Inflationary Universe (project A01)

Toward Understanding Physics/Mechanism of Inflation

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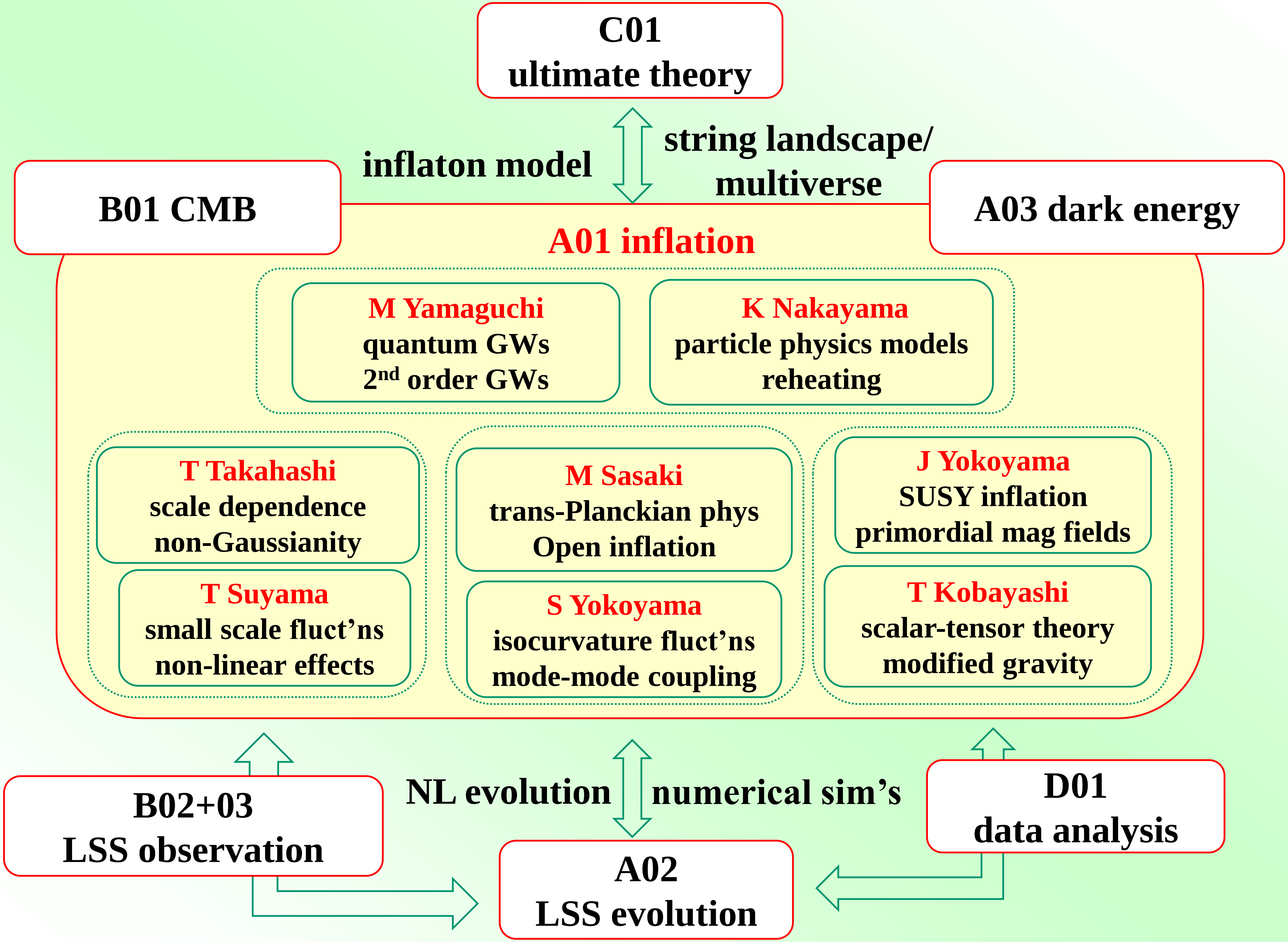
(Original version by Masahide Yamaguchi)

$$c = \hbar = 1, \quad M_G = 1/\sqrt{8\pi G} \sim 2.4 \times 10^{18}\mathrm{GeV}.$$


C01
ultimate theory
inflaton model
string landscape/
multiverse
B01 CMB
A03 dark energy
A01 inflation
M Yamaguchi
quantum GWs
2nd order GWs
K Nakayama
particle physics models
reheating
T Takahashi
scale dependence
non-Gaussianity
T Suyama
small scale fluct'ns
non-linear effects
M Sasaki
trans-Planckian phys
Open inflation
S Yokoyama
isocurvature fluct'ns
mode-mode coupling
J Yokoyama
SUSY inflation
primordial mag fields
T Kobayashi
scalar-tensor theory
modified gravity
B02+03
LSS observation
NL evolution
numerical sim's
D01
data analysis
A02
LSS evolution

Introduction

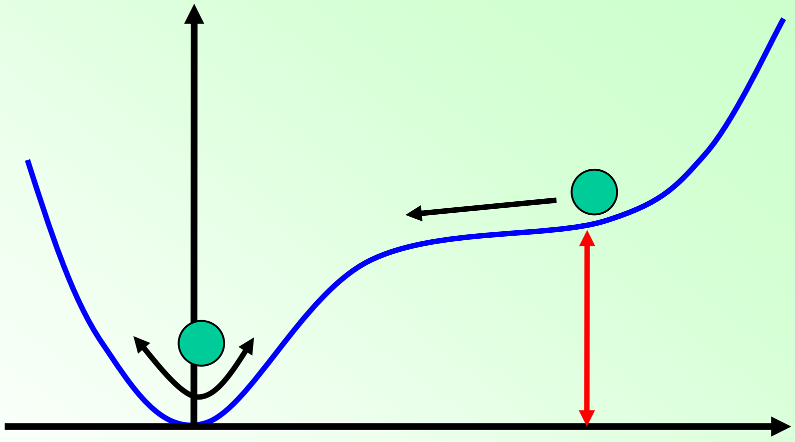
Inflation

The Universe rapidly expanded thanks to the vacuum energy density in the early stage.

