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GRεCO

General bouncing cosmologies

Primordial Features and Non-Gaussianities

Harish-Chandra Research Institute
Allahabad - India
14/12/10

Problems:

Singularity

Horizon

Flatness

Homogeneity

Perturbations

Dark matter

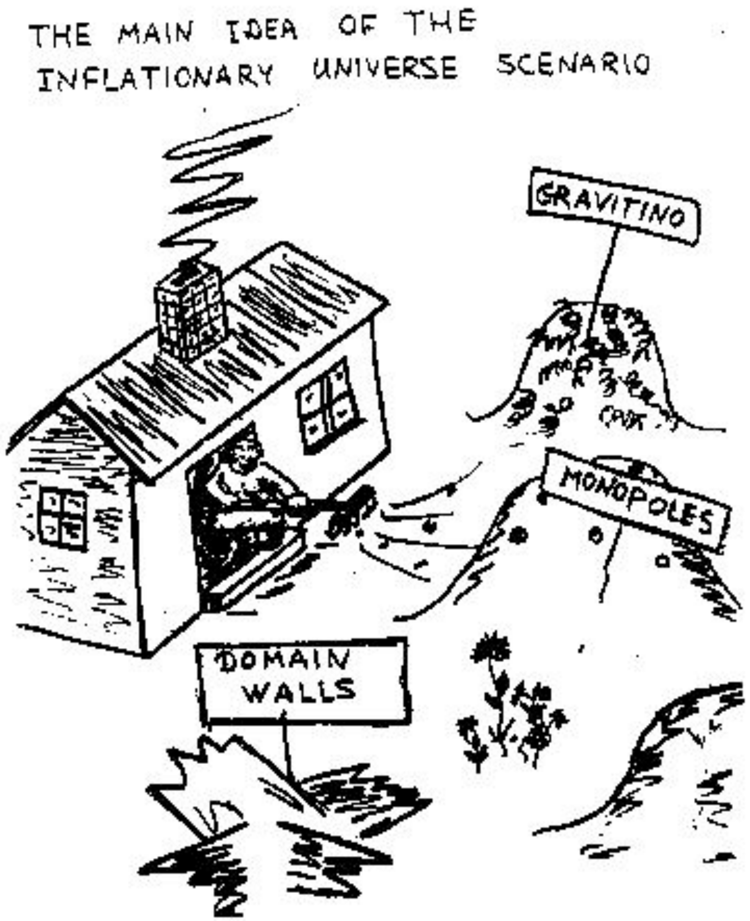
Dark energy / cosmological constant

Baryogenesis

...

Accepted solution = INFLATION

Topological defects (monopoles)



(Linde's book)

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, ...)**

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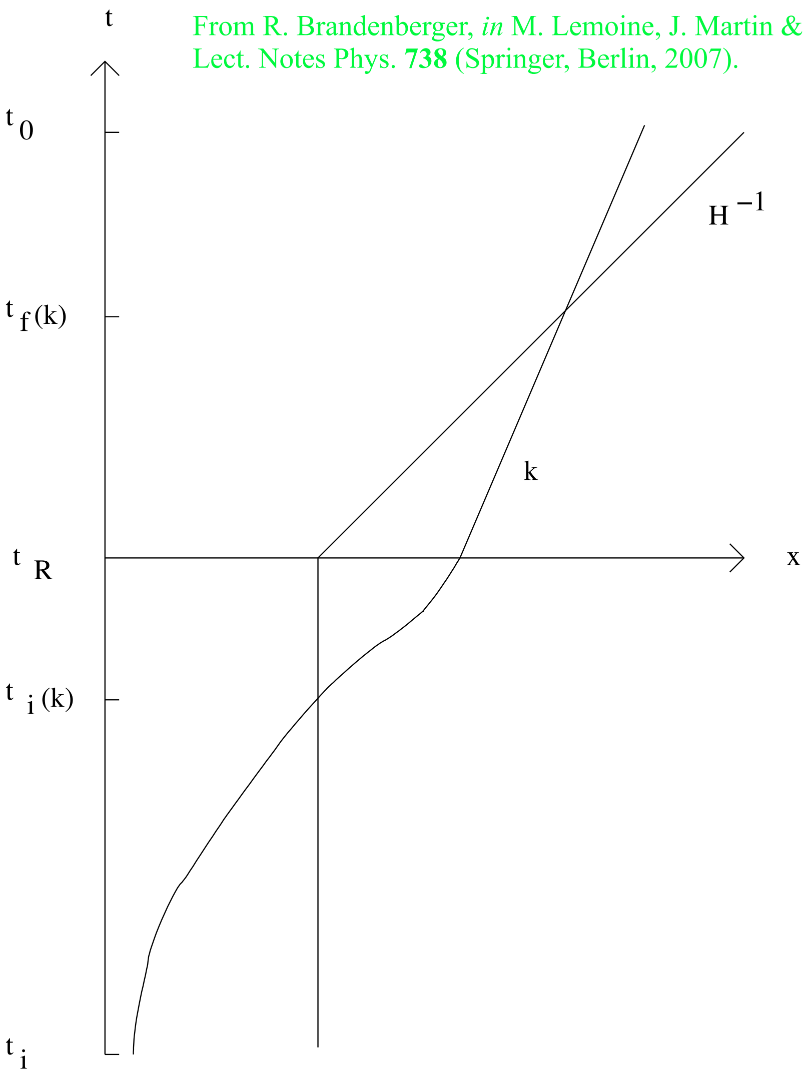
Alternative model???



- Scalar field origin?
- 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?**

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

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- string based ideas (PBB, other brane models, string gas, …)
- Quantum gravity / cosmology
- purely classical theory
- 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)

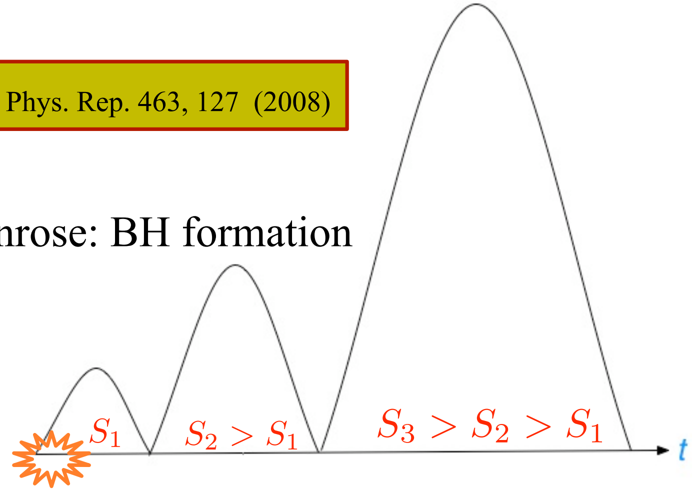
...

- 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)

