Cosmology after BICEP2

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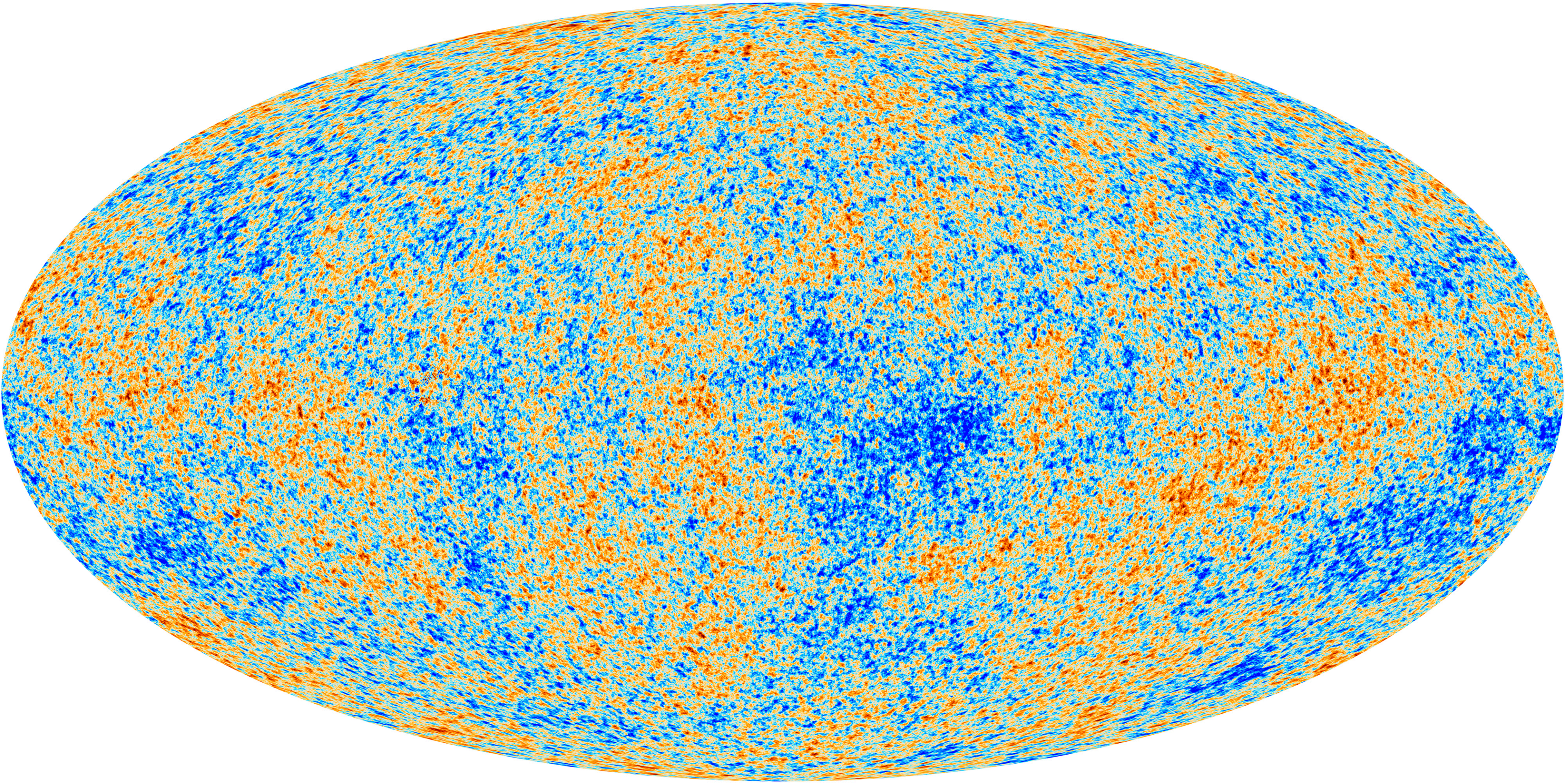
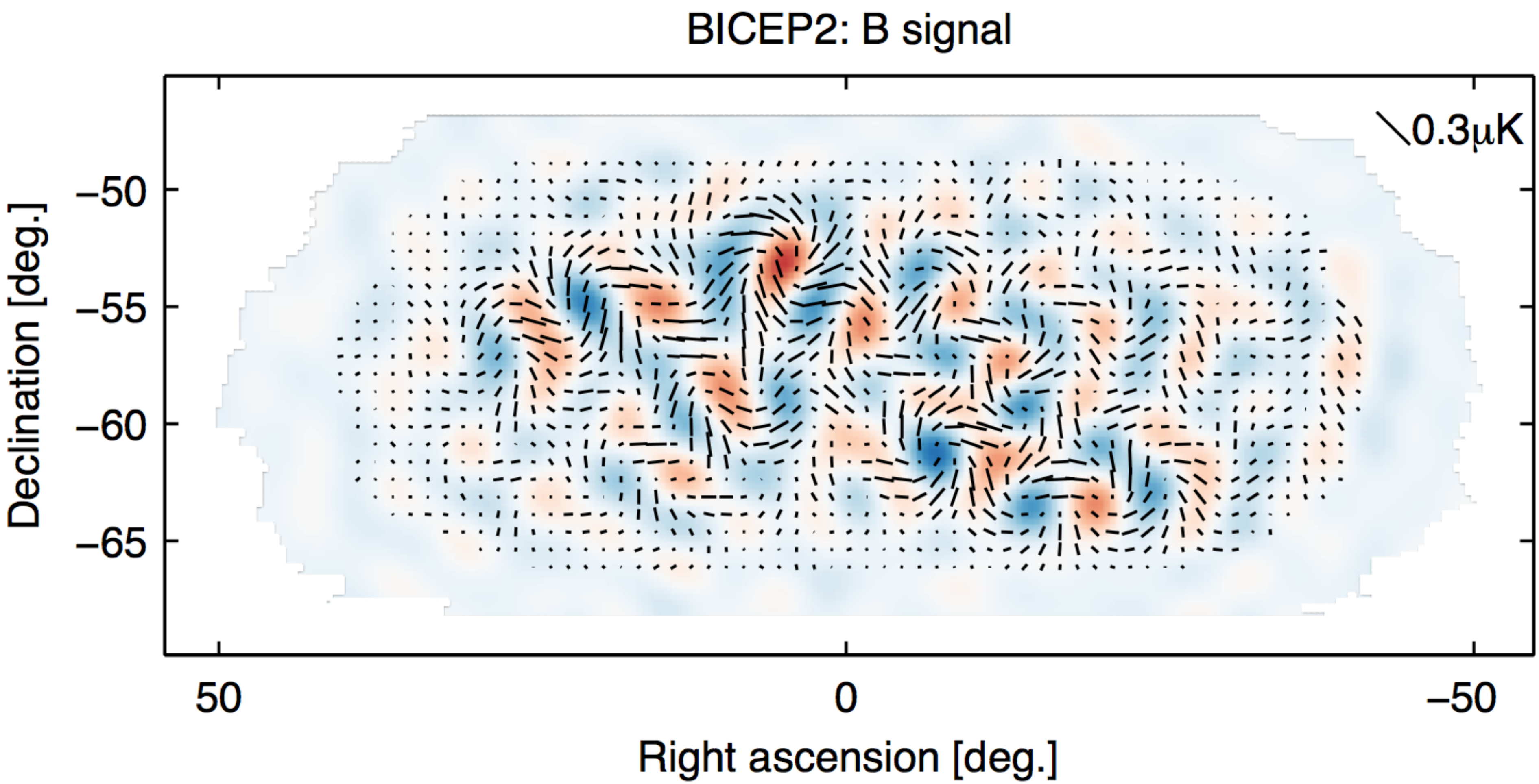
2014.04.10

TEMPERATURE ANISOTROPIES FROM PLANCK

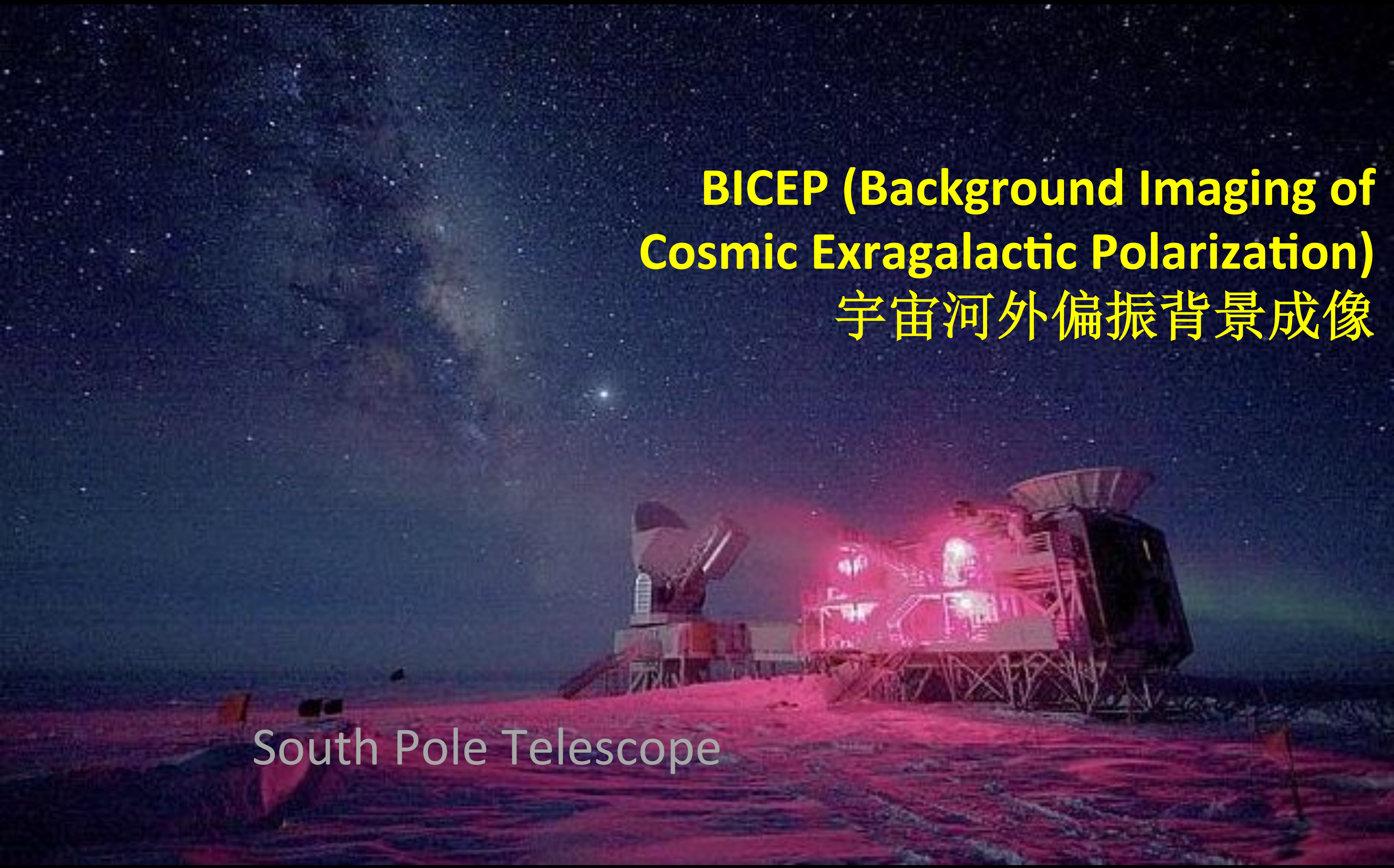


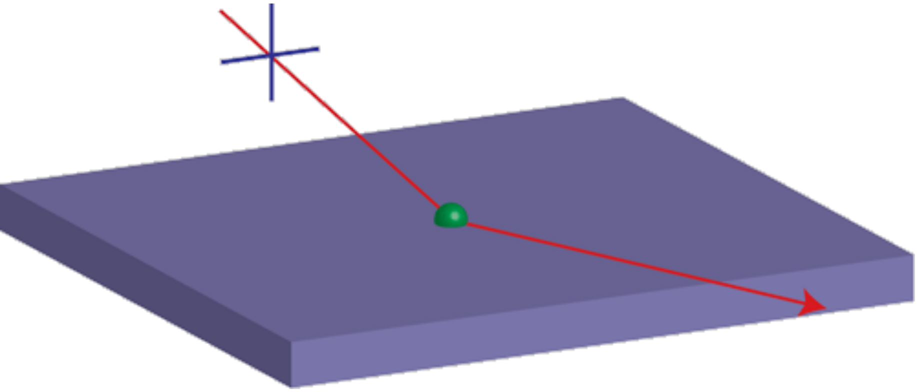
POLARIZATION IN CMB FROM BICEP2

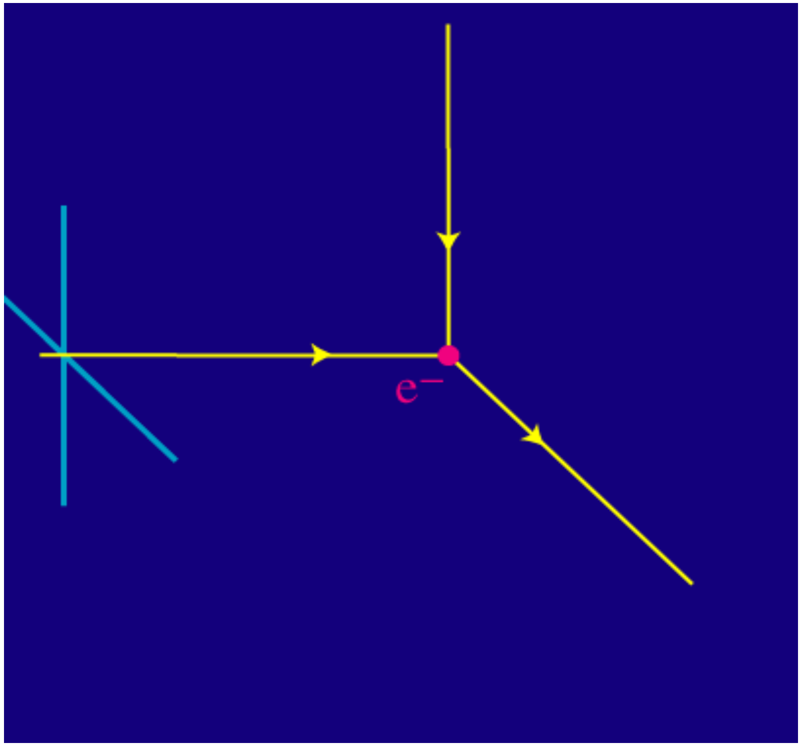


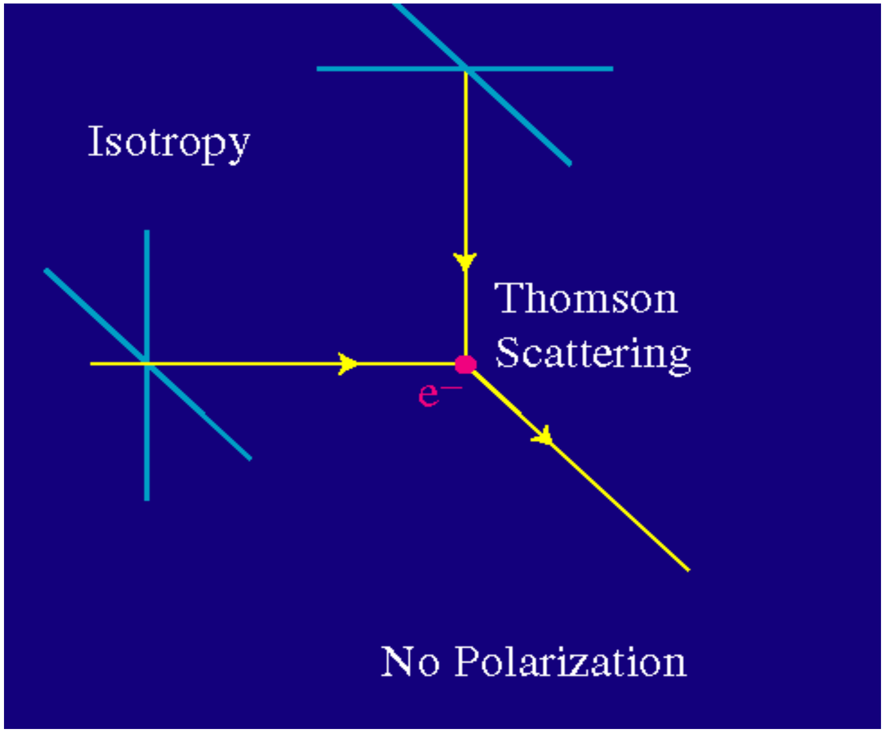
BICEP2 collaboration, arXiv:1403.3985

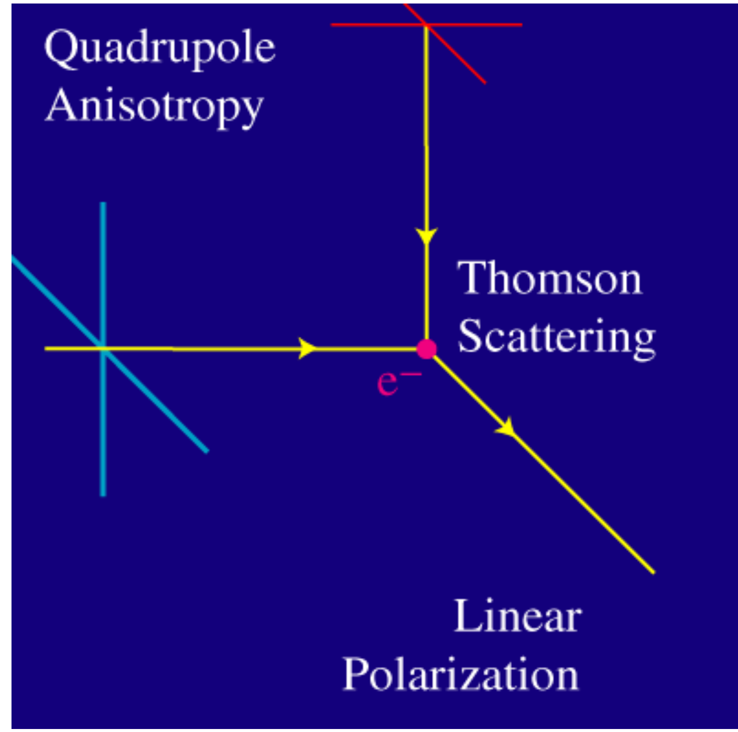
BICEP (Background Imaging of Cosmic Exragalactic Polarization)
宇宙河外偏振背景成像



