Future observations of the polarized Cosmic Microwave Background: expected science and challenges

Josquin Errard

Seminar @ LLR
7th of May, 2019

outline

1. Very general introduction: CMB, inflation and B-modes
2. CMB B-modes observations in practice
3. Race to inflation: an example, the Simons Observatory
4. Conclusions

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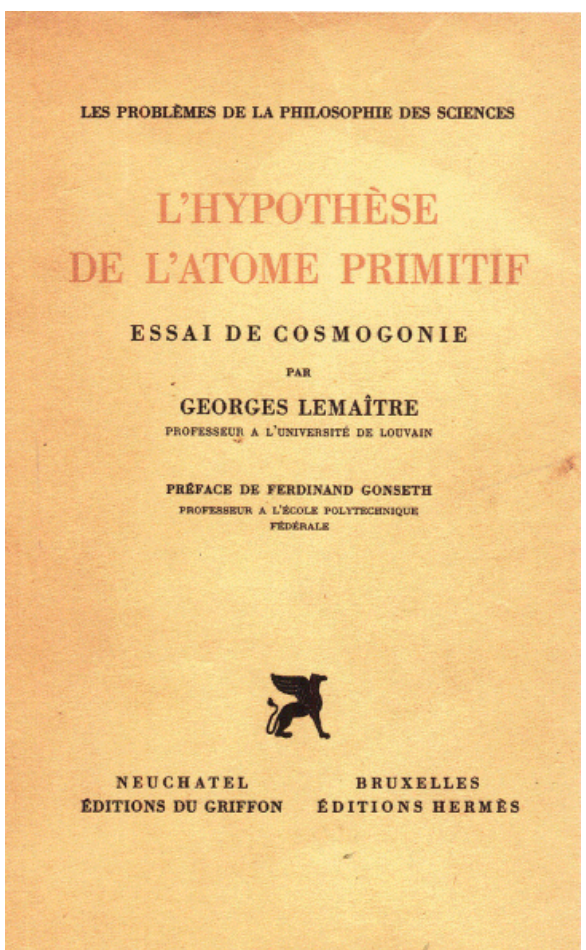
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Georges Lemaître
(1894-1966)



LES PROBLÈMES DE LA PHILOSOPHIE DES SCIENCES

L'HYPOTHÈSE
DE L'ATOME PRIMITIF

ESSAI DE COSMOGONIE

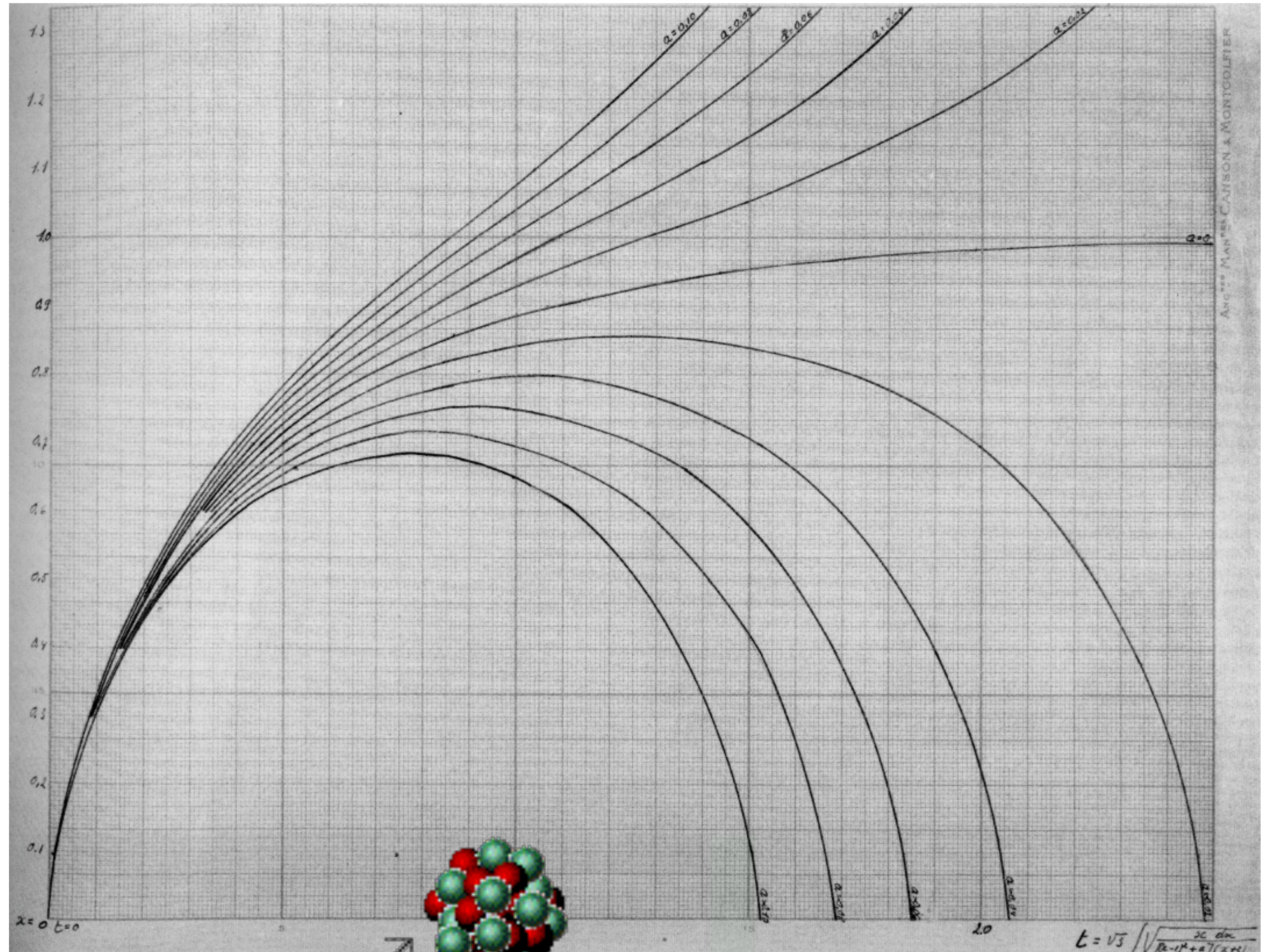
PAR

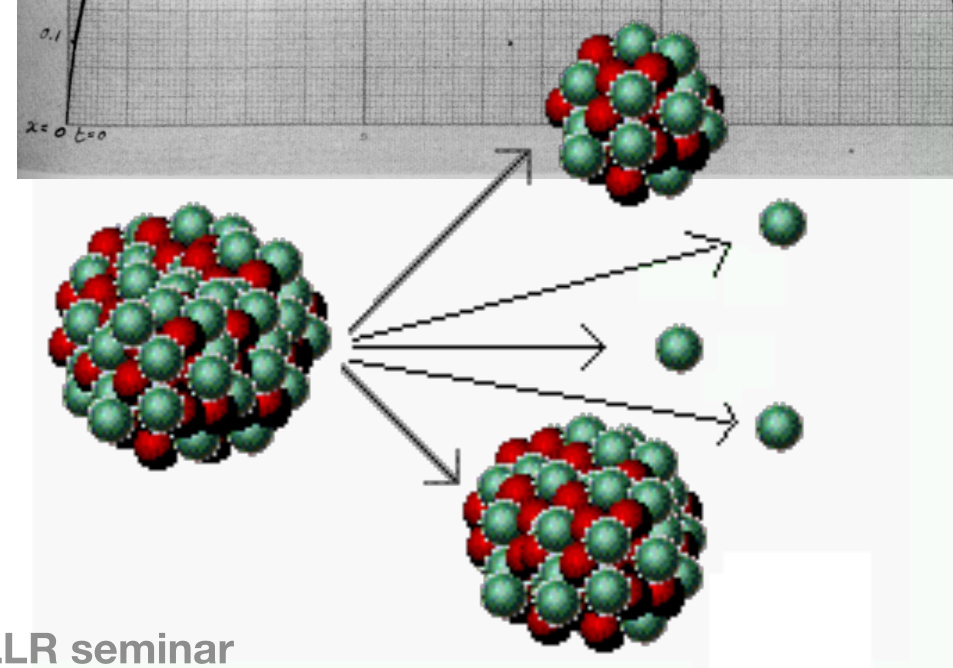
GEORGES LEMAÎTRE
PROFESSEUR A L'UNIVERSITÉ DE LOUVAIN

PRÉFACE DE FERDINAND GONSETH
PROFESSEUR A L'ÉCOLE POLYTECHNIQUE FÉDÉRALE

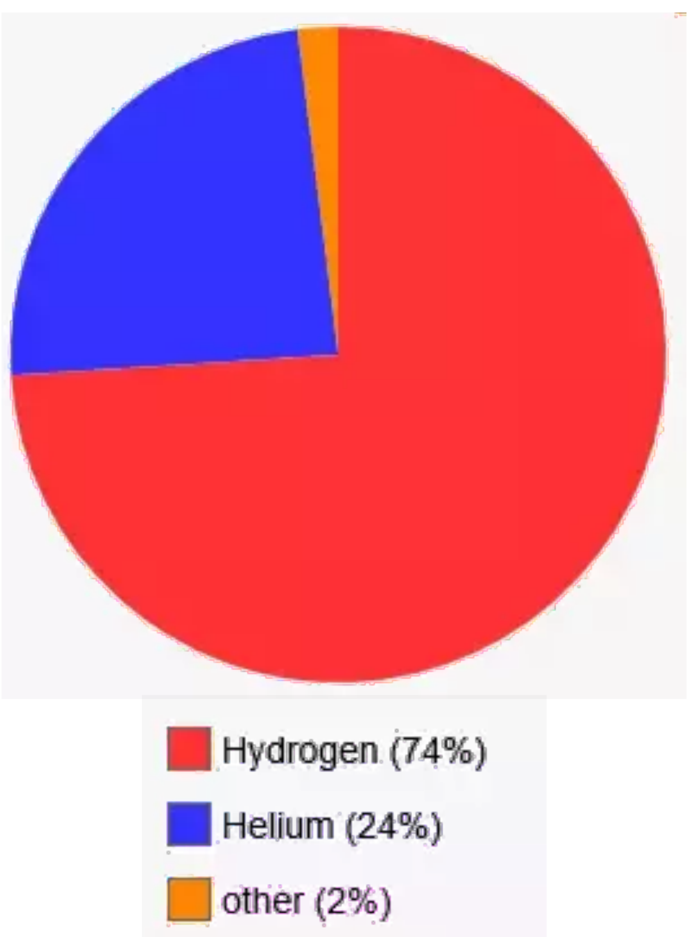
NEUCHATEL
ÉDITIONS DU GRIFFON

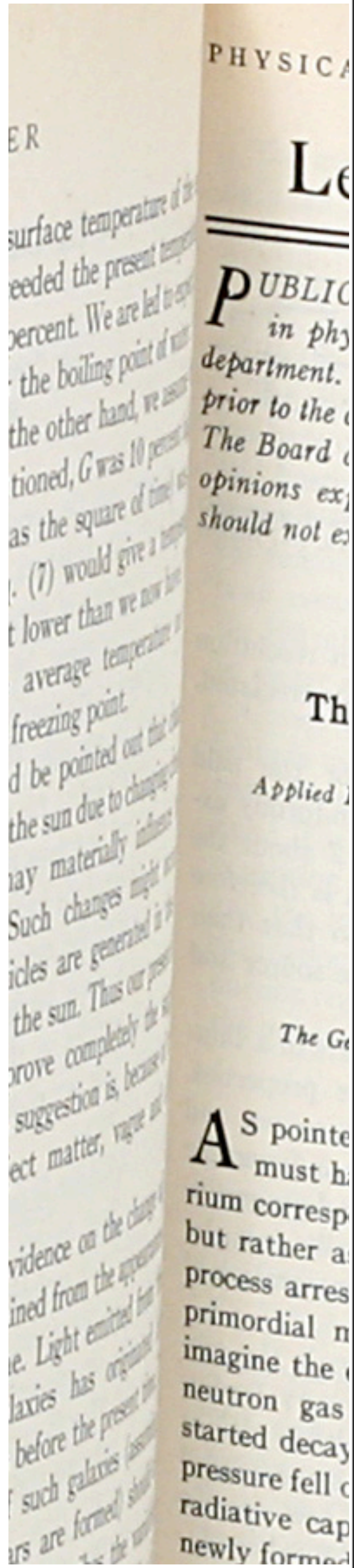
BRUXELLES
ÉDITIONS HERMÈS





Georgiy Antonovich Gamov (1904-1968)





As the Universe expands, the total mass of the Universe doesn't change, so the density of matter changes as the volume of the Universe, implying that as a function of time,

$$\rho_{\mathrm{mat}}(t) = \rho_{\mathrm{mat}}(t_0)\left(\frac{t_0}{t}\right)^3 = 10^{21}\frac{1}{t^3}\ \mathrm{gcm}^{-3}.$$

In a tour de force, Gamow pulled off a similar calculation about the density of radiation. Since the entire Universe could be safely assumed to be a blackbody, the Stefan-Boltzmann law applies. This means that the energy density of radiation is $\varepsilon_{\mathrm{rad}} = \sigma T^4$, except that, since $E = mc^2$, the corresponding 'mass density' of radiation is $\rho_{\mathrm{rad}} = \sigma T^4/c^2$.

The Universe expands adiabatically, so the temperature of the radiation in the early radiation-dominated Universe would fall off as $T \propto 1/R$, where R is the size of the Universe. Gamow borrowed an approximate result from classical mechanics to show that in the early stages of expansion, the value of R would depend on time as $R \propto 1/\sqrt{t}$. Thus, he calculated that the density of radiation would behave as

$$\rho_{\mathrm{rad}}(t) = 4.5 \times 10^5\frac{1}{t^2}\ \mathrm{gcm}^{-3}.$$

Thus, Gamow found the age t_* of the Universe at the time when $\rho_{\mathrm{rad}}(t_*) = \rho_{\mathrm{mat}}(t_*)$, i.e. when the energy density of radiation was the same as that of matter in the Universe, as

$$t_* = 7.3 \times 10^7\ \mathrm{yr},$$

which is 73 million years after the Big Bang. At this time, the density would be $\rho_{\mathrm{rad}} \equiv \rho_{\mathrm{mat}} = 9.4 \times 10^{-26}$ g cm^{-3}. From the Stefan-Boltzmann law he used above, he could then calculate the temperature at this time to be

$$T(t_*) = 320\mathrm{K}.$$

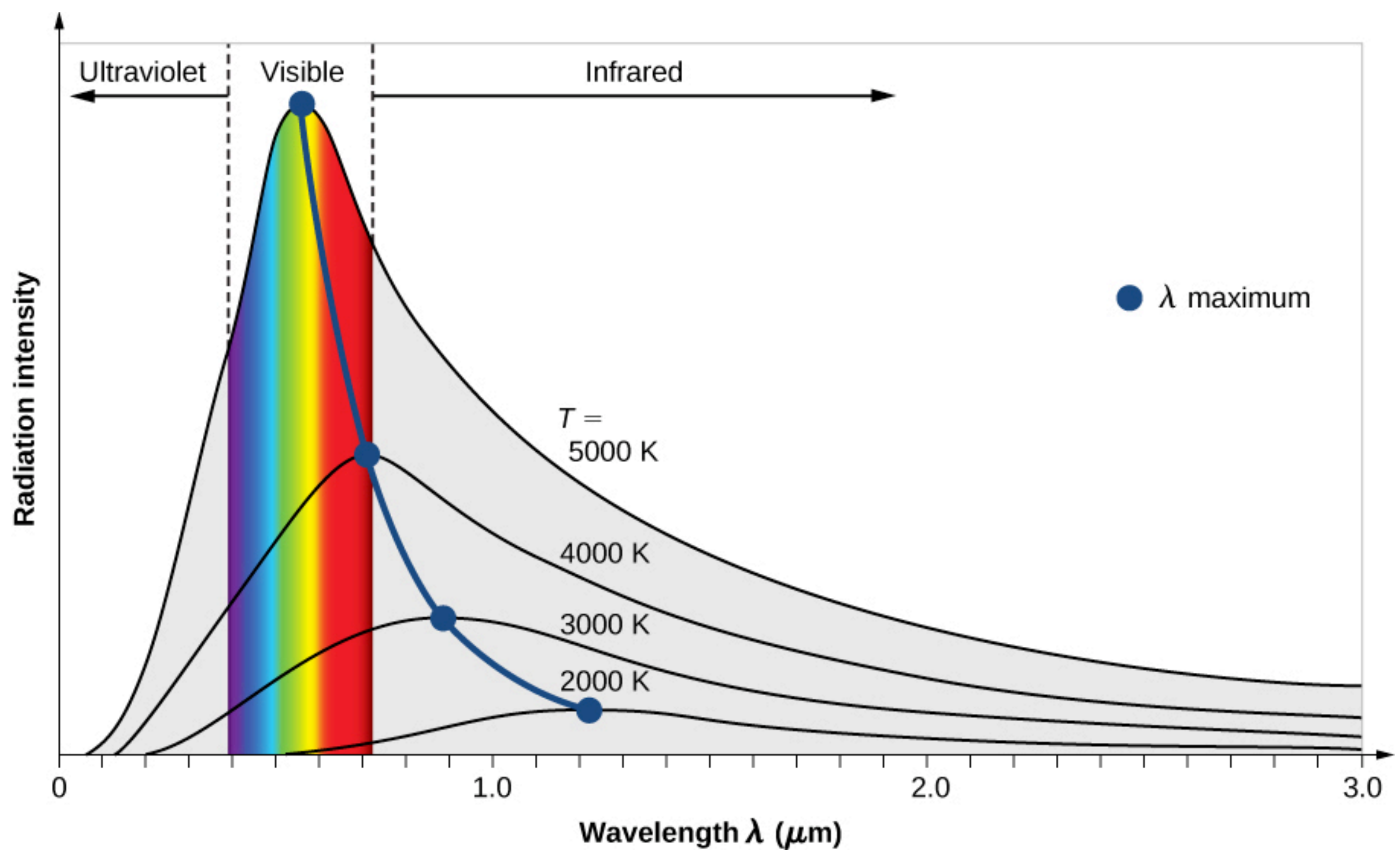
It follows from Gamow's initial assumption of the growth of R that

$$T(\mathrm{now}) = T(t_*)\left(\frac{t_*}{t_0}\right) = 7\mathrm{K}.$$

If he had used the currently favoured values of the age of the Universe $t_0 = 1.2 \times 10^{10}$ yr, and the current density of matter $\rho_{\mathrm{mat}}(t_0) = 8 \times 10^{-30}$ g cm^{-3}, he would have got the temperature of CMBR to be about five times larger. His largest source of error would have come from his approximate formula of the growth of the early Universe $R \propto 1/\sqrt{t}$, something that his student Alpher had done properly later to come to an estimate of 5 degrees K.

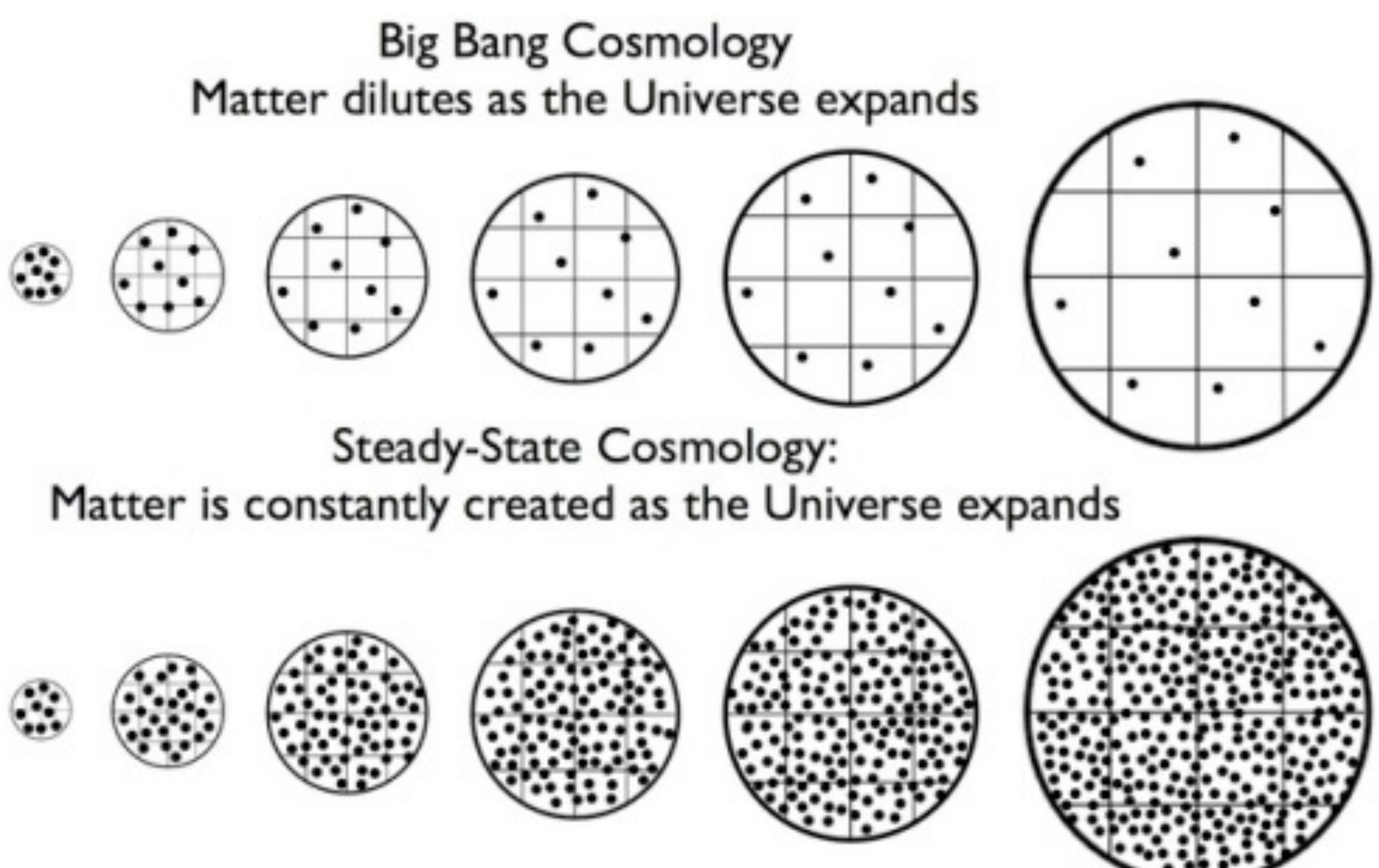
Suggested Reading

[1] A D Chernin, Physics-Uspekhi, 37, pp. 813-820, 1994.
[2] George Gamow, *My World Line*, Viking, New York, 1970.



if the Universe was at thermal equilibrium when it was 1000x smaller than today and 30000x younger, the cosmic radiation must perfectly remember it!

Fred Hoyle Thomas Gold Hermann Bondi



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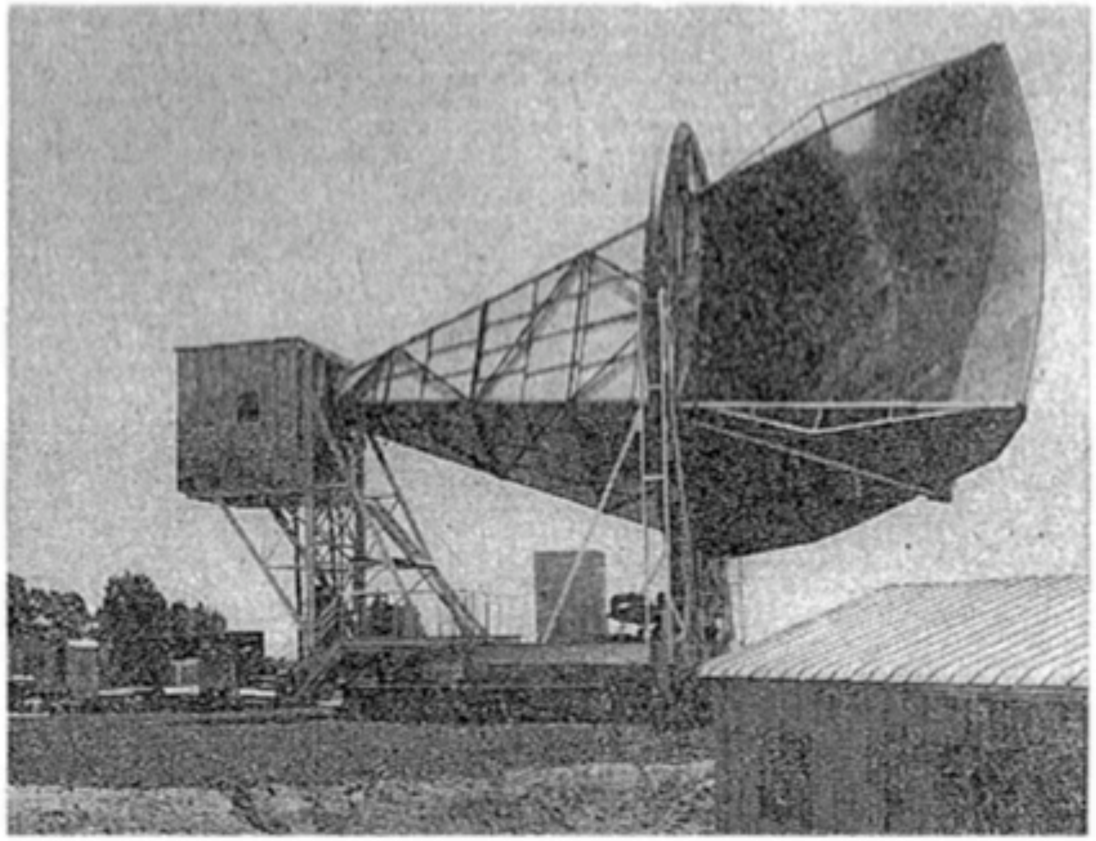
Signals Imply a 'Big Bang' Universe



Horn antenna, used in space exploration, at the Bell Laboratories in Holmdel, N. J.

By WALTER SULLIVAN

Scientists at the Bell Telephone Laboratories have observed what a group at Princeton University believes may be remnants of an explosion that gave birth to the universe.

These remnants are thought to have originated in the burst of light from that cataclysmic event.

Such a primordial explosion is embodied in the "big bang" theory of the universe. It seeks to explain the observation that virtually all distant galaxies are flying away from the earth. Their motion implies that they all originated at a single point 10 or 15 billion years ago.

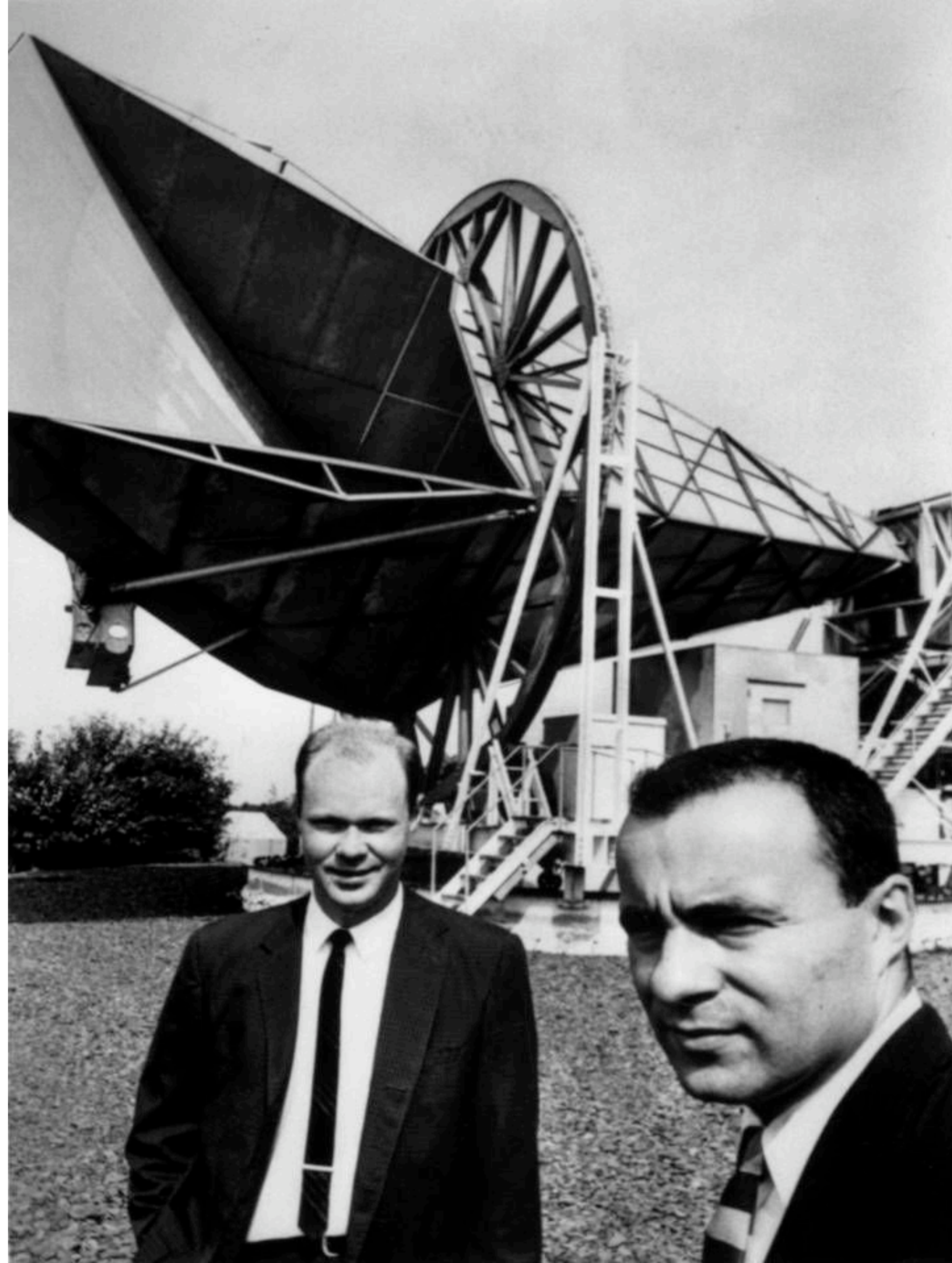
The Bell observations, made by Drs. Arno A. Penzias and Robert W. Wilson from a hilltop in Holmdel, N. J., were of radio waves that appear to be flying in all directions through the universe. Since radio waves and light waves are identical, except for their wavelength, these are thought to be remnants of light waves from the primordial flash.

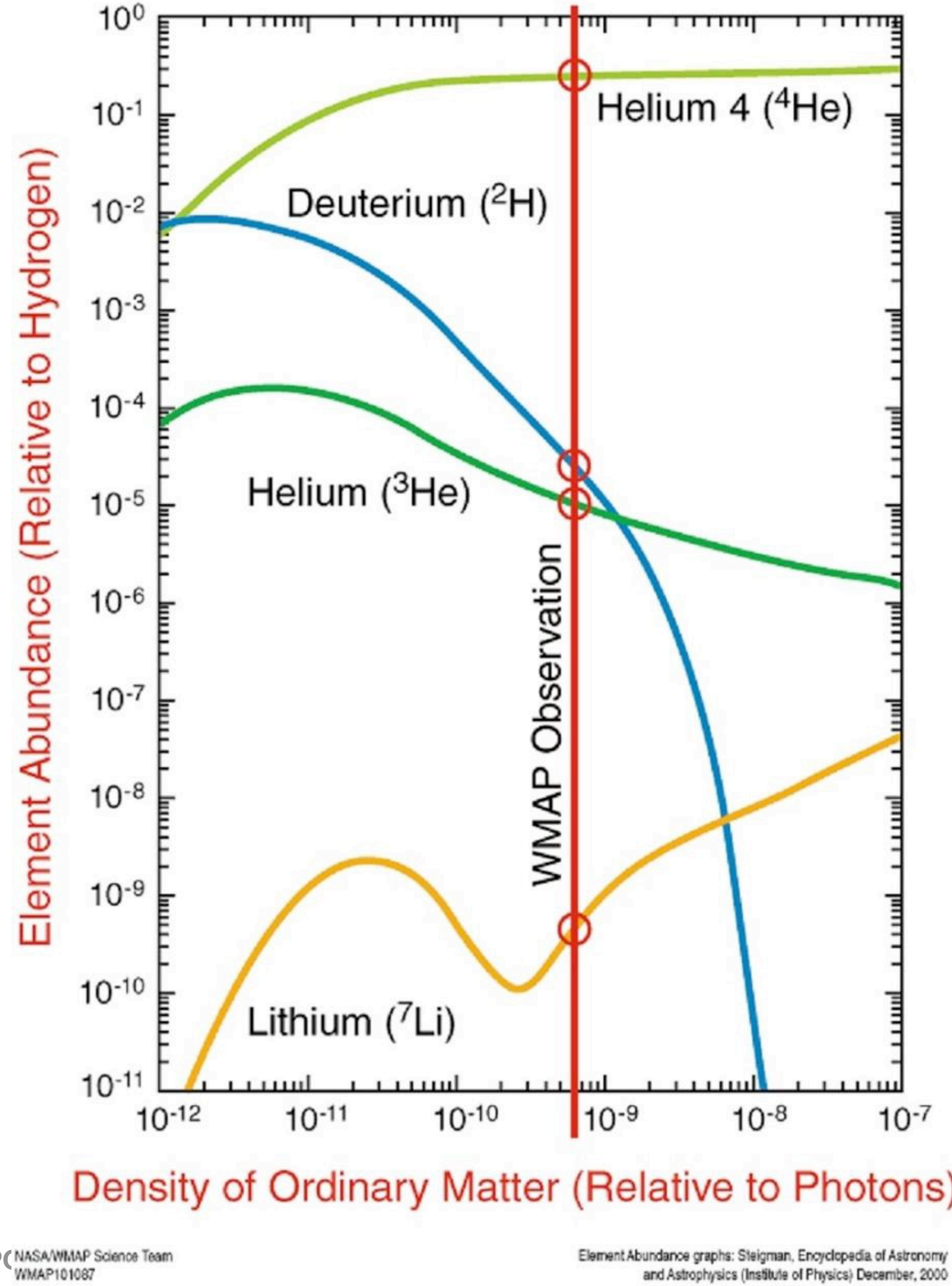
The waves were stretched into radio waves by the vast expansion of the universe that has occurred since the explosion and release of the waves from the expanding gas cloud born of the fireball.

In what may prove to be one of the most remarkable coincidences in scientific history, the existence of such waves was predicted at

Continued on Page 18, Column 1

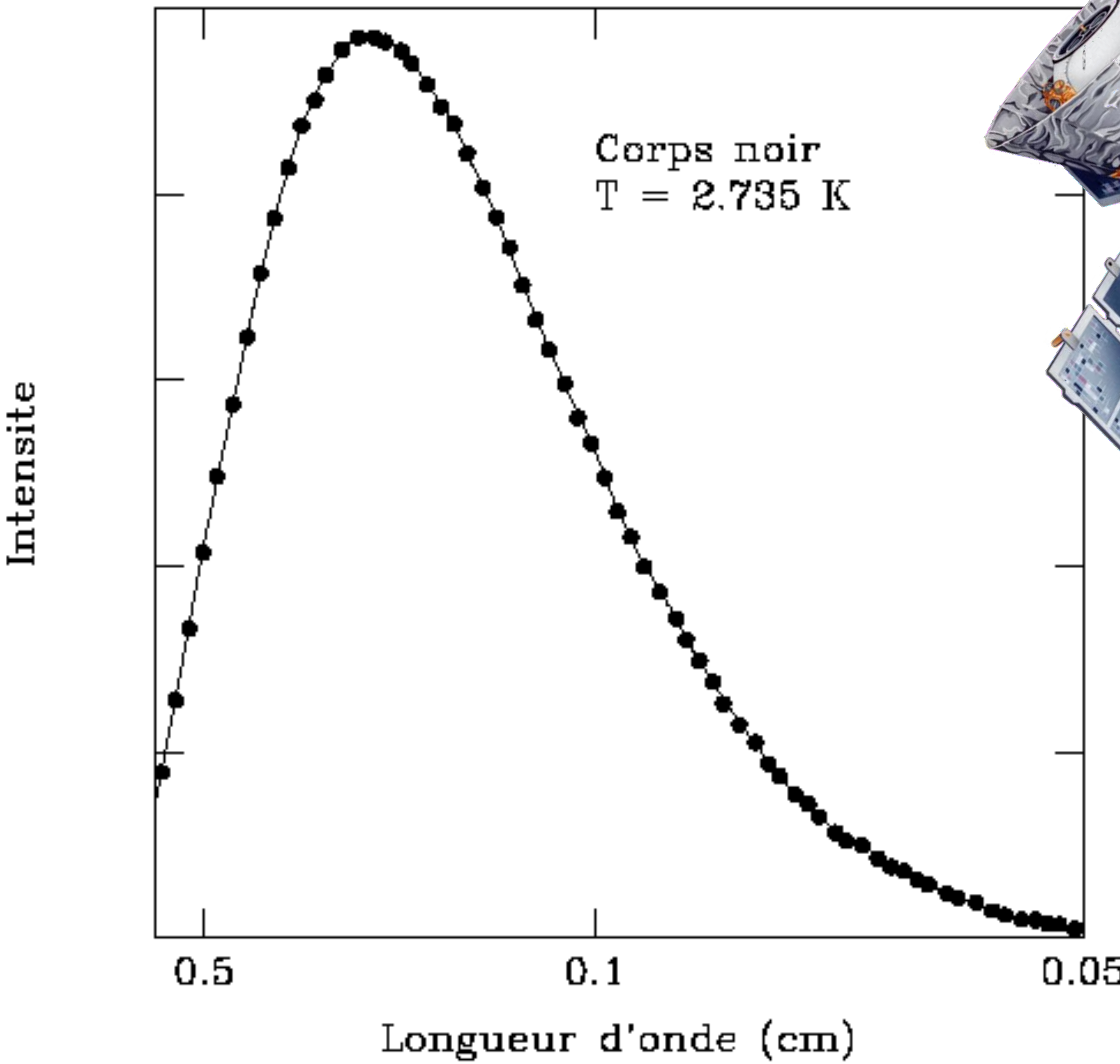
The New York Times
Published: May 21, 1965





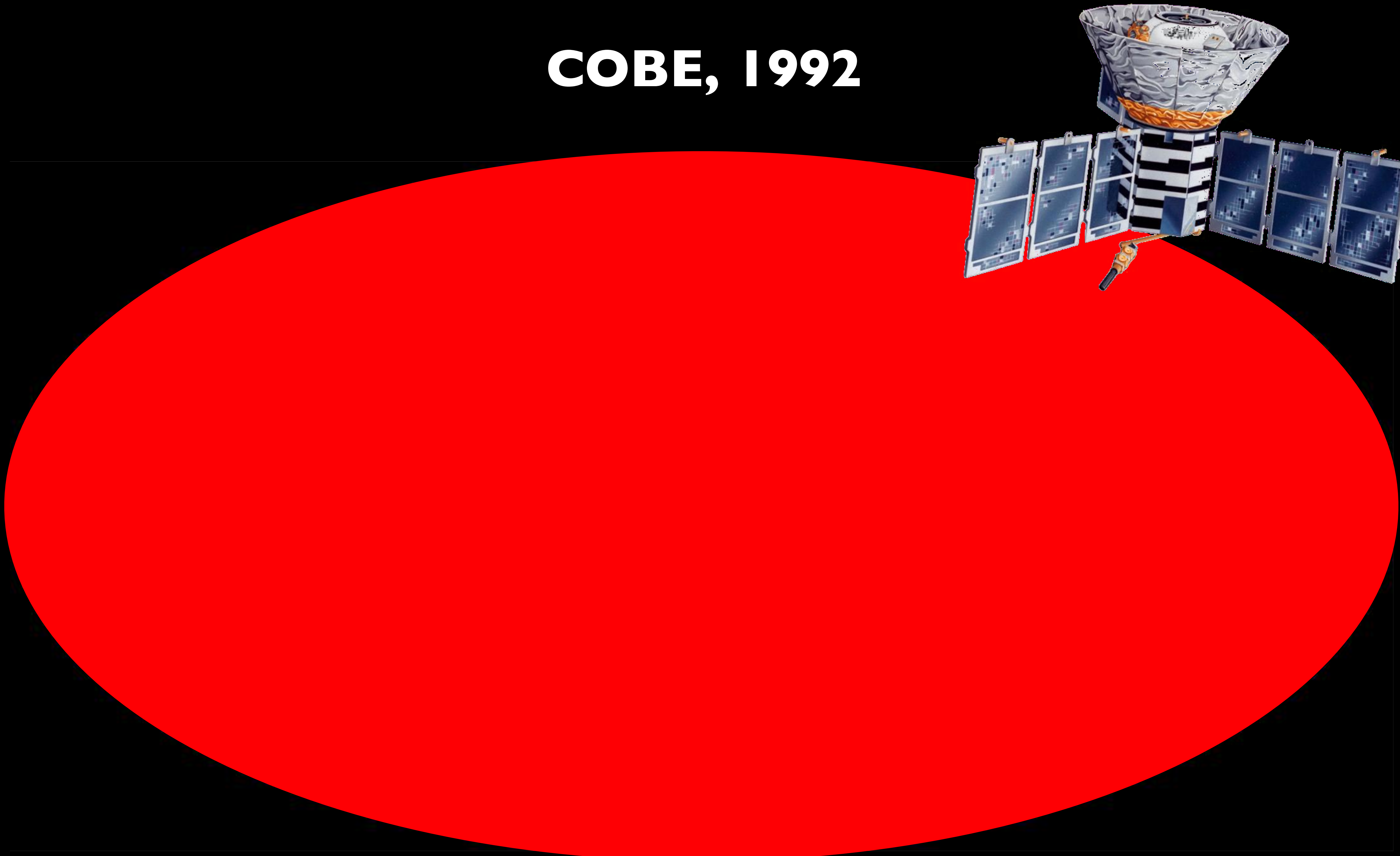
the hot Big Bang also predicts the good proportions of elements in the Universe!

the Cosmic Microwave Background follows a perfect black body spectrum

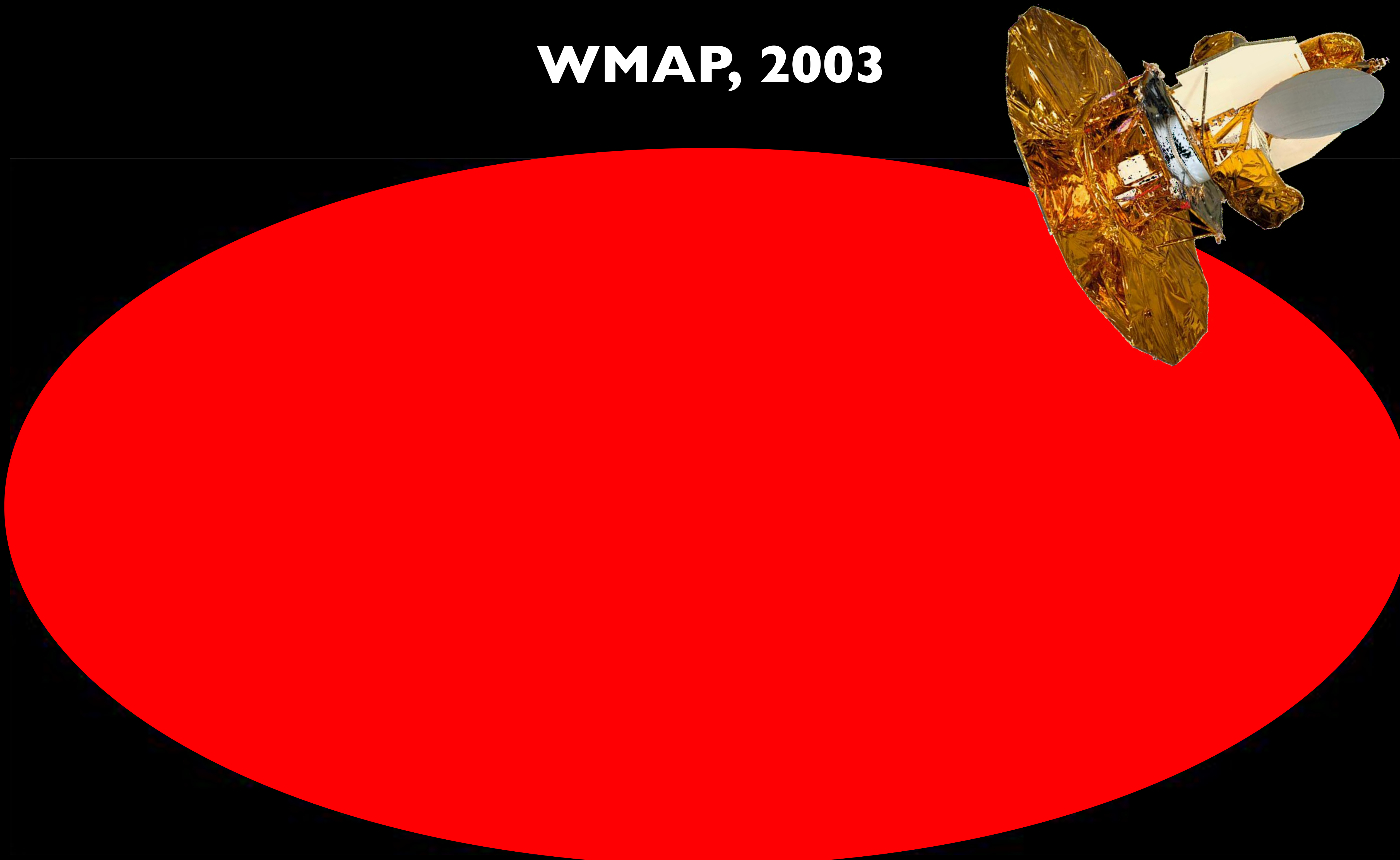


George F. Smoot and John C. Mather Nobel prize 2006 *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation*".

