What Can Cyclic Universes Explain?

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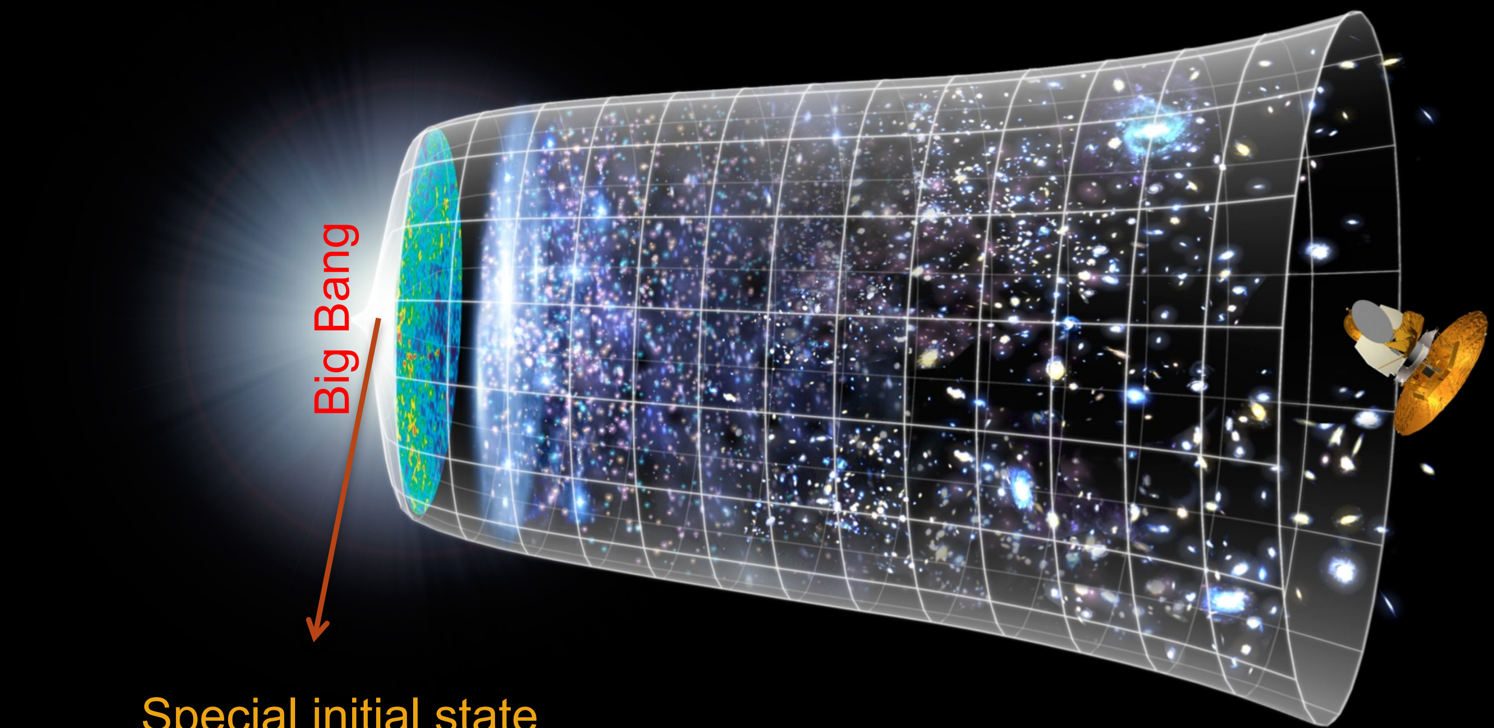
The early universe was very special:

dense, hot, homogeneous, isotropic, flat,
with in addition small, scale-invariant density perturbations



Special initial state

High entropy in matter
Low entropy in geometry

Can we explain the state of the early universe?

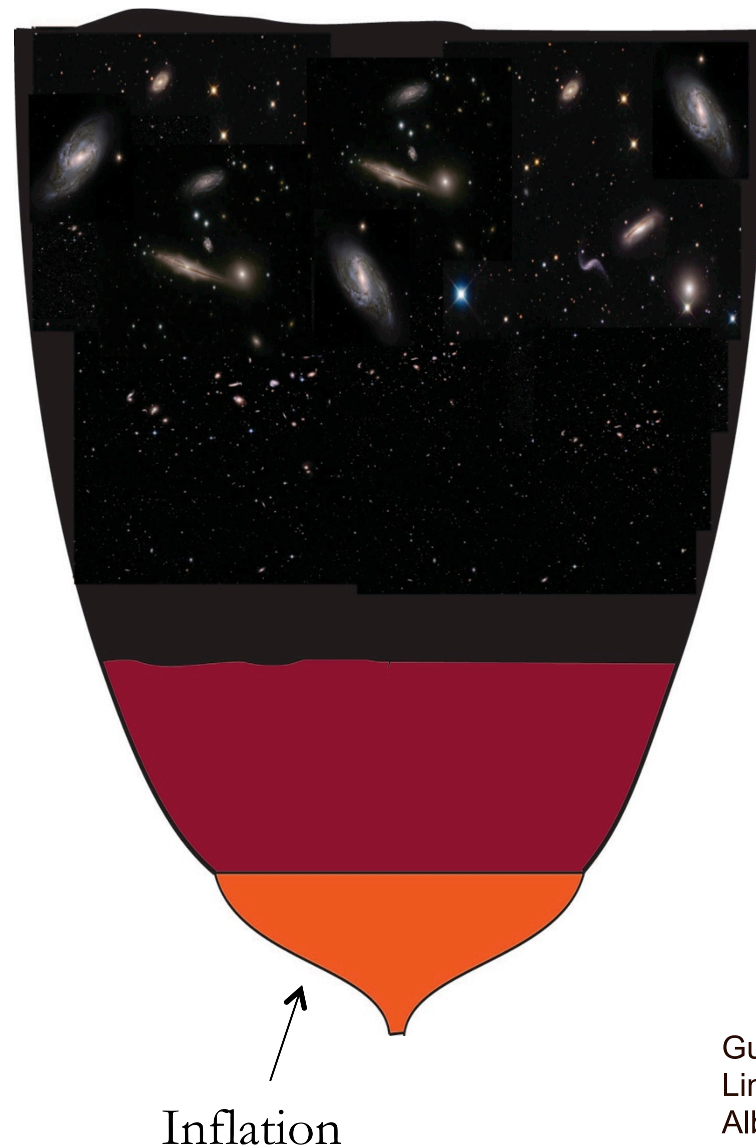
Most popular early-universe model: Inflation

Phase of quasi-exponential expansion at high energy density

Synchronizes the big bang over extended regions

Once underway, renders universe increasingly flat and isotropic

Quantum fluctuations get amplified into classical scale-invariant density perturbations



