Open Inflation Reviving

- a signature of string theory landscape?-

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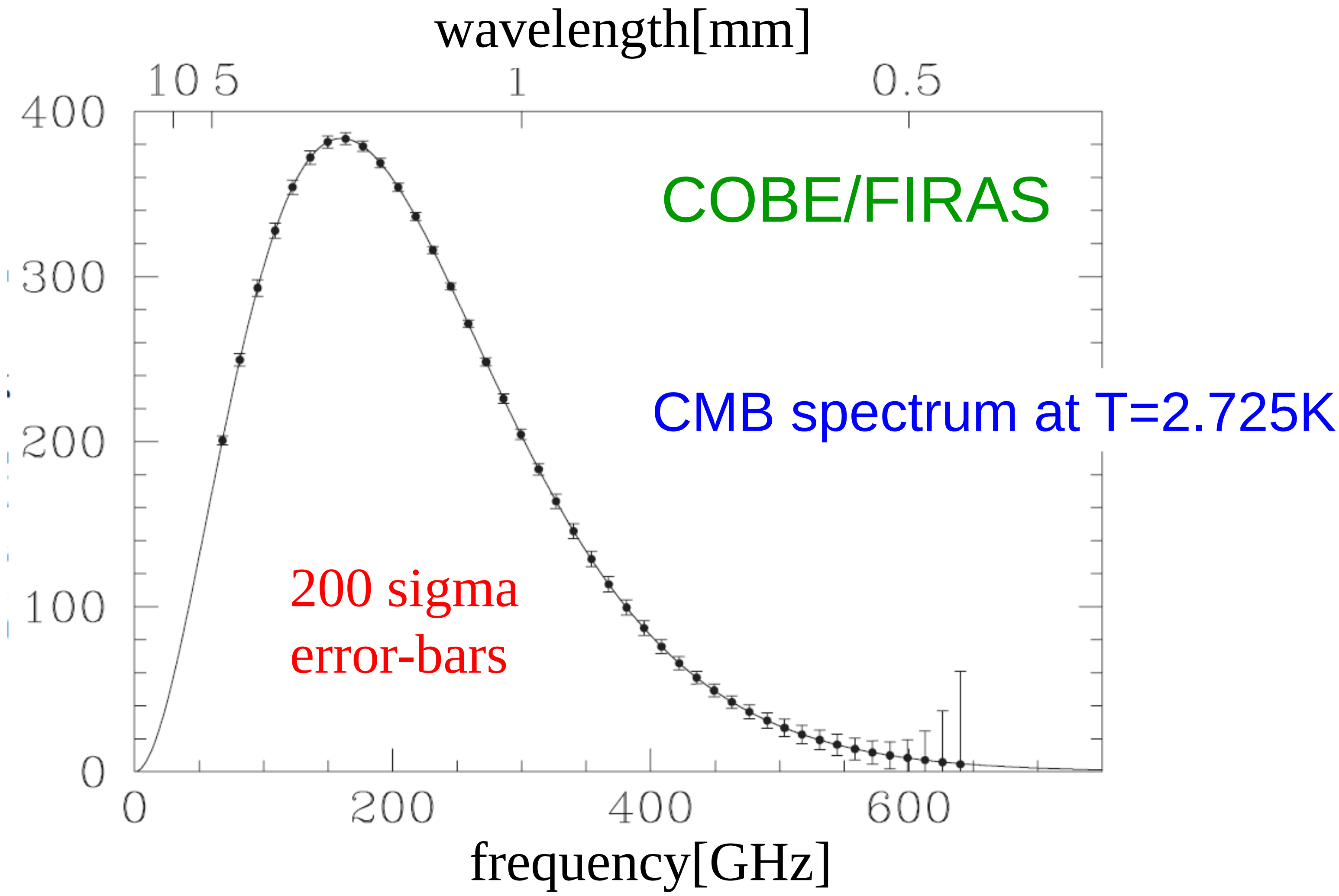
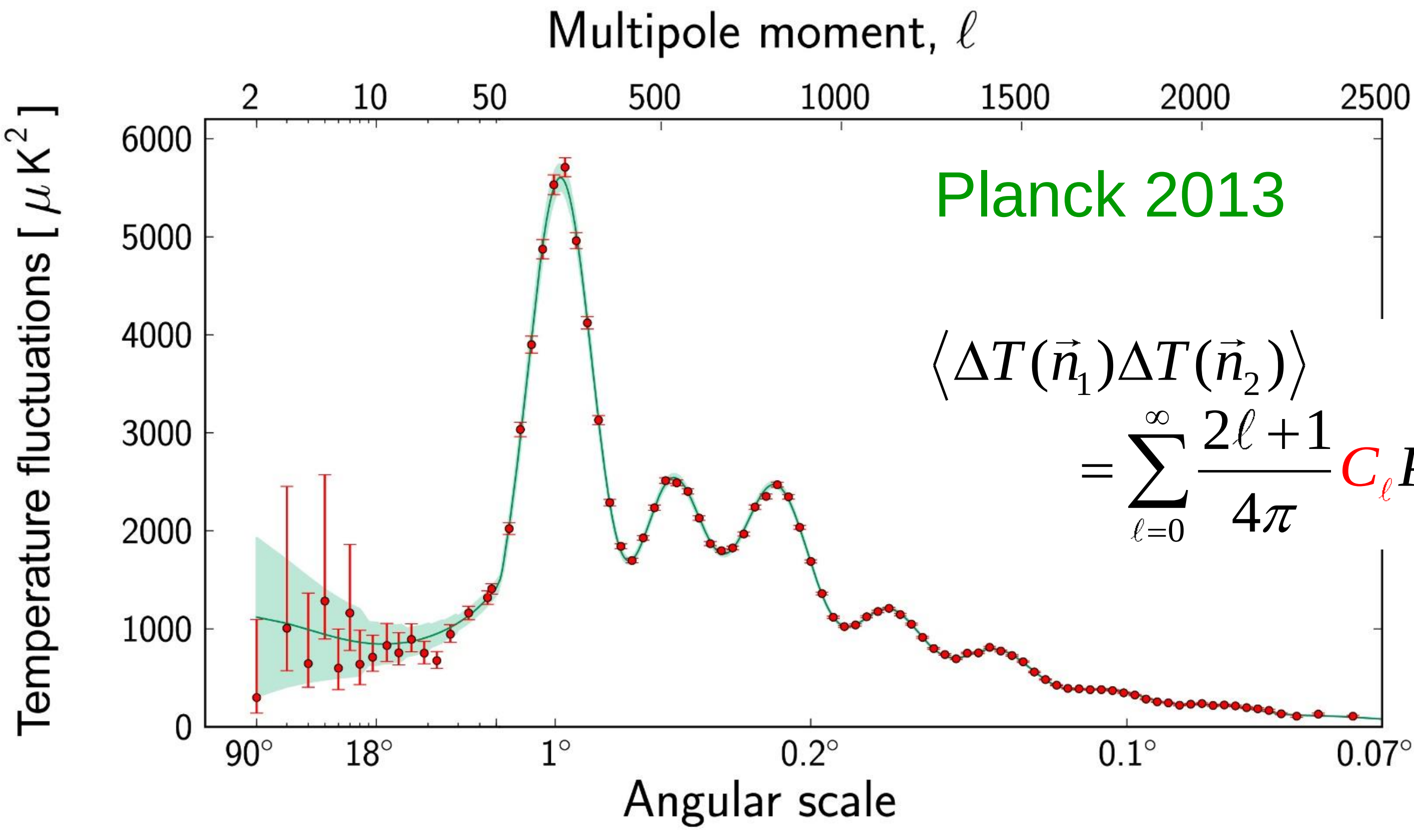
1. Era of precision cosmology

