YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

PPP11
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General Relativity and Cosmology

– Bigbang, Inflation & beyond –

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General Relativity

Einstein (1915)

$$\boxed{G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}; \quad \nabla_\mu T^{\mu\nu} = 0}$$

GR applied to homogeneous & isotropic universe

Friedmann (1916)

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -c^2 dt^2 + a^2(t) d\sigma_K^2 \quad \begin{cases} \text{open} : K = -1 \\ \text{flat} : K = 0 \\ \text{closed} : K = +1 \end{cases}$$

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 + \frac{Kc^2}{a^2} = \frac{8\pi G}{3} \rho \ ; \quad \dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + Pc^{-2}\right) = 0}$$

$H \equiv \dfrac{\dot{a}}{a}$: expansion rate (Hubble parameter)

Progress in Cosmology (1)

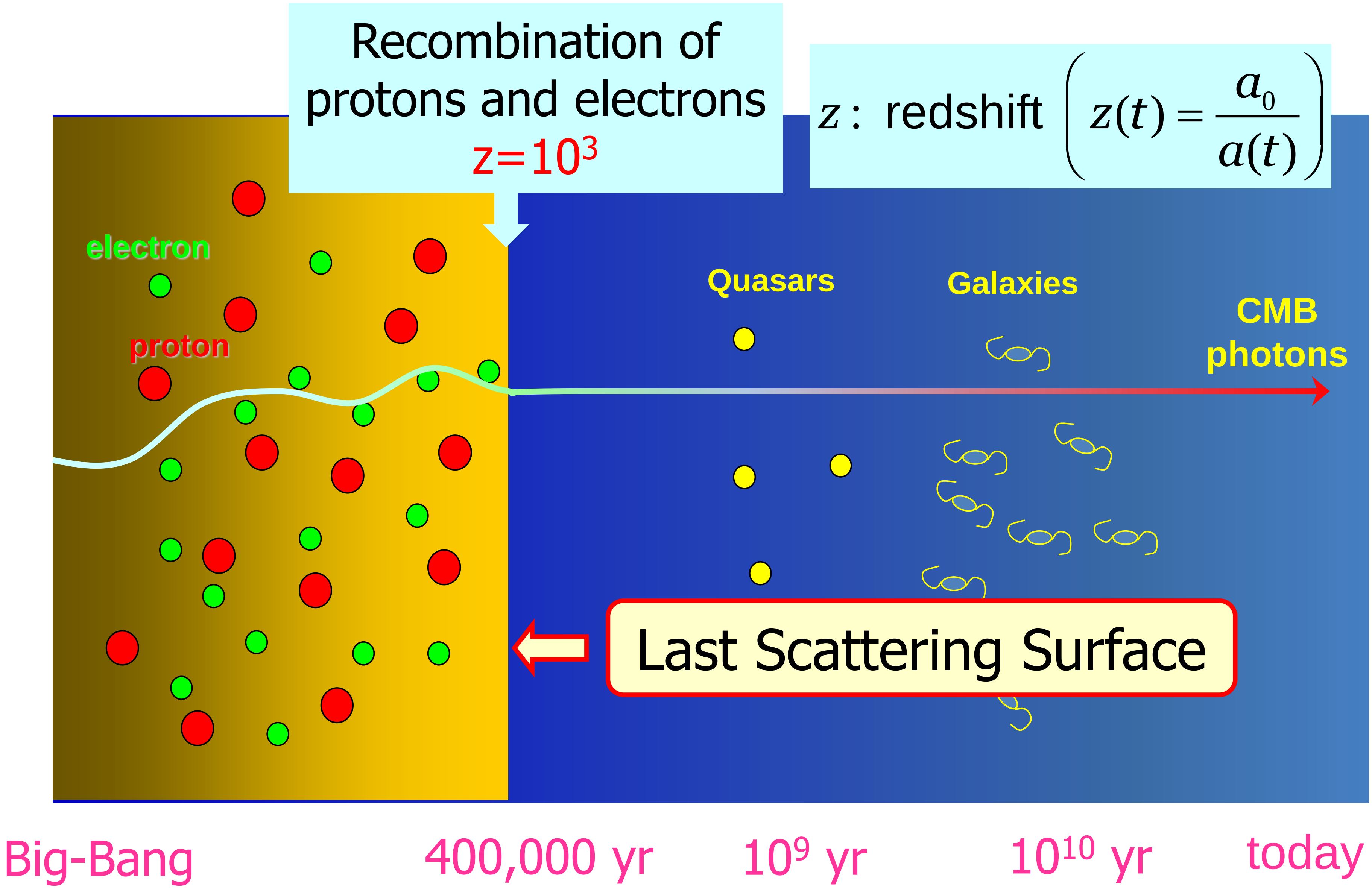
- 1^{st} stage: 1916 ~ 1980

- 1916~ General Relativity/Friedmann Universe
- 1929 Hubble's law: $V=H_0 R$ ···cosmological redshift
- 1946~ Big-Bang theory/Nuclear astrophysics
- 1960~ High redshift objects/Quasars
- 1965 Discovery of relic radiation from Big-Bang

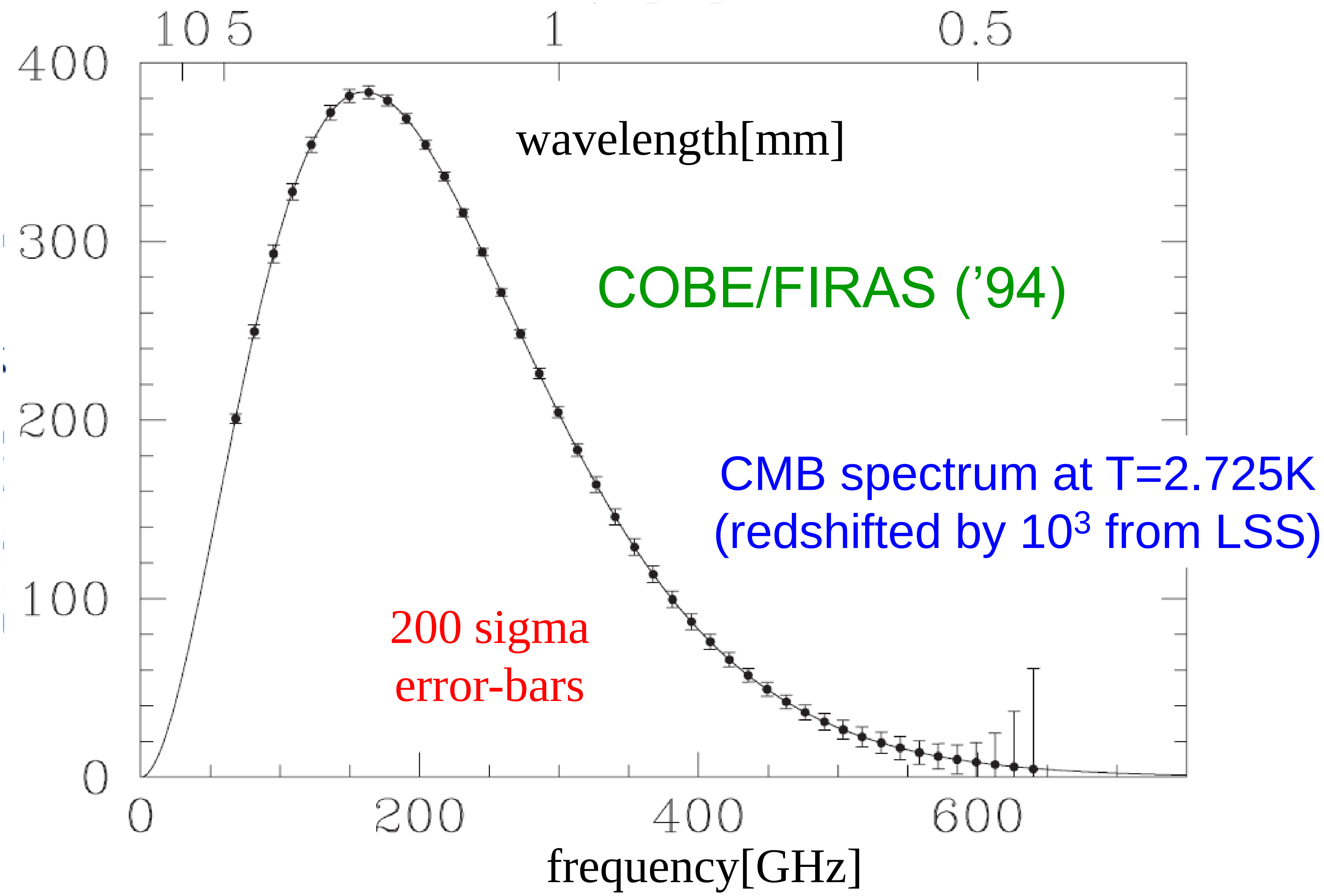
  Cosmic Microwave Background: T_0=2.7K
- 1970~ BBNucleosynthesis vs Observed Abundance

  → Existence of Dark Matter

Big-Bang Universe and CMB



Big Bang theory has been firmly established



Establishment of homogeneous & isotropic Big-Bang Universe Model

Progress in Cosmology (2)

2^{nd} stage: 1980 ~ 2013

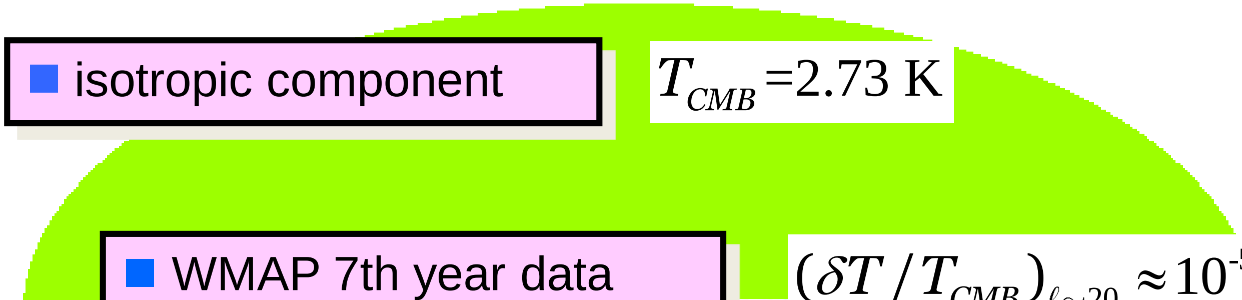
- 1980~ Revelation of Large Scale Structure
  Cosmological Perturbation Theory
  Particle Cosmology/Inflationary Universe
- 1992 Detection of CMB anisotropy (COBE)
  Evidence for Inflationary Universe
- 2003 Accurate CMB angular spectrum (WMAP)
  Confirmation of Flatness of the Universe
  Strong evidence for Dark Energy
- 2013 High precision CMB spectrum (Planck)
  Very strong evidence for Inflation

CMB Full Sky Map

COBE-DMR (1990)
WMAP (2003~)
Planck (2013~)

