Messages from the sky
:Matter, Dark matter and others:
Lecture #3

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on strings, Particles and Cosmology
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Summary Lec 2

Cosmological principle: isotropic, homogeneous

FRW metric: $$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

Conformal time:

$$ds^2 = a(\tau)^2 \left(d\tau^2 - d\chi^2 - S_k(\chi)^2 d\Omega^2\right) \quad S_k(\chi) = \begin{cases} \sinh\chi & \text{if } k = +1 \\ \chi & \text{if } k = 0 \\ \sin\chi & \text{if } k = -1 \end{cases}$$

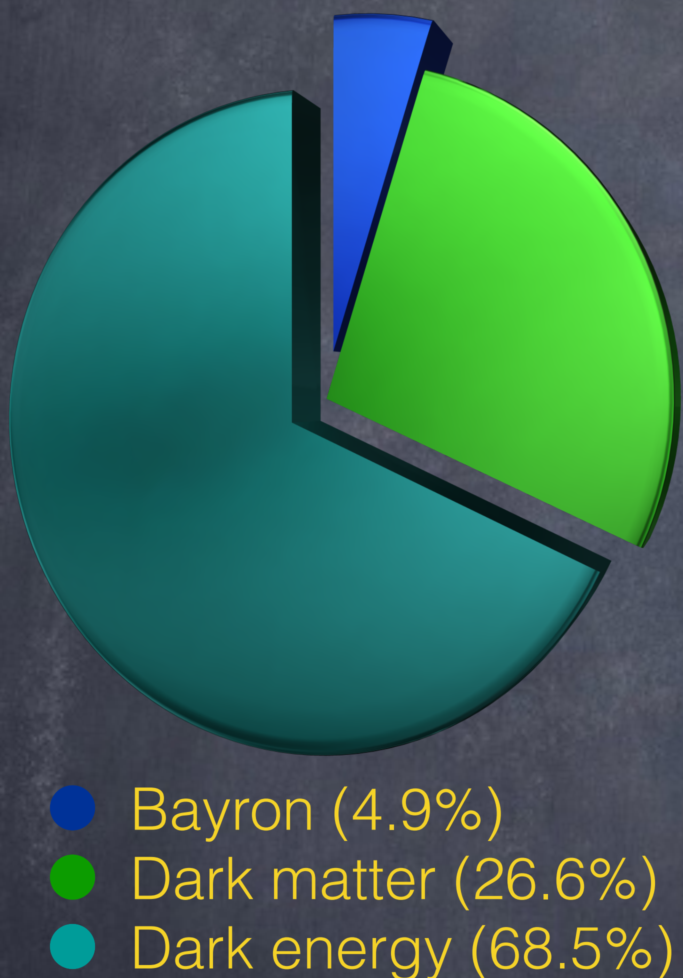
Friedman eq.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2}$$
$$\dot{\rho} = -3\frac{\dot{a}}{a}(\rho + P)$$

$$\rho \propto a^{-3(1+w)}$$

$$a(t) \propto \begin{cases} t^{\frac{2}{3(1+w)}} & \text{if } w \neq -1 \\ e^{Ht} & \text{if } w = -1 \end{cases}$$

	w	$\rho(a)$	$a(t)$	$a(\tau)$
MD	0	a^{-3}	$t^{2/3}$	τ^2
RD	$\frac{1}{3}$	a^{-4}	$t^{1/2}$	τ
Λ	-1	a^0	e^{Ht}	$-\tau^{-1}$



$$H^2(a) = H_0^2\left(\frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

$$\Omega_b = 4.9\%, \Omega_{dm} = 36.6\%, \Omega_\Lambda = 68.5\%$$

WIMP miracle

2>2: $\Omega_{WIMP}h^2 \simeq \frac{0.1\mathrm{pb}}{\langle\sigma v\rangle}$ $\langle\sigma v\rangle \simeq 1\mathrm{pb}$

$$\rho_{local} \simeq 0.3\mathrm{GeV/cm^3}$$

$$v_{sol} \simeq 240\mathrm{km/s}$$

Direct detection : sm +dm > sm +dm

Indirect detection : dm+dm> sm +sm,

collider : dm+dm < sm +sm,

barn

A unit made during Manhattan project to describe nuclear reactions

1 barn = 100 fm^2

,which was regarded as a '**huge**' size (you never fail to hit it when you throw a ball to it)

$$\hbar c = 197.3 \ \mathrm{MeV fm}$$

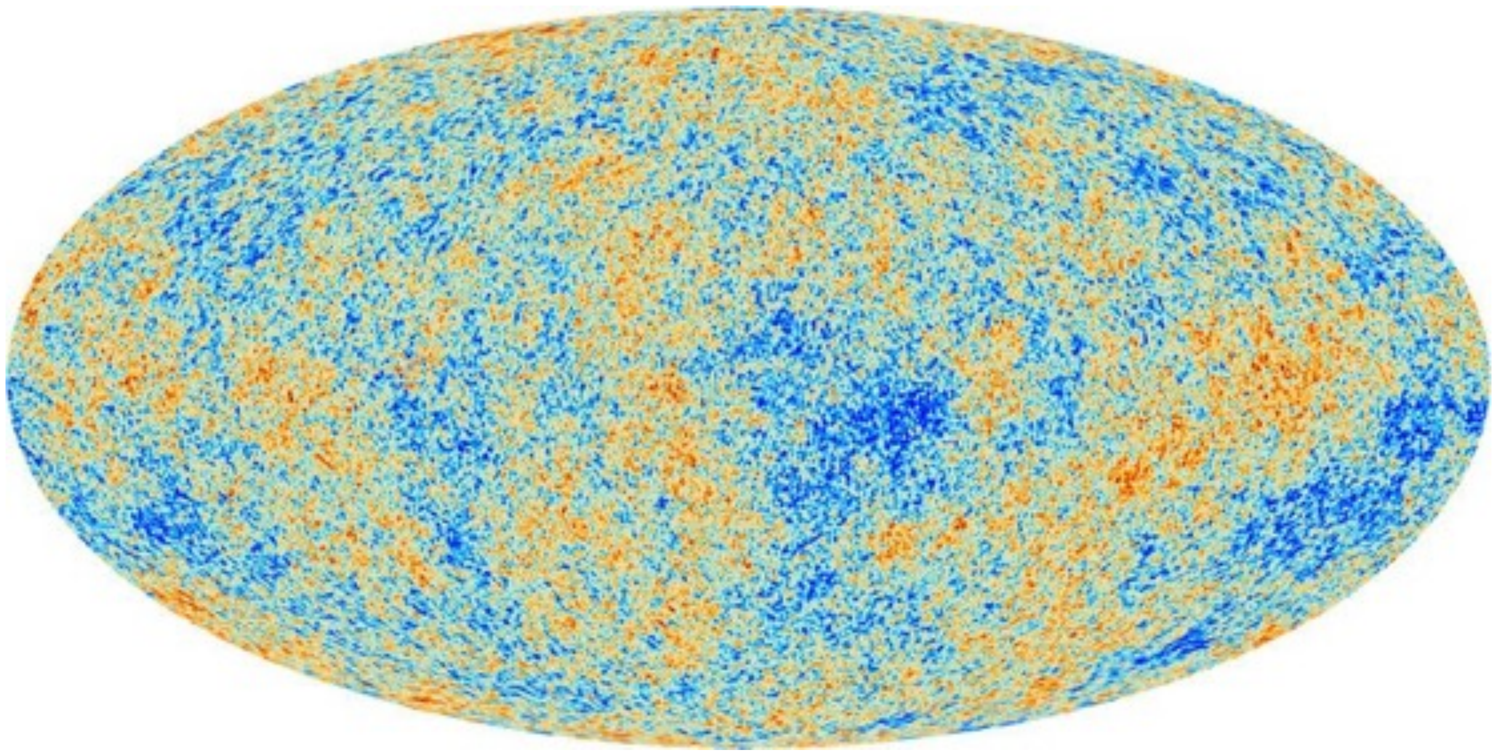
$$(\hbar c)^2 = 0.389 \ \mathrm{GeV}^2 \mathrm{mb}$$