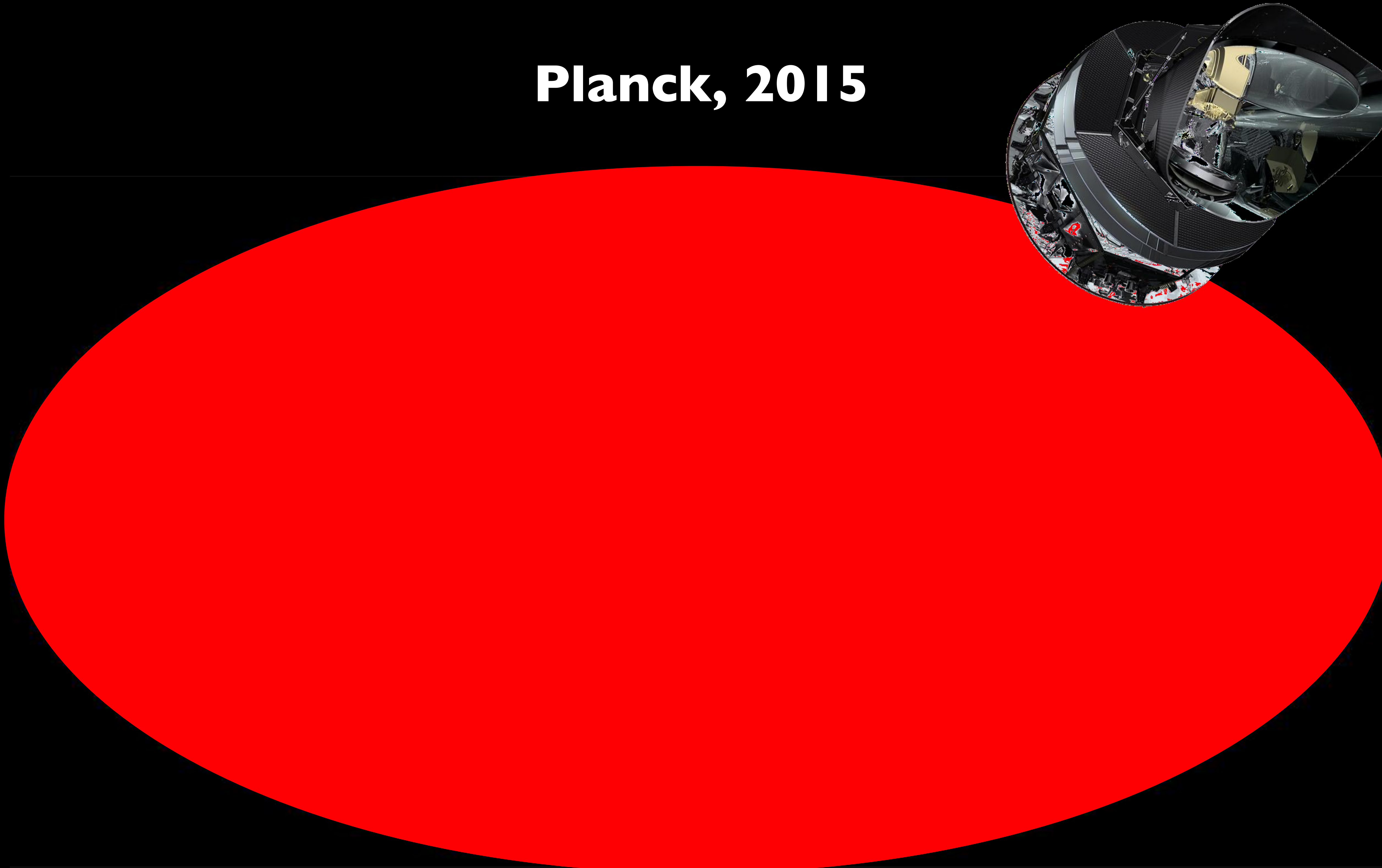
COBE, 1992

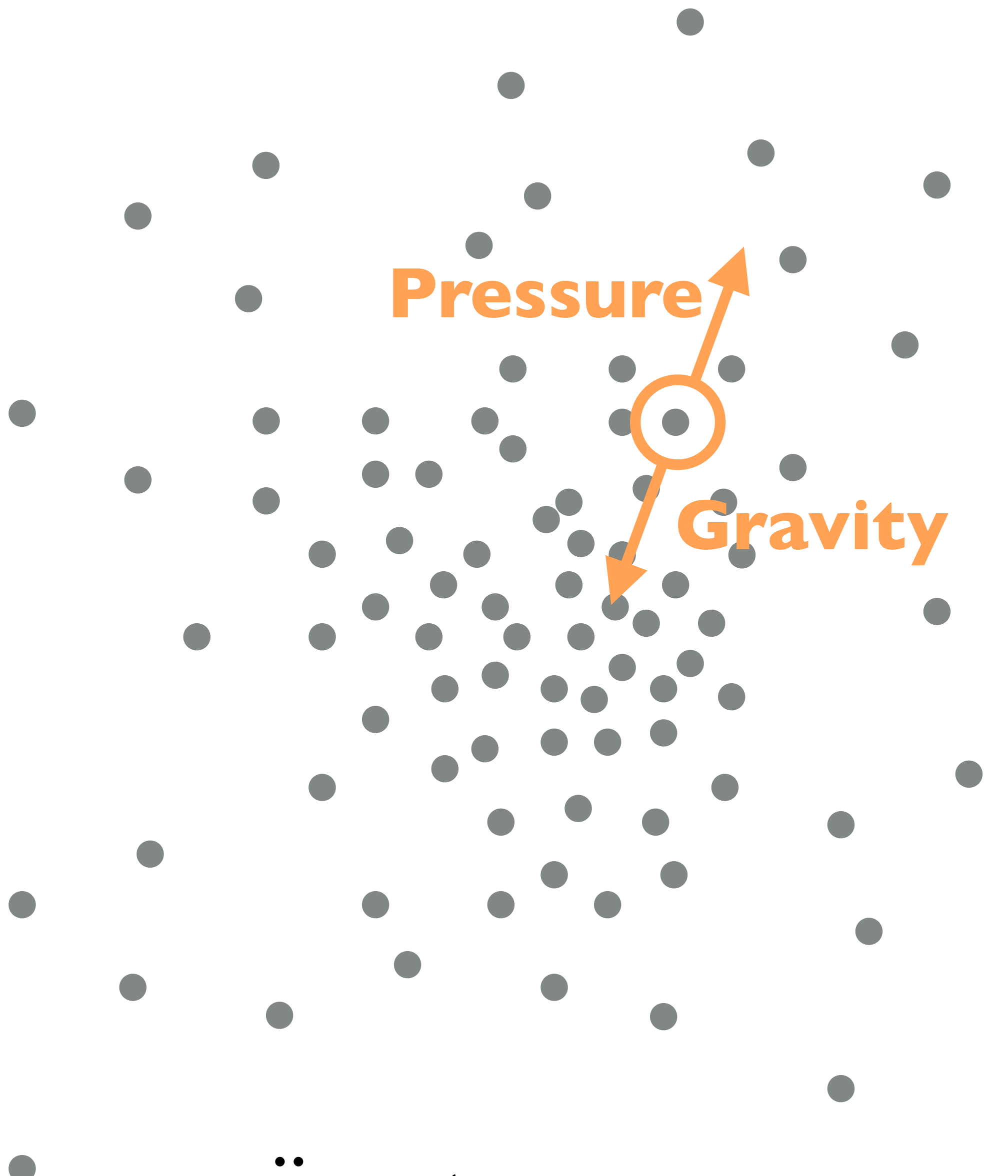


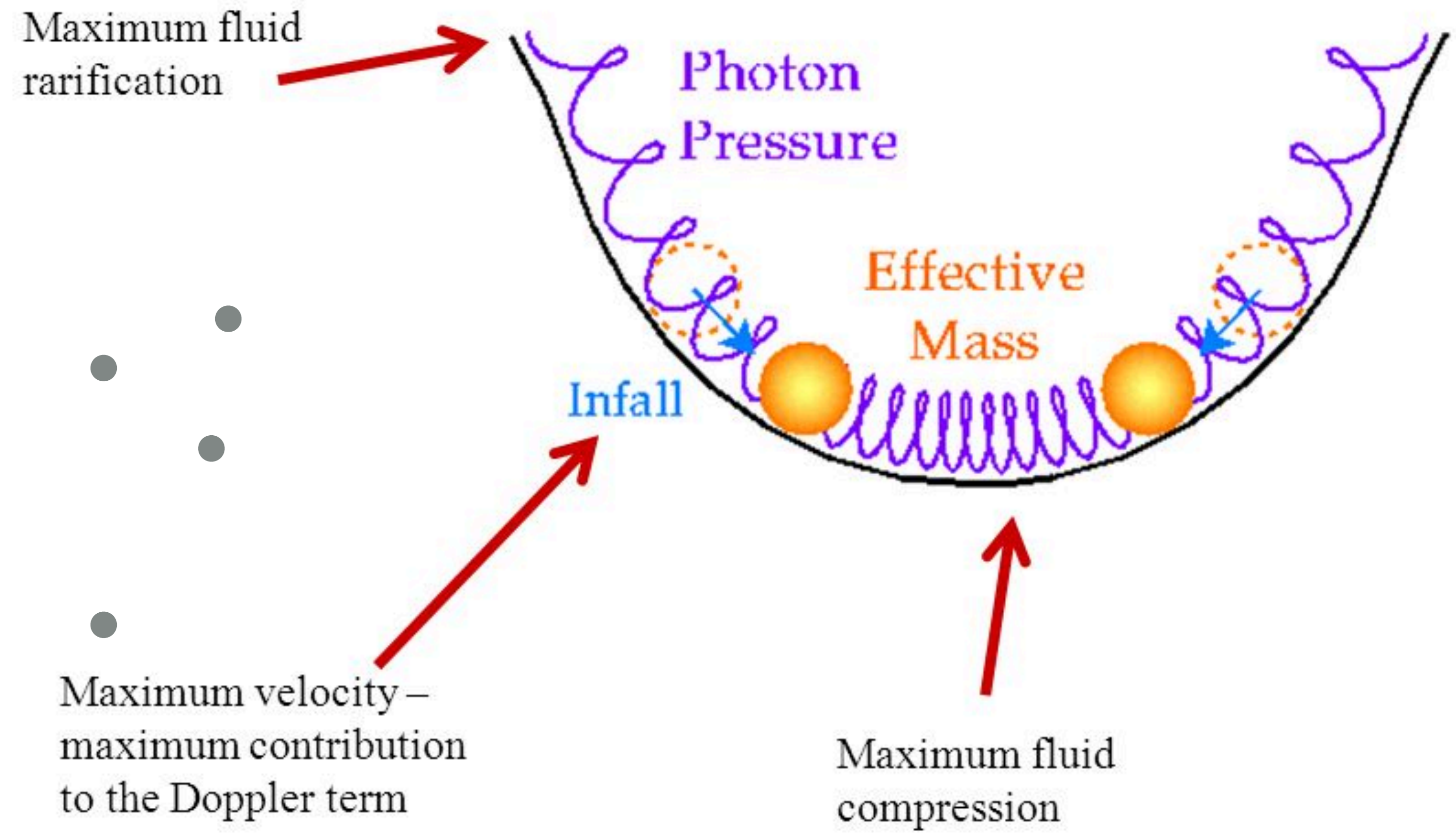
WMAP, 2003



Planck, 2015







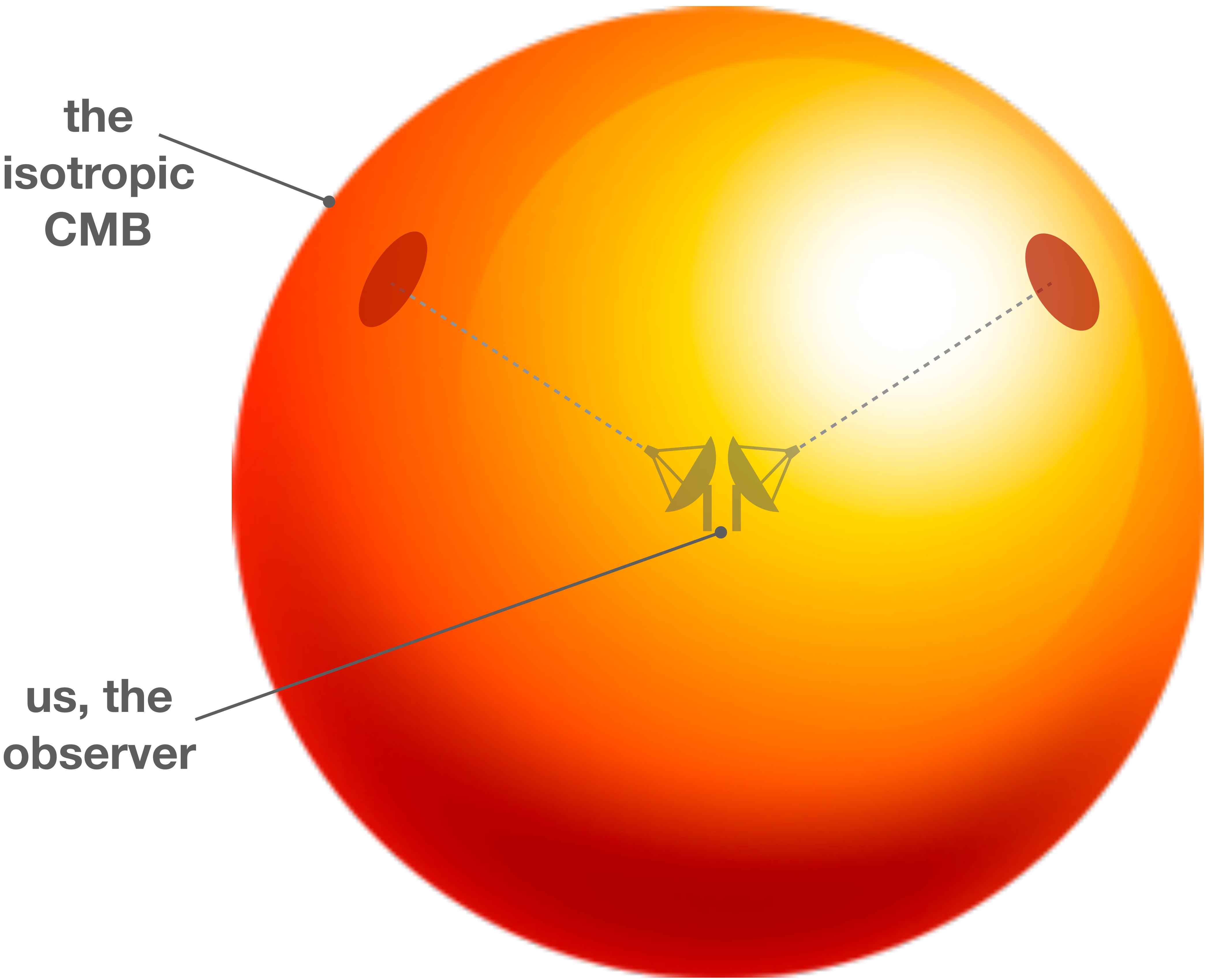
Gravitational instability. Mass near an overdense region is attracted to the center by gravity but repelled by pressure. If the region is dense enough, gravity wins and the over density grows with time.

$$\ddot{\delta} + (\text{Pressure} - \text{Gravity})\,\delta = 0$$

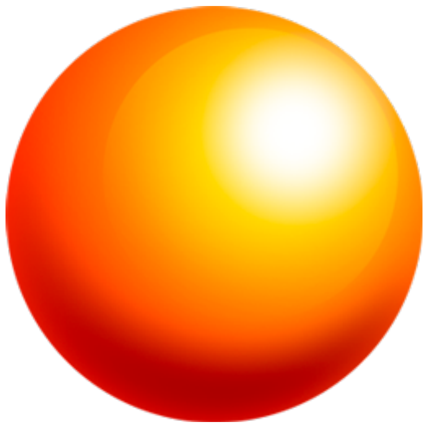
high pressure $\longrightarrow$ inhomogeneities do not grow
low pressure $\longrightarrow$ inhomogeneities grow exponentially
comparable to gravity $\longrightarrow$ inhomogeneities oscillates with time

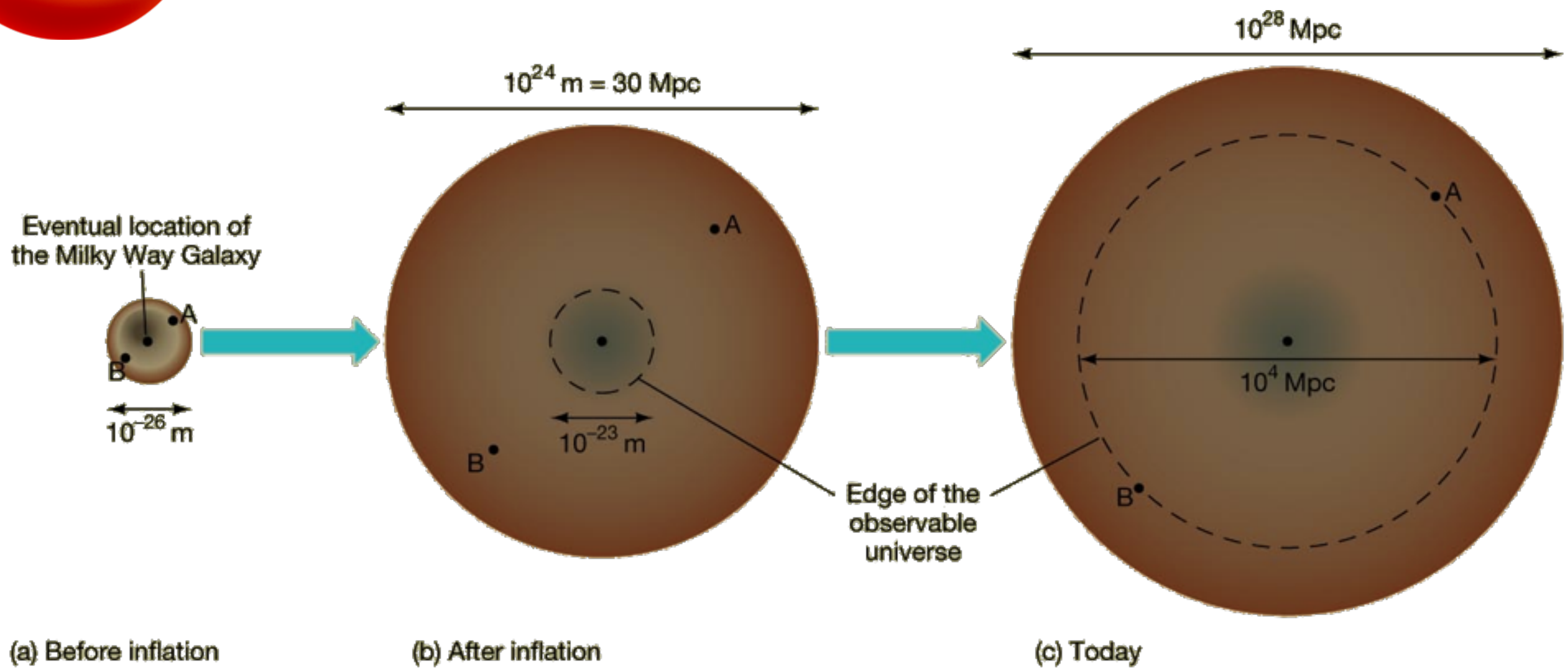
$$\ddot{\delta} + 2H\dot{\delta} - \frac{c_s^2}{a^2}\nabla^2\delta = 4\pi G\bar{\rho}\delta$$

the horizon problem



key predictions from cosmic inflation





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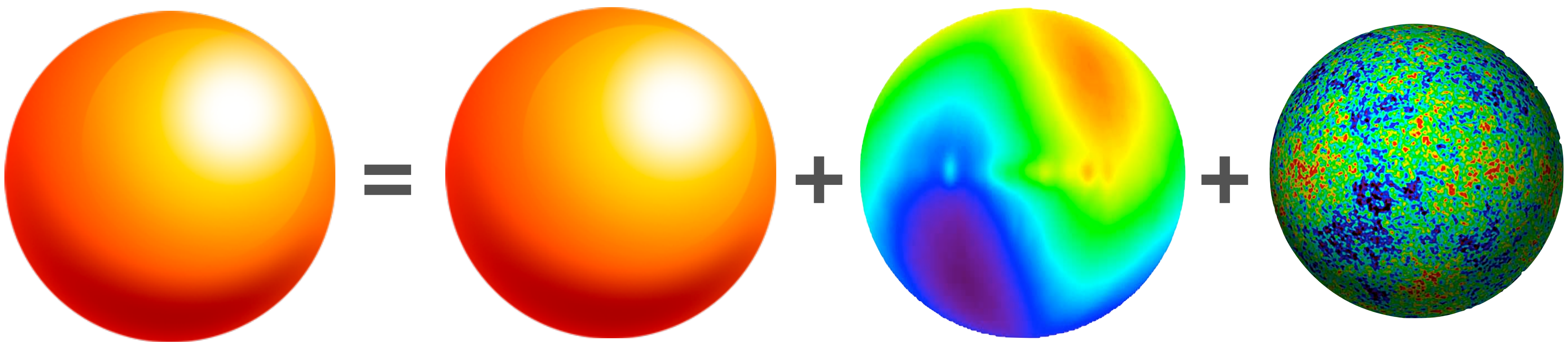


T = 2.7 K

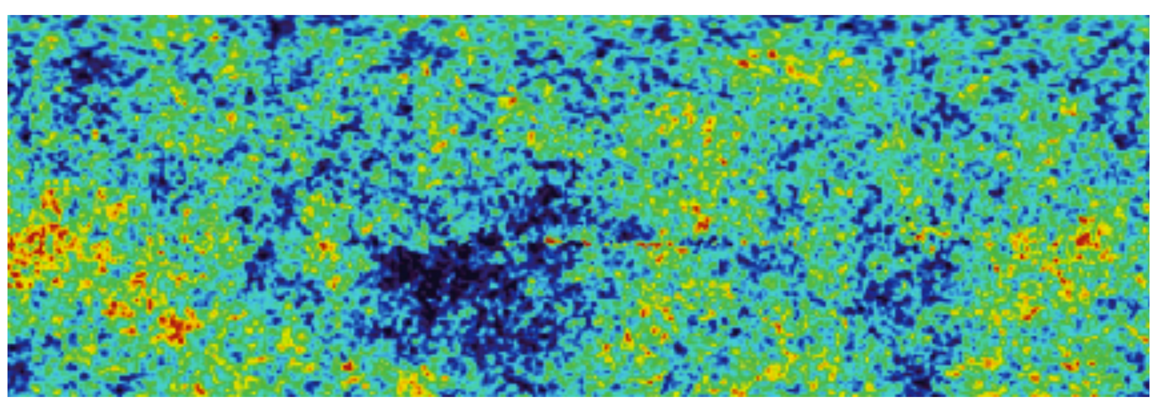
$\Delta T/T \sim 10^{-3}$

$\Delta T/T \sim 10^{-5}$

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

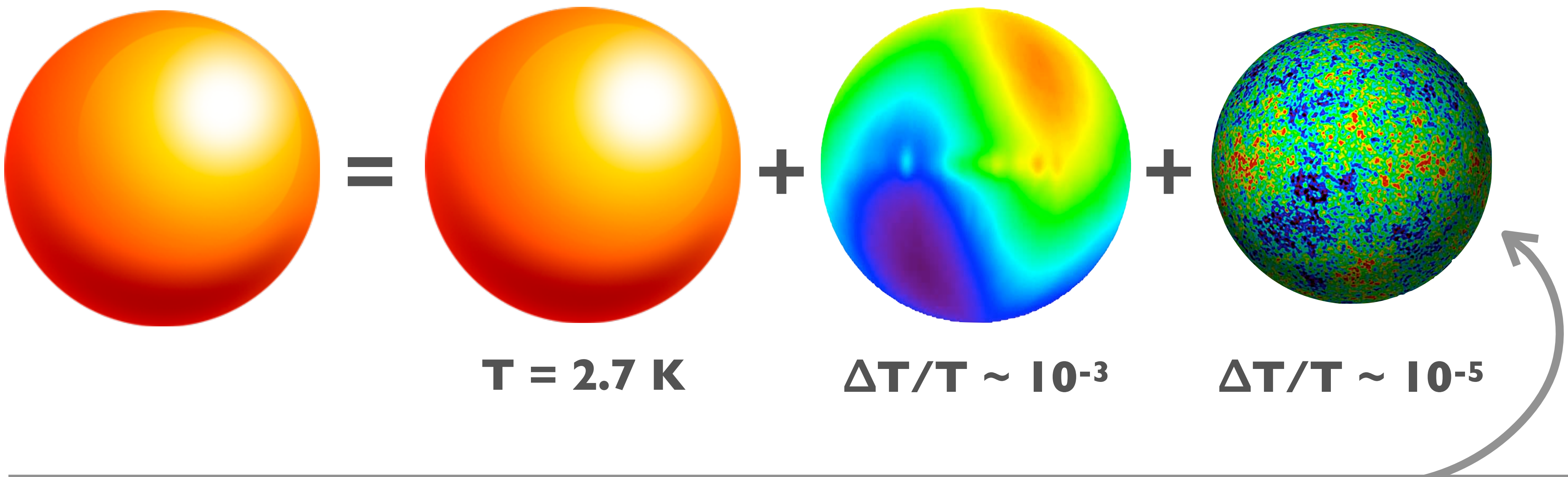
- Fluctuations we observe today in CMB and the matter distribution originate from quantum fluctuations during inflation

$\zeta \longrightarrow$



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

key predictions from cosmic inflation



observations are already in remarkable agreement with single-field slow-roll inflation:

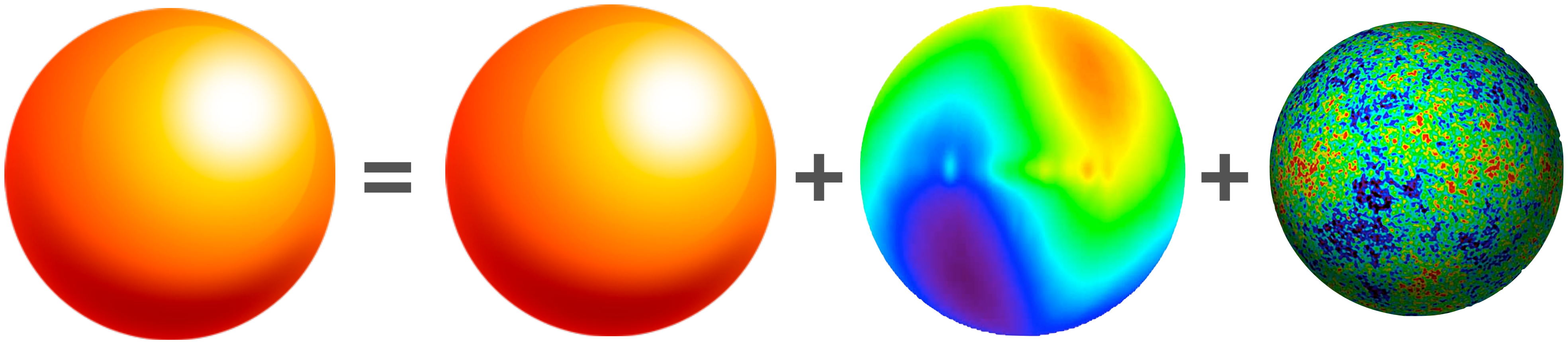
- super-horizon fluctuation
- adiabaticity
- gaussianity
- $n_s < 1$

but we want gravitational waves in addition

e.g. *The Best Inflationary Models After Planck*
J. Martin, C. Ringeval, R. Trotta, V. Vennin, JCAP, 2014

e.g. *Exploring Cosmic Origins with CORE: Inflation*
F. Finelli, M. Bucher et al., JCAP, 2017

key predictions from cosmic inflation



T = 2.7 K $\Delta T/T \sim 10^{-3}$ $\Delta T/T \sim 10^{-5}$

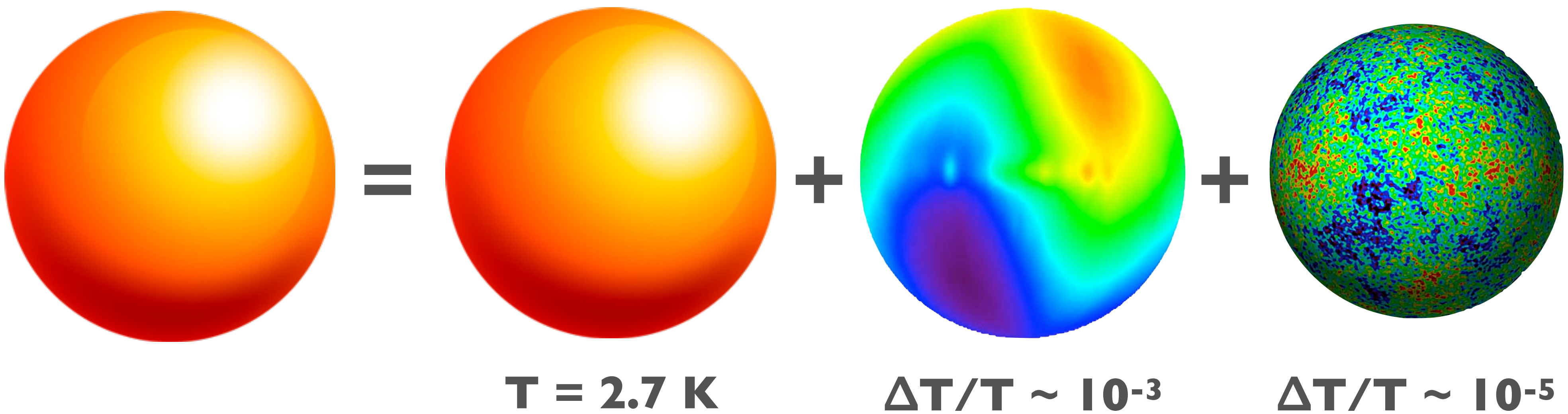
$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

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

h_{ij} →

Grishchuk (1974)
Starobinsky (1979)

key predictions from cosmic inflation

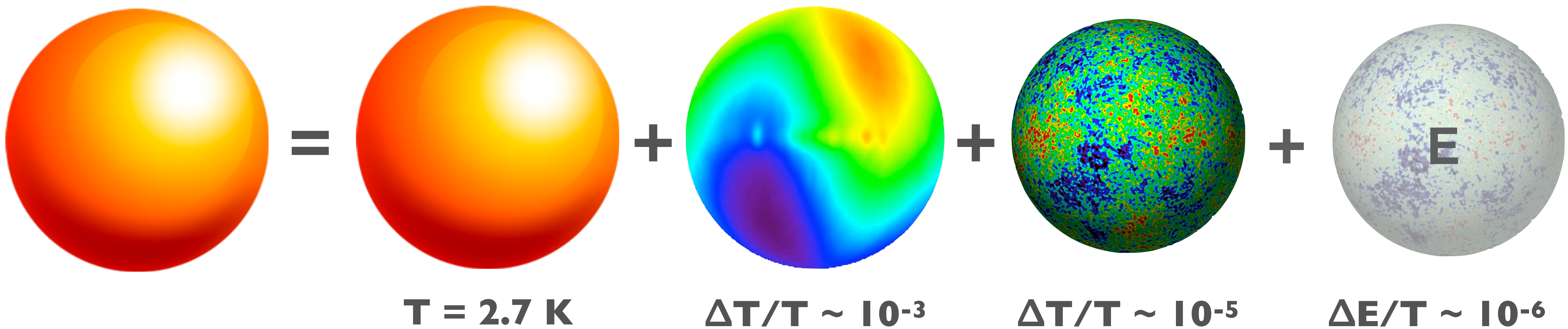


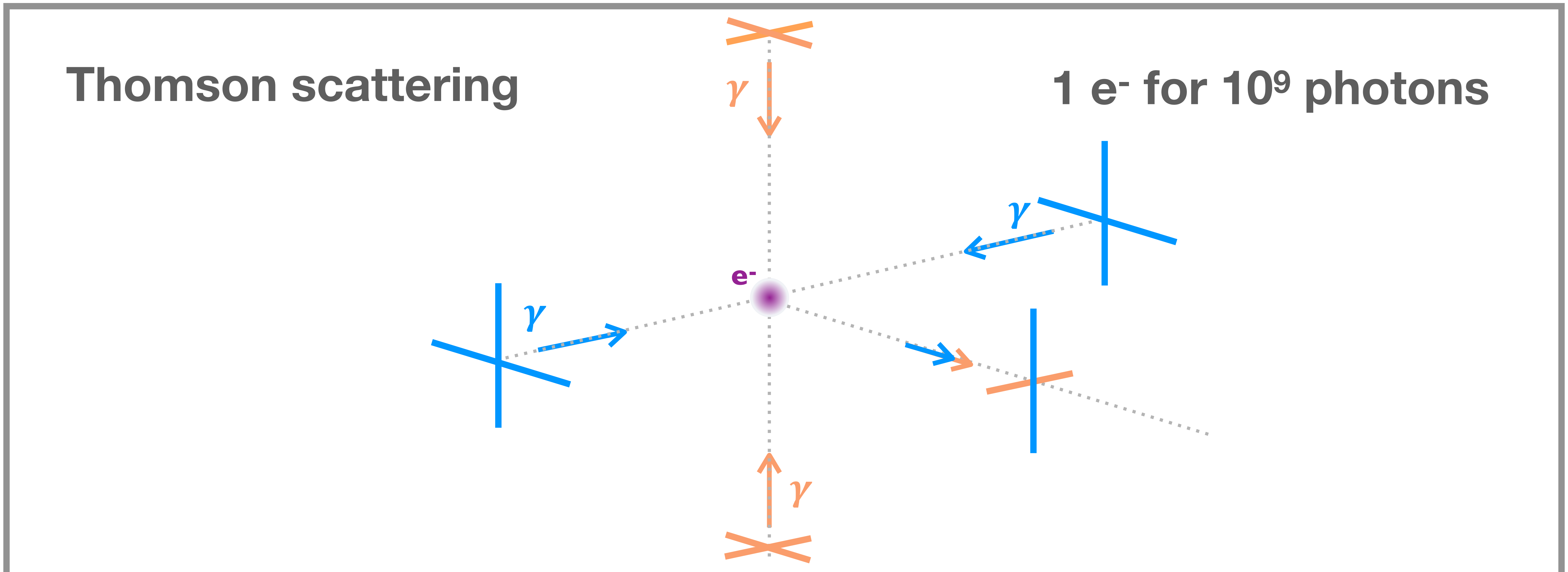
- LIGO/Virgo detected gravitational waves from binary blackholes, with the wavelength of thousands of kilometers
- But the primordial GW affecting the CMB has a wavelength of **billions of light-years**!

how to detect them?

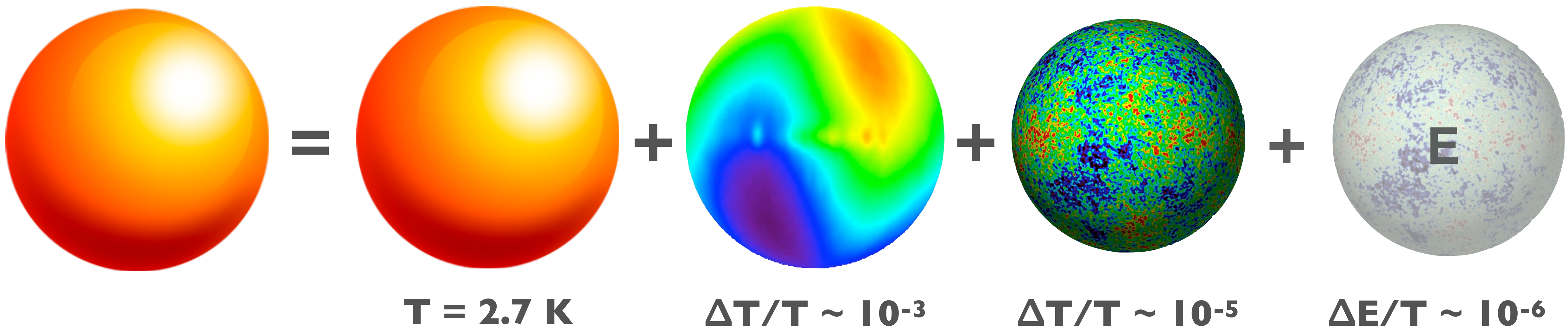
CMB POLARIZATION!

