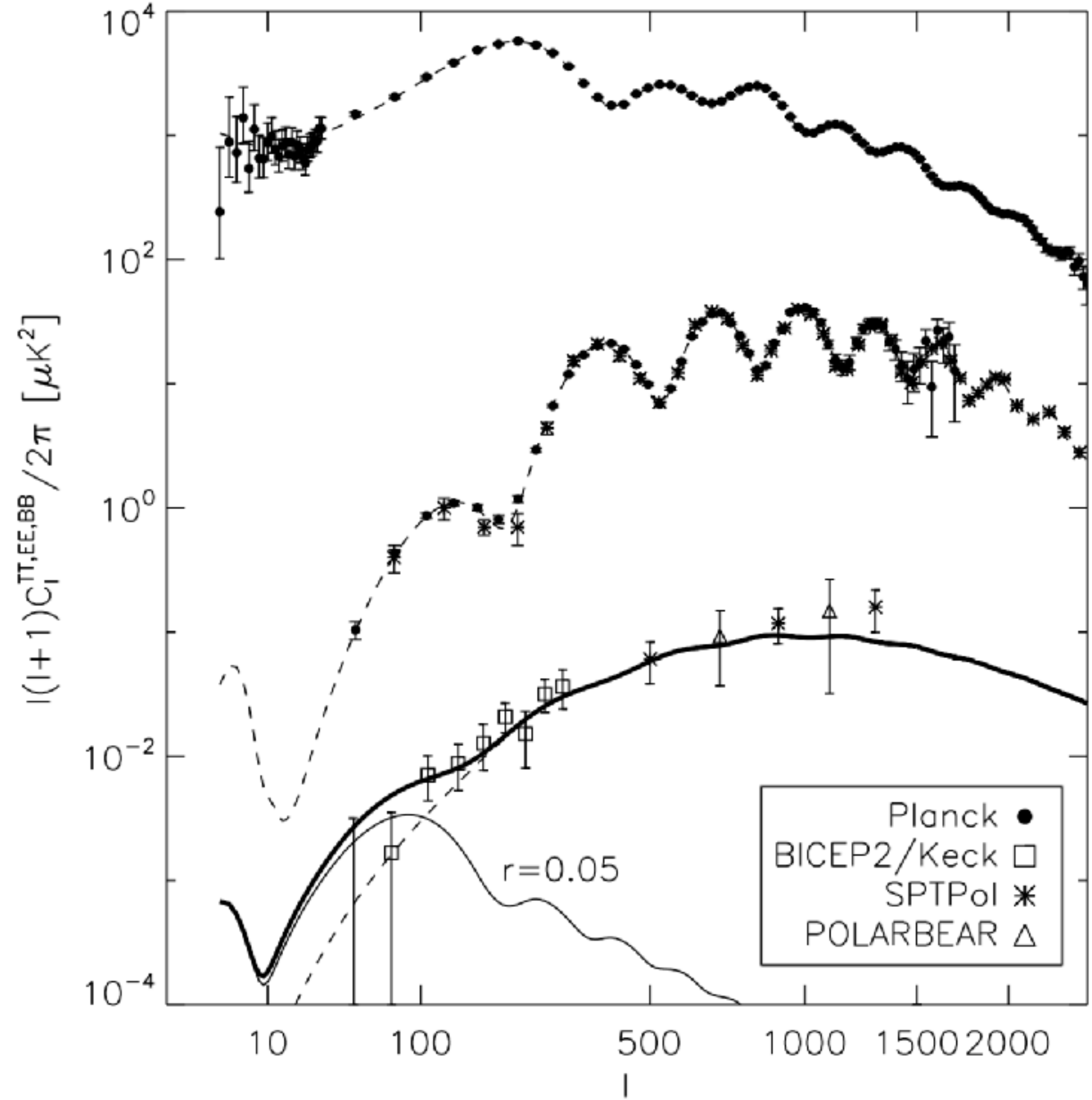
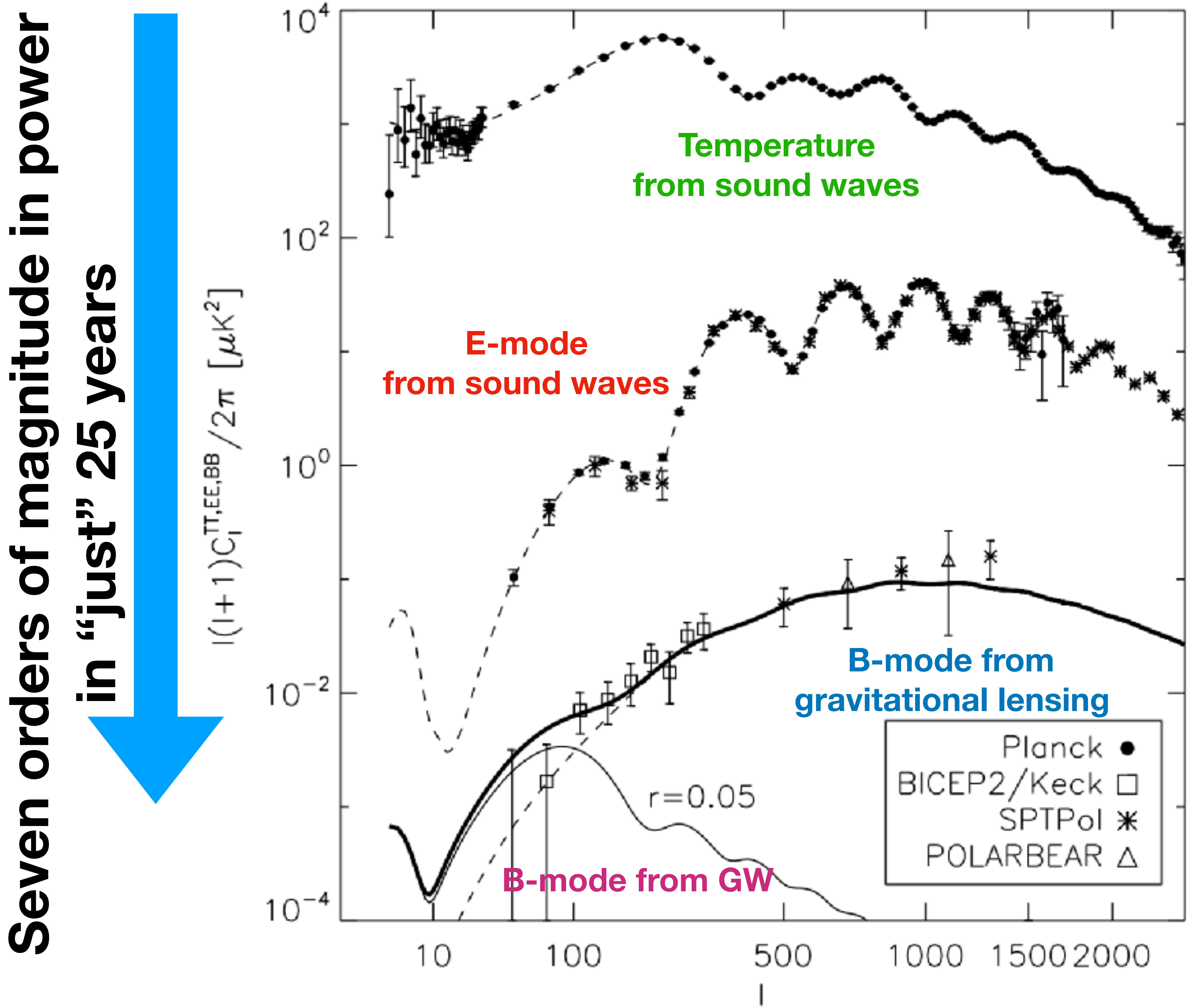
Critical Tests of Theory of the Early Universe using the Cosmic Microwave Background

Eiichiro Komatsu
[Max-Planck-Institut für Astrophysik]

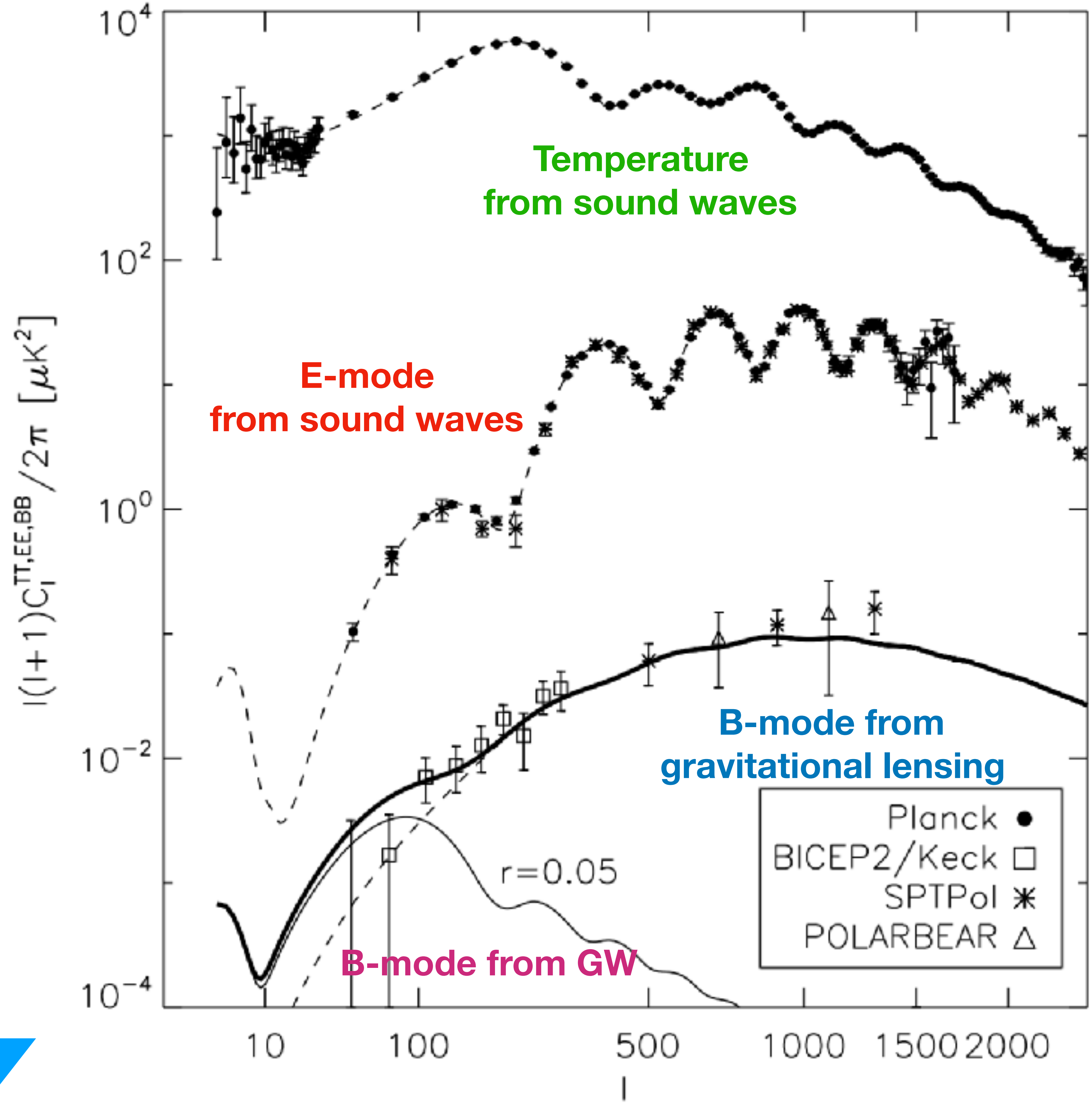
Simons Summer Workshop "*Forefronts in Cosmology and Numerical General Relativity*"
Schloss Leopoldskron, July 6, 2018



10^4
10^2
10^0
10^{-2}
10^{-4}
$l(l+1)C_l^{TT,EE,BB}/2\pi\ [\mu K^2]$
10
100
500
1000
1500
2000
l
r=0.05
Planck ●
BICEP2/Keck □
SPTPol ✳
POLARBEAR △

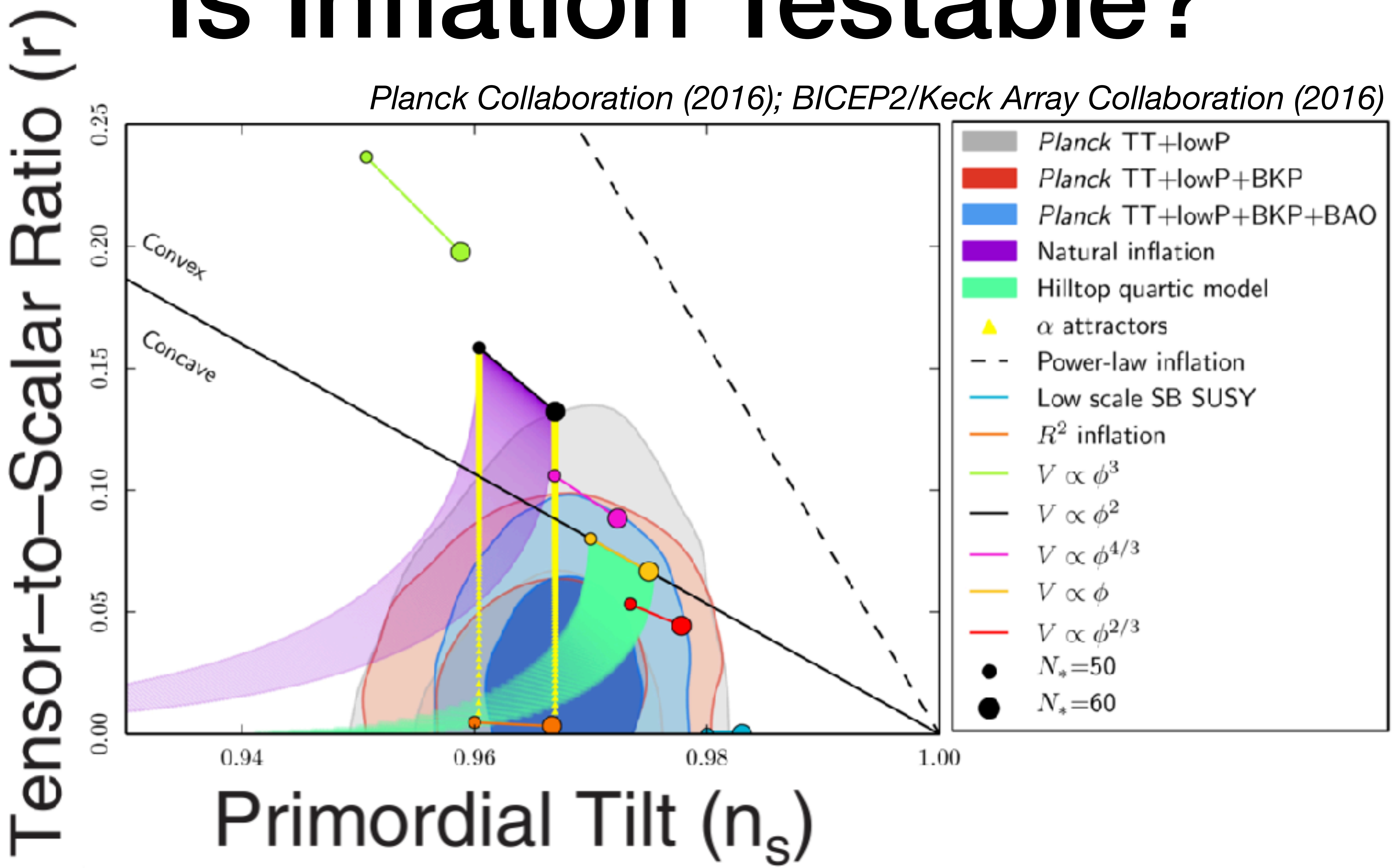

Seven orders of magnitude in power
in "just" 25 years
Temperature
from sound waves
E-mode
from sound waves
B-mode from
gravitational lensing
B-mode from GW
r=0.05
Planck
BICEP2/Keck
SPTPol
POLARBEAR
$l(l+1)C_l^{TT,EE,BB}/2\pi\ [\mu K^2]$
l

Another two orders of magnitude in the next 10–15 years



Is Inflation Testable?

Planck Collaboration (2016); BICEP2/Keck Array Collaboration (2016)



Is Inflation Testable?

No!

Is Inflation Testable?

No!

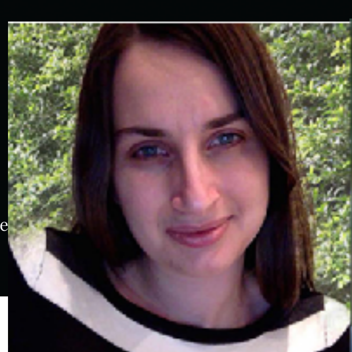
Yes!

COSMOLOGY

POP *goes the universe*

THE LATEST ASTROPHYSICAL MEASUREMENTS, COMBINED WITH THEORETICAL PROBLEMS, CAST DOUBT ON THE LONG-CHERISHED INFLATIONARY THEORY OF THE EARLY COSMOS AND SUGGEST WE NEED NEW IDEAS

By Anna Ijjas, Paul J. Steinhardt and Abraham Loeb



 ographs by The Voorhes

Observations

A Cosmic Controversy




Alan H. Guth

Victor F. Weisskopf Professor of Physic ts Institute of Technology

http://web.mit.edu/physics/people/fa

David I. Kaiser

Germeshausen Professor of the History of Science of Physics, Massachusetts Institute of Techno

http://web.mit.edu/physics/people/fa

Andrei D. Linde

Harald Trap Friis Professor of Physics, rsity

https://physics.stanford.edu/people/f

Yasunori Nomura

Professor of Physics and Director, Berkeley Center f Physics, University of California, Berkeley

http://physics.berkeley.edu/people/faculty/yasuno

Debate

- Ijjas et al. criticise inflation by saying that, if inflation produces multiverses, it is not a proper scientific model because **it makes all possible predictions with no preferences with equal probabilities.** In other words, inflation is not falsifiable

- Guth et al.'s rebuttal argues that we should focus on learning **which inflation model gave rise to our own Universe**, instead of worrying about all possible outcomes for multiverses that are outside of our Universe

These two arguments can be formulated using Bayes' formula, which helps sharpen the debate

- Ijjas et al. criticise inflation by saying that, if inflation produces multiverses, it is not a proper scientific model because **it makes all possible predictions with no preferences with equal probabilities.** In other words, inflation is not falsifiable

- Guth et al.'s rebuttal argues that we should focus on learning **which inflation model gave rise to our own Universe**, instead of worrying about all possible outcomes for multiverses that are outside of our Universe

Disclaimer

- I have spent most of my career “testing inflation”, so I am certainly biased
    - In fact, I signed Guth et al.’s letter
- I have posted my Bayesian interpretation of the debate to Facebook on May 13, 2017. I received numerous feedback, which improved my formulation. I would like to thank especially Tiberiu Teșileanu for useful discussion
    - https://www.facebook.com/eiichiro.komatsu/posts/10213084685537602

Starting Point: Bayes' Theorem

$$P(\theta|D, \text{inflation}) = \frac{P(D|\theta, \text{inflation})P(\theta|\text{inflation})}{P(D|\text{inflation})}$$

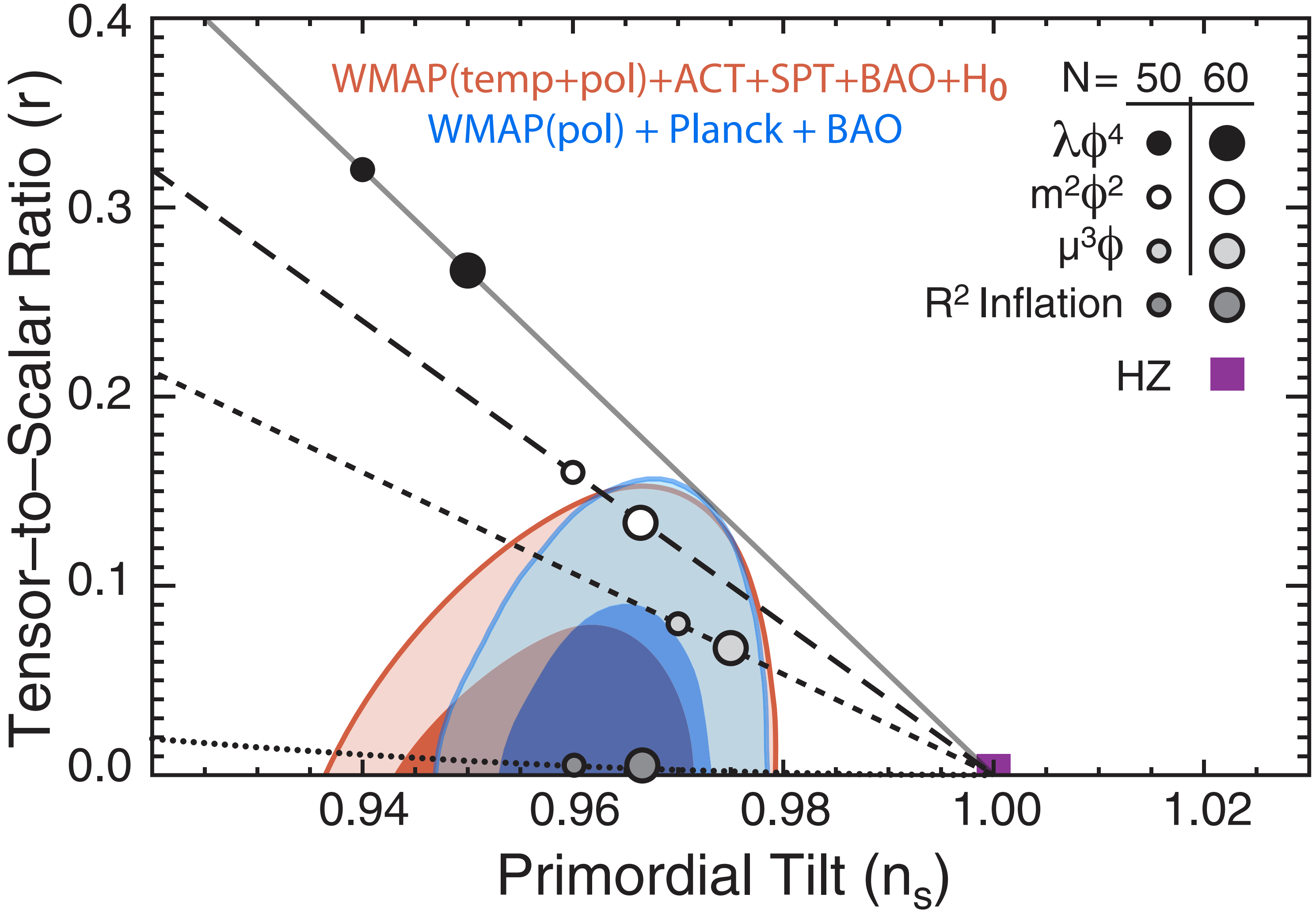
- θ: Parameters. E.g., Ω_k, A_s, n_s, r, f_{NL}, isocurvature, …
- D: Data. E.g., power spectrum/bispectrum of the CMB, galaxies, …
- All the probability densities are normalised to unity

Starting Point: Bayes' Theorem

Posterior distribution *of parameters, given data and the inflation paradigm*

$$P(\theta|D,\text{inflation}) = \frac{P(D|\theta,\text{inflation})P(\theta|\text{inflation})}{P(D|\text{inflation})}$$

