Title: Overview of the Challenges

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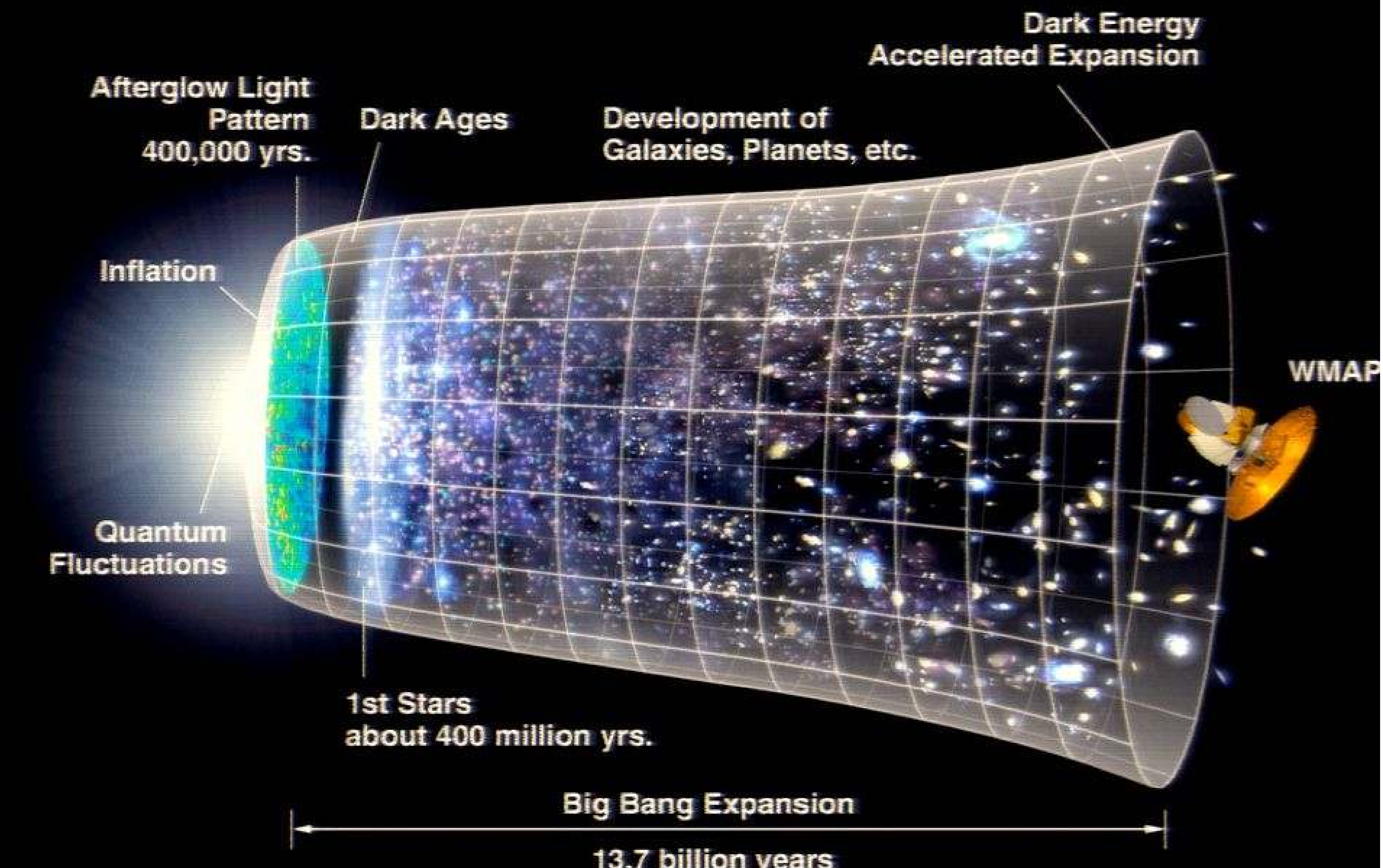
Abstract:

Challenges for Early Universe Cosmology

Neil Turok, Perimeter Institute

* Concordance Model
* Anthropics
* Measures

Concordance Model



Success!

fluctuation level:

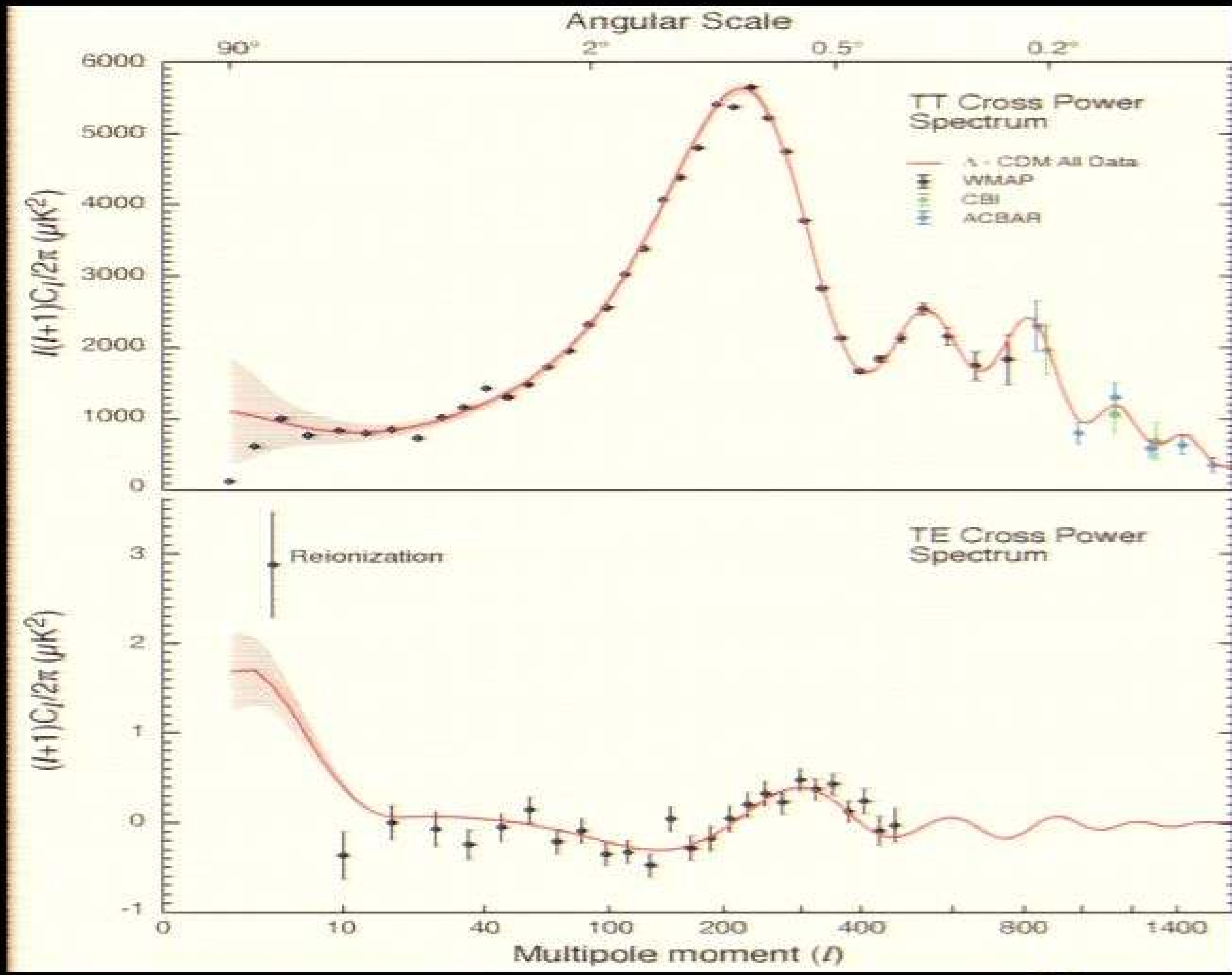
temperature

Z'eldovich, Peebles+Yu 70's

Bond+Efstathiou 80's

polarization

Coulson, Crittenden, NT 94

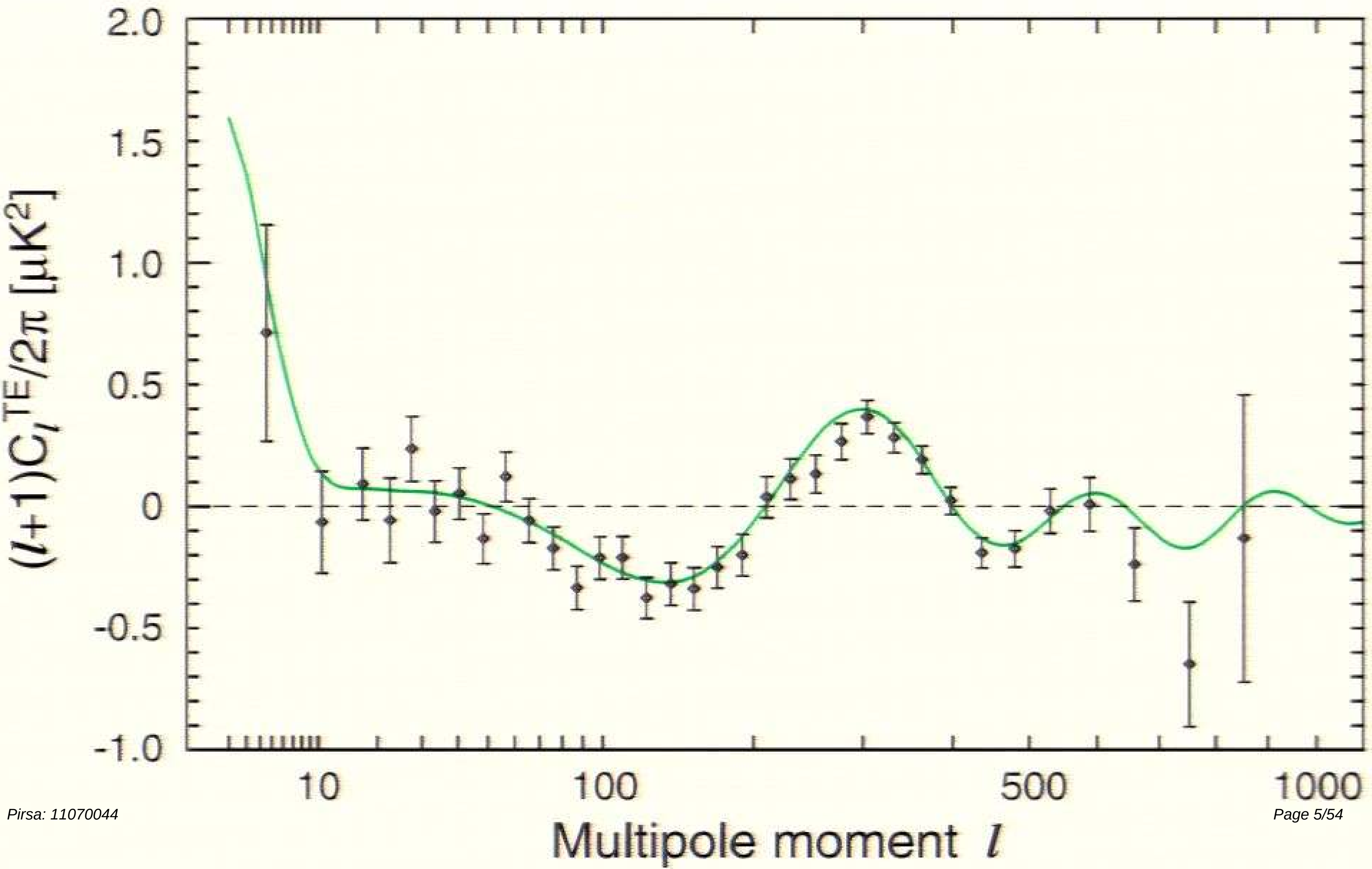


($l = 2\pi/\theta$)

100 10 1 .1

Angle on Sky (Degrees)

WMAP 5 year TE



good evidence for ...

