Bouncing Cosmologies: where do we stand after Planck

Patrick Peter

Institut d'Astrophysique de Paris

GReCO

COSMO
Cambridge
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Problems:

Singularity

Horizon

Flatness

Homogeneity

Perturbations

Dark matter

Dark energy / cosmological constant

Baryogenesis

...

Topological defects (monopoles)

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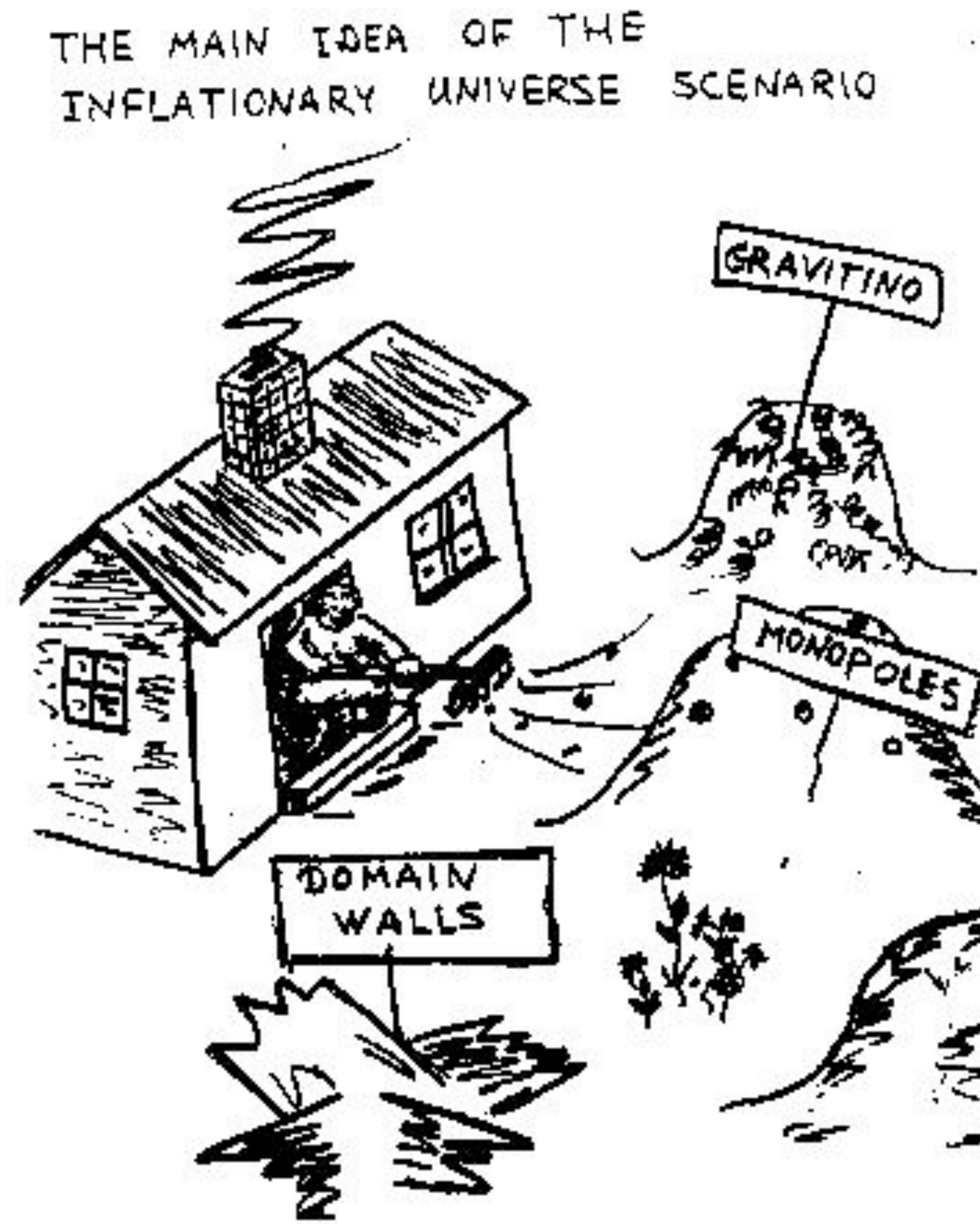
Accepted solution = INFLATION

Topological defects (monopoles)



Inflation:

- ☺ **solves cosmological puzzles**
- ☺ **uses GR + scalar fields [(semi-)classical]**
- ☺ **can be implemented in high energy theories**
- ☺ **makes falsifiable predictions ...**
- ☺ **... consistent with all known observations**

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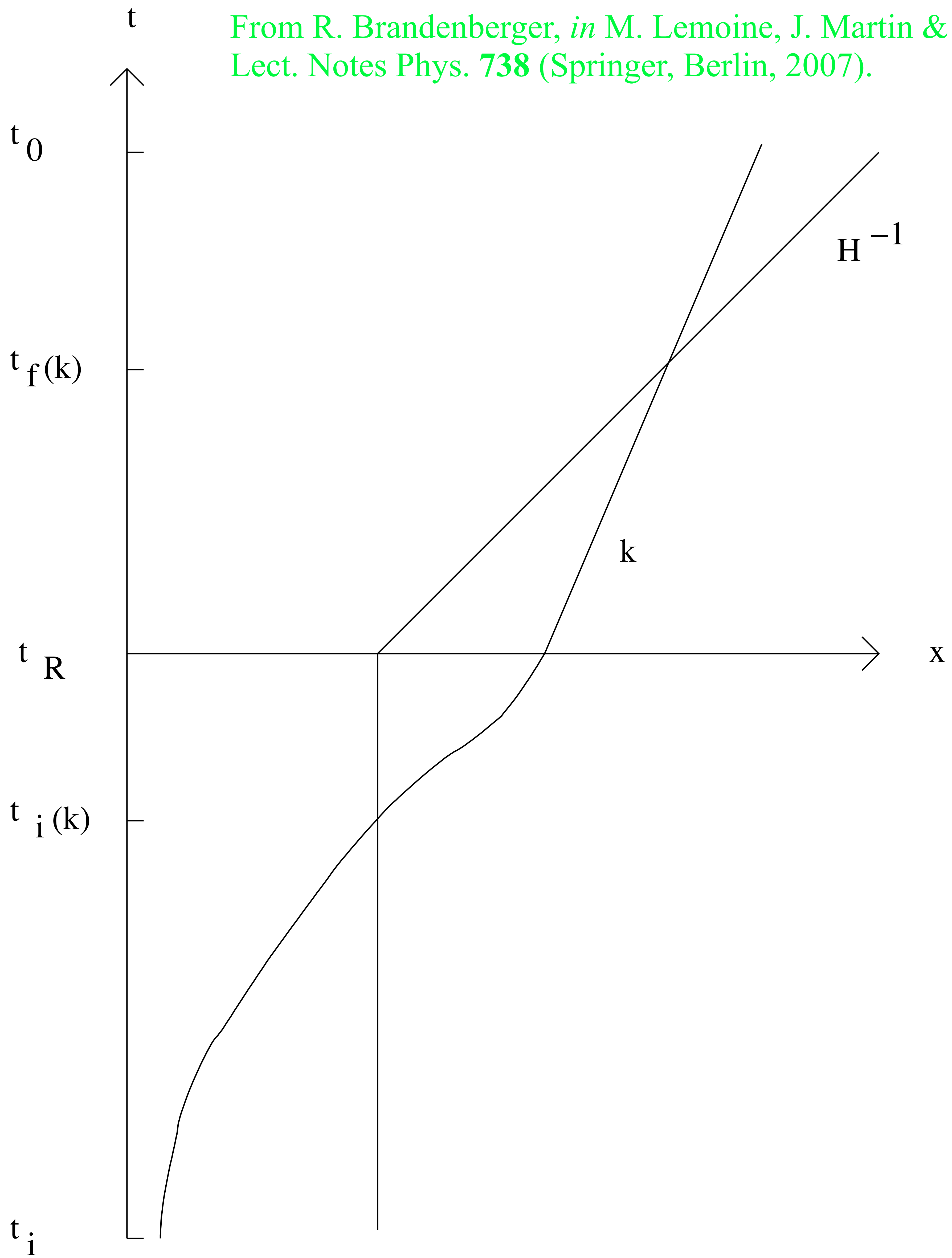
Alternative model???

From R. Brandenberger, *in* M. Lemoine, J. Martin & P. P. (Eds.), "Inflationary cosmology", Lect. Notes Phys. **738** (Springer, Berlin, 2007).



- Singularity

$$\exists t_{(\pm\infty)}; a(t) \rightarrow 0$$

- Trans-Planckian

$$\exists t; \ell(t) = \ell_0 \frac{a(t)}{a_0} \leq \ell_{\rm Pl}$$

- Hierarchy (amplitude)?

$$\frac{V(\varphi)}{\Delta\varphi^4} \leq 10^{-12}$$

- **Validity of classical GR?**

$$E_{\rm inf} \simeq 10^{-3} M_{\rm Pl}$$

Measure?