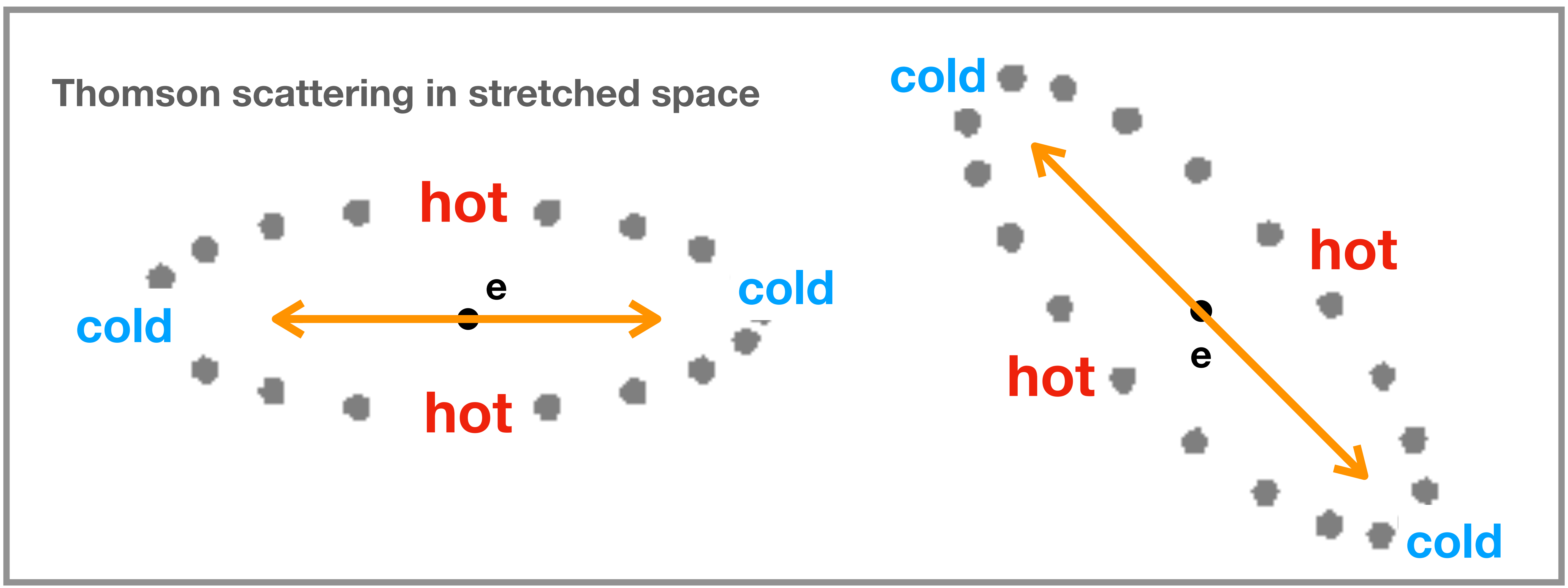
key predictions from cosmic inflation



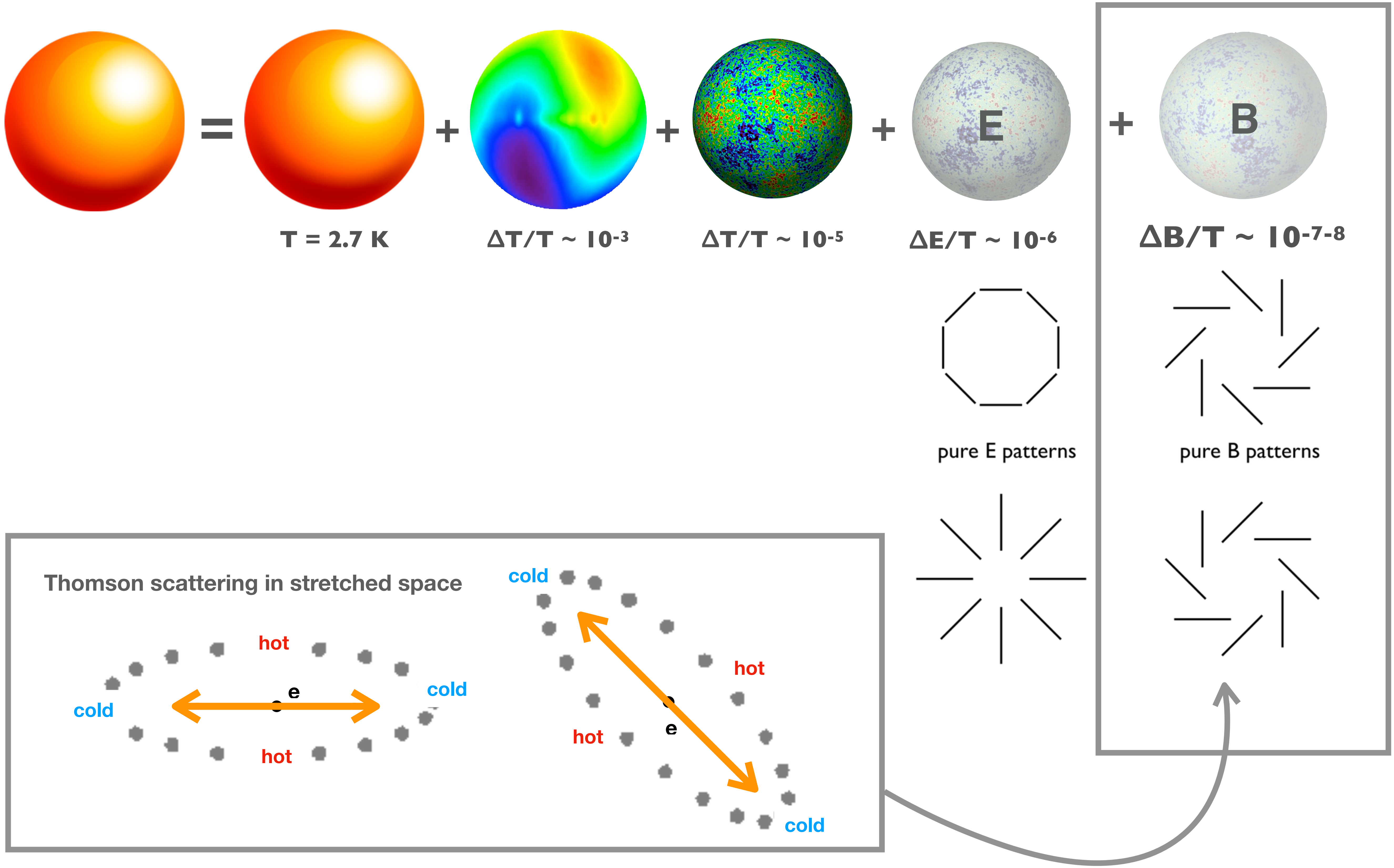


key predictions from cosmic inflation





key predictions from cosmic inflation



outline

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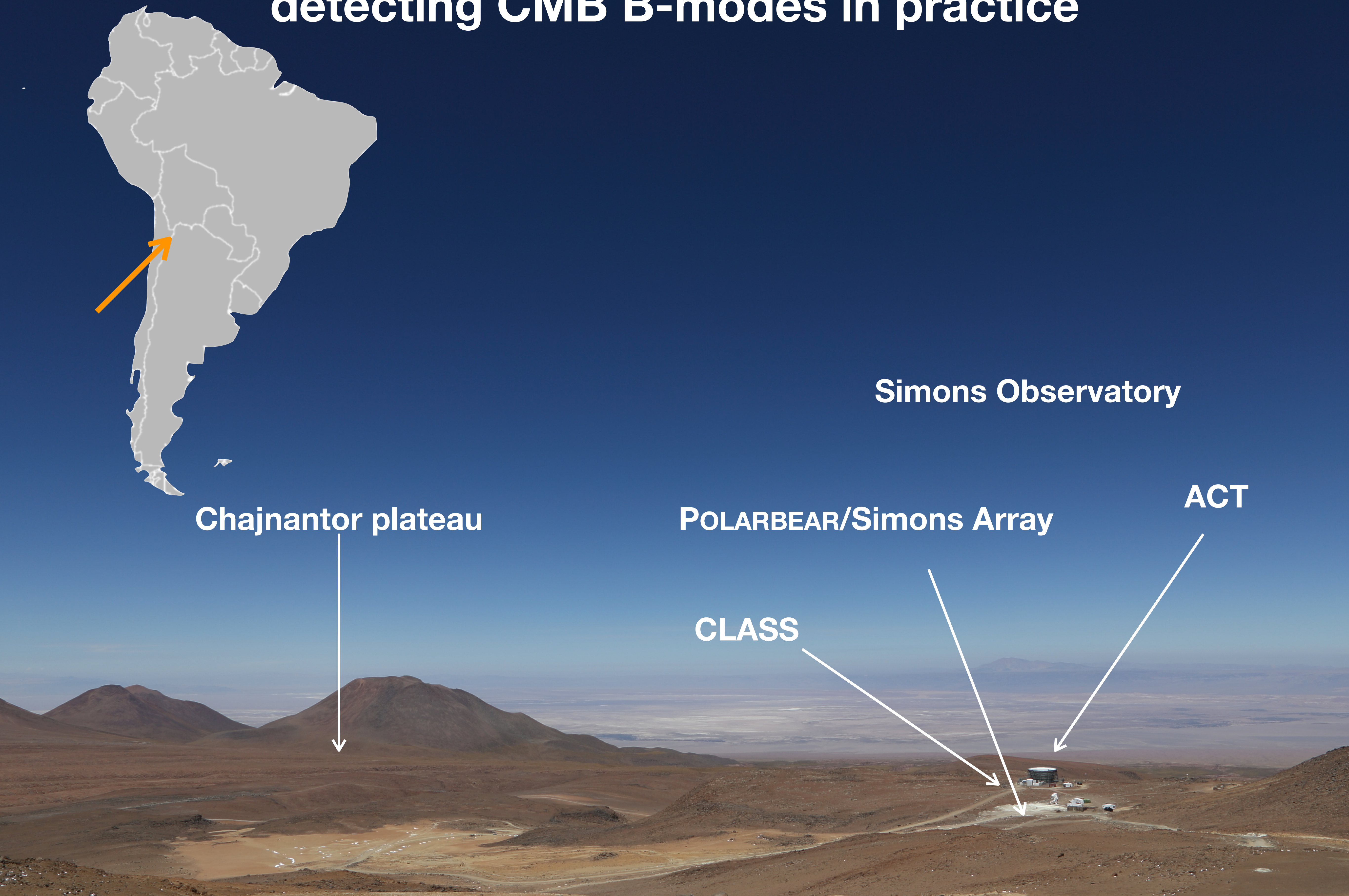
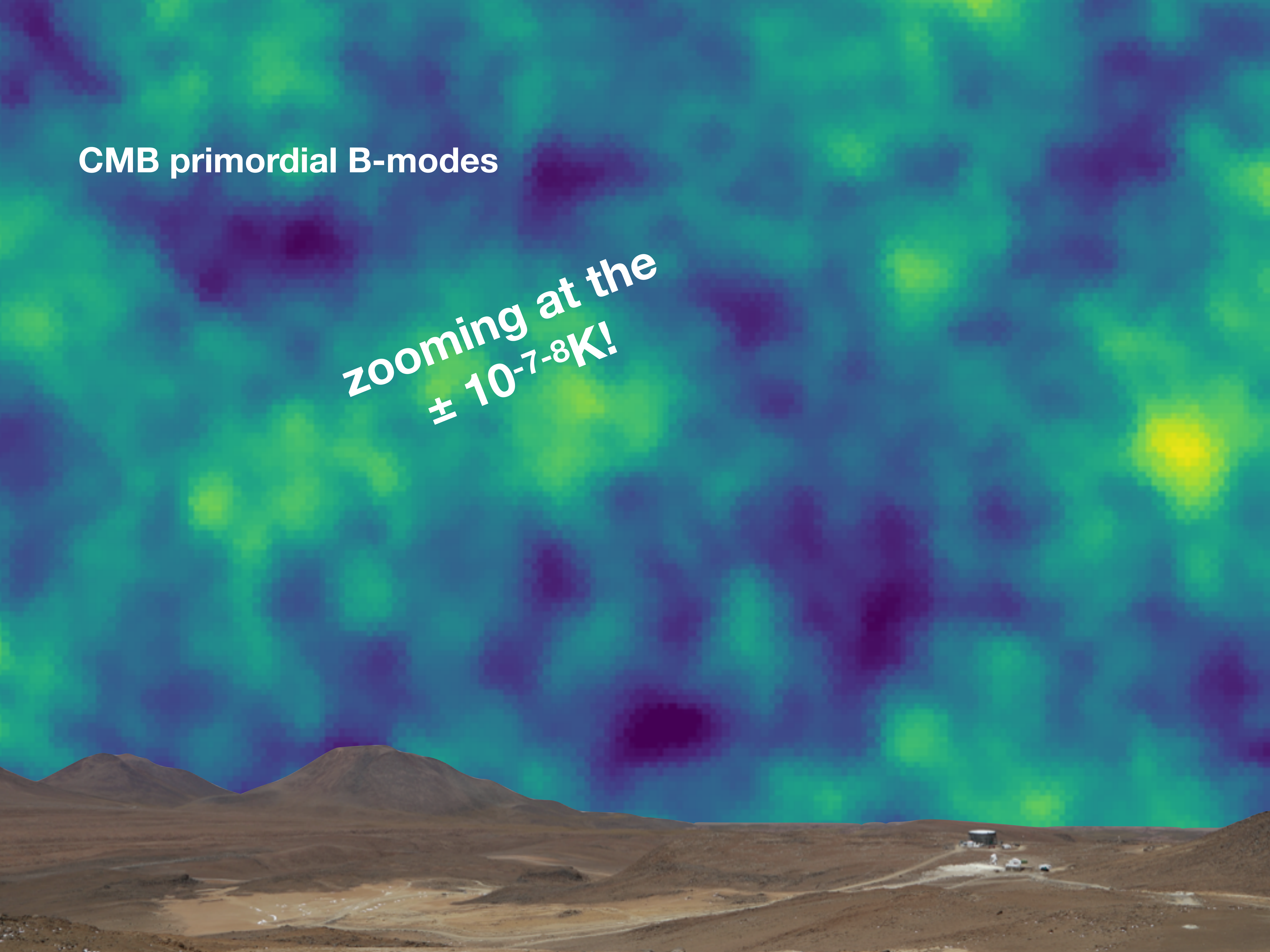
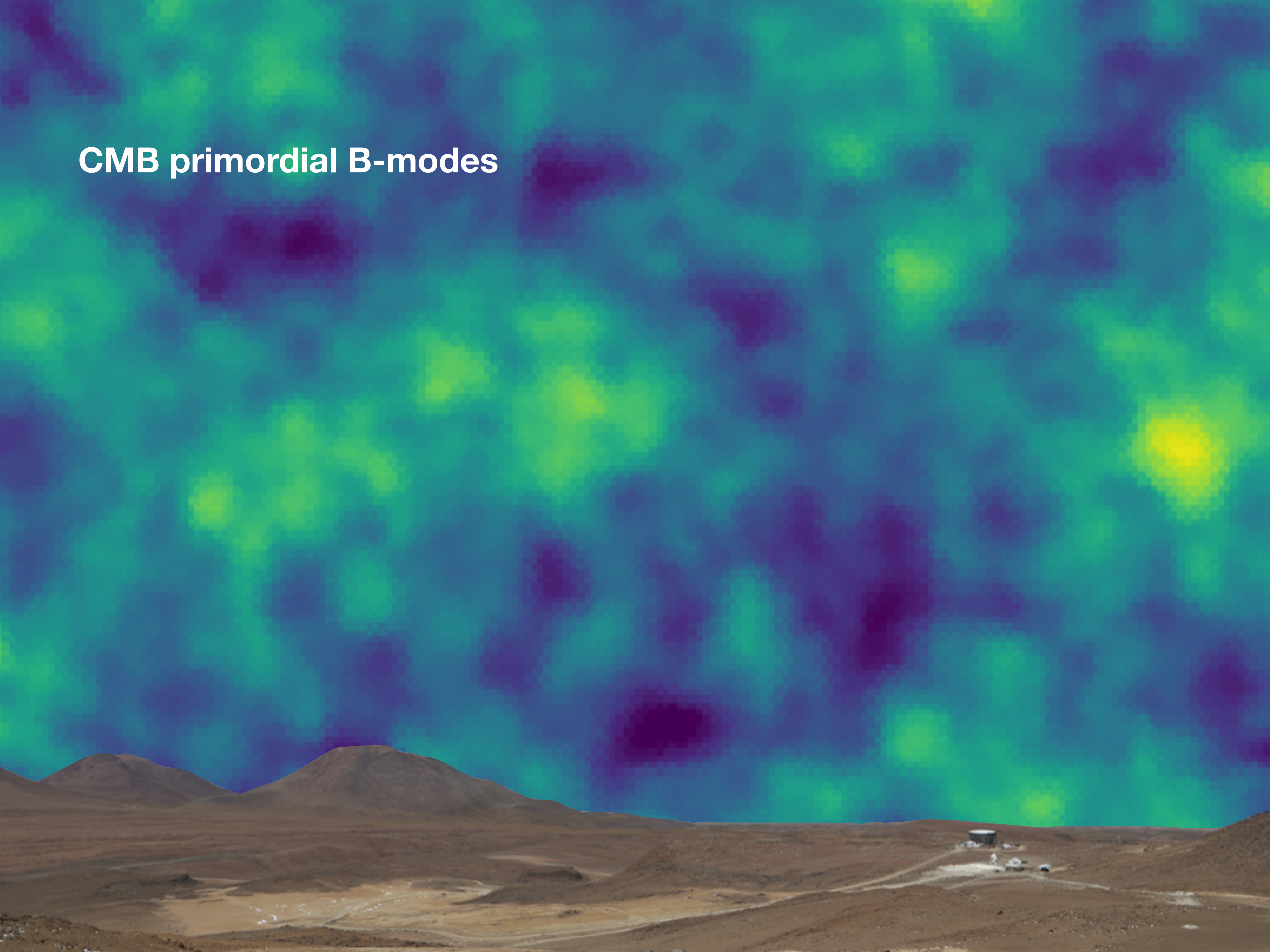
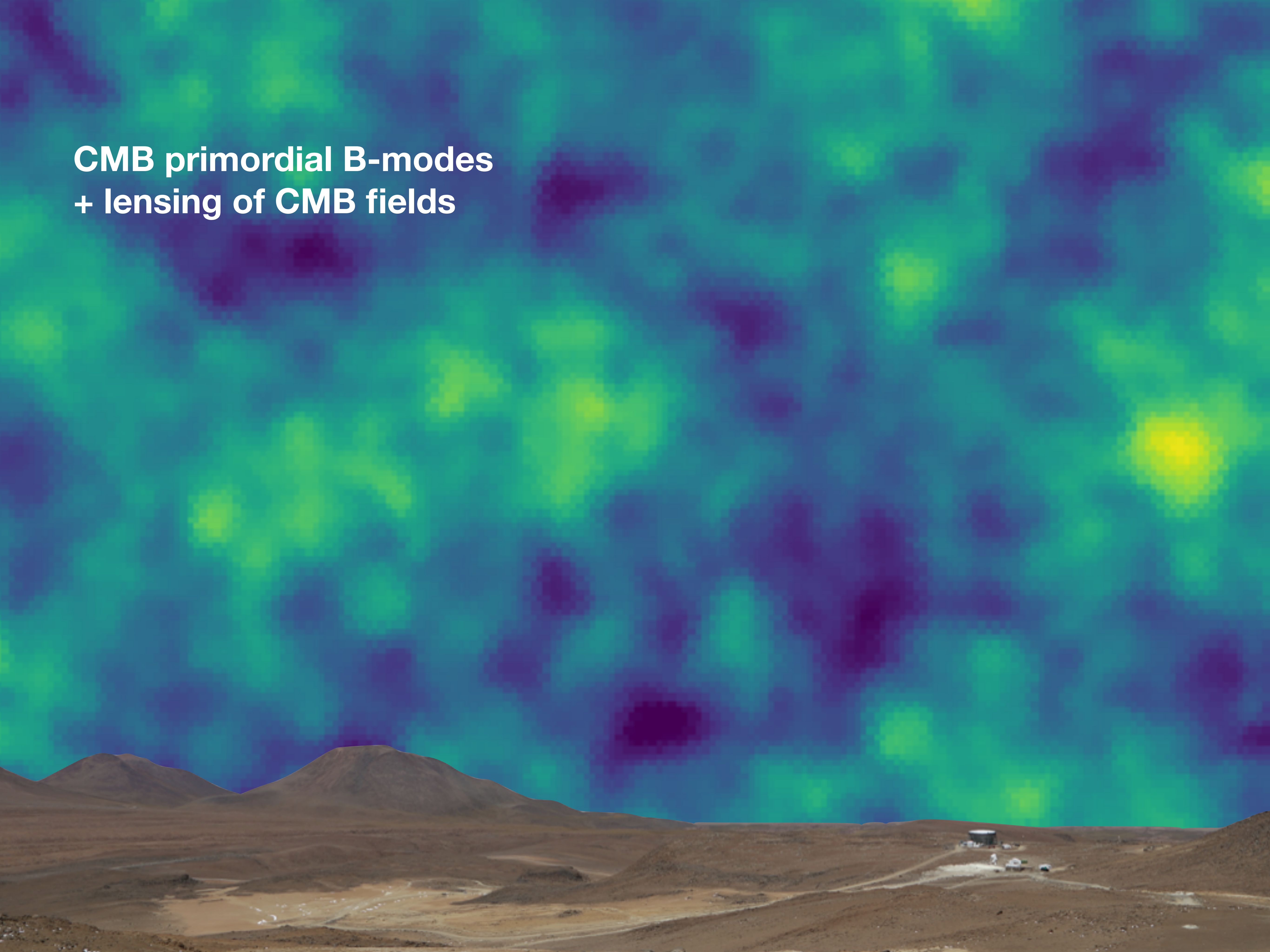
detecting CMB B-modes in practice



at mm wavelengths, we would see an isotropic signal, with a black body spectrum at a 2.7K temperature


CMB primordial B-modes
zooming at the
$\pm 10^{-7-8}$K!

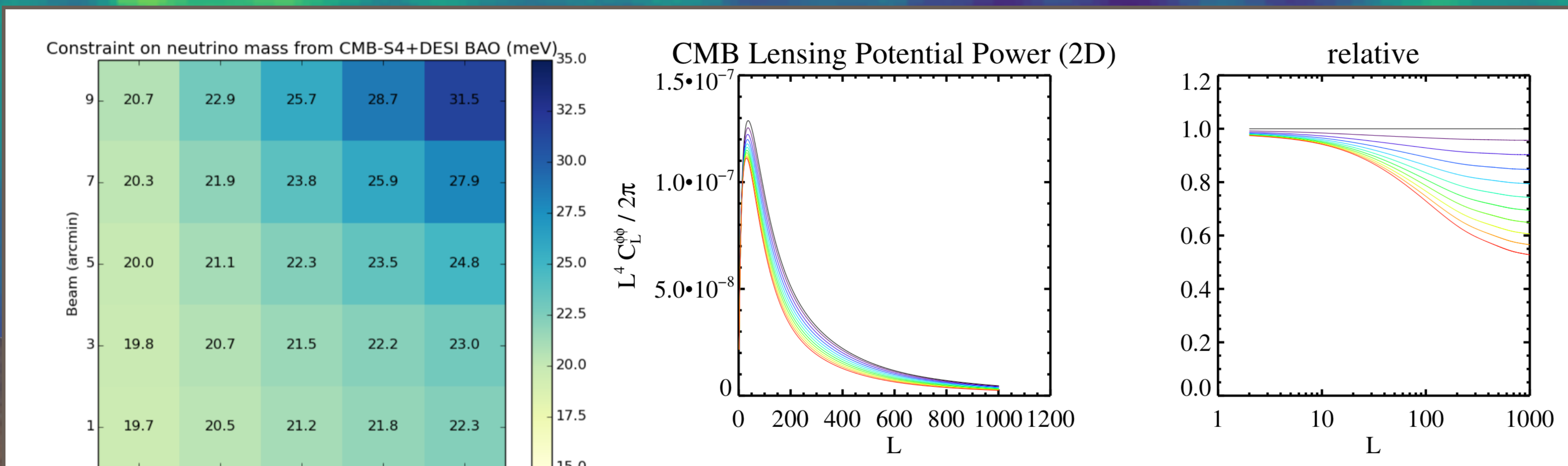

CMB primordial B-modes


CMB primordial B-modes
+ lensing of CMB fields

CMB primordial B-modes
+ lensing of CMB fields

$\vec{\alpha} = \vec{\nabla}\phi$

ϕ = **lensing potential** = the entire mass of the Universe
➔ constraints on all cosmological parameters governing the formation and evolution of structures
➔ Σm_ν (mass hierarchy), dark energy equation of state *w*, dark matter, …

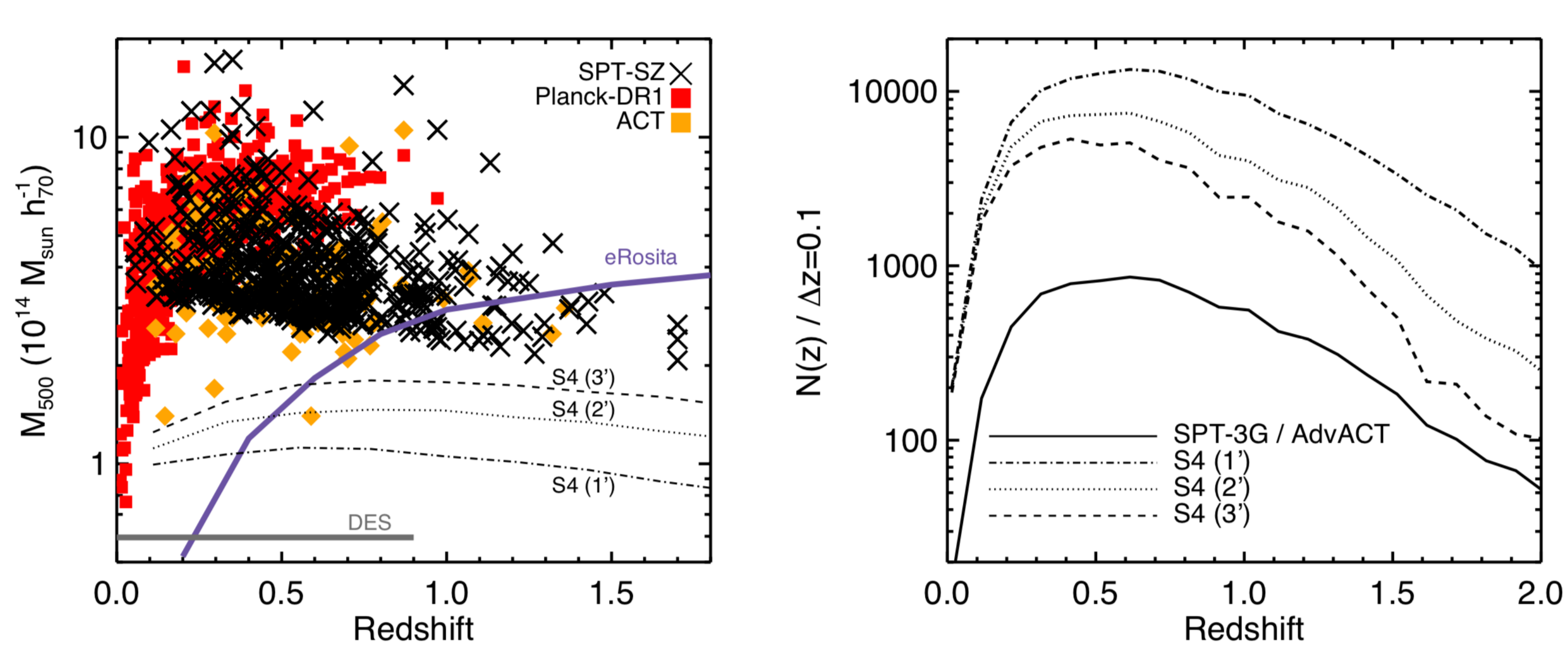


taken from CMB-S4 Science Book (2016)

CMB primordial B-modes
+ lensing of CMB fields

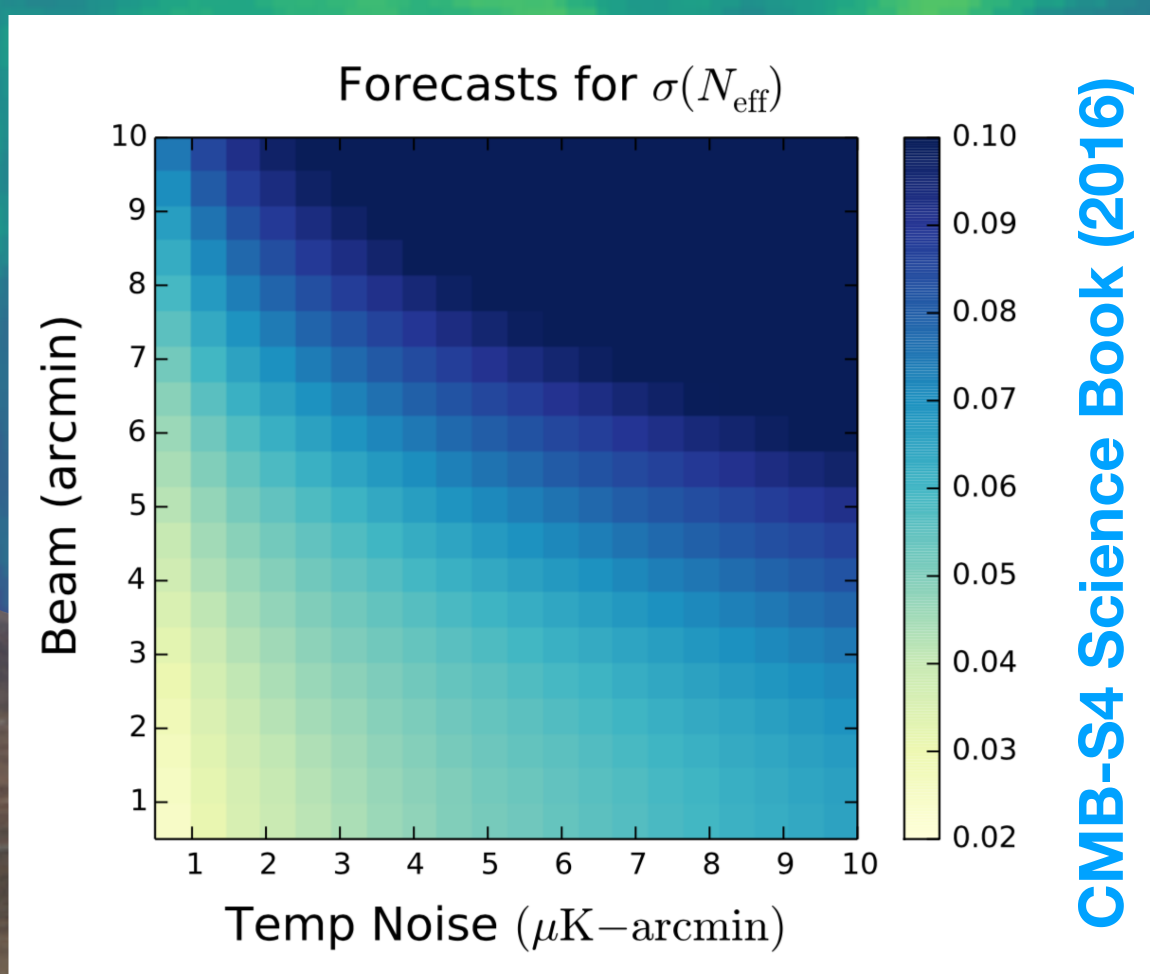
SZ clusters ➔ Σm$_\nu$, dark energy,
galaxy evolution, etc.

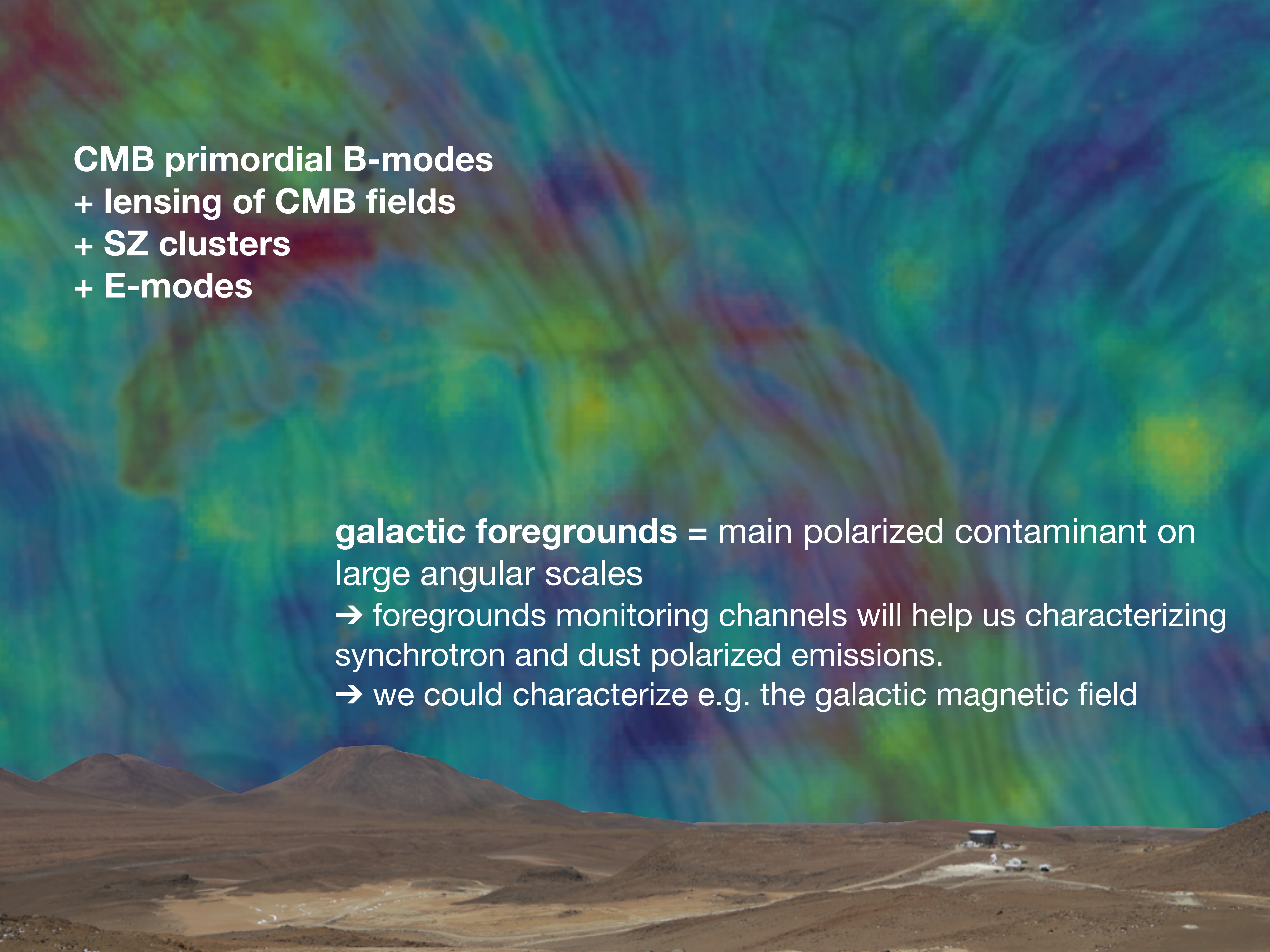
CMB-S4 Science Book (2016)



CMB primordial B-modes
+ lensing of CMB fields
+ SZ clusters

E-modes ➔ e.g. relativistic species N_{eff}





CMB primordial B-modes
+ lensing of CMB fields
+ SZ clusters
+ E-modes

galactic foregrounds = main polarized contaminant on large angular scales

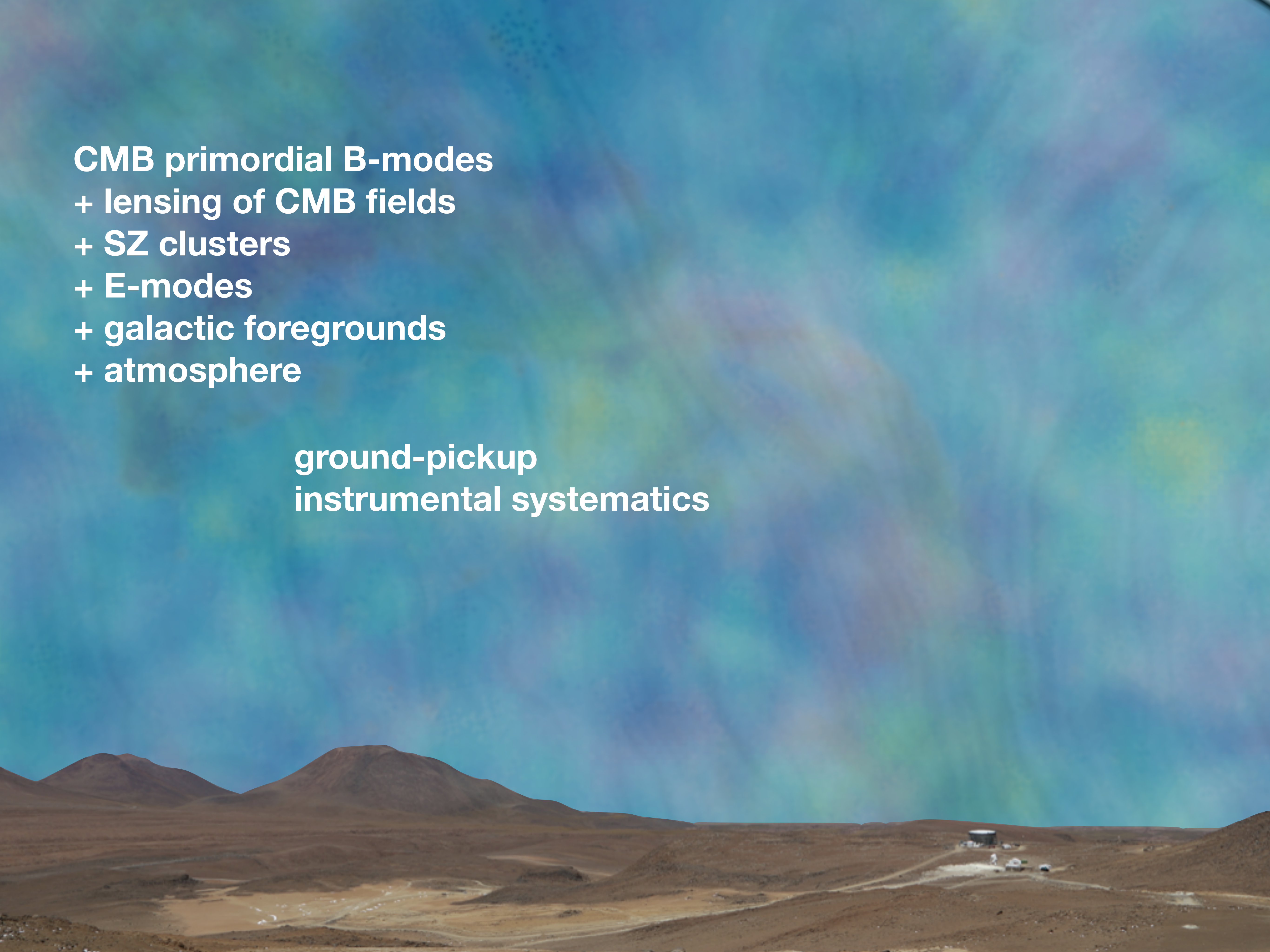
➔ foregrounds monitoring channels will help us characterizing synchrotron and dust polarized emissions.

