Gravitational Waves from the Early Universe

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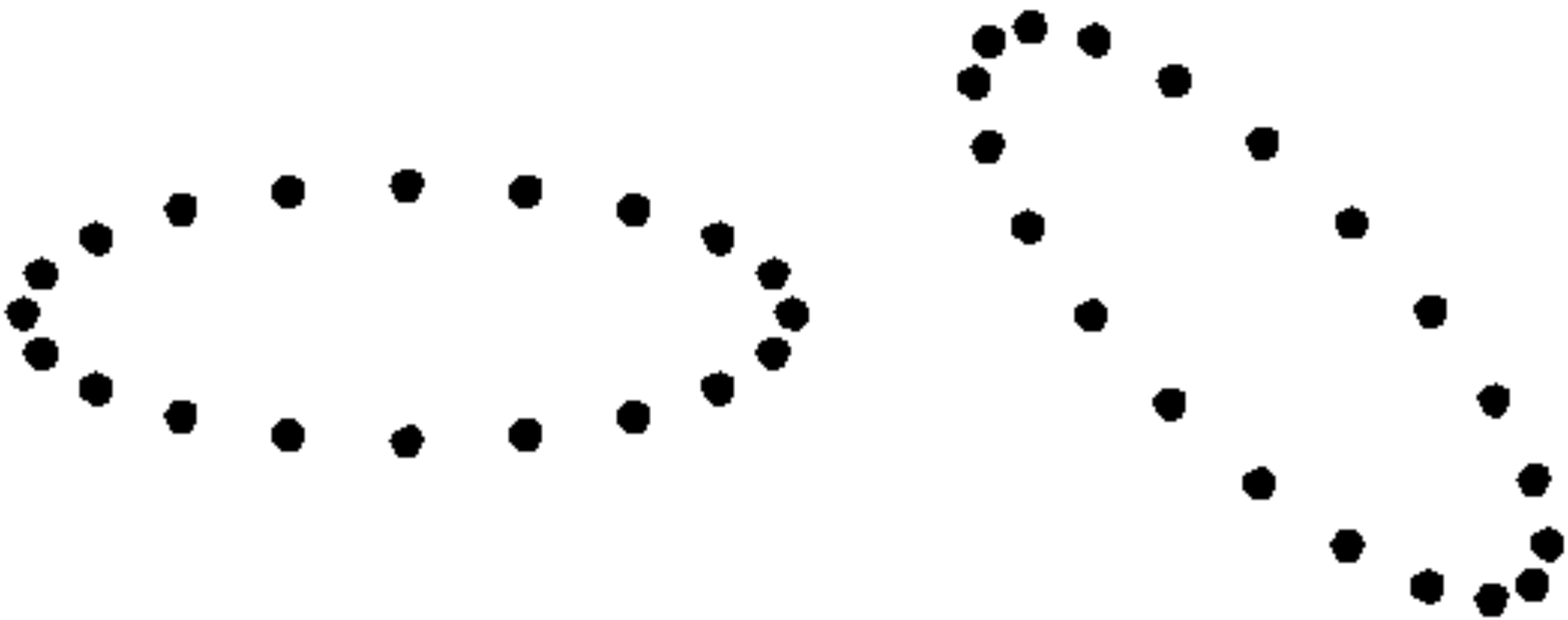
GW = Area-conserving distortion of distances between two points



Distance between two points in space

- Static (i.e., non-expanding) Euclidean space
  - In Cartesian coordinates $\boldsymbol{x} = (x, y, z)$

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

Distance between two points in space

- Homogeneously expanding Euclidean space
  - In Cartesian **comoving** coordinates $\boldsymbol{x} = (x, y, z)$

$$ds^2 = \boxed{a^2(t)}(dx^2 + dy^2 + dz^2)$$

"scale factor"

Distance between two points in space

- Homogeneously expanding Euclidean space
  - In Cartesian **comoving** coordinates $\boldsymbol{x} = (x, y, z)$

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

"scale factor"

δ_{ij} **=1 for i=j**

=0 otherwise

Distance between two points in space

- Inhomogeneous curved space
  - In Cartesian **comoving** coordinates $\boldsymbol{x} = (x, y, z)$

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

"**metric perturbation**"

-> CURVED SPACE!

Four conditions

- Gravitational waves shall be:
  - **Transverse**: the direction of the oscillation of space is perpendicular to the propagation direction $\vec{k}$
    - This means $\sum_{i=1}^{3} k^i h_{ij} = 0$

      3 conditions for h_{ij}
  - **Area-conserving**: the determinant of the distortion in space remains unchanged
    - This means that the trace vanishes: $\sum_{i=1}^{3} h_{ii} = 0$

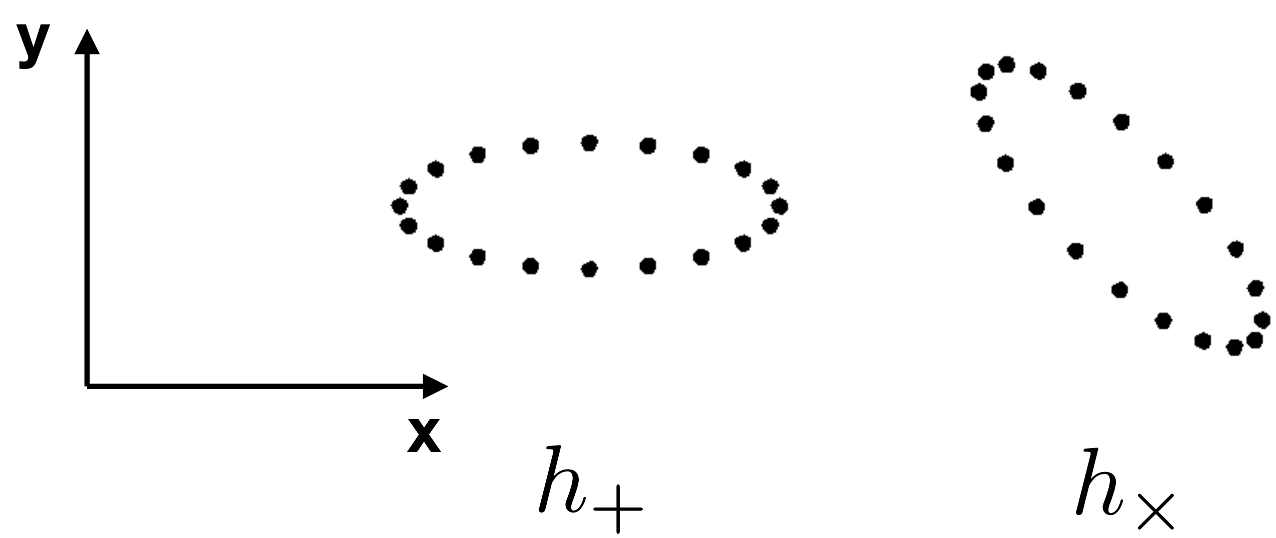
      1 condition for h_{ij}

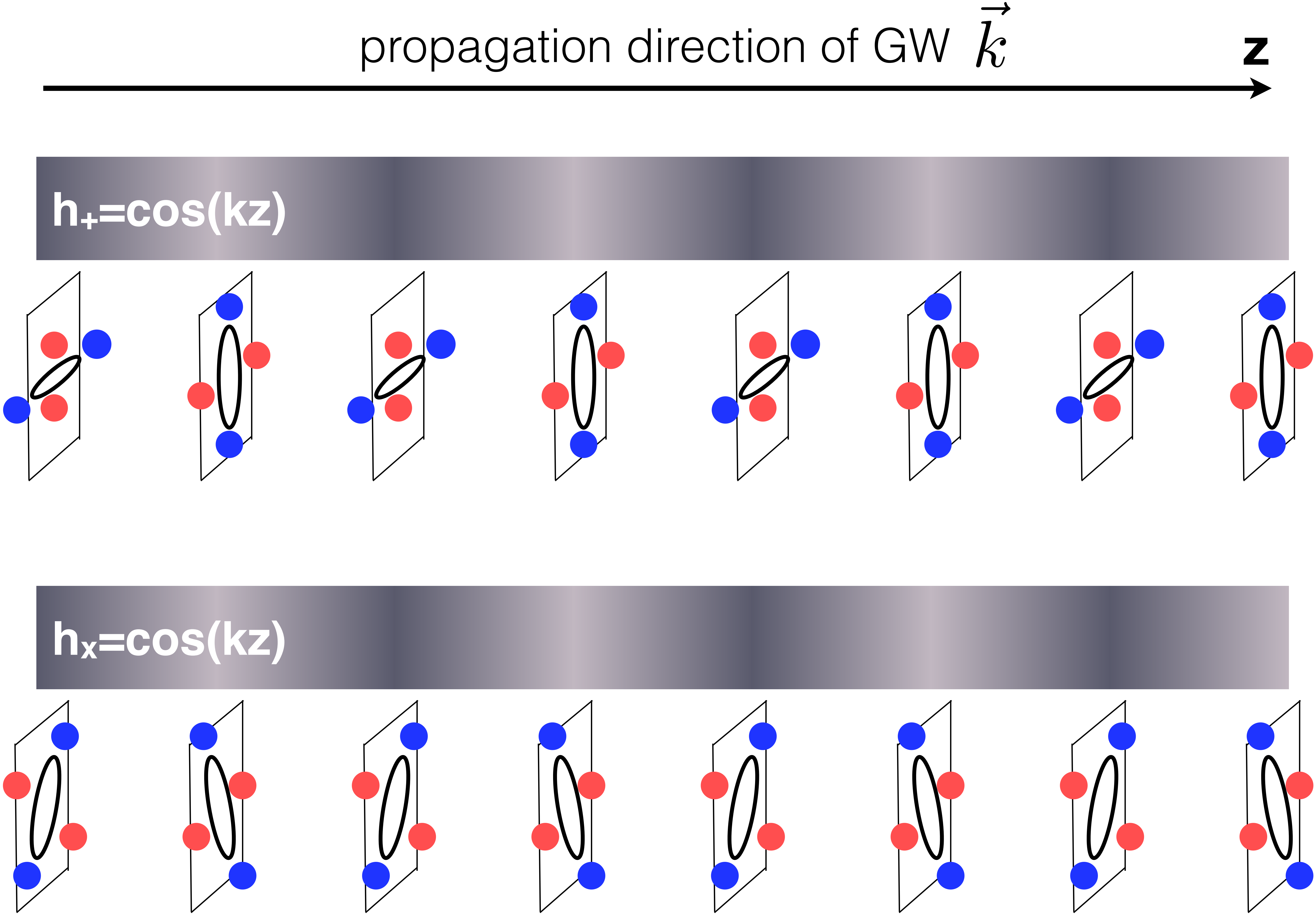
6 components of h_{ij} minus 4 conditions = 2 degrees of freedom

+ and x modes

- If the GW is propagating in the z (i=3) direction, we can write

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




propagation direction of GW $\vec{k}$
z
$h_+=\cos(kz)$
$h_\times=\cos(kz)$

Equation of motion

- Writing Einstein's gravitational field equation with

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

- We obtain, for a plane wave of GW with the wavenumber k,

$$\ddot{h}_{ij} + \frac{3\dot{a}}{a}\dot{h}_{ij} + \frac{k^2}{a^2}h_{ij} = 16\pi G T_{ij}^{GW}$$

source of GW

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source of GW

expansion of the Universe affects h_{ij}

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source of GW

expansion of the Universe affects h_{ij}

- Two tricks:

(1) Define "conformal time"

$$\eta = \int \frac{dt}{a(t)}$$

and use this instead of time derivatives

$$a(t)\frac{\partial}{\partial t} = \frac{\partial}{\partial \eta}$$

Equation of motion

$$h''_{ij} + \frac{2a'}{a} h'_{ij} + k^2 h_{ij} = 16\pi G a^2 T^{GW}_{ij}$$

source of GW

expansion of the Universe affects h_{ij}

Primes =
conformal time derivatives

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source of GW

expansion of the Universe affects h_{ij}

- <u>Two tricks:</u>

(2) Multiply h_{ij} by the scale factor and define

$$u_{ij} = a h_{ij}$$

Equation of motion

$$u''_{ij} + \left(k^2 - \frac{a''}{a}\right) u_{ij} = 16\pi G a^3 T_{ij}^{GW}$$

source of GW

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- Two tricks:

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Equation of motion

$$u_{ij}'' + \left(k^2 - \boxed{\frac{a''}{a}}\right) u_{ij} = 16\pi G a^3 T_{ij}^{GW}$$

source of GW

expansion of the Universe affects h_{ij}

Defining

$$m^2(\eta) = -\frac{a''}{a}$$

effect of the expansion of the Universe

We obtain a harmonic oscillator with a <u>time-dependent mass</u> term!

$$u_{ij}'' + \left[k^2 + m^2(\eta)\right] u_{ij} = 16\pi G a^3 T_{ij}^{GW}$$

Propagation of GW in vacuum: Two regimes

$$u''_{ij} + \left[k^2 + m^2(\eta)\right] u_{ij} = 0$$

- Two regimes:

  1. *Short wavelength* ($k >> |m|$)

     - $u_{ij} \sim \exp(ik\eta) \Rightarrow h_{ij} \sim a^{-1}\exp(ik\eta)$ [decaying]

  2. *Long wavelength* ($k << |m|$)

     - $u_{ij} \sim a \Rightarrow h_{ij} \sim$ **constant**

Meaning of m^2

$$m^2(\eta) = -\frac{a''}{a} = -a^2(2H^2 + \dot{H})$$

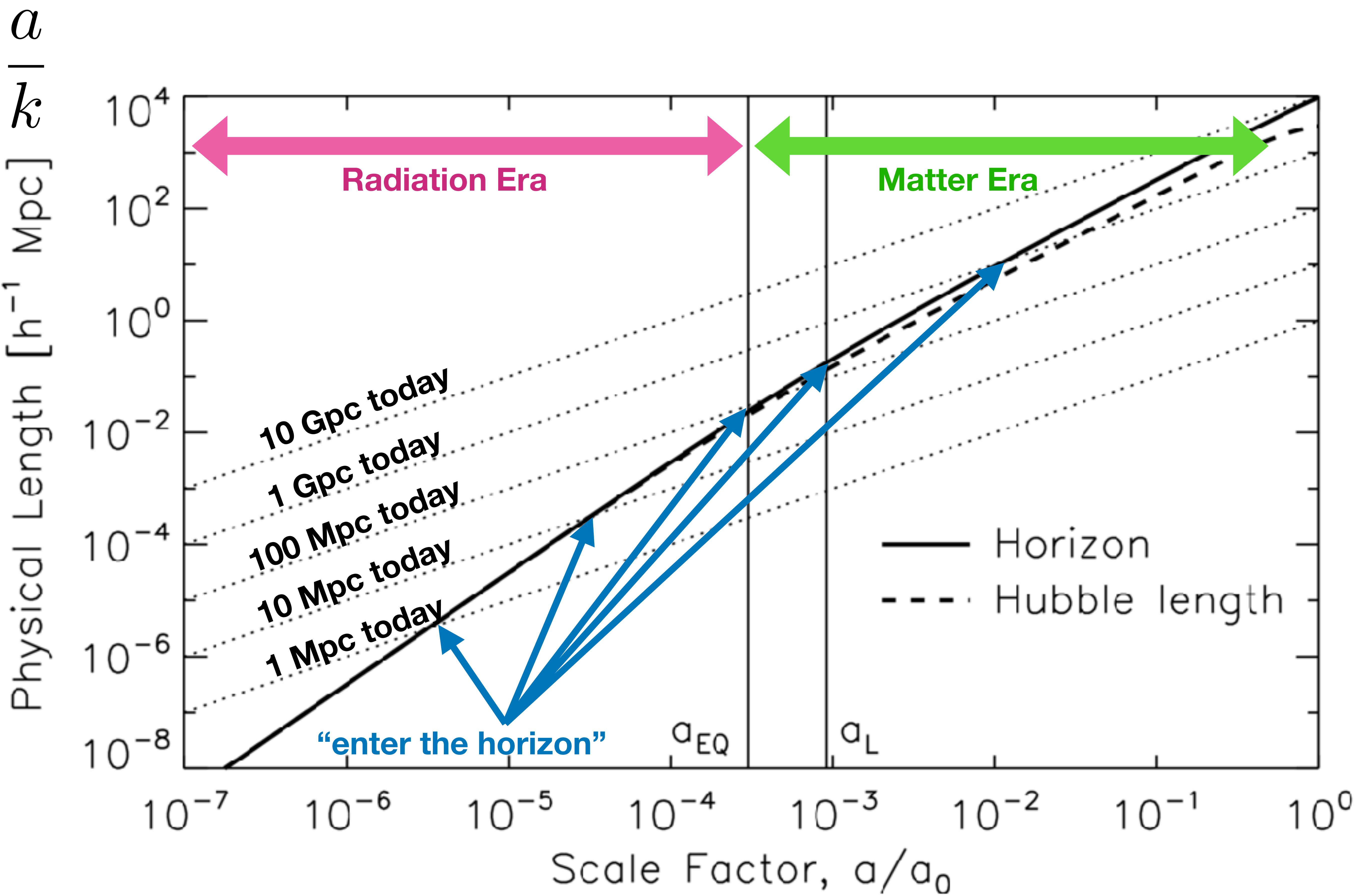
Hubble's expansion rate

$$H = \frac{\dot{a}}{a}$$

- The inverse of the expansion rate, $(aH)^{-1}$, gives an estimate of the (comoving) size of the observable Universe, or "*horizon*"
- So, $k \ll |m|$ is the "**super-horizon**" mode, and $k \gg |m|$ is the "**sub-horizon**" mode

GW “entering the horizon”

- This is a tricky concept, but it is important
- Suppose that GWs exist at all wavelengths
    - Let’s not yet ask the origin of these “super-horizon GW”, but assume their existence
- As the Universe expands, the horizon size grows and we can see longer and longer wavelengths
    - **Fluctuations “entering the horizon”**



a/k
Physical Length [h⁻¹ Mpc]
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
Scale Factor, a/a_0

GW Evolution: Summary

- **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!

Source of GW in the early Universe?

$$u_{ij}'' + \left(k^2 - \frac{a''}{a}\right) u_{ij} = 16\pi G a^3 T_{ij}^{GW}$$

- Was there any **source of GW** in the early Universe?
- Yes, in a sense that there are many papers on possible sources in the literature
  - See a recent review article by C. Caprini and D. Figueroa, *Classical and Quantum Gravity*, 35, 163001 (2018), arXiv:1801.04268

Quantum generation of GW in the early Universe!

$$u''_{ij} + \left(k^2 - \frac{a''}{a}\right) u_{ij} = \cancel{16\pi G a^3 T_{ij}^{GW}}$$

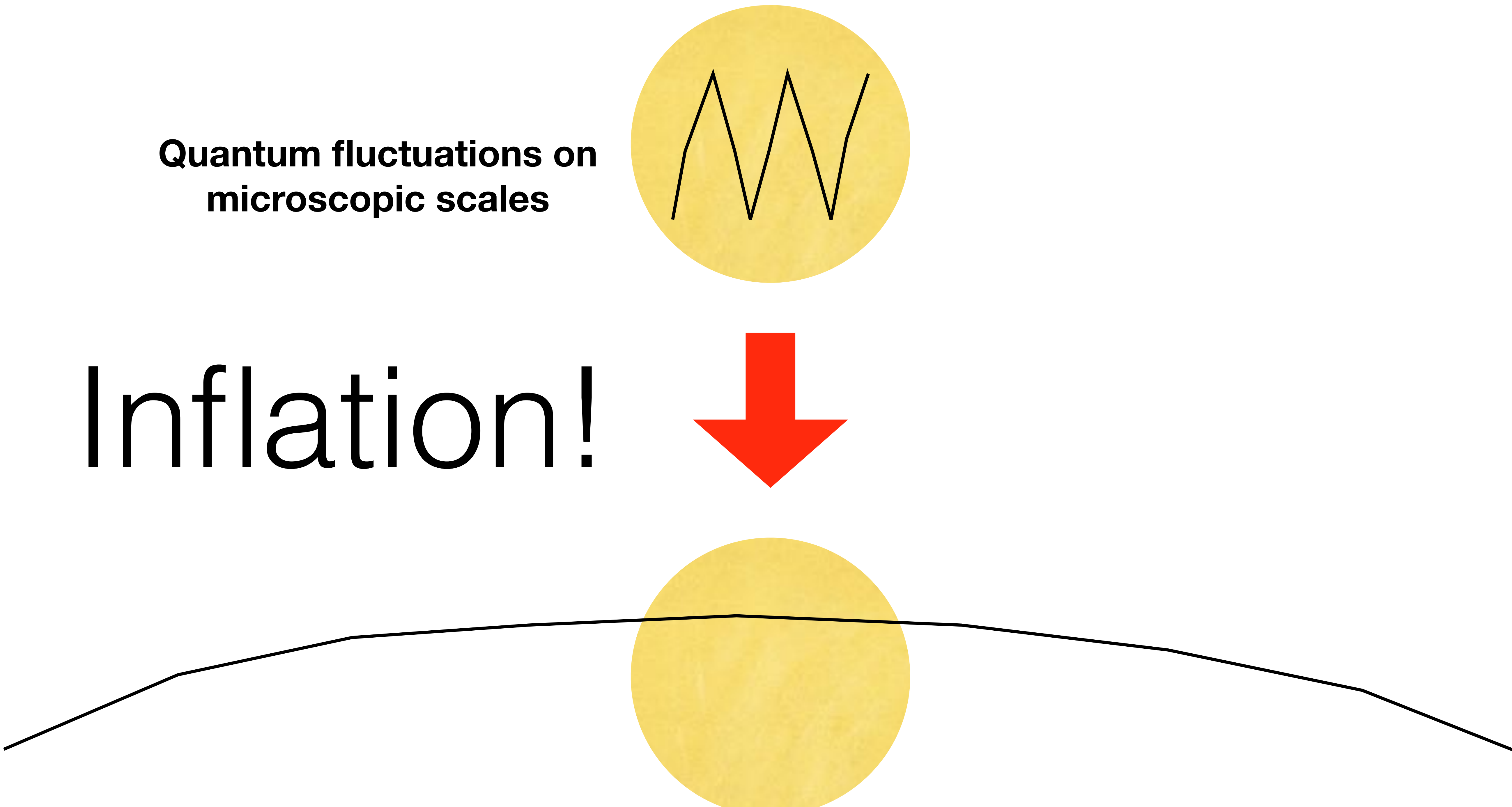
- But, even if there was no source, **GW can emerge quantum-mechanically!**

Grishchuk (1974); Starobinsky (1979)