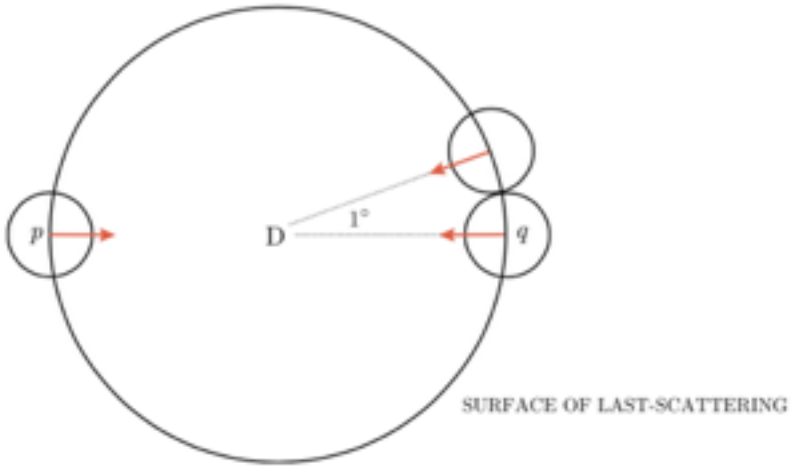
Lecture #3

- The IC problems of Big bang
- Inflation: slow-roll framework
- gravitational wave from inflation
- future perspectives

Horizon problem

$$\frac{\delta T}{T} \sim 10^{-5}$$





10^5 patches

Flatness problem

Friedman:

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

$$\dot{\rho} = -3\frac{\dot{a}}{a}(\rho + P)$$

$$\Omega(a) \equiv \frac{\rho(a)}{\rho_{\rm crit}(a)}\,, \qquad \rho_{\rm crit}(a) \equiv 3H(a)^2$$

$$\boxed{1 - \Omega(a) = \frac{-k}{(aH)^2}}$$

$|1-\Omega|$ diverge with time

$\Omega = 1$ is unstable fixed point

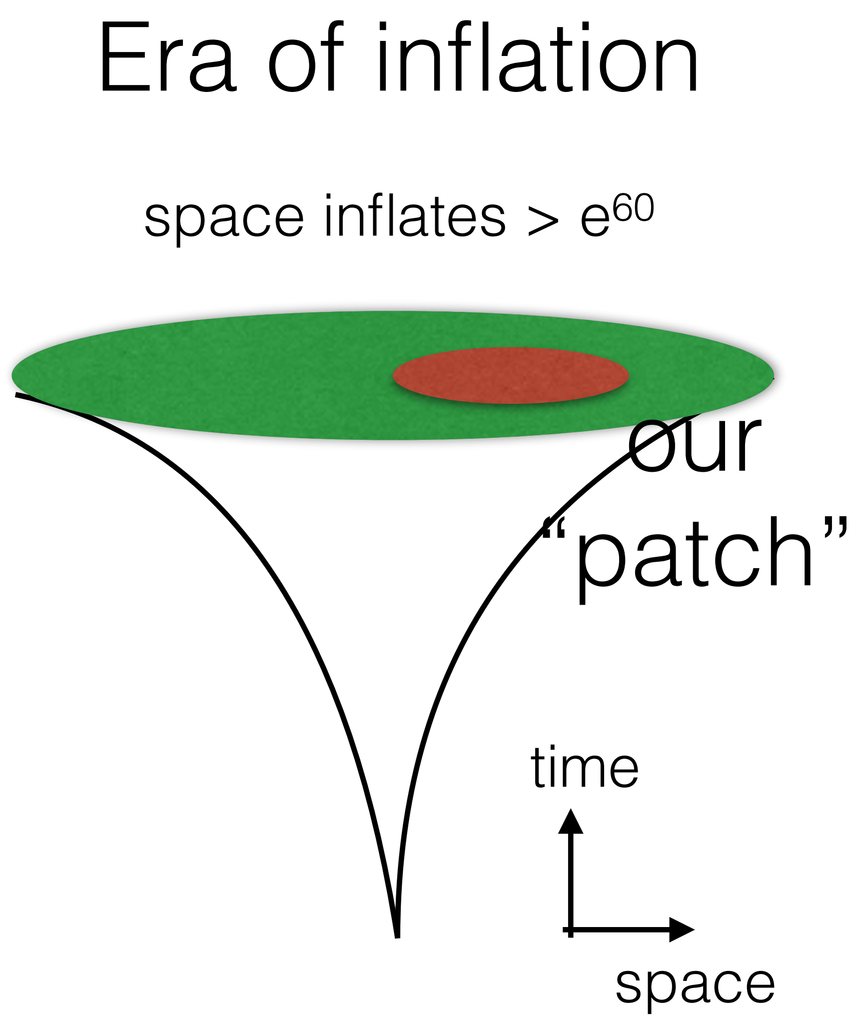
$$\begin{aligned} |\Omega(a_{\rm BBN}) - 1| &\leq \mathcal{O}(10^{-16}) \\ |\Omega(a_{\rm GUT}) - 1| &\leq \mathcal{O}(10^{-55}) \\ |\Omega(a_{\rm pl}) - 1| &\leq \mathcal{O}(10^{-61})\,. \end{aligned}$$

Why this fine tuned? : flatness problem

Magnetic monopole

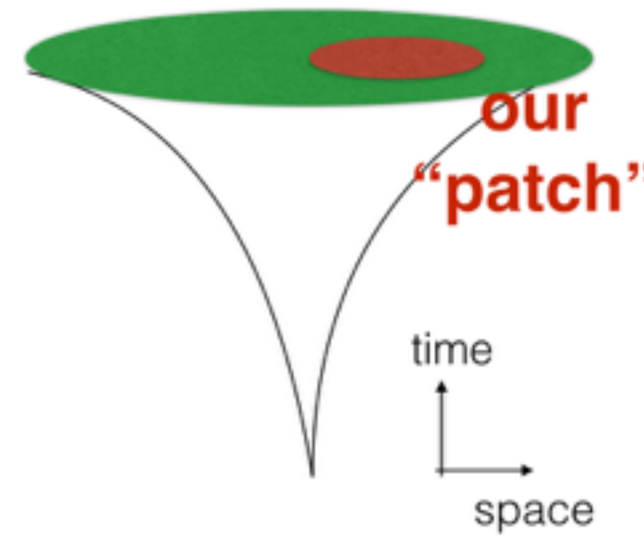
- In GUT, MM appears at high scale and its density is highly constrained by current experiments (why no monopole in our patch ?)
- Similarly, other objects like cosmic strings and cosmic defects should be extremely rare otherwise their presence is seen by inhomogeneity in CMBR.
- We call this “no magnetic monopole problem”

Inflation solves the problem



- Inflation gives **a chance to have causal connection in "our patch of universe"**
- **homogeneity and isotropy explained** and also no monopole, domain wall etc.
- It provides **seed** for structure formation provided.

In simplest realization, inflation takes place due to a scalar field

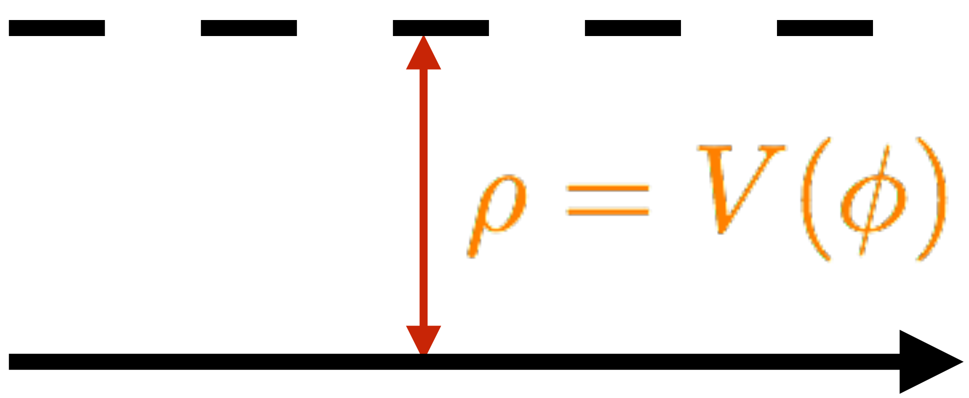


This is what we want: $a(t) = a_0 e^{H(t-t_0)}$

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

This is the equation: $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_p^2}$

It is realized if the potential is "flat"



"slow-roll conditions"

$$(V'/V)^2 \ll 1 \quad \sim \epsilon$$
$$V''/V \ll 1 \quad \sim \eta$$

(ex) $V = \lambda\phi^4, \lambda \sim 10^{-12}$

N.B. This guy is not be a vector or fermion unless it makes a composite state with s=0.

