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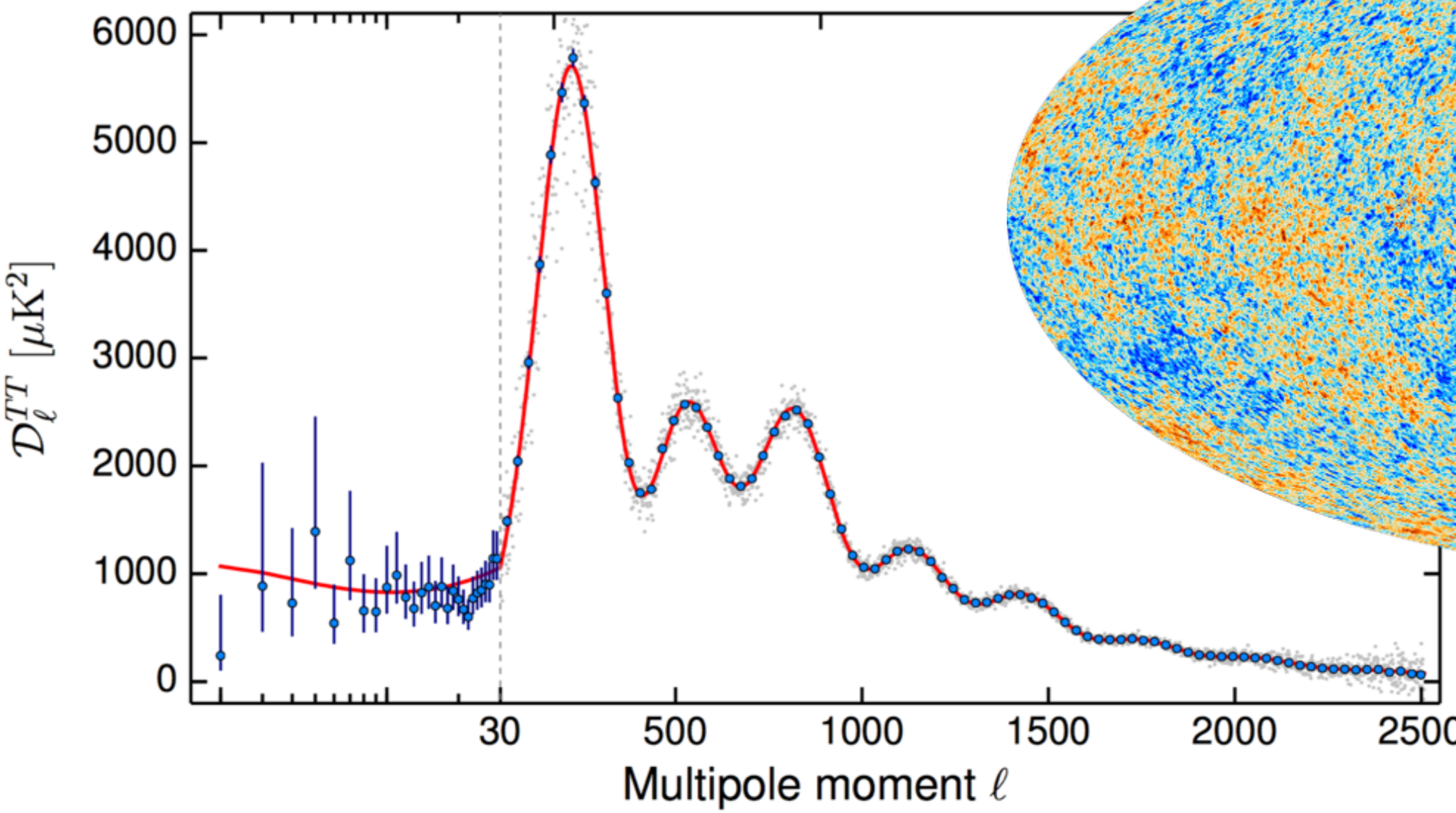
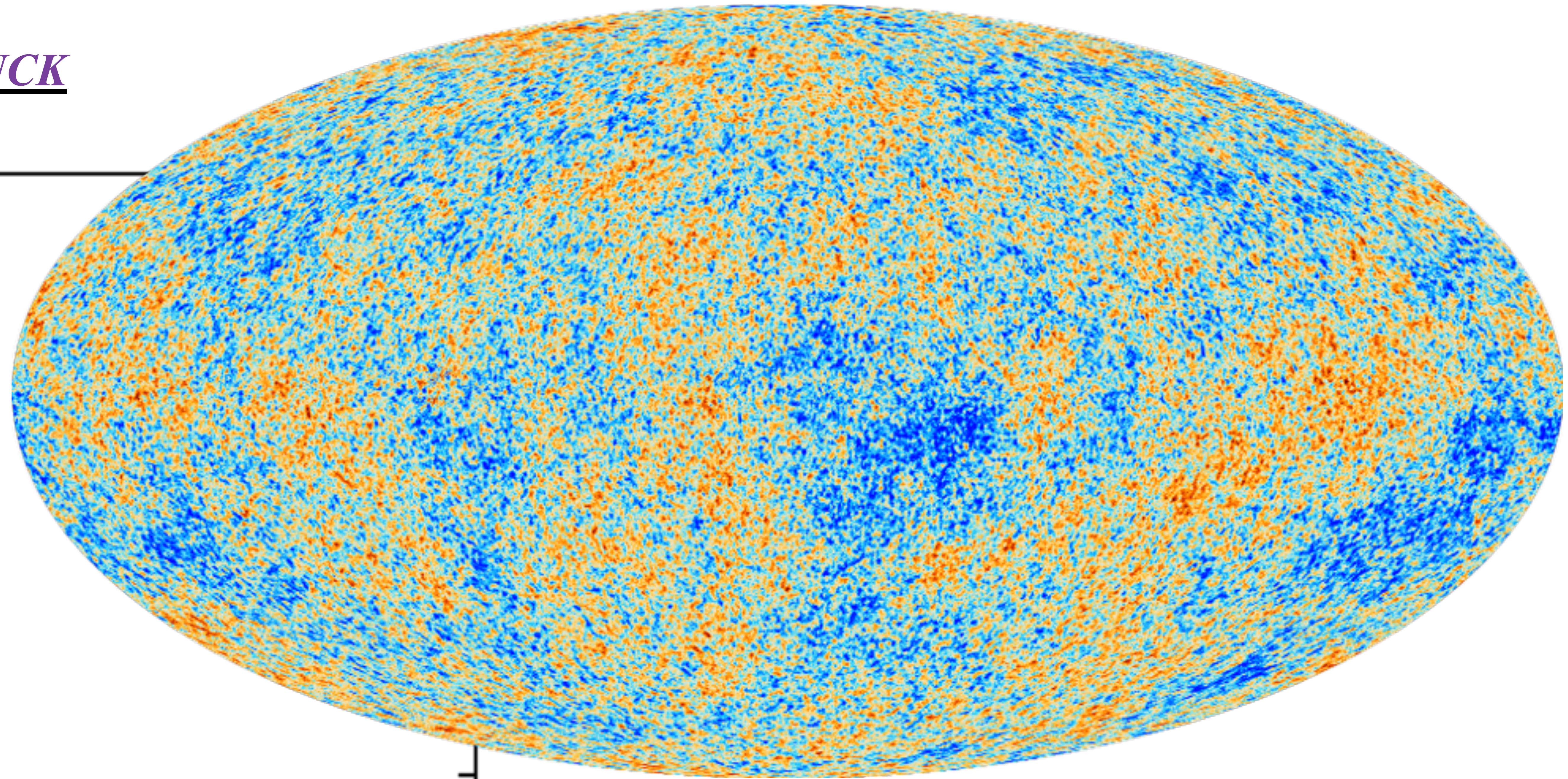
IAP conference
Paris
18/12/14

Classical Bouncing Cosmologies
(a critical review)

Paris - 18th December 2014

Currently available observational data: ***PLANCK***





$\Omega_{\mathcal{K}} = 0.000 \pm 0.005$

$n_{\rm s} = 0.9639 \pm 0.0047$ almost scale invariant

excluded

$f_{\rm NL}^{\rm local} = 0.71 \pm 5.1$
$f_{\rm NL}^{\rm equil} = -9.5 \pm 44$
$f_{\rm NL}^{\rm ortho} = -25 \pm 22$

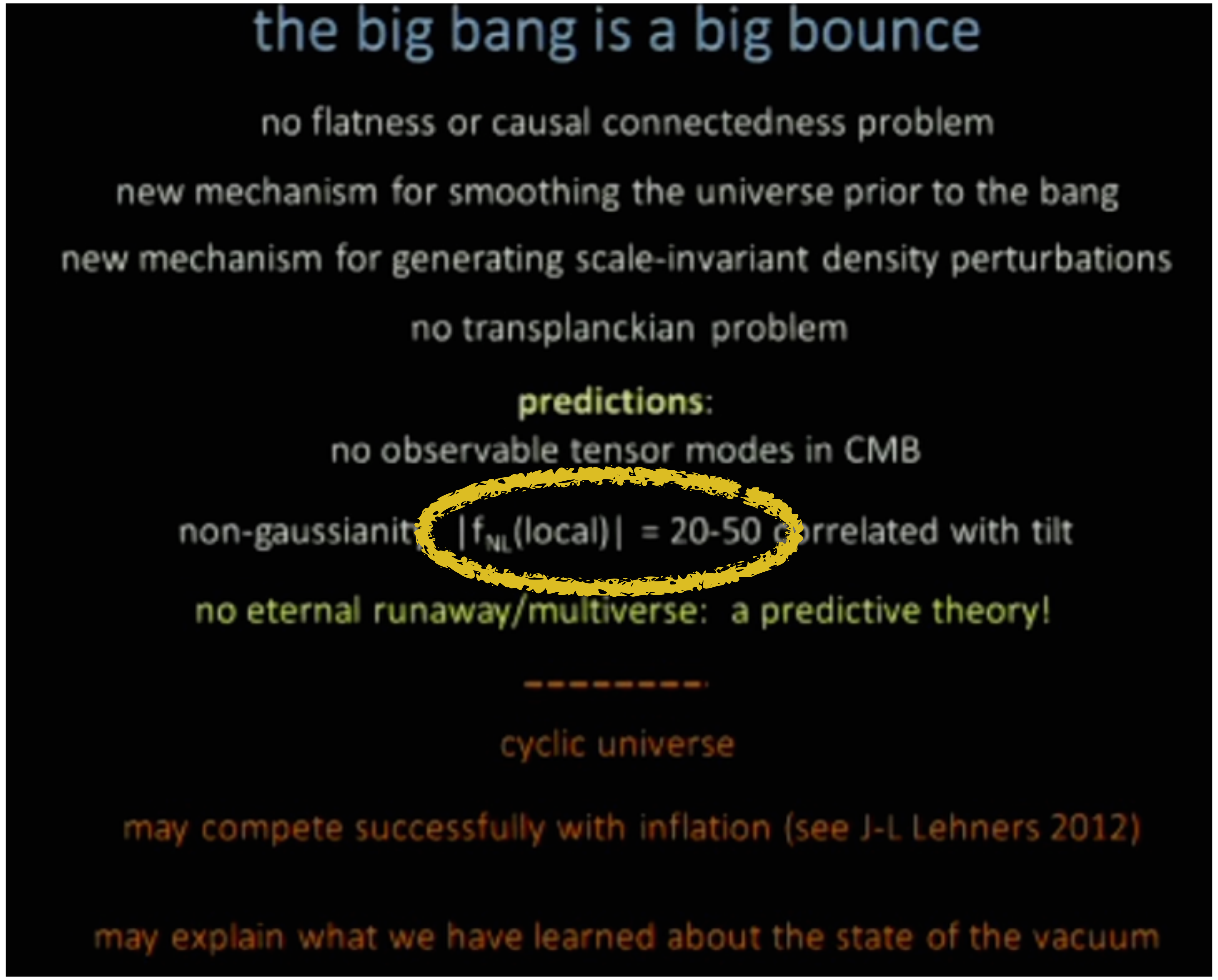
gaussian signal

isocurvature $\lesssim 1\%$

$r < 0.11$

quantum vacuum fluctuations of a single scalar d.o.f

compatible with ***INFLATION***



http://pirsa.org/13030079/

Planck 2013 results support the cyclic universe

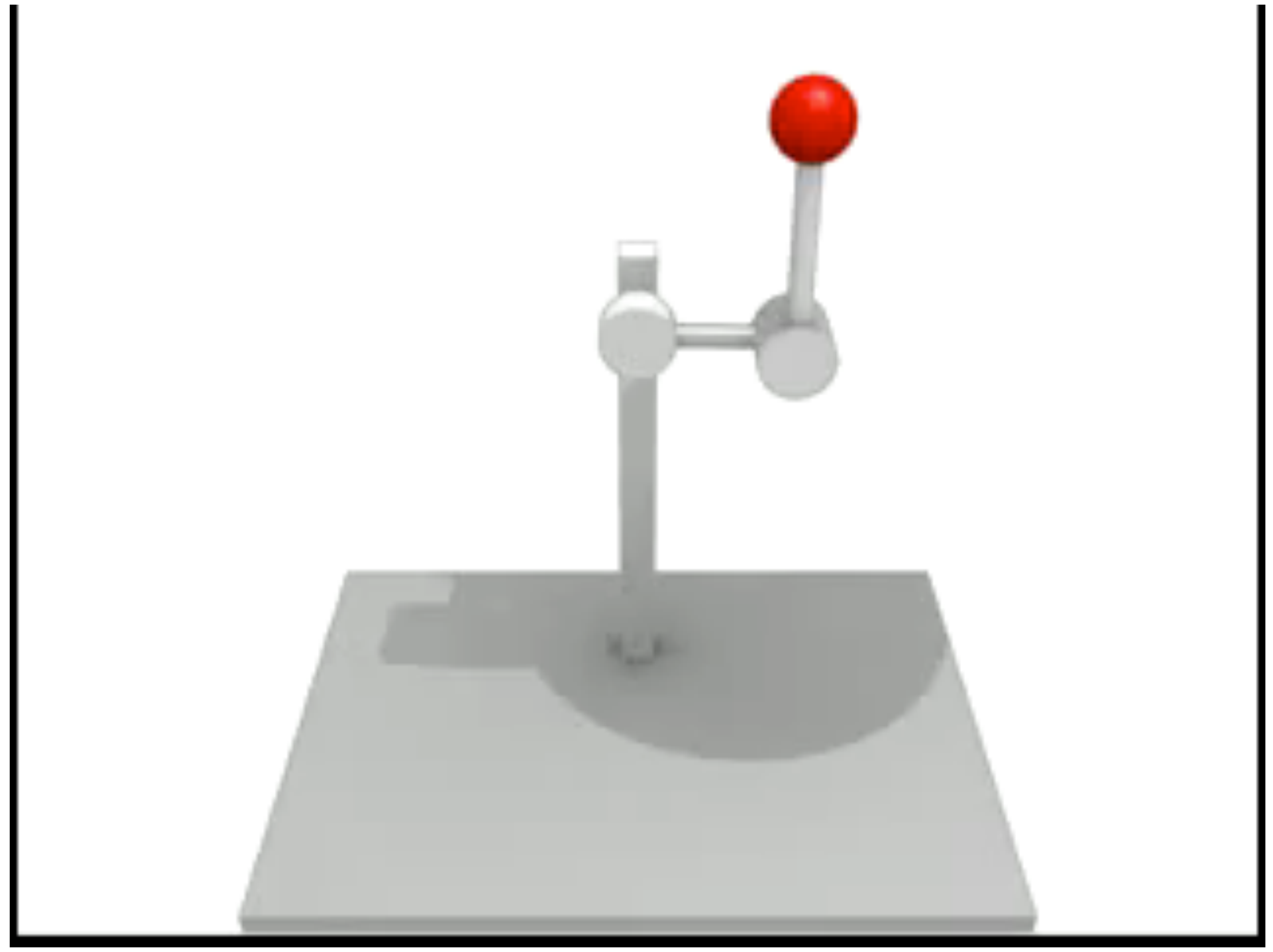
(Submitted on 10 Apr 2013 (v1), last revised 19 Jul 2013 (this version, v3))

arXiv:1304.3122

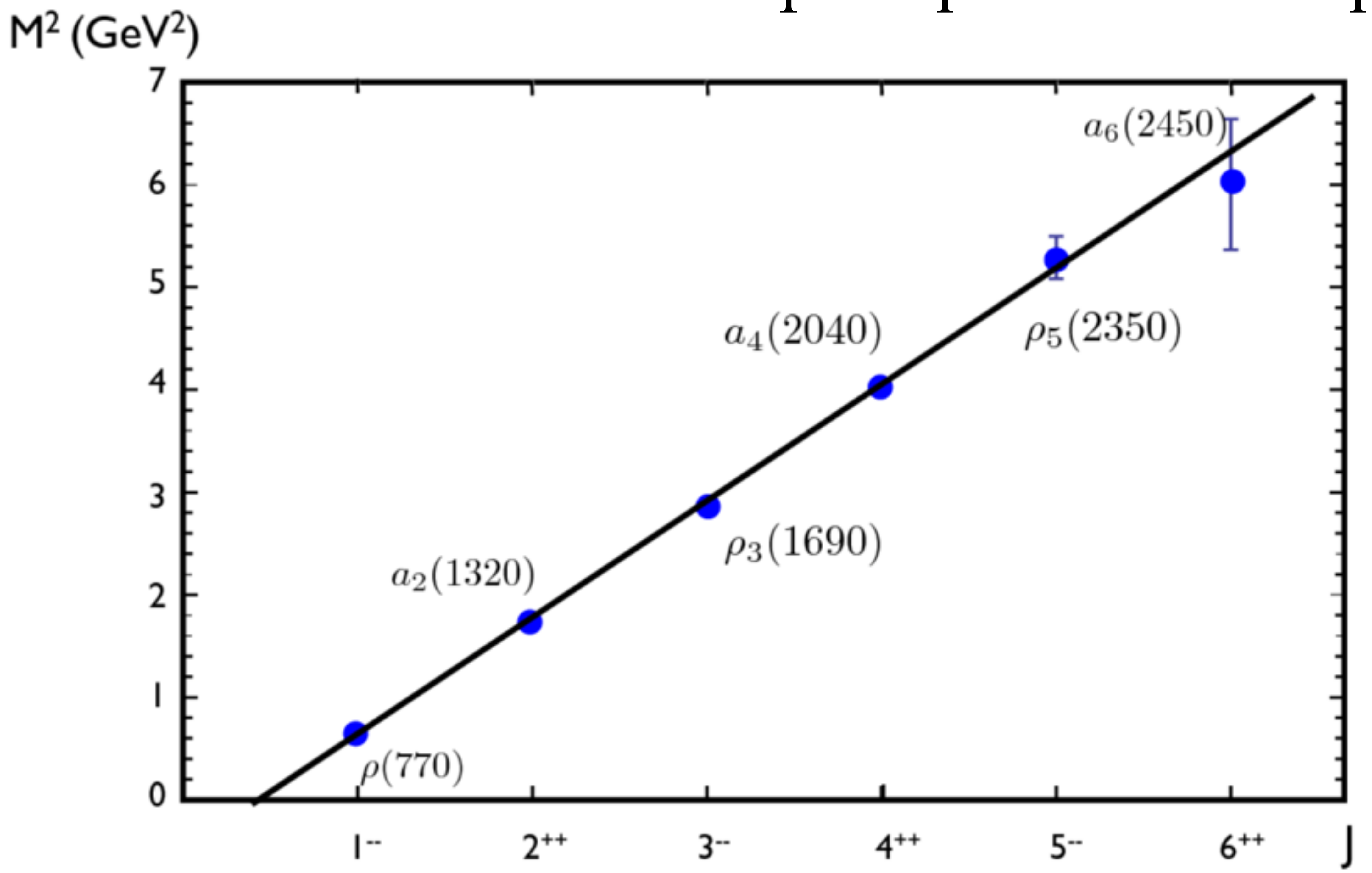
$$f_{NL} = \pm 5 + \frac{3}{2}\kappa_3\sqrt{\epsilon} \qquad (12)$$

Simple data $\Longrightarrow$ simple theory?

- Double pendulum: very simple… ($\boldsymbol{F} = m\gamma$)



- Regge trajectories: QCD, asymptotic freedom… perhaps not that simple



Simple data $\Longleftrightarrow$ simple theory?

not so.

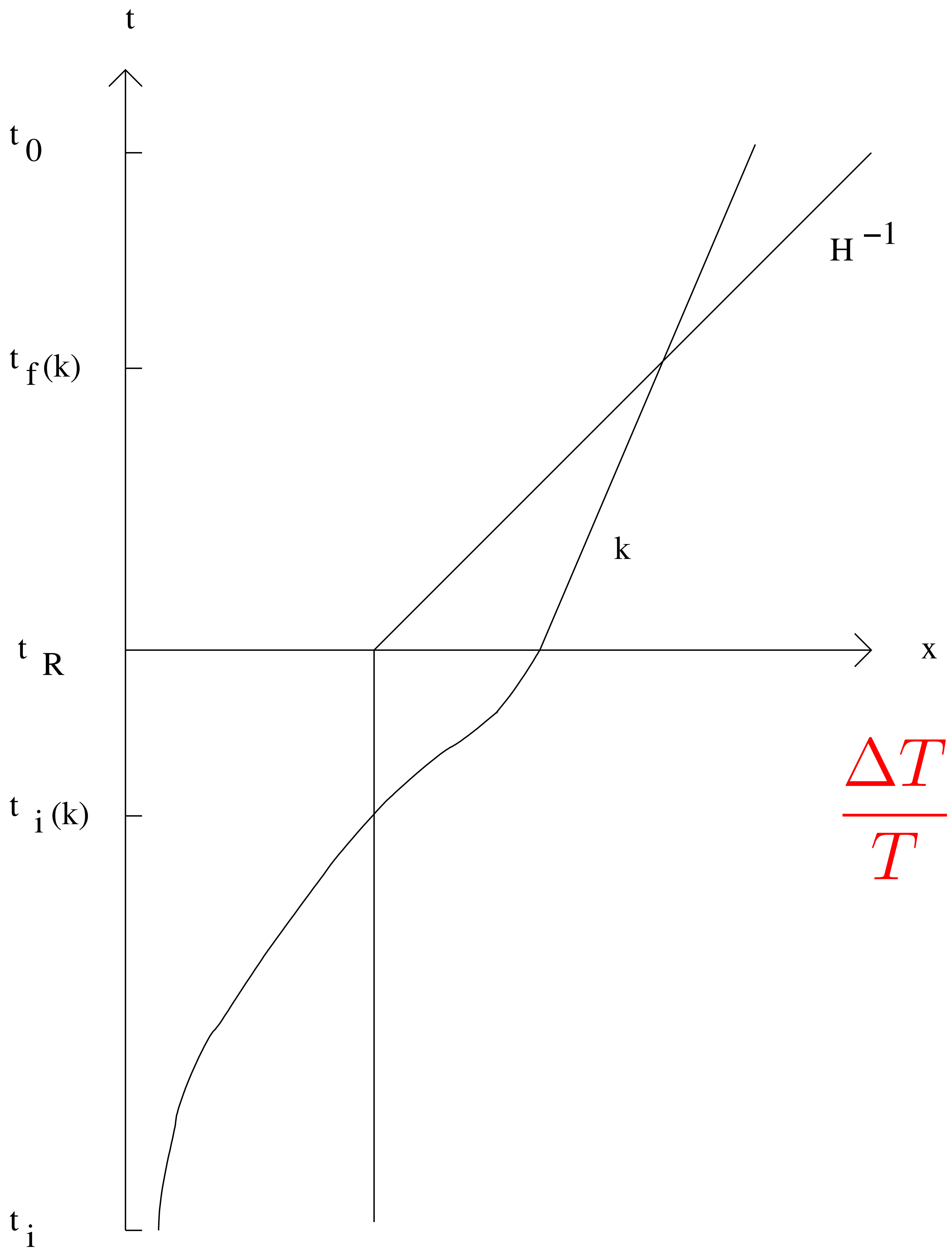
Inflation:

- ☺ solves cosmological puzzles
- ☺ uses GR + scalar fields [(semi-)classical]
- ☺ can be implemented in high energy theories
- ☺ string implementation (brane inflation, ...)