- Big Bang theory has been firmly established



Strong evidence for Inflation



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

- almost scale-invariant spectrum: $n_S = 0.960 \pm 0.0073 \;\; (68\%\ \mathrm{CL})$
- highly Gaussian fluctuations: $f_{NL}^{local} = 2.7 \pm 5.8 \;\; (68\%\ \mathrm{CL})$

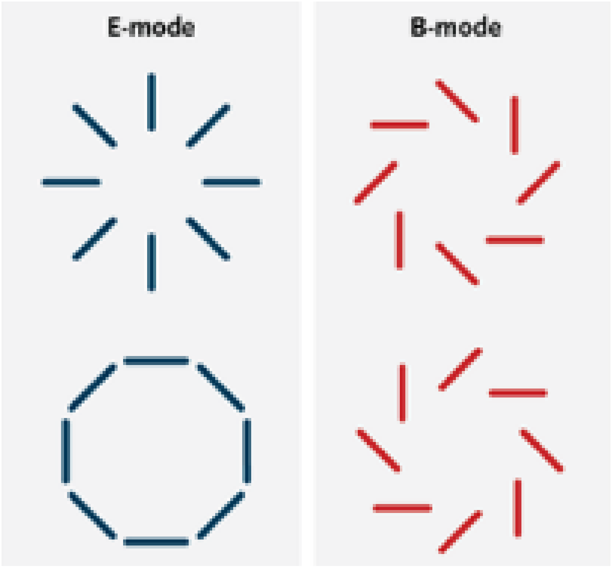
only to be confirmed (by tensor modes?!)

Discovery(?) of primordial GWs

BICEP2 (2014)

spacetime vacuum fluctuations from inflation

➡ B-mode polarization in CMB anisotropy



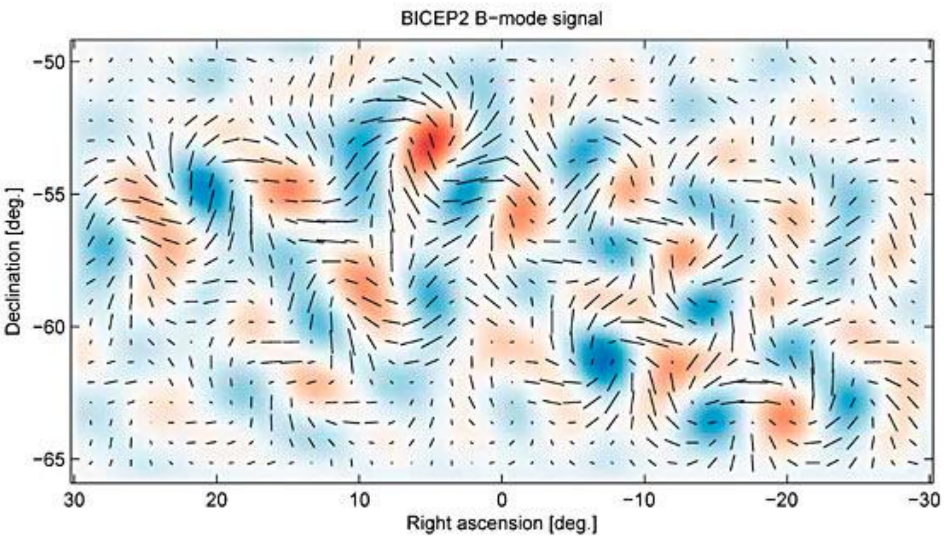
- E-mode (even parity)

⇕

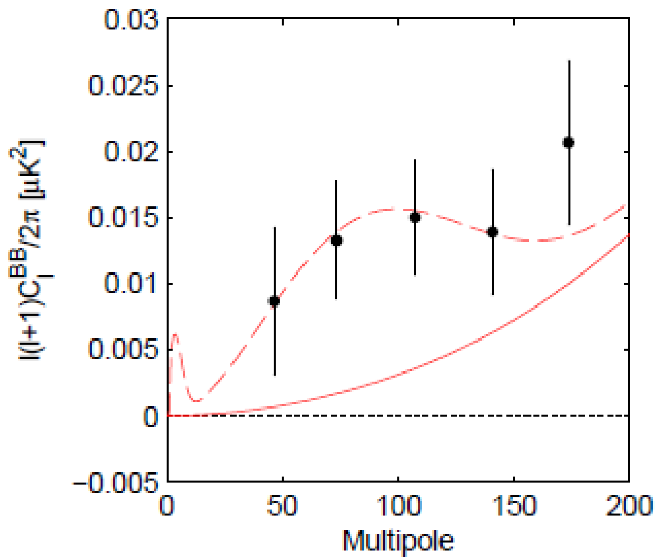
- B-mode (odd parity)
  = cannot be produced from
  density fluctuations