E.g.,

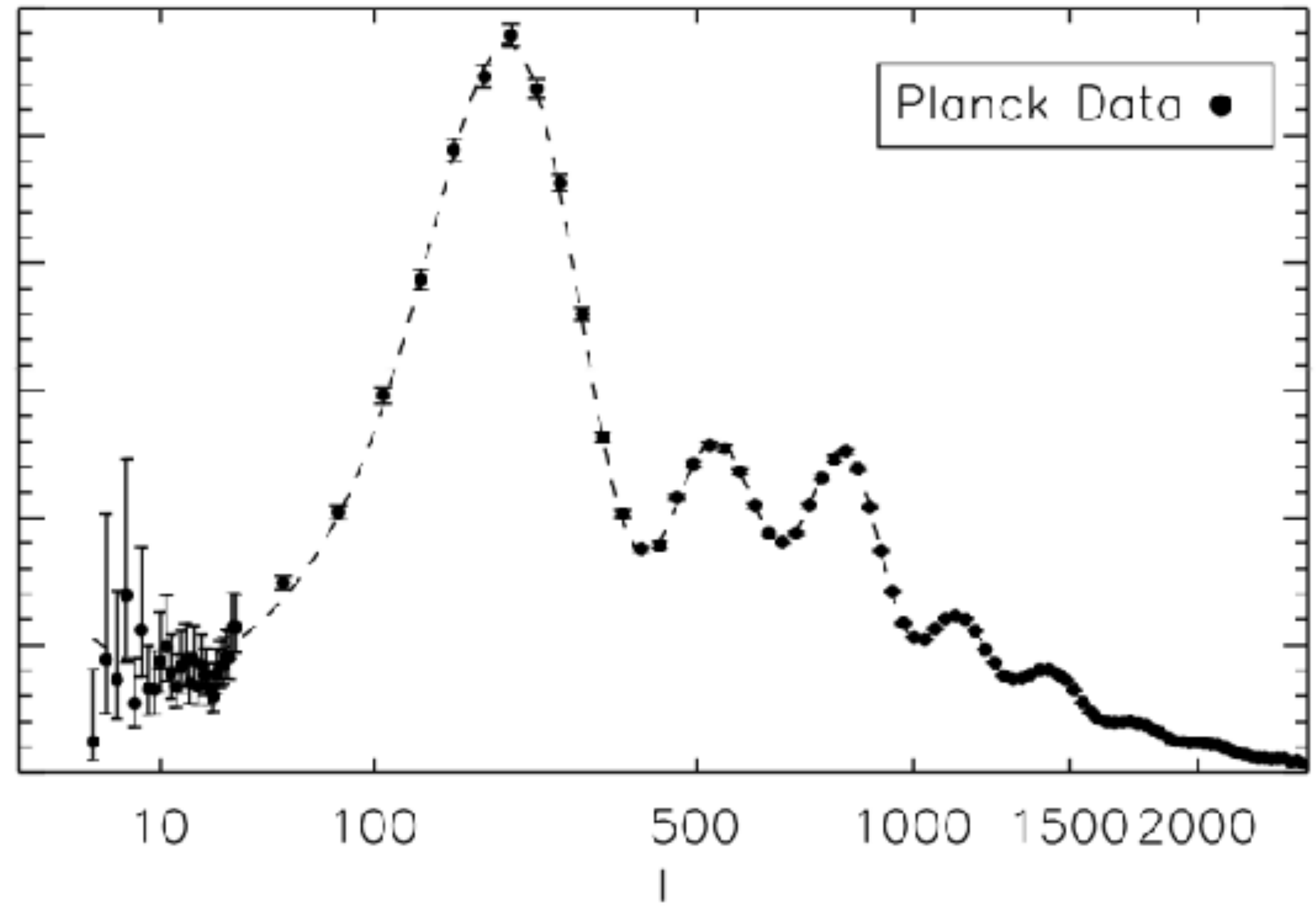


Starting Point: Bayes' Theorem

***Likelihood** of data, given parameters and the inflation paradigm*

$$P(\theta|D,\text{inflation}) = \frac{P(D|\theta,\text{inflation})P(\theta|\text{inflation})}{P(D|\text{inflation})}$$

- This is what CMB scientists (including myself) calculate by comparing the model CMB spectra with the measured ones



Starting Point: Bayes' Theorem

Prior *distribution of parameters given the inflation paradigm*

$$P(\theta|D,\mathrm{inflation}) = \frac{P(D|\theta,\mathrm{inflation})P(\theta|\mathrm{inflation})}{P(D|\mathrm{inflation})}$$

- This is the main source of the debate.

Starting Point: Bayes' Theorem

$$P(\theta|D, \text{inflation}) = \frac{P(D|\theta, \text{inflation})P(\theta|\text{inflation})}{P(D|\text{inflation})}$$

Normalisation factor to give

$$\int d^N\theta \; P(\theta|D, \text{inflation}) = 1$$

- Let's integrate both sides over the parameters

Result

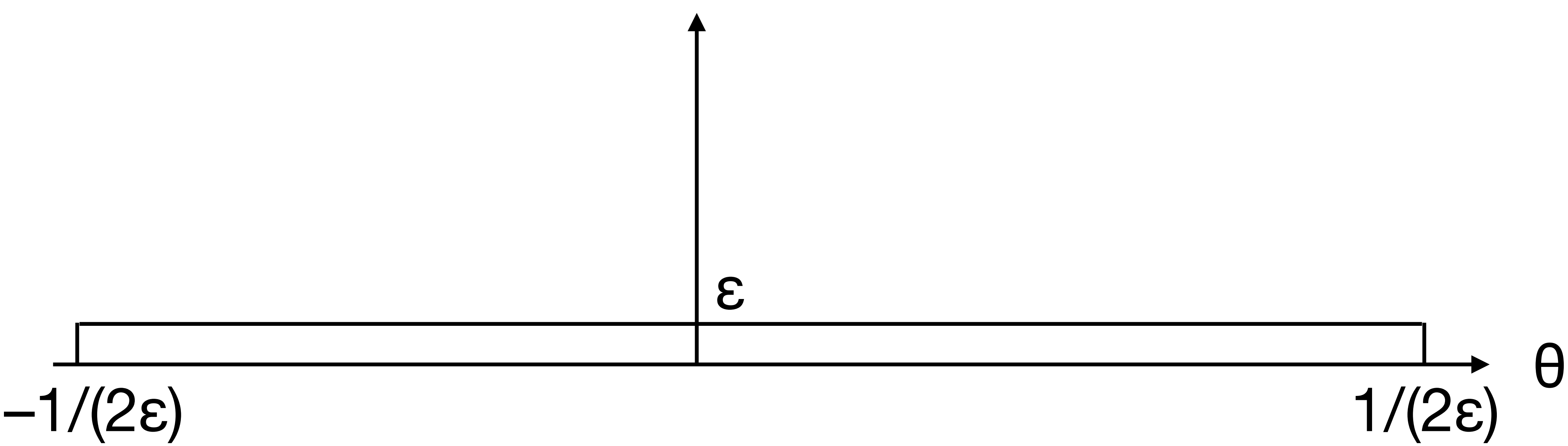
$$P(D|\text{inflation}) = \int d^N\theta \; P(D|\theta, \text{inflation}) P(\theta|\text{inflation})$$

- Left hand side (normalisation factor; a.k.a. Bayes' factor or "Evidence")
    - How likely is it to find the data we collect given the inflation paradigm?
- *The answer depends crucially on the prior knowledge, $P(\theta|\text{inflation})$!*

Ijjas et al.'s argument implies:

$$P(D|\text{inflation}) = \int d^N\theta \; P(D|\theta, \text{inflation}) \underline{P(\theta|\text{inflation})}$$

- **"Inflation makes all possible predictions for θ"**
  - Then, P(θ|inflation) would look like, for ε -> 0,



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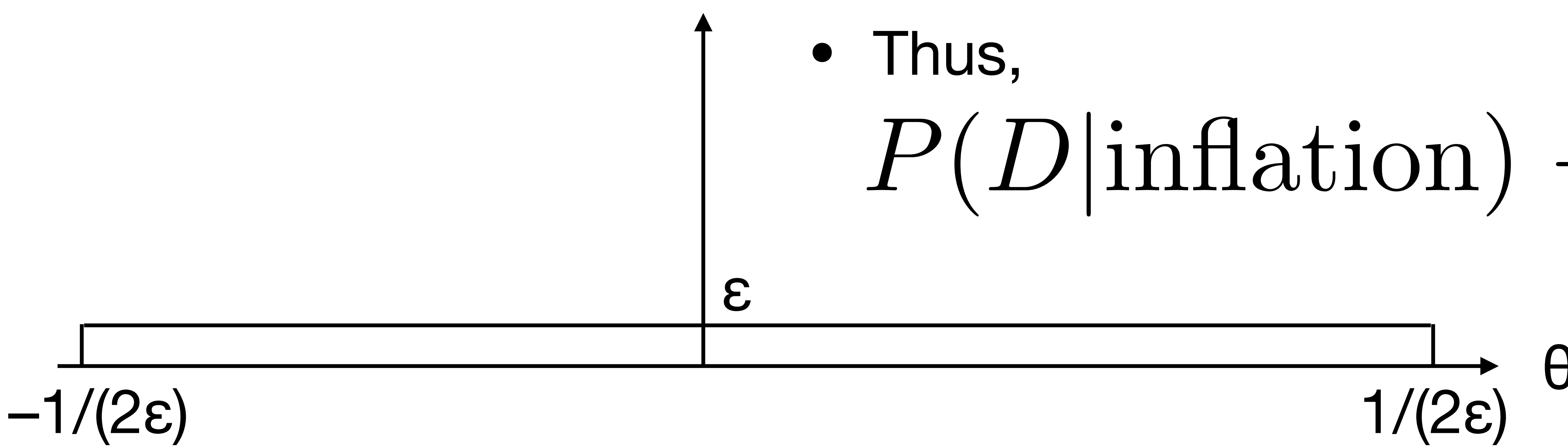


- Thus,

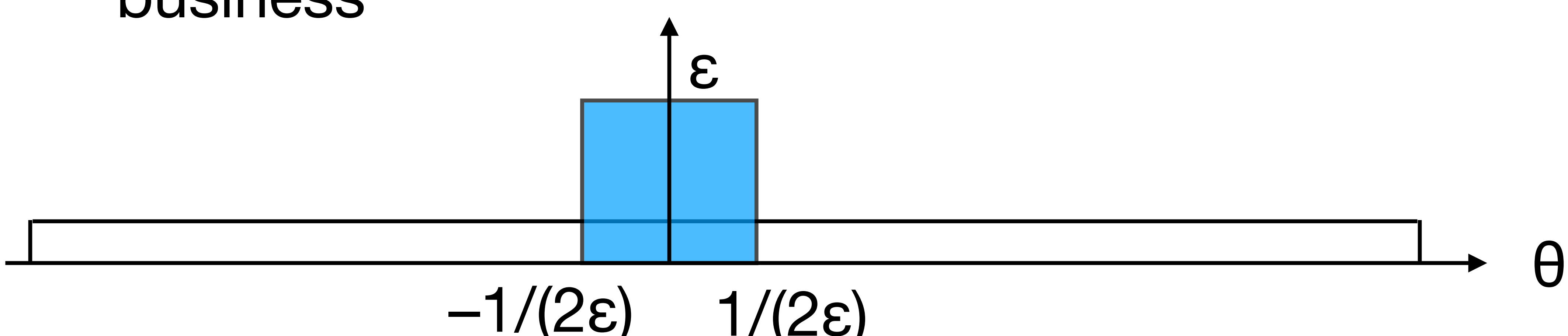
$$P(D|\text{inflation}) \to 0 \; !$$

Guth et al.'s argument implies:

$$P(D|\text{inflation}) = \int d^N\theta \; \underline{P(D|\theta, \text{inflation})} P(\theta|\text{inflation})$$

- **"We can always calculate the likelihood of data given an inflation model that led to our Universe"**

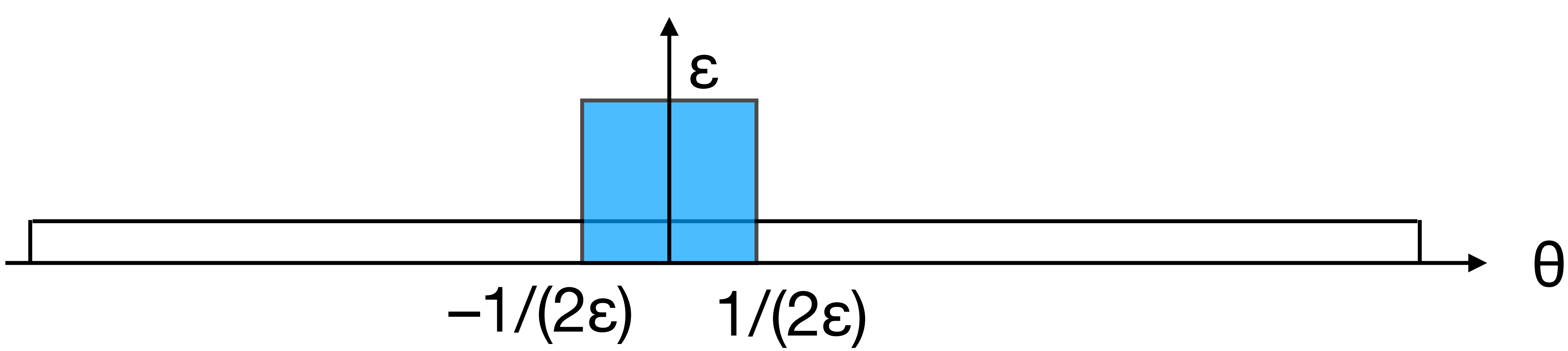
  - And, if we *assume* that ε remains finite, we are in business



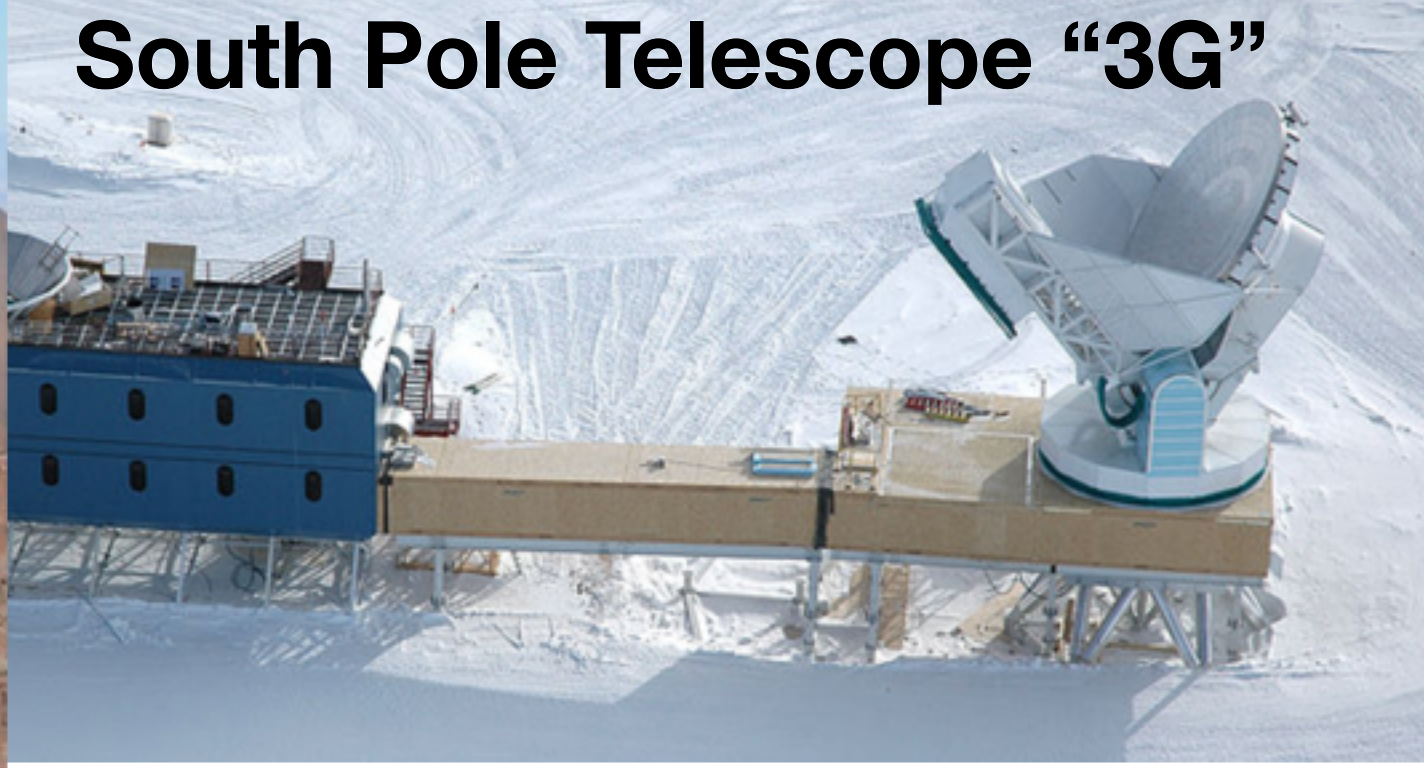
Another implication of Ijjas et al's argument

$$P(D|\text{alternative}) = \int d^N\theta \; P(D|\theta, \text{alternative}) P(\theta|\text{alternative})$$

- If we had an alternative scenario that has a narrower distribution for P(θ|alternative), then it would be favoured over inflation.
- The odds: $P(D|\text{alternative})/P(D|\text{inflation})$

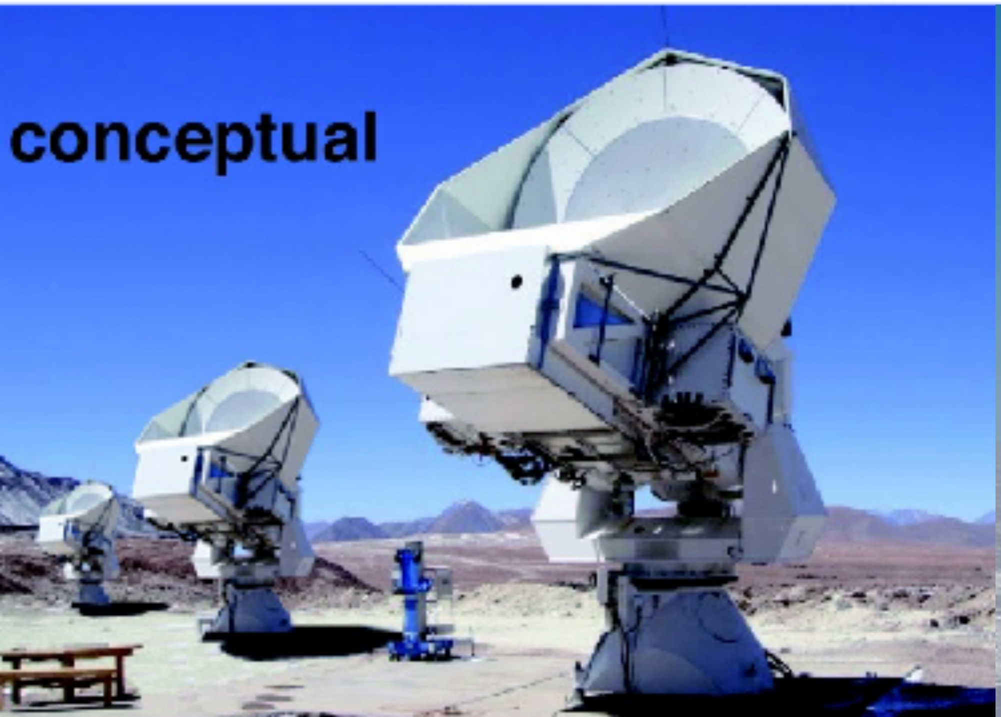


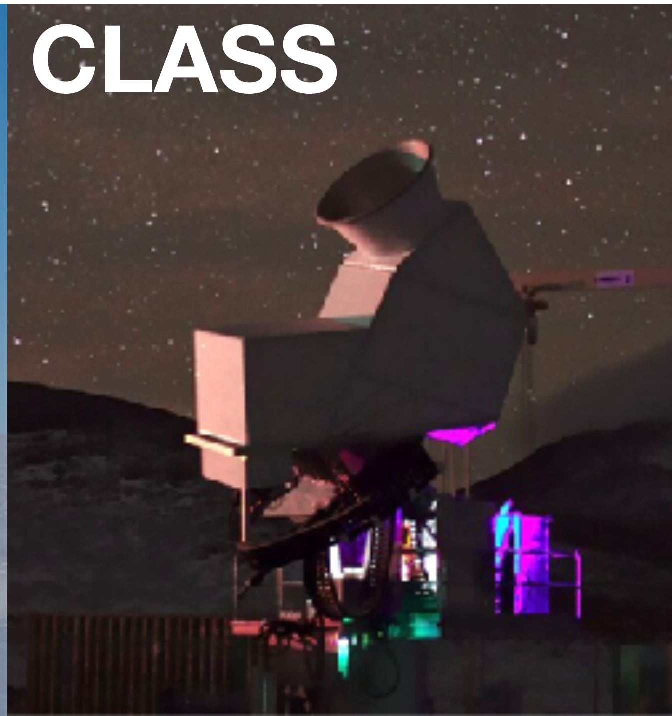
CMB Experiments: What comes next?



What comes next?

