

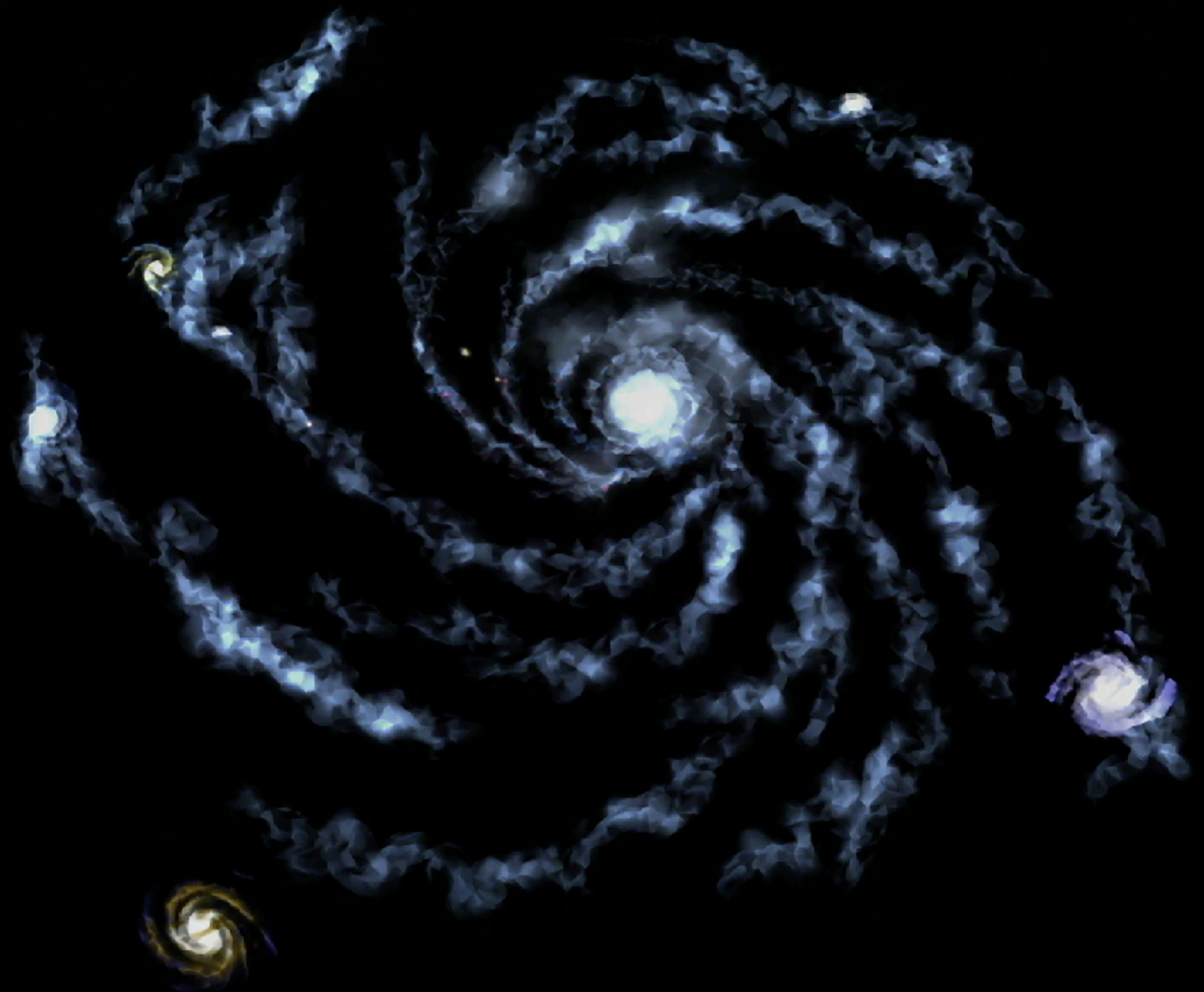
Finding gravitational waves from the early Universe

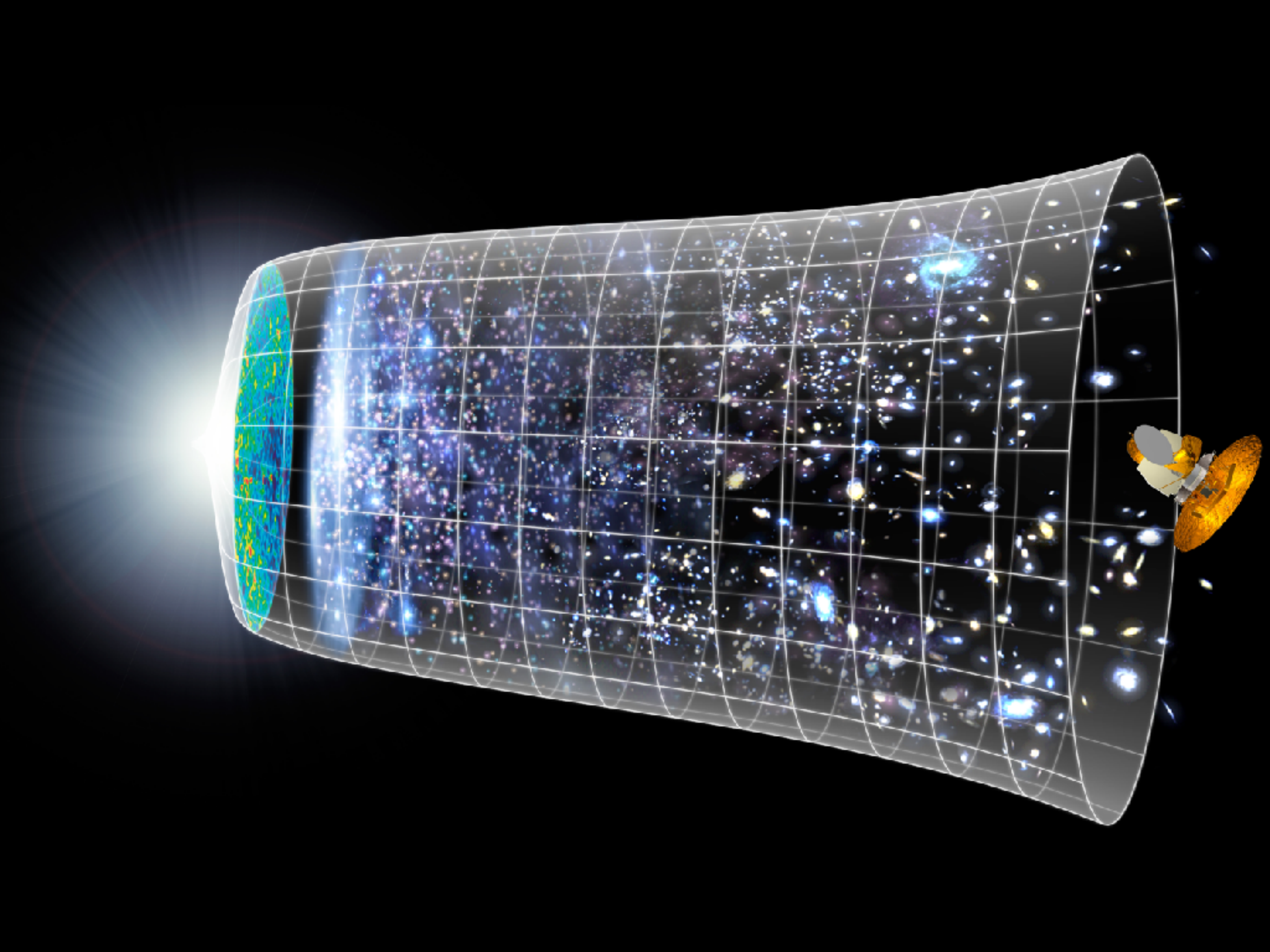
Eiichiro Komatsu

[Max Planck Institute for Astrophysics]

Seminar at ARC, Univ. of KwaZulu-Natal

September 11, 2020





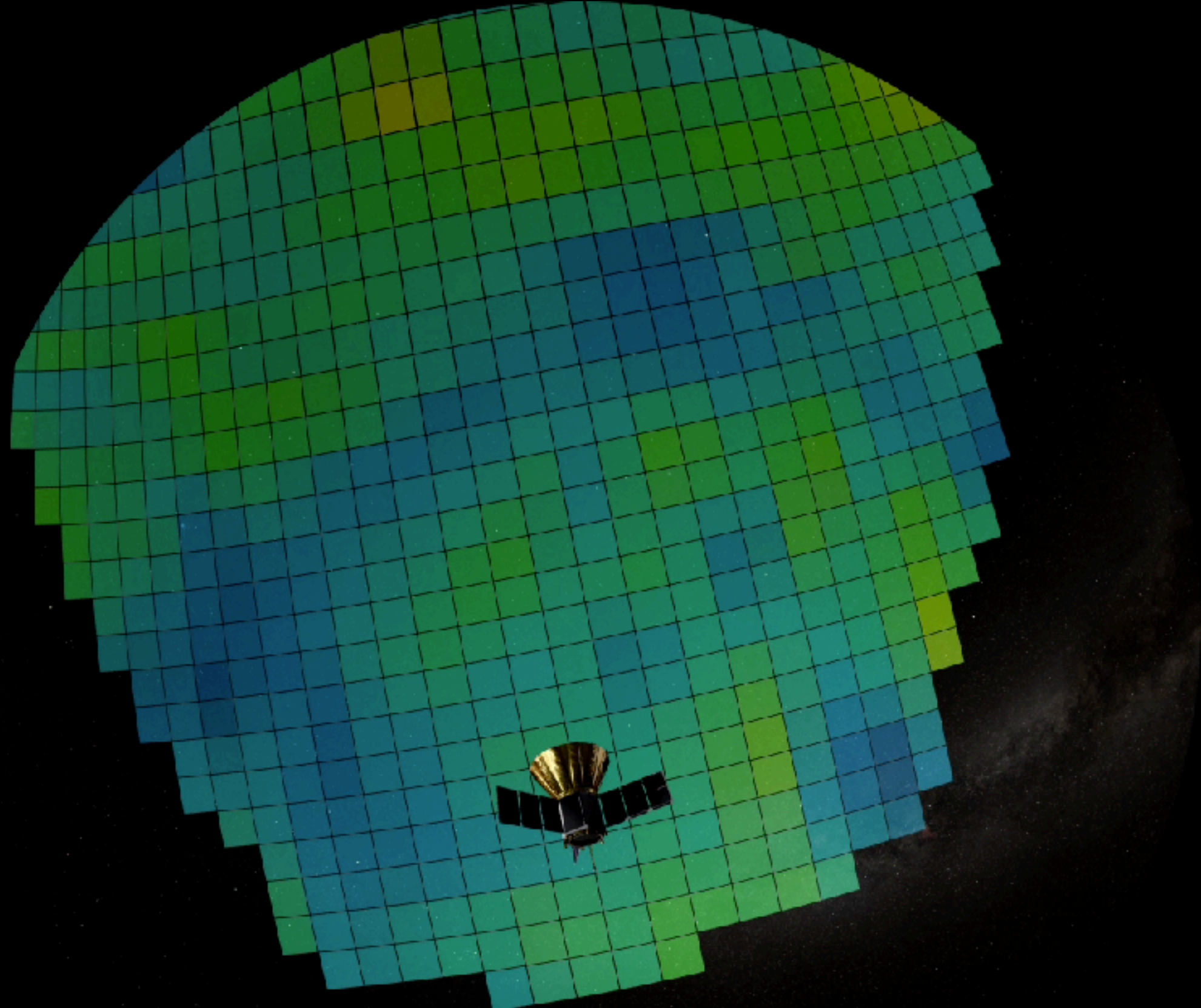


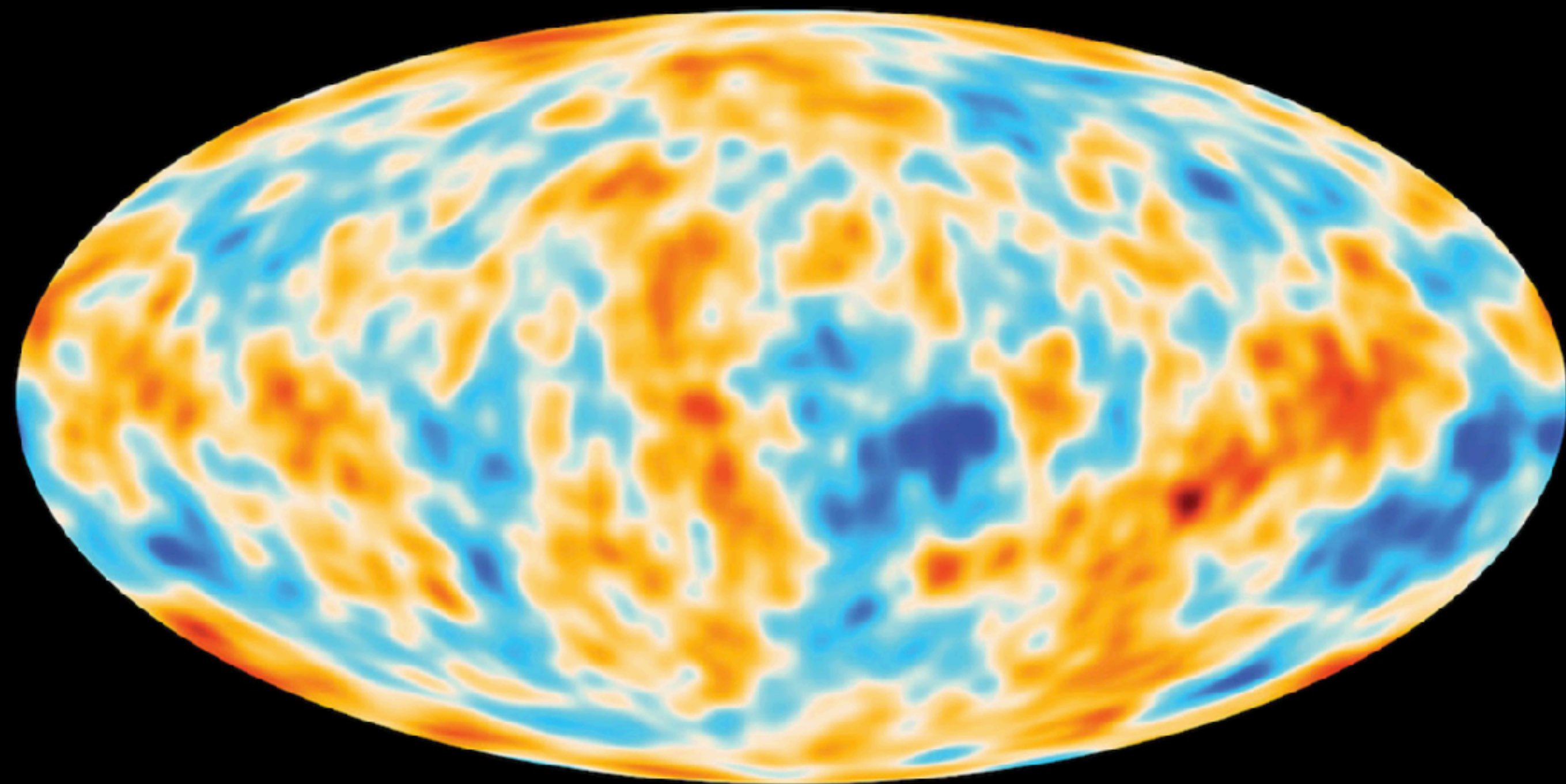
Full-dome movie for planetarium

Director: Hiromitsu Kohsaka

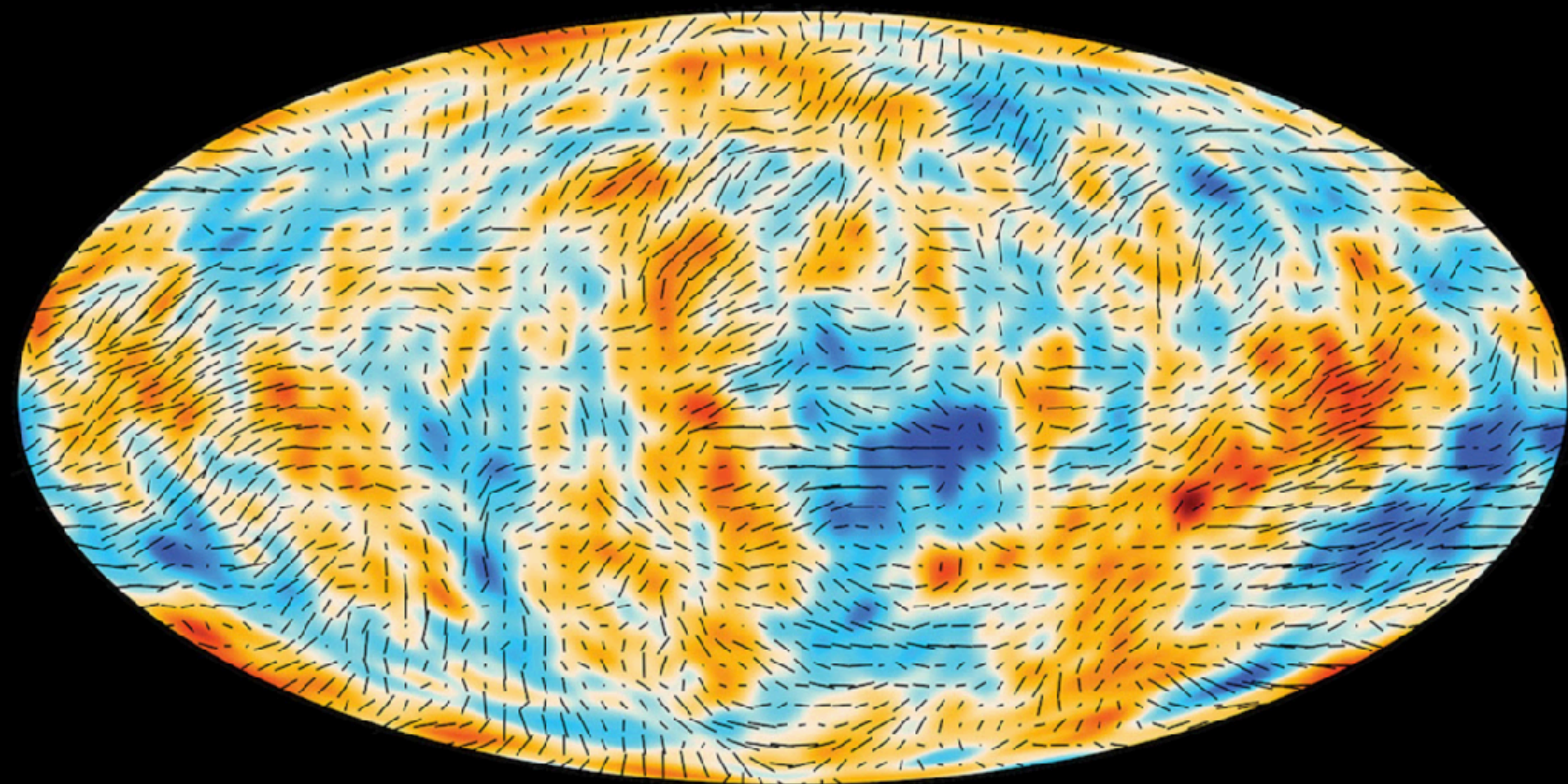


HORIZON :Beyond the Edge of the Visible Universe [Trailer]



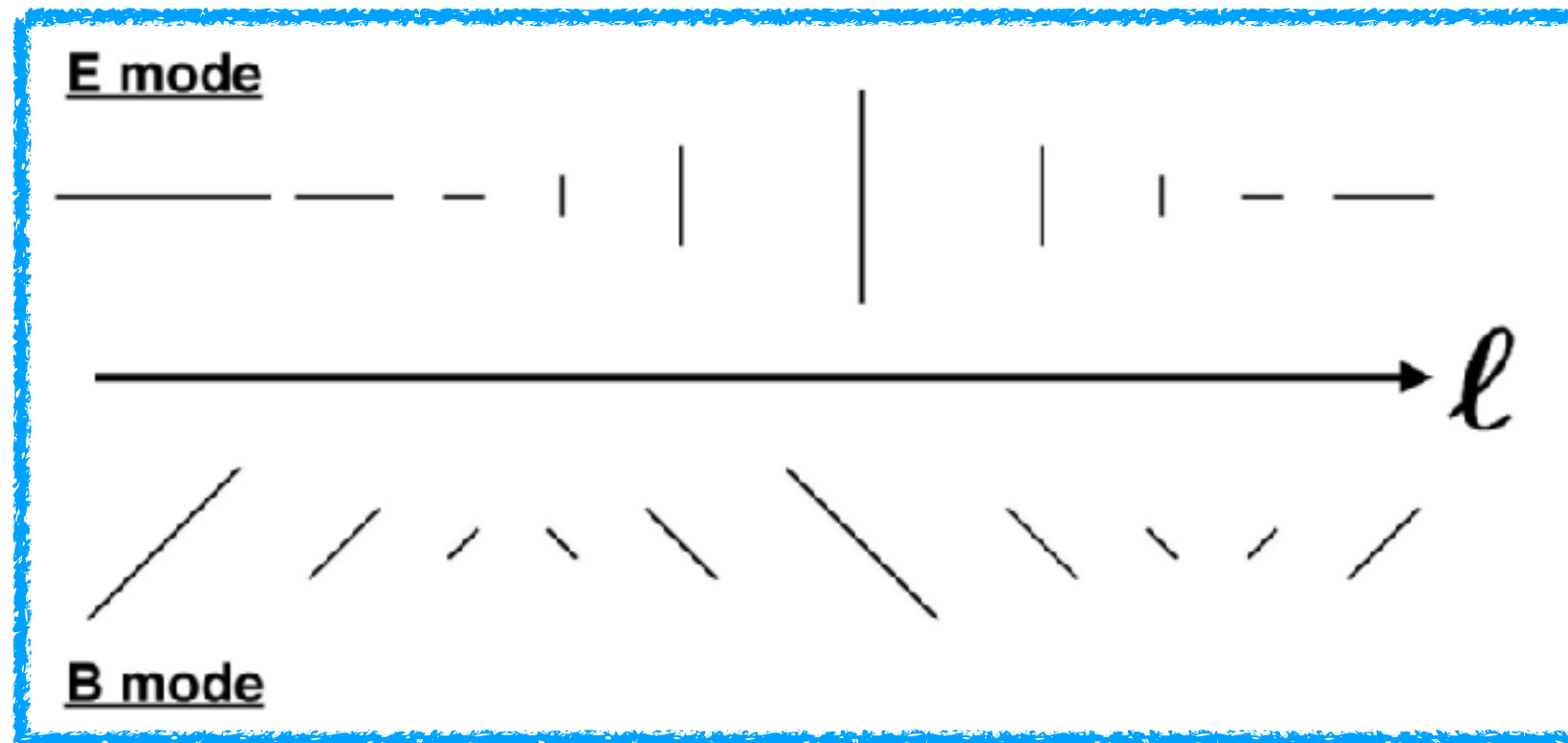


Temperature (smoothed)



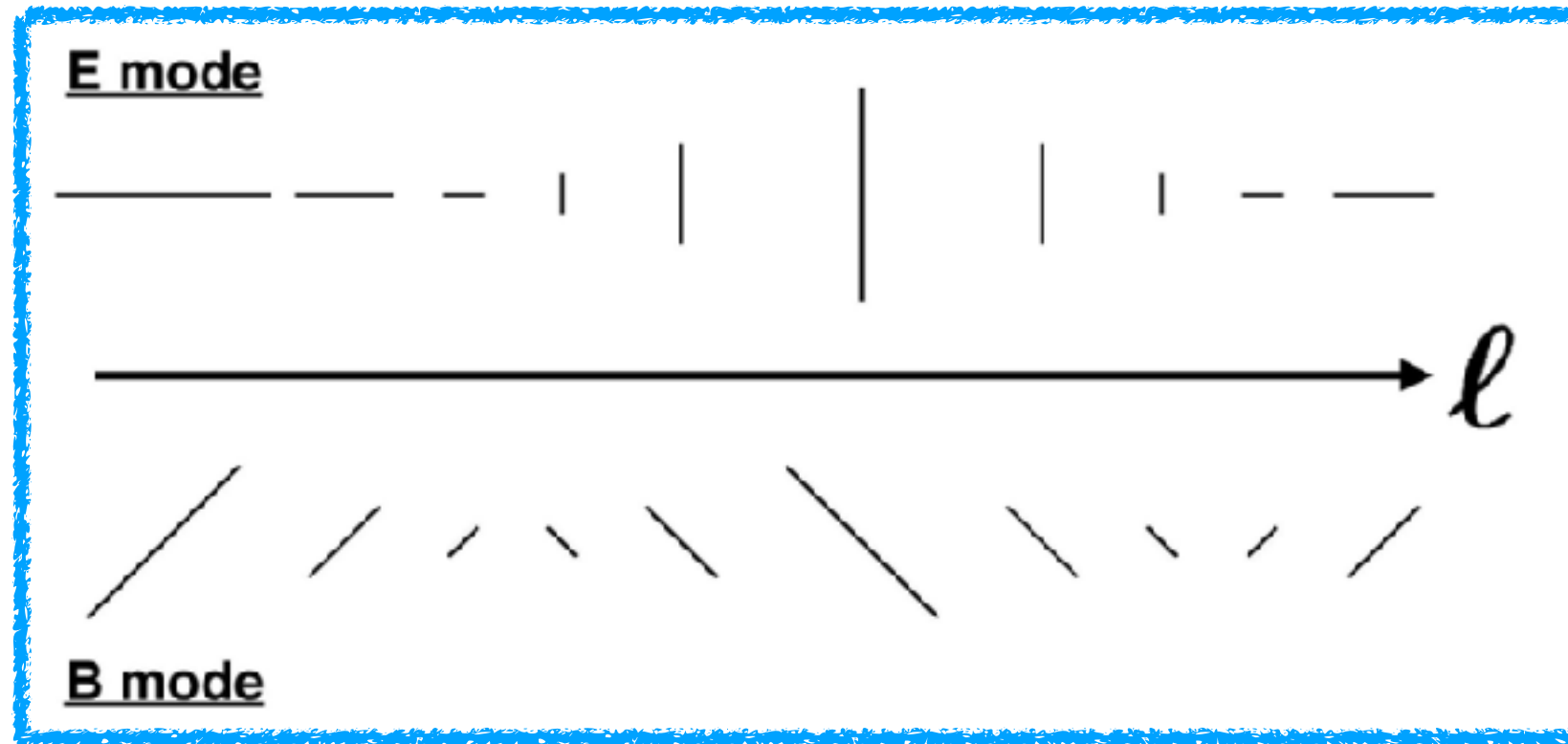
Temperature (smoothed) + Polarisation

E and B mode



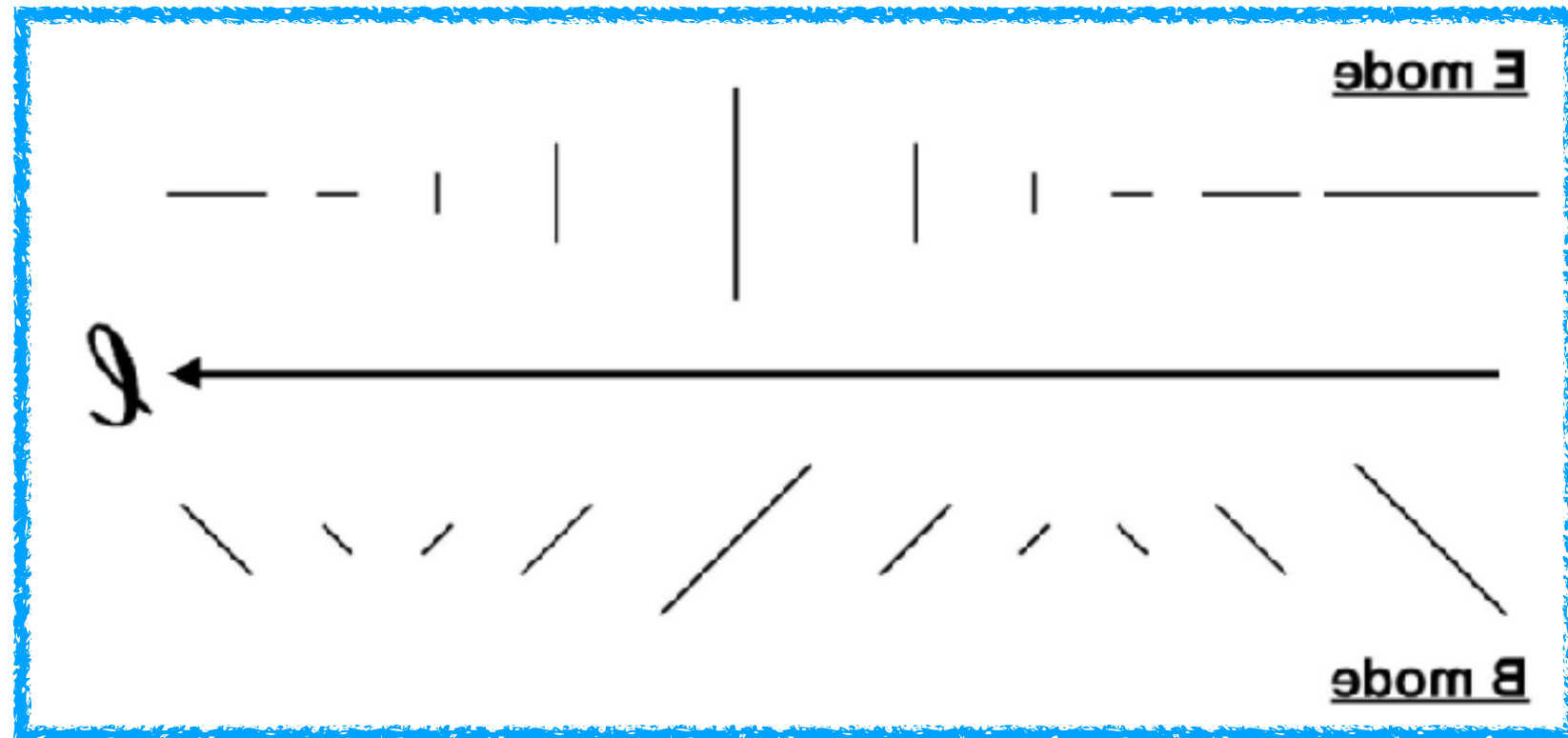
- **E mode**: Polarisation directions **parallel or perpendicular** to the wavevector
- **B mode**: Polarisation directions **45 degree tilted** with respect to the wavevector

