Cosmology with a Bounce

Paul Steinhardt, Princeton

KITP
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The Cyclic Universe

w/ N. Turok

Big bang
Radiation domination
Matter domination
Dark energy
Ekpyrotic contraction
Big crunch

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causal horizon problem

flatness problem

J. Khoury, B. Ovrut, PJS, N. Turok

The Cyclic Universe

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Big bang
Radiation domination
Matter domination
Dark energy
Ekpyrotic contraction (w > 1)
Big crunch

causal horizon problem

flatness problem

$$H^2 = \frac{8\pi G}{3}\left(\frac{\rho_m^0}{a^3} + \frac{\rho_r^0}{a^4} + \dots\right) + \frac{\sigma^2}{a^6} - \frac{k}{a^2} + \Lambda$$

$$+\frac{8\pi G}{3}\frac{\rho_\phi^0}{a^{3(1+w)}}$$

The Cyclic Universe

w/ N. Turok

Big bang

Radiation domination ($w \sim 2/3$)

Matter domination ($w \sim 0$)

Dark energy ($w \sim -1$)

Ekpyrotic contraction ($w >> 1$)

Big crunch ($w \rightarrow +1$)

The Cyclic Universe

w/ N. Turok

Big bang

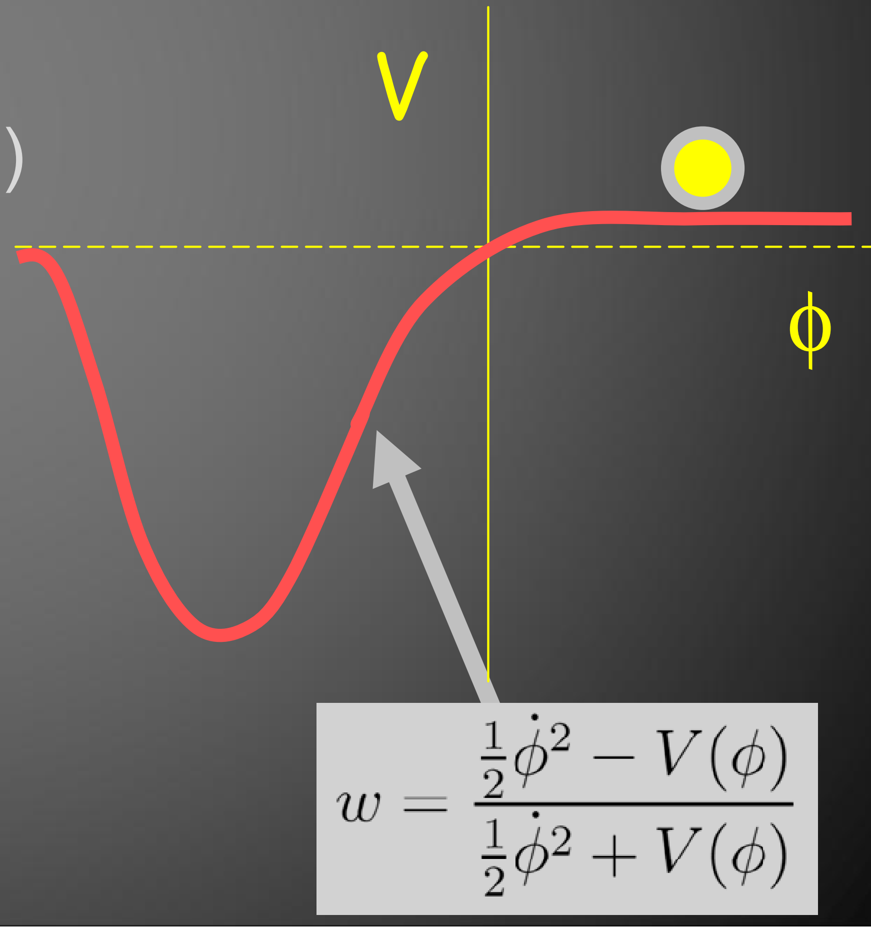
Radiation domination (w ~ 2/3)

Matter domination (w ~ 0)

