What Next for Cosmology ?

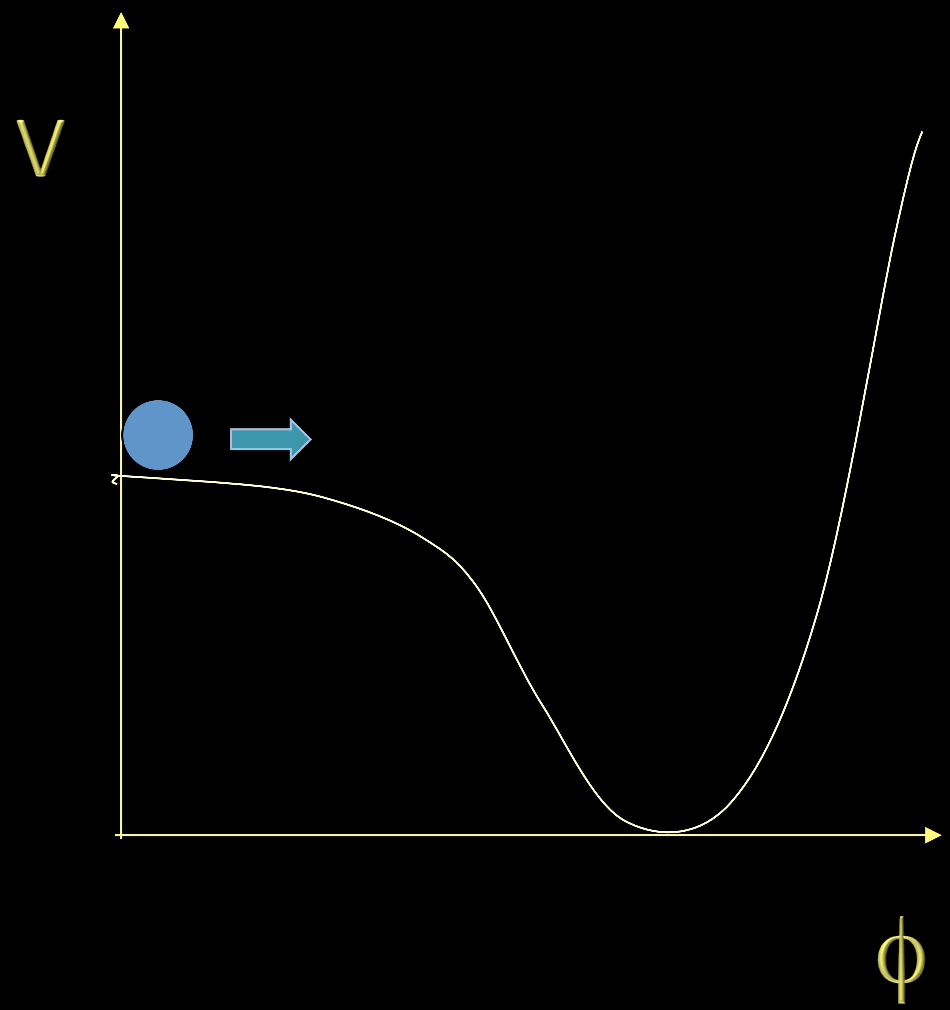
On the experimental front:

CMB polarization
Non-gaussianity
Baryon acoustic oscillations
Sunyaev-Zeldovich detection of clusters
Weak and strong lensing
Supernovae surveys
Dark matter searches
Direct g-wave detection

On the theoretical front:

CRISIS

Big bang inflationary picture



Guth
Linde
Albrecht & PJS

Explanatory & Predictive Power

Inflation explains homogeneity and flatness beginning from *arbitrary* initial conditions

Inflation is powerfully predictive

flat

nearly scale-invariant perturbations

slightly red tilt

adiabatic

gaussian

gravitational waves

consistency relations

Guth
Hawking
Bardeen, PJS, Turner
Mukhanov & Chibisov
Starobiniskii
....

Inflation explains homogeneity and flatness beginning from *arbitrary* initial conditions

$S_{max} > 10^{120}$ $S_{today} = 10^{100}$ $S_{inflation} < 10^{20}$

states ~ likelihood ~ e^{S}

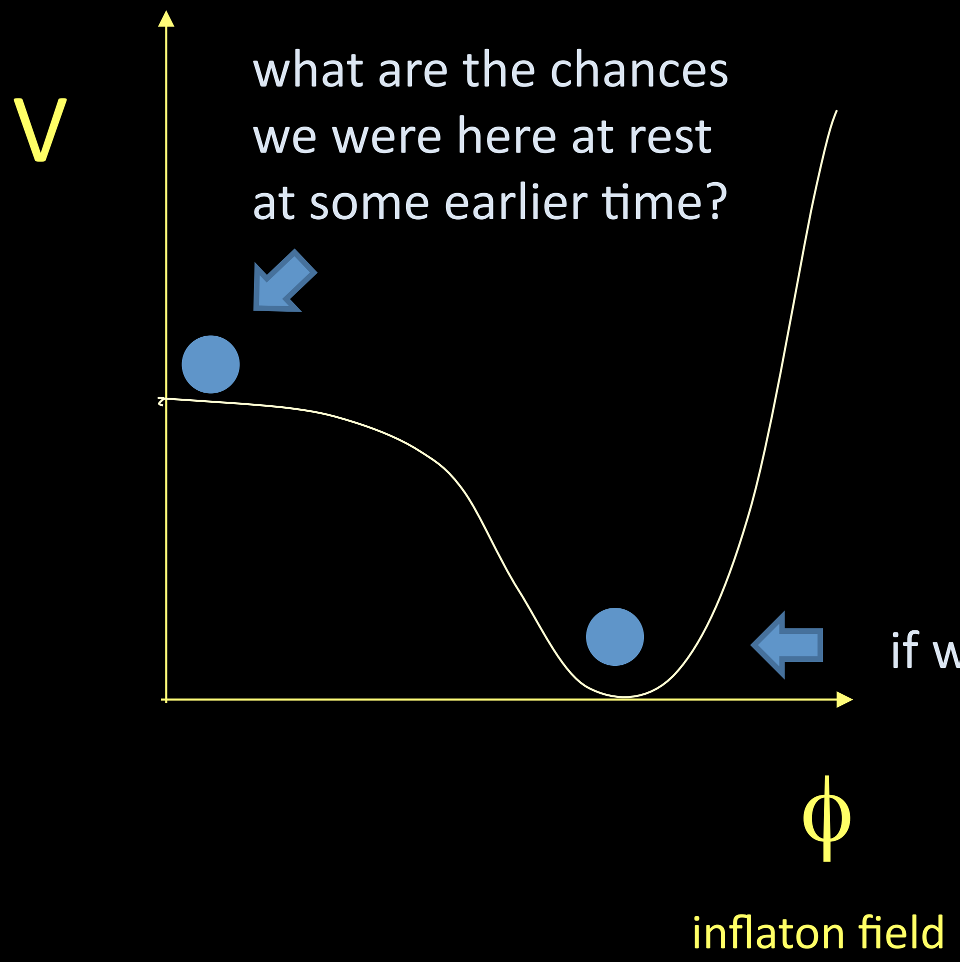
$$KE \sim 1/a^6 \text{ as } a \rightarrow 0$$

