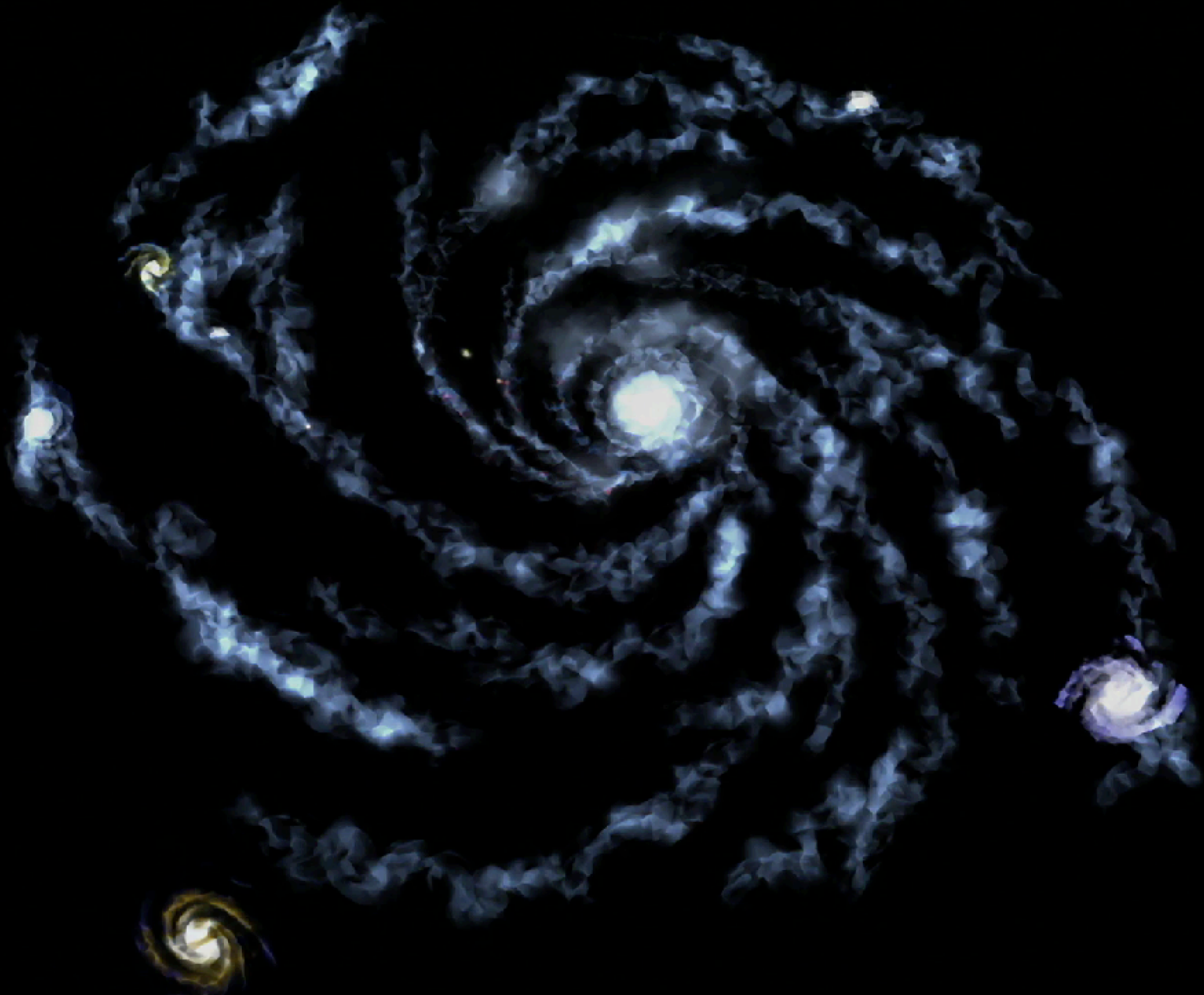
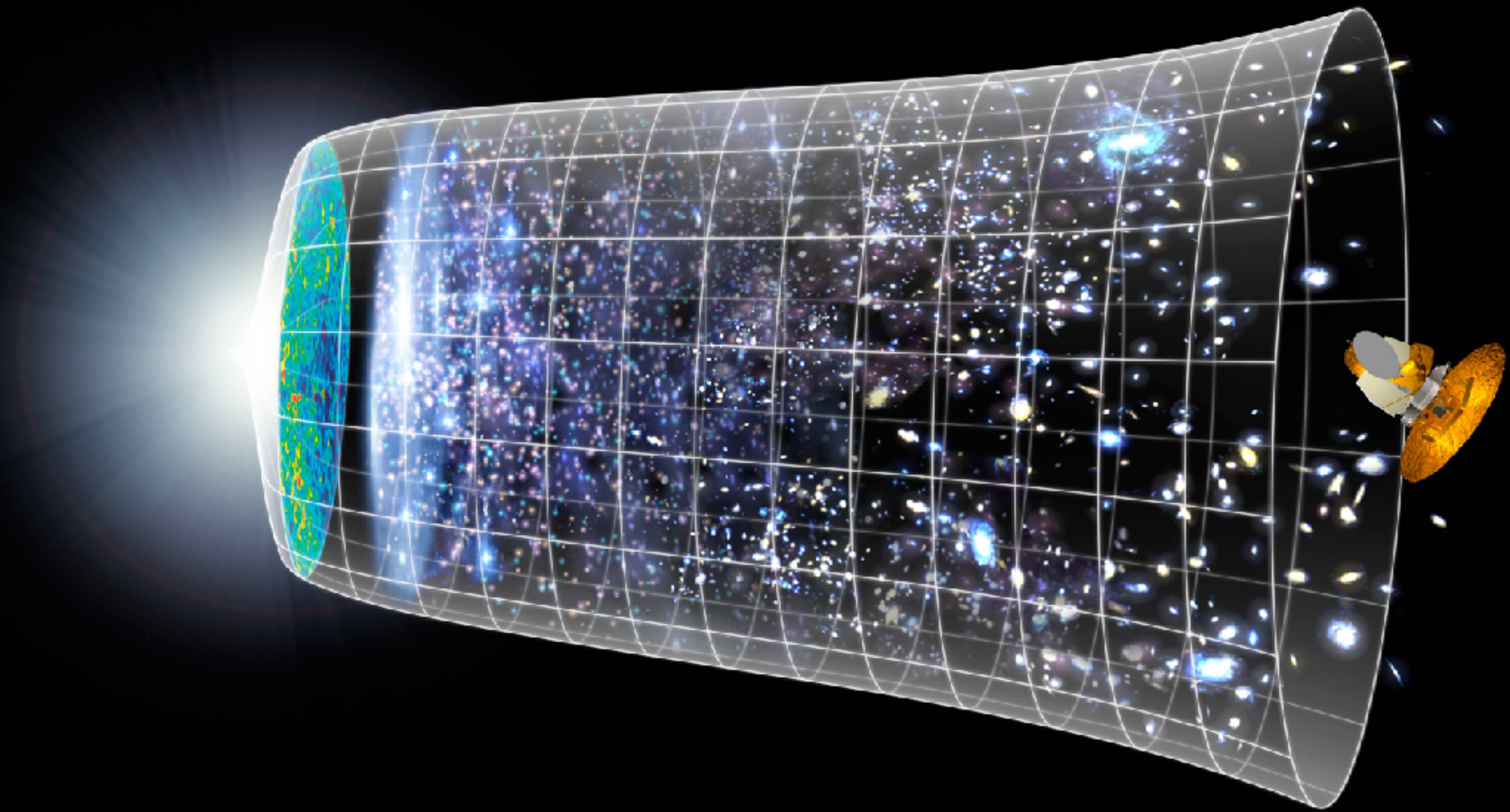
Finding gravitational waves from the early Universe

Eiichiro Komatsu
[Max Planck Institute for Astrophysics]

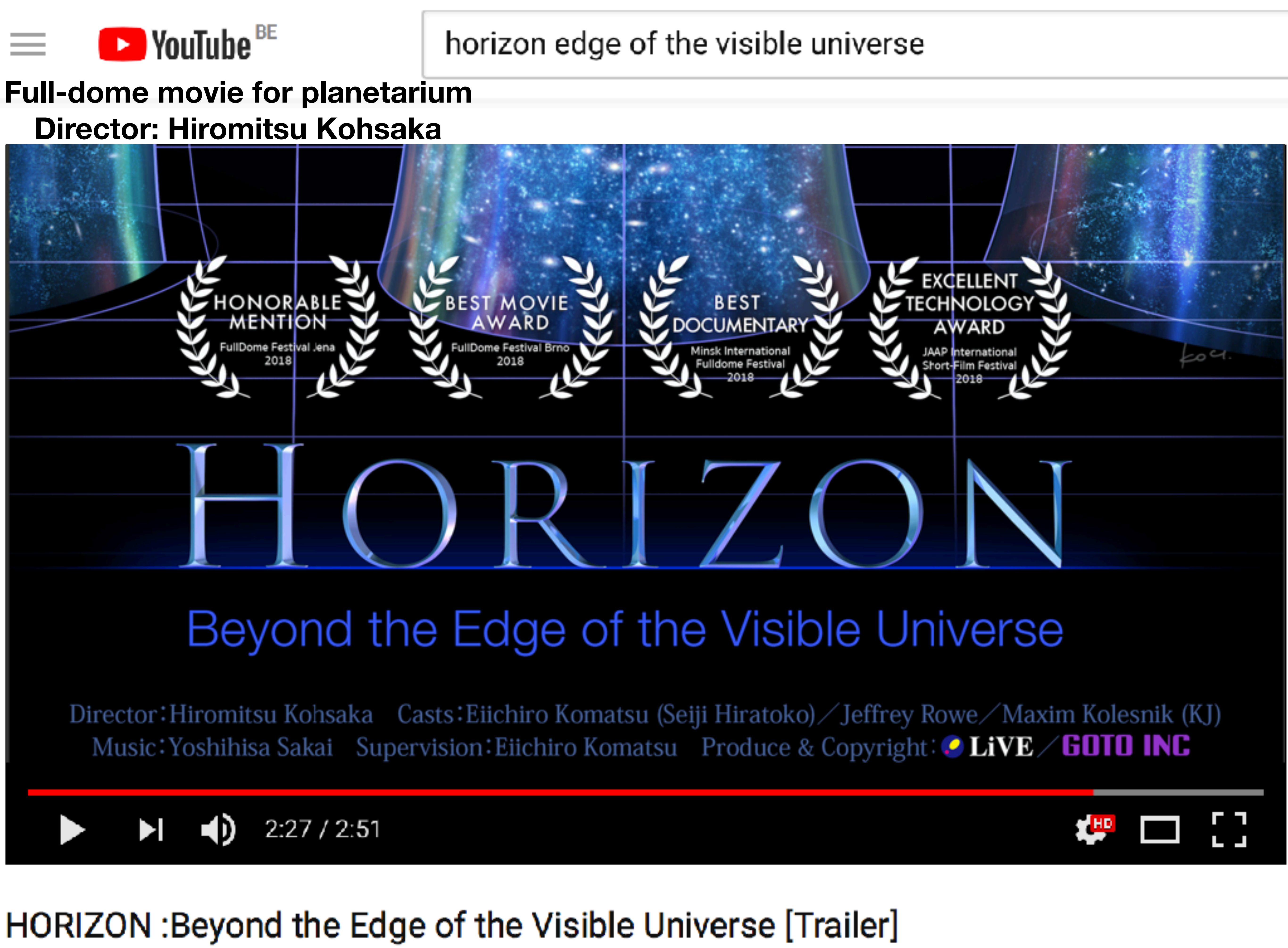
Colloquium, AEI Potsdam, February 7, 2020





Full-dome movie for planetarium

Director: Hiromitsu Kohsaka



horizon edge of the visible universe

HONORABLE MENTION
FullDome Festival Jena
2018

BEST MOVIE AWARD
FullDome Festival Brno
2018

BEST DOCUMENTARY
Minsk International Fulldome Festival
2018

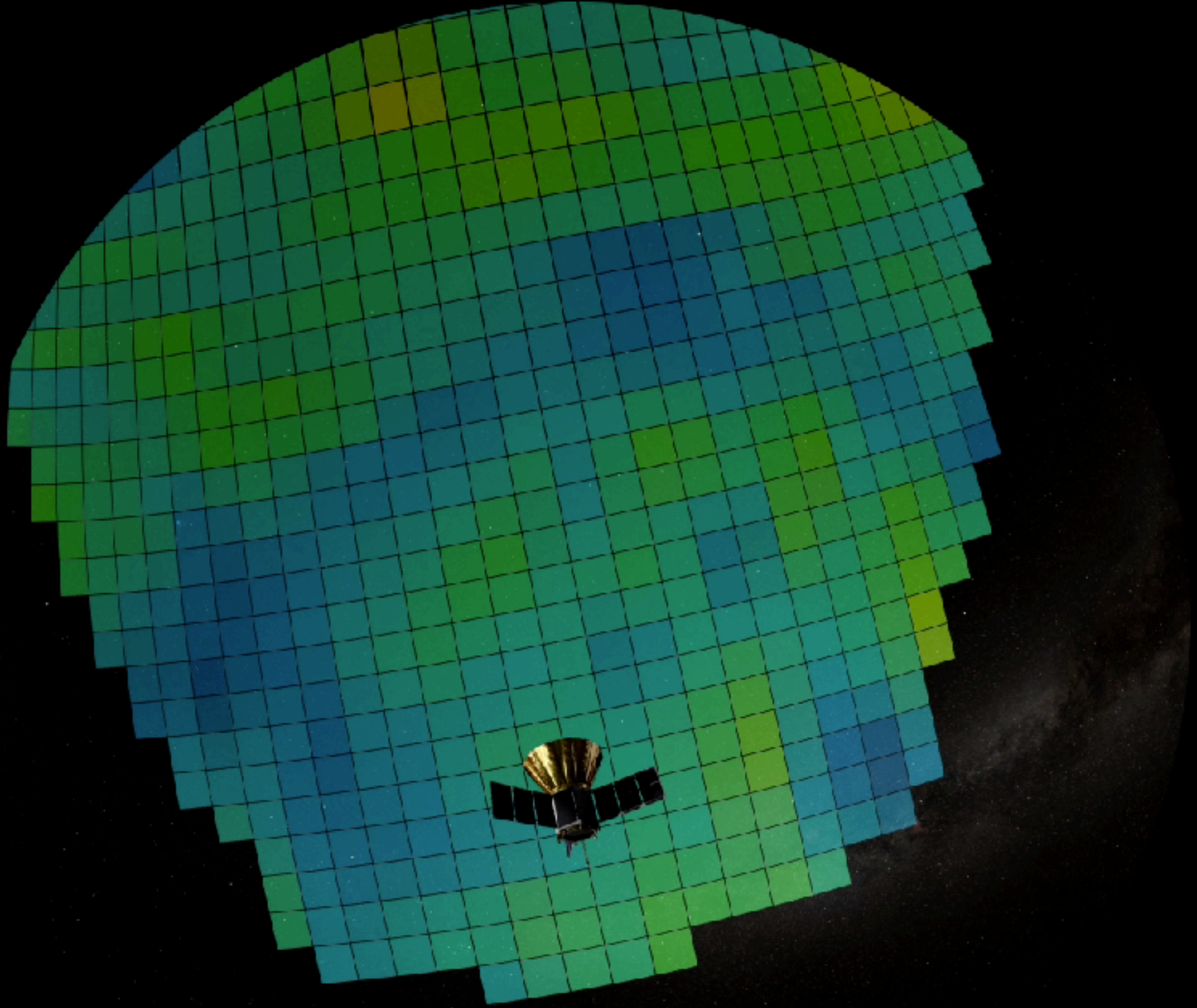
EXCELLENT TECHNOLOGY AWARD
JAAP International Short-Film Festival
2018

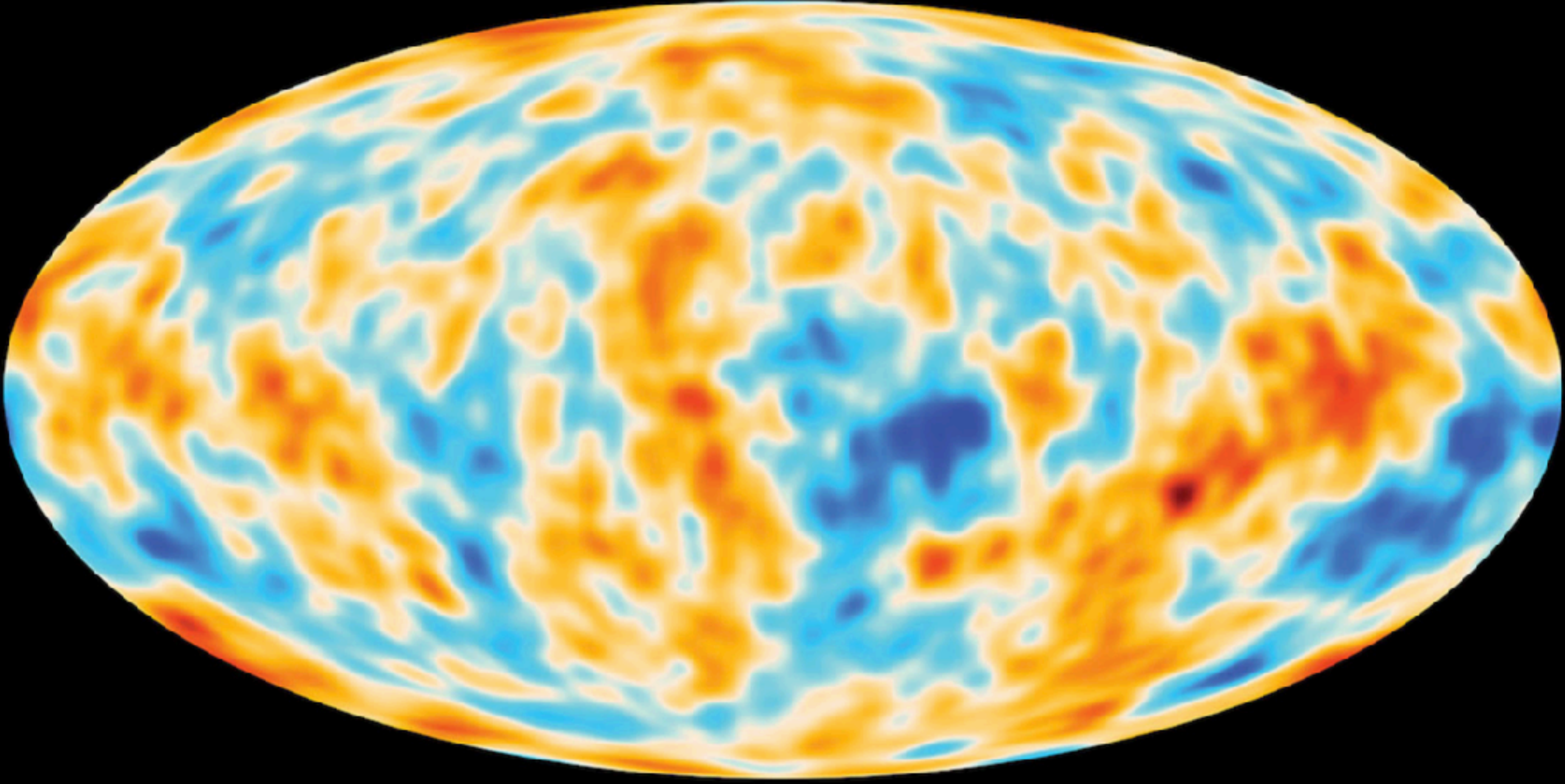
HORIZON

Beyond the Edge of the Visible Universe

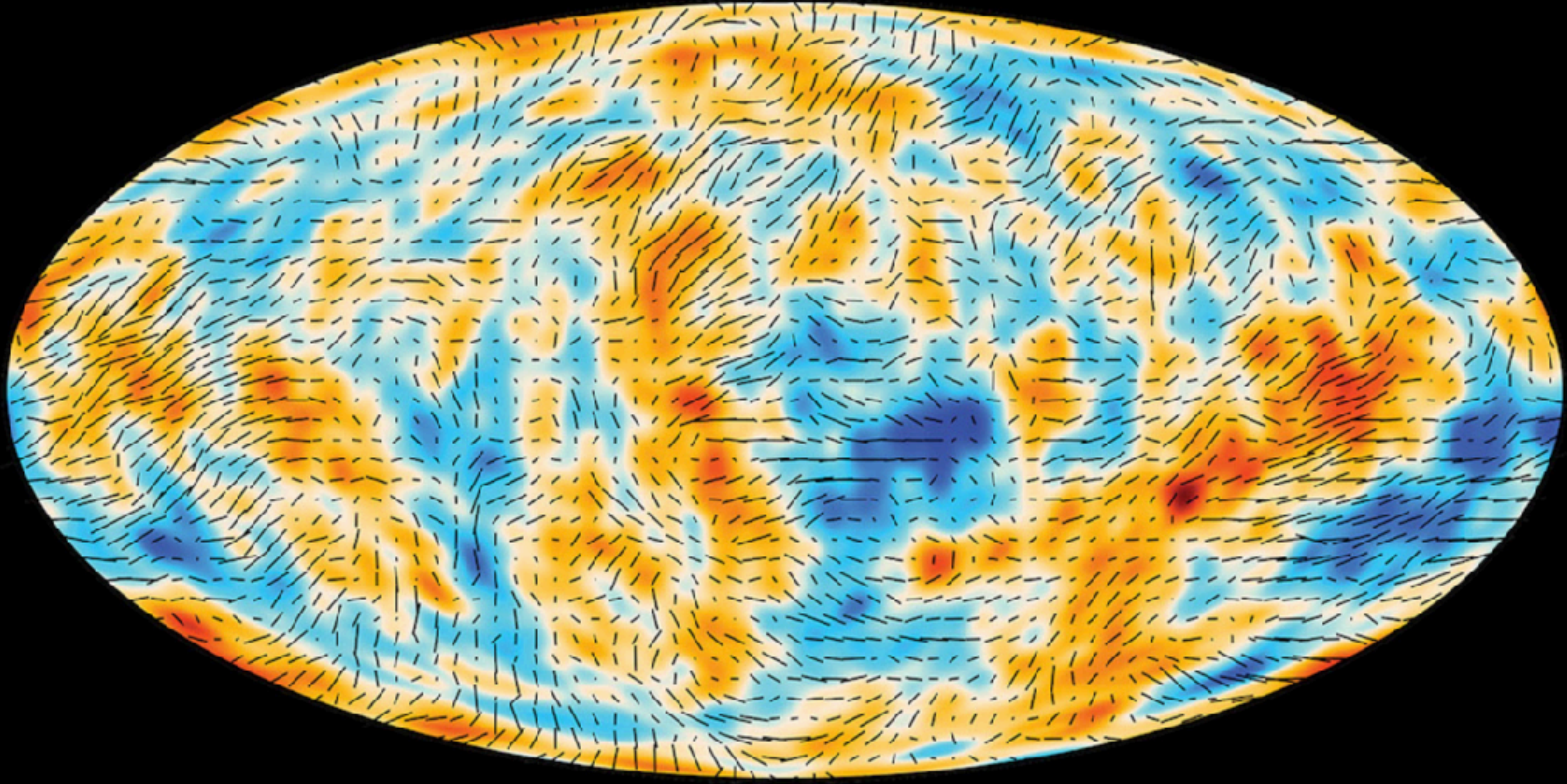
Director：Hiromitsu Kohsaka　Casts：Eiichiro Komatsu (Seiji Hiratoko)／Jeffrey Rowe／Maxim Kolesnik (KJ)
Music：Yoshihisa Sakai　Supervision：Eiichiro Komatsu　Produce & Copyright：LiVE／GOTO INC

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



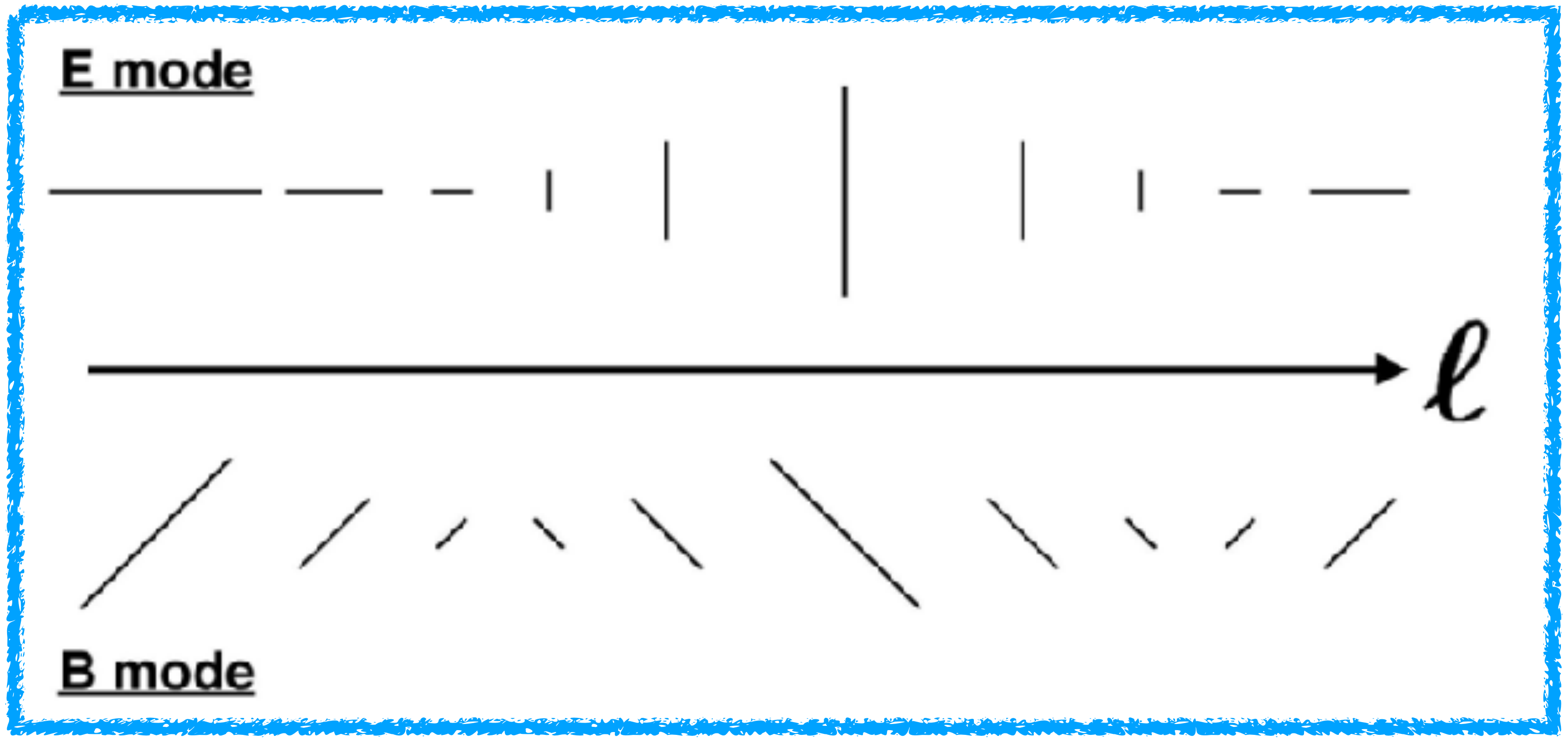


Temperature (smoothed)



Temperature (smoothed) + Polarisation

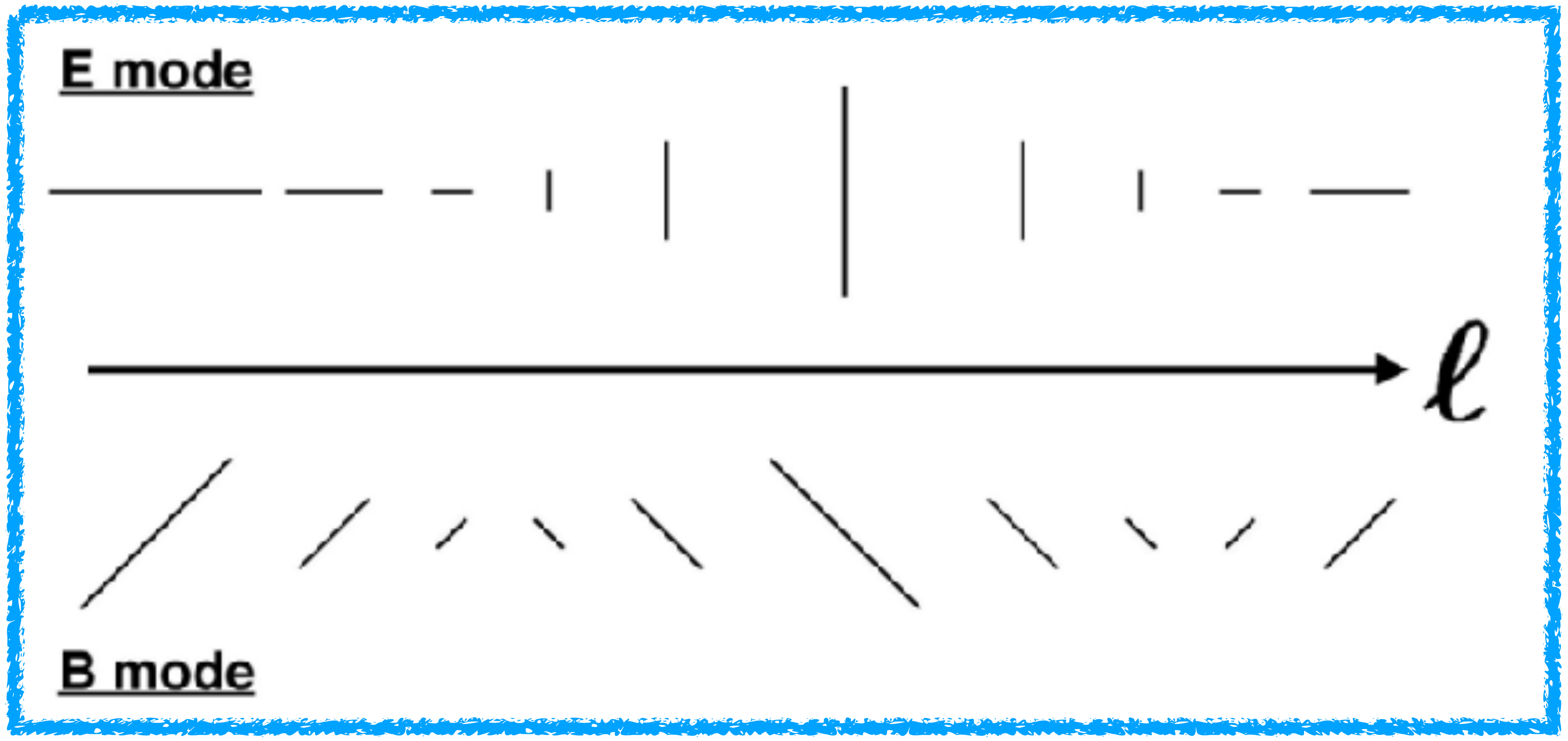
E and B mode



- **E mode**: Polarisation directions parallel or perpendicular to the wavevector

