Alternatives To Inflation

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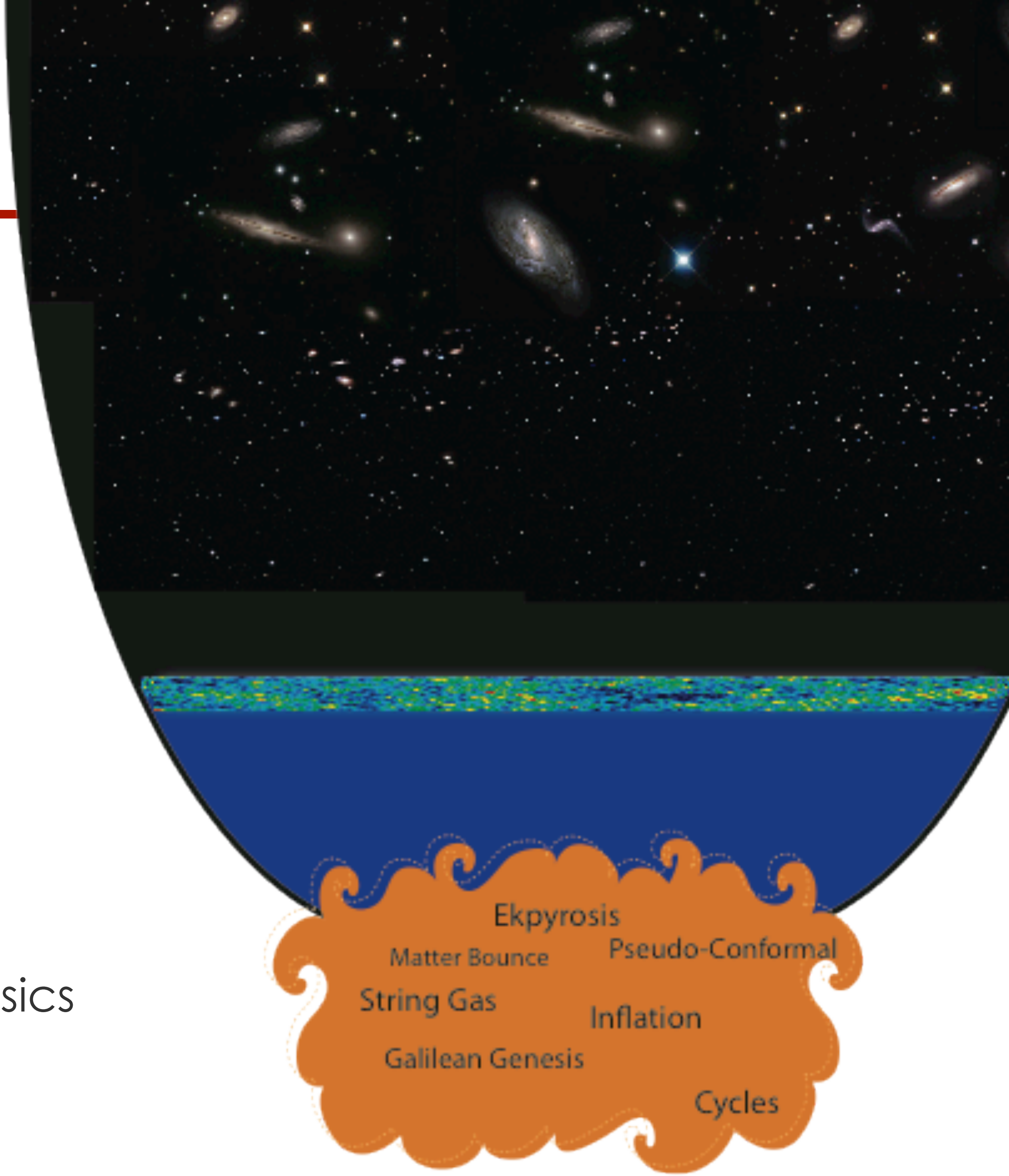
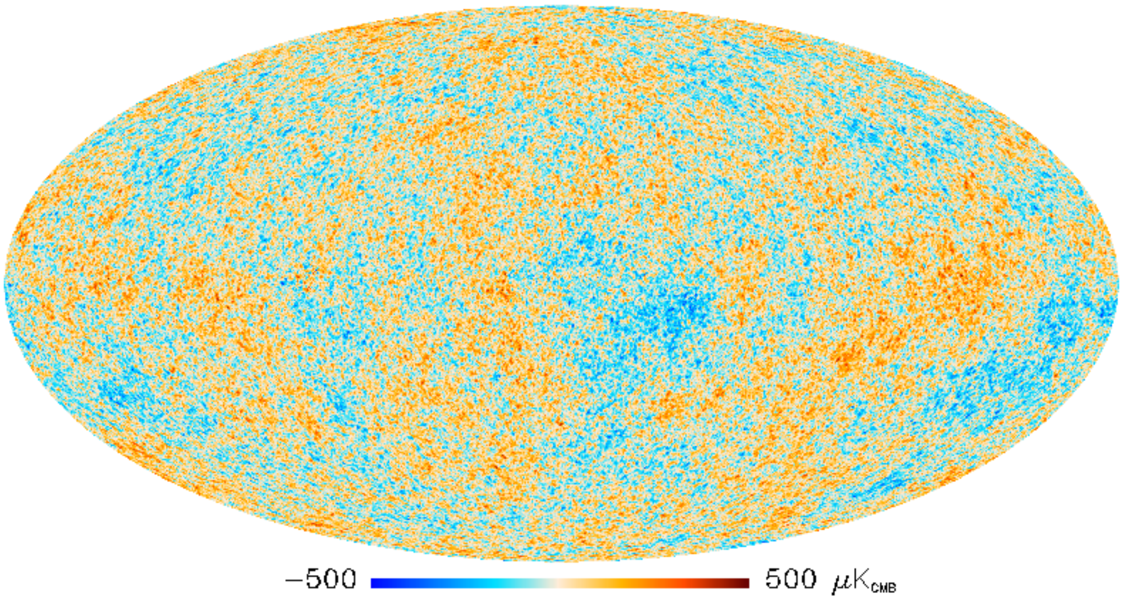
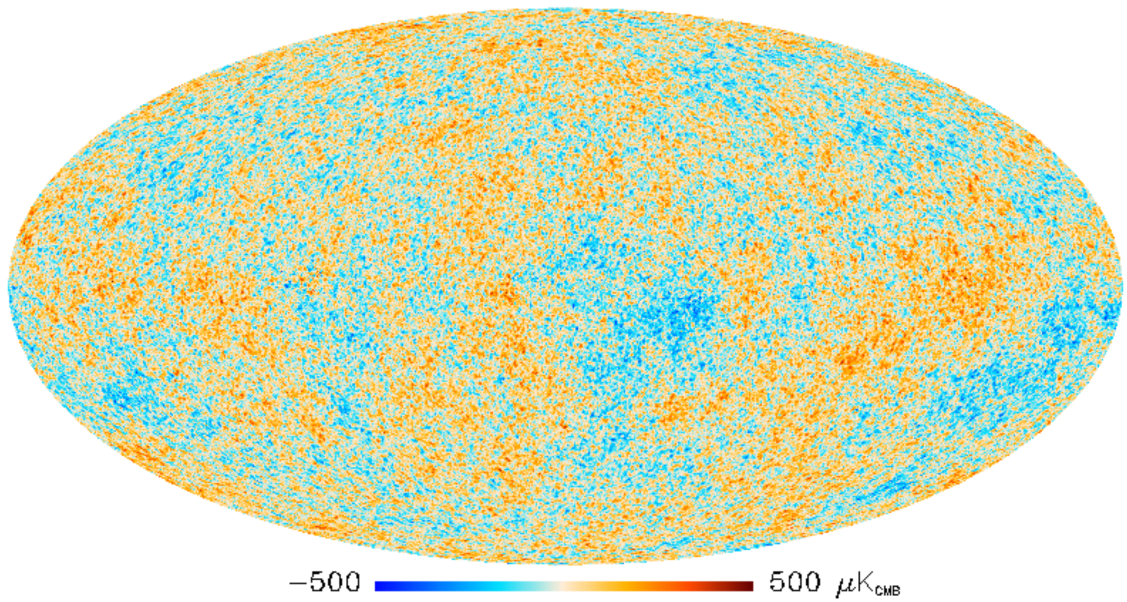


PLANCK data



- A *simple* universe: approximately homogeneous, isotropic, flat
- With, in addition, nearly *scale-invariant*, nearly *Gaussian*, density fluctuations at early times
- Currently no evidence for primordial gravitational waves

PLANCK data



- These features *cannot* be explained by the hot Big Bang picture!