Inflation:

- solves cosmological puzzles
- uses GR + scalar fields [(semi-)classical]
- can be implemented in high energy theories
- makes falsifiable predictions ...
- ... consistent with all known observations
- string based ideas (brane inflation, ...)

Alternative model???

- singularity, initial conditions & homogeneity
- bounces
- provide challengers / new ingredients!

A brief history of bouncing cosmology

- R. C. Tolman, "*On the Theoretical Requirements for a Periodic Behaviour of the Universe*", PRD 38, 1758 (1931)
- G. Lemaître, "*L'Univers en expansion*", Ann. Soc. Sci. Bruxelles (1933)

...

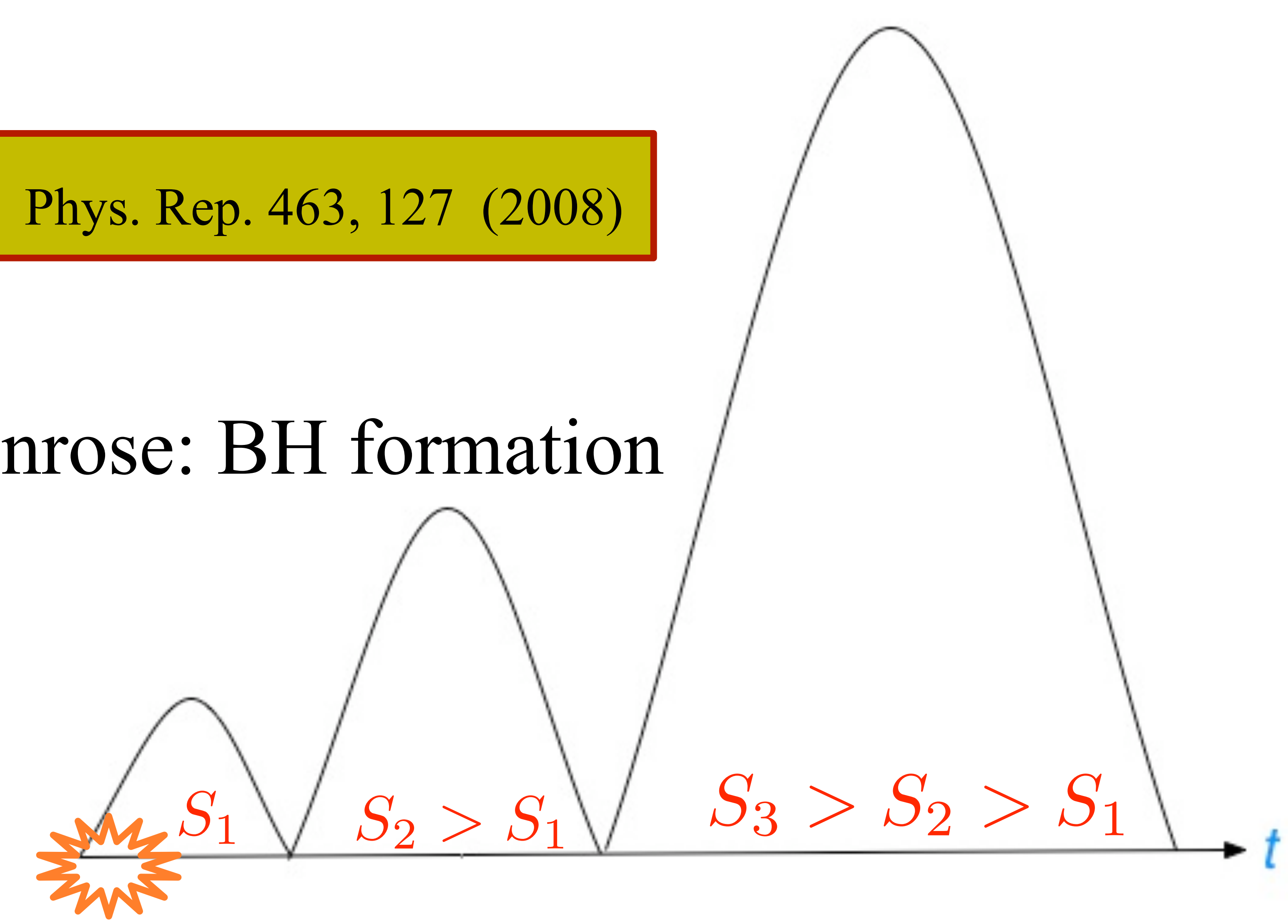
- A. A. Starobinsky, "*On one non-singular isotropic cosmological model*", Sov. Astron. Lett. 4, 82 (1978)
- M. Novello & J. M. Salim, "*Nonlinear photons in the universe*", Phys. Rev. 20, 377 (1979)
- V.N. Melnikov, S.V. Orlov, Phys. Lett. A 70, 263 (1979).
- R. Durrer & J. Laukerman, "*The oscillating Universe: an alternative to inflation*", Class. Quantum Grav. 13, 1069 (1996)

...

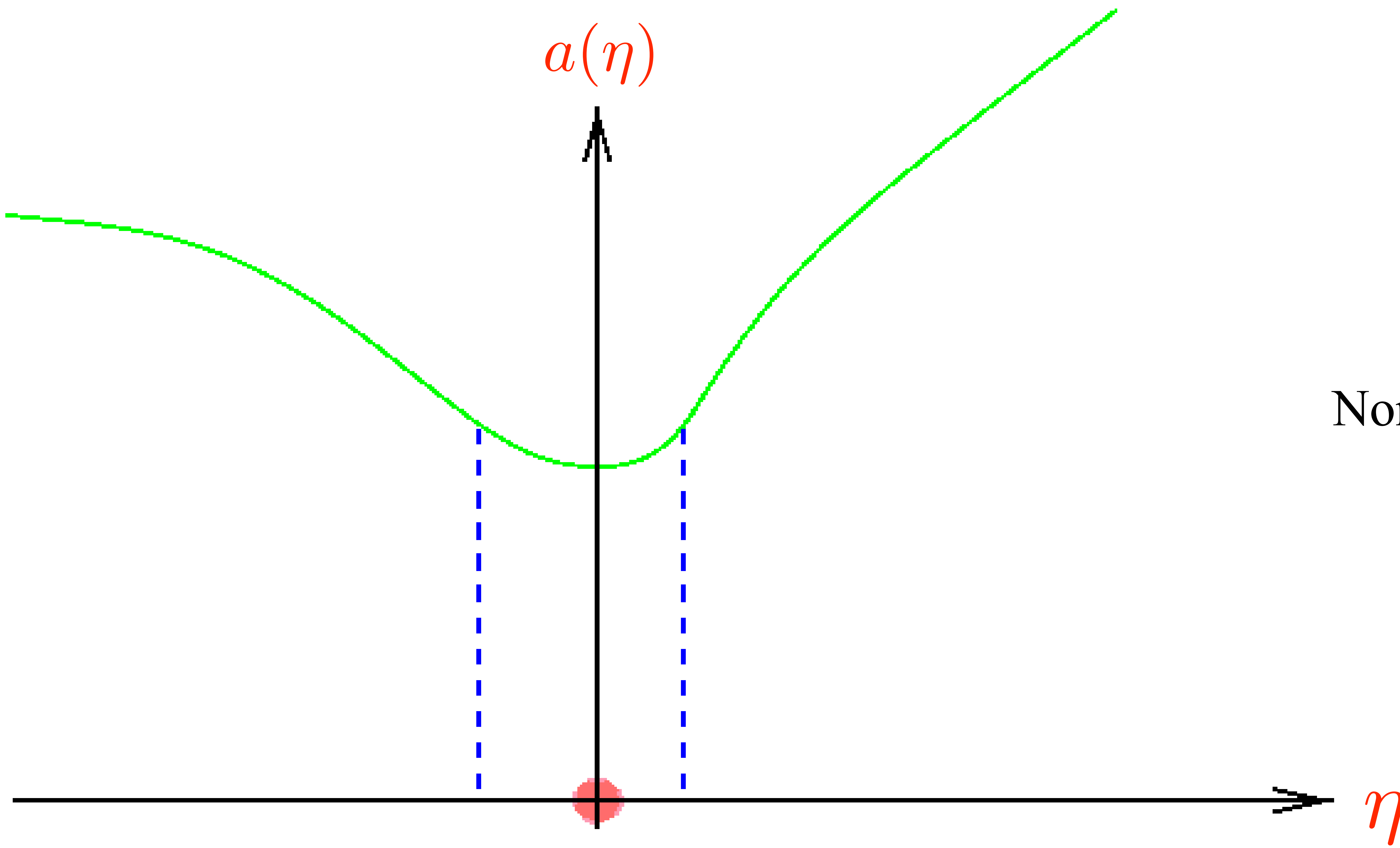
- M. Novello & S.E. Perez Bergliaffa, "*Bouncing cosmologies*", Phys. Rep. 463, 127 (2008)

- Penrose: BH formation

Quantum nucleation?

