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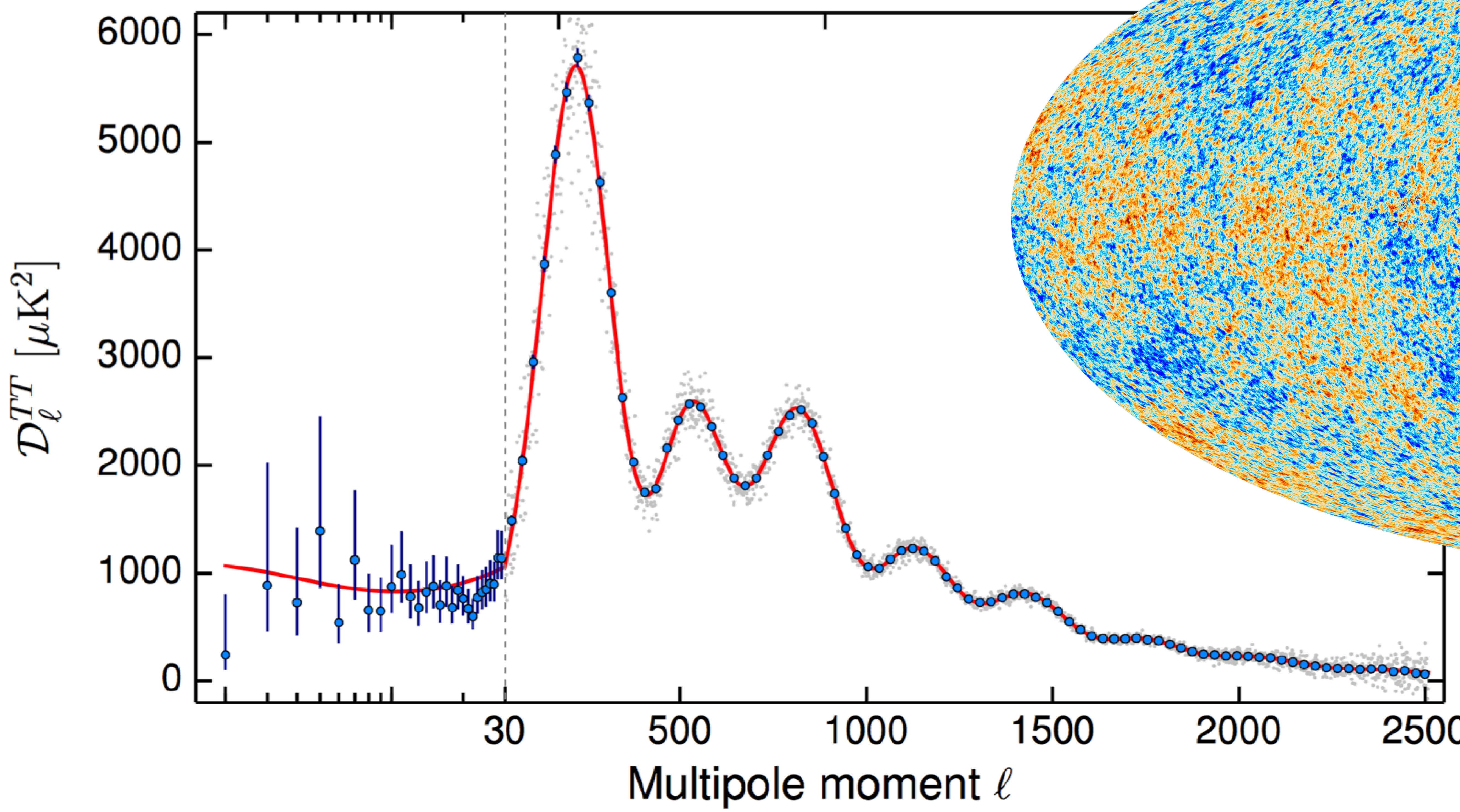
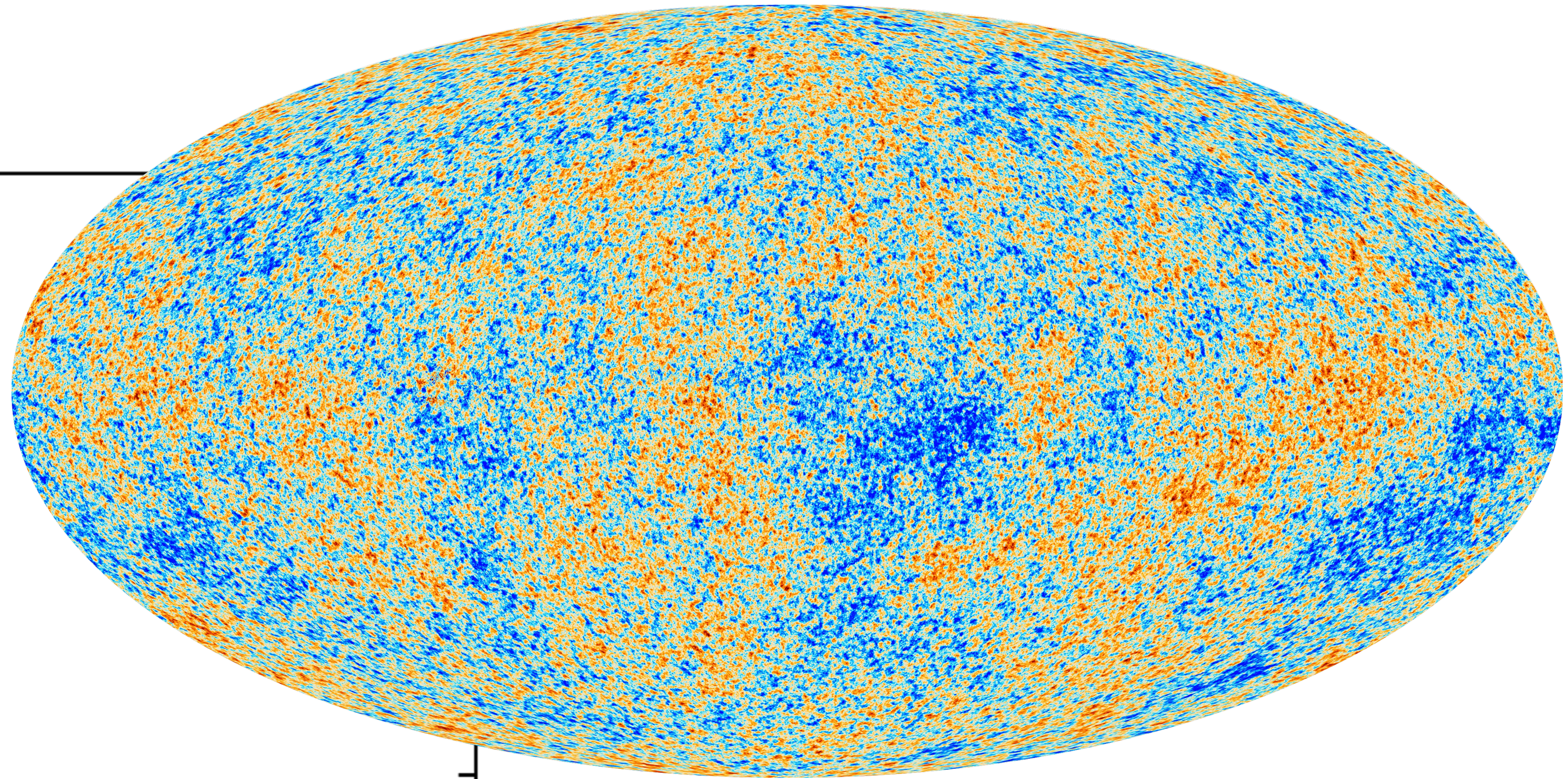
Evidences for inflation constraints on alternatives

THANKS TO JÉRÔME MARTIN FOR HIS HELP

Paris - 12th December 2017

Planck 2015





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

$n_{\rm s} = 0.9639 \pm 0.0047$ almost $\underbrace{\text{scale invariant}}_{\text{excluded}}$

$f_{\rm NL}^{\rm loc} = 0.8 \pm 5$
$f_{\rm NL}^{\rm eq} = -4 \pm 43$
$f_{\rm NL}^{\rm ort} = -26 \pm 21$
} gaussian signal

isocurvature $\lesssim 1\%$

$r < 0.11$

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

compatible with ***INFLATION***

Inflation: phase of accelerated expansion

... needs a fluid with negative pressure

$$\frac{\ddot{a}}{a} = -\frac{1}{6M_{\mathrm{P}}^2}(\rho + 3p) > 0$$

Inflaton (compatible with the cosmological principle)

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

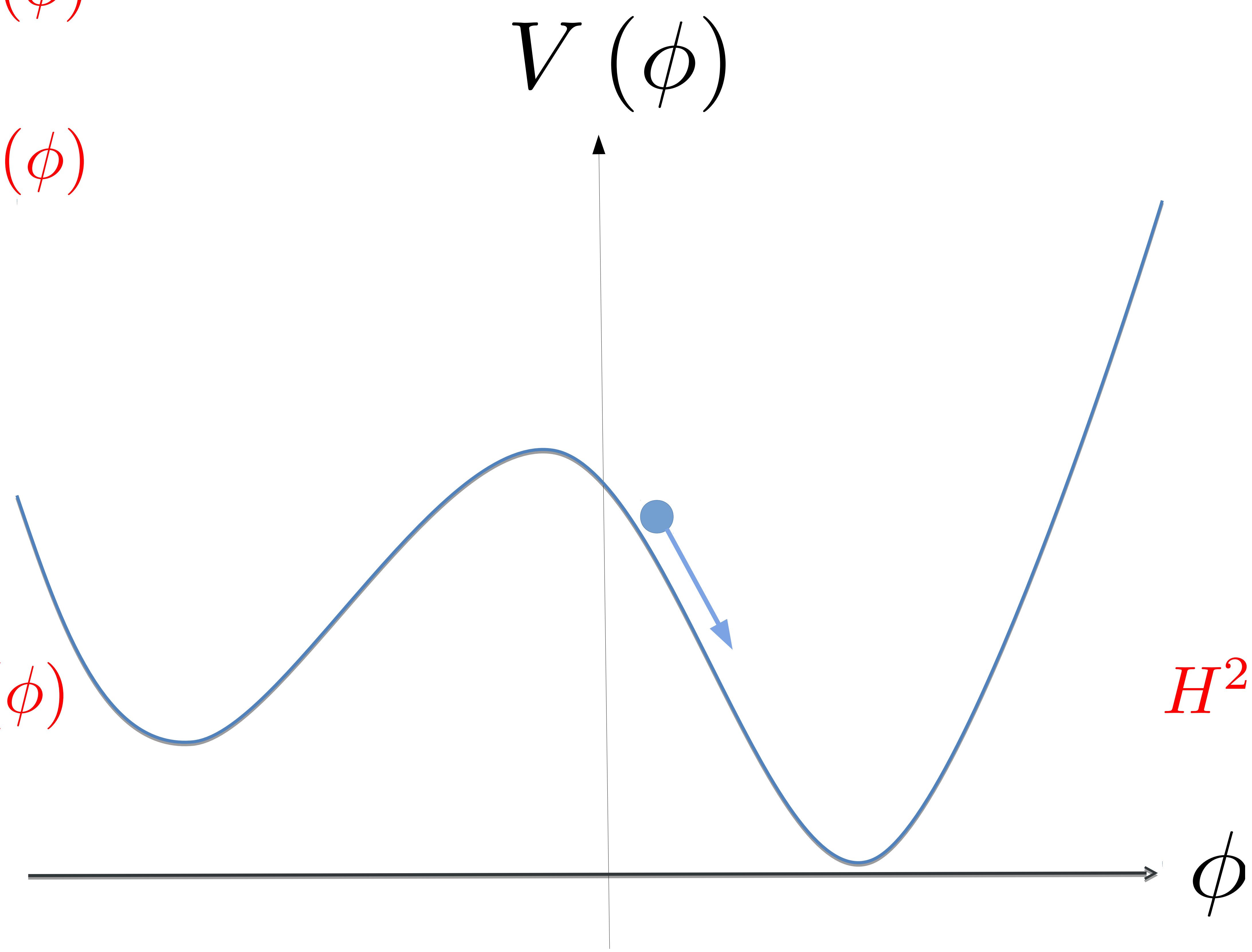
$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Slow-roll

$$\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$$

$$\downarrow$$

$$\rho + 3p \simeq -2V(\phi)$$



$$\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$$

$$\downarrow$$

$$p \simeq -\rho$$

$$\downarrow$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -3H(\rho + p) \simeq 0$$

$$\downarrow$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_{\mathrm{P}}^2} \simeq H_{\mathrm{inf}}^2$$

$$\downarrow$$

$$a(t) \simeq \mathrm{e}^{H_{\mathrm{inf}}t}$$

Standard questions and inflationary answers

Singularity Not solved... actually not addressed!

Horizon $d_{\mathrm{H}} \equiv a(t) \int_{t_{\mathrm{ini}}}^{t} \frac{\mathrm{d}\tau}{a(\tau)}$ can be made as big as one wishes

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

accelerated expansion (inflation)

