Quo vadis Cosmology?

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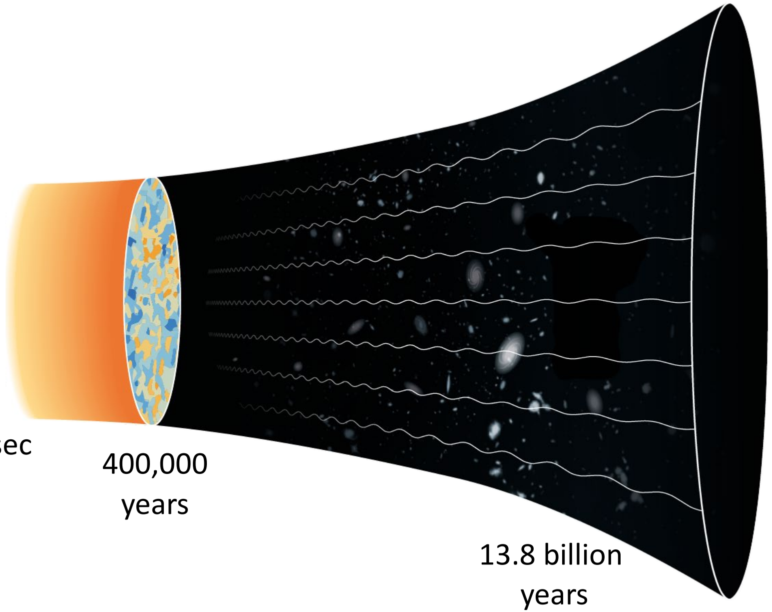
The Road to Precision Cosmology

Michael Turner, Ann. Rev. Nucl. Part. Sci. (2022)

The past 50 years has seen cosmology go from a field known for the errors being in the exponents to precision science . . . with the ΛCDM paradigm as its crowning achievement.



1 sec
400,000 years
13.8 billion years

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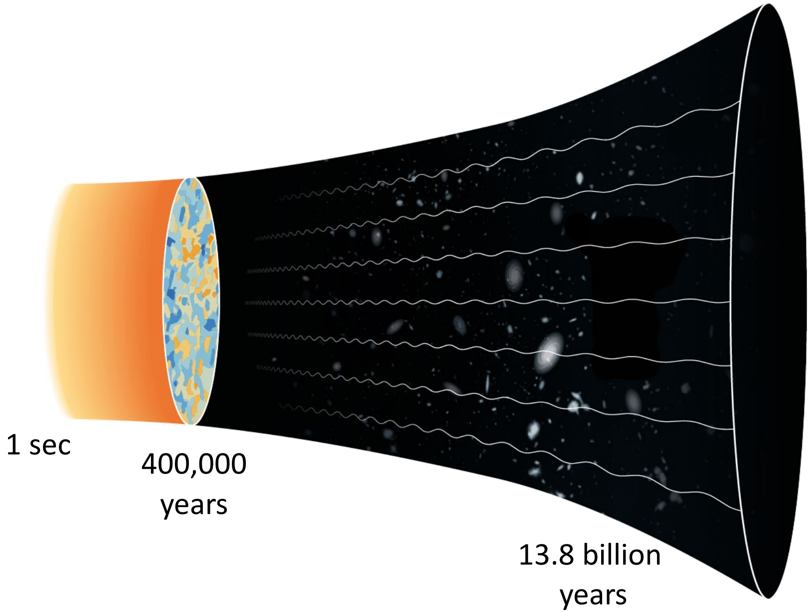
Kuhnian shift

We could be on the wrong track . . . the modern equivalent of Ptolemy's epicycles.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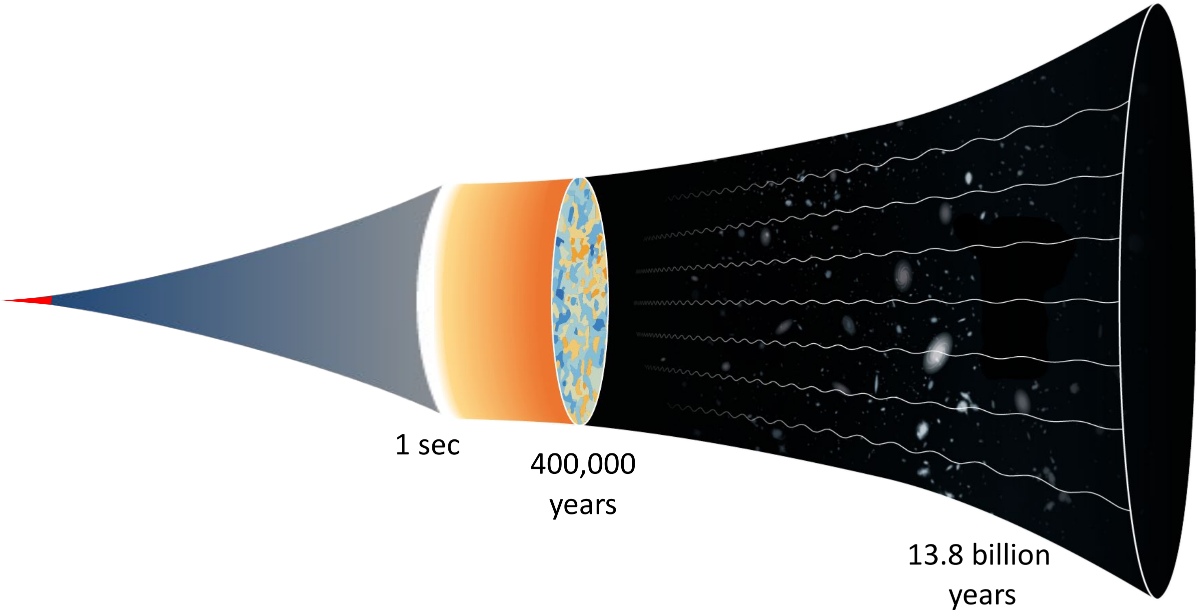
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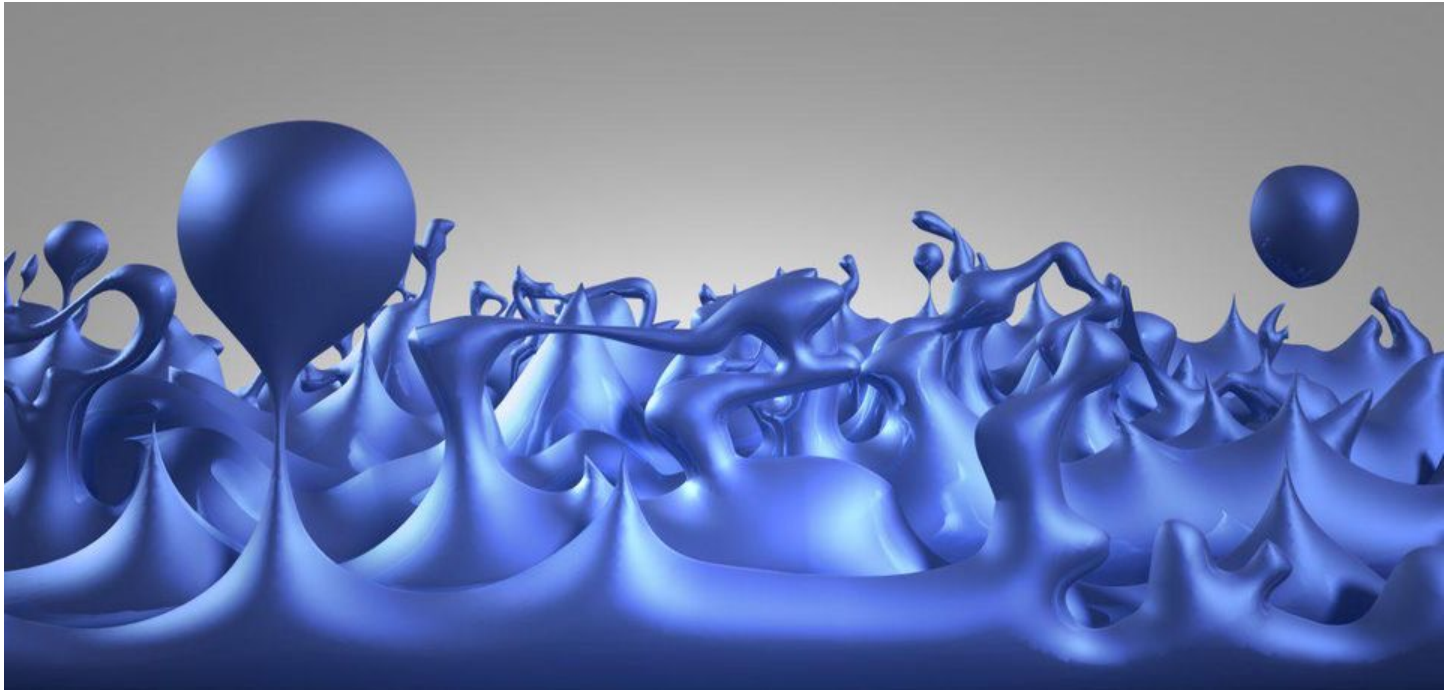


