YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

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Inflation
and Beyond

Misao Sasaki

Yukawa Institute for Theoretical Physics
Kyoto University

Introduction

What is Inflation?

Brout, Englert & Gunzig '77, Starobinsky '79, Guth '81, Sato '81, …

- Inflation is a quasi-exponential expansion of the Universe at its very early stage; perhaps at t~10^{-36} sec.

- It was meant to solve the initial condition (singularity, horizon & flatness, etc.) problems in Big-Bang Cosmology:
- if any of them can be said to be solved depends on precise definitions of the problems.

- Quantum vacuum fluctuations during inflation turn out to play the most important role. They give the initial condition for all the structures in the Universe.

- Cosmic gravitational wave background is also generated.

more on ∨ inflation

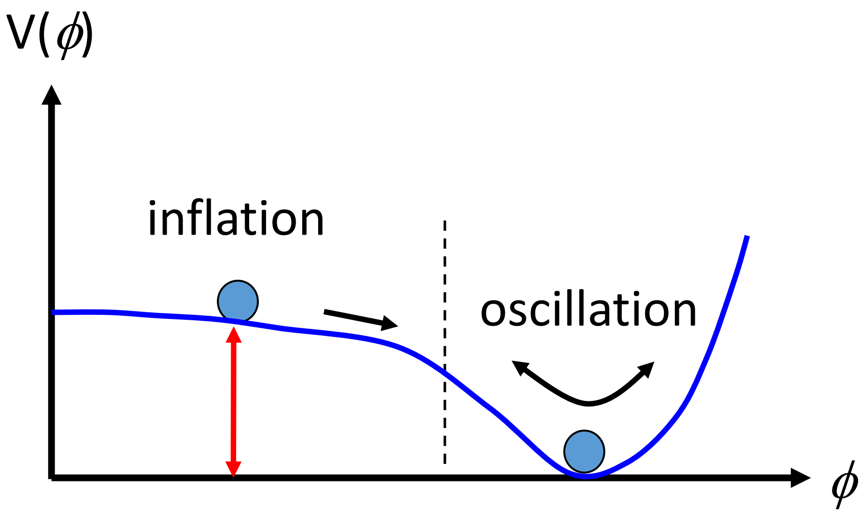
the meaning of

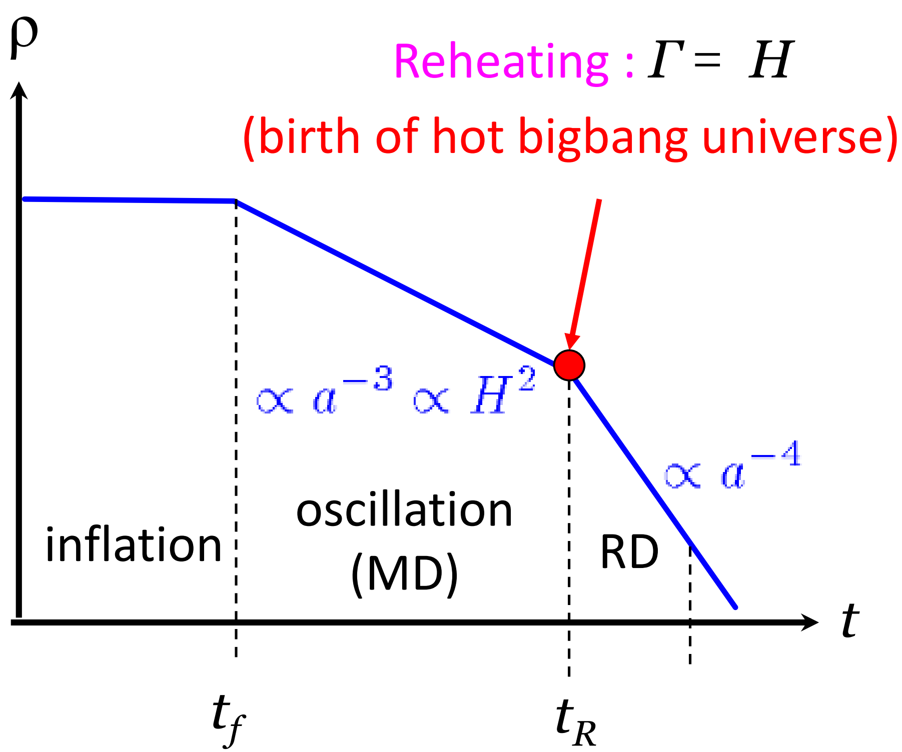
1. Homogeneity and isotropy are the (most important) assumption, NOT a consequence of inflation.
2. Quasi-exponential expansion in the "Einstein frame": conformal invariant definition.
3. At least 50-60 e-folds before the end of inflation: solving "horizon problem"
4. Don't care what happened before inflation: predictions are almost independent of initial conditions.

1 & 2: basic assumptions/definition of inflation

From inflation to bigbang

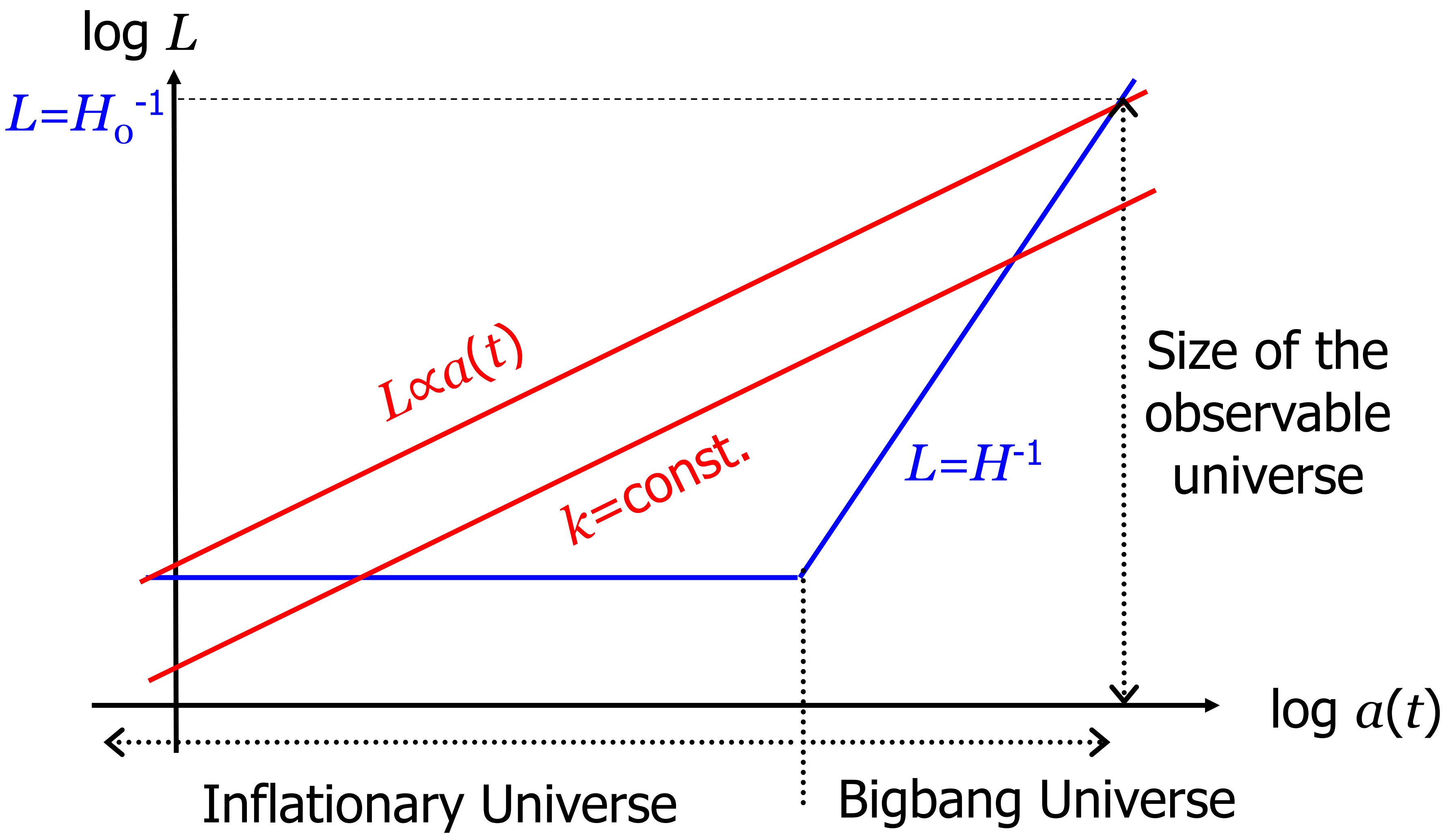
After inflation, vacuum energy is converted to thermal energy (called "re"heating) and hot Bigbang Universe is realized.



