Patrick Peter

GRεCO

Institut d'Astrophysique de Paris

Institut Lagrange de Paris

Bouncing cosmology: the question of shear

INSTITUT D'ÉTUDES SCIENTIFIQUES DE CARGESE

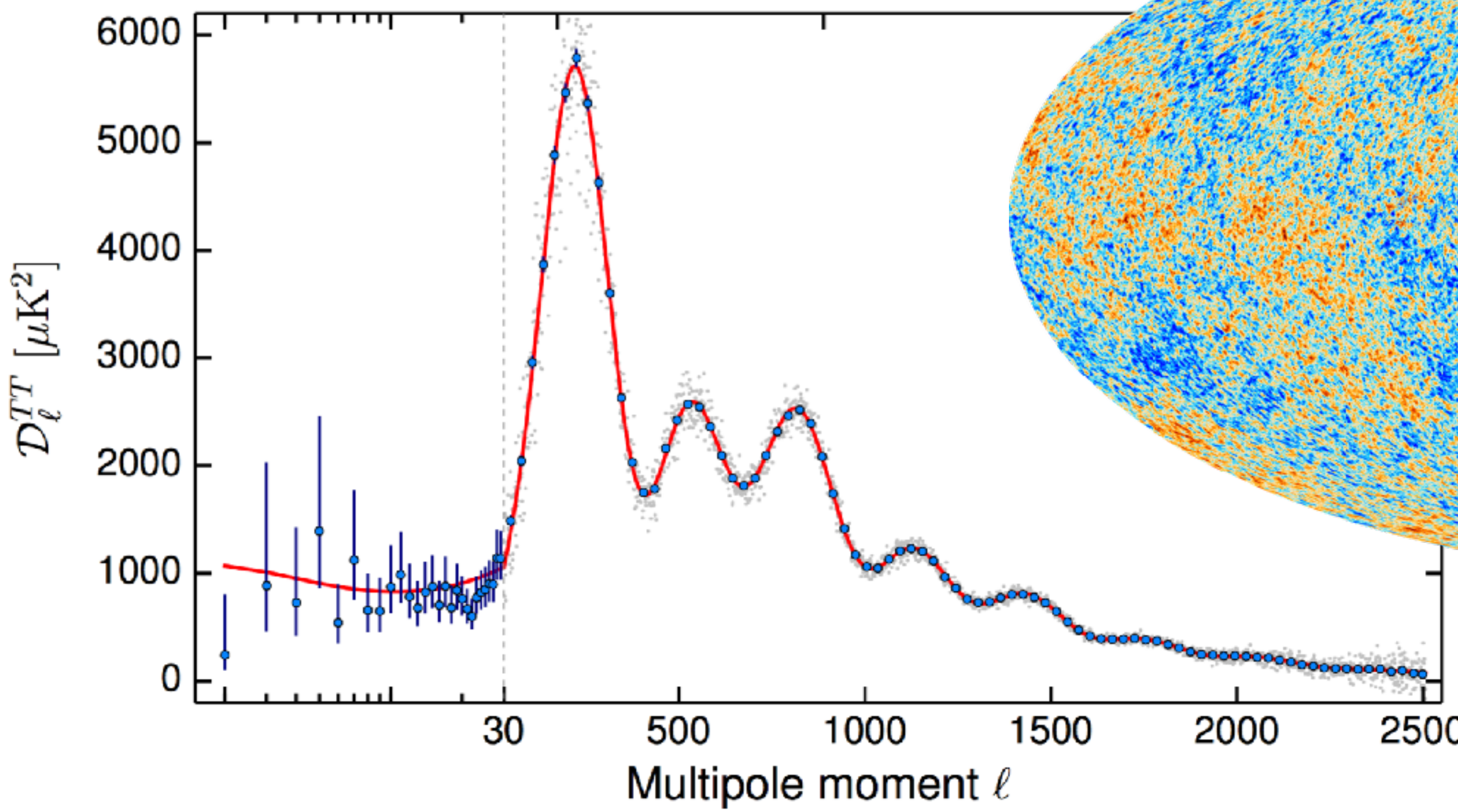
Modern Particle Physics Astrophysics & Cosmology

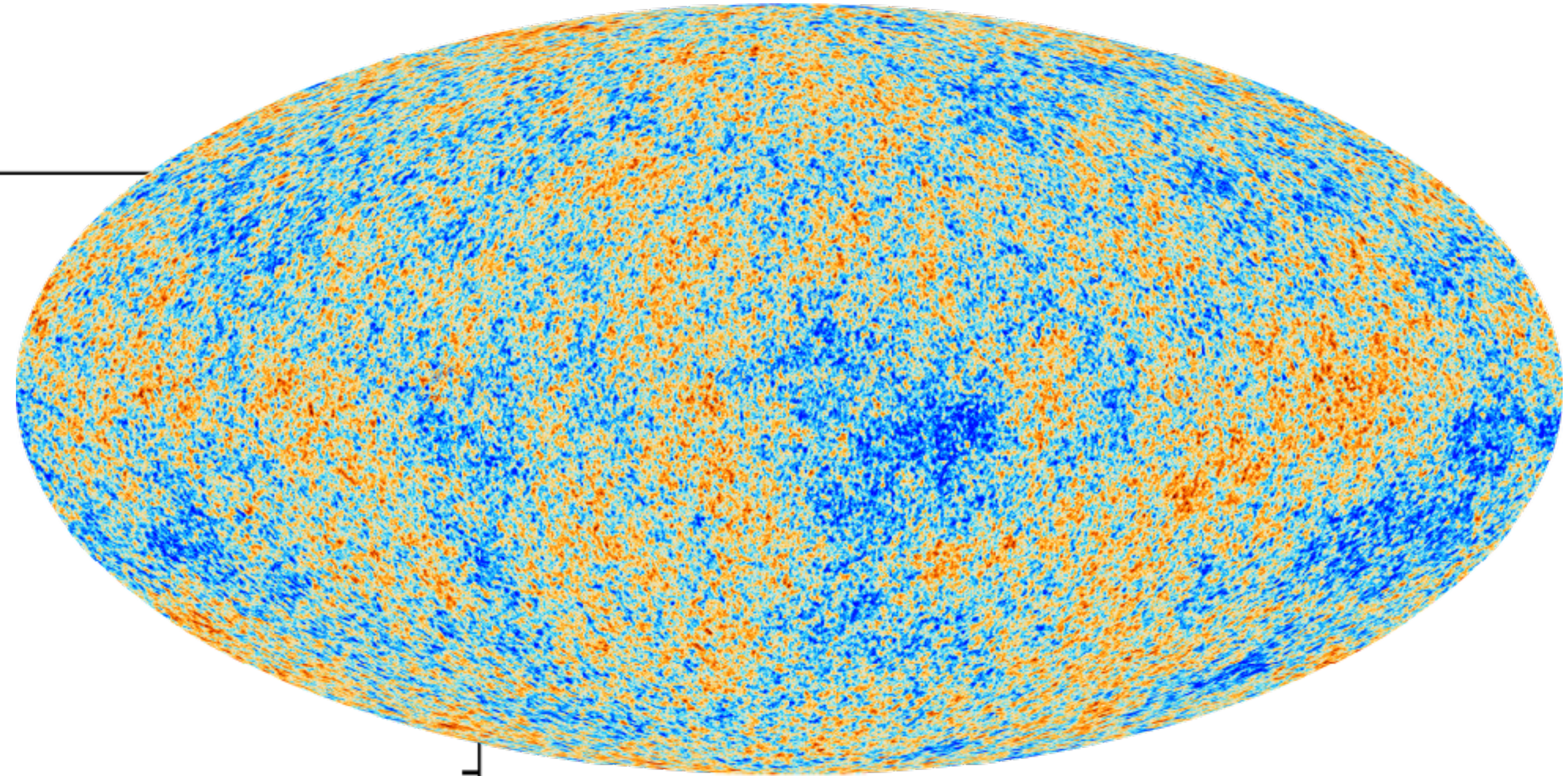
Hot topics in Modern Cosmology

Spontaneous Workshop XI

1 - 6 May 2017 Cargèse

Institut Lagrange de Paris





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

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

(scale invariant) excluded

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

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

} gaussian signal

isocurvature $\lesssim 1\%$

$r < 0.11$

compatible with ***INFLATION***

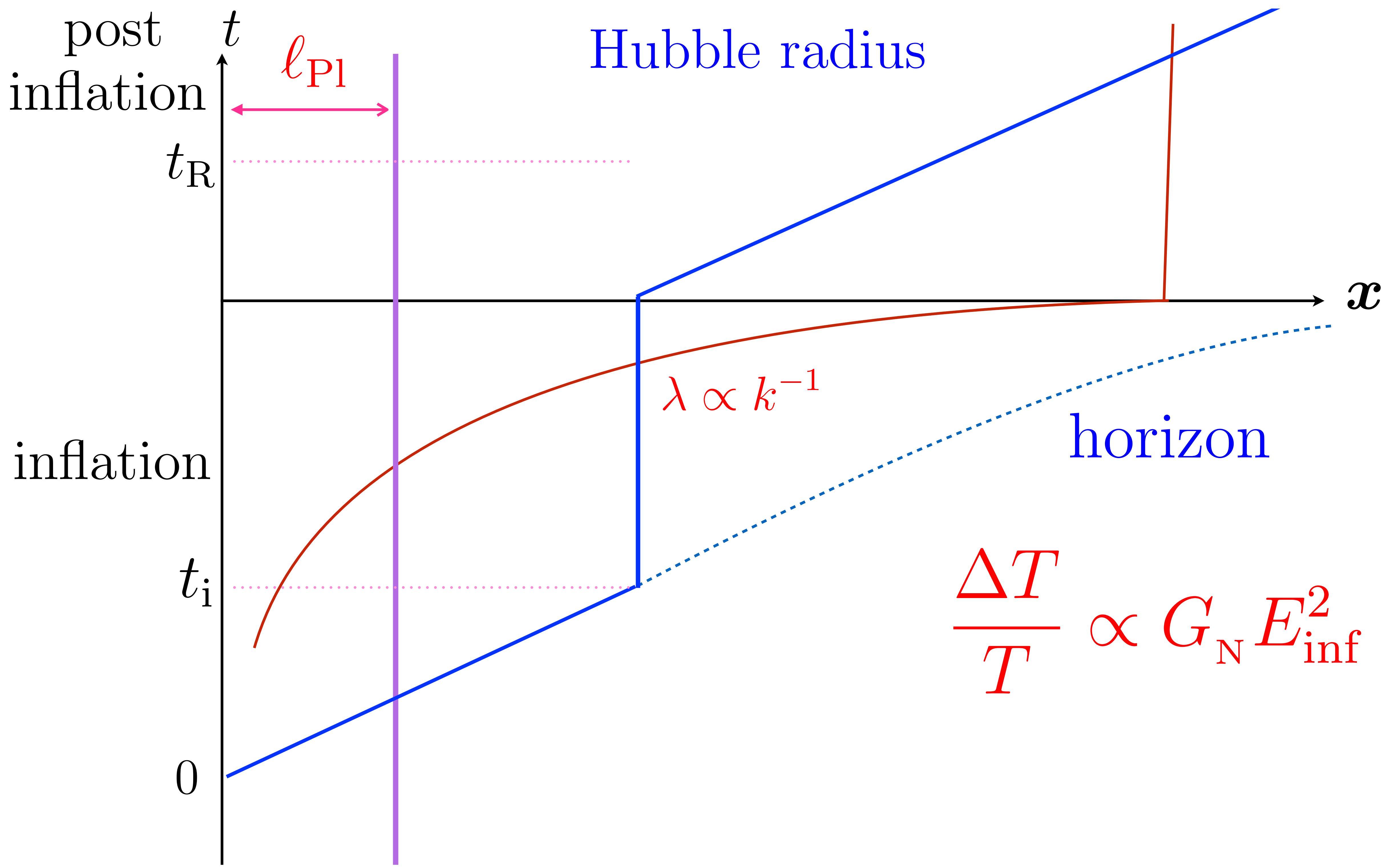
Inflation:

- ☺ **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 & PP (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)?

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

- Classical GR?

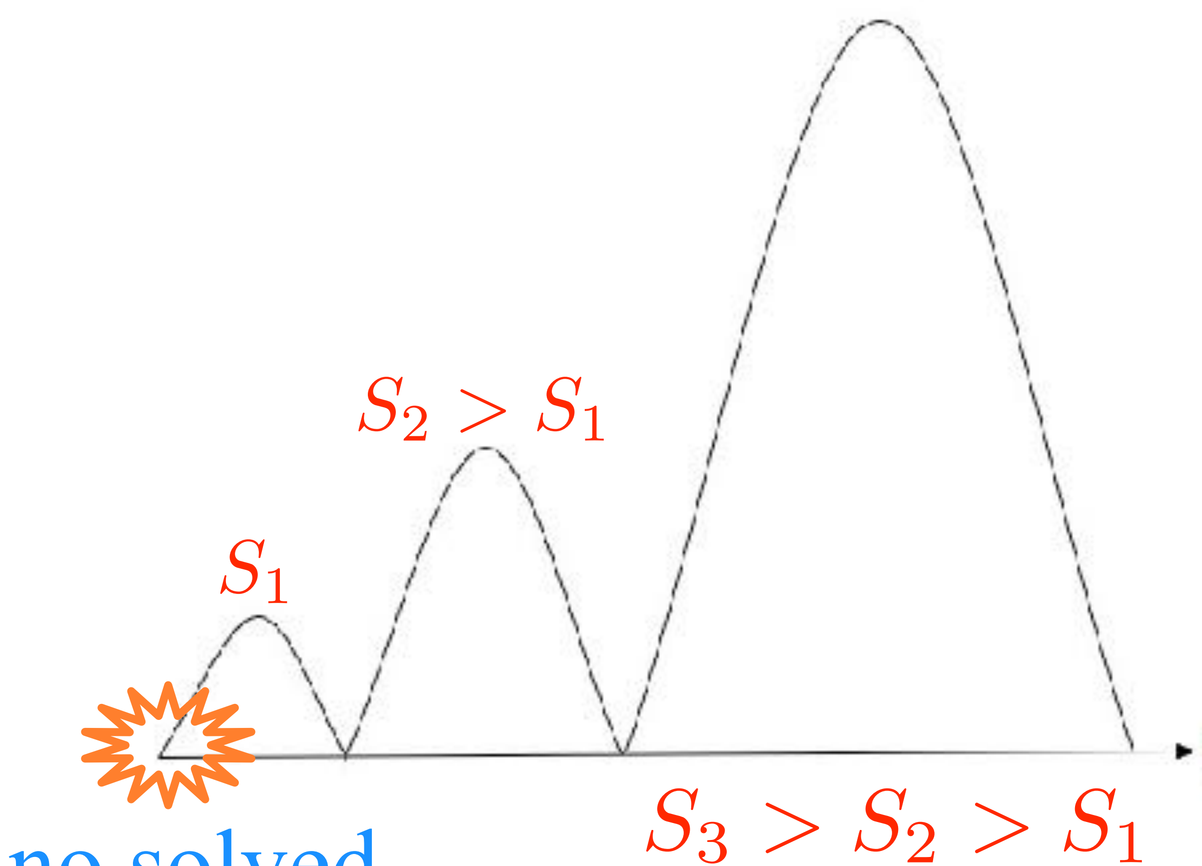
$$\frac{\Delta T}{T} \propto G_{\rm N} E_{\rm inf}^2 \sim \left(\frac{E_{\rm inf}}{M_{\rm Pl}}\right)^2 \longrightarrow E_{\rm inf} \simeq 10^{-3} M_{\rm Pl}$$