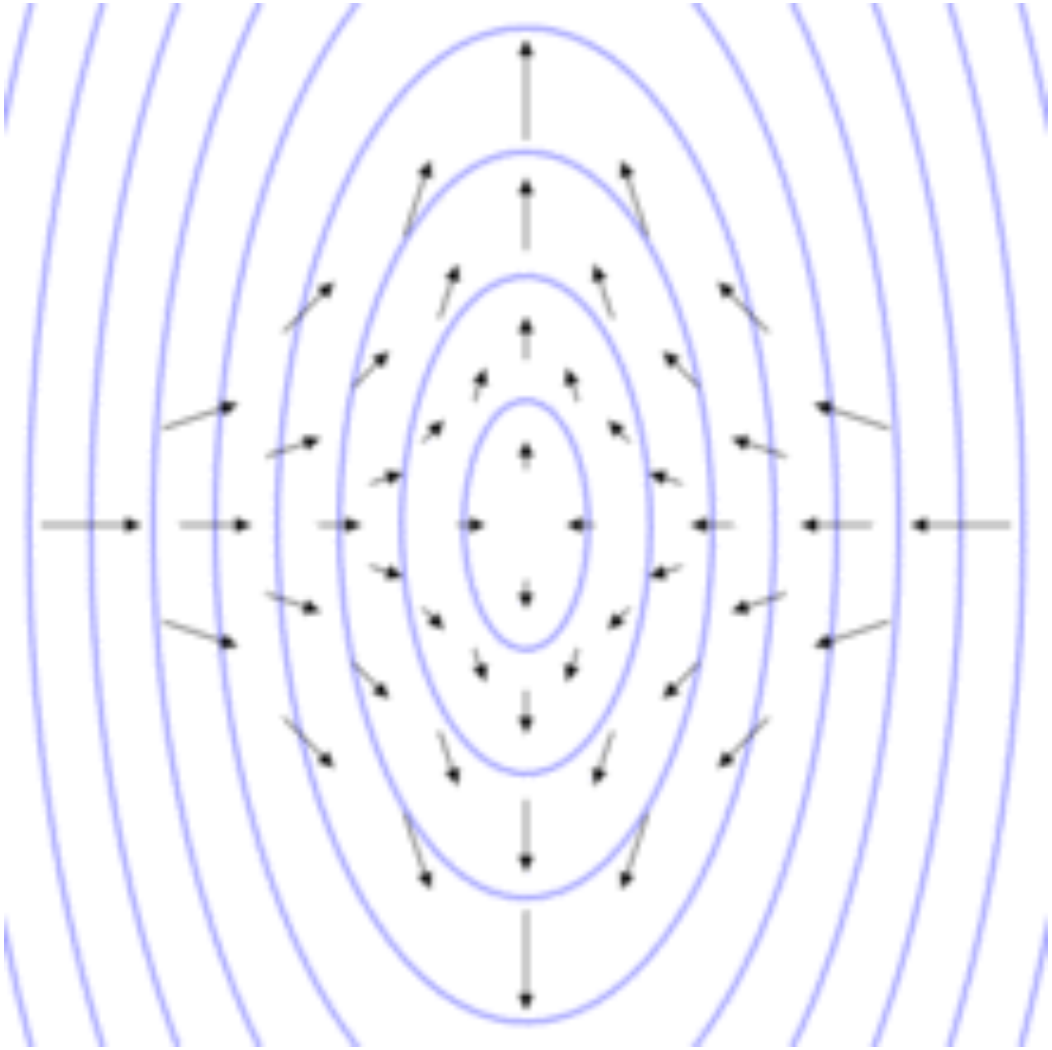


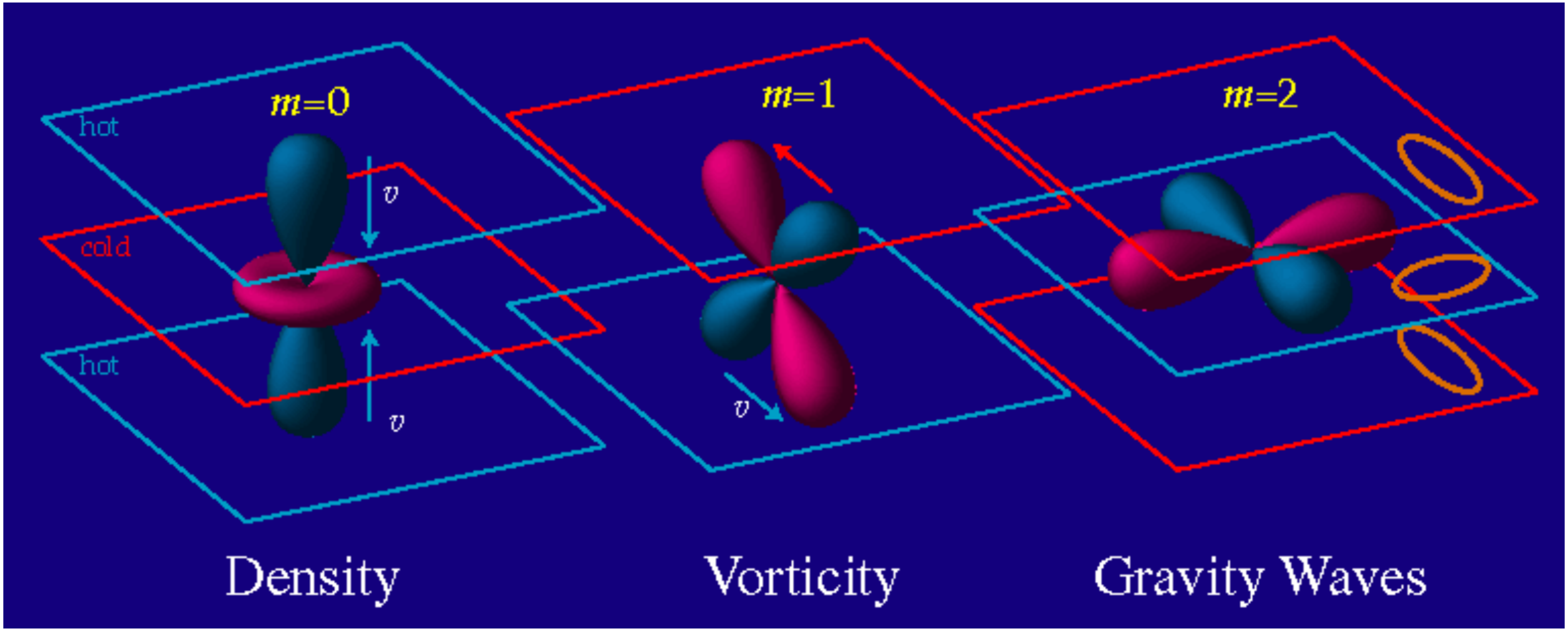

e⁻


Isotropy
Thomson
Scattering
e⁻
No Polarization

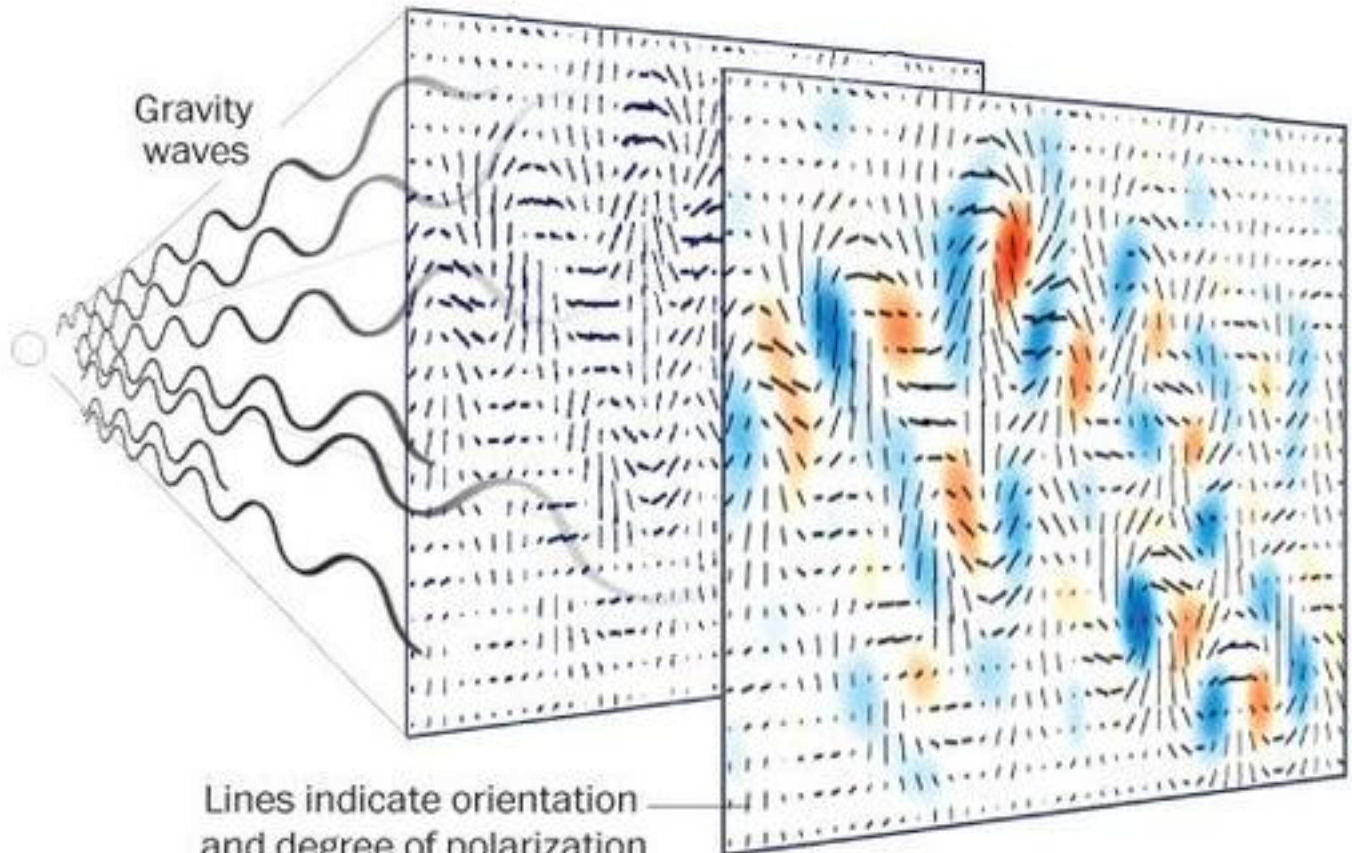

Quadrupole
Anisotropy
Thomson
Scattering
e⁻
Linear
Polarization

Gravitational Waves

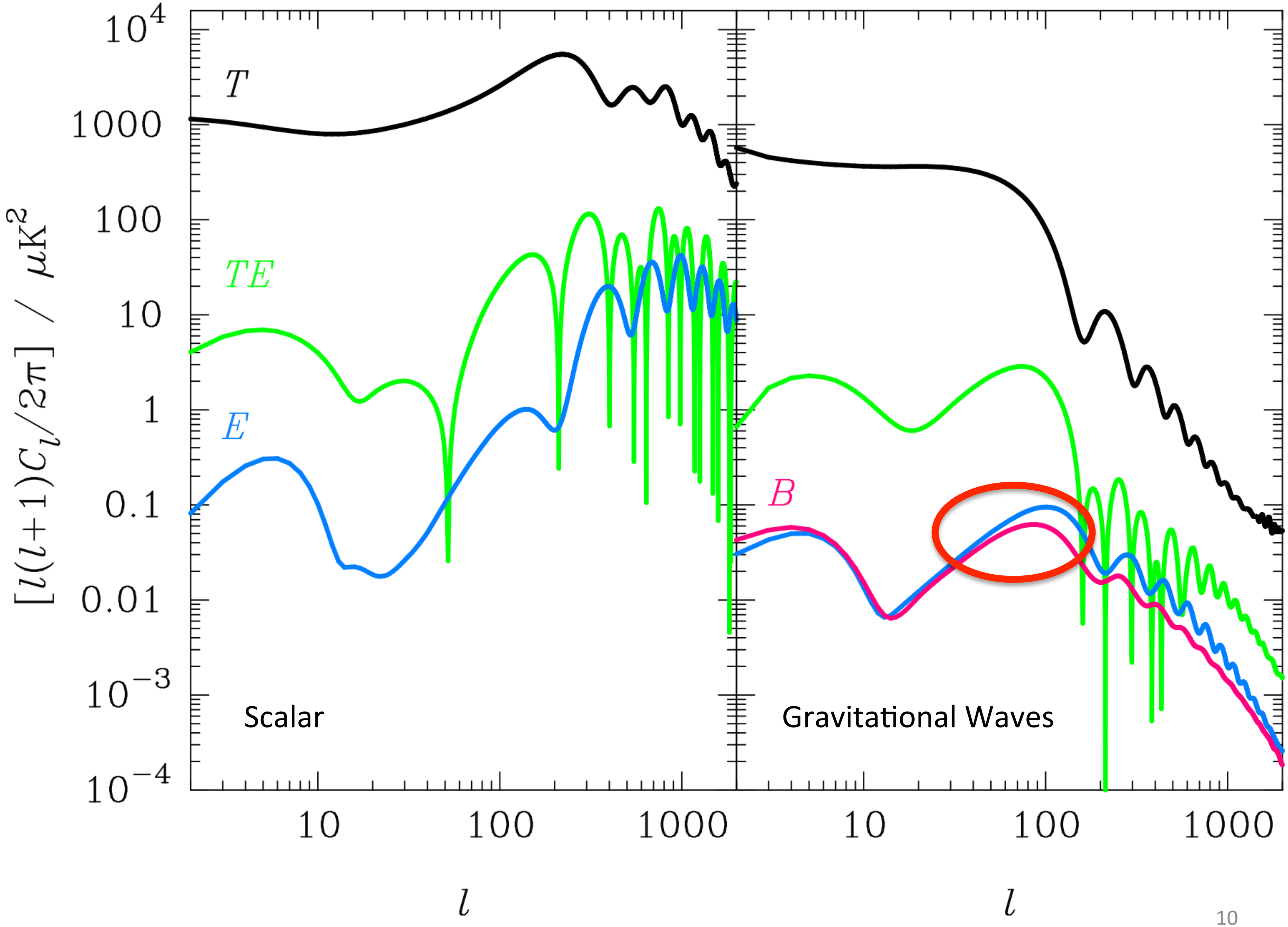




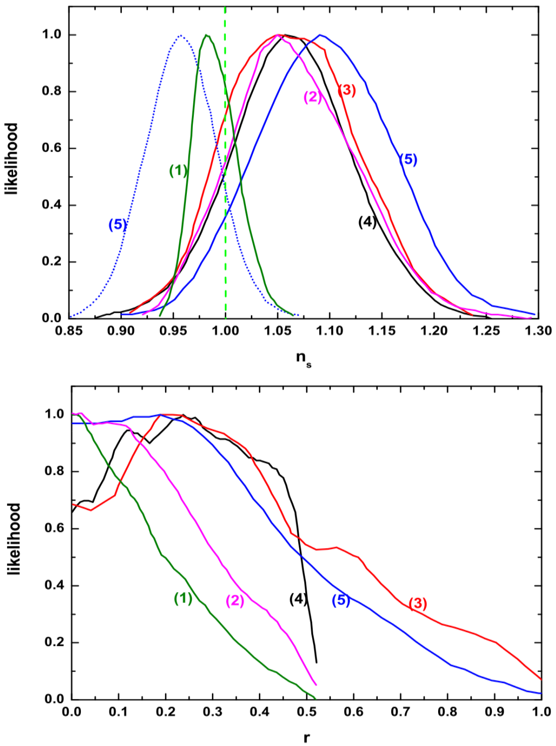
m=0
hot
cold
hot
v
v
m=1
v
m=2
Density
Vorticity
Gravity Waves

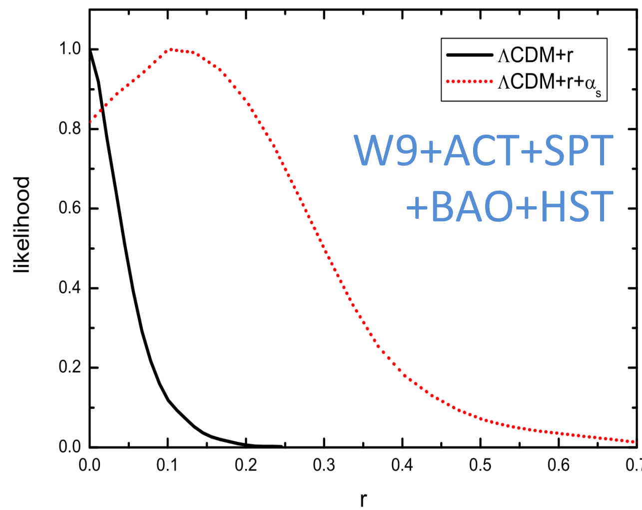


In the 1990s, physicists theorized that rapid inflation during the big bang would also generate **gravity waves**, which would leave their mark by polarizing light in the cosmic afterglow. Extremely sensitive telescopes at the South Pole have detected such skewed light waves, but scientists have spent almost a decade ensuring that the phenomenon was not the result of other factors.

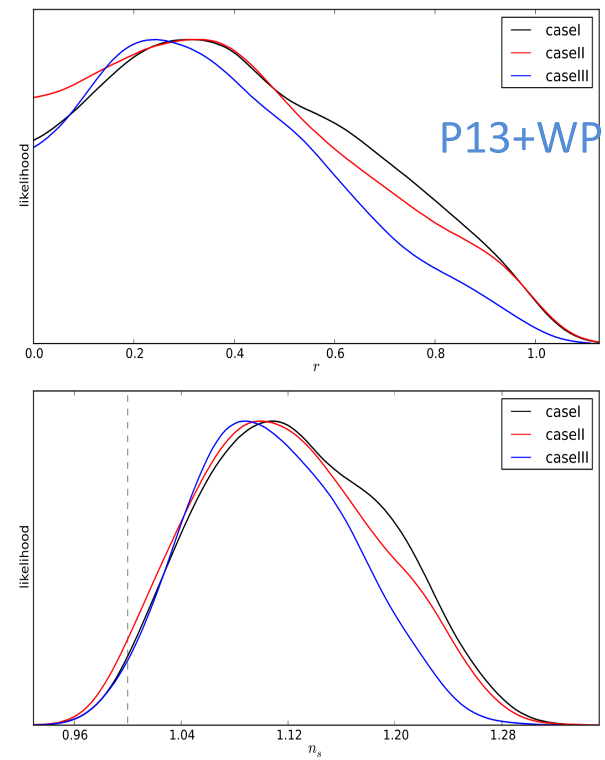

$[l(l+1)C_l/2\pi]$ / μK^2
10^4
1000
100
10
1
0.1
0.01
10^{-3}
10^{-4}
T
TE
E
B
Scalar
Gravitational Waves
10
100
1000
10
100
1000
l
l

Some hints from CMB before BICEP2





	ΛCDM	ΛCDM+r	ΛCDM+α_s	ΛCDM+r+α_s
n_s	0.961 ± 0.007	0.959 ± 0.006	1.018 ± 0.027	1.066 ± 0.040
$r(95\%CL)$	–	< 0.12	–	< 0.42
α_s	–	–	-0.021 ± 0.009	-0.035 ± 0.012
β_s	–	–	–	–
Best fit -ln(Like)	4921.52	4921.15	4917.30	4916.91
$\Delta\chi^2$	0	-0.74	-8.44	-9.22

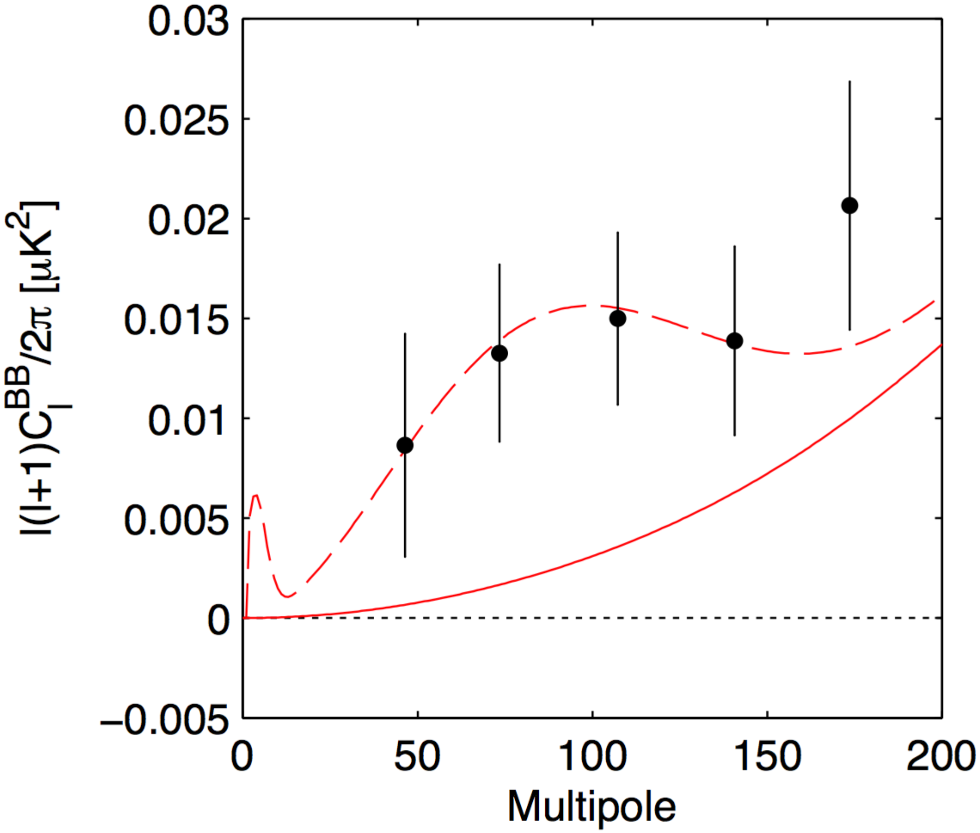


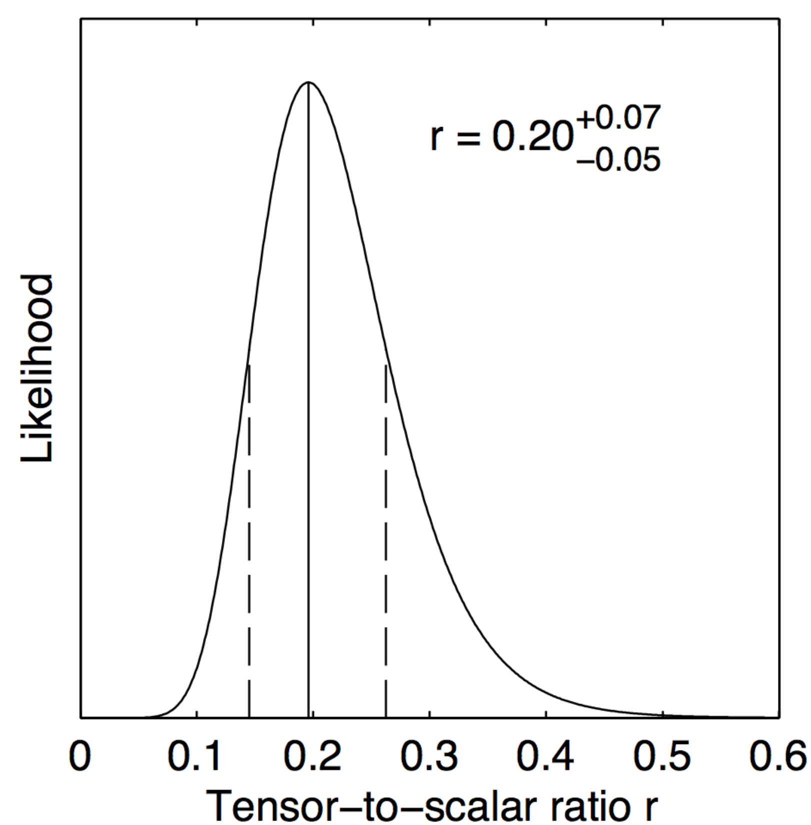
W. Zhao, Grishchuk, 2010

C. Cheng, QGH, Y. Ma, 2013

W. Zhao, C. Cheng, QGH, 2014

Discovery of relic gravitational waves (BICEP2)

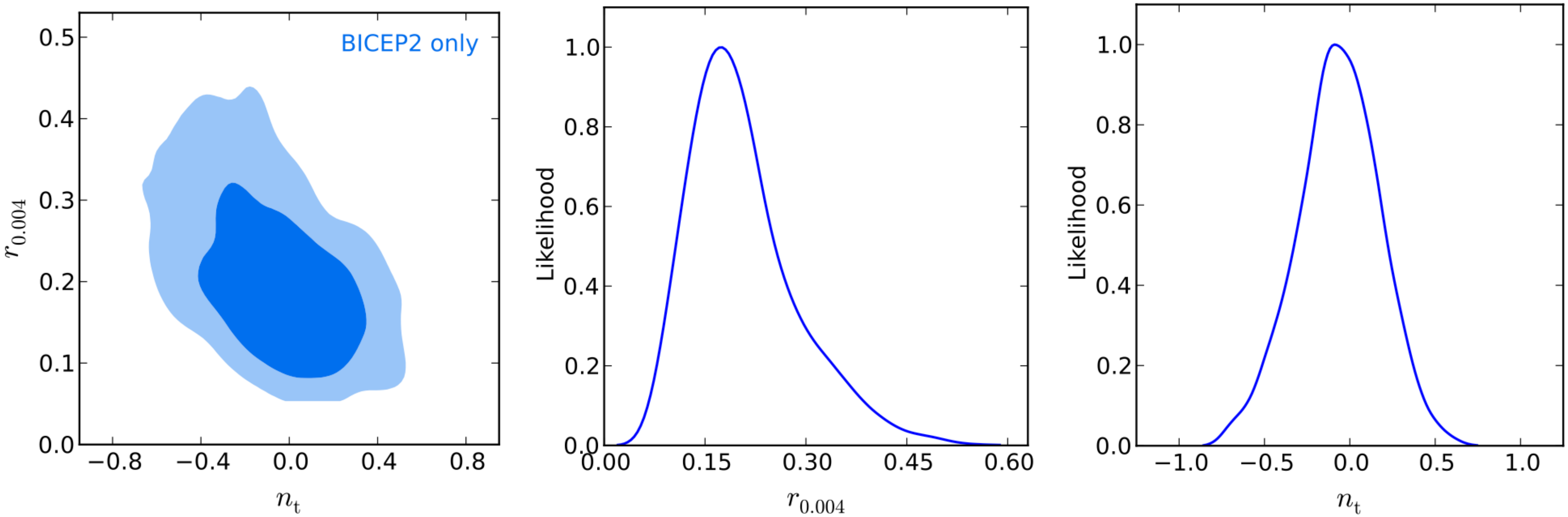




$$r = 0.2^{+0.07}_{-0.05},\ \text{with } r = 0 \text{ is disfavored at } 7.0\sigma$$

BICEP2 collaboration, arXiv:1403.3985

The tilt of primordial gravitational waves spectra



$$P_t = A_t \left(\frac{k}{k_p} \right)^{n_t}$$

$$r = 0.21^{+0.04}_{-0.10} \qquad n_t = -0.06^{+0.25}_{-0.23}$$

C. Cheng and QGH, arXiv:1403.5463

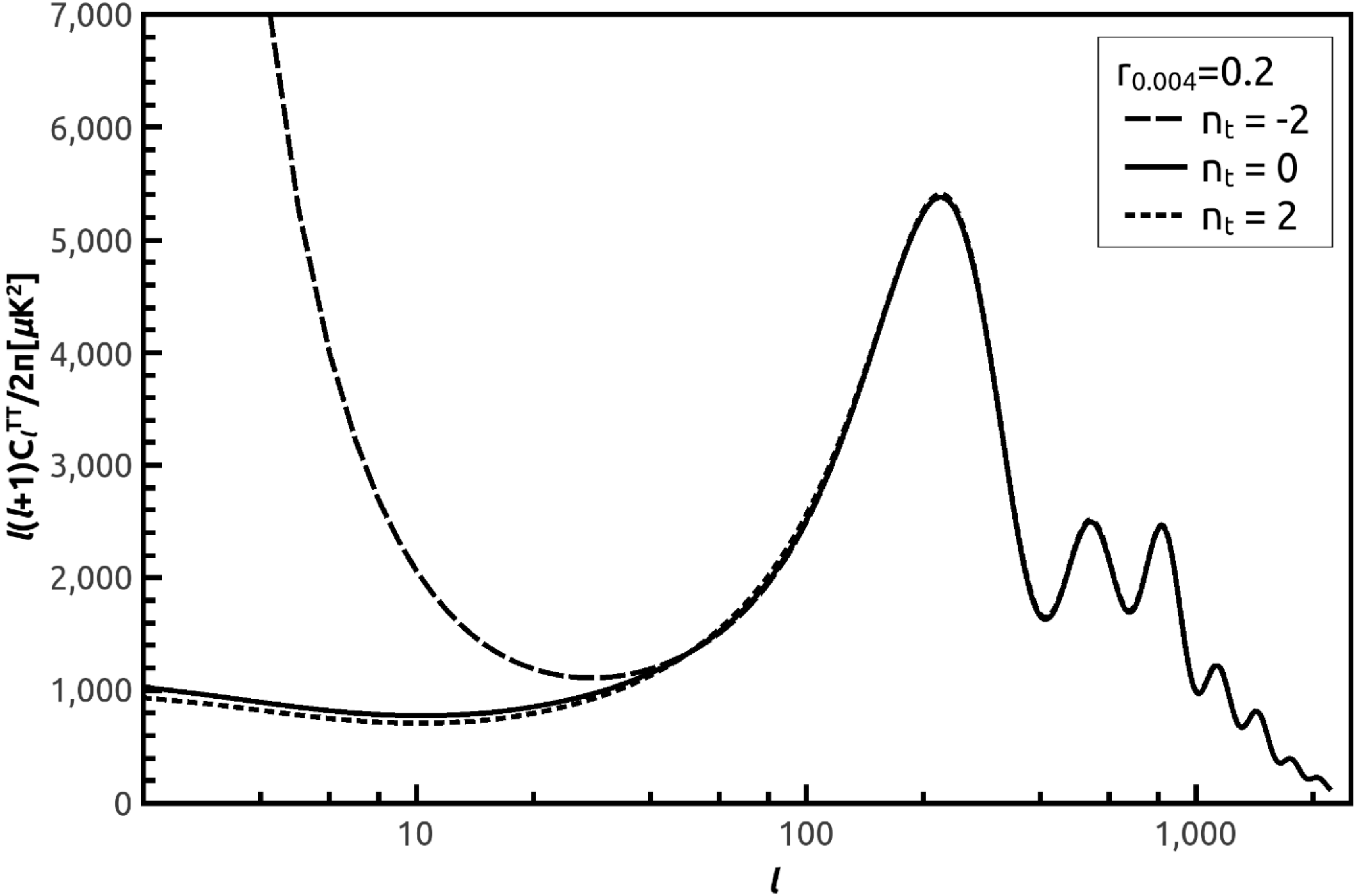
Our results provide
strong evidence for supporting inflation,
and
the alternative models,
for example the Ekpyrotic model (n_t =2),
is ruled out at more than 5σ level.

Consistency relation: $n_t = -r/8$

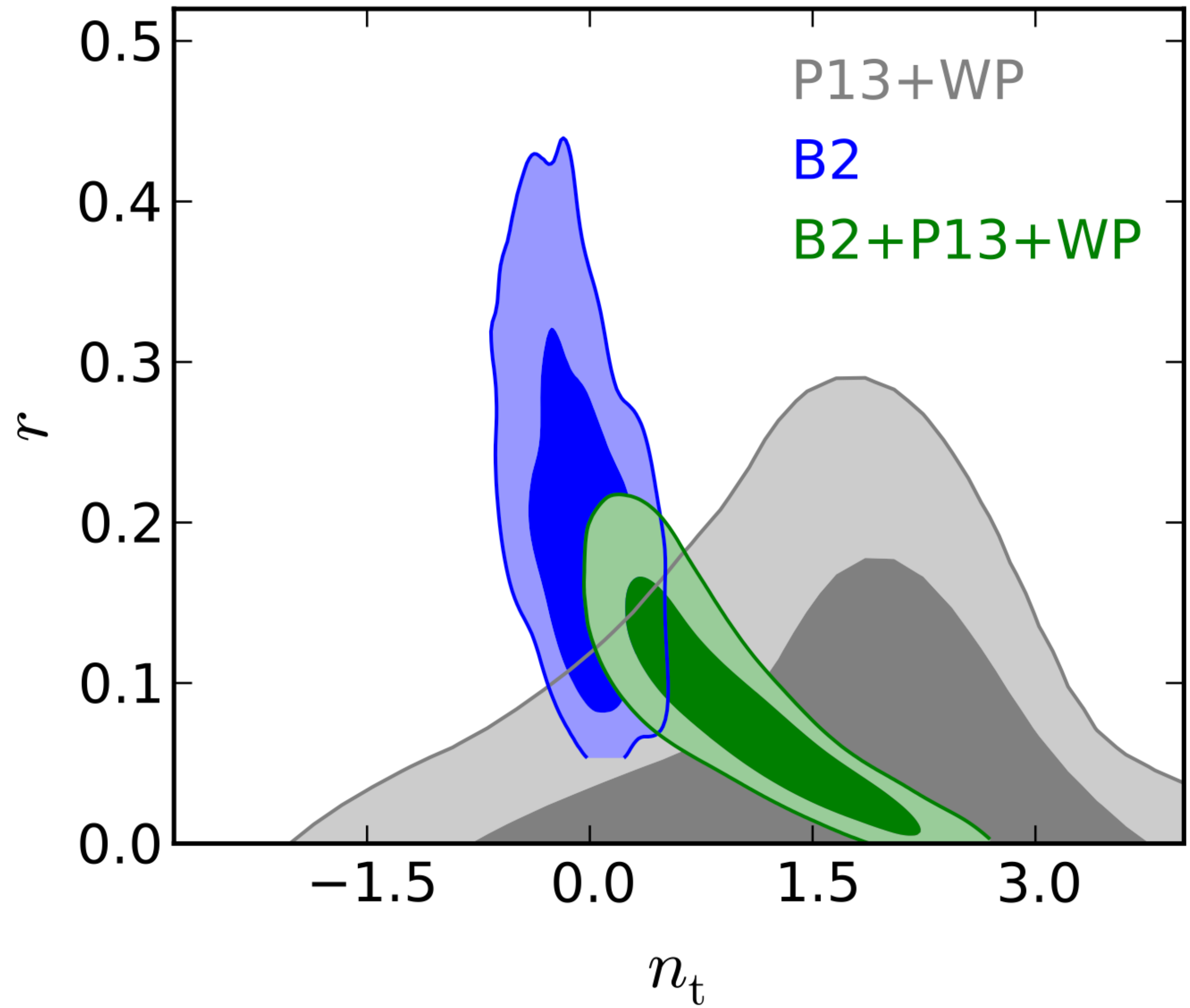
C. Cheng and QGH, arXiv:1403.5463

After our paper appeared on arXiv, several groups also did the similar work and reported a blue tilted spectra of relic gravitational waves.

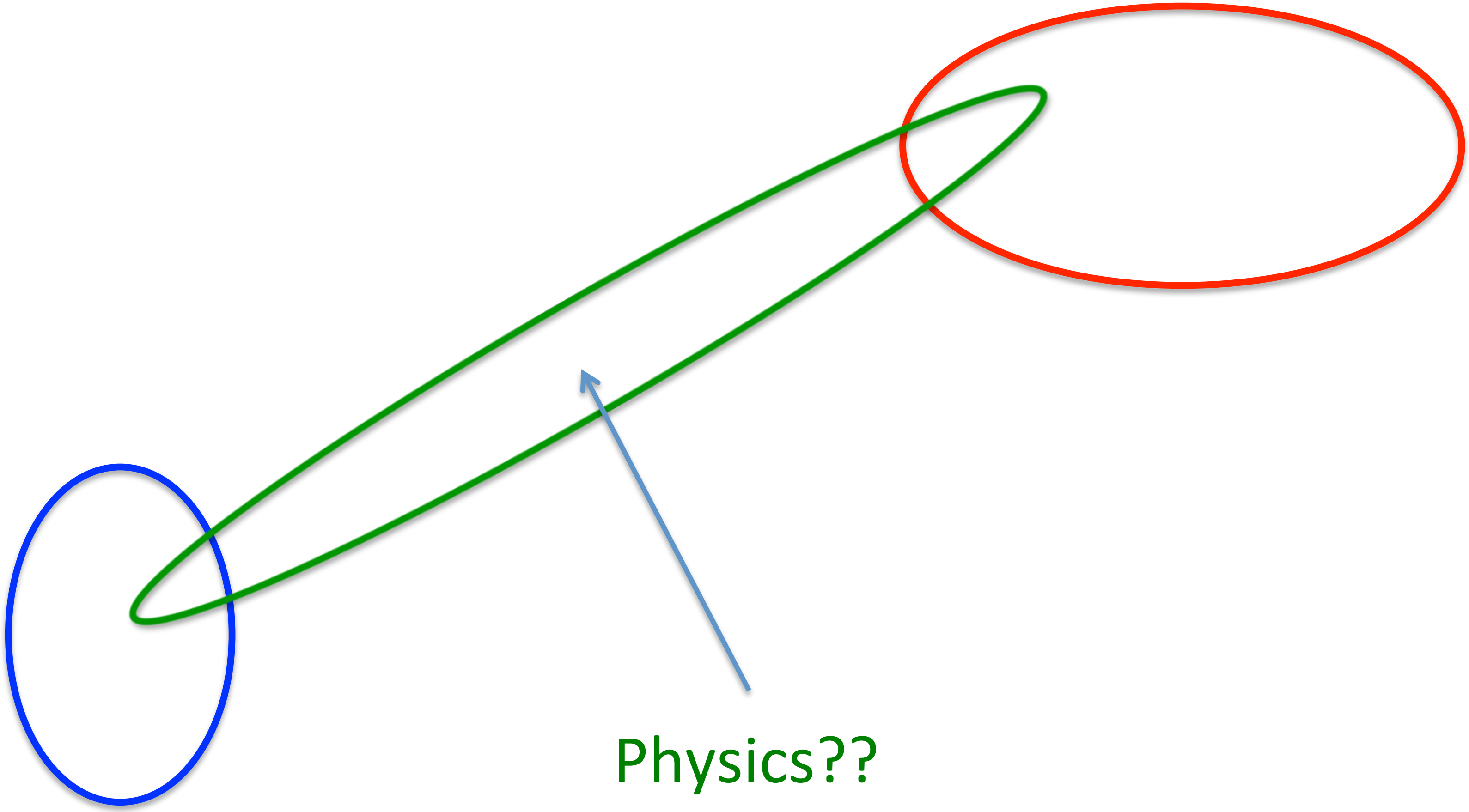
We believe that this apparently blue tilt is not reliable.

