Cyclic Inflation

Pre-Planckian Inflation

Tirthabir Biswas

LOYOLA UNIVERSITY NEW ORLEANS

With Mazumdar & Koivisto, **arXiv:1105.2636 [astro-ph.CO]**
With Mazumdar & Shafieloo, Phys.Rev. D82 (2010), **arXiv:1003.3206** [hep-th]
With Mazumdar, Phys Rev D 80, (2009), **arXiv:0901.4930** [hep-th]
With Alexander, Phys Rev D 80, (2009), **arXiv:0812.3182** [hep-th]

Background Cosmology

Asymetric cyclic evolution

- In each cycle the universe grows a little more than it contracts
- Cycles are very short:

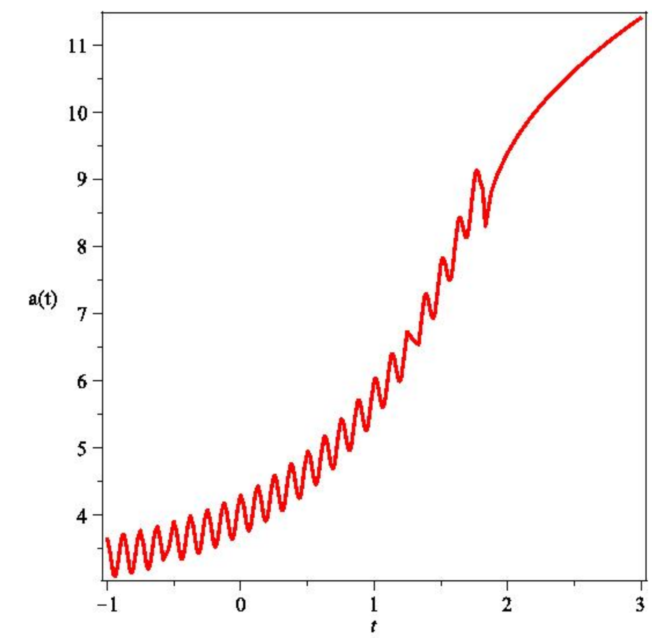
$$\tau = \frac{M_p^2}{\Lambda} \sim 10^6 l_p$$

Underlying conjecture:

- Universe bounces back at a critical Planckian density, ρ_c
- Details of bounce mechanism may not be important "observationally"

Goodies from Inflation

- Old cosmological puzzles are solved
- One obtains nearly scale invariant spectrum!



Specific Realizations:

- Universe begins with $-\Lambda$ [Linde et. al.]
- In presence of radiation, it leads to periodic evolution
- If there is more than one forms of matter which interact, entropy is produced.
  - This is a consequence of 2nd law thermodynamics
  - Typically this leads to overall growth [Tolman, 1931]
  - Universe expands a little more than it contracts.