- **B mode**: Polarisation directions 45 degree tilted with respect to the wavevector

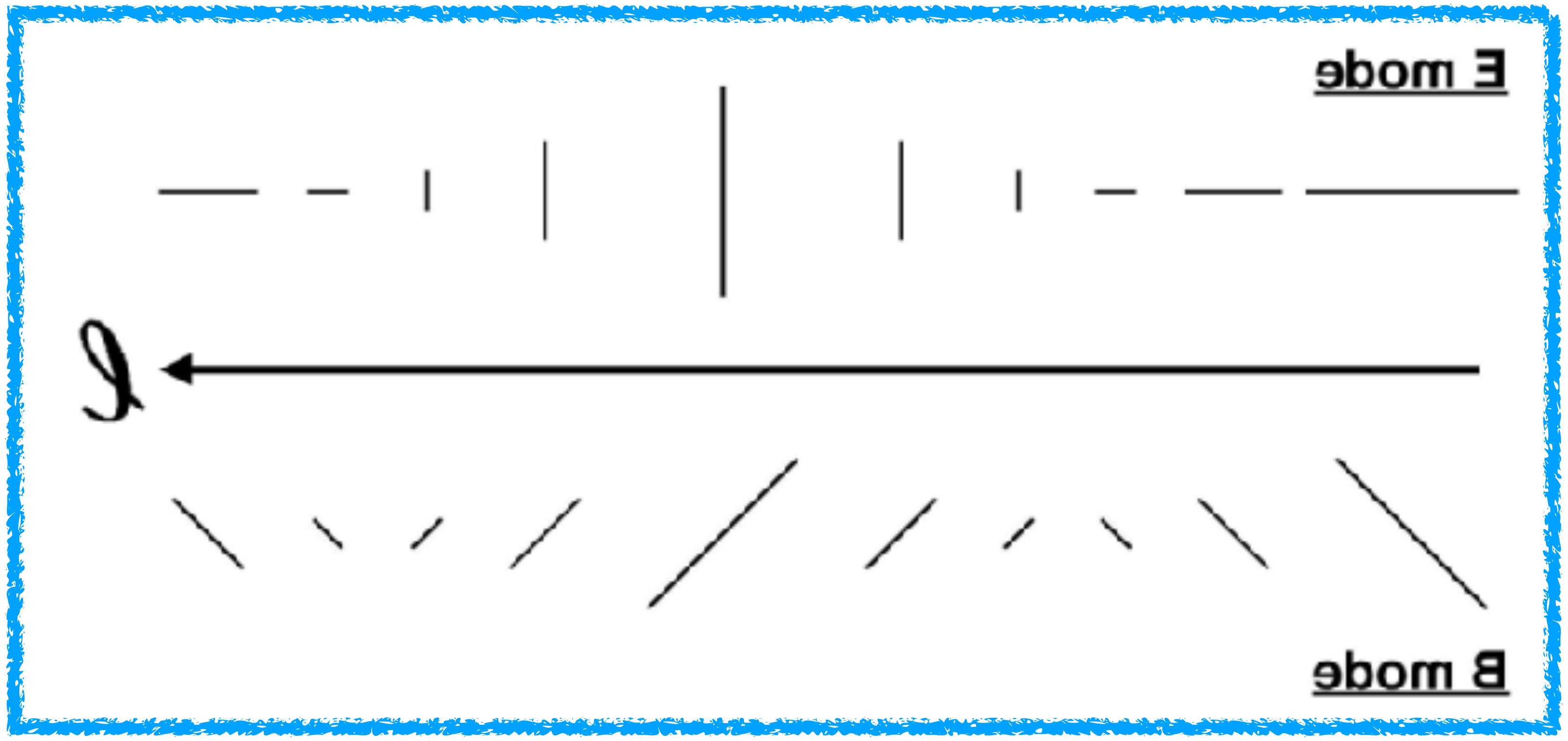
Parity



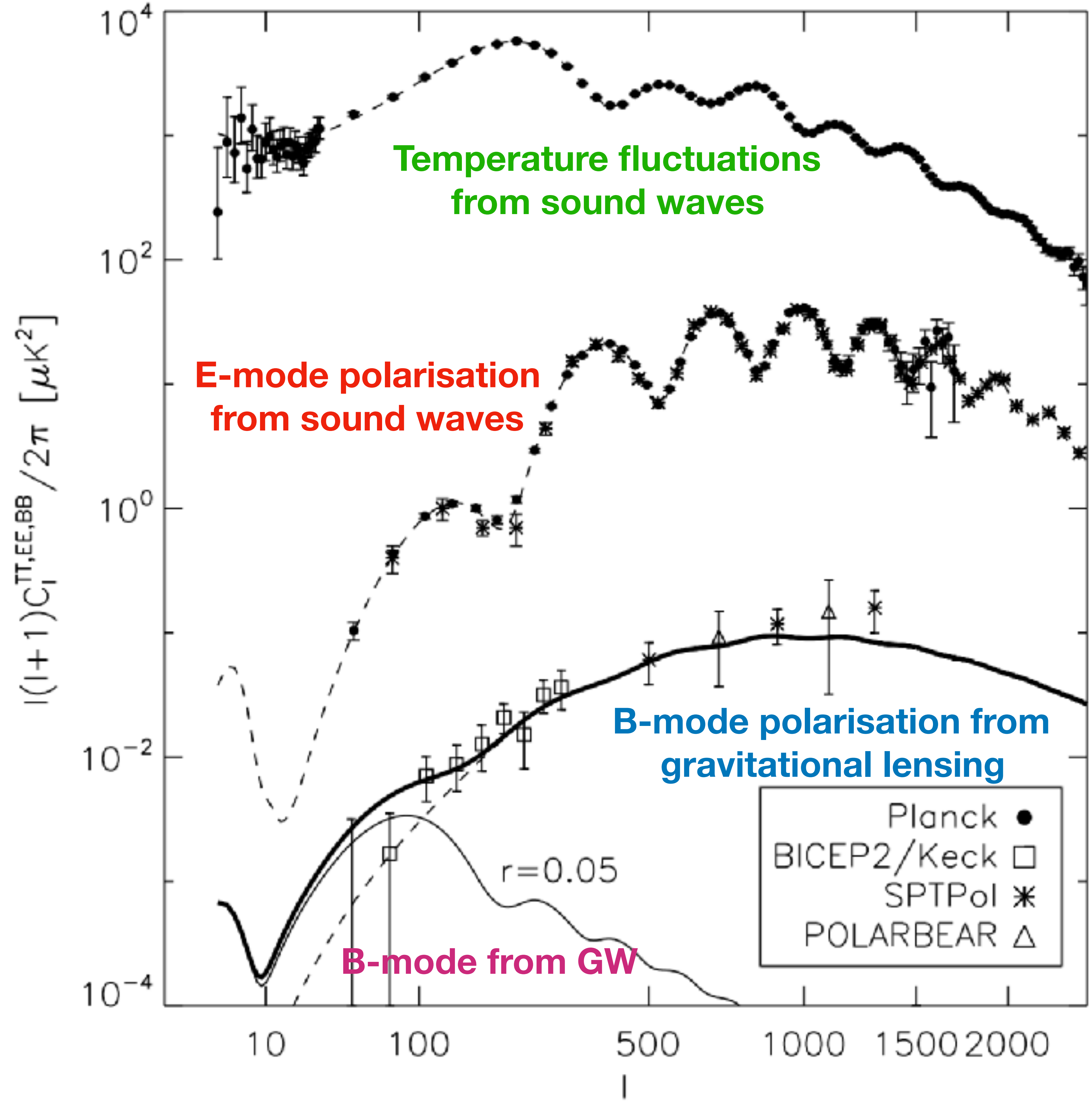
- **E mode**: Parity even

- **B mode**: Parity odd

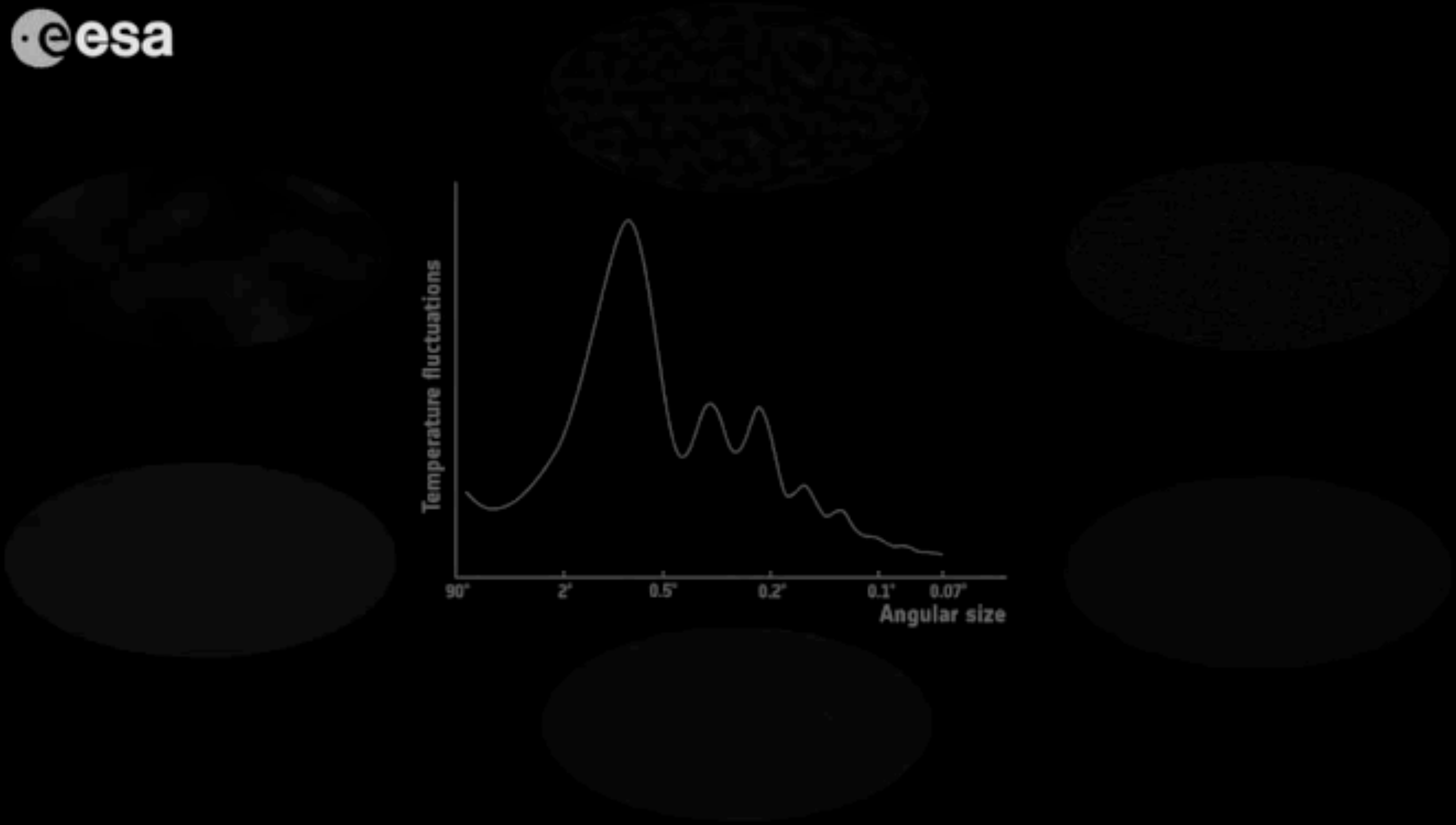
Parity



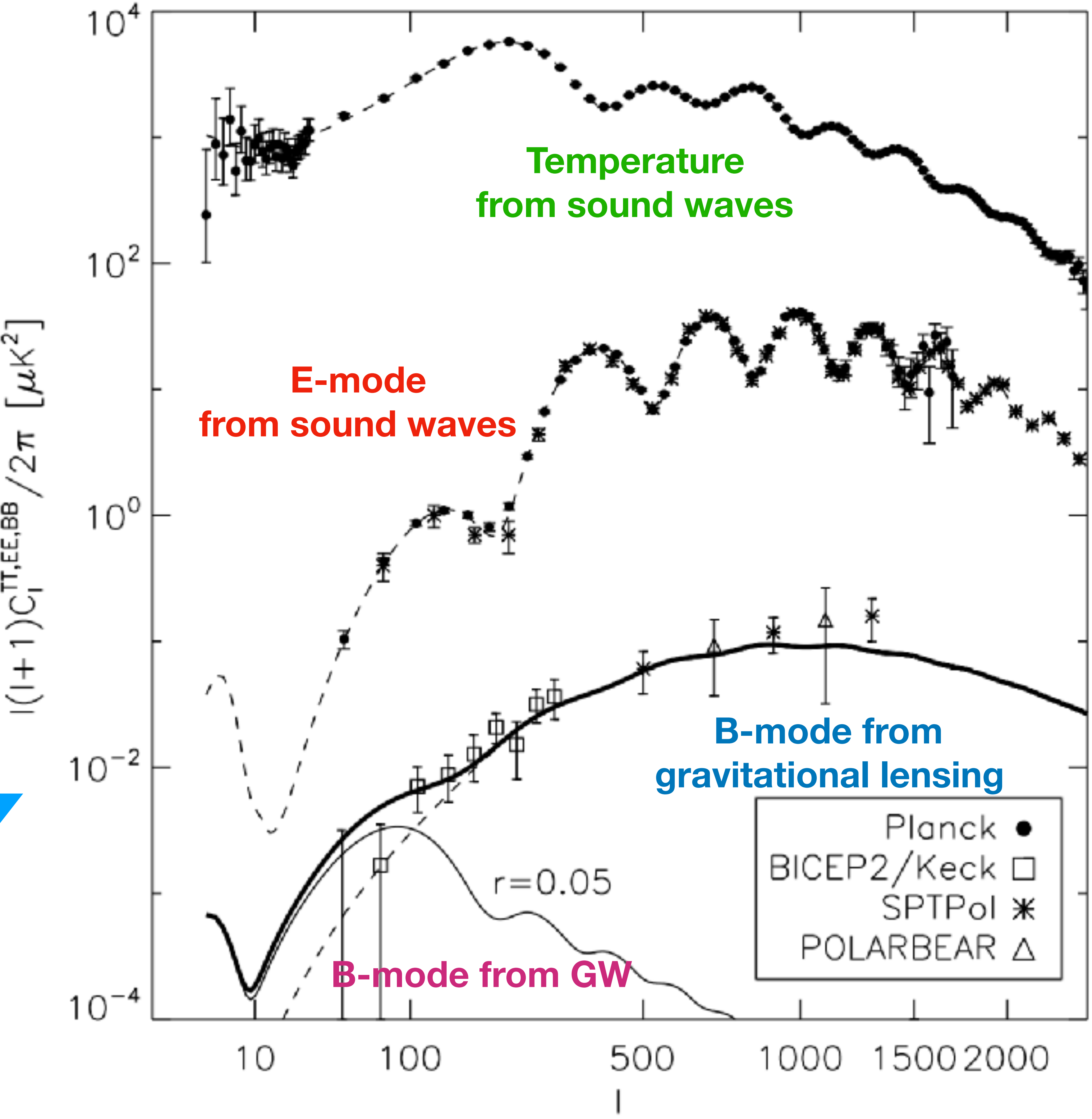
- **<u>E mode</u>**: Parity even
- **<u>B mode</u>**: Parity odd


Temperature fluctuations from sound waves
E-mode polarisation from sound waves
B-mode polarisation from gravitational lensing
B-mode from GW
r=0.05
Planck ●
BICEP2/Keck □
SPTPol ✳
POLARBEAR △
$l(l+1)C_l^{TT,EE,BB}/2\pi\ [\mu K^2]$
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100
500
1000
1500
2000
l

Power spectrum, explained



Seven orders of magnitude in power in "just" 25 years



CMB-S4
Next Generation CMB Experiment

CMB Stages

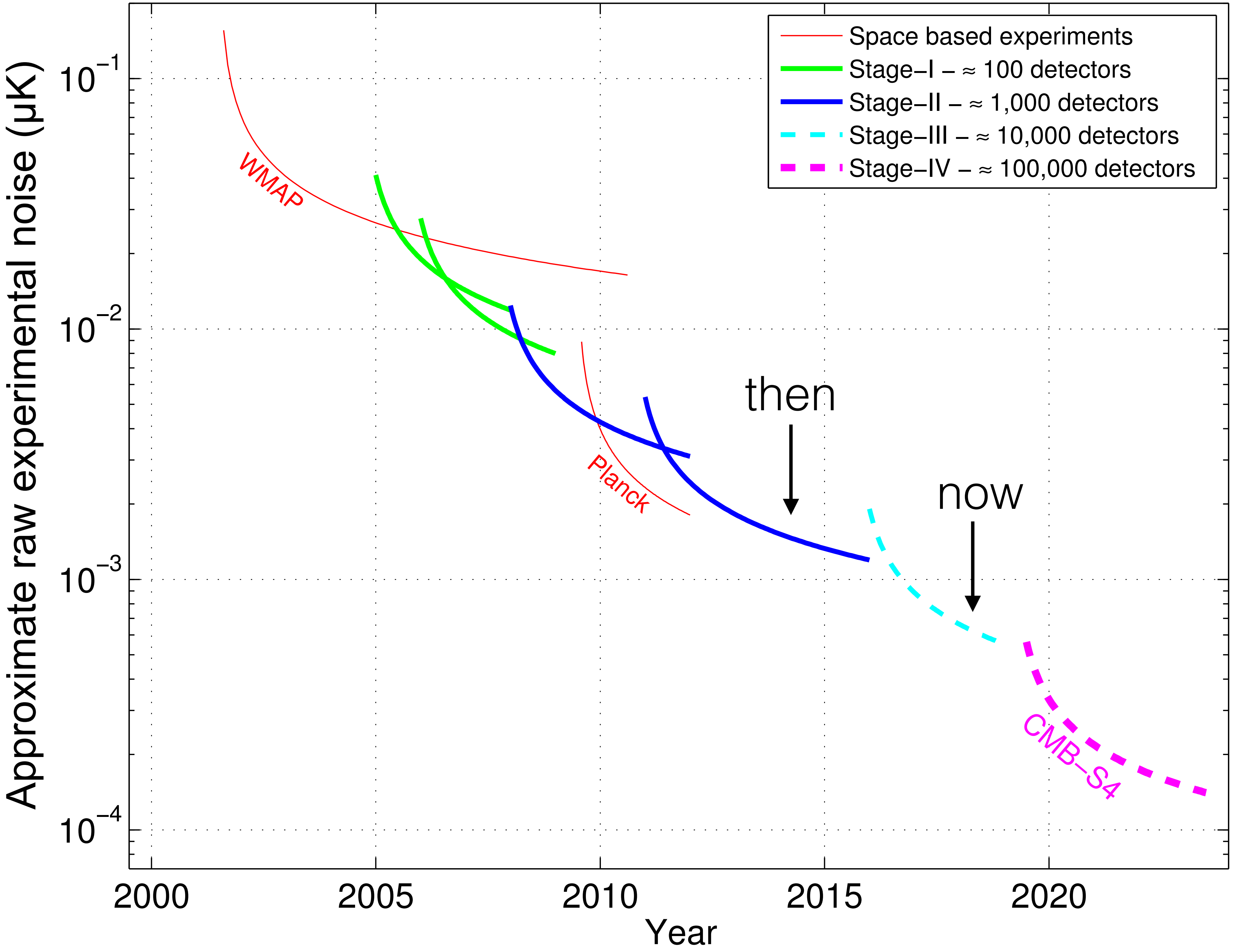
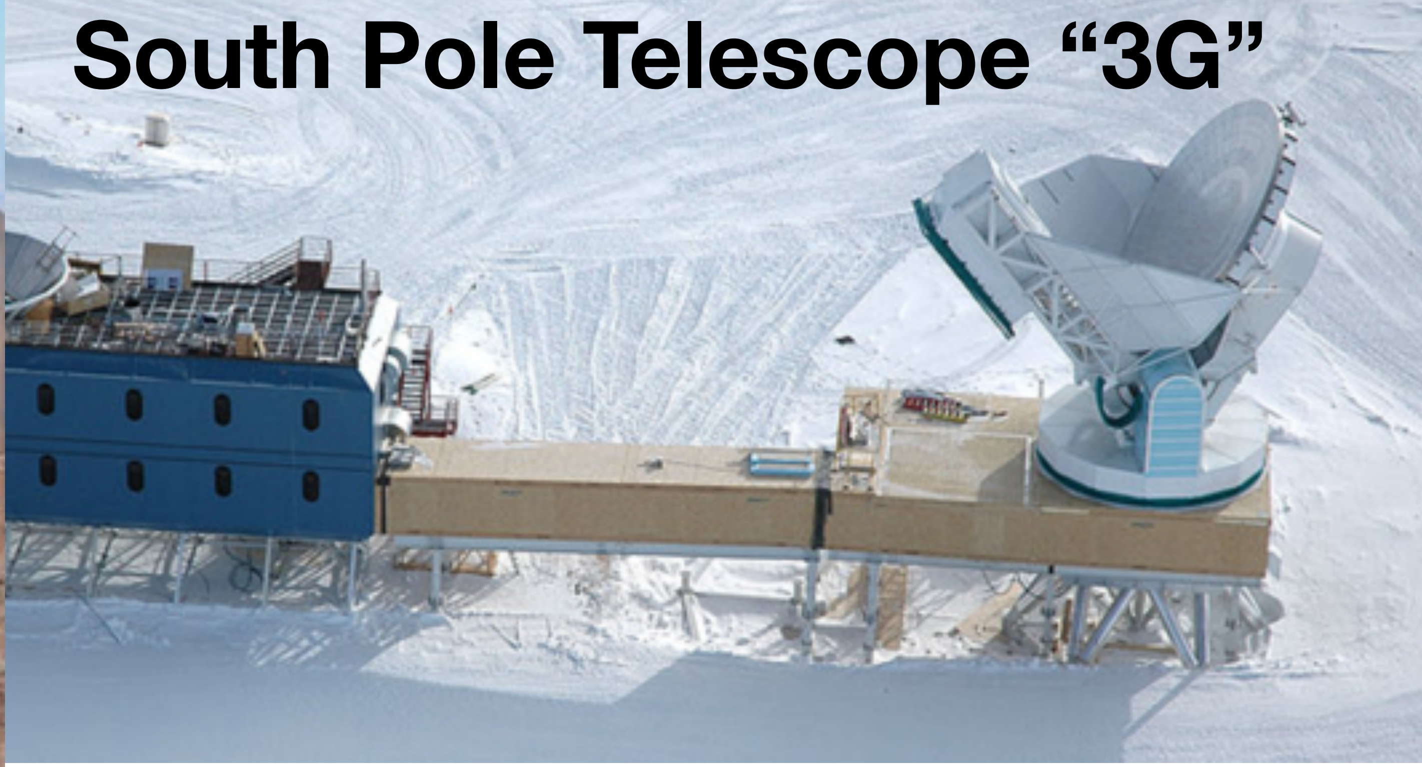


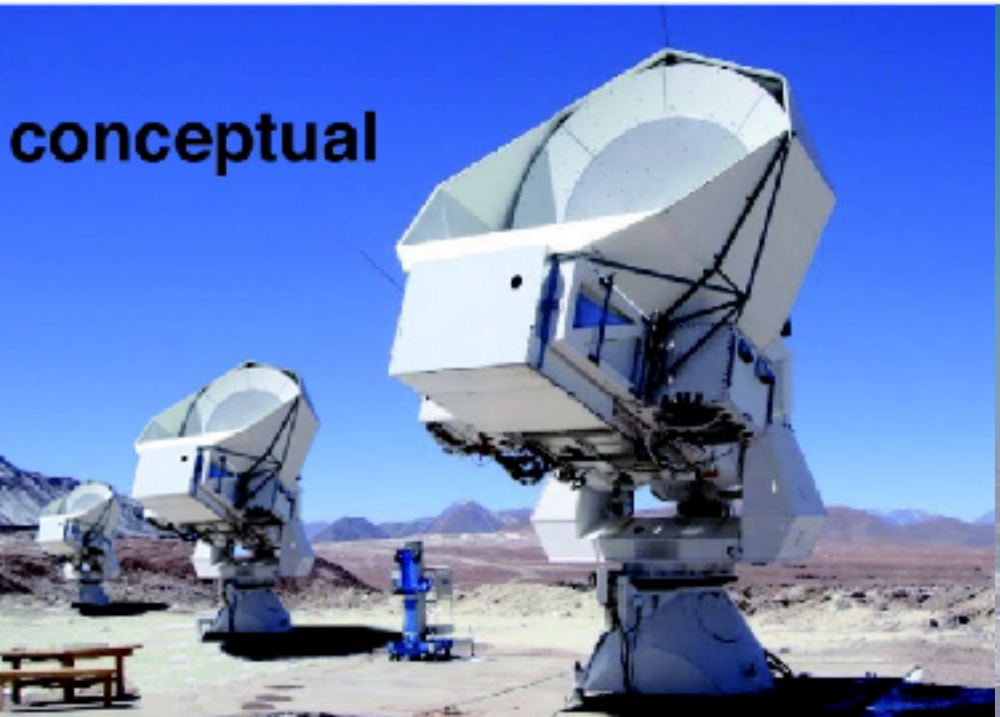
Figure by Clem Pryke for 2013 Snowmass documents


Advanced Atacama Cosmology Telescope

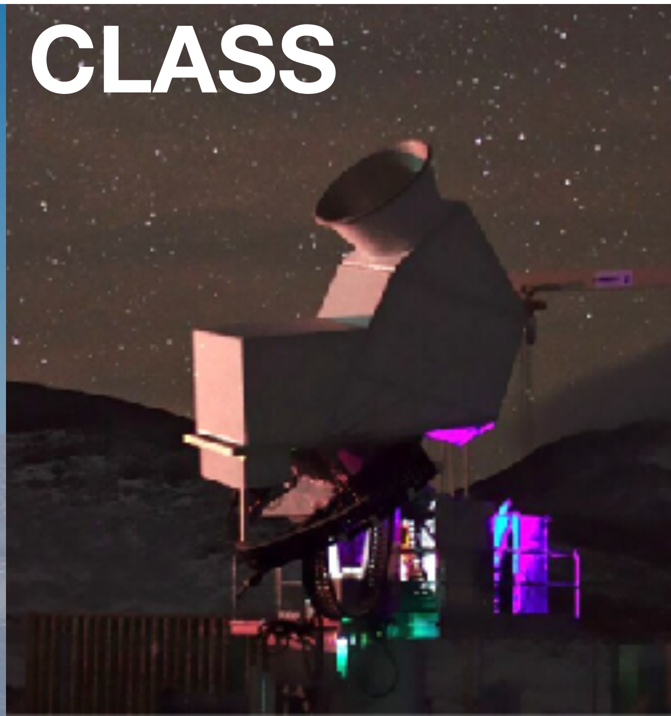

South Pole Telescope “3G”

What comes next?