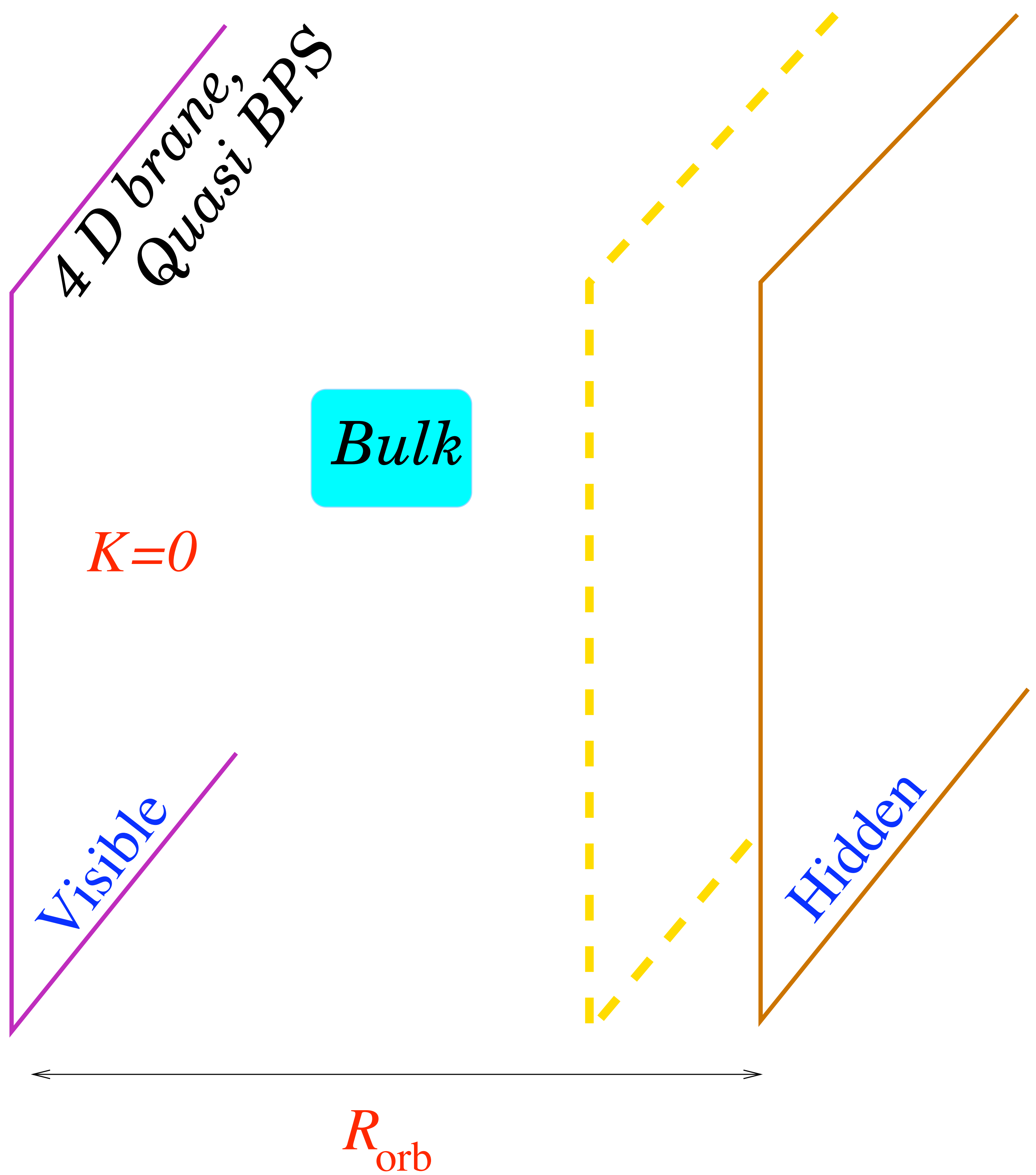


- PBB - Ekpyrotic - Modified gravity - Quantum cosmology - Quintom - Horava-Lifshitz - Lee-Wick - ...



Non singular bounce

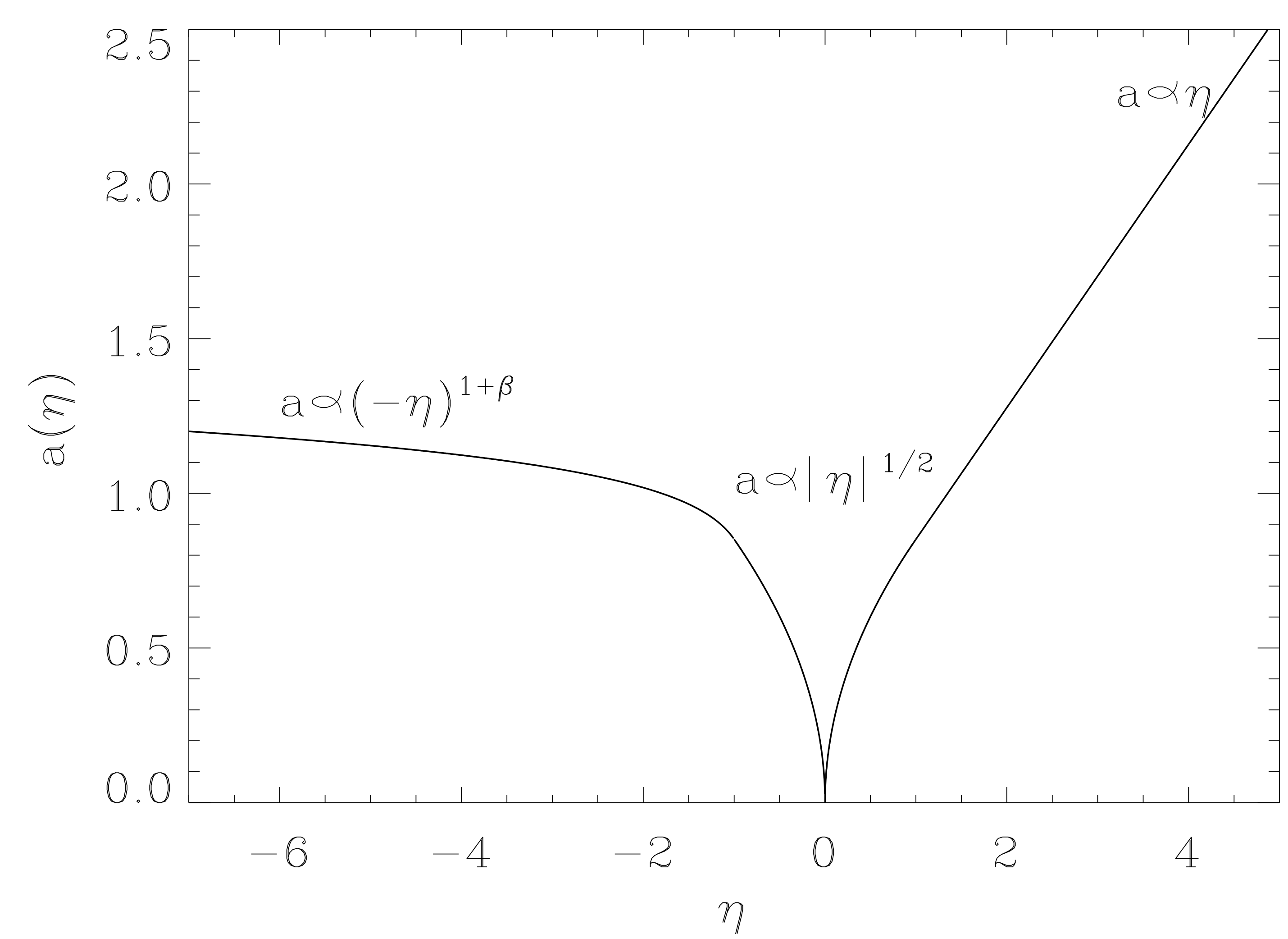
Ekpyrotic/cyclic scenario:



$$\mathcal{S}_5 \propto \int_{\mathcal{M}_5} \mathrm{d}^5 x \sqrt{-g_5} \left[R_{(5)} - \frac{1}{2} (\partial\varphi)^2 - \frac{3}{2} \frac{\mathrm{e}^{2\varphi} \mathcal{F}^2}{5\,!} \right],$$

$$\mathcal{S}_4 = \int_{\mathcal{M}_4} \mathrm{d}^4 x \sqrt{-g_4} \left[\frac{R_{(4)}}{2\kappa} - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right],$$

$$V(\varphi) = -V_{\mathrm{i}} \exp\left[- \frac{4\sqrt{\pi\gamma}}{m_{\mathrm{Pl}}} (\varphi - \varphi_{\mathrm{i}}) \right],$$



Singular ...