Parity

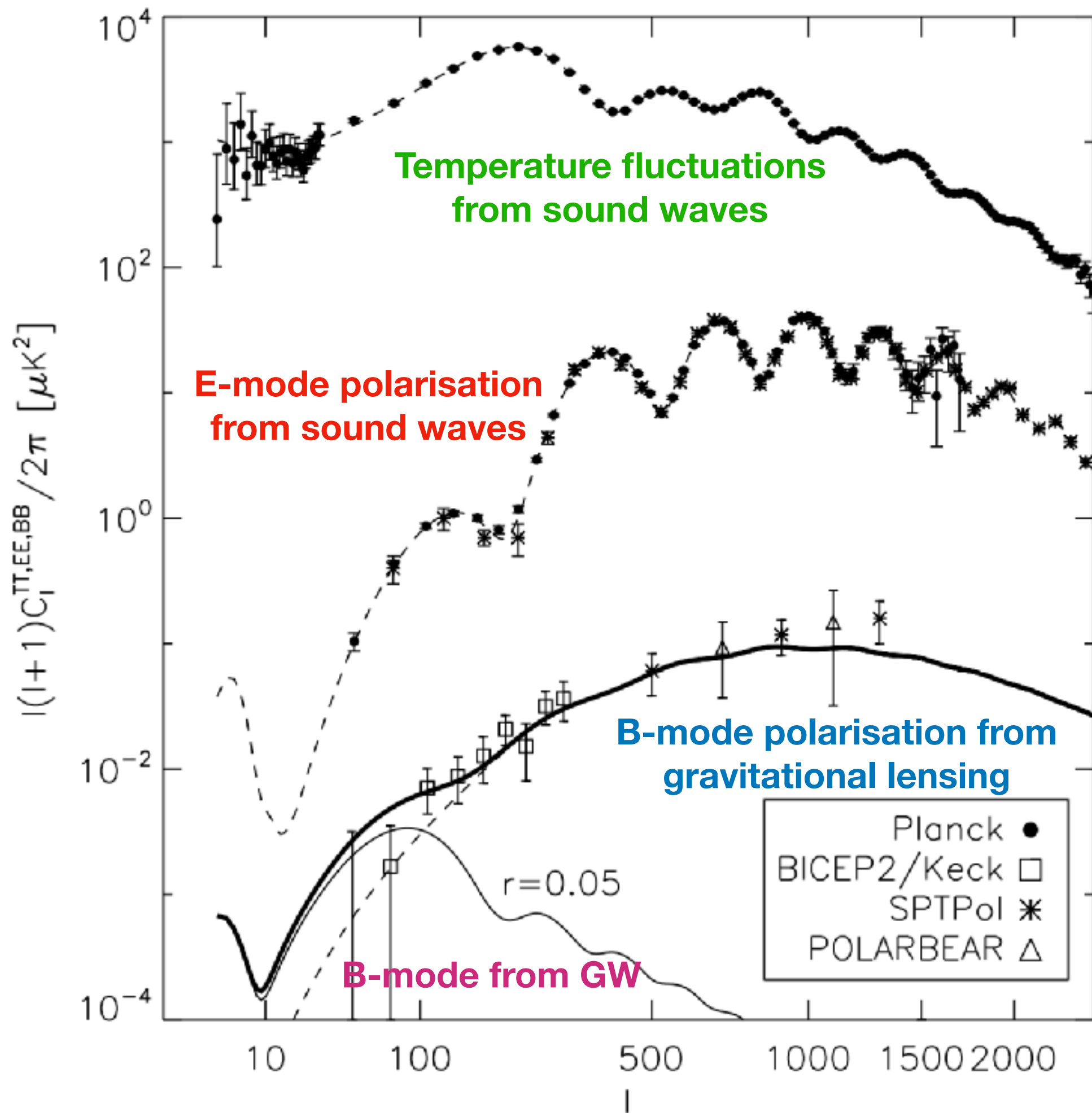


- E mode: Parity even
- B mode: Parity odd

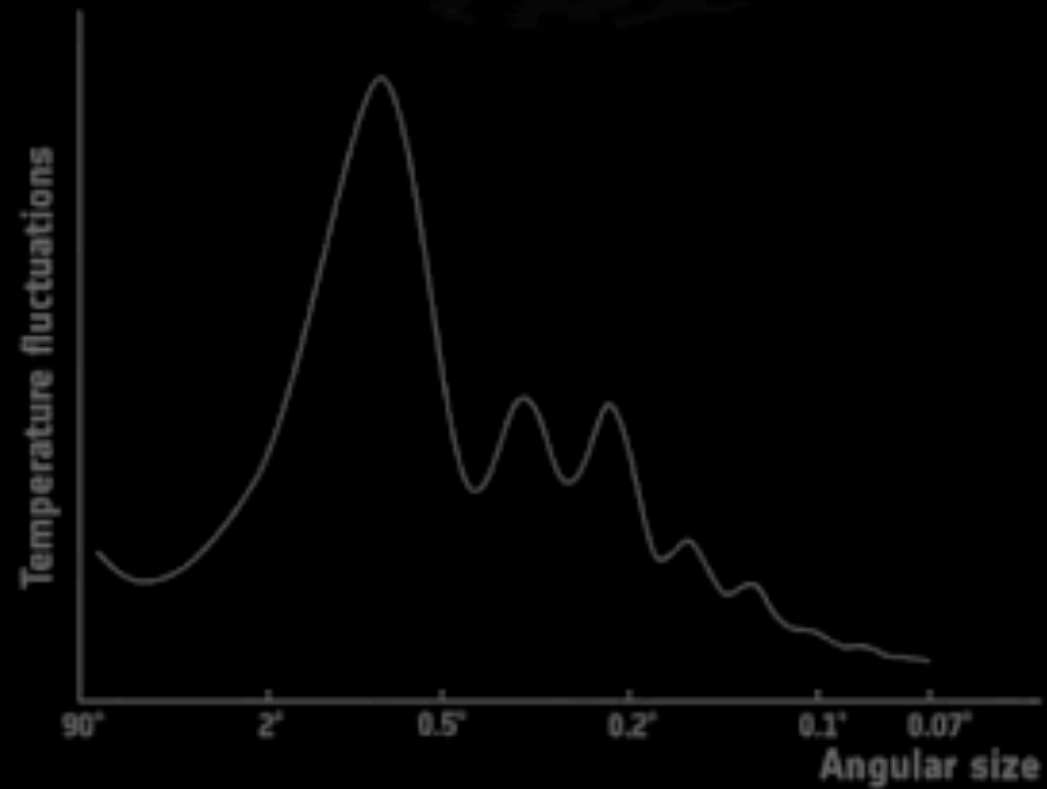
Parity



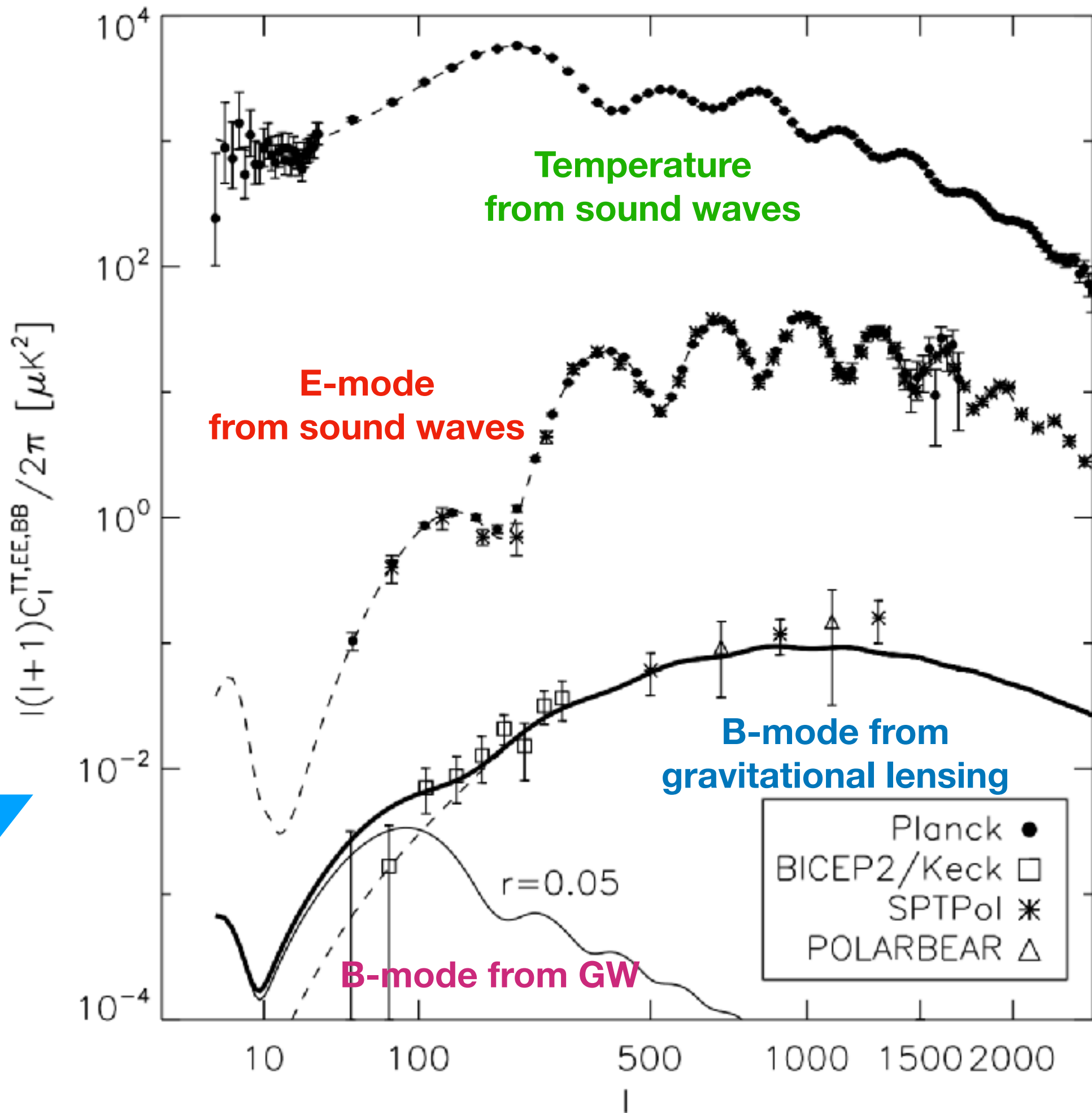
- E mode: Parity even
- B mode: Parity odd



Power spectrum, explained



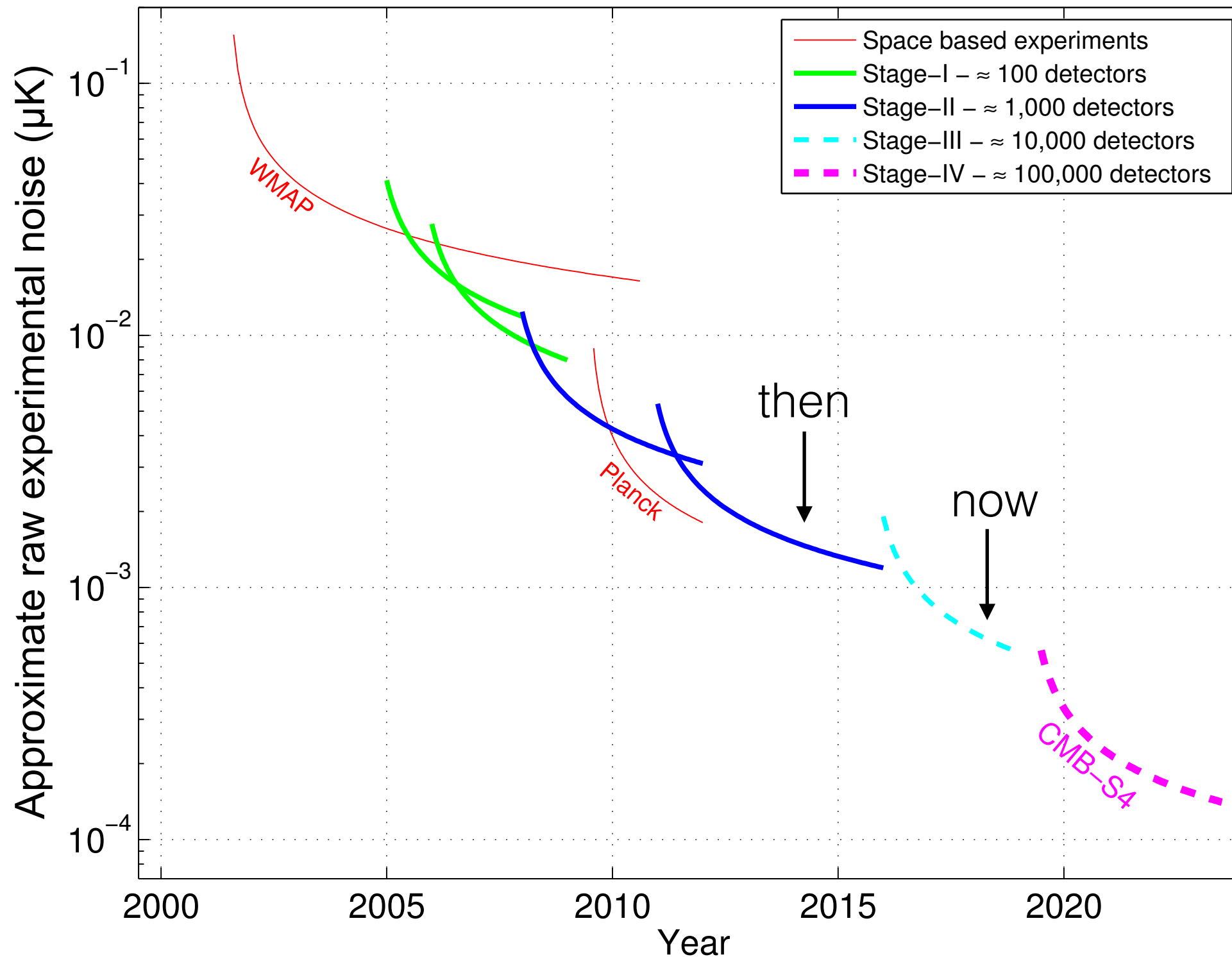
Seven orders of magnitude in power
in “just” 25 years



CMB-S4

Next Generation CMB Experiment

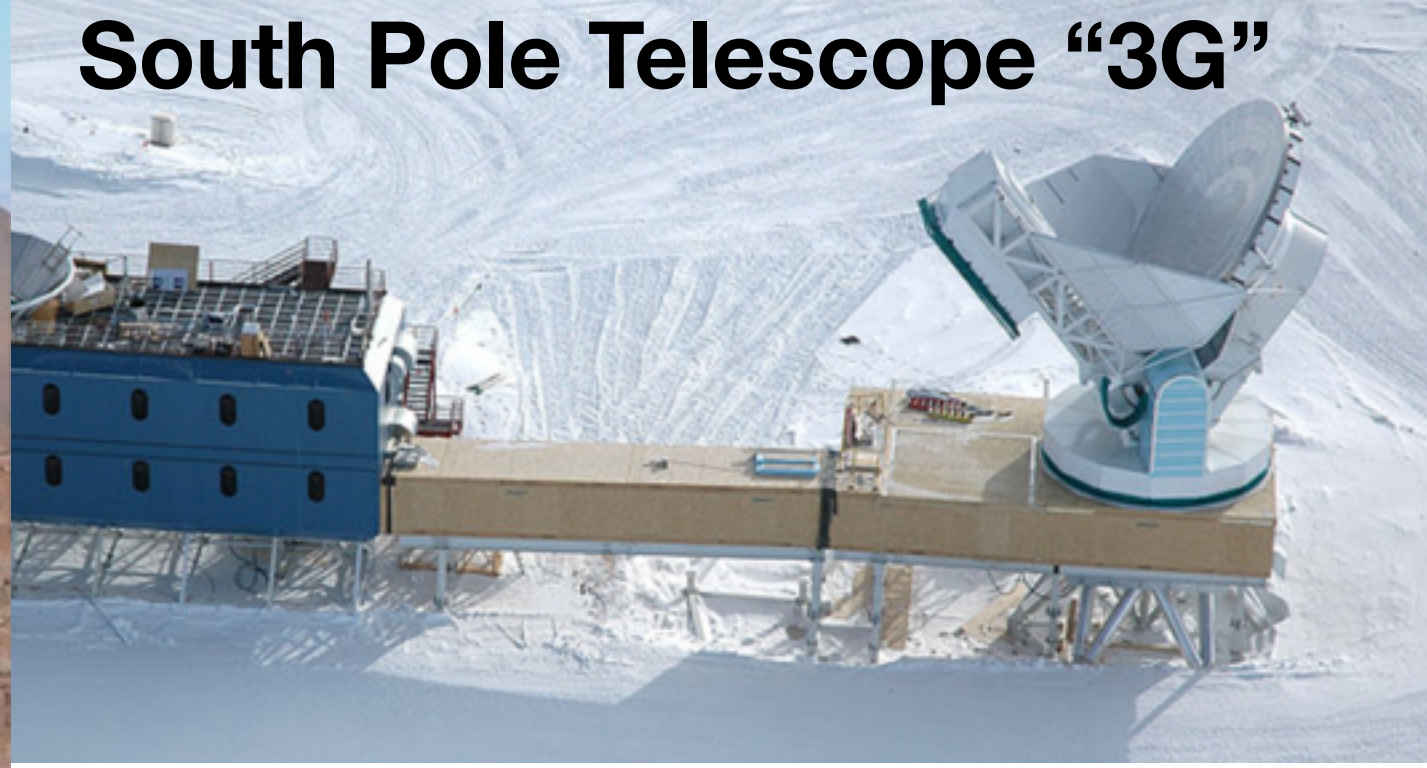
CMB Stages



**Advanced Atacama
Cosmology Telescope**

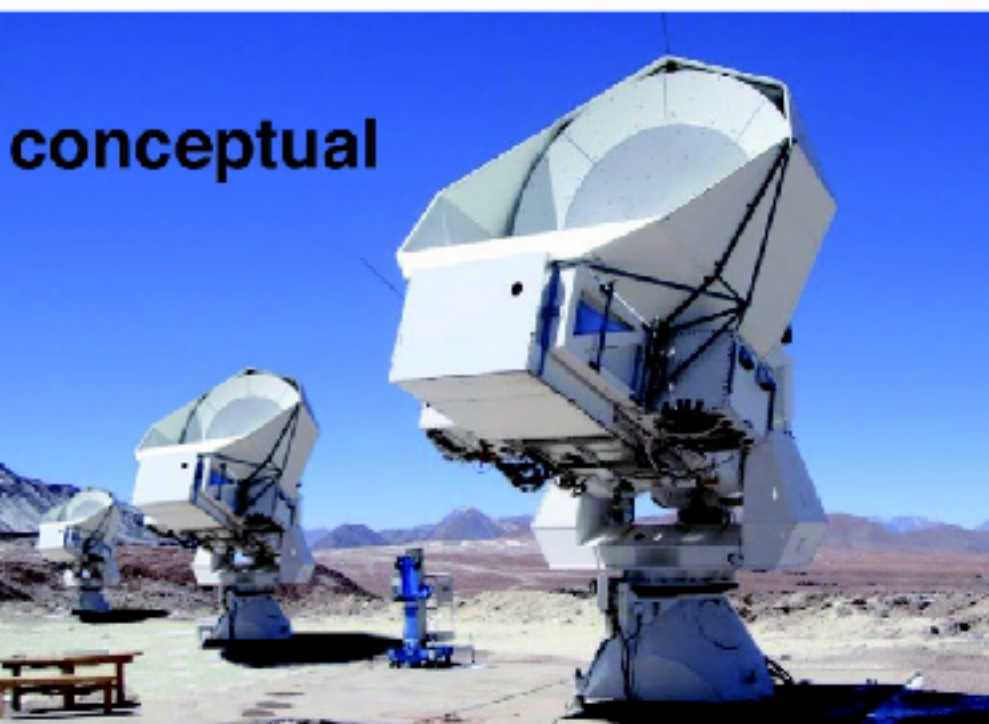


South Pole Telescope “3G”



What comes next?

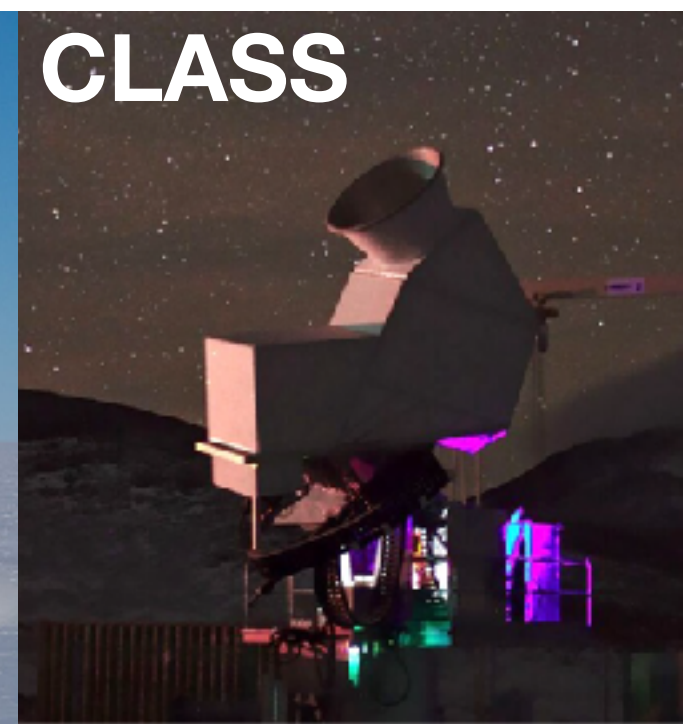
The Simons Array



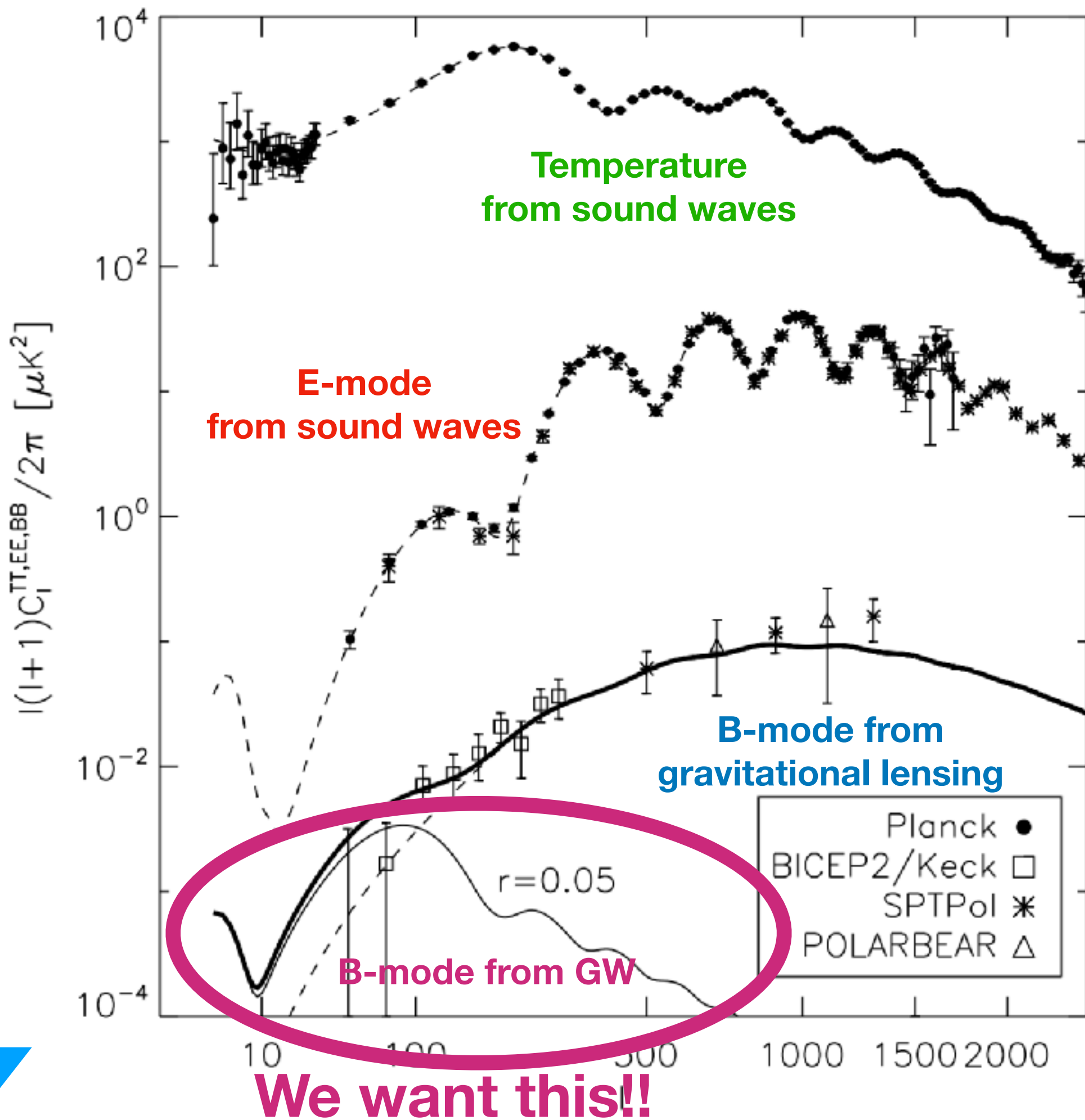
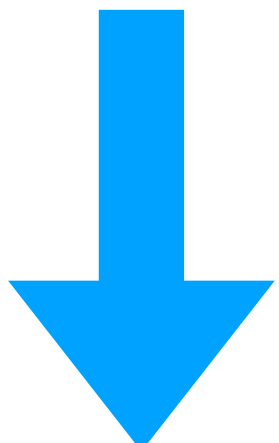
BICEP/Keck Array



