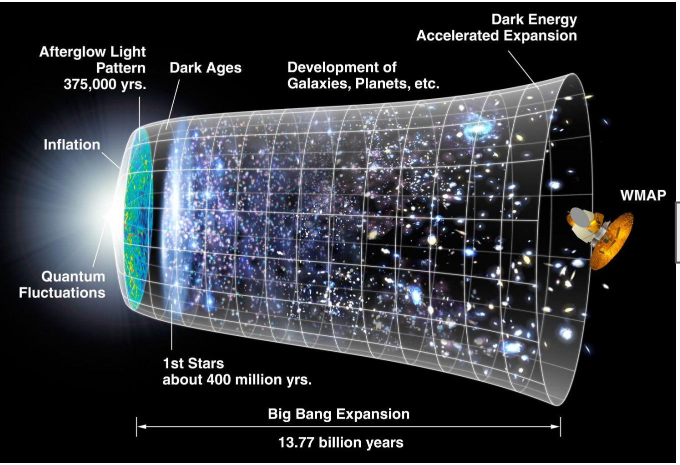
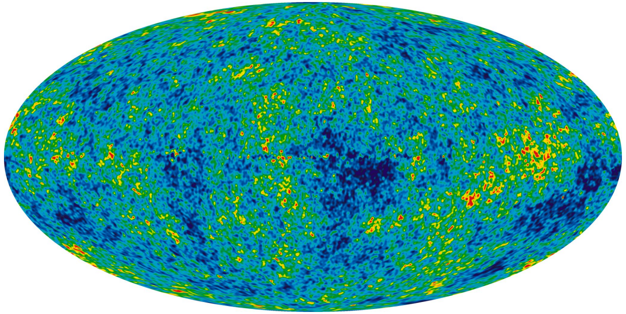
Current Status and Prospects of Cosmic Microwave Background Polarization Experiments

