Inflation and Beyond

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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 $t \sim 10^{-36}$ 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.

In summary, the picture that emerges is in complete accord with the kinematic generalities of causal cosmology presented in Section 2. For $y < y_0$, one has $p < 0$ ($p \simeq -\sigma$). For $y > y_0$, p becomes positive and λ undergoes an inflection. The situation is summarized in Figs. 1 and 2.

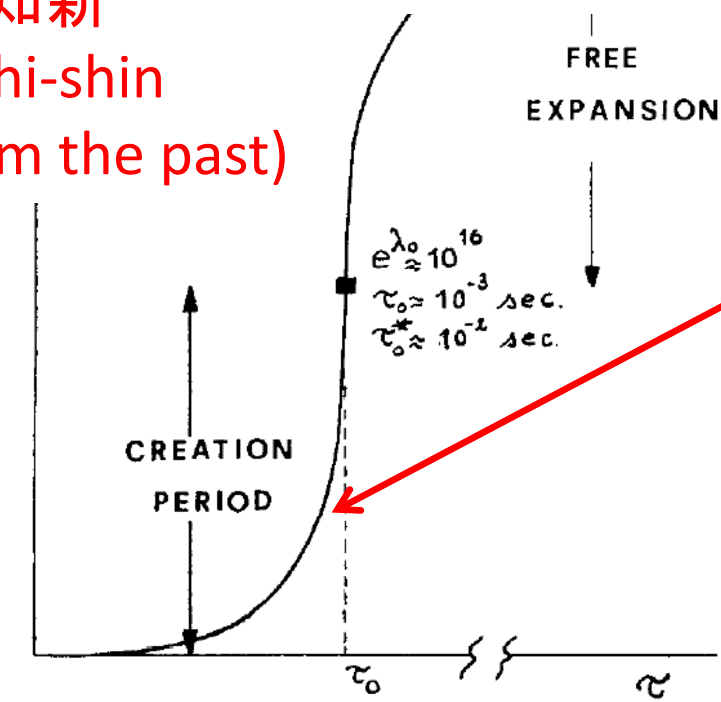
The Creation of the Universe as a Quantum Phenomenon

R. Brout, F. Englert, and E. Gunzig

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

Received July 7, 1977

温故知新
on-ko-chi-shin
(learning from the past)



$$ds^2 = -dt^2 + a^2(t)dH_{(3)}^2;$$

$$a(t) \simeq H^{-1}\sinh Ht$$

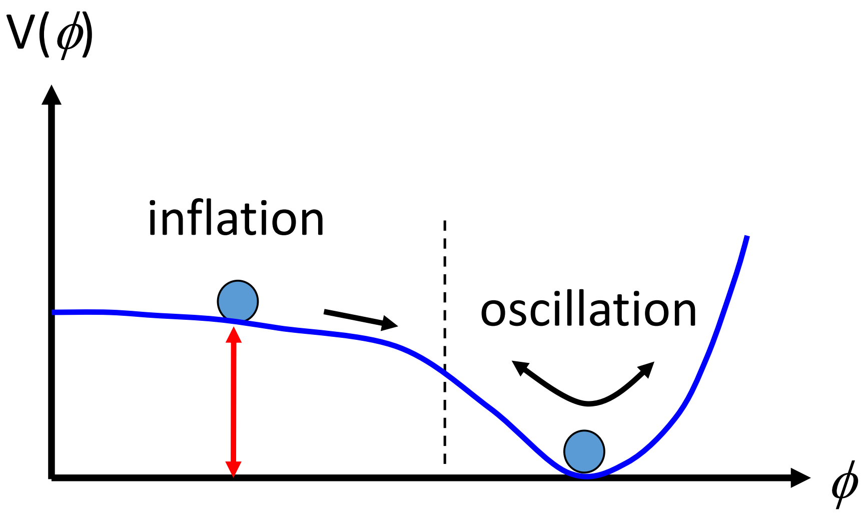
Creation of
Open Universe!

Now in the context of
String Landscape

Fig. 1. λ as a function of kinematical time τ for $\delta = 0$. Time scales are calculated for $m = 1$ GeV.