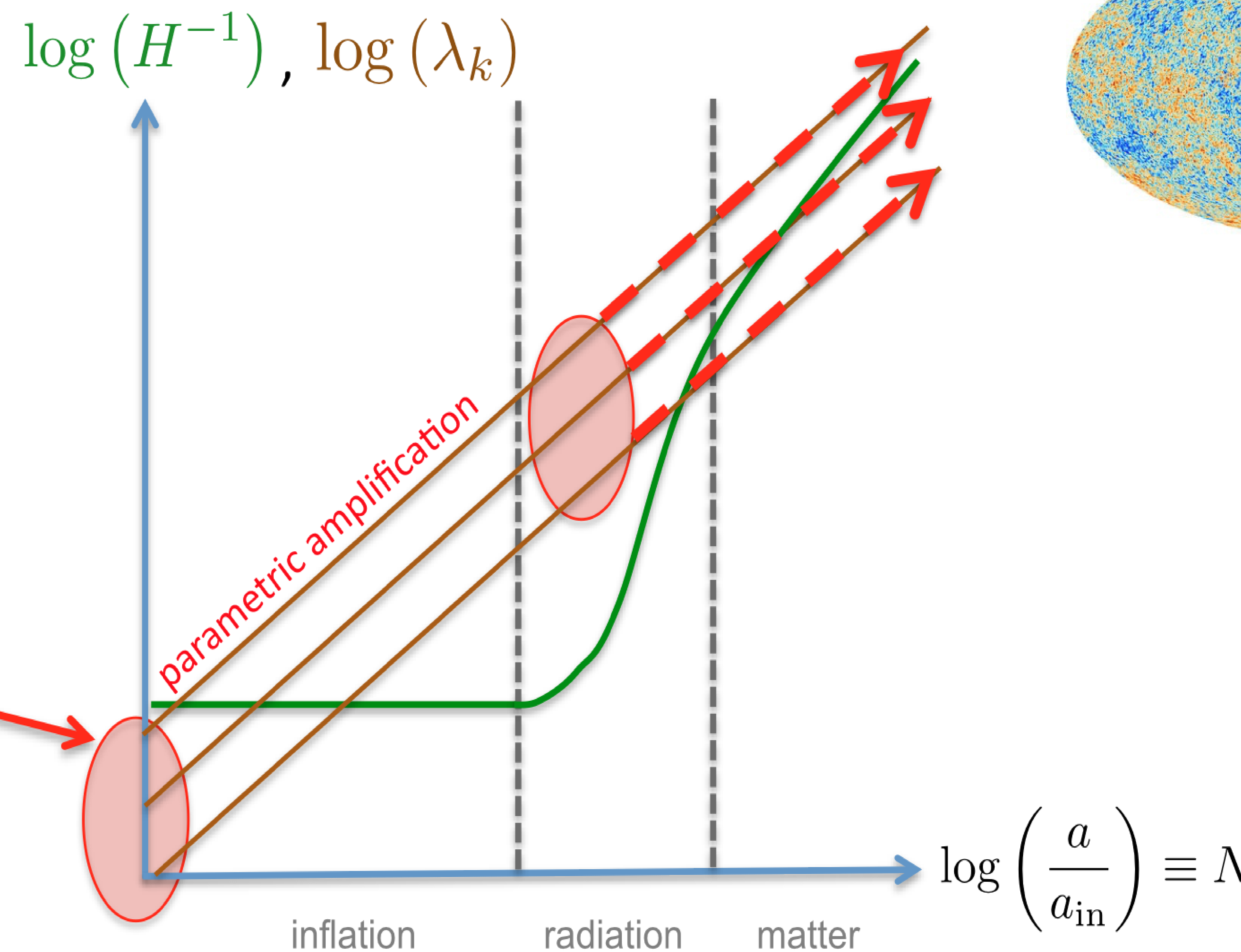
Homogeneity & Isotropy

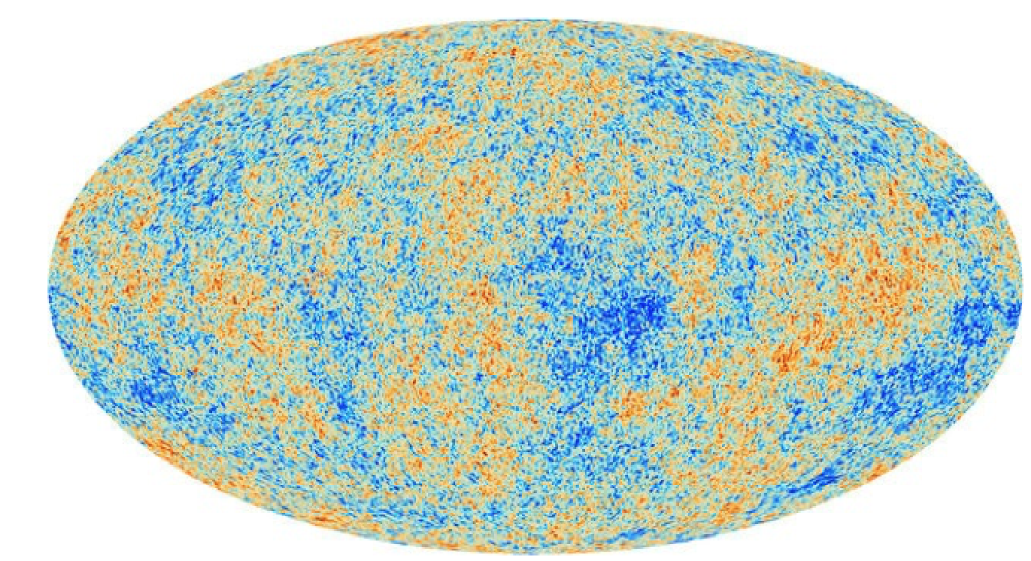
Initial Universe = very small patch
Accelerated expansion drives the shear to zero... $\Longrightarrow$ vacuum state!

Perturbations Bonus of the theory: predictions!!!

Others dark matter/energy, baryogenesis,...

Almost constant Hubble radius $R_{\mathrm{H}} = H_{\mathrm{inf}}^{-1}$





Harmonic oscillator fundamental state

$$\Psi_{\boldsymbol{k}} = \left(\frac{k}{\pi}\right)^{\frac{1}{4}} \mathrm{e}^{-\frac{k}{2} v_{\boldsymbol{k}}^2}$$

Everything depends on the slow roll parameters

$$\epsilon_1 \simeq \frac{1}{2M_{\rm P}^2}\left(\frac{V_{,\phi}}{V}\right)^2$$

$$\epsilon_2 \simeq \frac{2}{M_{\rm P}^2}\left[\left(\frac{V_{,\phi}}{V}\right)^2 - \frac{V_{,\phi\phi}}{V}\right]$$

Evaluated at $\phi_\star$(pivot scale leaves Hubble radius):

$$\left.\begin{aligned} \mathcal{P}_\zeta &\propto \frac{H_{\rm inf}^2}{M_{\rm P}^2\epsilon_{1\star}}\left[1+\mathcal{O}\left(k,\epsilon_\star\right)\right] \\ \mathcal{P}_h &\propto \frac{H_{\rm inf}^2}{M_{\rm P}^2}\left[1+\mathcal{O}\left(k,\epsilon_\star\right)\right] \end{aligned}\right\} \text{Spectral indices} \left\{\begin{aligned} n_{\rm S} &= 1+\frac{\mathrm{d}\ln\mathcal{P}_\zeta}{\mathrm{d}\ln k} = -2\epsilon_{1\star}-\epsilon_{2\star} \\ n_{\rm T} &= \frac{\mathrm{d}\ln\mathcal{P}_h}{\mathrm{d}\ln k} = -2\epsilon_{1\star} \end{aligned}\right.$$

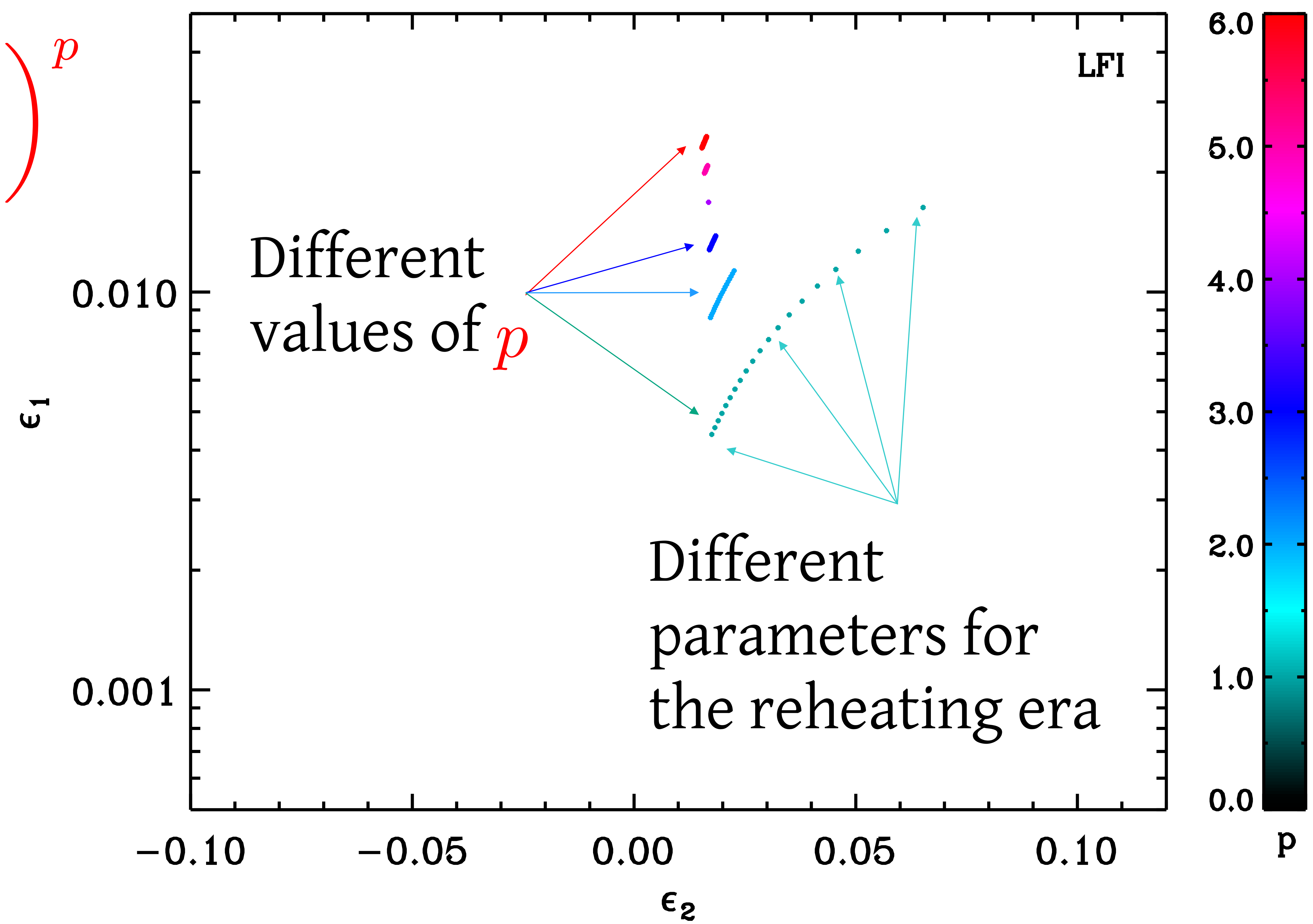
$\longrightarrow$ Consistency relation $r \equiv \frac{T}{S} = \frac{\mathcal{P}_\zeta}{\mathcal{P}_h} = 16\epsilon_{1\star} = -8n_{\rm T}$

+ running

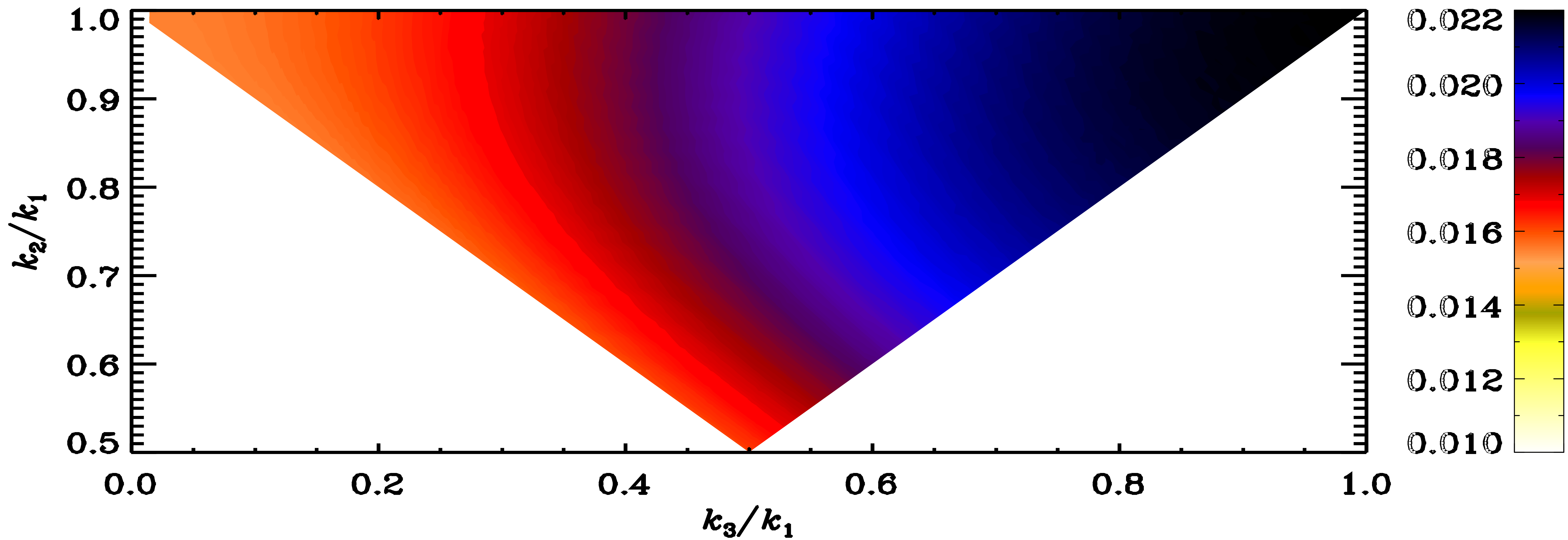
Various models, various predictions... (one example)

"Large field inflation"

$$V(\phi) = m^4 \left(\frac{\phi}{M_{\mathrm{P}}}\right)^p$$



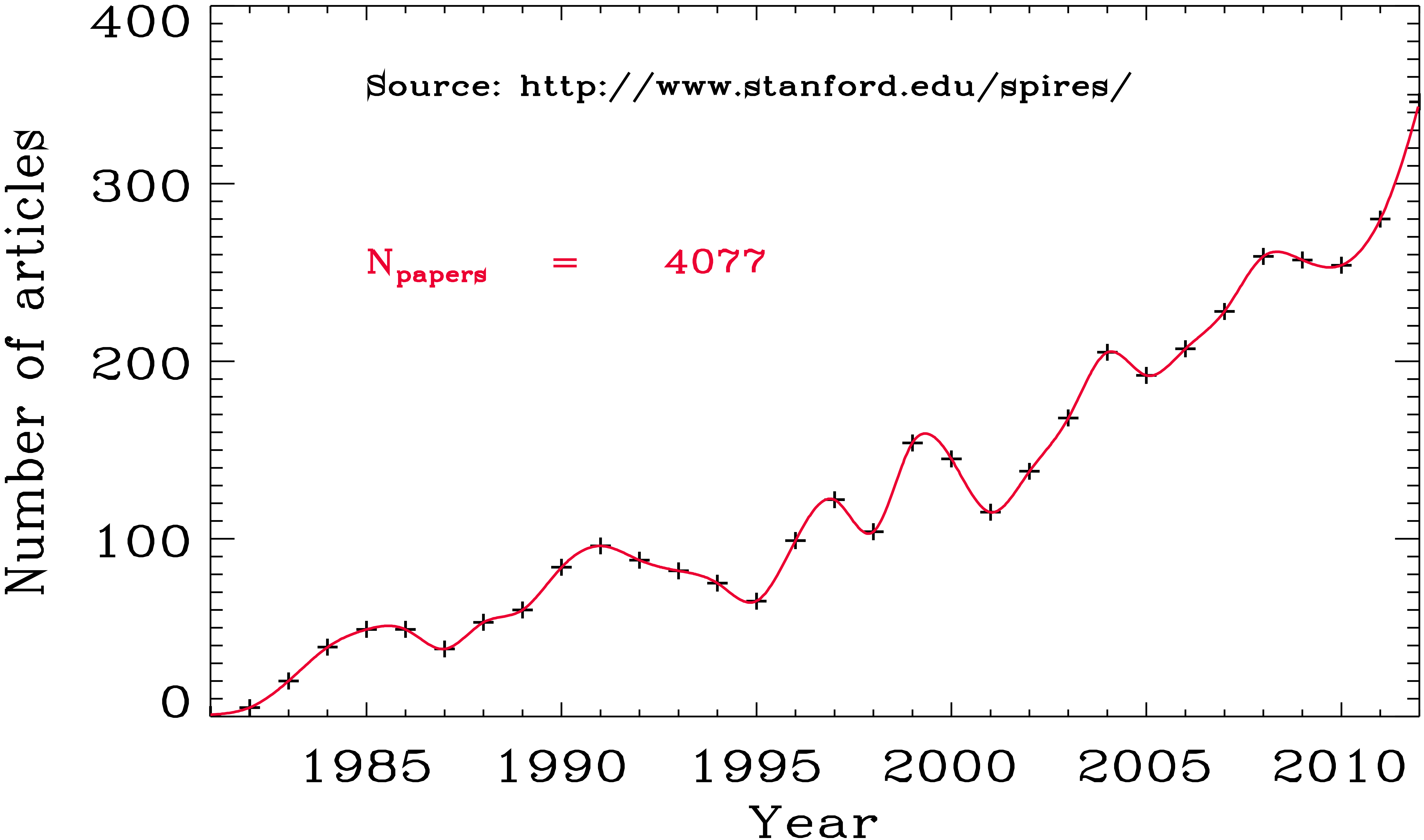
3 point correlation function...