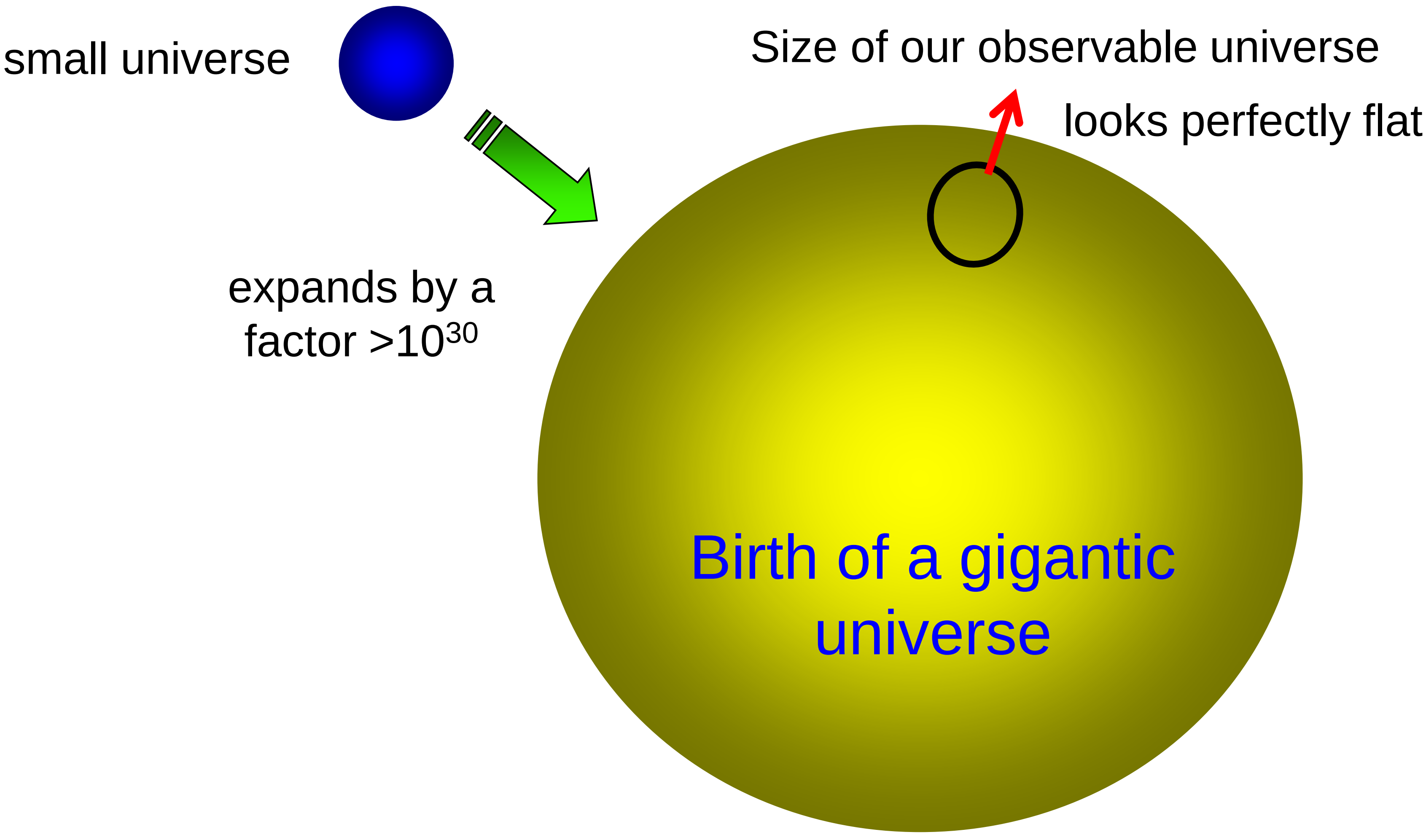


Kinematics

length scales of the inflationary universe



Flatness



Flatness can be explained only by Inflation

NB: Inflation may not always imply flatness

Dynamics

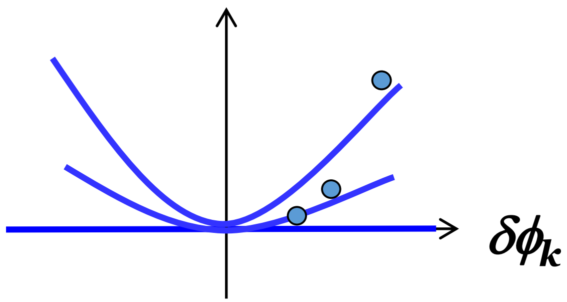
Seed of cosmological perturbations

Mukhanov '81, ….

Zero-point (vacuum) fluctuations of ϕ: $\delta\phi = \sum_k \delta\phi_k(t) e^{ik\cdot x}$

$$\delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \omega^2(t)\delta\phi_k = 0 \ ; \quad \omega^2(t) = \frac{k^2}{a^2(t)}$$

harmonic oscillator with friction term and time-dependent ω



$\delta\phi_k \rightarrow$ const.

… frozen when $\omega < H$
(on superhorizon scales)

tensor (gravitational wave) modes also satisfy the same eq.

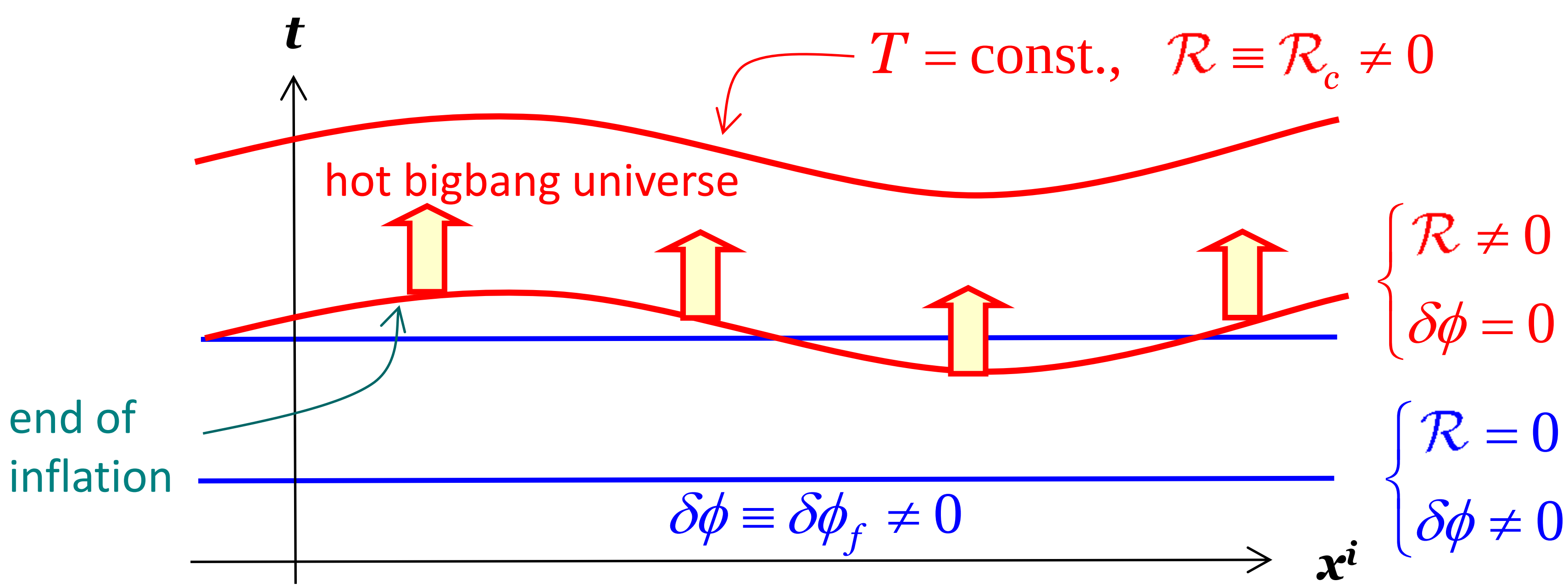
Starobinsky '79

Generation of Curvature Perturbation

curvature (potential) perturbation $\mathcal{R}$: $$\delta R^{(3)} = -\frac{4}{a^2}\nabla^2\mathcal{R}$$

comoving curvature perturbation $\mathcal{R}_c$ ~ - Newton potential

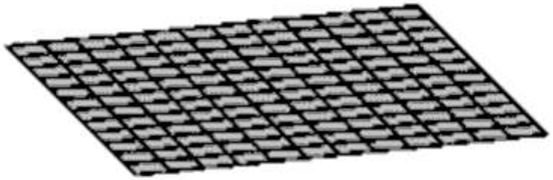
- $\delta\phi$ is frozen on "flat" **($\mathcal{R}$=0)** 3-surface (*t*=const. hypersurface) $$\mathcal{R}_c = -\frac{H}{\dot{\phi}}\delta\phi_f$$
- Inflation ends/damped osc starts "comoving" (ϕ =const.) on 3-surface.



generic predictions of ∨ inflation

slow-roll

- Spatially flat universe



- Almost scale invariant, adiabatic, Gaussian primordial scalar (curvature) perturbations

- Almost scale invariant, Gaussian primordial tensor (gravitational wave) perturbations

⇒ Generates CMB anisotropy
Origin of galaxies, stars, …

Quantitative Predictions

- Amplitude of curvature perturbation:

$$\mathcal{R}_c = \left.\frac{H^2}{2\pi\dot{\phi}}\right|_{k/a=H}$$

Mukhanov (1985), MS (1986)

- Power spectrum index:

$$M_{pl} \equiv \frac{1}{\sqrt{8\pi G}} \sim 2.4\times10^{18}\,\text{GeV: Planck mass}$$

$$\frac{4\pi k^3}{(2\pi)^3}P_S(k) = \left[\frac{H^2}{2\pi\dot{\phi}}\right]^2_{k/a=H} = Ak^{n_S-1}\ ;\ n_S - 1 = M_P^2\left(2\frac{V''}{V} - 3\frac{V'^2}{V^2}\right)$$

Stewart-Lyth (1993)

- Tensor (gravitational wave) spectrum:

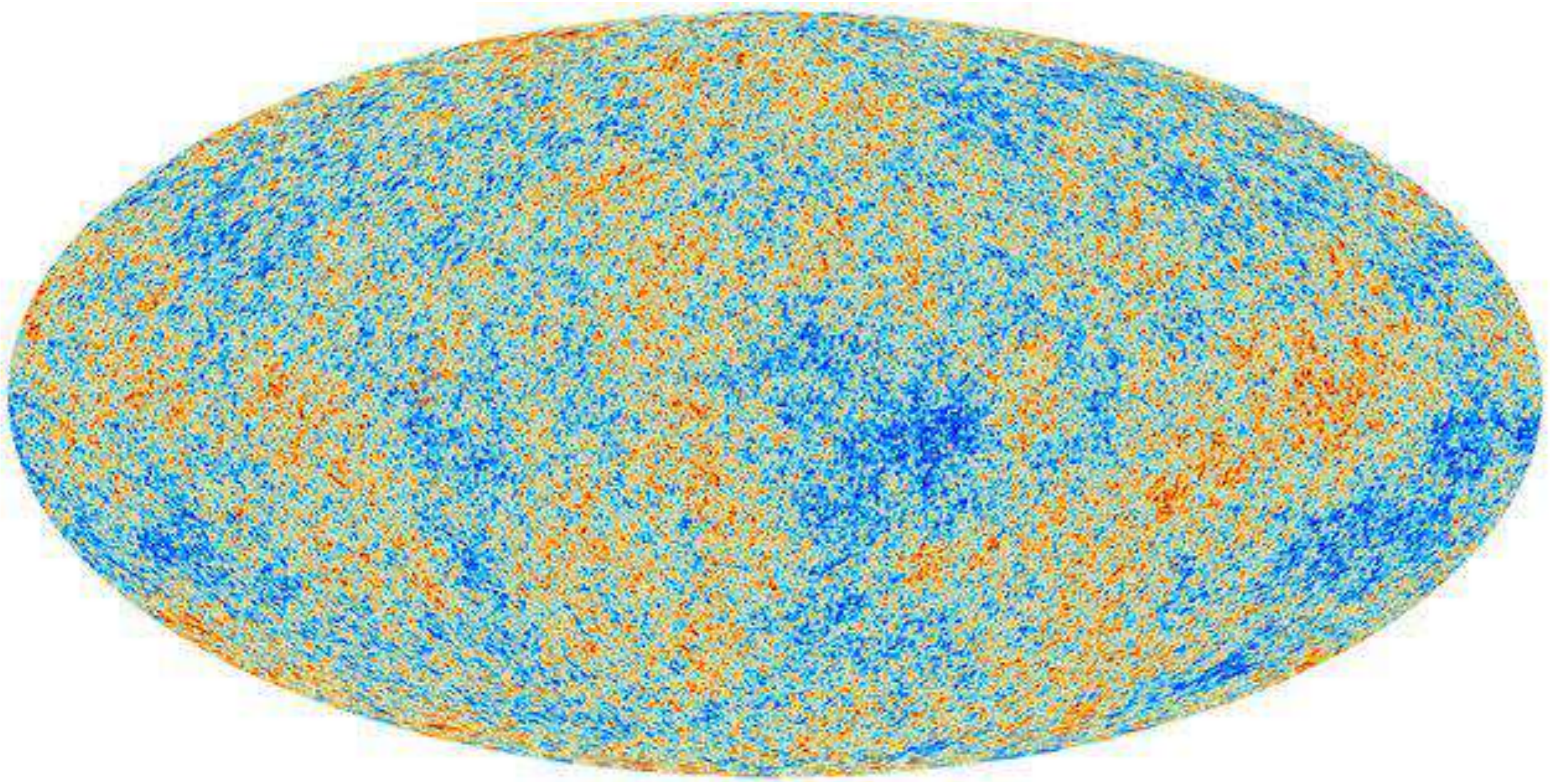
$$\frac{4\pi k^3}{(2\pi)^3}P_T(k) = Ak^{n_T}\ ;\ n_T = -\frac{1}{8}\frac{P_S(k)}{P_T(k)} \equiv -\frac{r}{8}$$

Liddle-Lyth (1992)

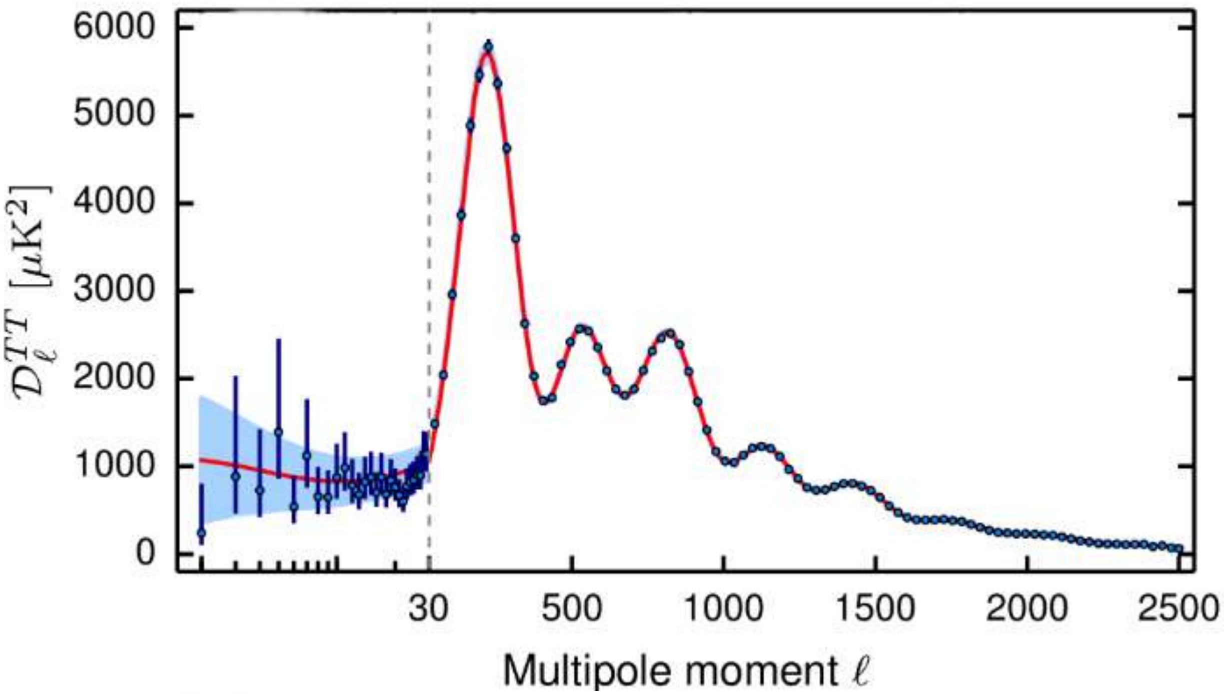
"consistency relation"

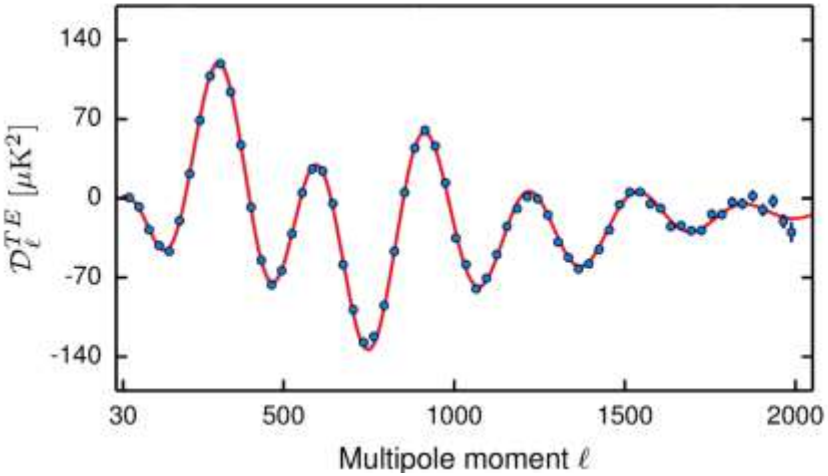
Observational results

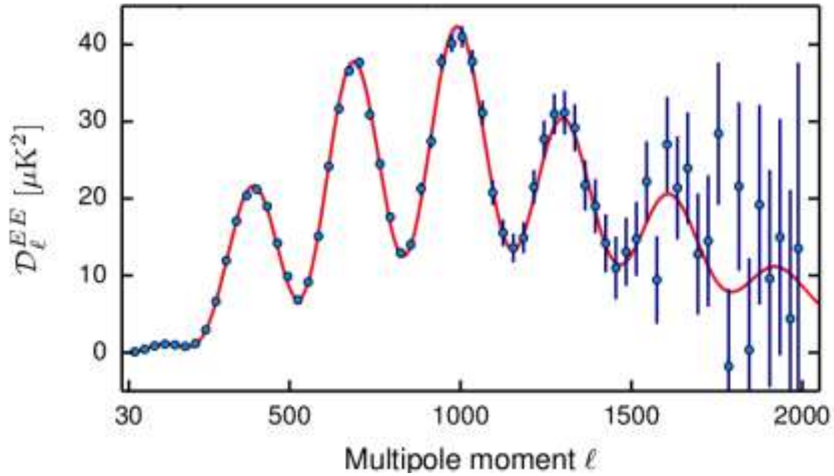
CMB Full Sky Map by PLANCK



Planck TT, TE & EE spectrum







- Amplitude of curvature perturbation:

$$\mathcal{R}_c = \left.\frac{H^2}{2\pi\dot{\phi}}\right|_{k/a=H}$$

Mukhanov (1985), MS (1986)

$$\mathcal{R}_{c,\mathrm{obs}} \sim 10^{-5} \Rightarrow V^{1/4}(\phi) \lesssim 10^{16}\,\mathrm{GeV}?$$

- Power spectrum index:

$$M_P \equiv \frac{1}{\sqrt{8\pi G}} \sim 2.4\times 10^{18}\,\mathrm{GeV}\text{: Planck mass}$$

$$\frac{4\pi k^3}{(2\pi)^3} P_S(k) = \left[\frac{H^2}{2\pi\dot{\phi}}\right]^2_{k/a=H} = Ak^{n_S-1} \ ; \ n_S - 1 = M_P^2\left(2\frac{V''}{V} - 3\frac{V'^2}{V^2}\right)$$