Kenji Kiuchi

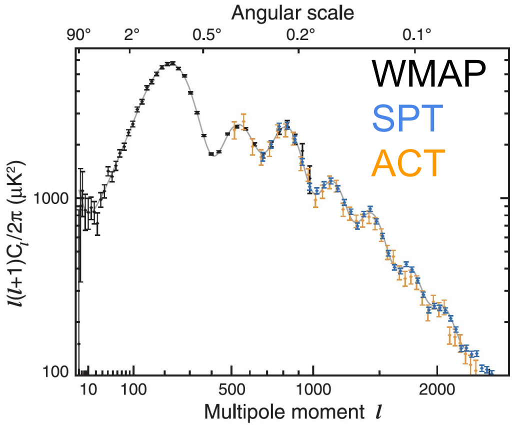
Lambda-CDM with temperature anisotropy



Temperature anisotropy
WMAP 9 years observation



Cross-power spectrum of ⊿T



G. Hinshaw *et al* 2013 *ApJS* 208 19

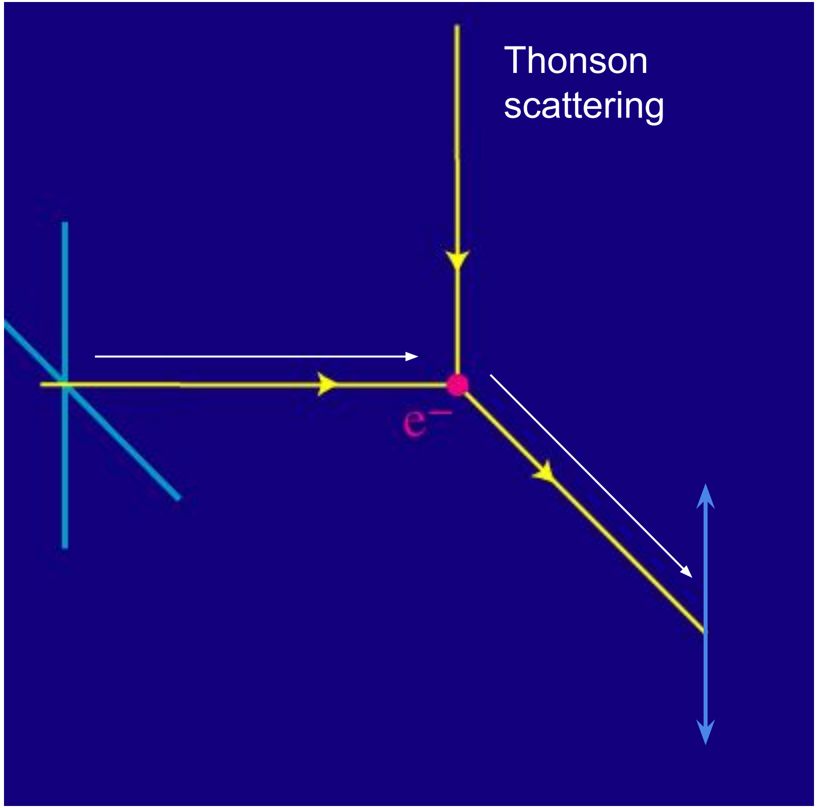
Parameter	Symbol	*WMAP* data
Fit ΛCDM parameters		
Physical baryon density	$\Omega_b h^2$	0.02256
Physical cold dark matter density	$\Omega_c h^2$	0.1142
Dark energy density ($w = -1$)	Ω_Λ	0.7185
Curvature perturbations, $k_0 = 0.002$ Mpc^{-1}	$10^9 \Delta^2_{\mathcal{R}}$	2.40
Scalar spectral index	n_s	0.9710
Reionization optical depth	τ	0.0851

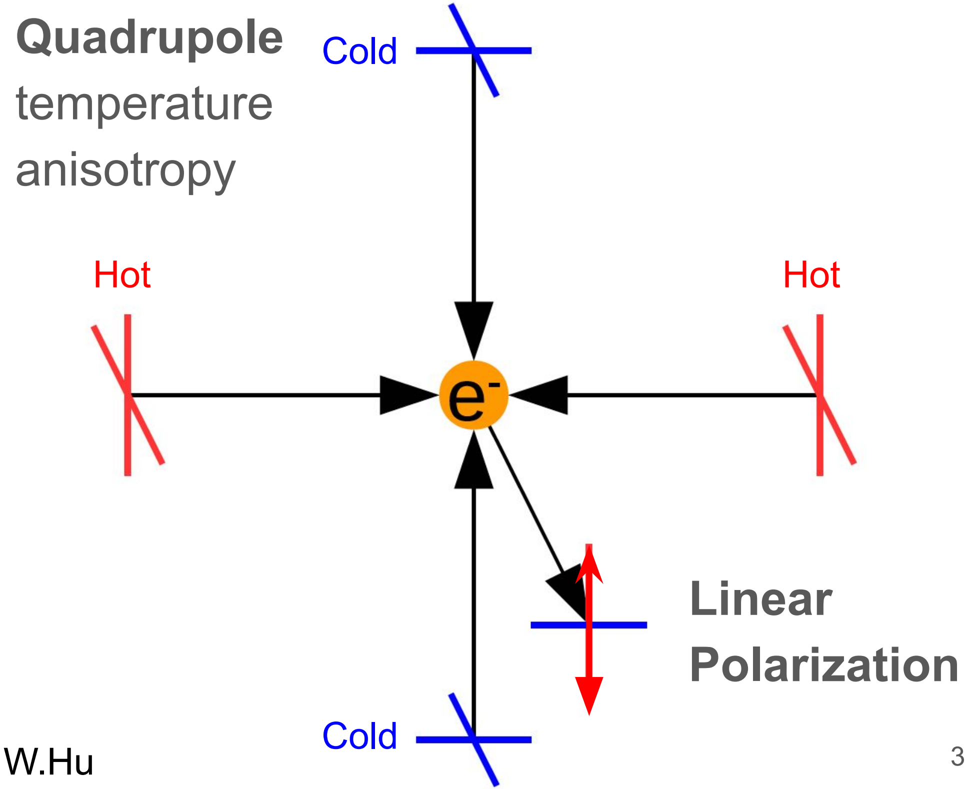
- baryon contains leptons!