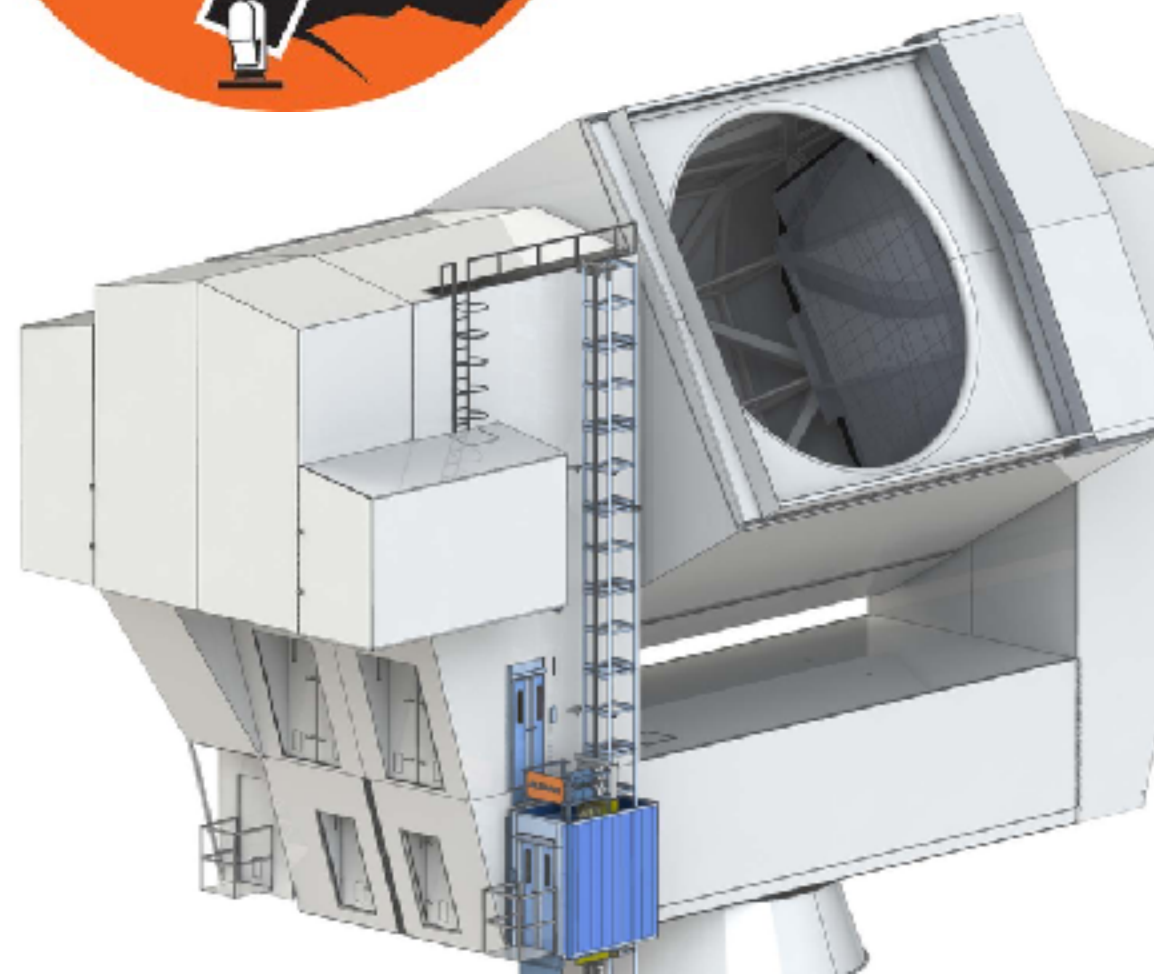
The Simons Array



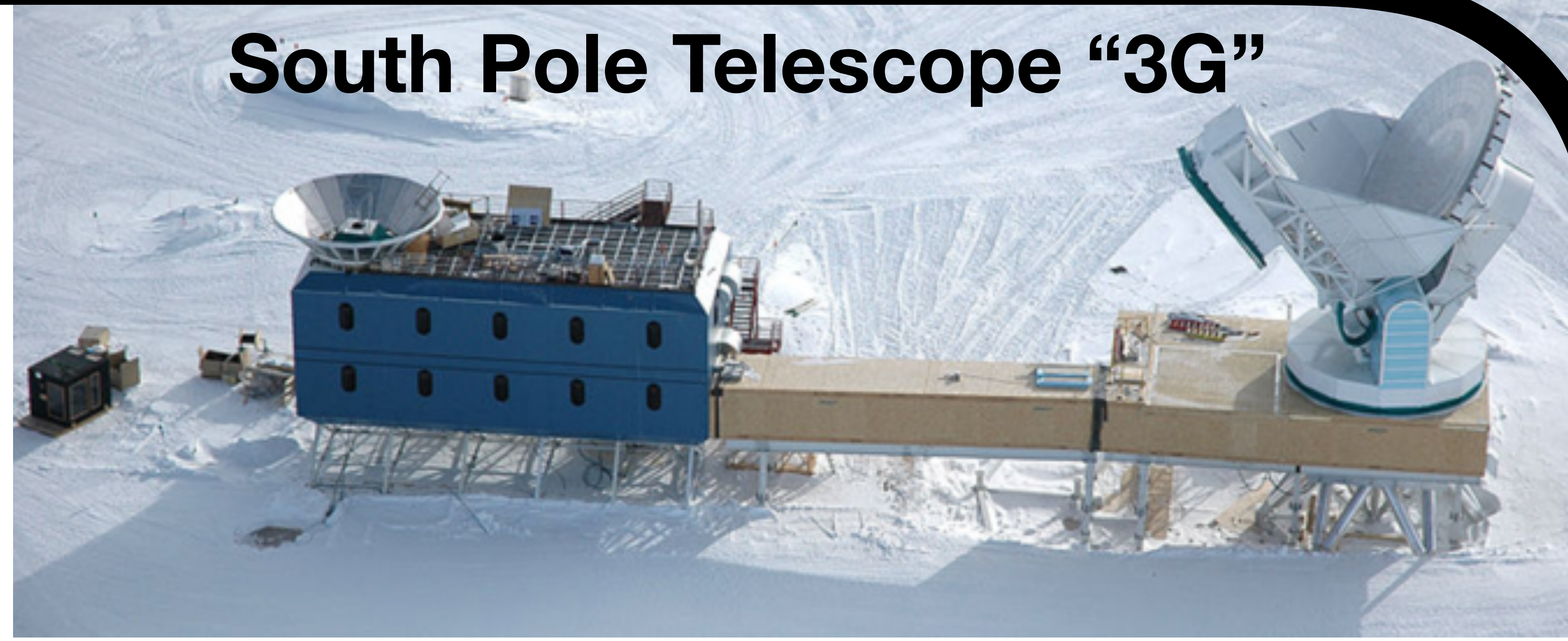


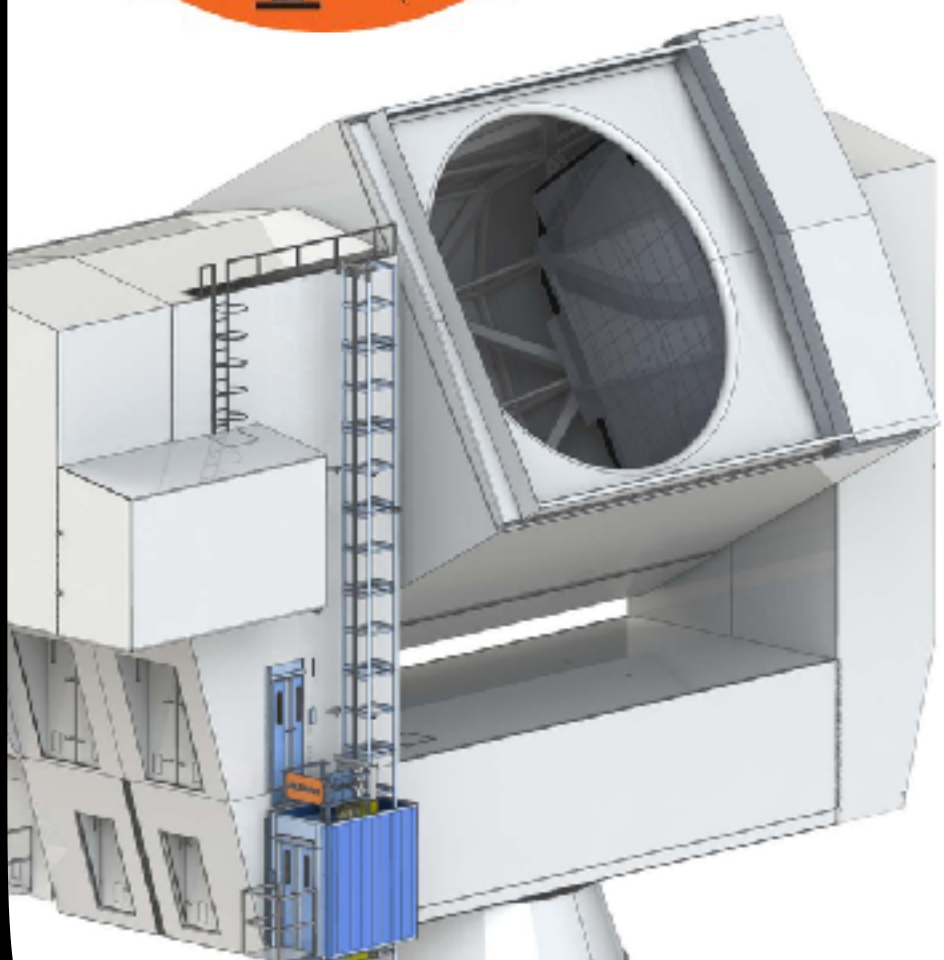
SIMONS
OBSERVATORY

The Simons Array



SIMONS OBSERVATORY





CMB-S4(?)

CMB-S4
Next Generation CMB Experiment

CMB Stages

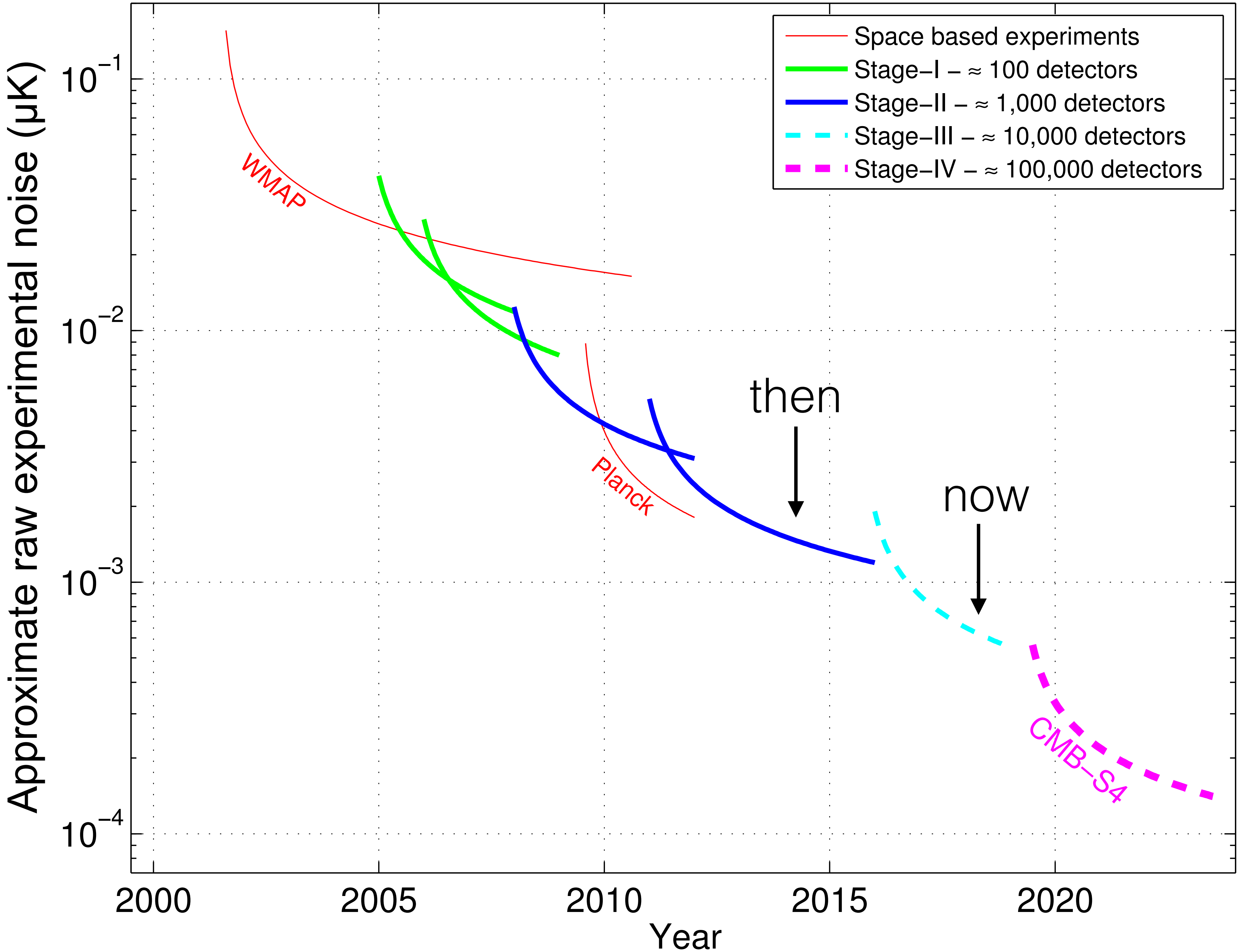


Figure by Clem Pryke for 2013 Snowmass documents

The Biggest Enemy: Polarised Dust Emission

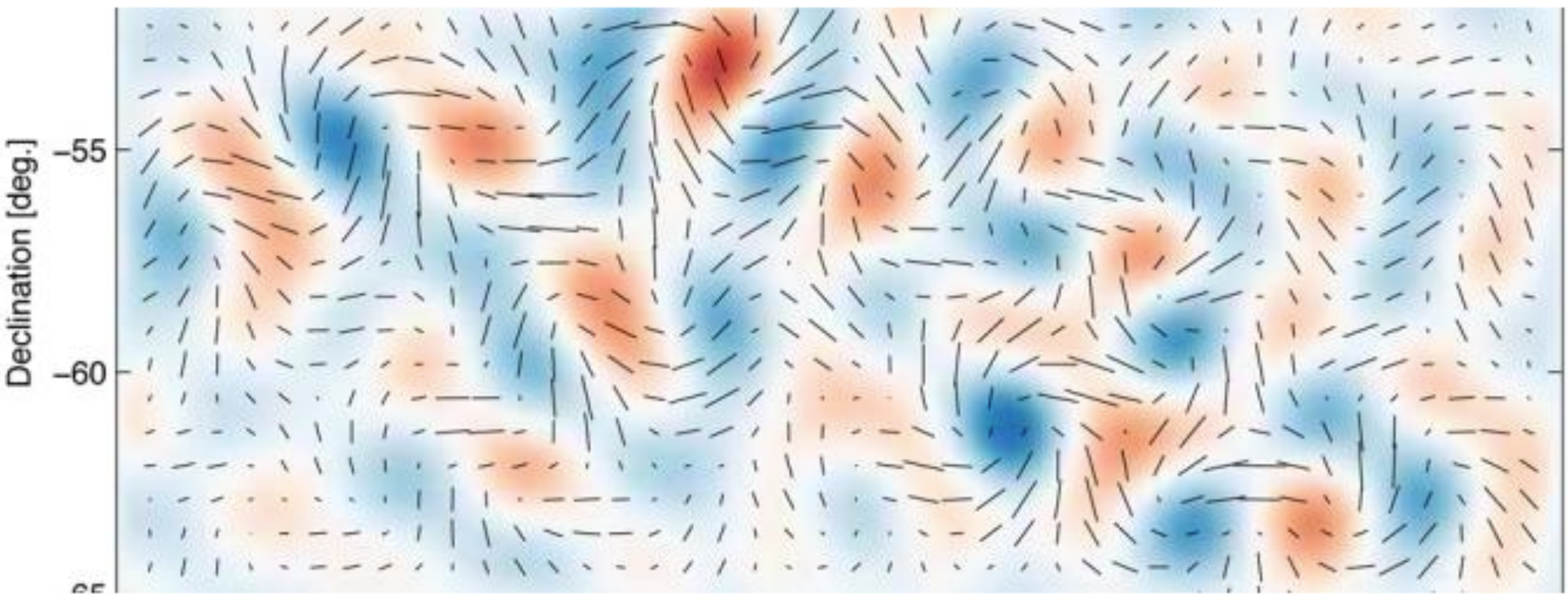
- The upcoming data will **NOT** be limited by statistics, but by systematic effects such as the Galactic contamination
- **Solution**: Observe the sky at multiple frequencies, especially at high frequencies (>300 GHz)
- This is challenging, unless we have a superb, high-altitude site with low water vapour
- CCAT-p!

March 17, 2014

BICEP2's announcement

First Direct Evidence of Cosmic Inflation

Release No.: 2014-05
For Release: Monday, March 17, 2014 - 10:45am



Cambridge, MA - Almost 14 billion years ago, the universe we inhabit burst into existence in an extraordinary event that initiated the Big Bang. In the first fleeting fraction of a second, the universe expanded exponentially, stretching far beyond the view of our best telescopes. All this, of course, was just theory.

SPACE & COSMOS

The New York Times

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

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17 March 2014 Last updated at 14:46 GMT

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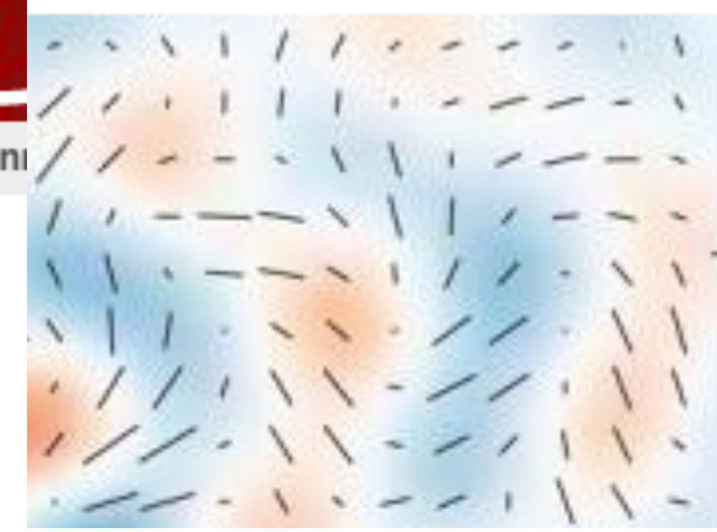

Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News

Cambridge, MA - Almost 14 billic
that initiated the Big Bang. In the
far beyond the view of our best tel

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Süddeutsche.de als Startseite einrichten

Hir

17. März 2014, 17:34 Gravitationswellen

Signale aus der Geburtsstunde des Universums

Von Patrick Illinger

January 30, 2015

Joint Analysis of BICEP2 data and Planck data

SCIENCE

The New York Times

Speck of Interstellar Dust Obscures Glimpse of Big Bang

By DENNIS OVERBYE JAN. 30, 2015

BBC

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30 January 2015 Last updated at 20:54 GMT

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Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

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Home Wissen Kosmologie - Urknall-Forscher gestehen Irrtum ein

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1. Februar 2015, 22:19 Kosmologie

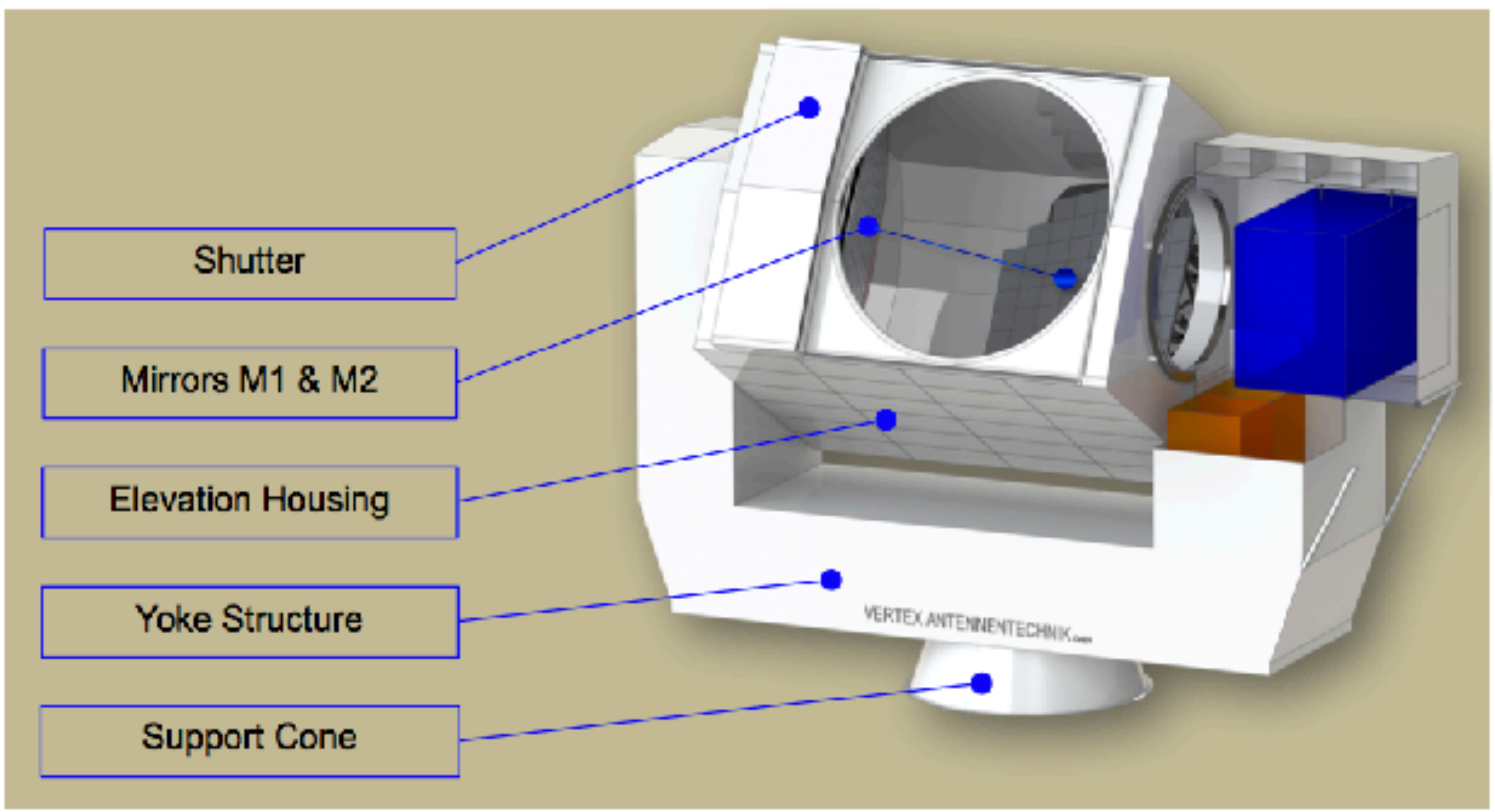
Urknall-Forscher gestehen Irrtum ein

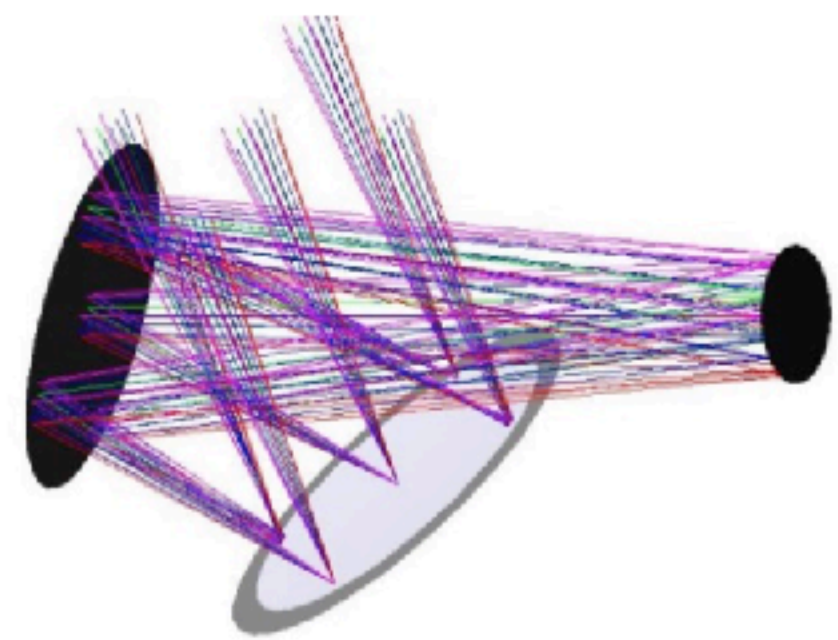
Von Marlene Weiß

Frank Bertoldi's slide from the Florence meeting

What is CCAT-p?

CCAT-prime is a high surface accuracy / throughput 6 m submm (0.3-3mm) telescope





Cornell U. + German consortium + Canadian consortium + …

Frank Bertoldi's slide from the Florence meeting

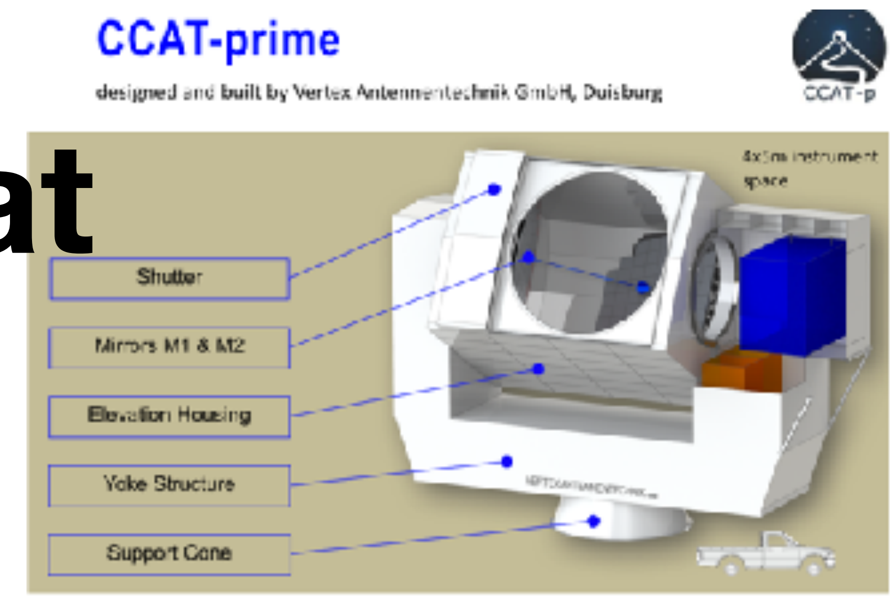
Where is CCAT-p?