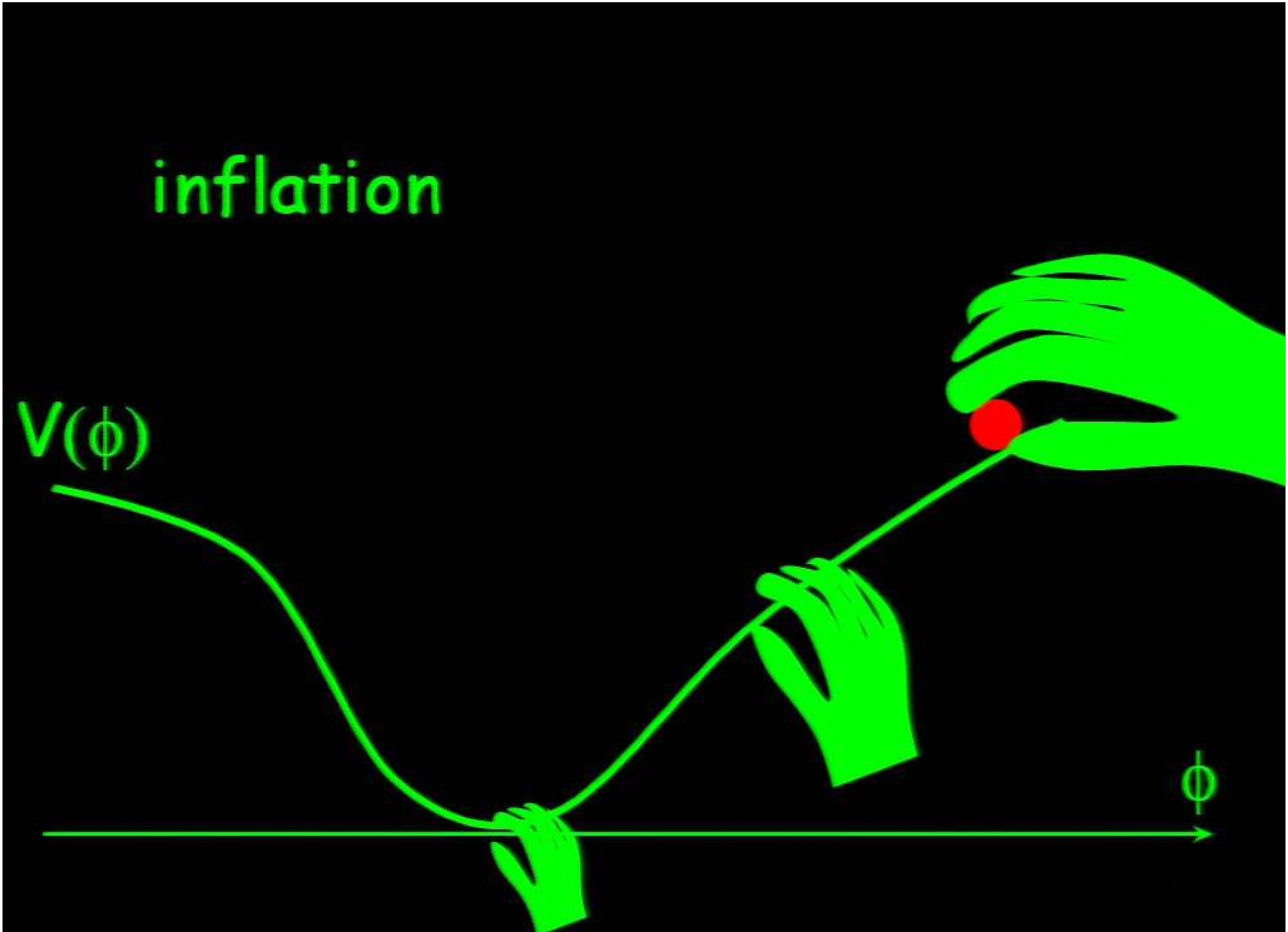
nearly flat FRW universe:

$\Omega_\Lambda : \Omega_{CDM} : \Omega_B : \Omega_\nu : \Omega_\gamma \sim 0.7 : 0.25 : 0.05 : 0.003 : 0.0003$

primordial perturbations

* linear
* growing mode
* nearly scale-invariant
* nearly 'adiabatic'
* nearly Gaussian

universe is: geometrically simple
compositionally complex


inflation
V(ϕ)
ϕ


Challenges for Inflation
* initial conditions
* fine-tuned potentials
* $\Lambda \sim 10^{-120}$; $\Lambda_I \sim 10^{-15}$
* eternal inflation
"anything that can happen will happen: and it will happen an infinite number of times" A. Guth, 2002
* landscape
measure problem
* reliance on anthropic arguments

Anthropics: the universe is the way it is because of a (gigantic) selection effect

why are we then not "close to extinction"?

why is the universe so geometrically simple?

* very nearly flat
* very nearly spatially homogeneous
* the fluctuations are scale-invariant on scales much larger than galaxy scales

for anthropic arguments to become convincing, we need well-defined

* measures
* projections

The Measure Problem

What is the natural measure on
the space of cosmological solutions?

What is the likelihood of a universe like ours,
in a given physical model? eg inflation, cyclic,.

Two key ingredients

I: Penrose critique of inflation - Hamiltonian evolution almost never turns a generic state into a highly unusual state. Canonical measure is invariant.

II: Counting of states in gravity can only be done in an asymptotic region where global properties of spacetime become sharp

In a specific setup, we shall construct a canonical measure and show a universe like ours is extremely unlikely in slow-roll inflationary models

- standard slow-roll inflation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\rho_\phi - \frac{k}{a^2}; \quad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

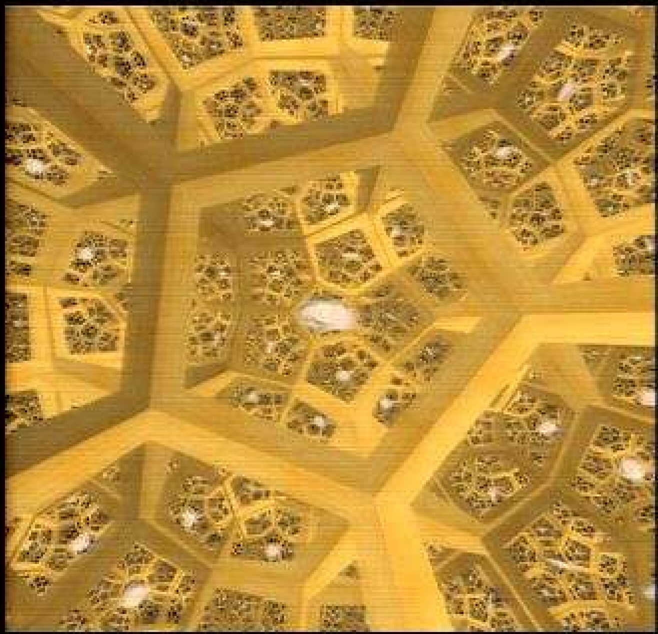
$$\ddot{\phi} + 3\frac{\dot{a}}{a}\dot{\phi} = -V_{,\phi}$$

$$\Rightarrow \dot{H} = -\frac{1}{2}\dot{\phi}^2 + \frac{k}{a^2}$$

- Hamiltonian and time reversal invariant

(focus on FRW spacetimes and assume V(ϕ) is monotonic away from its min)

Assume k=-1 (so a and H are monotonic), zero Λ, and compactify the spatial slices



* a mathematical device to keep everything finite: the results do not depend on the compactification volume
* (but in fact has been advocated as a very natural setup for chaotic inflation)

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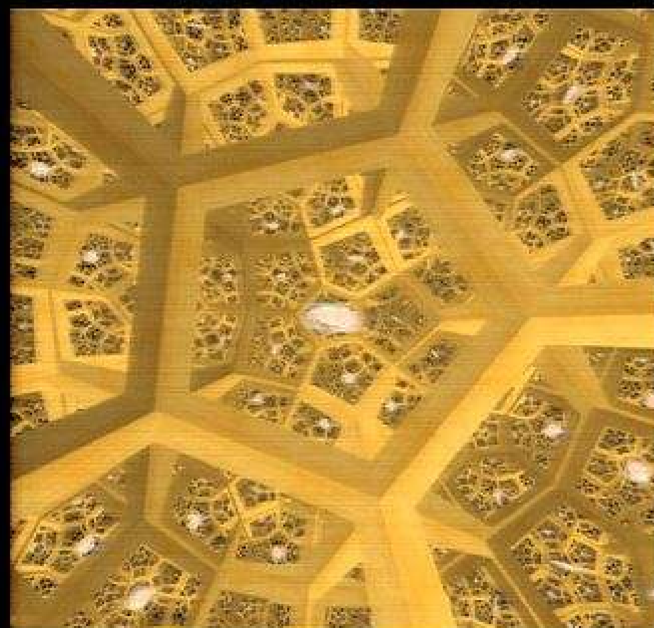

