Finding Gravitational Waves from the Early Universe

Finding the signature of gravitational waves in polarised light of the cosmic microwave background

Eiichiro Komatsu (Max Planck Institute for Astrophysics)

Ecole Internationale Daniel Chalonge-Héctor de Vega 2021, October 6, 2021

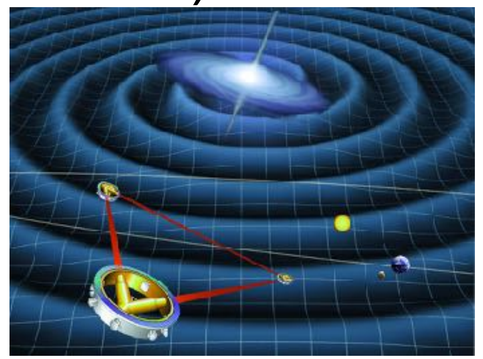
Let's find Gravitational Waves (GW)!

But how? The detection method depends on the GW frequency.

- **Laser interferometers** on the ground: **deca- to kilo Hz** (*LIGO, VIRGO, …, ET*)
  - The wavelength ~ the size of Earth



- **Laser interferometers** in space: **milli Hz** (*LISA*), deci Hz (future mission?)
  - The wavelength ~ Astronomical Unit



- **Pulsar timing arrays**: **nano Hz** (*EPTA*, *SKA*)
  - The wavelength ~ the size of the Milky Way

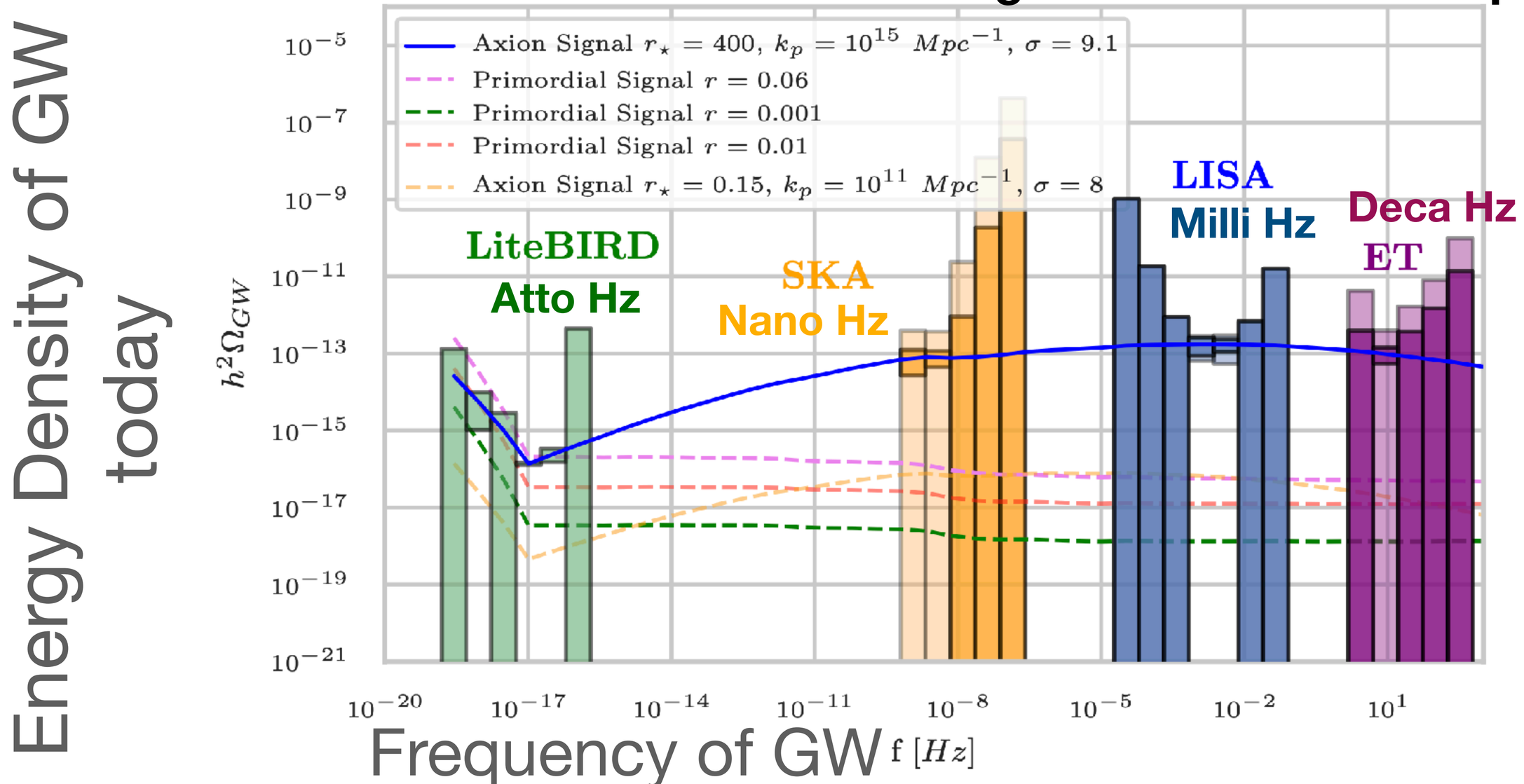


- **Cosmic microwave background**: **atto Hz** (*WMAP*, *Planck*, ***LiteBIRD***)
  - The wavelength ~ **billions of light years!**

Campeti, EK, Poletti, Baccigalupi (2021)

GWs from the early Universe are everywhere!

We can measure it across 21 orders of magnitude in the GW frequency



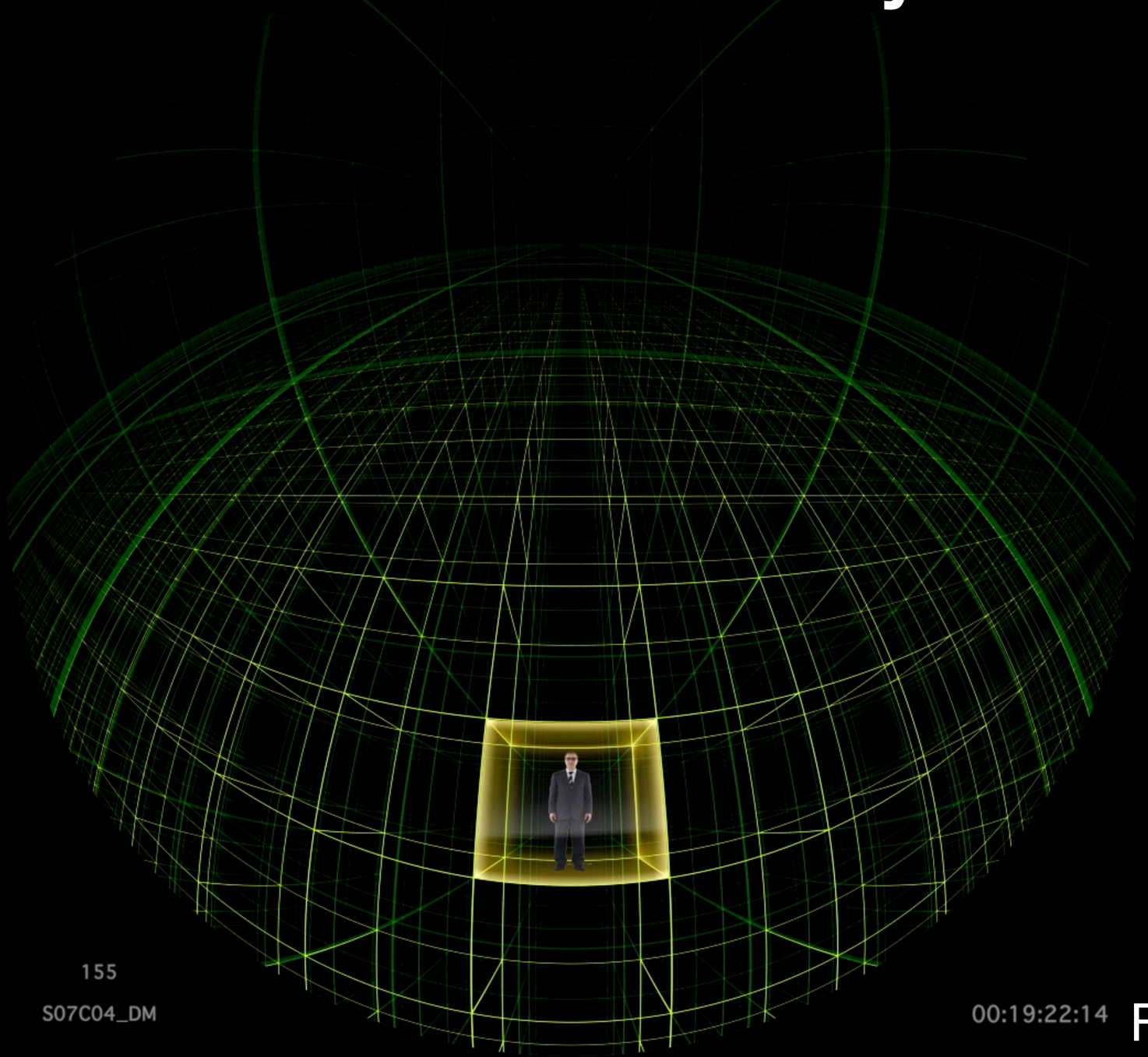
Credit: WMAP Science Team



The sky in various wavelengths

Visible -> Near Infrared -> Far Infrared -> Submillimeter -> Microwave

Where did the CMB we see today come from?

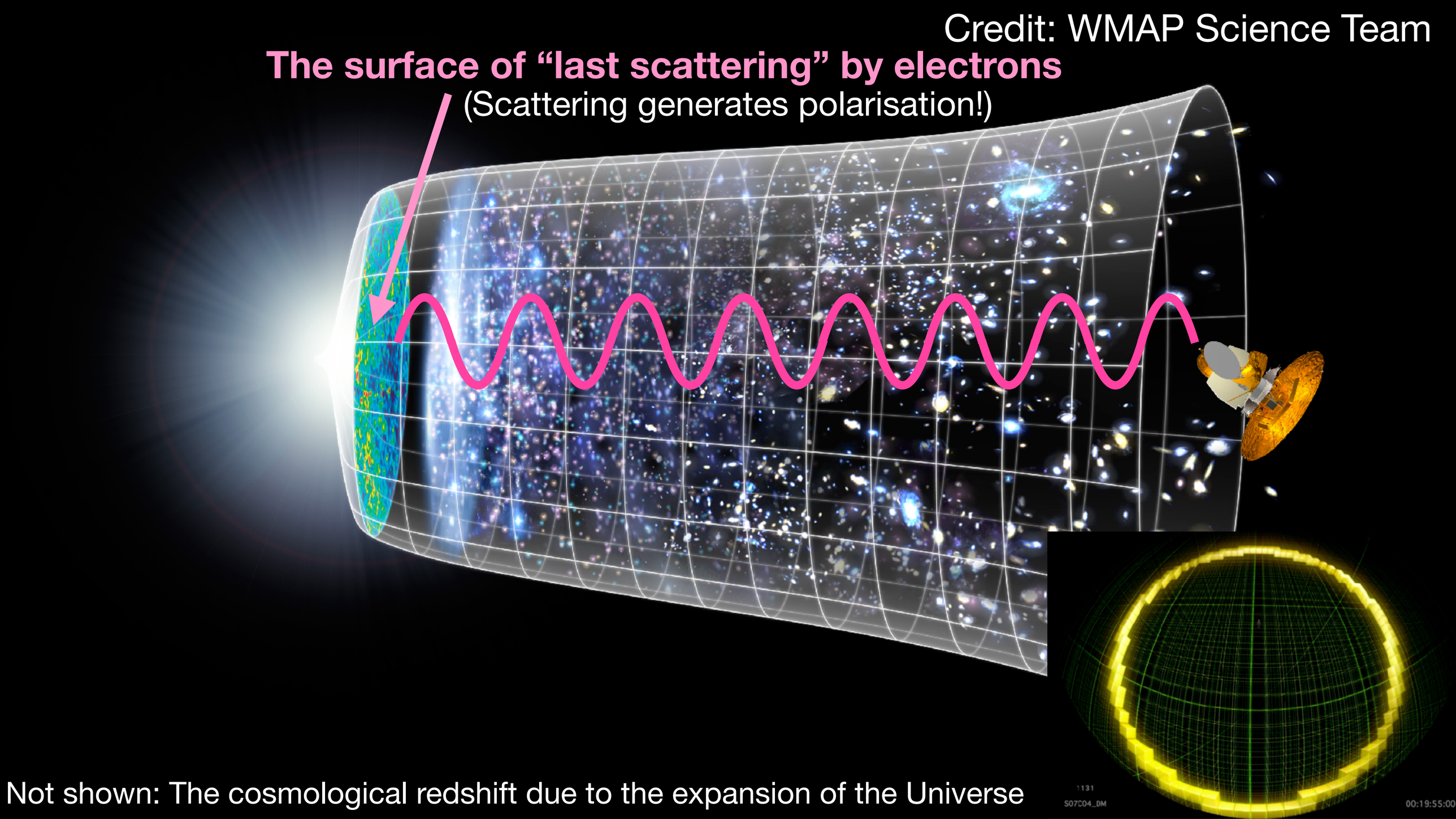


From “HORIZON”

Credit: WMAP Science Team

The surface of “last scattering” by electrons

(Scattering generates polarisation!)

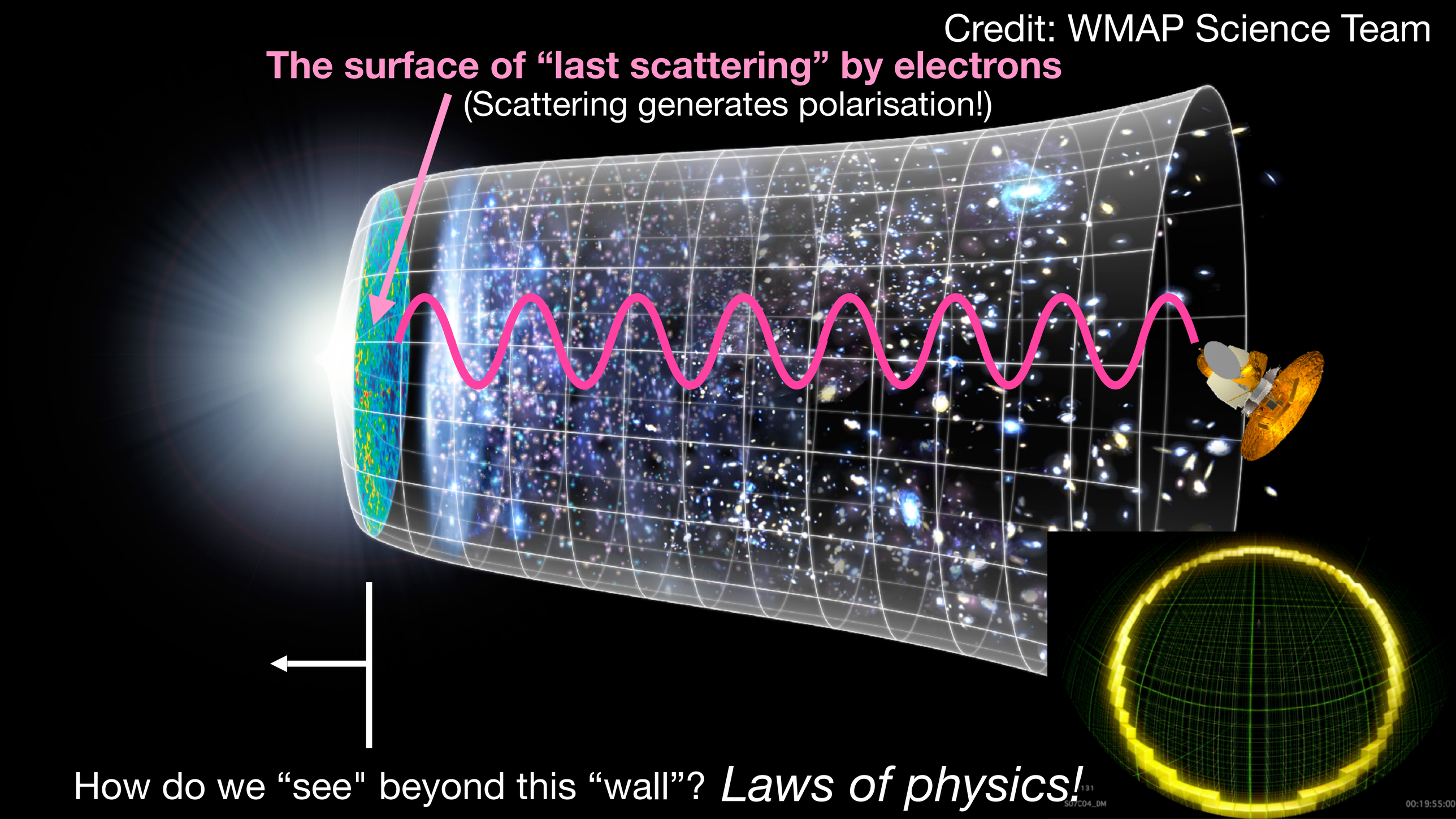


Not shown: The cosmological redshift due to the expansion of the Universe

Credit: WMAP Science Team

The surface of “last scattering” by electrons

(Scattering generates polarisation!)



How do we “see" beyond this “wall”? *Laws of physics!*

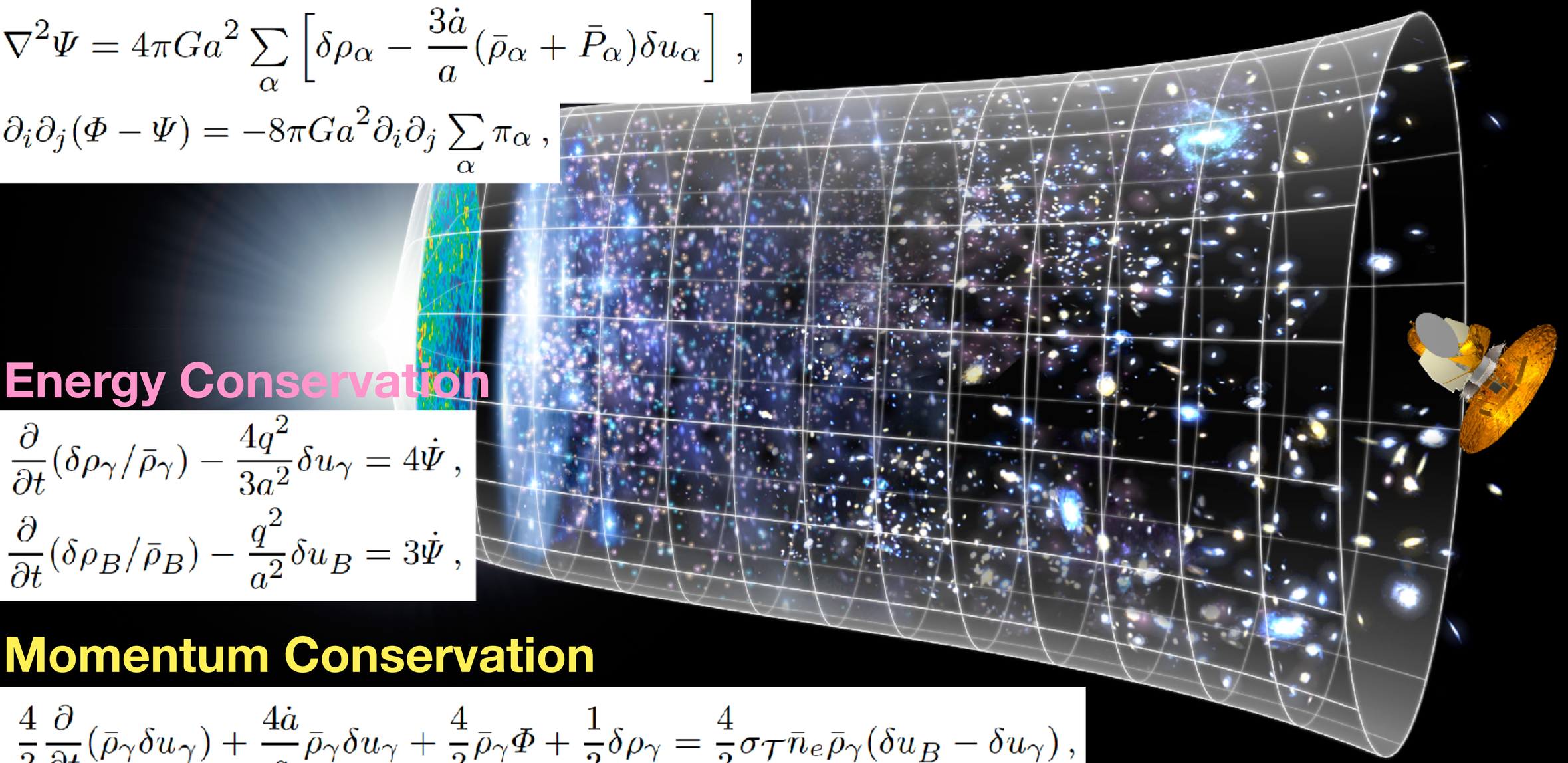
Before we talk about the GW, let’s talk about the sound waves (scalar modes)

Gravitational Field Equations (Einstein's Eq.)

$$\nabla^2\Psi = 4\pi G a^2 \sum_\alpha \left[\delta\rho_\alpha - \frac{3\dot{a}}{a}(\bar{\rho}_\alpha + \bar{P}_\alpha)\delta u_\alpha\right] ,$$

$$\partial_i\partial_j(\Phi - \Psi) = -8\pi G a^2 \partial_i\partial_j \sum_\alpha \pi_\alpha ,$$

Credit: WMAP Science Team



Energy Conservation

$$\frac{\partial}{\partial t}(\delta\rho_\gamma/\bar{\rho}_\gamma) - \frac{4q^2}{3a^2}\delta u_\gamma = 4\dot{\Psi} ,$$

$$\frac{\partial}{\partial t}(\delta\rho_B/\bar{\rho}_B) - \frac{q^2}{a^2}\delta u_B = 3\dot{\Psi} ,$$

Momentum Conservation

$$\frac{4}{3}\frac{\partial}{\partial t}(\bar{\rho}_\gamma\delta u_\gamma) + \frac{4\dot{a}}{a}\bar{\rho}_\gamma\delta u_\gamma + \frac{4}{3}\bar{\rho}_\gamma\Phi + \frac{1}{3}\delta\rho_\gamma = \frac{4}{3}\sigma_T\bar{n}_e\bar{\rho}_\gamma(\delta u_B - \delta u_\gamma) ,$$

$$\frac{\partial}{\partial t}(\bar{\rho}_B\delta u_B) + \frac{3\dot{a}}{a}\bar{\rho}_B\delta u_B + \bar{\rho}_B\Phi = -\frac{4}{3}\sigma_T\bar{n}_e\bar{\rho}_\gamma(\delta u_B - \delta u_\gamma) ,$$

Laws of physics!