Cerro Chajnantor at 5600 m w/ TAO

A Game Changer

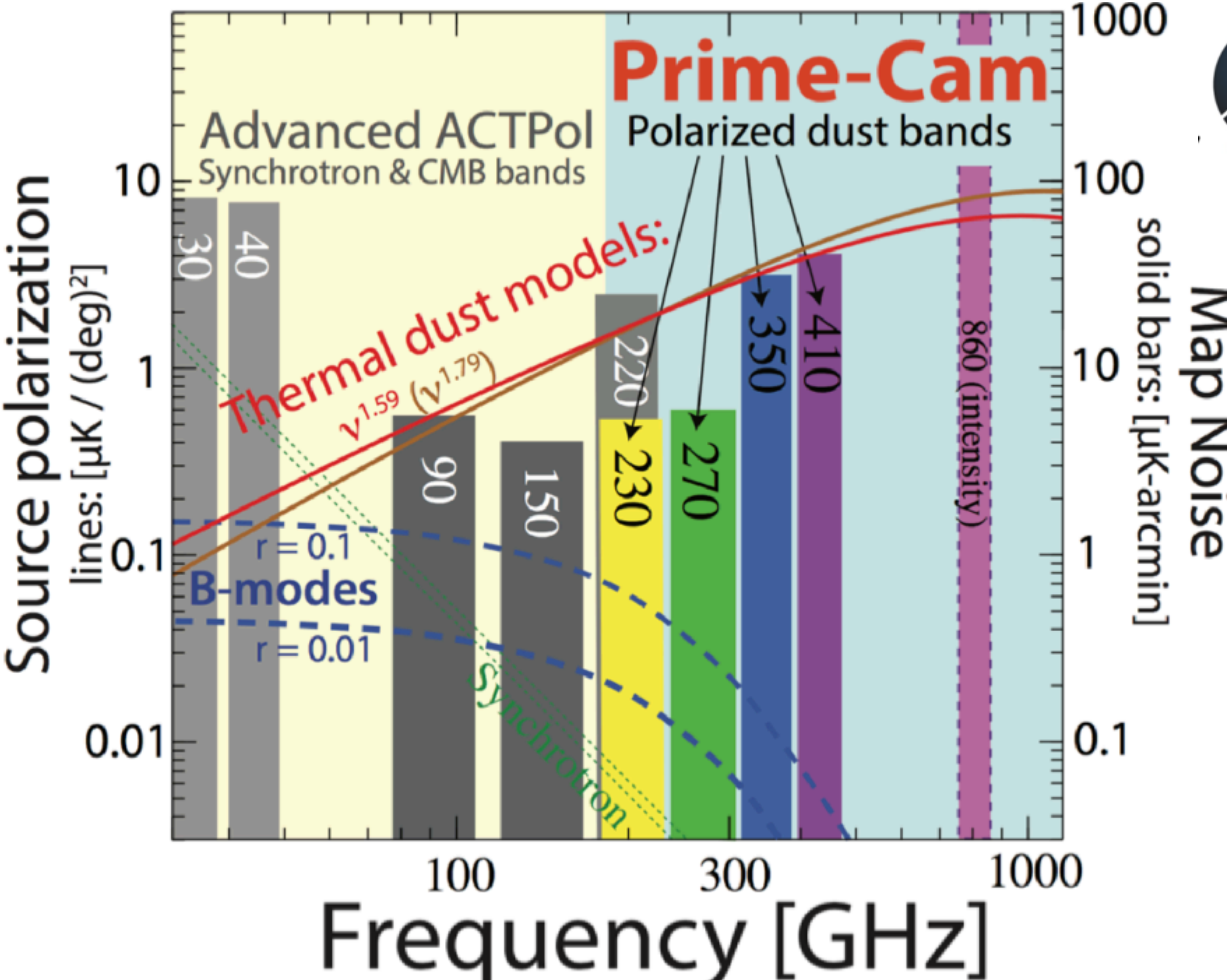
- **CCAT-p**: 6-m, **Cross-dragone** design, on Cerro Chajnantor (5600 m)

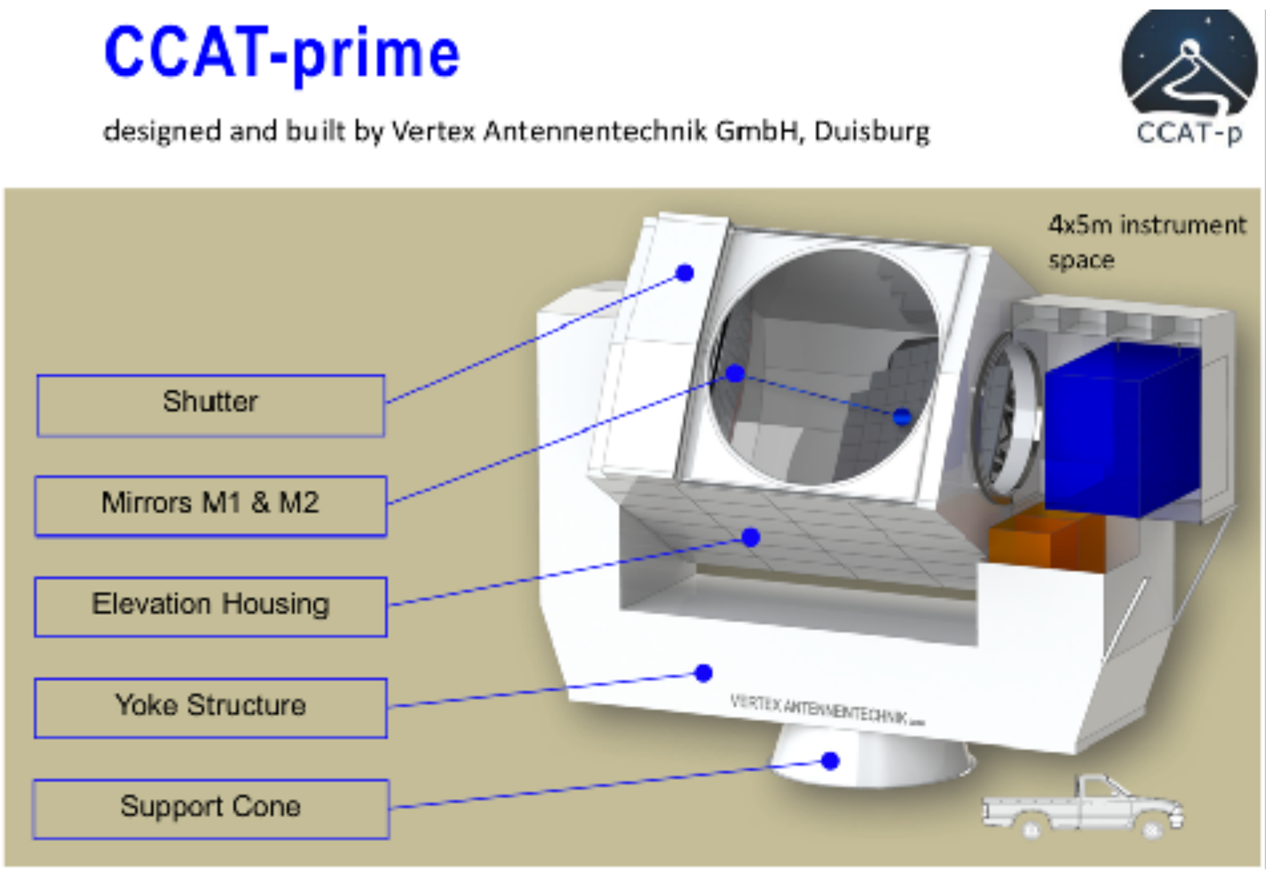
- **Germany makes great telescopes!**

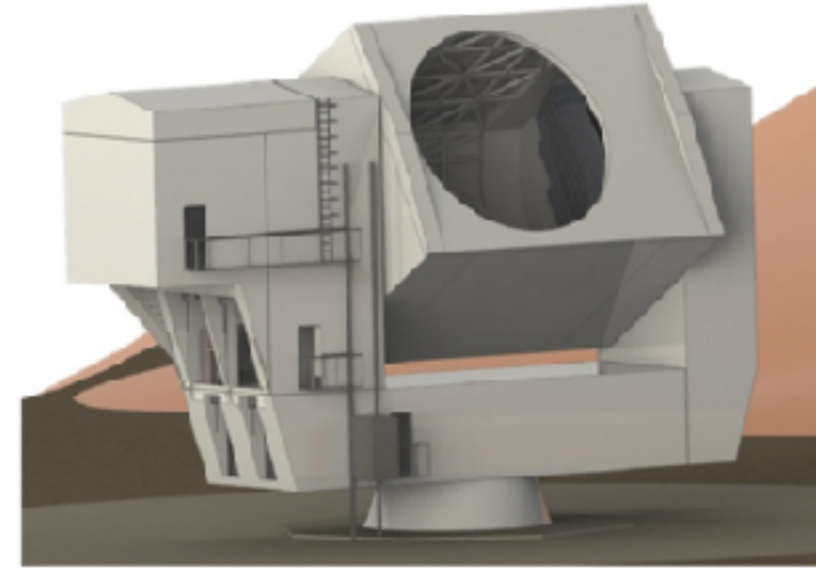


- Design study completed, and the contract has been signed by “VERTEX Antennentechnik GmbH”
  - CCAT-p is a great opportunity for Germany to make <u>significant contributions</u> towards the CMB S-4 landscape (both US and Europe) by providing telescope designs and the “lessons learned” with prototypes.

CCAT-p Collaboration





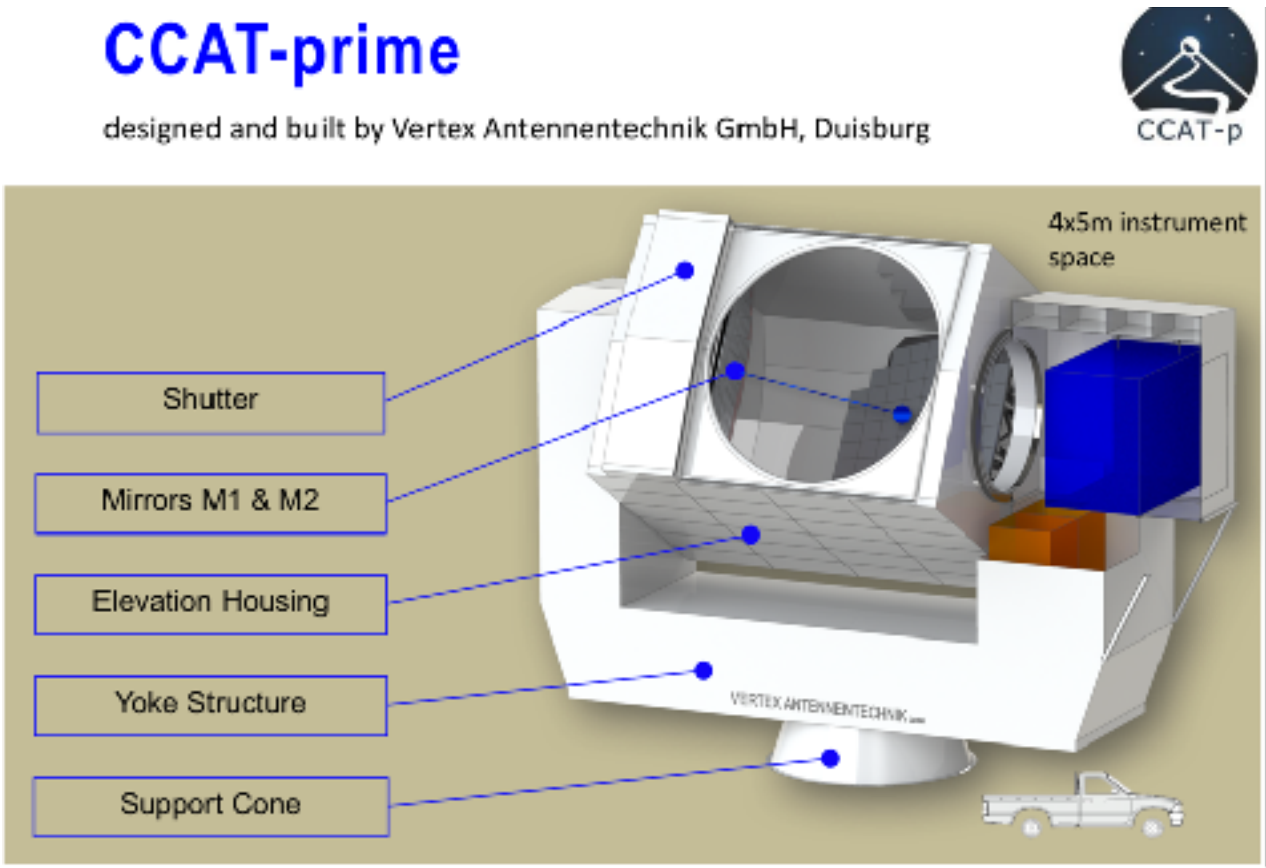

A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

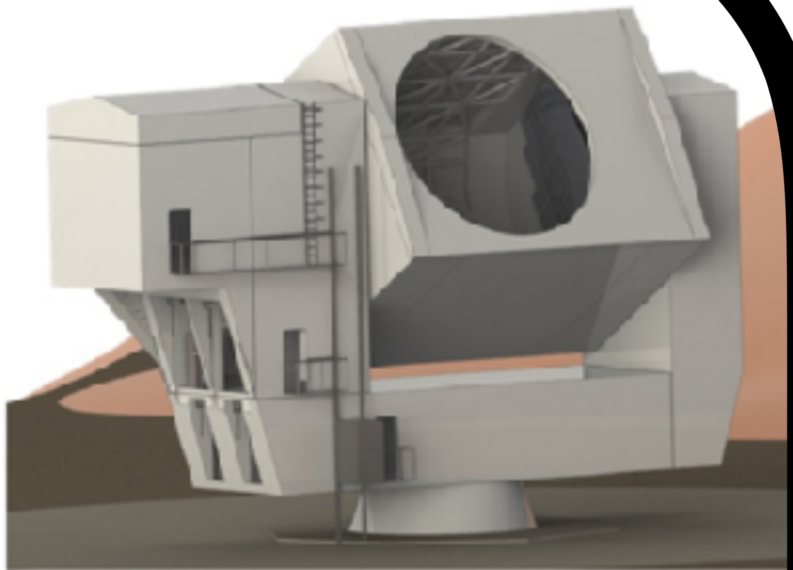
Simons Observatory (USA)

in collaboration

South Pole?

This could be "CMB-S4"





A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

Simons Observatory (USA)

in collaboration

South Pole?

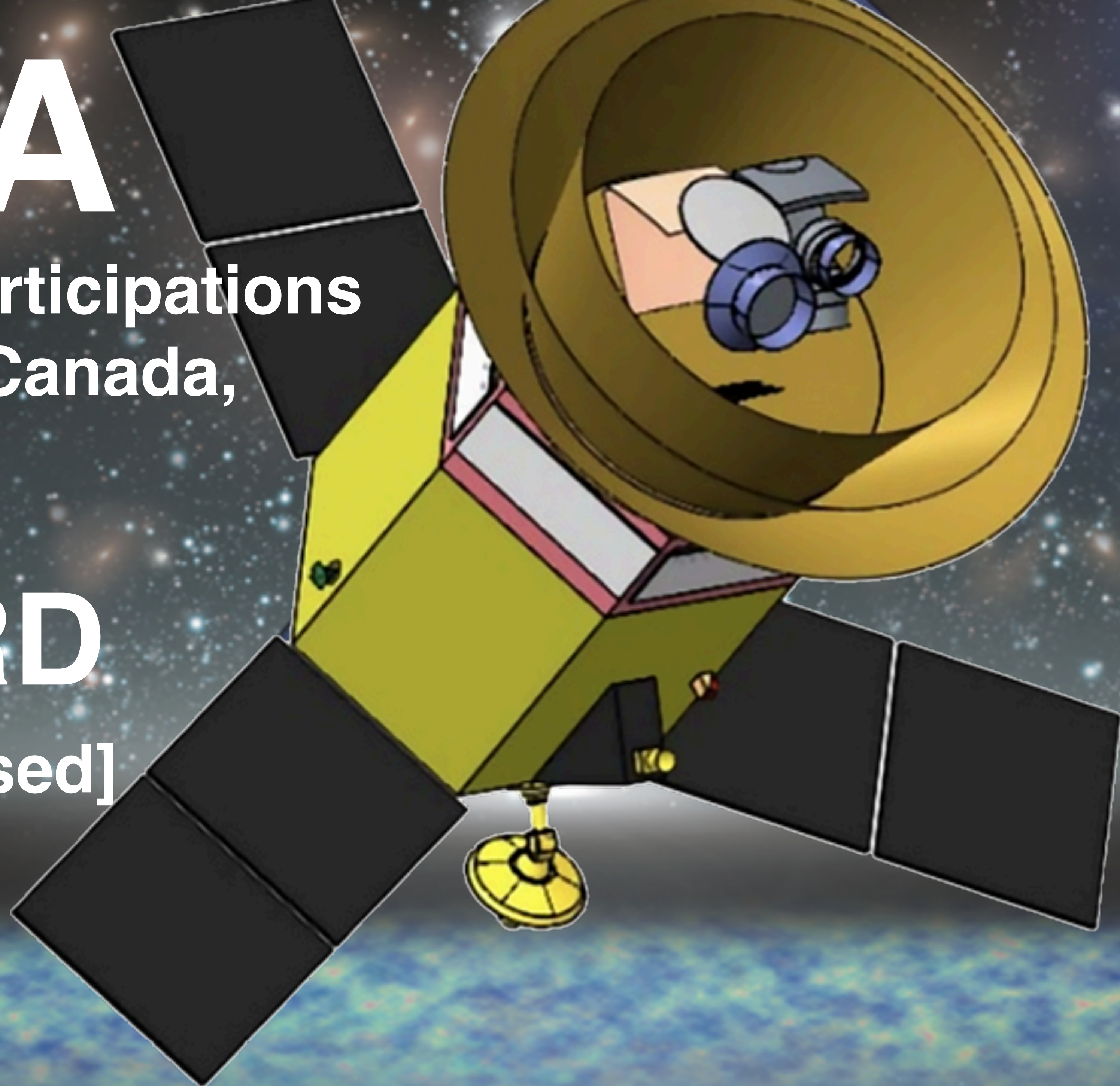
To have even more frequency coverage…

JAXA

+ possible participations from USA, Canada, Europe

LiteBIRD

2025– [proposed]



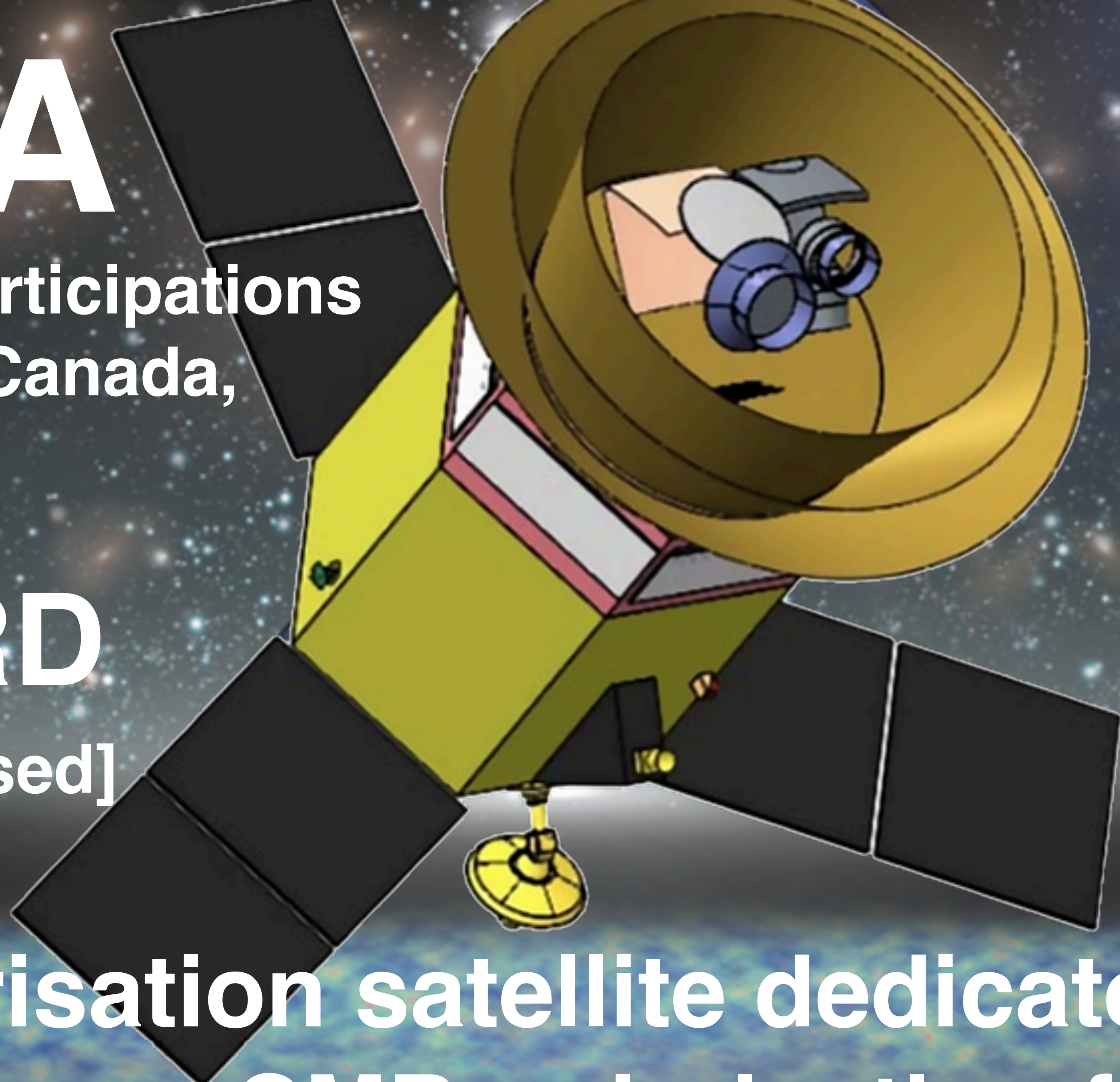
Target: $\delta r<0.001$ (68%CL)

JAXA

+ possible participations from USA, Canada, Europe

LiteBIRD

2025– [proposed]



Polarisation satellite dedicated to measure CMB polarisation from primordial GW, with a few thousand super-conducting detectors in space