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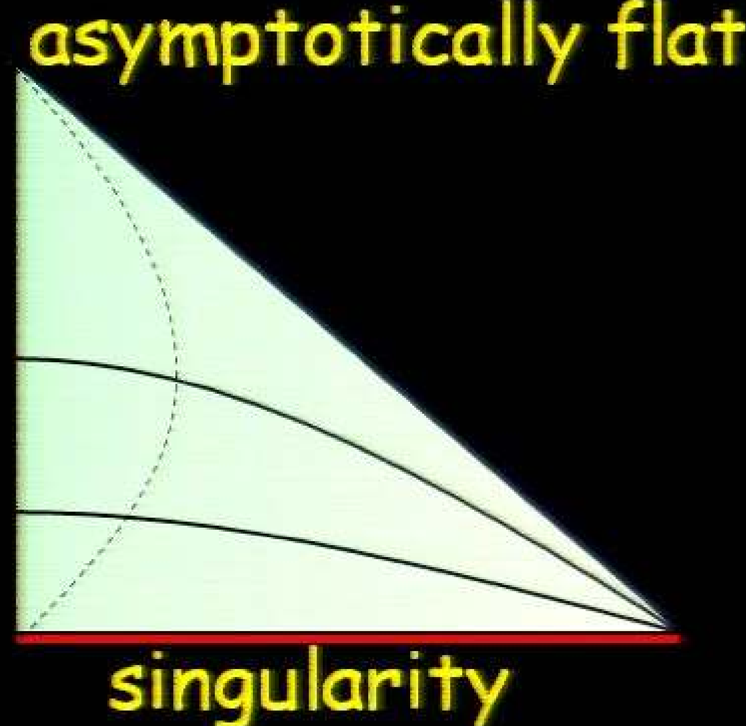
2-parameter family of solutions with an initial singularity:



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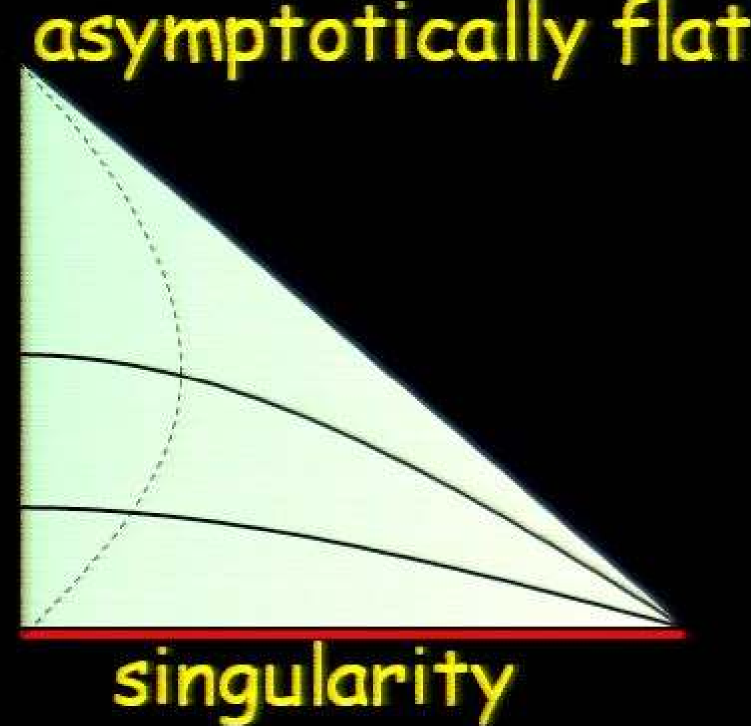

Criteria for a Measure

(i) Positive, normalisable
(ii) Independent of slicing or coordinates on either space-time or field space
(iii) Independent of ad hoc external structures eg cutoffs, comoving observers, "volume" factors ..
(iv) Natural extension of canonical quantum measure for fluctuations to the background (why use for one but not the other???)

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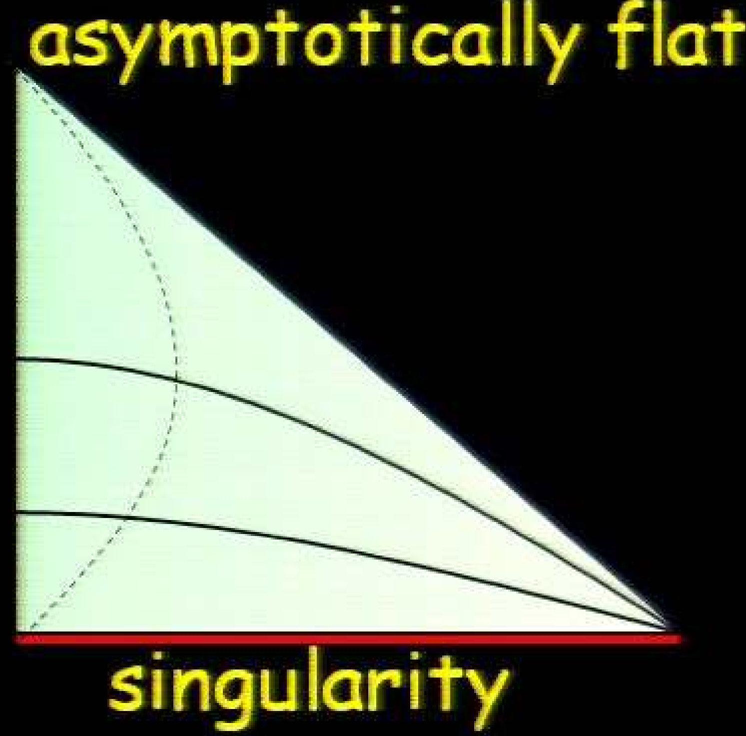

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Canonical measure on space of solutions

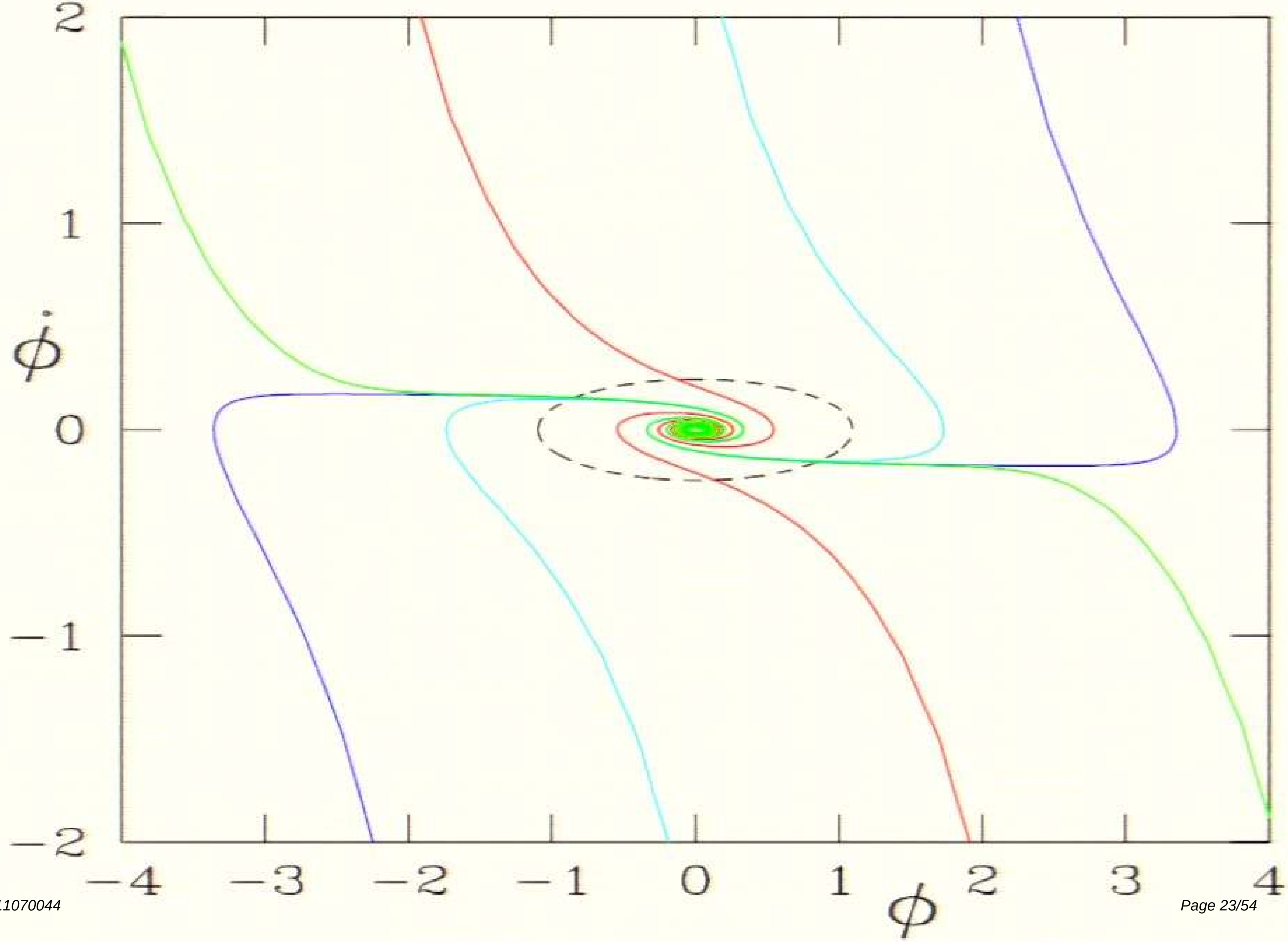
$$\omega_c = dp_a \wedge da + dp_\phi \wedge d\phi$$