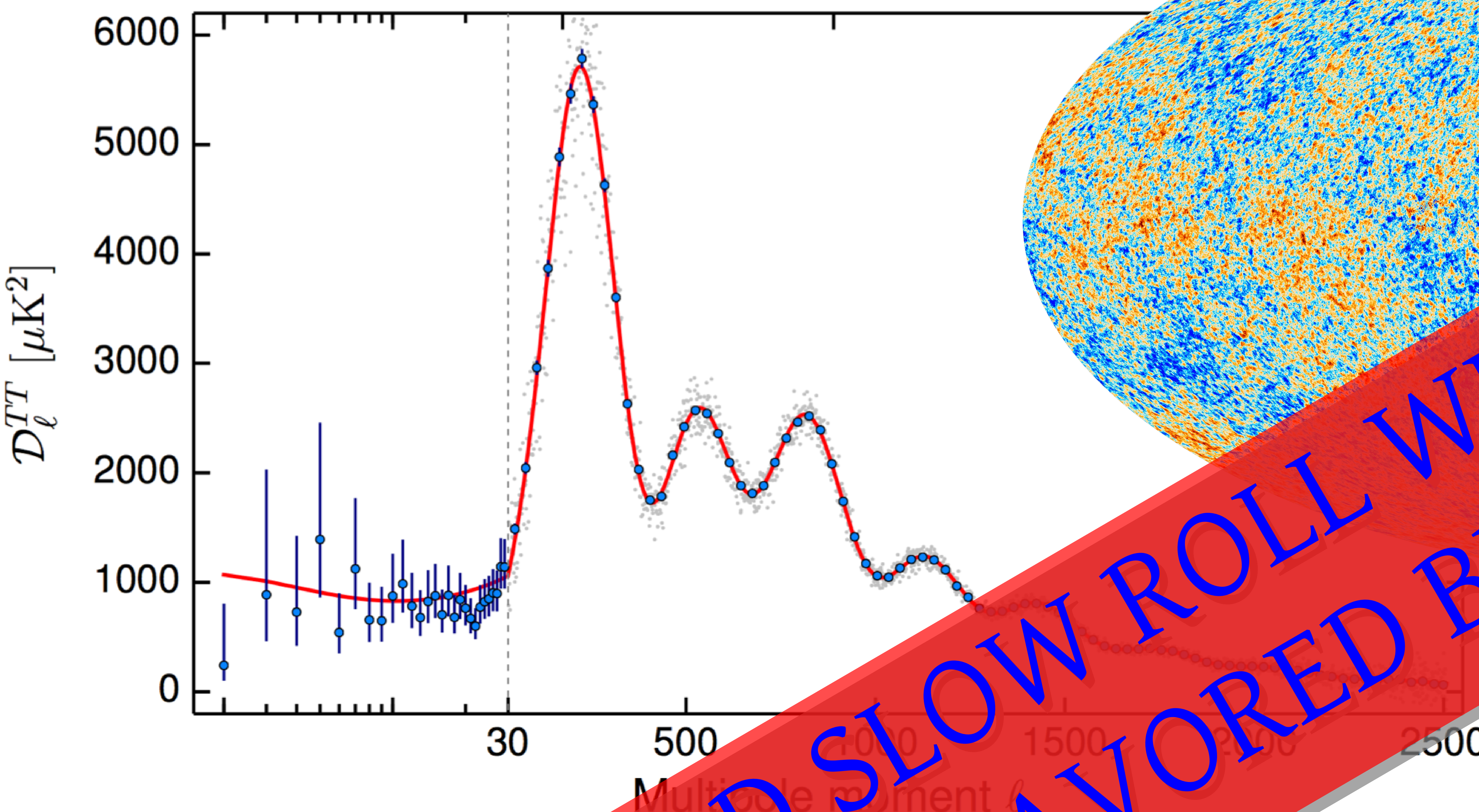
$$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \zeta_{\boldsymbol{k}_3} \rangle \propto f_{\rm NL}\left(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3\right) \frac{\delta\left(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3\right)}{k_1^3 k_2^3 k_3^3} \left[k_1^3 \mathcal{P}_\zeta\left(k_2\right) \mathcal{P}_\zeta\left(k_3\right) + 2 \text{ perms.}\right]$$

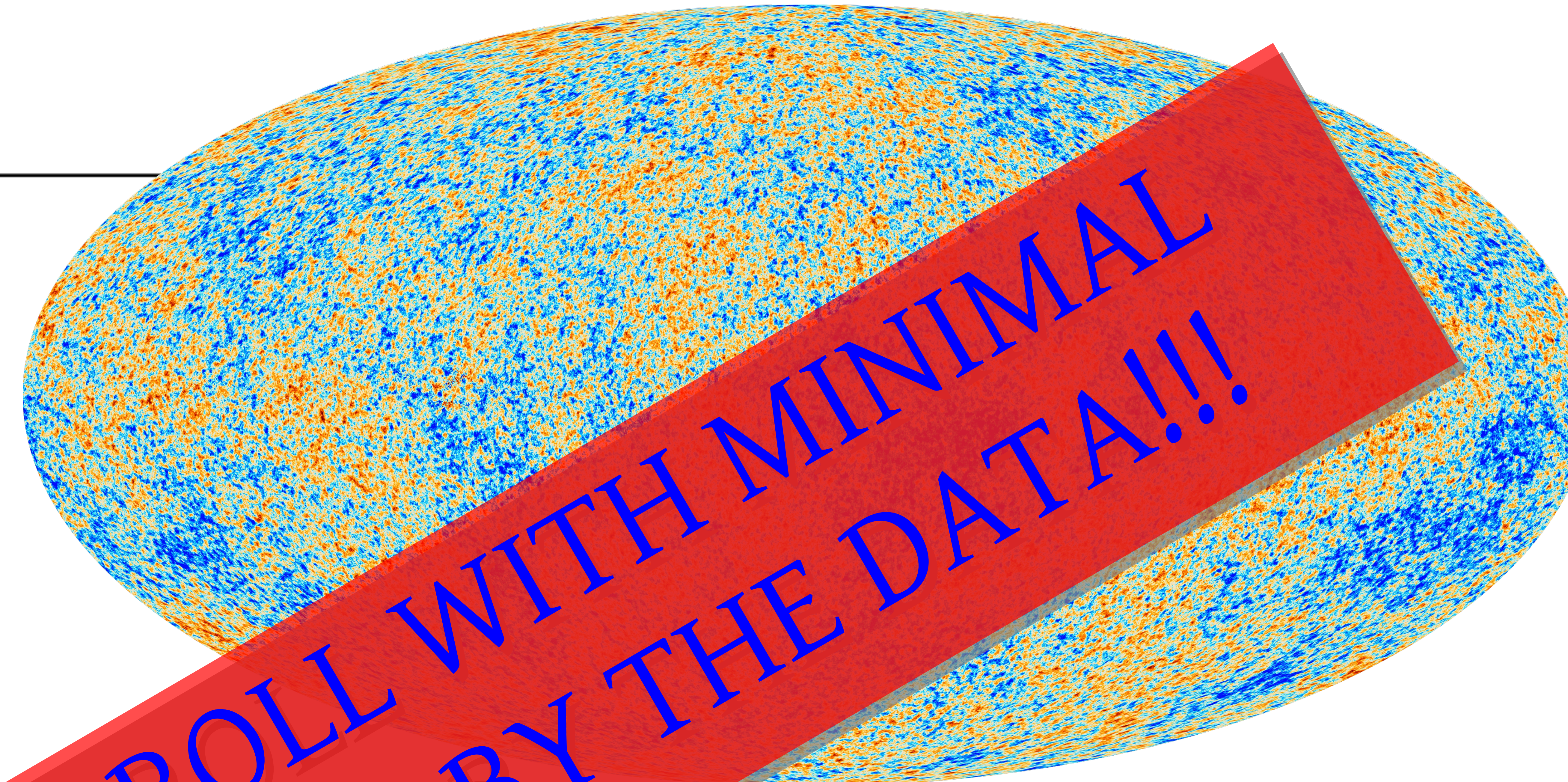
$\mathcal{O}\left(\epsilon_\star\right)$ Unobservable at the moment

Comparing with data: pb = 100's of different models



Planck 2015





$\Omega_{\mathcal{K}} = -0.040^{+0.038}_{-0.041}$

SINGLE FIELD SLOW ROLL WITH MINIMAL KINETIC TERM FAVORED BY THE DATA!!!

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

excluded

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gaussian signal

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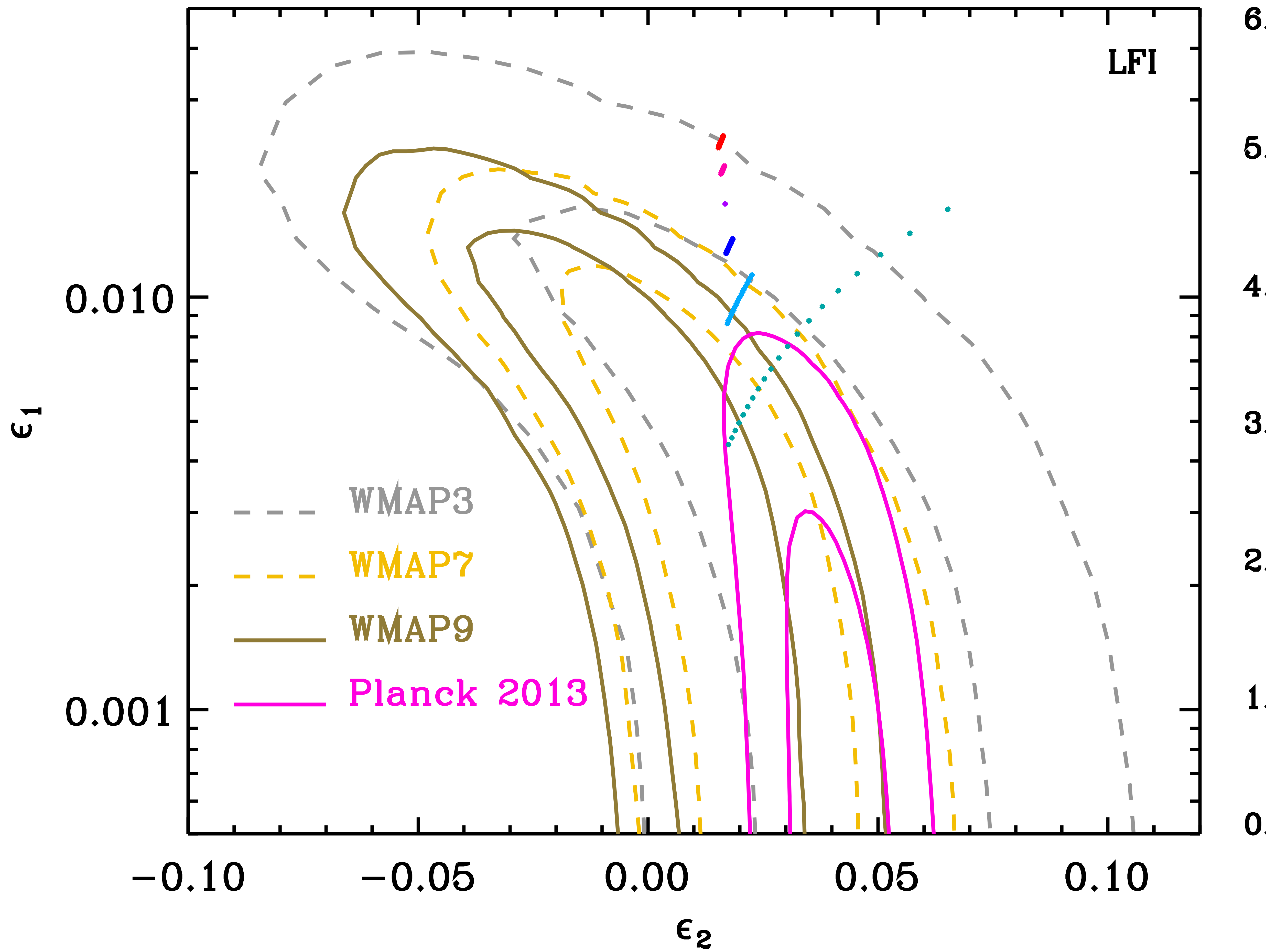
quantum vacuum fluctuations of a single scalar d.o.f

compatible with ***INFLATION***



CMB constraints on the slow-roll parameters

Planck 2015 constraints:

Deviation from exact scale invariance

$$n_{\rm S} = 0.9645 \pm 0.0049 < 1$$

Slow-roll parameters

$$\epsilon_{1\star} < 0.0068$$

$$\epsilon_{2\star} = 0.029^{+0.008}_{-0.007}$$

Inflaton potential

$$M_{\rm P}\frac{|V_{,\phi}|}{V} < 0.14$$

$$M_{\rm P}^2\frac{V_{,\phi\phi}}{V} = 0.01^{+0.005}_{-0.009}$$

No detection:

GW

$$r < 0.1$$

Running

$$\frac{\mathrm{d}n_{\rm S}}{\mathrm{d}\ln k} = -0.0134 \pm 0.009$$

Energy scale

$$H_{\rm inf}^2 \sim \mathcal{P}_\zeta \epsilon_{1\star} \propto \rho_\star$$

$$\rho_\star^{\frac{1}{4}} < 2.2 \times 10^{16}\,\mathrm{GeV}$$

$$H_{\rm inf} < 1.2 \times 10^{14}\,\mathrm{GeV}$$

Bayesian analysis $\Longrightarrow$ best models: J. Martin, C. Ringeval & V. Vennin, arXiv:1303.3787

Encyclopedia Inflationaris

Inflation:

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

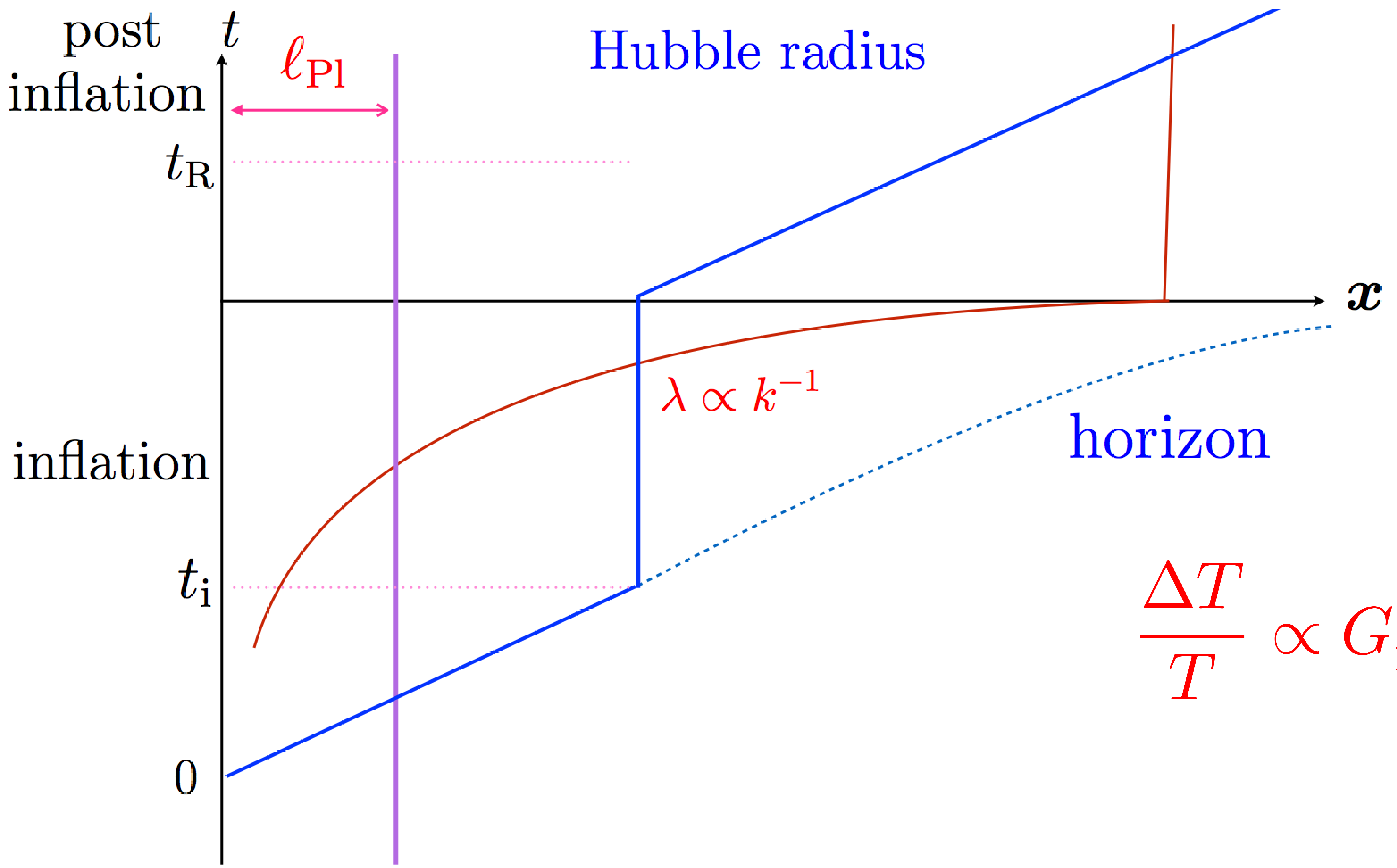
- ☺ makes falsifiable predictions...
- ☺ ... consistent with all known observations

why bother with alternatives?