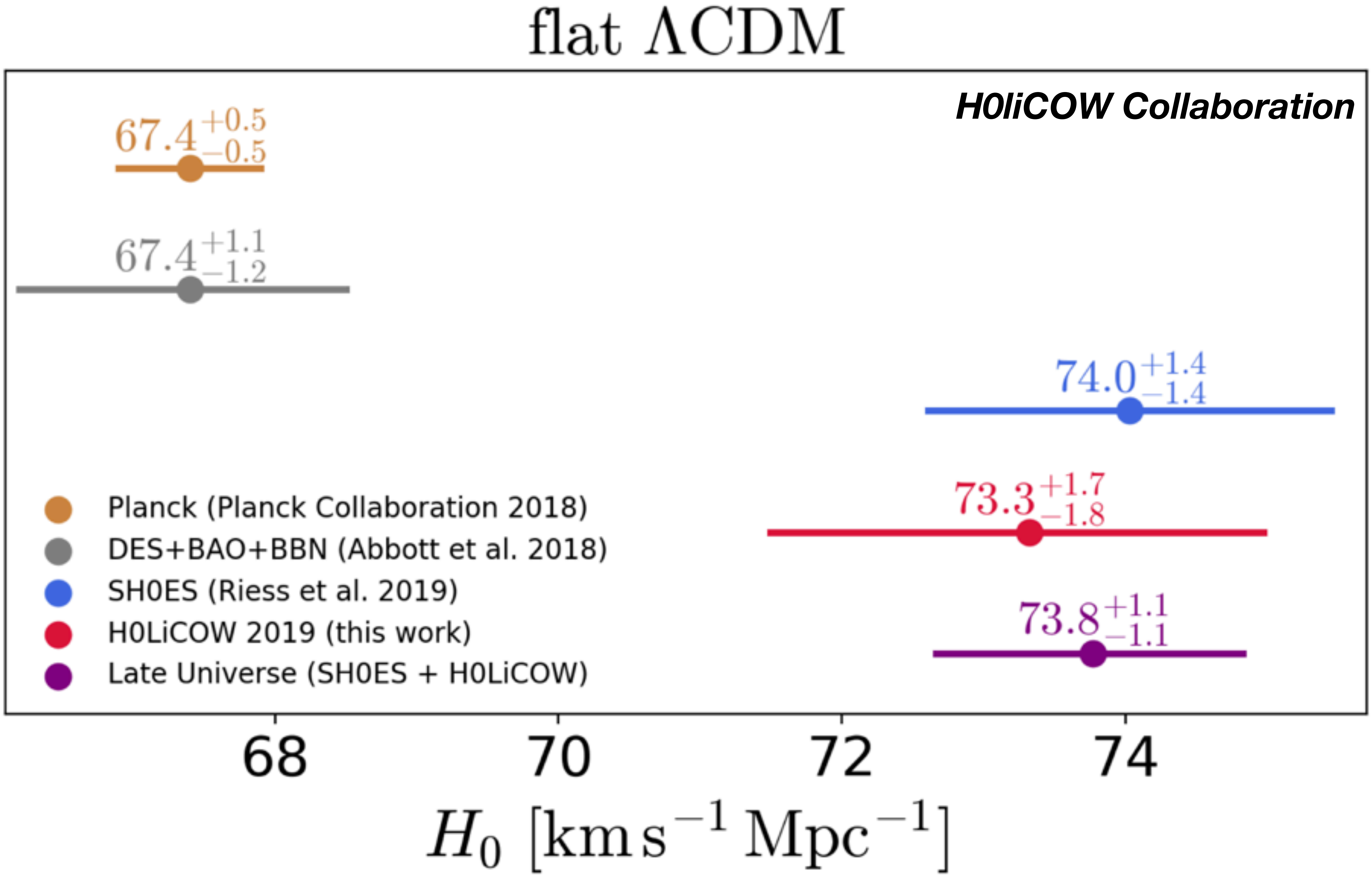
The Simons Array




BICEP/Keck Array

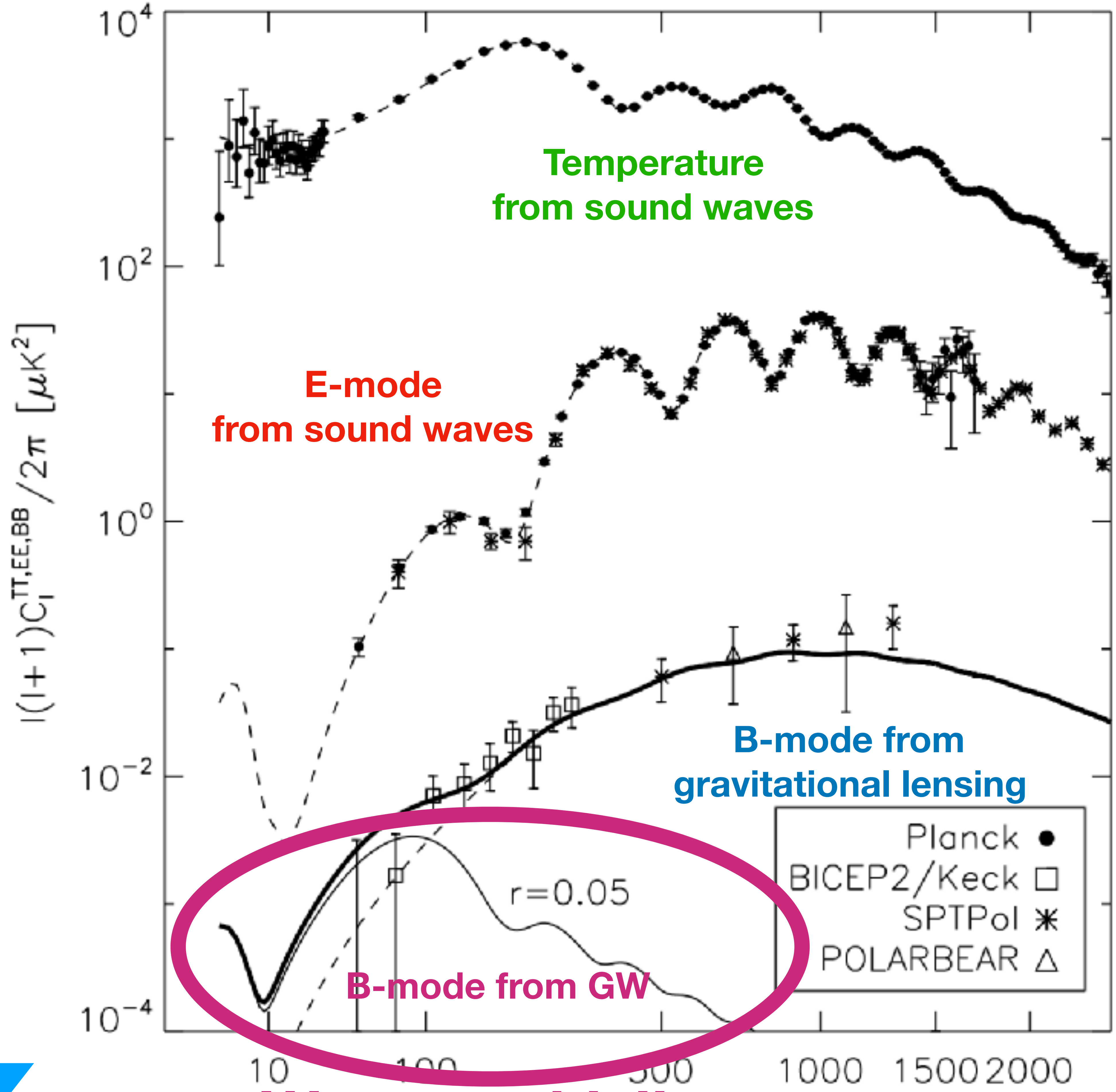

CLASS

Not just gravitational waves…



Ground-based CMB polarisation experiments measuring the E-mode polarisation from sound waves precisely will provide *independent* assessments of H_0 inferred from CMB, which has been derived mostly from temperature anisotropy so far.

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



We want this!!

JAXA

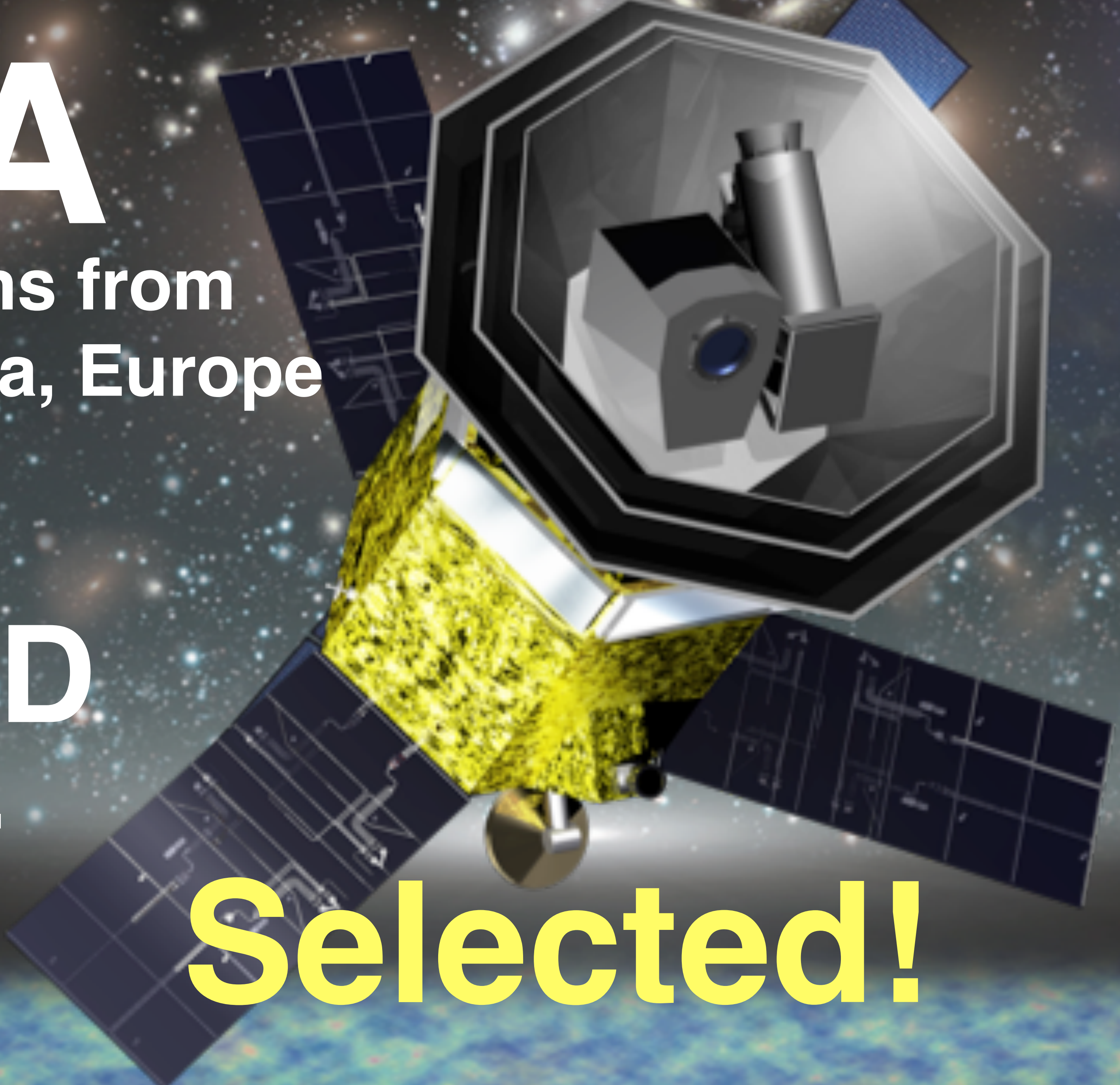
+ participations from
USA, Canada, Europe

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

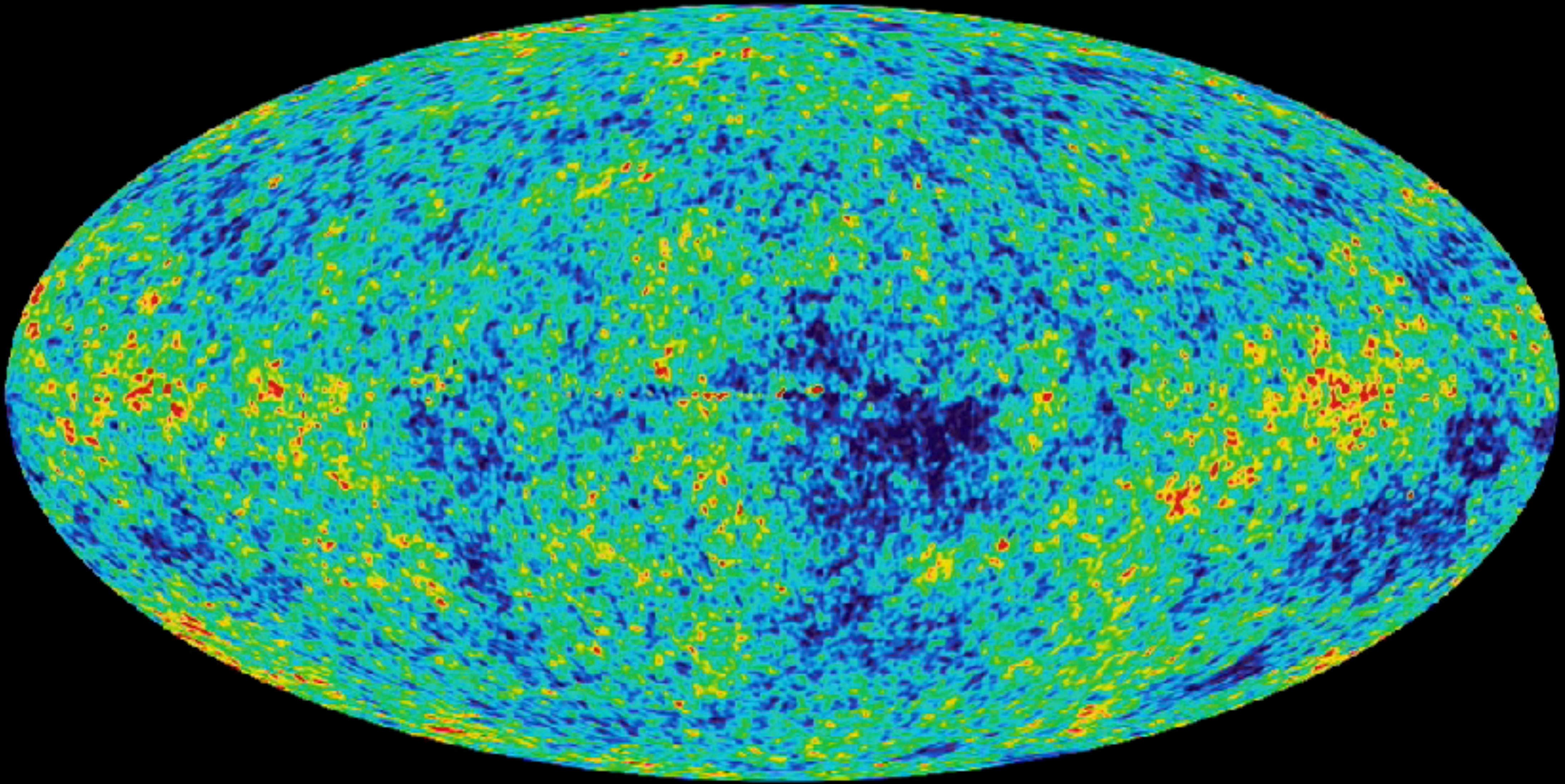


LiteBIRD
2028–

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?***

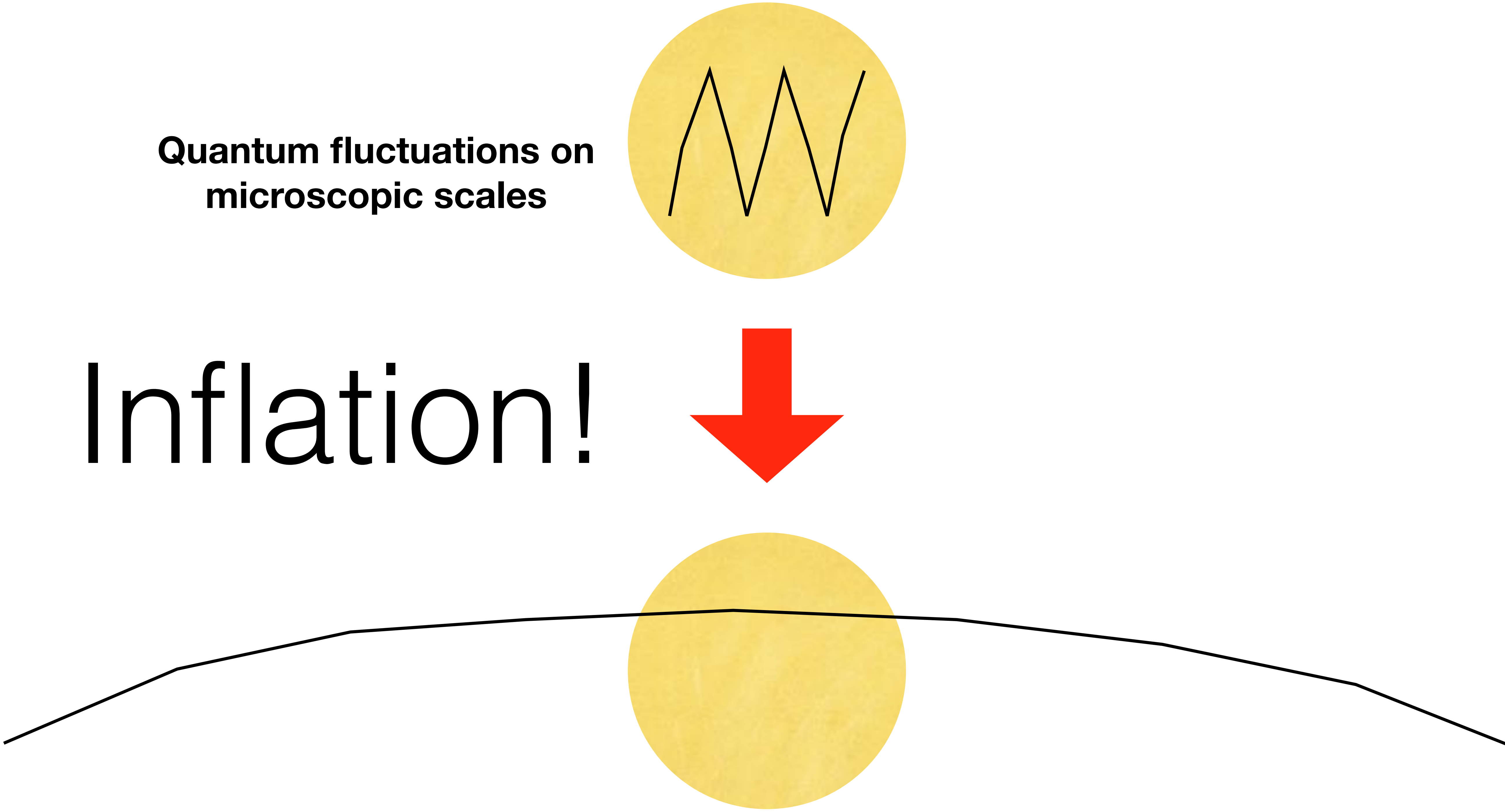
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

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?

Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation



Quantum fluctuations on microscopic scales

Inflation!

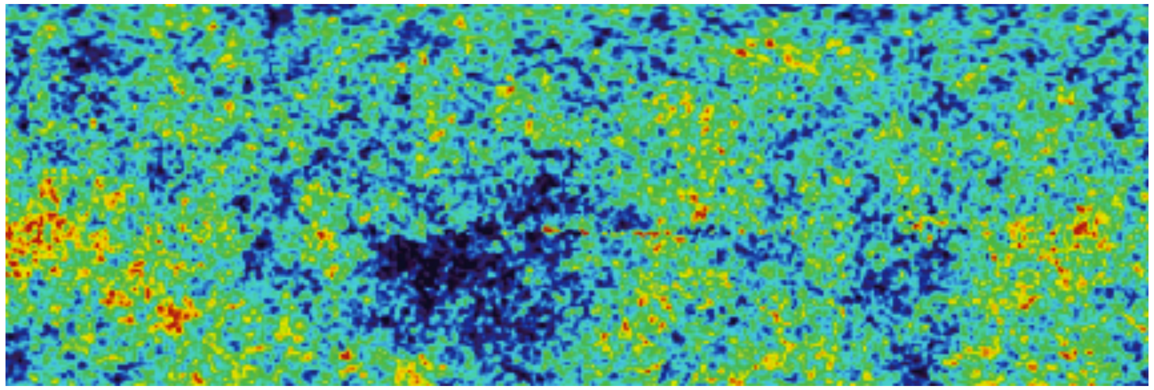
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

Inflationary Predictions

ζ

scalar mode

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



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

h_{ij}

tensor mode

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

Grishchuk (1974)
Starobinsky (1979)

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

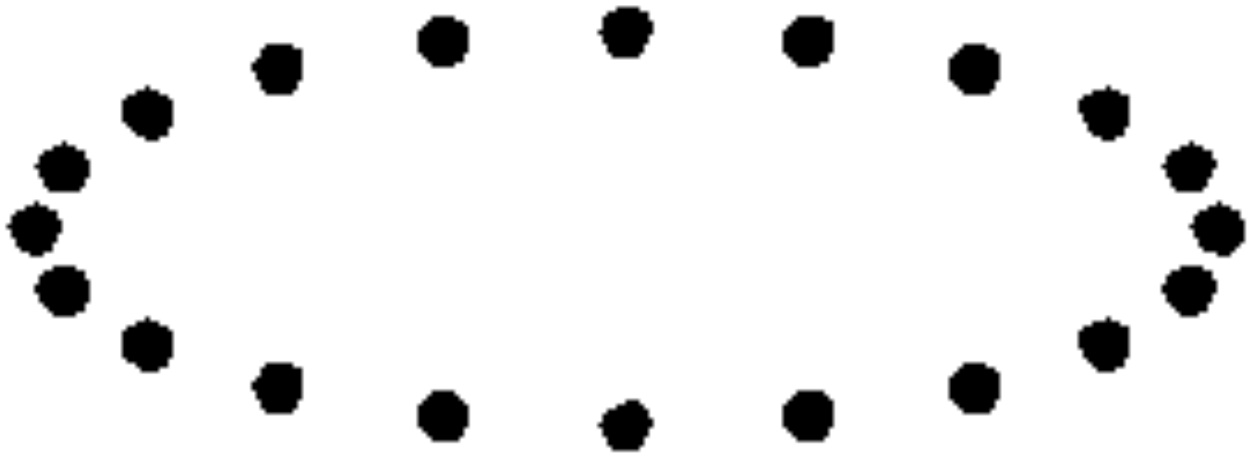
$$\sum_i h_{ii} = 0$$

Measuring GW

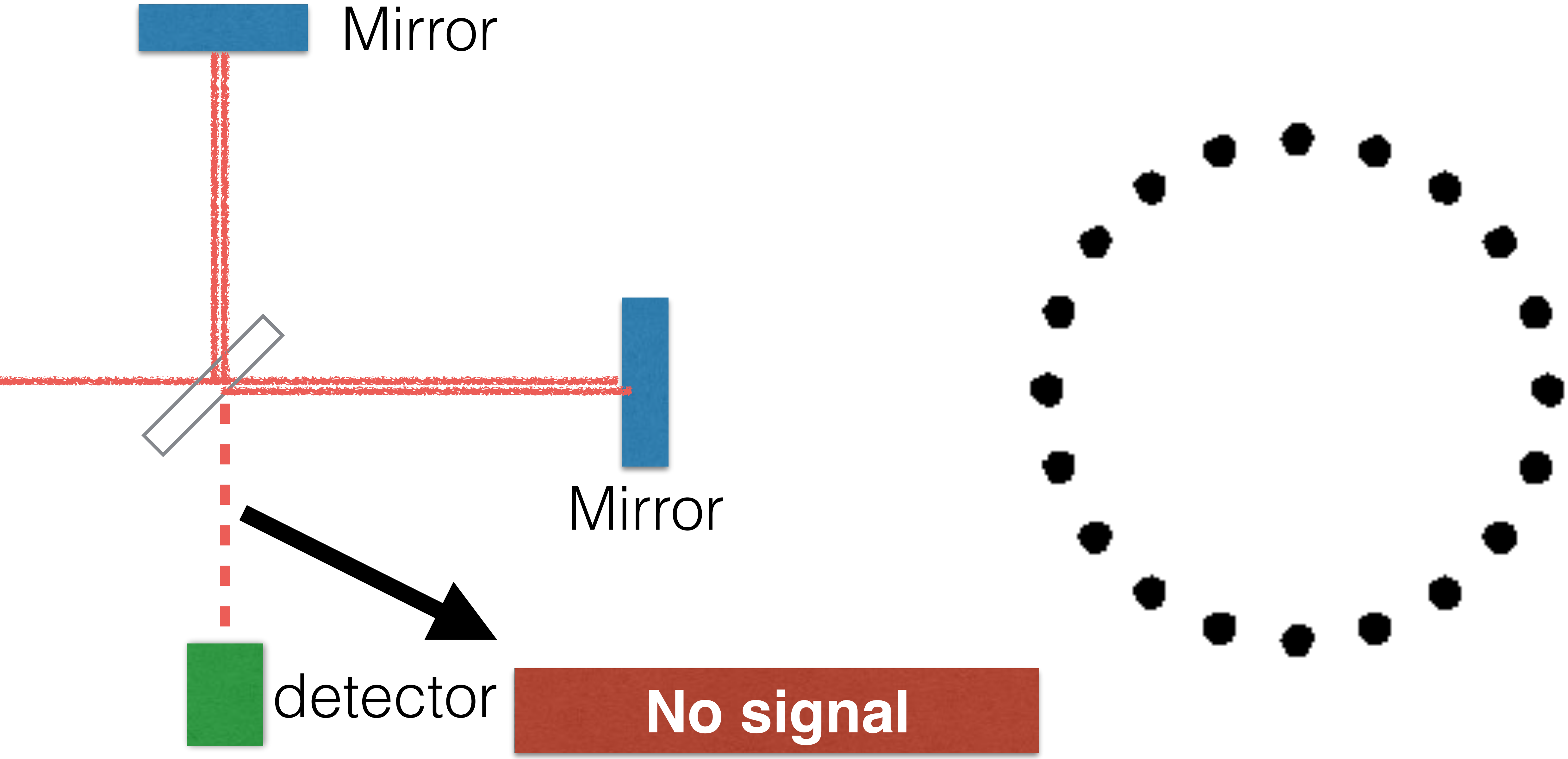
- GW changes distances between two points

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

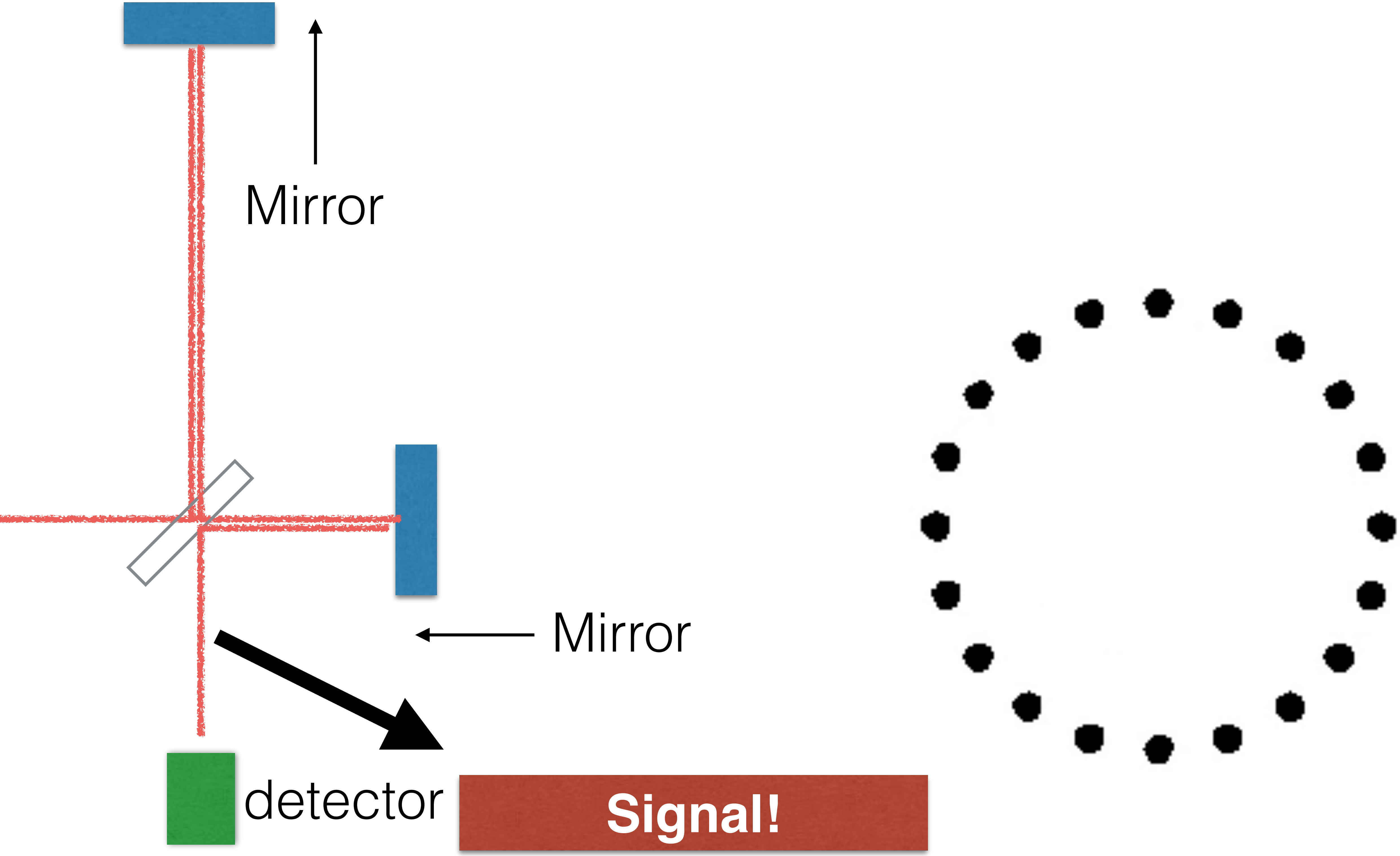
$$d\ell^2 = \sum_{ij} (\delta_{ij} + \underline{h_{ij}}) dx^i dx^j$$



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?