$$PE \rightarrow constant$$

"LIOUVILLE PROBLEM"

Fpr precise evalutation, see
Gibbons & Turok (2006)
Turok (2012)

what are the chances
we were here at rest
at some earlier time?



if we start from conditions at the
end of smoothing &
extrapolate backwards …

Why was this not appreciated before? Were we duped?

Chaotic inflating universe

A. D. Linde
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR

(Submitted 31 May 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 3, 149–151 (10 August 1983)

It is shown that inflation is a natural result of chaotic initial conditions in the early universe. These initial conditions are found in a wide class of elementary particle theories.

to point, and it is only later that the universe became uniform and isotropic.[5] Let us assume that the magnitude of the classical field ϕ at first also had different random values at different points in space,and let us follow the evolution of the field ϕ in time. We are interested in the regions of space where the field ϕ, for accidental reasons, was quite uniform. If the size of the corresponding region at first exceeded the size of the

Explanatory & Predictive Power

Inflation <u>explains</u> homo n y ar flatness beginning from *arbitrary* i ial c ions

Inflation is wer y <u>predictive</u>

at

nearly sc invar perturbations

slig ed tilt

adiabatic

gaussian

gravitational waves

consistency relations

“the classic(al) perspective”

dominantly a classical process…

an ordering process…

in which quantum physics plays
a small but important perturbative role

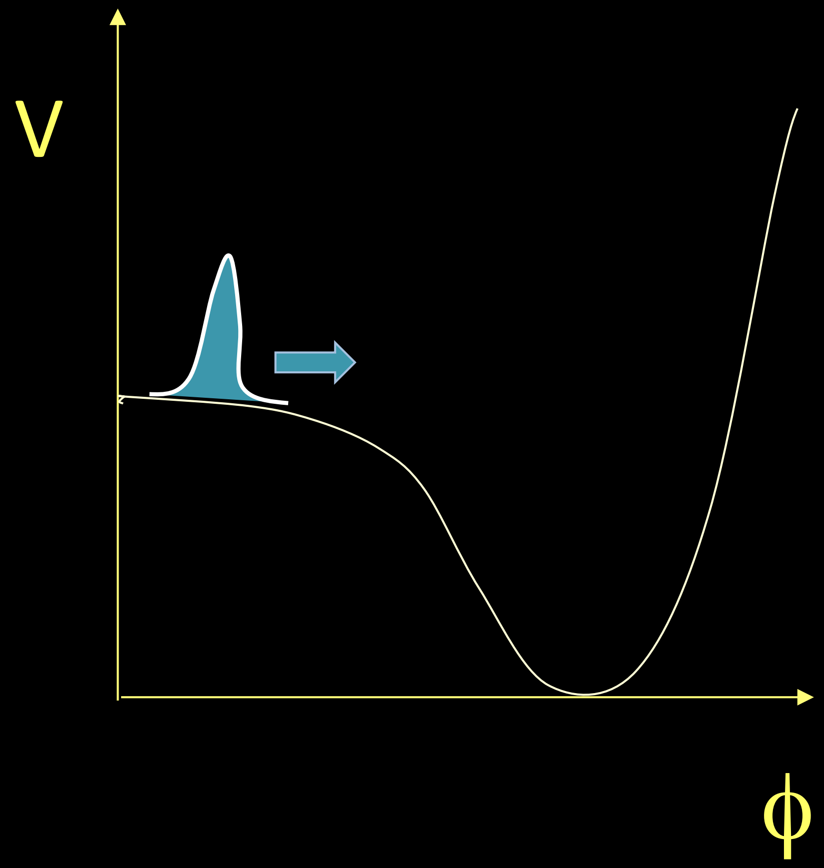
“the (true) quantum perspective”