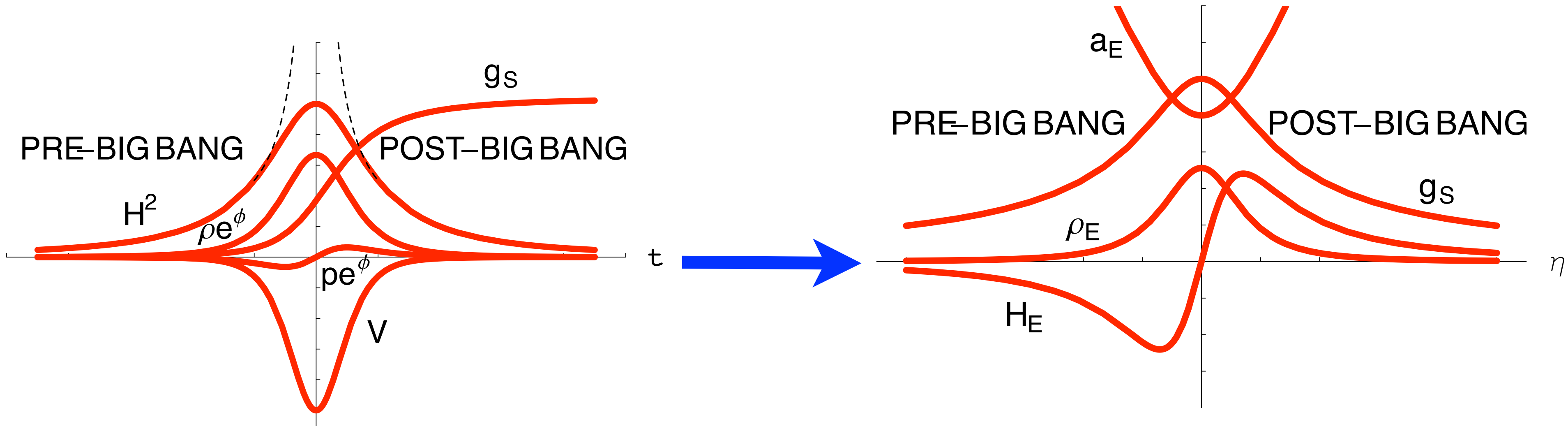
- Penrose: BH formation



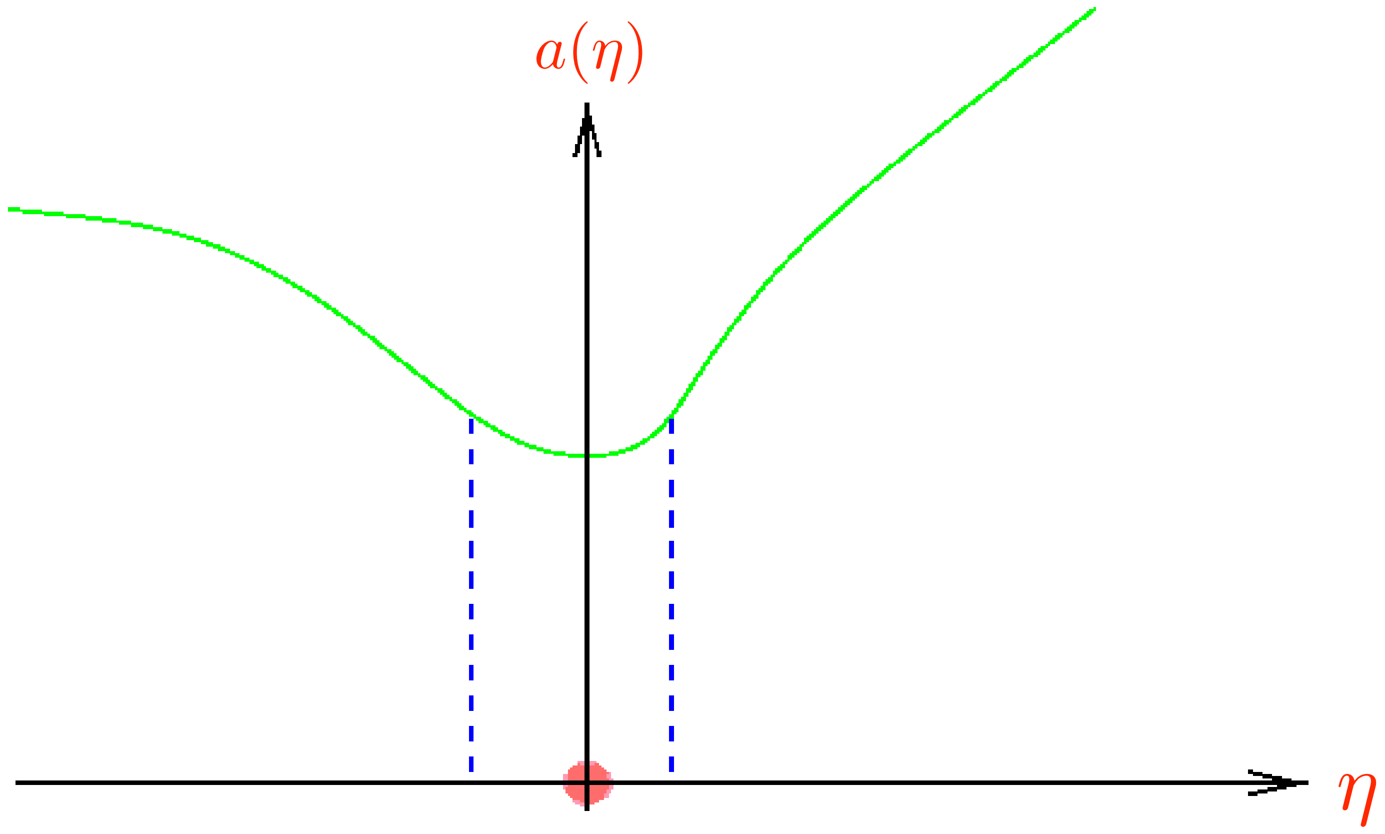
Quantum nucleation?

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

Pre Big Bang scenario: (cf. M.Gasperini & G. Veneziano, arXiv: hep-th/0703055)



string frame   Einstein frame

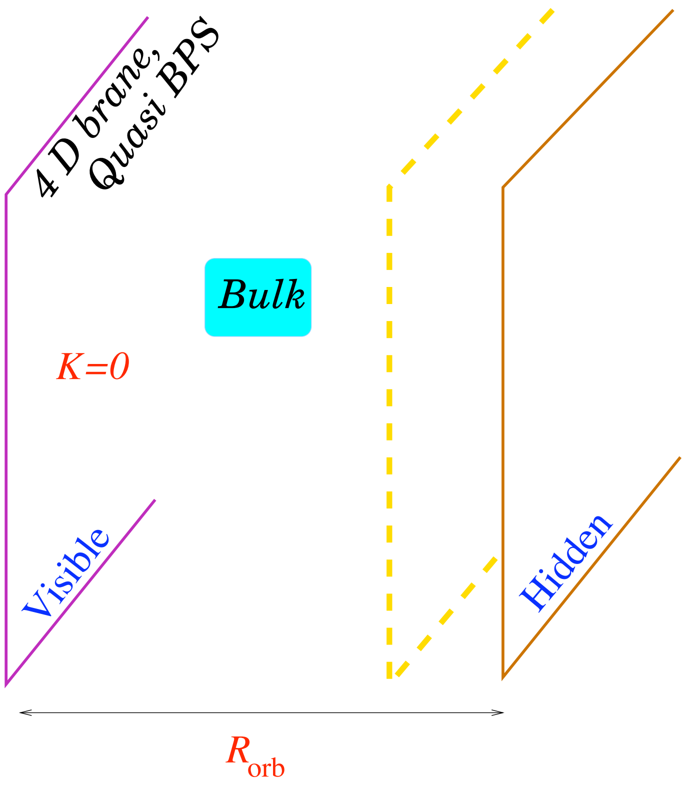

$a(\eta)$
η

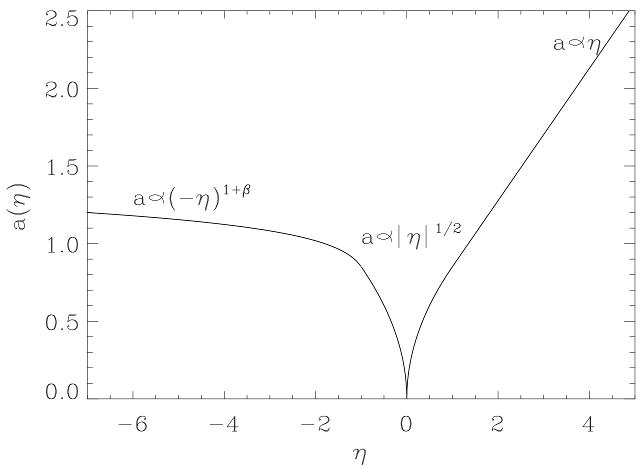
Ekpyrotic/cyclic scenario:

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

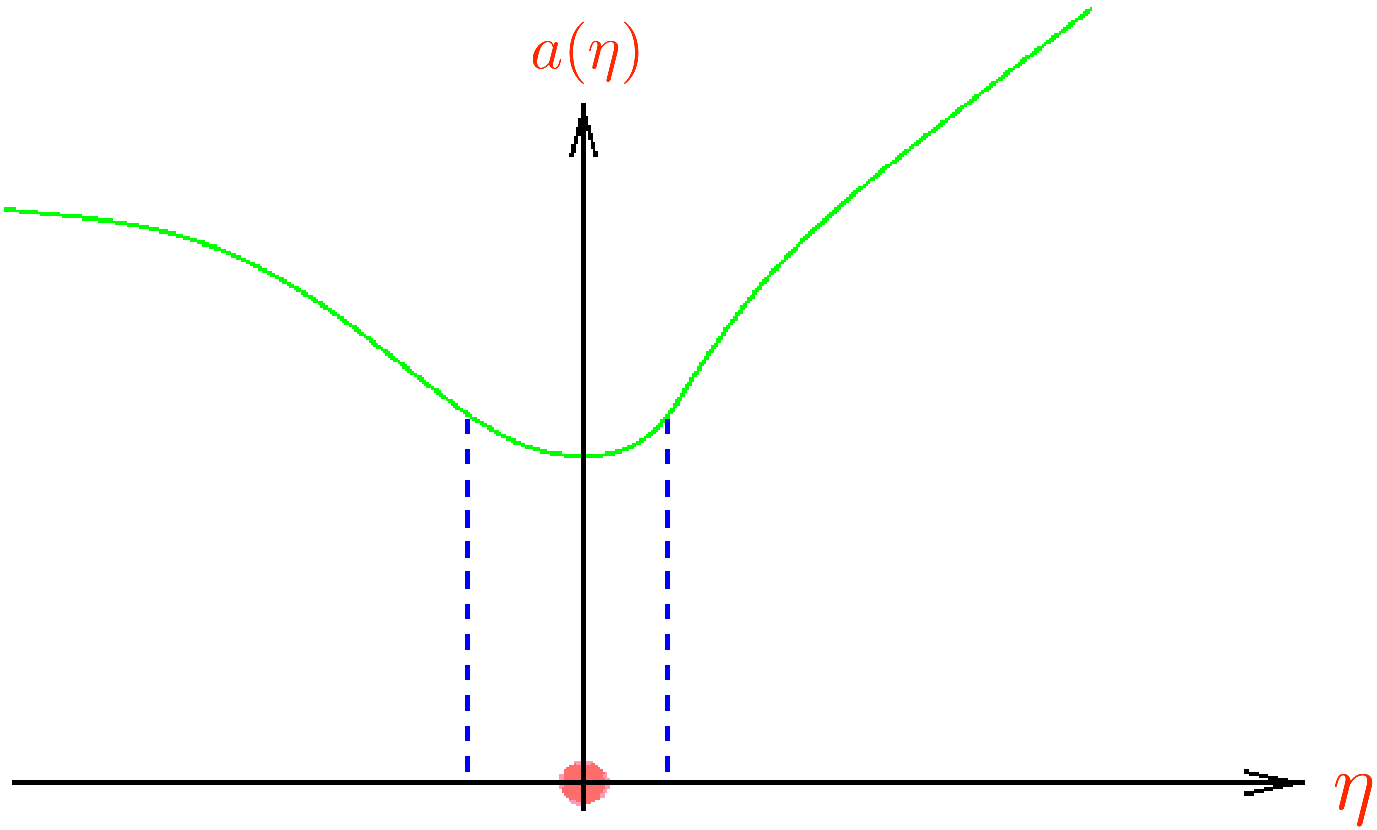
$$\mathcal{S}_4 = \int_{\mathcal{M}_4} \mathrm{d}^4x\sqrt{-g_4}\left[\frac{R_{(4)}}{2\kappa} - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

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





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

Standard puzzles and some (bouncing) solutions

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- Horizon
- Flatness
- Homogeneity
- Perturbations
- Others

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

  accelerated expansion (inflation) or decelerated contraction (bounce)
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  $\frac{t_{\rm dissipation}}{t_{\rm Hubble}} \propto \frac{\lambda}{R_{\rm H}^{1/3}} \left(1 + \frac{\lambda}{A R_{\rm H}^2}\right)$ enough time to dissipate any wavelength

  $\Longrightarrow$ vacuum state!
- **Perturbations**
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- **Perturbations** — see coming slides
- **Others** — dark matter/energy, baryogenesis, ...