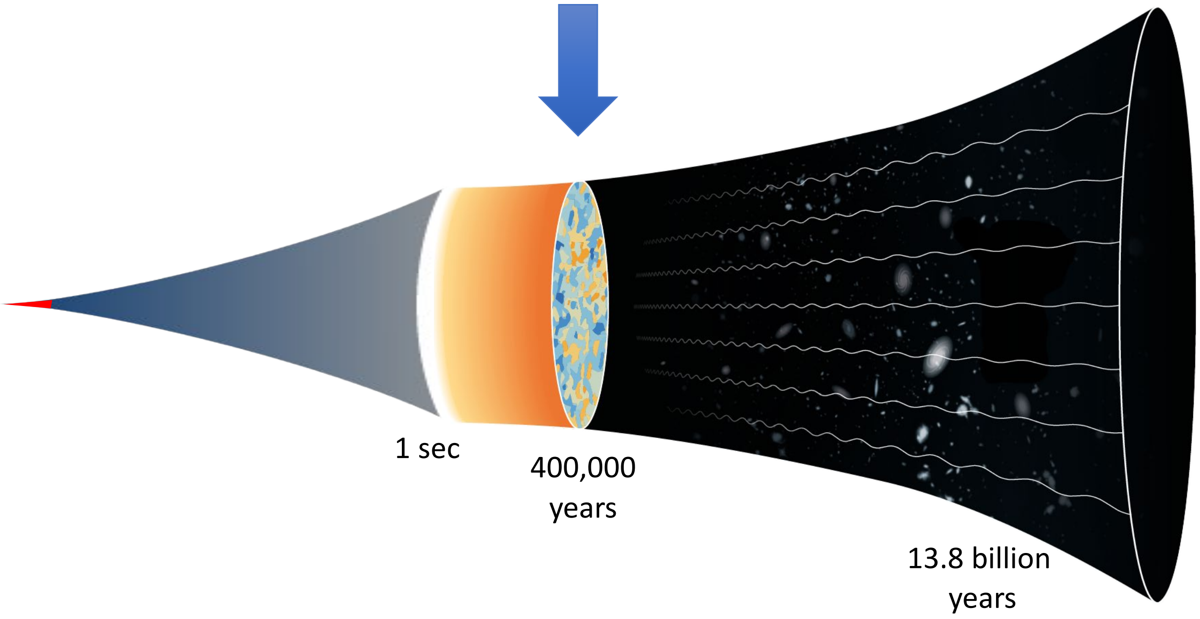
the big bang has always been a sketchy idea

mathematical singularity

quantum foam, emergent spacetime, tunneling from nothing, …

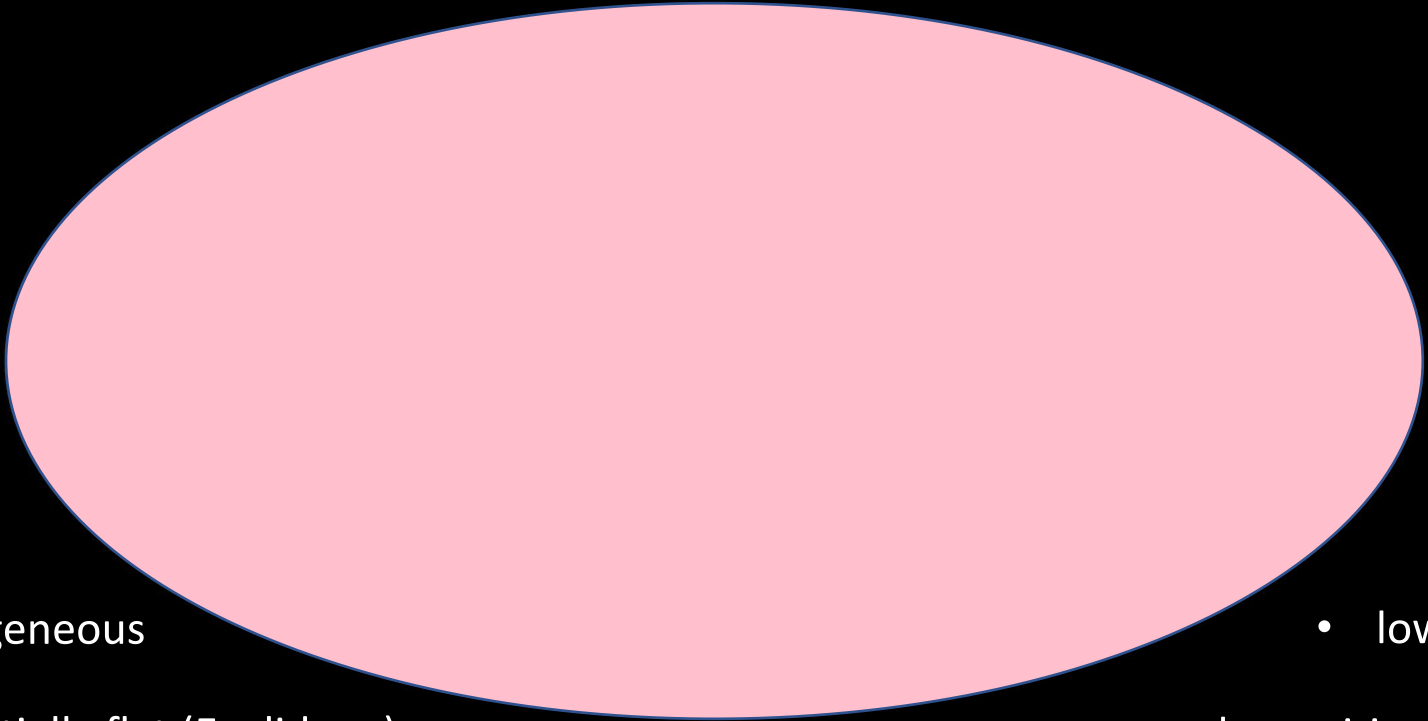
no accepted theory

cosmic microwave background radiation



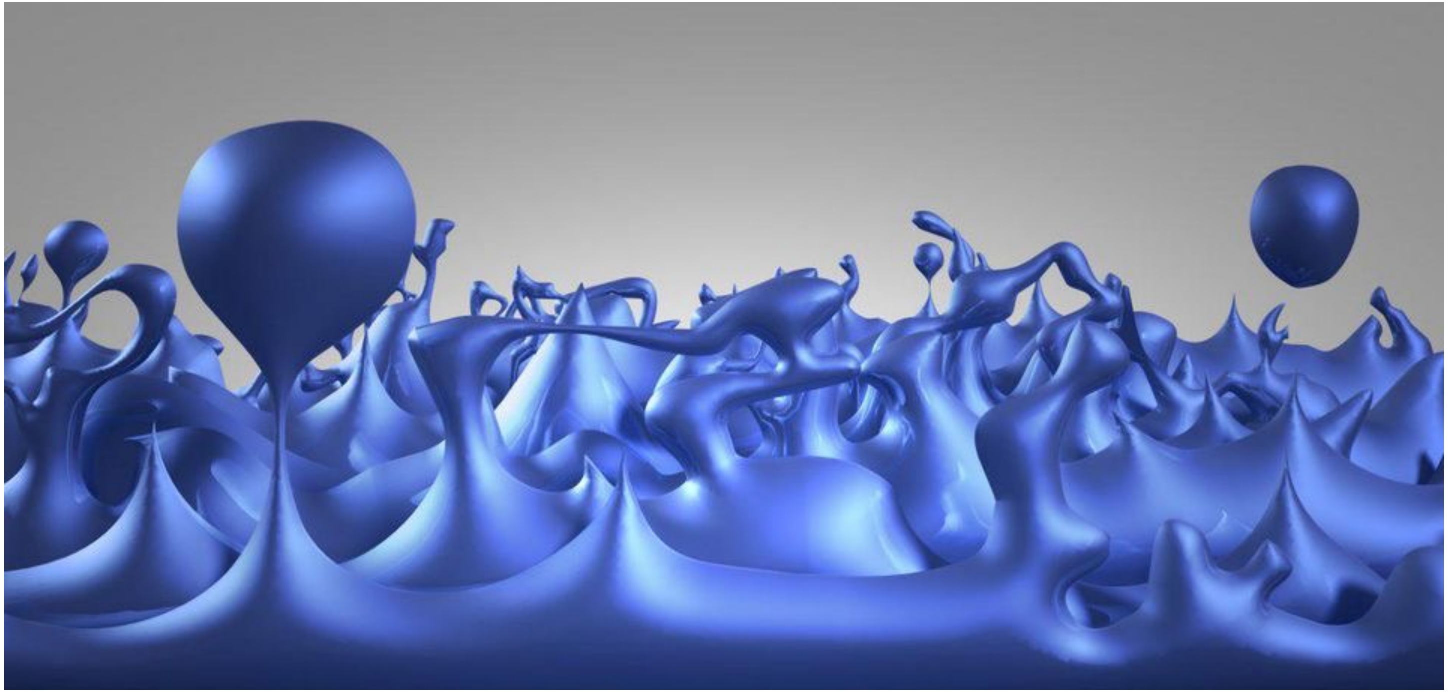
a big bang followed by expansion may not be able to explain
the salient observable features of our universe

