YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

IAS workshop
New Perspectives on Cosmology
HKUST, 21 May 2014

Open Inflation Reviving

- a signature of string theory landscape?-

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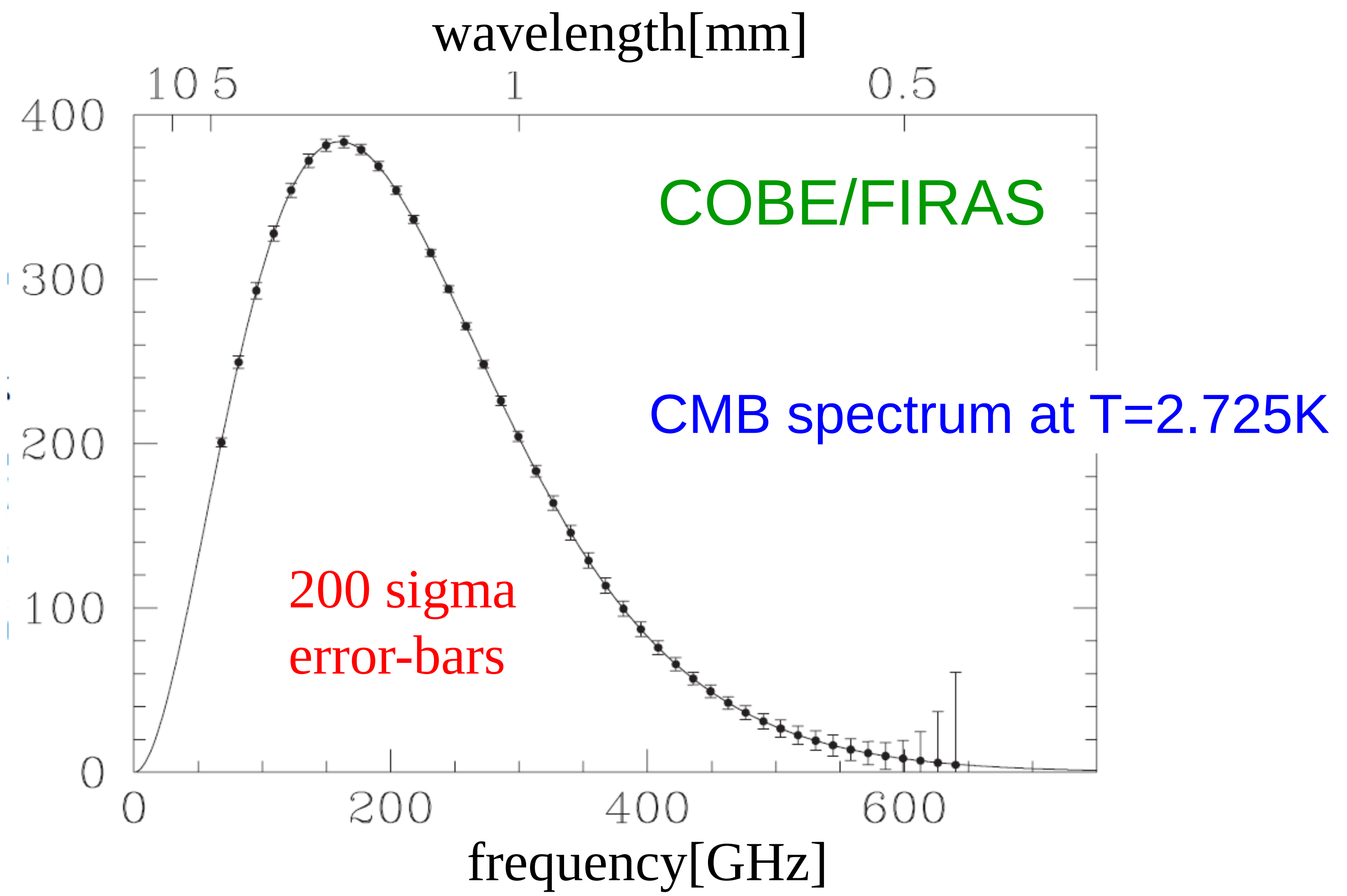
(YITP, Kyoto University)

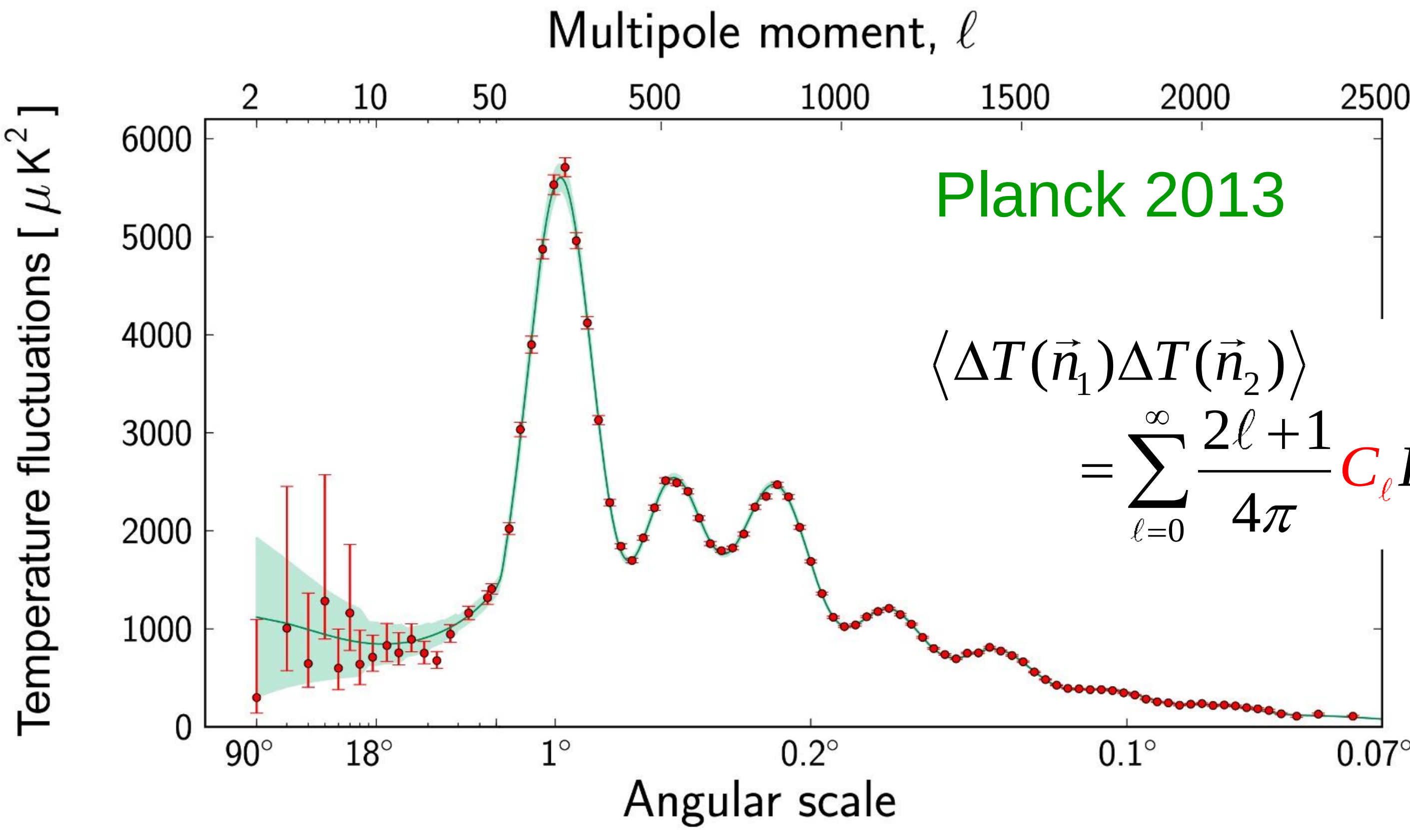
J. White, Y-L. Zhang & MS, in preparation