- η problem & Lyth bound
- Initial condition & entropy
- Eternal inflation & measure (anthropic)

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)

…



…

Singularity pb no solved

- A. A. Starobinsky, "*On one non-singular isotropic cosmological model*", Sov. Astron. Lett. 4, 82 (1978)
- 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)
- D. Battefeld & PP, "*A Critical Review of Classical Bouncing Cosmologies*", Phys. Rep. **571**, 1 (2015)
- R. Brandenberger & PP, "*Bouncing cosmologies: Progress and problems*", Found. Phys. (2017)

Model listing:

Quantum gravity

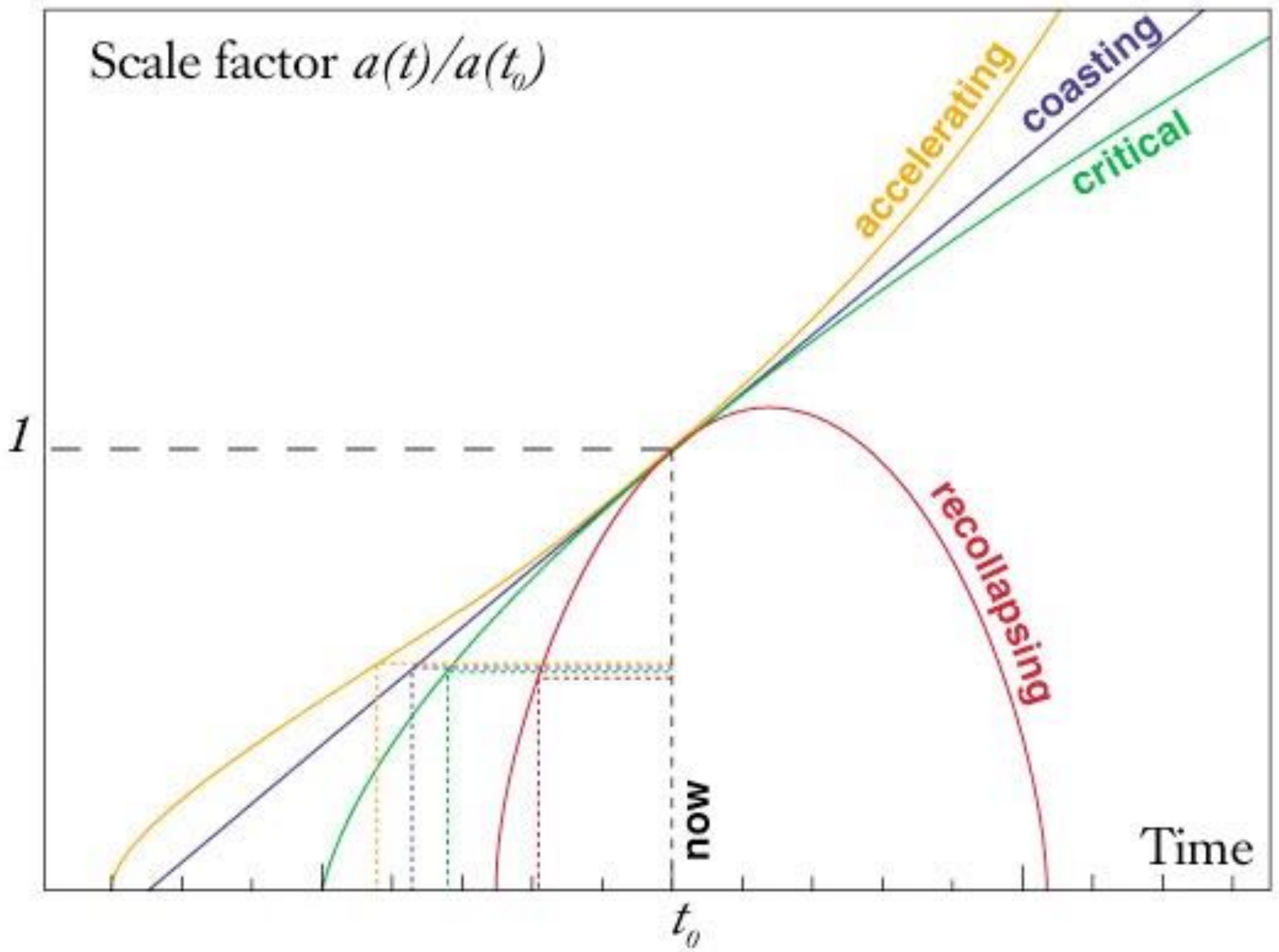
LQG & LQC

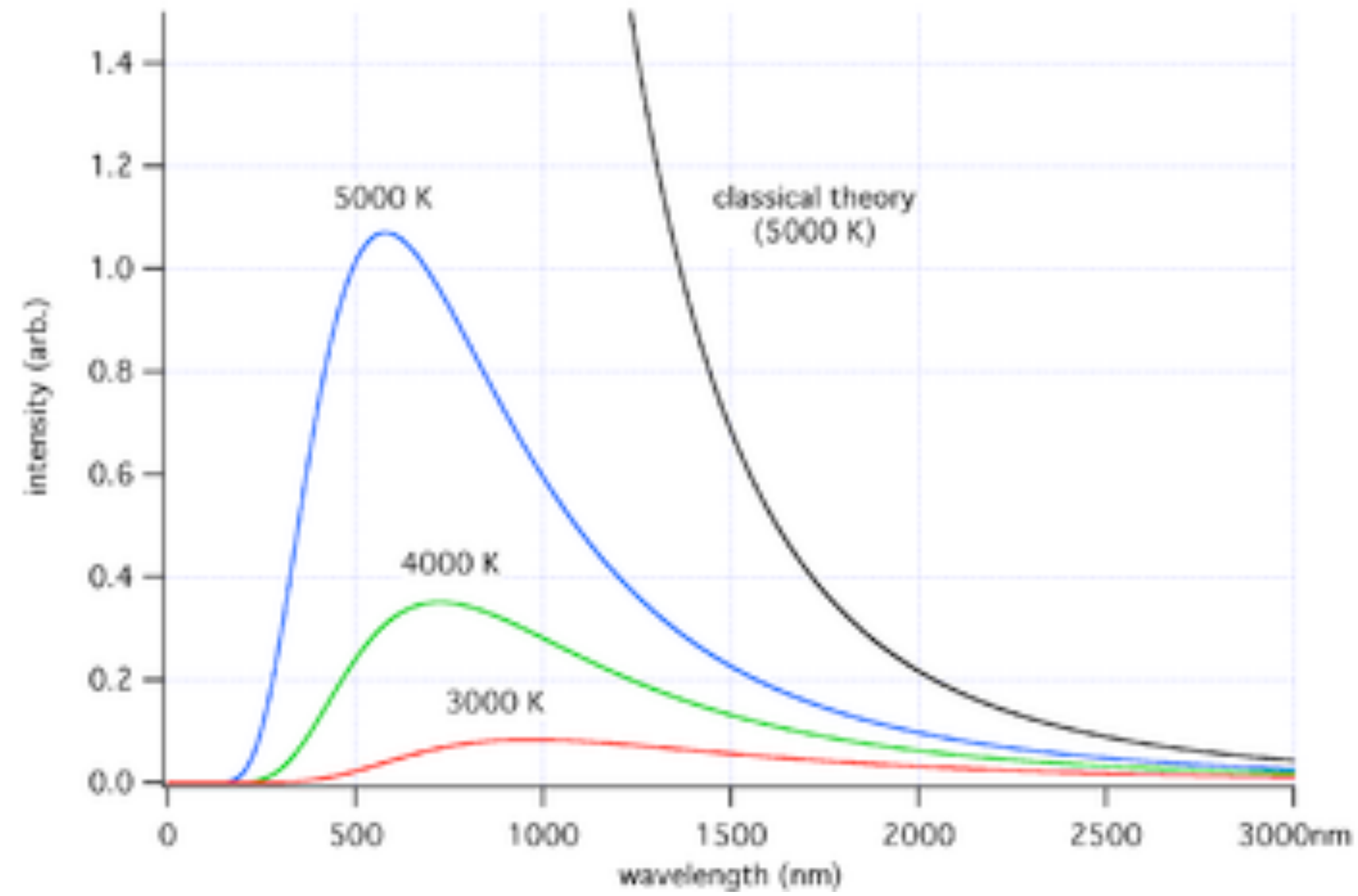
Canonical quantum gravity (WdW)

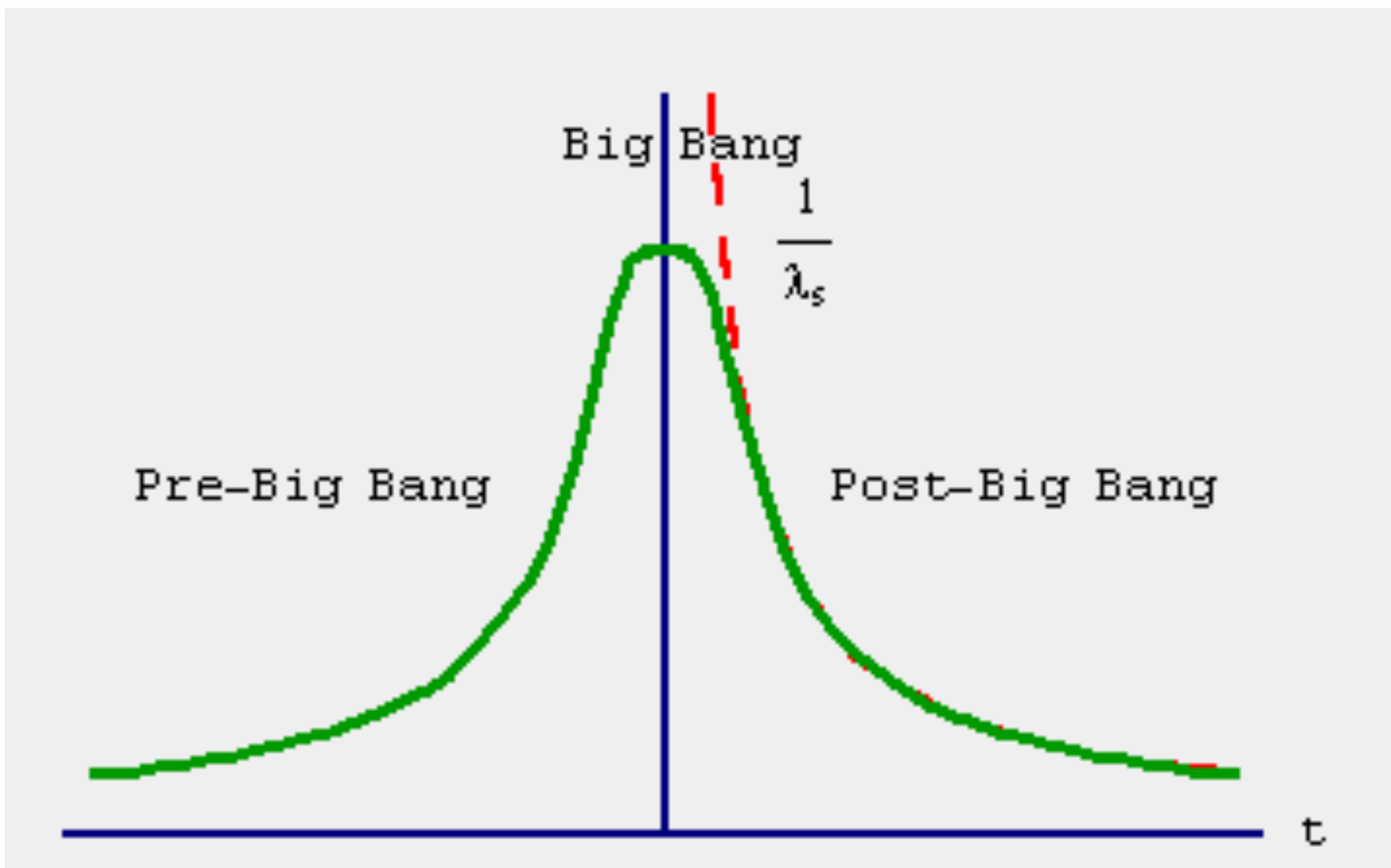
String theory

Non relativistic quantum gravity

Singularity problem   Quantum effect?

