Beyond the Big Bang

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work with I. Bars, P. Steinhardt
M. Smolkin

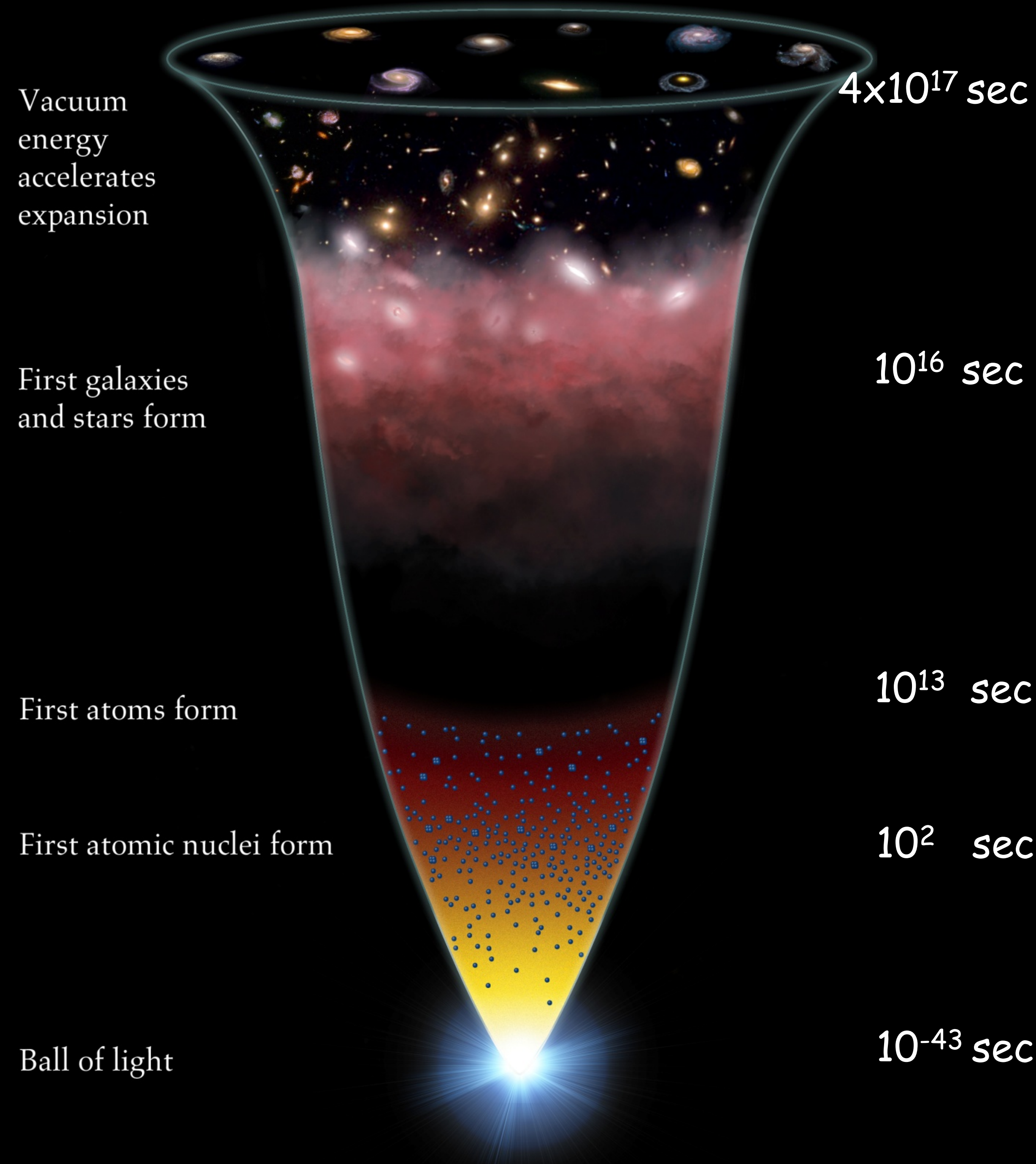
"Behind it all is surely an idea so simple,
so beautiful, that when we grasp it
- in a decade, a century or a millenium –
we will all say to each other: how
could it have been otherwise?"

John Wheeler

all known physics

$$\Psi = \int e^{\frac{i}{\hbar}\int\left(\frac{R}{16\pi G} - \frac{1}{4}F^2 + \bar{\psi} i \not{D} \psi - \lambda\varphi\bar{\psi}\psi + |D\varphi|^2 - V(\varphi)\right)}$$

Schrödinger
Feynman
Einstein
Maxwell-Yang-Mills
Yukawa
Euler
Planck
Newton
Dirac
Kobayashi-Maskawa
Higgs



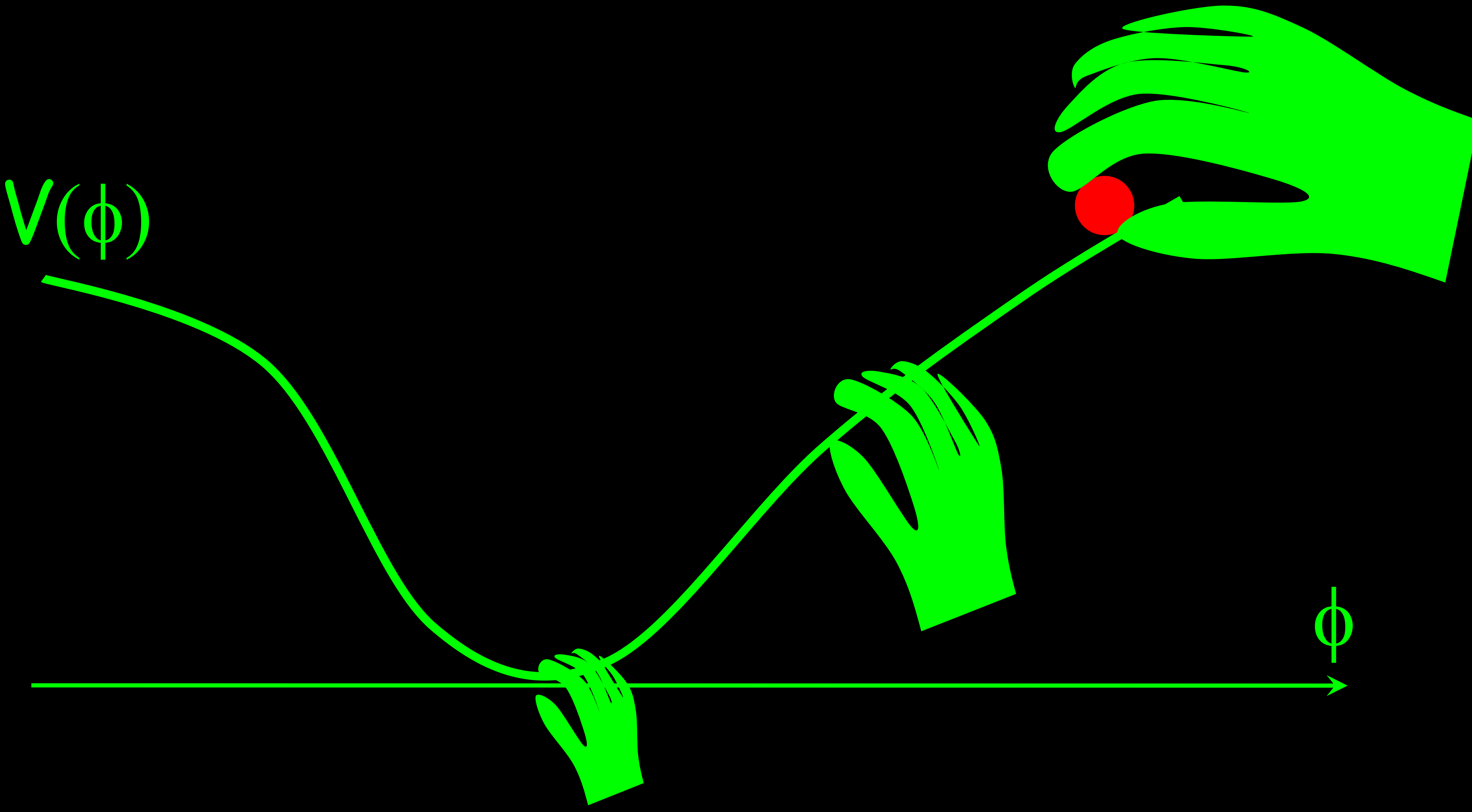
Vacuum energy accelerates expansion
4×10^{17} sec
First galaxies and stars form
10^{16} sec
First atoms form
10^{13} sec
First atomic nuclei form
10^{2} sec
Ball of light
10^{-43} sec

biggest questions

the singularity
inflation
dark matter
dark energy and the future

inflation

* initial conditions
* fine-tuned potentials
* $\Lambda \sim 10^{-120}$; $V_I \sim 10^{-15}$

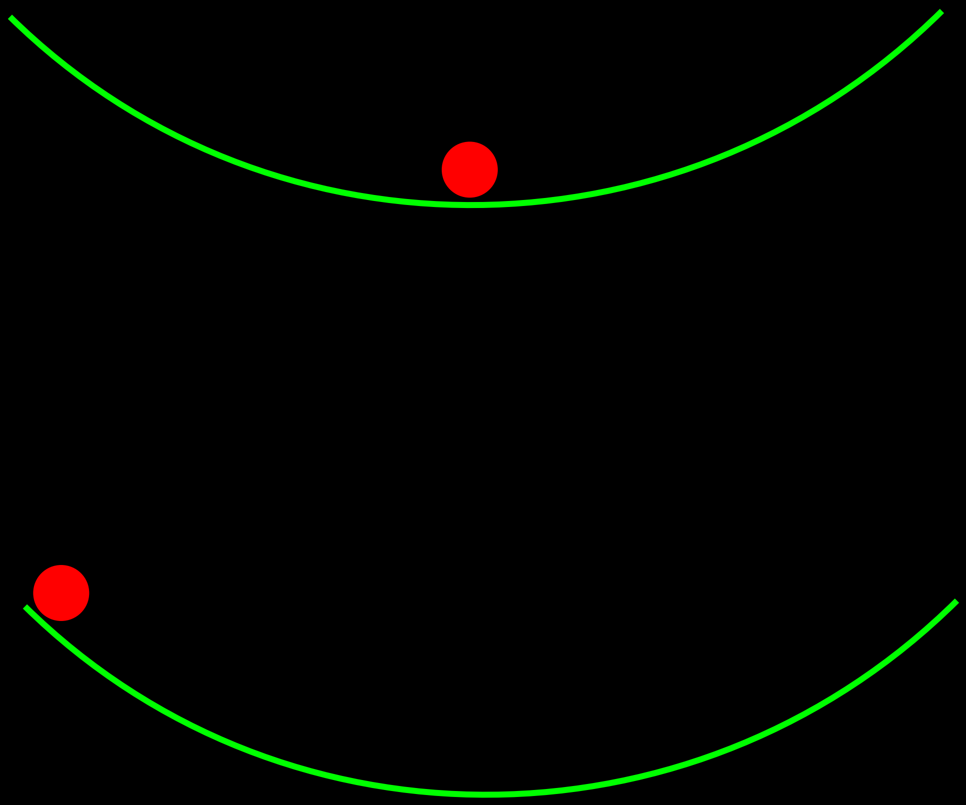


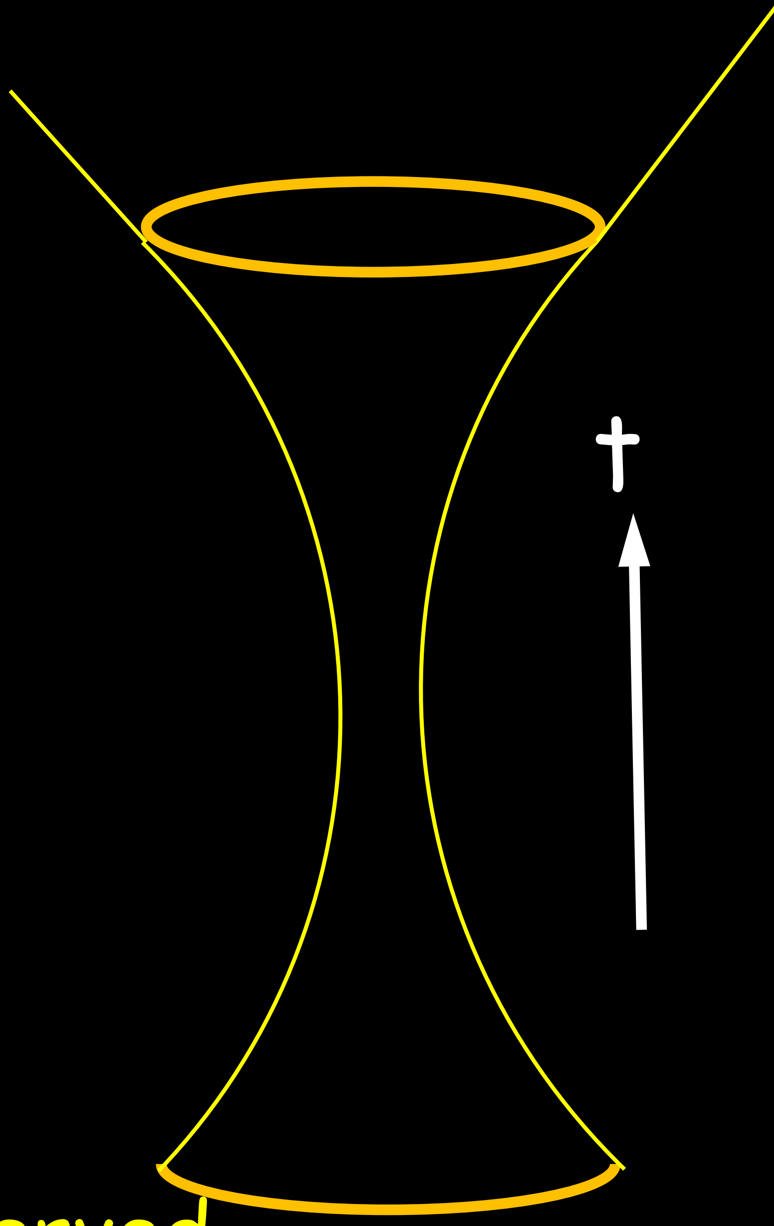
Inflation's claim:

"chaotic" initial conditions ->
* big
* expanding
* flat
* FRW universe
* w/ nearly scale-free perts

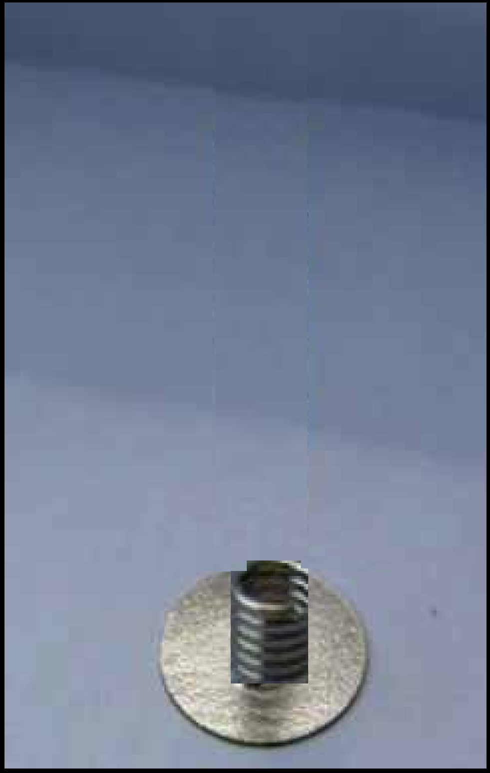
* the "ultimate free lunch"

Need a measure on space of cosmologies





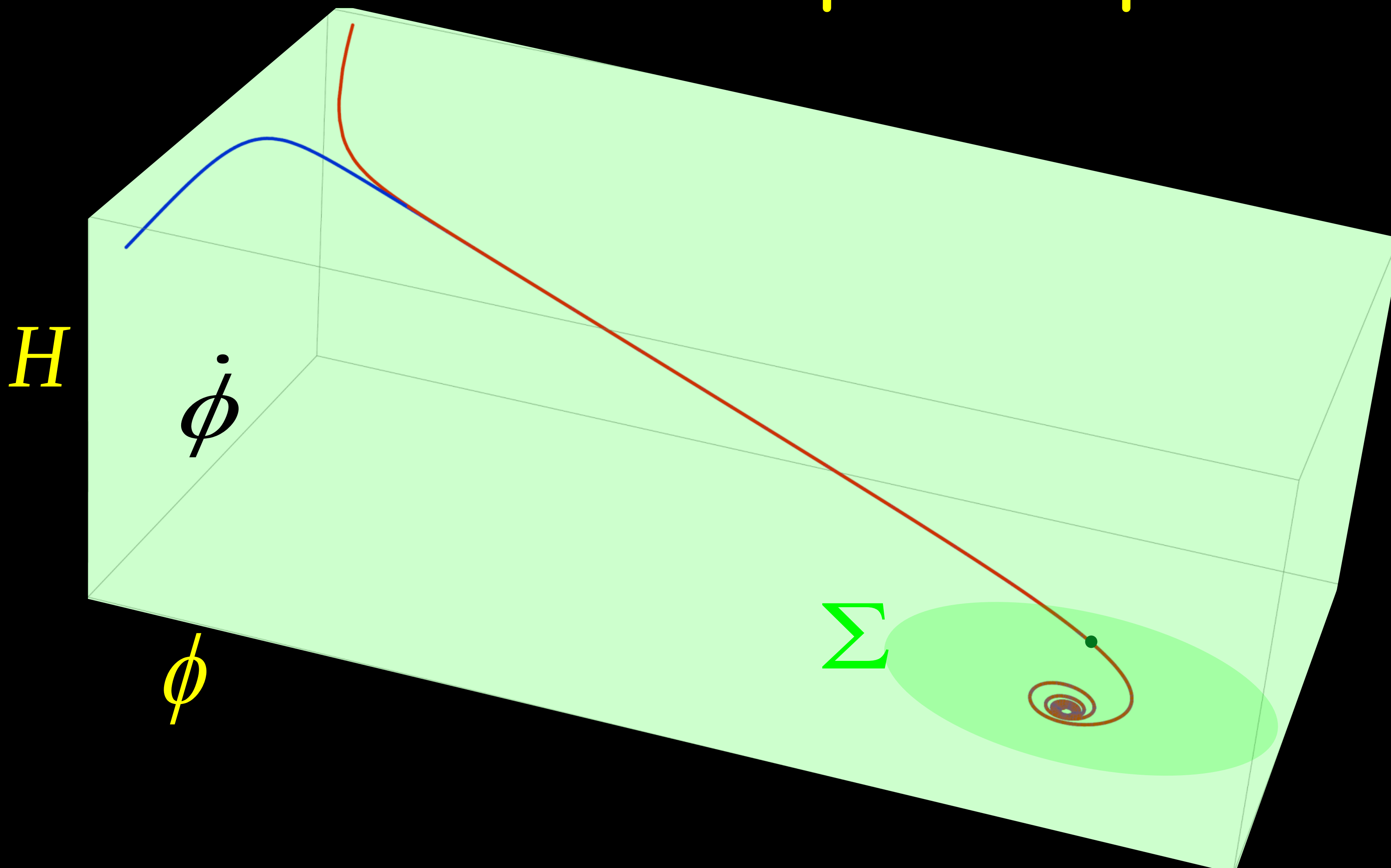
energy is not conserved
when space expands:
phase space volume is conserved
universe is not a “free lunch!

what is the correct measure, when gravity is included?

Lets be generous to inflation and just assume homogeneity+isotropy

Universes = curves in phase space



Hamiltonian, time reversal invariant

$$\mathbb{H}(p_a, a, p_\phi, \phi) = -\frac{p_a^2}{12Ua} + 3Ua + \frac{p_\phi^2}{2Ua^3} + Ua^3 V(\phi)$$

Canonical measure

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

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

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

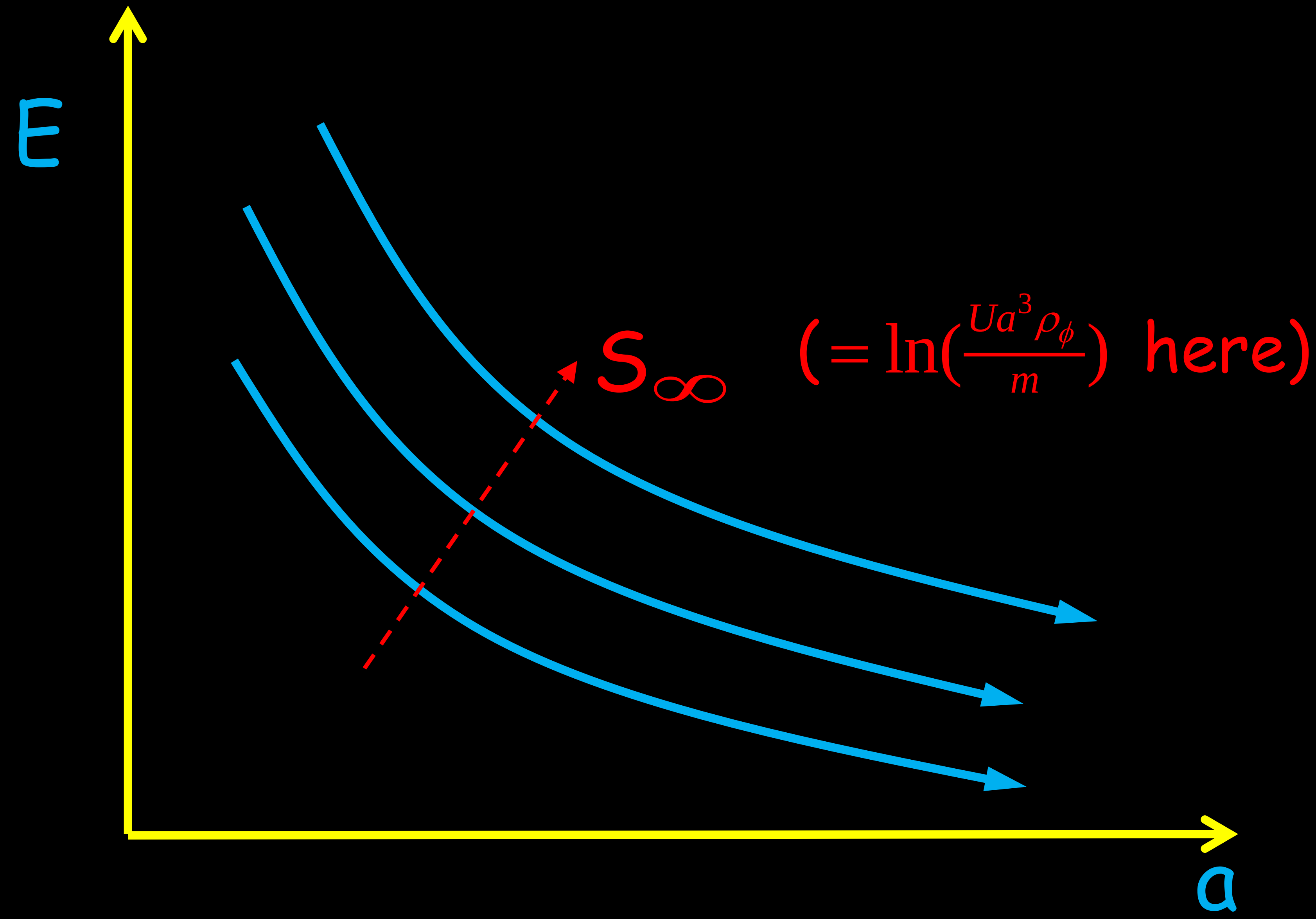
with Σ pierced once by every trajectory

Choose cosmology in which every trajectory ends an asymptotically flat universe ($k=-1$, $\Lambda=0$)

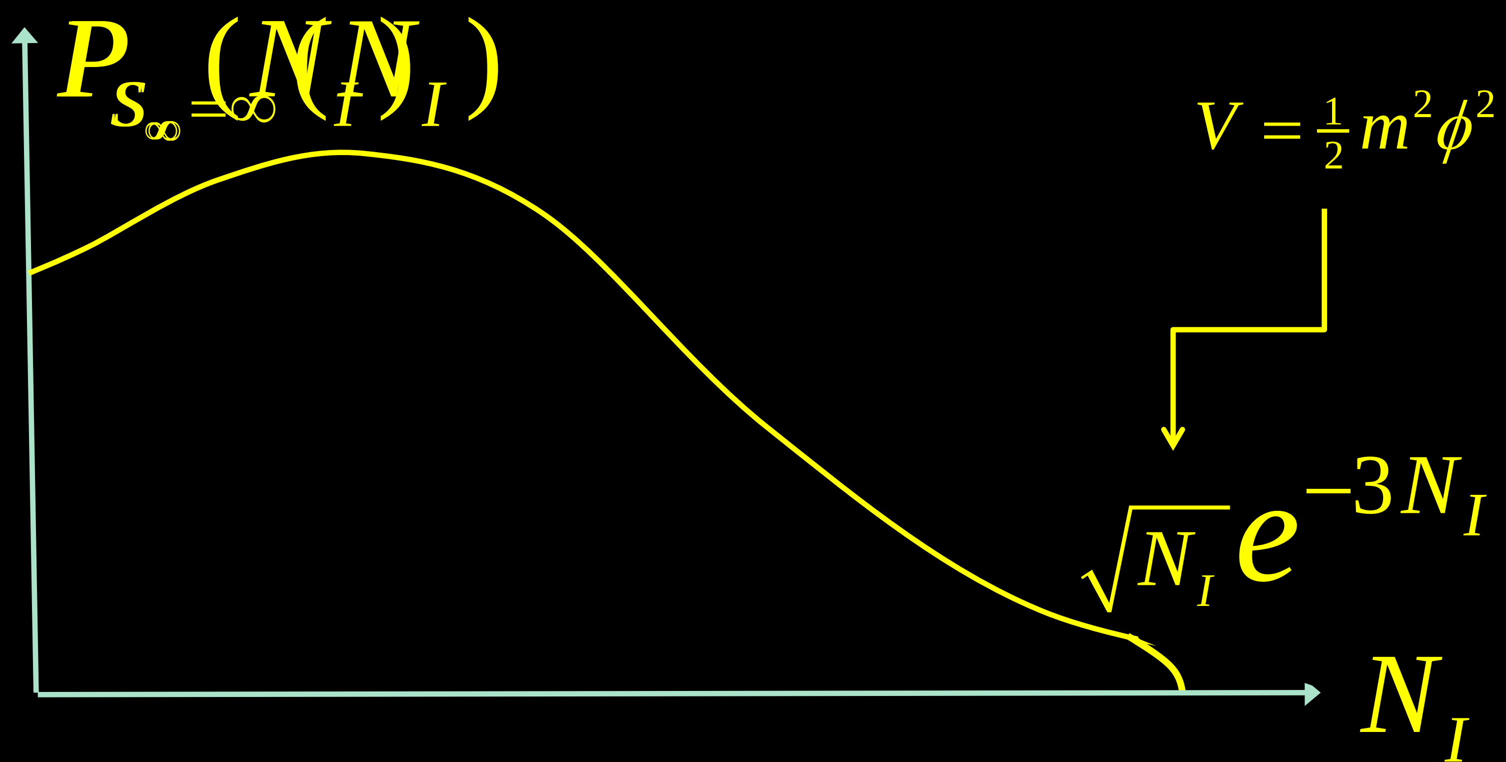
Every trajectory ends on adiabat $S(E_{matter}, a) = \text{const}$