- ☺ makes falsifiable predictions ...
- ☺ ... consistent with all known observations

why bother with alternatives?

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



- Singularity $\exists t_{(\pm\infty)}; a(t) \to 0$
- 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?**

$$\frac{\Delta T}{T} \propto G_{\rm N} E_{\rm inf}^2 \sim \left(\frac{E_{\rm inf}}{M_{\rm Pl}}\right)^2 \longrightarrow E_{\rm inf} \simeq 10^{-3} M_{\rm Pl}$$

- η problem & Lyth bound
- Initial condition & entropy
- Eternal inflation & measure
- BICEP2

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)

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Einstein eternal bouncing universe

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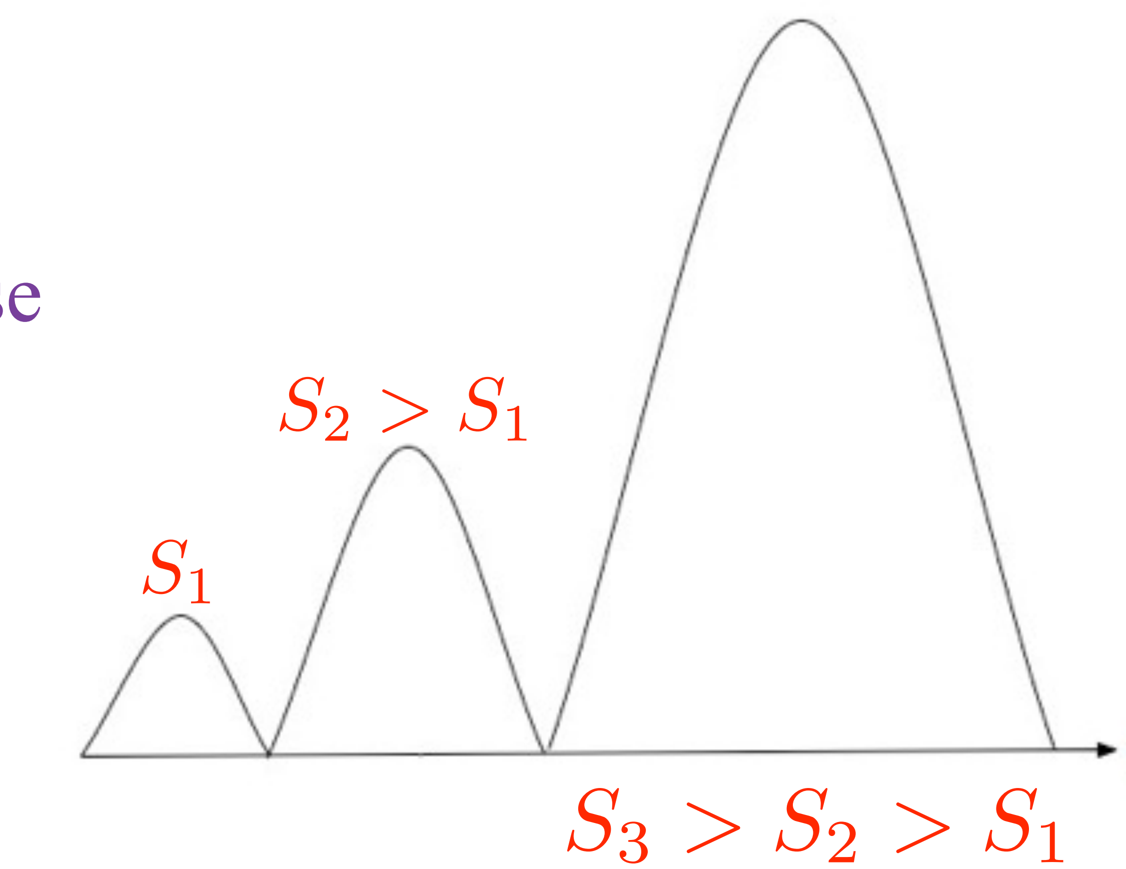

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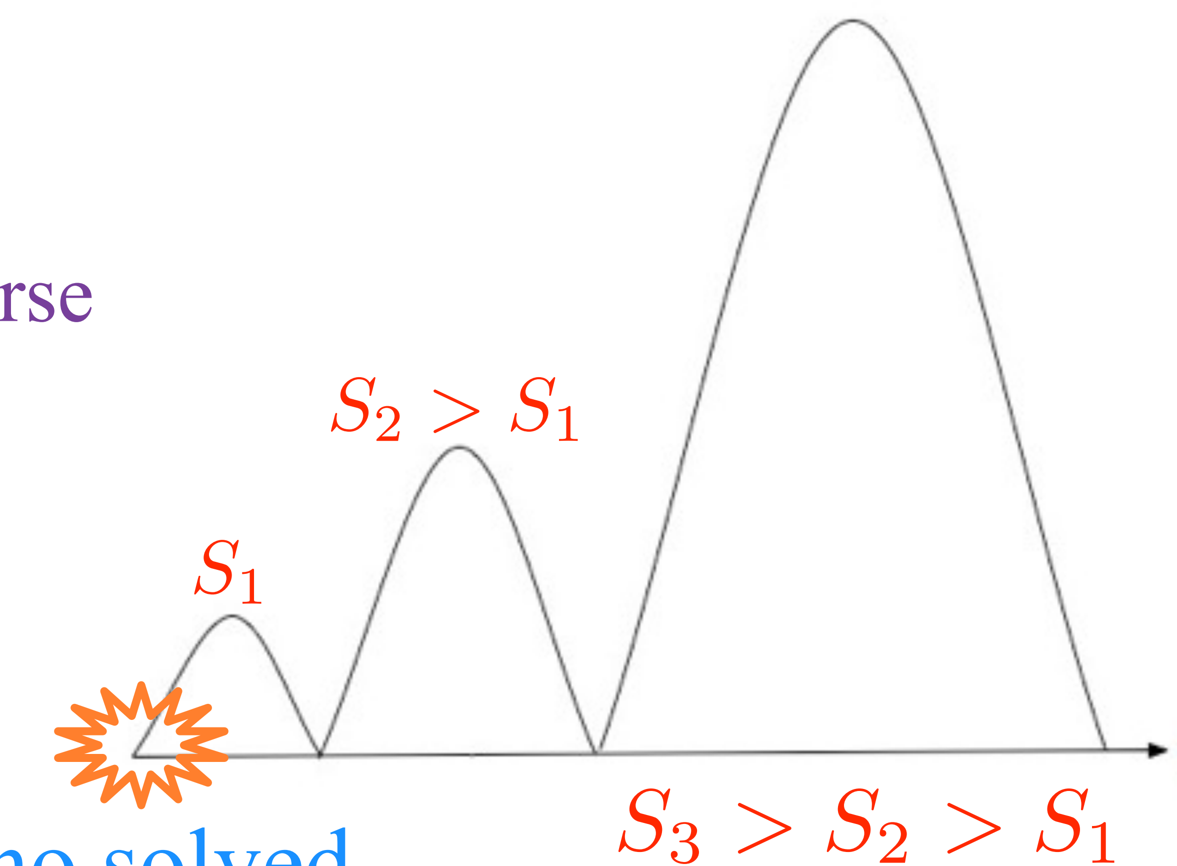

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Singularity pb no solved

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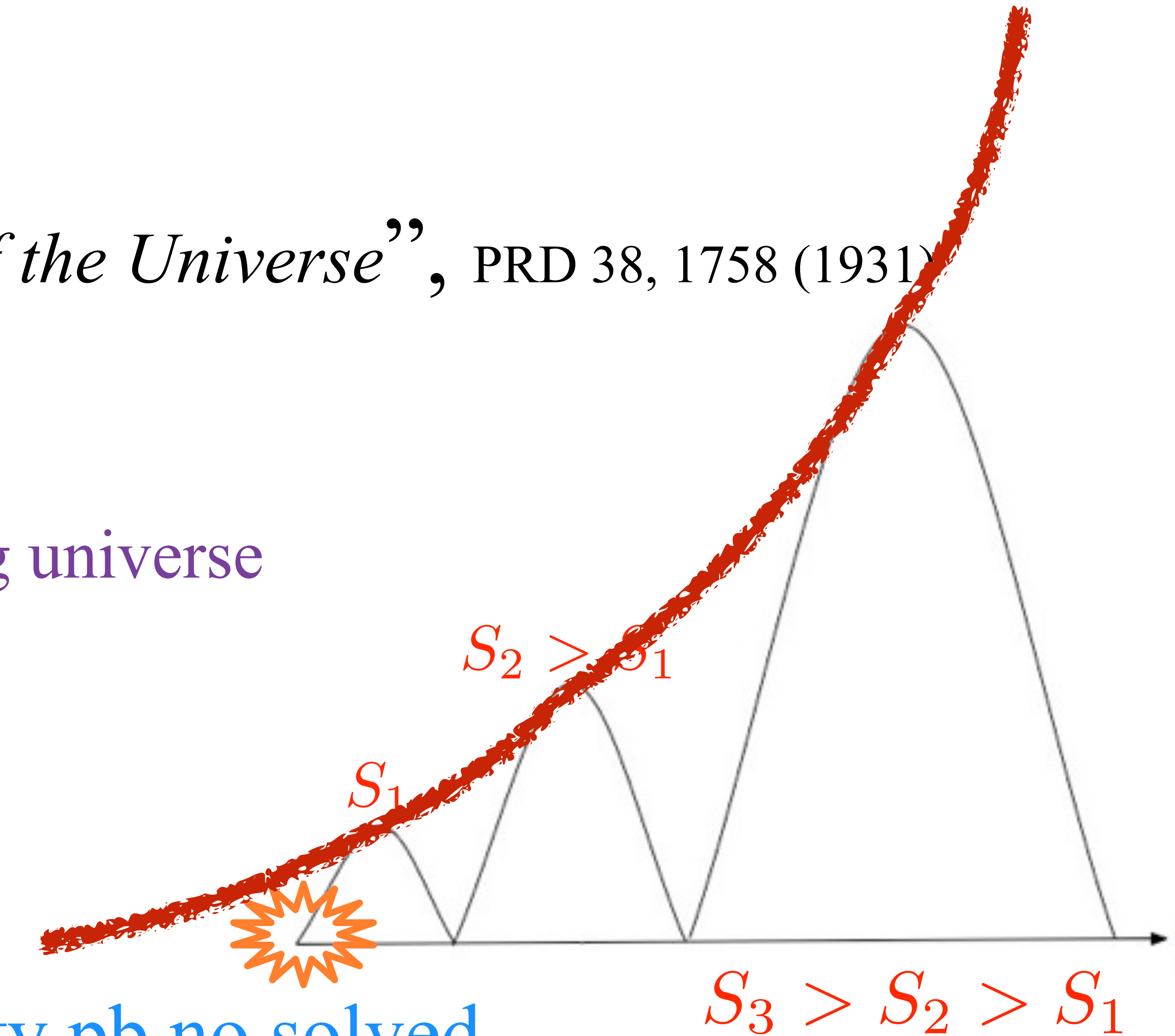

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Singularity pb no solved

Quantized scalar field effect model:

Parker & Fulling '73: massive scalar field, if $\langle a^\dagger a \rangle \gg 1$, then $\exists$ solution ($\kappa > 0$)

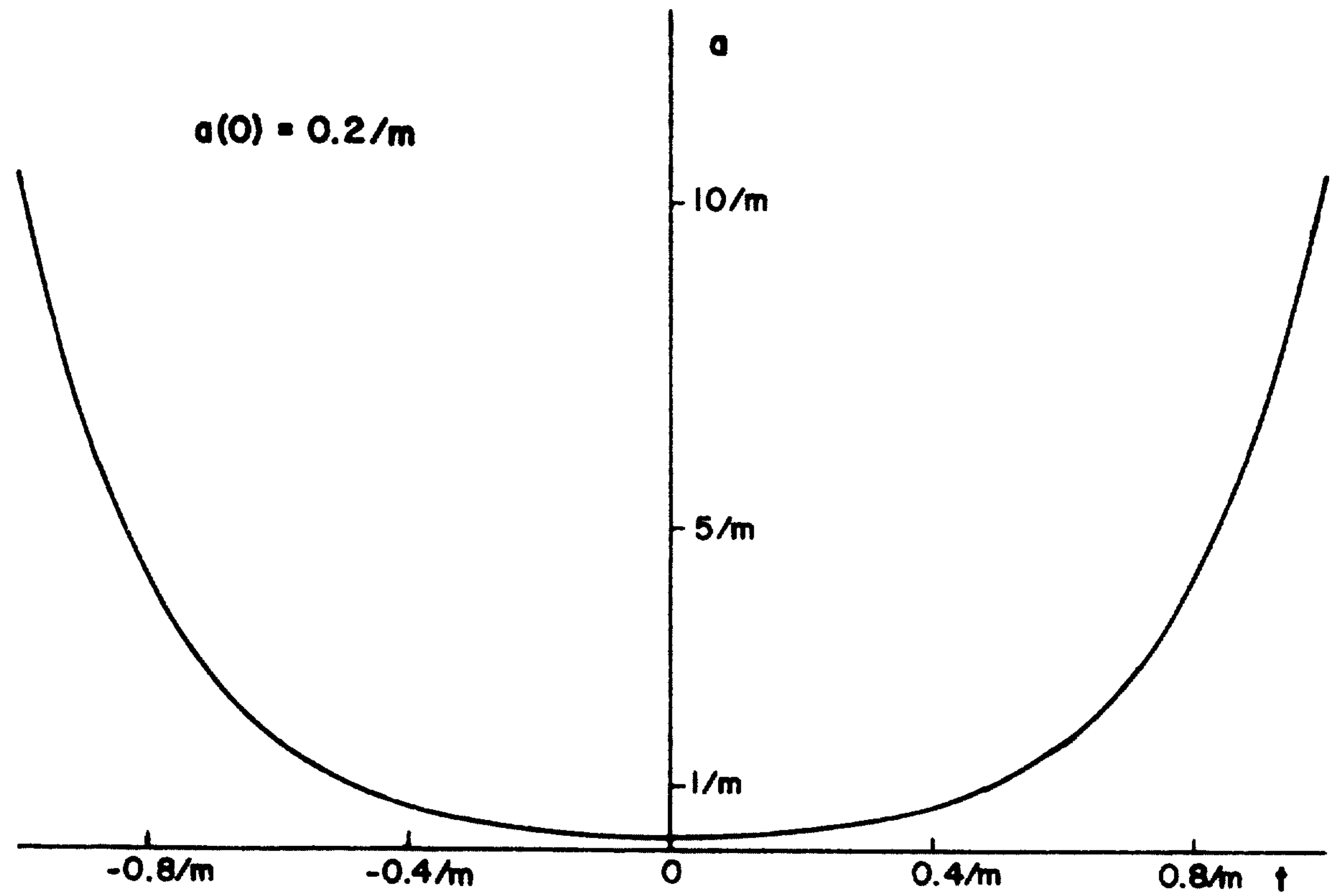

FIG. 1. Solution with $a(0) = 0.2m^{-1}$: time-symmetric expansion from the minimum radius.

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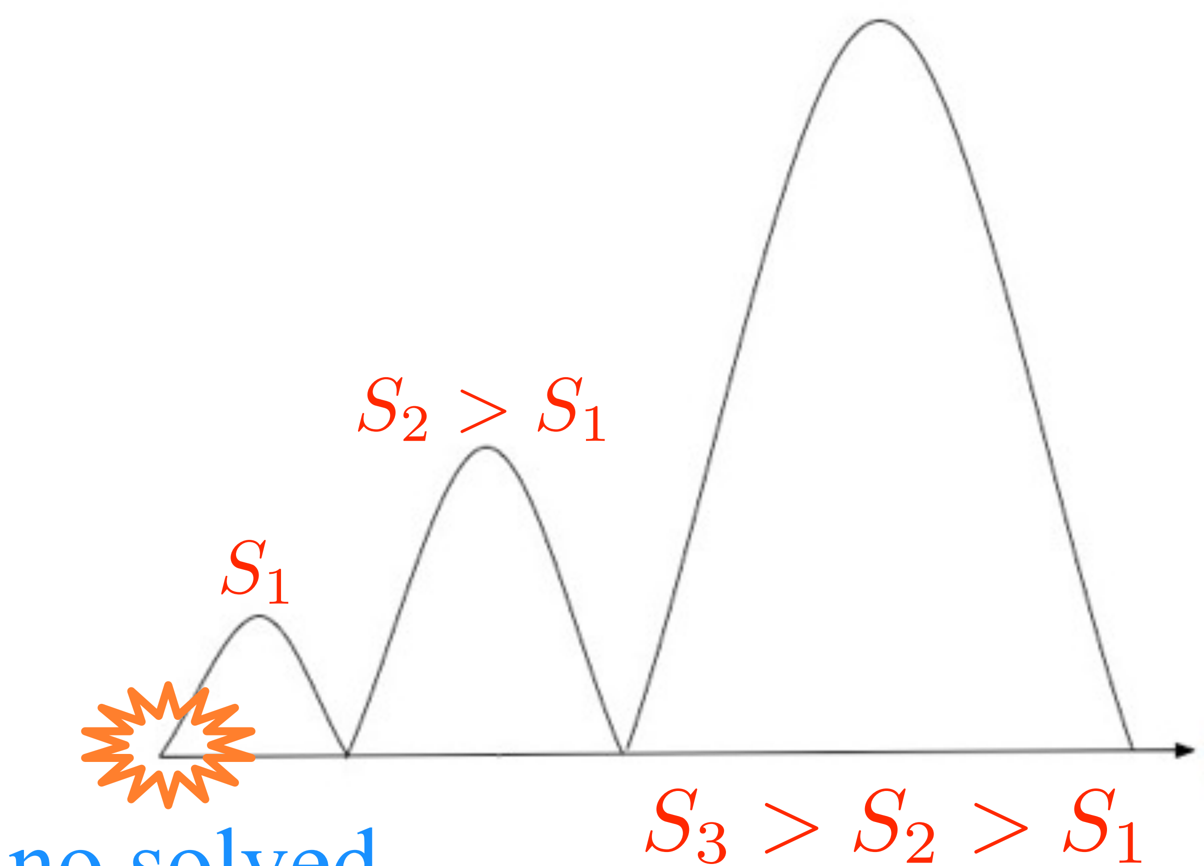

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Singularity pb no solved

- 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)

- Many new ideas, models…

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

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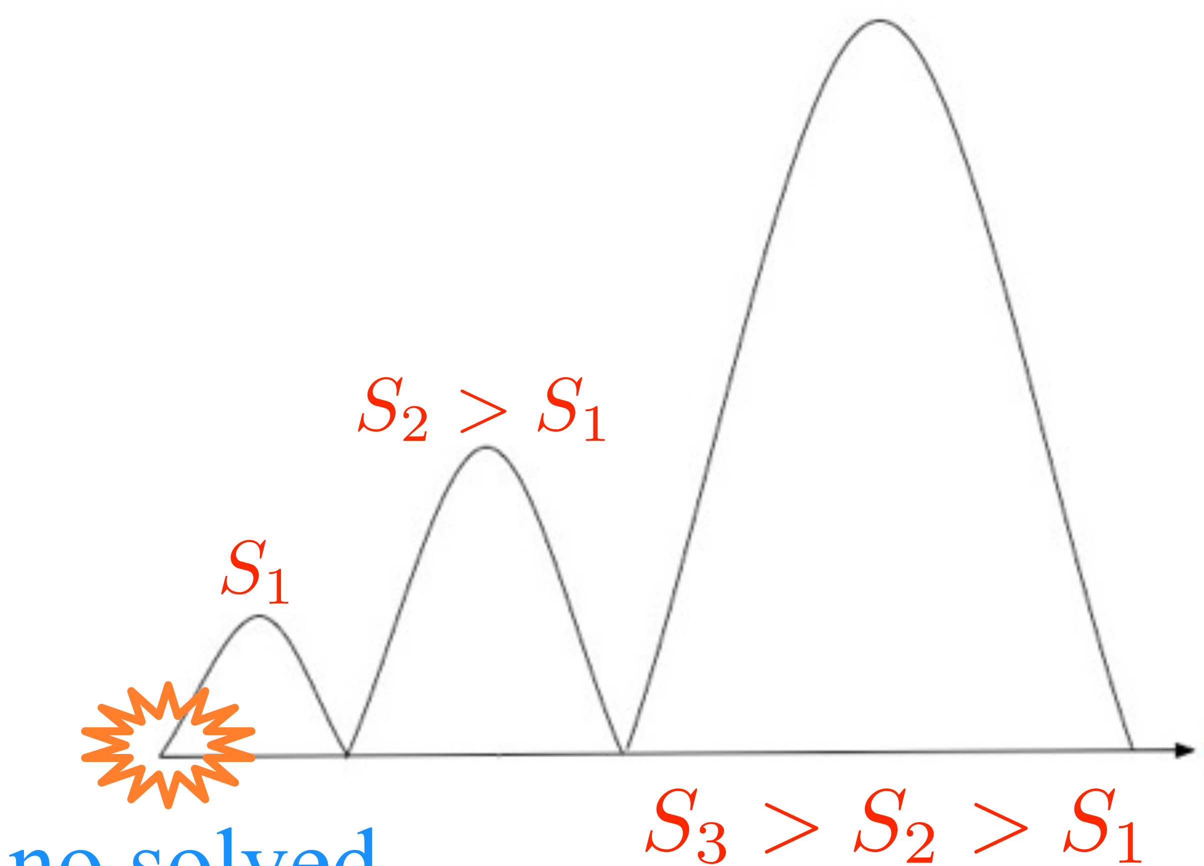

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- D. Battefeld & PP, "*A Critical Review of Classical Bouncing Cosmologies*", *1406.2790*

Model listing:

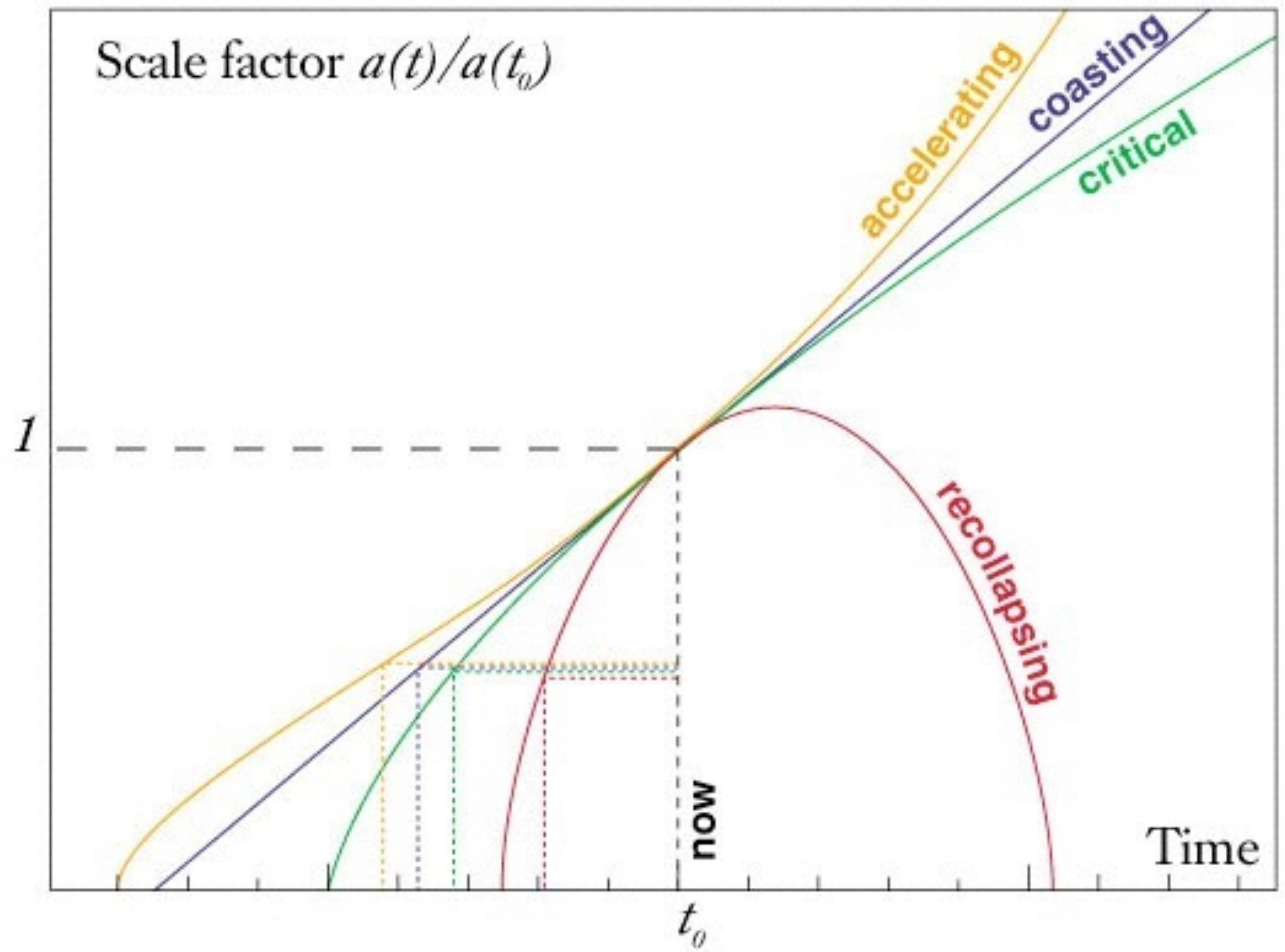
Quantum gravity

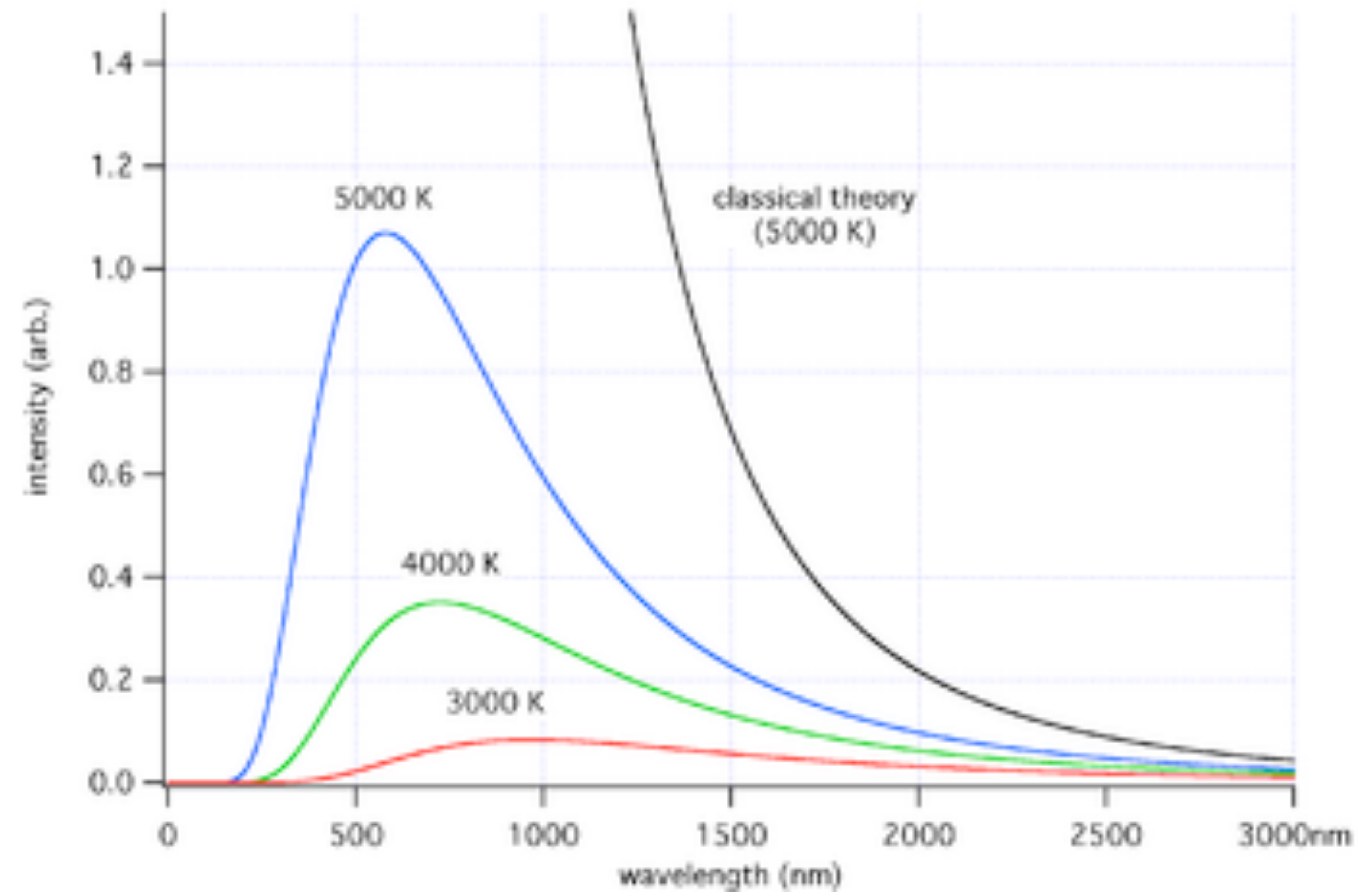
LQG & LQC (A. Ashtekar)

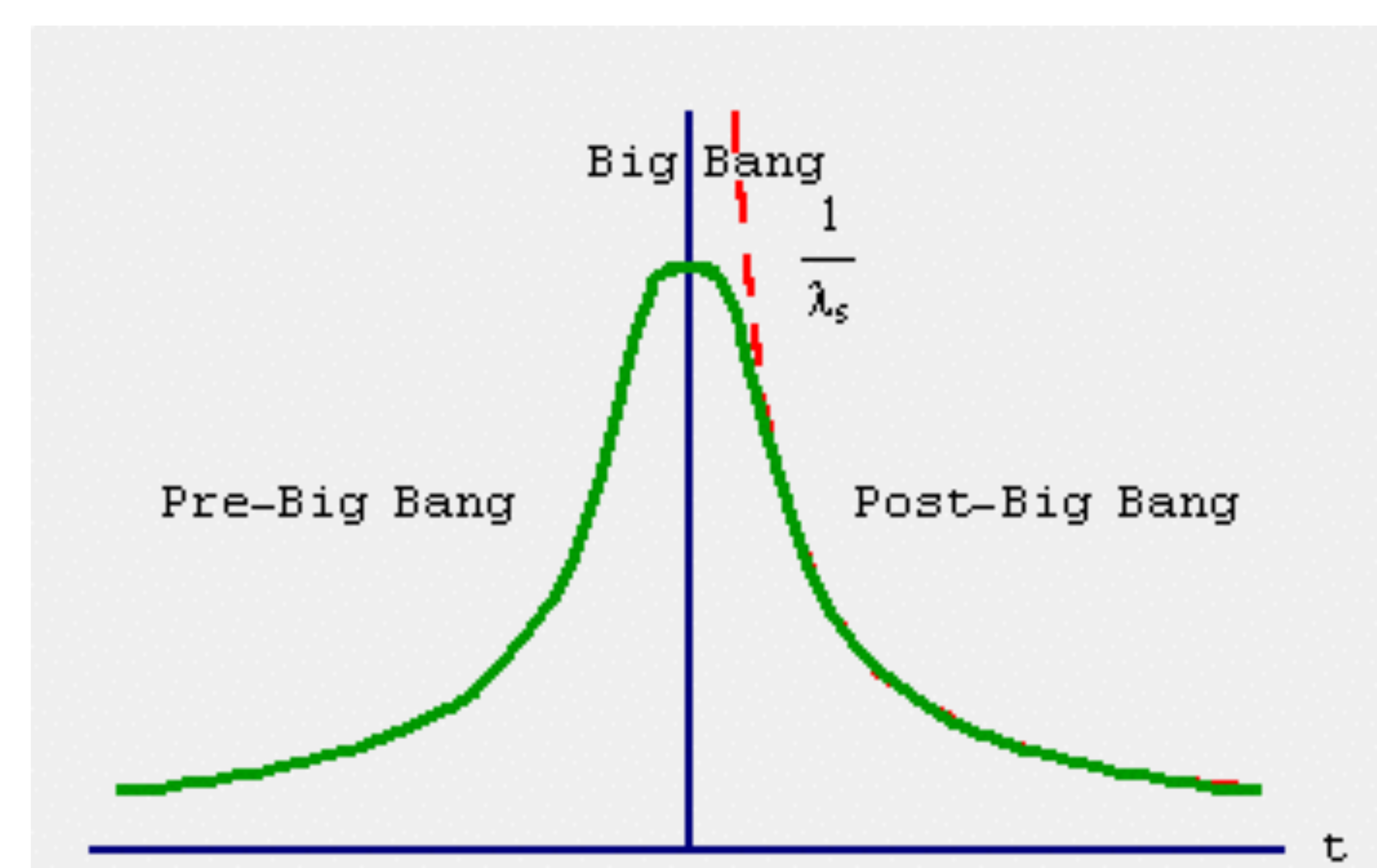
Canonical quantum gravity (WdW) (N. Pinto-Neto)

Non relativistic quantum gravity

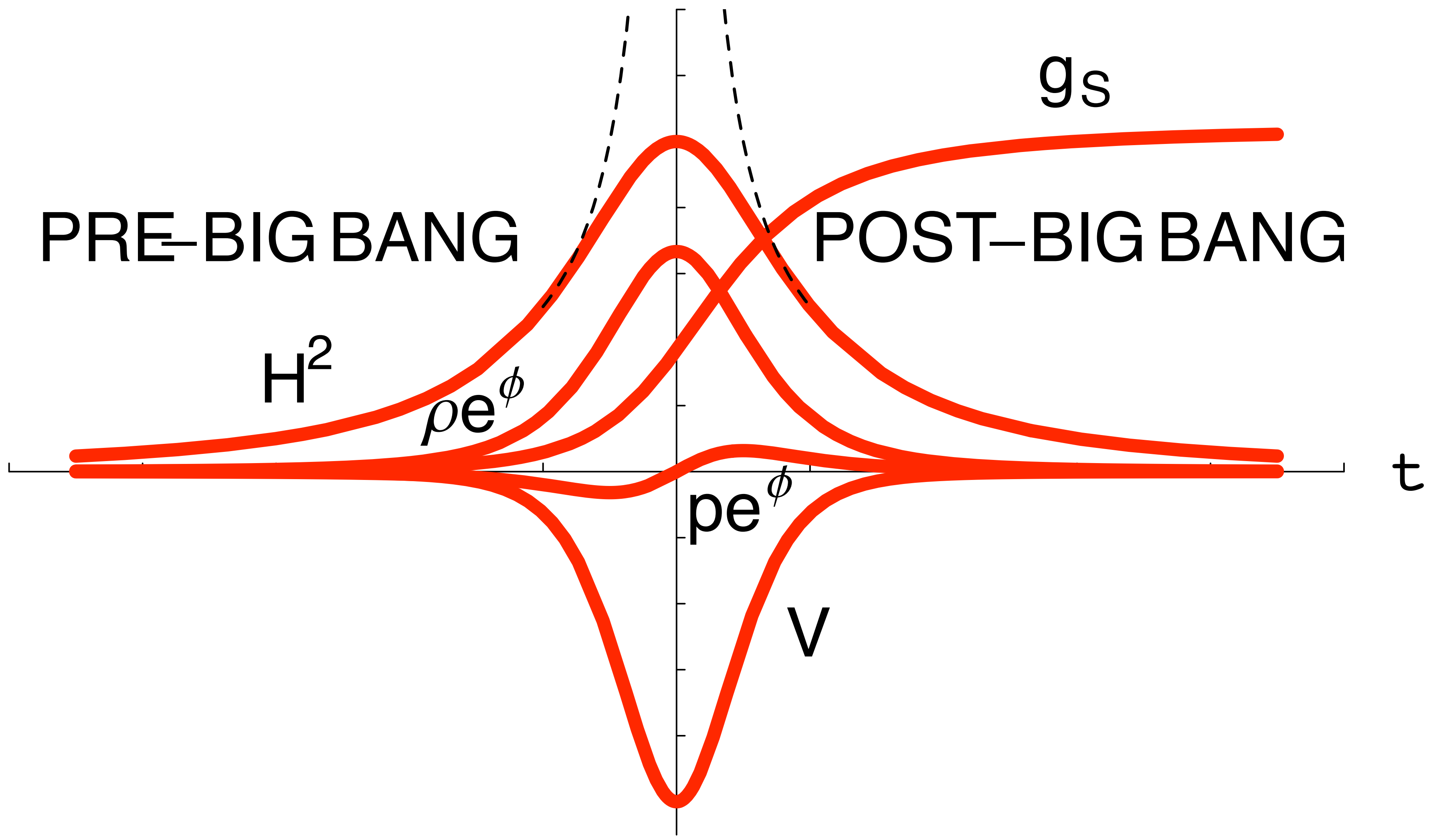
Singularity problem Purely classical effect?



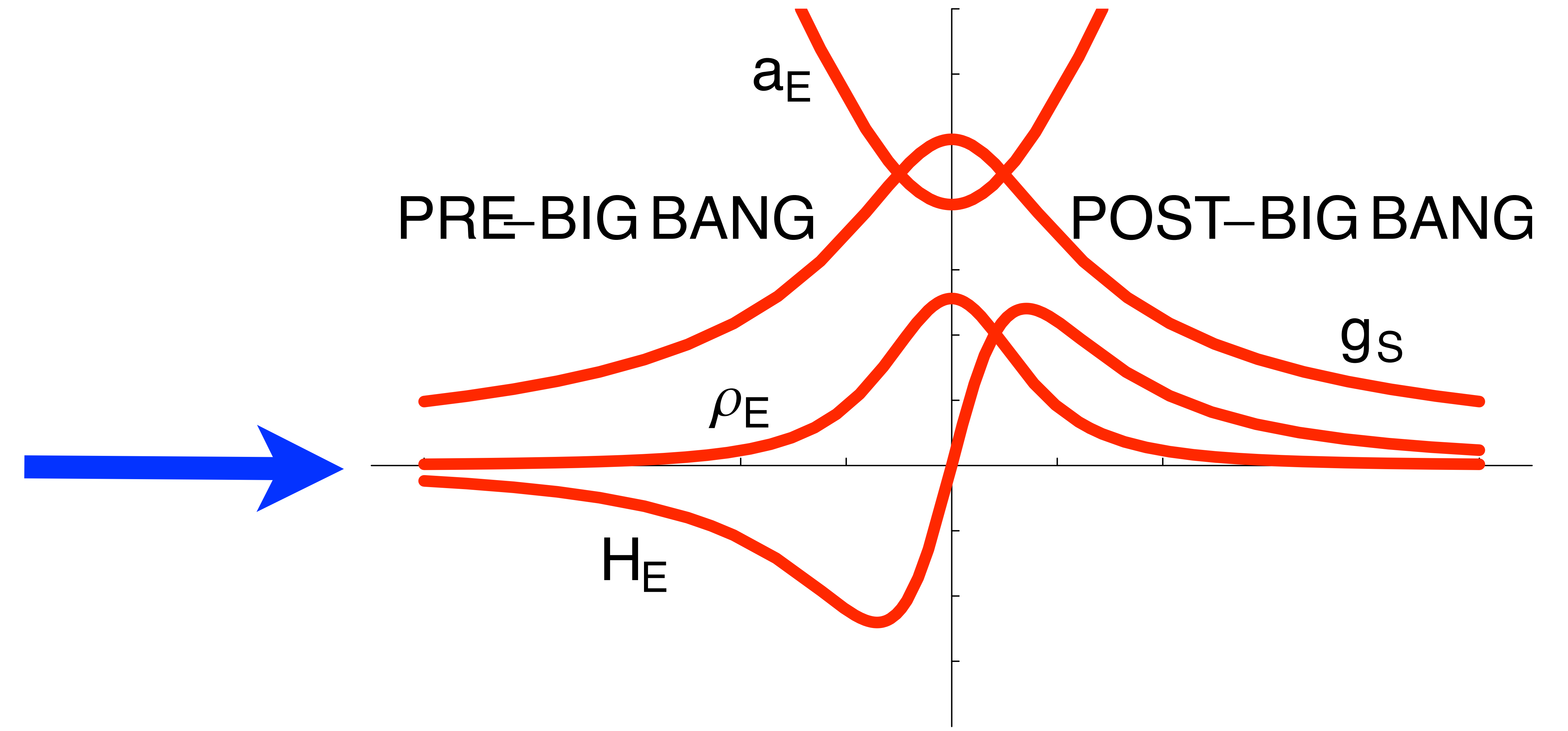




Pre Big Bang scenario:



string frame



Einstein frame

M.Gasperini & G. Veneziano, *Phys. Rep.* **373**, 1 (2003), hep-th/0207130 & hep-th/0703055

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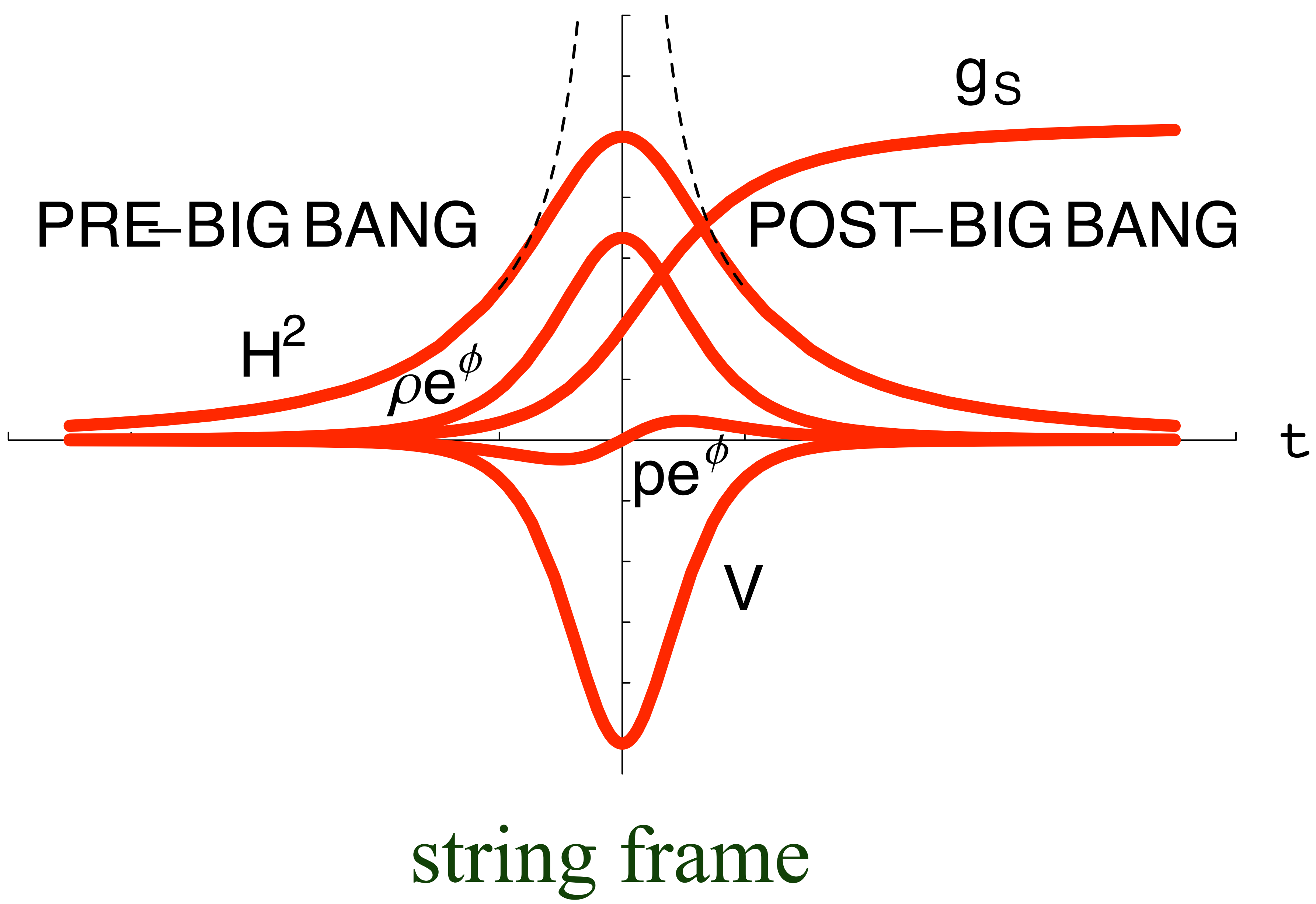

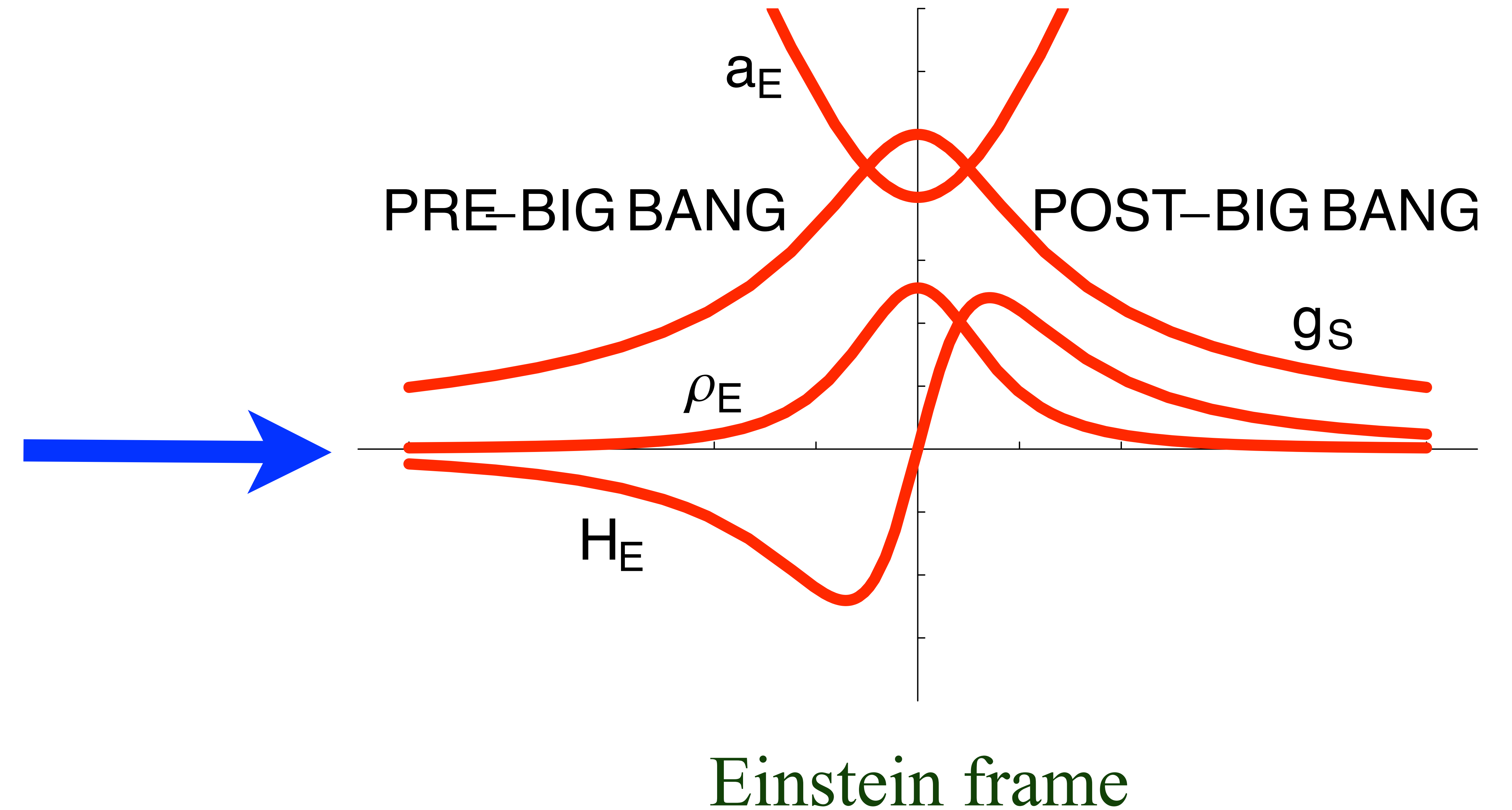

M.Gasperini & G. Veneziano, *Phys. Rep.* **373**, 1 (2003), hep-th/0207130 & hep-th/0703055