ΛCDM parameters are precisely estimated by temperature (unpolarized) anisotropy data

→ **NEXT IS POLARIZATION !**

Polarization by scattering with quadrupole anisotropy

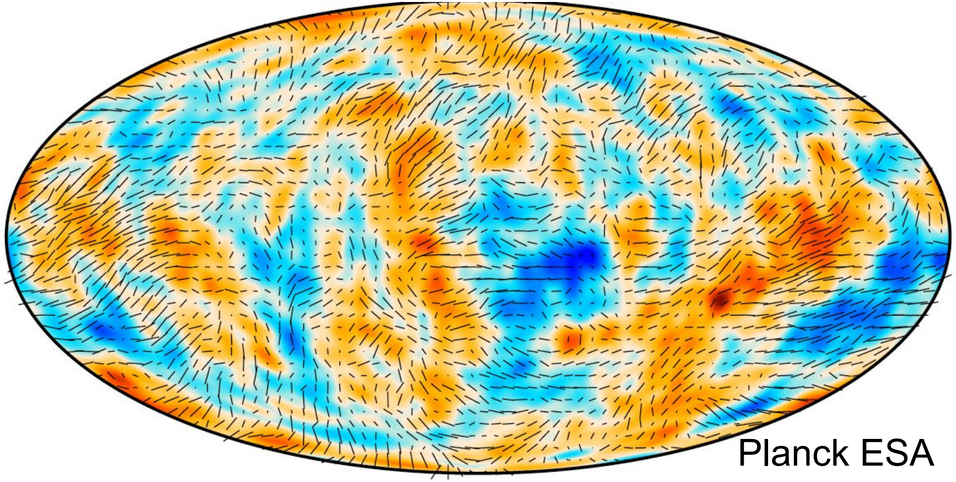




W.Hu

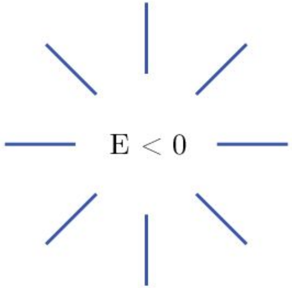
Polarization distribution: B-modes and E-modes

We can define two orthogonal polarization patterns

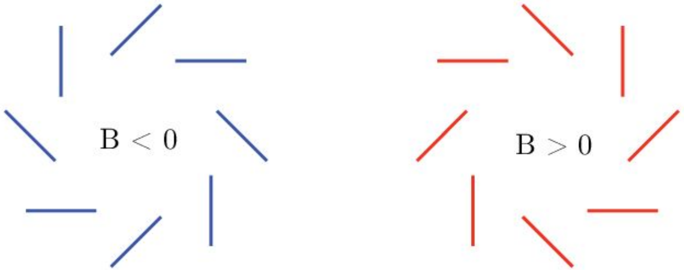


Planck ESA

E-mode: Electric field like (parity even)