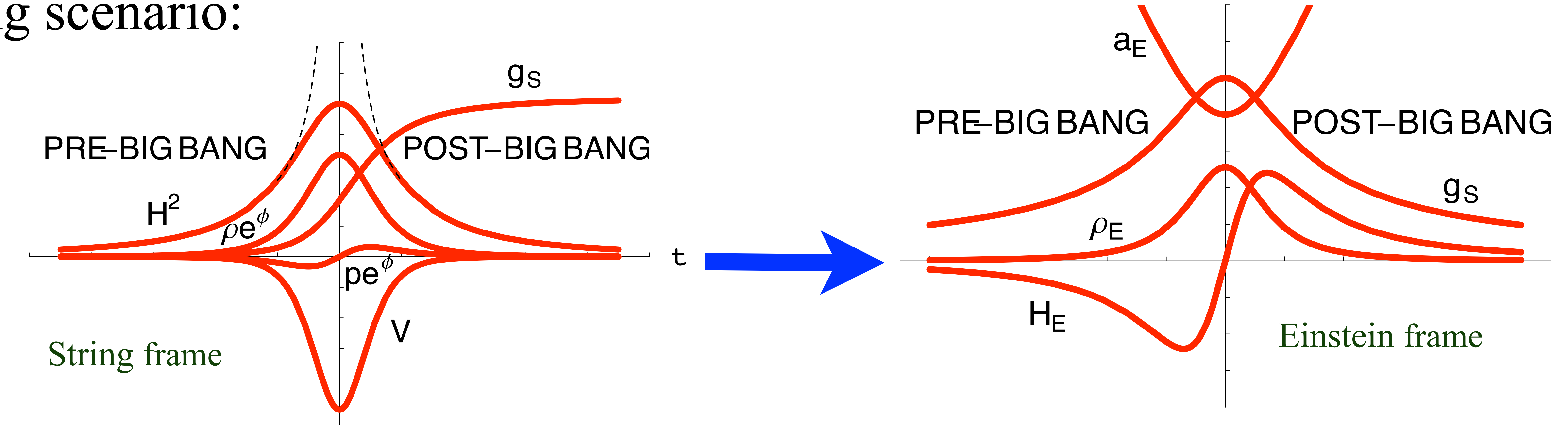




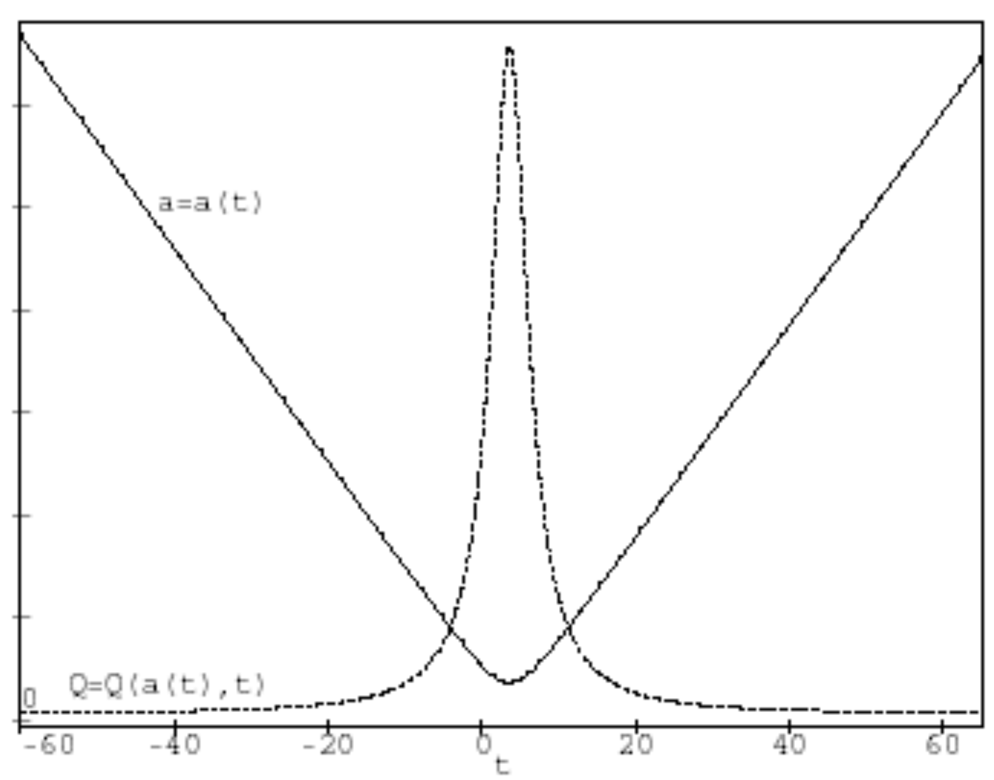


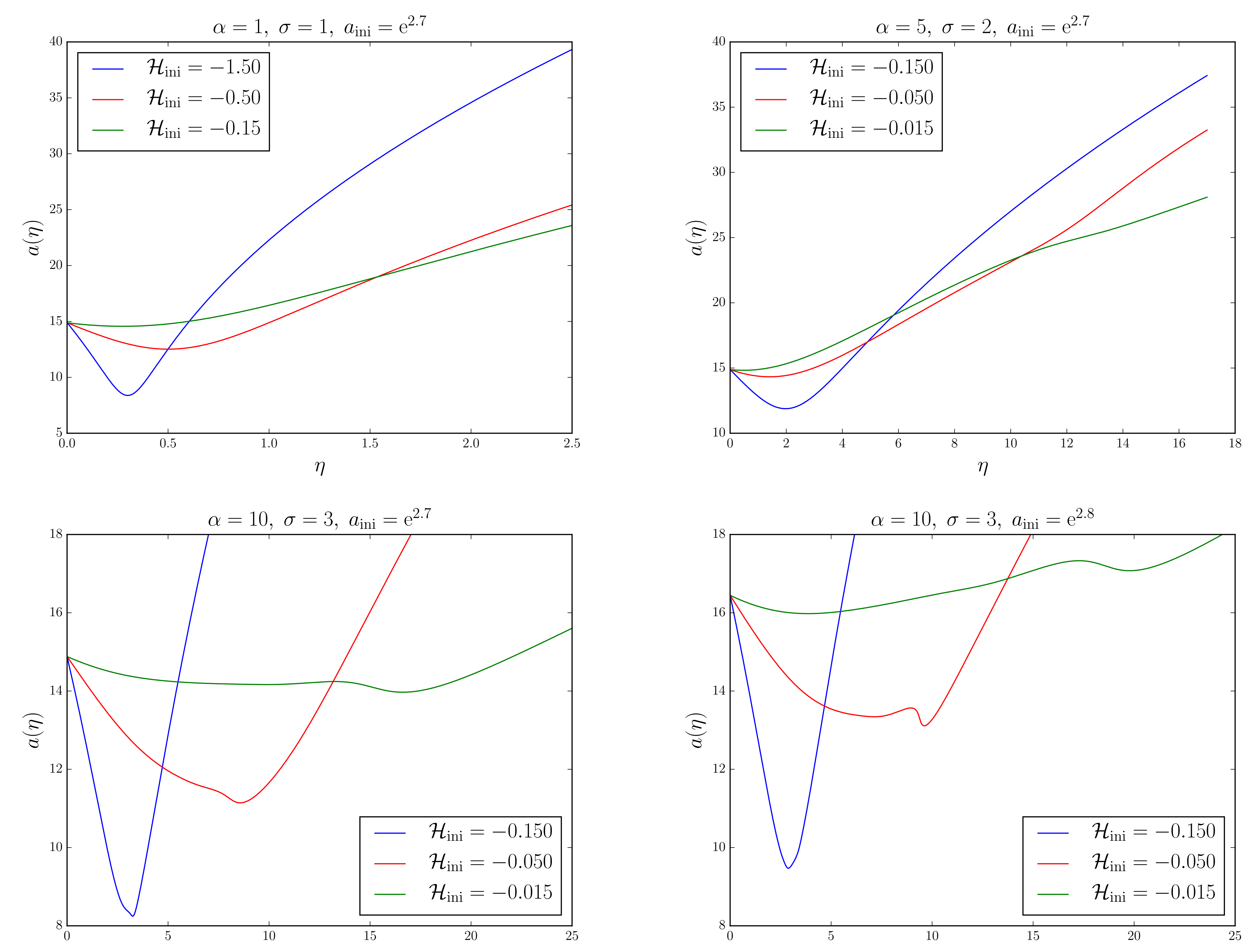
M.Gasperini & G. Veneziano, *Phys. Rep.* **373**, 1 (2003), hep-th/0207130 & hep-th/0703055

Pre Big Bang scenario:



dBB quantum cosmology:





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

S. Vitenti & PP
Mod.Phys.Lett. A**31**, 1640006 (2016).

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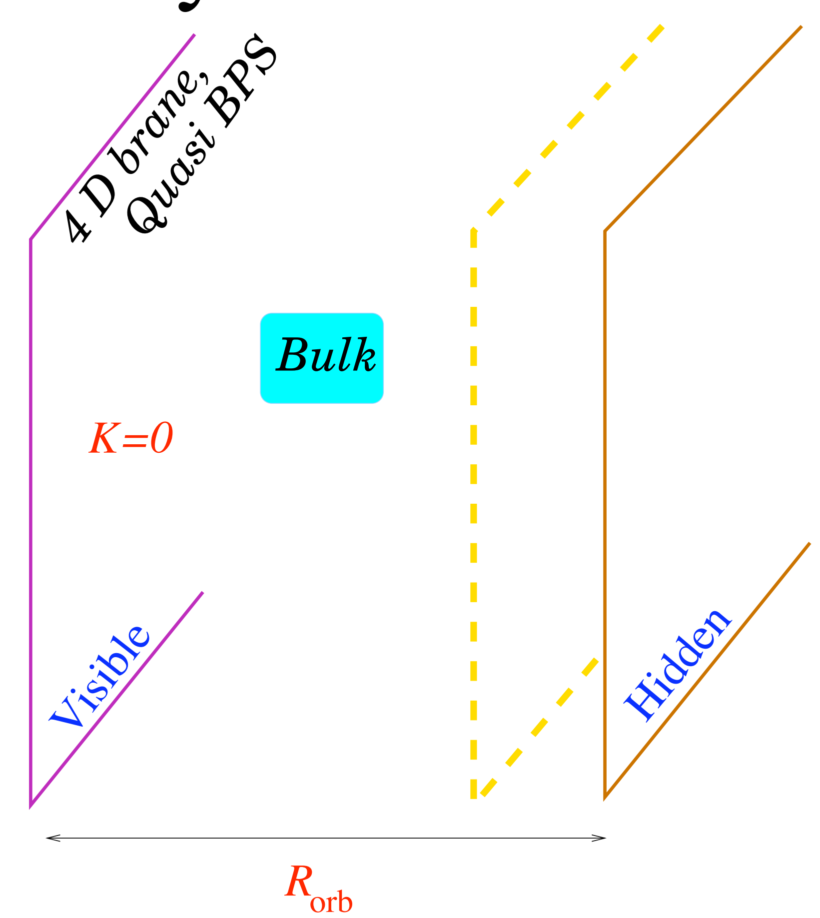
Ekpyrotic & cyclic