J. Acacio de Barros, N. Pinto-Neto & M. Sagorio-Leal, *Phys. Lett.* A**241**, 229 (1998)

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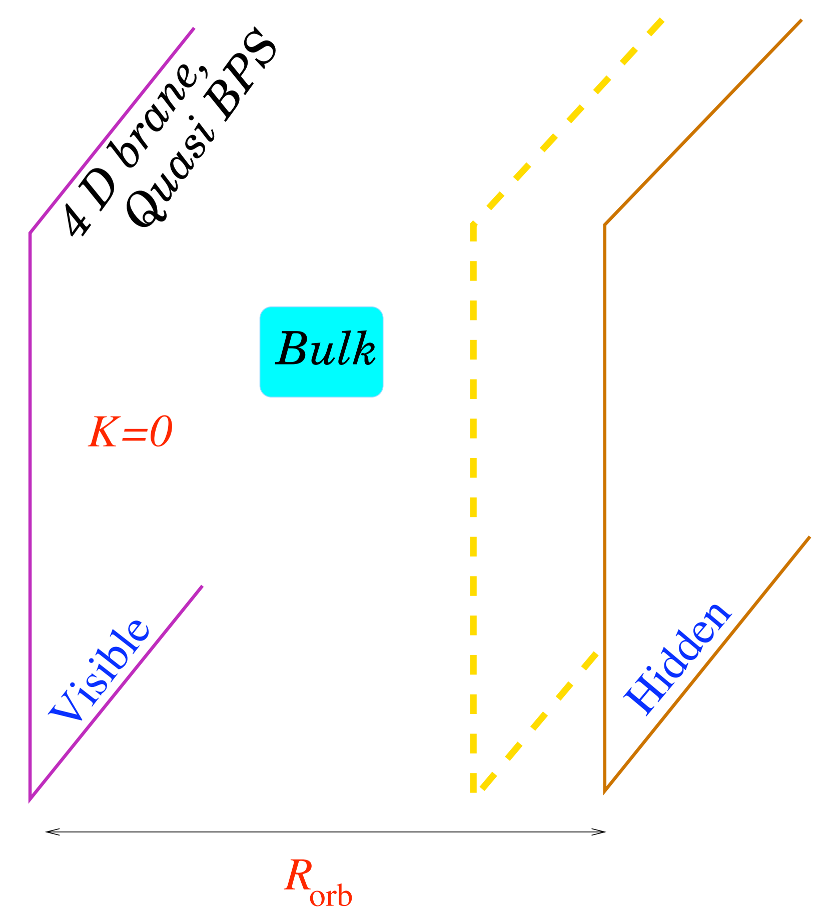
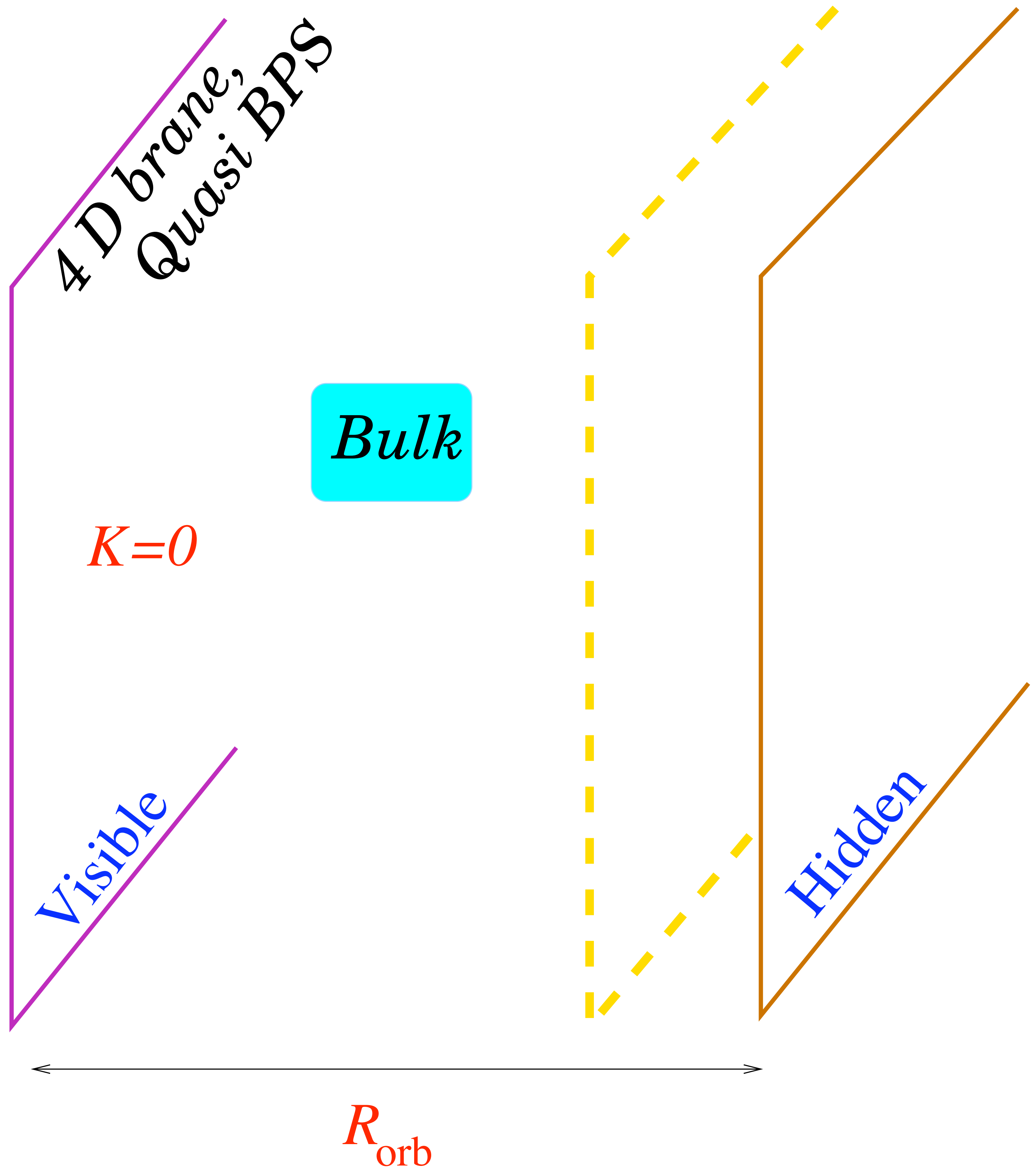
Ekpyrotic & cyclic

Branes (J.-L. Lehners)



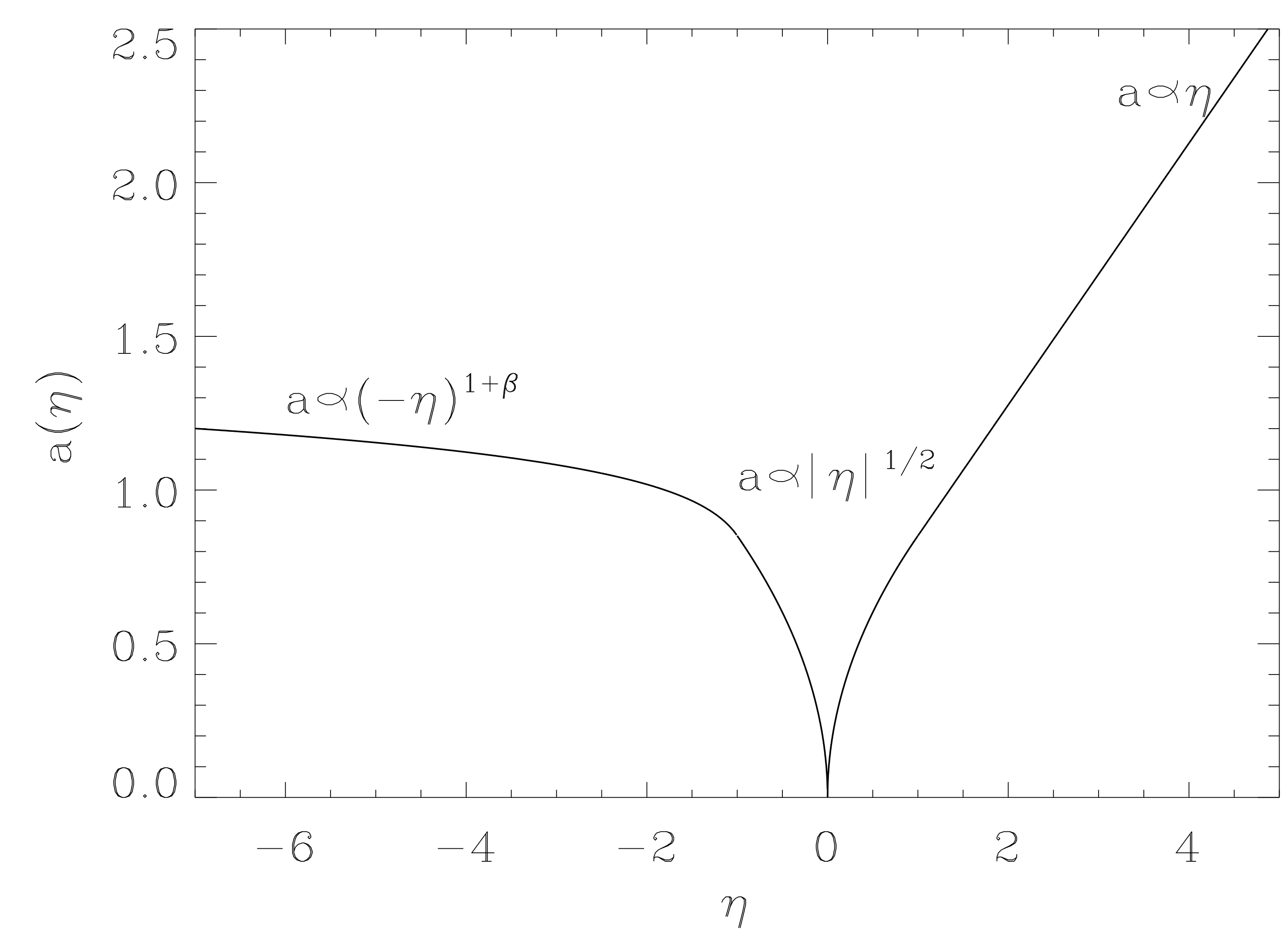
Ekpyrotic scenario:

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

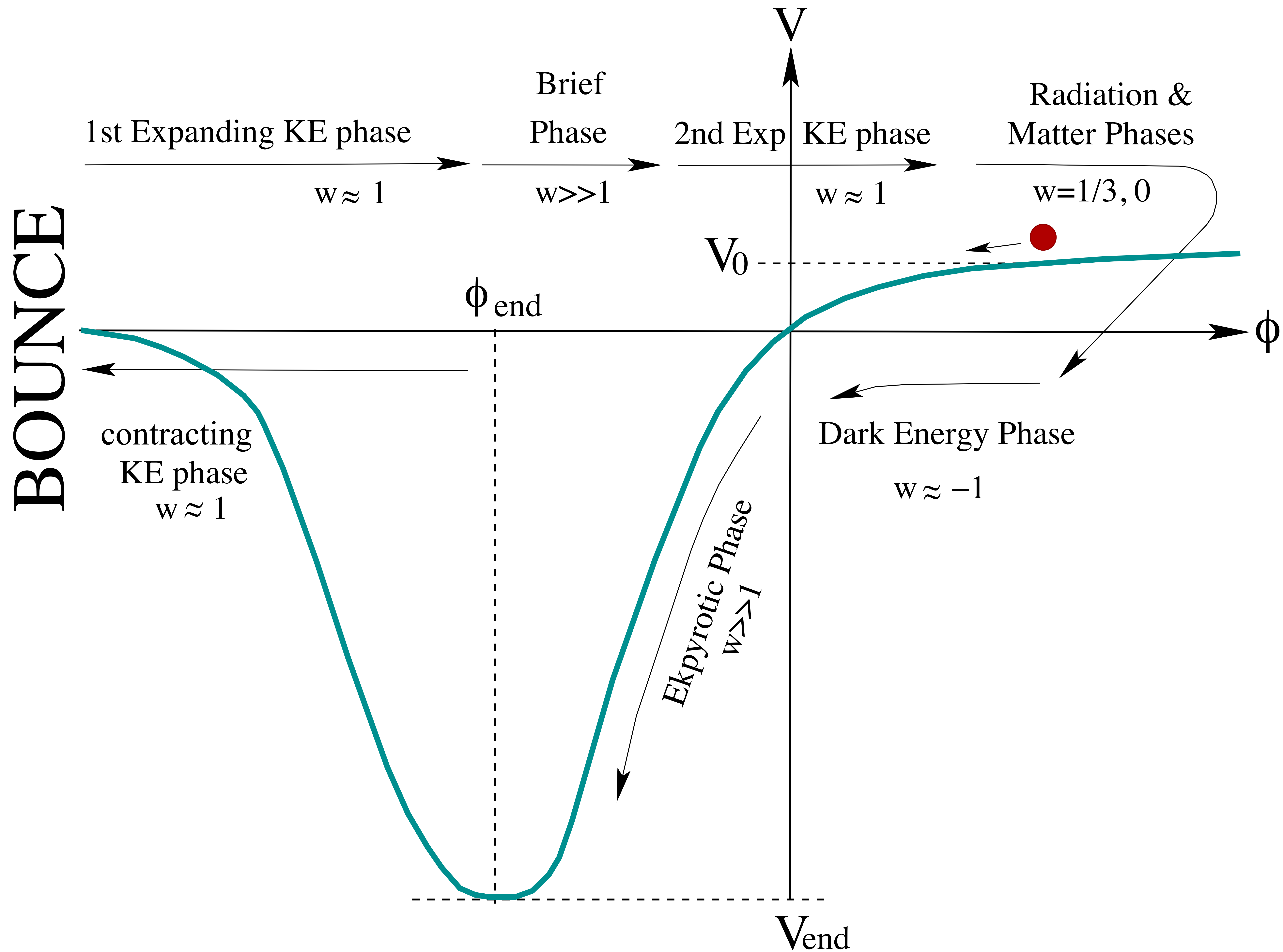


$$\mathcal{S}_4 = \int_{\mathcal{M}_4} \mathrm{d}^4x\sqrt{-g_4}\left[\frac{R_{(4)}}{2\kappa} - \frac{1}{2}\left(\partial\phi\right)^2 - V(\phi)\right],$$

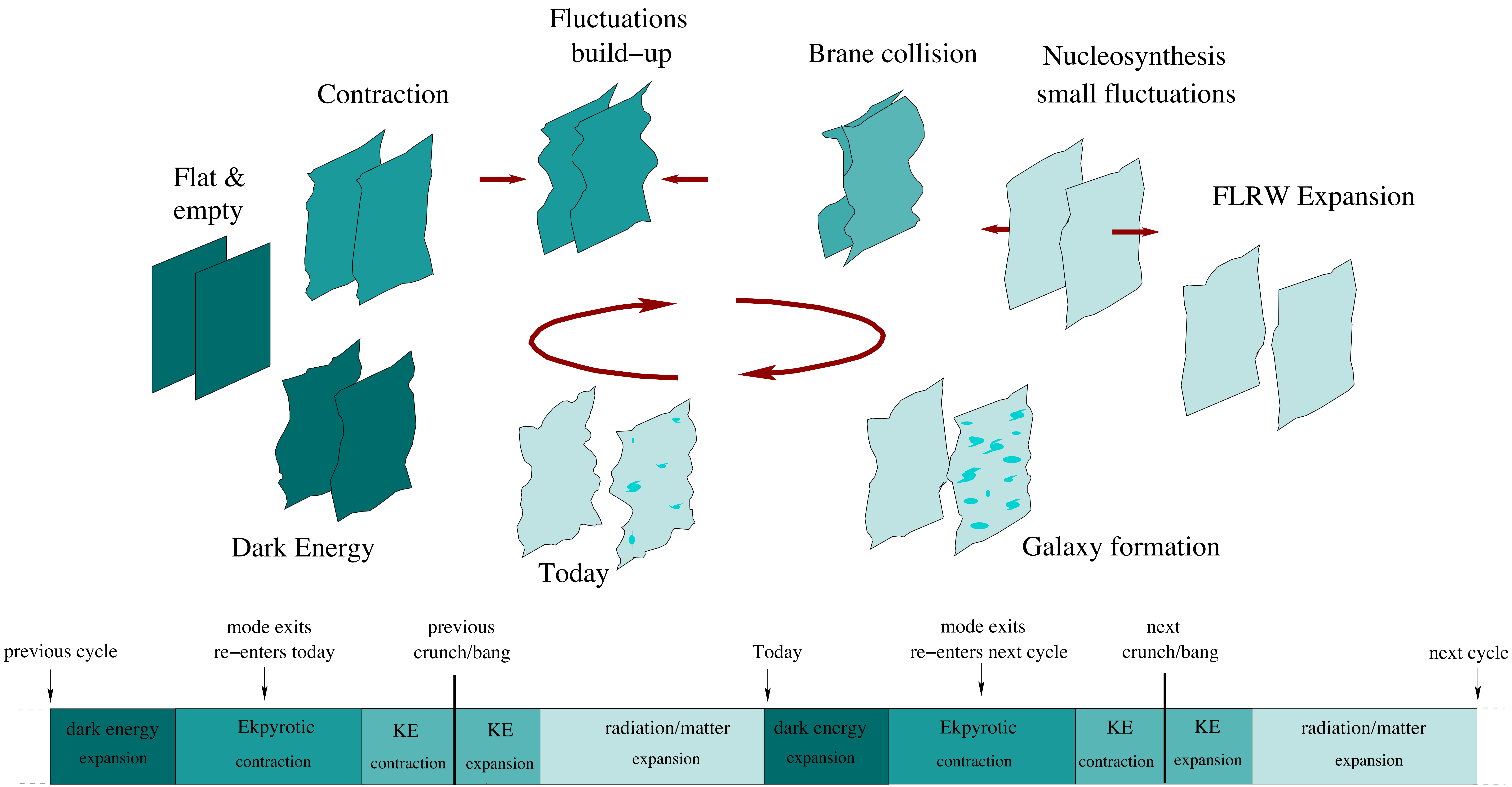
$$V(\varphi) = -V_{\rm i}\exp\left[-\frac{4\sqrt{\pi\gamma}}{m_{\rm Pl}}(\varphi - \varphi_{\rm i})\right],$$



Singular ...


V
Brief
Phase
1st Expanding KE phase
2nd Exp KE phase
Radiation &
Matter Phases
w ≈ 1
w>>1
w ≈ 1
w=1/3, 0
V0
ϕ end
ϕ
BOUNCE
contracting
KE phase
w ≈ 1
Dark Energy Phase
w ≈ −1
Ekpyrotic Phase
w>>1
Vend

Cyclic extension



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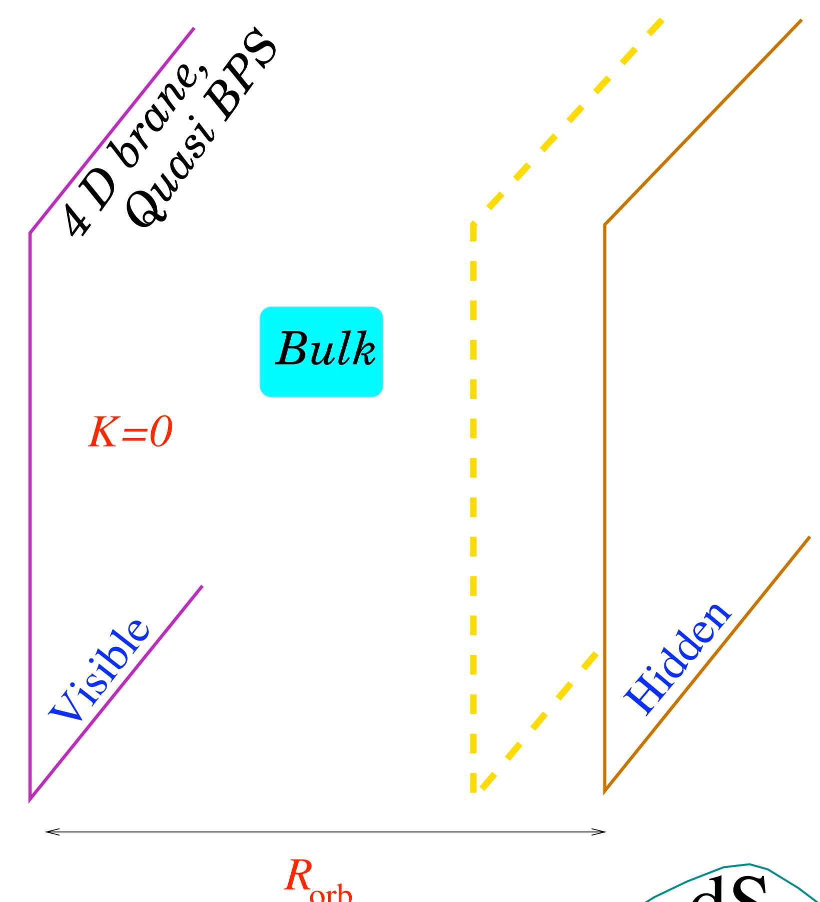