Guth, Linde, Albrecht, Steinhardt

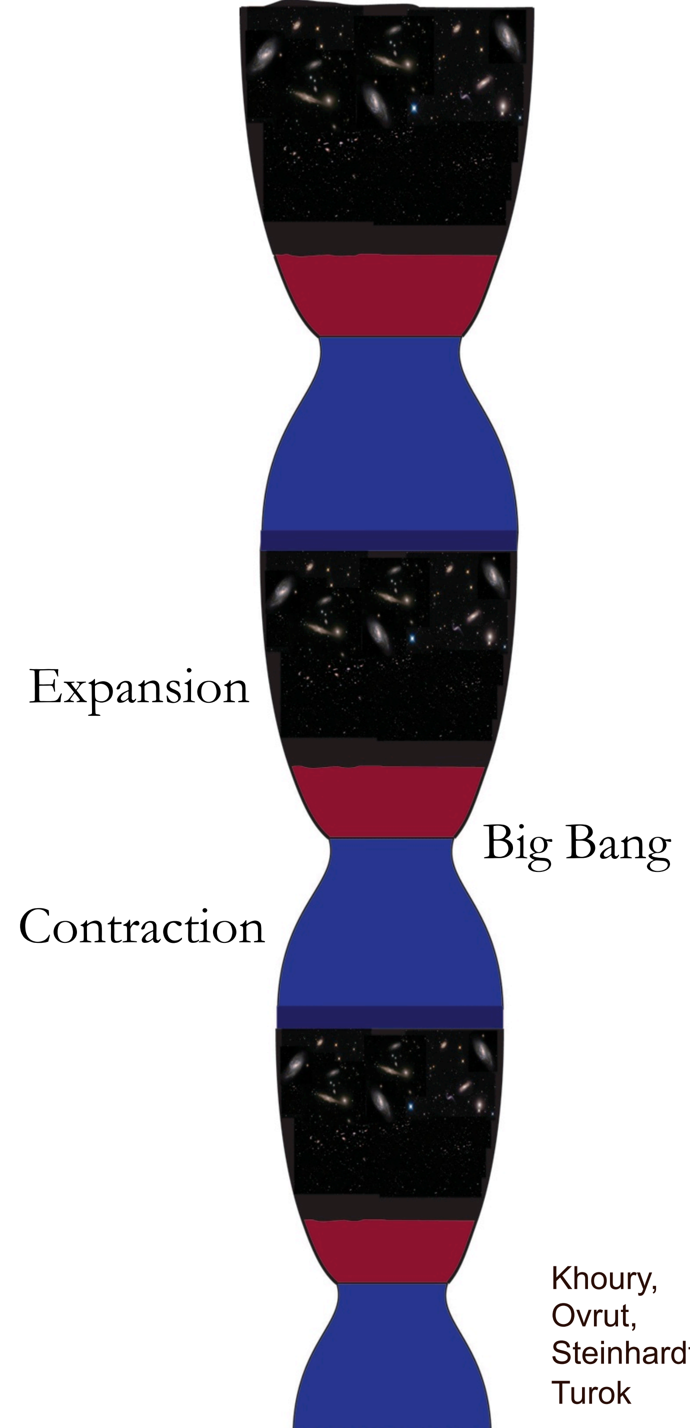
An alternative model: Cyclic Universe

Alternate phases of expansion and contraction

Contraction phase renders universe flat and isotropic

Synchronizes the big bang over extended regions

Quantum fluctuations get amplified into classical density perturbations



Flatness Problem

Inflation

Ultra-fast expansion

$$\Omega_k \propto \frac{1}{(aH)^2}$$

Grows rapidly — Almost constant

$$a \sim e^{Ht}, \;\; H \sim const.$$

$$\Omega_k \to 0 \text{ as } t \to \infty$$

$\longleftrightarrow$ dual

Ekpyrotic/Cyclic

Ultra-slow contraction

$$\Omega_k \propto \frac{1}{(aH)^2}$$

Almost constant — Grows rapidly

$$a \sim (-t)^{1/\epsilon}, \;\; H \sim \frac{1}{\epsilon t}$$

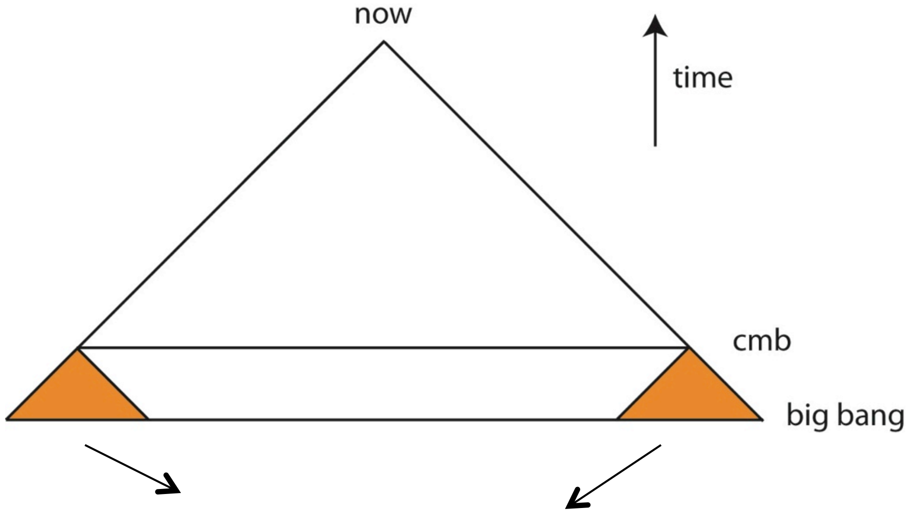
$$\epsilon \sim \mathcal{O}(100)$$

$$\Omega_k \to 0 \text{ as } t \to 0^-$$

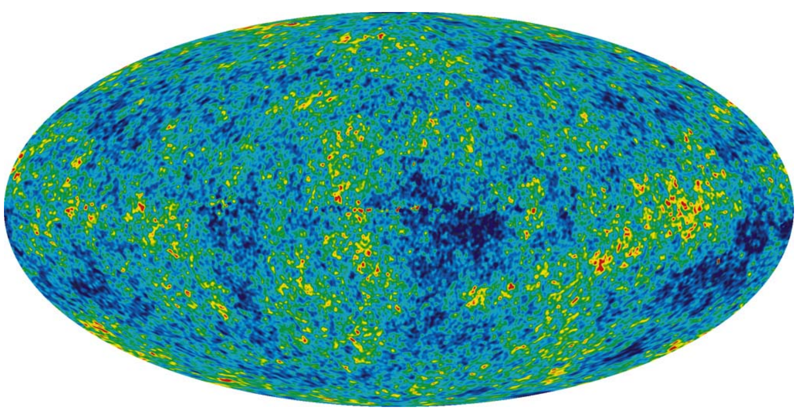
Flatness problem solved dynamically in both cases

→ this makes both models more attractive than other early universe models

Horizon Problem



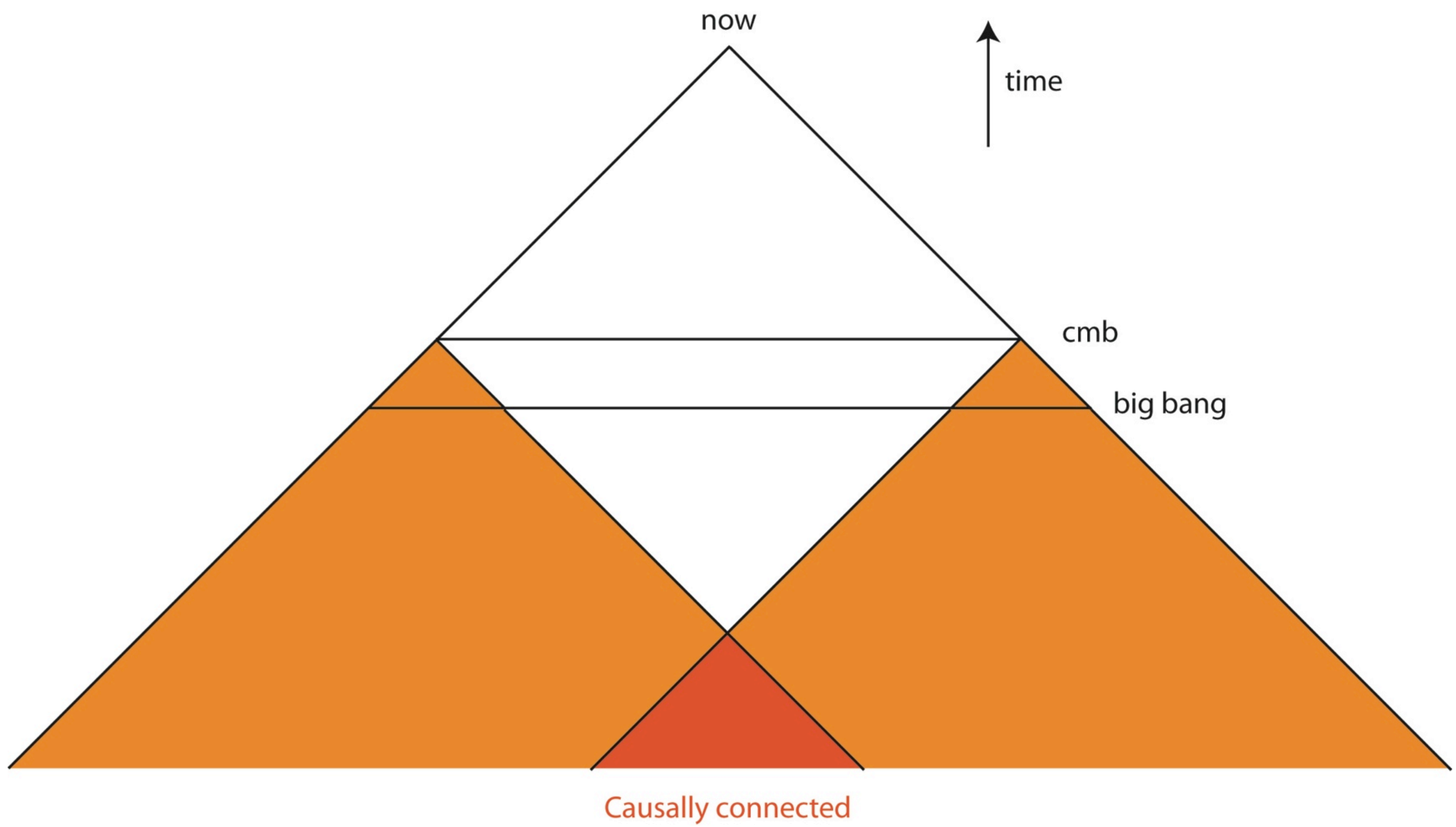
have never been in causal contact,
yet at almost exactly the same temperature



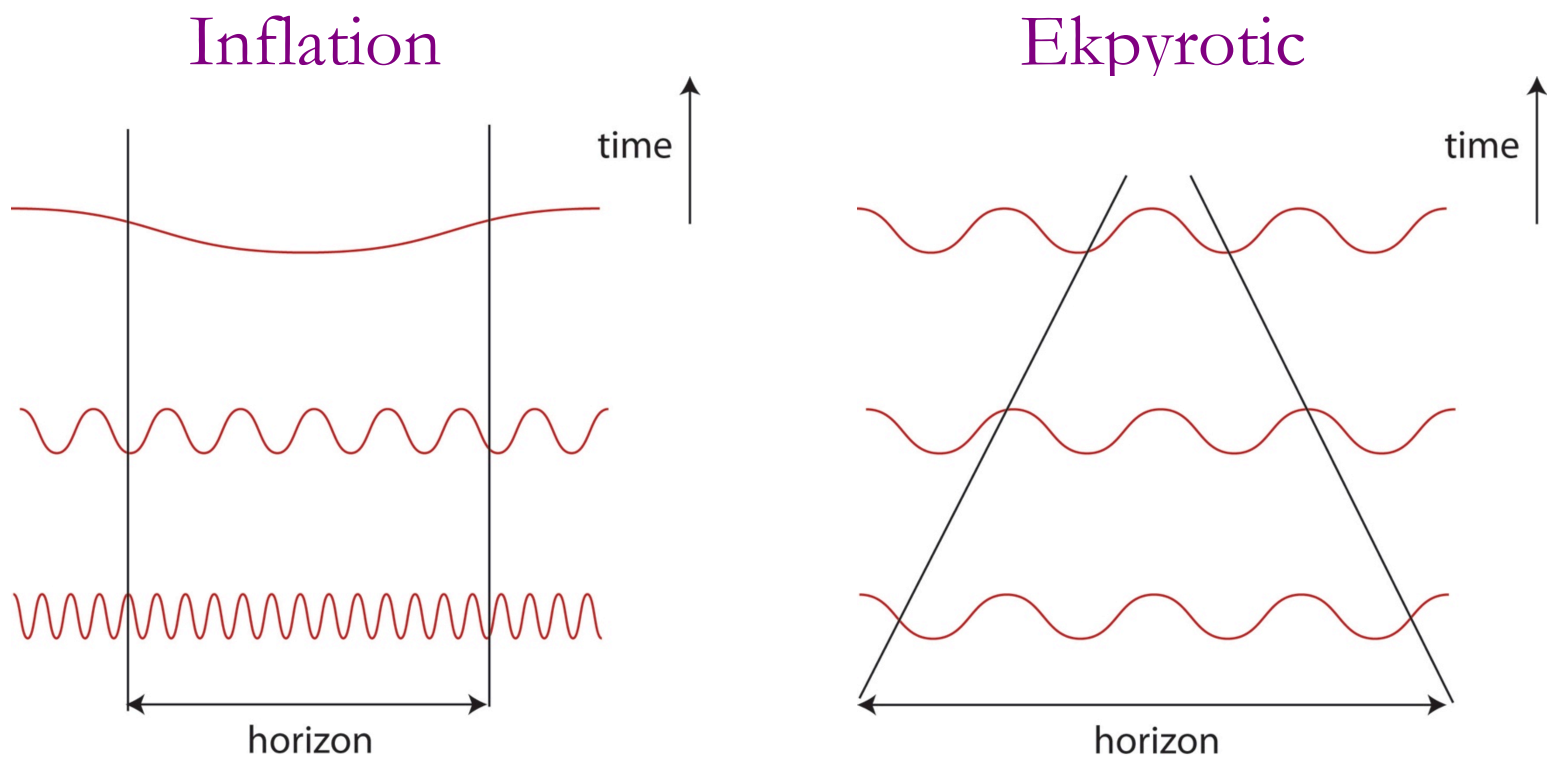
Would have needed Big Bang to occur simultaneously in at least 10^5 adjacent regions
Universe originating from single point is a wrong image