JAXA

+ possible participations from USA, Canada, Europe

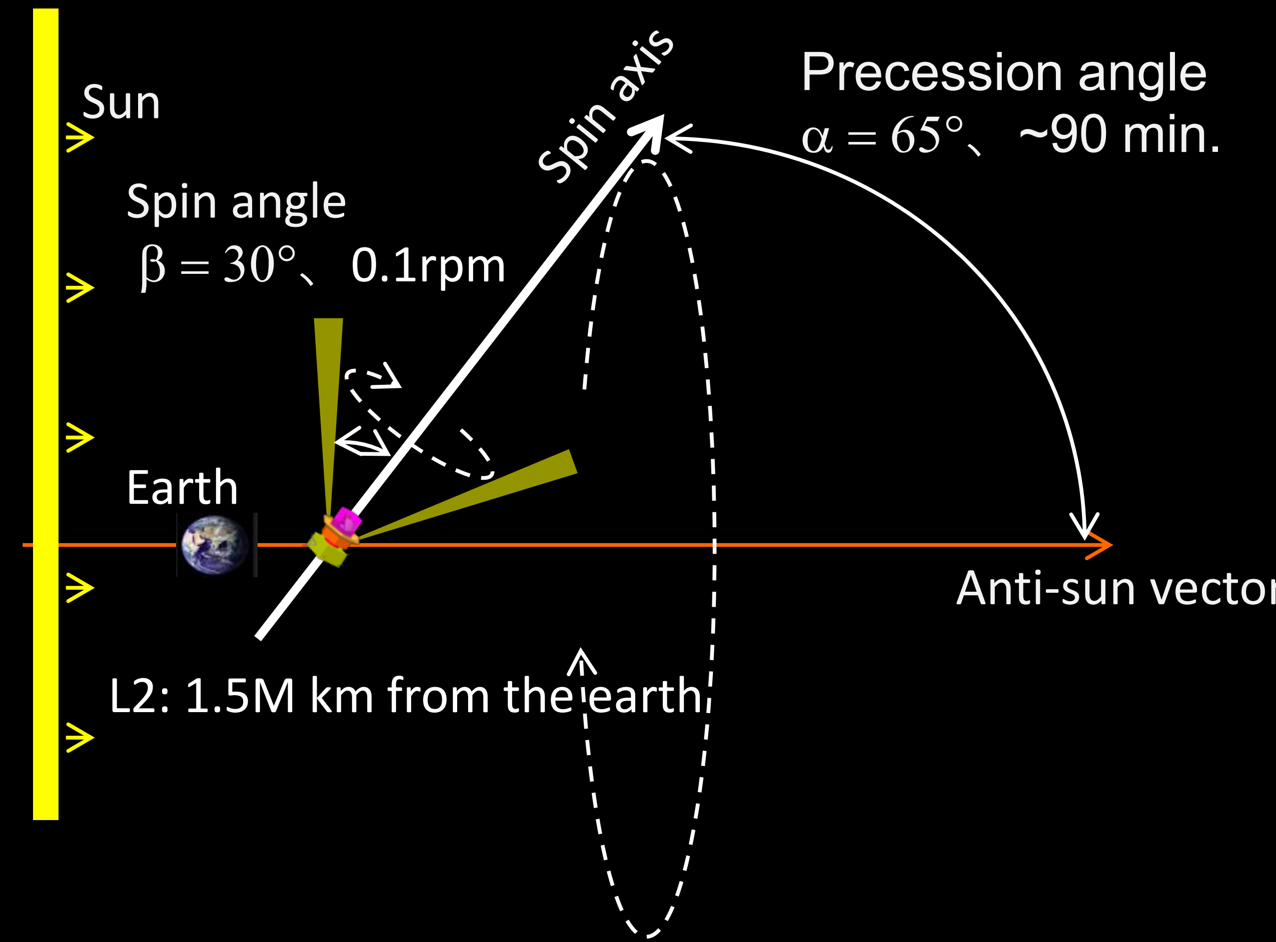
LiteBIRD

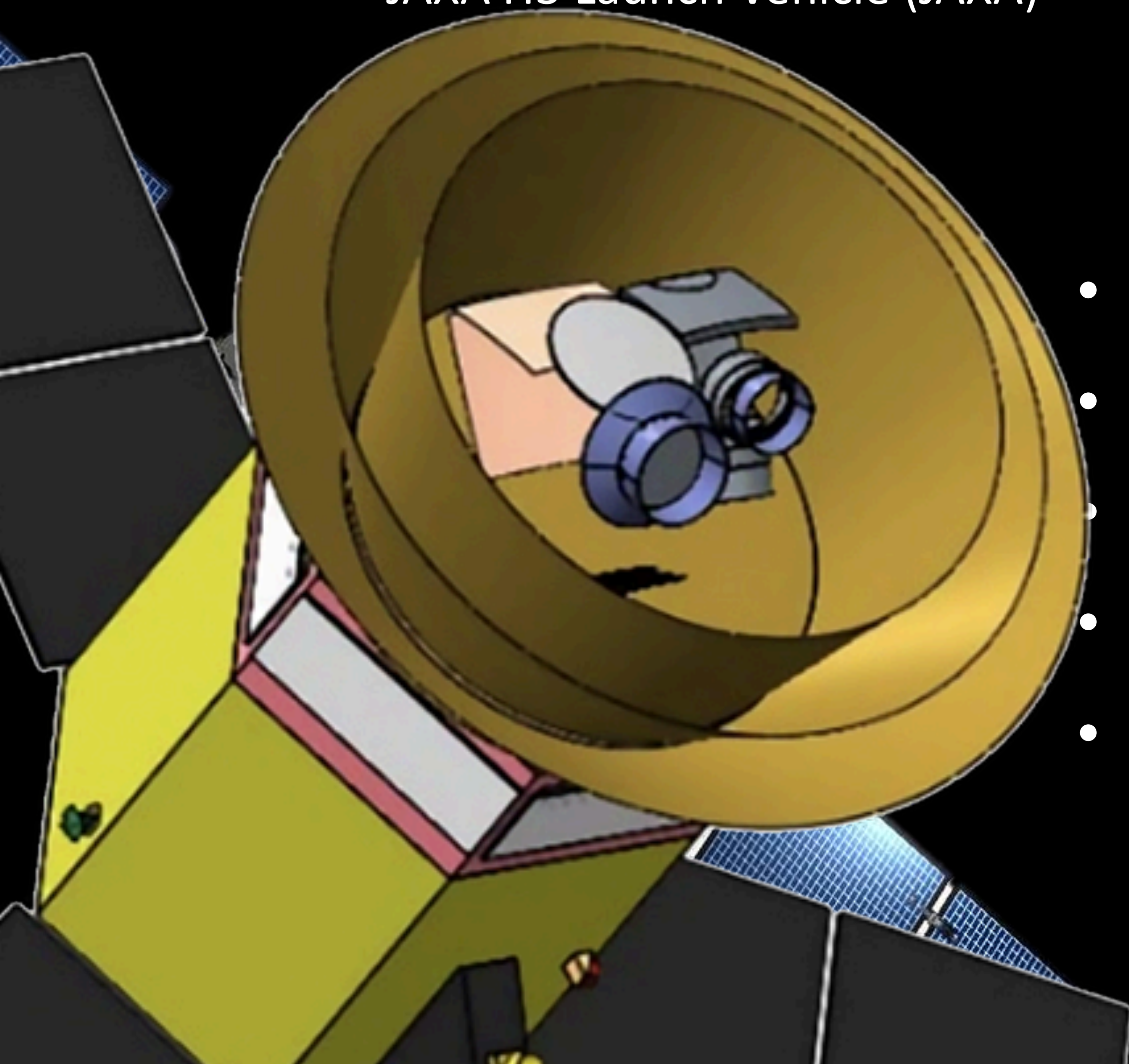
2025– [proposed]

Down-selected by JAXA as one of the two missions competing for a launch in mid 2020’s

Observation Strategy

JAXA H3 Launch Vehicle (JAXA)

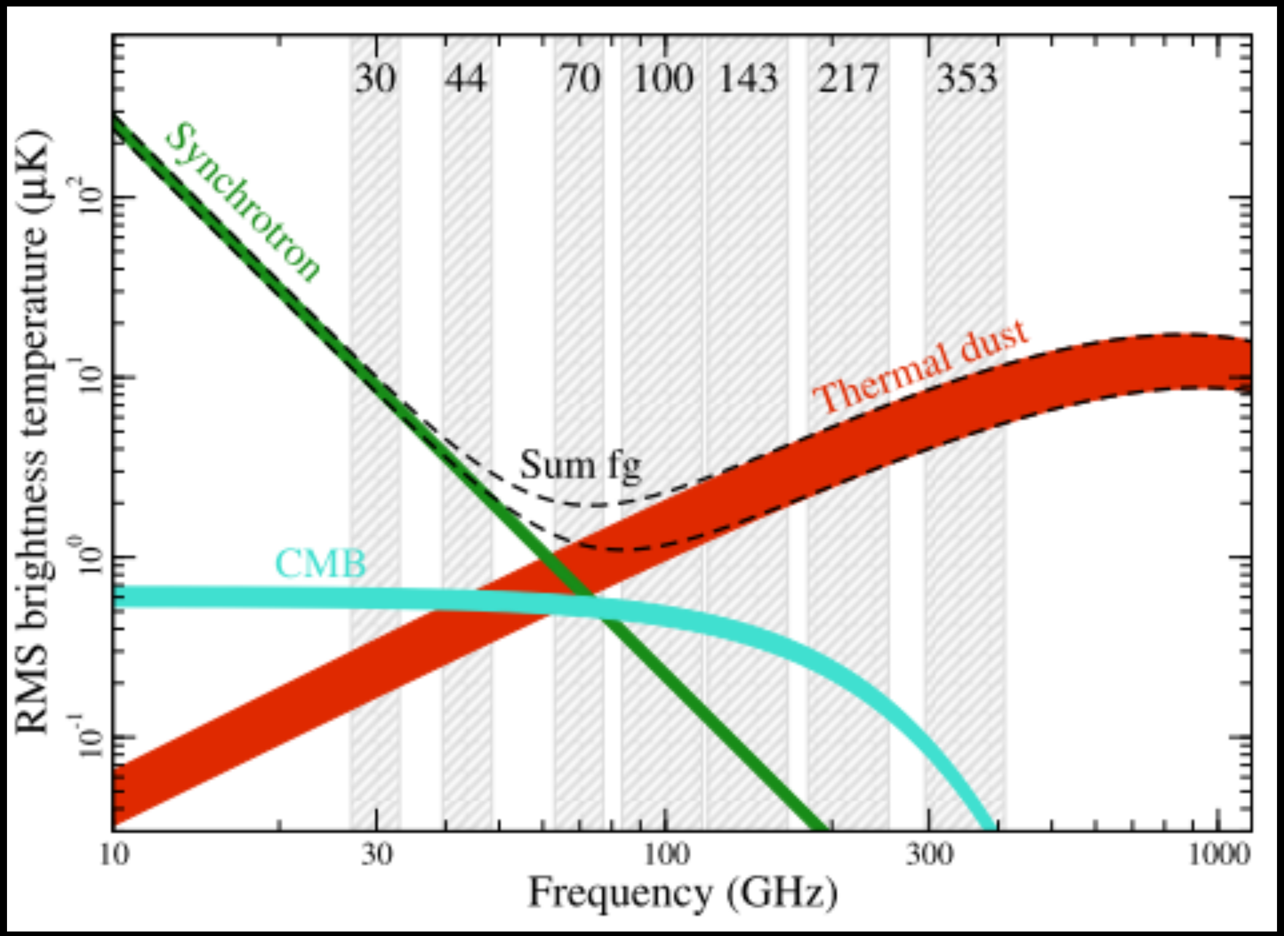




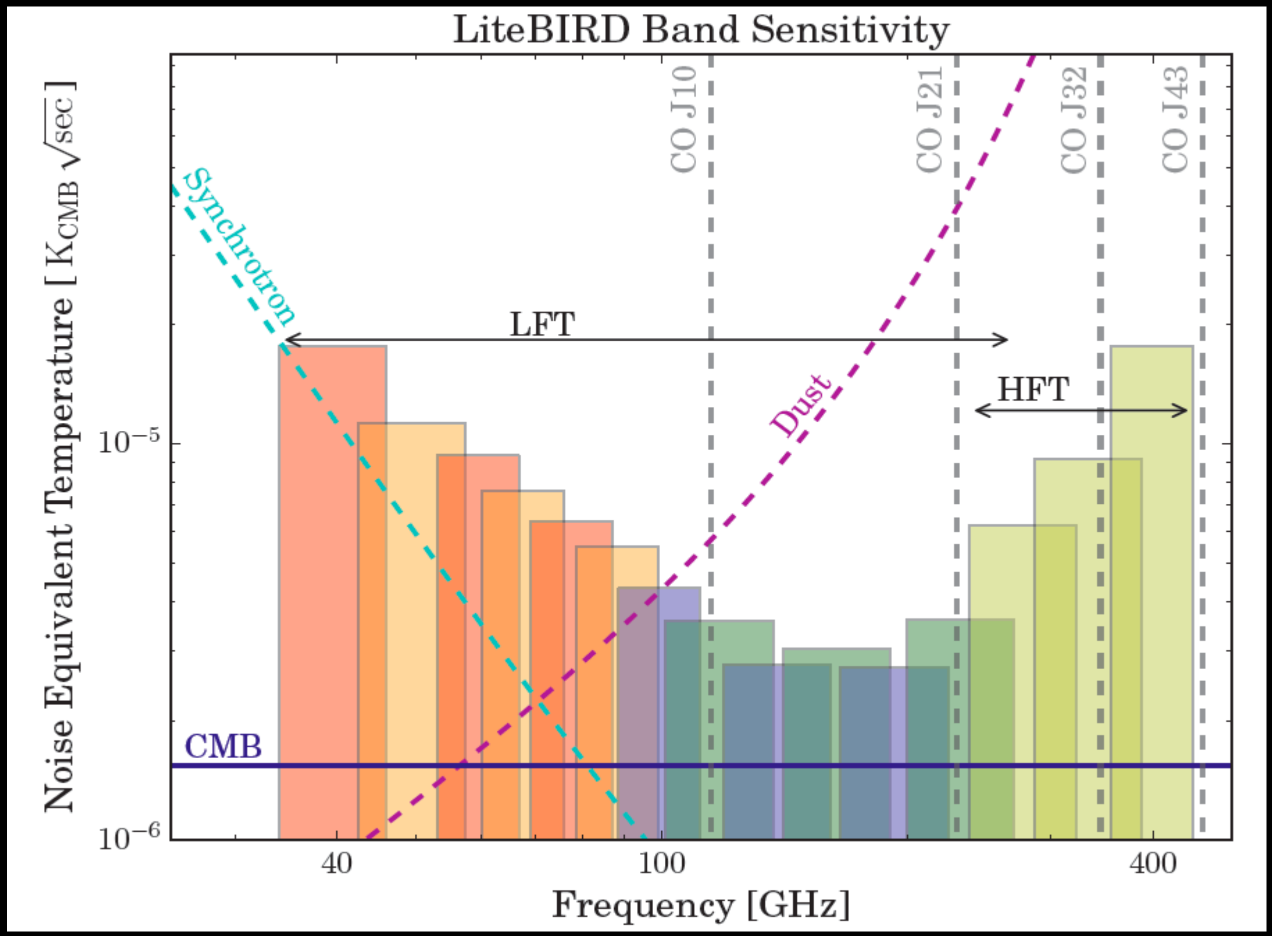
- Launch vehicle: JAXA H3
- Observation location: Second Lagrangian point (L2)
- Scan strategy: Spin and precession, full sky
- Observation duration: 3-years
- Proposed launch date: Mid 2020's

Slide courtesy Toki Suzuki (Berkeley)

Foreground Removal



Polarized galactic emission (Planck X)



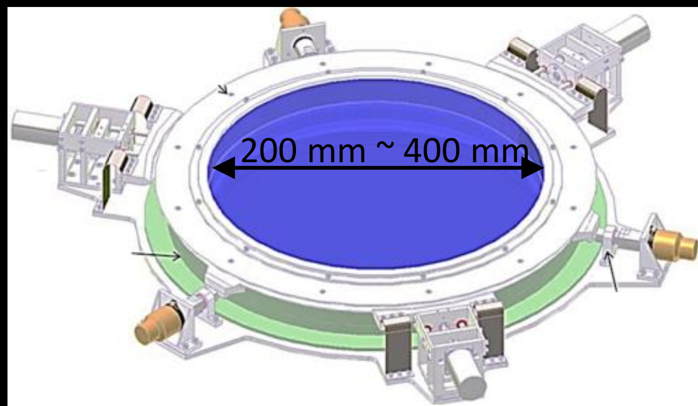
LiteBIRD: 15 frequency bands

- Polarized foregrounds
  - Synchrotron radiation and thermal emission from inter-galactic dust
  - Characterize and remove foregrounds
- 15 frequency bands between 40 GHz - 400 GHz
  - Split between Low Frequency Telescope (LFT) and High Frequency Telescope (HFT)
  - LFT: 40 GHz – 235 GHz
  - HFT: 280 GHz – 400 GHz

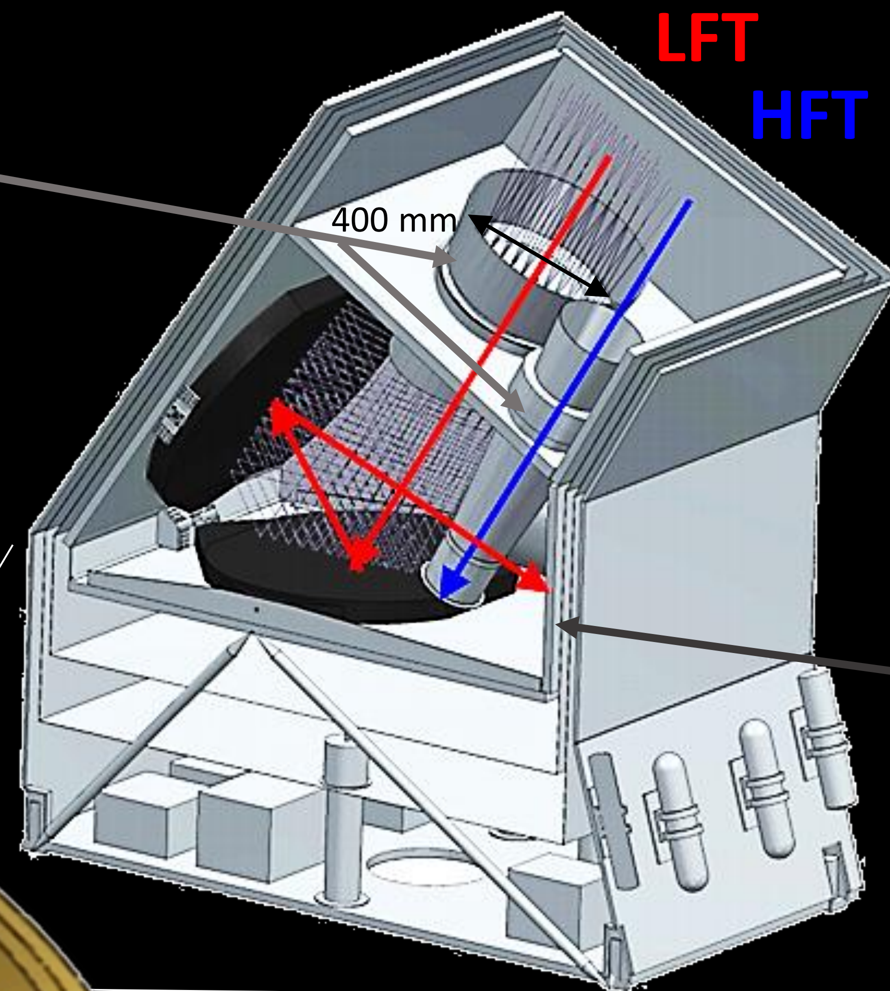
Slide courtesy Toki Suzuki (Berkeley)

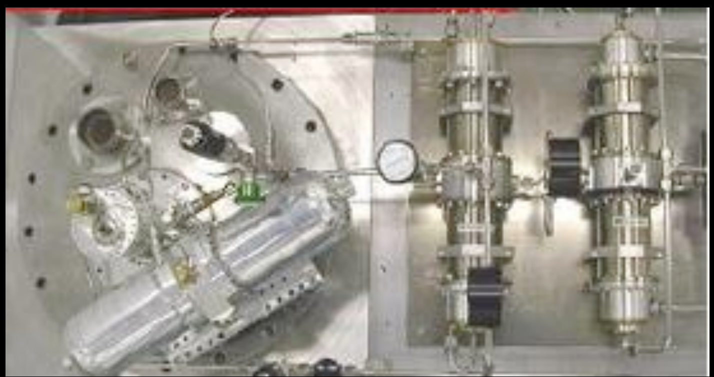
Slide courtesy Toki Suzuki (Berkeley)