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

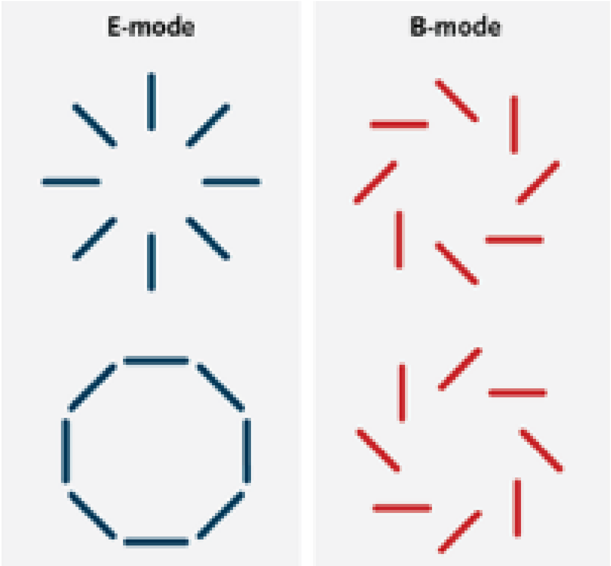
BICEP2 (2014)

spacetime vacuum fluctuations from inflation

Starobinsky (1979)

➡ B-mode polarization in CMB anisotropy

Seljak & Zaldarriaga (1996)

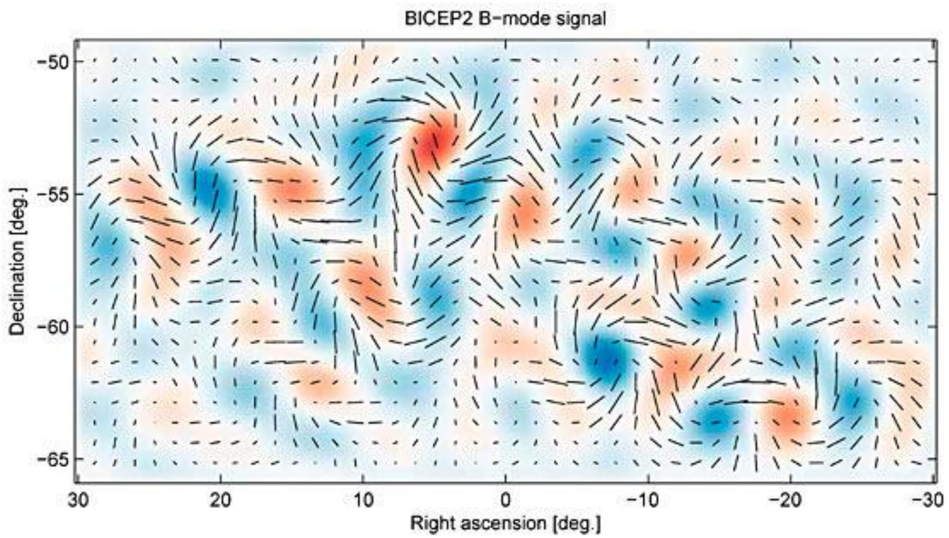


- E-mode (even parity)

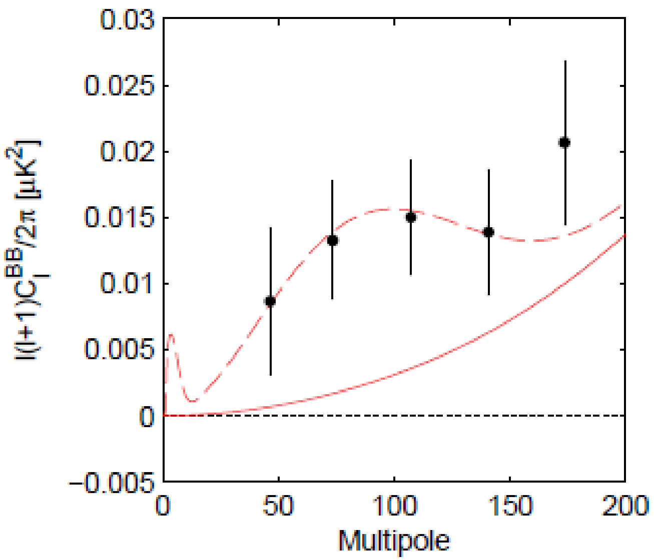
⇕

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

BICEP2 result



sky map



B-mode spectrum

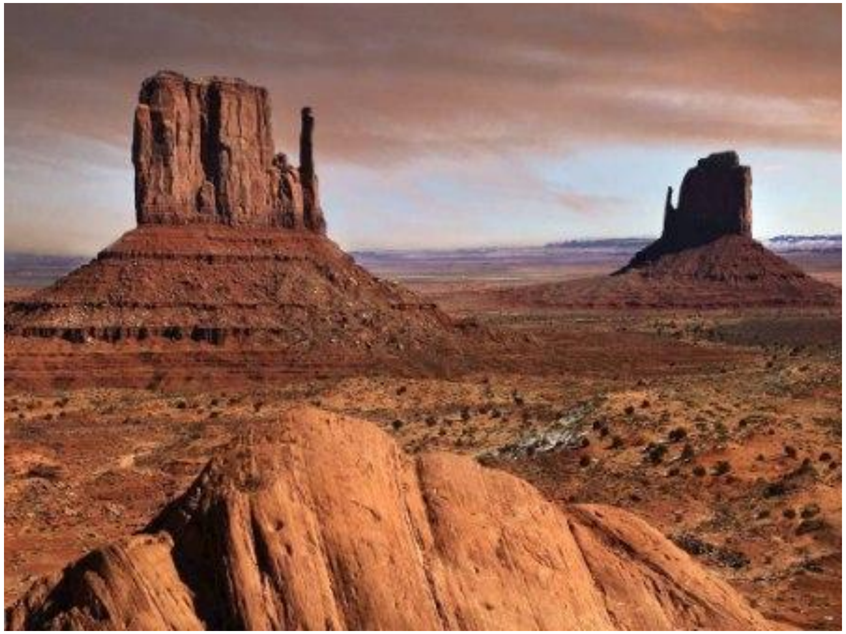
If confirmed, it "proves" (large field models of) primordial inflation & quantum gravity!