This is the horizon problem

Solution to the horizon/causality problem: extend the spacetime diagram to pre-Big Bang times



Density Perturbations



Horizon = region in causal contact $\approx 1/H$

In both cases, quantum fluctuations get squeezed as they exit horizon
$\rightarrow$ equivalent to stochastic distribution of classical density perturbations
In both cases, perturbations are scale-invariant

Subtlety: ekpyrotic models require two scalars

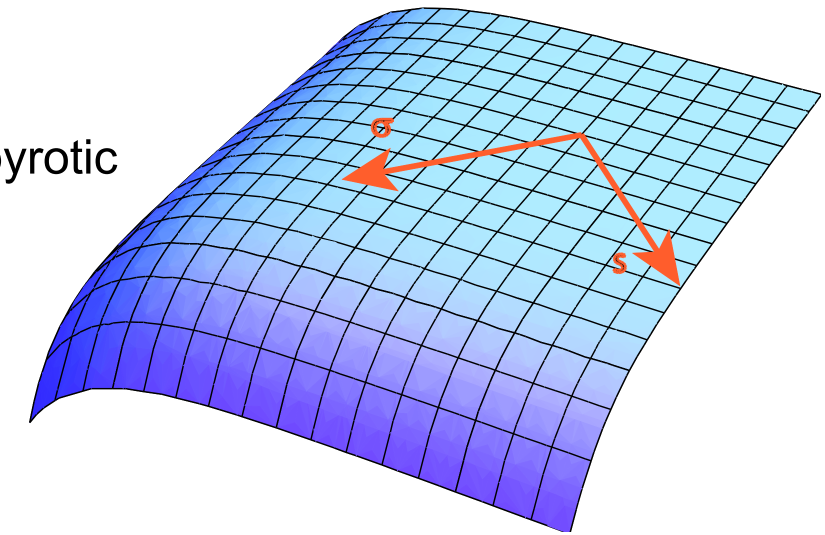
Starobinsky, Guth, Pi, Hawking, Bardeen, Steinhardt, Turner, Chibisov, Mukhanov

Khoury, Ovrut, Steinhardt, Turok, Creminelli, Nicolis, Zaldarriaga

JLL, McFadden, Turok, Steinhardt

The Entropic Mechanism

The 2-Field Ekpyrotic Potential



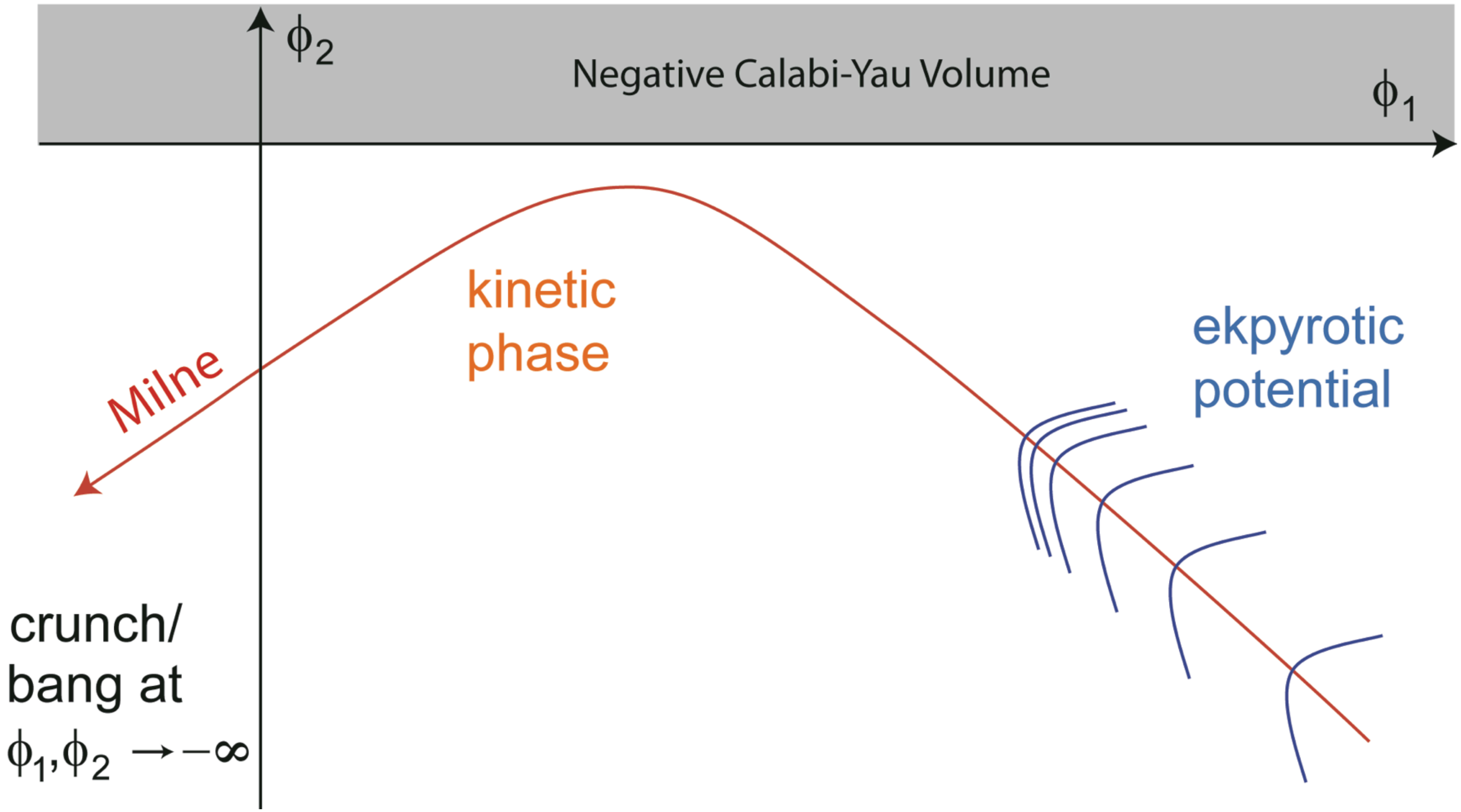
σ, adiabatic field
s, entropy field

Perturbations in adiabatic direction blue

Perturbations in entropy direction scale-invariant – they automatically get converted into adiabatic perturbation in approach to brane collision

Finelli
Notari, Riotto
JLL, McFadden, Steinhardt, Turok
Koyama, Mizuno, Wands
Buchbinder, Khoury, Ovrut
Tolley, Wesley

Conversion



Conversion: when trajectory bends, scale-invariant entropy/isocurvature perturbations get rotated into adiabatic/curvature perturbations with the same spectrum

Observational Predictions (since PLANCK is near...)

1. Test: Gravitational Waves

Scale factor almost constant

→ Spacetime almost Minkowski space

→ No measurable gravity waves

Boyle, Steinhardt, Turok

2. Test: Non-Gaussianity

For *local* non-gaussianities, expand curvature perturbation:

$$\zeta = \zeta_L + \frac{3}{5} f_{NL} \zeta_L^2 + \frac{9}{25} g_{NL} \zeta_L^3$$

Linear, Gaussian

3-pt function

4-pt function

Inflation

Flat potential $\rightarrow$ almost free field

$\rightarrow$ action $S \sim (\partial\phi)^2$ quadratic

$\rightarrow$ prob. dist. e^{-S} Gaussian

Simple models predict

$$f_{NL} \sim \mathcal{O}(1)$$

$$g_{NL} \sim \mathcal{O}(1)$$

(due to non-linear evolution after inflation)