Dark energy (w ~ -1)

Ekpyrotic contraction (w >> 1)

Big crunch (w → +1)



Quantum Physics & Density Perturbations

Scalar fields with steep potentials (w >> 1)
obtain scale invariant spectrum of quantum fluctuations

$$\mathcal{S} = \int \mathrm{d}^4x \left(-\frac{1}{2}(\partial\phi)^2 + V_0 e^{-c\phi} \right)$$

$$\phi \rightarrow \phi + \epsilon$$

$$x^\mu \rightarrow x^\mu e^{c\epsilon/2}$$

⇨ $$\mathcal{S} \rightarrow e^{c\epsilon}\,\mathcal{S}$$ ⇨ $$\phi_b = (2/c)\ln(-At)$$

scale-free background solution

N.B. non-gravitational mechanism

Converting scalar field fluctuations into density perturbations

Brane collision/modification of gravity near the bounce

cf. P. McFadden, PJS & N. Turok

Entropic mechanism

F Finellli & R Brandenberger ; J.-L Lehners, P. McFadden, N. Turok & PJS;
Buchbinder, Khoury, Ovrut; Koyama, Mizumo, Wands
Creminelli and Senatore; Wesley and Tolley; J.-L. Lehners & PJS
…

Adiabatic mechanism (single field w/ rapidly increasing w)

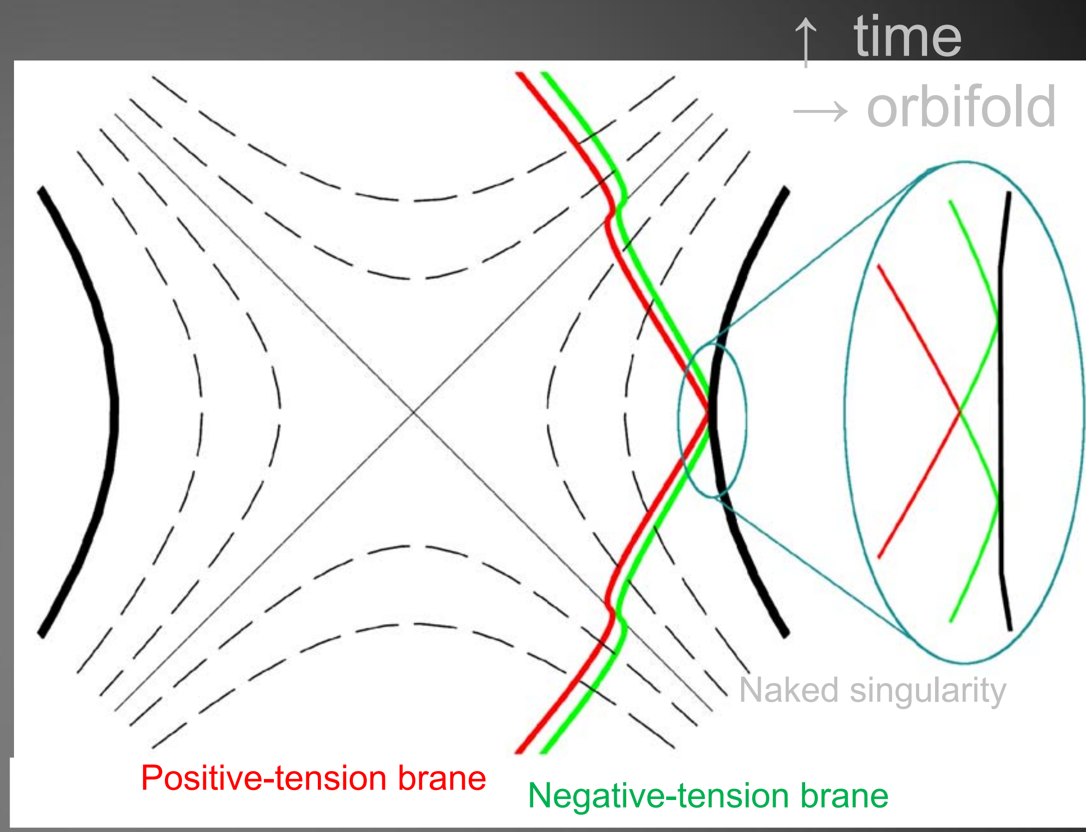
J. Khoury & PJS

The Colliding Branes Solution (5d View)

