CMB Anomalies in the Light of BICEP2

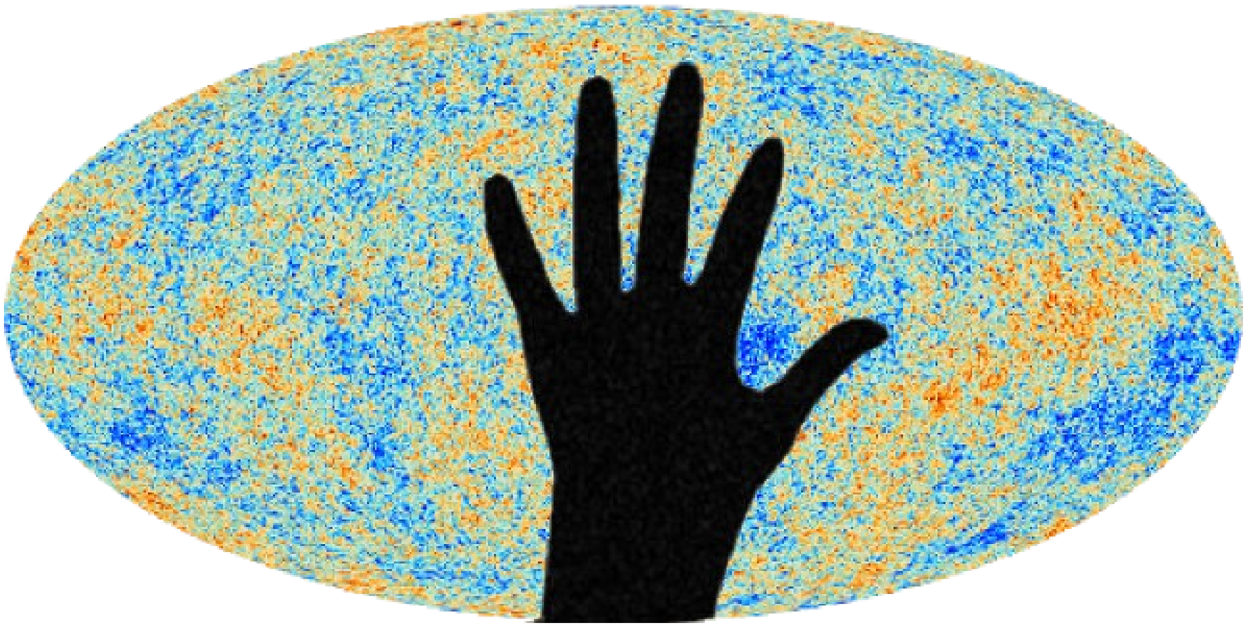
Yi Wang, DAMTP, Cambridge

Based on:

Y.-Z. Ma, YW, 1403.4585

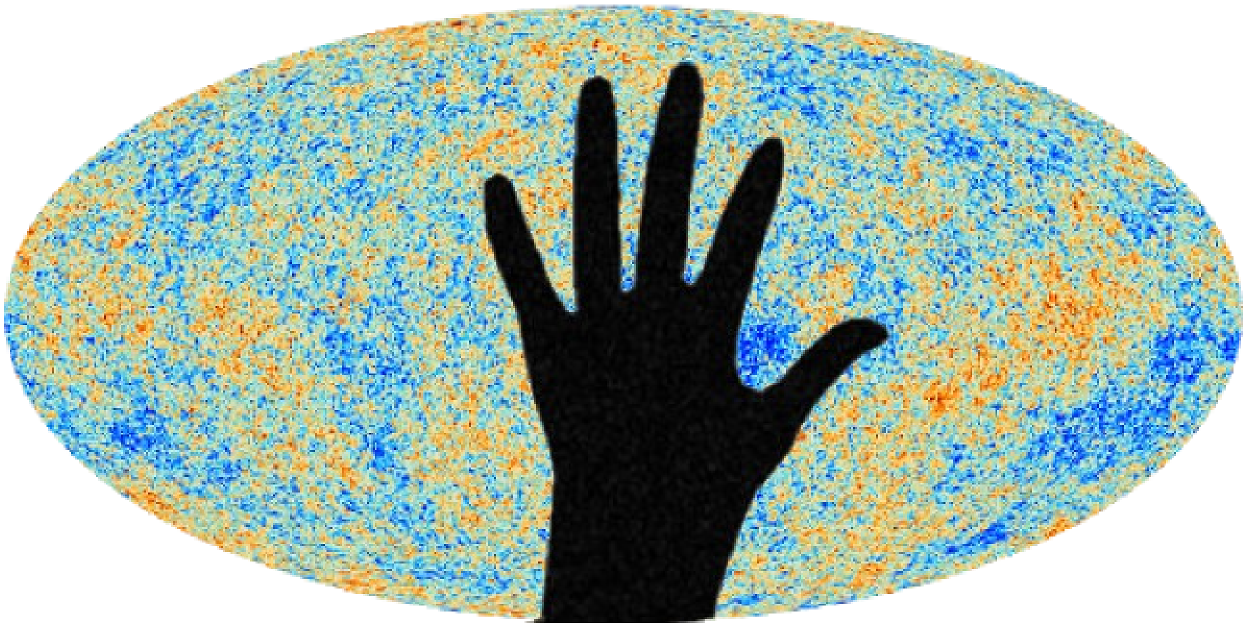
YW, W. Xue, 1403.5817
Y.-F. Cai, YW, 1404.6672
Y.-Z. Ma, YW, 1405.????
(blue spectra)

X. Chen, R. Emami, H. Firouzjahi, YW, 1404.4083
R. Emami, H. Firouzjahi, YW, 1404.5112
M. Akhshik, R. Emami, H. Firouzjahi, YW, 1405.4179
(anisotropies)



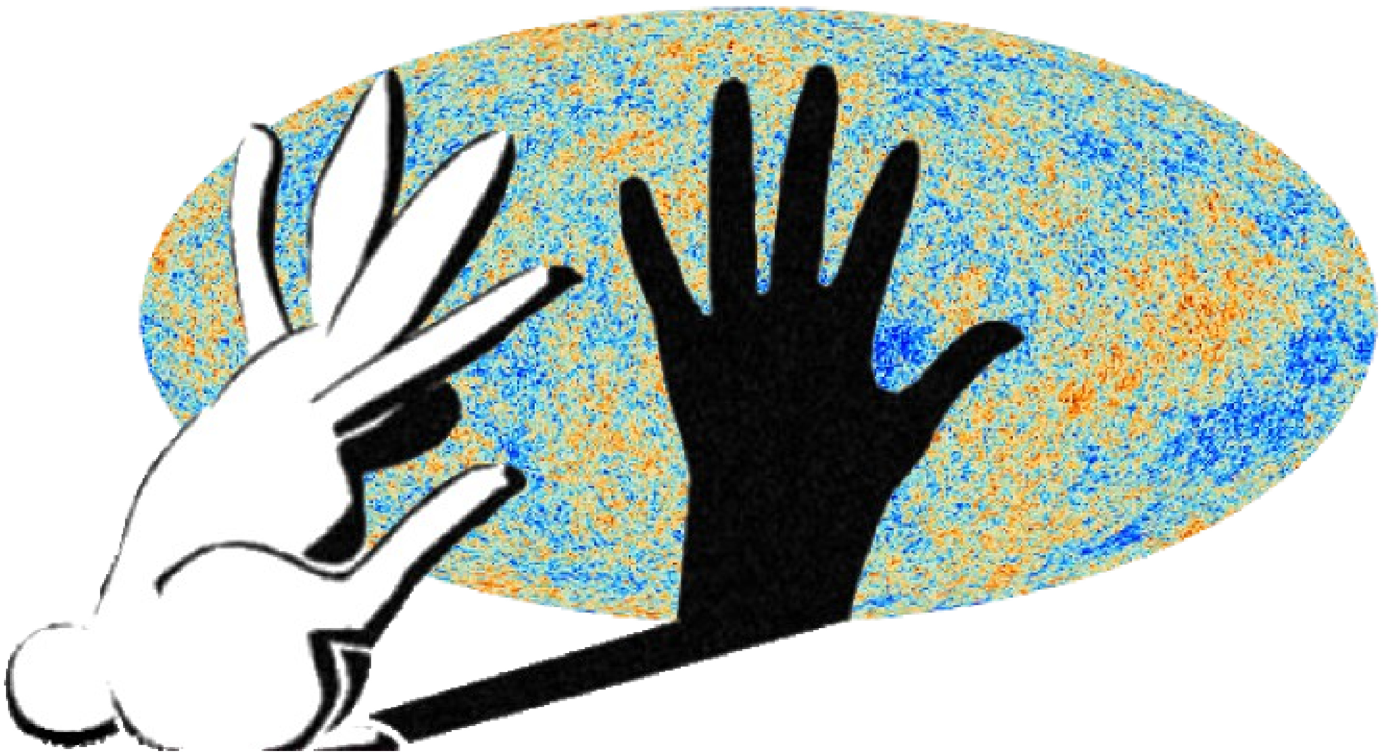
The BICEP2 discovery of r = 0.2
is considered to be “Fingerprint of God”,

Big surprise for us
小伙伴们都惊呆了
Figure from YouTube

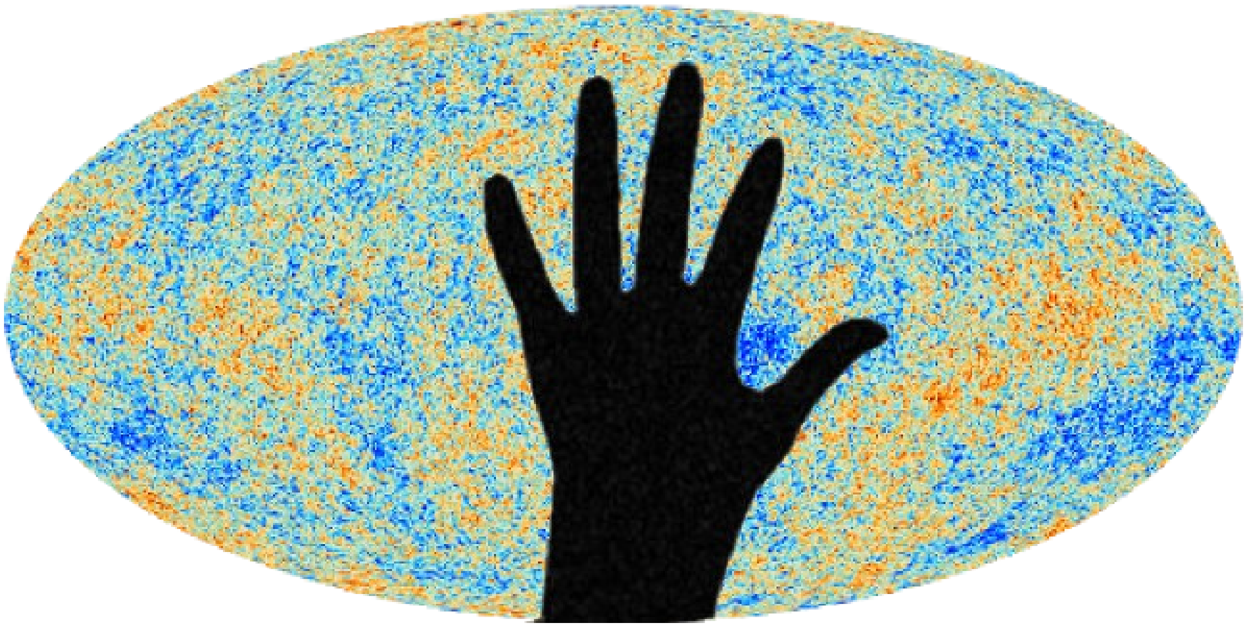


... if it is primordial.
Recently there is a debate about dust.
We need to be patient ...

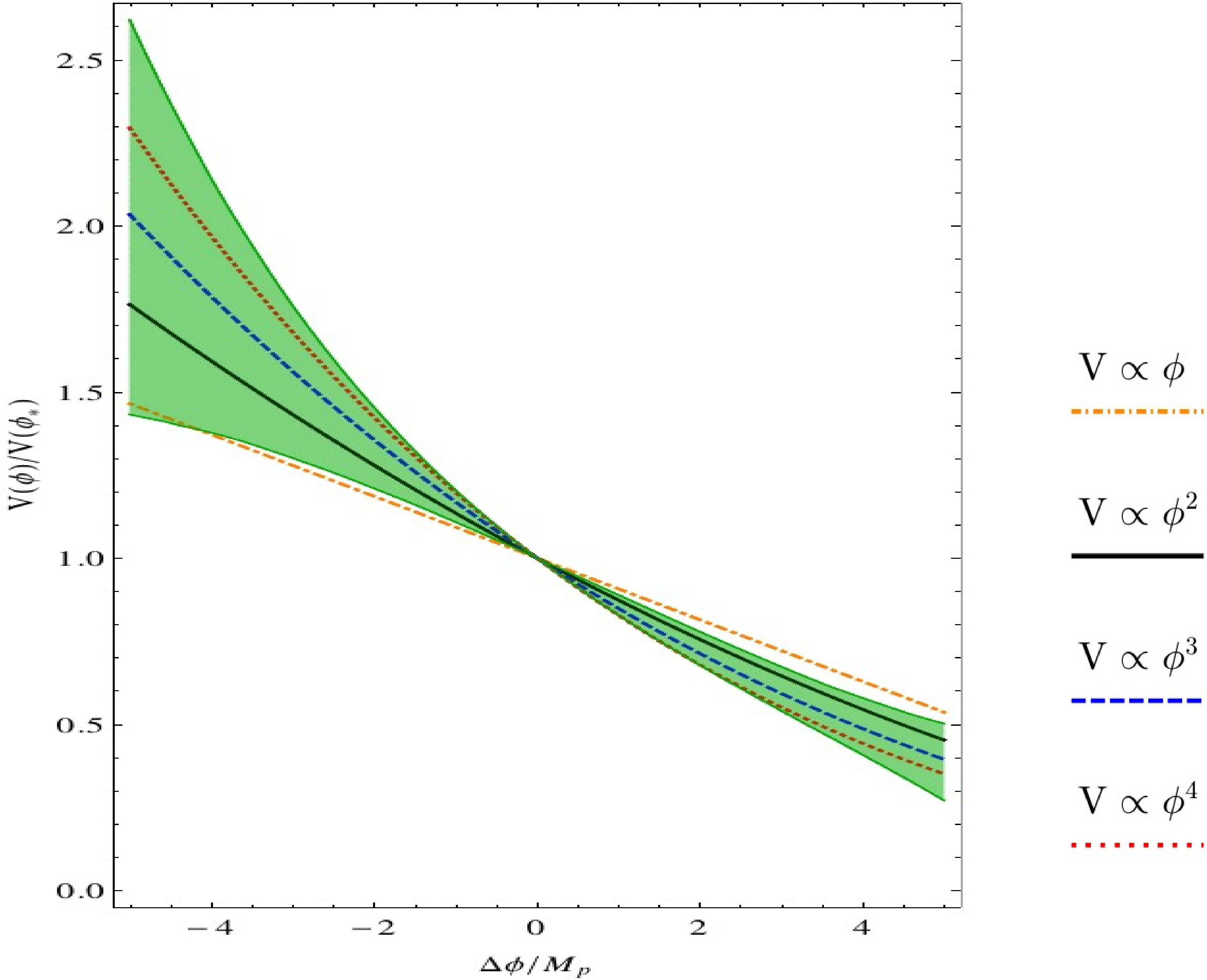
http://pcts.princeton.edu/PCTS/SpecialEventSimplicity2014/SpecialEventSimplicity2014.html



dust



Let's remove the rabbit (at least for now)
and think about cosmological implications