Branes

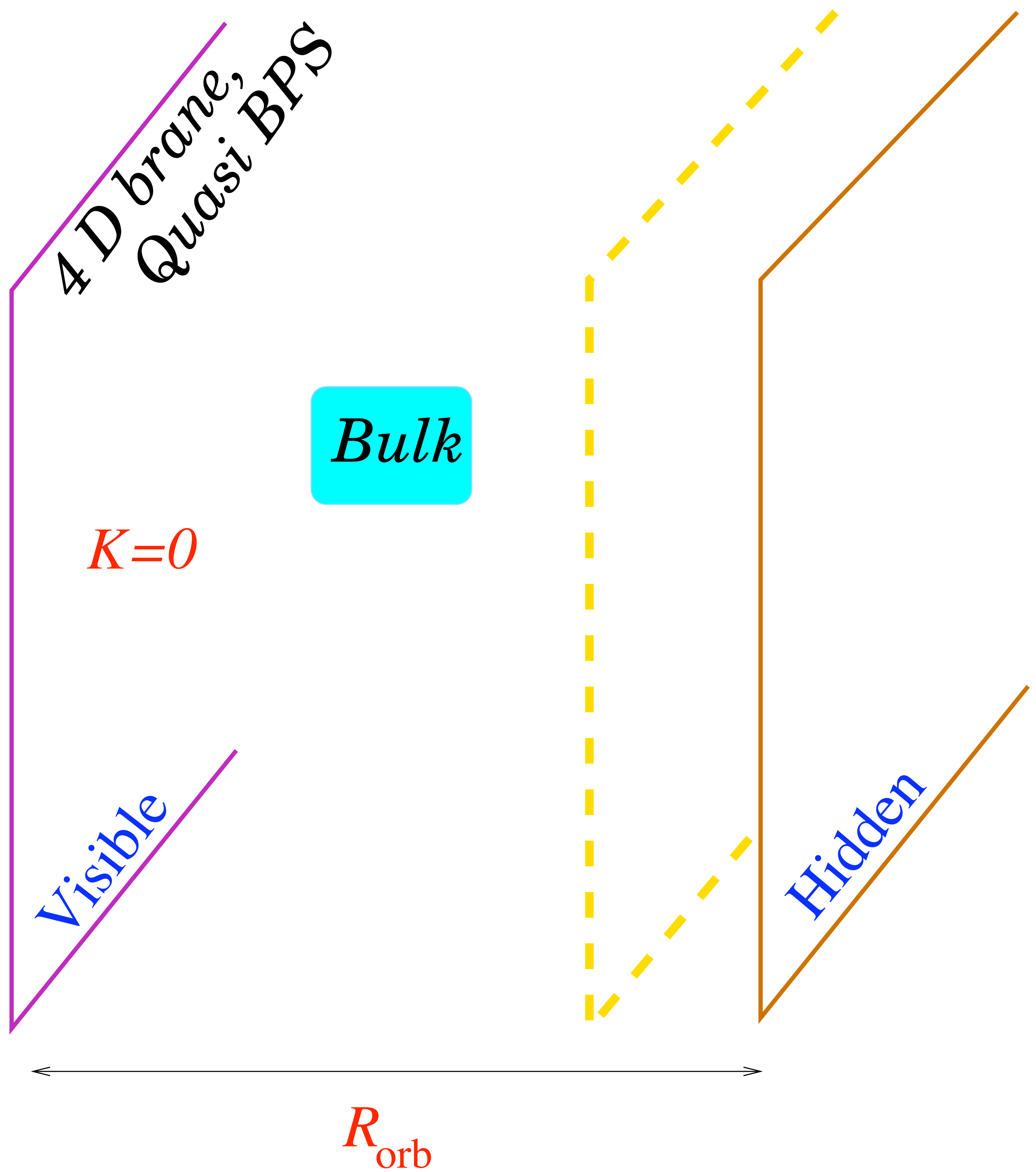


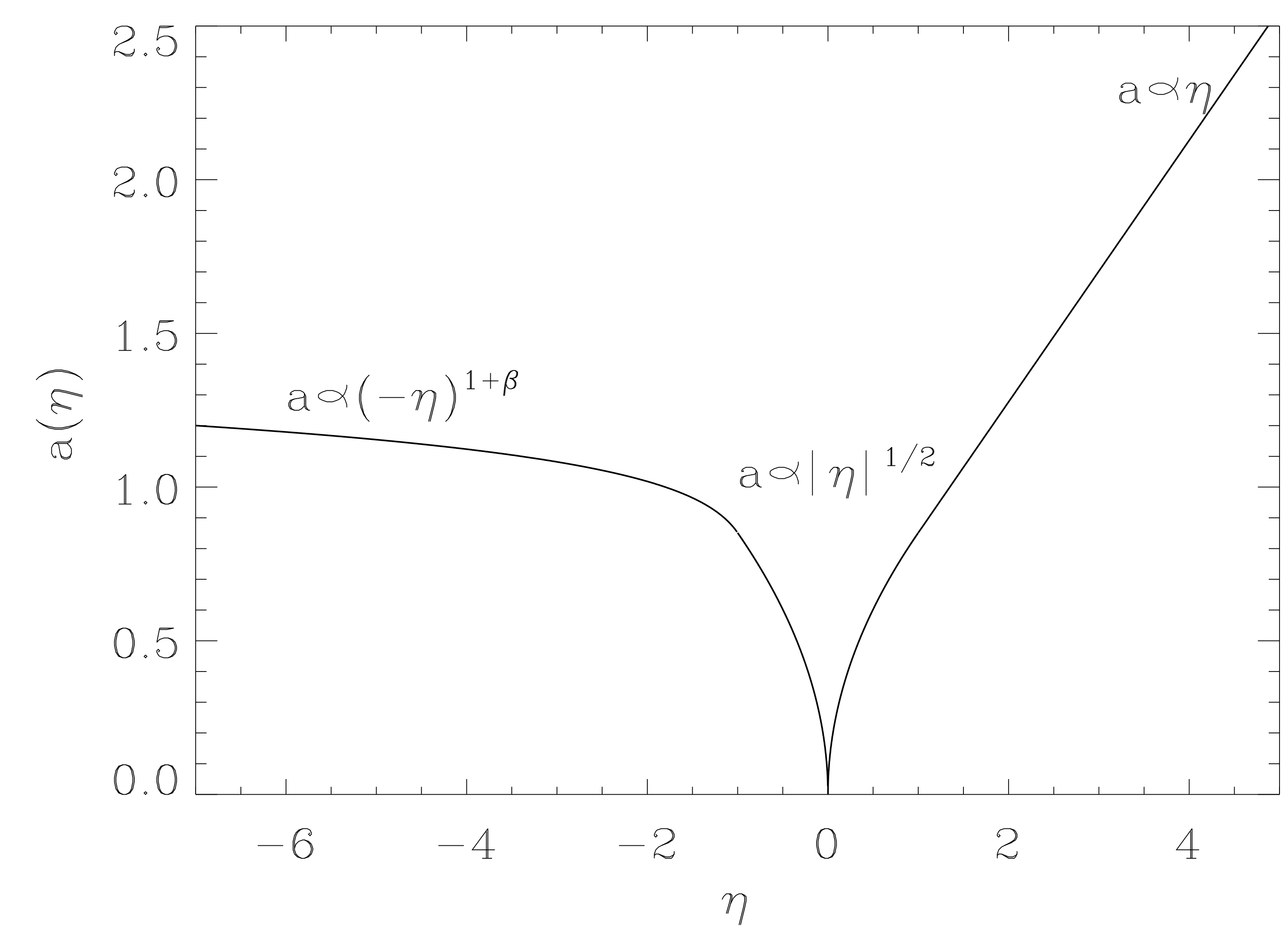
Ekpyrotic scenario:

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

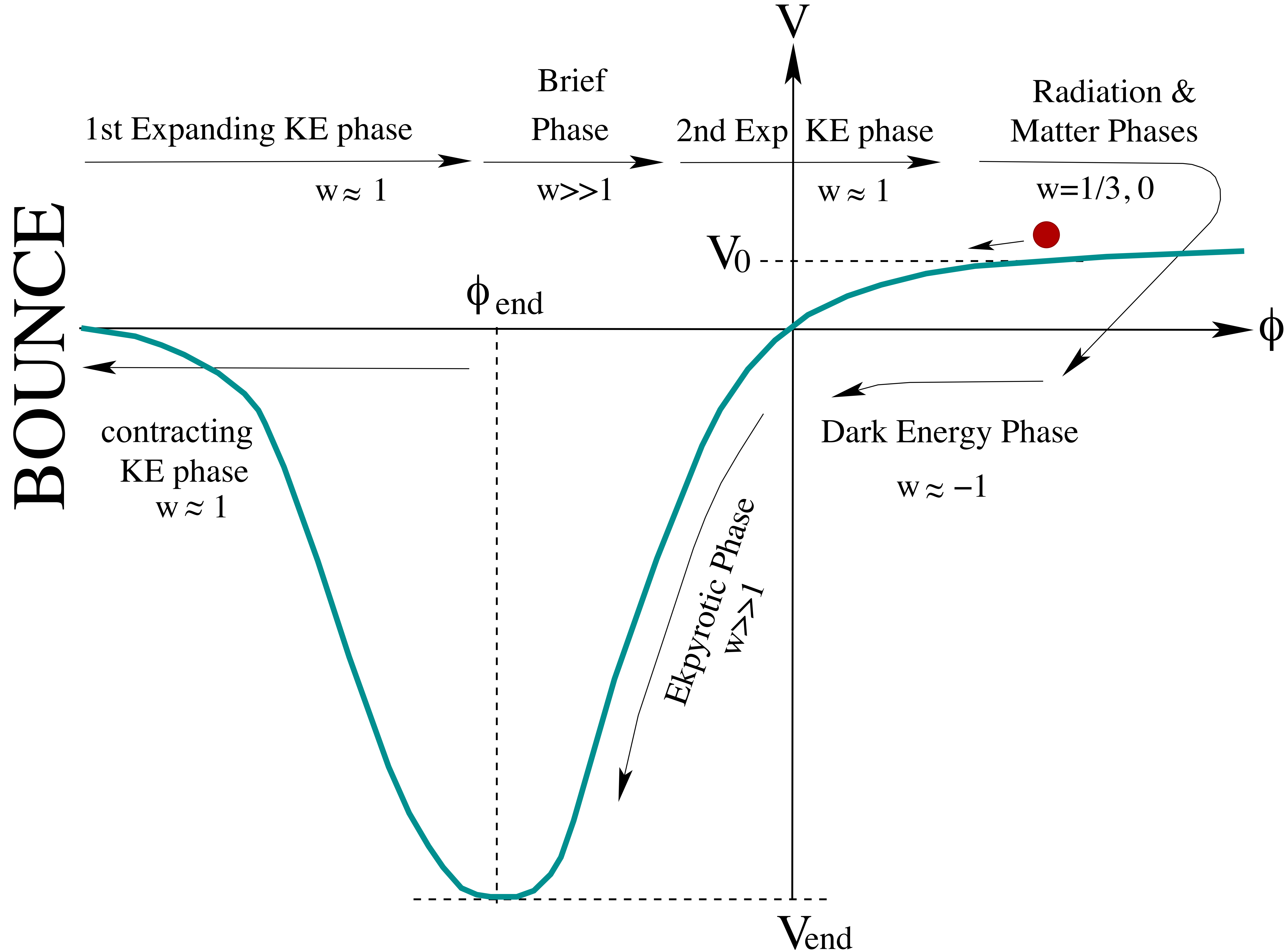
$$\mathcal{S}_4 = \int_{\mathcal{M}_4} \mathrm{d}^4 x \sqrt{-g_4} \left[\frac{R_{(4)}}{2\kappa} - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right],$$

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

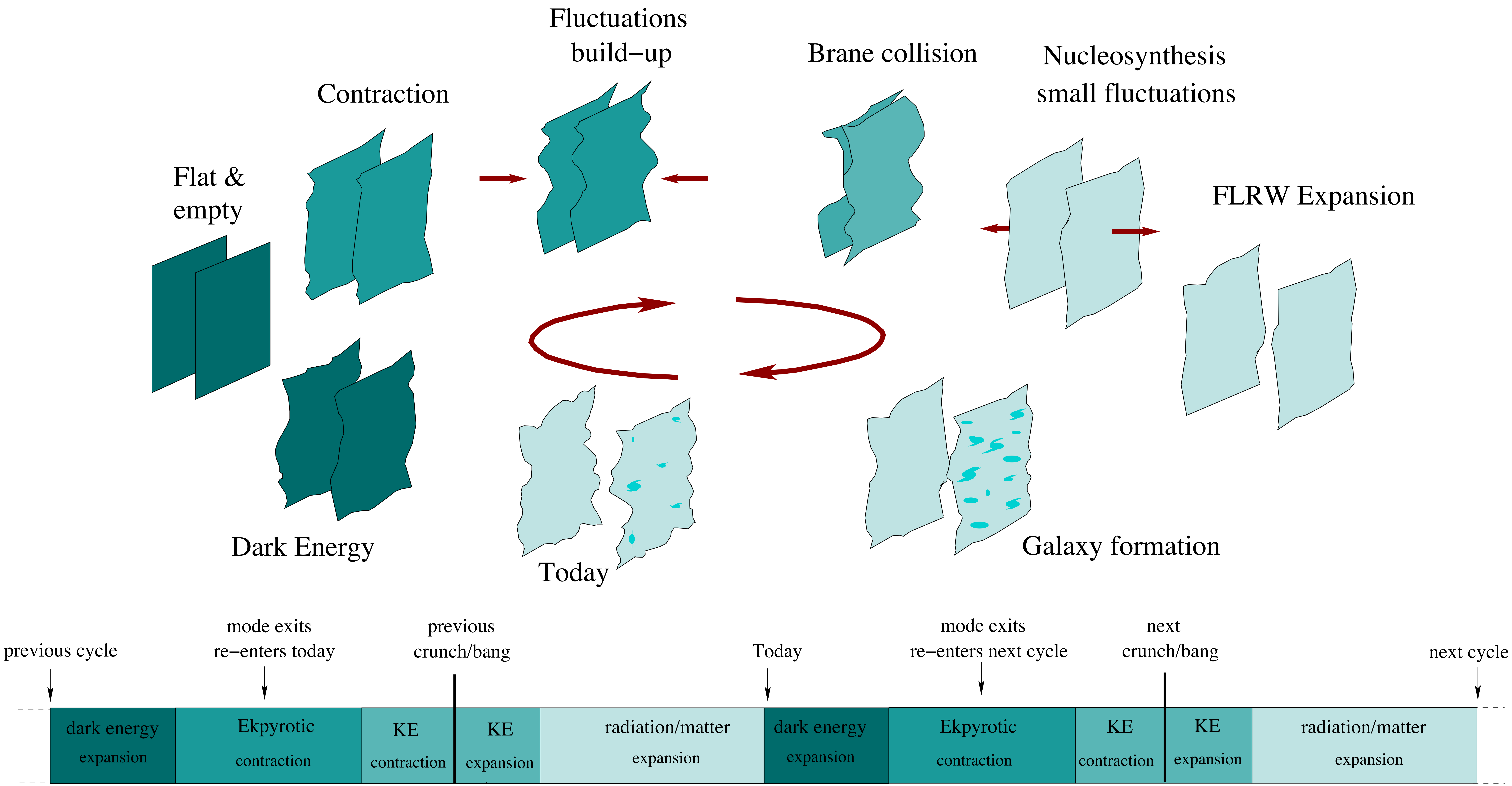




Singular…


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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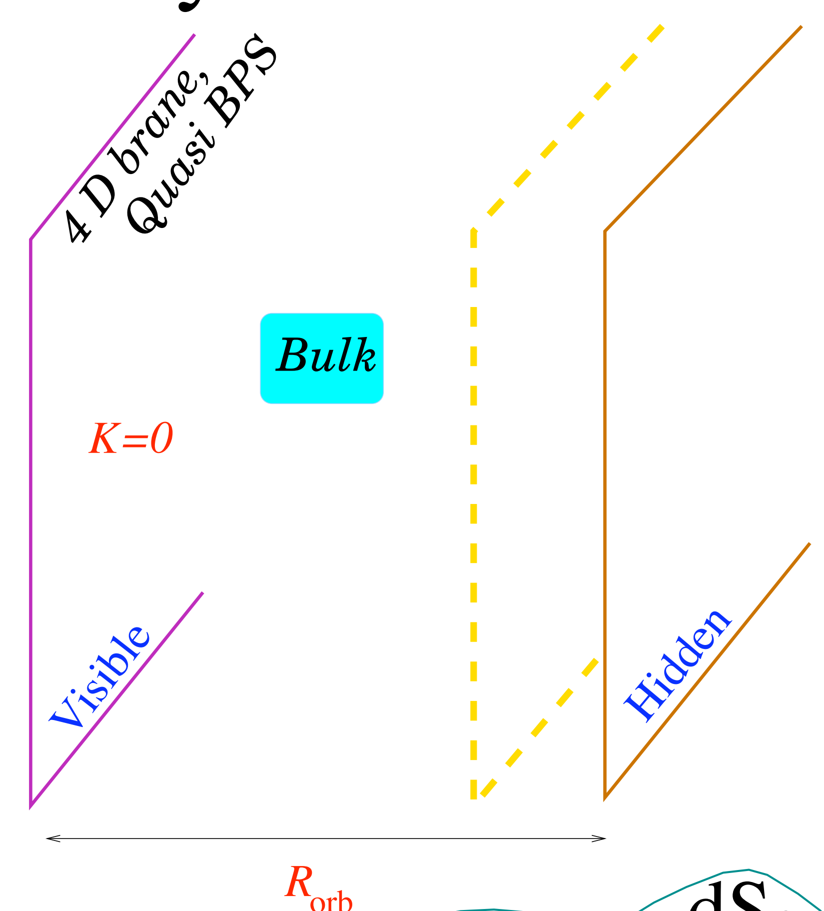