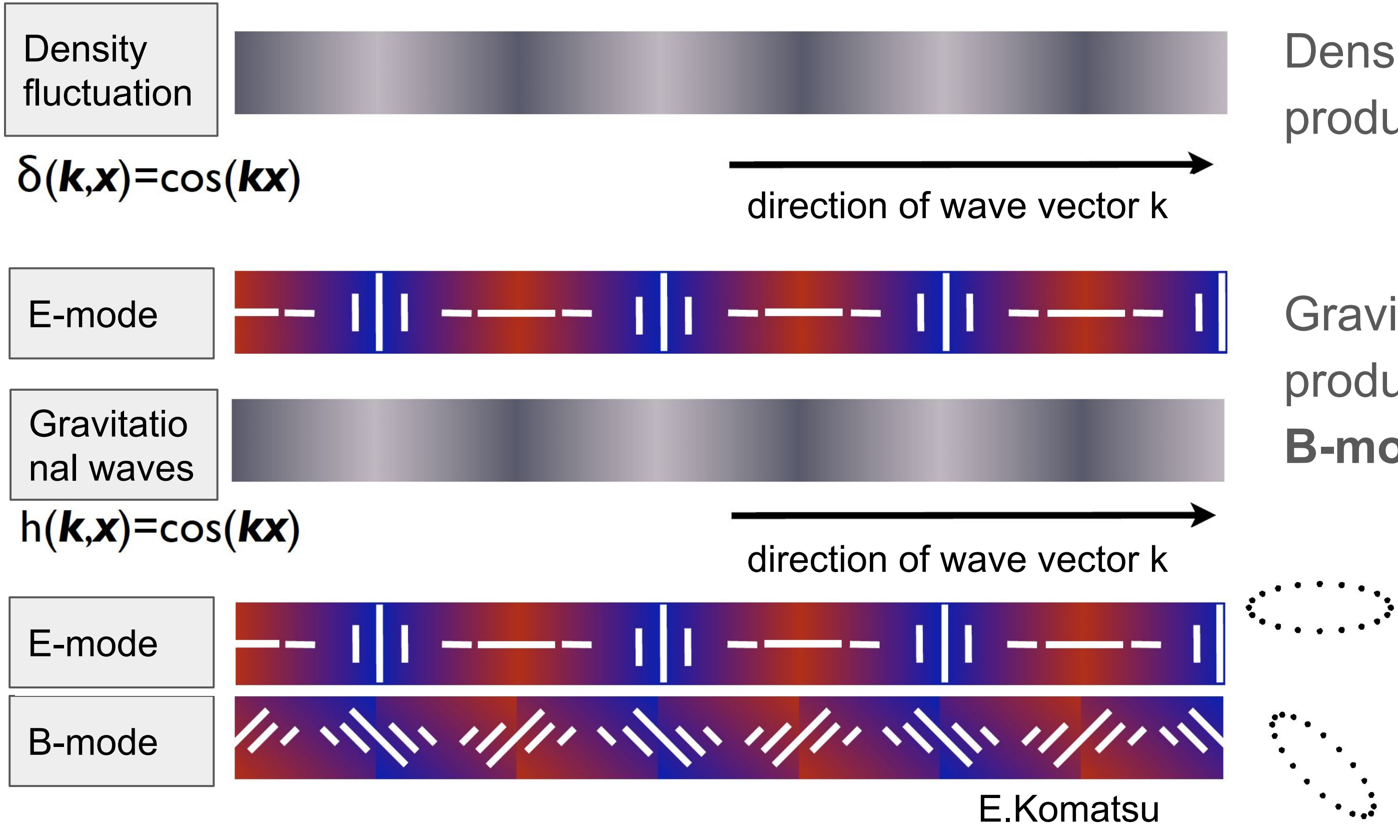
B-mode: Magnetic field like (parity odd)