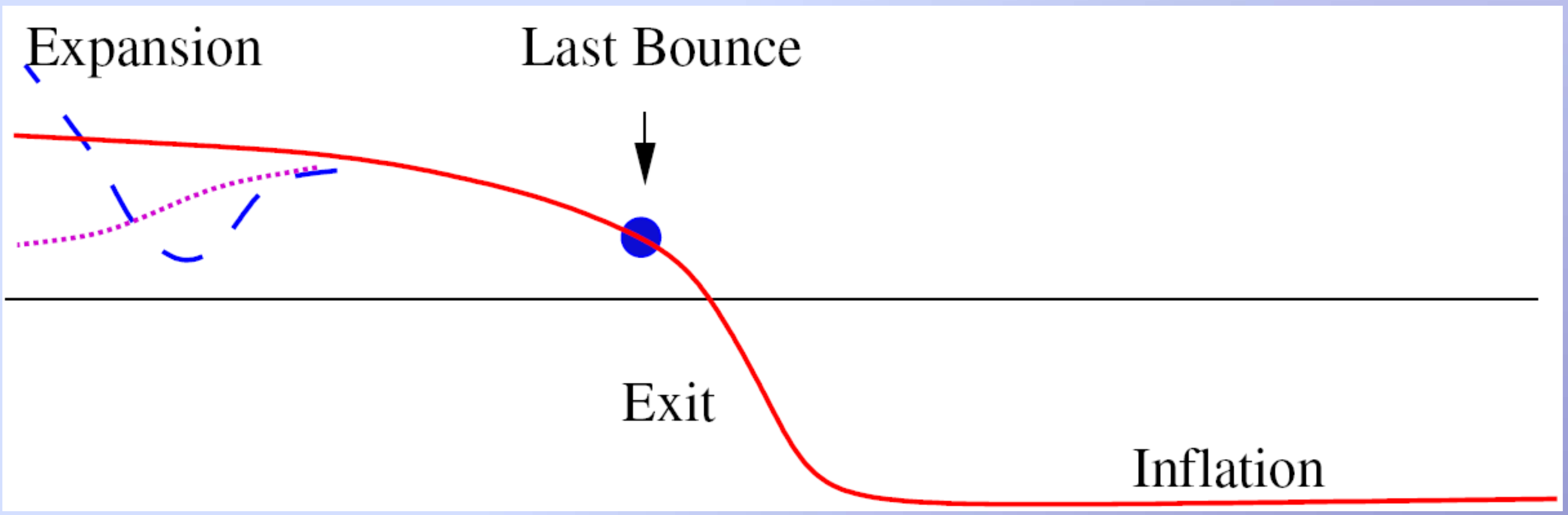
$$\frac{S_{n+1}}{S_n} = 1 + 3\kappa$$

$$\kappa \propto \frac{g^{1/4}\mu\Gamma M_p T_c}{\Lambda^{3/4}}$$

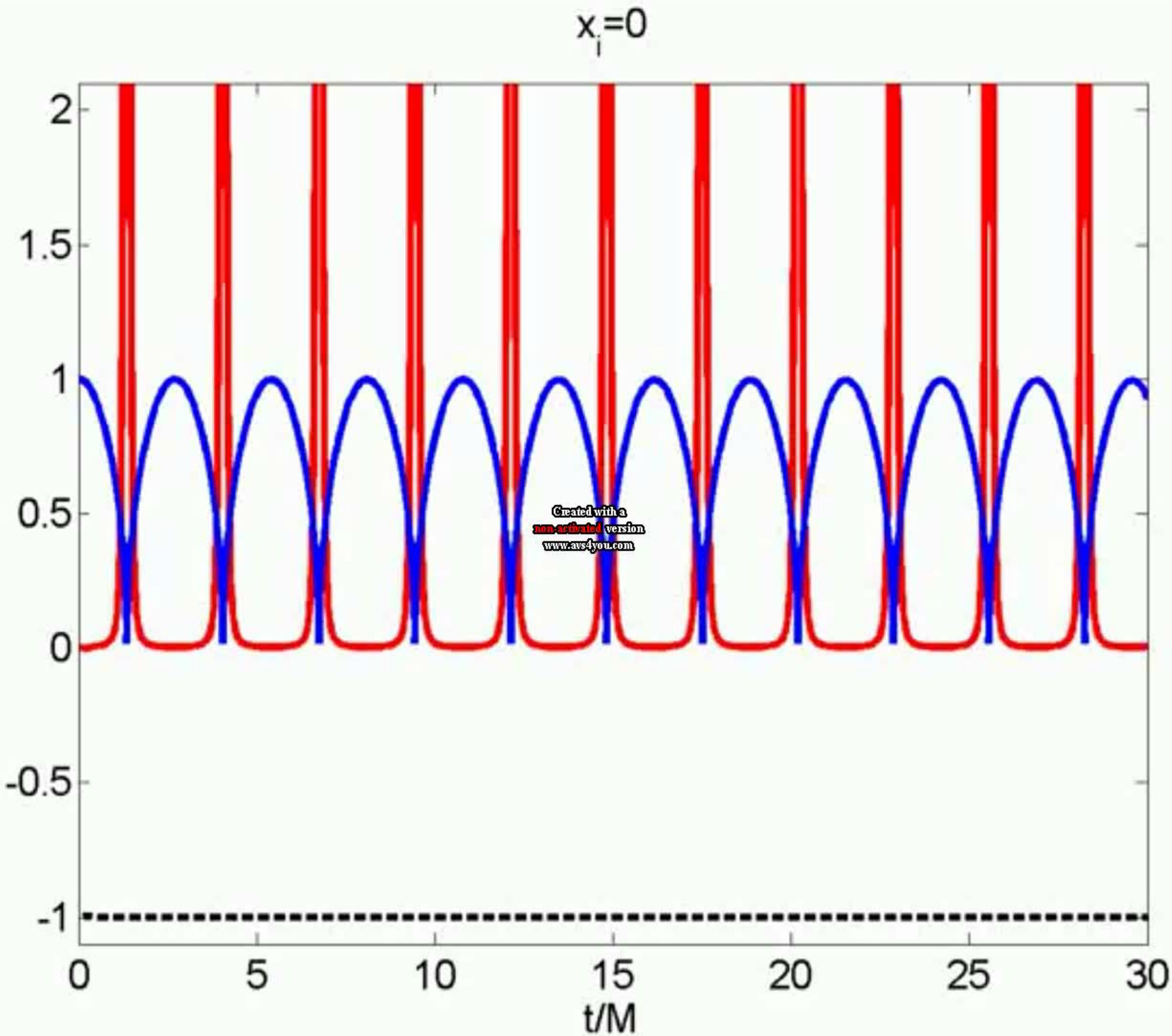
Grows by the same factor – Inflation

Is a Graceful Exit possible?

- *Yes*
- During contraction, kinetic energy blue shifts, & total energy increases [Linde et. Al.]
- Once K + V >0, can only turn back in the +ve region
- If the universe bounces back, may not be able to escape!



Success depends on parameters and IC's?


x_i=0
2
1.5
1
0.5
0
-0.5
-1
0
5
10
15
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25
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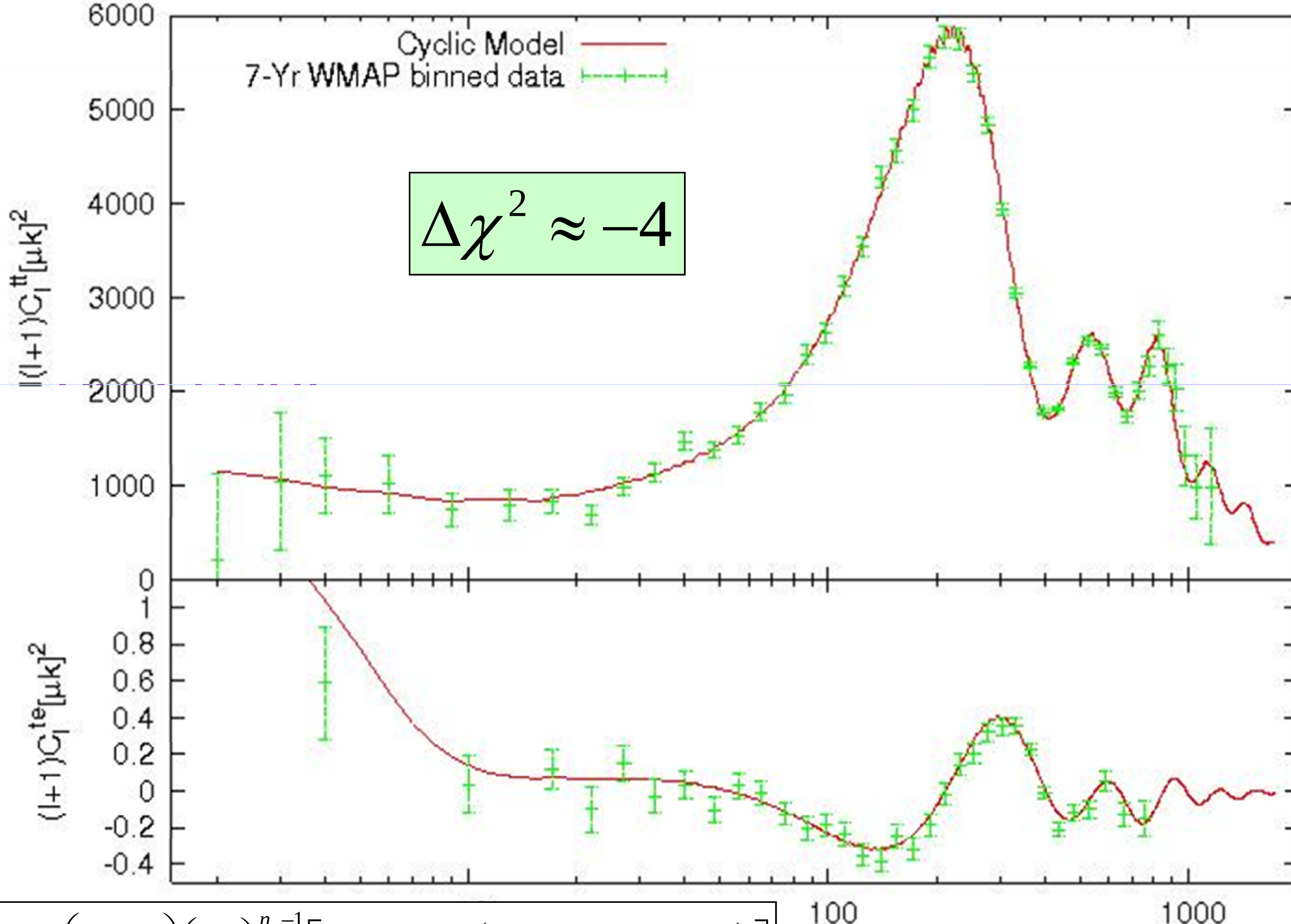
Periodic Scale-Invariance