String gas cosmology

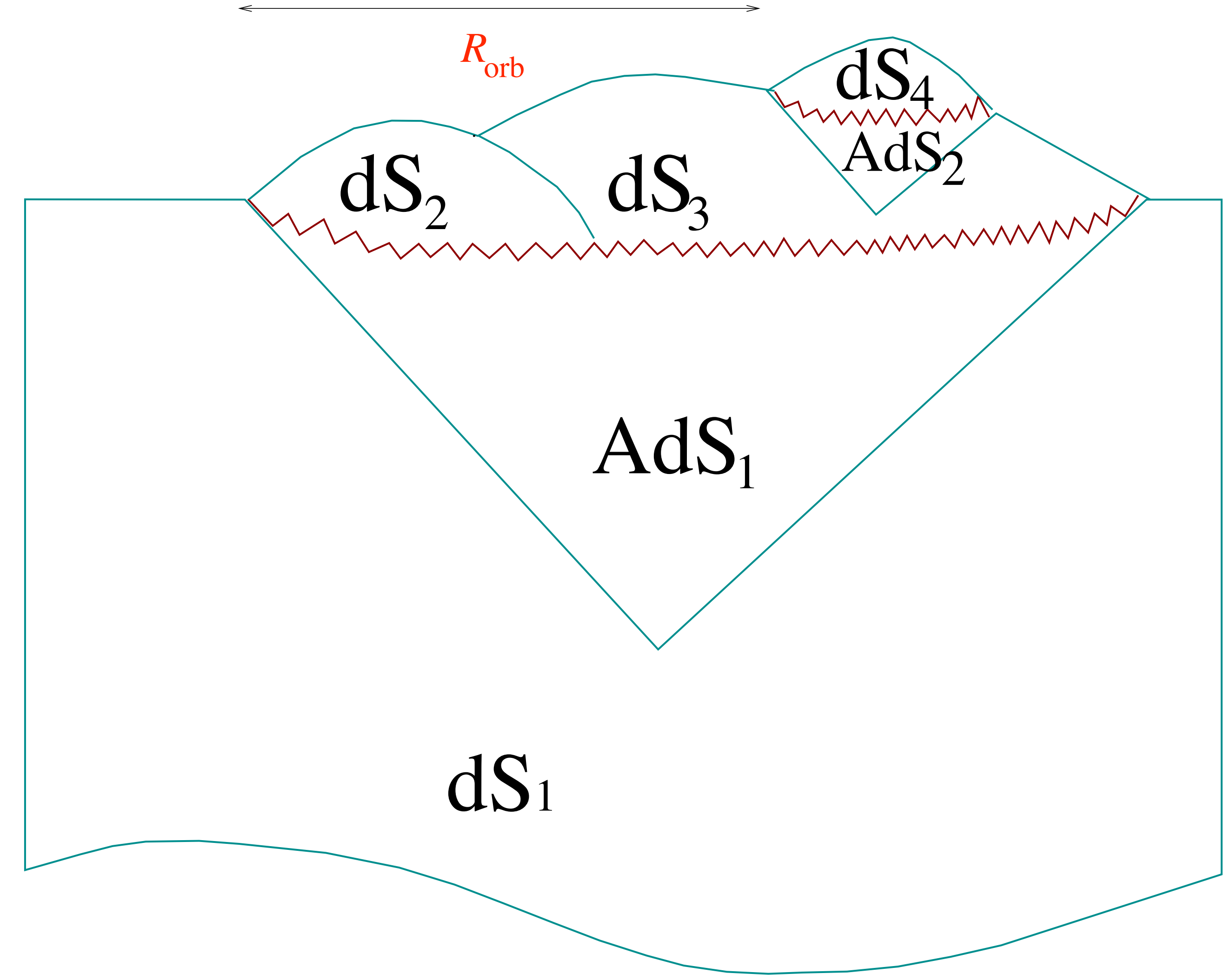
Antigravity

Galileon

Massive gravity

Multiverse models

Strings & AdS/CFT



Horava-Lifshitz

Lee-Wick & Quintom

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

Mimetic matter

Non-linear electromagnetic action

Spinors & torsion

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1406.2790

(see *Encyclopedia Inflationaris*)

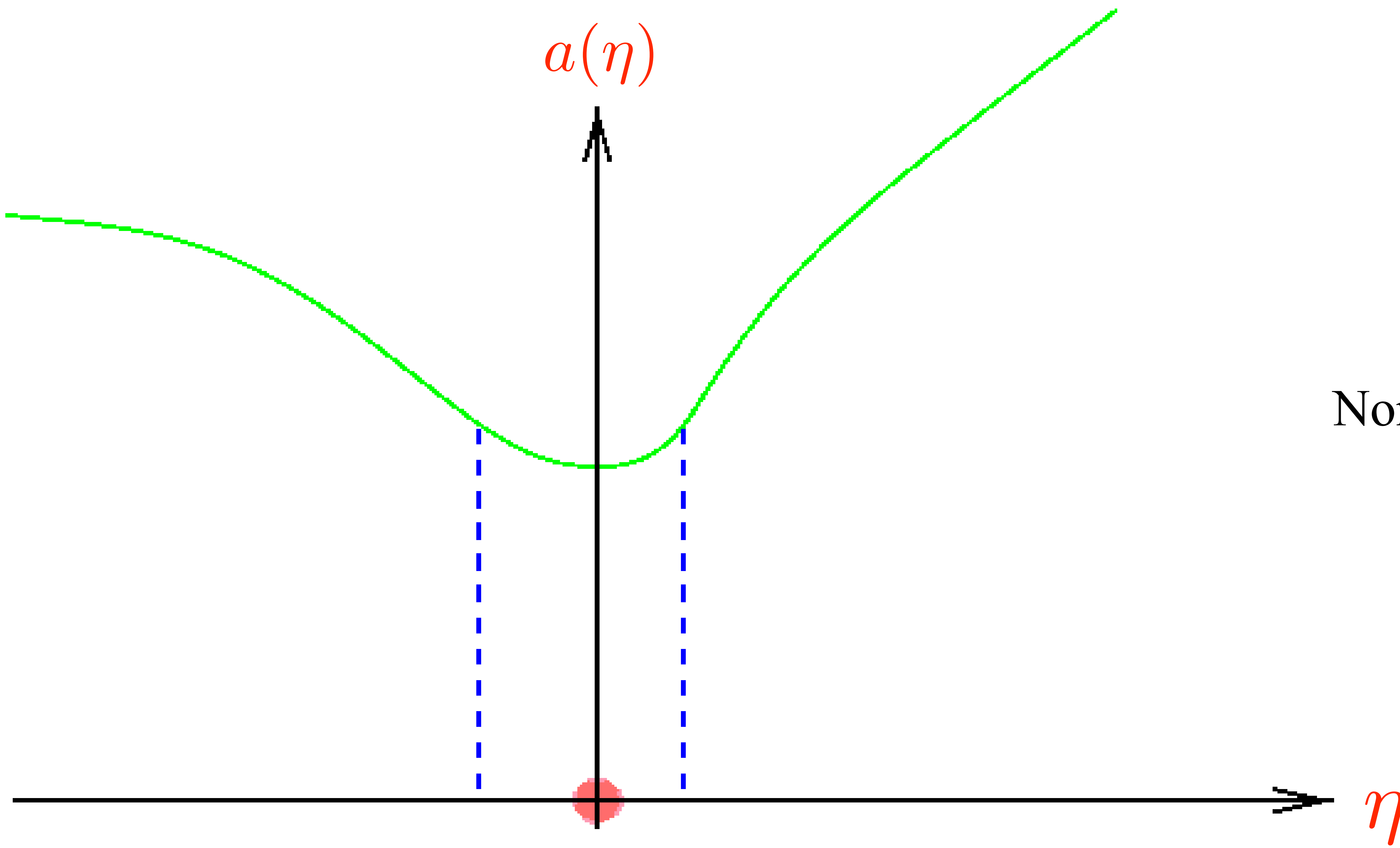
Singular …

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

… spectrum depending on a nonphysical normalization functions…



Non singular bounce

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, ...

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

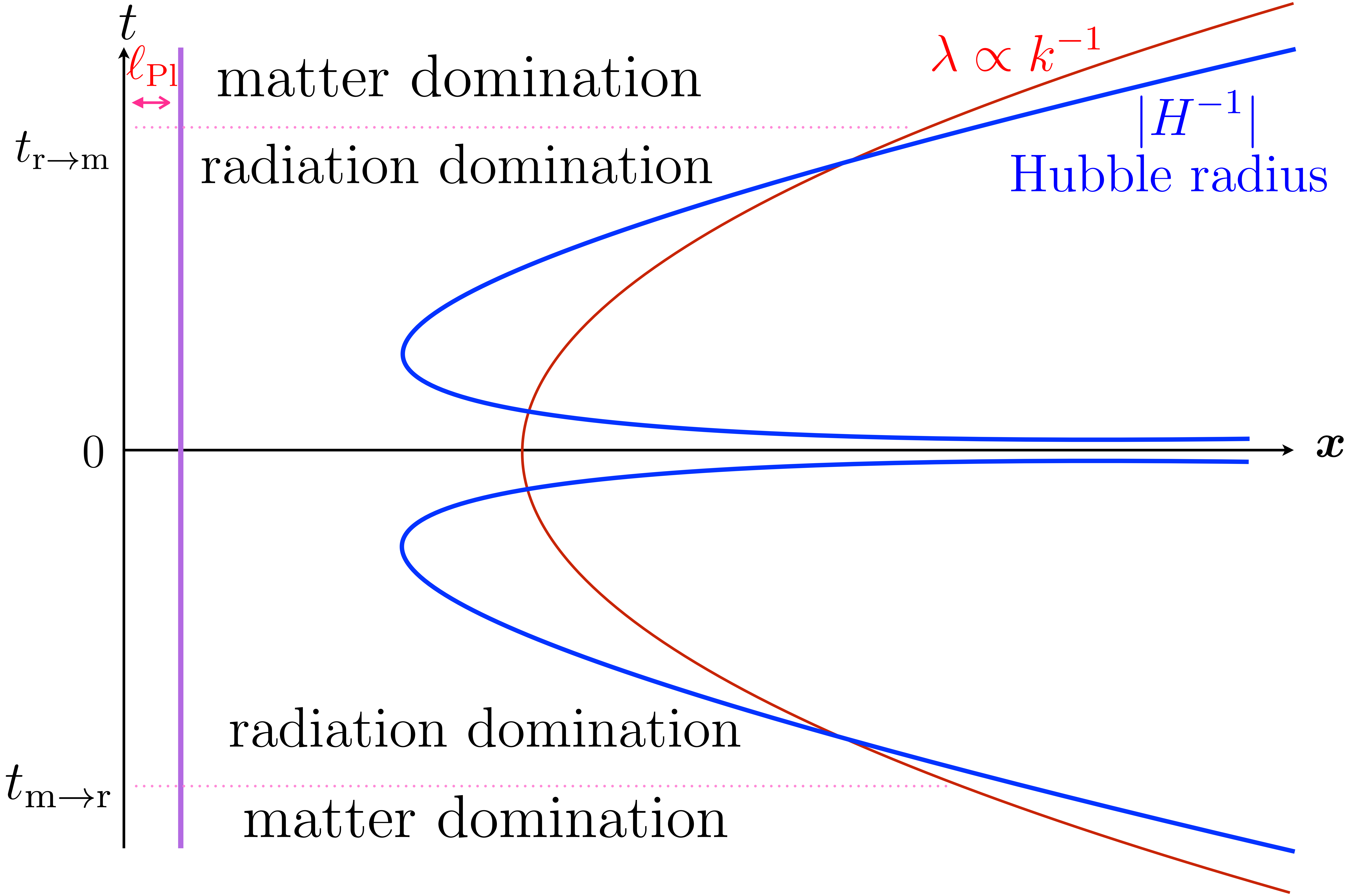
$$\frac{t_{\text{dissipation}}}{t_{\text{Hubble}}} \propto \frac{\lambda}{R_{\mathrm{H}}^{1/3}} \left(1 + \frac{\lambda}{A R_{\mathrm{H}}^2}\right)$$

enough time to dissipate any wavelength

$\Longrightarrow$ quantum vacuum fluctuations...

Isotropy Potentially problematic: model dependent

Others dark matter/energy, baryogenesis, ...



t
$\ell_{\rm Pl}$
matter domination
$\lambda \propto k^{-1}$
$t_{\rm r\to m}$
radiation domination
$|H^{-1}|$
Hubble radius
0
$\boldsymbol{x}$
radiation domination
$t_{\rm m\to r}$
matter domination

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 $t_{\mathrm{i}} \to -\infty$

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enough time to dissipate any wavelength

$\Longrightarrow$ quantum vacuum fluctuations...

Isotropy Potentially problematic: model dependent

Others dark matter/energy, baryogenesis, ...

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

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

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

Standard Failures and bouncing solutions

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Flatness $\frac{\mathrm{d}}{\mathrm{d}t} |\Omega - 1| = -2 \frac{\ddot{a}}{\dot{a}^3}$ $\ddot{a} < 0 \;\&\; \dot{a} < 0$

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enough time to dissipate any wavelength

$\Longrightarrow$ quantum vacuum fluctuations...