➔ we could characterize e.g. the galactic magnetic field

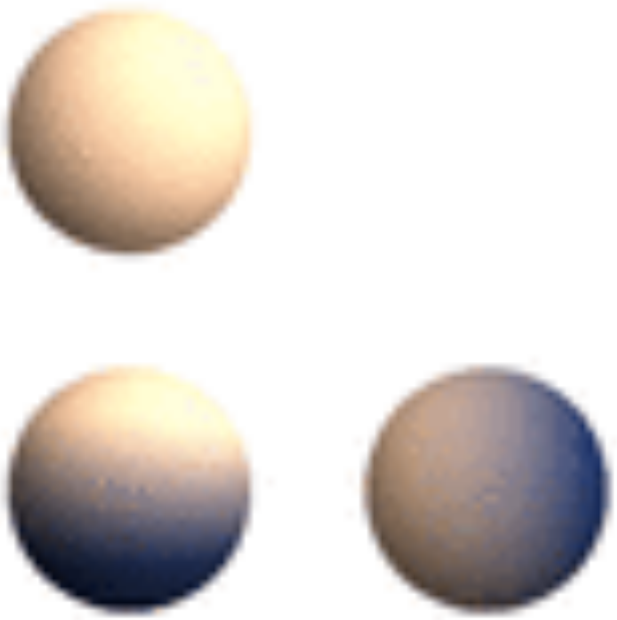
CMB primordial B-modes
+ lensing of CMB fields
+ SZ clusters
+ E-modes
+ galactic foregrounds

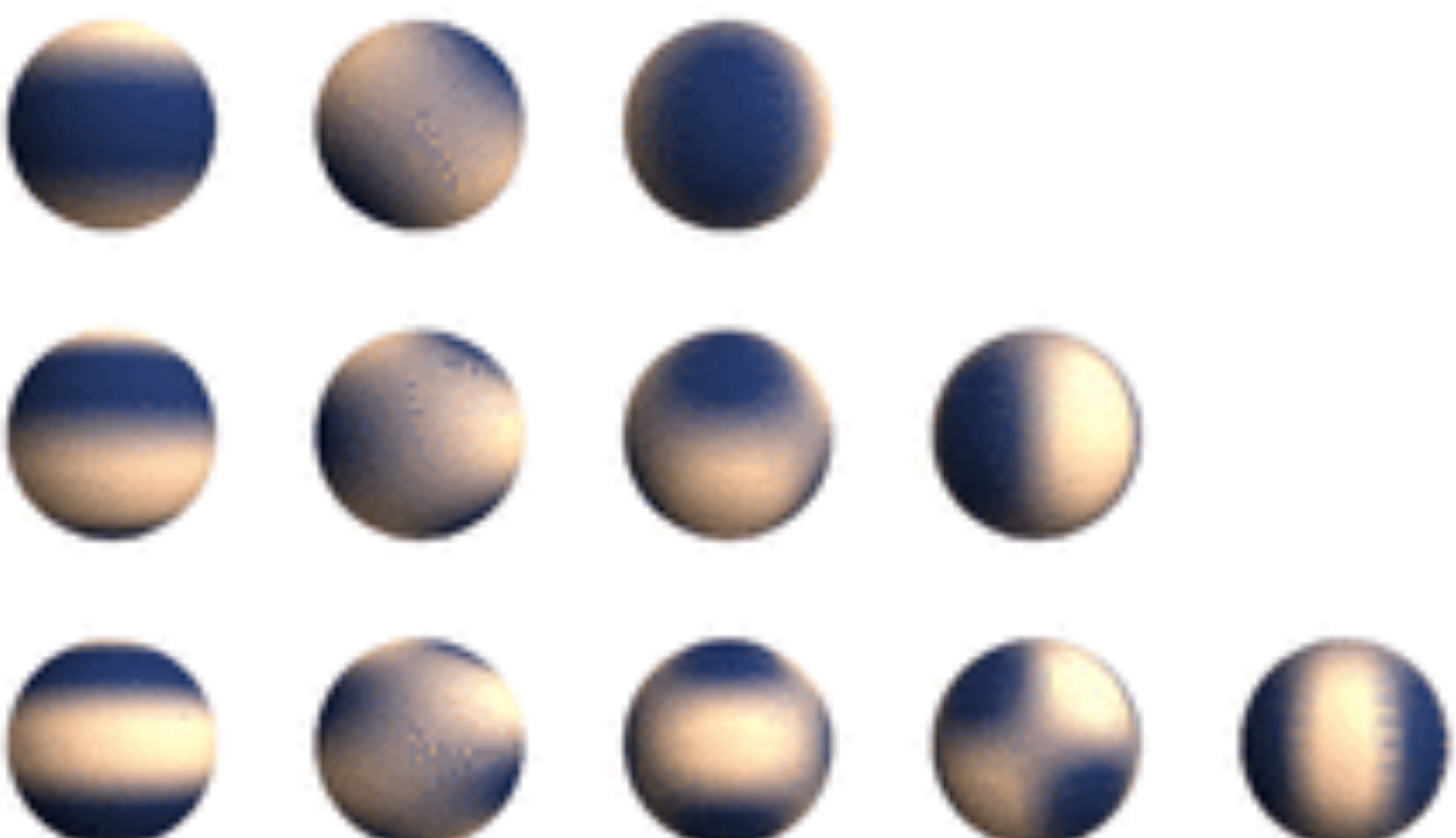
atmosphere

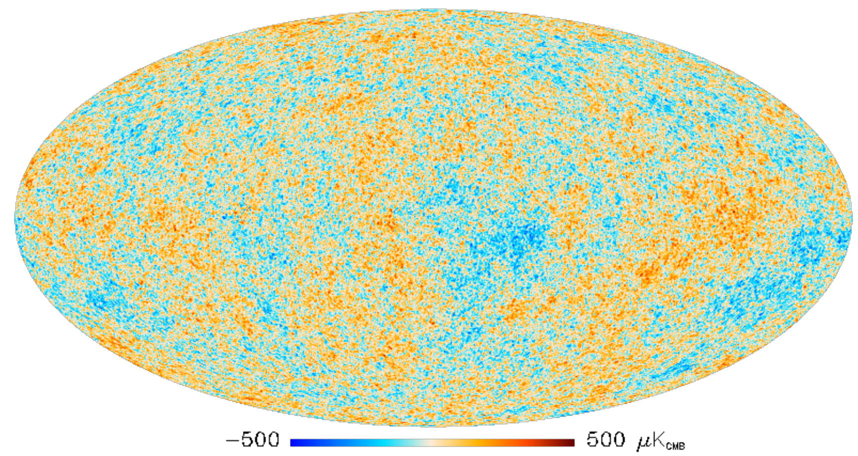
credits: R. Keskitalo (LBNL)
https://crd.lbl.gov/news-and-publications/news/2017/a-toast-for-next-generation-cmb-experiments/
Errard et al, The Astrophysical Journal, Volume 809, Issue 1, article id. 63, 19 pp. (2015)


CMB primordial B-modes
+ lensing of CMB fields
+ SZ clusters
+ E-modes
+ galactic foregrounds
+ atmosphere
ground-pickup
instrumental systematics

going to spherical harmonics

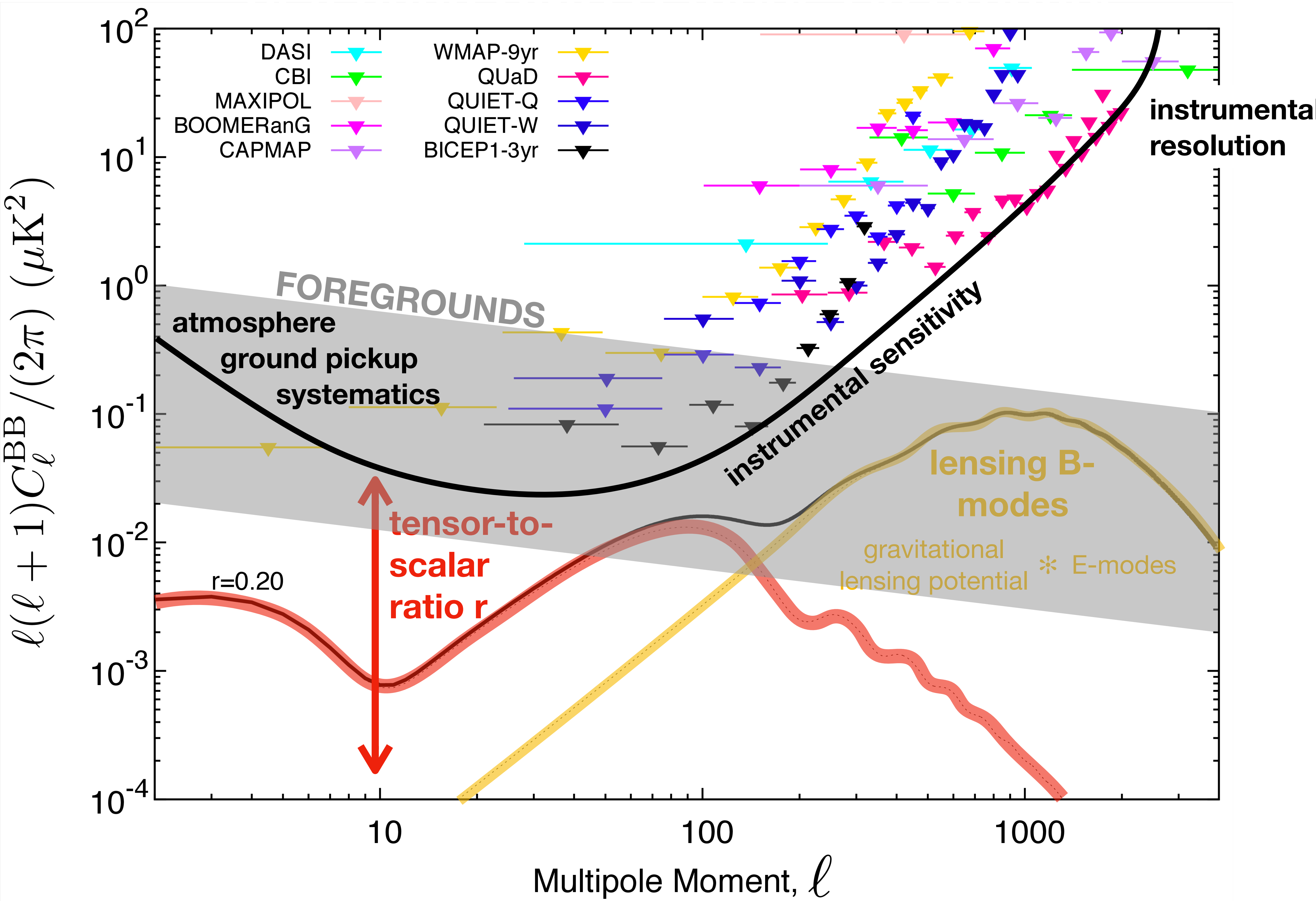




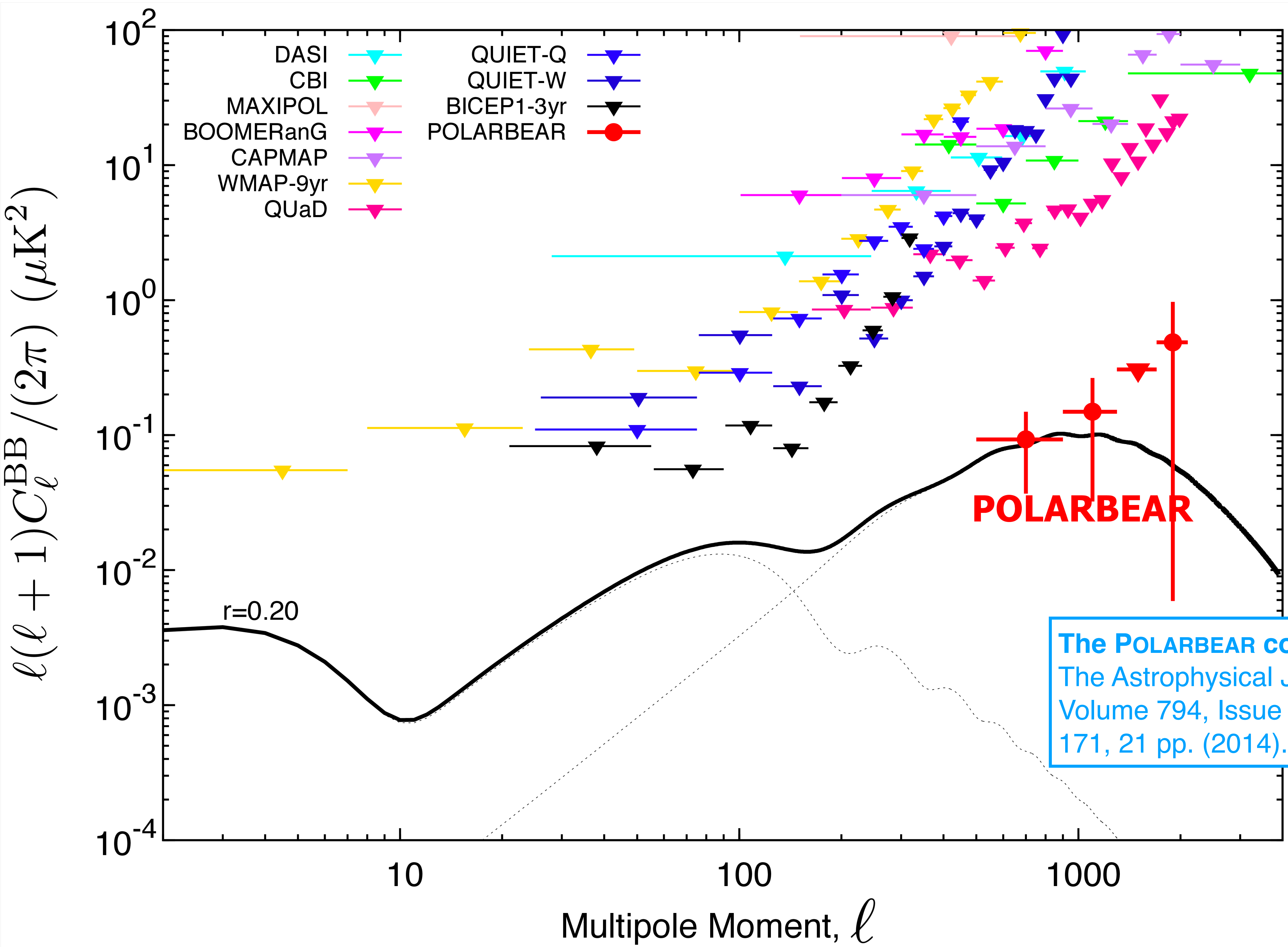


$$= \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^T_{\ell m} Y_\ell^m(\theta, \phi)$$

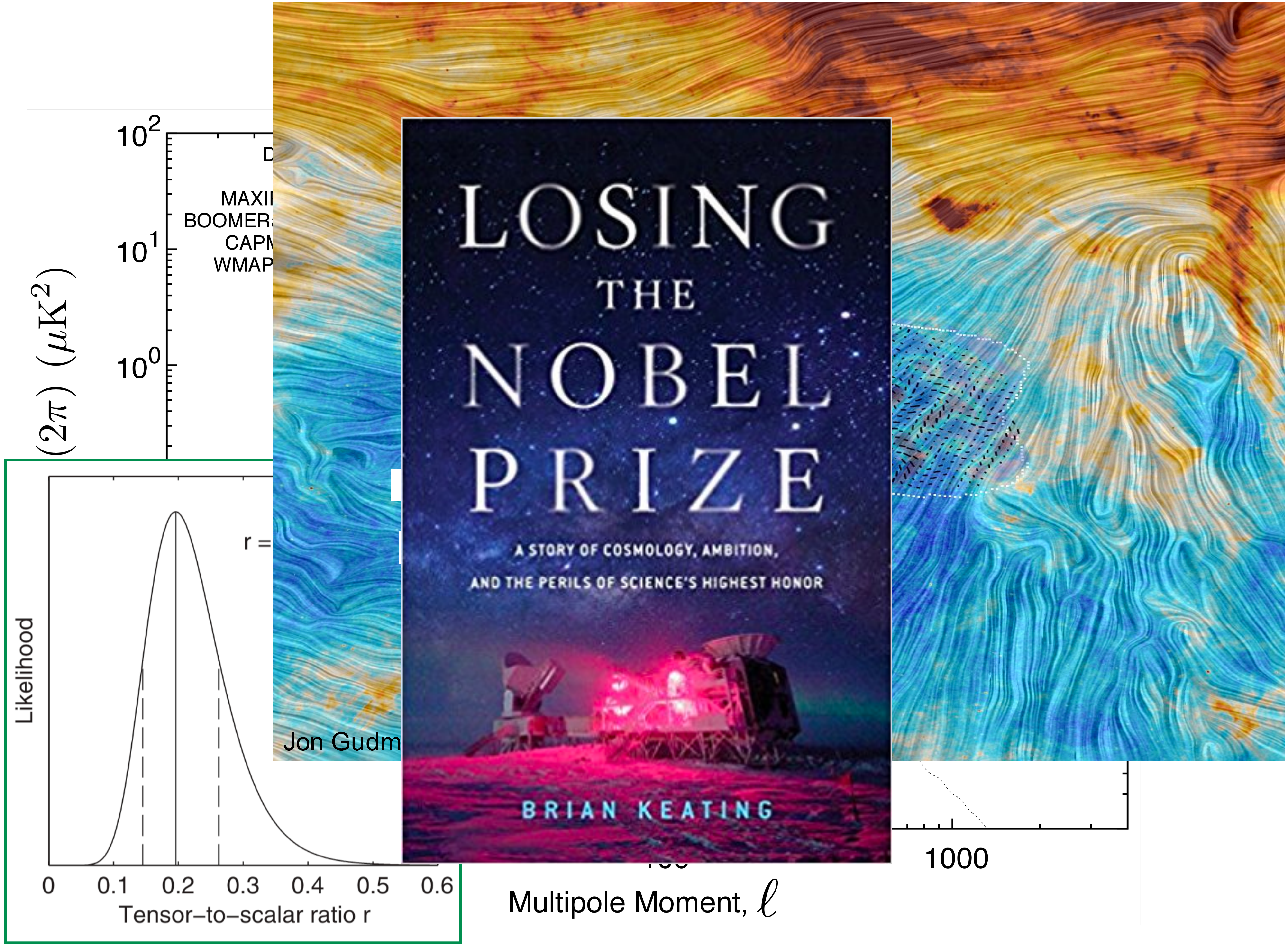
B-modes power spectrum



B-modes power spectrum

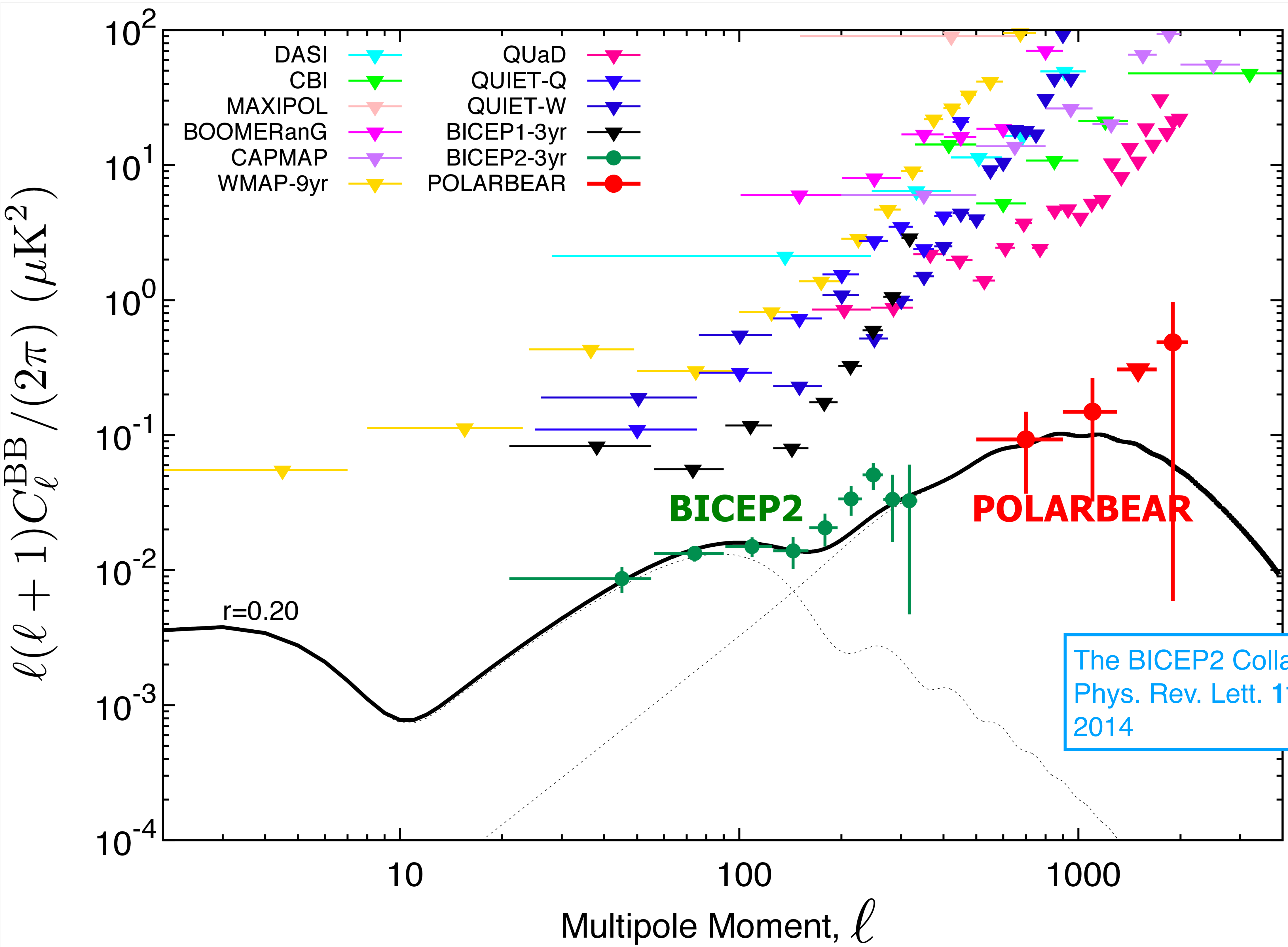


The POLARBEAR collaboration
The Astrophysical Journal, Volume 794, Issue 2, article id. 171, 21 pp. (2014).



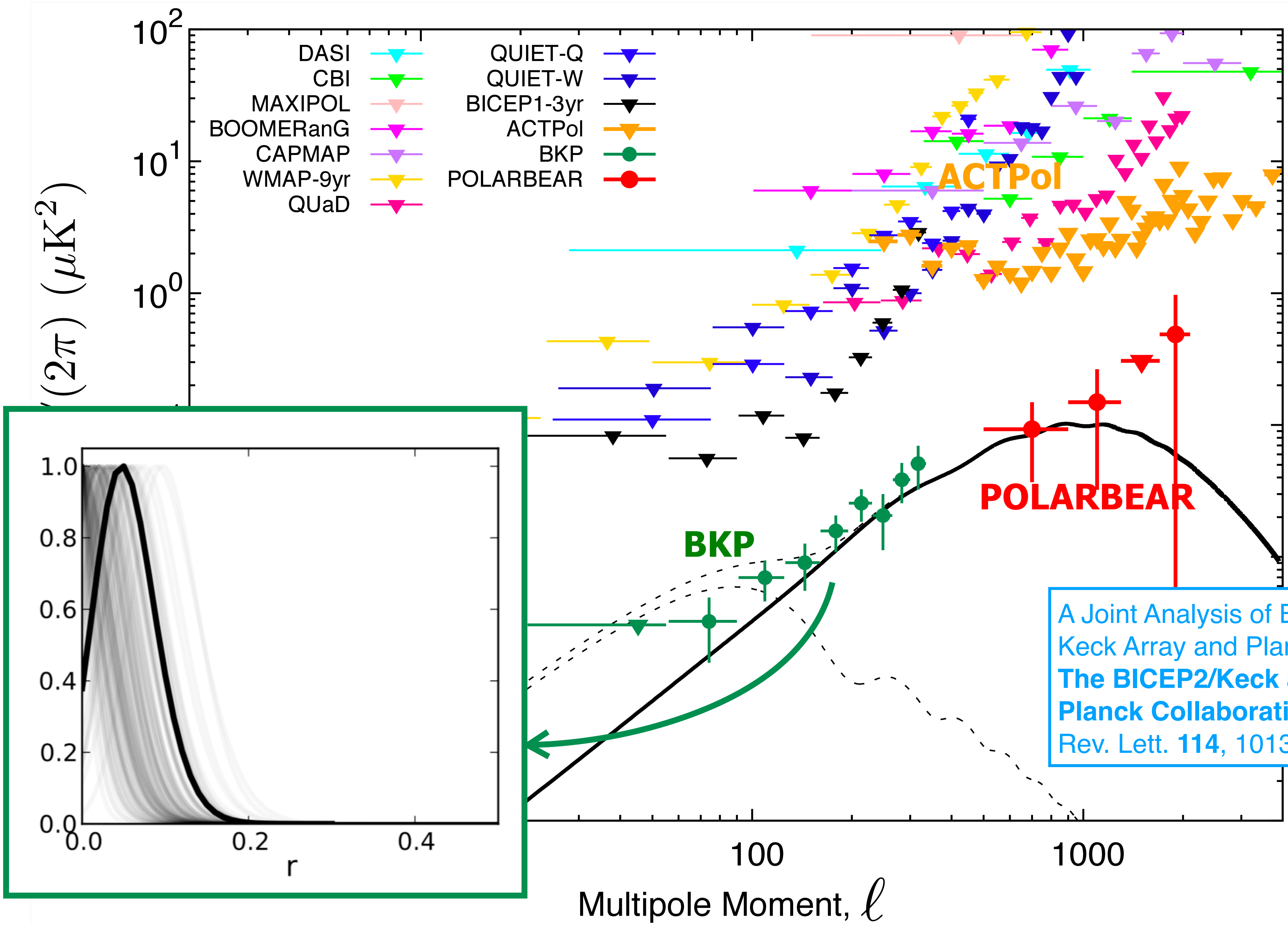
LOSING THE NOBEL PRIZE
A STORY OF COSMOLOGY, AMBITION,
AND THE PERILS OF SCIENCE'S HIGHEST HONOR
BRIAN KEATING
Likelihood
0 0.1 0.2 0.3 0.4 0.5 0.6
Tensor−to−scalar ratio r
10^2
10^1
10^0
$(2\pi)\ (\mu K^2)$
1000
Multipole Moment, ℓ

B-modes power spectrum



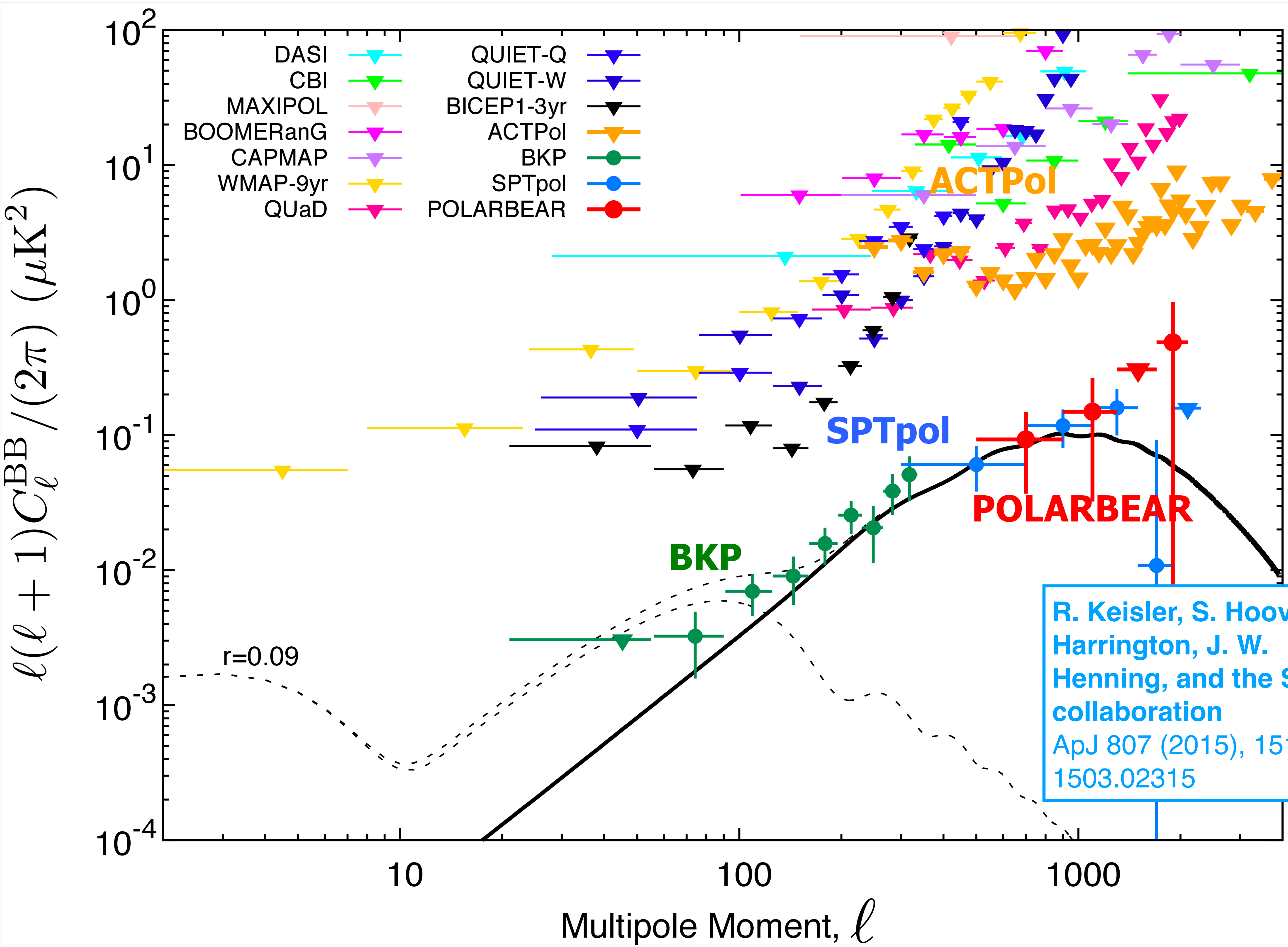
The BICEP2 Collaboration, Phys. Rev. Lett. **112**, 241101, 2014

B-modes power spectrum



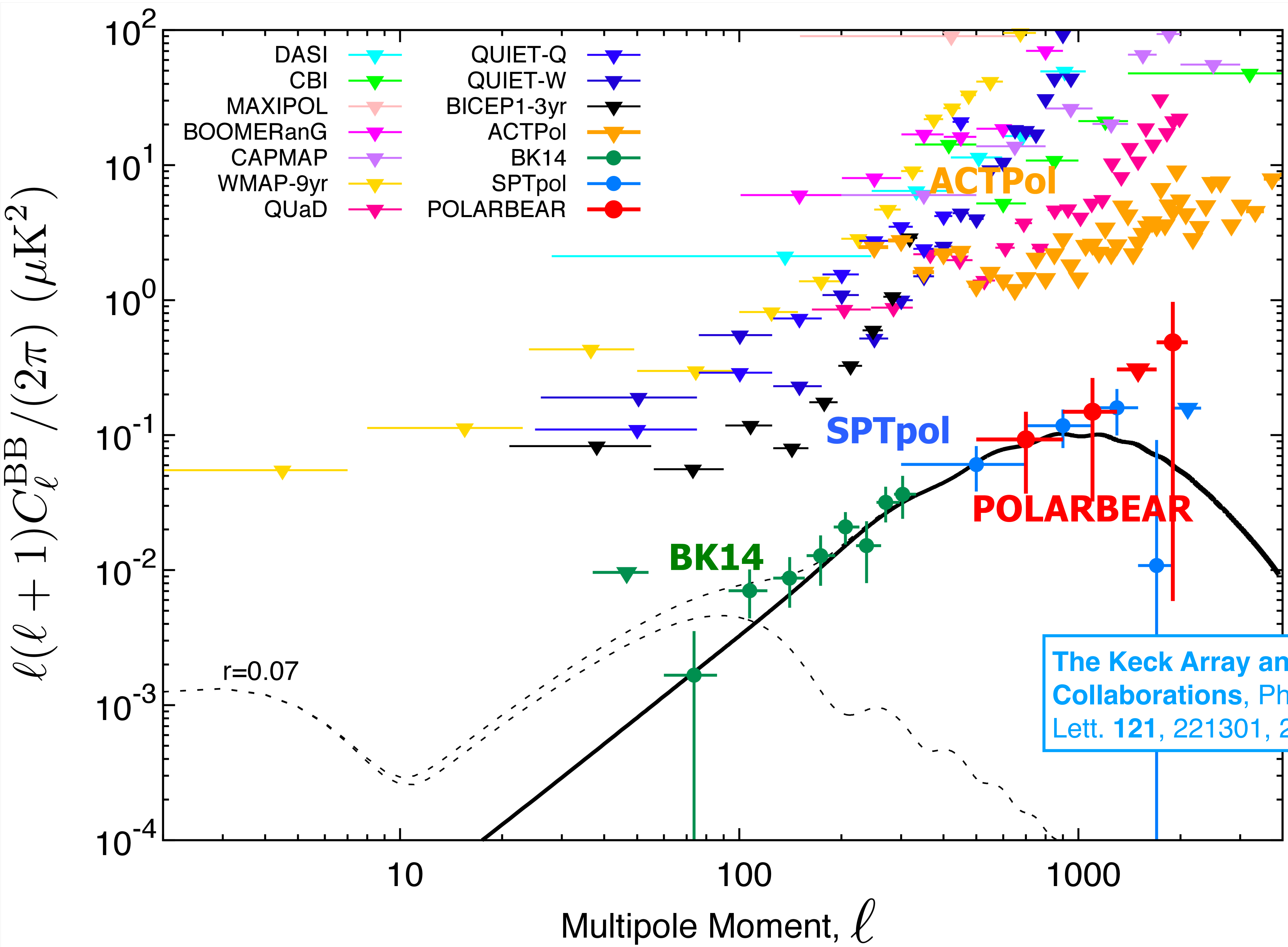
A Joint Analysis of BICEP2/ Keck Array and Planck Data
The BICEP2/Keck and Planck Collaborations, Phys. Rev. Lett. **114**, 101301, 2015

B-modes power spectrum



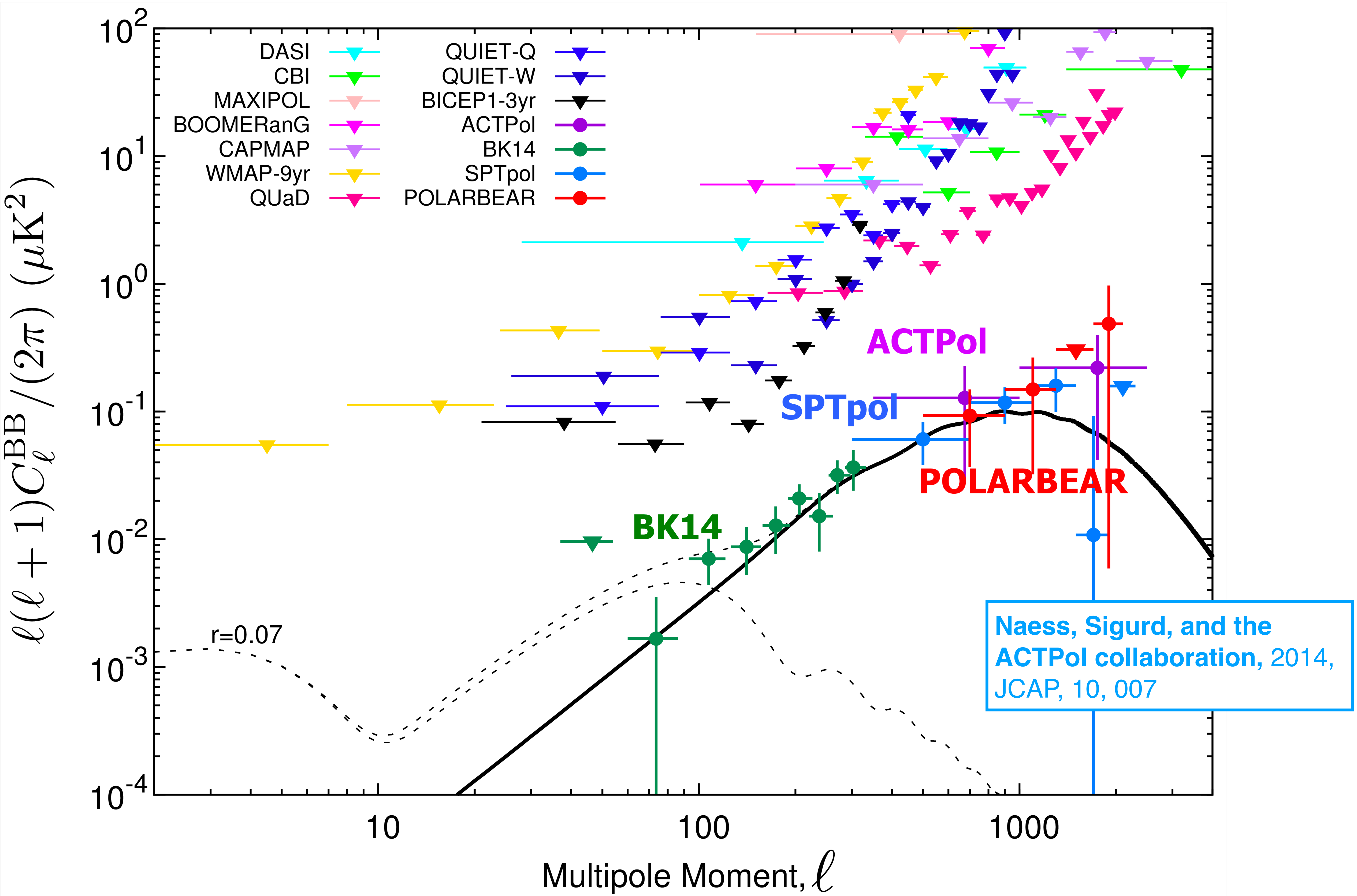
R. Keisler, S. Hoover, N. Harrington, J. W. Henning, and the SPTPol collaboration
ApJ 807 (2015), 151, arXiv: 1503.02315

B-modes power spectrum

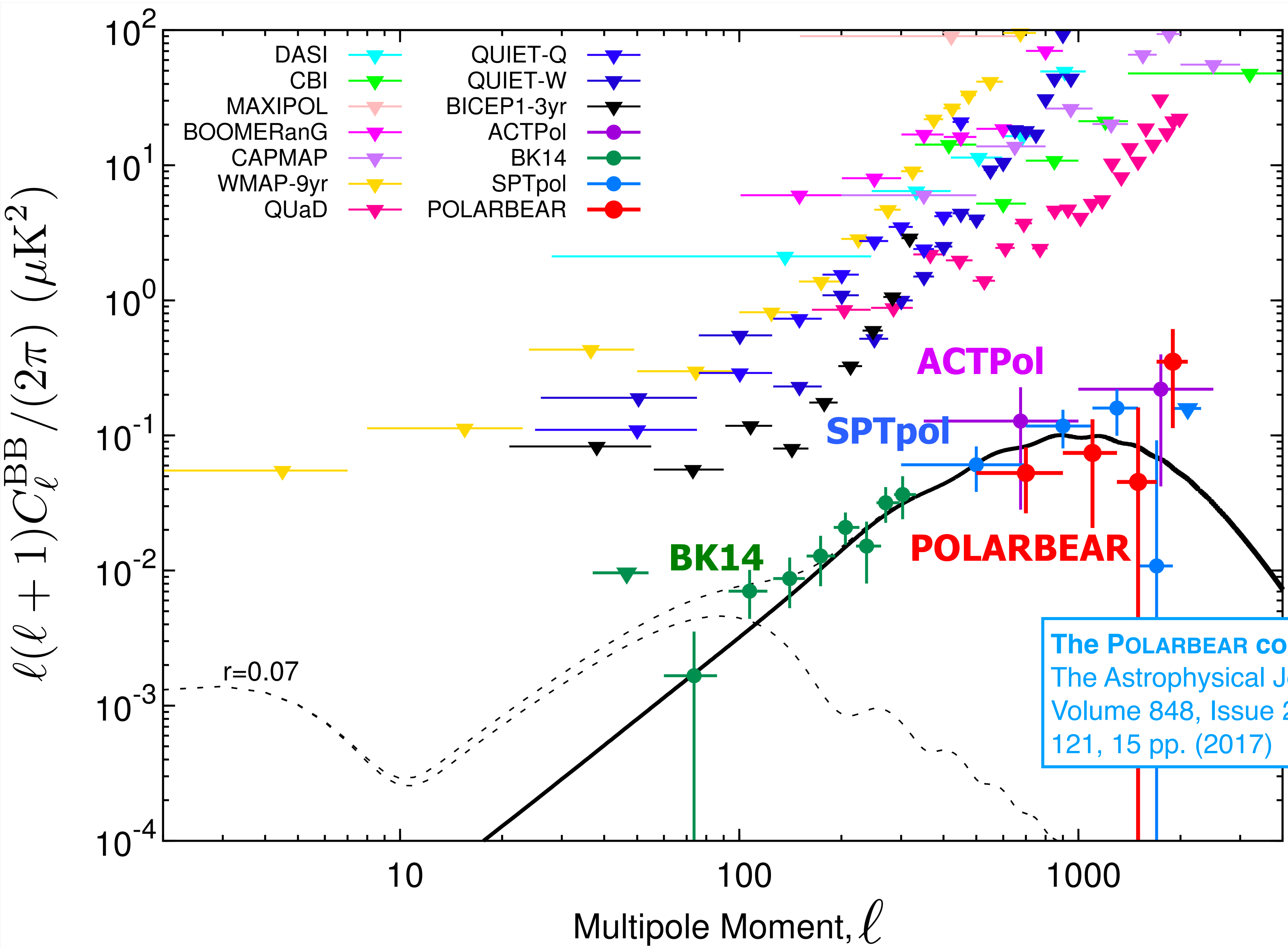


The Keck Array and BICEP2 Collaborations, Phys. Rev. Lett. **121**, 221301, 2018

B-modes power spectrum

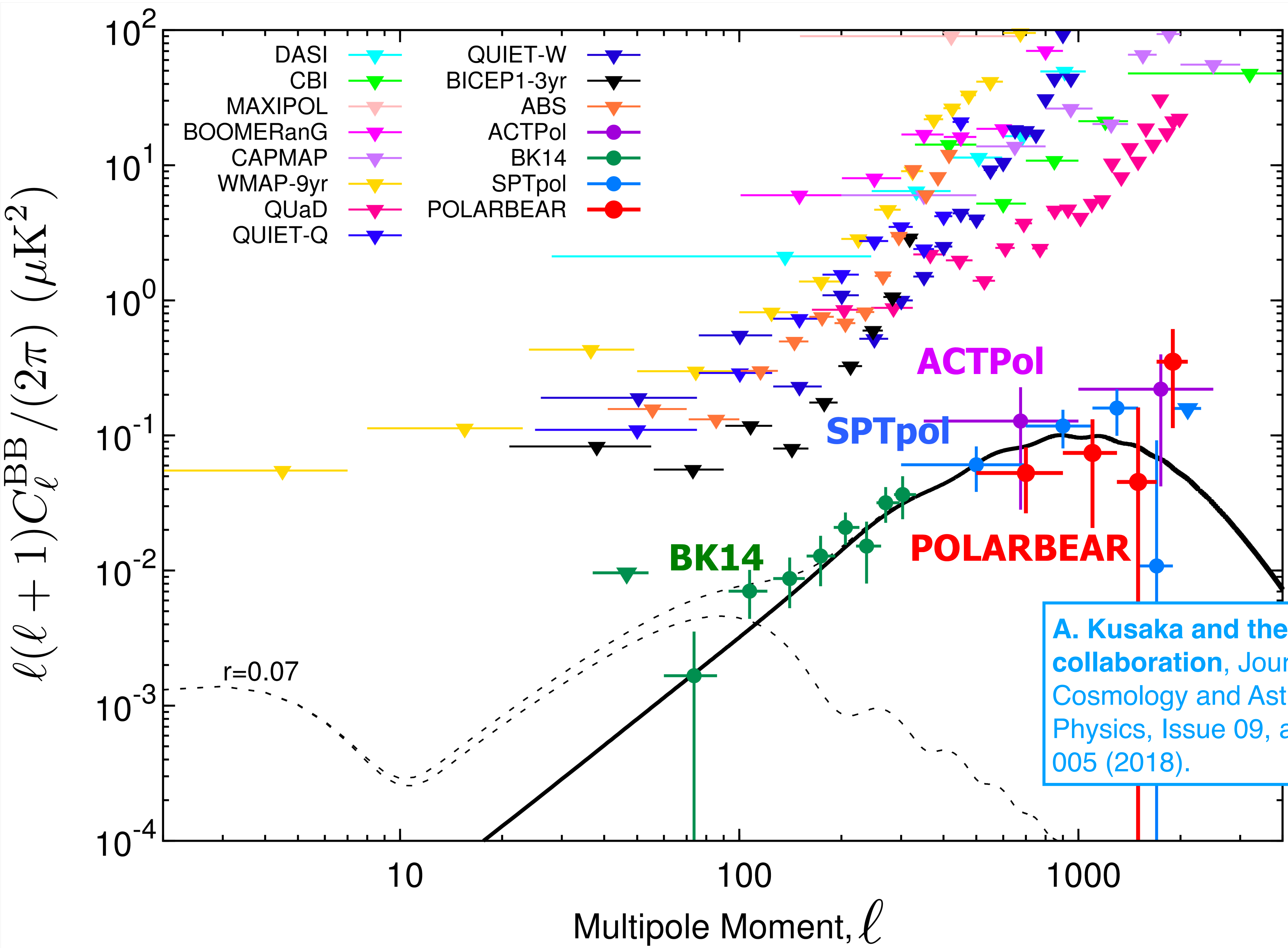


B-modes power spectrum



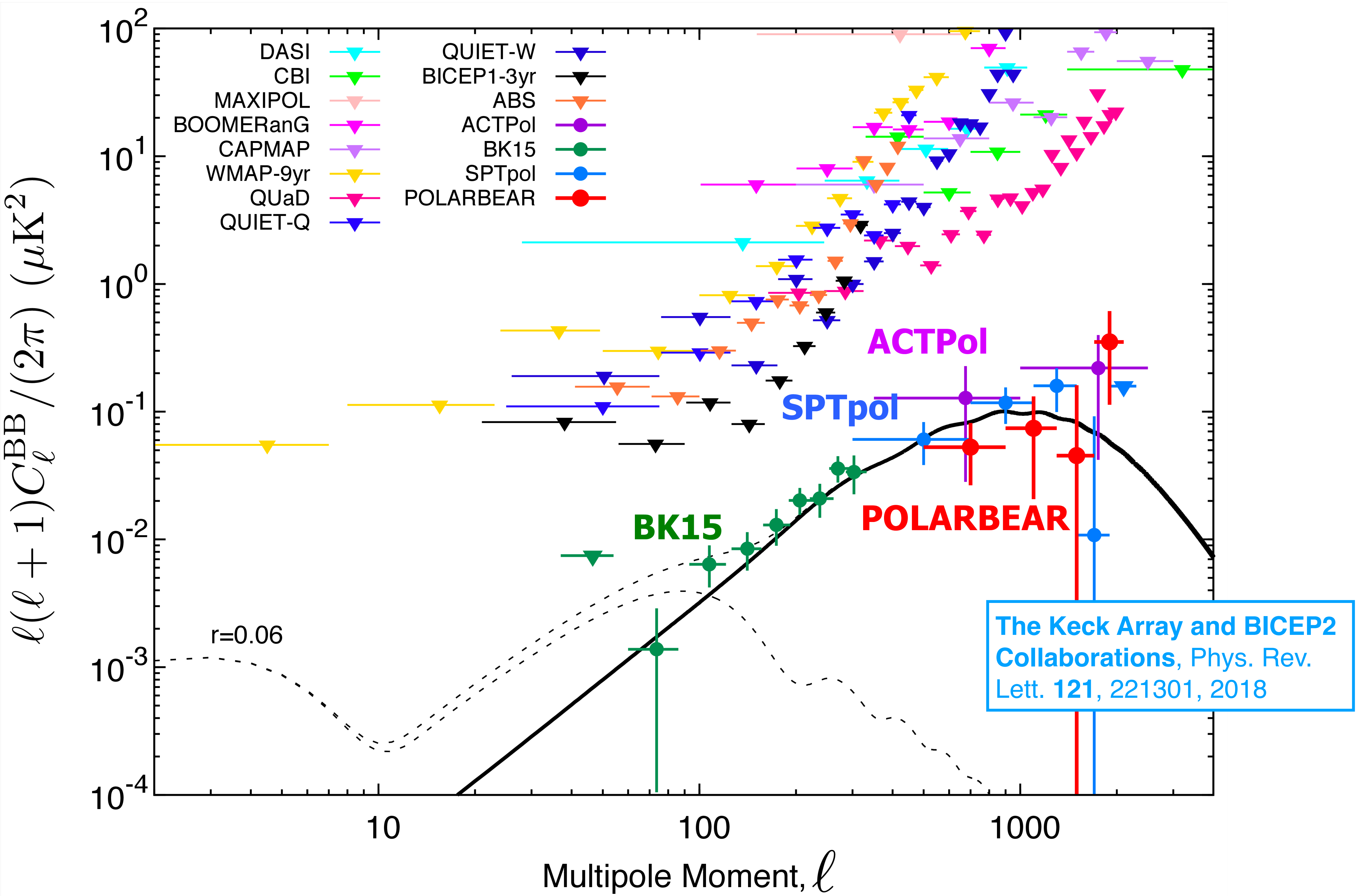
The POLARBEAR collaboration
The Astrophysical Journal, Volume 848, Issue 2, article id. 121, 15 pp. (2017)

B-modes power spectrum



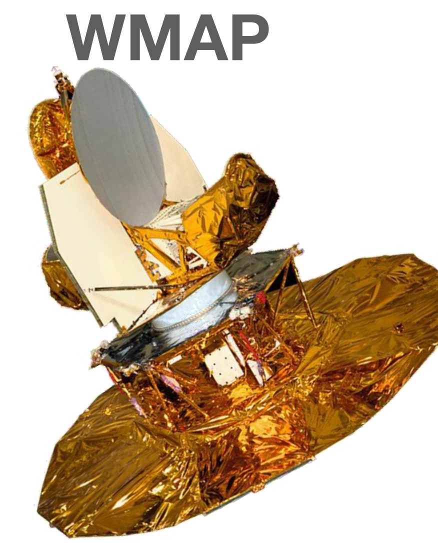
A. Kusaka and the ABS collaboration, Journal of Cosmology and Astroparticle Physics, Issue 09, article id. 005 (2018).