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 $\rho_v \ll M_P{}^4$



$\Leftrightarrow$

which ?

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

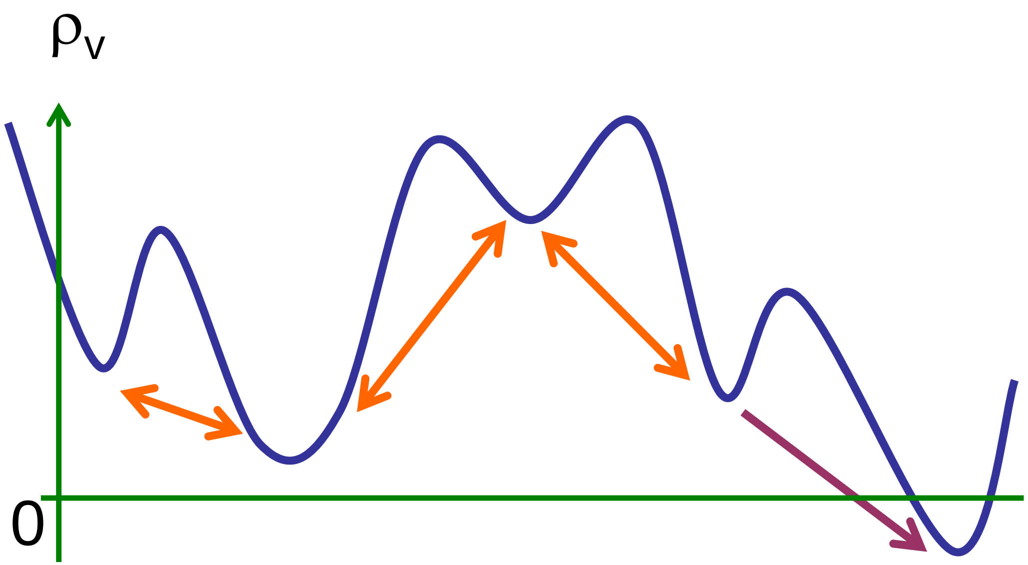
Or at least to know what kind of neighborhood we live in?

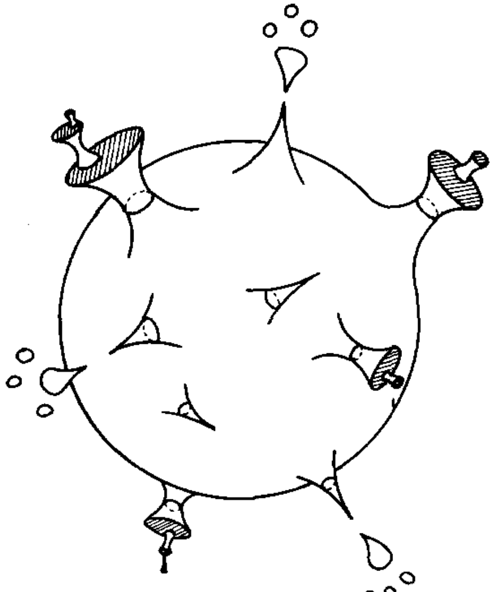
Cosmic Landscape

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
    (dS space ~ thermal state with $T = H/2\pi$: cf BH Lee's talk)
  - if it tunnels to a vacuum with negative ρ_v ,
    it collapses within t ~ $M_P/|\rho_v|^{1/2}$.
  - so we may focus on vacua with positive ρ_v: dS vacua





Sato et al. ('81)

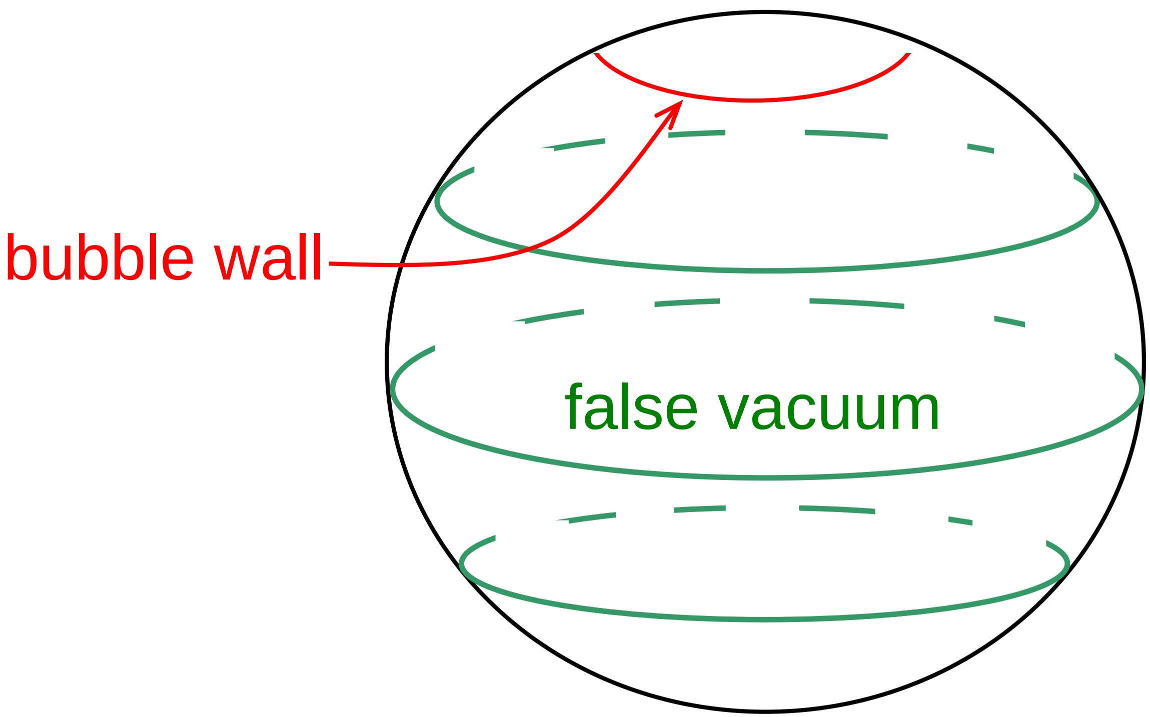
- Most plausible state of the universe before inflation is a dS vacuum with $\rho_v \sim M_P^4$. dS = O(4,1) → O(5) ~ S^4

