# The State of the Universe

70th Stephen Hawking Birthday Symposium, 5-8 January 2012
Centre for Theoretical Cosmology, DAMTP, University of Cambridge, UK
Scientific Conference at Centre of Mathematical Sciences

Frank Wilczek, MIT, "Time Crystals"

I am always inspired to come to Cambridge. I first met Stephen at a Nuffield Conference here 30 years ago.

Symmetry and its spontaneous breaking are at the heart of our modern understanding. Consider the possibility of breaking time symmet[ry]. But for lowest energy, nothing moves in Hamilton's equation. Not in Lagrangi[an] $E = \frac{3}{4}\dot{\phi}^4 - \frac{K}{2}\dot{\phi}^2$, $p = \dot{\phi}^3 - K\dot{\phi}$ has a cusp. Add potential: $E = \frac{3}{4}\dot{\phi}^4 - \frac{K}{2}\dot{\phi}^2 + V(\phi)$. If we choose initial conditions to minimize $E$ and $V$, problem that equat[ions] of motion break down at $\dot{\phi}^2 = \frac{K}{3}$. Safe for $E \geq -\frac{1}{12}K + V_{min}$

$E = \frac{\partial L}{\partial \dot{\phi}_j}\dot{\phi}_j - L$, $\frac{\partial E}{\partial \dot{\phi}_k} = \frac{\partial^2 L}{\partial \dot{\phi}_j \partial \dot{\phi}_k}\dot{\phi}_j \ldots$ $\left(\frac{\partial L}{\partial \dot{\phi}_k}\right)^{\cdot} = \frac{\partial^2 L}{\partial \dot{\phi}_j \partial \dot{\phi}_k}\ddot{\phi}_j + \ldots$ (EOM).

So if $\frac{\partial E}{\partial \dot{\phi}_k} = 0$ has a non-trivial solution $\dot{\phi}^0_j$, then EOM does not constrain a[...]

If we have motion at minimum energy, must be whole curve of sol[utions]. Fine-tuned models, and natural, associated with broken symmetry.

$L = f\dot{\phi}^4 + g\dot{\phi}^2 + h$ for functions $f, g, h$. If $\cdots = \cdots$, $\dot{\phi}_0^2 = -\frac{g}{6f}$.

Semi-classical quantization can avoid the singular zone, even with (small) pote[ntial]. Can also get natural models by having trajectories move along the orbit of a spontaneously broken symmetry. Special cases: "Universal" Q ball, current carrying ground state

Quantum mechanically, one has a similar (apparent) "no-go" $\langle 0|\dot{O}|0\rangle = 0$. Also appears perilously close to perpetual motion. Also, by what criterion do we pick out ground states that break $\tau$. Yet in the right circumstances, supercurrents will flow forever in the ground state. Time-translation symmetry $\tau$ is not broken.

$L = \frac{1}{2}\dot{\phi}^2 + \alpha\dot{\phi}$, $H = \frac{1}{2}(\pi_\phi - \alpha)^2$, $E_l = \frac{1}{2}(l-\alpha)^2$, $\langle l|\dot{\phi}|l\rangle = l - \alpha$

Particle on a ring threaded by a magnetic field. Thus if $\alpha$ is not an integer, the ground state has $\langle 0|\dot{\phi}|0\rangle \neq 0$. Time reversal $T$ is generally broken, but not time translation $\tau$.

Consider complex order value with real $\langle 0|\Phi|0\rangle = v \neq 0$. Energetically degenerate orthogonal** states with arbitrary phase $\langle 0|\Phi_\theta|0\rangle = ve^{i\theta}$.

Then $\Omega = \int^{2\pi} \psi_\sigma \, d\sigma$ gives $\langle 0 | \Omega | 0 \rangle = 0$. No finite product of local operators connects different $\sigma$ states. Thus the physical criterion that identifies useful "ground states" is not just energy but observability.

Take an infinite number $(N \to \infty)$ of copies of our ring particles, with an identical attractive $\delta$-function interaction between pairs. Consider first $\alpha = 0$. We take a product wave-function ansatz, and saturate with it ("mean field" approximation). Arrive at a non-linear Schrödinger equation, which have ~~moving~~ moving lump solutions. From Faraday's law, we can expect that turning on $\alpha$, the flux, torques the lumps. $i\frac{\partial \psi_l}{\partial t} = \frac{1}{2}(-i\partial_\phi - \alpha)^2 \psi_l - \lambda|\psi_l|^2 \psi_l$ with $\psi_l(\phi, t) = e^{-il\phi}\, \Phi(\phi + (l+\alpha)t, t)$, $i\frac{\partial \psi_l}{\partial t} = \frac{1}{2}(-i\partial_\phi)^2 \Phi - \lambda|\psi|^2 \cdots$

Minimum energy is for minimum $|l+\alpha|$. If nonzero, breaks $\tau$

Were we *literally* talking about charged particles, one would have radiation, going to $\Omega$ state.

We've been discussing the spontaneous emergence of clocks. Even if the world starts simple, it can break up into systems.

Quantum computers could dodge the heat death for a long time.

In imaginary time, $i$Time period $\beta = 1/T$, weighted by $e^{-S}$

Thus the partition function for $d$-dim system given by ... $dH$ ...

Crystal structure will fit without distortion iff $i$Time lattice period divides $\beta = 1/T$ evenly. Thus a signature is some approximately periodic behavior in $1/T$, especially for small $T$.

Many questions and possibilities:

- Directed 0-point motion, more generally?
- Concrete, practical realizations?
- $T \neq 0$ in real time?
- Classification of space-time and space-$i$Time crystals.
- All the usual SSB questions: excitation spectrum, phase transitions

[James Hartle: If you break the symmetries of the full Poincaré group, is there a connection with gravity?] Probably. Einstein-Hilbert Lagrangian looks like a $\sigma$-model, with $G_{\mu\nu}$ an expectation value of something. I strongly suspect gravity is a spontaneous symmetry breaking of a topological theory.

Renata Kallosh, Stanford University, "N=8 Supergravity"

Based on RK, 1103.

"Is the End in Sight for Theoretical Physics: An Inaugural Lecture" ... At the moment the N=8 SUGRA is the only candidate... possibility of some... that the theory is no good"

1981: 3-loop counterterms found

2007: Coefficient vanishes

Old Wisdom, and why did we quit in 1981

Construct invariant candidate counterterms RK; Howe, Lindstrom, 1981

Start at 8-loop level. $S^8 \sim k^{14} \int d^4x\, d^{32}\theta\, \mathrm{Ber}\,E\; T_{ijkl}(x,\theta)\, T^{ijkl}(x,\theta)\, T\, T$ ...

New era, new people, new computers, new rules: never use N=8 sugra rules, build it from N=4 Super-Yang-Mills.

No UV divergences at 3- and 4 loops. Explanation? Light-cone superspace counterterms are not available at any loop order (prediction of UV finiteness): RK 2008, 2009. Still the case in 2011

If we trust continuous global $E_{7(7)}$ at the 3-loop quantum level what is the prediction at higher loops? $E_{7(7)}$ revisited: RK, 2011.

Noether-Gaillard-Zumino current conservation is inconsistent with the $E_{7(7)}$ invariance. It requires that the action transforms in a particular way, <u>instead of being invariant</u>. $F = dA$, $G = 2\frac{\delta S}{\delta F}$. $\delta\begin{pmatrix}F\\G\end{pmatrix} = \begin{pmatrix}A & B\\C & D\end{pmatrix}\begin{pmatrix}F\\G\end{pmatrix}$

$\mathcal{L} = \frac{1}{4}(\tilde{F}CF + \tilde{G}BG)$. $\partial^\mu \tilde{F}_{\mu\nu} = 0$, $\partial^\mu \tilde{G}_{\mu\nu} = 0$: Duality symmetry rotates..

$\mathcal{L}_{Max} = -\frac{1}{4}F^2 \Rightarrow G = \tilde{F}$, $\tilde{G} = -F \Rightarrow \tilde{F}F + \tilde{G}G = 0$.

$\mathcal{L}_{eff} = -\frac{1}{4}F^2 + \frac{1}{32}g^2((F^2)^2 + (\tilde{F}F)^2) \to G_{eff} = \tilde{F}(1 - \frac{1}{4}g^2F^2) + \frac{1}{4}g^2 F(\tilde{F}F)$.

$F\tilde{F} + \tilde{G}_{eff}G_{eff} = O(g^4) \neq 0$. To preserve the U(1) NGZ current conservation one needs all powers of F, Born-Infeld.

Given some quantum generated duality-invariant terms in the effective action of some duality-preserving theory, is it possible to add higher-order terms...?

$I(T^-, T^{+*}, g) = \frac{6}{g^2}\left(1 - {}_3F_2\left(-\frac{1}{2}, -\frac{1}{4}, \frac{1}{4}; \frac{1}{3}, \frac{2}{3}; -\frac{1}{27}g^4(T^+)^2(T^-)^2\right)\right)$,

$T^+_{\mu\nu} = \frac{1}{16}g^2 T^{+*}_{\mu\nu}(T^-)^2\, {}_3F_2\left(\frac{1}{2}, \frac{3}{4}, \frac{5}{4}; \frac{4}{3}, \frac{5}{3}; -\frac{1}{27}g^4(T^{+*})^2(T^-)^2\right)$.

New U(1) duality invariant models, unknown before, 1112.0332

$I^{(1)}_A(T) = \frac{\Delta}{2^3} t^{(8)}_{\mu_1\nu_1\mu_2\nu_2\mu_3\nu_3\mu_4\nu_4}\, \partial_\alpha T^{*+\mu_1\nu_1}\, \partial^\alpha T^{-\mu_2\nu_2}\, \partial_\beta T^{*+\mu_3\nu_3}\, \partial^\beta T^{-\mu_4\nu_4}$

$S(F) = \frac{1}{4\lambda}\int d^4x\, d\lambda\, F\tilde{G}(\lambda)$. U(1) duality and N=2 susy: Broedel, Carrasco, Ferrara, RK, Roiban. All you need to do is to teach your computer to differentiate wrt Grassmann variables.

Lesson for N=8 supergravity: to be able to ... construct B:
New class of $E_{7(7)}$ ... Manifest $E_{7(7)}$ and local SU(8)?
Need to construct $I(\tau, \bar{\tau})$ for $T^{+}_{AB} \neq 0$.
The manifest $E_{7(7)}$ invariants are rare!
$J = F^{ij} G_{jk} F^{kl} G_{li} - \frac{1}{4} F^{ij} G_{ij} F^{kl} G_{kl} + \frac{1}{96} \epsilon^{ijklmnpq} G_{ij} G_{kl} G_{mn} G_{pq}$
$+ \frac{1}{96} \epsilon_{ijklmnpq} F^{ij} F^{kl} F^{mn} F^{pq}$ found by Cartan, later by Cremmer-Julia 8?
Groups of type E7 are groups of linear transformations ...
New $E_{7(7)}$ invariants: $J_{(8)} \equiv J_{[\mu_1 \nu_1][\mu_2 \nu_2][\mu_3 \nu_3][\mu_4 \nu_4]} = g(x ...$
When $E_{7(7)}$ is reduced to U(1), our new invariants describe the open string co
N = 4 YM → N = 8. Twistors → Octonions
N=8 Born-Infeld. Classical N=8 theory has one gra
coupling and is strictly quadratic in vector fields F.
If we find no consistent N=8 BI-type sugra. In such case an
unbroken $E_{7(7)}$ would predict UV finiteness.
If we can ~~stractru~~ construct it, we have to see
S. W. Hawking, an optimist! "These will be the outstandin
problems for theoretical physicists in the next twenty years or so"
on N=8 supergravity in 1980.
Happy Birthday! Stephen

Juan Maldacena, IAS, Princeton, "The Constraining Power of Higher Spin Symmetry"

Elementary particles can have spin, even massless particles. Interactions of massless particles with spin are very highly constrained. Spin 1 = Yang Mills. Spin 2 = Gravity. Spin $s > 2$ (higher spin) = No interacting theory in asymptotically flat space. Coleman-Mandula theorem. Can in $AdS_4 \to$ dual to $CFT_3$ d. Conjectured dual: N fields in singlet sect.

What are the CFT's with higher spin symmetry? Free fields. This is the analog of the CM theorem for CFT's, which do not have an S-matrix. We will also constrain theories with symmetries slightly broken.

Any boundary CFT that has a weak coupling limit has a higher spin conserved currents at zero coupling. In examples, such as N=4 SYM, this is smoothly connected to the phase where the fields are massive.

Vasiliev theory + b.c.'s that break the higher spin symmetry → Dual to the large N Wilson Fischer fixed point.

Assumptions: We have a CFT obeying all the usual assumptions. Locality, OPE, existence of the stress tensor with a finite 2-pt. function, unitary, d=3, higher spins.

Conclusions: There is $\infty$ number of higher spins, from OPE of stress tensor.

Unitarity bounds. Scalar operator has dimension $\Delta \geq \frac{1}{2}$ (d=3). Argument: Unitarity = reflection positivity in Euclidean space. $\langle O O \rangle = \frac{1}{r^{2\Delta}}$ $\langle \nabla^2 O \nabla^2 O \rangle = (\nabla^2)^2 \frac{1}{r^{2\Delta}} = (2\Delta)(2\Delta - 1)(\text{positive}) \frac{1}{r^{2\Delta+4}}$. Positivity $\Rightarrow \Delta > 1/2$. $\Delta = 1/2$ is free field.

For operators with spin $s$, bound is Twist $= \Delta - s \geq 1$. If Twist $= 1$, then the current is conserved. $\partial_{\mu_1} j_{\mu_1 \cdots \mu_s} = 0$, $Q_{\mu_2 \cdots \mu_s} = \int_{\text{space}} j_{0 \mu_2 \cdots \mu_s}$. Consider $j_s \equiv j_{- - \cdots -}$, $Q_s \equiv \int_{x^+ = \text{const}} dx^- dy\, j_s$, minus components only.

Removing operators in the twist gap. Scalars with $1 > \Delta \geq 1/2$. Assume we have a current of spin 4. $[Q_4, \Phi] = \partial^3 \Phi$, $\partial \equiv \partial_-$. $Q_s$ has spin $s-1$, Twist $= 0$. Charge conservation on the four point function implies (in Fourier space) $\sum^4 k_i^3 = 0$. Of course also $\sum^4 k_i = 0$, so momenta are equal in pairs ⇒ 4-pt function factorizes into 2-pt: $\langle 4pt \rangle = \langle \Phi(1) \Phi(2) \rangle \langle \Phi(3) \Phi(4) \rangle$ + perm. Now look at the OPE as $1 \to 2$ and we see that the stress tensor can appear only if $\Delta = 1/2$. So we have a free field! Same reason we get Coleman-Mandula theorem for S-matrix.