- Analyzing perturbations looks like a daunting task
- There is a very general argument for near scale-invariance.
- Evolution of fluctuations depend only on and $\{\rho_i(\lambda)\}$ for a given comoving mode

$$\Phi_{k,\lambda\lambda} + \frac{H_{,\lambda}}{H}\Phi_{k,\lambda} + \frac{1}{\lambda}(5+3\omega)\Phi_{k,\lambda} + \left[\frac{1}{H^2\lambda^4} + 2\frac{H_{,\lambda}}{\lambda H} + 3(1+\omega)H^2\right]\Phi_k = 0$$

  - deSitter gives exact scale invariance
  - Inflation has a tilt
  - k and $(1+\kappa)$ k have same $\{\rho_i(\lambda)\}$ leading to periodic scale-invariance
- A crude approximation is to calculate the amplitude at the last exit.



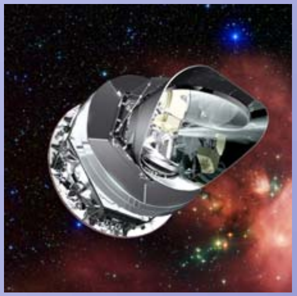
$$\mathcal{P}_\Phi = \left(\frac{\Lambda}{3M_p^2}\right)\left(\frac{k}{k_0}\right)^{n_s-1}\left[1+2\kappa\cos\left(\frac{2\pi\ln(k/k_0)}{\kappa}+\theta\right)\right]$$

$$\kappa \approx 0.05$$

Outlook

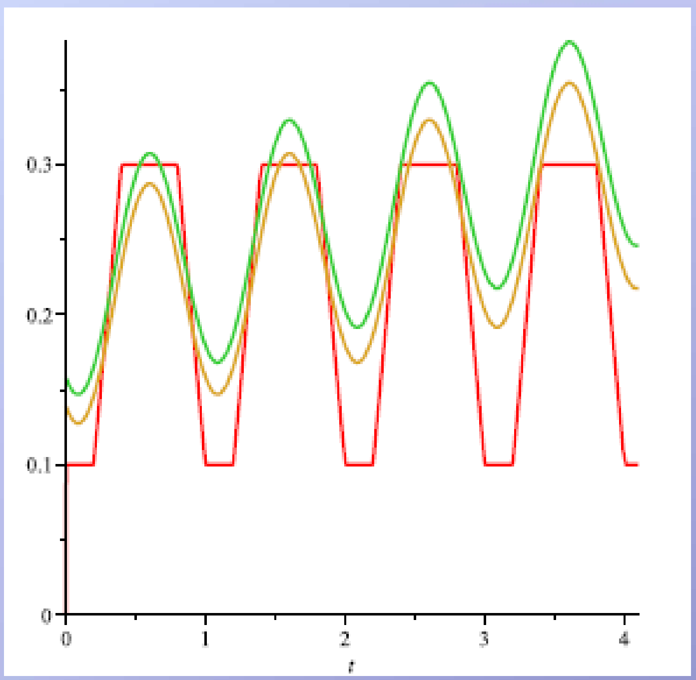
- Cyclic Models provide interesting alternatives to inflation, but it's very challenging to live without inflation.
- Cyclic Inflation seems an interesting compromise, although rigorous perturbation analysis is still pending.
- Cyclic Inflation can be made past geodesically complete, no beginning of time
- CMB signatures, what about non-gaussianity?
- Planck mission

  might have something to say



Perturbations

- A priori looks like a daunting task
- There is a very general argument for near scale-invariance
- Power-spectrum depends on energy densities at the Hubble crossing
- At the last Hubble crossing