the salient features of our universe

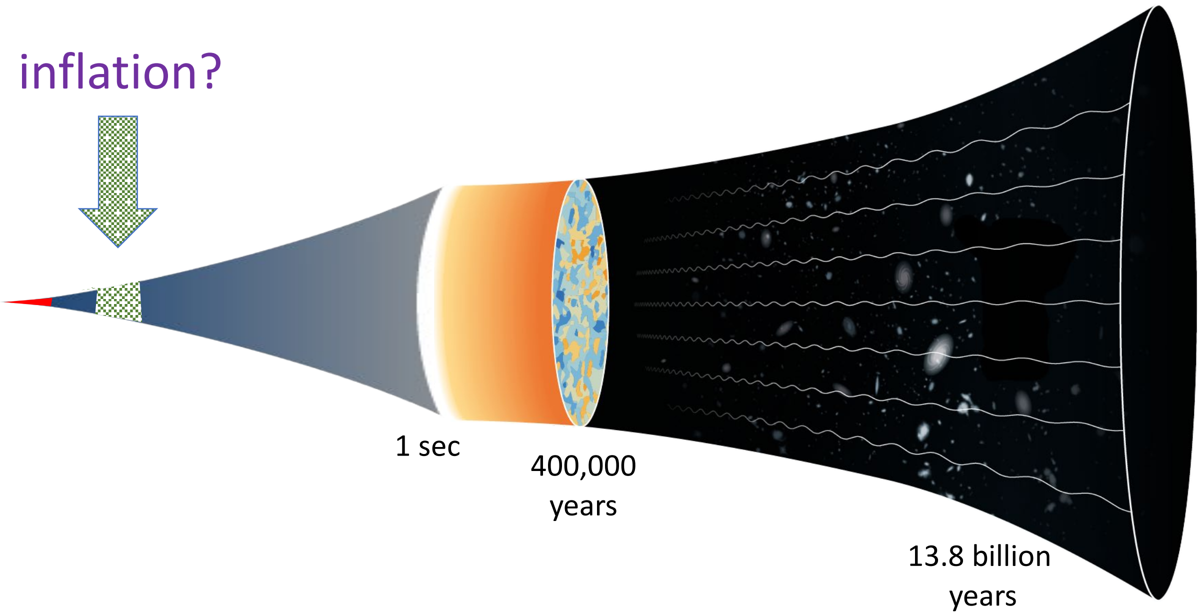


- homogeneous
- low entropy
- spatially flat (Euclidean)
- strangely partitioned entropy
- well-described by classical physics

a big bang is exactly the opposite



inhomogeneous, curvy, high entropy, and inherently quantum

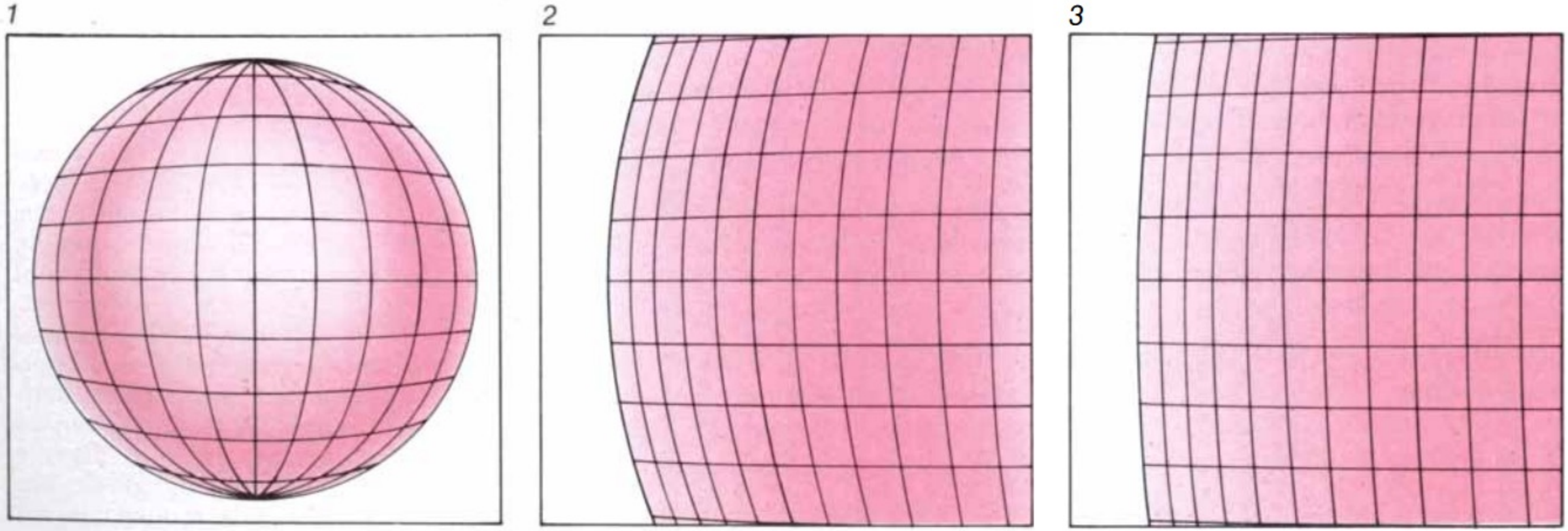


does this band-aid do the job?
and are there other options?

Does the band-aid do the job?

1. "Entropy" Problem: Inflation requires ultra-low entropy to start (but big bang produces ultra-high entropy)
2. Initial "$\dot{\phi}$" Problem: Inflation requires ultra-low "$\dot{\phi}$" (but"$\dot{\phi}$" is ultra-high at the Planck density)
3. Initial "ϕ" Problem: Inflation requires "ϕ" to lie within a narrow, bounded range of the potential over a Hubble radius or more to start
4. Singularity Problem: Inflation does not avoid it
5. Classical EofM Problem: Inflation requires a transition from quantum- to classical-dominated evolution
6. Multiverse Problem: Quantum runaway → eternal inflation → multiverse → no predictions
7. Bunch-Davies Problem: Smoothing not enough –after smoothing need enough time to relax to B-D vacuum
8. B-mode Problem: Simplest textbook models predict B-modes >> current limits
9. Amplitude Problem: Inflation does not predict the density fluctuation amplitude (it's set by hand)
10. Dark energy Problem: Dark energy was not predicted and is not explained (plays no essential role)
11. TCC Problem: May not be embeddable in a consistent theory of quantum gravity
12. Field range Problem: Inflaton ranges over superPlanckian values resulting in loss of perturbative control

How to solve the Flatness Problem



SOLUTION OF THE FLATNESS PROBLEM is illustrated by this sequence of perspective drawings of an inflating sphere.

The problem with this explanation is:

It’s wrong. . .

. . . and it misleads you into believing that **expansion is essential to flatten** the universe . . .

. . . when the truth is just the opposite!

Some Definitions:

a(t)   (the `scale factor')

= the factor by which the universe has expanded or contracted

H(t)   (the `Hubble parameter')

= the rate of expansion   ($\equiv \dot{a}/a$)

ε   (the `equation of state')

= $\frac{3}{2}\left(1+\frac{pressure}{energy\ density}\right)$ for the dominant form of energy

where $\varepsilon = 3/2$ corresponds to zero pressure

“Hubble radius”
~ how far you can see

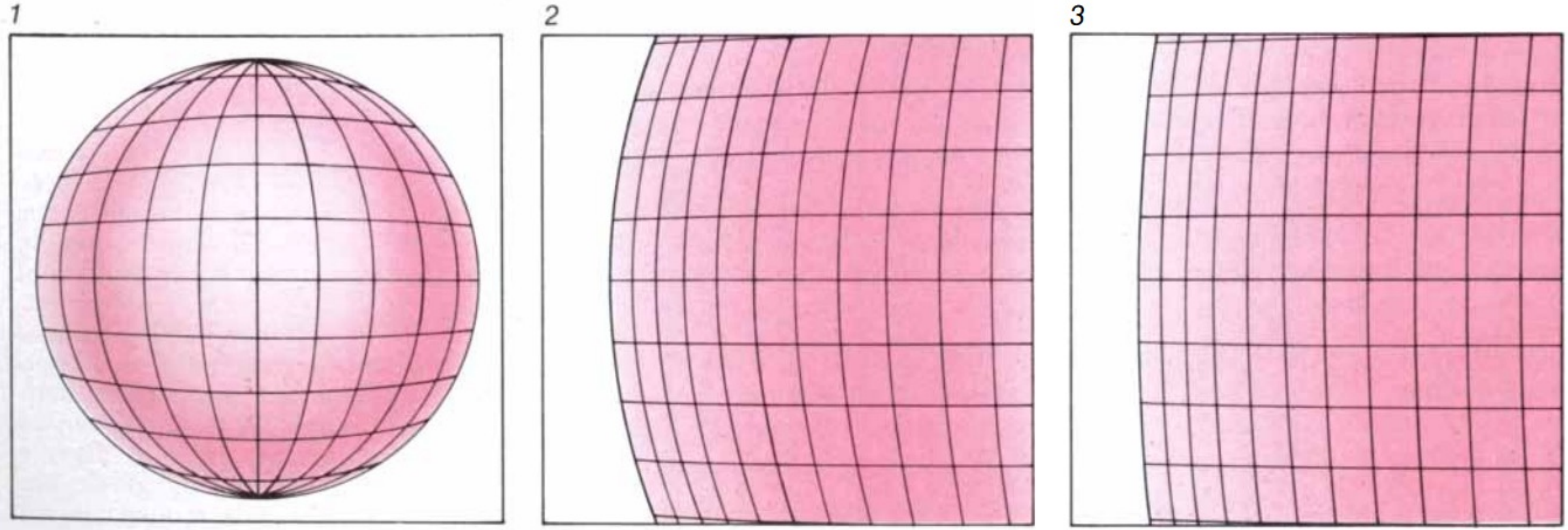
Pressure/energy density

$$\frac{c\,|H(t)|^{-1}}{c\,|H(t_0)|^{-1}} \sim \left(\frac{a(t)}{a(t_0)}\right)^{\varepsilon}$$