Now go to Twist on. $[Q_s, j_{s'}] = \sum_{s''} C_{s,s',s''} \partial^{s+s'-s''-1} j_{s''}$.
Sum over $s''$ has finite range. Some $c$'s are nonzero, e.g. $[Q_s, j_2] = \partial j_s + \cdots$ for stress tensor

Three point function of three conserved currents are constrained to only three possible structures: $\langle j_{s_1} j_{s_2} j_{s_3}\rangle = A\langle j_{s_1} j_{s_2} j_{s_3}\rangle_{\text{bosons}} + B\langle j_{s_1} j_{s_2} j_{s_3}\rangle_{\text{fermion}} + C\langle j_{s_1} j_{s_2} j_{s_3}\rangle_{\text{odd}}$. If we know the 3-point function for the stress tensor, we can get it for the spin fields.

$j_2 j_{2t} = \lim_{y_{12}\to 0} y_{12} \lim_{x^+_{12}\to 0} j_2(\vec{x}_1) j_2(\vec{x}_2) = \partial_1^2 \partial_2^2 B(x_1, x_2)$. This defines a quasi-~~local~~ bilocal operator $B$

We get an infinite number of even spin currents (since $2s-2>2$ for $s$: $[Q_s, B(x_1, x_2)] = (\partial_1^{s-1} + \partial_2^{s-1}) B(x_1, x_2)$. $Q_s$ charge conservation identities imply that $\langle B(x_1, x_2) \ldots B(x_{2n-1}, x_{2n})\rangle$ factorize into 2-pt functions o free fields. Same as correlators of $B(x_1, x_2) = \sum_{i=1}^{N} :\Phi_i(x_1)\Phi_i(x_2):$

Conclusion: Proved the Klebanov-Polyakov conjecture.

Generations: higher dimensions

Almost conserved higher spin currents. There are interesting theories where the currents are conserved up to $1/N$ correction

$\langle 3pt\rangle = \frac{1}{\sqrt{\tilde{N}}}\left[\frac{1}{1+\alpha^2}(\text{Fermions}) + \frac{\alpha}{1+\alpha^2}(\text{Odd}) + \frac{\alpha^2}{1+\alpha^2}(\text{Bosons})\right]$, $\alpha = \lambda + c_1\lambda^3 + \cdots = h(\lambda)$

$\tilde{N} = N f(\lambda)$. We do not know the relation to the microscopic parameters $N, k$.

As $\alpha \to \infty$ we can rescale to get ...

Discussion: Can be extended to the boson case. It could be extended to higher point functions but it looks a bit complicated.

Future: ...

Conclusion: Proved the analog of Coleman Mandula for CFT

Proved conserved higher spins $\Rightarrow$ free field theory.

Is there any other principle beyond locality and consistency ~~and~~ in constraining the quantum state of the universe?

[Andy Strominger: Could the bulk Vasiliev theory have weird internal degrees of freedom not captured by the boundary CFT?]

All the bulk gravity observables we know how to construct in asymptotically AdS are boundary observables.

Gary Gibbons, DAMTP, University of Cambridge, "Conformal Symmetry and Scaling Limits of Black Holes"

Stephen's discovery of radiation by black holes led to a lot of ideas for gravity. Renata talked about supergravity.

M. Cvetic and G.W. Gibbons, 1201.0601 on Cvetic-Finn papers

Known since early 1980's that BHs in ungauged sugra have many remarkable properties and that in particular one may use solution generating techniques based on symmetries of the EOM known as S and T.

N=2 SUGRA coupled to three vector multiplets.

$\mathcal{L}_6 = R * 1 + \cdots$ for 6d theory that reduces to 4d.

$ds_4^2 = -\Delta_0^{-1/2} G (dt + A)^2 + \Delta_0^{1/2} \left(\frac{dr^2}{X} + d\theta^2 + \frac{X}{G} \sin^2\theta \, d\phi^2\right)$, $X = r^2 - 2mr + a^2$, $G = r^2 - 2mr + a^2\cos^2\theta$

Massless scalar wave equation separates in these backgrounds.

Page, Frolov, Kubiznak, Houri, ... give partial explanations.

Unfortunately, the resulting radial equations have two regular singular points and a confluent singularity at infinity familiar from elementary QM.

Often one mutilates the singularity at $\infty$ to get hypergeometric equation, which is widely believed to have something to do with "conformal symmetry".

Bi-invariant metric on $SL(2,\mathbb{R})$ coincides with standard metric on $AdS_3$ which is thus $SL_2(R, ..) \times SL(L, ..) = SO(2,2)$ invariant.

In 1997 Cvetic and Larsen found that if they mutilated Cvetic-Youm to maintain separability but give hypergeometric equations, massless wave eq. is $\check{R}_i \check{R}_i = \check{L}_i \check{L}_i = l(l+1) = -J_i J_i$ where $\check{R}_i$ and $\check{L}_i$ are radial operators with the Lie algebra of $SL(2,\mathbb{R}) \times SL(2,\mathbb{R})$

Last summer Cvetic and Larsen found the subtracted metrics may be lifted to $AdS_3 \times 4S^2$ in 5 dimensions, the 4 meaning 4x metric. They thus solve the equations of simple supergravity.

Recently we have obtained the subtracted metrics as a suitable scaling limit of the unsubtracted metrics, and as a suitable 'infinite boost' Harrison transformation of the unsubtracted metric. BHs in asymptotical conical box, confining in the way AdS is confining.

In the static case, wlog we take three equal charges and the 4th different

$\tilde{r} = r\epsilon$, $\tilde{t} = t\epsilon^{-1}$, $\tilde{m} = m\epsilon$, $2\tilde{m}\sinh^2\delta \equiv Q = 2m\epsilon^{-1/3}(\Pi_c^2 - \Pi_s^2)^{1/3}$, $\sinh^2\tilde{\delta}_0 = \frac{\Pi_s^2}{\Pi_c^2 - \Pi_s^2}$, $\epsilon \to$

Scalar field $\sim \ln r$, so energy density $\sim \frac{1}{r^3}$, not asymptotically flat.

$\mathcal{L}_3 = \sqrt{\gamma}\left(R(\gamma_{ij}) - 2\gamma^{ij}(\partial_i U \partial_j U - \partial_i \phi \partial_j \phi + \cdots\right) = \sqrt{\gamma}\left(R(\gamma_{ij} + \frac{1}{1+a^2}\gamma^{ij}\, \mathrm{Tr}(\partial_i P \partial_j P^{-1})\right)$

$ds^2 \approx (-\frac{\bar{r}}{\bar{r}_0})^6 dt^2 + 16 d\bar{r}^2 + \bar{r}^2(d\theta^2 + \sin^2\theta^2 d\phi^2)$, asymptotically conical, AC, with deficit angle $\frac{\pi}{2}$. Since $|g_{tt}|$ increases monotonically without bound in the radial directions our BHs are confined within an AC box. Lifshitz scaling $z = -\frac{1}{2}$. Ther metrics are asymptotically conical because the energy density falls off as $\frac{1}{\bar{r}^2}$ and $|g_{tt}| \to \infty$.

Only 2 KVs, though action of $(SL(2,\mathbb{R}) \times SL(2,\mathbb{R}))/Z_2 \times SO(3)$. The explanation is that we have quotient of $AdS_3 \times 4S^2$, whose isom group is generated by the 6 vector fields $R_i, L_i, J_i$ by a 1-parameter subgroup of $(SL(2,\mathbb{R}) \times SL(2,\mathbb{R}))/Z_2 \times SO(3)$. Only 5d KV's that commute with ~~$L_i$ and $R_i$~~ $K = \frac{\partial}{\partial \alpha}$ remain KV's in the 4d metric.

$\langle \phi_1 | \phi_2 \rangle = \int (\bar{\phi}_1 \phi_2) d\rho\, dt\, d\phi \sin\theta d\theta$ is neither the spacetime $L^2$ norm nor the Klein Gordon inner product.

$AdS_3 \times 4S^2 \to AdS_3 \times S^3$ when $3+1 \to 4+1$, and the Hopf fibration comes into play.

May provide useful analytic approximations for the near horizon geometry of non-extreme astrophysical BHs.

Future: thermo and the notion of mass for AC metrics: Relation of algebra to QFT: nature of inner product.

David Spergel, Princeton University, "The State of the Universe: 380,000 Years After the Big Bang"

I want to mention Stephen's earliest imprint on the universe. Somehow he managed to etch himself into the microwave sky: SH

The universe is simple. 5 numbers: density of atoms, age, density of matter, amplitude of fluctuations, spectrum of fluctuations.

I'll focus on WMAP and the Atacama Cosmology Telescope (ACT) at high resolution to see universe through backscatter.

Recombination at 3000 K or $\frac{1}{40}$ eV ≪ 13 eV since so many more photons than electrons. It was a very fast transition.

Age 13.7 Gyr, 4% atoms, 23% matter, 73% dark energy, scale invariant fluctuations. The fluctuations at the moment are Gaussian, random phase. No spatial variations in the properties of the fluctuations. No evidence for nontrivial topology.

National Center for Supercomputer Applications ~~gave~~ computer models that fit observed large-scale structure.

The pieces seem to fit... Supernovae distance (Nobel Prize 2011), Hubble constant, age of universe, cluster properties, cosmic abundances, gravitational lensing, absorption line statistics. Lithium still out of line; don't know whether from early universe or destruction in stars.

SZ Clusters ~0.02° from ACT ~~at~~ 5300 m dry plateau.

ACT vs South Pole Telescope (SPT) give remarkably similar images.

ΛCDM model is looking good to $l = 3000$! Expect error bars about 5 times smaller for Planck.

There is an intriguing hint that the amplitudes of the peak are a bit smaller than ΛCDM, perhaps due to one extra neutrino, but only at 2σ, a bit better than the evidence for the Higgs, but we are not announcing a discovery.

Clusters cast shadows at 145 MHz. SZ signal is redshift independent. Gives ~~the g~~ a probe of the growth rate of structure and detect non-Gaussianities. Challenge is to convert observations to mass and avoid Eddington bias.

"El Gordo" is we think the largest collection of mass in the observable universe. A remarkable Bullet-like cluster at $z \sim 0.87$.

$M \sim 8 \times 10^{14} M_\odot$. It looks like two clusters merging.

2.7 arcmin deviation of CMB, rms. Lensing deflects photons and produces non-Gaussian signal that we have detected and found consistent with ΛCDM. Just the beginning of CMB lensing studies. New tool for dark energy studies. Cross-correlation with large-scale

Next step: ACT POL to measure polarization and polarization imaging. Scalar fluctuations generate E-modes. Lensing convert these to B-modes.

For $l \gtrsim 2000$, IR sources of dusty galaxies dominate. But they are only 1-2% polarized, whereas CMB is ~17% polarized, Martin Rees' Ph.D. thesis. Full sky polarization survey can get to $l = 5000$, which would have 6 times the number of modes as Planck

Conclusions: The Universe is strange, but simple. CMB Lensing: The fun is only just starting! Planck, ACTPOL,

First cosmology announcement [Planck] in Jan. 2013. I don't expect grav. wave evidence until 2014

Daniel Eisenstein, Harvard, "Dark Energy and Cosmic Sound"

In 1998, two groups argued from supernova data that the expansion rate of the universe is accelerating.

Baryon acoustic oscillations as a standard ruler. Before recombination, universe is ionized, photons provide enormous pressure and restoring force, and perturbations oscillate as acoustic w After recombination, universe is neutral, photons can travel freely, and density perturbations grow.

Each initial overdensity (in DM & gas) is an overpressure that launches a spherical wave at 57% speed of light. Galaxies preferentially form at 150 Mpc separation, which is where the wav stalls at recombination. This scale gives a sequence of harmonics, but there is only the one scale of how far the sound wave can travel. Depends on $\Omega_m h^2$ and $\Omega_b h^2$, measured to 1.7% (0.25% by Planck)

We can measure along and across the line of sight, $H(z)$ and $D_A(z)$

Redshift surveys are a popular way to measure the 3-dim clustering of matter. But there are complications. Nonlinearities push galaxies by 3-10 Mpc out of 150 Mpc. This broadens the peak, making it hard to measure the scale. N-body simulations show the acoustic peak to be stable - shifts of 0.3% at $z=0$, highly predictable.

The acoustic signature is created by physics at $z=1000$ when the perturbations are 1 in $10^4$. Linear perturbation theory is excelle 0.6% error in H, 0.1-0.2 [?] in $D(z)$.

The Sloan Digital Sky Survey yields a 4% distance erro $\Omega_m = (0.282 \pm 0.018)$, $H_0 = (68.6 \pm 2.2$ km/s/Mpc), both with small dependences o Combination with WMAP and SNe shows good consistency between the three data sets and between the two analyses. "Tensions" not statistically signif

Improving the acoustic peak. Most of the non-linear degradation is due to bulk flows. These are produced by the same large-scale structure that we are measuring by the BAO spectrum. Reconstruction improves the precision of the measurement of the acoustic peaks. Improves errors as if we had tripled the survey volume, sharpens error from 3.5% to 1.9% 1.5%

Could be a hint of another relativistic species, but for gullible theorists, no discovery.

SDSS-III Baryon Oscillation Spectroscopy Survey (BOSS) for 2008-2014, definitive study of BAO over 10,000 deg² (1/4 the sky). 50,000 galaxies in the can.

See "Observational Probes of Cosmic Acceleration" by Weinberg, Mortonson, Eisenstein, Hirata, Riess, & Rozo, on the arXiv within a week.

[Andrei Linde: There is a preference among theorists for pure Λ, since value of Λ can be explained by anthropics, but for other potentials there is also the fine tuning of the slope.]

Maybe at the end of the conference we can poll the theorists to see whether there is the unanimity you claim.

Alan Guth, MIT, "Eternal Inflation and Its Implications"

Eternal inflation is a concept almost as old as inflation, but it has taken off with the multiverse, string landscape, and $\Lambda$.

http://ctp.lns.mit.edu/guth/VEAM memories -- recounts 1987 conference

1) Background: Inflation is a big success. 2) Why should I take EI seriously

1. Successes of inflation: 1) The universe is big -- ~$10^{90}$ particles
2) Hubble expansion. 3) Homogeneity and isotropy (need ~100c w/o inflation)
4) Flatness problem. 5) Why no magnetic monopoles? 6) Fluctuations.

2. Why should I take eternal inflation and the multiverse seriously? Our own pocket universe appears to have $\Lambda > 0$, so entering inflation. If our vacuum is stable, our universe will become eternal. If metastable, it has to have a decay rate $\lambda \sim H^4$ to prevent EI. Tunneling events in our own pocket will produce an infinite number.

Almost all models are eternal. Inflating false vacuum is metastable, but decay rate << expansion rate. Therefore the volume of false vacuum increases exponentially. Once inflation starts, it never stops. The inflating region never disappears.