Inflation is dominantly a quantum process…

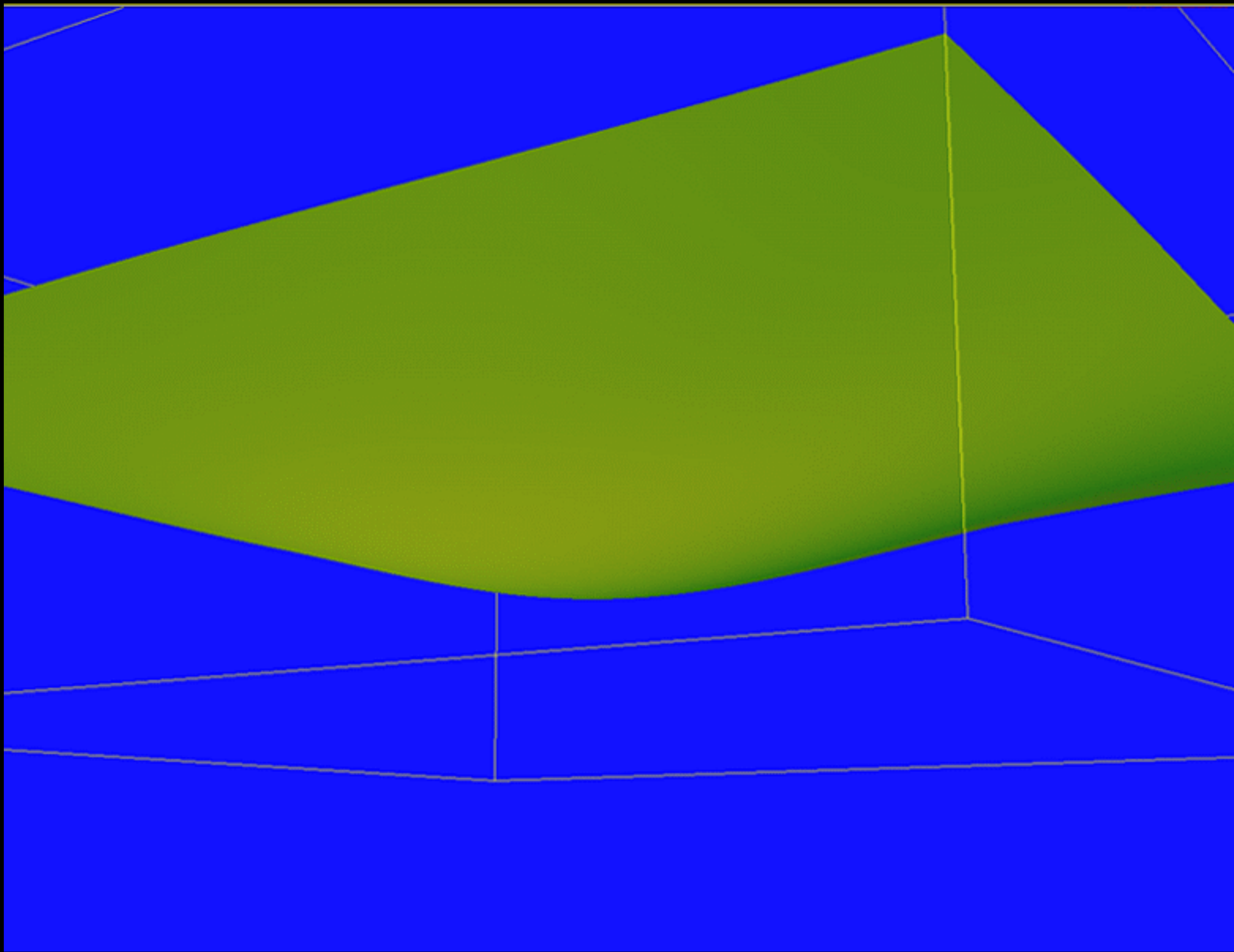
in which (classical) inflation amplifies
rare quantum fluctuations…