"When you have eliminated the impossible, whatever remains, however improbable, must be the truth."

Sherlock Holmes (The sign of the four):

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



- Singularity

$$\exists\, t_{\rm sing}\ ; a\left(t_{\rm sing}\right) = 0$$

- Trans-Planckian

$$\exists\, t_{\rm sub}\ ; \ell\left(t_{\rm sub}\right) = \ell_0 \frac{a\left(t_{\rm sub}\right)}{a_0} \leq \ell_{\rm P}$$

- Hierarchy (amplitude)?

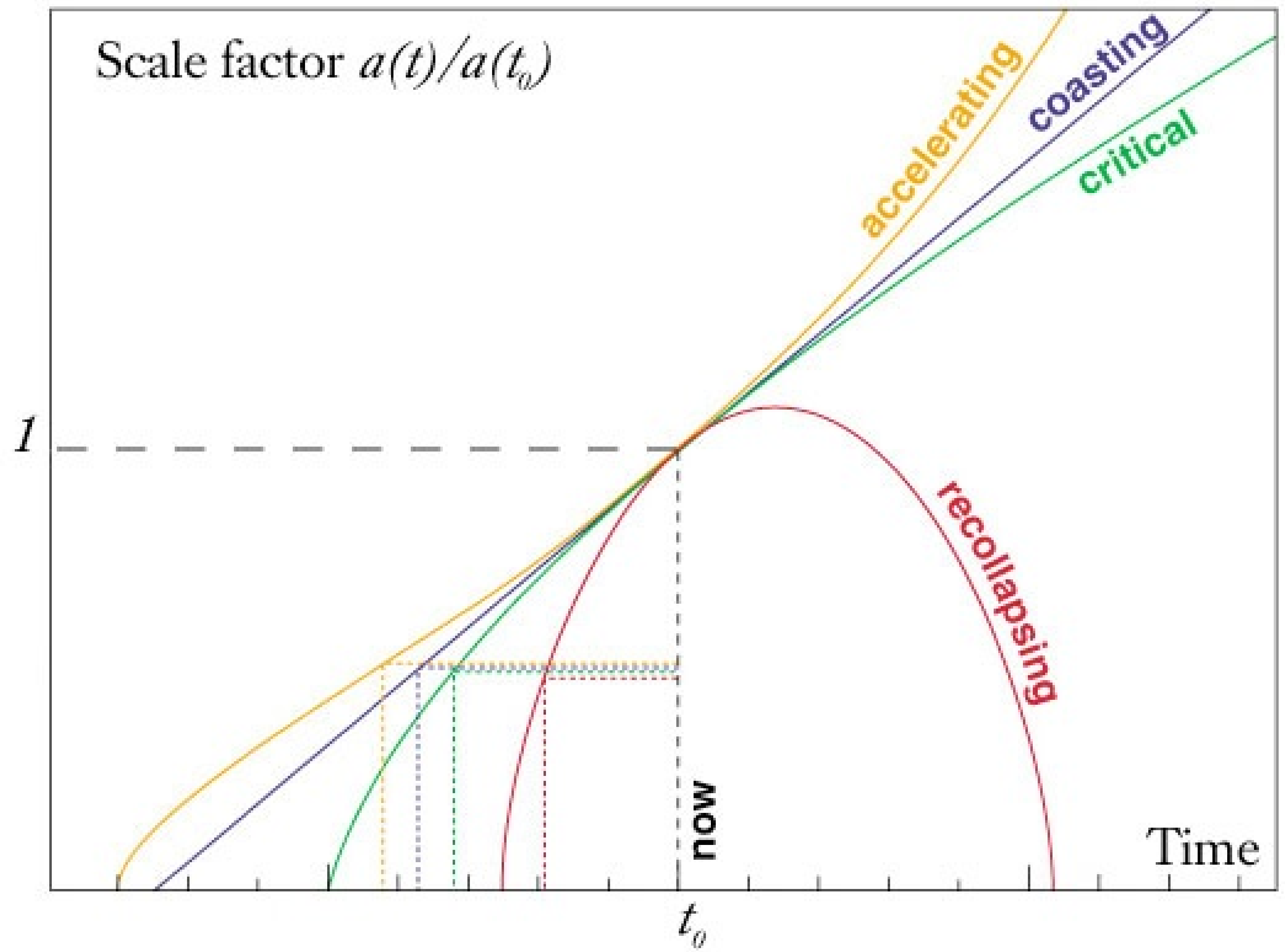
$$\frac{V(\phi)}{\Delta\phi^4} \leq 10^{-12}$$

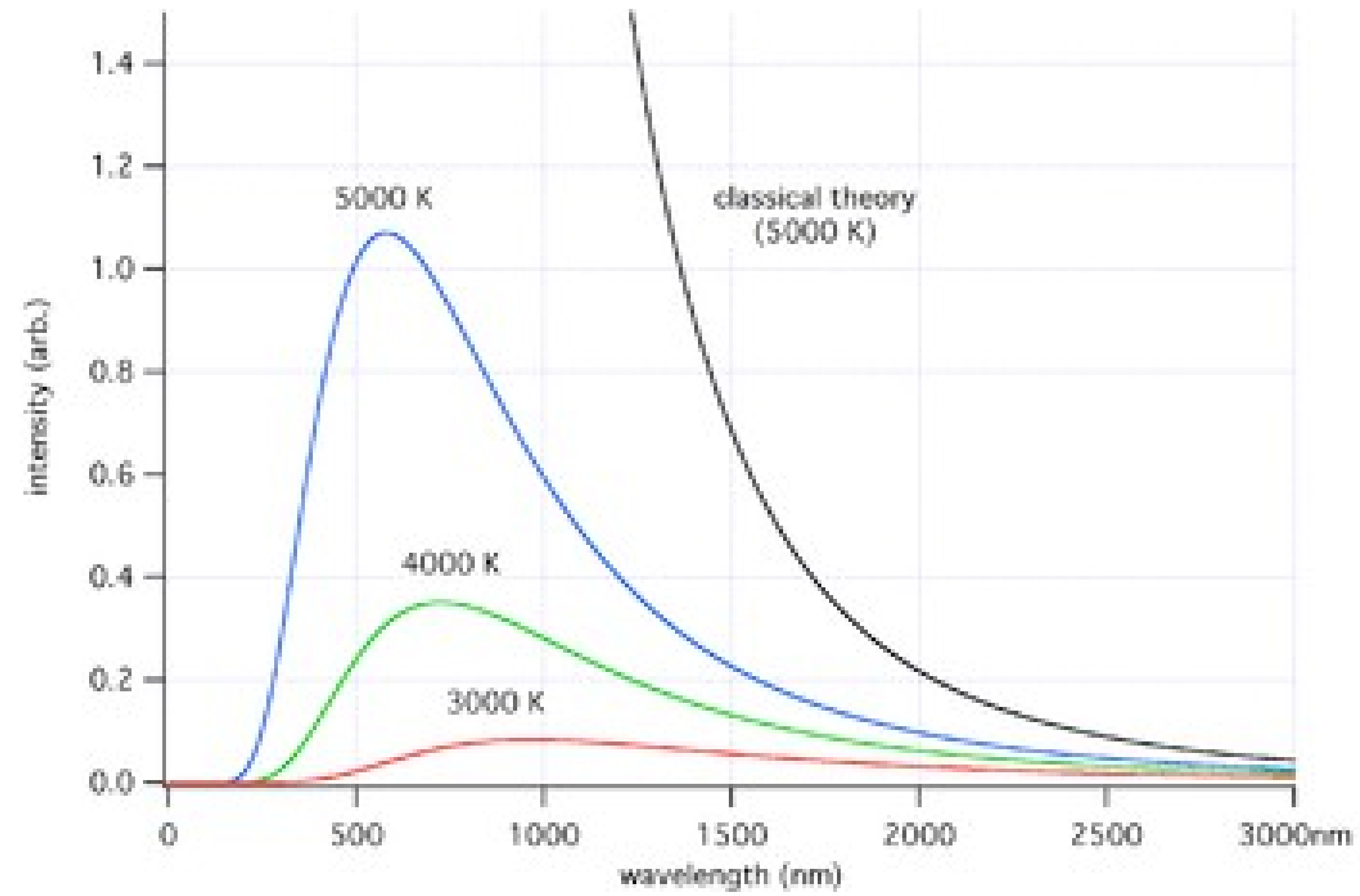
- Classical GR?

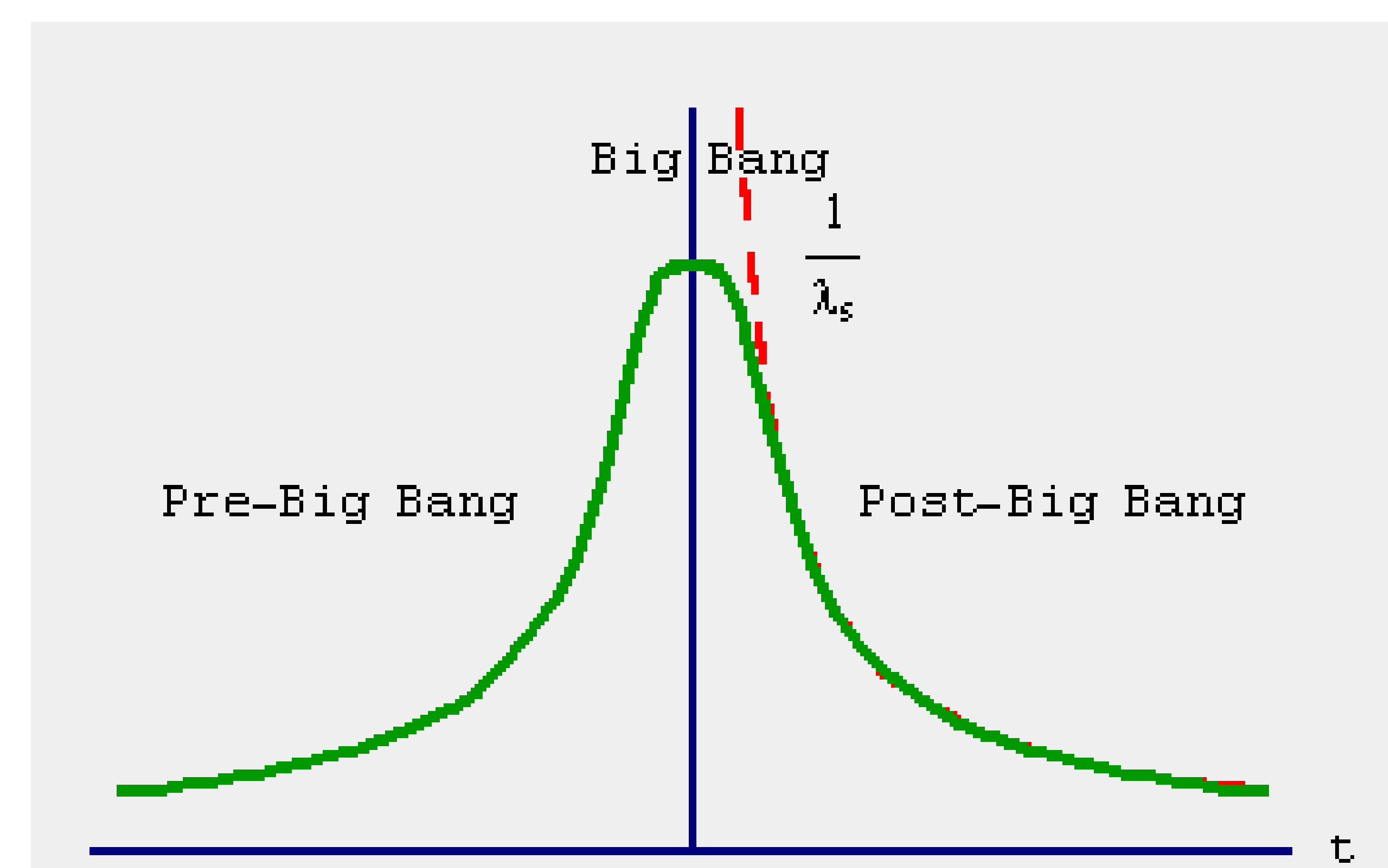
$$\frac{\Delta T}{T} \propto G_{\rm N} E_{\rm inf}^2 \sim \left(\frac{E_{\rm inf}}{M_{\rm P}}\right)^2 \longrightarrow E_{\rm inf} \sim 10^{-3} M_{\rm P}$$

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

Singularity problem   Quantum effect?