geometry

$$c\,|H|^{-1} \sim a^{\varepsilon}$$

How to solve the Flatness Problem



SOLUTION OF THE FLATNESS PROBLEM is illustrated by this sequence of perspective drawings of an inflating sphere.

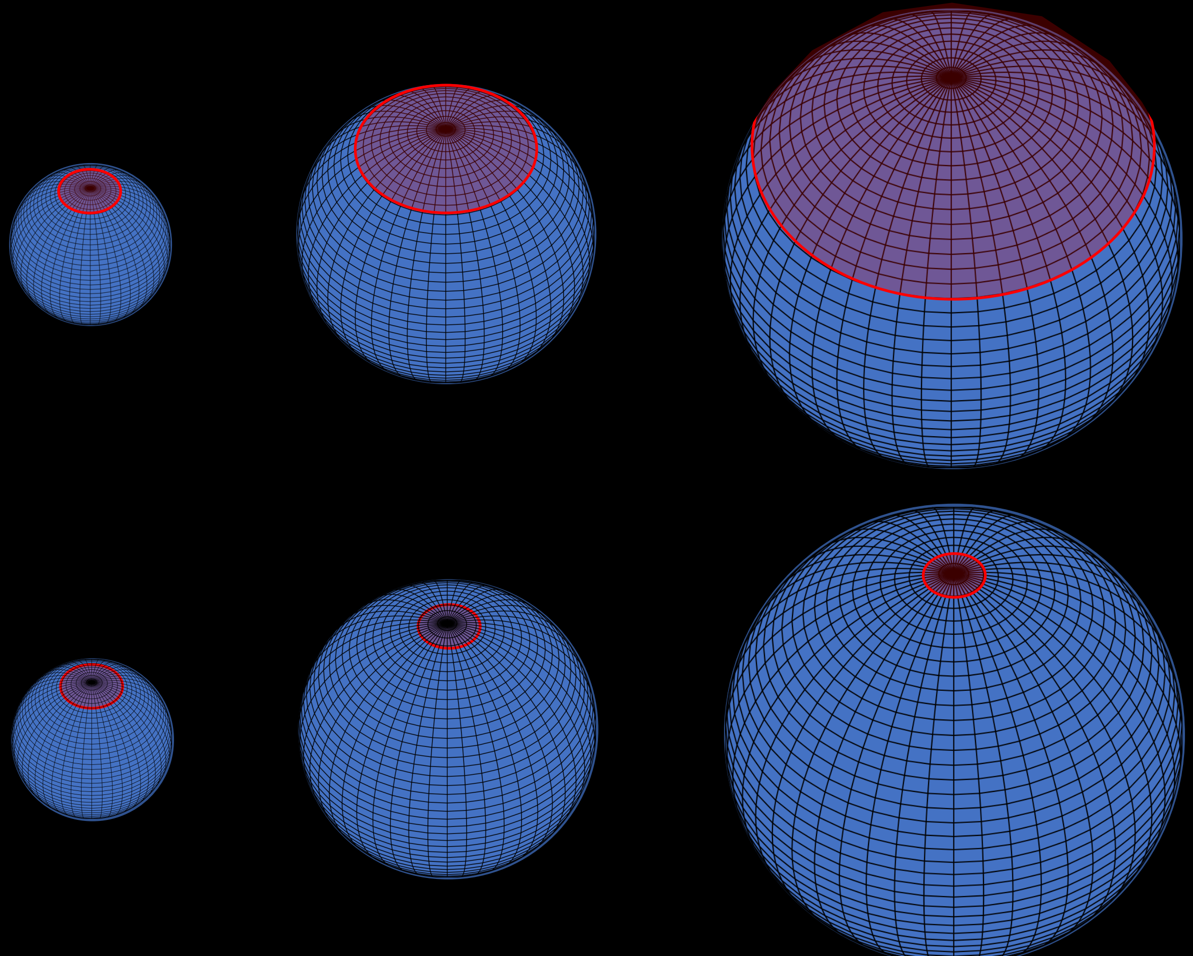
$$c\,|H|^{-1} \sim a^{\varepsilon}$$

Cosmological Flatness = “Apparent Flatness”

expanding
$\varepsilon > 1$

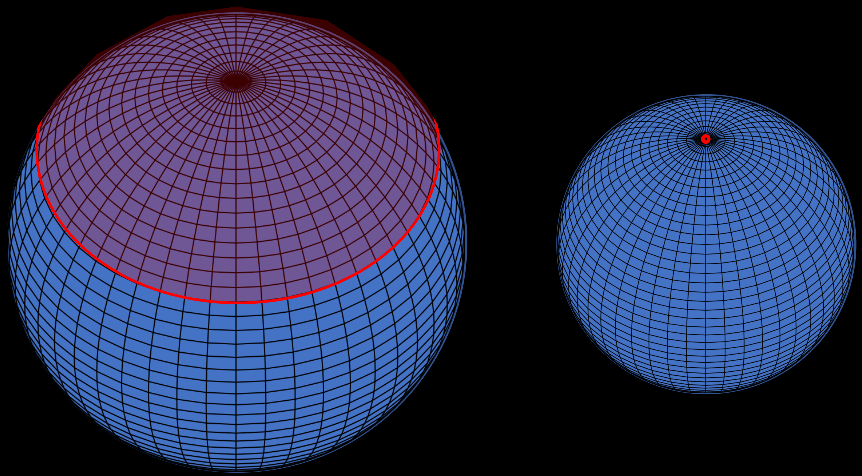
$$c\,|H|^{-1} \sim a^{\varepsilon}$$

inflating
$\varepsilon < 1$



Cosmological Flatness = "Apparent Flatness"

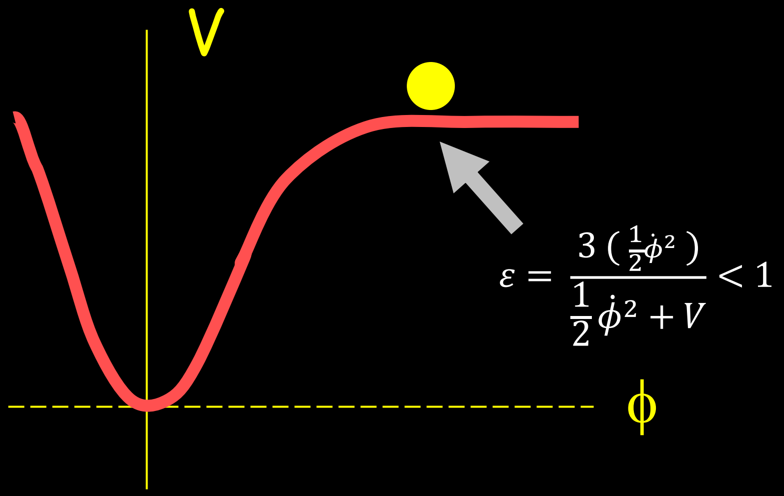
slow contraction
pressure >> 0
$\varepsilon \gg 1$



$$c\,|H|^{-1} \sim a^{\varepsilon}$$

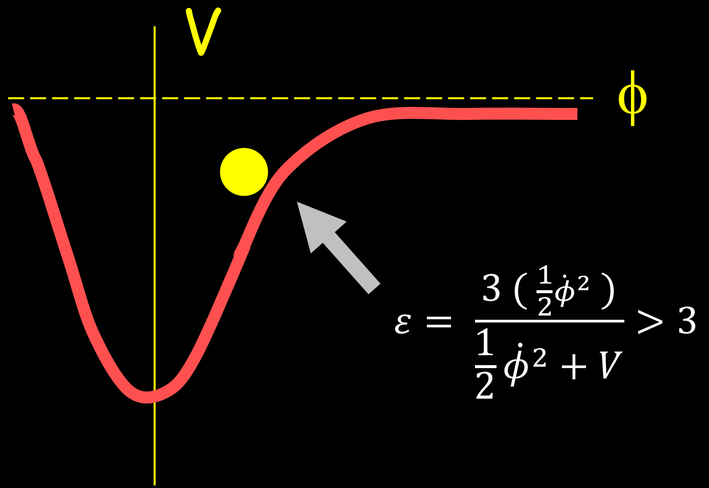
$$S = \int d^4 x \, [\tfrac{1}{2} R - \tfrac{1}{2} (\partial_\mu \phi)^2 - V(\phi) + \cdots]$$

$$\ddot{\phi} + 3\, H\, \dot{\phi} + V'(\phi) = 0$$



Inflation (accelerated expansion)