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... the Universe contracts towards a "big crunch" until the scale factor $a(t)$ is so small that quantum gravity effects become important. The presumption is that these quantum gravity effects introduce deviations from conventional general relativity and produce a bounce that preserves the smooth, flat conditions achieved during the ultraslow contraction phase.

PRL **105,** 261301 (2010)

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Non singular bounce

... where the Universe stops contraction and reverses to expansion at a finite value of $a(t)$ where classical general relativity is still valid. A significant advantage of this scenario is that the entire cosmological history can be described by 4D effective field theory and classical general relativity, without invoking extra dimensions or quantum gravity effects.

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Standard puzzles and some (bouncing) solutions

- **Singularity** Merely a non issue in the bounce case!
- **Horizon** $d_\mathrm{H} \equiv a(t) \int_{t_\mathrm{i}}^{t} \frac{\mathrm{d}\tau}{a(\tau)}$ can be made divergent easily if $t_\mathrm{i} \to -\infty$
- **Flatness** $\frac{\mathrm{d}}{\mathrm{d}t} |\Omega - 1| = -2 \frac{\ddot{a}}{\dot{a}^3}$ $\ddot{a} < 0 \;\&\; \dot{a} < 0$

  accelerated expansion (inflation) or decelerated contraction (bounce)

- **Homogeneity** Large & flat Universe + low initial density + diffusion

  $$\frac{t_\mathrm{dissipation}}{t_\mathrm{Hubble}} \propto \frac{\lambda}{R_\mathrm{H}^{1/3}} \left(1 + \frac{\lambda}{A R_\mathrm{H}^2}\right)$$ enough time to dissipate any wavelength

  $\Longrightarrow$ vacuum state! ... debatable though

- **Topological defects???**
- **Perturbations** Planck raises serious questions...

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Implementing a bounce = problem with GR!

Violation of Null Energy Condition (NEC) $\rho + p \geq 0$

$\Downarrow$

Instabilities for perfect fluids

Implementing a bounce = problem with GR!

Violation of Null Energy Condition (NEC) $\rho + p \geq 0$

Positive spatial curvature + scalar field

Modify GR?

Add new terms?

K-bounce, Ghost condensates, Galileons...?

Various instabilities may arise!
(e.g. radiation for matter bounce or curvature perturbations)

The problem with contraction: BKL/shear instability

$$\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\sum_i \mathrm{e}^{2\theta_i(t)}\sigma^i\sigma^i$$

Ricci flat:

$$\sigma^i = \mathrm{d}x^i$$

$$\sum_i \theta_i = 0$$

Average scale factor

$$\frac{\dot{a}}{a}$$ Mean Hubble parameter

$$H_i \equiv \frac{1}{a\mathrm{e}^{\theta_i}}\frac{\mathrm{d}}{\mathrm{d}t}\left(a\mathrm{e}^{\theta_i}\right) = H + \dot{\theta}_i$$

Friedman equations

$$\left.\begin{aligned} H^2 &= \frac{\rho_{\mathrm{T}}}{3M_{\mathrm{Pl}}^2} + \frac{1}{6}\sum_i \dot{\theta}_i^2 \\ \dot{H} &= -\frac{\rho_{\mathrm{T}} + p_{\mathrm{T}}}{2M_{\mathrm{Pl}}^2} - \frac{1}{2}\sum_i \dot{\theta}_i^2 \end{aligned}\right\} \ddot{\theta}_i + 3H\dot{\theta}_i = 0$$

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$$\ddot{\theta}_i + 3H\dot{\theta}_i = 0$$

$$\rho_{\mathrm{shear}} \propto a^{-6}$$

Ekpyrotic solution:

$$w_{\text{ekp}} \gg 1 \quad \Longrightarrow \rho_{\text{ekp}} \propto a^{-3\left(1+w_{\text{ekp}}\right)} \gg a^{-6} \text{ when } \quad a \to 0$$

Hence a singular bounce!

Problem: regular bounce $\exists$ phase with $w_{\text{bounce}} < -1$

So finally...

$$\rho_{\text{Shear}} \equiv \frac{M_{\text{Pl}}^2}{2} \sum_i \dot{\theta}_i^2 \propto a^{-6} \gg \rho_{\text{Fluid}}$$

Singularity!

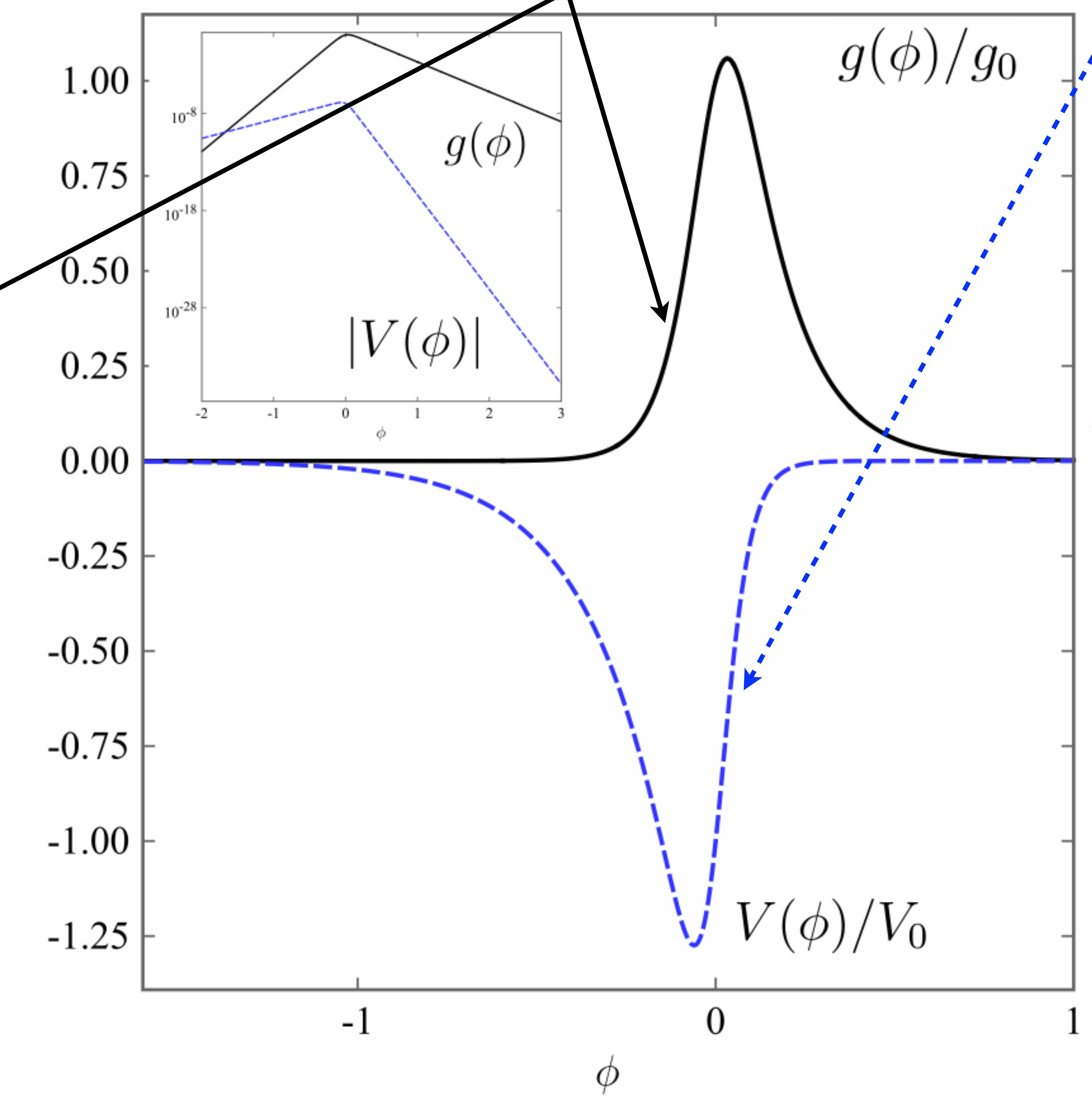
Y. Cai, R. Brandenberger & PP, Class. Quantum Grav. 30 (2013) 075019 [arXiv:1301.4703]

A nonsingular bounce model

$$\mathcal{L}\left[\phi\left(x\right)\right] = K(\phi, X) + G(\phi, X)\Box\phi$$ with kinetic term $$X \equiv \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$ + Fluid

Specific choices: $K(\phi, X) = M_{\rm Pl}^2\left[1 - g(\phi)\right]X + \beta X^2 - V(\phi)$ $\quad G(X) = \gamma X$

$$g(\phi) = \frac{2g_0}{e^{-\sqrt{\frac{2}{p}}\phi} + e^{b_g\sqrt{\frac{2}{p}}\phi}}$$