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Emergent Cyclic Universe

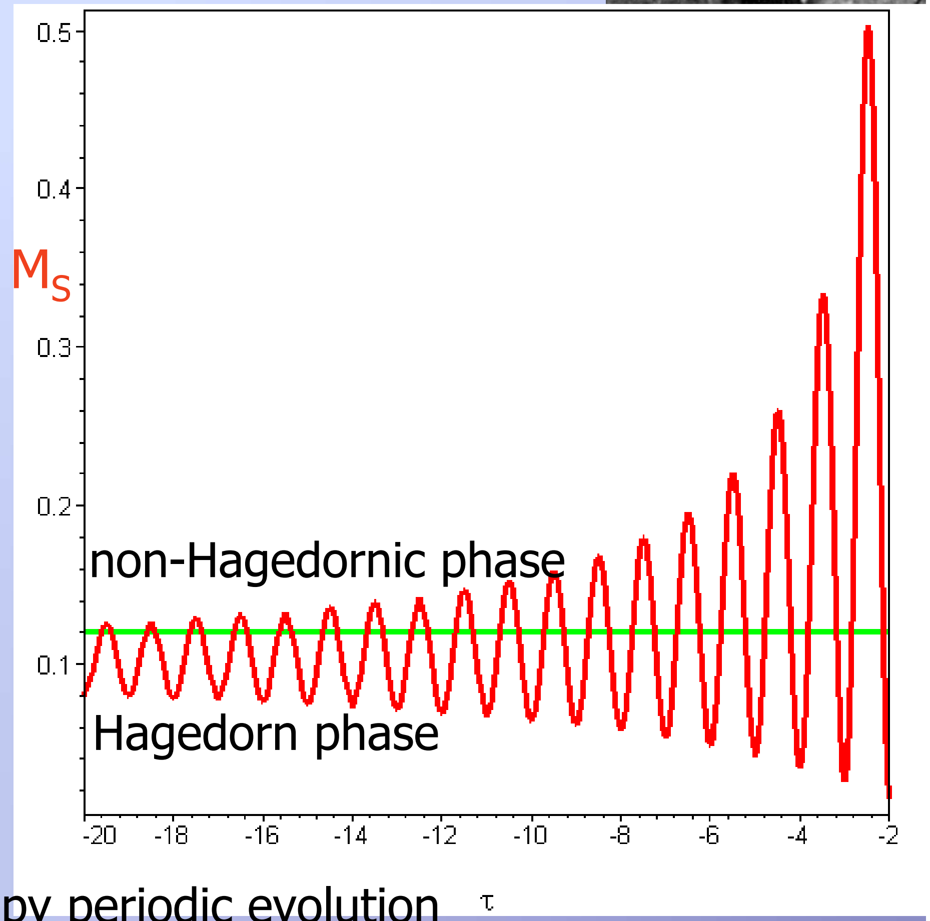
Tolman's Entropy Problem

- Entropy is monotonically increasing
- Universe atmost quasi-periodic
- Entropy (Energy, period) vanishes
  in a finite time in the past
  Beginning of time – back to square 1

- Thermal Hagedorn Phase, $T=T_H \sim M_S$
- All string states in thermal equilibrium
- entropy constant
- As cycles shrink, universe is hotter

- less time in entropy producing

- more time in



- Cycles assymptote to a constant entropy periodic evolution

Classic Puzzles

Flatness, Largeness & Entropy : Just like inflation

- curvature ~ a^{-2} , diluted away
- Small "spatially curved" patch expands just like inflation to resemble our universe
- Tolman's problem: initial emergent phase

Isotropy: Anisotropy ~ a^{-6}

- Anisotropy wins ⟹ chaotic Mixmaster behavior

- Ekpyrotic models successfully address this problem, ρ_{ekp} wins
- Cyclic Inflation: If we start with an initial smooth patch, it only becomes more isotropic over cycles. No Mixmaster behavior.

Homogeneity/ Blackhole overproduction

- Matter domination, structures grow, since gravity is always attractive.
- Sub Hubble modes don't grow significant radiation ⇒ $\lambda_J \sim H^{-1}$
- For Super Hubble modes $\delta \sim \frac{k^2 \Phi_k}{a^2 \rho}$

Is a Graceful Exit possible?