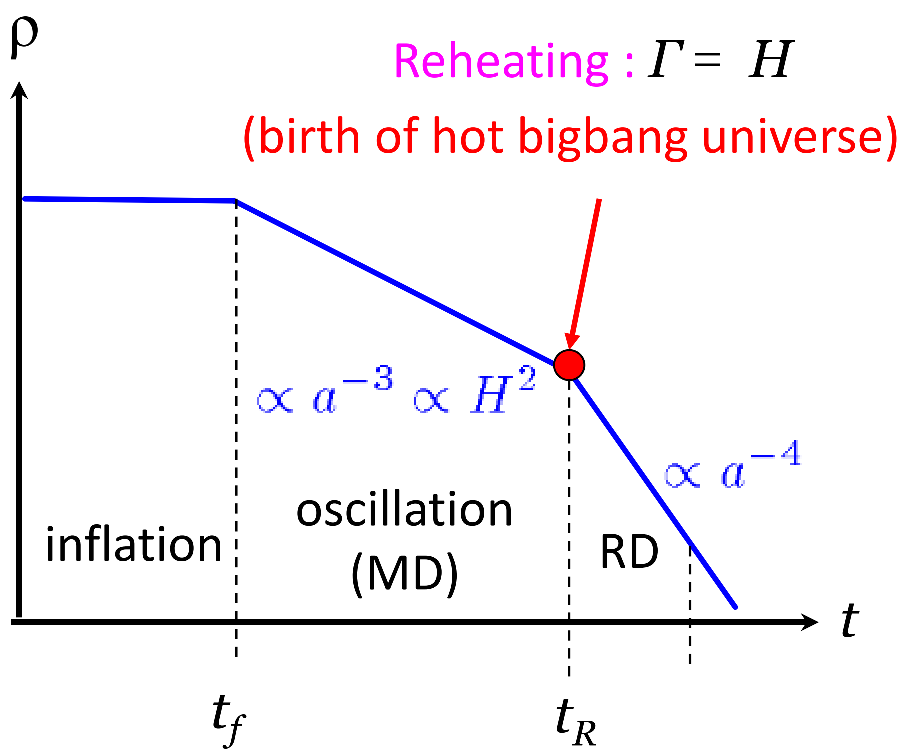
From inflation to bigbang

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



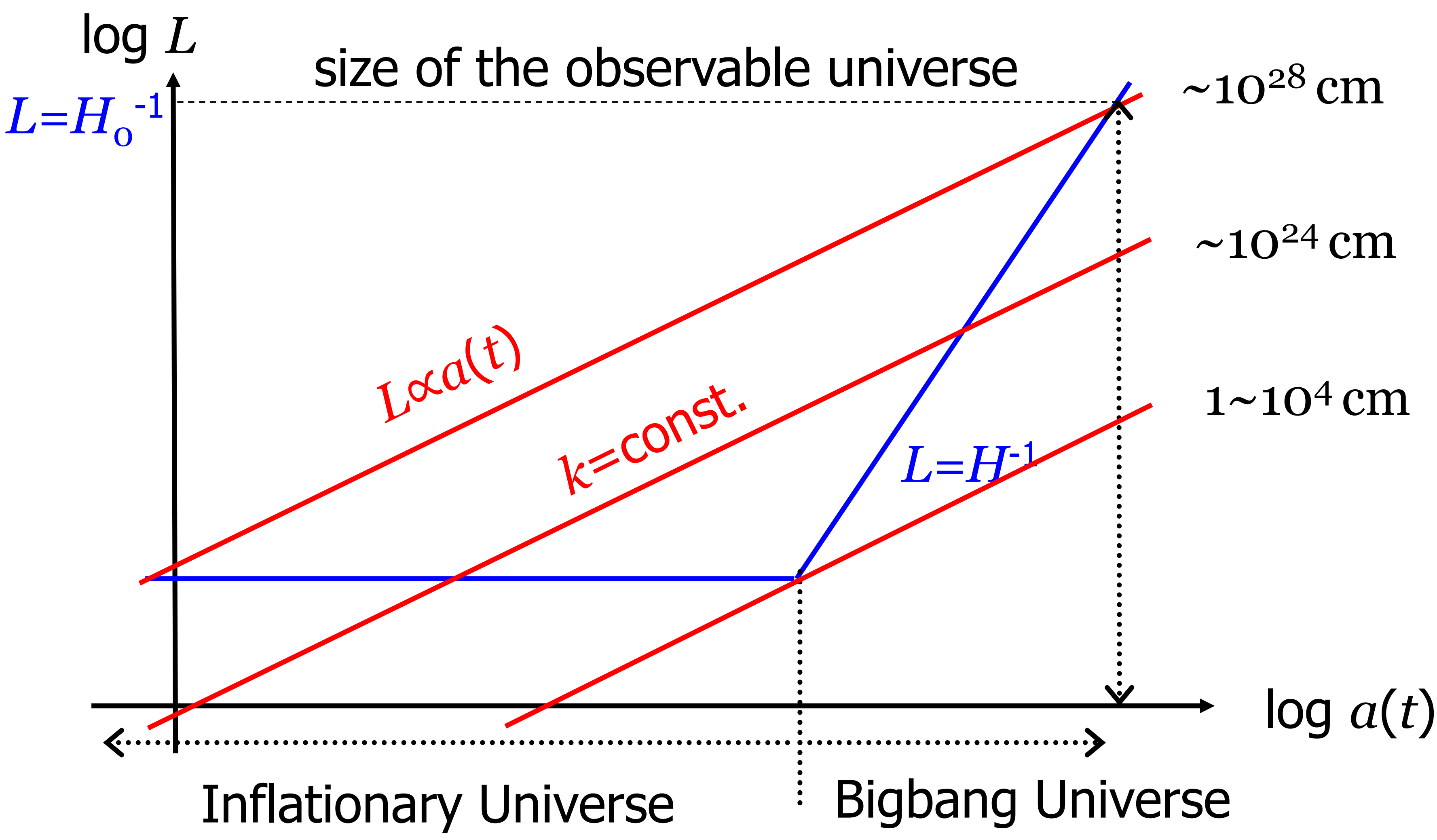
"slow-roll" inflation

Linde '83, ….

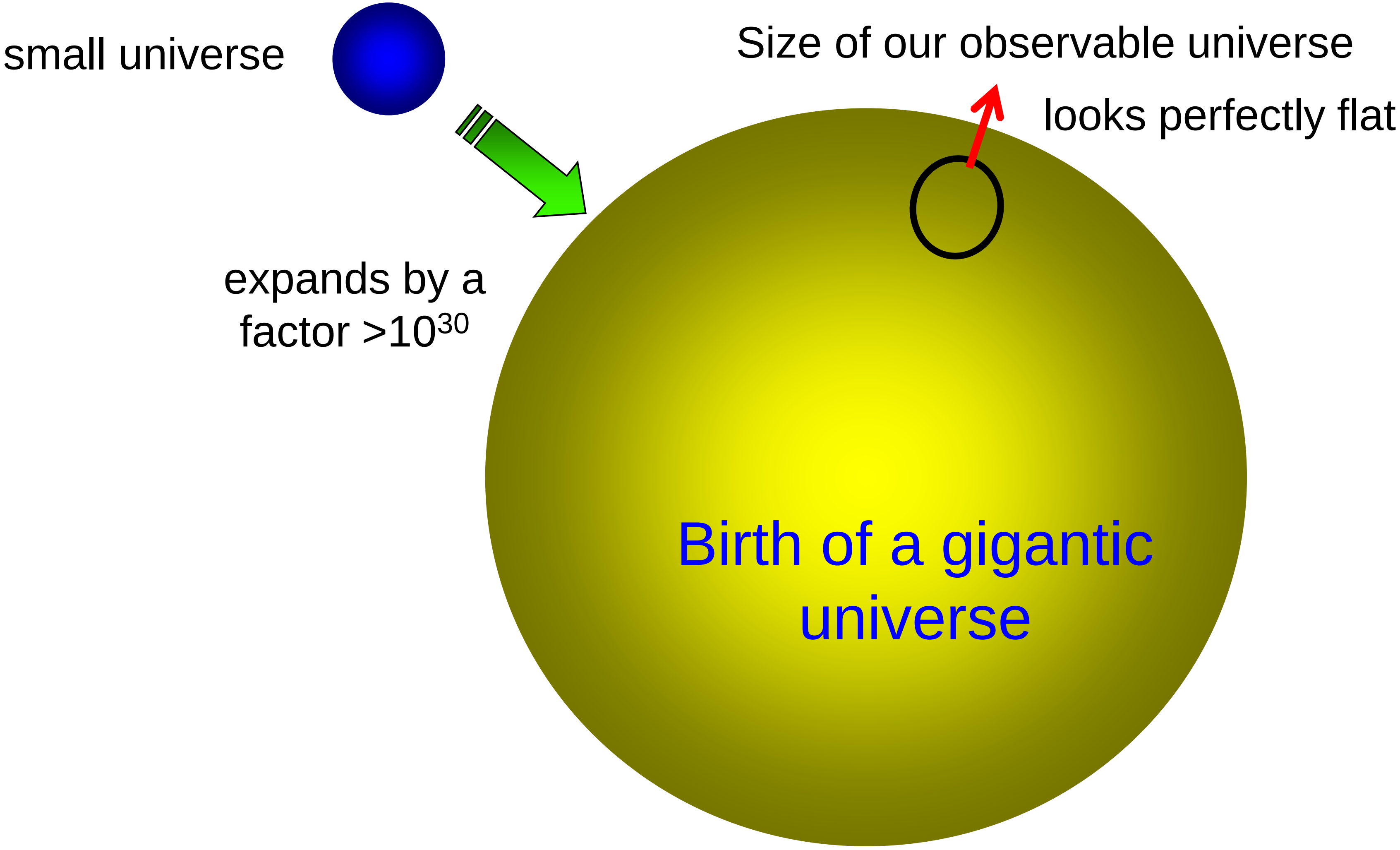


Kinematics

length scales of the inflationary universe



Flatness



Flatness can be explained only by Inflation

NB: Inflation may not always imply flatness

Dynamics

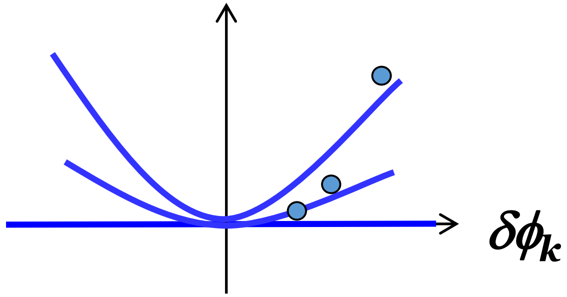
Seed of cosmological perturbations

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.