Stewart-Lyth (1993)

$$n_{S,\mathrm{Planck}} - 1 = -0.0355 \pm 0.0049 \Leftrightarrow n_S - 1 \sim -0.04$$ for a typical model

Mukhanov & Chibisov (1981)

- Tensor (gravitational wave) spectrum:

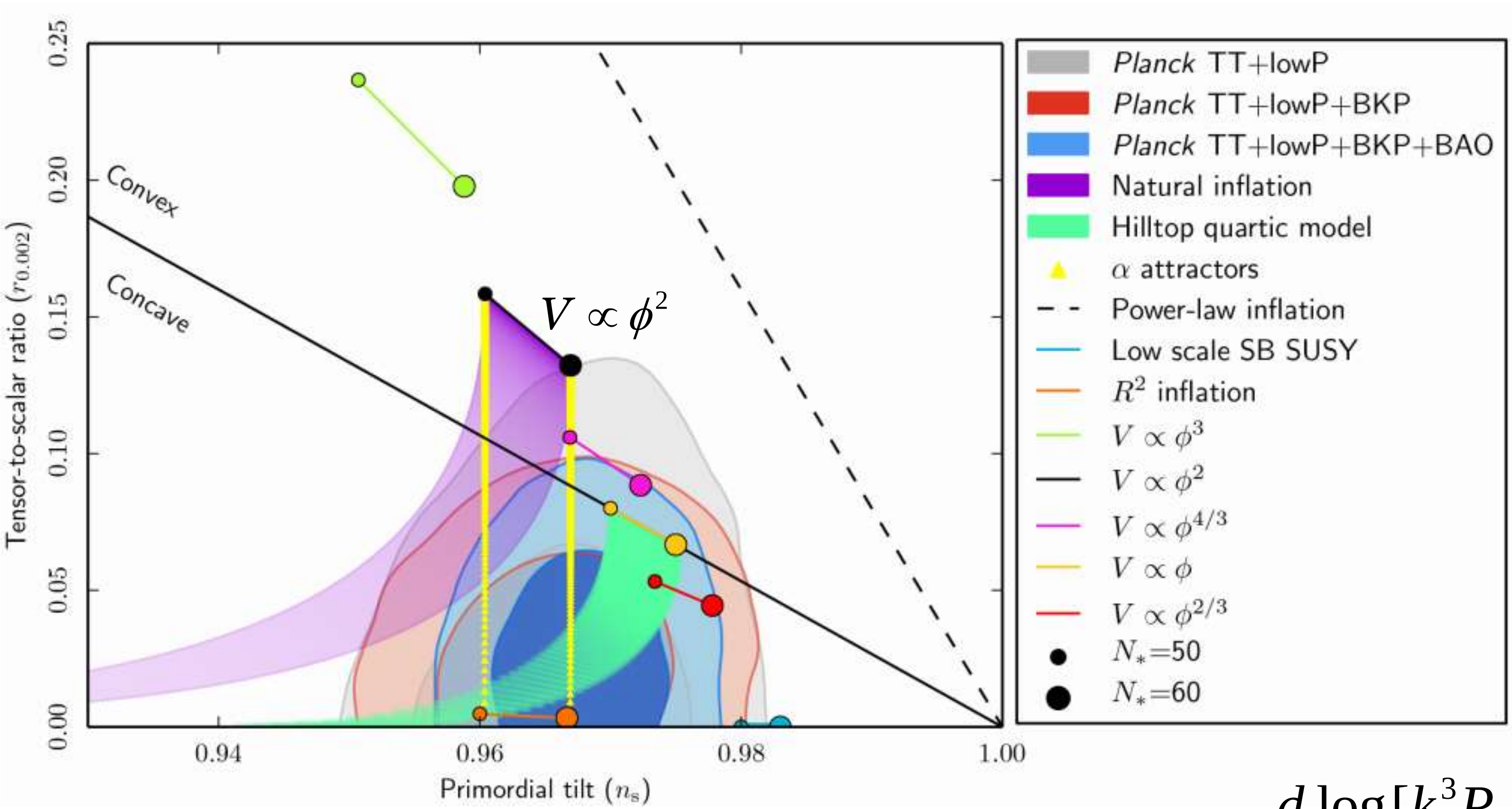
$$\frac{4\pi k^3}{(2\pi)^3} P_T(k) = Ak^{n_T} \ ; \ n_T = -\frac{1}{8}\frac{P_T(k)}{P_S(k)} \equiv -\frac{r}{8}$$

Liddle-Lyth (1992)

to be observed ...

Planck constraints on inflation

Planck 2015 XX



$$n_s - 1 \equiv \frac{d \log[k^3 P_S(k)]}{d \log k}$$

$$r \equiv \frac{P_T(k)}{P_S(k)}$$

- scalar spectral index: $n_s \sim 0.96$
- tensor-to-scalar ratio: $r < 0.1$
- simplest $V \propto \phi^2$ model is almost excluded

Implications

The most important message is:

Inflation as the Origin of
All Structures
in the Universe

Current status

- scalar spectral index: $n_s<1$ at ~ 5 σ
- tensor/scalar ratio: $r < 0.1$ implies $E_{inflation} < 10^{16}$ GeV
- simple, canonical models are on verge of extinction
  ($m^2\phi^2$ model excluded at > 2 σ)
- R^2 (Starobinsky) model seems to fit best. But why?
  (large R^2 correction but negligible higher order terms)
- f_{NL}^{local} <O(1) suggests (effectively) single-field slow-roll
  (but non-slow-roll models with f_{NL}^{local} =O(1) not excluded)

↓

element of non-canonicality is needed

Beyond
(standard model of)
Inflation

non-canonical models

- Non-canonical kinetic term? (c_s <1?)

$$P_S \propto \frac{1}{c_s} \quad (c_s\text{: sound speed})\ , \quad f_{\mathrm{NL}}^{equil} \propto \frac{1}{c_s^2}$$

Planck: $c_s > 0.024$ at 95% CL

- non-minimal coupling to gravity?

$$V(\phi) + \xi \phi^2 R \quad \Longrightarrow \quad r = \frac{P_T(k)}{P_S(k)} \propto \frac{1}{\xi}$$

Planck: $\xi > O(10)$?

- scalar-tensor with derivative couplings (Hordeski) ?

$$c_s < 1, \quad c_{s,T} < 1, \quad c_s \neq c_{s,T}$$

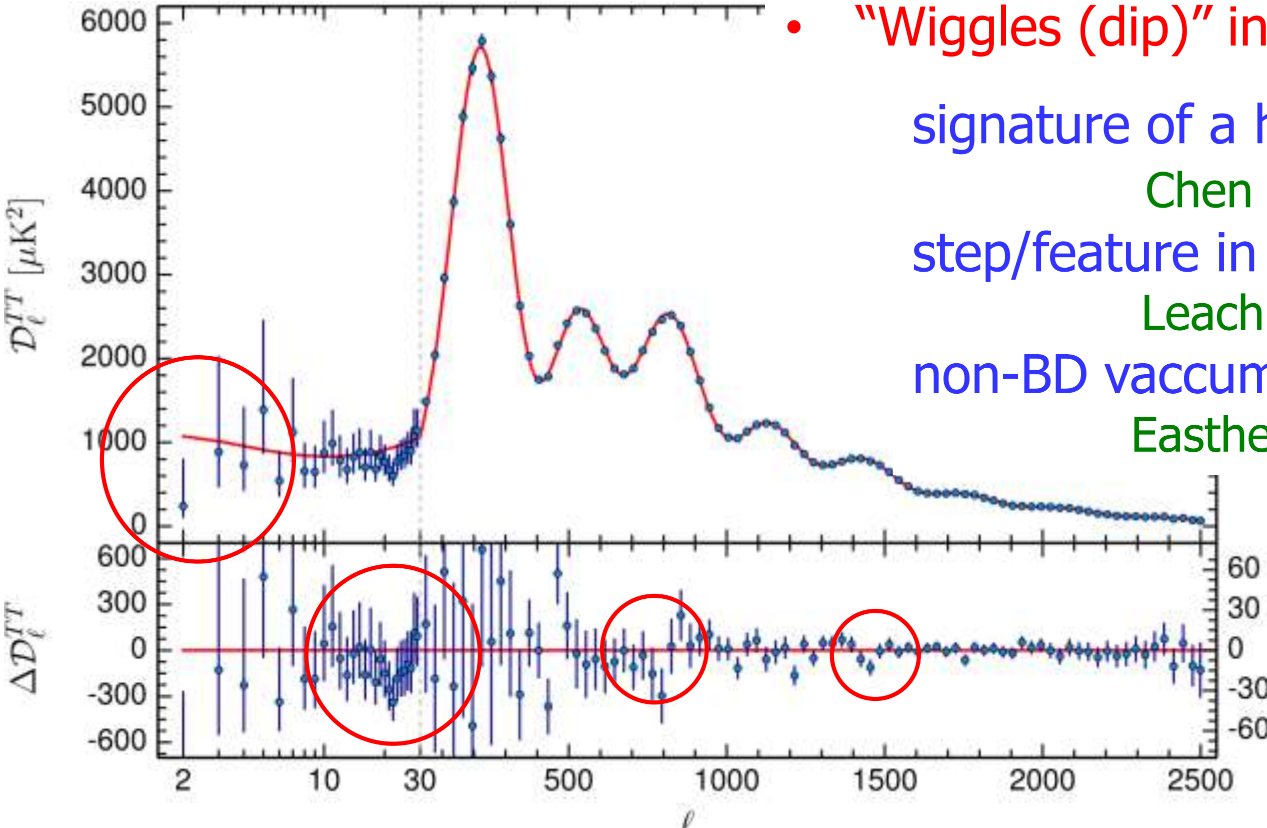
tensor propagation speed

non-existence of Einstein frame?

definition of inflation?

