Dynamical Dark Energy

Andrew Chamblin Memorial Conference

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General Relativity

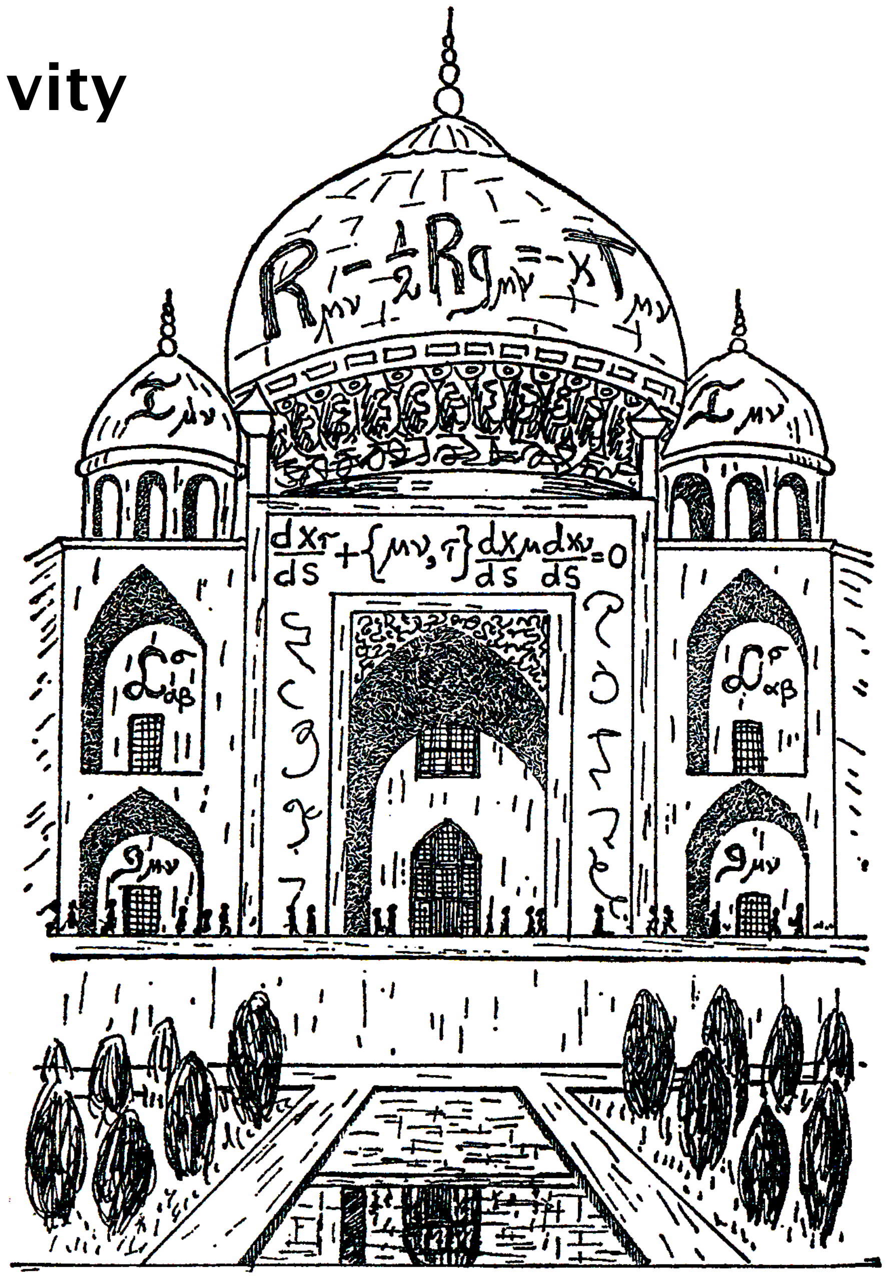


Fig. 29. The Temple of Gravity (the letterings on the temple are the basic equations of Einstein's relativistic theory of gravity).

Gamow (1962)

October 2006

Numerous observations and experiments support the hypothesis that our universe is filled by some sort of *dark energy* which is responsible for the cosmic acceleration.

1. low density $\Omega_m < 1$
   large-scale structure

2. little curvature $|\Omega_k| \ll 1$
   cosmic microwave background

3. accelerating $q < 0$
   supernova distances

simple explanation?

Physics Problems for the Next Millenium

"Why does the cosmological constant have the value that it has, is it zero and is it really constant?"