B-modes power spectrum

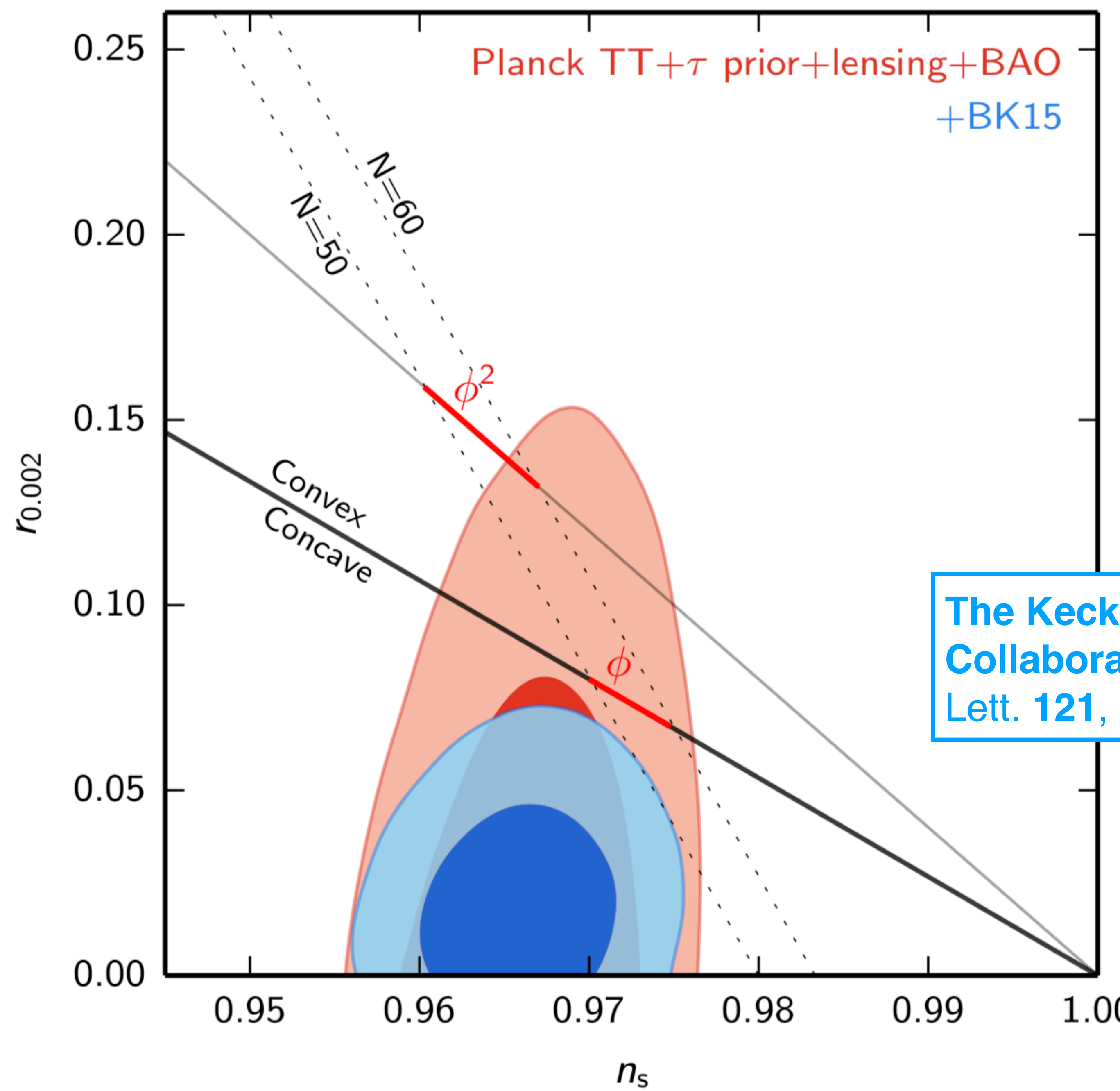


+

+

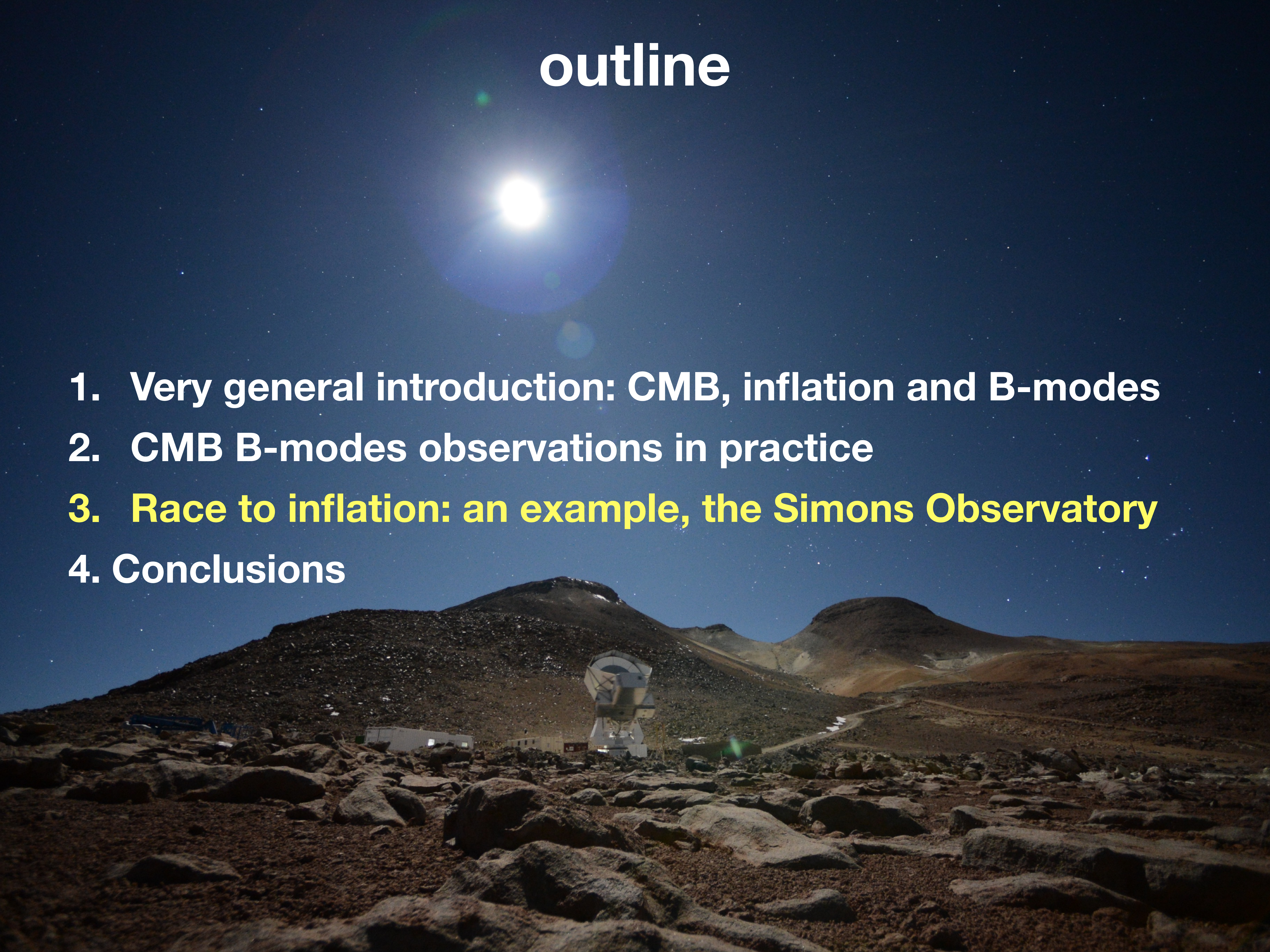


r<0.06 @ 2σ



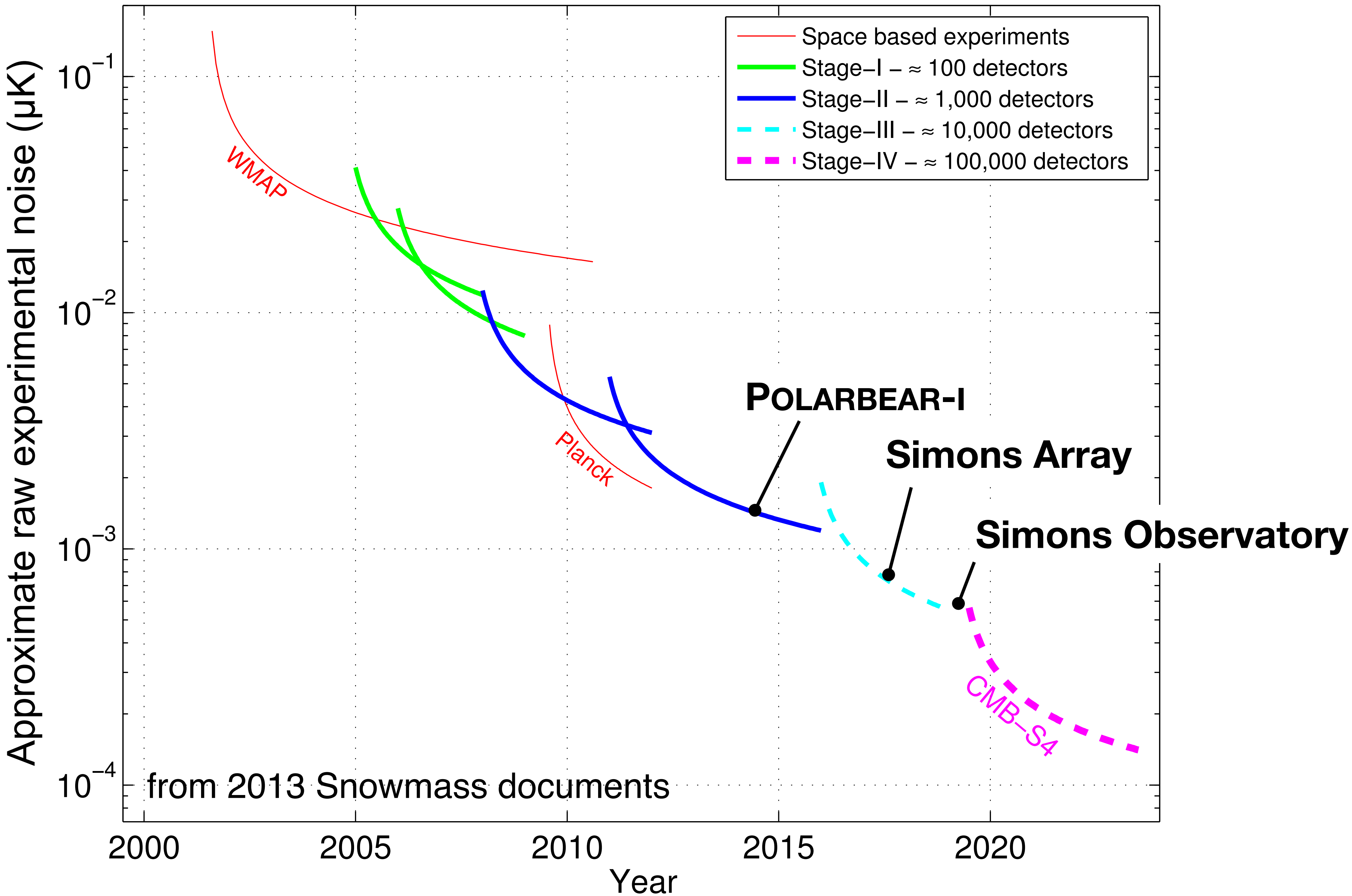
The Keck Array and BICEP2 Collaborations, Phys. Rev. Lett. **121**, 221301, 2018

outline

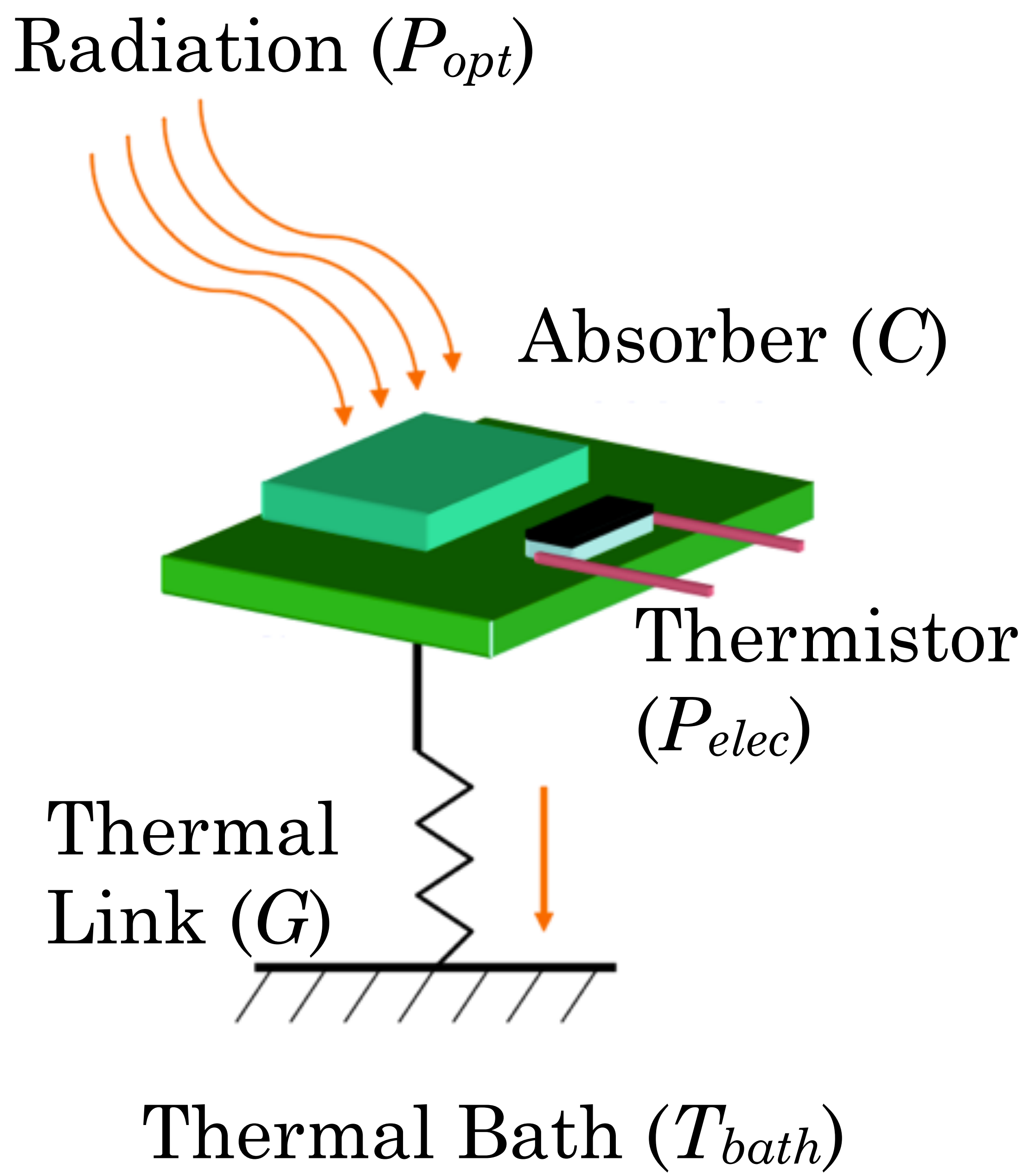


1. Very general introduction: CMB, inflation and B-modes
2. CMB B-modes observations in practice
3. Race to inflation: an example, the Simons Observatory
4. Conclusions

Moore's law of CMB sensitivity



CMB detectors are limited by photon noise ....



Power on the bolometer is the sum of optical and electrical power, that is conducted away through the "G-link

$$P = P_{opt} + P_{elec}$$

$$= \int_{T_{bath}}^{T_{bolo}} G(T)dT$$

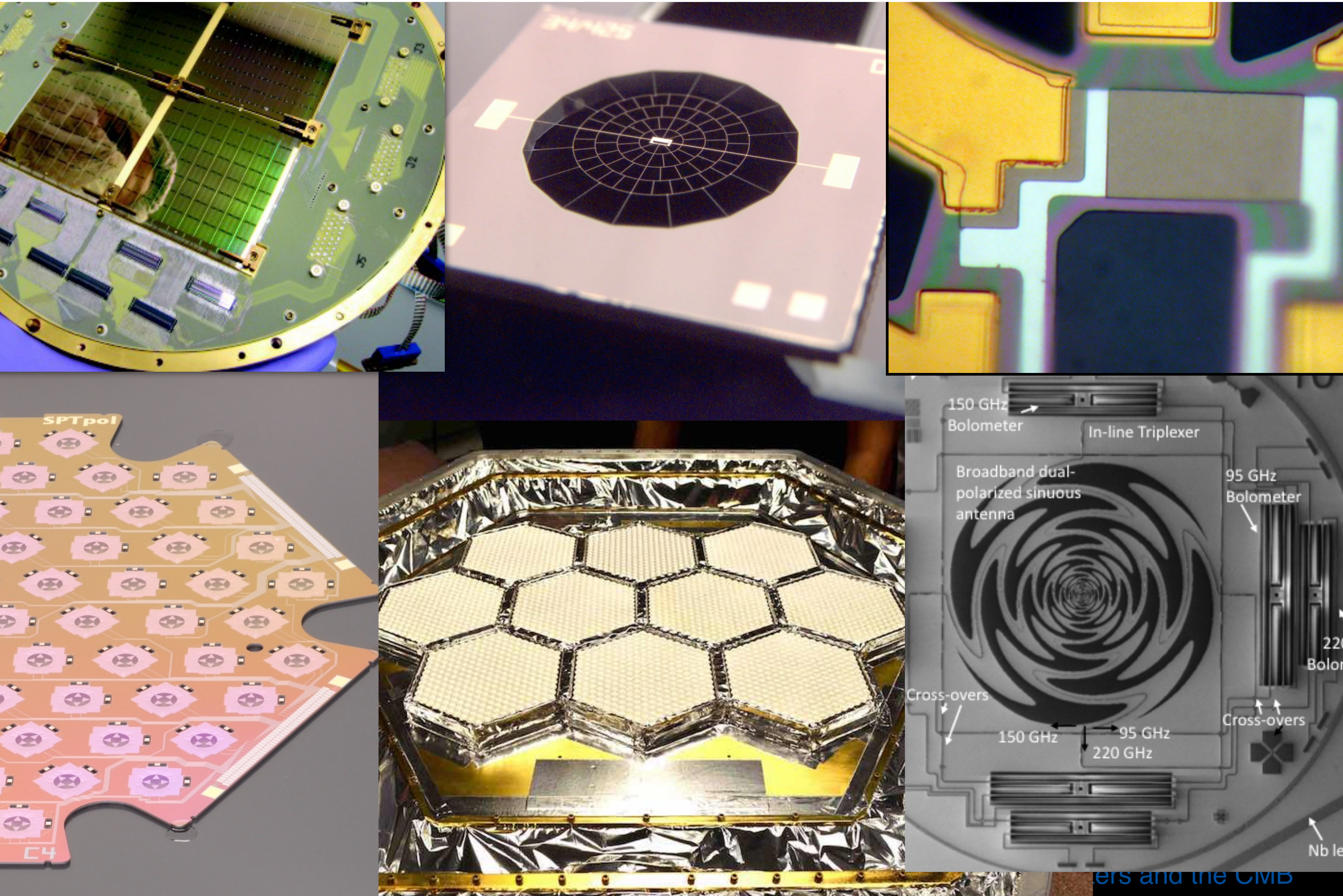
For an input power, bolometer heats up and goes down with a time constant, tau:

$$\Delta T = \Delta P / G$$

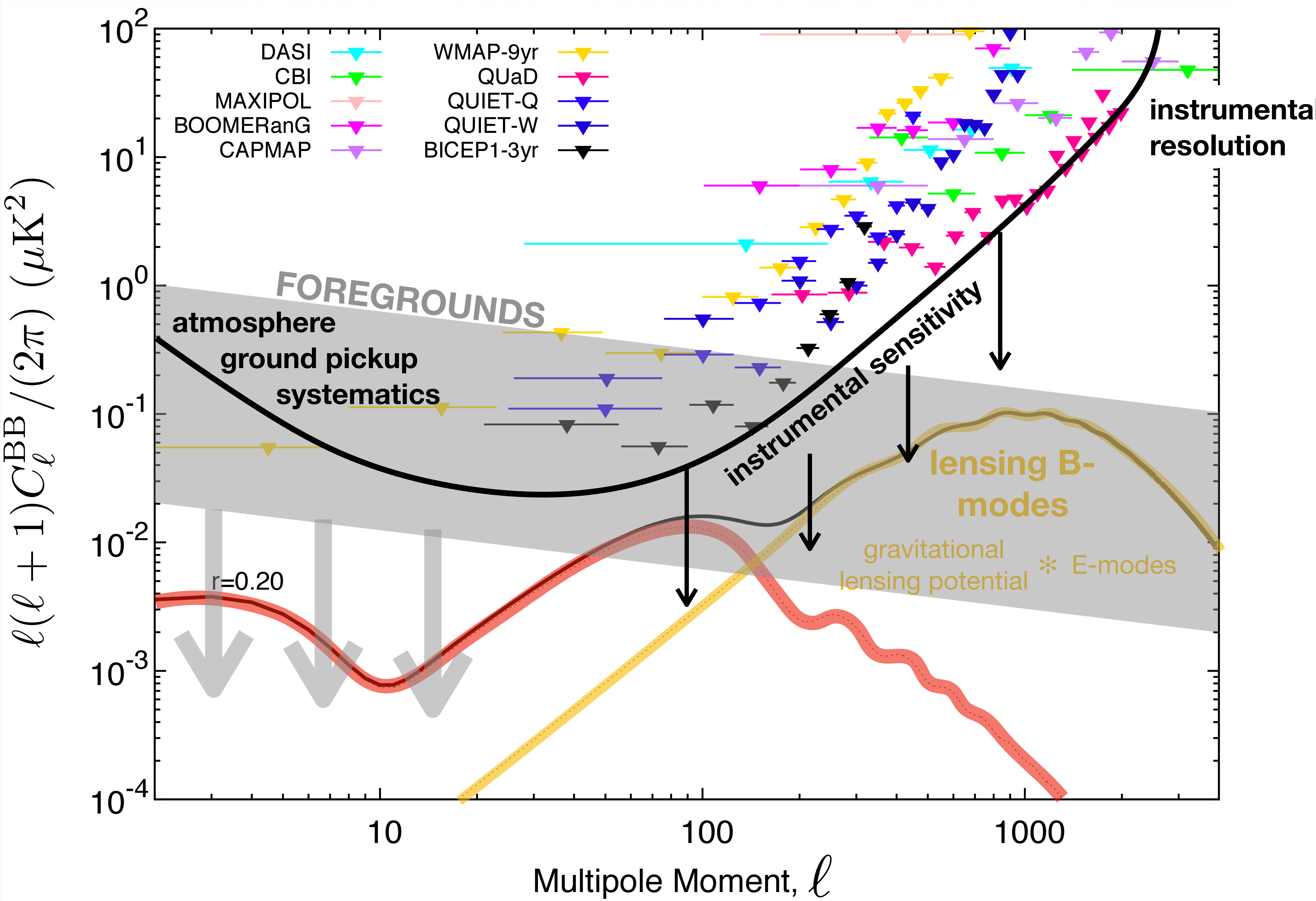
$$\tau = C/G$$

from Bradford A. Benson

…….. so we need more detectors!



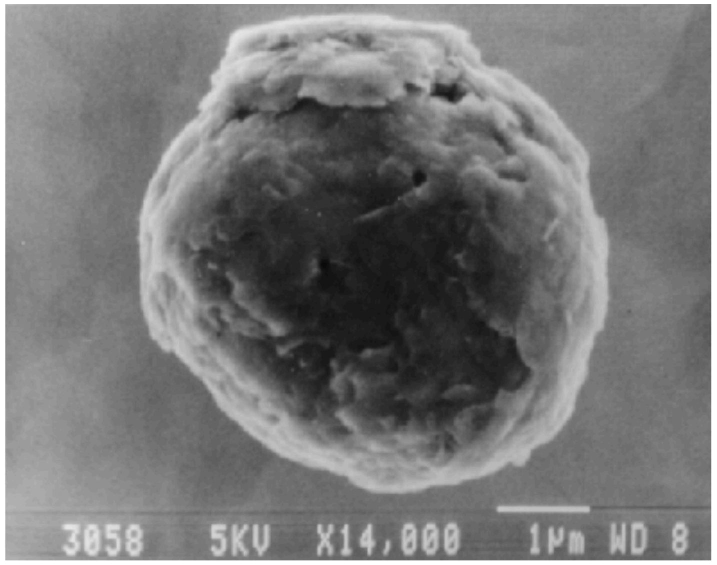
but with some complications :)

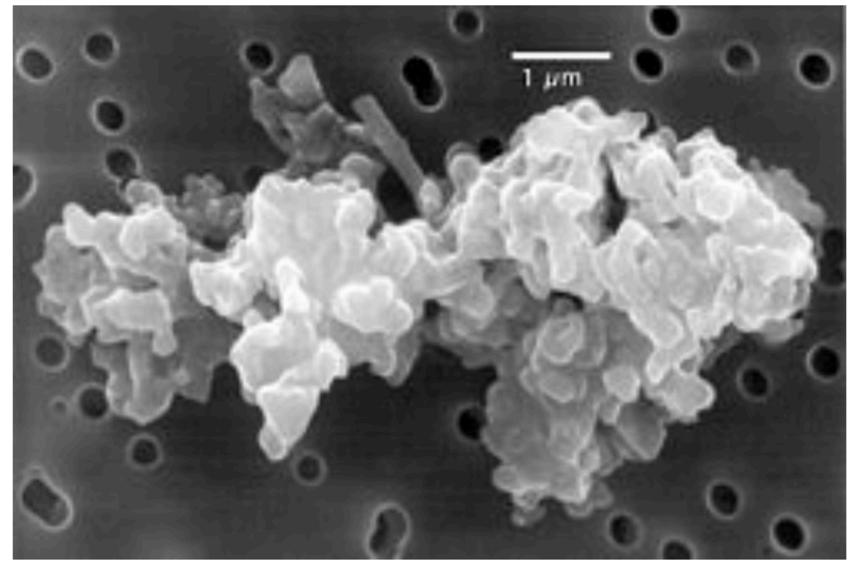


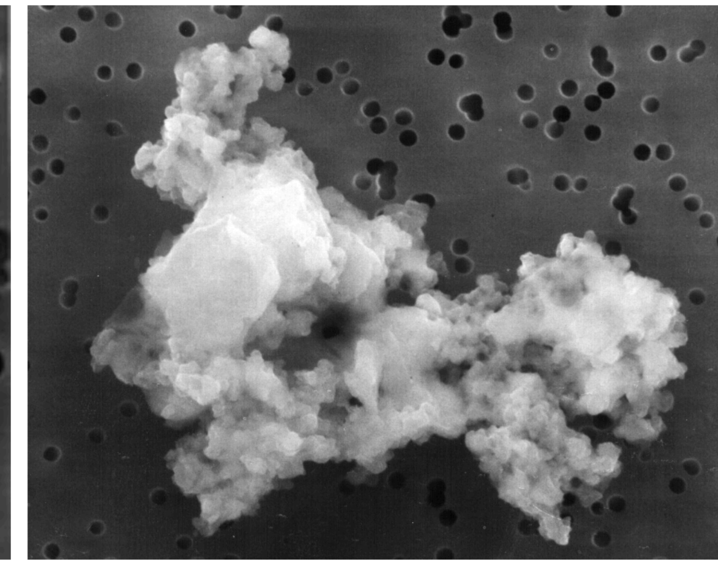
but with some complications :)

Interstellar medium

thermal dust

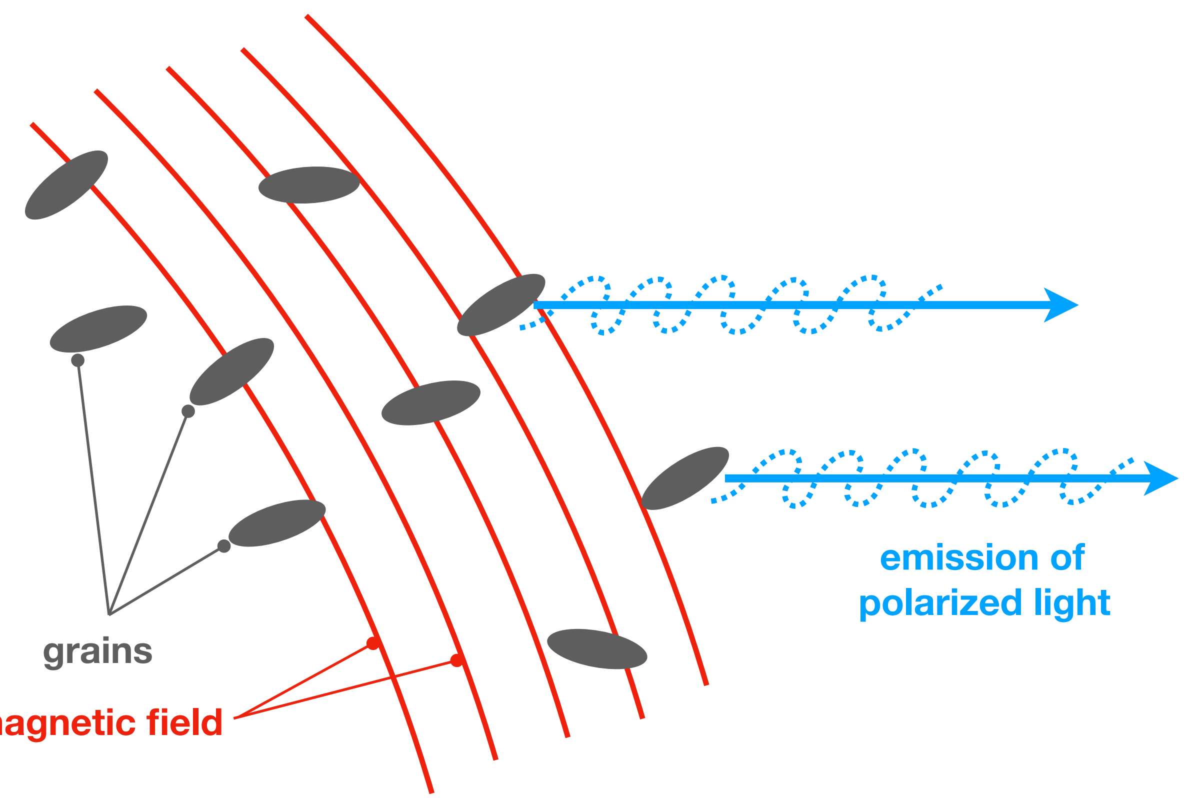




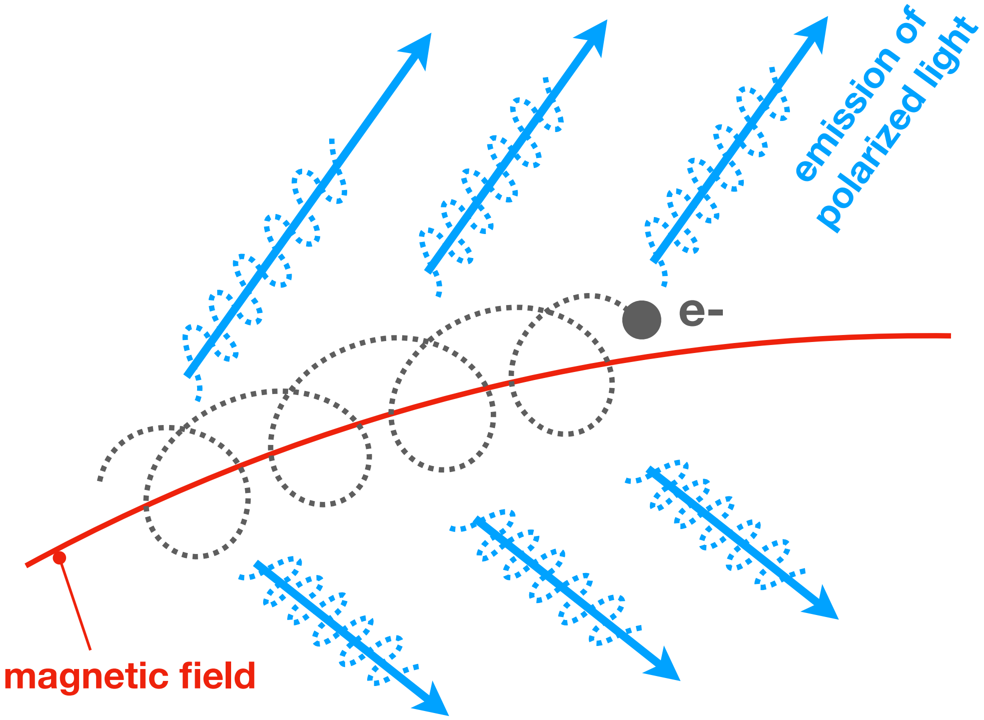


smooth and compact?

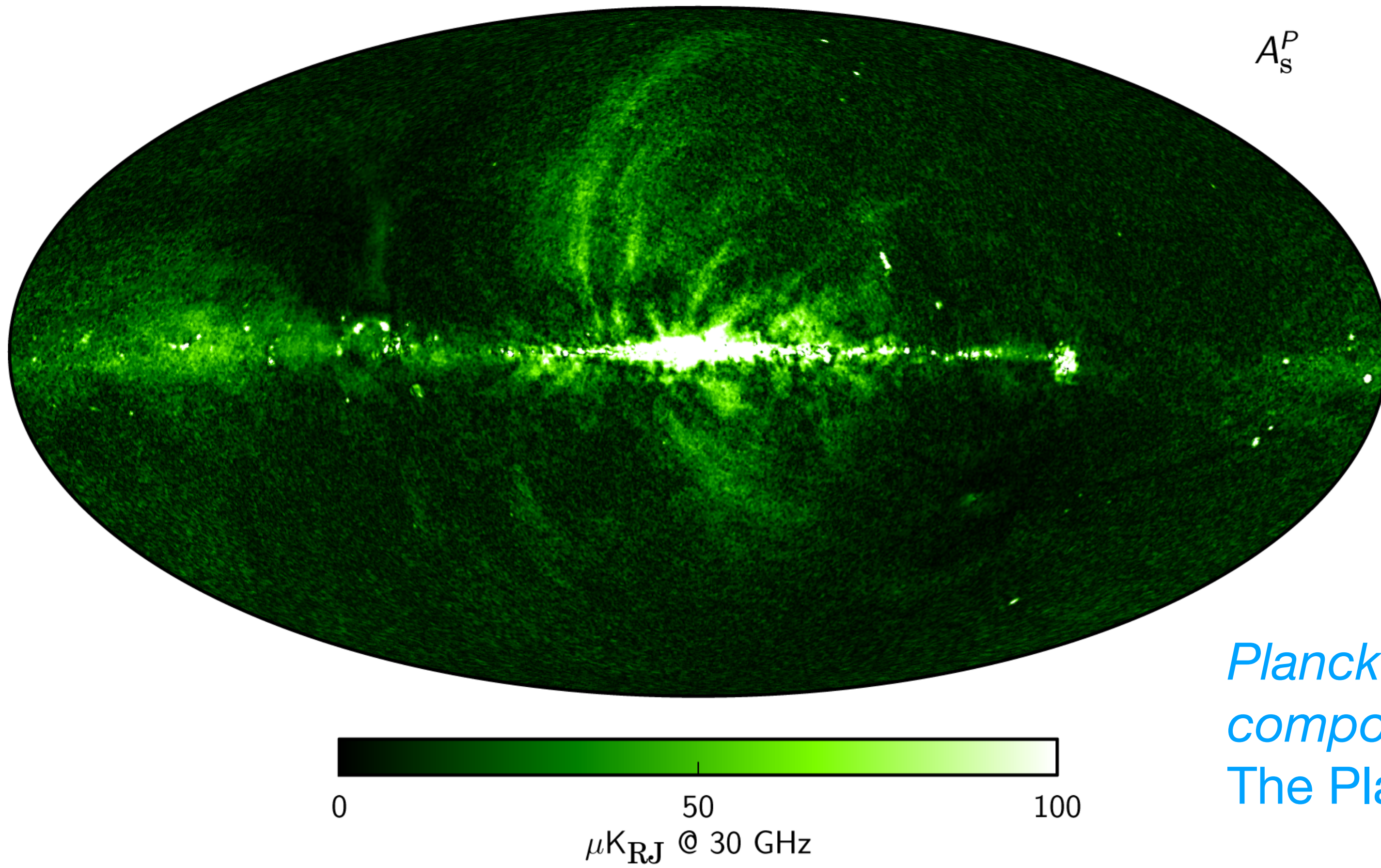
loose aggregates of smaller particles?