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

MS, Tanaka, Yamamoto & Yokoyama (1993)

ds vacuum :O(4,1)

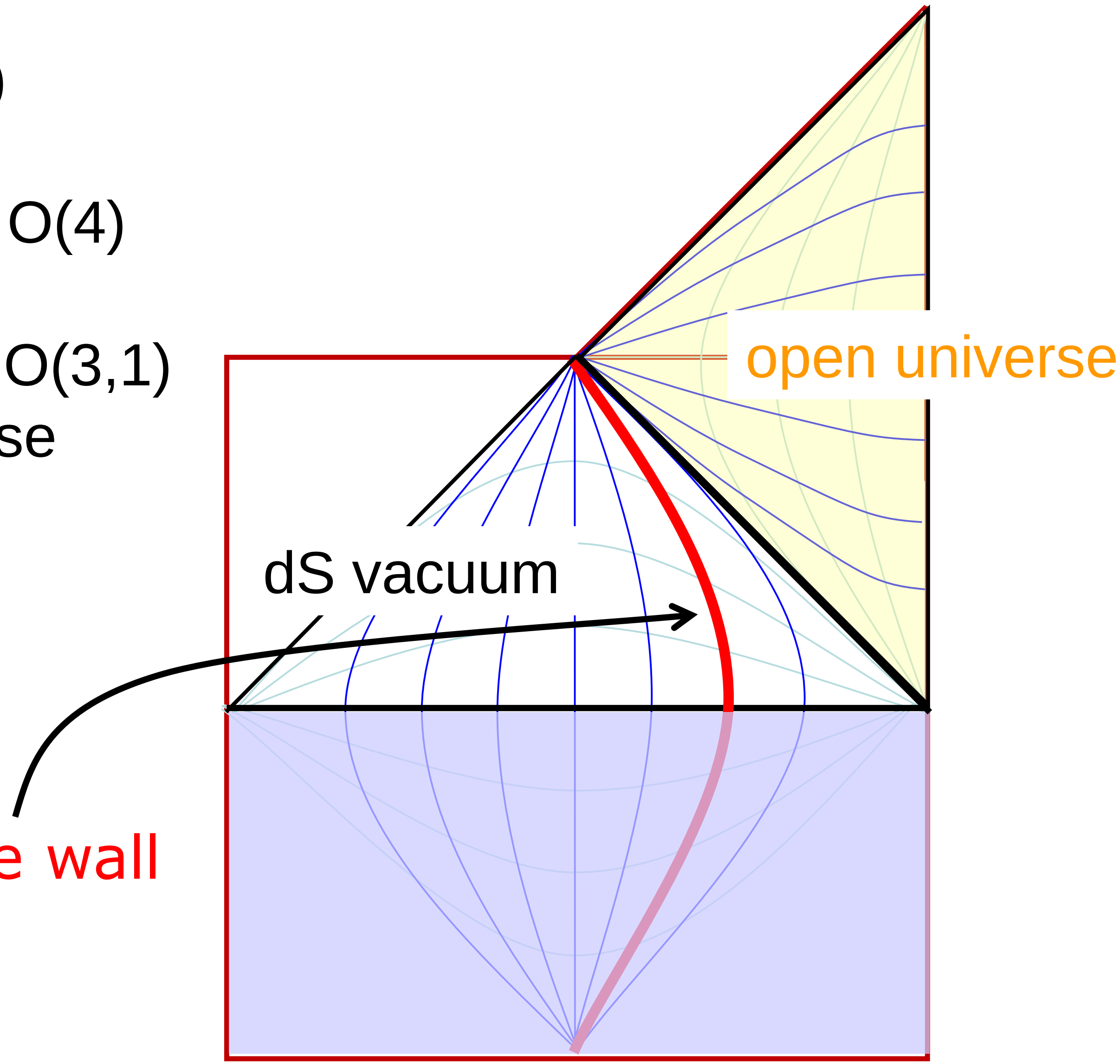
⇩

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 indicate $1\text{-}\Omega < 10^{-2}$: almost flat

➢ two possibilities

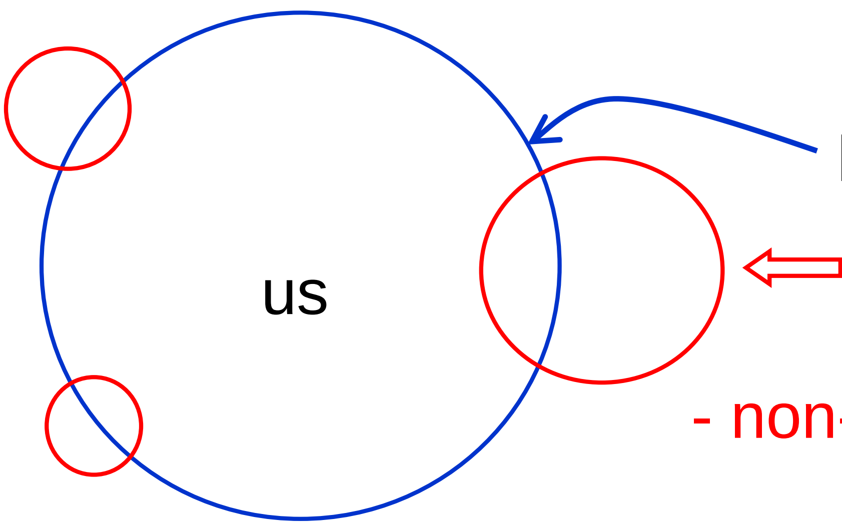
1. inflation after tunneling was long enough (N>>60)

$$1-\Omega_o \ll 1 \qquad \text{“flat universe”}$$

signatures from bubble collisions?

- tunneling rate may be enhanced in the landscape

Tye & Wohns (2009)



- non-Gaussianity from bubbles

Sugimura, Yamauchi & MS (2012)

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

$$1-\Omega_0 = 10^{-2} \sim 10^{-3}$$ “open universe”