Ekpyrotic phase renders the branes very flat and parallel close to the collision

→ compactified Milne space around brane collision as a boundary condition

Then there is a family of colliding brane solutions, with only one free parameter, the velocity of the branes at collision



This solution is the background solution for cosmic evolution close to the big bang

JLL, McFadden, Turok

The Colliding Branes Solution (5d ←→ 4d View)

w/ J.-L Lehners, P. McFadden & N. Turok

Fuller View of Cyclic Universe

Heterotic M-theory picture:

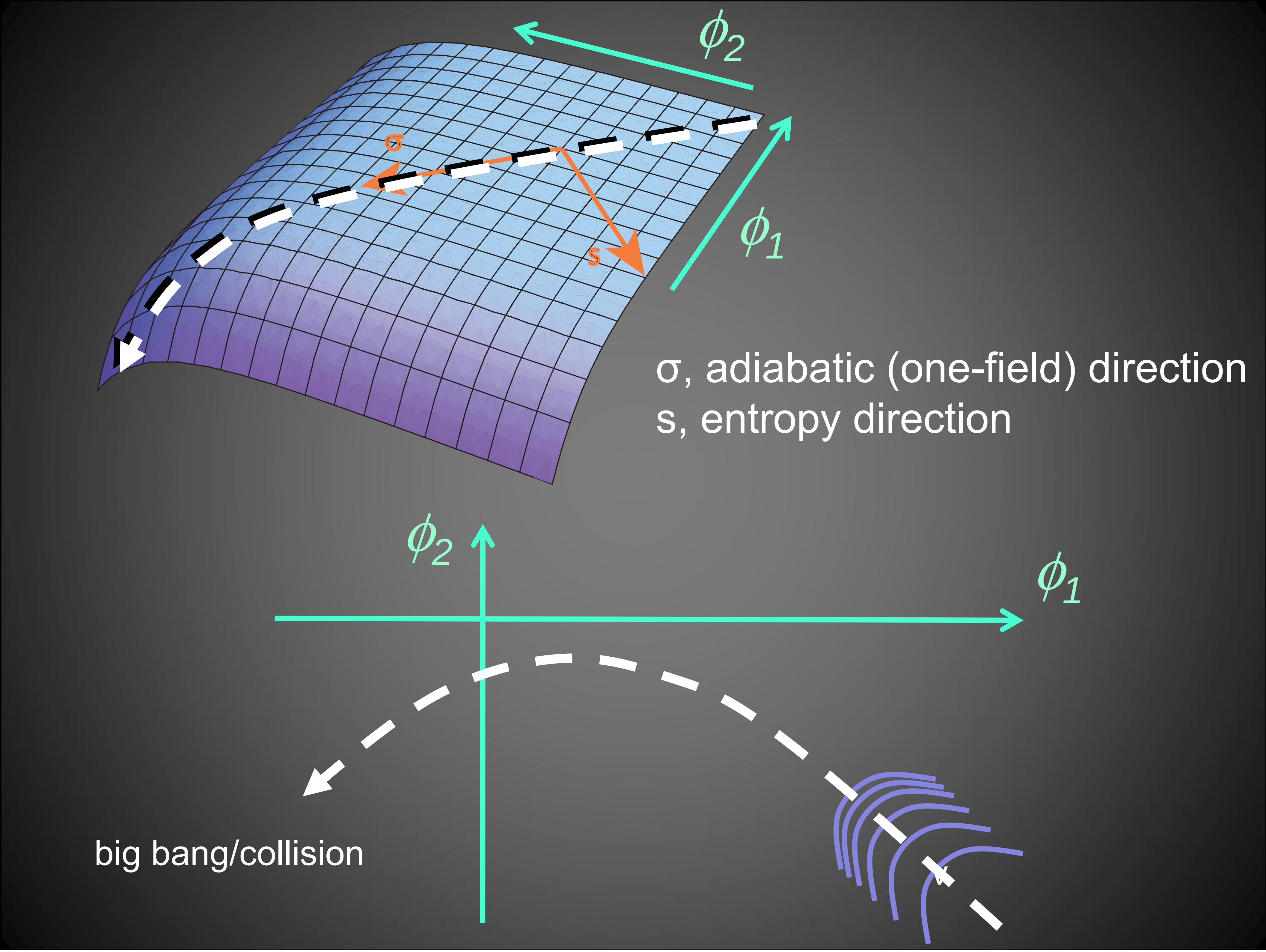
11d sugra compactified