$$\int_\Sigma \omega_c \Big|_{\mathbb{H}=0}$$

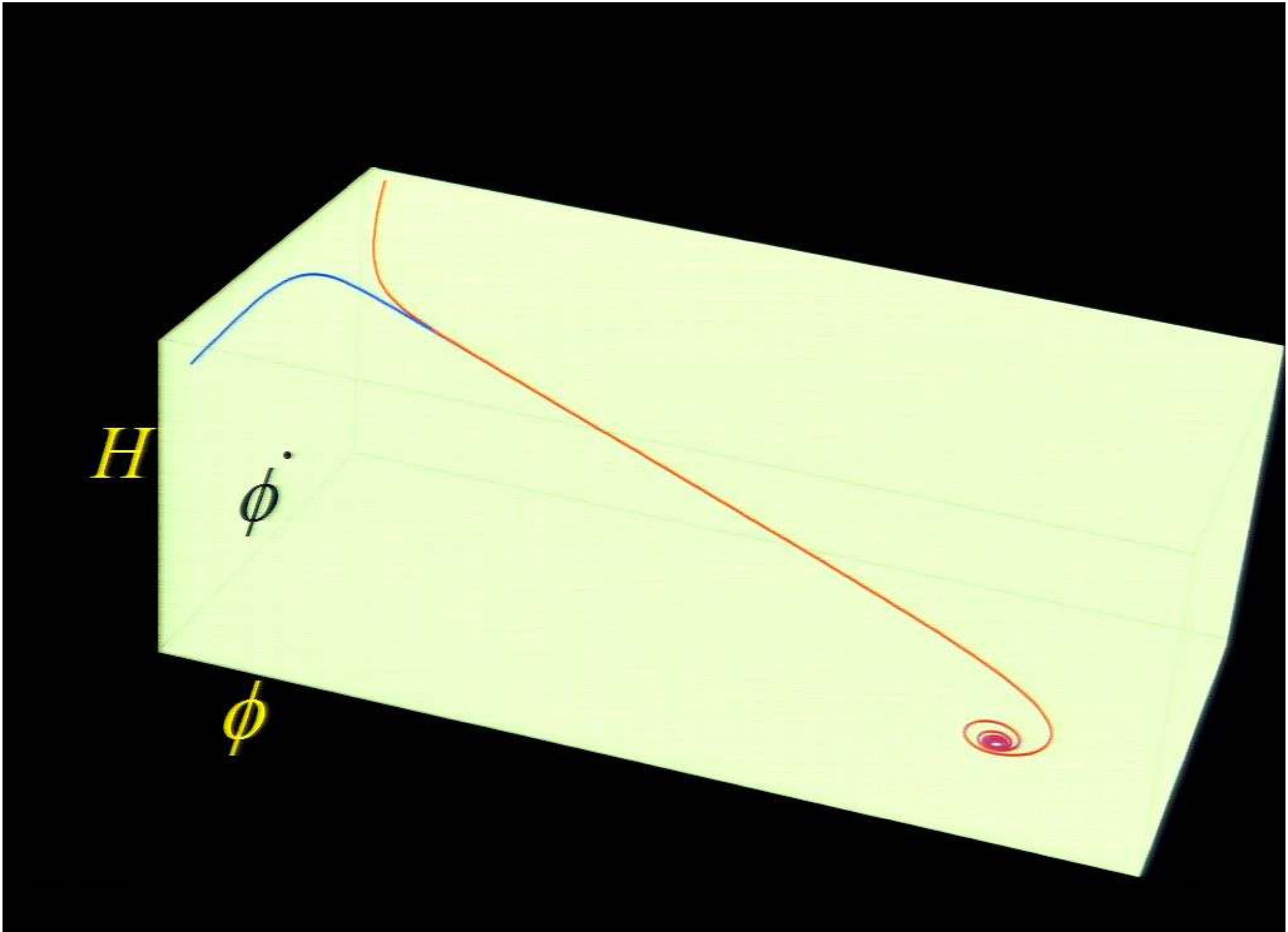
Liouville
Gibbons, Hawking, Stewar
Hawking, Page
Hollands Wald
Kofman, Linde, Mukhanov
Gibbons, NT
Carroll, Tan

with Σ pierced once by every trajectory
e.g. a=const or H=const

Satisfies all of conditions (i)-(iv)
except normalisability, because Σ is not compact (because $\mathbb{H}$ isn't positive)



2
1
0
−1
−2
−4
−3
−2
−1
0
1
2
3
4
$\dot{\phi}$
ϕ



H
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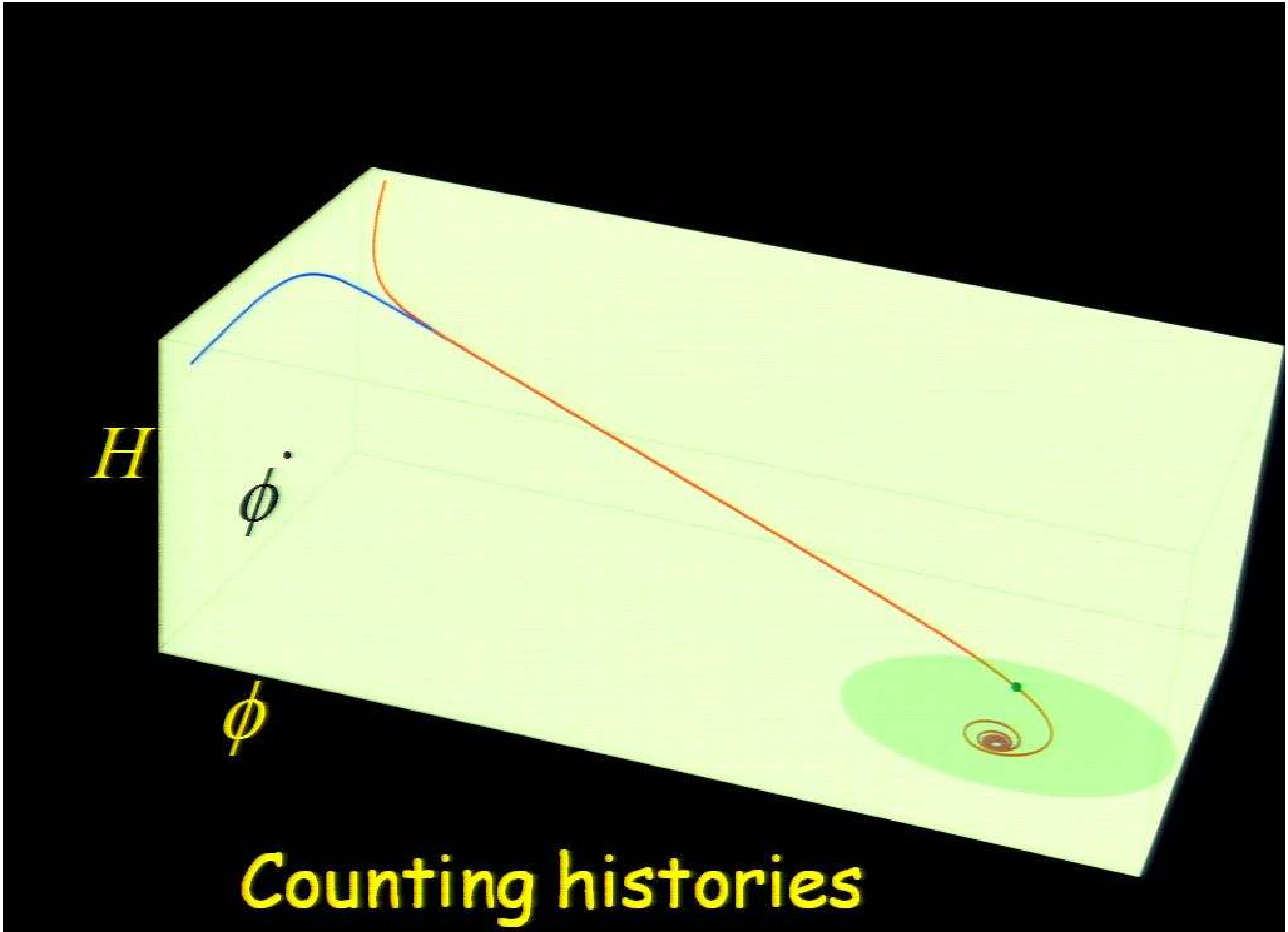
ϕ


H
$\dot{\phi}$
ϕ
Counting histories

Flat space canonical (Gibbs) ensemble.
Cannot just integrate over Liouville: instead, we maximise entropy $S = -\sum p_i \ln p_i$

subject to $E = \sum p_i E_i$ (assuming E_i b.b.)

Note: in information theory approach, max ent principle is very general, can even be applied to non-equilibrium situations (see e.g. papers of E.T. Jaynes)

But in GR, $\mathbb{H}=0$ on all physical states, so cannot constrain its expectation value

What do we do?

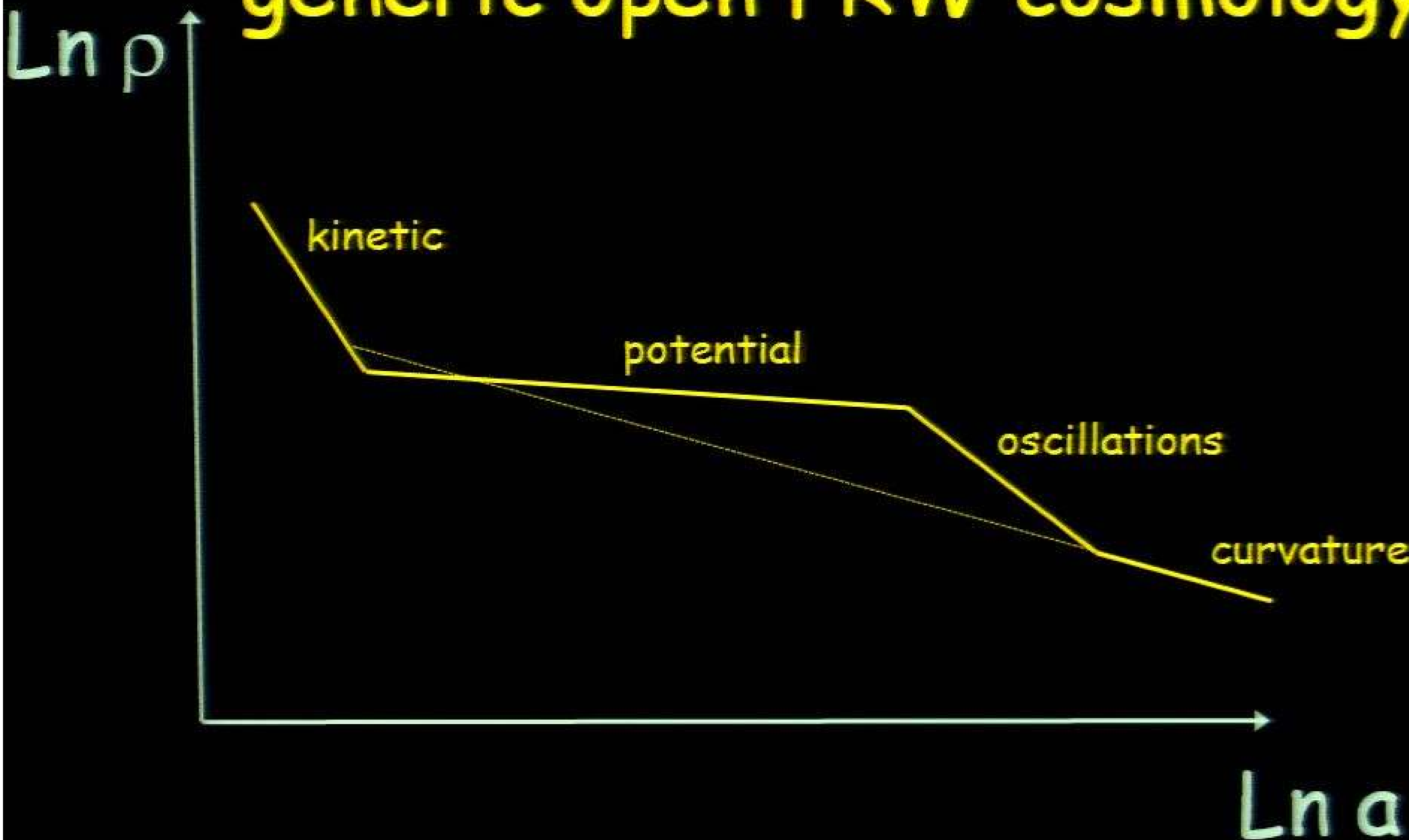
In k=-1, zero Λ cosmologies, matter density is diluted away at large a -> gravity becomes negligible, expansion becomes adiabatic