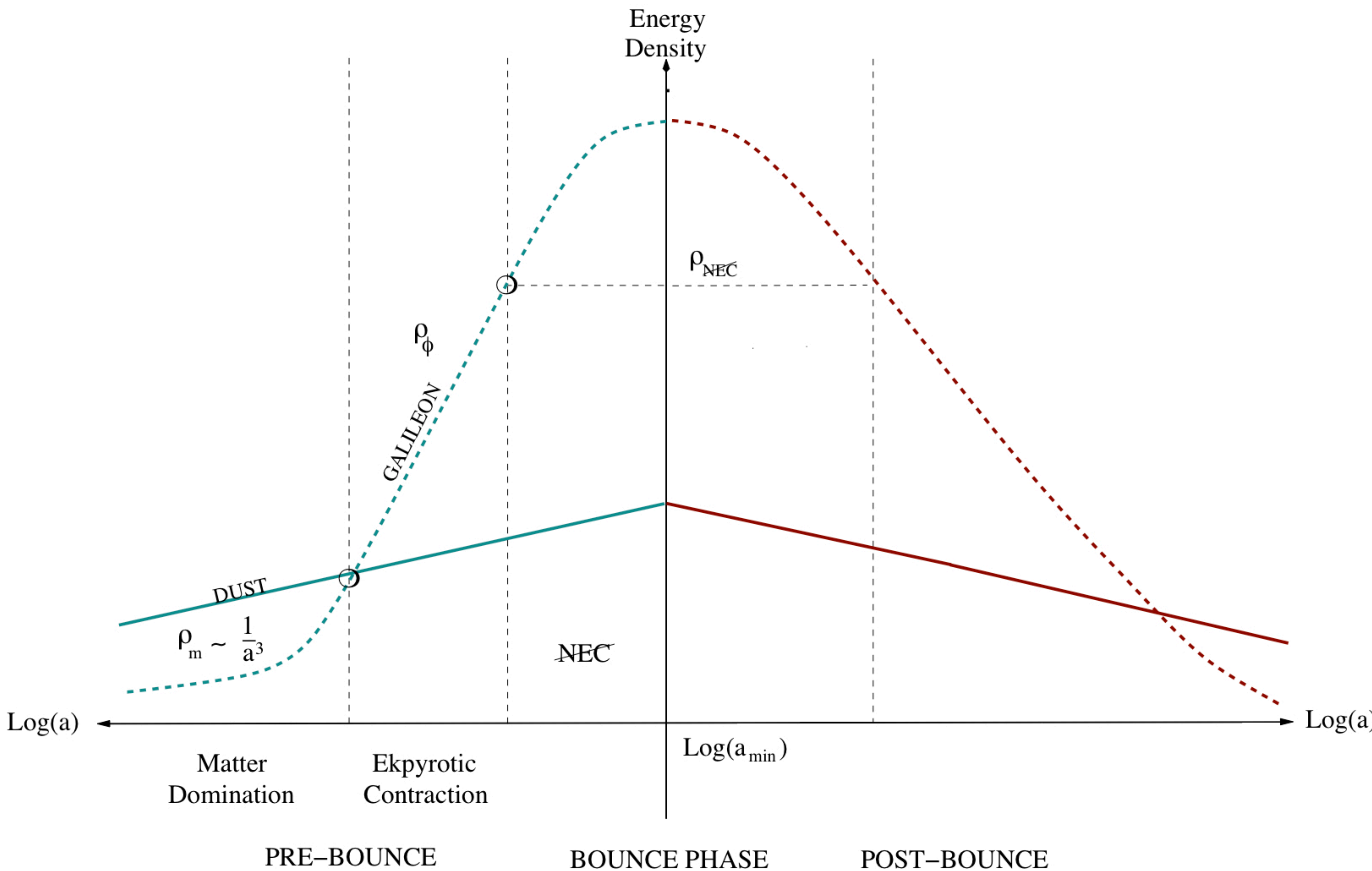
$$V(\phi) = -\frac{2V_0}{e^{-\sqrt{\frac{2}{q}}\phi} + e^{b_V\sqrt{\frac{2}{q}}\phi}}$$

+Bianchi

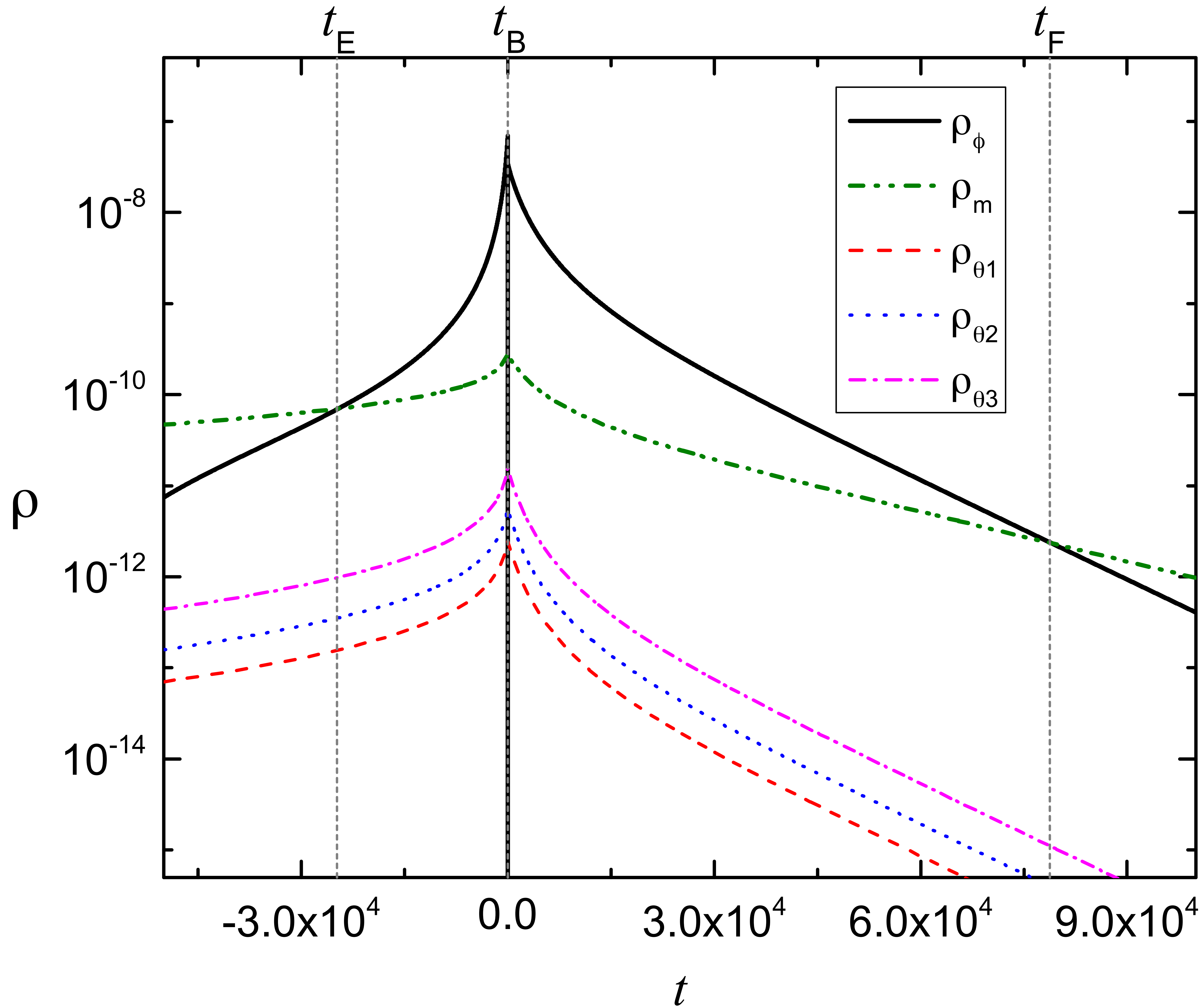
5 phases:

A.	Matter contraction	Produces scale invariant perturbations
B.	Ekpyrotic contraction	Removes anisotropies
C.	The bounce itself	Leads to expansion
D.	Fast-roll expansion	Connects to standard model!!
E.	Radiation + Matter + ...	BB cosmology