Gravitational Field Equations

+

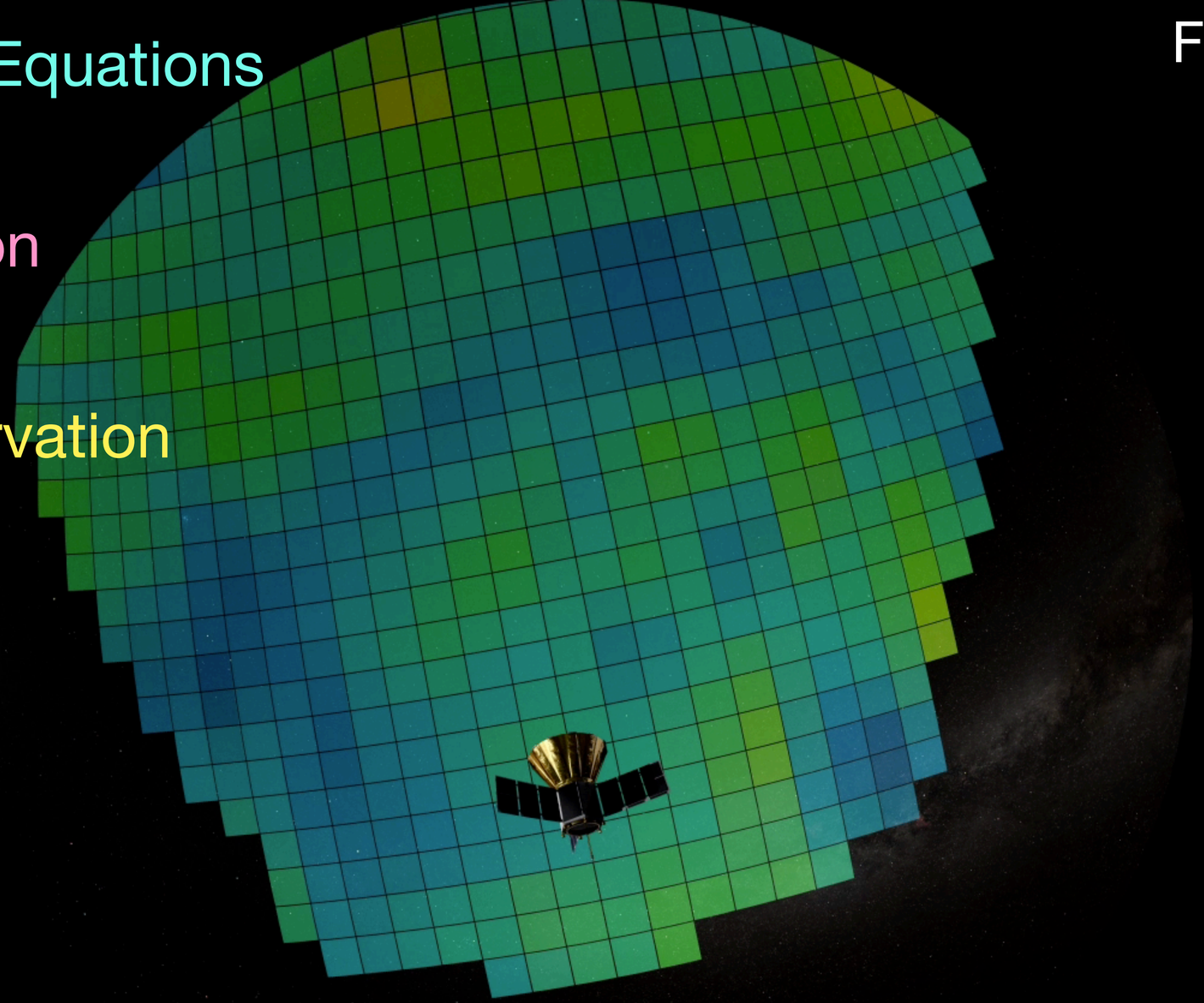
Energy Conservation

+

Momentum Conservation

=

Sound Waves!



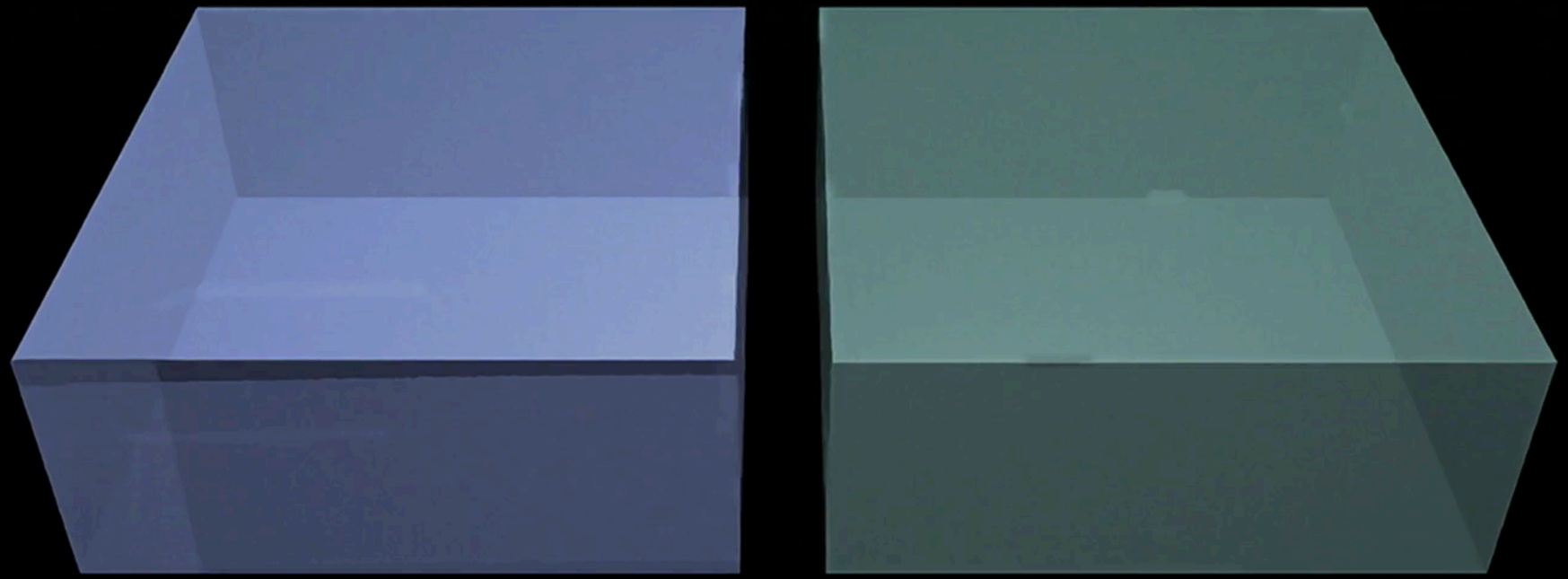
From “HORIZON”

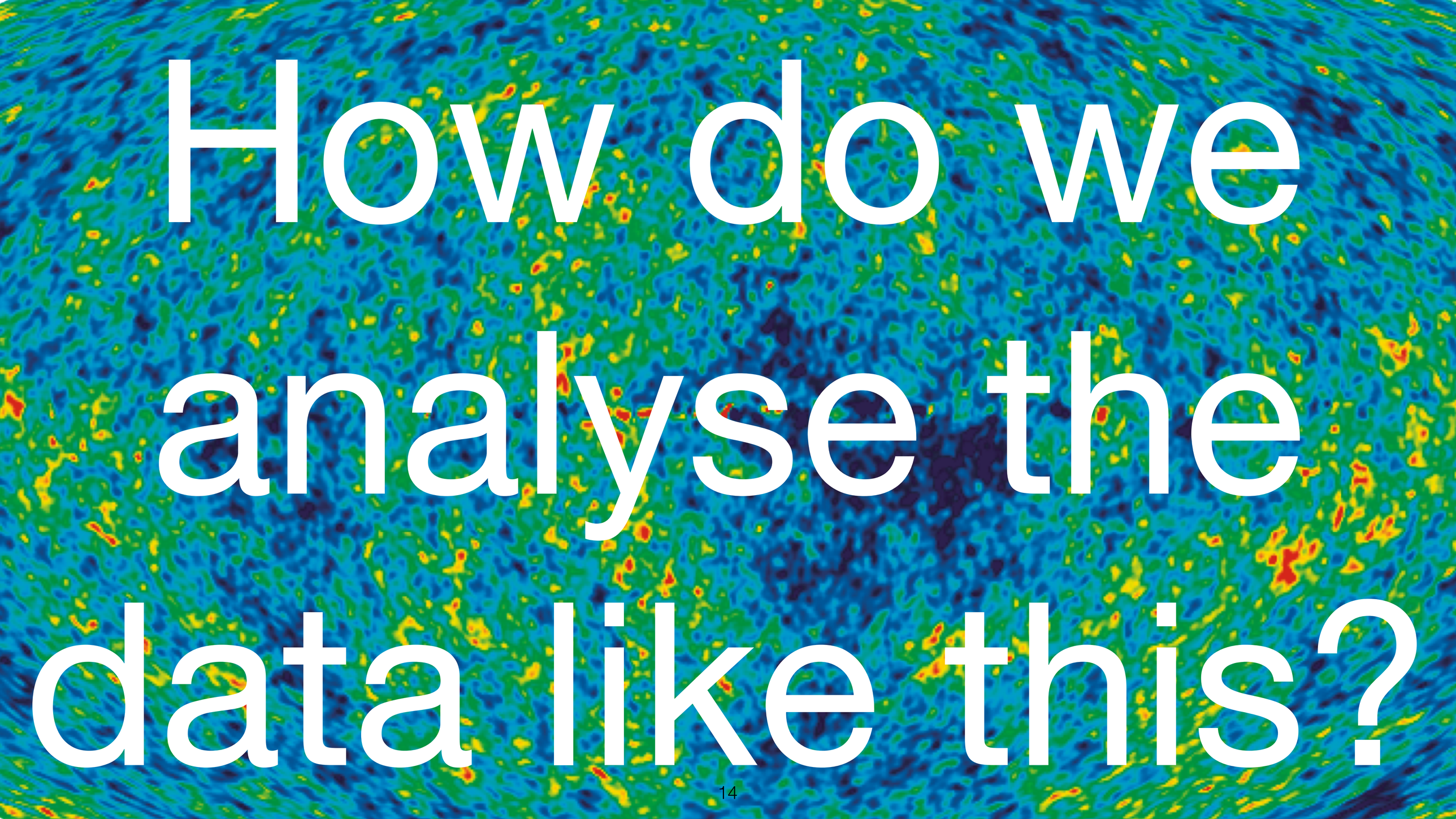


Soupe miso cosmique

- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching how ripples are created and propagate throughout the soup

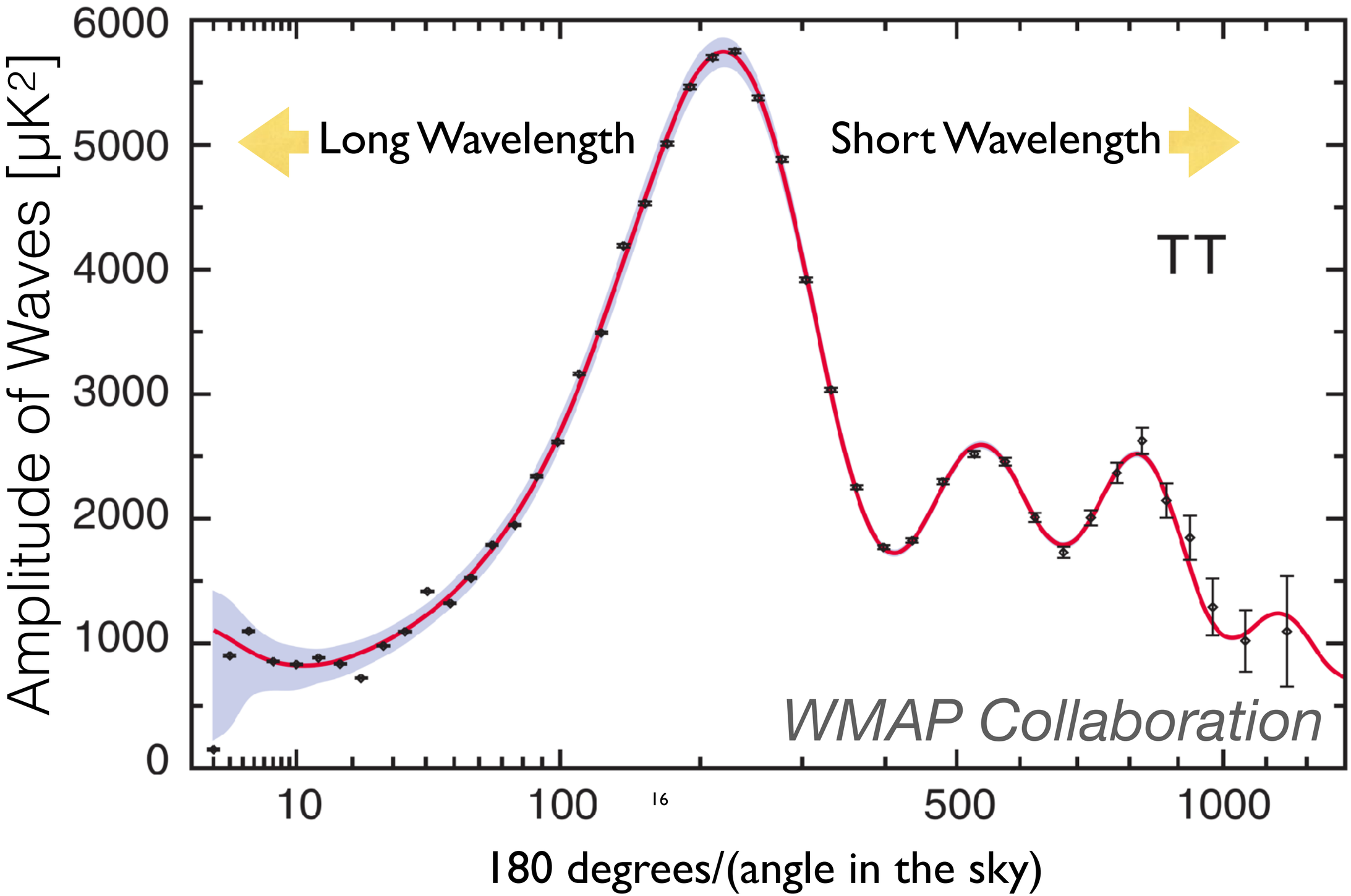
Credit: WMAP Science Team



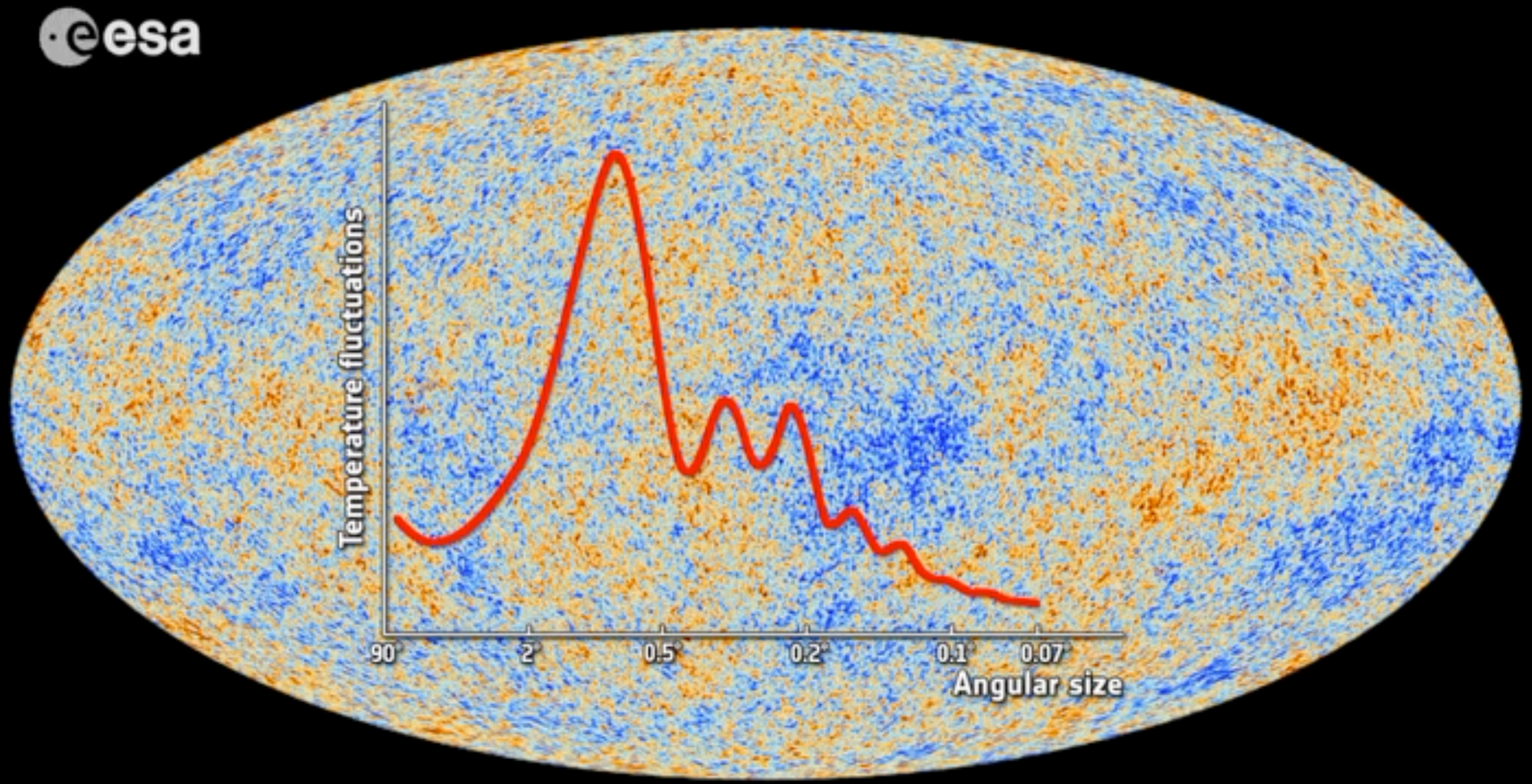

How do we
analyse the
data like this?

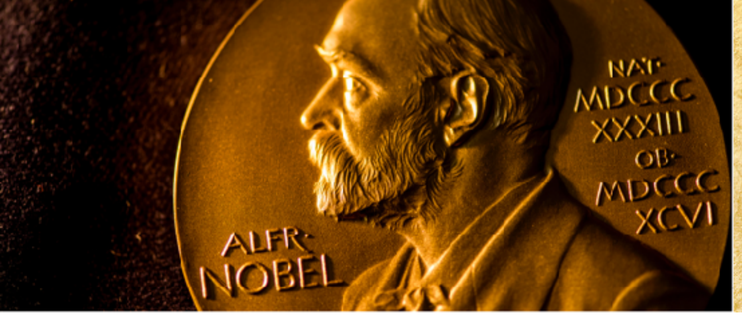
Data Analysis

- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength: **Power Spectrum**


Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
TT
WMAP Collaboration
10
100
500
1000
180 degrees/(angle in the sky)

Power Spectrum, Explained





The Royal Swedish Academy of Sciences has decided to award the 2019 Nobel Prize in Physics to

JAMES PEEBLES

"for theoretical discoveries in physical cosmology"

Sound waves in the fireball Universe, predicted in 1970

James Peebles
Facts



Ill. Niklas Elmedhed. © Nobel Media. **https://www.nobelprize.org**

James Peebles
The Nobel Prize in Physics 2019

Born: 1935, Winnipeg, Canada

Affiliation at the time of the award: I
Princeton, NJ, USA

Prize motivation: "for theoretical dis
cosmology."

Prize share: 1/2

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PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

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Joseph Henry Laboratories, Princeton University
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Goddard Institute for Space Studies, NASA, New York
Received 1970 January 5; revised 1970 April 1



At the *ICGC2011* conference, Goa, India

Sound waves in the fireball Universe, predicted in 1970

Astrophysics and Space Science 7 (1970) 3–19. *All Rights Reserved*
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SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

R. A. SUNYAEV and YA. B. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)





Determine the composition of the Universe

The Universe as a “hot soup”

- The power spectrum allows us to determine the composition of the Universe, such as the density of atoms, dark matter, and dark energy.



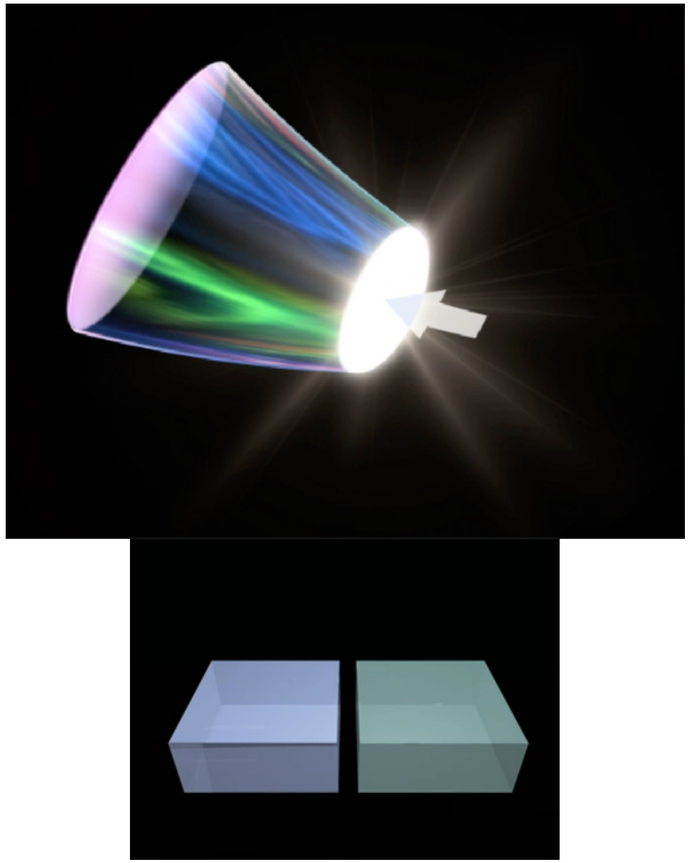
- **Definitive evidence for non-baryonic nature of dark matter!**



“Let’s give some impact to the beginning of this model”

- What gave the initial fluctuation to the cosmic hot soup?

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 the quantum fluctuation on the *microscopic* scale become *macroscopic* over large distances?
- **What is the missing link between the small and large scales?**

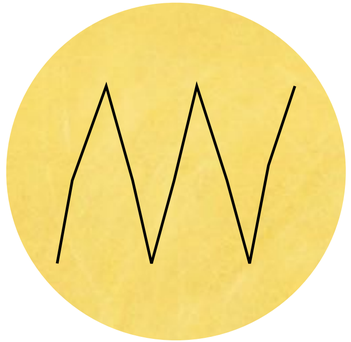
Gravity + Quantum

= The origin of all the structures we see in the Universe

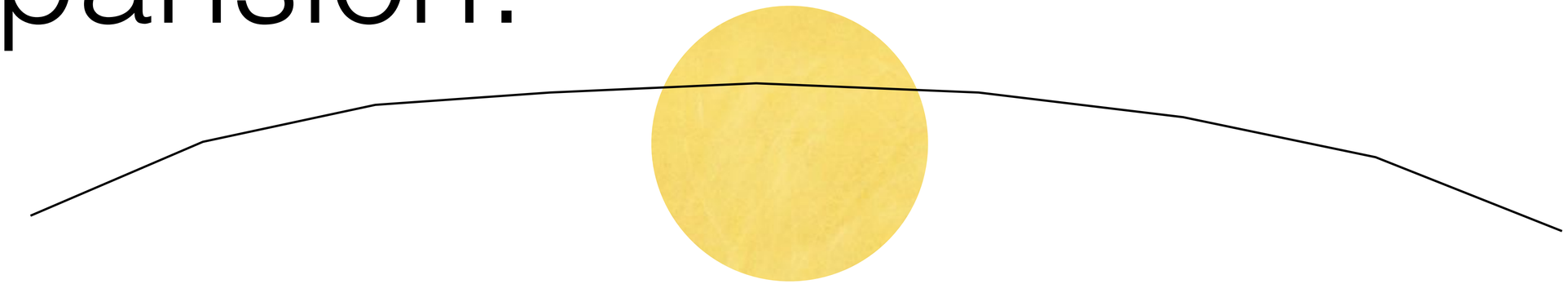
Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

Quantum mechanical fluctuation on microscopic scales



Exponential Expansion!



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

What? How can we believe such a statement?