$a(t) \sim |t|^{1/\varepsilon}$ *as* $t \to \infty$

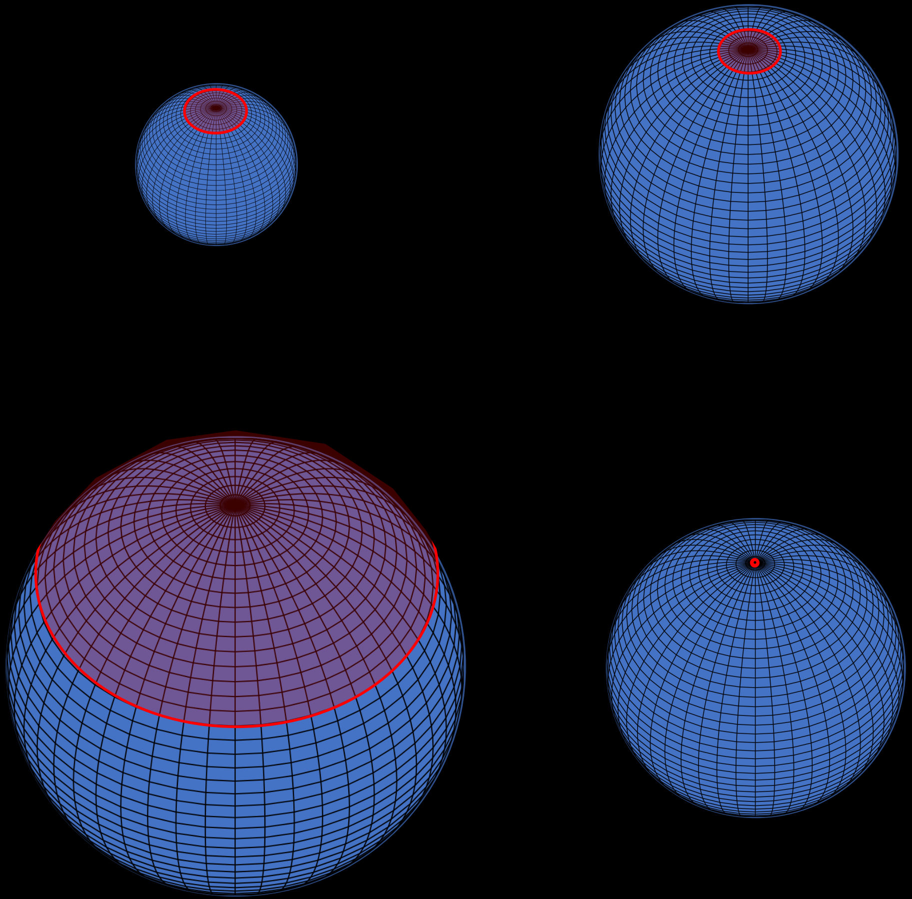


slow contraction

$a(t) \sim |t|^{1/\varepsilon}$ *as* $t \to 0$

slow contraction is much faster than inflation!

inflating
$\varepsilon < 1$



cap/surface area
reduced by 2^2

$$c\,|H|^{-1} \sim a^{\varepsilon}$$

slow contraction
pressure >> 0
$\varepsilon \gg 1$

cap/surface area
reduced by 2^{100}

How to solve the Homogeneity & Isotropy Problems

The problem with this explanation is . . .

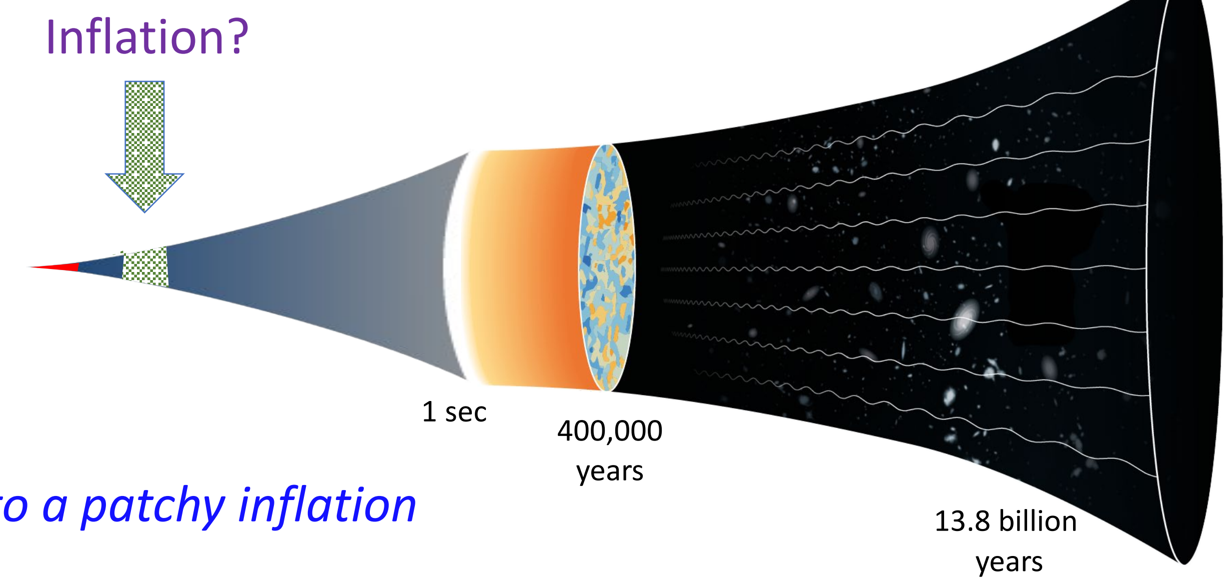
It’s wrong. . .

. . . and it misleads you into believing that **expansion is essential to smooth** the universe . . .

. . . when the truth is just the opposite!

How to solve the Smoothness Problem

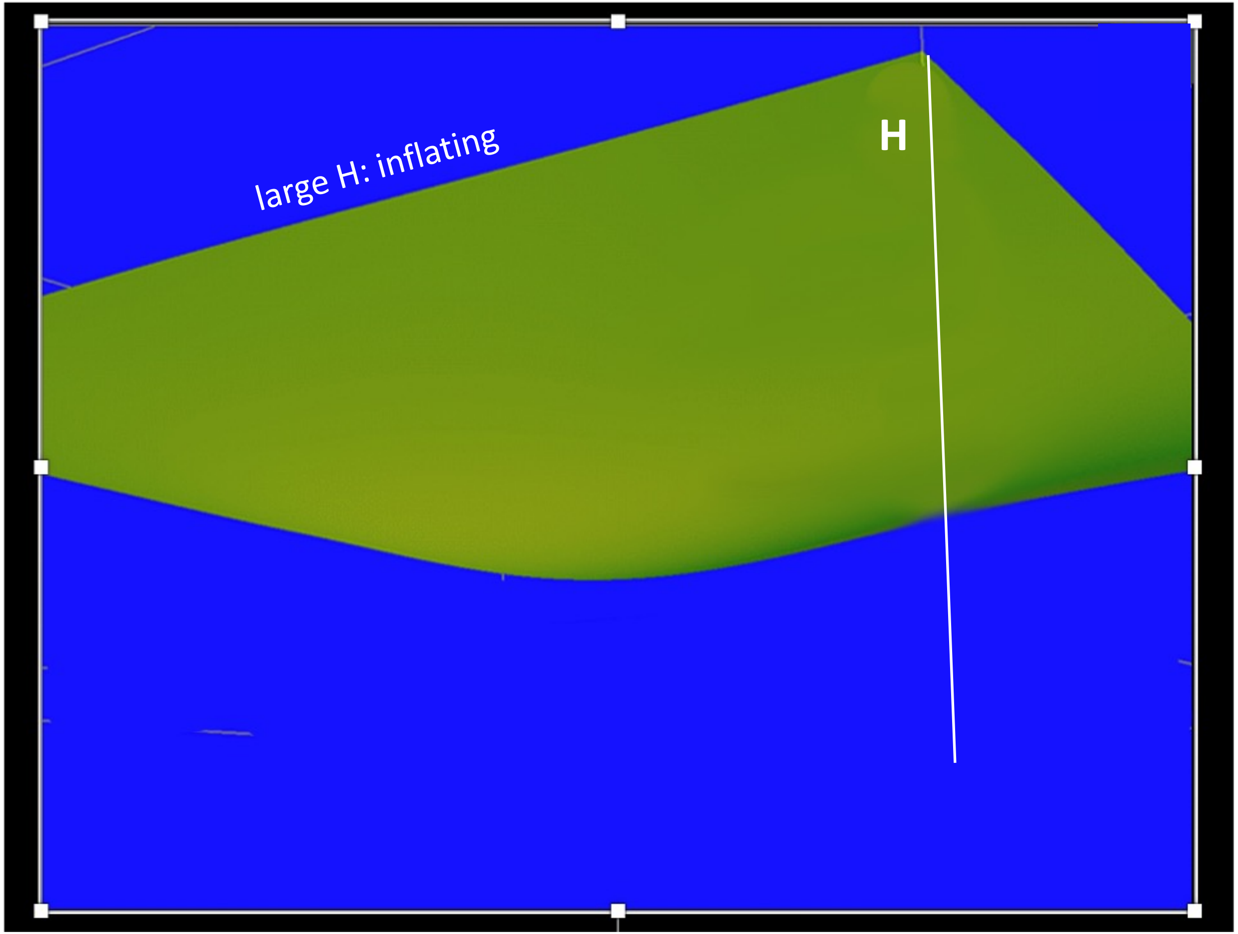
Inflation requires a nearly smooth spacetime to get started