Horava-Lifshitz

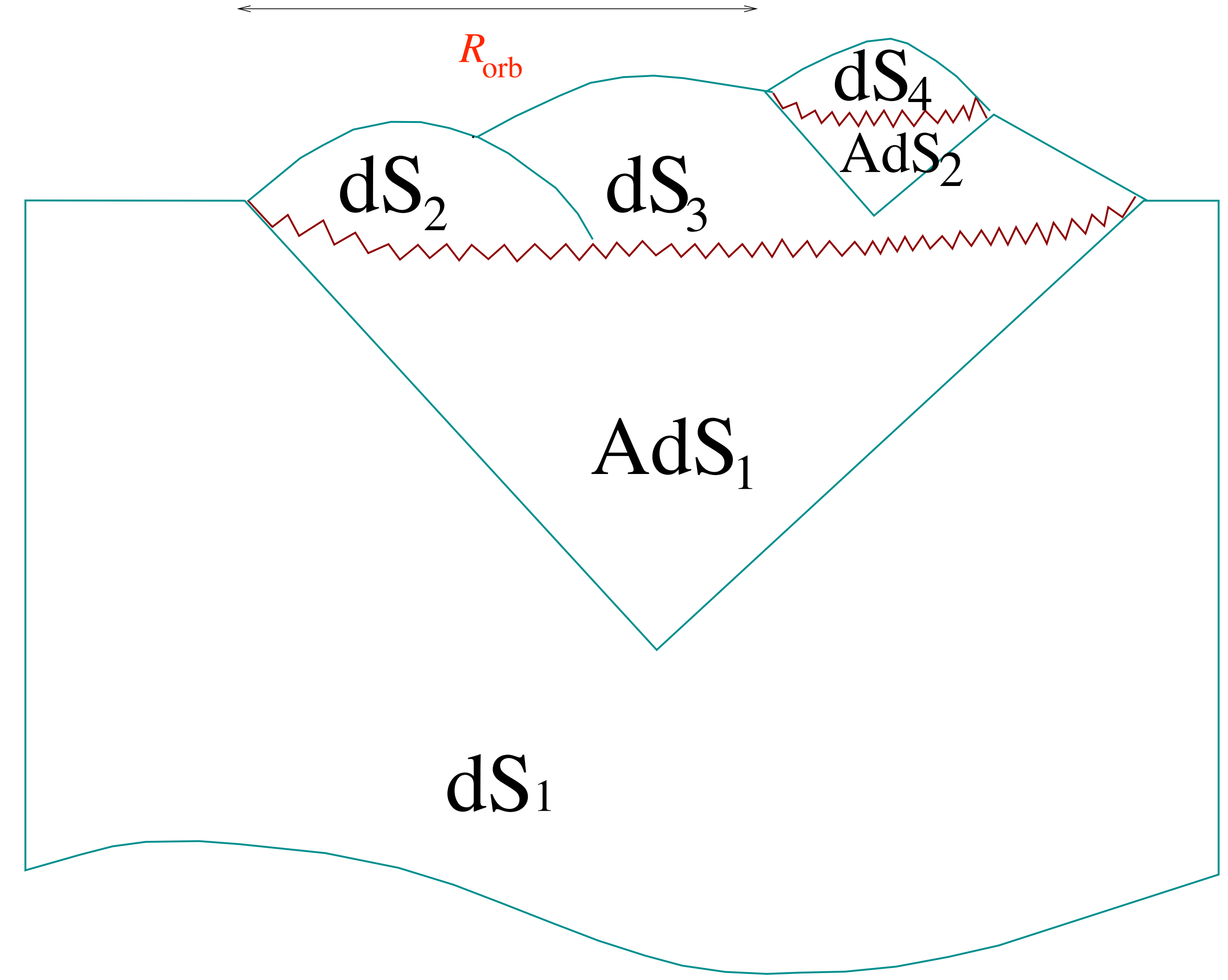
String gas cosmology (R. Brandenberger)

Lee-Wick & Quintom

Antigravity

F(R), *f(T)*, Gauss-Bonnet

Galileon



Massive gravity

Mimetic matter

Non-linear electromagnetic action

Multiverse models

Spinors & torsion

Strings & AdS/CFT

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D. Battefeld & PP, *1406.2790*

compare 196 models

Encyclopedia Inflationaris

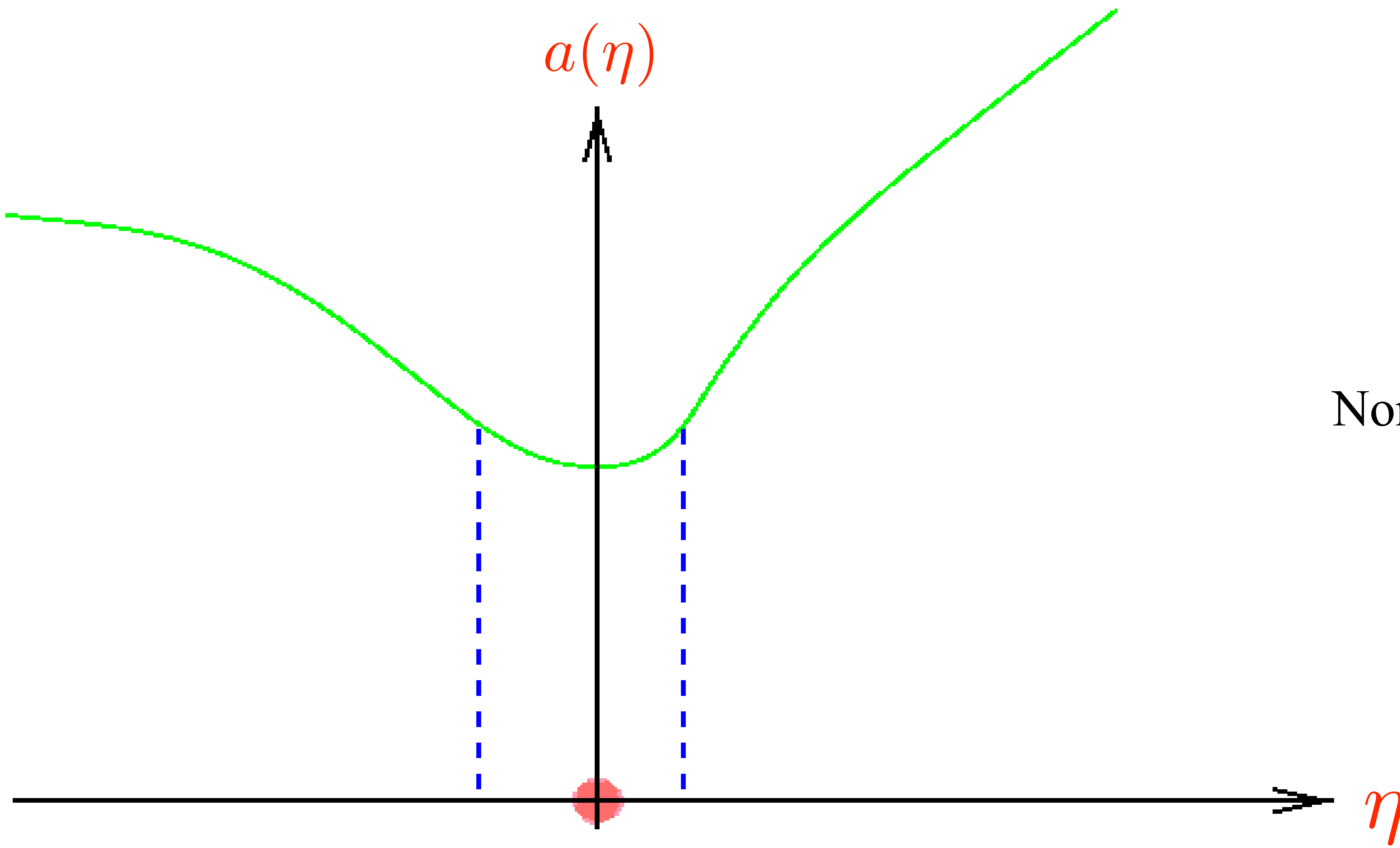
Singular …

… 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)

J. Martin, P. P., N. Pinto-Neto & D. Schwarz, *PR***D65**, 123513 (2002) + *PR***D67**, 028301 (2003)

… spectrum depending on a nonphysical normalization functions…



Non singular bounce

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.

PRL **105,** 261301 (2010)

Standard Failures and inflationary solutions

Singularity

Not solved... actually not addressed!

Horizon

$$d_{\rm H} \equiv a(t) \int_{t_{\rm i}}^{t} \frac{{\rm d}\tau}{a(\tau)}$$

can be made as big as one wishes

Flatness

$$\frac{\rm d}{{\rm d}t} |\Omega - 1| = -2 \frac{\ddot{a}}{\dot{a}^3}$$

$$\ddot{a} > 0 \quad \& \quad \dot{a} > 0$$

accelerated expansion (inflation)

Homogeneity & Isotropy

Initial Universe = very small patch
Accelerated expansion drives the shear to zero...

$\Longrightarrow$ vacuum state!

+ attractor

Perturbations

Bonus of the theory: predictions!!!

Others

dark matter/energy, baryogenesis, ...

P. P. & N. Pinto-Neto, *Phys. Rev.* **D78**, 063506 (2008)

Standard Failures and 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

$\Longrightarrow$ quantum vacuum fluctuations...

Isotropy Potentially problematic: model dependent

Others dark matter/energy, baryogenesis, ...

$$d_{\rm H}^{\rm cont} = \frac{3(1+w)}{1+3w} t_{\rm end} \left[1 - \left(\frac{t_{\rm ini}}{t_{\rm end}} \right)^{(1+3w)/[3(1+w)]} \right]$$

$$t_{\rm ini} \to -\infty$$

P. P. & N. Pinto-Neto, *Phys. Rev.* **D78**, 063506 (2008)

Standard Failures and bouncing solutions

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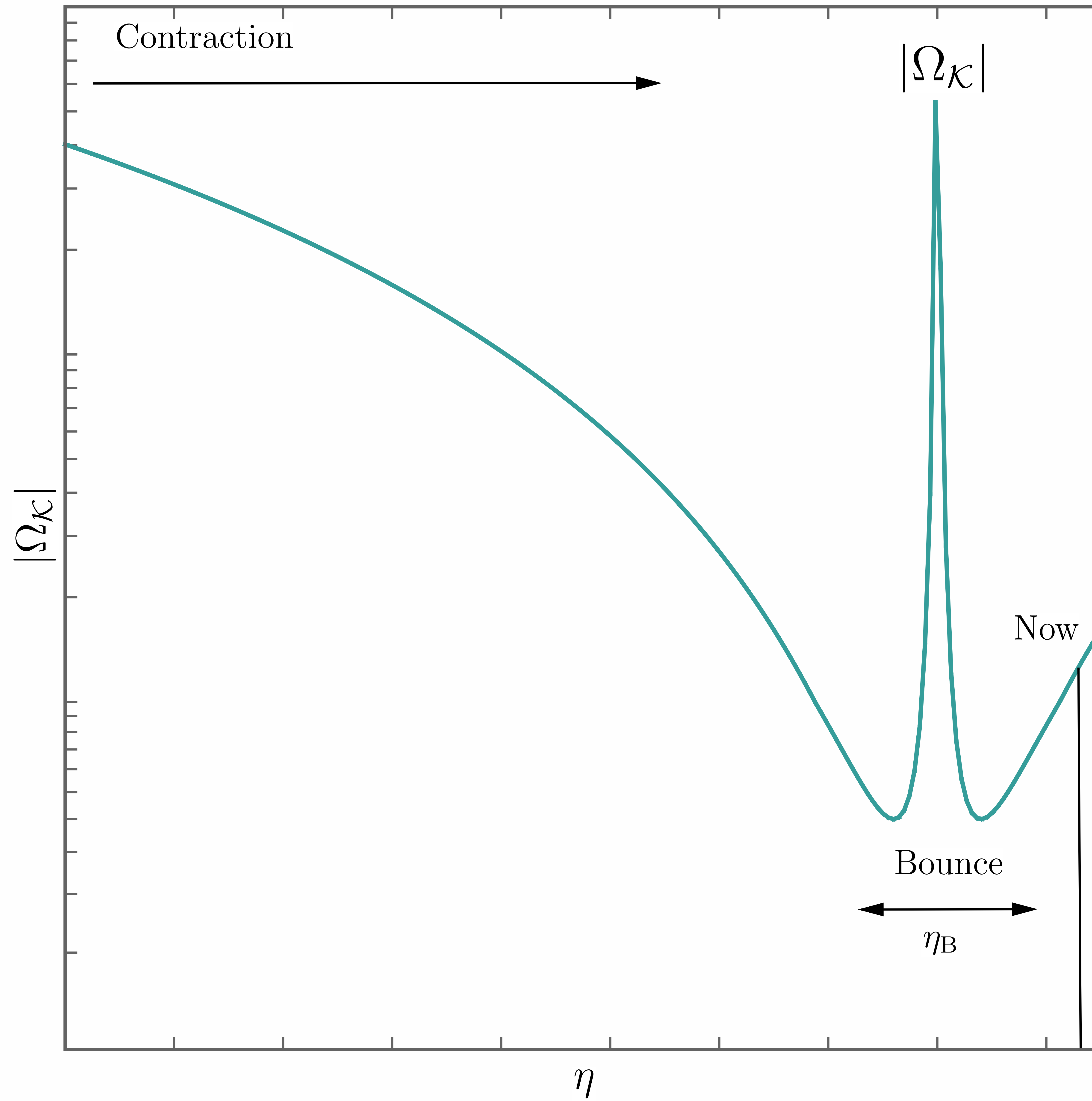
$$H^2 = \frac{1}{3}\left[-\frac{3\mathcal{K}}{a^2} + \frac{\rho_{\rm m0}}{a^3} + \frac{\rho_{\rm r0}}{a^4} + \frac{\rho_{\theta 0}}{a^6} + \ldots + \frac{\rho_{\phi 0}}{a^{3(1+w_\phi)}}\right]$$

Critical density

$$\rho_{\rm c} \equiv \frac{3H^2}{8\pi G_{\rm N}} \Longrightarrow \Omega \equiv \frac{\rho}{\rho_{\rm c}}$$

Density parameter



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Isotropy Potentially problematic: model dependent

Others dark matter/energy, baryogenesis, ...

Implementing a bounce = problem with GR!

$$\dot{H} = \frac{\mathcal{K}}{a^2} - \frac{1}{2}\left(\rho + P\right)$$

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

↓

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...?

Instabilities…

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

$$H^2 = \frac{\rho_\mathrm{T}}{3M_\mathrm{Pl}^2} + \frac{1}{6} \sum_i \dot{\theta}_i^2$$

$$\dot{H} = -\frac{\rho_\mathrm{T} + p_\mathrm{T}}{2M_\mathrm{Pl}^2} - \frac{1}{2} \sum_i \dot{\theta}_i^2$$

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

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

Ekpyrotic solution:

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

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!

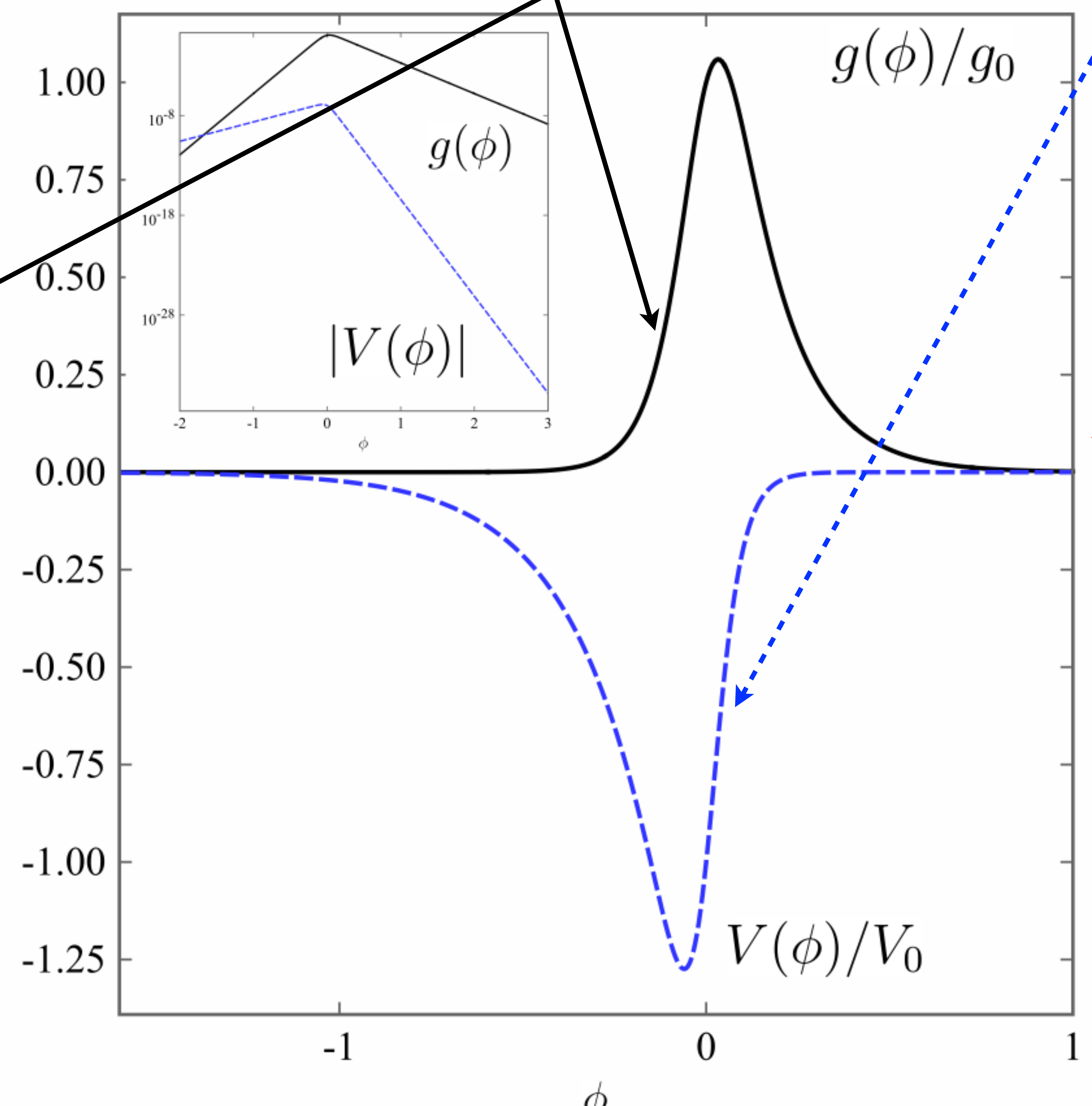
Y. Cai, D. Easson & R. Brandenberger JCAP **08,** 020 (2012)

A nonsingular bounce model: ghost condensate & Galileon

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

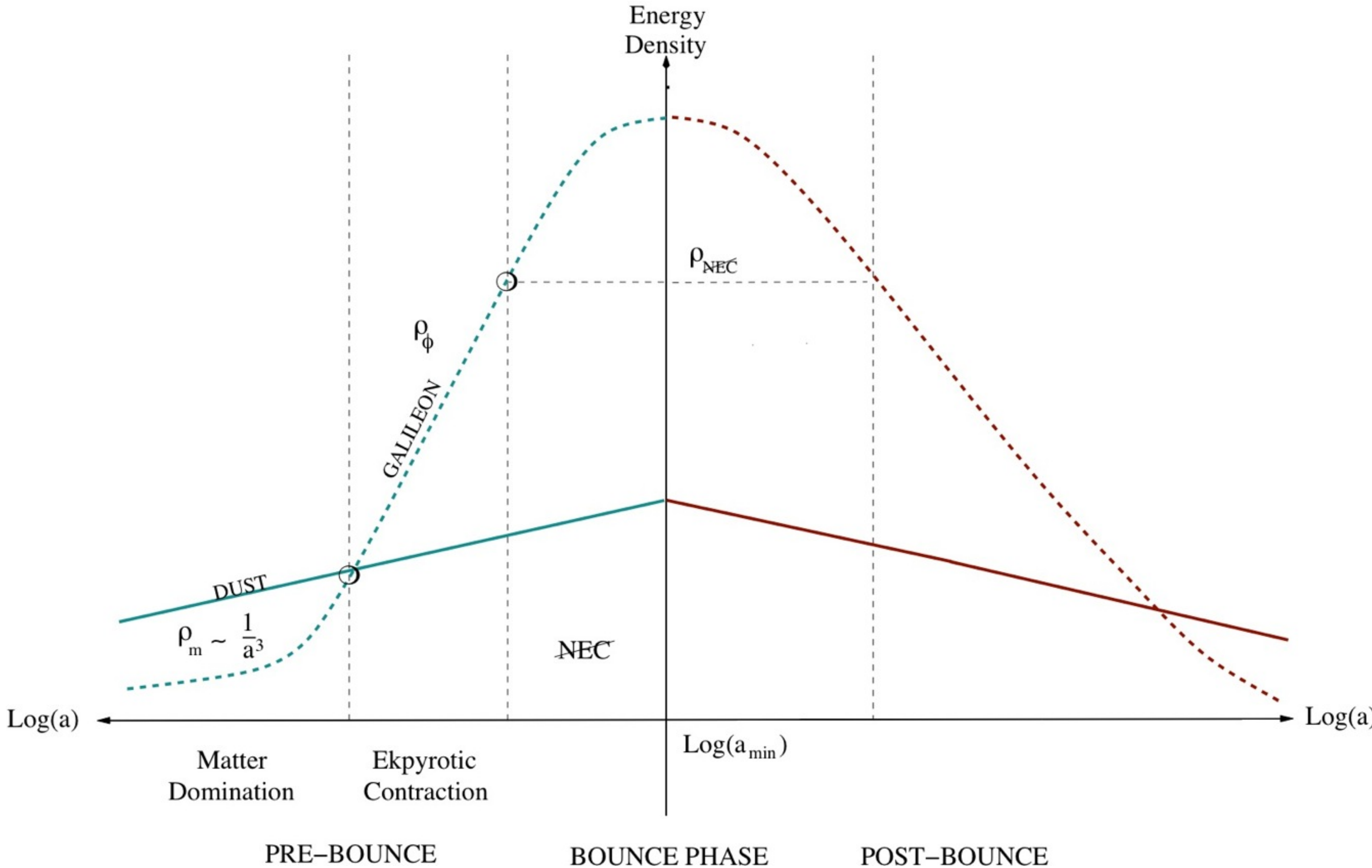
Specific choices: $$K(\phi, X) = M_{\rm Pl}^2\left[1 - g(\phi)\right]X + \beta X^2 - V(\phi)$$ $$G(X) = \gamma X$$

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



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

+Bianchi

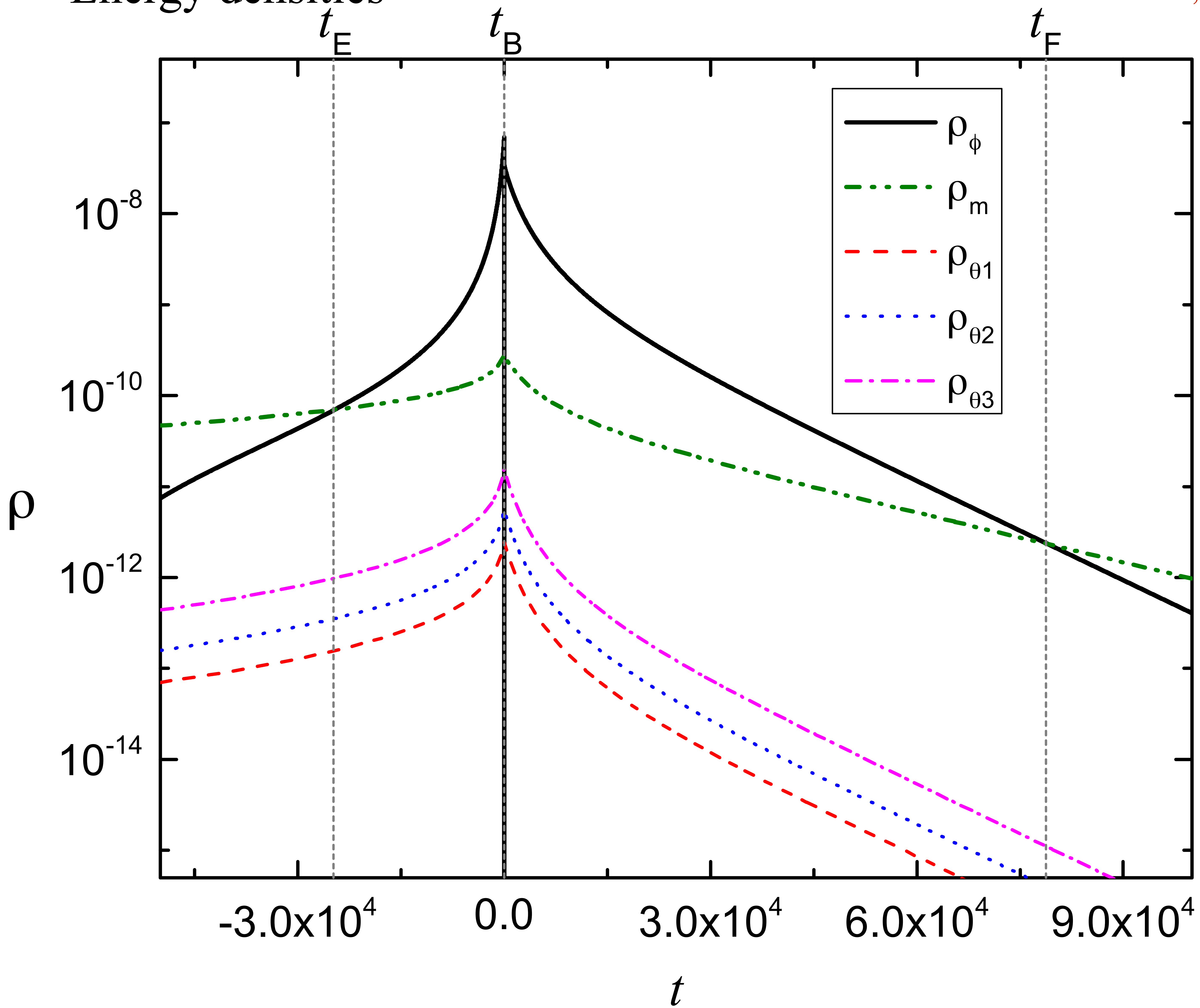

Energy Density
ρ_NEC
ρ_φ
GALILEON
DUST
ρ_m ~ 1/a³
NEC
Log(a)
Log(a)
Log(a_min)
Matter Domination
Ekpyrotic Contraction
PRE–BOUNCE
BOUNCE PHASE
POST–BOUNCE

