Title: Does the Cyclic Universe Avoid the Measure Problem?

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Abstract: In its best understood version, the Steinhardt-Turok cyclic universe contains two crucial ingredients: an unstable field trajectory during the ekpyrotic phase, and the subsequent brane collision corresponding to the crunch/bang transition. These two features act as strong selection principles and determine the broad physical properties of the universe emerging from the bang. As such, they significantly alleviate (and perhaps resolve) the measure problem that is inherent to all cosmological models that produce universes with a range of physical properties.

Does the Cyclic Universe Avoid the Measure Problem?

Jean-Luc Lehners
Max Planck Institute for Gravitational Physics
(Albert-Einstein-Institute)

Based on JLL, Paul Steinhardt – 0812.3388, 1008.4567
JLL, Paul Steinhardt and Neil Turok – 0910.0834
Adam Brown, Matt Johnson, JLL – to appear

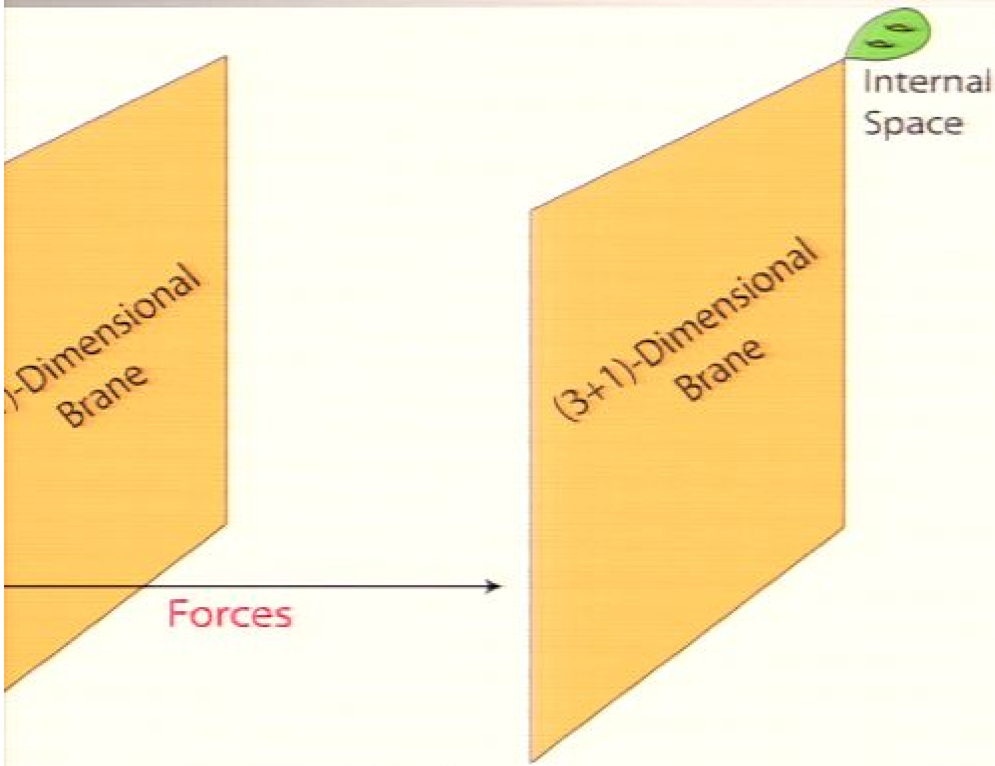
What Makes the Cyclic Universe Predictive?

Two key differences with inflation:

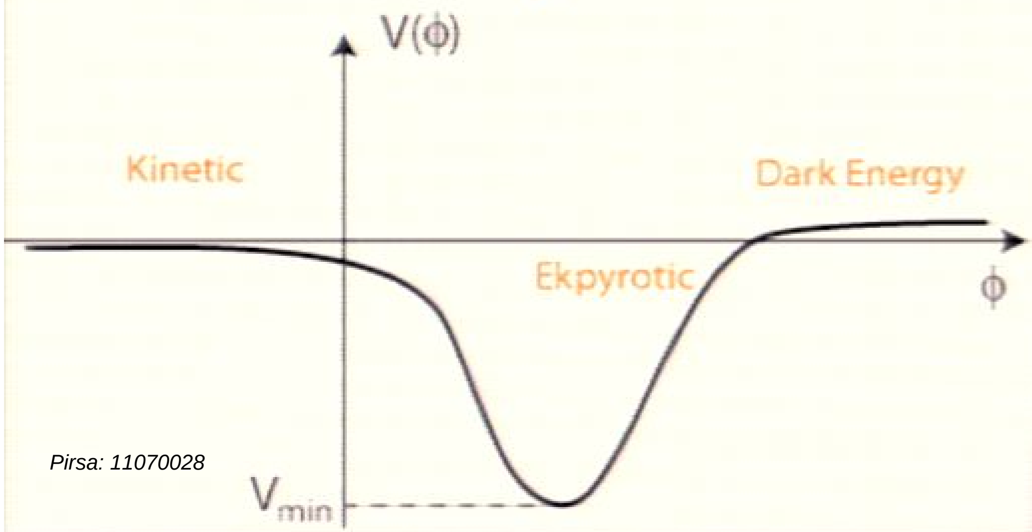
- Smoothing occurs at low H
- There is a strong instability in the model, which ends up playing the role of a selection principle