Andrew Chamblin

Problems for Cosmology

1. Test the foundations

   Is GR valid on the largest scales? On small scales?
   Is the universe homogeneous and isotropic on large scales?

2. Strengthen the evidence for Λ

   Most popular activity!

3. Find a quantum description of gravity

   Would seem to be necessary to understand CCP!
   What QG is not: RC + D. Grin, astro-ph/0606133

more: Peebles 2003

What is the Cosmological Constant?

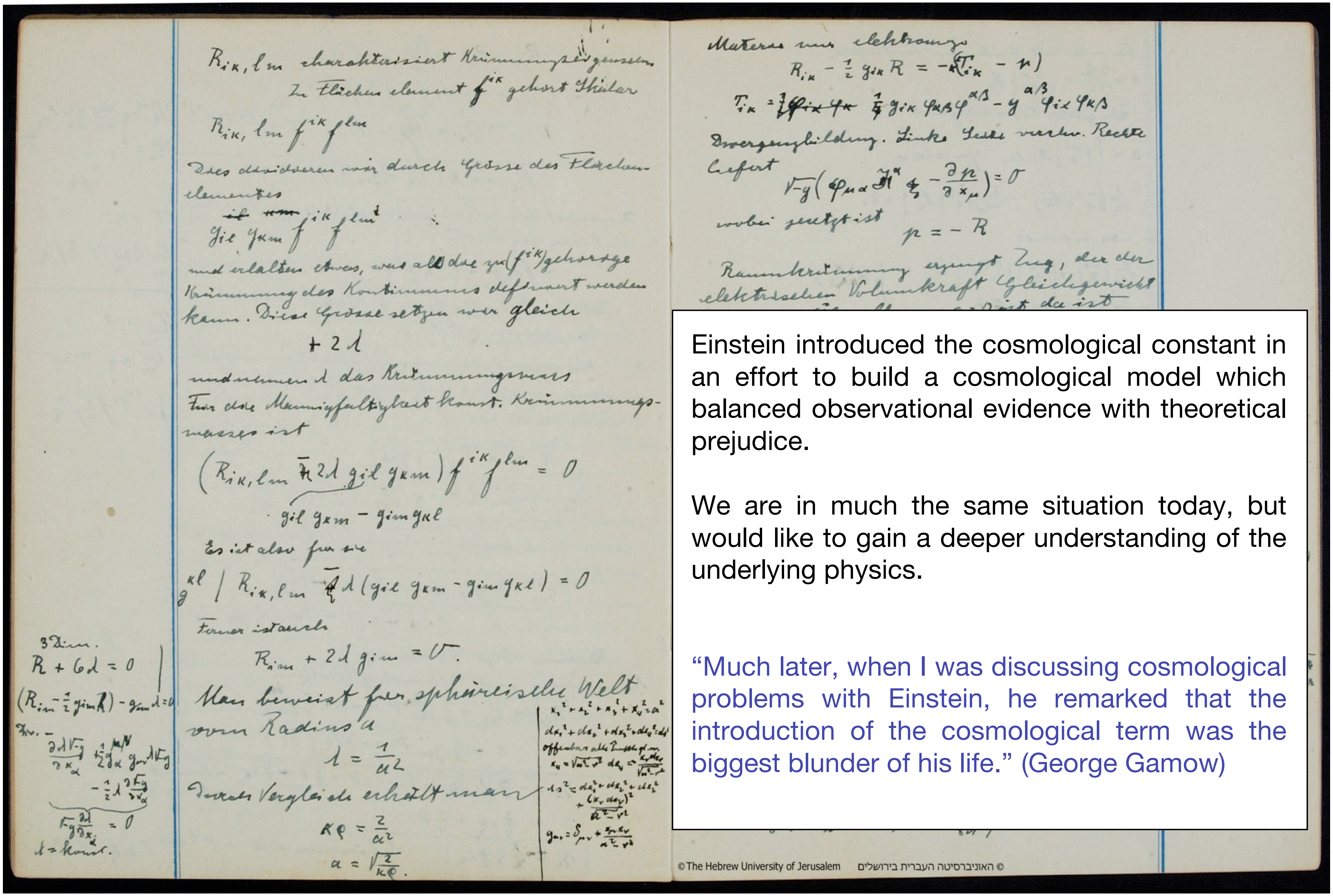
1917 Einstein, deSitter

1967 Zeldovich

$$\text{“}\Lambda_E = \Lambda_{dS} + \Lambda_Z\text{”}$$

catalog of solutions: Nobbenhuis 2004

Einstein’s Lecture Notes: Winter 1919



$R_{ik,lm}$ charakterisiert Krümmungseigenschaften.
Zu Flächenelement f^{ik} gehört Skalar
$R_{ik,lm} f^{ik} f^{lm}$
Dies dividieren wir durch Grösse des Flächenelementes
$g_{il} g_{km} f^{ik} f^{lm}$
und erhalten etwas, was als die zu (f^{ik}) gehörige Krümmung des Kontinuums definiert werden kann. Diese Grösse setzen wir gleich
$+2\lambda$
und nennen λ das Krümmungsmass
Für die Mannigfaltigkeit konst. Krümmungsmasses ist
$(R_{ik,lm} \mp 2\lambda g_{il} g_{km}) f^{ik} f^{lm} = 0$
$g_{il} g_{km} - g_{im} g_{kl}$
Es ist also für sie