Y. -Z. Ma, YW, 1403.4585

Inflation before BICEP2

η-problem: η is unnaturally small

Inflation before BICEP2

η-problem: η is unnaturally small

Inflation after BICEP2

ε-problem: ε is unnaturally large

Y. -Z. Ma, YW, 1403.4585

Two topics concerning anomalies

– New proposals for existing anomalies

– New anomalies brought by BICEP2

WMAP/Planck anomalies (at low ℓ)

WMAP/Planck anomalies (at low ℓ)

– Direction dependent power asymmetries

– About 2σ of local shape non-Gaussianity

– Deficit of power

– Mode alignment

– Cold spot …

(CMB is much less anomalous at high ℓ)

WMAP/Planck anomalies (at low ℓ)

(CMB is much less anomalous at high ℓ)

Possibility:

– Cosmic variance

– Introduce scale dependent features

WMAP/Planck anomalies (at low ℓ)

(CMB is much less anomalous at high ℓ)

Possibility:

– Cosmic variance

– Introduce scale dependent features

– Scale invariant physics $\Rightarrow$ scale dep. anomalies?

X. Chen, R. Emami, H. Firouzjahi, YW, 1404.4083
M. Akhshik, R. Emami, H. Firouzjahi, YW, 1405.4179

Scale invariant physics ⇒ scale dep. anomalies?

Now r=0.2 provides such a mechanism.

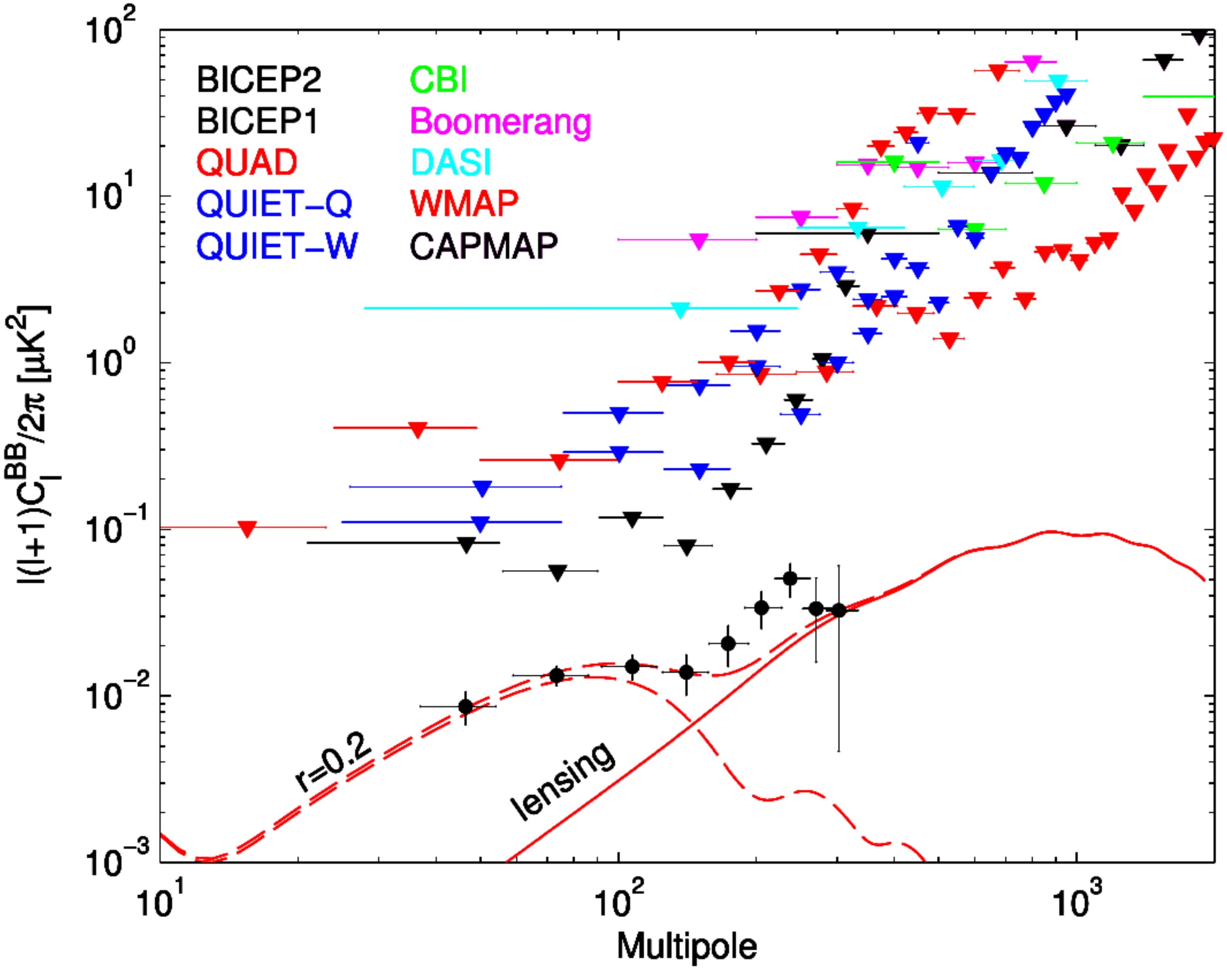


Figure from BICEP2

Scale invariant physics ⇒ scale dep. anomalies

Decay: the tensor-to-temperature transfer function

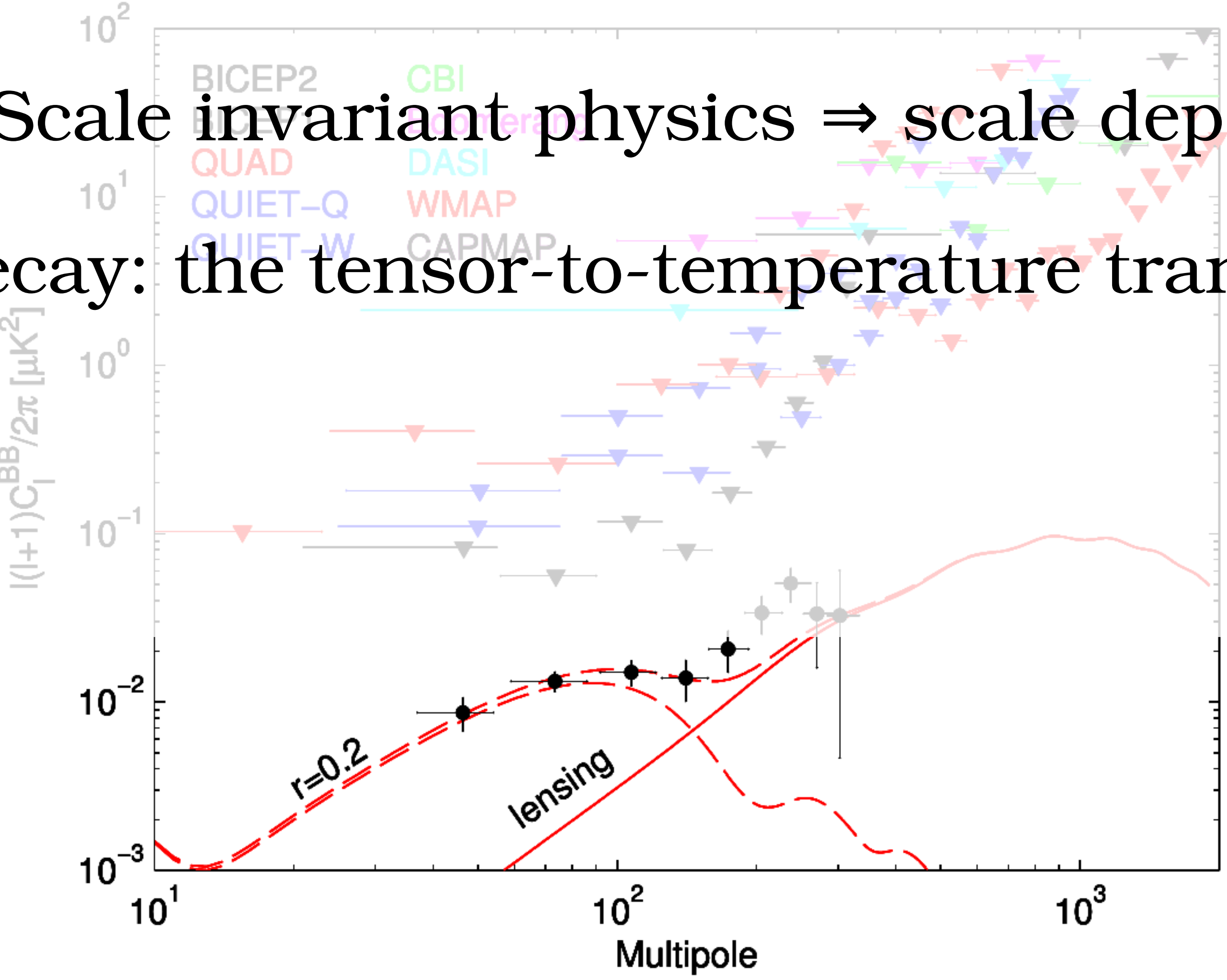
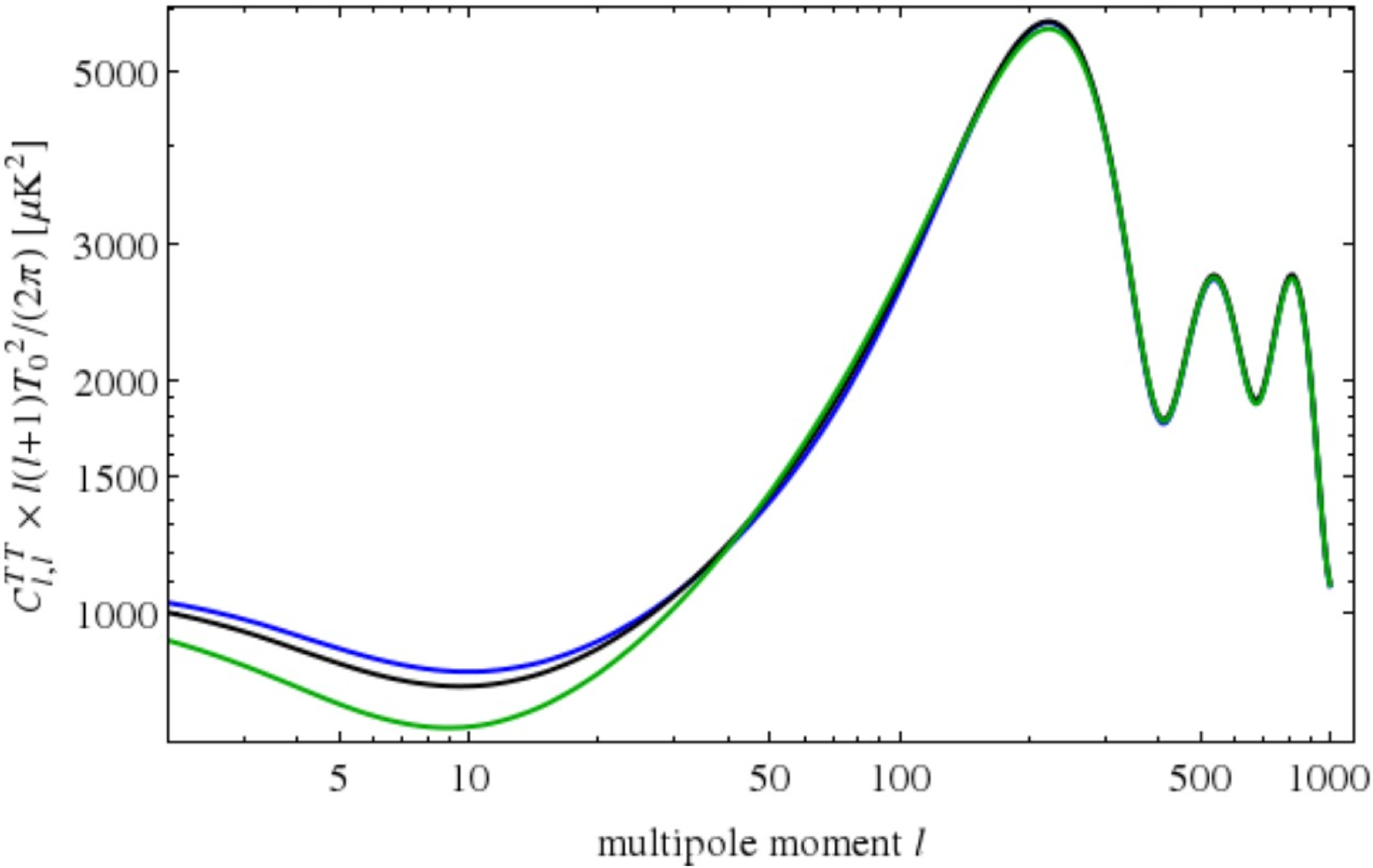


Figure from BICEP2



$C_{l,l}^{TT} \times l(l+1)T_0^2/(2\pi)$ [μK^2]
5000
3000
2000
1500
1000
5
10
50
100
500
1000
multipole moment l