CLASS



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



JAXA

+ participations from
USA, Canada, Europe

LiteBIRD 2028–



Polarisation satellite dedicated to
measure CMB polarisation from
primordial GW, with a few thousand
TES bolometers in space

JAXA

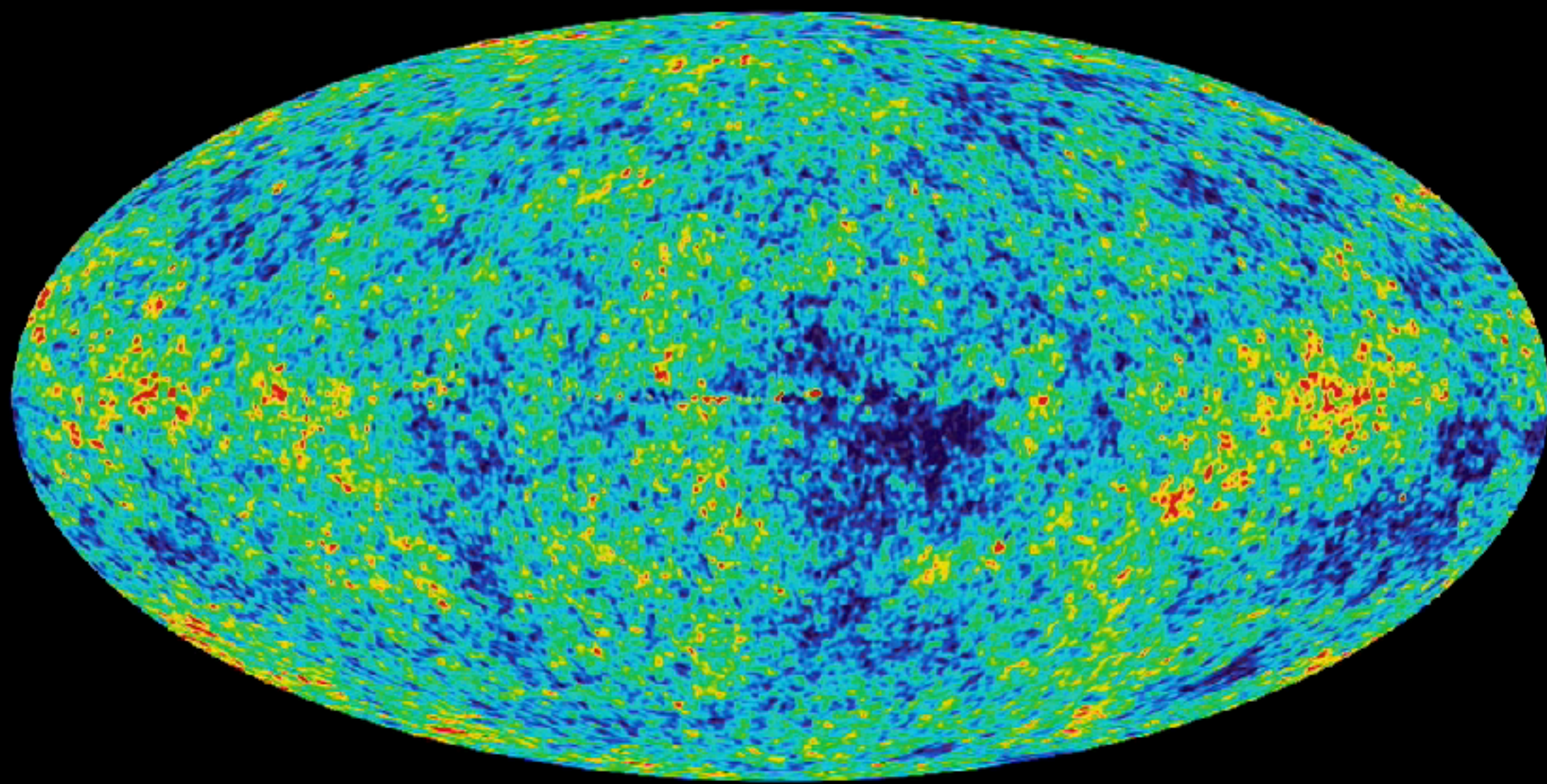
+ participations from
USA, Canada, Europe



LiteBIRD 2028—

Selected!

May 21: JAXA has chosen LiteBIRD
as the strategic large-class mission.
We will go to L2!



A Remarkable Story

- Observations of the cosmic microwave background and their interpretation taught us that **galaxies, stars, planets, and ourselves originated from tiny fluctuations in the early Universe**
- *But, **what** generated the initial fluctuations?*

Leading Idea

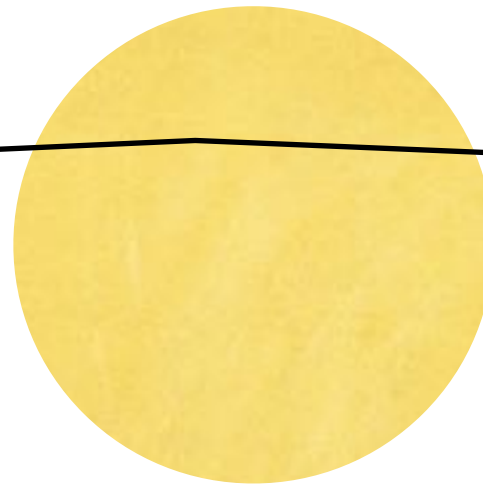
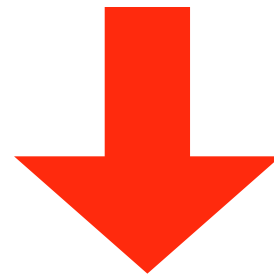
- Quantum mechanics at work in the early Universe
 - “*We all came from quantum fluctuations*”
- But, how did quantum fluctuations on the *microscopic* scales become *macroscopic* fluctuations over large distances?
- What is the **missing link** between small and large scales?

Cosmic Inflation

Quantum fluctuations on
microscopic scales



Inflation!

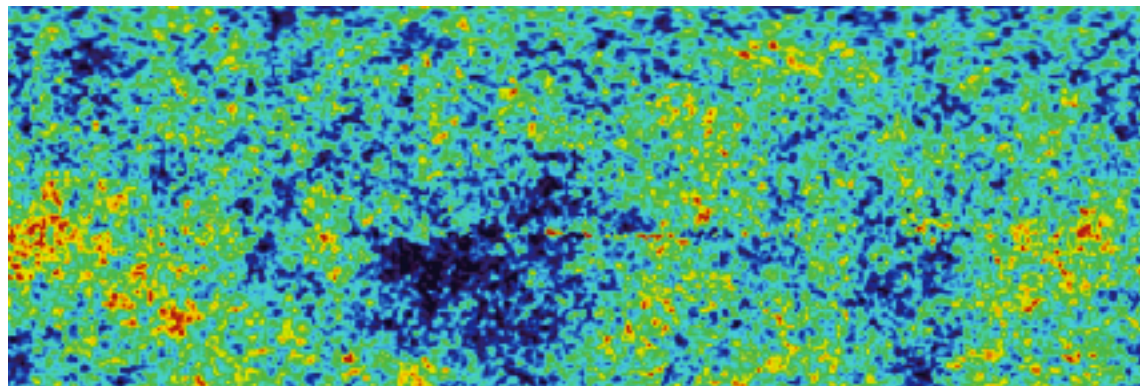
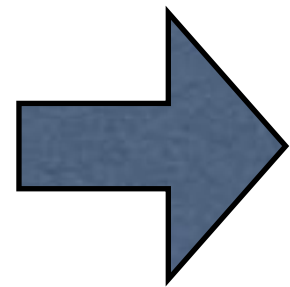


- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

Inflationary Predictions

 ζ

scalar
mode

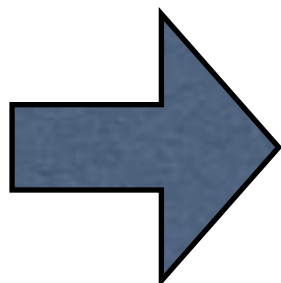


Mukhanov&Chibisov (1981)
Guth & Pi (1982)
Hawking (1982)
Starobinsky (1982)
Bardeen, Steinhardt&Turner (1983)

- Fluctuations we observe today in CMB and the matter distribution originate from quantum fluctuations during inflation

 h_{ij}

tensor
mode



Grishchuk (1974)
Starobinsky (1979)

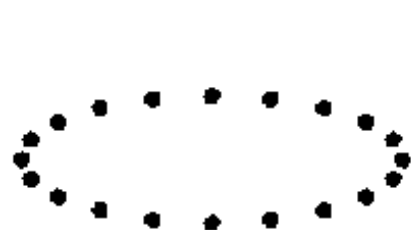
- There should also be *ultra long-wavelength* gravitational waves generated during inflation

We measure distortions in space

- A distance between two points in space

$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

- ζ : “curvature perturbation” (scalar mode)
 - Perturbation to the determinant of the spatial metric
- h_{ij} : “gravitational waves” (tensor mode)
 - Perturbation that does not alter the determinant

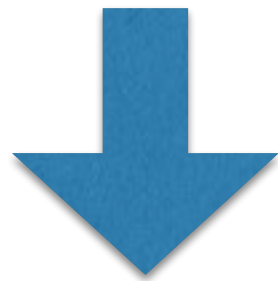


$$\sum_i h_{ii} = 0$$

Measuring GW

- GW changes distances between two points

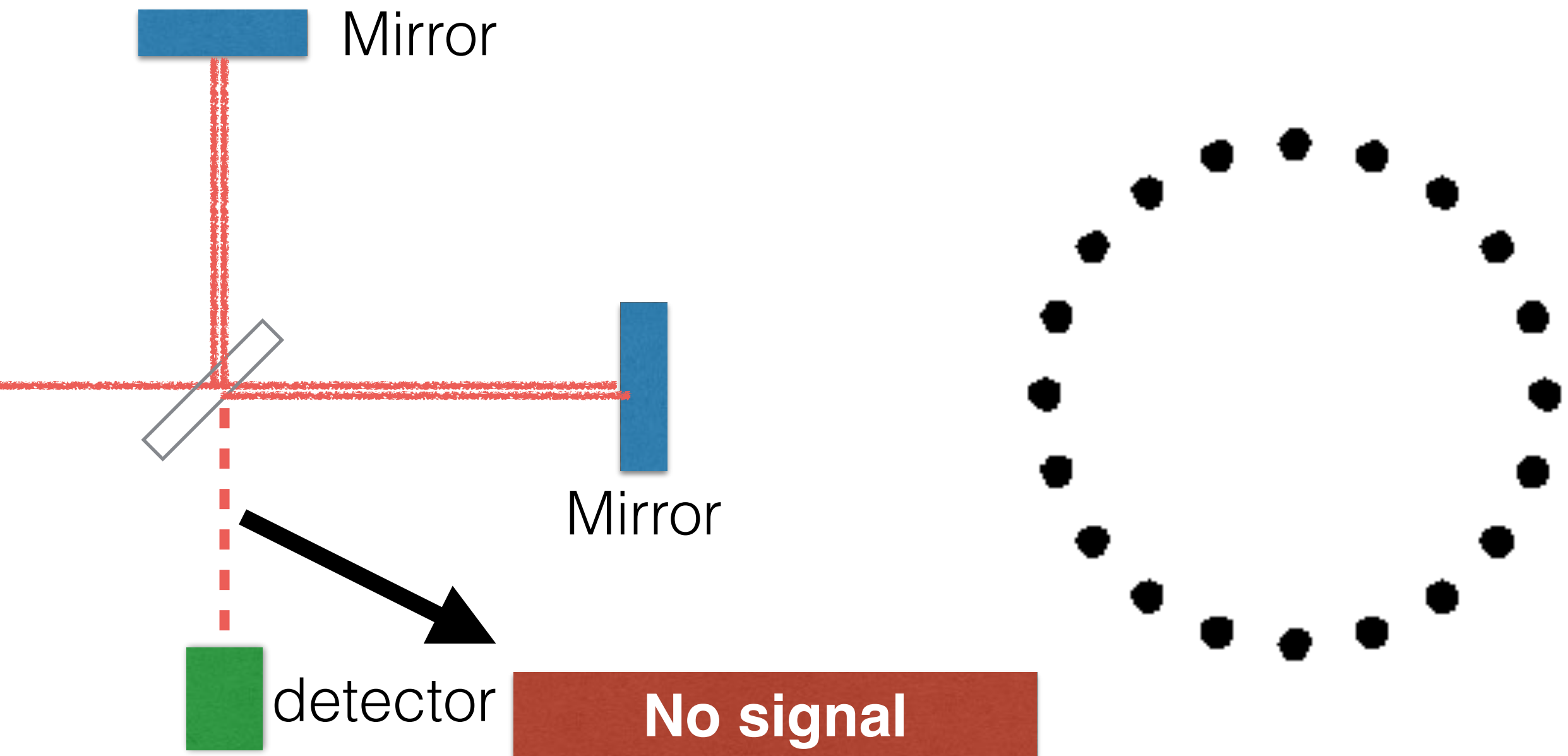
$$d\ell^2 = d\mathbf{x}^2 = \sum_{ij} \delta_{ij} dx^i dx^j$$



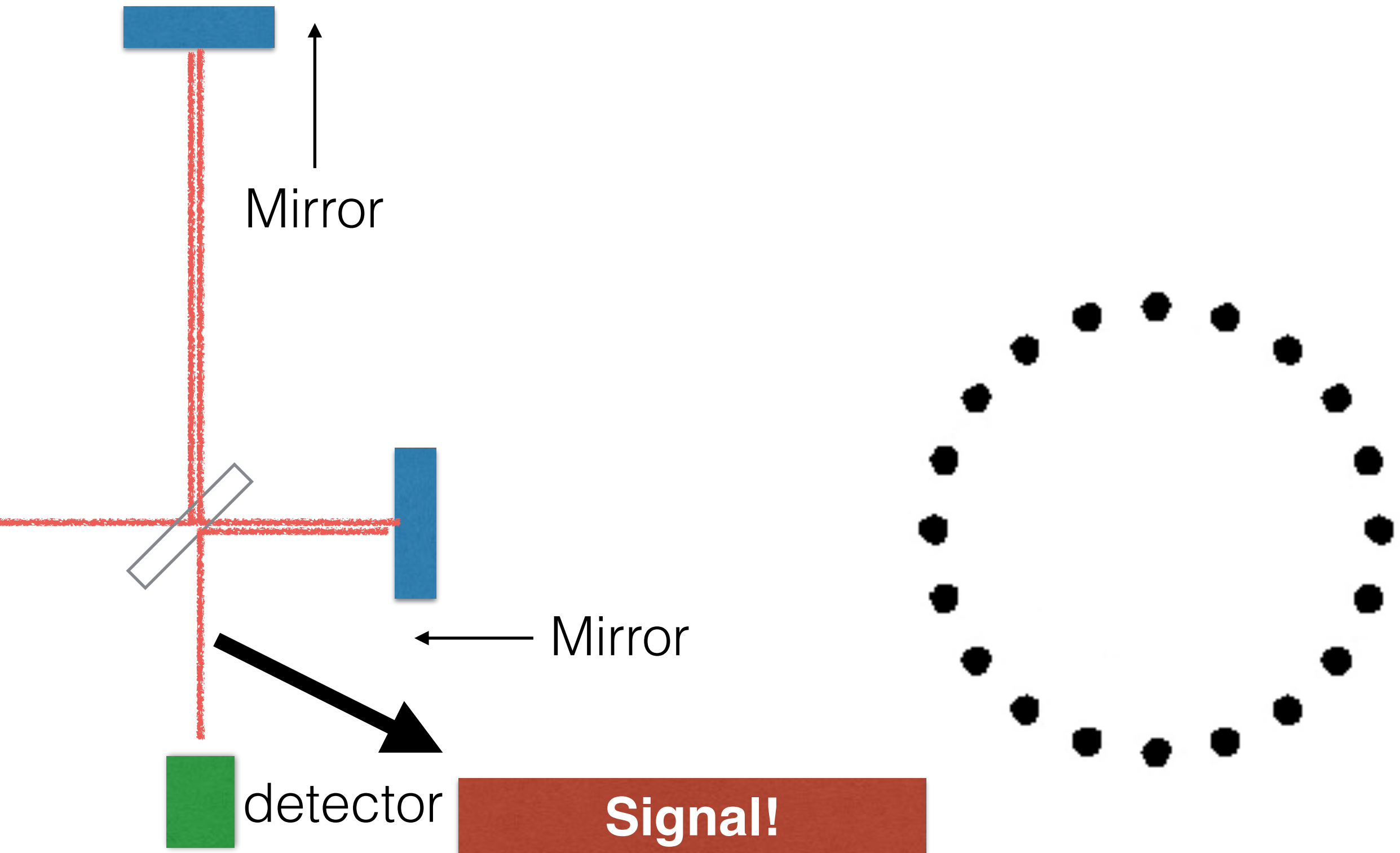
$$d\ell^2 = \sum_{ij} (\delta_{ij} + \textcolor{red}{h_{ij}}) dx^i dx^j$$



Laser Interferometer



Laser Interferometer



LIGO detected GW from a binary blackholes, with the wavelength of thousands of kilometres

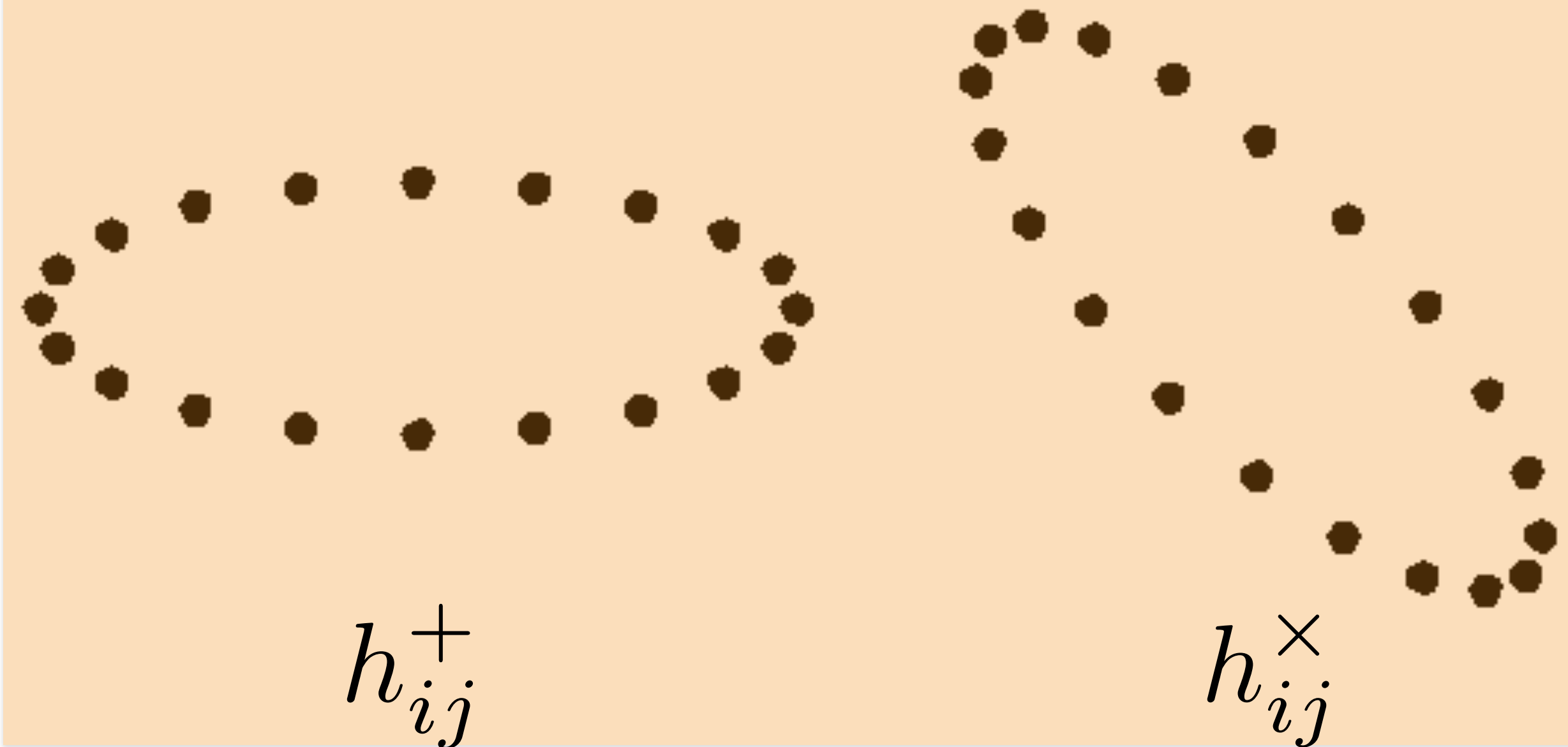
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years!!** How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

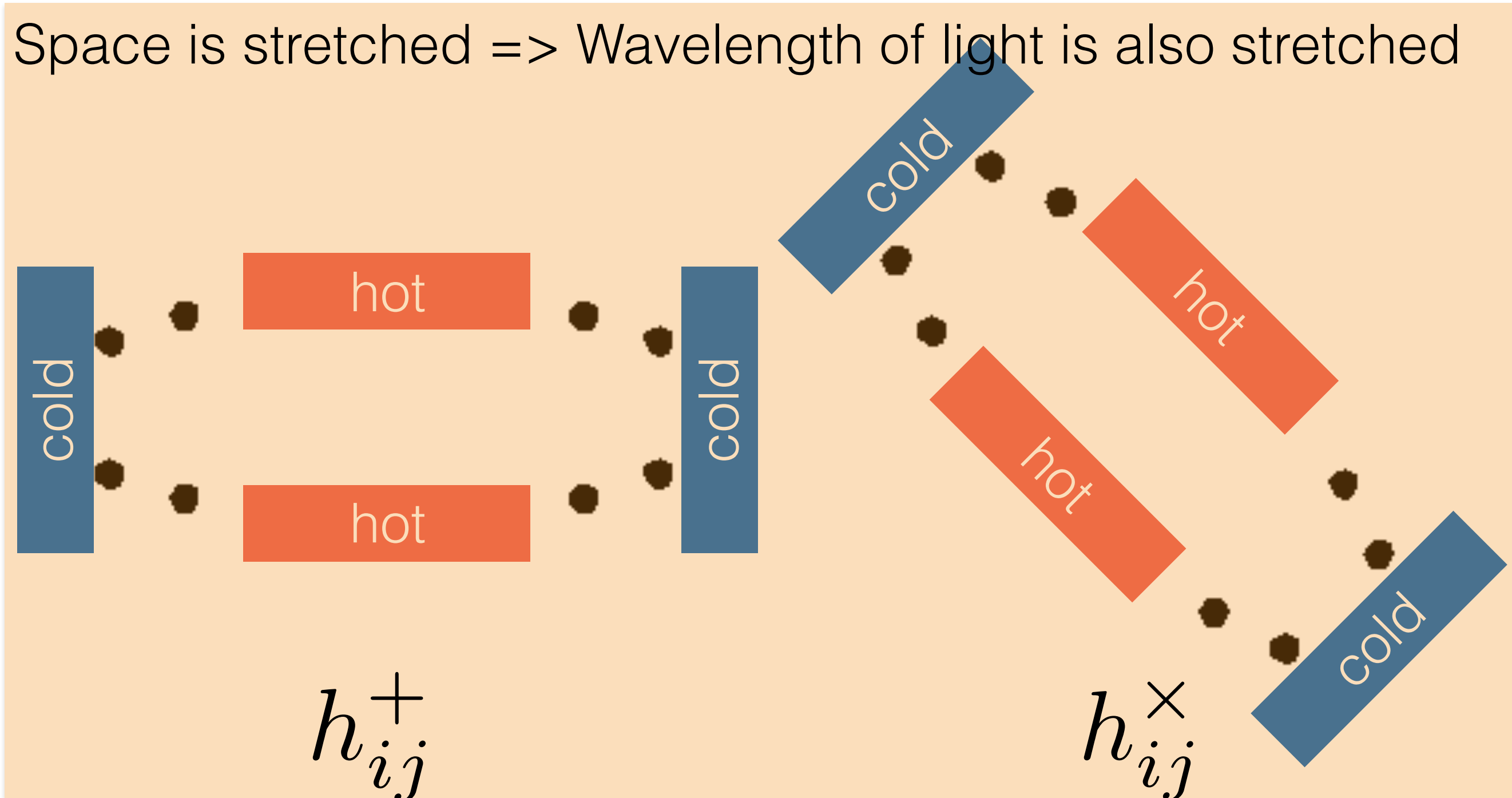
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



Detecting GW by CMB

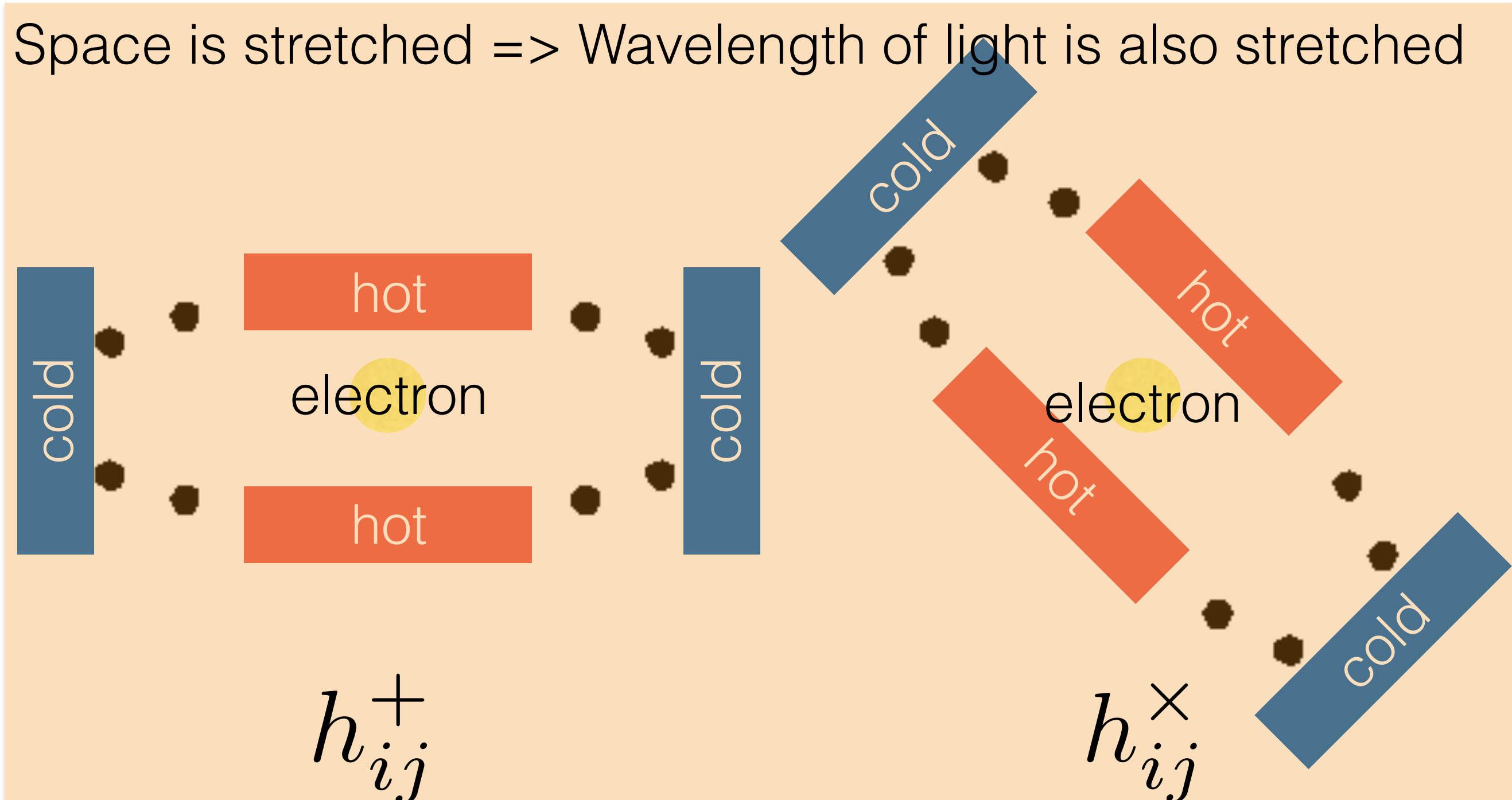
Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB

Polarisation

Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB

Polarisation

Space is stretched => Wavelength of light is also stretched

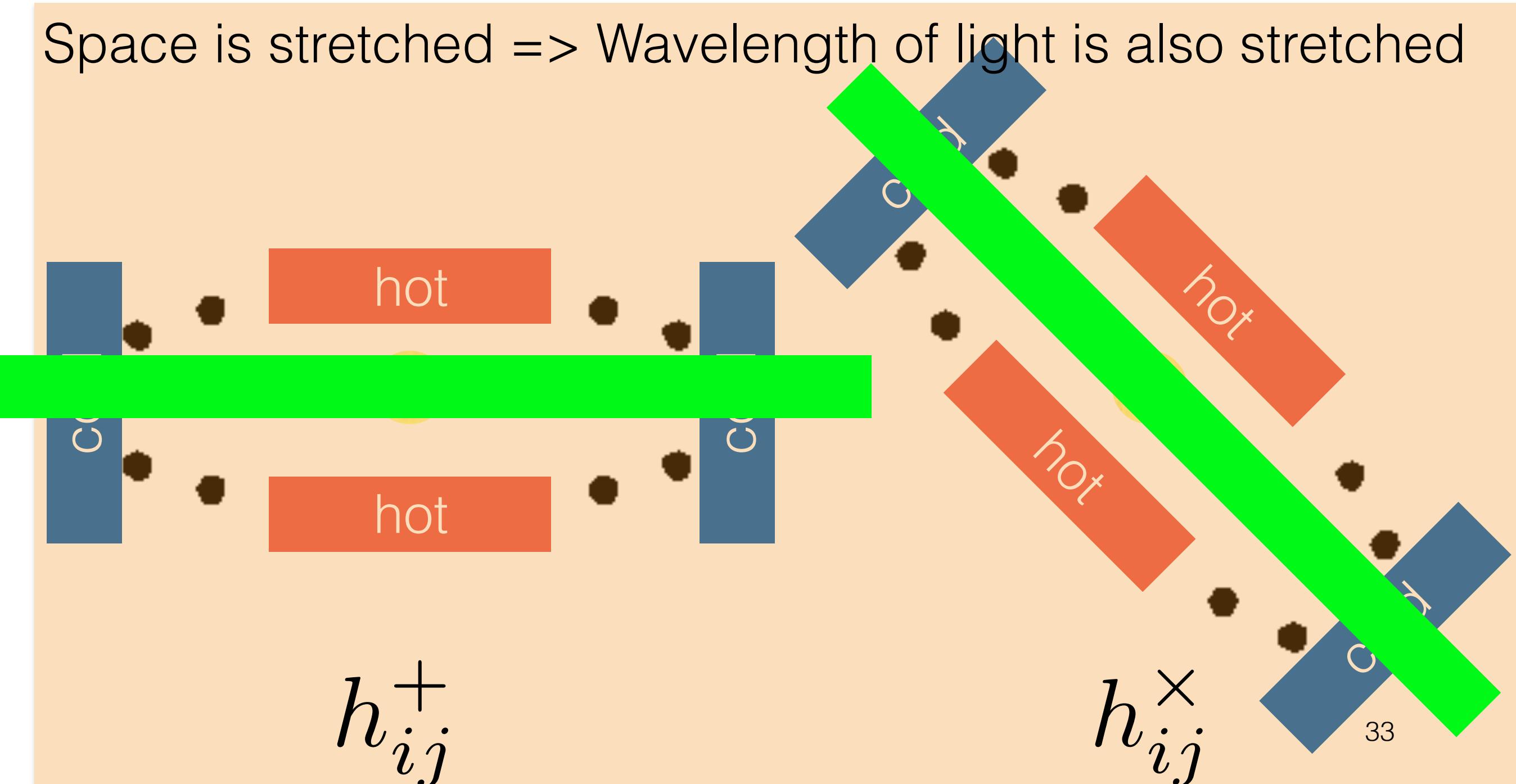


Photo Credit: TALEX

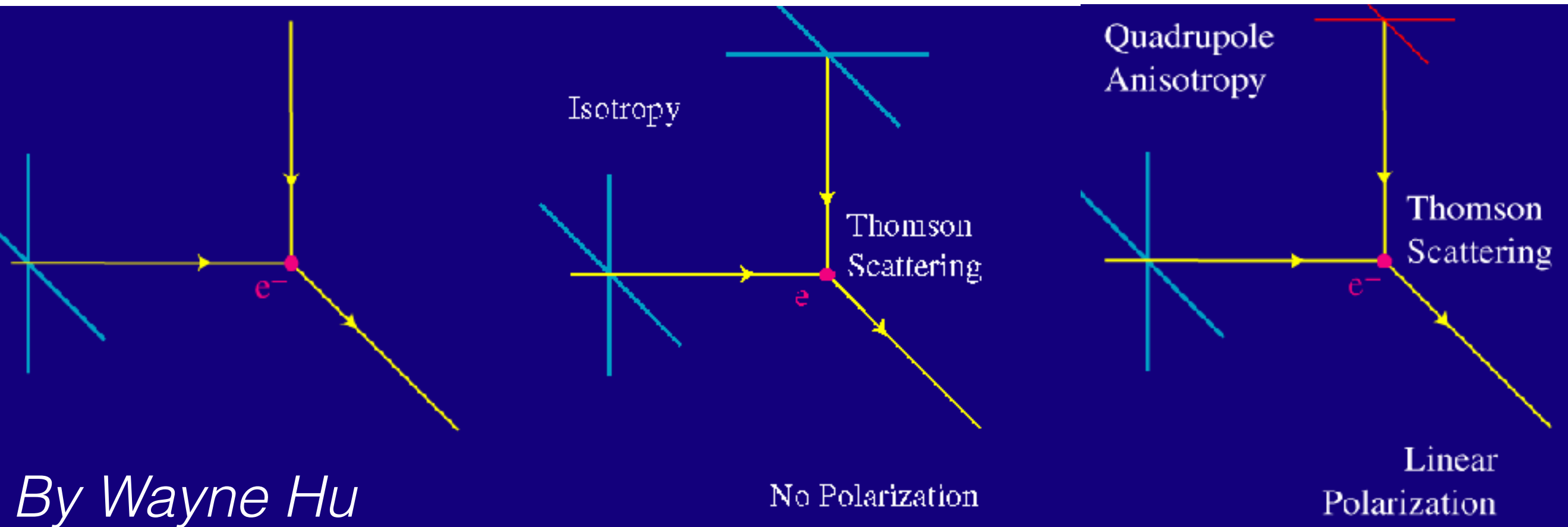


horizontally polarised

Photo Credit: TALEX



Physics of CMB Polarisation

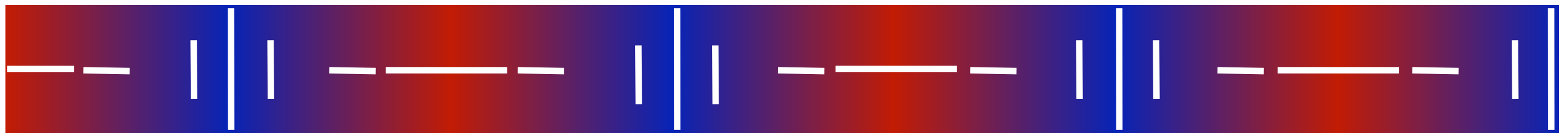
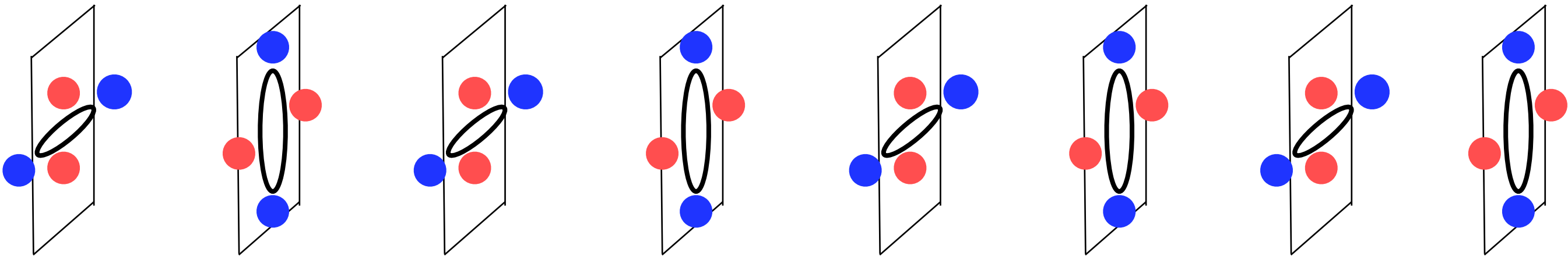


- Necessary and sufficient conditions for generating polarisation in CMB:
 - Thomson scattering
 - **Quadrupolar** temperature anisotropy around an electron

propagation direction of GW



$$h_+ = \cos(kx)$$

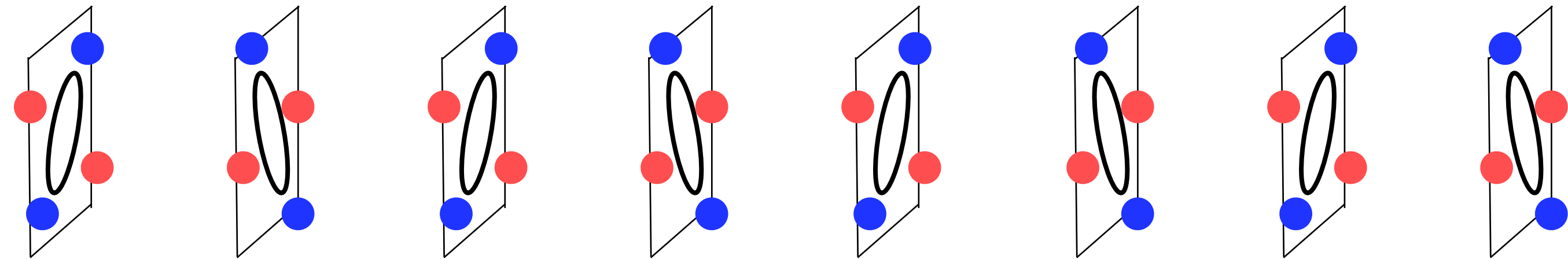


Polarisation directions perpendicular/parallel to the wavenumber vector -> **E mode polarisation**

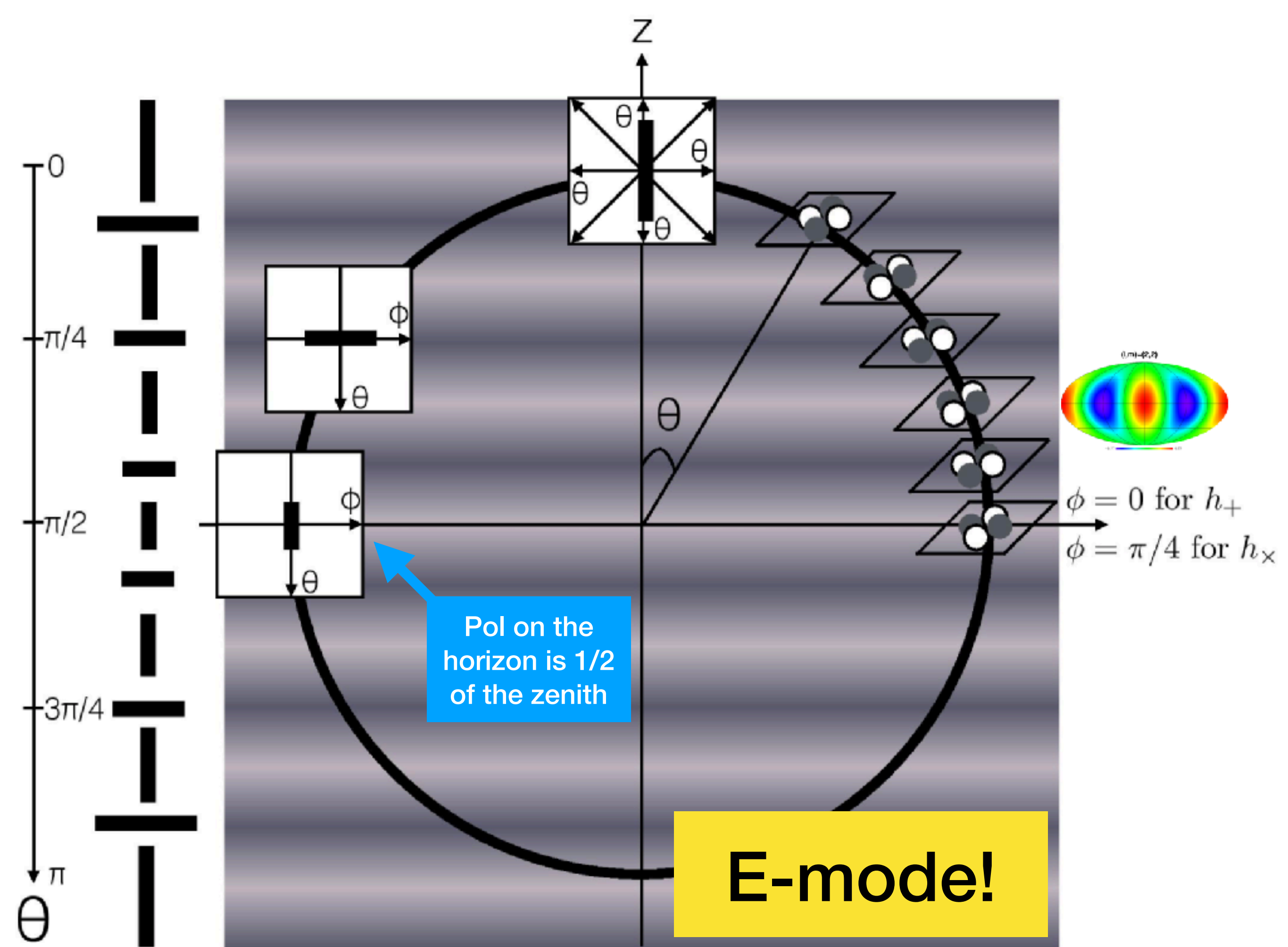
propagation direction of GW

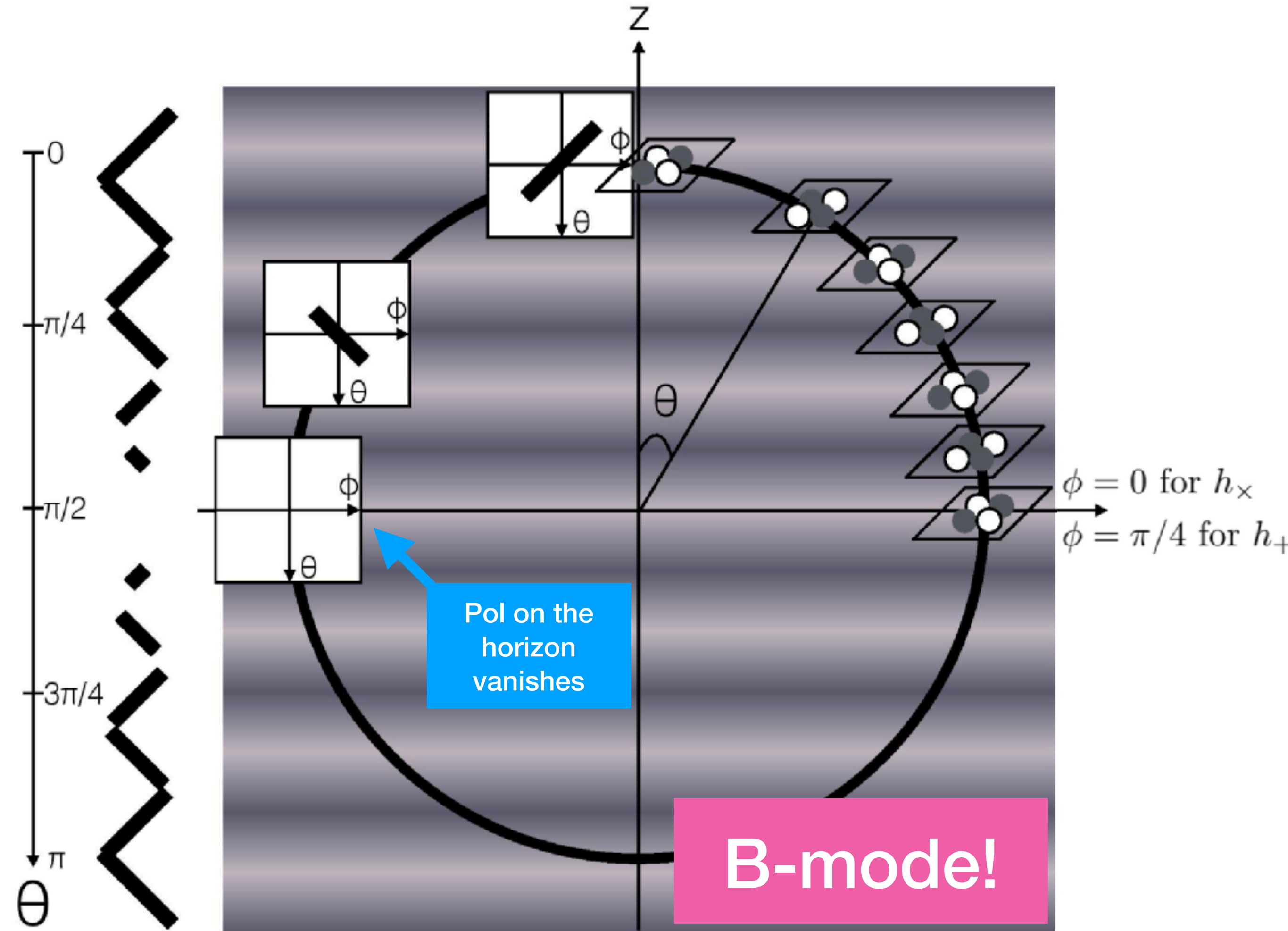


$$h_x = \cos(kx)$$



Polarisation directions 45 degrees tilted from to the wavenumber vector -> **B mode polarisation**





Gravitational waves as the quantum vacuum fluctuation in spacetime

- Quantising the gravitational waves in de Sitter space in **vacuum**

$$\square h_{ij} = 0$$

gives

$$k^3 \langle h_{ij}(\mathbf{k}) h^{ij*}(\mathbf{k}') \rangle$$

$$= (2\pi)^3 \delta_D(\mathbf{k} - \mathbf{k}') \frac{8}{M_{\text{pl}}^2} \left(\frac{H}{2\pi} \right)^2$$

scale-invariant spectrum

Propagation of GW

- In an expanding Universe,

$$\square h_{ij} = 0$$

gives

$$\ddot{h}_{ij} + \frac{3\dot{a}}{a} \dot{h}_{ij} + \frac{k^2}{a^2} h_{ij} = 0$$

=3H expansion of the Universe affects h_{ij}

GW Evolution

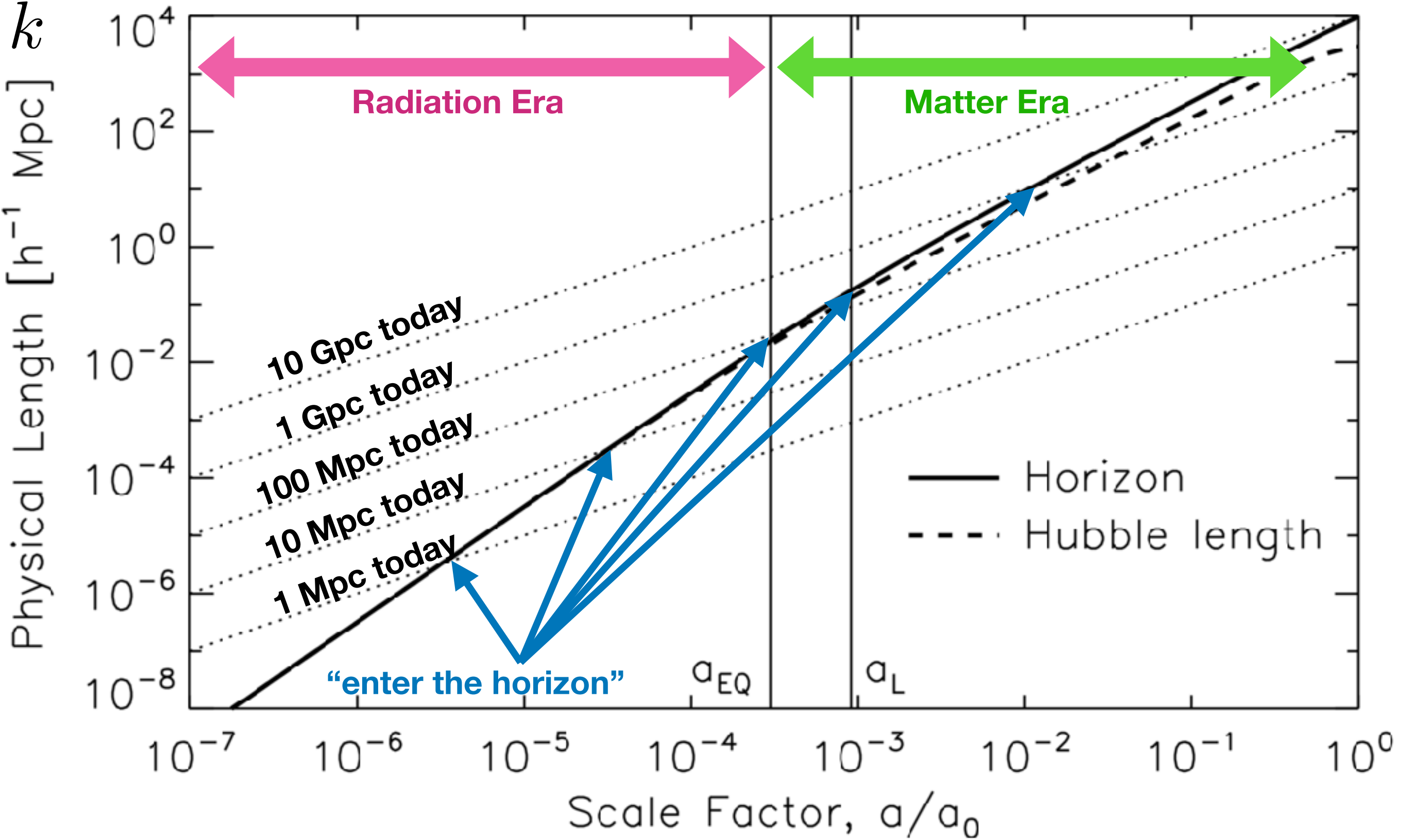
- **Super-horizon scales [$k \ll aH$]**
 - The amplitude of GW is **conserved** (i.e., $h_{ij} = \text{constant}$)
- **Sub-horizon scales [$k \gg aH$]**
 - The amplitude of GW decays (i.e., $h_{ij} \sim 1/a$)

Therefore, the long-wavelength GW preserves the initial condition: the beginning of the Universe!