- To see this, we need to quantise the left hand side of the equation

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

Cosmic Inflation



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

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

Cosmic Inflation

- Inflation is the accelerated, quasi-exponential expansion. Thus, we must have

$$\frac{\ddot{a}}{a} = \dot{H} + H^2 > 0 \quad \longrightarrow \quad \epsilon \equiv -\frac{\dot{H}}{H^2} < 1$$

Actually, we rather need ε << 1, to have a sustained period of inflation. So H(t) is a slowly-varying function of time

$$m^2(\eta) = -\frac{a''}{a} = -a^2(2H^2 + \cancel{\dot{H}})$$

GW from inflation

$$u''_{ij} + \left(k^2 - 2a^2H^2\right) u_{ij} = 0$$

- During inflation, the scale factor grows exponentially in time,

$$a(t) \propto \exp(Ht)$$

- In conformal time, this means

$$a(\eta) = -(H\eta)^{-1} \qquad \textbf{for } -\infty < \eta < 0$$

GW from inflation

$$u''_{ij} + \left(k^2 - \frac{2}{\eta^2} \right) u_{ij} = 0$$

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GW from inflation

$$u''_{ij} + \left(k^2 - \frac{2}{\eta^2} \right) u_{ij} = 0$$

- The solution is

$$u_{ij} = A_{ij} \left[\cos(k\eta) - \frac{\sin(k\eta)}{k\eta} \right] + B_{ij} \left[\frac{\cos(k\eta)}{k\eta} + \sin(k\eta) \right]$$

- How do we fix the integration constants, A_{ij} and B_{ij}? **We need QM!**
    - We find A_{ij} and B_{ij}, such that the u_{ij} coincides with the known flat-space (Minkowski) results for the quantum fluctuation in vacuum

Second-order Action

- The action that gives Einstein's field equations is the so-called "Einstein-Hilbert action", given by the Ricci scalar R:

$$I_{GR} = \int \sqrt{-g} d^4x \left(\frac{1}{2} M_{\rm pl}^2 R \right)$$

with

$$M_{\rm pl} = (8\pi G)^{-1/2}$$

$$\sqrt{-g} = a^3$$

- Expanding this to second-order in h_{ij}, we obtain the action that gives the equation of motion for h_{ij}:

$$I_{GR}^{(2)} = \int a^3 d^4x \, \frac{1}{4} M_{\rm pl}^2 \left(\frac{1}{2} \dot{h}_{ij}^2 - \frac{(\nabla h_{ij})^2}{2a^2} \right)$$

with

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

$$= \int a^3 d^4x \, \frac{1}{2} M_{\rm pl}^2 \sum_{\lambda=+,\times} \left(\frac{1}{2} \dot{h}_\lambda^2 - \frac{(\nabla h_\lambda)^2}{2a^2} \right)$$

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unwanted pre-factor

"Canonically-normalised" mode function

$$I_{GR}^{(2)} = \int a^3 d^4x \; \frac{1}{4} M_{\rm pl}^2 \left(\frac{1}{2} \dot{h}_{ij}^2 - \frac{(\nabla h_{ij})^2}{2a^2} \right)$$

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unwanted pre-factor

- <u>Two tricks again:</u>
  - (1) Use the conformal time: $a^3 d^4x = a^4 d\eta d^3x$
  - (2) Define: $u_\lambda = \frac{M_{\rm pl}}{\sqrt{2}} a h_\lambda$

“Canonically-normalised” mode function

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$$= \int d\eta d^3x \sum_{\lambda=+,\times} \left(\frac{1}{2} {u'_\lambda}^2 - \frac{1}{2} (\nabla u_\lambda)^2 + \frac{a''}{2a} u_\lambda^2 \right)$$

- Two tricks again:
  - (1) Use the conformal time: $a^3 d^4x = a^4 d\eta d^3x$
  - (2) Define: $u_\lambda = \frac{M_{\rm pl}}{\sqrt{2}} a h_\lambda$

This is the correct (“canonical”) normalisation!

GW from inflation

$$u''_{ij} + \left(k^2 - \frac{2}{\eta^2}\right) u_{ij} = 0$$

- The solution is

$$u_{ij} = A_{ij}\left[\cos(k\eta) - \frac{\sin(k\eta)}{k\eta}\right] + B_{ij}\left[\frac{\cos(k\eta)}{k\eta} + \sin(k\eta)\right]$$

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- In the very short wavelength limit, kη->∞, we want to reproduce the quantum field theory result in the flat (Minkowski) space, which is

$$u_\lambda \to \frac{\exp(-ik\eta)}{\sqrt{2k}}$$

GW from inflation

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$A_\lambda \rightarrow (2k)^{-1/2}$, $B_\lambda \rightarrow -i(2k)^{-1/2}$

- In the very short wavelength limit, $k\eta \to \infty$, we want to reproduce the quantum field theory result in the flat (Minkowski) space, which is

$$u_\lambda \to \frac{\exp(-ik\eta)}{\sqrt{2k}}$$

GW from inflation

$$u_\lambda'' + \left(k^2 - \frac{2}{\eta^2}\right) u_\lambda = 0$$

- The solution is

$$u_\lambda = \frac{1}{\sqrt{2k}} \left(e^{-ik\eta} - \frac{i}{k\eta} e^{-ik\eta} \right)$$

This term dominates in the super-horizon mode!
"*Particle Production by Inflation*"

GW from inflation

$$u''_\lambda + \left(k^2 - \frac{2}{\eta^2}\right) u_\lambda = 0$$

- The **super-horizon** solution is

$$u_\lambda \to -\frac{i}{\sqrt{2k^3}\eta} e^{-ik\eta}$$

GW from inflation

$$u_\lambda'' + \left(k^2 - \frac{2}{\eta^2}\right) u_\lambda = 0$$

- The **super-horizon** solution is

$$u_\lambda \to -\frac{i}{\sqrt{2k^3}\eta} e^{-ik\eta}$$

Since $u_\lambda = \frac{M_{\rm pl}}{\sqrt{2}} a h_\lambda$ **and** $a(\eta) = -(H\eta)^{-1}$ **…**

GW from inflation

$$u_\lambda'' + \left(k^2 - \frac{2}{\eta^2}\right) u_\lambda = 0$$

- The **super-horizon** solution is

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GW from inflation

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- The **super-horizon** solution is

$$h_\lambda \to \frac{i\boxed{H}}{\sqrt{k^3} M_{\rm pl}} e^{-ik\eta}$$

The amplitude of GW on super-horizon scale is proportional to H!

Quantum fluctuations during inflation are proportional to H

- Consequence of the uncertainty principle
  - [energy you can borrow] ~ [time you borrow]$^{-1}$ ~ H
- **THE KEY RESULT**: The earlier the fluctuations are generated, the more its wavelength is stretched, and thus the bigger the angles they subtend in the sky. **We can map H(t) by measuring fluctuations over a wide range of wavelengths**

Total Variance of GW

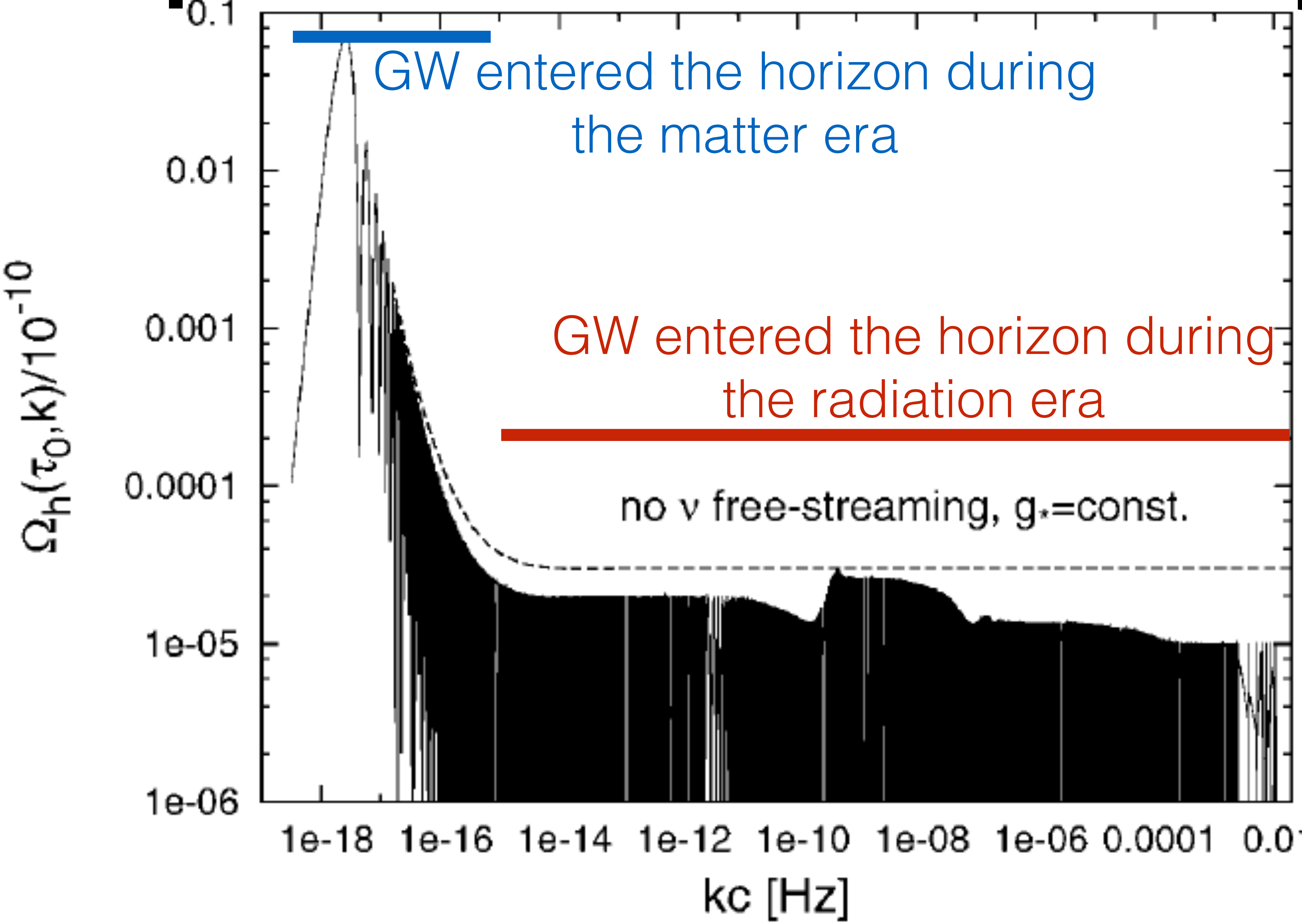
$$\frac{k^3}{2\pi^2}\sum_{ij}\langle h_{ij}h_{ij}^*\rangle = \frac{8}{M_{\rm pl}^2}\left(\frac{H}{2\pi}\right)^2$$

- Variance depends only on H; thus,
  - It is scale-invariant if H is constant during inflation; or
  - It is **nearly** scale-invariant if H changes slowly during inflation
- In general, H is a decreasing function of time; thus,
  - **The variance of GW is smaller at shorter wavelengths.** This is the key prediction of GW from the *vacuum fluctuation* during inflation

Watanabe & EK (2006)

Theoretical energy density

Spectrum of GW today



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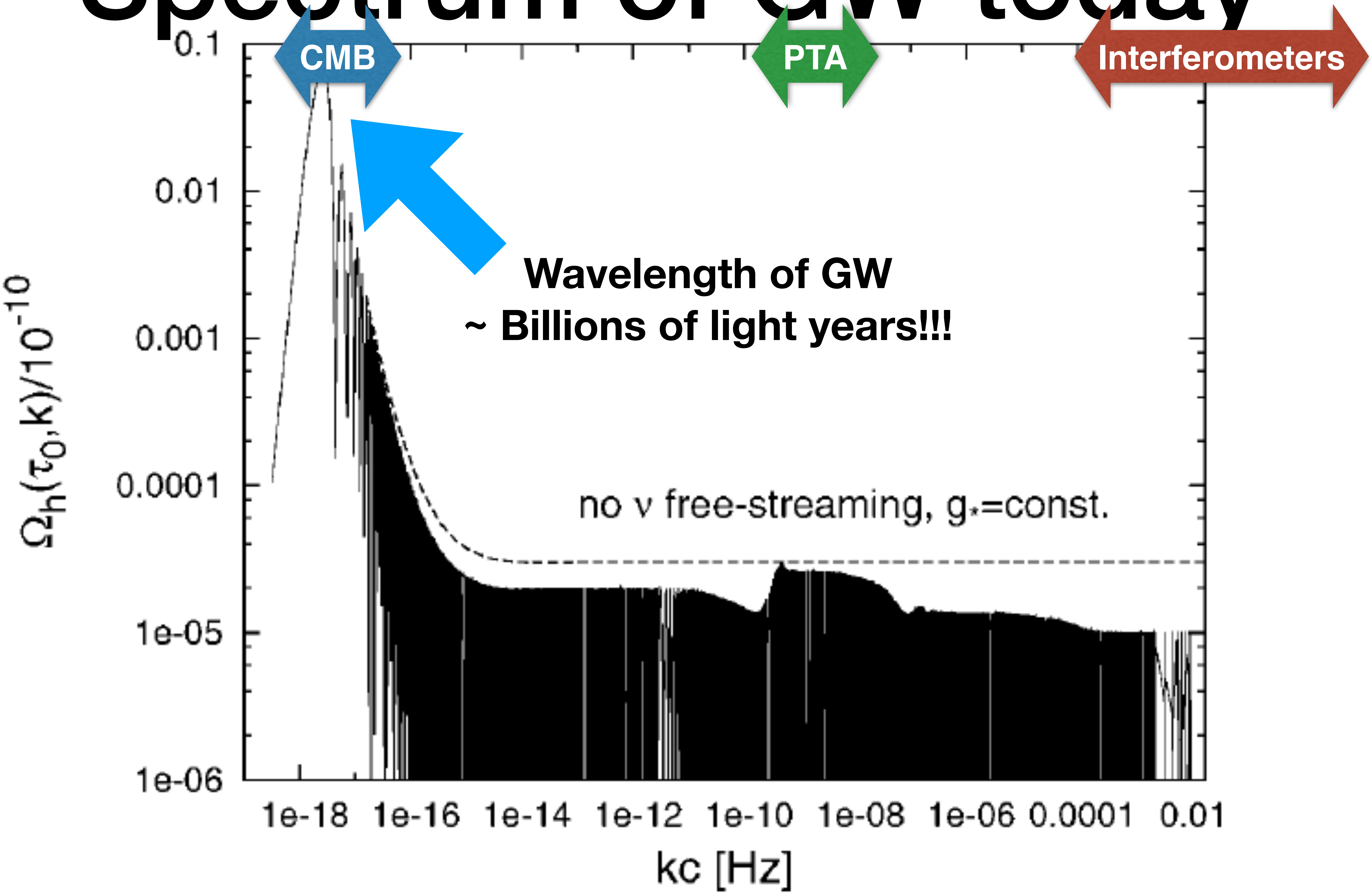


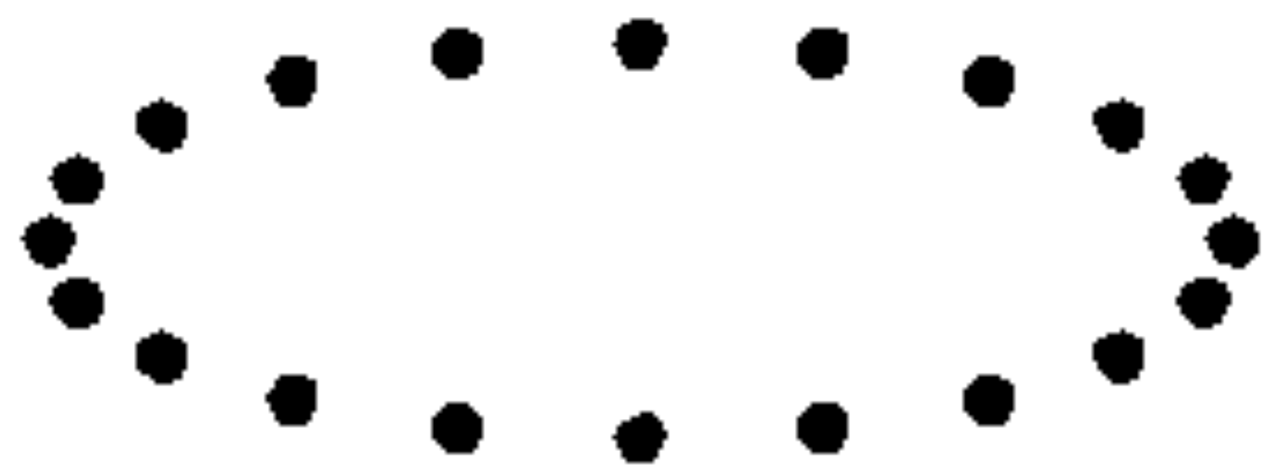
How do we measure GW?

Measuring GW

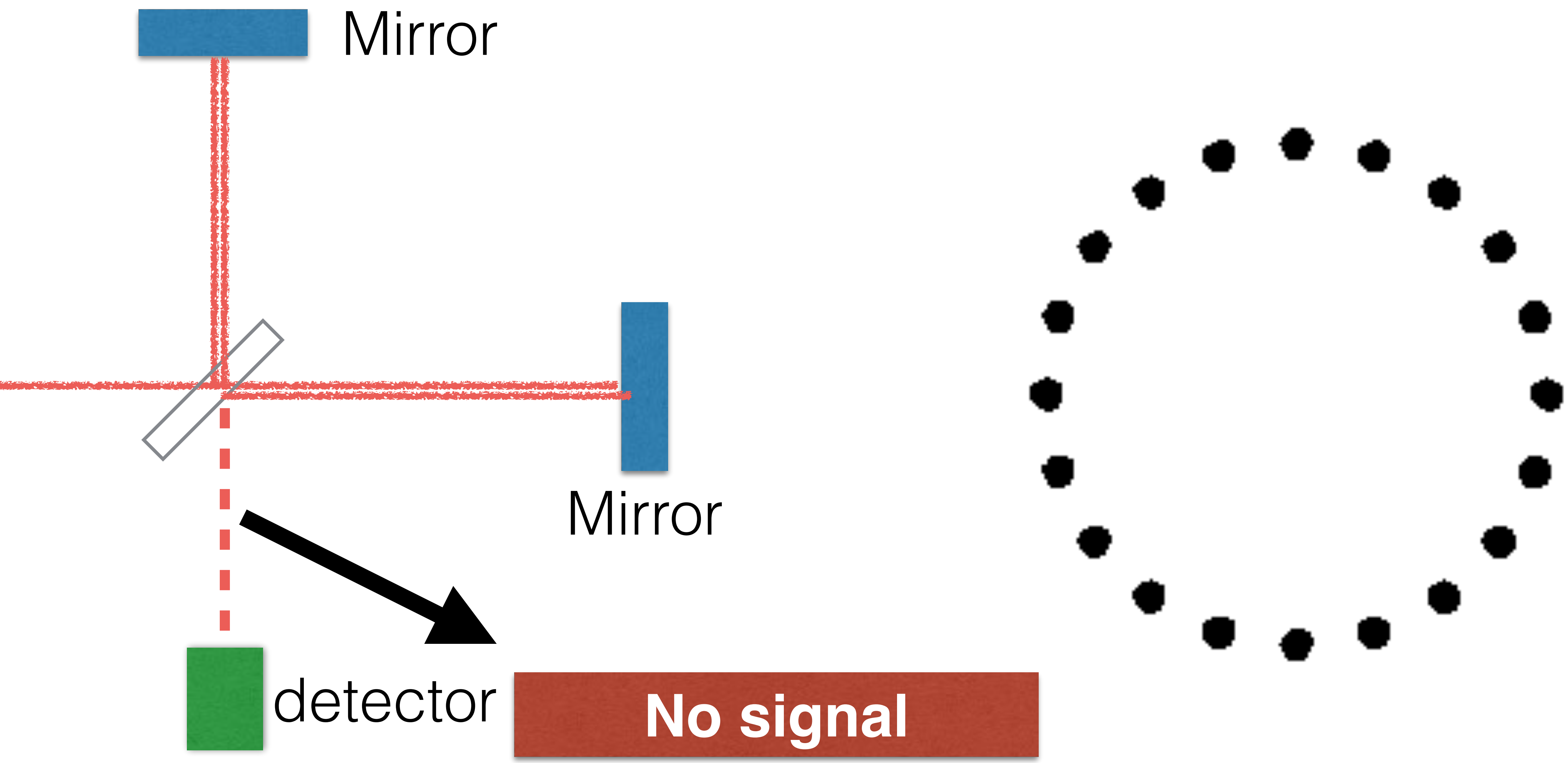
- GW changes distances between two points