$g^{kl} \mid R_{ik,lm} \mp \lambda (g_{il} g_{km} - g_{im} g_{kl}) = 0$
Ferner ist auch
$R_{im} + 2\lambda g_{im} = 0$.
Man beweist für sphärische Welt vom Radius a
$\lambda = \frac{1}{a^2}$
Durch Vergleich erhält man
$\kappa\rho = \frac{2}{a^2}$
$a = \sqrt{\frac{2}{\kappa\rho}}$.

3 Dim.
$R + 6\lambda = 0$
$(R_{im} - \frac{1}{2} g_{im} R) - g_{im}\lambda = 0$
λ = konst.

Materie nur elektromagn.
$R_{ik} - \frac{1}{2} g_{ik} R = -\kappa(T_{ik} - \nu)$
$T_{ik} = \frac{1}{4} g_{ik} \varphi_{\alpha\beta}\varphi^{\alpha\beta} - g^{\alpha\beta}\varphi_{i\alpha}\varphi_{k\beta}$
Divergenzbildung. Linke Seite verschw. Rechte liefert
$\sqrt{-g}\left(\varphi_{\mu\alpha}\mathfrak{J}^{\alpha} - \frac{\partial p}{\partial x_\mu}\right) = 0$
wobei gesetzt ist
$p = -R$
Raumkrümmung erzeugt Zug, der der elektrischen Volumkraft Gleichgewicht

Einstein introduced the cosmological constant in an effort to build a cosmological model which balanced observational evidence with theoretical prejudice.

We are in much the same situation today, but would like to gain a deeper understanding of the underlying physics.

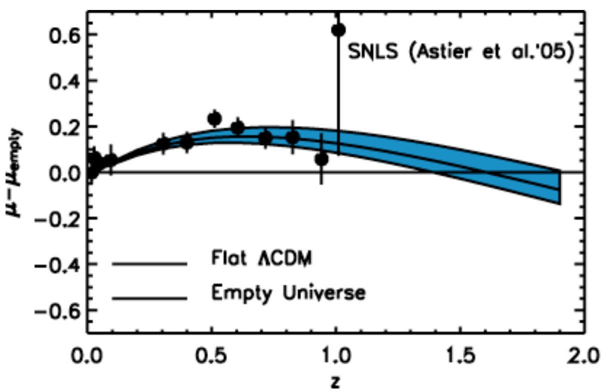
“Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder of his life.” (George Gamow)