5

BICEP2 result



sky map



B-mode spectrum

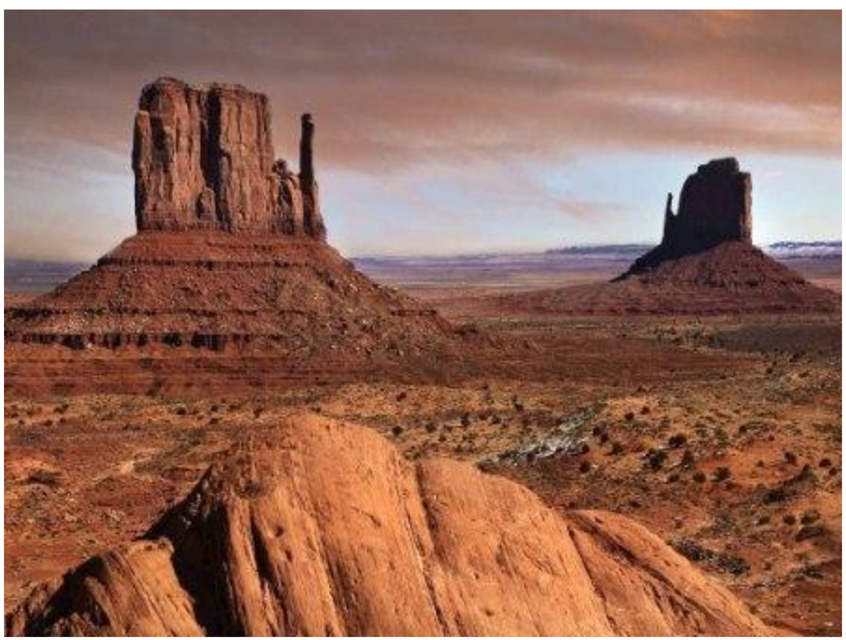
If confirmed, it "proves" primordial inflation & quantum gravity!

What’s next?

2. String theory landscape

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

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



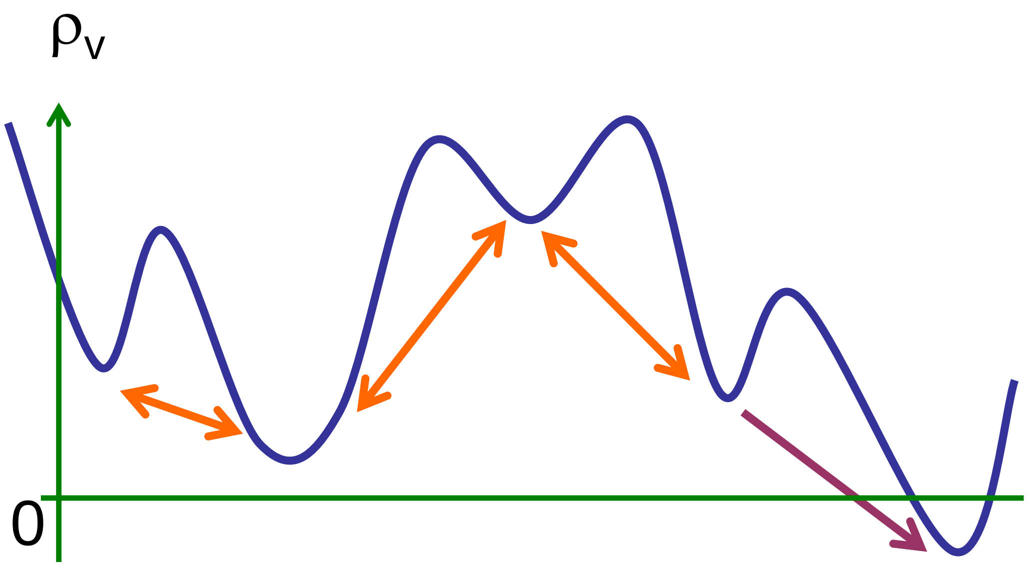
which ?

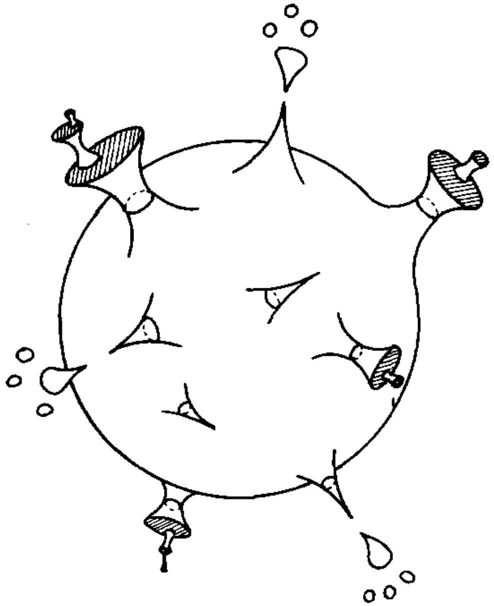
Is there any way to know what kind of landscape we live in?

Or at least to know what kind of neighborhood we live in?

- A universe jumps around in the landscape by quantum tunneling
  - it can go up to a vacuum with larger ρ_v

    (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 et al. ('81)

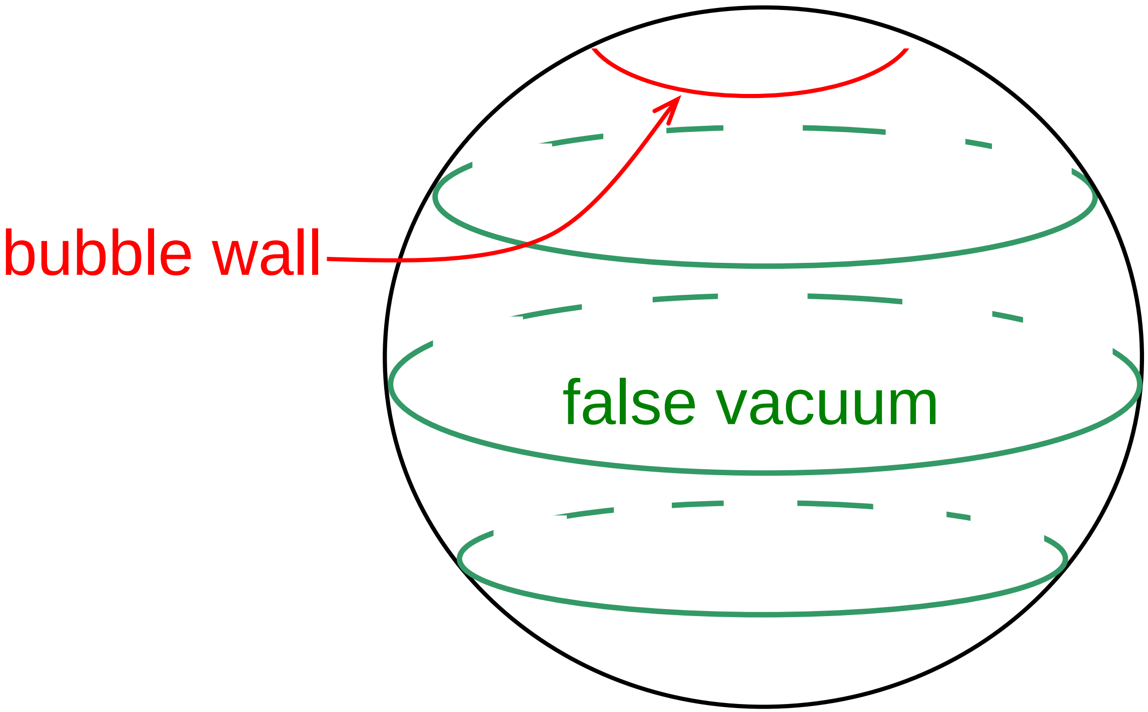
- Most plausible state of the universe before inflation is a dS vacuum with $\rho_v \sim M_P^4$. dS = O(4,1) → O(5) ~ S^4