Three strong winds blowing in the direction of the multiverse:
1) Theoretical cosmology (EI)
2) String theory: No unique vacuum. At least ~$10^{500}$ long-lived states
3) Observational cosmology: $\Lambda$. The most plausible known explanation for small $\Lambda$ is the anthropic one, using the multiverse. That is, the set of string theory vacua is expected to include many with $\Lambda$ as small as what we observe.

3. What does eternal inflation buy me?
1) Independence of initial conditions (This depends on the measure problem, but is true for many proposed measures, including all my favorites)
2) Possible explanation for small vacuum energy density
3) Avoidance of thermal equilibrium phase. Suppose reality can be described by some quantum system with a maximum possible entropy. Then the system will reach thermal equilibrium and undergo Poincare recurrences forever, and all microstates will occur and re-occur with equal probability. Life will continue to occur, but with overwhelming prob. the worlds they observe will look

nothing like ours. Boltzmann brains. In thermal equilibrium, probabilities are determined ONLY by state counting. Therefore I think we are not in a system of finite degrees of freedom. New ~~infinite~~ regions of phase space are constantly being explored. Classical phase space must be infinite, $\infty$ dim H.

d) Fine-tuning: Can Ham. evolution lead to fine tuning of parameters? No for finite phase space, but if available phase space is infinite, the answer is yes.

Larry Guth: $H = \tan^{-1}(-pq)$, $\dot{p} = \frac{p}{p^2q^2+1}$, $\dot{q} = -\frac{q}{p^2q^2+1}$.

For any normalizable initial prob. dist., for any $\epsilon > 0$, and for any $\delta > 0$, there exists a $T$ such that $t > T \Rightarrow P(|q| < \delta) > 1 - \epsilon$. Waiting is of course the key here. If phase space were finite, this wouldn't work for a uniform probability distribution.

e) Explanation of the arrow of time with infinite phase space

In an $\infty$ phase space, achieving an arrow of time from essentially arbitrary initial conditions is not a problem. Consider a gas of particles. Let the system evolve for a long time. The momentum distribution will remain approximately fixed, but the position distribution will grow.

Key point: there is no maximum entropy! Whatever the initial entropy was, it was small compared to the maximum. See Bousso 1112.3341

4. What does eternal inflation cost me? – a problem in defining probabilities. Anything that can happen will happen – an infinite number of times. To separate the probable from the improbable we need to compare infinities. A measure is a prescription for calculating probabilities. B

Is the measure problem a show-stopper. I don't think so. The description of the multiverse itself is not a problem. Measure problem arises only when we try to count events in the multiverse. The fact that we don't understand the measure problem is no reason

inflation is big success. Essentially all inflationary models lead to E.I. String landscape ∧ Buys independence of initial conditions, explains ∧ avoidance of thermal equilibrium phase, with $\infty$ phase space, fine tuning can be achieved.

Luis Lehner, Perimeter Institute/University of Guelph, Ontario,
"Black Holes & Membranes: Observables & Surprises?"

Within this decade: detection of, and observations with, grav waves examine our universe via all fundamental interactions - holographic ..

2 fronts for BHs and 'membranes'

Membrane paradigm (80s): [Damour, Thorne, McDonnald, Price] Dynamics of a "stretched horizon" is governed by the Navier-Stokes equations

Grav waves & detectors. BBH waveforms are under control in the process, interesting physics dug out (e.g., energetics, recoils, etc.

Radiation: convert ~ 5% of total initial mass and ang. mom. Asymmetric scenarios give rise to 'kicks', which can be as large as 3-7 $10^3$ km/s $E_{GW} \sim 10^{58}$ ergs $(M_T/10^6 M_{sun})$ in $\sim 100(M_T/10^6 M_{sun})$ second. $L_{GW} \sim 10^{23} L_{sun}$ A few 100s km/s kick more typical, $10^{53}$ ergs$(M_T/10^6 M_{sun}) \gg$ SN mechanical energy. Just a fraction of this into surrounding region can have observable effects.

Black holes in magnetic field and plasma emit EM waves not only from rotation (Blandford-Znajek) but also from motion. $L \sim (1[a/0.6]^2 + 100v^2) 10^{43}$ ergs $[M_8 B_4]^2$. EM flux acts as a "spacetime tracer". Can exploit 'standard' BBH result.

Stability of higher dimensional BHs [LL, F. Pretorius PRL 2010]. If cosmic censorship holds, ... For $D>4$, no Kerr bound, rich geometries AdS/CFT corresponds superconductivity etc. to higher-D BHs.

Gregory-Laflamme 93: Black string perturbations admit exponential growth. End state of the instability? Conjecture: BS bifurcates. Horowitz and Maeda proved BS cannot shrink to 0 area in finite affine parameter. Conjectured end-state would be a new static non-uniform solution.

We found string thin and more generations of bubbles occur. No tension with Horowitz-Maeda result. $\lambda \sim m e^{40}$ (at $t \sim 165m$ already) AH behavior. Hausdorff dimension? $L(t) = (t_c - t)^{1-d}$, $d \sim 1.05$ (simple fractal) At late times the horizon certainly looks like it can be described by a sequence of spherical black holes joined by strings. Generation 1 at $t_1/M = 118.1 \pm 0.5$, 2 at $203.1 \pm 0.5$, 3 at $223 \pm 2$, 4 at $\approx 227$. If $\Delta T \sim T_0 + \sum^{\infty} T_i$ $X^i = T_0 + \frac{T_1}{1-X}$, string should shrink to 0 at $t/M \sim 231$. Cosmic censorship is violated generically in higher dims. Fluid analogue: nothing drastic takes place at pinch off.

Bruce Allen, Albert Einstein Institute, Hannover, Germany, and University of Wisconsin-Milwaukee
The Einstein@Home Search for Gravitational Waves and Neutron Stars"

Einstein@Home: a volunteer supercomputer. Three distinct searches, in grav. wave data, radio data, and gamma ray data. One downloads the program and looks for signals among the data. More than 300,000 people have contributed, 600 teraflops. $10 million would pay electrical costs. This can be used for problems with high CPU time per data.

Neutron stars were discovered 5 miles SW of here, 50 m x 500 m ar built by Jocelyn Bell and Antony Hewish in 1967. Baade and Zwicky predicte neutron stars in 1934, two years after the discovery of the neutron in 19 Hewish and Bell had seen a lighthouse effect from neutron stars.

About 2000 known, ~10% binaries. Surface gravity 2GM/R ~ 1/3. High precision clocks. Precise tests of GR. Potential sources of grav. waves. Constrain EOS of nuclear matter. Galactic grav. wave detector.

Earlier pulsar detections: USAF Sergeant Charles Schisler Ballistic Early Warning System in Alaska, see Nature, 448, 974 (2007) of Crab.

PSR1913+16 is spiralling in from grav. wave emission (Hulse & Taylo Best tests: double pulsar. The interest in detecting them is that they would be a probe of strong field ~~results~~ effects. LIGO, VIRGO, and GEO proje are expected to make first direct detection in 4-5 years. So far, instruments are noise-dominated - low SNR regime. Can measure $\Delta L/L = 10^{-21}$, $\Delta L = 10^{-3}$ nuclear size.

Potential grav. wave sources: Binary inspiral of NS and/or BH (detections 2015-16), cosmological stochastic background (not by LIGO), burst sources (SN, string cusps, the unknown), spinning neutron stars. Mountain or pimple on NS or wobble or oscillations or accretion would give GW at twice orbital frequency.

$h < 2.3\times10^{-26}$ for J1603 ..., $\epsilon < 7\times10^{-8}$ on NS ... (mountains < mm

Regular pattern of emission gets modulated by earth's rotation and revolution in a way that depends on the direction in the sky, so it is a serious data-analysis problem.

We applied similar methods to search for radiopulsars, binary orbits with periods > 11 minutes. 8 new radio pulsars were found in Arecibo data, and 10 in another. 1st was 40.8 Hz isolated millisecond pulsar with broad pulse

Second: J1952+2630, 48 Hz, binary with 9.4 hr period, companion >0.94 $M_\odot$
One discoverer was former radio astronomer in Moscow who solves the traveling salesman problem for a trucking firm.

Gamma-ray pulsars: "Blind" searches of Fermi (2008 launch) found 24 in 1st year, 2 in 2nd, 0 in 3rd. New "Hannover Group" analysis: 13
Challenge: 8000 photons in 3 years, one in $10^5$ revolutions. 1st 9 published

Einstein@Home summary: 0 grav. wave signals so far, but methods and data are improving. 20 pulsars.

http://einstein.phys.uwm.edu/ Sign up your computer.

Hermann Nicolai, Albert Einstein Institute, Golm,
"Consistent Kaluza Klein Universes from Maximal Supergravity"
Kaluza-Klein-Consistency and Gary's Hat (Gary Gibbons).
Cambridge-Mitchell-Texas Conference, 20-26 August 2006.

The landscape of $N=8$ supergravity. 70 scalars = local coordi[nates] on $E_{7(7)}/SU(8)$ [Cremmer, Julia (1979)]. $\mathcal{V}(x) = \begin{pmatrix} u_{ij}{}^{IJ} & v_{ij IJ} \\ v^{ij IJ} & u^{ij}{}_{IJ} \end{pmatrix} \in 56$ of $E_7$. The potential of $SO(8)$ gauged $N=8$ supergravity is $P(\mathcal{V}) = g^2\left(-\frac{3}{4}|A_1{}^{ij}|^2 + \frac{1}{24}|A_{2i}{}^{jkl}|^2\right)$ → non-polynomial function on coset space $E_{7(7)}/SU(8)$ which is unbounded from below (and above). $A_1{}^{ij}$ and $A_{2i}{}^{jkl}$ from T tensor (in 912 rep of $E_7$). Stationary points with $SU(3) \subset G_2 \subset SO(8)$ found by N. P. Warner, PL 128B (1983) 169 and Ph.D. thesis.

A strange coincidence? $SO(8) \to SU(3) \times U(1)$ breaking and "family color locking." Supergravity and Standard Model assignments agree if spurion charge is chosen as $q = \frac{1}{6}$ [Gell-Mann]

T. Fishbacher, "The encyclopedic reference of critical points for $SO(8)$ gauged $N=8$ supergravity," 1109.1424. Among 160 stationary points, only one breaks supersymmetry but is stable (obeys Freedman-Breitenlohner bound).

Consistent KK reductions and maximal supergravity. Stationary points ≅ warped products $AdS_4 \times M^7$, $ds_{11}^2 = \Delta^{-1} ds^2_{AdS_4} + ds^2_{M^7}$, $F = f\,\Delta^{-2}\,\mathrm{vol}_{AdS_4} + \frac{1}{4!} F_{abcd}\, e^a \wedge e^b \wedge e^c \wedge e^d$ ⇒ a rich variety of new solutions for maximal supergravity via consistent embeddings? [Cf. Gibbons at this conf.] Need: Lift formulas for metric and p-form fields! Done for $AdS_4 \times S^7$, $AdS_7 \times S^4$, but no complete proof as yet for $AdS_5 \times S^5$

Metric lift formula for $SUGRA_{11}$. 'Generalized geometry' ≡ re-write $D=11$ theory in terms of $D=4$ fields and symmetries (from 4+7 split). In particular: define new ('generalized') vielbein $e^m_{AB}(x,y) = i\Delta^{-1/2} e_a{}^m (\Phi^T \Gamma^a \Phi)_{AB}$, $\Delta \equiv \det(\mathring{e}_a{}^m e_m{}^b)$ with 'alignment rotation' $\Phi(x,y) \in SU(8)$. Comparison with $D=4$ shows (with $K^{mIJ} = \mathring{e}_a{}^m \eta^I \Gamma^a \eta^J$) $e^m_{ij}(x,y) \equiv e^m_{AB}\eta_i^A \eta_j^B = K^{mIJ}(y)(u_{ij}{}^{IJ}(x) + v_{ij IJ}(x))$. $SU(8)$ invariant contraction yields lift formula
$$8\Delta^{-1} g^{mn}(x,y) = (K^{mIJ} K^{nKL})(y)(u_{ij}{}^{IJ} + v_{ij IJ})(u^{ij}{}_{KL} + v^{ij KL})(x).$$
This formula has passed numerous non-trivial tests and can also be generalized to IIB on $AdS_5 \times S_5$.

Generalized Vielbein Postulate (GVP):

Generalized vielbein is <u>covariantly constant</u>: $\hat{D}_m e^n_{AB} + \mathcal{B}_{m[A}{}^C e^n_{B]C} + \mathcal{A}_{mABCD}\, e^{nCD} = 0$ with respect to 'internal' $E_{7(7)}$ connection.

GVP from $D=4$. Replacing $e^m_{AB} \to e^m_{ij}$ ...

First show that the $\mathcal{U}_1$ and $\mathcal{U}_2$ tensors transform in $912 \subset 56$ and ... Get standard inhomogeneous solution.

The non-linear flux formulas. Idea: flux lift formulas by comparison $D=4$ vs. $D=11$. Complication: $SU(8)$ rotation $\Phi(x,y)$ is non-trivial and not generally known (or constructible) in closed form.

Outlook: Flux lift formulas only valid <u>on-shell</u> in general. Flux lift formulas have been tested analytically and numerically for several non-trivial stationary points. Rich potential landscape $\Rightarrow$ many new $D=11$ solutions from consistent embeddings.
Even if we are not yet sure about $N=8$ supergravity, similar ideas should be applied to other higher-dimensional theories.

Michael Green, DAMTP, University of Cambridge,
"Scattering Amplitudes in String and Field Theory"

Stephen's work has spearheaded a unification of Theoretical Physics within DAMTP that was not conceivable 40 years ago (GR + HEP + cosmology)

String theory is an extension of quantum field theory that reduc[es] to Einstein's theory of (super)gravity coupled to matter in the "low energ[y]" or "large distance". UV completion of QFT. Absence of UV divergen[ces]. Rich dependence on moduli. Deep mathematics.

Scattering in conventional perturbative field theory has UV divergences at coincidence of nodes in functional integral. String theory gives tori with no nodes and so no UV divergences.

(i) Maximally supersymmetric Yang-Mills theory is a limit of open string theory on D3-branes and dual to closed string theory in 5d

(ii) Maximally supersymmetric supergravity. Massless sector of closed string theory. Connections with maximal YM (open strings can form closed strings by joining endpoints).
But not from ... and probably not finite on its own.
Can be obtained from 11d supergravity by curling up extra dimension on $(d+1)$-torus. Defines theory in $D = 10 - d$ dimensions. The parameter of the torus and others give moduli. The continuous duality grou[p] $G(\mathbb{R})$ is unbroken. No dependence on moduli. BUT Presence of non-perturbative charged black holes and instantons is consistent with Dirac quantization lattice breaking continuous symmetry.