- multi-field models, non-attractor inflation, …

Anomalies & Features



- "Wiggles (dip)" in the power spectrum

  signature of a heavy field?

  Chen '11, …

  step/feature in potential?

  Leach et al. '01, ….

  non-BD vaccum?

  Easther et al. '02,….

- Suppressed large scale fluctuations

  featured potential? open inflation?

  Linde, MS & Tanaka '99, ….

Cosmic Landscape?

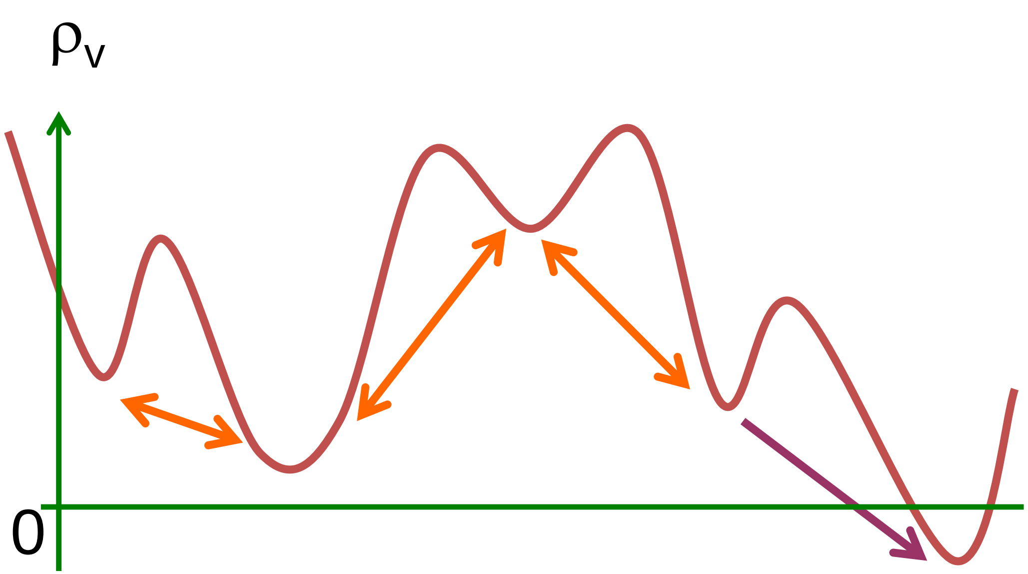
string theory suggests an intriguing picture of the early universe

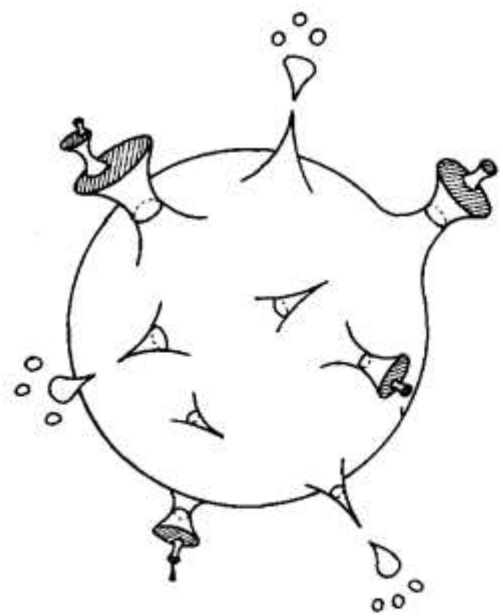
Maybe we live in one of these vacua…

- Universe jumps around in the landscape by quantum tunneling
  - it can go up to a vacuum with larger ρ_V

    de Sitter (dS) space ~ thermal state with $T = H/2\pi$ (expansion rate)

  - if it tunnels to a vacuum with negative ρ_V, it collapses within $t \sim M_P/|\rho_V|^{1/2}$.
  - so we may focus on vacua with positive ρ_V: dS vacua





Sato, Kodama, MS & Maeda ('81)

Open Inflation in Cosmic Landscape

Universe inside nucleated bubble = spatially open universe

Friedmann eq.

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_P^2} + \frac{1}{a^2}$$

negative spatial curvature

$$1 = \frac{\rho}{3M_P^2 H^2} + \frac{1}{a^2 H^2} \equiv \Omega + \Omega_K$$

density parameter

Observational data indicate $1-\Omega_0 = \Omega_{K,0} \sim< 10^{-2}$: almost flat

("0" stands for current value)

What if this is the case?

- two possibilities

1. inflation after tunneling was short enough (N~60)

$$\Omega_{K,0} = 1 - \Omega_0 = 10^{-2} \sim 10^{-3}$$ "open universe"

⇒ signatures in large angle CMB anisotropies?

Kanno, MS & Tanaka ('13), White, Zhang & MS ('14), ...

2. inflation after tunneling was long enough (N>>60)

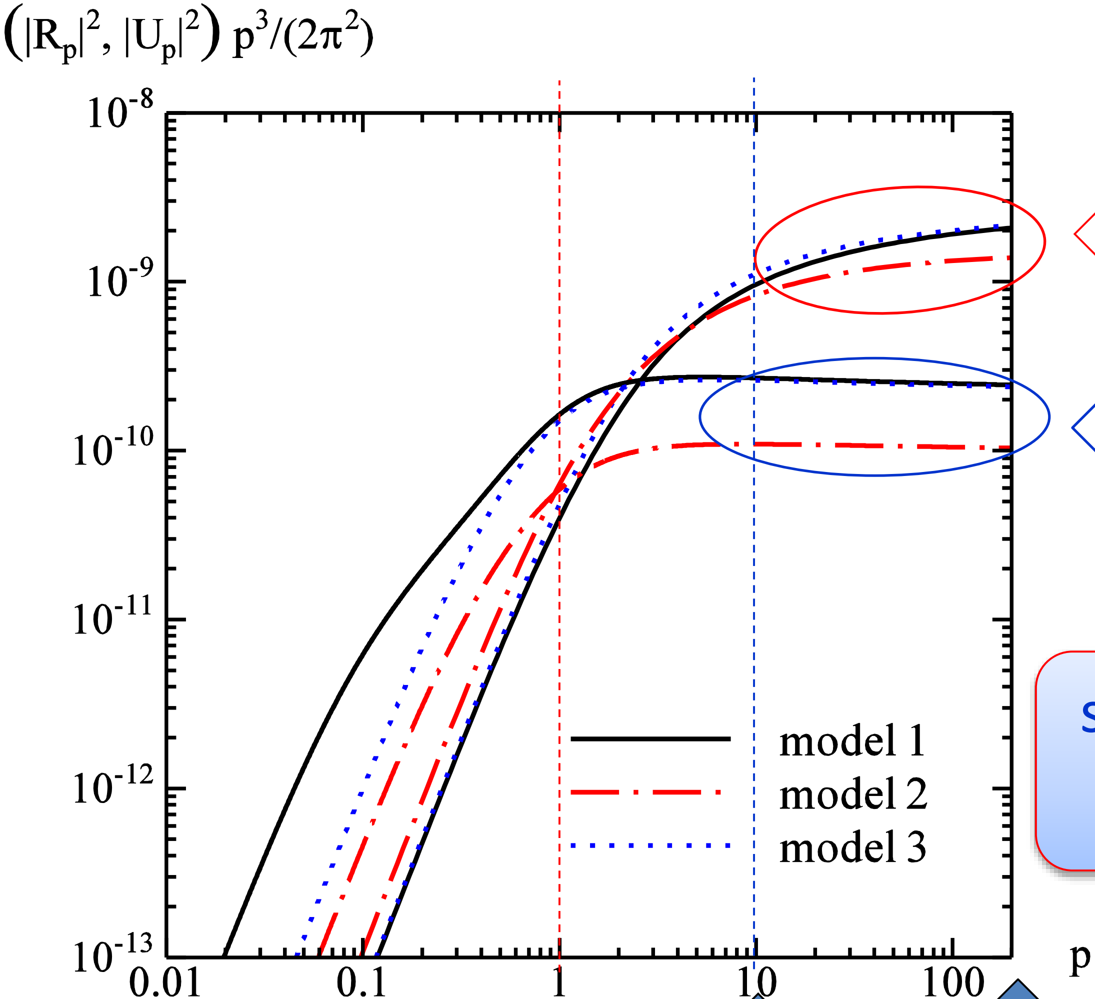
$$\Omega_{K,0} = 1 - \Omega_0 \ll 1$$ "flat universe"

⇒ signatures from bubble collisions

Sugimura, Yamauchi & MS ('12), ...