Scale invariant physics ⇒ scale dep. anomalies

Decay: the tensor-to-temperature transfer function

Example: Anisotropy

- Case 1: anisotropic inflation
- Case 2: solid inflation

Scalar (relatively) isotropic, tensor anisotropic

Charged anisotropic inflation, $V = m^2\phi^2$

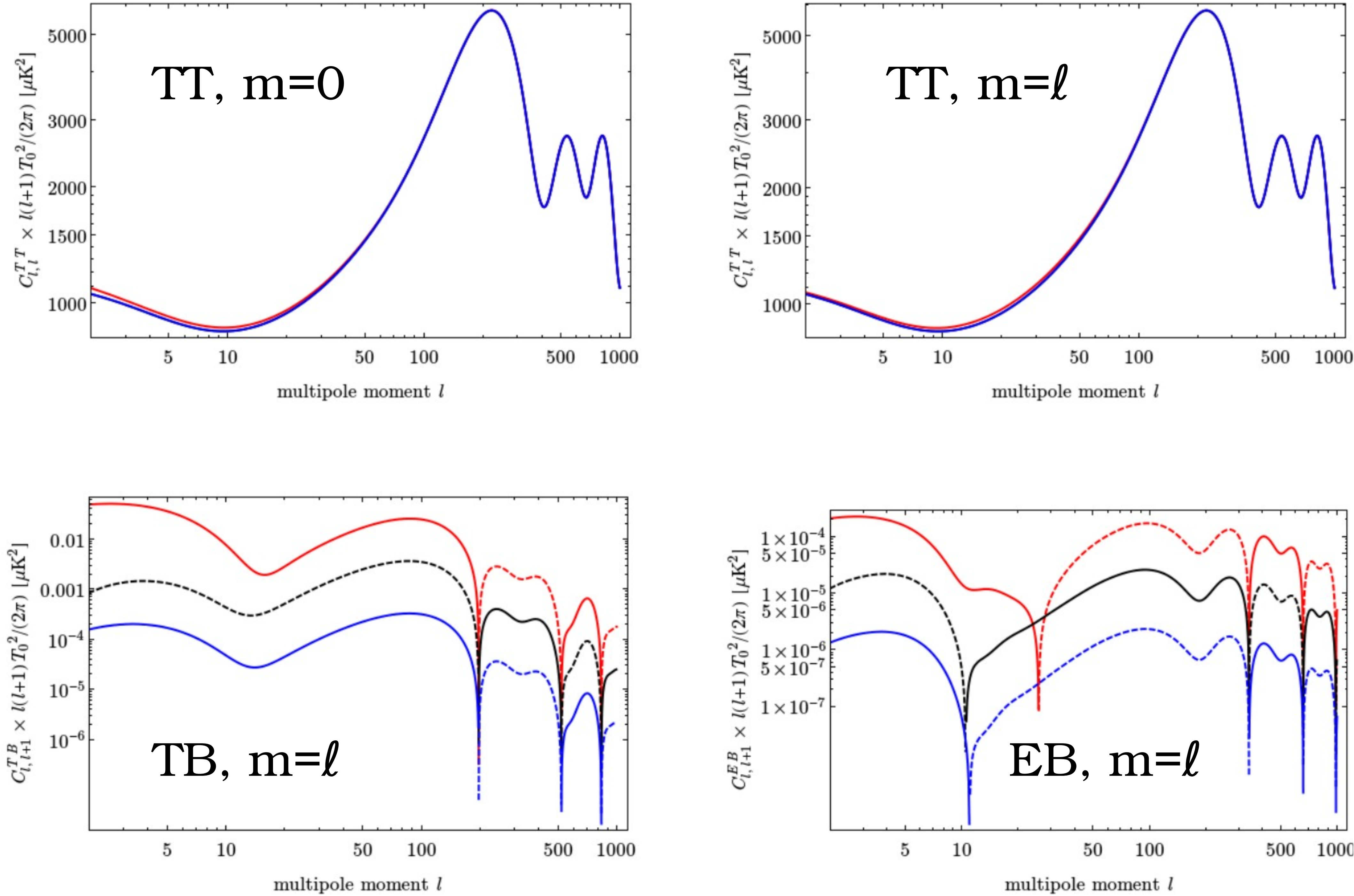
$$g^{\mu\nu}\mathcal{D}_\mu\phi\mathcal{D}_\nu\phi \quad \to \quad -e^2 g^{ij}\phi^2 A_i A_j$$

$$g^{ij}\phi^2 A_i A_j \;\to\; g^{ij}\delta\phi^2 A_i A_j \;\to\; P^\zeta(\mathbf{k}) = P_0^\zeta(k)(1 + g_*^\zeta \cos^2\theta)$$

$$g^{ij}\phi^2 A_i A_j \;\to\; h^{ij}\phi^2 A_i A_j \;\to\; P^h(\mathbf{k}) = P_0^h(k)(1 + g_*^h \cos^2\theta)$$

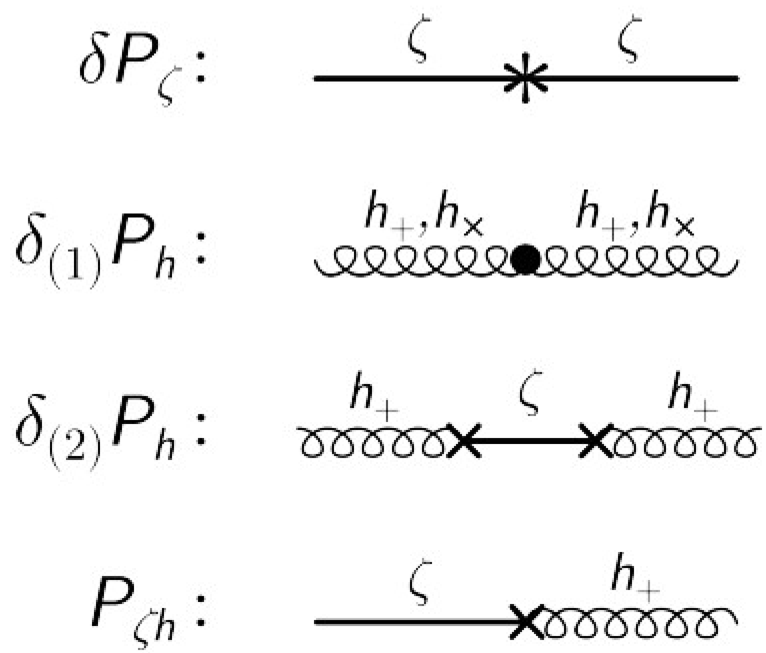
Tensor-tensor → TT dominates

X. Chen, R. Emami, H. Firouzjahi, YW, 1404.4083



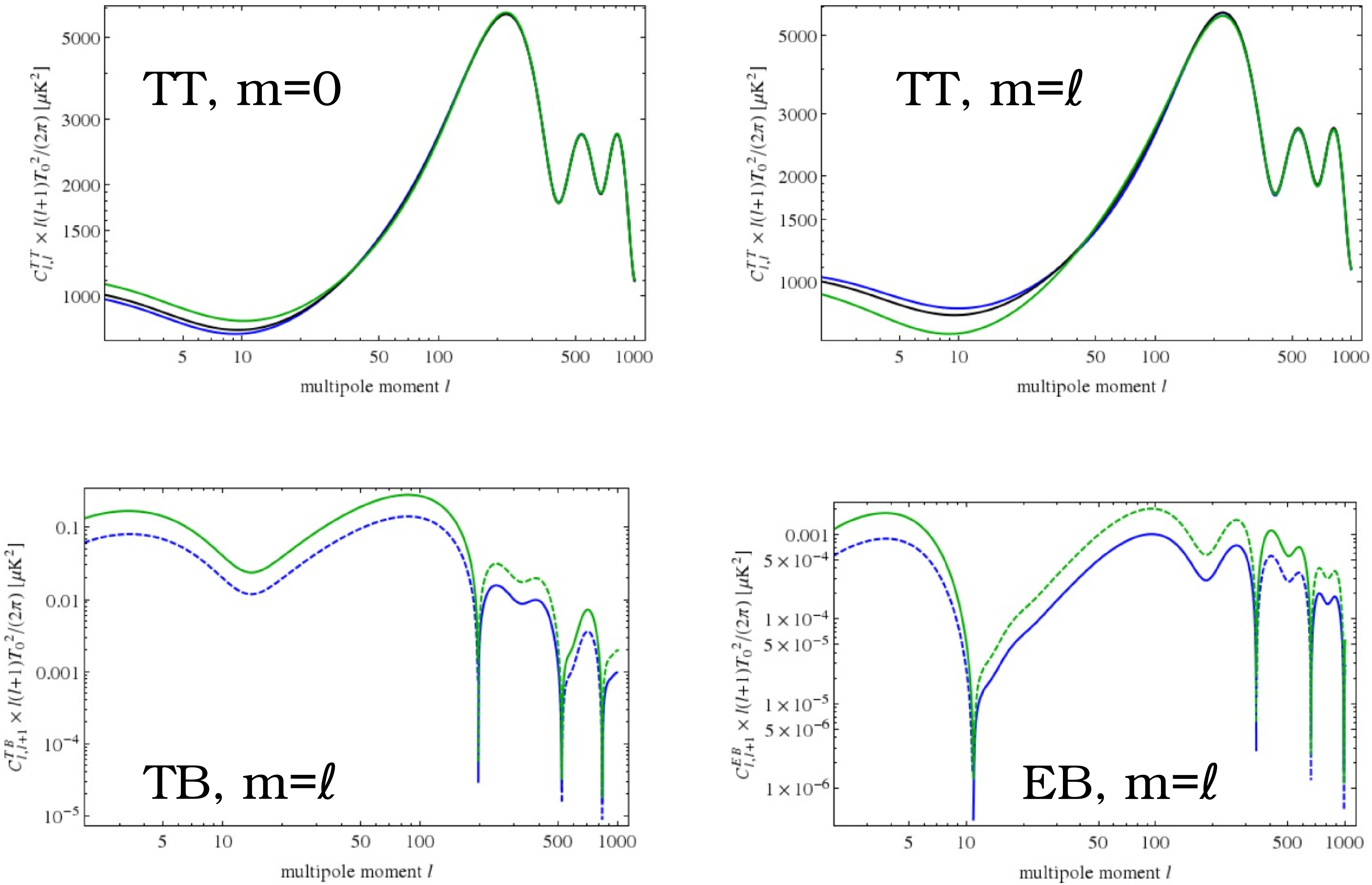
TT, m=0
TT, m=ℓ
TB, m=ℓ
EB, m=ℓ
$C_{l,l}^{TT} \times l(l+1)T_0^2/(2\pi)$ [μK^2]
$C_{l,l+1}^{TB} \times l(l+1)T_0^2/(2\pi)$ [μK^2]
$C_{l,l+1}^{EB} \times l(l+1)T_0^2/(2\pi)$ [μK^2]
multipole moment l
5000
3000
2000
1500
1000
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
1×10^{-4}
5×10^{-5}
1×10^{-5}
5×10^{-6}
1×10^{-6}
5×10^{-7}
1×10^{-7}
5
10
50
100
500
1000

Solid inflation,



Scalar-tensor → TT dominates

M. Akhshik, R. Emami, H. Firouzjahi, YW, 1405.4179



TT, m=0
5000
3000
2000
1500
1000
5
10
50
100
500
1000
multipole moment l
$C^{TT}_{l,l} \times l(l+1)T_0^2/(2\pi)$ [μK^2]
TT, m=ℓ
5000
3000
2000
1500
1000
5
10
50
100
500
1000
multipole moment l
$C^{TT}_{l,l} \times l(l+1)T_0^2/(2\pi)$ [μK^2]
TB, m=ℓ
0.1
0.01
0.001
10^{-4}
10^{-5}
5
10
50
100
500
1000
multipole moment l
$C^{TB}_{l,l+1} \times l(l+1)T_0^2/(2\pi)$ [μK^2]
EB, m=ℓ
0.001
5×10^{-4}
1×10^{-4}
5×10^{-5}
1×10^{-5}
5×10^{-6}
1×10^{-6}
5
10
50
100
500
1000
multipole moment l
$C^{EB}_{l,l+1} \times l(l+1)T_0^2/(2\pi)$ [μK^2]

New anomalies brought by BICEP2

Tension implies $n_t > 0$?

A. Ashoorioon, K. Dimopoulos, M. M. Sheikh-Jabbari, G. Shiu, 1403.6099

YW, W. Xue, 1403.5817

How precise do we know about n_t?

need to know k-space vs ℓ-space

How precise do we know about n_t?

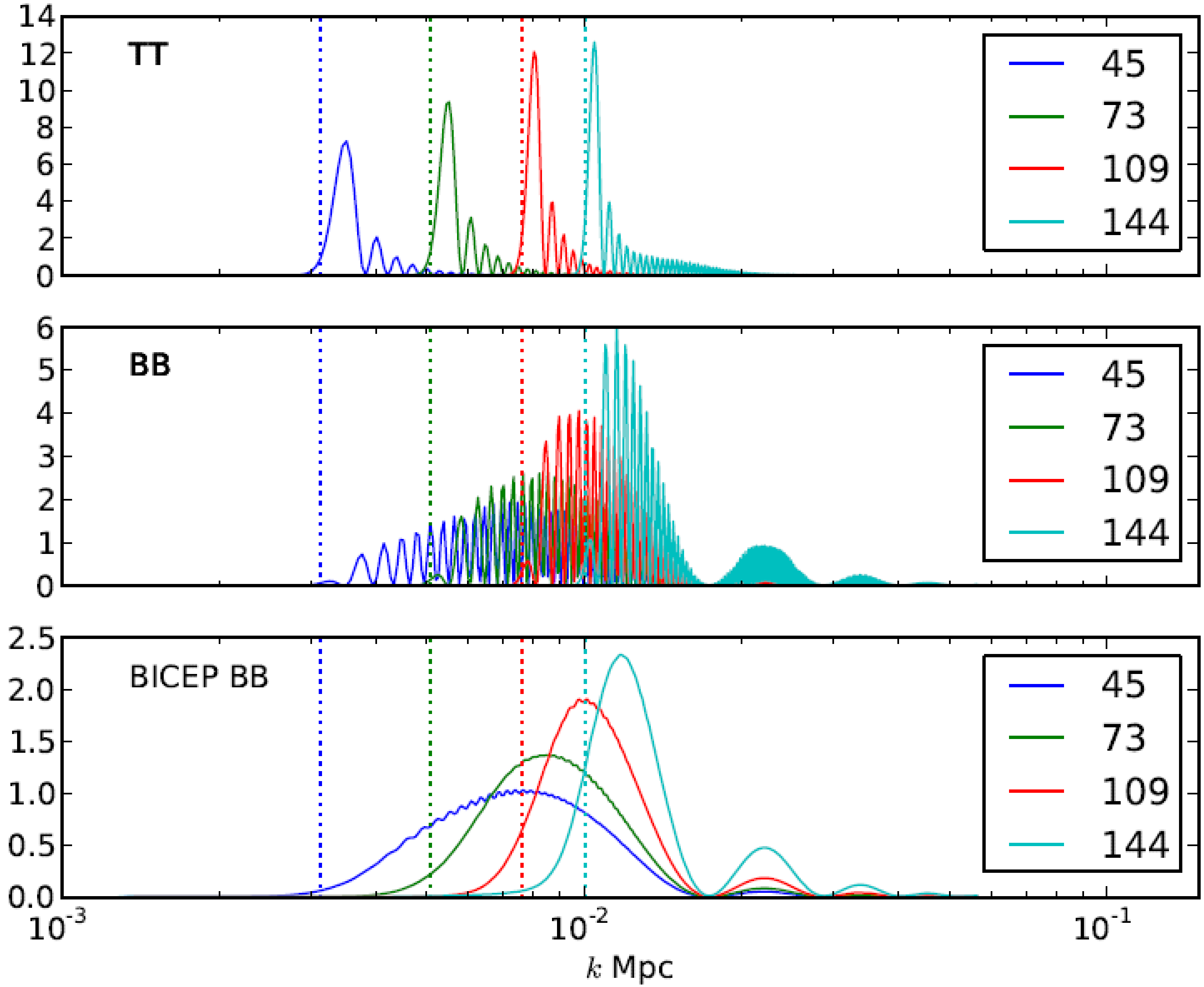


Figure by Lewis (CosmoCoffee)

How precise do we know about n_t?