D. Battefeld (2013)



Energy densities



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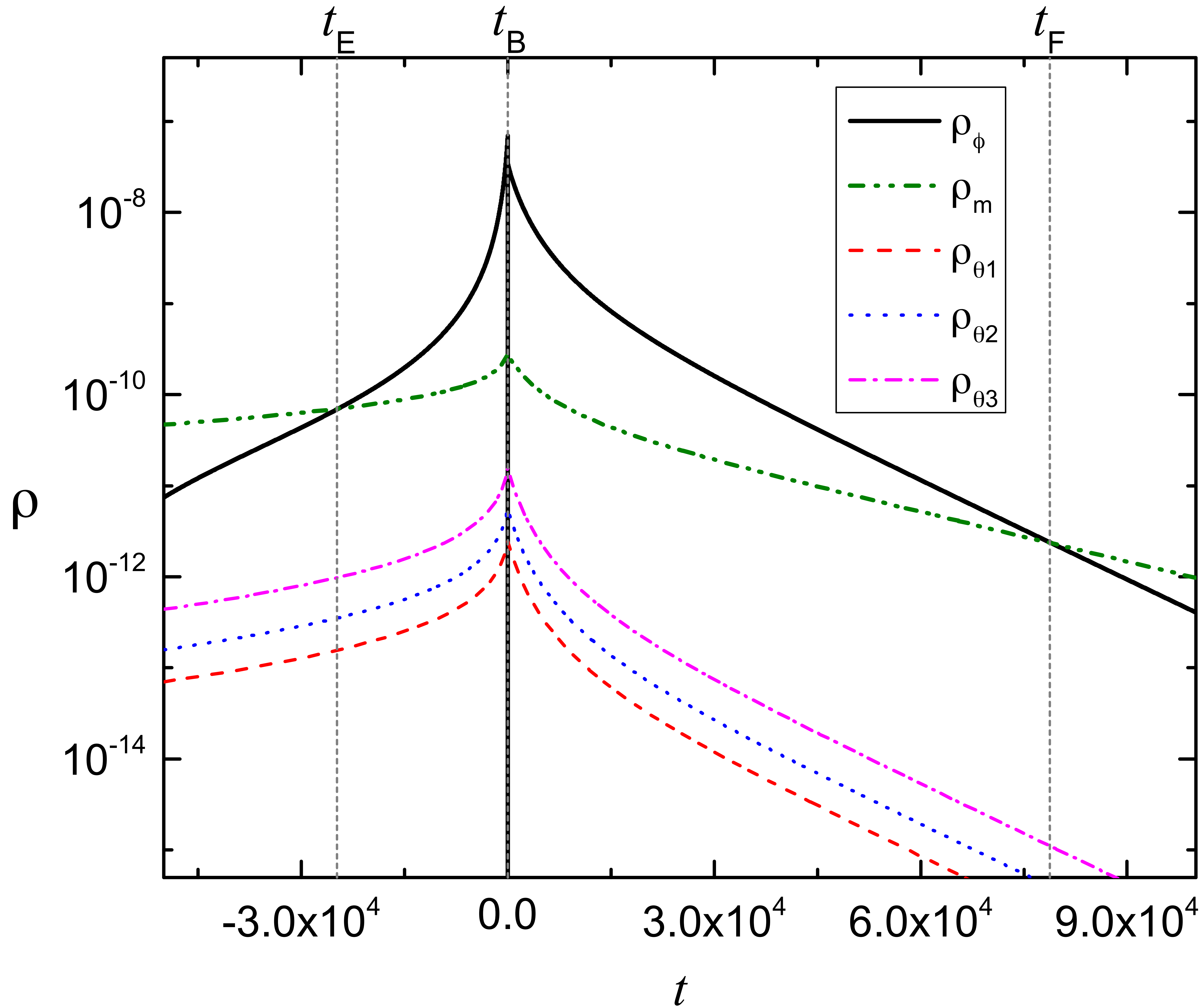
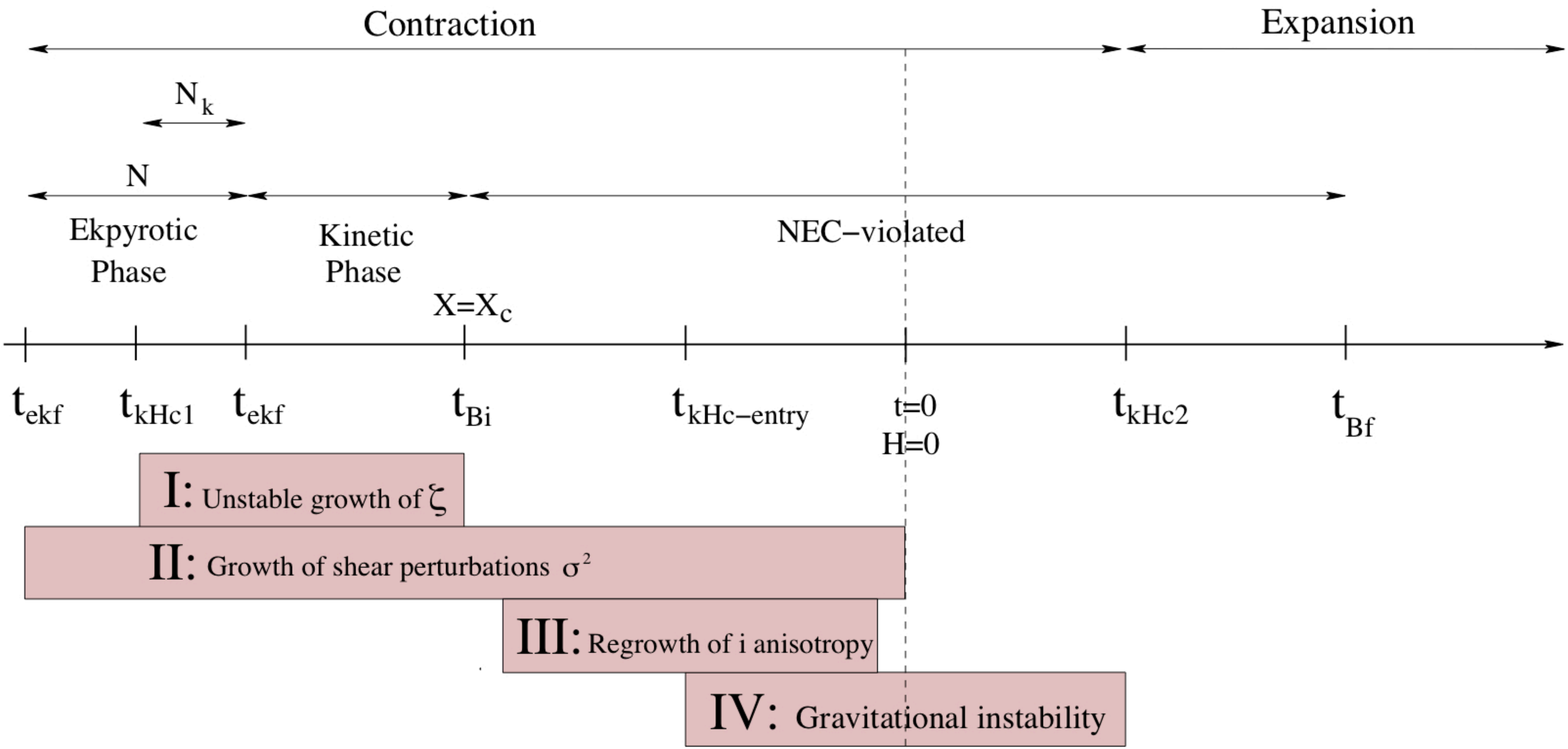


Anisotropies can remain small all throughout!!!!