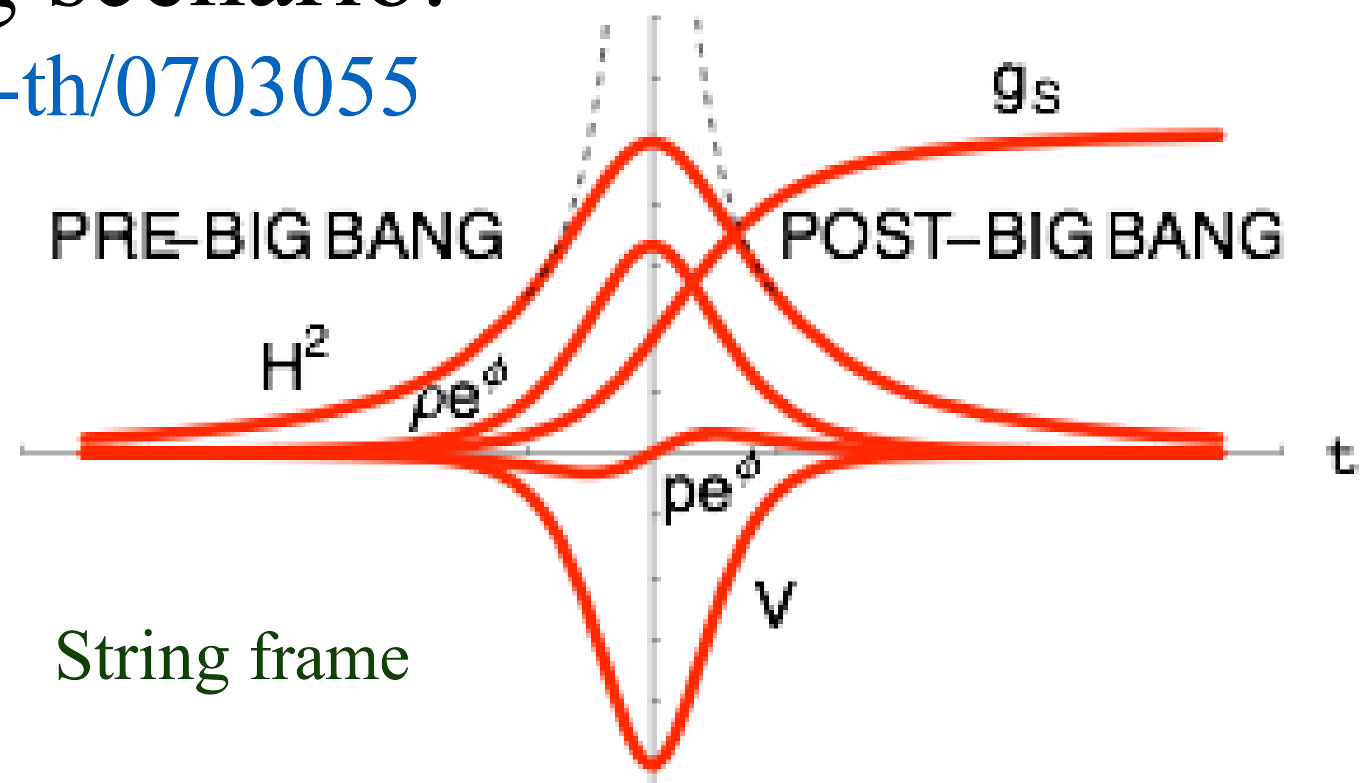


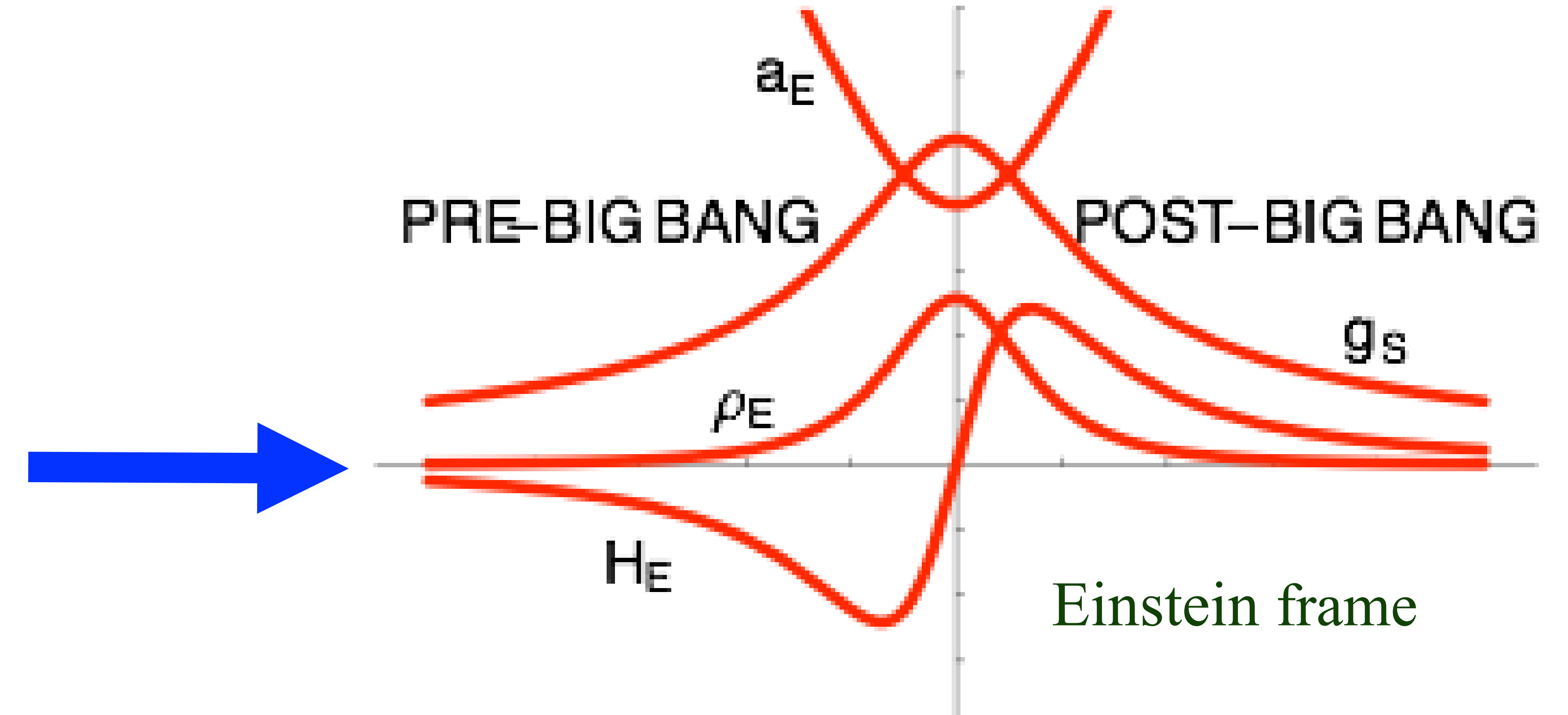




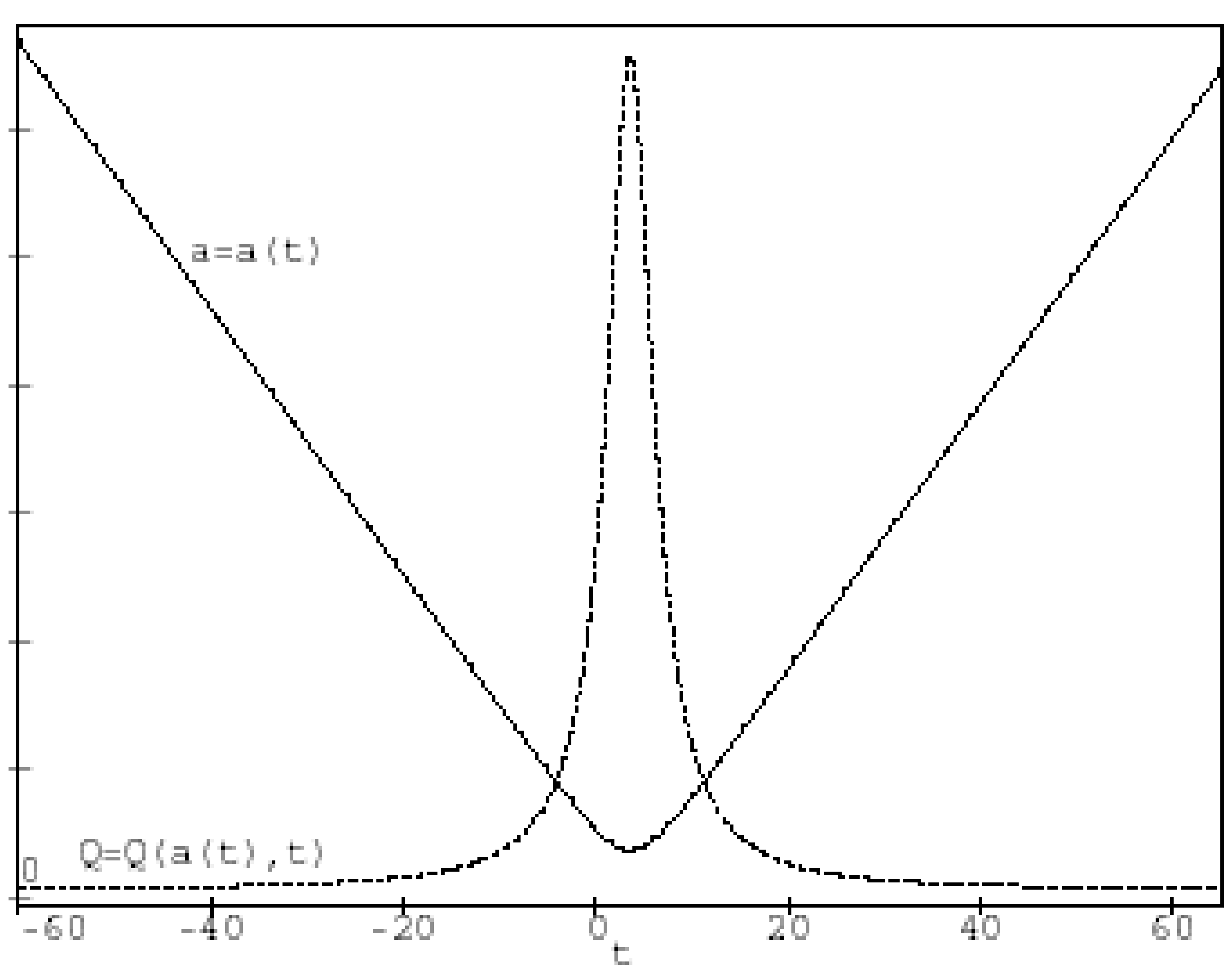
Pre Big Bang scenario:

hep-th/0207130 & hep-th/0703055

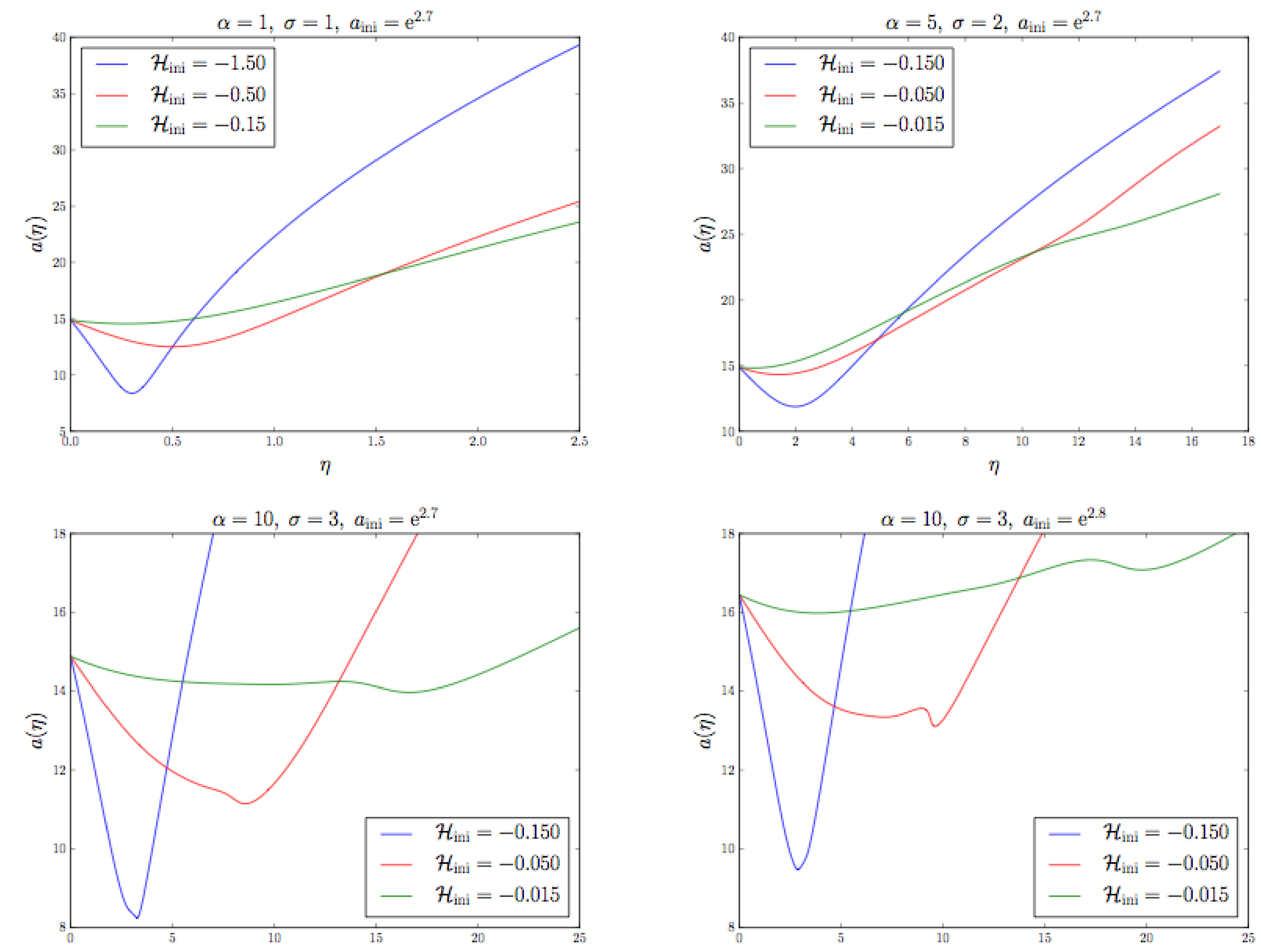




WdW quantum cosmology:



PLA **241**, 229 (1998)

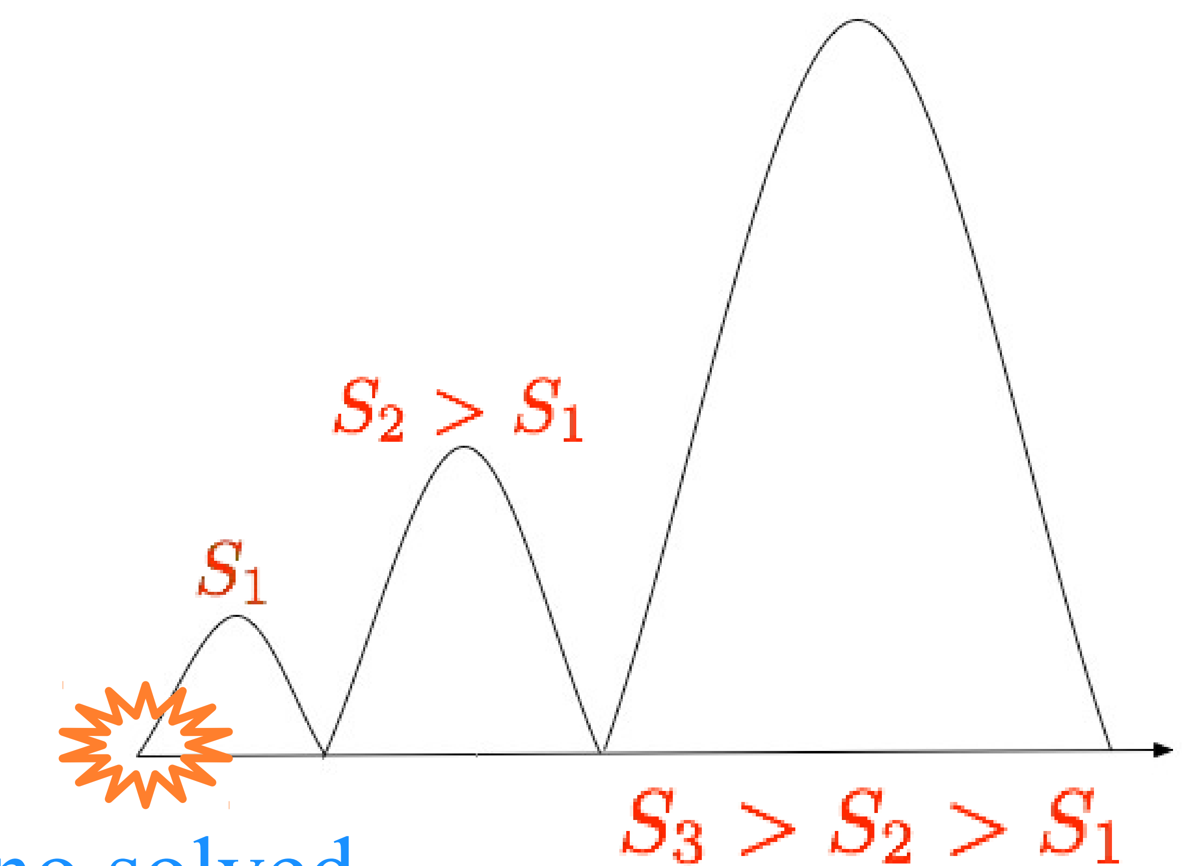


arXiv:1603.02342

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

Model listing:

Quantum gravity

LQG & LQC

Non relativistic quantum gravity

Canonical quantum gravity (WdW)