Which leads to a patchy inflation

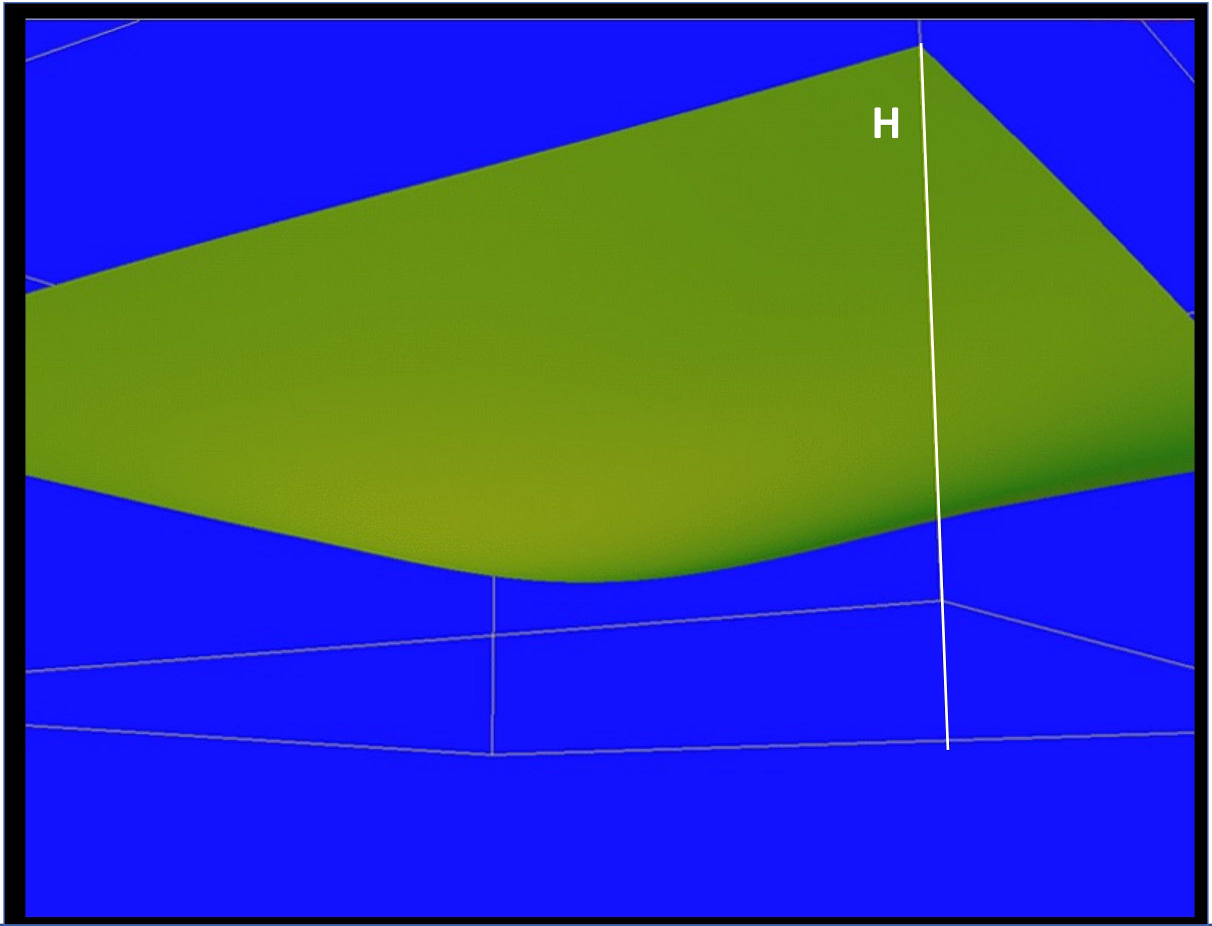
where "bad inflation is more likely than good inflation"

“QUANTUM PHYSICS” ADDED



a simple litmus test

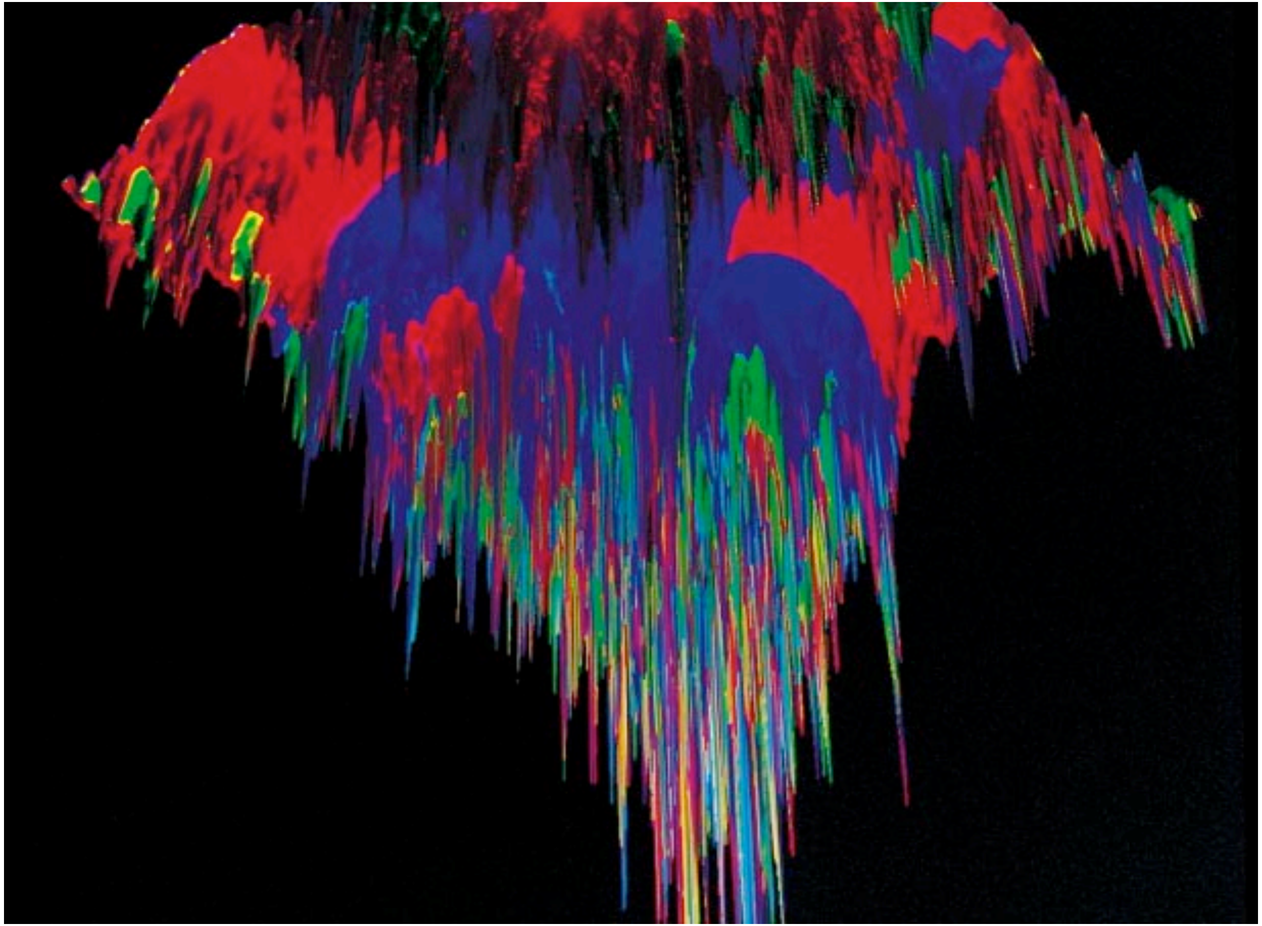
"QUANTUM PHYSICS" ADDED



quantum runaway!