The origin of inflaton

- A slow-rolling scalar field can explain inflation
- but which scalar?
- how to decide the shape (flat!) of the potential?
- Many many models have been suggested but none of them are experimentally established.

Higgs inflation

- The only observed fundamental scalar particle is **the Higgs field**!
- **Higgs field may play the role of inflaton!** [Bezrukov, Shaposhinikov 2008], [SCP, Yamaguchi 2008],
- **Planck results and the Higgs data are compatible with the Higgs inflation scenario.** That's interesting! [Hamada, Kawai, Oda, SCP, PRL 2014]

But…. apparently they look different

Higgs

$$V(H) \approx \frac{1}{8}(|H|^2 - v^2)^2$$

quartic Inflation

$$V(\phi_{\rm inf}) \approx 10^{-12}\phi_{\rm inf}^4$$

But!

The Higgs potential becomes flat at high energy by RGE!

The SM Higgs

$$\lambda(\mu_{\mathrm{EW}}) \sim \mathcal{O}(1)$$

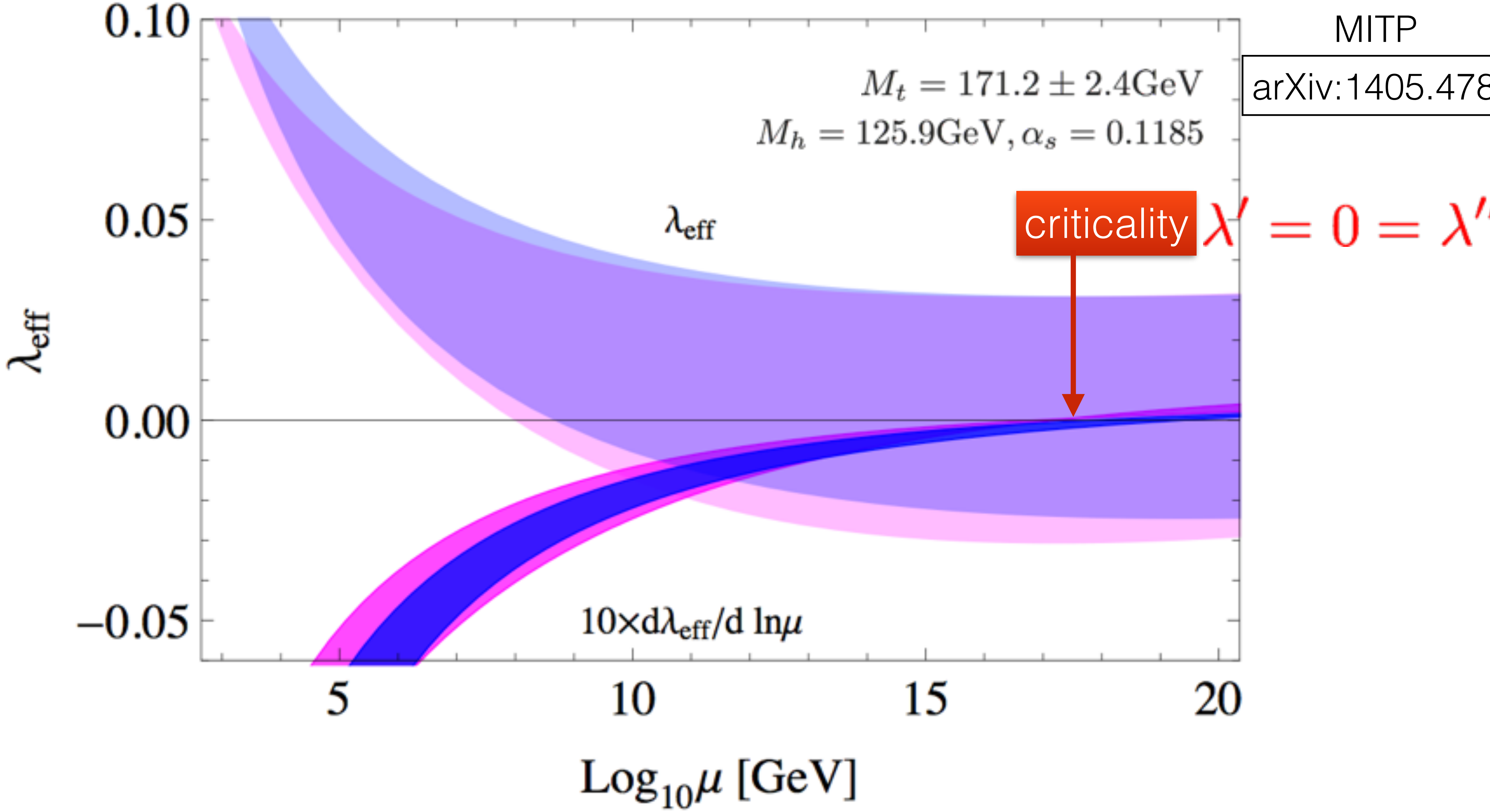
$$\lambda(\mu_{\mathrm{Inflation}}) \ll \mathcal{O}(1)$$

2-loop effective potential

- [Hamada, Kawai, Oda, SCP, PRL 2014]