Natural to label an ensemble of cosmologies by their asymptotic entropy $S_\infty = \ln\left(\int dpdq_{matter}\right)$

Meaningful quantity is $P_{S_\infty}(N_I)$


E
S_∞
$(=\ln(\frac{Ua^3\rho_\phi}{m})$ here)
a

Canonical measure for inflation



$$N_{I,\max} = \tfrac{1}{3} S_\infty - \tfrac{2}{3} \ln\left(\tfrac{m_{Pl}}{m}\right)$$

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

* illustrates a problem identified by Penrose long ago: if include inhomogeneities, then expect even smaller probability of inflation:

$$P(V_I) \sim e^{S_{grav}(V_I)} / e^{S_{grav}(\Lambda)} \approx e^{-10^{120}}$$

$$(S_{grav} \sim m_{Pl}^4 / V)$$

It is perfectly OK to view inflation as a phenomenological parameterization, without interpreting it as a fundamental explanation

The problem with claiming it is both is that this may discourage people from seeking better explanations

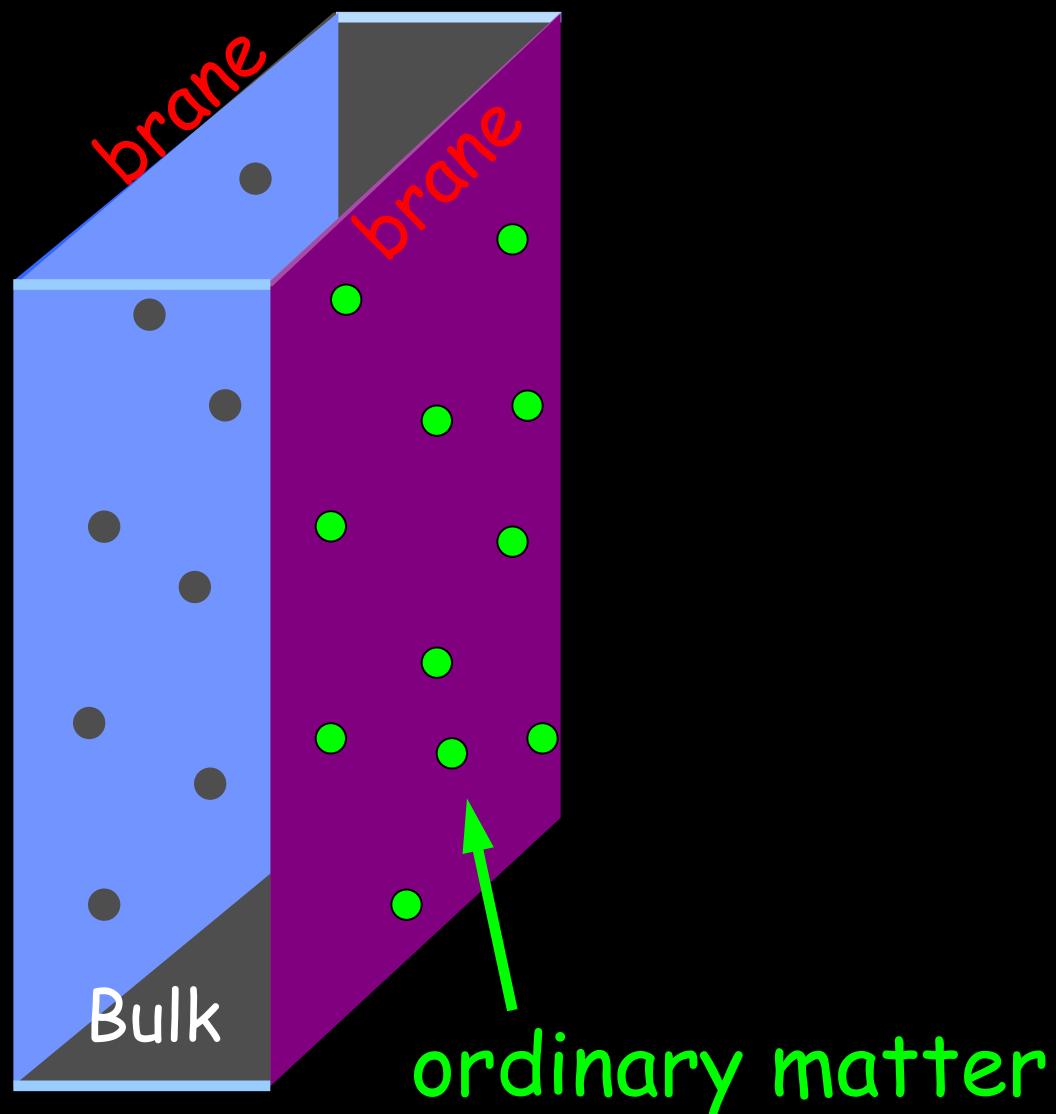
Note: inflation has many other problems... (Steinhardt talk yesterday)

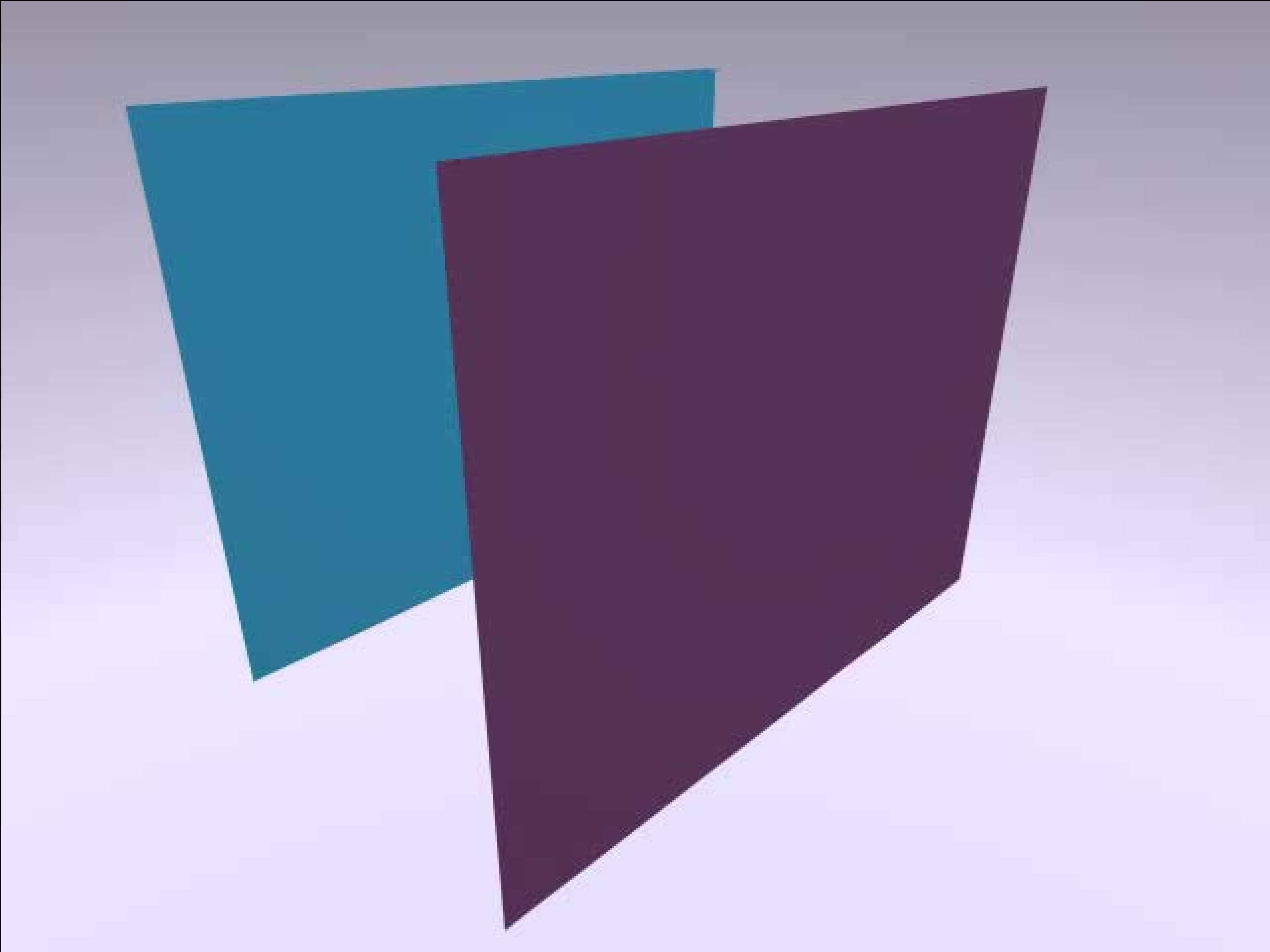
What if the singularity was a bounce?

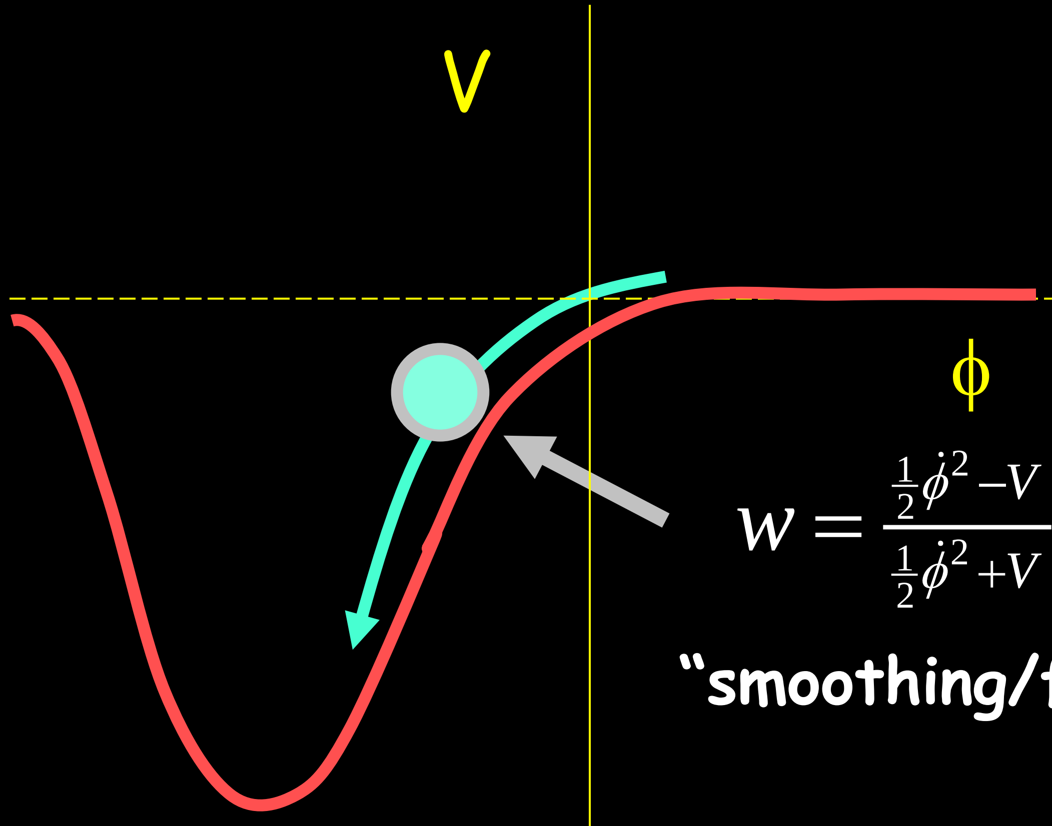
A cyclic scenario becomes feasible, in which inflation is not needed

Heterotic M-theory
-> ekpyrotic universe scenario

Horava-Witten
Lukas et al...
Khoury, Ovrut,
Steinhardt, NT
Lehners et al...