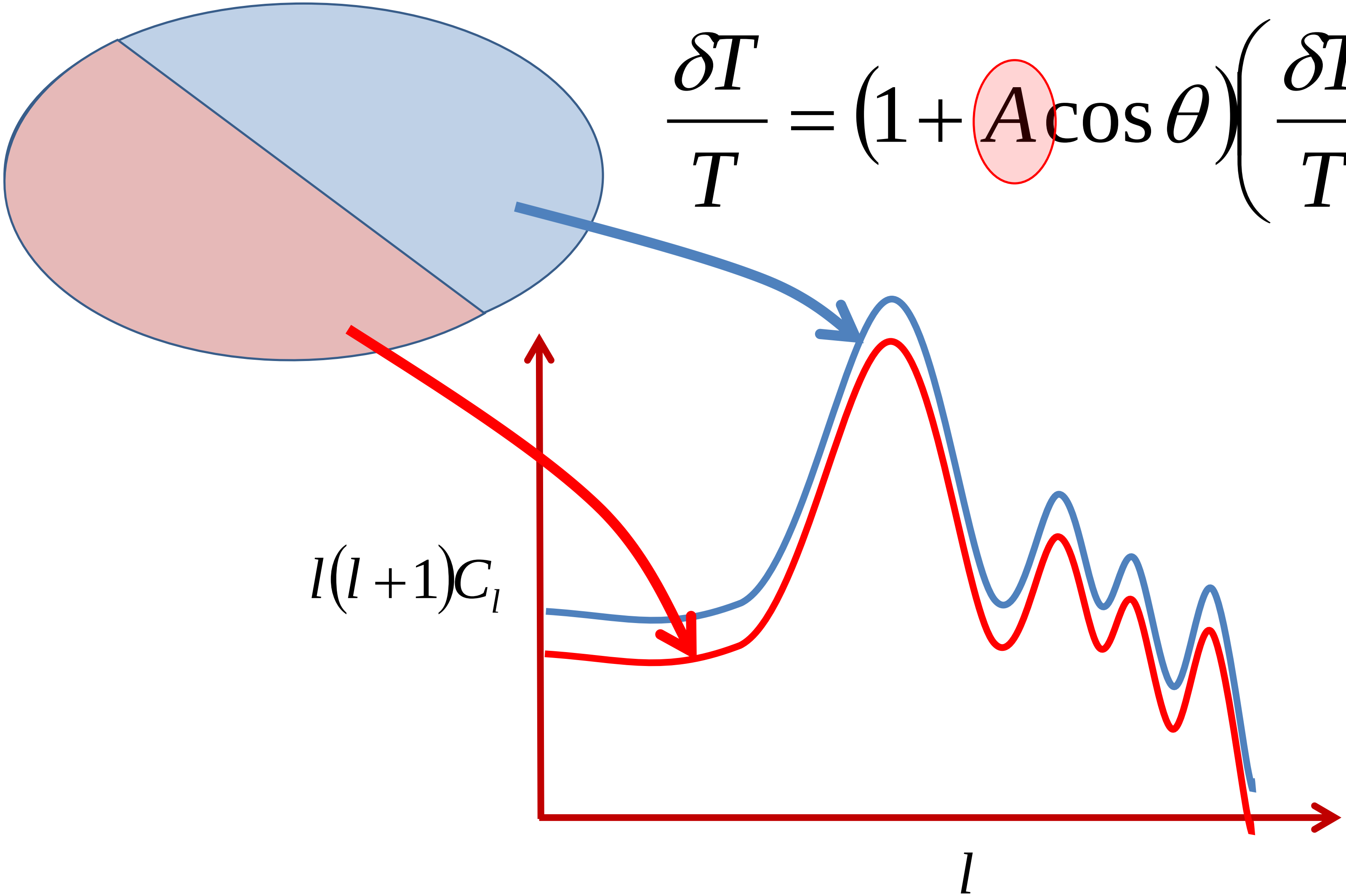
any signatures in large angle CMB anisotropies?

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

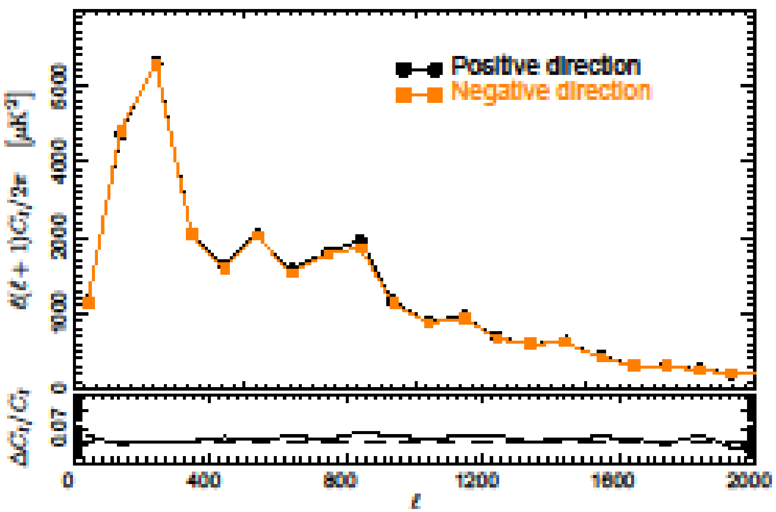
- dipolar statistical anisotropy
- tensor-scalar ratio: Planck vs BICEP2