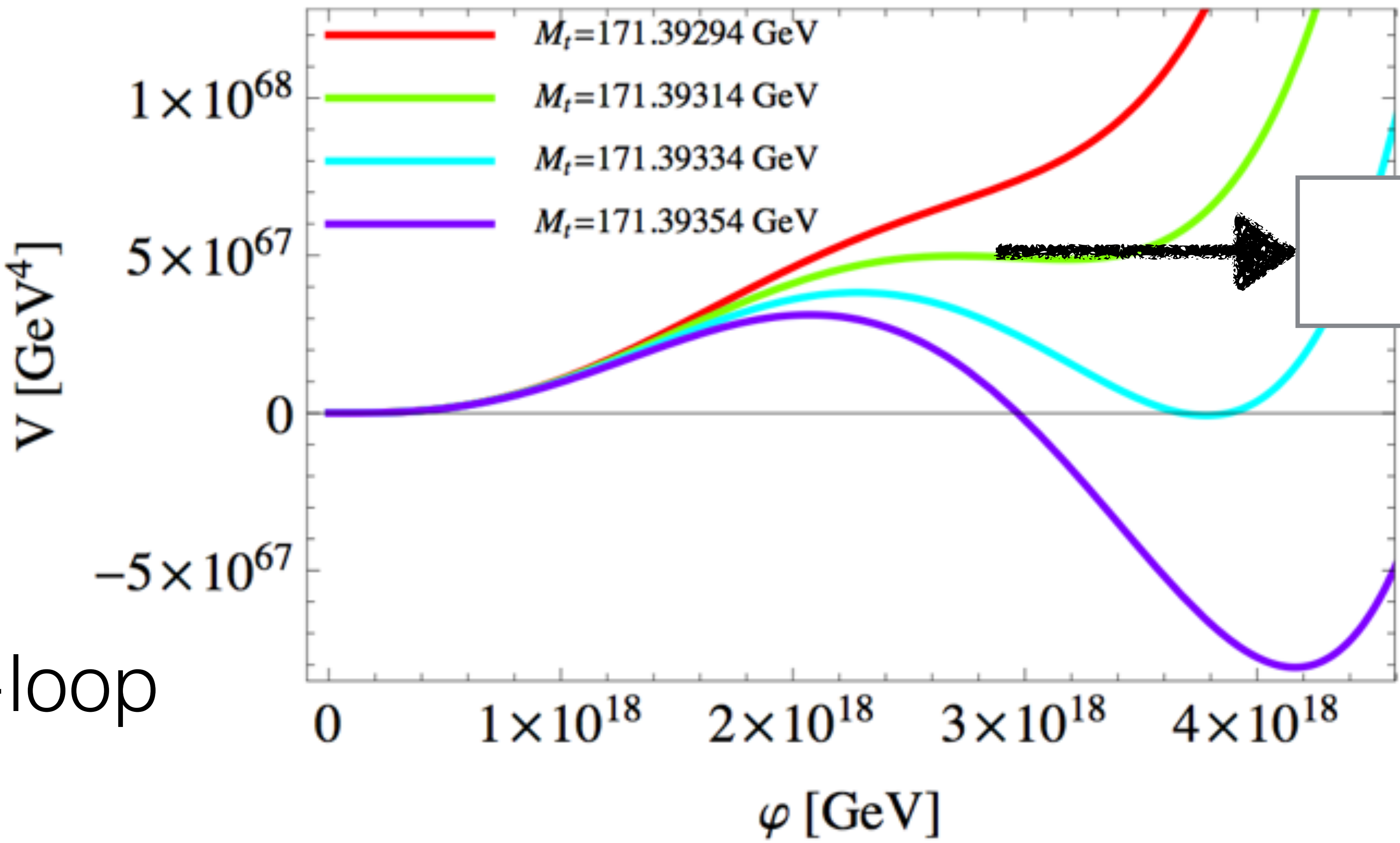
MITP

arXiv:1405.4781



Criticality of the SM

- [Hamada, Kawai, Oda, SCP, PRL 2014]



+loop

Plateau!
This helps.

Another source: non-minimal coupling

[SCP, S.Yamaguchi (2008)]

$$S = \int d^4x \sqrt{-g} \left[-\frac{M^2 + K(\phi)}{2} R + \frac{1}{2}(\partial\phi)^2 - V(\phi) \right]$$

$$g_{\mu\nu} = e^{-2\omega} g^E_{\mu\nu}, \qquad e^{2\omega} := \frac{M^2 + K(\phi)}{M^2_{\rm Pl}}.$$

$$U = \frac{M^4_{\rm Pl}}{(M^2 + K(\phi))^2} V(\phi).$$

$$\to M^4_{\rm Pl} \frac{V}{K^2}$$

Thus, as long as V/K² is asymptotically flat, the slow-roll inflation can take place!

An interesting topic for model building

Origin???

$$K(\phi) \sim \sqrt{V}$$

(ex) monomial

$$K(\phi) = a\phi^m$$

$$V(\phi) = \frac{\lambda}{2m}\phi^{2m}$$

m=2

(ex) monomial

$K(\phi) = a\phi^m$

$V(\phi) = \frac{\lambda}{2m}\phi^{2m}$

$\phi^2 = HH^\dagger$

"Higgs Inflation"

[Bezrukov,Shaposhinikov (2008)]

$K = \xi\phi^2 \qquad V(\phi) \simeq \frac{\lambda(\phi)}{4}\phi^4$

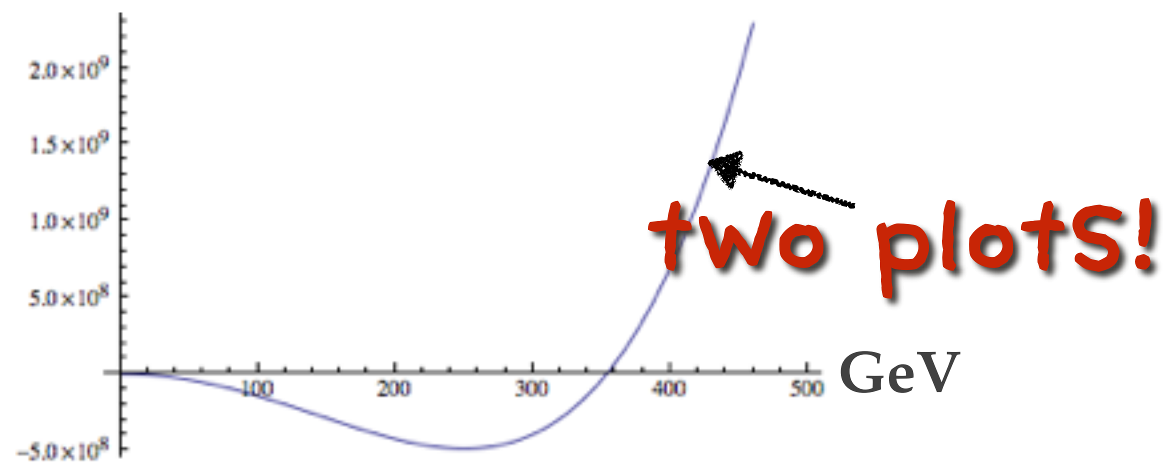
$$V_E \to \frac{\lambda M_P^4}{4\xi^2} \to const.$$

COBE normalization:

$\delta\rho/\rho \sim 10^{-5} \Rightarrow \quad \frac{\lambda}{\xi^2} \simeq 10^{-10}$

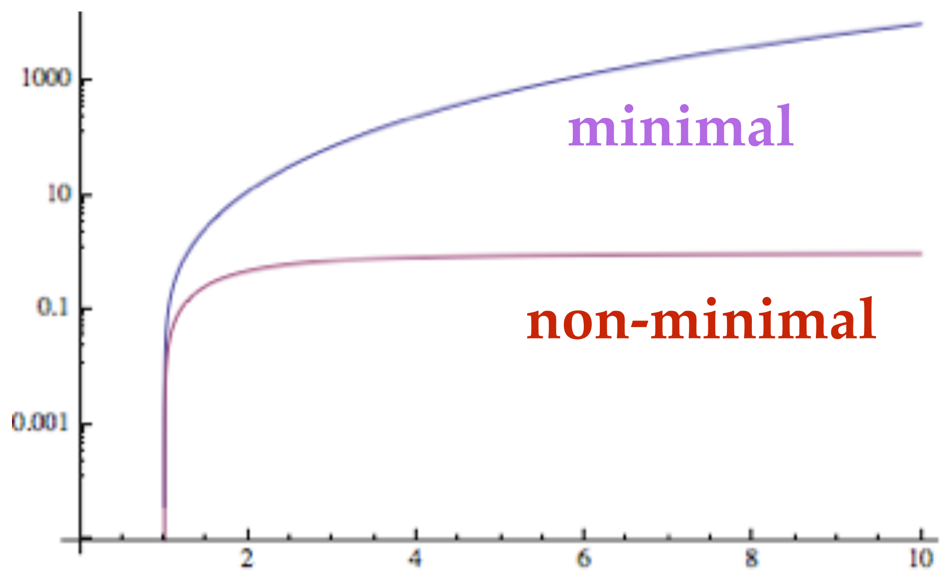
$$\boxed{\xi \simeq 10^5}$$

At low scale, Higgs potential
with / without non-minimal coupling term look just same.



consistent with the low energy measurements!