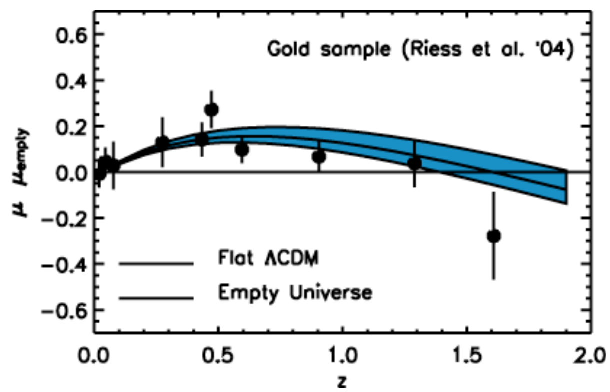
Influence of Dark Energy

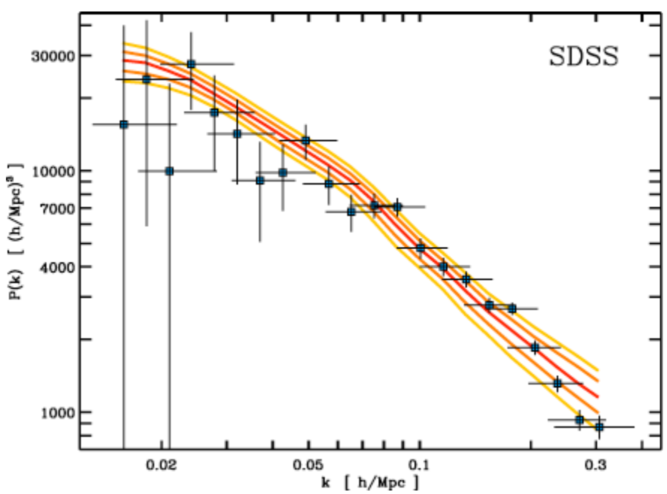
figures from Spergel et al, 2006

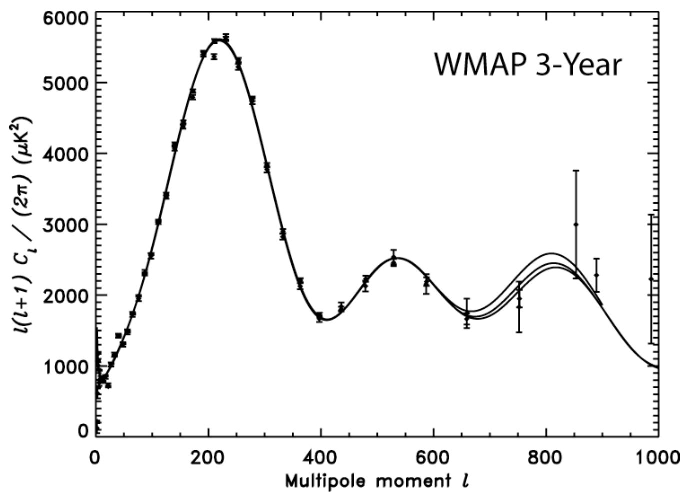
$$w \equiv p/\rho$$

$$\Omega_{de} = 1 - \Omega_m$$





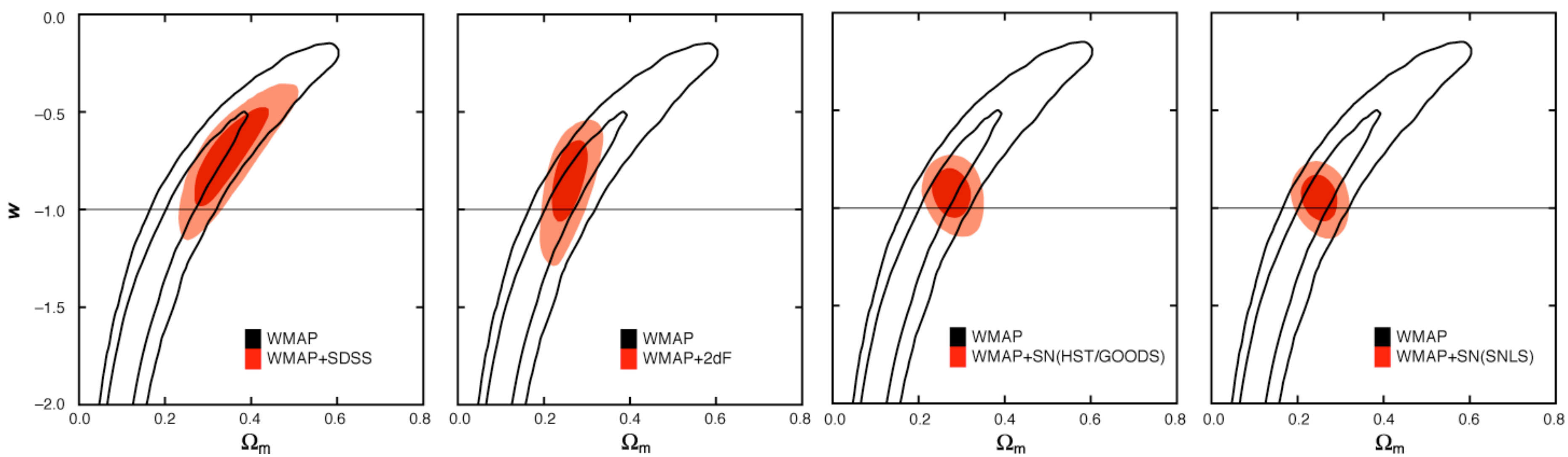




WMAP: 3 year

Spergel et al, 2006

$$w = -1.06^{+0.13}_{-0.08}$$



$$q = \frac{1}{2}[1 + 3w(1 - \Omega_m)]$$

Current Constraints

global fits (CMB, LSS, SNe)