Two polarization pattern named E and B due to analogy with electromagnetic

BUT THIS IS JUST A NAMING ISSUE

Density distributions and gravitational waves



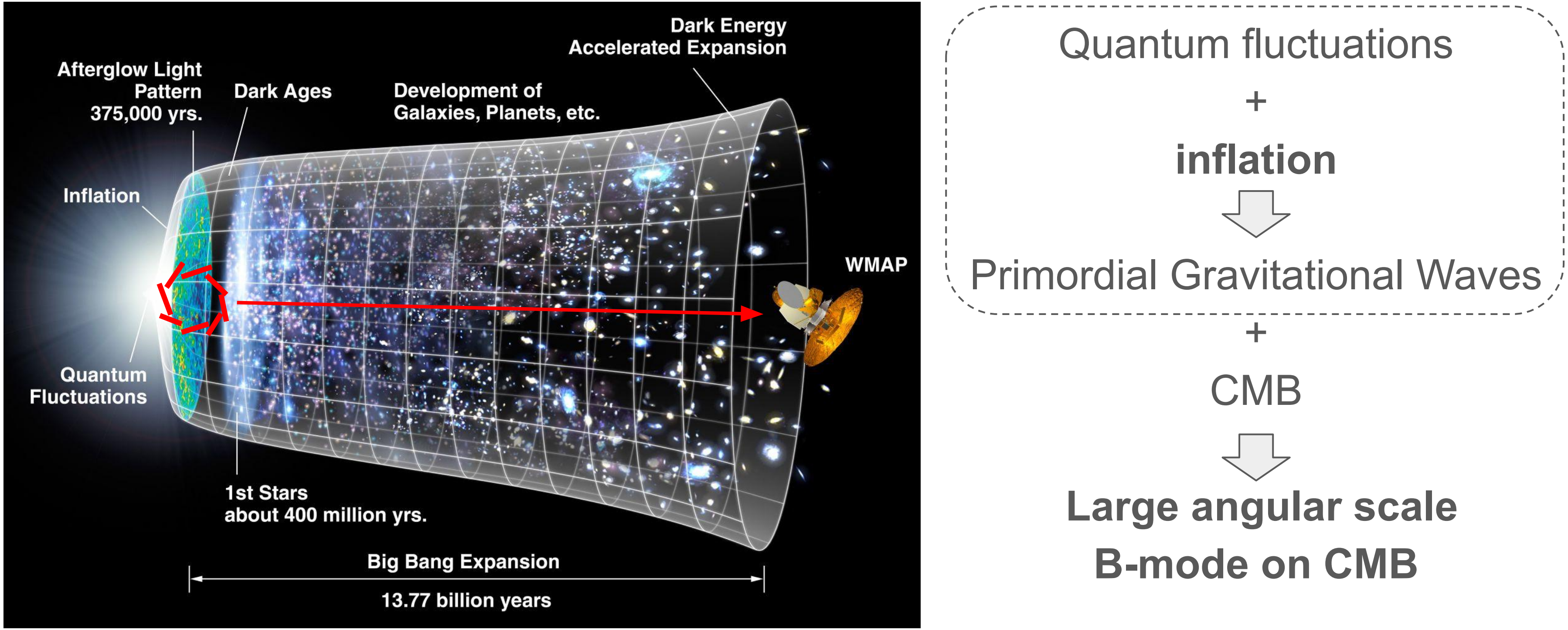
E.Komatsu

Density fluctuations produce **only** E-mode

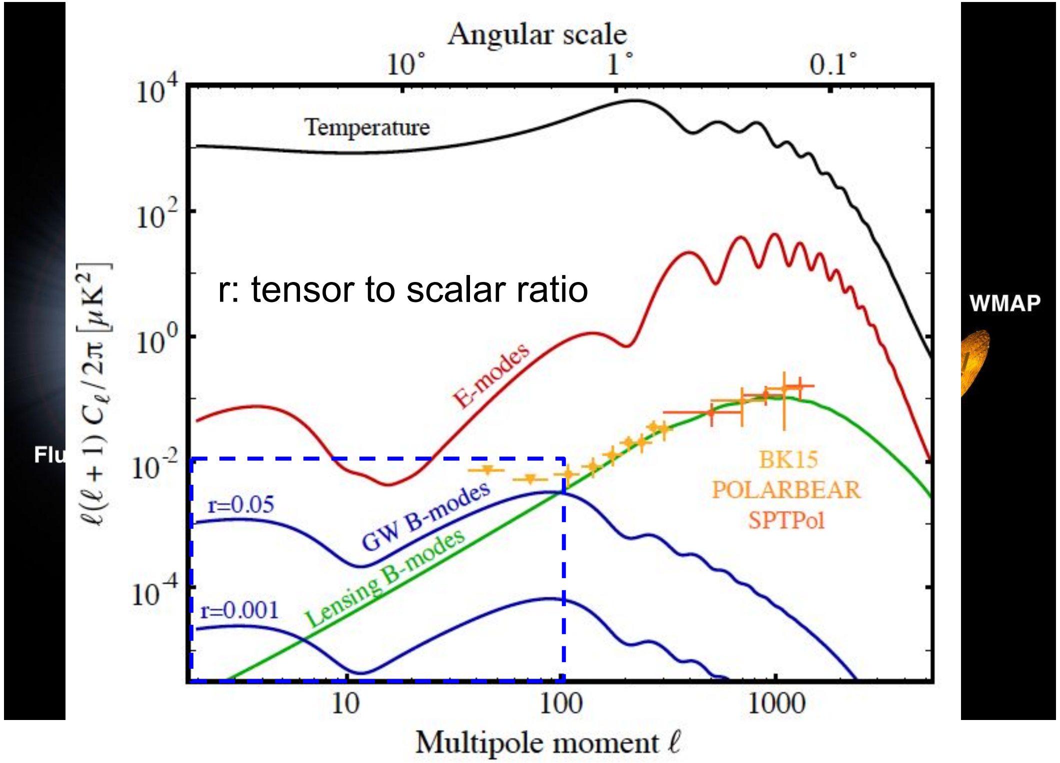
Gravitational waves produce E-modes and **B-modes**