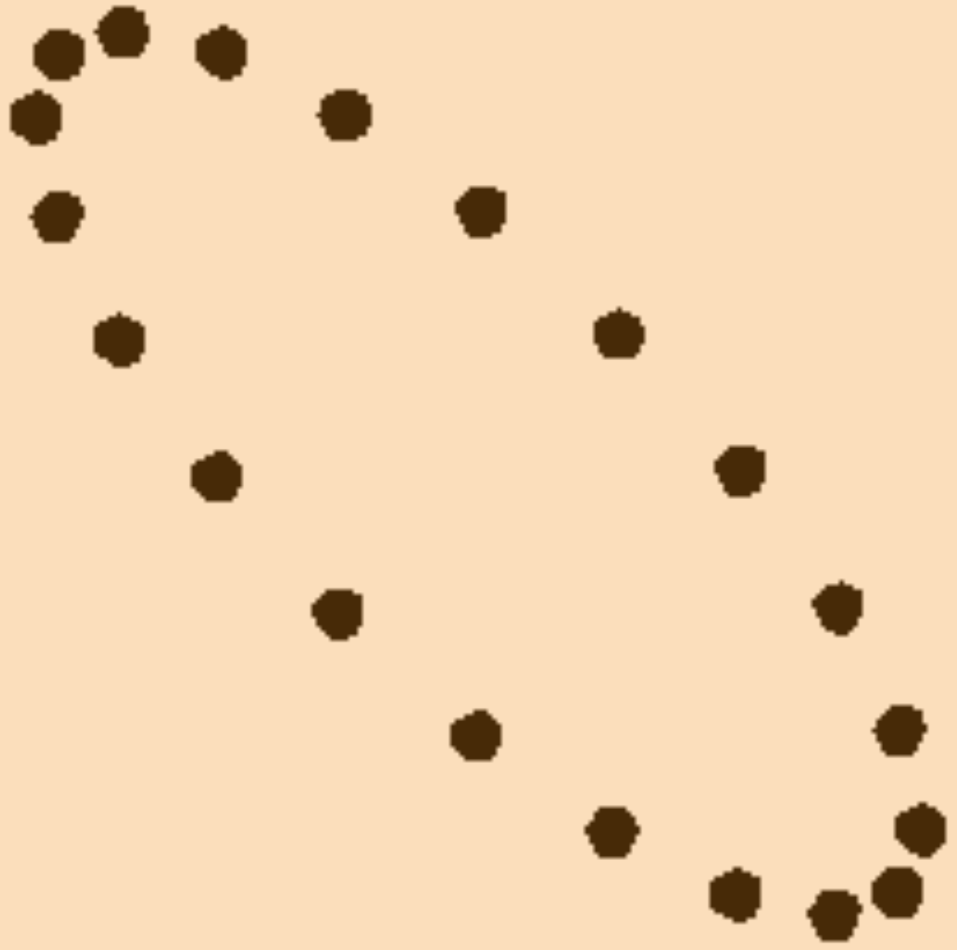
Detecting GW by CMB

Isotropic electro-magnetic fields

Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields

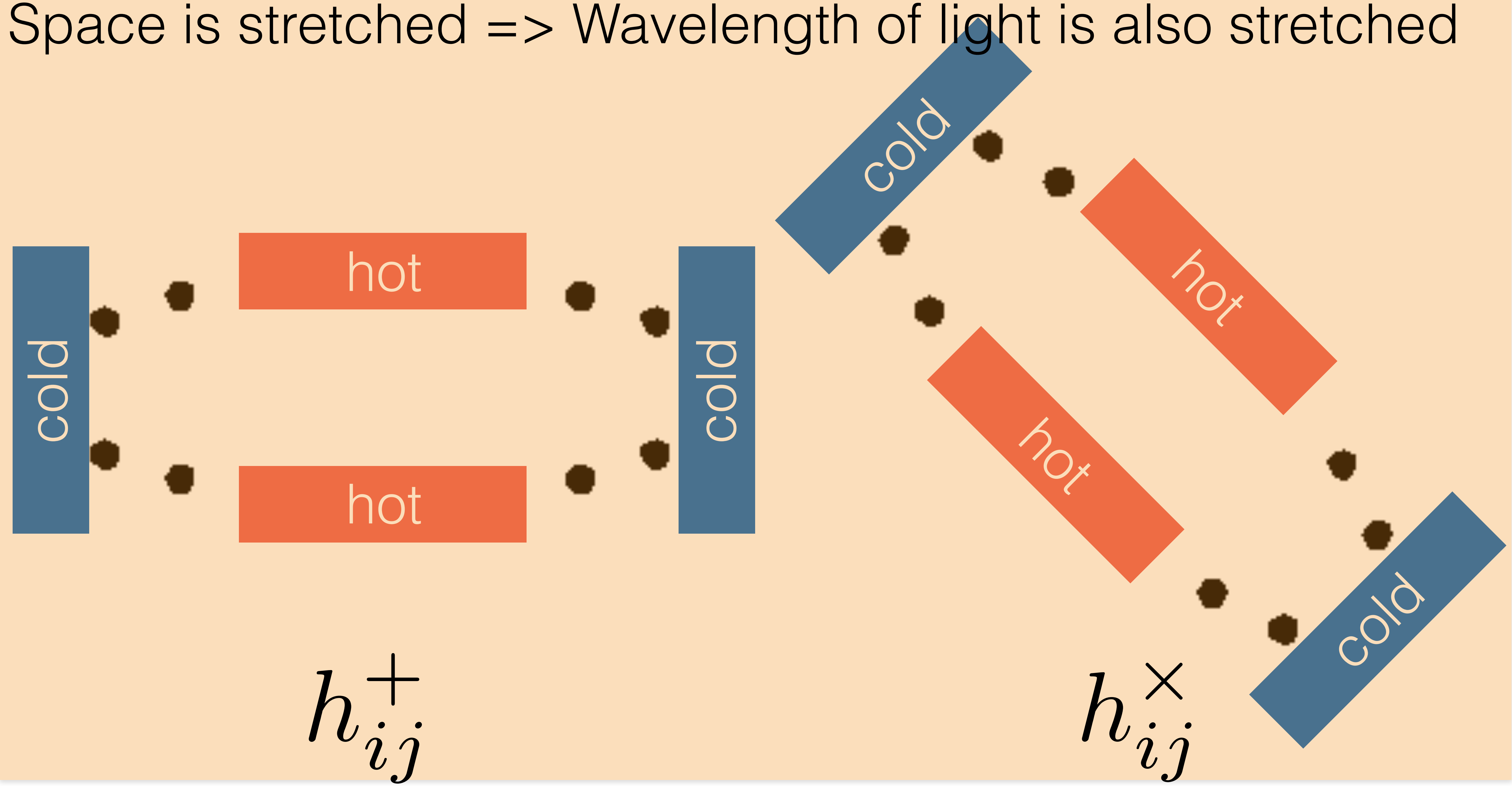
h_{ij}^{+}



$h_{ij}^{\times}$

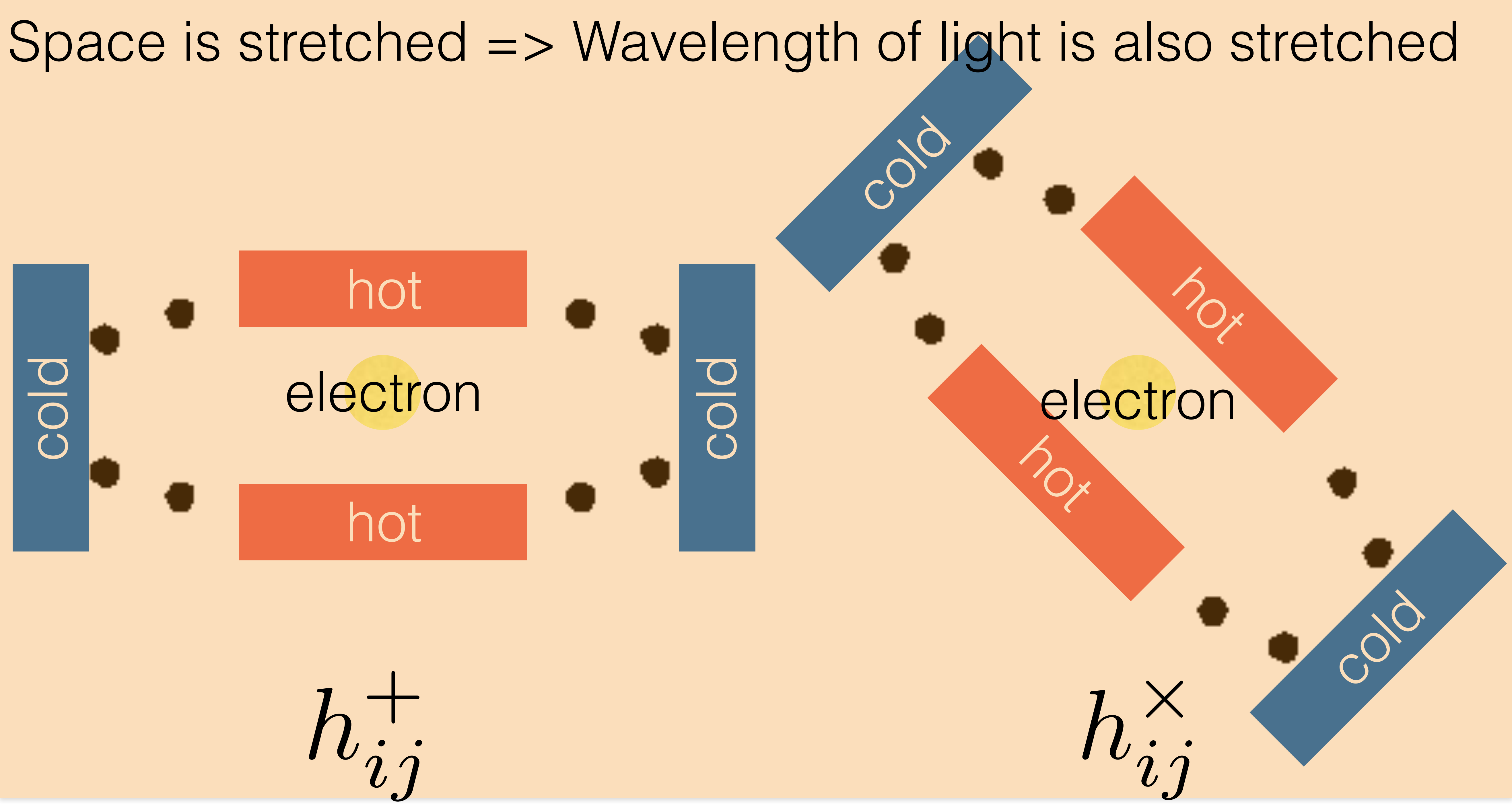
Detecting GW by CMB

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

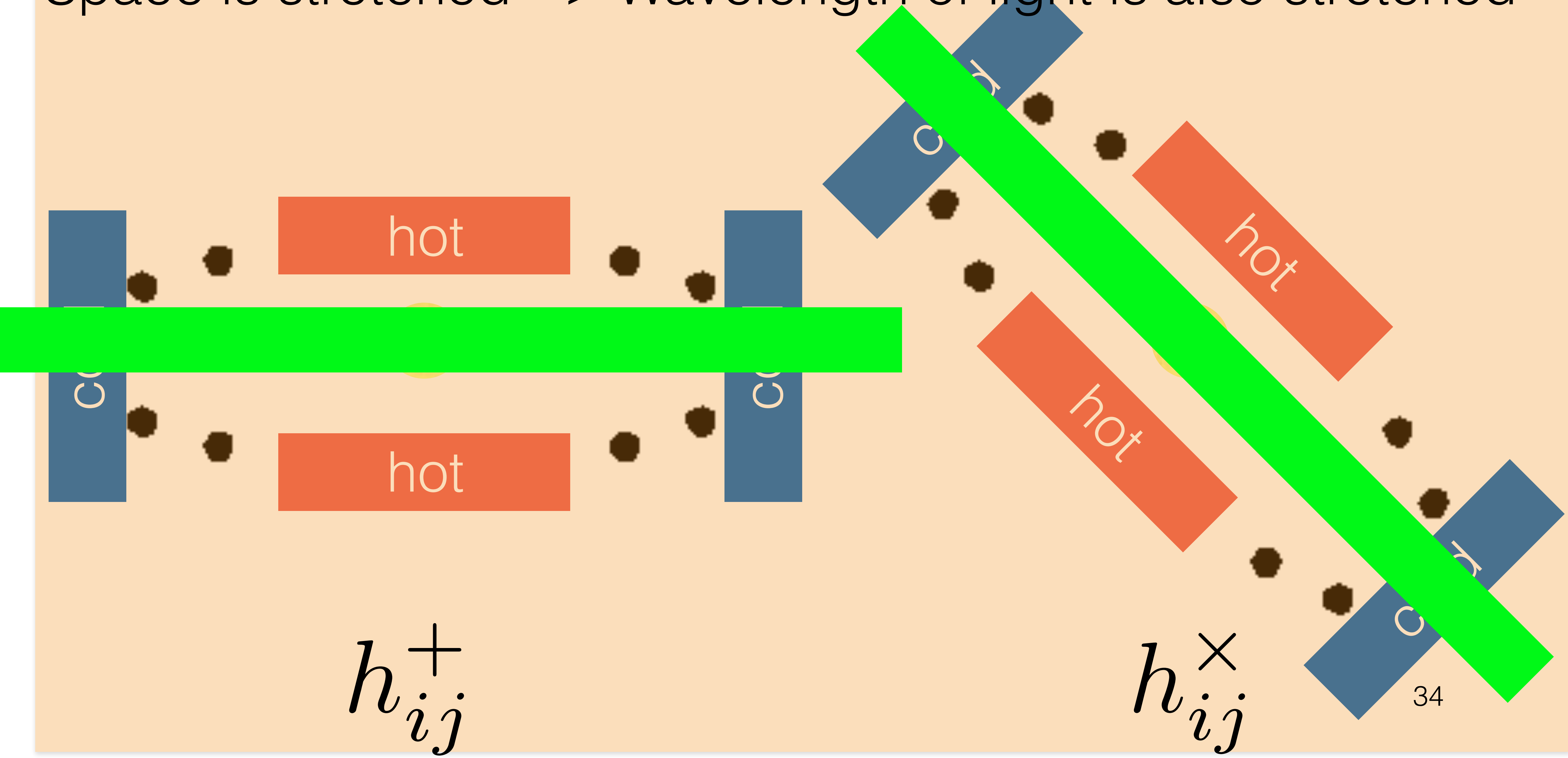
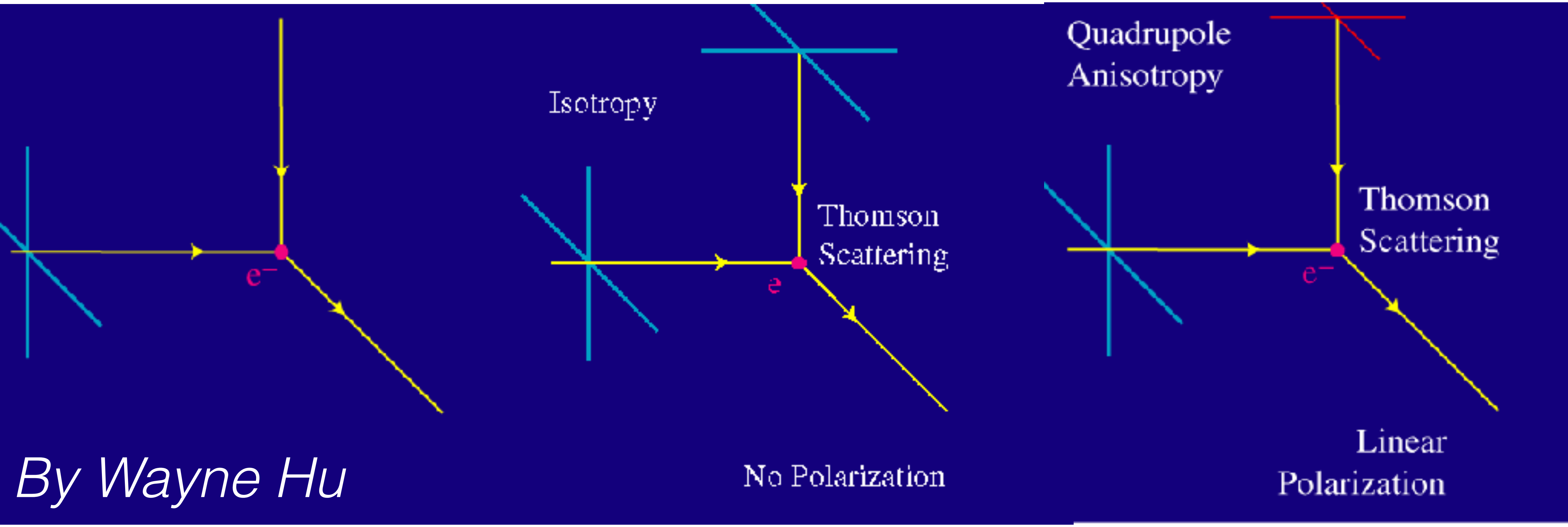


Photo Credit: TALEX

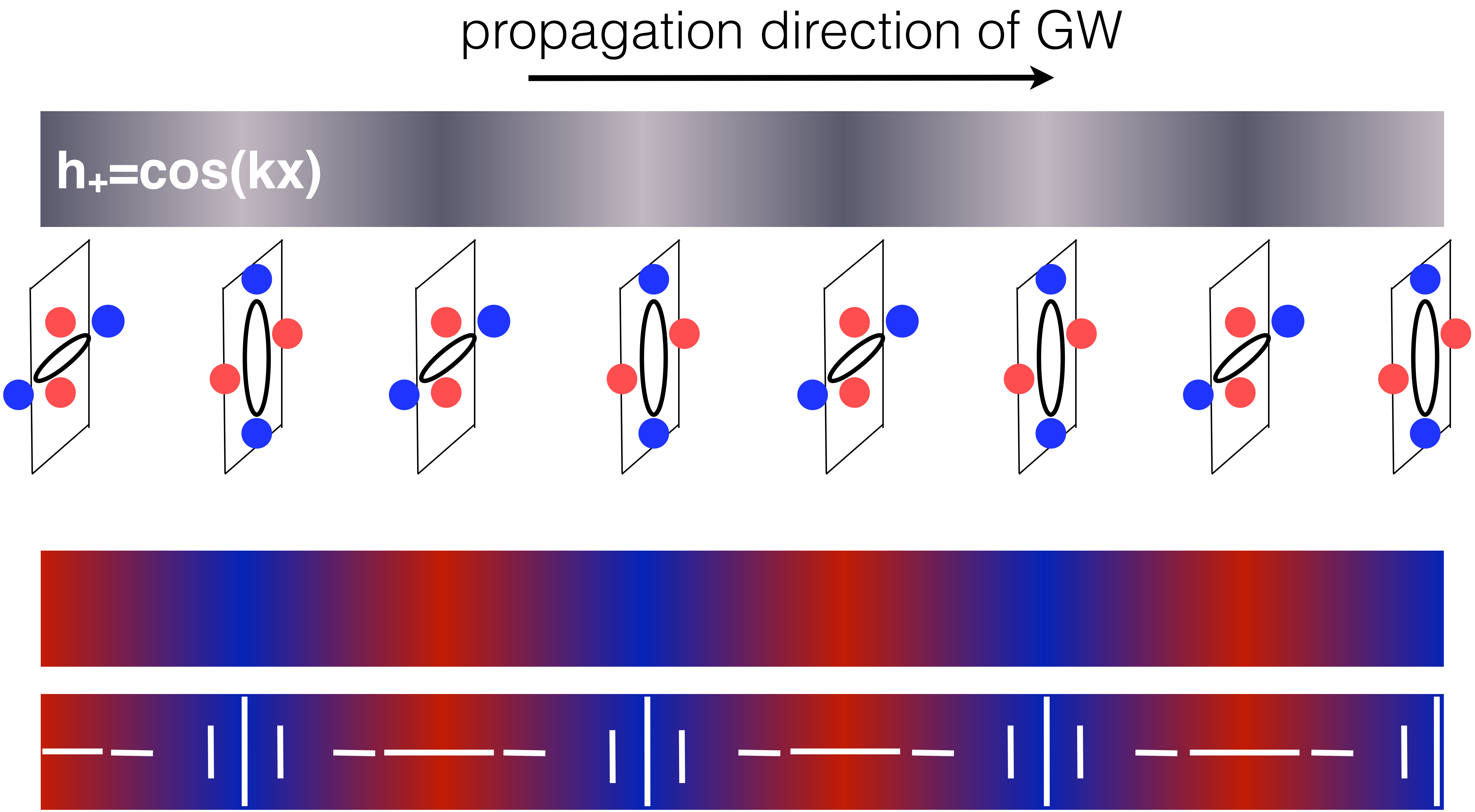
Photo Credit: TALEX

Physics of CMB Polarisation

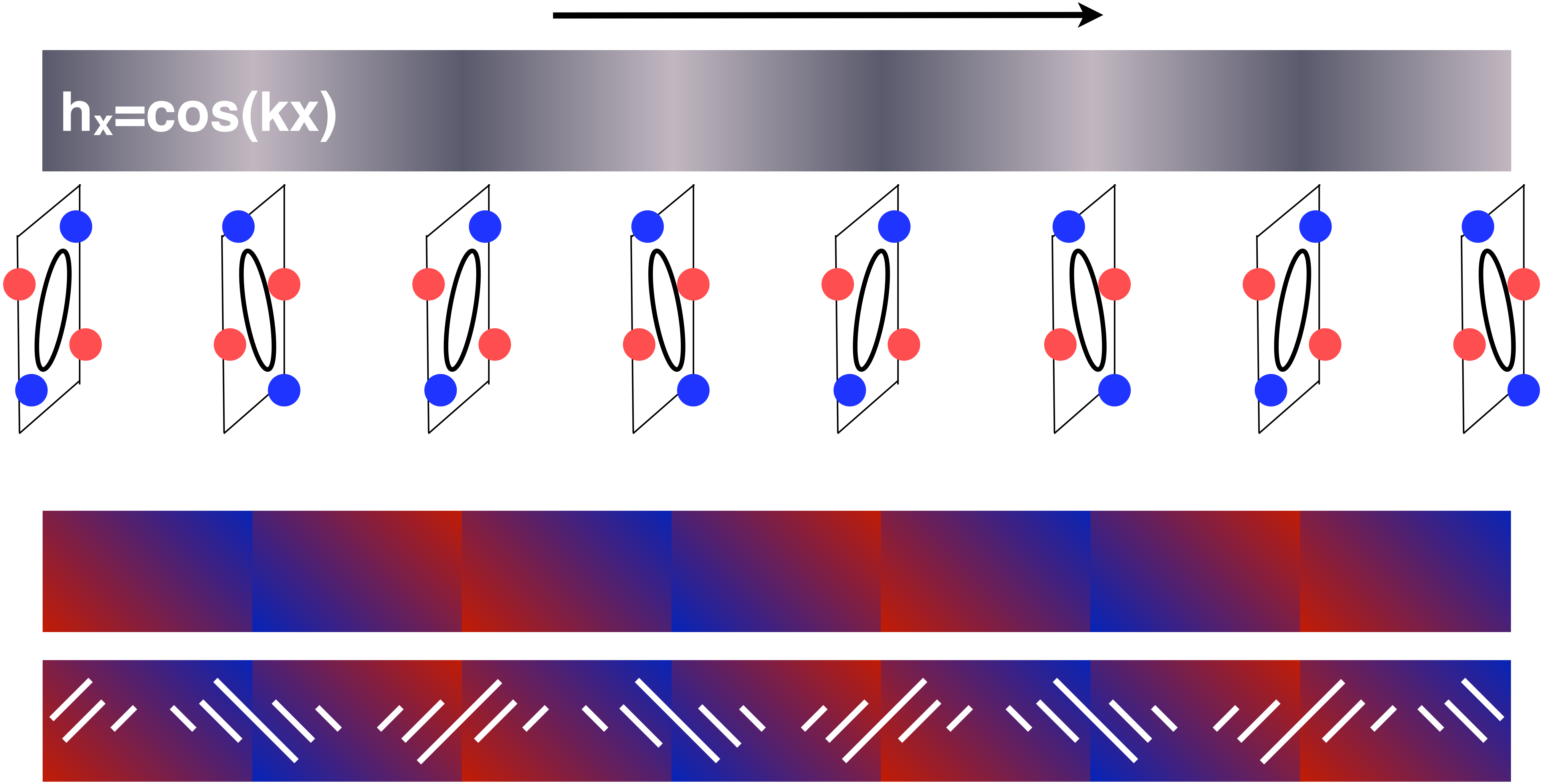


By Wayne Hu

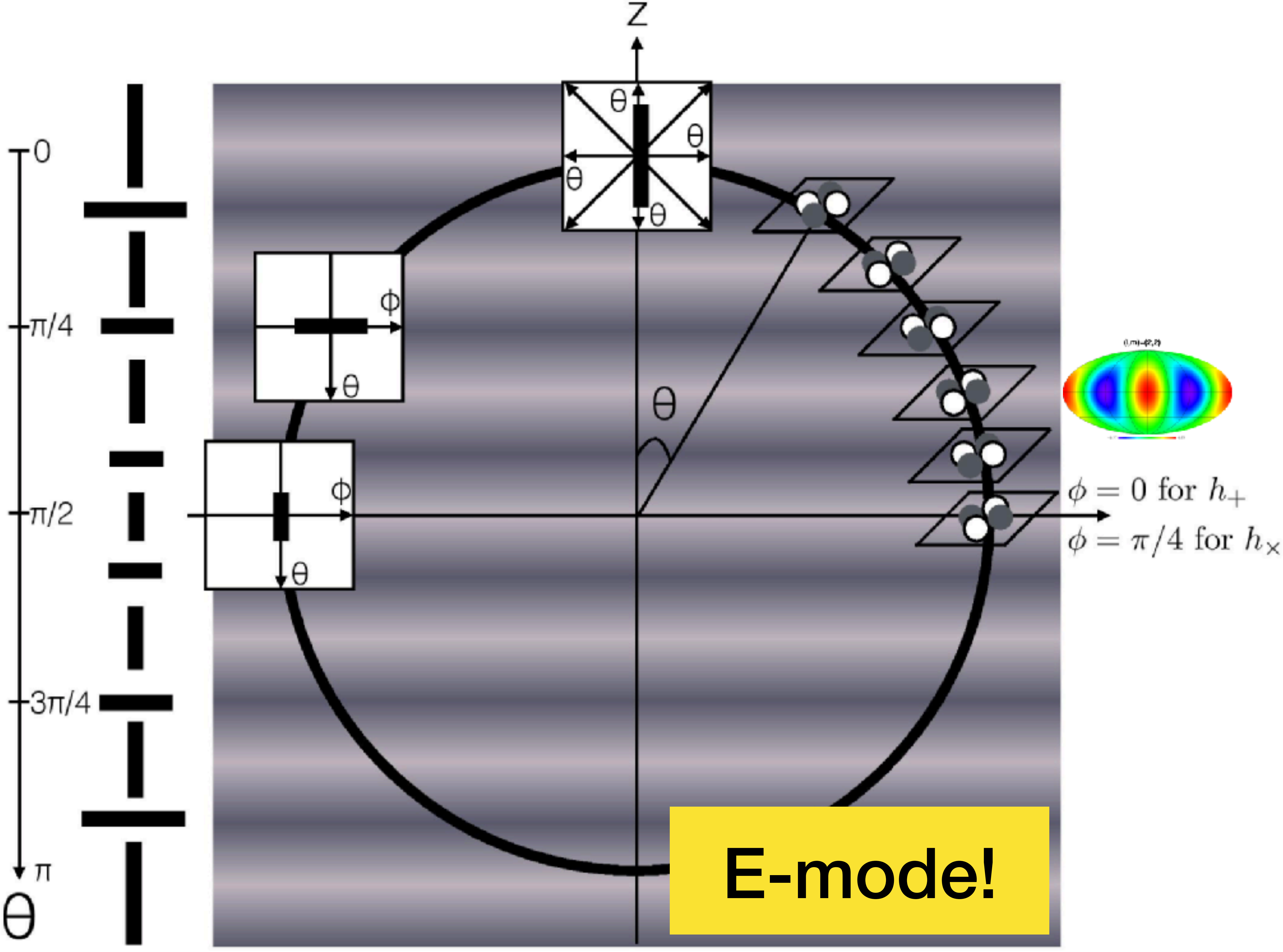
- Necessary and sufficient conditions for generating polarisation in CMB:
  - Thomson scattering
  - **Quadrupolar** temperature anisotropy around an electron



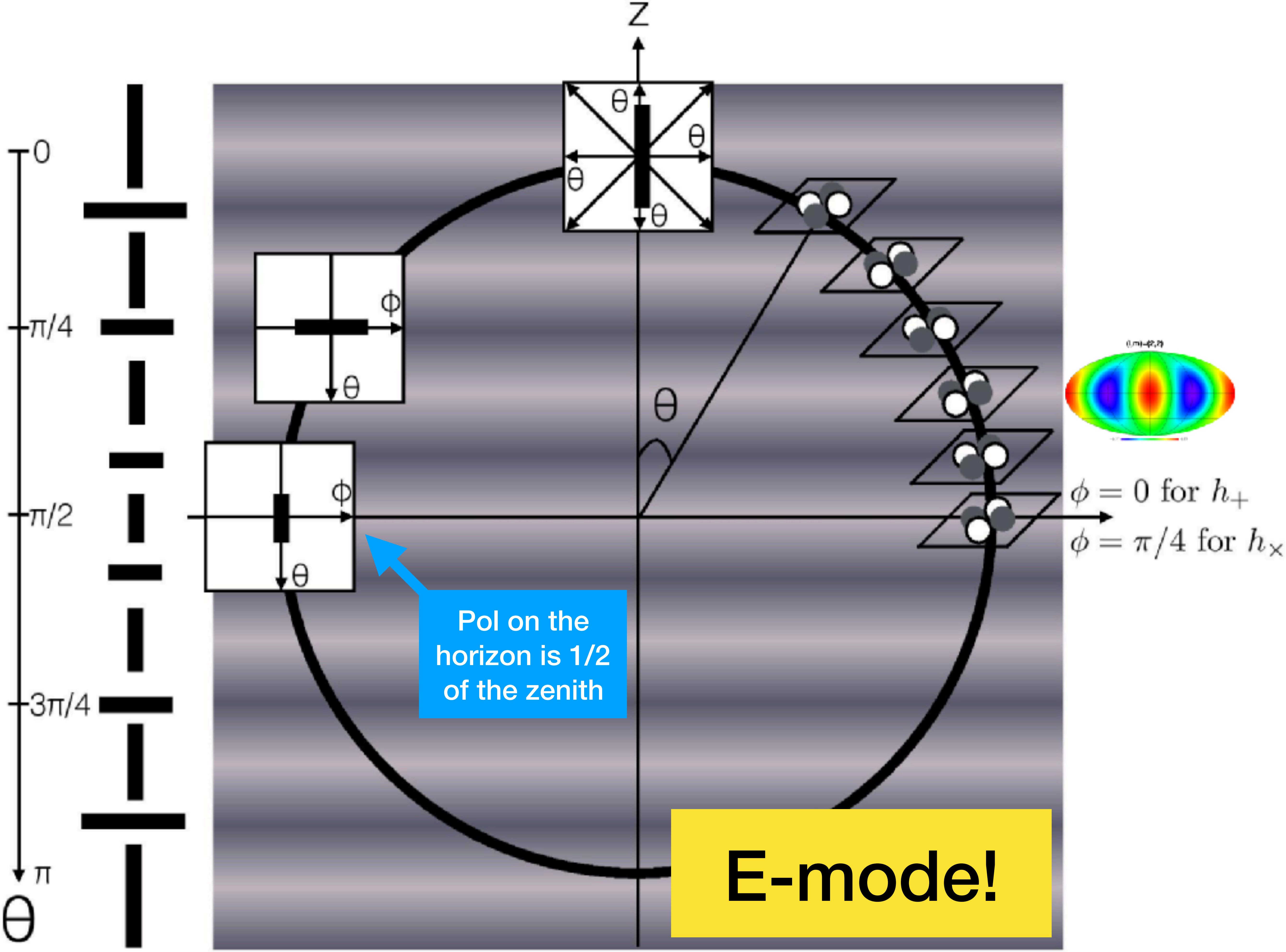
Polarisation directions perpendicular/parallel to the wavenumber vector -> **E mode polarisation** propagation direction of GW



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

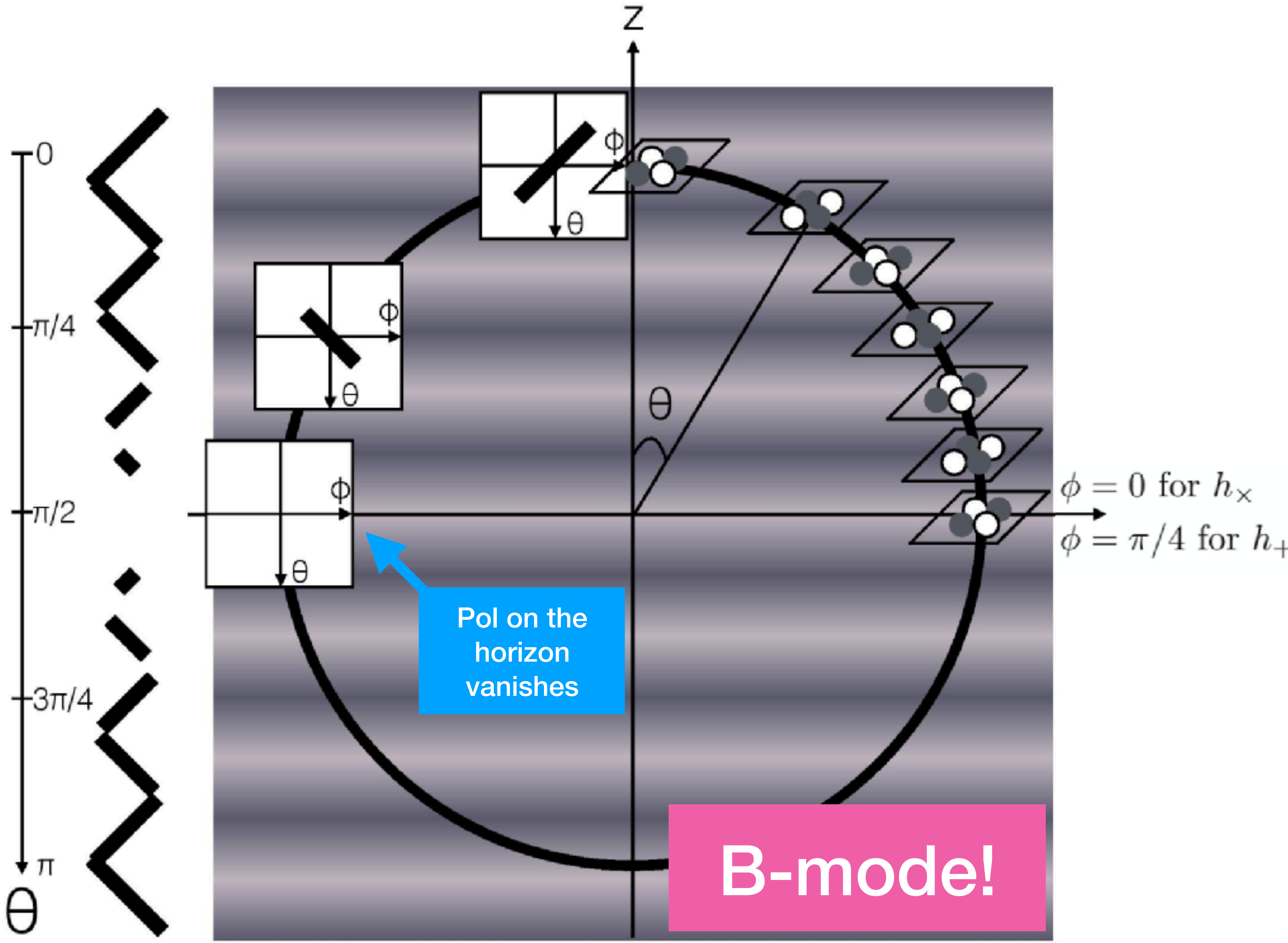


E-mode!