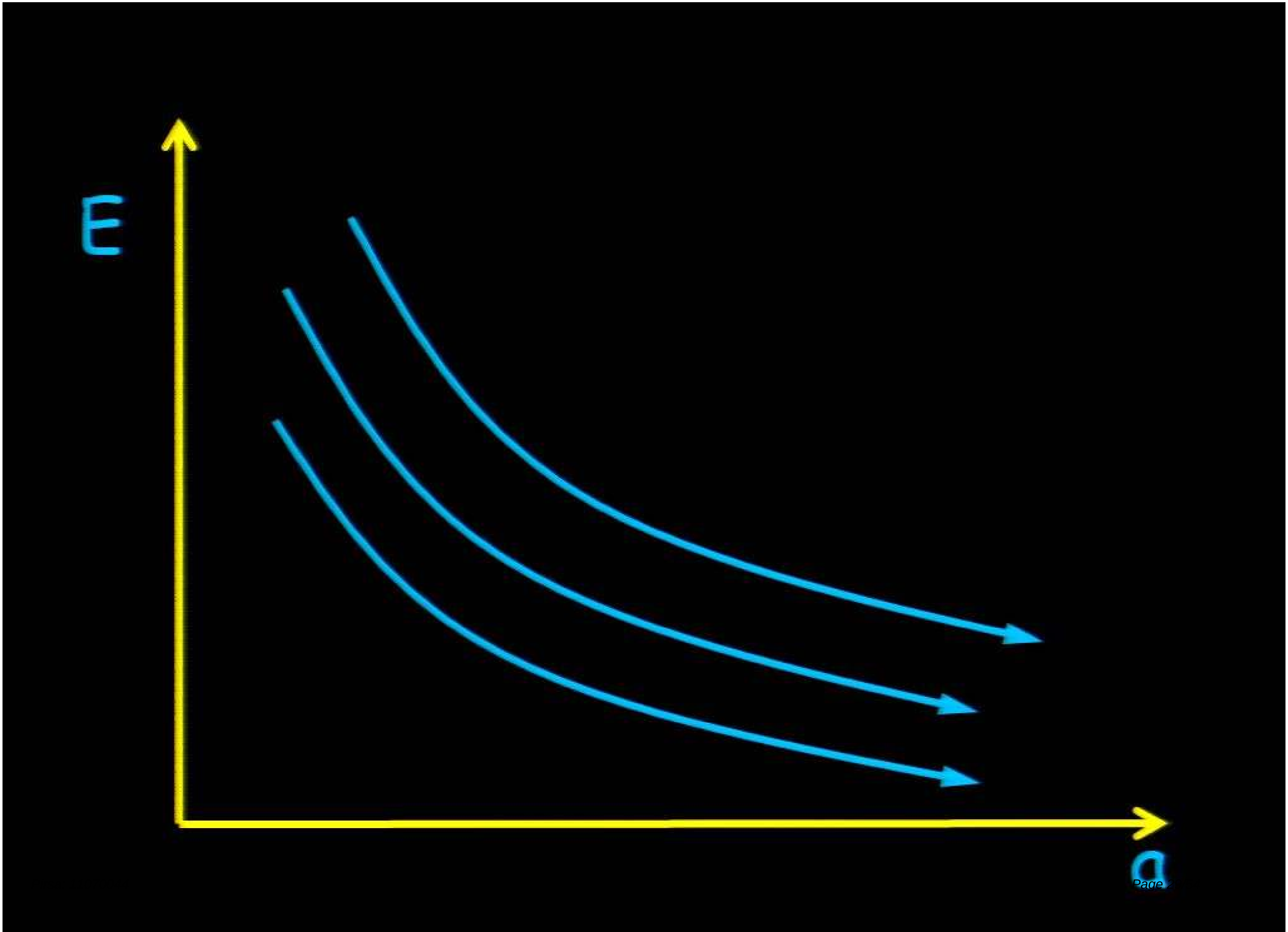
-> entropy reduces to that of the matter (inc grav waves), and is an adiabatic invariant

Every trajectory ends up on an adiabat curve $S_m(E_m, a)$= const

Natural to label an ensemble of spacetimes by the asymptotic entropy $S=S_m$

generic open FRW cosmology




E
a

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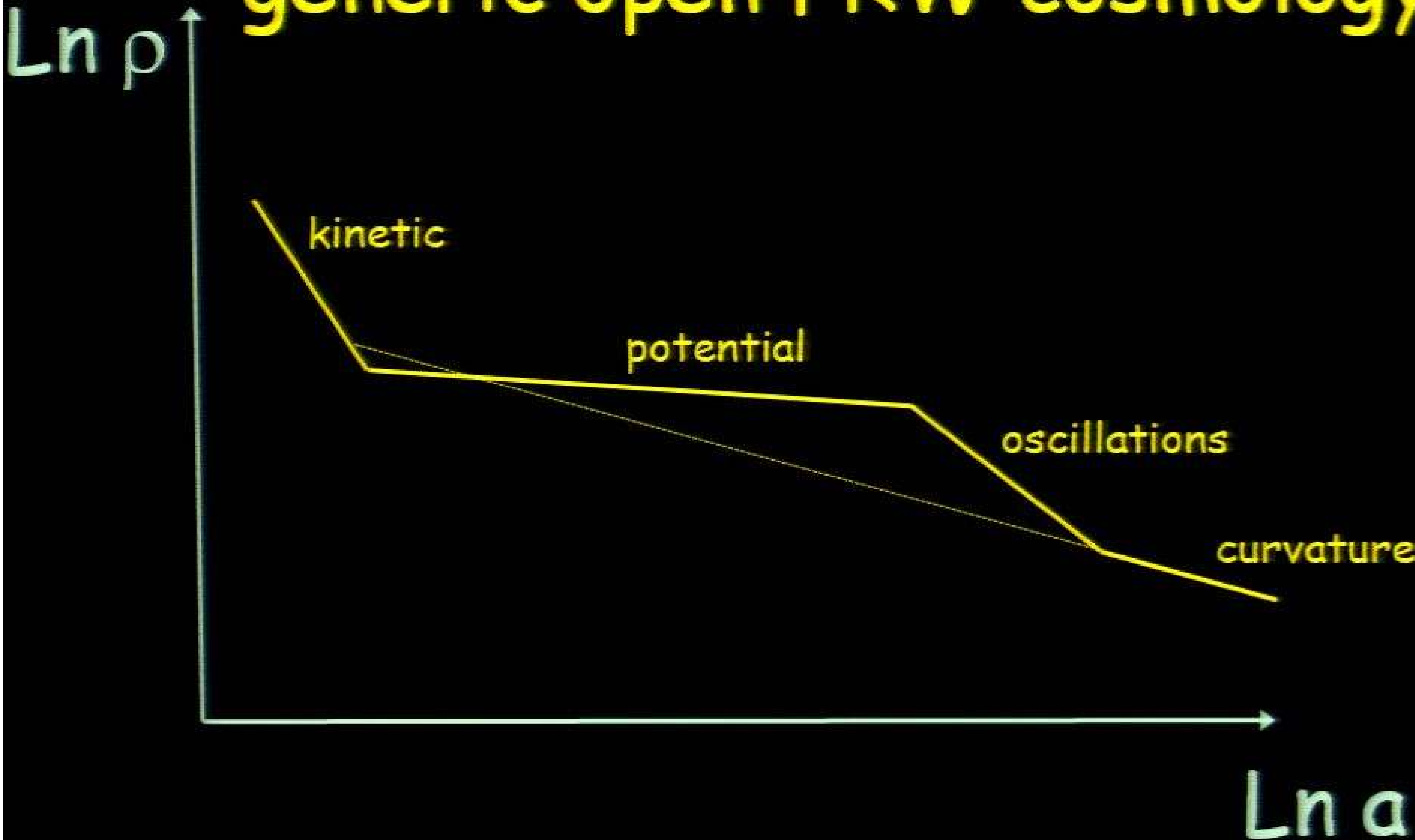