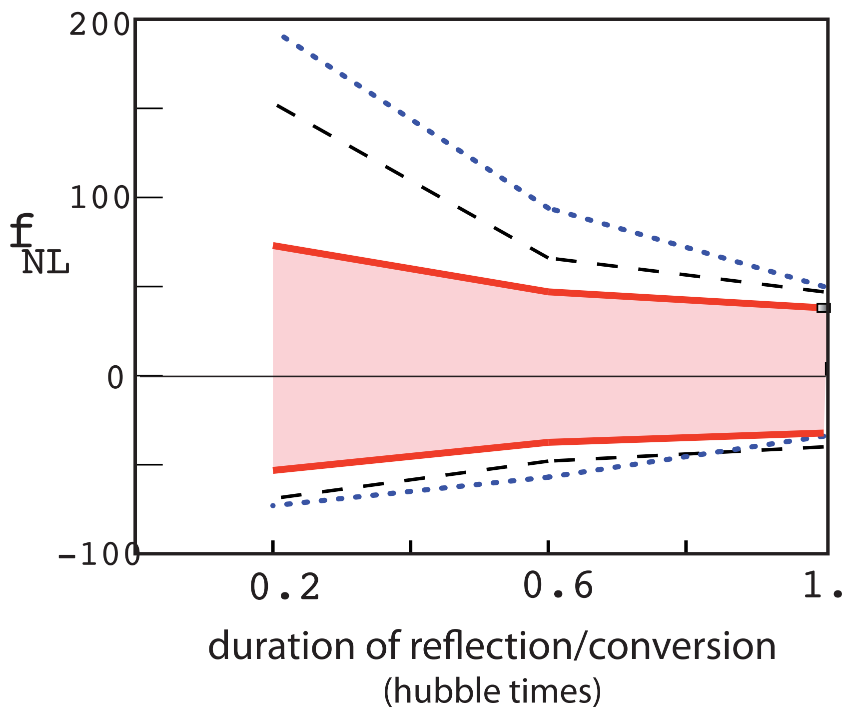
Maldacena, Seery, Lidsay

2. Test: Non-Gaussianity

Ekpyrotic/Cyclic Universe

Steep potential → scalar self-interactions

→ significant non-Gaussianity



Best-motivated models predict

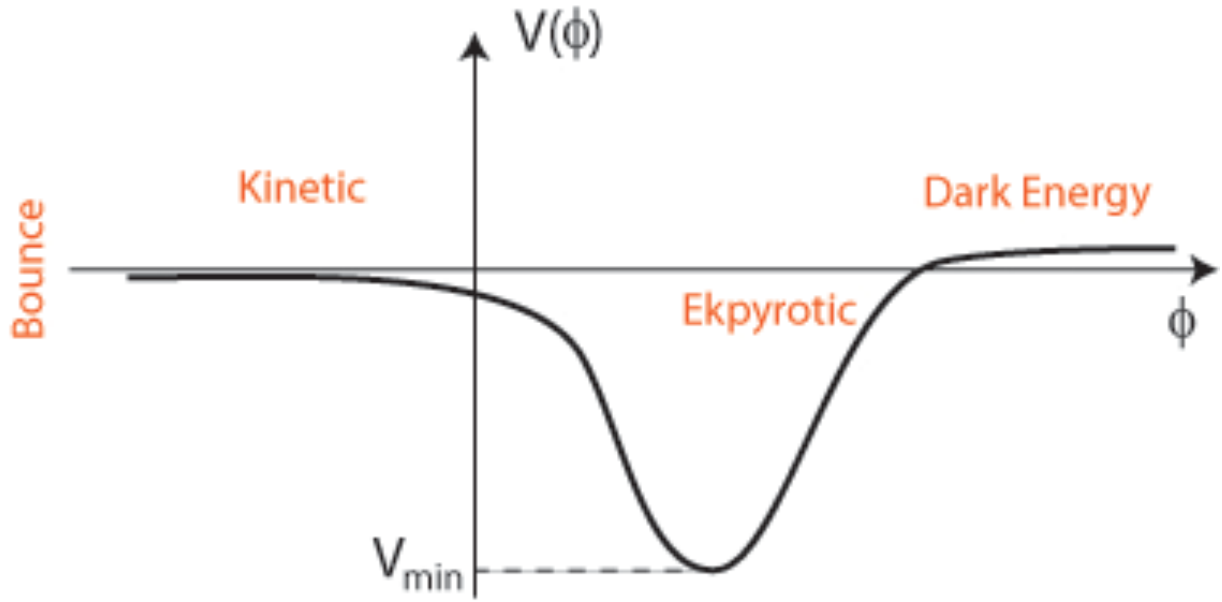
$$f_{NL} \sim \mathcal{O}(\pm 10)$$

$$g_{NL} \sim \mathcal{O}(-10^3)$$

Koyama, Mizuno, Wands
Buchbinder, Khoury, Ovrut
JLL, Renaux-Petel, Steinhardt

Steinhardt & Turok

Cyclic Universe

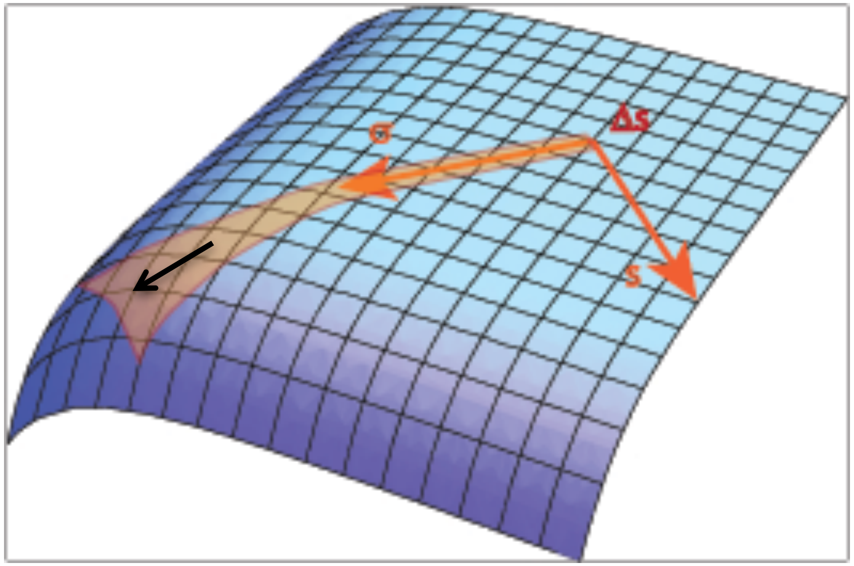


Phases of Evolution	a	H	Time spent
Radiation and Matter	Exp(55)	Exp(-110)	10 Billion yrs
Dark Energy	Exp(N)	1	N*10 Billion yrs
Ekpyrotic	1	Exp(120)	1 Billion yrs
Kinetic	Exp(5)	Exp(-10)	1 s
TOTAL	Exp(60 + N)	1	(N+1)*10 Billion yrs

Necessity of Dark Energy

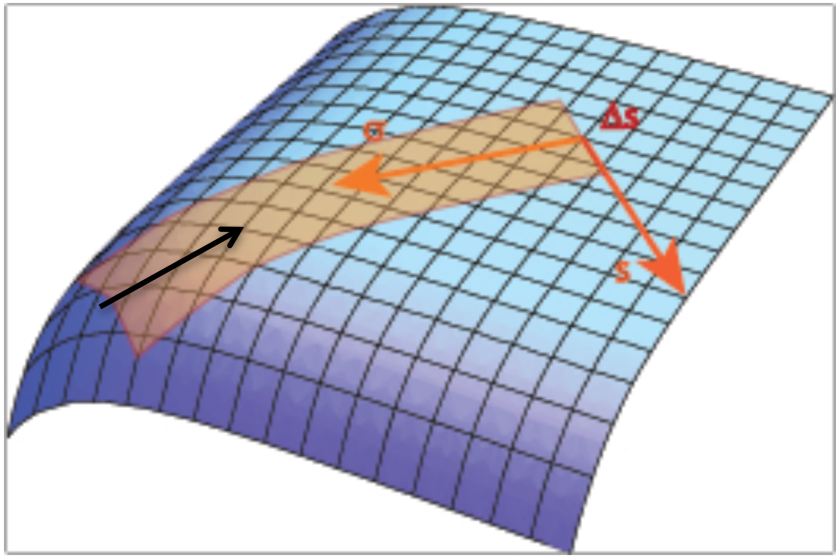
Before the Crunch

Due to instability field values spread



After the Bang

No further instability



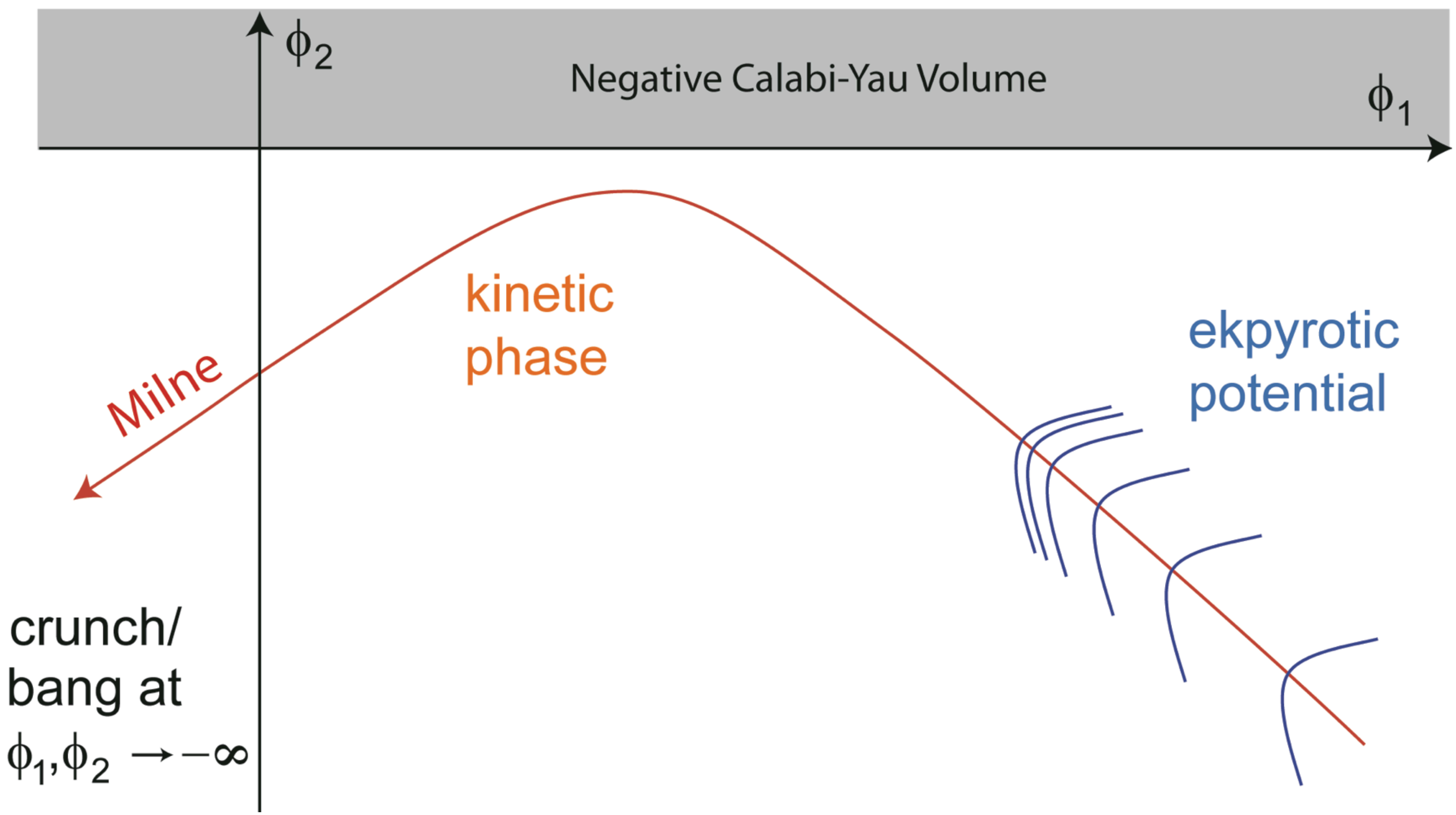
Total losses: Exp(-120) for 120 e-folds of ekpyrosis