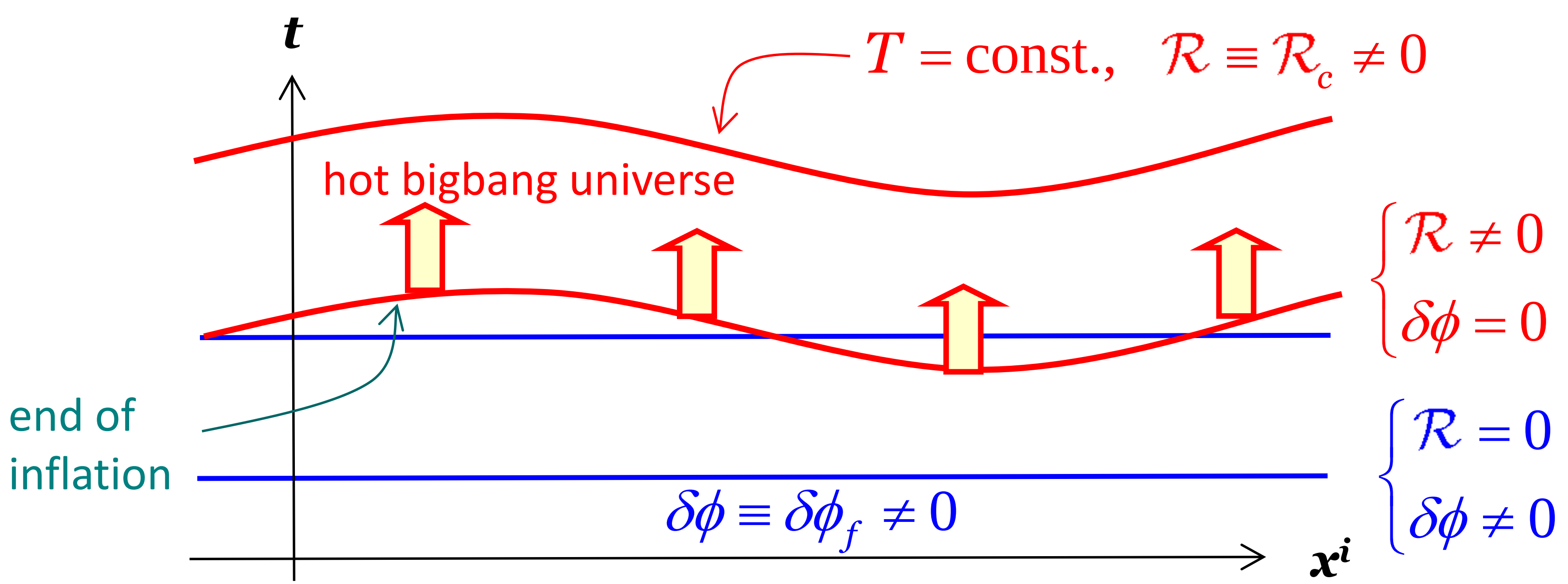
Starobinsky '79

Generation of Curvature Perturbation

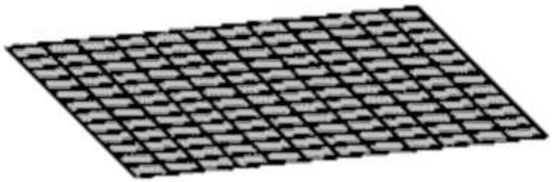
curvature (potential) perturbation $\mathcal{R}$: $$\delta R^{(3)} = -\frac{4}{a^2}\nabla^2\mathcal{R}$$

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.



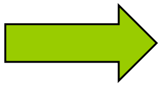
Generic predictions of inflation



- (Almost) spatially flat universe
  *open universe is possible

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

- Nearly 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:

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

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

Stewart-Lyth (1993)

- Tensor (gravitational wave) spectrum:

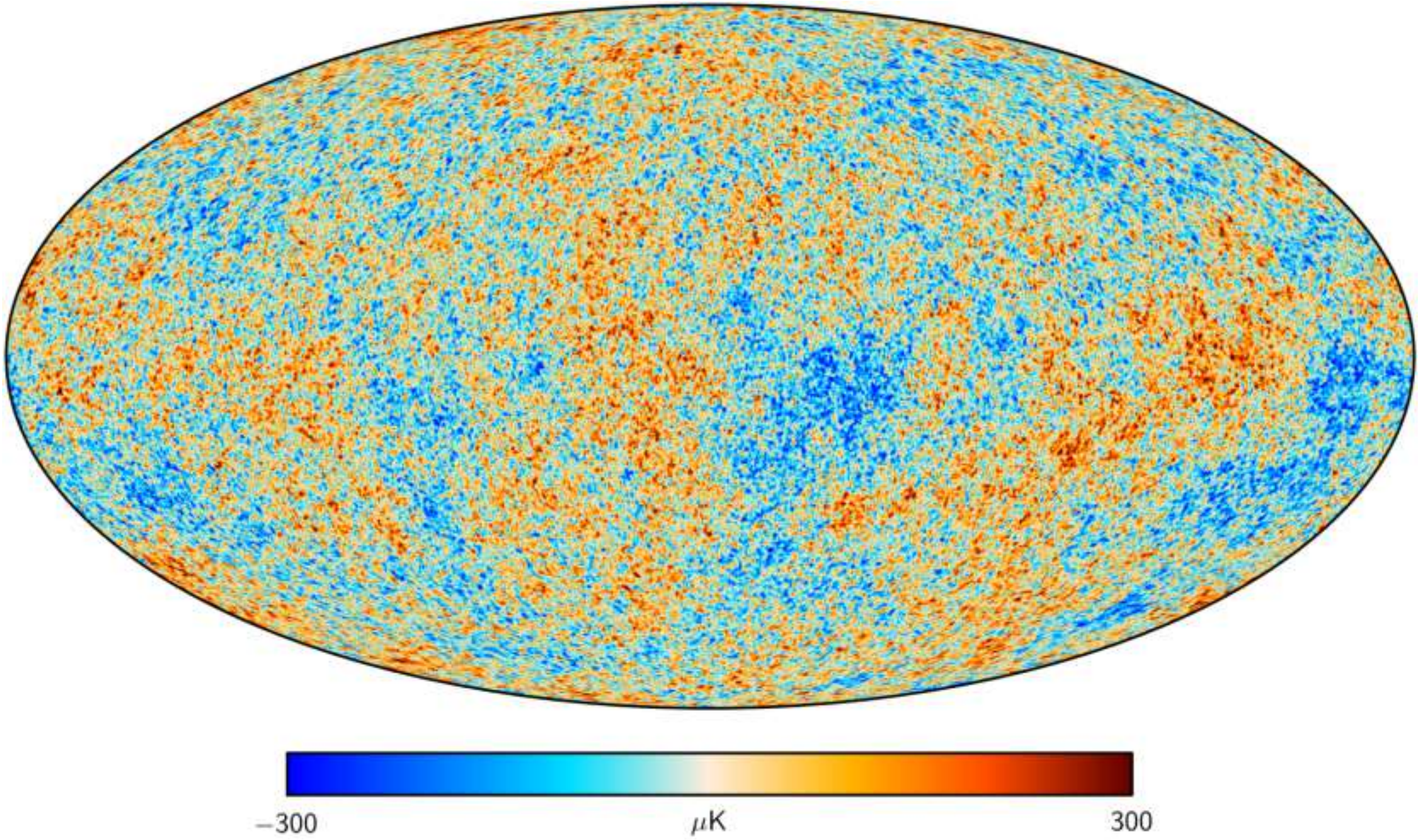
$$\frac{4\pi k^3}{(2\pi)^3} P_T(k) = Ak^{n_T} \;\; ; \;\; n_T = -\frac{1}{8}\frac{P_S(k)}{P_T(k)} \equiv -\frac{r}{8}$$

Liddle-Lyth (1992)

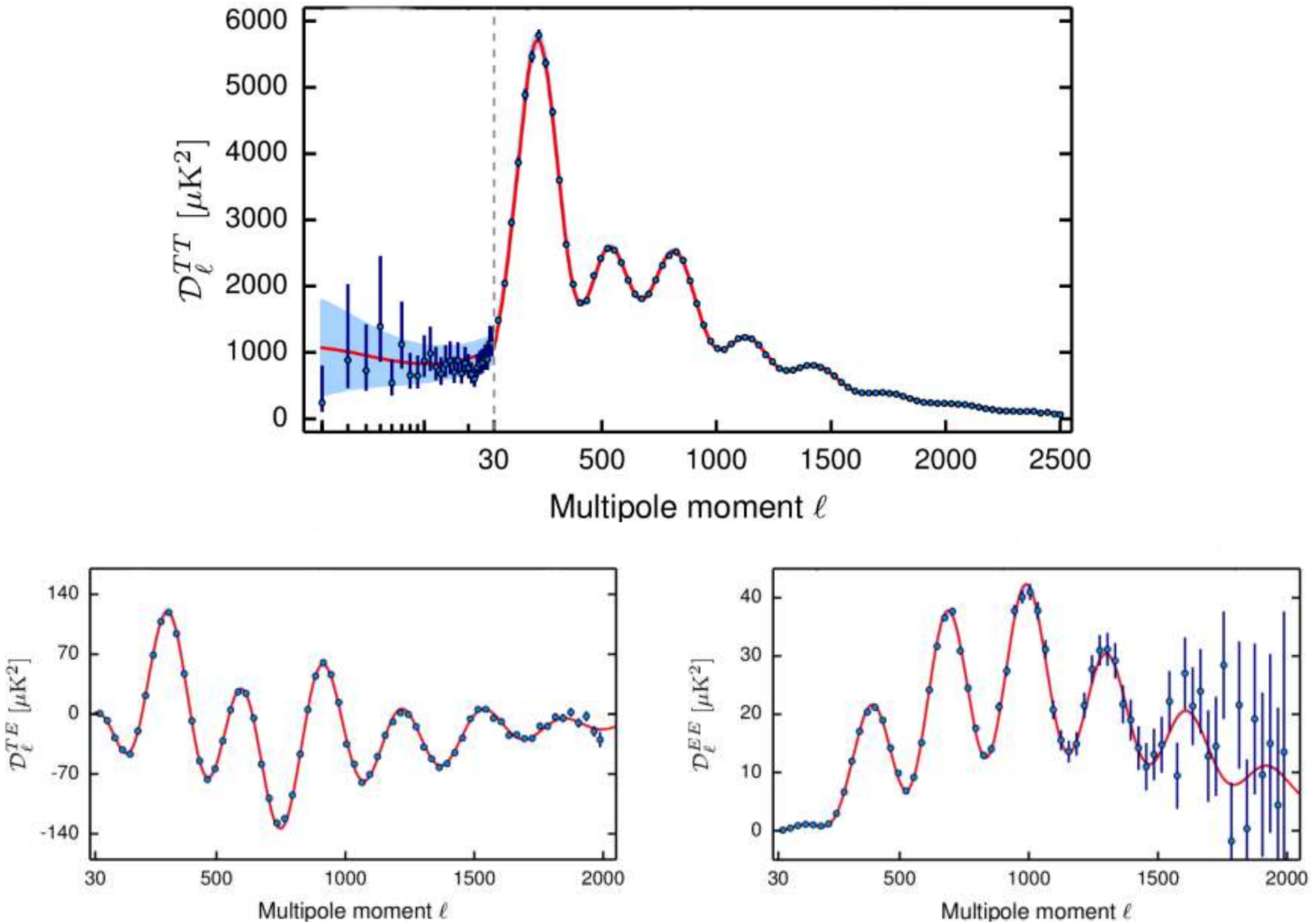
"consistency relation"