Colliding Branes vs. 4d EFT

Khoury, Ovrut, Steinhardt & Turok



Higher-dimensional picture
Brane collision = Big Bang



4d effective potential models inter-brane forces

Derivation from string theory is an open problem

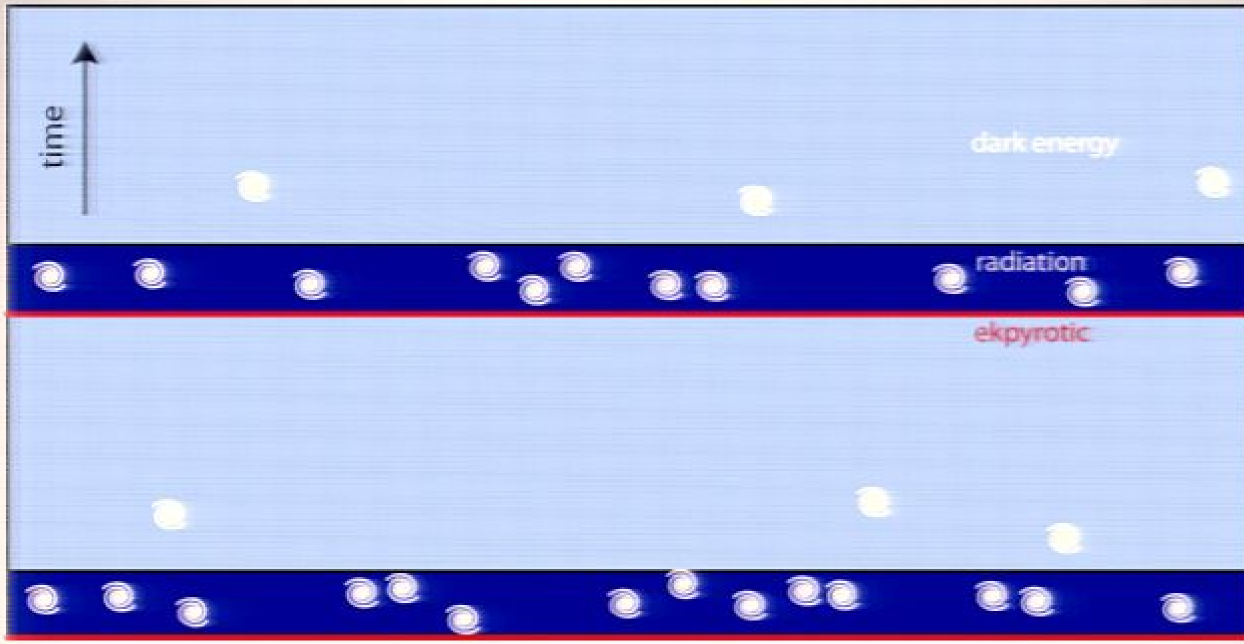
Dynamics and Timescales

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

Evolution of H cyclic

Large net expansion each cycle

Low Hubble Rate, Except When Ordinary Observers are Produced



No strong measure problem:

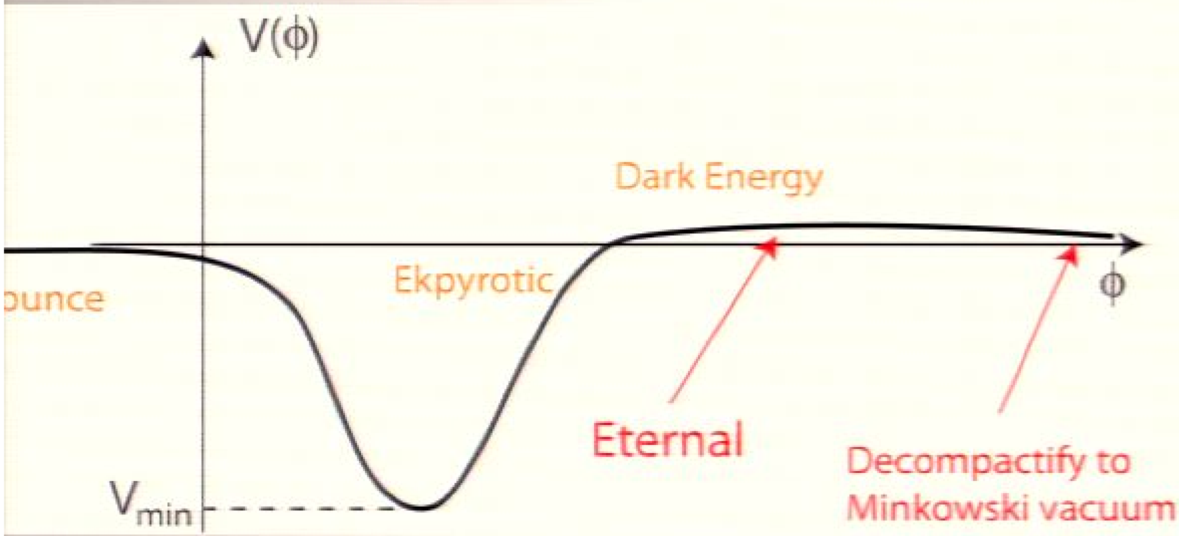
- No amplification of rare large quantum fluctuations
- Vast majority of observers do not live right next to cut-off
- No Boltzmann brain problem