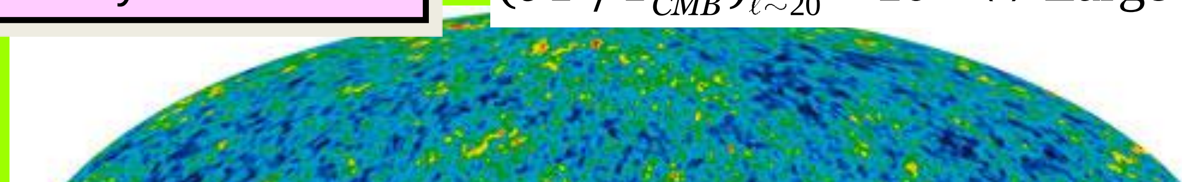
- isotropic component

$T_{CMB} = 2.73\text{ K}$

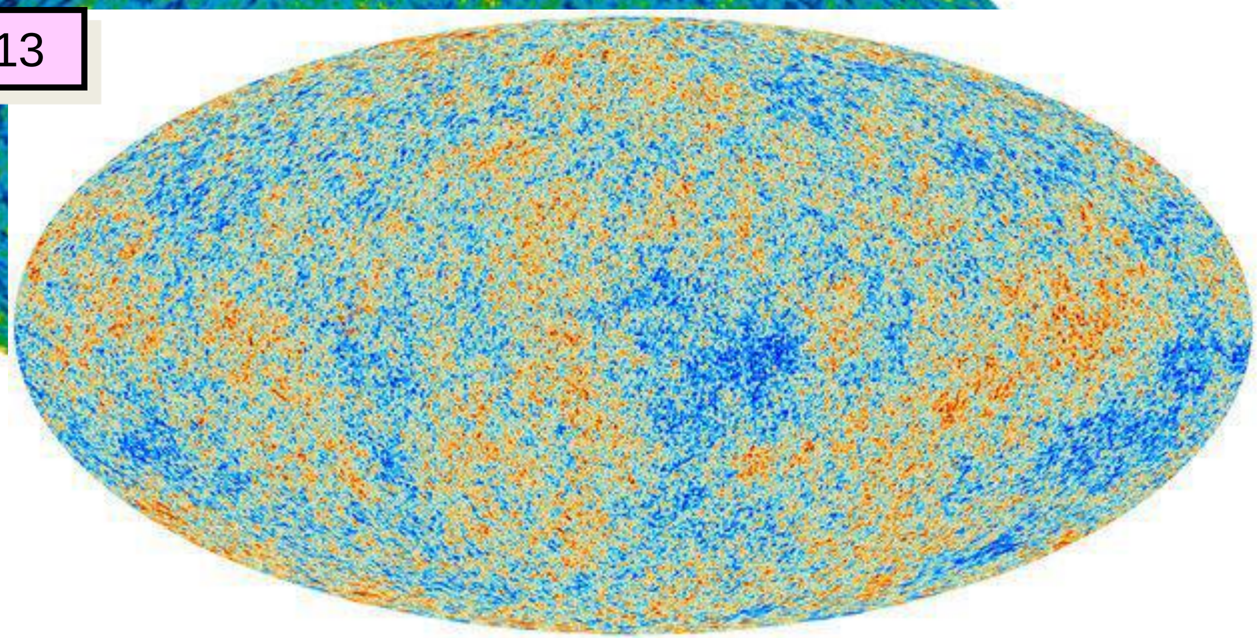


- WMAP 7th year data

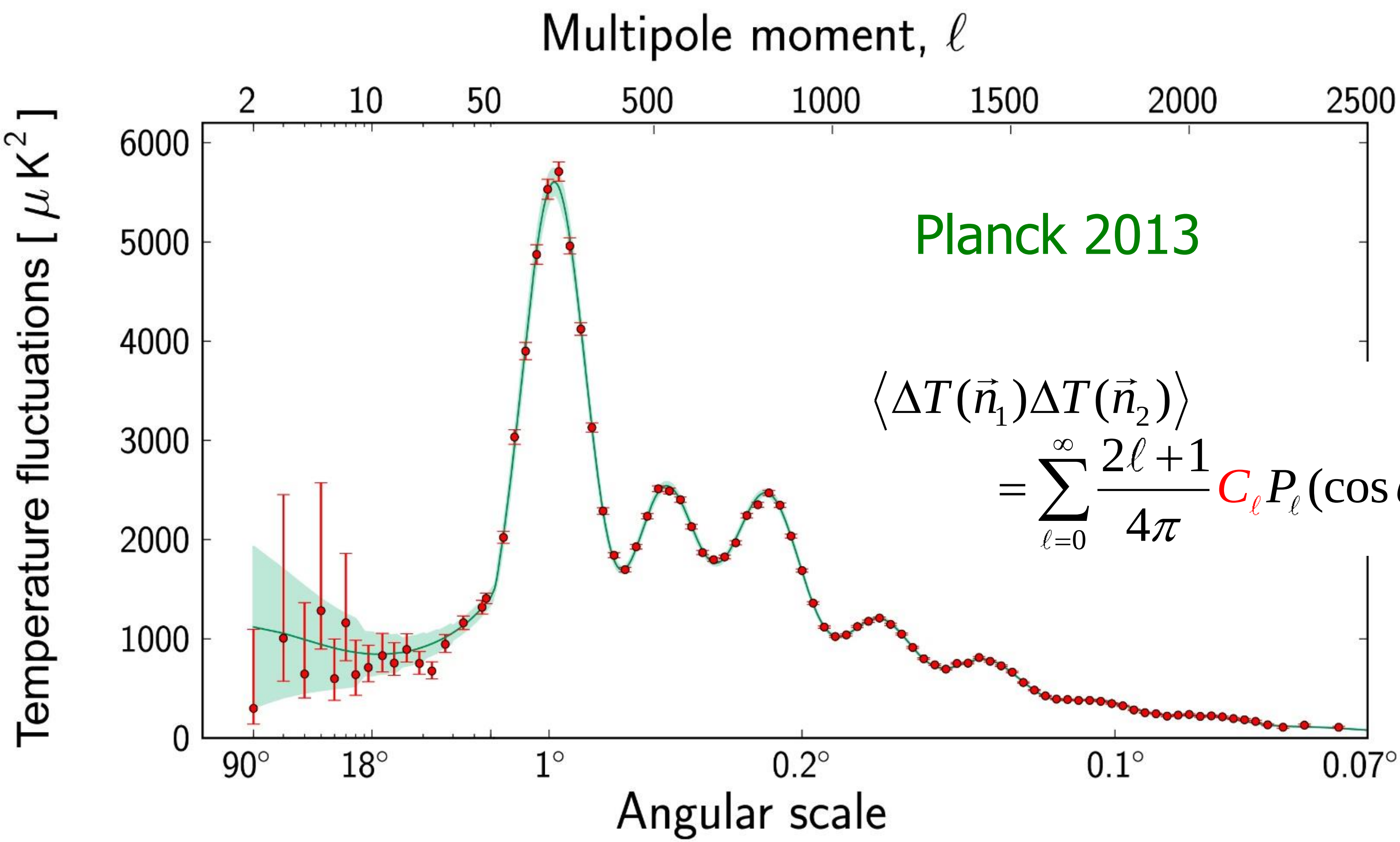
$(\delta T / T_{CMB})_{\ell \sim 20} \approx 10^{-5} \Leftrightarrow$ Large Scale Structure



- Planck 2013



CMB Anisotropy Spectrum



$$\left\langle \Delta T(\vec{n}_1)\Delta T(\vec{n}_2)\right\rangle = \sum_{\ell=0}^{\infty}\frac{2\ell+1}{4\pi}C_\ell P_\ell(\cos\theta).$$

Horizon Problem

Why the detection of $\delta T/T$ at $\theta > 10^{o}$ was so important?

- Because in the standard Friedmann universe, the size of causal volume (horizon size) grows like ~ ct.

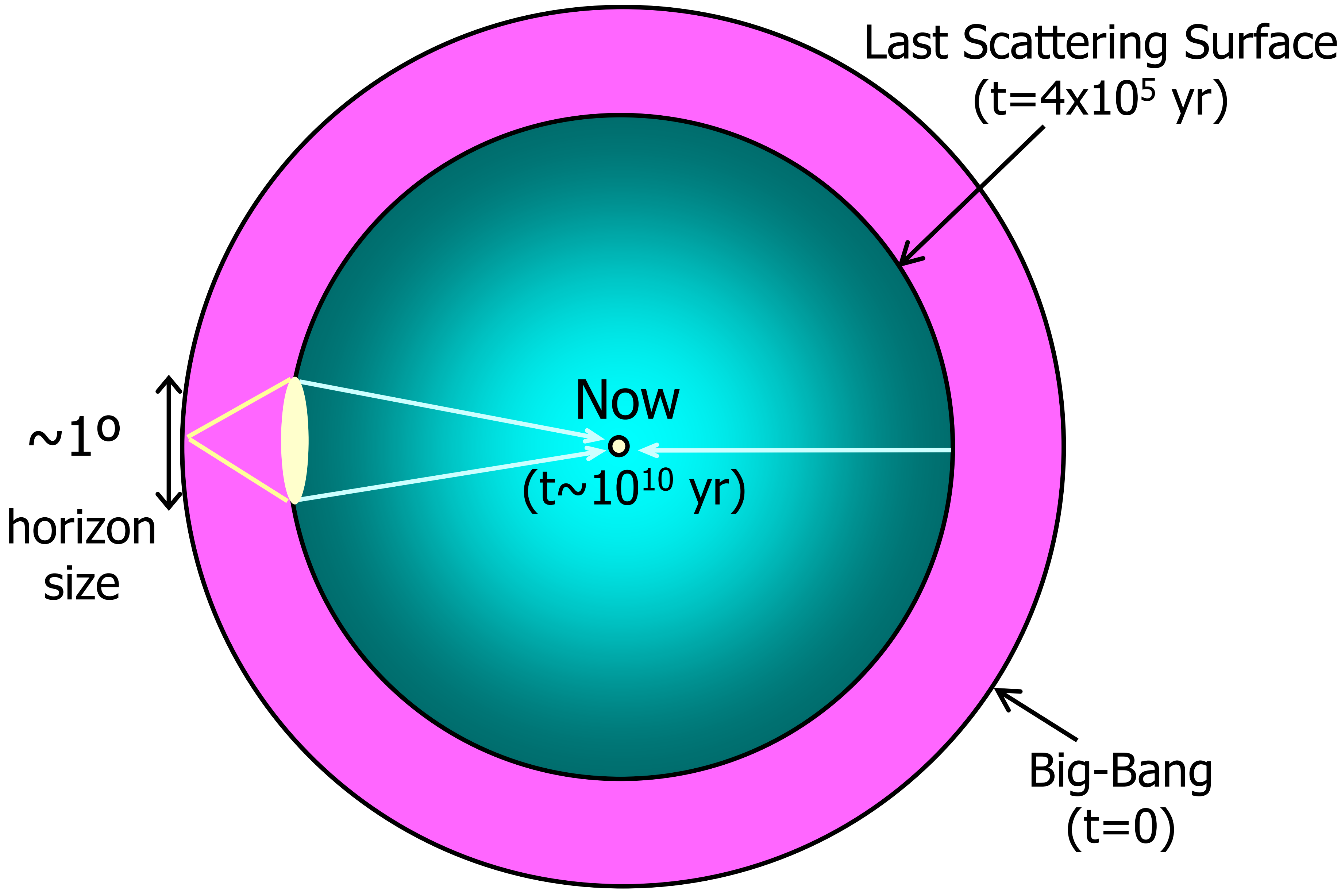
While, the expansion of the universe is slower than ~ ct because gravity is attractive (if $\rho + 3P > 0$)
⟺ decelerated expansion

- The angle sustaining the horizon size at LSS is ~ 1^{o}.

- Thus, any causal, physical process cannot produce correlation on scales $\theta > 1^{o}$.

- But $(\delta T/T)_{\theta > 10^{o}} \neq 0$ means there exists non-zero correlation.

There are ~10^4 causally independent patches on LSS



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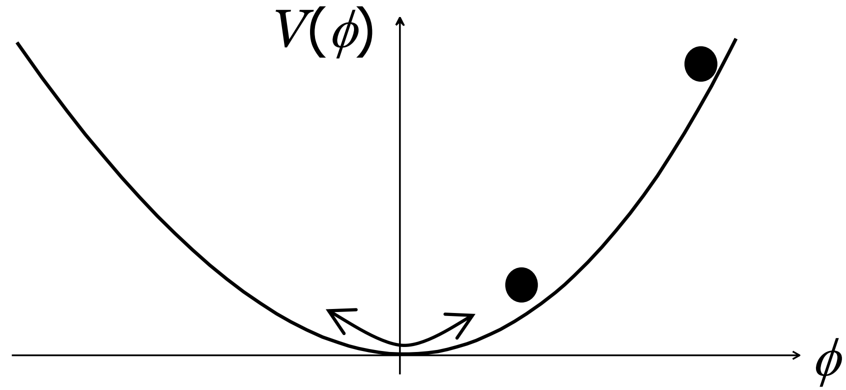
Inflationary Universe

Universe dominated by a scalar (inflaton) field

For sufficiently flat potential:

$$H^2 \approx \frac{8\pi G}{3} V(\phi) \quad \left(\Leftarrow \frac{1}{2}\dot{\phi}^2 \ll V(\phi) \right)$$

$$\Rightarrow \quad \frac{|\dot{H}|}{H^2} = \frac{3\dot{\phi}^2}{2V(\phi)} \ll 1$$



- H is almost constant ~ exponential expansion = inflation
- ϕ slowly rolls down the potential: slow-roll (chaotic) inflation

Linde (1983)

- Inflation ends when ϕ starts damped oscillation.

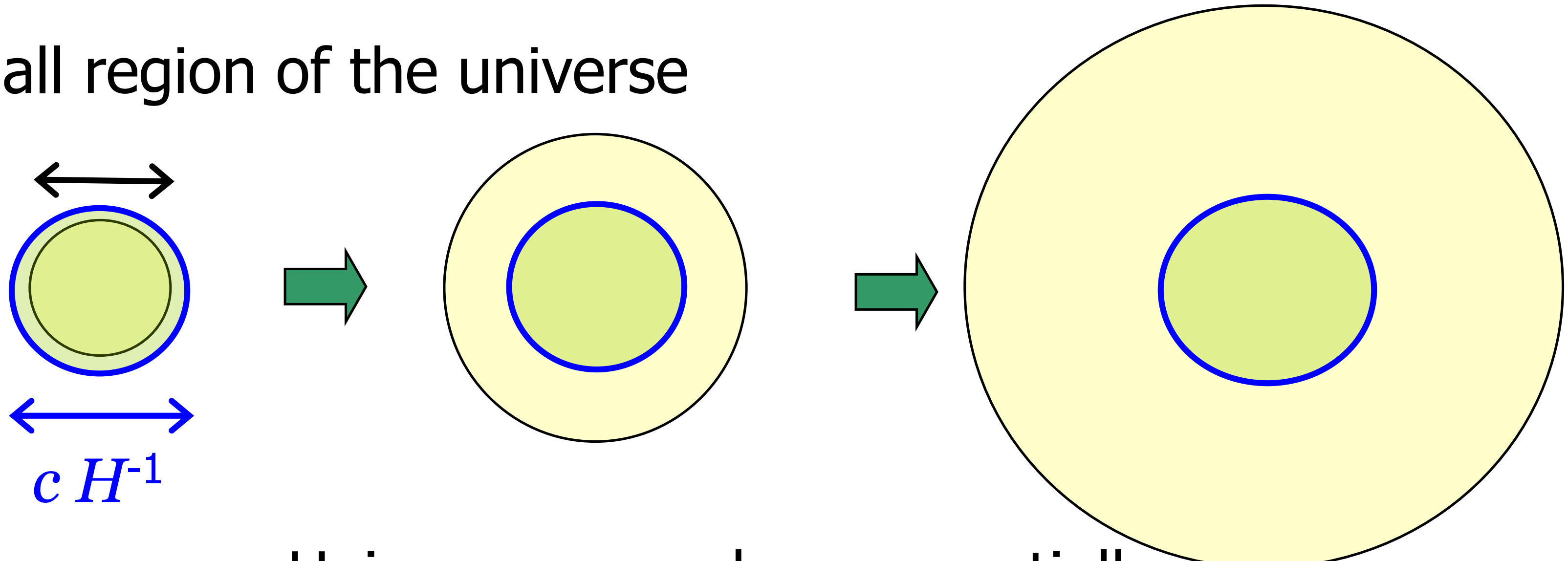
⇨ ϕ decays into thermal energy (radiation)

Birth of Hot Bigbang Universe

Hubble horizon during inflation

$a(t) \sim e^{Ht}$; $H \sim$const.

A small region of the universe

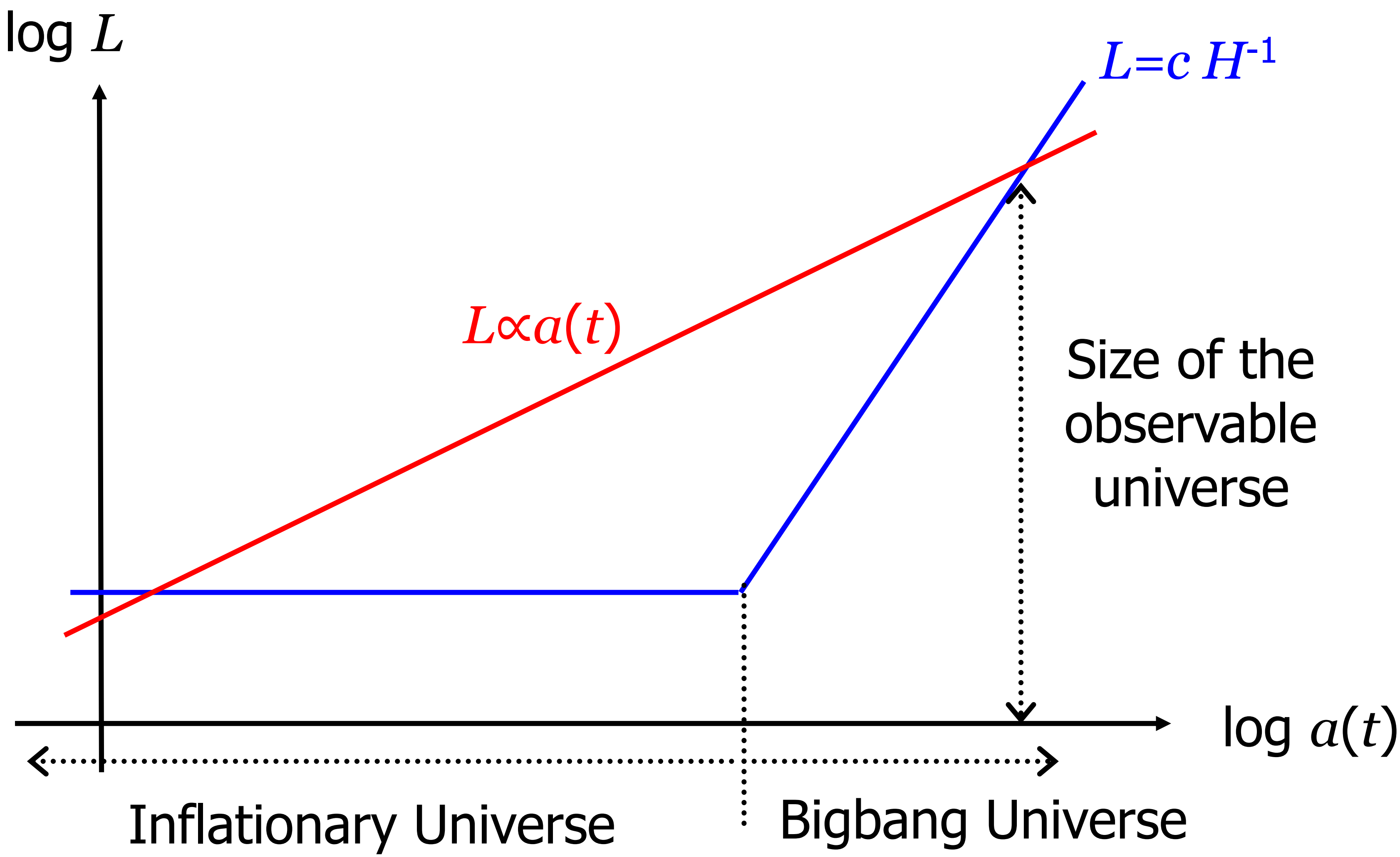


Universe expands exponentially,
while the Hubble horizon size remains almost constant.