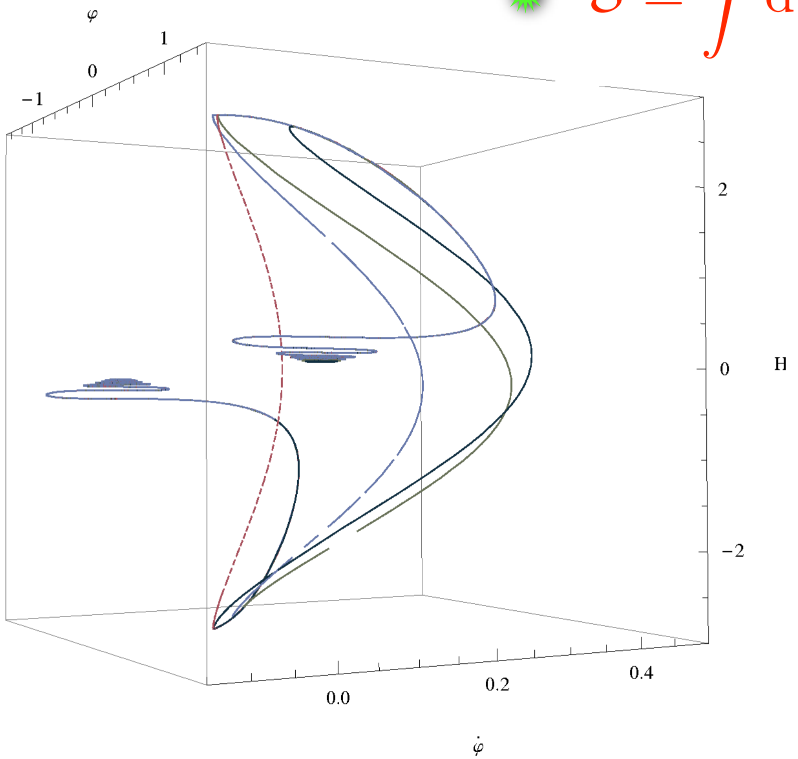
Self consistent bounce:

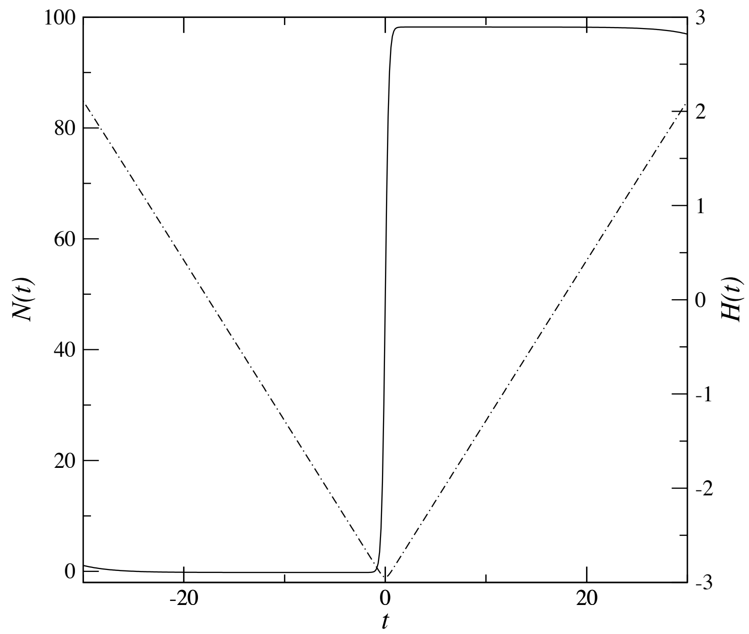
$$\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\left(\frac{\mathrm{d}r^2}{1-\mathcal{K}r^2} + r^2\mathrm{d}\Omega^2\right)$$

→ One d.o.f. + 4 dimensions G.R.

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{6\ell_{\mathrm{Pl}}^2} - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)\right]$$

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\varphi}^2 + V\right) - \frac{\mathcal{K}}{a^2}$$ Positive spatial curvature





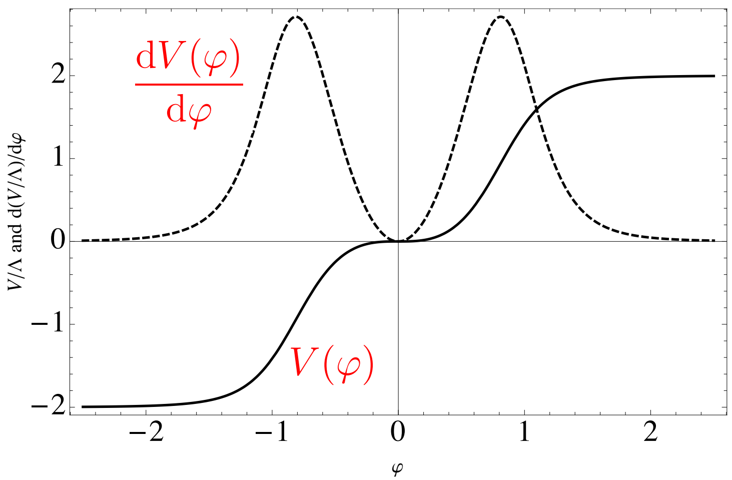
F. Falciano, M. Lilley & P. P., *Phys. Rev.* **D77**, 083513 (2008)

Influence of the spatial curvature?

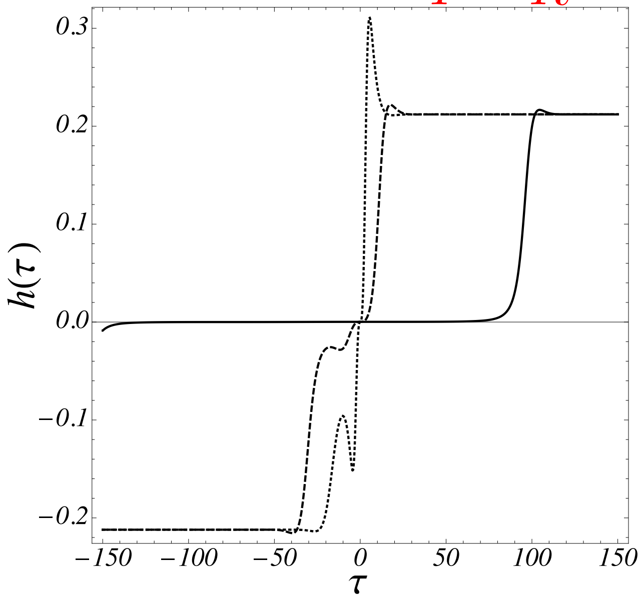
→ Modify GR to non singular theories (curvature invariants)

$$\mathcal{S} = \frac{1}{16\pi G_{\mathrm{N}}} \int \mathrm{d}^4x \sqrt{-g} \left[R + \sum_{i=1}^{N} \varphi_i I^{(i)} - V(\varphi) \right] \quad \Longrightarrow \quad \frac{\mathrm{d}V}{\mathrm{d}\varphi} = I$$

R. Brandenberger, V. F. Mukhanov and A. Sornborger, *Phys. Rev.* **D48**, 1629 (1993)



$$I = R - \sqrt{3\left(4R_{\mu\nu}R^{\mu\nu} - R^2\right)}$$



R.Abramo, P. P. & I. Yasuda, *Phys. Rev.* **D81**, 023511 (2010)

K-bounce: $\mathcal{L} = p(X, \varphi)$

$$X \equiv \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$$

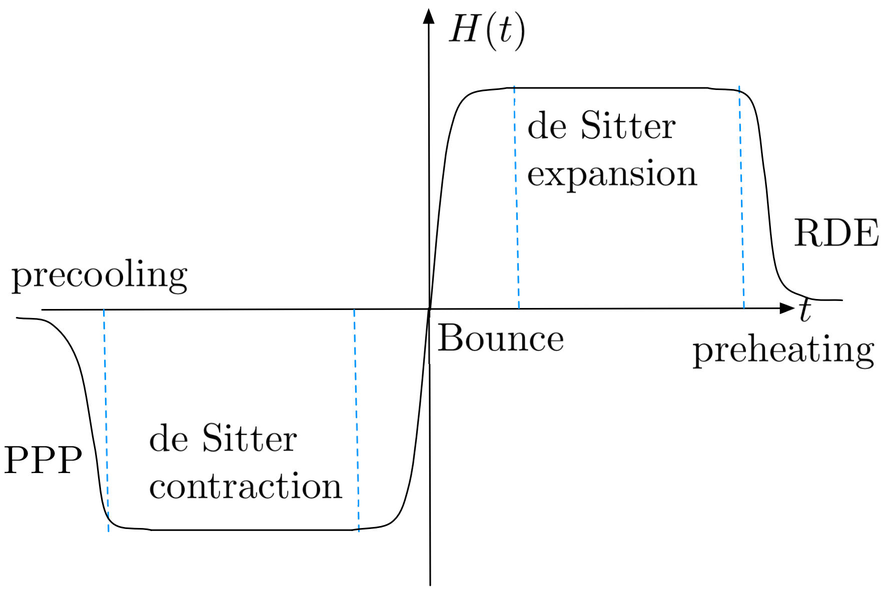
$$\Longrightarrow \quad T^{\mu\nu} = (\rho + p)\, u^\mu u^\nu - p g^{\mu\nu}$$

$$\rho \equiv 2X \frac{\partial p}{\partial X} - p$$

$$u_\mu \equiv \frac{\partial_\mu \varphi}{\sqrt{2X}}$$

vanishing spatial curvature possible in 4 dimensions G.R.?