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

Coleman & De Luccia ('80)

O(4) → O(3,1)

inside bubble is an open universe



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

$$\Downarrow$$

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

creation of open universe

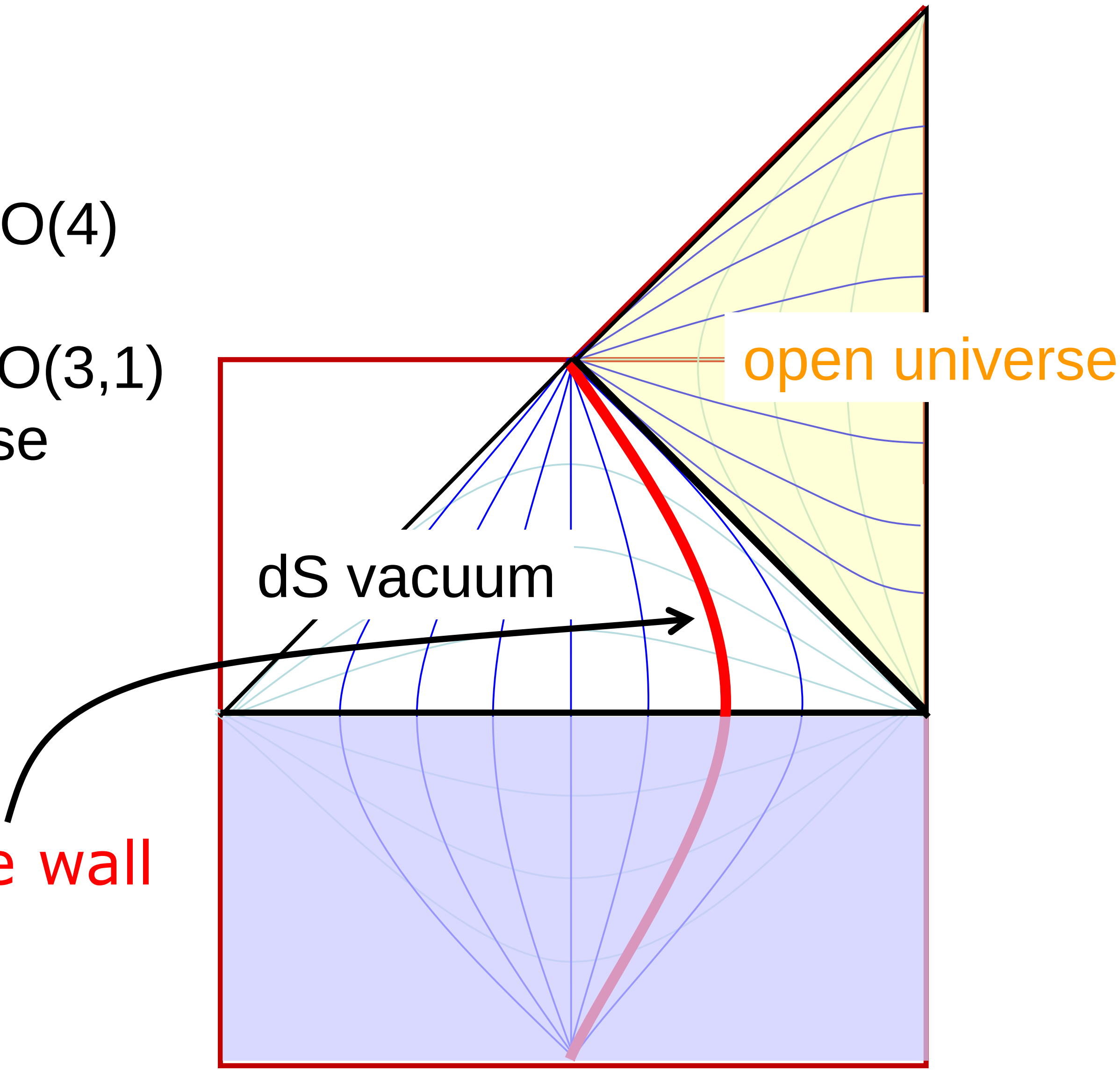
ds vacuum :O(4,1)

⇩

Euclidean bubble: O(4)

⇩

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



3. Open inflation in the landscape

- universe is inside nucleated bubble = open universe
- observational data imply $1\text{-}\Omega < 10^{-2}$: almost flat