(accelerated expansion: $\ddot{a} > 0$)

Brout, Englert & Gunzig '78, Starobinsky '79, Sato '80, Guth '80, …

Vacuum energy density



State of vacuum
(expectation value of scalar field)

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho \simeq const.$$

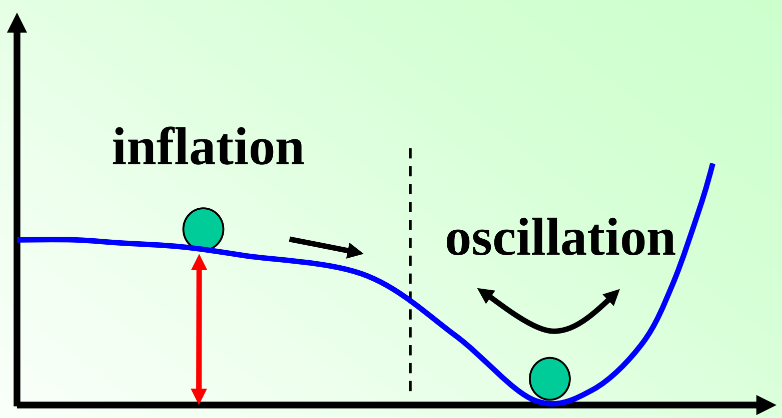
$$\Downarrow$$

$$a(t) \propto \exp[Ht]$$

From inflation to bigbang

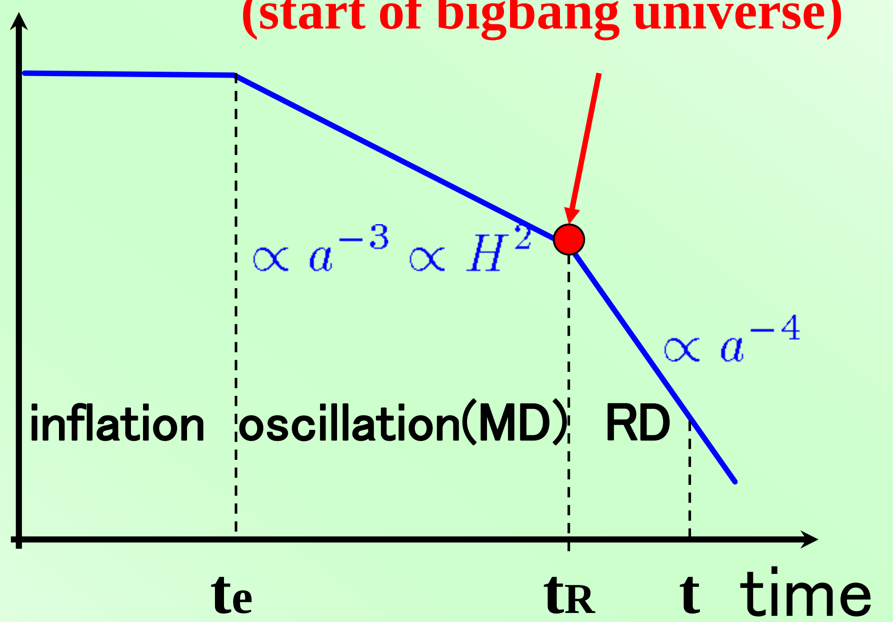
At the end of inflation, the vacuum energy is released as latent heat (called "re"heating) and hot Bigbang Universe is realized.