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

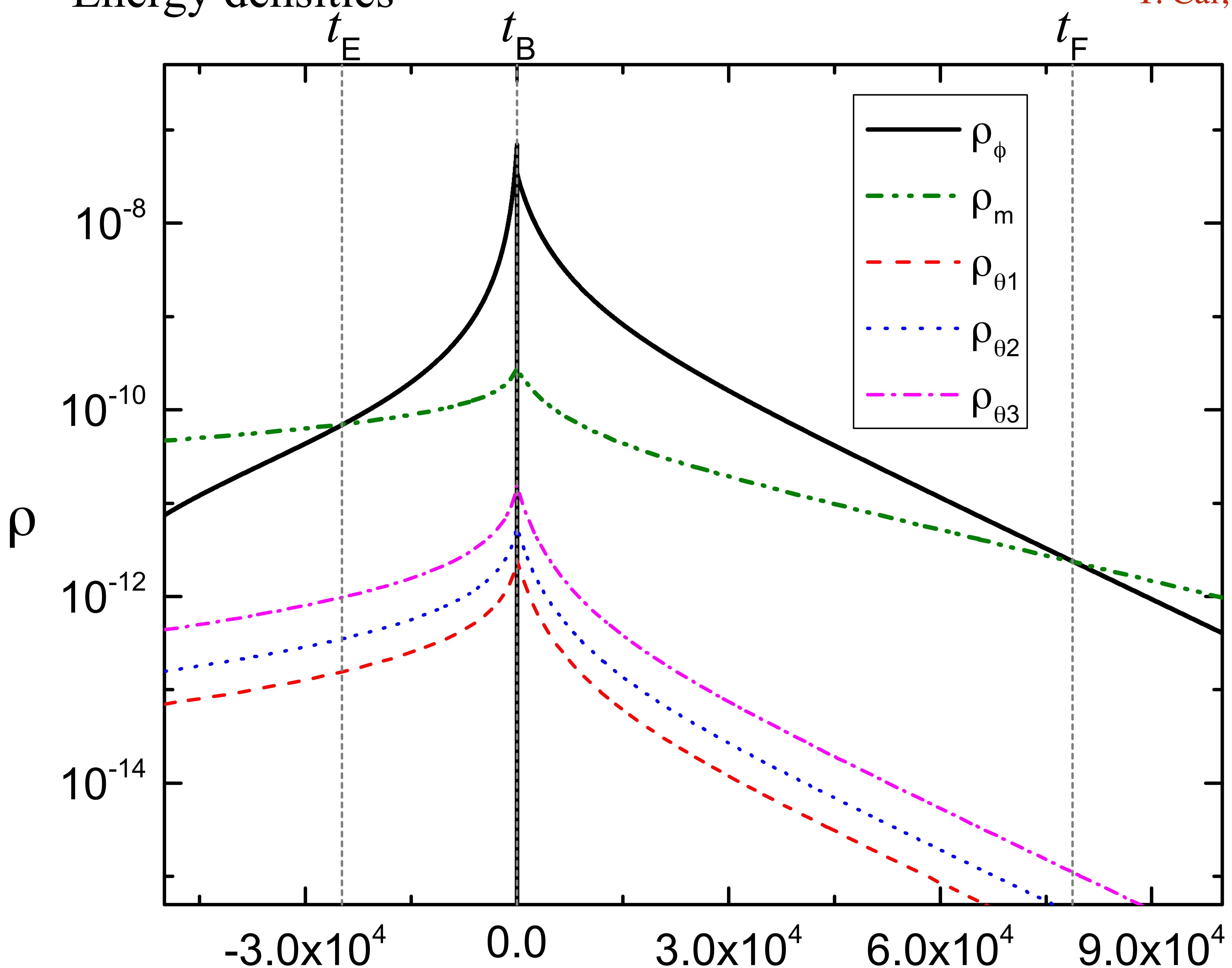
Energy densities

Y. Cai, R. Brandenberger & PP, CQG **30,** 075019 (2013)



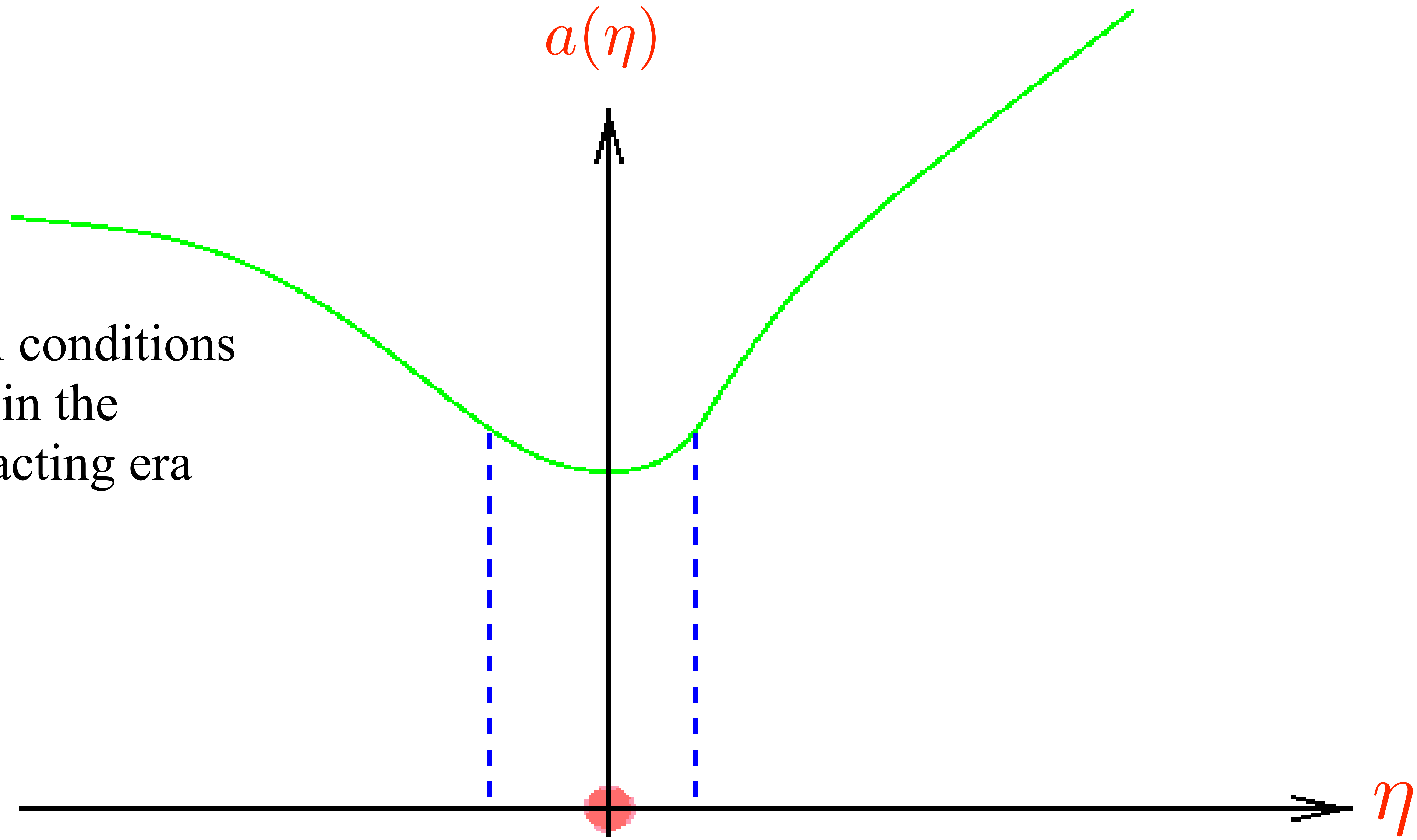
Energy densities

Y. Cai, R. Brandenberger & PP, CQG **30,** 075019 (2013)



→ Anisotropies can remain small all throughout

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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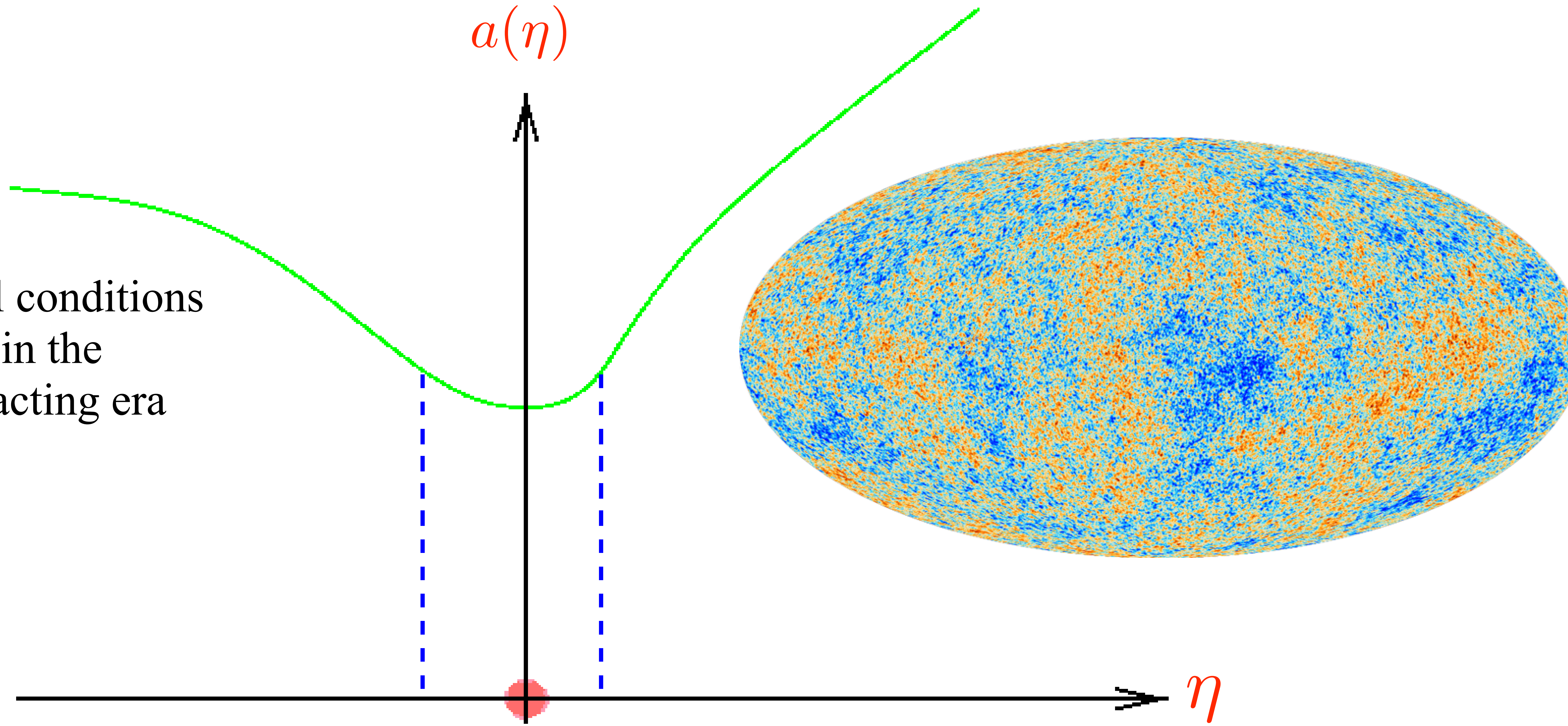

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???????

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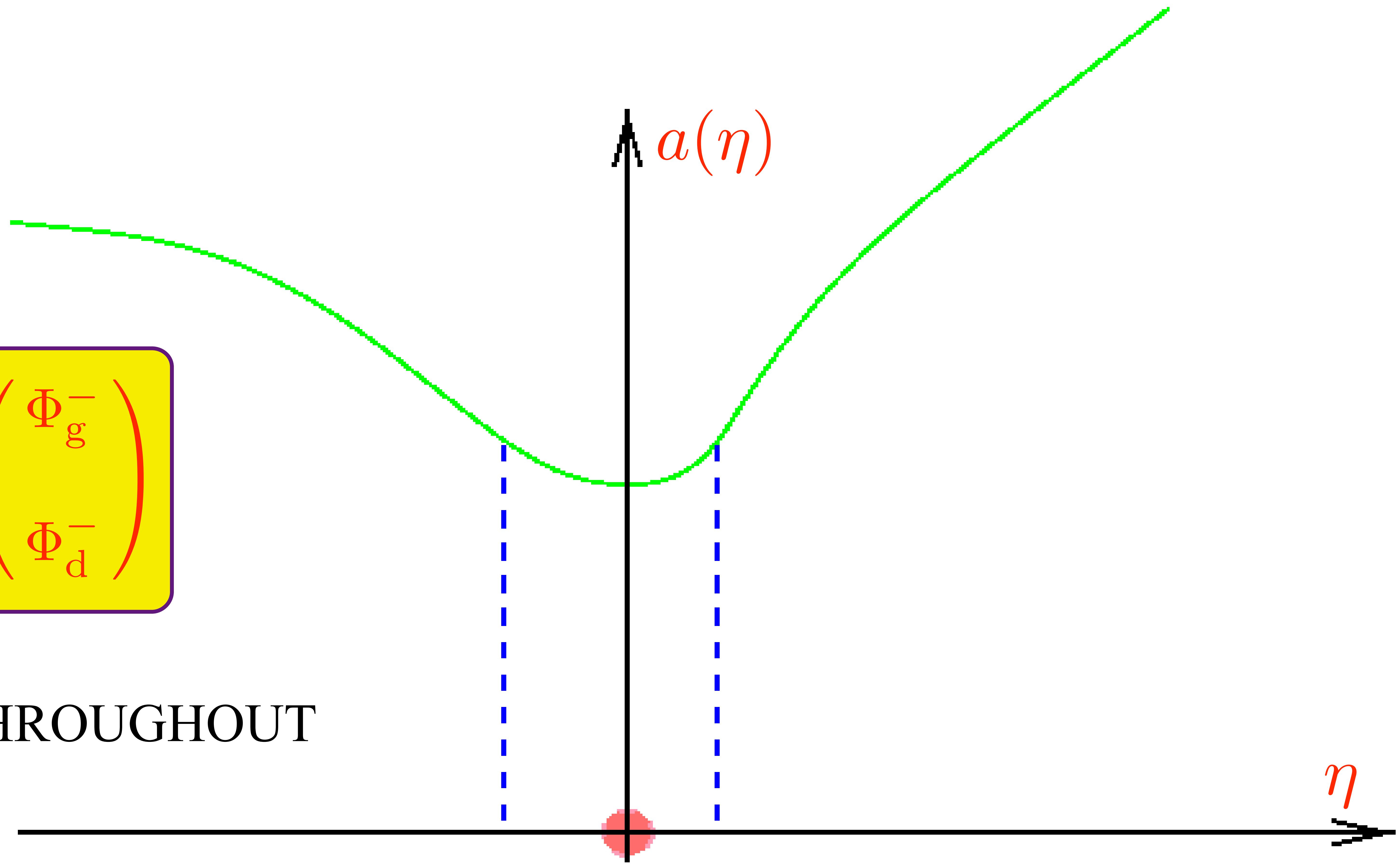


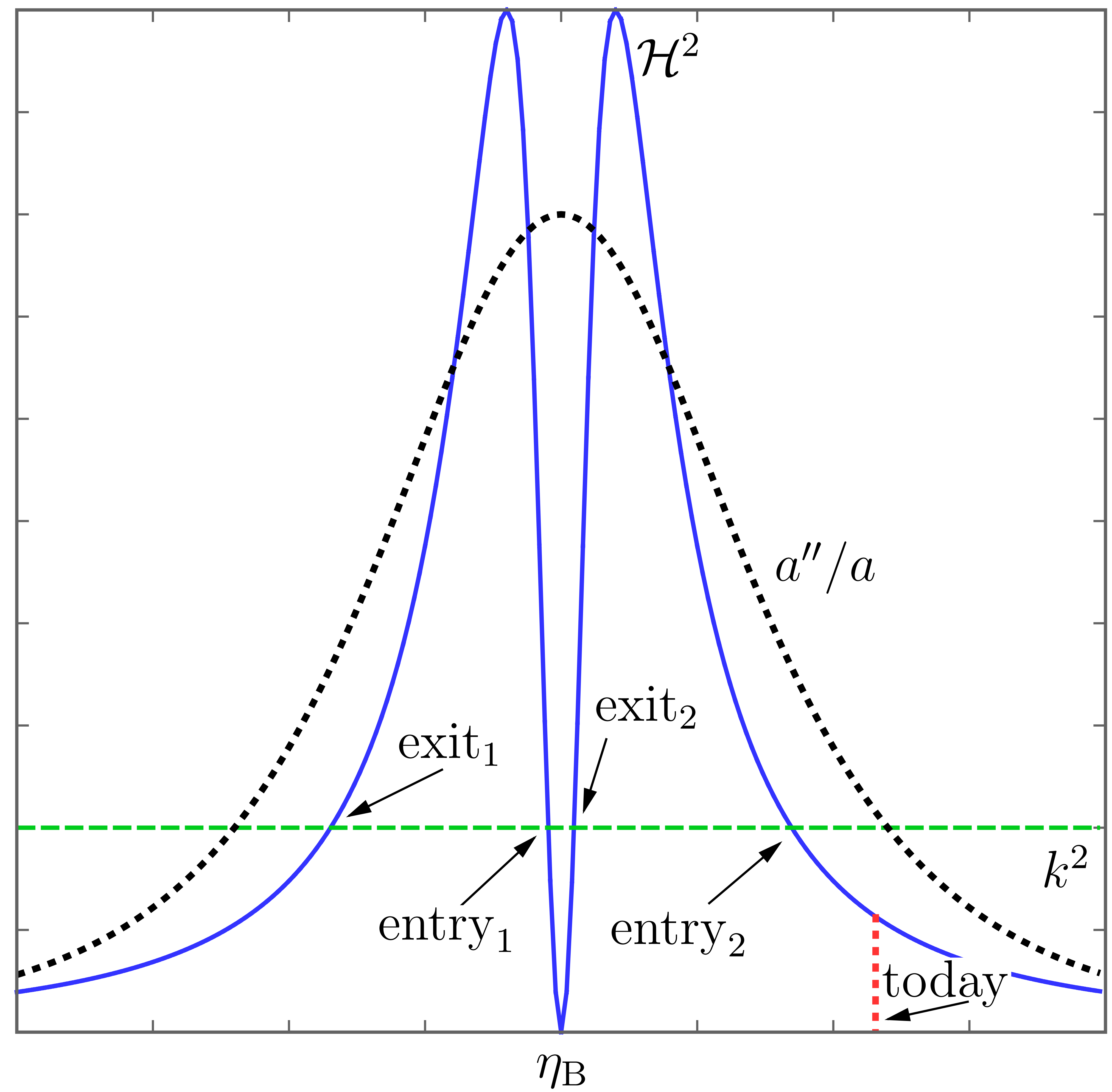
$$\begin{pmatrix} \Phi_{\mathrm{g}}^{+} \\ \Phi_{\mathrm{d}}^{+} \end{pmatrix} = \mathbf{T}_{ij}(k) \begin{pmatrix} \Phi_{\mathrm{g}}^{-} \\ \Phi_{\mathrm{d}}^{-} \end{pmatrix}$$

ASSUME LINEARITY THROUGHOUT

``central feature of bouncing cosmology = the bounce''… (C. Burgess)