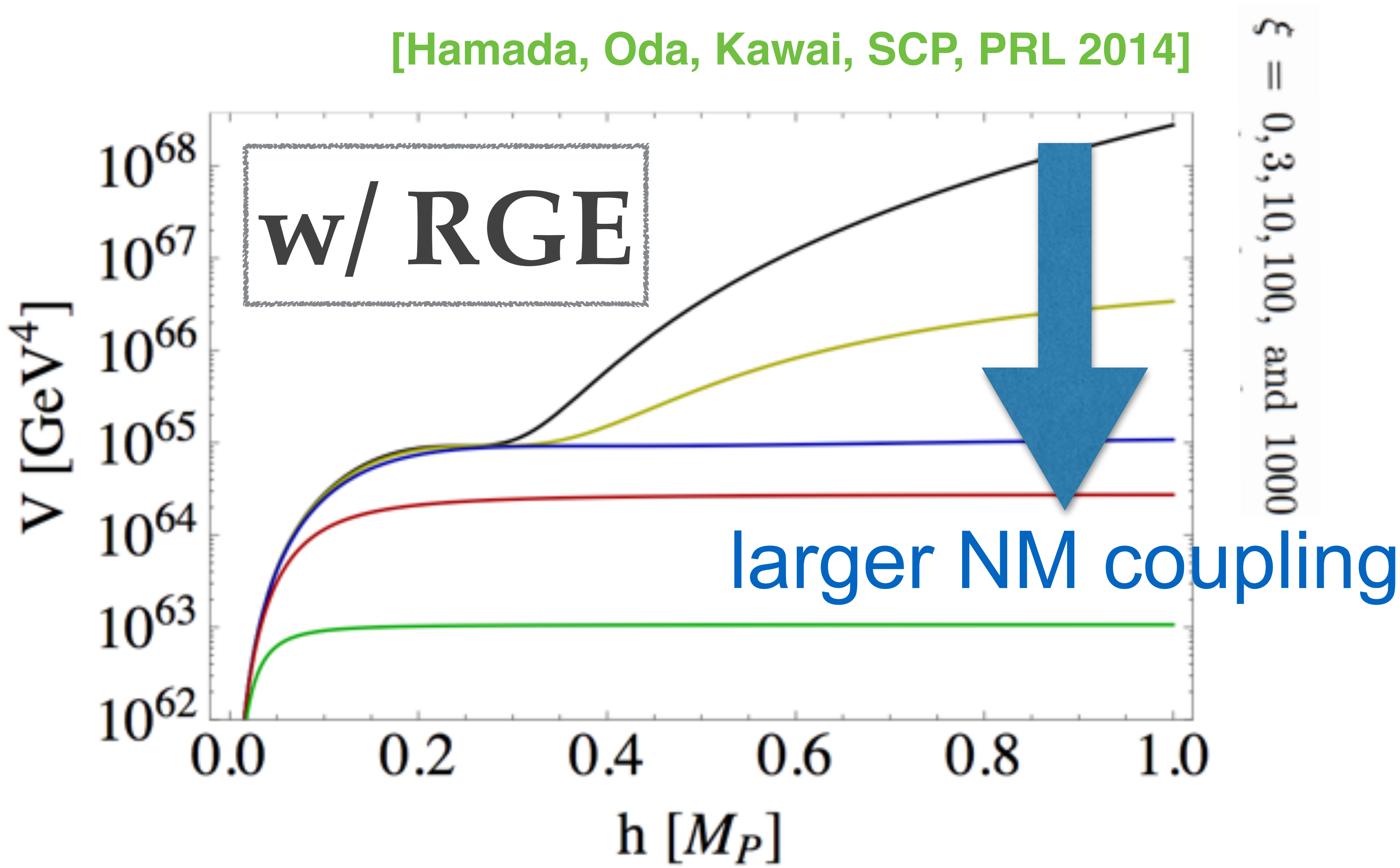
At high scale, the potential becomes flat with NMC:



good for inflation!

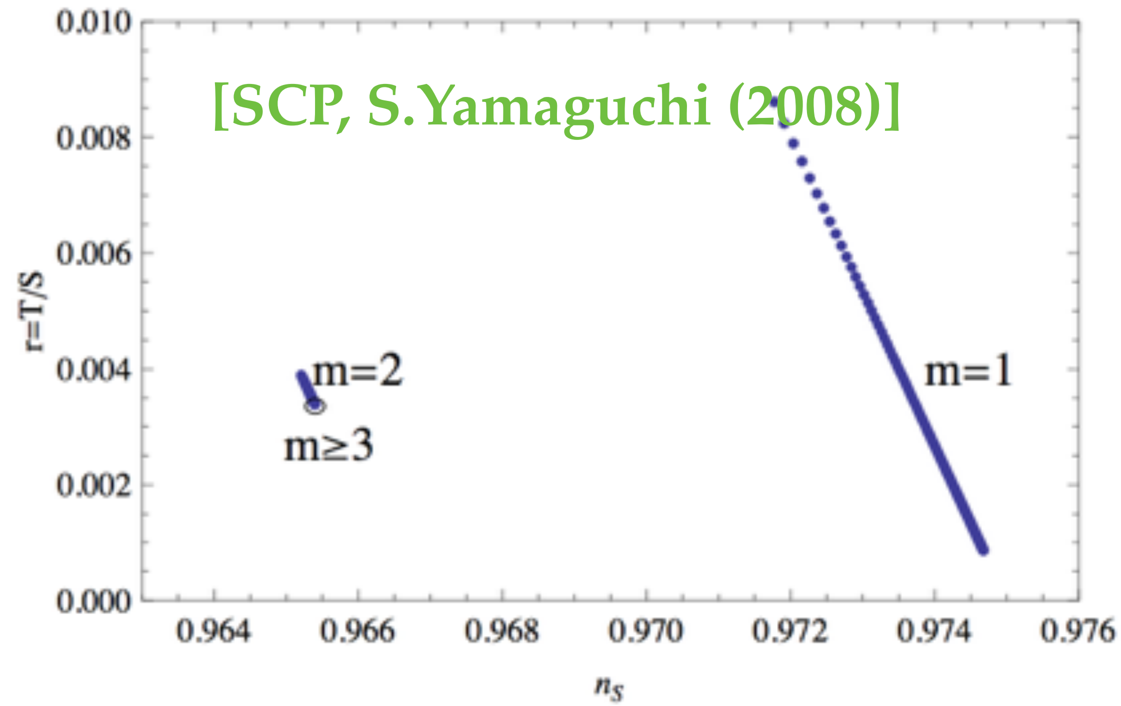
SM Criticality+ Non-minimal coupling explains inflation!

[Hamada, Oda, Kawai, SCP, PRL 2014]



W/O RGE

$$r \equiv \frac{\Delta_t^2}{\Delta_s^2} = \frac{8}{M_{\rm pl}^2}\left(\frac{\dot\phi}{H}\right)^2$$