We have accumulated very good evidence so far

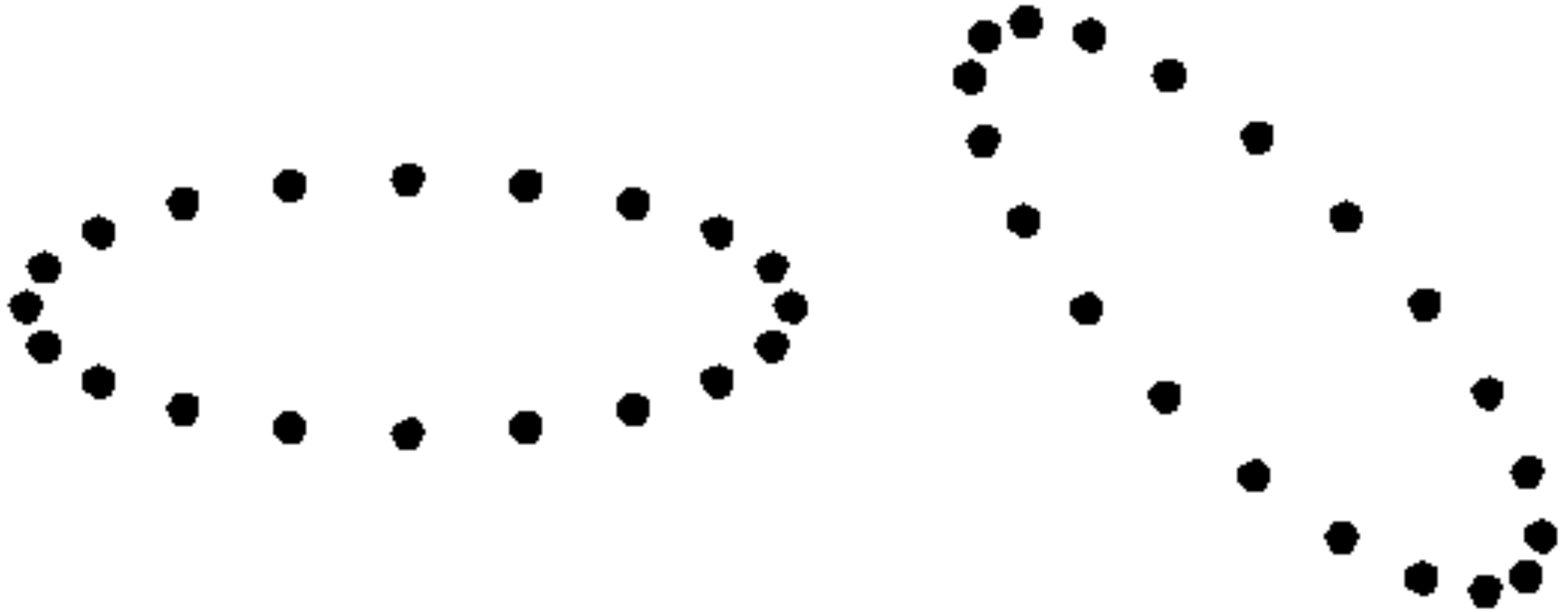
The next step: Primordial Gravitational Waves

- Since the first discovery of the CMB temperature fluctuation by COBE in 1992, we have made a tremendous progress in making much more detailed measurements of the CMB over the last three decades.
    - Three space missions, COBE (NASA) -> WMAP (NASA) -> Planck (ESA), as well as a host of ground-based and balloon-borne experiments. **Truly the global community effort!**
- What more do we want? **Primordial gravitational waves.** (Starobinsky 1979)
    - Why more evidence? Because "***the extraordinary claim requires extraordinary evidence***" (Carl Sagan)

Let’s talk about the GW (tensor modes)

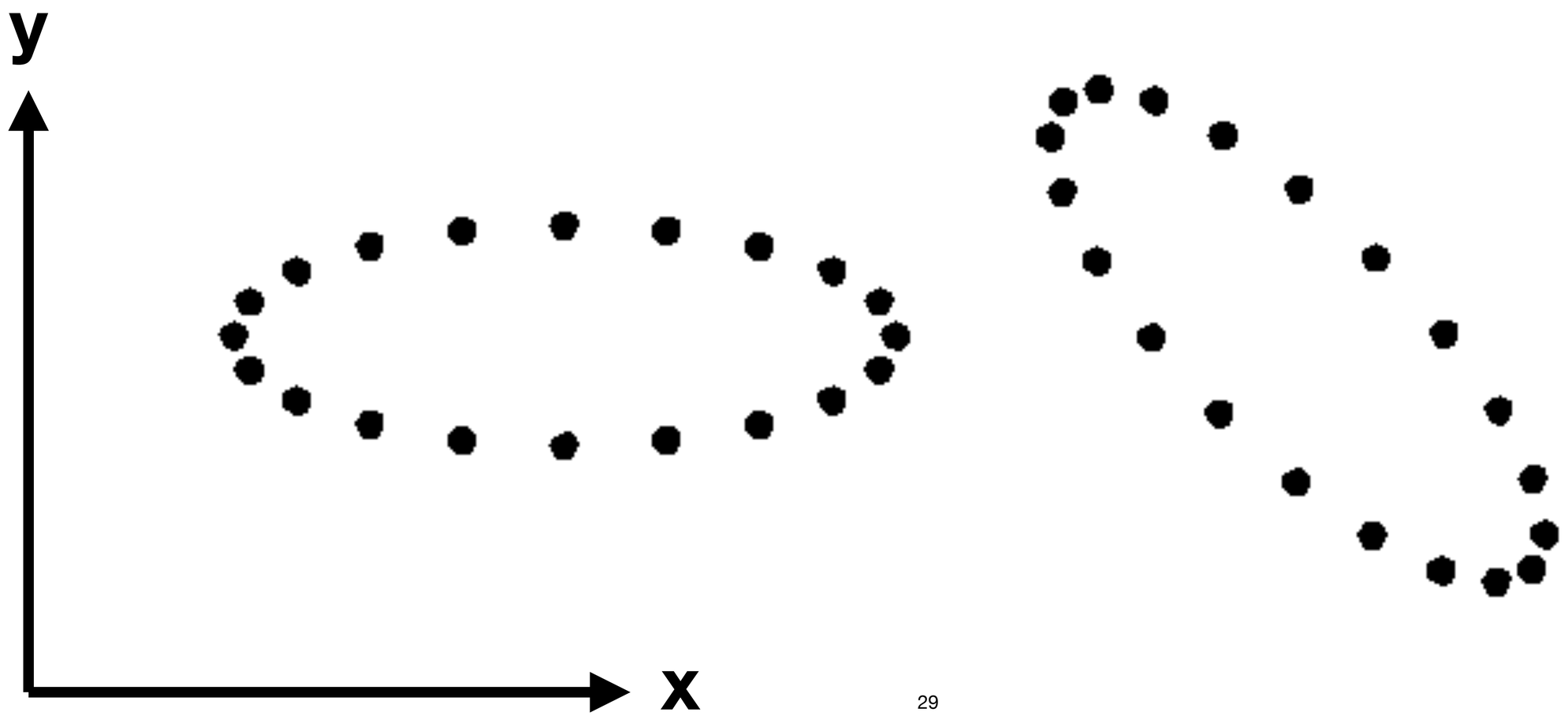
Gravitational waves are coming towards you!

To visualise the waves, watch motion of test particles.

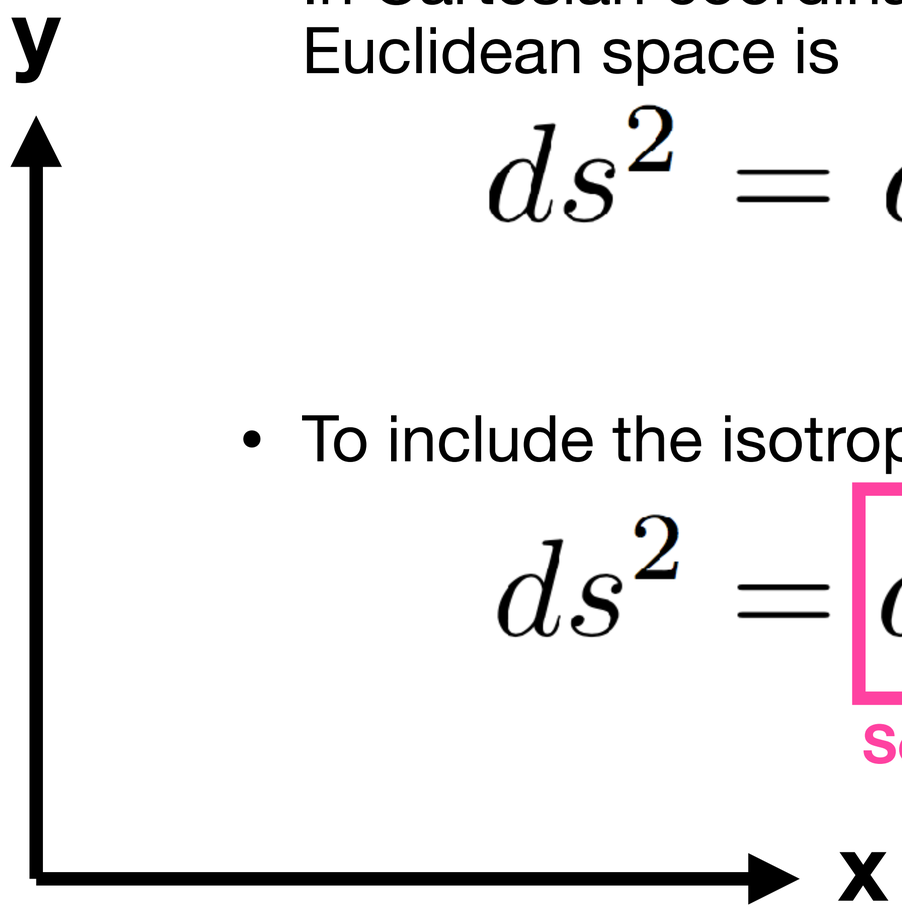


Gravitational waves are coming towards you!

To visualise the waves, watch motion of test particles.



Distance between two points



- In Cartesian coordinates, the distance between two points in Euclidean space is

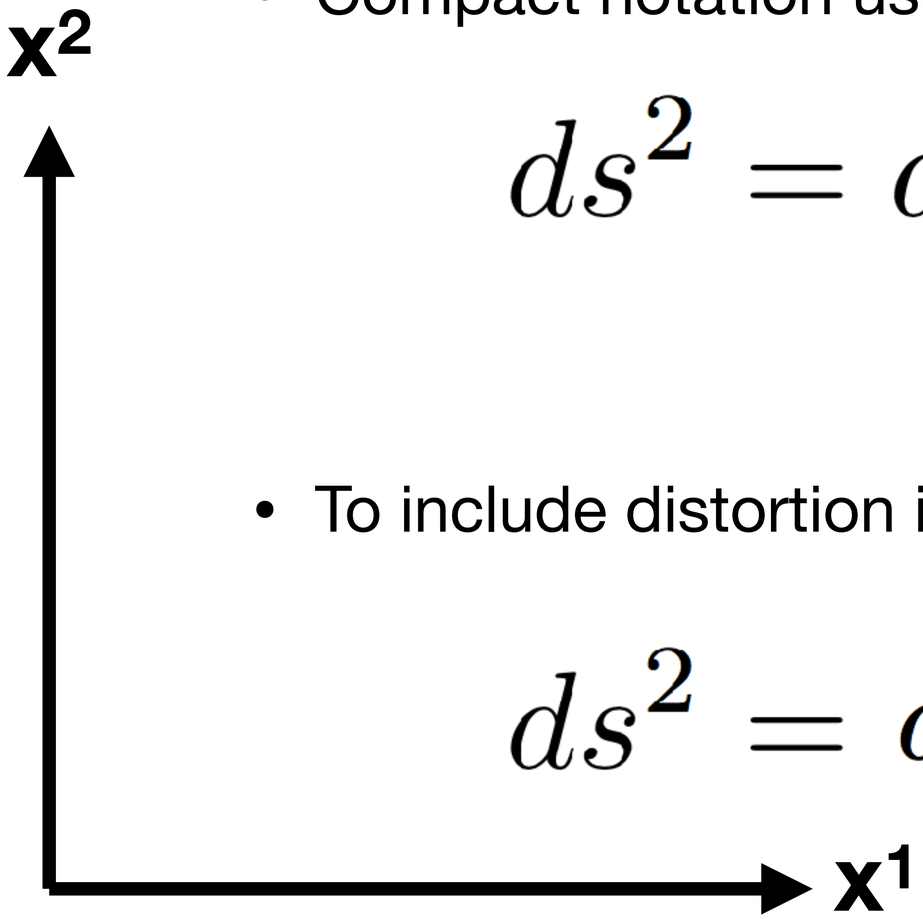
$$ds^2 = dx^2 + dy^2 + dz^2$$

- To include the isotropic expansion of space,

$$ds^2 = a^2(t)(dx^2 + dy^2 + dz^2)$$

Scale Factor

Distortion in space



- Compact notation using Kronecker's delta symbol:

$$ds^2 = a^2(t) \sum_{i=1}^{3} \sum_{j=1}^{3} \delta_{ij} dx^i dx^j \qquad x = (x, y, z)$$

δ_{ij} = 1 for i=j;
δ_{ij} = 0 otherwise

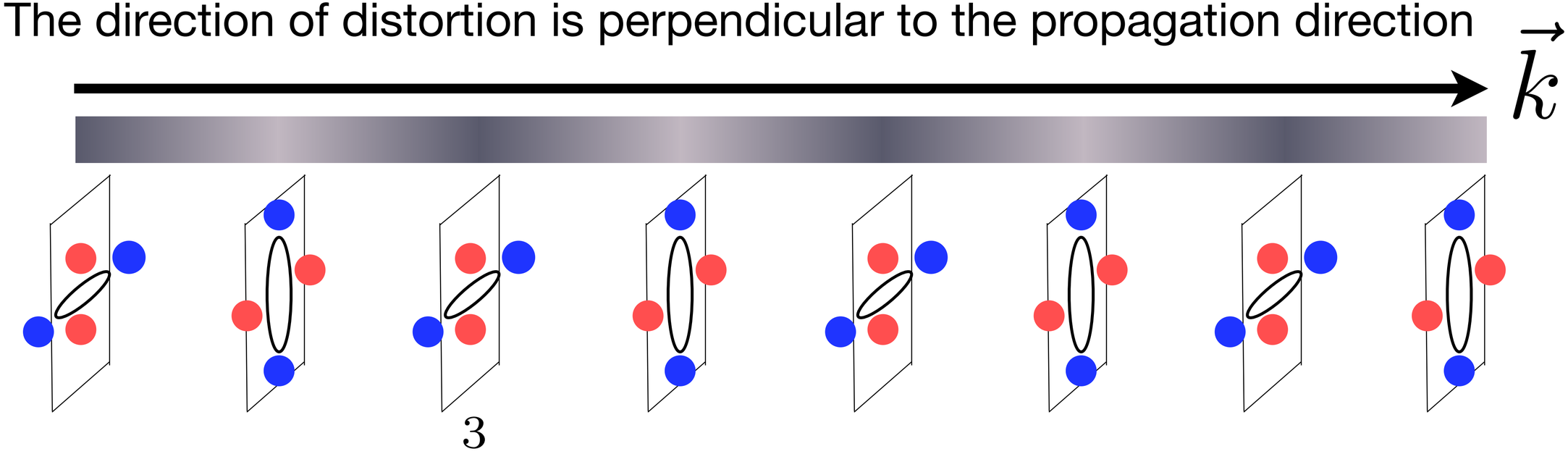
- To include distortion in space,

$$ds^2 = a^2 \sum_{i=1}^{3} \sum_{j=1}^{3} (\delta_{ij} + h_{ij}) dx^i dx^j$$

Distortion in space!

Four conditions for gravitational waves

- **The gravitational wave shall be <u>transverse.</u>**
  - The direction of distortion is perpendicular to the propagation direction



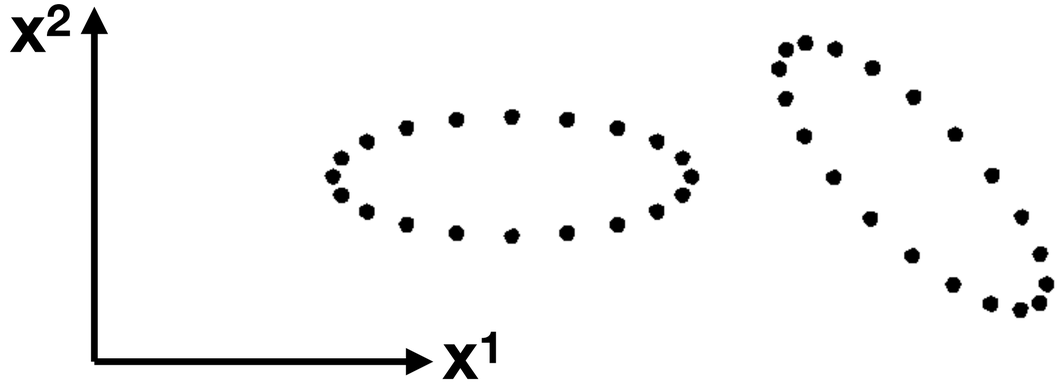
Thus, $\sum_{i=1}^{3} k^i h_{ij} = 0$

3 conditions for h_{ij}

Four conditions for gravitational waves

- **The gravitational wave shall <u>not change the area</u>**
  - The determinant of $\delta_{ij}+h_{ij}$ is 1

$$ds^2 = a^2 \sum_{i=1}^{3} \sum_{j=1}^{3} (\delta_{ij} + h_{ij}) dx^i dx^j$$



Thus, $\sum_{i=1}^{3} h_{ii} = 0$

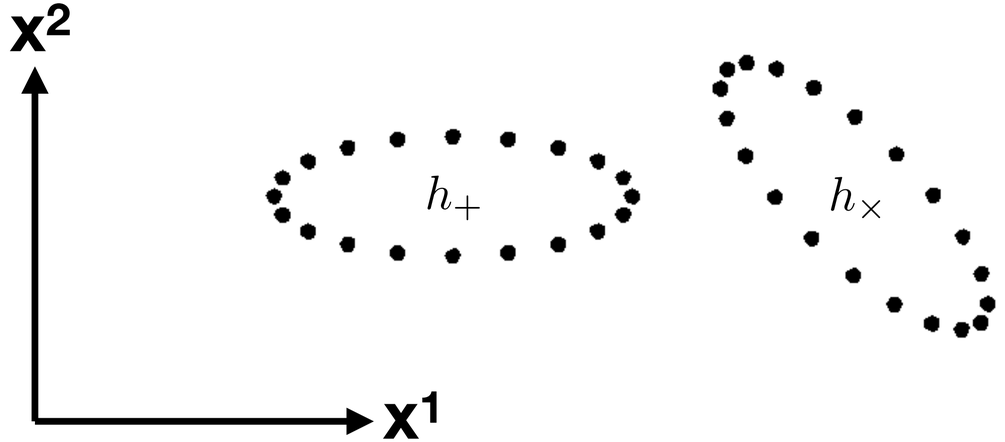
1 condition for h_{ij}

6 – 4 = 2 degrees of freedom for GW

We call them “plus” and “cross” modes

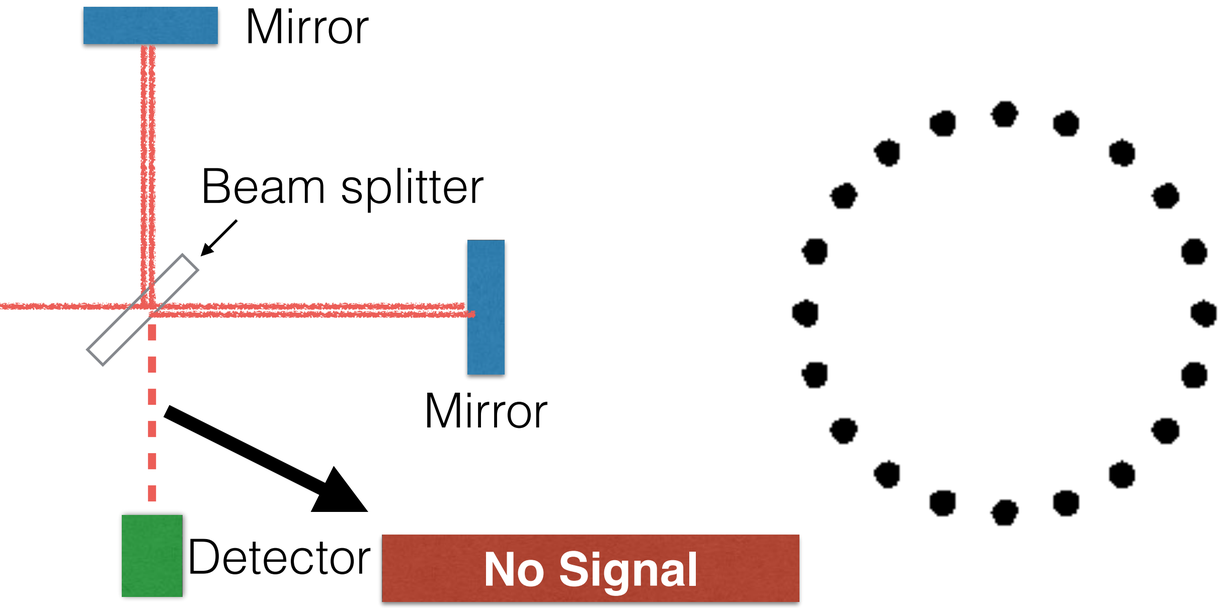
- The symmetric matrix h_{ij} has 6 components, but there are 4 conditions. Thus, we have two degrees of freedom.
- If the GW propagates in the x^3=z axis, non-vanishing components of h_{ij} are

$$h_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

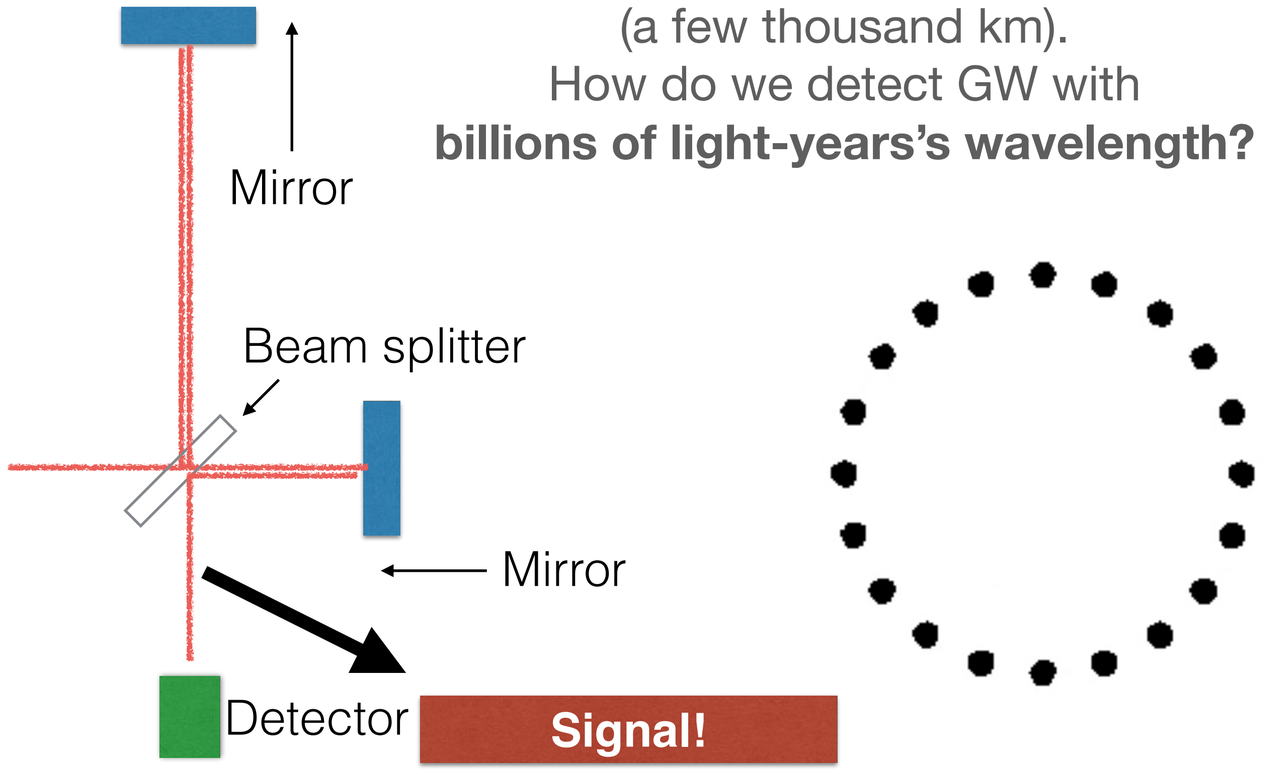


How to detect GW?