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

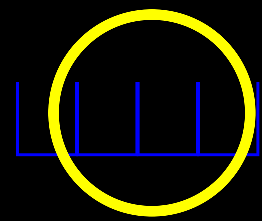
"smoothing/flattening phase"

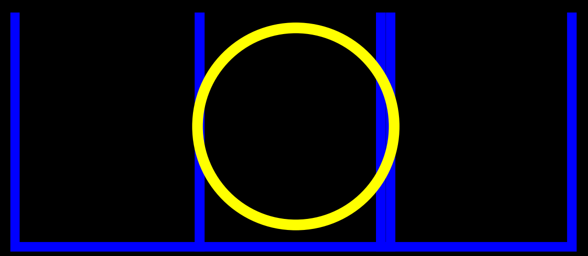
-> scale-invariant perturbations

-> require negative potentials

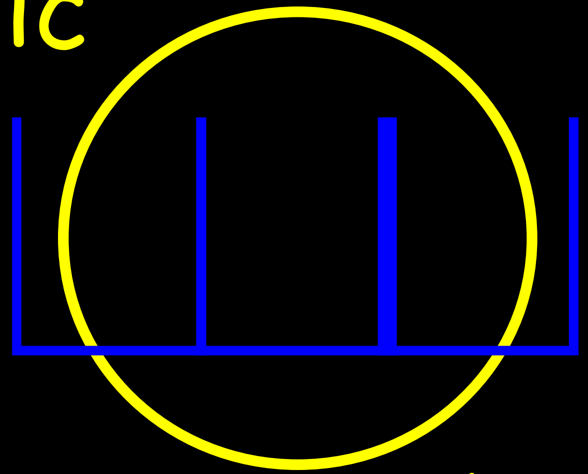
quantum fluctuations->perturbations

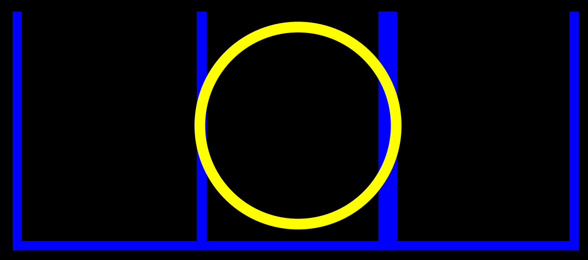
inflation





cyclic

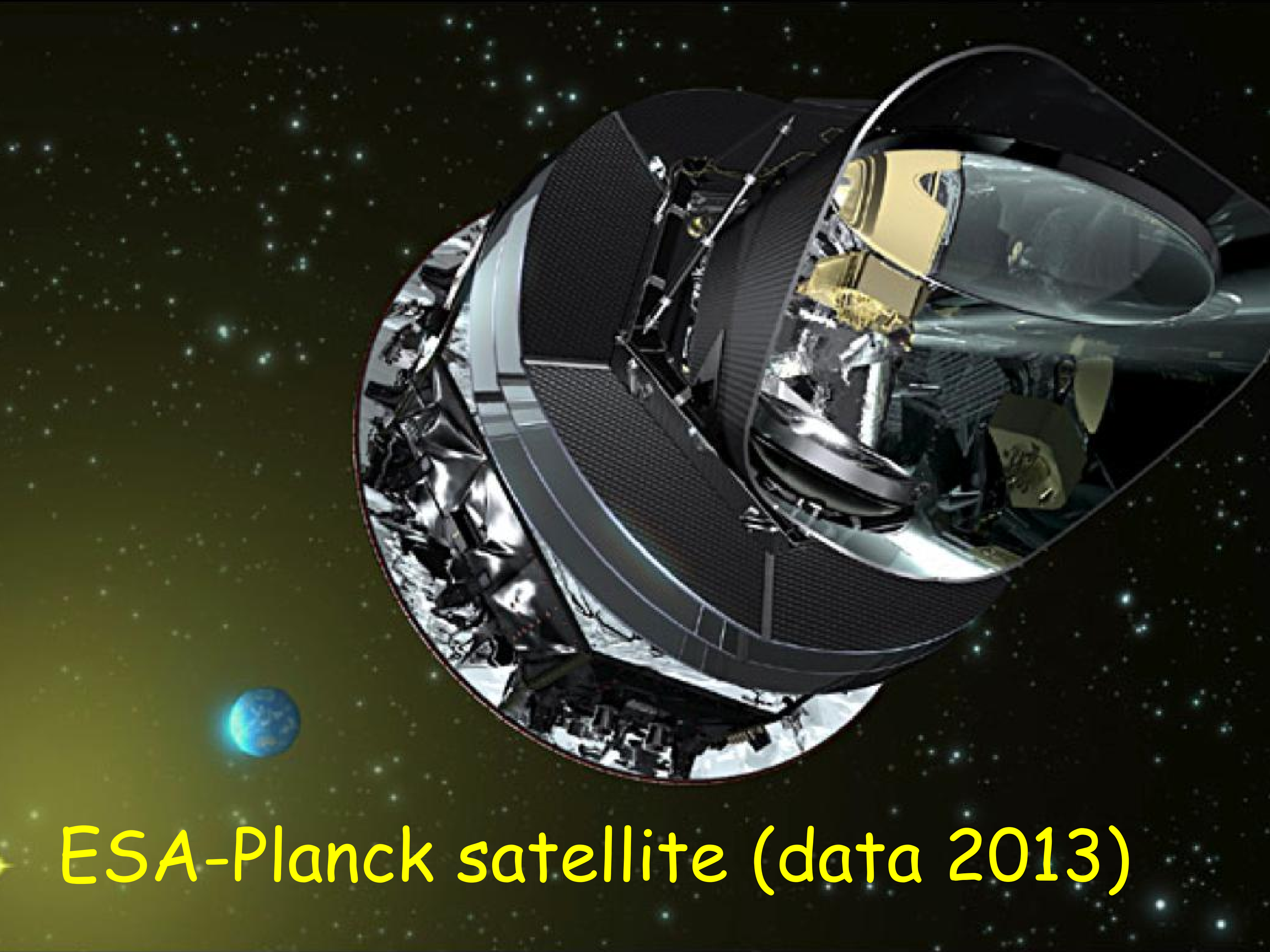




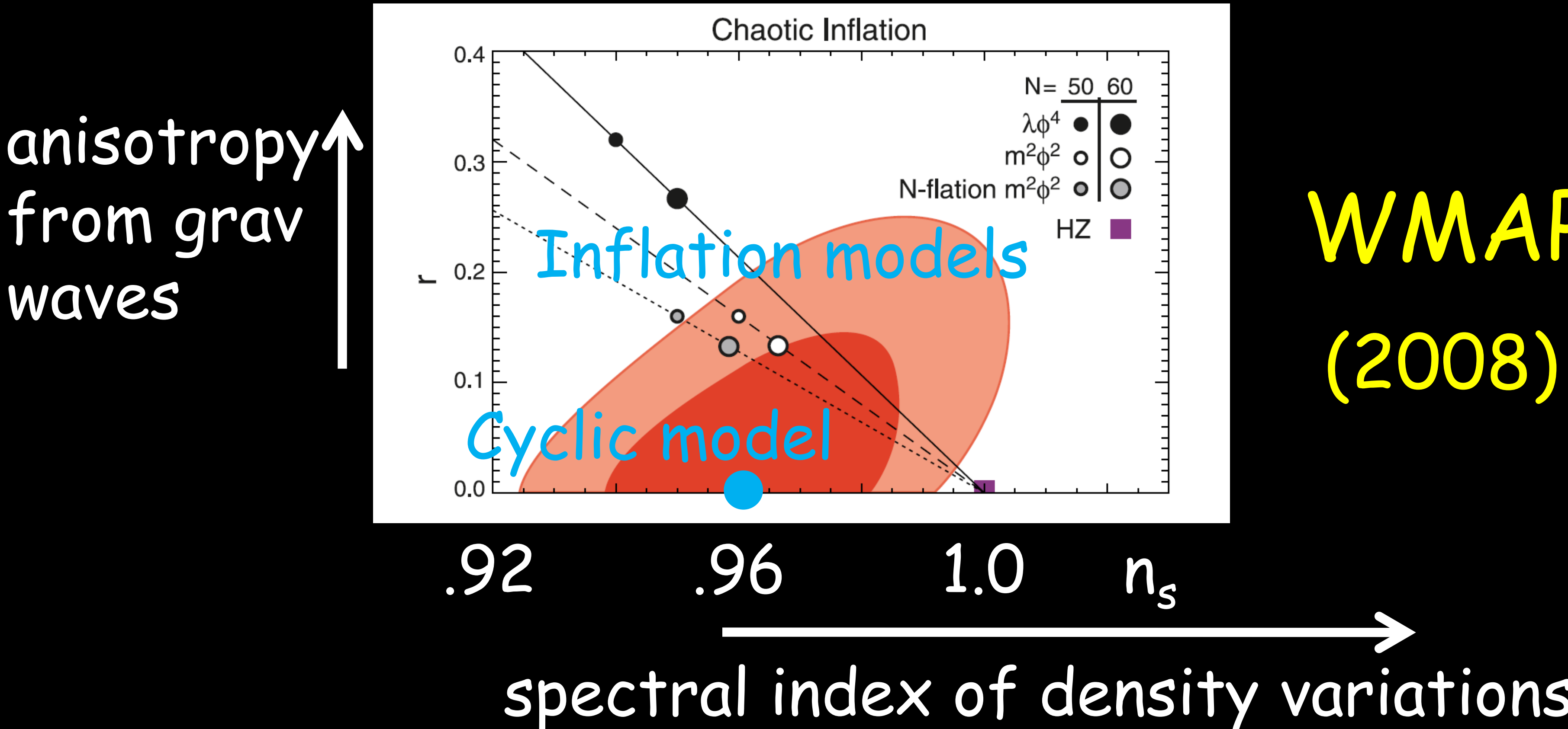
both-> slightly red spectrum

observational test

Gravitational Waves

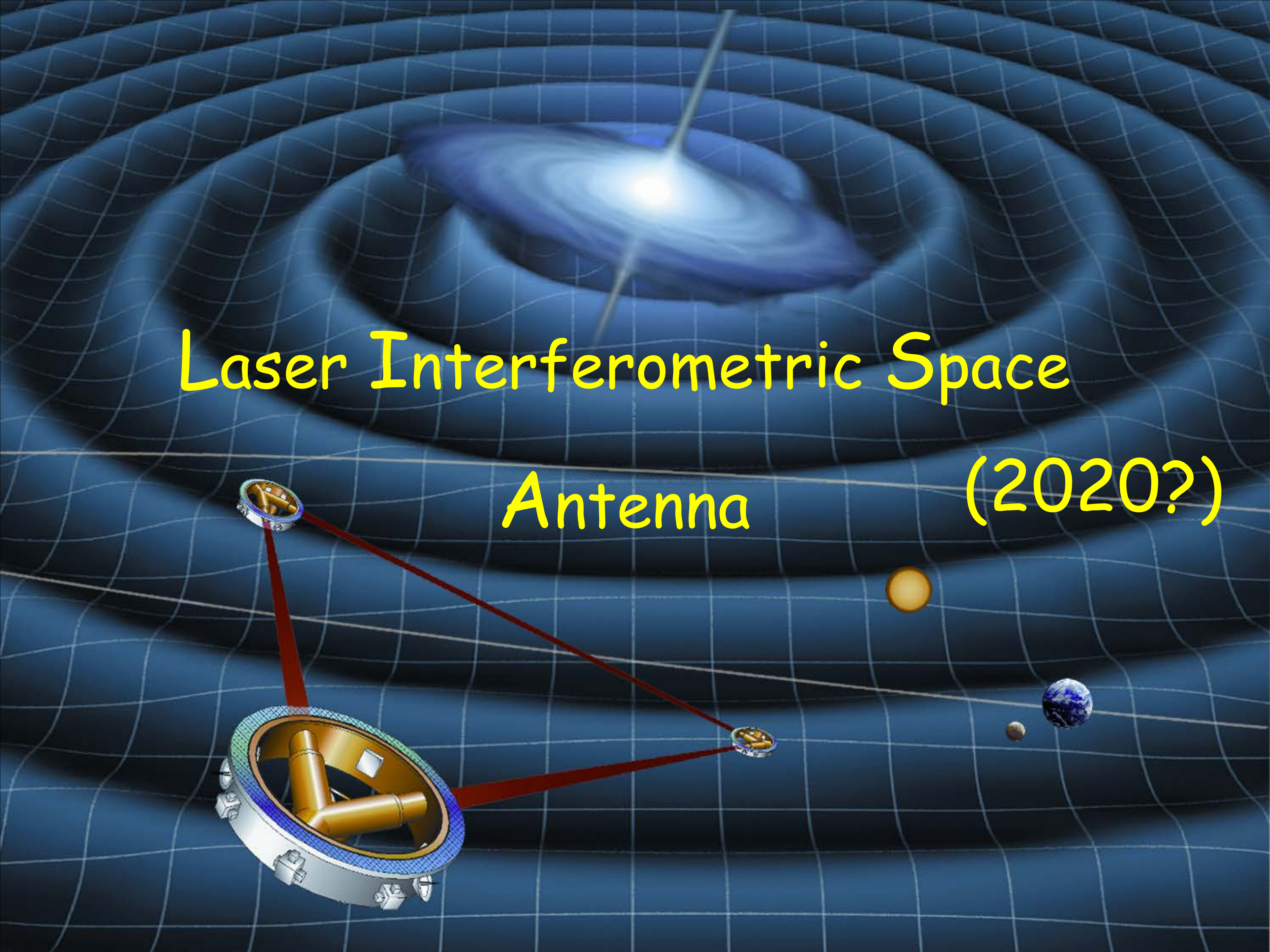

ESA-Planck satellite (data 2013)

limits on grav. waves, n_s, inflation



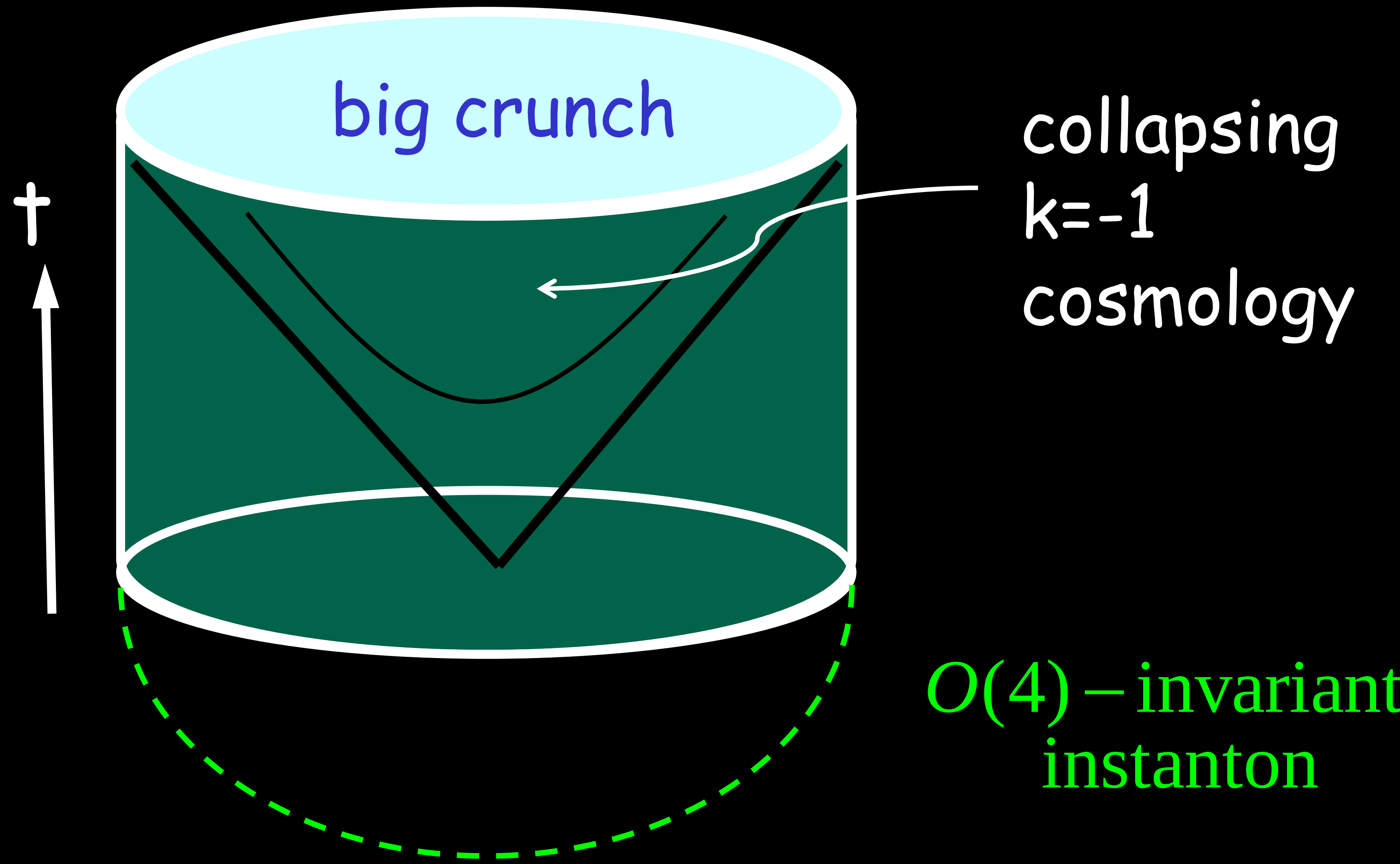
WMAP (2008)

Other tests: nonGaussianity, axions...