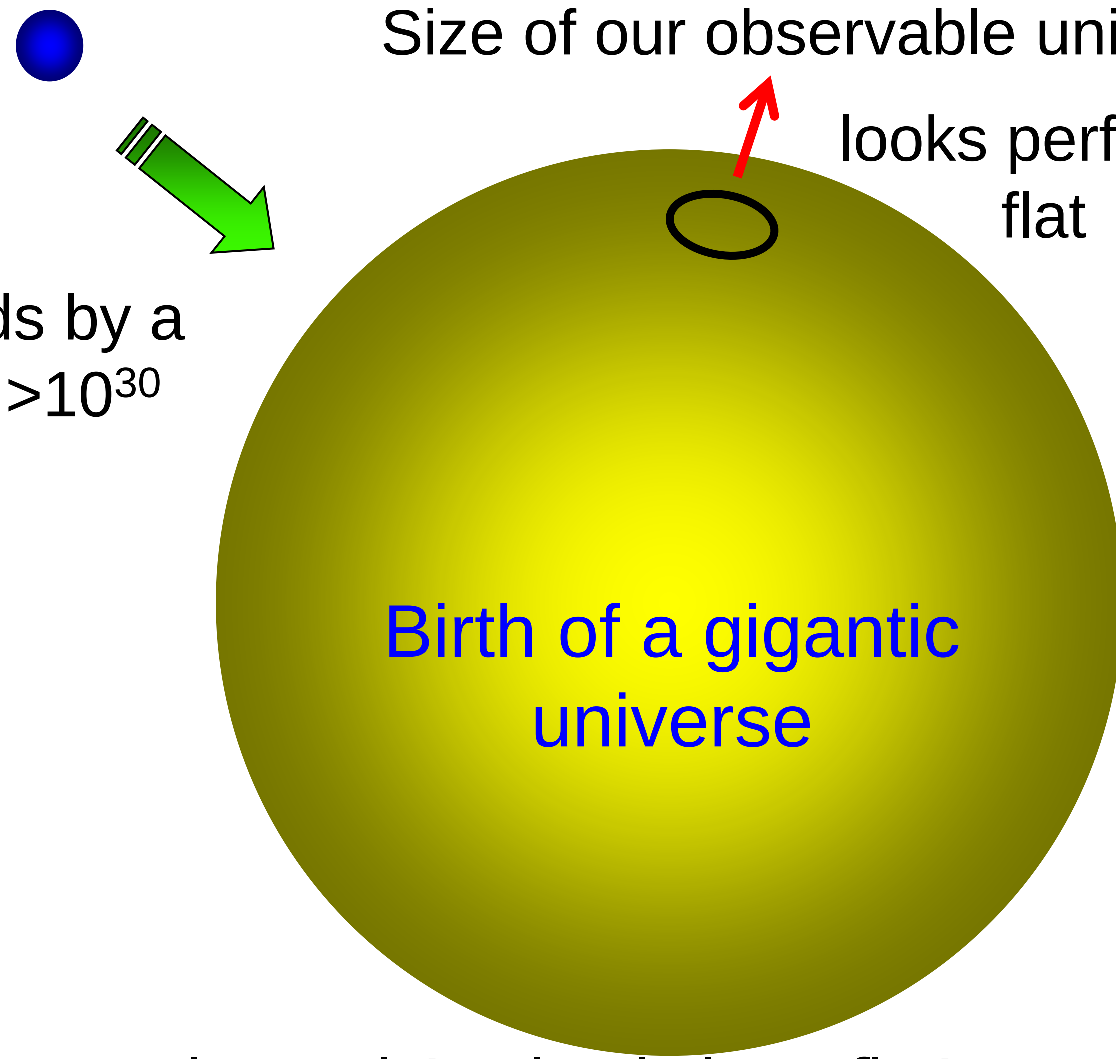
An initially tiny region can become much larger than the entire observable universe

$\rightarrow$ solves the horizon problem.

length scales of the inflationary universe



Flatness of the Universe



Flatness can be explained only by Inflation

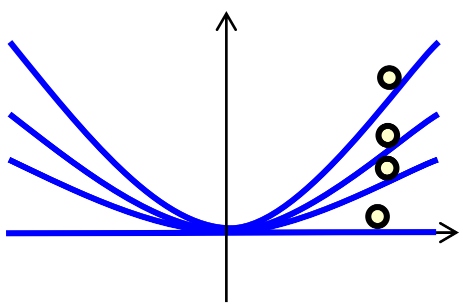
Seed of Cosmological Perturbations

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

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

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

harmonic oscillator with friction term and time-dependent ω



$\delta\phi_k \ \rightarrow$ const.

$\cdots$ frozen when $\lambda > c\,H^{-1}$

(on superhorizon scales)

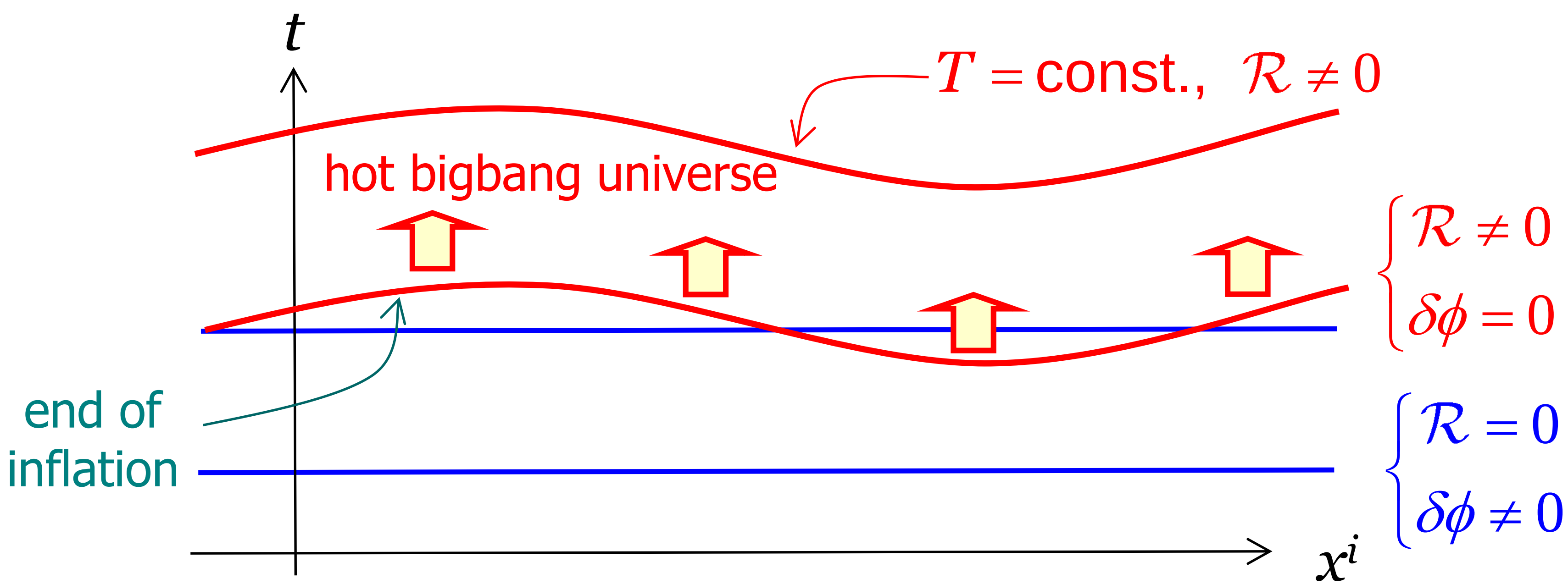
gravitational wave (tensor) modes also satisfy the same eq.

Generation of Curvature Perturbation

curvature perturbation $\mathcal{R} \approx -\Psi$: gravitational potential

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

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



Theoretical Predictions

- 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:

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

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

- Tensor (gravitational wave) spectrum:

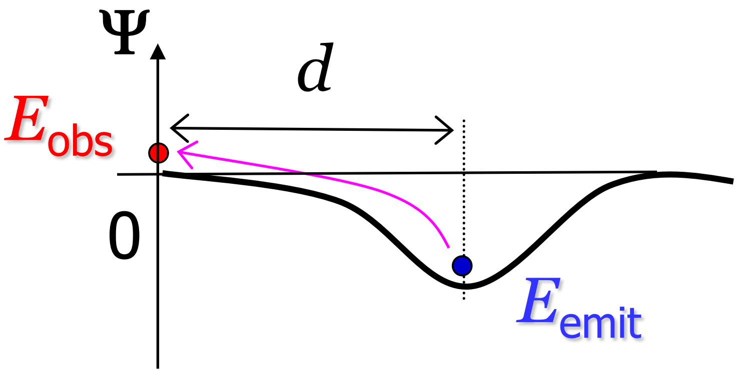
$$\frac{4\pi k^3}{(2\pi)^3} P_T(k) = Ak^{n_T} \;\; ; \;\; n_T = -\frac{1}{8}\frac{P_T(k)}{P_S(k)} \equiv -\frac{r}{8}$$

Liddle-Lyth (1992)

"consistency relation"

CMB Anisotropy from Curvature Perturbation

- Photons climbing up from gravitational potential well are redshifted.



For Planck distribution,

$$\frac{\Delta T}{T}(\vec{n}) \equiv \frac{T_{\mathrm{obs}}}{T_{\mathrm{emit}}} - 1 = \Psi(\vec{x}_{\mathrm{emit}})$$

$$\vec{x}_{\mathrm{emit}} = \vec{n}\, d\ ;\ \ \vec{n} = \text{line of sight}$$

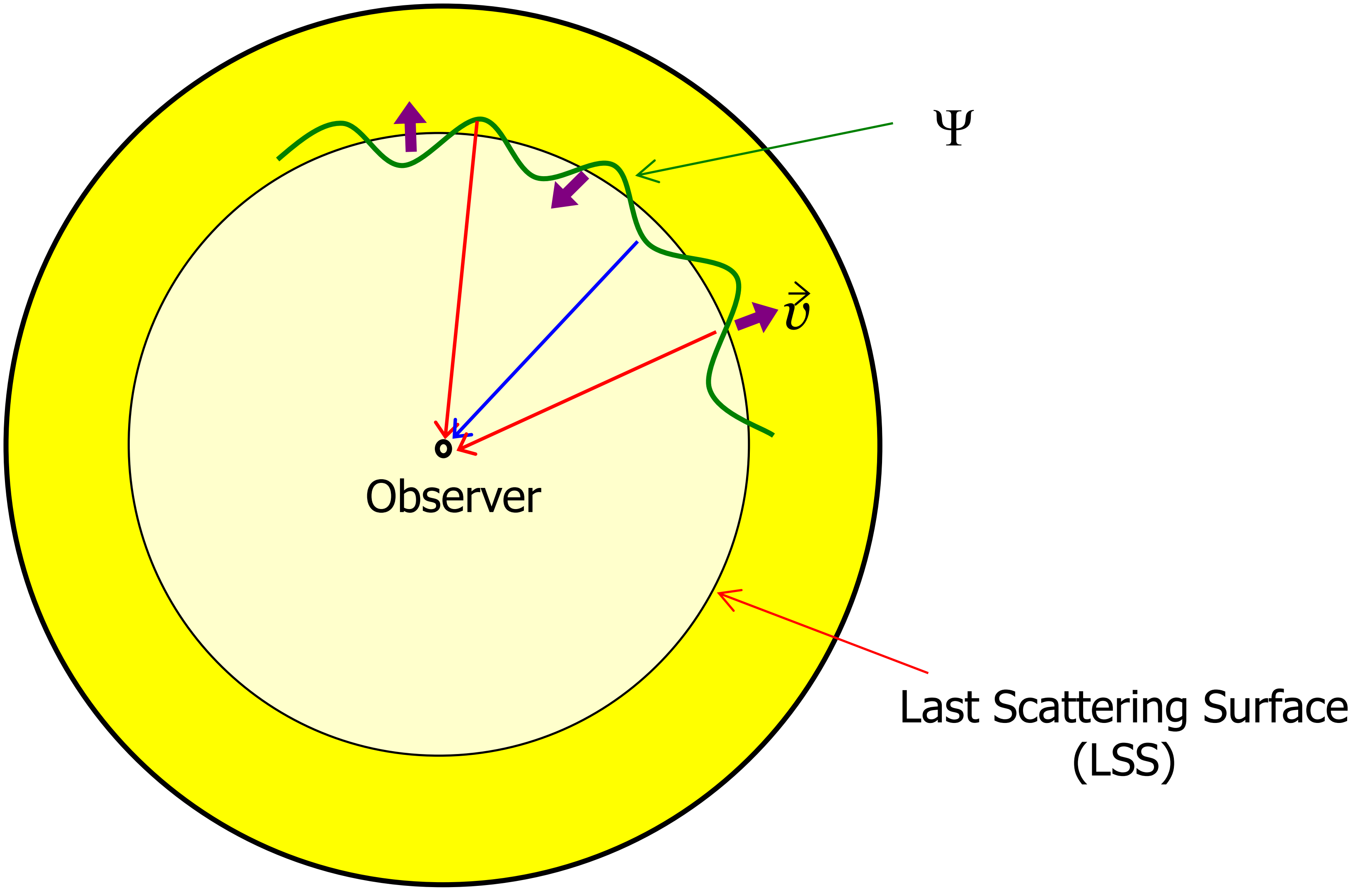
- In an expanding universe, this is modified to be $\frac{\Delta T}{T}(\vec{n}) = \frac{1}{3}\Psi(\vec{x}_{\mathrm{emit}})$

Sachs-Wolfe effect

- There is also the standard Doppler effect:

$$\frac{\Delta T}{T}(\vec{n}) = -\vec{n} \bullet \vec{v}(\vec{x}_{emit})$$

$$\frac{\Delta T}{T}(\vec{n}) = \frac{1}{3}\Psi(\vec{x}_{\mathrm{LSS}}) - \vec{n}\bullet\vec{v}(\vec{x}_{\mathrm{LSS}}) + \cdots (\text{minor corrections})$$



- Amplitude of curvature perturbation:

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

Mukhanov (1985), MS (1986)

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

- Power spectrum index:

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

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

$$\boxed{n_{S,\rm Planck} - 1 = -0.040 \pm 0.0073 \;\Leftrightarrow\; n_S - 1 \sim -0.04 \;\text{ for a typical model}}$$

- Tensor (gravitational wave) spectrum:

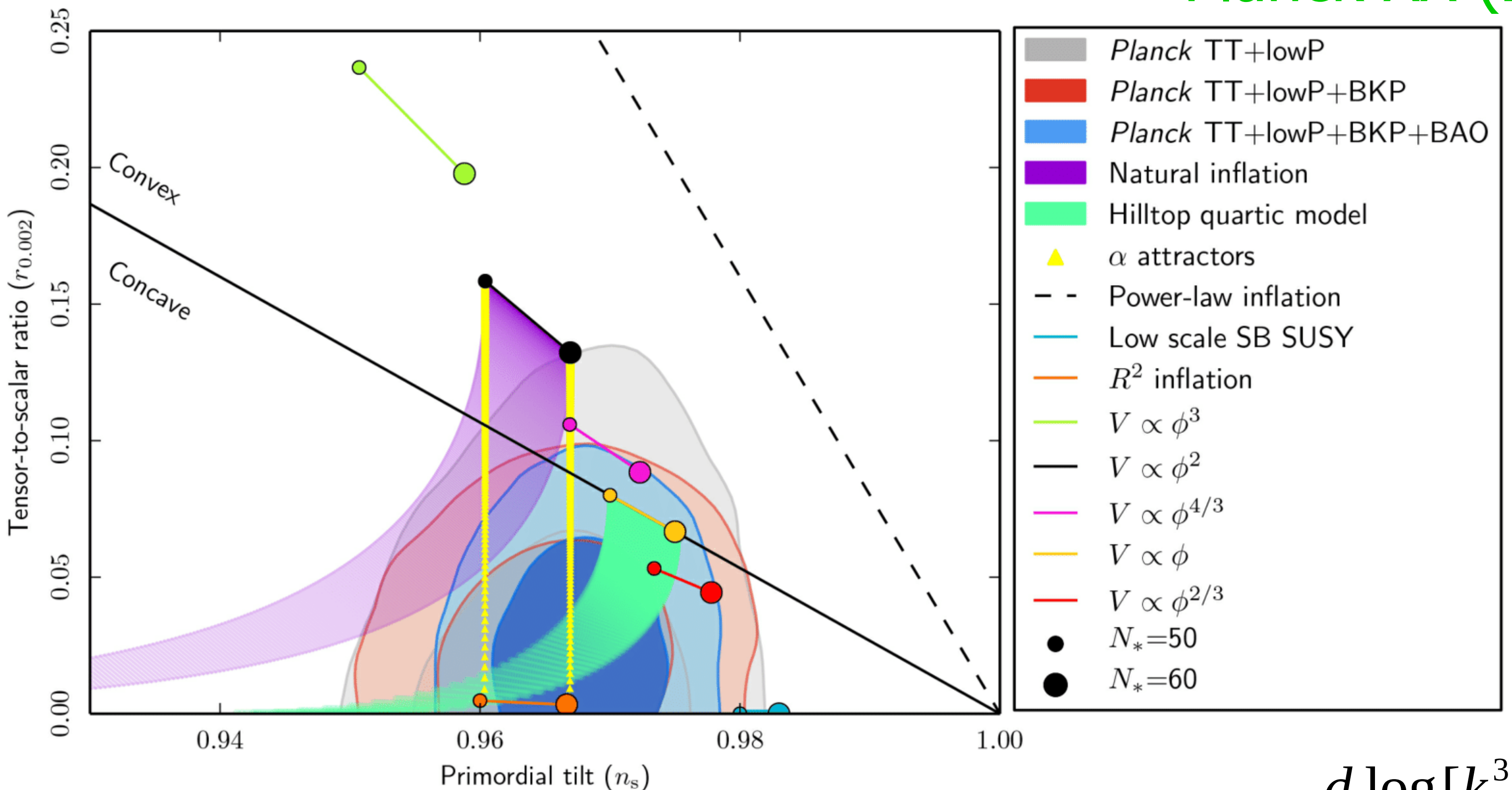
$$\frac{4\pi k^3}{(2\pi)^3} P_T(k) = A k^{n_T} \;;\; n_T = -\frac{1}{8}\frac{P_T(k)}{P_S(k)} \equiv -\frac{r}{8}$$

Liddle-Lyth (1992)

to be observed ...

CMB constraints on inflation

Planck XX (2015)



- scalar spectral index: $n_s \sim 0.96$
- tensor-to-scalar ratio: $r < 0.1$

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

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

single-field models with constant n_s are severely constrained

Inflation as the Origin of Large Scale Structure

Post WMAP/Planck Era

- Standard (single-field, slow-roll) inflation predicts almost scale-invariant Gaussian curvature perturbations.

- Observational data are consistent with theoretical predictions.
  - almost scale-invariant spectrum: $n_S = 0.968 \pm 0.006 \ \ (68\% \ \ \mathrm{CL})$

    Planck 2015 XIII
  - highly Gaussian fluctuations: $f_{NL}^{\mathrm{local}} = 0.8 \pm 5.0 \ \ (68\% \ \mathrm{CL})$

    Planck 2015 XVII

$$\mathcal{R} = \mathcal{R}_{\mathrm{gauss}} + \frac{3}{5} f_{NL}^{\mathrm{local}} \mathcal{R}_{\mathrm{gauss}}^2 + \cdots$$

only to be confirmed by tensor (=GW) modes?!

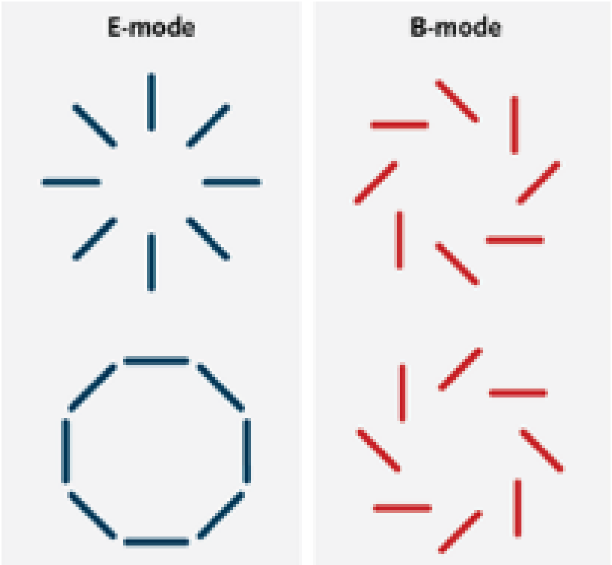
signature of primordial GWs

spacetime(graviton) vacuum fluctuations from inflation

Starobinsky (1979)

➡ B-mode polarization in CMB anisotropy

Seljak & Zaldarriaga (1996)



- E-mode (even parity)

⇕

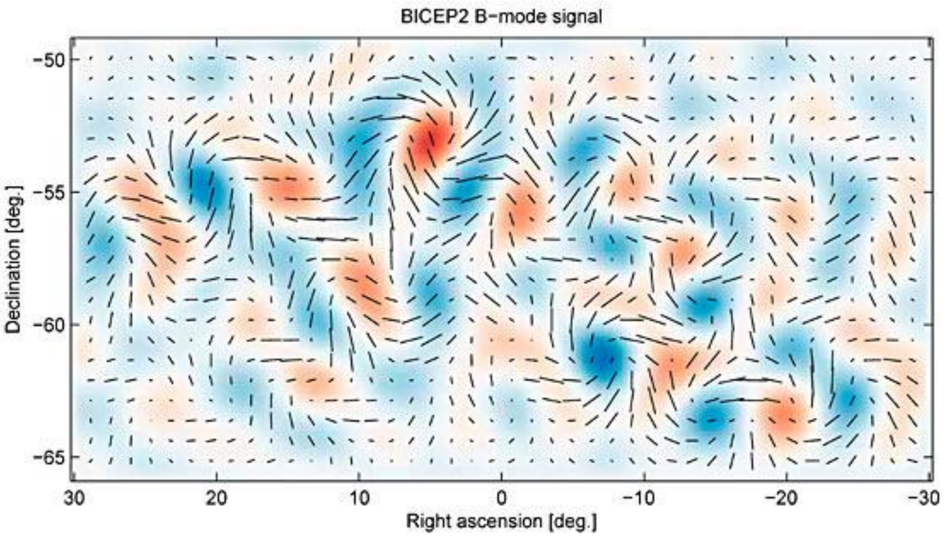
- B-mode (odd parity)

= cannot be produced from density fluctuations

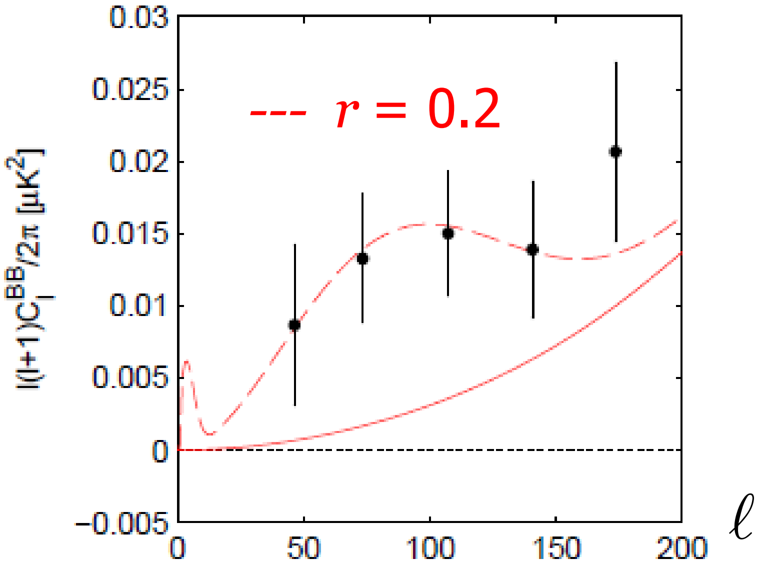
No trace of primordial
B-mode had been found
so far…

Discovery(?) of primordial GWs

BICEP2 (2014)



sky map



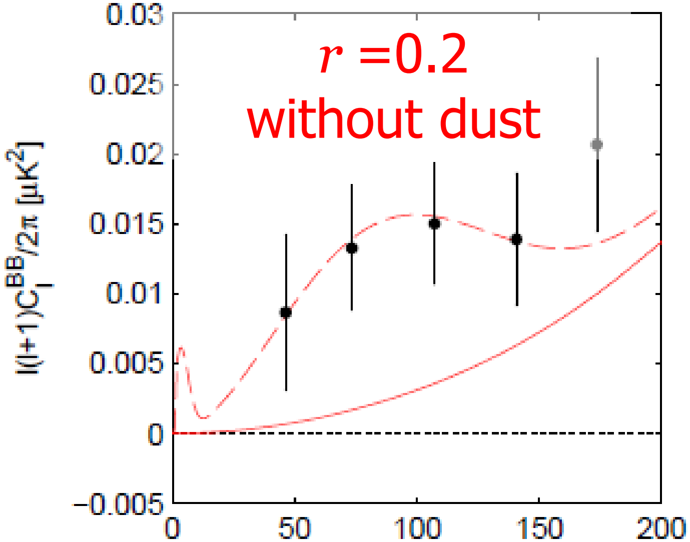
B-mode spectrum

If confirmed, it "proves" [large field models*) of] primordial inflation & quantum gravity!

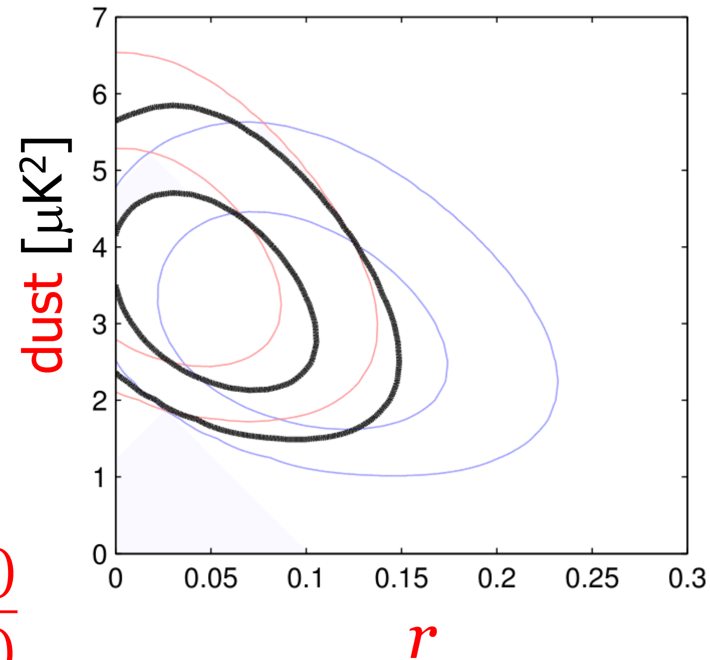
*) $\phi > M_{Planck} \sim 10^{18}$GeV : a challenge for string theorists

BICEP2 → *Planck*-BICEP2/*Keck*

(2014) (2015)



B-mode spectrum



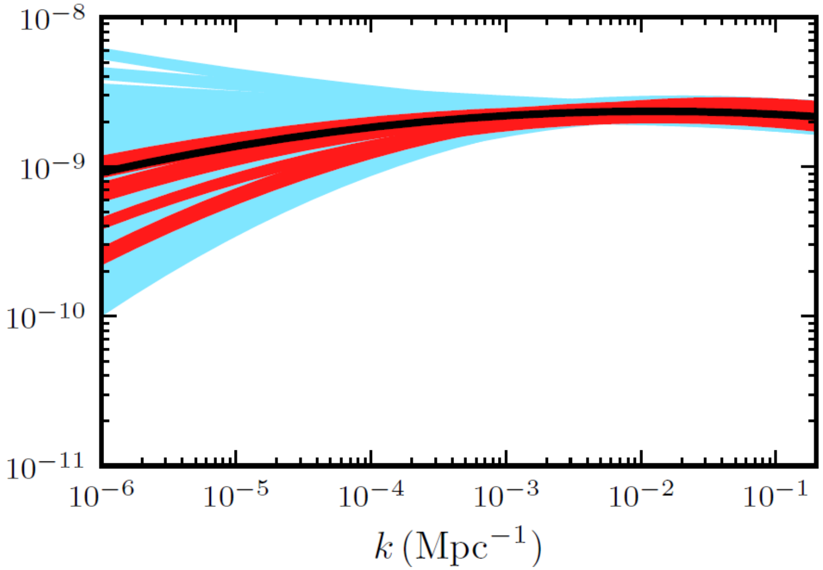
$$r \equiv \frac{P_T(k)}{P_S(k)}$$

detected B-mode seems mostly to be due to galactic dust…

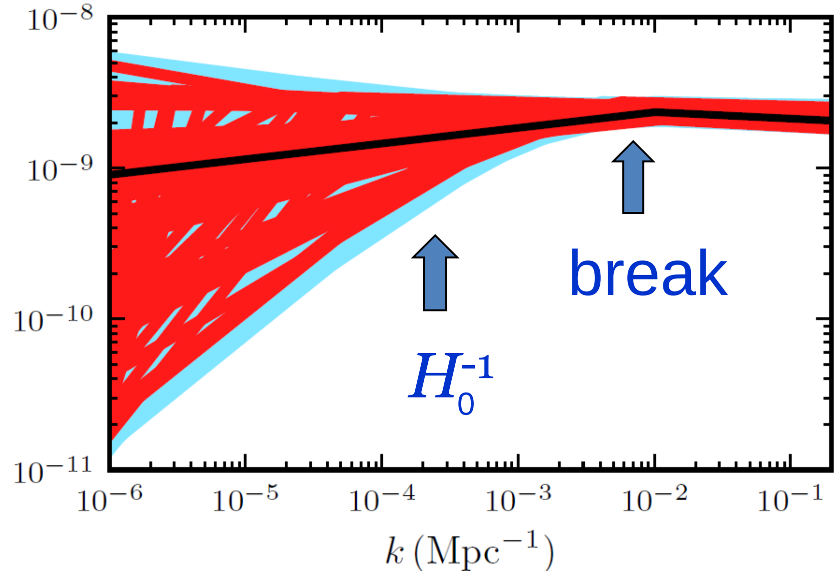
Yet, $r \sim 0.05$ is still possible, which would confirm primordial inflation & quantum gravity!