Laser interferometer technique, used by LIGO and VIRGO



The wavelength of GW detectable by this method is the size of Earth (a few thousand km).
How do we detect GW with **billions of light-years's wavelength?**

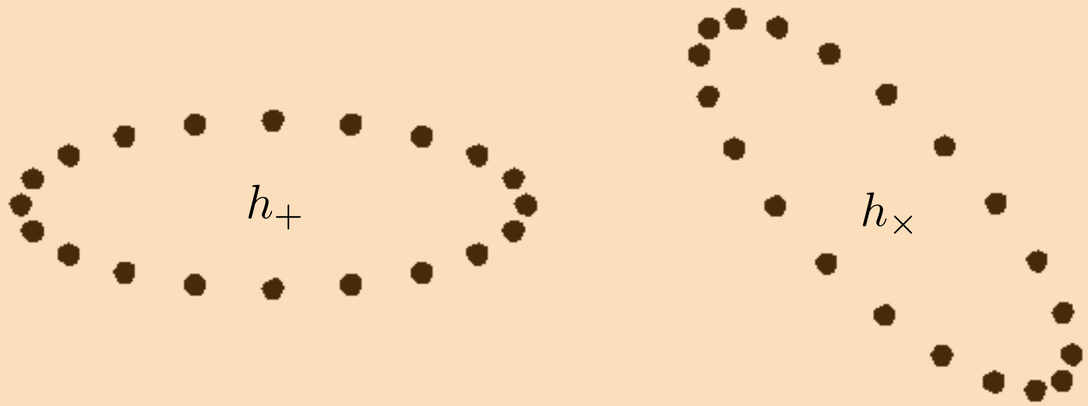


Sachs & Wolfe (1967)

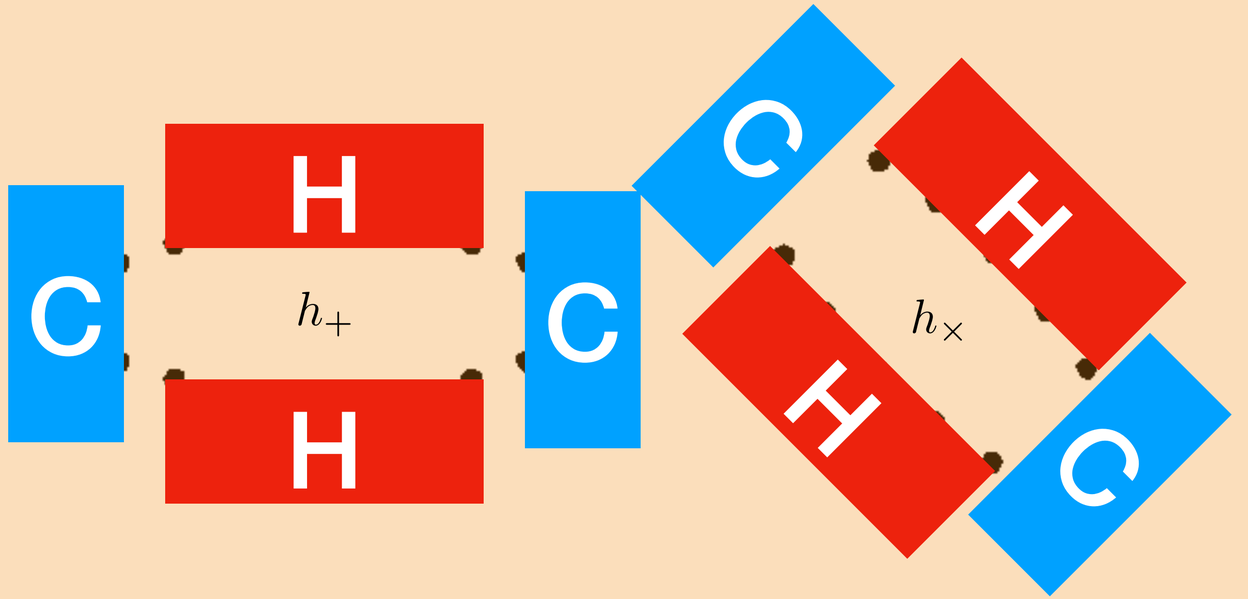
Detecting GW by CMB

Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

Isotropic radiation field (CMB)



Isotropic radiation field (CMB)

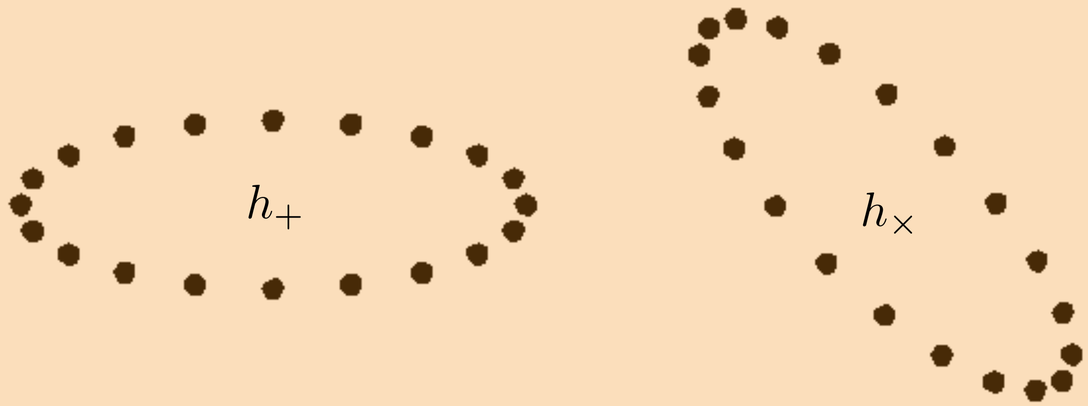


Sachs & Wolfe (1967)

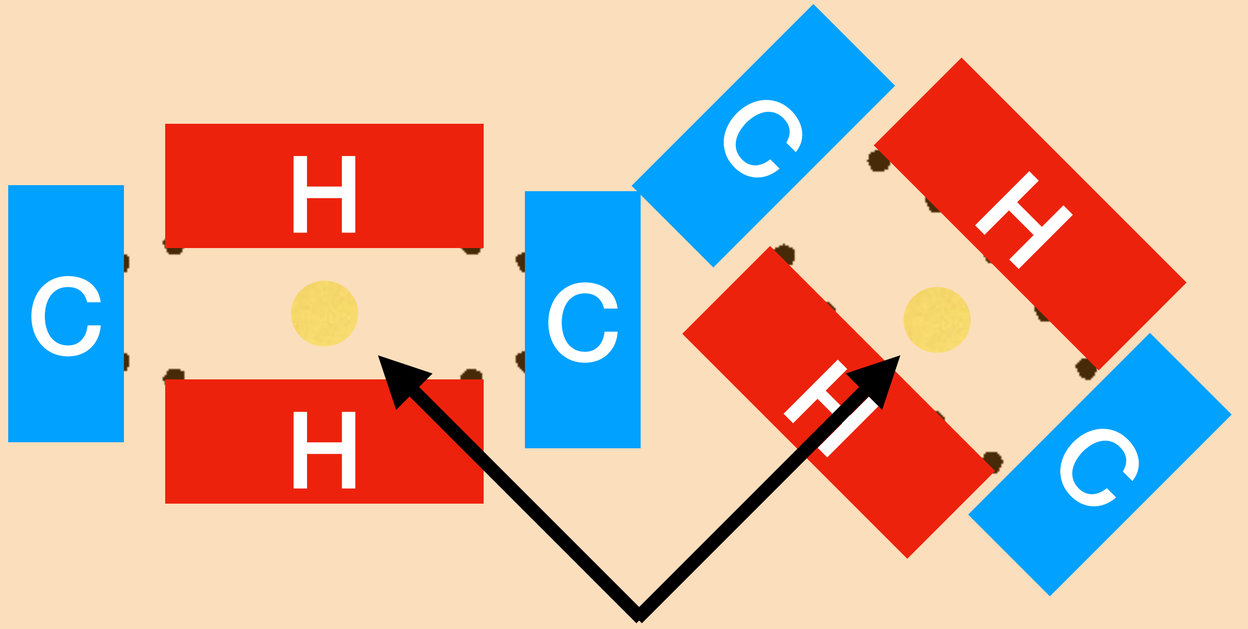
Detecting GW by CMB

Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

Isotropic radiation field (CMB)



Isotropic radiation field (CMB)



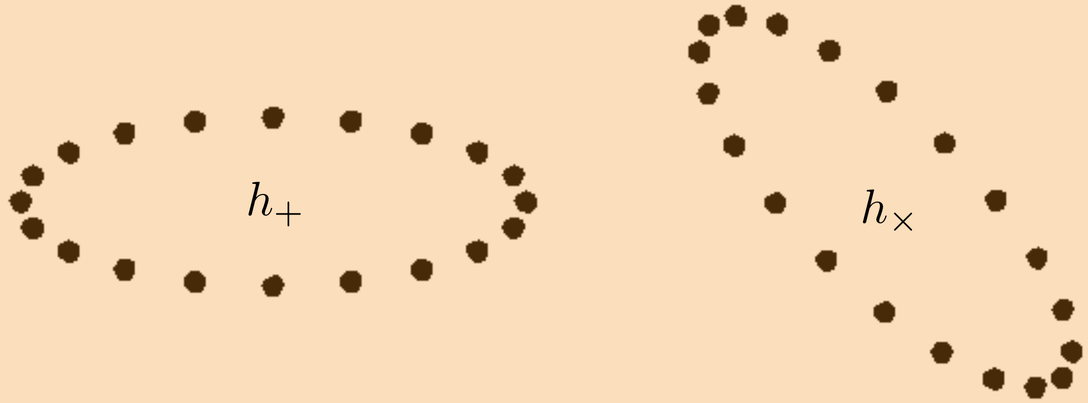
Electron

Polnarev (1985)

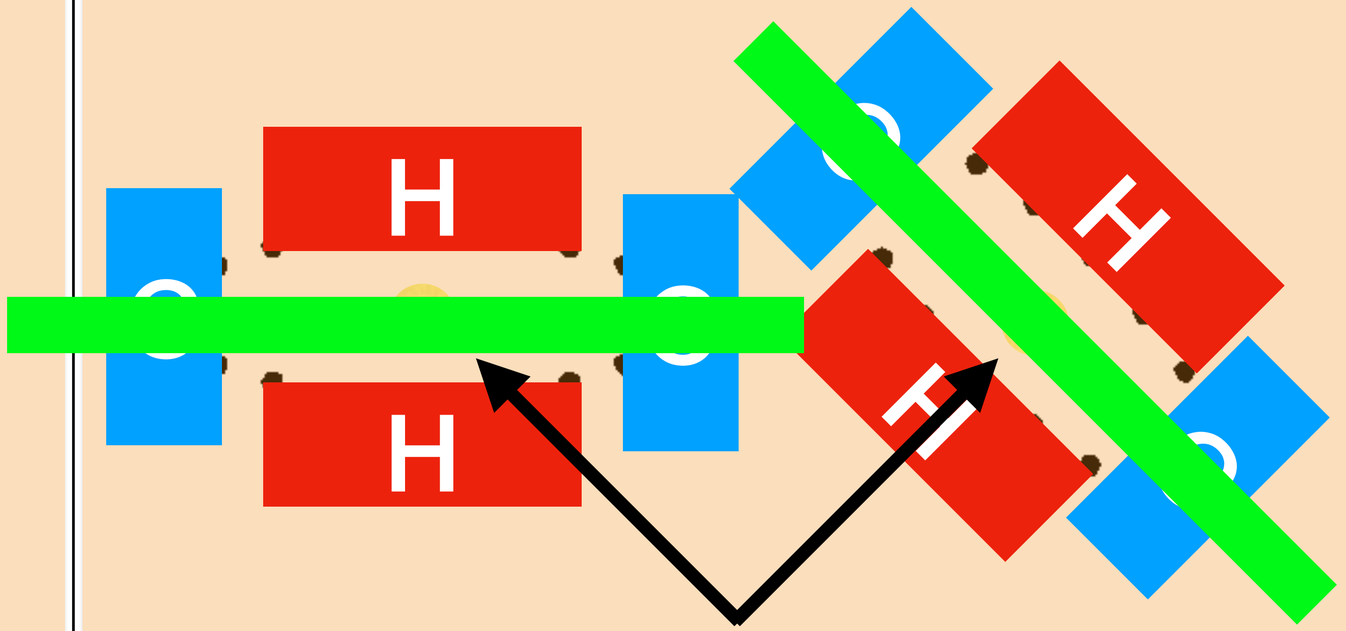
Detecting GW by CMB *Polarisation*

Quadrupole temperature anisotropy scattered by an electron

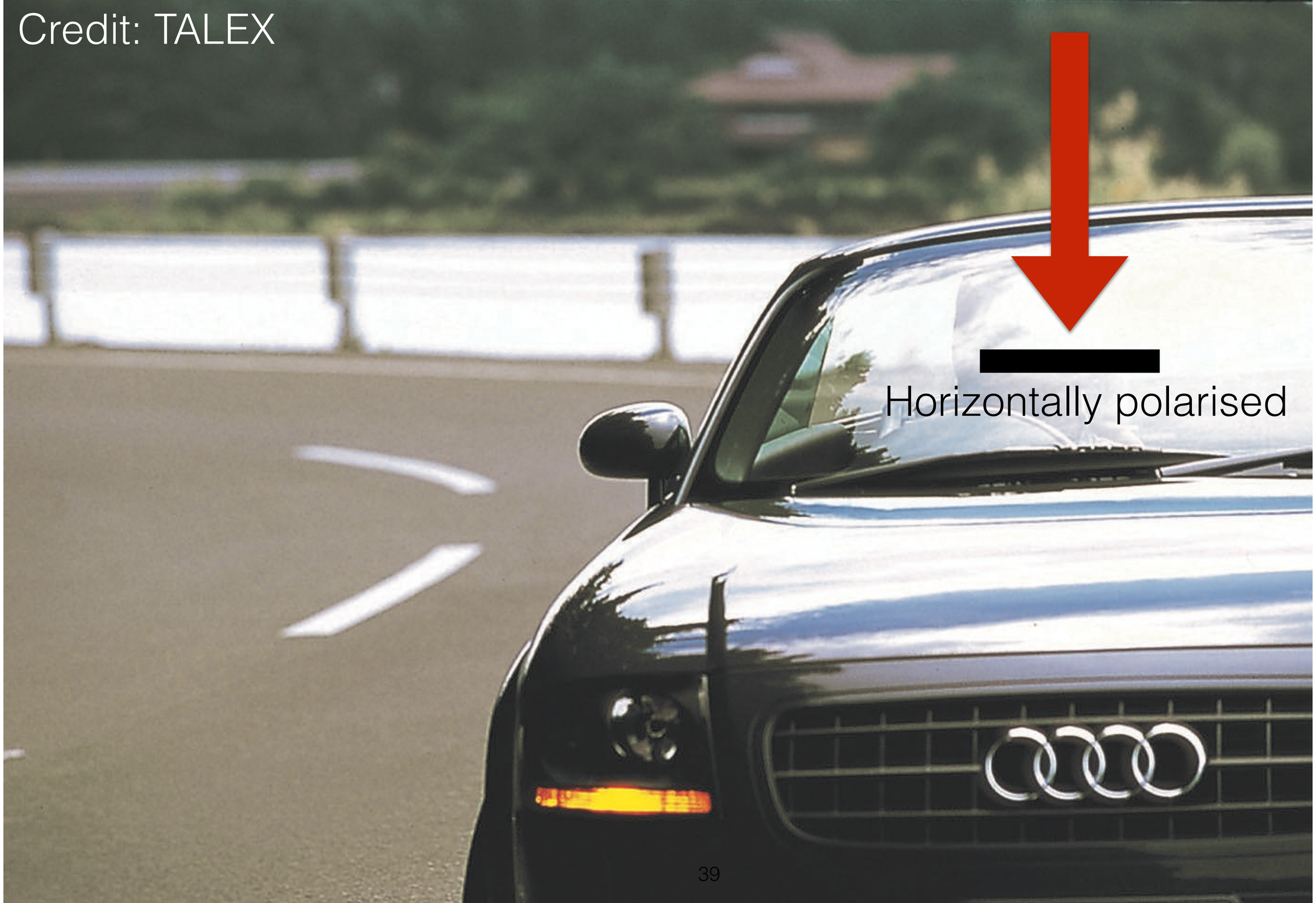
Isotropic radiation field (CMB)



Isotropic radiation field (CMB)



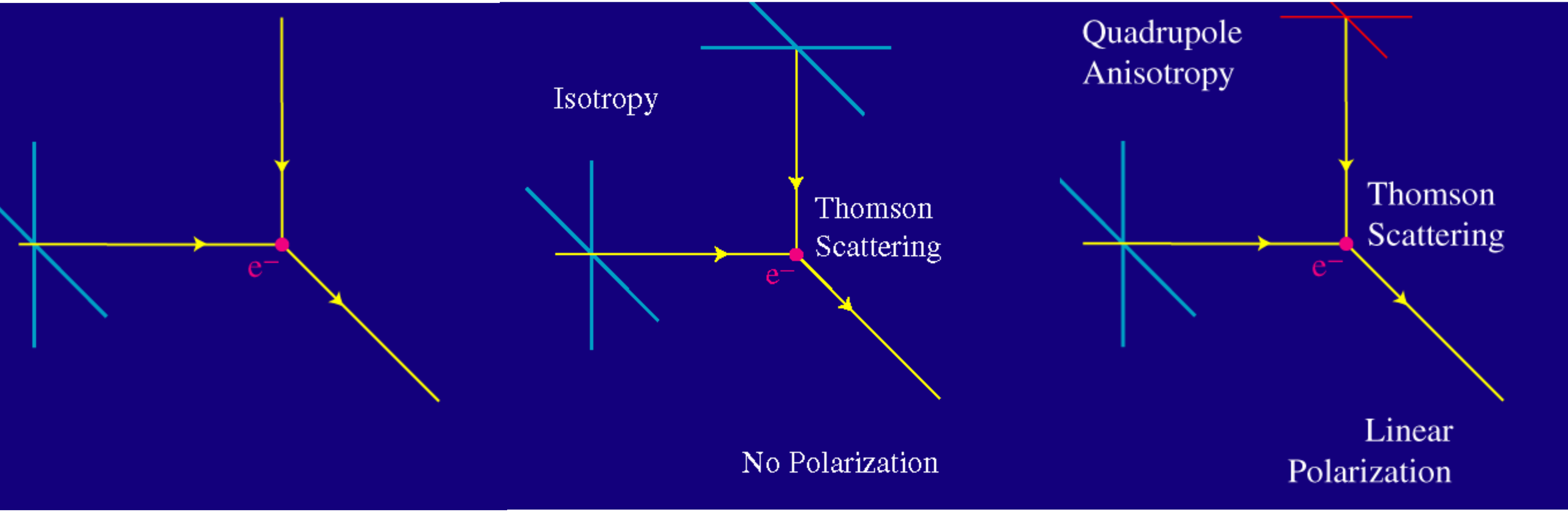
Electron


Credit: TALEX
Horizontally polarised

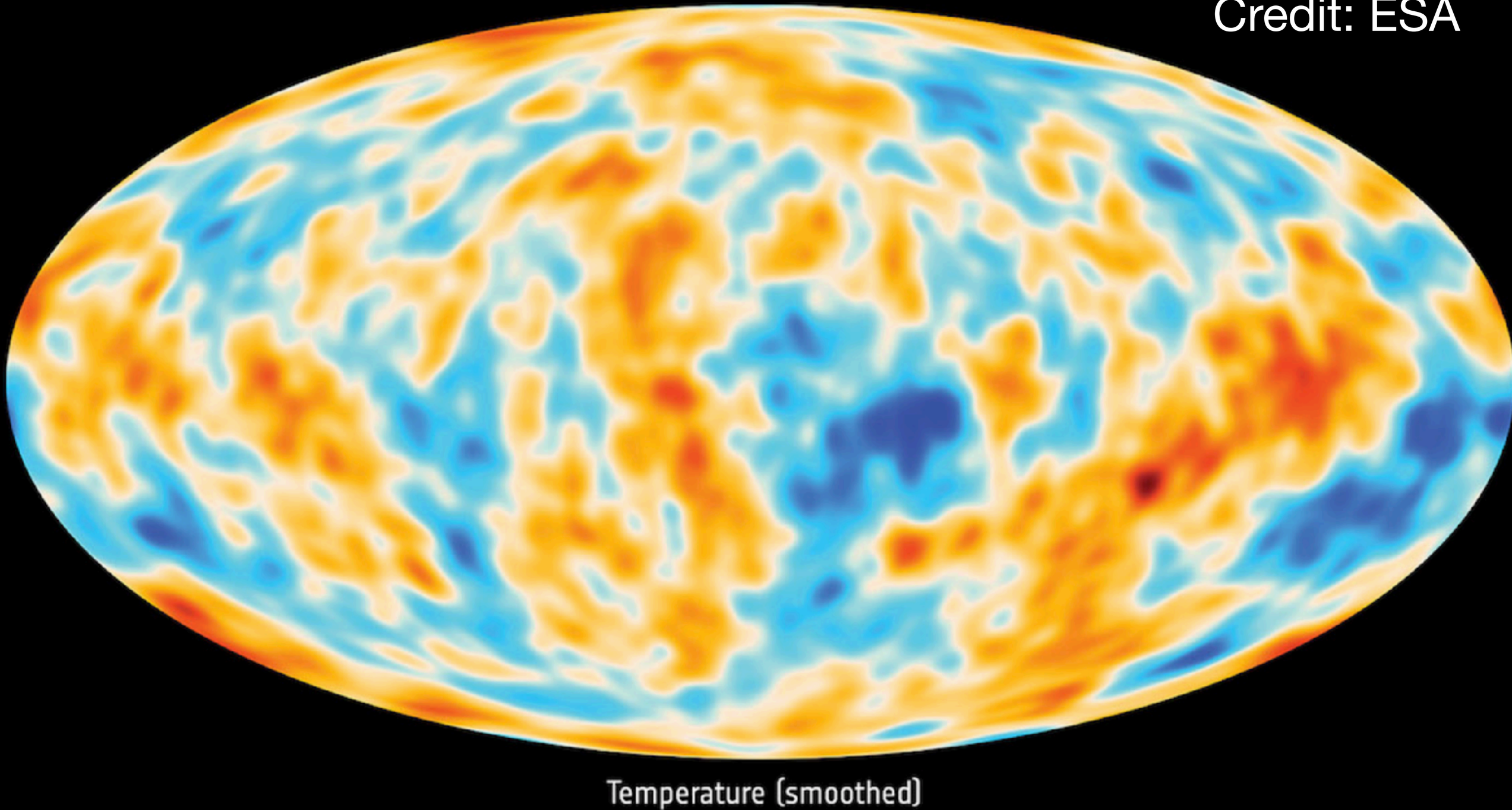

Credit: TALEX

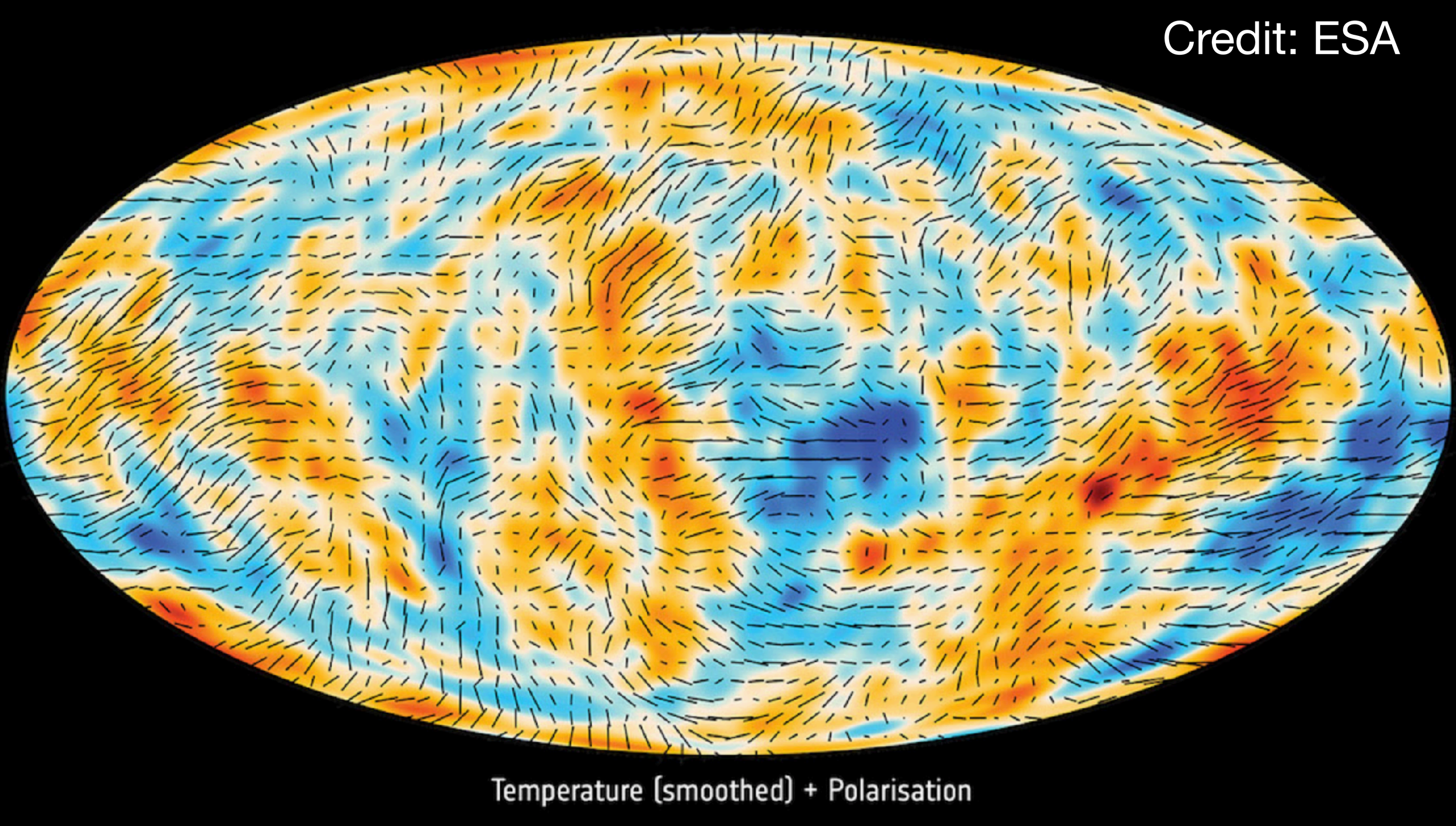
Physics of CMB Polarisation

Necessary and sufficient condition: Scattering and Quadrupole Anisotropy



Credit：Wayne Hu

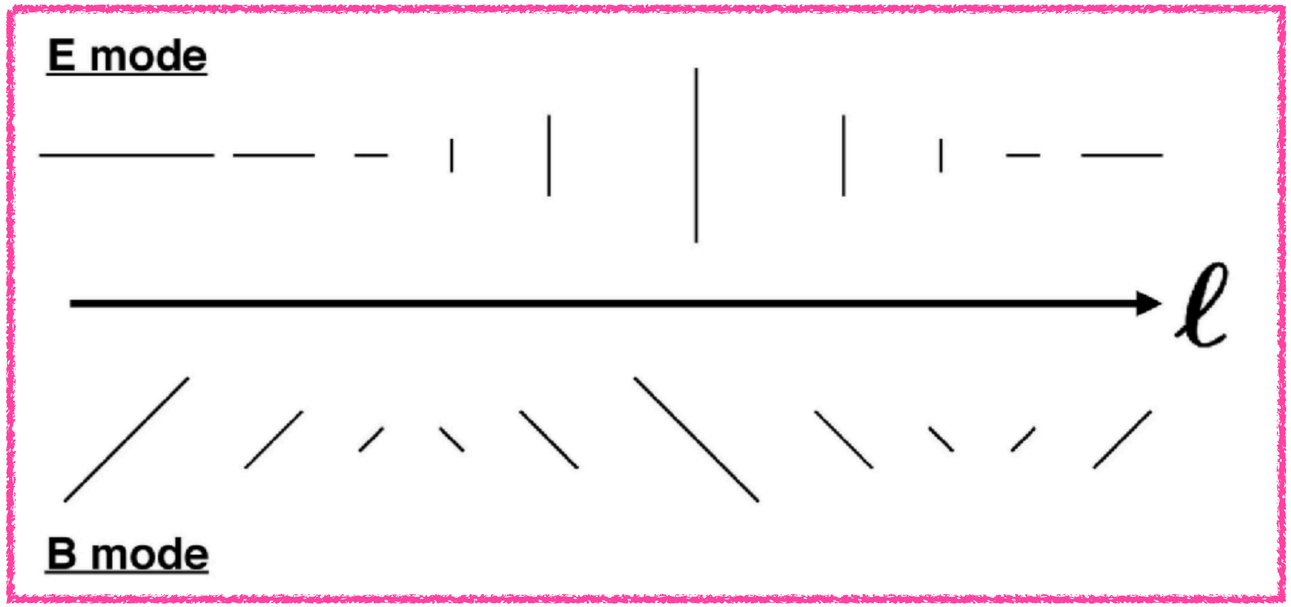

Credit: ESA
Temperature (smoothed)