Vacuum energy density



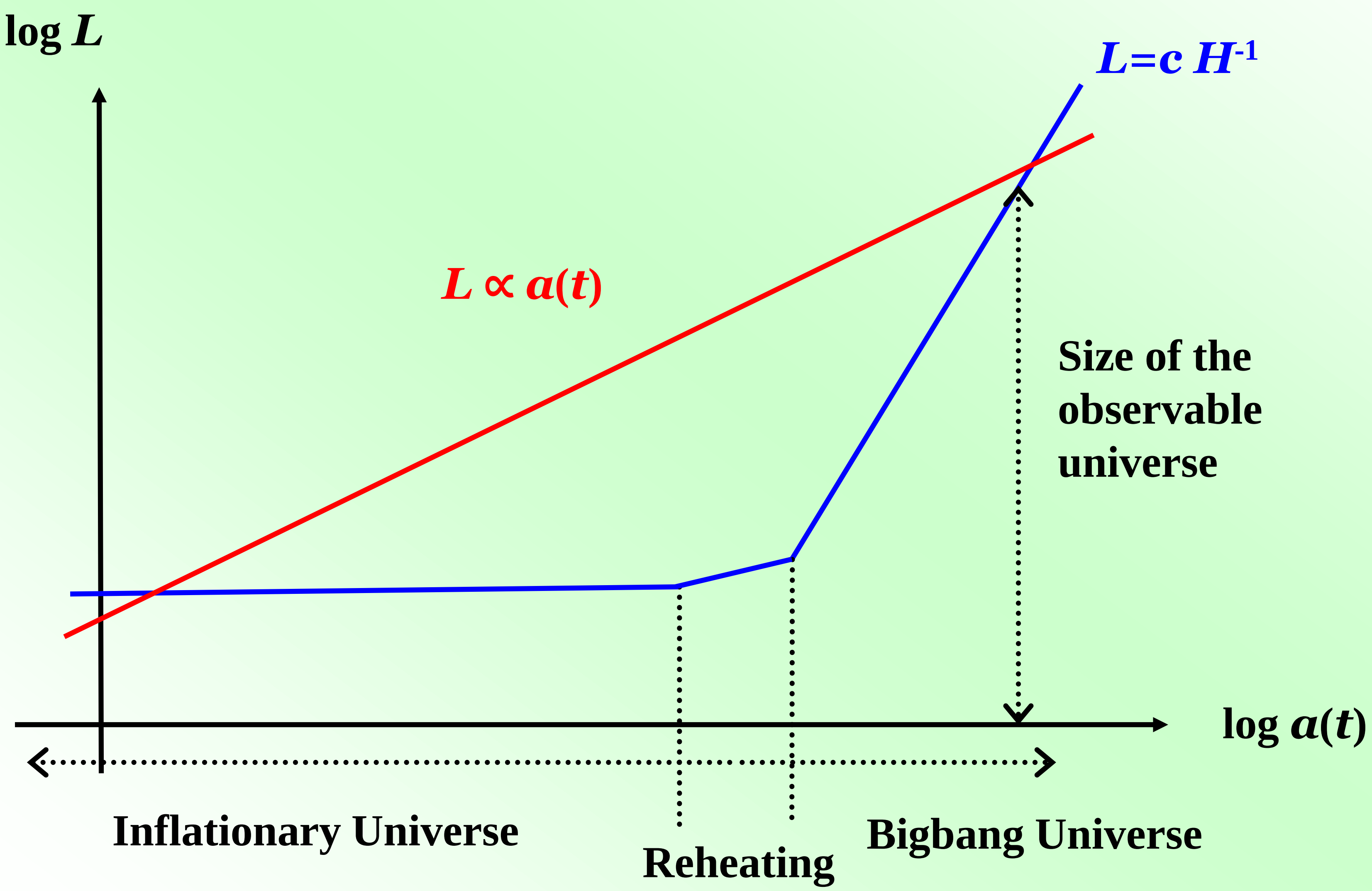
State of vacuum
(expectation value of scalar field)

Reheating : $\Gamma = H$
(start of bigbang universe)