Spergel et al, 2006 $w = -1.06\,^{+0.13}_{-0.08}\,(1\sigma)$

Seljak et al, 2006 $w = -1.04 \pm 0.12\,(2\sigma)$

Wang et al, 2006 $w = -0.89 \pm 0.2$

$w = -0.99 \pm 0.17$

weak lensing

Jarvis et al, 2005 $w = -0.89\,^{+0.16}_{-0.21}$

BAO from LSS

Eisenstein et al, 2005 $w = -0.80 \pm 0.18$

Dynamical Dark Energy

Allow for a dynamical solution to the problems of missing energy and acceleration -- like a low energy inflaton/axion

Particle physics theories provide motivations as well as barriers

$$L = -\frac{1}{2}(\partial\phi)^2 - V(\phi) \qquad\qquad -1 \le w \le 1$$

extreme values of field, mass

$$\phi \sim M_p$$
$$V'' \sim (10^{-33}\,\mathrm{eV})^2$$

troublesome couplings

$$\frac{\phi}{M} F^{\mu\nu} F_{\mu\nu}$$

Cosmological Four-Form

Aurilia et al 1980

$$S = \int d^4x \sqrt{-g} \left[-\frac{R}{16\pi G} - \frac{1}{2\cdot 4!} F_{\lambda\mu\nu\rho} F^{\lambda\mu\nu\rho} + L_{\mathrm{m}} \right]$$

$$F^{\lambda\mu\nu\rho} = \nabla^{[\lambda} A^{\mu\nu\rho]}$$

$$\nabla_\lambda F^{\lambda\mu\nu\rho} = 0 \rightarrow F^{\lambda\mu\nu\rho} = f \epsilon^{\lambda\mu\nu\rho}$$

F has no dynamics: $\Lambda = 4\pi G f^2$

Model for the dynamical adjustment of the cosmological constant by the nucleation of "charged" membranes with current $J^{\mu\nu\rho}$

Brown & Teitelboim 1987
...
Bousso & Chamblin 1998
...

Cosmological Four-Form: Dynamics

Add a Stueckelberg mass (Aurilia et al 2004)

$$L = \frac{1}{2\cdot 4!} F_{\lambda\mu\nu\rho} F^{\lambda\mu\nu\rho} - \frac{1}{4!} F_{\lambda\mu\nu\rho} \nabla^{[\lambda} A^{\mu\nu\rho]}$$
$$- \frac{m^2}{2\cdot 3!} \left(A_{\mu\nu\rho} + \frac{1}{m} \nabla_{[\mu} B_{\nu\rho]} \right)^2$$

sourceless equations

$$\nabla_\lambda F^{\lambda\mu\nu\rho} + m^2 \left(A^{\mu\nu\rho} + \frac{1}{m} \nabla^{[\mu} B^{\nu\rho]} \right) = 0$$

$$\nabla_\mu \left(A^{\mu\nu\rho} + \frac{1}{m} \nabla^{[\mu} B^{\nu\rho]} \right) = 0$$

mass reveals new degrees of freedom

Cosmological Four-Form: Dynamics

$$F^{\lambda\mu\nu\rho} = f\epsilon^{\lambda\mu\nu\rho}$$

$$T_{\mu\nu} = \frac{1}{m^2}\left[\partial_\mu f \partial_\nu f - \frac{1}{2} g_{\mu\nu}\left((\partial f)^2 + m^2 f^2\right)\right]$$

✓ looks just like a scalar field $\phi \equiv f/m$

$$(\nabla^2 - m^2)\phi = 0$$

✓ cosmological perturbations: same-same
✓ couplings perhaps more difficult
✓ dynamical mass to set small scale

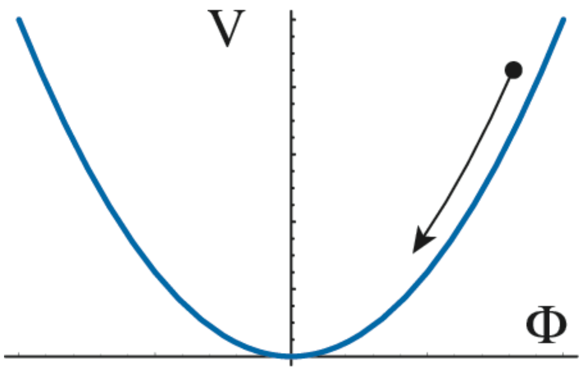
RC + Bob Scherrer 2006

Scalar Fields

Free, massive field	$V(\varphi) = \frac{1}{2} m^2 \varphi^2$
Axion / PNGB	$M^4 (1 + \cos \varphi / \mu)$
Vacuumless Condensate	M^6 / φ^2
Moduli	$M^4 \mathrm{e}^{-g\varphi / M_P}$

Surveys: Hall et al, "Evolving Dark Energy with w≠-1," PRL 95 141302 (2005);
Steinhardt, "Quintessential Ideas," Physical Scripta T117, 34 (2005).