- *Yes*
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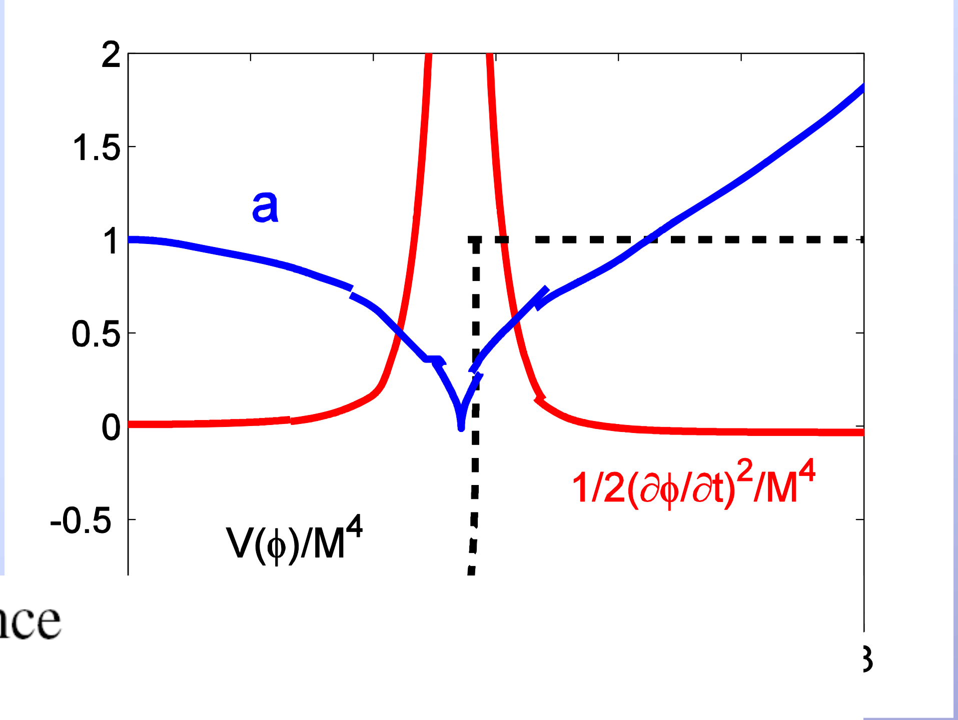
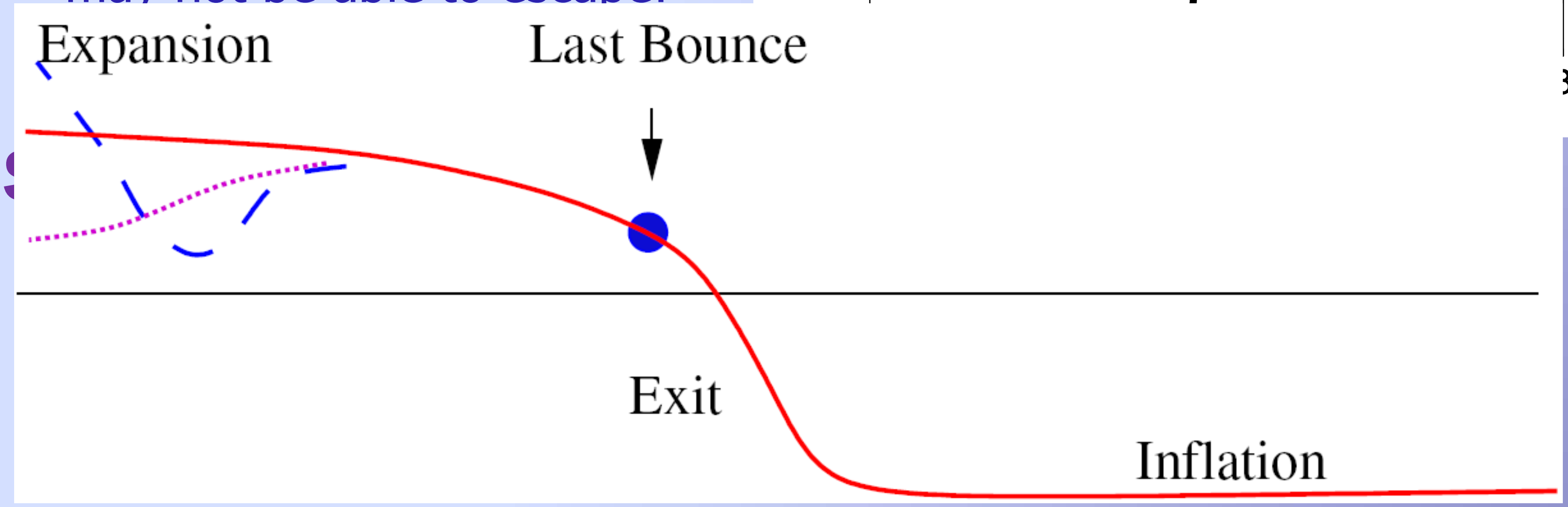
- Once K + V >0, can only turn back in the +ve region
- If the universe bounces back, may not be able to escape!



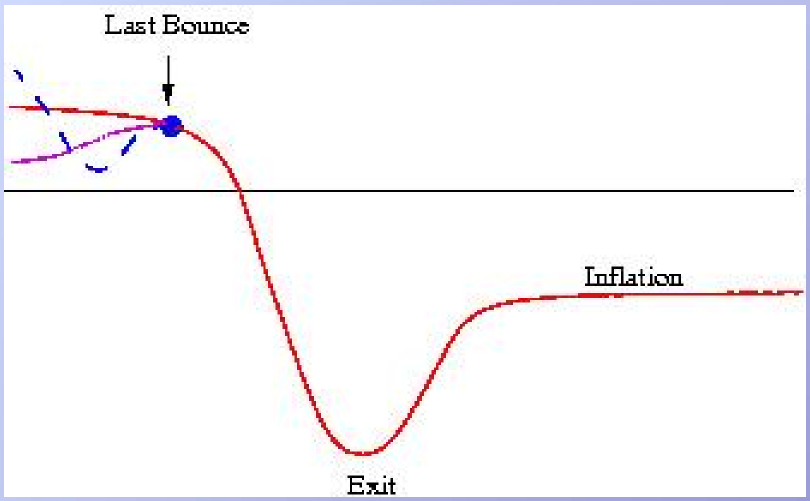


How to exit from Cyclic-Inflation?

Graceful Exit Problem

- Eventually we want a long expanding phase

  In this short cycles no time to even form nucleus, atoms!
- Turnaround requires a –ve CC, we live in small +ve CC



How to exit?

- Introduce a scalar potential
- Kinetic energy increases during contraction
- Increase depends on slope

  Total energy can go from – ve to + ve
- Once +ve, field cannot turn around

  Can zoom past the minimum and into + ve potential region

Could the Universe have started with Negative potential Energy?

- It seems to be in obvious contradiction with current observation
- Early Universe (Inflation) requires positive energy as well
- In GR, during expansion scalar energy density can only decrease
- Nevertheless String Theory predicts Negative Energy Regions
- No apriori reasons why it didn't begin with negative energy
- Inflation is not past geodesically complete [Borde,Vilenkin,Linde,1994]

So what happens if we have - Λ?

- As long as matter density is larger than Λ, we can do cosmology
- Universe is not stuck at an AdS vacuum, -Λ facilitates a turnaround
- In GR this results in a Big Crunch, but…
- A conjecture: Universe bounces back at a critical Planckian density
- Cyclic Universe Multiple bounces & "Turnarounds"
- *Cycles are very short:*