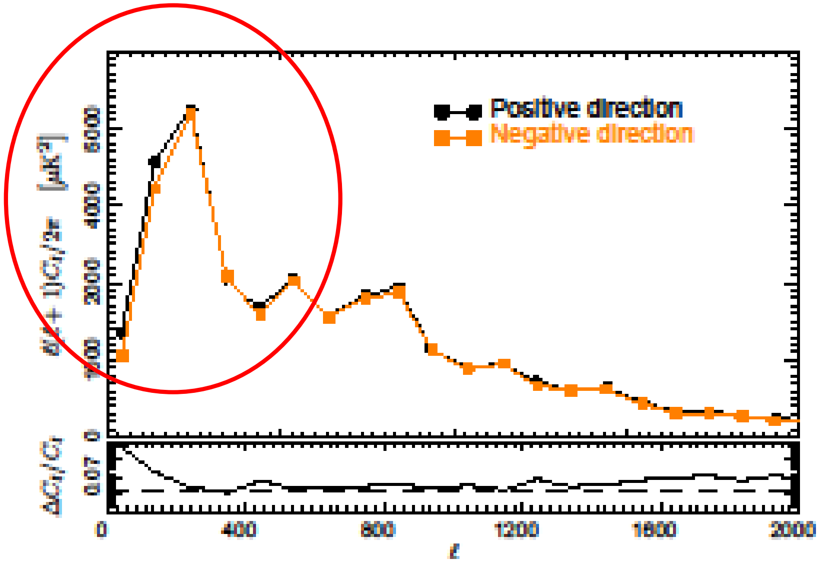
4. Dipolar statistical anisotropy

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



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

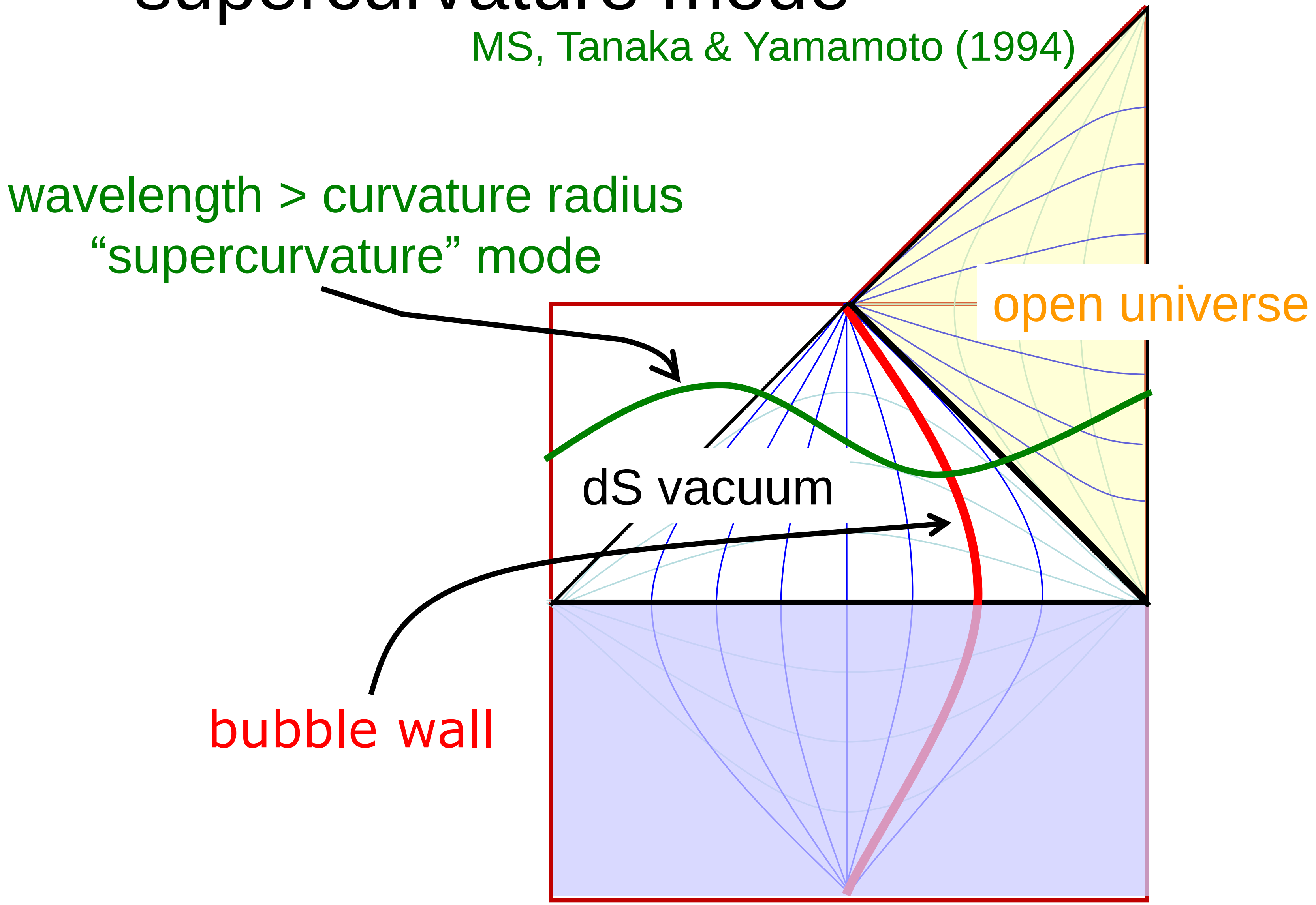
$$\frac{\delta T}{T} = \left(1 + A\cos\theta\right)\left(\frac{\delta T}{T}\right)_{iso}$$

$$A \approx 0.07$$

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
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
*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

creation of open universe & supercurvature mode

MS, Tanaka & Yamamoto (1994)



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 $f(\sigma)$

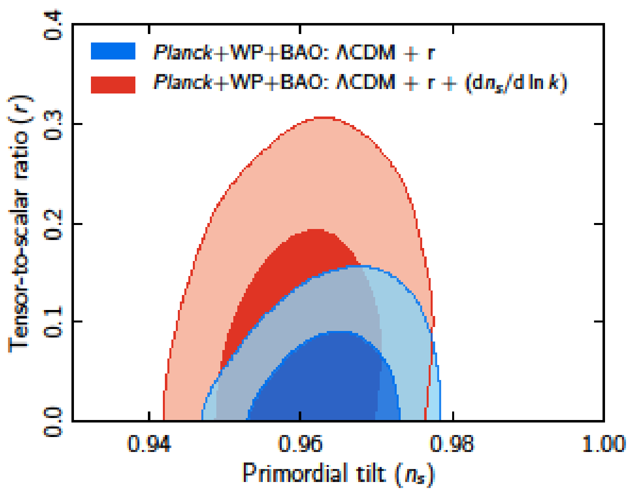
χ-field is a "free" field (no direct coupling to inflaton)

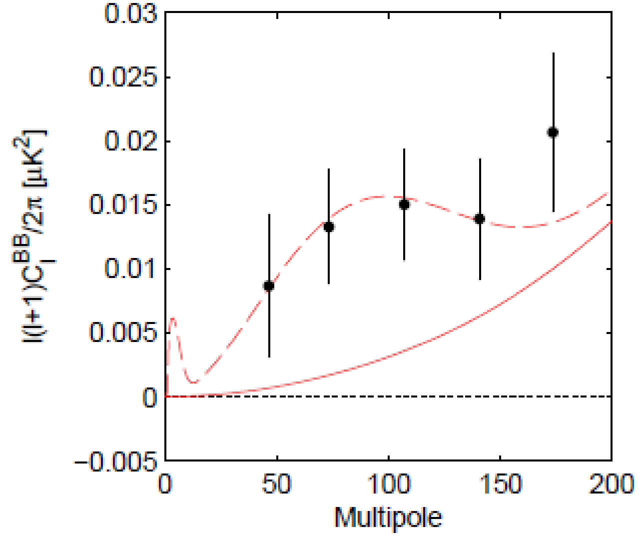
⇨ no significant non-Gaussianity, nor quadrupole

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 ~ 0.2

resolved if dn_s/dln$k$<0 (running spectral index)