$$K(\phi) = a\phi^m \qquad \Delta_s^2 \sim H^4/\dot\phi^2$$

$$\Delta_t^2 \sim H^2/M_p^2$$

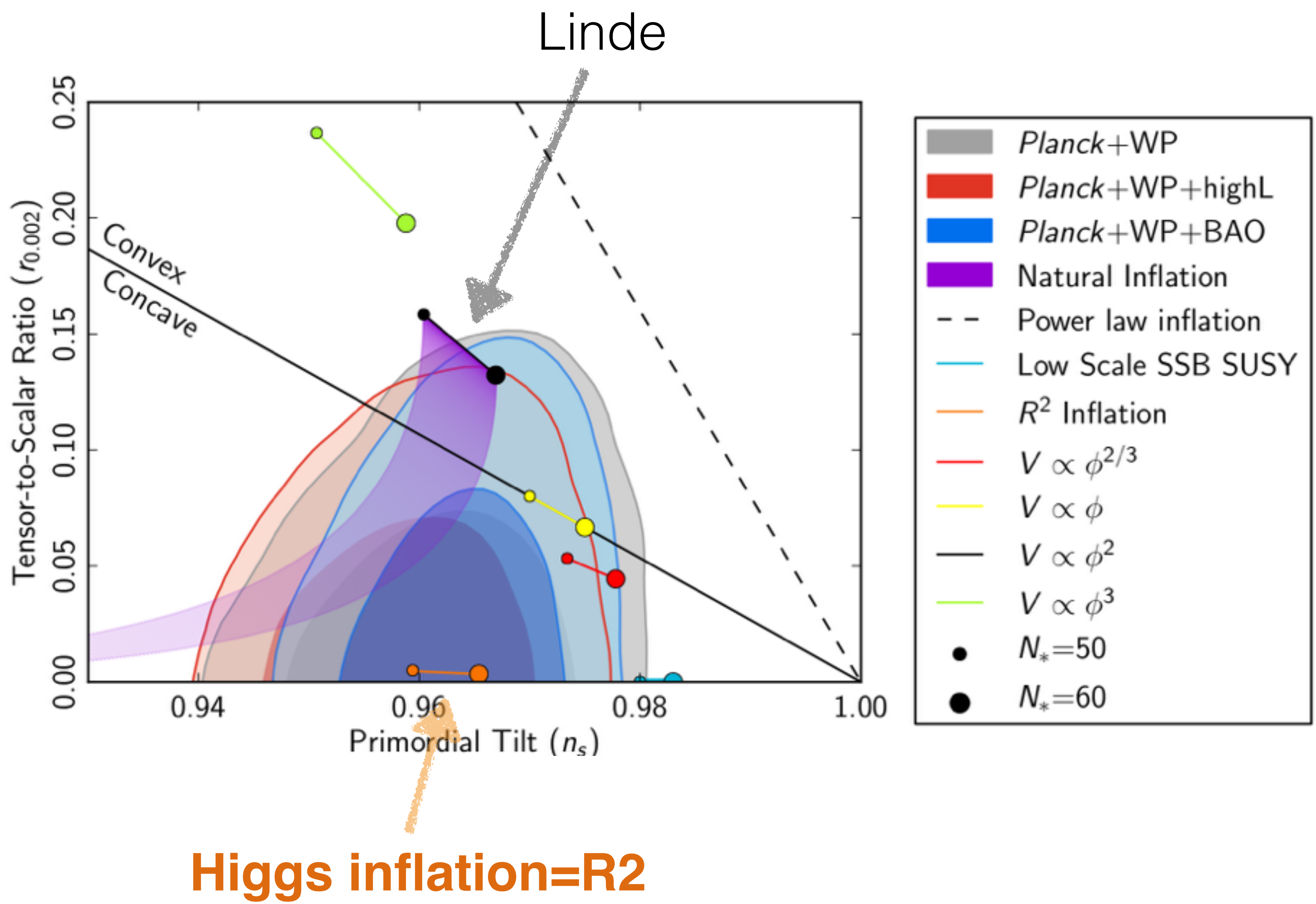
$$V(\phi) = \frac{\lambda}{2m}\phi^{2m}$$

$$V_{Einstein} \sim \frac{V}{K^2}$$

$$n_s = \begin{cases} 1 - \frac{3}{2a_0 N^{3/2}} - \frac{3}{2N}, & (m=1) \\ 1 - \frac{9(1+1/(6a_0))}{2N^2} - \frac{2}{N}, & (m=2) \\ 1 - \frac{9}{2N^2} - \frac{2}{N}, & (m \geq 3) \end{cases}, \qquad r = \begin{cases} \frac{4}{a_0 N^{3/2}}, & (m=1) \\ \frac{12(1+1/(6a_0))}{N^2}, & (m=2) \\ \frac{12}{N^2}, & (m \geq 3) \end{cases}$$

n_s is around 0.965

r is expected to be ‘small’~0.003 !



Linde
Higgs inflation=R2
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Convex
Concave
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
$N_*=50$
$N_*=60$

Higgs inflation=R2 inflation

$$\mathcal{L} = \sqrt{g}[R + \xi\phi^2 R - \lambda\phi^4]$$ "Higgs"

$$\delta\mathcal{L}/\delta\phi = \sqrt{g}[2\xi\phi R - 4\lambda\phi^3] = 0$$

$$\phi^2 = \frac{\xi}{2\lambda}R \qquad \Rightarrow \mathcal{L} = \sqrt{g}[R + \frac{\xi^2}{4\lambda}R^2]$$ "R2"

$$\frac{\xi^2}{4\lambda} \approx 10^{10}$$ [COBE]

Any other observational test?

- The precision SM test (e.g. top quark mass, strong coupling constant, Higgs quartic couplings)
- “Gravitational wave” a.k.a. “B-mode” polarization in CMBR

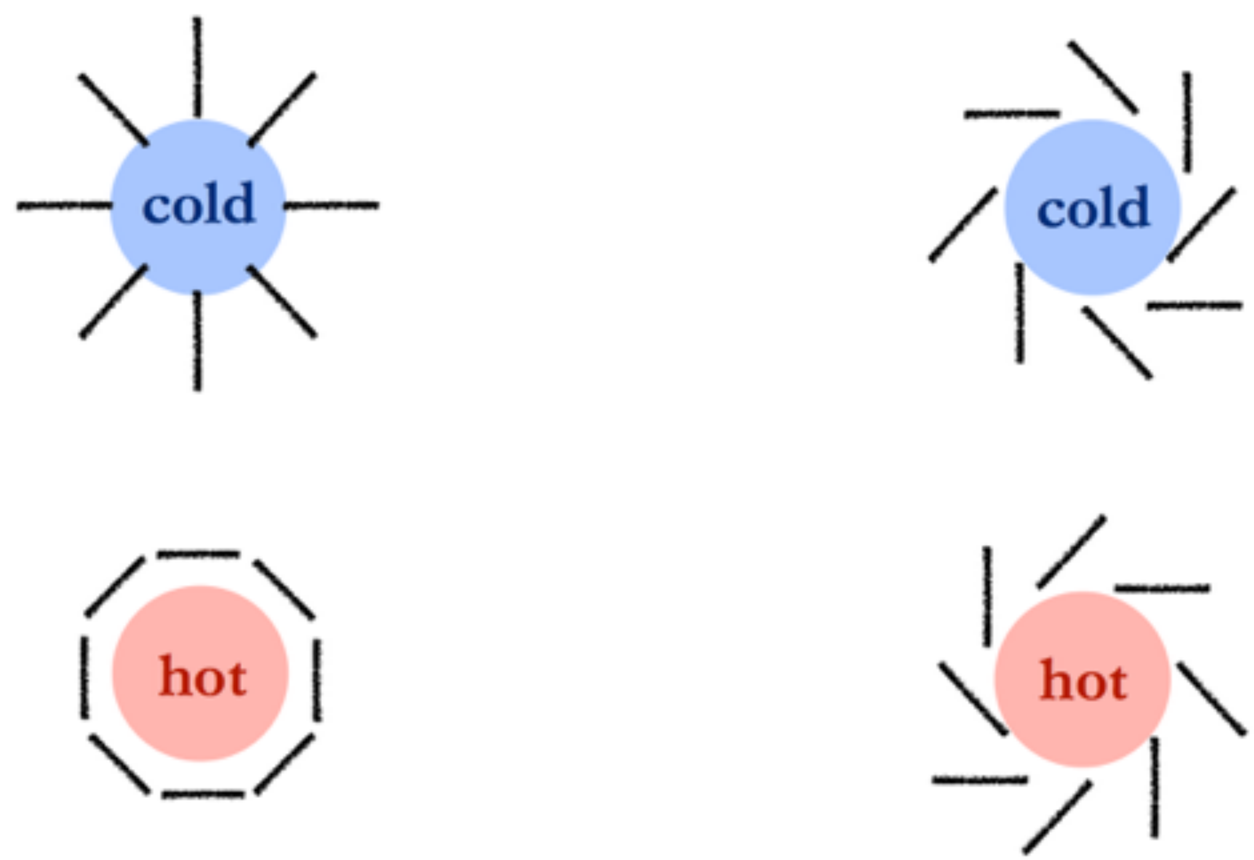
“B-mode” polarization in CMBR

Not surprising!