But universe grows by factor Exp(60+N) each cycle

→ Need 60 e-folds (or more) of dark energy

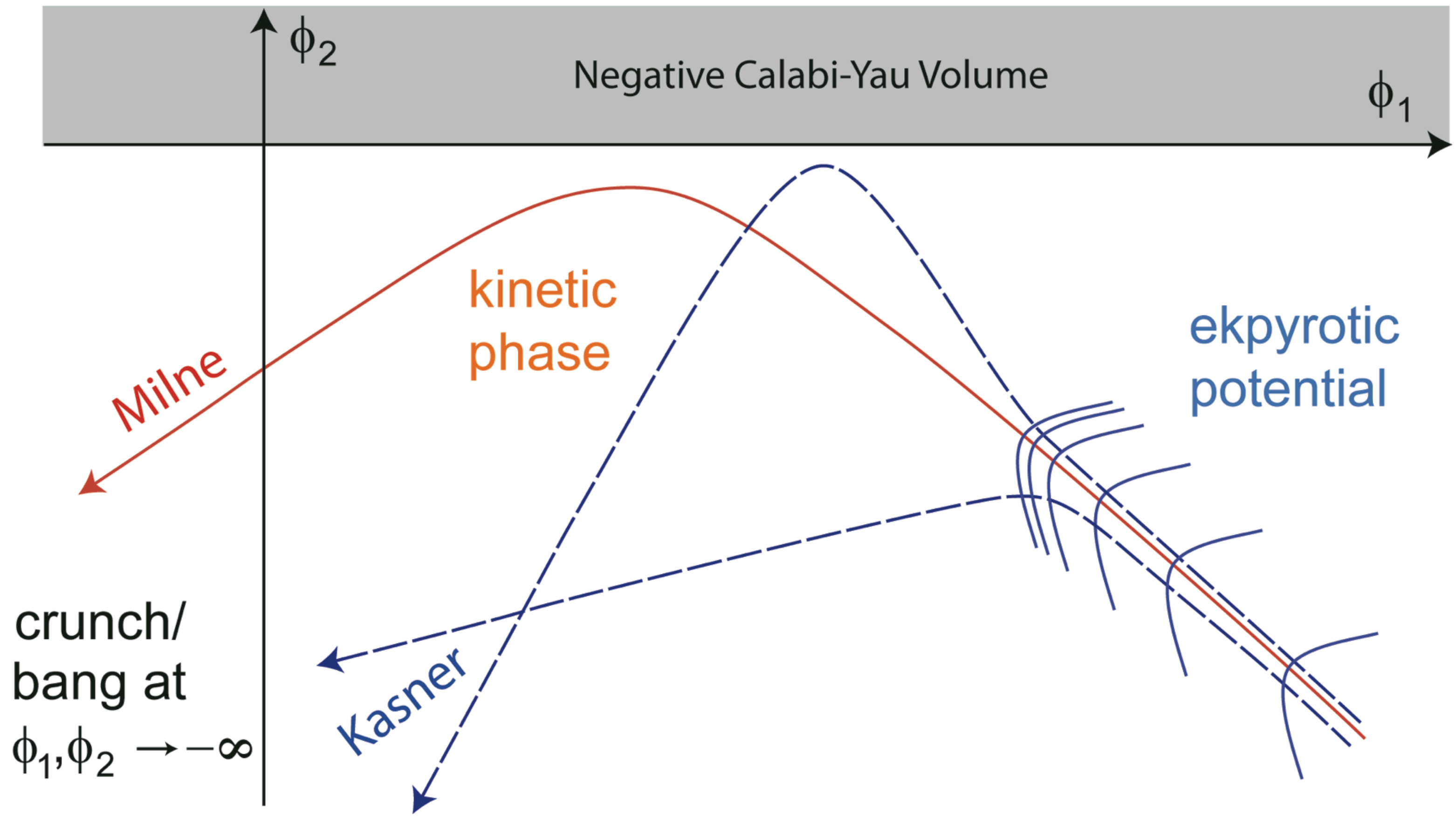
JLL, Steinhardt

Selection at Brane Collision



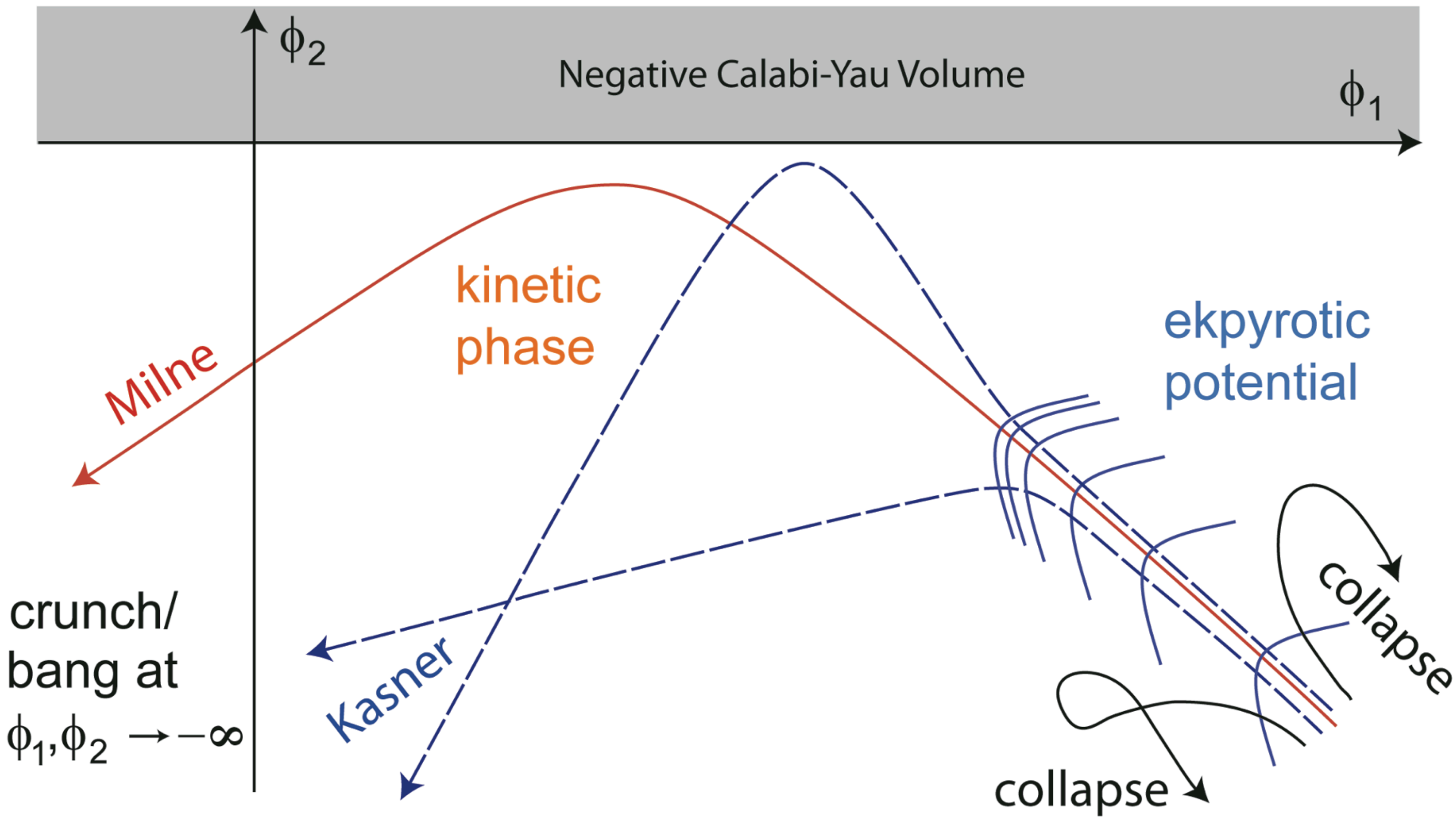
Kinetic conversion & large Q

Selection at Brane Collision



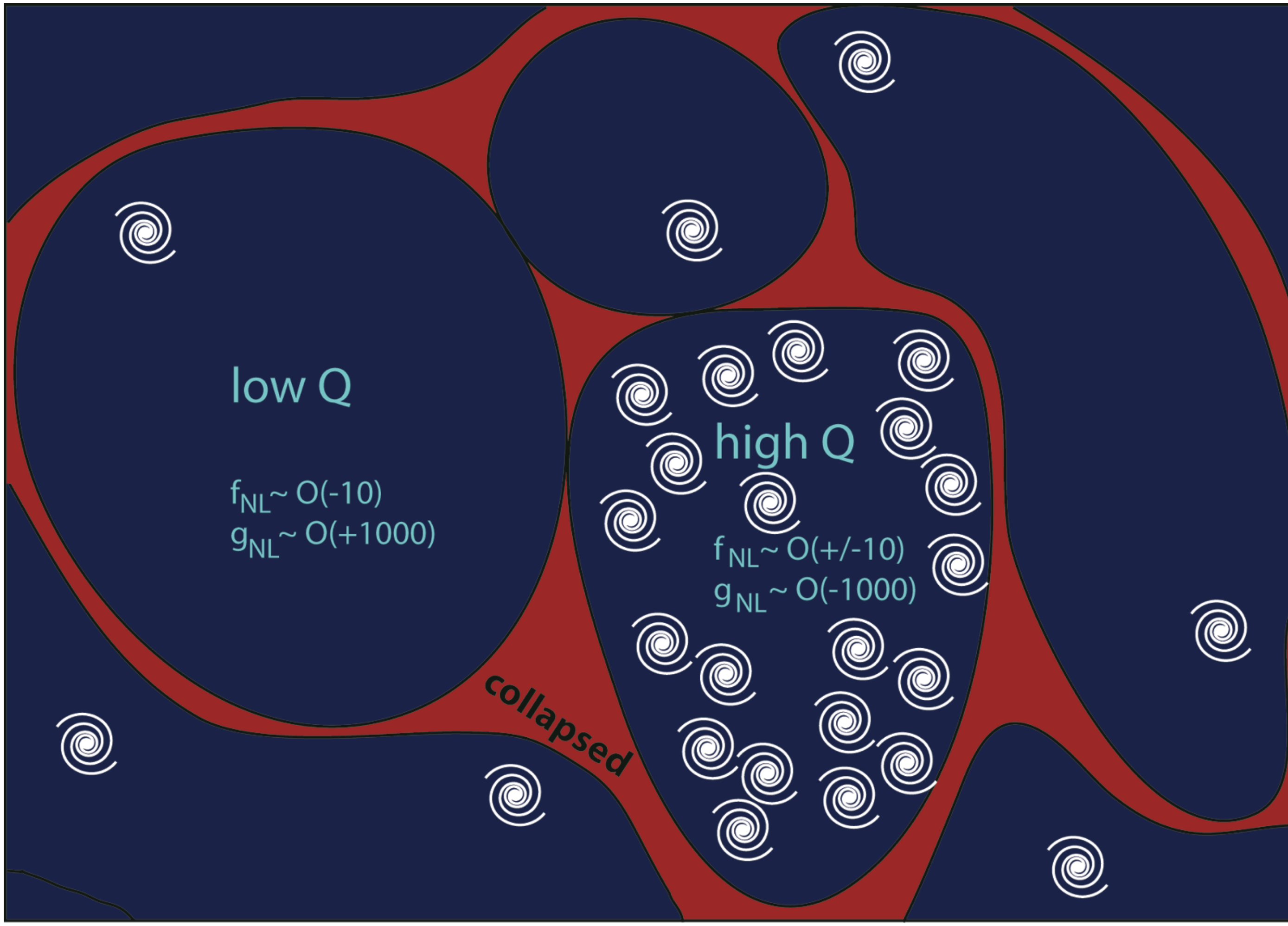
Ekpyrotic conversion & smaller Q

Selection at Brane Collision



Big Crunch acts like a *filter* $\longrightarrow$ high predictivity

Phoenix Universe



We are overwhelmingly likely to live in a high-Q region.
No regions with a significantly higher density of galaxies exist!

JLL, Steinhardt

The Bounce – Non-Singular

In a flat universe $$\dot{H} = -\frac{1}{2}(\rho + p)$$

A non-singular bounce requires $\rho + p < 0$

i.e. a violation of the NEC

Scalar field models:

Ghost condensate

Arkani-Hamed et al.