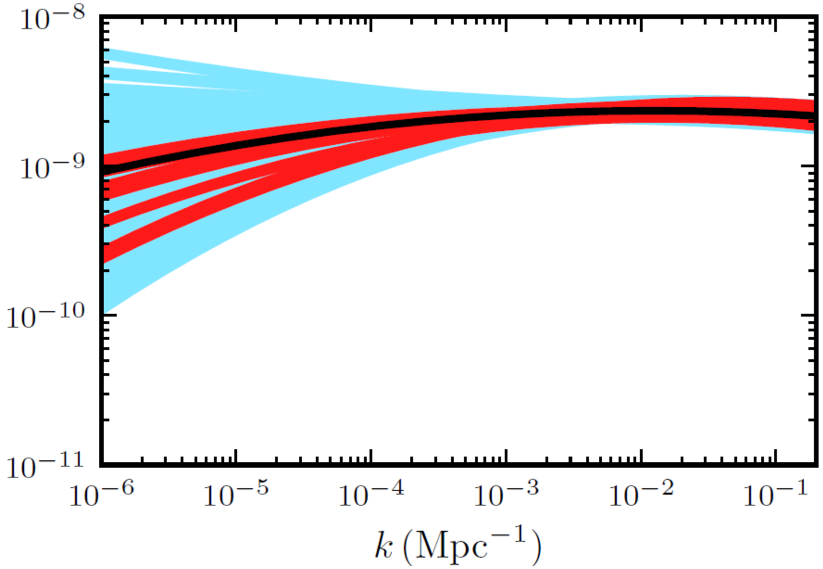
cf. QG Huang' talk

broken spectrum is more favored than running

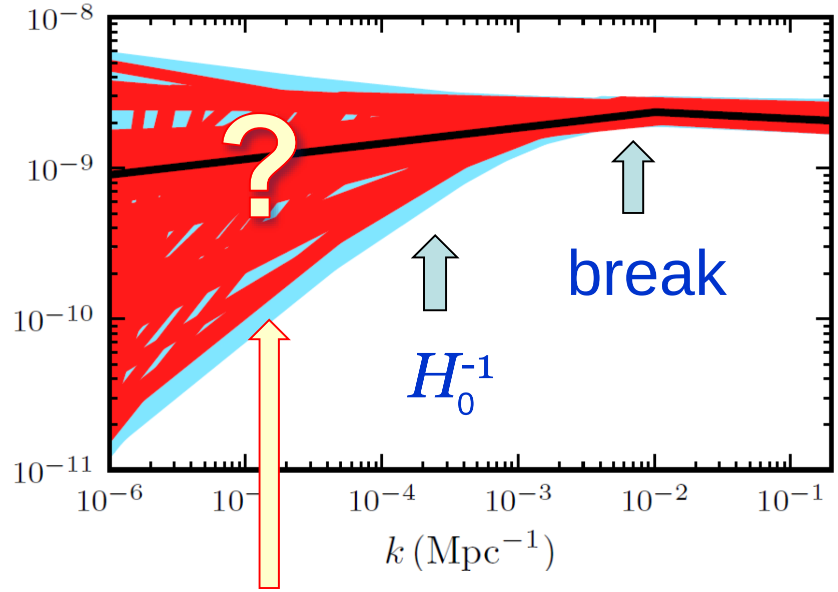
Abazajian et al. (2014)

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

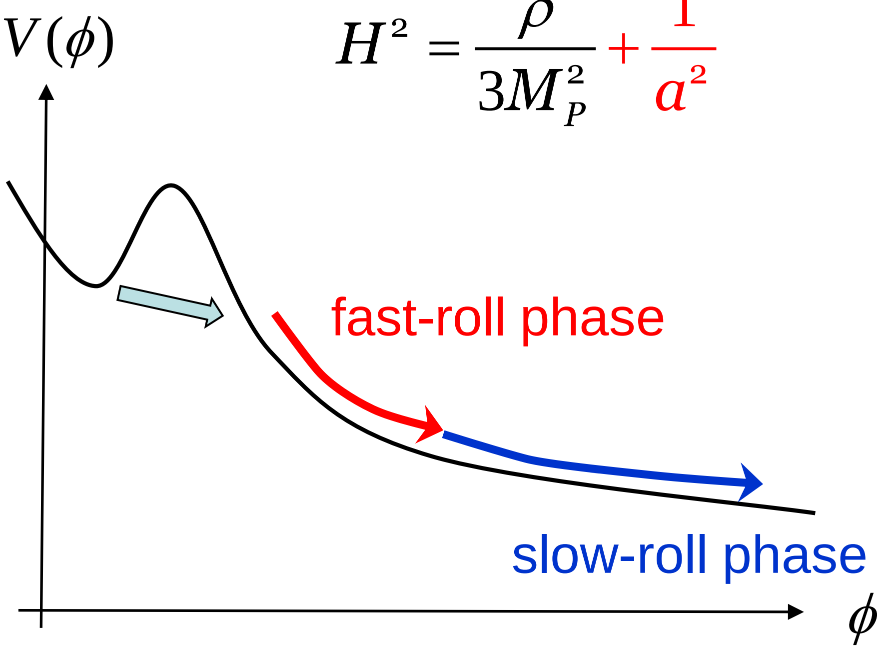
right after tunneling, H is dominated by curvature:

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

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.

duration of fast-roll phase ΔN

approximate estimate:

$$\frac{d\ln\varepsilon_V}{dN} \approx -2\eta_V; \quad \eta_V \equiv M_P^2\frac{V''}{V}$$

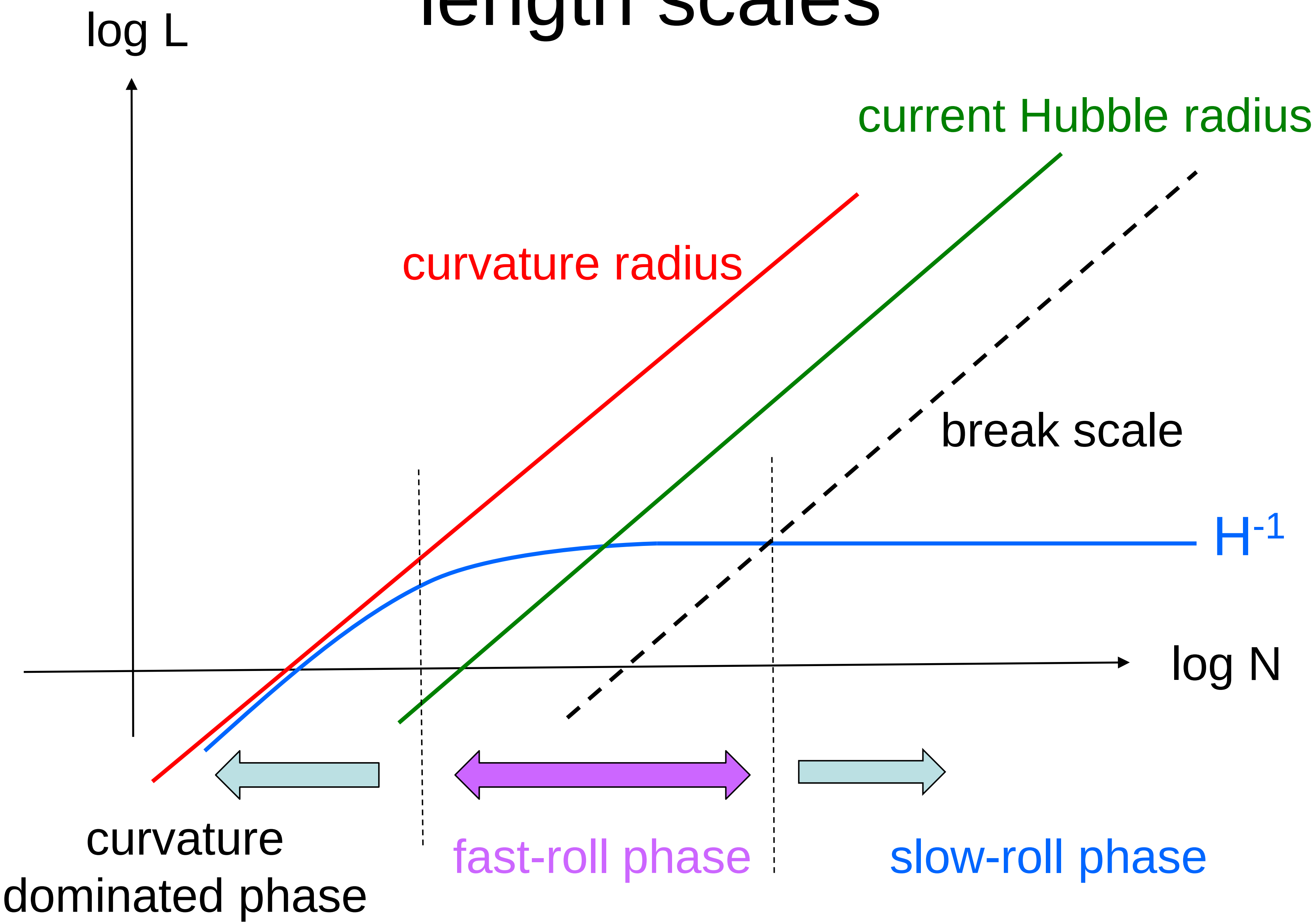
$$\Rightarrow \quad \varepsilon_V \approx \varepsilon_{V*}\exp\left[-2\int_0^\infty \eta_V\, dN\right]$$