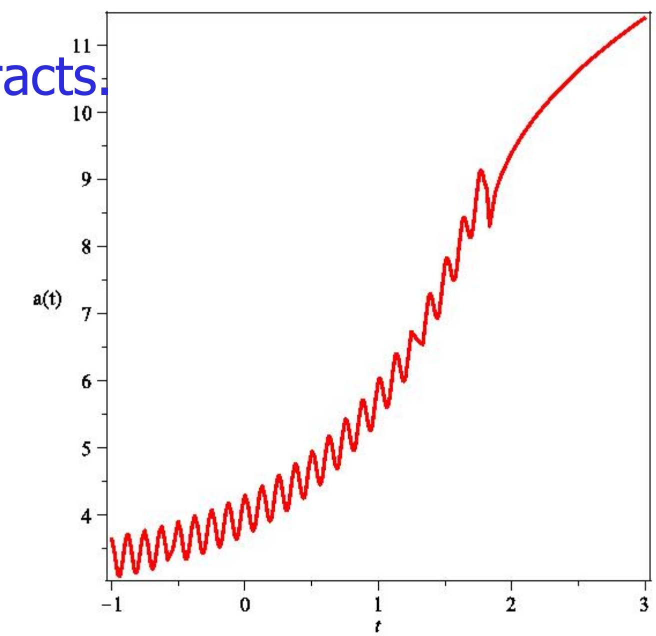
$$\tau = \frac{M_p^2}{\Lambda} \sim 10^6 \tau_p$$

$$\frac{S_{n+1}}{S_n} = 1 + 3\kappa$$

Background Cosmology

- If there is more than one forms of matter which interact, entropy is produced
- This is a consequence of 2nd law thermodynamics [Tolman, 1931]
- Typically this leads to o
- Universe expands a littl contracts.
- *Grows by the same factor – Inflation*

$$\tau = \frac{M_p^2}{\Lambda} \sim 10^6 l_p$$



$$\mathcal{P}_\Phi = \left(\frac{\Lambda}{3M_p^2}\right)\left(\frac{k}{k_0}\right)^{n_s - 1}\left[1 + 2\kappa\cos\left(\frac{2\pi\ln(k/k_0)}{\kappa} + \theta\right)\right]$$

CMB Summary

Amplitude

- determined by time scale of cycle

Spectrum

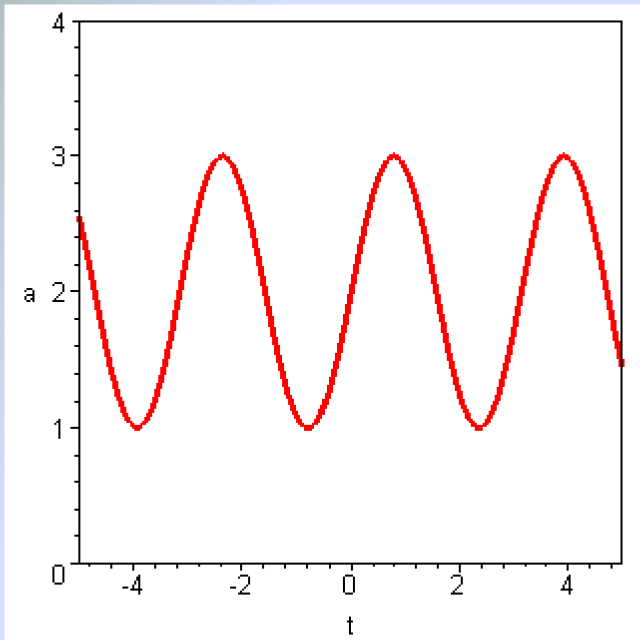
- Distinctive signature: periodic modulations in ln(k)
- Produces a pretty good fit to the 7-yr data

$$\Delta\chi^2 \approx -4$$

w.r.t. Standard Inflationary model without wiggles

- 2 additional parameters consistent with improvement of
- Can Planck shred some light?

Cyclic Cosmologies: Good, Bad & Ugly



Cyclic Universe
Einstein,Freedman,
Tolman, Lemaitre 30's
Bondi,Gold,Narlekar
& Hoyle (Steady State) 50's
Steinhardt & Turok (ekpyrotic), '02
TB, Mazumdar
& Shafeloo (Cyclic-Inflation)

Good

- Cyclic Models solve the Horizon problem
- There is no beginning of time
  Time is past and future eternal
- Non-singular and geodesically complete
- Finding new models is good science

Bad

- Problems with homogeneity/isotropy
- Reproducing CMB Fluctuations
  - Correct amplitude requires huge asymmetry
  - Getting scale-invariant spectrum have proved extremely challenging

Ugly

Transferring fluctuations from the contracting to the expanding branch

Transferring fluctuations via bounce

- Inflation, V″(Φ)≈0, a~-1/Hτ

$$\sigma_k'' + \left(k^2 - \frac{a''}{a}\right)\sigma_k = 0 \qquad \sigma \equiv \frac{\phi}{a}$$