Quantum corrections: Higher derivative interactions may arise as counterterms in supergravity but arise at tree level in string theory.
$S \sim l_D^{2-D} \int d^D x \sqrt{-G^{(D)}} \left( R + l_D^6 R^4 + l_D^8 \partial^2 R^4 + l_D^{10} \partial^4 R^4 \right)$,
$l_D^{D-2} = g_D^2 \, l_s^{D-2}$, $l_s^2 = \alpha'$, $g_D$ is string coupling in $D$ dim (one of the moduli fo[r]
String perturbation theory has fixed $l_s$ and $g_D \to 0$ ($l_D \ll l_s$).
Supergravity pert. " has fixed $l_D$.
Supergravity limit of string theory: -decoupling string modes $l_s \to 0 \ni g_D$
String theory doesn't decouple from supergravity.

4-graviton scattering $A_L \sim \Delta^{B_L} R^4 \Lambda^{(D-2)L-6-2B_L}$, $\Delta$ = Mandelstam
$\Delta^{B_L} R^4$ means $\partial^{2B_L} R^4$. Results for $L = 1, 2, 3, 4$: $B_1 = 0$, $B_2 = 2$, $B_3 = 3$, $B_4 = 4$, proportional to $L$, the number of loops.

IF $B_L = L$ for all $L>1$, UV divergences should be absent for $D<4+\frac{6}{L}$
So $D=4$, $N=8$ supergravity would be UV finite to all orders.
BUT susy strongly suggest $B_L=4$ for $L\geq 4$ which implies log div. at $D=2+\frac{14}{L}$
Would give seven-loop divergence in $D=4$, $N=8$ supergravity.

Four-graviton scattering in closed string theory

Expansion in power series of $\sigma_2 = s^2+t^2+u^2$, $\sigma_3 = s^3+t^3+u^3 = 3stu$.
$T_D(s,t,u) = \sum_{p,q} \mathcal{E}^D_{(p,q)} \sigma_2^p \sigma_3^q$. $A^{tree}_{10} = e^{-2\phi} R^4 T^{tree}_{10}(s,t,u)$,
$T^{tree}_{10}$ by Veneziano formula
$T^{tree}_{10} = \frac{3}{\sigma_3} + 2\zeta(3)\alpha'^3 + \zeta(5)\alpha'^5\sigma_2 + \frac{2\zeta(3)^2}{3}\alpha'^6\sigma_3 + \frac{\zeta(7)}{2}\alpha'^7\sigma_2^2 + \ldots$

Beyond string tree level: 1 loop. Corresponding systematics of the low energy expansion.

What is nonperturbative completion? Duality-invariant effective action summarizes structure of amplitude.

Properties of the coefficients $\mathcal{E}^D_{(p,q)}$. $\Delta_\Omega \mathcal{E}^{(10)}_{(0,0)} = \frac{3}{4}\mathcal{E}^{(10)}_{(0,0)}$
$\Omega_2 = e^{-\phi} = \frac{1}{g_B}$. $\Omega = \Omega_1 + i\Omega_2$. $\Delta_\Omega = \Omega_2^2(\partial^2_{\Omega_2} + \partial^2_{\Omega_1})$. $E_s = \sum_{(m,n)\neq(0,0)} \frac{\Omega_2^s}{|m+n\Omega|^{2s}}$
$= \sum_{\gamma\in\Gamma_\infty\backslash SL(2,\mathbb{Z})} (\mathrm{Im}\,\gamma\Omega)^s$. Two power-behaved (perturbative) terms + series of exponentially suppressed (instantons).

In lower dimensions, $3\leq D<10$, higher-rank duality groups $G=E_{d+1}$
$E^G_{\beta;s} := \sum_{\gamma\in P_\beta(\mathbb{Z})\backslash G(\mathbb{Z})} \cdots$ Coefficients $E^{(E_{d+1})}_{\alpha_1;s}$ subtle and beautiful (connections with number theory). Remarkable simplifications for $s=3/2$, $s=5/2$ (for $R^4$, $\partial^4 R^4$)
Perturbative terms – zero Fourier modes. Instantons – non-zero Fourier modes
Many instantons in decompactification limit are warped black holes.

Maximal SUGRA has log $\Lambda$ UV divergences in "critical" dimensions $D=D_c$. $L=1, D_c=8$, $R^4\log\Lambda$; $L=2, D_c=7$, $\partial^4 R^4 \log\Lambda$. $D=4+\frac{6}{L}$
4-loop supergravity UV divergence in $D_c=\frac{11}{2}$

Whether or not there are perturbative UV divergences, supergravity does not decouple from string theory. $g_D\to 0$ gives $\infty$ towers of charged non-pert. BPS BH of zero mass or instantons of zero action, a catastrophe. Limit doesn't exist for string theory

Is there a 5-loop contribution to $\partial^8 R^4$?? If so, would lead to 7-loop UV divergence in $D=4$, $N=8$ supergravity (also suggested by certain superspace arguments).

Andrew Strominger, Harvard University, "Microscopic Realization of the dS/CFT Correspondence"

HAPPY BIRTHDAY STEPHEN

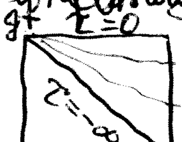
We've already heard that de Sitter space is important in cosmology and inflation, but it is also important in theoretical gravity. Gibbons-Hawking $S_{dS} = \frac{A_H}{4G_N\hbar}$. LHS is thermodynamics or statistical mechanics, and RHS is gravity divided by QM. We don't have the foggiest idea what this formula means.

The puzzle of de Sitter space is to give a calculation giving the $\frac{1}{4}$. In BH physics, we did get the $\frac{1}{4}$ from string theory. There we had some idea of ~~the number of~~ where the microstates a In dS they move around ~~[illegible]~~ with the observer world lines.

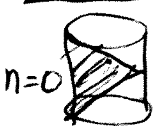
Other issues I won't answer:

1. What are the physical observables in dS? In Minkowski space we can say they are the S-matrix. In AdS they are correlators on the boundary.
2. Does eternal dS exist? I'll argue yes
3. Does dS have a finite number of states? (including perturbations
4. How does time start?
5. Is there a notion of unitarity in dS?

I made a proposal for addressing these questions at Steph 60th birthday, the dS/CFT correspondence, taking ideas from AdS/C The future boundary of dS resembles the boundary at spacelike infinity of AdS.




$ds^2 = l_{dS}^2 \left(\frac{-d\tau^2 + d\vec{x}^2}{\tau^2}\right)$. Isometry group $G = SO(4,1)$, which is the conformal group of the future boundary, $\mathcal{I}^+$. The metric is infinite there, but there is a conformal metric g




Compare this to the Poincare patch of AdS

$ds^2_{AdS} = l^2_{AdS}\left(\frac{-dt^2 + dx^2 + dy^2 + dz^2}{\eta^2}\right)$. Infinity again has only a conformal met

$\tau \to i\eta$, $z \to it$, $l_{dS} \to i l_{AdS}$ gives $ds^2_{dS} \to ds^2_{AdS}$.

Euclidean AdS has boundary conformal group $SO(4,1)$.

Minimalist version of dS/CFT: Push n-point functions to boundary and rescale in unique way, and this gives a CFT on the boundary. So there exists some CFT on the boundary.

$(\Box - m^2)\Phi = 0$ in dS for $\tau \to 0$ has $\Phi \sim \tau^{h_+} + \tau^{h_-}$, $h_\pm = \frac{3}{2} \pm \sqrt{\frac{9}{4} - m^2}$
AdS results differs just by a sign. Rescale by these factors to give the purported correlators of the CFT on the boundary.

Comments:

. $h_1$ in general is complex
. CFT not unitary, but this is not a problem.

One kind of fatal problem was that we didn't have examples. We didn't have examples of quantum gravity in de Sitter. String theory just does not like de Sitter. There is no known stable solutions of string theory that looks like de Sitter.

(Vasiliev gravity + dS) Vasiliev gravity loves de Sitter
Unlike string theory, Vasiliev gravity works beautifully

Juan talked about a duality between the free or critical O(N) $CFT_3$ and Vasiliev on $AdS_4$. It only works in 4 dimensions. We just used all that hard work and continued to de Sitter. We didn't do quite as little work as it sounds.

$N = \frac{1}{\Lambda G_N \pi}$. Taking AdS to dS takes $\Lambda$ to $-\Lambda$ and so $N \to -N$. We found a model with correlators like O(N) with negative N. $\phi^a$, $a = 1, \dots, N$, $\phi^a \partial^k \phi^a$. We took $\phi$ to be an anticommuting scalars and $\int \partial\phi^a \partial\phi^b \Omega_{ab}$, giving correlators $\sim -N$. Interactions of this Sp(N) model also replace N by $-N$. Vasiliev's theory has $N \to -N$ as AdS $\to$ dS. So the duality carries over.

This dS/CFT correspondence shows that the duality is internally mathematically consistent. However, the theory has an infinite tower of higher spin states.

[Gary Gibbons: There is a real difference between dS and AdS.

Raphael Bousso, University of California, Berkeley, "The State of the Multiverse: The String Landscape, the Cosmological Constant, and the Arrow of Time"

I'm going to talk mainly about a new paper on the arrow of time but first on an older paper on the cosmological constant.
Each known contribution is much larger than $10^{-121}$ (long known upper value). Then we learned $\Lambda \approx 0.4 \times 10^{-121} \neq 0$. Why is the energy so small, and why is it so close to matter density?

Many ways to make empty space. A 6-d manifold contains hundreds of topological cycles, say, 500. Suppose each can contain 0 to 9 units of flux. Then $10^{500}$ vacua. In each vacuum, $\Lambda$ receives many different large contributions. Most have $|\Lambda| > 10^{-121}$. But fluxes can deca[y] Metastability and bubble formation. Typical regions have $\Lambda \sim 1$ and adm[it] only structures of Planck size, with at most a few quantum states, according to the holographic principle. They do not contain observers.
$\Lambda \sim t_{gal}^{-2}$ Weinberg 1987; RB, Harnik, Kribs & Perez 2007; RB, ..., 20..

What we call big bang was actually the decay of our parent ~~universe~~ vacuum. Neighboring vacua in the string landscape have vastl[y] different $\Lambda$ ("Large Step Size") → The decay of our vacuum released much free energy. Theories with small steps don't work, a theor[y] that leads to a multiverse that has been falsified.

String theory is special.

Definition: The observed arrow of time is the entrop[y] $\Delta S \equiv S(t_f) - S(t_i)$ produced in our past light-cone since the time $t_i$. With $t_i = t_{BBN} = 3$ min, one finds $\Delta S = 10^{103 \pm 1}$, mostly from supermassive [black holes], $10^{86}$ from matter alone.

Whether or not a theory predicts an arrow of time depends primarily on its vacuum structure. In particular, low-entro[py] final conditions are not necessary nor sufficient.

The arrow of time in monovacuous theories. Consider a flat, open universe with $\Lambda < 0$ that begins with a big bang and radiation domination. It will end in a big crunch. Since $S(t_i) \geq 0$, $S(t_f) > 10^{103}$. Covariant entropy bound [RB 1999] $\Rightarrow S(t_f) \leq \Lambda^{-2}$, so need $|\Lambda| \leq 10^{-52}$. The rate for large downward fluctuations is $\exp(-10^{103})$, and time is short, so need small initial entropy.

For flat or open FRW with $\Lambda>0$, do not get arrow of time. After $t_\Lambda \sim \Lambda^{-1/2}$, universe becomes empty de Sitter, thermal state with $T\sim\Lambda^{1/2}$. What happens at early time is irrelevant. $P_i \sim \exp(S_i - E_i/T)$. Higher CMB T would be preferred. Most preferred is empty de Sitter. With observers, contains minimal one (a "Boltzmann brain"). A state such as ours, far from equilibrium, does not occur (Dyson, Kleban, Susskind).

Goal: a model with $\Lambda>0$ and an arrow of time.

I will use the causal patch measure [RB 2006]: $\frac{P_I}{P_J} = \frac{\langle N_I\rangle}{\langle N_J\rangle}$, where $N_I$ is the expected number of times events of type I happen within the event horizon. Without a measure, $N_I$ and $N_J$ would diverge. This particular regulator is motivated by the resolution of the xeroxing paradox in unitary BH evolution.

If initial conditions are low-energy, and if vacuum A decays faster than it produces Boltzmann brains, then get arrow of time. If initial high entropy, $N_{BB} \sim \Gamma_{BB\,A} > \Gamma_A$. If $\Gamma_{BB,\Lambda} < \Gamma_A$? $N_{BB} \sim \Gamma_A^{-1} >>> N_{oc}$

Goal: a model with $\Lambda>0$ that predicts an arrow of time, despite initial conditions with high energy. Two landscapes with four vacua, but with different order. Observers only in B. Start in C, lowest positive $\Lambda$. In theory (b), vacuum A acts as a bottleneck. Ordinary observers dominate, despite high ~~energy~~ entropy initial state.

I was always sceptical of the Hartle-Hawking state, which selects for the empty de Sitter vacuum of highest entropy, $\exp(3\pi/\Lambda)$. But this saves it. So happy birthday, Stephen! Well, Don Page spoiled it a bit, but I won't mention that.

The string landscape shares features with theory (b):
No fine-tuning → No observers in initial vacuum
Even BBs require $\Lambda \ll 1$

Assuming $\Gamma_{BB,A} < \Gamma_A$, one can solve the arrow of time.

[David Spergel: You need the right microphysics, the right cosmological constant, and fast enough decay.] The more things you put together, the more it seems likely the decay will be faster.

[Hermann Nicolai: Where do you need a theory of quantum gravity? It is like cosmology, in that we can do a lot of things without understanding full quantum gravity.

Andrei Linde, Stanford University, "Inflation in Supergravity and String Theory"

"Happy Birthday, Stephen! Thanks for making our lives so beautifully difficult" I agree with this statement

Subtitle: Brief History of the Multiverse

This is all in a state of flux

Two of my heroes: Stephen Hawking and Andrei Sakharov

Many ways to think about the multiverse

1. Many different universes described by quantum cosmology
2. Many different exponentially large parts of the same inflationary univer[se]

Tryon 1973: Creating the universe, an idea of an idea

Problems: 1. One cannot create our universe from nothing if the baryon number is c[onserved]
2. Anthropic considerations do not require uniformity
3. No real theoretical description of creation of the universe was given

1. solved by Sakharov 2. by inflation. 3. by Vilenkin.

Remaining problems: $P \sim e^{\pm \frac{24\pi^2}{V(\phi)}}$

Hawking 1984: $P \sim e^{\frac{24\pi^2}{\Lambda(F)}}$ if $\Lambda$ determined by 4-form $F$

Duff 1989: $\Lambda = 0$ is least probable. Coleman, Giddings, Strominger 1988 $P \sim e^{e^{\frac{24\pi^2}{\Lambda}}}$

Using tunneling wave function $P \sim e^{-\frac{24\pi^2}{V(\phi, F)}}$ or assume that $P$ is not exponentially suppressed at all. Then prob. dist. is flat near $\Lambda = 0$. This leads to the anthropic expectation $|\Lambda| \sim 10^{-120}$ A.L. 1984. Bound was really derived only 3 years later, in 1987, by Weinberg.