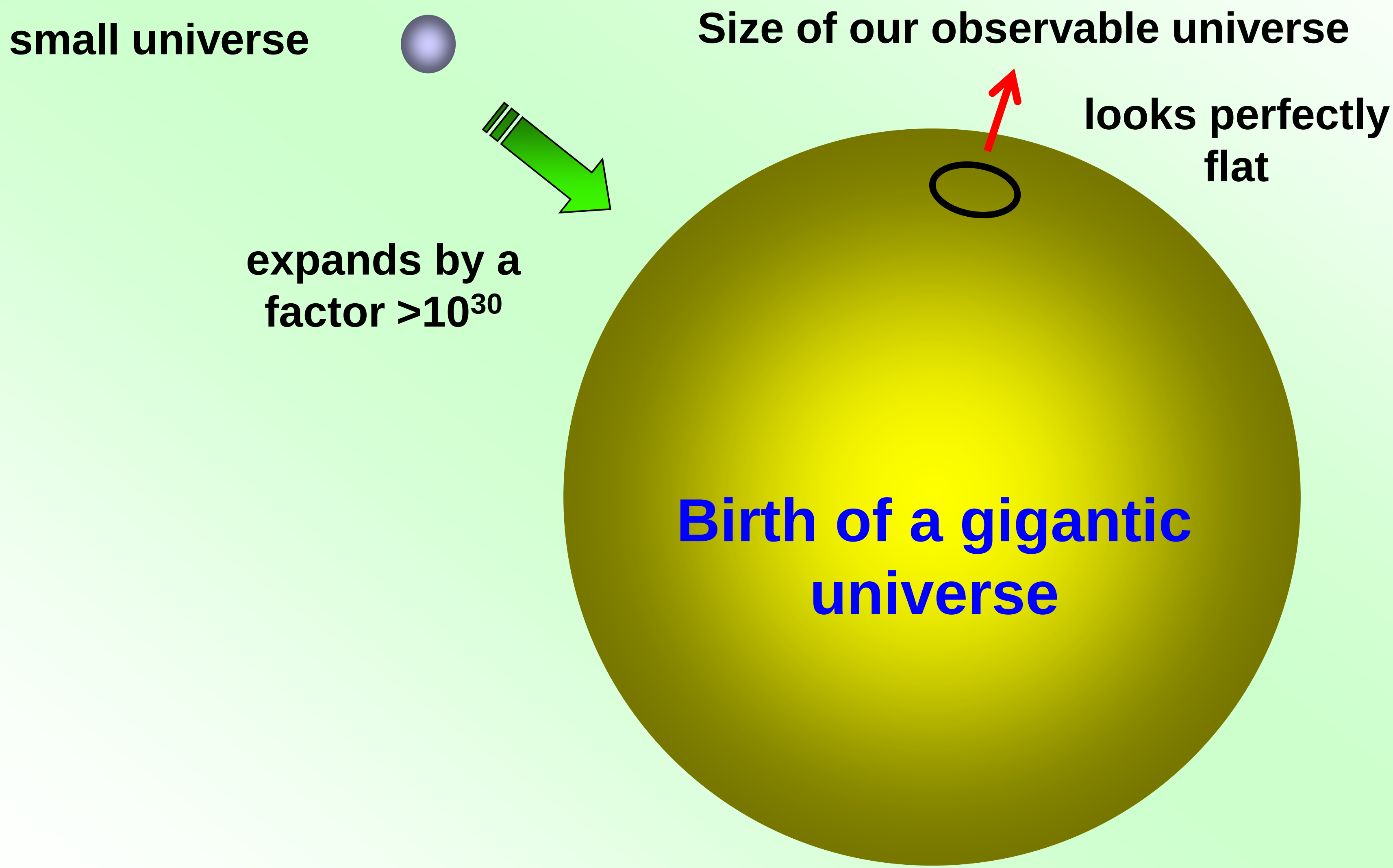


Kinematics

Length scales of inflationary universe



Flatness



Flatness can be explained only by Inflation

Dynamics

seeds of cosmological perturbations

Mukhanov '81, ….

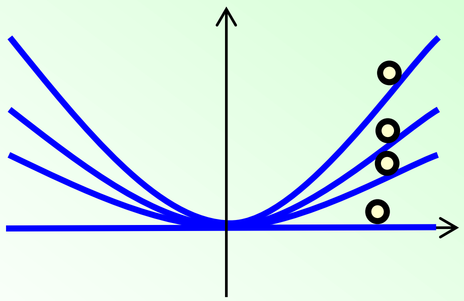
Zero-point (vacuum) fluctuations of ϕ :

$$\delta\phi = \sum_k \delta\phi_k(t) e^{ik\cdot x}$$

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

physical wavelength $\lambda(t) \propto a(t)$

harmonic oscillator with friction term and time-dependent ω



$$\delta\phi_k \rightarrow \text{const.}$$

… frozen when $\lambda > c\, H^{-1}$
(on superhorizon scales)

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

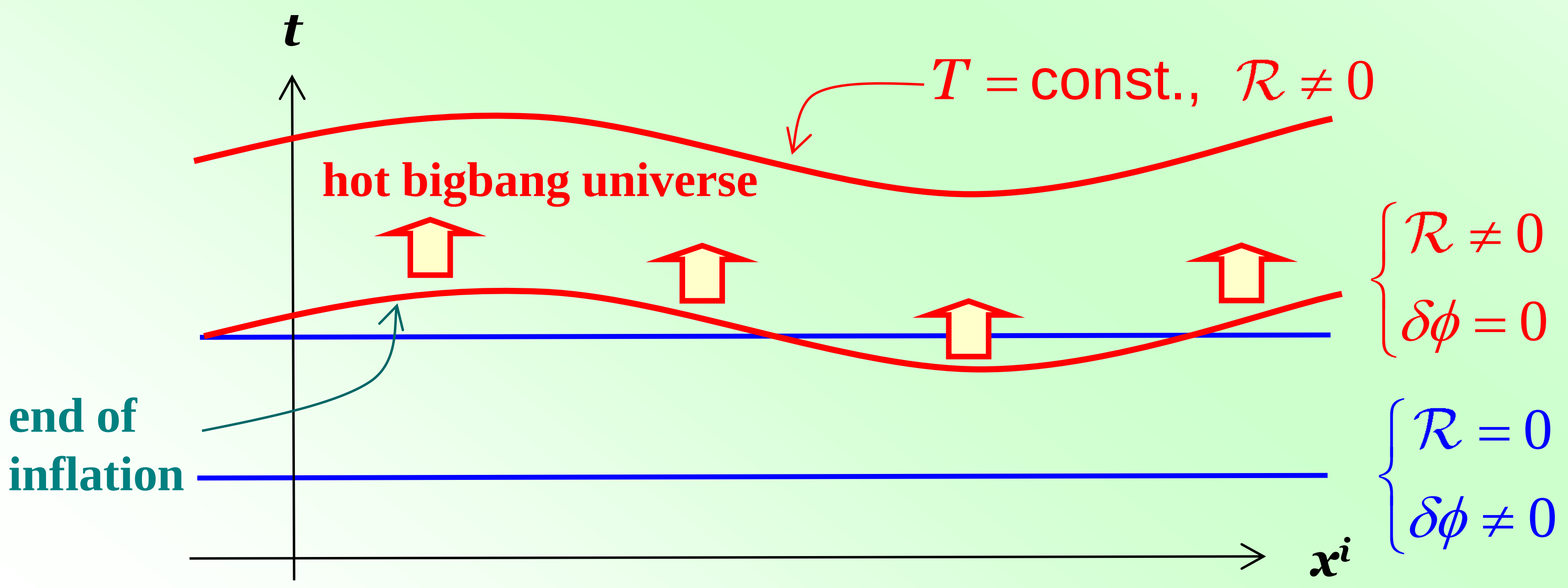
Starobinsky '79

generation of curvature perturbation

Mukhanov '81, '85; MS '86, …

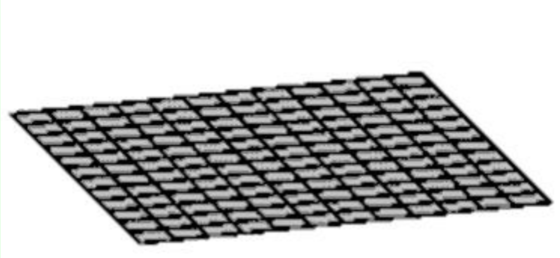
curvature perturbation $\mathcal{R}$ ≈ gravitational potential Ψ