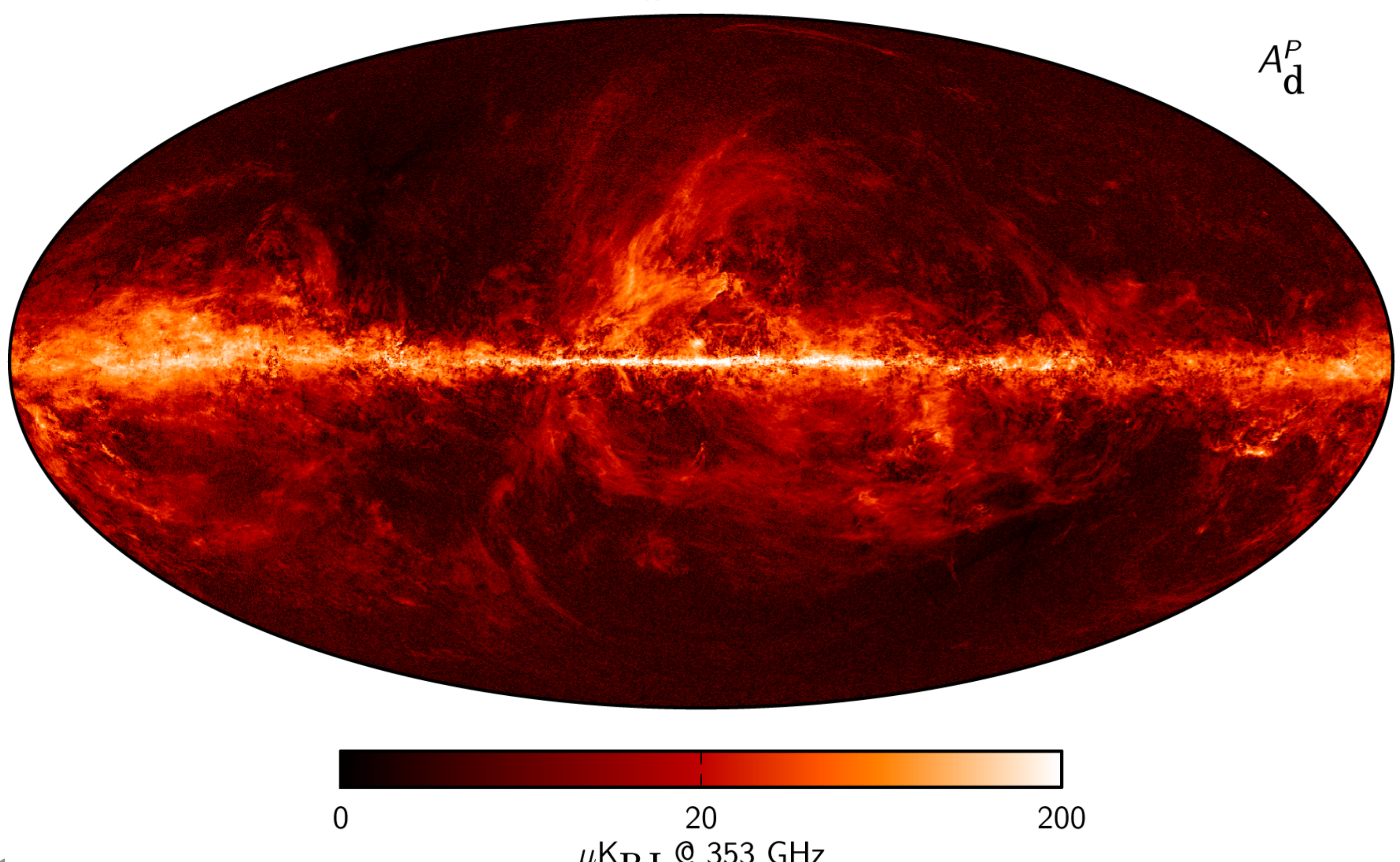
synchrotron



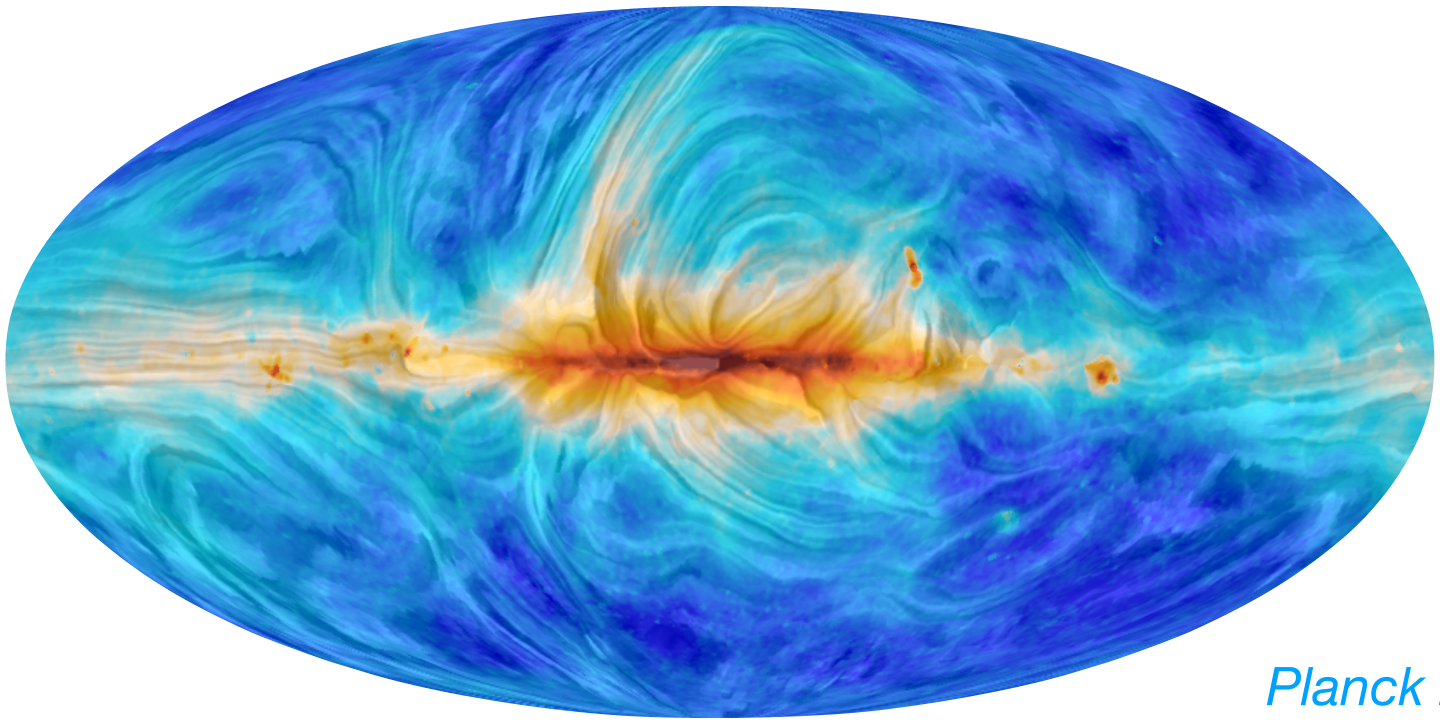
synchrotron and dust polarized emissions follow the galactic magnetic field



Planck 2015 results. X. Diffuse component separation: Foreground maps
The Planck collaboration, A&A, 2015

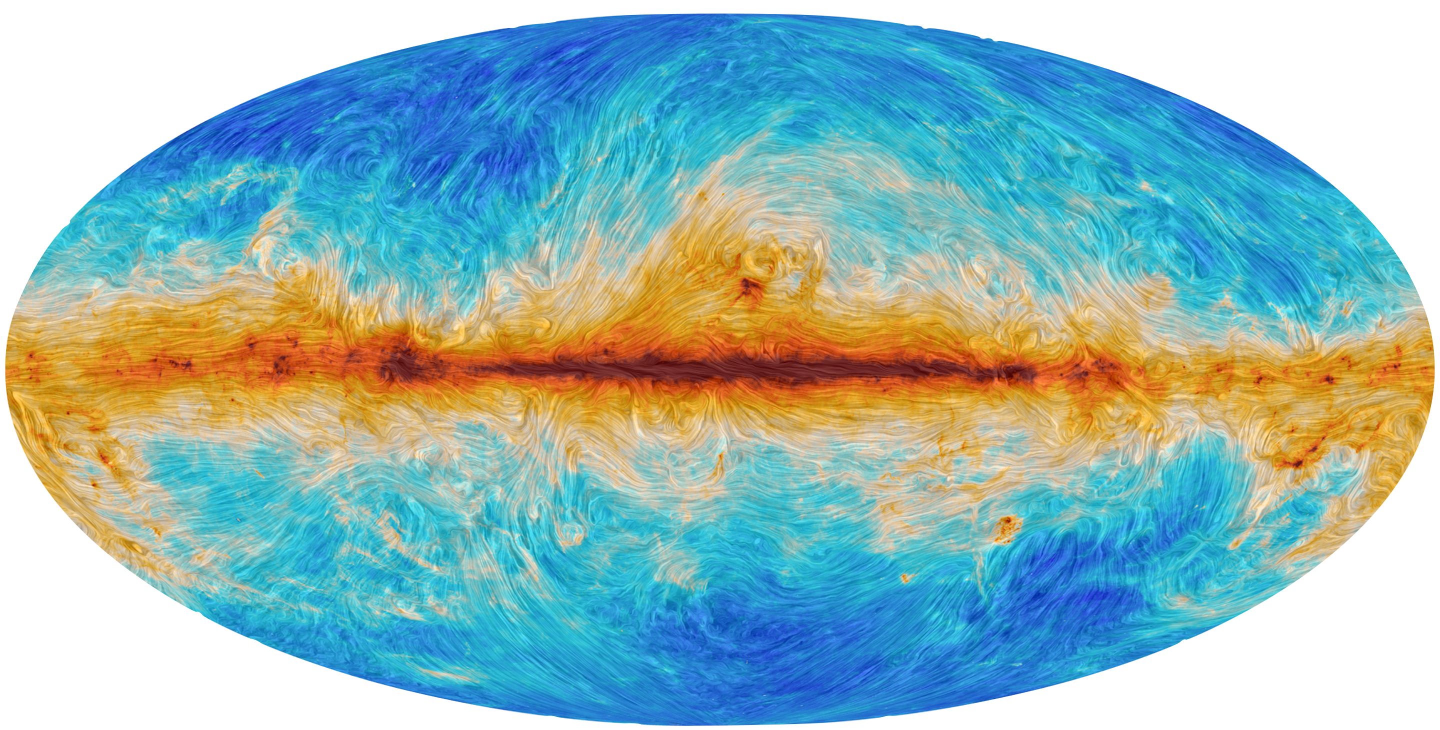


synchrotron and dust polarized emissions follow the galactic magnetic field

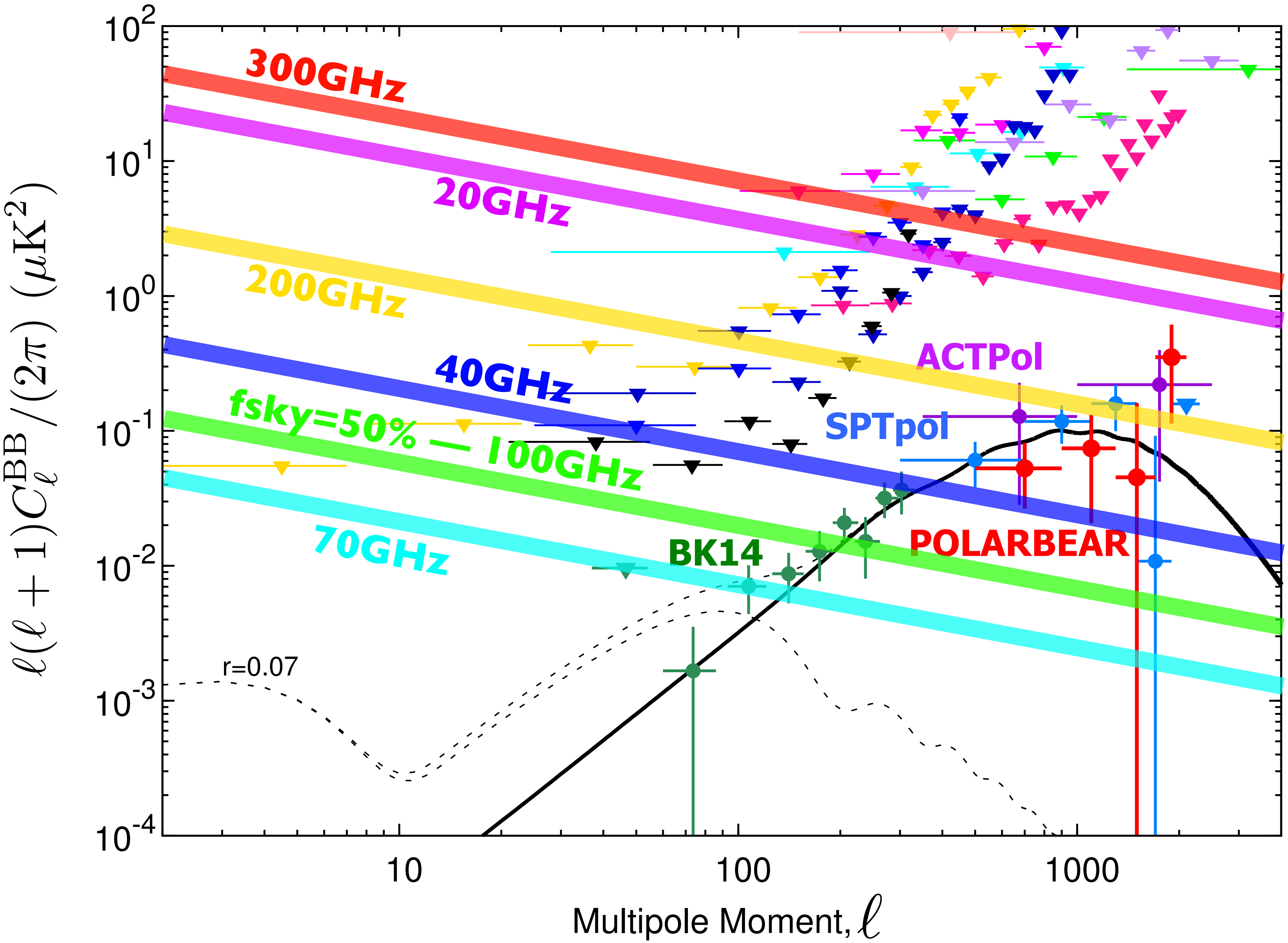


intensity @ 30GHz
+ B-field from polarization

Planck 2015 results. X. Diffuse component separation: Foreground maps
The Planck collaboration, A&A, 2015

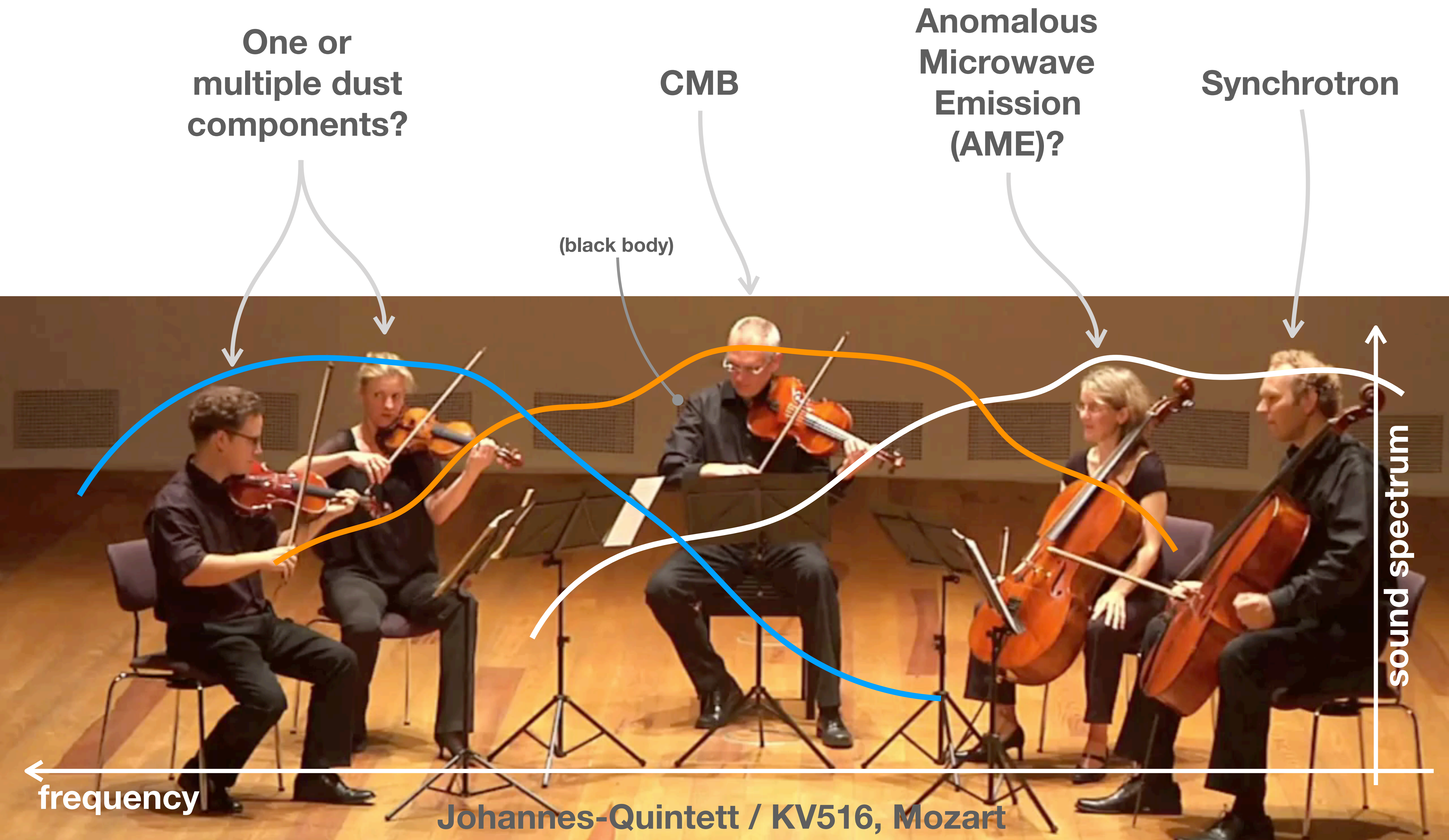


amplitude of galactic foregrounds for different frequencies



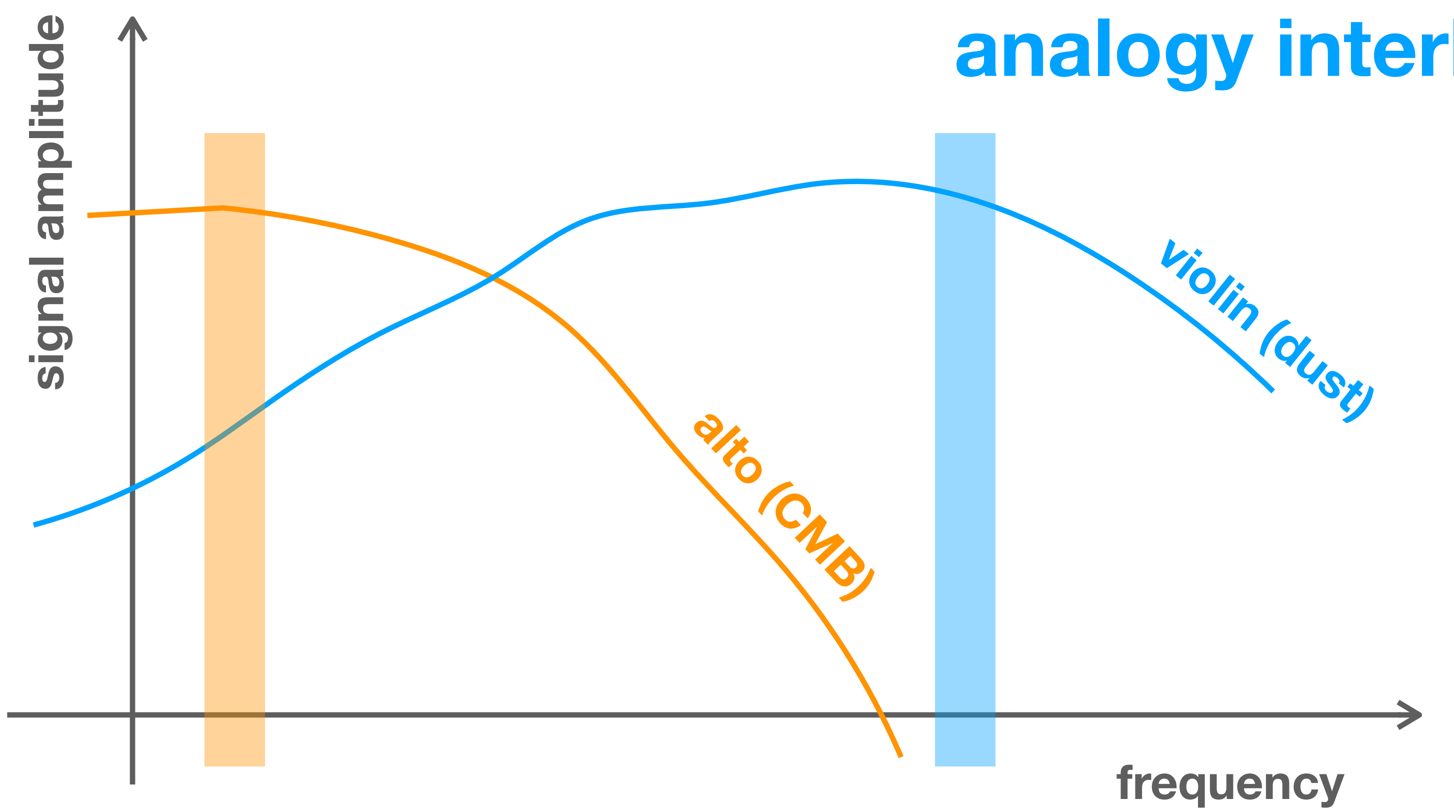
removing galactic foregrounds

analogy interlude



removing galactic foregrounds

analogy interlude



- removing one or several components increase the noise variance in the final “clean” component
- misestimating a spectrum leaks components to the “clean” component (can be statistical or systematic misestimation)

$$d_{\nu_0} = a_0\,\mathrm{CMB} + b_0\,\mathrm{dust} + n_{\nu_0}$$

$$d_{\nu_1} = a_1\,\mathrm{CMB} + b_1\,\mathrm{dust} + n_{\nu_1}$$

$$d_{\nu_0} b_1 - d_{\nu_1} b_0 = CMB\,\left(b_1 a_0 - b_0 a_1\right) + n_{\nu_0} b_1 - n_{\nu_1} b_0$$

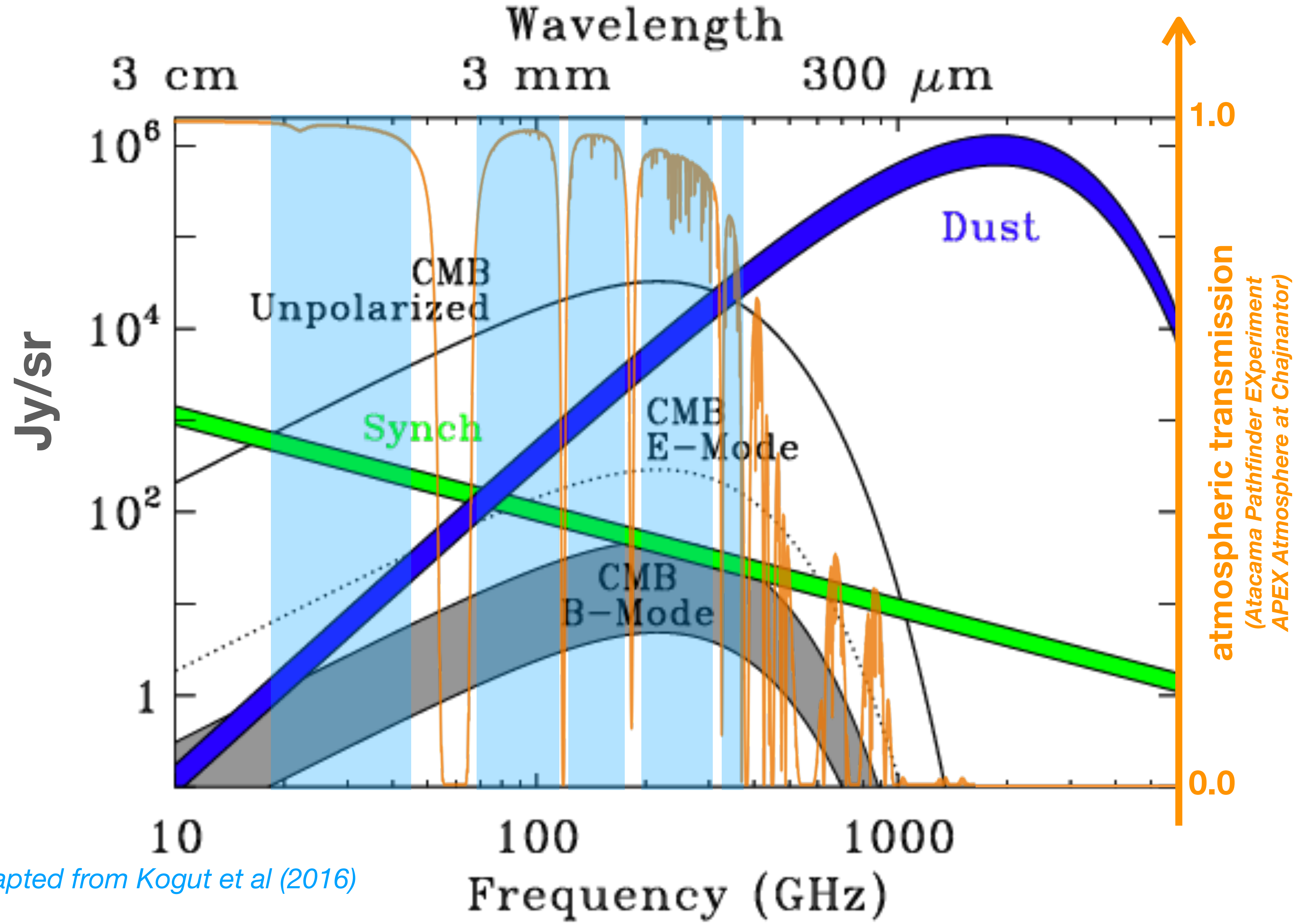
boosted variance

$$\sigma^2_{\mathrm{CMB}} = \frac{\sigma^2_{\nu_0} b_1^2 + \sigma^2_{\nu_1} b_0^2}{\left(b_1 a_0 - b_0 a_1\right)^2}$$

statistical/systematic residuals in the cleaned signal

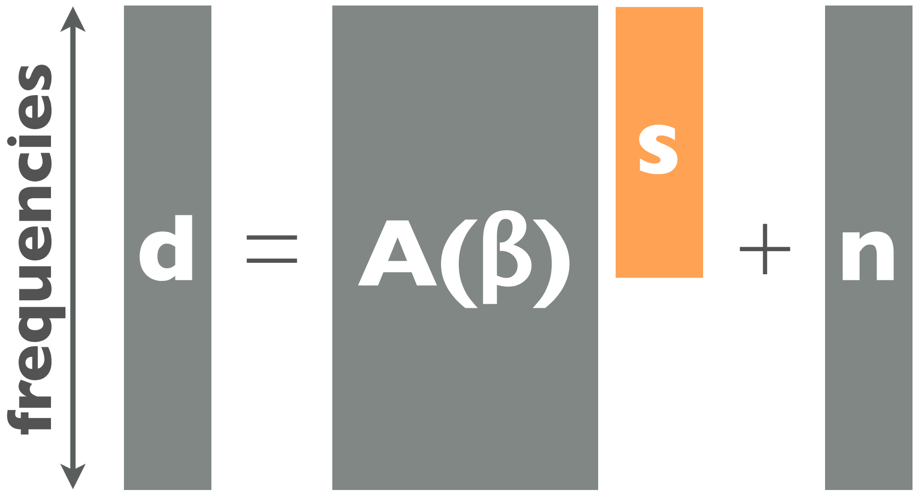
$$\delta\mathrm{CMB} \propto \delta b_1\,\left(\alpha\, d_{\nu_0} + \beta\, d_{\nu_1}\right)$$

removing galactic foregrounds

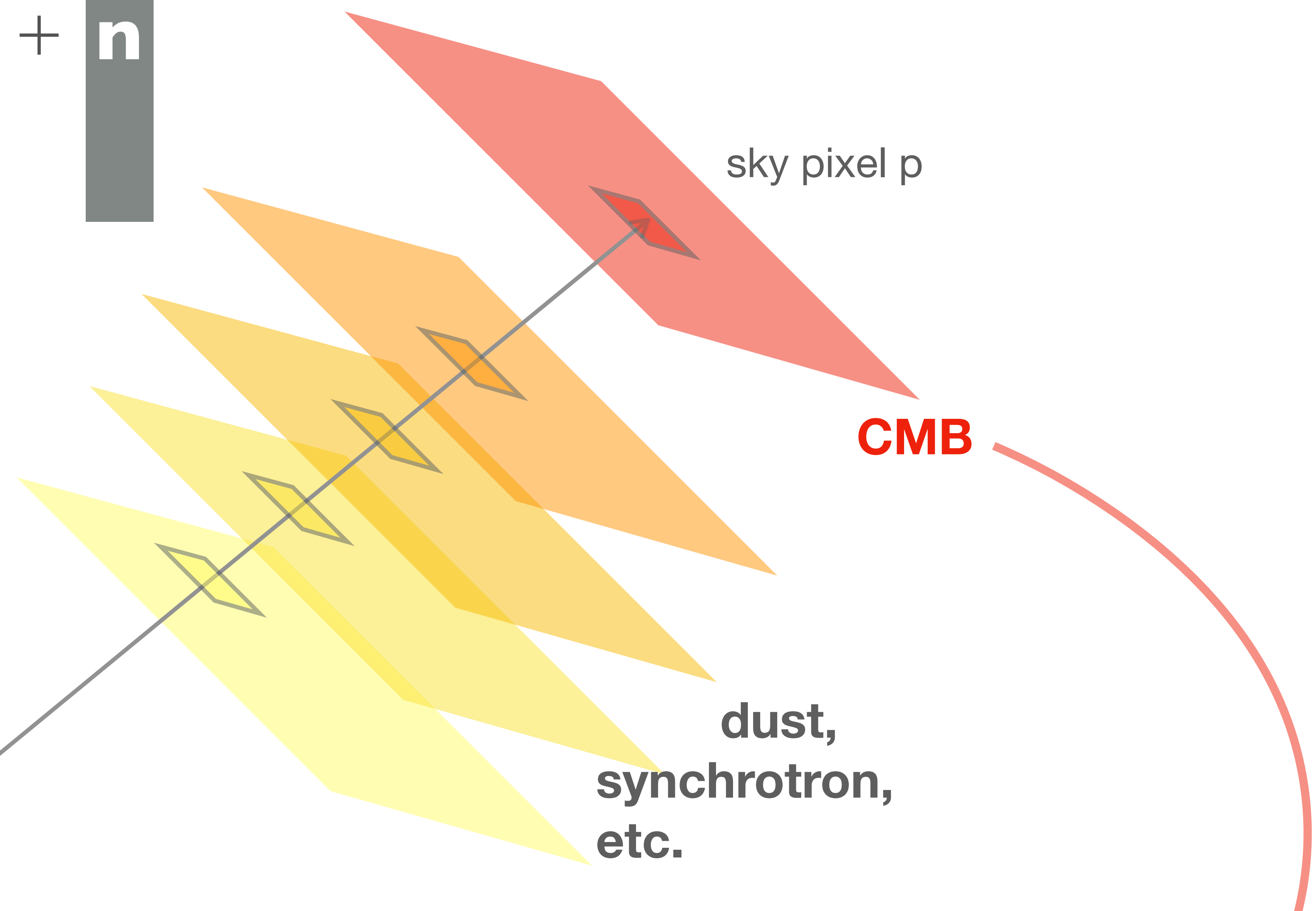


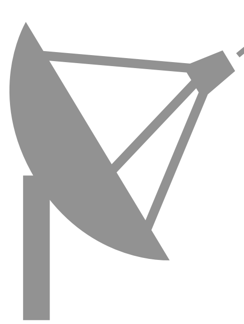
adapted from Kogut et al (2016)

$$d_i(p) = A_{ij}\, s_j(p) + n_i(p)$$



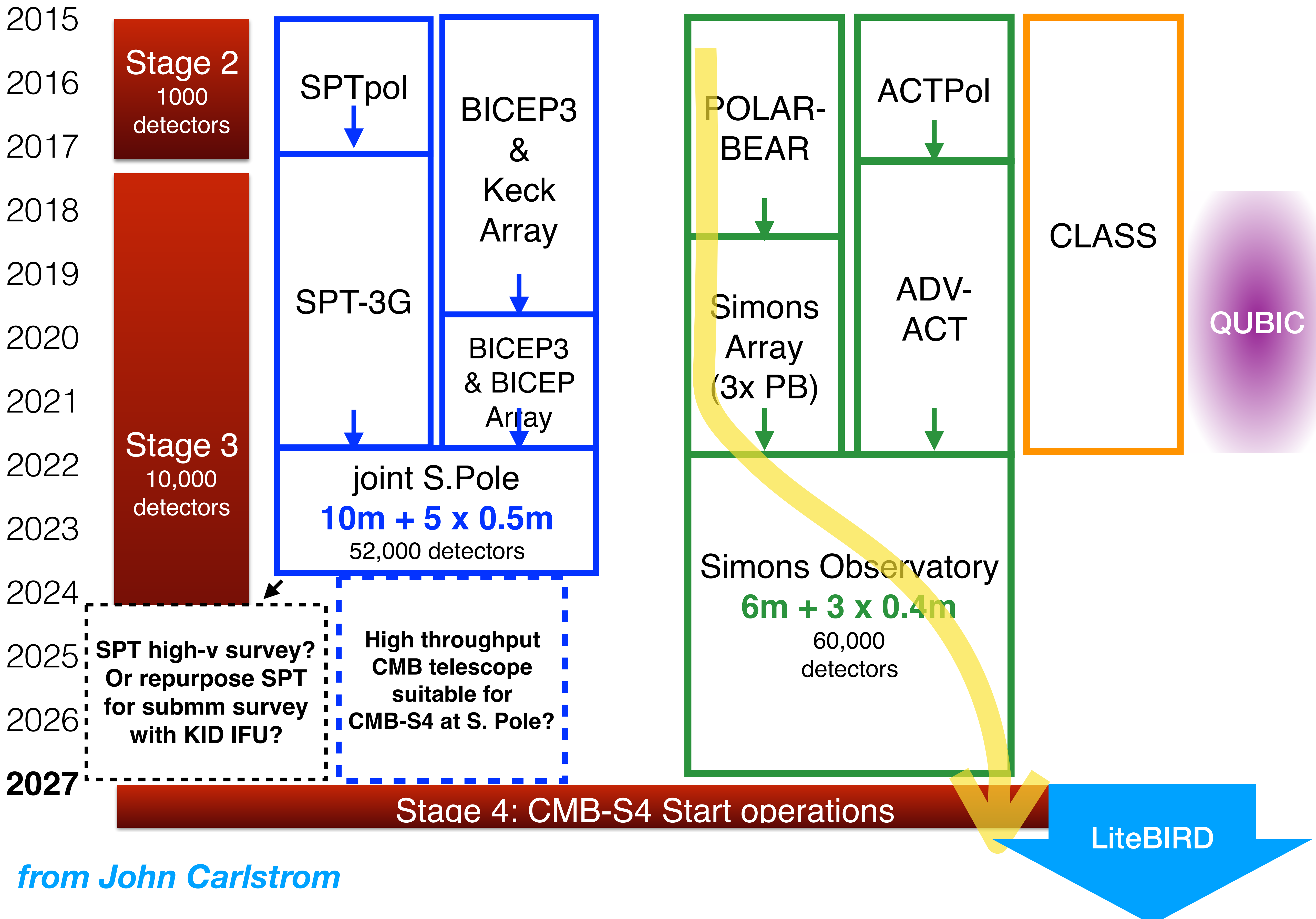
astrophysical foregrounds are one of the biggest challenges (if not the biggest one) for the B-modes quest



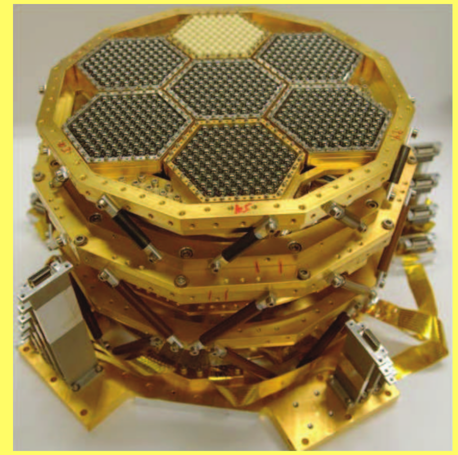
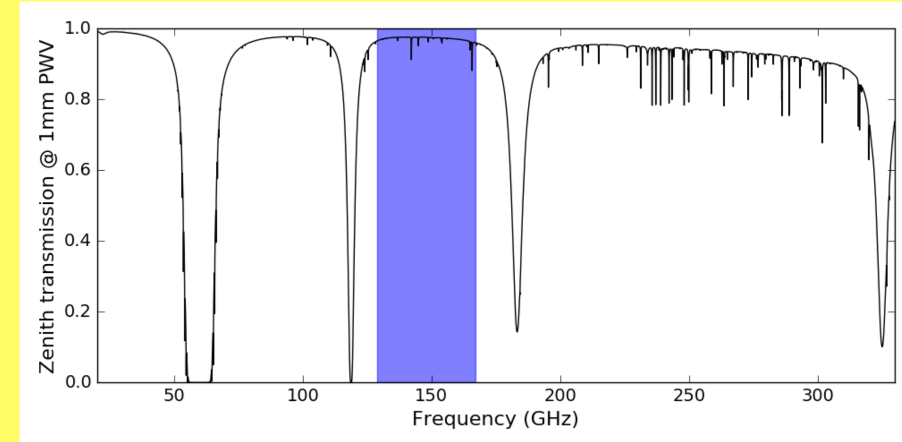
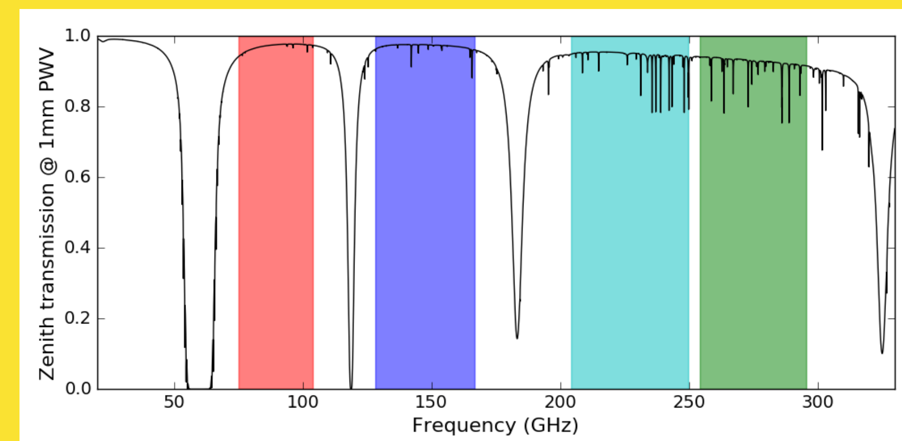
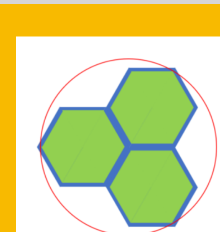
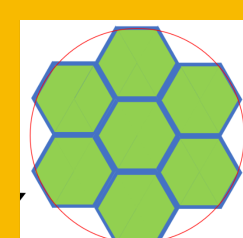
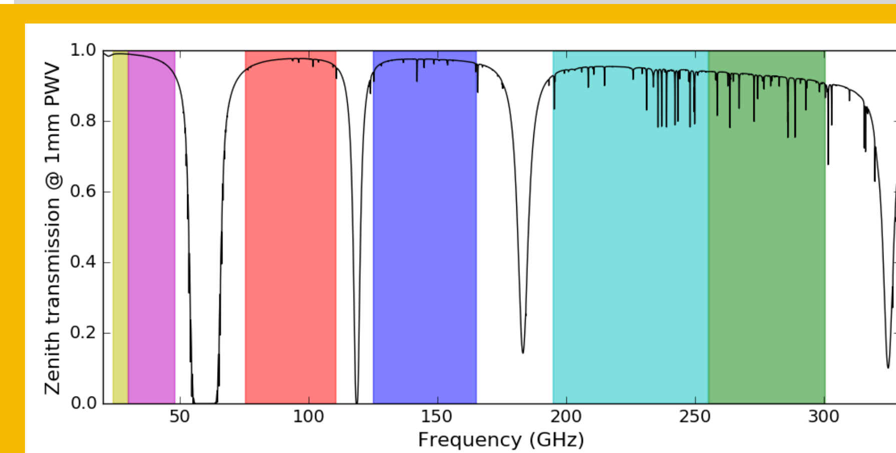