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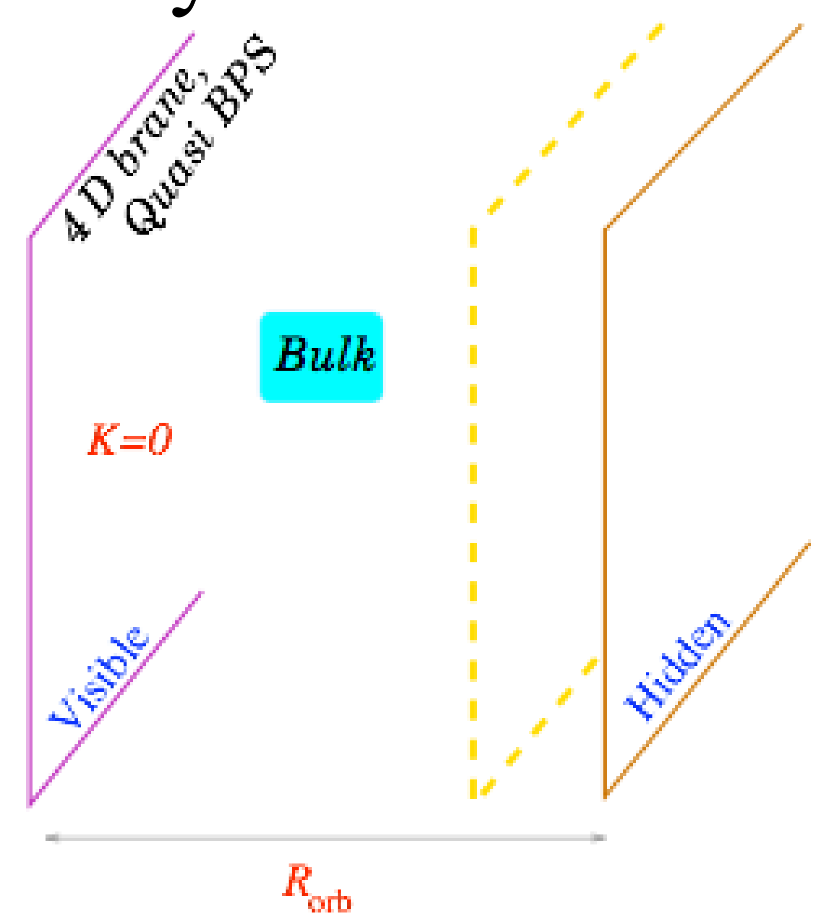
Ekpyrotic & cyclic

Branes

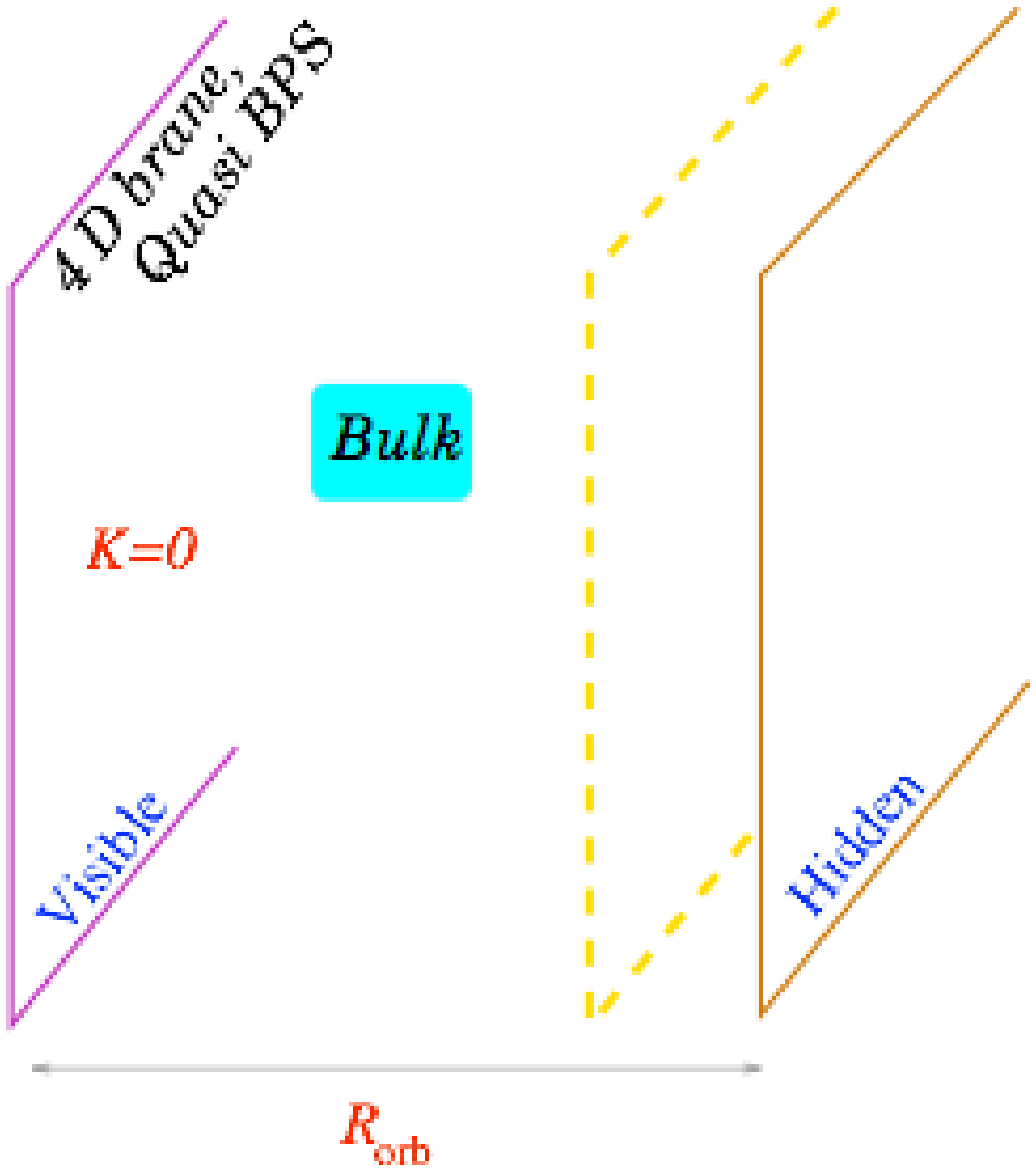


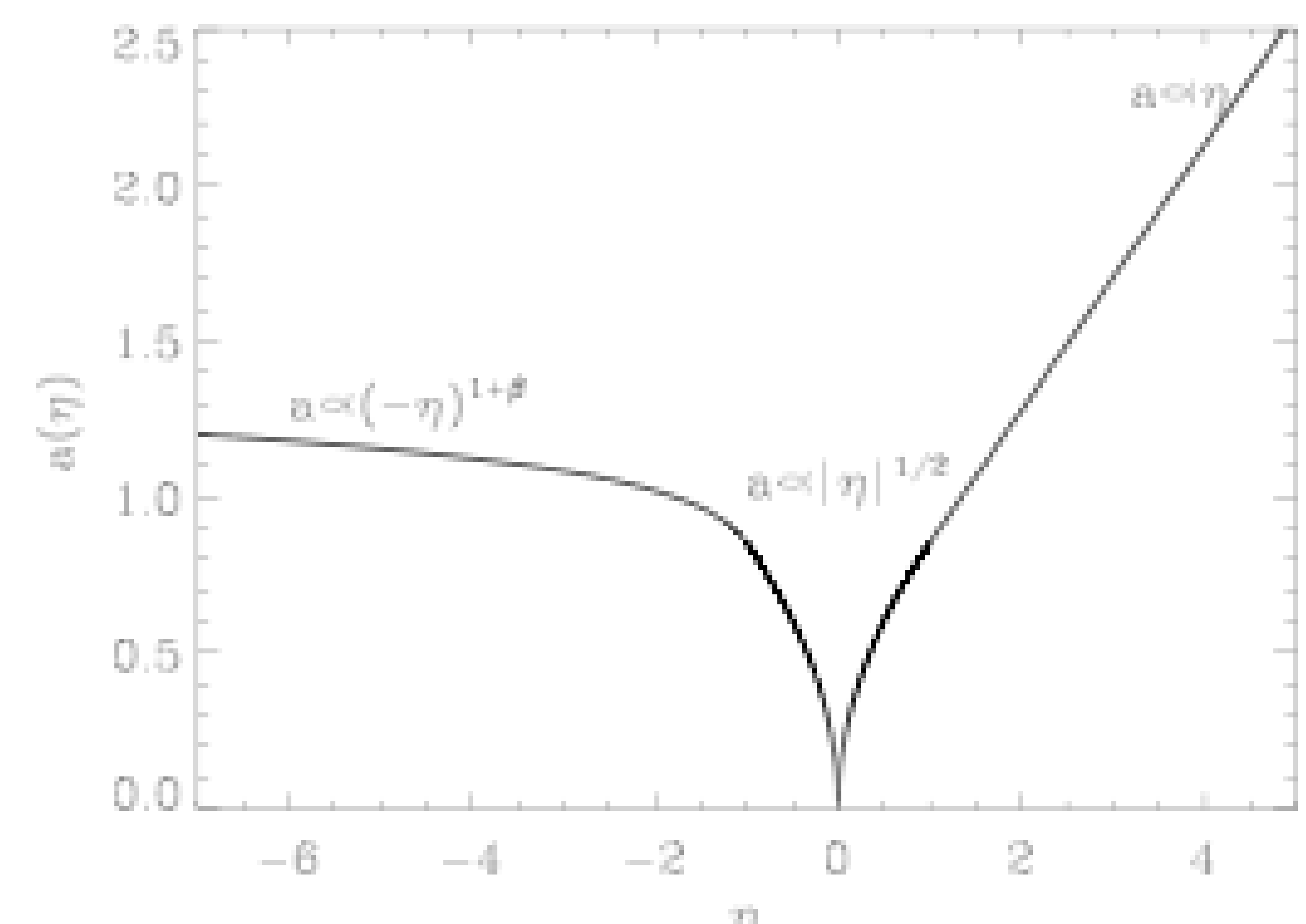
Ekpyrotic scenario:

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

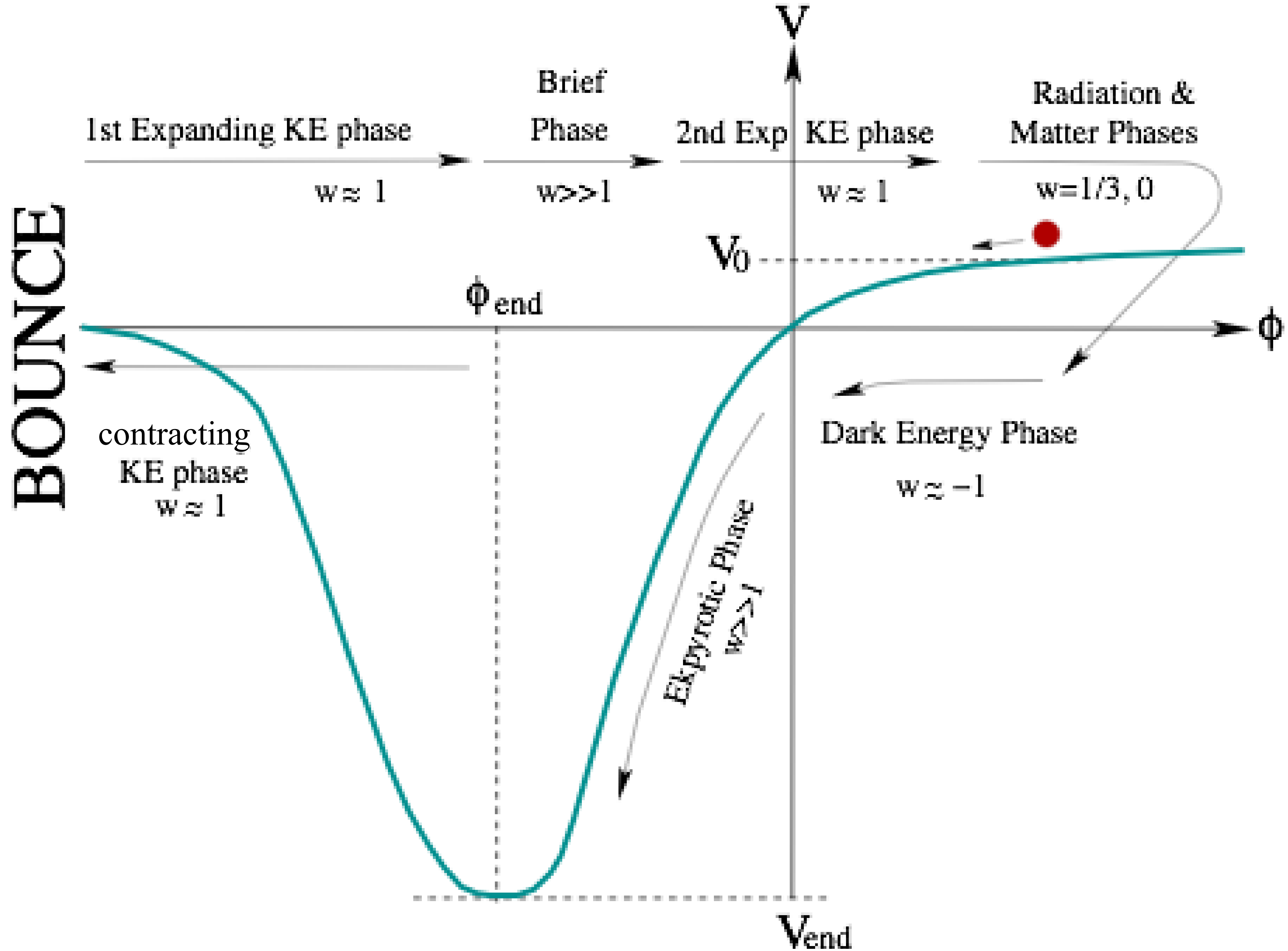
$$\mathcal{S}_4 = \int_{\mathcal{M}_4} \mathrm{d}^4x\sqrt{-g_4}\left[\frac{R_{(4)}}{2\kappa} - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right],$$

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

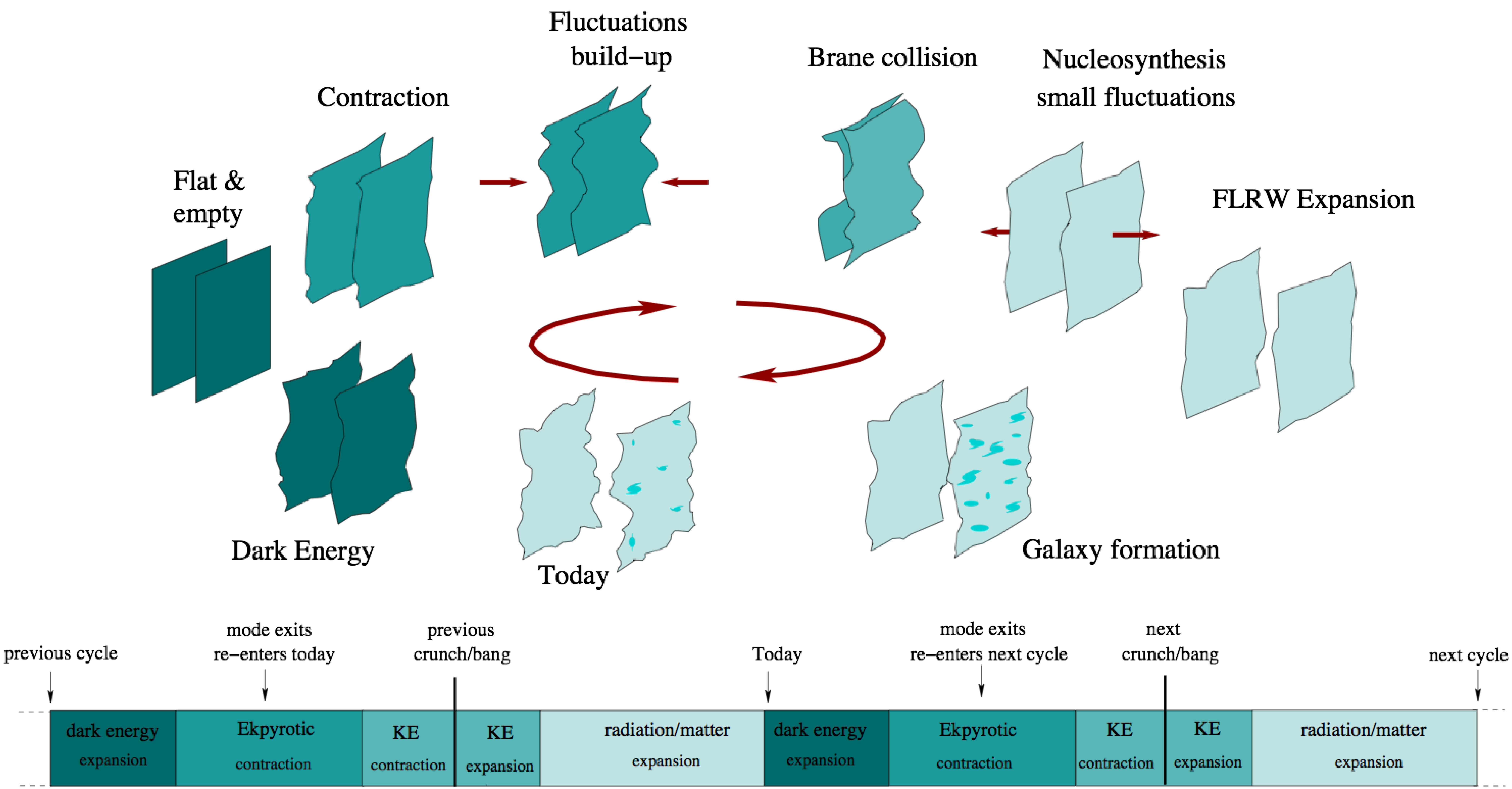




Singular…


V
1st Expanding KE phase
w ≈ 1
Brief
Phase
w>>1
2nd Exp KE phase
w ≈ 1
Radiation &
Matter Phases
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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Non relativistic quantum gravity