Credit: ESA
Temperature (smoothed) + Polarisation

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

E- and B-mode decomposition

Concept defined in Fourier space



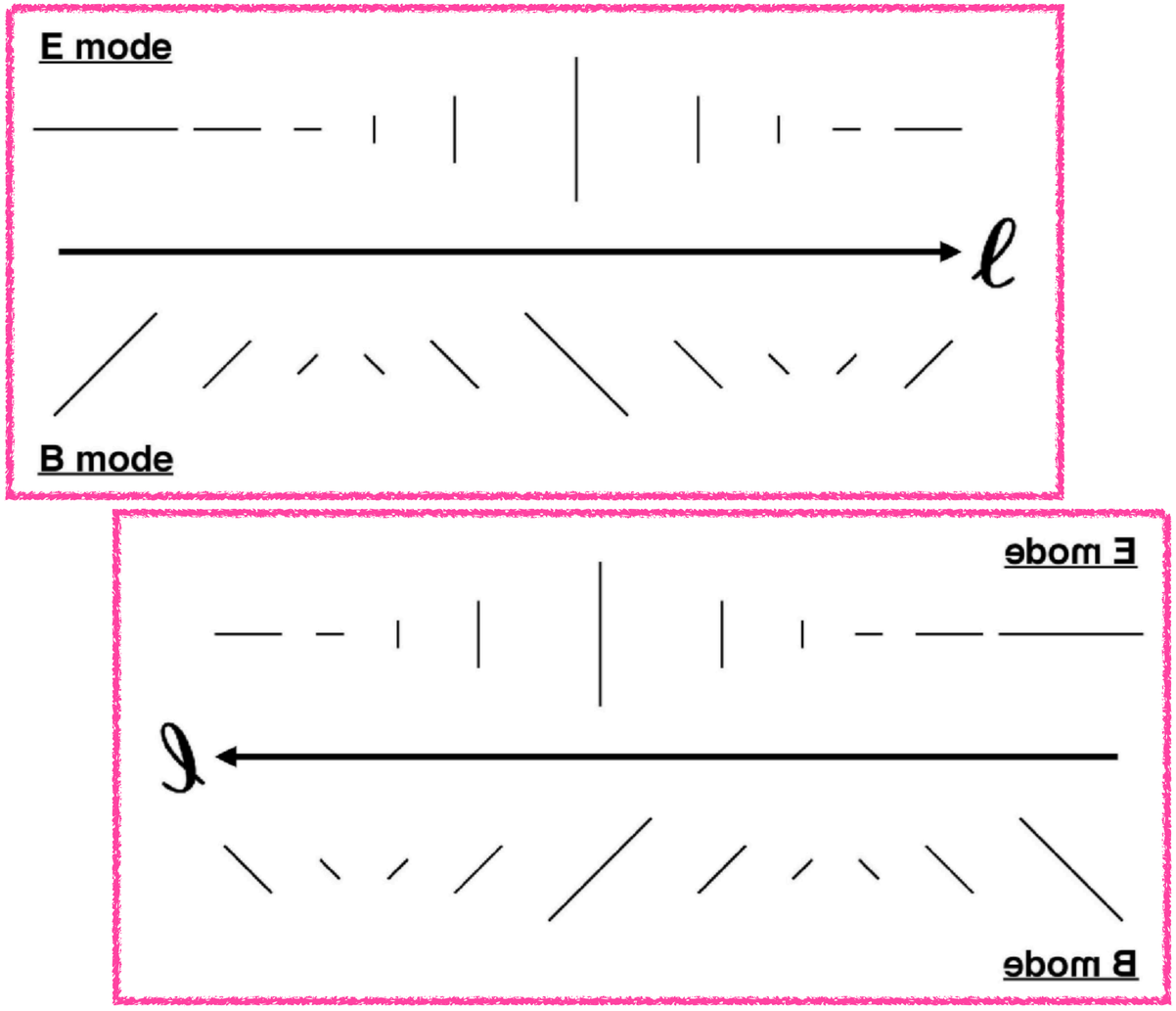
Direction of the Fourier wavenumber vector

- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity Flip

E-mode remains the same, whereas B-mode changes the sign



- Two-point correlation functions invariant under the parity flip are

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

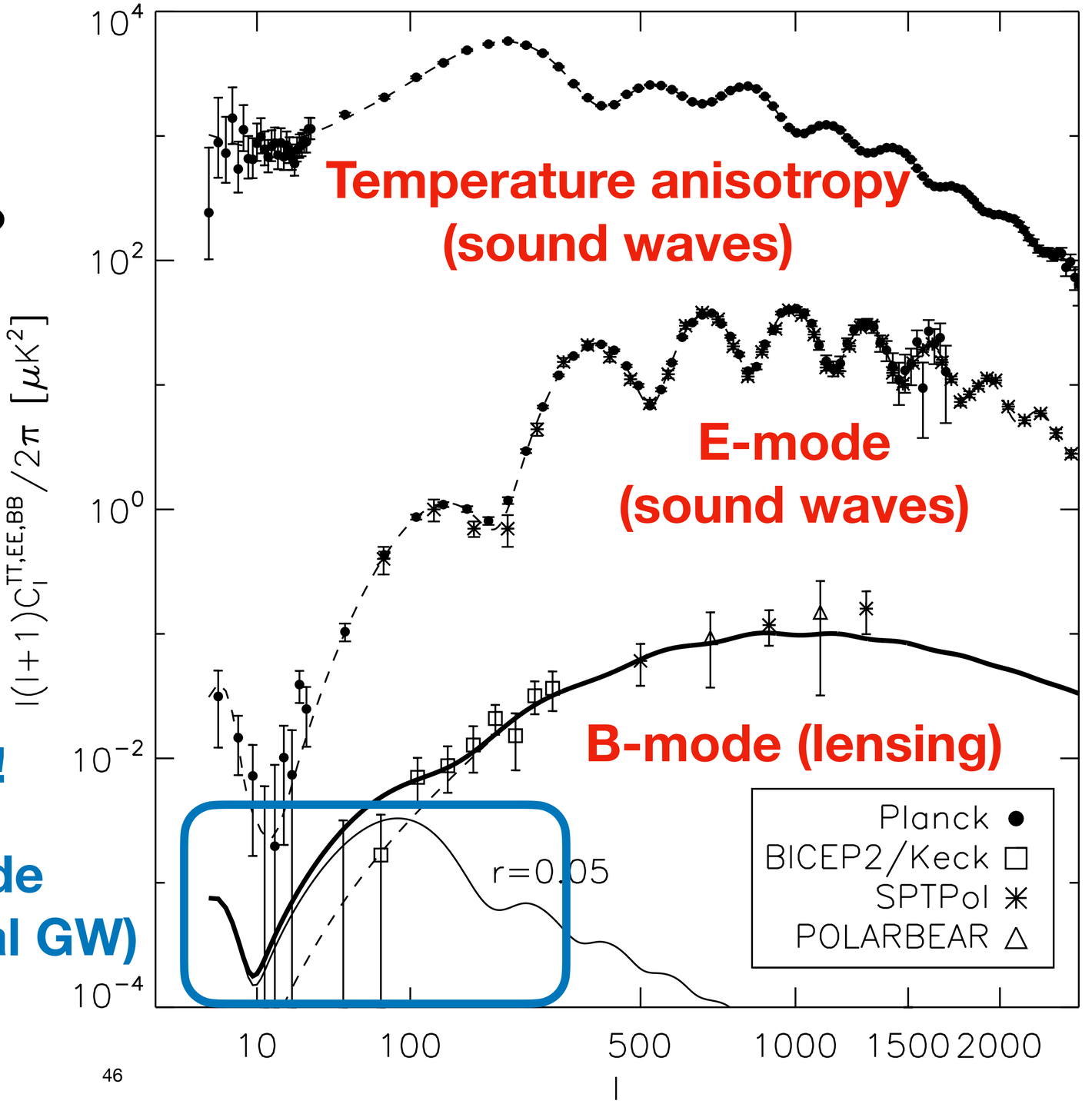
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **[Side Note] We can use these combinations to probe parity-violating physics (e.g., axions)**

Power Spectra

Where are we? What is next?

- The temperature and polarisation power spectra originating from **the scalar (density) fluctuation** have been measured.
- The next quest: **B-mode power spectrum from the primordial GW!**

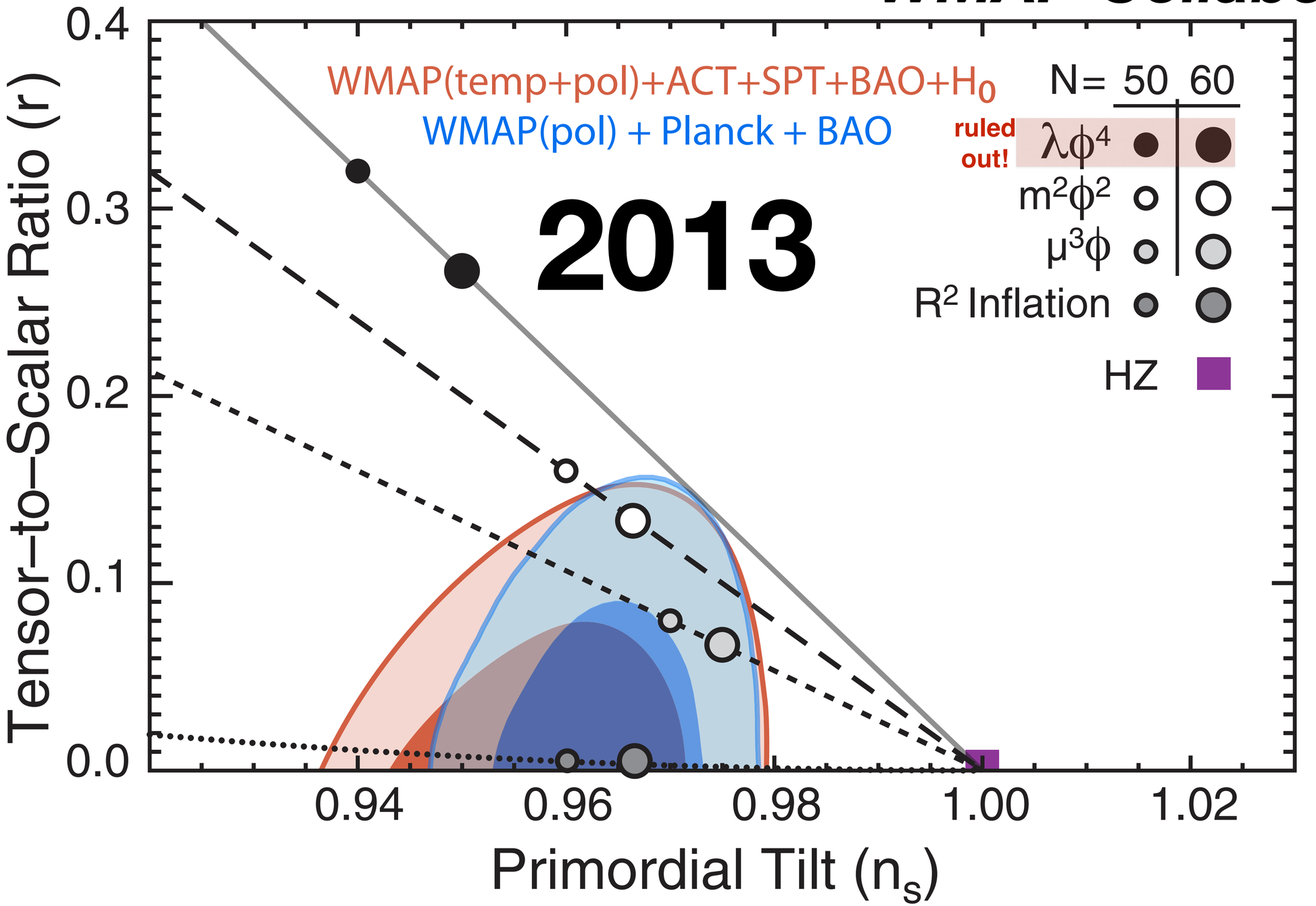


Tensor-to-scalar Ratio

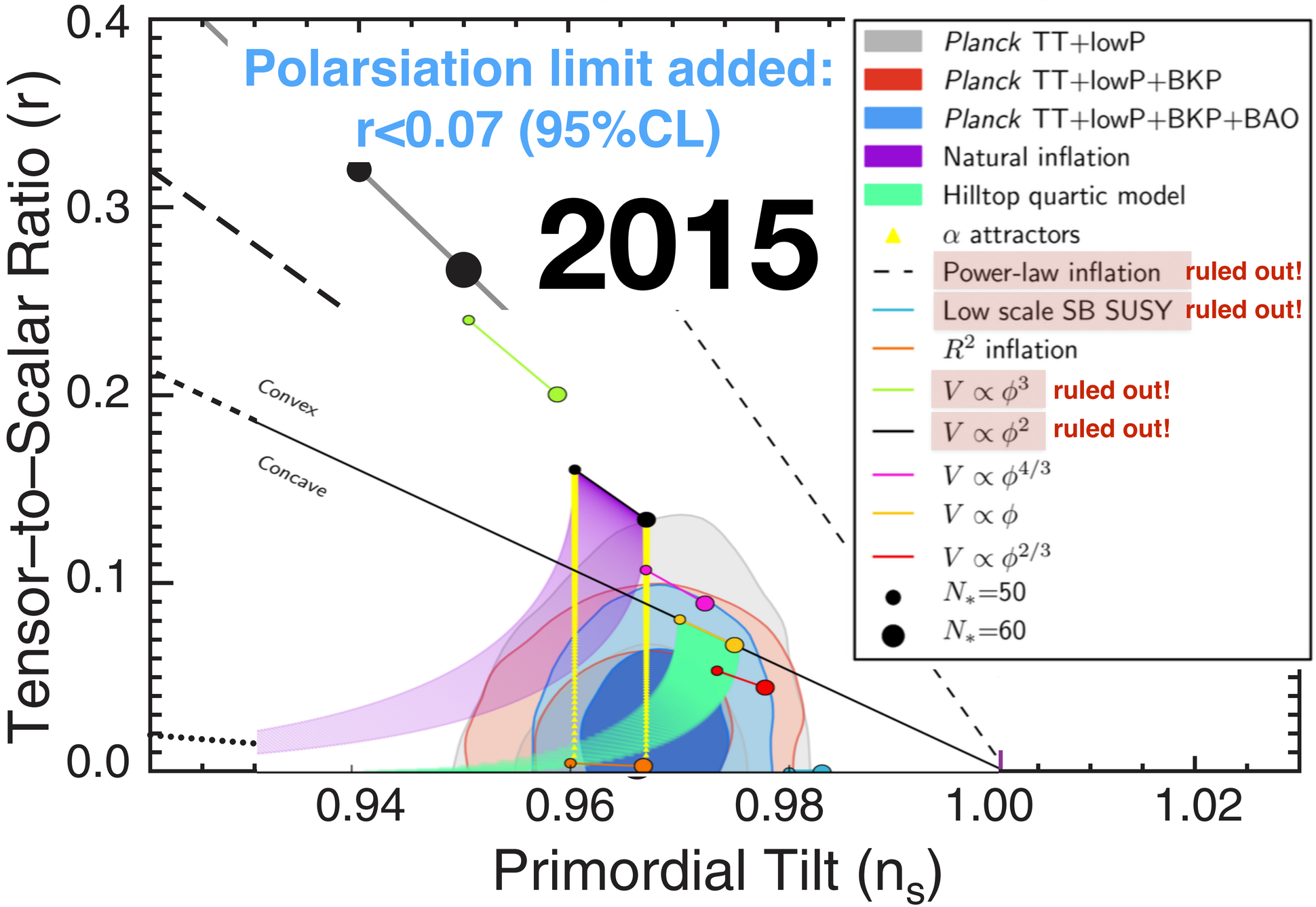
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

Scalar mode

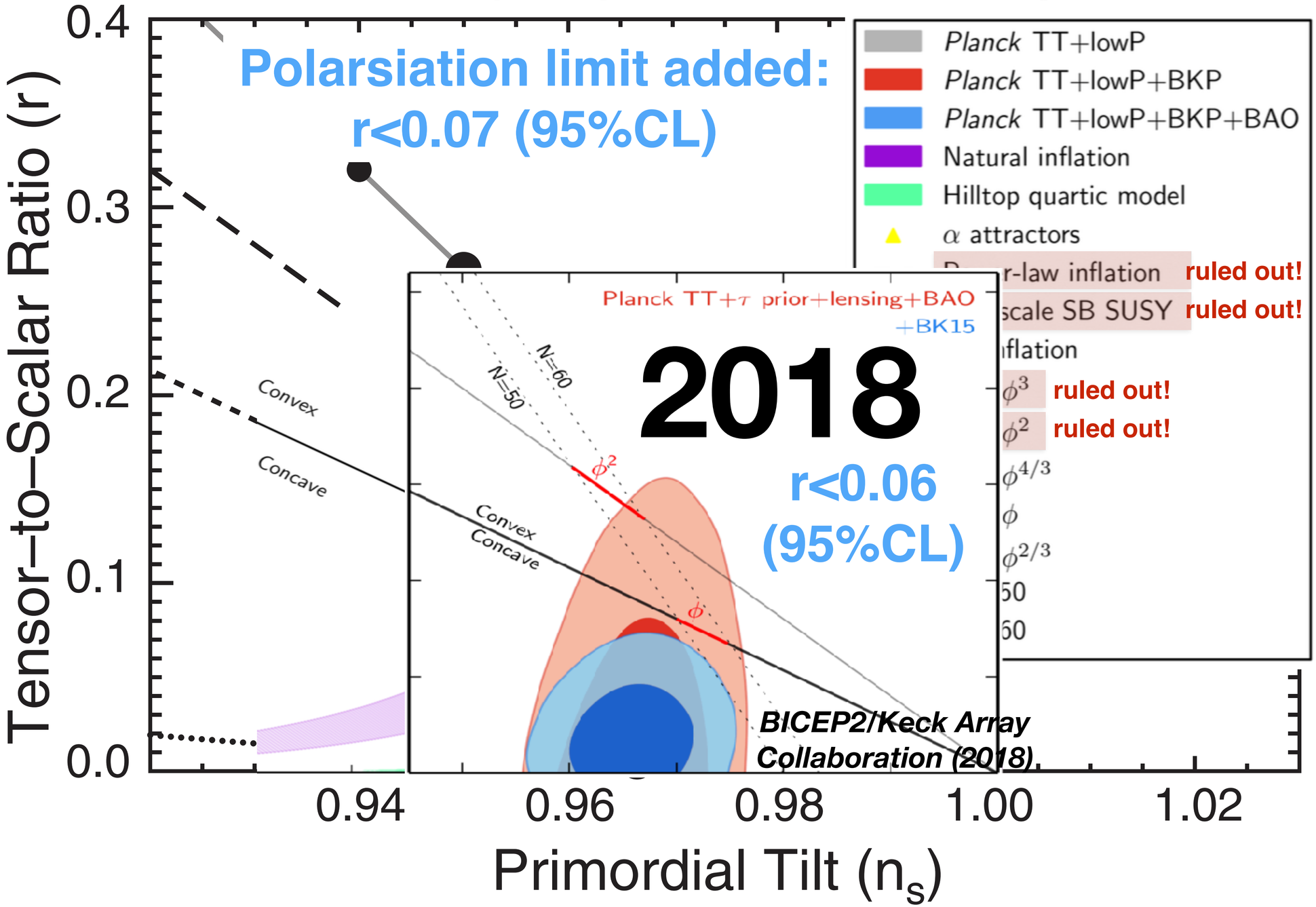
- We really want to find this! The current upper bound is **r<0.036** [95%CL; *BICEP2/Keck Array Collaboration (2021)*]


WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
2013
N= 50 60
ruled out!
λϕ4
m2ϕ2
μ3ϕ
R2 Inflation
HZ
Tensor–to–Scalar Ratio (r)
Primordial Tilt (ns)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02

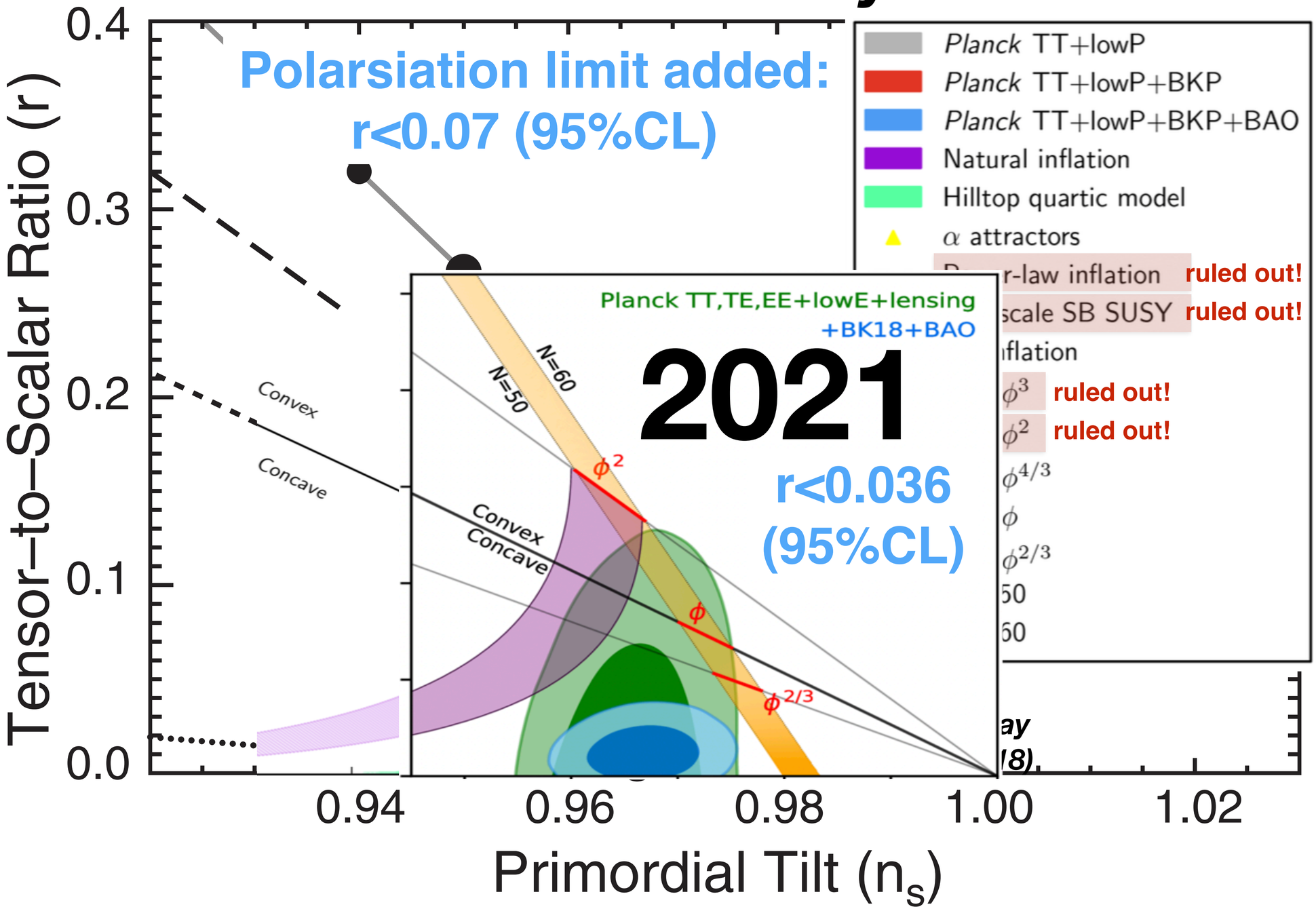
Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)