scalar suppression on large scales

Linde, MS & Tanaka (1999)
White, Zhang & MS (2014)



scalar

tensor
(no suppression)

scalar suppression begins at smaller scale

break scale

curvature radius

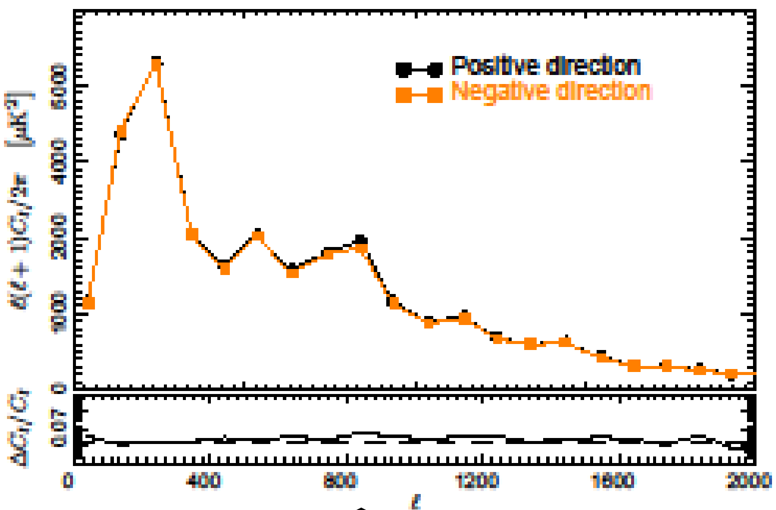
H_0^{-1} if $\Omega_K \approx 0.01$

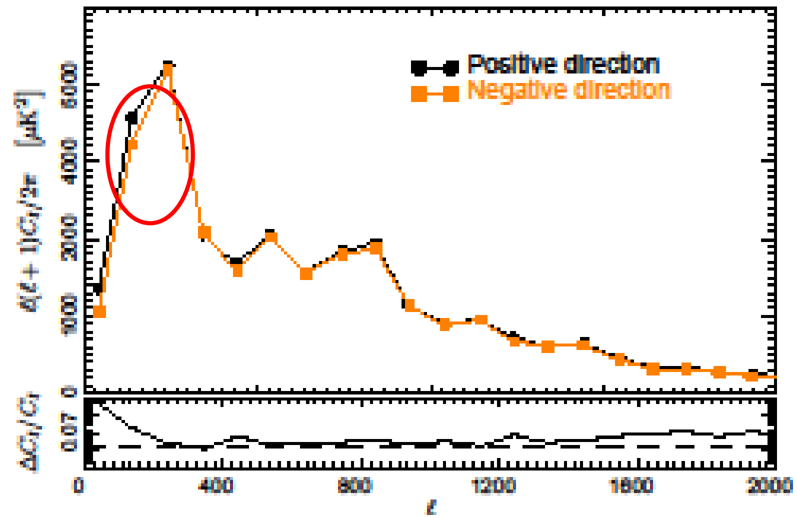
dipole power asymmetry

$$P(k;\boldsymbol{n}) = \left(1 + 2A\hat{\boldsymbol{d}}\cdot\boldsymbol{n}\right)P_{iso}(k)$$

line of sight

dipole





no asymmetry in the direction of ell=1

dipole asymmetry in the direction maximizing the asymmetry

Planck 2013 XXIII

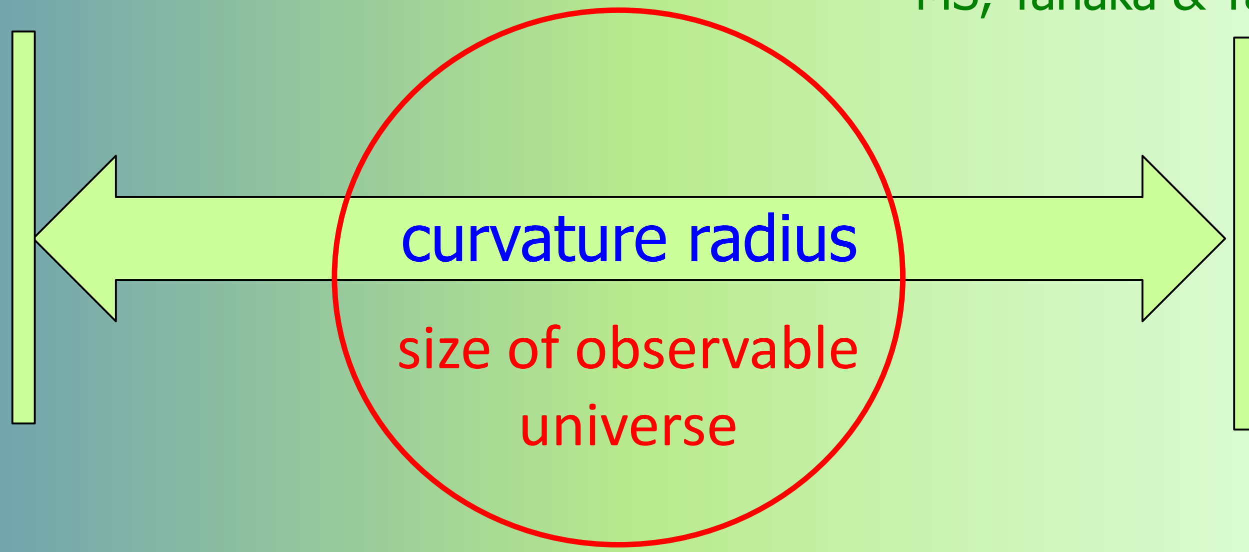
$$\frac{\delta T}{T} = \left(1 + A\cos\theta\right)\left(\frac{\delta T}{T}\right)_{iso}$$

$$A \approx 0.07$$

Data set	FWHM [°]	A	(l,b) [°]	$\Delta \ln \mathcal{L}$	Significance
Commander	5	$0.078^{+0.020}_{-0.021}$	$(227, -15) \pm 19$	8.8	3.5σ
NILC	5	$0.069^{+0.020}_{-0.021}$	$(226, -16) \pm 22$	7.1	3.0σ
SEVEM	5	$0.066^{+0.021}_{-0.021}$	$(227, -16) \pm 24$	6.7	2.9σ
SMICA	5	$0.065^{+0.021}_{-0.021}$	$(226, -17) \pm 24$	6.6	2.9σ
*WMAP*5 ILC	4.5	0.072 ± 0.022	$(224, -22) \pm 24$	7.3	3.3σ
Commander	6	$0.076^{+0.024}_{-0.025}$	$(223, -16) \pm 25$	6.4	2.8σ
NILC	6	$0.062^{+0.025}_{-0.026}$	$(223, -19) \pm 38$	4.7	2.3σ
SEVEM	6	$0.060^{+0.025}_{-0.026}$	$(225, -19) \pm 40$	4.6	2.2σ
SMICA	6	$0.058^{+0.025}_{-0.027}$	$(223, -21) \pm 43$	4.2	2.1σ
Commander	7	$0.062^{+0.028}_{-0.030}$	$(223, -8) \pm 45$	4.0	2.0σ
NILC	7	$0.055^{+0.029}_{-0.030}$	$(225, -10) \pm 53$	3.4	1.7σ
SEVEM	7	$0.055^{+0.029}_{-0.030}$	$(226, -10) \pm 54$	3.3	1.7σ
SMICA	7	$0.048^{+0.029}_{-0.029}$	$(226, -11) \pm 58$	2.8	1.5σ
Commander	8	$0.043^{+0.032}_{-0.029}$	$(218, -15) \pm 62$	2.1	1.2σ
NILC	8	$0.049^{+0.032}_{-0.031}$	$(223, -16) \pm 59$	2.5	1.4σ
SEVEM	8	$0.050^{+0.032}_{-0.031}$	$(223, -15) \pm 60$	2.5	1.4σ
SMICA	8	$0.041^{+0.032}_{-0.029}$	$(225, -16) \pm 63$	2.0	1.1σ
Commander	9	$0.068^{+0.035}_{-0.037}$	$(210, -24) \pm 52$	3.3	1.7σ
NILC	9	$0.076^{+0.035}_{-0.037}$	$(216, -25) \pm 45$	3.9	1.9σ
SEVEM	9	$0.078^{+0.035}_{-0.037}$	$(215, -24) \pm 43$	4.0	2.0σ
SMICA	9	$0.070^{+0.035}_{-0.037}$	$(216, -25) \pm 50$	3.4	1.8σ
*WMAP*3 ILC	9	0.114	$(225, -27)$	6.1	2.8σ
Commander	10	$0.092^{+0.037}_{-0.040}$	$(215, -29) \pm 38$	4.5	2.2σ
NILC	10	$0.098^{+0.037}_{-0.039}$	$(217, -29) \pm 33$	5.0	2.3σ
SEVEM	10	$0.103^{+0.037}_{-0.039}$	$(217, -28) \pm 30$	5.4	2.5σ
SMICA	10	$0.094^{+0.037}_{-0.040}$	$(218, -29) \pm 37$	4.6	2.2σ

Gradient of a field over the horizon scale = Super-curvature mode in open inflation

MS, Tanaka & Yamamoto '95



may modulate the amplitude of perturbation depending on the direction.