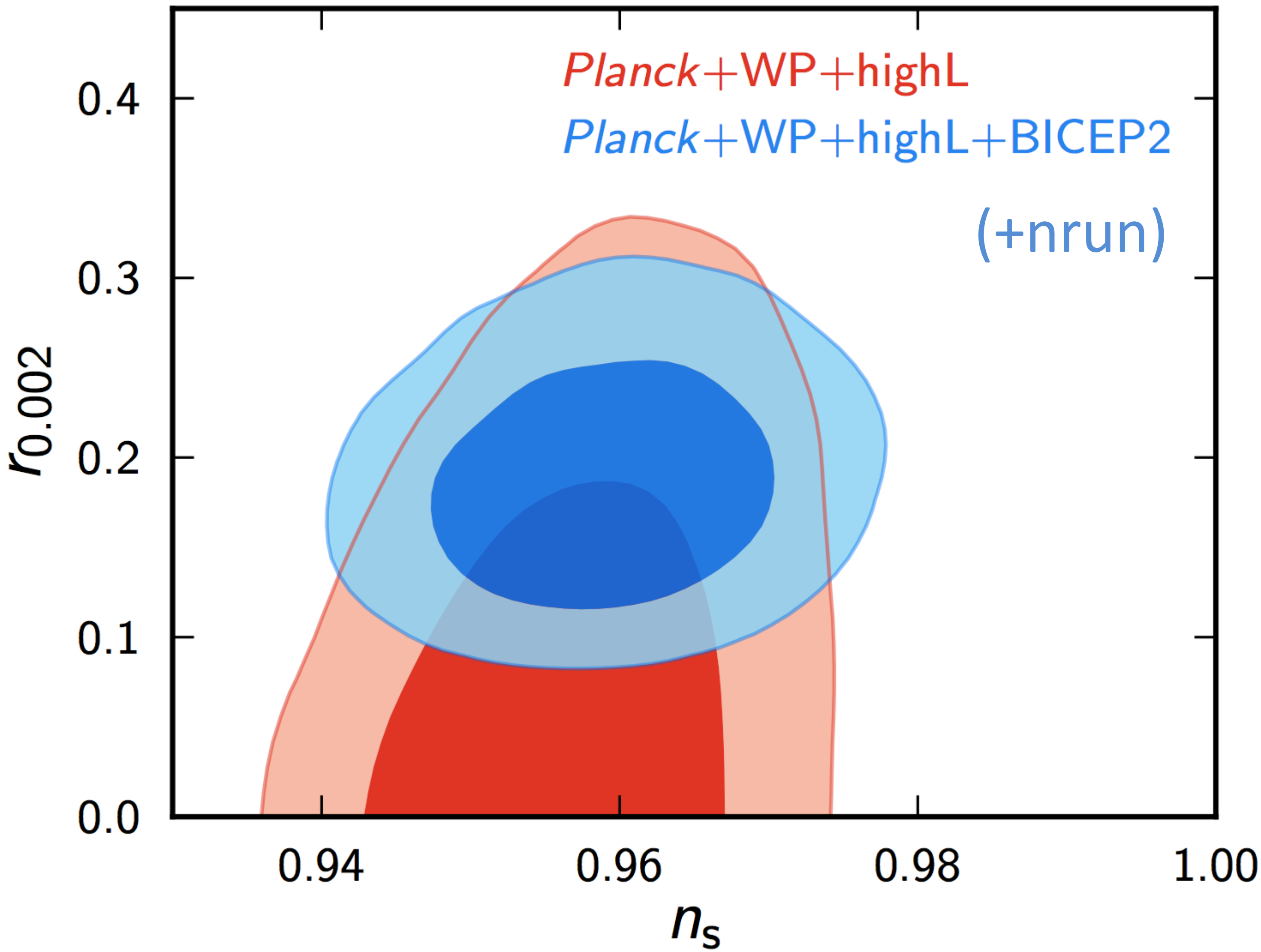


C. Cheng and QGH, arXiv:1403.7173

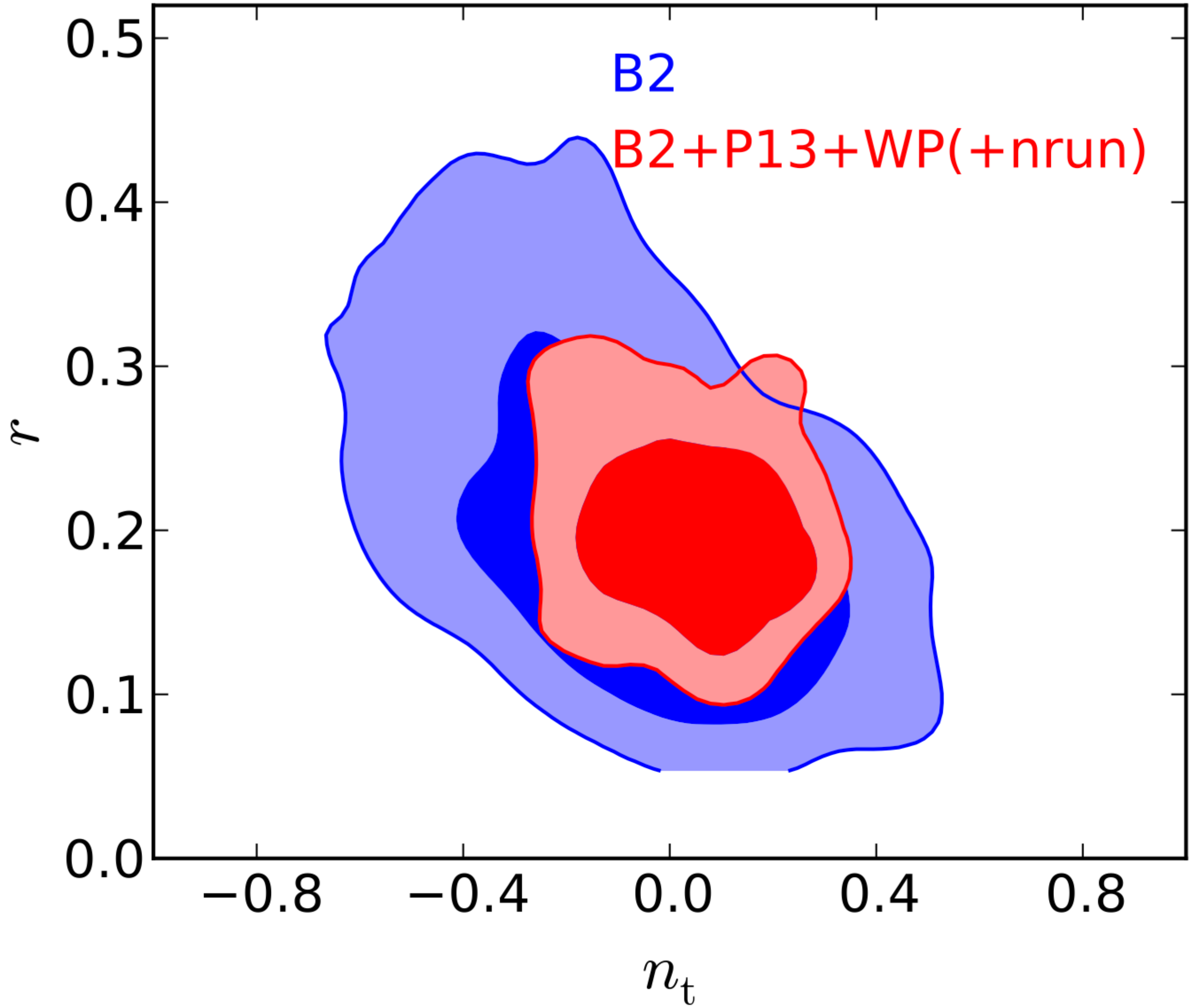


C. Cheng and QGH, arXiv:1403.7173


Physics??



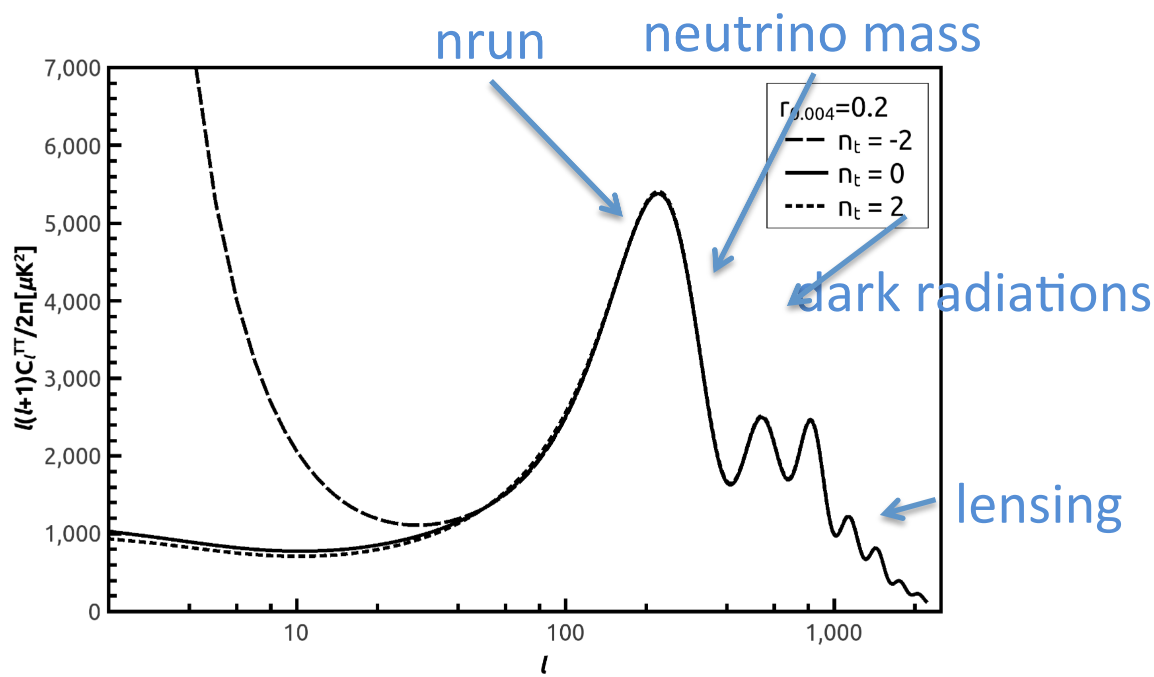
BICEP2 collaboration, arXiv:1403.3985



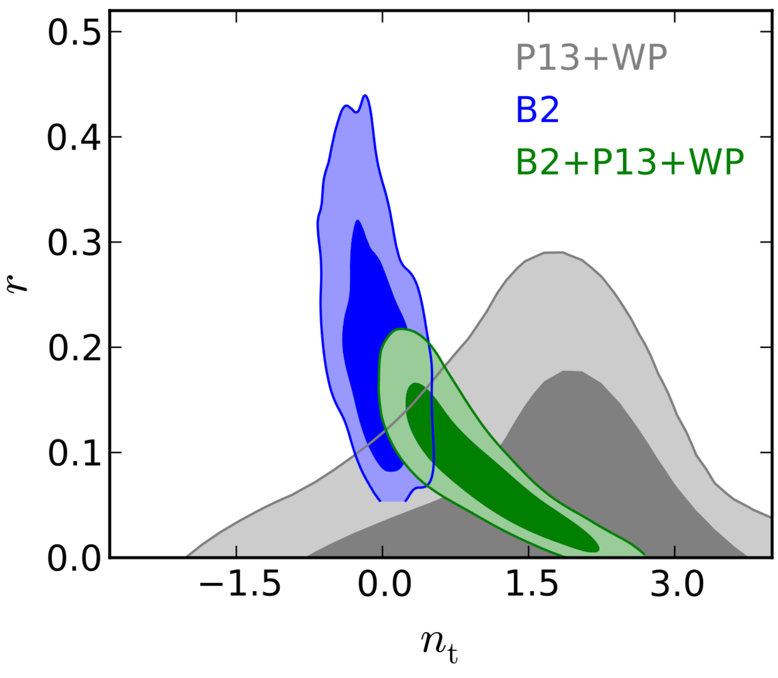
C. Cheng and QGH, arXiv:1403.7173

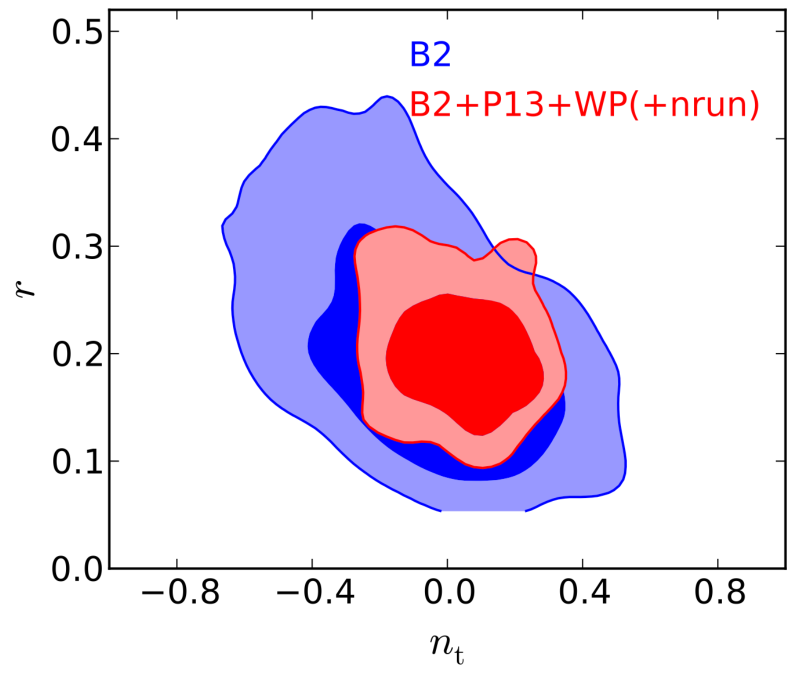
It indicates that the apparently blue tilted spectrum of relic gravitational waves is not reliable and it can be explained by the tension between B2 and P13+WP in the ΛCDM+r+n_t model.

Actually it is dangerous to use the CMB temperature spectrum to constrain the properties of relic gravitational waves, e.g. the tilt n_t , because the relic gravitational waves just make a small contribution to the CMB temperature spectrum which can be affected by a lot of complicated physics, such as the running of spectral index, the total mass of active neutrinos, the number of relativistic species and so on.

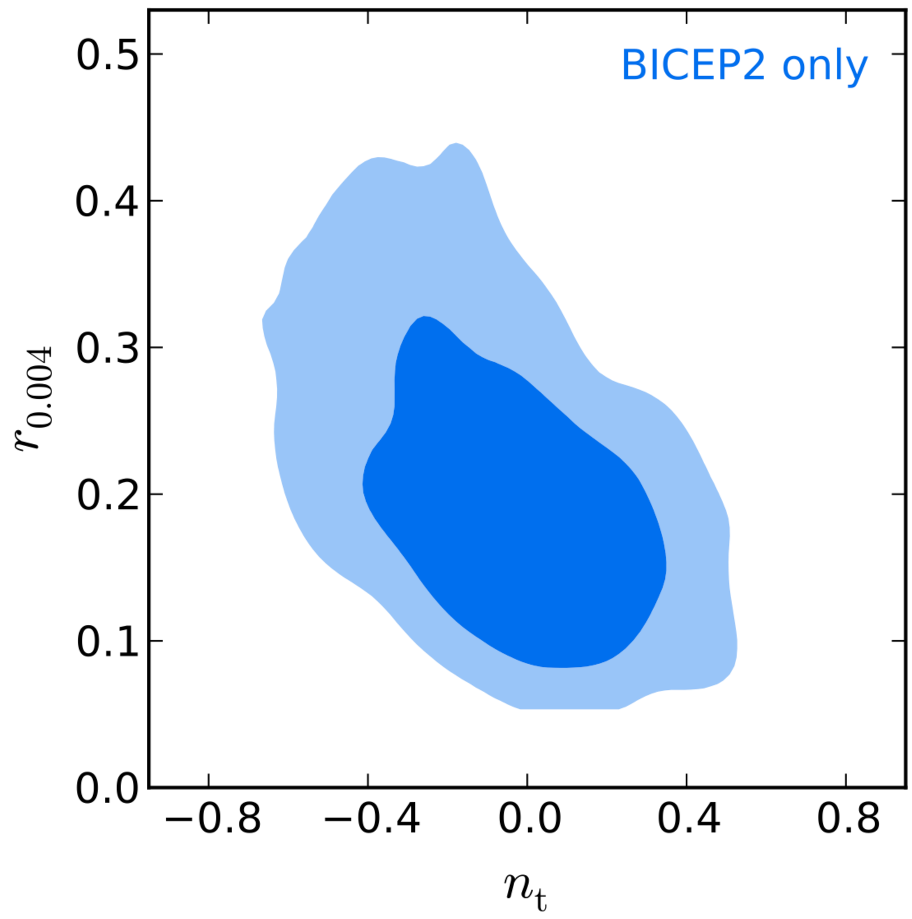


All of these complicated physics can bring strong bias on the data analysis.



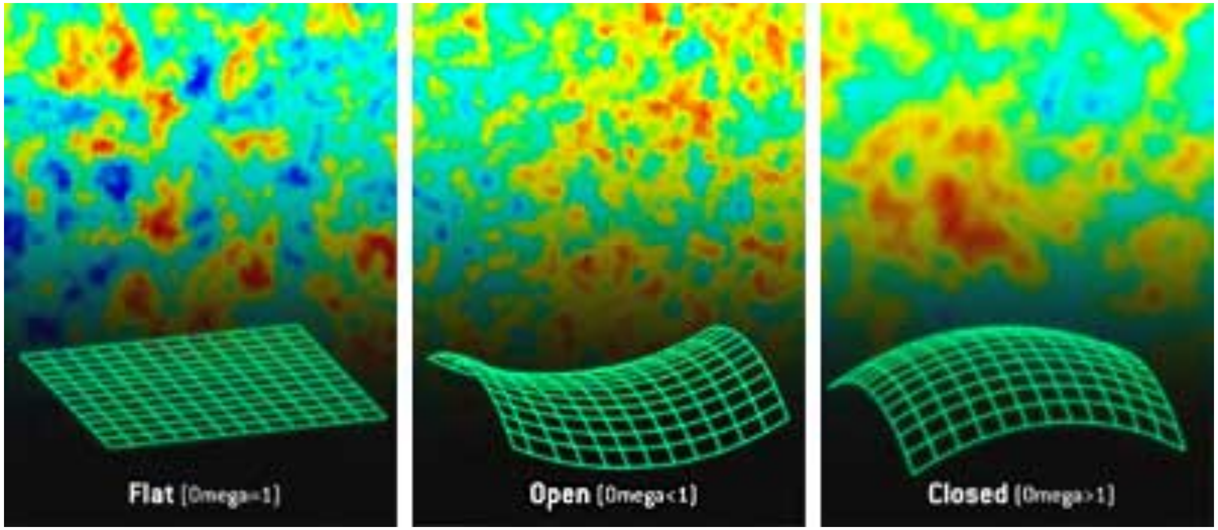


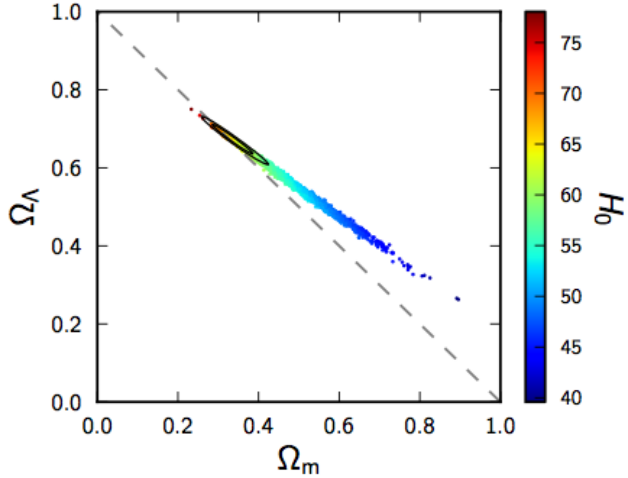
In a word, the polarization data like those released by B2 is supposed to be the best one for us to constrain the tilt of primordial gravitational waves spectrum.

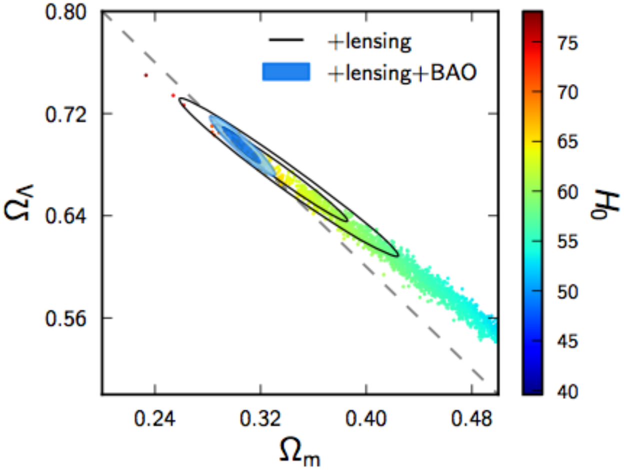


- Inflation in the early universe
- Discussion and summary

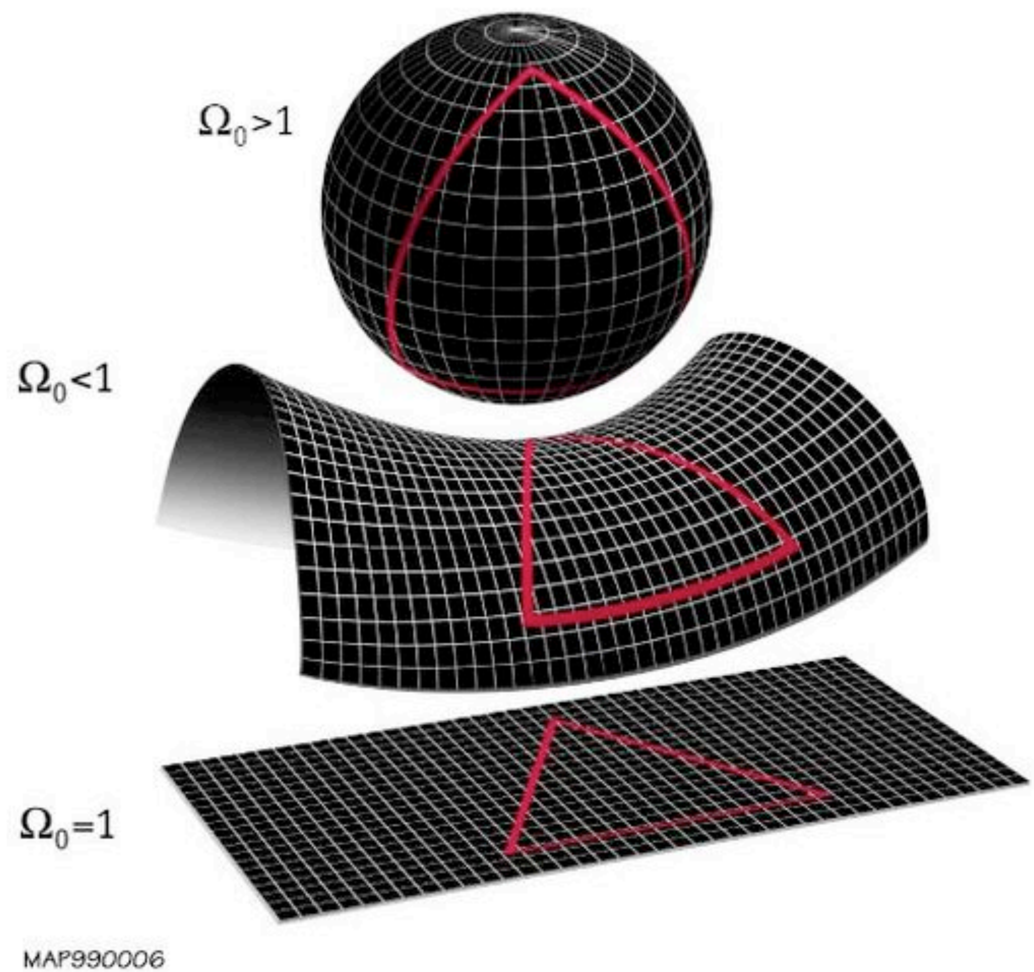
Inflation in the early universe





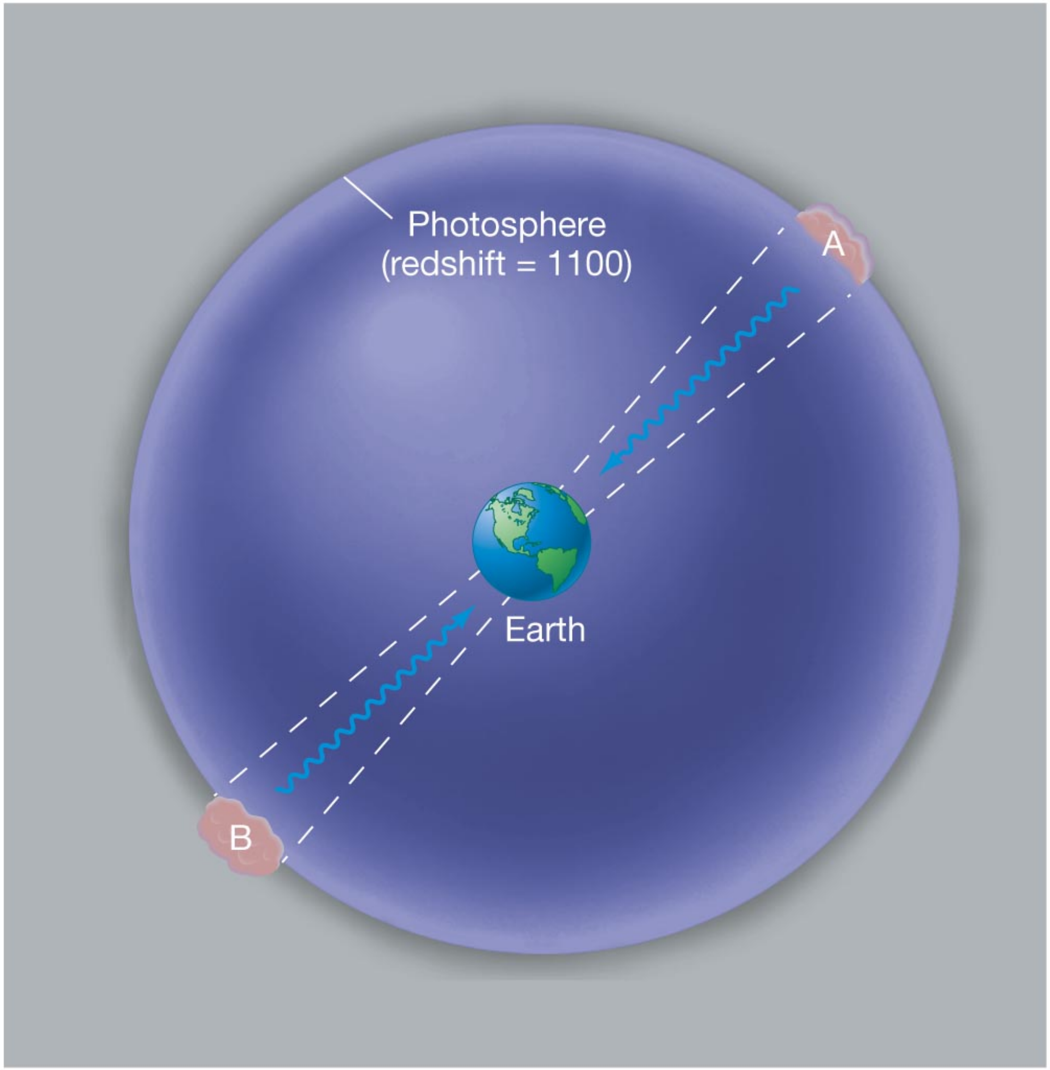


$$100\Omega_k = -0.10^{+0.62}_{-0.65} \text{ (95\%; Planck+lensing+WP+highL+BAO)}$$