observational indication

running spectrum



broken spectrum



Model	$\Delta \log Z_{\mathrm{Broad}}$	$\Delta \log Z_{\mathrm{Informative}}$	$2\Delta \log \mathcal{L}_{\mathrm{max}}$
No Knots	—	—	
1 Knot	1.6	3.1	6.2

Model	$\Delta \log Z_{\mathrm{Broad}}$	$\Delta \log Z_{\mathrm{Informative}}$	$2\Delta \log \mathcal{L}_{\mathrm{max}}$
$\Lambda\mathrm{CDM} + r$	—	—	—
Cutoff	0.2	0.6	1.9
Running	1.1	—	3.8

Bayesian evidence

Abazajian et al.,
arXiv:1403.5922 [astro-ph.CO]

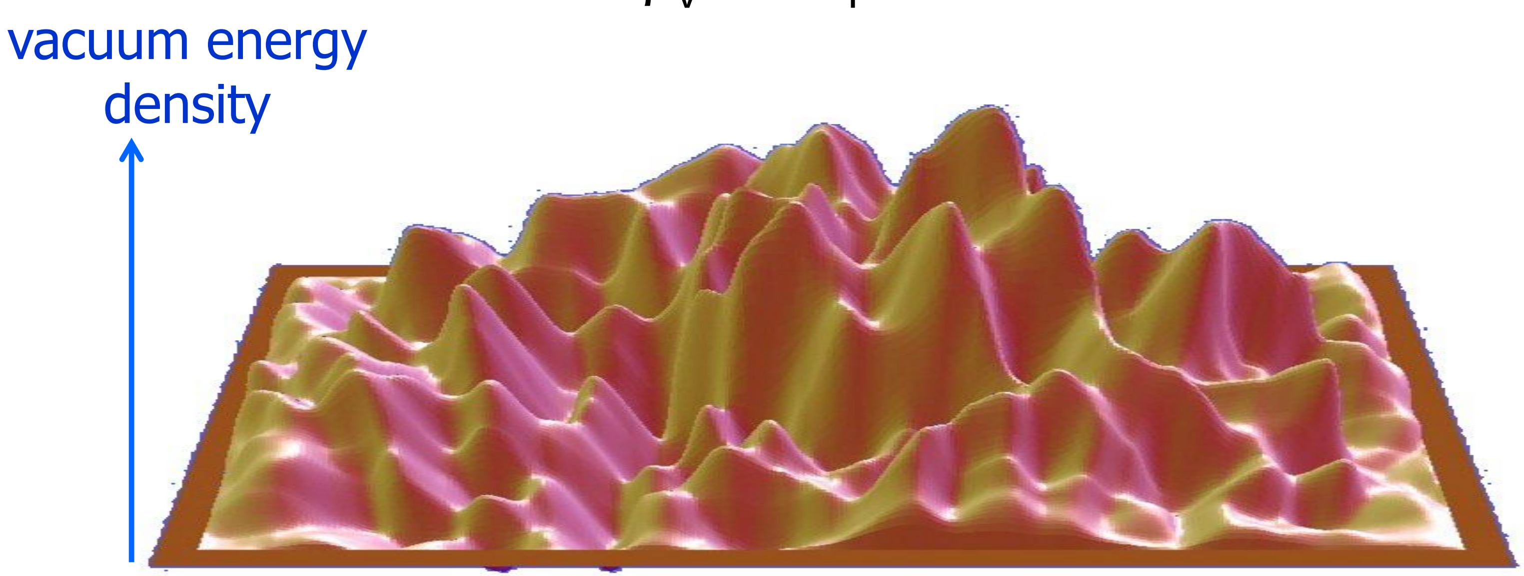
broken spectrum is favored
with r~0.1

a signature from physics beyond inflation?

String Theory Landscape

Lerche, Lust & Schellekens ('87), Bousso & Pochinski ('00), Susskind, Douglas, KKLT ('03), ...

- There are ~ 10^{500} vacua in string theory
  - vacuum energy density ρ_v may be positive or negative
  - typical energy scale ~ $M_P{}^4$
  - some of them have $\rho_v \ll M_P{}^4$



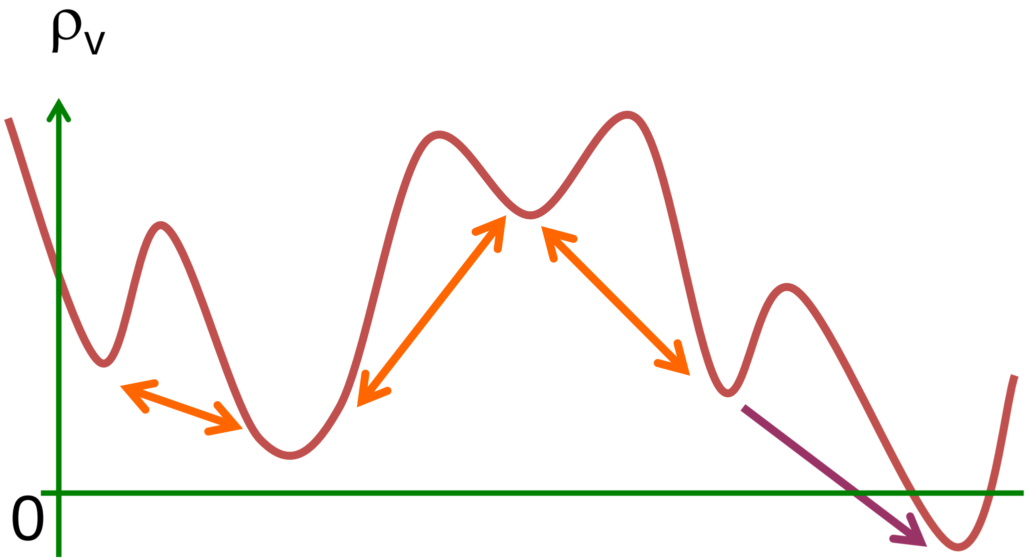
taken from http://ipht.cea.fr/

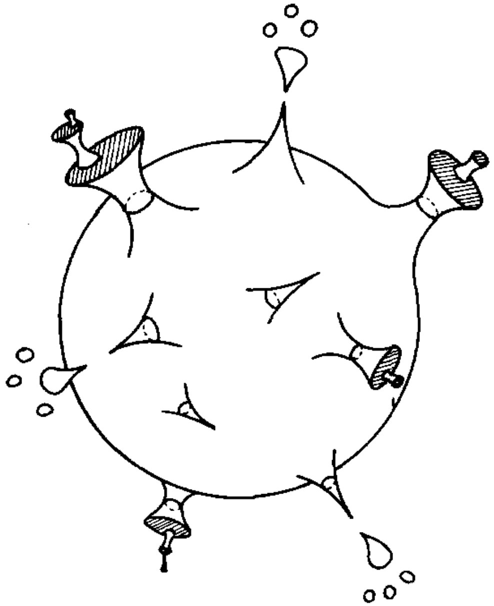
Cosmic Landscape

string theory landscape implies an intriguing picture of the early universe

Maybe we live in one of these vacua…

- A 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 $T = H/2\pi$
  - 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)

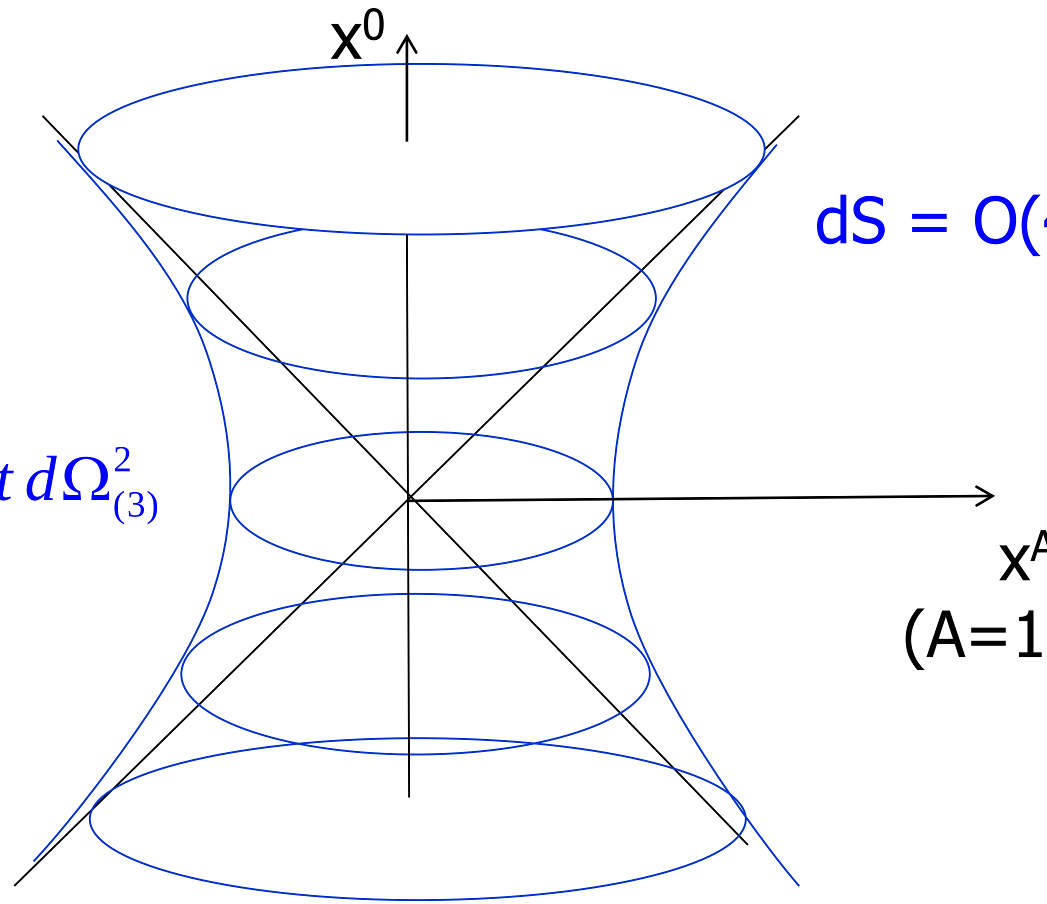
- Most plausible state of the universe before inflation is dS vacuum with $\rho_v \sim< M_P^4$

dS space = solution with maximal symmetry (dS symmetry)

a hyperboloid in 5 dim Minkowski space

dS = O(4,1)

$$ds^2 = -dt^2 + \cosh^2 Ht \, d\Omega_{(3)}^2$$



quantum tunneling = classically forbidden = imaginary time

(~ WKB approximation)

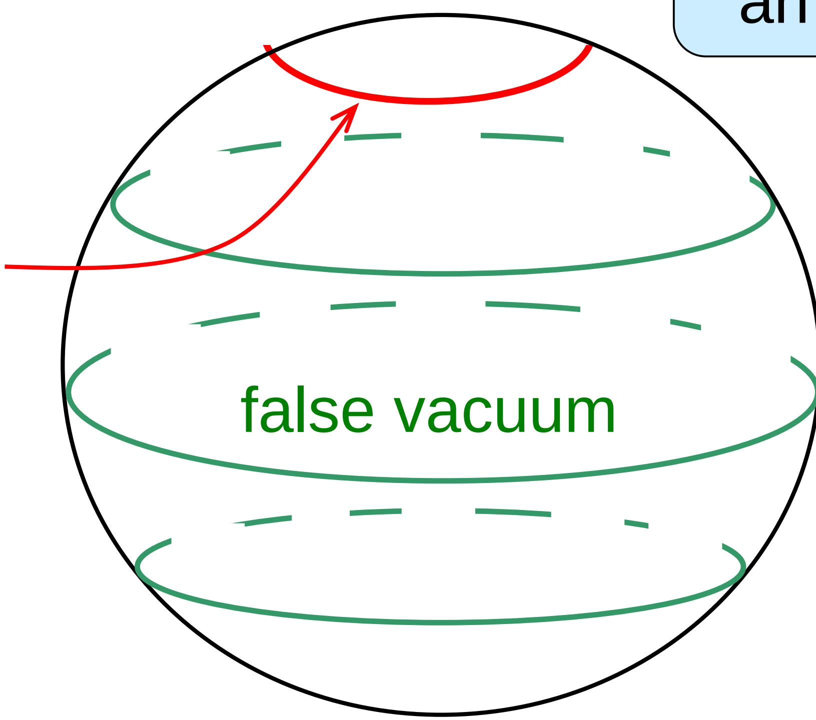
dS = O(4,1) → O(5) = S^4 : 4-sphere in 5 dim Euclidean space

false vacuum decay via O(4) symmetric (CDL) instanton

Coleman & De Luccia ('80)

forbidden O(4) → allowed O(3,1) ⟷ inside bubble is an open universe

bubble wall



$$\tau^2 + \vec{x}^2 = R^2$$

(sphere)

$$\Downarrow$$

$$-t^2 + \vec{x}^2 = R^2$$

(hyperboloid)

creation of open universe

MS, Tanaka, Yamamoto & Yokoyama (1993)

ds vacuum :O(4,1)

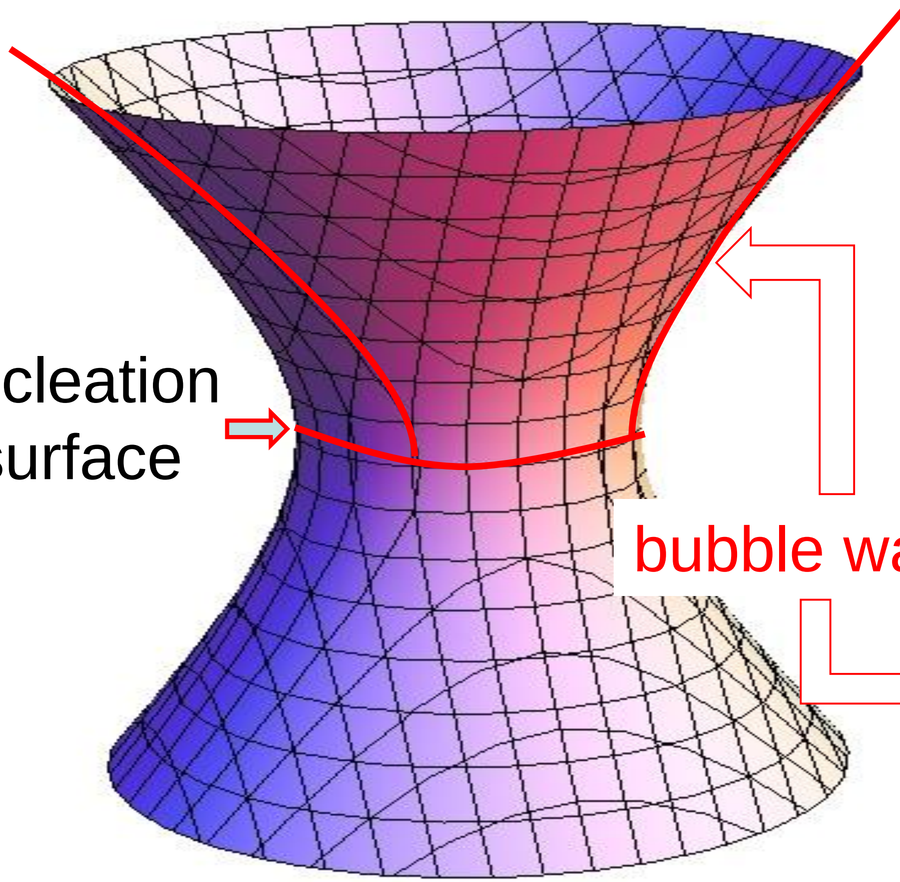
⇩

Euclidean instanton: O(4)