Sakharov 1984: If the dimensionality of the compactified space is sufficiently large, it can be compactified in an enormously large number of ways. For success, one must have $> 10^{120}$ compactificati[ons]

The approach based on QC is most general and powerful, but it requires understanding.

Pessimist: If each part of the multiverse is so large, we will never see its other parts, so it is impossible to prove that we live in the multiverse. Optimist: prove → disprove.

Picture of universe divided into many exponentially large parts was first put forward here at the Nuffield Symposium, July 1982. "This may give us a possible basis for some kind of anthropic principle."

Enormous number of compactifications may be a virtue — A.L. 1986.

Lerche, Lust, Shellekens 1987 claimed $10^{1500}$ vacua. Bousso and Polchinski (2000) suggested using it to solve $\Lambda$ problem.
KKLT mechanism of moduli stabilization in a susy AdS minimum and then uplifting to dS breaks SUSY. $m_{3/2}^2 = |V_{AdS}/3|$, small. Condition that universe not decompactify gives $H < m_{3/2}$. KL model 2004 can have a high barrier for any gravitino mass, so H can be larger.

Problems with inflation in supergravity. $V(\Phi) = e^{K} \ldots$, $K \sim \Phi\bar{\Phi}$. But $K = S\bar{S} - \frac{1}{2}(\Phi - \bar{\Phi})^2$ gives $V = \frac{1}{2}m\phi^2$. Functional freedom in choosing inflational potential. The inflaton potential can have arbitrary shape determined by the choice of the superpotential $W = S f(\Phi)$. This allows to describe observations with any values of $n_s$ and $r$. Depending on the choice of the Kahler potential, ...

"The most incomprehensible thing about the universe is that it is comprehensible" — Einstein. "The unreasonable efficiency of mathematics in science is a gift we neither understand nor deserve" — Wigner

if the universe is everywhere the same, it can be an undeserved gift of God.

In the inflationary multiverse, this problem disappears. The laws of mathematics and physics are efficient only if they allow us to make predictions.

Physicists can only live where the universe is comprehensible

Neil Turok, Perimeter Institute, "The Big ~~Bang~~ Crunch/Big Bang Transition"

1. Measure for inflation. 2. Crunch → bang: "no beginning" state

Things have gotten worse: fine-tuned potential, initial conditions. Claim was generic initial conditions ⇒ inflation. Need a measure on set of universes. Focus on a very simple setup with measure respecting all symmetries. Slow-roll inflation, $V_{min}=0$, $k=-1$ FRW, 3-space compactified to U to keep everything finite.

I will be really generous to inflation, since that is my m[ain?] and just assume homogeneity + isotropy. 2-parameter family of soluti[ons] with an initial singularity. $a$ is curvature radius, $\phi$ is scalar field.

$H(p_a, a, p_\phi, \phi) = -\frac{p_a^2}{12Ua} + 3Ua + \frac{p_\phi^2}{2Ua^3} + Ua^3 V(\phi)$, Canonical measure $\omega_c = dp_a \wedge da + dp_\phi \wedge d\phi$, $\int_\Sigma \omega_c |_{H=0}$ with $\Sigma$ pierced once by every traject[ory]

Liouville; Gibbons, Hawking, Stewart; Hawking, Page; Hollands, Wald; Kofman, Linde, Mukhanov; Gibbons, NT; Carroll, Tan.

Universes = curves in phase space

Recall: flat space Gibbs ensemble. Maximise entropy $S = -\Sigma_i p_i \ln p_i$ subject to $E = \Sigma_i p_i E_i$. But in GR, $H=0$ on all physical states so cannot constrain ~~it~~. Only one natural constraint:

Every trajectory ends on adiabat $S(E, a) = \text{const}$. Natural to label an ensemble of cosmologies by their asymptotic entropy $S_\infty$. Meaningful quantity is $P_{S_\infty}(N_I)$

Here $S_\infty = \ln \frac{Ua^3 p_\phi}{m}$ [Gary: the mass in the dust] Exactly. For $V = \frac{1}{2}m^2\phi^2$, $P_{S_\infty=\infty}(N_I) = \sqrt{N_I}\, e^{-3N_I}$. For any finite $S_\infty$, $N_{I,max} = \frac{1}{3}S_\infty - \frac{2}{3}\ln\left(\frac{m_{Pl}}{m}\right)$, worse than $S_\infty = \infty$.

Why did this happen? Because statistical ensemble defined in asymptotic region where gravity becomes unimportant: the future, inflationary "attractor" becomes "repeller". With this canonical measure, slow-roll / 'chaotic' inflation cannot be considered an explan[ation] for the observed flatness of the cosmos. Makes precise a problem identified by Penrose long ago.

Ways out (other suggestions welcome!):

1) Inhomogeneities (!)

2) Modify measure with unobservable volume factors (!)

3) Evolve forwards from some initial ensemble: (i) "chaotic" (ii) asymp. flat in pa[st]

What if the singularity was a bounce? A cyclic universe becomes feasible, in which inflation may be entirely unnecessary

Example: Einstein-scalar gravity $S = \int d^4x \sqrt{-g}\left[\frac{1}{2\kappa^2} R + \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$

Near singularity, Einstein eqns reduce ultralocally to: $\frac{a_E^2}{a_E^4} = \cdots$

"Lift" to a Weyl-invariant theory $S = \int d^4x \sqrt{-g}\left[\frac{1}{2}\left((\partial\phi)^2 - (\partial s)^2\right) + \frac{1}{12}(\phi^2 - s^2) R\right]$

Scalar ghost removed by gauge symmetry: $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$, $\phi \to \Omega^{-1}\phi$, $s \to \Omega^{-1} s$

Gauges: 1. Einstein gauge $\phi^2 - s^2 = 6\kappa^{-2}$: $\phi_E = \pm(\sqrt{6}/\kappa)\cosh(\kappa\sigma/\sqrt{6})$, $s_E = \cdots$

"Supergravity-like" 3. $\phi = \phi_0$. 4. "String frame"

$\chi = \frac{\kappa^2}{6}(-g)^{\frac{1}{4}}(\phi^2 - s^2)$ is Weyl and $O(1,1)$-invariant. $a_E^2 = |\chi|$.

Weyl symm restored at gravity / antigravity transition.

Uniqueness of solution: unique extension of $\sigma$, $\alpha_{1,2}$ to complex $\tau$-plane. Also, as approach singularities, action has asymptotic symmetries. Don't generate linear gravitational perturbations: zero particle product. Even nonlinearly, things come back

Conclusions: Unique continuation of classical 4d GR-scalar effective theory 'around' singu

Alexander Vilenkin, Tufts University, "Did the Universe Have a Beginning?"

Penrose-Hawking singularity theorems (1960s). Assume strong energy condition + make assumptions about the global structure of spacetim[e]

Candidate scenarios with no beginning: EI, Cyclic are good [...]

inflation is generically eternal to the future. Could it have no beginning in the past? Strong energy condition is violated duri[ng] inflation ⇒ Penrose-Hawking singularity theorems do not apply. Borde & A.V. (1990s) assumed weak energy condition, but even the WE[C] is violated by EI.

Kinematic incompleteness theorem: A spacetime that is on average expanding, $H_{av} > 0$, is past geodesically incomplete. Borde, Guth & A.V. (2003). Does not rely on Einstein's eqs. or energy c[onditions]

We say a spacetime is expanding if it can be filled with an expanding congruence of "comoving test particles". If $H_{av} > 0$ along the worldline, the worldline must be past-incomplete.

Corollary: Inflating spacetimes are past geodesically incomplete ⇒ have a beginning.

Attempts to evade the theorem: Aguirre & Grafton (2001), Carroll & Chen (2004), Hartle & Hertog (2011). Assume reversal of arrow of time at some point. I count this as a beginning.

Cyclic universe: "The solutions where the universe successively expands and contracts... have an incontestable poetic charm and bring to mind the Phoenix of the legend" - Lemaître (193[?]) Must have a past boundary.

Emergent universe scenario. Assumes that the universe is closed & static in the asymptotic past. "Cosmic egg" (Rig Veda) $H_{av} = 0$ ⇒ the theorem does not apply.

If universe was sitting there forever, what triggers the expans[ion]? Need a mechanism to end the static phase, e.g., a rolling scalar field. Ellis et al (2004). What Hindu's needed was a scalar field.

~~Assume matter with~~ To ensure stability, need 'exotic' matter or modified gravity. Assume matter with $P = w\rho$ plus $\Lambda < 0$, $-1 < w < -1/3$ giving stable static solutions. Stanford group took $w = -2/3$,

$\rho(a) = \Lambda + \rho_0 a^{-1}$, $a(t) = \omega^{-1}(\gamma - \sqrt{\gamma^2 - 1}\cos(\omega t))$, $\omega = \sqrt{\frac{8\pi}{3} G|\Lambda|}$, $\gamma = \sqrt{\frac{2\pi G \rho_0^2}{3|\Lambda|}}$.

For $\gamma = 1$, static solution: $a(t) = \omega^{-1}$. However, I will argue this has quantum instabilities

$$\mathcal{H} = \frac{G}{3\pi a}\left(p_a^2 + U(a)\right), \quad p_a = -\frac{3\pi}{2G} a\dot{a}, \quad U(a) = \left(\frac{3\pi}{2G}\right)^2 a^2\left(1 - \frac{8\pi G}{3} a^2 \rho(a)\right).$$

$p_a \to -i\frac{d}{da}$, $\mathcal{H}\Psi = 0$, $\left(-\frac{d^2}{da^2} + U(a)\right)\Psi = 0$. Potential is not harmonic oscillator

Turning points: $a_\pm = \omega^{-1}\left(\gamma \pm \sqrt{\gamma^2 - 1}\right)$. Universe can collapse to $a = 0$

$T \sim e^{-2S}$, $S = \int_0^{a_-} \sqrt{U(a)}\, da = \frac{3M_P^4}{16|\Lambda|}\left[\frac{\gamma^3}{2} + \frac{\gamma}{4}(\gamma^2 - 1)\ln\left(\frac{\gamma - 1}{\gamma + 1}\right) - \frac{1}{3}\right]$. For $\gamma = 1$, $S = \frac{3M_P^4}{32|\Lambda|}$

Solving the WDW equation. $E = 0 \Rightarrow$ We have freedom to impose only one b.c. We choose $\Psi(a \to \infty) = 0$. The wave function is nonzero at $a = 0$, indicating a nonzero probability for collapse.

Can quantum collapse be avoided in a more general class of models? $\rho(a) = \Lambda + \frac{C_1}{a} + \frac{C_2}{a^2} + \frac{C_3}{a^3} + \frac{C_4}{a^4} + \cdots$

(walls, strings, dust, radiation)

$n \geq 6$, $C_n < 0$

Is it possible to arrange for $\Psi(0) = 0$? $\Psi(0)$ depends on $\Lambda$ and $\gamma \Rightarrow \Psi(0)$ can be arranged by fine-tuning the parameters. $|\Lambda|/M_P^4 = 0.0266$, $\gamma = 1.3$. Can this construction be extended beyond minisuperspace? Probably not.

Did the universe have a beginning? Probably yes. Inflationary spacetimes are past incomplete

Cyclic.

Simon Ross, Durham University, "Holography and (Lorentzian) Black Holes"

Holography, BHs as thermal states; Lorentzian BHs; static solution; time-dependent perturbations; fluid-gravity correspondence; BH formation and thermalization;

Holography: A class of QFTs are dual to gravity in at least one more dimension (Maldacena). For $CFT_d$, dual is $AdS_{d+1} \times X$. $SO(d,2)$ isometries of AdS. Radial direction geometrizes RG flow.

$\langle e^{\int \phi_0 O} \rangle = Z_{string}(\phi \to \phi_0)$

Black holes as thermal states. $Z = tr(e^{-\beta H})$. Dominant bulk saddle-point is the Schwarzschild-AdS BH $ds^2 = \frac{r^2}{\ell^2}[f(r)dt^2 + dx^2] + \frac{\ell^2 dr^2}{r^2 f(r)}$

Horizon at $r_+$ where $f(r_+) = 0$, $S^1 \to 0$. "IR end" to geometry corresponds to a deconfined phase in CFT: $S \sim O(N^2)$. Can have non-trivial phase structure if you introduce a scale (Hawking Page). Recent example: hairy BHs (Gubser; HHH = Hartnoll, Herzog, ...)

Lorentzian BHs have qualitatively different picture, with interior. Does the holographic description extend across the horizon? How is observer desc.

Classical evolution: Event horizon is not locally special. Causally, outside not sensitive to inside.

Boundary observables (Marolf): There is a set of "b. obs." identified with CFT observables. Grav. Ham. is a boundary term, so time evolution preserves the set of boundary observables.

Eternal BH has two boundaries $\to CFT_1 \otimes CFT_2$ in entangled $|\psi\rangle = \sum_n e^{-\beta E_n/2} |E_n\rangle_1 \otimes |E_n\rangle_2$. Correlation functions $\langle O_1(x_1) O_2(x_2) \rangle$ approximated by geodesics which cross horizon. Integration over the bulk can be done either over whole spacetime or outside the horizon.

Time-dependent perts. Perturbations decay: corresponds to thermalization in field theory. Membrane paradigm says that for long-distance one integrates out scales shorter than the thermal scale and gets a universal low-energy theory: fluid dynamics, in local thermal equilibrium. Kubo formula relating transport coefficients to microscopic correlators. $\frac{\eta}{s} = \frac{1}{4\pi}$, so shear viscosity is as small as possible.

Fluid-gravity correspondence. Make $T(t,\vec{x})$, $\vec{u}(t,\vec{x})$ functions. Read off stress tensor from asymptotics of bulk. $\partial_\mu T^{\mu\nu} = 0$: direct result of bulk and boundary. Area of event horizon gives an entropy current in field theory. But event horizon is teleological. CFT entropy not given by event horizon area. AH?

Black hole formation: Describes process of thermalization in F
Add energy by a change in boundary conditions: e.g., part of boundary metr
$ds^2 = -dt^2 + e^{B_0(t)} dx_\perp^2 + e^{-2B_0(t)} dx_\parallel^2$. $\tau_{isotropization} \approx 0.7\, T^{-1}$
Model by Vaidya metric in bulk, $ds^2 = \frac{1}{z^2}\left[-(1-m(v)z^d)dt^2 - 2dz\,dv + d\vec{x}^2\right]$
Study non-local observables: $\langle O(x_1) O(x_2)\rangle$, Wilson loops, entanglem
Approximated by minimal surfaces in bulk. For entanglement entropy
$\tau_{sat} \sim l/2$ — saturates causality bound. Local revs (cf. $S_{thr}(x_0)$) thermalize instantly.
Local observables thermalize first, long-distance correlations thermalize later
This is opposite to ordinary field theory, where IR thermalizes first

BHs on boundary. Study geometries with a BH on the boundary of the spacetime. Sch-AdS boundary, bulk $ds^2 = \frac{l^2}{\cos^2\theta}\left[d\theta^2 + ds^2_{S\text{-}AdS}\right]$
Surprise: boundary CFT stress tensor is not thermal at leading ord
"Top-down" thermalization

In late-time hydro regime, simple, direct map of long-wavelen excitations to bulk geometry.