Helmholtz theorem

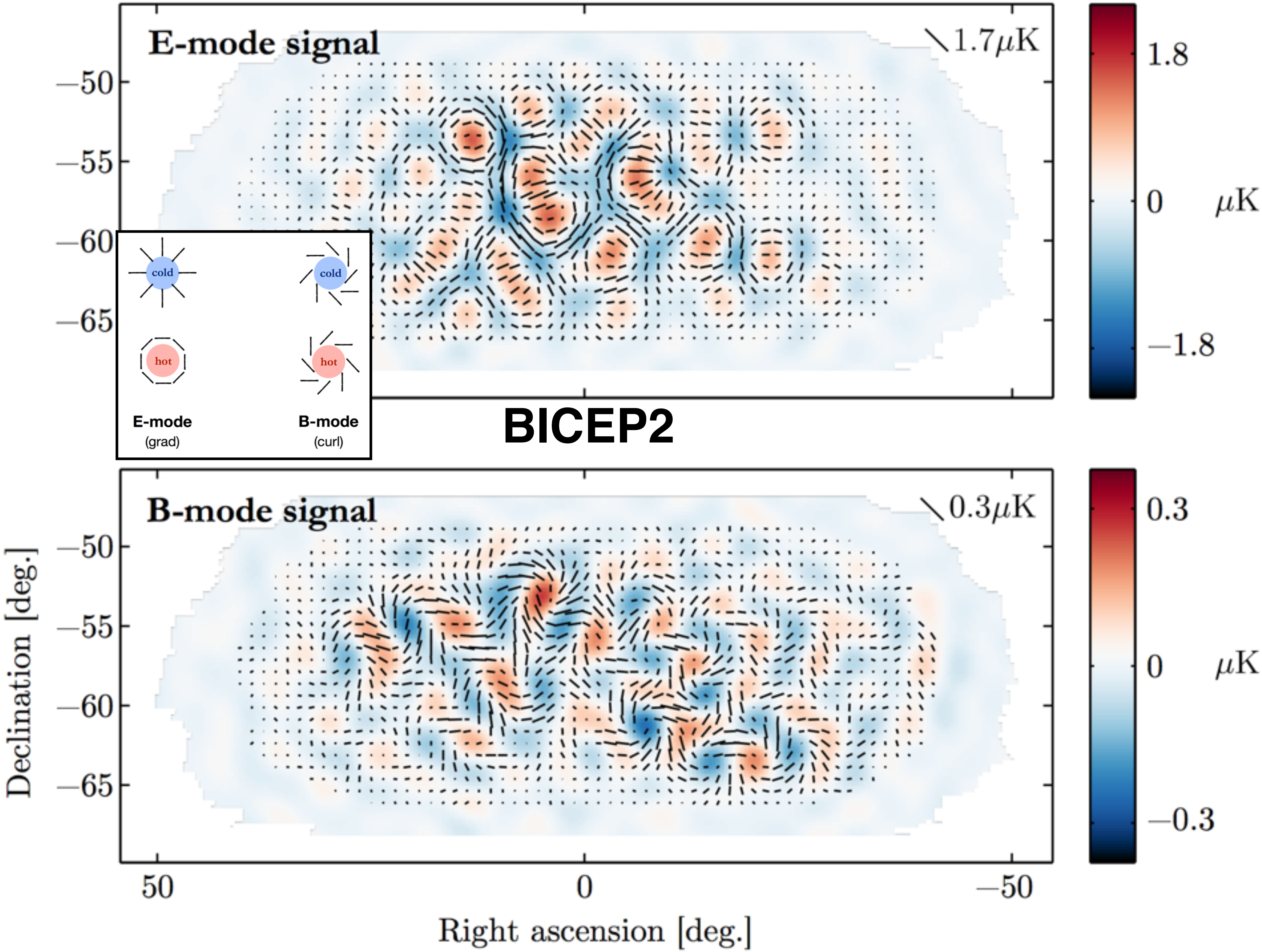
curl-free — divergence free

$$\vec{C} = \underbrace{-\nabla\Phi}_{\text{curl-free}} + \underbrace{\nabla \times \vec{A}}_{\text{divergence free}}$$



E-mode
(grad)

B-mode
(curl)

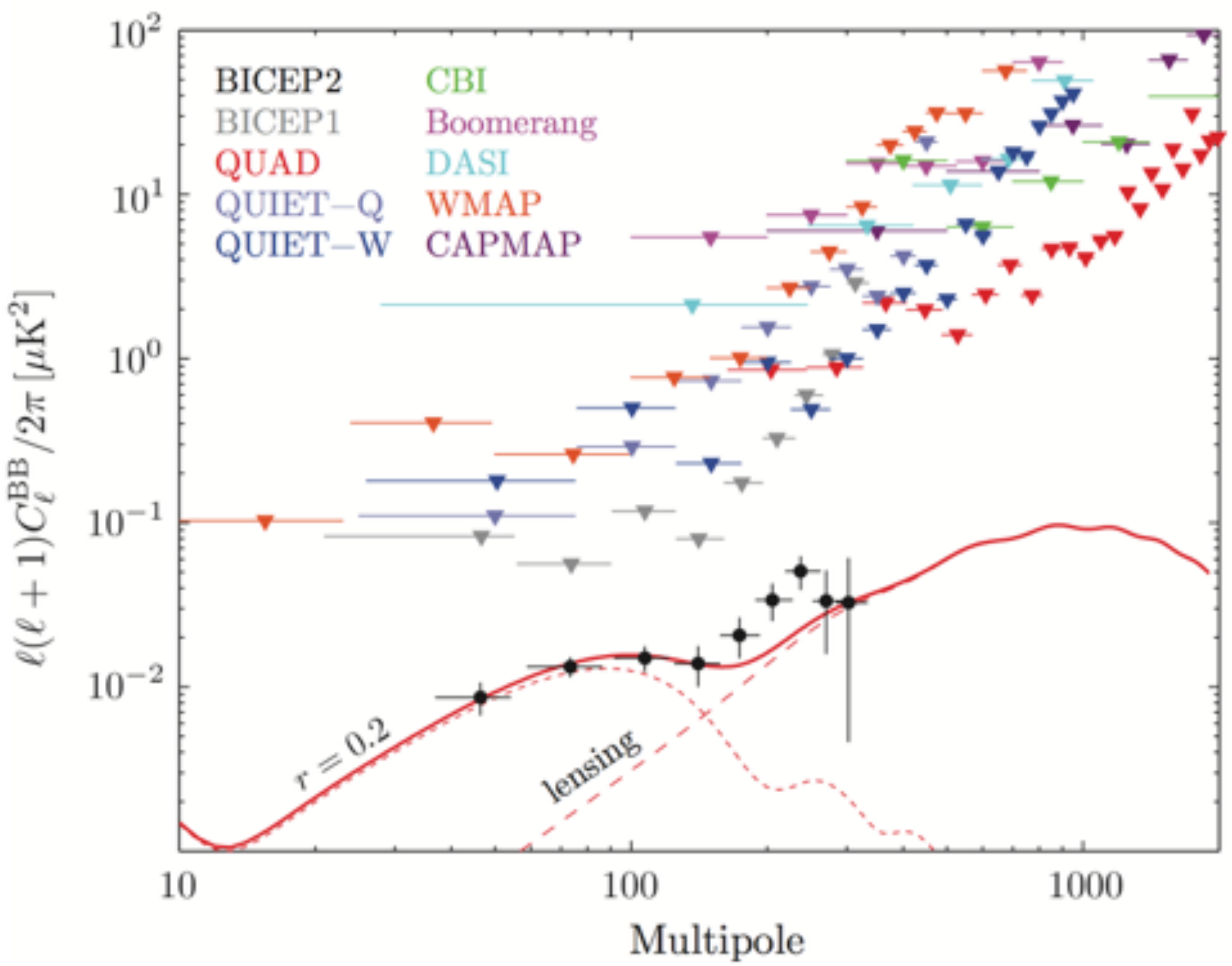

E-mode signal
1.7μK
B-mode signal
0.3μK
cold
hot
E-mode
(grad)
B-mode
(curl)
BICEP2
Declination [deg.]
Right ascension [deg.]
−50
−55
−60
−65
50
0
1.8
−1.8
0.3
−0.3
μK