⇩

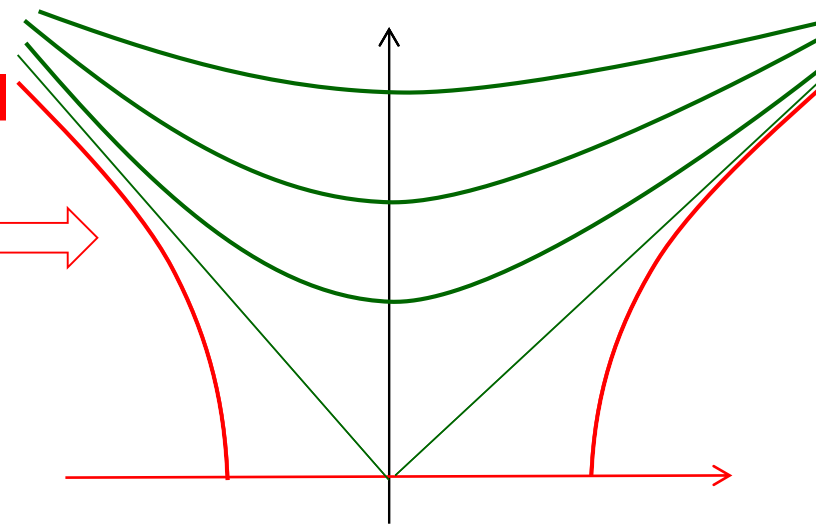
nucleated bubble: O(3,1)
=open universe

nucleation surface



bubble wall

t = const slice = open



http://www.georgehart.com/skewers/skewer-hyperboloid.html

creation of open universe in conformal diagram

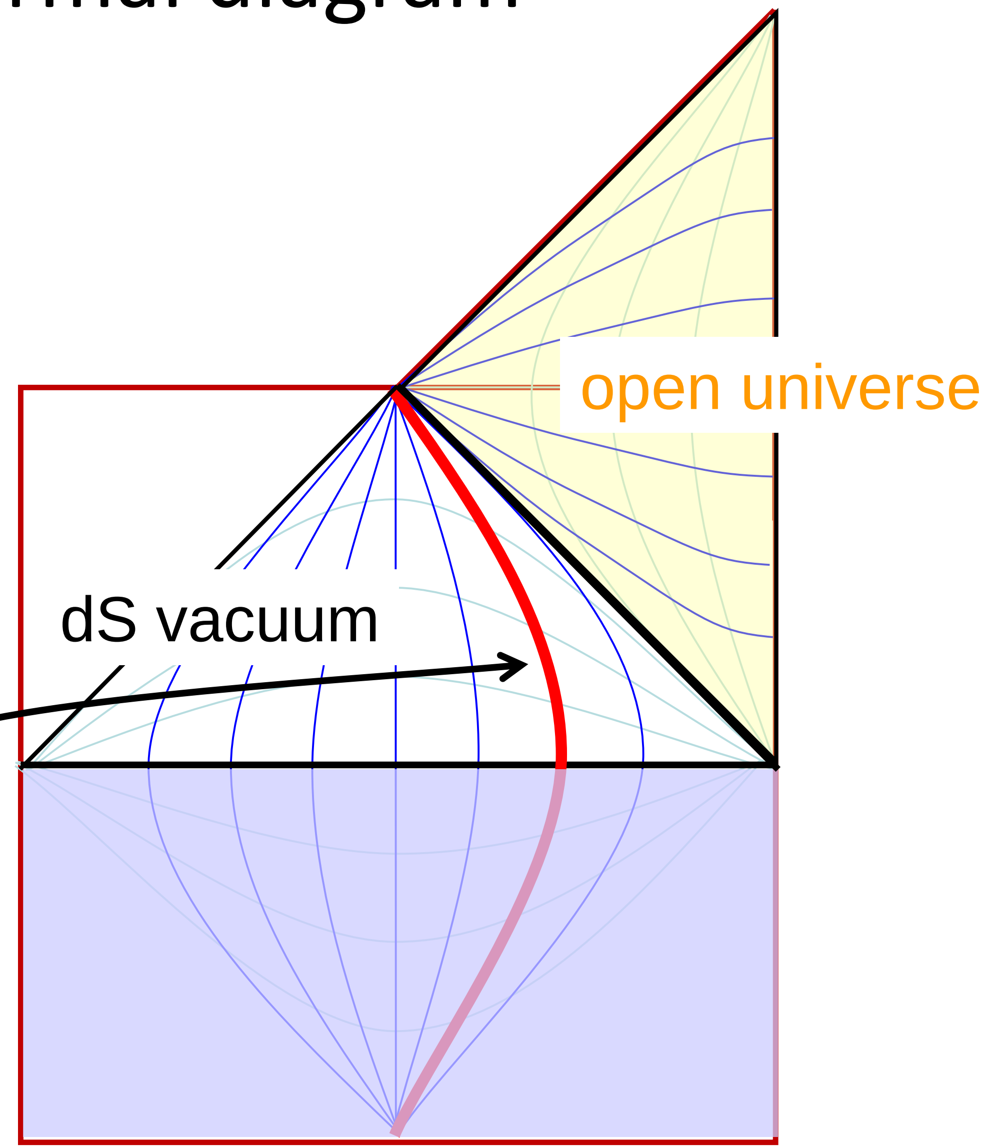
ds vacuum :O(4,1)

⇩

Euclidean bubble: O(4)

⇩

nucleated bubble: O(3,1)
=open universe



Open Inflation

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

$a(t)$: cosmic scale factor (= curvature radius)

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

density parameter

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

("0" stands for current value)

If inflation after tunneling was short enough (N = 50 ~ 60)

$$1-\Omega_o = 10^{-2} \sim 10^{-3}$$ open universe is still possible

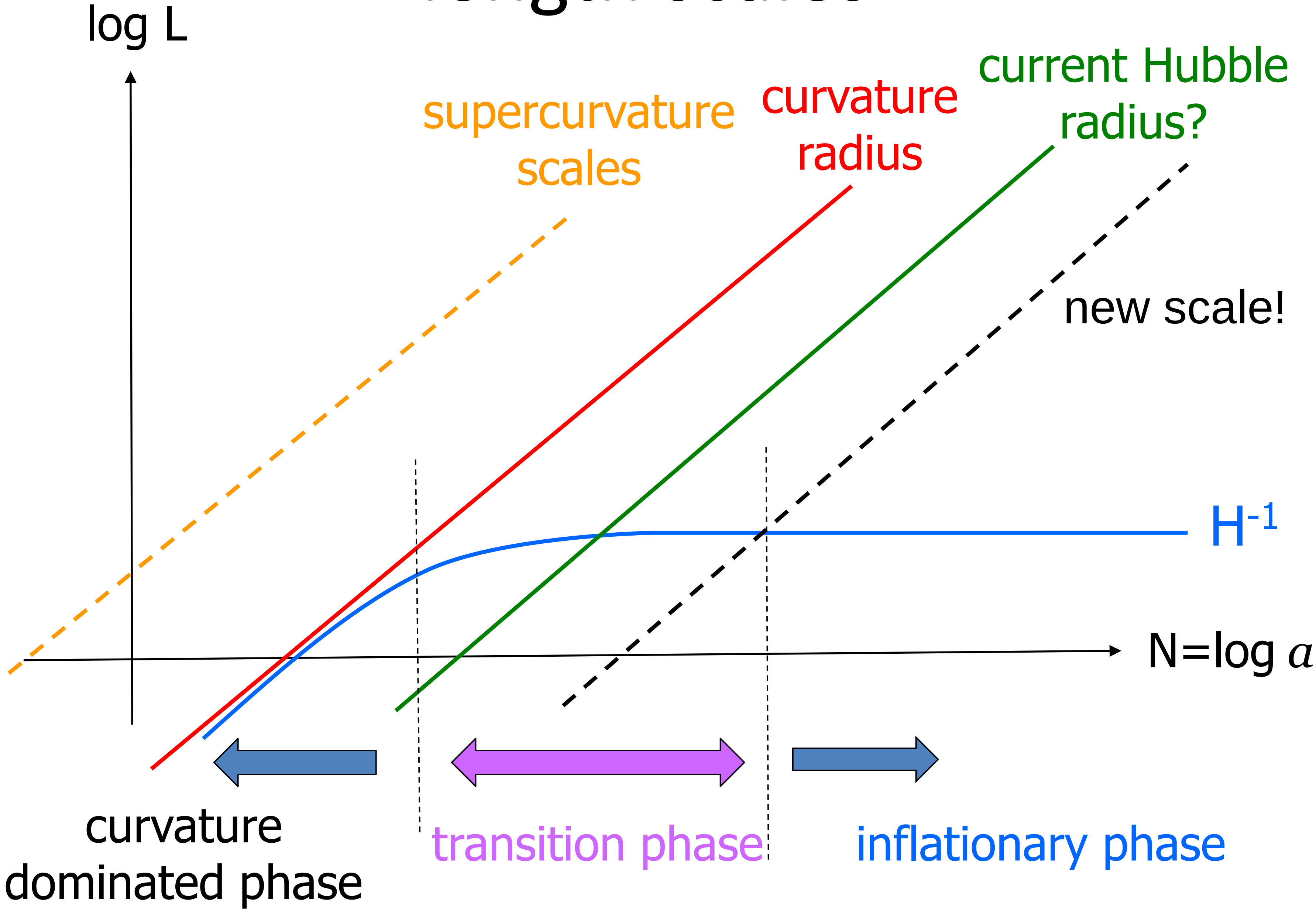
eg, anthropic argument by Garriga, Tanaka & Vilenkin '99

any signature in large angle CMB anisotropies?

Here we argue that we are already seeing a couple of such signatures on large angle CMB

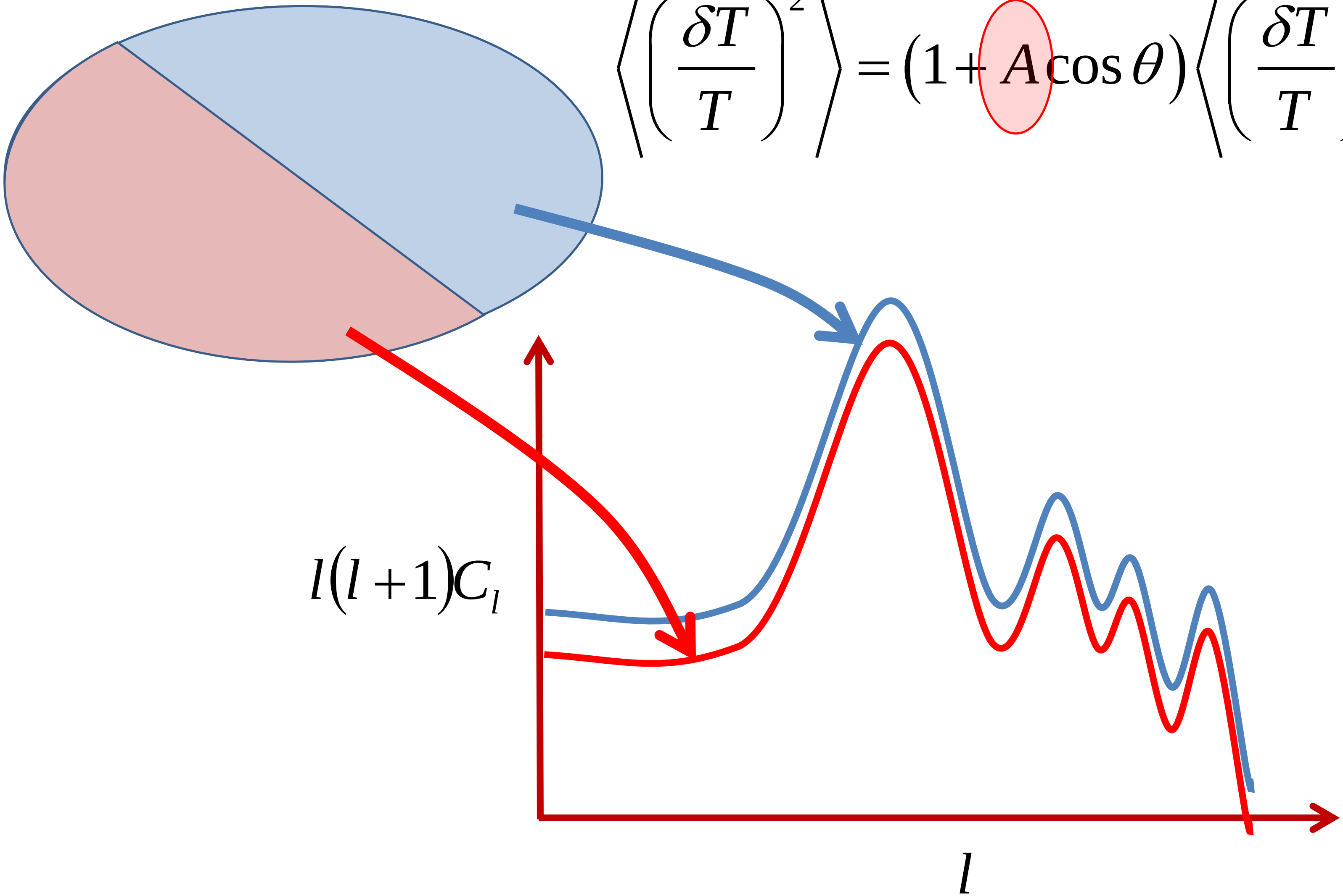
- dipolar statistical anisotropy
- tensor-scalar ratio: Planck & BICEP2/Keck