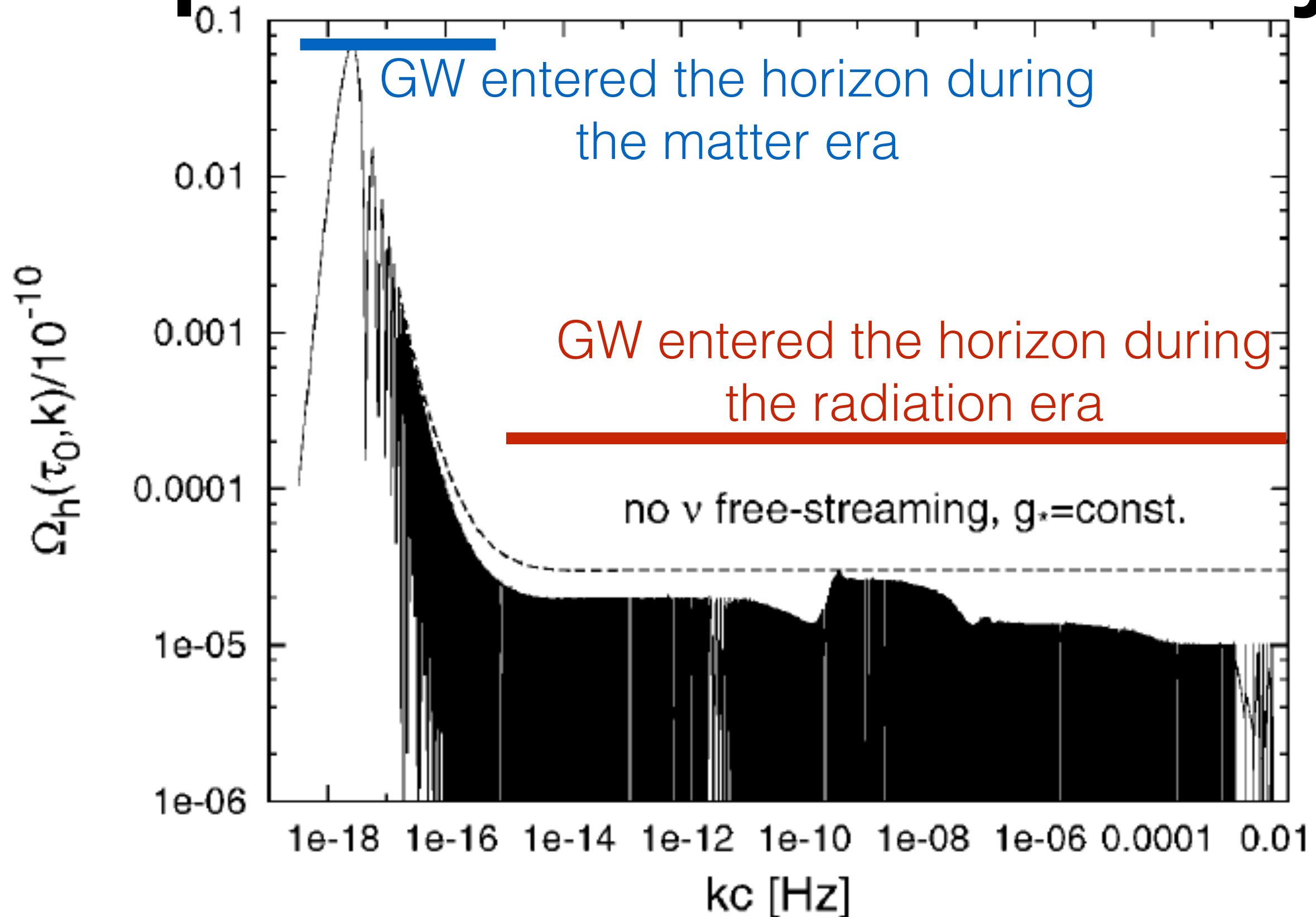
GW “entering the horizon”

- This is a tricky concept, but it is important
- Suppose that GWs were created at all wavelengths
- As the Universe expands, the horizon size grows and we can see longer and longer wavelengths
 - **Fluctuations “entering the horizon”**

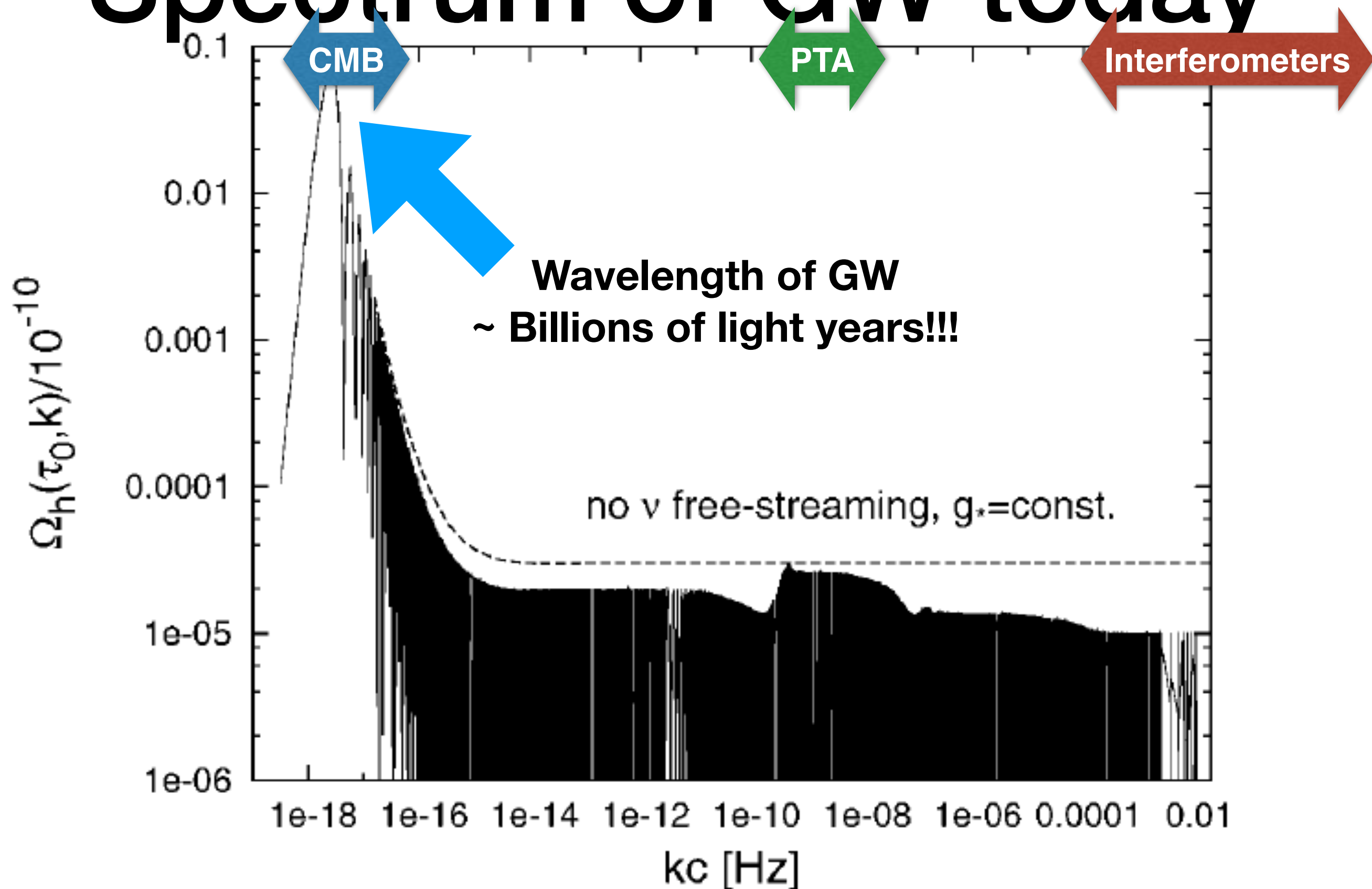
a
 $|k|$



Theoretical energy density Spectrum of GW today



Theoretical energy density Spectrum of GW today

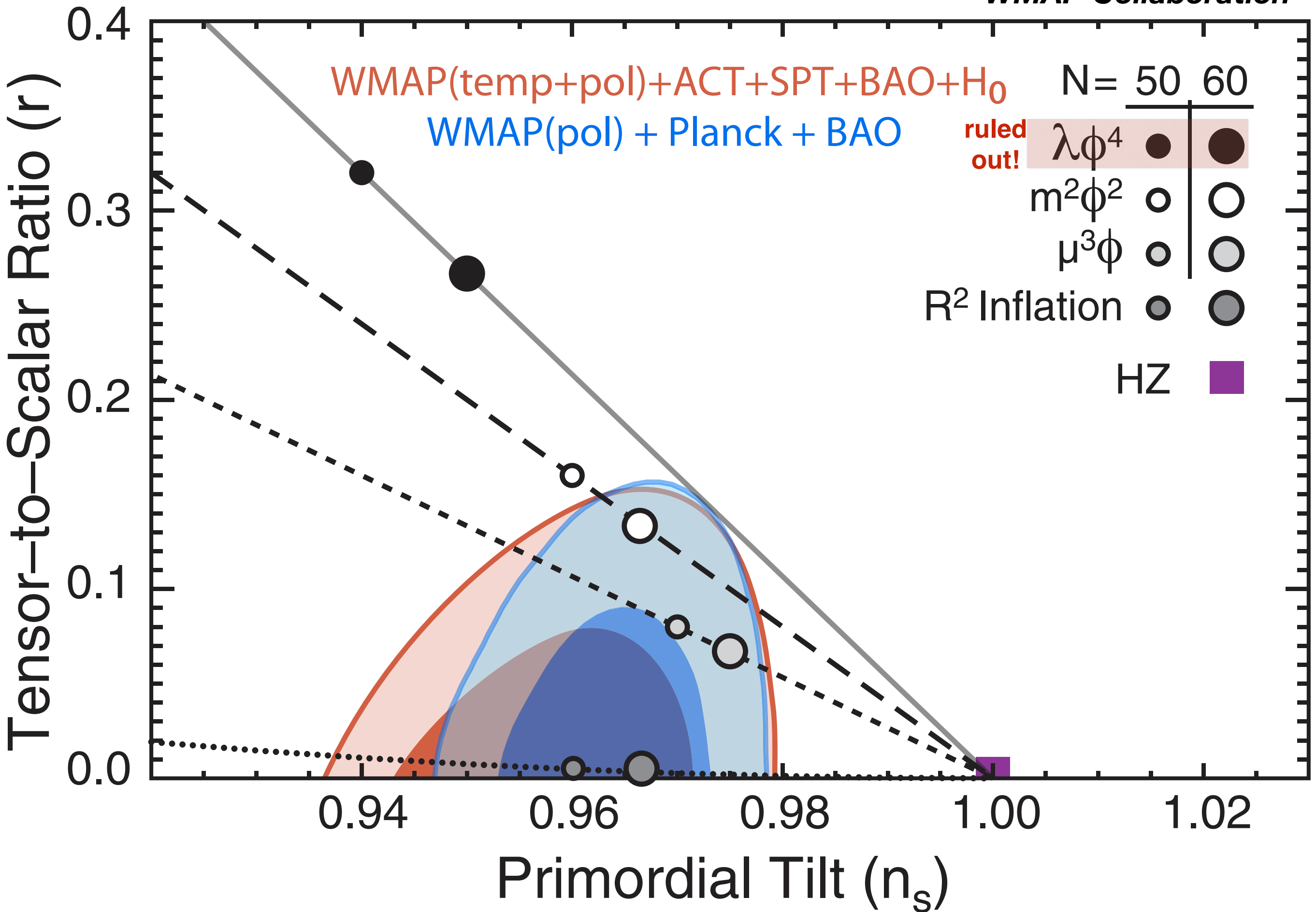


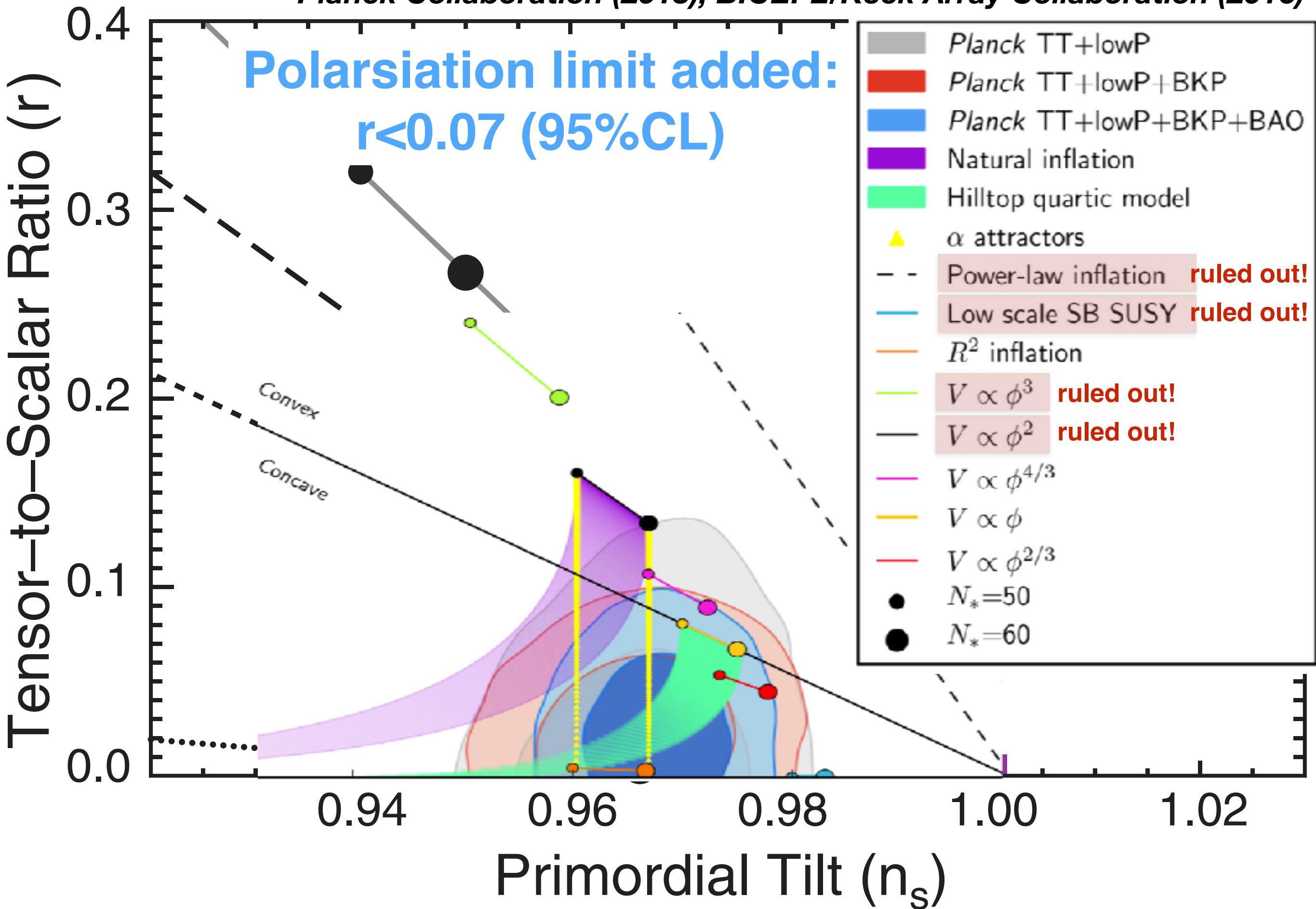
Tensor-to-scalar Ratio

$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

- We really want to find this! The current upper bound is **$r < 0.06$** (95%CL)

BICEP2/Keck Array Collaboration (2018)

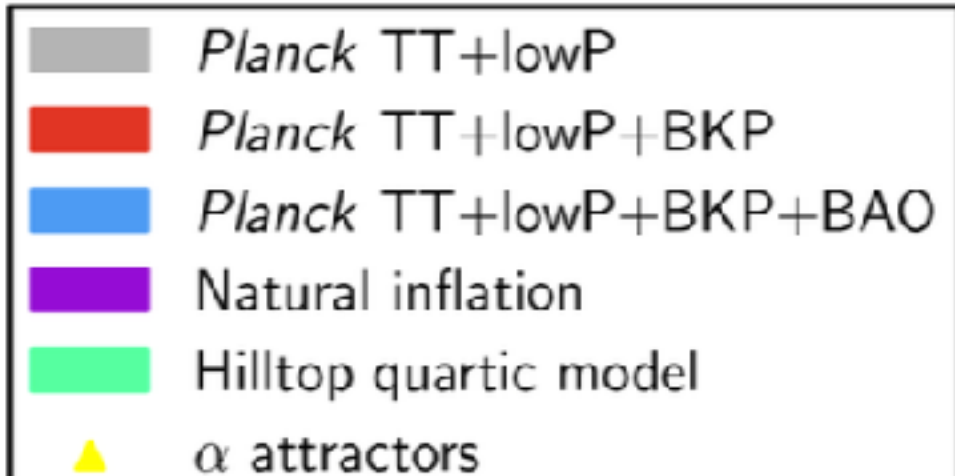




Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)

Tensor-to-Scalar Ratio (r)

Polarisation limit added:
 $r < 0.07$ (95%CL)



0.4
0.3
0.2
0.1
0.0

Convex
Concave

Convex
Concave

Planck TT+ τ prior+lensing+BAO

+BK15

2018

$r < 0.06$
(95%CL)

BICEP2/Keck Array
Collaboration (2018)

0.94

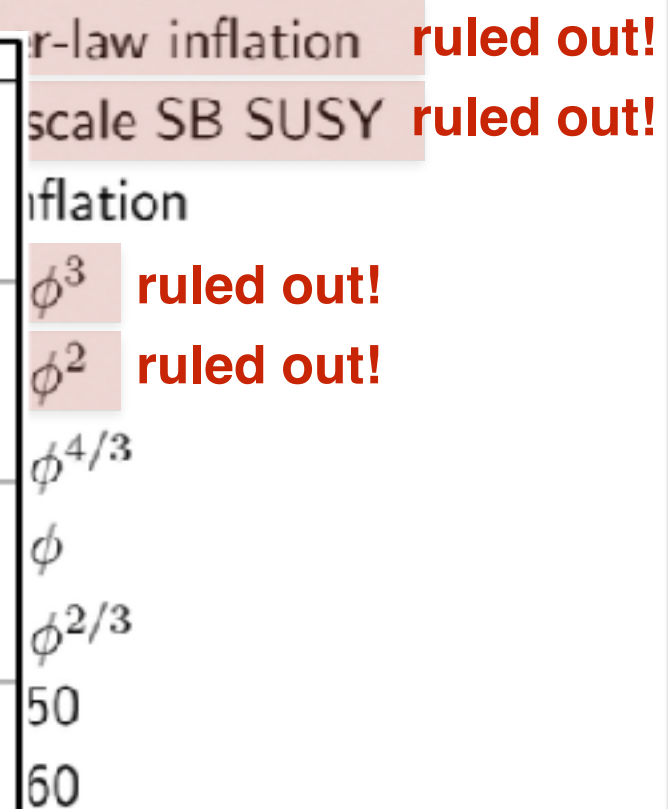
0.96

0.98

1.00

1.02

Primordial Tilt (n_s)



JAXA

+ participations from
USA, Canada, Europe

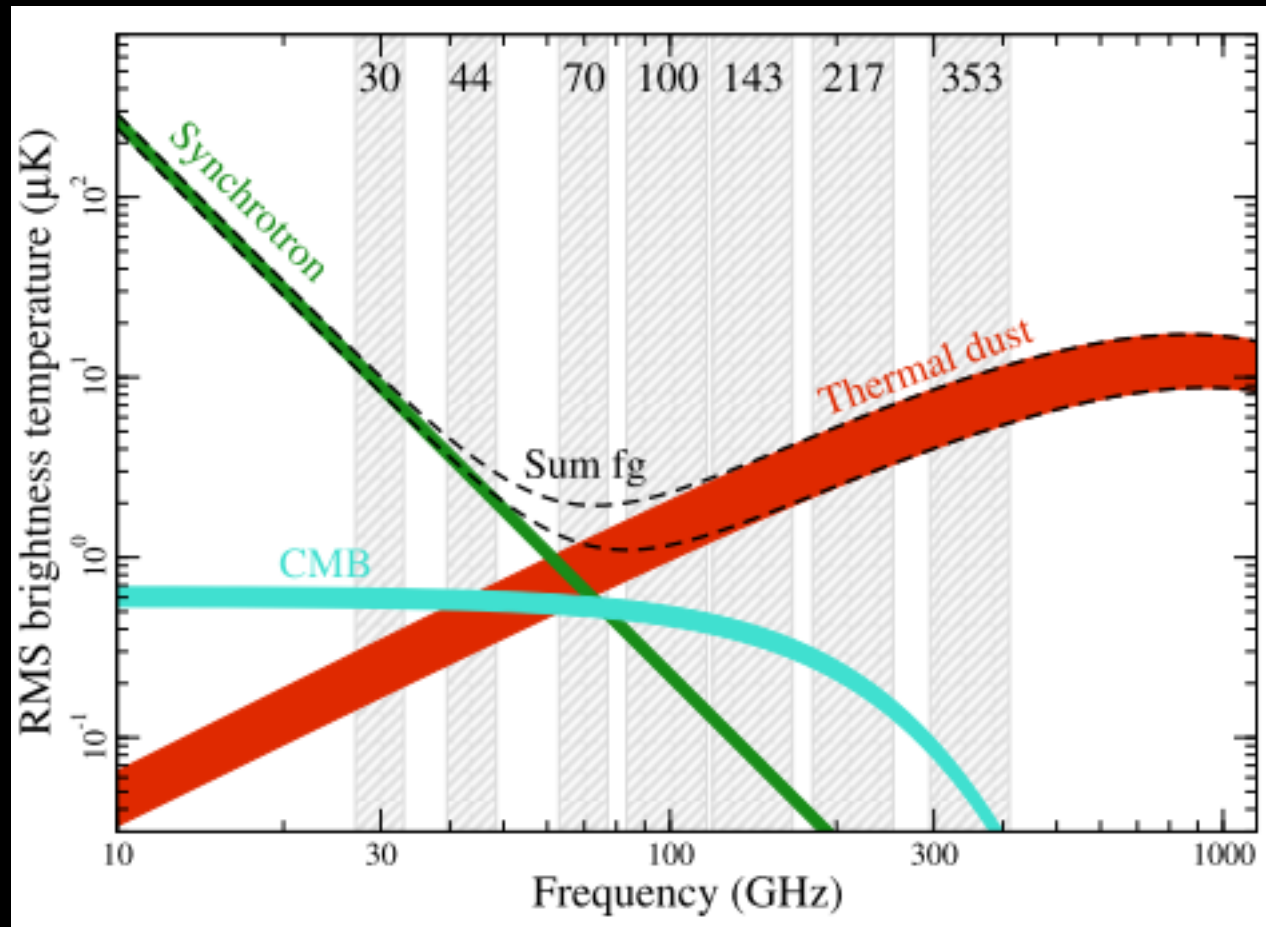
LiteBIRD
2028–

Selected!

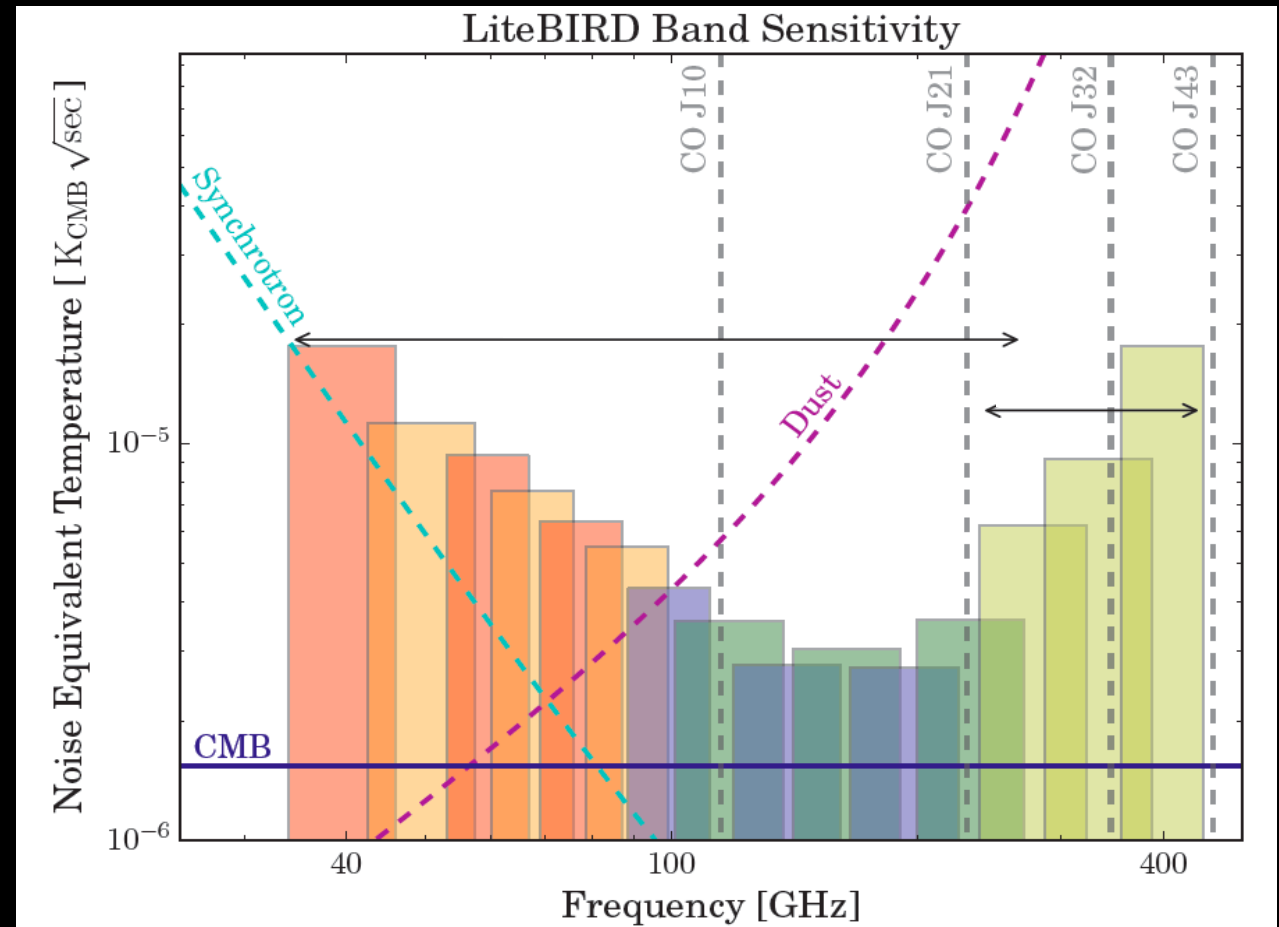
Target: $\delta r < 0.001$ (68%CL)



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)