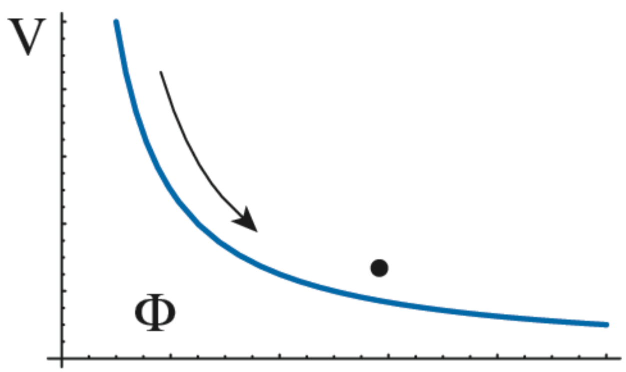
Thawing and Freezing Fields



thawing

Field is critically damped until Hubble friction drops; ***w*** starts at -1 and grows larger

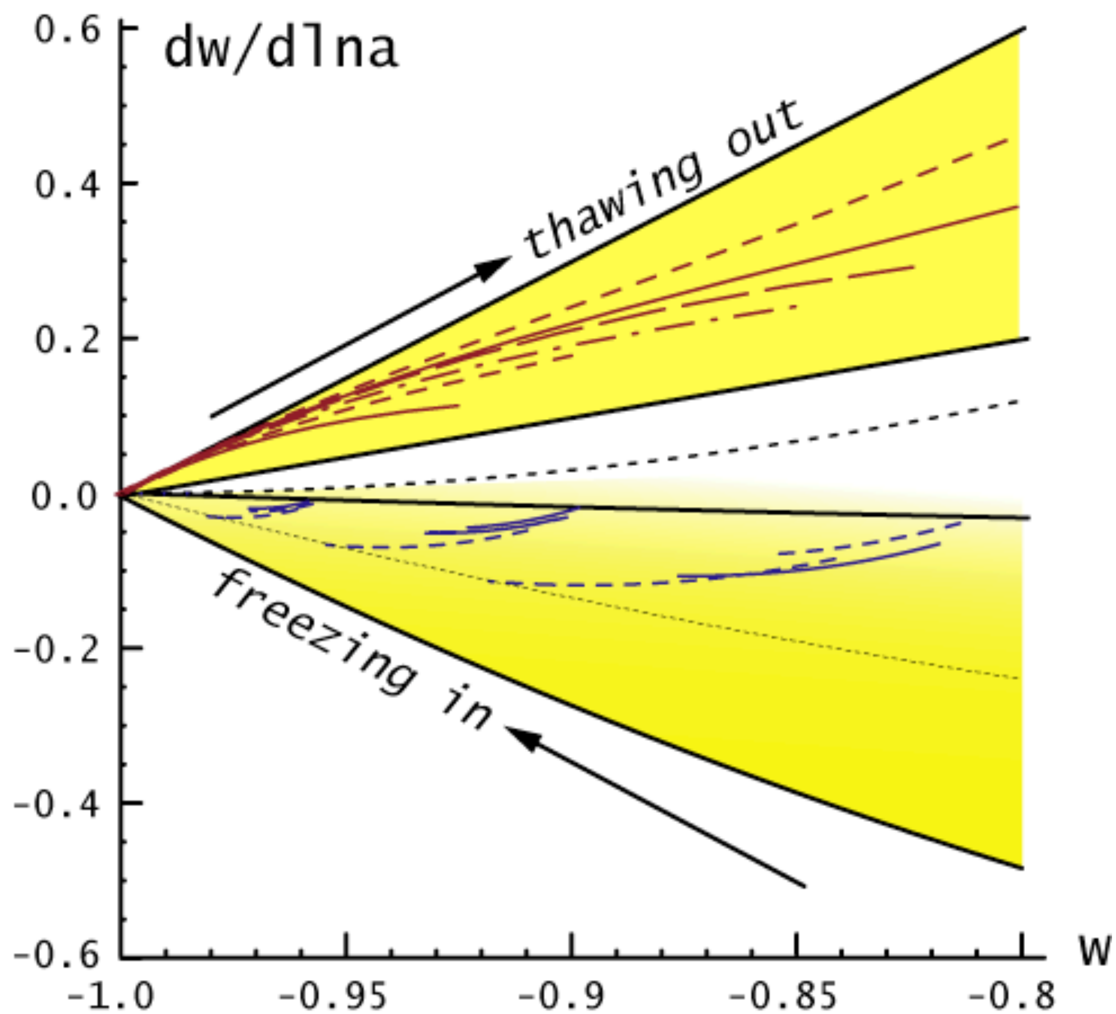
Any field near minimum: V=V'=0
massive scalar, axion / pngb