length scales

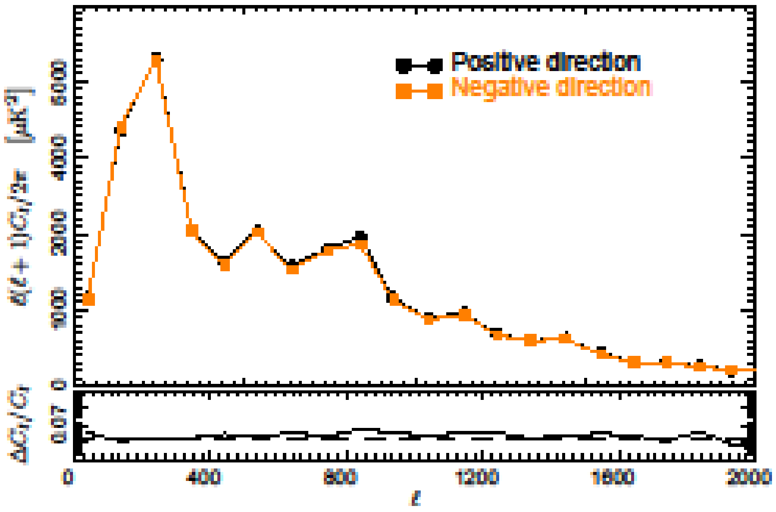


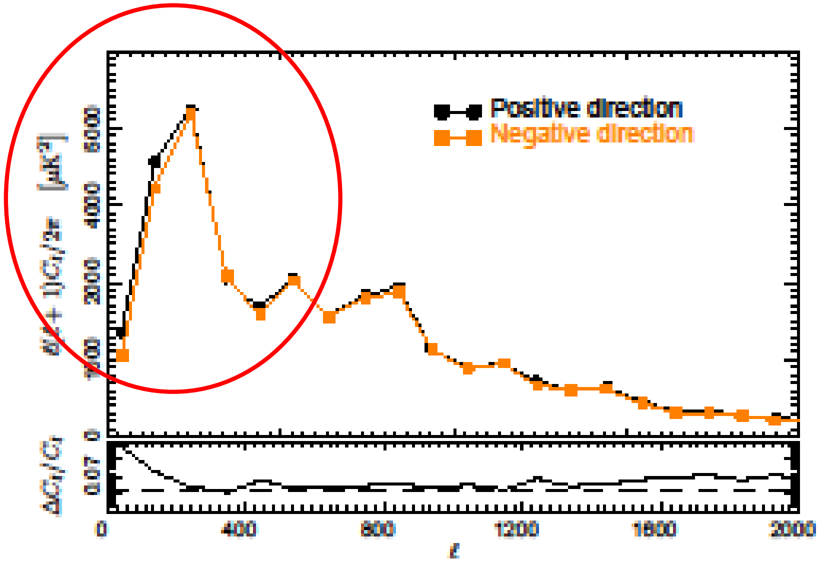
Dipolar Statistical Anisotropy

$$\left\langle \left(\frac{\delta T}{T} \right)^2 \right\rangle = \left(1 + A\cos\theta\right) \left\langle \left(\frac{\delta T}{T} \right)^2 \right\rangle_{\text{iso}}$$



dipole asymmetry observed by WMAP/Planck





asymmetry of C_l in the direction of ell=1

dipole asymmetry of C_l in the direction maximizing the asymmetry

Planck 2013 XXIII

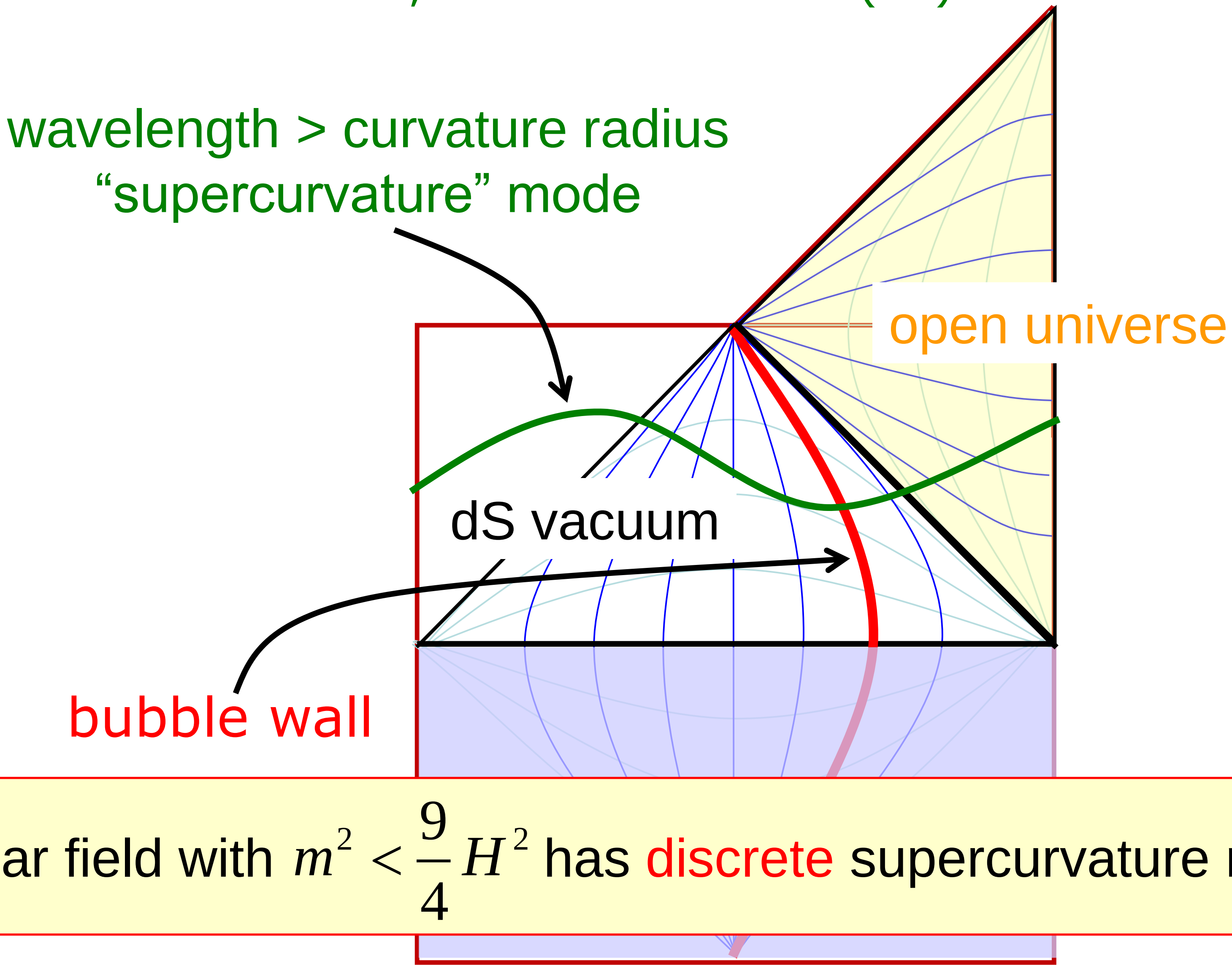
$$\left\langle\left(\frac{\delta T}{T}\right)^2\right\rangle = (1 + A\cos\theta) \times \left\langle\left(\frac{\delta T}{T}\right)^2\right\rangle_{\text{iso}}$$

$$A \approx 0.07$$

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
[illegible]der	7	$0.062^{+0.028}_{-0.030}$	$(223, -8) \pm 45$	4.0	2.0σ
[illegible]	7	$0.055^{+0.029}_{-0.030}$	$(225, -10) \pm 53$	3.4	1.7σ
[illegible]	7	$0.055^{+0.029}_{-0.030}$	$(226, -10) \pm 54$	3.3	1.7σ
[illegible]	7	$0.048^{+0.029}_{-0.029}$	$(226, -11) \pm 58$	2.8	1.5σ
[illegible]der	8	$0.043^{+0.032}_{-0.029}$	$(218, -15) \pm 62$	2.1	1.2σ
[illegible]	8	$0.049^{+0.032}_{-0.031}$	$(223, -16) \pm 59$	2.5	1.4σ
[illegible]	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

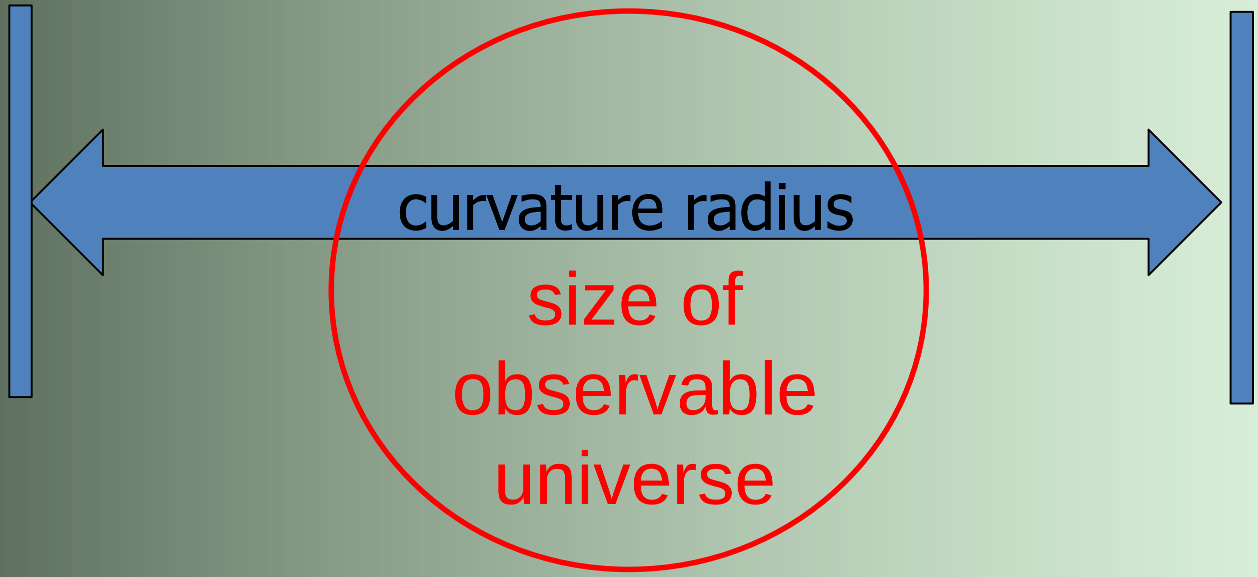
supercurvature mode

MS, Tanaka & Yamamoto ('94)



scalar field with $m^2 < \frac{9}{4}H^2$ has discrete supercurvature mode

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



may modulate the amplitude of perturbation depending on the direction.

leading order effect is dipolar

a viable model

Kanno, MS & Tanaka (2013)

$$L = -\frac{1}{2}(\nabla\phi)^2 - V(\phi) - \frac{1}{2}(\nabla\sigma)^2 - m_\sigma^2\sigma^2 - \frac{1}{2}f^2(\sigma)(\nabla\chi)^2 - \frac{1}{2}m_\chi^2\chi^2$$

(σ, χ)-sector ~ "axion"-like

ϕ : inflaton

σ : isocurvature mode with super-curvature perturbation $\Delta\sigma$

χ : curvaton

H_F : Hubble at false vacuum ⇨ $H_F^2 \gg m_\sigma^2 \approx H^2 \gg V''(\phi) \gg m_\chi^2$

- curvature perturbation is almost Gaussian

$$\mathcal{R}_c = N_\phi \delta\phi + N_\chi \delta\chi + \cancel{\frac{1}{2}N_{\chi\chi}\delta\chi^2} + \cdots$$

$$\left\langle \delta\phi^2 \right\rangle \approx H^2, \quad \left\langle \delta\chi^2 \right\rangle \approx \frac{H^2}{f^2(\sigma+\Delta\sigma)}$$

$$P_S(k) \approx \left[N_\phi^2 H^2 + N_\chi^2 \frac{H^2}{f^2(\sigma + \Delta\sigma)} \right]_{k/a=H}$$

dipolar modulation through $f(\sigma)$

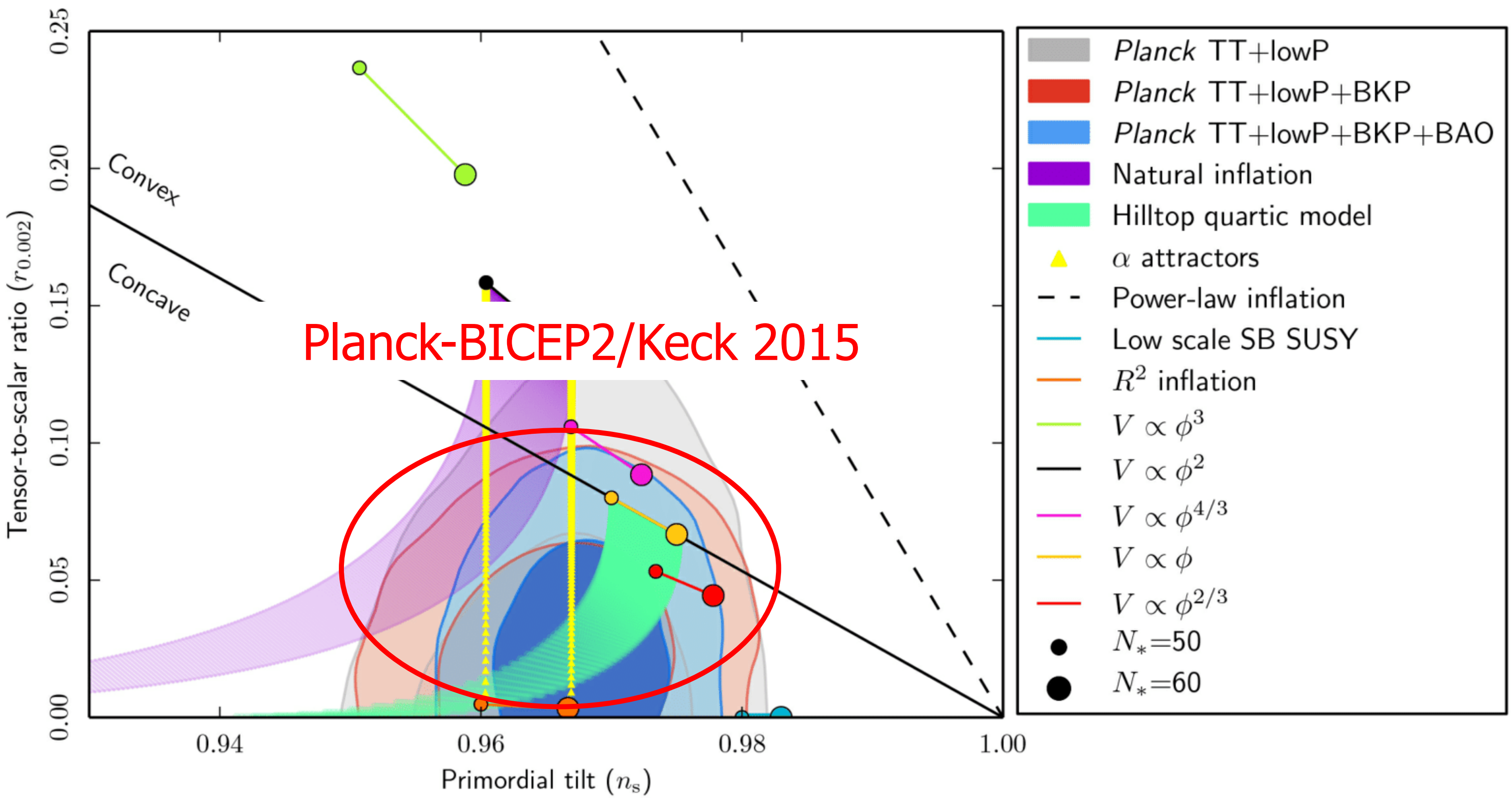
χ-field is a "free" field (no direct coupling to inflaton)

⇨ no significant non-Gaussianity, nor quadrupole

σ-field eventually dies out (because $m_\sigma \sim H$)