Radiation-dominant era: $a \sim t^{1/2},\ H \sim 1/t\ \Rightarrow |\Omega_k| \sim t$

Matter-dominant era: $a \sim t^{2/3},\ H \sim 1/t\ \Rightarrow |\Omega_k| \sim t^{2/3}$


Photosphere
(redshift = 1100)
A
Earth
B

Original idea of inflation

PHYSICAL REVIEW D VOLUME 23, NUMBER 2 15 JANUARY 1981

Inflationary universe: A possible solution to the horizon and flatness problems

Alan H. Guth*

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 11 August 1980)

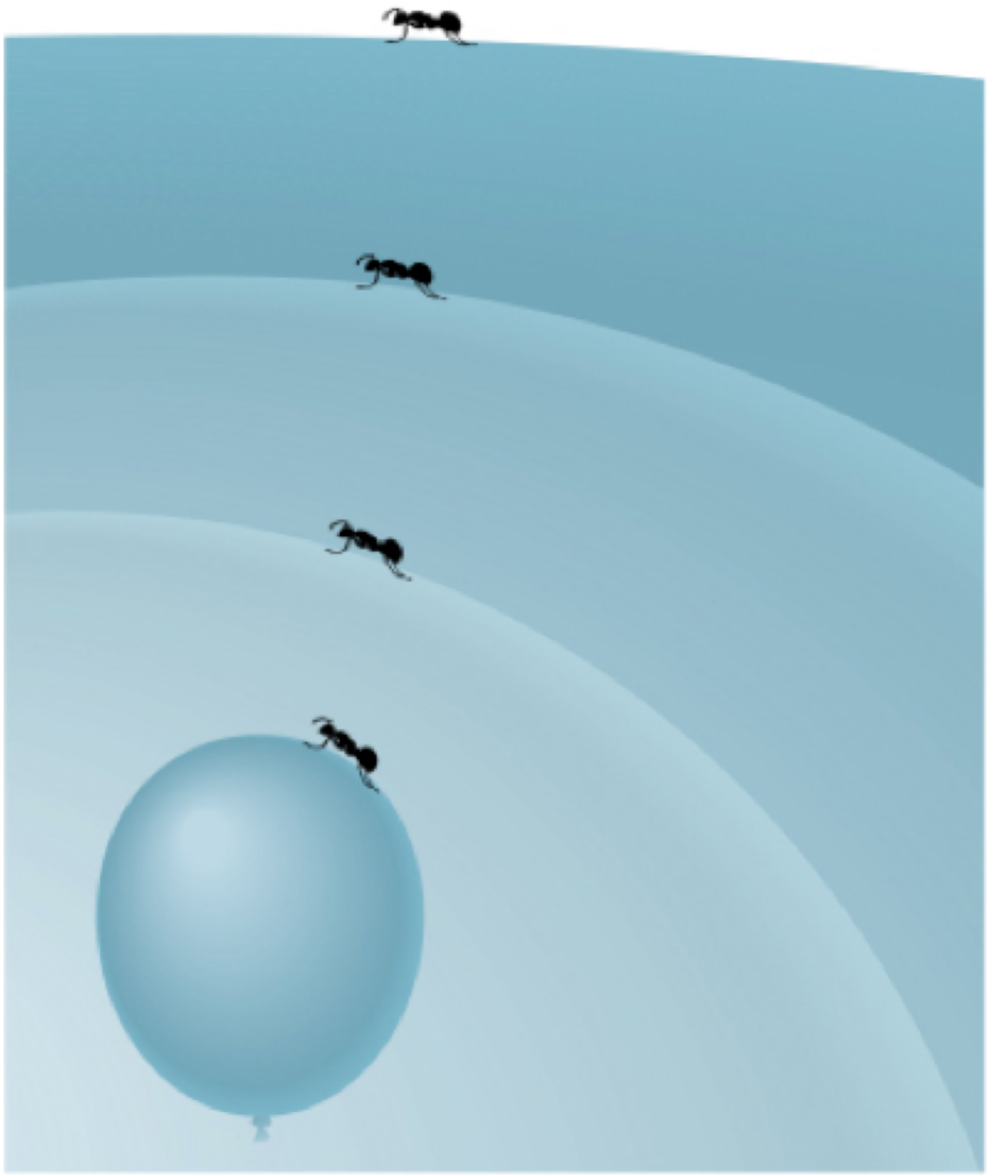
The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

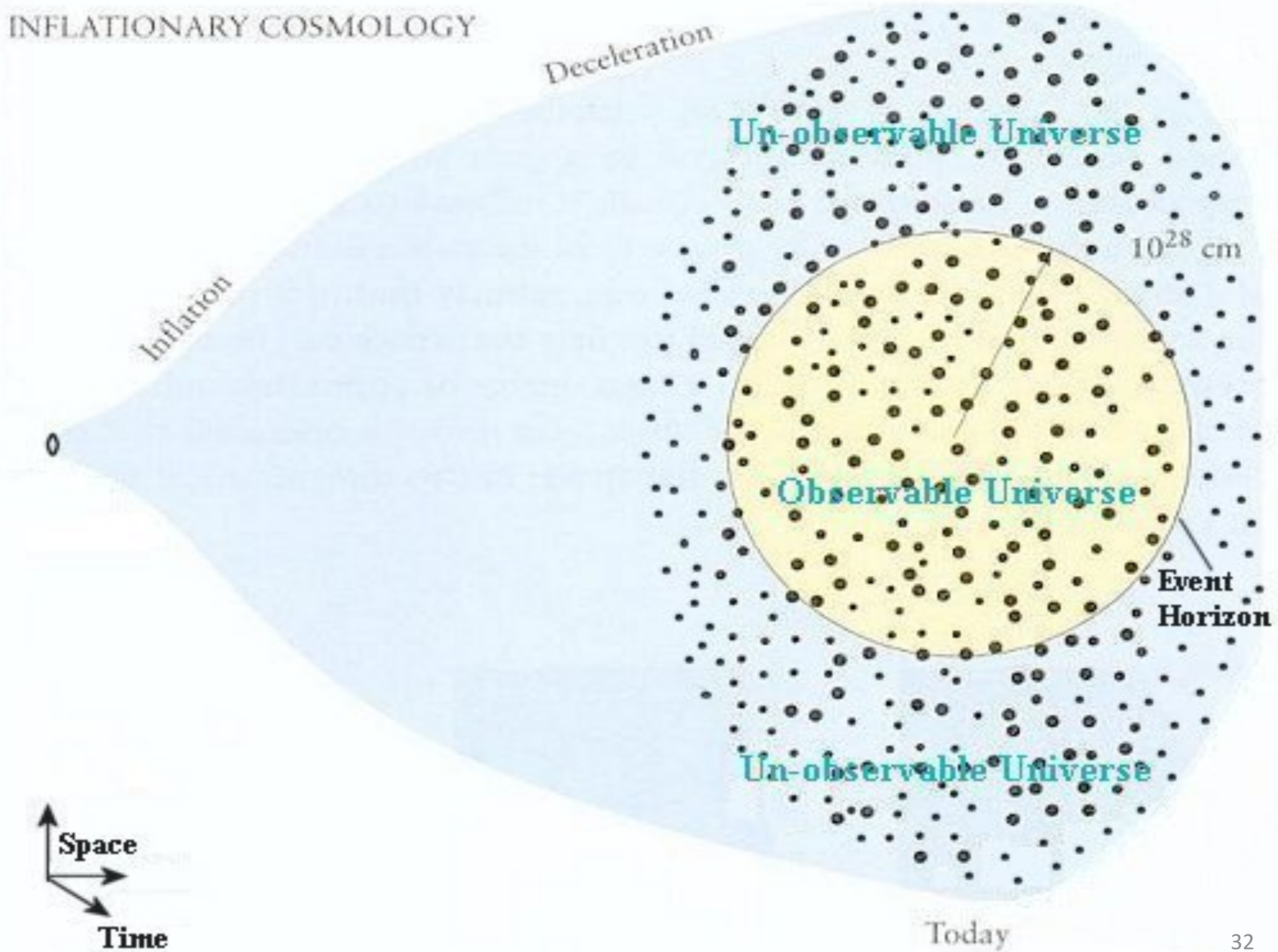
A. Guth, 1981

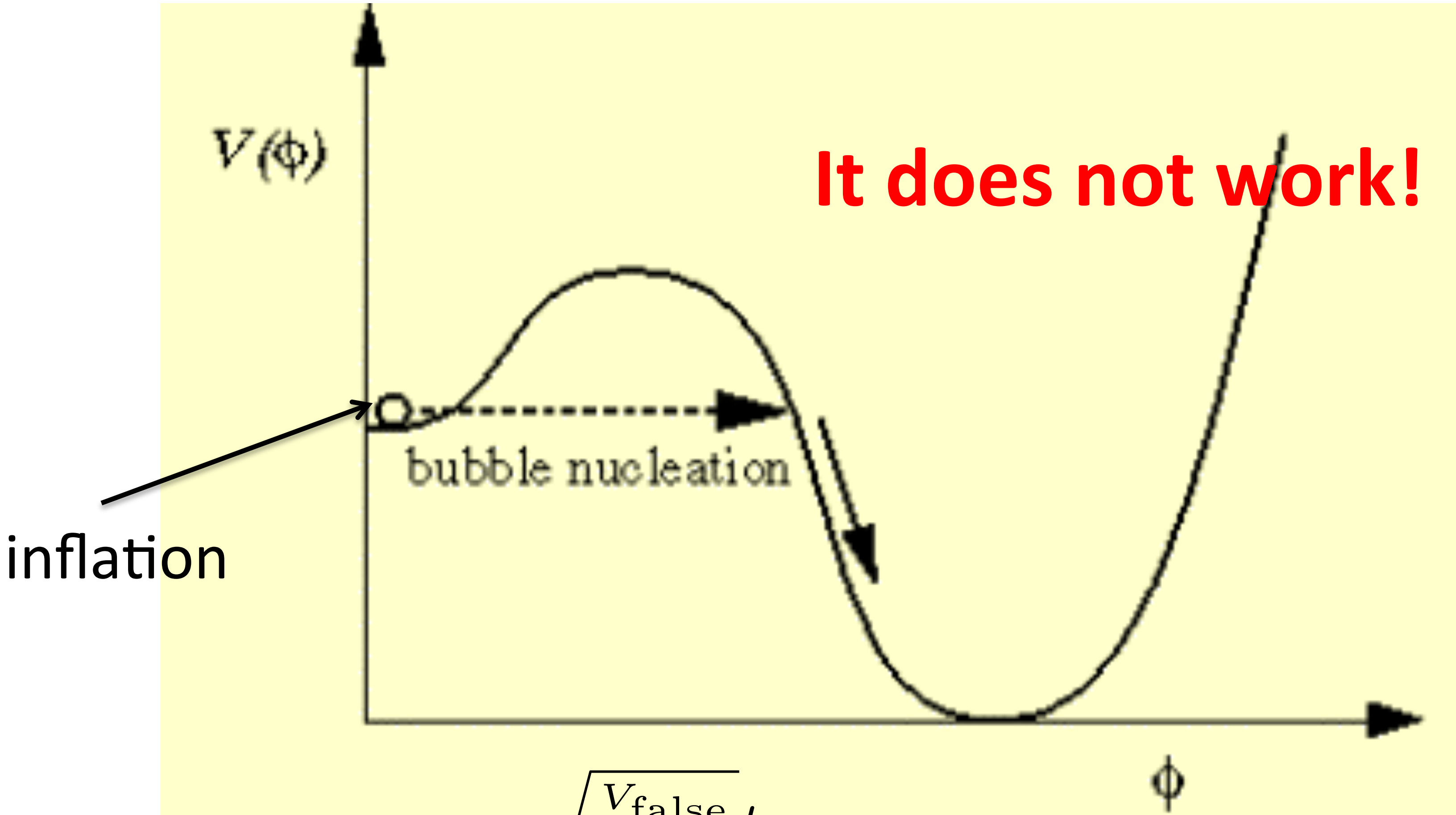
Friedmann Equation:

$$|\Omega_k| \sim \frac{1}{a^2 H^2} \sim e^{-2Ht}$$

Spatially Flat!

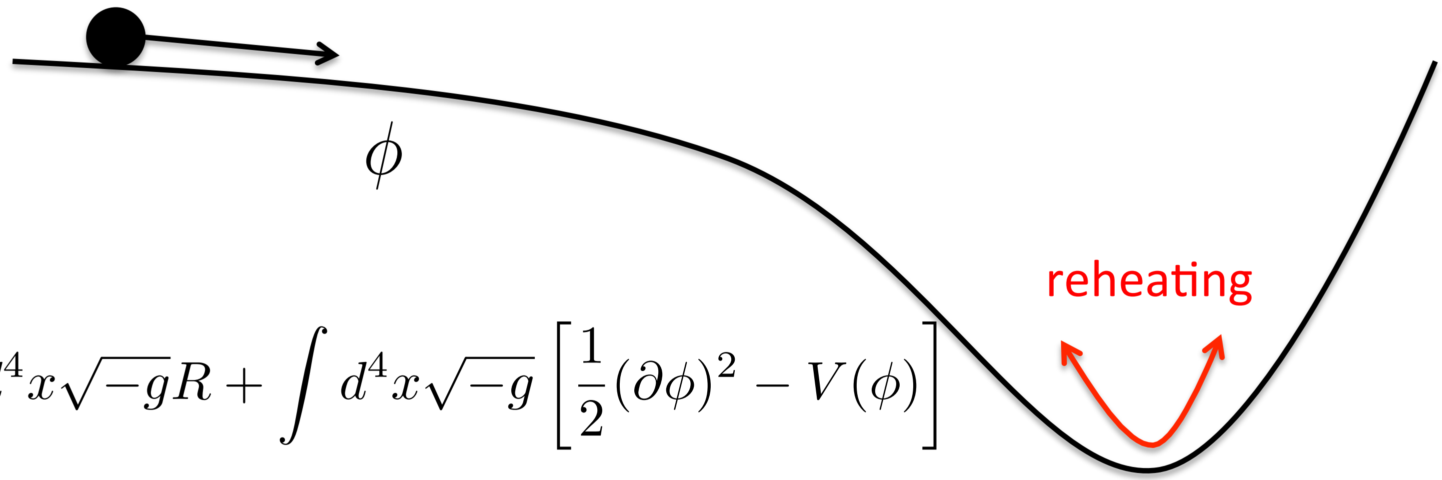



INFLATIONARY COSMOLOGY
Deceleration
Inflation
Un-observable Universe
10^{28} cm
Observable Universe
Event Horizon
Un-observable Universe
Space
Time
Today



$$a(t) \sim e^{\sqrt{\frac{V_{\text{false}}}{3M_p^2}}\,t}$$

Slow-roll inflation



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

$$H^2 = \frac{1}{3M_p^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right) \qquad \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\left|\eta = M_p^2\frac{V''}{V}\right| \ll 1$$

$$H^2 \simeq \frac{V}{3M_p^2}$$

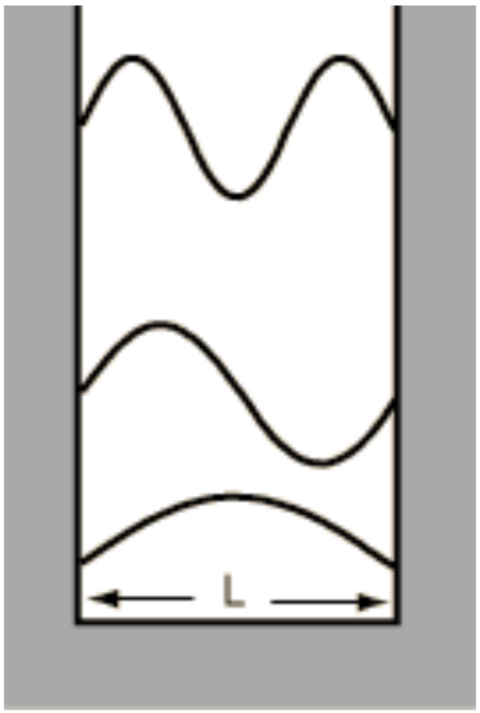
$$3H\dot{\phi} \simeq -V'$$

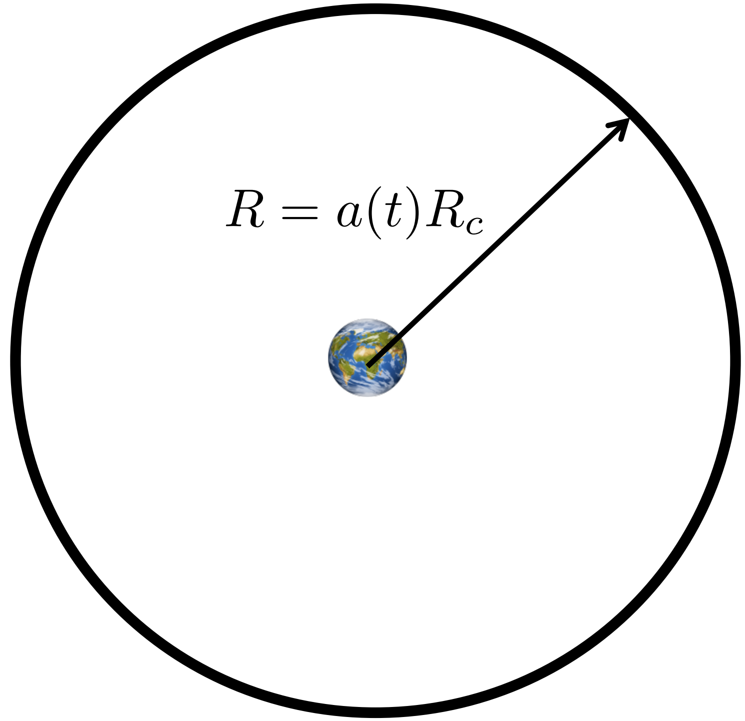
$$a(t) \sim e^{Ht}$$

A. Linde, 1982

A. Albrecht, P. Steinhardt, 1982

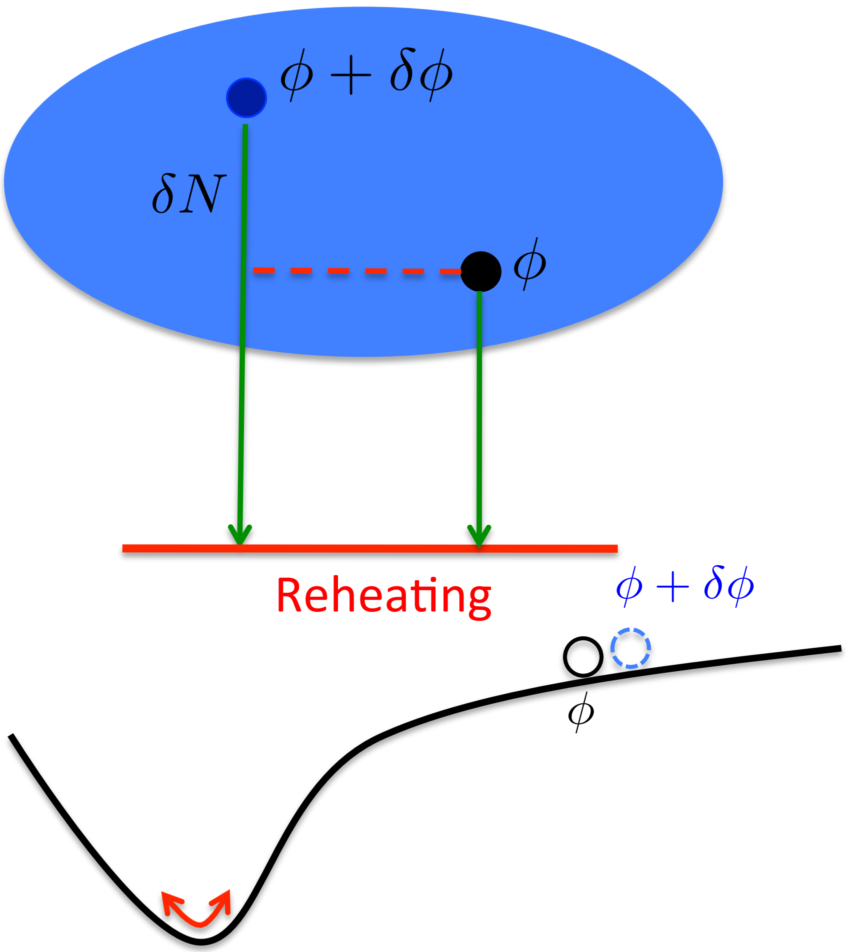
What is the origin of cosmic structure?



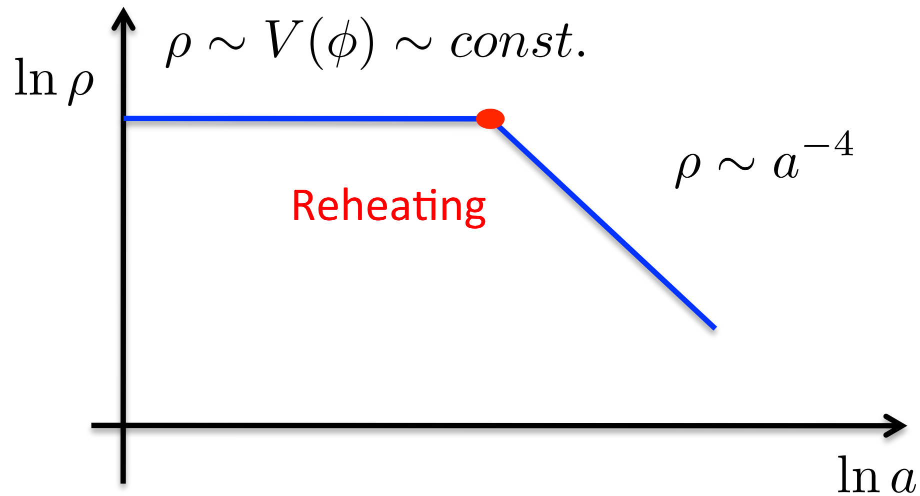


$$v = \frac{dR}{dt} = HR \;\Rightarrow\; R_{causal} = 1/H$$

$$\delta\phi = H/2\pi$$



$$a \sim e^{Ht} \sim e^{N}$$



$$\zeta \sim \delta\rho/\rho \sim \delta \ln a \sim \delta N$$

$$\sim N(\phi_i + \delta\phi_i) - N(\phi_i)$$

dynamics of inflation

Scalar perturbations:

$$\zeta = \delta N = H\delta t = \frac{H}{\dot{\phi}}\delta\phi = -\frac{1}{\sqrt{2\epsilon}M_p}\delta\phi$$

$$P_s = \frac{H^2/M_p^2}{8\pi^2\epsilon}$$

$$n_s \equiv 1 + \frac{d\ln P_s}{d\ln k} = 1 - 6\epsilon + 2\eta$$

Gravitational waves:

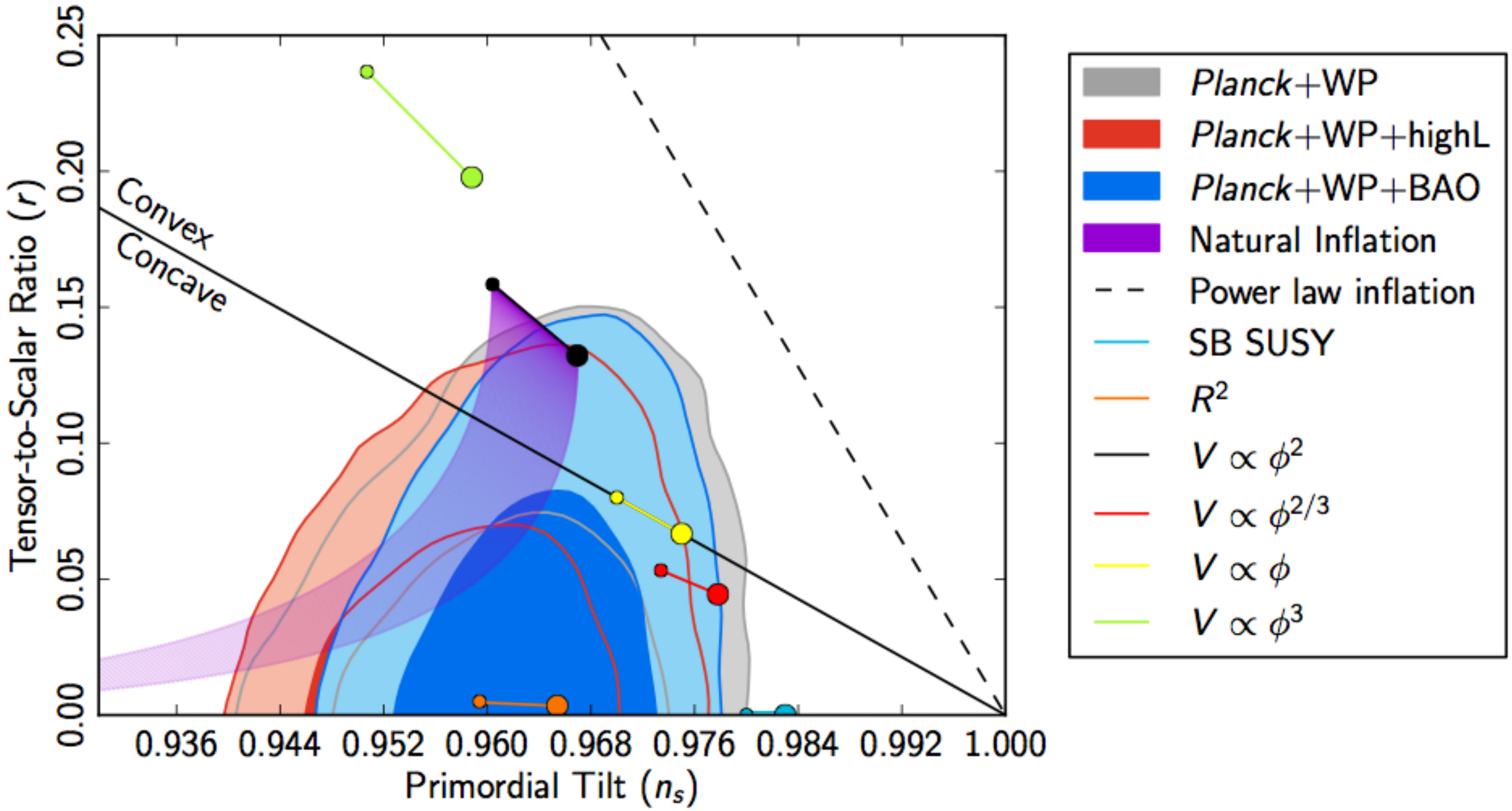
$$P_t = \frac{H^2/M_p^2}{\pi^2/2}$$

$$r = P_t/P_s = 16\epsilon$$

$$n_t = -2\epsilon$$

Near scale-invariance!

Potential of inflaton in single-field slow-roll inflation



Nearly scale-invariant density perturbation predicted by inflation is confirmed by Planck!