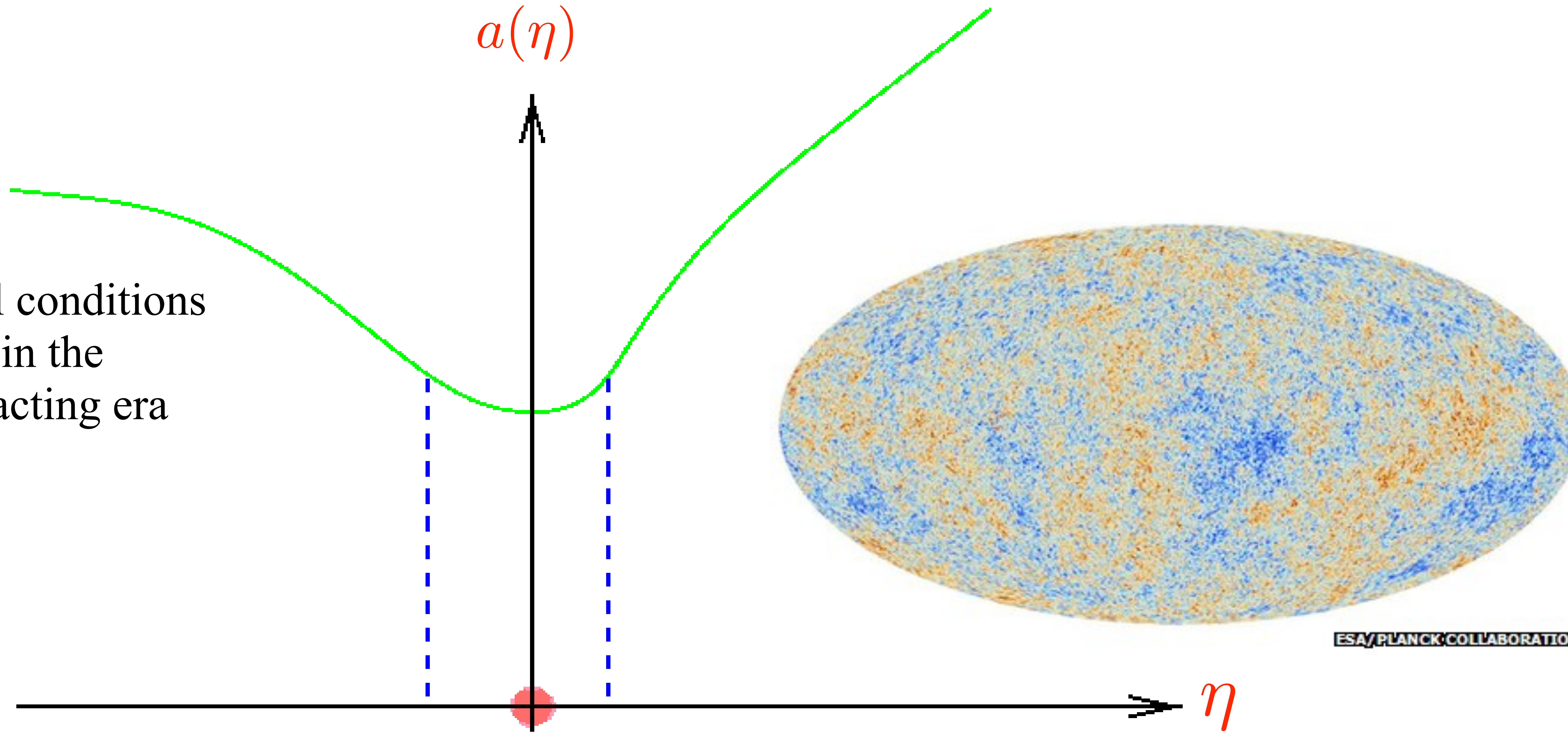
Summary of bouncing problems

D. Battefeld (2013)



Perturbations: $\mathrm{d}s^2 = a^2(\eta)\left\{(1+2\Phi)\,\mathrm{d}\eta^2 - \left[(1-2\Phi)\,\gamma_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}$

Initial conditions fixed in the contracting era



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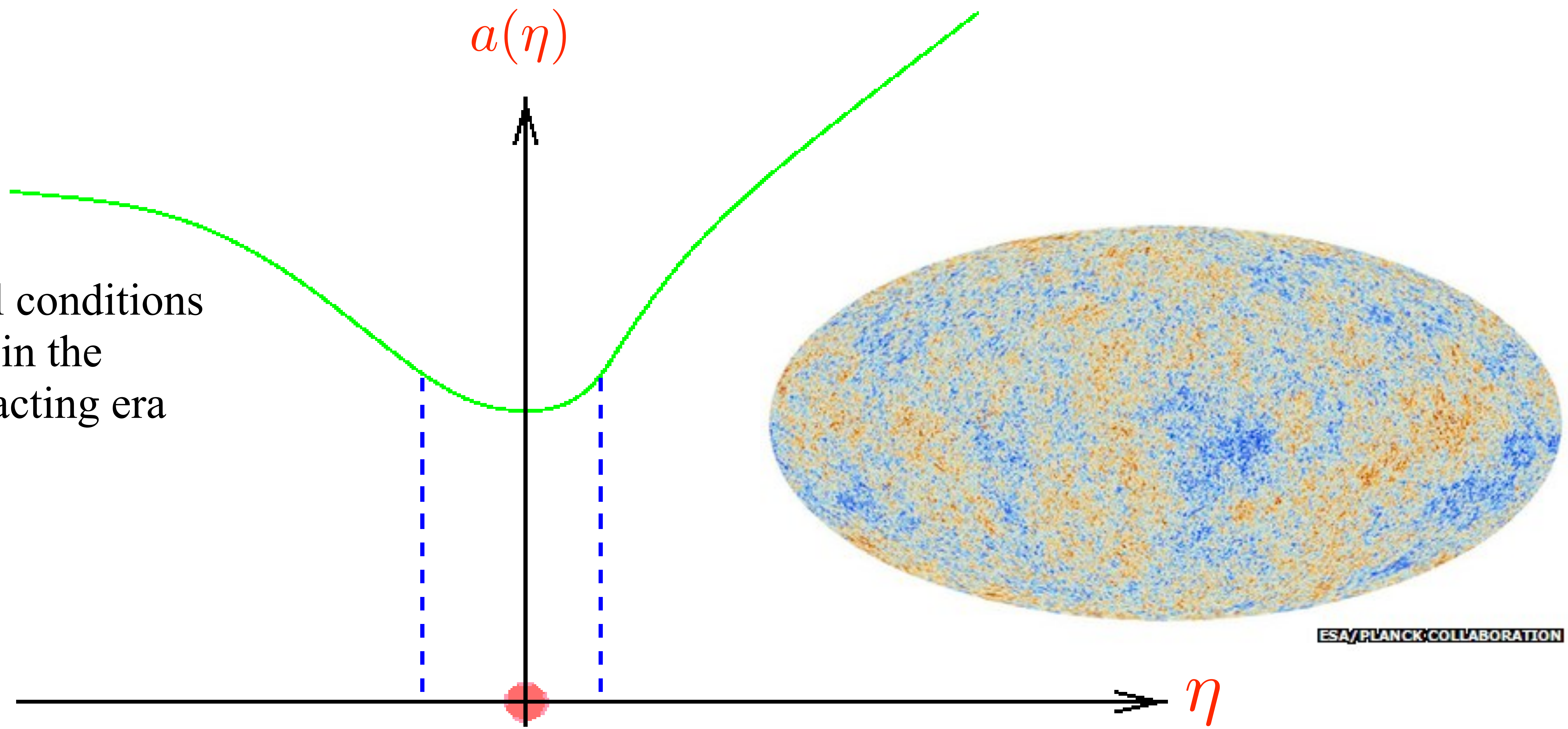

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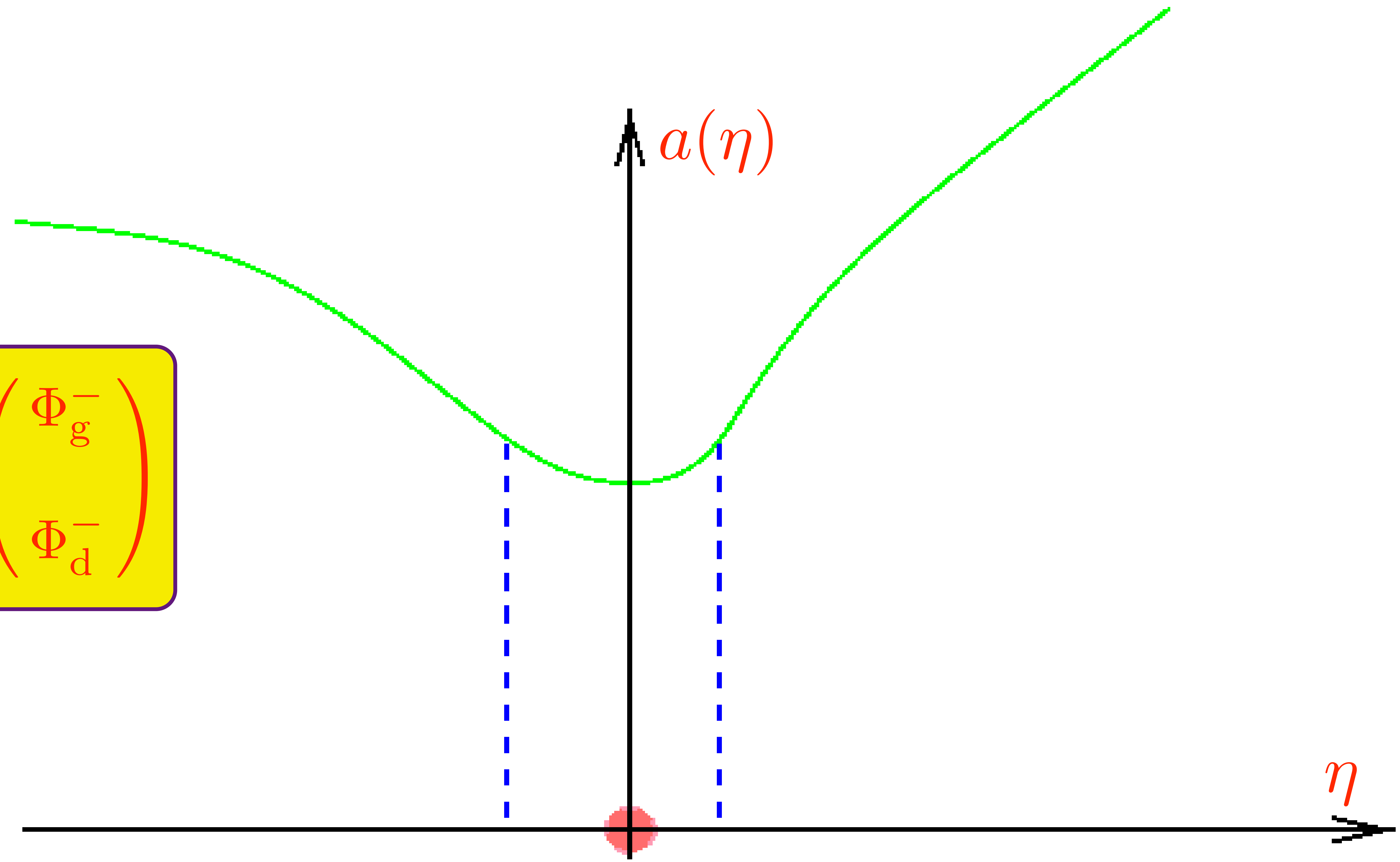