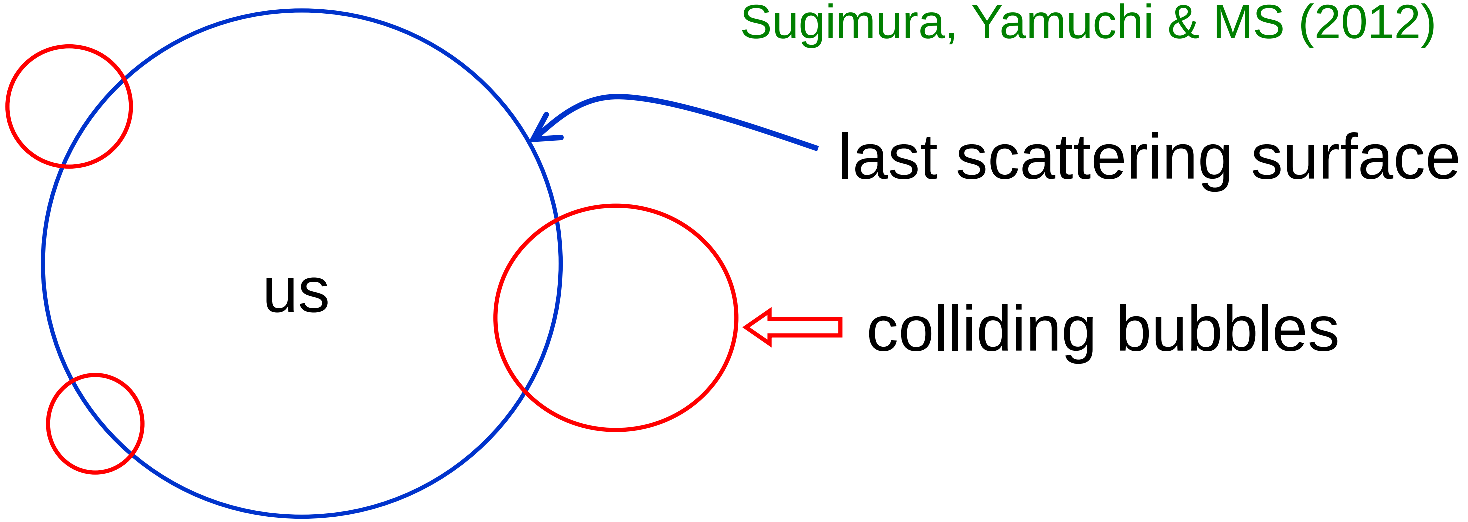
➢ two possibilities

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

$$1-\Omega_o \ll 1$$ “flat universe”

signatures from bubble collisions?

Sugimura, Yamuchi & MS (2012)



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

$1-\Omega_o = 10^{-2} \sim 10^{-3}$ "open universe"

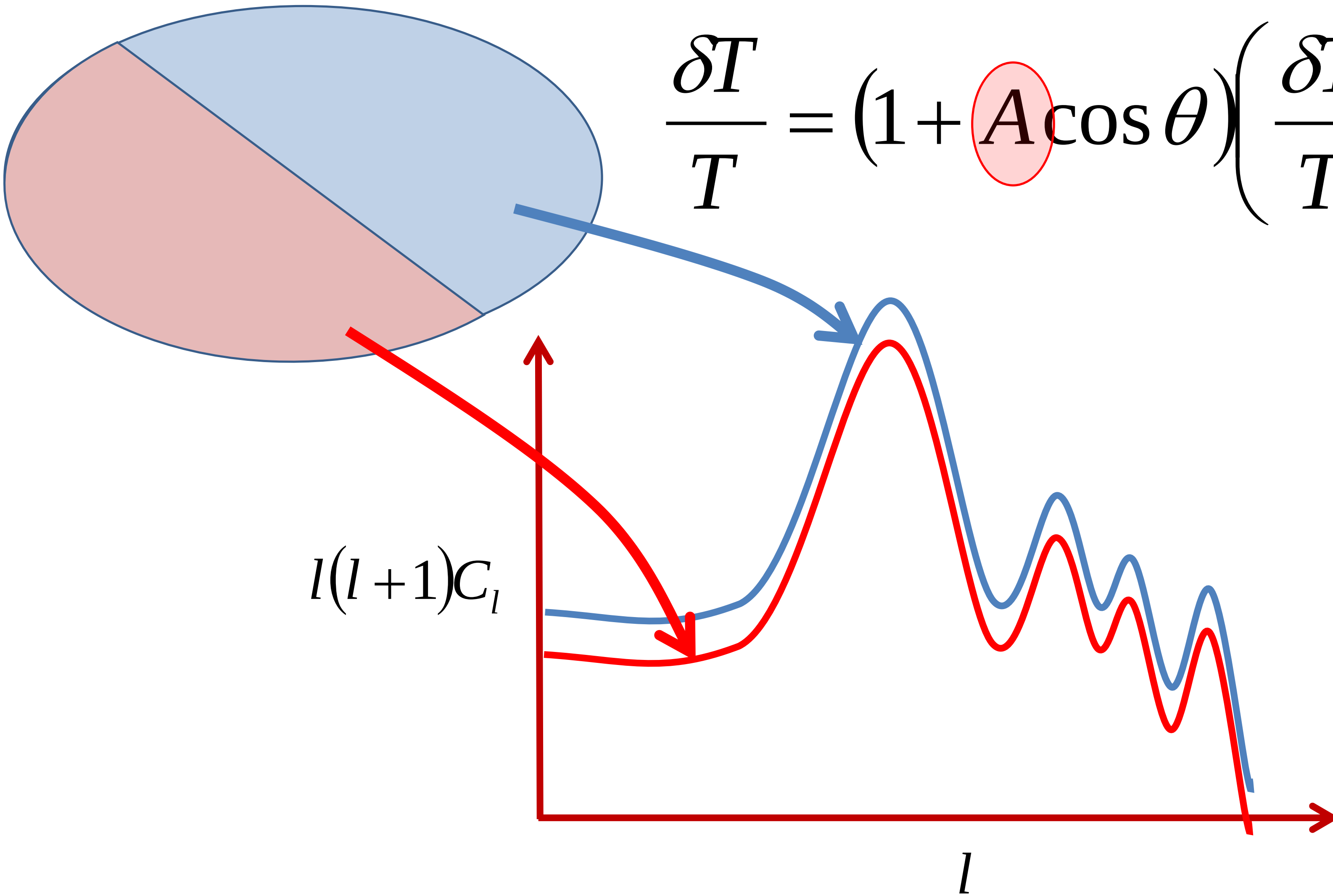
any signatures in large angle CMB anisotropies?

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

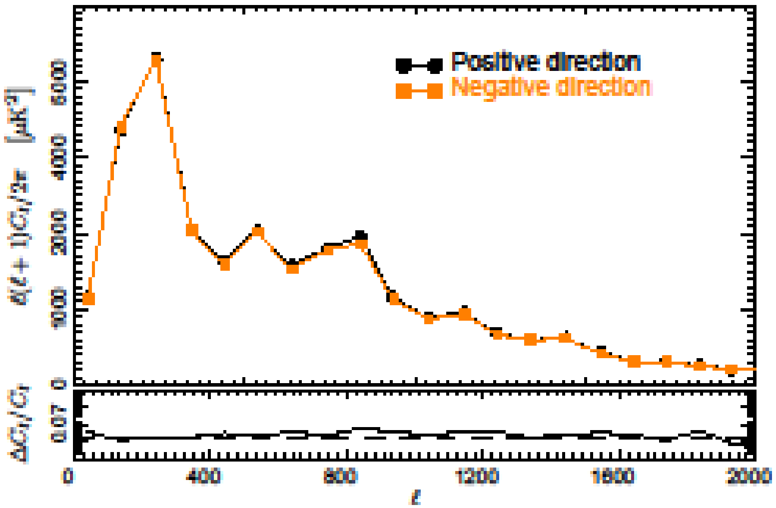
- dipolar statistical anisotropy
- tensor-scalar ratio: Planck vs BICEP2