Naturalness of inflation?

$$\frac{\Delta T}{T} \sim 10^{-5} \quad \Longleftrightarrow \quad \text{A small dimensionless parameter}$$

Lyth bound and challenge for string inflation

Lyth Bound:

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 = \frac{1}{2}\frac{\dot{\phi}^2}{M_p^2 H^2}$$

$$r = 16\epsilon$$

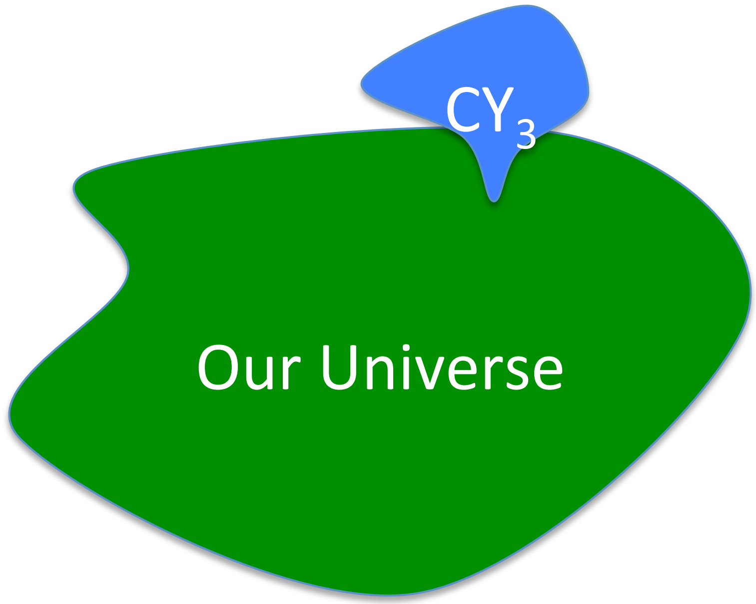
$$\frac{d\phi}{M_p} = \sqrt{\frac{r}{8}} H dt = \sqrt{\frac{r}{8}} dN$$

$$\frac{|\Delta\phi|}{M_p} \simeq \sqrt{\frac{r}{8}}\Delta N$$

$$\text{For } r = 0.2, \ \frac{|\Delta\phi|}{M_p} \simeq 0.16\Delta N$$

Lyth, 1997(PRL)

Warped D-brane inflation

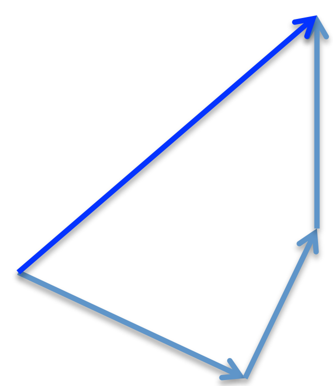


$$M_p^2 \sim \frac{M_s^8}{g_s^2} V_6$$

Single brane: $|\Delta\phi| = \sqrt{T_3}r \leq \frac{2}{\sqrt{N_B}} M_p$

A stack of D-branes (N): $|\Delta\phi| = \sqrt{T_3}r \leq \frac{2}{\sqrt{N}} M_p$

$$\Delta\Phi \equiv \sqrt{\sum (\Delta\phi_i)^2} \leq 2M_p$$



Baumann, McAllister, 2007

Extra-natural inflation

A five-dimensional U(1) gauge theory compactifies on a circle with size R.

The effective action for the Wilson line $\theta = \oint A_5 dx^5$

$$S \sim \int d^4x \left[\frac{f^2}{2}(\partial\theta)^2 - \frac{1}{R^4}\cos\theta\right] = \int d^4x \left[\frac{1}{2}(\partial\phi)^2 - \frac{1}{R^4}\cos\frac{\phi}{f}\right]$$

where $f = \dfrac{1}{2\pi g_4 R}$

Requiring slow-roll parameter $\epsilon \sim \dfrac{M_p^2}{f^2} \ll 1$ yields $f \gg M_p$.

Arkani-Hamed, Cheng, Creminelli and Randall, 2003(PRL)

$$g_4^2 \sim g_s / \sqrt{M_s^6 V_6} \qquad M_p^2 \sim \frac{M_s^8}{g_s^2} V_6$$

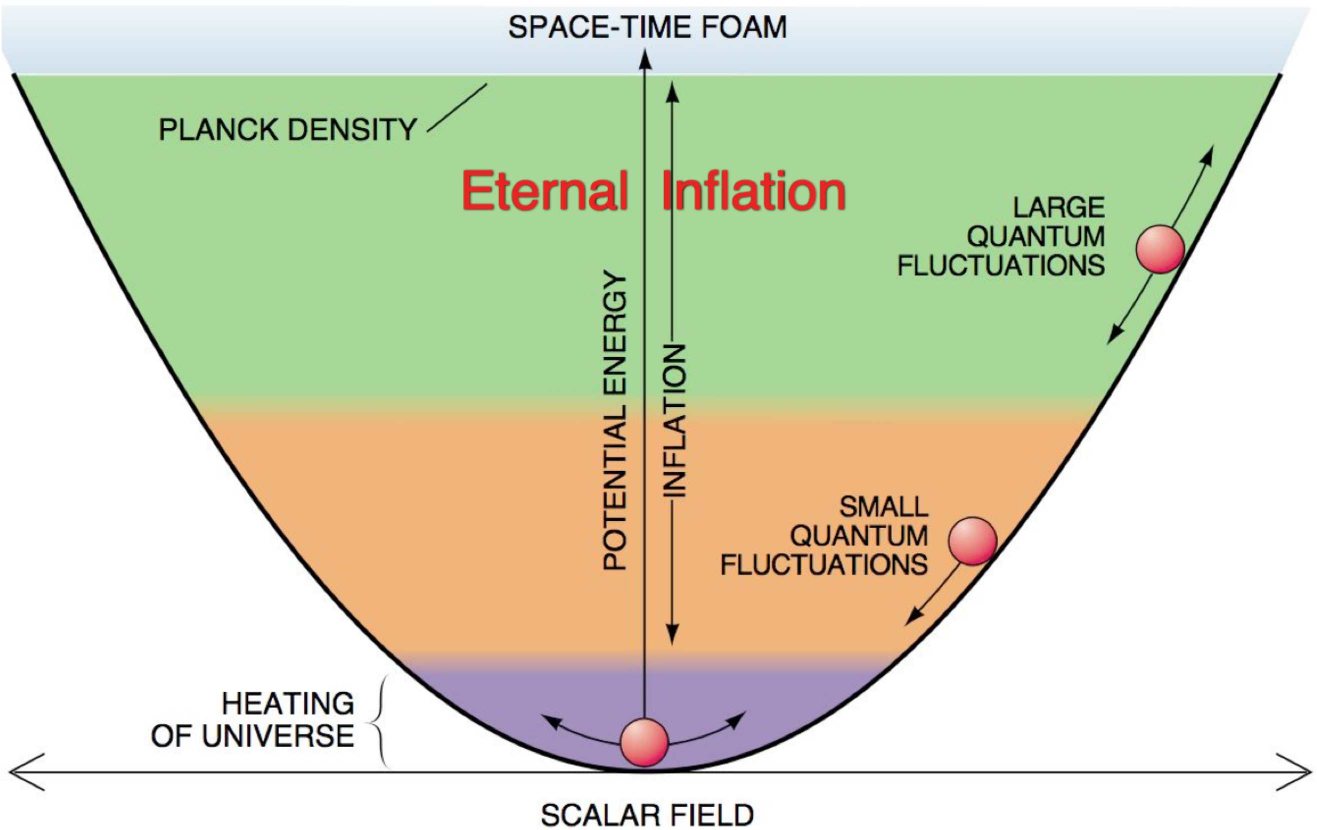
$$f \sim \frac{1}{g_4 R} \sim \frac{g_s^{1/2}}{R M_s} M_p < M_p$$

$$\text{for } R > \ell_s \sim 1/M_s,\ g_s < 1$$

Extra-natural inflation cannot be embedded into string theory.

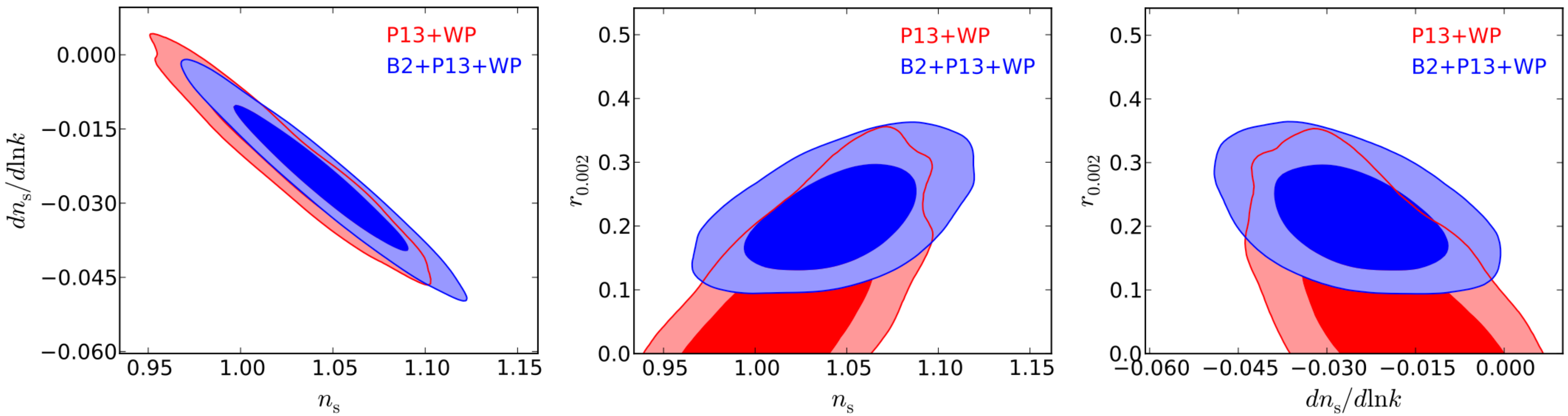
The potential of inflaton field

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



$$V \sim \phi^p \quad \Rightarrow \quad r = \frac{4p}{N} \qquad n_s = 1 - \frac{p+2}{2N} \qquad \frac{dn_s}{d\ln k} = -\frac{p+2}{2N^2}$$

For $p = 2$ and $N = 50$, $r = 0.16$, $n_s = 0.96$, $\frac{dn_s}{d\ln k} = -0.0008.$



$$n_s = 1.0447^{+0.0295}_{-0.0297}, \quad dn_s/d\ln k = -0.0253 \pm 0.0093$$

C. Cheng, QGH, W. Zhao, in preparation

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WMAP

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WMAP Cosmological Parameters

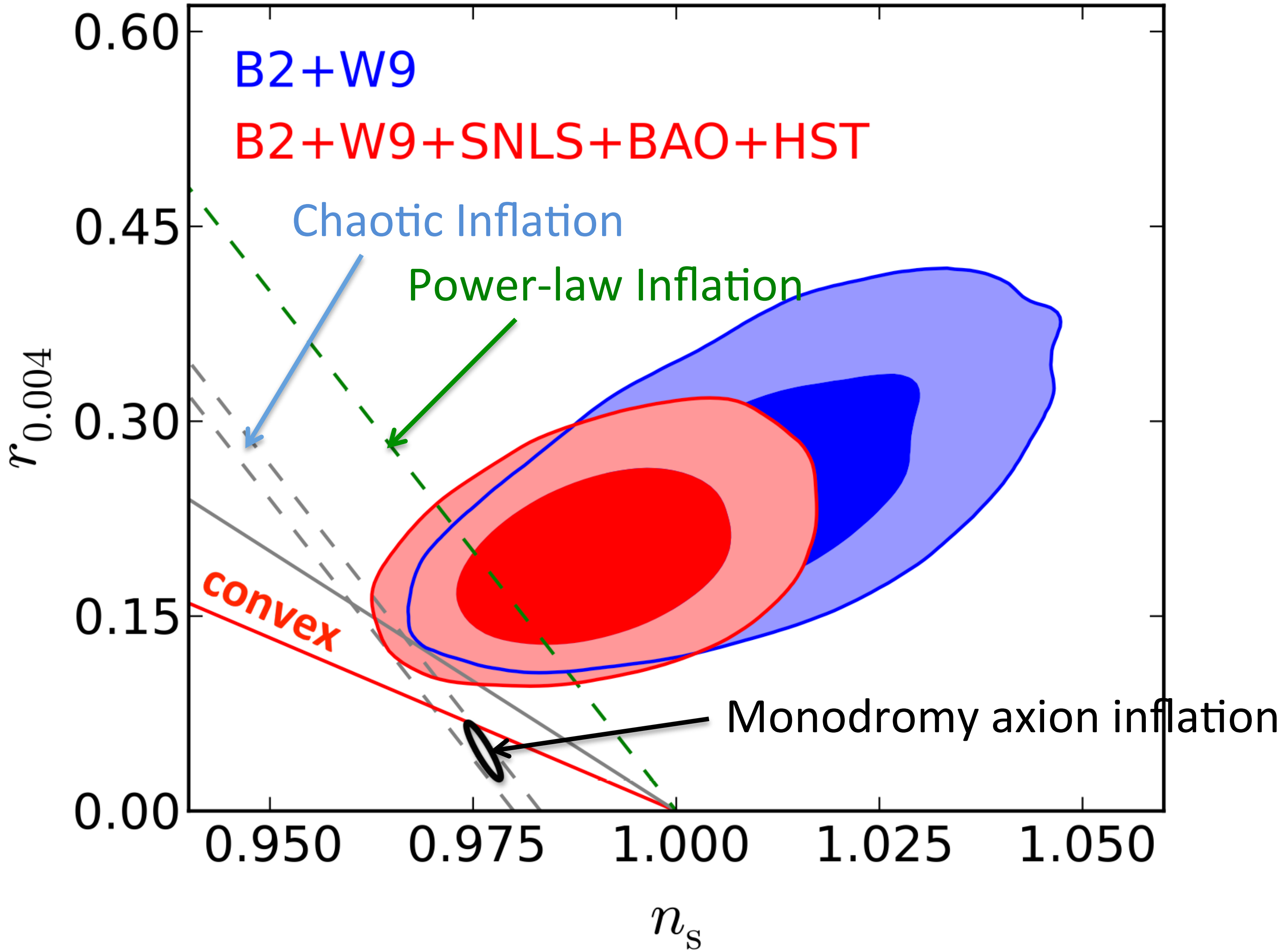
- Monte Carlo Markov Chain: wmap_lcdm_tens_wmap9_chains_v5.tar.gz (359.06 MBytes)

WMAP Cosmological Parameters

Model: lcdm+tens

Data: wmap9

$10^9\Delta^2_{\mathcal{R}}$	2.26 ± 0.15	H_0	72.6 ± 2.9 km/s/Mpc
$\ell(\ell+1)C_{220}/(2\pi)$	5750^{+36}_{-35} μK^2	$d_A(z_{\rm eq})$	14248 ± 123 Mpc
$d_A(z_*)$	14083^{+125}_{-124} Mpc	$D_v(z=0.57)/r_s(z_d)$	12.95 ± 0.39
η	$(6.34 \pm 0.18) \times 10^{-10}$	$k_{\rm eq}$	0.00969 ± 0.00037
$\ell_{\rm eq}$	136.4 ± 4.2	ℓ_*	302.02 ± 0.70
n_b	$(2.605 \pm 0.074) \times 10^{-7}$ cm^{-3}	n_s	0.992 ± 0.019
n_t	> -0.048 (95% CL)	Ω_b	0.0442 ± 0.0027
$\Omega_b h^2$	0.02320 ± 0.00066	Ω_c	0.210 ± 0.027
$\Omega_c h^2$	$0.1095^{+0.0054}_{-0.0055}$	Ω_Λ	0.746 ± 0.029
Ω_m	0.254 ± 0.029	$\Omega_m h^2$	0.1327 ± 0.0051
r	< 0.38 (95% CL)	$r_s(z_d)$	152.8 ± 1.3 Mpc
$r_s(z_d)/D_v(z=0.106)$	0.359 ± 0.016	$r_s(z_d)/D_v(z=0.2)$	0.1955 ± 0.0079



C. Cheng, QGH, arXiv:1404.1230

Power-law inflation

$$V(\phi) = V_0 \exp\left(-\sqrt{\frac{2}{p}}\frac{\phi}{M_p}\right)$$

$$n_s = 1 - \frac{2}{p}$$

$$r = \frac{16}{p}$$

Usually $$V(\phi) = V_0 + \mu^4 \sum_{i=1} \alpha_i \left(\frac{\phi}{M_p} \right)^i$$

Since ϕ> M_p , $$V(\phi) = V_0 + \mu^4 \sum_{i=1} \alpha_i \left(\frac{M_p}{\phi} \right)^i$$

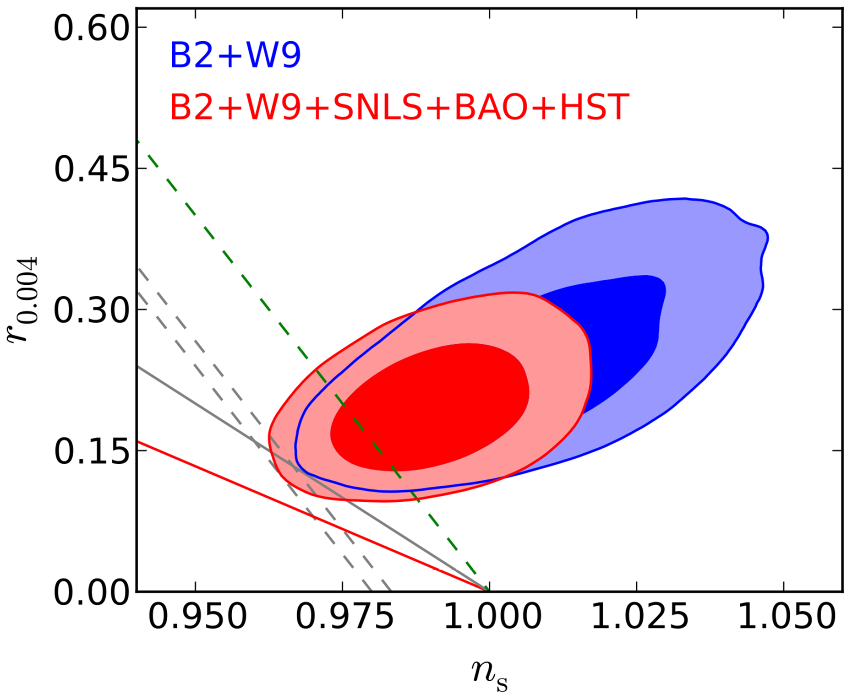
C. Cheng, QGH, arXiv:1404.1230

For example, $V(\phi) = \mu^4 \left(\frac{M_p}{\phi} \right)^n$

$$\phi_N^2 = 2n(N_* - N)M_p^2$$

$$r = \frac{4n}{N_* - N}$$

$$n_s = 1 - \frac{n-2}{2(N_* - N)}$$

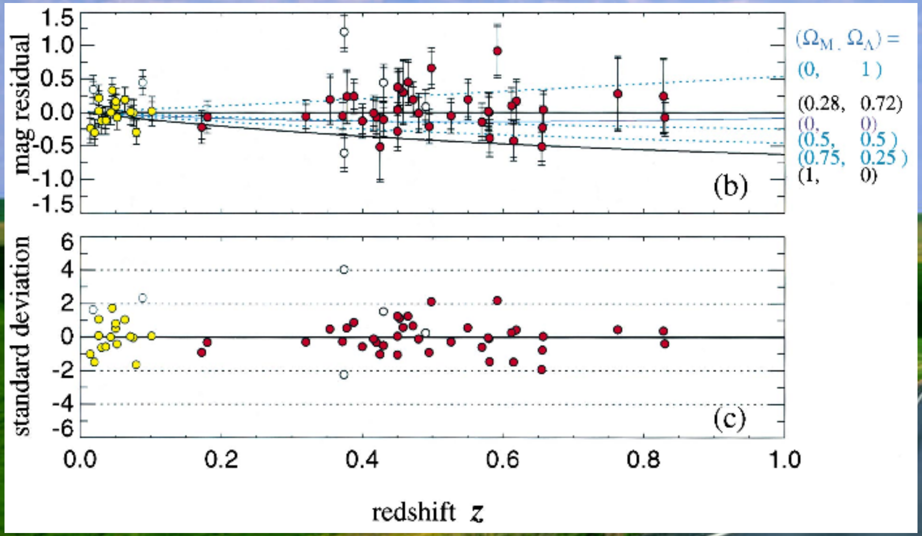


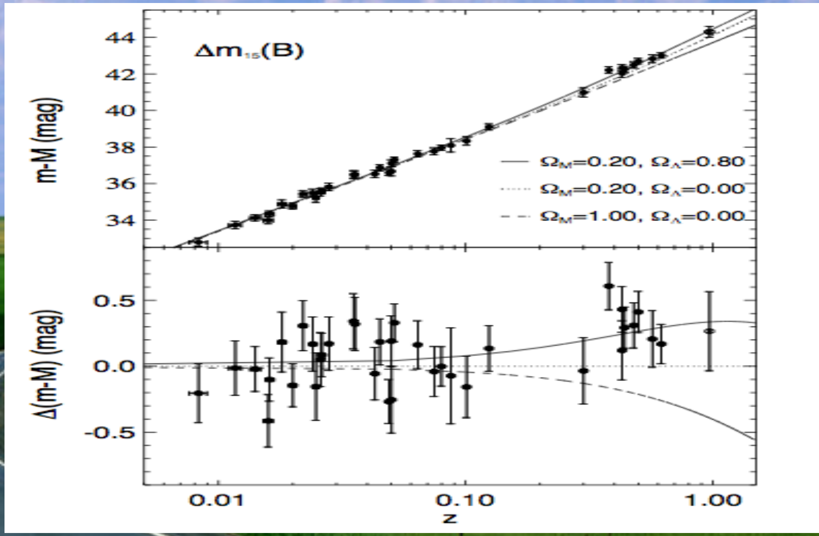
In particular, for $n = 2$, $n_s = 1$ and $r = \frac{8}{N_* - N}$.

C. Cheng, QGH, arXiv:1404.1230

Landscape inflation

Λ





Supernova cosmology project collaboration, S. Perlmutter et al, APJ 517(1999)565

Supernova search team collaboration, A.G. Riess et al, APJ 116(1998)1009

Photo: Ariel Zambelich, Copyright © Nobel Media AB

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

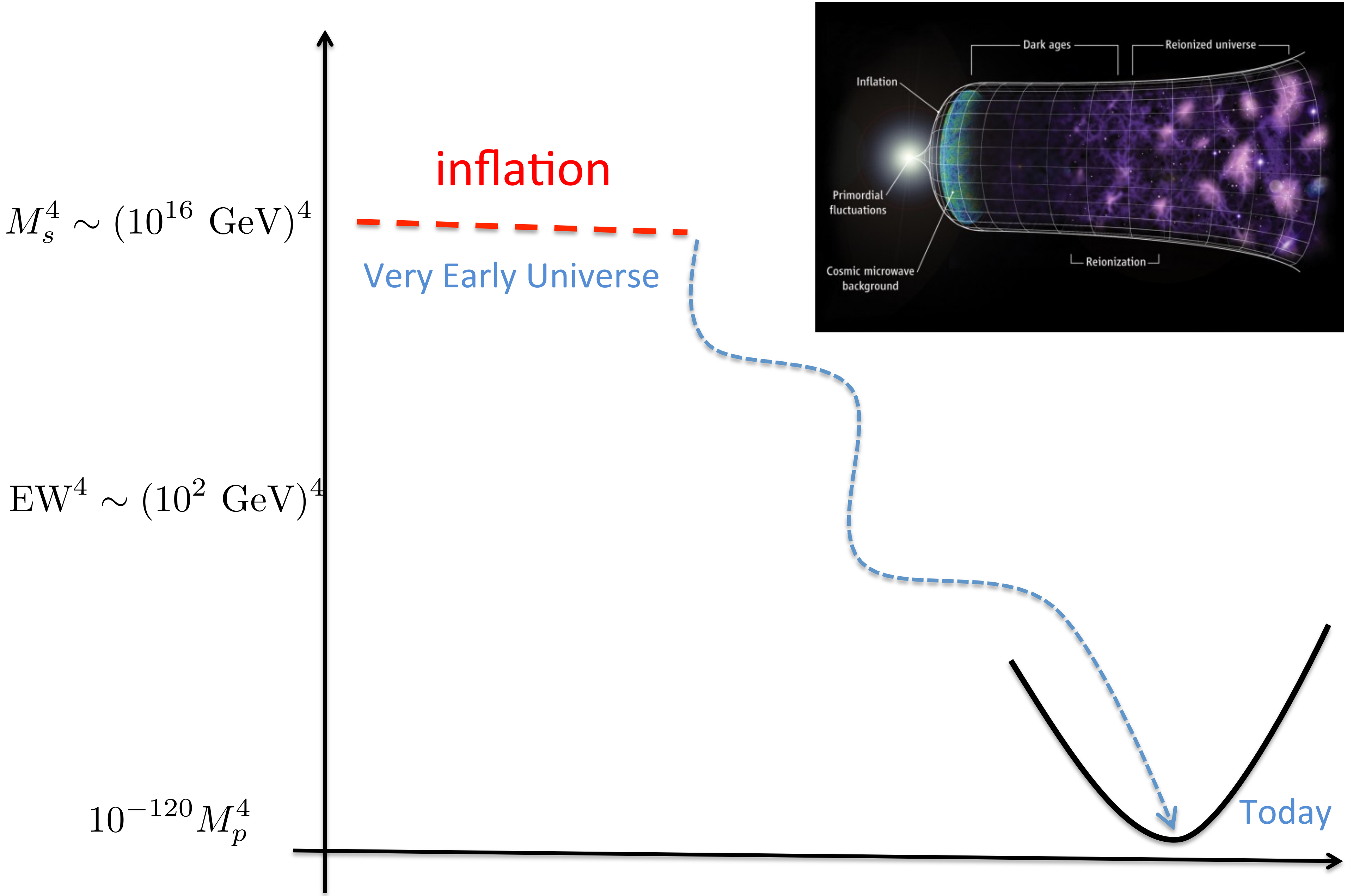
The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

- Why is the cosmological constant so small? (Quantum)