$\Delta n_t \sim \Delta \ln k \,/\, \Delta \ln r \sim (0.003/0.01) \,/\, (0.06/0.2) \sim 1$

$\Delta k \sim 0.003/\mathrm{Mpc}$ at $k \sim 0.01/\mathrm{Mpc}$

→ ← $\Delta r \sim 0.06$ at $r \sim 0.2$

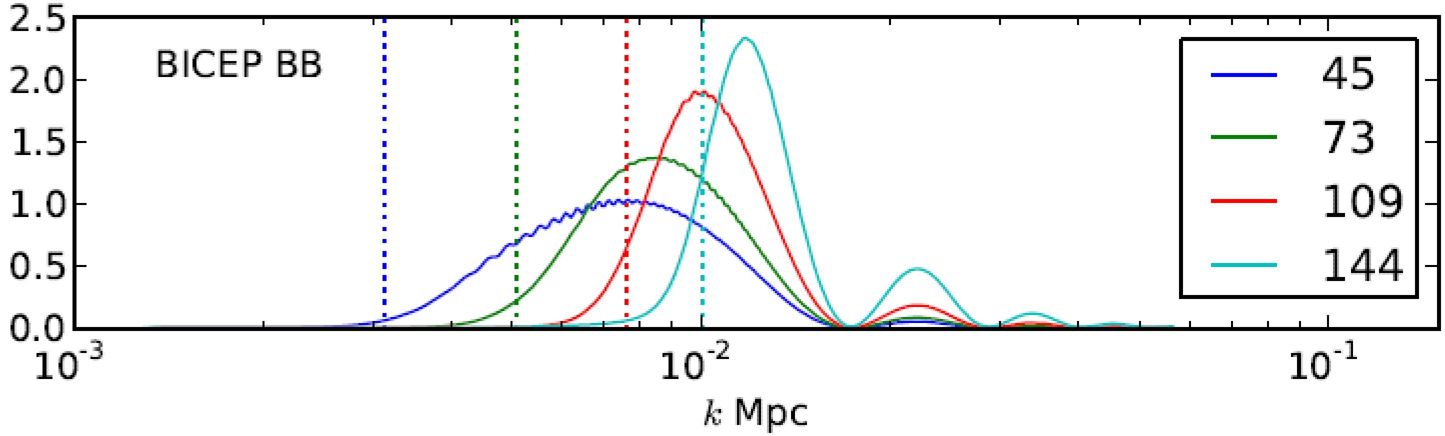
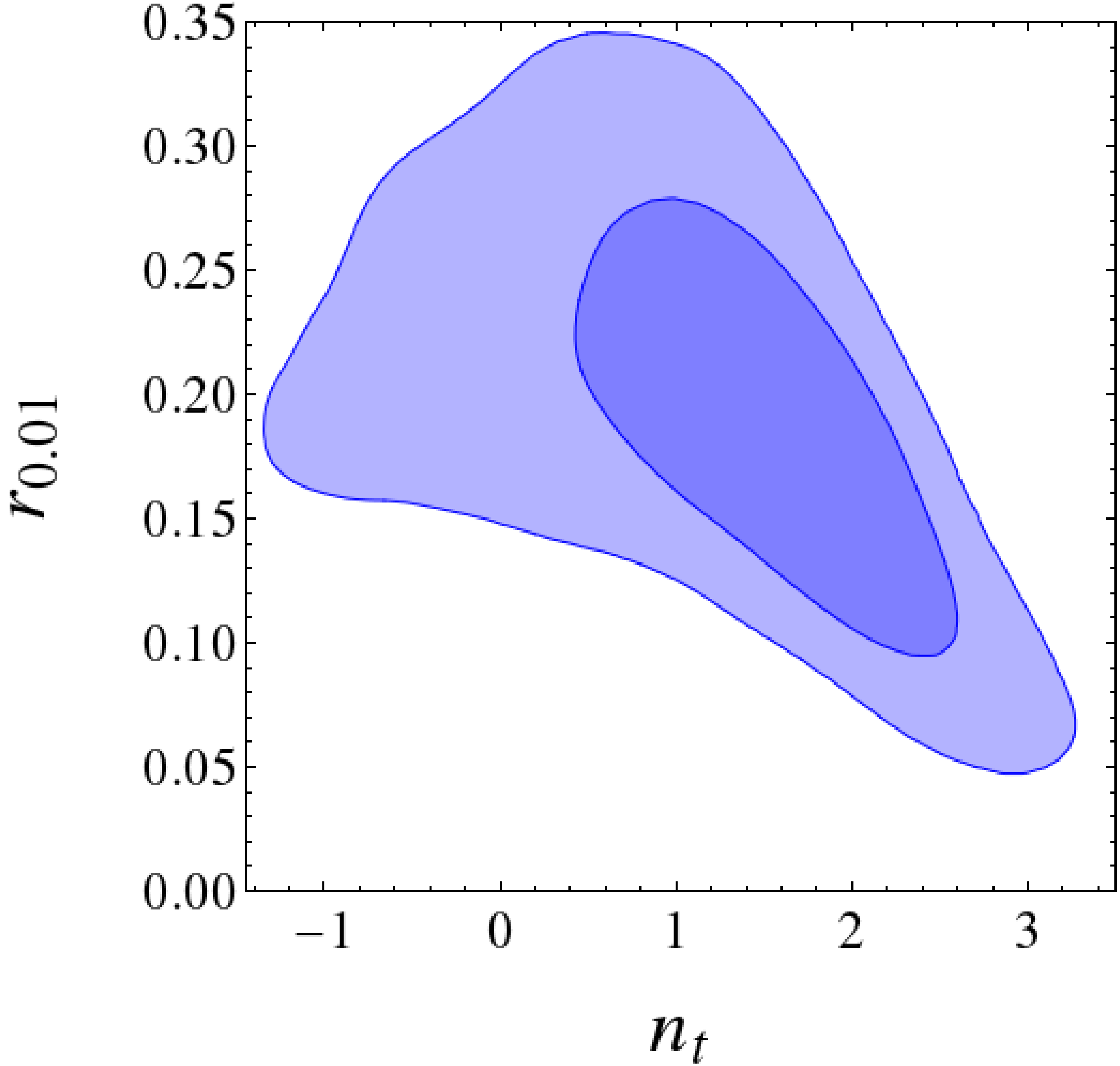


Figure by Lewis (CosmoCoffee)



BICEP2 only:
blue $n_t \sim 1.5\sigma$

M. Gerbino, A. Marchini, L. Pagano, L. Salvati, E. Di Valentino, A. Melchiorri, 1403.5732
YW, W. Xue, 1403.5817
A. Ashoorioon, K. Dimopoulos, M. M. Sheikh-Jabbari, G. Shiu, 1403.6099

Why positive n_t better fits data?

The BICEP2 side:

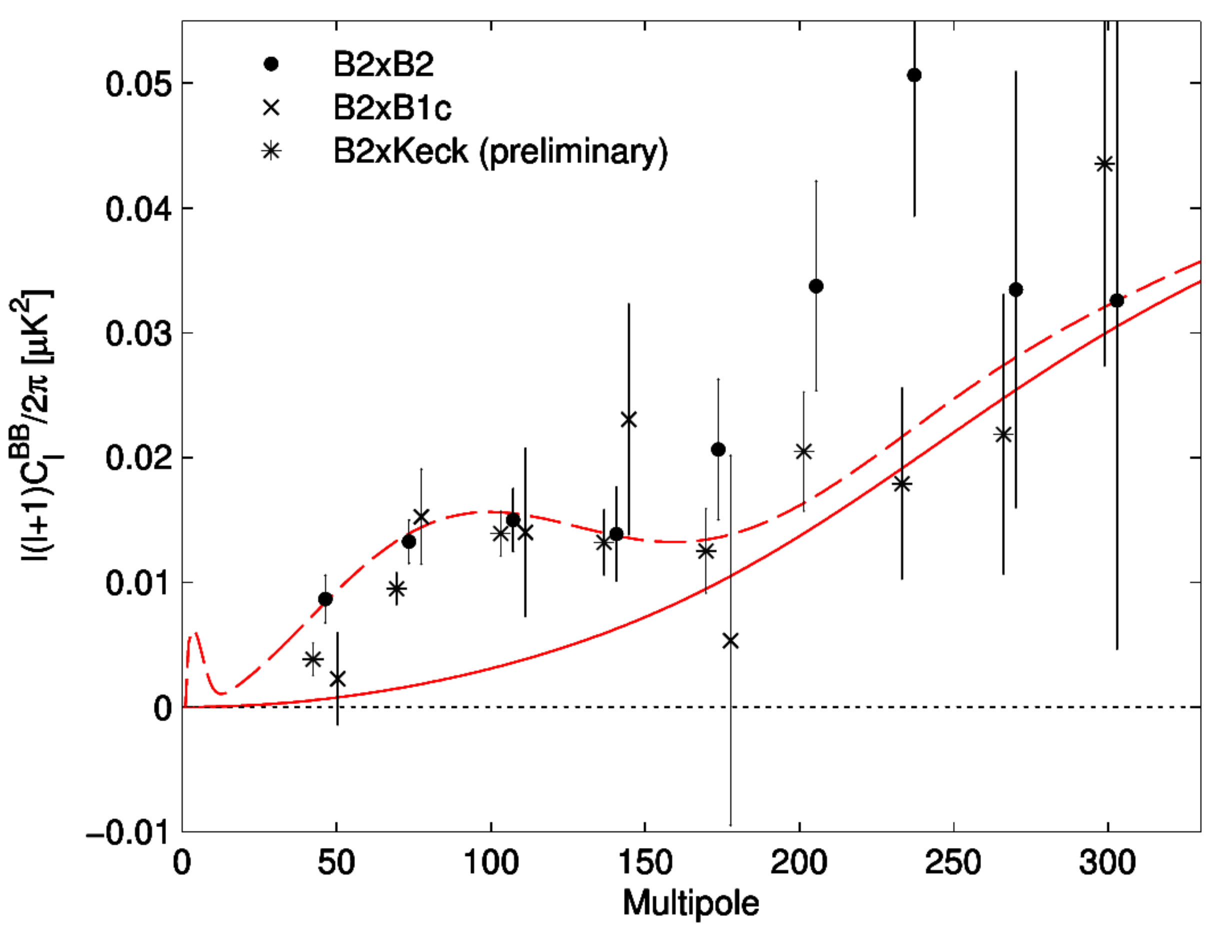
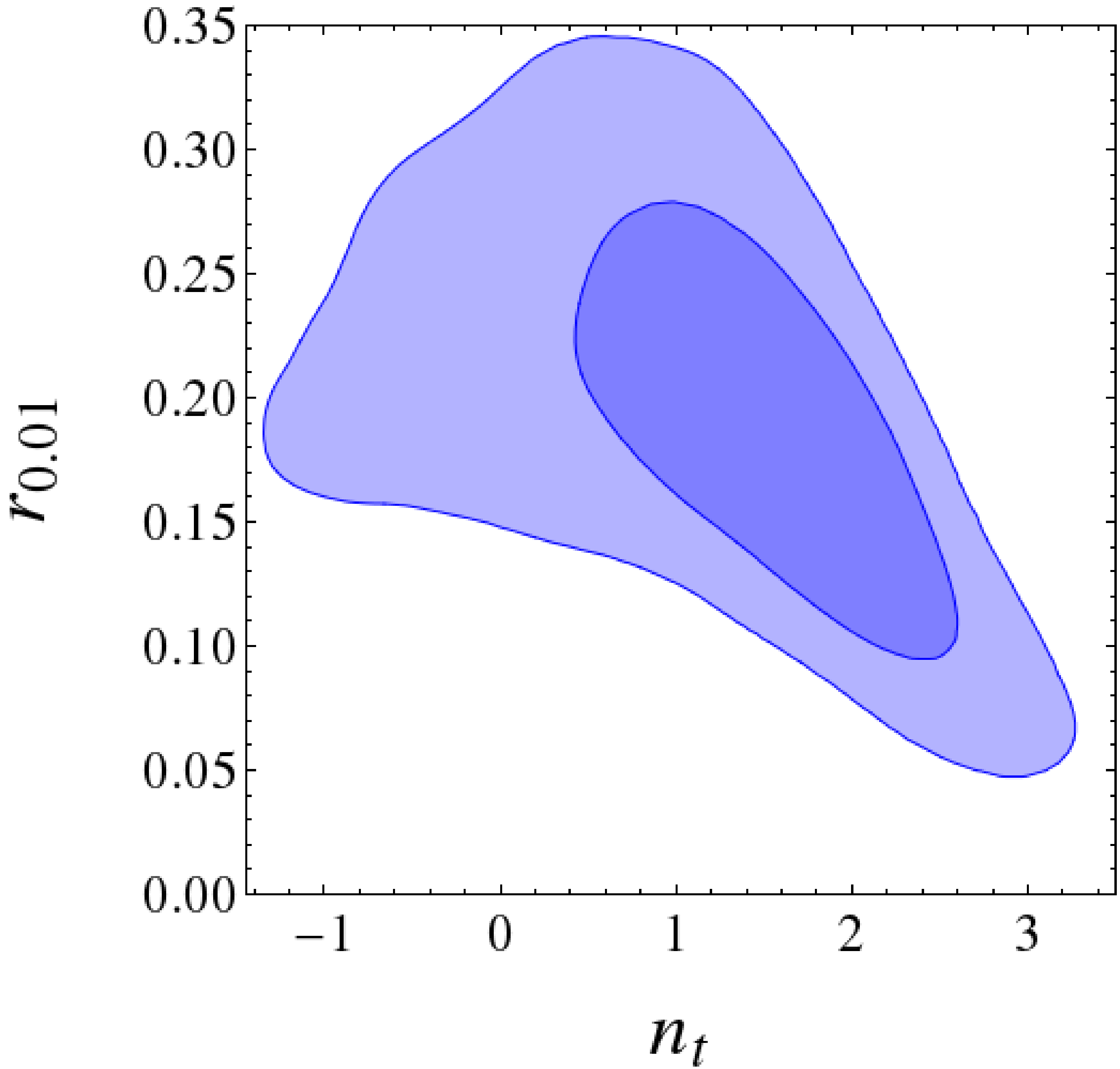