model for η_V :

$$\eta_V \approx \eta_{V*}\exp\left[-\beta N\right] + \eta_{V,\text{slow-roll}}; \;\; \beta \lesssim 1, \;\; \eta_{V,\text{slow-roll}} \ll 1$$

for $\varepsilon_{V*} \sim \eta_{V*} \sim 1$, above estimate gives $\varepsilon_V \sim \varepsilon_{V*}\, e^{-\Delta N}$
where $\Delta N = H\Delta t$ ~ 2-4 e-folds of fast-roll phase

length scales



theoretical (qualitative) predictions

- suppression of curvature perturbation during the first few e-folds (↔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

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

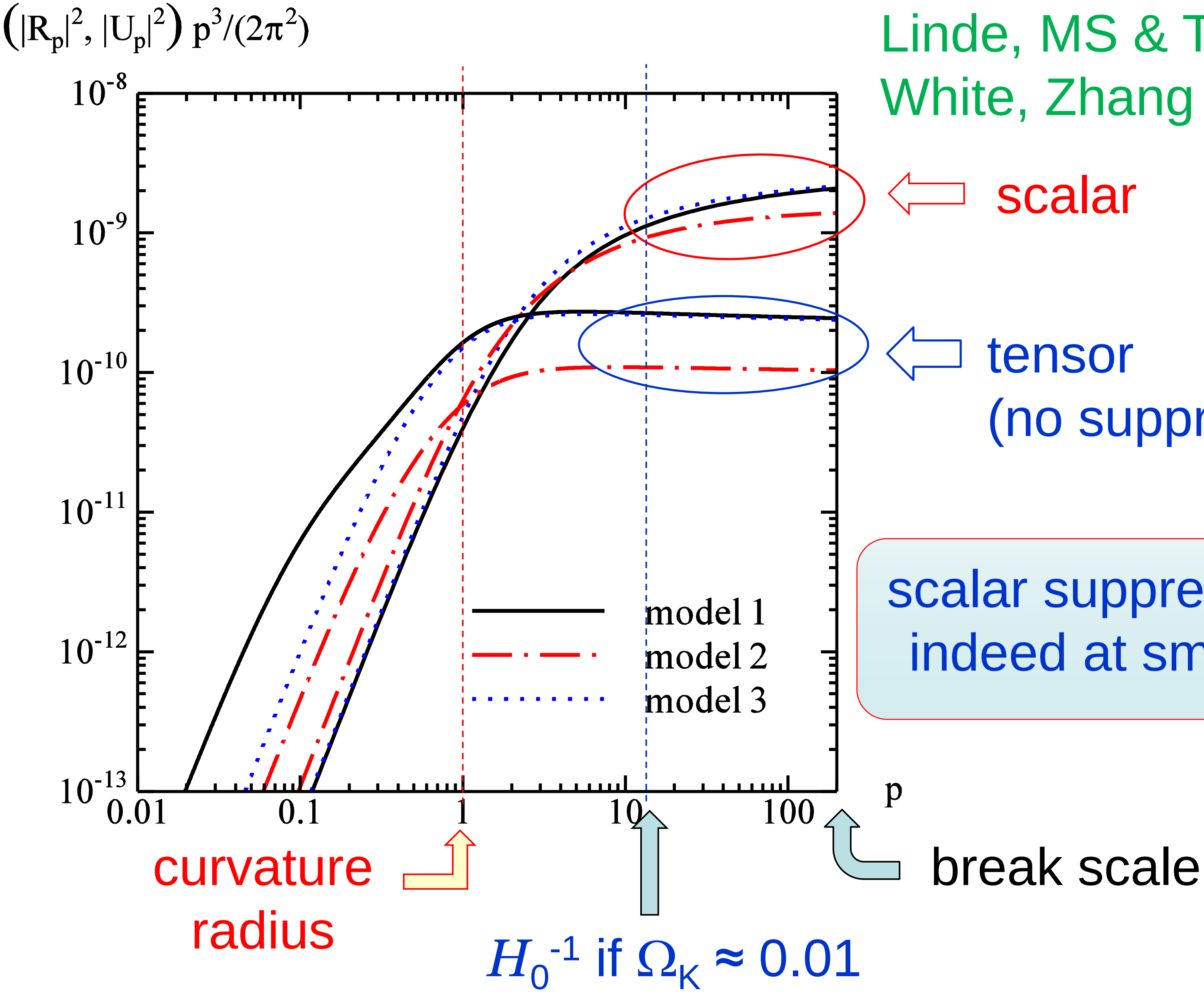
- curvature scale at the beginning of fast-roll phase t = t*

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

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

scalar & tensor spectrum in open inflation

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



scalar suppression begins indeed at smaller scales

6. Summary

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

⇨ Modulation of the fluctuation amplitude by supercurvature 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?
- How accurately can Ω_K be determined?
- any other testable predictions?
- other features in CMB? LSS? ...?

We are beginning to test string landscape!