Isotropy Potentially problematic: model dependent

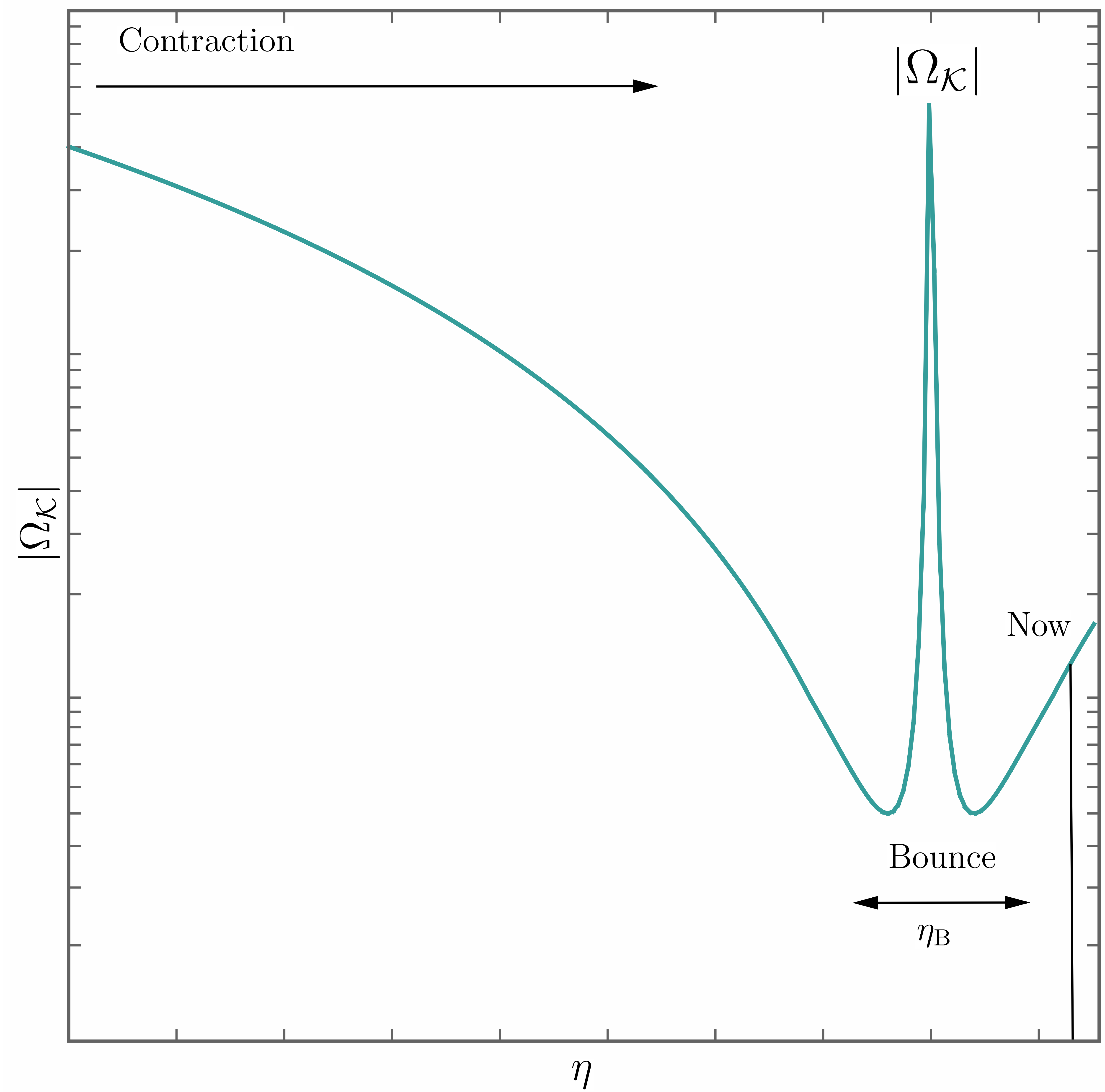
Others dark matter/energy, baryogenesis, ...

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

Critical density

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

Density parameter



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

Standard Failures and bouncing solutions

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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

$$\frac{t_{\text{dissipation}}}{t_{\text{Hubble}}} \propto \frac{\lambda}{R_{\mathrm{H}}^{1/3}} \left(1 + \frac{\lambda}{A R_{\mathrm{H}}^2}\right)$$

enough time to dissipate any wavelength

$\Longrightarrow$ quantum vacuum fluctuations...

Shear Potentially problematic: model dependent

Others dark matter/energy, baryogenesis, ...

The problem with contraction: BKL/shear instability

$$ds^2 = dt^2 - a^2(t)\sum_i e^{2\theta_i(t)}\sigma^i\sigma^i$$

Ricci flat:

$$\sigma^i = dx^i$$

$$\sum_i \theta_i = 0$$

Average scale factor

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

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

Friedman equations

$$H^2 = \frac{\rho_T}{3M_{Pl}^2} + \frac{1}{6}\sum_i \dot\theta_i^2$$

$$\dot H = -\frac{\rho_T + p_T}{2M_{Pl}^2} - \frac{1}{2}\sum_i \dot\theta_i^2$$

$$\ddot\theta_i + 3H\dot\theta_i = 0$$

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

Ekpyrotic solution:

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

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

So finally...

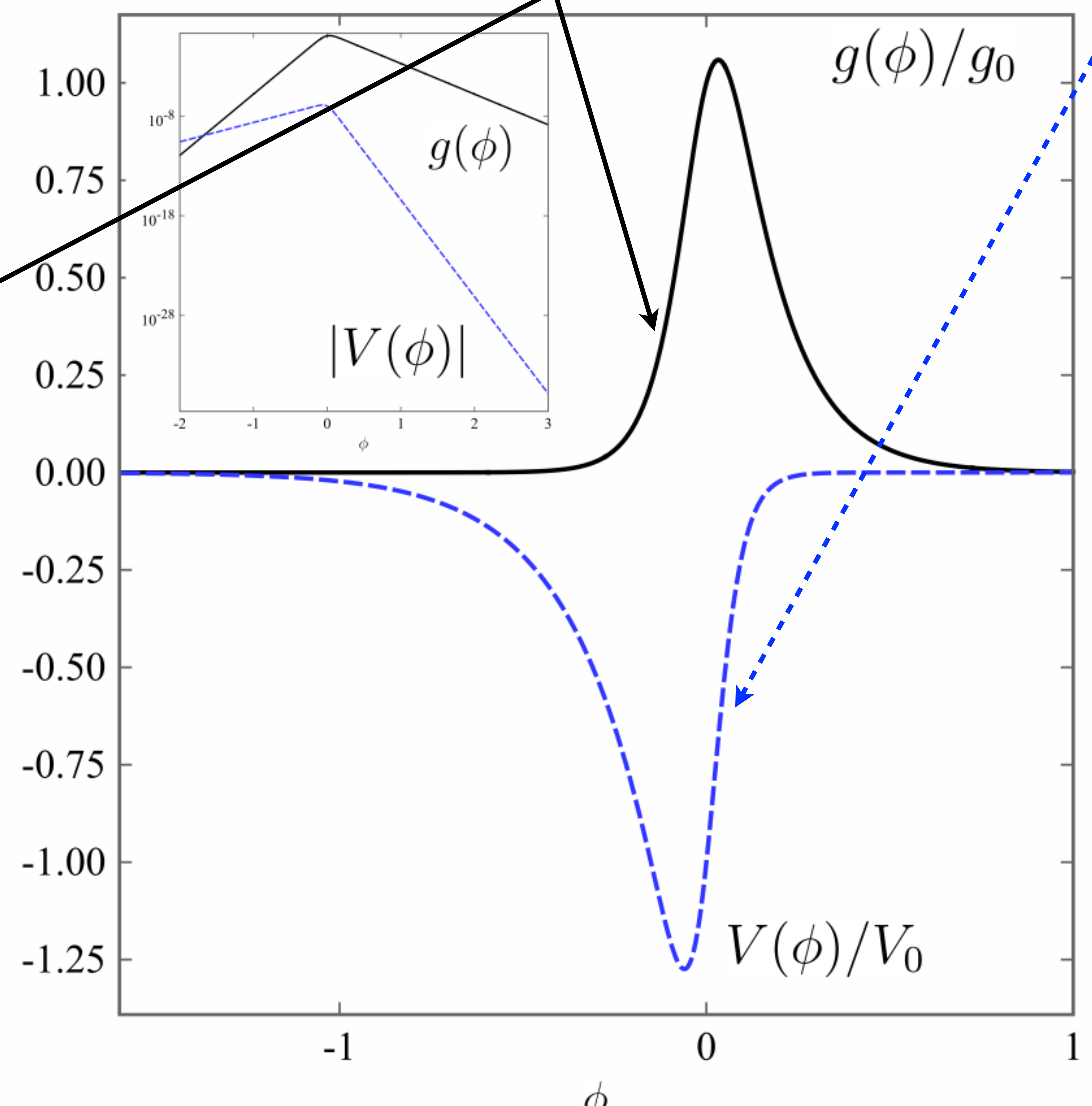
$$\rho_{\rm Shear} \equiv \frac{M_{\rm Pl}^2}{2} \sum_i \dot{\theta}_i^2 \propto a^{-6} \gg \rho_{\rm Fluid}$$

➡ Singularity!

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



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

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

+Bianchi

$V_0 = 10^{-7}$, $g_0 = 1.1$, $\beta = 5$, $\gamma = 10^{-3}$

$b_V = 5$, $b_g = 0.5$, $p = 0.01$, $q = 0.1$

Stress-energy tensor

$$T^{\phi}_{\mu\nu} = \left(-K + 2XG_{,\phi} + G_{,X}\nabla_\sigma X \nabla^\sigma \phi\right) g_{\mu\nu} + (K_{,X} + G_{,X}\Box\phi - 2G_{,\phi})\nabla_\mu\phi\nabla_\nu\phi - G_{,X}(\nabla_\mu X \nabla_\nu \phi + \nabla_\nu X \nabla_\mu \phi)$$

→ Energy density & Pressure

$$\rho_\phi = \frac{1}{2}M^2_{\rm Pl}(1-g)\dot\phi^2 + \frac{3}{4}\beta\dot\phi^4 + 3\gamma H\dot\phi^3 + V(\phi)$$

$$p_\phi = \frac{1}{2}M^2_{\rm Pl}(1-g)\dot\phi^2 + \frac{1}{4}\beta\dot\phi^4 - \gamma\dot\phi^2\ddot\phi - V(\phi)$$

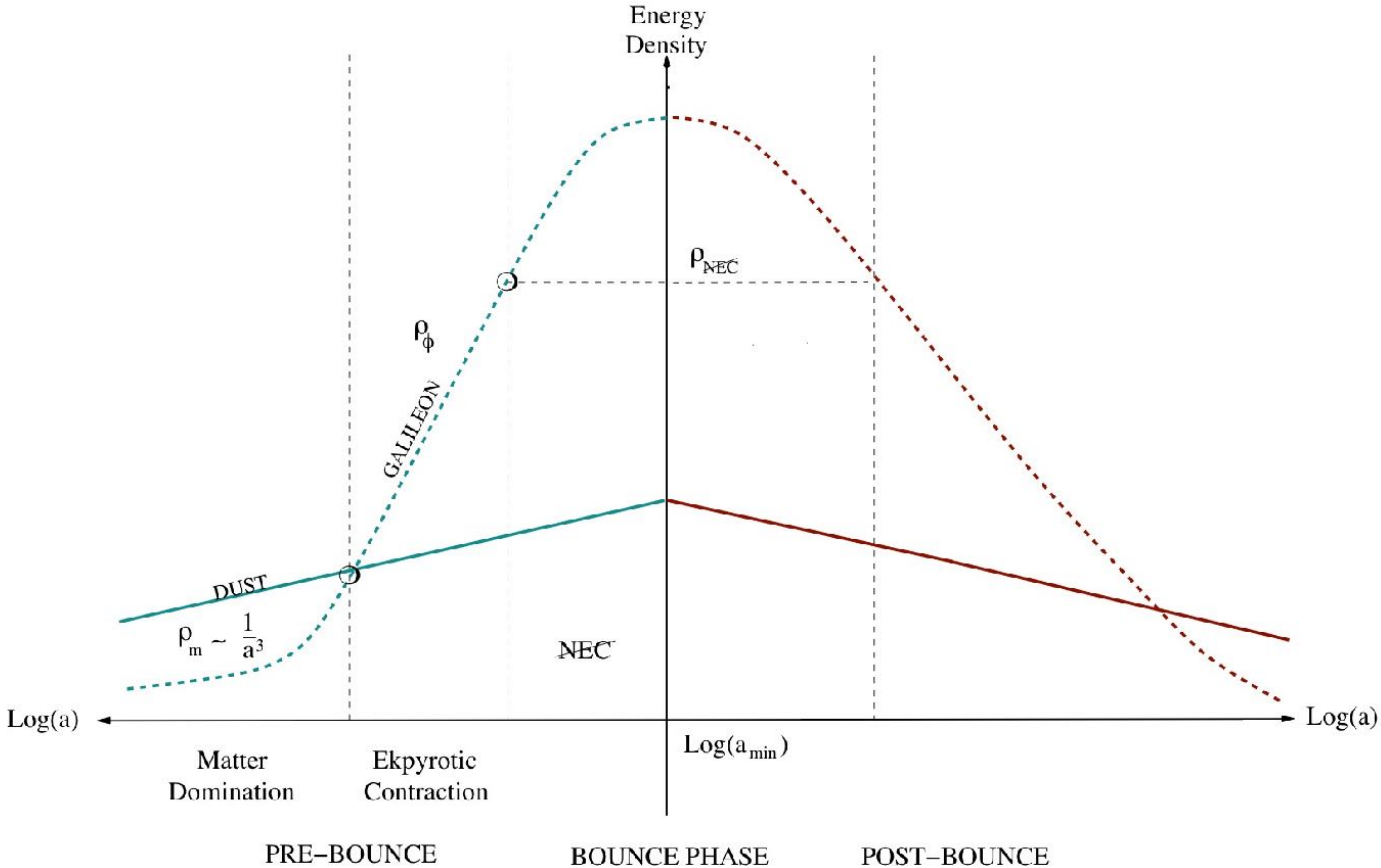
Einstein equations

+ modified Klein-Gordon $\mathcal{P}\ddot\phi + \mathcal{D}\dot\phi + V_{,\phi} = 0$

with...

$$\mathcal{P} = (1-g)M_{\rm Pl}^2 + 6\gamma H\dot{\phi} + 3\beta\dot{\phi}^2 + \frac{3\gamma^2}{2M_{\rm Pl}^2}\dot{\phi}^4$$

$$\mathcal{D} = 3(1-g)M_{\rm Pl}^2 H + \left(9\gamma H^2 - \frac{1}{2}M_{\rm Pl}^2 g_{,\phi}\right)\dot{\phi} + 3\beta H\dot{\phi}^2 - \frac{3}{2}(1-g)\gamma\dot{\phi}^3 - \frac{9\gamma^2 H\dot{\phi}^4}{2M_{\rm Pl}^2} - \frac{3\beta\gamma\dot{\phi}^5}{2M_{\rm Pl}^2} - \frac{3}{2}G_{,X}\sum_i \dot{\theta}_i^2\dot{\phi} - \frac{3G_{,X}}{2M_{\rm Pl}^2}(\rho_{\rm m} + p_{\rm m})\dot{\phi}$$