Figure: BICEP2



BICEP2 only:
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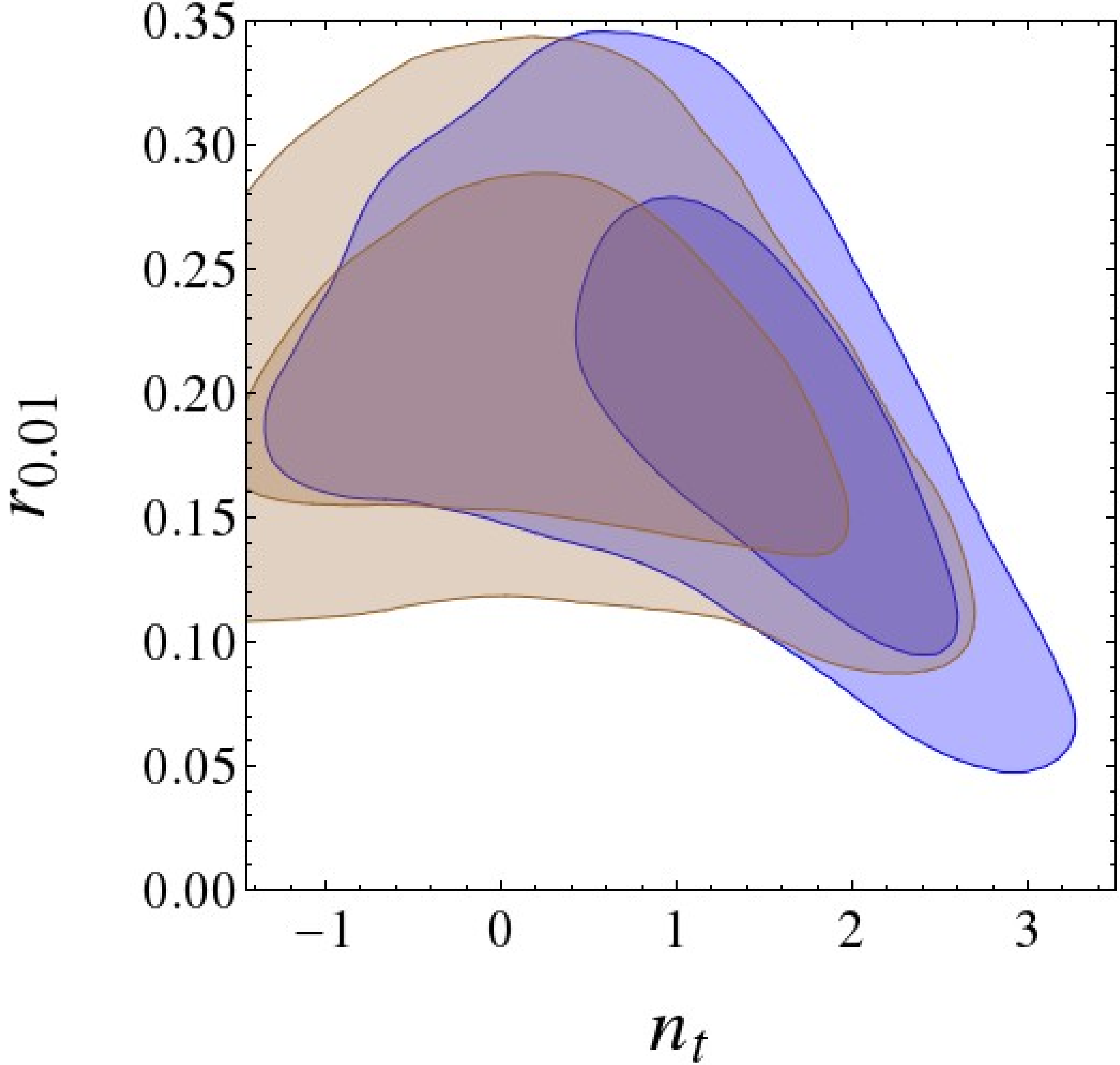


BICEP2 5bins

Why positive n_t better fits data?

The Planck side:

power deficit @ $\ell \leq 40$
@ 5%~10% @ 2.5 ~ 3σ

Another enhancement by
5% (r=0.1) ~10% (r=0.2)
would be another 2.5 ~ 3σ

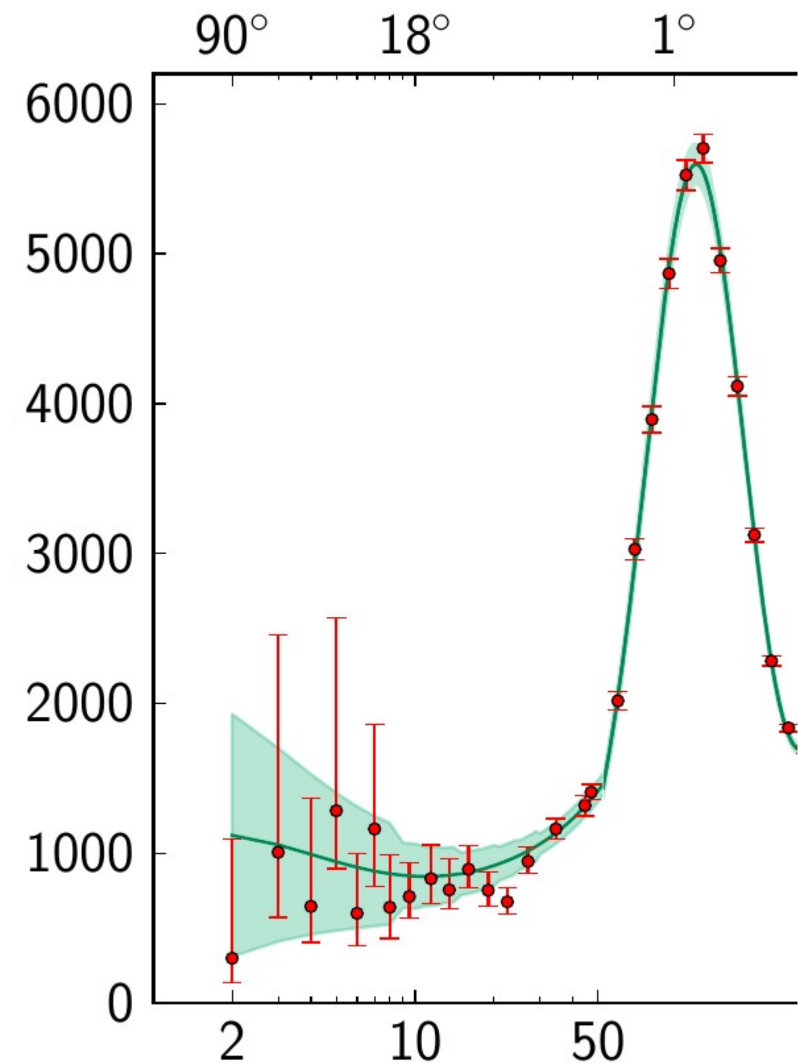
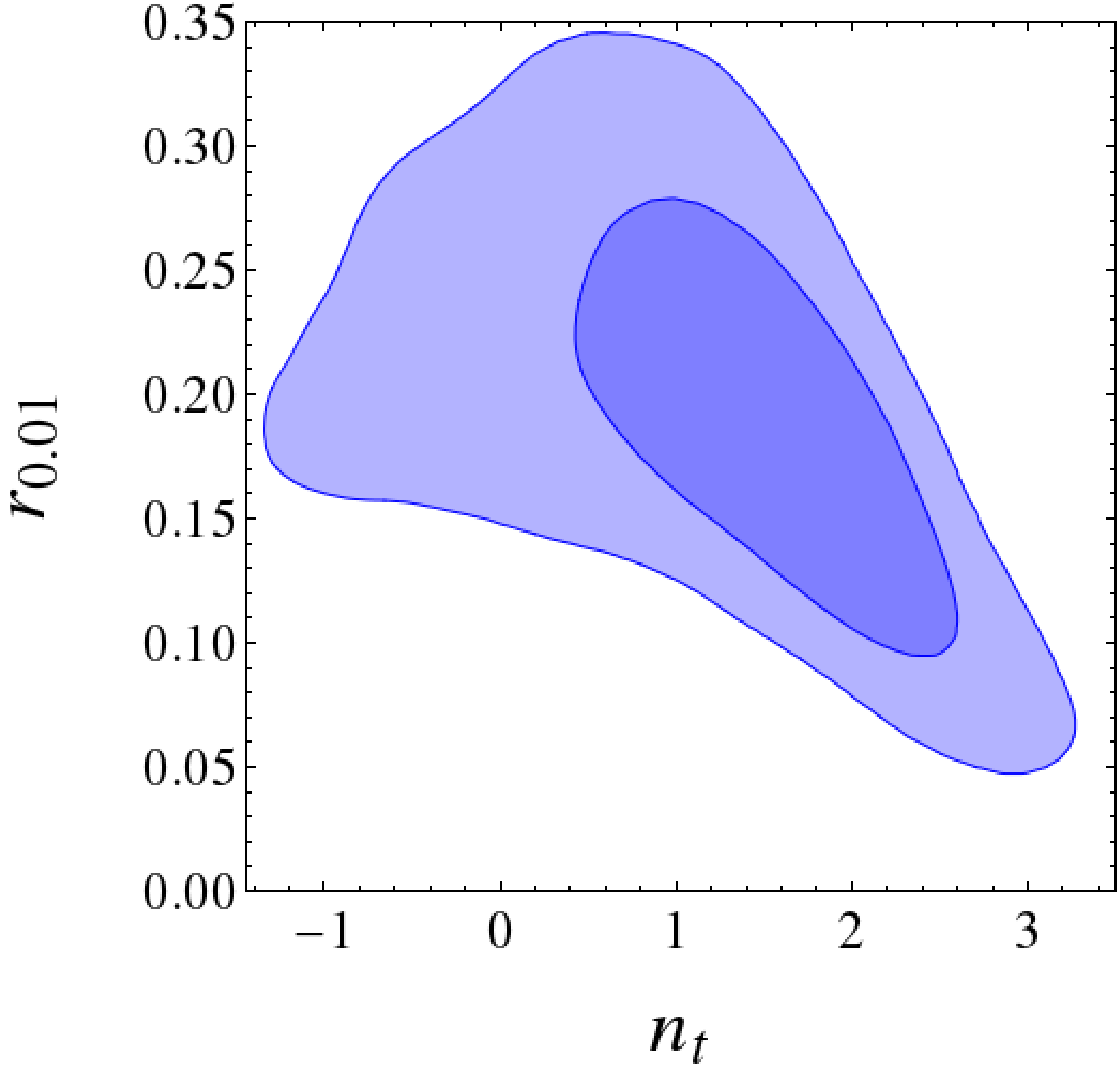
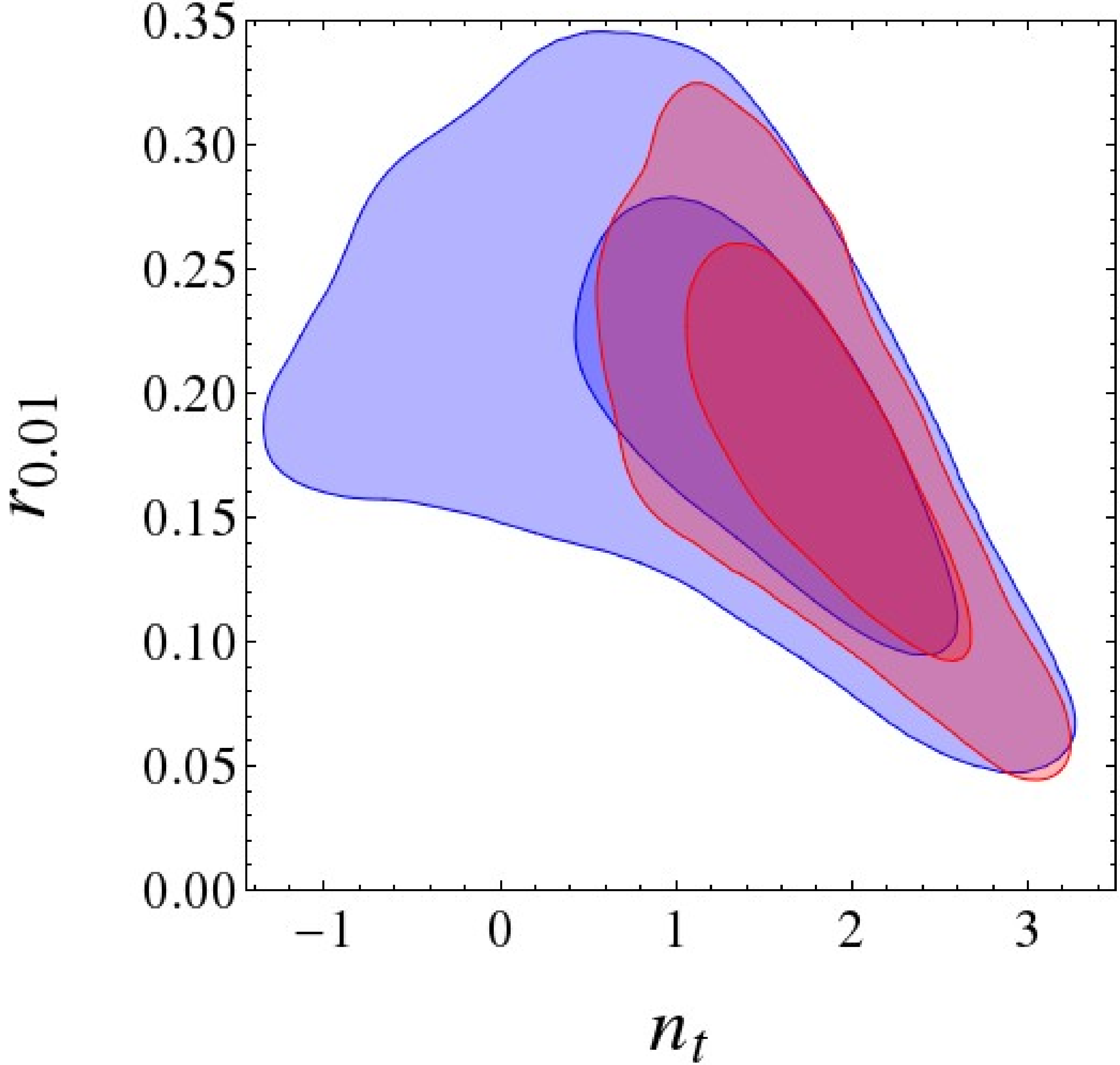