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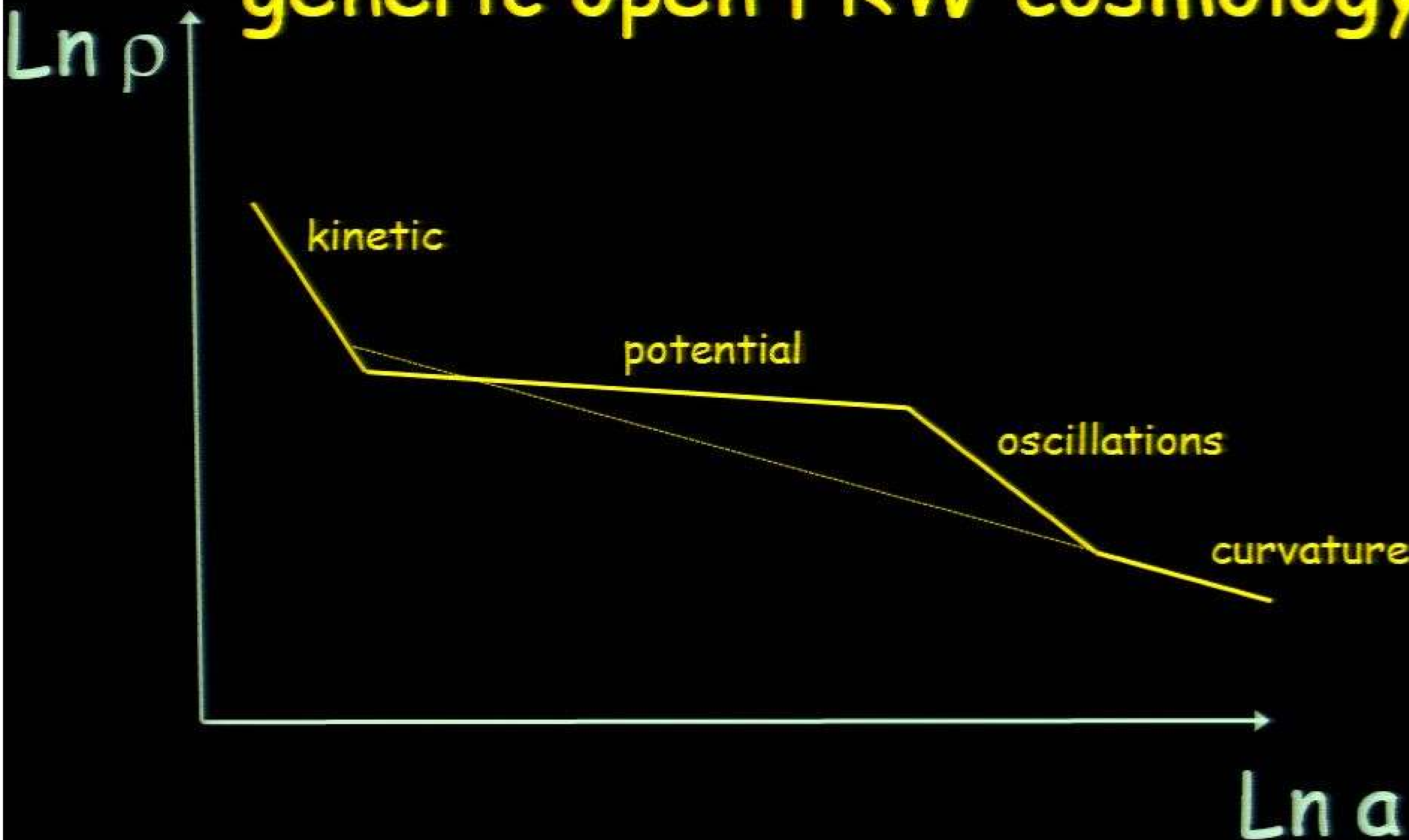
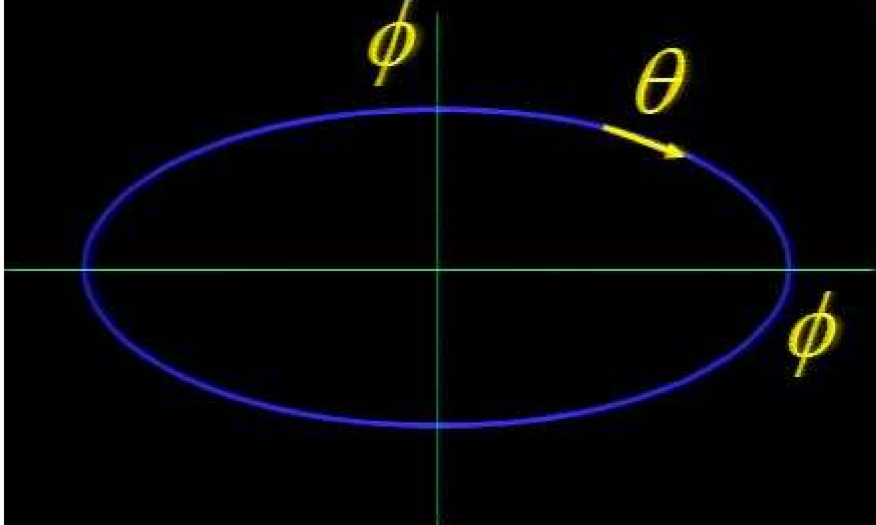


a =const slicing

$$\omega_c = a^3 d\dot{\phi}\, d\phi$$



$$\rho = \tfrac{1}{2}(\dot{\phi}^2 + m^2\phi^2)$$

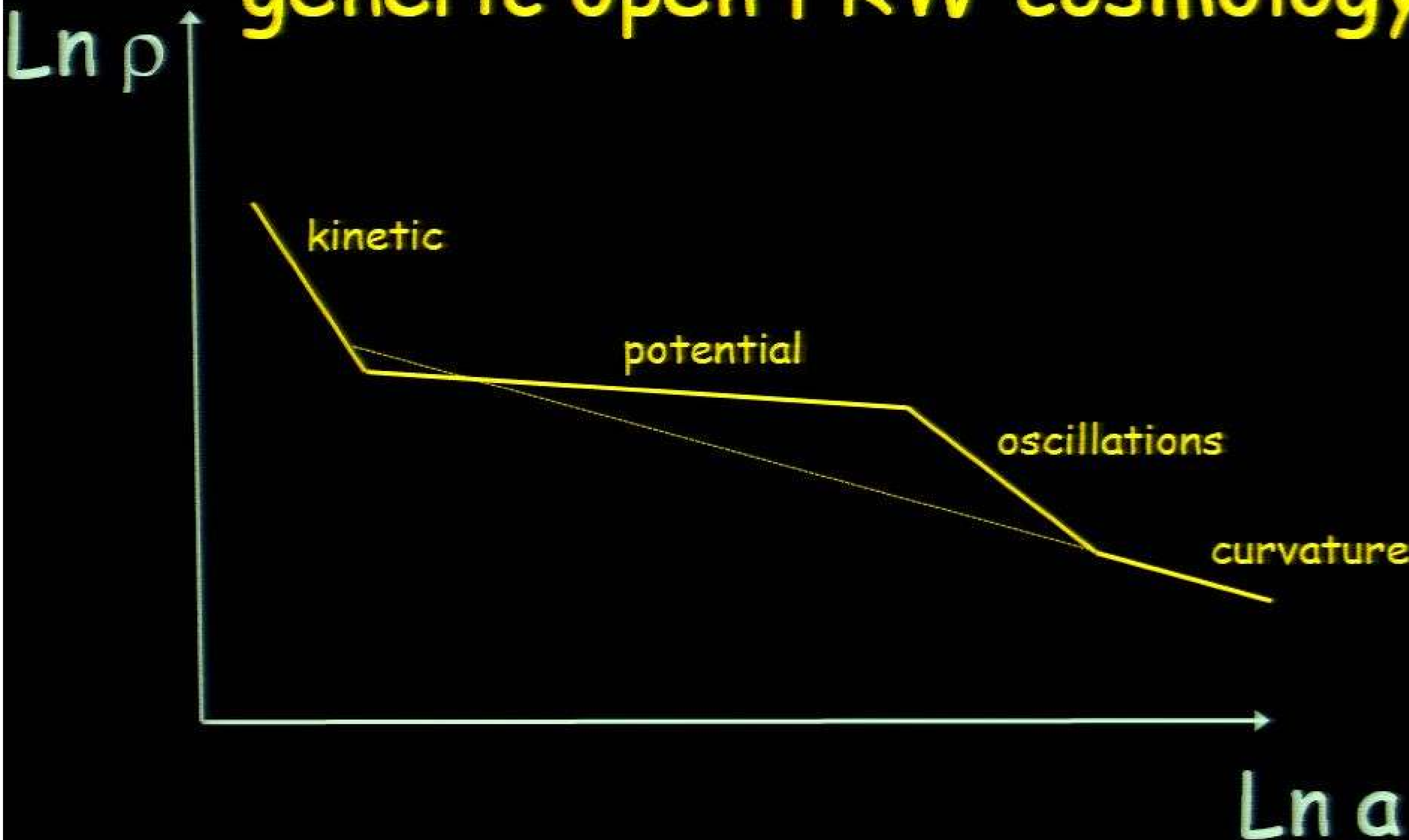
$$\sim C/a^3,\ \ a \to \infty,$$

ρa^3 adiabatically conserved

$$ds^2 = \frac{da^2}{1 + 8\pi G \rho a^2/3} + a^2 dH_3^2 \approx dM_4^2 - \frac{8\pi G}{3}\frac{C}{a} da^2$$

(*C* is analogous to the AdM mass)

generic open FRW cosmology



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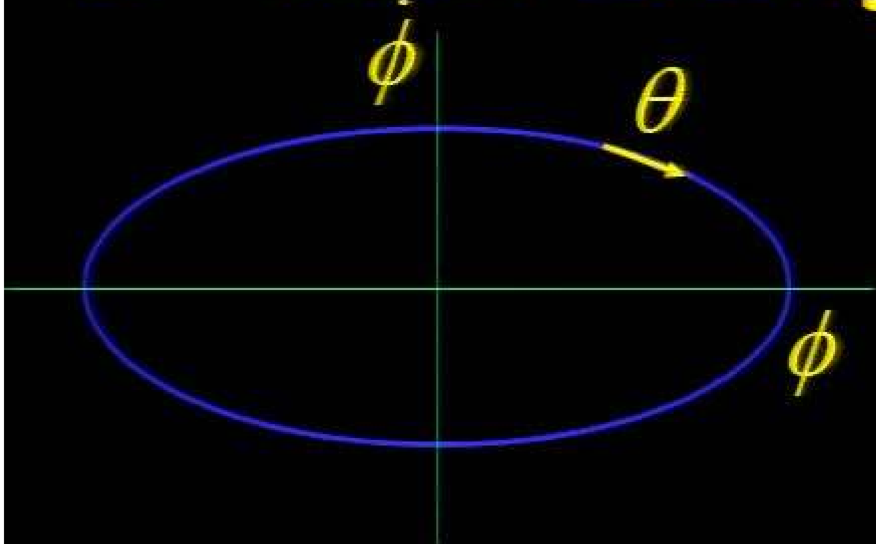

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Including backreaction

$$\phi \sim \frac{(2C)^{\frac{1}{2}}}{ma^{\frac{3}{2}}}\left(\cos\theta + \frac{C\cos^3\theta}{24a}\right) + \ldots,$$

$$\rho_\phi \sim \frac{C}{a^3}\left(1 + \frac{3\sin 2\theta}{2ma} + \frac{C(2\cos 2\theta + \sin^2 2\theta)}{24a}\right) + \ldots$$

where $\theta = m(a - \frac{5C}{24}\ln(ma)) + \theta_0$

in large a limit, effect of matter on background spacetime (i.e. gravity) becomes negligible

we just have flat spacetime, and an adiabatically expanding box filled with matter