resulting in a peculiar kind of disorder

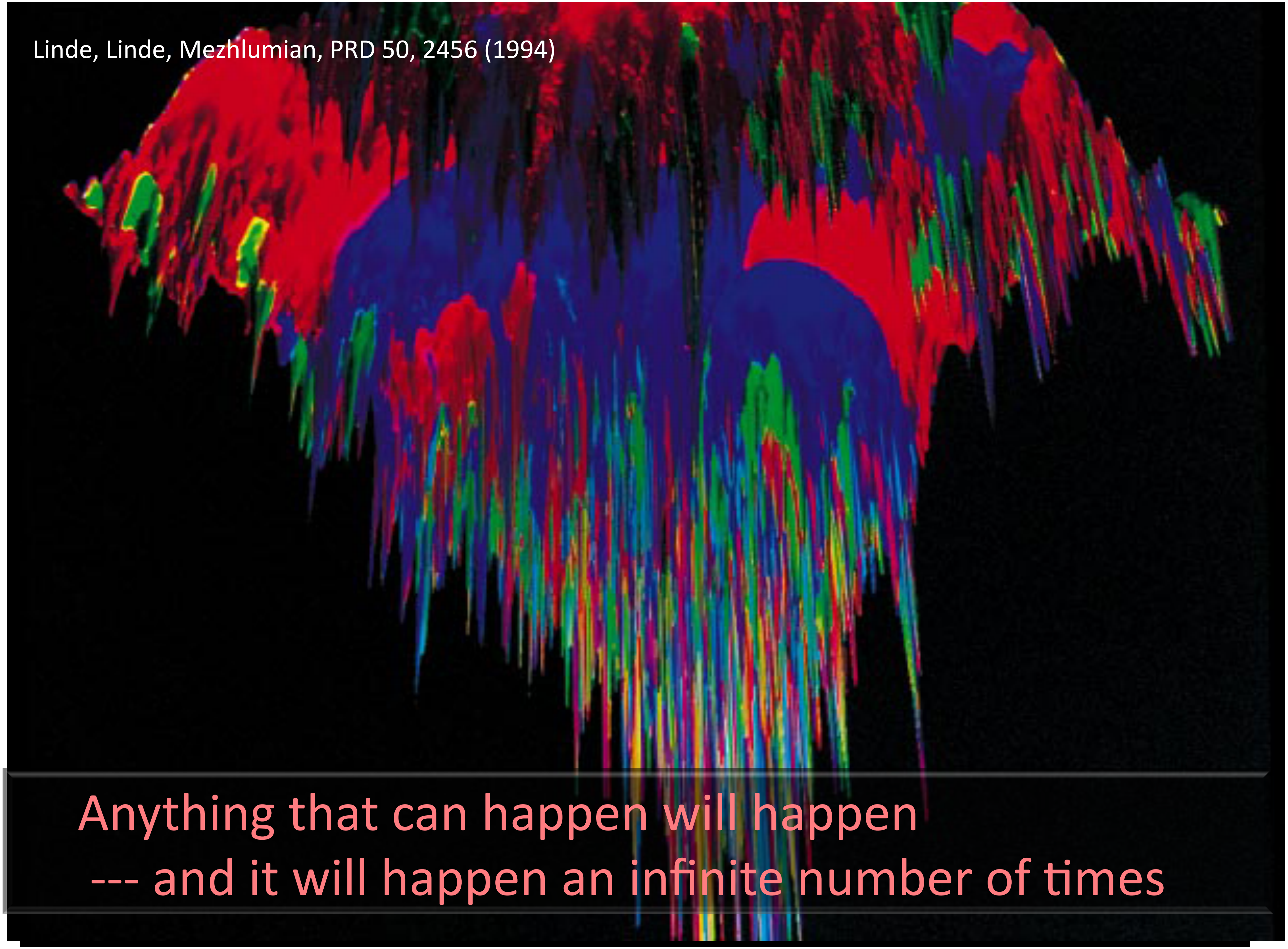
Eternal Inflation



Vilenkin, 1983
PJS, 1983



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



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

Anything that can happen will happen

--- and it will happen an infinite number of times

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

Predictability Problem

The Great Leap Backwards

volume measures
(Boltzmann brain & youngess problem)

proper time measures
(youngness problem)

causal patch measures
(predictions depends on initial conditions)

scale factor measures
(many versions, our universe not preferred)

anthropic principle

Maybe we should be satisfied that at least some regions can be like what we observe ?

Noooooooo !!!!!

Time to Rethink Cosmology

Inflation is the only way of solving the *causal* horizon problem

Inflation is the only way of “flattening” the universe

Time to Rethink Cosmology

Inflation is t e nly ay of solving
the *caus* ho problem

Inflatio the nly way
of "flatte ng th universe

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

Time to Rethink Cosmology

Inflation is t… e … nly … ay of solving
the *caus*… hor… problem

Inflatio… the … nly way
of "flatte… ng … th… universe

$$H^2 = \frac{8\pi G}{3}\left(\frac{\rho_m^0}{a^3} + \frac{\rho_r^0}{a^4} + \ldots\right) - \frac{k}{a^2} + \frac{8\pi G}{3}\rho_{\text{inflaton}}$$

Time to Rethink Cosmology

Inflation is t nly ay of solving
the *caus* hor problem

Inflatio the nly way
of “flatte ng h universe

Inflatio the nly way
of generating sc e i ar nt perturbations

ultra-slow contraction with w >>1:

$$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2}$$

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

w >> 1

$$a(t) \sim t^{2/3(1+w)} \equiv t^{1/\varepsilon}$$

Khoury, Ovrut, PJS, Turok
Wesley, Erickson, PJS, Turok

ultra-slow contraction with w >>1:

quantum fluct. exit horizon & re-enter later

$$\varepsilon \equiv \tfrac{3}{2}(1+w)$$

wavelength ~ $a(t) \sim t^{\frac{1}{\varepsilon}} \sim (H^{-1})^{\frac{1}{\varepsilon}}$ ~ (Horizon)$^{1/\varepsilon}$

rapid expansion

wavelength grows
much faster than horizon

$\varepsilon << 1$ (or $w \sim -1$)

slow contraction

wavelength shrinks
much slower than horizon

$\varepsilon >> 1$ (or $w >> 1$)

Khoury, Ovrut, PJS, Turok

ultra-slow contraction with w >>1:

Tensor fluctuations are completely different

Amplitude ~ H^2

rapid expansion	slow contraction
H large	H exponentially small
H nearly constant	H increasing
r ~ 25%	r ~ exponentially small

same argument applies to axions

Khoury, Ovrut, PJS, Turok
See also Mack & PJS

In sum, with a bounce & no inflation:

Can causally smooth

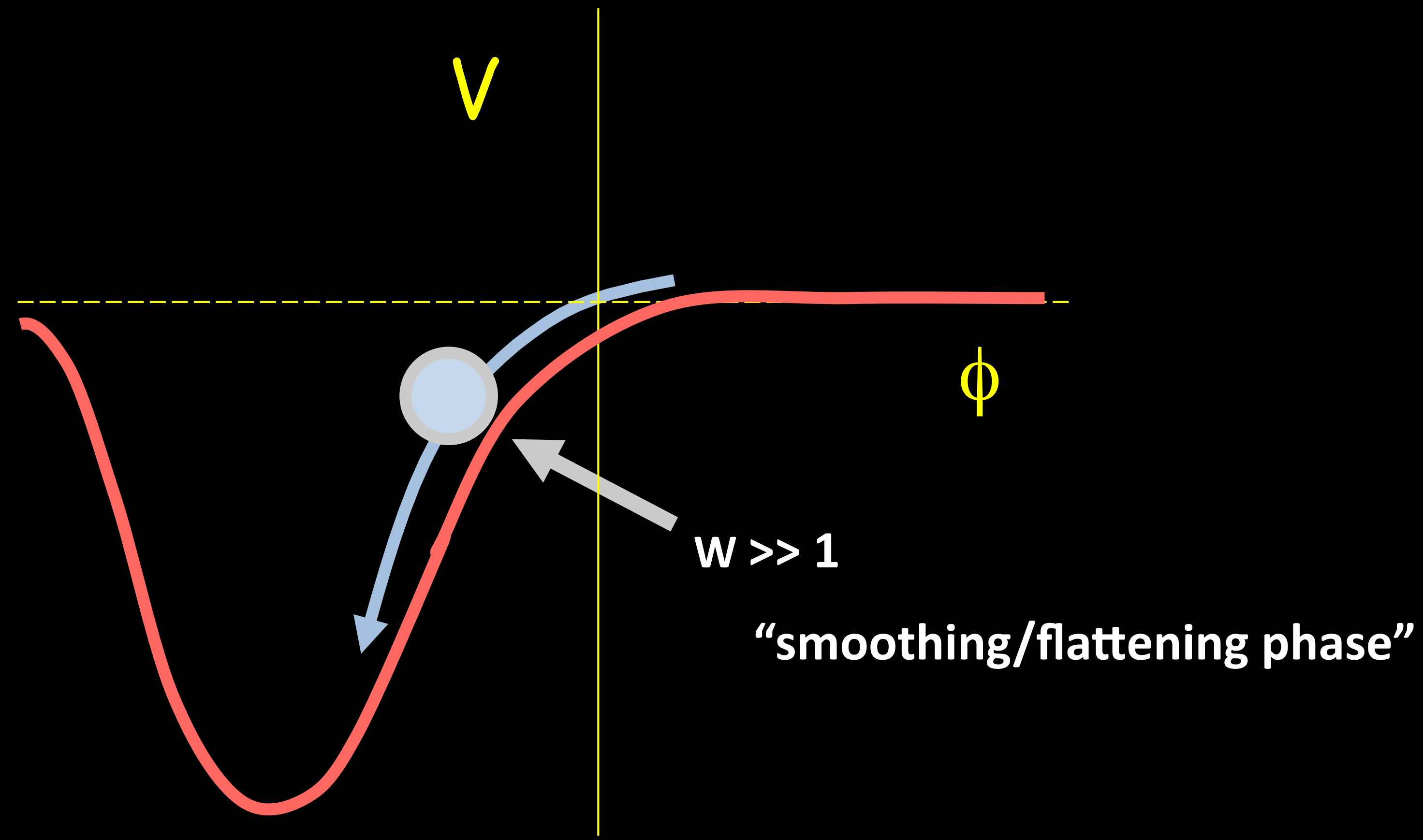
Can flatten

Can isotropize

Can make density perturbations

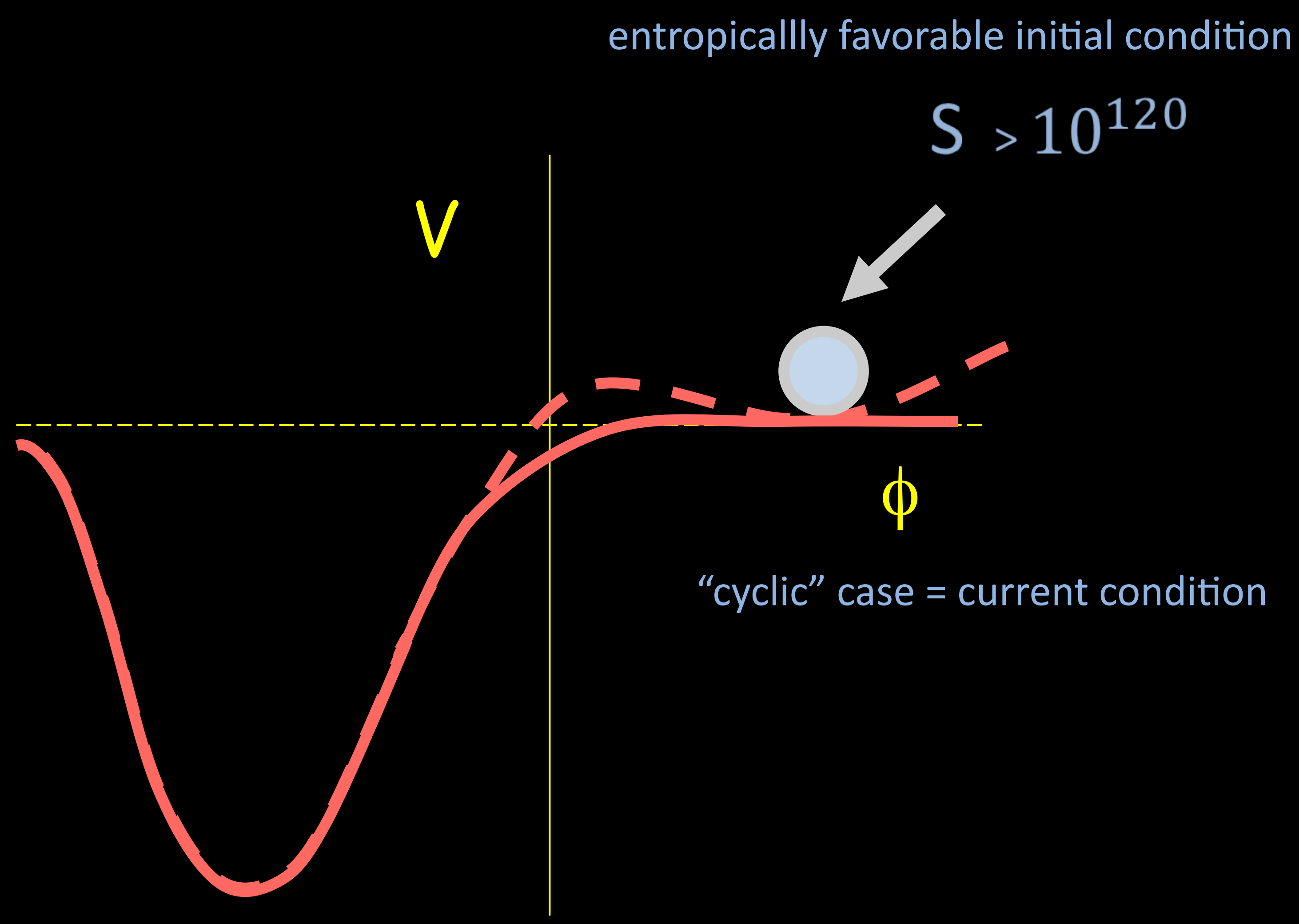
But is that all ?

w >1 ?