on 6d Calabi-Yau manifold

4d effective theory

Gravity + 2 scalars

parameterizing distance between branes & volume of internal 6d manifold



ϕ_2
ϕ_1
σ
s
σ, adiabatic (one-field) direction
s, entropy direction
ϕ_2
ϕ_1
big bang/collision

Converting scalar field fluctuations into density perturbations

Brane collision/modification of gravity near the bounce

cf. P. McFadden, PJS & N. Turok

Purely 4d Entropic mechanism

F Finellli & R Brandenberger ; J.-L Lehners, P. McFadden, N. Turok & PJS;
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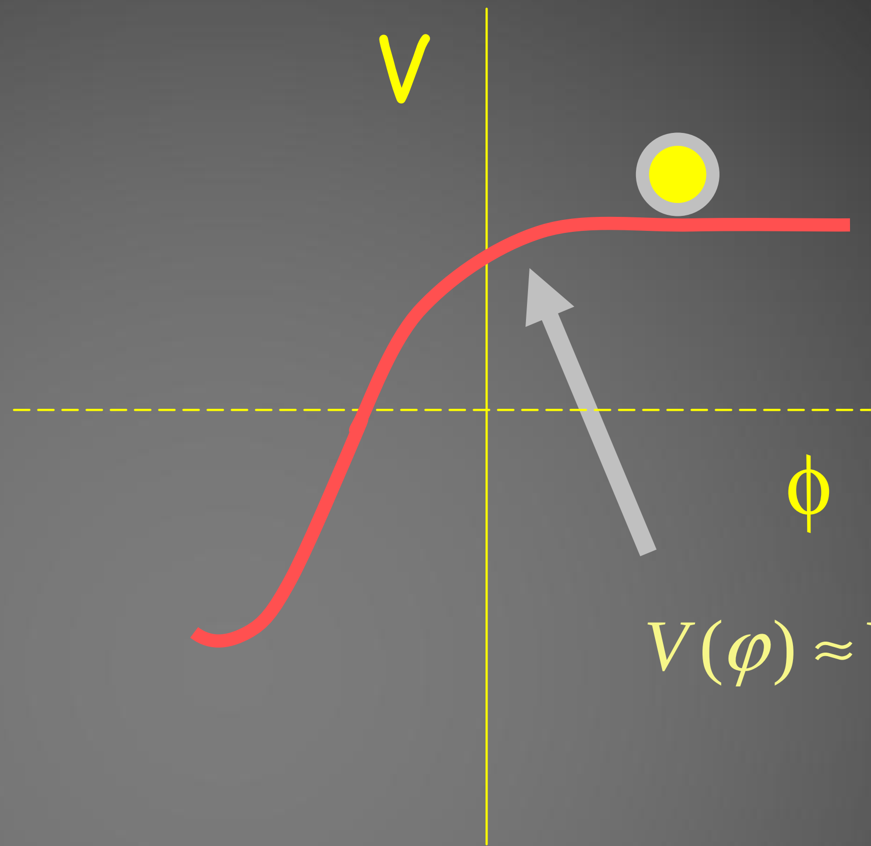
Adiabatic mechanism