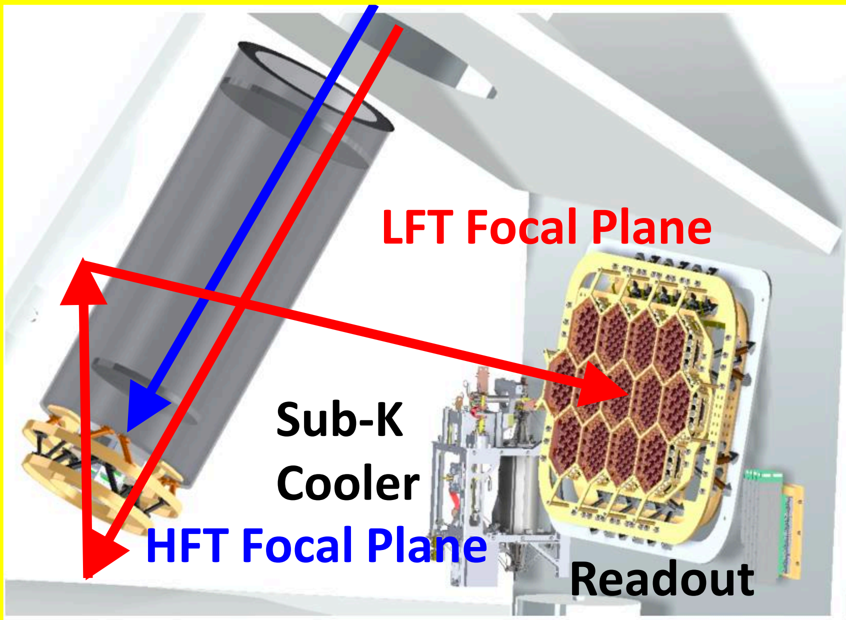
Instrument Overview



Half-wave plate

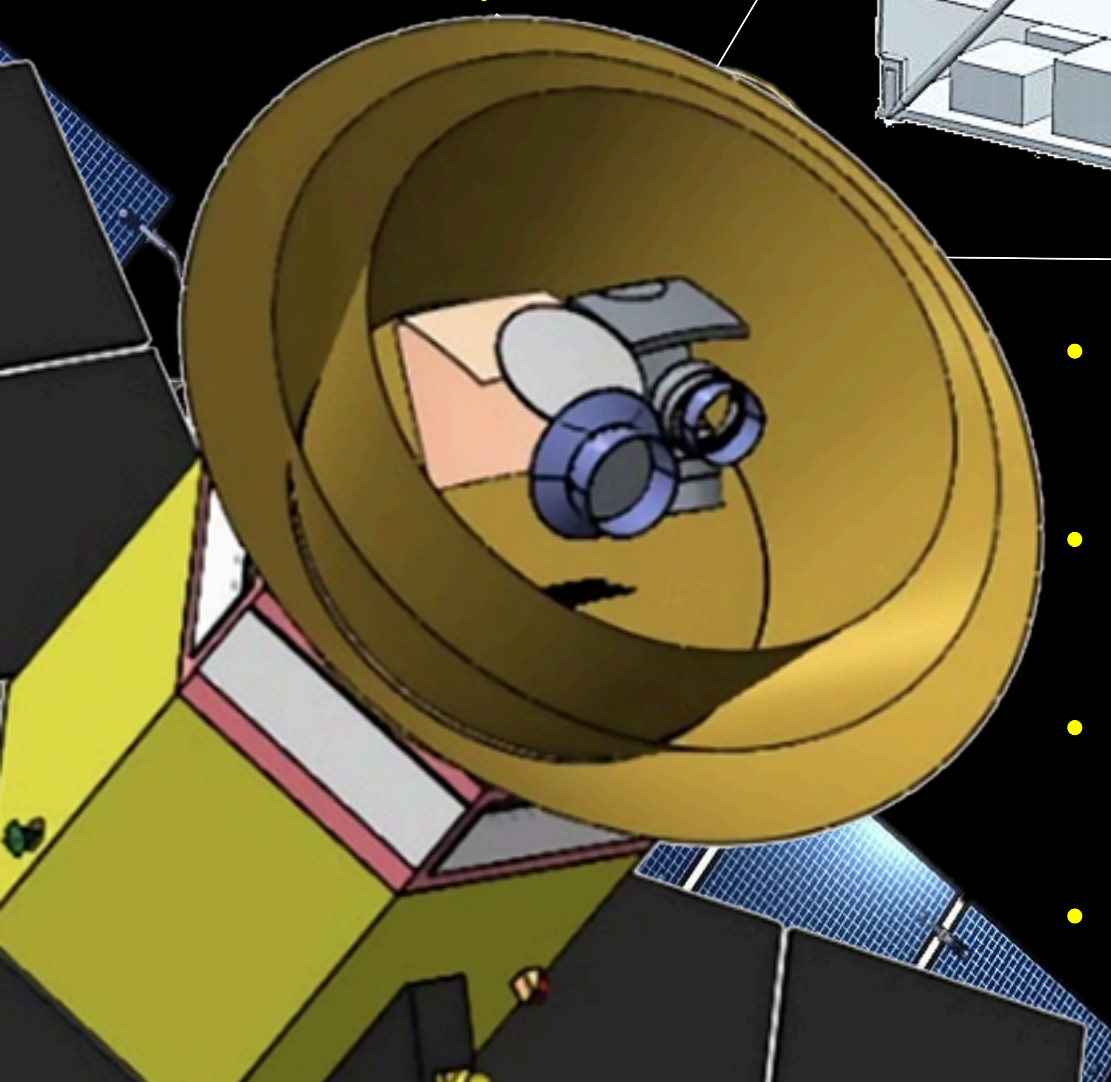



Stirling & Joule Thomson Coolers

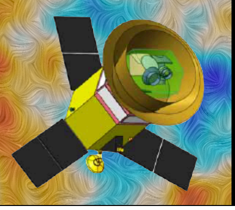


Sub-Kelvin Instrument

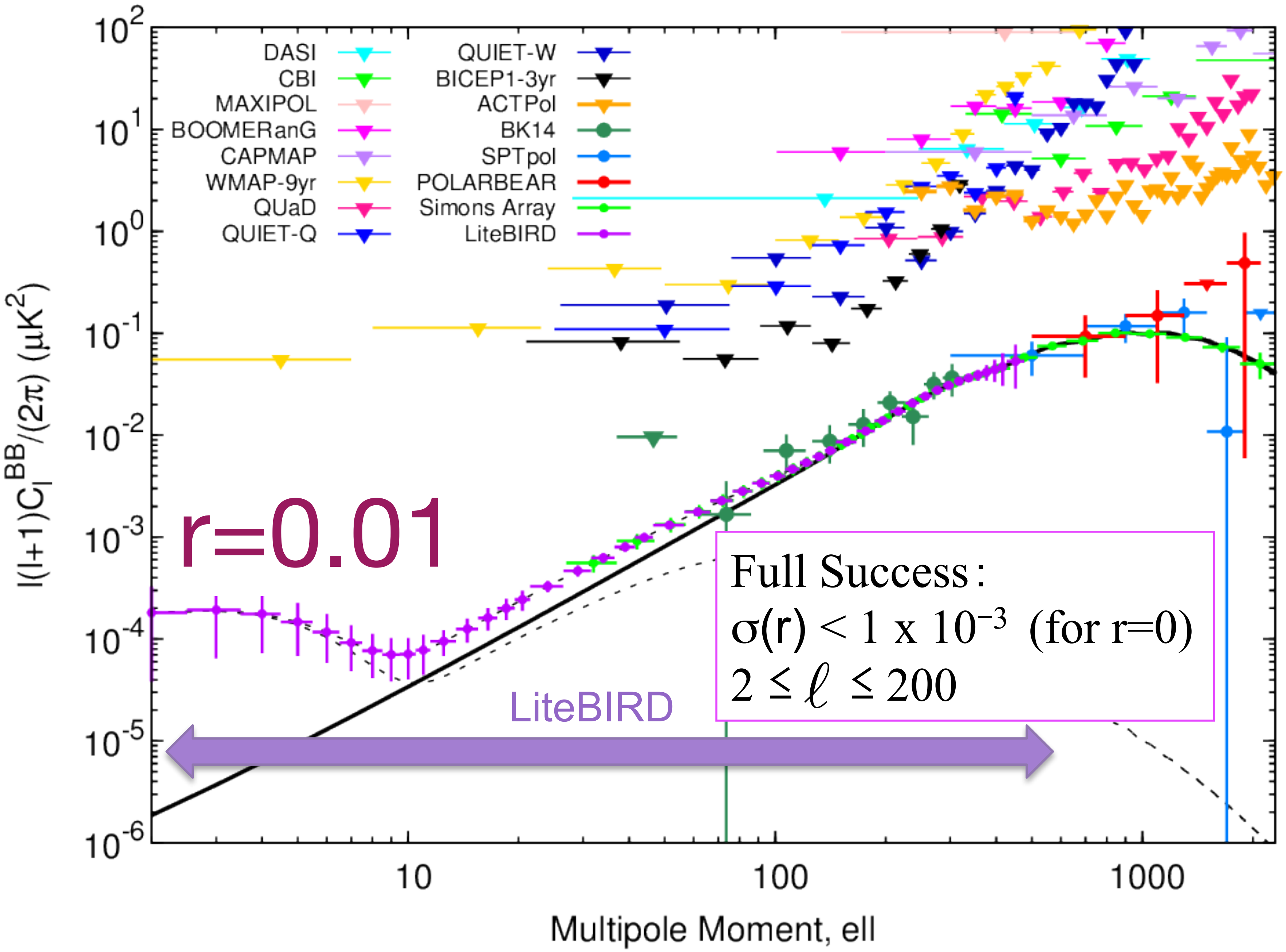
Cold Mission System



- Two telescopes
  - Crossed-Dragone (LFT) & on-axis refractor (HFT)
- Cryogenic rotating achromatic half-wave plate
  - Modulates polarization signal
- Stirling & Joule Thomson coolers
  - Provide cooling power above 2 Kelvin
- Sub-Kelvin Instrument
  - Detectors, readout electronics, and a sub-kelvin cooler



LiteBIRD Expectation

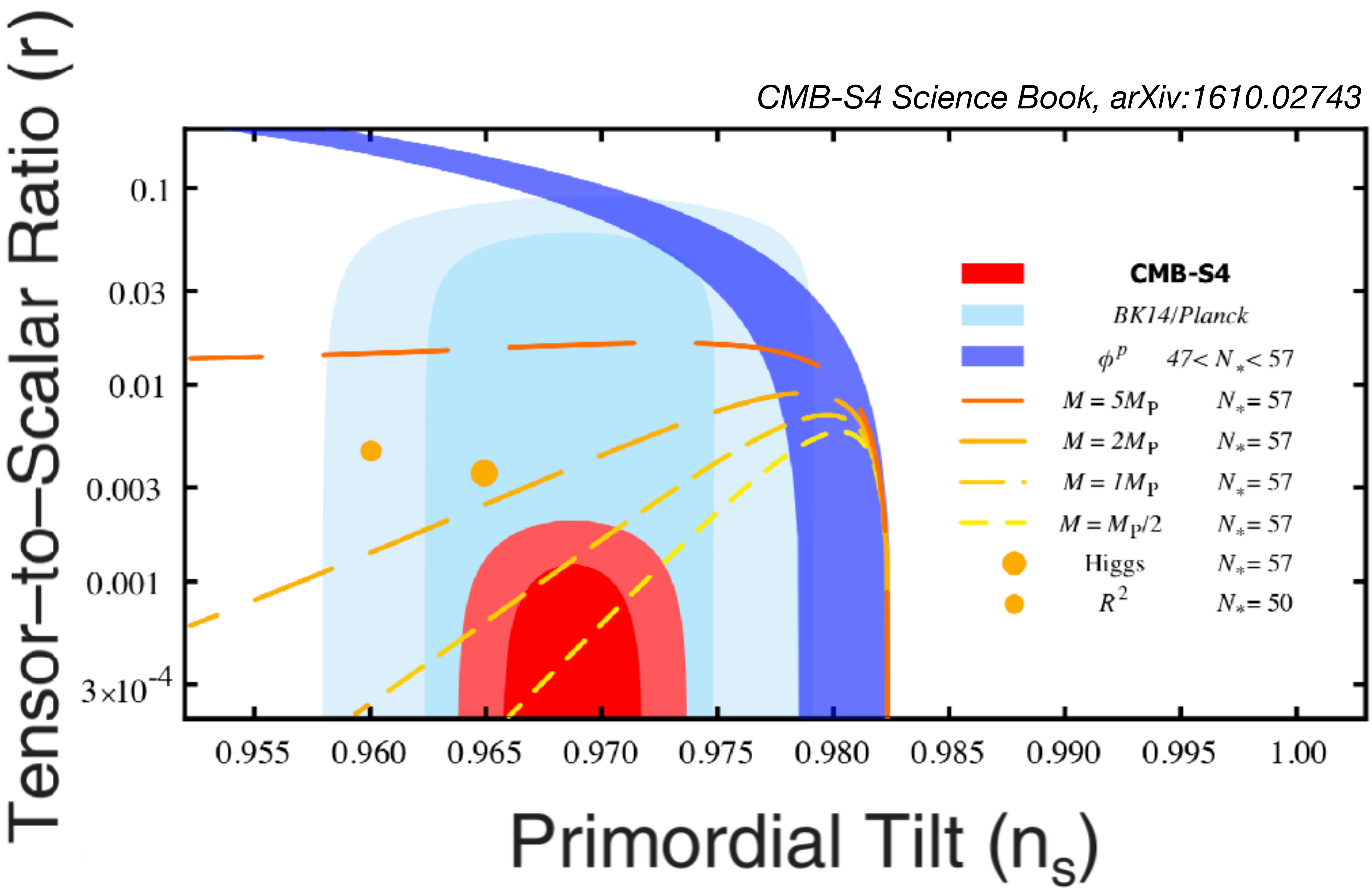


LiteBIRD only (without de-lensing)

Slide courtesy Ludovic Montier

Target Constraints (CMB Only)

	Today (Planck)	<2025 (SO)	>2025 (LB, CMB-S4)
Scalar power spectrum tilt (n_s)	0.9645 ± 0.0049		± 0.0019
Tensor-to-scalar Ratio (r)	< 0.07 (95%CL)	< 0.006 (95%CL)	< 0.002 (95%CL)
Non-Gaussianity Parameter (f_{NL}^{local})	0.8 ± 5.0	± 3.0	± 1.8
Axion Isocurvature Power Fraction	< 0.038 (95%CL)		< 0.008 (95%CL)


CMB-S4 Science Book, arXiv:1610.02743
Tensor–to–Scalar Ratio (r)
Primordial Tilt (n_s)
0.1
0.03
0.01
0.003
0.001
3×10^-4
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
1.00
CMB-S4
BK14/Planck
φ^p 47< N_*< 57
M = 5M_P N_*= 57
M = 2M_P N_*= 57
M = 1M_P N_*= 57
M = M_P/2 N_*= 57
Higgs N_*= 57
R^2 N_*= 50

GW from Inflation

- You might have heard that detection of the B-mode polarisation from primordial gravitational waves gives a measurement of the energy scale of inflation

- This is because, quantising the vacuum equation of motion for a tensor mode perturbation, $\Box h_{ij} = 0$, gives $h_{ij} \propto H \propto \sqrt{V/M_{\rm pl}^2}$ in de Sitter space
(Grishchuk 1974; Starobinsky 1979)

But, wait a minute…

Are GWs from vacuum fluctuation in spacetime, or from sources?

$$\Box h_{ij} = -16\pi G \pi_{ij}$$

- **Homogeneous solution**: "GWs from vacuum fluctuation"
- **Inhomogeneous solution**: "GWs from sources"
  - Scalar and vector fields cannot source tensor fluctuations at linear order (possible at non-linear level)
  - SU(2) gauge field can!

Maleknejad & Sheikh-Jabbari (2013); Dimastrogiovanni & Peloso (2013); Adshead, Martinec & Wyman (2013); Obata & Soda (2016); …

Important Message

$$\Box h_{ij} = -16\pi G \pi_{ij}$$

- **Do not take it for granted if someone told you that detection of the primordial gravitational waves would be a signature of "quantum gravity"!**
  - Only the homogeneous solution corresponds to the vacuum tensor metric perturbation. **There is no *a priori* reason to neglect an inhomogeneous solution!**
  - Contrary, we have several examples in which detectable B-modes are generated by **sources** [U(1) and SU(2)]

Experimental Strategy Commonly Assumed So Far

1. Detect CMB polarisation in multiple frequencies, to make sure that it is from the CMB (i.e., Planck spectrum)

2. Check for scale invariance: Consistent with a scale invariant spectrum?

    - Yes => Announce discovery of the vacuum fluctuation in spacetime

    - No => WTF?

New Experimental Strategy: New Standard!

1. Detect CMB polarisation in multiple frequencies, to make sure that it is from the CMB (i.e., Planck spectrum)

2. Consistent with a scale invariant spectrum?

3. Parity violating correlations consistent with zero?

4. Consistent with Gaussianity?

- If, and **ONLY IF** Yes to **all** => Announce discovery of the vacuum fluctuation in spacetime

If not, you may have just discovered new physics during inflation!

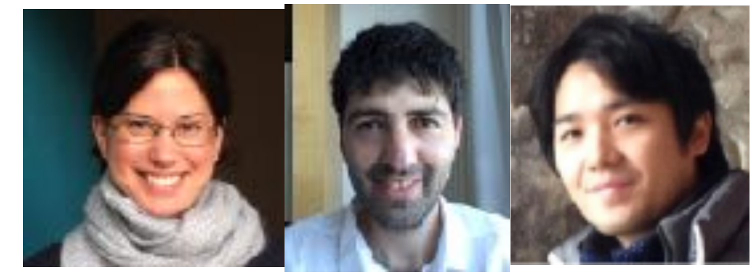
2. Consistent with a scale invariant spectrum?

3. Parity violating correlations consistent with zero?

4. Consistent with Gaussianity?

- If, and **ONLY IF** Yes to **all** => Announce discovery of the vacuum fluctuation in spacetime

Dimastrogiovanni, Fasielo & Fujita (2017)



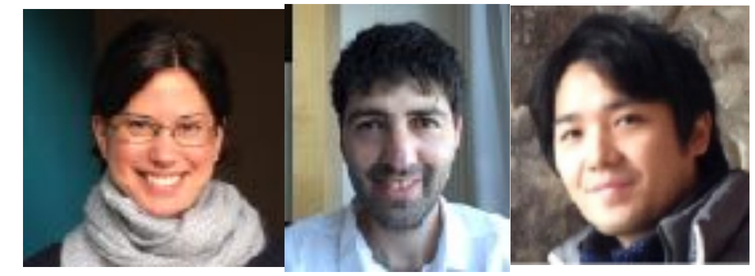
GW from Axion-SU(2) Dynamics

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{\phi} + \mathcal{L}_{\chi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{\lambda\,\chi}{4f} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

- ϕ: inflaton field => Just provides quasi-de Sitter background
- χ: pseudo-scalar “axion” field. Spectator field (i.e., negligible energy density compared to the inflaton)
- Field strength of an SU(2) field A^a_ν :

$$F^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g\epsilon^{abc} A^b_\mu A^c_\nu$$

Dimastrogiovanni, Fasielo & Fujita (2017)



Background and Perturbation

- In an inflating background, the SU(2) field has a background solution:

$$A_i^a = [\text{scale factor}] \times Q \times \delta_i^a$$

$$Q \equiv (-f\partial_\chi U/3g\lambda H)^{1/3}$$

U: axion potential

- Perturbations contain a tensor mode (as well as S&V)

$$\delta A_i^a = t_{ai} + \cdots$$

$$t_{ii} = \partial_a t_{ai} = \partial_i t_{ai} = 0$$

Scenario

- The SU(2) field contains tensor, vector, and scalar components

- The tensor components are amplified strongly by a coupling to the axion field

    - **<u>Only one helicity is amplified</u>** => GW is **chiral** (well-known result)

- Brand-new result: **GWs sourced by this mechanism are strongly non-Gaussian!**

  Agrawal, Fujita & EK, PRD, 97, 103526 (2018)

Dimastrogiovanni, Fasiello & Fujita (2017)

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

$$\psi_{L,R} \equiv (aM_{\rm Pl}/2)(h_+ \pm i h_\times)$$

- The equations of motion for L and R modes are ($x \equiv k/aH$)

$$\partial_x^2 \psi_{R,L} + \left(1 - \frac{2}{x^2}\right)\psi_{R,L} = \frac{2\sqrt{\epsilon_E}}{x}\partial_x t_{R,L} + \frac{2\sqrt{\epsilon_B}}{x^2}(m_Q \mp x)\, t_{R,L}$$

$$\left(\begin{array}{l} m_Q \equiv gQ/H \ \text{ = a few} \\ \epsilon_B \equiv g^2 Q^4/(HM_{\rm Pl})^2 \ll 1 \\ \epsilon_E \equiv (HQ + \dot{Q})^2/(HM_{\rm Pl})^2 \ll 1 \end{array}\right.$$

Dimastrogiovanni, Fasielo & Fujita (2017)

Spin-2 Field from SU(2)

- The equations of motion for L and R modes of SU(2) are

$$\partial_x^2 t_{R,L} + \left[1 + \frac{2}{x^2}\left(m_Q\,\xi \mp x(m_Q + \xi)\right)\right] t_{R,L}$$

the minus sign gives an instability -> exponential amplification of t_R!

$$= -\frac{2\sqrt{\epsilon_E}}{x}\partial_x \psi_{R,L} + \frac{2}{x^2}\left[(m_Q \mp x)\sqrt{\epsilon_B} + \sqrt{\epsilon_E}\right]\psi_{R,L}$$

$$\xi \equiv \frac{\lambda}{2fH}\dot{\chi} \simeq m_Q + \frac{1}{m_Q}$$

$$m_Q \equiv gQ/H \quad = \text{a few}$$

$$\epsilon_B \equiv g^2 Q^4/(HM_{\rm Pl})^2 \ll 1$$

$$\epsilon_E \equiv (HQ + \dot{Q})^2/(HM_{\rm Pl})^2 \ll 1$$

Dimastrogiovanni, Fasielo & Fujita (2017)

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$$= -\frac{2\sqrt{\epsilon_E}}{x}\partial_x\psi_{R,L} + \frac{2}{x^2}\left[(m_Q \mp x)\sqrt{\epsilon_B} + \sqrt{\epsilon_E}\right]\psi_{R,L}$$

- **The produced gravitational waves are totally chiral!**

- The solution (when all the parameters are constant and the terms on the right hand side are ignored):

$$t_R(x) = \frac{1}{\sqrt{2k}} i^\beta\, W_{\beta,\alpha}(-2ix) \quad \left(\begin{array}{l}\alpha \equiv -i\sqrt{2m_Q\xi - 1/4} \\ \beta \equiv -i(m_Q+\xi)\end{array}\right.$$

[Whittaker function]

Dimastrogiovanni, Fasielo & Fujita (2017)

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

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$$\partial_x^2 \psi_{R,L} + \left(1 - \frac{2}{x^2}\right)\psi_{R,L} = \frac{2\sqrt{\epsilon_E}}{x}\partial_x t_{R,L} + \frac{2\sqrt{\epsilon_B}}{x^2}(m_Q \mp x)\, t_{R,L}$$

- Inhomogeneous solution:

$$\lim_{x\to 0}\psi_R^{(s)}(x) = \frac{1}{\sqrt{2kx}}\left[\mathcal{F}_E\sqrt{\epsilon_E} + \mathcal{F}_B\sqrt{\epsilon_B}\right]$$

F_E, F_B: some complicated functions

Dimastrogiovanni, Fasielo & Fujita (2017)

Power Spectrum!

$$\mathcal{P}_h^{(s)}(k) = \frac{H^2}{\pi^2 M_{\rm Pl}^2}\left|\sqrt{2k}x \lim_{x\to 0}\psi_R^{(s)}(x)\right|^2 = \frac{\epsilon_B H^2}{\pi^2 M_{\rm Pl}^2}\mathcal{F}^2$$

$$\boxed{\mathcal{F}^2 \equiv \left|\mathcal{F}_B + \sqrt{\epsilon_E/\epsilon_B}\mathcal{F}_E\right|^2 \approx \exp(3.6 m_Q)}$$

- This exponential dependence on m_Q makes it possible to have $P_{\rm sourced} >> P_{\rm vacuum}$
- **New Paradigm**

Phenomenology

$$\partial_x^2 t_{R,L} + \left[1 + \frac{2}{x^2}\left(m_Q\,\xi \mp x(m_Q+\xi)\right)\right] t_{R,L} = \ldots$$

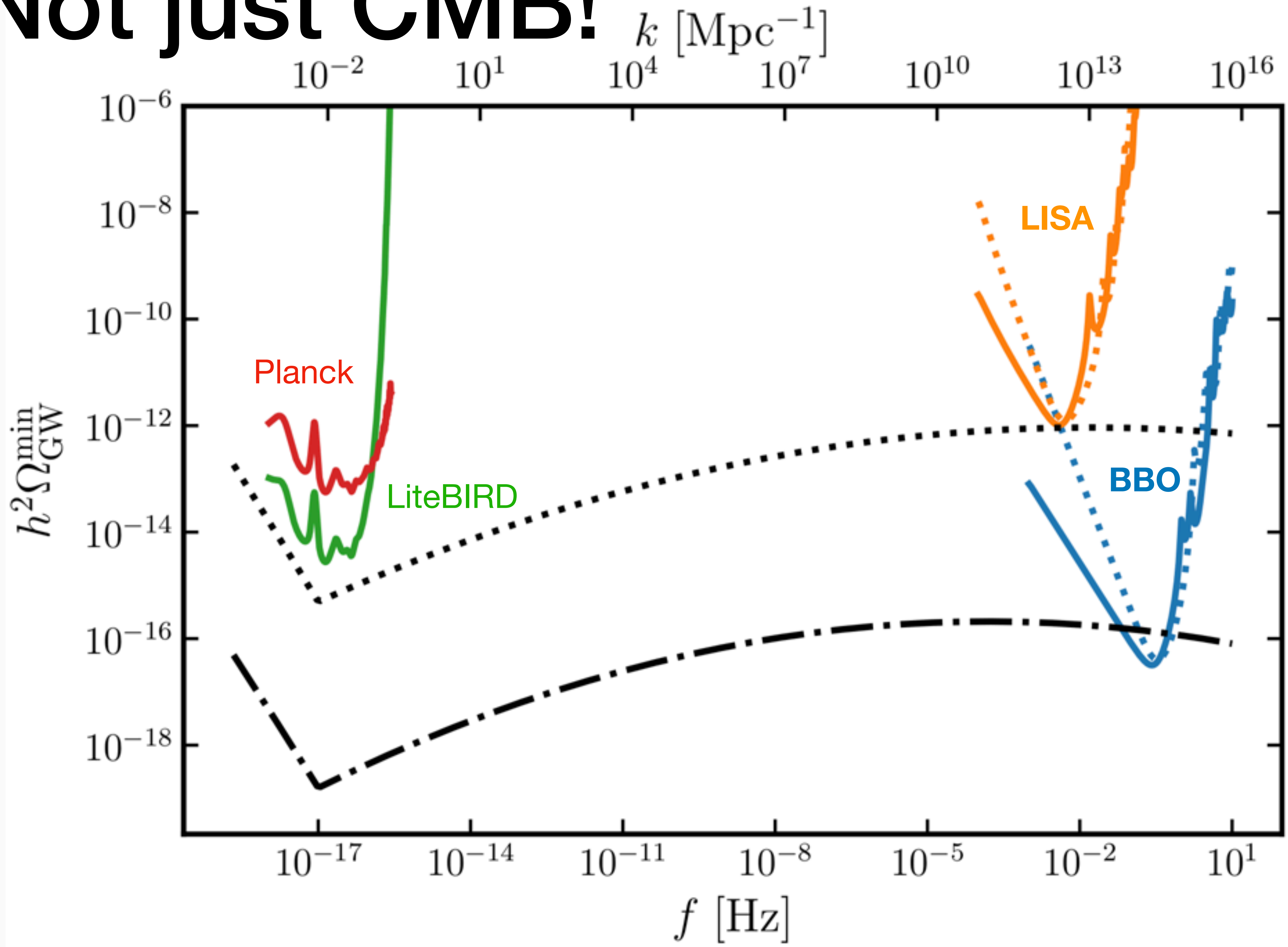
the minus sign gives an instability -> exponential amplification of t_R!