No eternal runaway !

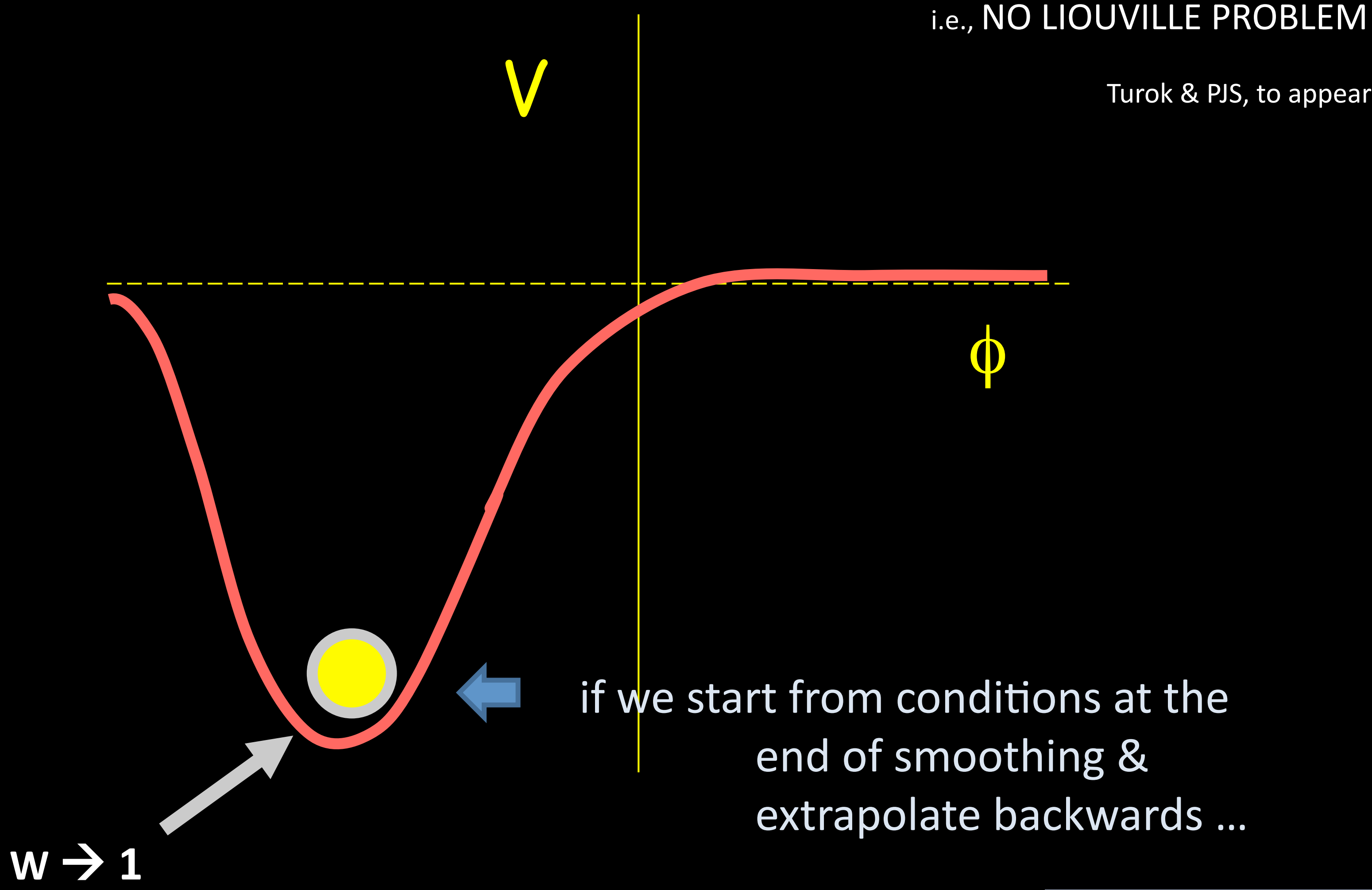
$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$



$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

extrapolating backwards: $KE \sim 1/a^6$ shrinks as $a \rightarrow$ *increases*

$|PE| \rightarrow$ *also decreases* as $1/a^6$



"end of smoothing phase"

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

In sum, with a bounce & no inflation:

Can causally smooth

Can flatten

Can isotropize

Can make density perturbations

Avoid eternal runaway

Avoid Liouville/entropy (initial conditions) problem

Avoid axion overproduction

Can the big bang be a bounce ?

Gasperini & Veneziano
Brandenberg & Wafa
Khoury, Ovrut, PJS, Turok
Tsujikawa, Brandenberger, Finelli
Khoury, Buchbinder & Ovrut
Tolley, Turok, PJS
Biswas, Mazumdar, and Siegel
Bojawald
Cai, Qiu, Piao, Li, Zhang
Penrose
Turok, Craps, Hertog
Cai, Brandenberger, Zhang

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.

big crunch/big bang transition

Itzhak Bars, Shih-Hung Chen, PJS and Neil Turok
arxiv:1112.2470

Introduces a Weyl invariant extension of Einstein gravity

For appropriate choice of Weyl gauge, find geodesically complete solutions with big crunch/big bang transition

Unique solution that preserves unitarity, analyticity, momentum

Wheeler-de Witt equation produces same results (to appear)

Analytlic continuation in comlex-t plane produces simliar results (to appear)

What Next for Cosmology ?

Big Bang:
Beginning or Bounce ?