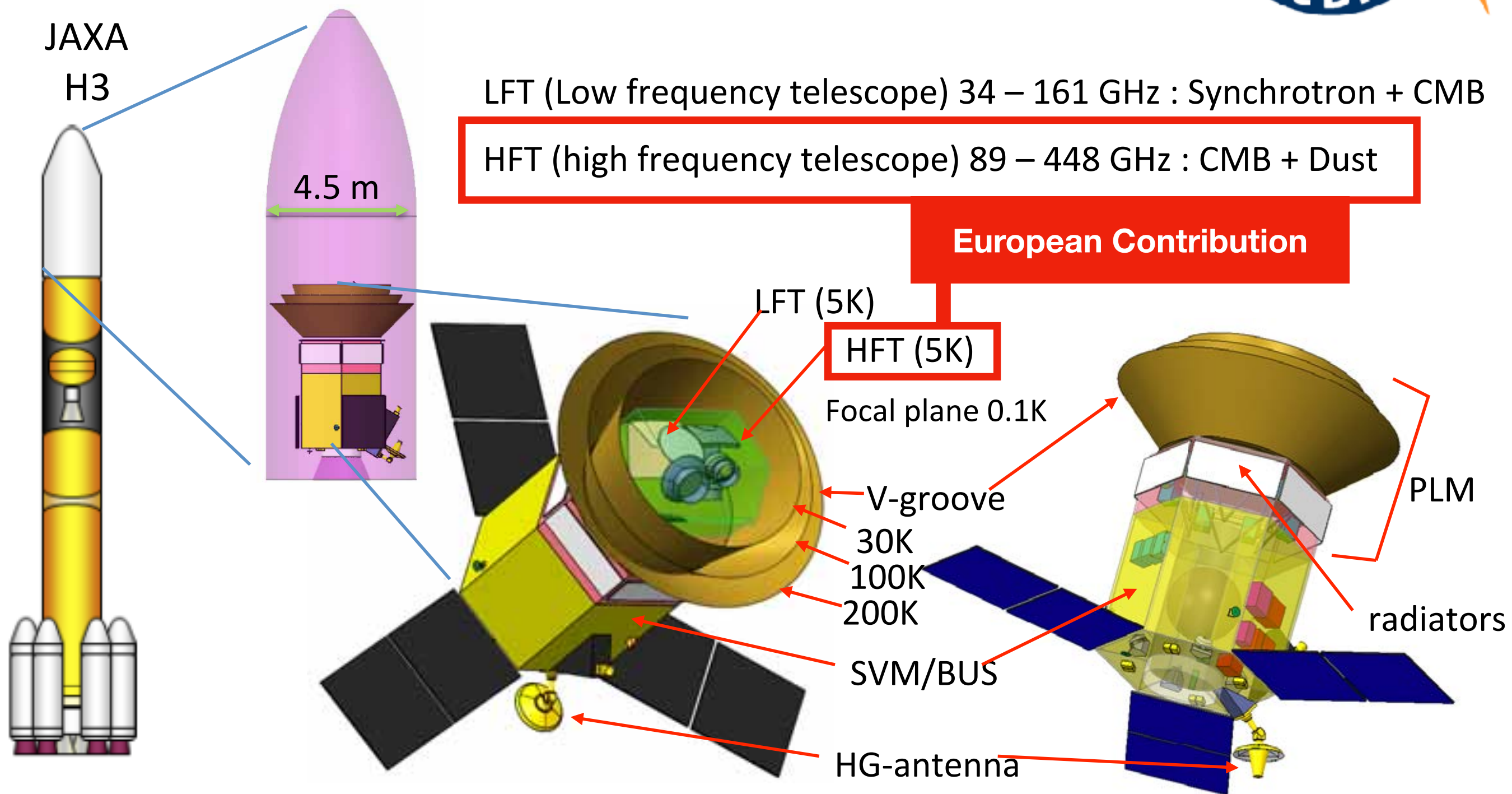
LiteBIRD Spacecraft

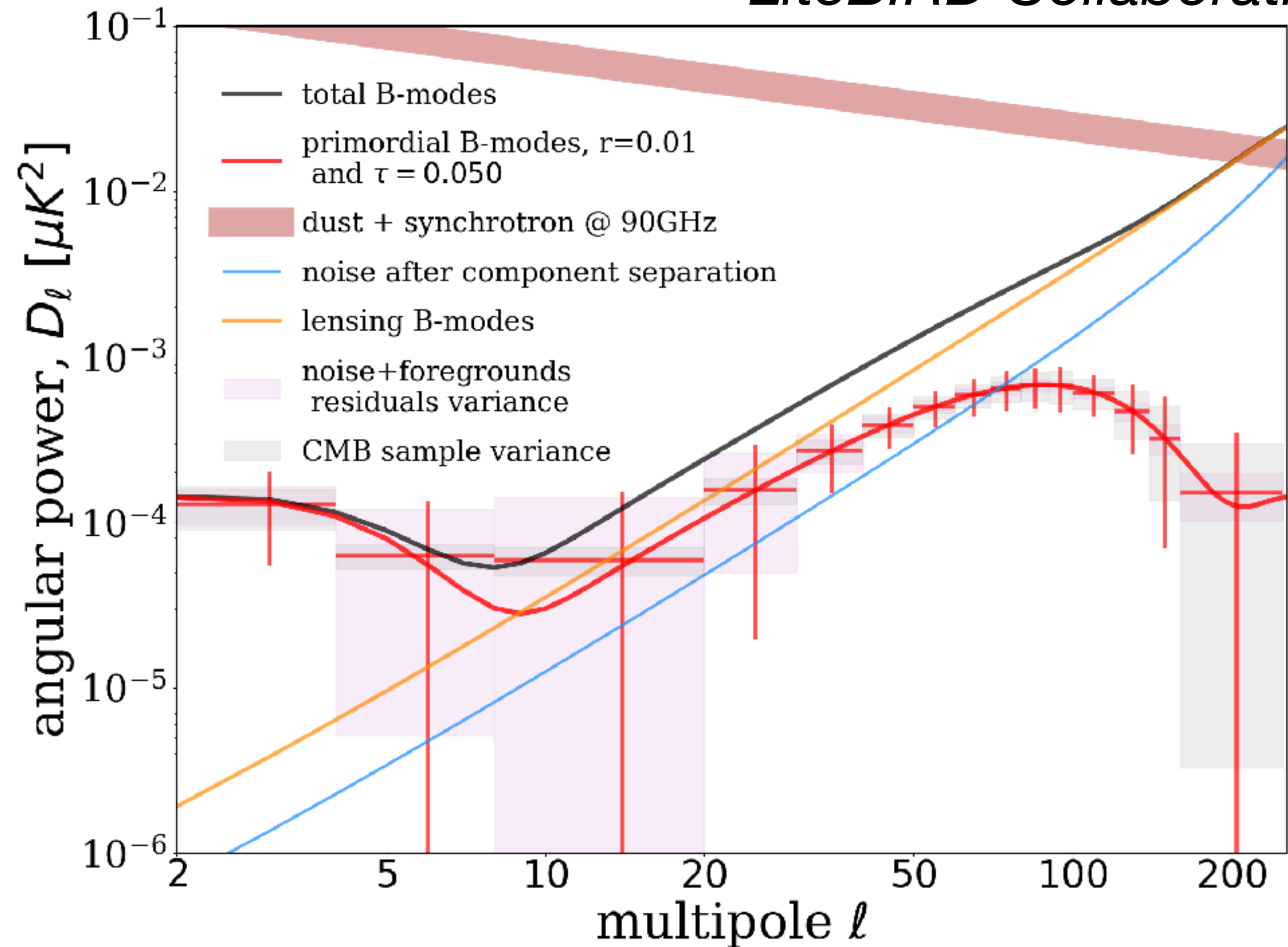


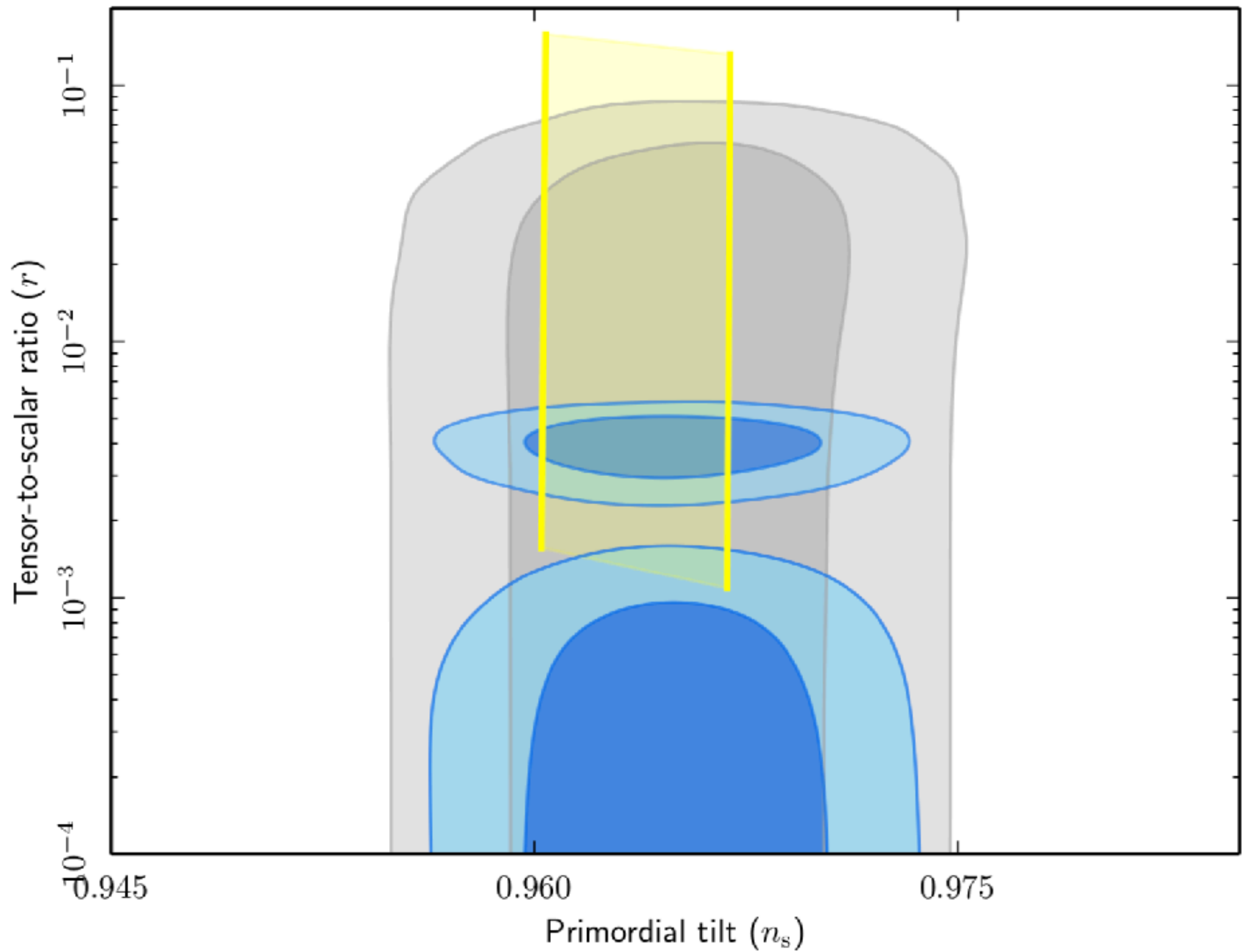
LFT (Low frequency telescope) 34 – 161 GHz : Synchrotron + CMB

HFT (high frequency telescope) 89 – 448 GHz : CMB + Dust

European Contribution







But, wait a minute...

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

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

- **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)
Many papers by Sorbo, Peloso, and others
 - SU(2) gauge field can!

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

Important Message

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

- 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

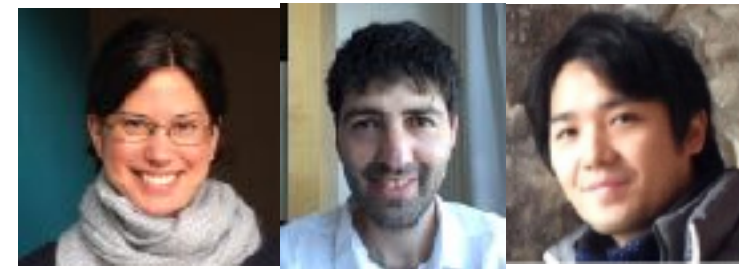
If not, you may have just discovered new physics during inflation!

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

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 $r \gg 0.001$ 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!**

GW from Axion-SU(2) Dynamics



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

- ϕ : inflaton field => Just provides quasi-de Sitter background
[I don't want to touch this sector because I don't understand inflaton]
- χ : pseudo-scalar “axion” field. Spectator field (i.e., negligible energy density compared to the inflaton)

- Field strength of an SU(2) field A_ν^a :

$$F_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g\epsilon^{abc} A_\mu^b A_\nu^c$$

self-interaction term

[a=1,2,3; $\mu=0,1,2,3$]

A well-defined set up:

Axion-SU(2) gauge field dynamics in a given de-Sitter background.

Everything is calculable!

- ϕ : inflaton field => Just provides quasi-de Sitter background
[I don't want to touch this sector because I don't understand inflaton]
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self-interaction term

[a=1,2,3; $\mu=0,1,2,3$]

Background and Perturbation



A. Maleknejad
(MPA)

- In an inflating background, the SU(2) field has an **isotropic** 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 (spin-2) mode (as well as S&V)

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

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

Scenario

- The SU(2) field contains 1 tensor, 2 vectors, and 3 scalars (9 DOF = $12 - 3$)
- The tensor components are amplified strongly by a coupling to the axion field
- Only one helicity is amplified $\Rightarrow$ GW is **chiral** (well-known result, also for U(1))
- New result: **GWs sourced by this mechanism are strongly non-Gaussian!**

Agrawal, Fujita & EK, PRD, 97, 103526 (2018); JCAP 1806, 027 (2018)

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

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

- The equations of motion for L and R modes are

$$\square \psi_{L,R} \neq 0$$

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

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

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

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

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

Spin-2 Field from SU(2)

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

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

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

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

$$\left(\begin{array}{l} \xi \equiv \frac{\lambda}{2fH} \dot{\chi} \simeq m_Q + \frac{1}{m_Q} \\ m_Q \equiv gQ/H = \text{a few} \\ \epsilon_B \equiv g^2 Q^4 / (H M_{\text{Pl}})^2 \ll 1 \\ \epsilon_E \equiv (H\dot{Q} + \dot{Q})^2 / (\dot{H} M_{\text{Pl}})^2 \ll 1 \end{array} \right.$$

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- 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):

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

[Whittaker function]

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

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

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

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

- Inhomogeneous solution:

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

$\mathcal{F}_E, \mathcal{F}_B$: some complicated functions

Power Spectrum!

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

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

- This exponential dependence on m_Q makes it possible to have $\mathbf{P_{sourced} \gg P_{vacuum} = (2/\pi^2)H^2/M_{Pl}^2}$
- **New Paradigm**

Phenomenology

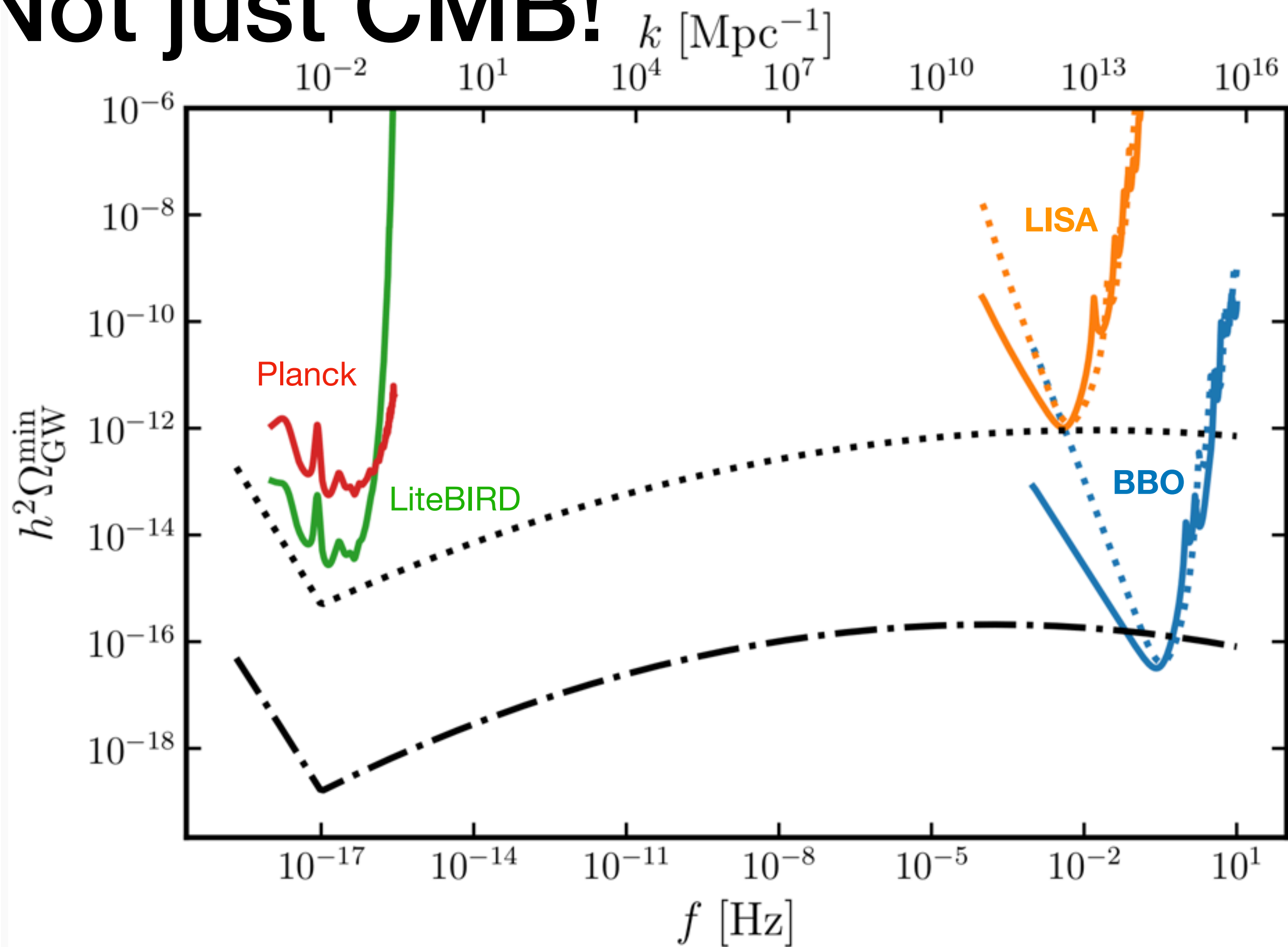
$$\partial_x^2 t_{R,L} + \left[1 + \frac{2}{x^2} (m_Q \xi \mp x(m_Q + \xi)) \right] t_{R,L} = \dots$$

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

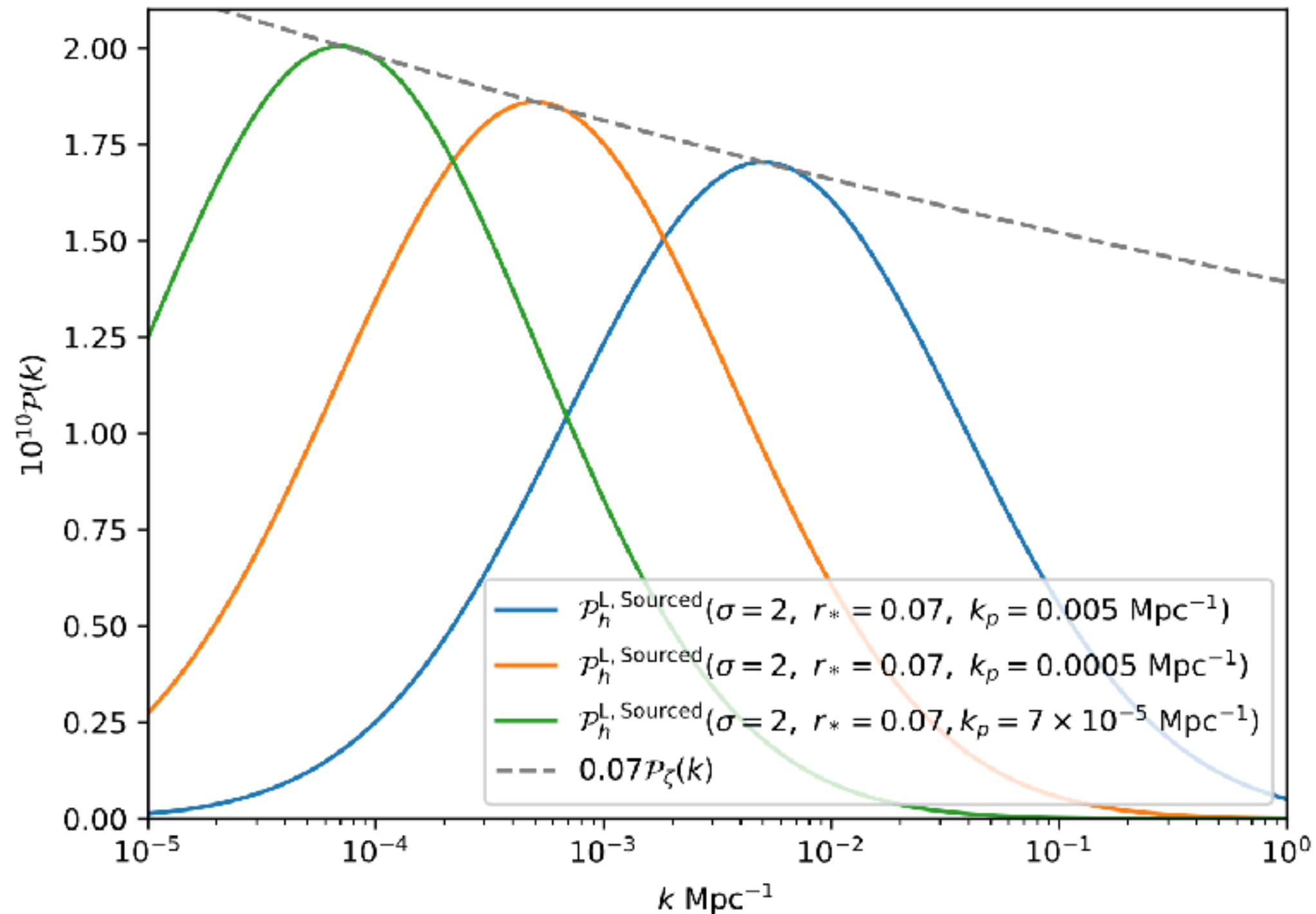
$$\left(\begin{array}{l} \xi \equiv \frac{\lambda}{2fH} \dot{\chi} \simeq m_Q + \frac{1}{m_Q} \\ m_Q \equiv gQ/H = \text{a few} \end{array} \right.$$

- 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...

Not just CMB!



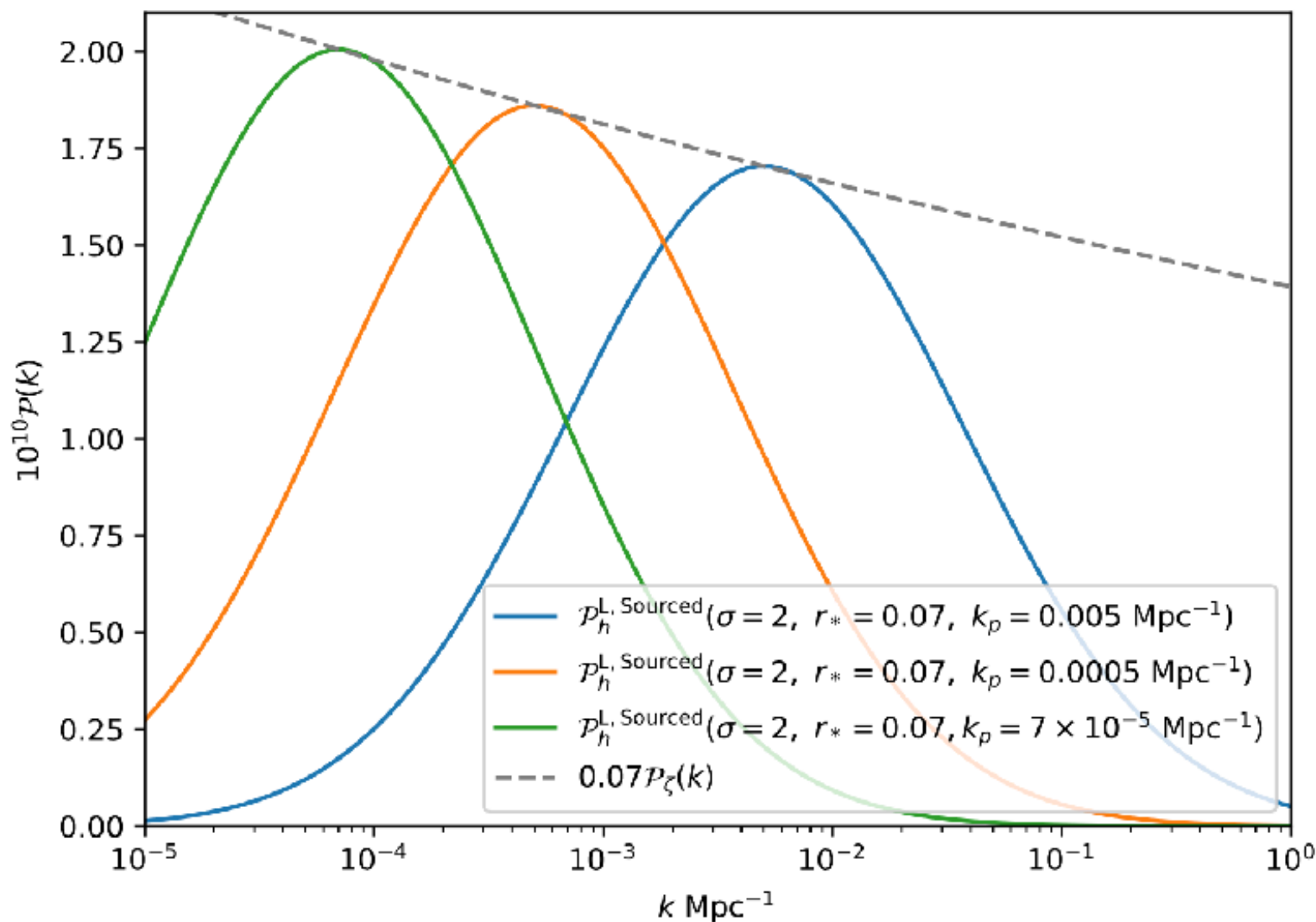
Example Tensor Spectra



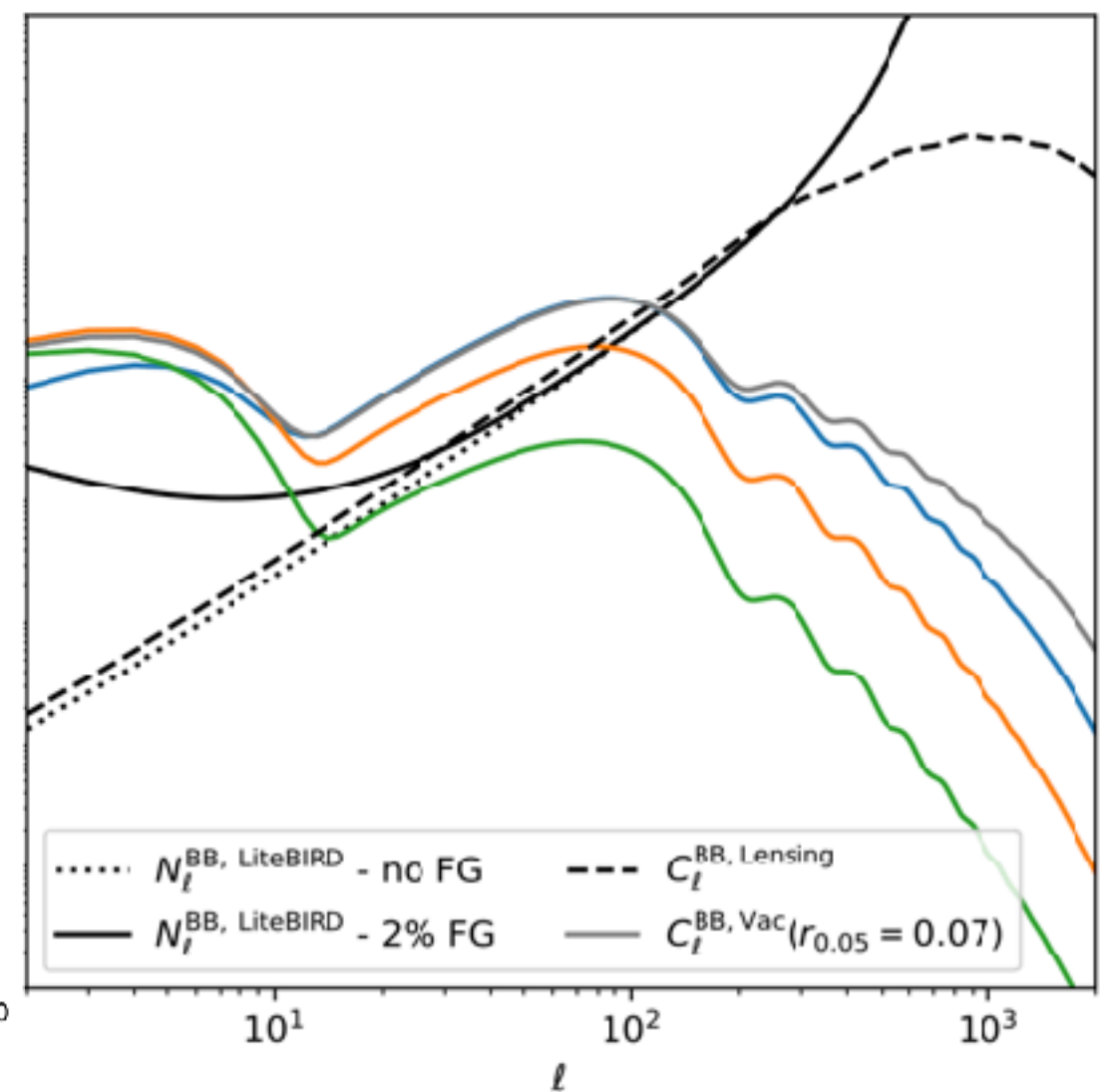
- Sourced tensor spectrum can also be bumpy

Example Tensor Spectra

Tensor Power Spectrum, $P(k)$



B-mode CMB spectrum, C_l^{BB}



- The B-mode power spectrum still looks rather normal

Large bispectrum in GW from SU(2) fields



Aniket Agrawal
(MPA)

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



Tomo Fujita
(Kyoto)