$$P(X) = -X + X^2$$

Galileons

Nicolis et al.

$$\mathcal{L} = (\partial\phi)^2 \Box\phi + \cdots$$

Buchbinder, Khoury, Ovrut
Creminelli, Senatore
Cai, Easson, Brandenberger
Osipov, Rubakov

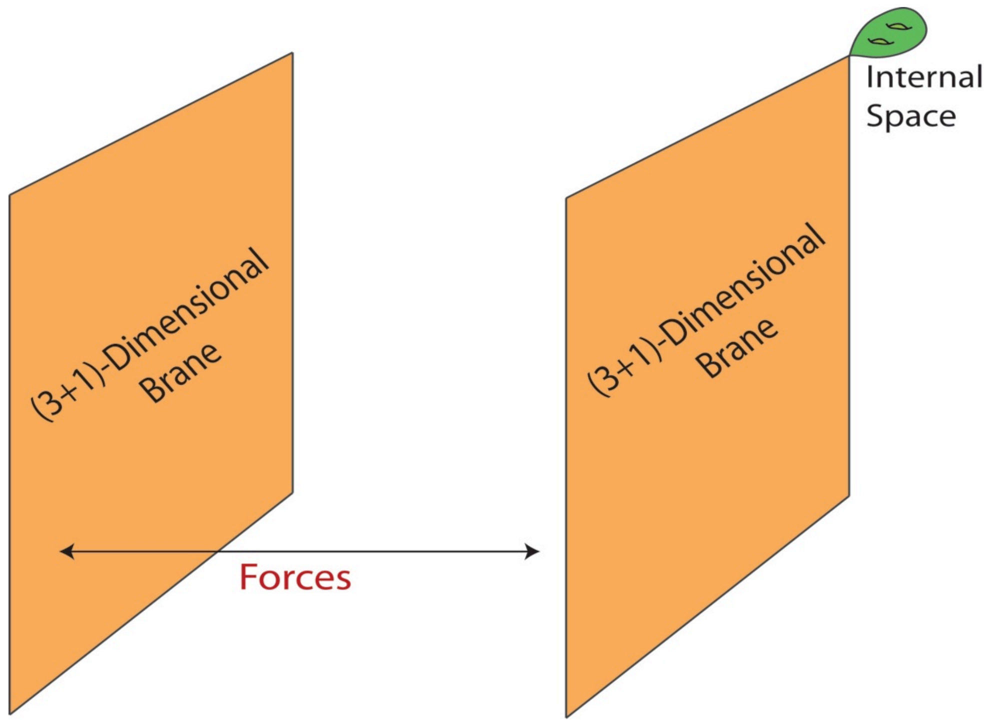
Can such models arise in string theory?
First step: embed in supergravity

Ghost condensate surprisingly unproblematic
- Auxiliary field still auxiliary
- No Higgs mechanism – gravitino remains massless

Galileons
- In supersymmetry always have ghosts
- Open question whether a bounce can occur in regime of validity of a perturbative description

Koehn, JLL, Ovrut

The Bounce - Colliding Branes

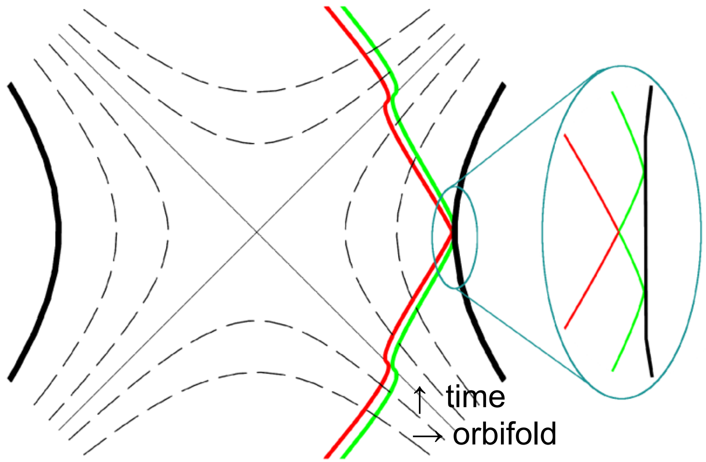


brane collision = big bang

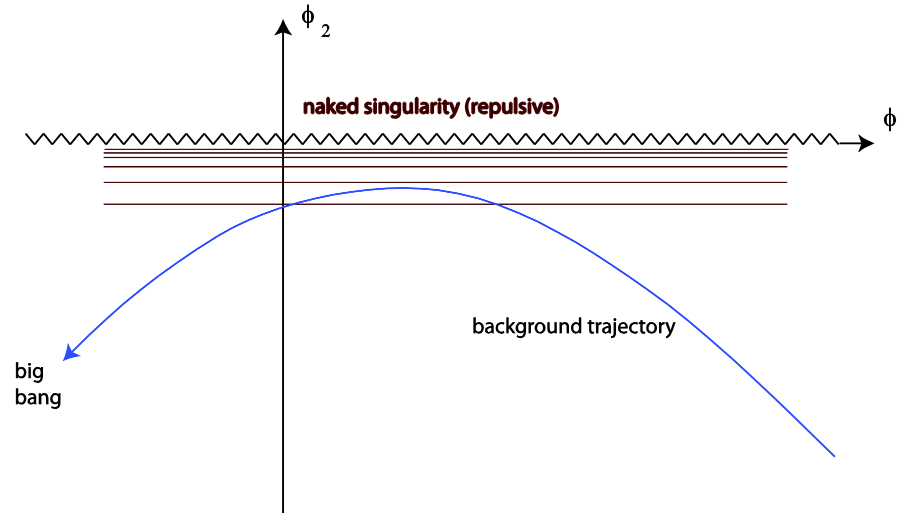
5d (11d) pt of view: brane scale factors finite,
CY volume finite,
orbifold shrinks to zero