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

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



Laser Interferometer



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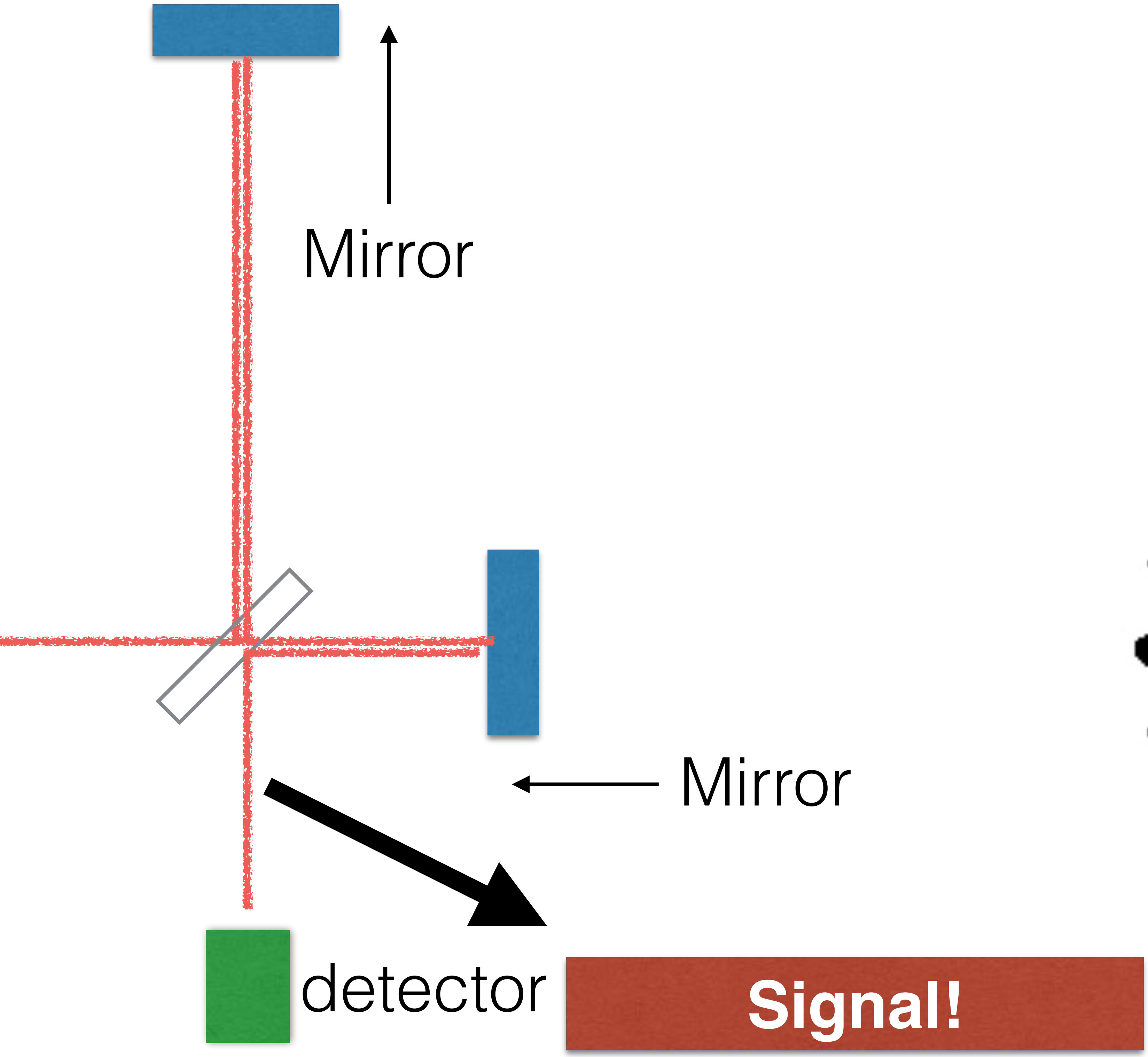
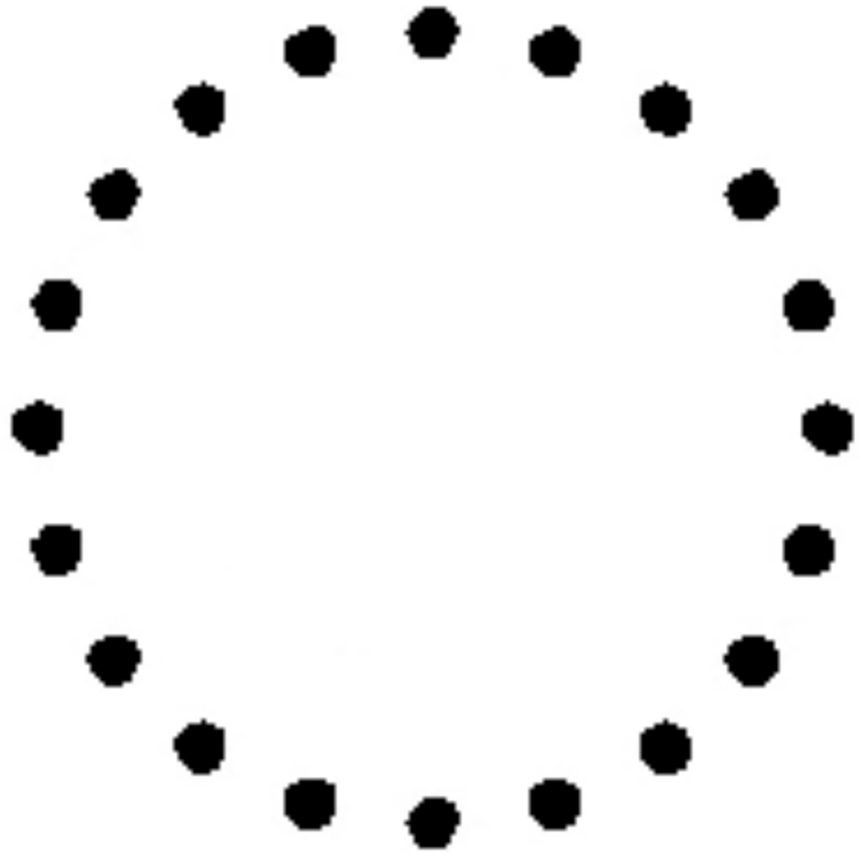




LIGO detected GW from a binary blackholes, with the wavelength of thousands of kilometres

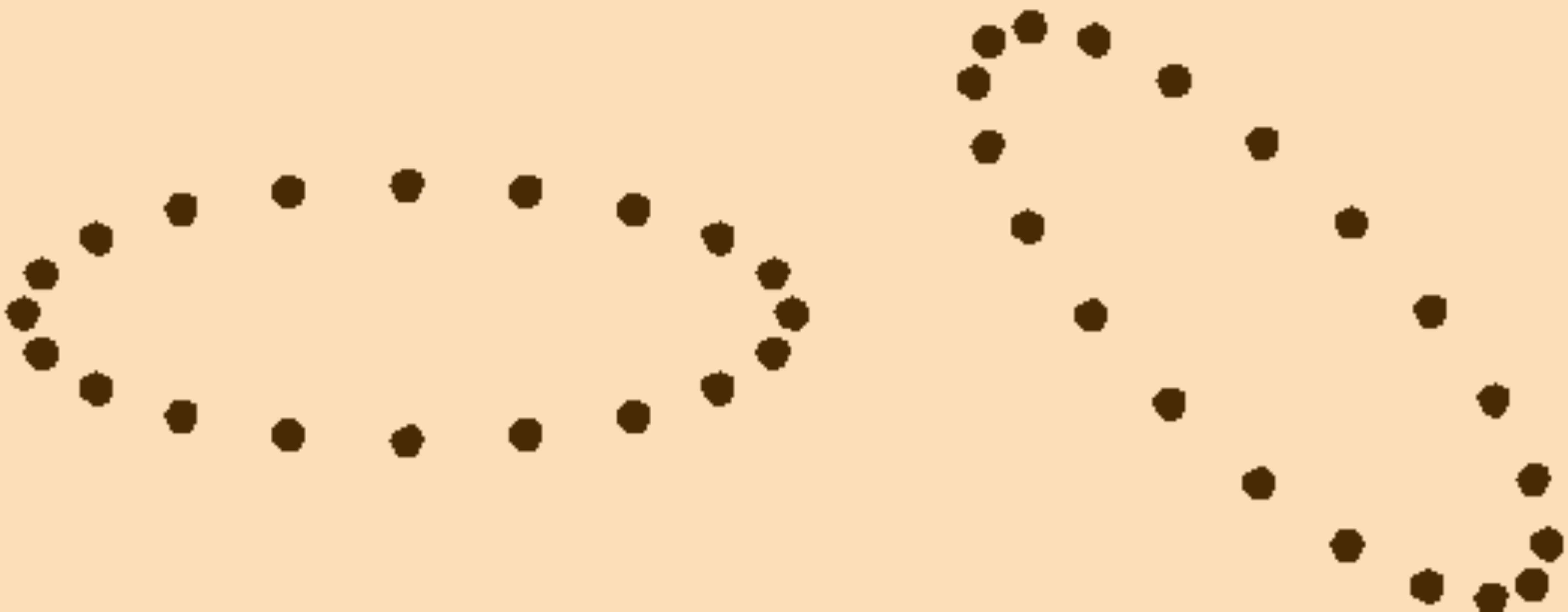
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

Detecting GW by CMB

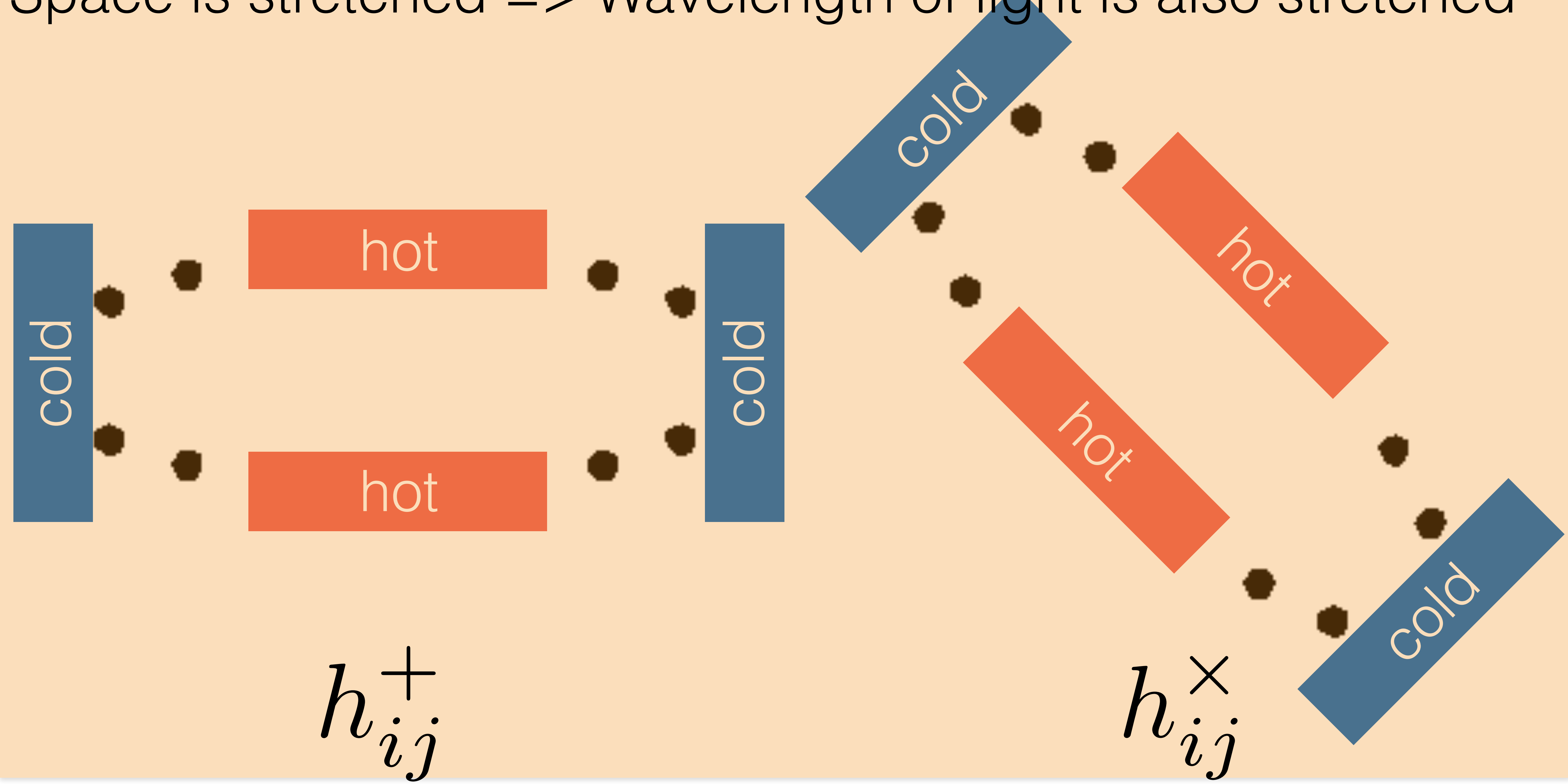
GW propagating in isotropic electro-magnetic fields



h_{ij}^{+} $h_{ij}^{\times}$

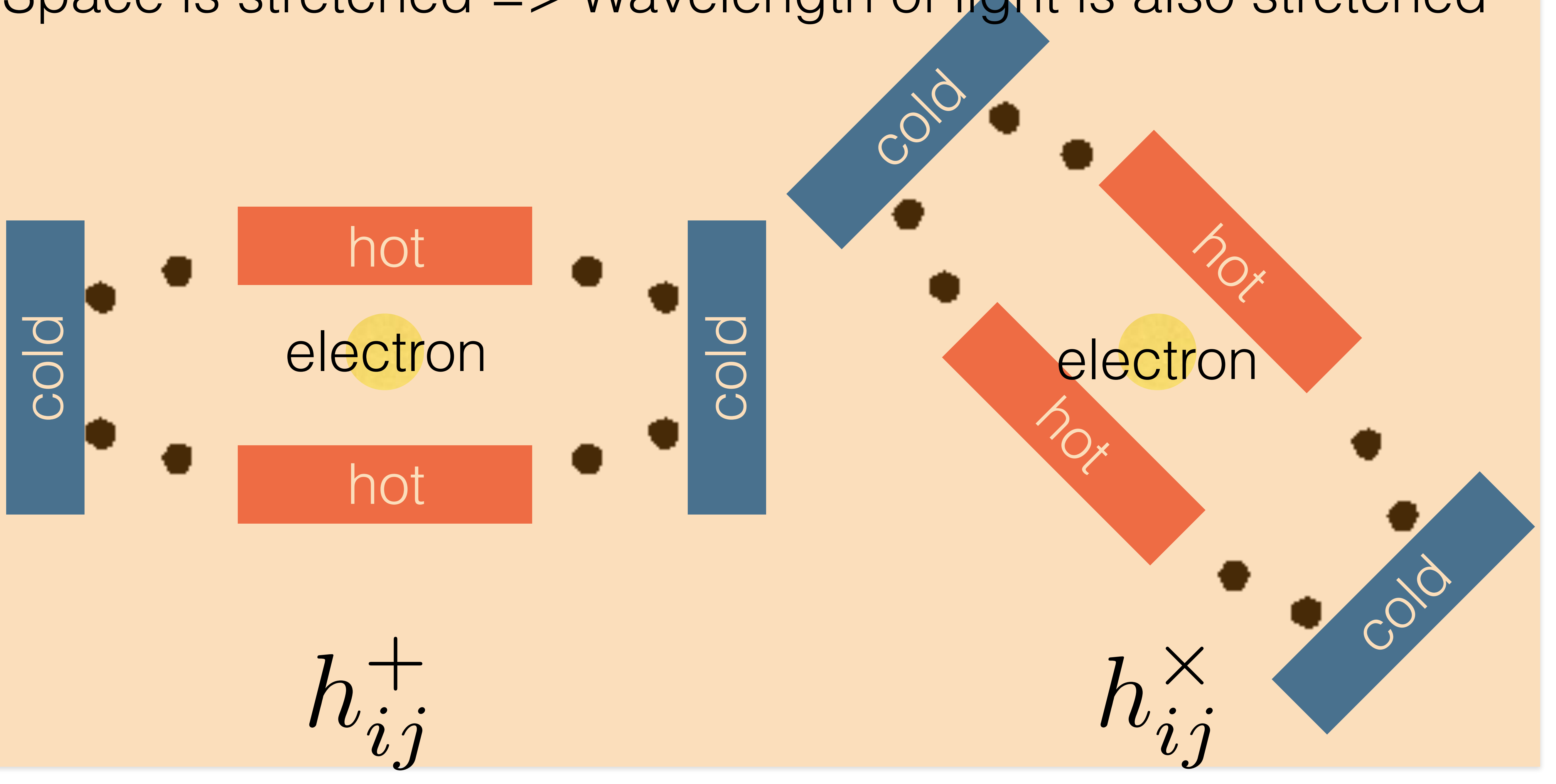
Detecting GW by CMB

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

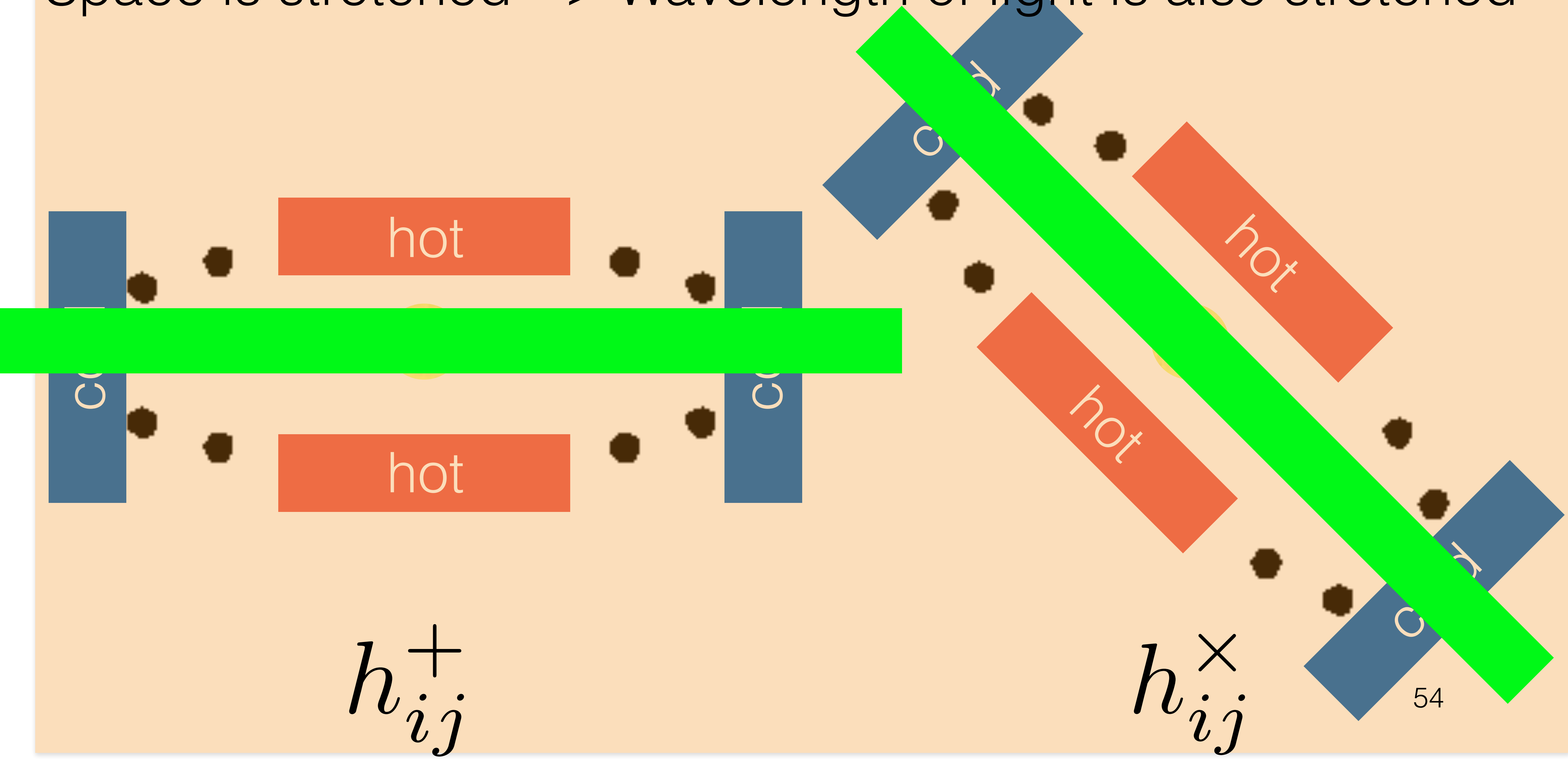
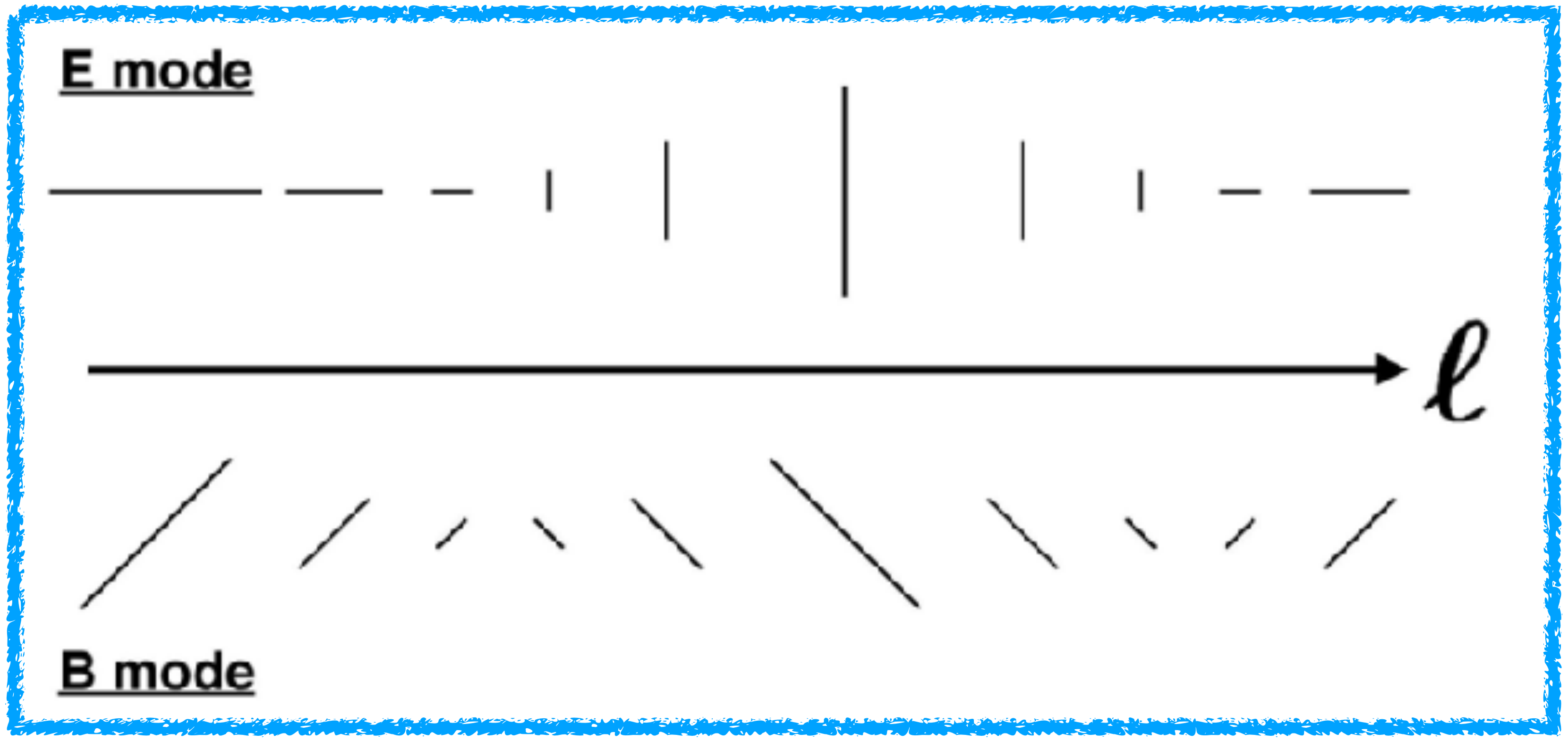