Observational results

Planck sky map



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:

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

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

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:

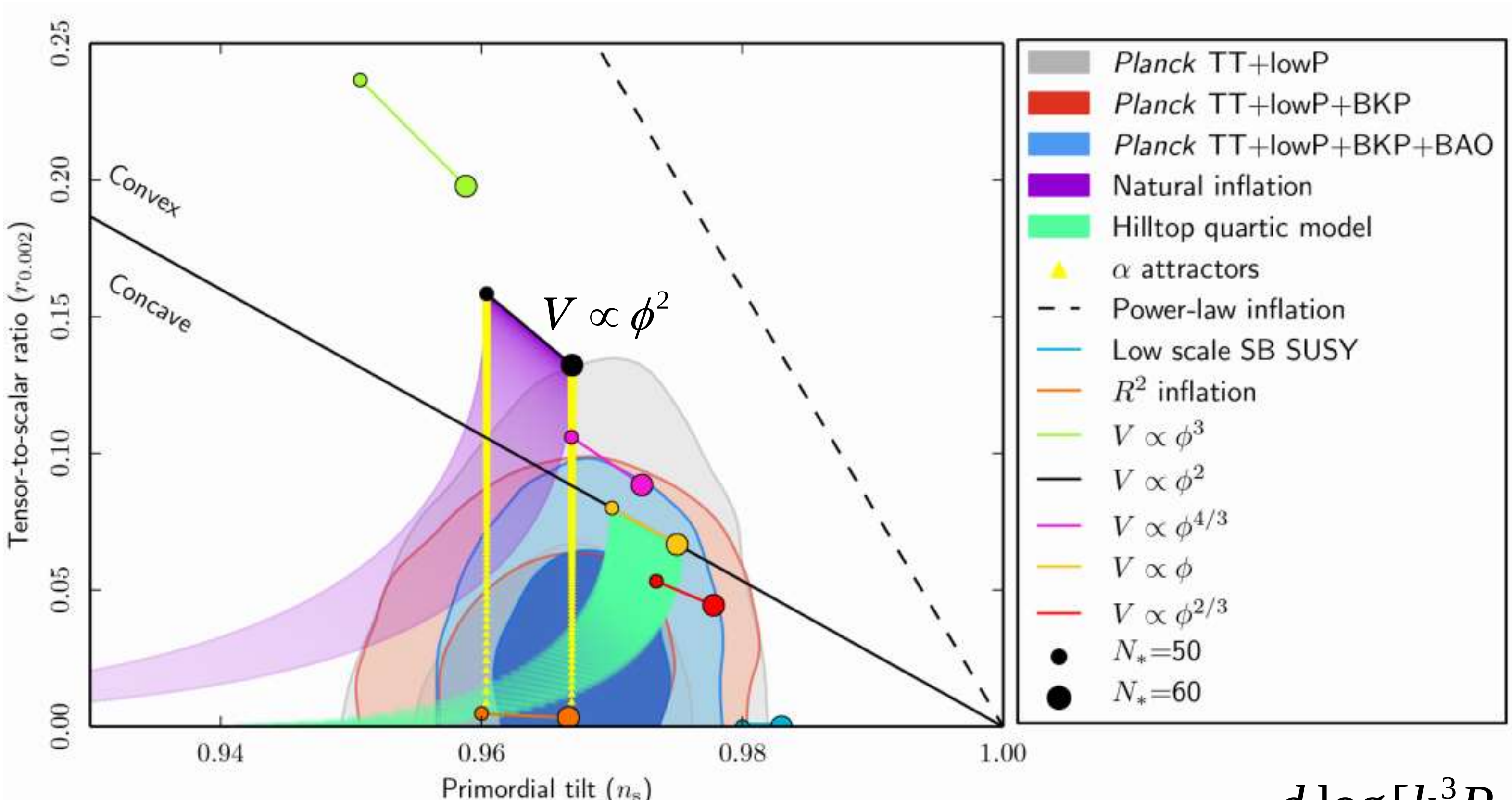
$$\frac{4\pi k^3}{(2\pi)^3}P_T(k) = Ak^{n_T} \;;\; n_T = -\frac{1}{8}\frac{P_S(k)}{P_T(k)} \equiv -\frac{r}{8}$$

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

All in all …

Inflation as the Origin of
All Structures
of the Universe

Nevertheless…

- 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)

Beyond
(standard model of)
Inflation?

non-canonical models

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

$$P_{\mathcal{R}} \propto \frac{1}{c_s} \quad (c_s\text{: sound speed}) \;,\; f_{\rm NL}^{equil} \propto \frac{1}{c_s^2}$$

Planck: $c_s > 0.024$ at 95% CL

- non-minimal coupling to gravity?

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

Planck: $\xi > \mathrm{O}(10)$?

- scalar-tensor with derivative couplings (Hordeski) ?

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

↑ tensor propagation speed

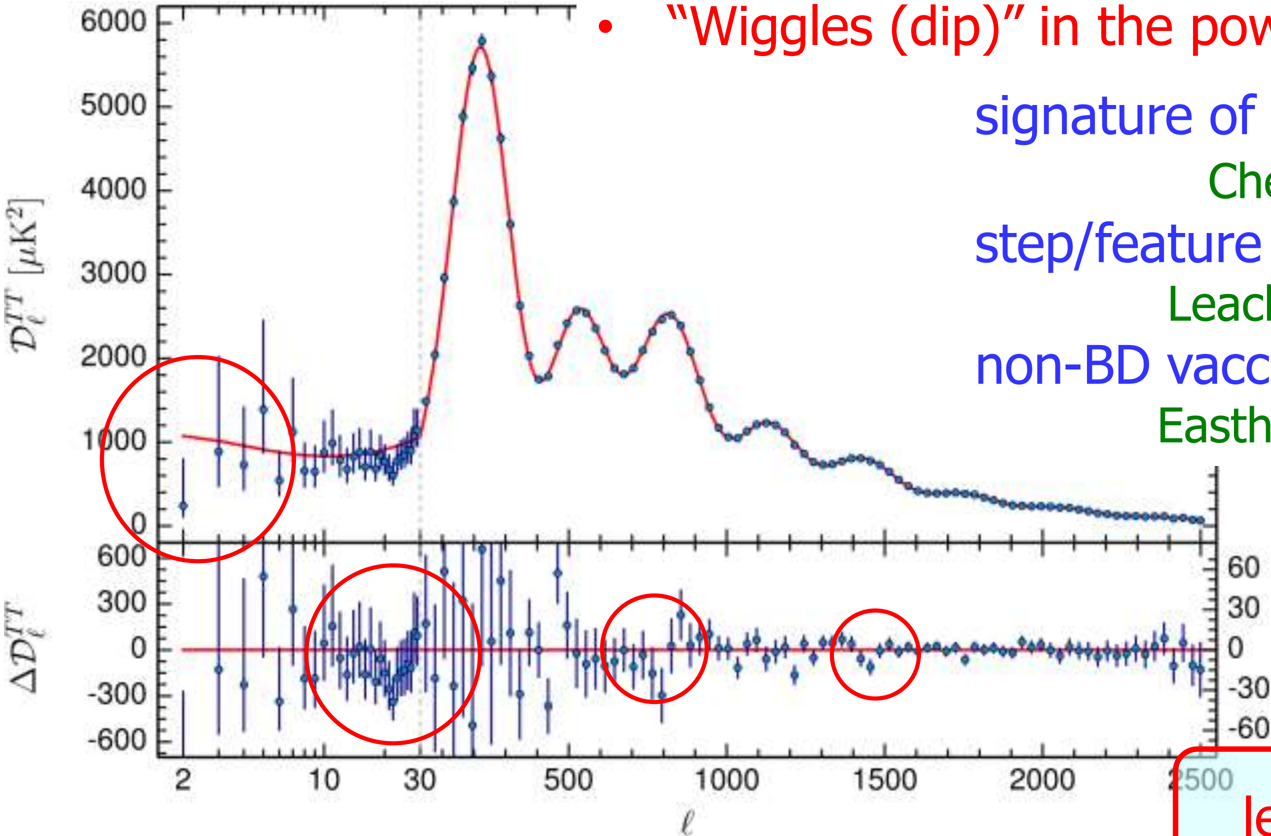
non-existence of Einstein frame?