Inflationary Phase

- Initial flatness & isotropy can be explained by an early phase of inflation – consider the Friedmann equation:

$$3\left(\frac{\dot{a}}{a}\right)^2 \equiv 3H^2 = \sum_i \rho_i \quad \text{(energy densities)}$$

$$= -\frac{\rho_{curv,0}}{a^2} + \frac{\rho_{mat,0}}{a^3} + \frac{\rho_{rad,0}}{a^4} + \frac{\rho_{aniso,0}}{a^6} + \frac{\rho_{\phi,0}}{a^{3(1+w_\phi)}}$$

$$w = \frac{pressure}{\rho}$$

- In an expanding universe, scalar matter with w < - 1/3 comes to *dominate* over anything else, i.e. suppresses curvature and anisotropies, and leads to accelerated expansion:

$$3\frac{\ddot{a}}{a} = -\frac{1}{2}\rho(1+3w) > 0$$

[Brout, Englert & Gunzig; Guth; Linde; Albrecht & Steinhardt, ...]

Ekpyrotic Phase

- Initial flatness & isotropy can also be explained by a phase of *slow contraction* – consider the Friedmann equation:

$$3\left(\frac{\dot{a}}{a}\right)^2 \equiv 3H^2 = \sum_i \rho_i \quad \text{(energy densities)}$$

$$= -\frac{\rho_{curv,0}}{a^2} + \frac{\rho_{mat,0}}{a^3} + \frac{\rho_{rad,0}}{a^4} + \frac{\rho_{aniso,0}}{a^6} + \frac{\rho_{\phi,0}}{a^{3(1+w_\phi)}}$$

- In an contracting universe, scalar matter with a large pressure (i.e. w > 1, negative potential) comes to *dominate* over anything else, i.e. suppresses curvature and anisotropies!

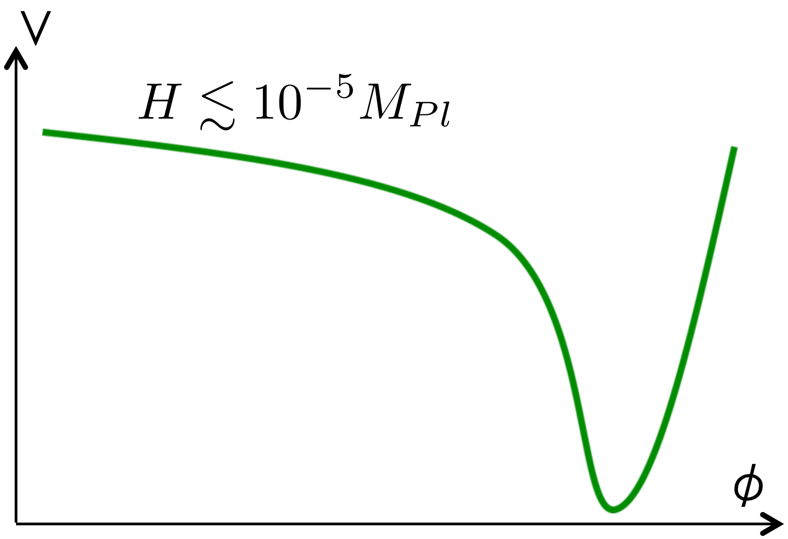
$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V} > 1 \quad \leftrightarrow \quad V < 0$$

- Ekpyrotic phase must be followed by a bounce

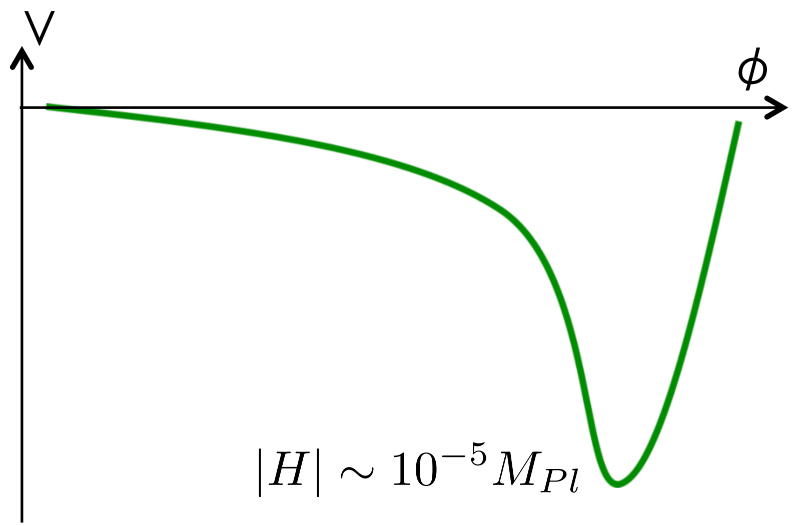
[Khoury, Ovrut, Steinhardt & Turok]

Broad Features

- Inflation and Ekpyrosis are the only two dynamical mechanisms that can explain the broad features seen in the CMB



Inflation



Ekpyrosis

Detailed Features: Amplification of Quantum Fluctuations

- Scalar fluctuations:

$$S_{(2)} \sim \int d\tau d^3x \, \frac{1}{\tau^2} (\partial\zeta)^2$$

- In the quasi-de Sitter limit, inflation generates a nearly scale-invariant spectrum of curvature perturbations with a (fine-tuned) amplitude H^2/ε
- These perturbations obey Gaussian statistics to a good approximation
- Similarly, nearly scale-invariant tensor fluctuations are generated with amplitude H^2

[Chibisov & Mukhanov; Starobinsky; Hawking; Guth & Pi; Bardeen, Steinhardt & Turner;...]

Alternative mechanisms for producing the scalar fluctuations

- Many alternatives exist – typically they involve a second field feeling "as if" in de Sitter space:

$$S_{(2)} \sim \int d\tau d^3x \, \frac{1}{\tau^2} (\partial\chi)^2$$

- In a second stage, perturbations in this field get transferred to the curvature perturbations via a conversion mechanism, such as the curvaton, modulated reheating,...