Figure: Planck XV



BICEP2 only:
blue $n_t \sim 1.5\sigma$



BICEP2 only:
blue $n_t \sim 1.5\sigma$

+Planck+WP:
blue $n_t > 3.5\sigma$

But n_t cannot be too blue

When $n_t > 2$,
primordial B-mode dominates over lensing

So the POLARBEAR signal of lensing B-mode starts to constraint n_t

(need direct detection)
(cross correlation does not help)

But n_t cannot be too blue

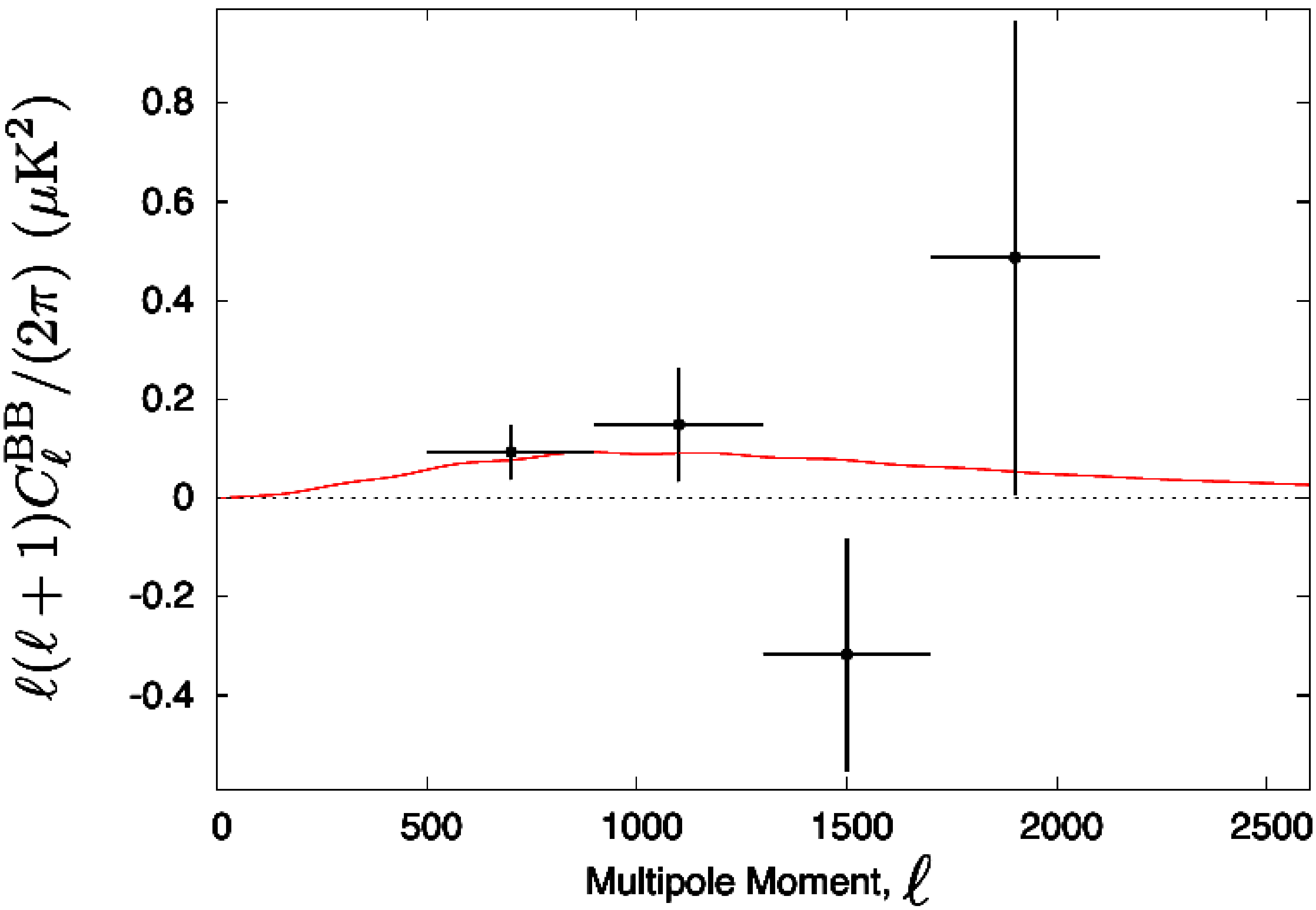
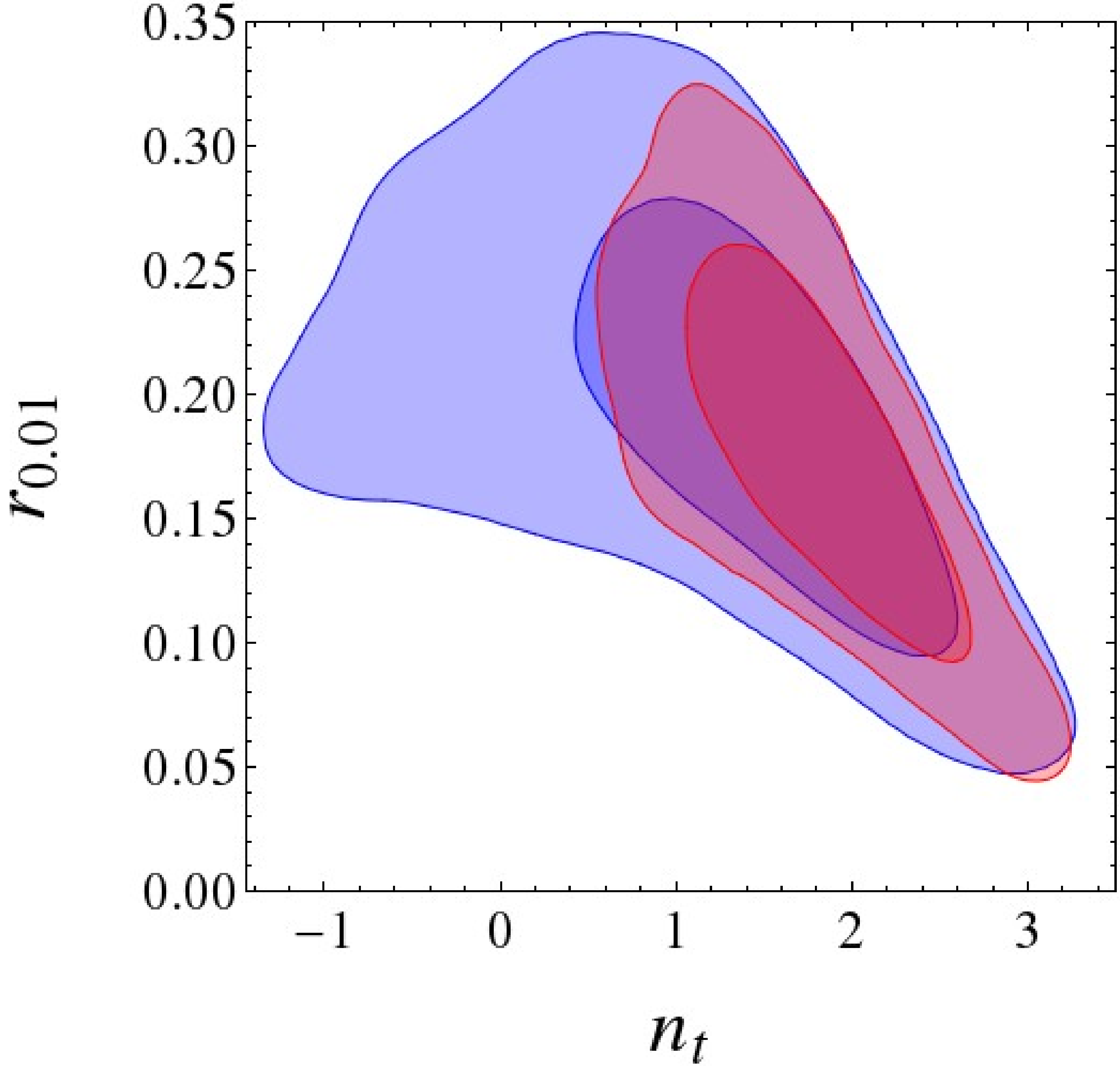
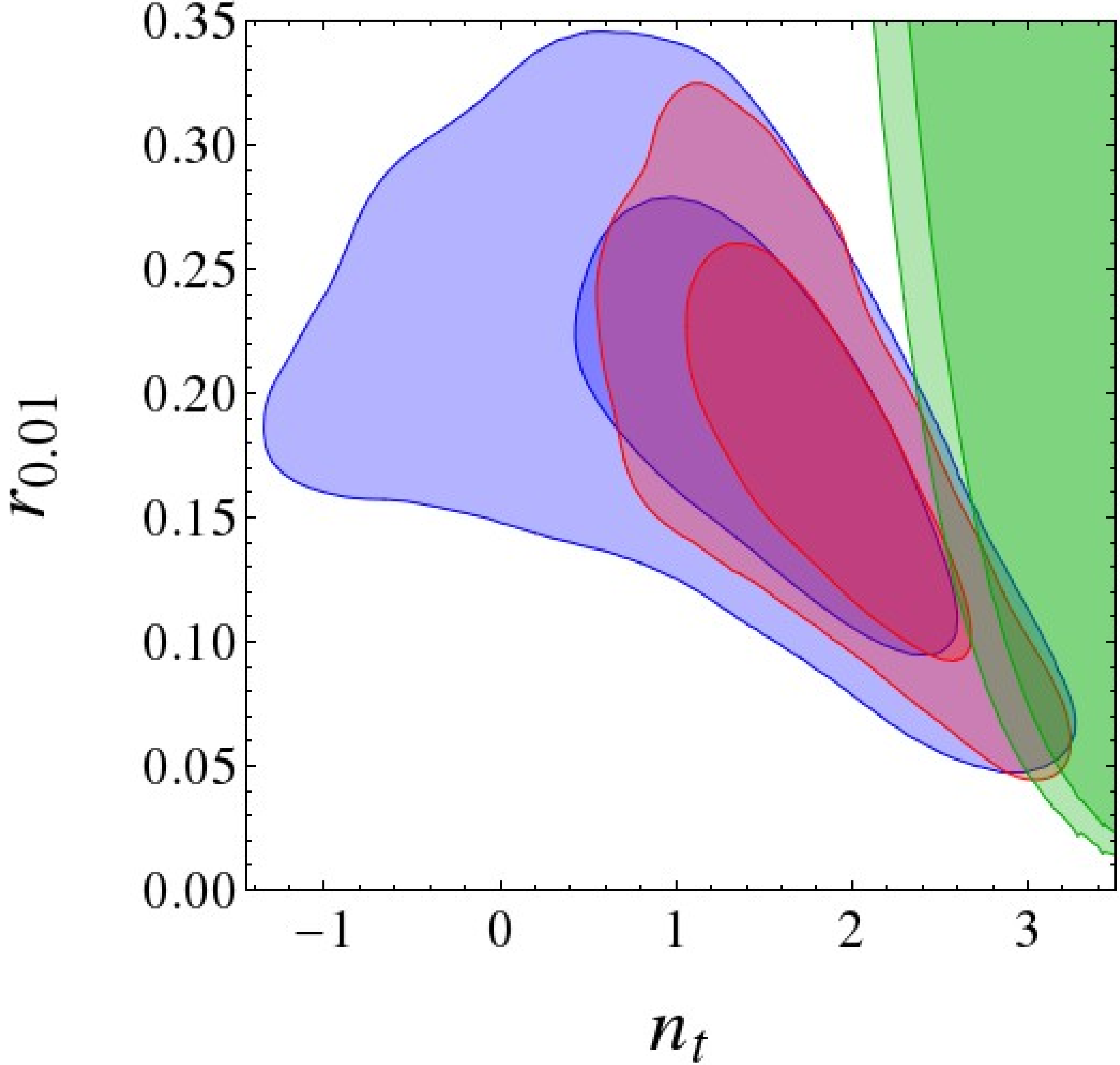