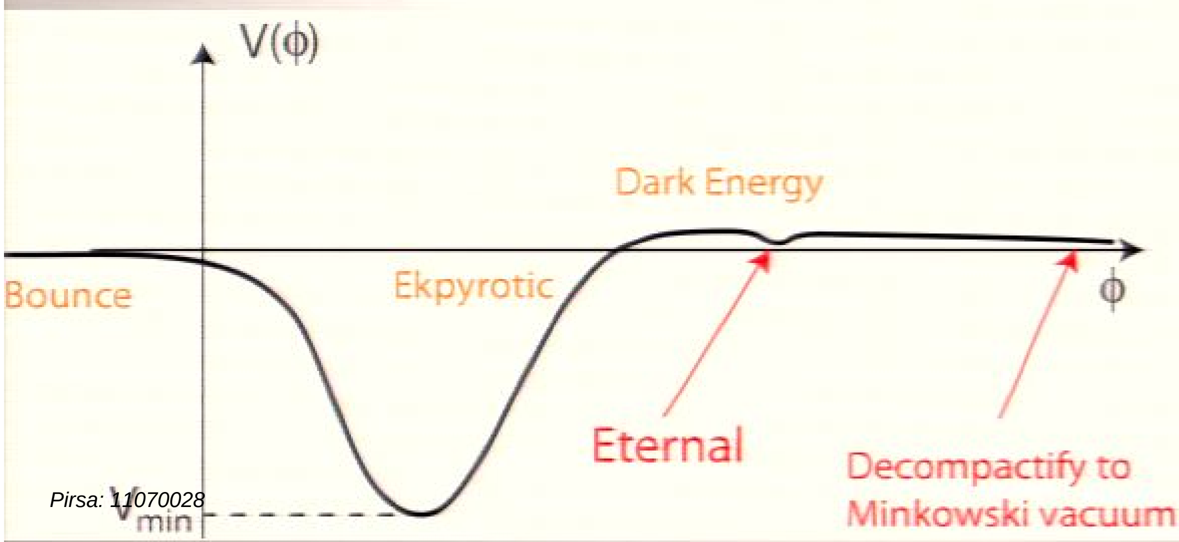
Ordinary Observers produced every Trillion years

vs. one BB produced every Exp(10^60) years

A. Brown, M. Johnson, JLL

Special case: Incorporating Eternal Inflation

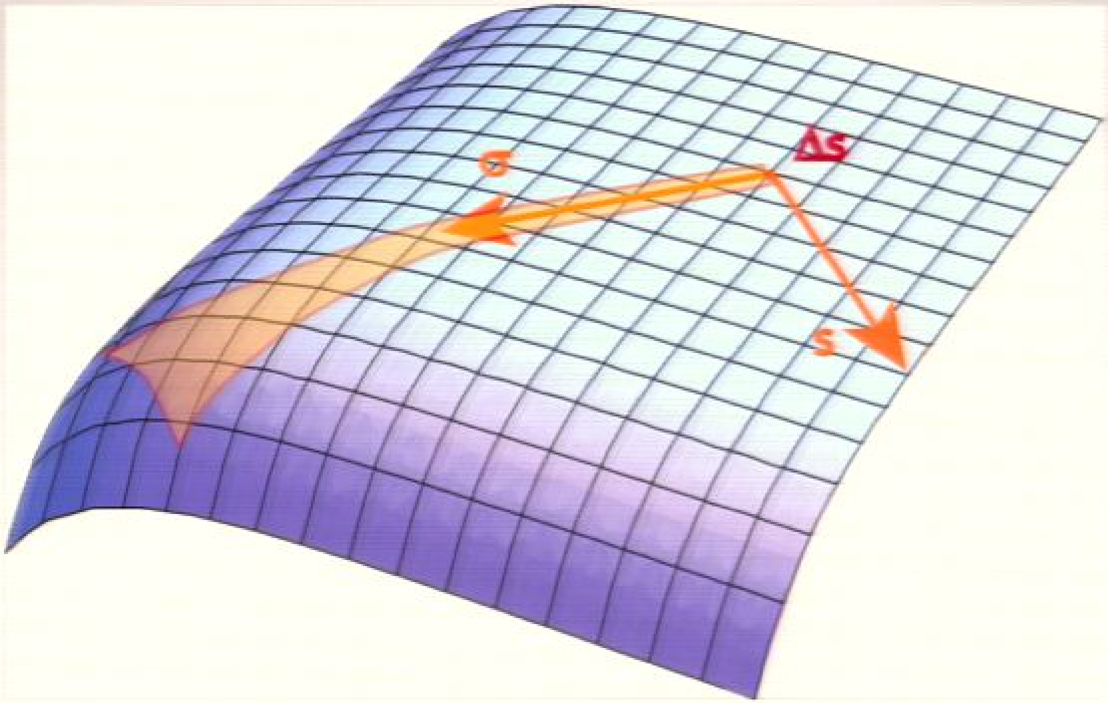




- Assume no higher-Lambda vacuum accessible
- Still no (strong) measure problem, as long as rate of tunneling is faster than rate of producing Boltzmann brains
- Cf. de Sitter equilibrium framework of A. Albrecht

Instability of the Potential

Finelli
Notari, Riotto
JLL, McFadden, Steinhardt, Turok
Koyama, Mizuno, Wands
Buchbinder, Khoury, Ovrut
Creminelli, Senatore
JLL, Renaux-Petel