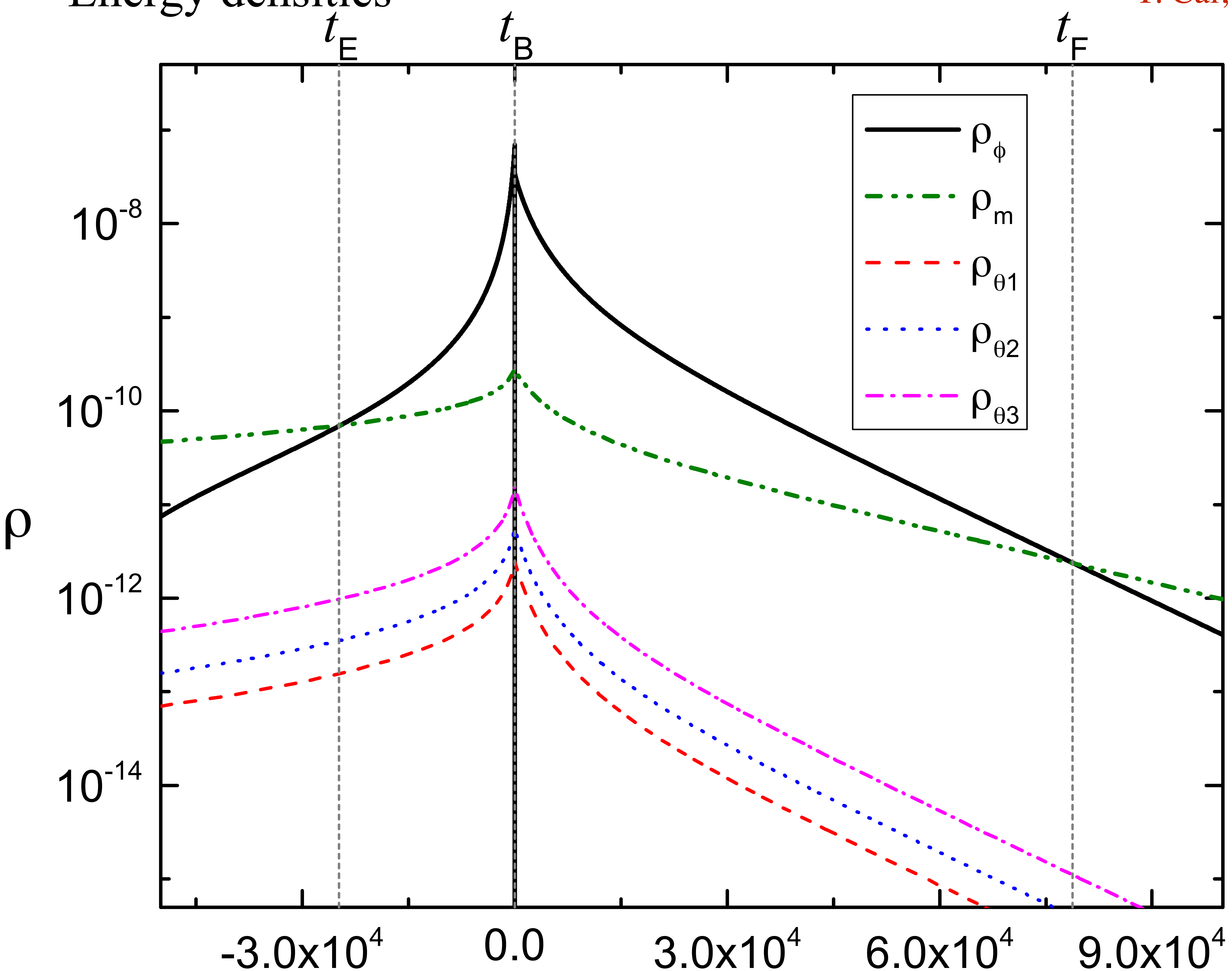
Energy
Density
$\rho_{\not{NEC}}$
ρ_ϕ
GALILEON
DUST
$\rho_m \sim \frac{1}{a^3}$
$\not{NEC}$
Log(a)
Log(a)
Log(a_{min})
Matter
Domination
Ekpyrotic
Contraction
PRE–BOUNCE
BOUNCE PHASE
POST–BOUNCE

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)



$\phi_{\rm ini} = -2, \dot{\phi}_{\rm ini} = 7.8 \times 10^{-6}$

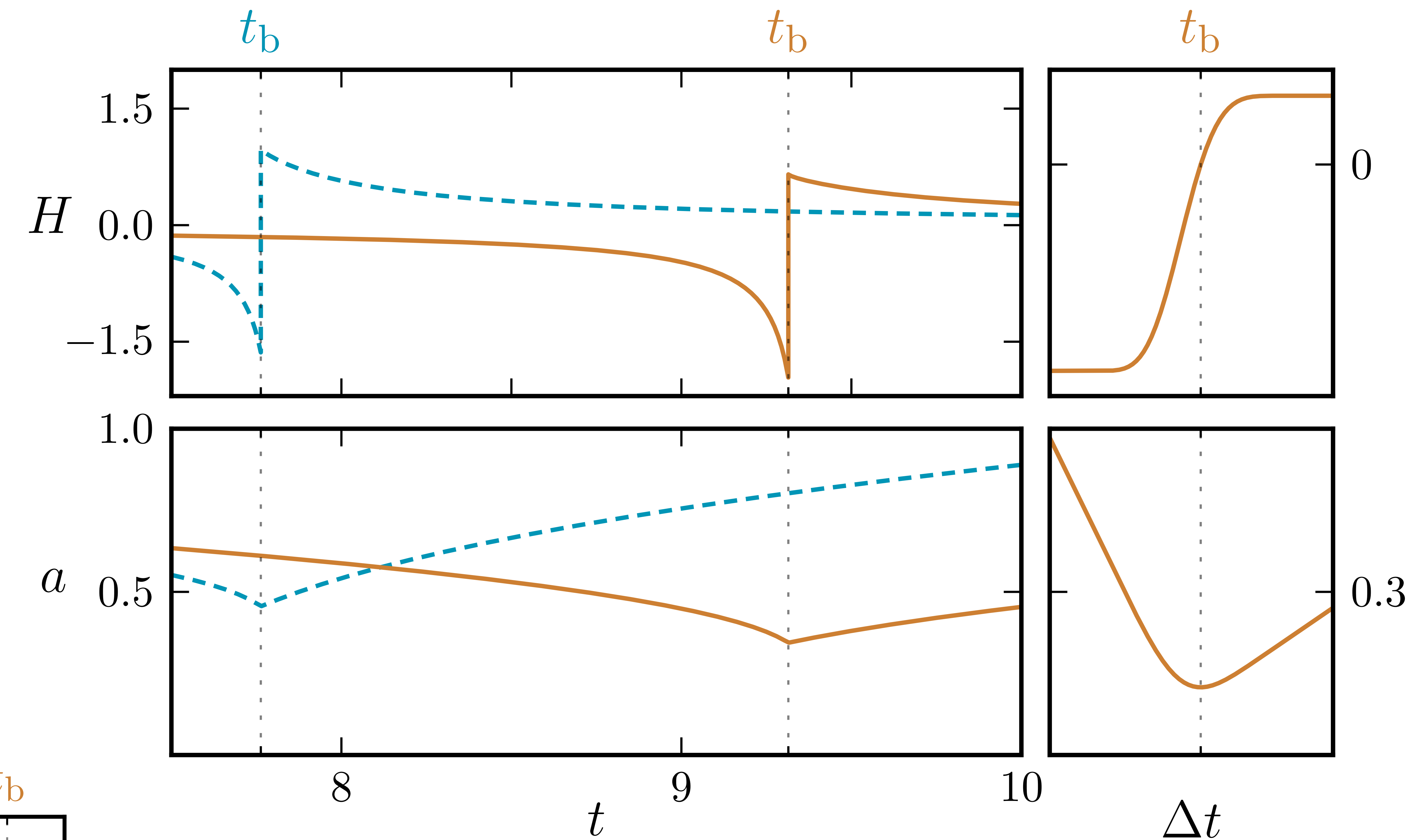
Anisotropies can remain small all throughout

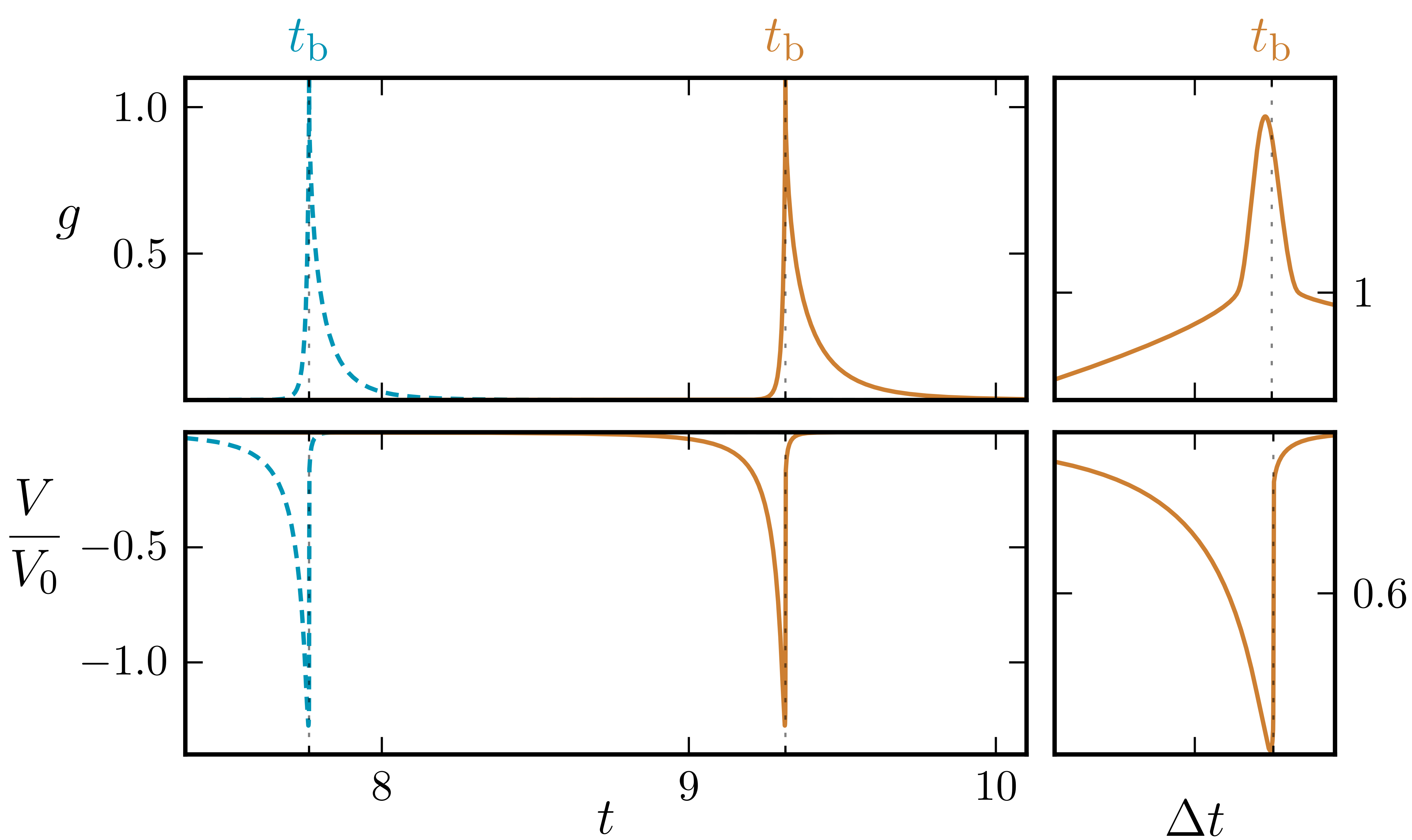
$$\dot{\phi} = \varphi,$$

$$\dot{\varphi} = -\frac{\mathcal{D}\varphi}{\mathcal{P}} - \frac{V_{,\phi}}{\mathcal{P}},$$

$$\dot{H} = -\frac{\rho_\phi + p_\phi}{2} - \frac{\sigma_{\rm ini}^2}{2}\left(\frac{a_{\rm ini}}{a}\right)^6$$