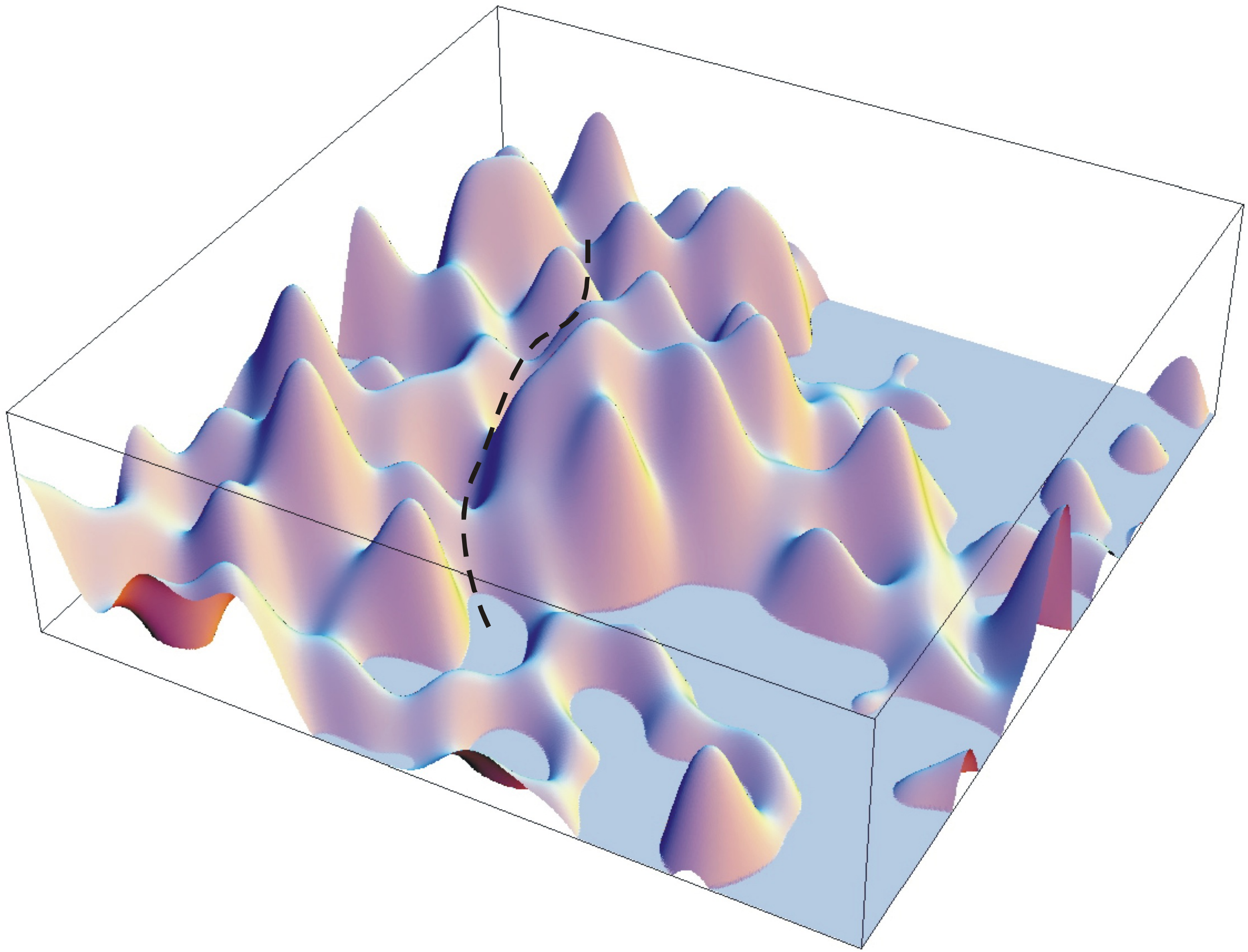
$$< \rho >_{VAC} = \int_0^E \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \simeq \frac{E^4}{16\pi^2}$$

$$E \sim M_{pl}, \quad < \rho >_{obs} \sim 10^{-120} < \rho >_{VAC}$$

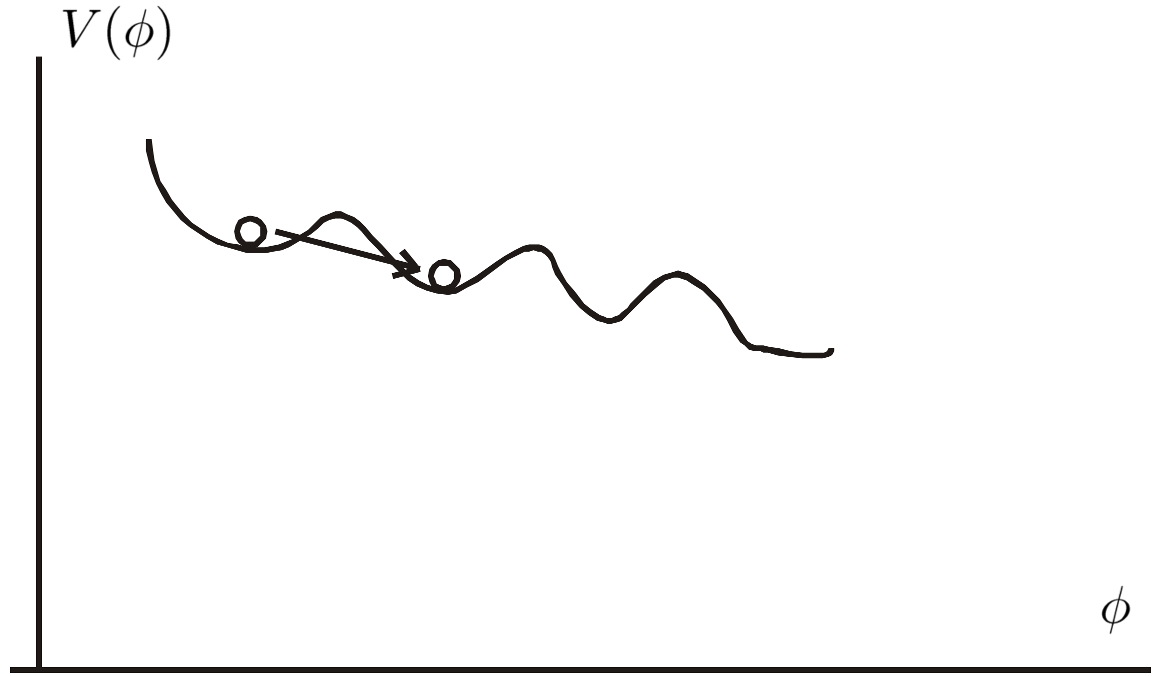
$$E \sim v_{EW} \sim 10^2 \mathrm{GeV}, \quad < \rho >_{\mathrm{obs}} \sim 10^{-60} < \rho >_{\mathrm{VAC}}$$



inflation
Very Early Universe
Today
$M_s^4 \sim (10^{16}\ \mathrm{GeV})^4$
$\mathrm{EW}^4 \sim (10^2\ \mathrm{GeV})^4$
$10^{-120} M_p^4$
Dark ages
Reionized universe
Inflation
Primordial fluctuations
Cosmic microwave background
Reionization



Turner, Weinberg and Widrow, PRD 46(1992)2384



The tunneling rate per unit volume is Γ.

$$p(t) \sim e^{-\frac{4\pi}{3}\beta H t}$$

where the dimensionless parameter β is $\beta = \Gamma/H^4$.

The lifetime of the field in this meta-stable vacuum is estimated as

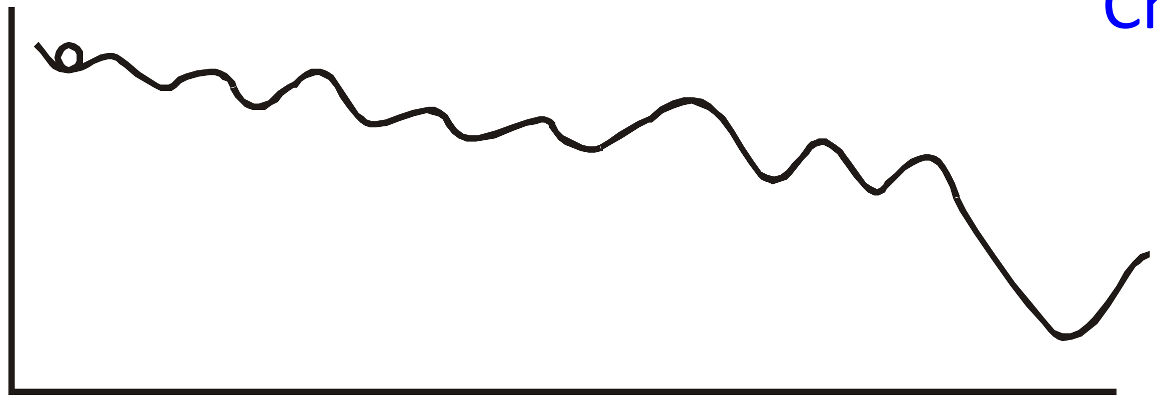
$$\tau \sim \frac{3}{4\pi\beta H}$$

In order for percolation and thermalization to be achieved, a low bound on β is obtain

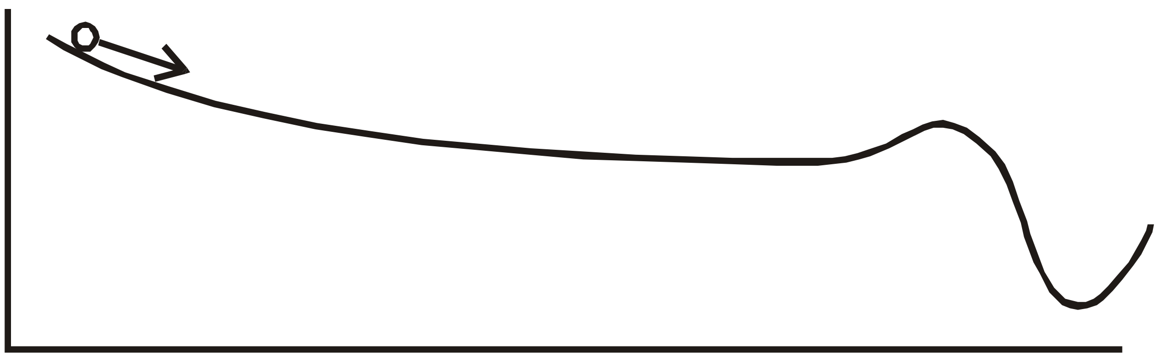
$$\beta \gtrsim \frac{9}{4\pi}$$

We focus on the case with $\tau \ll H^{-1}$, or equivalently $\beta \gg 1$.

Chain Inflation



$\tau \ll H^{-1}$ simplified to be



QGH, JCAP 05(2007)009

A Toy Model

$$\rho_{V,n+1} - \rho_{V,n} = \sigma$$

$$\rho_V = M_s^4 - \frac{\sigma}{\tau} t$$

$$H^2 = \frac{\rho_V}{3M_p^2} = \frac{M_s^4 - \frac{\sigma}{\tau} t}{3M_p^2}$$

$$N_* = \int_{t_*}^{t_{\rm end}} H dt \simeq \frac{2}{3\sqrt{3}} \frac{\tau}{M_p \sigma} \rho_{V*}^{3/2}$$

$$H^2 \simeq \left(\frac{\sigma/\tau}{2M_p^2} N_* \right)^{2/3}$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{1}{3N_*}$$

Observational Consequences

$$P_s = \frac{H^2/M_p^2}{8\pi^2\epsilon} = \frac{3}{2^{11/3}\pi^2}\left(\frac{\sigma/\tau}{M_p^5}\right)^{2/3} N_*^{5/3}$$

$$P_t = \frac{H^2/M_p^2}{\pi^2/2} = \frac{2^{1/3}}{\pi^2}\left(\frac{\sigma/\tau}{M_p^5}\right)^{2/3} N_*^{2/3}$$

$$n_s \equiv 1 + \frac{d\ln P_s}{d\ln k} = 1 - \frac{5}{3N_*}$$

$$r \equiv P_t/P_s = \frac{16}{3N_*}$$

$$P_{s,\mathrm{obs}} \simeq 2 \times 10^{-9}$$

$$\Updownarrow$$

$$\frac{\sigma/\tau}{M_p^5} \simeq 1.4 \times 10^{-15}$$

$$\rho_{V,*}/M_p^4 \simeq 3.2 \times 10^{-9} \qquad H_*/M_p \simeq 3.3 \times 10^{-5}$$

Requiring $\sigma \ll \rho_{V,*}$ yields

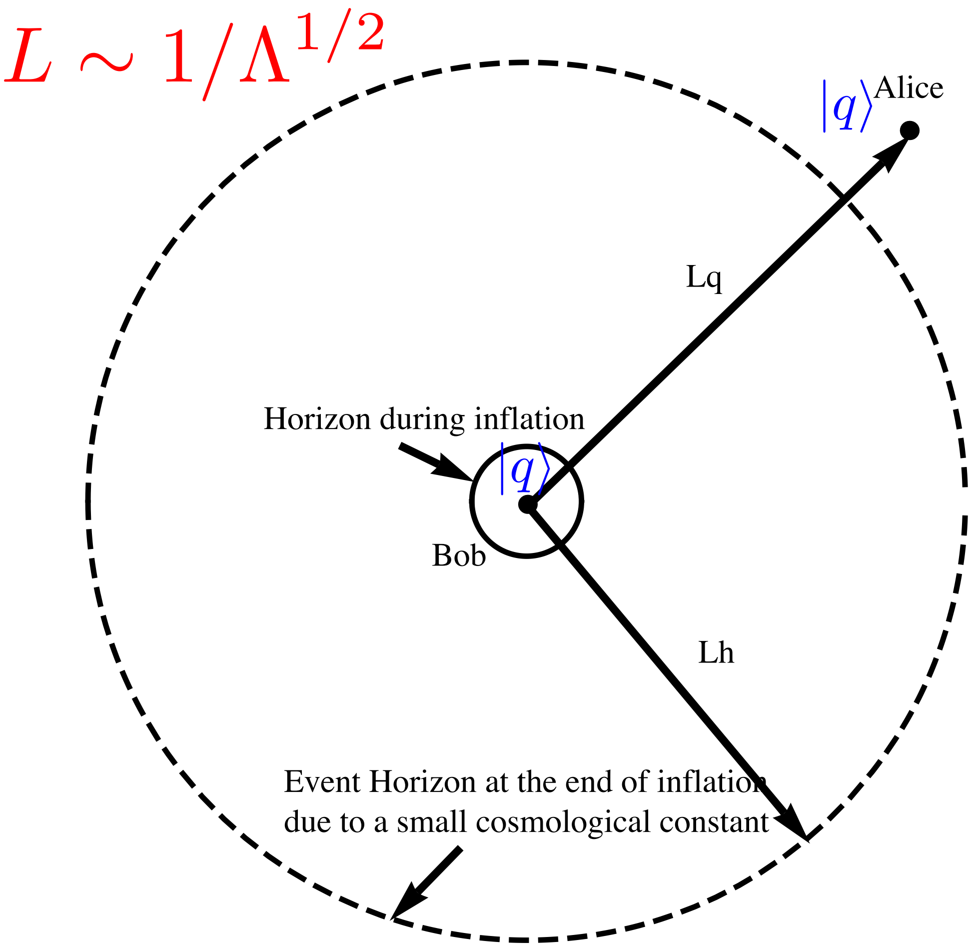
$$\tau/t_p \ll 2.3 \times 10^6 \qquad \tau/H^{-1} \ll 69$$

Requirement of $t_p \ll \tau \ll H^{-1}$ is quite reasonable.

Connection between dark energy and inflation


Λ
How
to fit it in
a consistent
quantum gravity?
Why so small?
Why a positive cosmological constant?

No-cloning theorem: positive cosmological constant



In order to keep the no-cloning theorem, or equivalently the unitarity in quantum mechanics,

$$L_h \lesssim L_q = e^{H_* t_*} R_*$$

$$\Lambda \gtrsim e^{-2H_* t_*} \Lambda_*$$

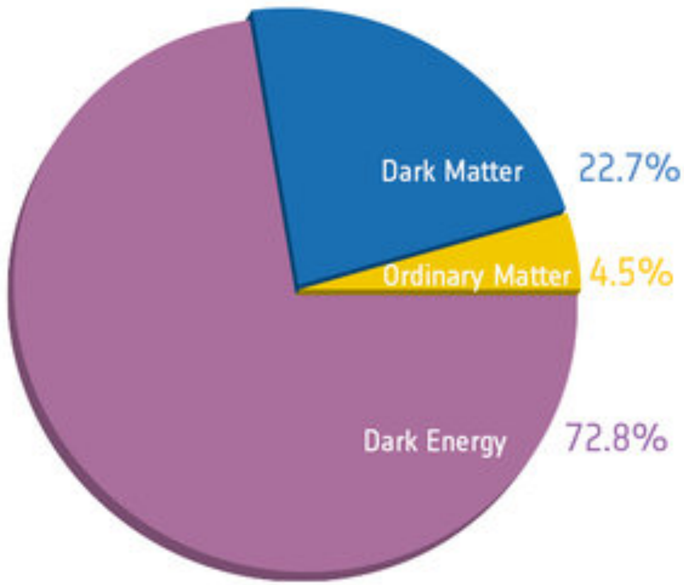
$$t_* \sim R_* \ln(R_*/\ell_p)$$

Why small?

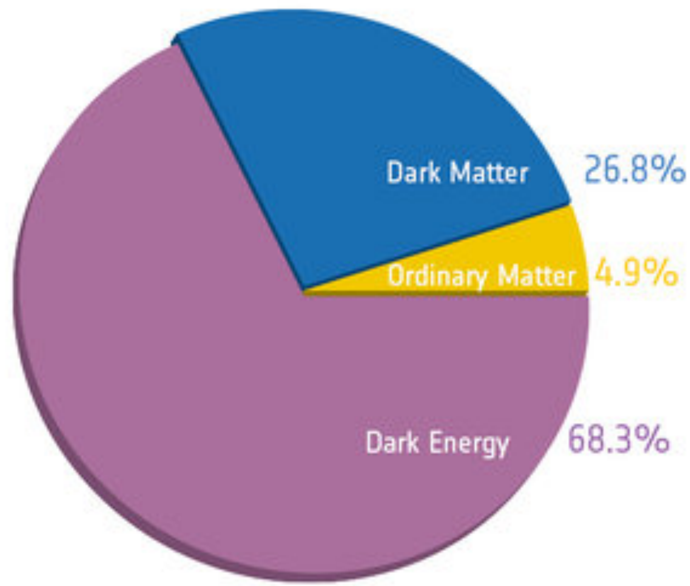
Please ask Henry Tye!

QGH and F.L. Lin, Phys.Lett.B 712(2012)143

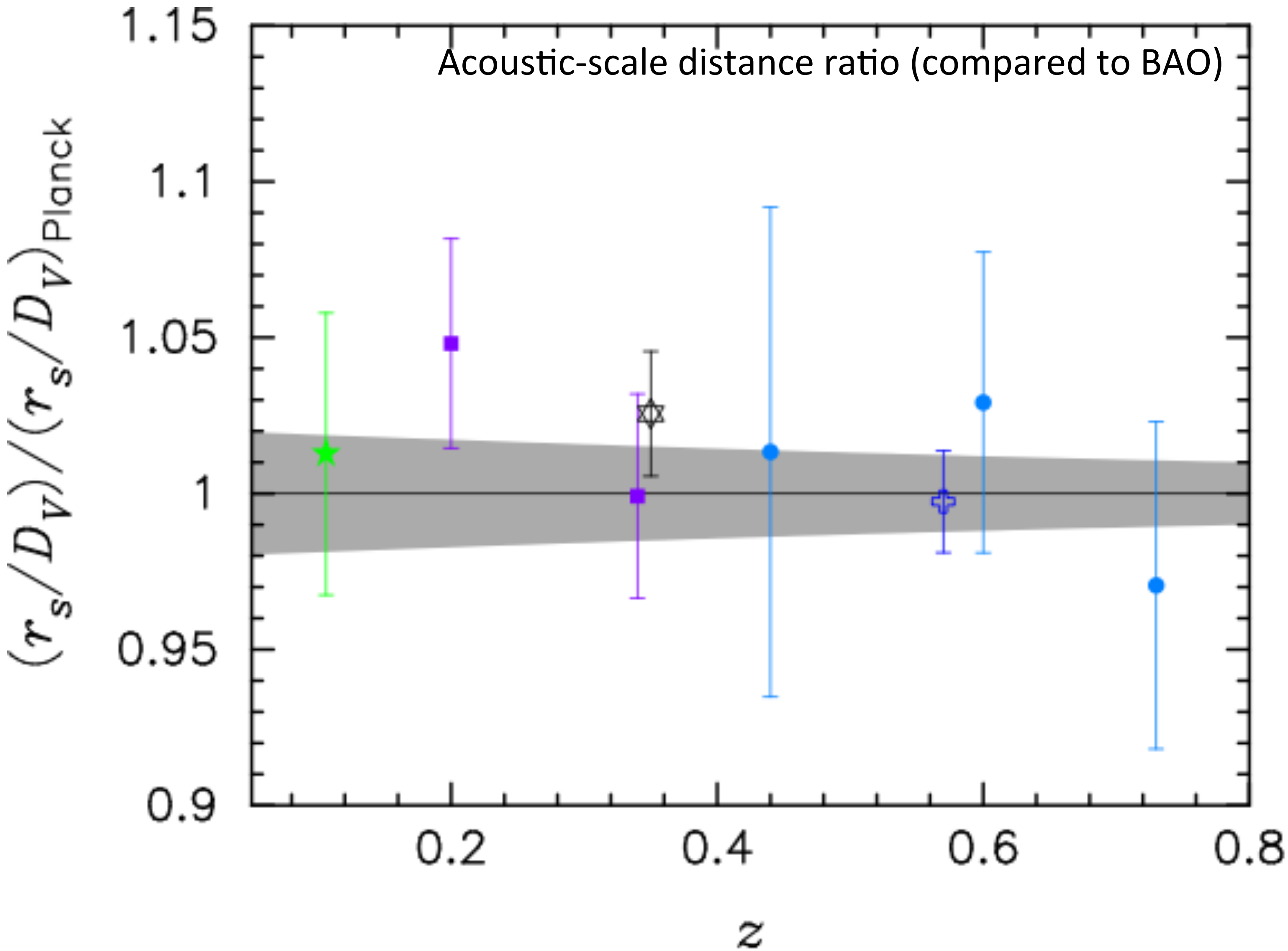
E.O.S. of dark energy from Planck data



Before Planck

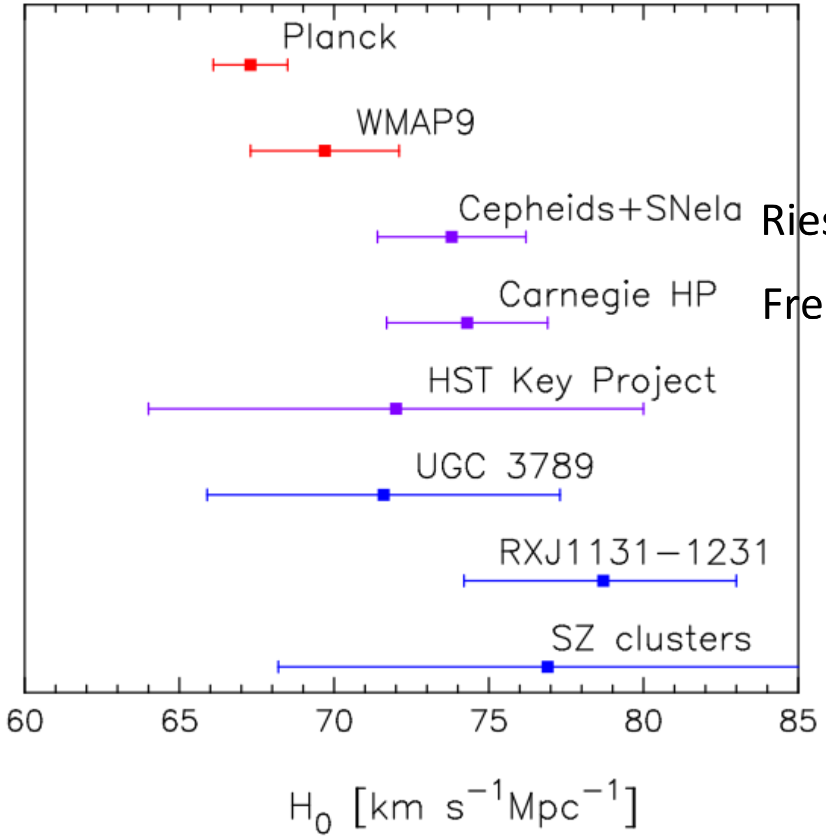


After Planck



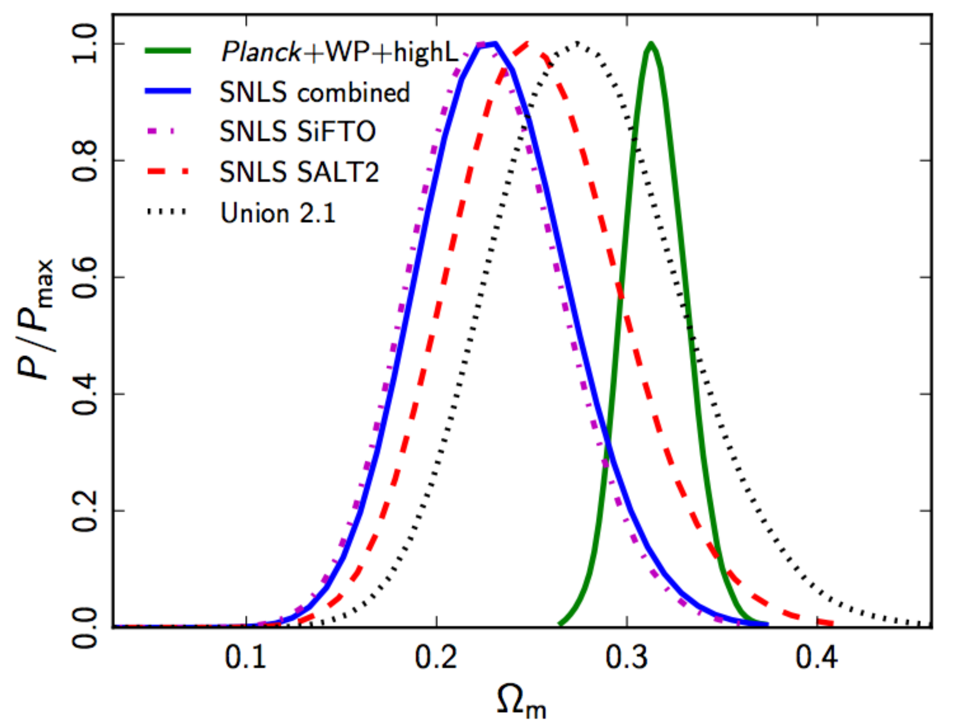
Acoustic-scale distance ratio (compared to BAO)
$(r_s/D_V)/(r_s/D_V)_{\rm Planck}$
1.15
1.1
1.05
1
0.95
0.9
0.2
0.4
0.6
0.8
z

$H_0 = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$



Riess et al. (2011) $H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$

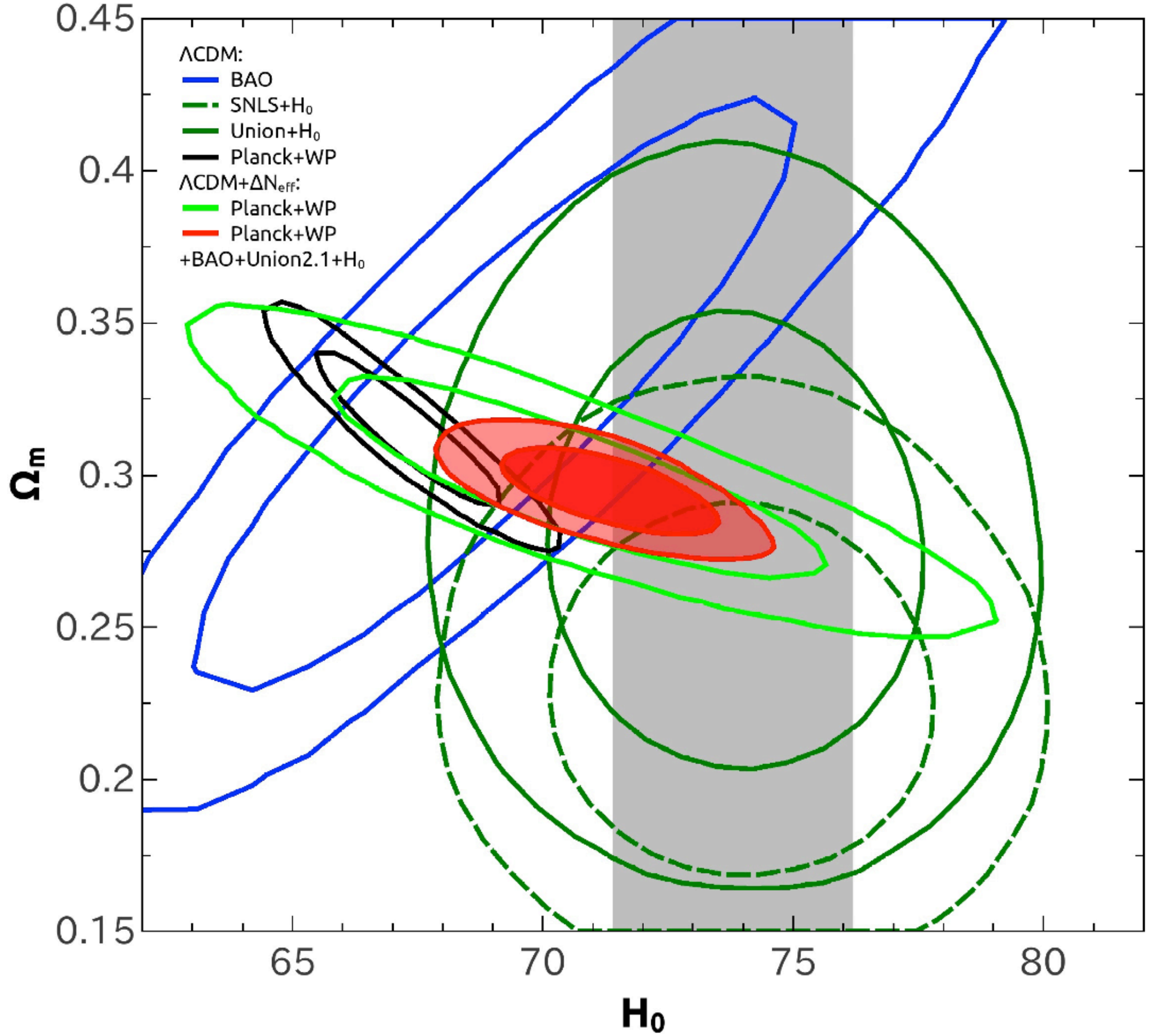
Freedman et al. (2012)