Unitarity, Emergence of Time, Null Energy Condition

big crunch/big bang transition

Itzhak Bars, Shih-Hung Chen, PJS and Neil Turok

After the smoothing phase , life is simple as we approach the bounce!

$$S = \int d^4x\sqrt{-g}[\frac{1}{2\kappa^2}R(g) - \frac{1}{2}(\partial\sigma)^2 \text{ + radiation}]$$

Smooth & Flat; Massless degrees of freedom; Ultralocal

Natural to consider a "Weyl invariant extension" :

$$S = \int d^4x\sqrt{-g}\left[\frac{(\partial\phi)^2 - (\partial s)^2}{2} + \frac{\phi^2 - s^2}{12}R \text{ + radiation}\right]$$

Weyl invariant: $g_{\alpha\beta} \to e^{2\omega(x)}\, g_{\alpha\beta}$, $\phi \to e^{-\omega(x)}\, \phi$ and s$\to e^{-\omega(x)}\, s$

fix $\omega(x)$ *so that* $\frac{1}{12}(\phi^2 - s^2) = 1/2\kappa^2$ *to recover Einstein eqs.*

Every solution of the Einstein equations

$$S = \int d^4x\sqrt{-g}[\frac{1}{2\kappa^2}R(g) - \frac{1}{2}(\partial\sigma)^2 \text{ + radiation}]$$

. . . is also a solution of the Weyl invariant extension . . .

$$S = \int d^4x\sqrt{-g}\left[\frac{(\partial\phi)^2 - (\partial s)^2}{2} + \frac{\phi^2 - s^2}{12}R \text{ + radiation}\right]$$

. . . and also a solution of other gauge-fixed versions (e.g., g = a = 1)

$$S = \int d^4x\sqrt{-g}\left[\frac{(\partial\phi)^2 - (\partial s)^2}{2} + \frac{\phi^2 - s^2}{12}R + \text{radiation}\right]$$

$$\Rightarrow \int d\tau \left\{ \frac{1}{2e}\left[-\dot{\phi}^2 + \dot{s}^2 + \frac{\kappa^2}{6}(\phi^2 - s^2)(\dot{\alpha}_1^2 + \dot{\alpha}_2^2) \right] - e\rho_r \right\}$$

Can translate from one to the other:

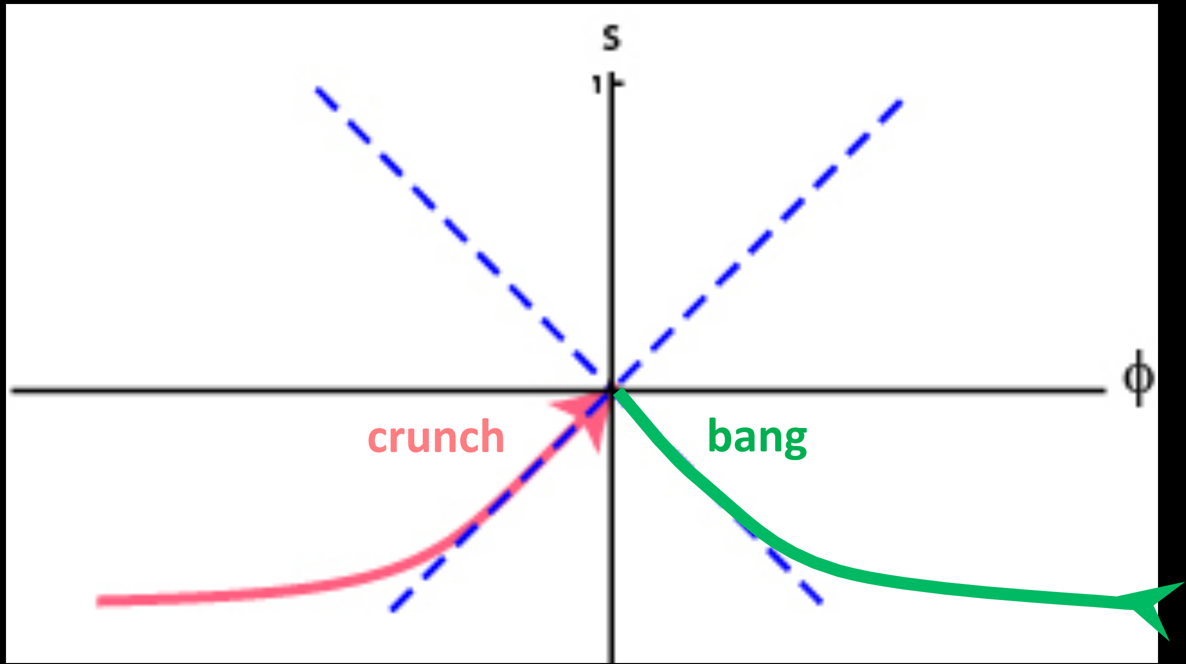
$$a_E^2 \equiv \frac{\kappa^2}{6}\left(\phi^2 - s^2\right)$$

BUT … geodesically incomplete solutions in one
may be geodesically complete solutions in the other !

$$\int d\tau \left\{ \frac{1}{2e} \left[-\dot{\phi}^2 + \dot{s}^2 + \frac{\kappa^2}{6}(\phi^2 - s^2)(\dot{\alpha}_1^2 + \dot{\alpha}_2^2) \right] - e\rho_r \right\}$$