$$\dot{a} = aH,$$

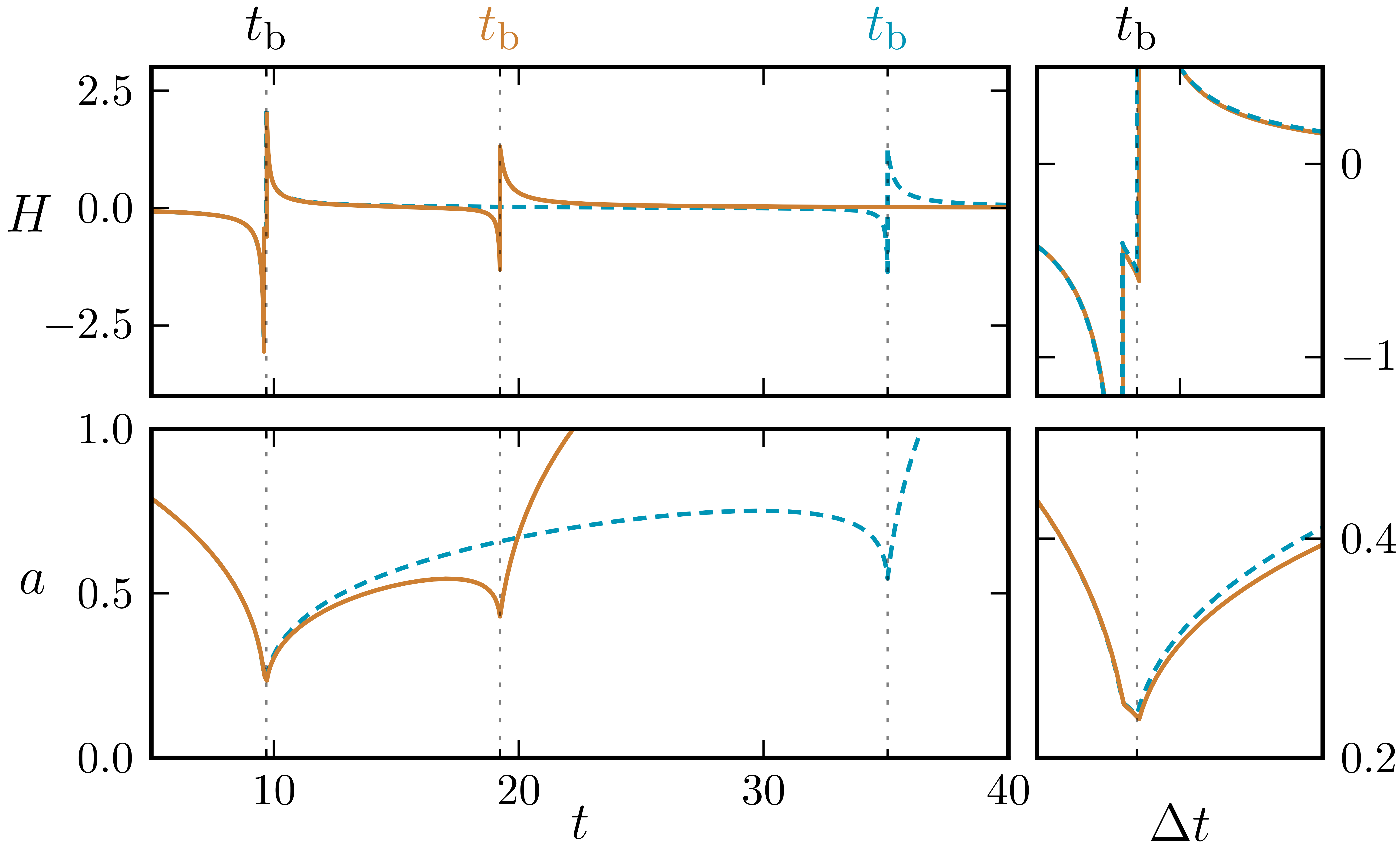




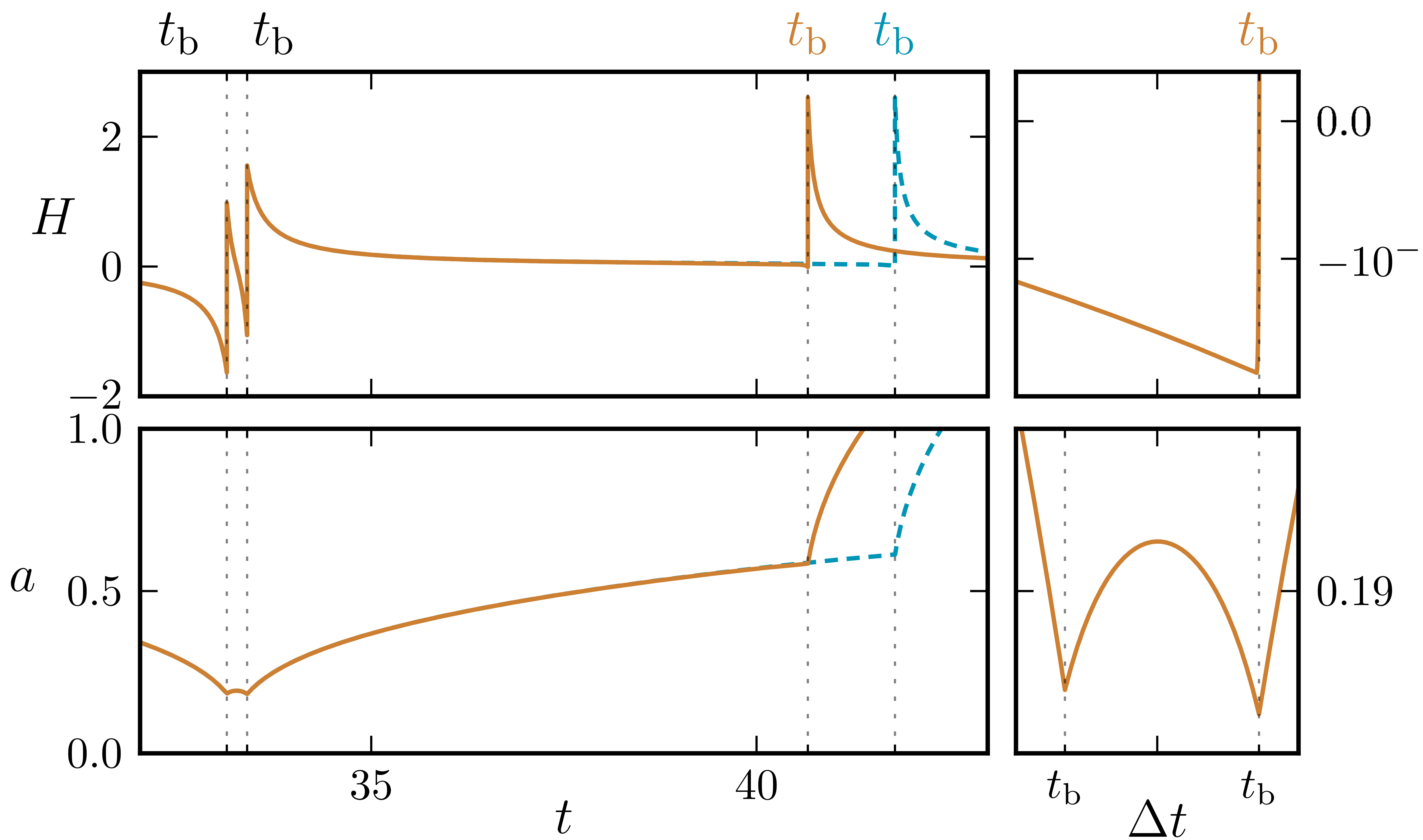
$$\theta = (\phi_{\rm ini},\ \varphi_{\rm ini},\ \sigma_{\rm ini}^2)$$

$$\theta_{\rm sb1} = (-2.5,\ 8\times10^{-6},\ 5\times10^{-12})$$

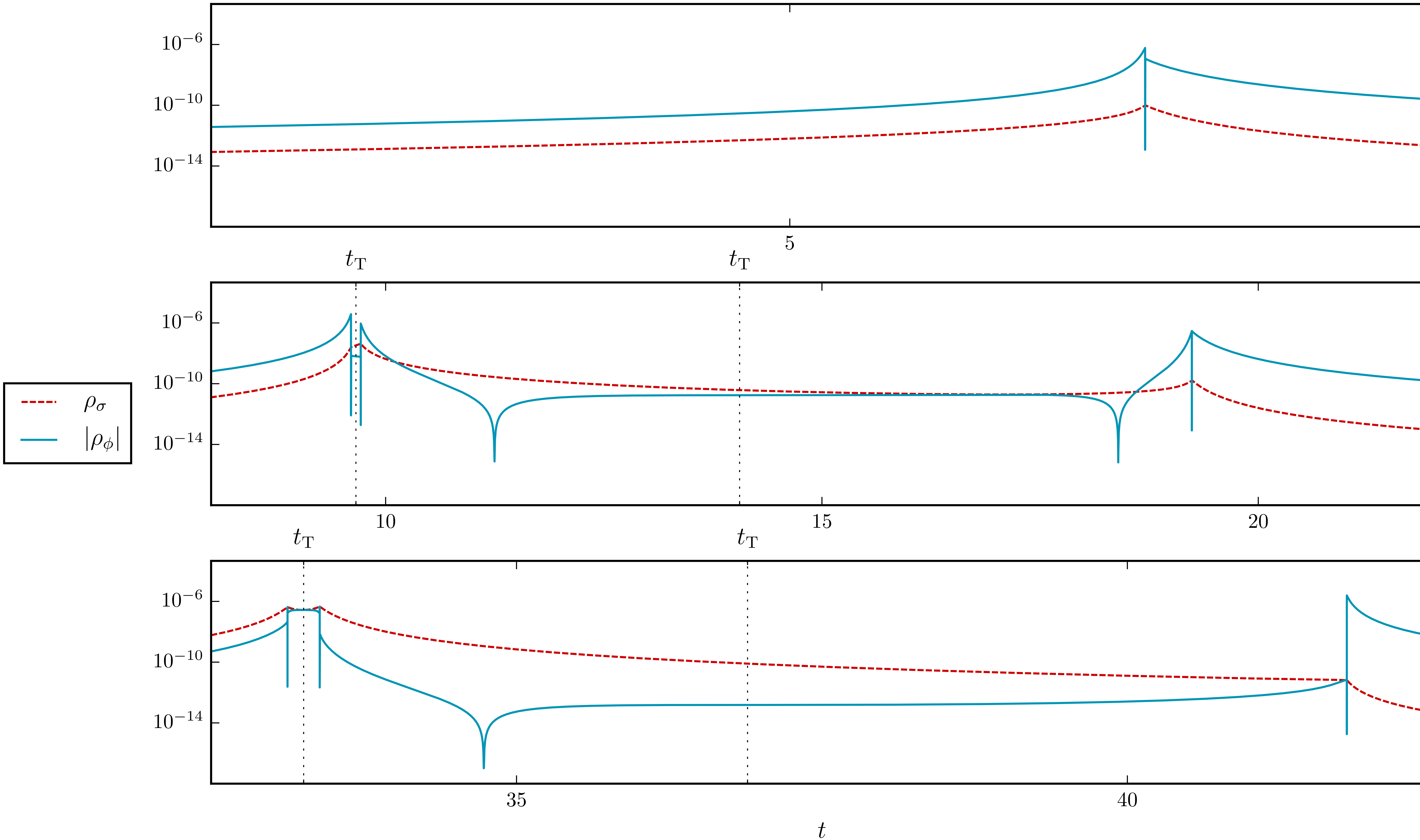
$$\theta_{\rm sb2} = (-3.0,\ 8\times10^{-6},\ 5\times10^{-12})$$



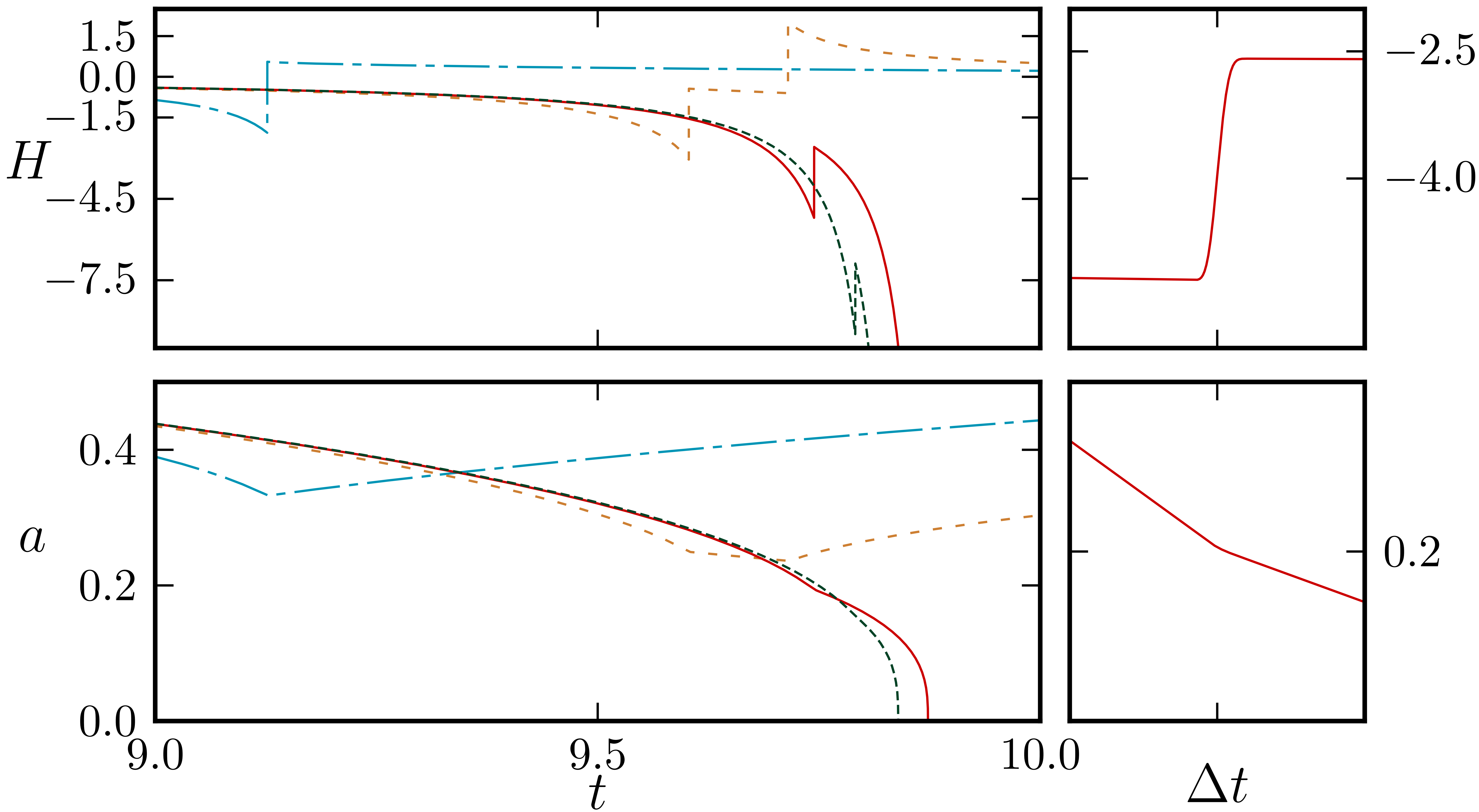
$$\theta_{\rm db1} = \left(-3.49,\ 8\times10^{-6},\ 5\times10^{-12}\right)$$
$$\theta_{\rm db2} = \left(-3.50,\ 8\times10^{-6},\ 5\times10^{-12}\right)$$



$$\theta_{\mathrm{tb1}} = \left(1.9,\ -10^{-6},\ 5 \times 10^{-12}\right),$$
$$\theta_{\mathrm{tb2}} = \left(1.9001,\ -10^{-6},\ 5 \times 10^{-12}\right)$$



10^{-6}
10^{-10}
10^{-14}
5
10
t_T
t_T
10
15
20
t_T
t_T
35
40
t
ρ_σ
$|\rho_\phi|$


1.5
0.0
−1.5
H
−4.5
−7.5
−2.5
−4.0
0.4
a
0.2
0.0
0.2
9.0
9.5
10.0
t
Δt

Conclusions:

Bounce model parameter dependent

Very rich structure

Perturbations (SVT, NG, …)

Compatibility with data…

More in 1705.xxxxx [A. Bacalhau, PP & S. Vitenti (to appear)]