Khoury,
Ovrut,
Seiberg,
Steinhardt,
Turok

Solution in Heterotic M-Theory



5d spacetime diagram



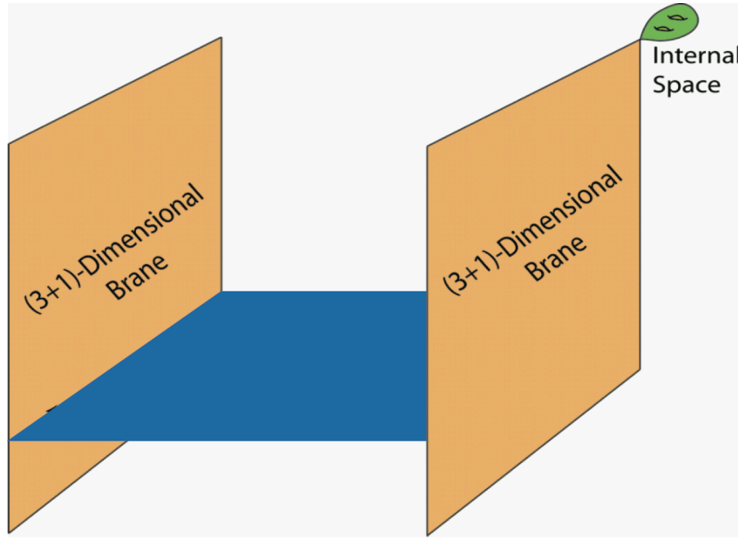
4d scalar field space/moduli space

For small collision velocities, use moduli space approximation

Repulsive potential due to bounce of negative-tension brane

JLL, McFadden, Turok

Lightest States: Winding Membranes



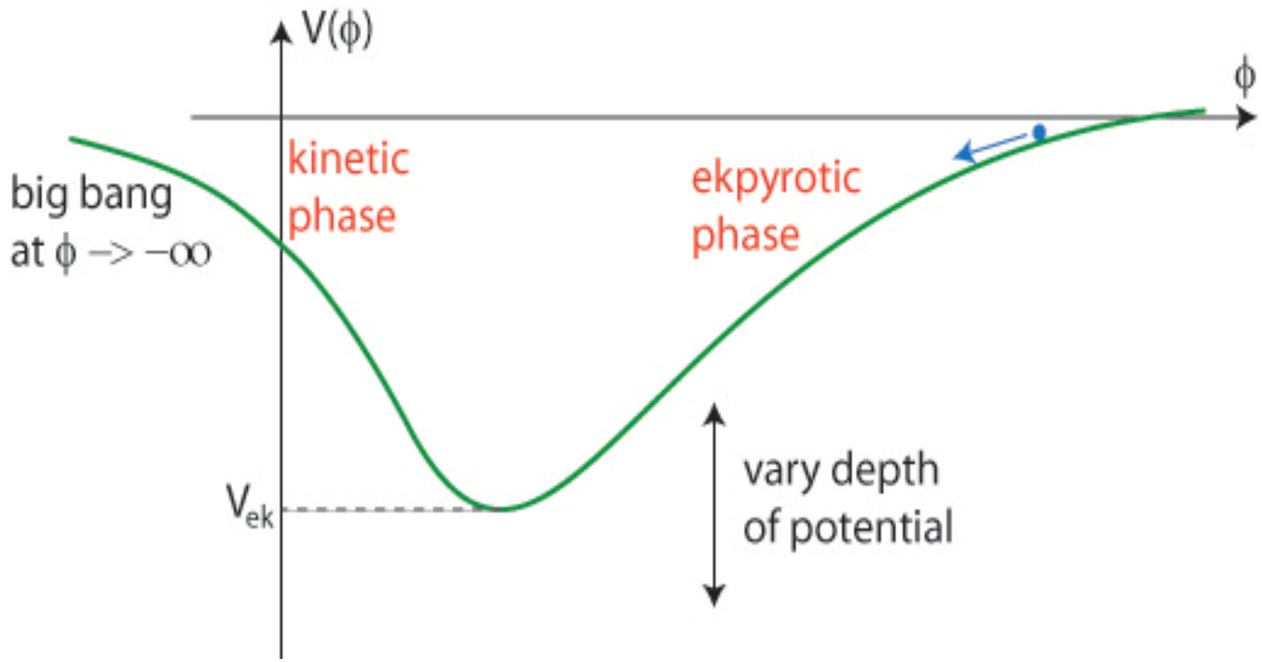
Branes are flat and parallel near crunch – opposite of chaotic mixmaster crunch

Lightest states: winding membranes – hence perturbative gravity is described by these winding states

- Eqs. Of motion of winding membranes are regular at t=0
- Semi-classical production of membranes at crunch is small as long as collision velocity is non-relativistic

Turok
Perry,
Steinhardt

Implications for the Amplitude Q



Consider varying the depth of the potential:

- Deeper potential implies larger amplitude of fluctuations
- Deeper potential implies higher collision velocity

Implications for the Amplitude Q

- Amplitude Q of perturbations

$$Q^2 \approx \frac{\epsilon V_{ek}}{10^3}$$

$\epsilon = \mathcal{O}(10^2)$ Equation of state

Larger ε would lead to more structure, but is also more tuned (and perhaps unnatural in string theory)
Take value of ε that gives observed spectral tilt

- Speed of collision y_0

$$y_0 \approx d_{11}\sqrt{\frac{V_{ek}}{\epsilon}}$$

d_{11} Initial brane separation

Combining these relations:

$$Q \approx \frac{y_0}{d_{11}} = \frac{\text{collision velocity}}{\text{initial brane separation}}$$

In order to get observed value of Newton's constant, must take

$$d_{11} \approx 10^{3.5}$$

Witten
Banks & Dine

Bound on the speed: must be non-relativistic

$$y_0 \lesssim 0.1$$

Turok, Perry
& Steinhardt

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Witten
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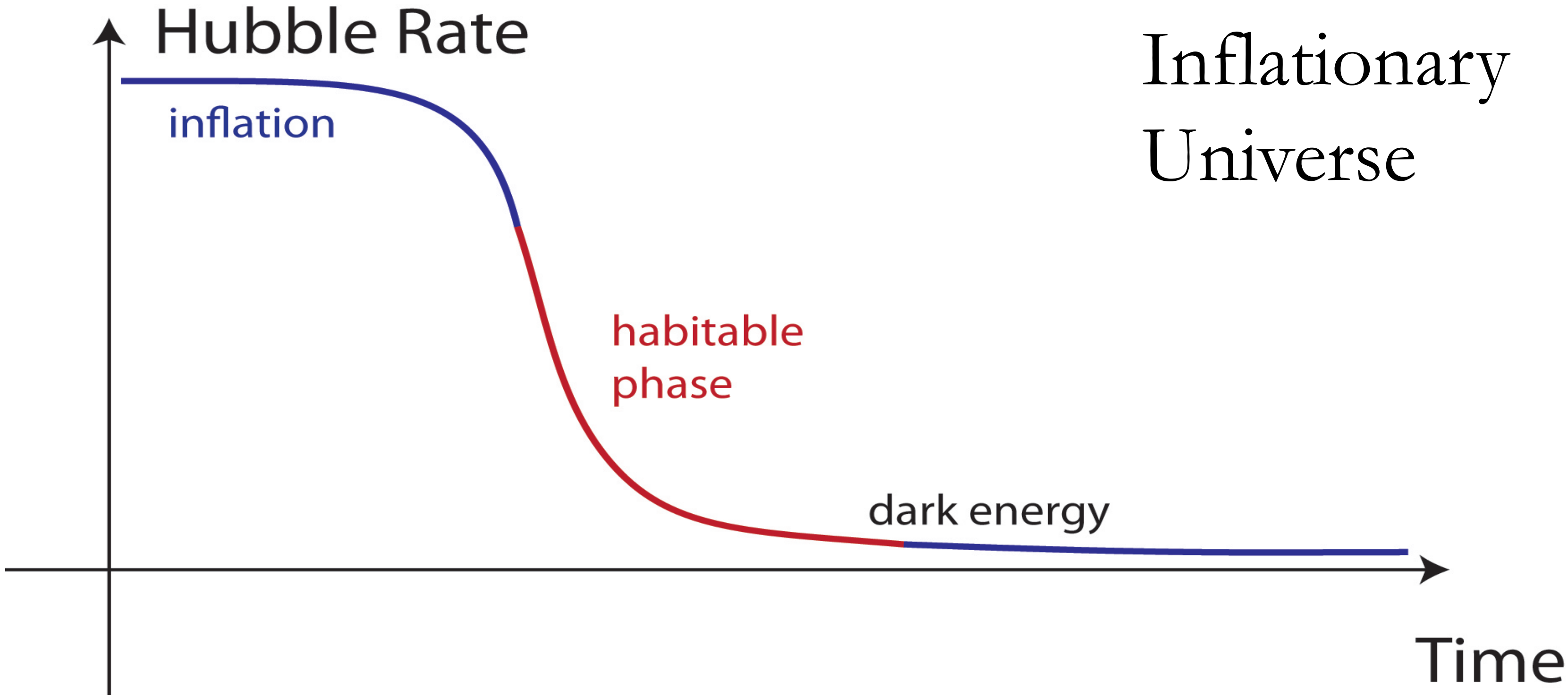
Turok, Perry & Steinhardt

→ Bound on Q, namely

$$\boxed{Q \leq 10^{-4.5}}$$

JLL, Steinhardt

Quantum Stability: Inflation



Inflationary Universe

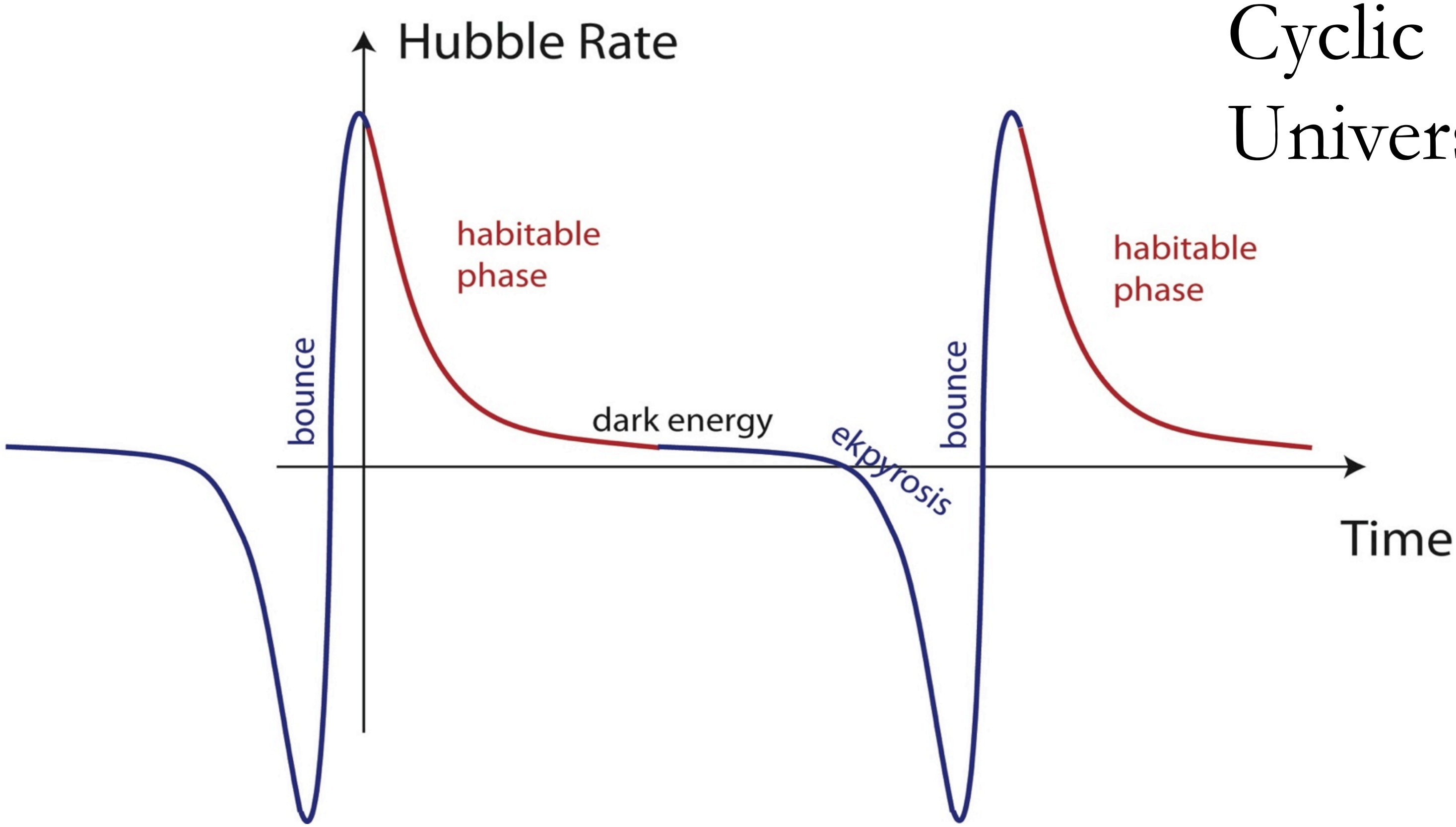
$$H_{smoothing} \gg H_{life}$$

Size of quantum fluctuations ~ H

Rogue regions amplified

⟶ Quantum instability (slow-roll eternal inflation)