↕

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,….

learning from the past!

- 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…

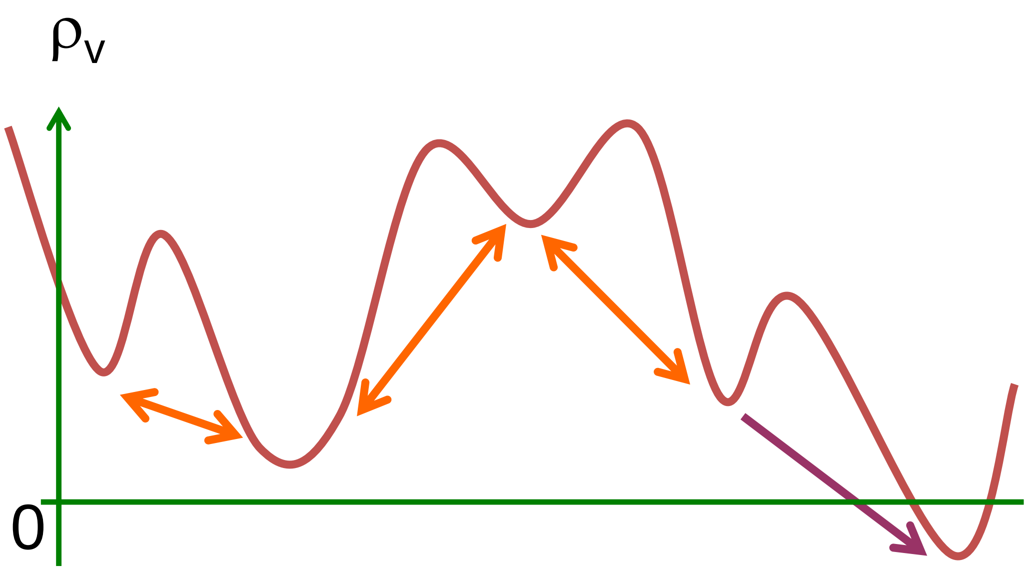
- Universe jumps around in the landscape by quantum tunneling

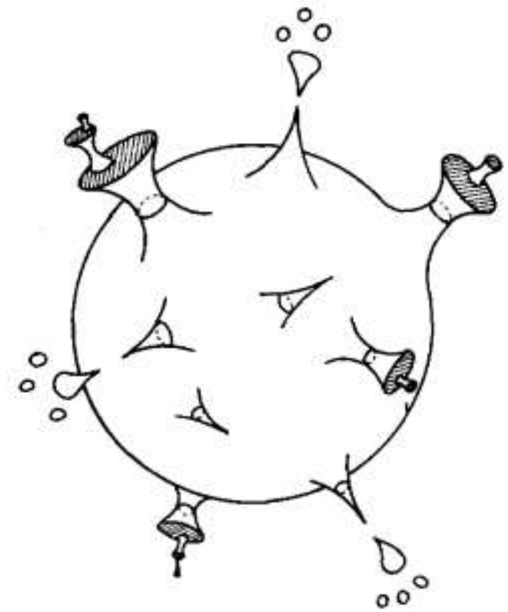
expansion rate

- it can go up to a vacuum with larger ρ_v
  de Sitter (dS) space ~ thermal state with $T = H/2\pi$

- if it tunnels to a vacuum with negative ρ_v ,
  it collapses within $t \sim M_P/|\rho_v|^{1/2}$.

- so we 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)

$$\Omega_{K,\mathrm{o}} = 1 - \Omega_{\mathrm{o}} = 10^{-2} \sim 10^{-3}$$ "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)

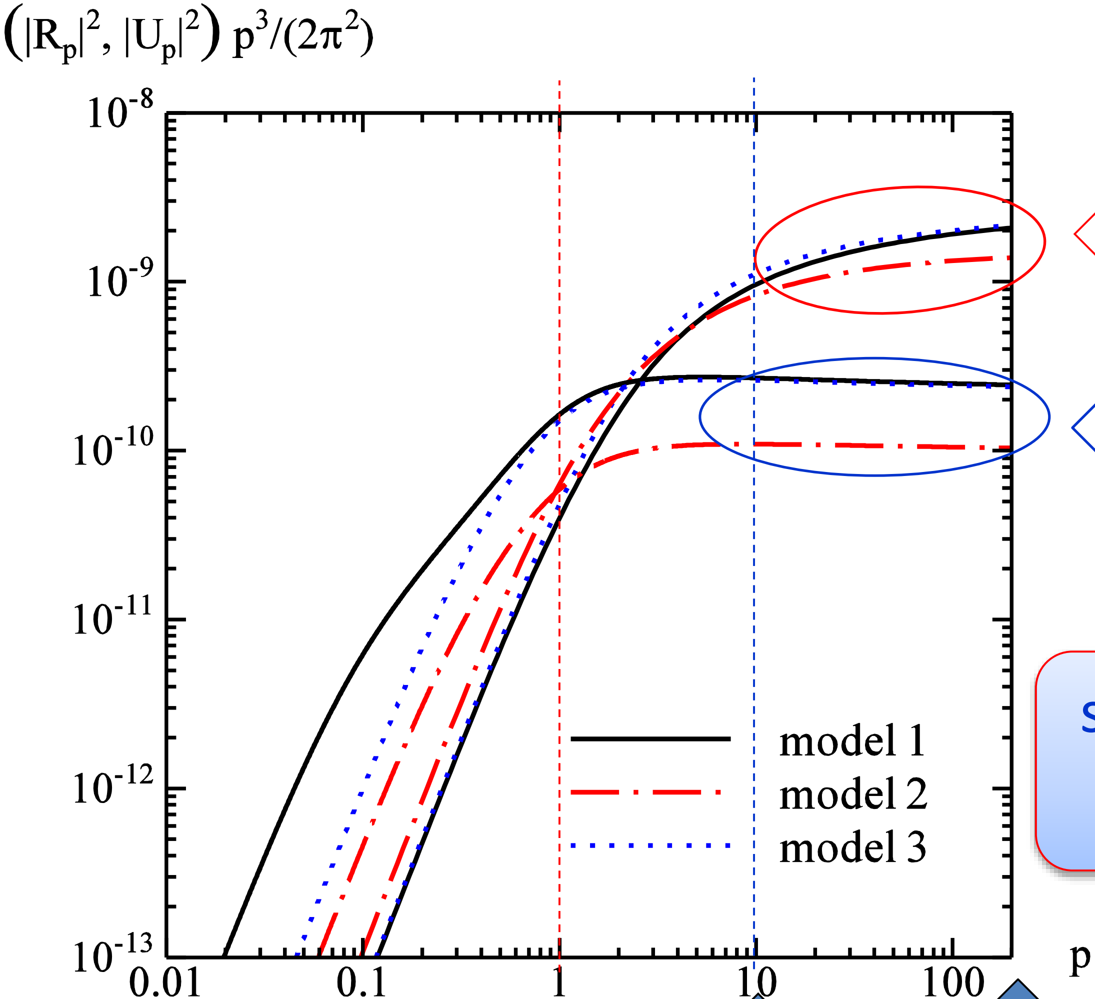
$$\Omega_{K,\mathrm{o}} = 1 - \Omega_{\mathrm{o}} \ll 1$$ "flat universe"