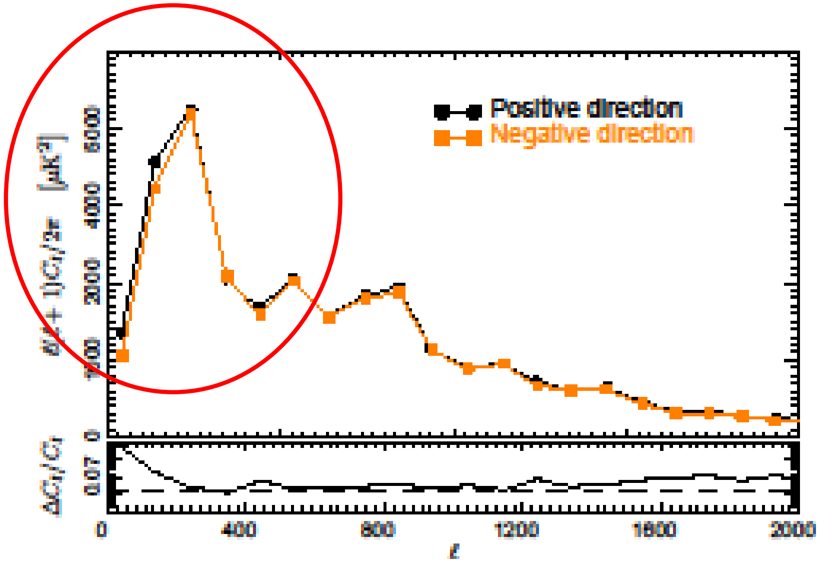
4. Dipolar statistical anisotropy

$$\frac{\delta T}{T} = \left(1 + A\cos\theta\right)\left(\frac{\delta T}{T}\right)_0$$



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

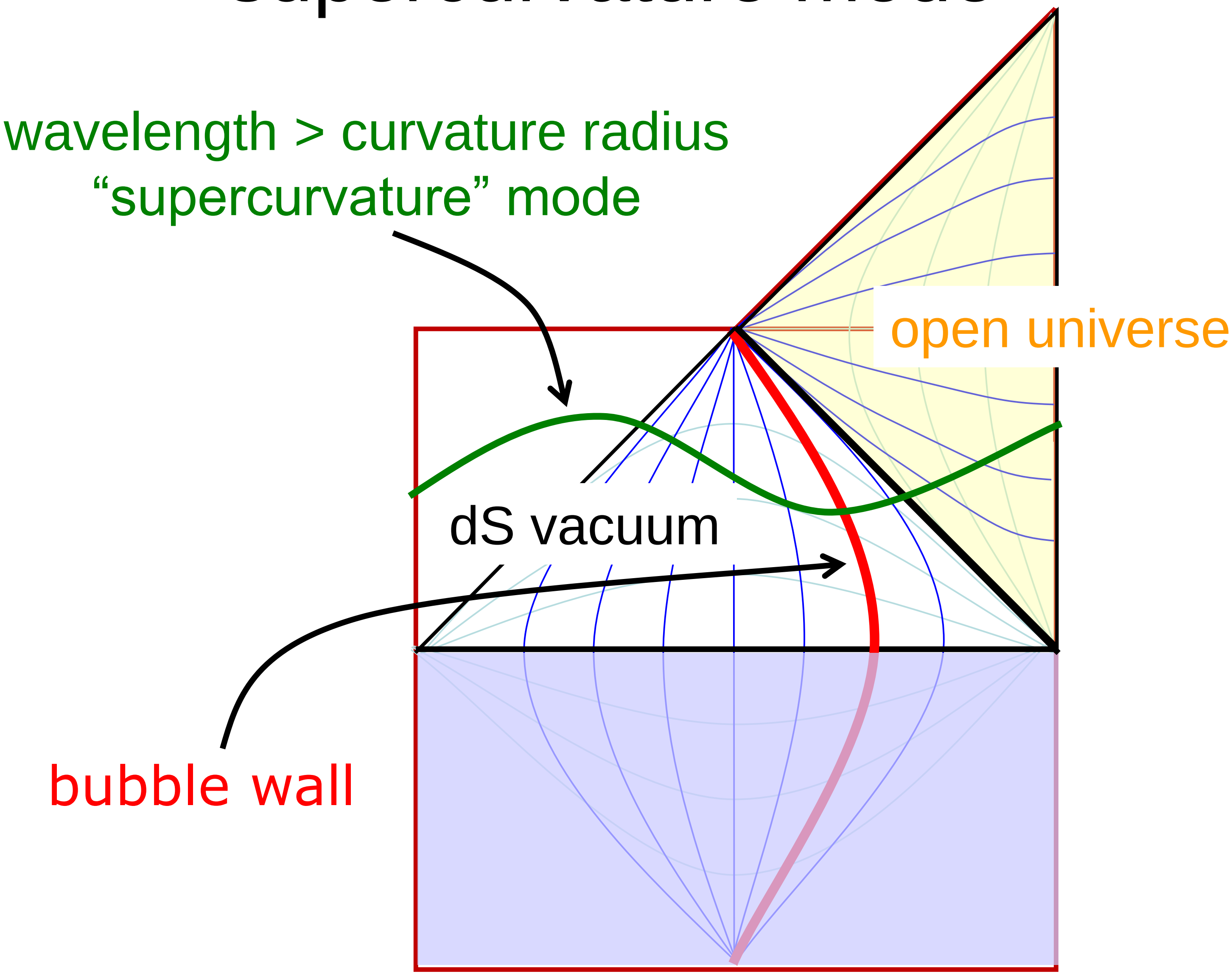
Planck XXIII

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

$$A \approx 0.07$$

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
EM	7	$0.055^{+0.029}_{-0.030}$	$(226, -10) \pm 54$	3.3	1.7σ
CA	7	$0.048^{+0.029}_{-0.029}$	$(226, -11) \pm 58$	2.8	1.5σ
mander	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

creation of open universe & 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.