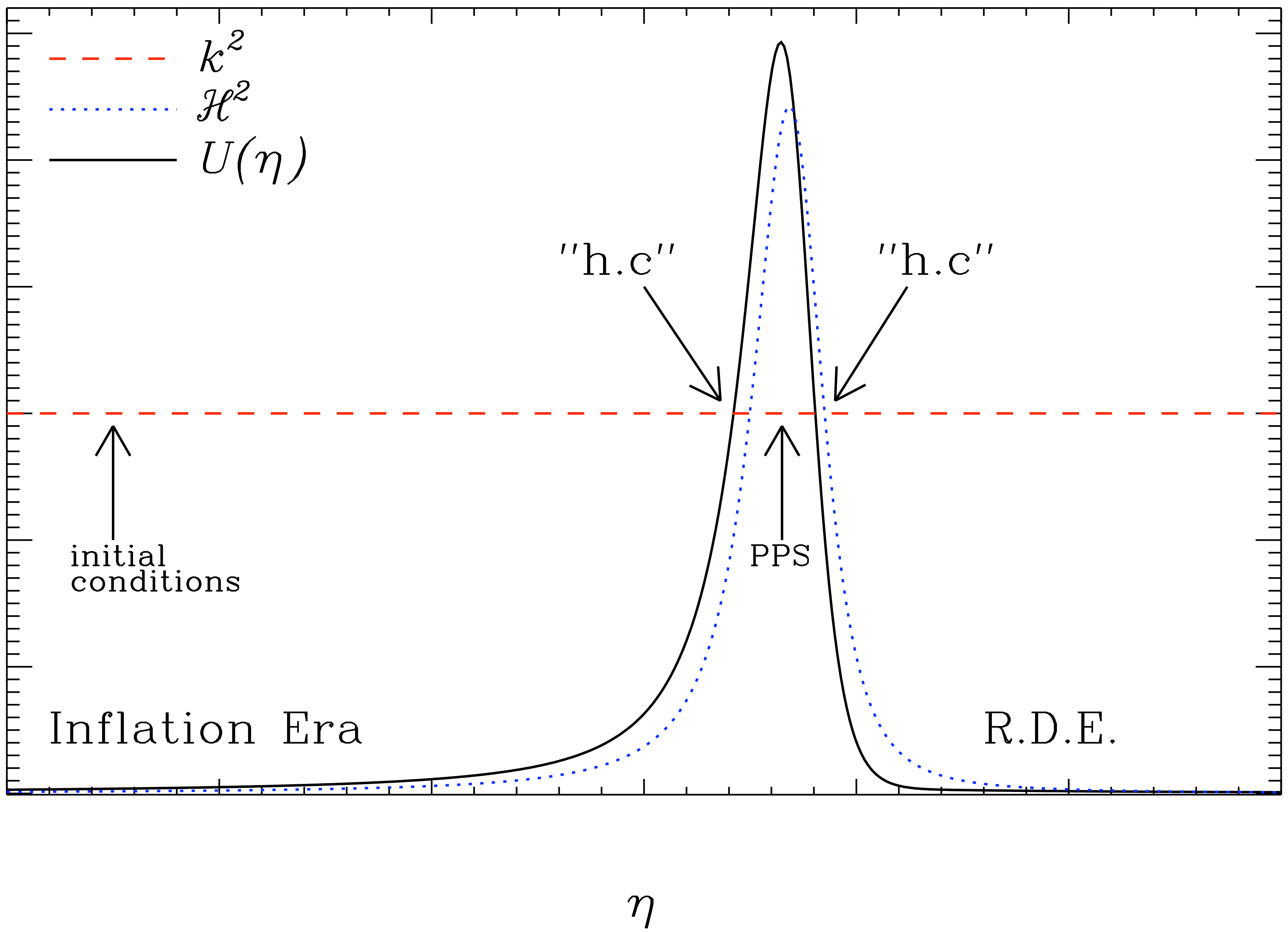
Hubble & potential: tensor example

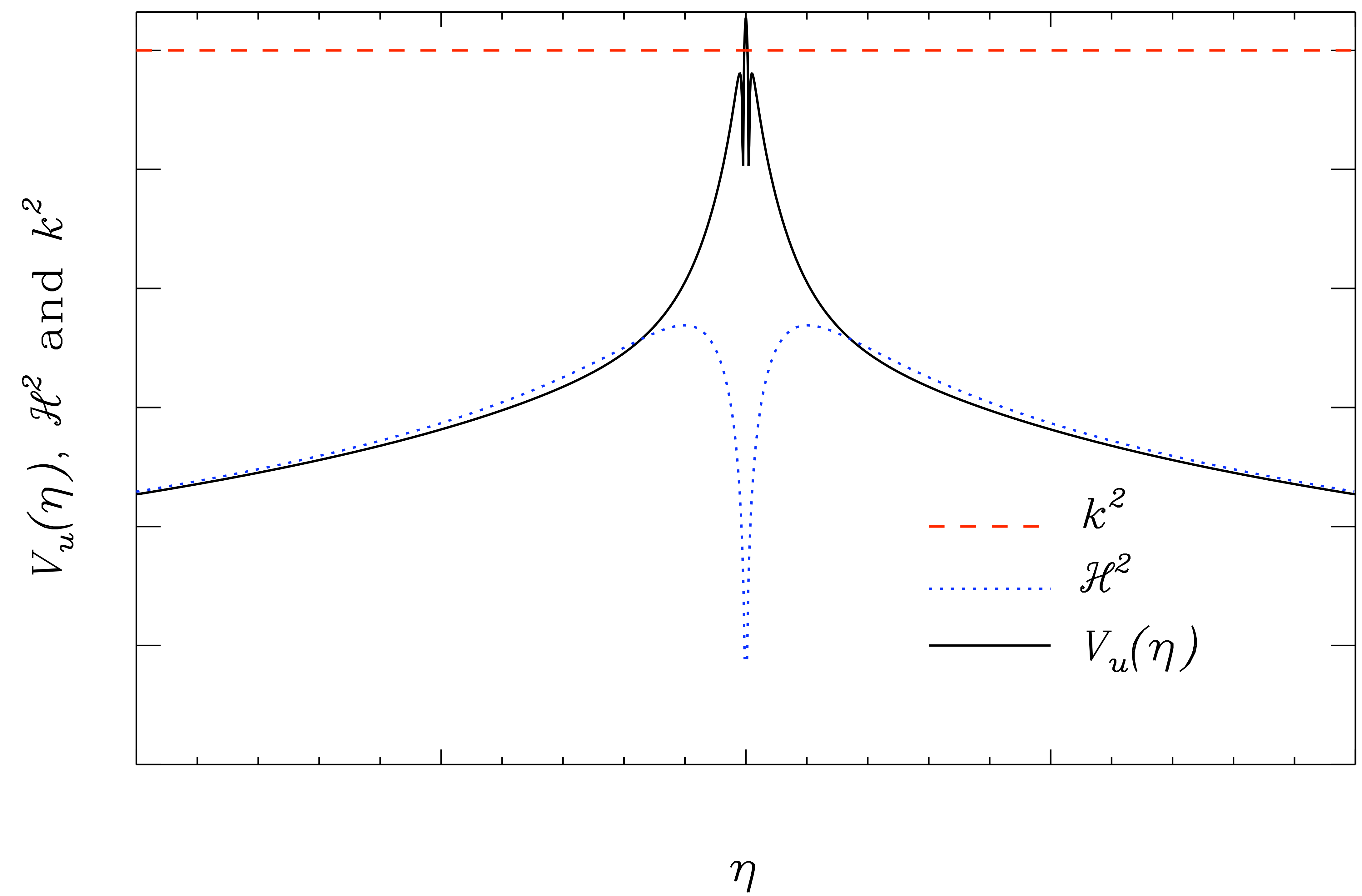
$$\mu_{\mathrm{T}}'' + \left(k^2 + \frac{a''}{a}\right)\mu_{\mathrm{T}} = 0$$



Hubble & potential: scalar example

J. Martin& PP, *PR***D68,** 103517 (2003)

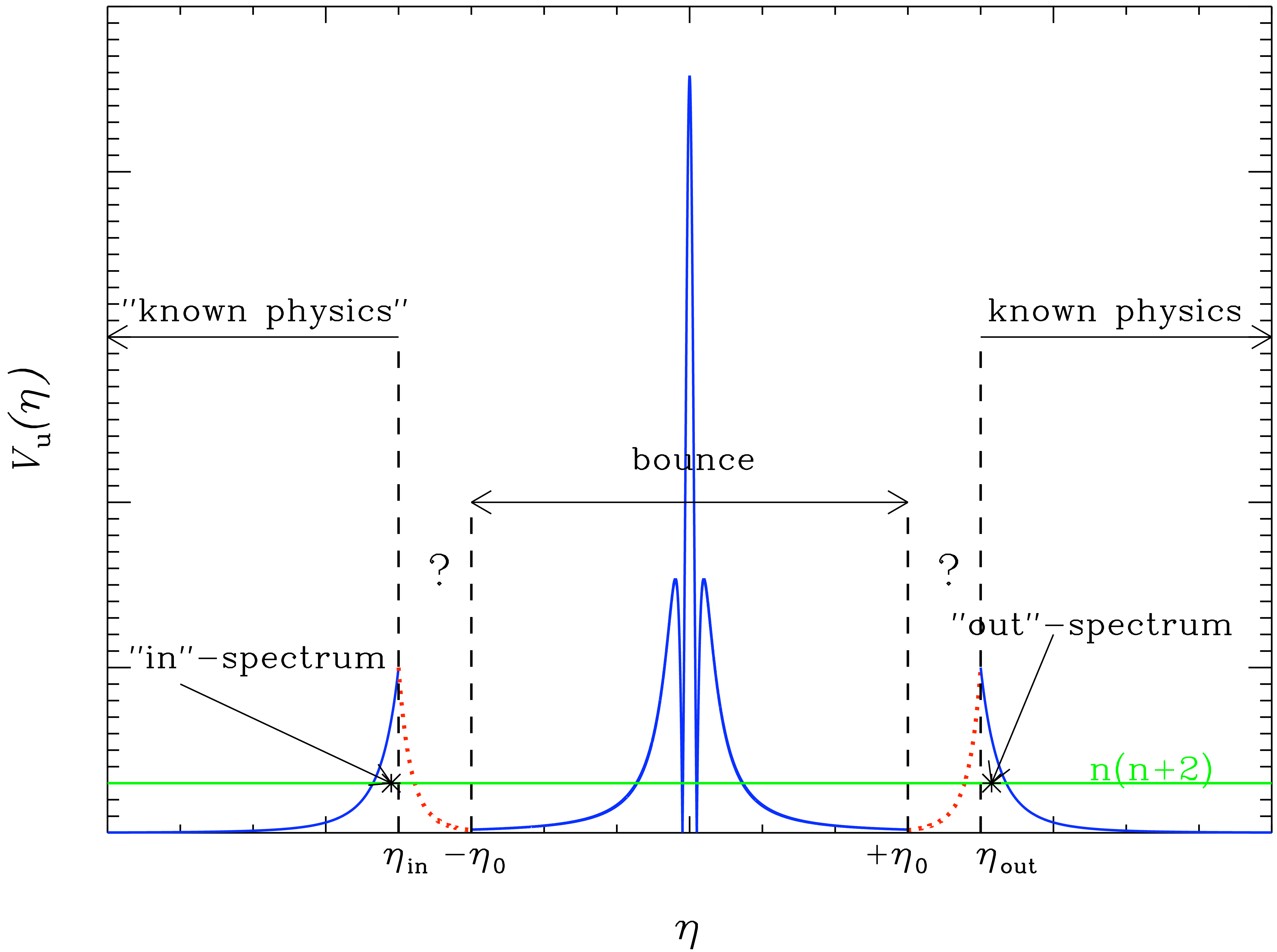




$$u_{\boldsymbol{k}}'' + \left[k^2 - V_u(\eta)\right] u_{\boldsymbol{k}} = 0$$

Resulting spectrum: very much model dependent…

J. Martin& PP, *PR* **D68,** 103517 (2003)



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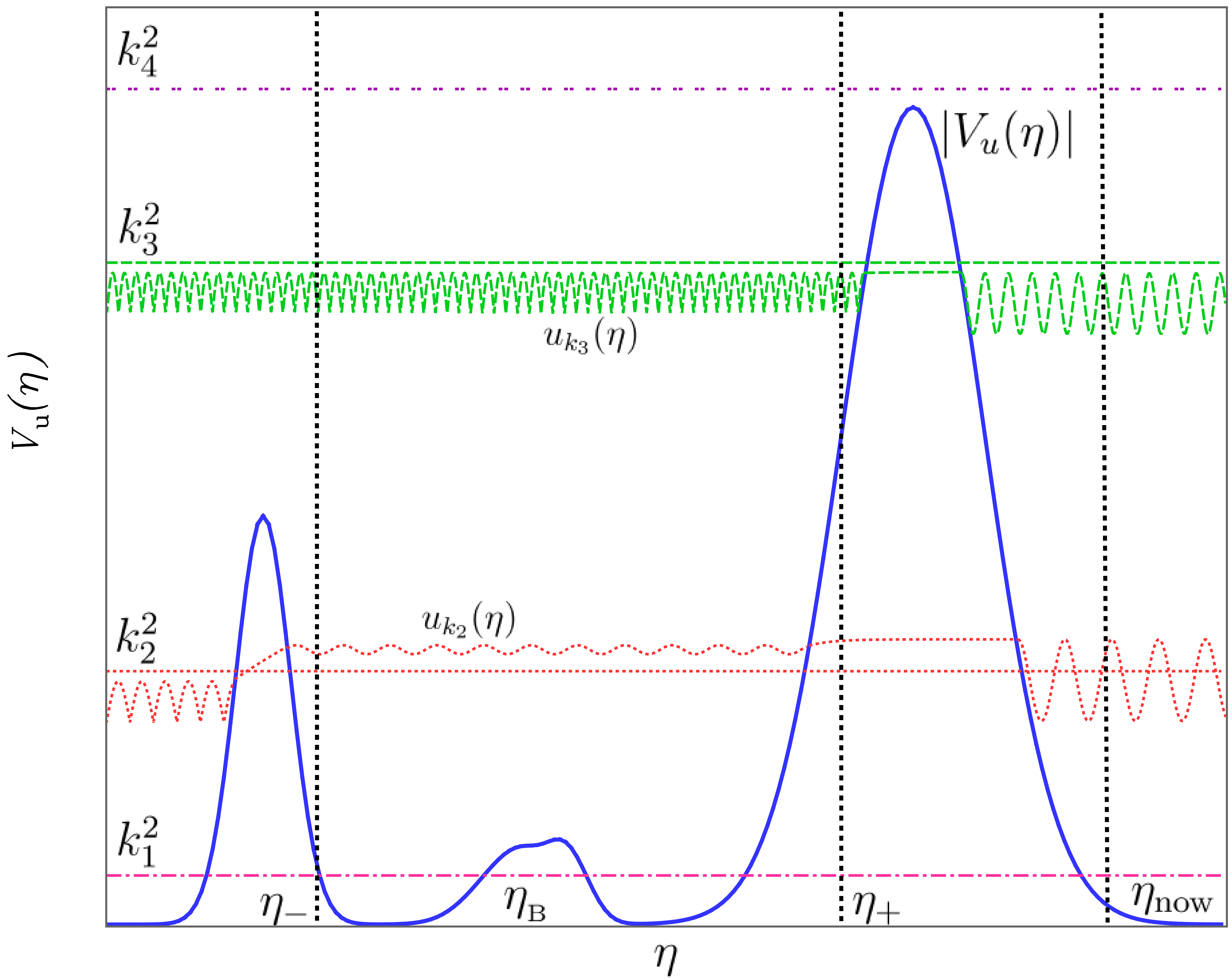
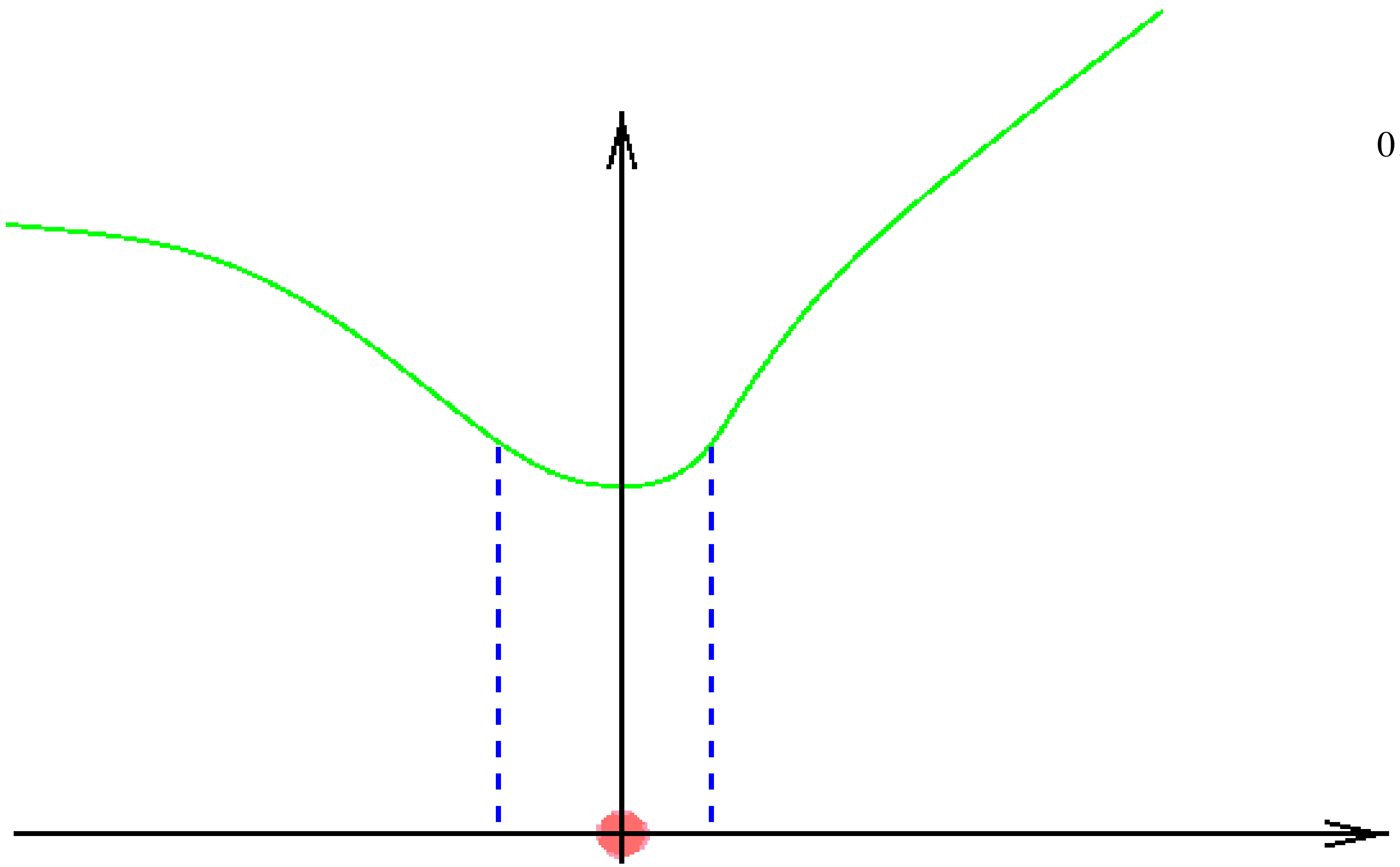
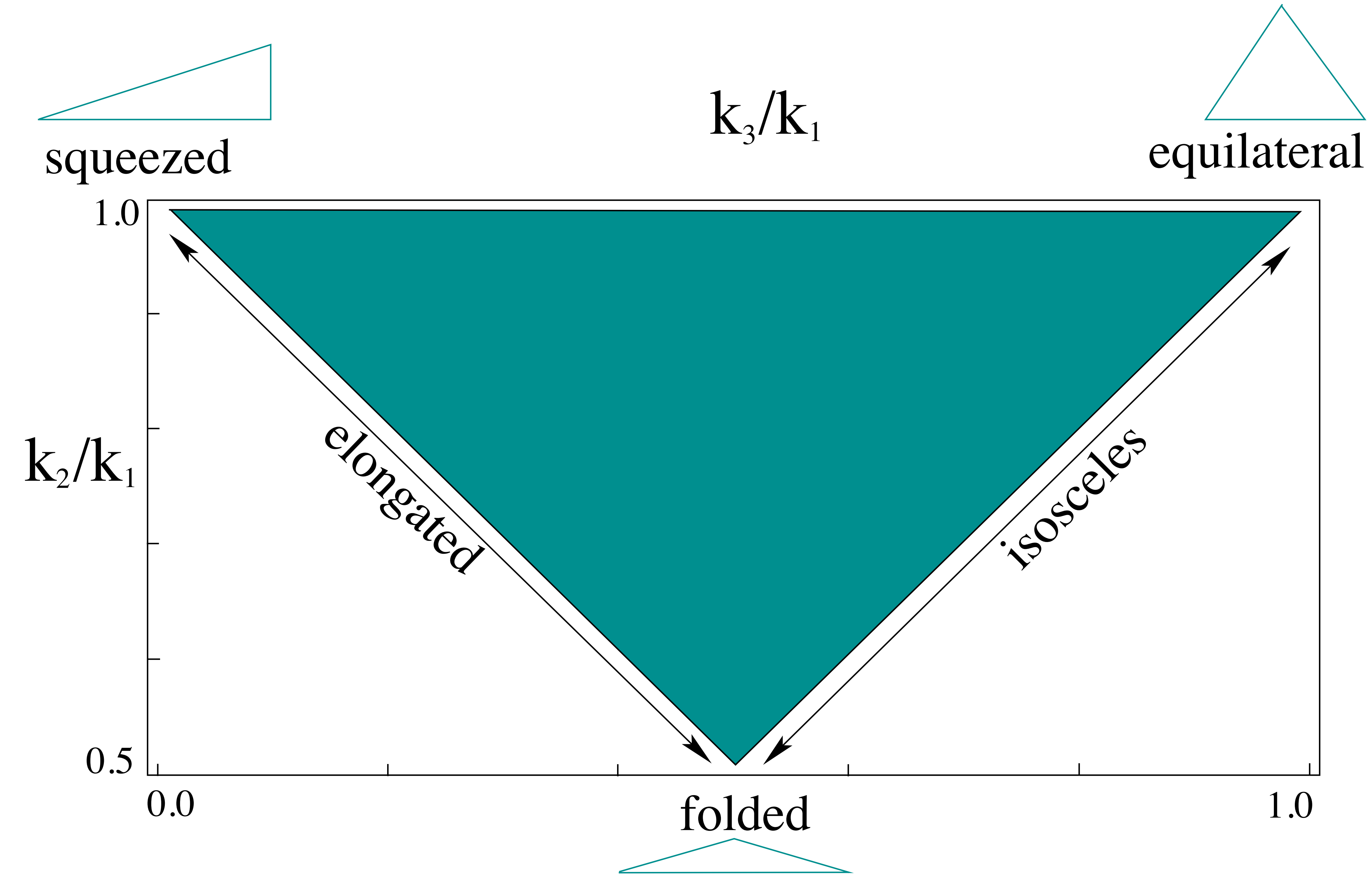


Non-Gaussianities

$$S = -\int \mathrm{d}^4 x \sqrt{-g}\left[R + (\partial\phi)^2 + V(\phi)\right]$$

$$\mathrm{d}s^2 = a^2\left(-\mathrm{e}^{2\Phi}\mathrm{d}\eta^2 + \mathrm{e}^{-2\Psi}\gamma_{ij}\mathrm{d}x^i\mathrm{d}x^j\right)$$





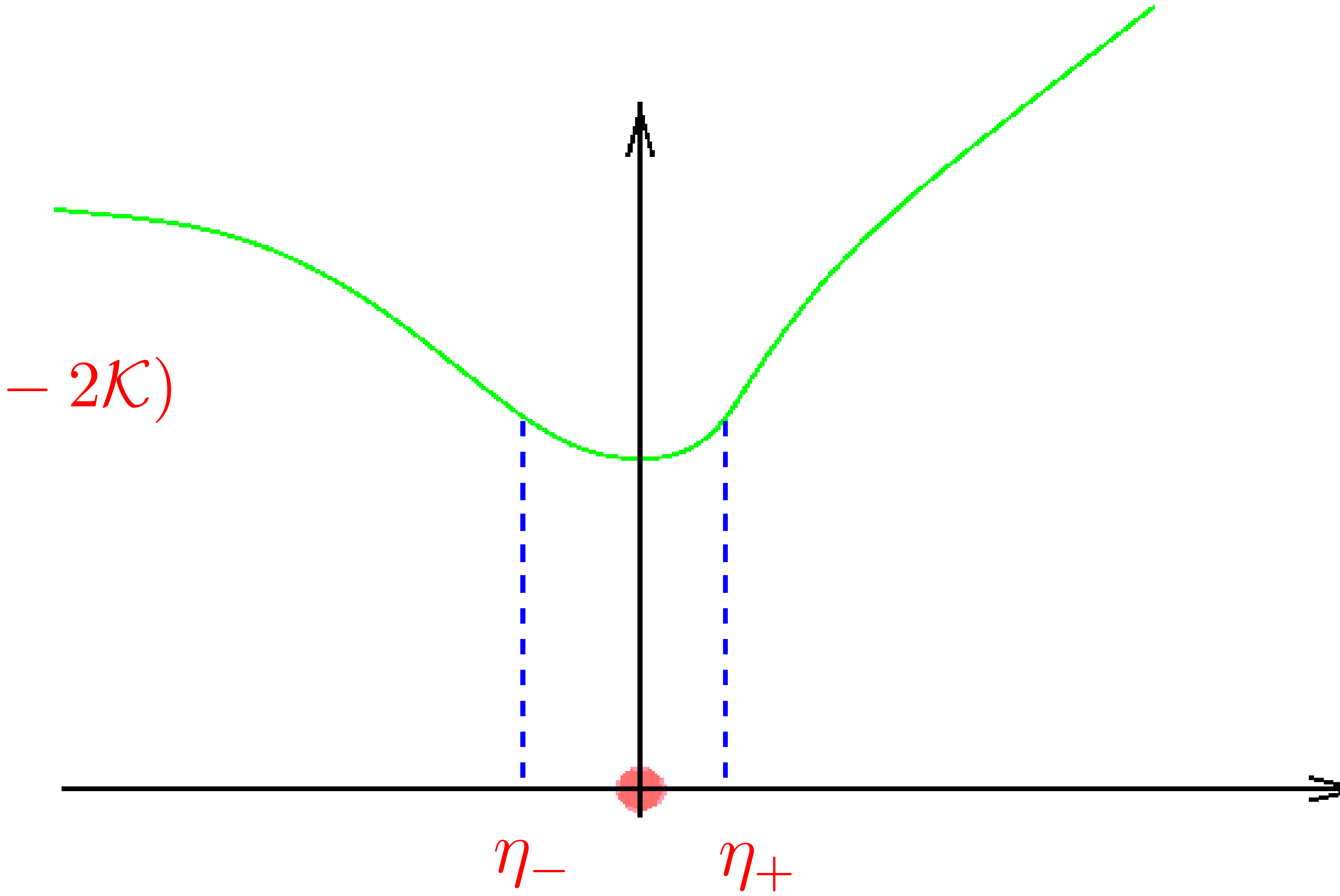
$$\frac{a}{a_0} = 1 + \frac{1}{2}\left(\frac{\eta}{\eta_c}\right)^2 + \lambda_3\left(\frac{\eta}{\eta_c}\right)^3 + \frac{5(1+\lambda_4)}{24}\left(\frac{\eta}{\eta_c}\right)^4 + \cdots$$

$$\Upsilon = \phi_{\mathrm{B}}'^2/2$$

equation of motion for perturbations $\mathcal{D}\,\Psi_{(i)} = \mathcal{S}\left[\Psi_{(i-1)}\right]$

$$\mathcal{D} = \partial_\eta^2 + F\left(\eta\right)\partial_\eta + k^2 + W\left(\eta\right)$$

$$F(\eta) = 2\left(\mathcal{H} - \phi''/\phi'\right) \qquad W(\eta) = 2\left(\mathcal{H}' - \mathcal{H}\phi''/\phi' - 2\mathcal{K}\right)$$



random variables $\hat{x}_a \equiv \left\{\Psi_{(1)}(\eta_-), \Psi'_{(1)}(\eta_-)\right\}$

spectral matrix $\langle \hat{x}_a\left(\boldsymbol{k}_1\right)\hat{x}_b\left(\boldsymbol{k}_2\right)\rangle = \delta_{\boldsymbol{k}_1\boldsymbol{k}_2} P_{ab}\left(k\right)$

bispectrum $\mathcal{B}_\Psi$ at η_+ $\langle \Psi_{\boldsymbol{k}_1}\Psi_{\boldsymbol{k}_2}\Psi_{\boldsymbol{k}_3}\rangle = \frac{1}{2}\mathcal{G}_{\boldsymbol{k}_1\boldsymbol{k}_2\boldsymbol{k}_3}\mathcal{B}_\Psi\left(k_1, k_2, k_3\right)$