$$\rho\left(t_{\text{bounce}}\right) = 0 \Longrightarrow p\left(t_{\text{bounce}}\right) < 0$$



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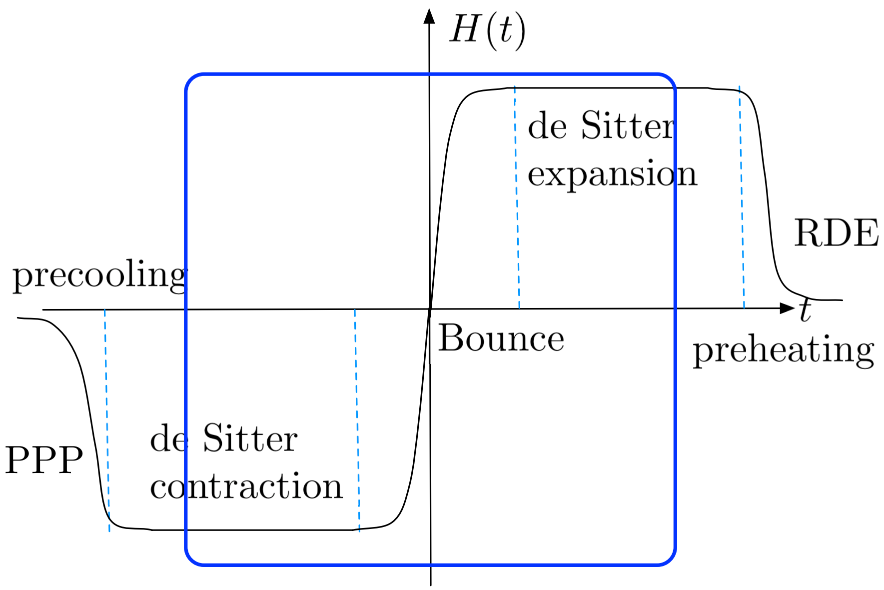
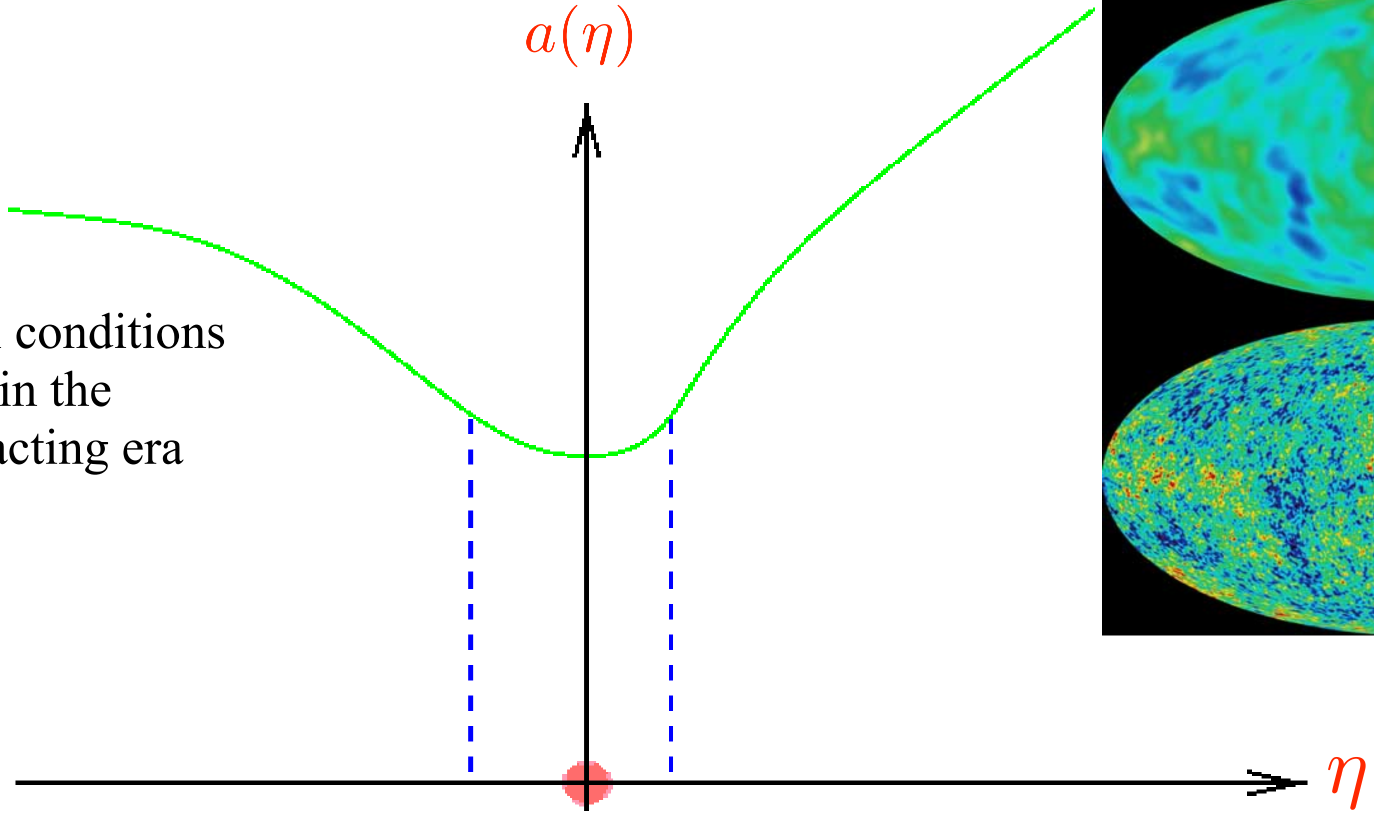
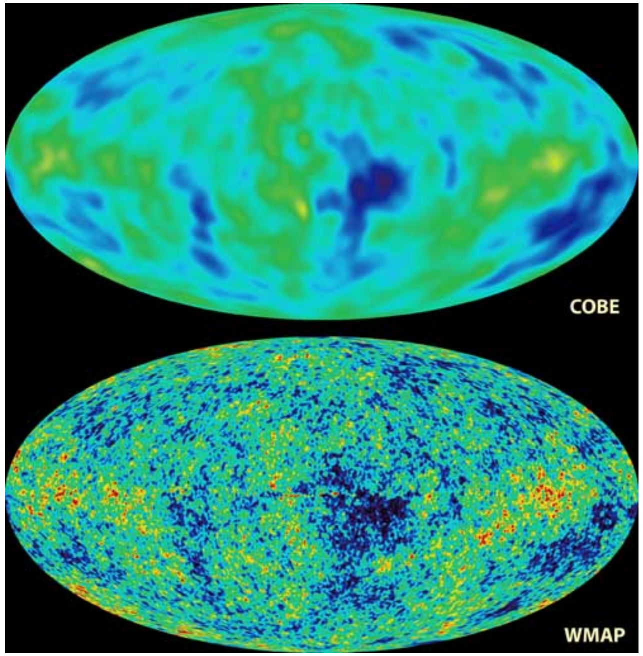


Perturbations: $$\mathrm{d}s^2 = a^2(\eta)\left\{(1+2\Phi)\,\mathrm{d}\eta^2 - \left[(1-2\Phi)\,\gamma_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}$$



Initial conditions
fixed in the
contracting era



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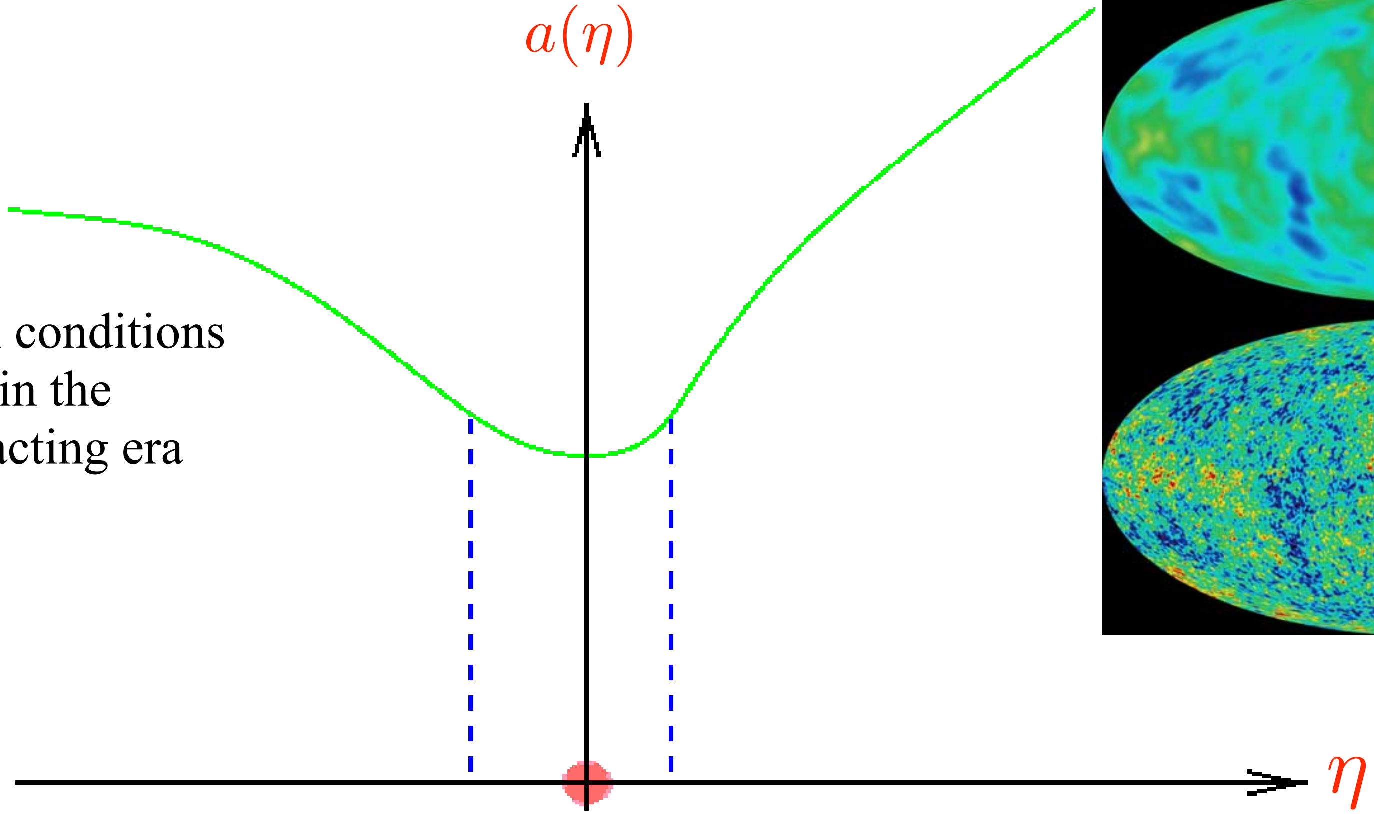