$$a_E^2 \equiv \frac{\kappa^2}{6}(\phi^2 - s^2)$$

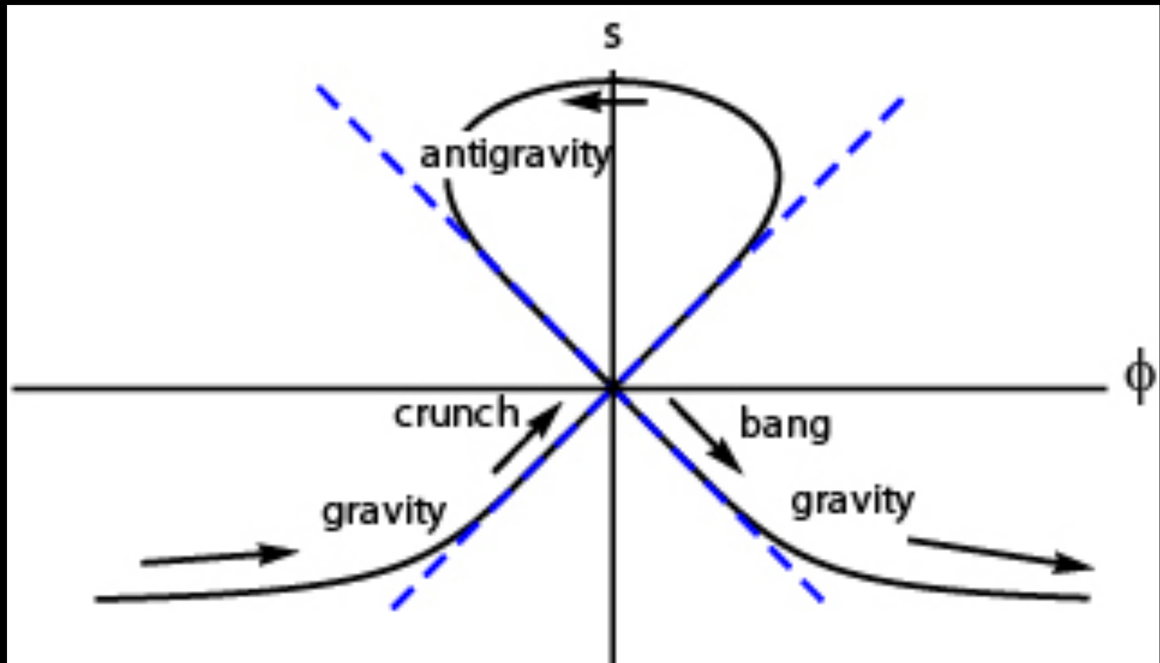
Einstein gauge: incomplete at $a_E = 0$



$$\int d\tau \left\{ \frac{1}{2e}\left[-\dot{\phi}^2 + \dot{s}^2 + \frac{\kappa^2}{6}(\phi^2 - s^2)(\dot{\alpha}_1^2 + \dot{\alpha}_2^2) \right] - e\rho_r \right\}$$

$$a_E^2 \equiv \frac{\kappa^2}{6}\left(\phi^2 - s^2\right)$$

New gauge: geodesically complete!

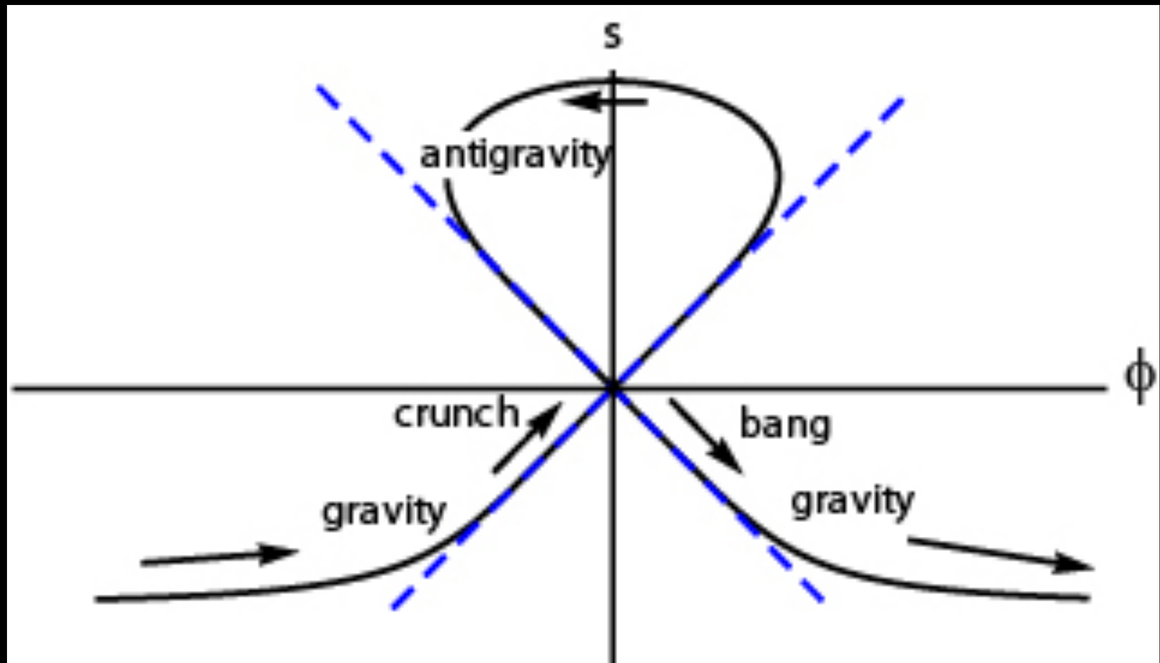


$$S = \int d^4x \sqrt{-g}\left[\frac{(\partial\phi)^2 - (\partial s)^2}{2} + \frac{\phi^2 - s^2}{12} R + \text{radiation} \right]$$

$$\int d\tau \left\{ \frac{1}{2e} \left[-\dot{\phi}^2 + \dot{s}^2 + \frac{\kappa^2}{6}(\phi^2 - s^2)(\dot{\alpha}_1^2 + \dot{\alpha}_2^2) \right] - e\rho_r \right\}$$

$$a_E^2 \equiv \frac{\kappa^2}{6}(\phi^2 - s^2)$$

New gauge: geodesically complete!



Unique solution that preserves unitarity, analyticity, momentum

Wheeler-de Witt equation produces same results

Analytic continuation in complex-*t* plane also gives similar results

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Big Bang:
Beginning or Bounce ?

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