Perturbations in adiabatic direction blue

Perturbations in entropy direction scale-invariant

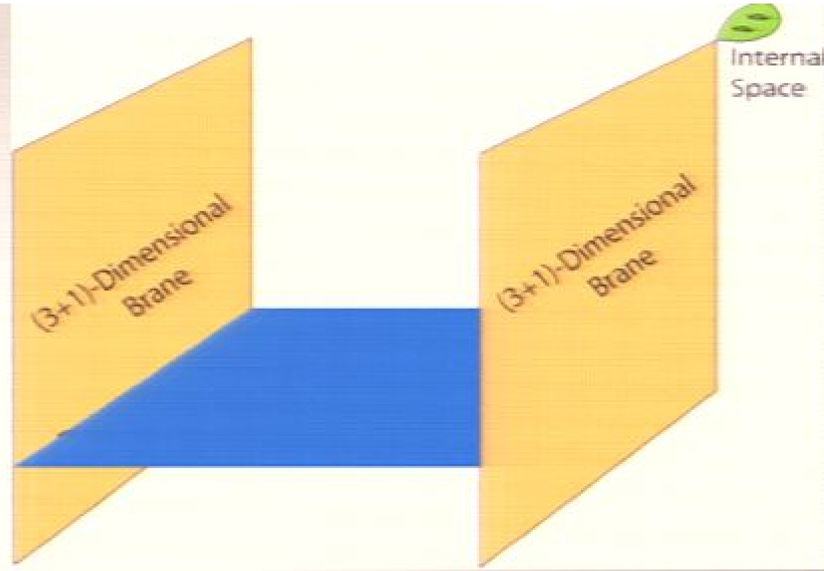
They get converted to adiabatic perturbations as trajectory bends, either:

- During the ekpyrotic phase fNL ~ O(-10) gNL ~ O(+1000)
- During the kinetic phase fNL ~ O(+/- 10) gNL ~ O(-1000)

Q ~ V^(1/2) Amplitude larger as the turn occurs further down the potential

Selection at 11d

Brane Collision

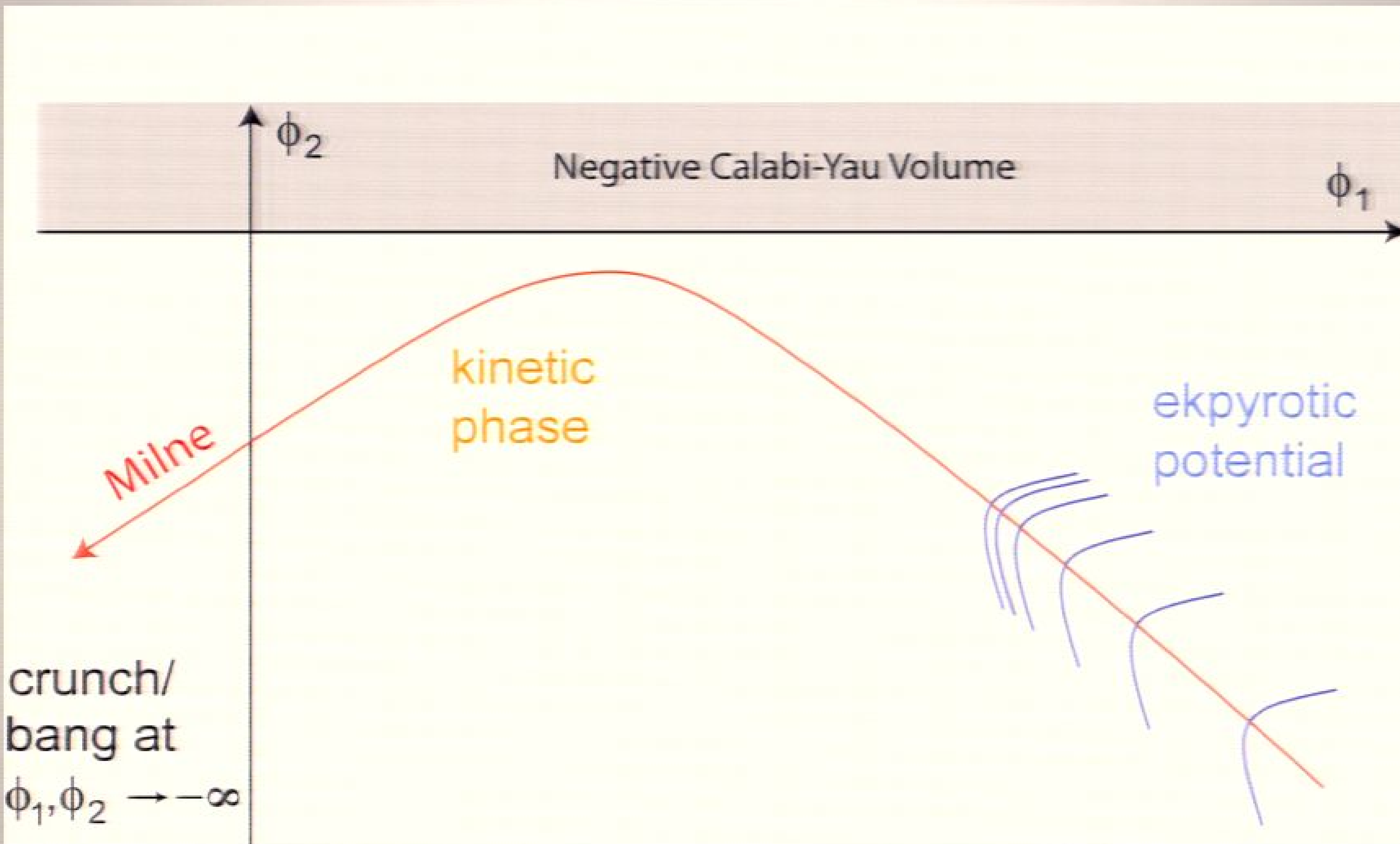


ajectories with long ekpyrotic phase:
4d spacetime flat in approach to collision (curvature corrections small)
→ branes flat
ightest states: M2-branes stretching between boundary branes
their eqs. of motion are regular at t=0
semi-classical particle production ~ (collision velocity)^#
onjecture these regions to make it through the bounce