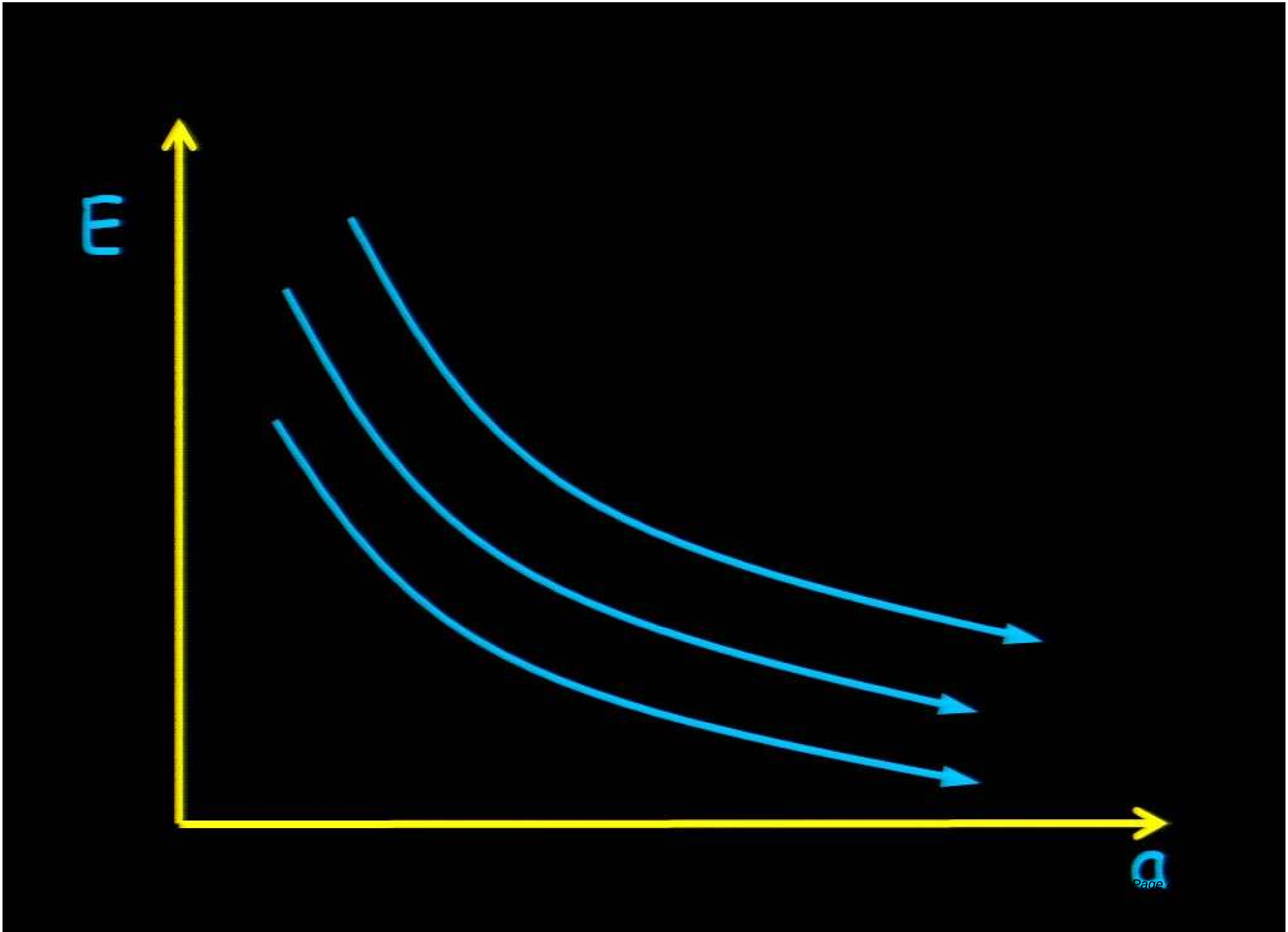
statistical ensemble: minisuperspace

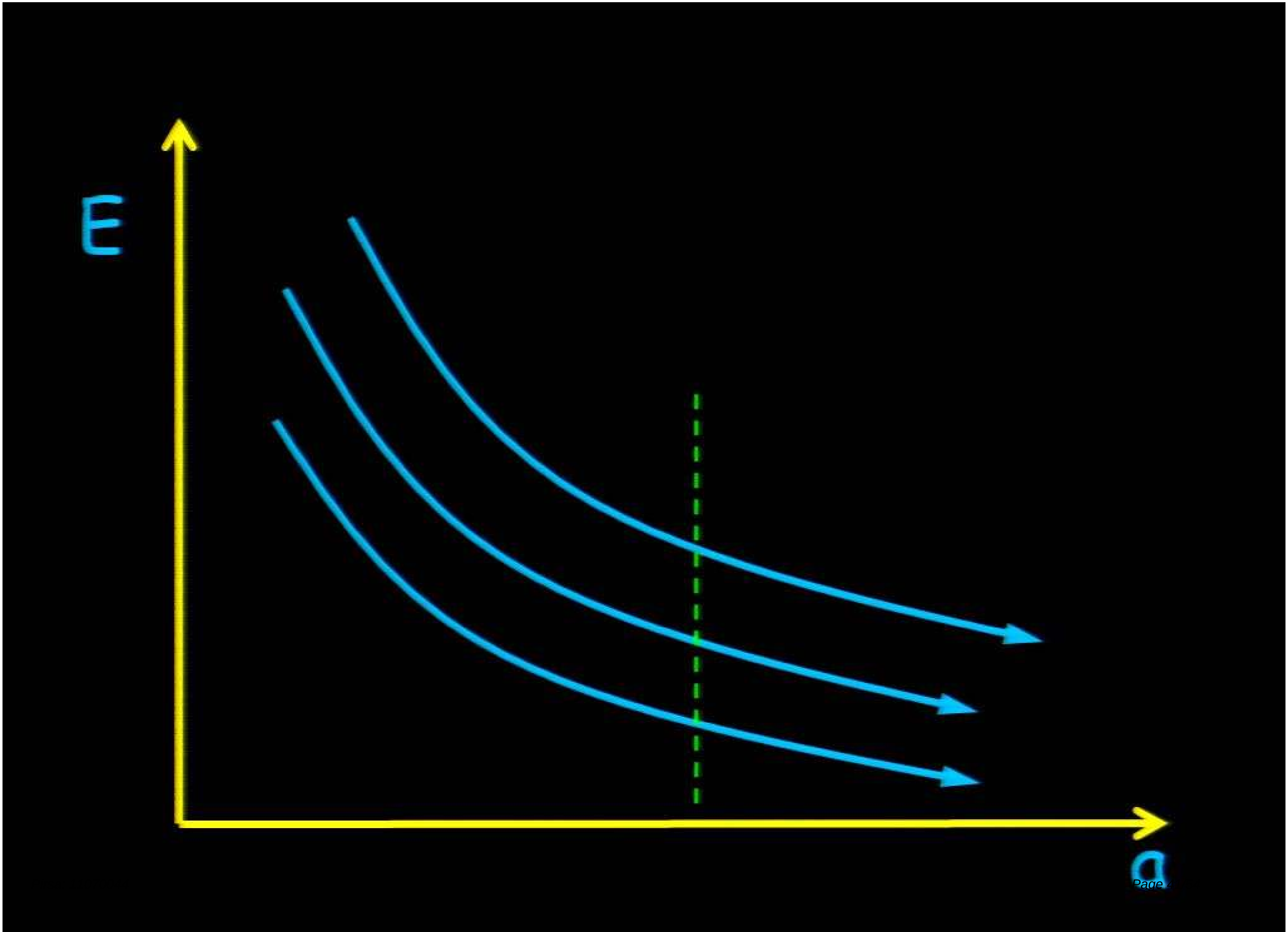
$$\mathbb{H}_{\mathrm{m}}(p_\phi,\phi)=\tfrac{1}{2}\left(\frac{p_\phi^2}{Ua^3}+Ua^3V(\phi)\right)$$

$$\left\langle \mathrm{H}_{\mathrm{m}} \right\rangle = \frac{\int dp_\phi d\phi e^{-\beta \mathrm{H}_{\mathrm{m}}} \mathrm{H}_{\mathrm{m}}}{\int dp_\phi d\phi e^{-\beta \mathrm{H}_{\mathrm{m}}}} = E(a,\beta)$$