$$V(\varphi) \approx V_0\,(1 - e^{-c\varphi})$$

$$\zeta_k = v_k / z$$

$$v_k'' + \left(k^2 - \frac{z''}{z}\right) v_k'' = 0$$

$$z \equiv a\sqrt{3(1+w)}$$

$$during\ transition\ \ phase:\ 1 + w \sim 1/t^2$$

Converting scalar field fluctuations into density perturbations

Brane collision/modification of gravity near the bounce

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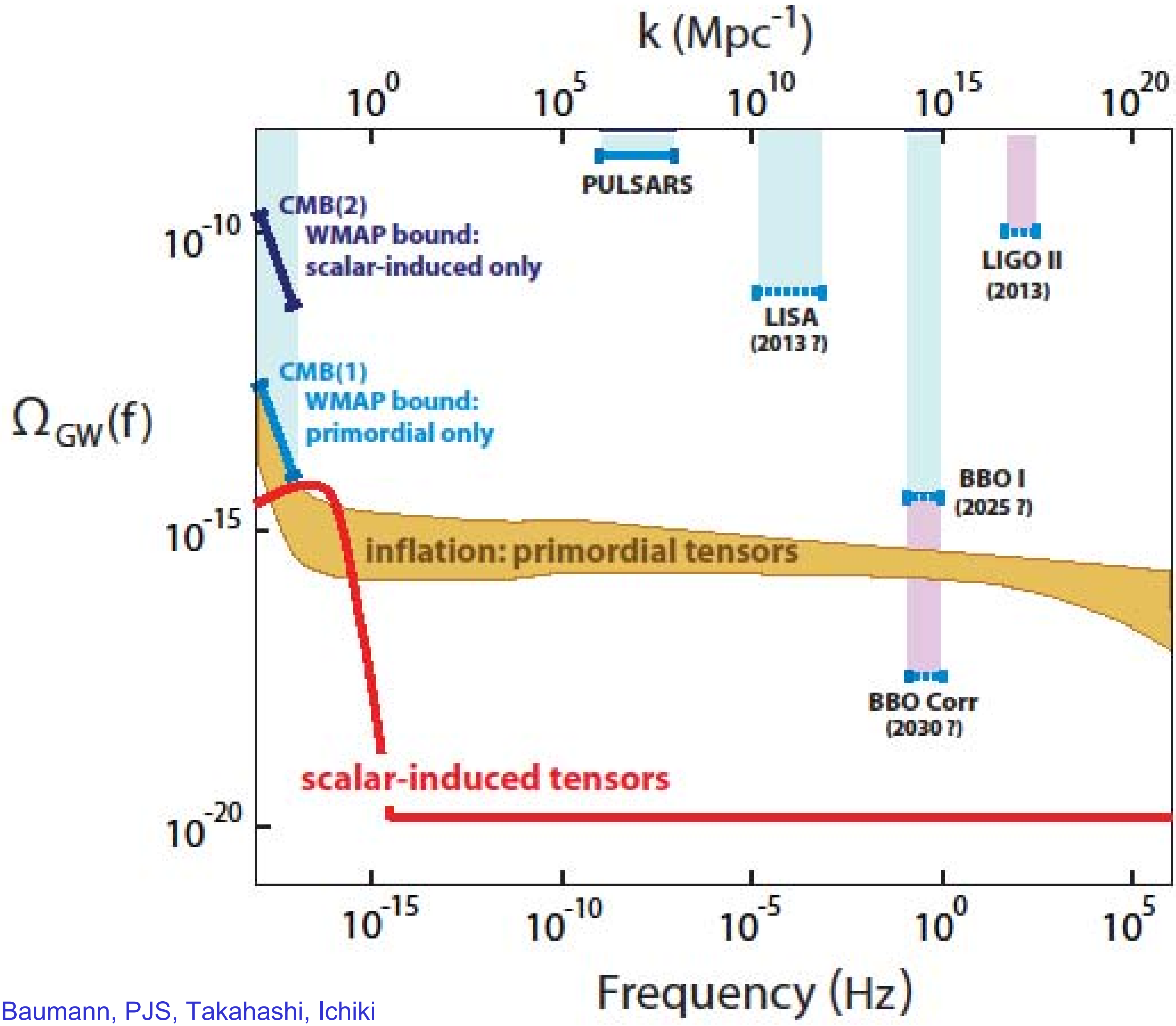
Generic predictions:

primordial g-waves: exponentially small and blue

H exponentially small and increasing in magnitude



from Baumann, PJS, Takahashi, Ichiki
see also Mollerach, Harari, Mattarese
Ananda, Clarkson, Wands