Laser Interferometric Space
Antenna
(2020?)

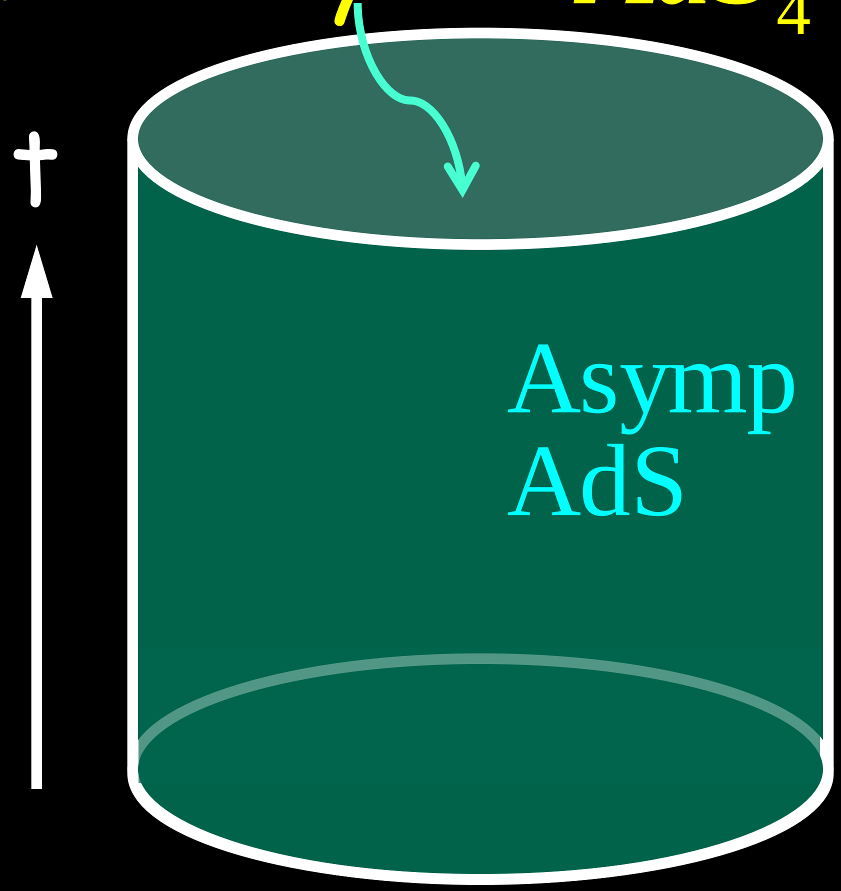
What about the singularity?

holographic cosmology



Hertog+Horowitz

Studying the singularity in M theory on $AdS_4 \times (S_7/\mathbb{Z}_k)$

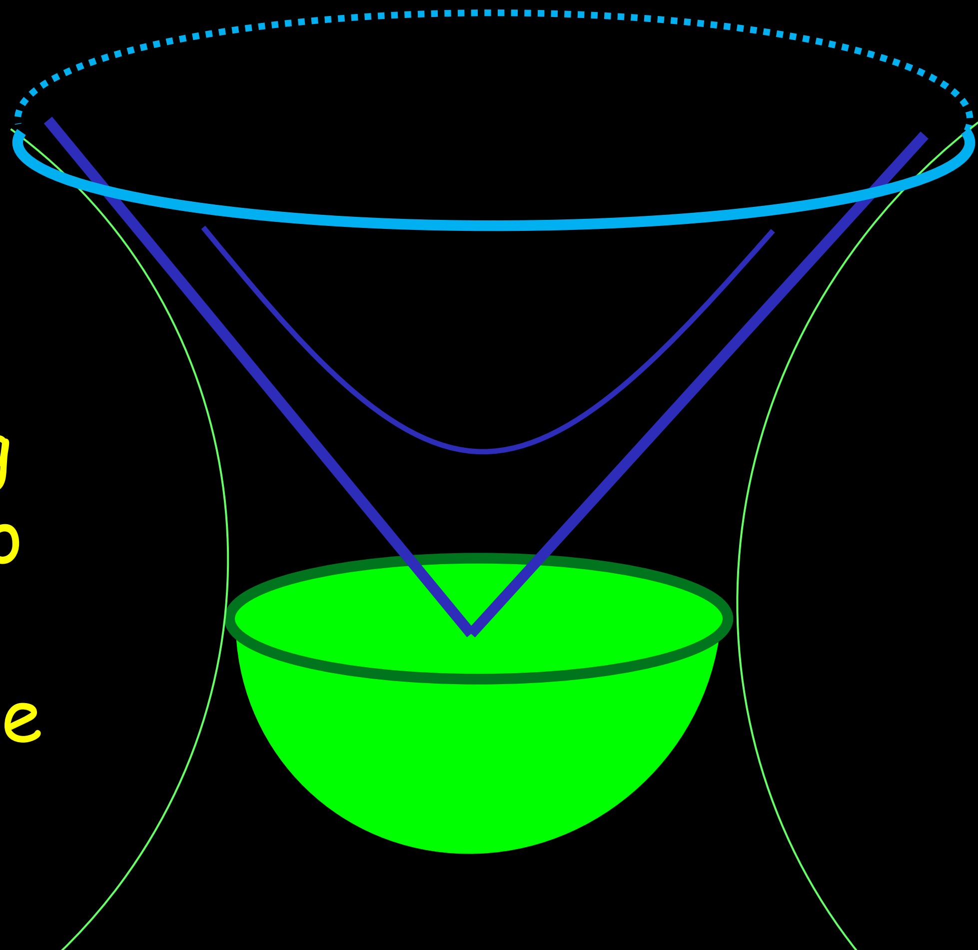


CFT_3 on $S_2 \times \mathbb{R}$

Conformal Invart

Craps, Hertog, NT 2009
Smolkin, NT 2012

Boundary picture

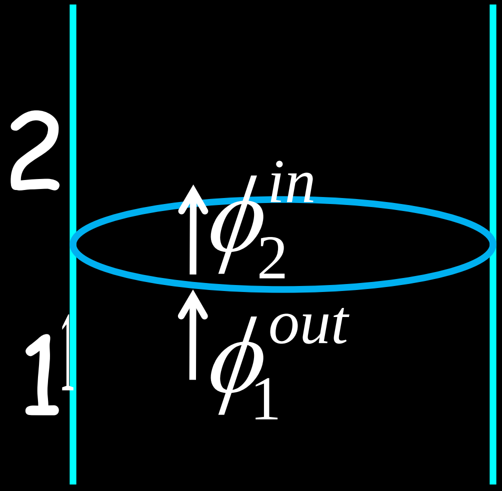


By choosing boundary to be dS^3, we avoid the singularity!

Dual CFT can be studied on dS^3 in large N limit

Crossing the singularity

dS_3 conformal to Einstein cylinder



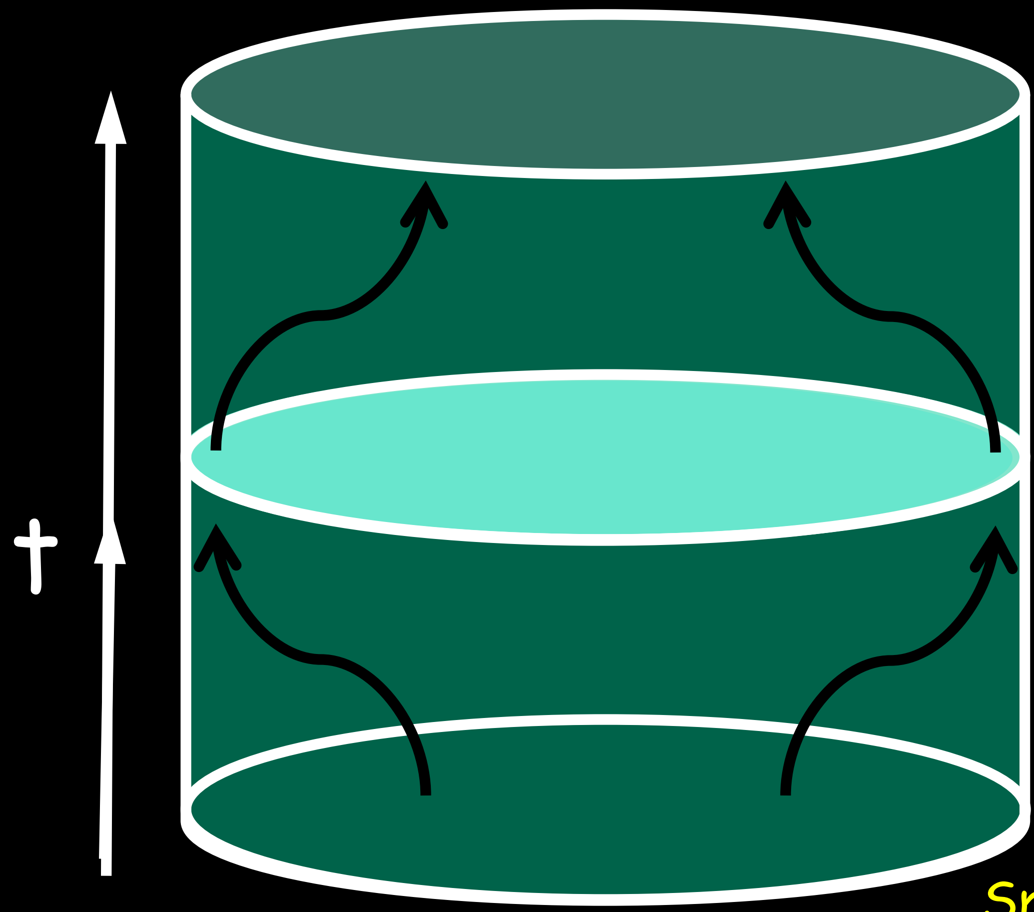
"S matrix": ϕ_1^{out} to ϕ_2^{in}

demand $SO(3,1)$ -invariant

-> unique matching rule

$\Rightarrow$ a perfectly cyclic universe, with calculable 1/N corrections

holographic cosmology



Smolkin, NT 2012
to appear

Above description is only reliable when dual theory is weakly coupled, i.e. when bulk is stringy: not realistic at all.

Can we somehow understand the passage around singularities in the bulk low-energy effective theory directly?