⇨ signatures from bubble collisions

Sugimura, Yamauchi & MS ('12), …

scalar suppression on large scales

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



scalar

r~0.1 is still within 1 σ

tensor
(no suppression)

scalar suppression begins at smaller scale

break scale

curvature radius

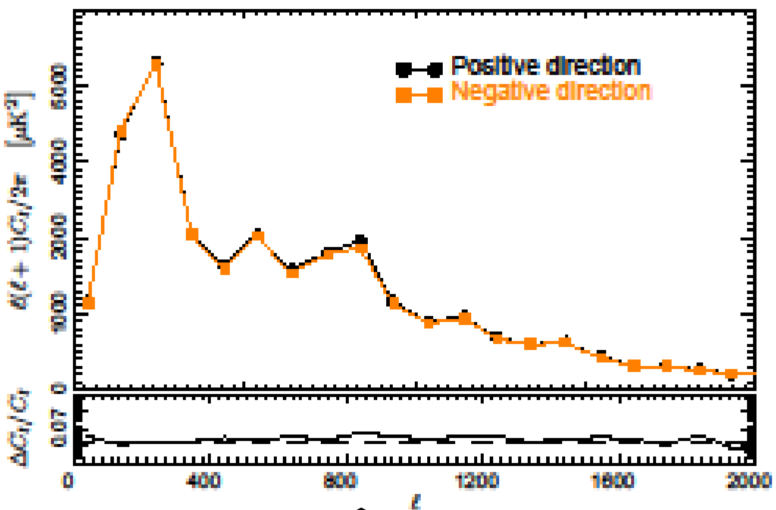
H_0^{-1} if $\Omega_K \approx 0.01$

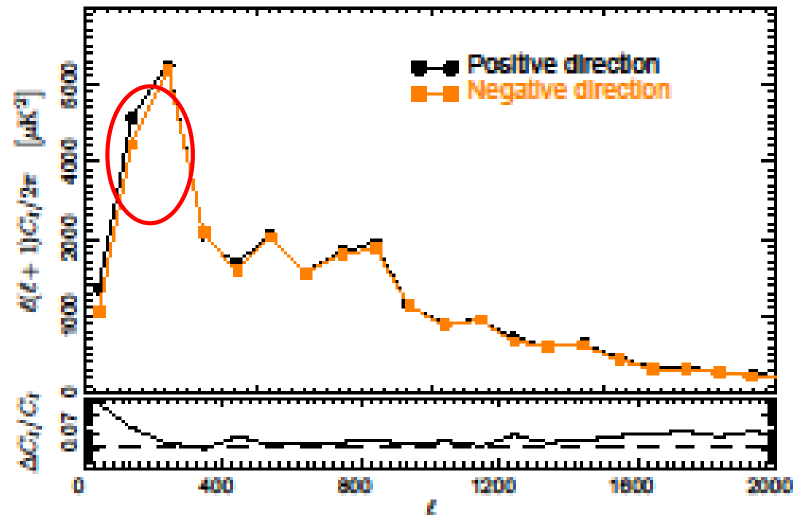
dipole power asymmetry

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

line of sight

dipole





no asymmetry in the direction of ell=1

dipole asymmetry in the direction maximizing the asymmetry

Planck 2013 XXIII

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

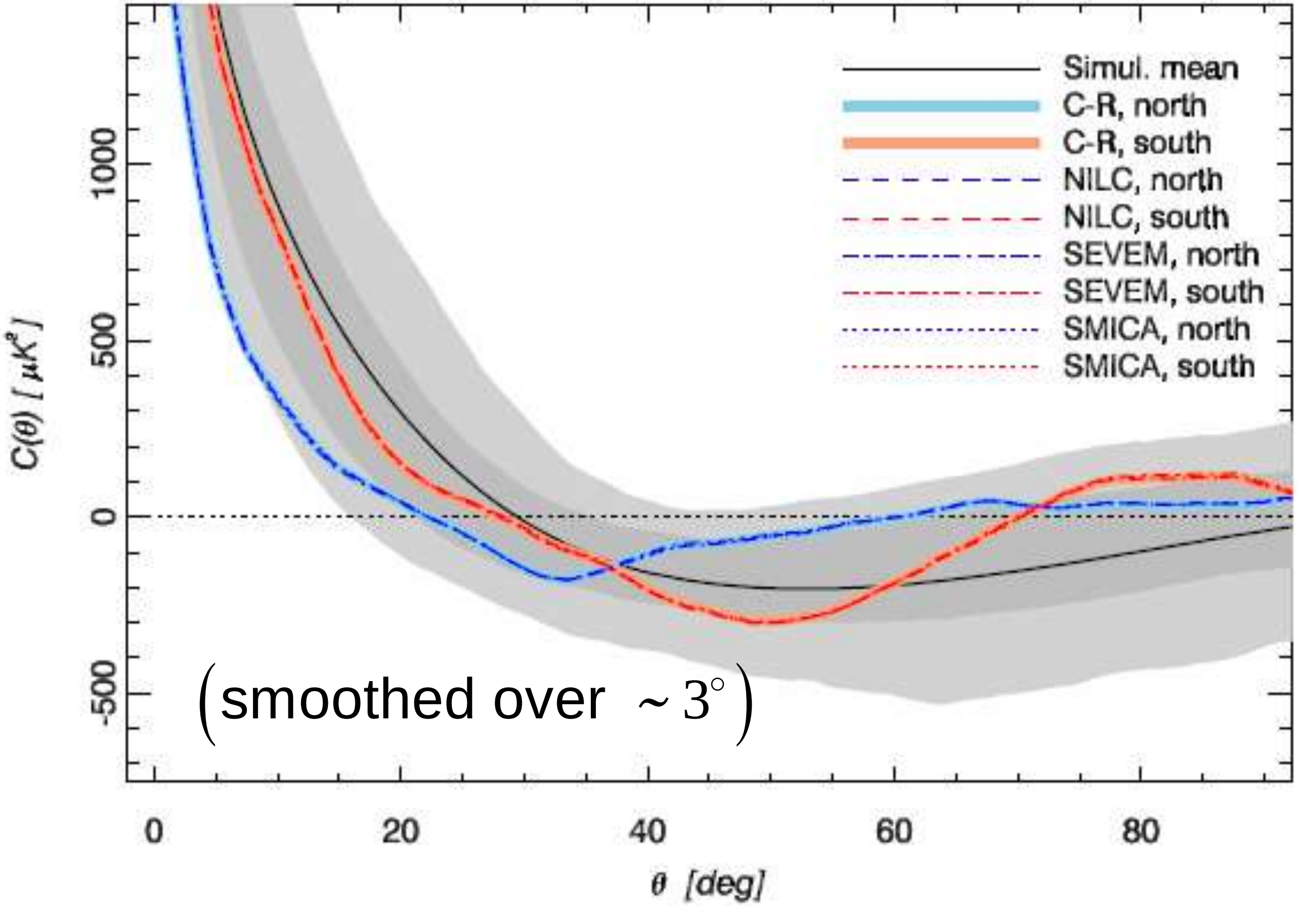
$$A \approx 0.07$$

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
WMAP5 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
WMAP3 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