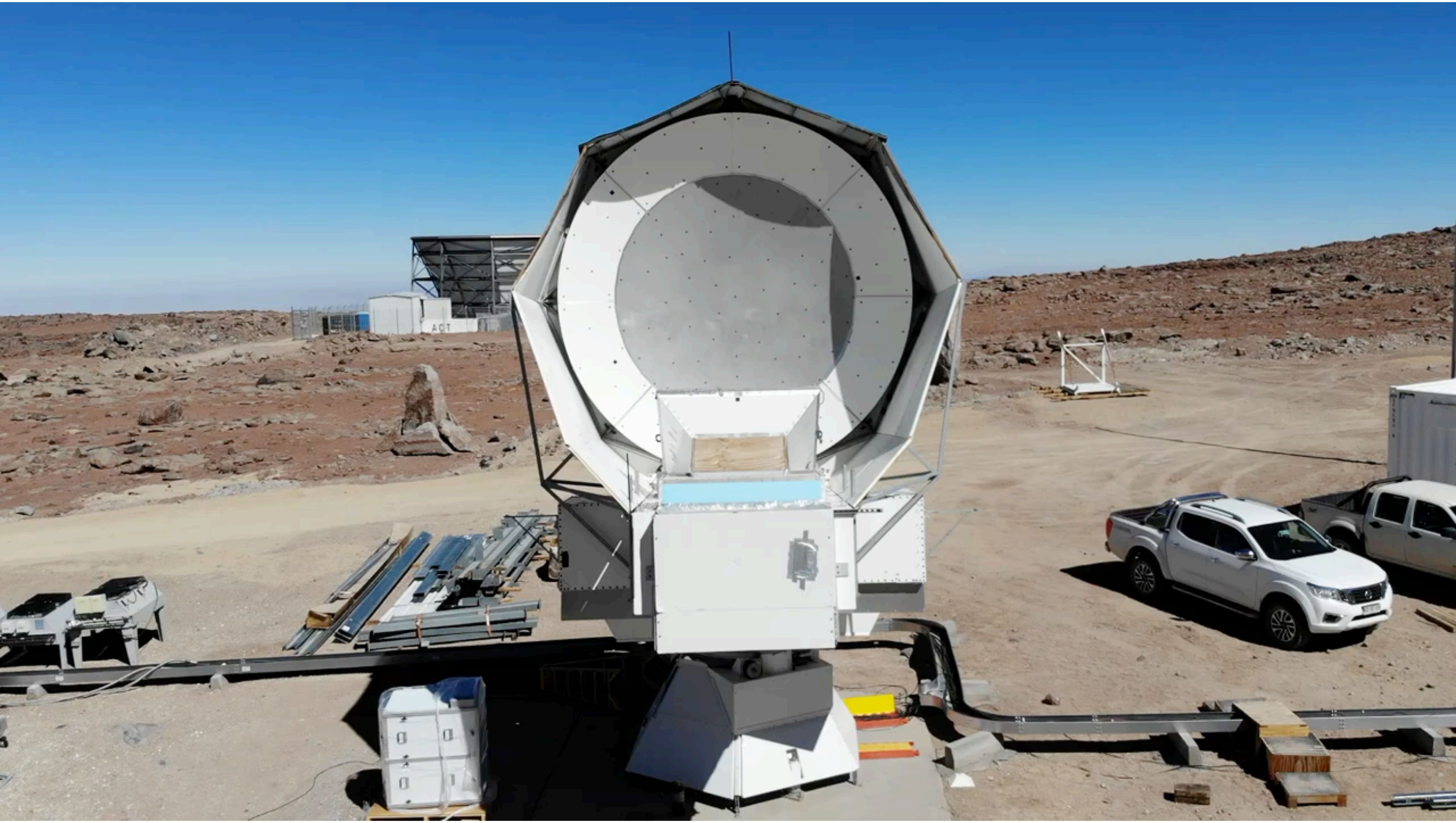
1. what are the foregrounds scaling law (fit for the spectral indices β)?
2. get a clean estimate of the CMB

the race to B-modes



from John Carlstrom

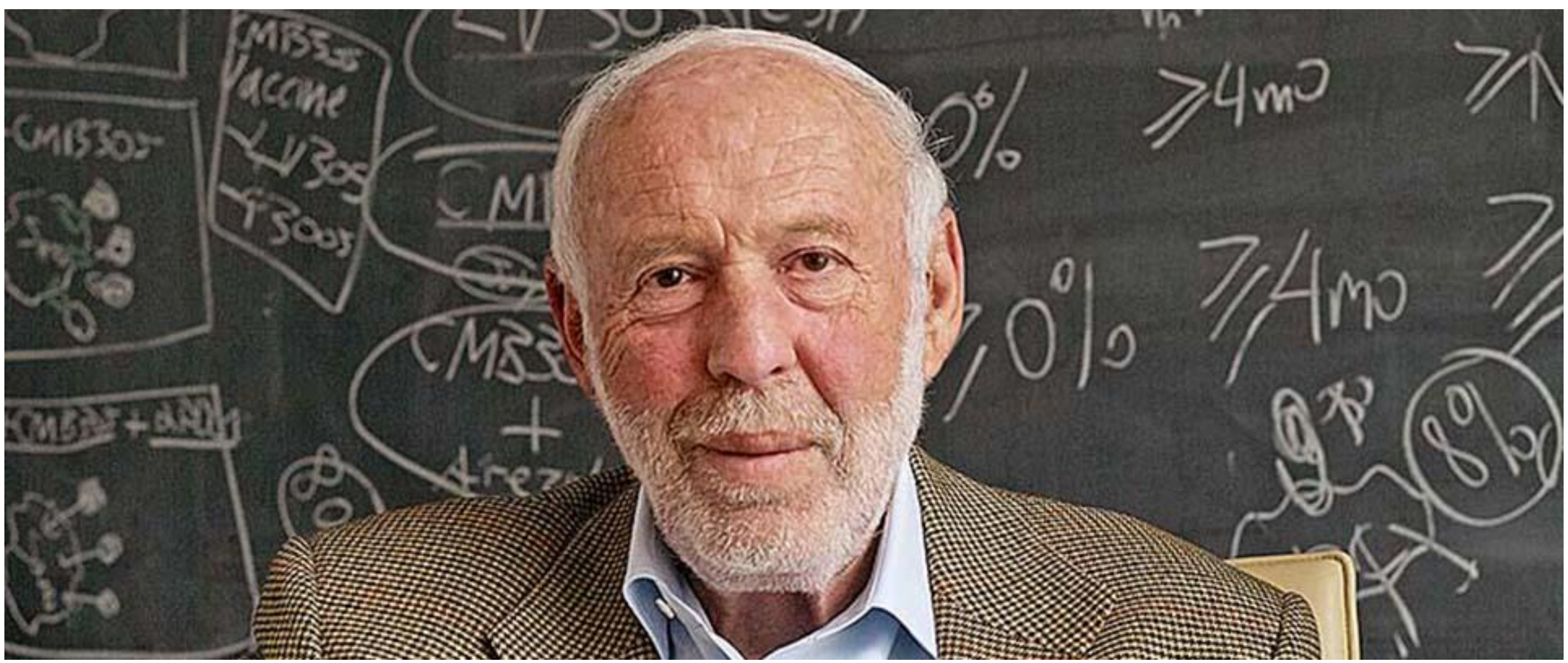
	angular resolution (available science targets)	detector count (sensitivity)	frequency coverage (foregrounds removal)
POLARBEAR-I	 $50 \leq \ell \leq 3000$	 > 1200 detectors	 1 observational band
Simons Array	 $50 \leq \ell \leq 3000$	 **x3** > 22 000 detectors	 4 observational bands
Simons Observatory	 $30 \leq \ell \leq 8000$	 LAT optics tube focal plane array **x7** +  SAT focal plane array **x3** > 60 000 detectors	 6 observational bands


ACT

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

The Simons Observatory is funded by a generous grant from the **Simons Foundation** and the **Heising-Simons Foundation**

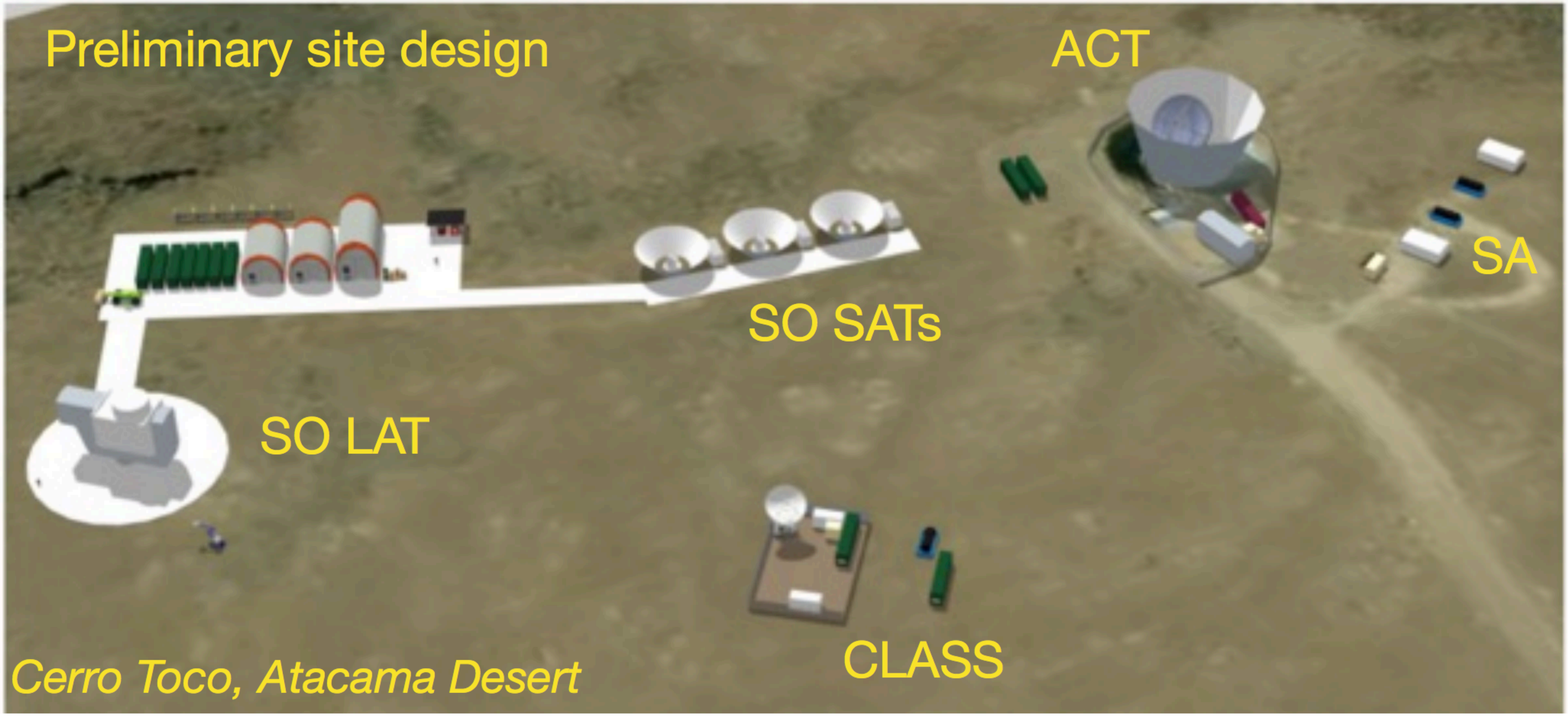


The Simons Observatory

- 10 countries
- > 40 institutions
- > 160 researchers

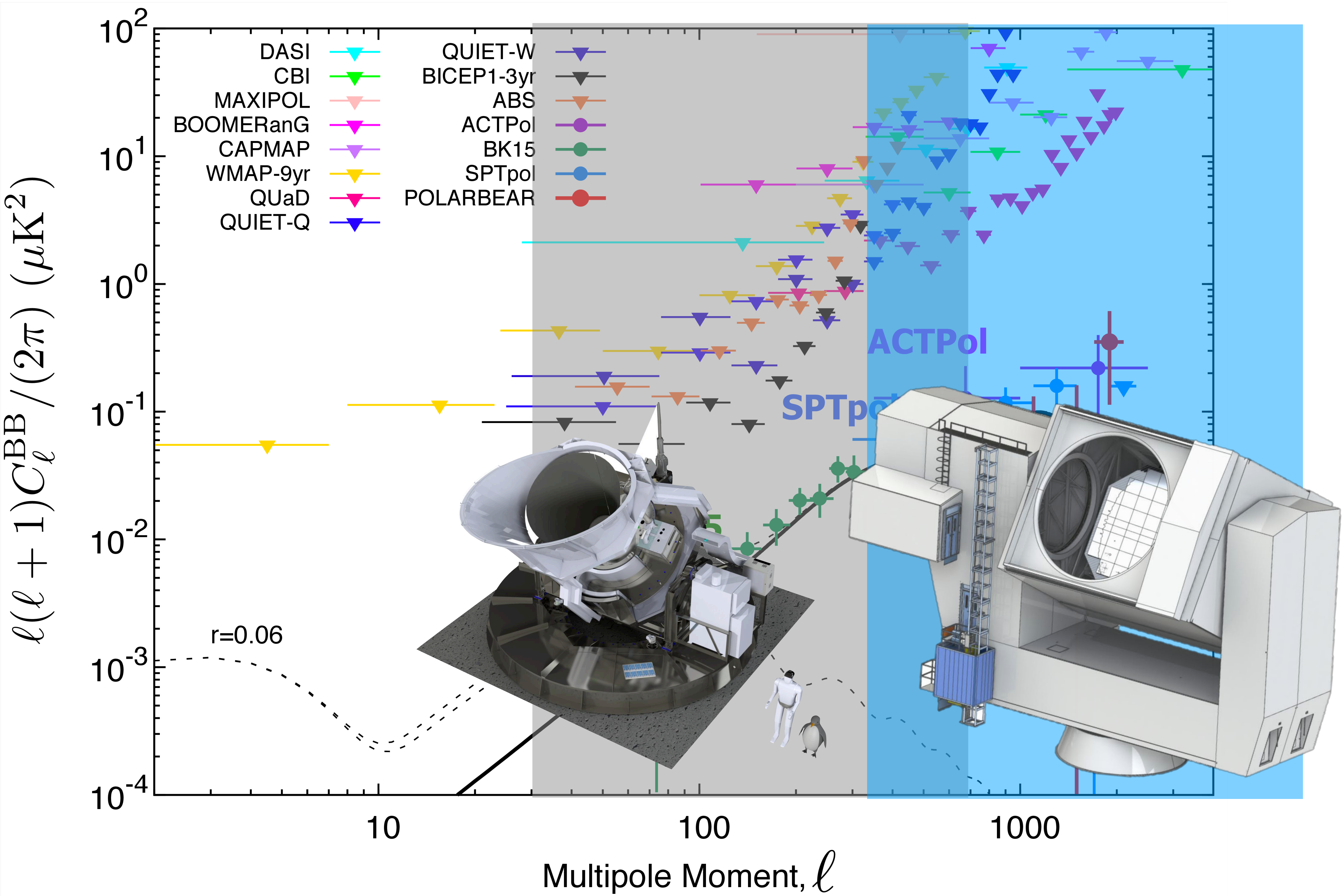
The Simons Observatory

One 6m Large Aperture Telescope
Three 0.5m Small Aperture Telescopes
Five-year survey planned 2021-26, six frequencies 30-280 GHz

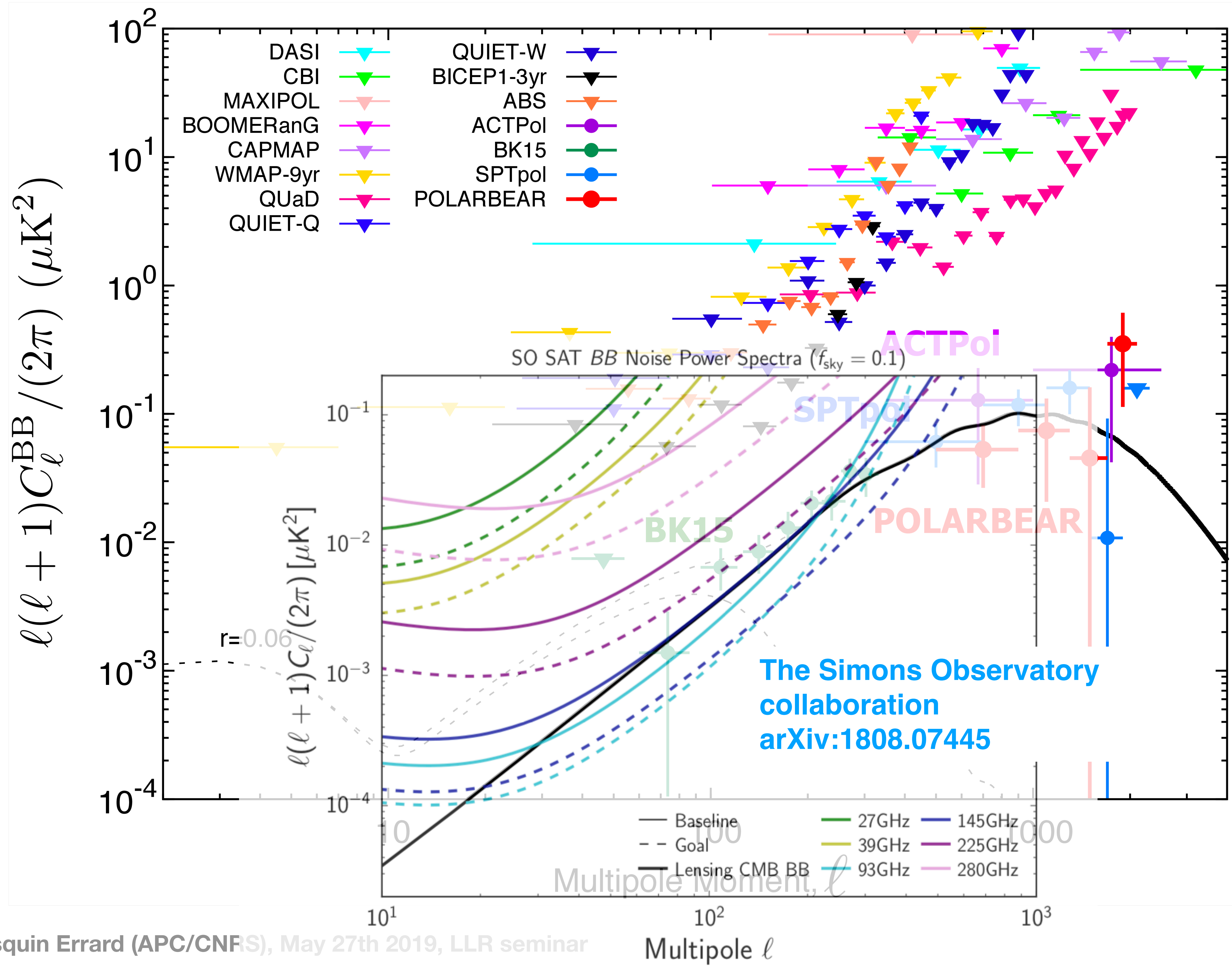


Large telescope: resolution needed for all science goals except tensor-to-scalar ratio
Small telescopes: lower noise at the few-degree-scale B-mode signal, for tensor-to-scalar ratio

The Simons Observatory: both large and small angular scales



The Simons Observatory: both large and small angular scales



A lot of science beyond B-modes

primordial fluctuations

large scale B-modes
➔ tensor-to-scalar ratio (BB)

damping tail
➔ primordial power on small scales (TE, TT, EE)
➔ primordial bispectrum (f_{NL} via TTT,TTE,… + lens/kSZ)

relativistic species

damping tail
➔ N_{eff} (TE, TT, EE)

reionization

sources
➔ duration of reionization (kSZ)
➔ mean free path of photons (kSZ)

neutrino mass

lensing potential (TT+EB), tSZ
➔ Σm_ν

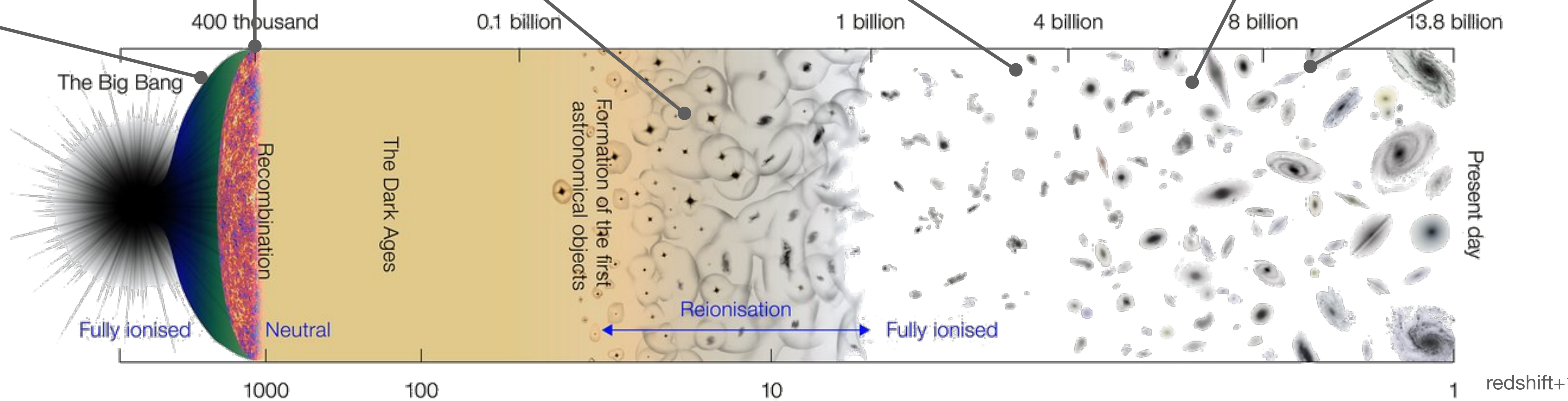
galaxy evolution

tSZ, kSZ
➔ non-thermal pressure (tSZ+kSZ)
➔ feedback efficiency (tSZ+kSZ)

dark energy

tSZ, lensing
➔ σ_8 at z=2-3 (lensing, tSZ)
➔ growth of structure (kSZ)

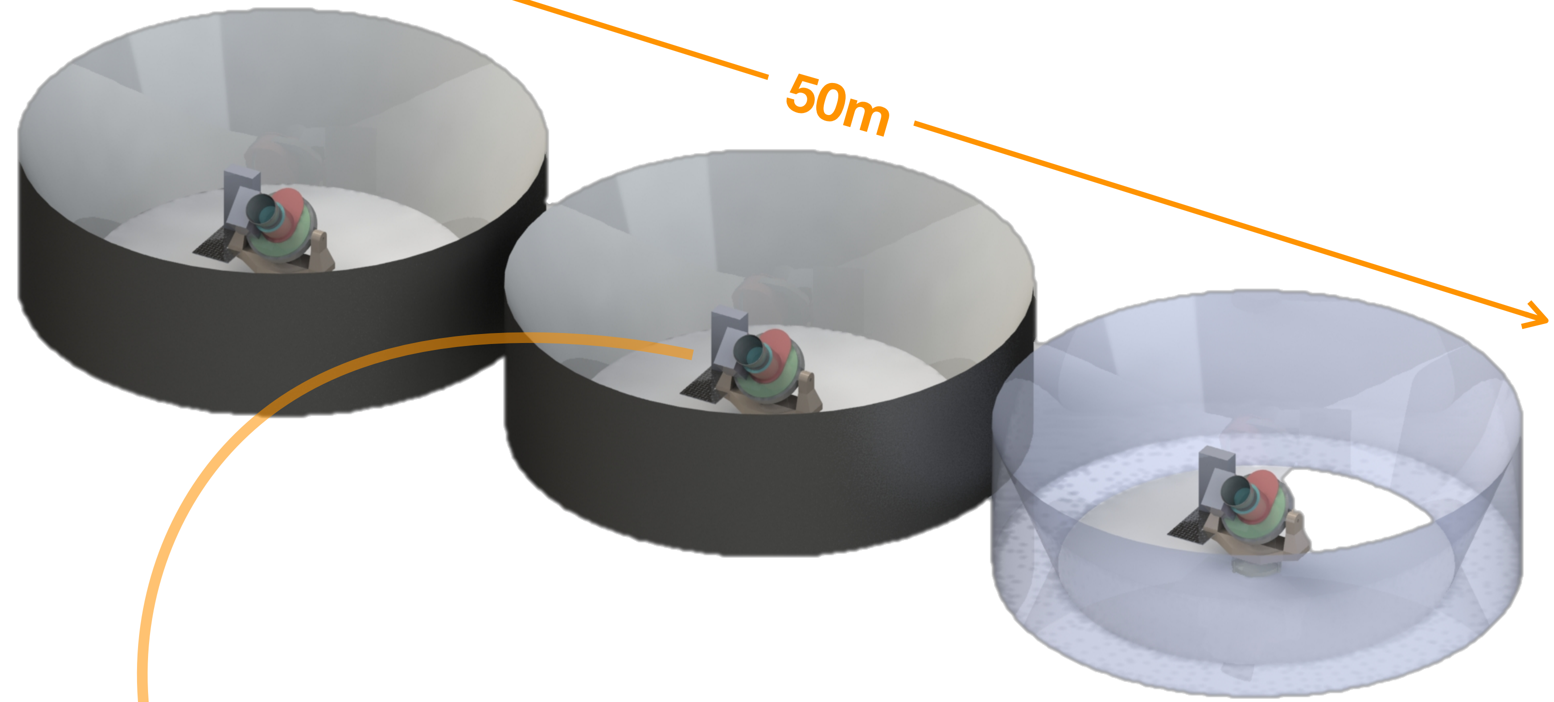
credits: ESO



Additional science includes (but is not limited to):

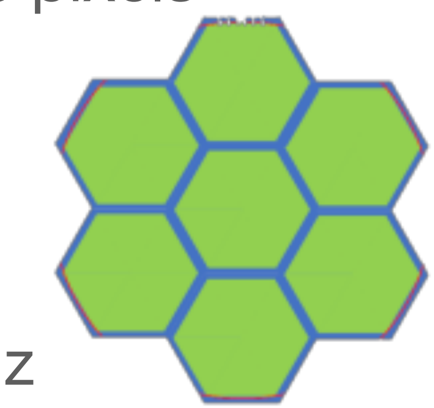
- helium fraction, cosmic birefringence, primordial magnetic fields
- high-redshift clusters
- dark matter annihilation and interactions
- isocurvature
- calibration of multiplicative shear bias (e.g., for LSST)
- new sample of dusty star-forming galaxies
- transient sources
- cosmic infrared background

The Simons Observatory

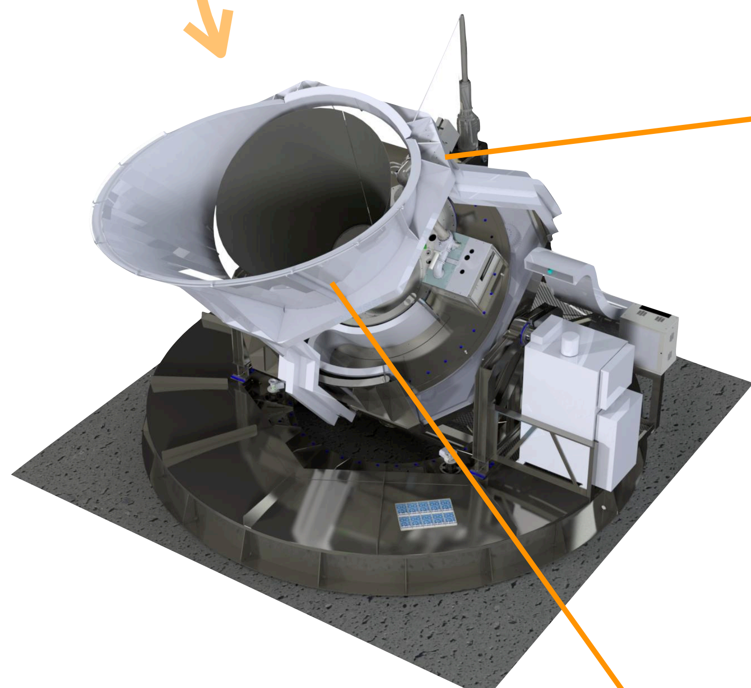


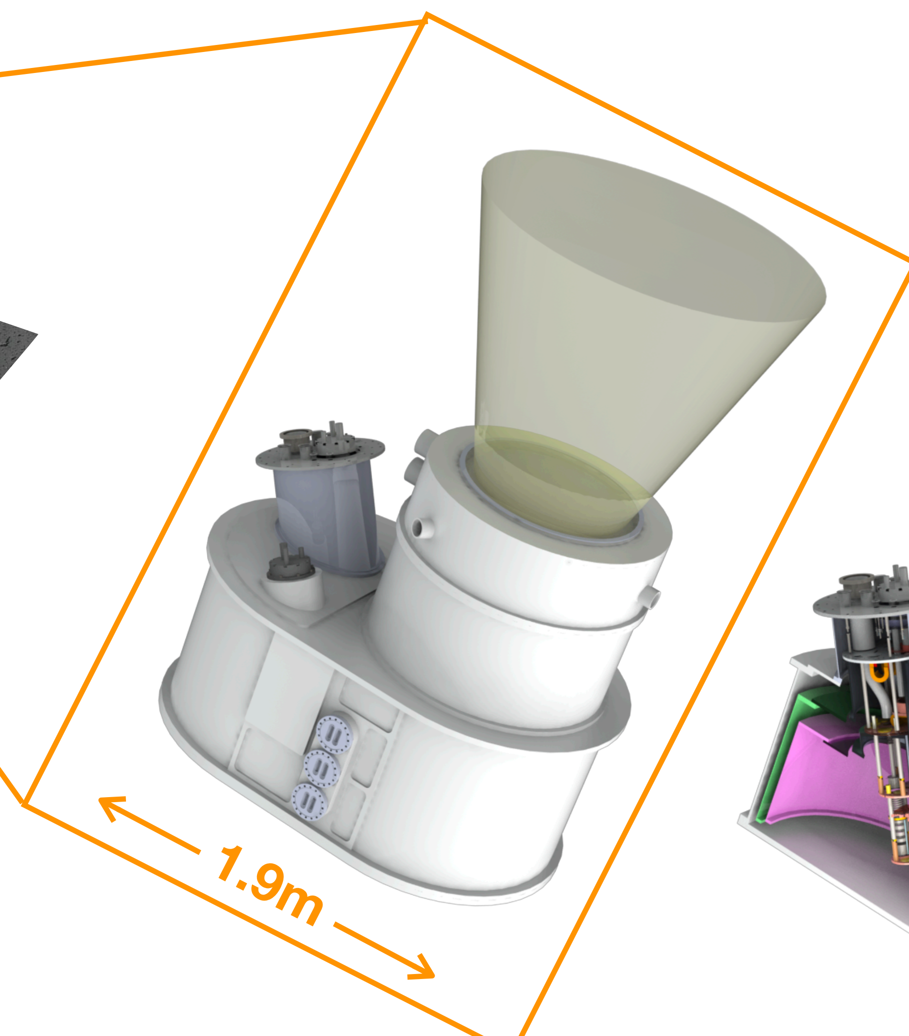
Small Aperture Telescopes

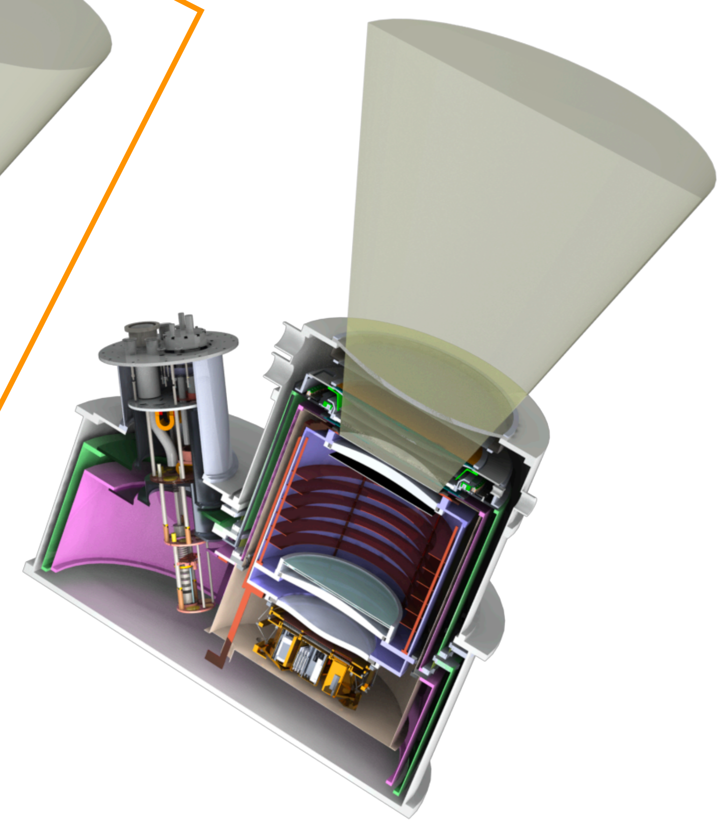
- three mounts
- four 42cm aperture refractors, baseline dichroic pixels
  - 30/40GHz
  - 90/150GHz
  - 90/150GHz
  - 220/270GHz



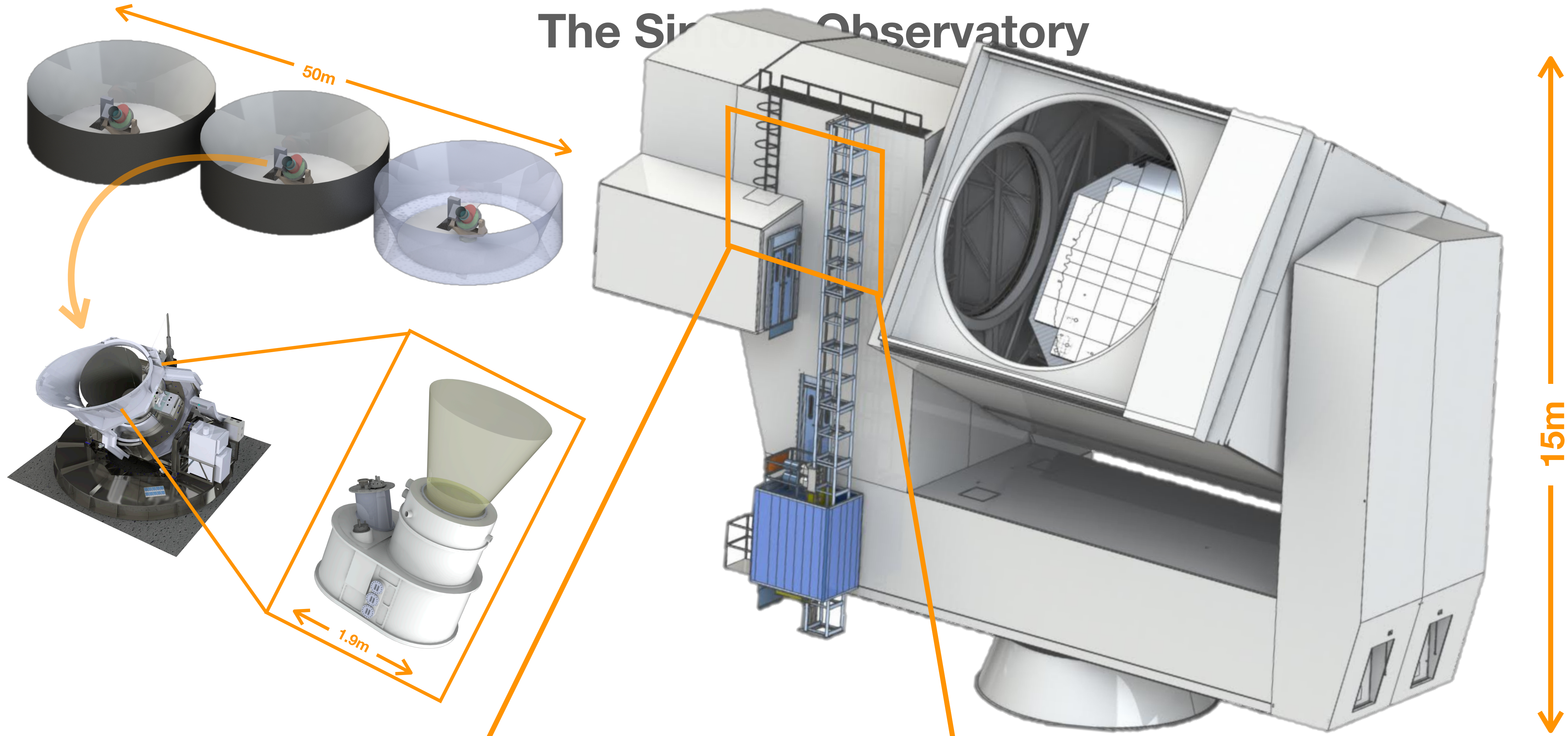
~ 20 wafers → 40,000 detectors







The Si… Observatory



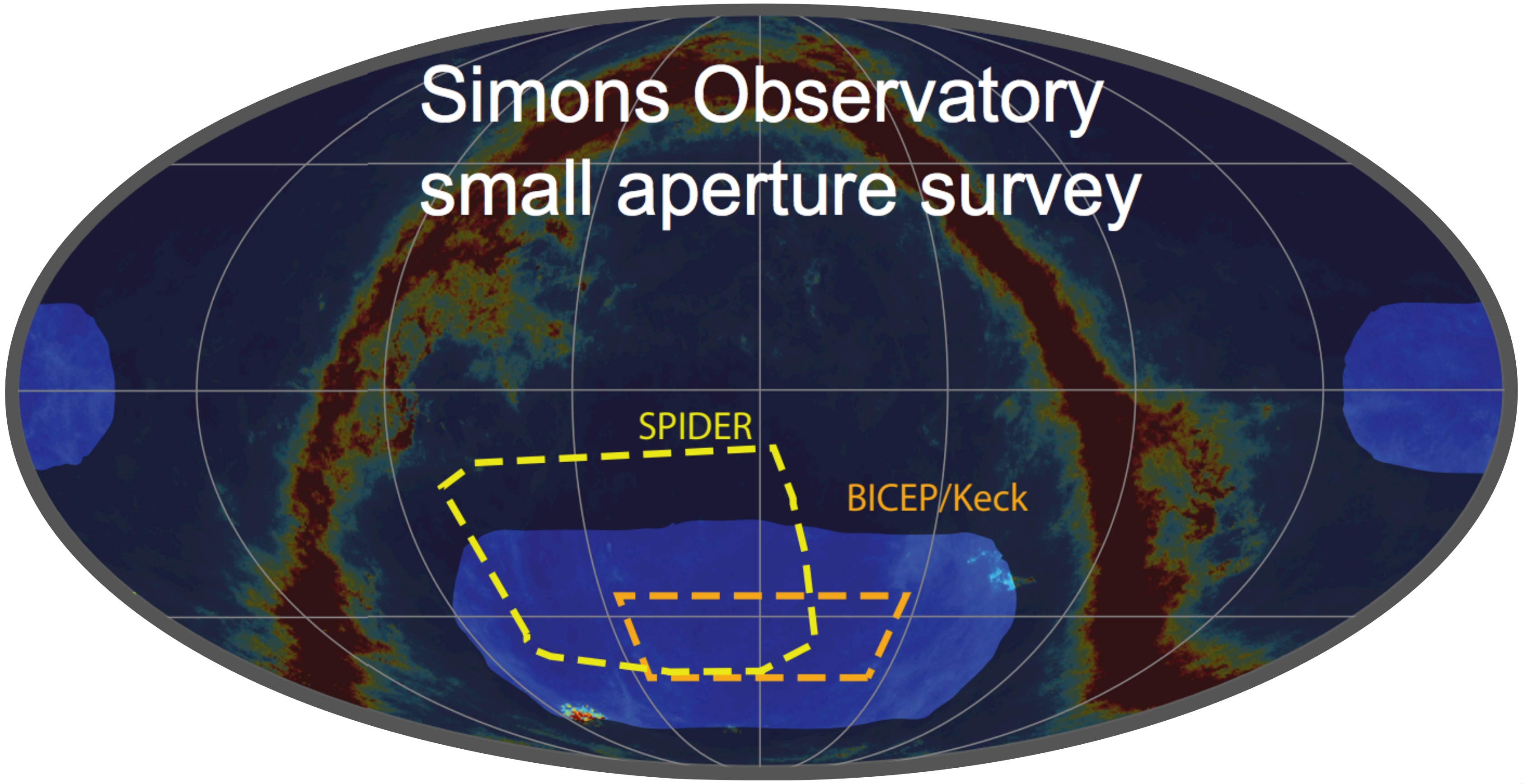
Large Aperture Telescope

- 6m crossed Dragone
- telescope coupled to up to 13, 38cm optics tubes
- 7 tubes populated with baseline dichroic pixels
  - 1 x 30/40GHz
  - 4 x 90/150GHz
  - 2 x 220/270GHz

~ 20 wafers → 40,000 detectors

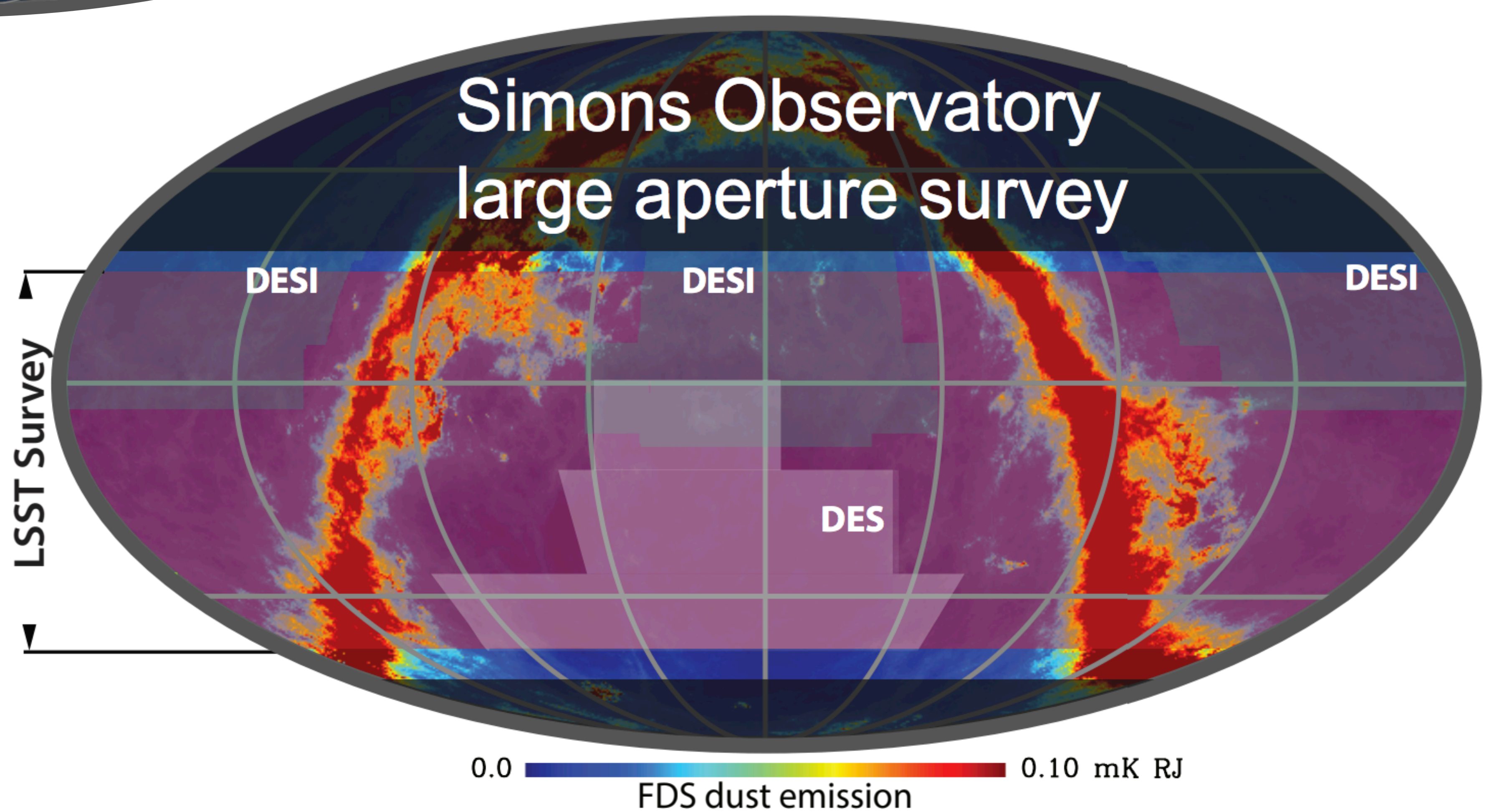
The Simons Observatory: it is happening!