⇨ modulation is larger on larger scales
= consistent with Planck 2013

tensor-scalar ratio

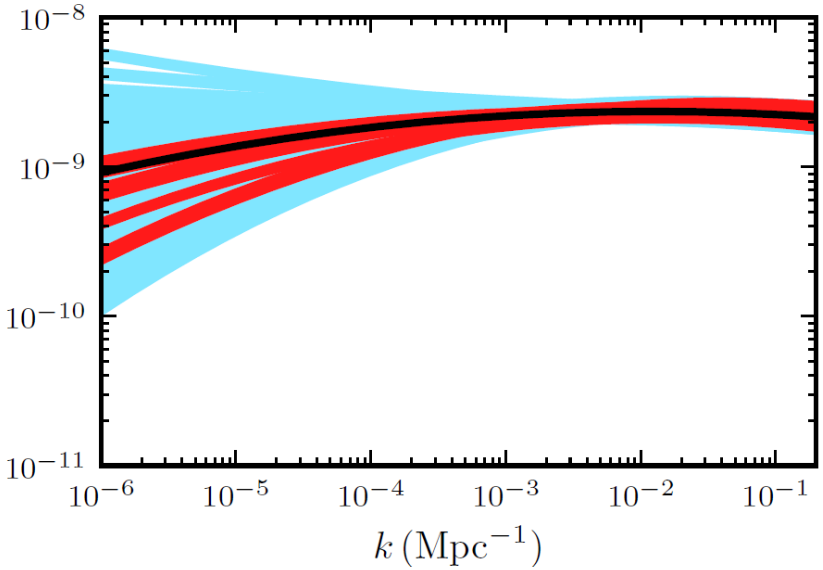


if r >~ 0.05, models with non-constant n_s are favored

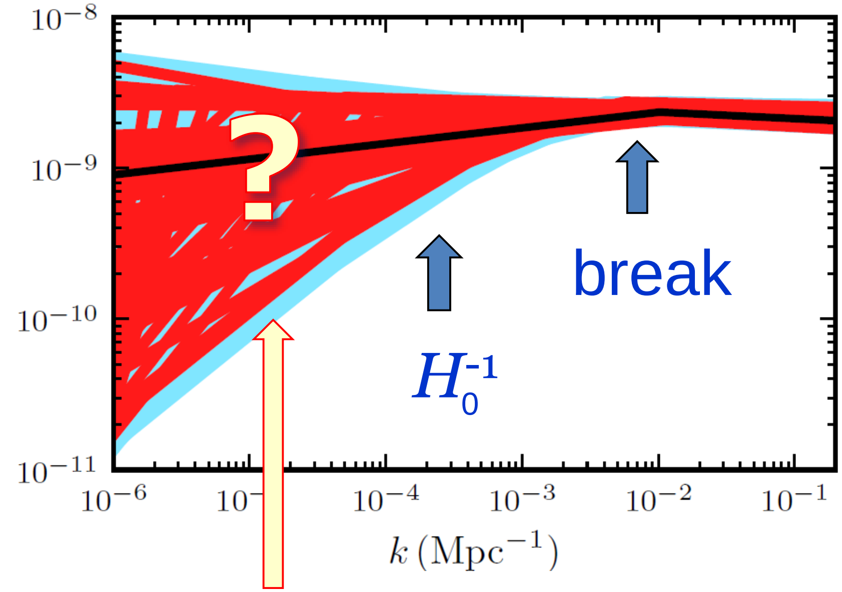
can open inflation explain this? -- Yes!

observational indication

running spectrum



broken spectrum



Model	$\Delta \log Z_{\text{Broad}}$	$\Delta \log Z_{\text{Informative}}$	$2\Delta \log \mathcal{L}_{\max}$
No Knots	—	—	
1 Knot	1.6	3.1	6.2

Model	$\Delta \log Z_{\text{Broad}}$	$\Delta \log Z_{\text{Informative}}$	$2\Delta \log \mathcal{L}_{\max}$
$\Lambda\text{CDM} + r$	—	—	—
Cutoff	0.2	0.6	1.9
Running	1.1	—	3.8

Bayesian evidence

curvature radius?

broken spectrum is favored with r~0.1

Abazajian et al.,
arXiv:1403.5922 [astro-ph.CO]

fast-roll phase in open inflation

- curvature dominant phase

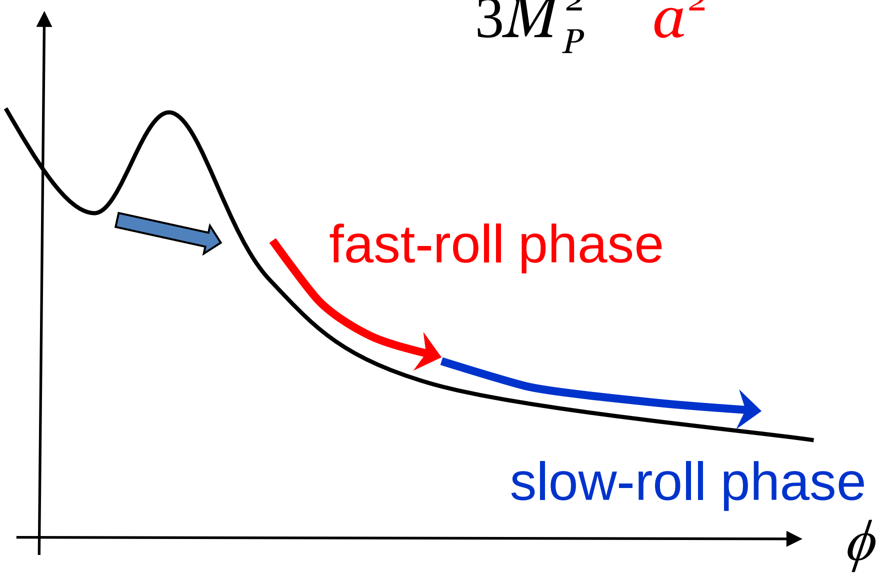
  right after tunneling, H is dominated by curvature:

  $$a \approx t, \quad \dot{\phi} \approx -\frac{V'(\phi)}{4} t$$

  curvature dominance ends at $t_* \approx H_*^{-1} \approx M_P \sqrt{3/V}$ for $\varepsilon_{V*} \lesssim 1$

  $$\varepsilon_V \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2$$

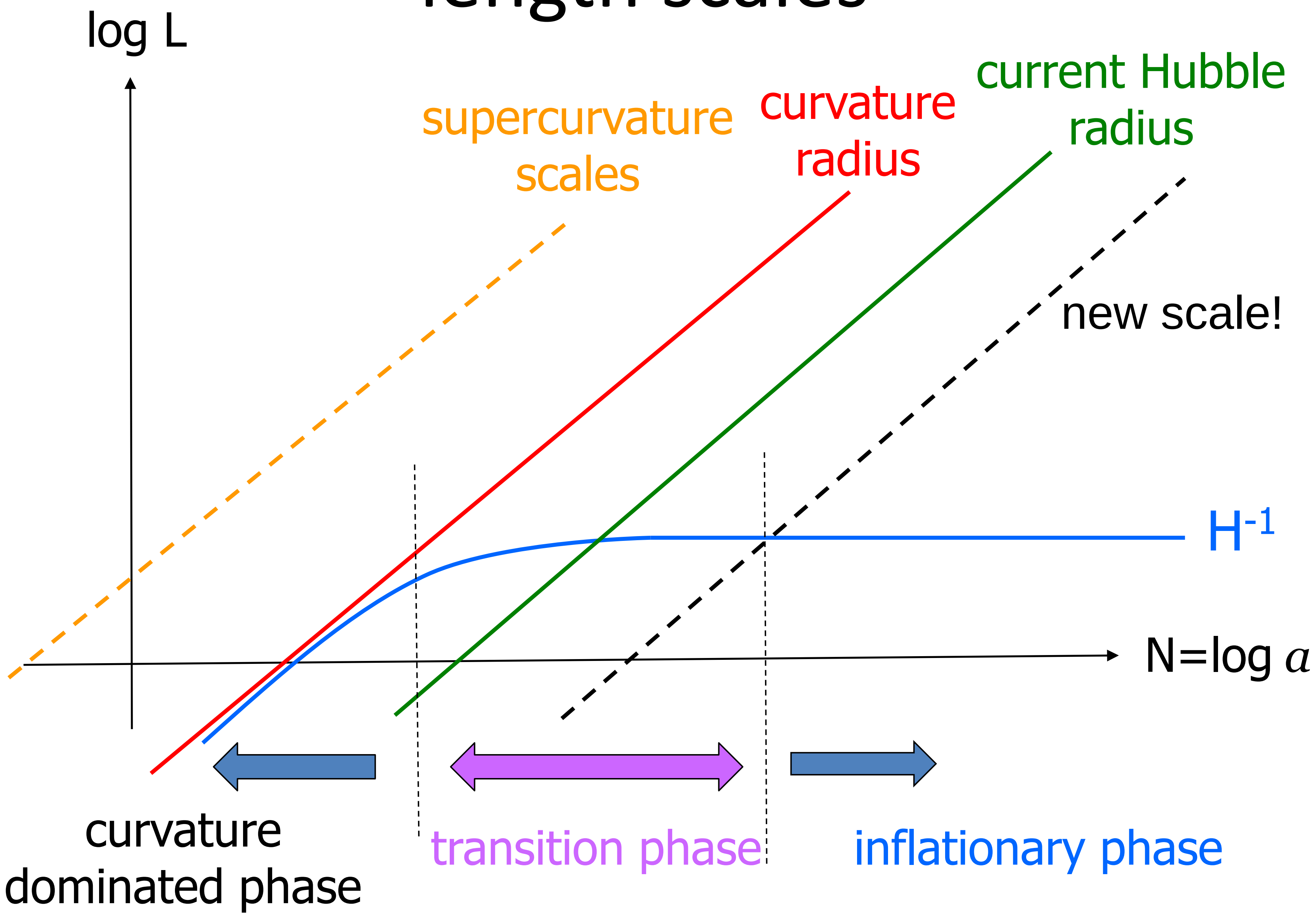
$$H^2 = \frac{\rho}{3M_P^2} + \frac{1}{a^2}$$



- fast-roll phase

  lasts for a few e-folds until ε_V becomes small.

length scales



theoretical (qualitative) predictions

- suppression of curvature perturbation during the first few e-folds (↔large scales) of open inflation

$$P_S(k) \approx \frac{H^2}{2\varepsilon(2\pi)^2 M_{pl}^2} \; : \qquad \varepsilon \equiv -\frac{\dot{H}}{H^2}$$

- no suppresion in tensor perturbation

$$P_T(k) = \frac{8H^2}{(2\pi)^2 M_{pl}^2} \quad \Rightarrow \quad \boxed{r \equiv \frac{P_T}{P_S} = 16\varepsilon}$$

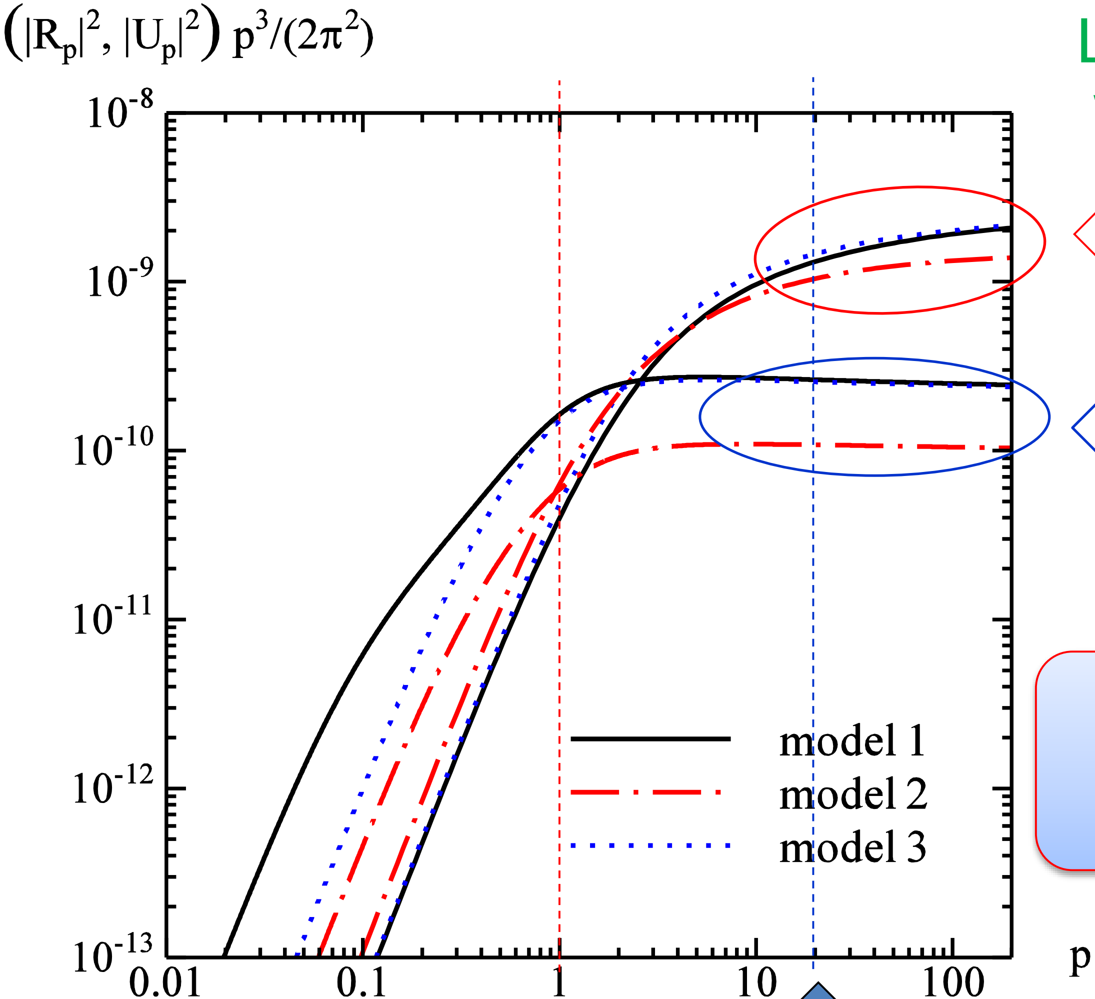
- curvature scale at the beginning of fast-roll phase t = t*

$$\left.\frac{R_{\rm curv}}{H^{-1}}\right|_* \sim e^{O(1)} \;(\text{say} \sim 5) < \left.\frac{R_{\rm curv}}{H^{-1}}\right|_0 = \Omega_K^{-1/2}$$

$$\Rightarrow \quad \boxed{\Omega_K < 0.04}$$

scalar & tensor spectrum in open inflation

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



scalar

tensor
(no suppression)

scalar suppression begins indeed at smaller scales

curvature radius

H_0^{-1} if $\Omega_K \approx 0.003$

Summary

1. Dipolar statistical anisotropy requires a non-standard inflation scenario

⇨ Modulation of the fluctuation amplitude by supercurvatue mode in open inflation

2. If r>~0.05, Planck result may be explained with $P_s(k)$ suppressed on large scales

⇨ Suppression due to fast-roll phase at the beginning of in open inflation

These may be signatures from string landscape

- embedding models in string theory?
- any other testable predictions?
- other features in CMB? LSS? ...?

Maybe we are beginning to see physics beyond inflation!

string theory landscape?