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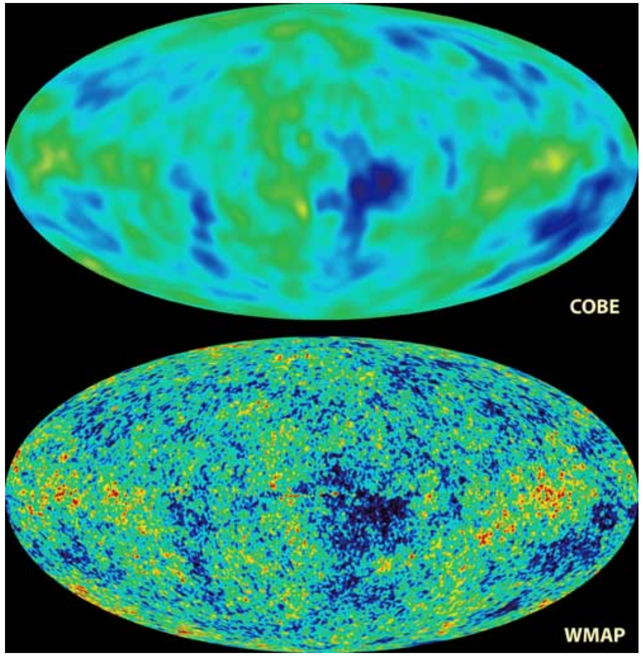

???????

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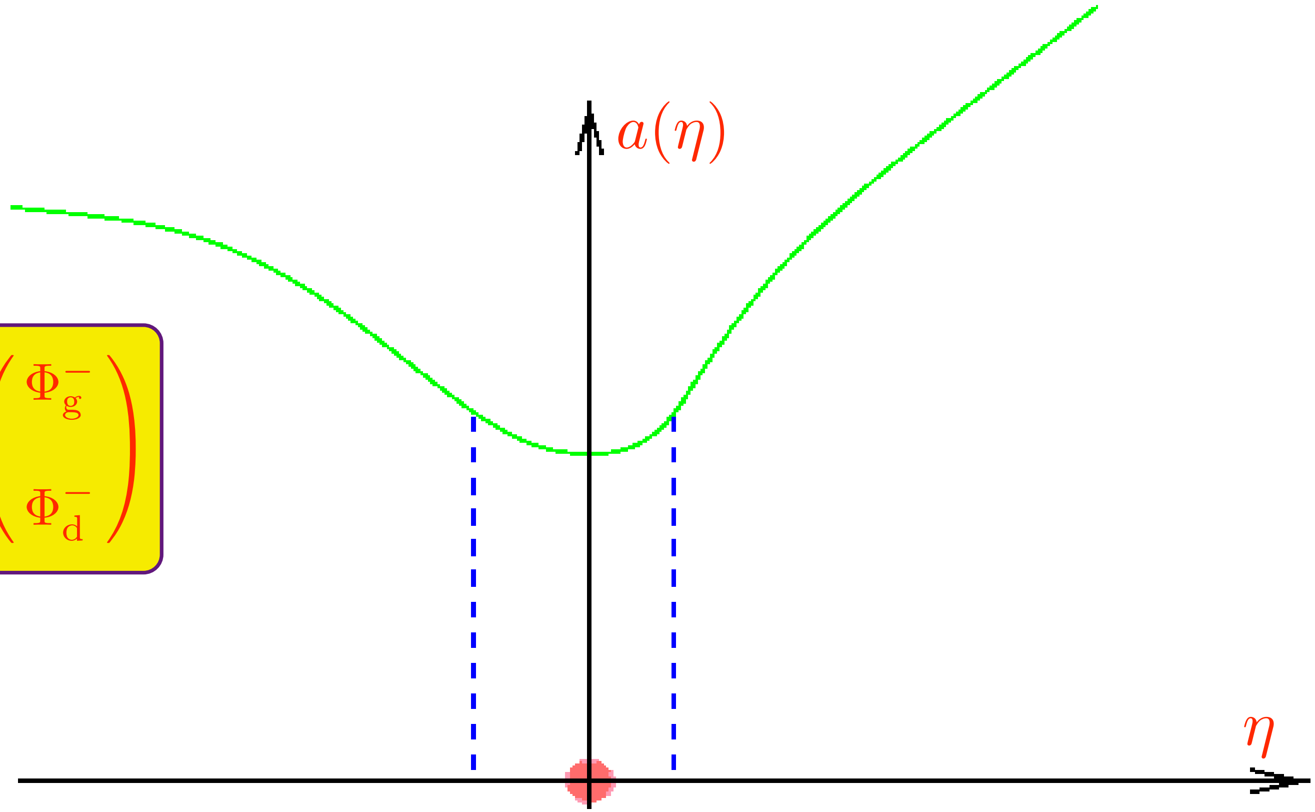
$$\begin{pmatrix} \Phi_{\mathrm{g}}^{+} \\ \Phi_{\mathrm{d}}^{+} \end{pmatrix} = \mathbf{T}_{ij}(k) \begin{pmatrix} \Phi_{\mathrm{g}}^{-} \\ \Phi_{\mathrm{d}}^{-} \end{pmatrix}$$



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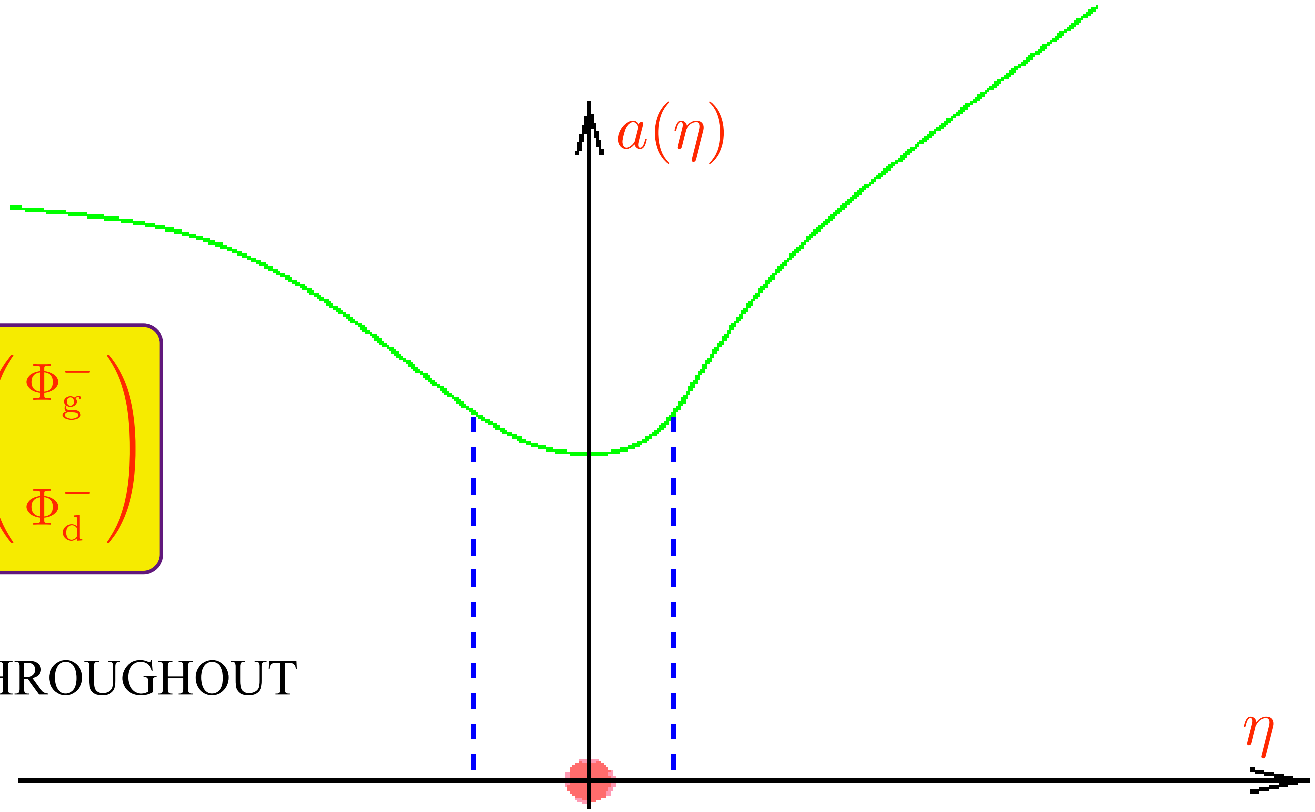