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



BICEP2/Keck Array Collaboration (2021)



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)

    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

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

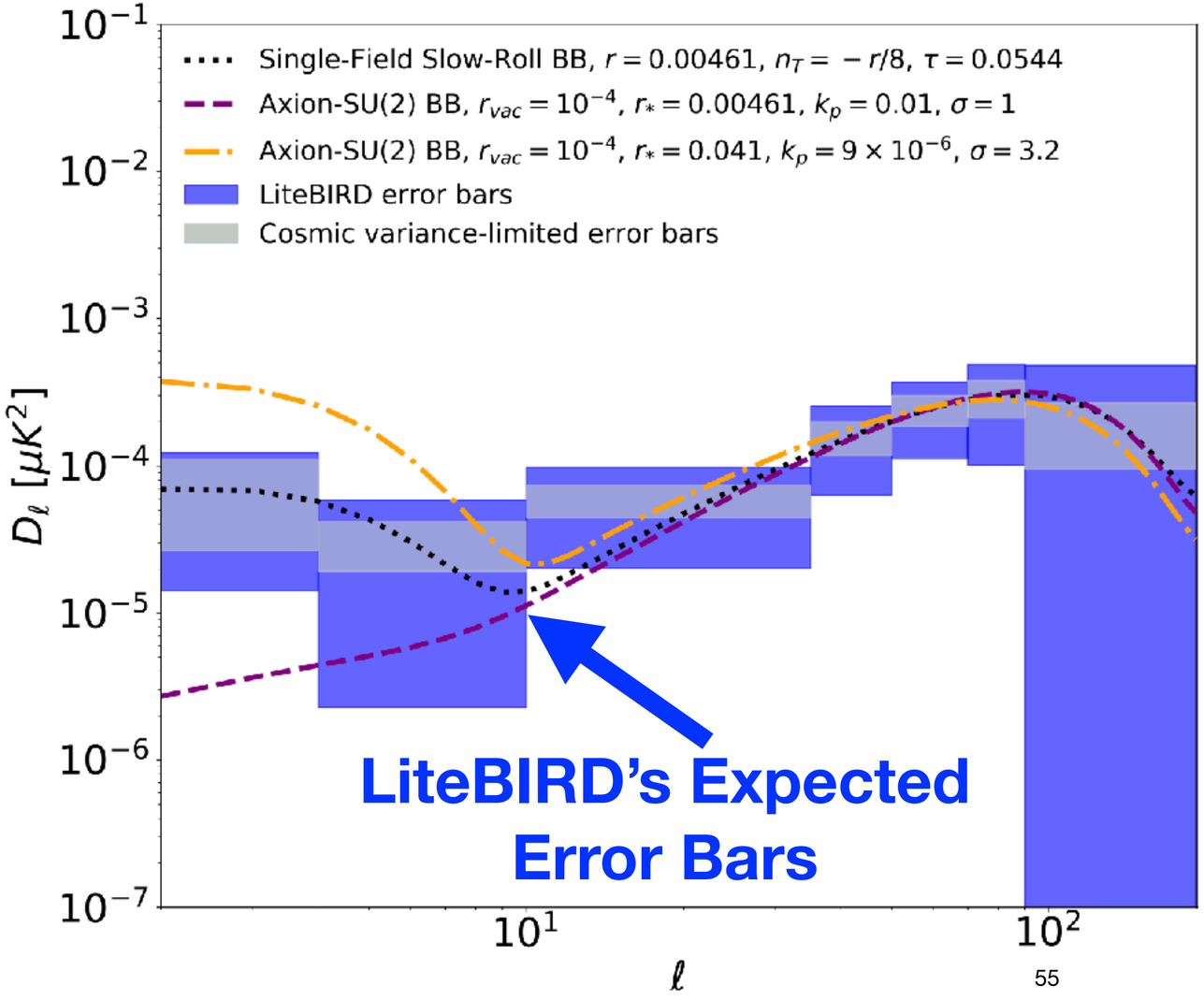
- **Do not take it for granted if someone told you that detection of the primordial gravitational waves would be a signature of “quantum gravity”!**

  - 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)]

B-mode power spectrum

Vacuum fluctuation versus the Gauge field contribution



- **Dotted**: Vacuum fluctuation in spacetime (homogeneous solution)
- **Other curves**: the Gauge field contributions (inhomogeneous solution) for two representative cases
- **Message**: we need to measure both low and high multipoles!

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. Check for scale invariance: Consistent with a scale invariant spectrum?
3. Parity violating correlations consistent with zero?
4. Consistent with Gaussianity?

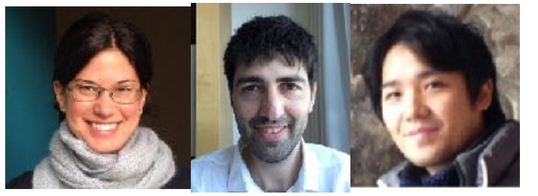
- If, and **ONLY IF** Yes to **all** => Announce discovery of the vacuum fluctuation in spacetime

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

1. De
   ma rum)
2. Check for scale invariance: 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

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

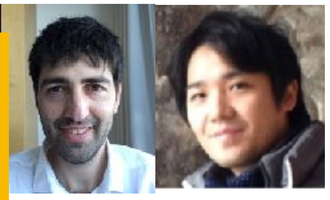
- ϕ: inflaton field => Just provides quasi-de Sitter background
  [I don't want to touch this sector because I don't understand inflaton]
- χ: pseudo-scalar "axion" field. Spectator field (i.e., negligible energy density compared to the inflaton)
- Field strength of an SU(2) field A^{a}_{ν}

$$F^{a}_{\mu\nu} \equiv \partial_{\mu} A^{a}_{\nu} - \partial_{\nu} A^{a}_{\mu} - g \epsilon^{abc} A^{b}_{\mu} A^{c}_{\nu}$$

[a=1,2,3; μ=0,1,2,3]

self-interaction term

Dimastrogiovanni, Fasielo & Fujita (2017)



GW fr

A well-defined set up:
Axion-SU(2) gauge field dynamics in a given de-Sitter background.
Everything is calculable!

$$\mathcal{L} = \mathcal{L} \qquad , \tilde{F}^{a\mu\nu}$$

$$4 \qquad\qquad 4f$$

- 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

Maleknejad & Sheikh-Jabbari (2011)

Background and Perturbation



A. Maleknejad (CERN)

- 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 ($x \equiv k/aH$)

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

spin-2 field

spin-2 field

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

Spin-2 Field from SU(2)

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

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

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

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

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

$m_Q \equiv gQ/H$ = a few

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

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

Dimastrogiovanni, Fasiello & Fujita (2017)

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

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

[Whittaker function]

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

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

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

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

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

- **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!

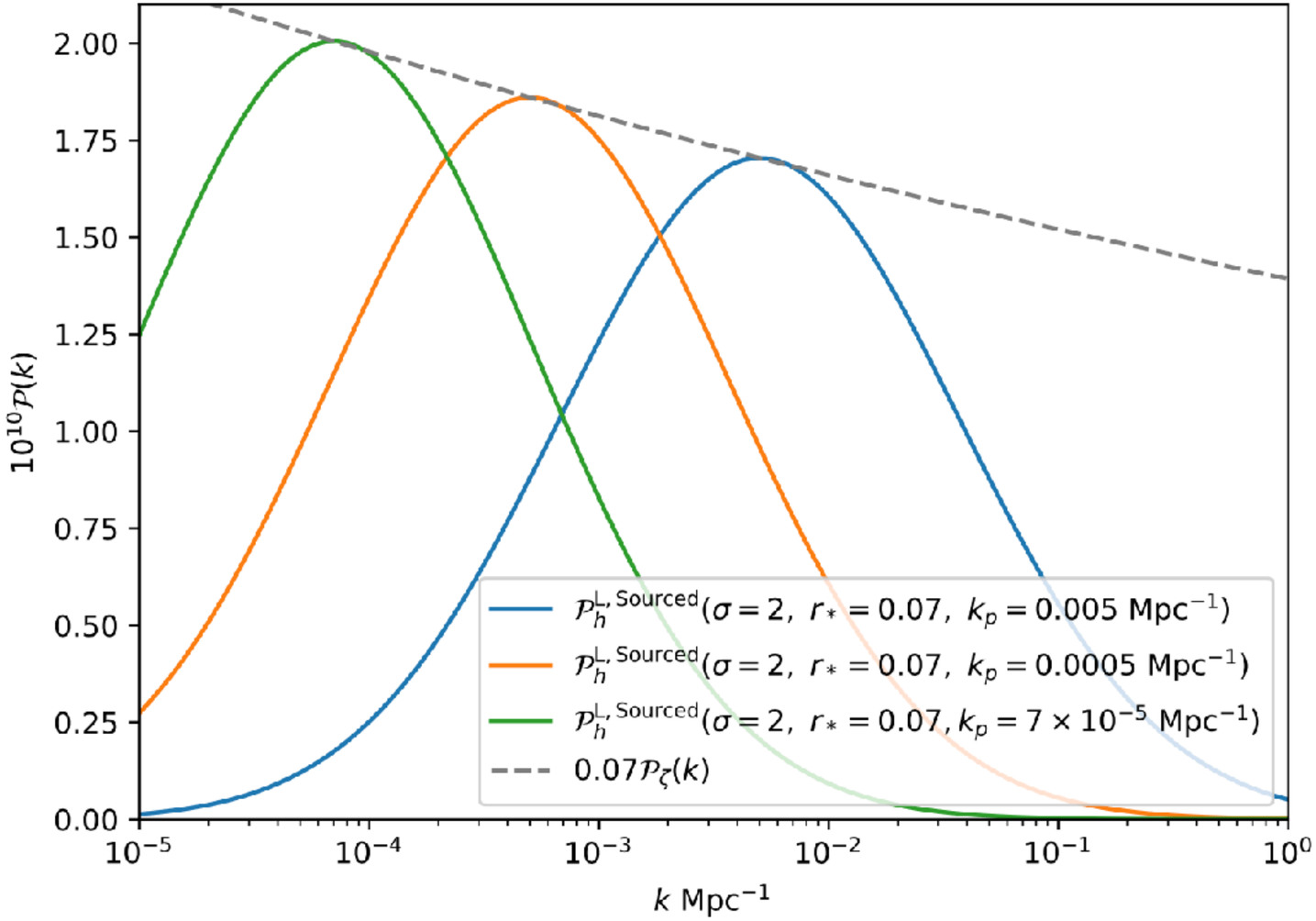
$$\begin{cases} \xi \equiv \dfrac{\lambda}{2fH}\dot{\chi} \simeq m_Q + \dfrac{1}{m_Q} \\ m_Q \equiv gQ/H \;\; = \text{a few} \end{cases}$$

- 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!

Dimastrogiovanni, Fasiello & Fujita (2017)

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

Example Tensor Spectra



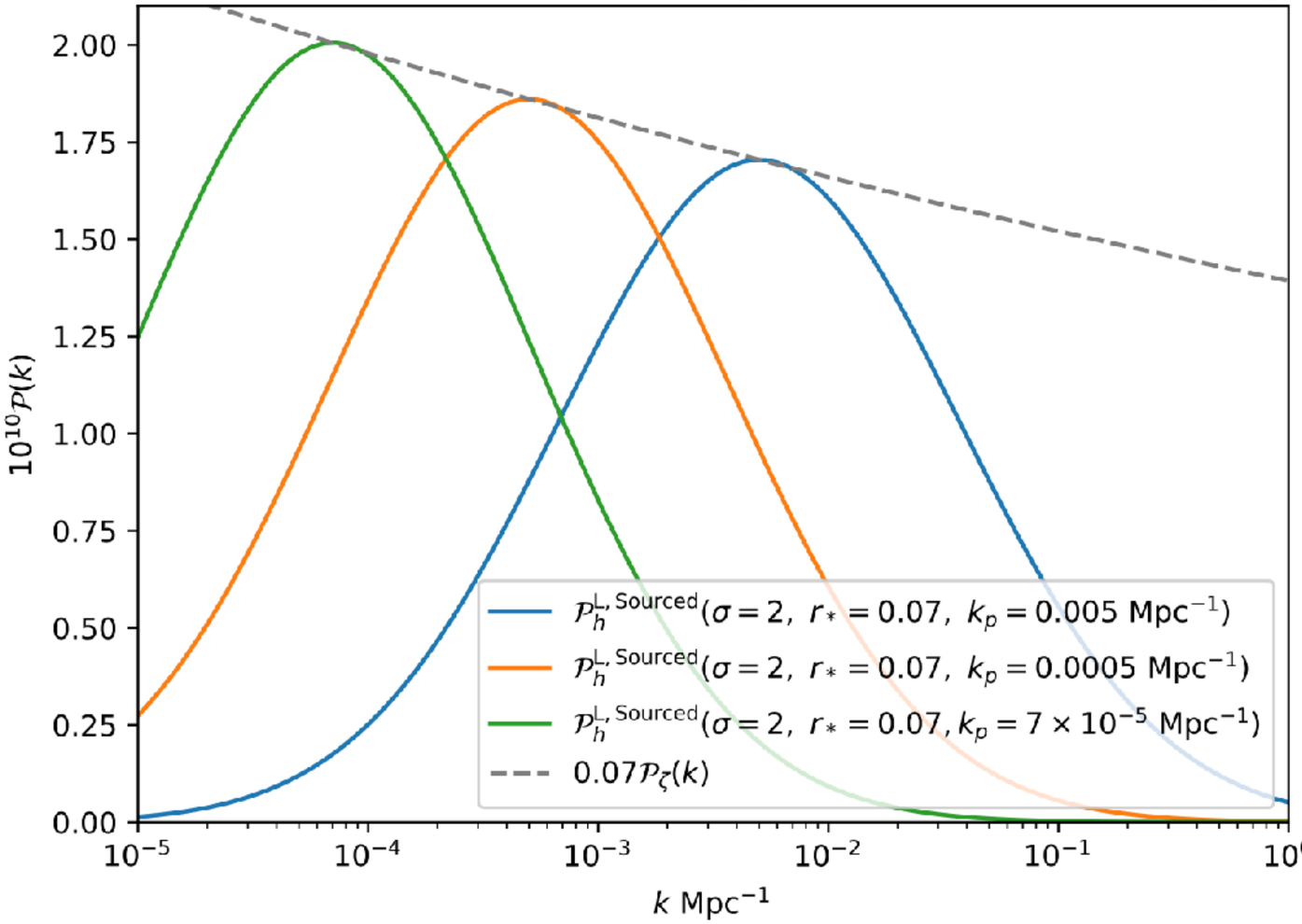
- Sourced tensor spectrum can be bumpy

Dimastrogiovanni, Fasiello & Fujita (2017)

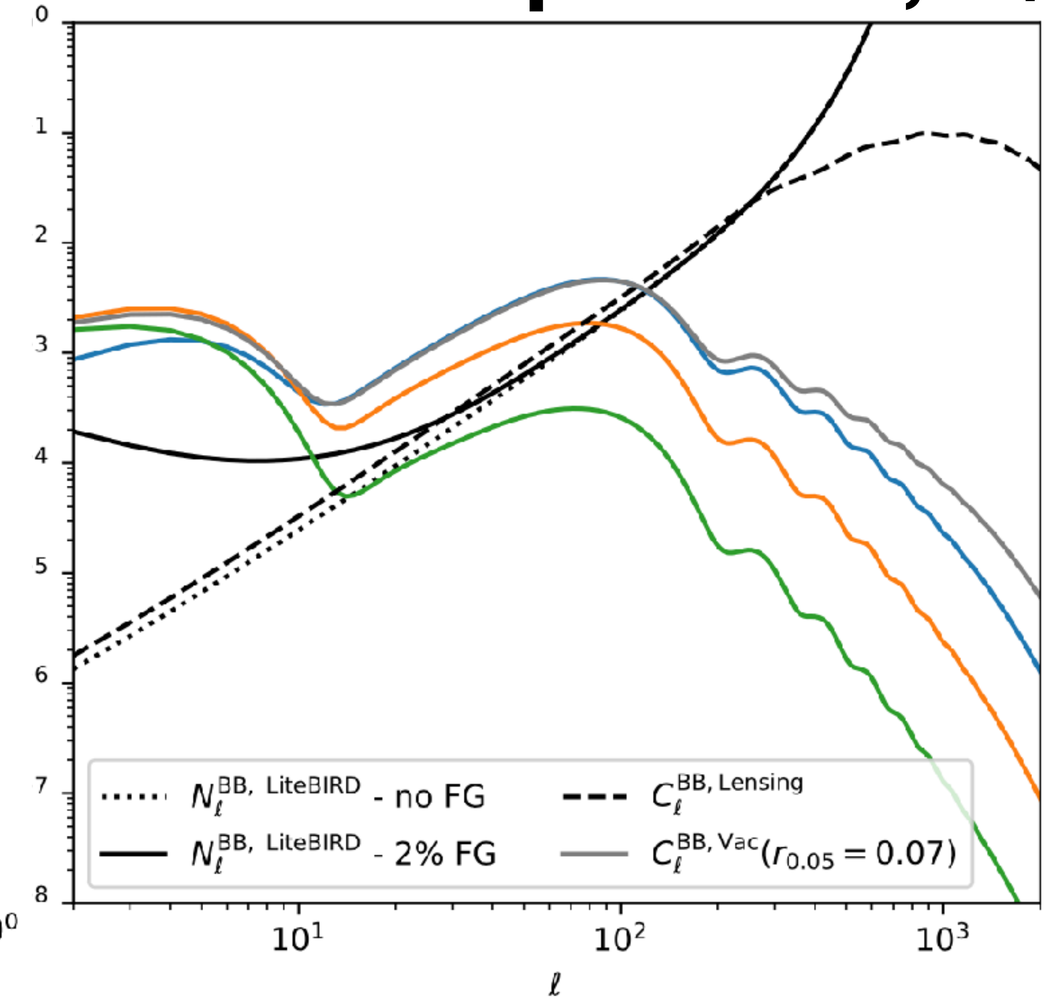
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Example Tensor Spectra

Tensor Power Spectrum, P(k)



B-mode spectrum, C_l^{BB}



Experimental Landscape

CMB-S4
Next Generation CMB Experiment

CMB Stages

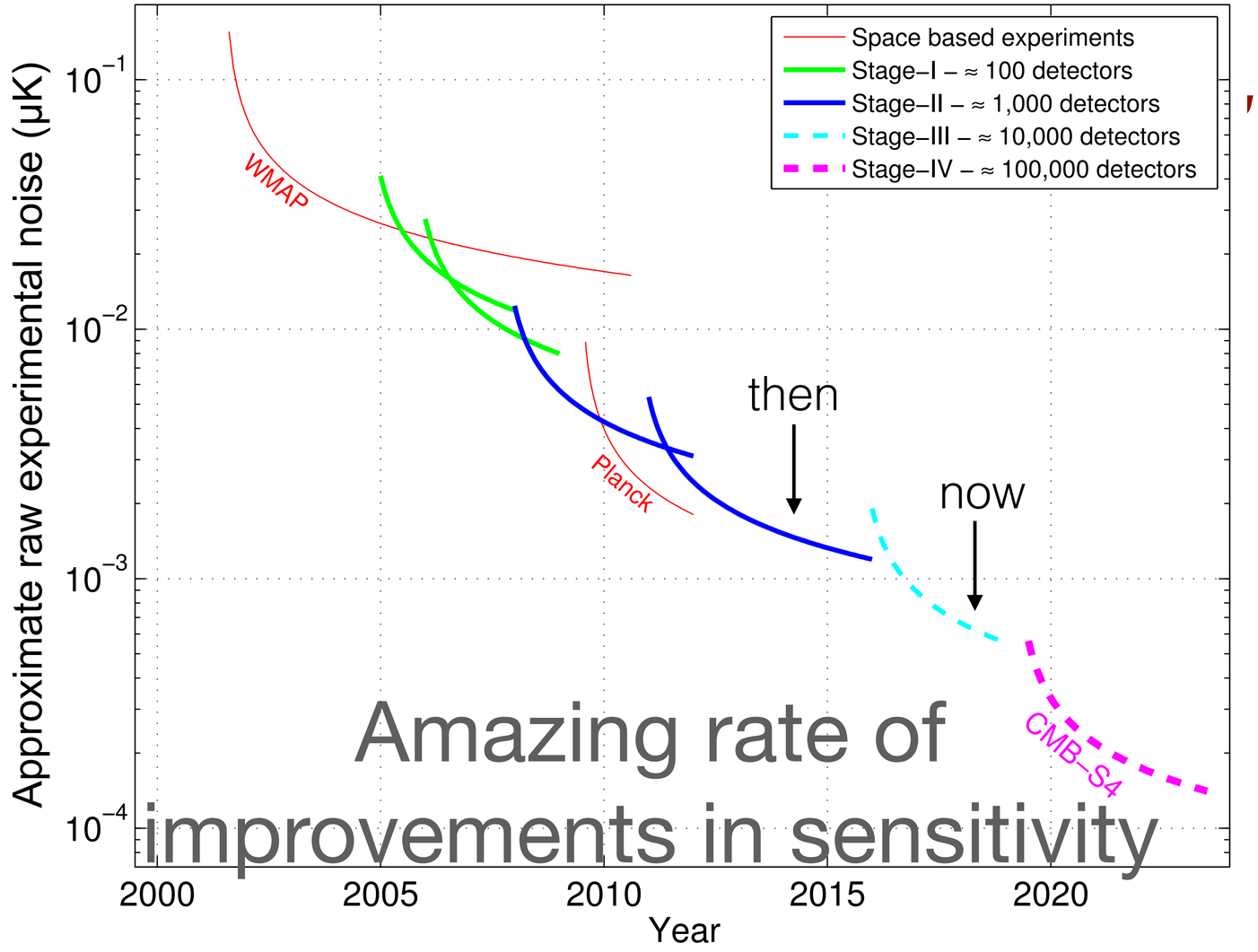
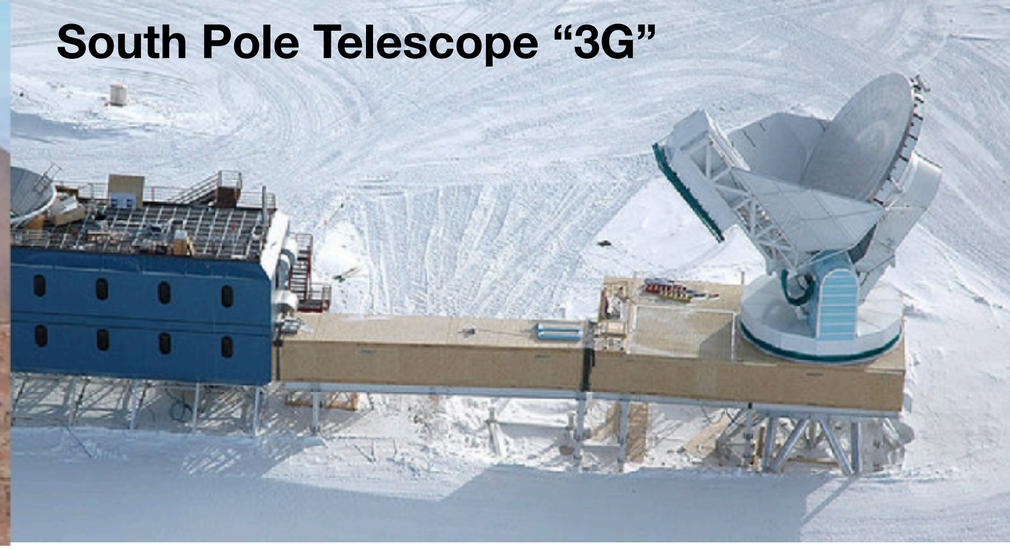