Generic predictions:

primordial g-waves: exponentially small and blue

H exponentially small and increasing in magnitude

non-gaussian perturbations

Koyama, Mizuno, Vernizzi, Wands
Buchbinder, Khoury, Ovrut
Lehners, PJS

$$\zeta = \zeta_L + \frac{3}{5} f_{NL} \zeta_L^2 + \frac{3}{5} g_{NL} \zeta_L^3$$

$$\delta s'' + 3H\delta s' + (V_{,ss} + 3\theta'^2)\delta s + \frac{\theta'}{\bar{\sigma}'}(\delta s')^2$$
$$+(2\frac{\theta''}{\bar{\sigma}'} + 2\frac{\theta' V_{,\sigma}}{\bar{\sigma}'^2} - 3H\frac{\theta'}{\bar{\sigma}'})\delta s\delta s' + (\frac{1}{2}V_{,sss} - 5\frac{\theta' V_{,ss}}{\bar{\sigma}'} - 9\frac{\theta'^3}{\bar{\sigma}'})(\delta s)^2 = 0$$

$$\zeta' = \frac{H}{\bar{\sigma}'^2}[2V_{,s}\delta s + V_{,ss}(\delta s)^2 + \frac{4}{\bar{\sigma}'^2}V_{,s}^2(\delta s)^2 - \frac{1}{\bar{\sigma}'}V_{,\sigma}\delta s\delta s'],$$

for intuitive argument, see Lehners & PJS

Generic predictions:

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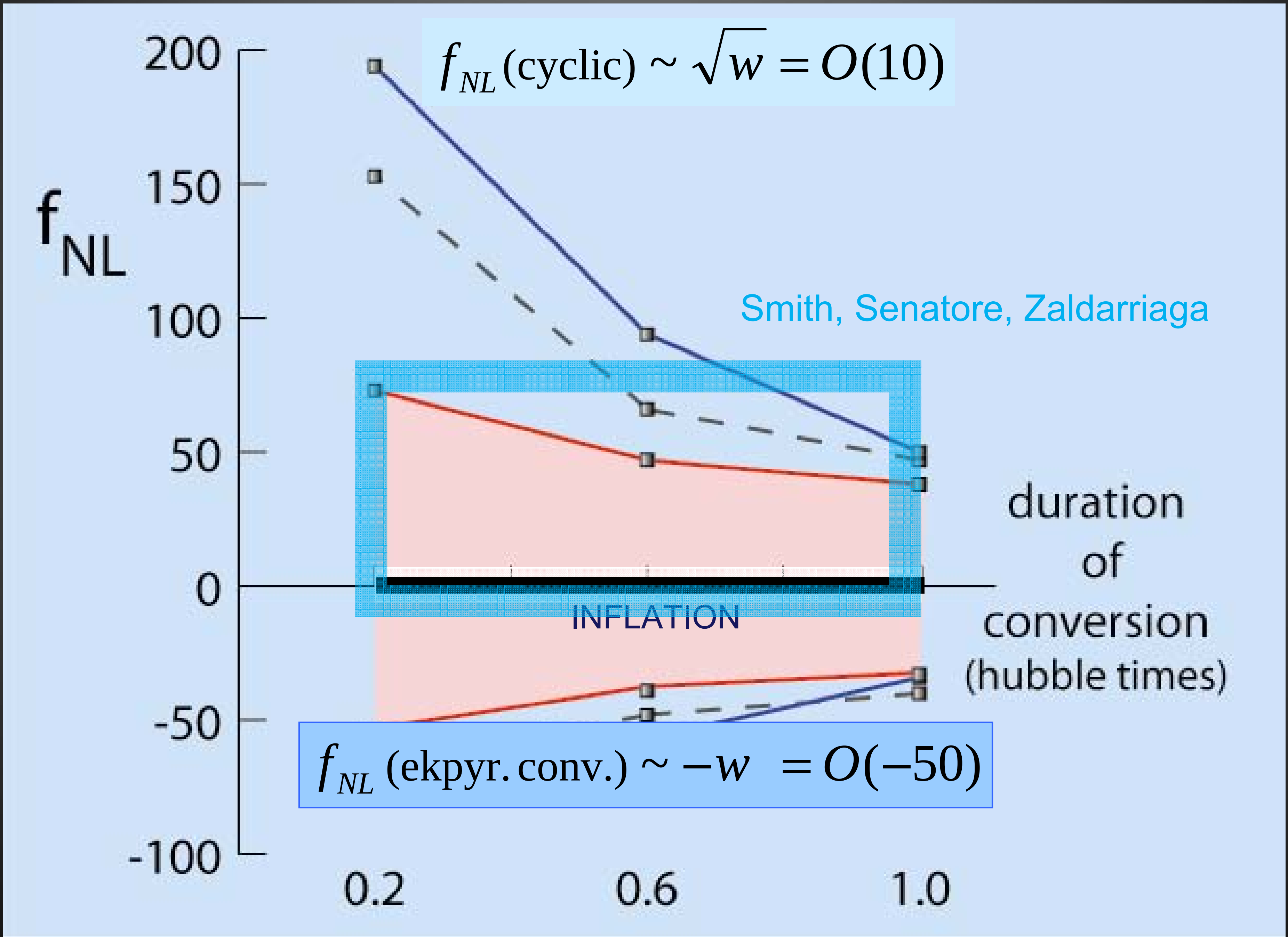
$$\zeta = \zeta_L + \tfrac{3}{5} f_{NL} \zeta_L{}^2 + \tfrac{3}{5} g_{NL} \zeta_L{}^3$$