Linde, Linde, Mezhlumian, PRD 50, 2456 (1994)

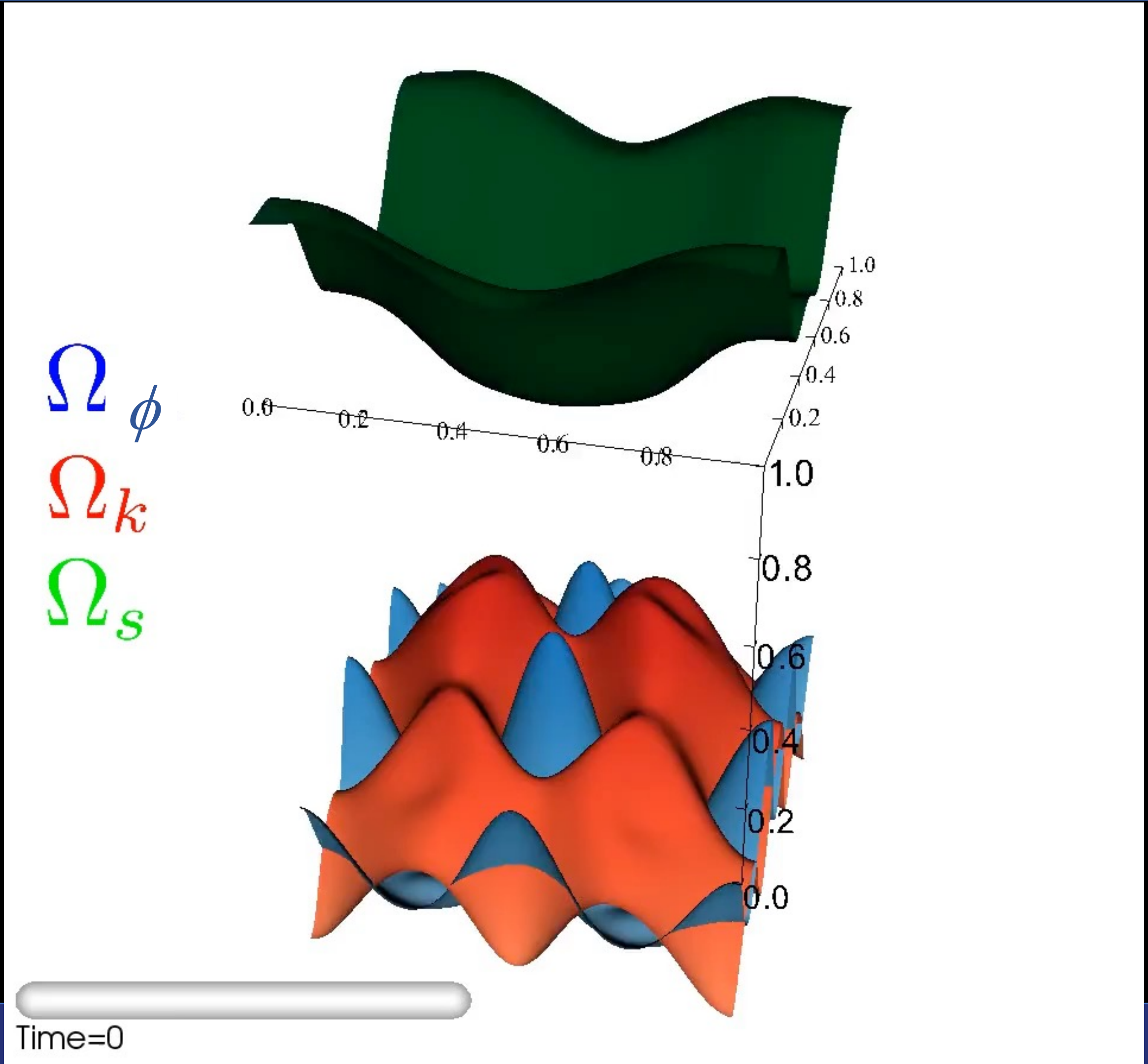
"QUANTUM PHYSICS" VIEW



smoothness
flatness
are not
the generic
outcome

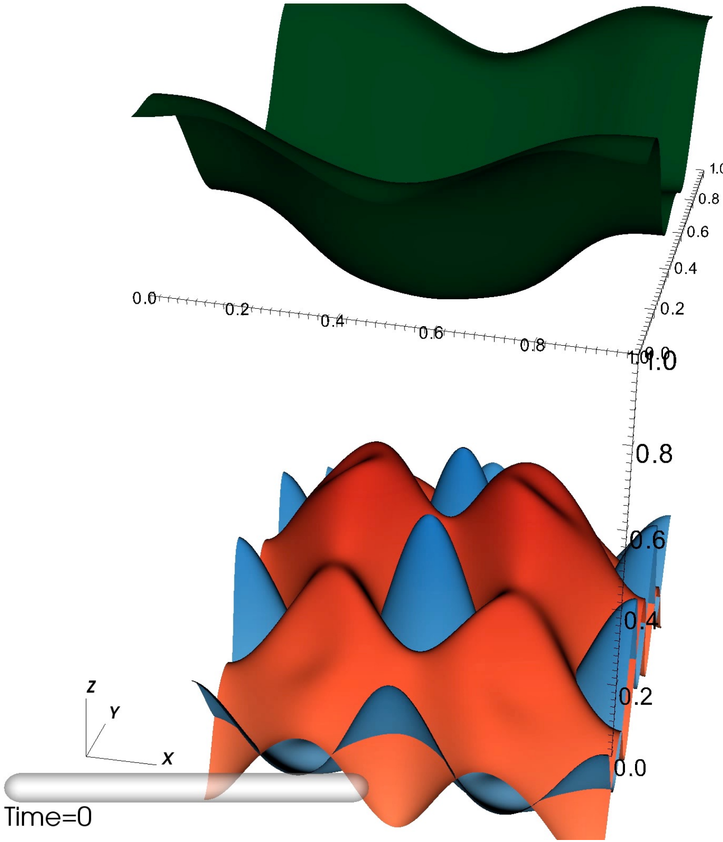
Anna Ijjas,

Numerical Relativity as a New Tool for Fundamental Cosmology, Physics 4, 301 (2022

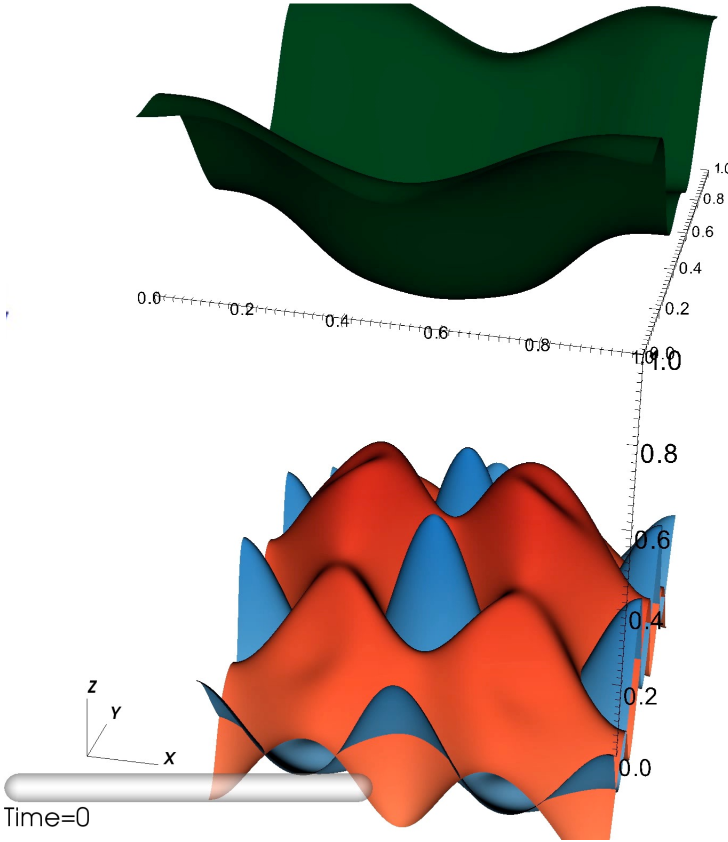


what about smoothing by slow contraction

begins far from slow contraction conditions fast contraction ($\varepsilon < 3$)



slow contraction ($\varepsilon > 3$)



Ω_ϕ

Ω_k

Ω_s

universal smoother !!