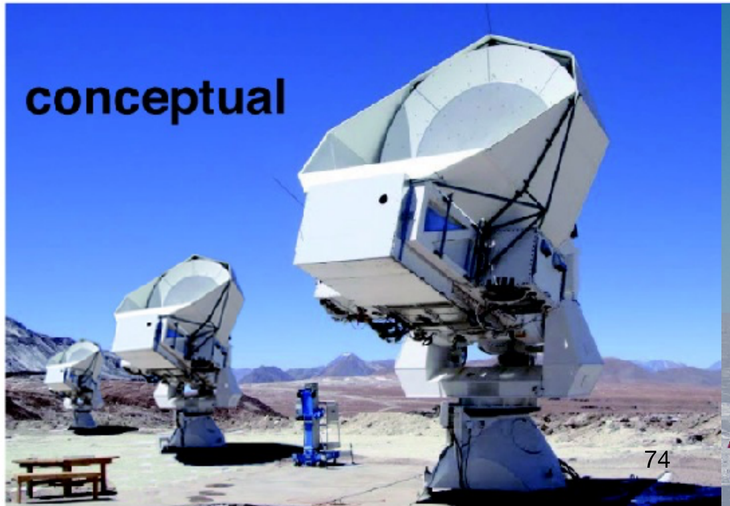
Figure by Clem Pryke for 2013 Snowmass documents



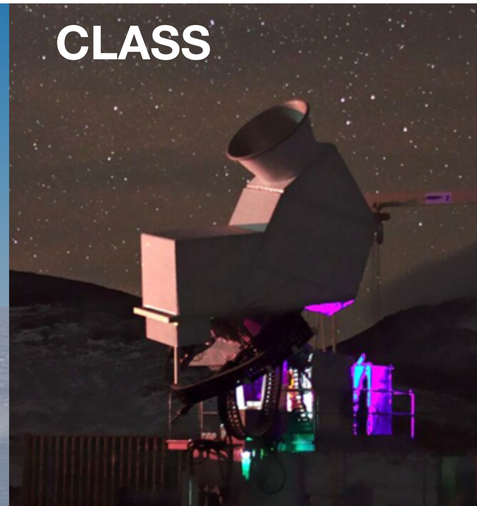


On-going Ground-based Experiments

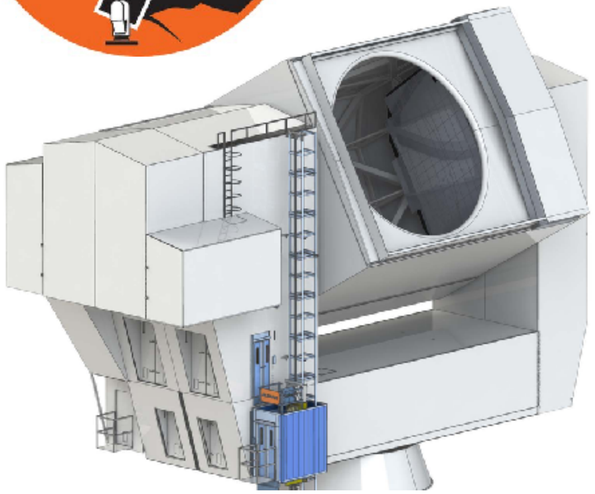
The Simons Array







SIMONS OBSERVATORY



Early 2020s

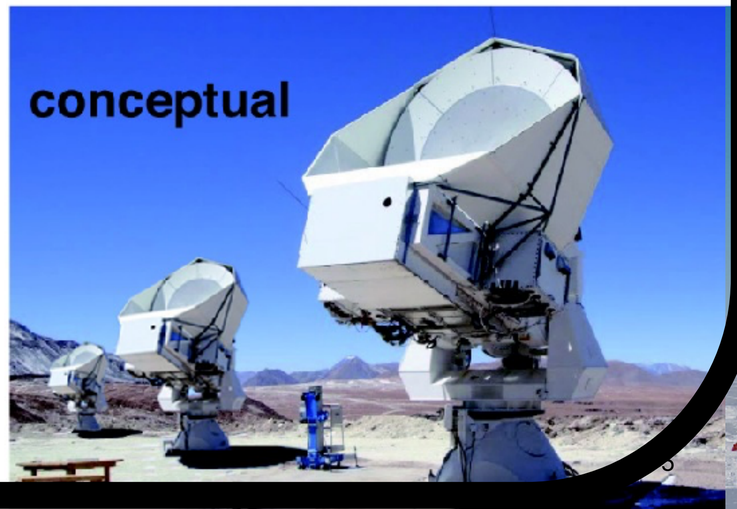
~$100M

Advanced Atacama Cosmology Telescope

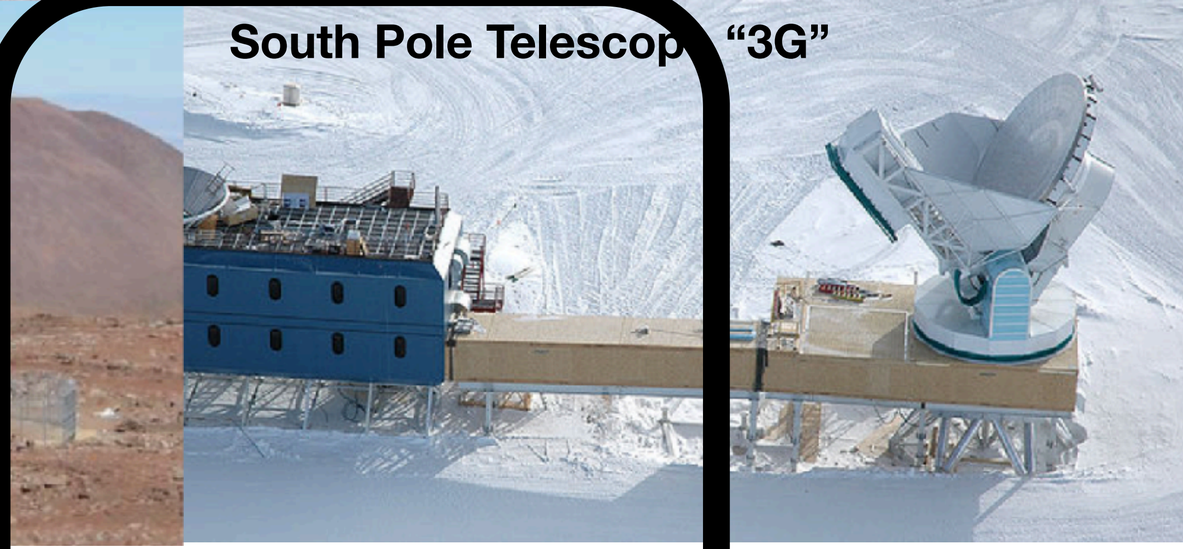


= +

The Simons Array



South Pole Telescop “3G”



+ =

The South Pole Observatory

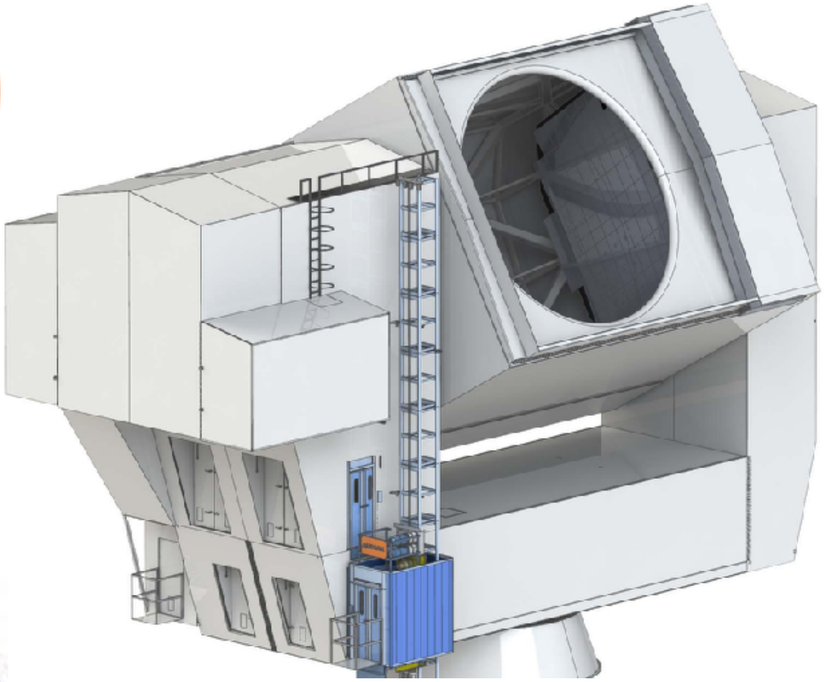
BICEP/Keck Array



CLASS



SIMONS OBSERVATORY



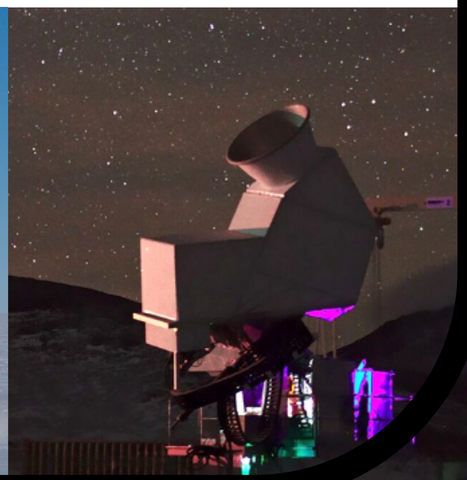


CCAT-p



Bringing all together: US-led CMB Stage IV Late 2020s (~$600M)





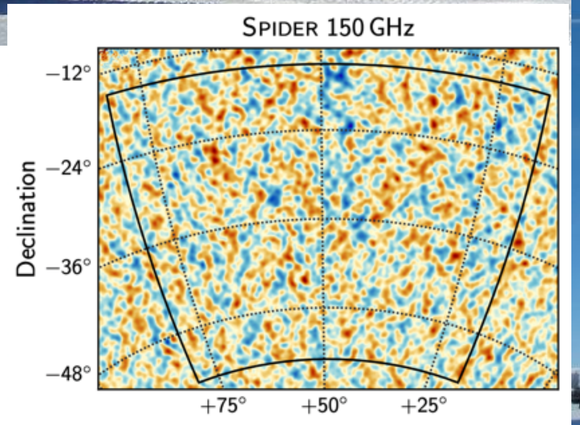
Balloons!

“Almost space”



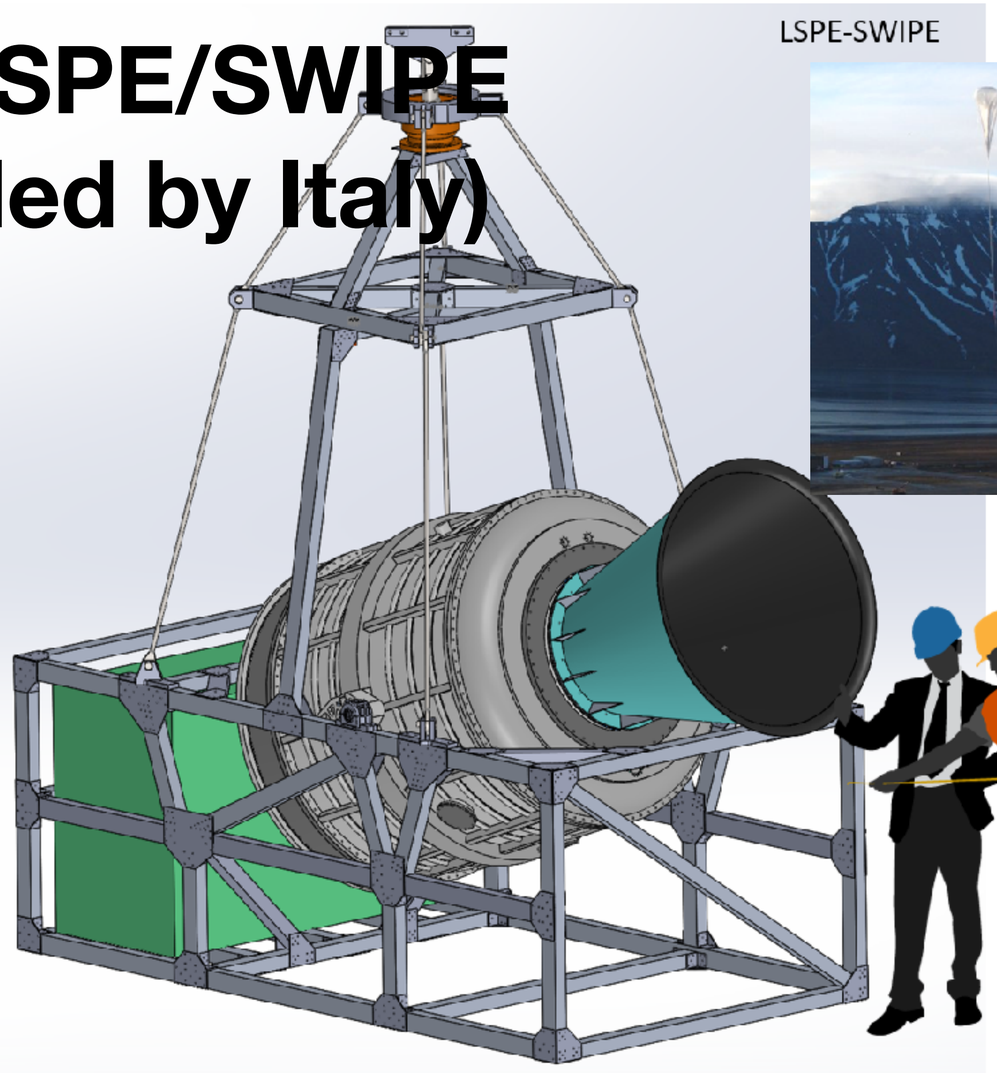
SPIDER (led by USA)

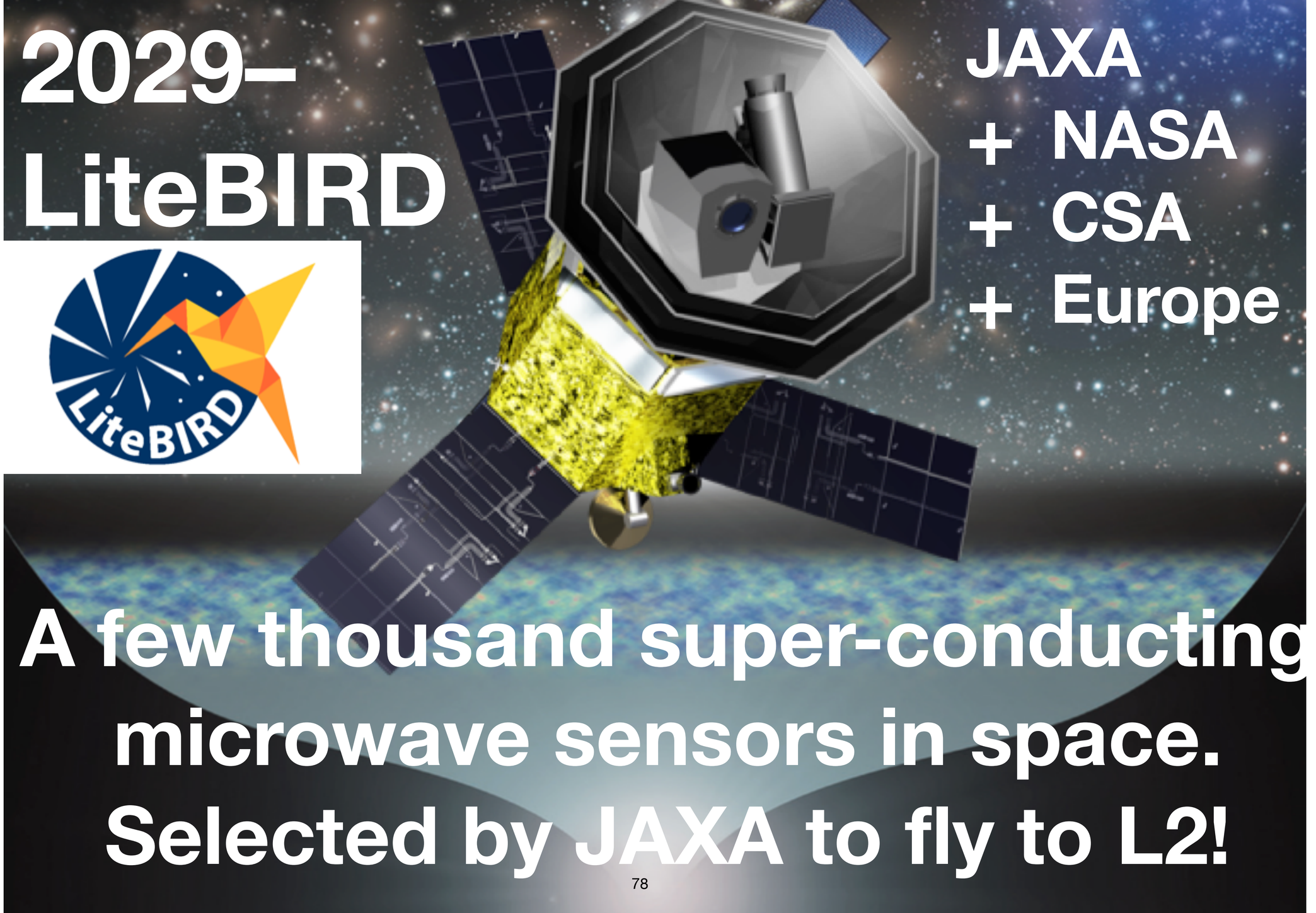
First B-mode result: arXiv:2103.13334





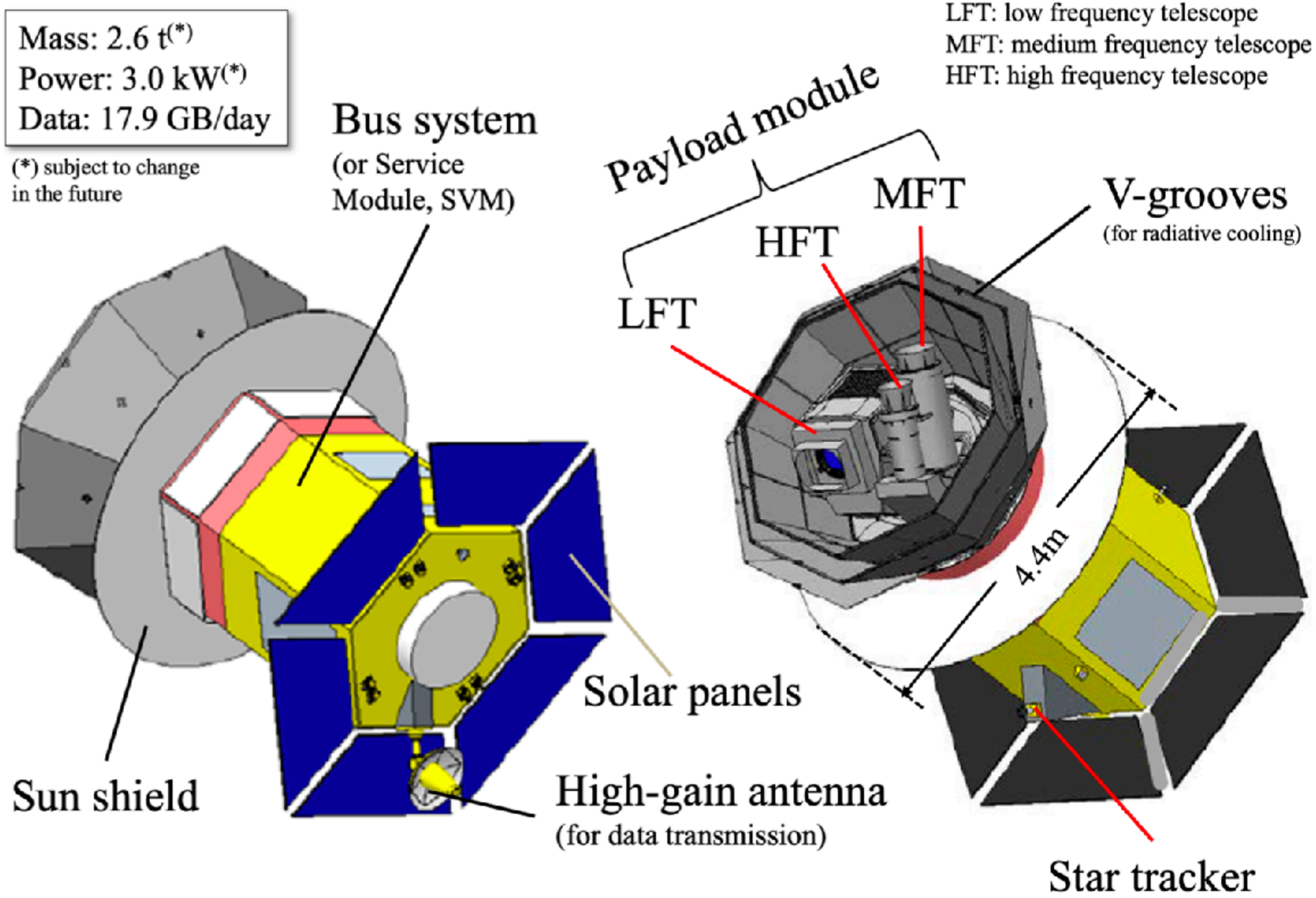
LSPE/SWIPE (led by Italy)

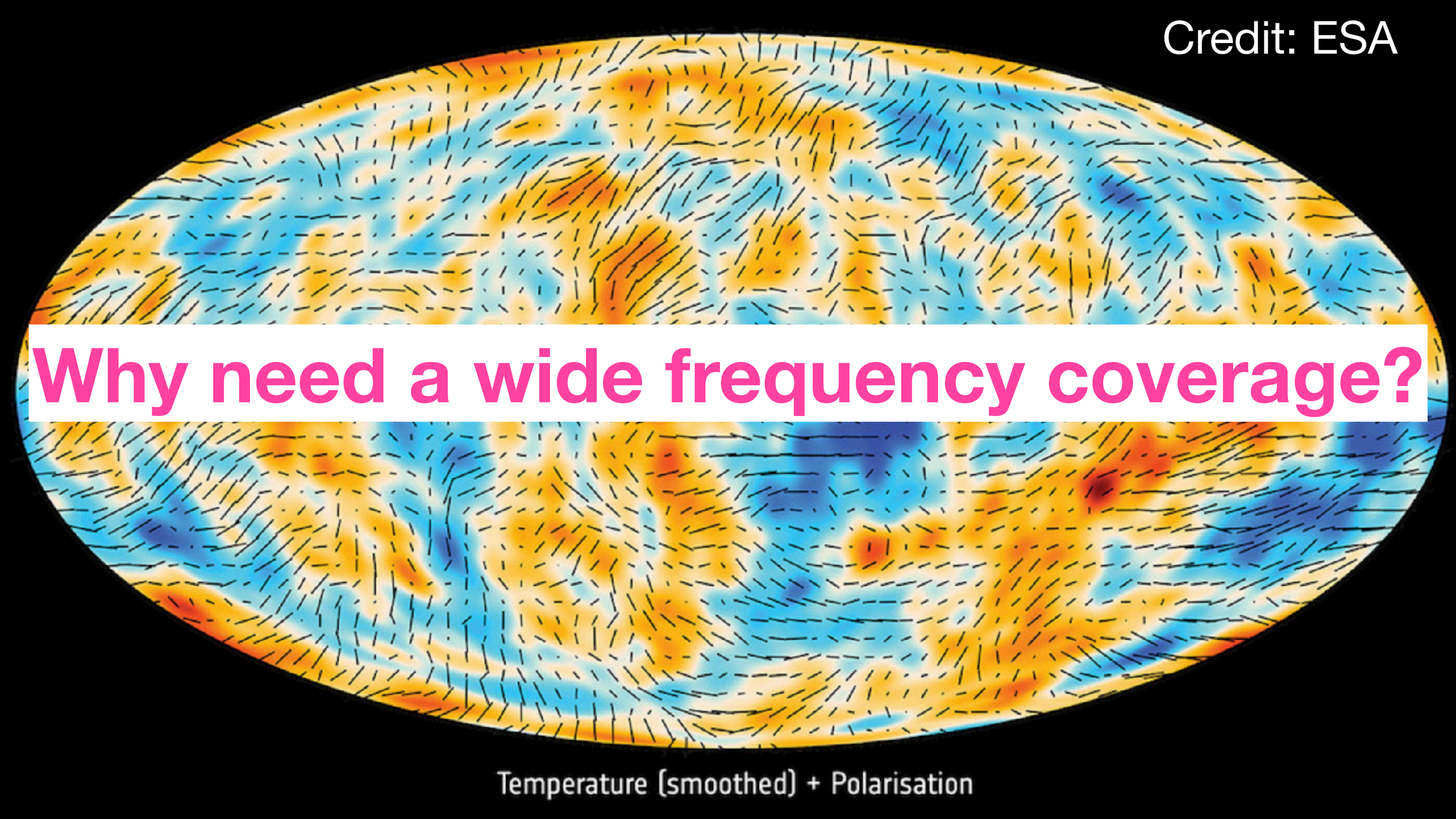



2029–
LiteBIRD
JAXA
+ NASA
+ CSA
+ Europe
A few thousand super-conducting
microwave sensors in space.
Selected by JAXA to fly to L2!