$$\left(\begin{array}{l} \xi \equiv \dfrac{\lambda}{2fH}\dot{\chi} \simeq m_Q + \dfrac{1}{m_Q} \\ m_Q \equiv gQ/H \;\; = \text{a few} \end{array} \right.$$

- The scale-dependence of the produced tensor modes is determined by how m_Q changes with time
- E.g., Axion rolling faster towards the end of inflation: BLUE TILTED power spectrum! Therefore…

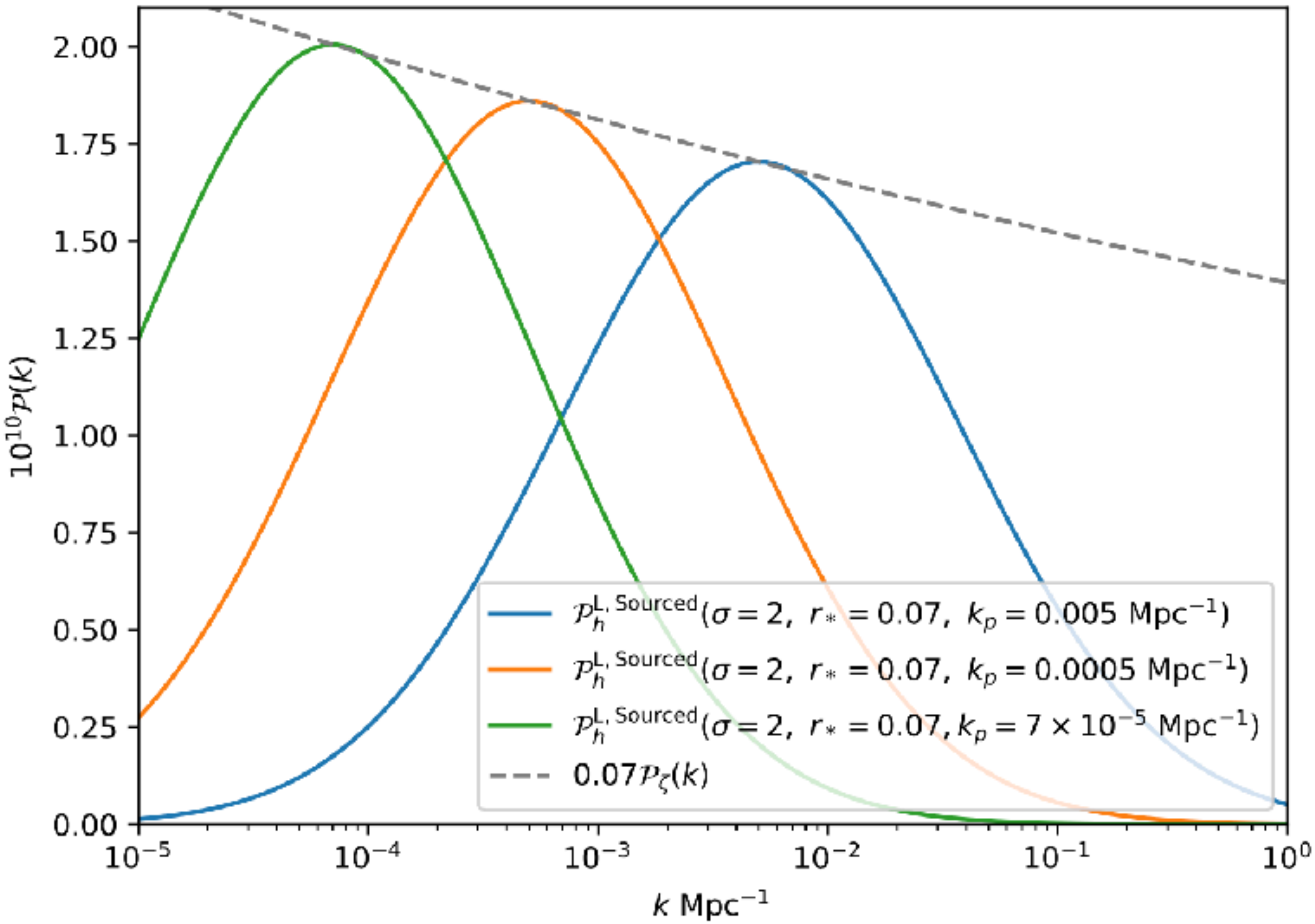
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Not just CMB!



Dimastrogiovanni, Fasiello & Fujita (2017)
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Example Tensor Spectra



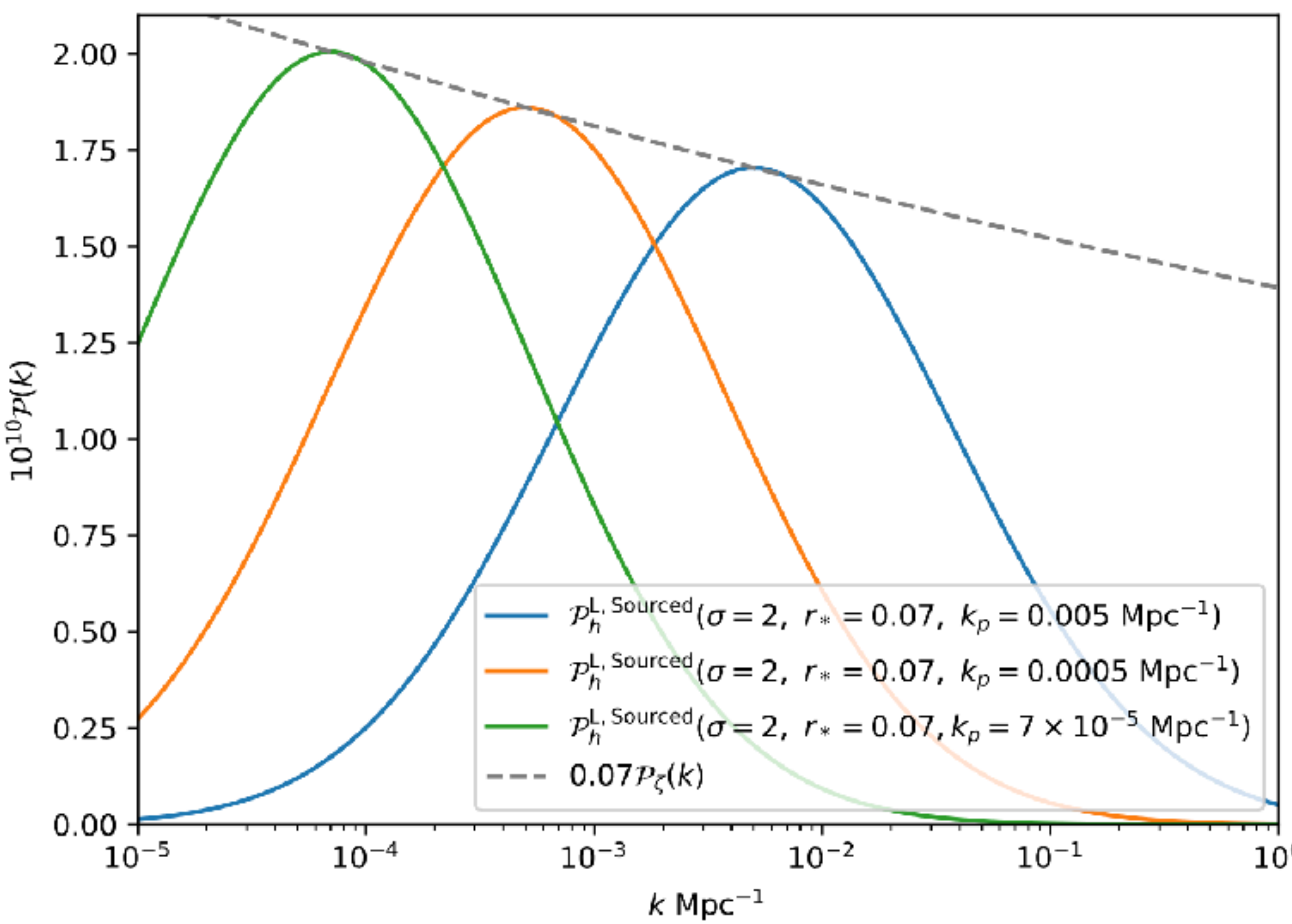
- Sourced tensor spectrum can also be bumpy

Dimastrogiovanni, Fasiello & Fujita (2017)

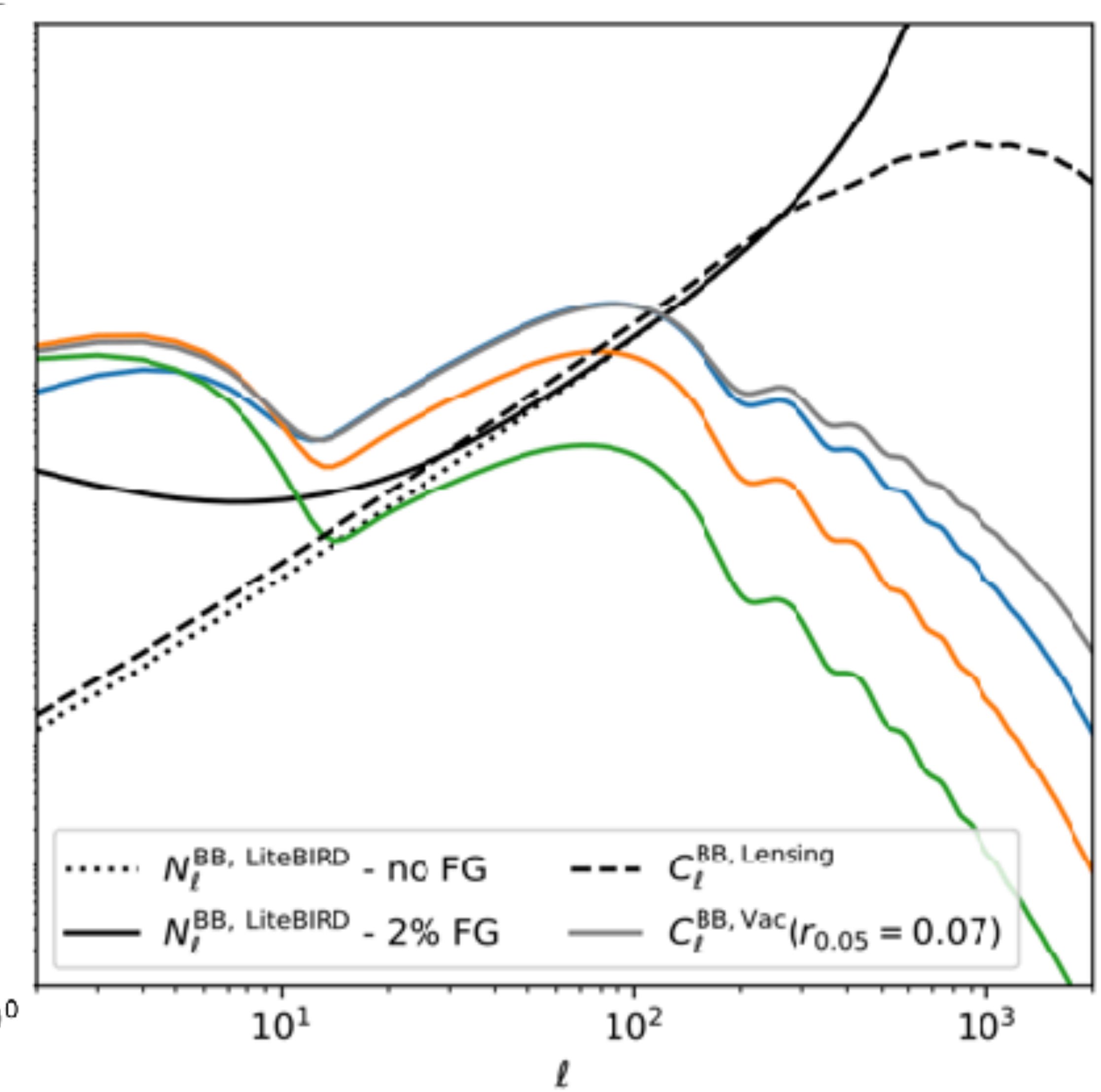
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Example Tensor Spectra

Tensor Power Spectrum, P(k)



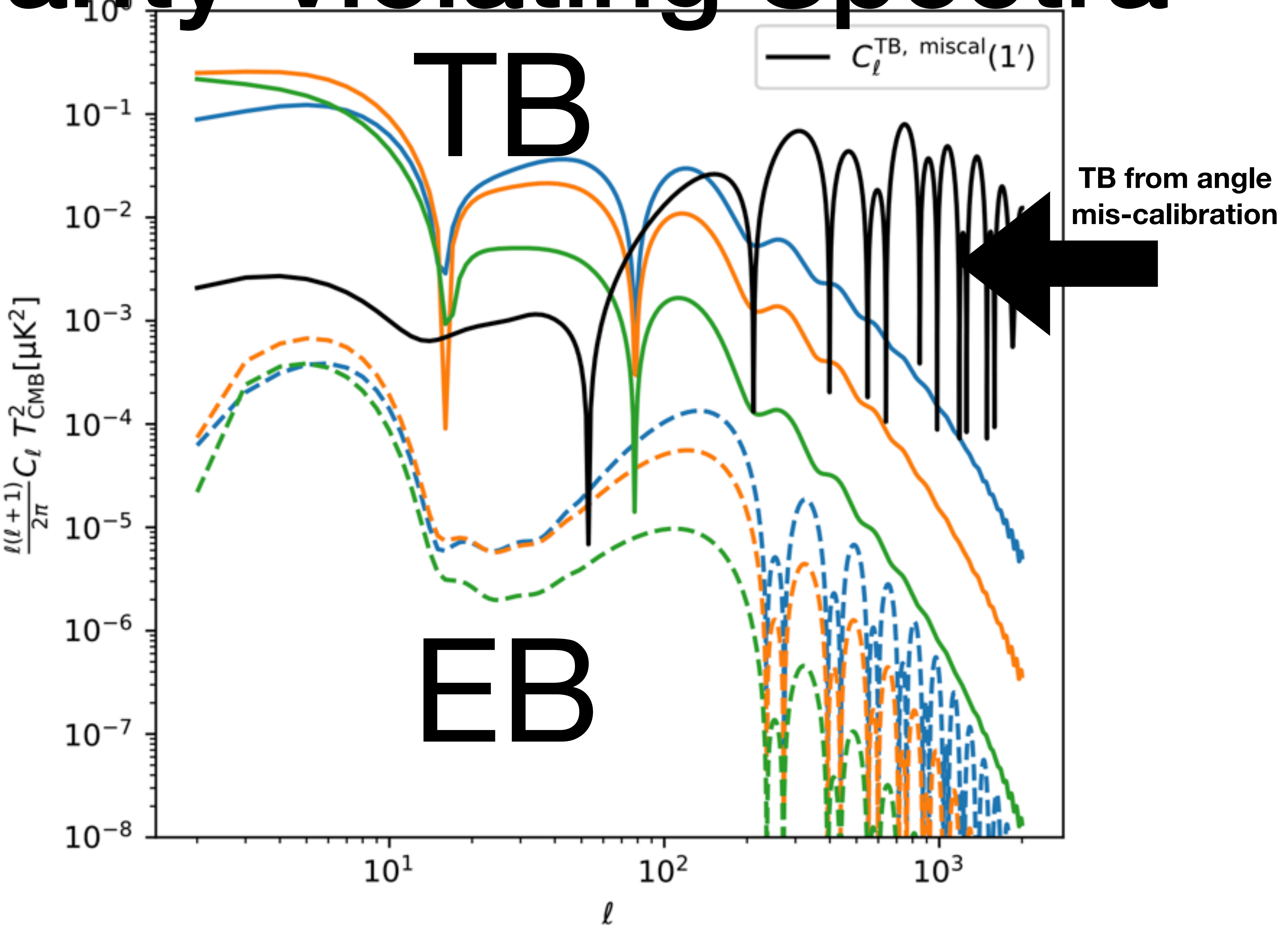
B-mode CMB spectrum, C_l^{BB}



- The B-mode power spectrum still looks rather normal

Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Parity-violating Spectra



- Angle mis-calibration can be distinguished easily!

Agrawal, Fujita & EK, PRD, 97, 103526 (2018)

Large bispectrum in GW from SU(2) fields

Aniket Agrawal
(MPA)

Tomo Fujita
(Kyoto)

$$\frac{B_h^{RRR}(k,k,k)}{P_h^2(k)} \approx \frac{25}{\Omega_A}$$

$$\langle \hat{h}_R(\boldsymbol{k}_1)\hat{h}_R(\boldsymbol{k}_2)\hat{h}_R(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta\left(\sum_{i=1}^{3}\boldsymbol{k}_i\right)B_h^{RRR}(k_1,k_2,k_3)$$

- $\Omega_A << 1$ is the energy density fraction of the gauge field
- **B_h/P_h^2 is of order unity for the vacuum contribution**

[Maldacena (2003); Maldacena & Pimentel (2011)]

- ***Gaussianity offers a powerful test of whether the detected GW comes from the vacuum or sources***

Agrawal, Fujita & EK, PRD, 97, 103526 (2018)

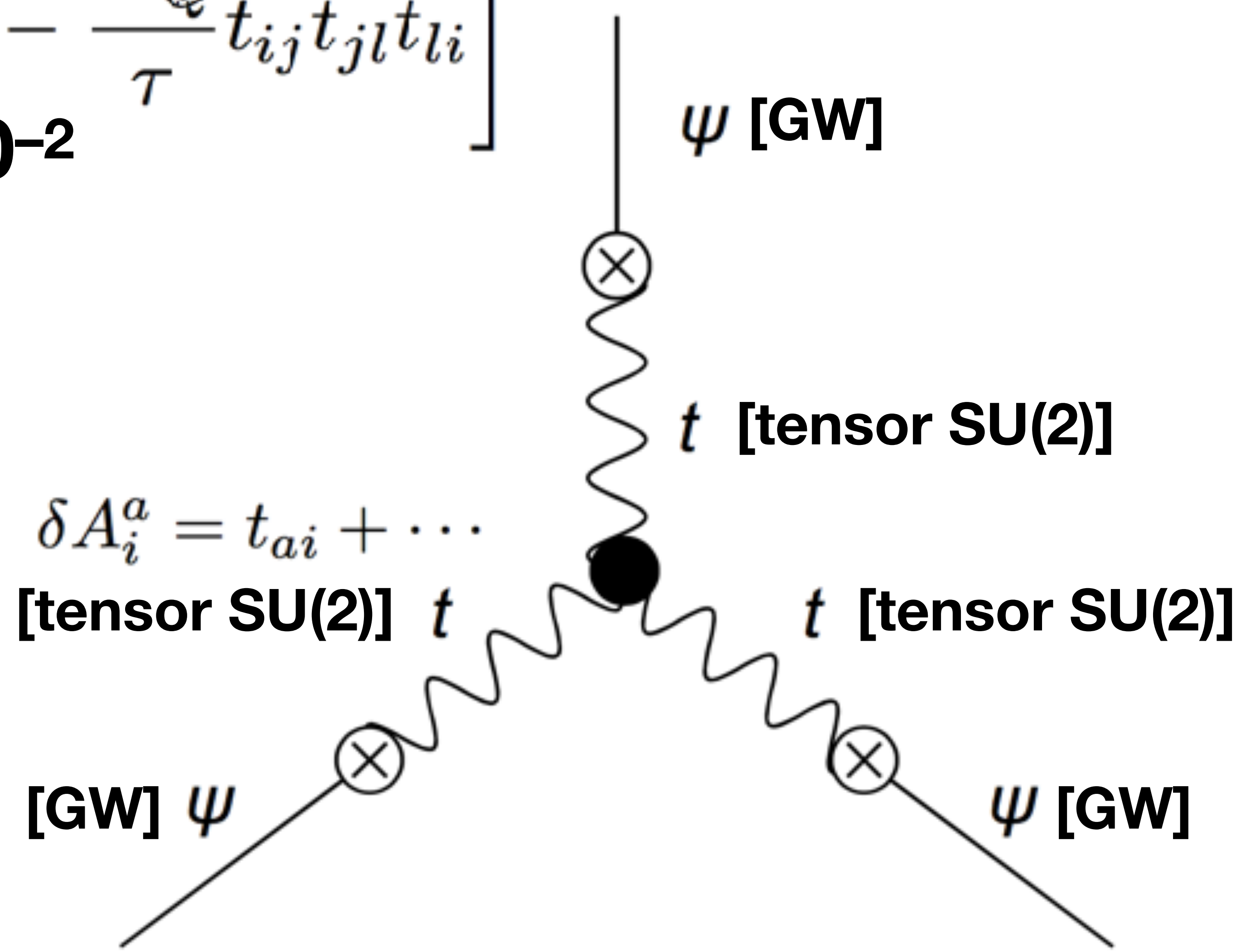
NG generated at the tree level

$$L_3^{(i)} = c^{(i)} \left[\epsilon^{abc} t_{ai} t_{bj} \left(\partial_i t_{cj} - \frac{m_Q^2 + 1}{3 m_Q \tau} \epsilon^{ijk} t_{ck} \right) - \frac{m_Q}{\tau} t_{ij} t_{jl} t_{li} \right]$$

$$c^{(i)} = g = m_Q^2 H / \sqrt{\epsilon_B} M_{\rm Pl} \sim 10^{-2}$$

$$\epsilon_B \equiv \frac{g^2 Q^4}{H^2 M_{\rm Pl}^2} \simeq \frac{2\Omega_A}{1 + m_Q^{-2}} \ll 1$$

$m_Q \equiv gQ/H$ **[m_Q ~ a few]**



- This diagram generates second-order equation of motion for GW

Agrawal, Fujita & EK, PRD, 97, 103526 (2018)