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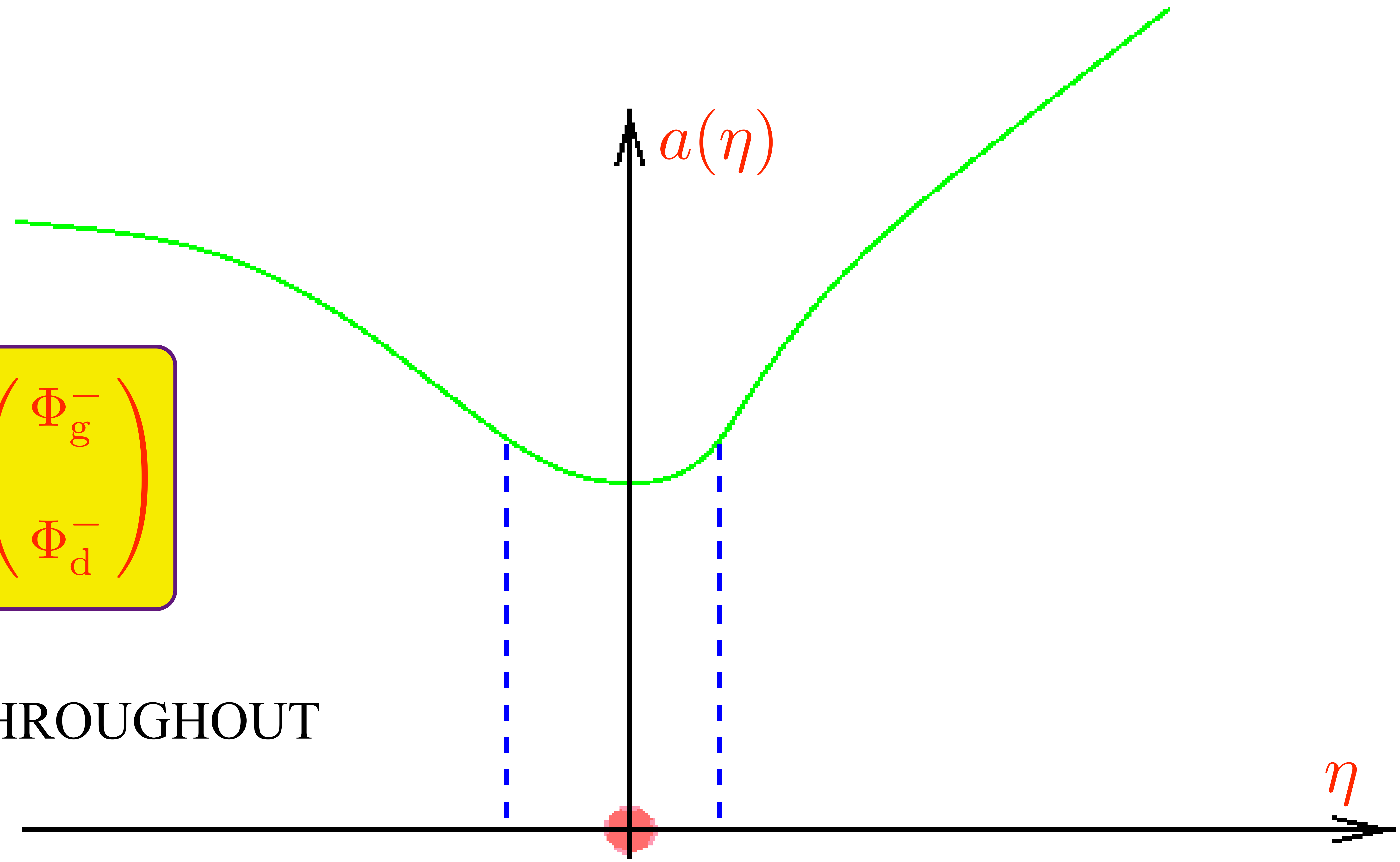
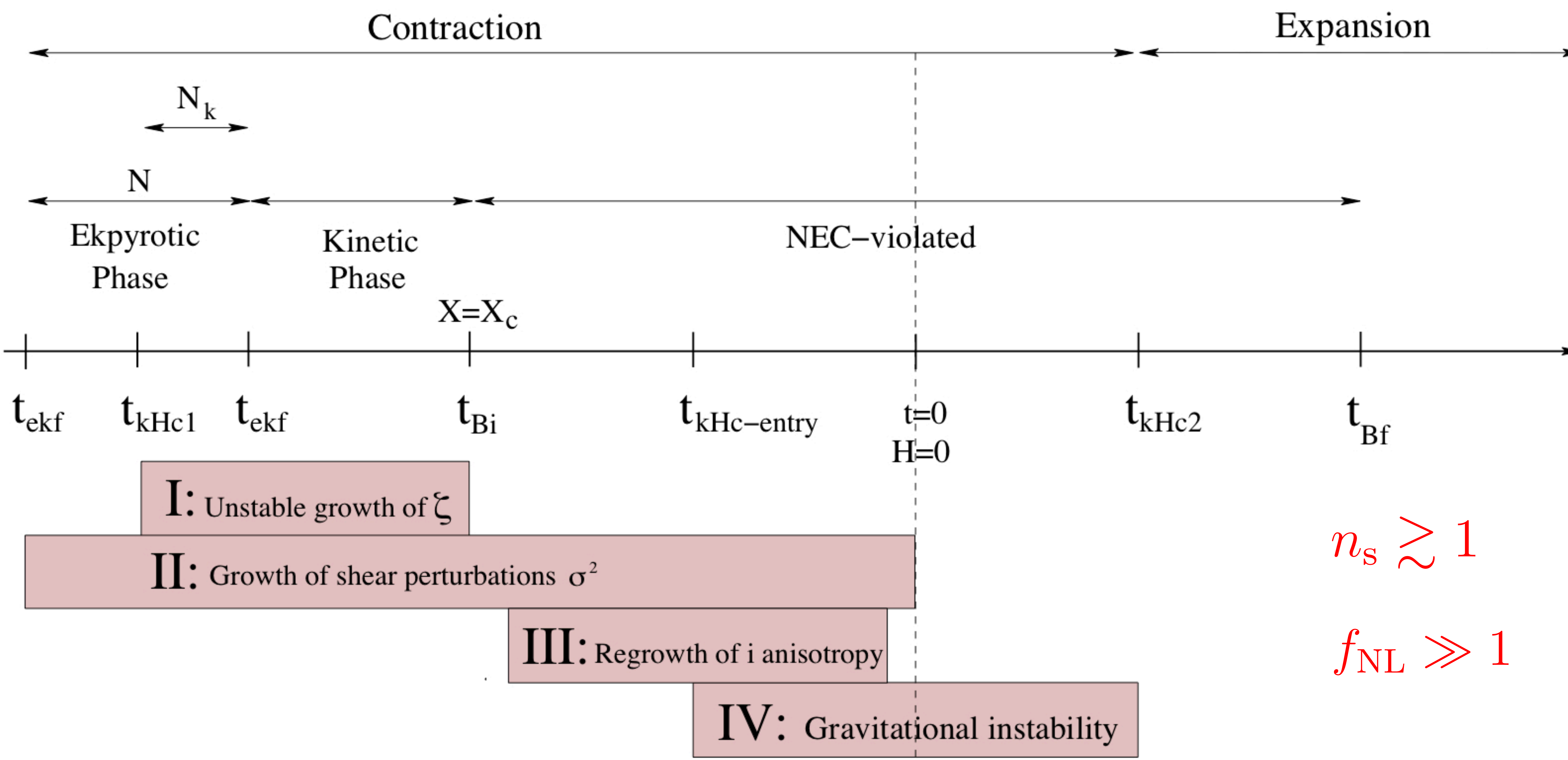


ASSUME LINEARITY THROUGHOUT

Summary of bouncing problems

D. Battefeld (2013)



$n_s \gtrsim 1$

$f_{NL} \gg 1$

+ phase initial conditions