Examples

- Ekpyrosis (non-minimally coupled):

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + e^{c\phi} - \frac{1}{2}e^{c\phi}(\partial\chi)^2$$

[Li; Gao, Qiu & Saridakis; Fertig, JLL & Mallwitz, Ijjas, JLL & Steinhardt]

- Pseudo-conformal mechanism so(4,2) ➔ so(4,1) [Hinterbichler & Khoury]
  - Conformal rolling

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \lambda\phi^4 - \frac{1}{2}\phi^2(\partial\chi)^2$$

[Rubakov]

  - Galilean Genesis

$$\mathcal{L} = \mathcal{L}_\phi(\phi, \partial\phi, \partial^2\phi) - \frac{1}{2}\phi^2(\partial\chi)^2$$

[Creminelli, Nicolis & Trincherini]

In each case the background generates the pre-factor $\frac{1}{\tau^2}$

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[Creminelli, Nicolis & Trincherini]

- In all cases models exist with small 3-pt function
- Biggest difference with inflation: they generate no tensor modes

- A special case: contracting matter phase
- Here no second scalar is needed

$$a \propto (-t)^{2/3}$$
$$\propto \tau^2 \quad \rightarrow 0$$
$$\rightarrow \frac{a''}{a} = \frac{2}{\tau^2}$$

- Issues:
  - Background evolution is unstable (w=0 -> anisotropies grow)
  - A very large tensor amplitude gets produced

    (r = 16 ε = 24)

    The hope is that the bounce could amplify scalar modes relative to tensor modes

[Wands; Brandenberger]

Remarks about tensors

- A more direct probe of the background dynamics & hence usually no gravity waves arise in a contracting phase (because slow contraction is required to avoid the catastrophic growth of anisotropies)

- However:
  - A matter phase even over-produces tensors
  - Modified gravity theories can also lead to gravity waves in a contracting universe, e.g. scalar-tensor gravity

$$\mathcal{L} = \sqrt{-g}\left[\underbrace{f(\phi)}_{\frac{1}{\tau^2}}\frac{R}{2} + P(X,\phi)\right] + \mathcal{L}_{matter}(g)$$

[Li]

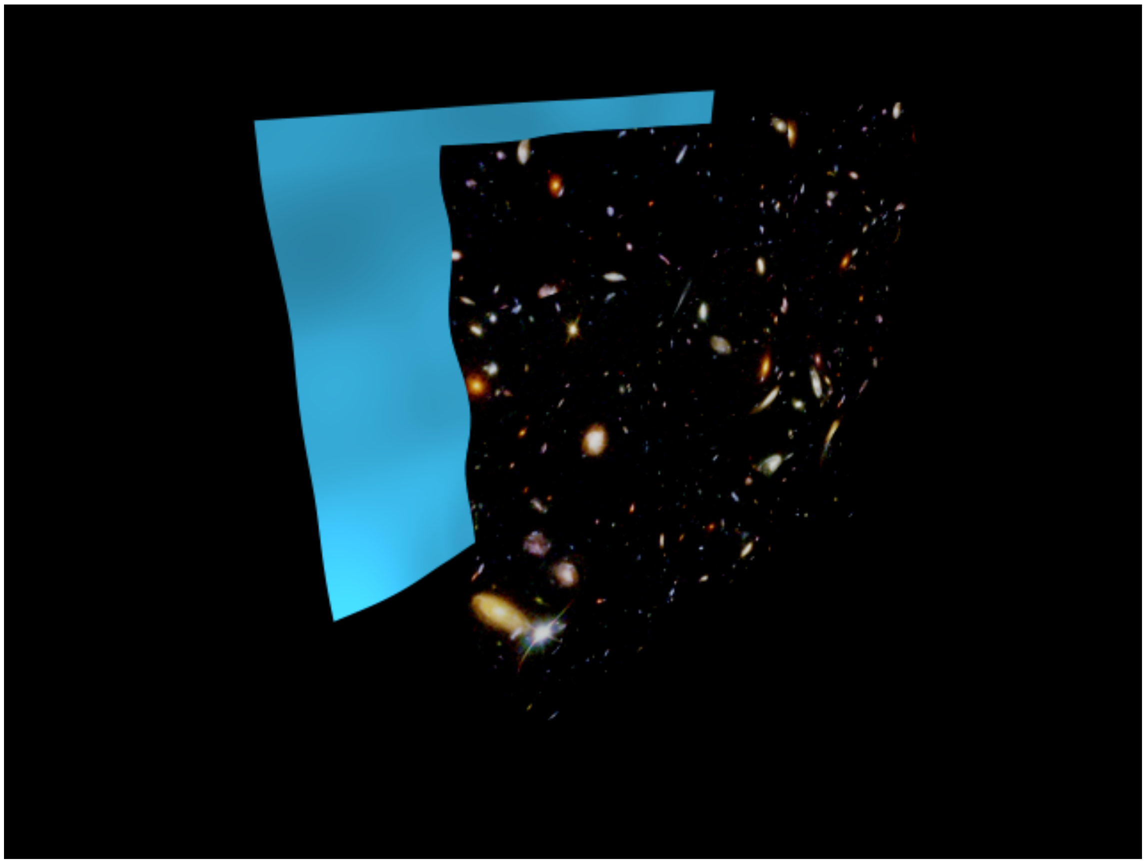
Non-minimal coupling can lead to scale-invariant tensor modes

  - Maybe tensor modes can be produced at the bounce?

Big Issues: Bounce

- Many alternative models rely on an early contracting phase ➔ they require a bounce
- Inflation might have been preceded by a bounce from an earlier phase

Brane Collisions



- A brane collision would look like a big bang to a brane-bound observer like us
- Concrete microphysical model for a bounce
- At the brane collision matter and radiation can be created, thus explaining their origin
- Matter on the second brane appears as *dark matter*
- Really nice idea, but how do we calculate the consequences?

[Khoury, Ovrut, Steinhardt & Turok]

Non-Singular Bounces

- Non-singular bounces in a flat FLRW universe require a violation of the null energy condition (NEC)

$$\dot{H} = -\frac{1}{2}(\rho + p) > 0 \quad \rightarrow \rho + p < 0$$

- Scalar fields with higher-derivative kinetic terms can lead to NEC violation without the appearance of ghost fluctuations

[Arkani-Hamed et al.; Nicolis, Rattazzi & Trincherini]

- Such models have been constructed in non-supersymmetric theories, but have not been derived from a fundamental framework, such as string theory, yet

[Buchbinder, Khoury & Ovrut; Creminelli & Senatore; Easson, Sawicki & Vikman]

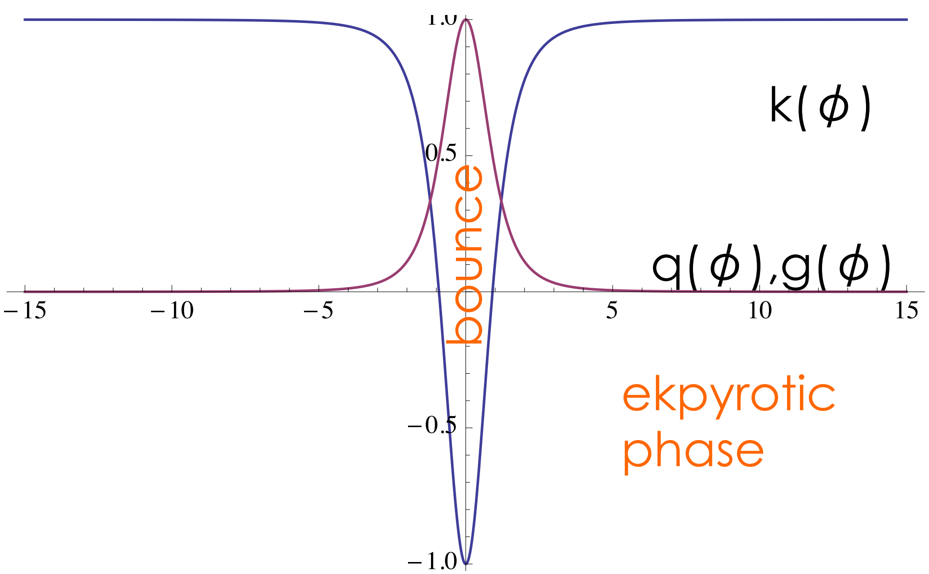
- Have recently shown that non-singular bounces can exist in supergravity