figure from POLARBEAR



BICEP2 only:
blue $n_t \sim 1.5\sigma$

+Planck+WP:
blue $n_t > 3.5\sigma$



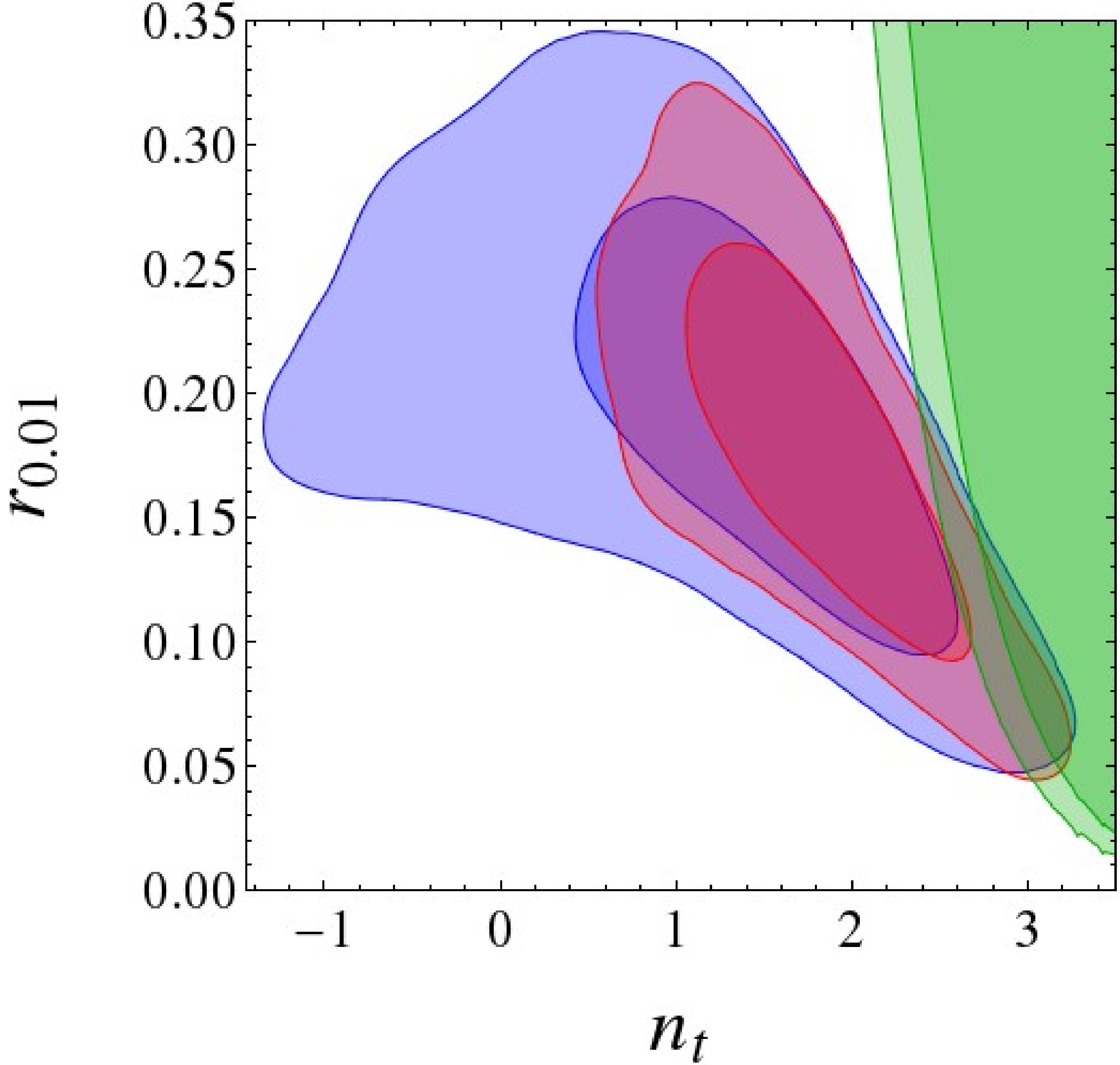
POLARBEAR constraint when $n_t > 2.5$

But n_t cannot be too blue

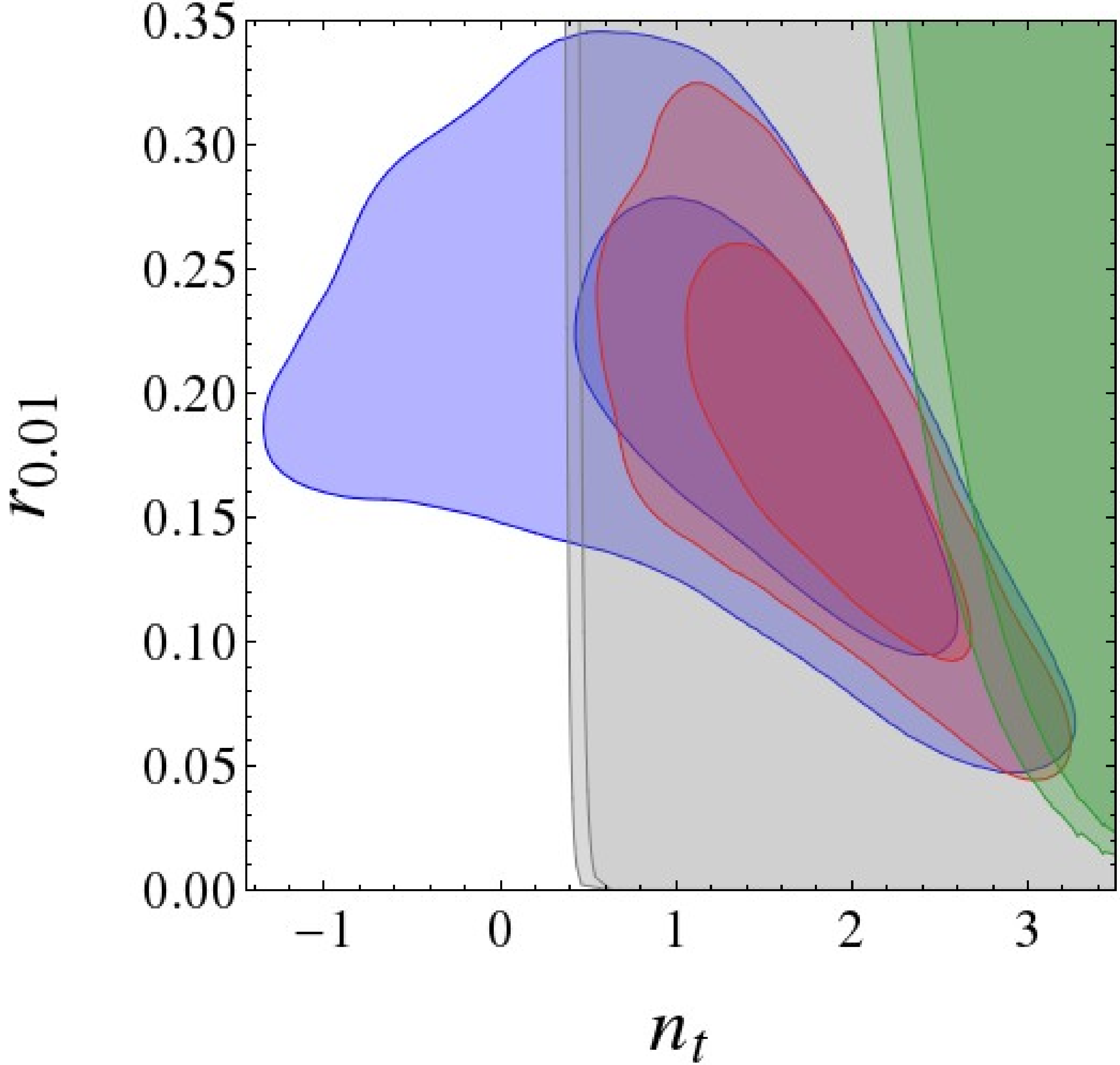
When $n_t > 2$,
primordial B-mode dominates over lensing

So the POLARBEAR detection of lensing B-mode starts to constraint n_t .

Further, if assuming zero running of n_t ,
the tensor spectrum becomes non-perturbative near the end of inflation.



POLARBEAR
constraint
when $n_t > 2.5$



Assuming constant n_t for 50~60 e-folds

Implications:

$n_t > 0$ at more than 3.5σ?

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~~$n_t > 0$ at more than 3.5σ?~~

$n_t > 0$ at more than 3.5σ
compared with the minimal model

Implications:

$n_t > 0$ at more than 3.5σ
compared with the minimal model

But there may also be
foreground, running, isocurvature, neutrinos...

Advantage of n_t:
– Higher confidence level
– Can be tested soon (Planck)

Disadvantage of n_t:
– Smaller theoretical prior (read: challenge)

Tension between BICEP2 and Planck:

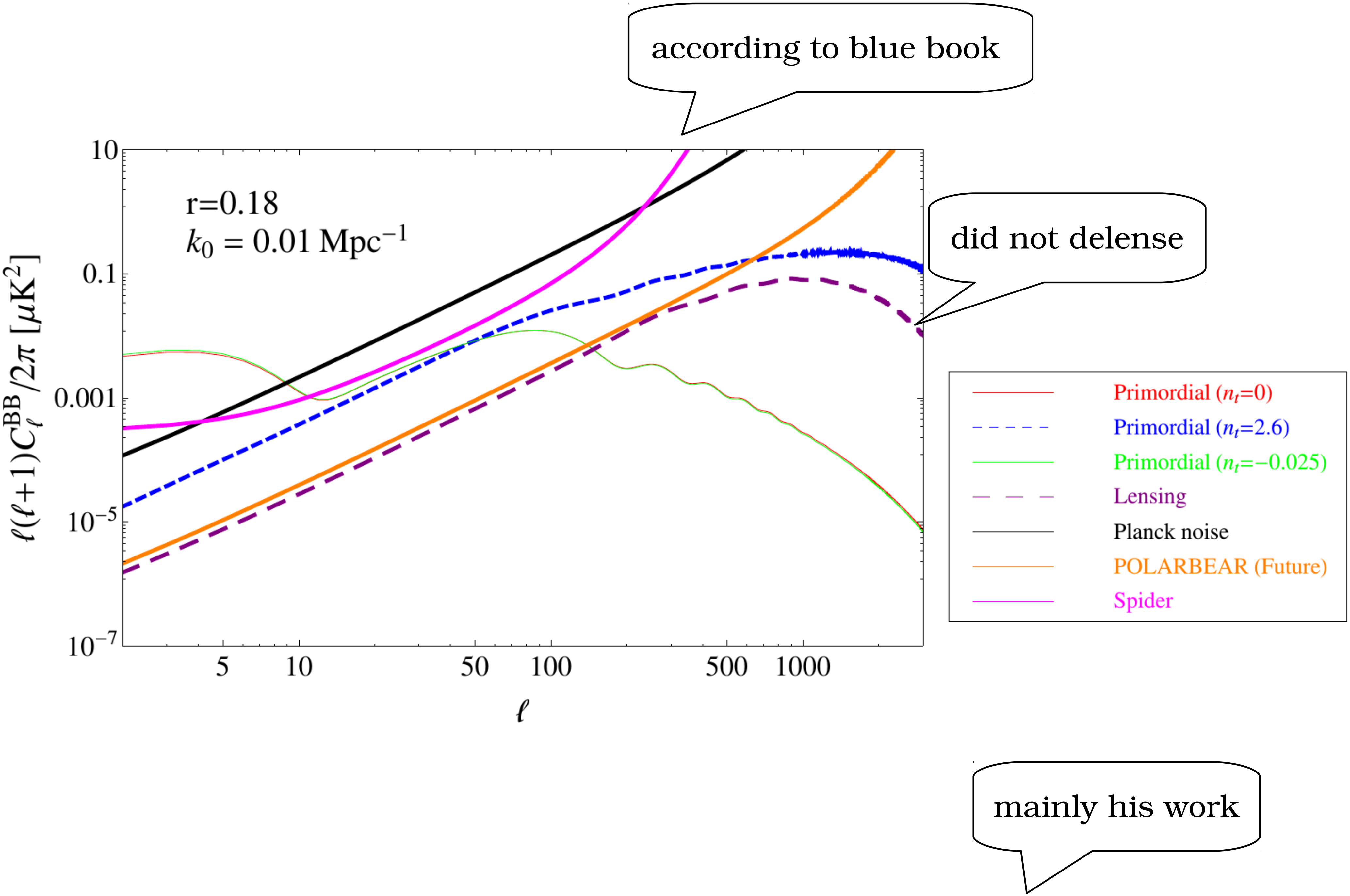
Not in tension? B. Audren, D. G. Figueroa, T. Tram, 1405.1390

Dangerous to measure tension of huge data sets by one number!

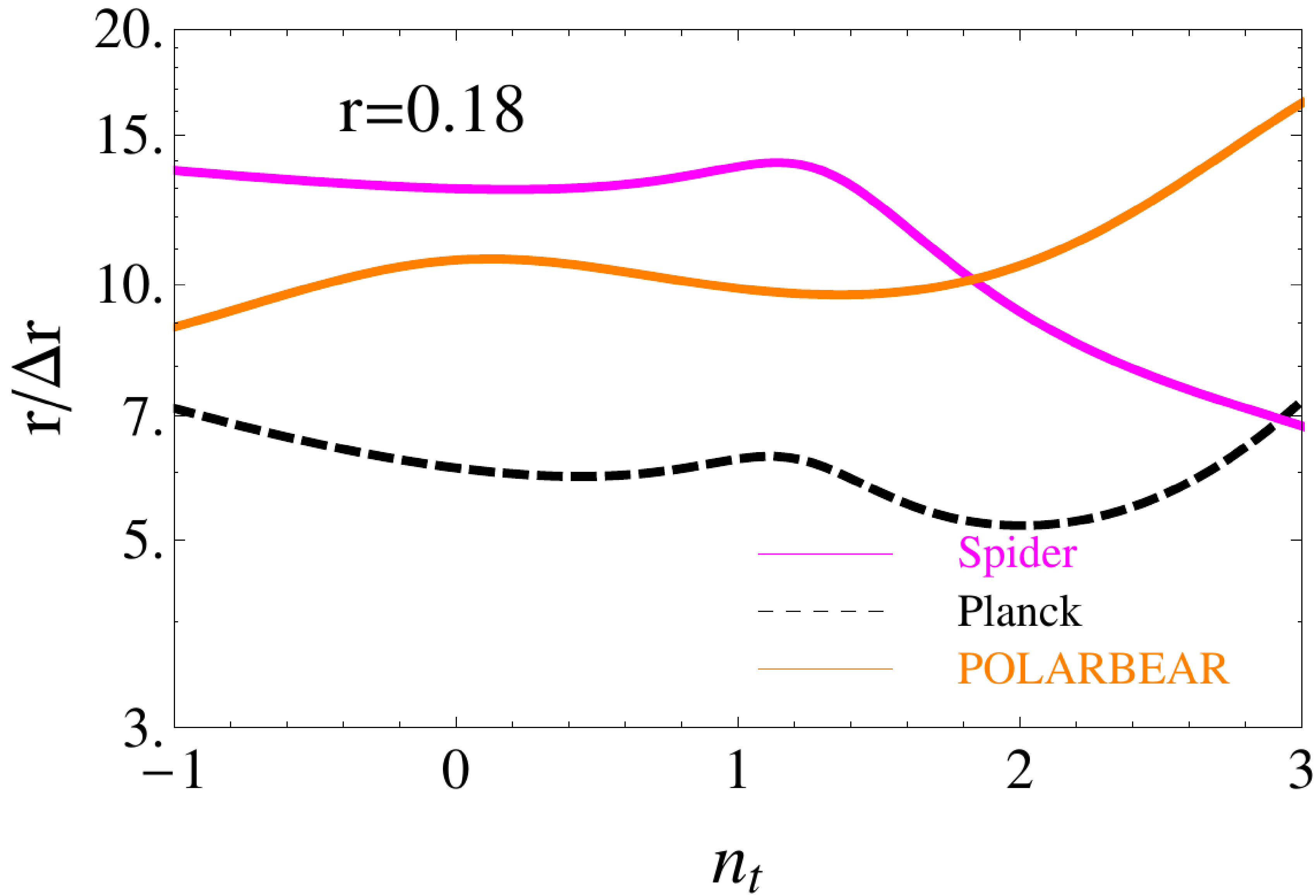
Need to define null/alternative hypothesis