Happy Birthday Stephen!

[Alex Vilenkin: Is BH complementarity reflected in AdS/CF
I don't see it. One would have to look at finer-grained question how the information gets returned.

James Sparks, University of Oxford, "The Nuts and Bolts of AdS/CFT"

I'm probably the youngest here of Stephen's former students, as I was a student during Stephen's 60th birthday. Stephen set me to understand nuts and bolts, from Hawking-Hunter-Page etc. As a student I didn't really make any progress on this. However, after 10 years I'd like to report back.

Taub-NUT-AdS is a one-parameter family of negatively curved complete Einstein metrics on $\mathbb{R}^4$: $R_{ij} = -3g_{ij}$

$$ds^2 = \frac{dr^2}{\Omega(r)} + 4s^2\Omega(r)(d\psi + \cos\theta d\phi)^2 + (r^2 - s^2)(d\theta^2 + \sin^2\theta d\phi^2)$$

$$\Omega(r) = \frac{(r-s)[1+(r-s)(r+3s)]}{r+s}$$

$r=s$ is a "nut". At large $r$ the metric is asymp. locally AdS4 with a "squashed" $S^3$ boundary:

$$ds^2 \simeq \frac{dr^2}{r^2} + r^2[4s^2(d\psi + \cos\theta d\phi)^2 + (d\theta^2 + \sin^2\theta d\phi^2)].$$

When $s = 1/2$ the metric is (Euclidean) AdS4 with round $S^3$ boundary.

"One can ask whether the partition function of a CFT on the boundary is related to the action of these solutions" — Hawking-Hunter-Page

"Another issue that has to be resolved is what CFT to use on the squashed $S^3$. Here we are on shakier ground... On the 3-dim boundary of AdS4 YM theory is not conformally invariant."

$AdS_4 \times S^7$ is a susy soln to d=11 sugra. 4-form field G with $\mathbb{N} \ni N = \frac{1}{(2\pi l_p)^6}\int_{S^7} *G$. AdS/CFT dual to the 3d theory on N M2-branes. The AdS radius is $R \propto N^{1/6} l_p$, so we can use supergravity only in the large N limit.

What is this 3d CFT on N M2-branes? One answer is that it is the strong coupling limit of... Better description was found by Aharony-Bergman-Jafferis-Maldacena in 2008, using a string theory dual construction. It is a $U(N) \times U(N)$ Chern-Simons gauge theory, with two matter fields transforming in the $(N, \bar{N})$ representation, and two in the conjugate...

Imamura-Yokoyama (Sept 2011) showed that any $\mathcal{N}=2$ Chern-Simons-Yang Mills gauge theory, with arbitrary matter content and interactions, can be put on the squashed $S^3$, preserving susy. Key is that one must turn on $U(1)$ $A^{(3)} = s\sqrt{1-4s^2}(d\psi + \cos\theta d\phi)$, gauging the $U(1)_R$ symmetry of the theory. (The Killing spinors are charged under this.)

$Z = \int_{\text{all fields}} e^{-S} = \int_{Q\text{-inv fields}} e^{-S}$ (one-loop determinant) is exactly computable. This is a form of fixed point theorem: $Q$ is a supercharge. This reduces the $\infty$-d functional integral to a finite-dim integral

$$Z[\Delta; N] = \prod_{n=1}^{N} \int_{-\infty}^{\infty} dx_n \int_{-\infty}^{\infty} dy_n \exp\left[4\pi i \Delta^2 \sum_{n=1}^{N}(x_n^2 - y_n^2)\right] \frac{\prod_{m<n} s_b[\ldots(x_n - x_m - i)]\, s_b[\ldots(y_n - y_m - i)]}{\prod_{n,m} s_b[\ldots(x_n - y_m)]}$$

$r = b(\Delta) = 2\Delta + i\sqrt{1-4\Delta^2}$ and $s_b$ is the double sine function or dilogarithm ...

$\log Z[\Delta; N] = \frac{4\sqrt{2}\pi\Delta^2}{3} N^{3/2} + o(N^{3/2})$ in $N \to \infty$ limit.

We can now try to match this to Euclidean. The key difference to Hawking-Hunter-Page is that the dual field theory is supersymmetric plus we turned on a boundary background gauge field.

Martelli and I made the Taub-NUT-AdS solution susy by turning on a specific finite action self-dual $U(1)$ gauge field $A$.

$$ds_{11}^2 = R^2\left[ds^2_{TN\text{-}AdS} + (\eta + \tfrac{1}{2}A)^2 + ds^2_{CP^3}\right], \quad G = R^3\left[\tfrac{3}{8}\,\mathrm{vol}_{TN\text{-}AdS} - *_4\, dA \ldots\right]$$

$$Z_{\text{gravity}} = e^{-S_{\text{regularized}}}, \quad S_{\text{regularized}} = S^{\text{bulk}}_{\text{Einstein-Hilbert}} + S^{\text{bulk}}_{\text{Maxwell}} + S^{\text{boundary}}_{\text{Gibbons-Hawking}} + S^{\text{boundary}}_{\text{counterterm}}$$

$= \frac{2\pi\Delta^2}{G_N}$. 4 d $\frac{1}{G_N} = \frac{2\sqrt{2}N^{3/2}}{3}$ is computed via Kaluza-Klein. Coefficient is right.

We thus find exact agreement between field theory and gravity calculations, as a function of the squashing parameter $s$.

This result generalizes in many directions. For example, one can put different CFTs on the squashed $S^3$. One way to engineer such field theories is to put the N M2-branes at a Calabi-Yau singularity. $-\log Z[\Delta; N] = \frac{32\pi\ldots N^{3/2}}{3}\ldots$. Near-horizon limit at CY sing. is now $(TN\text{-}AdS) \times Y_7$, where $Y_7$ is an Einstein manifold, unknown, but volume is known.

We have other interesting examples, e.g. $U(1)\times U(1)$-invariant $S^3$. Taub-Bolt-AdS is replaced by Eguchi-Hanson-AdS type metric (non-Einstein) with squashed $S^3/Z_2$ boundary.

[Would it be possible to take this calculation beyond the partition function?] Yes, certainly.

Harvey Reall, DAMTP, University of Cambridge, "Black Holes and Extra Dimensions"

I was given *A Brief History of Time* at Christmas as a student, which motivated me to become a physicist. We had a lot of banter. I often pointed out negative aspects of Stephen's ideas, and he began calling me his miserable student. At my wedding he told my mother I was his *most* miserable student. I don't know whether this was for that time or for all time, so I know I am more miserable than James Sparks but don't know whether I am more miserable than Gary Gibbons.

GR in d dimensions. For $d>4$: BH non-uniqueness, instabilities, cosmic censor violations, simpler asymptotics.

Myers-Perry black holes – generalization of Kerr to d dimensions. Topological spherical, uniquely parametrized by mass and angular mom. Hidden symmetries (Frolov, ... Kubiznak, Page 2001-8).

Black rings $d=5$. Rotating loop of black string. Centrifugal forces balances gravity. Topology $S^1 \times S^2$. Not uniquely specified by mass and angular momenta; 2 with same, and with same as Myers-Perry.

Black Saturn: MP black hole with concentric black ring. First example of regular stationary vacuum multi black hole. Frame dragging effect: central hole rotating even when zero ang. mom.

Topology theorem (Galloway & Schoen 2005). Hawking's topology theorem generalizes to $d>4$. Horizon cross-section must admit metric of positive scalar curvature. $d=4$: $S^2$. $d=5$: $S^3$ (or quotient), $S^1 \times S^2$, connected sum.

Rigidity theorem (Hollands, Ishibashi & Wald 2006). Hawking's generalizes to $d>4$. A stationary, rotating, asymp. flat, vacuum BH solution must admit a rotational symmetry. All known $d>4$ solutions admit *multiple* symmetries. Pert. evidence for solutions with only one.

Blackfolds (Emparan, Harmark, Niarchos, Obers 2009-11). $d>4$ horizon can have 2 length scales with small ratio. New topologies: $S^{\#} \times \ldots \times S^{\#} \times s^{\#} \leftarrow$ small $s^{\#}$.

Classification

Schwarzschild is unique static vacuum BH for any $d>4$ (Gibbons 2002)

$d=5$ stationary BHs with 2 rot. sym. classified by ang. mom. and rod structure

Stability: linear

$d>5$ MP BHs: no upper bound on ang. mom. Ultraspinning BHs conjectured to be unstable (Emparan & Myers 2003). Confirmed by study of rotationally symmetric linearized perturbation (Dias, Emparan, Figueras, Monteiro, HSR & Santos 2009-2010). Teukolsky decoupling does not work, so one needs to use the best students available.

Stability: nonlinear (Shibata & Yoshino 2009-10)

Nonlinear numerical evolution of non-rotationally symmetric perts of MP: emission of grav. waves, settles down to MP with lower ang. mom. Cosmic censorship respected (maybe not for very high ang mom)

Local Penrose inequality (Figueras, Murata & HSR 2011)

Initial data: small pert of BH. If BH stable, must settle down to stationary BH in same family. Horizon area ↑ (Hawking), Bondi energy ↓: $A_{initial} \le A_{BH}(E_{final}, J_{final}) \le A_{BH}(E_{initial}, J_{final})$. Assume $J_{final} = J_{initial}$, hence $A_{initial} \le A_{BH}(E_{initial}, J_{initial})$ (Gibbons 1972)

Construct initial data by conformal rescaling of BH initial data.

$d=5$ black string: local Penrose inequality violated if $r_+/L < 0.8745$ (exact result: 0.8762 for Gregory-Laflamme instability threshold)

MP: local Penrose inequality violated for $d>5$ for sufficiently large $J$, though critical value is off by a factor of 2.

Heuristic arguments indicate rotationally symmetric instability of "fat" rings, confirmed by local Penrose inequality argument. Sufficiently thin rings probably GL unstable. Possible all black rings are unstable, though I'd guess some susy ones are stable.

Outlook: Still far from understanding "landscape" of higher-dim BHs: what topology, symmetries are possible? Need new methods for solving Einstein eq.

Happy Birthday, Stephen!

Gary Horowitz, UCSB, "Instability of Anti-de Sitter Spacetime"
O. Dias, J. Santos, G.H., 1109.1825; Bizon ... 1104.3702
Stephen's research was often ahead of its time.
"Thermodynamics of Black Holes in Anti-de Sitter Space" Hawking-Page became key 15 years later. But then, few studied AdS.
Consider asymp. (global) AdS solutions to pure gravity with $\Lambda < 0$ in $D=4$. If one requires that the metric (conformally) approach the static cylinder, waves bounce off the cylinder.
At the linearized level, AdS is stable. Claim: AdS is nonlinearly unstable. Generic small (but finite) perts of AdS grow, forming small BHs.
Doesn't this contradict the fact that AdS is supersymmetric? Doesn't it contradict positive energy? No.
Any pert. of AdS will grow.
$S = \int R - (\nabla\phi)^2$ has +ve energy and is stable in Mink space.
$S = \int R + (\nabla\phi)^2$ does not have +ve energy but still is nonlinearly stable.
Why is AdS nonlinearly unstable?
AdS is like a closed universe, so should be singular.
Special solutions need not be singular. There are an number of such geons, exactly periodic in time and invariant under a continous symmetry.
I can't give you a proof, but evidence.
Perturbative construction of solutions. Scalar, vector, and tensor perts (no tensors on $S^2$). At each order, can reduce the metric perturbation to two functions, $\Phi_{\ell m} \sim O(r^\ell)$ near origin
$\Phi_{\ell,m} \sim R_{\ell,m}(t) + \frac{S_{\ell,m}(t)}{r} + O(r^{-2})$ with $S_{\ell,m}(t) = 0$ to keep metric fixed at $\infty$
$\omega_\ell = 1 + \ell + 2p$ to 1st order, $p = \#$ of radial modes. If the source has harmonic time dependence $\cos\omega t$, solution will have same, except at a resonant frequency, where one gets linear growth.
Start with a single $\ell=2, m=2$ mode. At 2nd order no resonances
At 3rd order, one res mode $\omega_2 = 3 - \frac{14703}{17920}\epsilon^2$ removes growing mode
Continuing should give geon.
Start with linear combination of two modes. $\ell=6, m=6$ with $\omega=7$ mode is growing; energy is going into this mode. Then expect to go to high

Spherical scalar field collapse in AdS (Bizon and Rostworowski 2011)
When $\Lambda = 0$ (Choptuik, Christodoulou); $\phi = \alpha f(r)$, $M_{BH} \sim (\alpha - \alpha_*)^{\gamma}$, $\gamma = 0.37$.
In AdS, field can bounce off $\infty$ and then come back, so sequence of critical $\alpha$'s. No matter how small $\alpha$, one gets a BH. The scalar curvature $R$ at the origin oscillates with period about two. Starting with small amplitude, $R$ grows. $\epsilon^{-2}\Pi^2(\epsilon^2 t, 0)$ vs. $\epsilon^2 t$ gives a universal curve that grows.

Holzegel and Smulevici recently showed a linear scalar field outside a Kerr-AdS BH decays very slowly, like $1/\log t$. Imaginary part of quasi-normal mode frequency drops exponentially with $l$.
All asymptotically AdS BHs may be unstable (Damas).
The instability appears similar to the instability of AdS. E.g. $V$ = BH ↘ ∞
May form small BH (black moon) in minimum. May spiral in, radiate, form smaller black moons which spirals in, etc.
It may take forever, but if you continue to form smaller and smaller BHs, you violate the spirit of cosmic censorship: Get Planck curvature in finite time.

There are special "black moons" that are stable.

This is not a problem for the dual field theory
The fact that perturbations evolve to BHs can be viewed as thermalization (in a microcanonical ensemble). The instability probably does not occur for finite $N$.

Geons are dual to high energy states that do not thermalize.

Conclusions: (1) AdS is nonlinearly unstable.
(2) Resulting BHs are unstable. (3) Geons.

Open questions: (1) Prove sing. theorem.

[Gary Gibbons: The geons sound like breathers in the CFT. Are there known CFTs of this type that have breathers?

Thomas Hertog, University of Leuven, "A New Twist on the No-Boundary State"
arXiv: 0803.1663, 1009.2525, 1111.6090

I only got to know Stephen in the late 90s. My interview consisted with Stephen's typing out a speech of what was wrong with Andrei Linde.