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



Generic predictions of inflation

- Spatially flat universe



- Almost scale invariant, adiabatic, and Gaussian primordial density fluctuations

- Almost scale invariant and Gaussian primordial tensor fluctuations

→ Generates anisotropy of CMBR.
Origin of galaxies, stars, …

- **Amplitude of curvature perturbation:**

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

Mukhanov (1985), MS (1986)

- **Power spectrum index:**

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

$$\frac{4\pi k^3}{(2\pi)^3} P_{\mathcal{R}}(k) = Ak^{n_S-1} \;\; ; \;\; n_S - 1 = M_{pl}^2\left(2\frac{V''}{V} - 3\frac{V'^2}{V^2}\right)$$

- **Tensor (gravitational wave) spectrum:**

$$\frac{4\pi k^3}{(2\pi)^3} P_T(k) = Ak^{n_T} \;\; ; \;\; n_T = -3\frac{\dot{\phi}^2}{V} = -\frac{1}{8}\frac{P_{\mathcal{R}}(k)}{P_T(k)}$$

Liddle-Lyth (1992)

Observational results

Map of CMBR by PLANCK

Temperature anisotropy **Feb 2015**

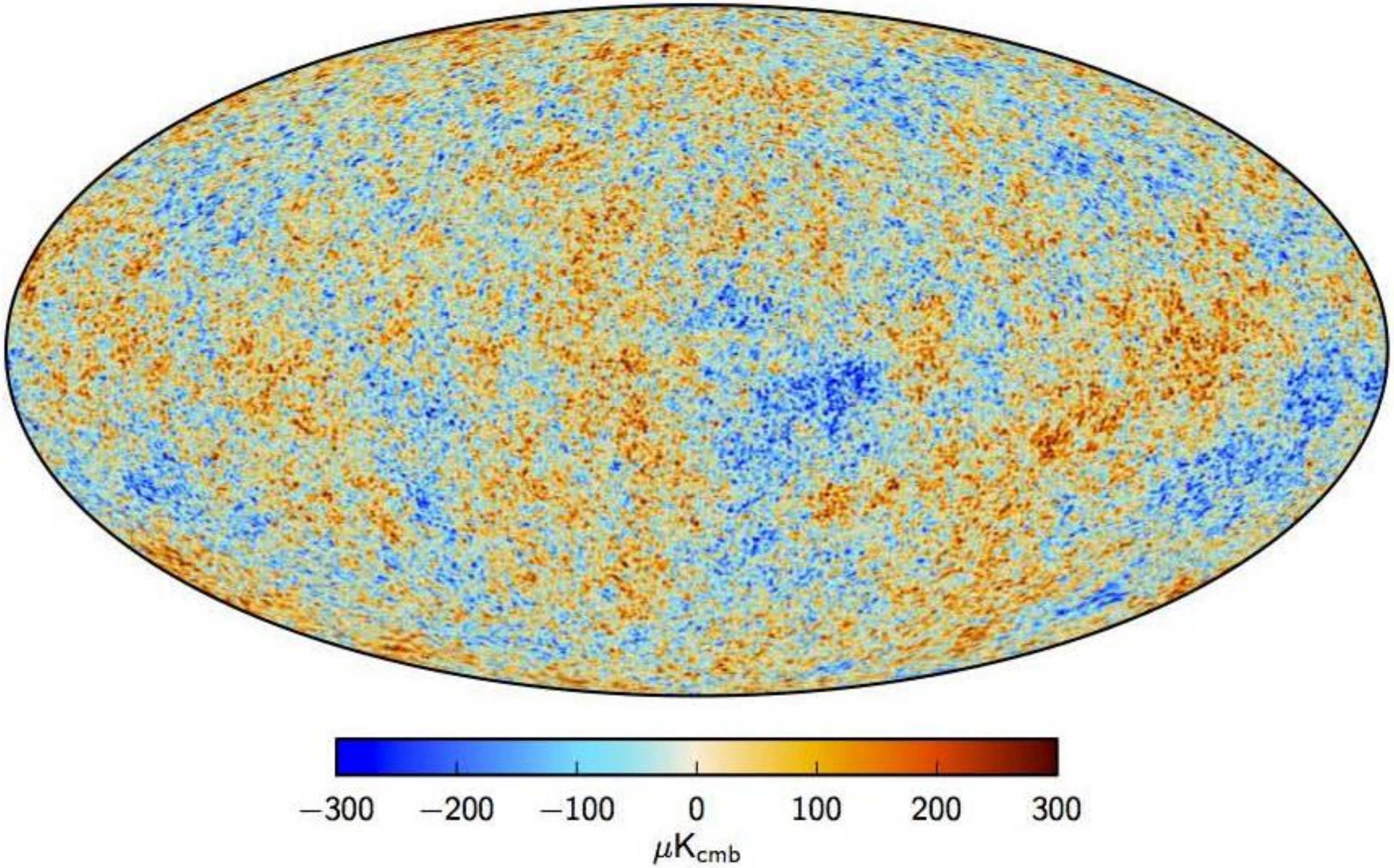
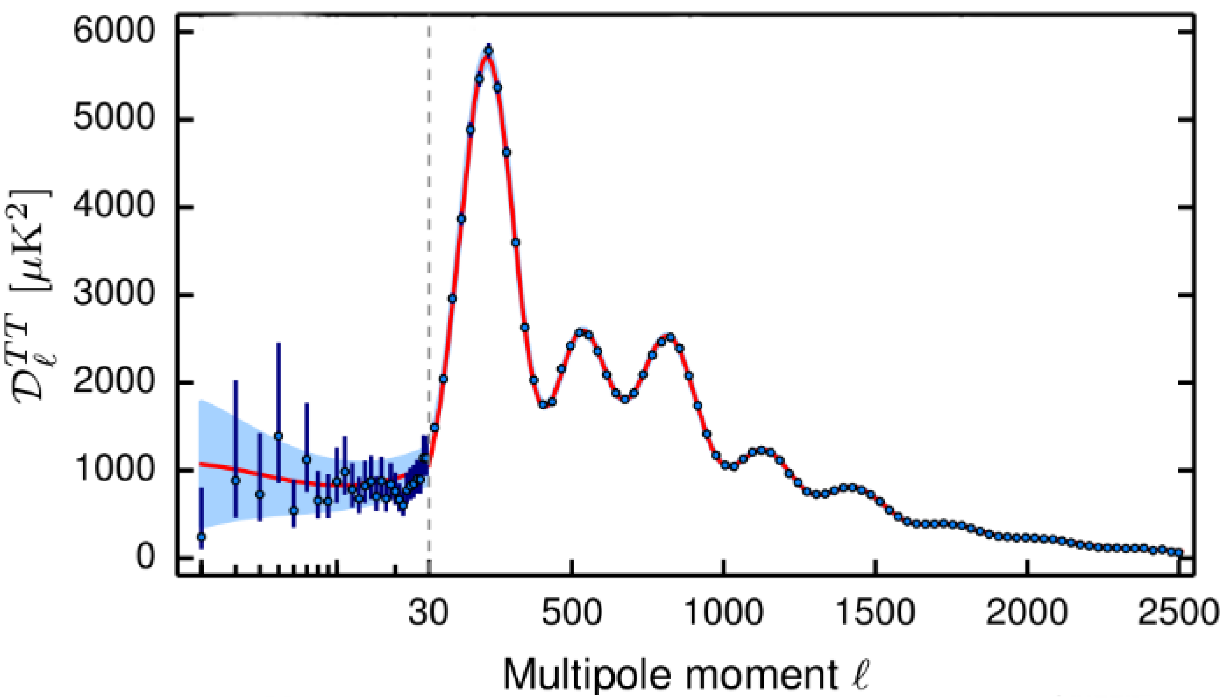
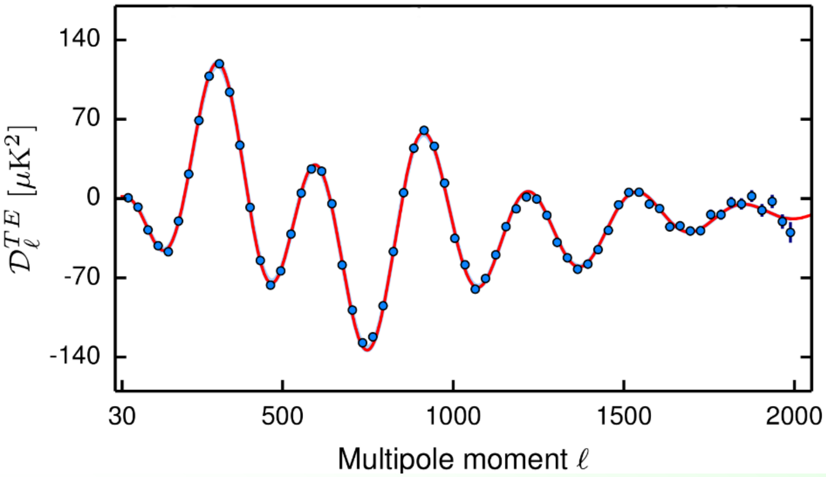