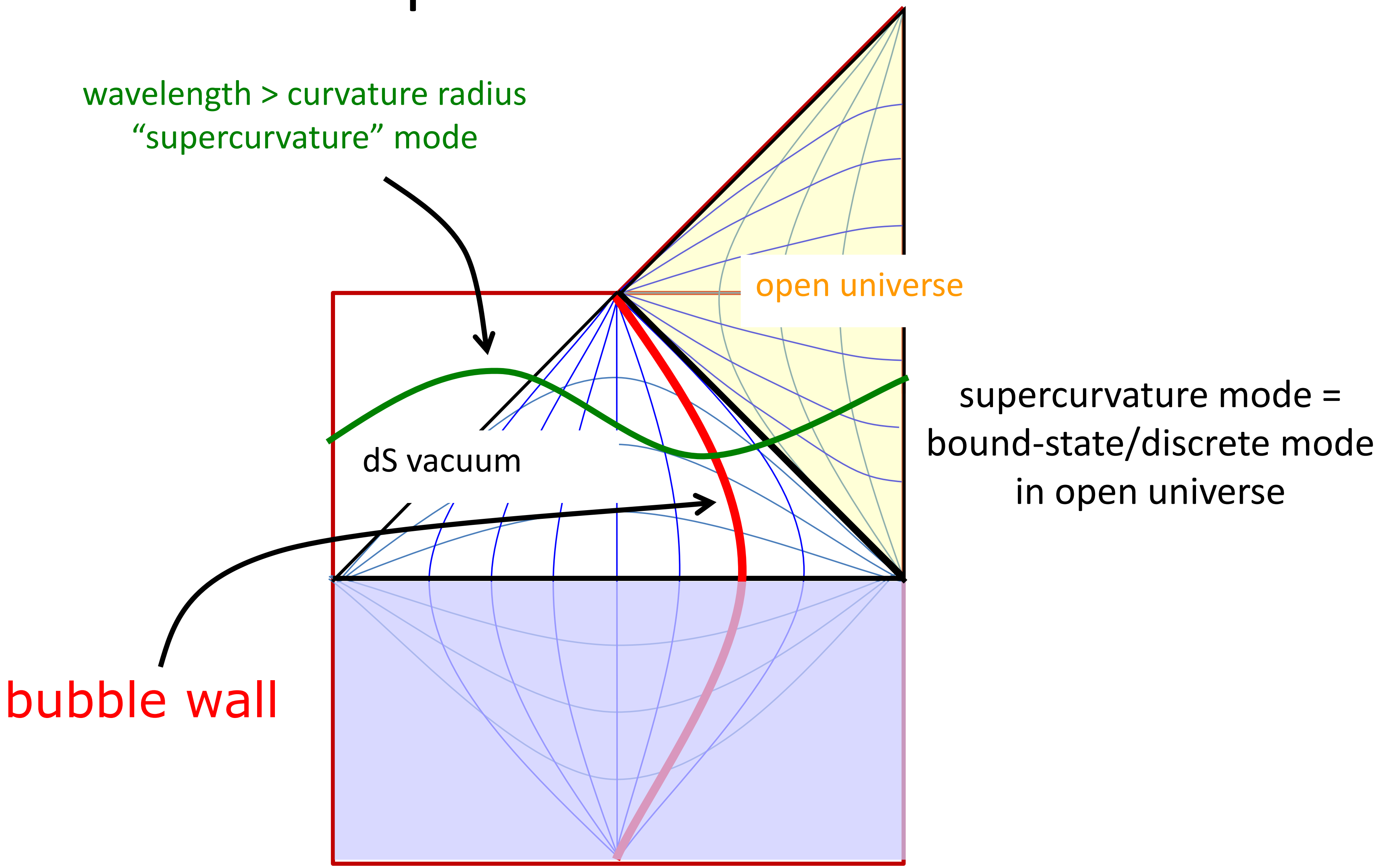
asymmetry in angular 2-pt fcn.

Planck XIII 2013

hemispherical asymmetry

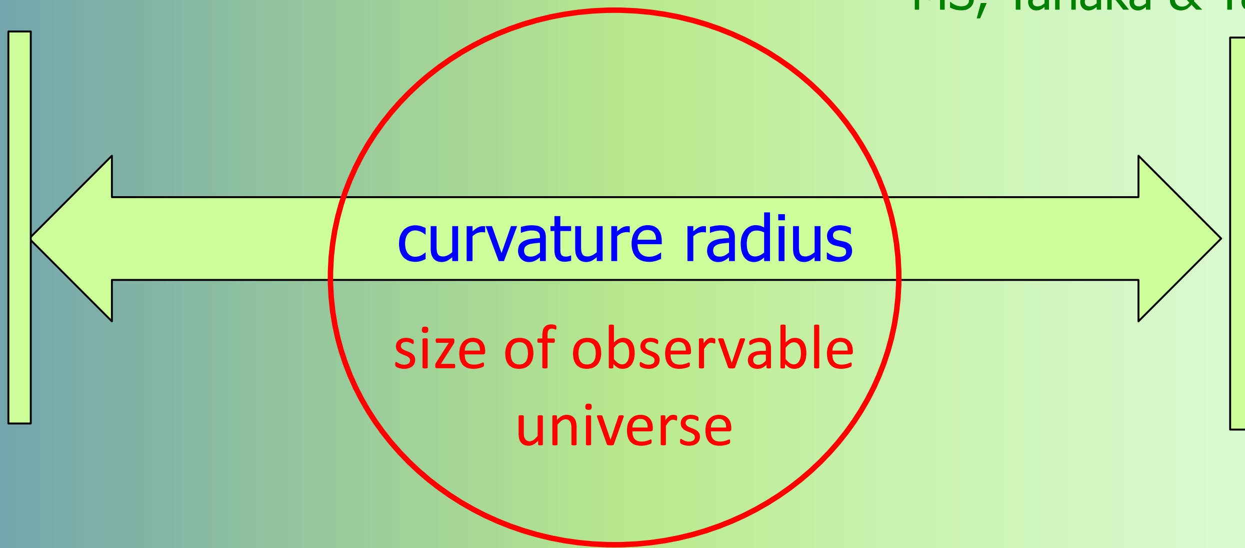


creation of open universe & supercurvature mode



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.