Ekpyrotic & cyclic

Branes

String gas cosmology

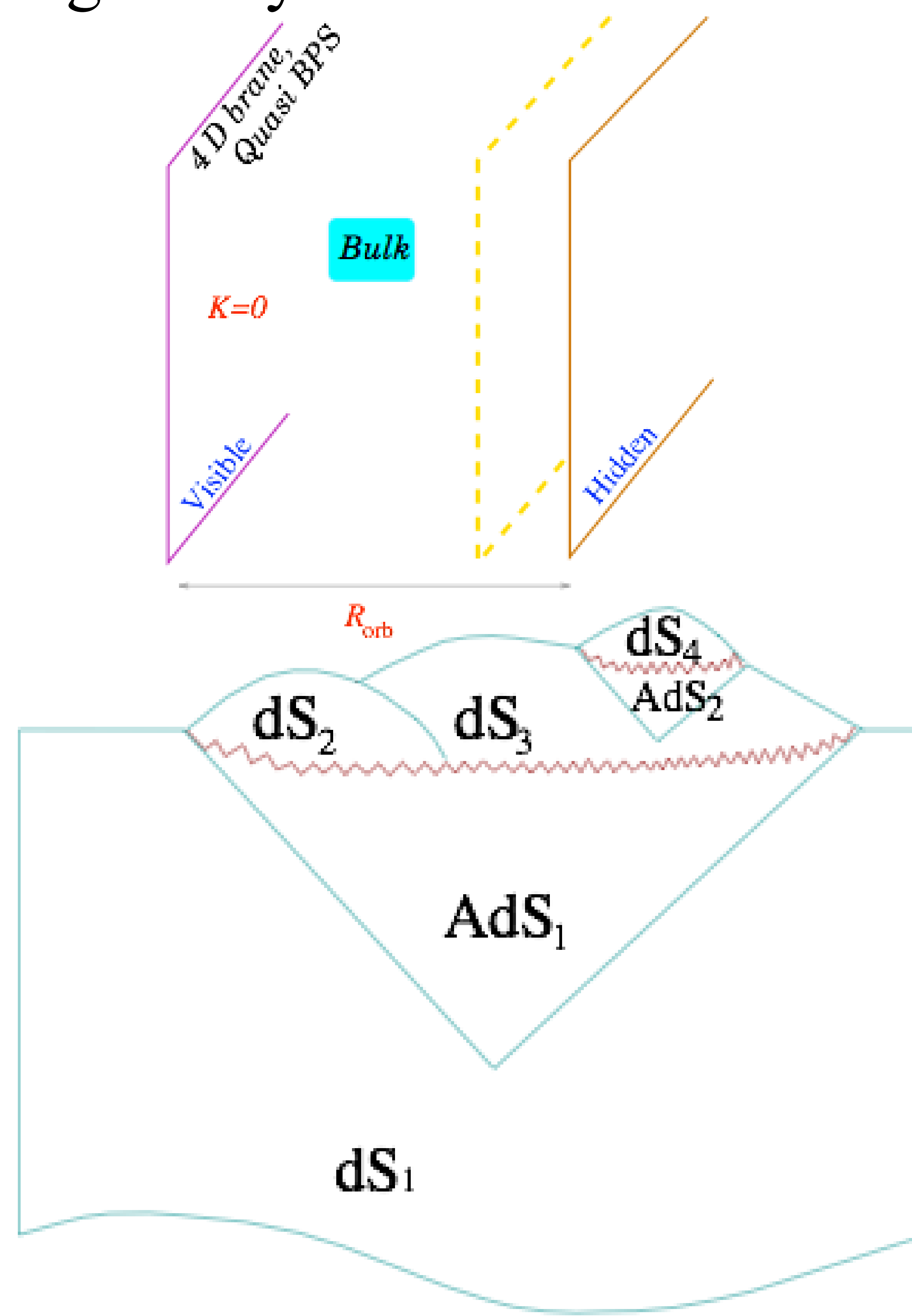
Antigravity

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

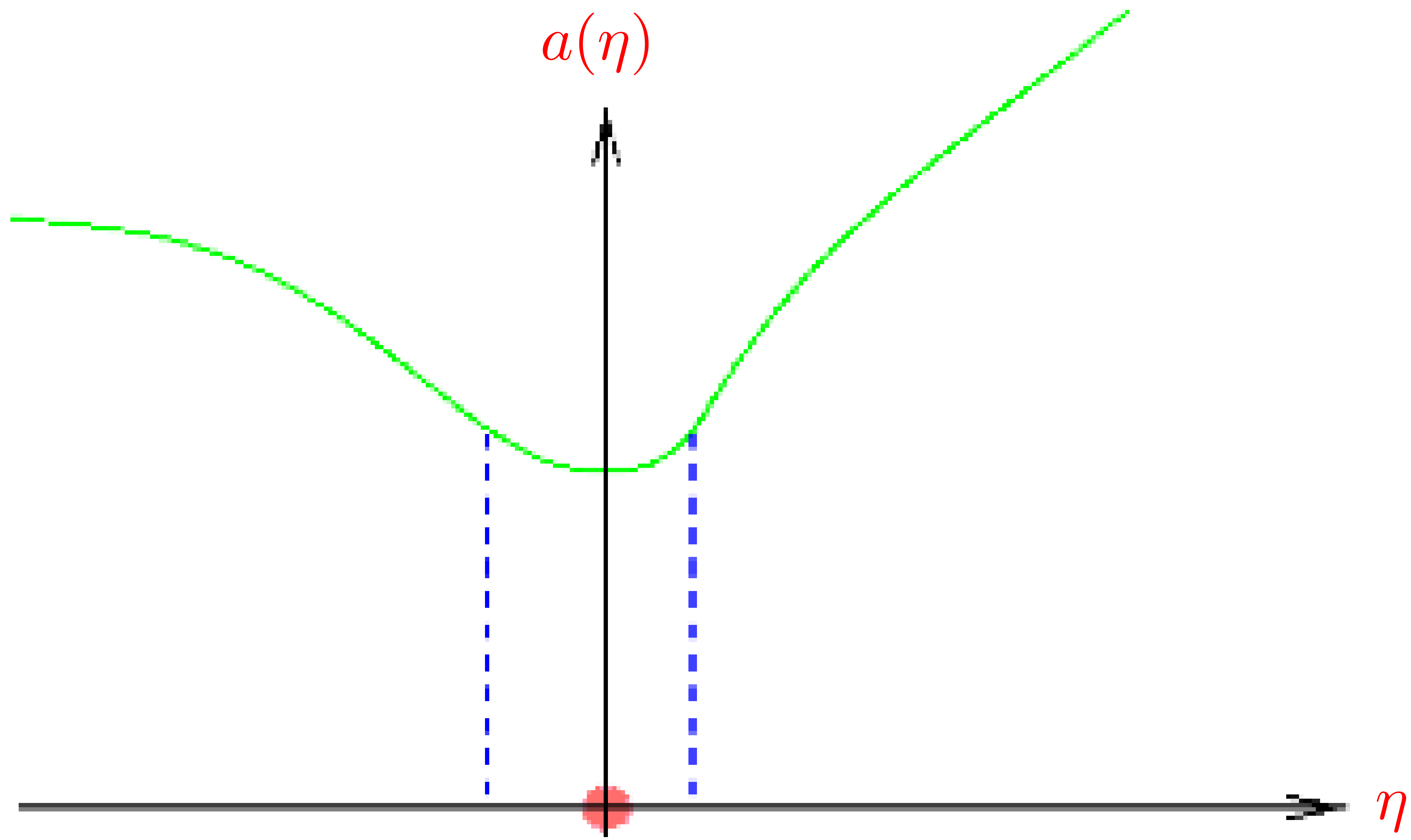
(see *Encyclopedia Inflationaris*)

Standard questions and bouncing answers

arXiv:0809.2022

Singularity

Merely a non issue in the bounce case!



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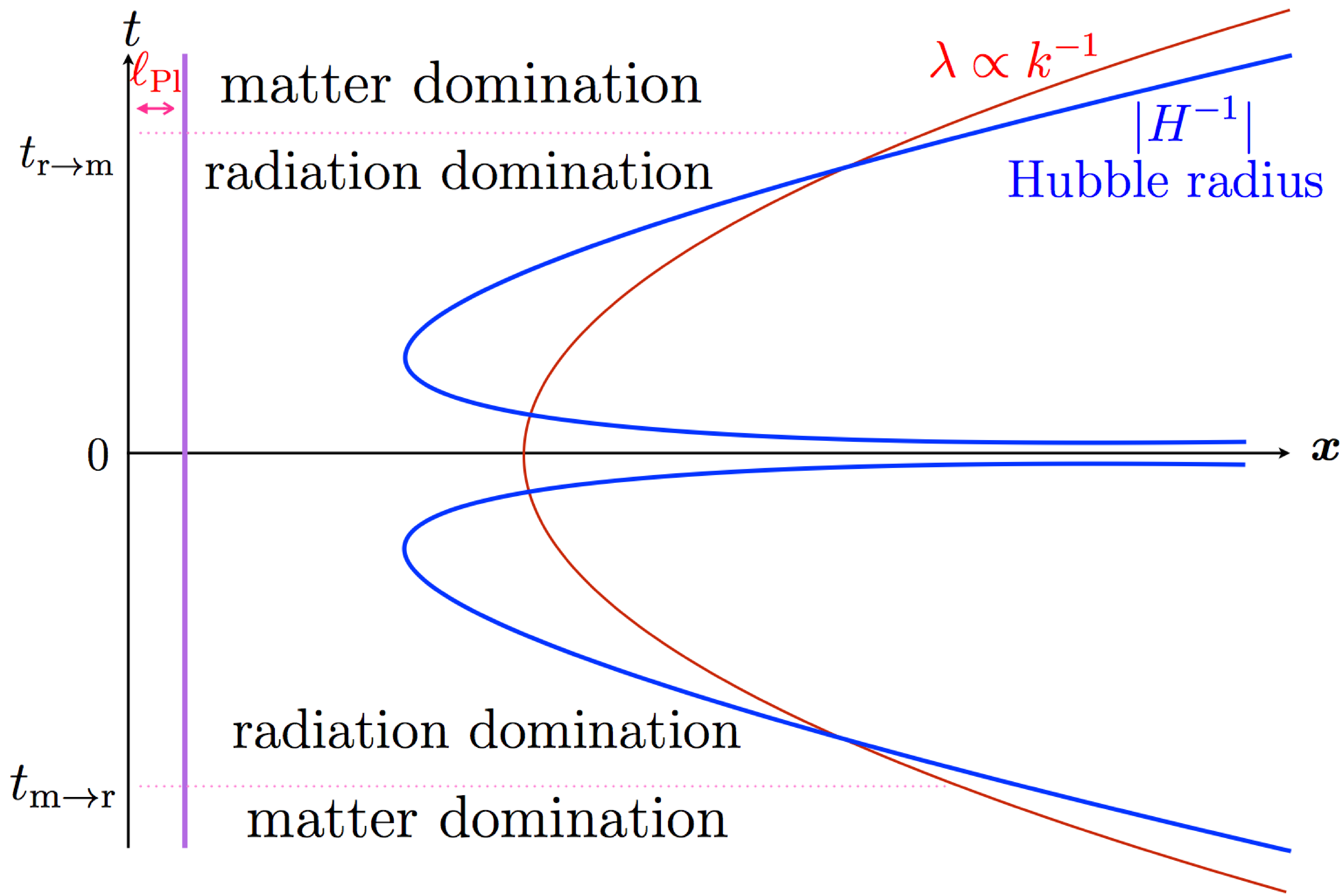

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Singularity Merely a non issue in the bounce case!

Horizon $d_{\rm H} \equiv a(t) \int_{t_{\rm ini}}^{t} \frac{\mathrm{d}\tau}{a(\tau)}$ can be made divergent easily if $t_{\rm ini} \to -\infty$

Example:
$$\begin{cases} d_{\rm H}(t) = \dfrac{3(1+w)}{1+3w}|t| \left\{ 1 - \left(\dfrac{t_{\rm ini}}{t} \right)^{(1+3w)/[3(1+w)]} \right\} \\ w > -\dfrac{1}{3} \implies \lim\limits_{t_{\rm ini}\to-\infty} d_{\rm H} = \infty \end{cases}$$