Turok, Perry, Steinhardt
Copeland, Niz, Turok

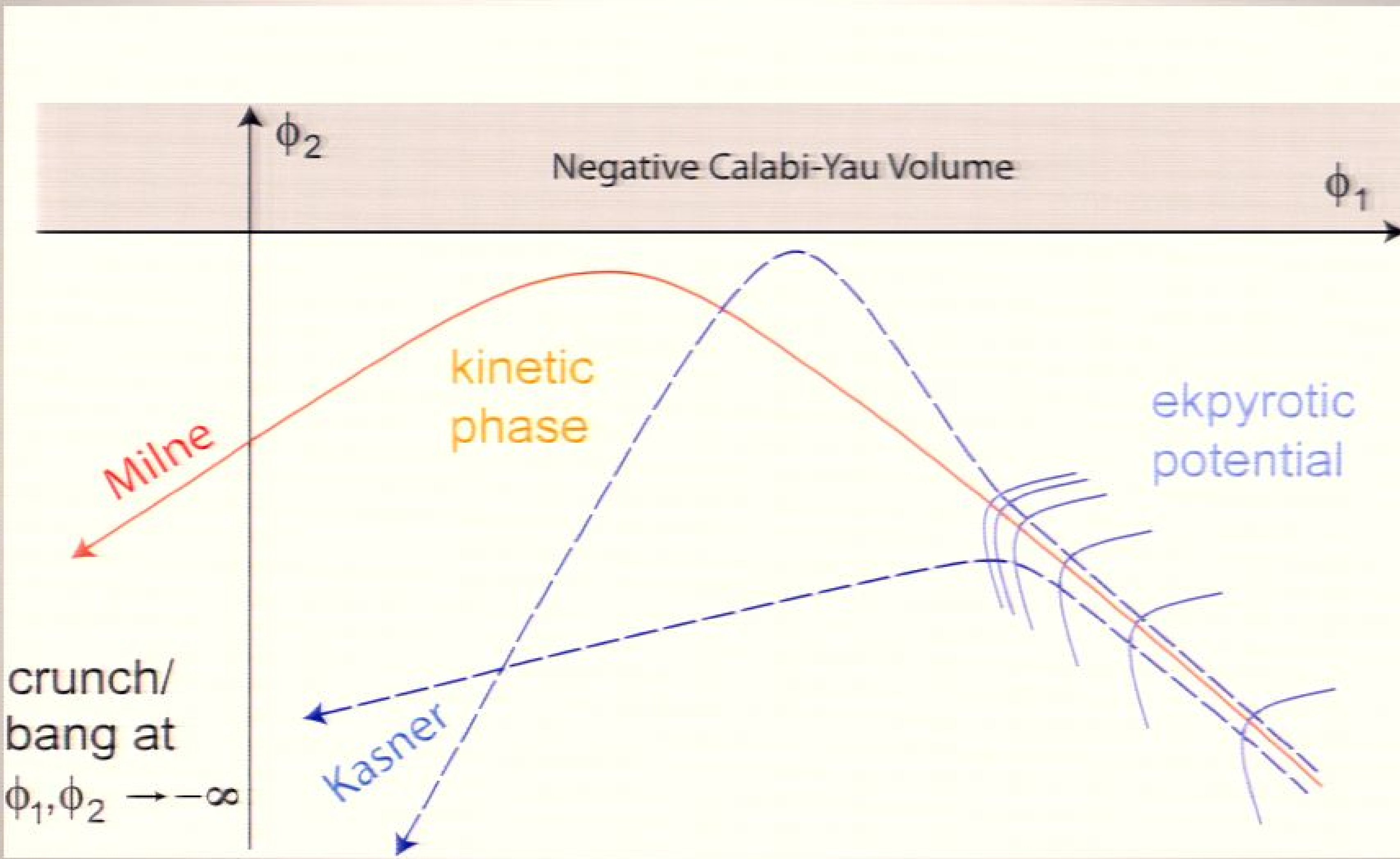
ajectories with short ekpyrotic phase:
develop large curvature anisotropies in approach to crunch
arge particle production at crunch
onjecture these regions to re-collapse rapidly