n_t=0/blue n_t: Tension is at about 2~3σ

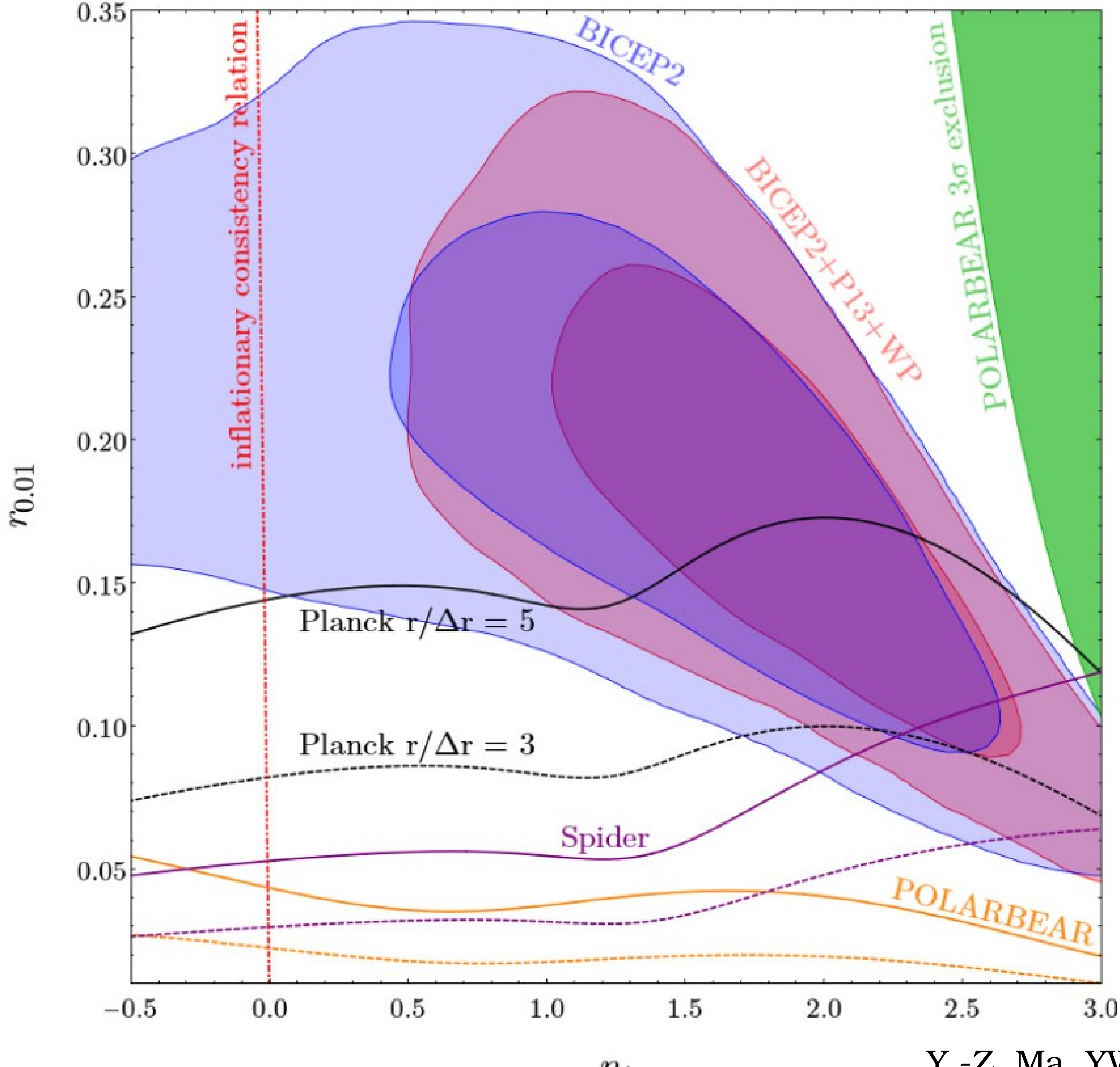
A. Ashoorioon, K. Dimopoulos, M. M. Sheikh-Jabbari, G. Shiu, 1403.6099
YW, W. Xue, 1403.5817
K. M. Smith, C. Dvorkin, L. Boyle, N. Turok, M. Halpern, G. Hinshaw, B. Gold, 1404.0373
Y.-Z. Ma, YW, 1405.????


according to blue book
did not delense
mainly his work
r=0.18
k_0 = 0.01 Mpc^{-1}
$\ell(\ell+1)C_\ell^{BB}/2\pi$ [μK^2]
10
0.1
0.001
10^{-5}
10^{-7}
5
10
50
100
500
1000
ℓ
Primordial (n_t=0)
Primordial (n_t=2.6)
Primordial (n_t=−0.025)
Lensing
Planck noise
POLARBEAR (Future)
Spider

Y.-Z. Ma, YW, 1405.????

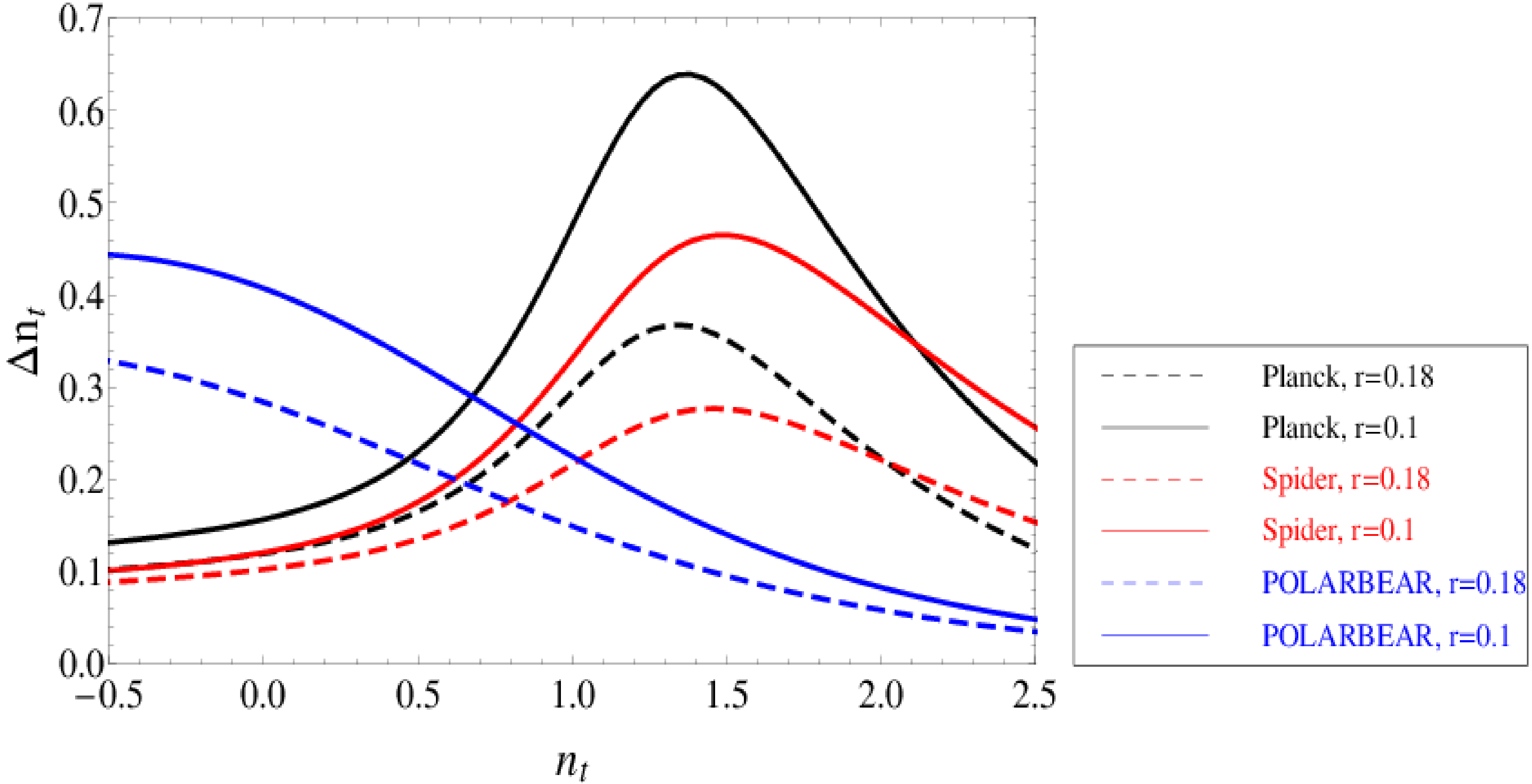


Y.-Z. Ma, YW, 1405.????



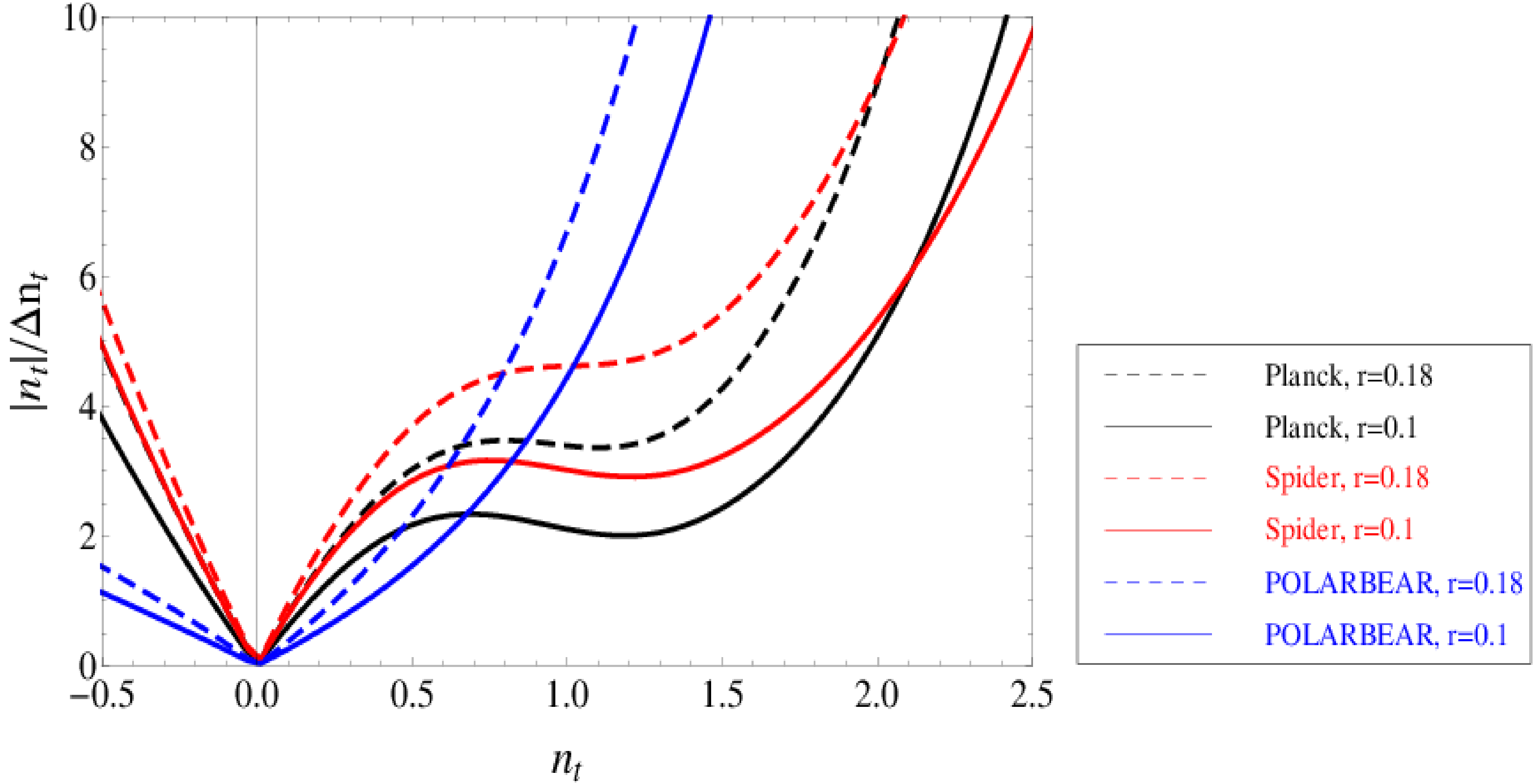
BICEP2
BICEP2+P13+WP
POLARBEAR 3σ exclusion
inflationary consistency relation
Planck r/Δr = 5
Planck r/Δr = 3
Spider
POLARBEAR
$r_{0.01}$
n_t
0.35
0.30
0.25
0.20
0.15
0.10
0.05
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Y.-Z. Ma, YW, 1405.????



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Δn_t
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
n_t
Planck, r=0.18
Planck, r=0.1
Spider, r=0.18
Spider, r=0.1
POLARBEAR, r=0.18
POLARBEAR, r=0.1

Y.-Z. Ma, YW, 1405.????



10
8
6
4
2
0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
$|n_t|/\Delta n_t$
n_t
Planck, r=0.18
Planck, r=0.1
Spider, r=0.18
Spider, r=0.1
POLARBEAR, r=0.18
POLARBEAR, r=0.1

Y.-Z. Ma, YW, 1405.????

Theories with blue n_t :

Inflation:
– Modified vacuum
– Particle production
– Modified tensor dispersion relation
– Galileons
– Solid inflation

Alternative to inflation:
– String gas cosmology (prediction)
– Matter bounce

YW, W. Xue, 1403.5817

A. Ashoorioon, K. Dimopoulos, M. M. Sheikh-Jabbari, G. Shiu, 1403.6099

Y.-F. Cai, YW, 1404.6672

S. Mukohyama, R. Namba, M. Peloso, G. Shiu, 1405.0346

Two topics concerning anomalies

– New proposals for existing anomalies

– New anomalies brought by BICEP2

Thank you!