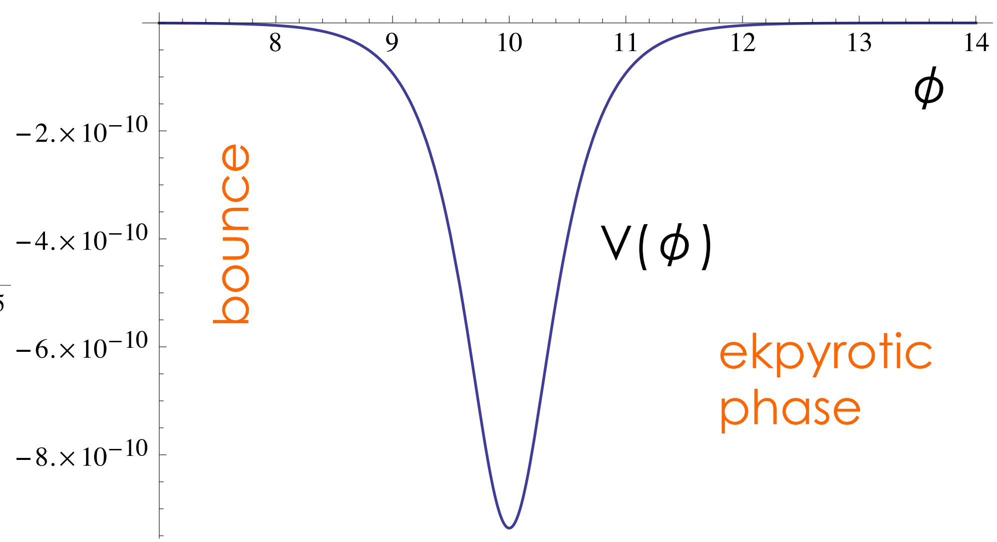
[Koehn, JLL & Ovrut]

Bounce Model – Example

$$\mathcal{L} = \sqrt{-g}\frac{1}{2}\left(R - k(\phi)(\partial\phi)^2 + \frac{1}{2}q(\phi)(\partial\phi)^4 - g(\phi)(\partial\phi)^2\Box\phi - 2V(\phi)\right)$$

Galileon



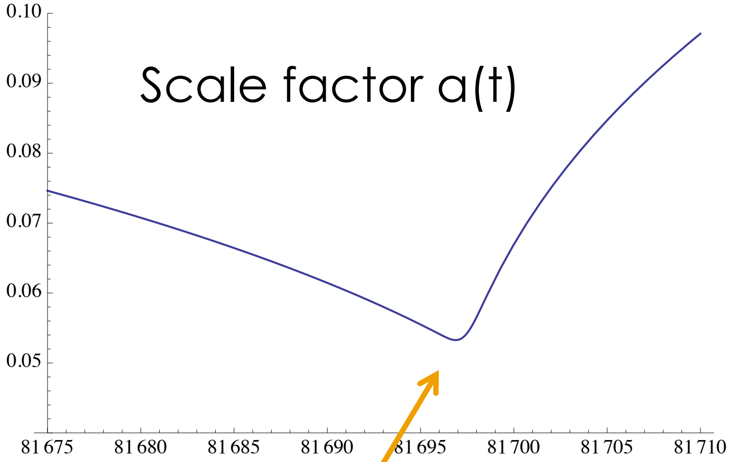


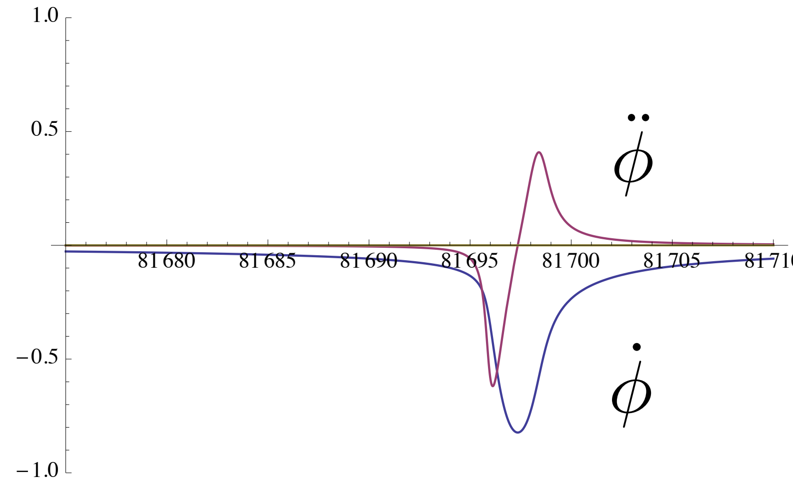
All of the kinetic terms contribute to NEC violation:

$$\rho + p = k(\phi)\dot{\phi}^2 + q(\phi)\dot{\phi}^4 + g(\phi)\dot{\phi}^2\ddot{\phi} - 3g(\phi)H\dot{\phi}^3 + \dot{g}(\phi)\dot{\phi}^3$$

[Cai, Easson & Brandenberger]