Bars, Chen, Steinhardt, NT, 2011

Continuation past singularities

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

Initial conditions:
contracting, perturbed FRW universe w/radiation

Near singularity, KE of scalar σ dominates, removes mixmaster chaos, ensures smooth ultralocal dynamics

V typically becomes dynamically negligible

Einstein eqns reduce ultralocally to:

Anisotropy

Parameterises radiation

$$\frac{\dot{a}_E^2}{a_E^4} = \frac{\kappa^2}{3}\left[\frac{\dot{\sigma}^2 + \dot{\alpha_1}^2 + \dot{\alpha_2}^2}{2a_E^2} + \frac{\rho_r}{a_E^4}\right],$$

$$\ddot{\sigma} + 2\frac{\dot{a}_E}{a_E}\dot{\sigma} = 0; \qquad \ddot{\alpha}_i + 2\frac{\dot{a}_E}{a_E}\dot{\alpha}_i = 0$$

following from the effective action:

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

canonical momenta for $\sigma, \alpha_1, \alpha_2$ conserved

"lift" to a Weyl-invariant theory

$$\int d^4x\sqrt{-g}\left[\frac{1}{2}\left((\partial\phi)^2-(\partial s)^2\right)+\frac{1}{12}(\phi^2-s^2)R\right]$$

i.e. two conformally coupled scalars w/opp sign L

- scalar ghost removed by gauge symmetry:
  $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$, $\phi \to \Omega^{-1}\phi$, $s \to \Omega^{-1} s$

- gravitational trace anomaly cancels
- global O(1,1) symmetry: $\phi'^2 - s'^2 = \phi^2 - s^2$

-the lifted theory allows one to choose gauges which may be less singular than Einstein gauge

Special quantity: Weyl and O(1,1)-invariant:

$$\chi \equiv \frac{\kappa^2}{6}(-g)^{\frac{1}{4}}(\phi^2 - s^2)$$ ($a_E^2 = |\chi|$)

- obeys Friedmann-like equation:

$$\dot{\chi}^2 = \frac{2\kappa^2}{3}\left(p^2 + 2\rho_r \chi\right)$$

$$p \equiv \sqrt{p_\sigma^2 + p_1^2 + p_2^2}$$

- analytic at generic cosmic singularities

Gauges:

1. Einstein gauge $\phi^2 - s^2 = 6\kappa^{-2}$:

2. "Supergravity-like" gauge $\phi=\phi_0=$const:

3. "γ–gauge": Det g = -1:

$$\int d\tau \left[-\frac{1}{2}\dot{\phi}_\gamma^2 + \frac{1}{2}\dot{s}_\gamma^2 + \frac{\kappa^2}{12}(\phi_\gamma^2 - s_\gamma^2)(\dot{\alpha}_1^2 + \dot{\alpha}_2^2) \right]$$

-Reln w/ einstein

$$a_E^2 = |\chi| \, , \; \chi \equiv \frac{\kappa^2}{6}\left(\phi_\gamma^2 - s_\gamma^2\right) \, , \; \sigma = \frac{\sqrt{6}}{2\kappa} \ln \left| \frac{\phi_\gamma + s_\gamma}{\phi_\gamma - s_\gamma} \right|$$

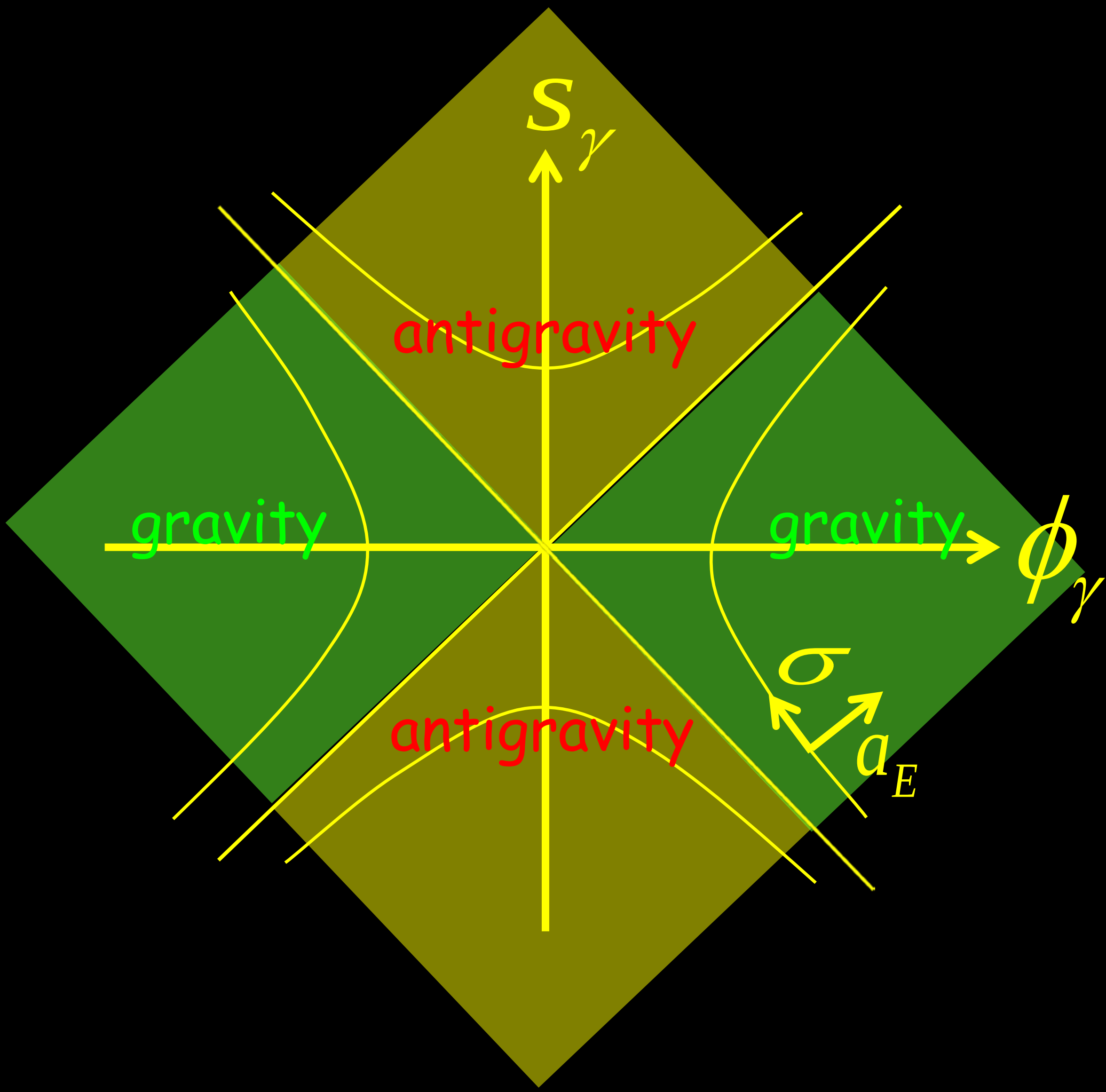
4. "String frame" gauge

$$\phi - s = (\phi + s)^2; \quad \phi + s = e^{-2\varphi/3}$$

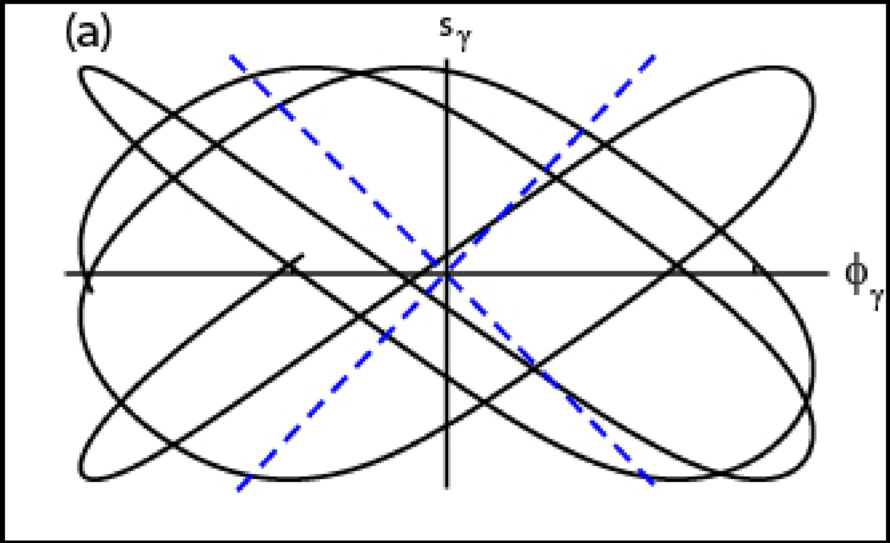
$$g_s = e^{\varphi}$$

$$d = 10 : \mathcal{S} = \int \sqrt{-g} e^{-2\varphi} \left(R + 4(\partial\varphi)^2 \right)$$

Weyl- extended superspace

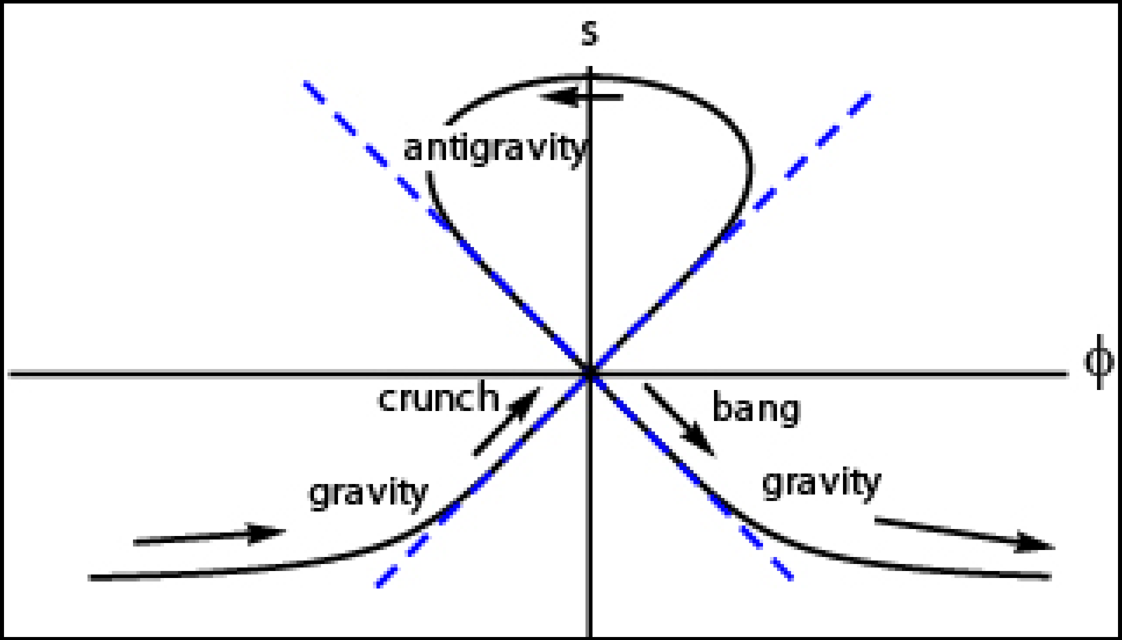


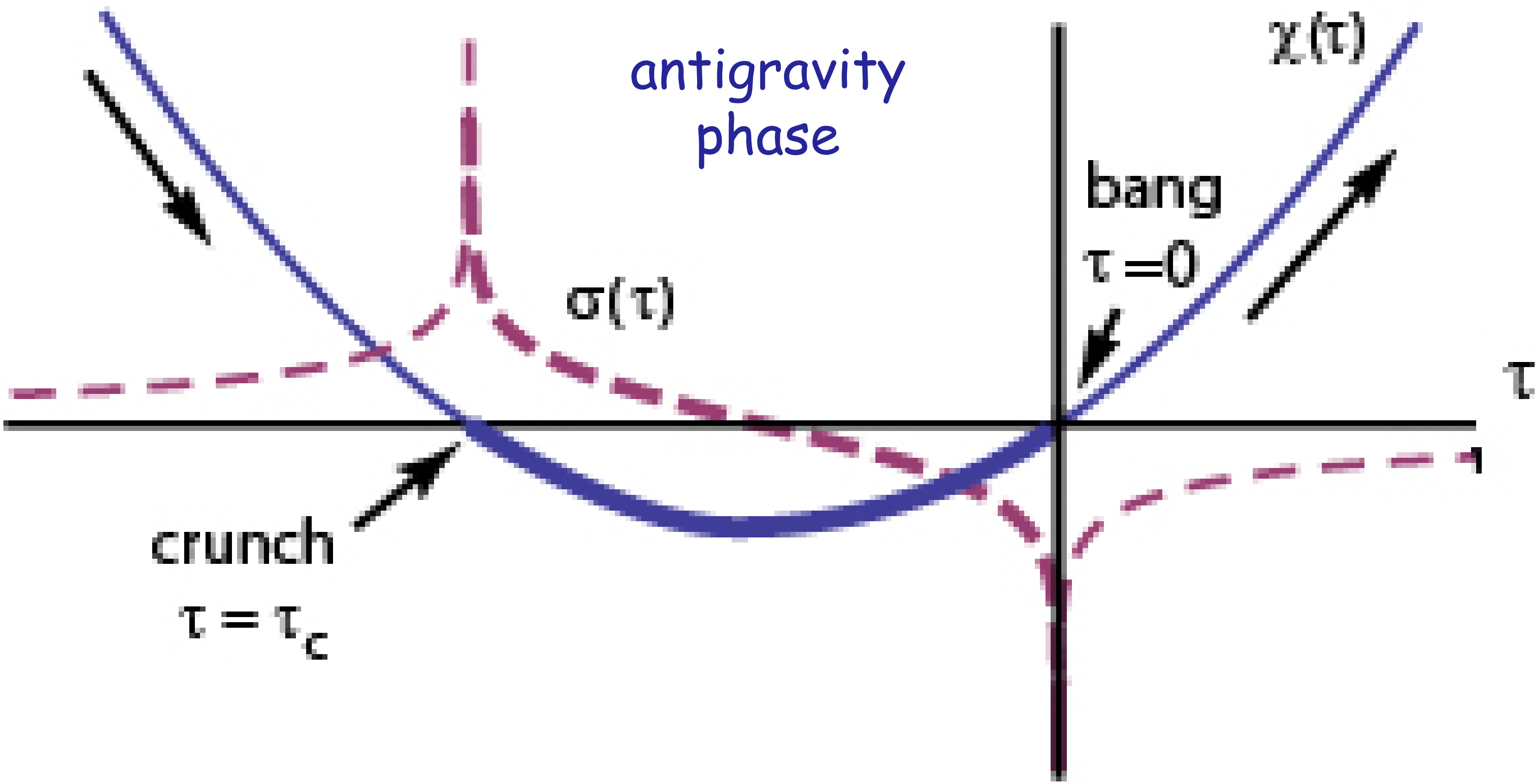
Isotropic case:
$\alpha_1 = \alpha_2 = 0$



Generic case w/anisotropy:

Weyl symm restored at transition





antigravity
phase
χ(τ)
bang
τ =0
σ(τ)
τ
crunch
$\tau = \tau_c$

Uniqueness of solution

Start with flat universe with radiation

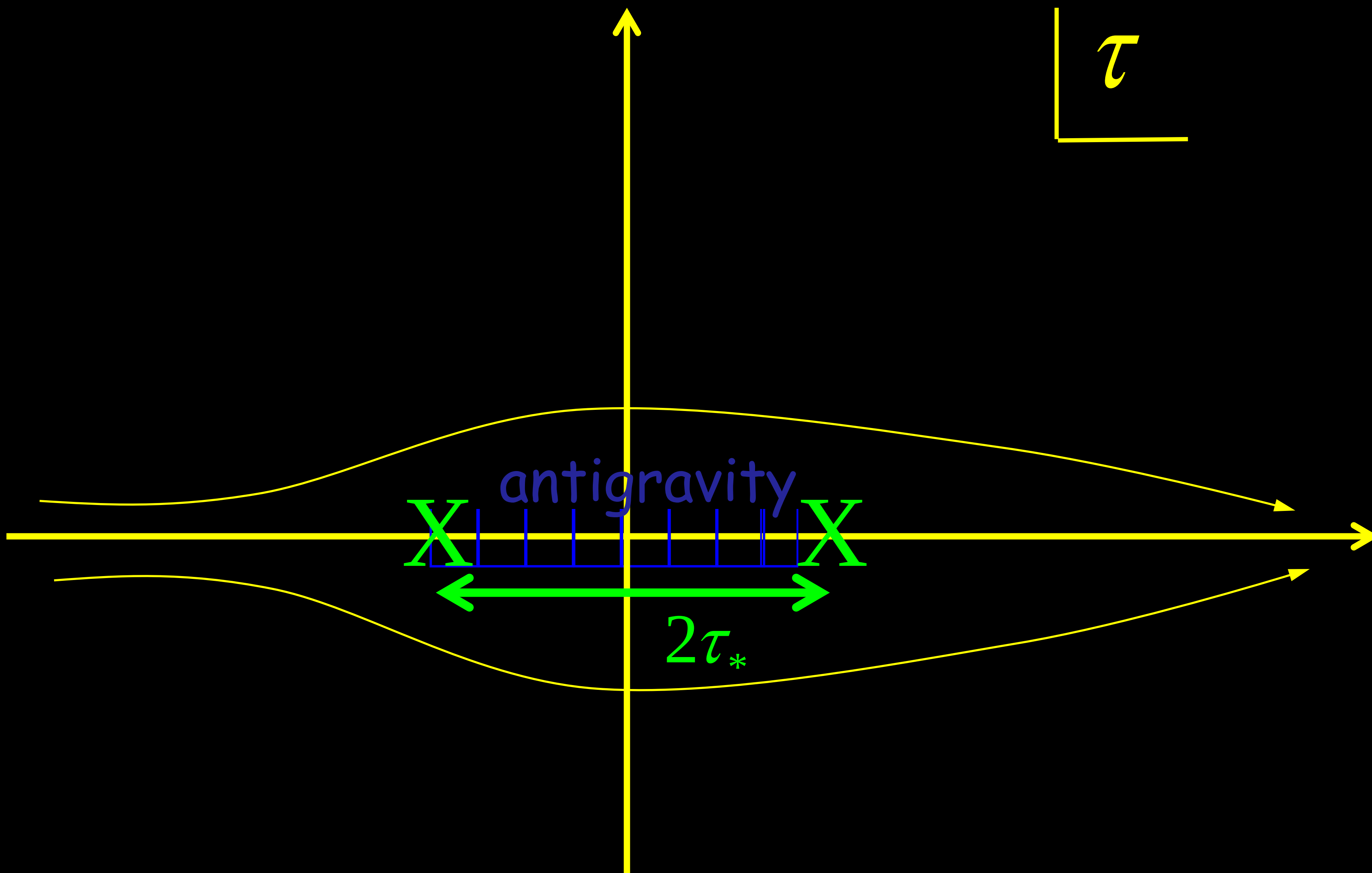
$$ds_E^{\ 2} = \tau^2(-d\tau^2 + d\vec{x}^{\,2})$$; analytic in τ - plane

add scalar kinetic energy

$$ds_E^{\ 2} = (\tau^2 - \tau_*^2)(-d\tau^2 + d\vec{x}^{\,2})$$

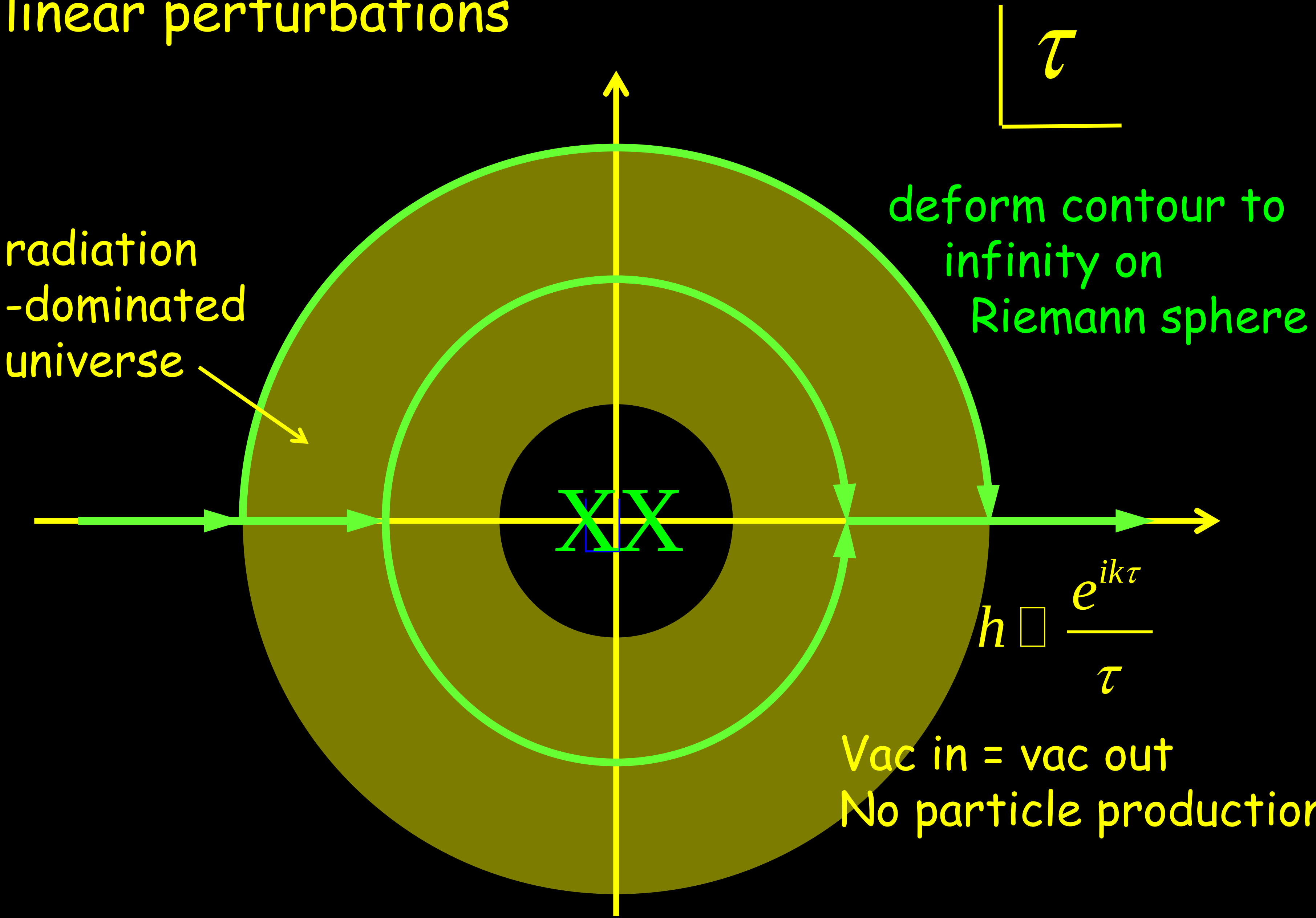
add curvature and anisotropy

unique extension of σ, $\alpha_{1,2}$ to complex τ–plane



Near singularities, action has asymptotic O(4,2) symmetry: matching its (conserved) generators across singularities also yields this as the unique solution

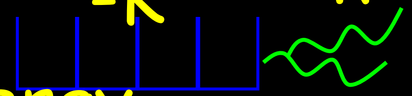
linear perturbations



$h \sim \frac{e^{ik\tau}}{\tau}$

Vac in = vac out
No particle production

Antigravity region -> unstable?

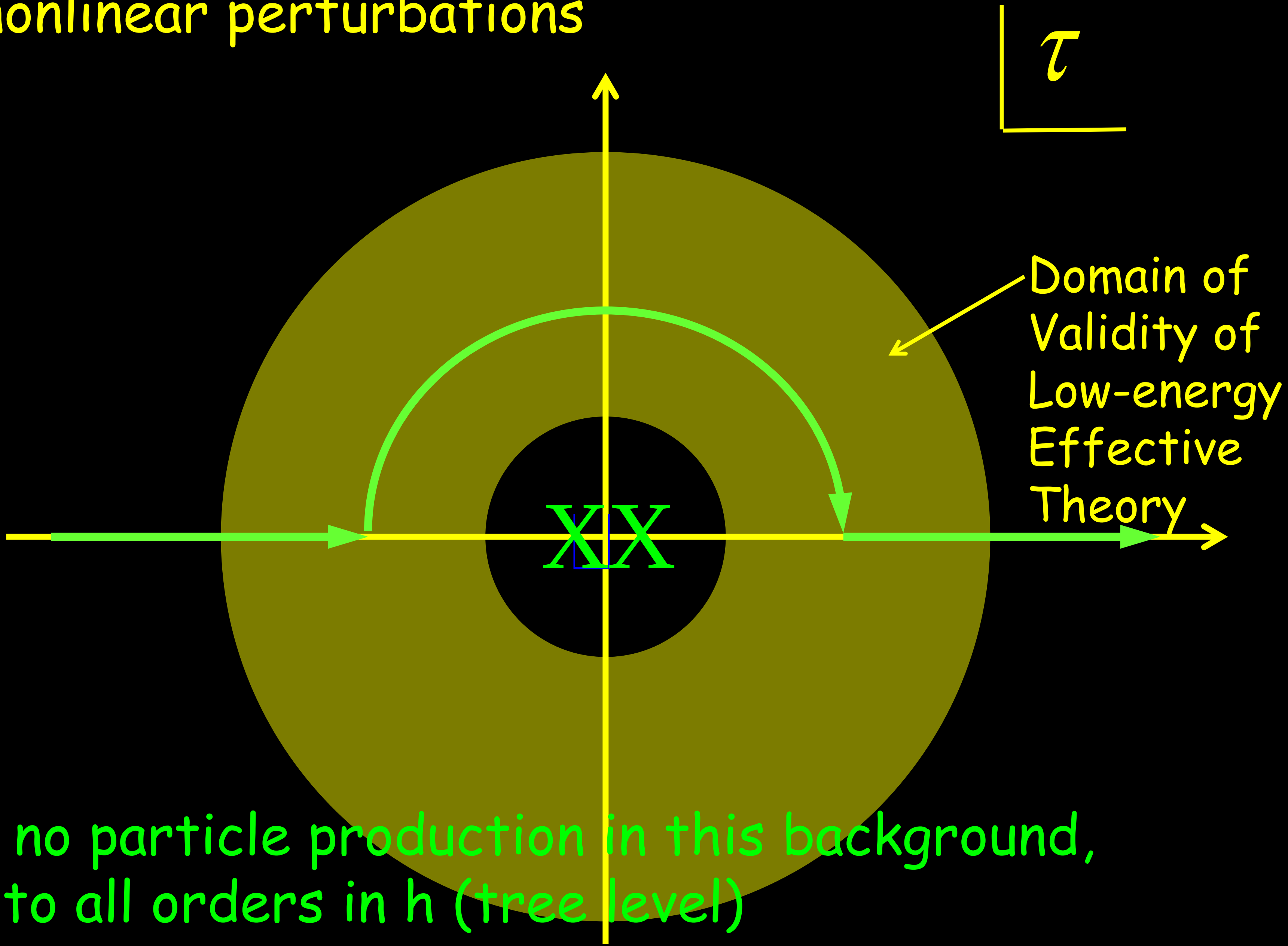


(only consider k-modes for which low-energy effective action is valid)

No: asymptotic states are positive energy,

$$\text{amplitude} \sim \int_{-\infty}^{\infty} \frac{d\tau}{\tau}\, e^{i(K+k+|K-k|)\tau} = 0 \quad \text{(Jordan)}$$

nonlinear perturbations



-> no particle production in this background, to all orders in h (tree level)