$$f_{NL}(\text{cyclic}) \sim \sqrt{w+1} = O(10)$$

$$g_{NL}(\text{cyclic}) \sim -40\,(w+1) = -O(1000)$$

for intuitive argument, see Lehners & PJS

Consequence III: non-gaussian perturbations



Key Advantage

The achilles heel: eternal inflation

Eternal inflation is not an option – it is a feature:

A consequence of the fact that you want the inflationary expansion rate to exceed the decay rate of the inflationary phase

"Anything that can happen will happen: and it will happen an infinite number of times."

Alan Guth, 2000

Hence, inflation (=accelerated expansion) does NOT explain/predict anything !

avoids the eternal inflation nightmare

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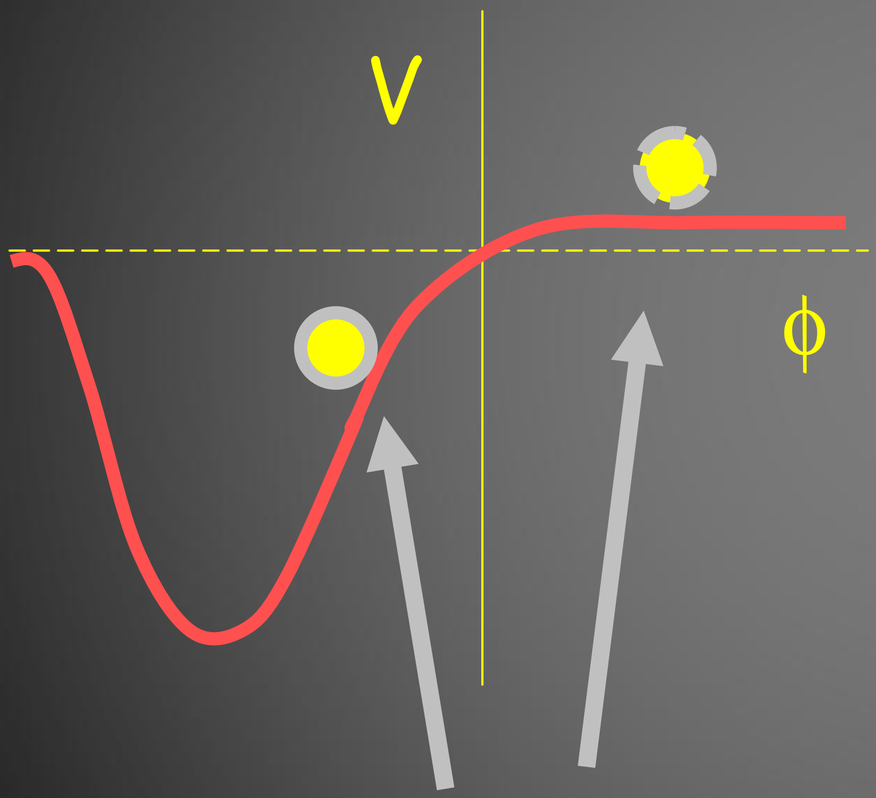
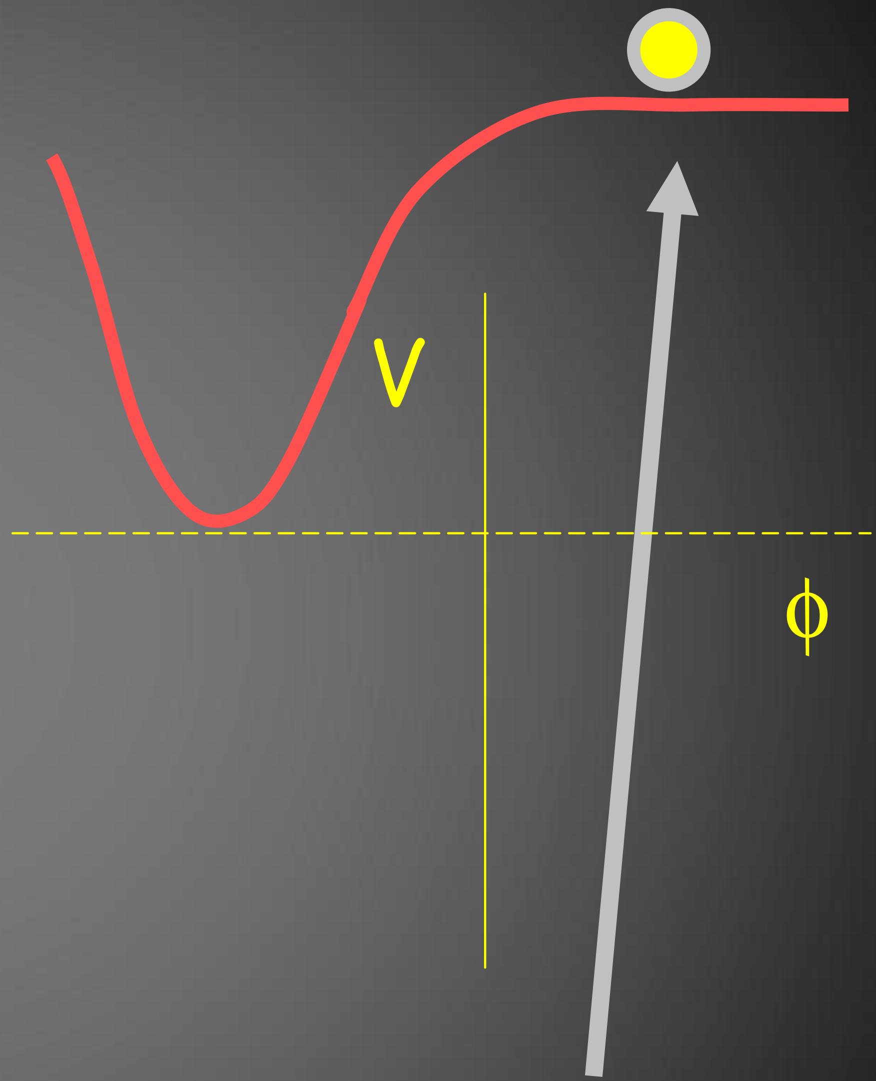
What about introducing a measure?





No eternal runaway

rare regions that delay reheating contract or expand slower

Eternal runaway

rare regions that delay reheating expand faster