freezing

Field decays until curvature of potential causes field to slow; ***w*** evolves towards -1

"tracker" / runaway or vacuumless field



dw/dlna
thawing out
freezing in
w
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1.0
-0.95
-0.9
-0.85
-0.8

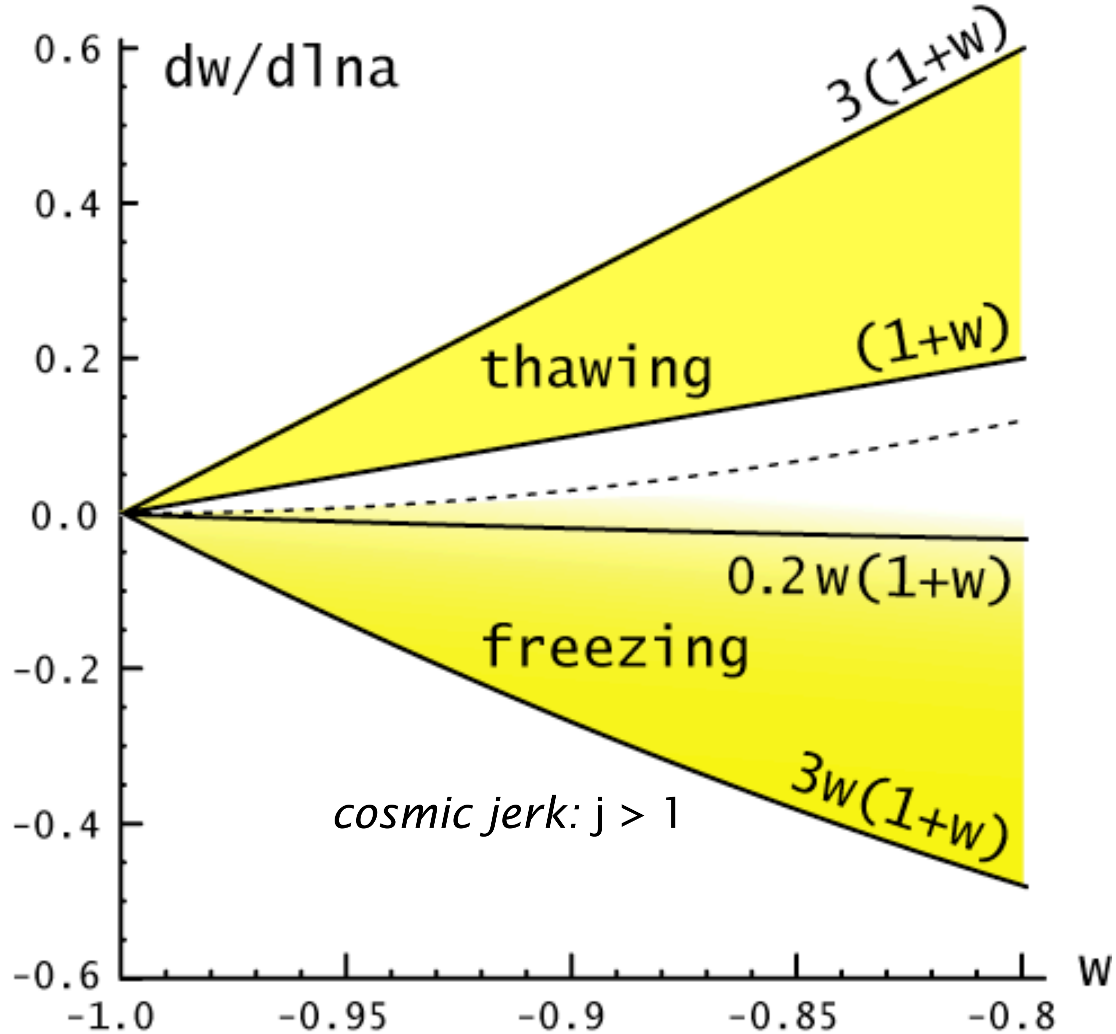
Limits of Quintessence

RC & Linder 2005

$\Omega_Q < 0.8$

$w < -0.8$

$\min(V) = 0$



Limits of Quintessence

$$\nabla^2 \varphi = V'$$ *recast equation of motion*

$$w' = -3(1-w^2) + (1-w)\frac{V'}{V}\sqrt{\frac{3}{8\pi G}\Omega_Q(1+w)}$$

If dark energy is thawing $w' < 3(1+w)$

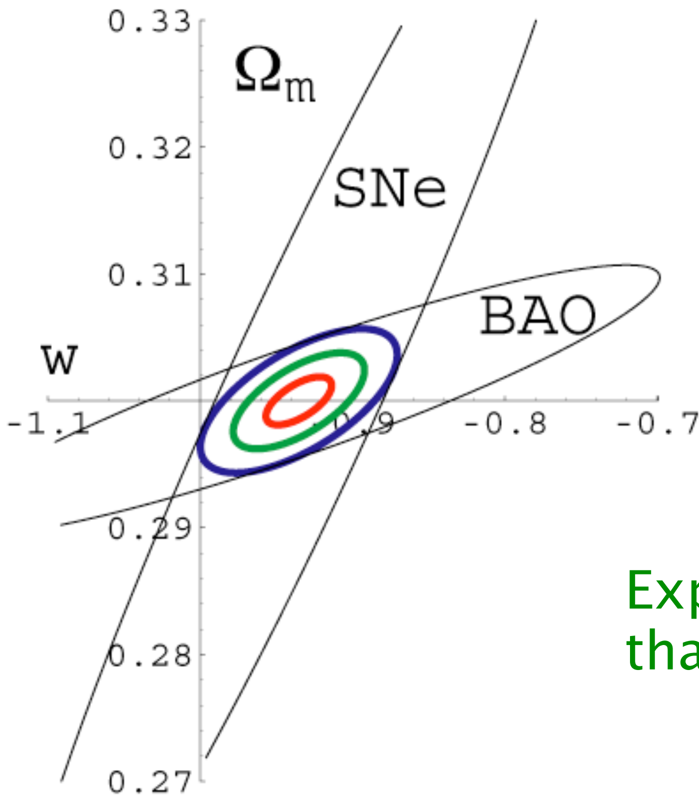
If the field is not too strong $\varphi < M_P$

Then the field must be evolving

$$1 + w > \frac{\Omega_Q}{54\pi G}\left(\frac{V'}{V}\right)^2 \approx 0.017$$

~1% difference from LCDM in distance to z=1

Dark Energy: Prospects



rough estimate:

distinguish a thawing field

Expect to do better
than $|1+w|<0.05$ at 3σ

SNe/SNAP: Aldering et al, 2004

BAO: Seo & Eisenstein 2003

Future Experiments

ground: Dark Energy Survey, LSST, …

space: NASA/DOE Joint Dark Energy Mission
Adept, Destiny, SNAP, …

DUNE, VADER, …

aim for simpler goals: Falsify $w=-1$?
Was $w<-1$ ever?
Is w a constant?

14 April 1917: Einstein to deSitter

"In any case, one thing stands. The general theory of relativity allows the addition of the [cosmological constant] in the field equations. One day, our actual knowledge of the composition of the fixed-star sky, the apparent motions of the fixed stars, and the position of spectral lines as a function of distance, will probably have come far enough for us to be able to decide empirically the question of whether or not λ vanishes."

Einstein Papers: volume 8 (translated)

18 April 1917

Dear Einstein,

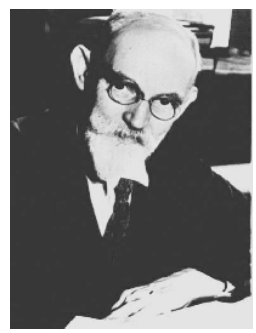
The main point in our “difference in creed” is that you have a specific belief and I am a skeptic.

Observations will never be able to prove that λ vanishes, only that λ is smaller than a given value. Today I would say that λ is *certainly* smaller than $10^{-45}cm^{-2}$ and is probably smaller than 10^{-50}. Maybe one day observations will also provide a specific value for λ, but up to now I have no knowledge of anything pointing to this.

…

With cordial regards,

W. de Sitter



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