Selection at Brane Collision



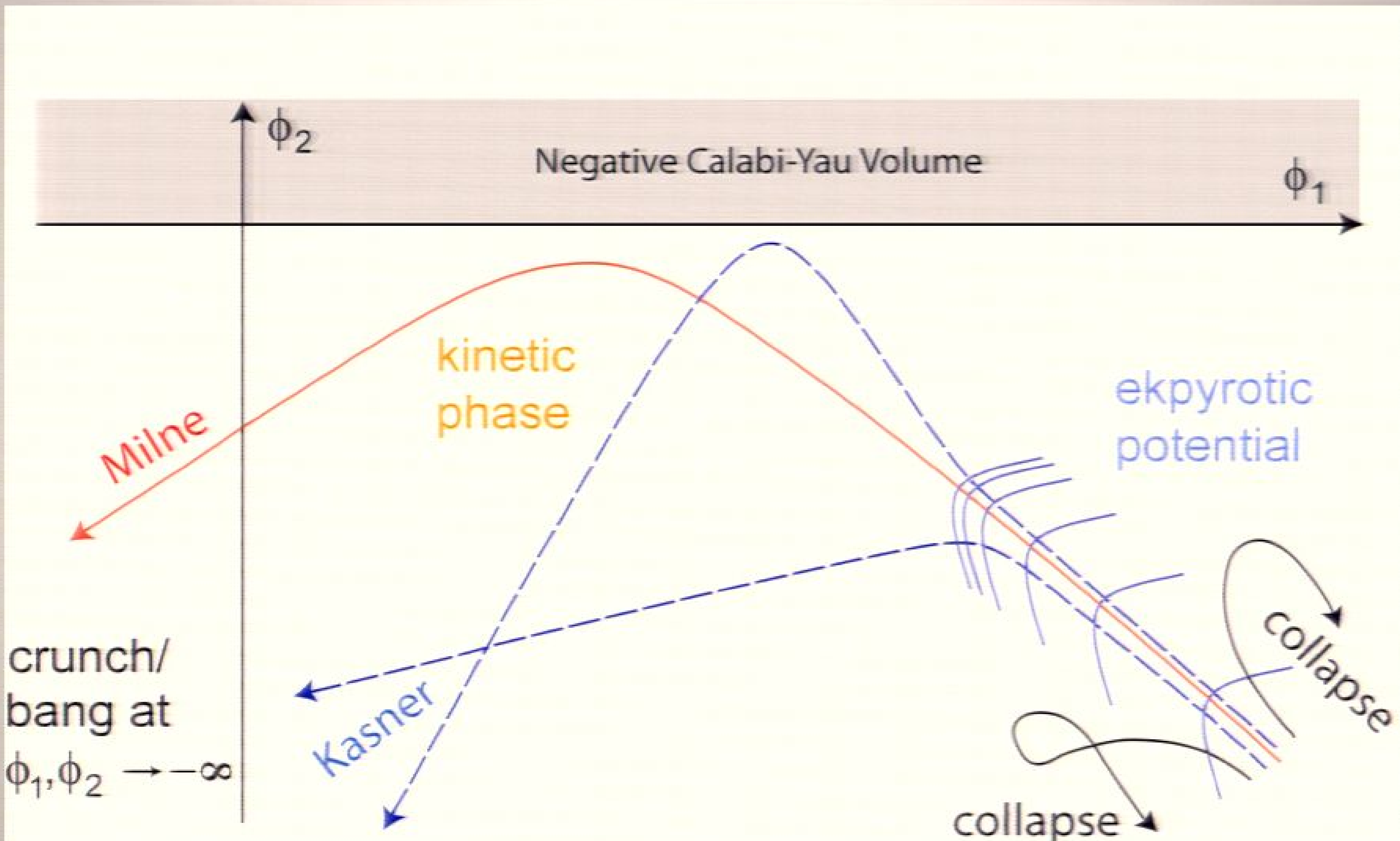
Kinetic conversion & large Q

Selection at Brane Collision

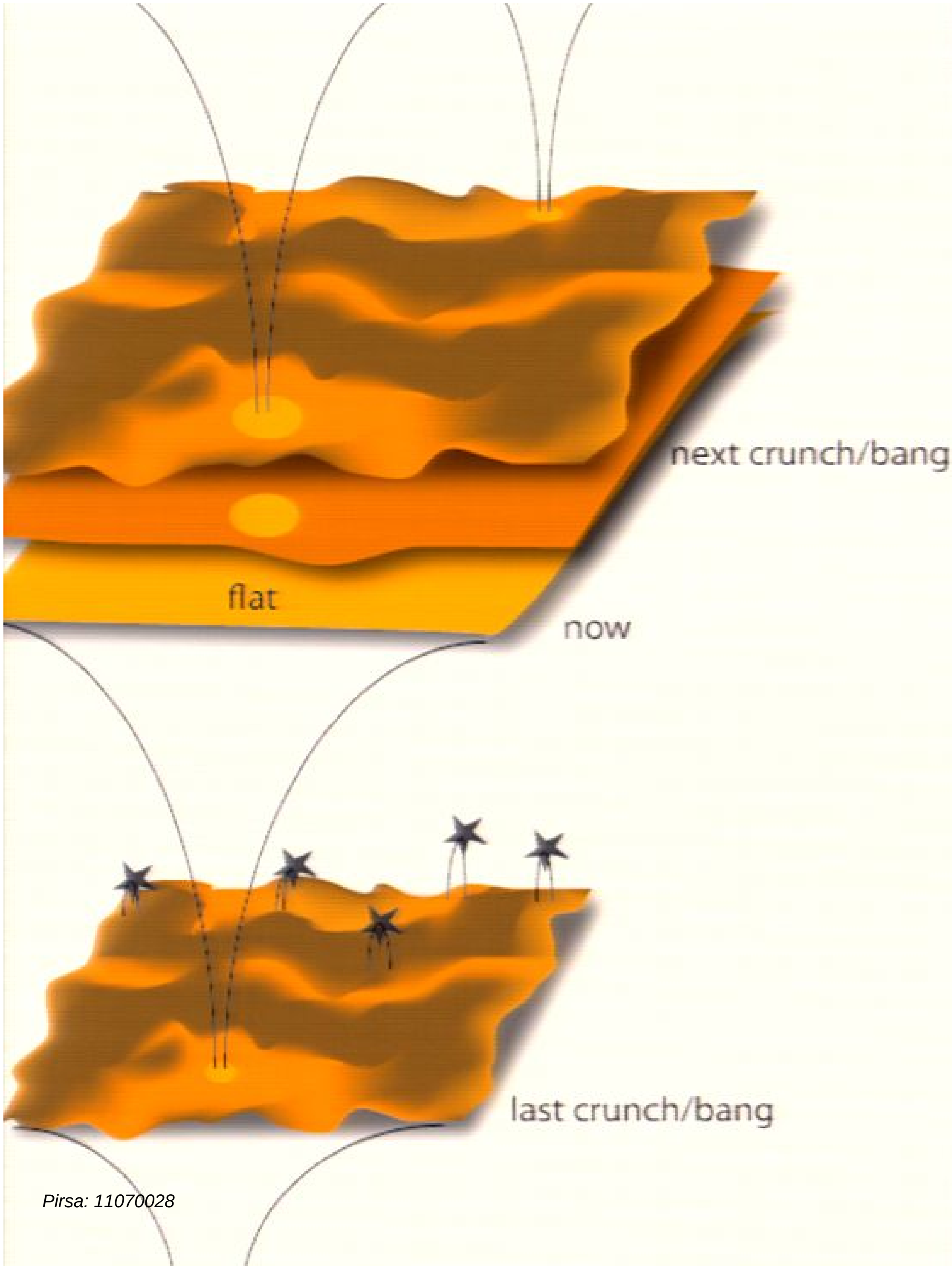


Ekpyrotic conversion & smaller Q

Selection at Brane Collision



All trajectories

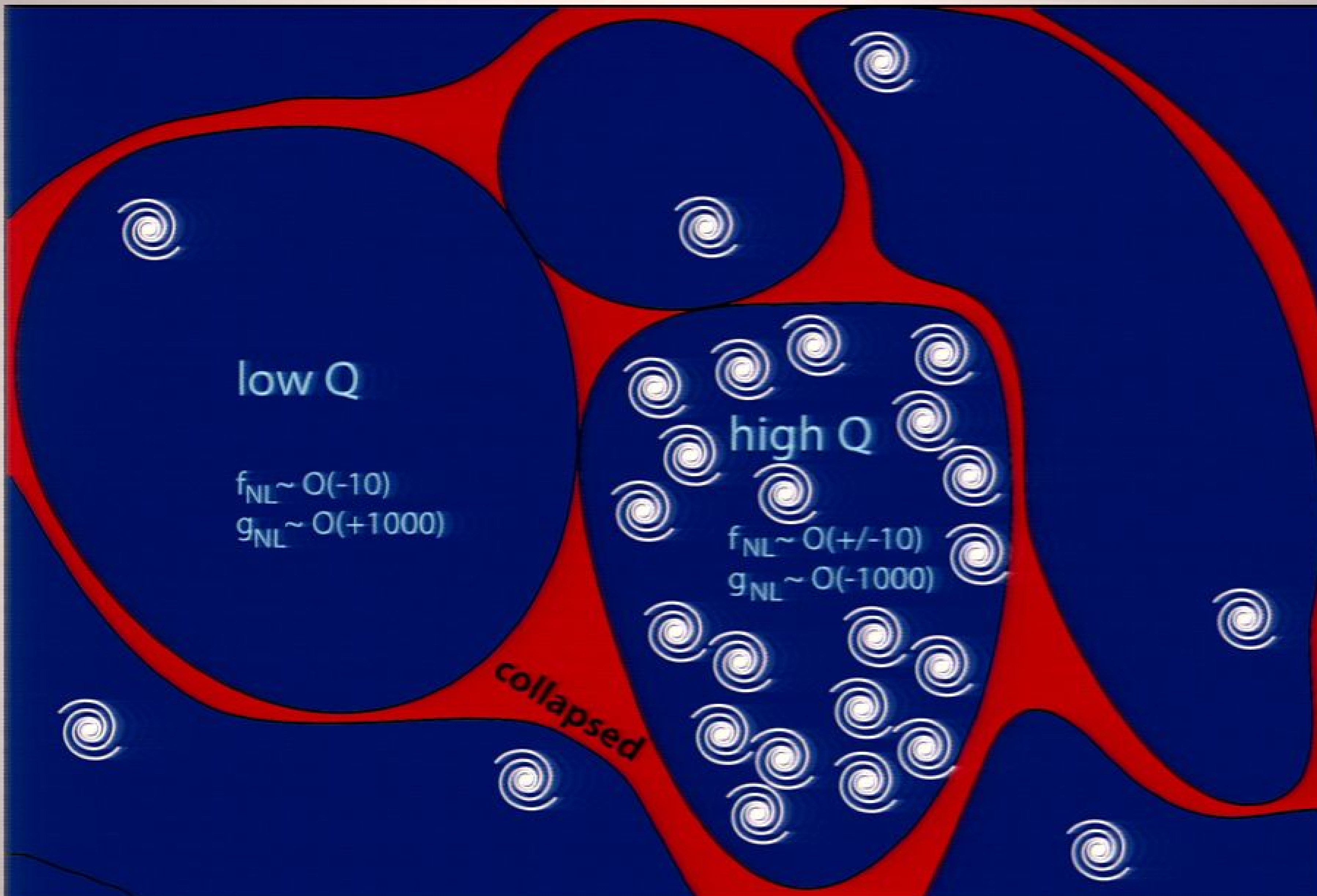


Phoenix Universe: Global History

Flat/habitable regions are **selected** at crunch/bang and expand vastly in radiation, matter and dark energy phases
Virtually all other regions collapse and stop growing and cycling

Dark energy plays an essential role in **amplifying** selected regions

Phoenix Universe: Spatial Slice



ighest-Q region contains more structure than all lower-Q regions combined

Dynamically Selecting 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:

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

What value of d_{11} should we take?