Stephen has taken his own singularity theorem very seriously. Being a genius, he and Jim came up with the no-boundary proposal.

90's: bottom-up approach → 'the' instanton

2002: top-down approach → prior on multiverse

Stephen changed his mind at Harvey's wedding. I don't know whether this was before or after he talked to Harvey's mother.

Stephen said, "The history of the universe depends on the question that is asked"

→ local observations: conditional, coarse-grained

2007: dominated by histories with many efolds → eternal inflation

2010: local observations in eternal inflation: $P(CMB_1)/P(CMB_2) \approx \exp[\pi(1/V_{e1} - 1/V$

Coarse graining in eternal inflation are huge. Higher-order corrections?

Outline: No-Boundary state, AdS representation, implications

No-Boundary: $\Psi[b, h, \chi] = \int_C \cdots$ Semiclassical limit

$\Psi(b, h, \chi) \approx \sum_e \exp\{[-A_e(b, h, \chi)]/\hbar\}$, $A_e = I(b, h, \chi) + \hbar I^{(1)}(b, h, \chi) + \cdots$

$I = I_R + iS$, $\Psi \approx \exp\{[-I_R(b, h, \chi) + iS(b, h, \chi)]/\hbar\}$. When $|\nabla_A I_R| \ll |\nabla_A S|$

$p_A = \nabla_A S$, $P_{hist} \propto \exp[-2 I_R/\hbar]$ → no boundary measure: prior on multiverse

Complex saddle points. $ds^2 = d\tau^2 + a^2(\tau)\, d\Omega_3$, $\phi(\tau)$, $V(\phi) = \Lambda + \frac{1}{2} m^2 \phi^2$

Tune $\phi(0) = \phi_0 e^{i\alpha}$ at South Pole so $|\nabla_A I_R| \ll |\nabla_A S|$ at large scale factor

→ 1-parameter set of FLRW backgrounds. $I(v) = \frac{3\pi}{2} \int_{C(v)} d\tau\, a[a^2(H^2 + 2V) - 1]$.

Remarkably, 1-parameter slice predicts inflation.

If you evaluate the Lorentzian histories completely, they are approximately time symmetric for large $\phi_0$, singular for small $\phi_0$. Typically have gaussian fluctuations

Part II: Dual description. Lorentzian histories always lie on asymptotically vertical curves in complex $\tau$-plane. Analytic, so one can move the contour around. Can match to final point going horizontally rather than vertically at the end. Vertical part is AdS. With matter, Euclidean ADS domain wall. The signature of the complex saddle point metric varies in $\tau$-plane.

Domain Wall/Cosmology correspondence in SUGRA [Cvetic '96; Skenderis, Townsend, Van Proeyen

→ realized here through universe's quantum state. $V^{eff}_{AdS} = -\Lambda - V$.
Vice versa; starting from Euclidean AdS SUGRA we predict Lorentzian asymptotically deSitter universes.

Does the AdS/dS connection hold independently of the saddle pt. approx

What happens along horizontal branch?

Asymptotic expansion of metric and fields in small $u = e^{z} = e^{-y+ix}$

$g_{ij}(u, \Omega) = \frac{-1}{4u^2}[h_{ij}(\Omega) + h^{(2)}_{ij}(\Omega)u^2 + h^{(-)}_{ij} \ldots$

Action along horizontal part: $I_h = \int_h I[g, \phi] = +S_{ct}(b, h, \chi) - i S_{ct}(b, h, \chi)$

and no finite contribution. $S_{ct} = a_0 \int \sqrt{h} + a_1 \int \sqrt{h} R^{(3)} + a_2 \int \sqrt{h} \phi^2$.

$I_{...} = -I^{R}_{AdS}(b, \chi) - S_{ct}(b, h, \chi)$ where $I^{R}_{AdS}$ is finite as $a \to \infty$

$\Psi(b, h, \chi) \approx \exp\{[+I^{R}_{AdS}(h, \chi) + i S_{ct}(b, h, \chi)]/\hbar\}$ AdS/CFT [Maldacena, Witten

→ $\Psi(b, h, \chi) = \frac{1}{Z_{QFT}[h, \tilde{\chi}, \epsilon]} \exp\{[i S_{ct}(b, h, \chi)]/\hbar\}$. Z provides measure on configurations $(b, h, \chi)$. Scale factor evolution as inverse RG flow [Strominger's
Physical interpretation of counterterms. Coarse graining over UV modes at finite a

Part III: Eternal Inflation. Replace inner region of eternal inflation by dual CFT on its boundary: R CFT with deformation given by $\phi = \phi_{EI}$. ⟨O⟩ on inner boundary replaces regularity at SP
→ remaining saddle point with inner boundary.

Conclusion: EAdS/dS connection in no-boundary cosmology
· dual description in terms of relevant deformations of the CFTs that occur in AdS/CFT
Reinterpretation of eternal inflation

[Andrei Linde: We are right now in the eternal inflation regime without any slow roll, if string theory is correct and we are in a metastable vacuum. If you replace EI by a dual field theory, how do you describe the present for observers?]

Shing-Tung Yau, Harvard University, "Quasi Local Mass and Momentum in General Relativity"

By the equivalence principle, it is not possible to define mass density in GR. Given the metric and first-order deformation of a top. sphere in ST, we like to associate a 4-vector for momentum.

Many important statements in GR make sense only with the presence of a good definition of quasi-local mass.

Proposals: Hawking JMP 9, 598 (1968), Penrose, .., Brown-York

Properties: (1) ADM or Bondi mass at spatial or null infinity
2) Correct limits when surface converges to a point
(3) Nonnegative in general and zero in Minkowski (hard)
4) Behave well when the spacetime is spherical

Thorne hoop conjecture (1972).

Schoen-Yau (1983): If $\mu - |J| \geq \Lambda$ on $\Omega \subset N$ and $Rad(\Omega) \geq \sqrt{\frac{3}{2}} \frac{\pi}{\sqrt{\Lambda}}$, then N contains an apparent horizon.

Yau (2001): Suppose mean curvature H --

$I(g, \phi) = \int_M (\frac{1}{16\pi} R + L(g,\phi)) + \frac{1}{8\pi} \int_{\partial M} K$. Replace I by $I(g,\phi) - I(g_0, \phi_0)$

$= \int_M (\frac{1}{16\pi} R + L(g,\phi)) + \frac{1}{8\pi} \int_{\partial M} (K - K_0)$, where $g_0$ is Minkowski space.

Physical Hamiltonian $-\frac{1}{8\pi} \int_{S_t} (N(^2K - {}^2K_0) - N^{\mu} p_{\mu\nu} \tau^{\nu})$ : Brown-York & Hawking-Horowitz

Liu-Yau defined a gauge independent mass to be $-\frac{1}{8\pi} \int_S (\sqrt{(^2K)^2 - (tr_S p)^2} - {}^2K$ positive whenever the mean curvature vector of S is space-like and the Gauss curvature is positive. However, nonzero in Mink. space.

Work with Mu-Tao Wang. Given a surface S, we assume that its mean curvature is positive. Then can be embedded into $\mathbb{R}^{3,1}$

$\langle H_0, W \rangle = \langle H, \overline{W} \rangle$. $W^2 = N n^2 + N^2$, $\overline{W}^2 = N \overline{n}^2 + N^2$

.. $8\pi E(w) = \int_S N\, {}^2K + N^{\mu} (\overline{p})_{\mu 2} \overline{n}^2 - \int_S N\, {}^2K_0 + N^{\mu}(p_0)_{\mu 2} \overline{n}^2$ and define

$E = \inf E(w)$ under all possible embeddings of S into $\mathbb{R}^{3,1}$

Euler-Lagrange equation for minimizing $E(w)$ is an elliptic problem.

In summary, given a closed space-like 2-surface in spacetime whose mean curvature vector is space-time... get quasi-local momentum.

Misner-Sharp $m = M - \frac{M^2}{2r}$ in terms of our mass M. $\frac{1}{2} M \leq m \leq M$.

On AH, $M = 2m$; at space-like $\infty$, $M = m$.

Our mass gives the ADM and Bondi mass. In small-sphere limit, get Bel-Robinson tensor: $\frac{1}{90} r^5 Q(e_0, e_0, e_0, -) + O(r^6)$, with additional term quadratic in Weyl.

Strictly speaking, we associate each closed surface not a 4-vector, but a function defined on the light cone in Minkowski space. If it is linear, one gets a 4-vector.

[Jim Hartle: Another useful quantity would be the flux of quasi-local mass through a boundary.] We can do it.

[Comparison with Penrose one?] His is not even a real number.

[Gary Gibbons: Is there some Penrose inequality?] I believe so but haven't worked it out.

James Hartle, University of California, Santa Barbara,
"The State of the No Boundary Wave Function"

I can't say, as many here have, that Stephen was my boyhood hero, as I am slightly older than he.

I want to survey one of his greatest achievement, the no-boundary wave function.

If the universe is a quantum system, it has a quantum stat No state – no probabilities.

Contemporary final theories have two parts, H and Ψ. Which regularities of the universe come mainly from H and which from Ψ.

H: classical dynamics, laboratory experiments

Ψ: classical spacetime, early homo/iso + inflation, fluctuations in ground state, arrows of time, CMB, large scale structure, isolated systems, topology of spacetime, number of large and small dimensions, number of time dimensions, coupling constants of effective theories.

A final theory (H, Ψ) predicts prob. p(hist) for alternative histories of the universe. A theory is successful when it predicts high probabilities for the history of the universe that we observe.

p(hist|us) = (TD factor) × p(hist). If we are rare, (TD factor) ∝ (volume of reheating surfaces. If common, = 1

Treat everything quantum. Focus on prob. for observatio in our Hubble volume and coarse grain.

Assume geometry is QM variable, usual QM, no further mea semiclassical approx (no resolution of Page-Susskind), no susy

The state is not an initial condition but 4d notion.

$ds^2 = (3/\Lambda)[N^2(\lambda)d\lambda^2 + a^2(\lambda)d\Omega_3^2]$, matter: cosm. const plus scalar fi

$\Psi = \Psi(b, \chi)$ No-boundary is cosm. analog of ground state

$\Psi(b,\chi) \equiv \int_C \delta N \delta a \delta\phi \exp(-I[N(\lambda), a(\lambda), \phi(\lambda)]/\hbar)$ over all $(a(\lambda), \phi(\lambda))$ regular on a disk and matching $(b, \chi)$ on boundary.

Departures from symmetry cost action and decrease bottom-up probs. Those that increase volume increase top-down probs.

$\Psi(b,\chi) \approx \exp\{[-I_R(b,\chi)+iS(b,\chi)]/\hbar\}$. Predicted ensemble of classical histories (WKB): $p_A = \nabla_A S$ (integral curves of S), prob (class hist) $\propto \exp(-2I_R/\hbar)$ Provided! $|\nabla_A I_R| \ll |\nabla_A S|$ (classicality)
Not all classical spacetimes predicted

By itself, NBWF + classicality favor low inflation, but we are more likely to live in a universe that has undergone more inflation, because there are more places for us to be.

NBWF flucts start in their ground states (Halliwell & Hawking)
Essentially the Bunch-Davies vacuum. $\Psi(3g_{ij}|\phi) = \Psi^c$

$\Psi$ predictions
classical spacetime – yes
early homo/iso "
flucts in ground state "

Arrows of time: flucts, thermo, radiation, psychological; growth of flucts, growth of entropy, retardation, past-present-future
These arrows cannot be explained by time neutral laws, but by the state.

NBWF arrows of time
NBWF flucts vanish at only one place on the fuzzy instanton – SP
This means flucts are small at only one of the places where U is small
For bouncing universe flucts increase away from the bounce on both sides

CMB, large scale structure. NBWF predicts that typical histories become highly inhomo on superhorizon scales.
We are common, so Top Down = Bottom Up.
Our observations are influenced only by events in our past light cone.
We assume probs for the $C_\ell^{obs}$ are the same as for a universe with no big large scale flucts (cosmic no-hair, specific calcs, dual forms?)
[Bousso: How do you regulate the sum?] I do the top down.

Isolated systems and separation from the Planck scale
The behavior of subhorizon flucts is independent of superhorizon structures.
Expansion + Nuclear physics + cosmic censorship saves us from having to do Planck scale physics

Topology of spacetime. What is our topology?
No evidence for interesting topology from the CMB (Spergel).

Some sum over topology is suggested by dualities (Maldacena, Hawking)
Large and small dimensions: Little info. Given we observe 4 large what is prob others are small.
4-d saddle points can be constructed by matching a real Lorentzian to real Euclidean, but get only one time.
A model landscape. Which minimum we are in is a question of history. Objective: $p(\Lambda, m|D)$, given our data $D$. Select for potentials that allow classical spacetime.
Anthropic reasoning is automatic in QC. We won't see what is where we can't exist.

$p(\Lambda|us) = \frac{p(us|\Lambda)p(\Lambda)}{\Sigma}$

$$p(\Lambda, m|D) = \frac{p(D|\Lambda, m)p(\Lambda, m)}{\Sigma_{\Lambda,m} p(D|\Lambda,m)p(\Lambda,m)}$$

$p(D|\Lambda, m)$ is the basis for traditional anthropic selection. Nonzero $p$ is anth. allowed. Weinberg got good results by putting in the observed $m$, $\Lambda$.
NBWF favors the lowest value of $Q$ in the anthrop allowed range. This restores Weinberg's anthropic argument for $\Lambda$
The early universe is simple — homogeneous, isotropic, matter nearly in thermal equilibrium. The middle universe is complex. The late universe will be simple — no protons, no stars, no BHs.
Is there a connection between the mathematical simplicity of the theory and of the results?
Yes for classical spacetime, ...
Happy Birthday Stephen. We're not finished yet!
[Vilenkin: If you have EI, late universe not sensitive to early universe. So are successes those of $\Psi$ or of EI? ] The tunneling wave function would give similar results.]
I don't claim this is the unique wave function. Same sh'.
[Guth: You said arrow of time cannot be explained by time-neutral laws, but Raphael and I say not.] Agreed.
[Bousso: Consider two vacua that differ only for Higgs. How would you calculate the probabilities?] We've had this discussion. We have a lot to calculate.
[Parker: How does position of transition to Lorentzian influence things. In the dS case we have only one single saddle point?

How do we test the theory? We divide the data into two parts. We assume one part and predict the other part. We favor the theory that explains the most correlations from the least data.

Public Symposium at Lady Mitchell Hall, Sidgwick Avenue, Cambridge, 2012 Jan. 8 (SW
Martin Rees, University of Cambridge, "From Planets to Universes"

I am honored to speak here today. Astronomers are used to large numbers, but when I first met Stephen, the odds I would have given against his reaching 70 were large.

Stephen and I had the luck of advisor Dennis Sciama and new astrophysics.

The State of the Universe?

· Cosmic exploration... Why things are as they are?