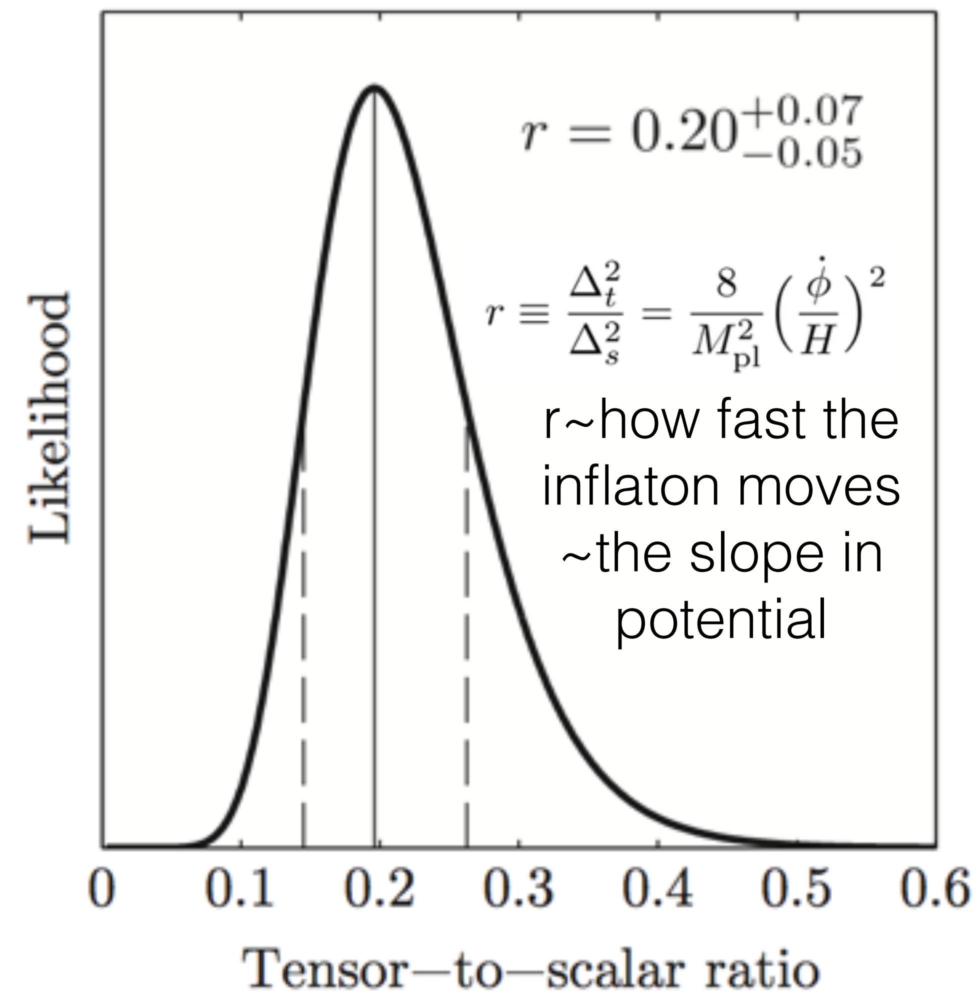
$$\Delta_s^2 \sim H^4/\dot{\phi}^2$$
$$\Delta_t^2 \sim H^2/M_p^2$$

BICEP2

w/o foreground noise

B-mode Power Spectrum





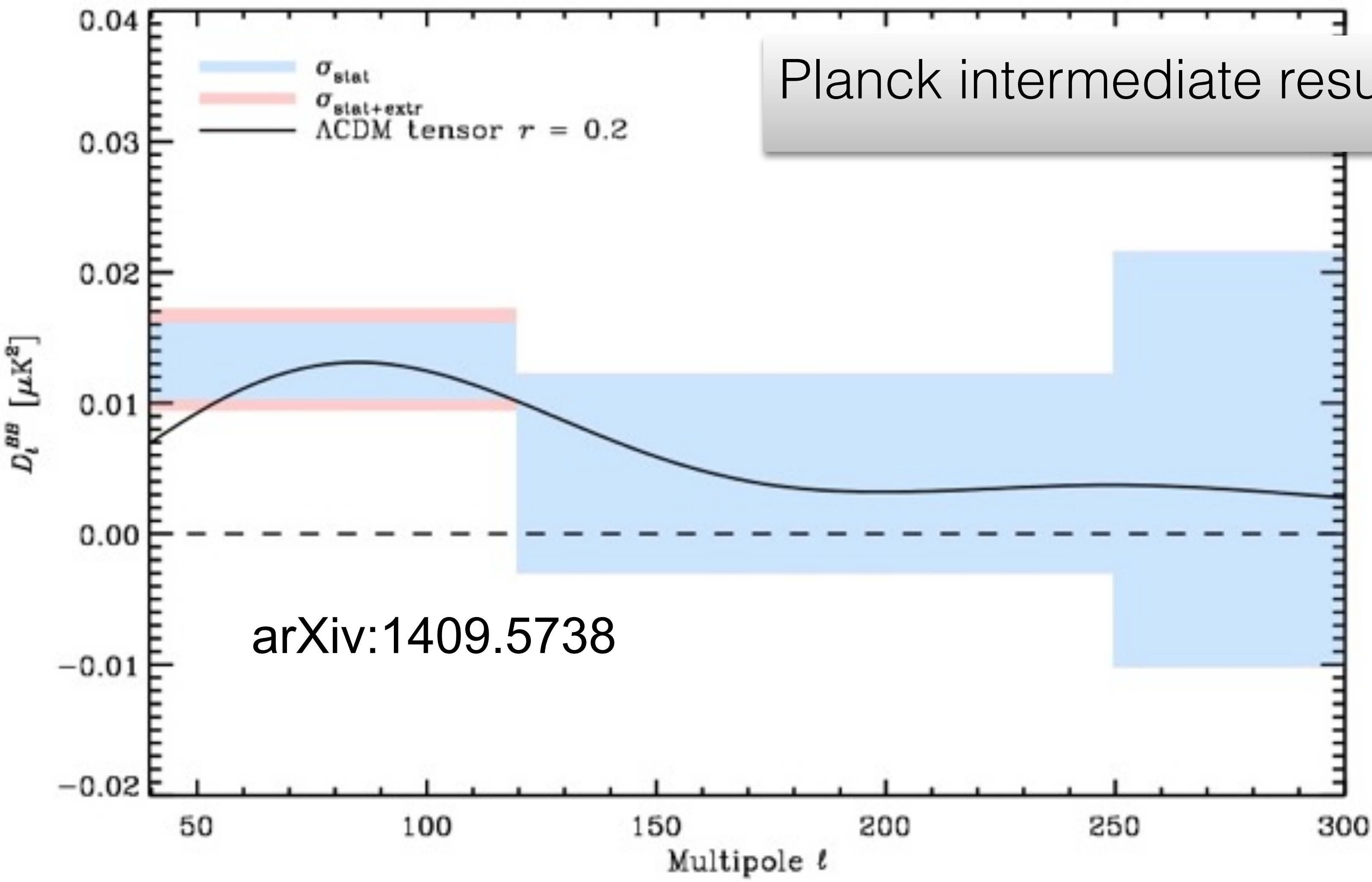
-Foreground dust must be better understood!

r	unsubtracted	DDM2 cross	DDM2 auto
BICEP2	$0.2^{+0.07}_{-0.05}$	$0.16^{+0.06}_{-0.05}$	$0.12^{+0.05}_{-0.04}$
BICEP2×Keck	$0.13^{+0.04}_{-0.03}$	$0.10^{+0.04}_{-0.03}$	$0.06^{+0.04}_{-0.03}$

1405.7351 by Faluger, Hill and Spergel

Also, "astro-5 sigmas" often disappear (rate~1/2)

Planck showed that the power spectrum indicates that the **uncertainty is comparable in magnitude to the BICEP2** measurements at these multipoles.



Planck intermediate results. XXX.

Assessing the dust contribution to the B-mode power measured by the BICEP2 experiment requires a dedicated joint analysis with Planck, incorporating all pertinent observational details of the two data sets, such as masking, filtering, and color corrections. (Further analysis is needed to rule out any sign of B-Mode observation by BICEP2.)