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

- $\Omega_A \ll 1$ 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***

NG generated at the tree level

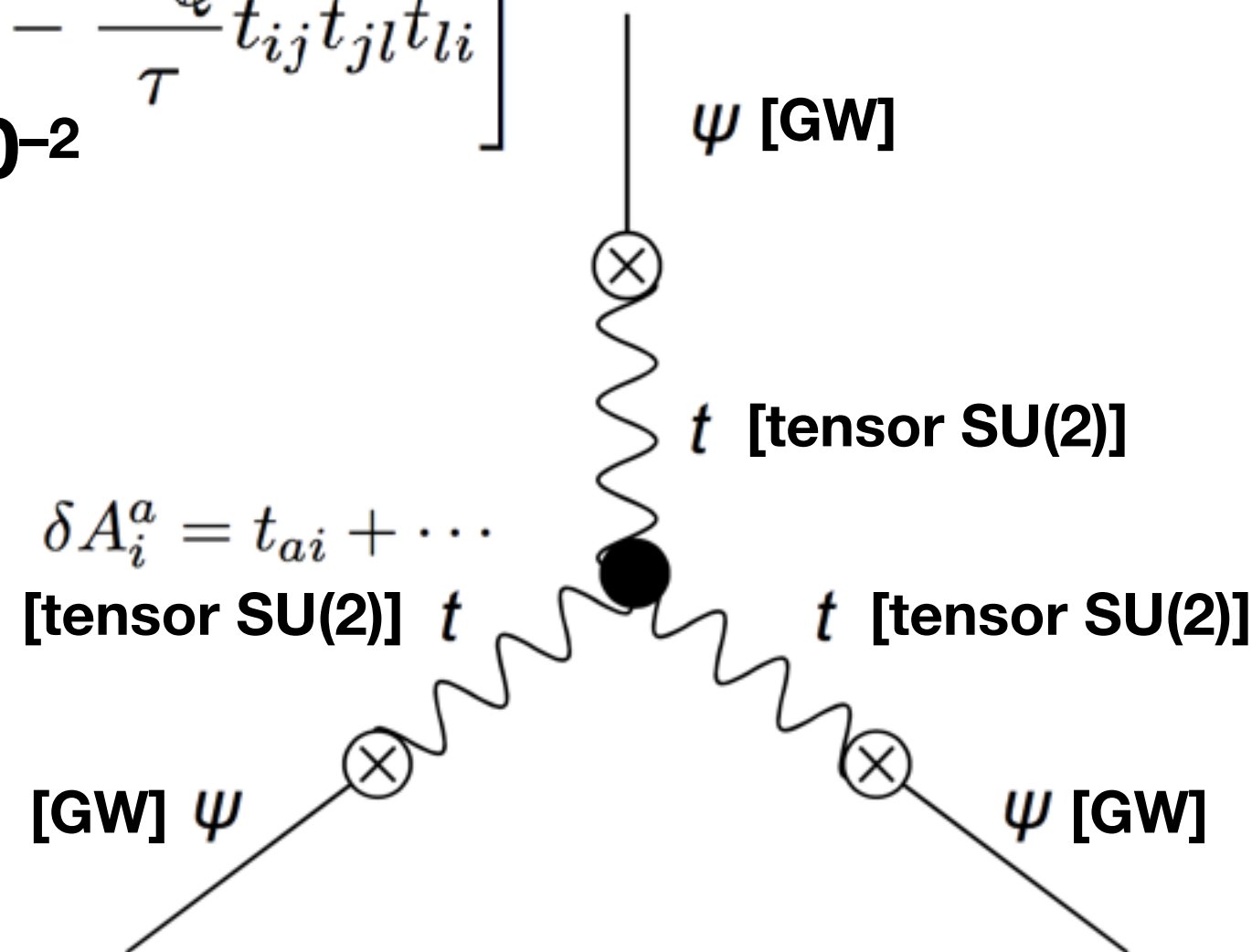
$$L_3^{(i)} = c^{(i)} \left[\epsilon^{abc} t_{ai} t_{bj} \left(\partial_i t_{cj} - \frac{m_Q^2 + 1}{3m_Q \tau} \epsilon^{ijk} t_{ck} \right) \right.$$

$$\left. - \frac{m_Q}{\tau} t_{ij} t_{jl} t_{li} \right] \\ c^{(i)} = g = m_Q^2 H / \sqrt{\epsilon_B} M_{\text{Pl}} \sim 10^{-2}$$

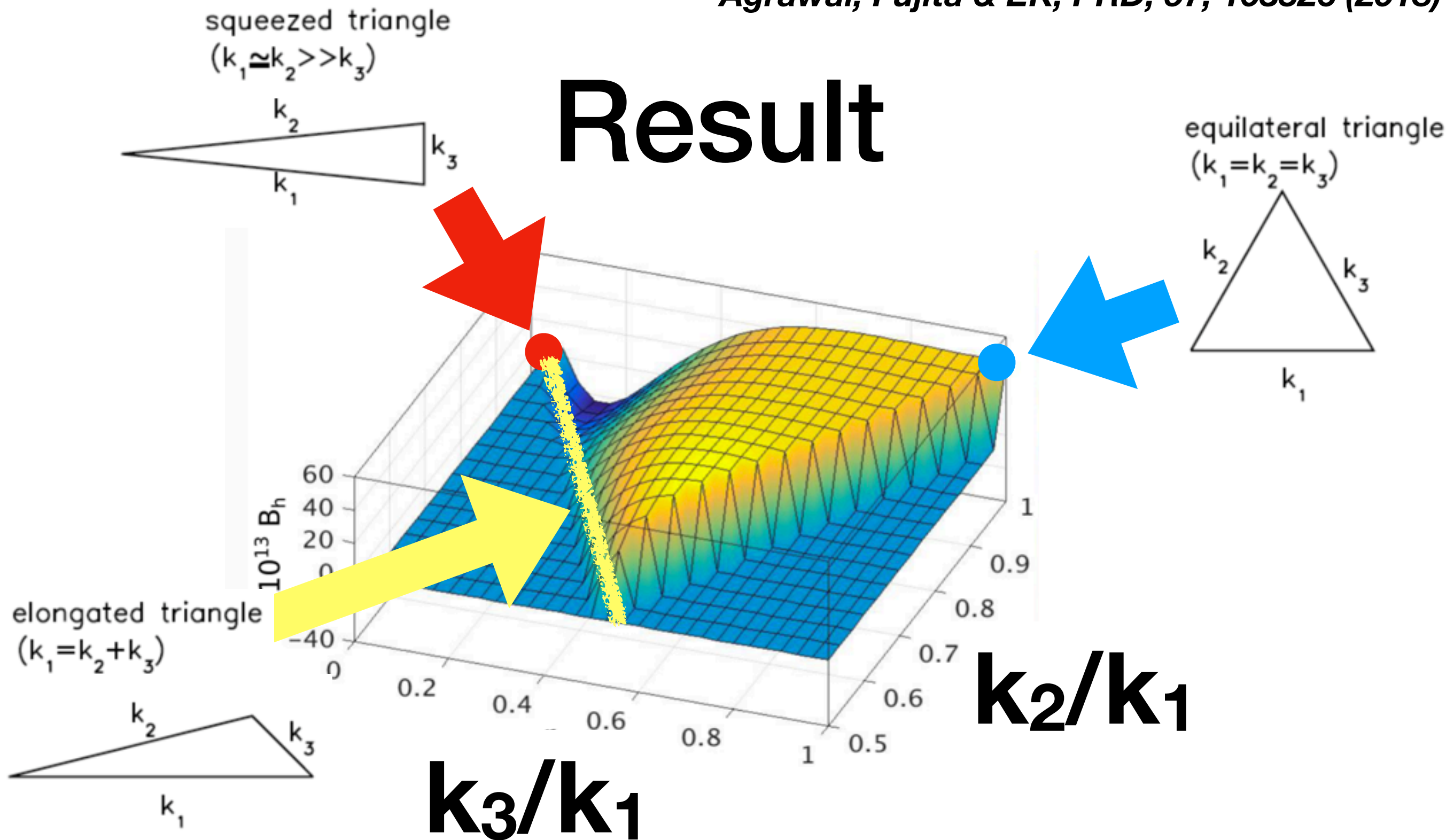
$$\epsilon_B \equiv \frac{g^2 Q^4}{H^2 M_{\text{Pl}}^2} \simeq \frac{2\Omega_A}{1 + m_Q^{-2}} \ll 1$$

$$m_Q \equiv gQ/H \quad [m_Q \sim \text{a few}]$$

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

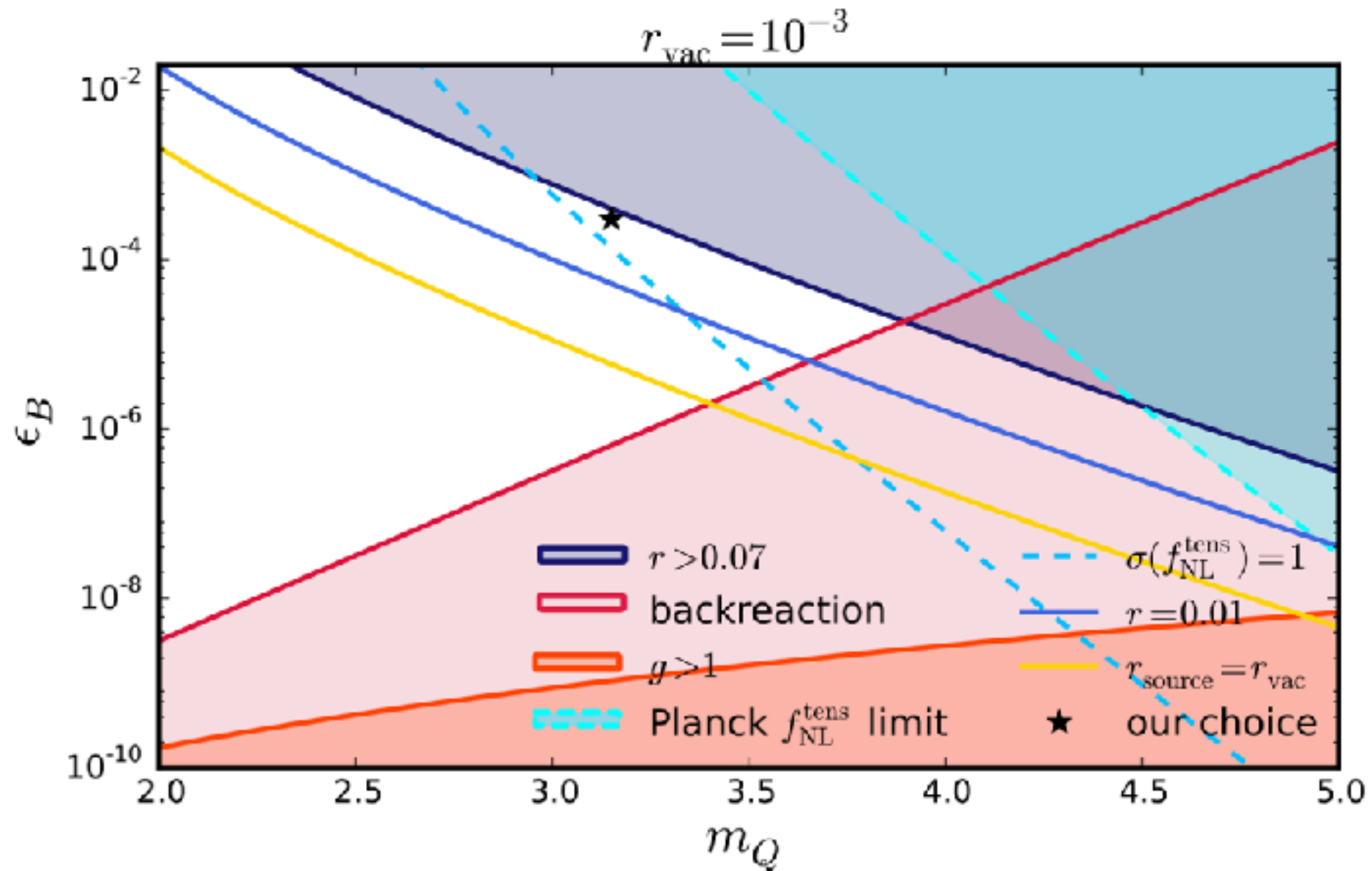


Result



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

Parameter Scan



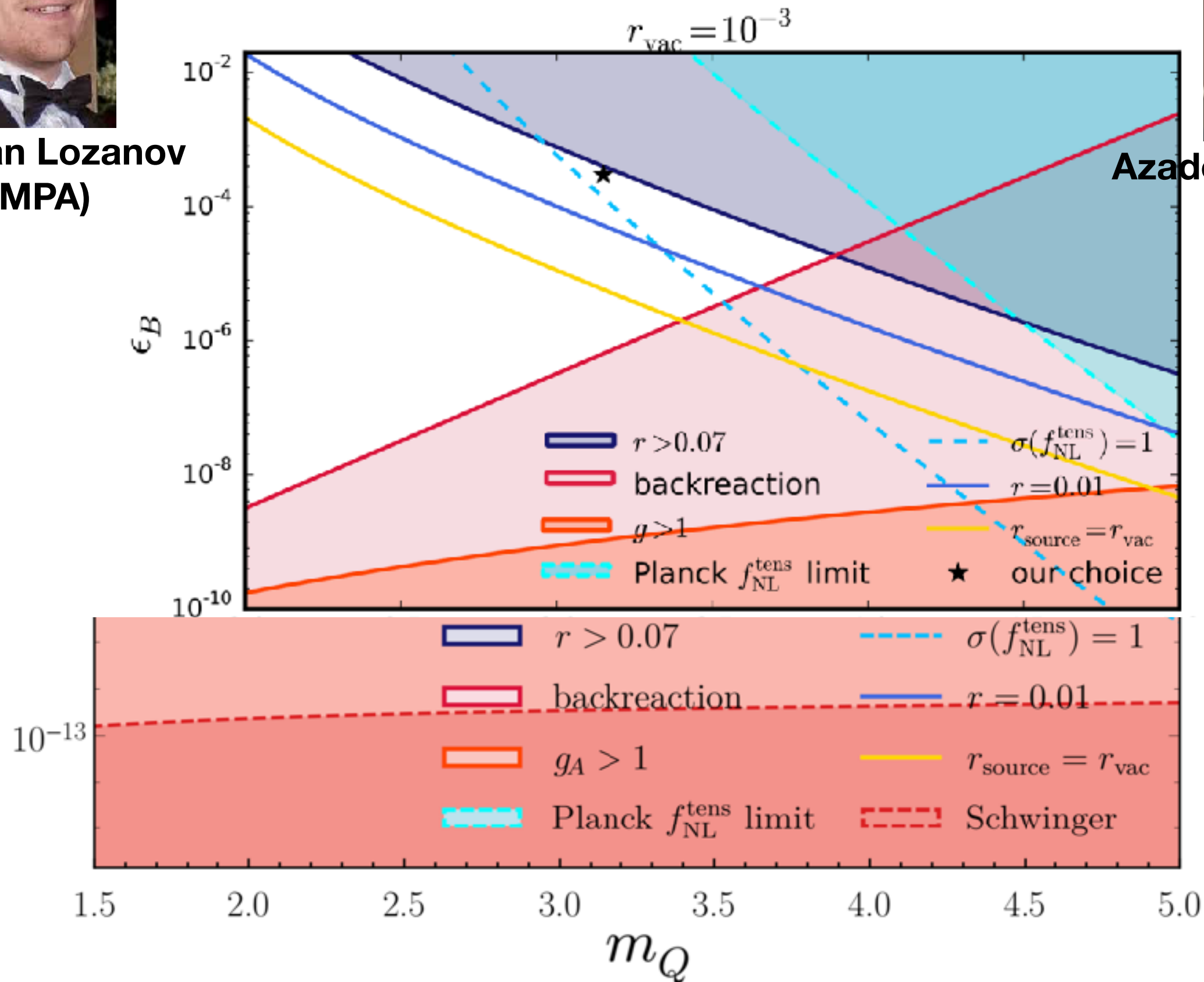
Schwinger Effect



Kaloian Lozanov
(MPA)



Azadeh Maleknejad
(MPA)



Summary

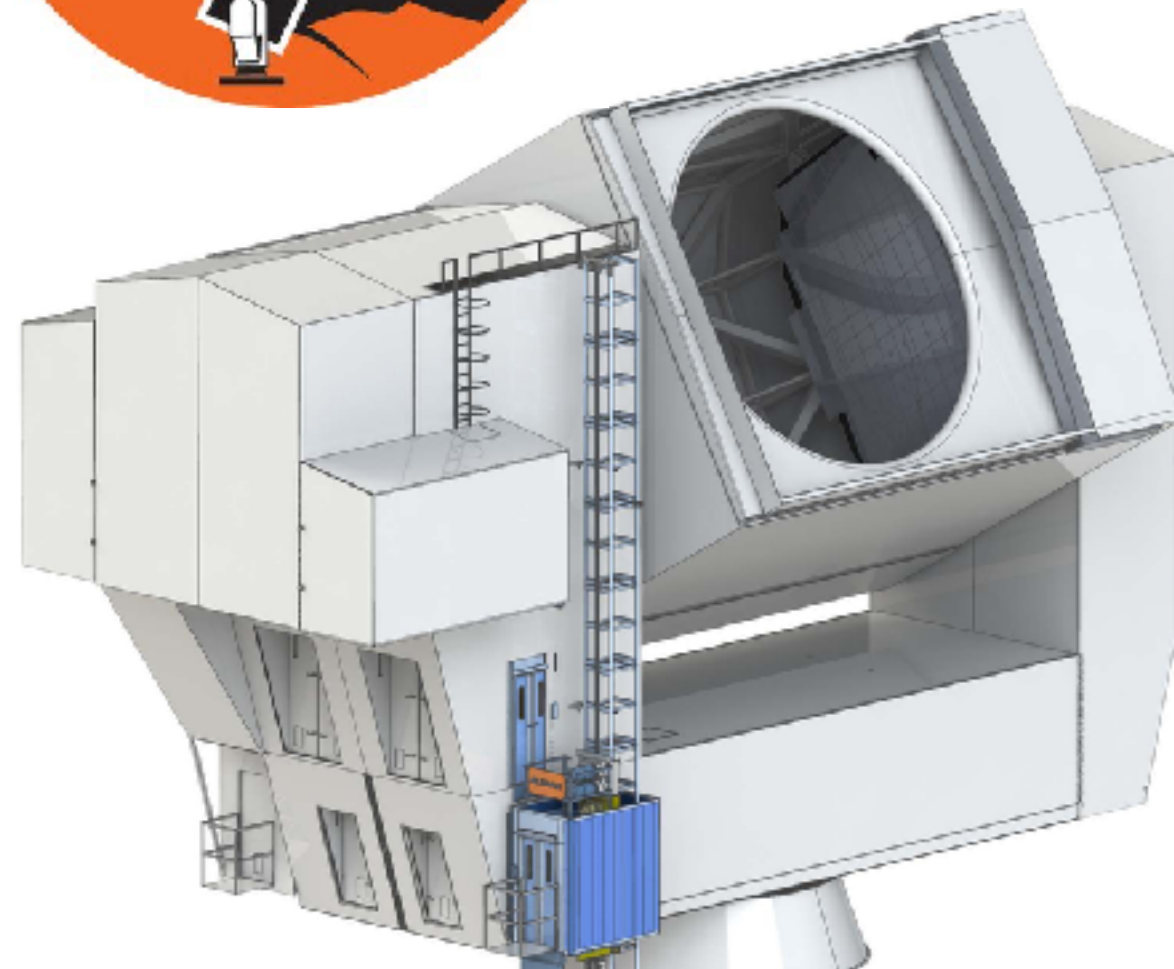
- **Next frontier**: Using CMB polarisation to find **primordial GW**. **Critical test of the physics of the early Universe!**
- With *LiteBIRD* we plan to reach $r \sim 10^{-3}$, i.e., 100 times better than the current bound
- GW from vacuum or sources? An exciting window to new physics
- Check not only for scale invariant, but also for chirality and **non-Gaussianity**

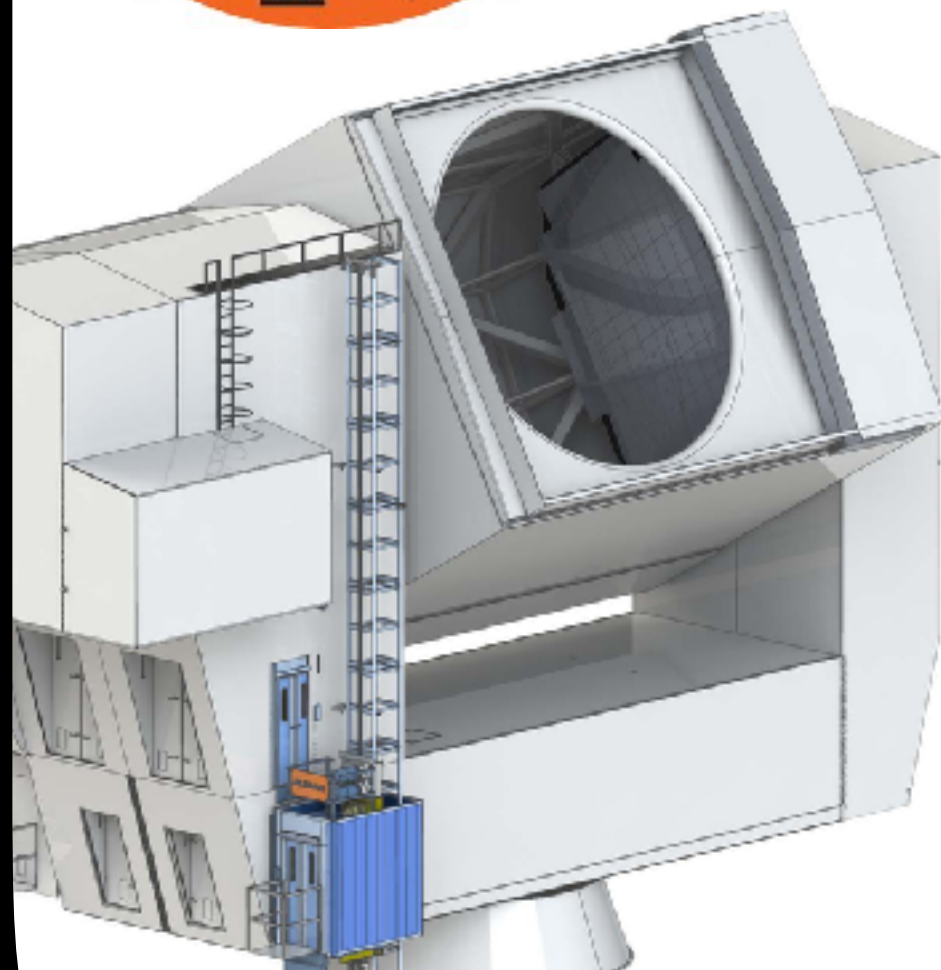
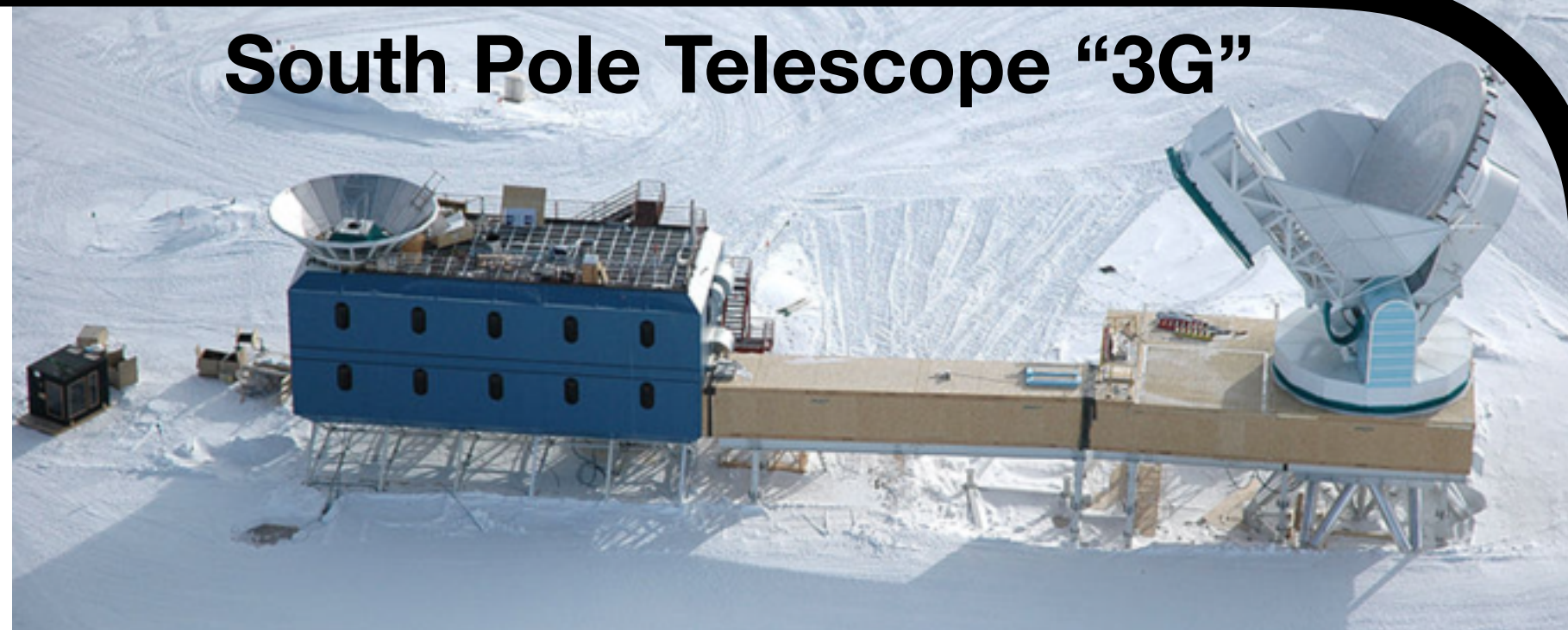
Ground-based Experiments

Advanced Atacama Cosmology Telescope

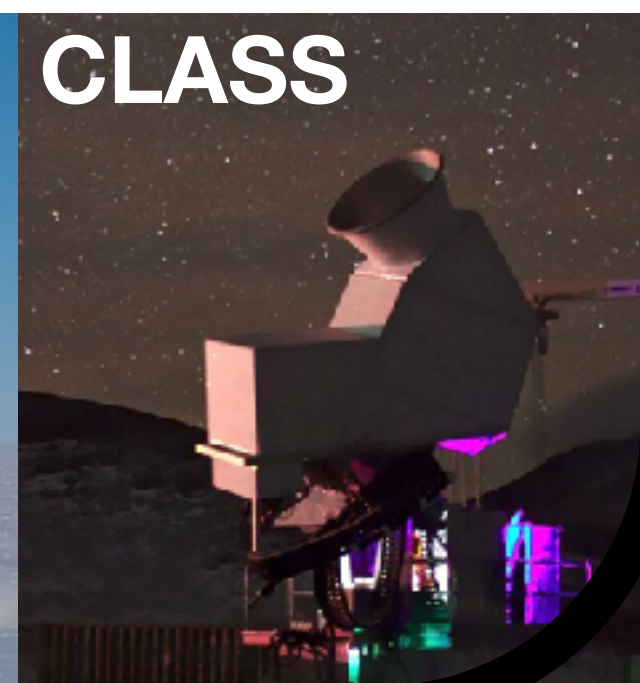


The Simons Array



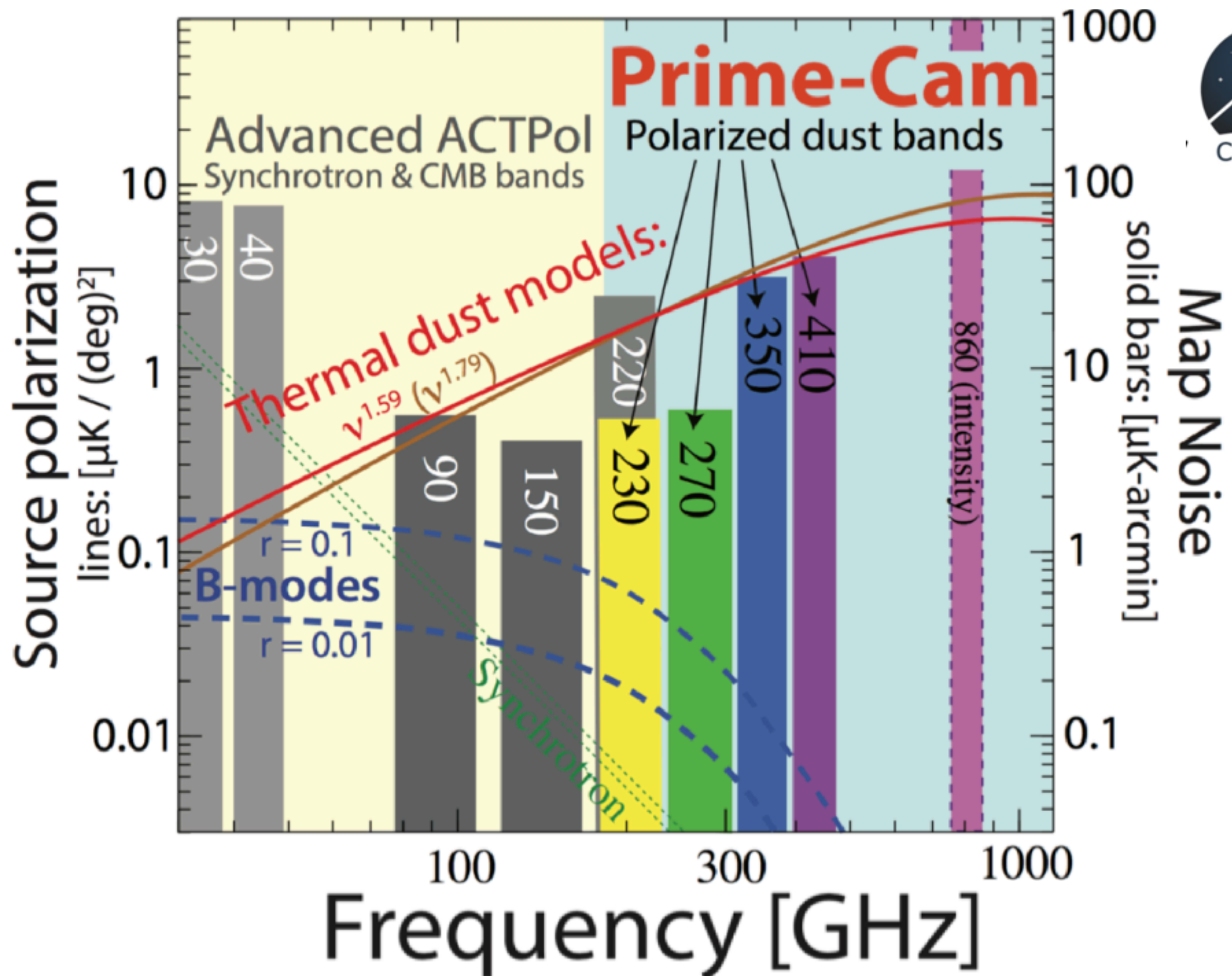


CMB-S4(?)