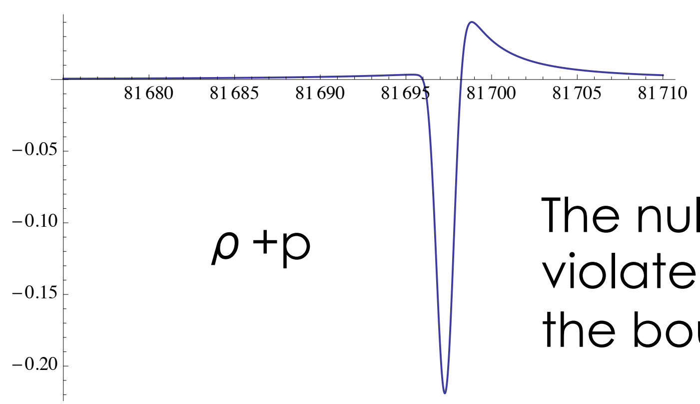
Bounce Model – Numerical Example





Expansion is under control

Smooth,
non-singular
bonce



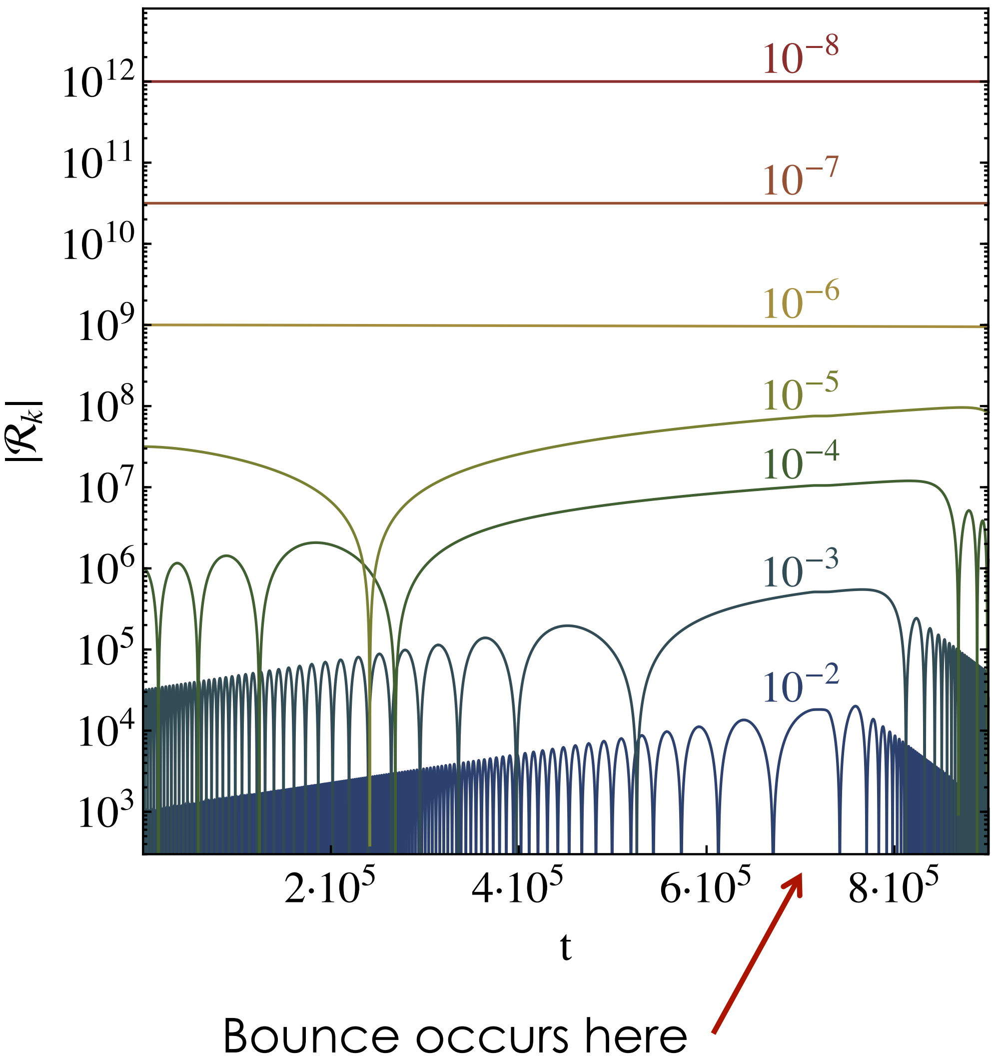
The null energy condition is violated around the time of the bounce

[Koehn, JLL & Ovrut]

Comments

- There are no ghost fluctuations, despite the NEC violation – Supersymmetry and NEC violation can coexist!
- In this bounce there is a gradient instability – must be improved!
- The model uses many tunings – it will be important to see if simpler models can be constructed
- Can this model, or any other non-singular bouncing model, be embedded in string theory?
- What happens to the cosmological perturbations as they go through the bounce?

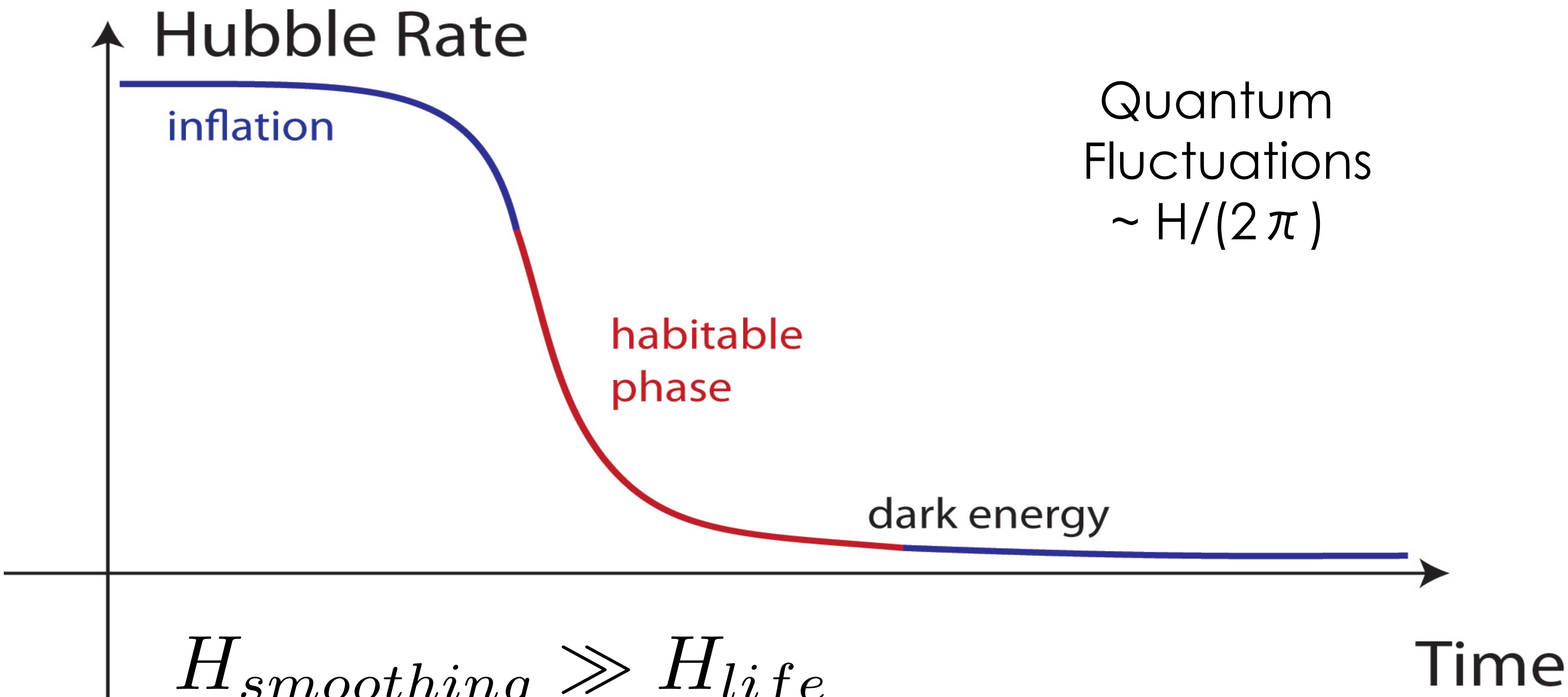
Perturbations Through the Bounce



- The great advantage of non-singular bounces is that one can calculate everything explicitly
- Can see that long-wavelength perturbations are *preserved* across bounce
- Hence one obtains a reliable history from the generation of fluctuations up until today

[Battarra, Koehn, JLL & Ovrut]

Big Issues: Eternal Inflation



Quantum Fluctuations $\sim H/(2\pi)$

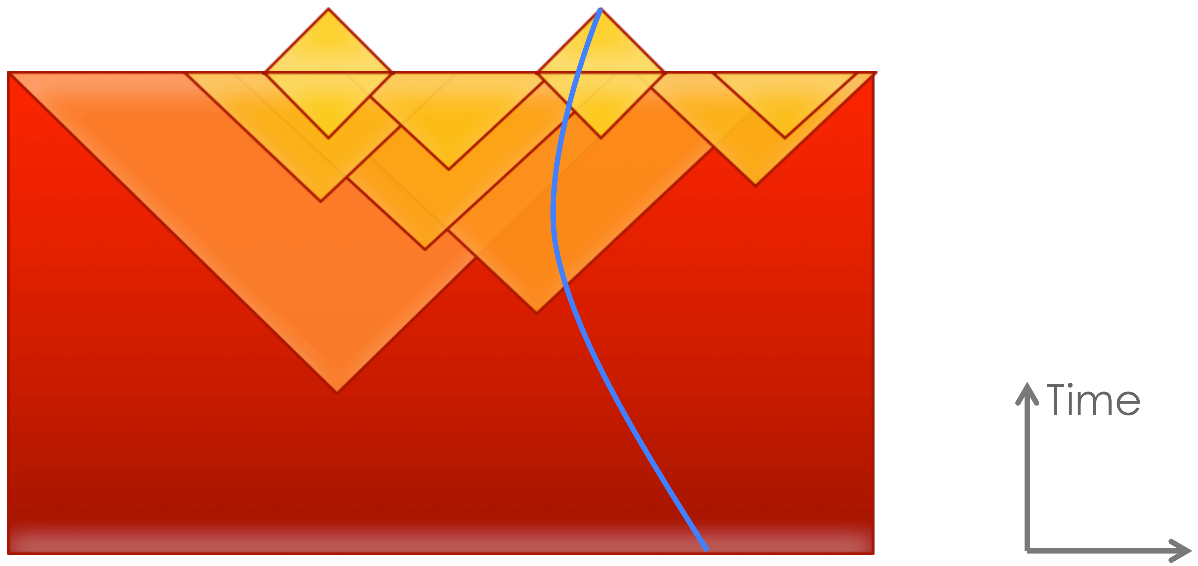
$$H_{smoothing} \gg H_{life}$$

Large upwards quantum fluctuations get amplified and effectively evolve as separate universes