The Simons Observatory: anticipated sky coverage



effective f_{sky} ~ 10%

for SO noise and coverage, dedicated delensing survey not required



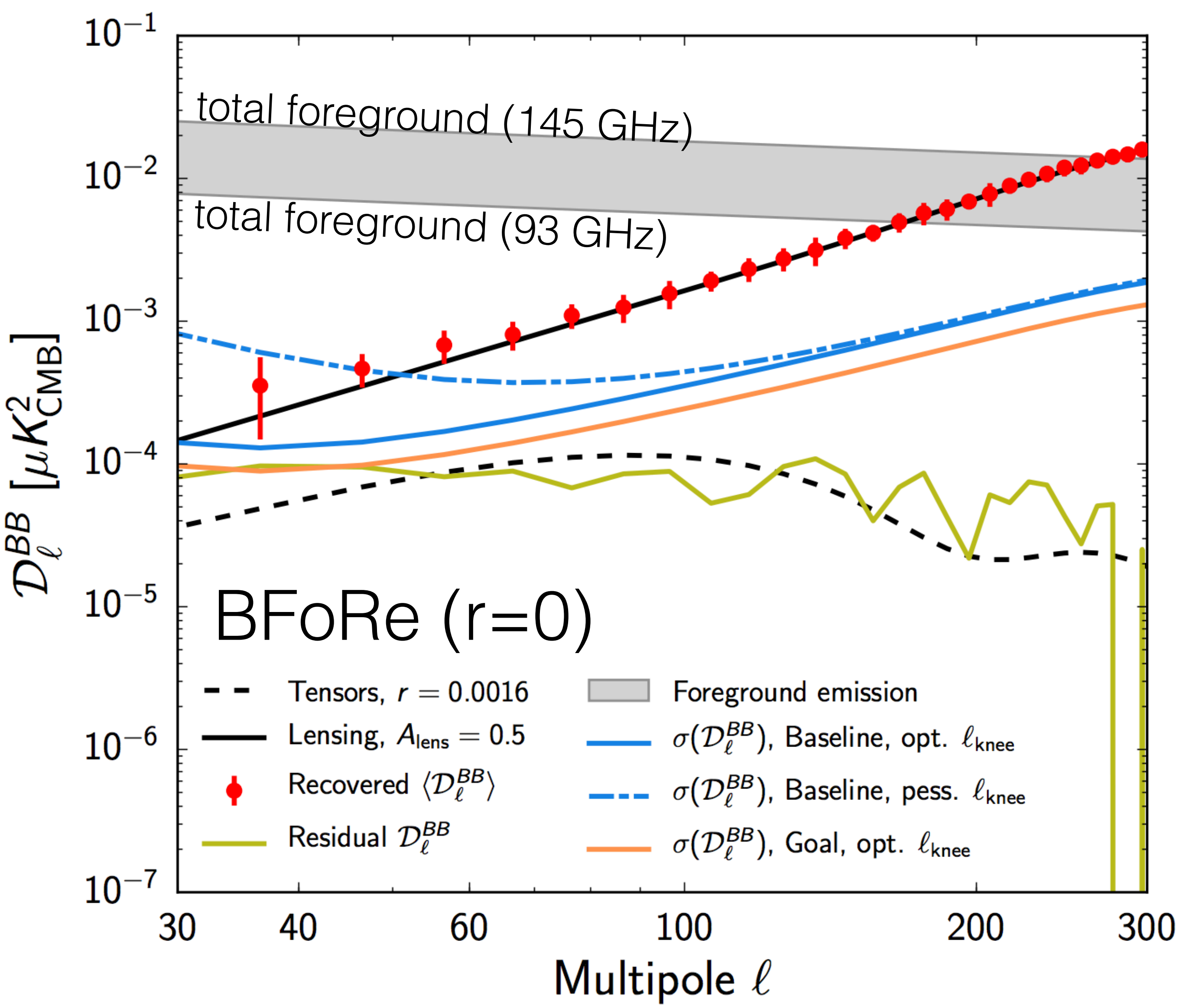
effective f_{sky} ~ 40%

maximal overlap with LSST, large overlap with DESI

SO SAT Science: Primordial Tensor Modes

SAT BB forecasting based on full-sky simulated maps (PySM) with multiple sets of realistic foregrounds

Sky models are combined with SO SAT noise model, then coupled to several foreground mitigation schemes (cross-spectrum analysis, xForecast, BFoRe, harmonic-space ILC) to infer r



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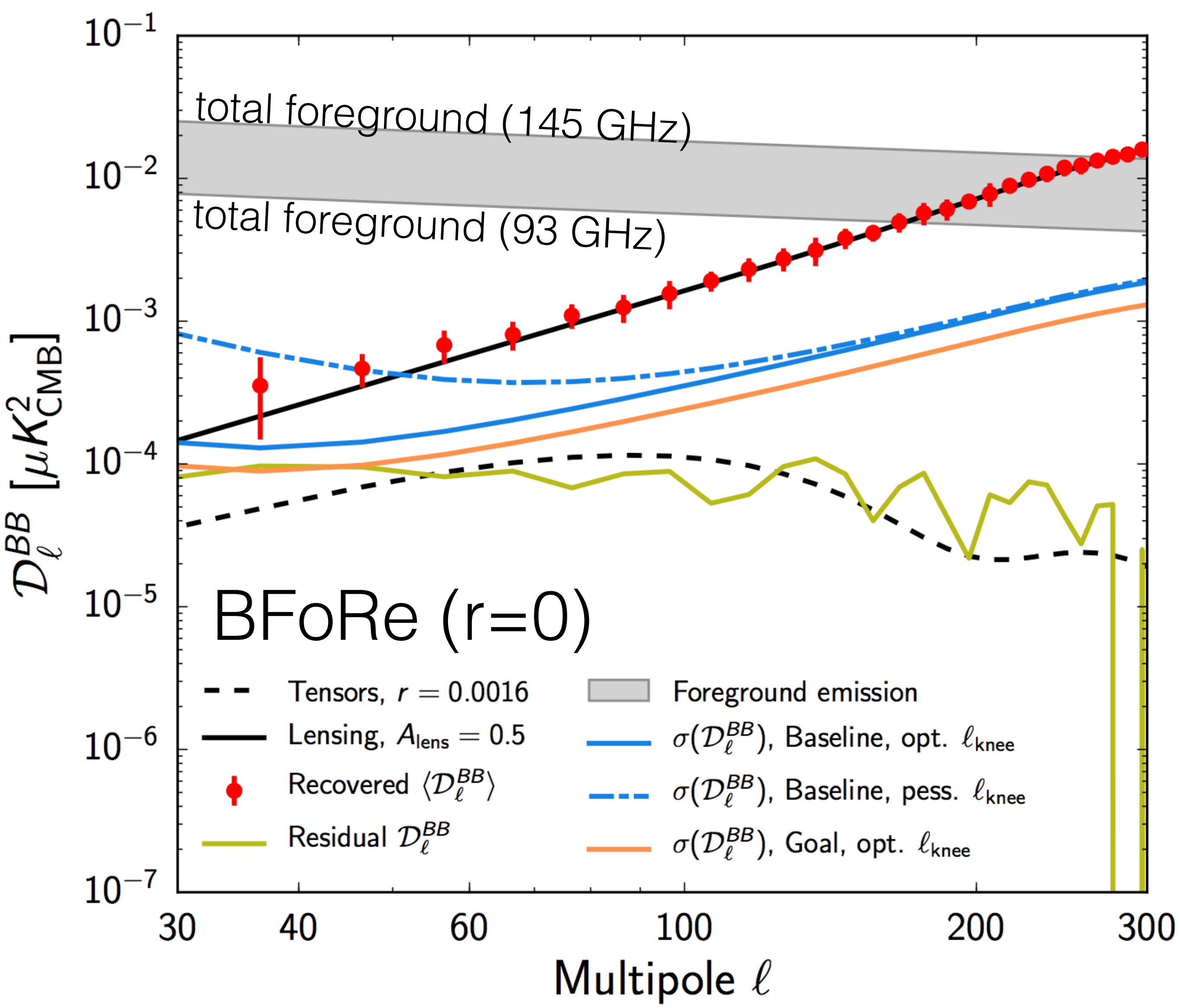
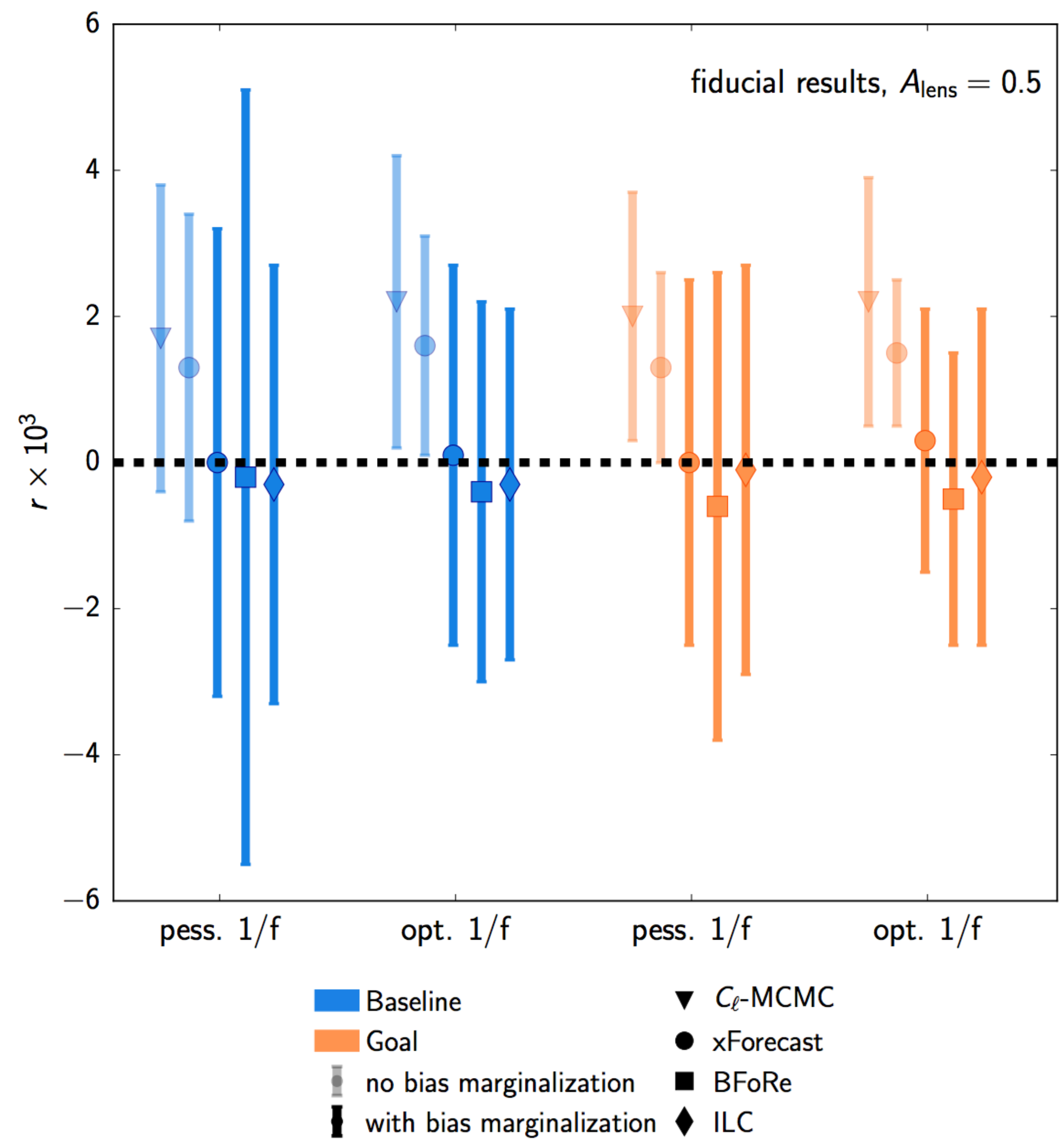
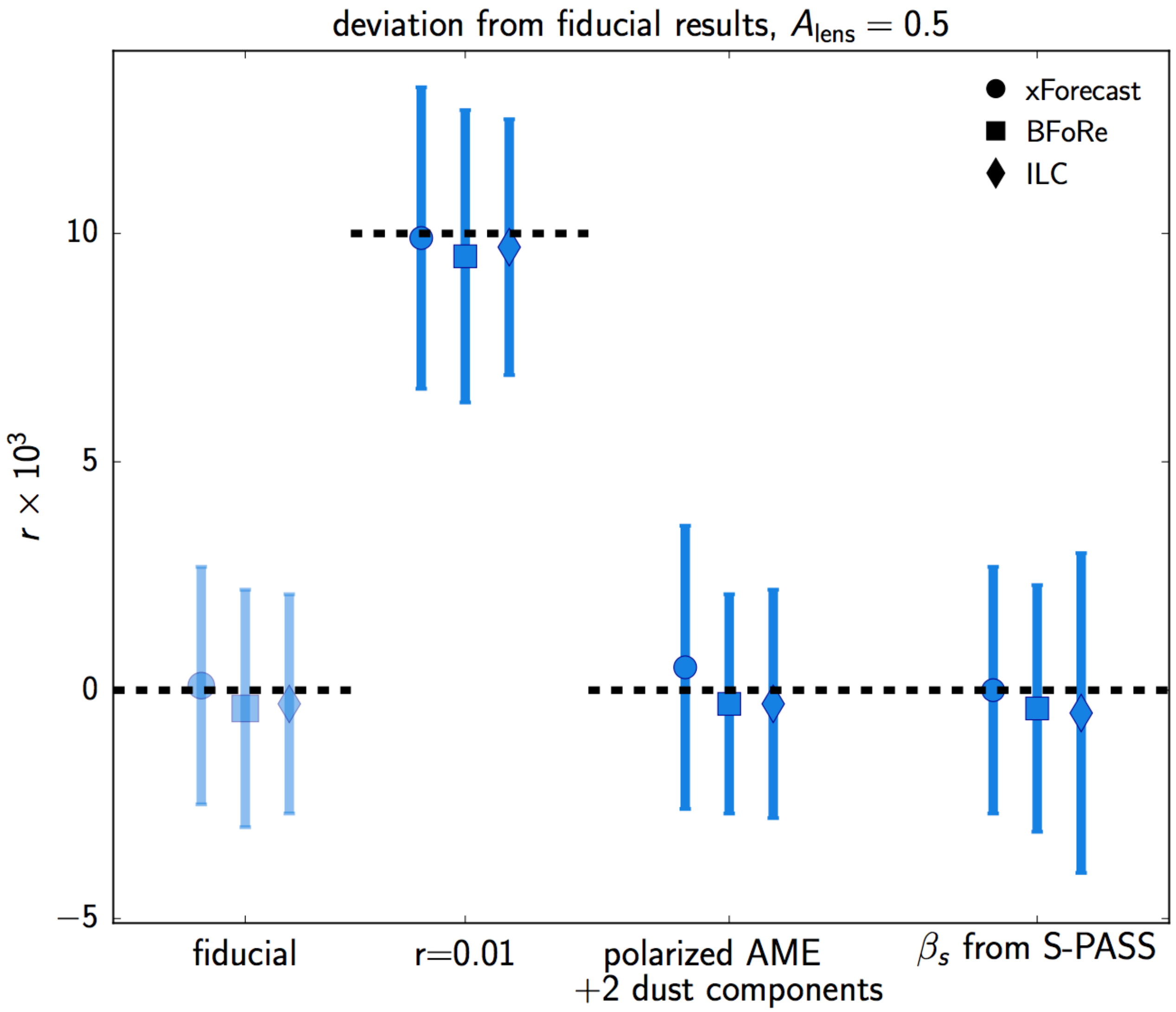




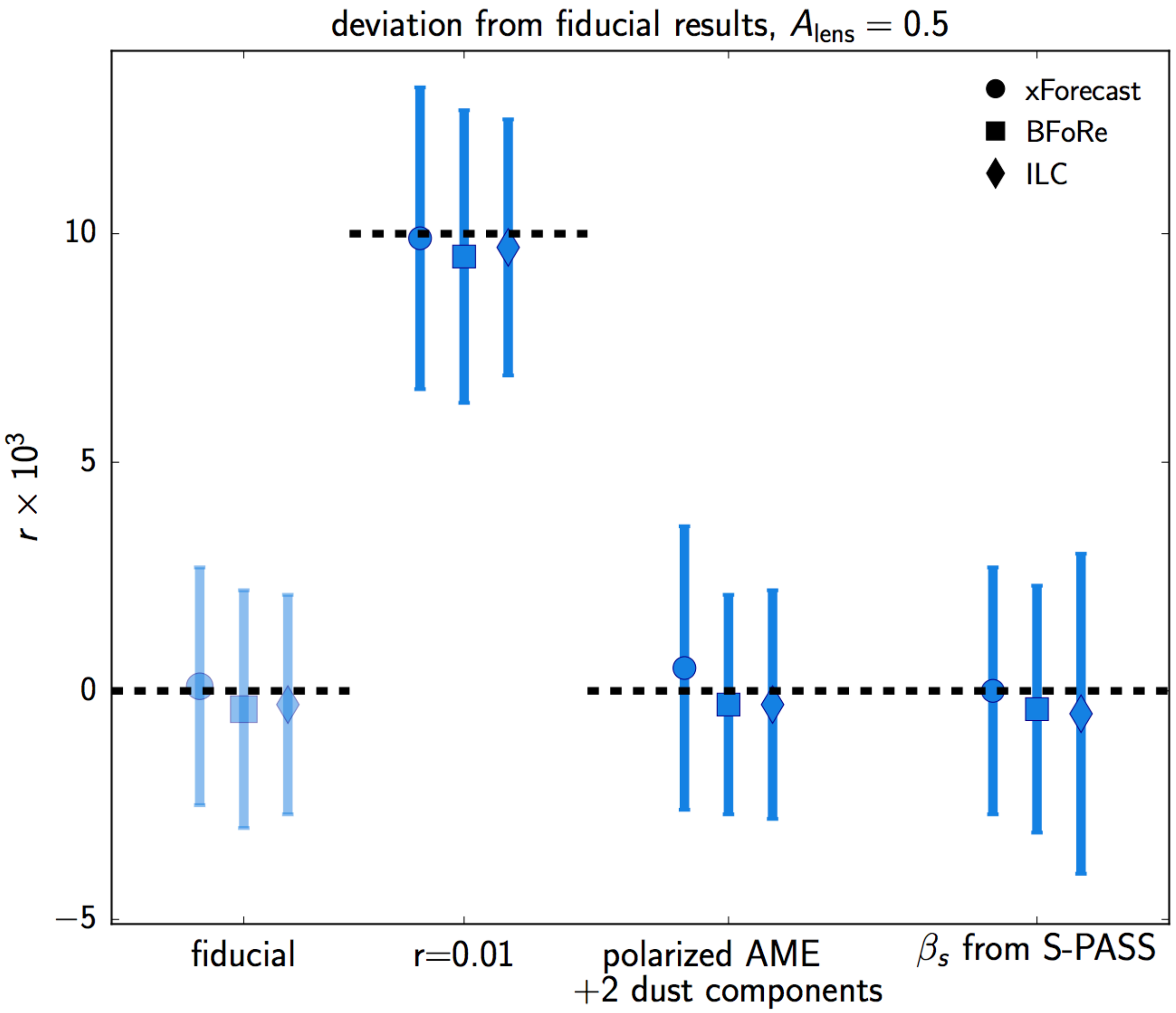
SO SAT Science: Primordial Tensor Modes

Robust to variations in foreground model complexity (within the space of models explored)

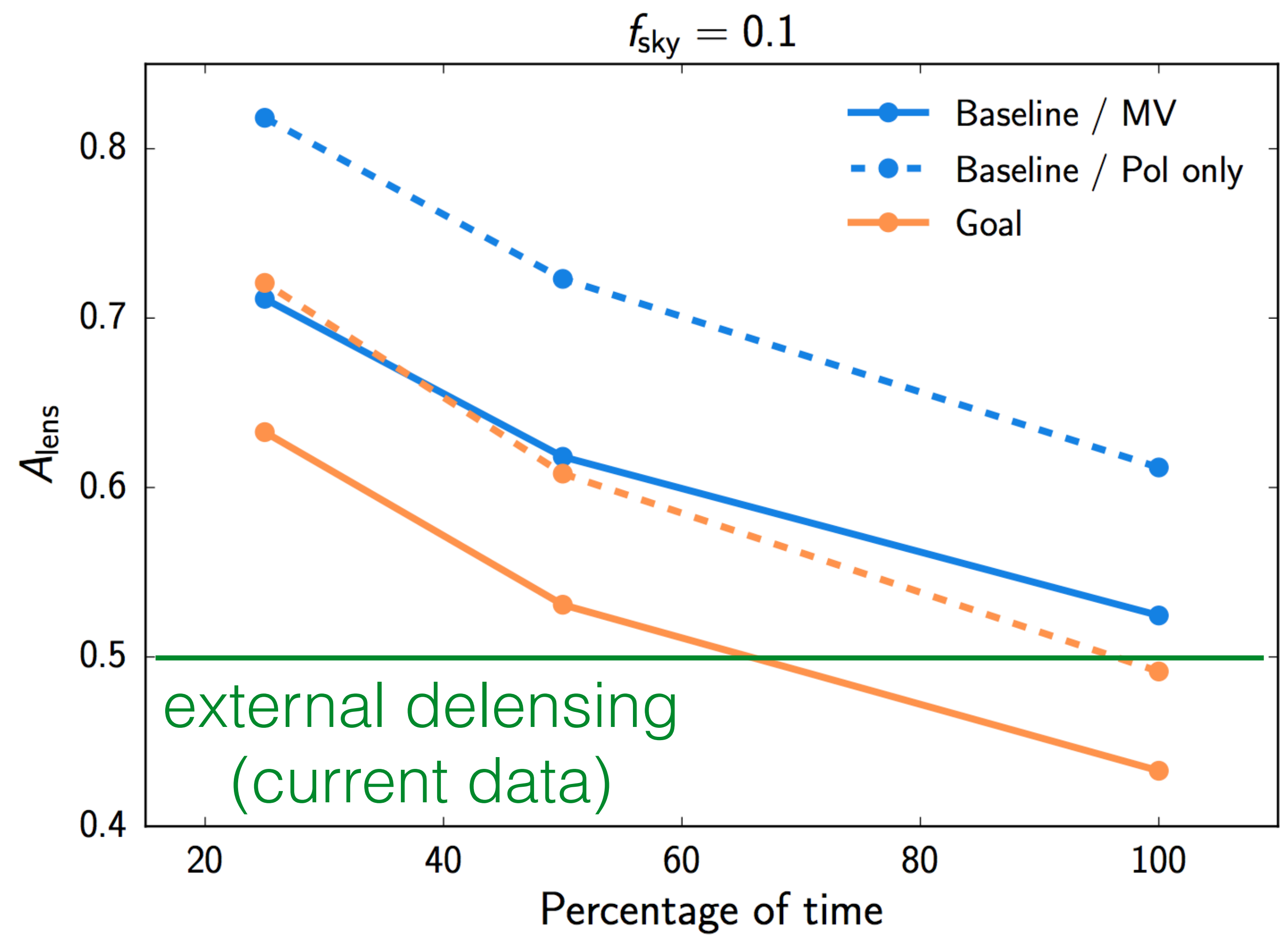


SO SAT Science: Primordial Tensor Modes

Robust to variations in foreground model complexity (within the space of models explored)



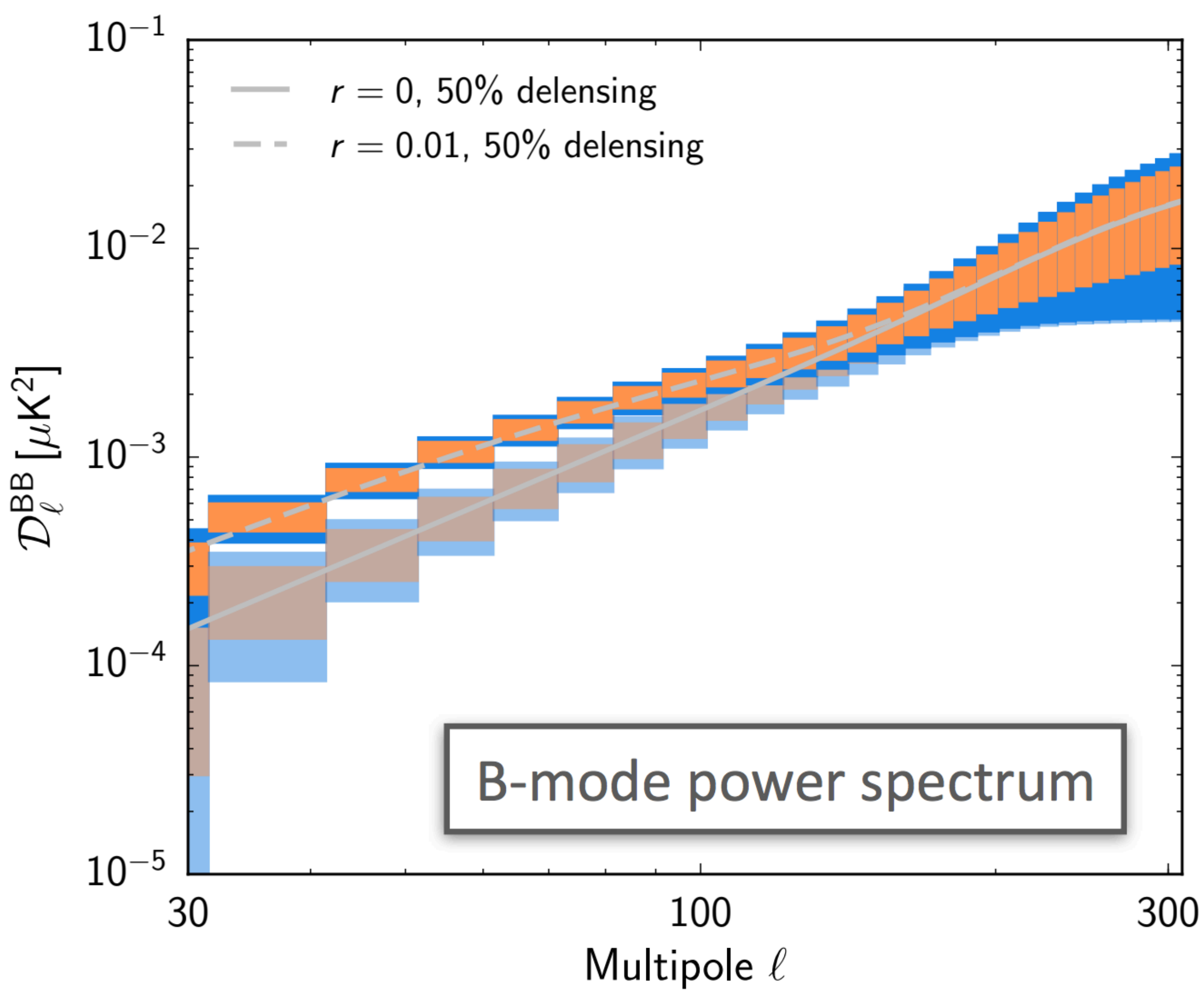
A dedicated delensing survey is not necessary; external delensing suffices

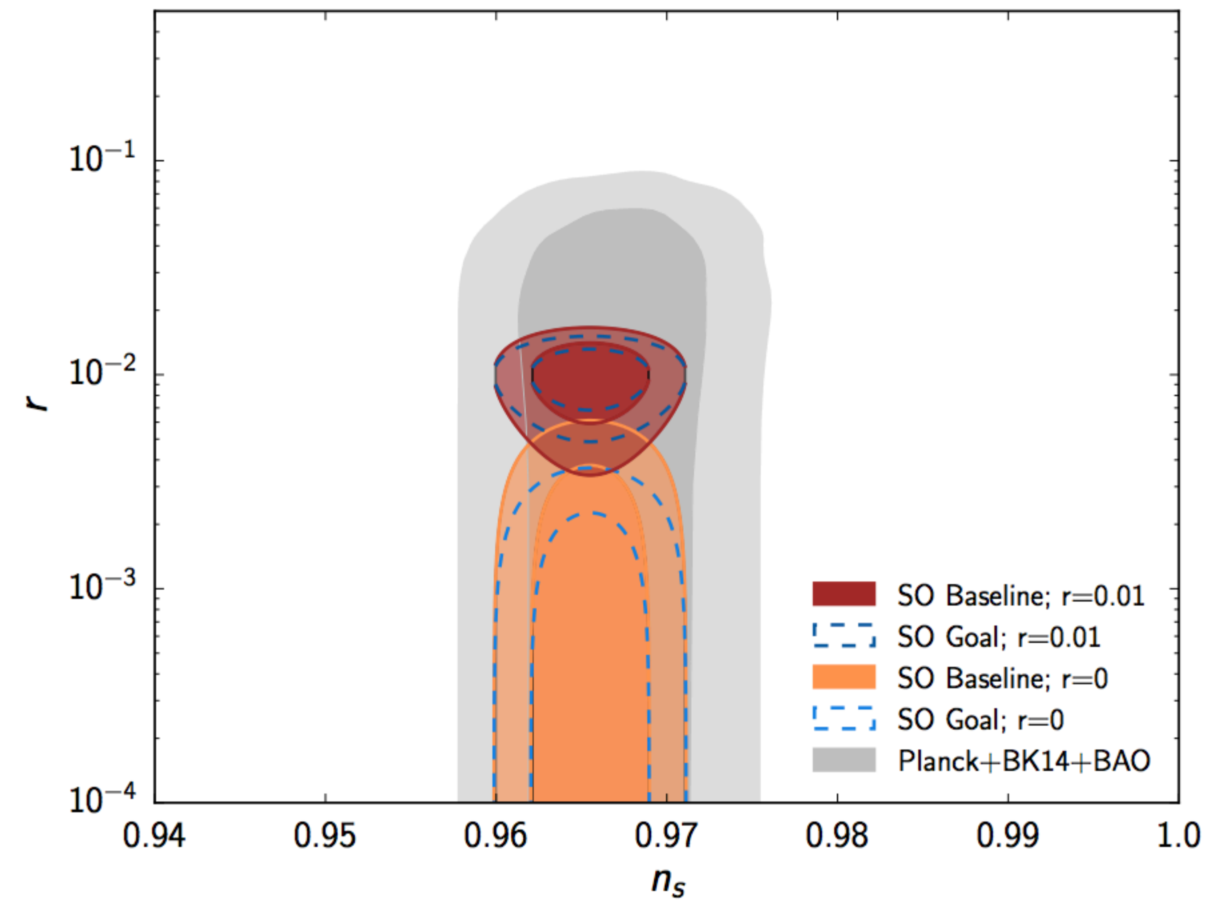


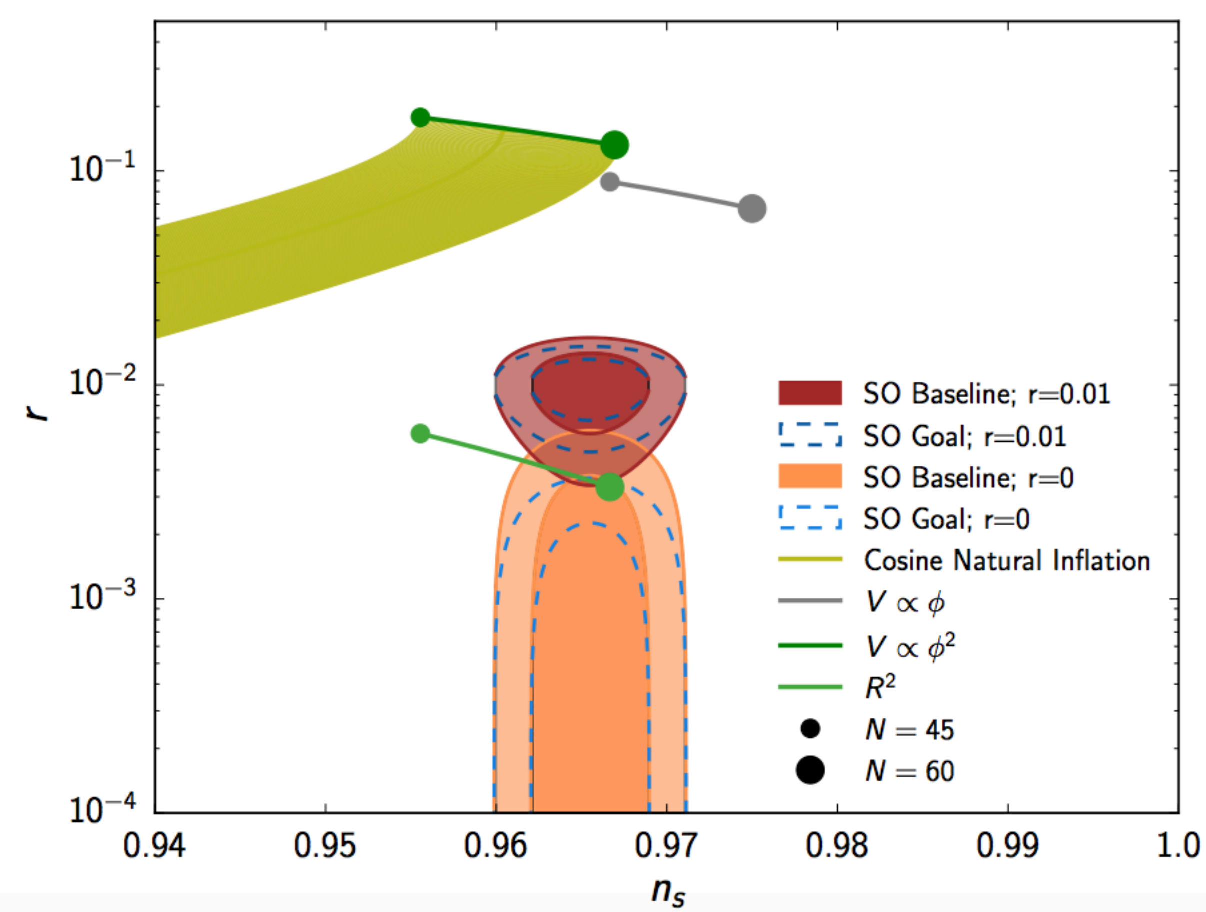
Conclusion: σ(r=0) = 0.003 (SO Baseline)

more infos at: https://simonsobservatory.org/

SO SAT Science: Primordial Perturbations







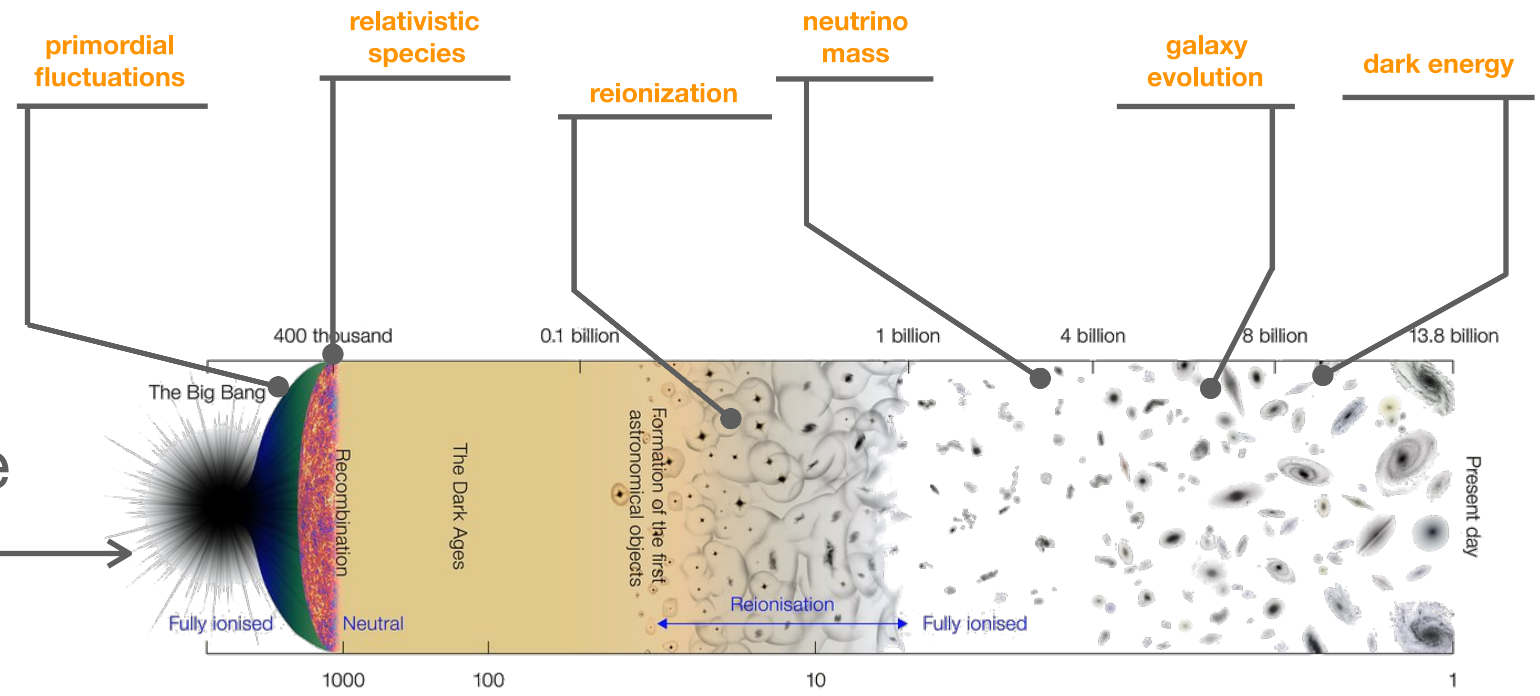
SO will detect or rule out models with r >= 0.01 at 3σ or greater

more infos at: https://simonsobservatory.org/

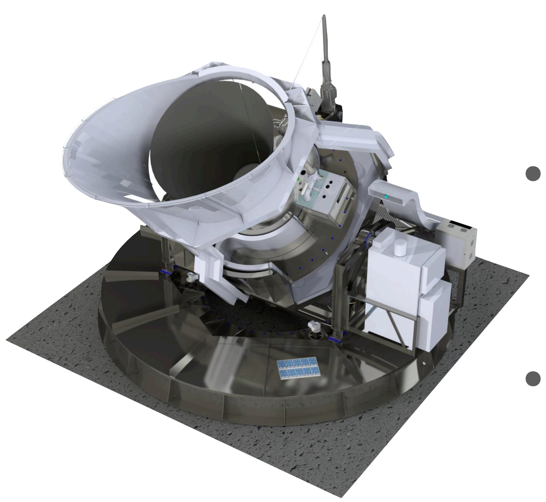
outline

1. Very general introduction: CMB, inflation and B-modes
2. CMB B-modes observations in practice
3. Race to inflation: an example, the Simons Observatory
4. Conclusions

Conclusions



- CMB is an open window onto the physics at the highest energies
- a lot of exciting science to be done looking at the early and late Universe
- detection of primordial CMB B-modes would be a wonderful observational evidence for cosmic inflation



- bigger focal planes and larger observatories are being designed and built
- a lot of challenges ahead, in particular the control of astrophysical and instrumental systematics

- stay tune for the deployment of the **Simons Observatory!** and later, for the launch of **LiteBIRD**!

LiteBIRD

the next-generation CMB satellite selected by JAXA as its second Strategic Large Mission to be launched in 2027

4700 multichroic TES detectors
50x Planck sensitivity on large angular scales

15 frequency bands
$40 \leq \nu \leq 402$ GHz
70' ≥ FWHM ≥ 10'

3 telescopes + 3 instruments
3 rotating half-wave plates
3 year observation at L2

target: **σ(r=0) < 0.001** covering 2 ≤ ℓ ≤ 200, and accounting for astrophysical foreground removal, and instrumental noise and systematics. Beyond studying **the primordial Universe** with CMB B-mode polarization, there will be a lot of exciting **cosmological** (reionization, cosmic birefringence, non-Gaussianity, anomalies, etc.) and **astrophysical** (dust, synchrotron, Galactic magnetic field, etc.) **science!**