entropy $S = S_m = \ln(\frac{Ua^3\rho_\phi}{m}) =$ adiabatic invariant

constant entropy=fixed C


E
a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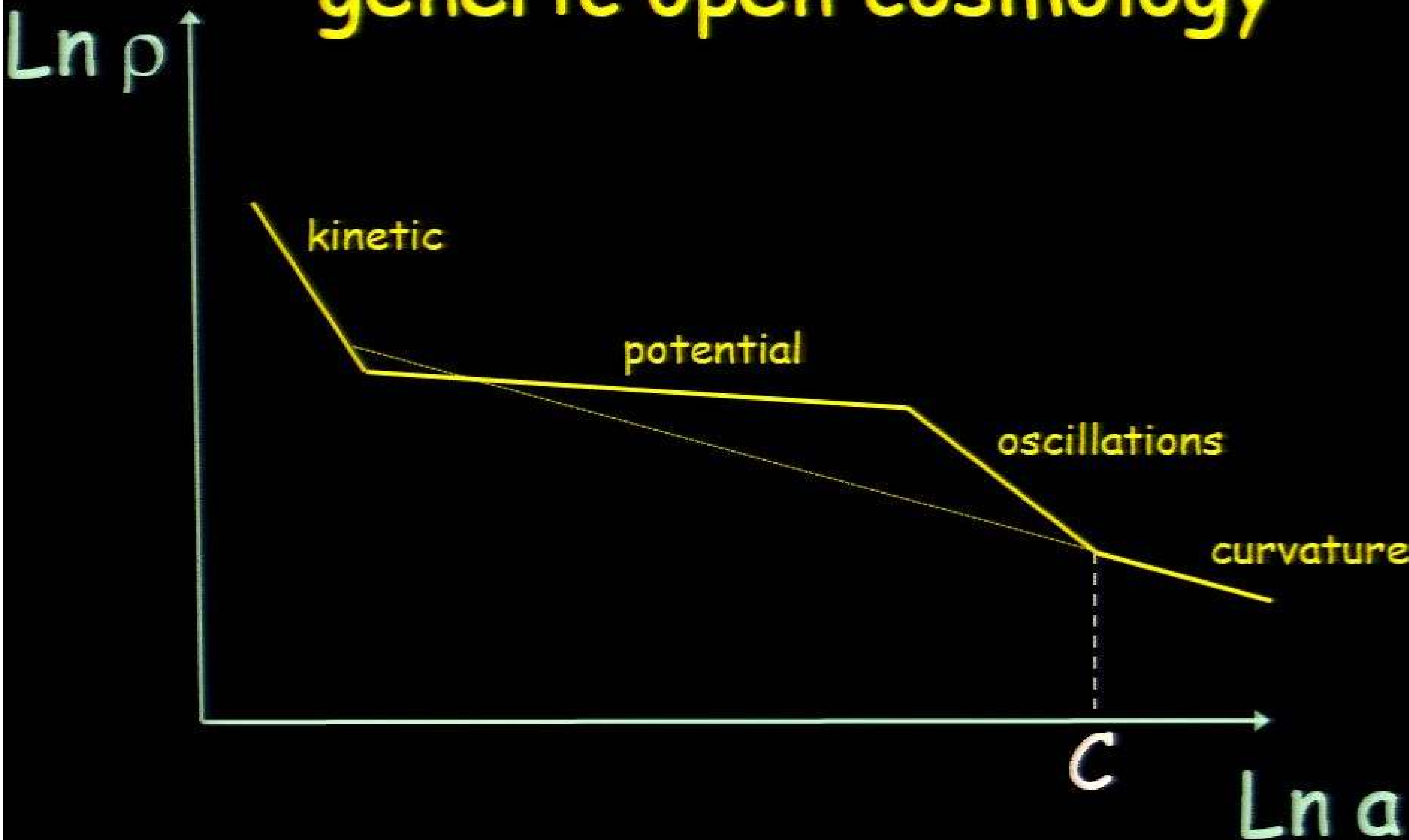
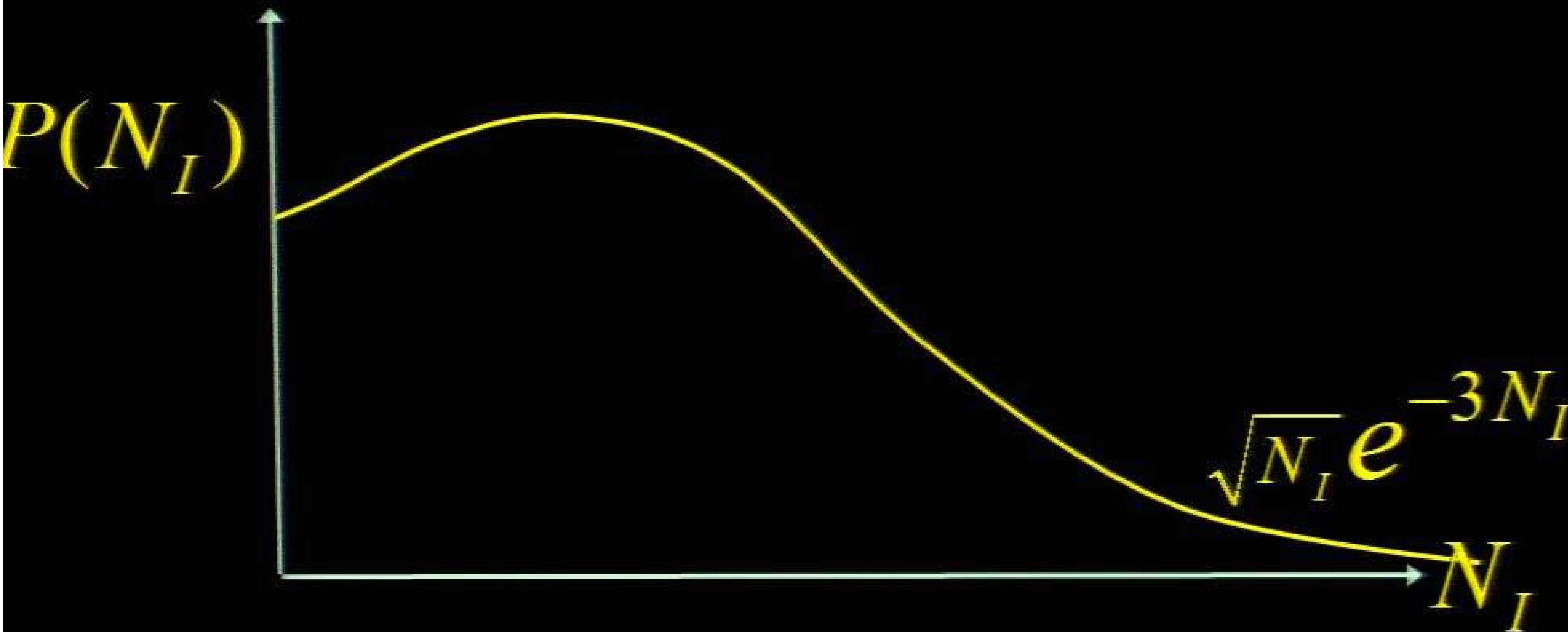
a

generic open cosmology



Canonical measure for inflation



Finite C result is always lower than $C=\infty$ result at large N_I

* Note: "attractor" becomes "repeller" because statistical ensemble defined in asymptotic region where gravity becomes unimportant: the future

* N slow-roll inflaton fields (N-flation) makes problem worse

$$P_>(N_I) \propto \prod_i \delta\theta_i \sim e^{-3N_I N}$$

* this analysis makes precise a problem identified by Penrose long ago (Annals NYAS, 1989)

* with this canonical measure, slow-roll/`chaotic' inflation cannot be considered a viable explanation for the observed state of the cosmos

* can be extended to landscape with inclusion of complex solutions describing tunneling: false vacua don't help

* Could add further restrictions
  e.g. insist ϕ bounded -> 1-parameter family $\phi_0 (S_{final})$

* Large entropy -> many e-folds, but large final entropy (or flatness) is then an input, not a prediction

* Could restrict to non-singular spacetimes (eg Page) and just reject all k=-1 solutions

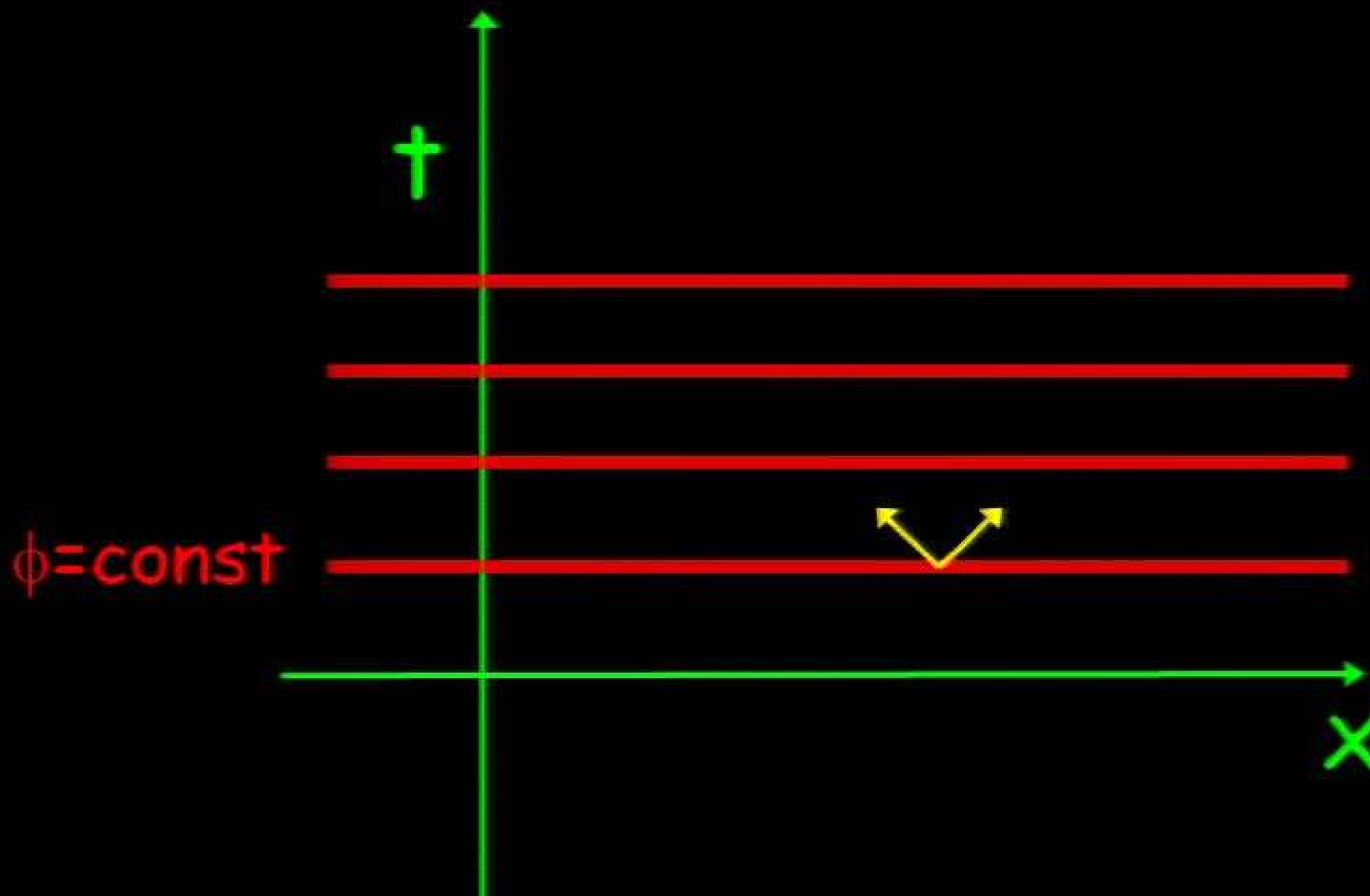
* k=+1 "bounce" solutions possible, have finite measure but collapsing phase very unstable

* How do we justify rejecting cosmic singularities but allowing black holes? What about white holes?

What could be wrong?

* canonical measure?
* neglect of: entropy production?

ϕ decays: information stored in radiation



But the relative proportions of phase space corresponding to N_I or more efolds are preserved (by unitarity or Liouville)

What could be wrong?

* canonical measure?
* neglect of: entropy production?
: inhomogeneities?
: quantum fluctuations?
* constraint on final entropy?
maybe, but what alternative?
* global structure?
* inflation?

compare "cyclic/ekpyrotic" theory, where gravity is unimportant in the past, and according to the corresponding canonical measure, every trajectory undergoes near-maximal ekpyrosis

(w/P. Steinhardt)

Scale Invariant perturbations

* near-massless scalar in de Sitter

* exponentially flat potentials in collapsing phase (cyclic)

* scale-invariant duals via holography

Summary

concordance cosmology has plenty of challenges

- singularity
- tuning
- reliance on anthropics
- measure: a good one exists!

No Signal

VGA-1

No Signal

VGA-1