Pol on the horizon is 1/2 of the zenith

E-mode!



Pol on the horizon vanishes

B-mode!

Grishchuk (1974); Starobinsky (1979)

Gravitational waves as the quantum vacuum fluctuation in spacetime

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

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

gives

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

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

Propagation of GW

- In an expanding Universe,

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

gives

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

=3H

expansion of the Universe affects h_{ij}

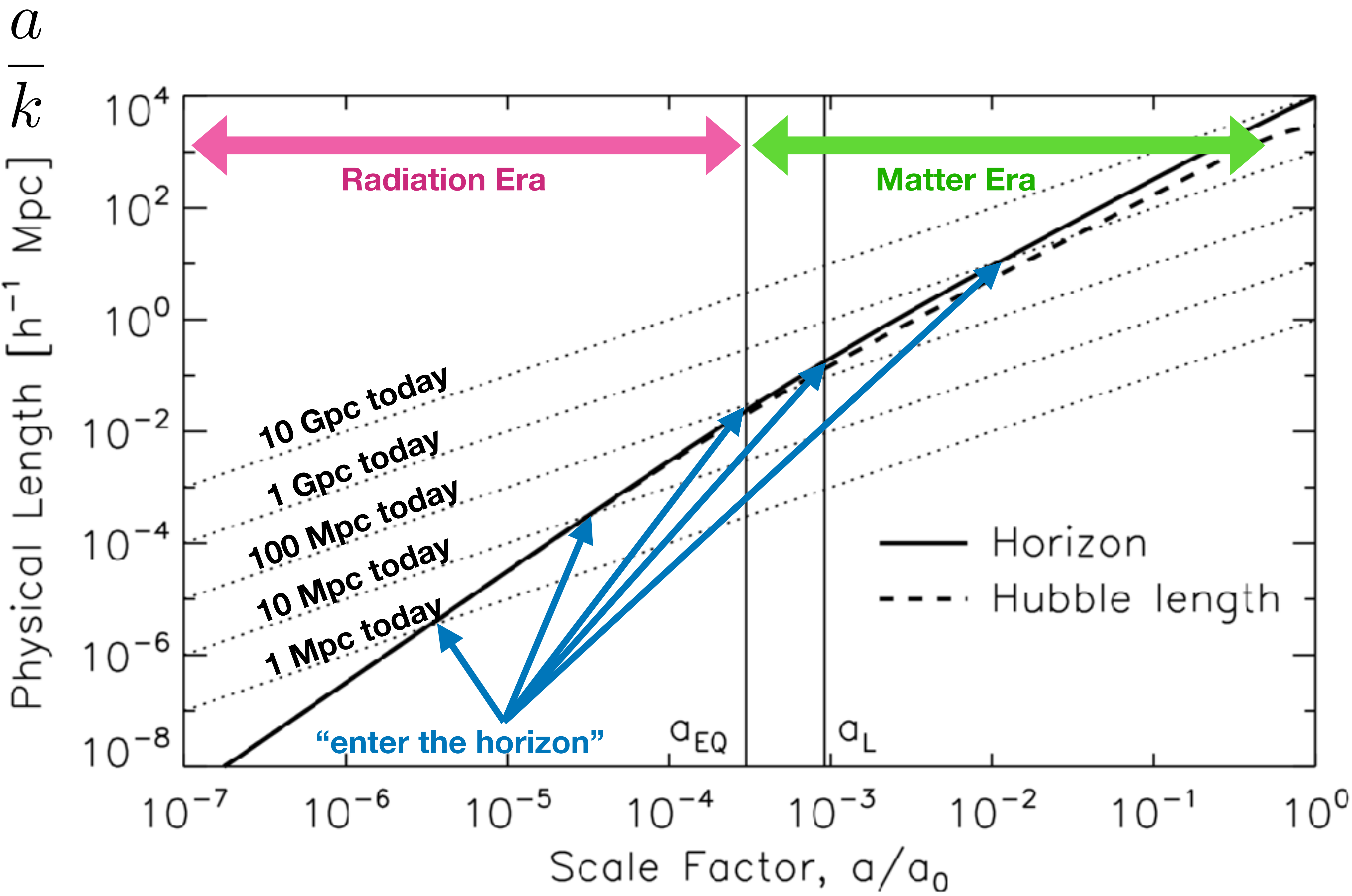
GW Evolution

- **Super-horizon scales [k << aH]**
  - The amplitude of GW is **conserved** **(i.e., h_{ij} = constant)**
- **Sub-horizon scales [k >> 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”**

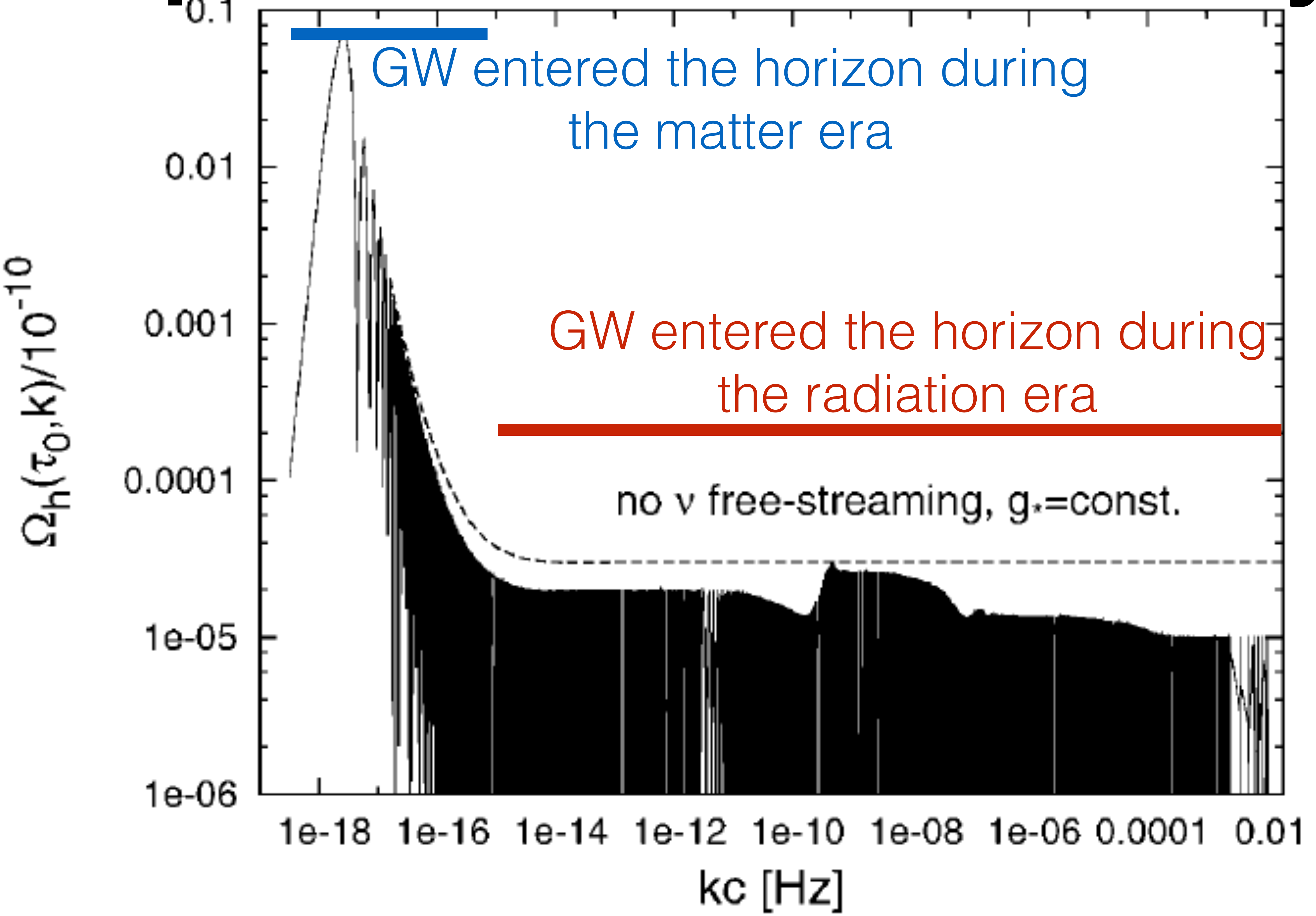


$\frac{a}{k}$
Radiation Era
Matter Era
10 Gpc today
1 Gpc today
100 Mpc today
10 Mpc today
1 Mpc today
"enter the horizon"
a_{EQ}
a_L
Horizon
Hubble length
Physical Length [h^{-1} Mpc]
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Scale Factor, a/a_0

Watanabe & EK (2006)

Theoretical energy density

Spectrum of GW today



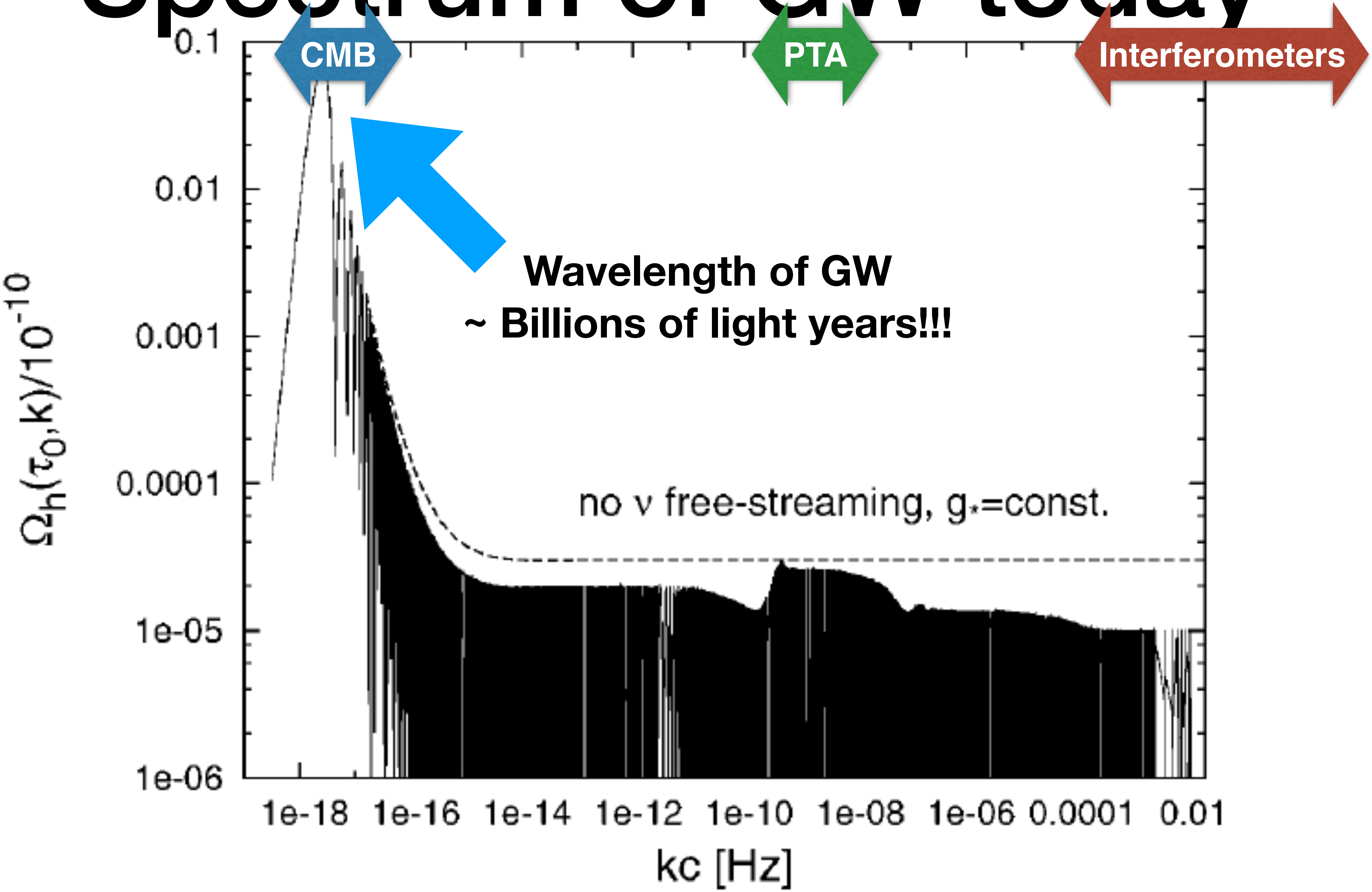
GW entered the horizon during the matter era

GW entered the horizon during the radiation era

Watanabe & EK (2006)

Theoretical energy density

Spectrum of GW today



Wavelength of GW

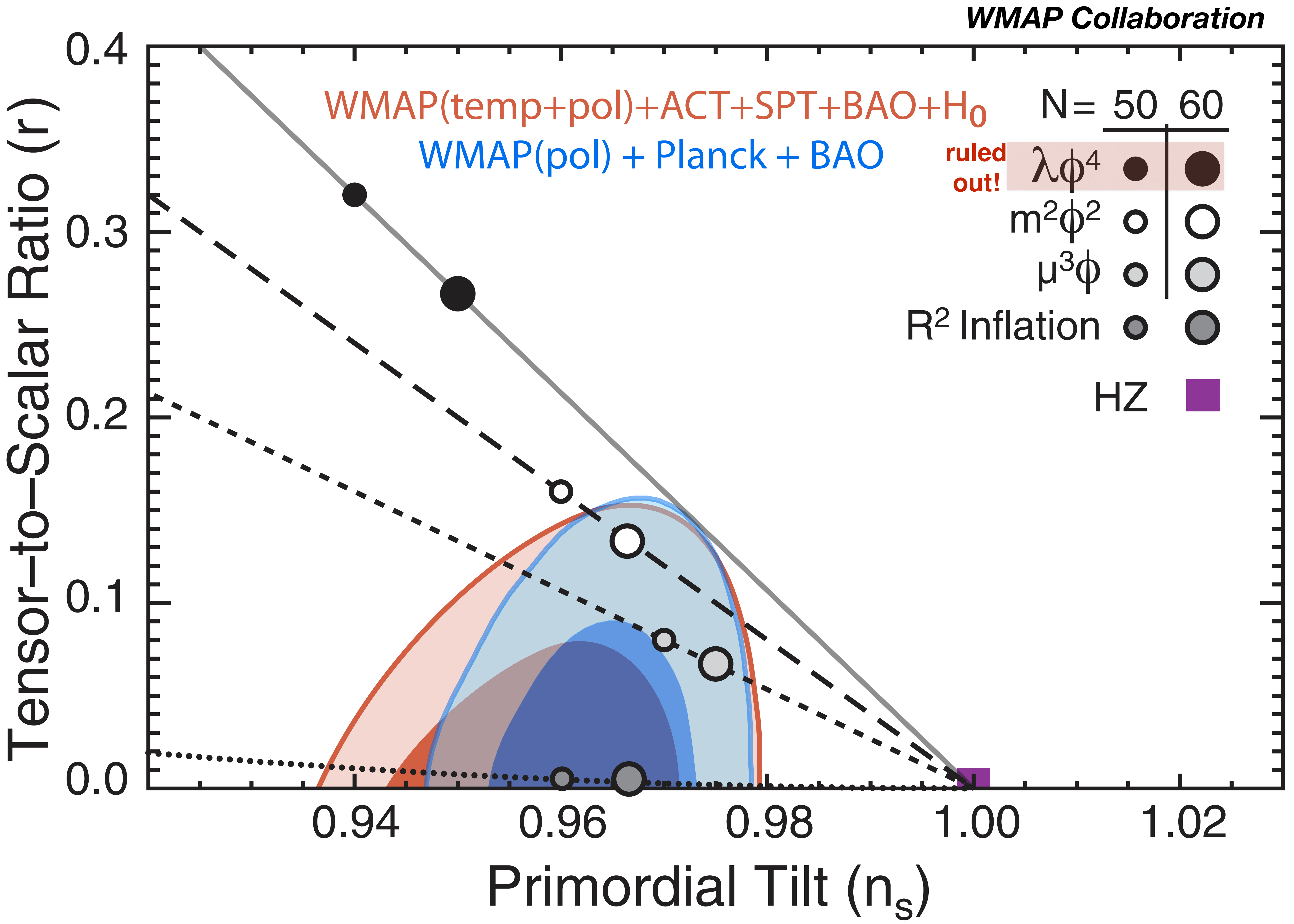
~ Billions of light years!!!

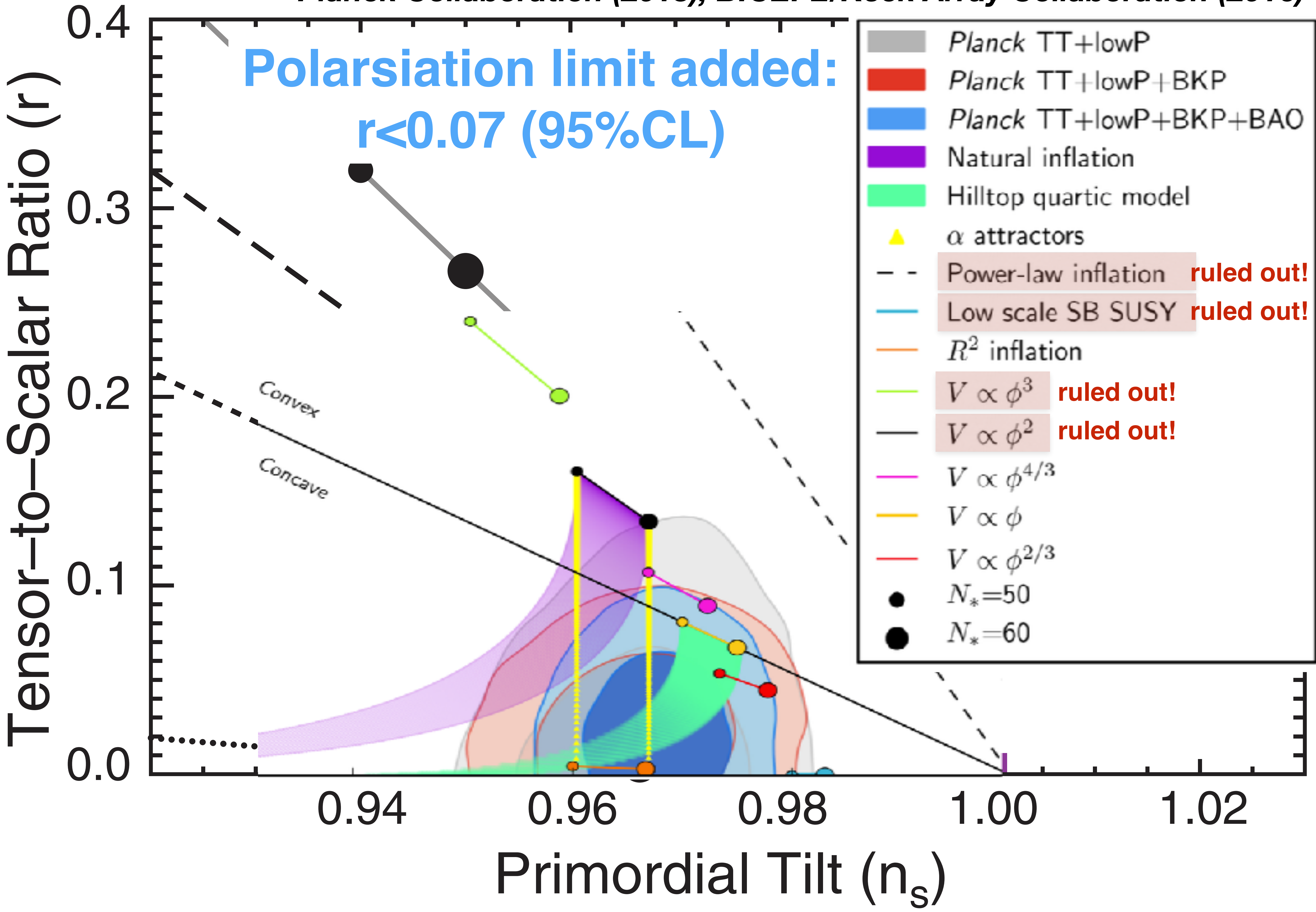
Tensor-to-scalar Ratio

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

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

BICEP2/Keck Array Collaboration (2018)

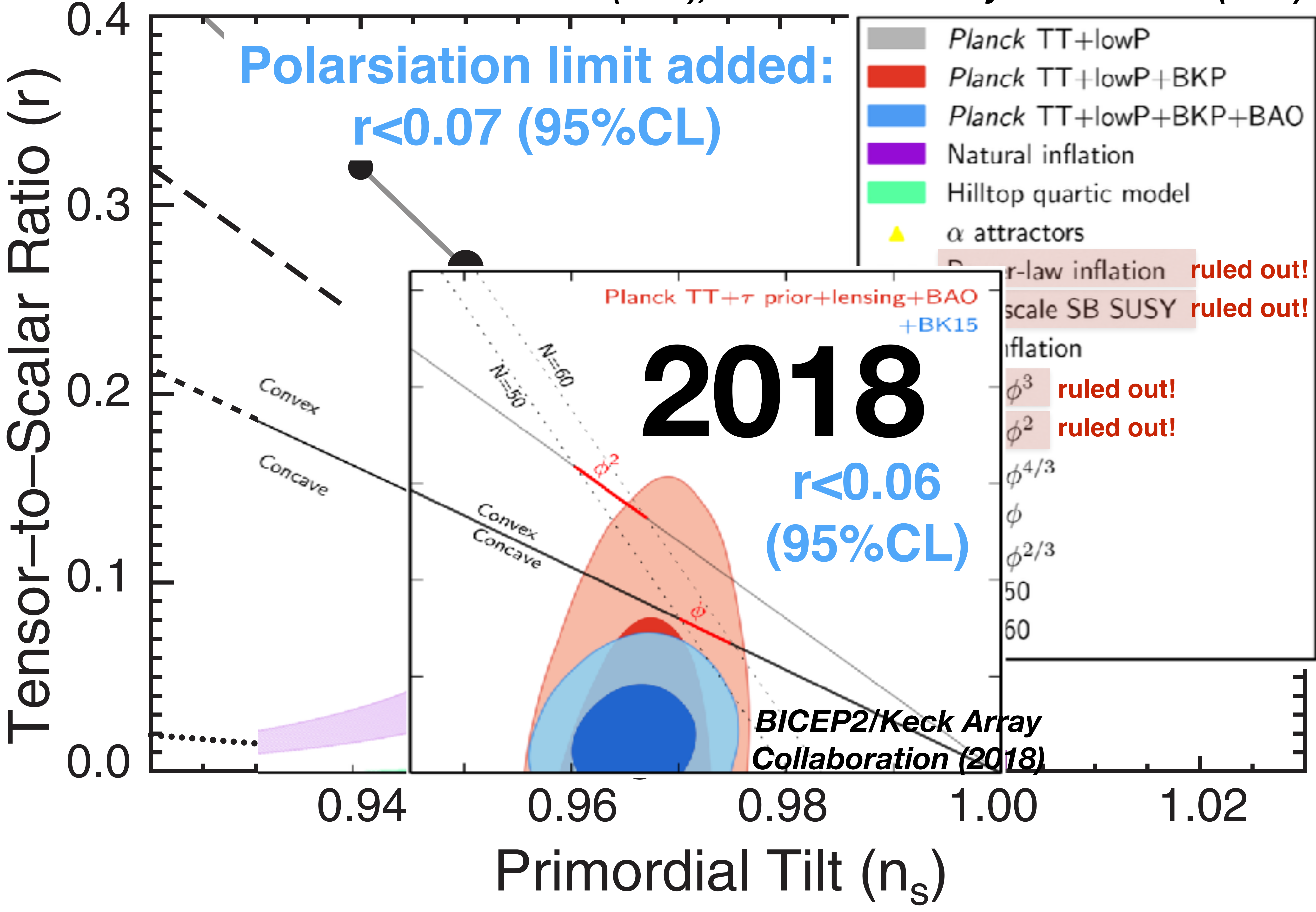

WMAP Collaboration
WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
λφ⁴
m²φ²
μ³φ
R² Inflation
HZ
Tensor–to–Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (ns)



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

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

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



Polarsiation limit added:
r<0.07 (95%CL)

2018

r<0.06 (95%CL)

ruled out!
ruled out!
ruled out!
ruled out!