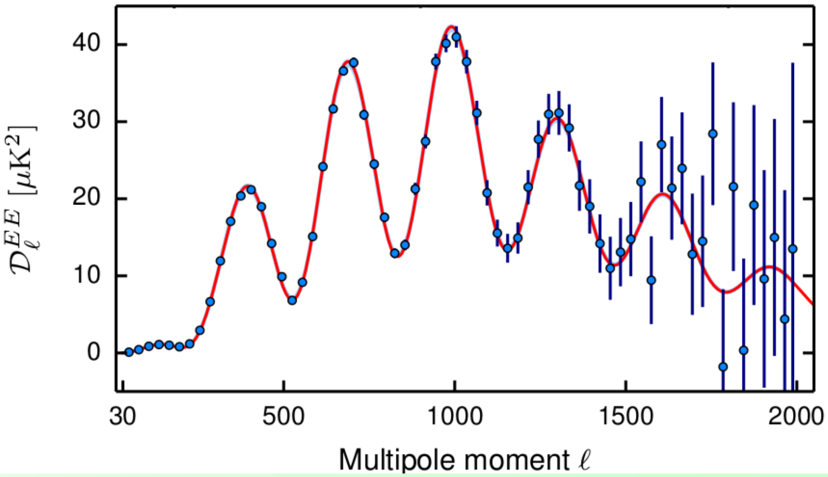
Fig. 7. Maximum posterior CMB intensity map at 5′ resolution derived from the joint baseline analysis of *Planck*, WMAP, and 408 MHz observations. A small strip of the Galactic plane, 1.6 % of the sky, is filled in by a constrained realization that has the same statistical properties as the rest of the sky.