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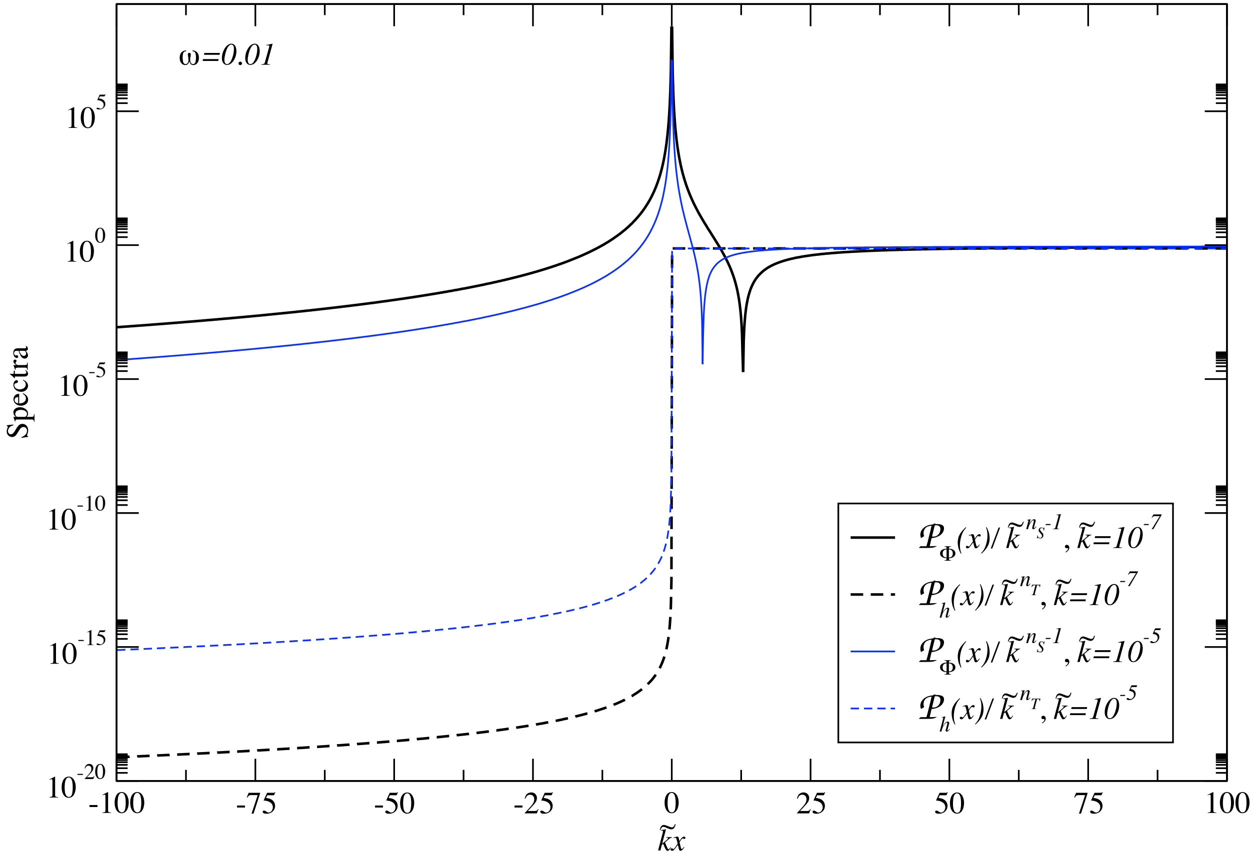
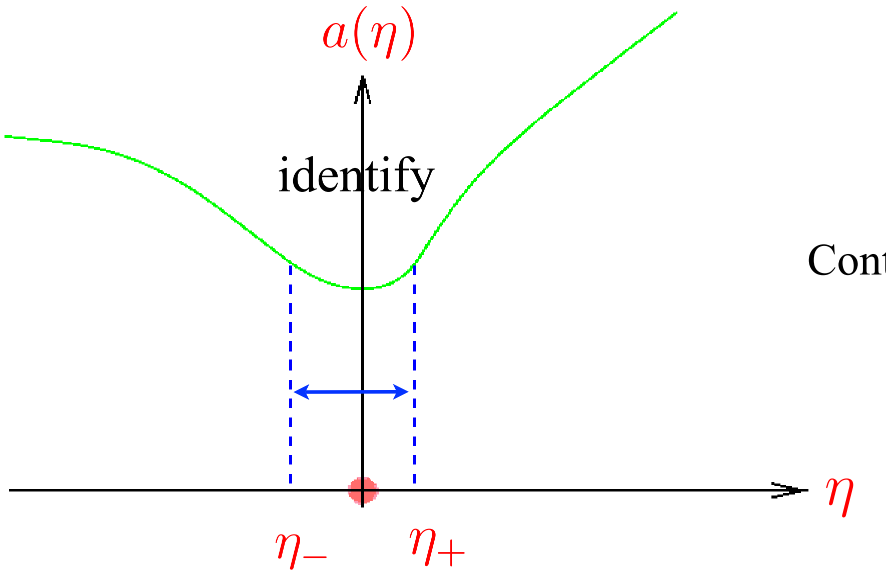
ASSUME LINEARITY THROUGHOUT

A potential problem with bouncing cosmologies: Does linear perturbation theory still make sense?

$|\Phi_k| \gg 1$



A generic model-independent treatment of the bounce phase?



Geometric matching conditions?

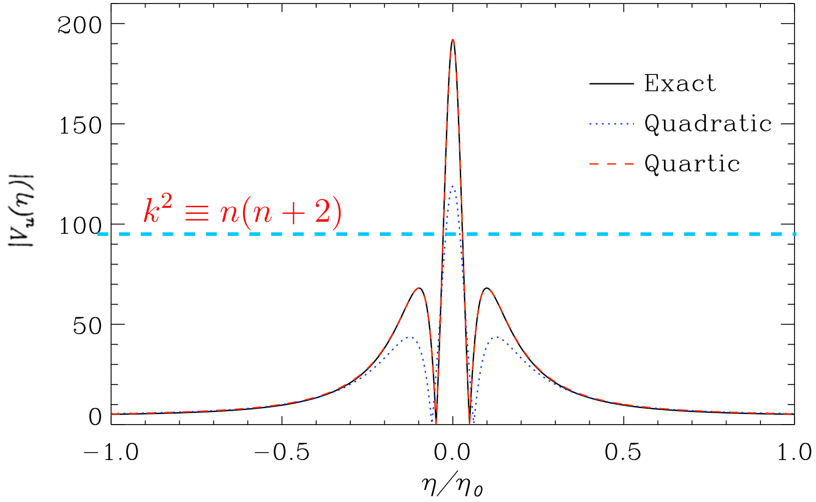
Continuity of metric	$[a]_\pm = 0$	OK
Continuity of extrinsic curvature	$[H]_\pm = 0$	???
Perturbations?	$[\zeta]_\pm = 0$	???

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

$\Longleftrightarrow$ $$\Phi = \frac{3\mathcal{H}u}{2a^2\theta} \qquad \theta \equiv \frac{1}{a}\sqrt{\frac{\rho_\varphi}{\rho_\varphi + p_\varphi}\left(1 - \frac{3\mathcal{K}}{\rho_\varphi a^2}\right)}$$

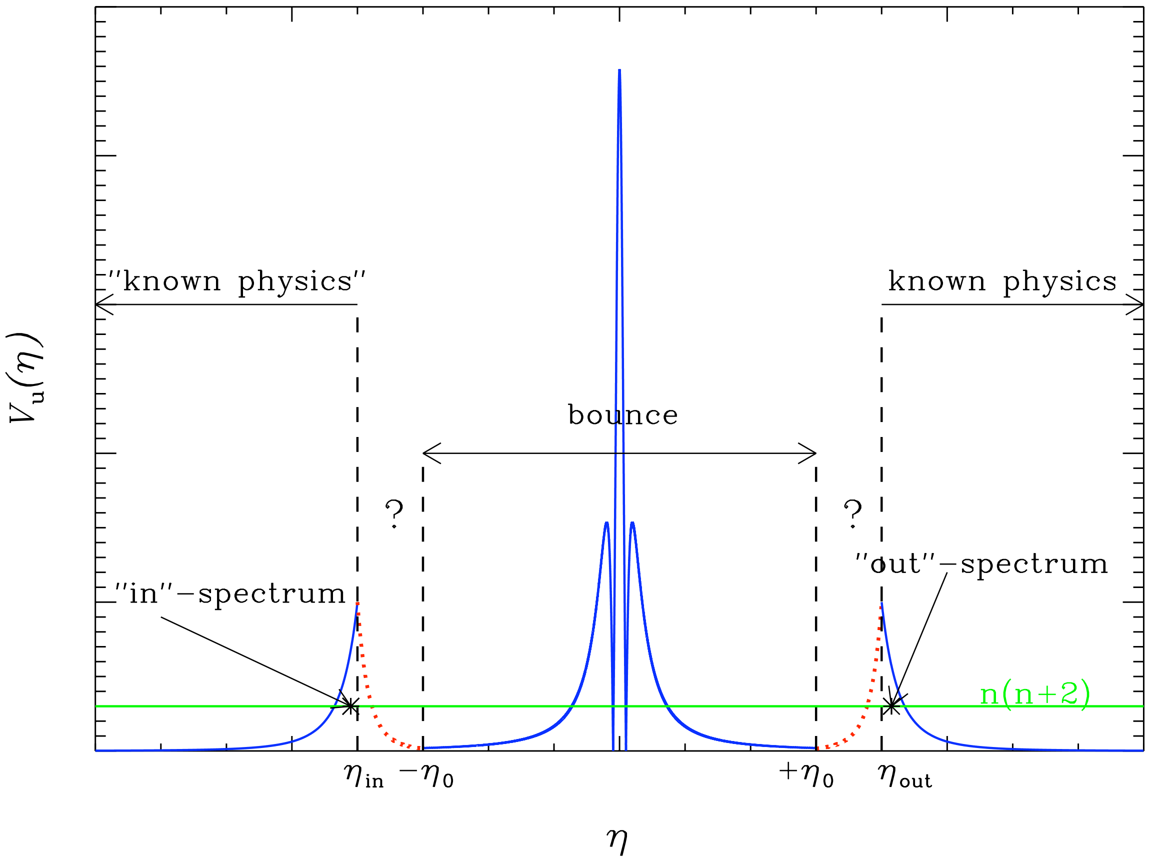
$$u'' + \left[k^2 - \frac{\theta''}{\theta} - 3\mathcal{K}\left(1 - c_{\mathrm{S}}^2\right)\right]u = 0$$