In heterotic M-theory d_{11} and the volume of the Calabi-Yau space determine Newton's constant G_N and the grand unified gauge coupling α_{GUT}

If we use as input the observed value of G_N and α_{GUT} then we should take ($8\pi G = 1$)

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

Witten

What about the collision speed?

Energy of collision $\propto y_0^2$

For higher collision speeds, more matter is produced at the bang

When the speed is too high, the universe over-closes and re-collapses (the branes stick together)

Turok, Perry & Steinhardt

→ Bound on the speed: must be non-relativistic

$$y_0 \lesssim 0.1$$

Bound on Q, namely

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

→ Correlation between Q, ε, G_N, α_{GUT} and spatial flatness,

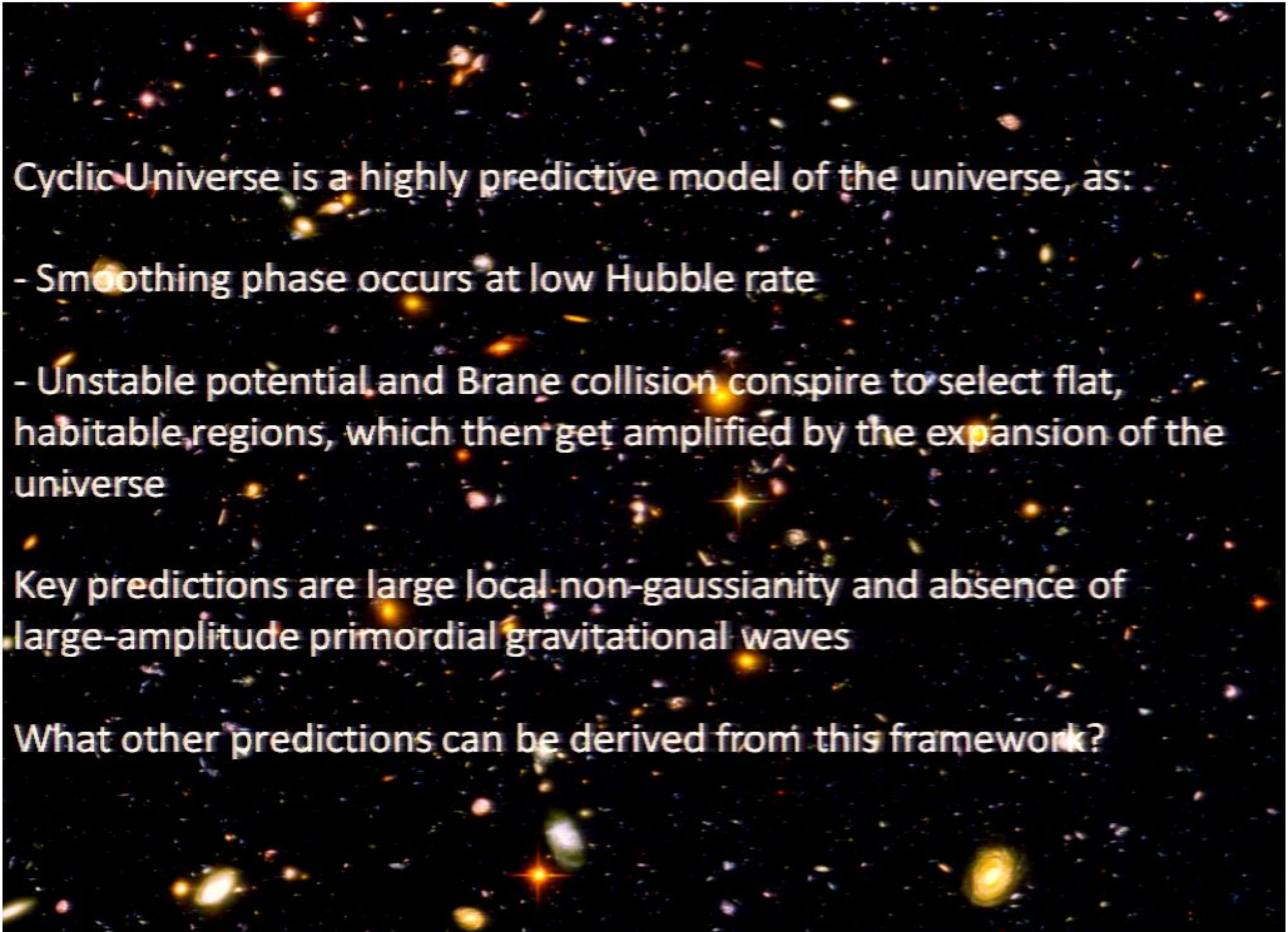
as well as non-gaussianity parameters (for saturation of Q bound)

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

$$g_{NL} \sim \mathcal{O}(-1000)$$

and absence of large primordial gravity waves

PJ. Steinhardt



Cyclic Universe is a highly predictive model of the universe, as:

- Smoothing phase occurs at low Hubble rate

- Unstable potential and Brane collision conspire to select flat, habitable regions, which then get amplified by the expansion of the universe

Key predictions are large local non-gaussianity and absence of large-amplitude primordial gravitational waves

What other predictions can be derived from this framework?