→ Quantum instability

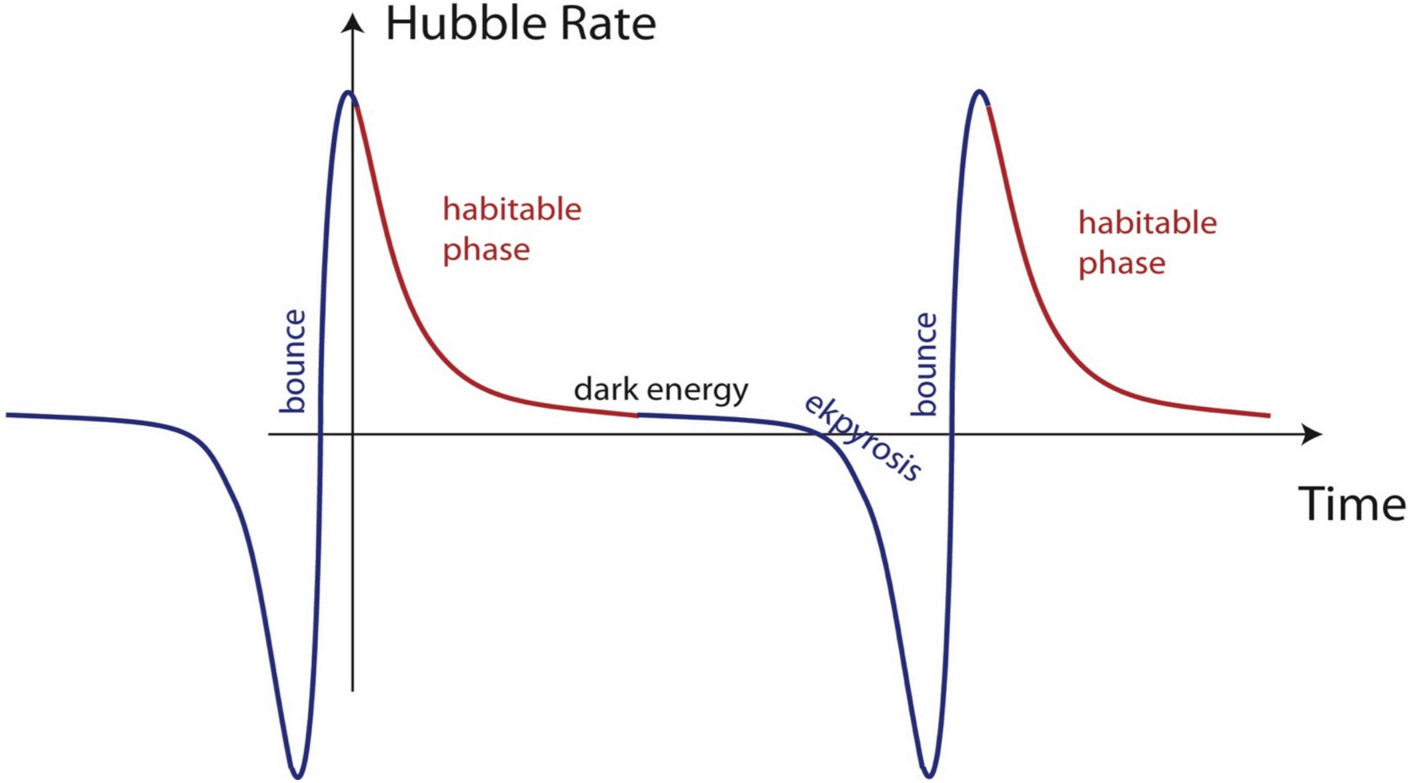
[Vilenkin; Steinhardt]

Leads to an Inflationary Multiverse



- A *measure* is required to regulate the infinities that arise in this way
  [Garriga, Vilenkin; Susskind;...]
- Without a measure, (eternal) inflation has *no* predictive power at all
- By contrast, in a contracting phase, weighting by physical volume gives sensible results
  [Johnson & JLL]

Counter-example: cyclic model



$$H_{smoothing} < H_{life}$$

Large upwards quantum fluctuations simply cause a time delay in the cycle

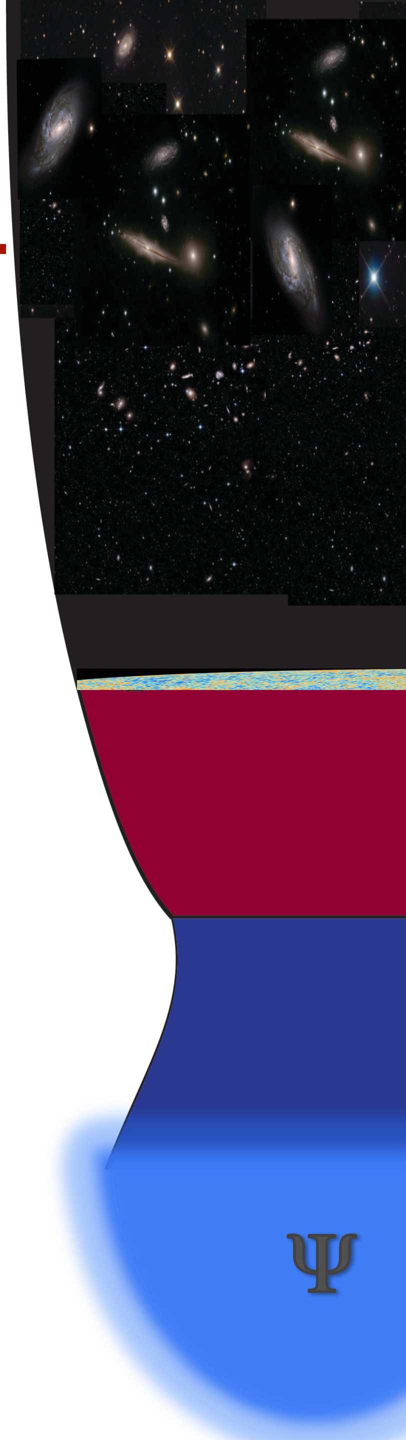
⟶ Quantum stability

[Johnson & JLL]

Initial Conditions

Can Semi-Classical Quantum Gravity, together with the No-Boundary Proposal, address the question of initial conditions?

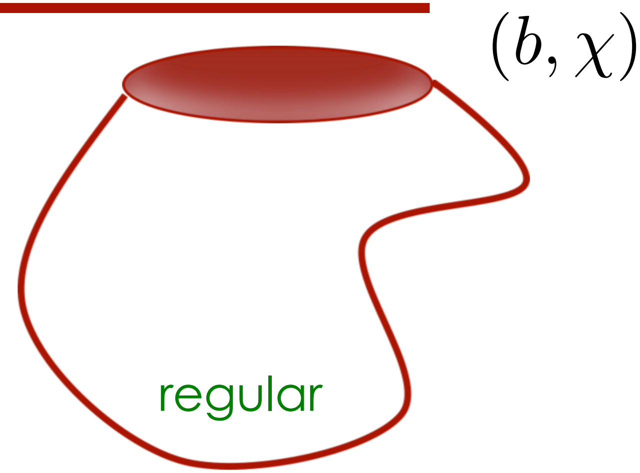
Can we understand why space and time already behaved so classically in the early universe?