$$V_u(\eta) \equiv \frac{\theta''}{\theta} + 3\mathcal{K}(1 - c_{\mathrm{S}}^2) = \frac{P_{24}(\eta)}{Q_{24}(\eta)},$$



Non trivial transfer matrix

$$\boldsymbol{T}_{ij}(k) = \begin{bmatrix} A(k) & B(k) \\ C(k) & D(k) \end{bmatrix}$$



Actual shape depends on the microscopic parameters

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

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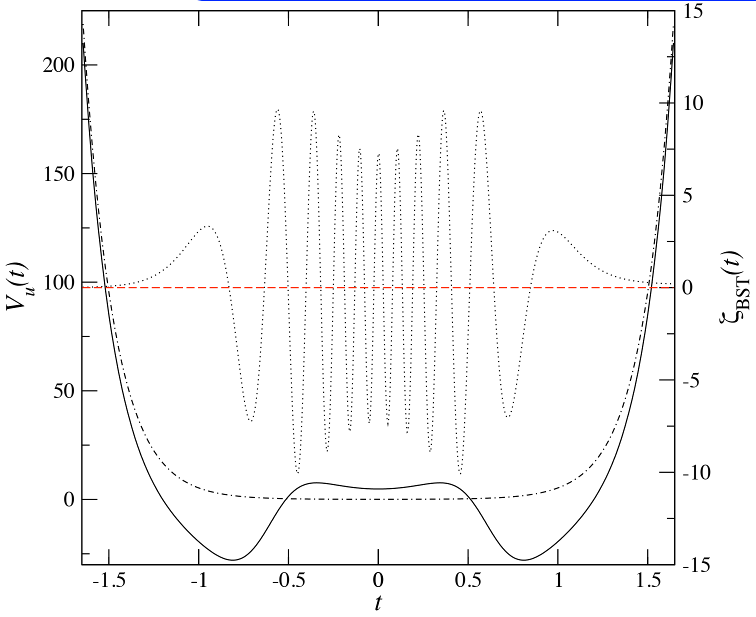
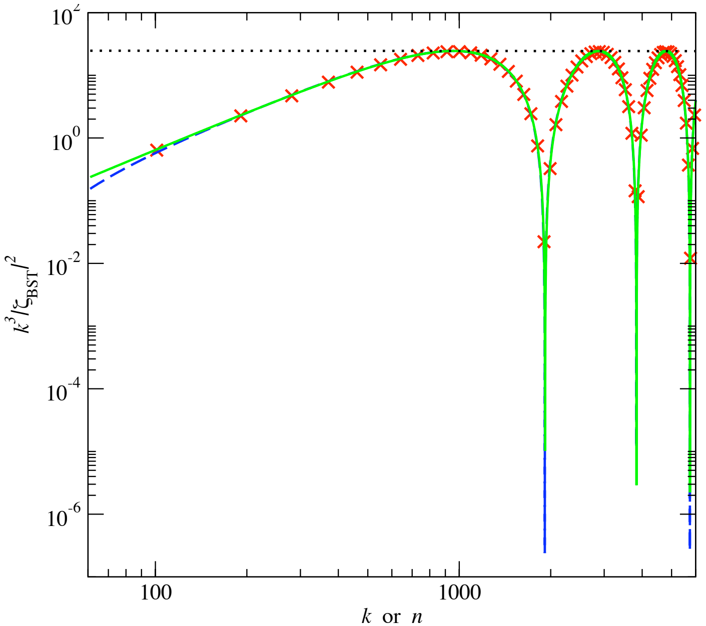
$$u'' + \left[k^2 - \frac{\theta''}{\theta} - 3\mathcal{K}\left(1 - c_{\mathrm{S}}^2\right)\right]u = 0$$

$$\mathcal{P}_\zeta = \mathcal{A}k^{n_{\mathrm{S}}-1}\cos^2\left(\omega\frac{k_{\mathrm{ph}}}{k_\star} + \psi\right)$$



Different parameters

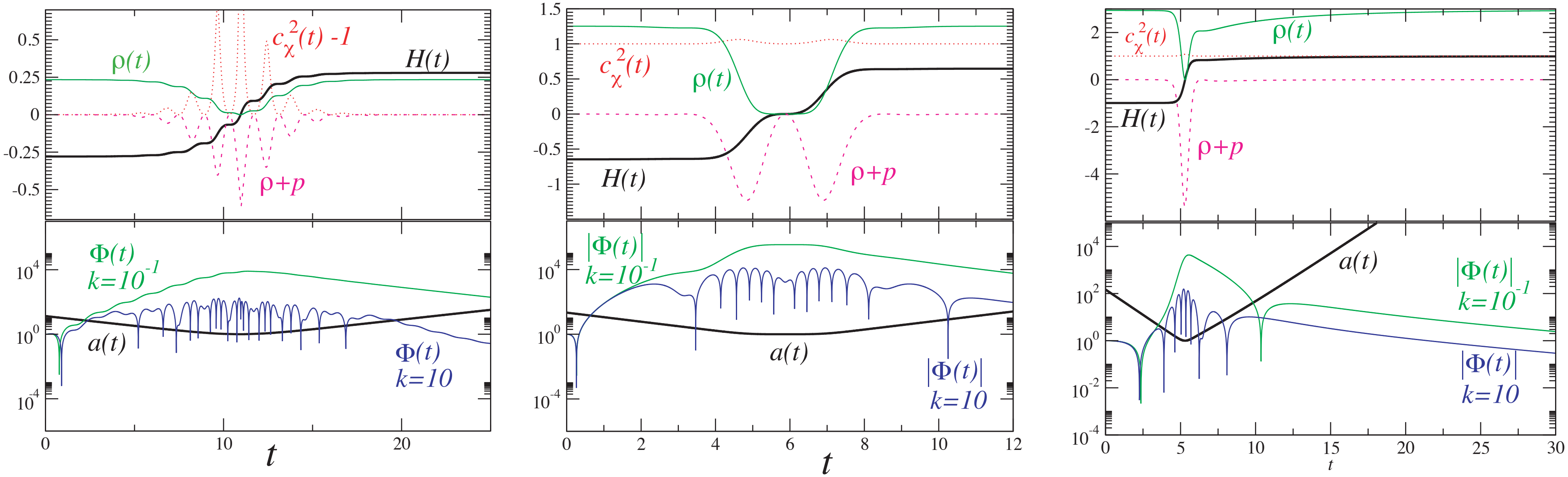
primordial spectrum →



More on this: cf. M. Lilley's talk tomorrow!

Model for the bounce phase only:

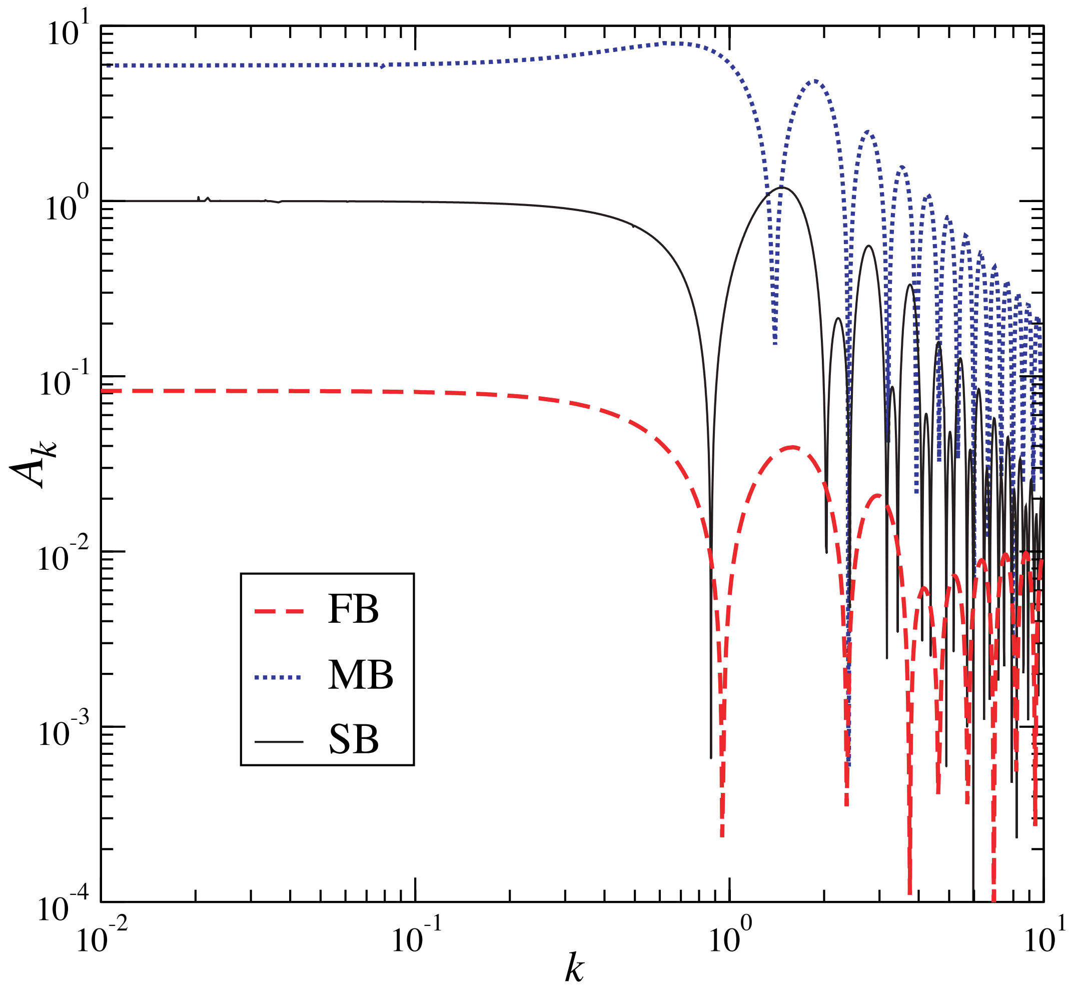
$$p = p_0 + p_X(X - X_0) + p_\varphi \varphi + p_{X\varphi}\varphi(X - X0) + \frac{1}{2}p_{XX}(X - X_0)^2 + \frac{1}{2}p_{\varphi\varphi}\varphi^2 + \cdots$$