- Sub-Hubble

$$H << k \qquad \Rightarrow \qquad \sigma_k \sim k^{-1/2} e^{ik\tau}$$

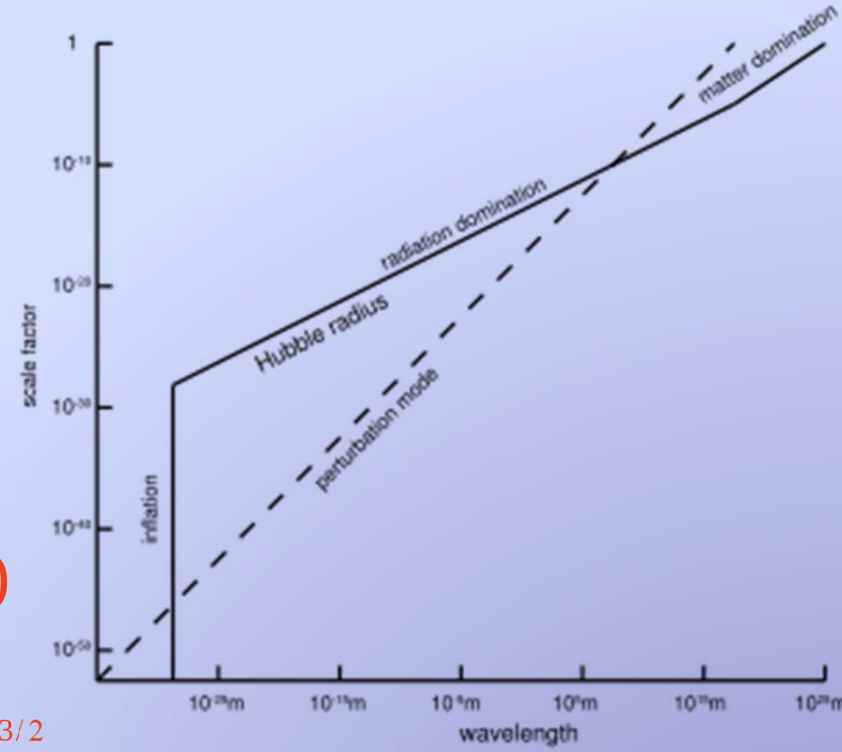
- Super-Hubble

$$H >> k/a \qquad \sigma_k \sim A(k)a(\tau)$$

- Matching at Hubble crossing

$$H = k/a \qquad \Leftrightarrow \qquad k \sim 1/|\tau| \qquad \varphi_k \sim k^{-3/2}$$

- Power Spectrum
- $P_\phi \sim k^3 |\varphi_k|^2 \sim const.$
- Ekpyrotic
- Generates scale-invariant spectrum in the “growing mode” during contraction phase.



Why should we care about Cyclic Cosmologies?

Can we avoid the beginning of time ?

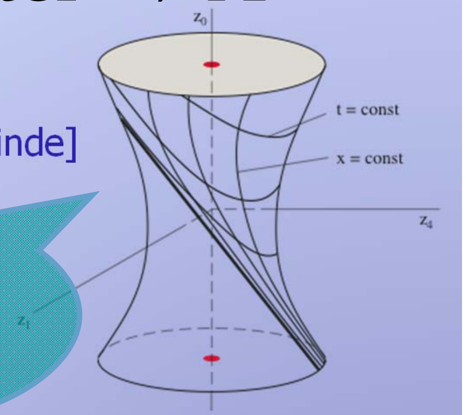
- Standard Cosmological Model

$$\text{inflation} \xrightarrow{\textit{reheating}} \text{radiation} \rightarrow \text{matter} \rightarrow \Lambda$$

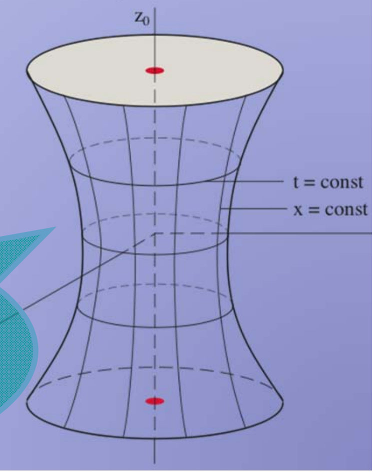
- Can Inflation be past-eternal? [Guth,Vilenkin,Borde,Linde]

$$a(t) = e^{Ht}$$

- Ordinary GR takes you back to singularity
  - QG Phase, no geometry
  - Space-time continuum as 0th order approximation
- QG may give us a "Big Bounce"



Open or flat: geodesically incomplete

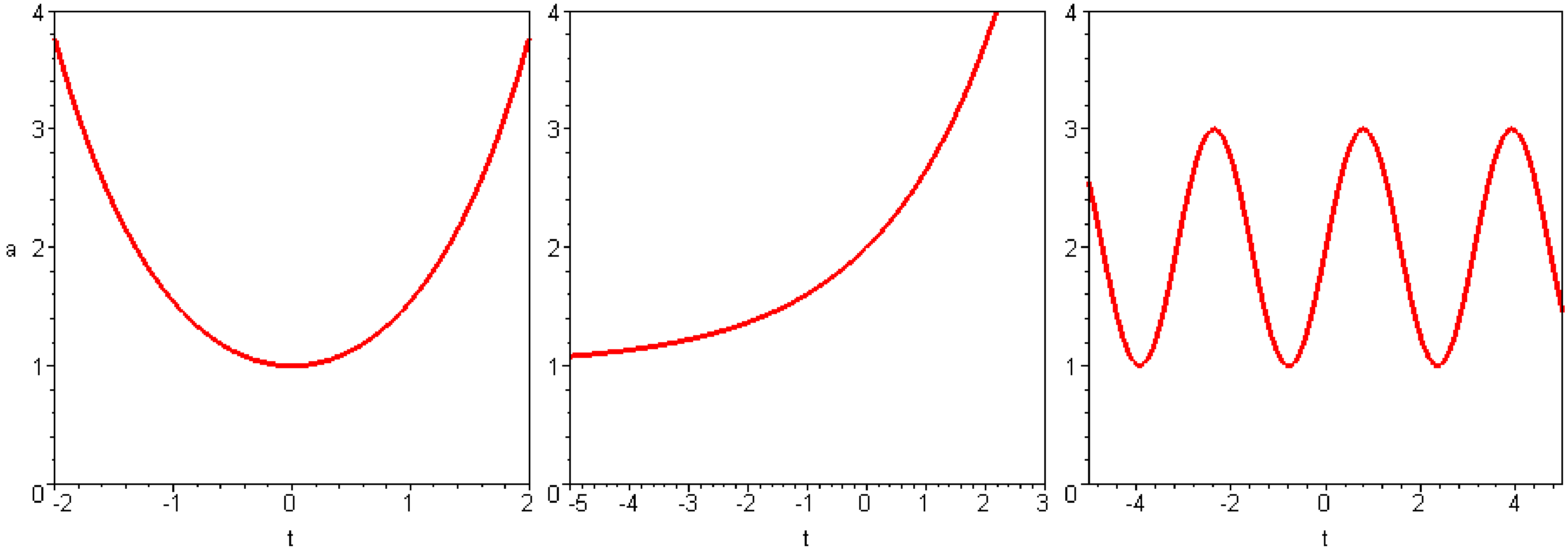


Closed: geodesically complete

Non-singular Cosmologies

- "Effective" 4D metric description
- Stick to FLRW cosmologies: BKL conjecture
- Look into the "eternal past"

$$R \sim H^2 \sim (\dot{a}/a)^2$$



Bouncing Universe
Novello,Salim; Melnikov,Orlov,70's
Gaperini, Maggiore & Veneziano
(pre-big bang) '97