LiteBIRD: 3 telescopes to cover wide frequencies

LFT/MFT/HFT to cover 34 to 448 GHz




Credit: ESA
Why need a wide frequency coverage?
Temperature (smoothed) + Polarisation



ESA's Planck

Credit: ESA

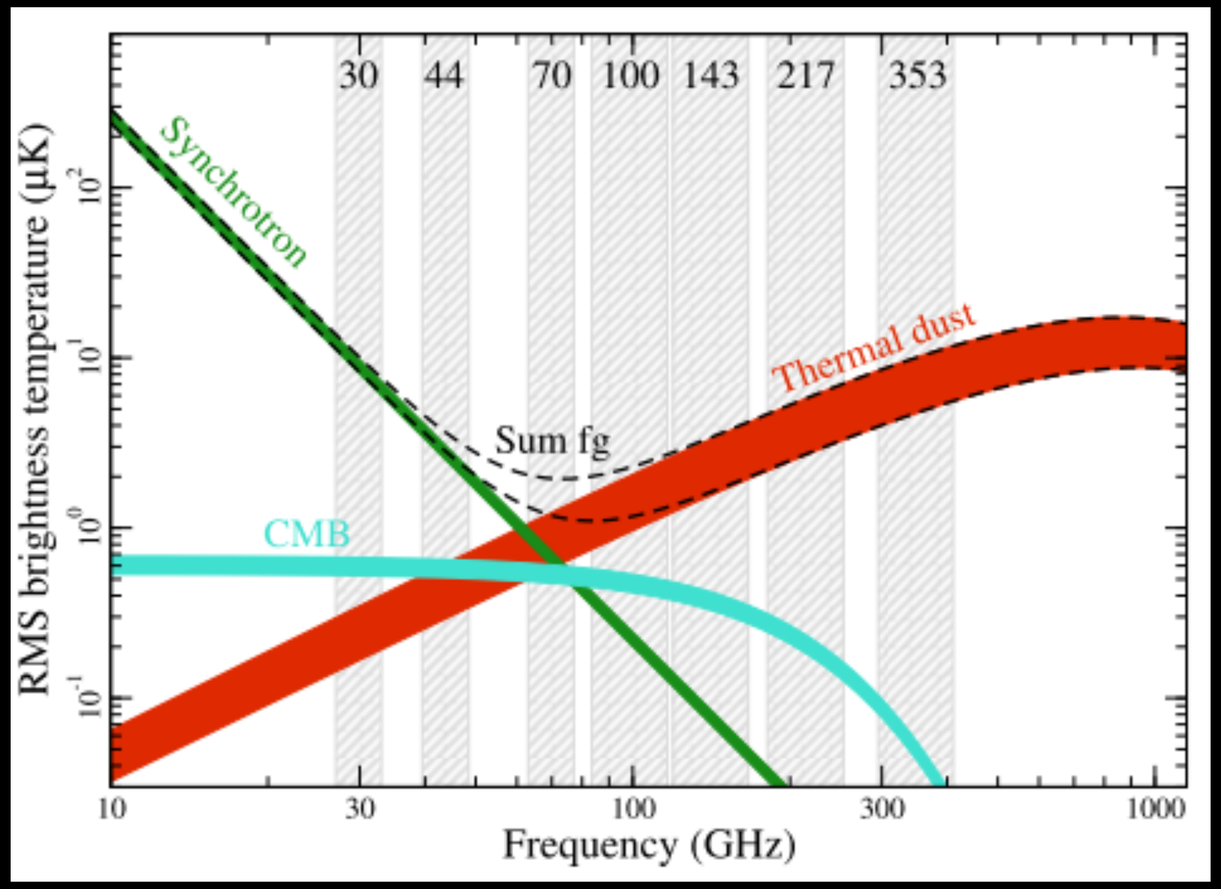
Sky at 353 GHz; dominated by polarised thermal dust emission

We need to remove the "foreground emission".

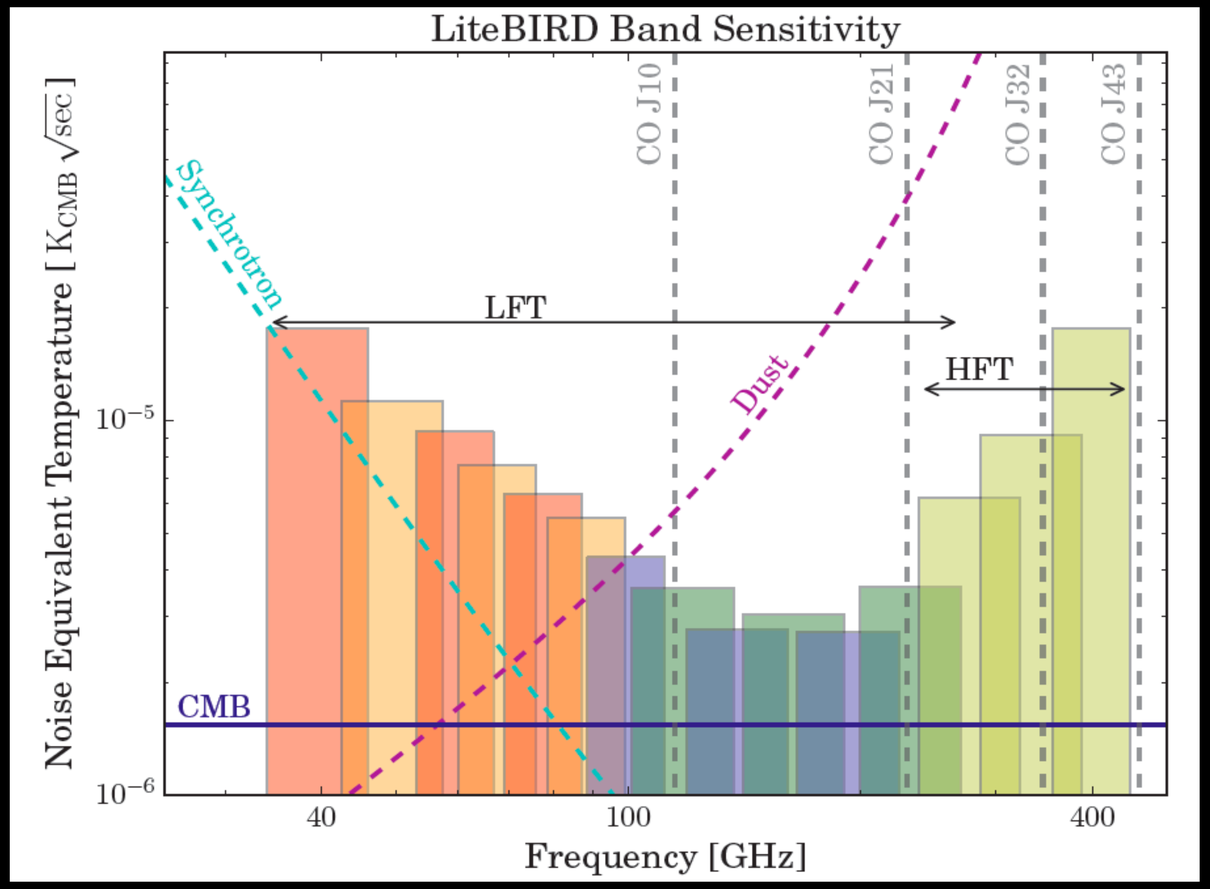
Directions of the magnetic field inferred from polarisation of the thermal dust emission in the Milky Way

Foreground Removal

Slide courtesy Toki Suzuki (Berkeley)



Polarized galactic emission (Planck X)

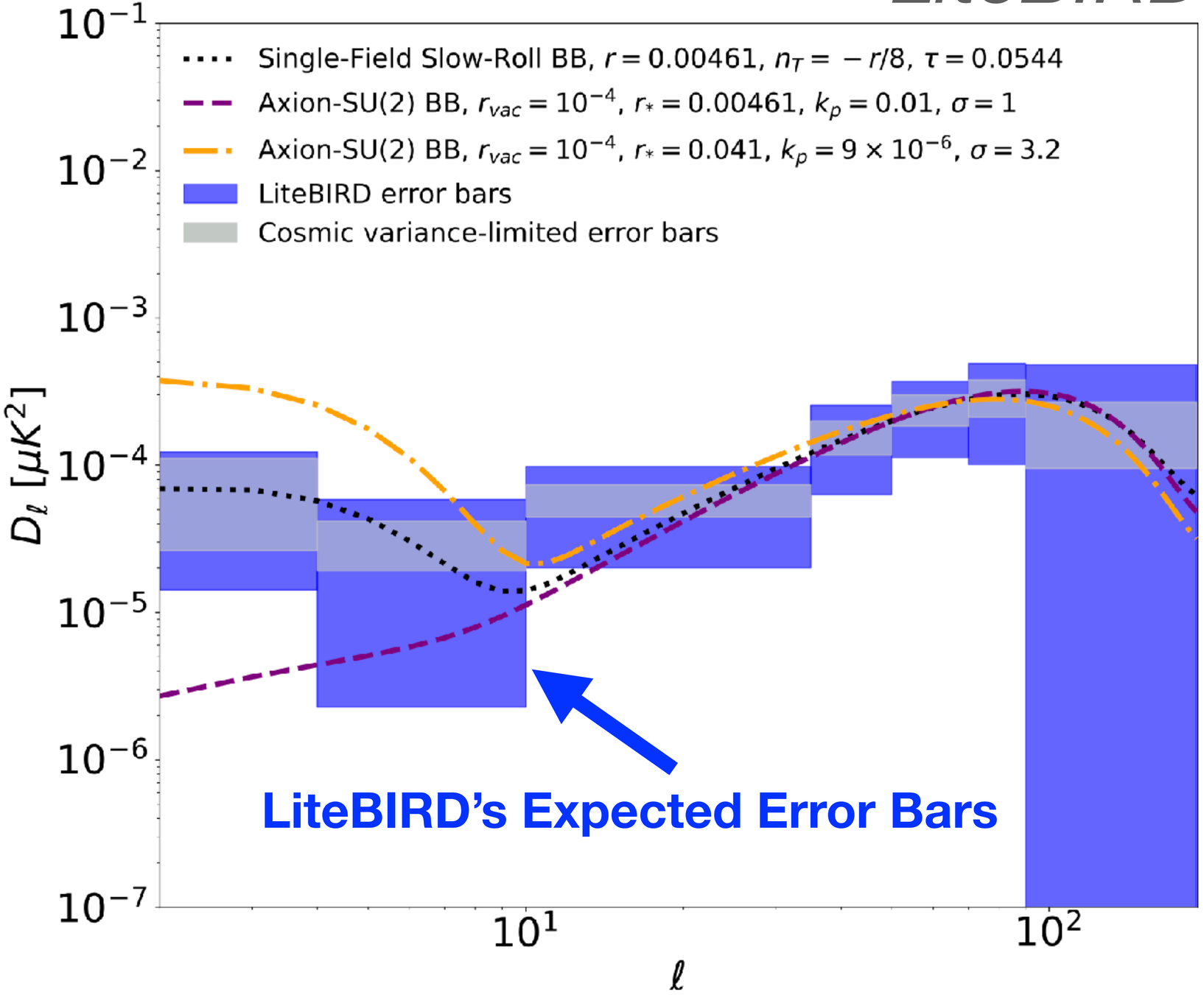


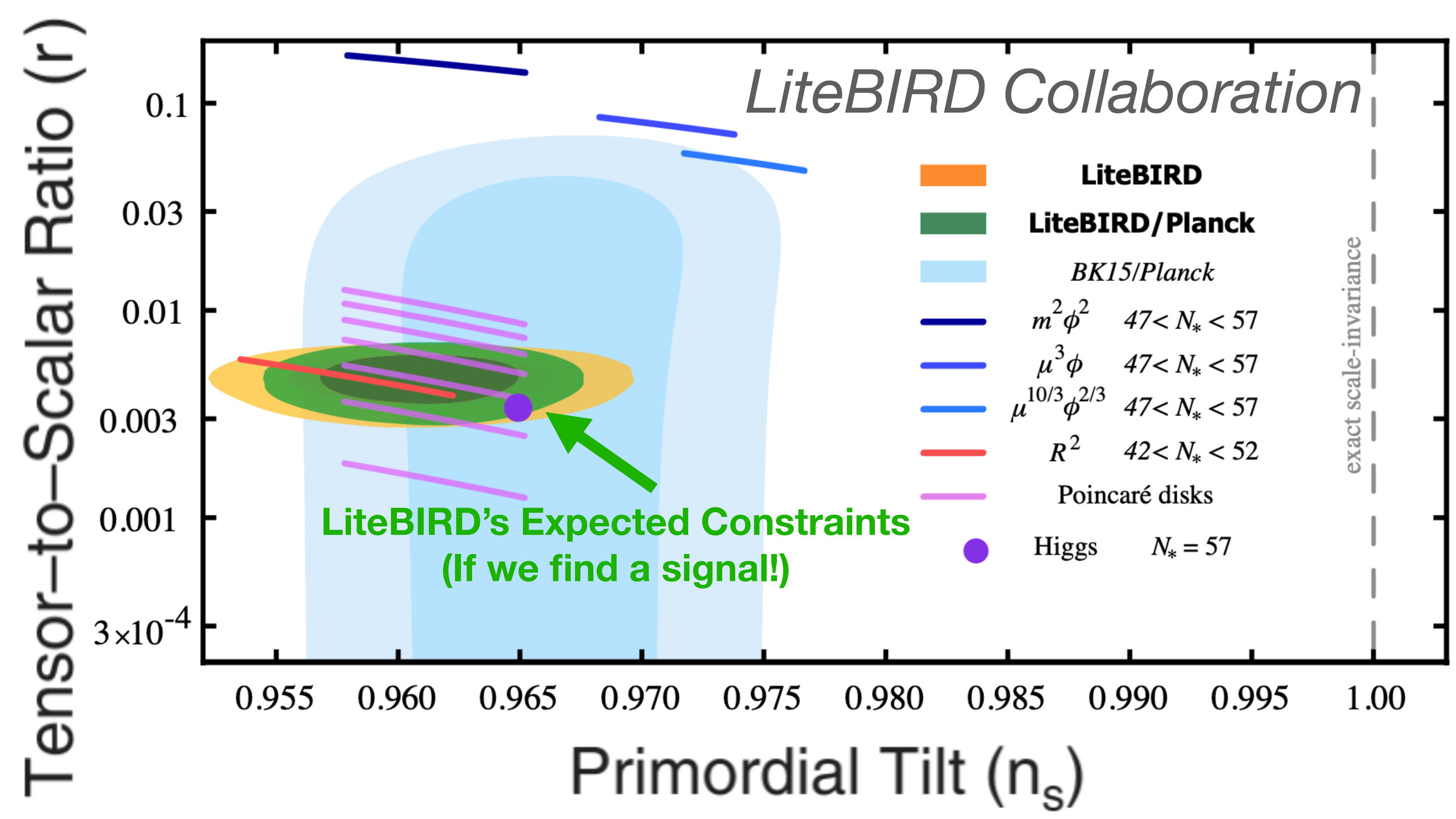
LiteBIRD: 15 frequency bands

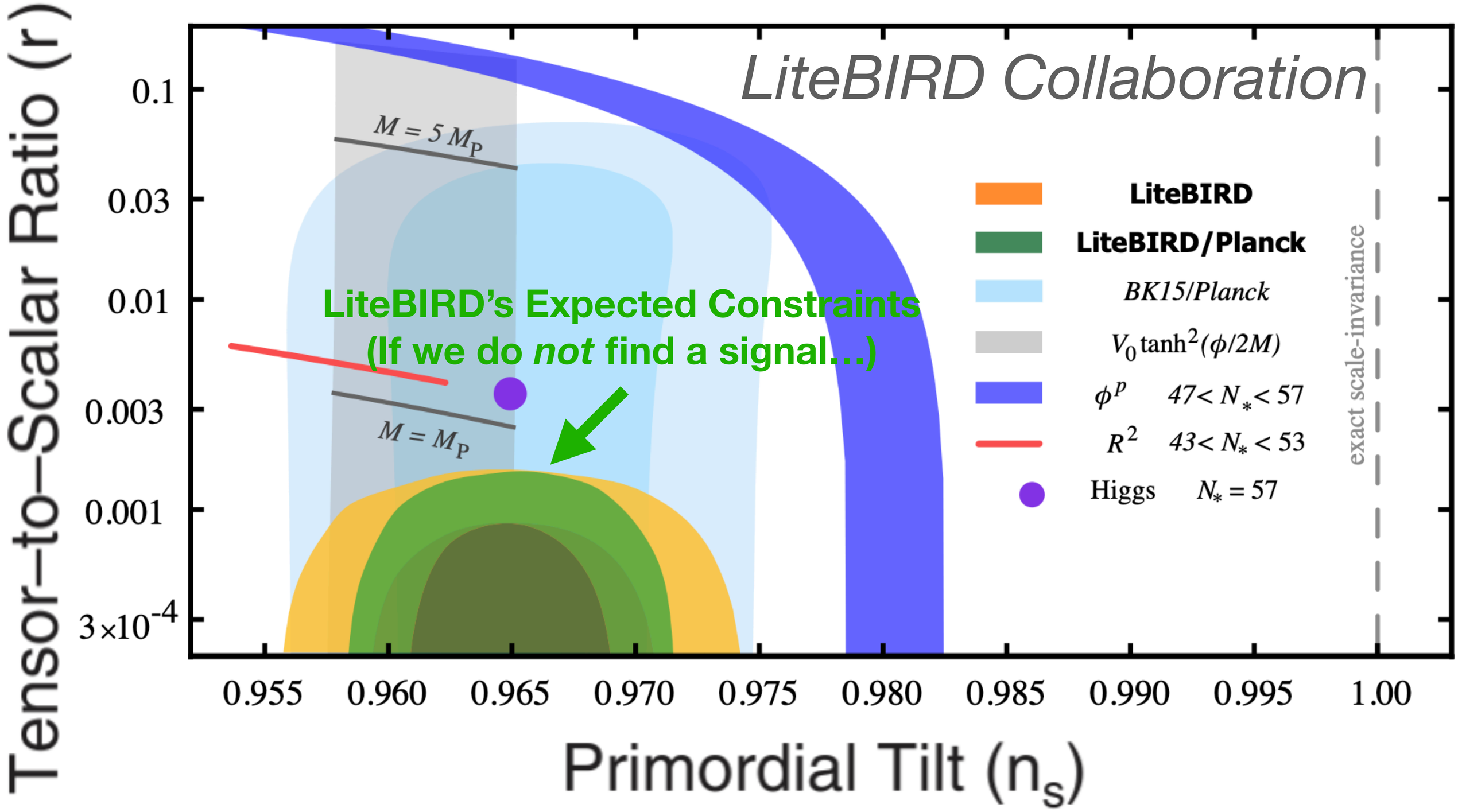
- Polarized foregrounds
  - Synchrotron radiation and thermal emission from inter-galactic dust
  - Characterize and remove foregrounds

B-mode Power Spectrum

LiteBIRD Collaboration



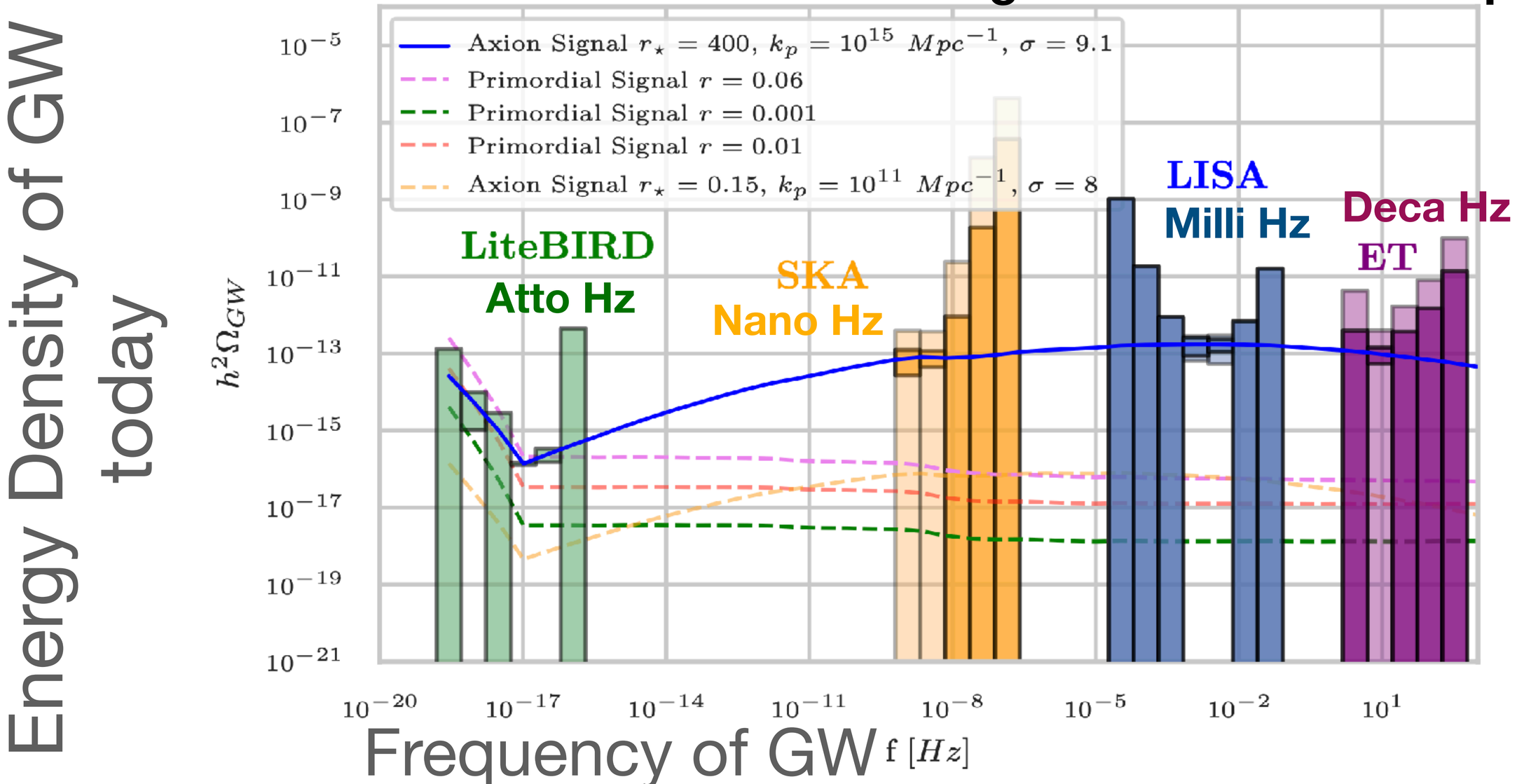

LiteBIRD Collaboration
Tensor–to–Scalar Ratio (r)
Primordial Tilt (n_s)
0.1
0.03
0.01
0.003
0.001
3×10^{-4}
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
1.00
LiteBIRD
LiteBIRD/Planck
BK15/Planck
$m^2\phi^2$ $47< N_* < 57$
$\mu^3\phi$ $47< N_* < 57$
$\mu^{10/3}\phi^{2/3}$ $47< N_* < 57$
R^2 $42< N_* < 52$
Poincaré disks
Higgs $N_* = 57$
exact scale-invariance
LiteBIRD's Expected Constraints
(If we find a signal!)


LiteBIRD Collaboration
Tensor–to–Scalar Ratio (r)
Primordial Tilt (n_s)
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0.03
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3×10^{-4}
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
1.00
$M = 5\,M_P$
$M = M_P$
LiteBIRD's Expected Constraints
(If we do *not* find a signal…)
LiteBIRD
LiteBIRD/Planck
BK15/Planck
$V_0 \tanh^2(\phi/2M)$
ϕ^p $47 < N_* < 57$
R^2 $43 < N_* < 53$
Higgs $N_* = 57$
exact scale-invariance

Campeti, EK, Poletti, Baccigalupi (2021)

But let's recall again: not just CMB!

We can measure it across 21 orders of magnitude in the GW frequency



Summary

Towards finding our origins

- **The Quest So Far:**
  - There is very good evidence that we all came from the quantum fluctuation in the early Universe, generated during the period of **cosmic inflation**.
- **The New Quest:**
  - Discovery of the primordial gravitational wave with the wavelength of billions of light years gives **definitive evidence for inflation.**
  - Hoping to find the first evidence from ground-based and balloon-borne experiments within the next 10 years.
  - Then, the definitive measurement will come from **LiteBIRD** in early 2030s.