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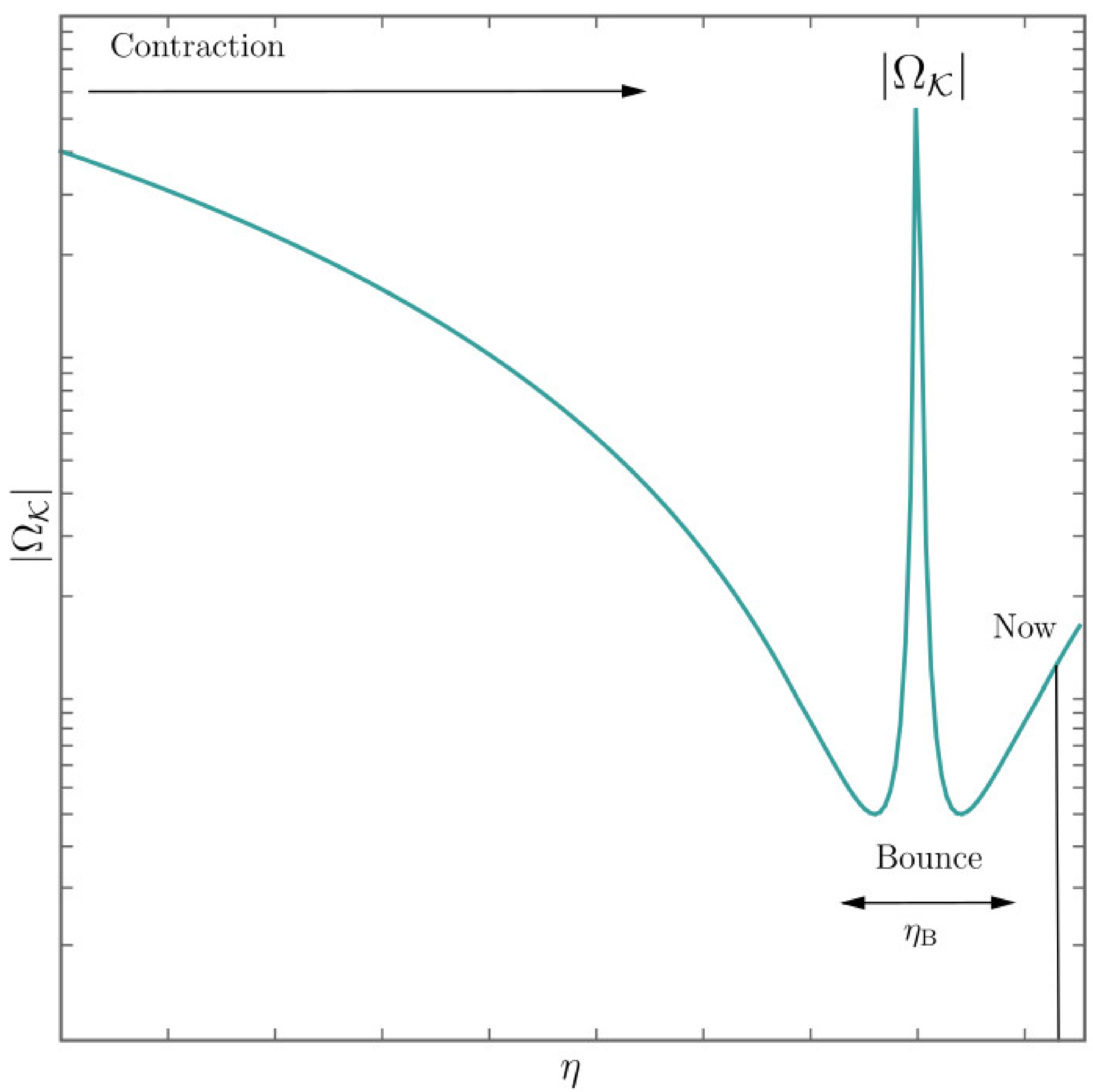
Flatness $$\frac{\mathrm{d}}{\mathrm{d}t}|\Omega-1| = -2\frac{\ddot{a}}{\dot{a}^3} \longrightarrow \ddot{a}<0 \;\&\; \dot{a}<0$$



decelerated contraction (bounce)
[accelerated expansion (inflation)]

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accelerated expansion (inflation) or decelerated contraction (bounce)

Homogeneity Large & flat Universe + low initial density + diffusion

$t_{\rm dissipation}(\lambda) \ll t_{\rm Hubble}$ enough time to dissipate any wavelength

$\Longrightarrow$ quantum vacuum fluctuations...

Implementing a bounce = problem with GR!

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

Null Energy Condition (NEC)

$$\rho + p \leq 0$$

Many working examples:
K-bounce, Ghost condensates, Galileons...?

$\Downarrow$

Instabilities

Standard questions and bouncing answers

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Isotropy Potentially problematic: model dependent

The problem with contraction: BKL/shear instability

Ricci flat Bianchi I anisotropic universe

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\sum_i \mathrm{e}^{2\theta_i(t)}\left(\mathrm{d}x^i\right)^2$$

$$\sum_i \theta_i = 0$$

Average scale factor

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

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

Friedman equations

$$H^2 = \frac{\rho}{3M_{\mathrm{P}}^2} + \frac{1}{6}\sum_i \dot{\theta}_i^2$$

$$\dot{H} = -\frac{\rho+p}{2M_{\mathrm{P}}^2} - \frac{1}{2}\sum_i \dot{\theta}_i^2$$

$$\ddot{\theta}_i + 3H\dot{\theta}_i = 0 \implies \dot{\theta}_i \propto a^{-3}$$

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

Ekpyrotic solution: $w_{\mathrm{ekp}} \gg 1$

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

Problem: regular bounce $\xrightarrow{\cancel{\text{NEC}}}$ phase with $w_{\mathrm{bounce}} < -1$

So finally...

$$\rho_{\mathrm{shear}} = \frac{M_{\mathrm{P}}^2}{2} \sum_i \dot{\theta}_i^2 \propto a^{-6} \gg \rho_{\mathrm{fluid}}$$

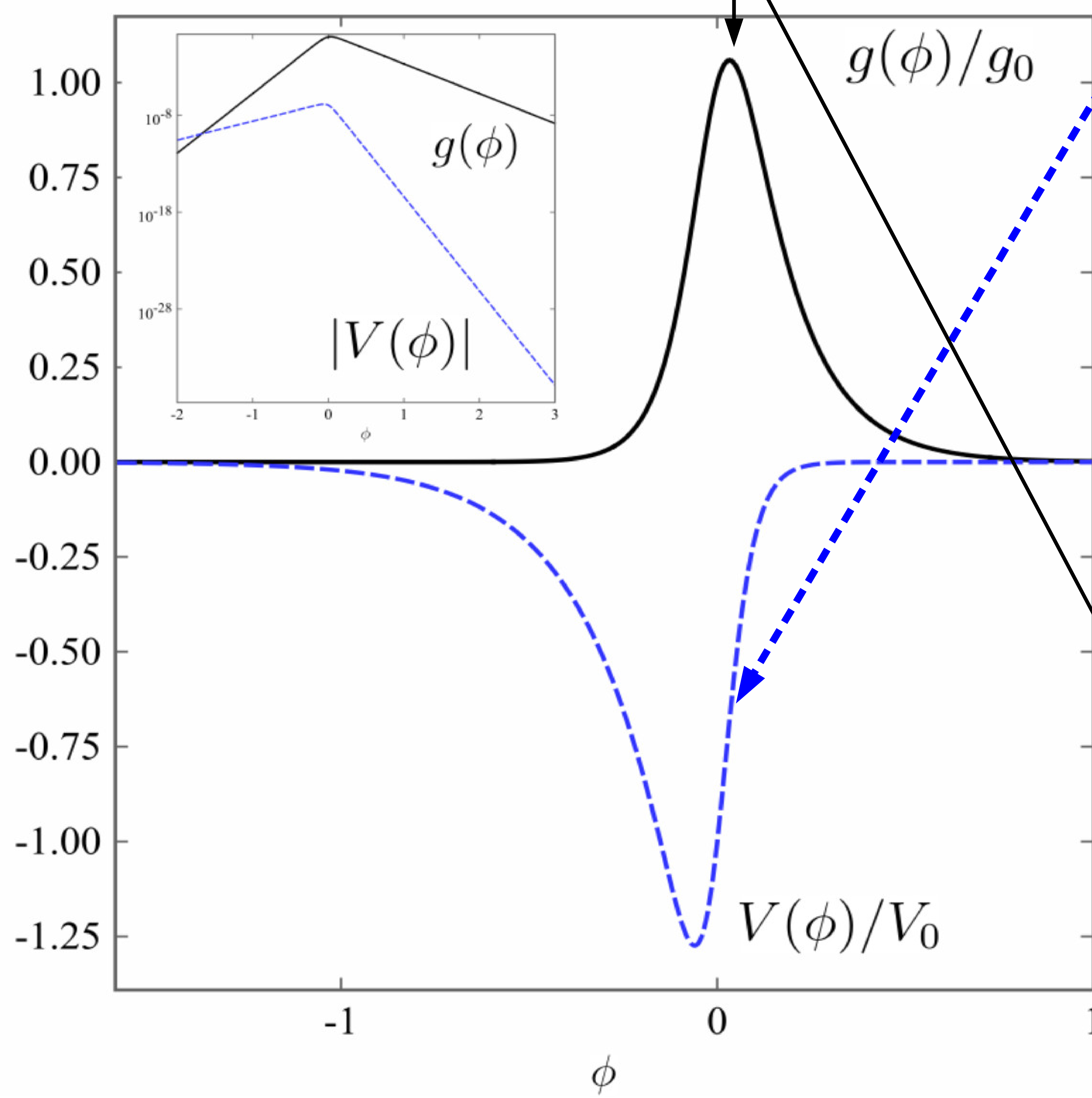
$\longrightarrow$ back to the singularity!

A nonsingular bounce model: ghost condensate & Galileon

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

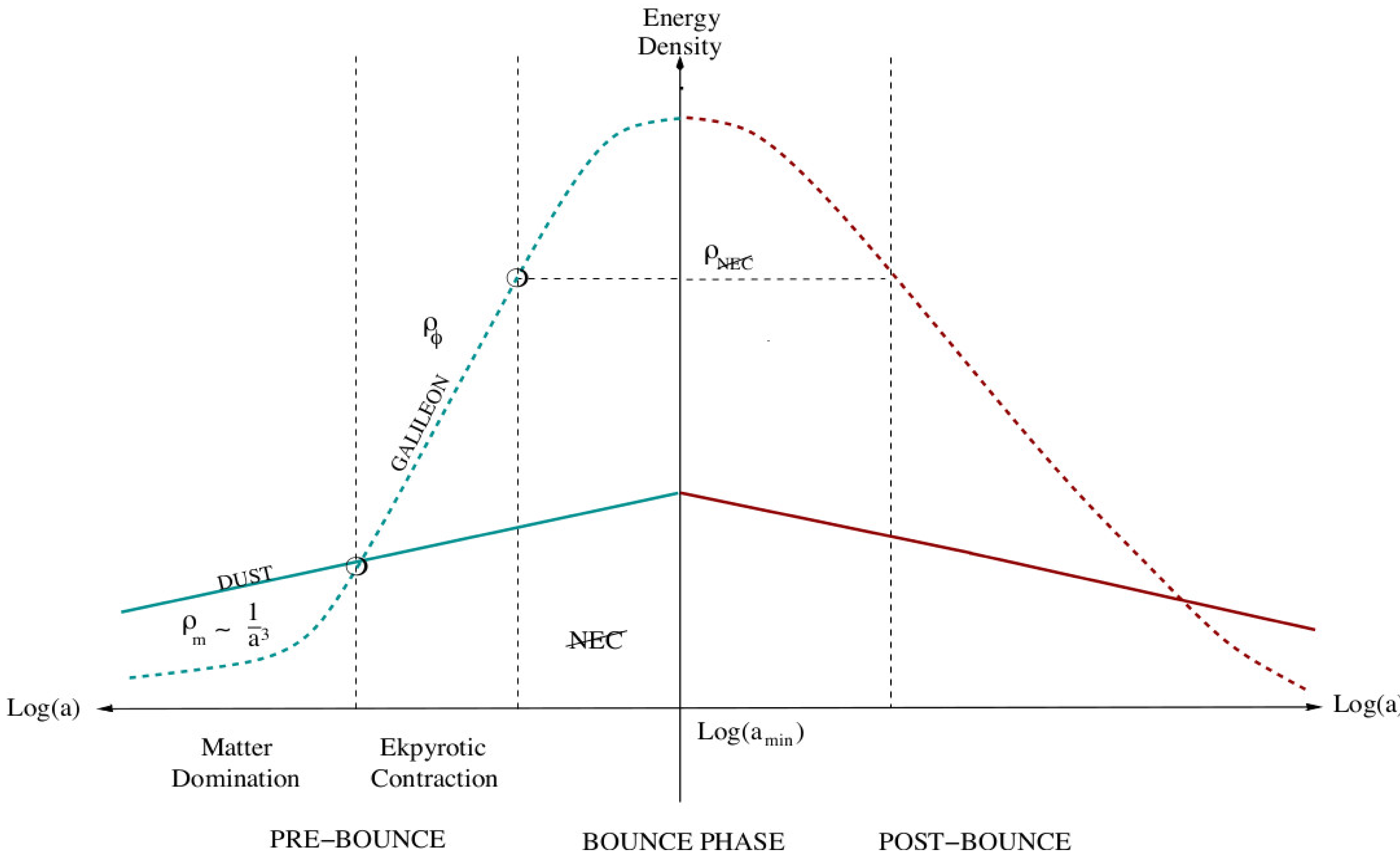
Specific choices: $K(\phi, X) = M_{\mathrm{P}}^2\left[1 - g(\phi)\right]X + \beta X^2 - V(\phi)$ kinetic term

$G(X) = \gamma X$



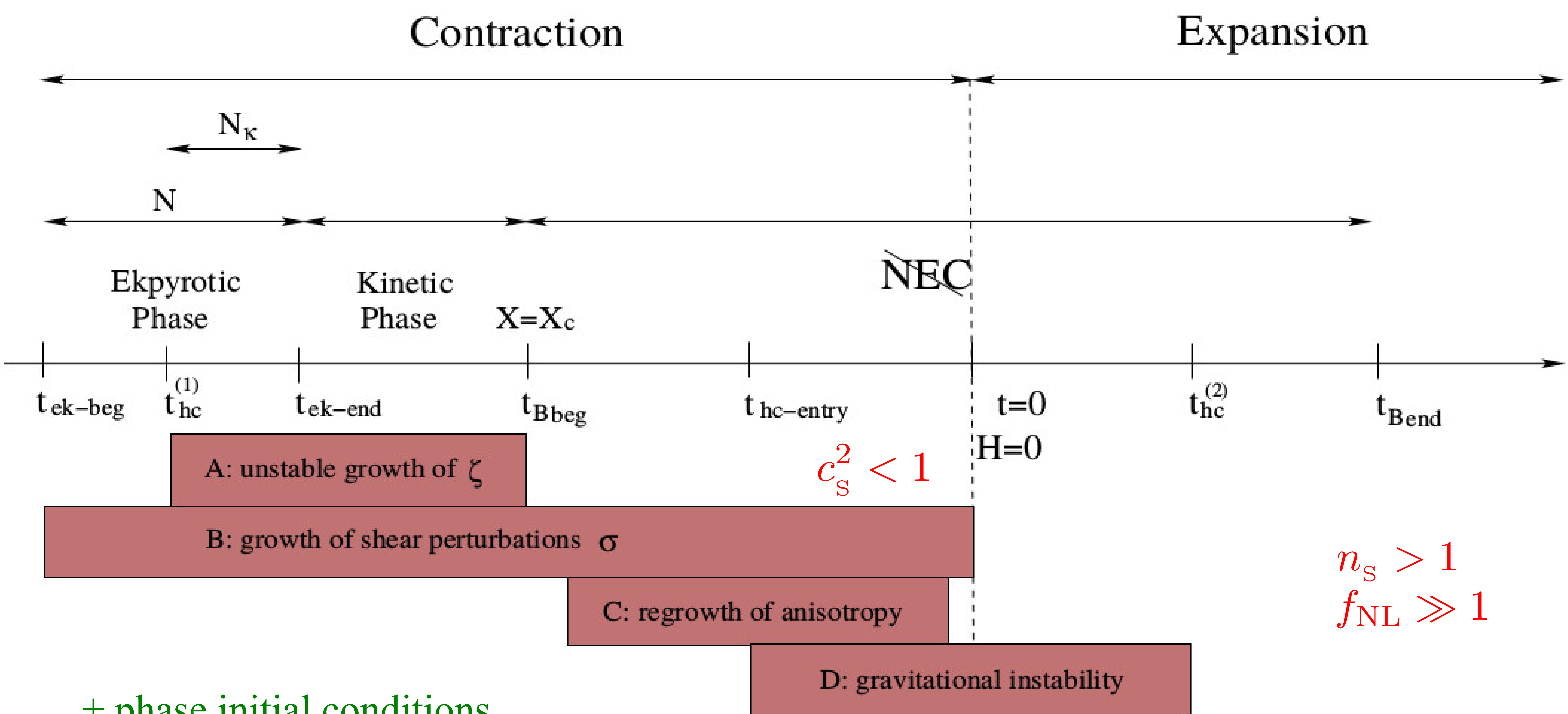
$$V(\phi) = \frac{-2V_0}{\mathrm{e}^{-\alpha_q\phi} + \mathrm{e}^{b_V\alpha_q\phi}}$$

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



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

Summary of possible problems



+ phase initial conditions

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Others dark matter/energy, baryogenesis, ...