BICEP2/Keck Array Collaboration (2018)

JAXA

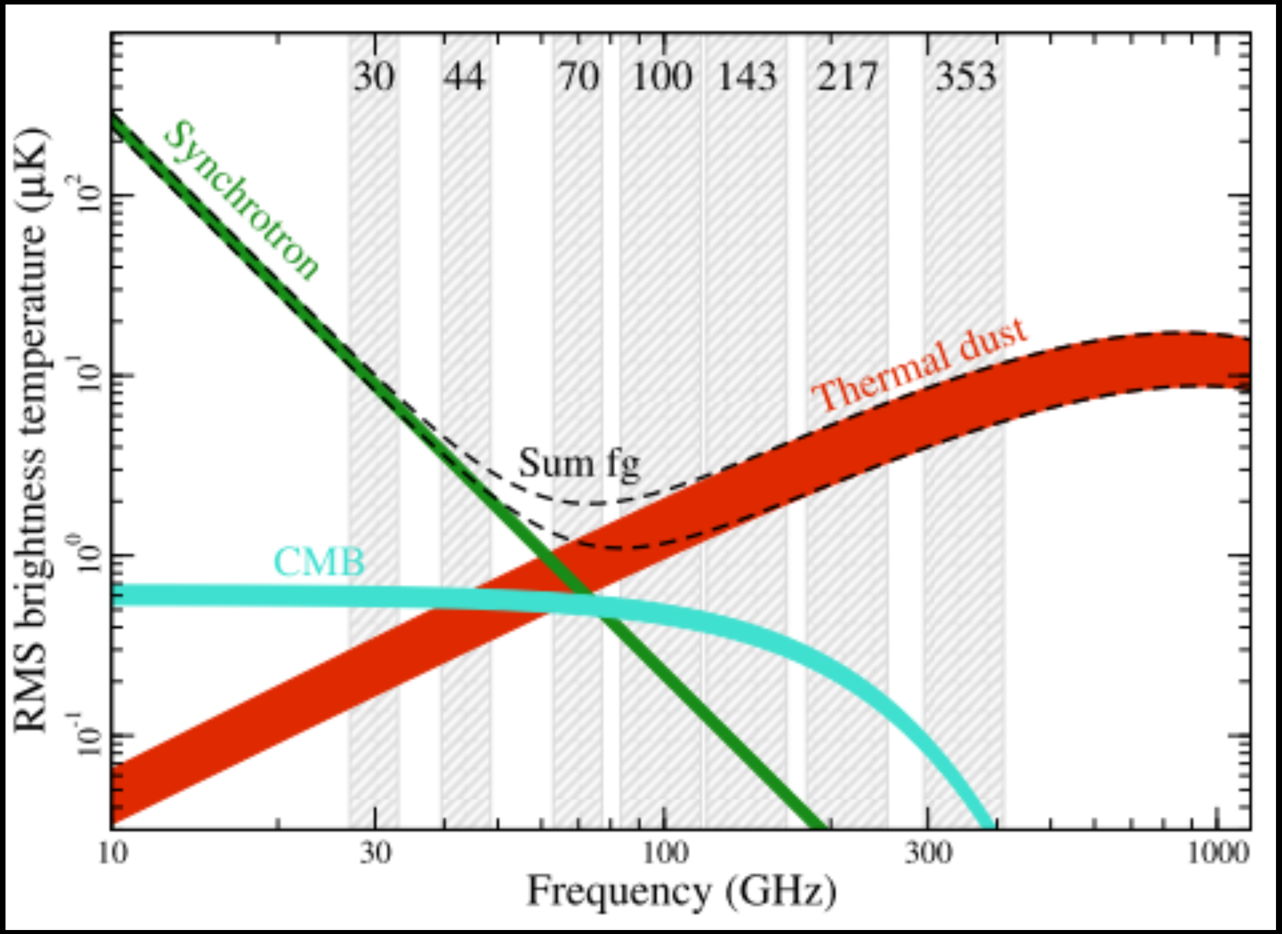
+ participations from
USA, Canada, Europe

LiteBIRD
2028–

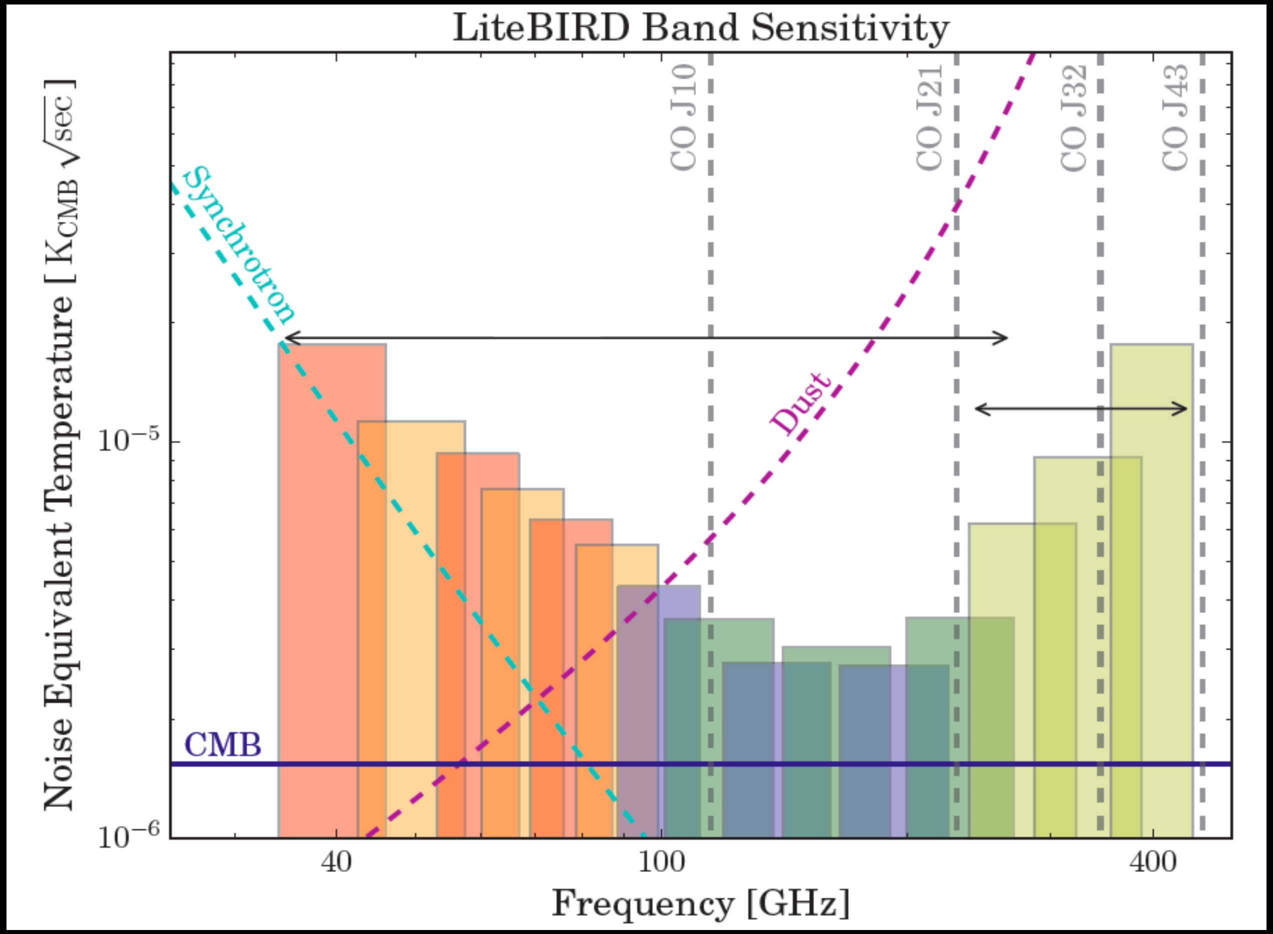
Selected!

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)

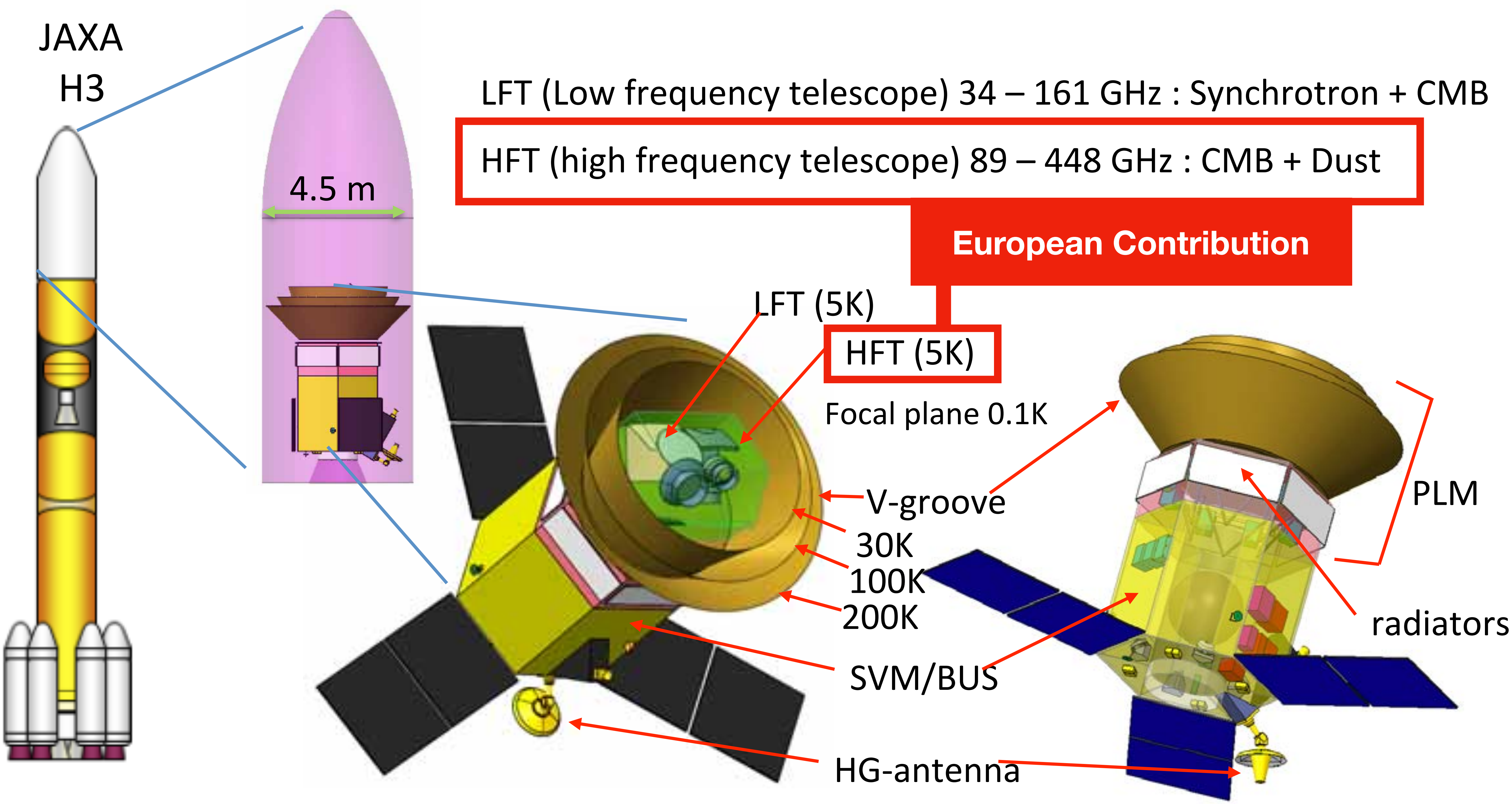
Slide courtesy Yutaro Sekimoto (ISAS/JAXA)

LiteBIRD Spacecraft

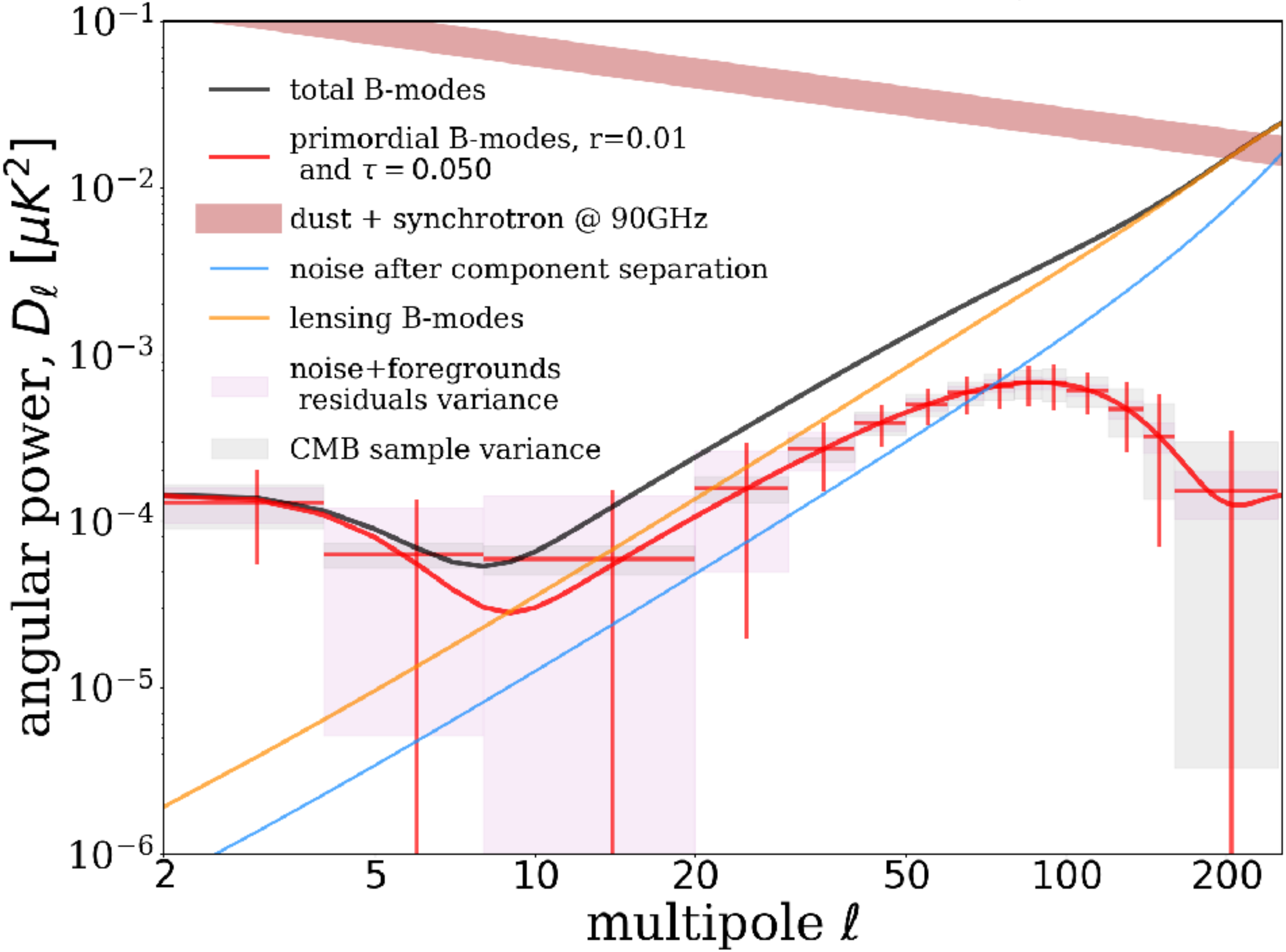
LFT (Low frequency telescope) 34 – 161 GHz : Synchrotron + CMB

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

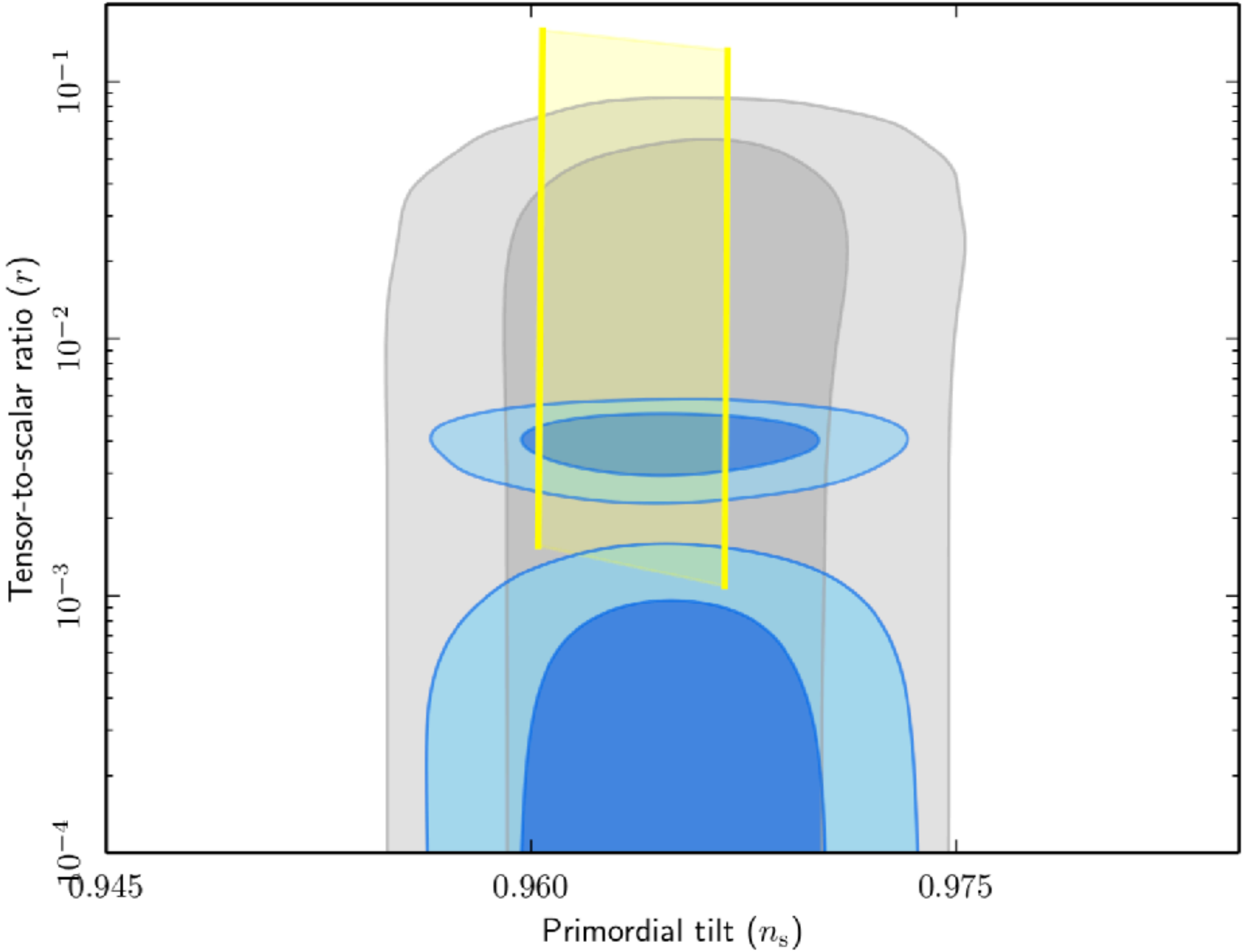
European Contribution



LiteBIRD Collaboration



LiteBIRD Collaboration



But, wait a minute…

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

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

- **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

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

- **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?

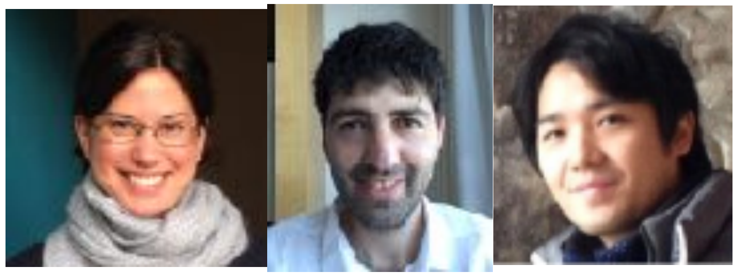
- If, and **ONLY IF** Yes to **all** => Announce discovery of the vacuum fluctuation in spacetime

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>>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!**

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
  [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^a_ν :

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

self-interaction term

[a=1,2,3; μ=0,1,2,3]

Dimastrogiovanni, Fasiello & Fujita (2017)

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]
- χ: pseudo-scalar "axion" field. Spectator field (i.e., negligible energy density compared to the inflaton)
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self-interaction term

[a=1,2,3; μ=0,1,2,3]

Maleknejad & Sheikh-Jabbari (2011)

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)

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

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

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** => 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)

Dimastrogiovanni, Fasiello & Fujita (2017)

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

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

- The equations of motion for L and R modes are

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

Dimastrogiovanni, Fasiello & Fujita (2017)

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

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

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

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

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

Dimastrogiovanni, Fasiello & Fujita (2017)

Spin-2 Field from SU(2)

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

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

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

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

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

Dimastrogiovanni, Fasiello & Fujita (2017)

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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):

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

[Whittaker function]

Dimastrogiovanni, Fasiello & Fujita (2017)

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

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

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

- 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, Fasiello & 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 **$P_{\rm sourced} >> P_{\rm vacuum} = (2/\pi^2)H^2/M^2_{\rm Pl}$**

- **New Paradigm**

Phenomenology

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

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

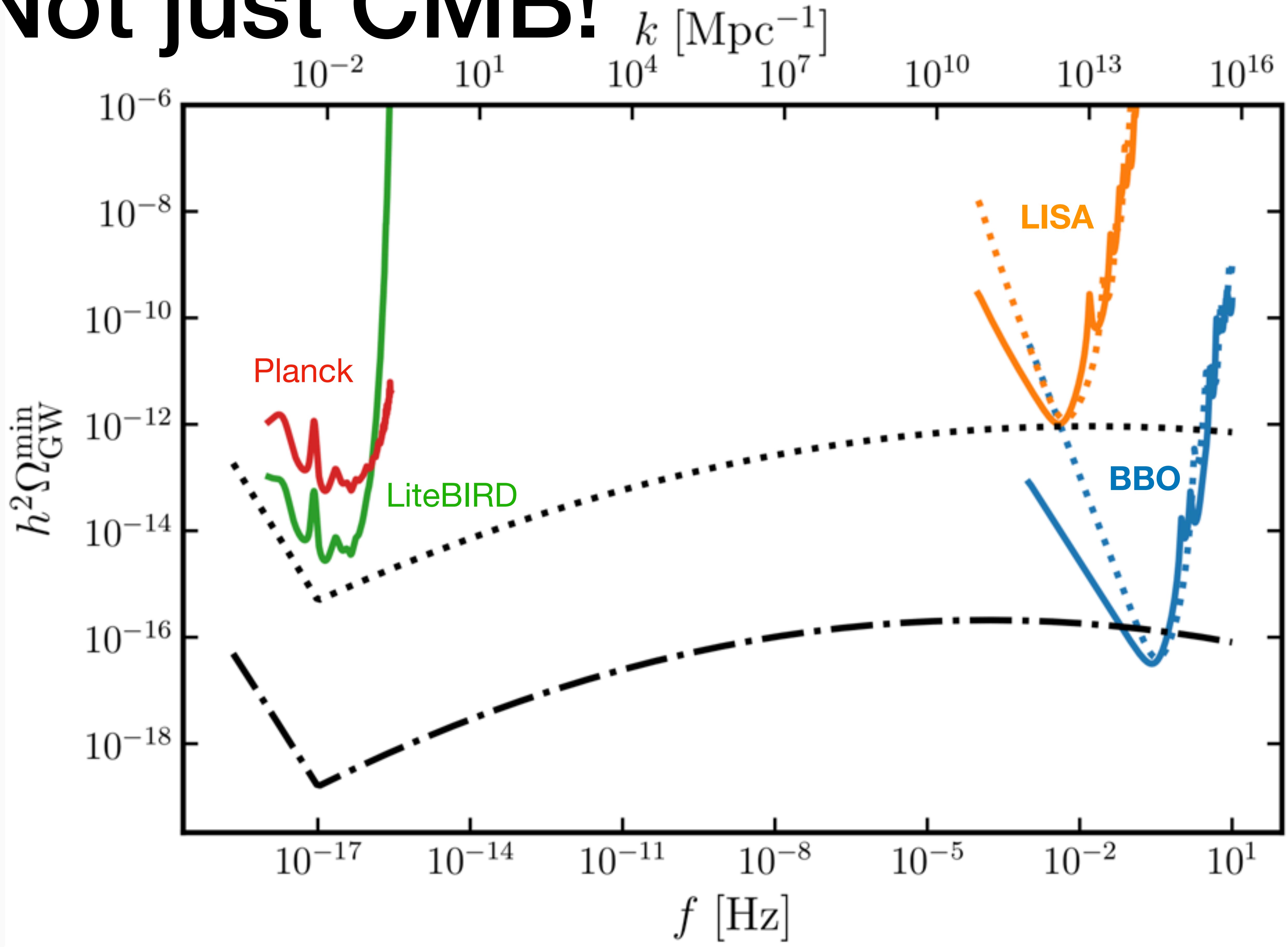
$$\left(\begin{array}{l} \xi \equiv \dfrac{\lambda}{2fH}\dot{\chi} \simeq m_Q + \dfrac{1}{m_Q} \\ m_Q \equiv gQ/H \ = \text{a few} \end{array}\right.$$

- 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)

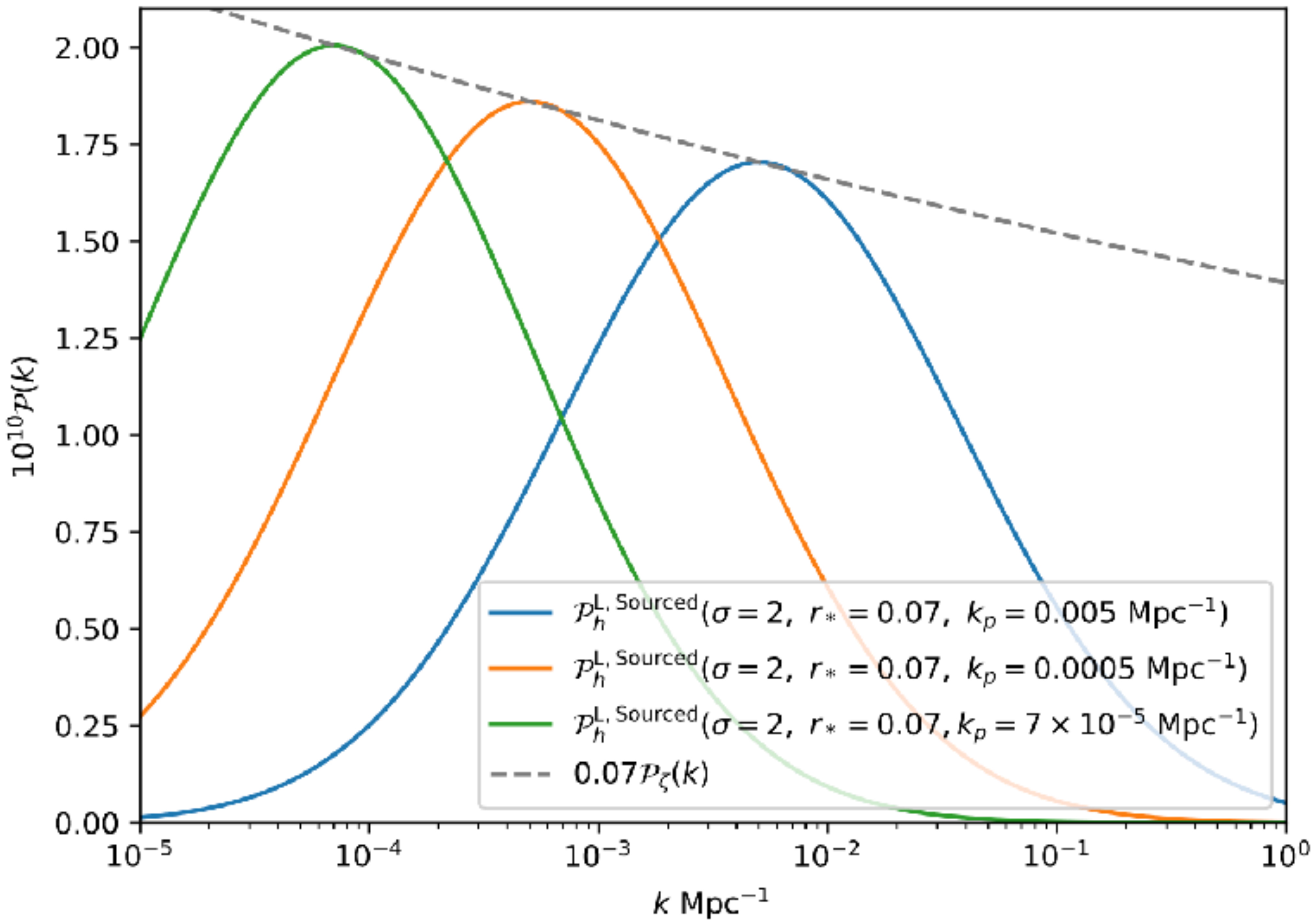
Not just CMB!