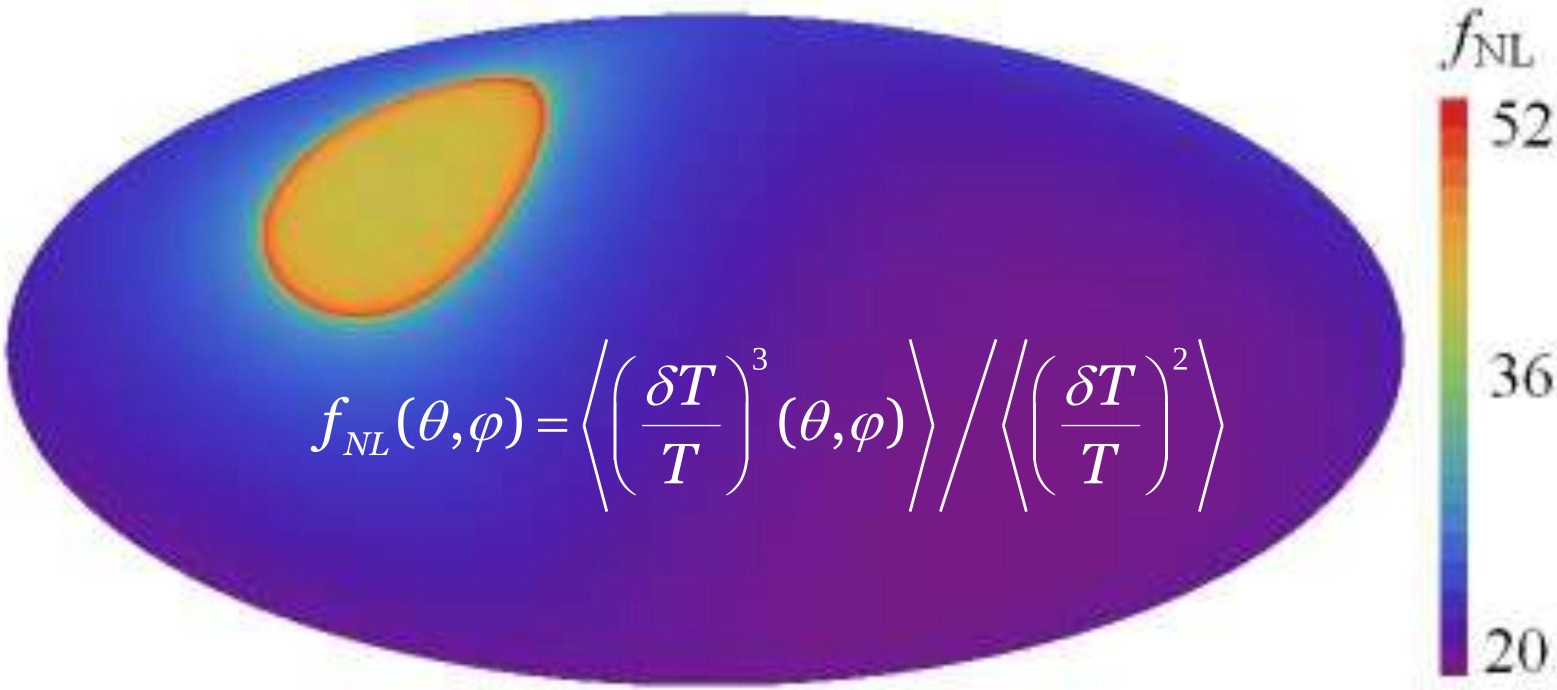
leading order effect is dipolar

if this is the case, then $\Omega_K \gtrsim 10^{-3}$

Kanno, MS & Tanaka '13
Brynes, Domenech, MS & Takahashi '16

non-Gaussian bubbles in the sky?

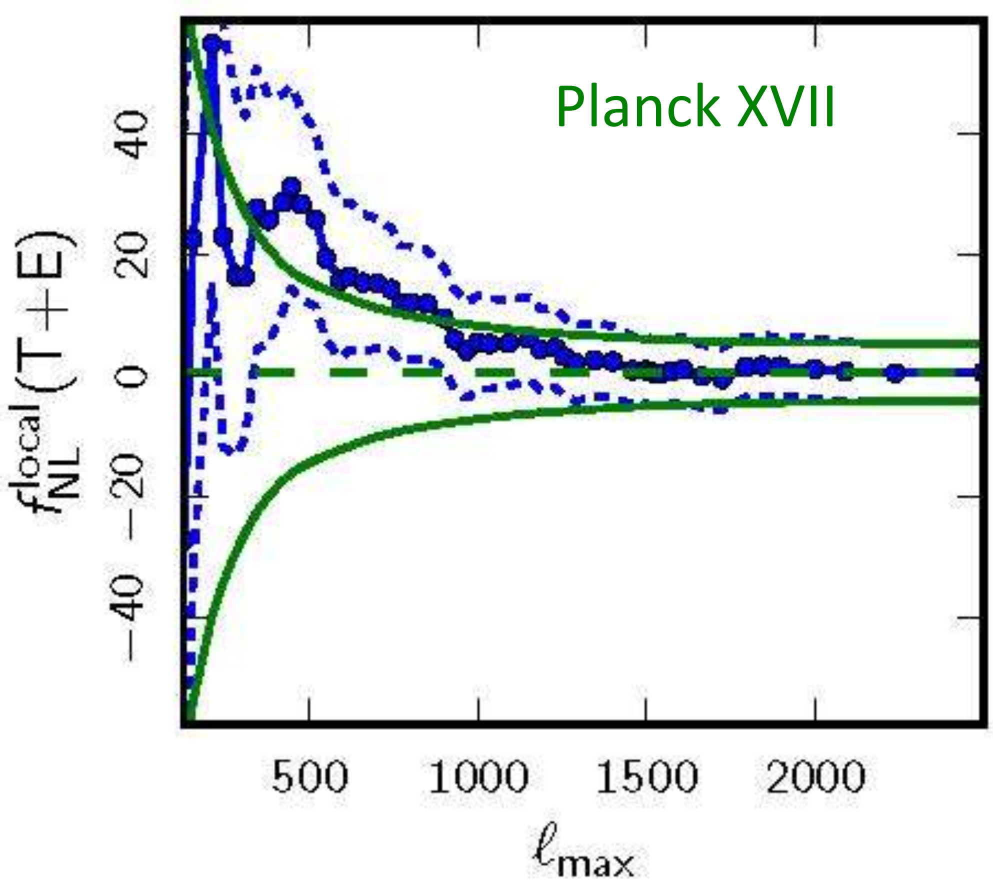
Sugimura, Yamauchi & MS '12



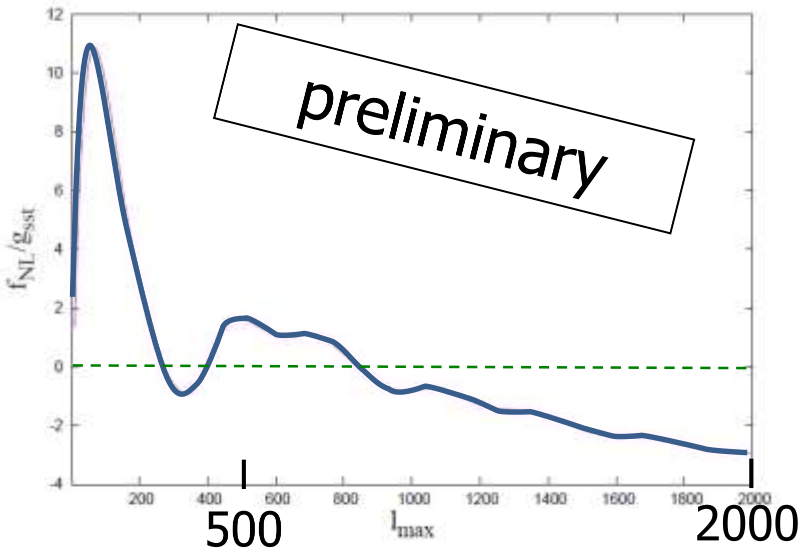
$$f_{NL}(\theta,\varphi)=\left\langle\left(\frac{\delta T}{T}\right)^3(\theta,\varphi)\right\rangle \Big/ \left\langle\left(\frac{\delta T}{T}\right)^2\right\rangle$$

detection of a spherically symmetric "localized" non-Gaussianity will be the first observational signature of string theory!

Scale-dependent non-Gaussianity?



- Slightly above 1-σ deviation from zero
- What if this is primordial?