Photo Credit: TALEX
horizontally polarised

Photo Credit: TALEX

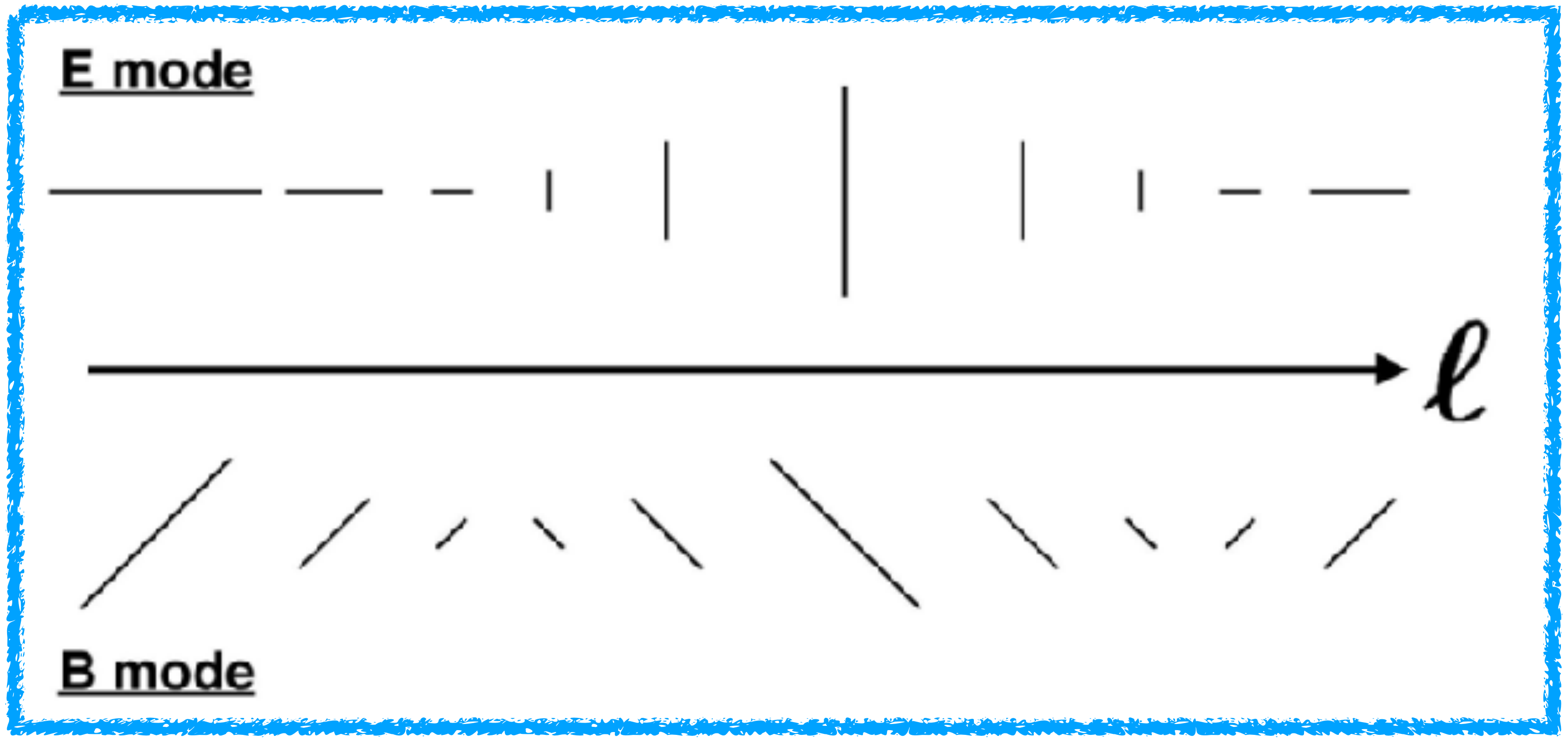
E and B mode



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

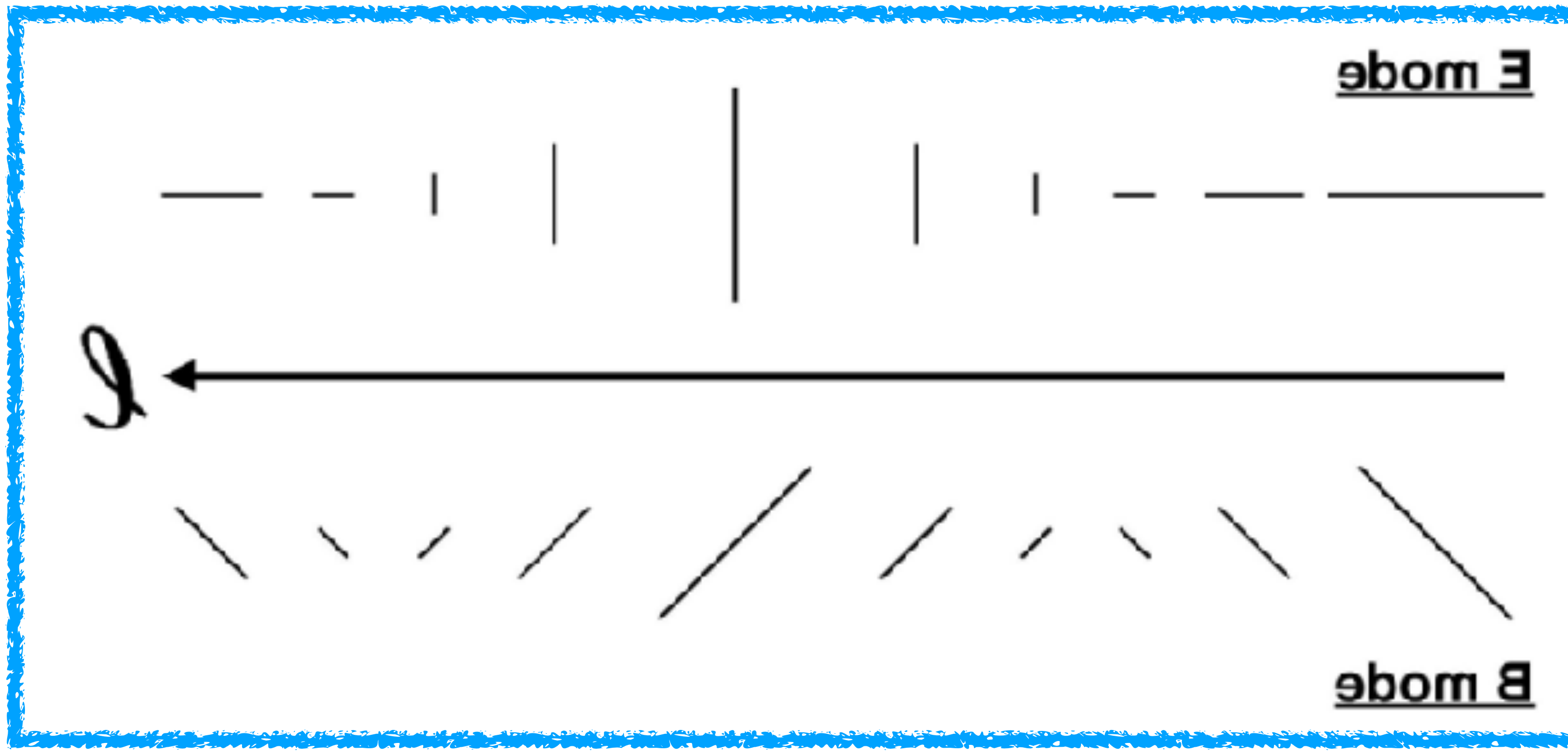
- **B mode**: Polarisation directions 45 degree tilted with respect to the wavevector

Parity



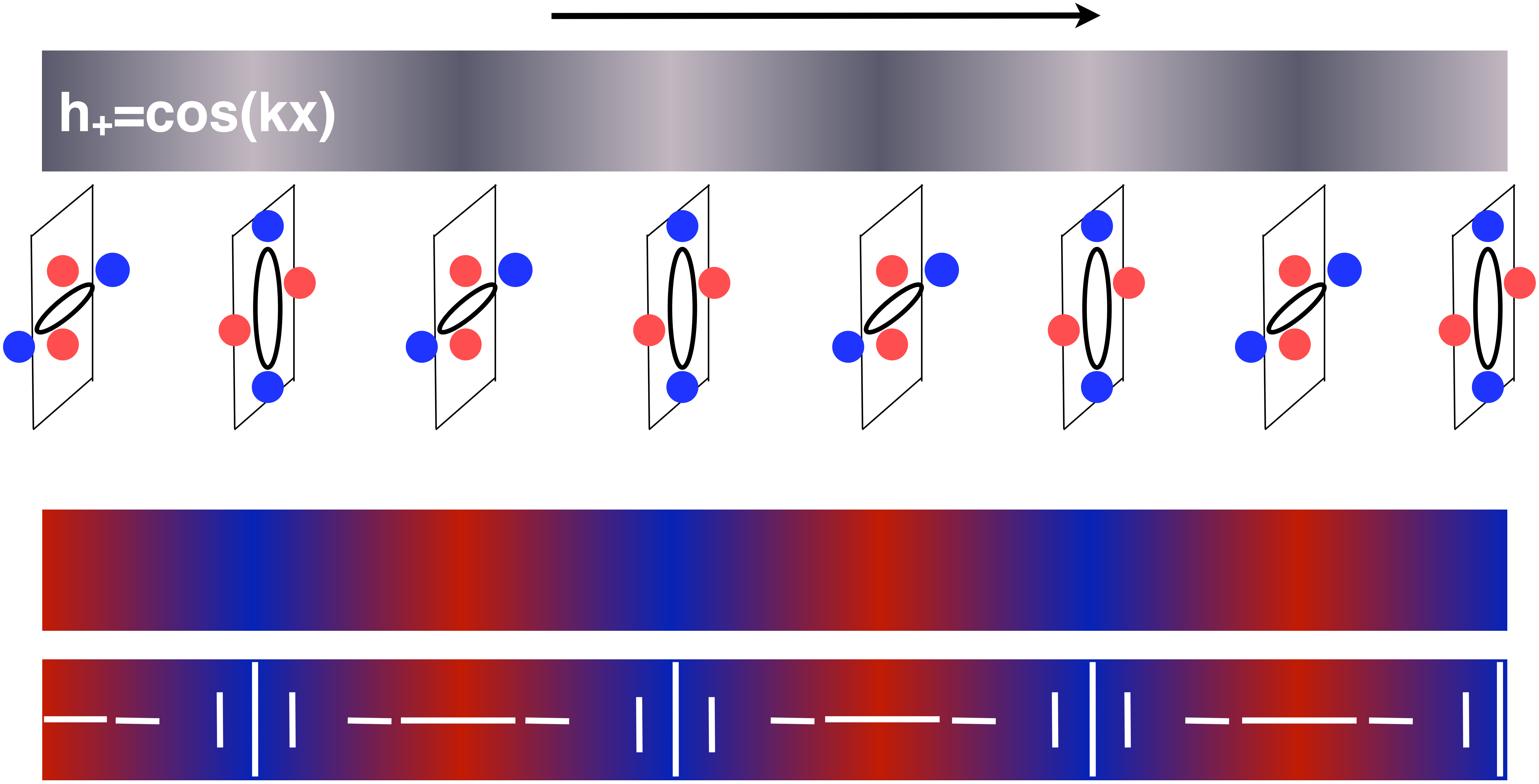
- **E mode**: Parity even
- **B mode**: Parity odd

Parity

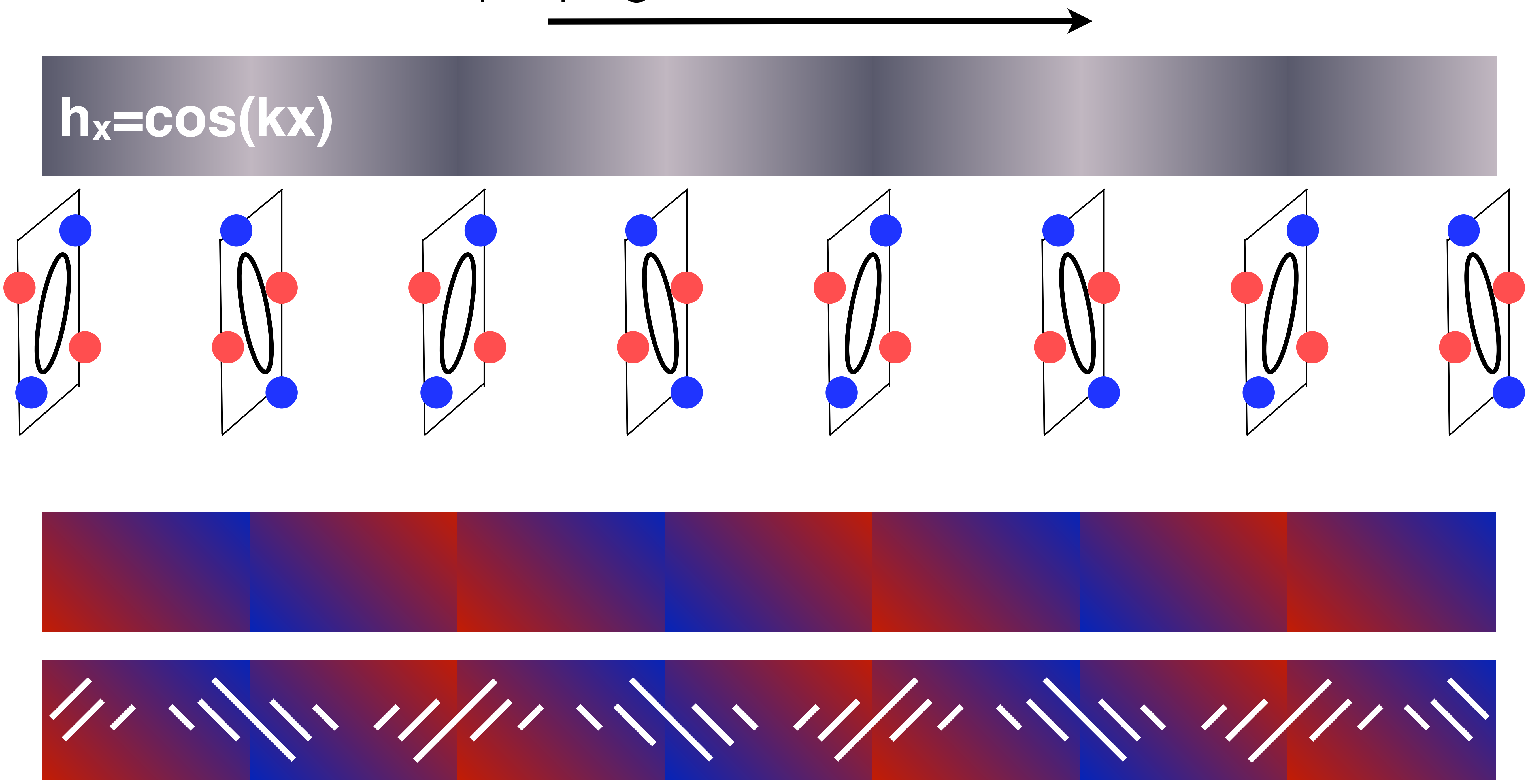


- **E mode**: Parity even
- **B mode**: Parity odd

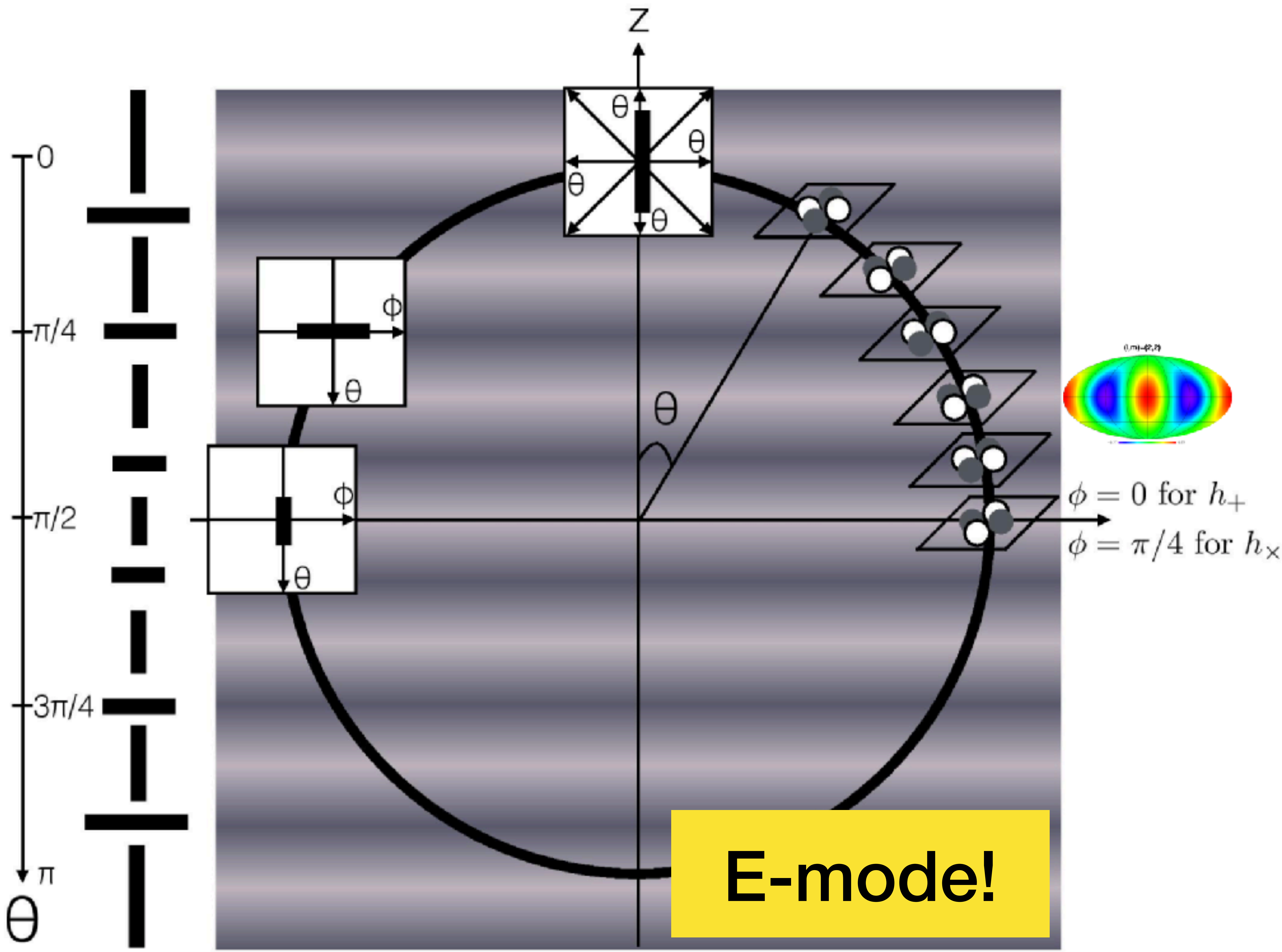
propagation direction of GW



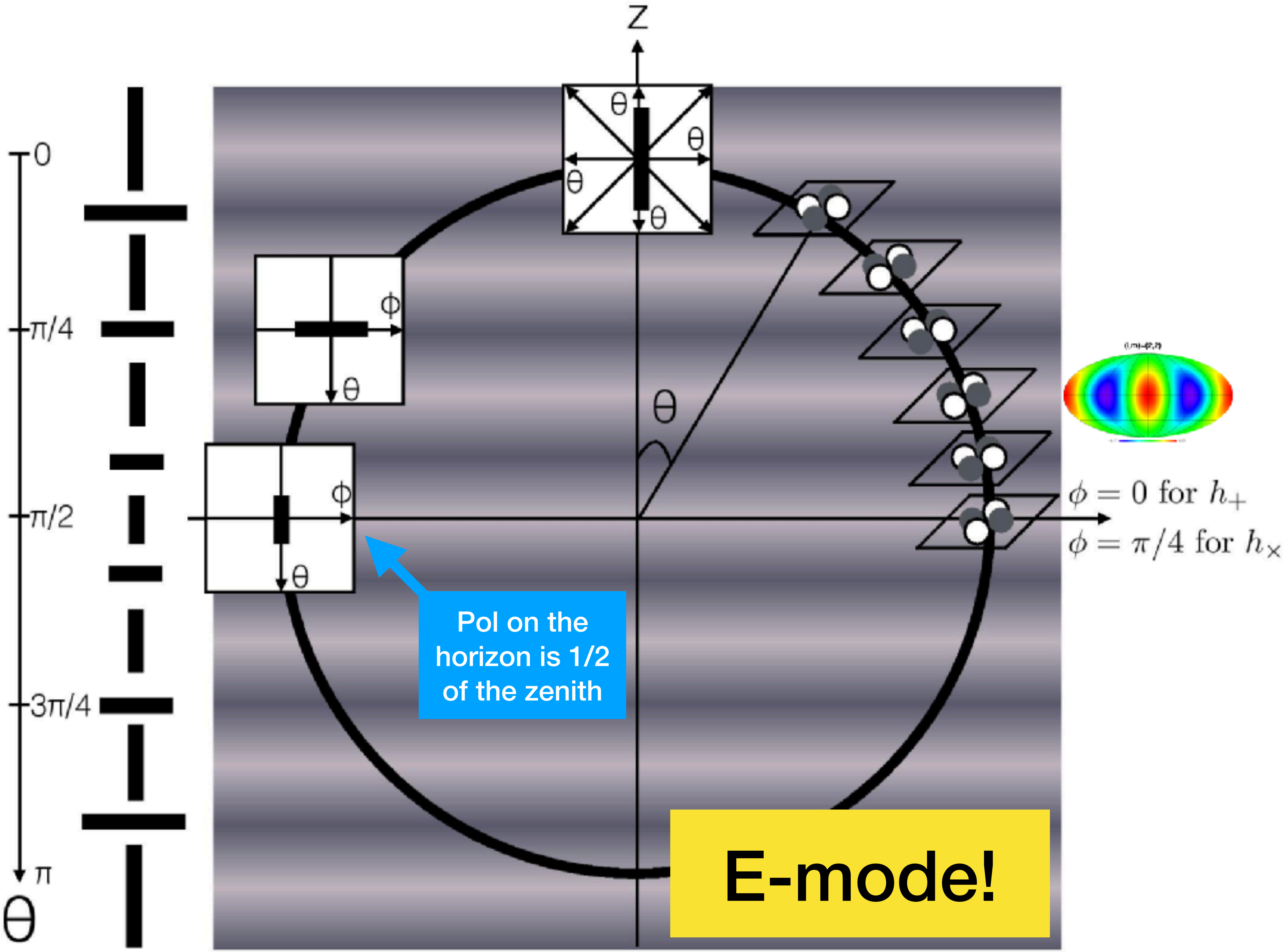
Polarisation directions perpendicular/parallel to the wavenumber vector -> **E mode polarisation** propagation direction of GW