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 $\Rightarrow$ $H_F^2 \gg m_\sigma^2 \approx H^2 \gg V''(\phi) \gg m_\chi^2$

- curvature perturbation is almost Gaussian

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

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

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

dipolar modulation through $f(\sigma)$

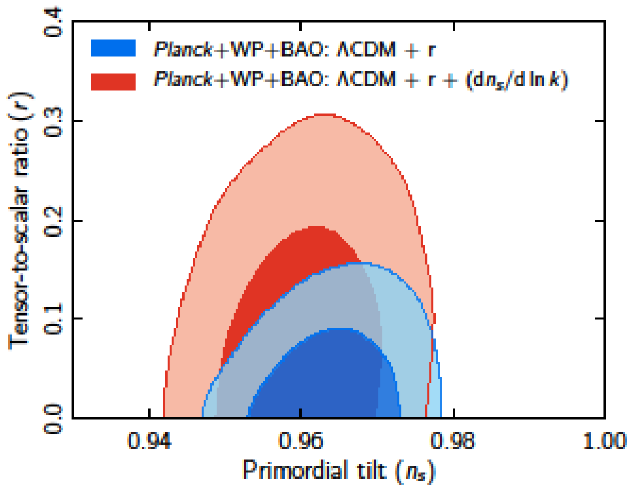
χ-field is a "free" field (no direct coupling to inflaton)

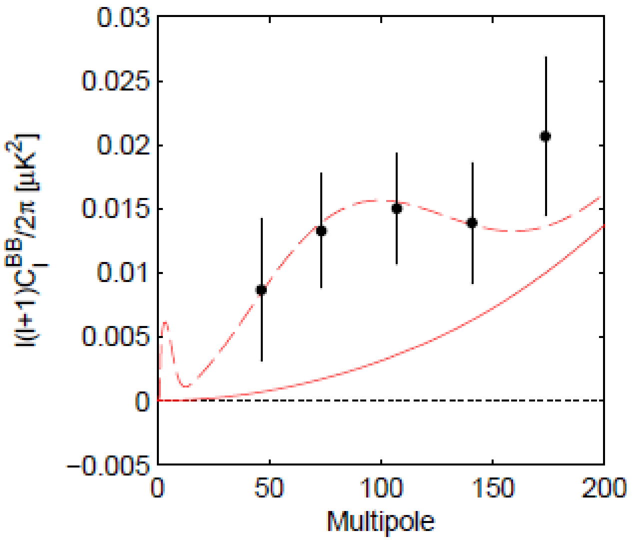
⇨ no significant non-Gaussianity, nor quadrupole

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

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

5. r-controversy?:Planck vs BICEP2





$r < 0.1$ if n_s=const.

$r \sim 0.2$

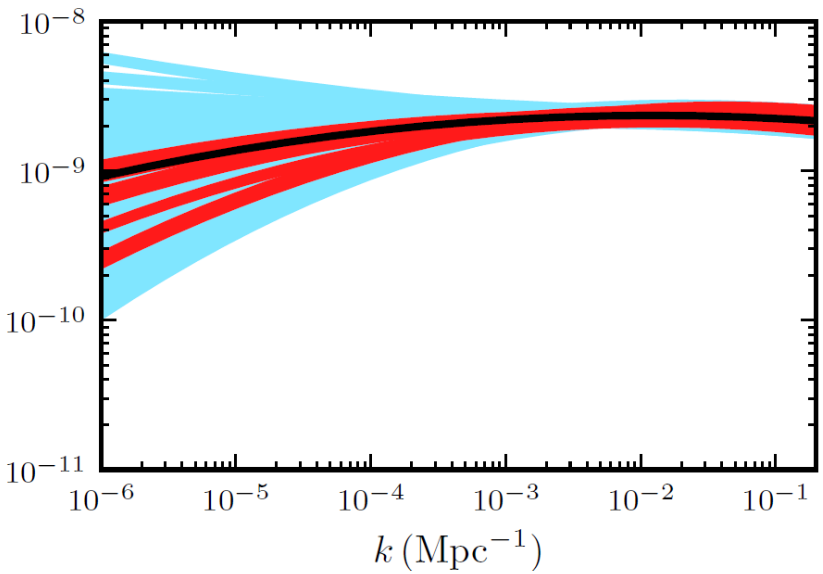
resolved if $dn_s/d\ln k<0$ (running spectral index)

broken spectrum is more favored than running

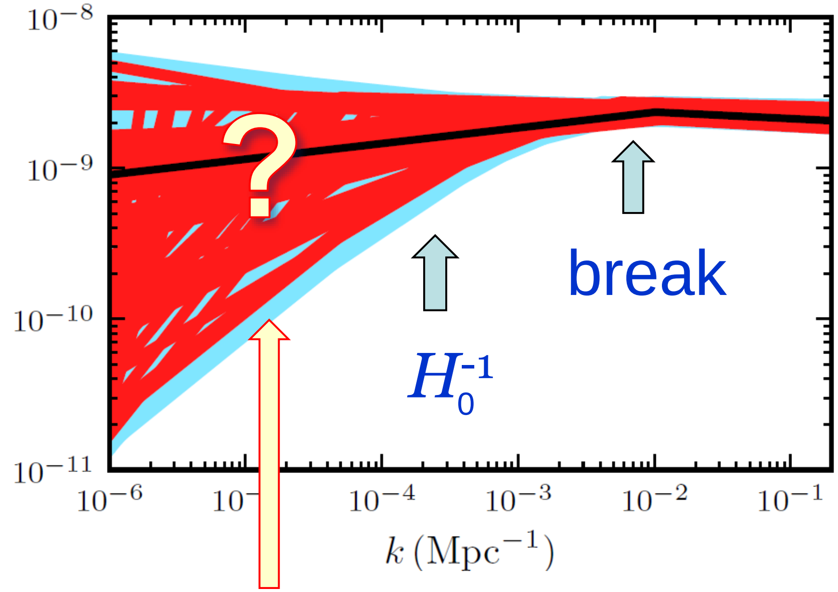
Abazajian et al. (2014)

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

curvature radius?