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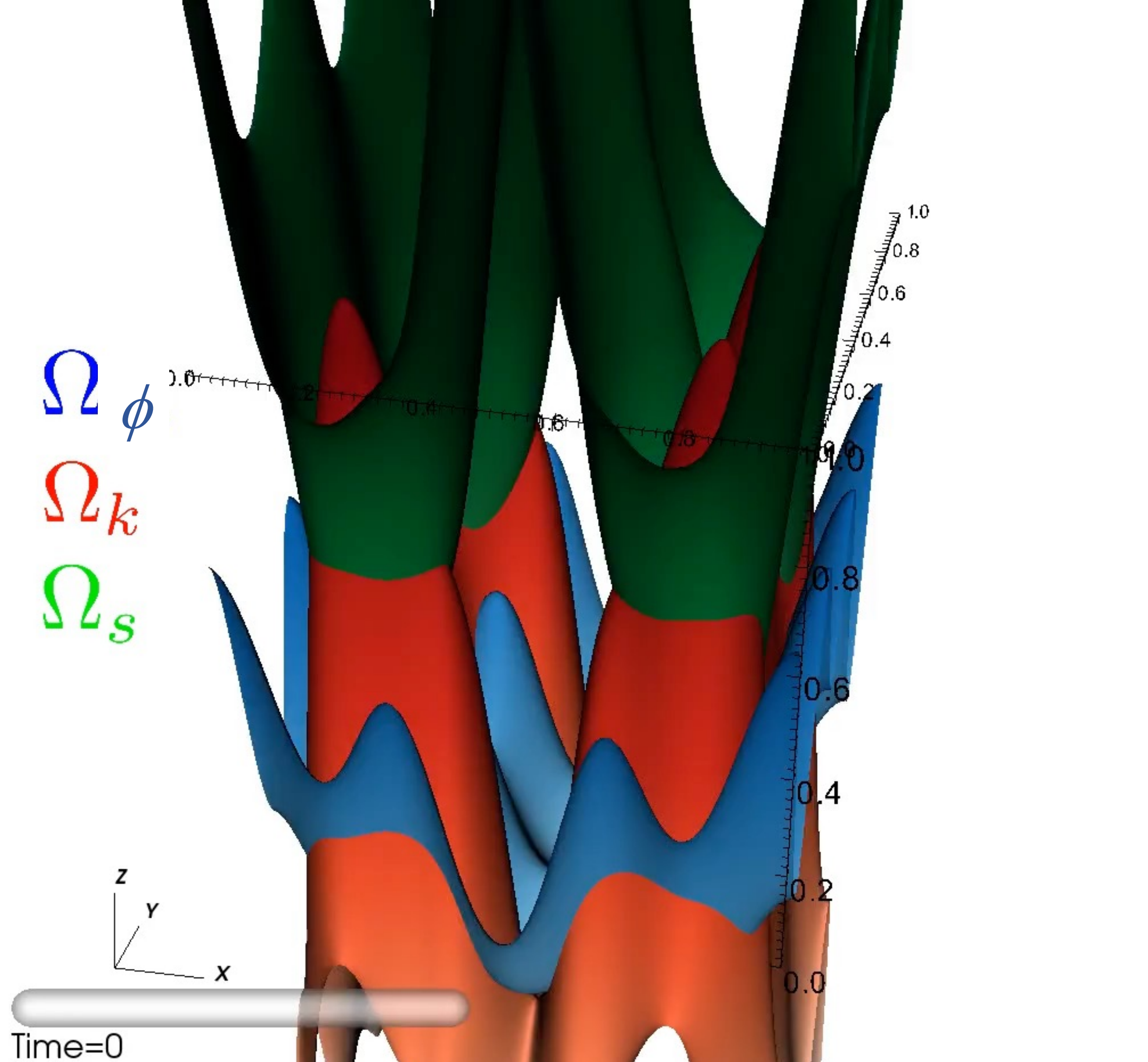
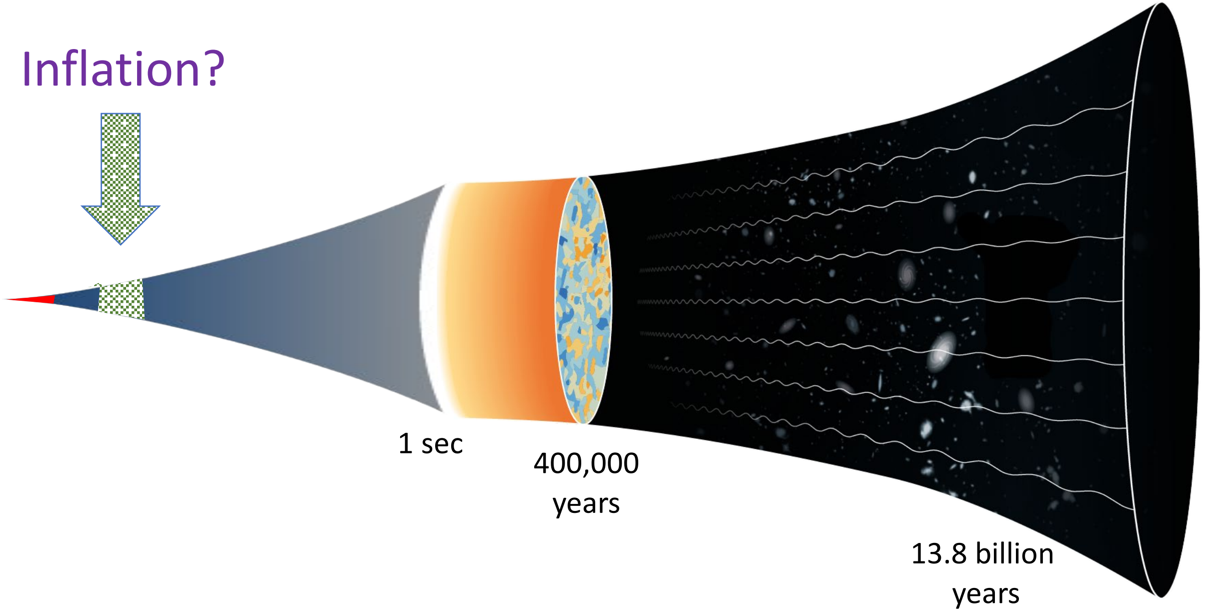


What about smoothing by slow contraction

begins far from slow contraction conditions

How to solve the Big Bang "Entropy" Problem

any theory with a big bang/quantum gravity-dominated phase is susceptible to having an "entropy" problem



A universe that begins with a bang and expands forever…

. . . has an entropy problem

(and inflation cannot resolve it)

. . . has a smoothness problem

(and inflation cannot resolve it)

. . . has a flatness problem

(and inflation cannot resolve it)

Quo vadis Cosmology?

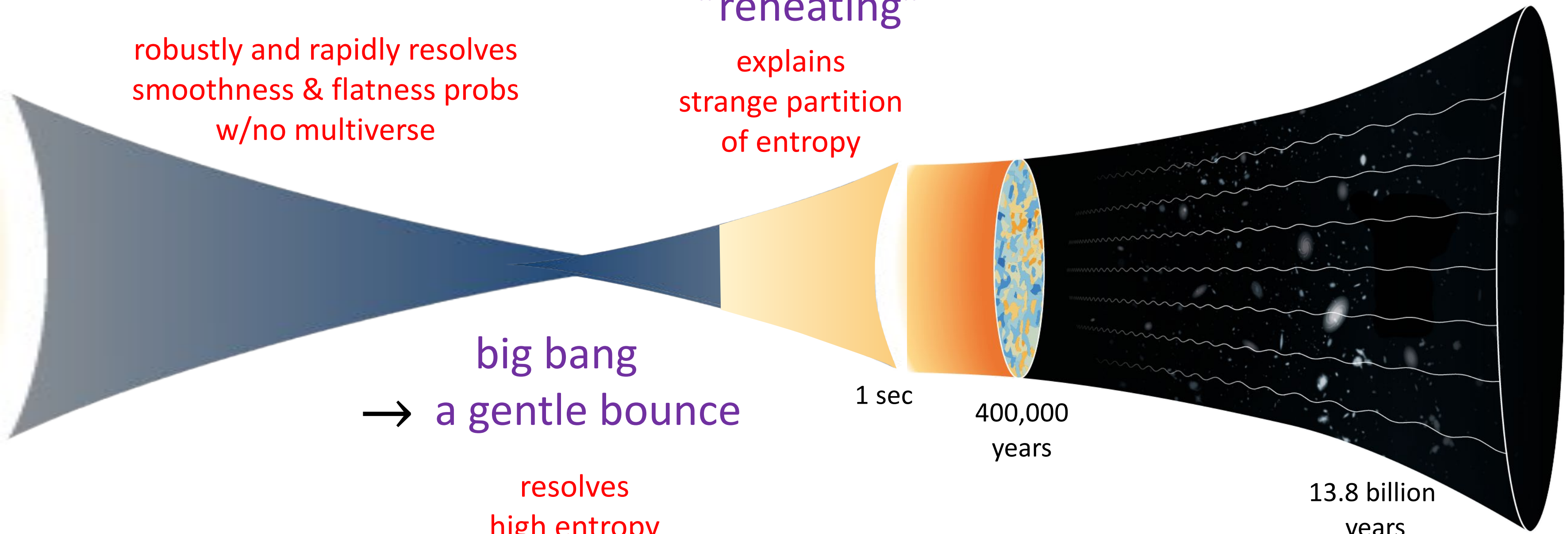
A universe with a bounce can avoid all of these problems

slow contraction

robustly and rapidly resolves
smoothness & flatness probs
w/no multiverse

”reheating”

explains
strange partition
of entropy



big bang
→ a gentle bounce

resolves
high entropy
w/no quantum->classical
transition

OBSERVATIONS

- homogeneity
- flatness
- entropy
- no detectable B-mode polarization
- dark energy is time-varying
- acceleration era will come to an end

The Atacama Desert: Site of the forthcoming Simons Observatory