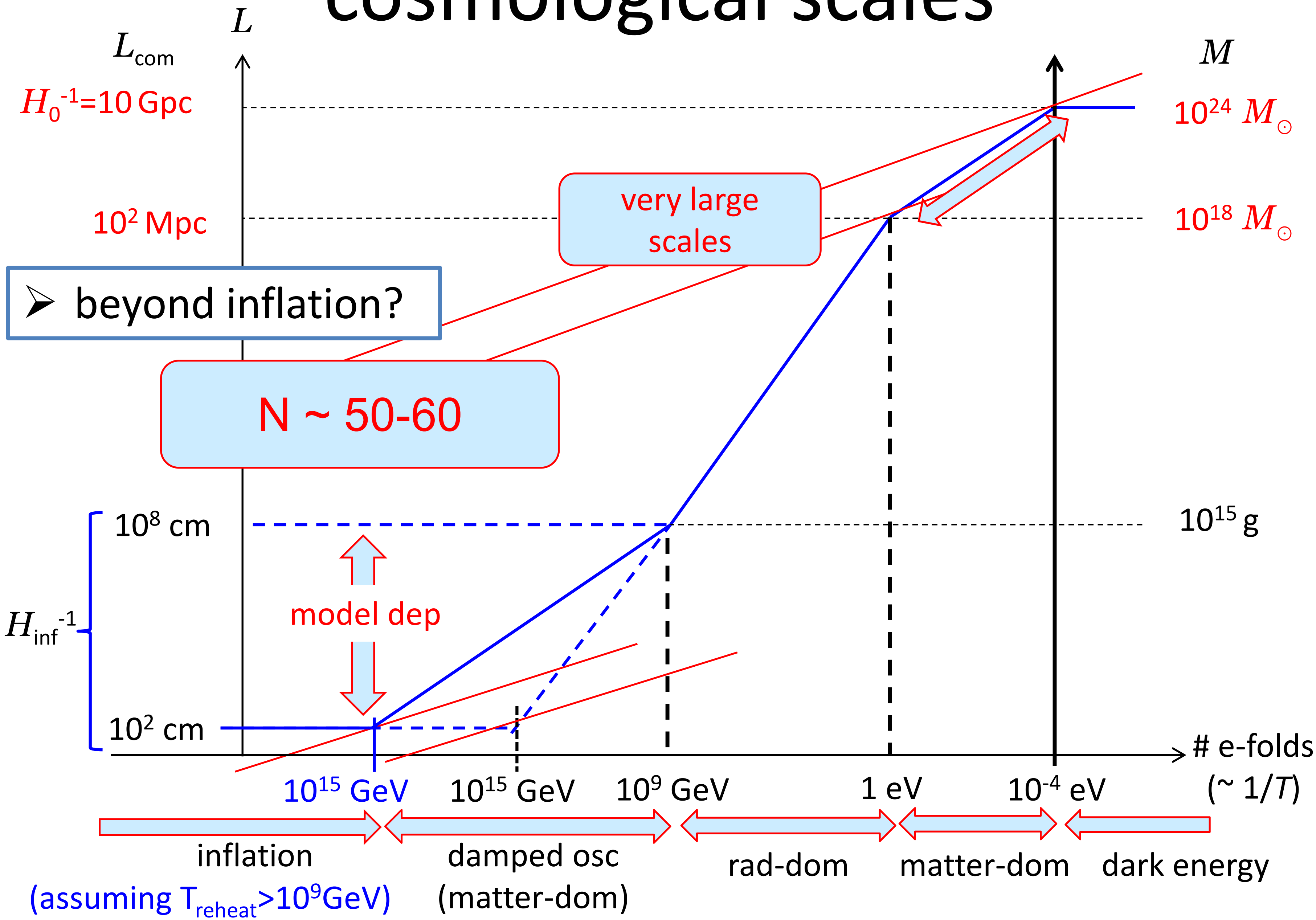


may be due to TSS coupling in a massive tensor theory

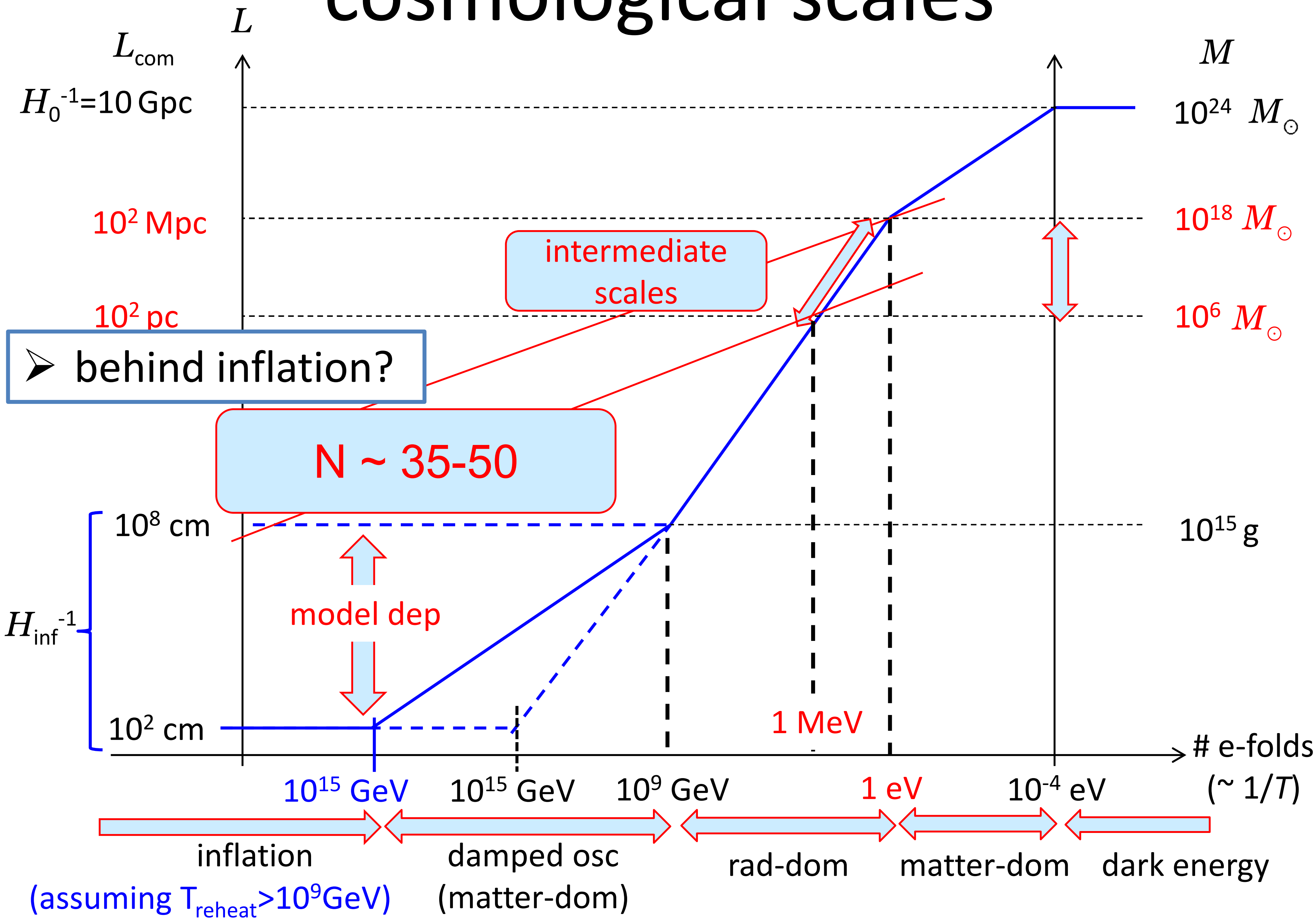
Domenech, Hiramatsu, Lin, MS, Shiraishi, Wang '16

Future issues

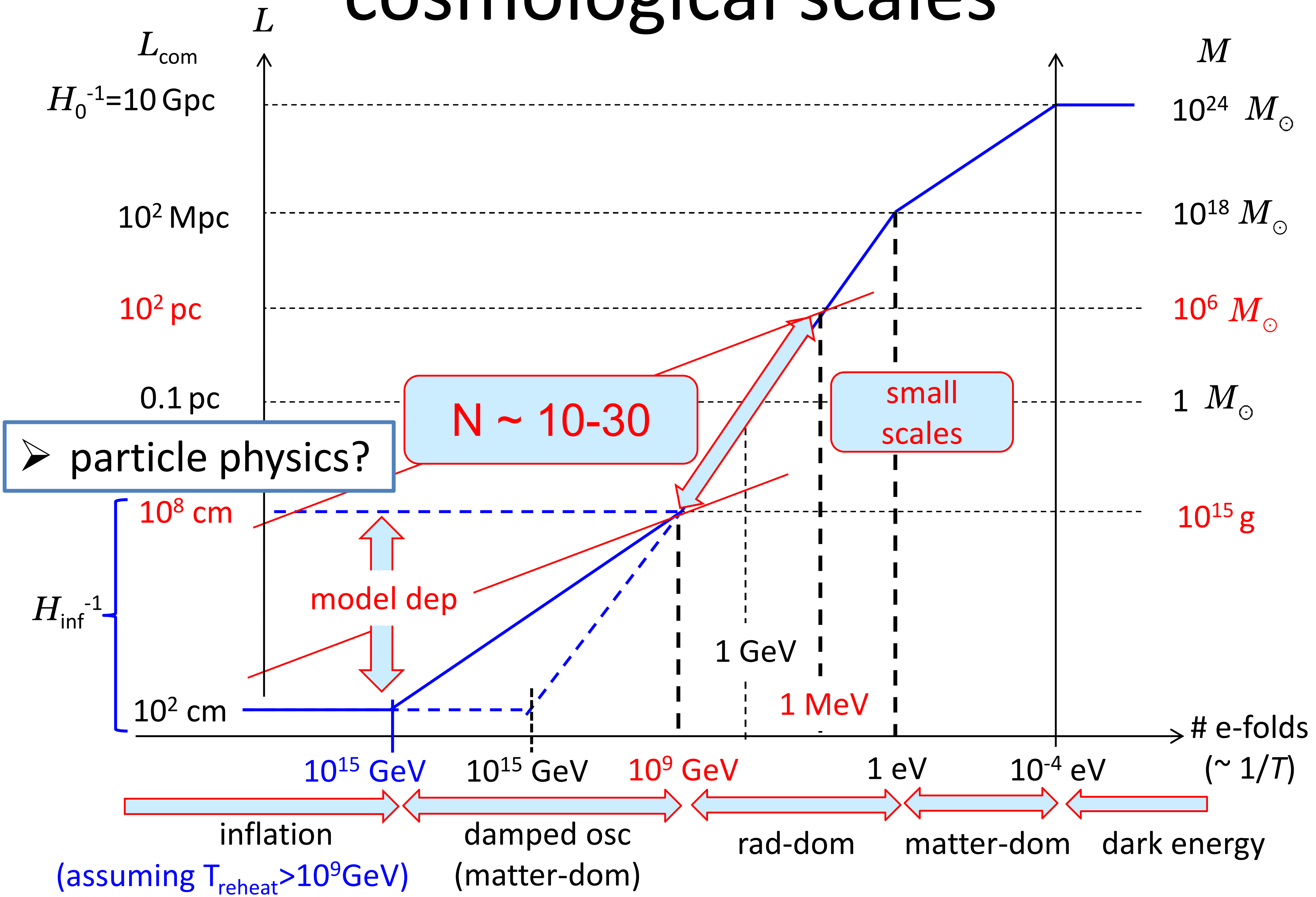
cosmological scales



cosmological scales



cosmological scales



- definition of inflation?
  (conformal trans can realize any expansion law)
  Domenech & MS '15

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

$$d\tilde{s}^2 = \Omega^2(t)ds^2 \Rightarrow d\tilde{t} = \Omega(t)dt, \ \tilde{a}(\tilde{t}) = \Omega(t)a(t)$$

- initial condition before inflation, multiverse?
- successful reheating?
- non-linear effects, non-Gaussianities?
- gravitational waves at second order, PBHs?
- massive gravity?
- ……

Identification of Inflaton!

Inflation as the tool to explore
Physics of the Early Universe

Era of

Observational/Experimental
Inflationary Cosmology!