Slow Fast

Oscillations + ζ conserved

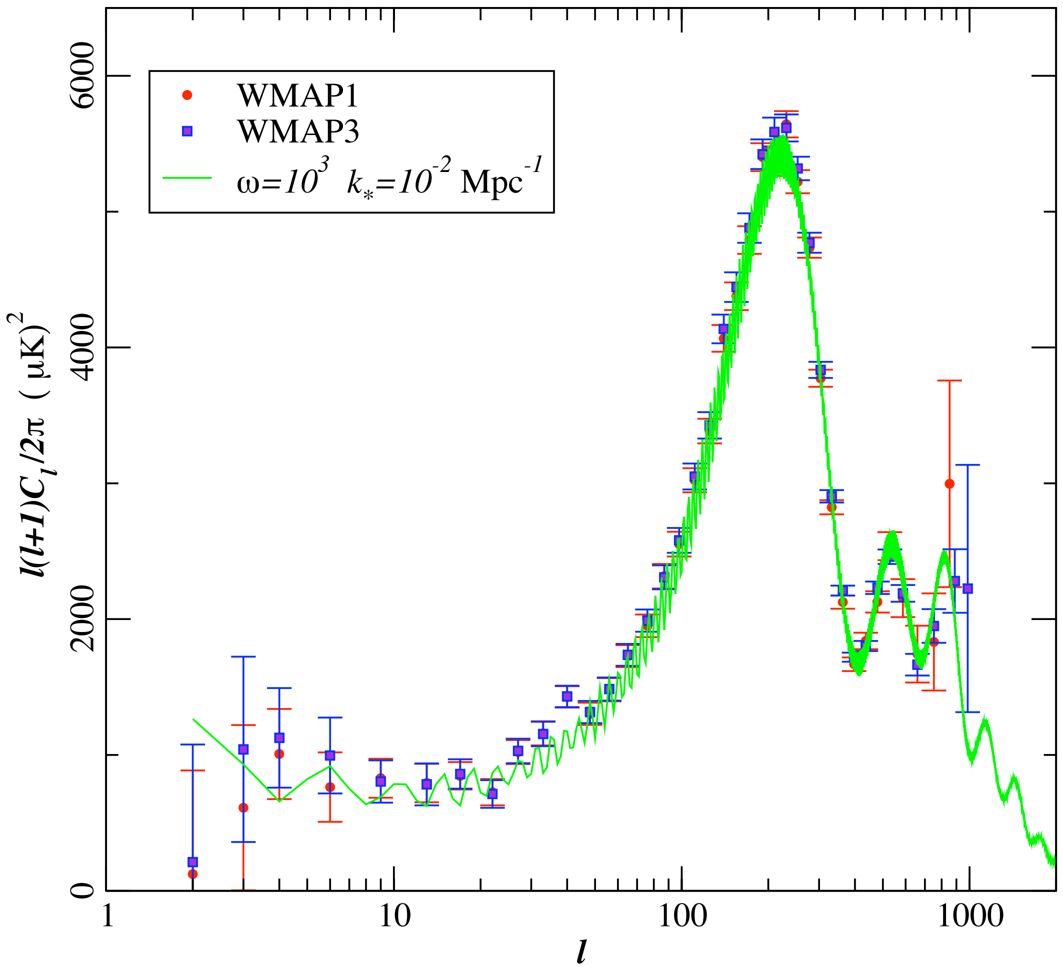
R. Abramo & P. P., *JCAP* **09**, 001 (2007)



k-mode mixing ...

Features ...

Figure provided by C. Ringeval



F. Falciano, M. Lilley & P. P., *Phys. Rev.* **D77**, 083513 (2008)

Bouncing cosmology!

- New solutions to old puzzles
- No singularity

- G.R. ...

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monopoles = ???

Dark energy ...

Model dependence ...

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$$\omega = 0 \quad \Longleftrightarrow \quad n_{\rm s} = 1$$

matter bounce = contraction phase dominated by dust

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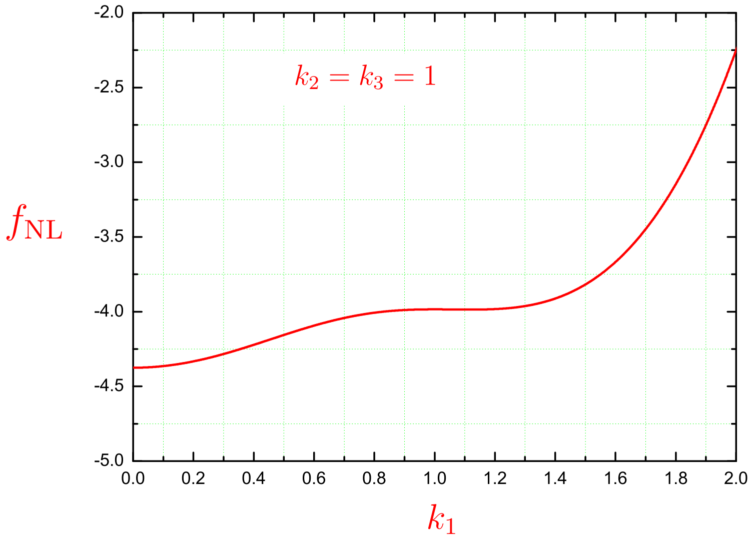

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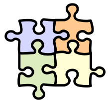

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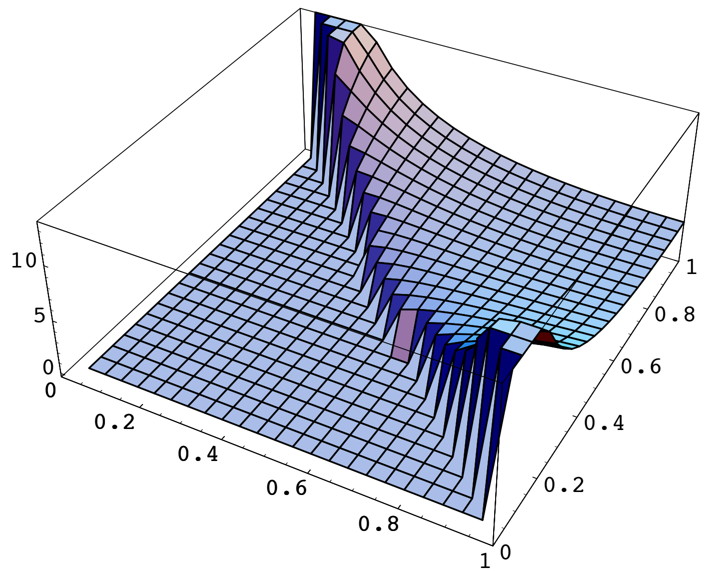

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शुक्रिया

Thank you for your attention!

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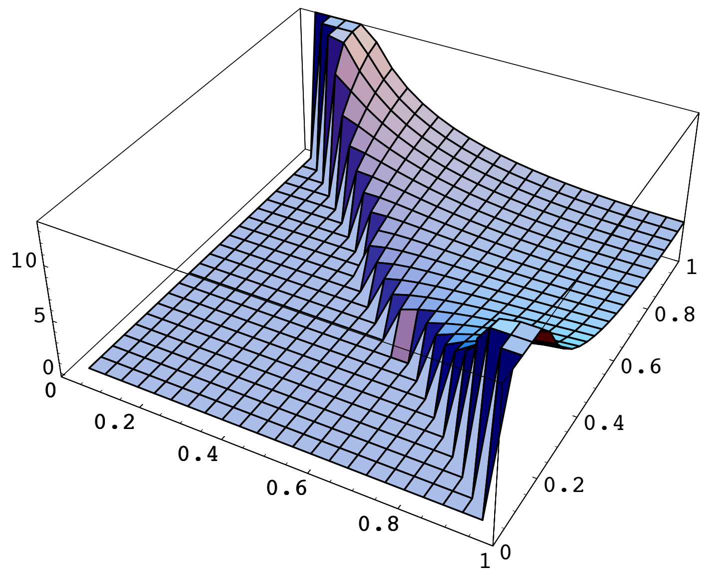

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