Dimastrogiovanni, Fasiello & Fujita (2017)

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

Example Tensor Spectra

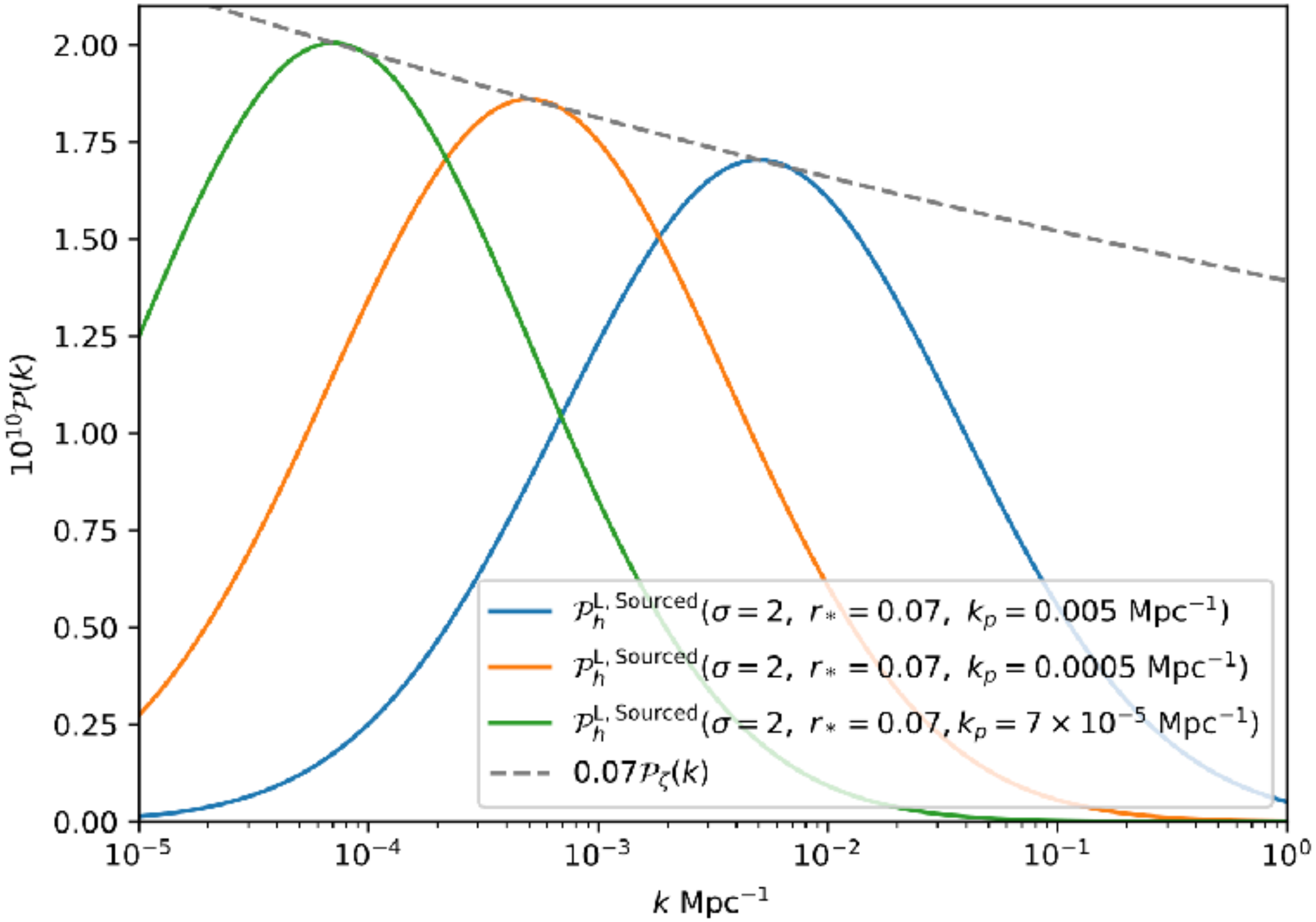


- Sourced tensor spectrum can also be bumpy

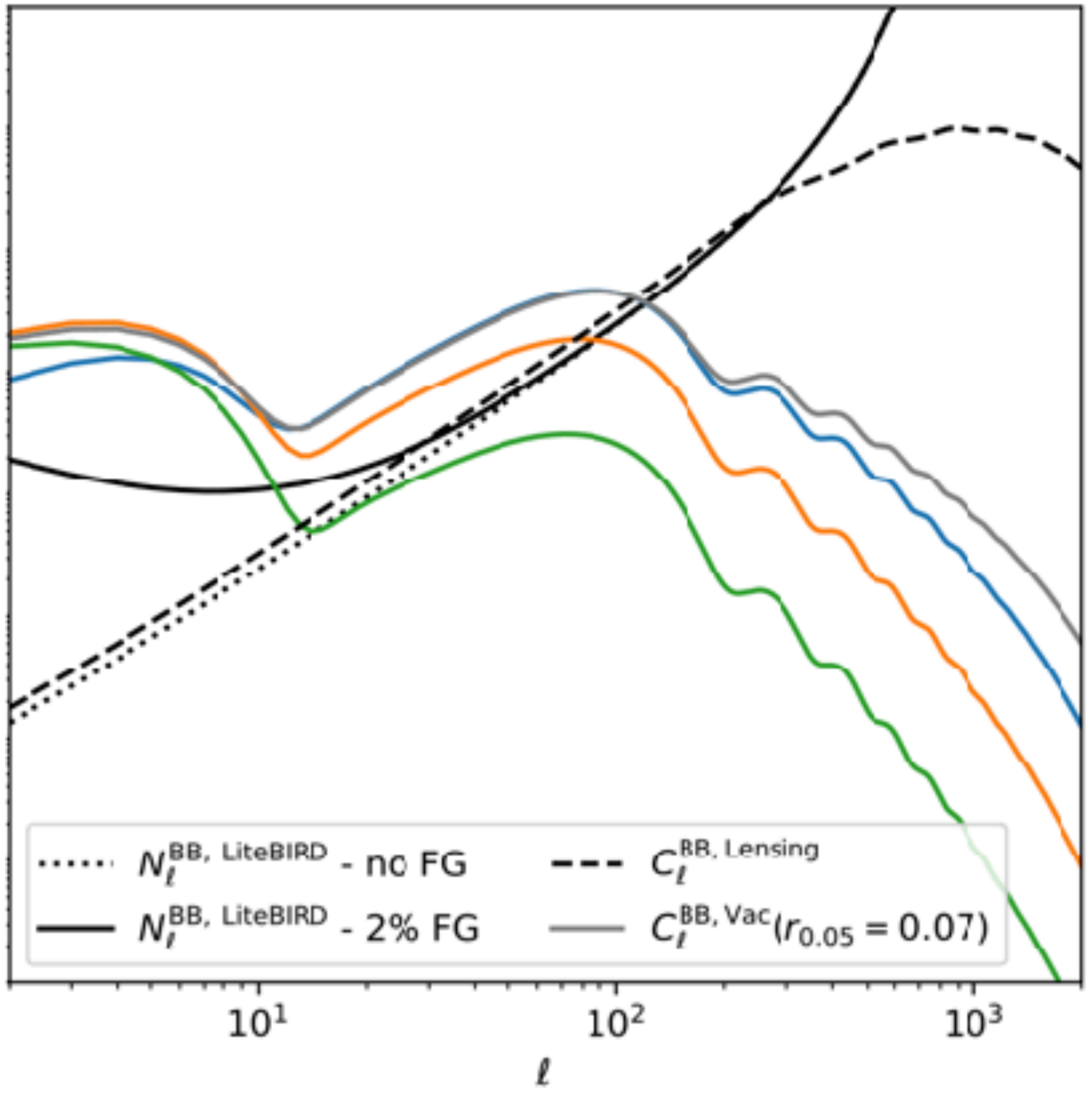
Dimastrogiovanni, Fasiello & Fujita (2017)
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Example Tensor Spectra

Tensor Power Spectrum, P(k)



B-mode CMB spectrum, C_l^{BB}



- The B-mode power spectrum still looks rather normal

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

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)

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

- $\Omega_A << 1$ 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)

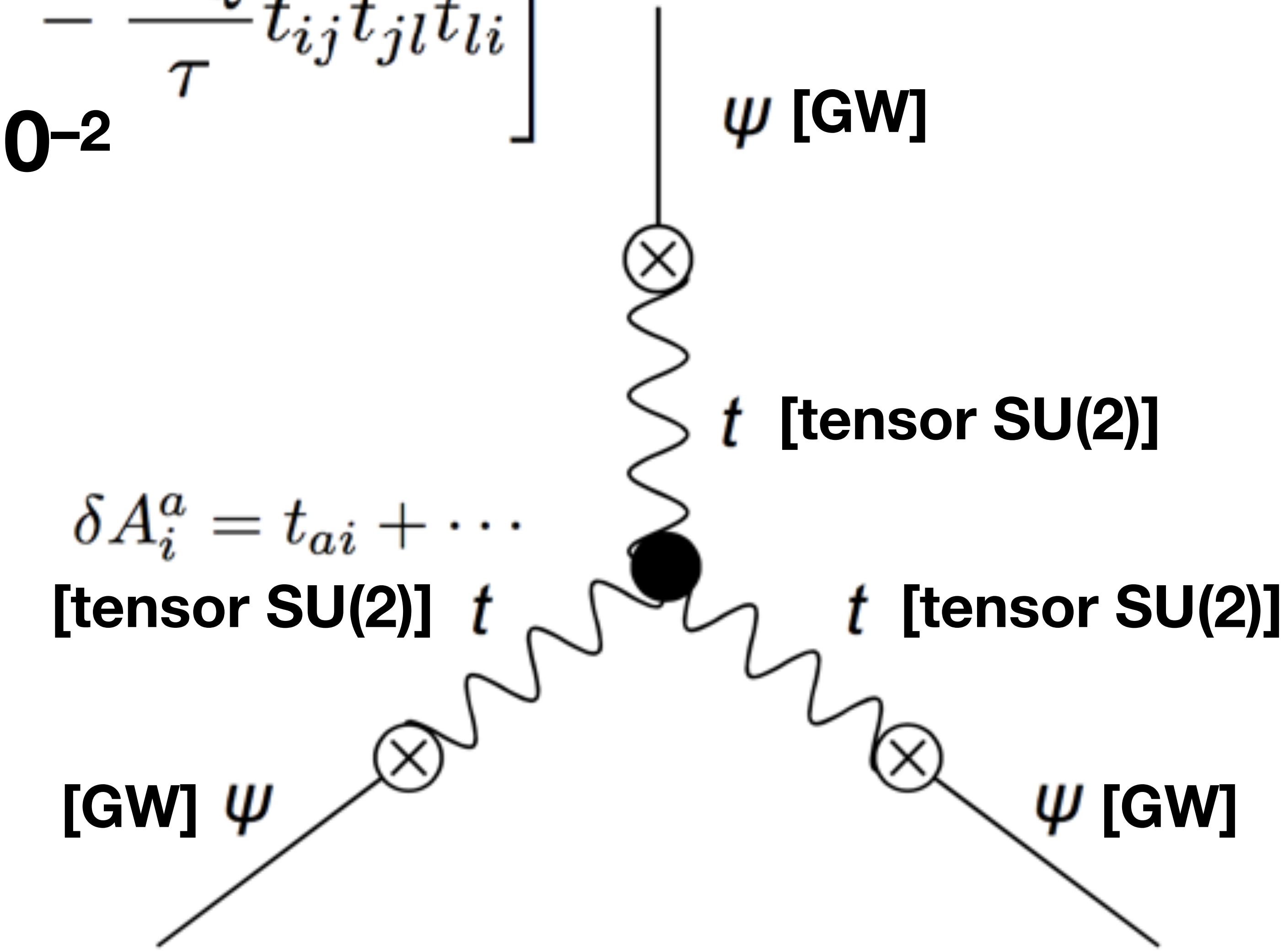
NG generated at the tree level

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

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

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

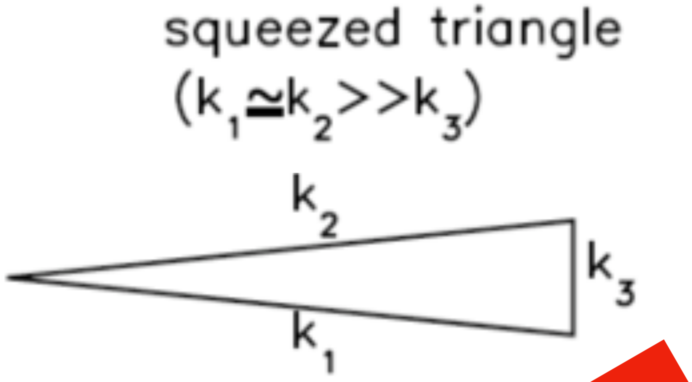
$m_Q \equiv gQ/H$ **[m_Q ~ a few]**

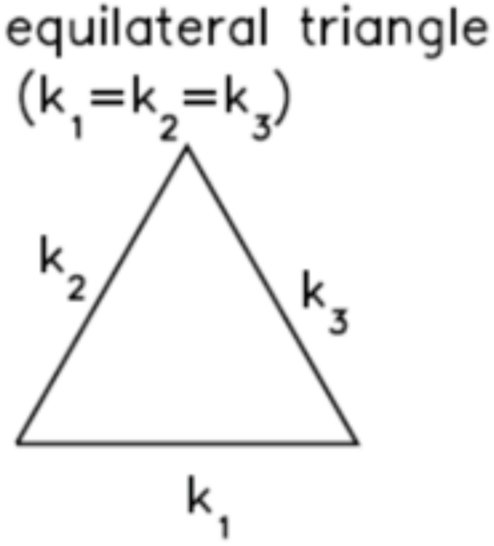


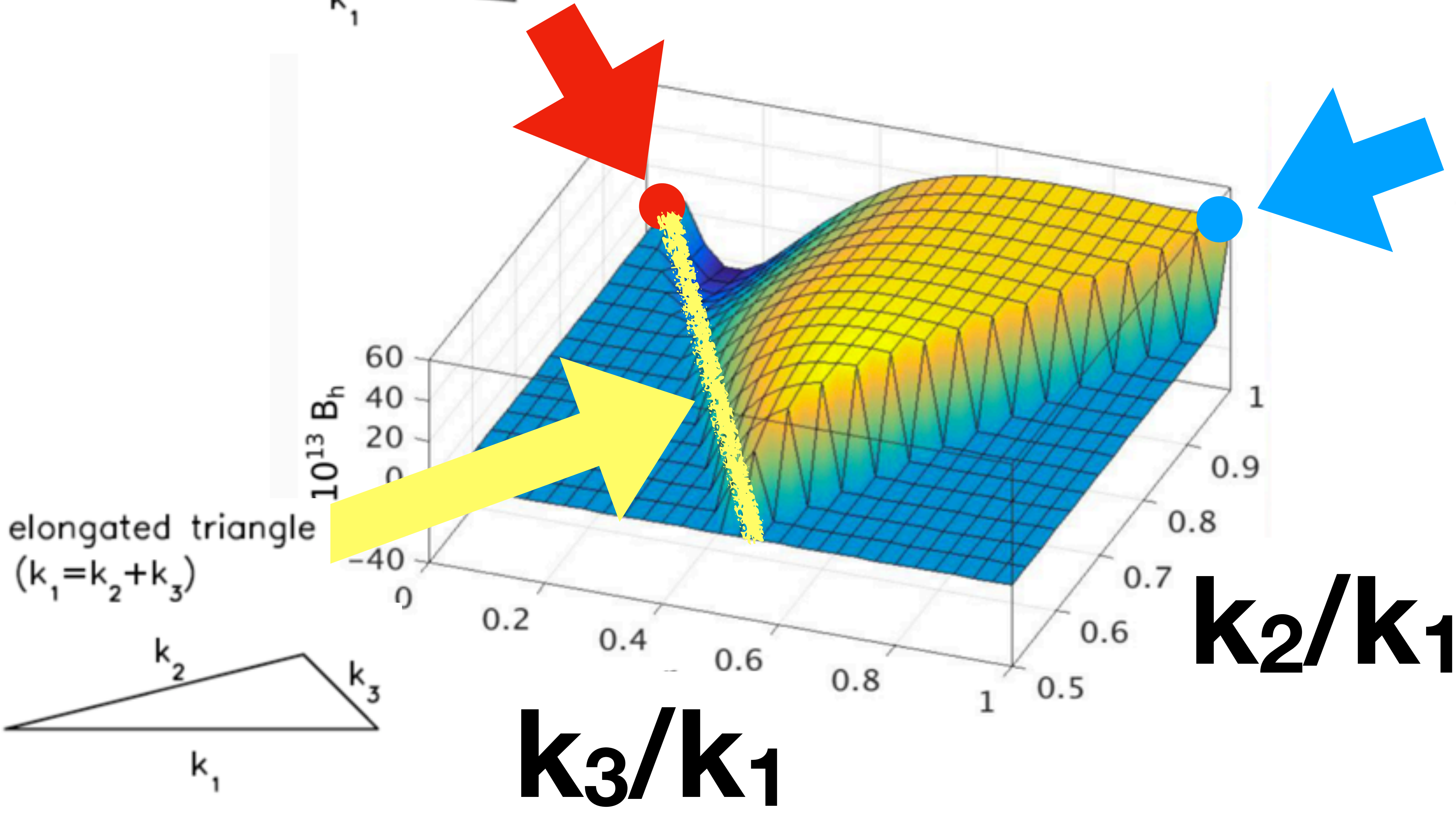
- This diagram generates second-order equation of motion for GW

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

Result



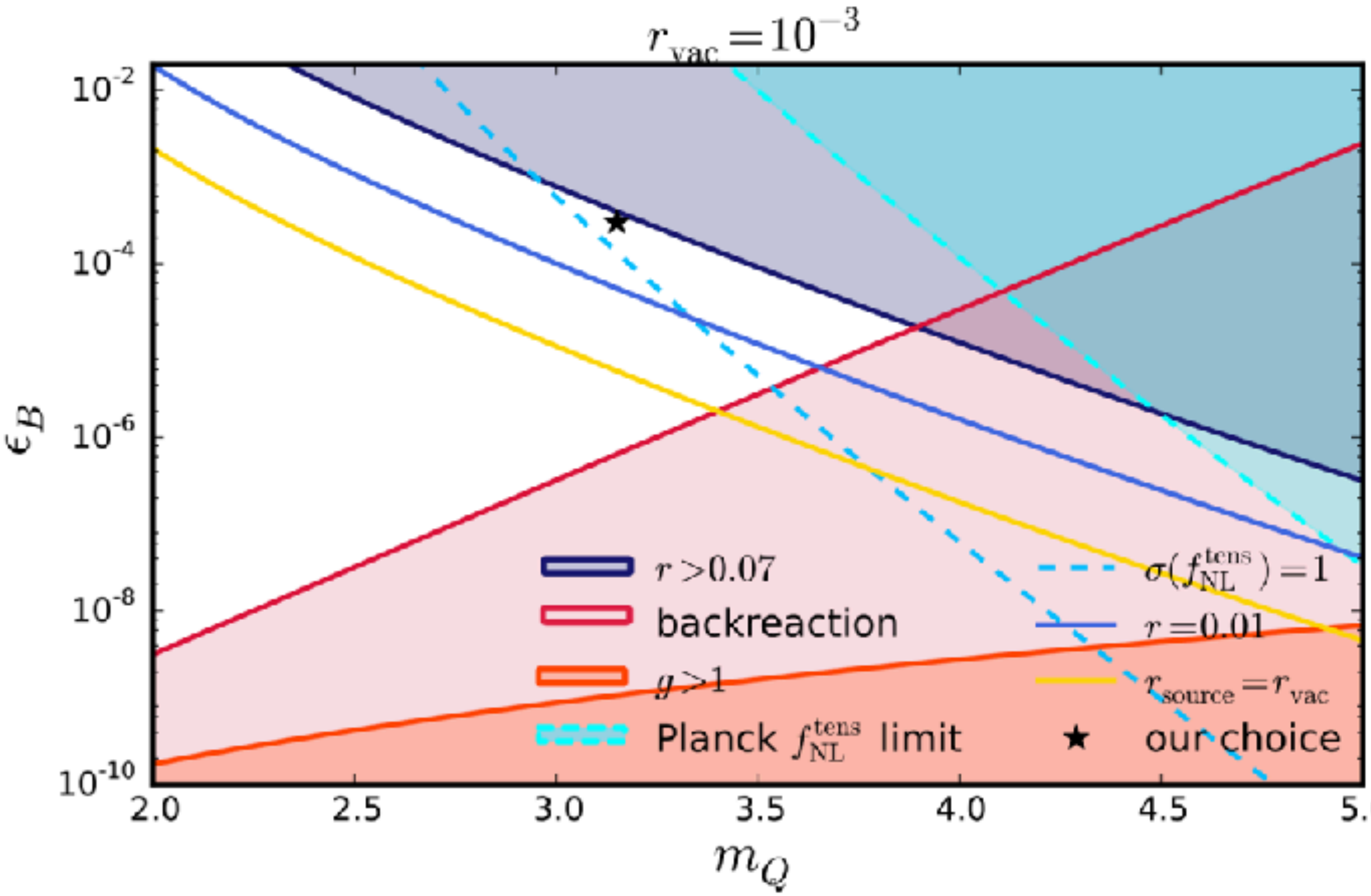




- This shape is similar to, but not exactly the same as, what was used by the Planck team to look for tensor bispectrum

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

Parameter Scan

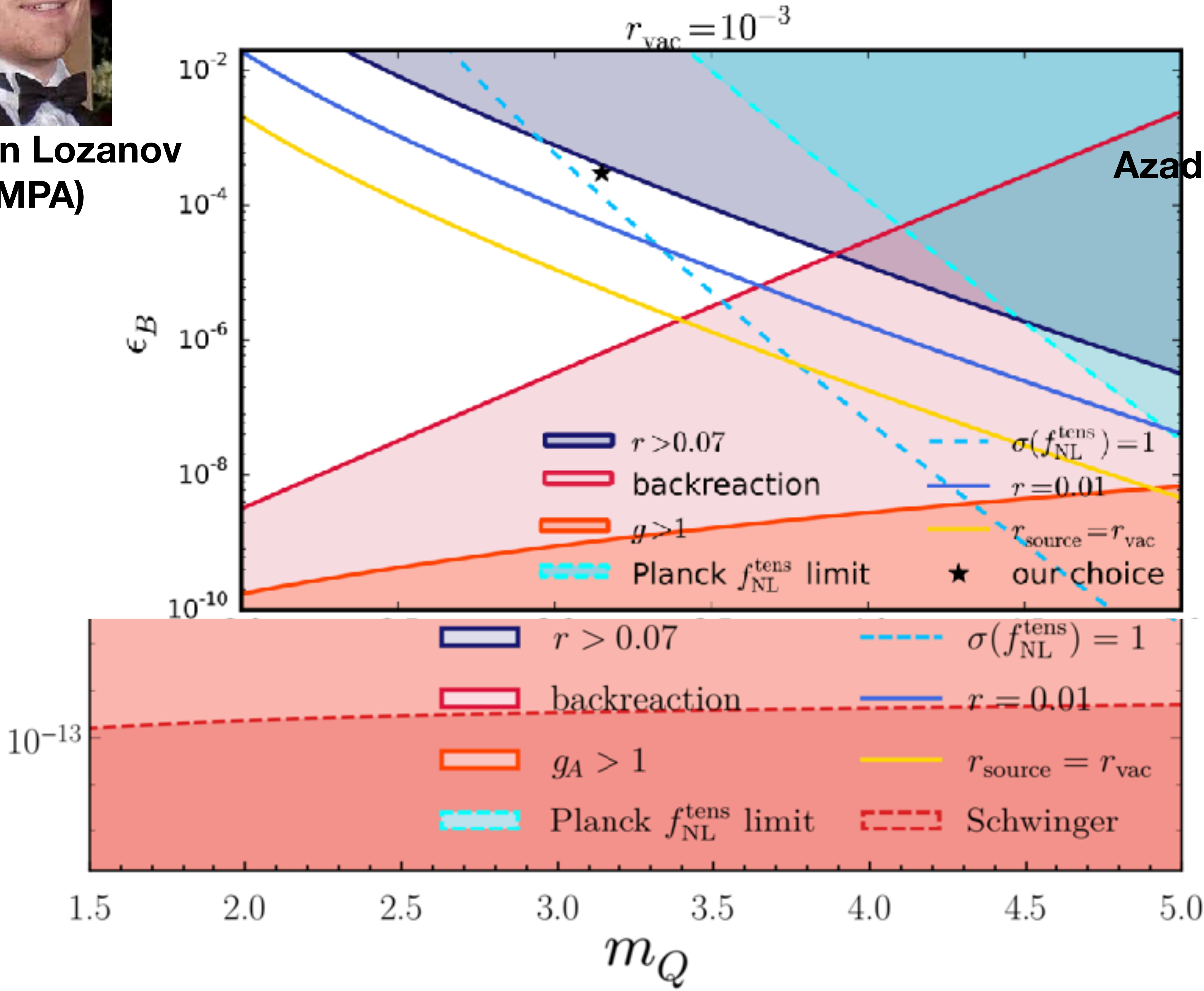


Lozanov, Maleknejad & EK, arXiv:1805.09318

Schwinger Effect

Kaloian Lozanov
(MPA)

Azadeh Maleknejad
(MPA)



Summary

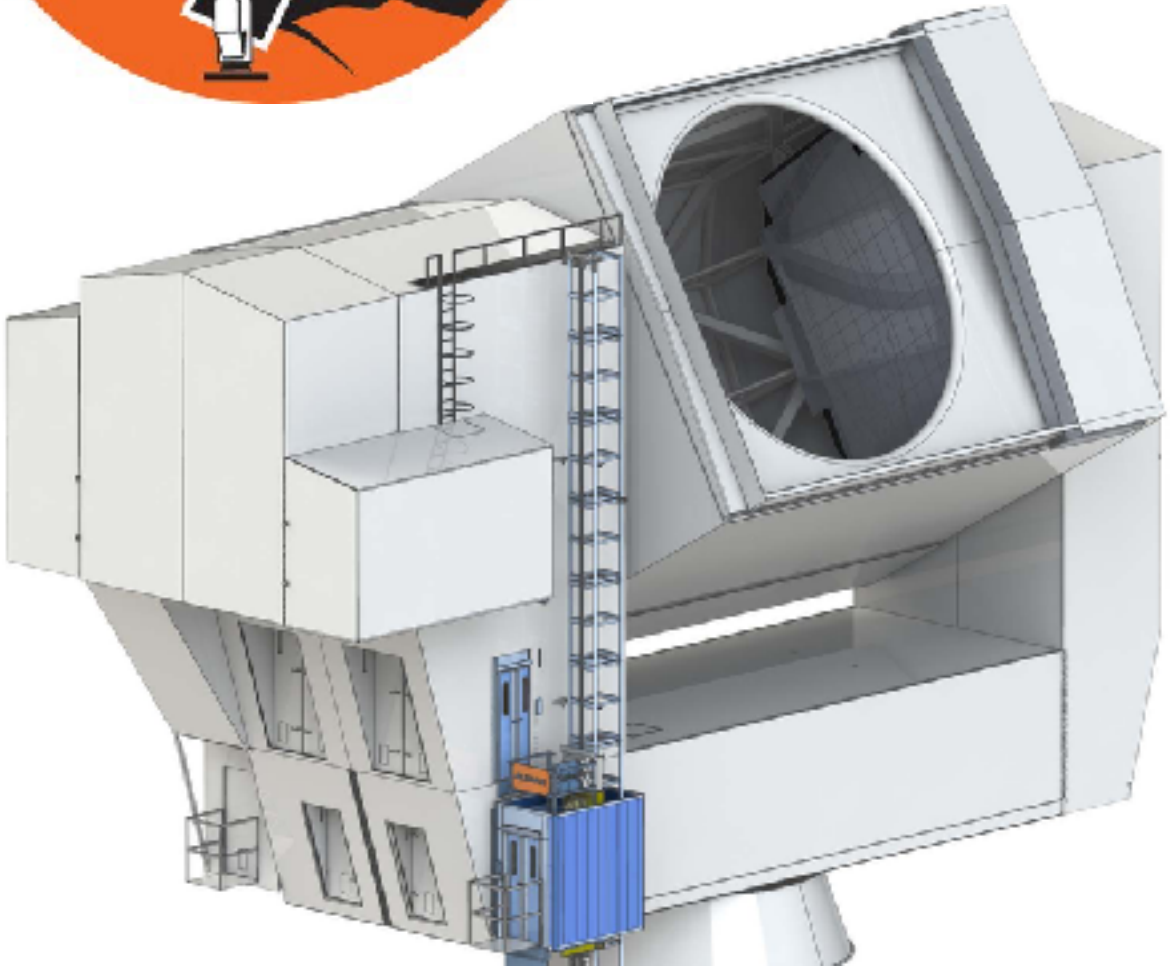
- **Next frontier**: Using CMB polarisation to find **primordial GW**. **Critical test of the physics of the early Universe!**
  - With *LiteBIRD* we plan to reach r~10^{-3}, i.e., 100 times better than the current bound
  - GW from vacuum or sources? An exciting window to new physics
    - Check not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

Ground-based Experiments

Advanced Atacama Cosmology Telescope

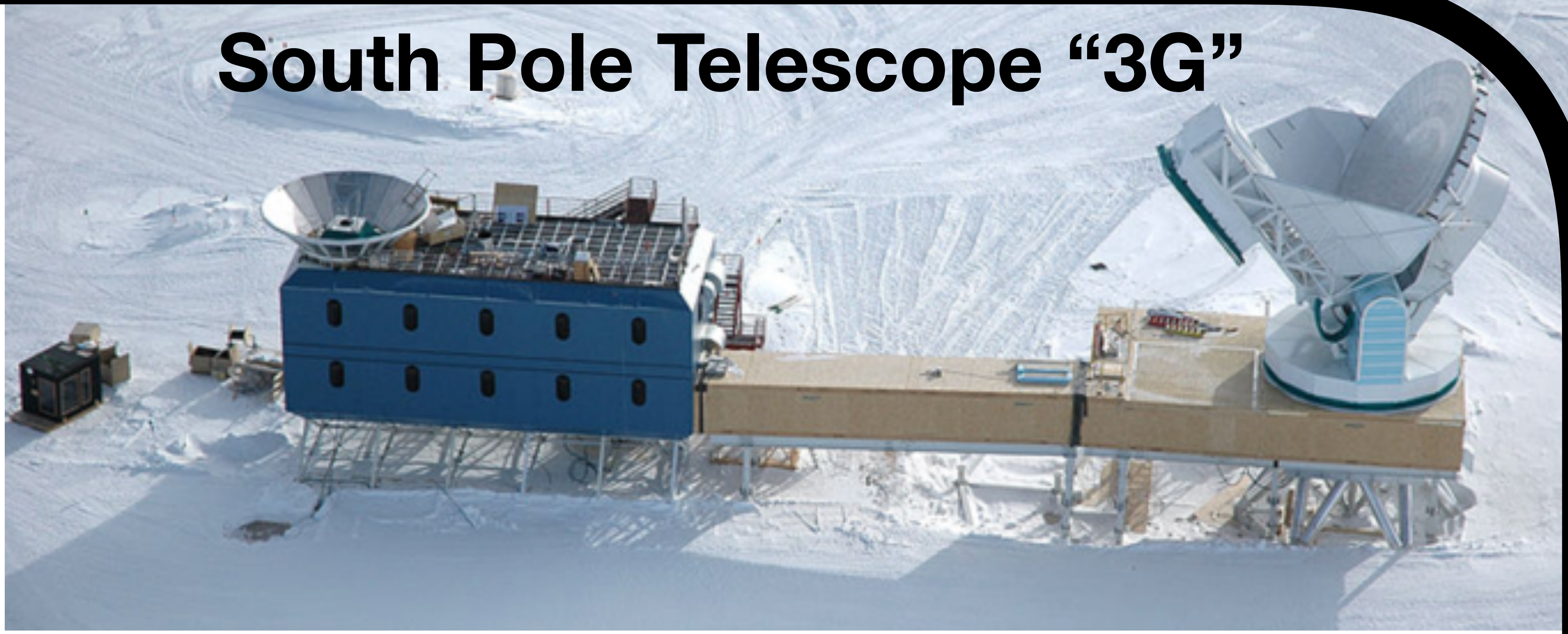
SIMONS OBSERVATORY

The Simons Array

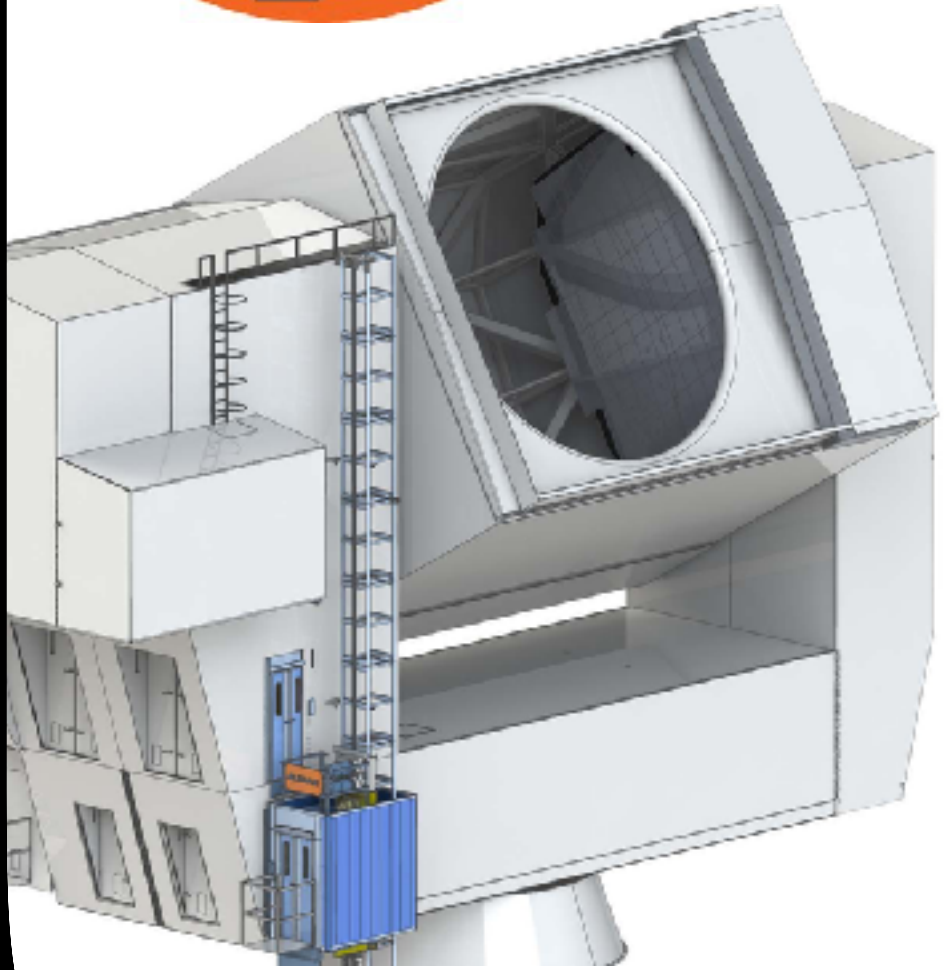


CMB-S4(?)