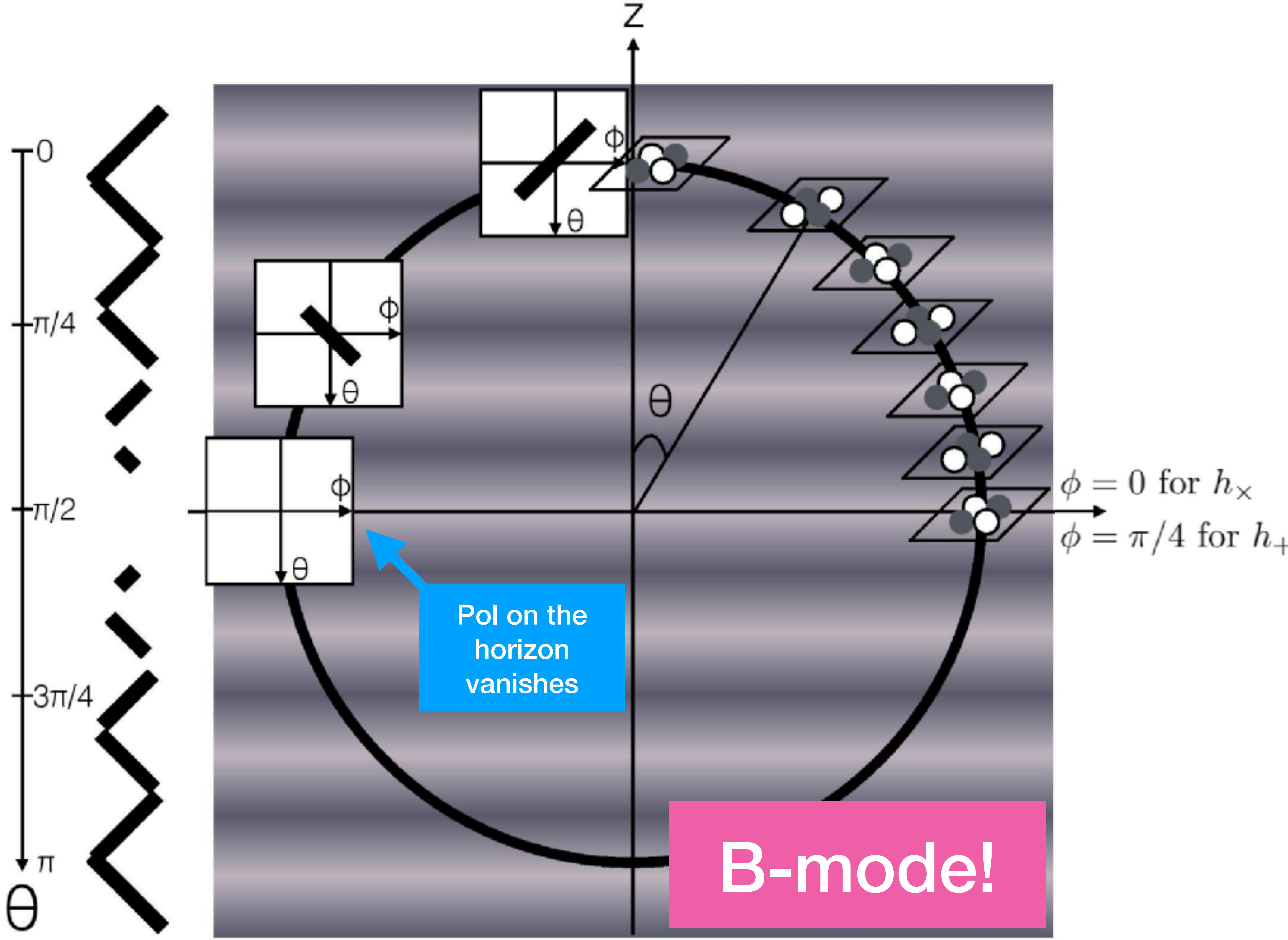


Polarisation directions 45 degrees tilted from to the wavenumber vector -> **B mode polarisation**



z
0
π/4
π/2
3π/4
π
θ
ϕ
$\phi = 0$ for h_+
$\phi = \pi/4$ for $h_\times$
E-mode!


Z
0
π/4
π/2
3π/4
π
θ
θ
φ
φ = 0 for h₊
φ = π/4 for h×
Pol on the horizon is 1/2 of the zenith
E-mode!



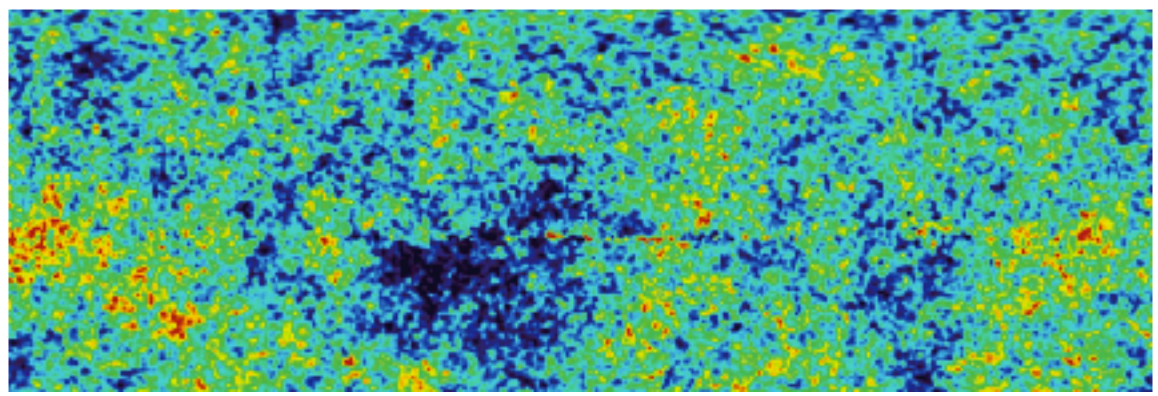
z
0
π/4
π/2
3π/4
π
θ
ϕ
θ
$\phi = 0$ for $h_\times$
$\phi = \pi/4$ for h_+
Pol on the horizon vanishes
B-mode!

Inflationary Predictions

ζ

scalar mode

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

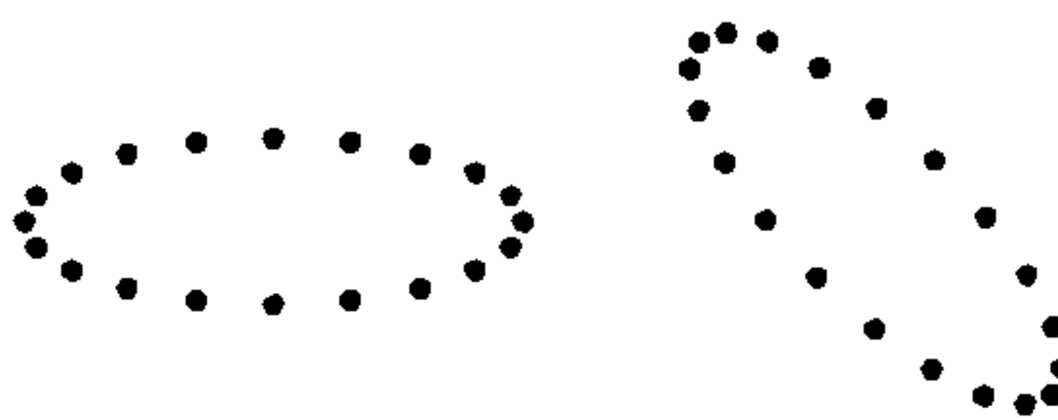


Mukhanov&Chibisov (1981)
Guth & Pi (1982)
Hawking (1982)
Starobinsky (1982)
Bardeen, Steinhardt&Turner (1983)

h_{ij}

tensor mode

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



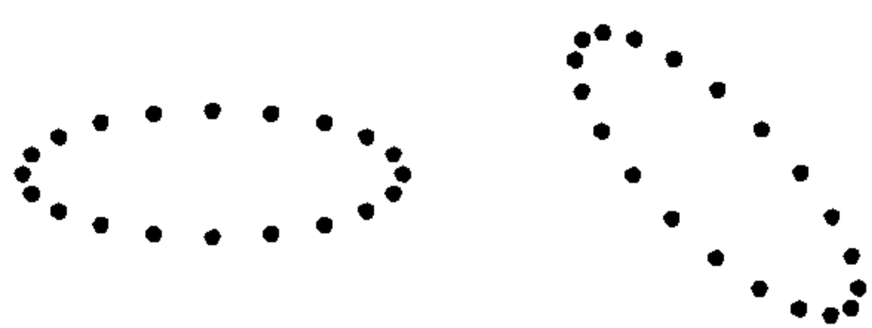
Grishchuk (1974)
Starobinsky (1979)

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
- $\mathbf{h_{ij}}$: "gravitational waves" (tensor mode)
  - Perturbation that does not alter the determinant



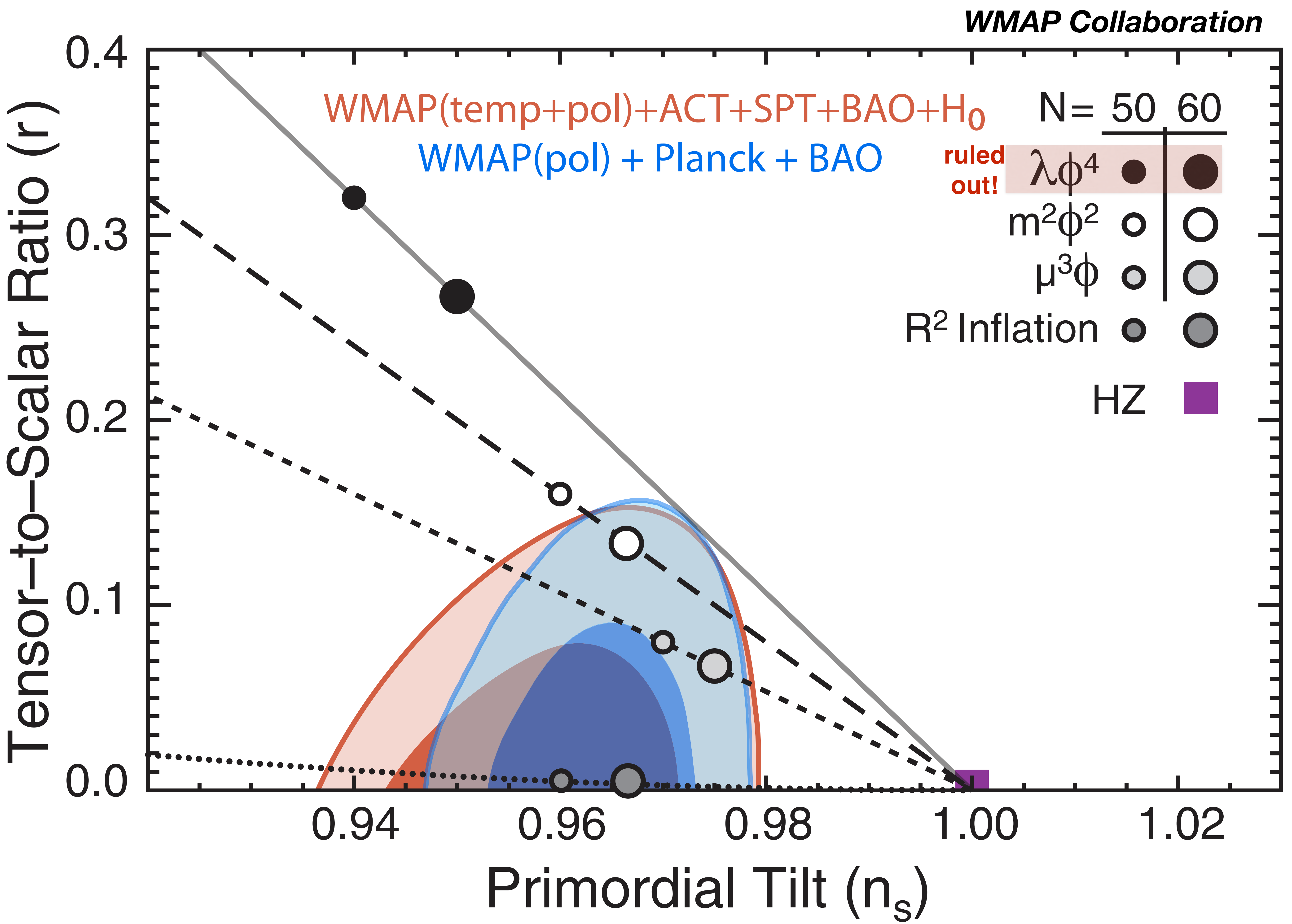
$$\sum_i h_{ii} = 0$$

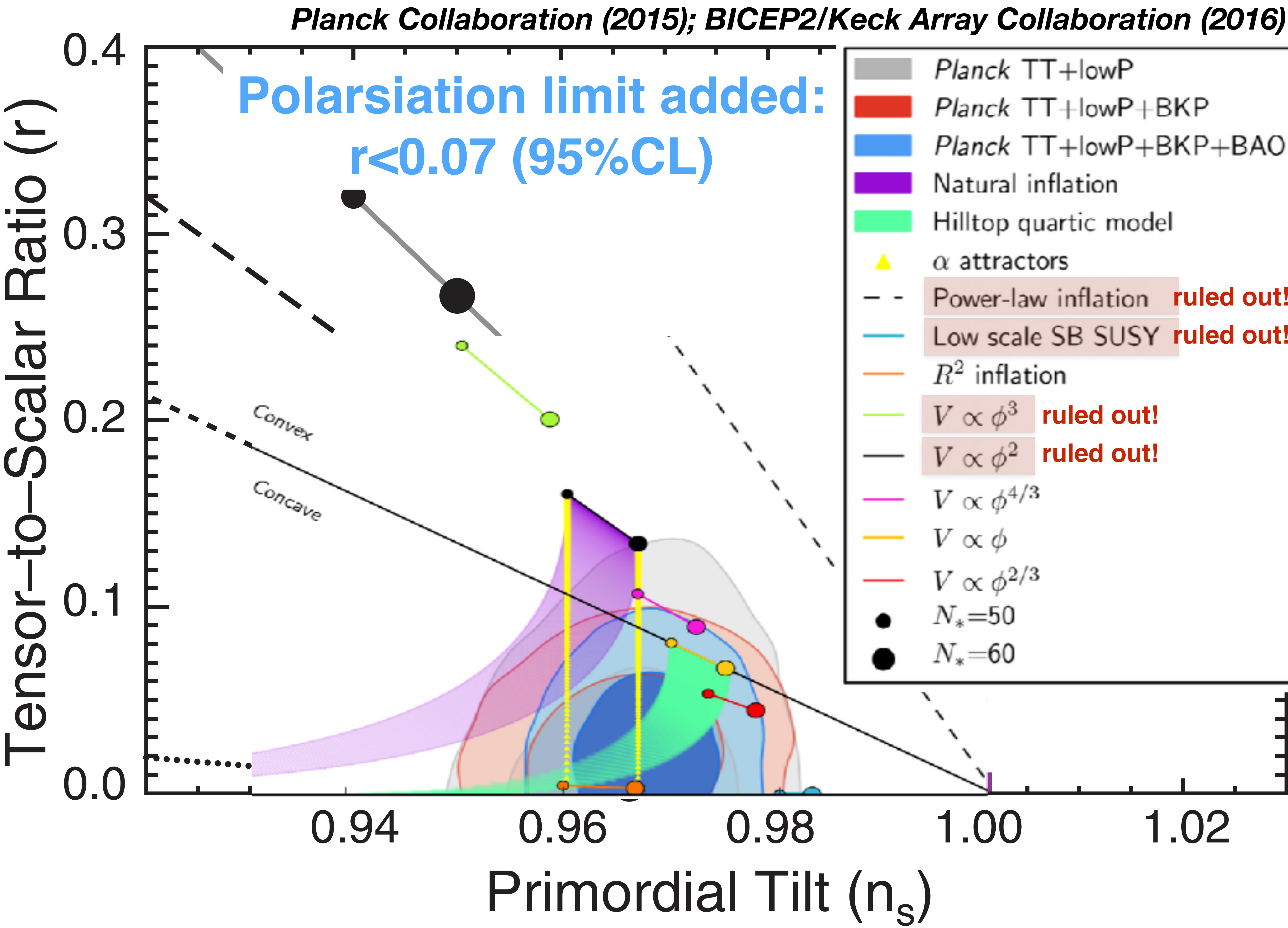
Tensor-to-scalar Ratio

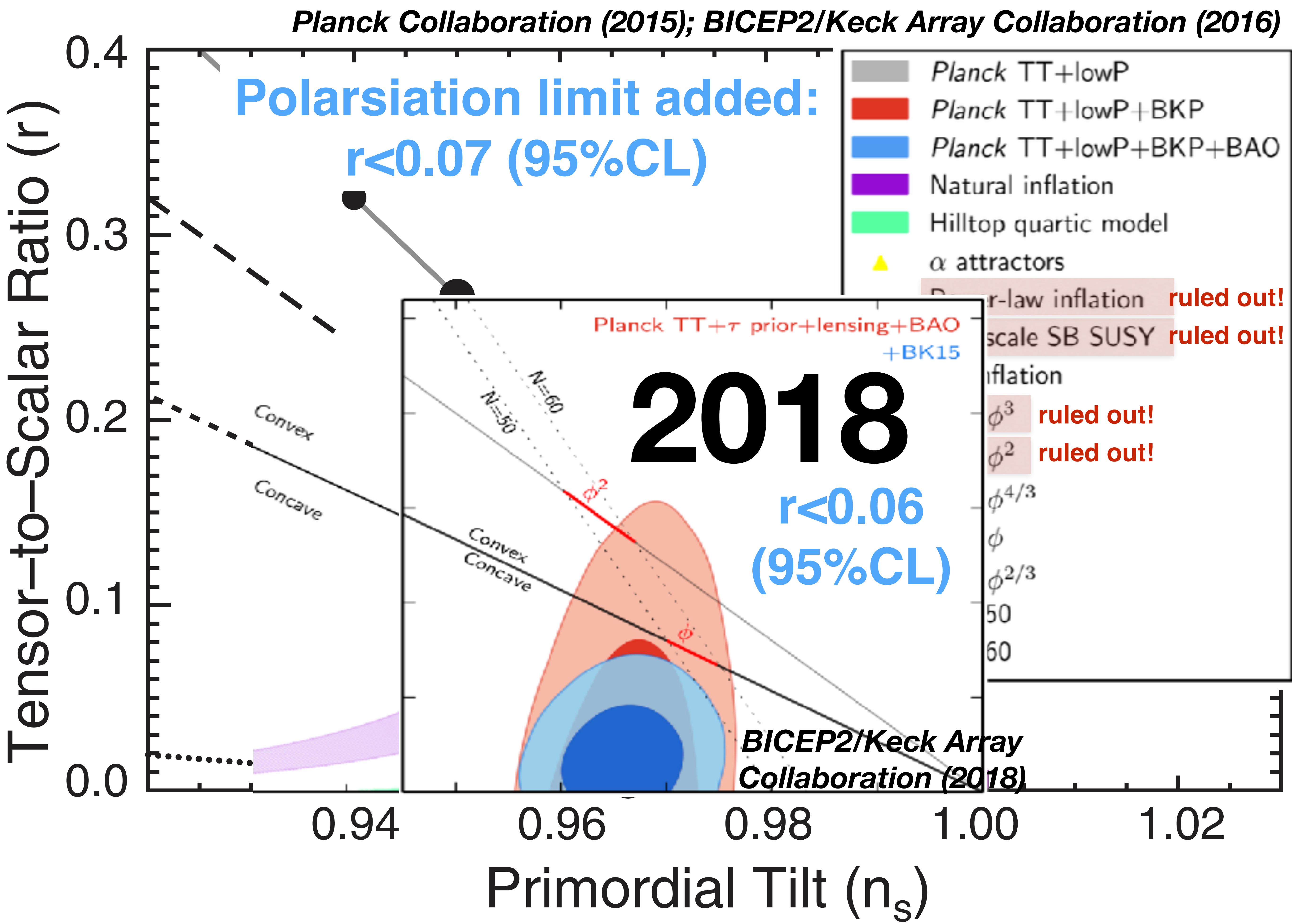
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

- 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)
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 (n_s)
Convex
Concave
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
ruled out!
Low scale SB SUSY
ruled out!
R^2 inflation
$V \propto \phi^3$
ruled out!
$V \propto \phi^2$
ruled out!
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
N_*=50
N_*=60



Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Tensor–to–Scalar Ratio (r)
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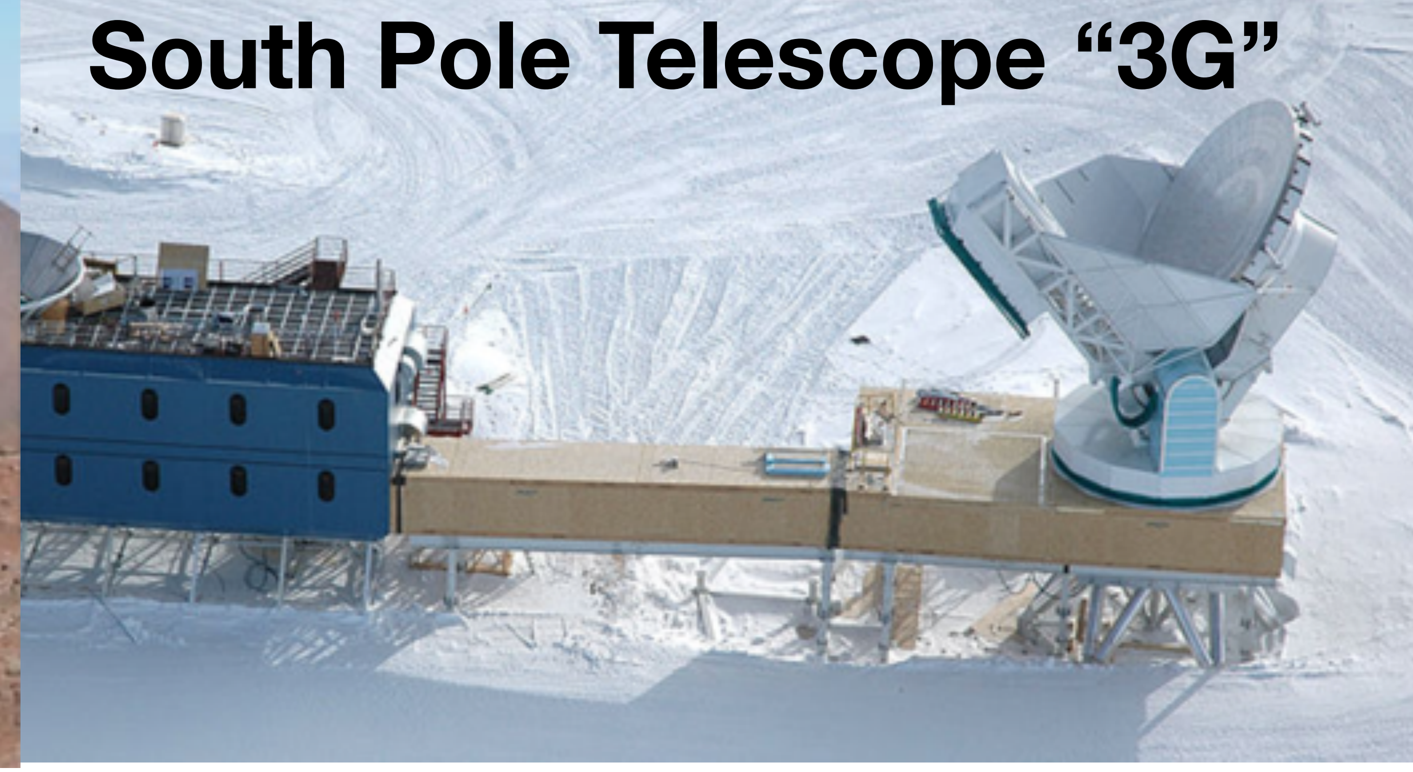
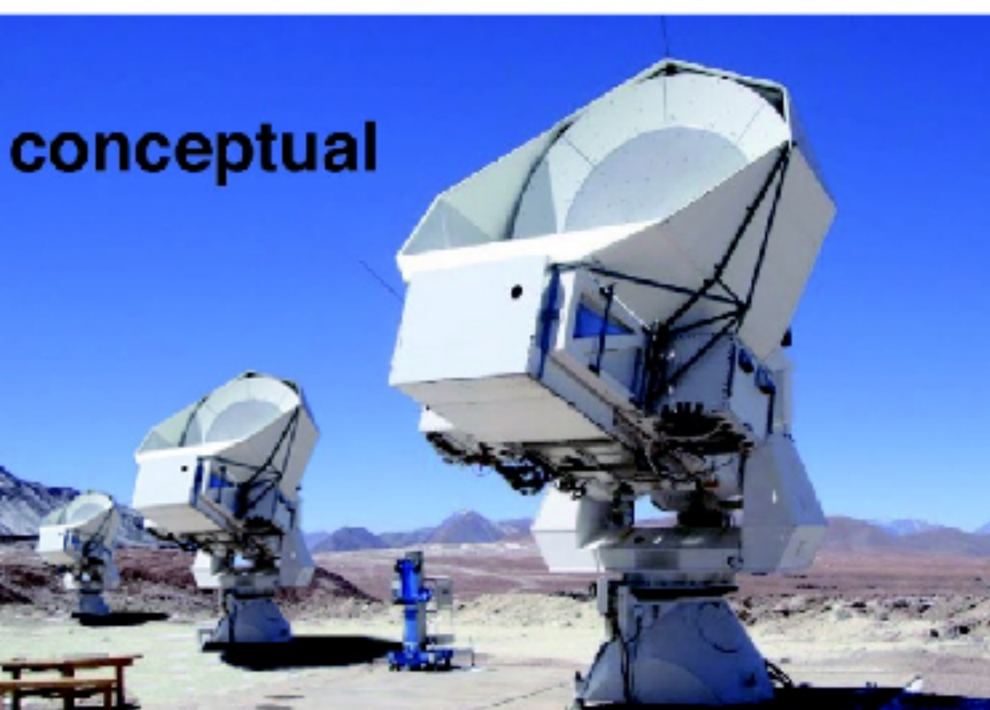
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
ruled out!
ruled out!
ϕ^3
ruled out!
ϕ^2
ruled out!
$\phi^{4/3}$
ϕ
$\phi^{2/3}$
Convex
Concave
Planck TT+τ prior+lensing+BAO
+BK15
2018
r<0.06
(95%CL)
N=60
N=50
ϕ^2
ϕ
Convex
Concave
BICEP2/Keck Array
Collaboration (2018)

CMB: Experimental Landscape



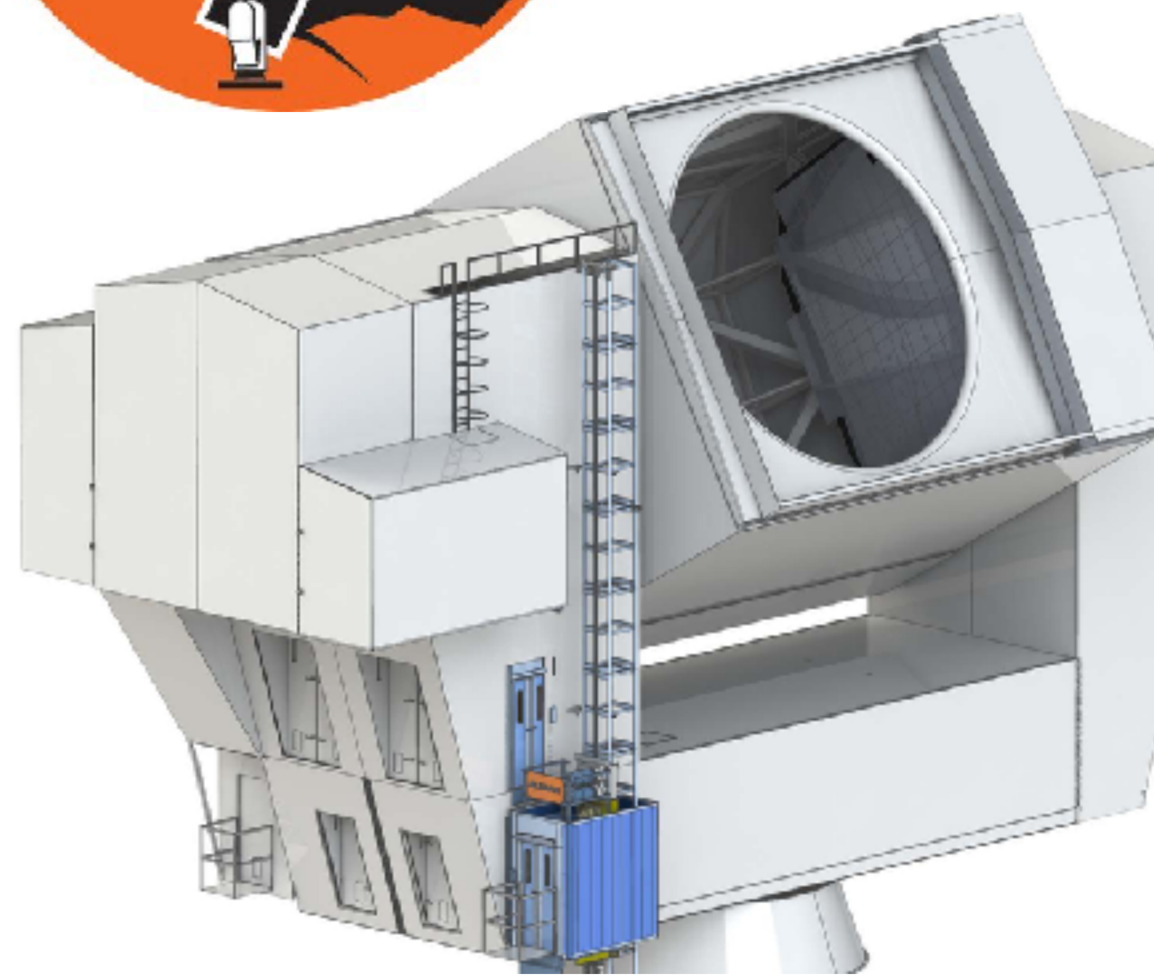
What comes next?

The Simons Array

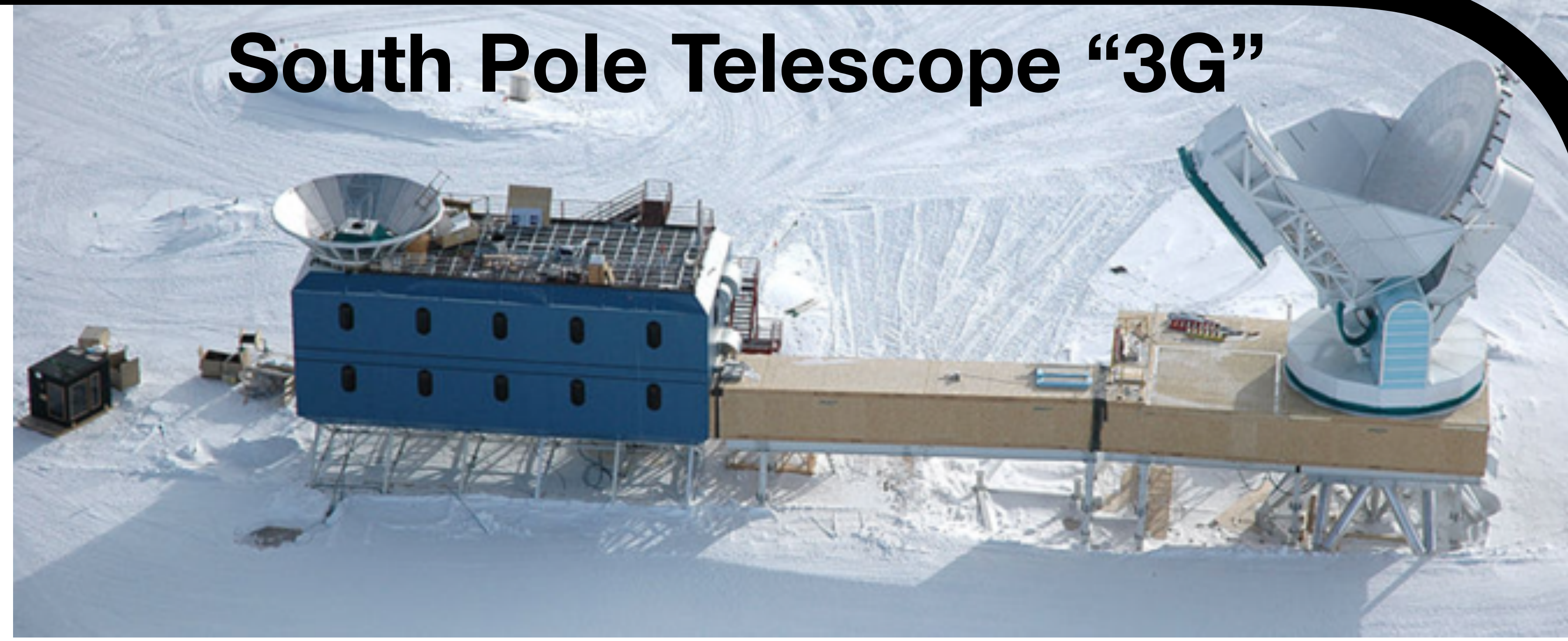


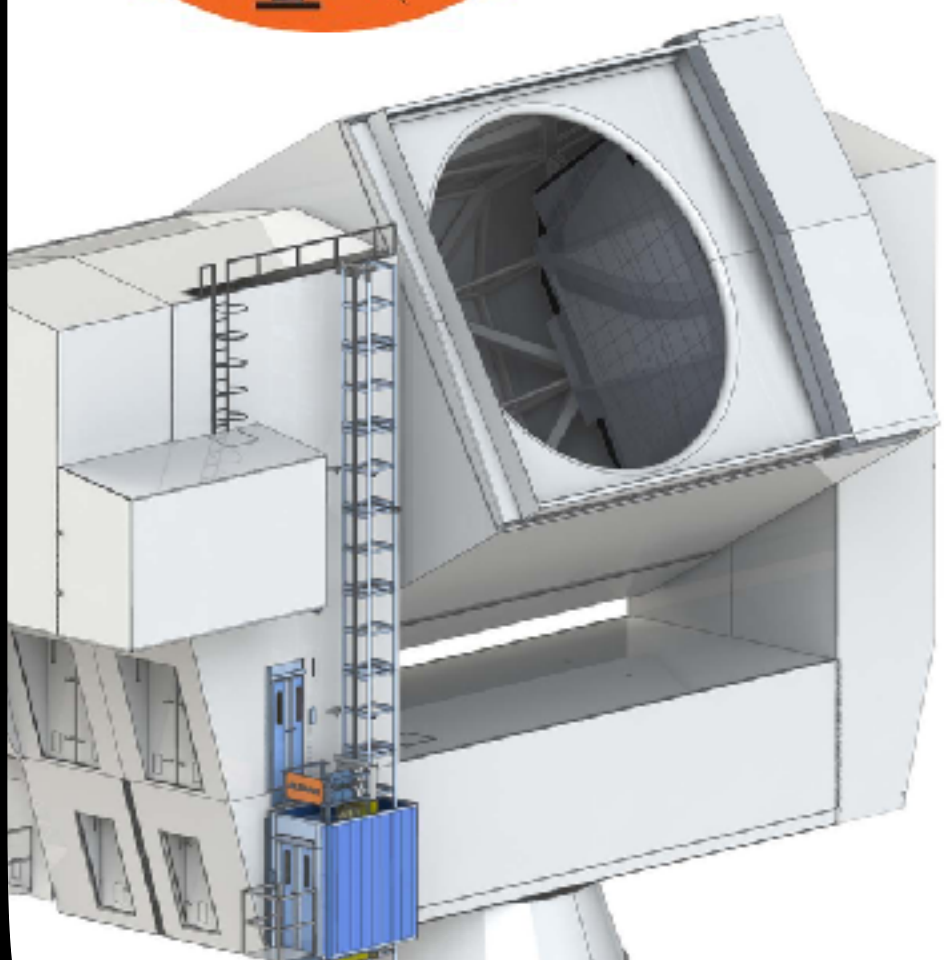
SIMONS
OBSERVATORY

The Simons Array



SIMONS OBSERVATORY





CMB-S4(?)

The Biggest Enemy: Polarised Dust Emission

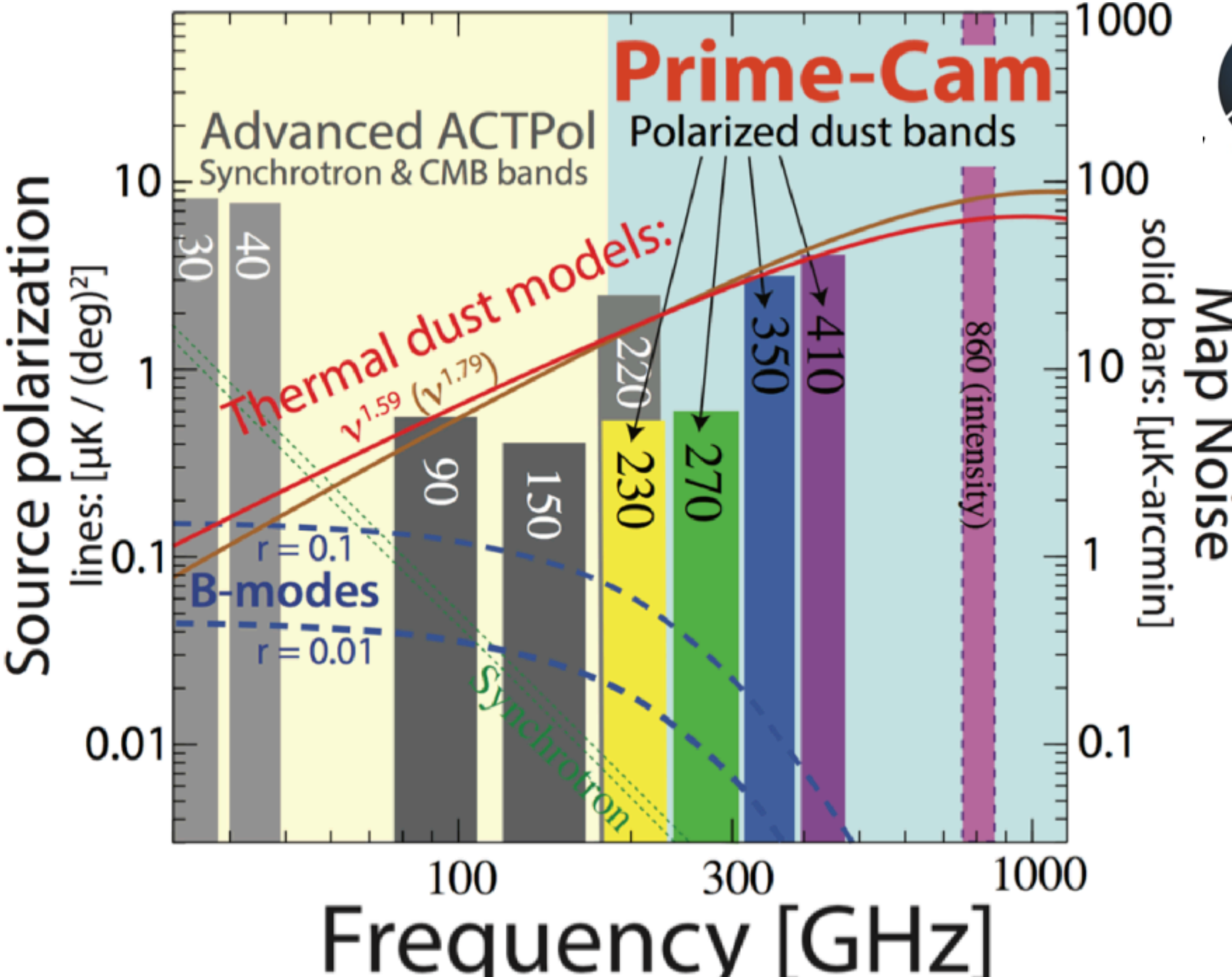
- The upcoming data will **NOT** be limited by statistics, but by systematic effects such as the Galactic contamination

- **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!

CCAT-p Collaboration



Frank Bertoldi's slide from the Florence meeting

Where is CCAT-p?

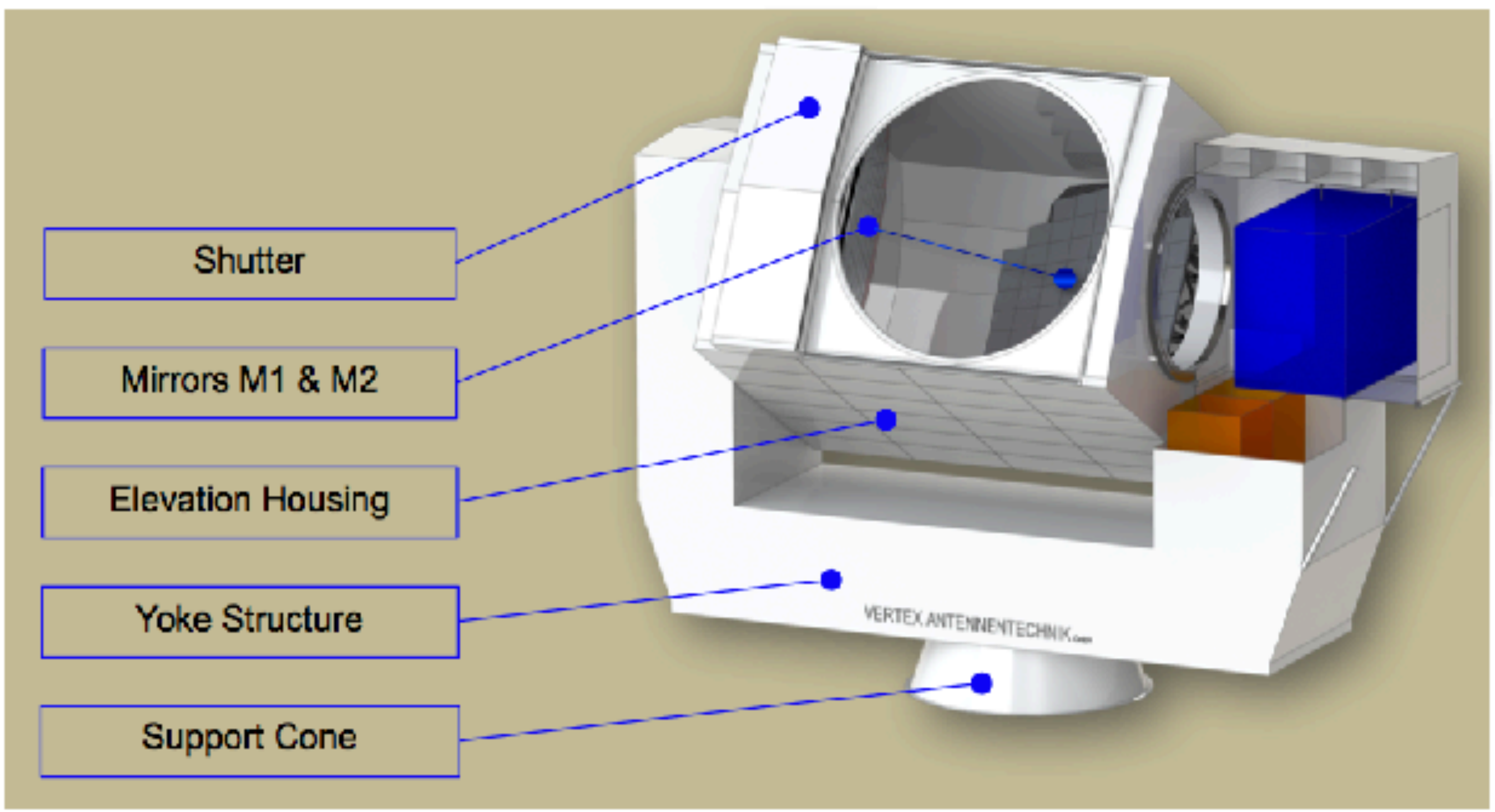
Cerro Chajnantor at 5600 m w/ TAO

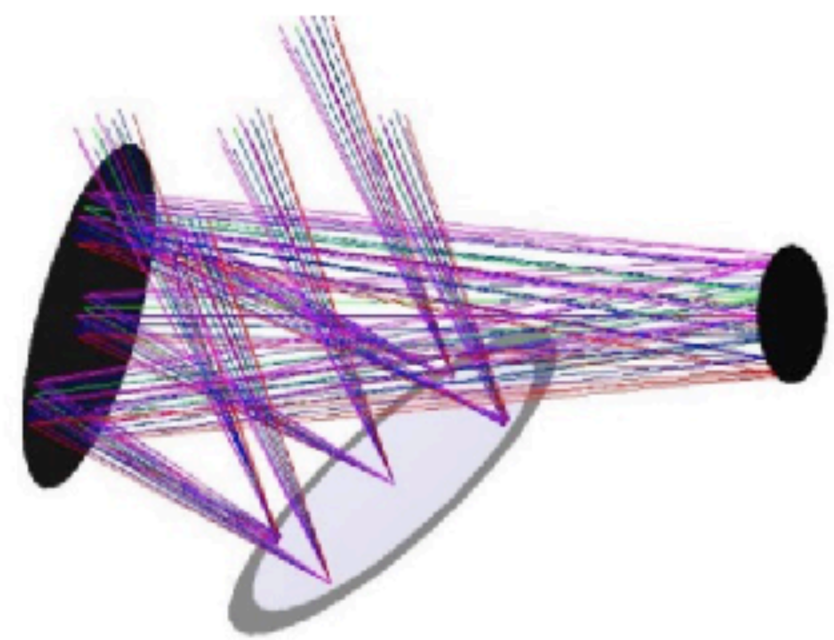
Frank Bertoldi's slide from the Florence meeting

What is CCAT-p?