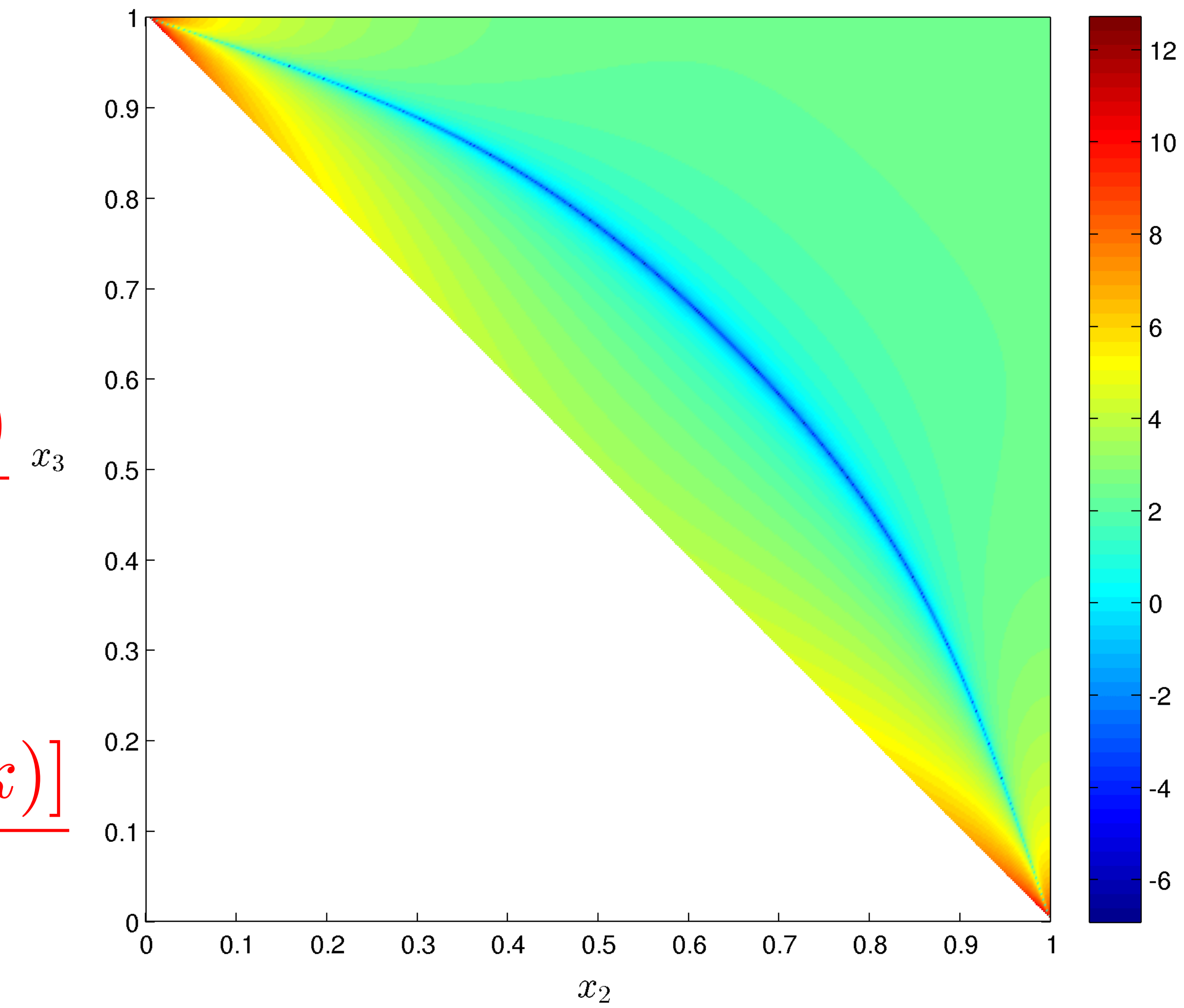
$$\mathcal{B}_\Psi(k_1,k_2,k_3) = \frac{6}{5} f_{\rm NL}\left[P_{\Psi\Psi}(k_1)P_{\Psi\Psi}(k_2) + P_{\Psi\Psi}(k_2)P_{\Psi\Psi}(k_3) + P_{\Psi\Psi}(k_3)P_{\Psi\Psi}(k_1)\right]$$

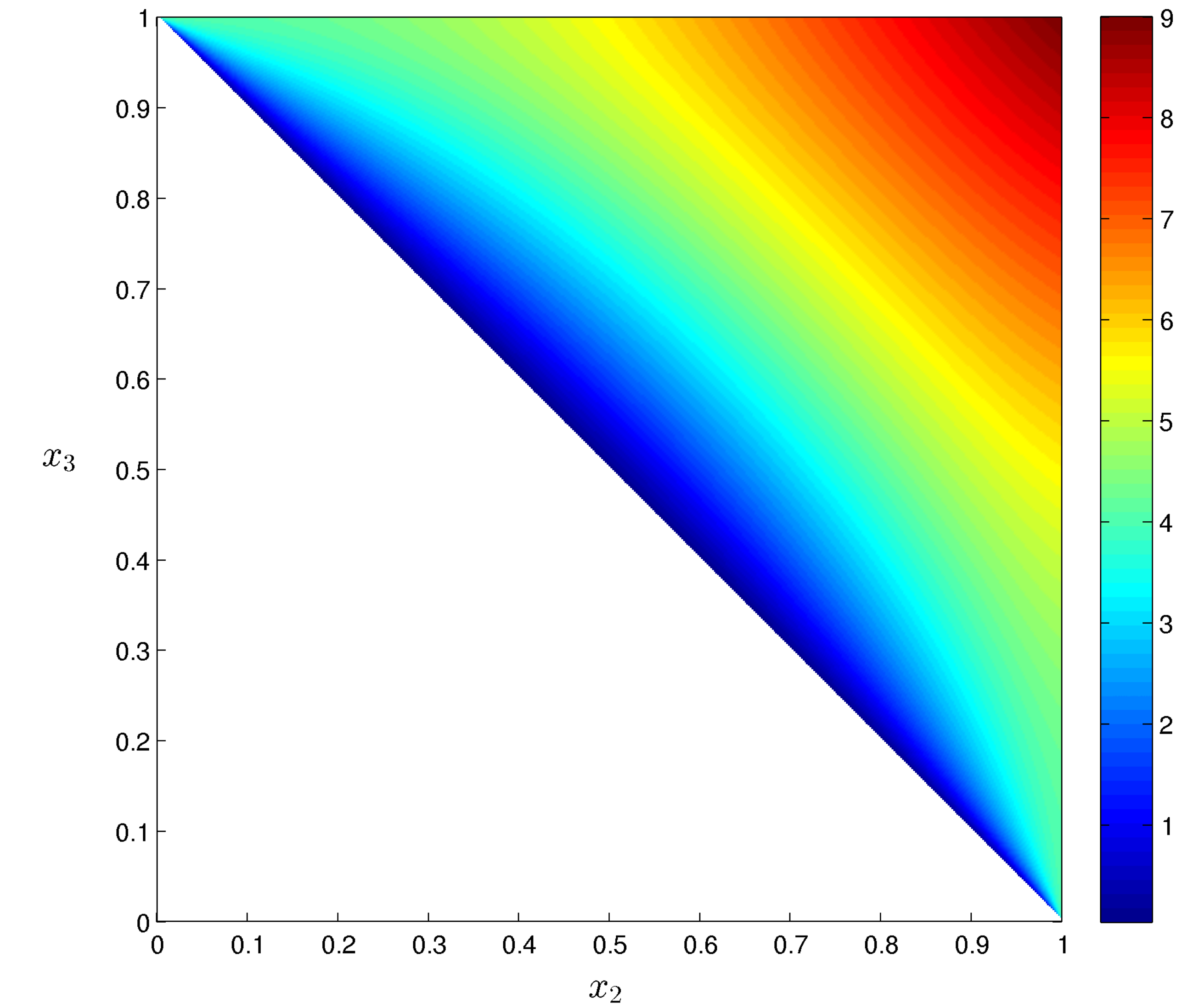
$$f_{\rm NL} = -\frac{5(k_1+k_2+k_3)}{3\Upsilon K_3\left(k_1,k_2,k_3\right)}\left[\prod_{\sigma(i,j,\ell)}\left(k_i+k_j-k_\ell\right)\right]\left\{\sum_{\sigma(i,j,\ell)}\frac{K_1(k_i)K_1(k_j)}{k_\ell^2} - 4\left[\frac{K_1(k_i)K_2(k_j)}{k_j^2k_\ell^2} + \frac{K_1(k_j)K_2(k_i)}{k_i^2k_\ell^2}\right]\right\}$$
$$+\frac{5}{3\Upsilon K_3\left(k_1,k_2,k_3\right)}\sum_{\sigma(i,j,\ell)}\left[\frac{7}{3} + \frac{2}{3}\left(\frac{k_i^2+k_j^2}{k_\ell^2}\right) - 3\left(\frac{k_i^2-k_j^2}{k_\ell^2}\right)^2\right]K_1(k_i)K_1(k_j) + \cdots$$

$$f_{\rm NL}^{\rm equi} = -\frac{15k^2}{\Upsilon}\frac{K_1^2(k)}{K_3(k,k,k)}$$

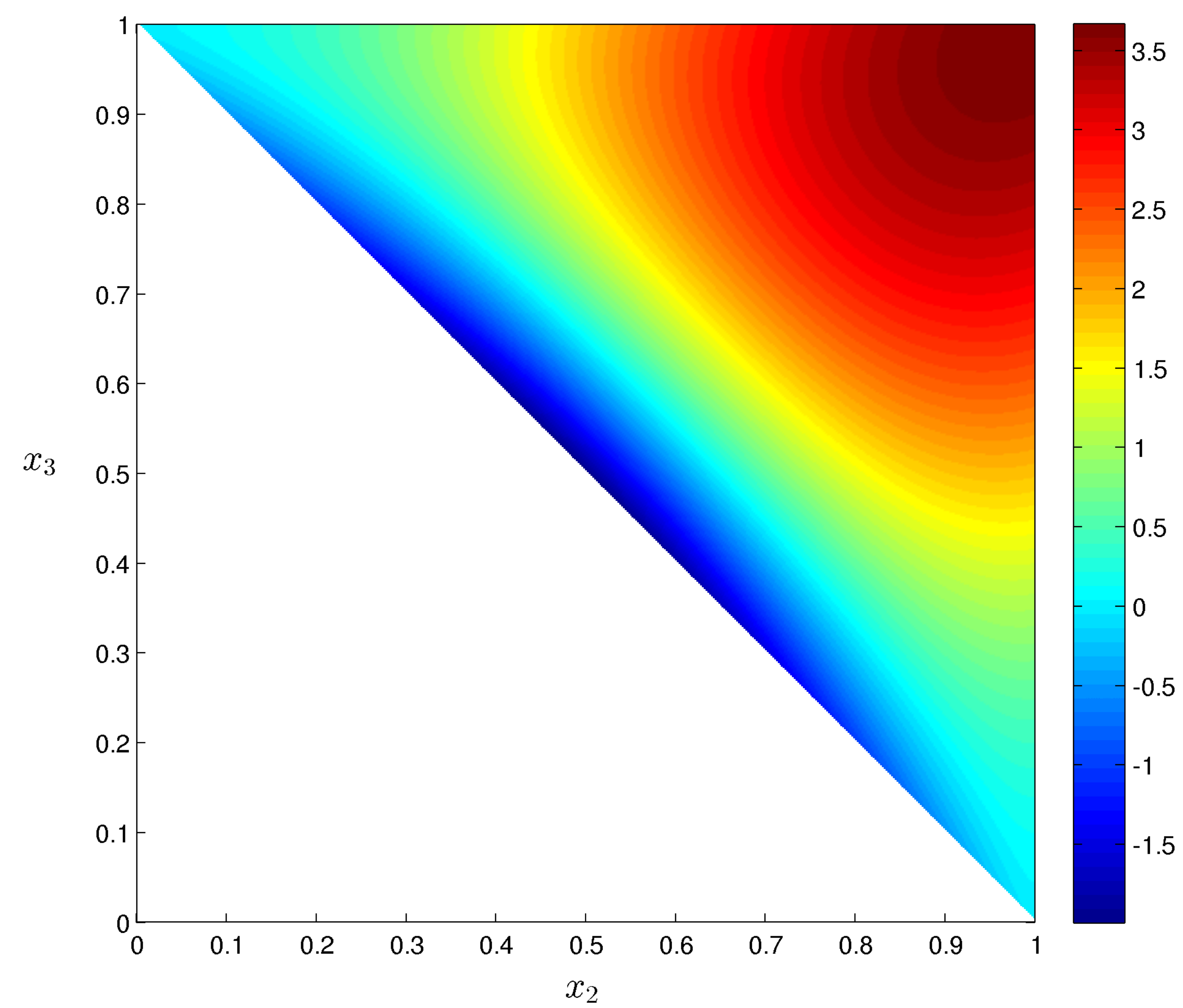
$$f_{\rm NL}^{\rm sq} = -\frac{20k^2}{3\Upsilon}\frac{K_1^2(k)+K_1(k)K_1(p)}{K_3(k,k,p)}$$

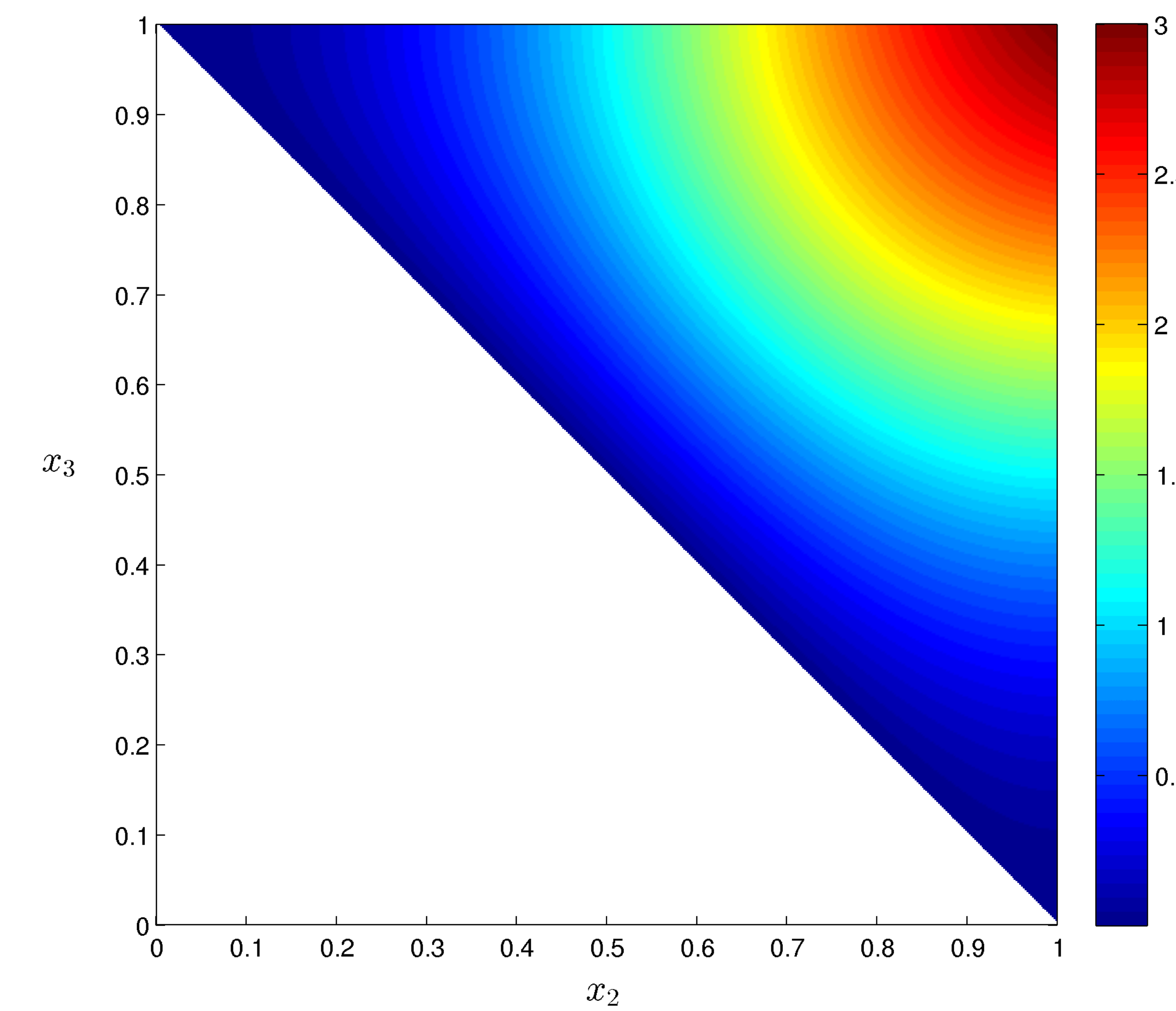
$$f_{\rm NL}^{\rm fold} = \frac{40}{9\Upsilon}\frac{K_1(k)\left[K_1(k)-16K_1(2k)\right]}{K_3(k,k,2k)}$$





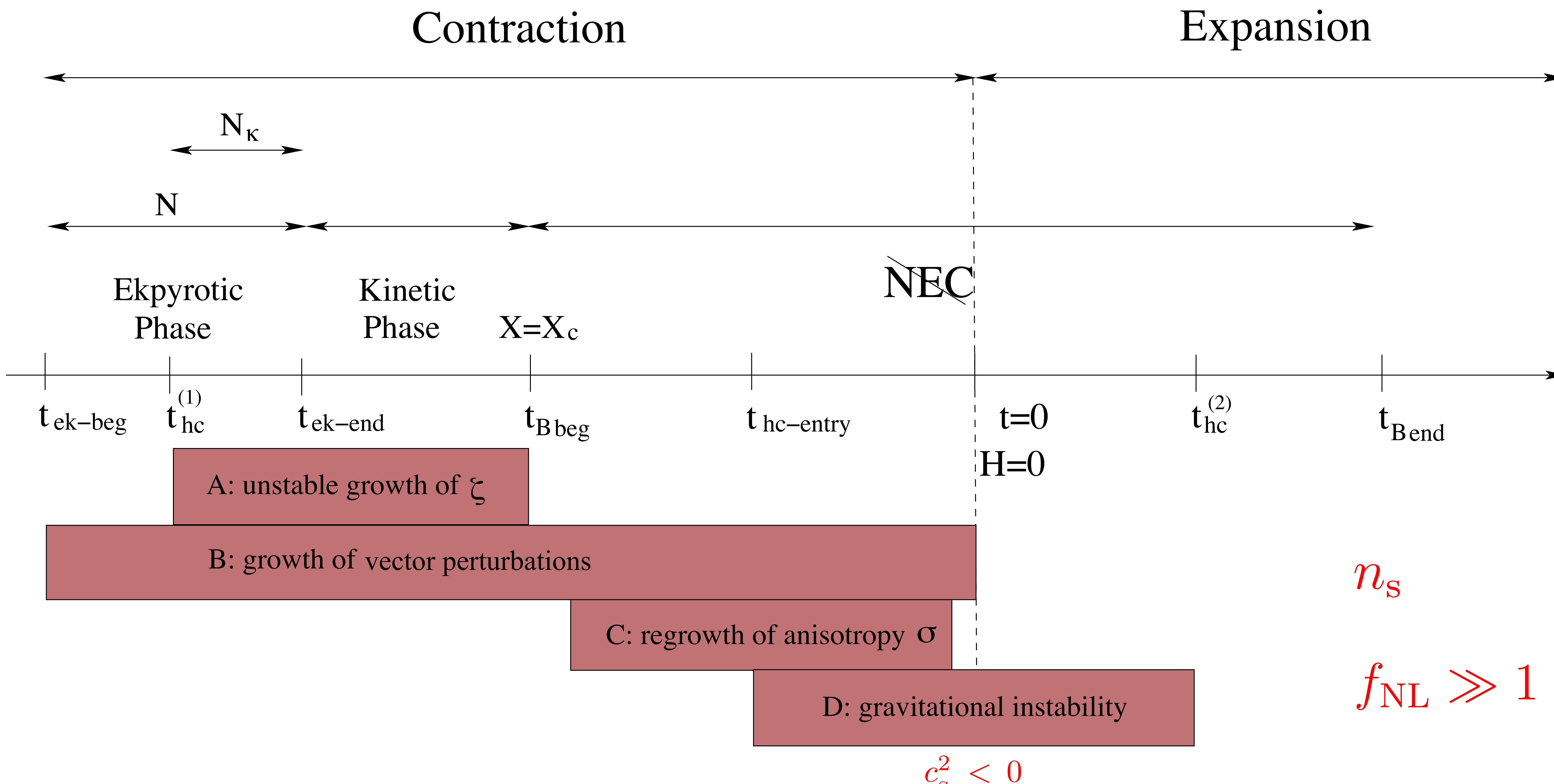
$$\boxed{f_{\rm NL} \simeq \frac{k^2}{\Upsilon} \gg 1}$$





X. Gao, M. Lilley & PP, JCAP **07**, 010 (2014)
X. Gao, M. Lilley & PP, 1406.4119 (2014)

Summary of possible problems



n_s

$f_{NL} \gg 1$

+ phase initial conditions

Thank you

Paris - 18th December 2014