Review of the No-Boundary Proposal

$$\Psi(b,\chi) = \int_{\mathcal{C}} \mathcal{D}a\mathcal{D}\phi e^{-S_E(a,\phi)}$$

$$\approx e^{-S_{E,ext}(b,\chi)}$$



- The wavefunction is given by a path integral over all possible four-geometries that are regular in the past (i.e. the possible paths are *restricted*)
- Hartle-Hawking b.c.: the universe is *finite and self-contained*
- No-Boundary Proposal is *supported by AdS/CFT*
- Saddle point approximation: the geometries that are an extremum of the action with the required boundary conditions are typically *complex* – *"fuzzy" instantons*

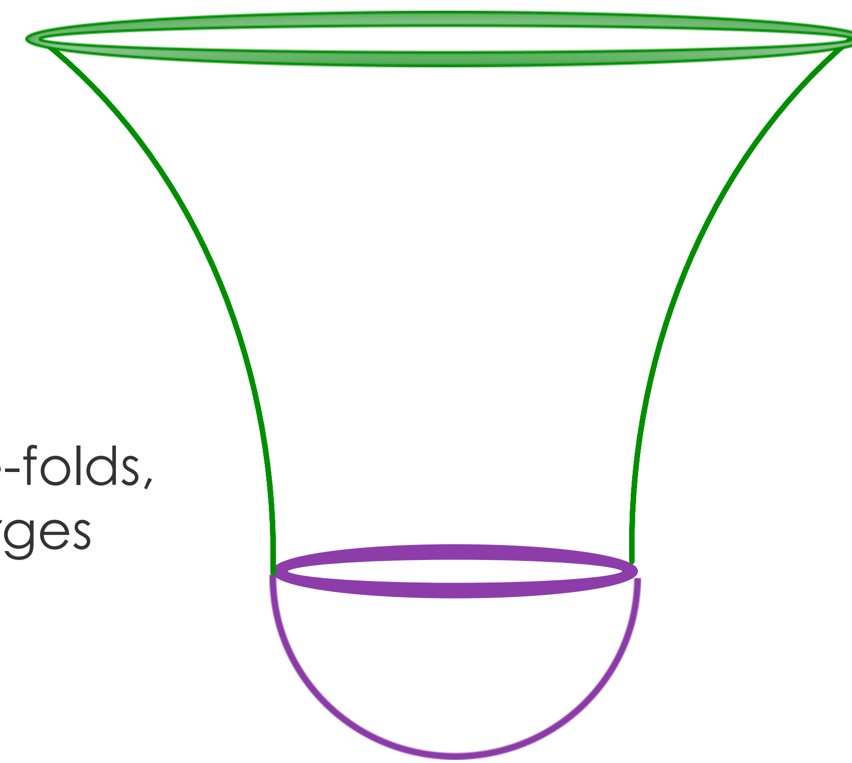
[Hartle, Hawking & Hertog]

Inflationary Instantons

- The bottom of the instanton is approximately a half-4-sphere
- Probability

$$e^{-2Re(S)} = e^{\frac{24\pi^2}{H^2}}$$

- If inflation lasts more than a few e-folds, a classical inflating universe emerges



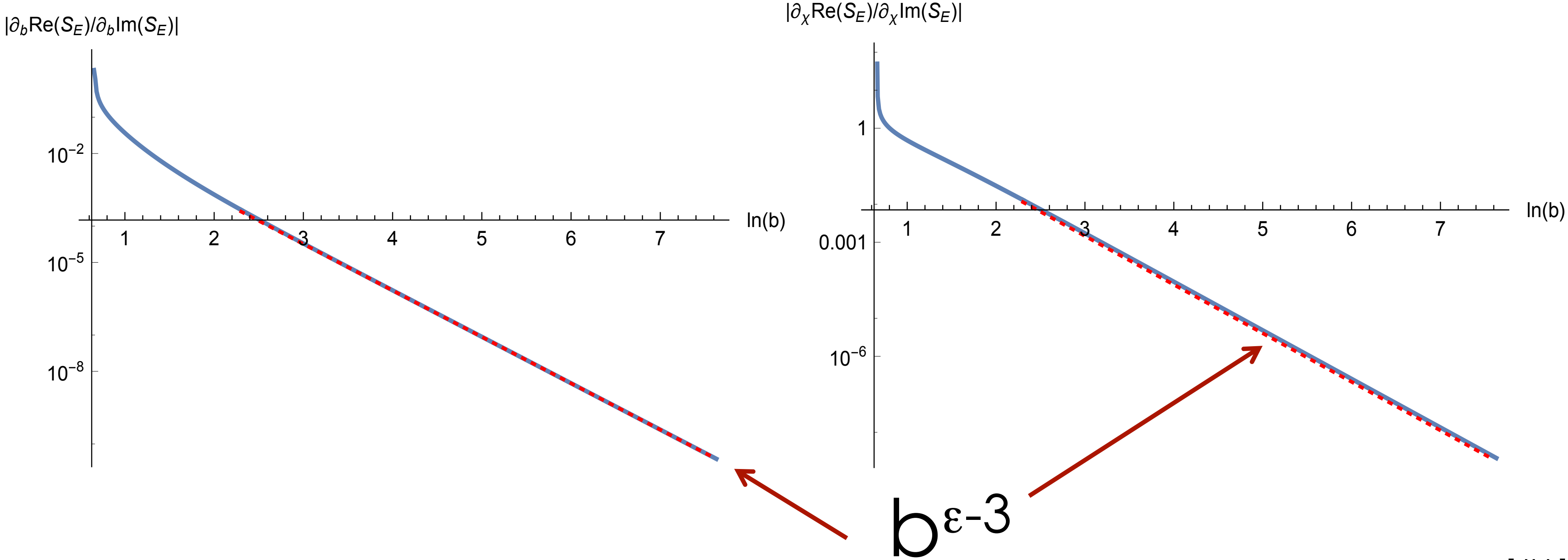
(standard representation)

[Hartle, Hawking & Hertog]

WKB Classicality - Inflation

- As the inflationary phase proceeds, the wavefunction of the universe becomes increasingly classical, in the sense that the phase of the wavefunction varies rapidly compared tot he amplitude – WKB conditions:

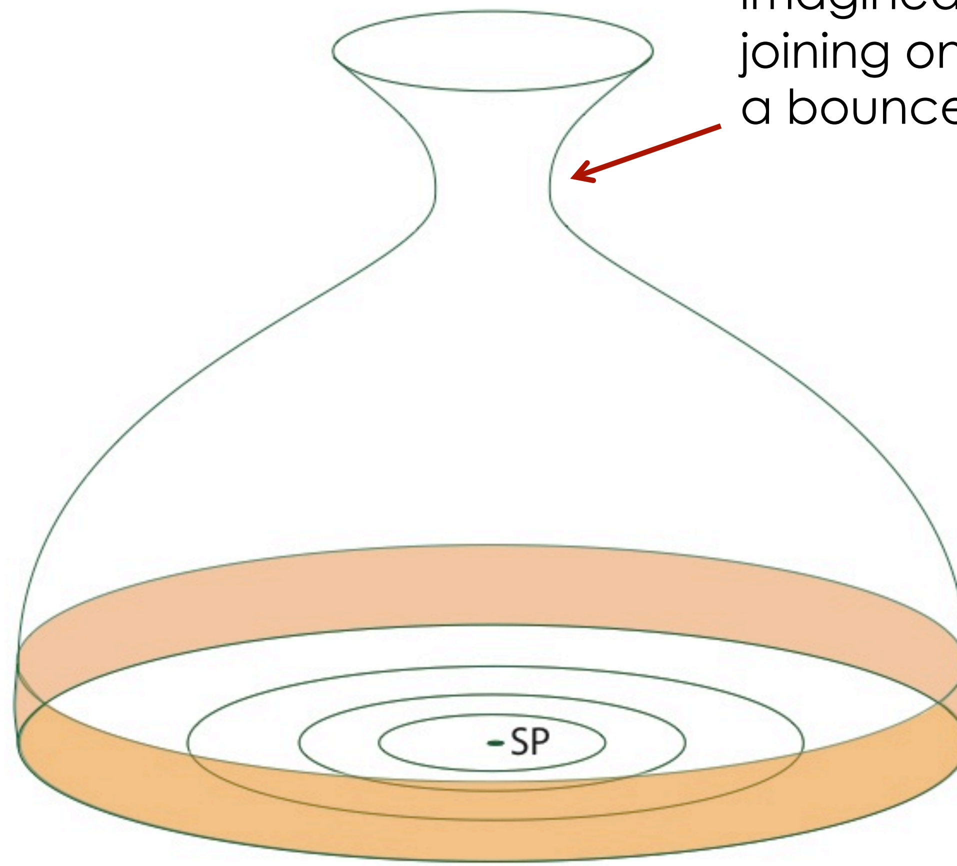
$$\left|\partial_b S_E^R \,/\, \partial_b S_E^I\right| \ll 1, \qquad \left|\partial_\chi S_E^R \,/\, \partial_\chi S_E^I\right| \ll 1$$



[JLL]

Ekpyrotic Instantons

- How can a contracting universe emerge from nothing?
- Bottom: portion of Euclidean space
- Middle: fully complex
- Top: increasingly classical contracting universe



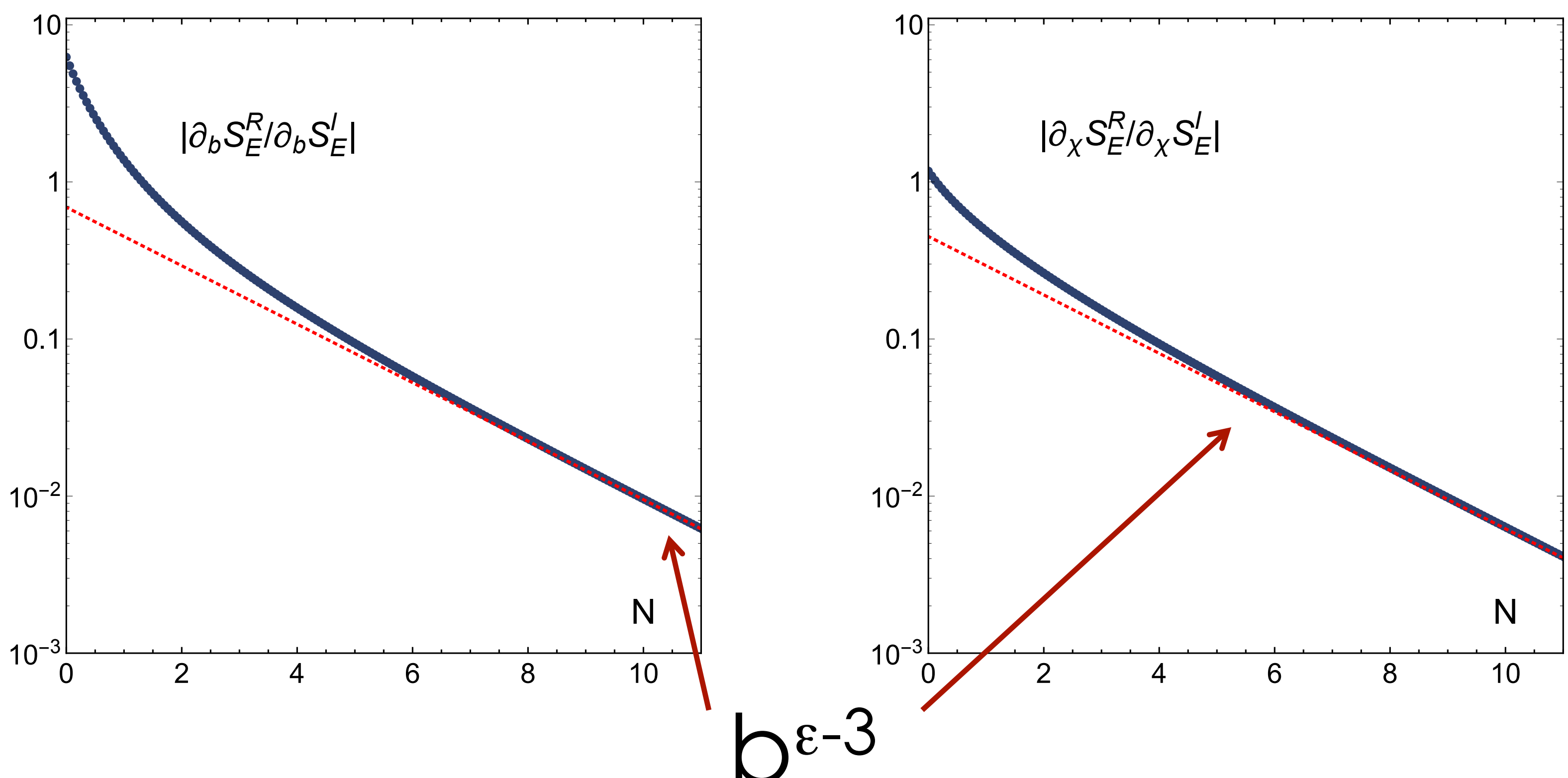
We have imagined joining onto a bounce

[Battarra & JLL]

WKB Classicality - Ekpyrosis

- In this case also, the wavefunction becomes increasingly classical in a WKB sense

$$|\partial_b S_E^R \,/\, \partial_b S_E^I| \ll 1, \qquad |\partial_\chi S_E^R \,/\, \partial_\chi S_E^I| \ll 1$$



[Battarra & JLL]

Implications

- Inflation and ekpyrosis are the only two theories known that can render the universe classical, starting from a quantum state
- In both cases classicality is reached as a power-law in the scale factor of the universe
- In a potential energy landscape the relative probability of the various classical histories is given by a simple formula

$$\Psi^\star \Psi \propto e^{\frac{1}{|V(\phi^R_{SP})|}}$$

- This implies that ekpyrotic histories are vastly preferred (but an important open question is whether one can add a successful bounce, which also preserves classicality)

Summary

- Inflation

Initial Conditions Eternal Inflation	Slow-roll inflation	Reheating	Hot big bang

- Ekpyrotic/Cyclic Universe

Initial conditions	Ekpyrosis	Bounce & reheating	Hot big bang

→ Time

Summary

- Pseudo-Conformal Universe

Initial Conditions	Slow contraction	Bounce & Reheating	Hot big bang

- Galilean Genesis

Initial Conditions Large Minkowski	Long phase of NEC violating expansion	End of NEC violation Reheating	Hot big bang

- Contracting Matter Phase

Initial conditions Large flat universe	Matter contraction Large Tensors	Bounce & reheating	Hot big bang

→ Time

A Final Comment

- It is interesting to note that many of the big open issues (bounce, up-fluctuating, up-tunneling, genesis: getting from low-H to high-H) require a better understanding of violations of the null energy condition
- How can these be described in quantum gravity?