The hottest current topic in astronomy is the realization th most other stars are orbited by a retinue of planets, as ours is. 555 planets, June 2011. One can see Doppler motion and dimmin by one part in ten thousand for transits. Kepler has found 2000 plan One planet is orbiting a double star. We'd like to image the planets directly, but that is hard. From 30 light years, our planet would look like a pale blue dot. We could deduce the length of day. The European Extremely Large Telescope, 39 m, will look.

It is better to read first rate science fiction than second rate sc

Planets in a plane are a natural outcome of a dusty disk spun out from the sun.

Does astronomy give us any perspective on our position I think it shows the long times ahead. The sun has six billion year ahead. Post-human evolution could go far beyond humans.

1216 Å → 1 micron for ULAS J1120+0841, stretched by a factor of from the most distant known galaxy, actually a quasar.

We can't collide real galaxies but can do simulations. Andromeda will crash into us in four billion years.

Evidence for Dark Matter: ... gravitational lensing.

We have learned the expansion is speeding up, by Λ.

Let's look background. At 1 s, ten billion decays, as well tested as anything geologists can tell you about the history of the ear How can patterns arise, with the second law of thermodynamics. The answer is gravity. Clumps develop. The initial fluctuations are derived from some of the best observations, CMB ripples of one part in 100,000, (

Hydrogen converts to helium. Universe becomes transparent.
Dark ages. Universe lights up again by stars.

Gravity is crucial not only to the formation of structure but also for stars. Gravity is very weak, $10^{40}$ weaker than EM. My favorite diagram ($M/M_{proton}$ vs. $r/r_{proton}$). Normal matter is on a line $M \propto r^3$, up to Jupiter. BHs $M \propto r$. Quantum $M \propto r^{-1}$. If gravity weren't so weak, you'd have to compress the scale. It is important for us that gravity is so weak. Oroborus $10^{-30}$ cm – $10^{-25}$ cm

Gravity and quantum theory are two pillars of science, but normally they don't overlap. However, in the early universe, quantum fluctuations shake the entire universe.

At the geometric mean of the mass of a proton and the mass of a star, 50 kg (within a factor of 2 or so of all here), is a third domain of complexity, ants, humans, and mountains.

The entire universe we can see came from something much smaller than this dot.

Much much lies beyond our horizon ($10^{10}$ l.y. distant)? Cannot be sure of anything beyond present causal horizon. Moreover, topology could be complex or 'kaleidoscope'. But lack of discernible gradients suggests much larger from our big. There may also be many big bangs. How many? If one, or if many but no variety in physical laws/constants, no role for anthropic explanations. If yes, our laws just bylaws.

Prerequisites for complex cosmos: Gravity (the weaker the better). Departures from thermo equil. Matter/antimatter asymmetry. Non-trivial chemistry. At least one star. Tuned anthropic.

What part of parameter space allows interesting complexity? Constraints on $\Lambda$, on $Q$ (fluctuation parameter $\sim \frac{\Delta T}{T} \sim 10^{-5}$). If $Q > 10^{-5}$, huges BHs and no galaxies. $Q = 10^{-4}$ perhaps more interesting than ours. Anaemic universe ($Q = 10^{-6}$) might not allow galaxies at all. We don't know what determines $\Lambda$ and $Q$ and are even further from being able to give a measure of likelihood to say whether we are typical.

Our big bang may not be unique. Our search for explanations may be as vain as Kepler's hope for explanations for the sizes of the planetary orbits.

Paul Perlmutter, University of California, Berkeley,
"Supernova, Dark Energy and the Accelerating Universe"

It's a pleasure and honor to be here to celebrate Stephen's birthday. I represent a token experimentalist among a conference of mostly theorists. Science is often a tennis game between theorists and experimentalists.

Aristotle said we live in a finite universe, or else there would be no special place, like the center where we are.

Einstein applied his theory to the universe. He found it easy to make a universe expanding or contracting but hard to make it stand still. He introduced a fudge factor, Λ. But when Hubble found the universe is expanding, Einstein kicked himself. A mind-boggling idea: The universe is expanding. It is not an explosion into space because that space would be part of the universe... I don't whether we should call it the big bang or the big soup.

Is the expansion going on at the same rate, or is it slowing down because of gravity?

One exploding star can get brighter than an entire galaxy. Thus one can see it far away. Light takes time to travel. If the sun went out, we wouldn't notice it for 8 minutes. 4 years for nearest star. Nearest galaxy , nearest cluster 65 million years, supernova in distant galaxy 10 billion years, 3/4 the way back. The supernovae last only a few months, and we see them after ten billion years. A certain kind are standard candles, Type IIa. We think these are triggered by accretion from a companion.

Most supernovae emit mostly in blue light. This expands to become red, the redshift. The stretching of the wavelengths corresponds to the stretching of the universe.

From one ~~universe~~ supernova, its brightness tells how far away it is, and its redshift tells how much the universe has stretched. How to measure the fate of the Universe with tools you can find in your house (except for the largest telescopes in the world). The telescope is difficult, since supernovae are unpredictable, and you have to catch them on the way up to measure the peak. We had to develop a more systematic way with wide-angled camer

We used 6-7 telescopes at once. Once we made it systematic, we could even use the Hubble Space Telescope.

By 1997 we had enough measurements to be able to make the calculation. We thought we were going to find whether the universe would slow down forever or whether it would crunch, and we found something better: none of the above. The universe is accelerating expanding faster.

What does this mean? We don't know what this means. It may be dark energy, 3/4 of the energy of the universe, or a modification of Einstein's universe.

Dark energy, quintessence, supergravity, K-essence, cyclic universe, phantom energy, extra dimensions, ..

"Everybody talks about dark energy, but no one does anything about it" — this is not true.

Now 500 supernovas, almost all better measured than any of the first 50. But we need a factor of 20 better to distinguish between different theories. We know a lot how to do it. There are effects of SN variation, dust, grav. lensing, atmosphere absorption, ... SN grow up in slightly different demographics, leading to variation. We want to compare similar ones. Ones with broad stretch to time scale tend to be brighter. But one also has the spectrum at each point along the light curve. First one sees the outer shells and then further and further in, a CAT scan. It's like a striptease act. It is hard for the SN to be different without that showing up. SN factory of nearby SN (>1000) in ~28 months of searching to 2008: 200 were watched closely, so we have a catalogue of spectra. Supernova twins match very precisely. We calibrate on close ones and use these to measure far ones.

Baryon acoustic oscillation technique and gravitational lensing provide complementary techniques. We may be able to parse out dark energy from changes to Einstein's theory. Euclid, WFIRST, LSST, BigBOSS, ..? ~~This~~

This is a highly collaborative effort. Theorists are also highly interactive. If you really want to work with people, you should go into science.

Kip Thorne, Caltech, "Black Holes: A New Golden Age"

I first met Stephen in 1965 when I had just completed my Ph.D. under John Wheeler and Stephen was completing his Ph.D. under Dennis Sciama. Stephen is, by a large measure, the most stubborn person I have met.

Everything likes to live where it ages more slowly. Space and time are warped by matter and energy. That warping is responsible for grav Gravity gives a time warp.

Karl Schwarzschild discovered what Wheeler named a black hole Einstein showed it couldn't be made of static matter. Oppenheimer and Sn showed how to form it. Wheeler: from warped space & warped tim. Penrose defined a BH as trapping light and proved a singularity inside. Diameter >> Circumference. Time slows to a halt at the surface of a Inside the BH, time flows in a direction that we normally call radial. Singularity in BHs core. Lifshitz, Khalatnikov, Belinsky - 1971. We believe that quantum gravity applies.

1963: Discovery of quasars by Maarten Schmidt et al. In the same year, Roy Kerr discovered the rotating black hole. Penrose noted energy extraction. 1964-76: Lynden-Bell, Blandford, ... showed how this powers quasars. 1971-73: Compact X-ray sources. A hundred million small black holes in our galaxy.

Stephen Hawking was really the person who told us how black holes behave. Nov. 1970 he defined the interior of a black hole, the event horizon as the boundary, and the second law of BH dynamics surface area of horizon can never decrease. 3 laws (with Bardeen & Carte 1974-76: Quantum physics predicts that black holes radiate! [Hawking radi The laws of BH dynamics are really the laws of thermodynamics in disguise [Hawking and Bekenstein].

Bifurcation: astro BH, size >> 1 mm; quantum BH, size << 1 mm The quantum BH era: 1976-2000s. Info loss down BHs. I will not dis

Research on astro BHs largely stalled. In 2006, quiescent BH understood though not observed. Wildly dynamic BHs neither understood nor observed, except for Penrose's singularity theorem and Hawking's area theorem.

A new golden age: 2007-??

driven by numerical simulation of colliding BHs, and by observations to detect grav. waves.

Collisions of BHs: the most violent events in the universe. Power output: 10,000 times all the stars in the universe. No EM waves emitted, except from matter nearby.

Identical holes, not spinning: I'll show an early simulation.

Vortexes sticking out of spinning black hole. Vortex lines: integral curves of eigenvectors of "magnetic" part of Weyl curvature tensor. Vortexes on the combined BH oscillate between clockwise and counterclockwi Tendex lines: integral curves of eigenvectors of "electric" part of Weyl tenso As these vortex and tendex lines move out, they become grav. waves. Merging holes have tendex lines that stretch objects head-to-foot at the end and squash them at the joining neck.

Our groups are building a dictionary of gravitational waveforms

Black hole rips a neutron star apart. BH 3 times heavier than NS. BH spins at half the maximum rate. About 90% of NS matter goes into BH, and 10% emit gamma rays, neutrinos, etc.

Laser Interferometer Gravitational-Wave Detector — "GW Interferomet $\delta L = hL \leq 4\times10^{-16}$ cm with $h \leq 10^{-21}$, $L = 4$ km. Need noise $< 1\times10^{-16}$ cm. Data analysis teams, with Bruce Allen a leader, can do this. $10^{-2}$ cm: human hair. $10^{-4}$ cm: wavelength of light...

Earth-based GW interferometers for 10-1000 $M_\odot$ BHs in distant galaxies. Network required. LIGO: Laser Interferometer Grav. wave Observato 1989 proposal for 2-step: Initial plausible but not likely to see GWs. Advanced likely to see GWs. 2002 birthday promise to Stephen: advanced test his BH predictions by his 70th birthday. Now think 2016. 3 yr to G.W. Bush

European Laser Interferometer Space Antenna (eLISA) Pathfinder test 2014, LISA: ~2022. USA pulled out for financial reason

$10^8$-$10^{10}$ $M_\odot$ BHs could be detected by pulsar-timing detection of grav. waves. Correlated fluctuations in pulse arrival times from all pulsars. This is likely to succeed after about five years.

Conclusion: highly dynamical BHs show an amazing richness of structure and behavior. Stephen, I offer to you a birthday gift of GW detection in the next few years, well before your 80th birthday.

Stephen Hawking, University of Cambridge, "A Brief History of Mine" (in absentia

I am very happy to be here today. I hope you will forgive me for looking back.

I was born Jan. 8, 1942, 300 years after the death of Galileo. However, I estimate 200,000 babies born that day.

I was born in Oxford, as Germany agreed not to bomb Cambridge and Oxford. I later lived in Highgate, England, which our family bought cheap because it was thought London would be flattened.

I didn't learn to read until age 8.

I took electric trains apart but was not so good putting them back together. I wanted to build things I could control. That need was met by my research. If you understand something, you control it in a way.

Pre-war taxi put together in a Nissen hut.

I was never more than half way up the class, but it was a bright class.

I had 6-7 close friends, and we used to have discussions on everything from radios to God. I heard of the redshift but thought a static universe was nicer. Only in my second year as a research student did I realize I was wrong.

My father thought there would be no job for me as a mathemat[ician]. He had gone to University College, Oxford, and wanted me to apply there. In the end I was been a professor of mathematics but had no formal training in mathematics after leaving St. Albans at 17.

I did about 1000 hours of study at university, an hour a day. I planned to pass by doing questions in theoretical physics, which didn't require detailed knowledge.

I came to DAMTP in Cambridge. I applied to work with Fred Hoyle, but he had too many students. It is just as well, as I would have had to defend his steady-state theory, which would have been harder than saving the euro.

I worked with Dennis Sciama on astrophysics.

I noticed something was wrong with me at Oxford and then after going to Cambridge I fell over and was taken in for tests.

The disease progressed rapidly, and I became depressed. But then the disease slowed. After my expectations were reduced to zero, every day was a bonus.

The big question was whether the universe had a beginning. Many were uncomfortable with this. Steady State was an alternative but the 1964 discovery of the microwave background radiation ended this. Another alternative was a bounce, and I studied it.

Lifshitz and Khalatnikov argued for a bounce, which fits in well with Marxism. Penrose found a new approach, showing a singularity inside a dying star. I realized similar arguments could be applied to the universe. GR predicted that the universe should have a beginning.

My work on black holes began with a eureka moment after Lucy was born. While getting into bed I found the area cannot decrease. It seemed like entropy but couldn't be if, as thought then, black holes had zero temperature.

I was at a loss after publication of The Large Scale Structure. I thought about quantum fields near black holes. I expected waves to be scattered and absorbed, but I found emission. I found $S = \frac{Ac^3}{4\hbar G}$, the black hole entropy formula. I am proud to have discovered it.

One can replace ordinary time with Euclidean time. It solved the singularity problem.

The BH will radiate and shrink. My calculations showed thermal radiation. So how could it carry off the information? This was a problem for 30 years. Eventually I found information was not lost, but it is very hard to read. The fact that I thought information was lost was my biggest blunder. Well, at least it was my biggest blunder in science.

The primordial seeds were produced by quantum fluctuations. Several people contributed to the answer in 1982, before COBE satellite results 1993. WMAP satellite results 2003 shows the perturbations. It is the blueprint for all the structure of the universe. ESA Planck satellite 2013 may show grav. waves. This would be quantum gravity written across the sky.

To predict, what was needed was a model of the universe without singularities. I visited Santa Barbara and talked to Jim Hartle. We formulated the no boundary proposal for the quantu state of the universe. We sidestepped the problem of the begin of the universe by turning time sideways.

I wrote A Brief History of Time. I never expected it to do so well. People can learn that we live in a rational universe. I wrote The Grand Design to help understand why does the universe exist, why do we exist, and why the laws are as they are. I believe the answer is M theory. It is not a single theory but a whole collection. Multiple universes. Although we are puny, we are, in a sen lords of the universe.

The Large Hadron Collider may show M theory. I bet $100 against the Higgs, but it now looks as if I may lose another bet.

There are many ambitious experiments planned beyond Planck. Perhaps we can use GW to probe back to the big bang.

I don't think we will survive another thousand years on earth without expanding into space.

It has been a glorious time to be a theoretical physics I want to share my excitement about the quest. Look up at the stars and not just down at your feet. Never give up. There is always more you can do.