Quantum Stability: Cyclic Universe



Cyclic Universe

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

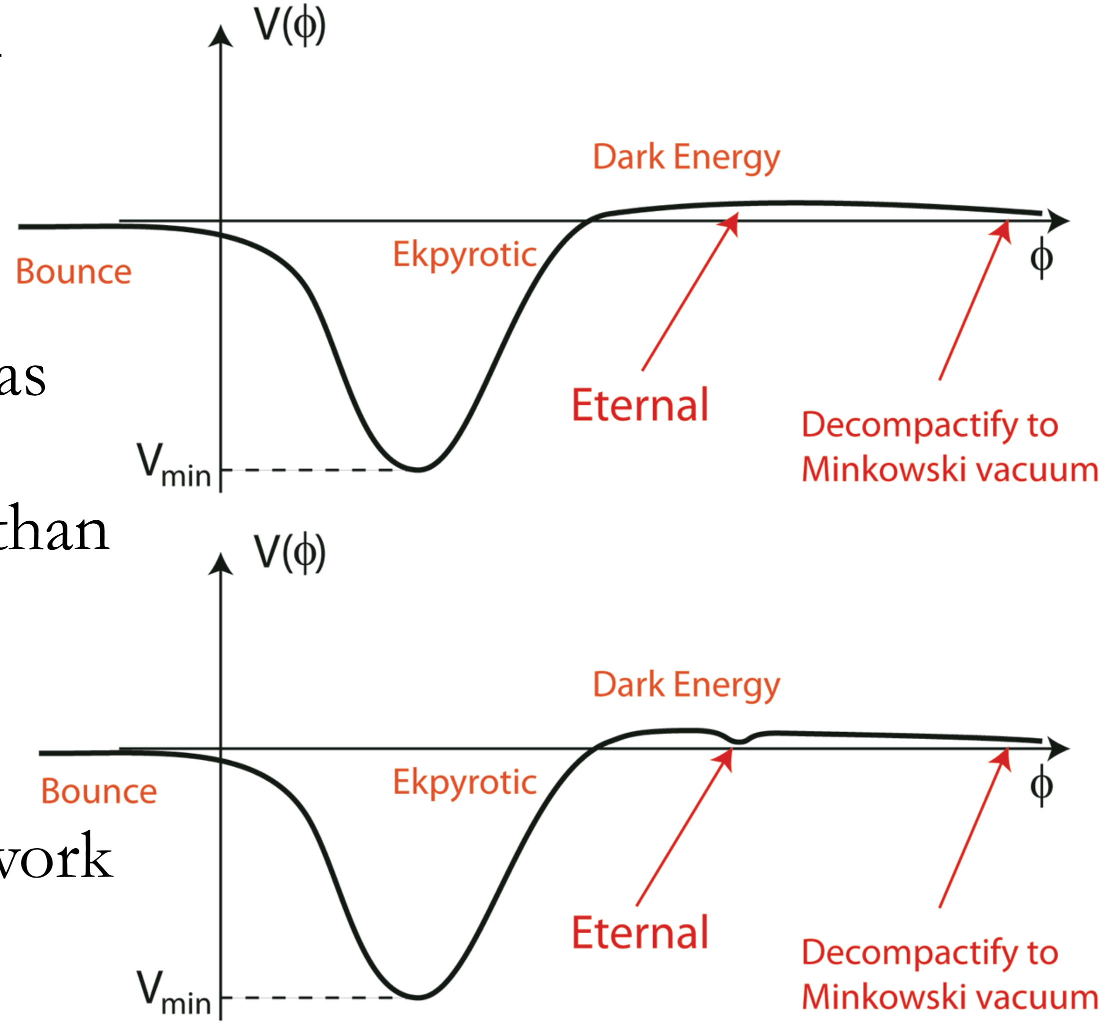
Rogue regions simply cause small time delay

→ Quantum stability

M. Johnson, JLL

Extension of the basic model: Incorporating Eternal Inflation

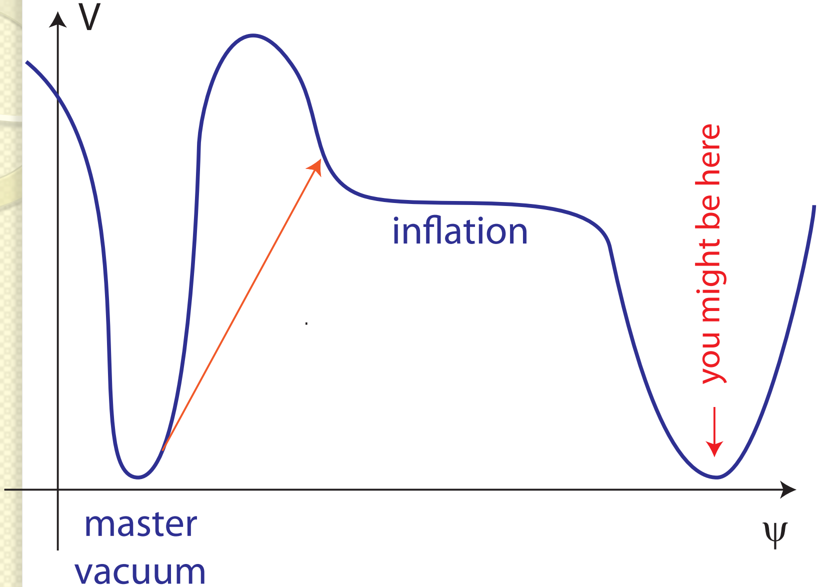
- Assume no higher-Lambda vacuum accessible
- Still no (strong) measure problem, as long as rate of tunneling is faster than rate of producing Boltzmann brains
- Cf. de Sitter equilibrium framework of A. Albrecht

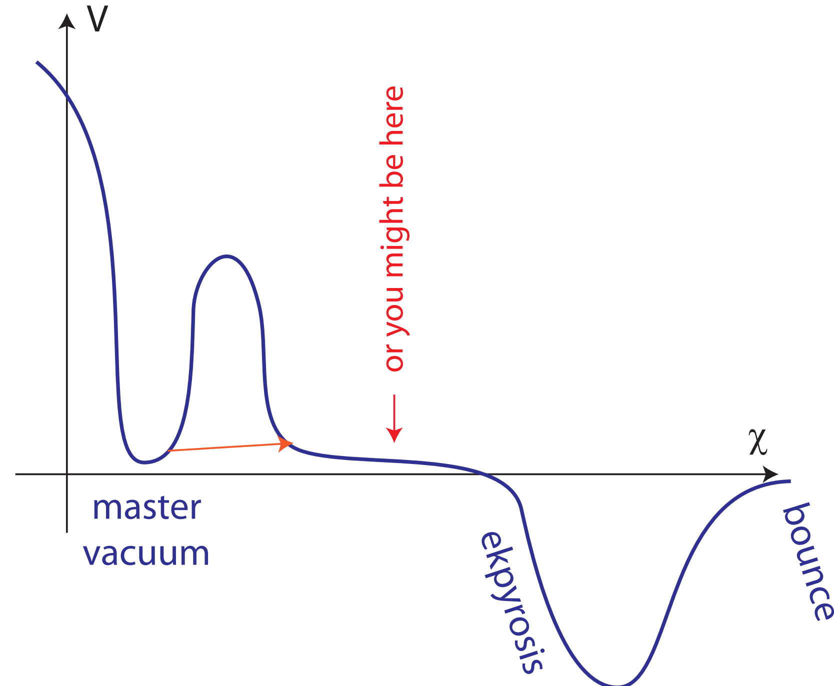


Extending to the Landscape

The Diverse Multiverse – 4d view

Pocket universes will contain *all* possible cosmologies





$$\frac{Q_{Cyc}}{Q_{Inf}} \approx \frac{\Gamma_{M\to Cyc}}{\Gamma_{M\to Inf}} \frac{p}{(1-p+t_{Cyc}\Gamma_{Cyc\to M})}$$

Probability to make it through bounce

For inflation need large up-tunneling; not so for cyclic models

Cycles are further preferred because they produce observers repeatedly

Johnson, JLL

Scorecard - Inflation

Positive:

- Scale invariance comes out naturally
- No unknown physics (except reheating) between inflation and now

Negative:

- Quantum instability
- No explanation for amplitude of perturbations
- No role for dark energy (100 orders of magnitude difference in vacuum energy is puzzling)

Mixed:

- Classical stability: attractor but small number of e-folds (<<60) preferred Better explanation after tunneling?

Scorecard – Cyclic Universe

Positive:
- Quantum stability
- Amplitude of perturbations can be explained
- Dark energy plays an essential role

Negative:
- Insufficient understanding of bounce
- In current models there is no evolution from cycle to cycle and hence no possibility of explaining fine-tuning of a number of parameters

Mixed:
- Classical instability: makes ekpyrosis less likely but enhances predictivity