Planck 2015 results. I

Planck TT, TE & EE spectrum







- **Amplitude of curvature perturbation:**

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

Mukhanov (1985), MS (1986)

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

- **Power spectrum index:**

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

$$\frac{4\pi k^3}{(2\pi)^3} P_{\mathcal{R}}(k) = A k^{n_S - 1} \;;\; n_S - 1 = M_{pl}^2 \left(2\frac{V''}{V} - 3\frac{V'^2}{V^2} \right)$$

$n_{S,\mathrm{Planck}} - 1 = -0.032 \pm 0.006 \;\Leftrightarrow\; n_S - 1 \sim -0.04$ for a typical model

- **Tensor (gravitational wave) spectrum:**

$$\frac{4\pi k^3}{(2\pi)^3} P_T(k) = A k^{n_T} \;;\; n_T = -3\frac{\dot{\phi}^2}{V} = -\frac{1}{8}\frac{P_{\mathcal{R}}(k)}{P_T(k)}$$

Liddle-Lyth (1992)

to be observed by LiteBIRD/...

PLANCK constraints

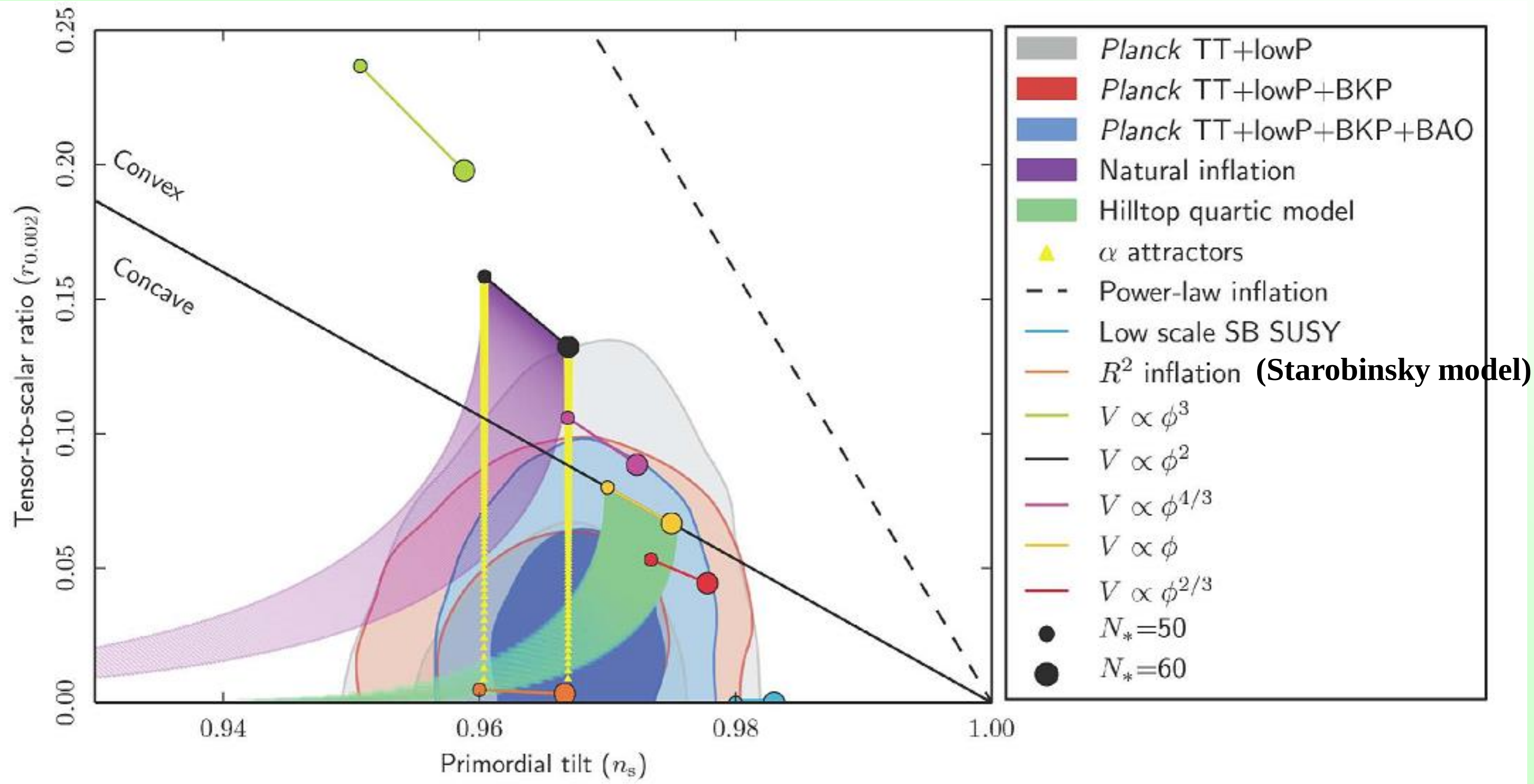


Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

Planck 2015 results. XX

Implications

Planck implications

- 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)

perhaps elements of non-canonicality is needed

non-canonical single-field models

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

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

Planck: $c_s > 0.024$ at 95% CL

- **non-minimal coupling to gravity?**

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

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

- **scalar-tensor with derivative couplings (Hordeski) ?**

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

non-existence of Einstein frame?

↑ tensor propagation speed

other possibilities

WMAP/Planck anomalies:

suppression of $\delta T/T$ at l<10?