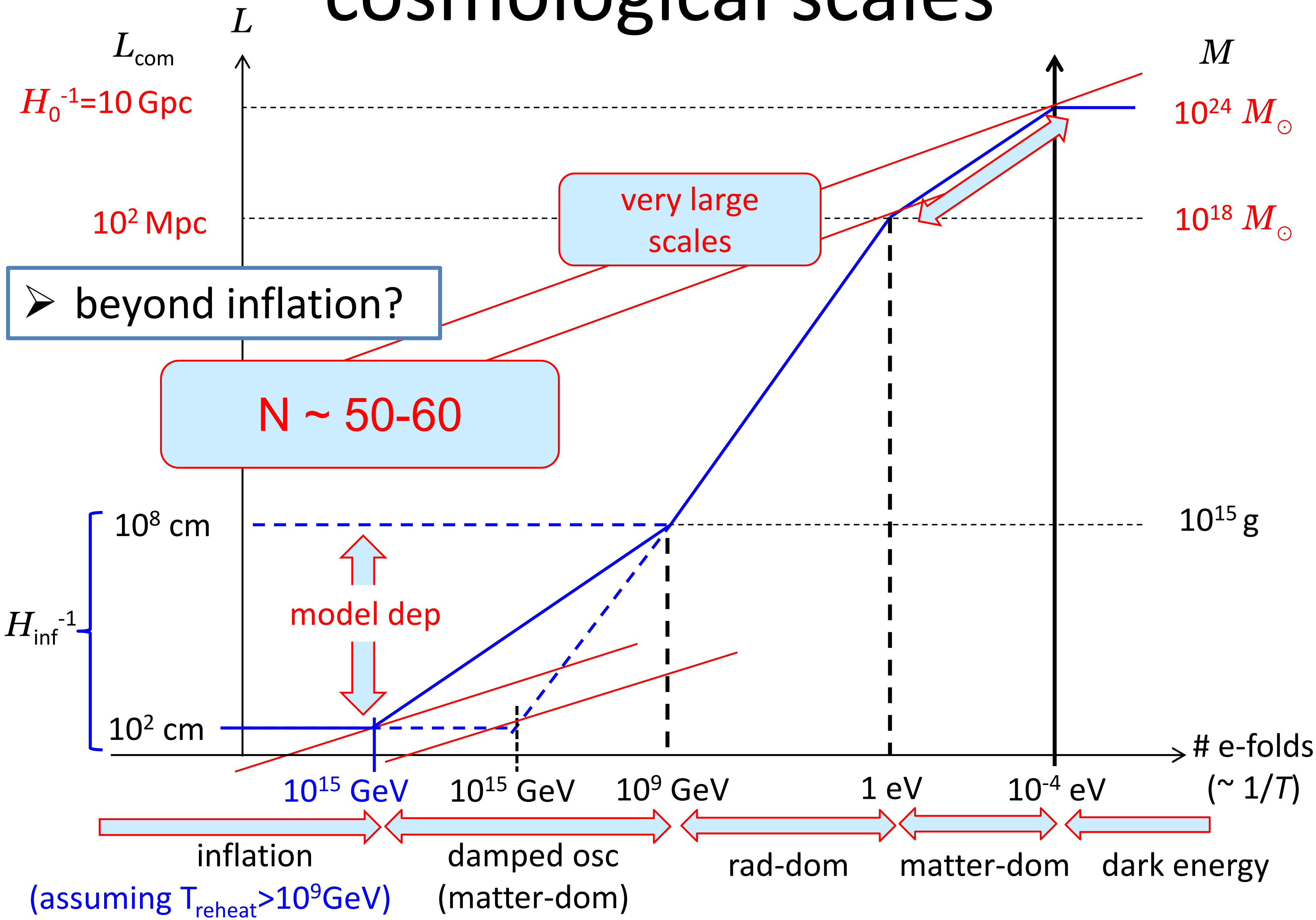
leading order effect is dipolar

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

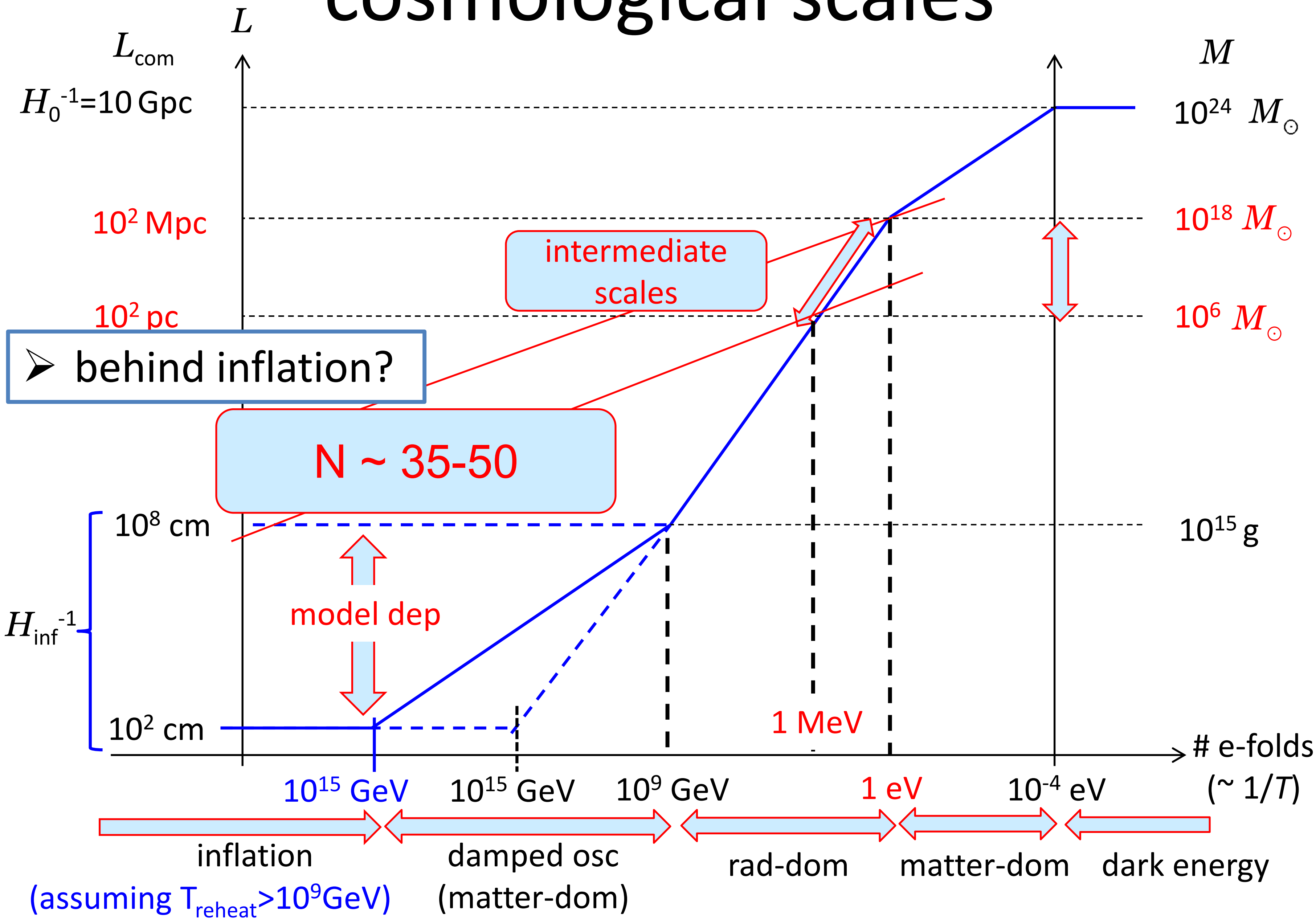
Kanno, MS & Tanaka '13
Brynes, Domenech, MS & Takahashi '16

Future issues

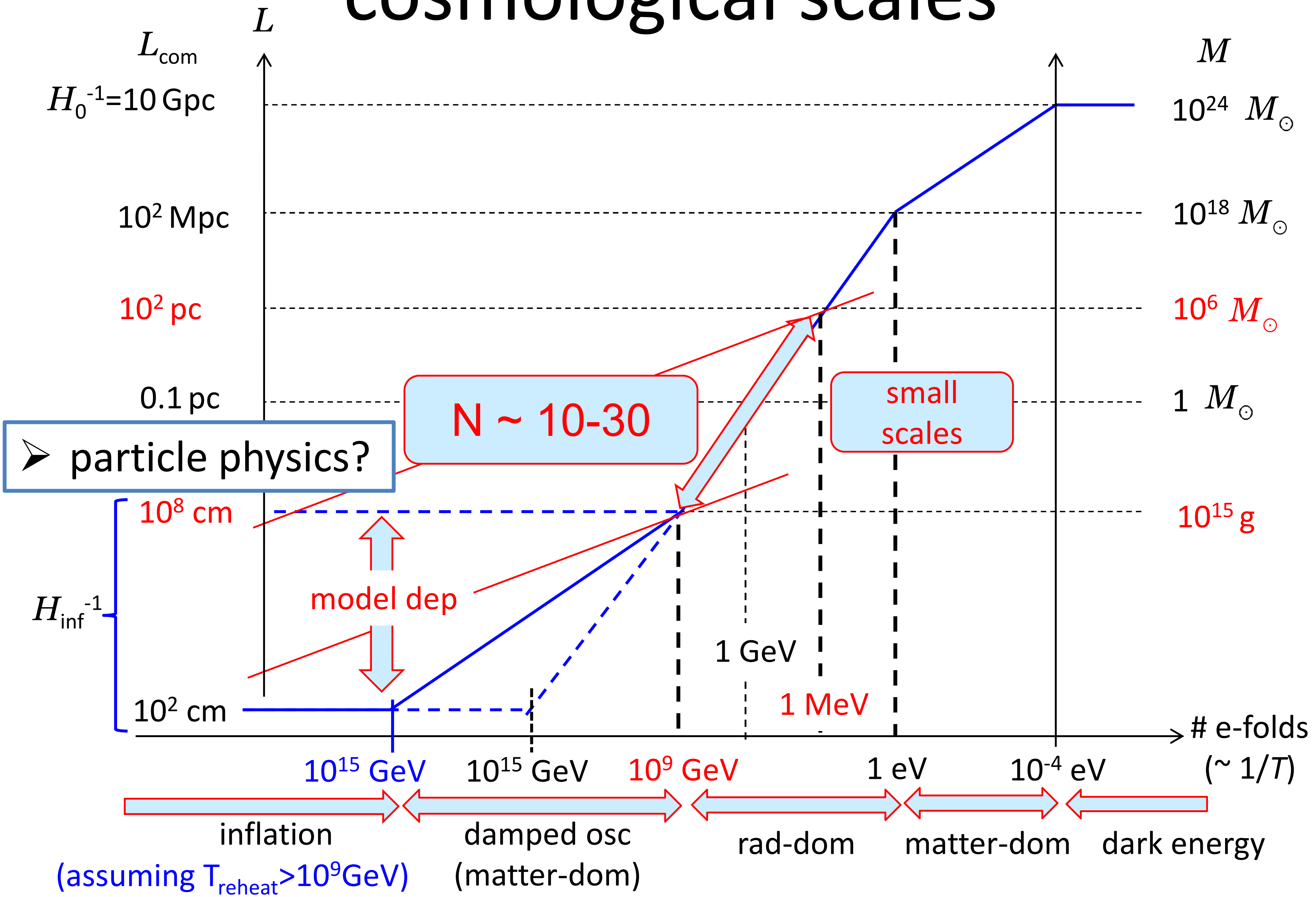
cosmological scales



cosmological scales



cosmological scales



- definition of inflation?
  (conformal trans can give 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?
- gravitational waves at second order, PBHs?
- massive gravity?
- non-linear effects, non-Gaussianities?
- ……

Identification of Inflaton!

Inflation as the tool to explore physics of the early Universe

Era of

Observational Inflationary Cosmology!