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!



Where is CCAT-p?

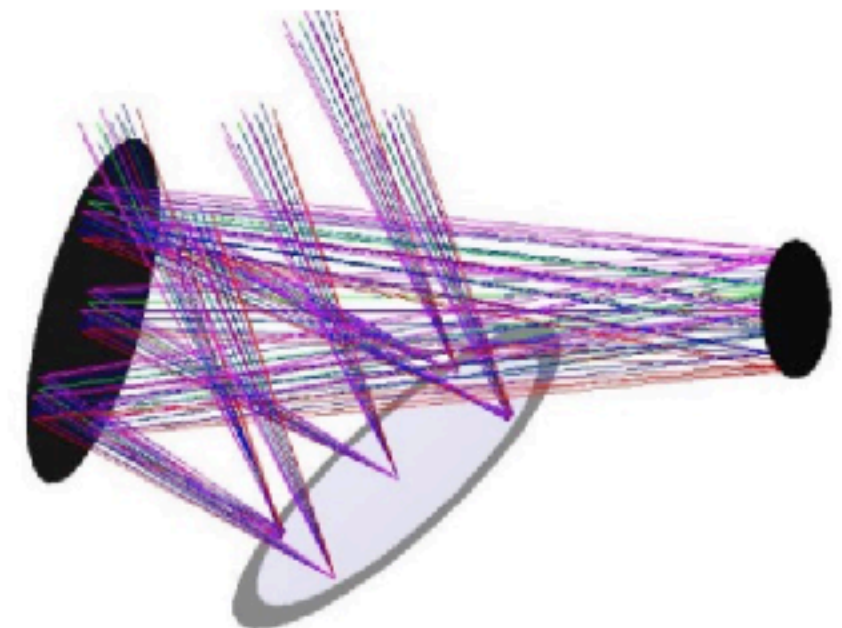
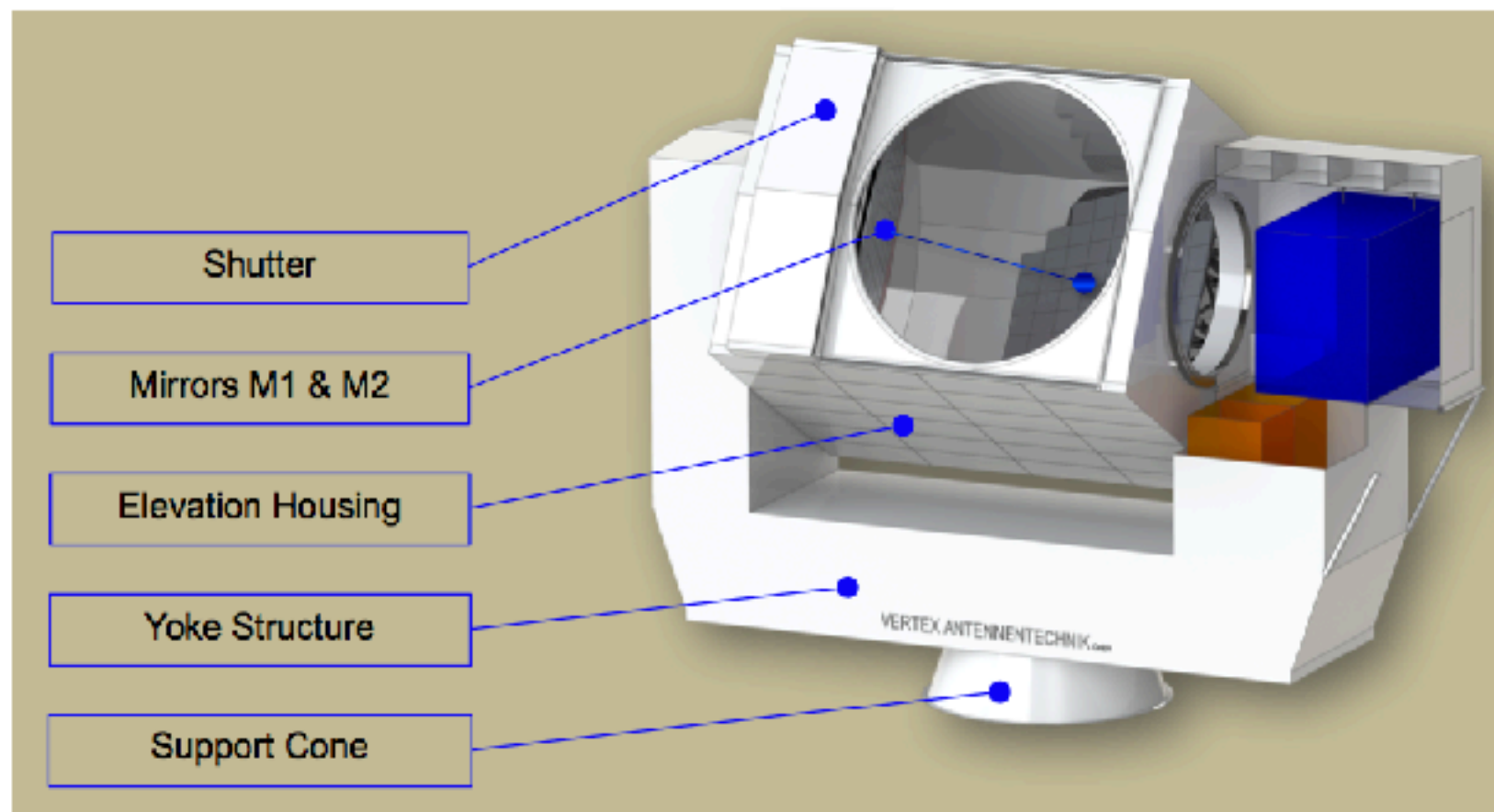
Cerro Chajnantor at 5600 m w/ TAO





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 + ...

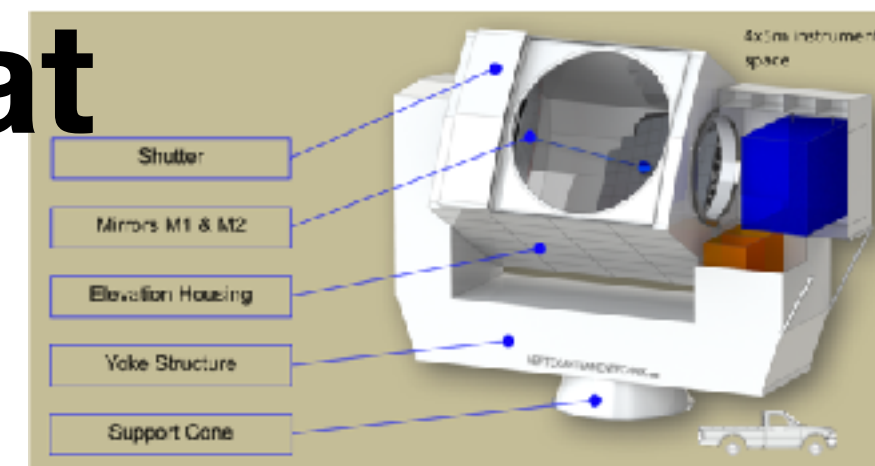
A Game Changer

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

- **Germany makes great telescopes!**

CCAT-prime

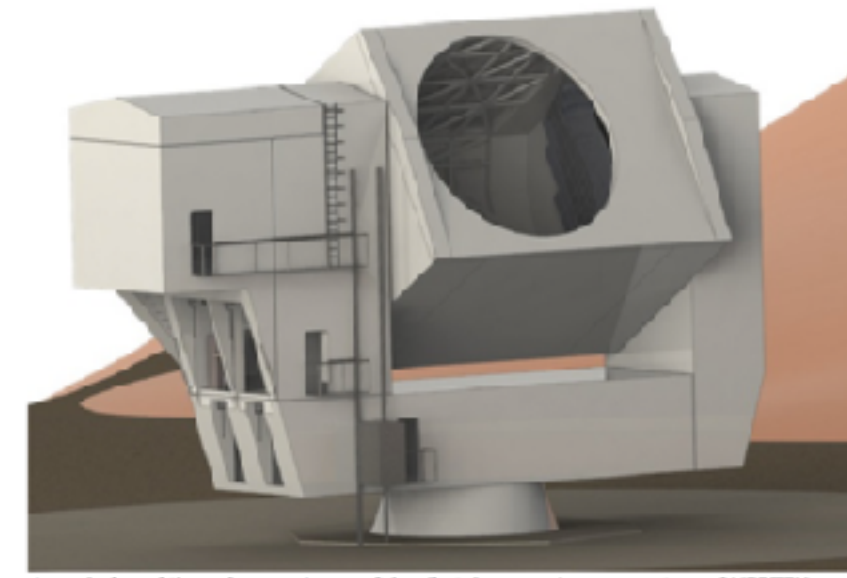
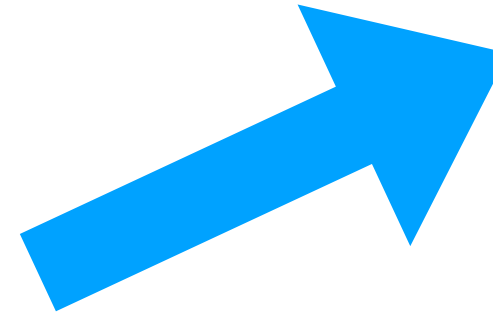
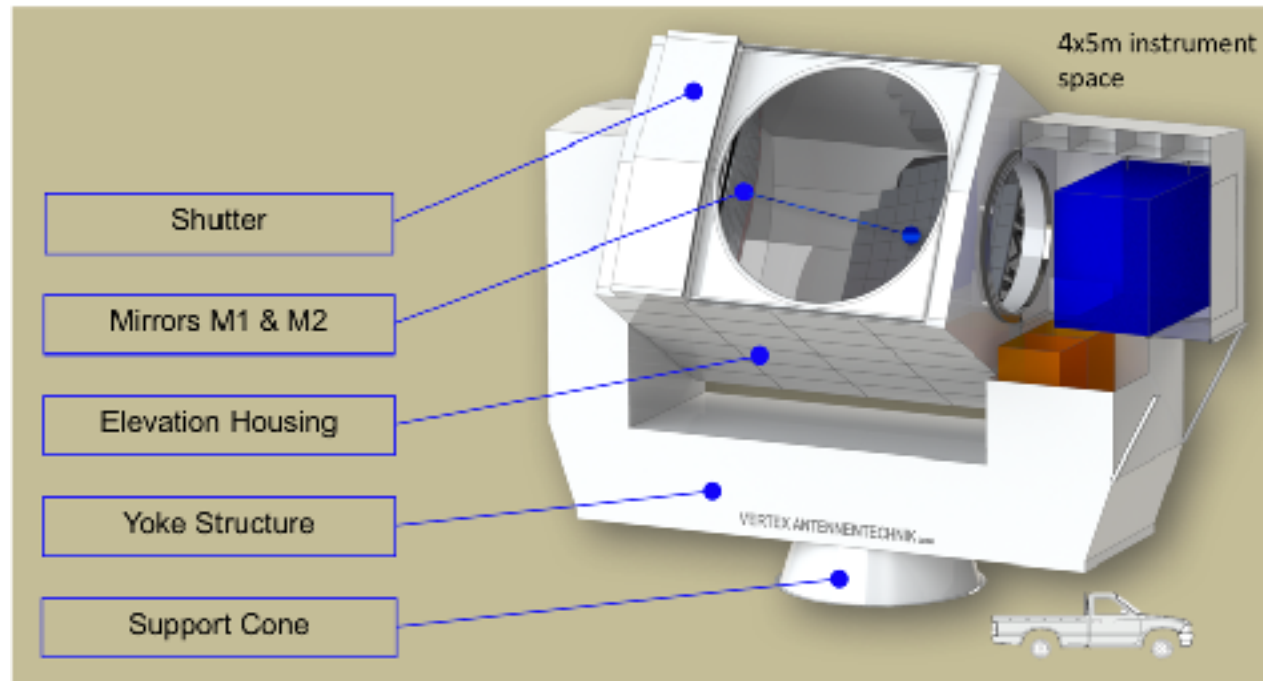
designed and built by Vertex Antennentechnik GmbH, Duisburg



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

CCAT-prime

designed and built by Vertex Antennentechnik GmbH, Duisburg



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

Simons Observatory (USA)

in collaboration

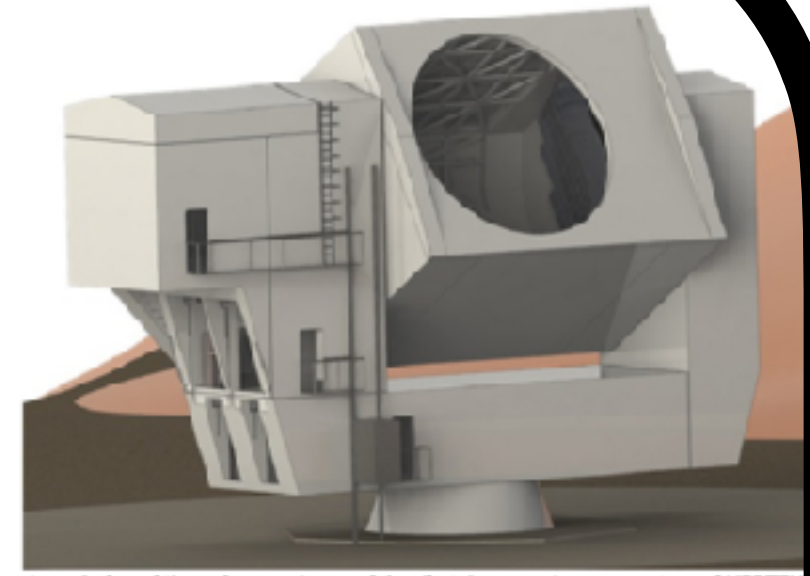
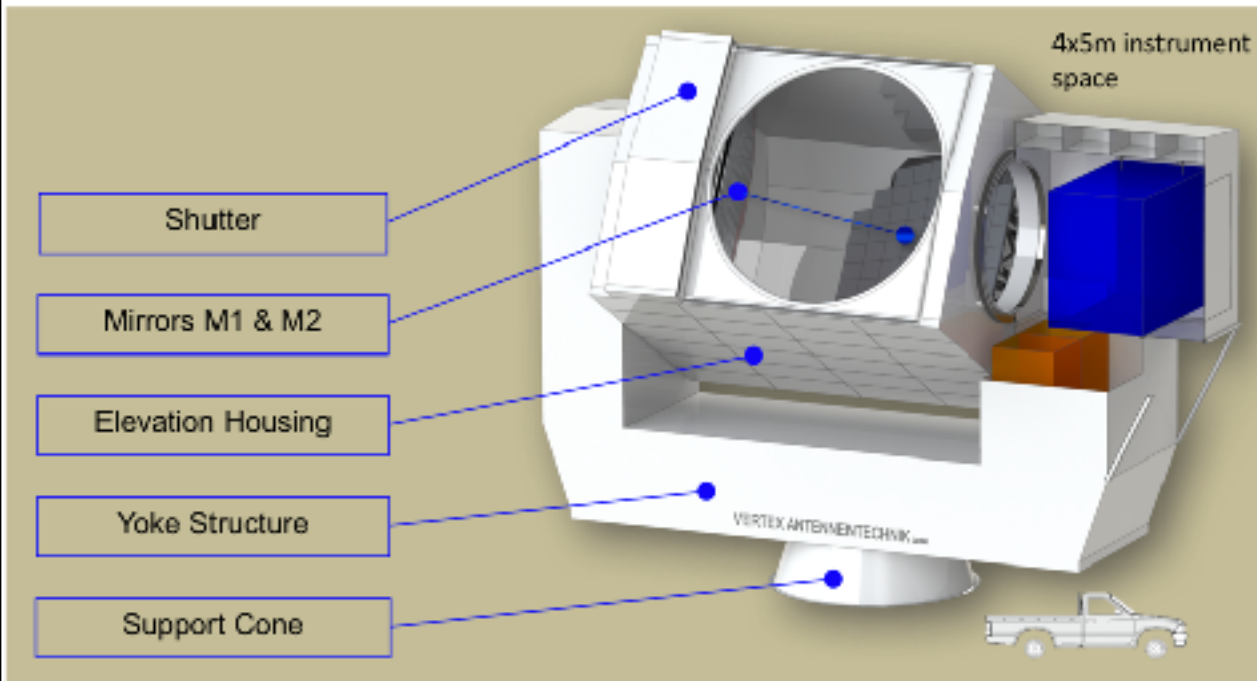


South Pole?

This could be “CMB-S4”

CCAT-prime

designed and built by Vertex Antennentechnik GmbH, Duisburg



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

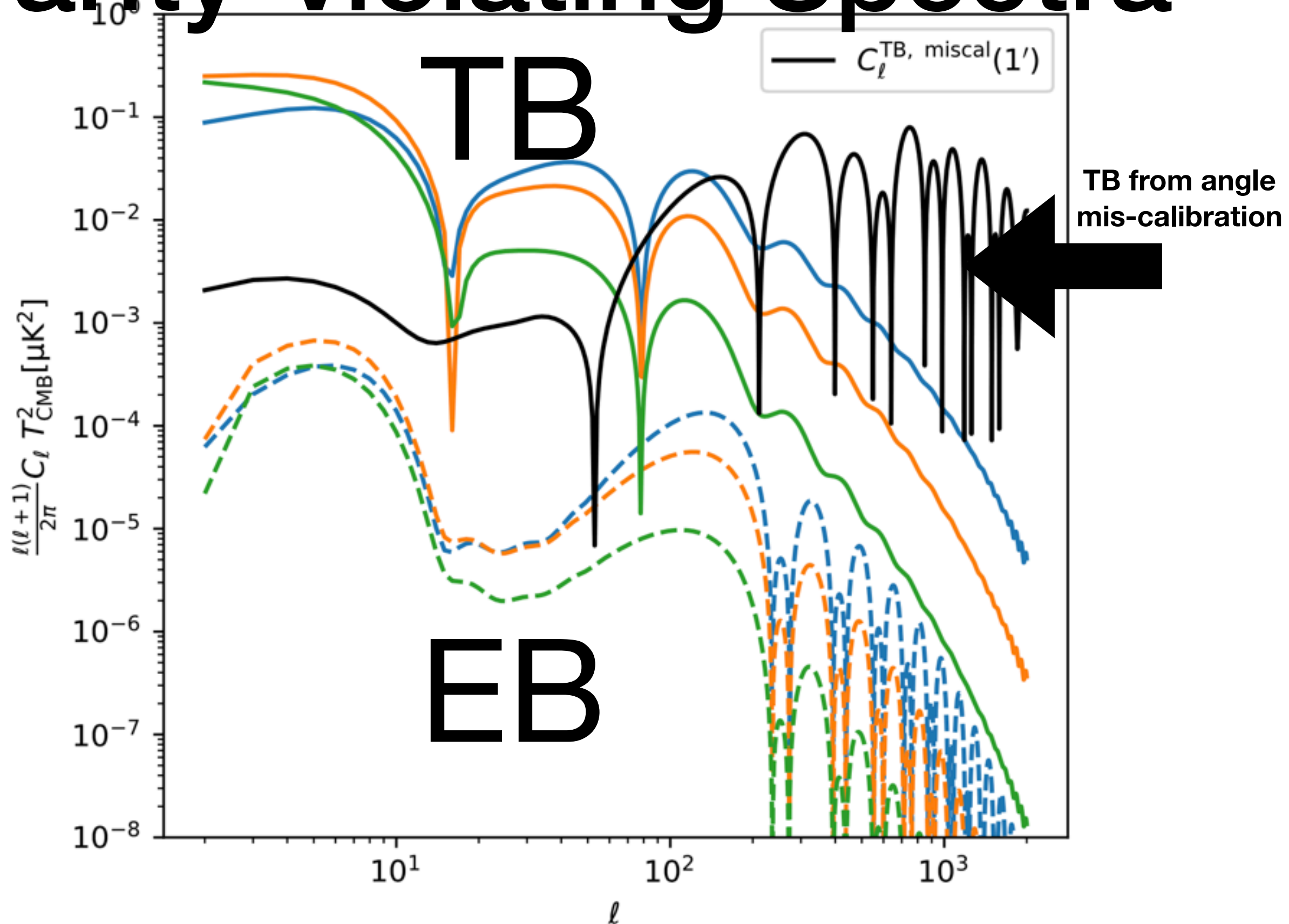
**Simons Observatory
(USA)**

in collaboration



South Pole?

Parity-violating Spectra



- Angle mis-calibration can be distinguished easily!

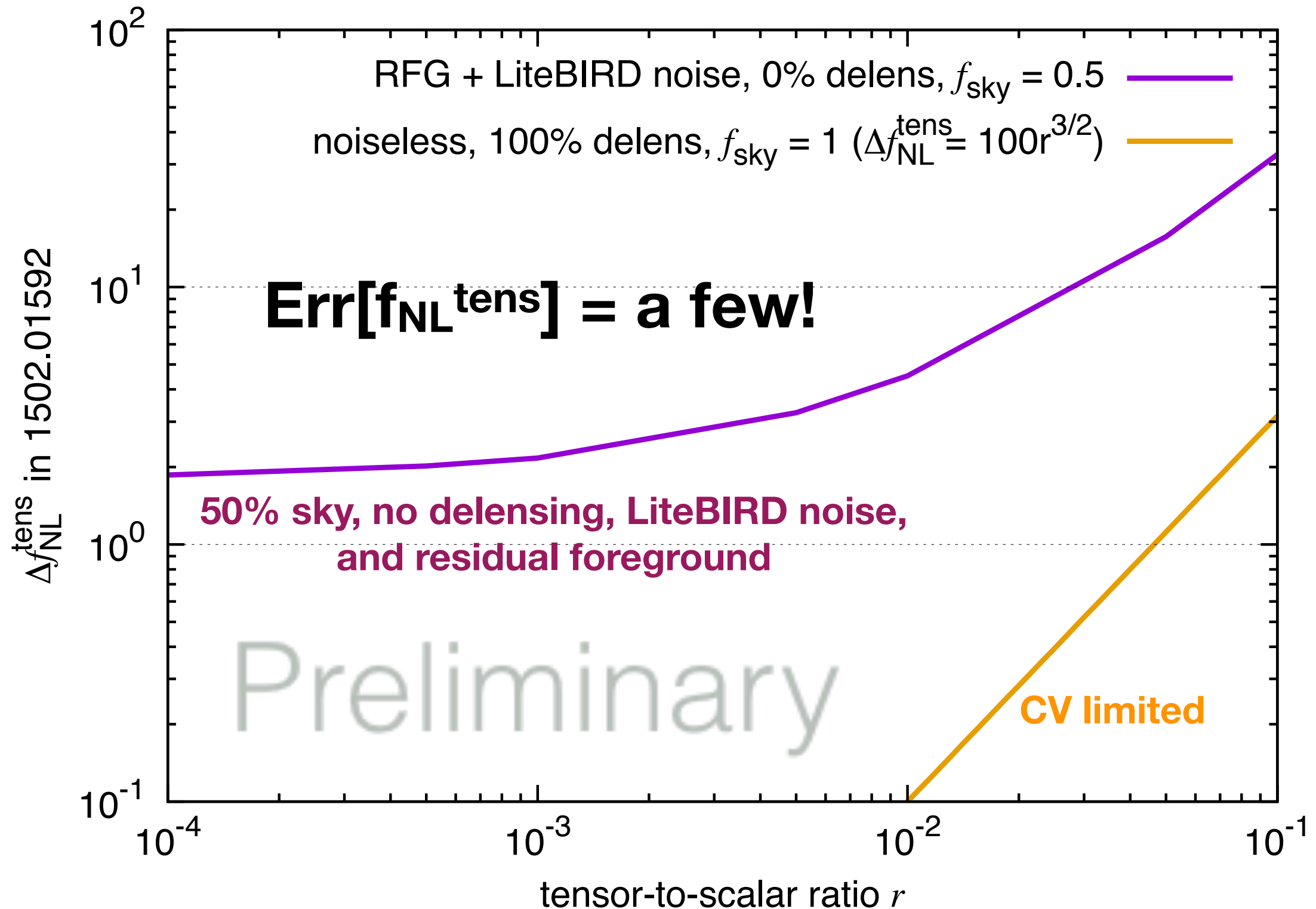
Current Limit on Tensor NG

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

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

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

LiteBIRD would nail it!



SU(2), confronted

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

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

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