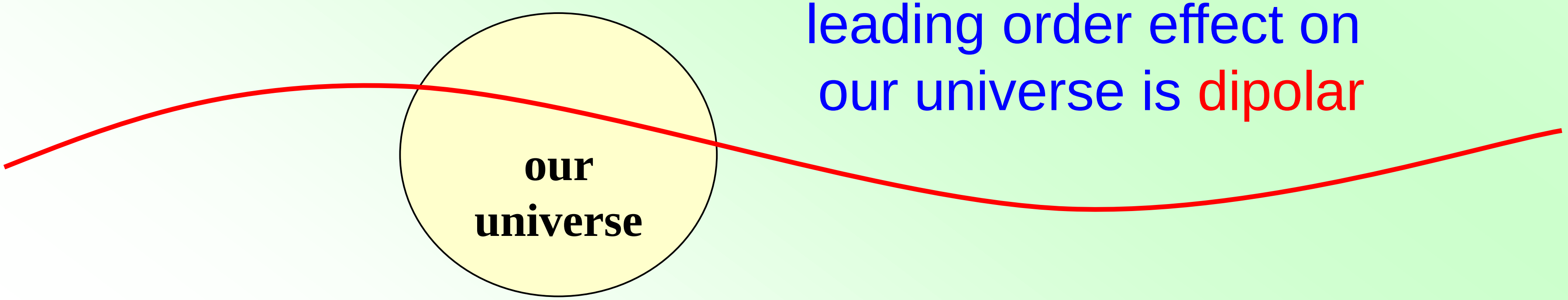
hemispherical asymmetry of $\delta T/T$ at l< 30?

- **featured models: heavy fields, particle creation, trans-Planckian, …**
- **open inflation, supercurvature modulation, …**

still viable if Ω_K >10^{-3}

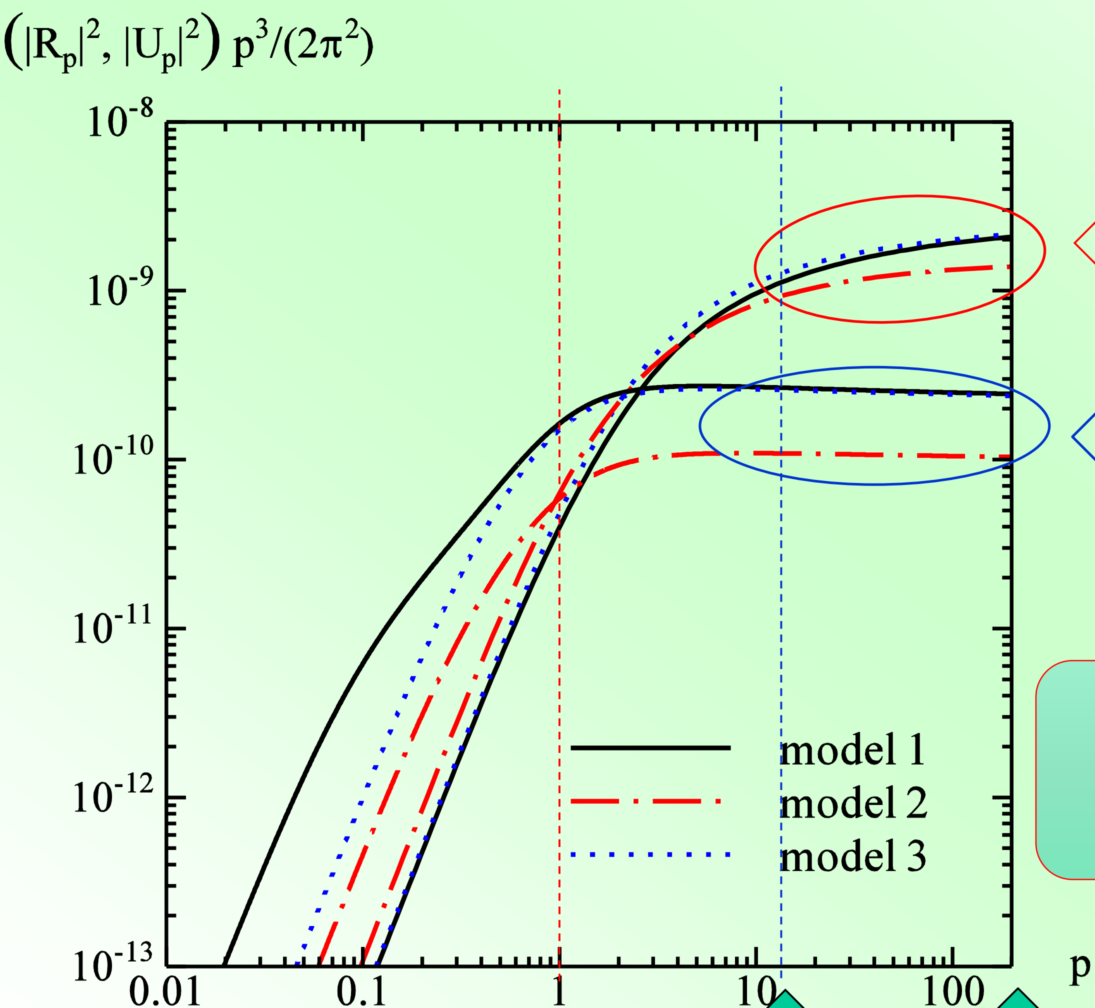
$$\lambda \gg R_{\text{curvature}} \gg H_0^{-1}: \text{ supercurvature mode}$$

leading order effect on our universe is dipolar



scalar & tensor spectrum in open inflation

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 $\Omega_K \approx 0.01$

Future Issues

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

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

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

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

Identification of Inflaton!