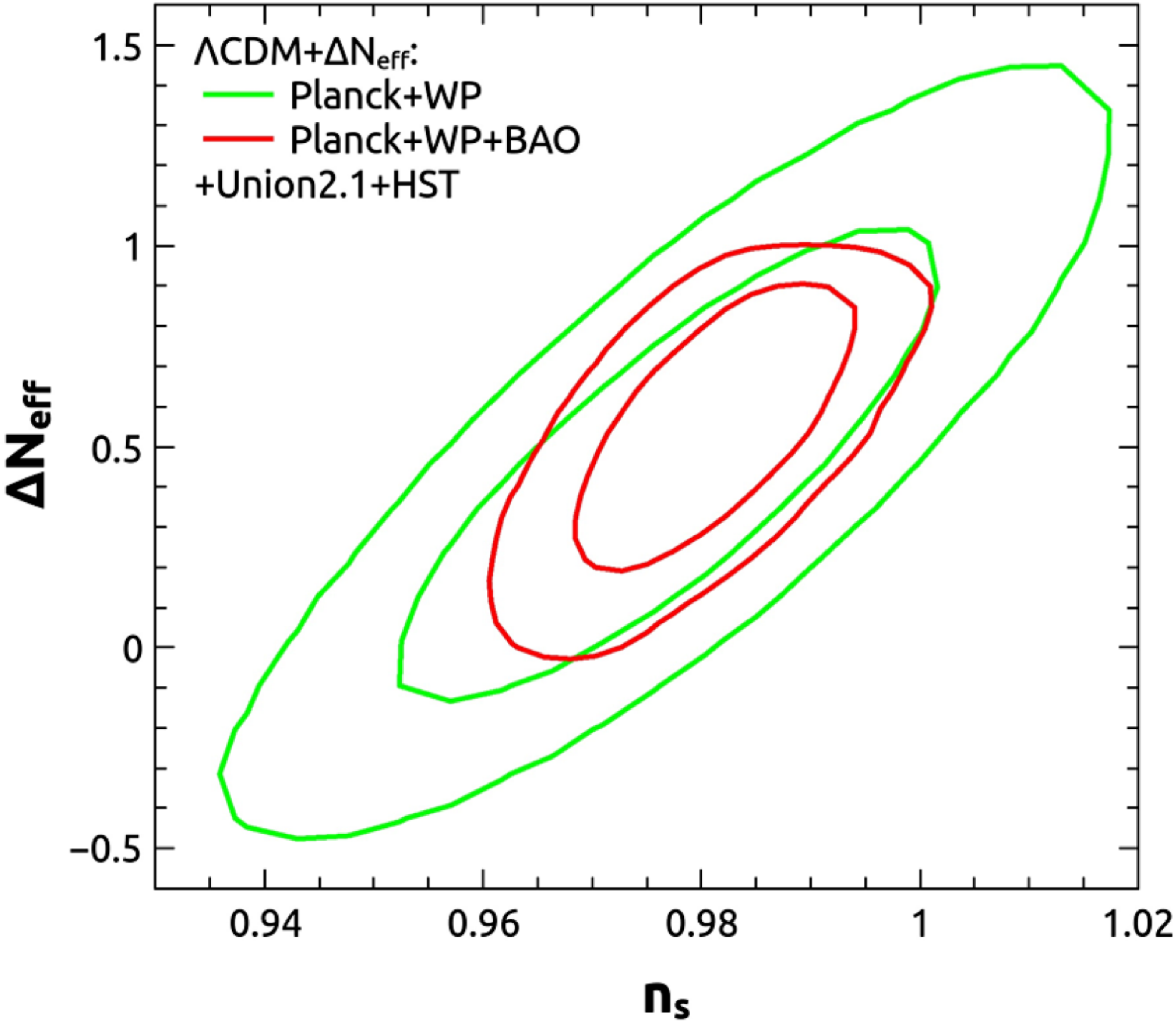
Three possibilities:

- ❑ The data analysis is wrong.
- ✔ The model is wrong.
- ❑ Both the data analysis and model are wrong.

$$w_{DE} = p/\rho = -1$$

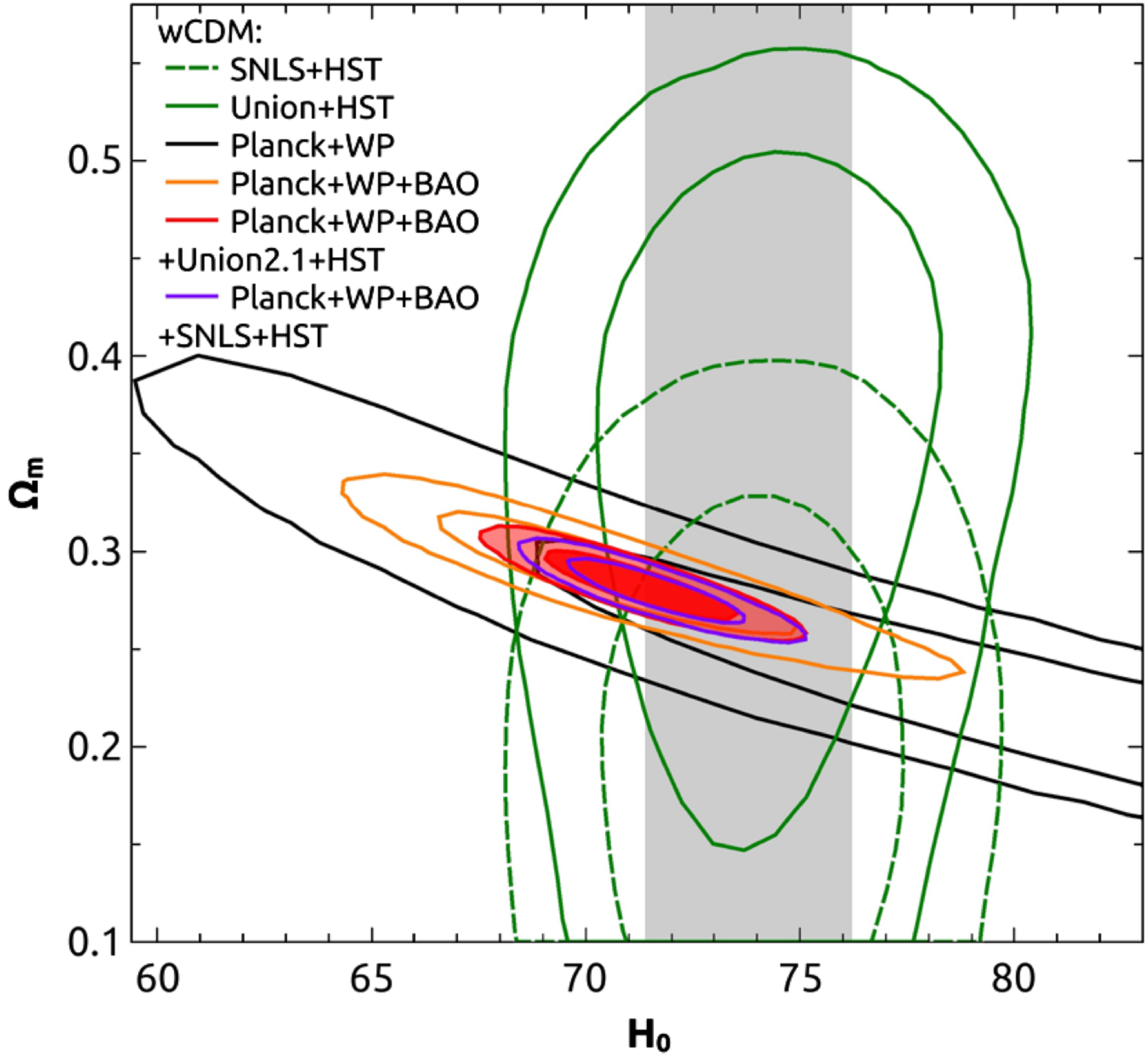


C. Cheng & QGH, Phys.Rev.D 89, 043003 (arXiv:1306.4091)

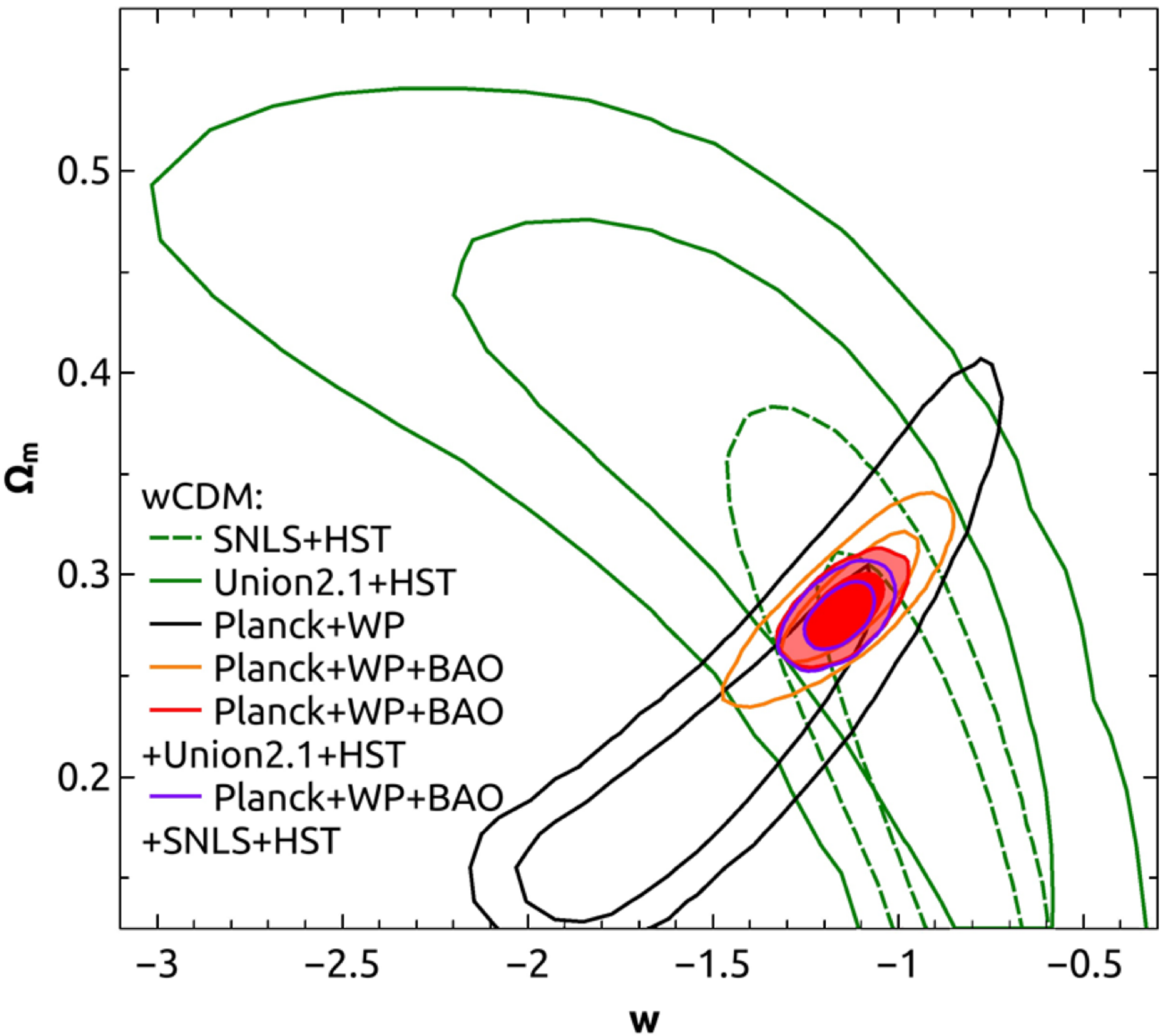


ΛCDM+ΔN_eff:
Planck+WP
Planck+WP+BAO
+Union2.1+HST
1.5
1
0.5
0
−0.5
0.94
0.96
0.98
1
1.02
ΔN_eff
n_s

$$w_{DE} = p/\rho = const.$$



C. Cheng & QGH, Phys.Rev.D 89, 043003 (arXiv:1306.4091)

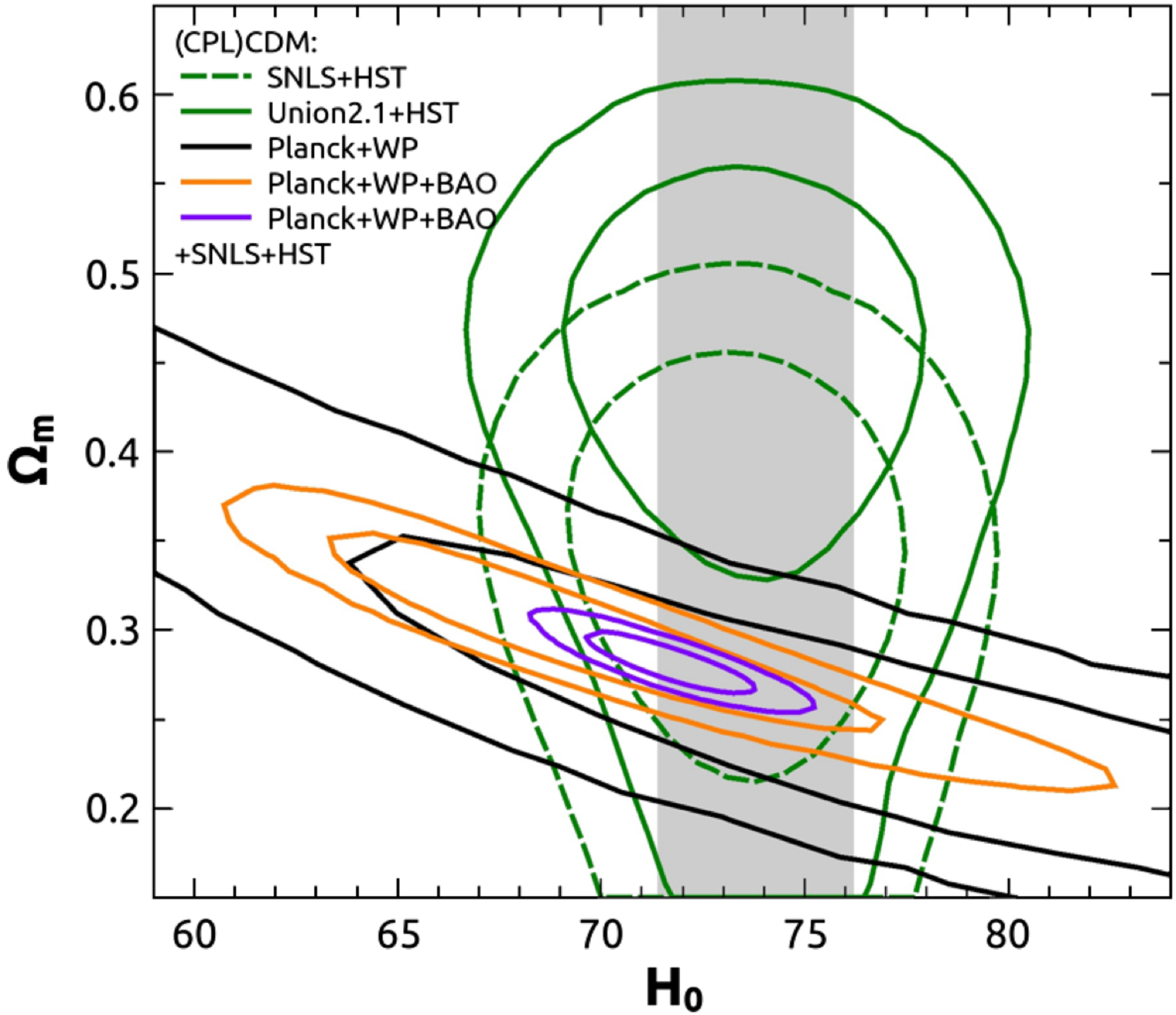


$$\Omega_m = 0.283 \pm 0.012$$
$$w = -1.15 \pm 0.07$$

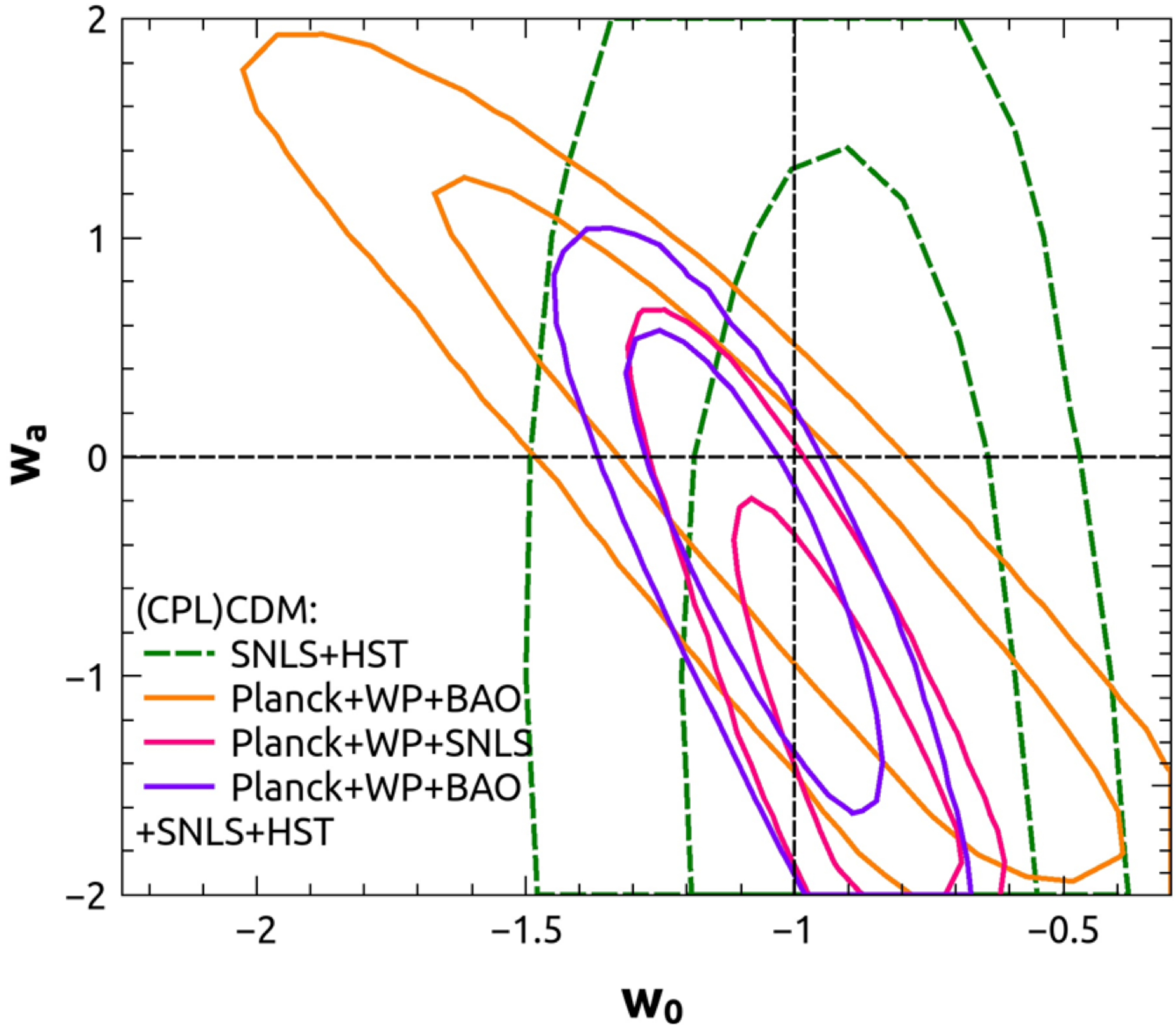
$$\Omega_m = 0.279^{+0.011}_{-0.010}$$
$$w = -1.16 \pm 0.06$$

C. Cheng & QGH, Phys.Rev.D 89, 043003 (arXiv:1306.4091)

$$w = \frac{p}{\rho} = w_0 + w_a(1-a)$$



C. Cheng & QGH, Phys.Rev.D 89, 043003 (arXiv:1306.4091)



$$w_0 = -1.05 \pm 0.15$$

$$w_a = -0.596^{+0.717}_{-0.723}$$

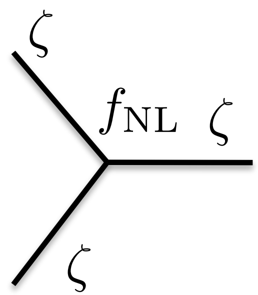
C. Cheng & QGH, Phys.Rev.D 89, 043003 (arXiv:1306.4091)

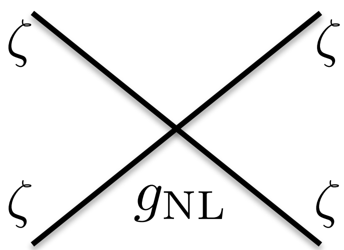
$$w = \frac{p}{\rho} = w_0 + w_a(1-a)$$

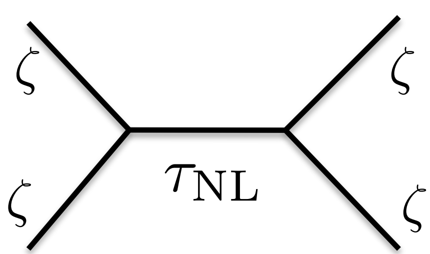
Parameters	Planck+WP+BAO+Union2.1+H_0		Planck+WP+BAO+SNLS+H_0	
$\Omega_b h^2$	$0.02246^{+0.00026}_{-0.00025}$	0.02202 ± 0.00026	$0.02202^{+0.00025}_{-0.00026}$	$0.02193^{+0.00027}_{-0.00026}$
$\Omega_c h^2$	0.1266 ± 0.0042	$0.1207^{+0.0021}_{-0.0022}$	0.1207 ± 0.0021	0.1220 ± 0.0025
$100\theta_{\rm MC}$	$1.04071^{+0.00068}_{-0.00067}$	1.04122 ± 0.00060	$1.04122^{+0.00058}_{-0.00059}$	1.04102 ± 0.00061
τ	$0.0958^{+0.0134}_{-0.0133}$	$0.0879^{+0.0127}_{-0.0126}$	0.0882 ± 0.0125	$0.0861^{+0.0126}_{-0.0127}$
$\ln(10^{10} A_s)$	3.12 ± 0.028	$3.22^{+0.029}_{-0.028}$	$3.09^{+0.024}_{-0.025}$	3.09 ± 0.024
n_s	0.9805 ± 0.0080	$0.9587^{+0.0064}_{-0.0063}$	0.9584 ± 0.0063	$0.9556^{+0.0070}_{-0.0069}$
w_0	-1	-1.15 ± 0.07	-1.16 ± 0.06	-1.05 ± 0.15
w_a	-	-	-	$-0.596^{+0.717}_{-0.723}$
$\Delta N_{\rm eff}$	$0.536^{+0.229}_{-0.224}$	-	-	-
H_0	$71.23^{+1.36}_{-1.37}$	71.28 ± 1.49	71.65 ± 1.33	71.69 ± 1.37
Ω_m	0.295 ± 0.009	0.283 ± 0.012	$0.279^{+0.011}_{-0.010}$	0.282 ± 0.011
$-\ln$ (like)	4968.69	4968.79	5114.43	5114.28

C. Cheng & QGH, Phys.Rev.D 89, 043003 (arXiv:1306.4091)

Non-Gaussianity



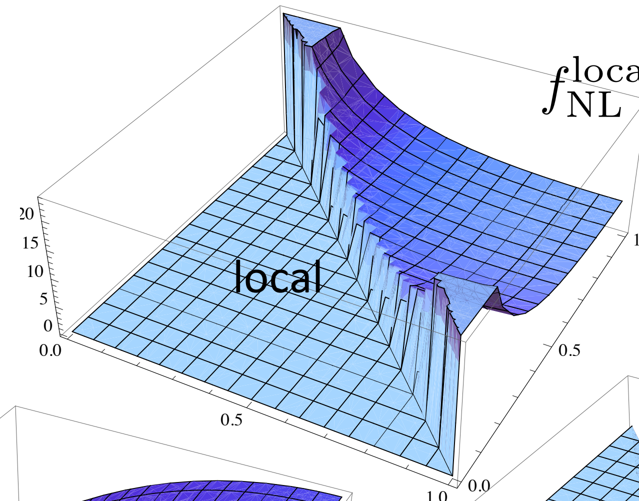


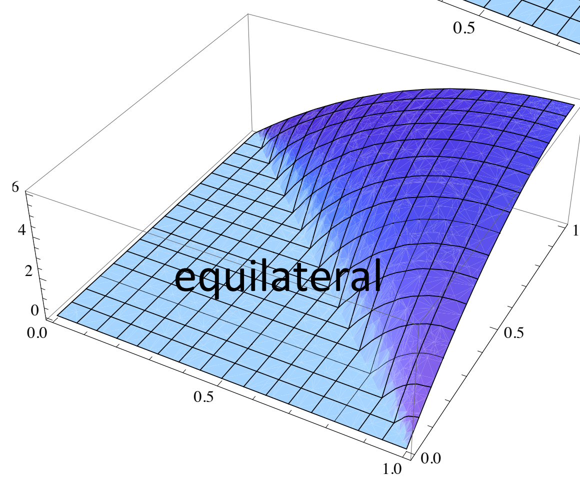


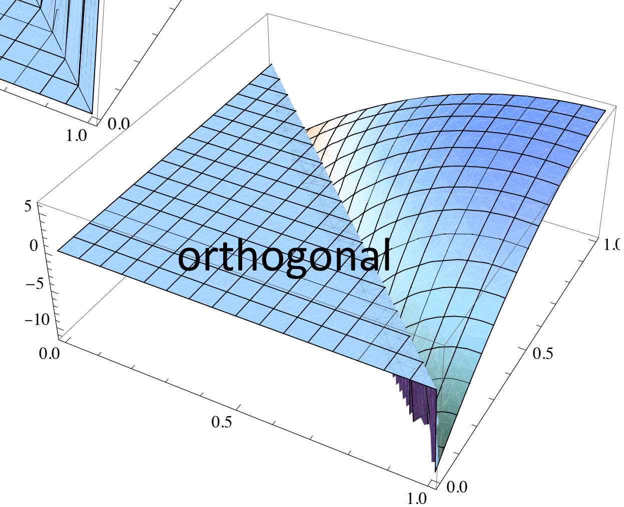
$$\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle = (2\pi)^3\delta^{(3)}(\sum_{i=1}^{3}\mathbf{k}_i)F(k_1,k_2,k_3)$$

$$F(k_1,k_2,k_3) = \frac{12\pi^4}{5} f_{NL} P_\zeta^2 \cdot \tilde{F}(k_1,k_2,k_3)$$

$$f_{\rm NL}^{\rm local} = \frac{5}{12}(1-n_s)$$







Planck 13:

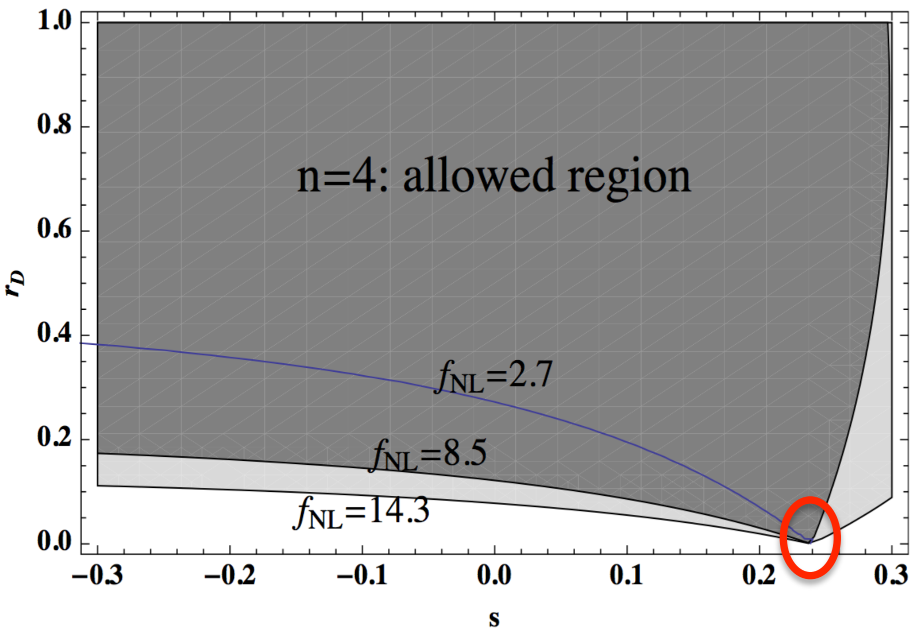
- The non-Gaussianity parameters are assumed to be scale-independent.