CCAT-p

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



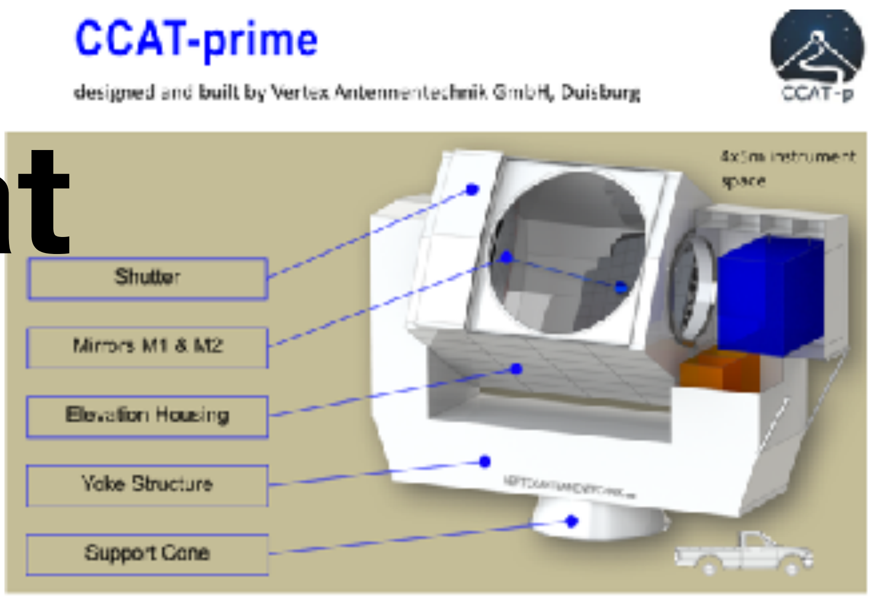


Cornell U. + German consortium + Canadian consortium + …

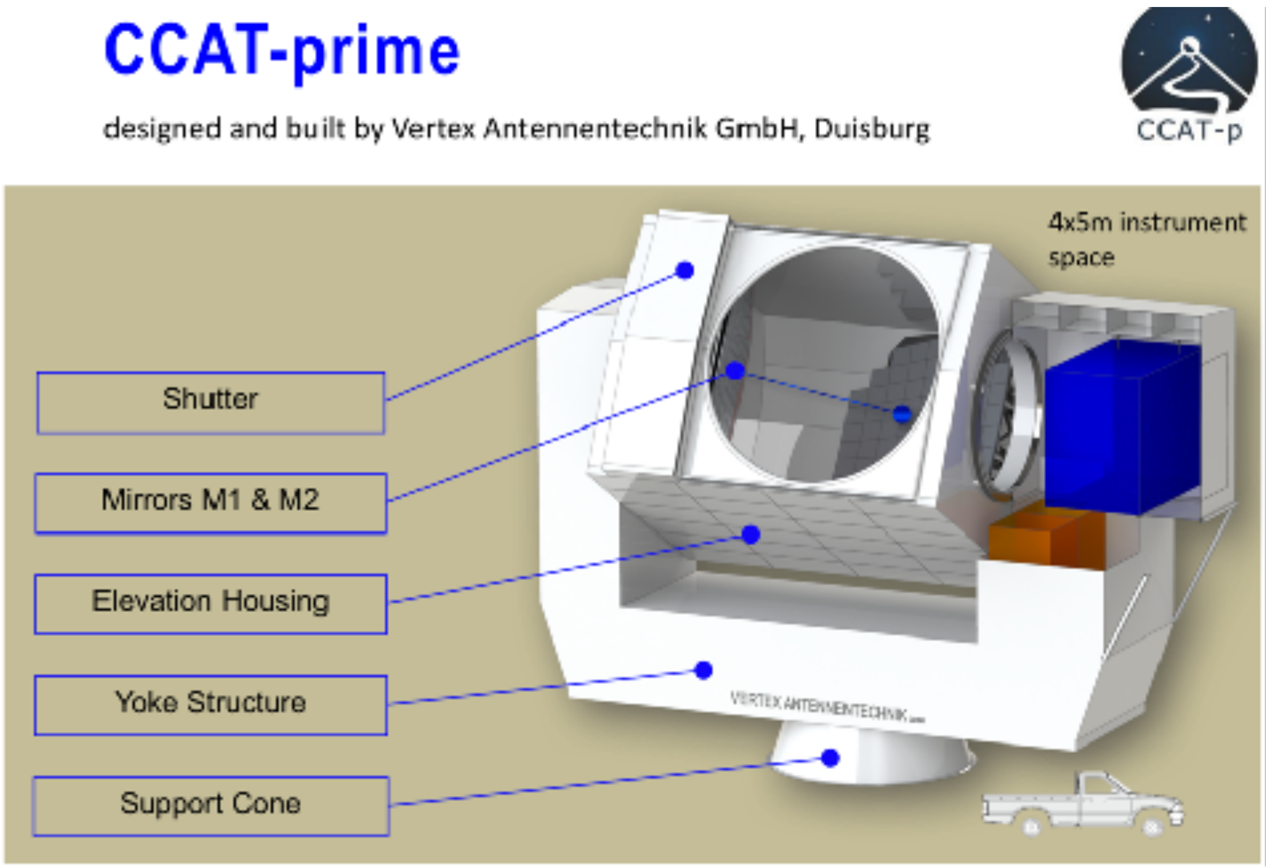
A Game Changer

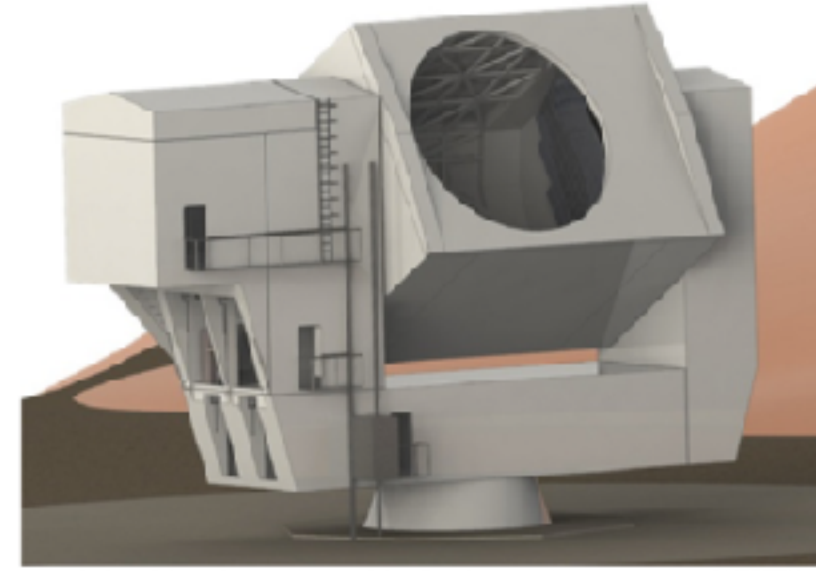
- **CCAT-p**: 6-m, **Cross-dragone** design, on Cerro Chajnantor (5600 m)

- **Germany makes great telescopes!**



- 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.





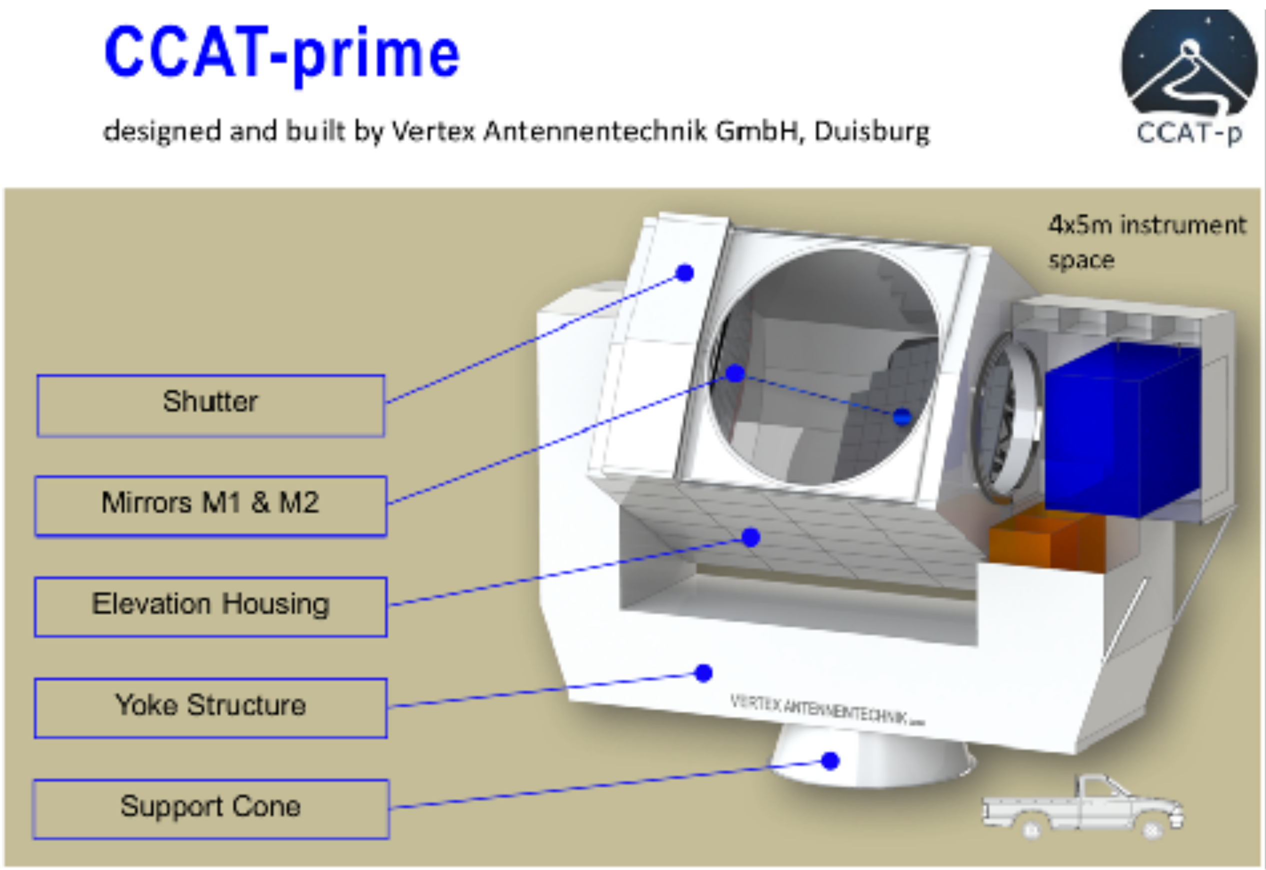
A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

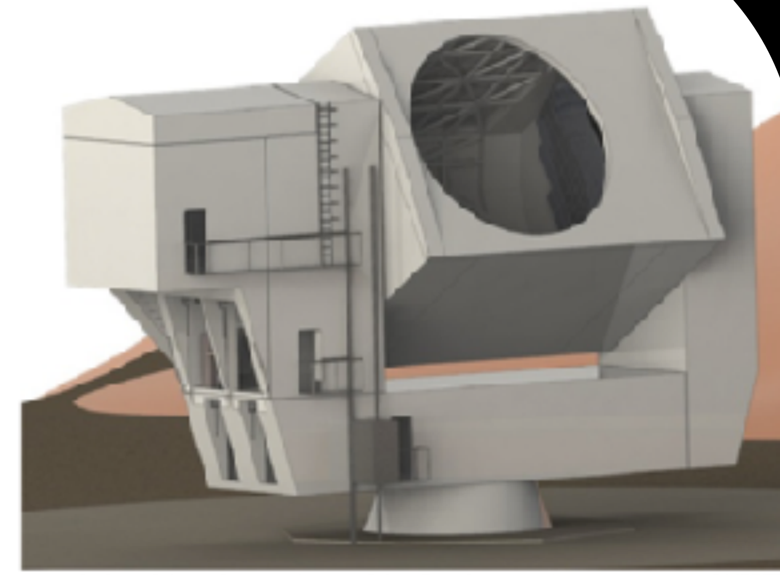
Simons Observatory (USA)

in collaboration

South Pole?

This could be "CMB-S4"





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

Simons Observatory (USA)

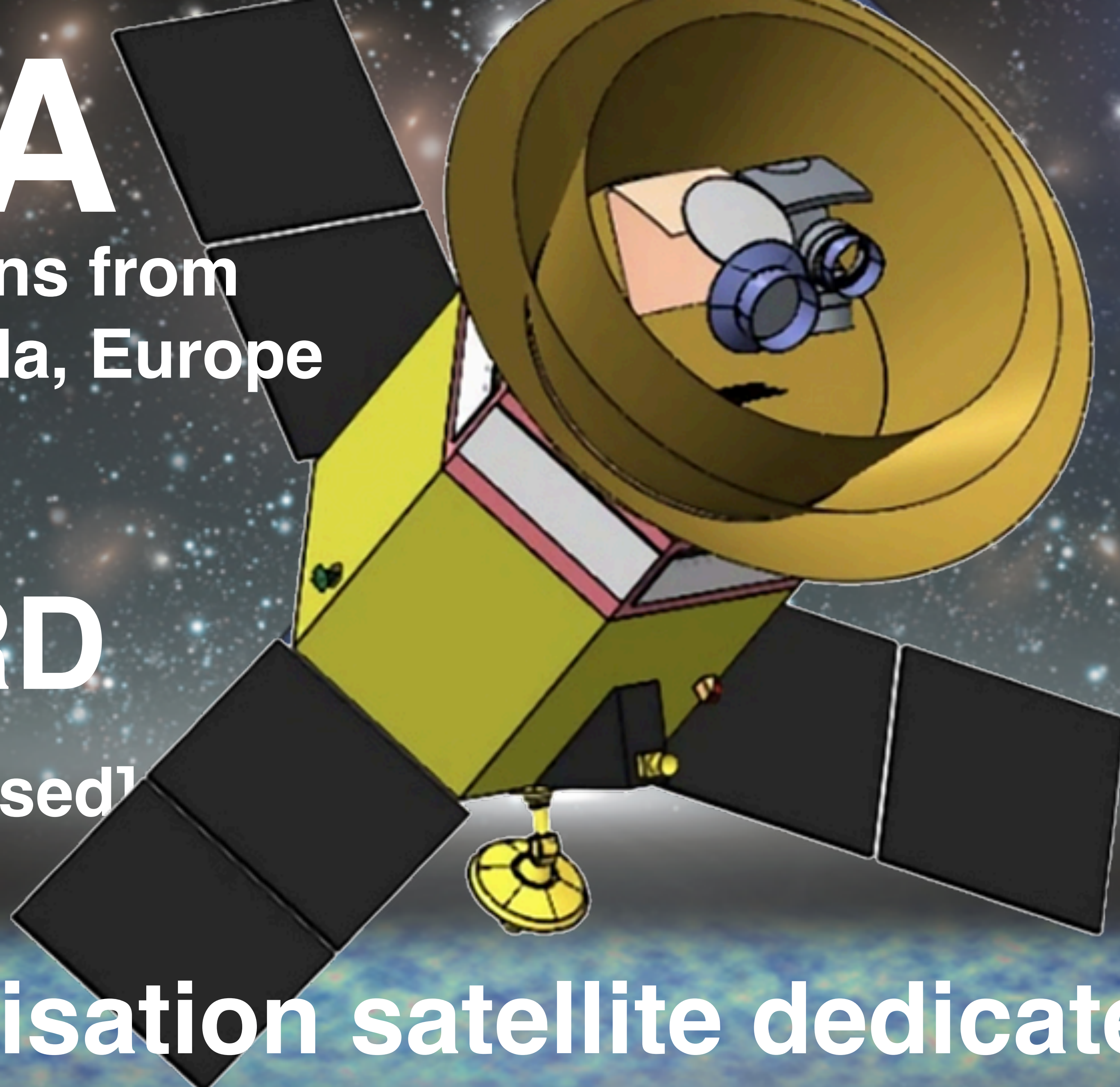
in collaboration

South Pole?

To have even more frequency coverage…

JAXA

+ participations from USA, Canada, Europe



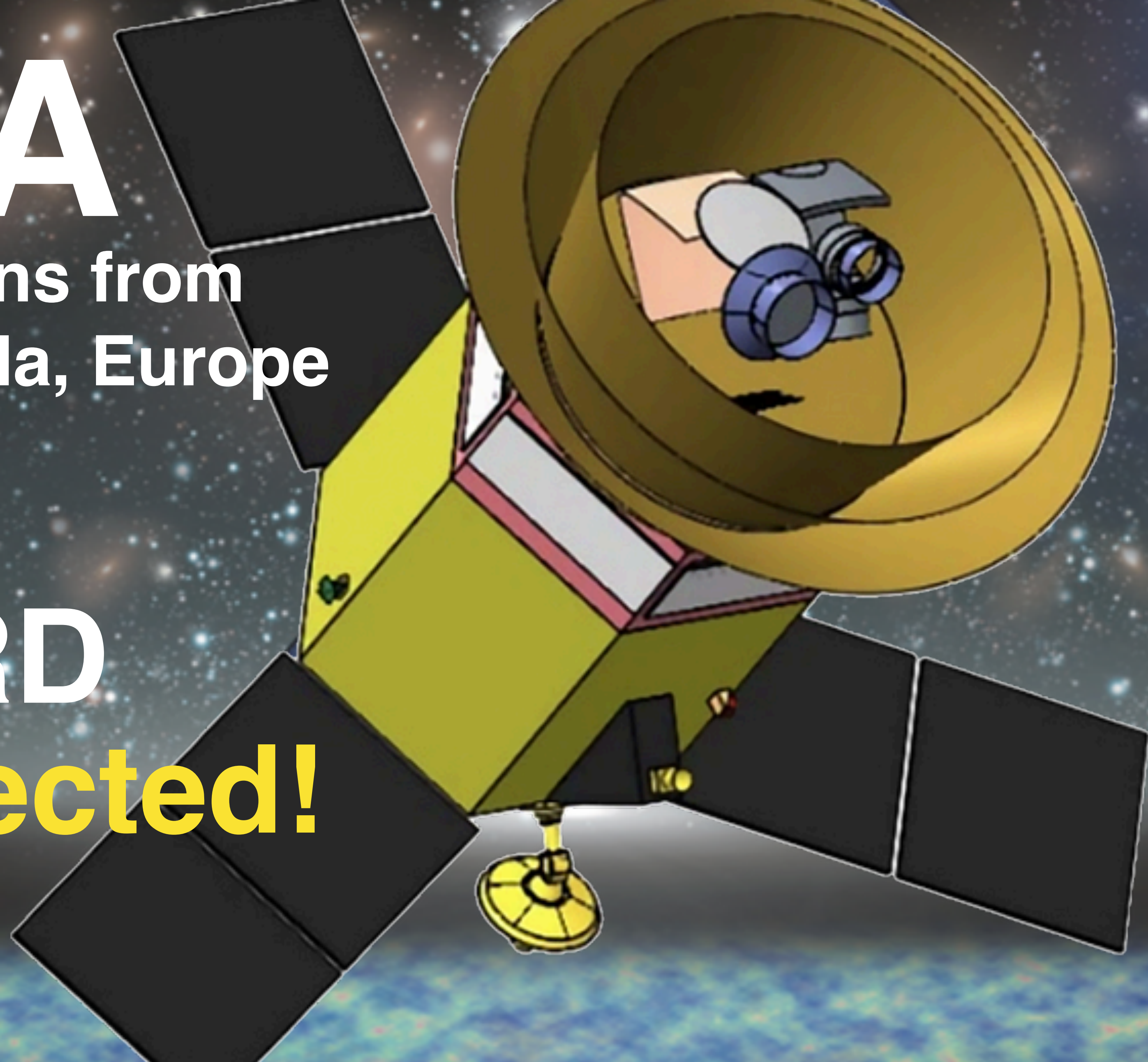
LiteBIRD

2027– [proposed]

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

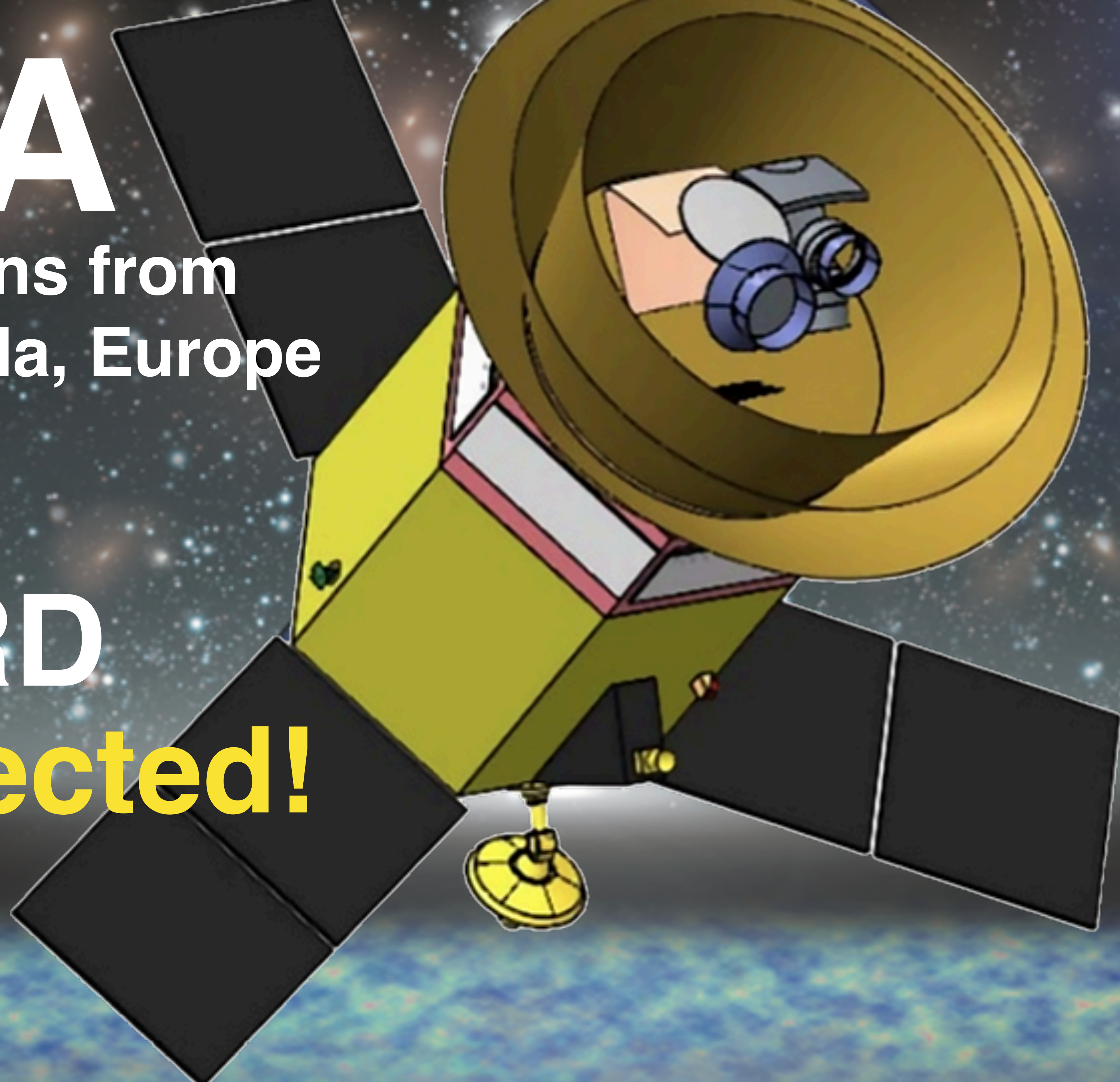
2027– **Selected!**

May 21: JAXA has chosen LiteBIRD as the strategic large-class mission.