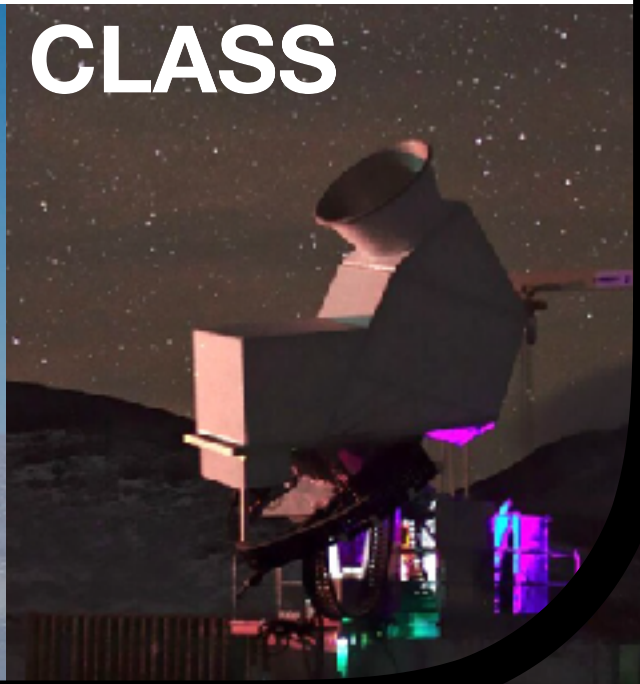
SIMONS
OBSERVATORY



South Pole Telescope “3G”



BICEP/Keck Array



CLASS

The Biggest Enemy: Polarised Dust Emission

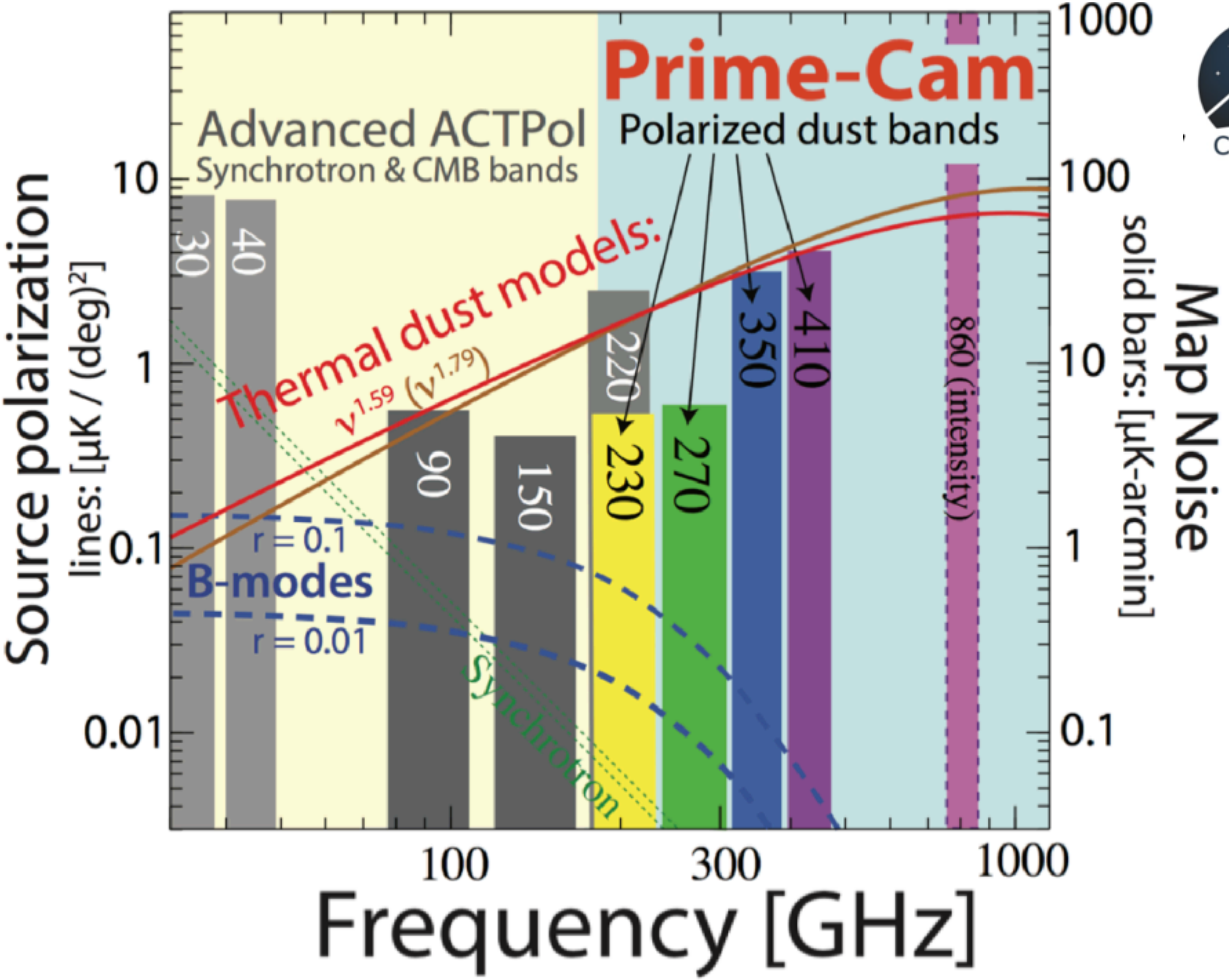
- The upcoming data will **NOT** be limited by statistics, but by systematic effects such as the Galactic contamination

- **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!

CCAT-p Collaboration



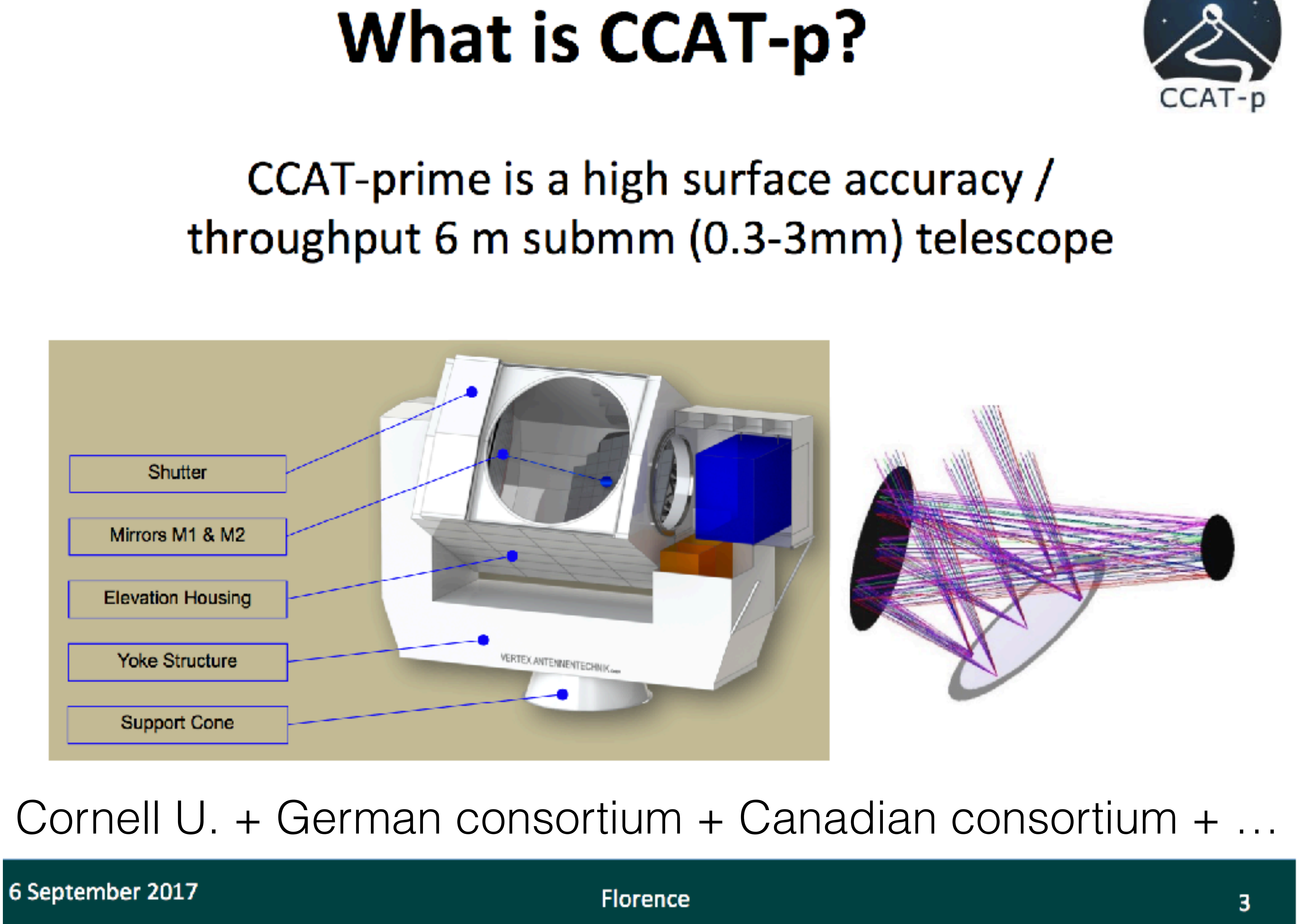
CCAT-p

Frank Bertoldi's slide from the Florence meeting

Where is CCAT-p?

Cerro Chajnantor at 5600 m w/ TAO

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

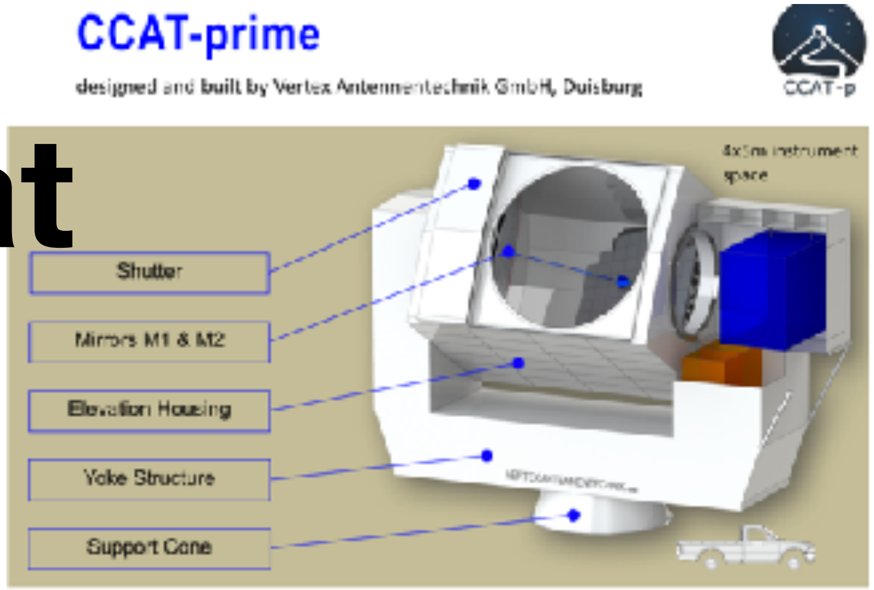
Cornell U. + German consortium + Canadian consortium + …

6 September 2017 Florence

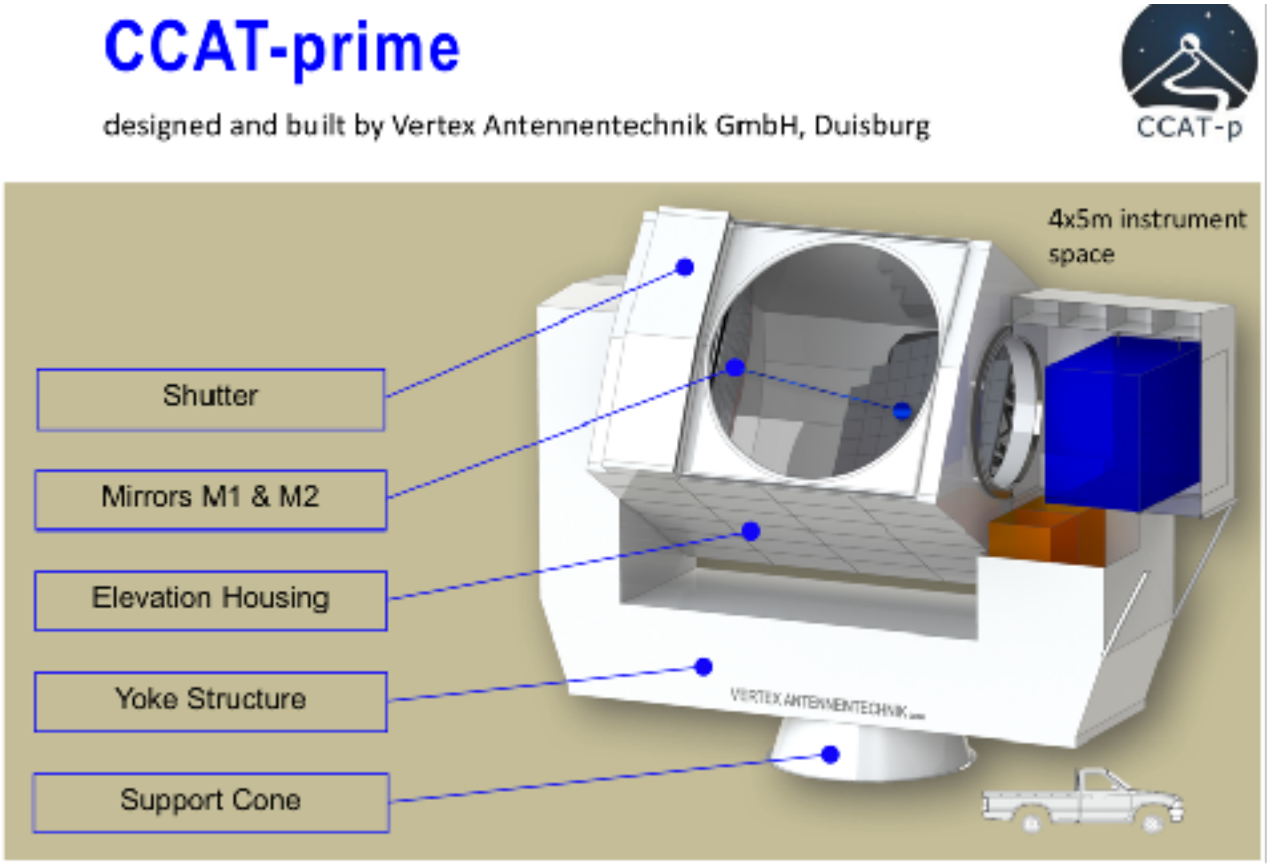
A Game Changer

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

- **Germany makes great telescopes!**

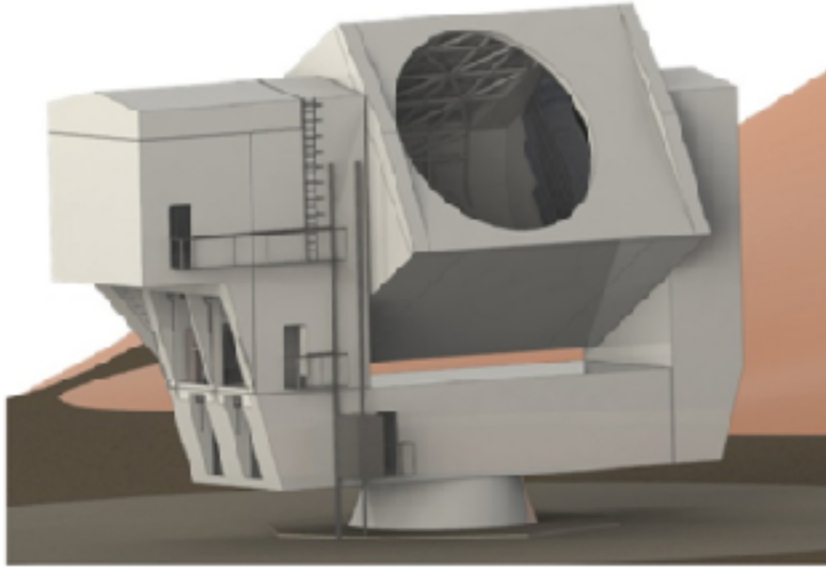


- Design study completed, and the contract has been signed by “VERTEX Antennentechnik GmbH”
    - CCAT-p is a great opportunity for Germany to make <u>significant contributions</u> towards the CMB S-4 landscape (both US and Europe) by providing telescope designs and the “lessons learned” with prototypes.



CCAT-prime

designed and built by Vertex Antennentechnik GmbH, Duisburg



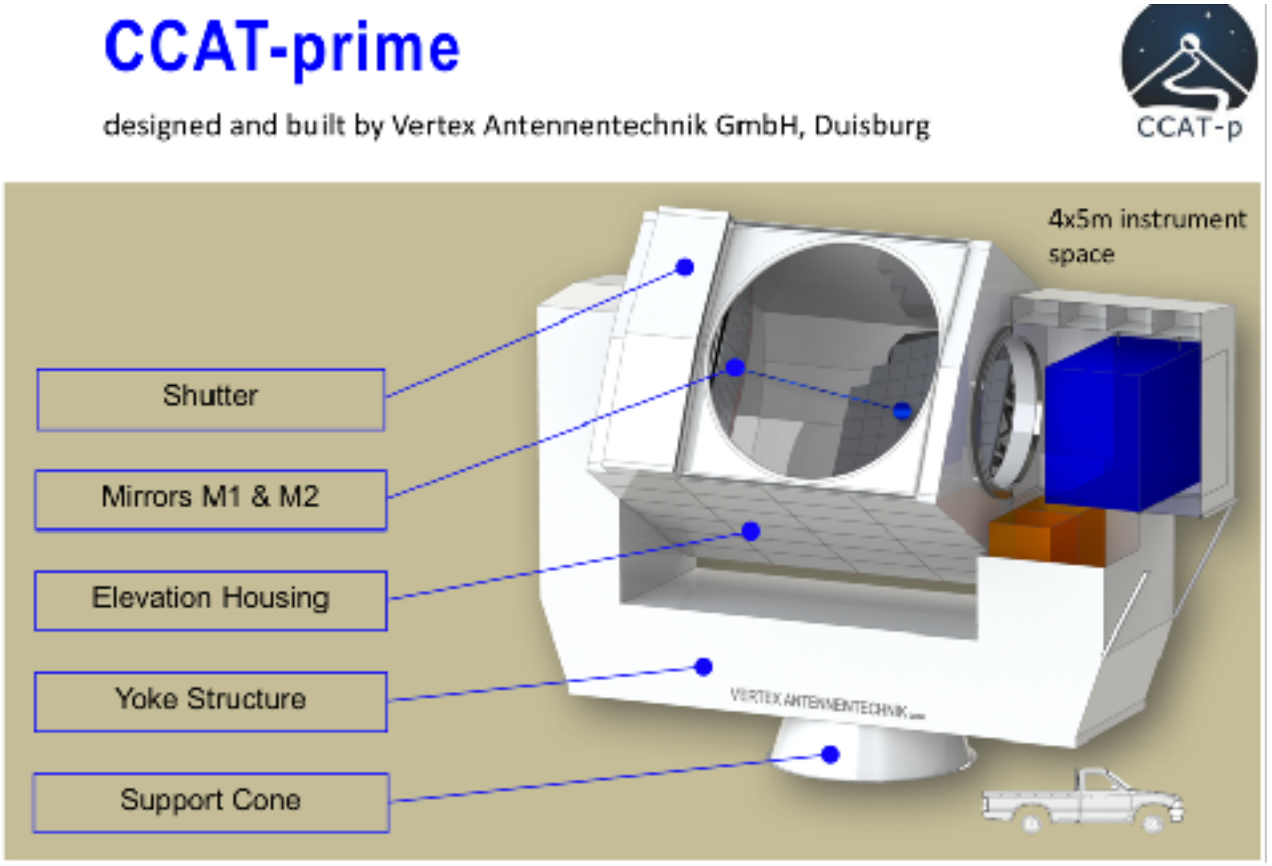
A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

Simons Observatory (USA)

in collaboration

South Pole?

This could be "CMB-S4"



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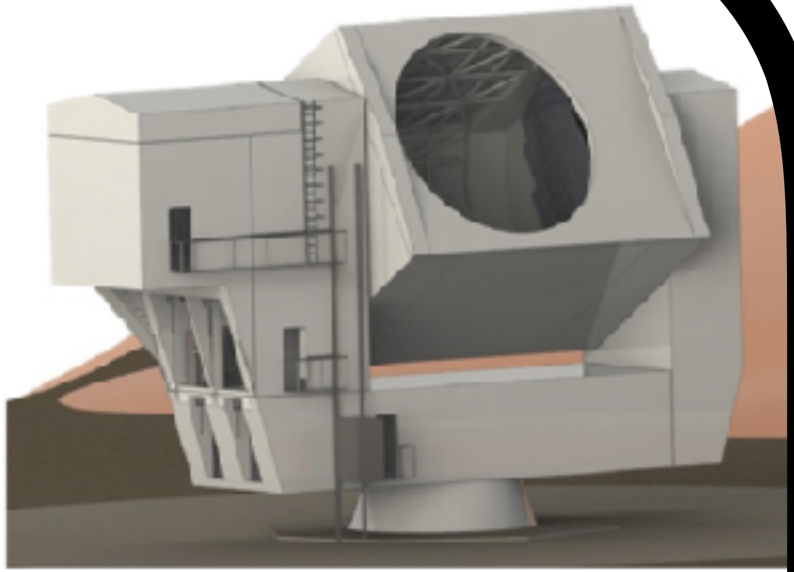


A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

Simons Observatory (USA)

in collaboration

South Pole?

Planck Collaboration (2015)

Current Limit on Tensor NG

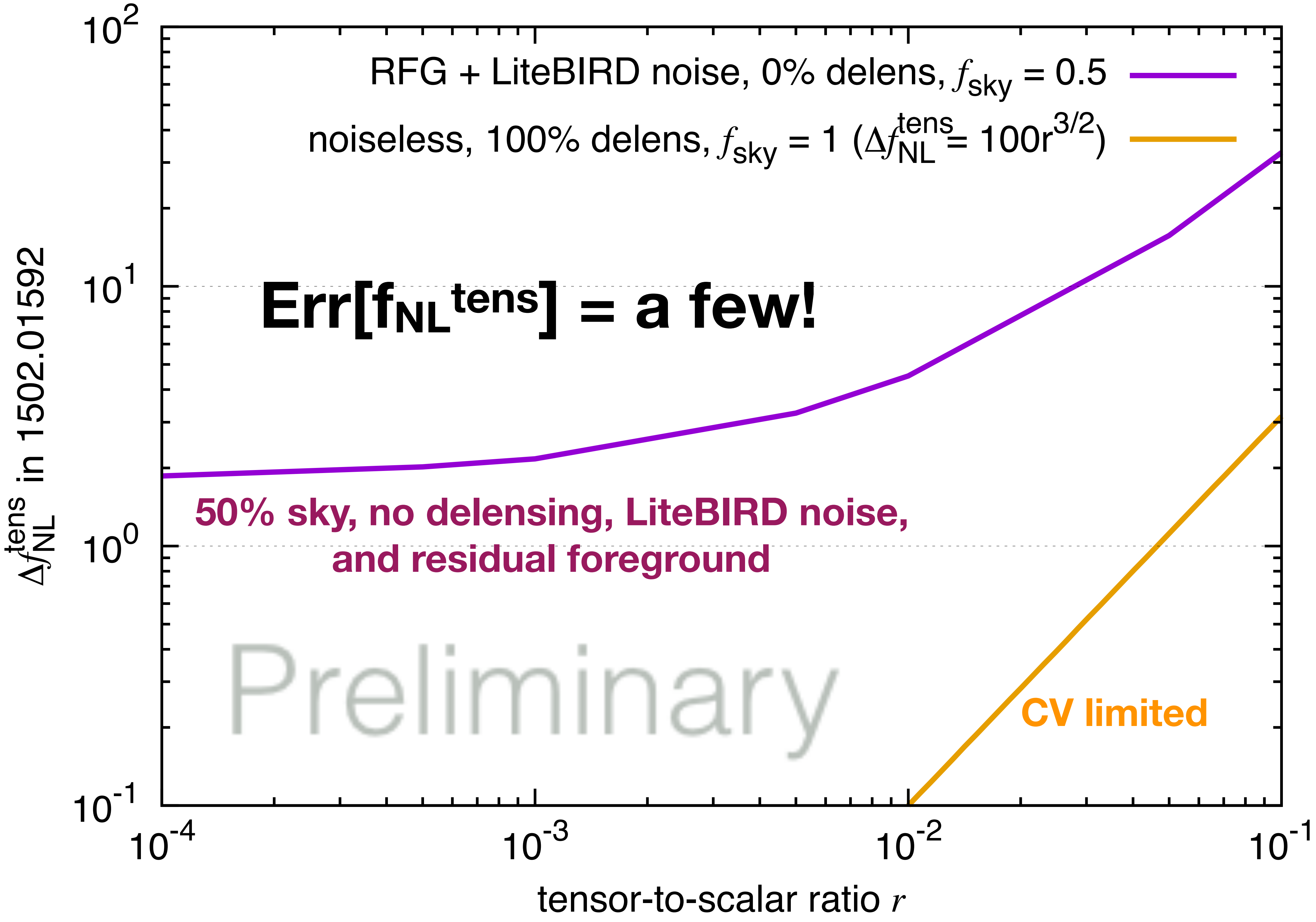
- The Planck team reported a limit on the tensor bispectrum in the following form:

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

- 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 $f_{\rm NL}^{\rm tens} = 400 \pm 1500$

Courtesy of Maresuke Shiraishi

LiteBIRD would nail it!



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

SU(2), confronted

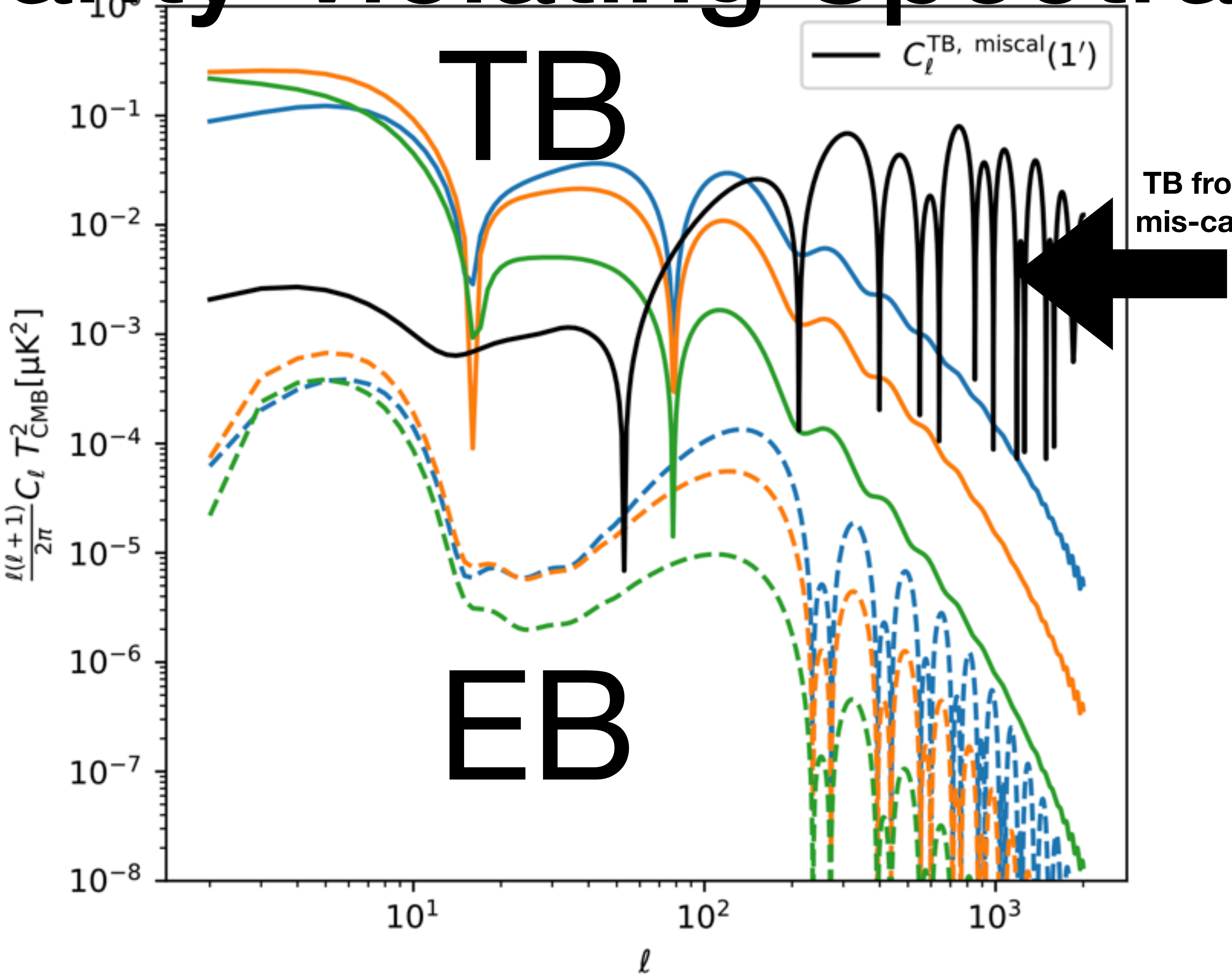
- The SU(2) model of Dimastrogiovanni et al. predicts:

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

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

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

Parity-violating Spectra



TB from angle mis-calibration

- Angle mis-calibration can be distinguished easily!