Emergent Universe
Ellis & Maartens '04

Cyclic Universe
Einstein,Freedman,Tolman,Lemaitre, 30's
Bondi,Gold,Narlekar,Hoyle (steady state) 50's
Steinhardt ,Turok,Ovrut,Khoury (ekpyrotic)

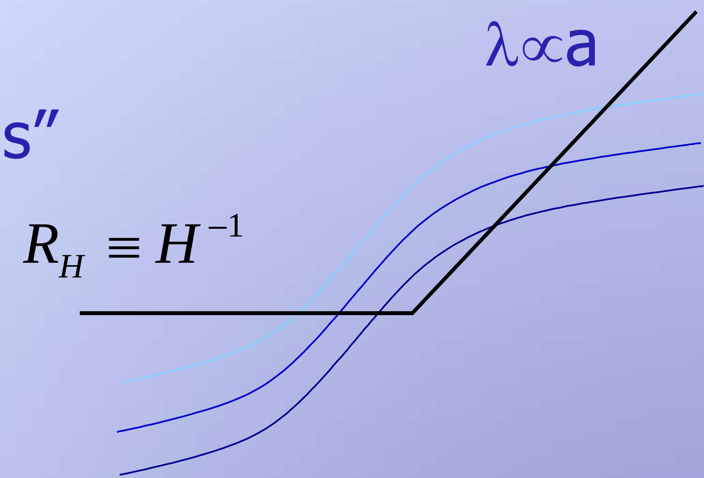
<u>CMB Fluctuations</u>

Inflation

$$ds^2 = a^2(\tau)[-(1+\Phi(x,\tau))d\tau^2 + (1-\Phi(x,\tau))dx^2]$$

- Perturbed metric
- Start from "sub-Hubble fluctuations"
  - wavelength << cosmological expansion
  - They oscillate

$$\mathcal{P}_\Phi \sim \frac{\rho_\varphi}{M_p^4}$$



  - Starting from Bunch Davis vacuum
- During inflation they become super-Hubble and freeze
  - Amplitude

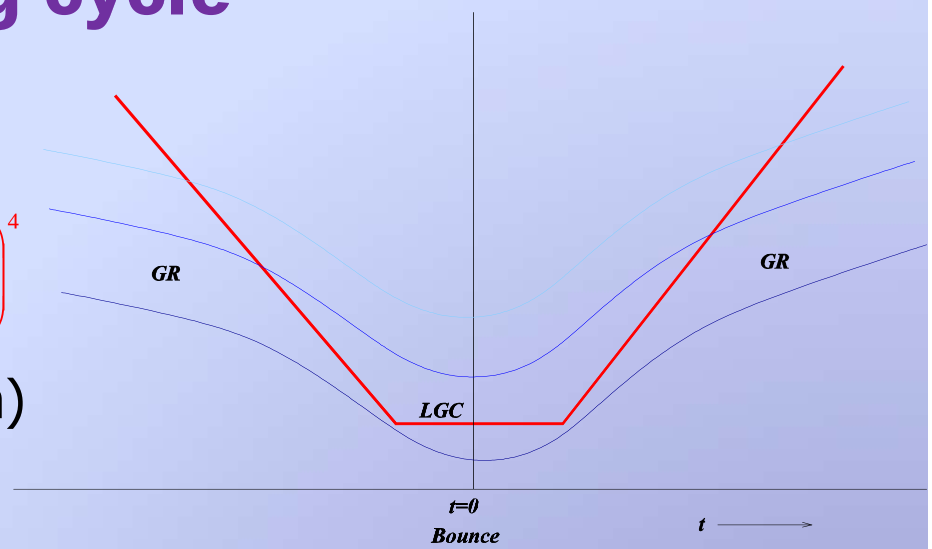
$$\mathcal{P}_\Phi \sim 10^{-10} \Rightarrow \rho_\varphi \sim (10^{-3} M_p)^4$$

  - Explains why you have near scale-invariant spectrum

The Amplitude Problem

Bouncing universe / long cycle

- Hydrodynamical fluctuations
  - Logical starting point at t = -∞
  - Vacuum initial conditions $\mathcal{P}_\Phi \sim \left(\frac{meV}{M_p}\right)^4$
  - Amplitude is suppressed
    (if during bounce it remains frozen)
  - Symmetric bounce means trouble



- Thermal Fluctuations: $\mathcal{P}_\Phi \sim \left(\frac{T}{M_p}\right)^3$
- Fixing this require asymmetry
  - Ekpyrotic Scenario: slow contraction → normal expansion
  - Inflation: normal contraction → fast expansion
    Don't need exponential inflation,
    no trans-Planckian problem, spectral break – unique signature

$$\rho_b >> M_p^4$$

- Generating fluctuations over many many cycles

2^{nd} Law of Thermodynamics & Tolman's Entropy Problem

Tolman's Observations

- Entropy is monotonically increasing
  - Universe atmost quasi-periodic
  - Entropy (Energy, period) vanishes in a finite time in the past
    Or the universe is again geodesically complete
  - Beginning of time – back to square 1
- Can we use 2^{nd} law to generate asymmetry?
  - Suppose around bounce, we have thermal equilibrium between some heavy non-relativistic particles and massless modes
  - When $T<T_c \sim M$, thermal equilibrium is lost
  - Matter can decay into radiation

$$\left(\frac{S_{n+1}}{S_n}\right) = \left(\frac{S_r}{S_m}\right) \sim \frac{\rho_r^{3/4} V}{\rho_m V M^{-1}} \sim \frac{T_c}{T_d} \equiv \kappa$$

  - Entropy increases by a constant factor
  - So does the scale factor!

$$S \sim V \Rightarrow \frac{a_{n+1}}{a_n} \sim (1+\kappa)^{1/3}$$