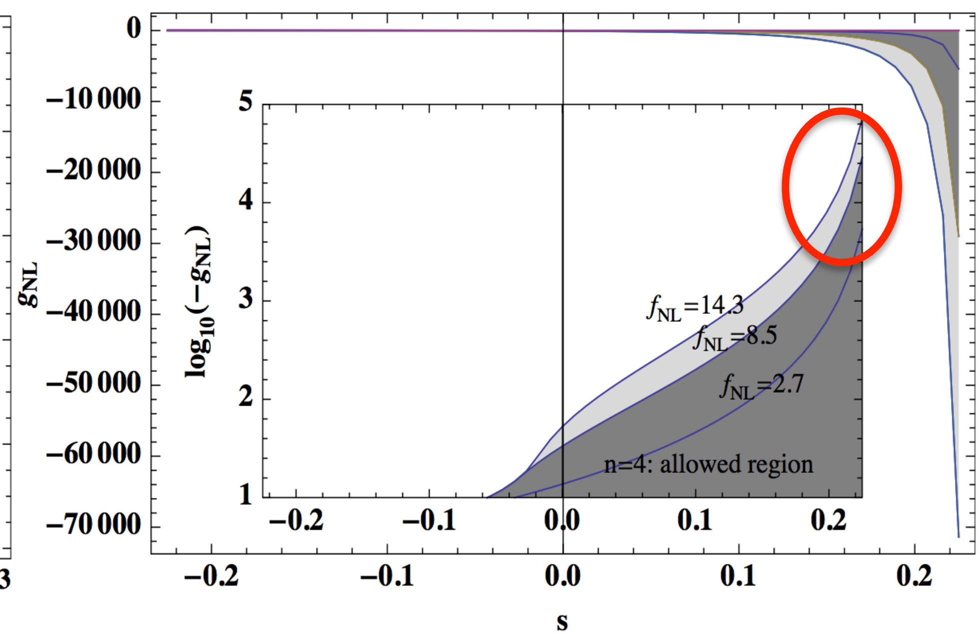
- The analysis of the trispectrum is still absent.

	f_{NL}	
Local	Equilateral	Orthogonal
2.7 ± 5.8	−42 ± 75	−25 ± 39

WMAP9: 37.2 ± 19.9 51± 136 -245± 100

$$V(\sigma) = \frac{1}{2}m^2\sigma^2 + \lambda m^4(\sigma/m)^n \equiv \frac{1}{2}m^2\sigma^2(1+s)$$





Planck 2013: f_{NL}=2.7±5.8

Prediction: $-g_{NL}<O(10^4 \sim 10^5)$

QGH, JCAP 05(2013)030

- Scale-dependent f_{NL}?

	f_{NL}	
Local	Equilateral	Orthogonal
2.7 ± 5.8	-42 ± 75	-25 ± 39
WMAP9: 37.2 ± 19.9	51± 136	-245± 100

KSW	$\ell_{max} = 500$	$\ell_{max} = 1000$	$\ell_{max} = 1500$	$\ell_{max} = 2000$	$\ell_{max} = 2500$
Local	38 ± 18	6.4 ± 9.7	6.9 ± 6.2	9.1 ± 5.8	9.8 ± 5.8
Equilateral	-119 ± 121	-45 ± 88	-41 ± 75	-40 ± 75	-37 ± 75
Orthogonal	-163 ± 109	-89 ± 52	-57 ± 45	-45 ± 40	-46 ± 39
Diff.ps $\cdot 10^{29}$	$(-1.5 \pm 1.3)\times 10^4$	$(-7.9 \pm 3.1)\times 10^2$	-39 ± 18	10.0 ± 3.1	7.7 ± 1.5
ISW-lensing	3.2 ± 1.2	1.00 ± 0.43	1.00 ± 0.35	0.83 ± 0.31	0.81 ± 0.31

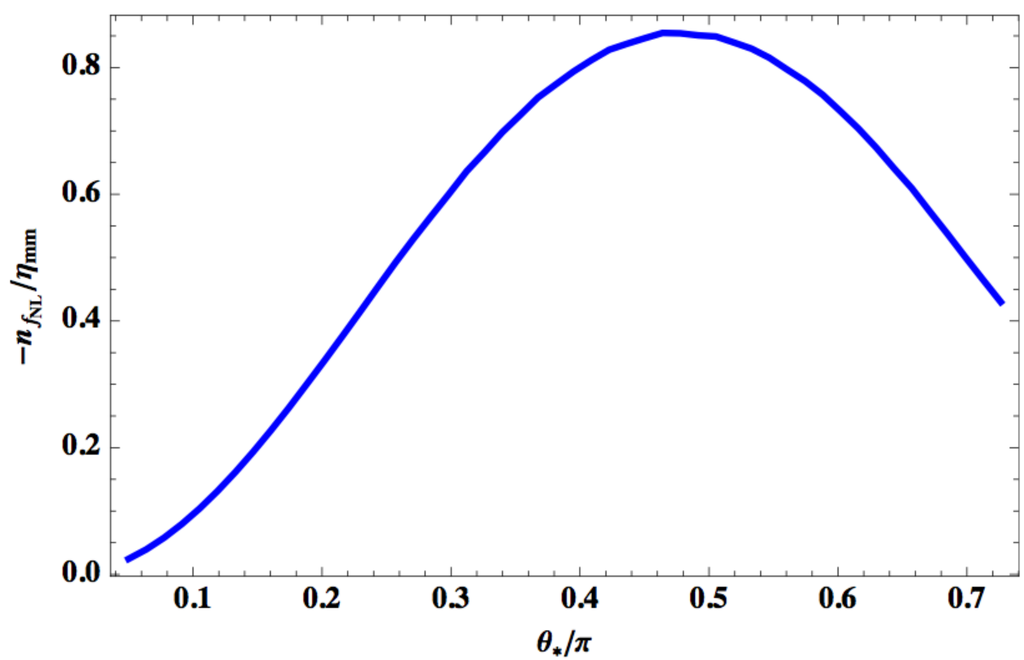
$$f_{\rm NL}^{local}(k) = f_{\rm NL}^{*}\left(\frac{k}{k_0}\right)^{n_{f_{\rm NL}}} \qquad n_{f_{\rm NL}} < 0$$

$$S_\sigma = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\partial_\mu\sigma\partial^\mu\phi - V(\sigma)\right]$$

$$n_{f_{\rm NL}} = \frac{V'''(\sigma)}{3H^2}\frac{N_{,\sigma}}{N_{,\sigma\sigma}}$$

1. $V(\sigma) = \frac{1}{2}m^2\sigma^2 - \lambda m^4(\sigma/m)^n$

2. $V(\sigma) = m^2 f^2(1-\cos\frac{\sigma}{f})$



QGH, JCAP 11(2010)026

Anomalies

Axis of Evil?

$$P(\mathbf{k}) = P_0(k)\left[1 + g_*(\hat{\mathbf{k}} \cdot \hat{\mathbf{n}})^2\right]$$

WMAP

$$g_* = 0.29 \pm 0.031 \ (68\% \ \mathrm{CL})$$

Groemeboom, Ackerman, Wehus, Eriksen, 0911.0150

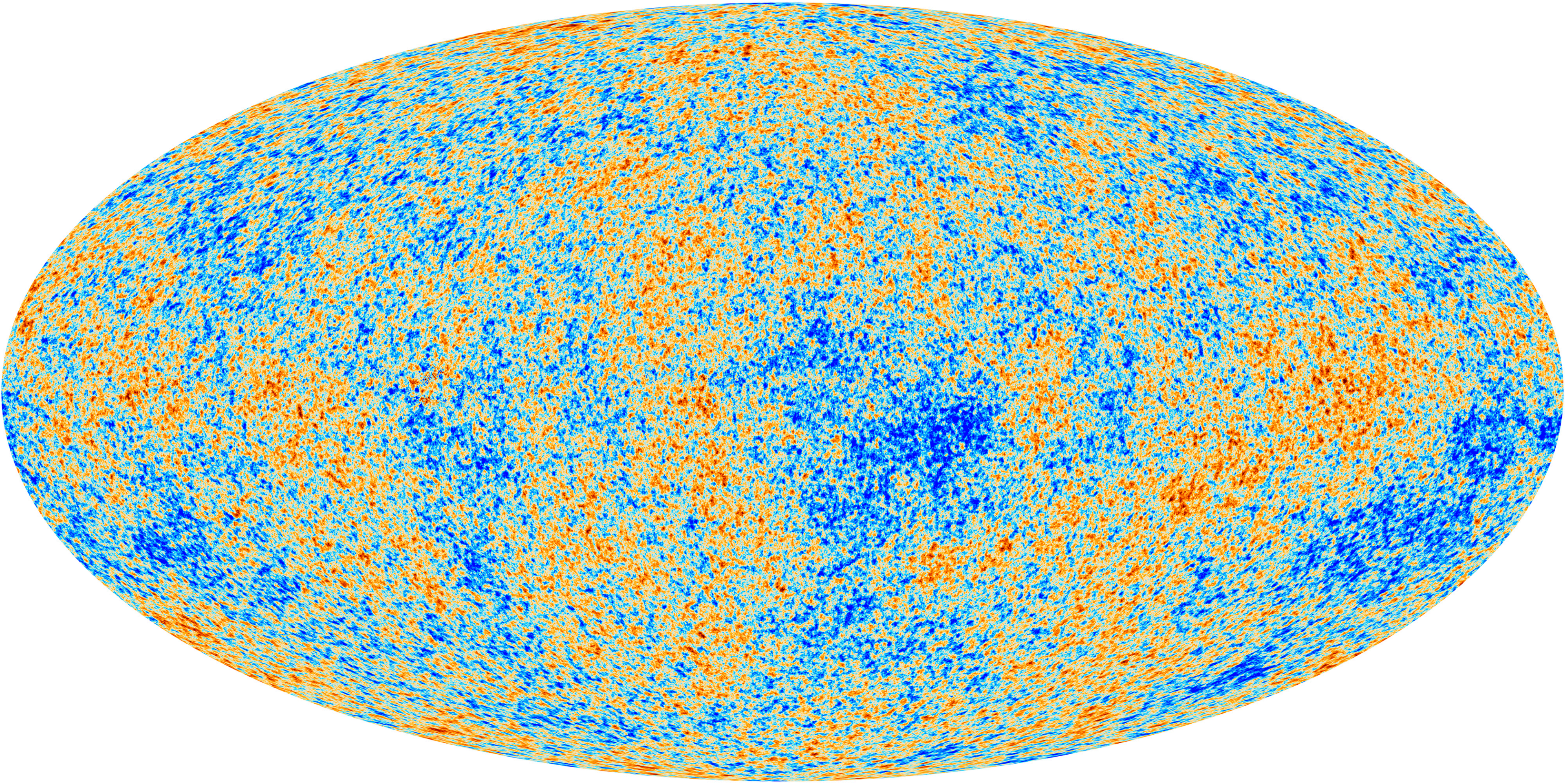
$\Rightarrow$

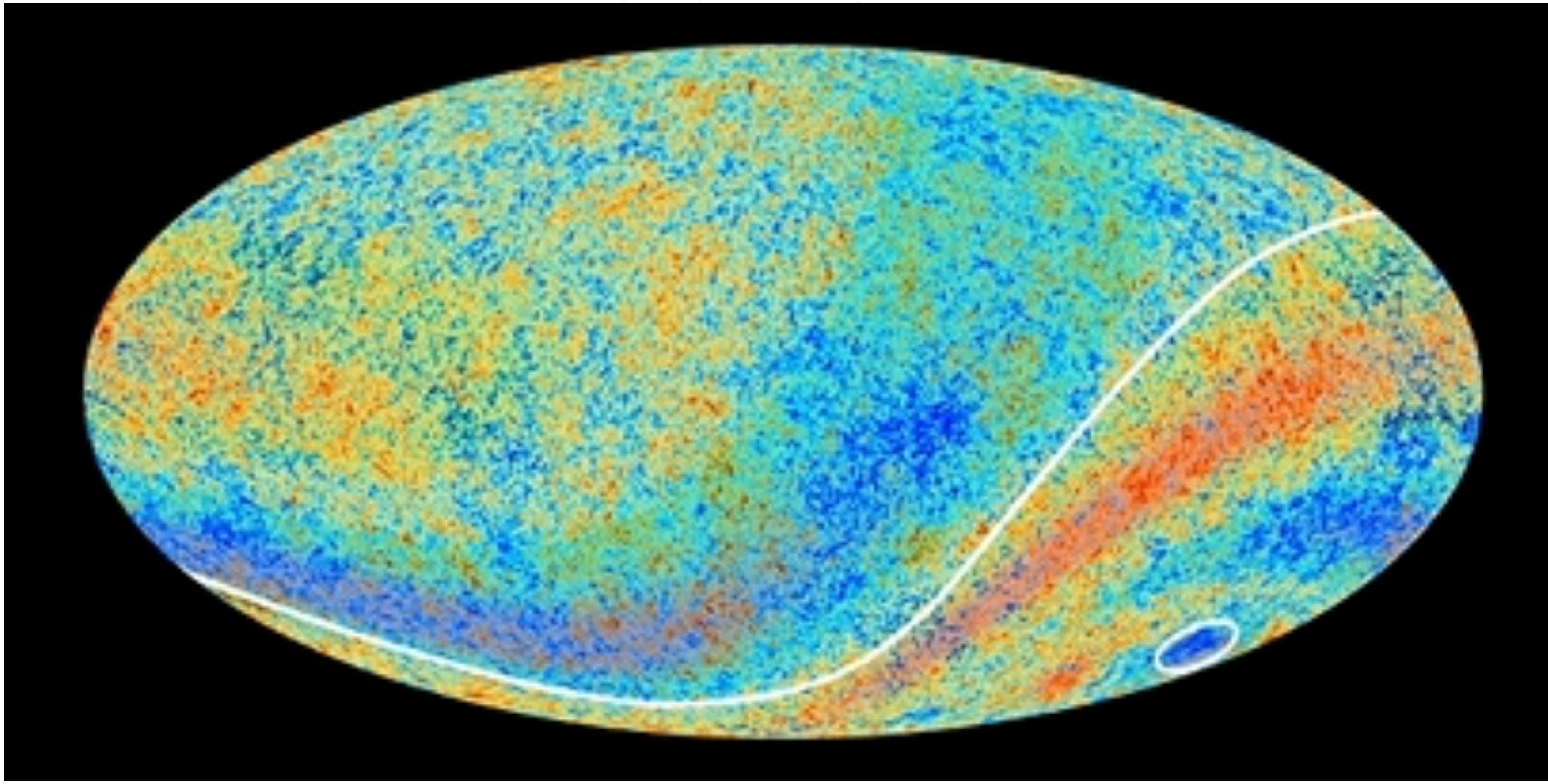
Planck

$$g_* = 0.002 \pm 0.016 \ (68\% \ \mathrm{CL})$$

Kim, Komatsu, 1310.1605

Dipolar modulation?





$$\mathbf{d} = (1 + A\mathbf{p} \cdot \mathbf{n})\mathbf{s}_{\rm iso} + \mathbf{n}$$

[The anomalous regions have been enhanced with red and blue shading to make them more clearly visible.]

WMAP5:

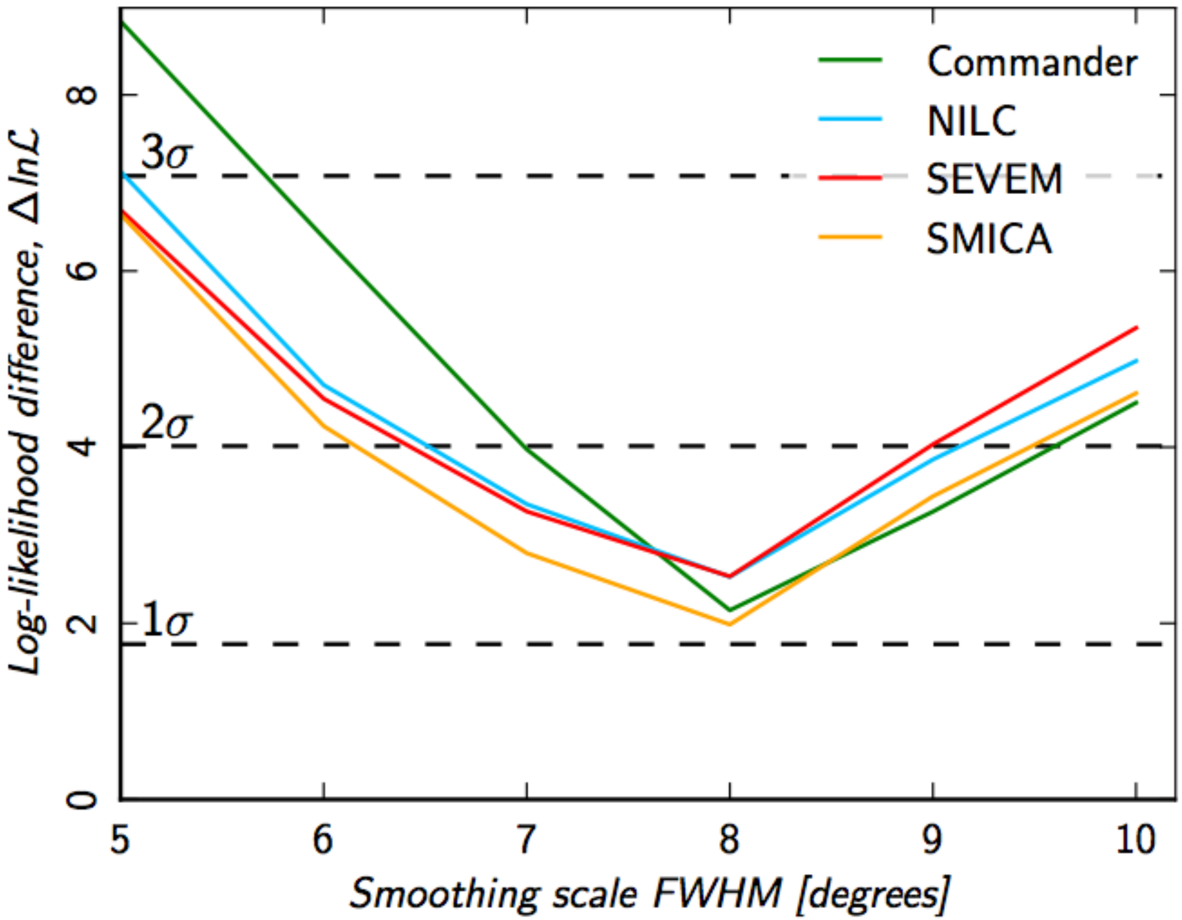
$A(k)=0.072 \pm 0.022$ (l<=64)

$A(k)=0.11 \pm 0.04$ (l<=40)

Hoftuft, Eriksen, Banday, Gorski, Hansen and Lilje, APJ 699(2009)985 (arXiv:0903.1229)

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	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
NILC
SEVEM
SMICA
3σ
2σ
1σ
Log-likelihood difference, Δ ln ℒ
Smoothing scale FWHM [degrees]
0
2
4
6
8
5
6
7
8
9
10

$$A(k) < 4.5 \times 10^{-3} \text{ on the } \sim 10 \text{ Mpc scale, at } 95\%$$

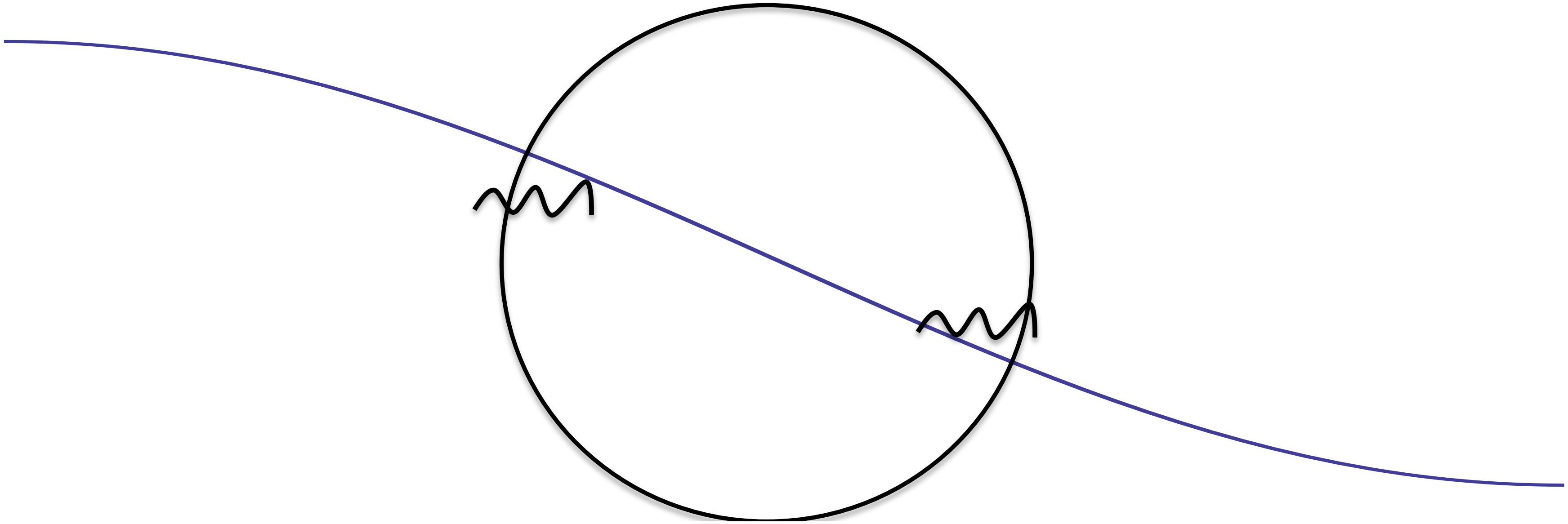
$$\ell \in [601, 2048]$$

Flender&Hotchkiss, arXiv:1307.6069, JCAP 09(2013)033

A(k)<0.015 (99%) on 1 Mpc

Hirata, JCAP 09(2009)011

$$\zeta_{\mathbf{k}}(\mathbf{x}) = \zeta_{\mathbf{k}}(1 + A\hat{\mathbf{n}} \cdot \mathbf{d} + \dots)$$



$$\begin{aligned}
\zeta(\mathbf{x}) &= N(\phi(\mathbf{x}, t_k) - N(\phi_0) \\
&= N'(\phi_0(t_k))\,(\delta\phi(\mathbf{x}) + \delta\phi_{\rm L}(\mathbf{x})) + \frac{1}{2}N''(\phi_0(t_k))\,(\delta\phi(\mathbf{x}) + \delta\phi_{\rm L}(\mathbf{x}))^2 \\
&\equiv (\zeta_{\rm S}(\mathbf{x}) + \zeta_{\rm L}(\mathbf{x})) + \frac{3}{5}f_{\rm NL}(k)\,(\zeta_{\rm S}(\mathbf{x}) + \zeta_{\rm L}(\mathbf{x}))^2 + \cdots \\
&= \left(1 + \frac{6}{5}f_{\rm NL}(k)\zeta_{\rm L}(\mathbf{x})\right)\zeta_{\rm S}(\mathbf{x}) + \zeta_{\rm L}(\mathbf{x}) + \frac{3}{5}f_{\rm NL}(k)\zeta_{\rm L}^2(\mathbf{x}) + \cdots,
\end{aligned}$$

$$A \lesssim \mathcal{O}(10^{-2} \sim 10^{-1})\, f_{\rm NL}^{\rm local}$$

$$f_{\rm NL}^{\rm local} \sim \mathcal{O}(1)$$

$$A(k) \sim f_{\rm NL}(k) = f_{\rm NL}^{*}\left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$

$$n_{f_{\rm NL}} < 0$$

Erickcek, Kamionkowski, Carroll, 0806.0377
Lyth, 1304.1270

Discussion and summary

Inflation predicts that
both scalar and gravitational waves perturbations
are nearly scale-invariant!

What is the smoking-gun for inflation?

Flatness,
Nearly scale-invariant density perturbation?

Nearly scale-invariant
Gravitational waves perturbation!

“Standard Model” of Cosmology

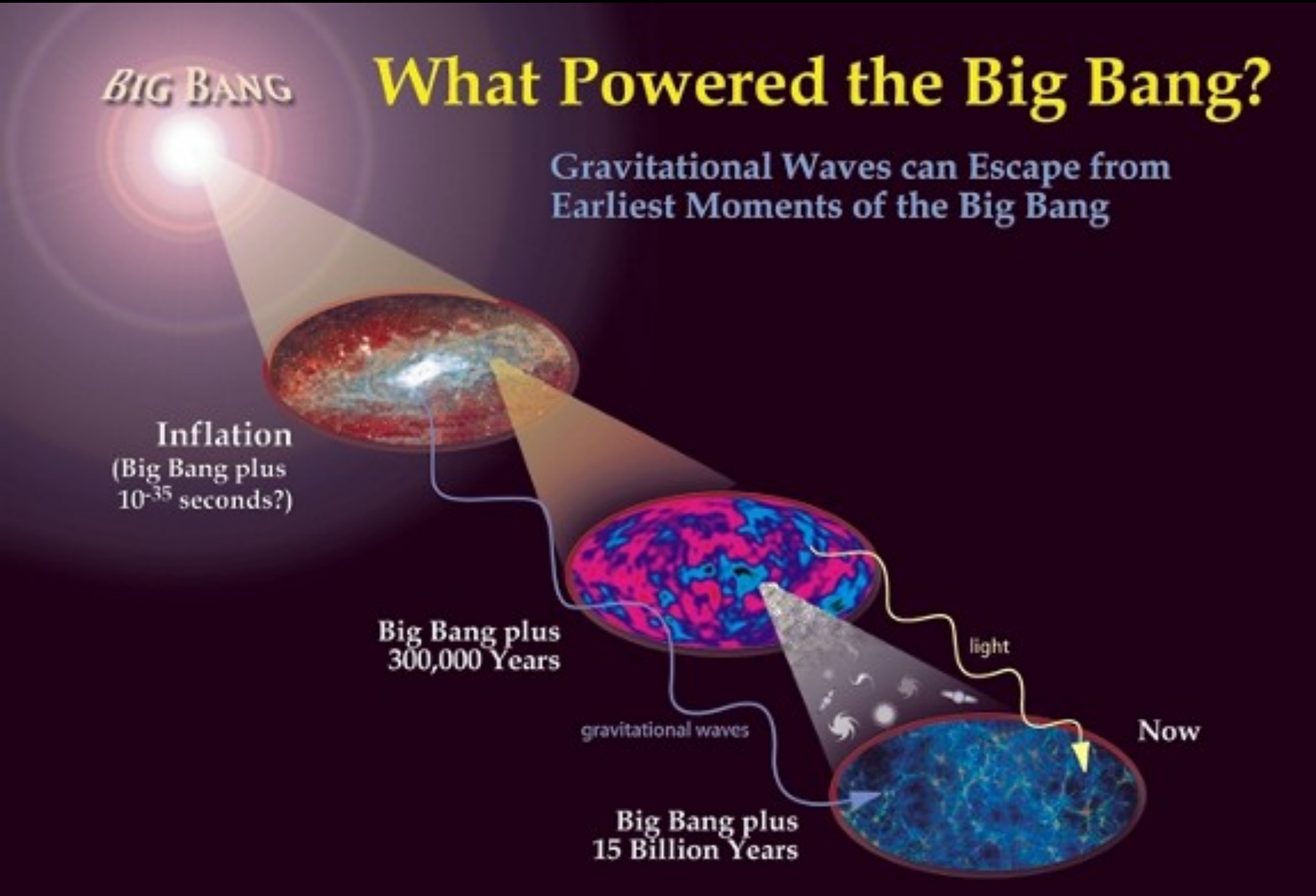
Inflation + ΛCDM model

How to fit the inflation into
a well-established fundamental theory?

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

What is the nature of inflation?

What is the origin of inflation?


BIG BANG
What Powered the Big Bang?
Gravitational Waves can Escape from
Earliest Moments of the Big Bang
Inflation
(Big Bang plus
10-35 seconds?)
Big Bang plus
300,000 Years
light
gravitational waves
Now
Big Bang plus
15 Billion Years

Thank You!