Conclusions

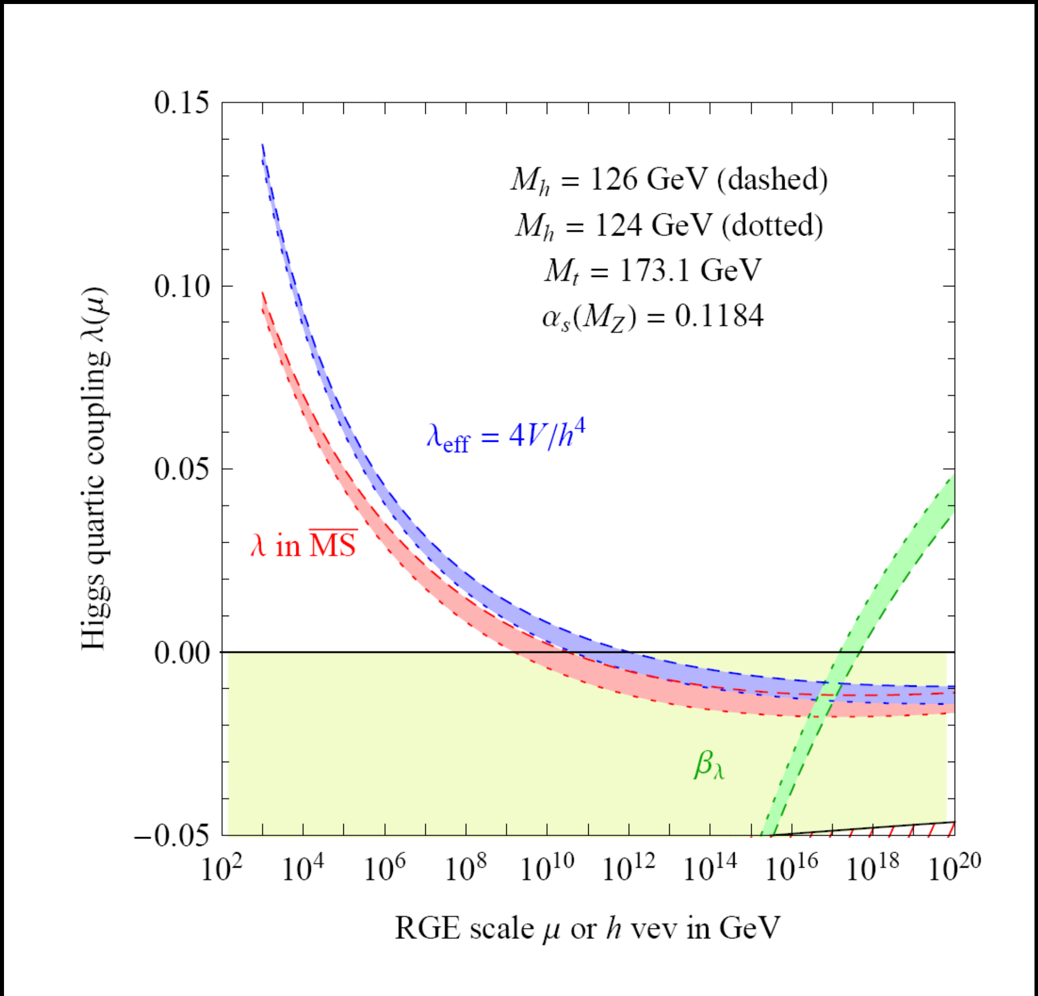
* Simple cosmologies (like ours!) seem to possess a natural and unique continuation of classical 4d effective theory 'around' cosmological singularities

*Surprisingly, it involves a brief antigravity phase, (in the low-energy effective description)

* Particle production is under control
  (massive fields -> finite particle production)

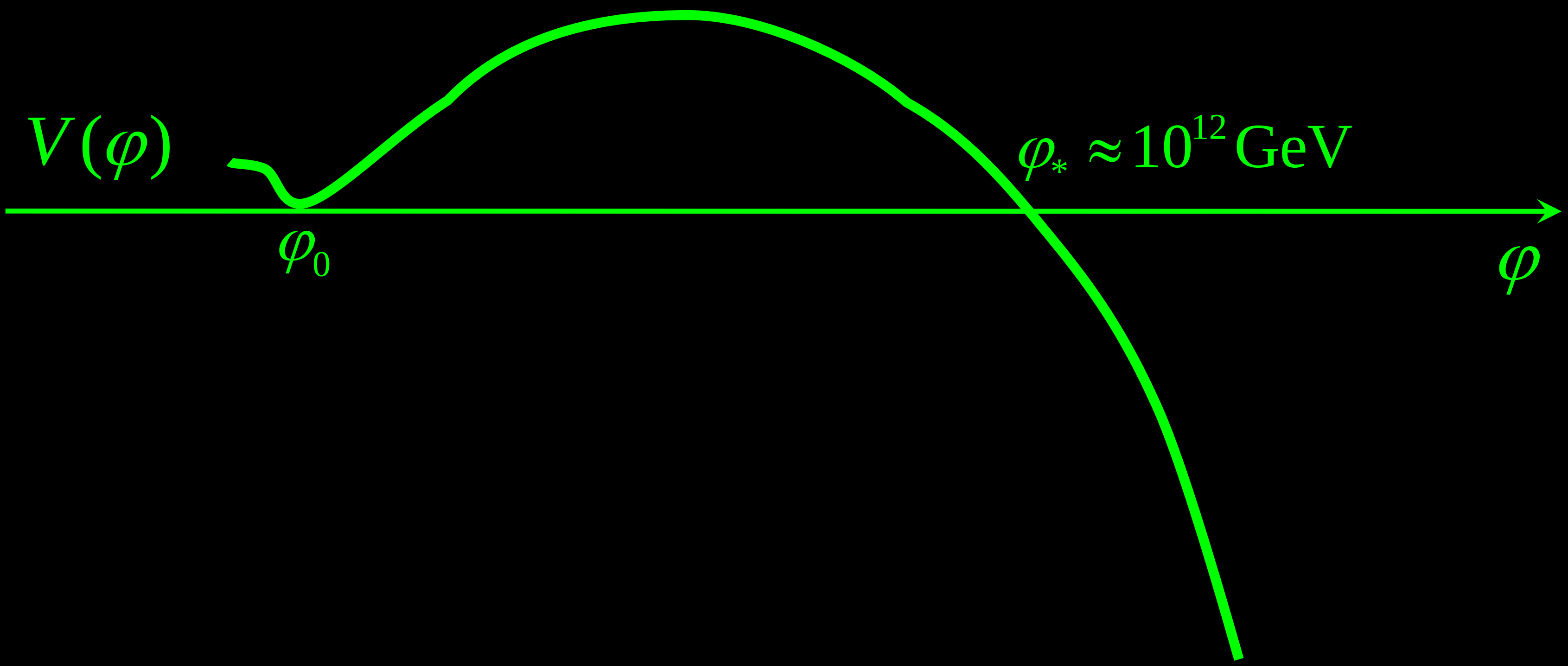
* Can be used to study cosmological ensembles, to compare inflation and cyclic theories (in progress)

Naive extrapolation of EW Higgs potential is negative at large Higgs vev -> metastability

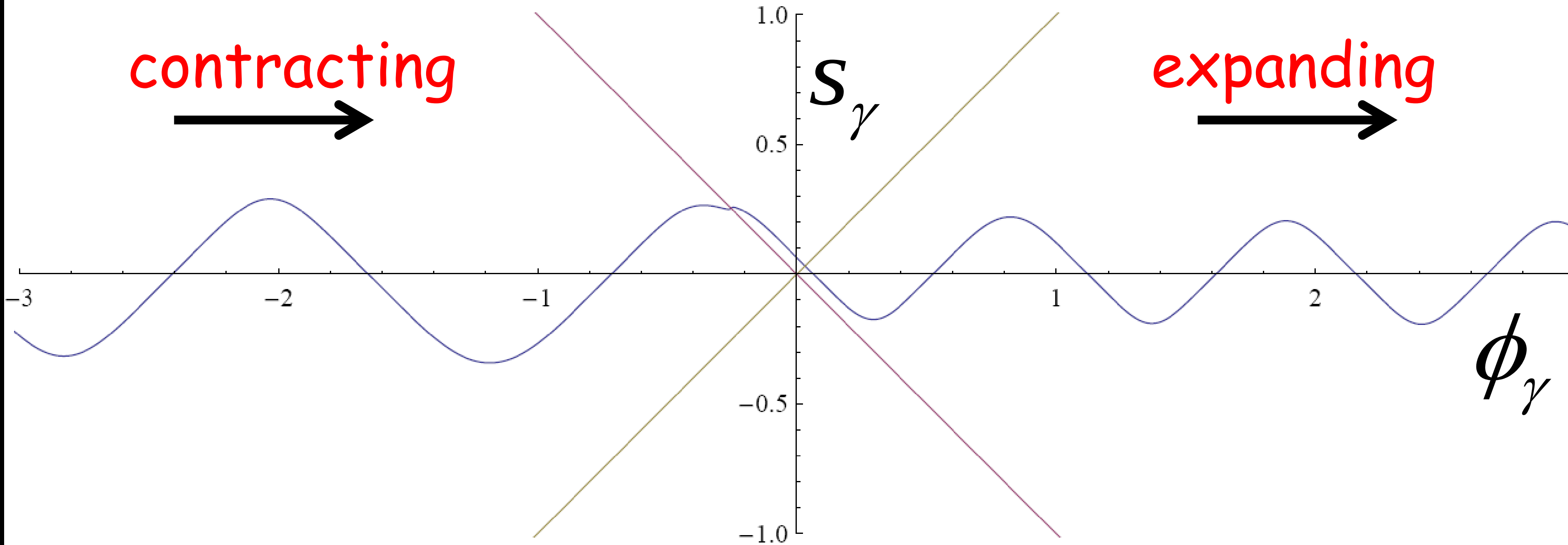


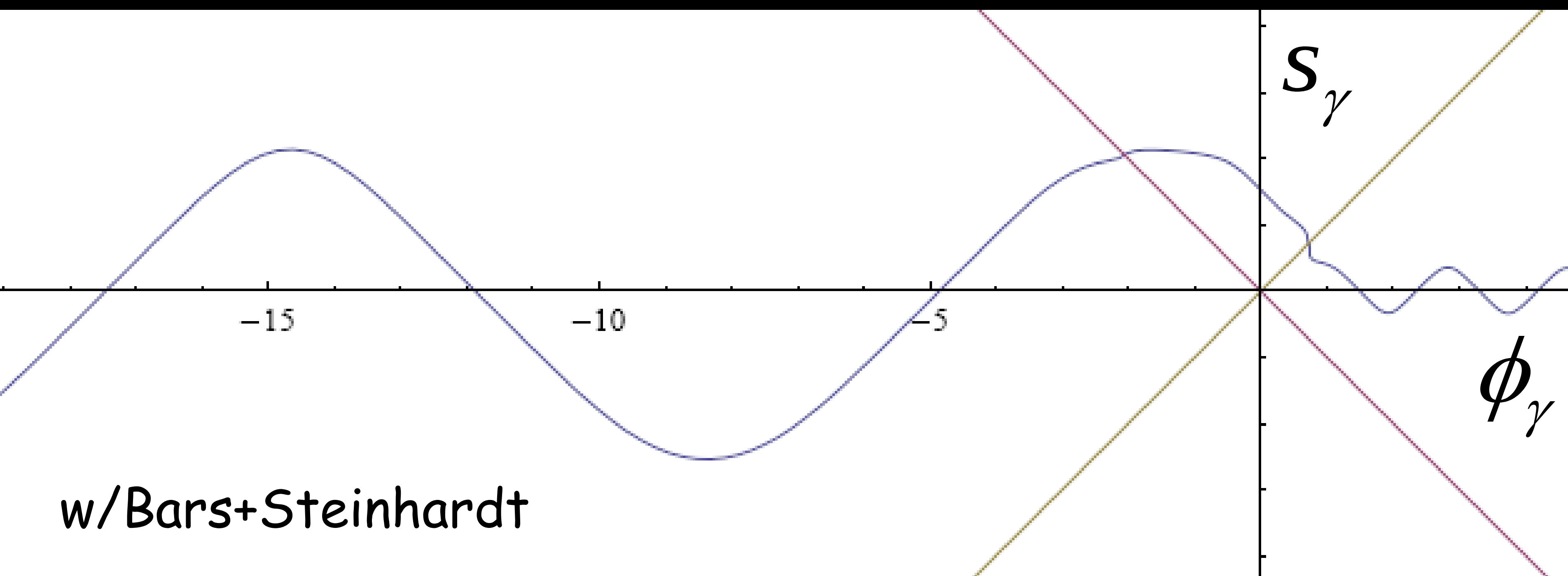
…
M Sher 1989
Degrassi et al 2012

-> our vacuum is metastable



(cf string landscape)


contracting
expanding
s_γ
ϕ_γ
1.0
0.5
−0.5
−1.0
−3
−2
−1
1
2
3


s_γ
ϕ_γ
−15
−10
−5
w/Bars+Steinhardt

it seems metastability may not be a problem for cyclic cosmologies

(-> suggests they may be unitary, as opposed to cosmologies with "terminal" singularities)

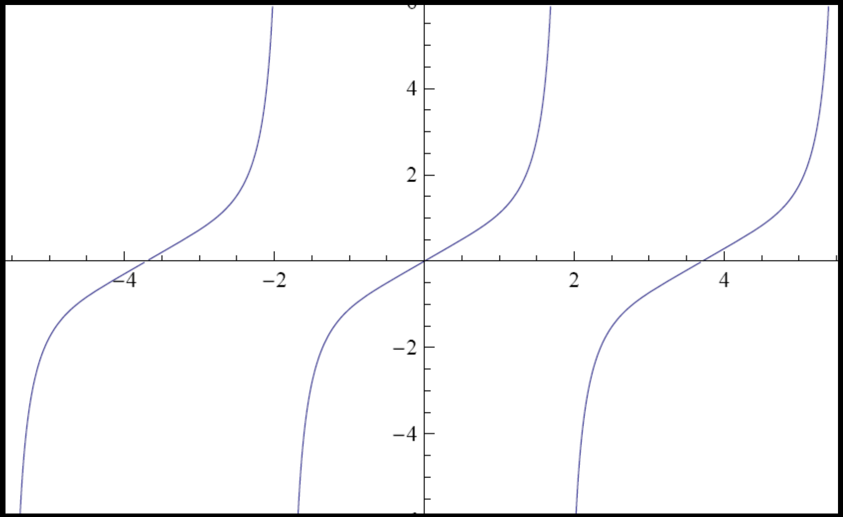
Flat universe with only Λ, radiation

$$ds^2 = a(\tau)^2(-d\tau^2 + d\vec{x}^2)$$

$$a'^2 = \frac{8\pi G}{3}\left(\rho_r + \rho_\Lambda a^4\right)$$

$$\Rightarrow a = -e^{i\pi/4}(\rho_r / \rho_\Lambda)^{1/4} sn(e^{3i\pi/4}((\rho_r\rho_\Lambda)^{1/4}\tau, -1)$$

$a(\tau)$



τ

Only singularities are poles -> unique analytic continuation in complex τ–plane