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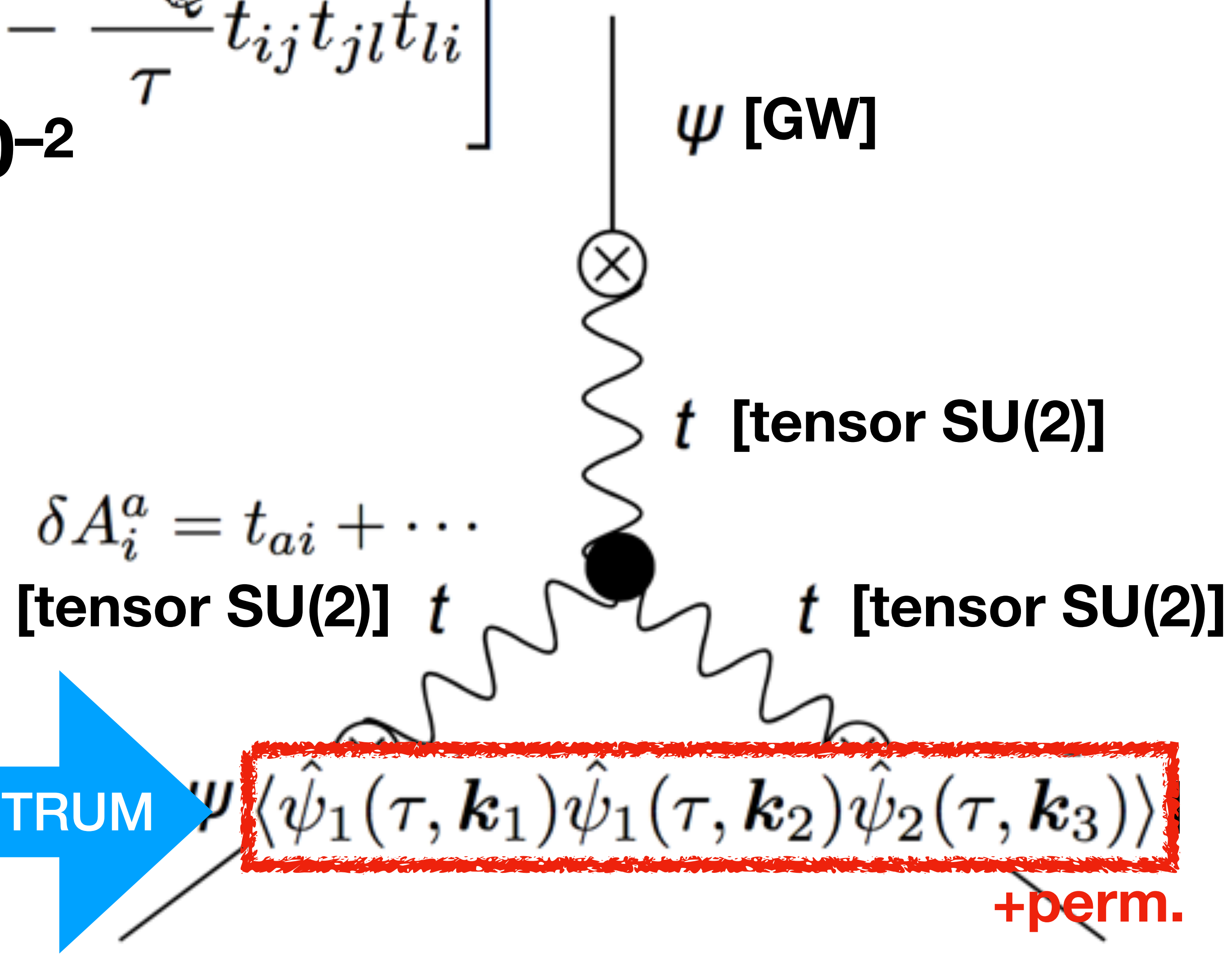
$$L_3^{(i)} = c^{(i)} \left[\epsilon^{abc} t_{ai} t_{bj} \left(\partial_i t_{cj} - \frac{m_Q^2 + 1}{3 m_Q \tau} \epsilon^{ijk} t_{ck} \right) - \frac{m_Q}{\tau} t_{ij} t_{jl} t_{li} \right]$$

$$c^{(i)} = g = m_Q^2 H / \sqrt{\epsilon_B} M_{\rm Pl}$$ **~10^{-2}**

$$\epsilon_B \equiv \frac{g^2 Q^4}{H^2 M_{\rm Pl}^2} \simeq \frac{2\Omega_A}{1 + m_Q^{-2}} \ll 1$$

$m_Q \equiv gQ/H$ **[m_Q ~ a few]**



- This diagram generates second-order equation of motion for GW

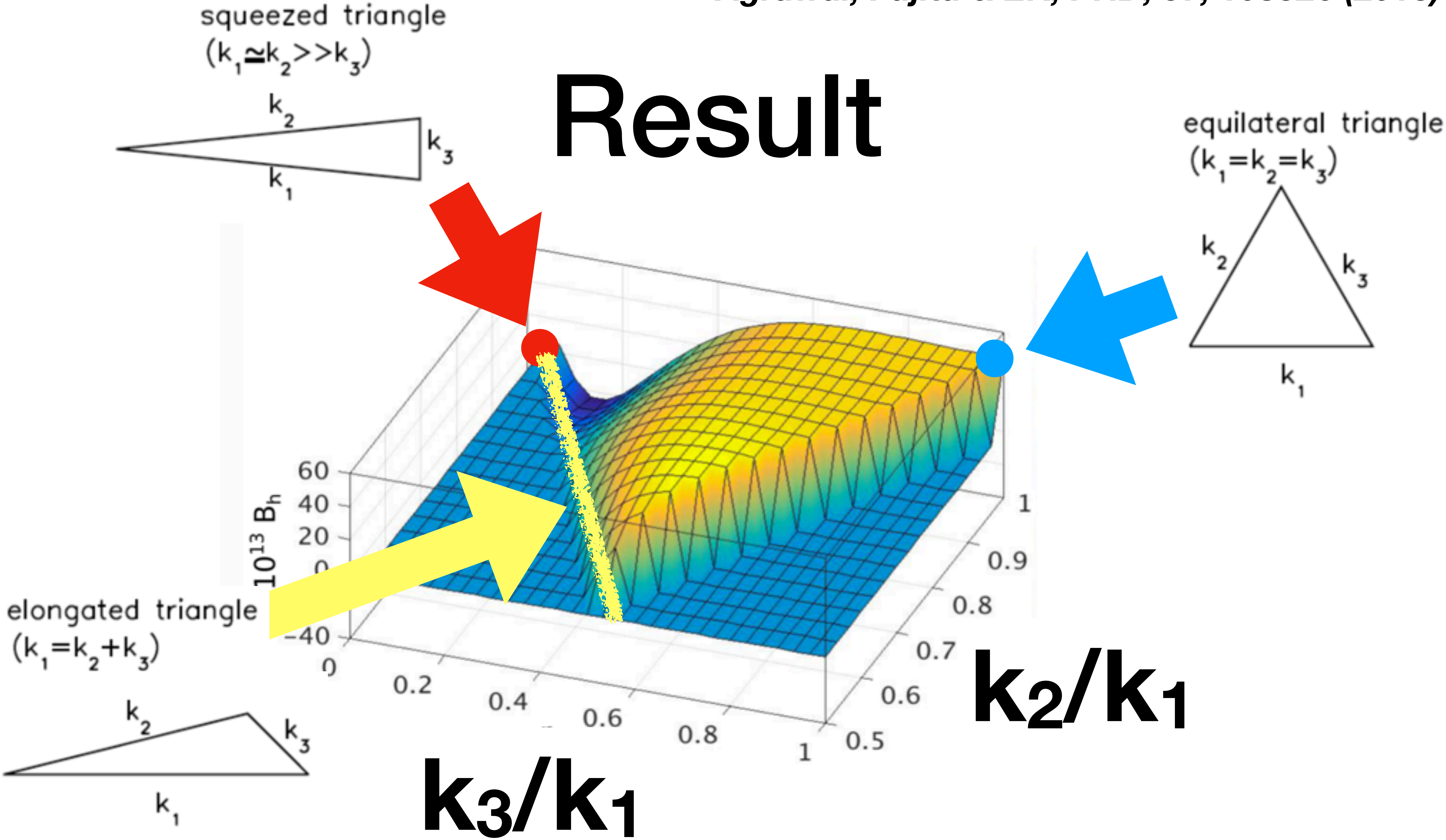
BISPECTRUM

$$\langle \hat{\psi}_1(\tau, \boldsymbol{k}_1) \hat{\psi}_1(\tau, \boldsymbol{k}_2) \hat{\psi}_2(\tau, \boldsymbol{k}_3) \rangle$$

+perm.

Agrawal, Fujita & EK, PRD, 97, 103526 (2018)

Result



- This shape is similar to, but not exactly the same as, what was used by the Planck team to look for tensor bispectrum

Planck Collaboration (2015)

Current Limit on Tensor NG

- The Planck team reported a limit on the tensor bispectrum in the following form:

$$f_{\rm NL}^{\rm tens} \equiv \frac{B_h^{+++}(k,k,k)}{F_{\rm scalar}^{\rm equil.}(k,k,k)}$$

- The denominator is the **scalar** equilateral bispectrum template, giving $F_{\rm scalar}^{\rm equil.}(k,k,k) = (18/5)P_{\rm scalar}^2(k)$
- The current 68%CL constraint is $f_{\rm NL}^{\rm tens} = 400 \pm 1500$

Agrawal, Fujita & EK, PRD, 97, 103526 (2018)

SU(2), confronted

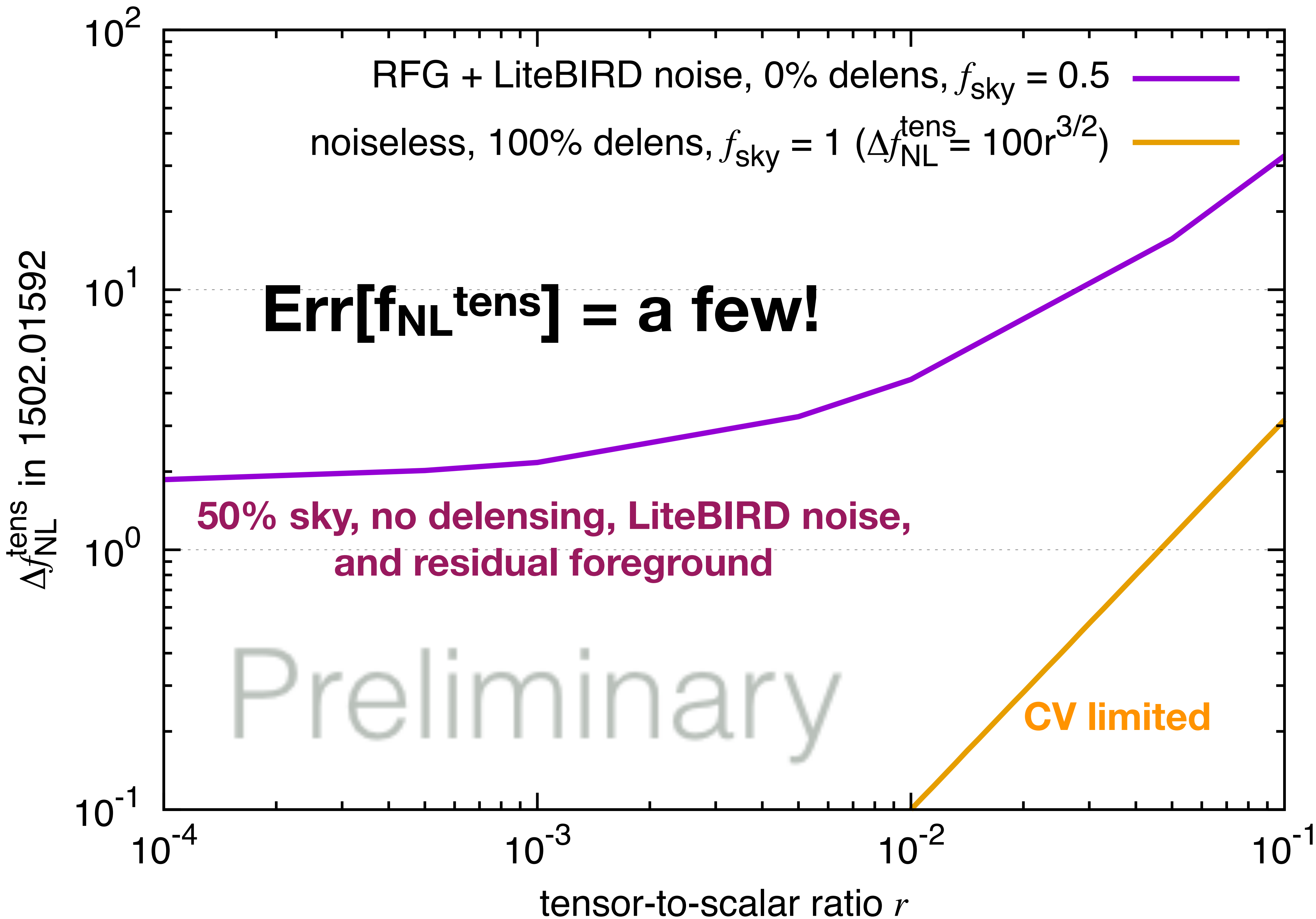
- The SU(2) model of Dimastrogiovanni et al. predicts:

$$f_{\rm NL}^{\rm tens} \approx \frac{125}{18\sqrt{2}}\frac{r^2}{\epsilon_B} \approx 2.5\frac{r^2}{\Omega_A}$$

- The current 68%CL constraint is $f_{\rm NL}^{\rm tens} = 400 \pm 1500$
  - This is already constraining!

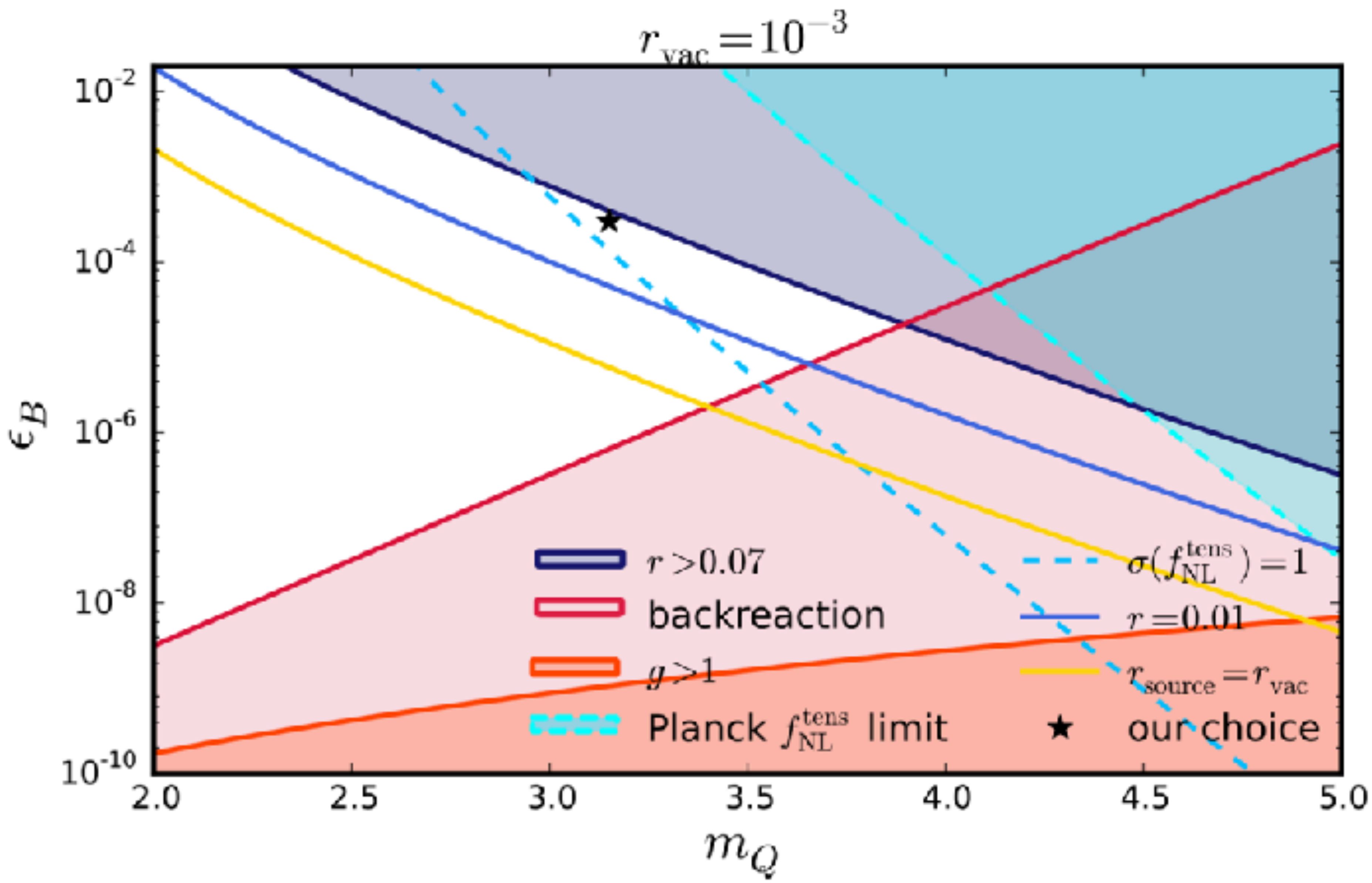
Courtesy of Maresuke Shiraishi

LiteBIRD would nail it!



Agrawal, Fujita & EK, JCAP, 97, 103526 (2018)

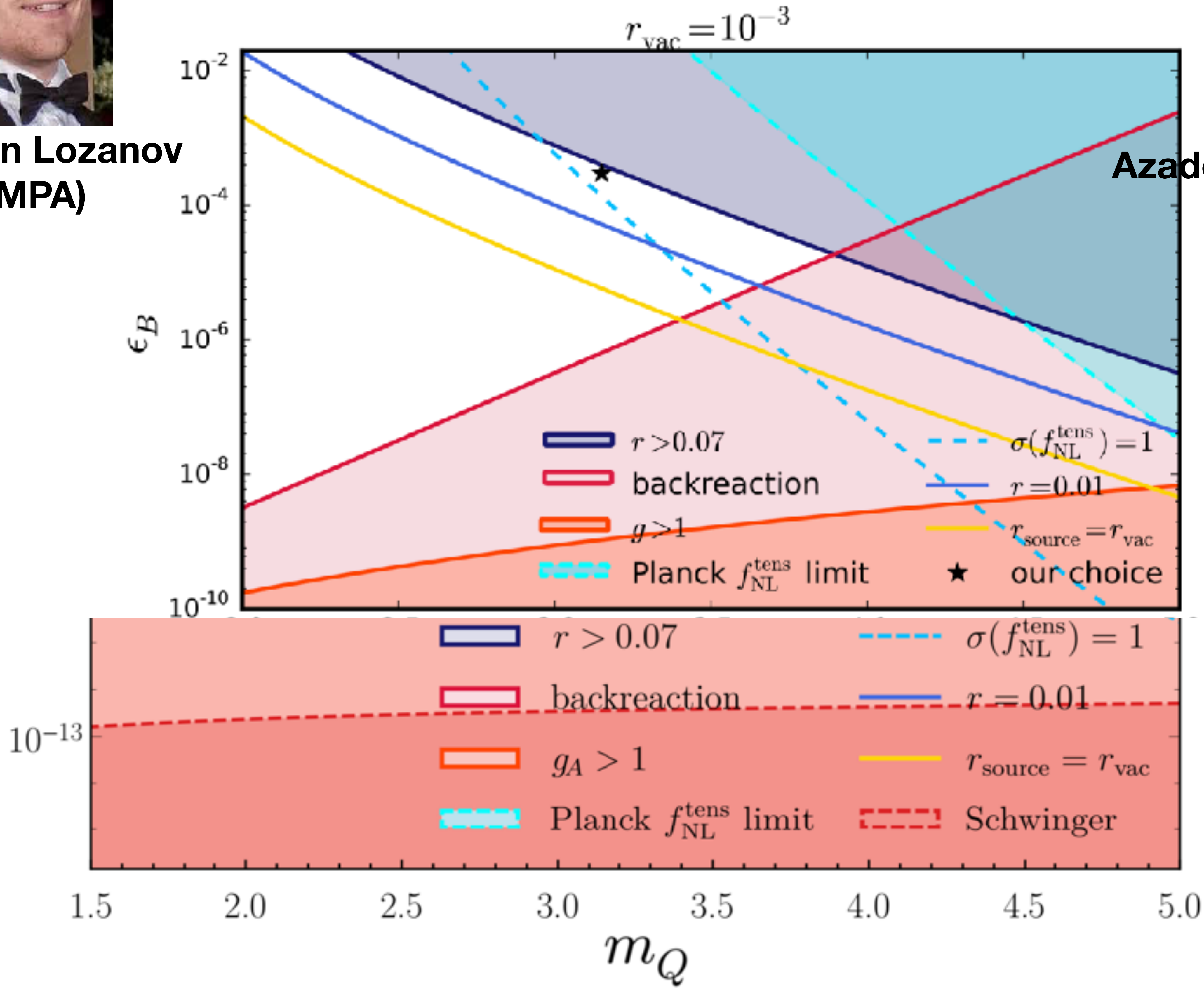
Parameter Scan



Lozanov, Maleknejad & EK, arXiv:1805.09318

Schwinger Effect

Kaloian Lozanov (MPA)



Azadeh Maleknejad (MPA)

Further Remarks

- "*Guys, you are complicating things too much!*"

- **No.** These sources (eg., gauge fields) should be ubiquitous in a high-energy universe. They have every right to produce GWs if they are around

- Sourced GWs with r>>0.001 can be phenomenologically more attractive than the vacuum GW from the large-field inflation [requiring super-Planckian field excursion]. Better radiative stability, etc

- Rich[er] phenomenology: Better integration with the Standard Model; reheating; baryon synthesis via leptogenesis, etc. **Testable using many more probes!**

Better embedding in String Theory?

Observable Chiral Gravitational Waves from Inflation in String Theory

Evan McDonough[1,*] and Stephon Alexander[1,†]

[1]*Department of Physics, Brown University, Providence, RI, USA. 02903*

We consider gravitational wave production during inflation in type IIB string theory, and the possibility of observable gravitational waves in small field inflation. We show that the gauge field excitations on a set of coincident D7 branes, itself critical for moduli stabilization and hence intrinsic to inflation in string theory, coupled with axion fields from bulk fluxes, can act as a spectator sector during inflation. This results in a large production of chiral gravitational waves, even for relatively small values of the axion-gauge field coupling. We extend this to include a monodromy for the axion, and demonstrate that in both cases an observable level of gravitational waves is produced in small field inflation in string theory, with a spectrum that is maximally chiral. Finally, we demonstrate the consistency with moduli stabilization and with arbitrary (large or small field) inflationary dynamics of the host model, considering as an explicit example Kahler Moduli Inflation.

arXiv:1806.05684

Speculation

- You might have heard that the Ekpyrotic/Cyclic/Bounce cosmologies cannot produce detectable gravitational waves
- Can we use the axion-SU(2) mechanism to produce detectable gravitational waves from these cosmologies?
  - To do this, you first need to show that the isotropic configuration of SU(2) is an attractor in these cosmologies
  - I don’t know if this is the case; worth checking?

Conclusions

- CMB has played and continues to play vital roles in testing our wild ideas about the physics of the early Universe
  - Tremendous progress (7 orders of magnitude in power!) over the last 25 years
  - Another two orders of magnitude in planning over the next decade
- **New paradigm for the gravitational waves from the early Universe!** Do not ignore the right hand side of the wave equation!