We will go to L2!

JAXA

\+ participations from USA, Canada, Europe

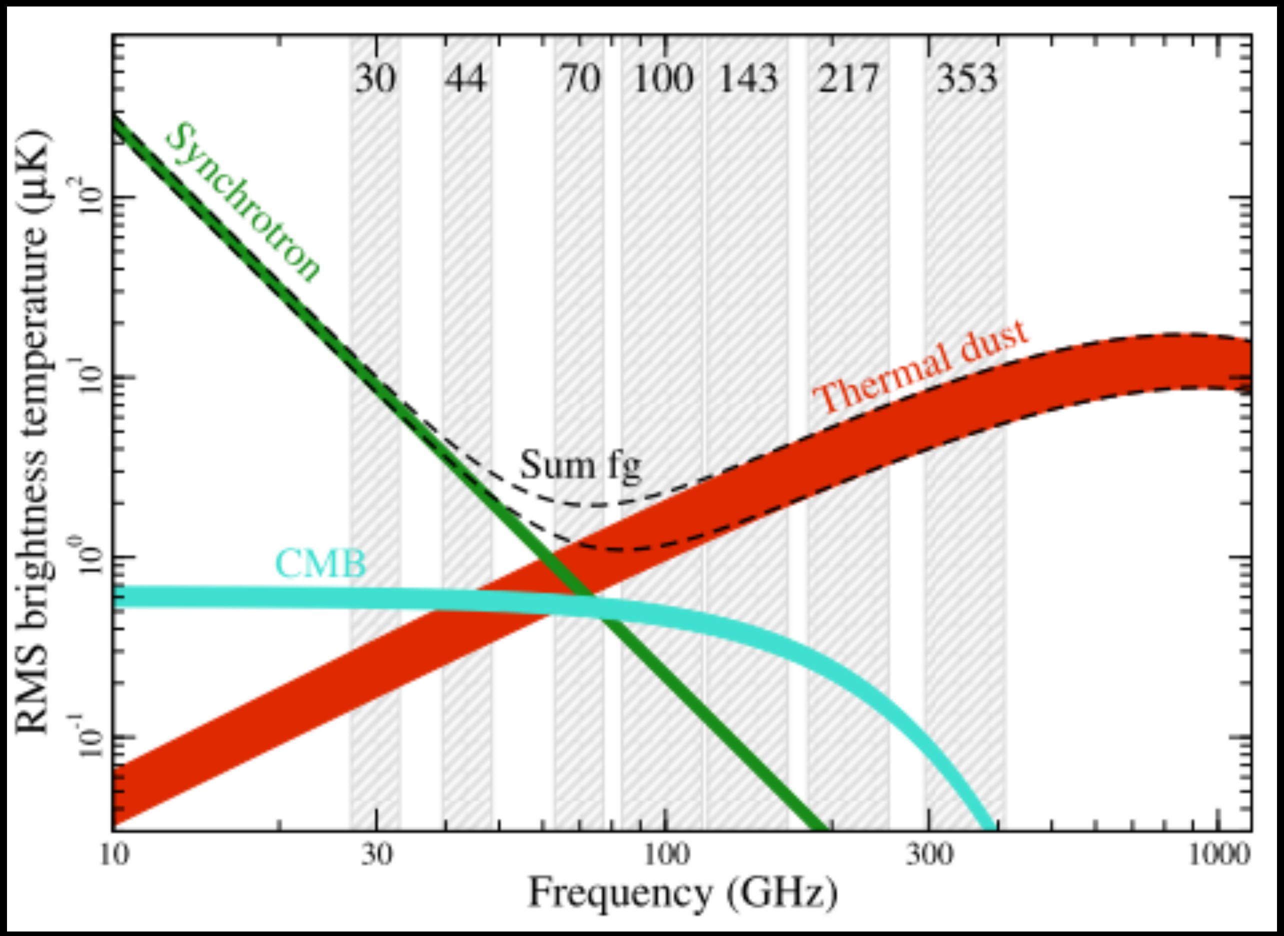


LiteBIRD

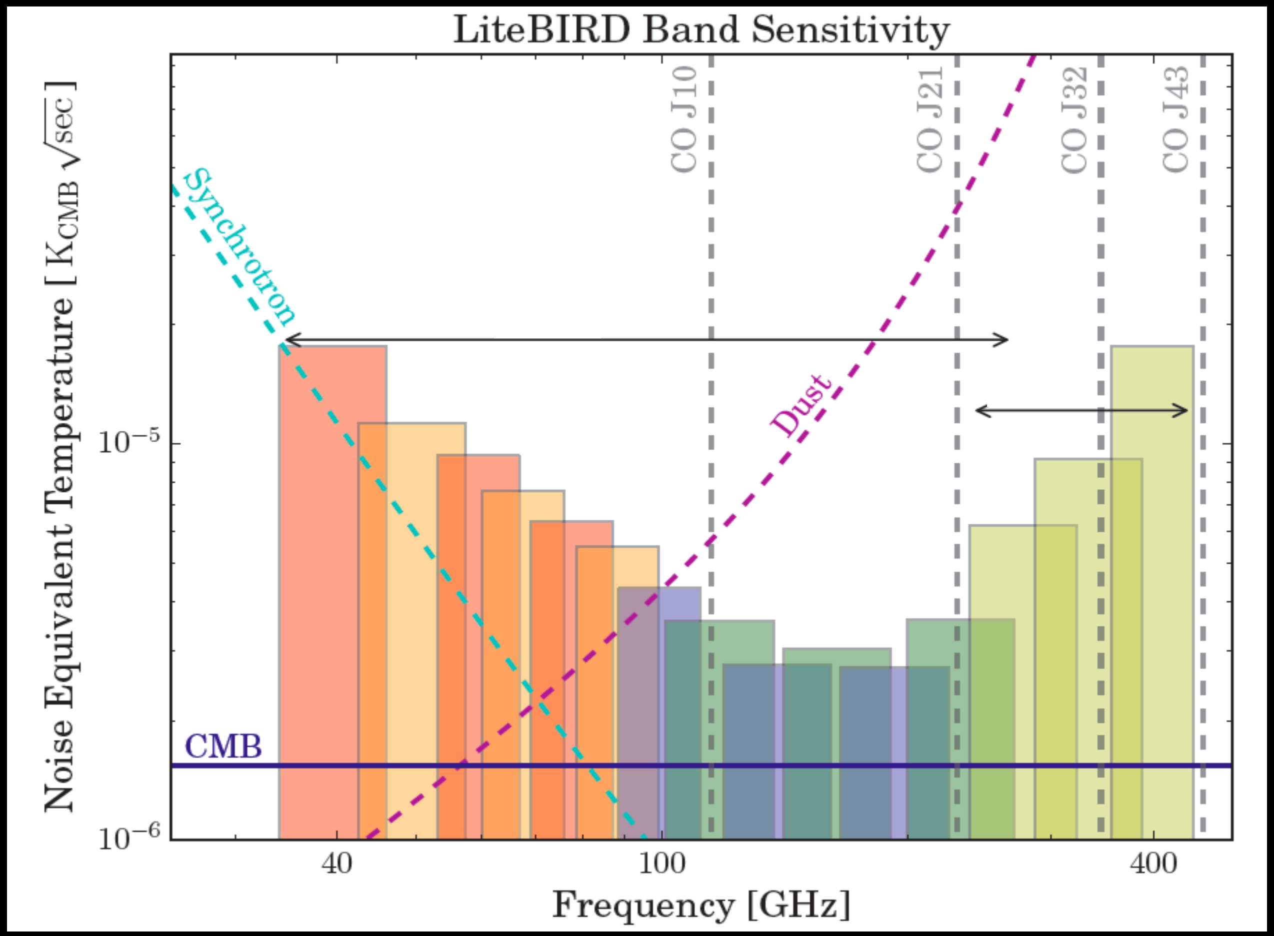
2027– **Selected!**

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

Foreground Removal



Polarized galactic emission (Planck X)



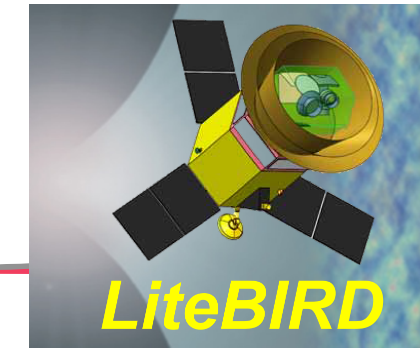
LiteBIRD: 15 frequency bands

- 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)

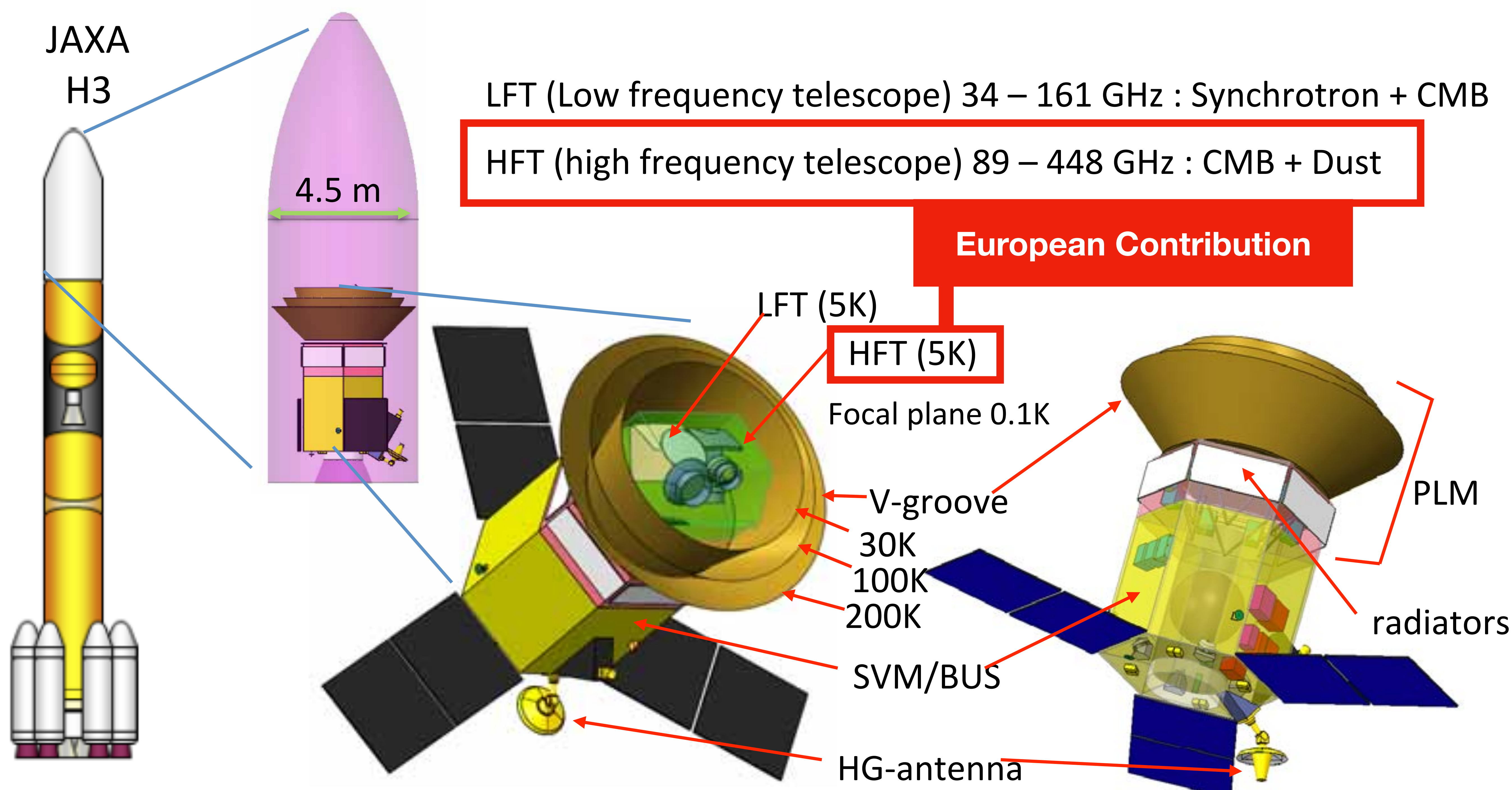
LiteBIRD Spacecraft



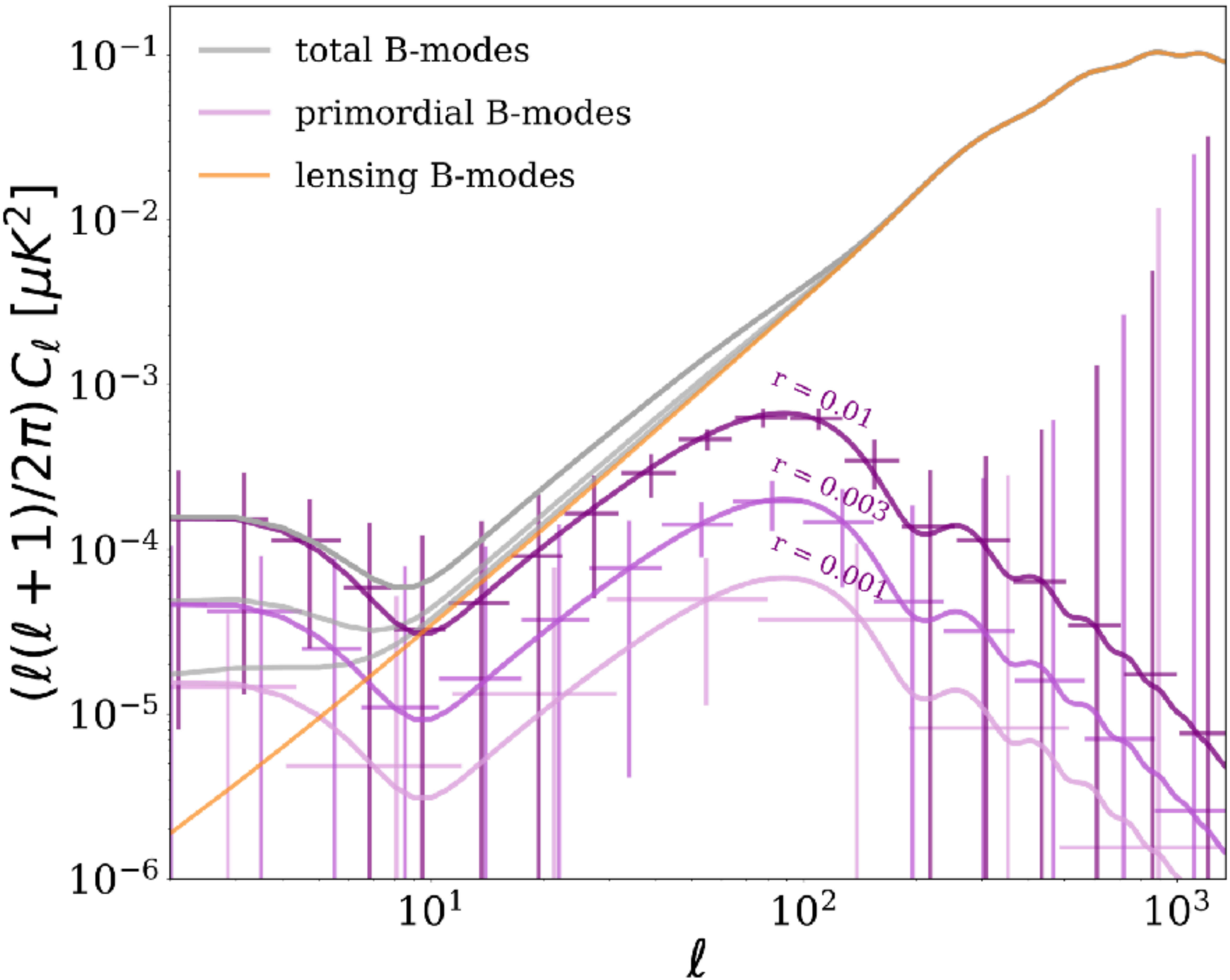
LFT (Low frequency telescope) 34 – 161 GHz : Synchrotron + CMB

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

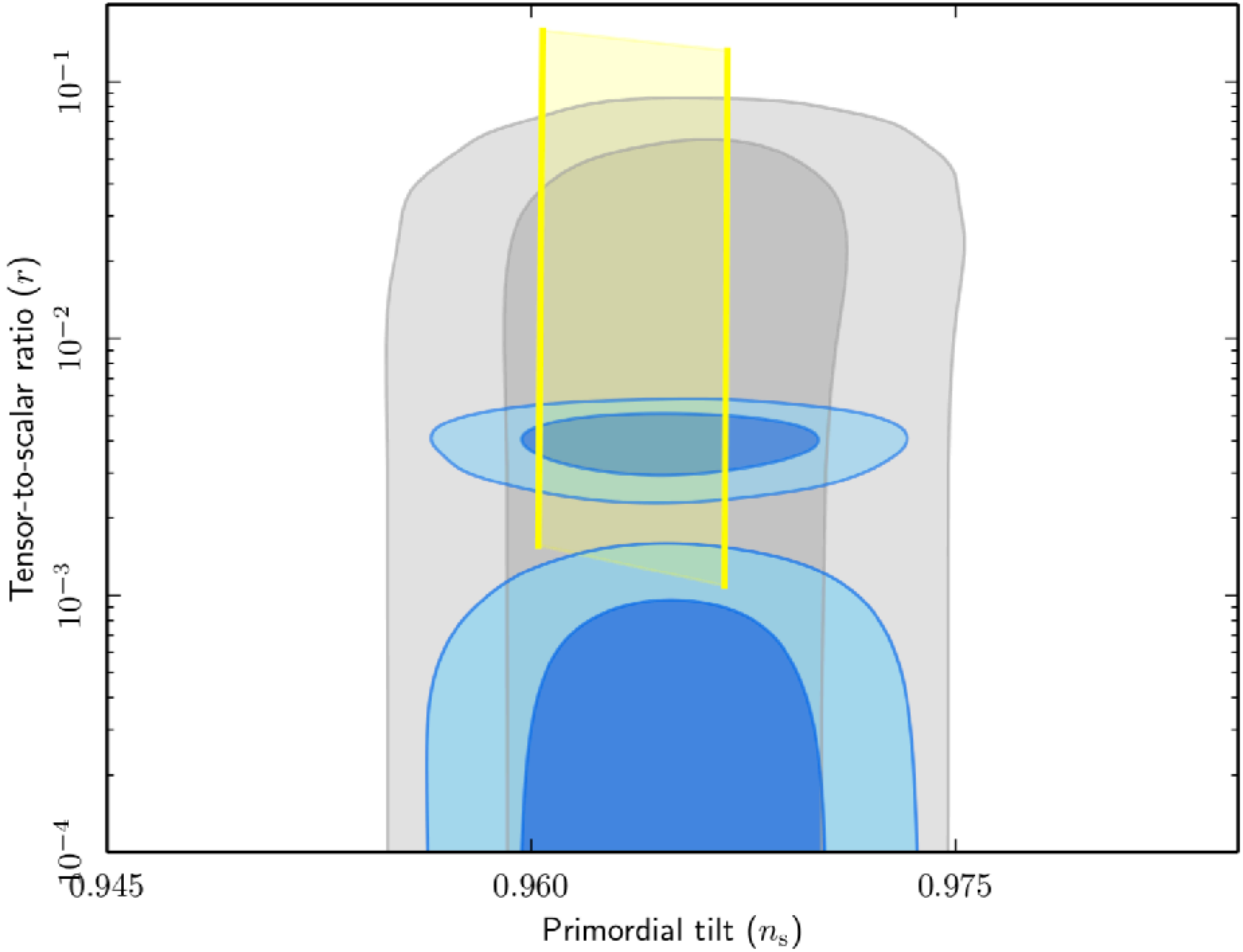
European Contribution



LiteBIRD Collaboration



LiteBIRD Collaboration



Final Remark

$$u''_{ij} + \left(k^2 - \frac{a''}{a}\right) u_{ij} = 16\pi G a^3 \boxed{T^{GW}_{ij}}$$

- We have ignored the source term during inflation, and considered only the vacuum fluctuation. Is this justified? **Maybe not!**

- *Further reading:*
    - B. Thorne et al., Phys. Rev. D, 97, 043506 (2018), arXiv:1707.03240
    - A. Agrawal et al., Phys. Rev. D, 97, 103526 (2018), arXiv:1707.03023
    - A. Maleknejad & E. Komatsu, JHEP, 05, 174 (2019), arXiv:1808.09076

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

Effect of T^{GW}