broken spectrum is favored

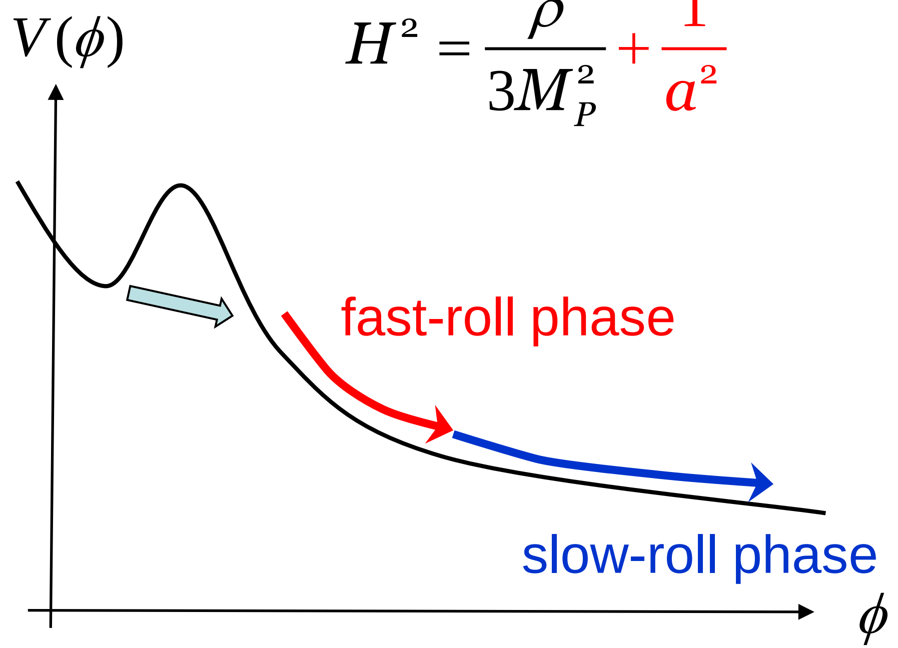
Abazajian et al., arXiv:1403.5922 [astro-ph.CO]

fast-roll phase in open inflation

- curvature dominant phase

  right after tunneling, H is dominated by curvature:

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



- fast-roll phase

  kinetic energy grows until

$$\frac{\dot{\phi}^2}{2} \approx V \quad \text{at} \quad t_* \approx 2.3 \frac{H_*^{-1}}{\sqrt{\varepsilon_V}}$$

$$\varepsilon_V \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2$$: "slow-roll" parameter

for $\varepsilon_V \sim 0.01$, there is $\Delta N = H\Delta t \sim 20$ e-folds of fast-roll phase

theoretical (qualitative) predictions

- suppression of curvature perturbation during first $\Delta N \gtrsim \varepsilon_V^{-1/2}$ e-folds ($\leftrightarrow$large scales) of open inflation

$$P_S(k) = \frac{H^2}{2\varepsilon(2\pi)^2 M_{pl}^2} \; : \qquad \varepsilon \equiv -\frac{\dot{H}}{H^2} \; \left(\gtrsim \varepsilon_V\right)$$

- no suppresion in tensor perturbation

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

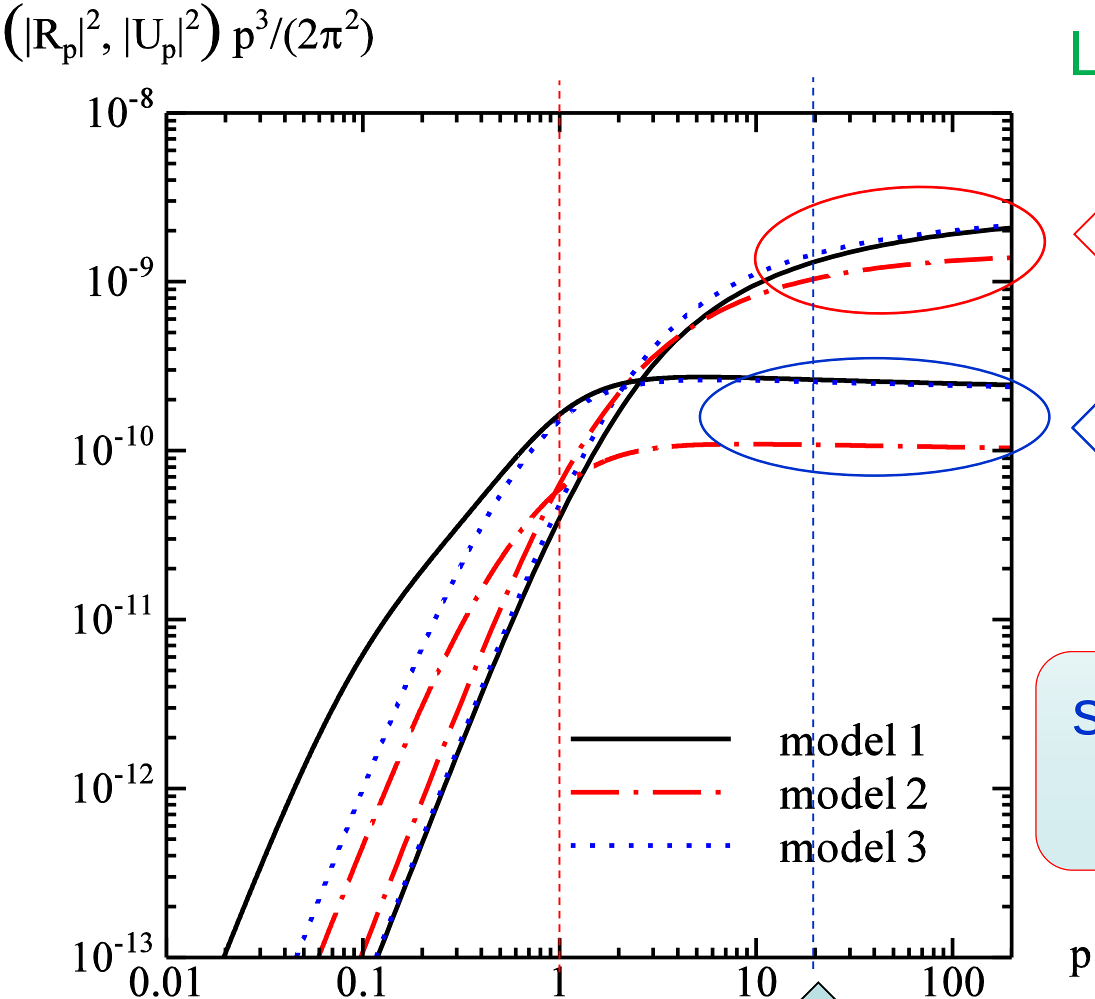
- curvature scale at the end of fast-roll phase

$$\frac{R_{\text{curv}}}{H^{-1}} \approx \frac{t_*}{H_*^{-1}} \approx 2.3\,\varepsilon_V^{-1/2} \left(\sim 20 \text{ if } \varepsilon_V = 0.01\right)$$

$$\Longrightarrow \quad \boxed{\Omega_K \lesssim 0.01}$$

scalar & tensor spectrum in open inflation

Linde, MS & Tanaka (1999)



scalar

tensor
(no suppression)

scalar suppression begins indeed at smaller scales

curvature radius

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

6. Summary

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

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

2. Tension between Planck & BICEP2 may be resolved if $P_s(k)$ is 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? ...?

We are beginning to test string landscape!