Only gravitational waves can produce B-modes

Large angular scale B-mode: Direct evidence of inflation



Large angular scale B-mode: Direct evidence of inflation



Quantum fluctuations

\+

inflation

⇩

Primordial Gravitational Waves

\+

CMB

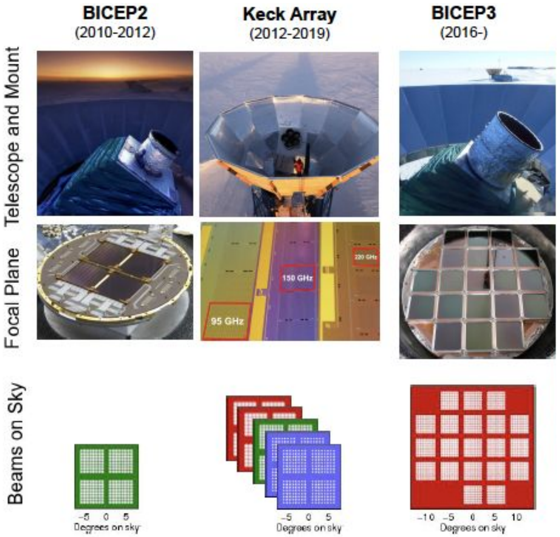
⇩

Large angular scale B-mode on CMB

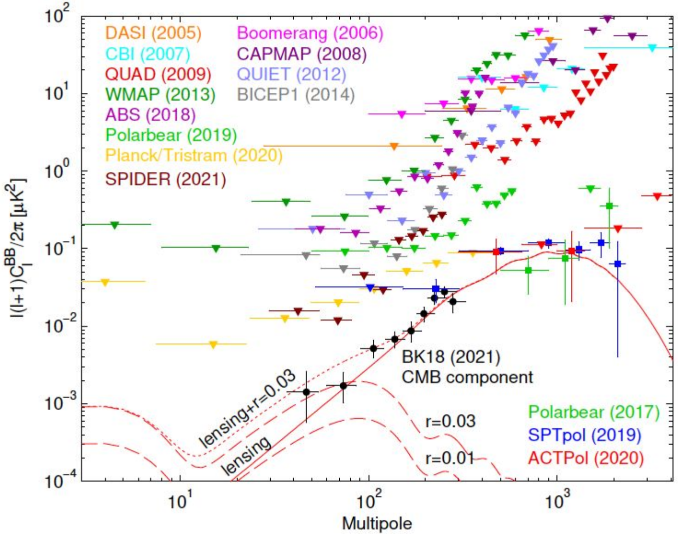
arXiv:1907.04473

Best limit on r: BICEP & Planck combined result

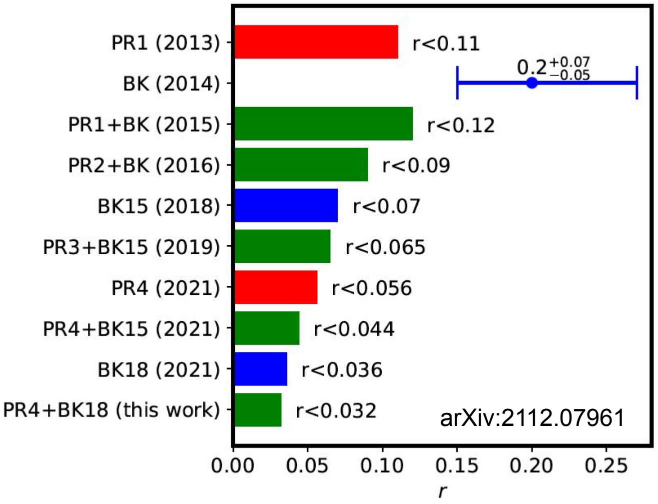
BICEP&Keck



arXiv:2203.16556



Phys. Rev. Lett. ***127****, 151301, 2021*



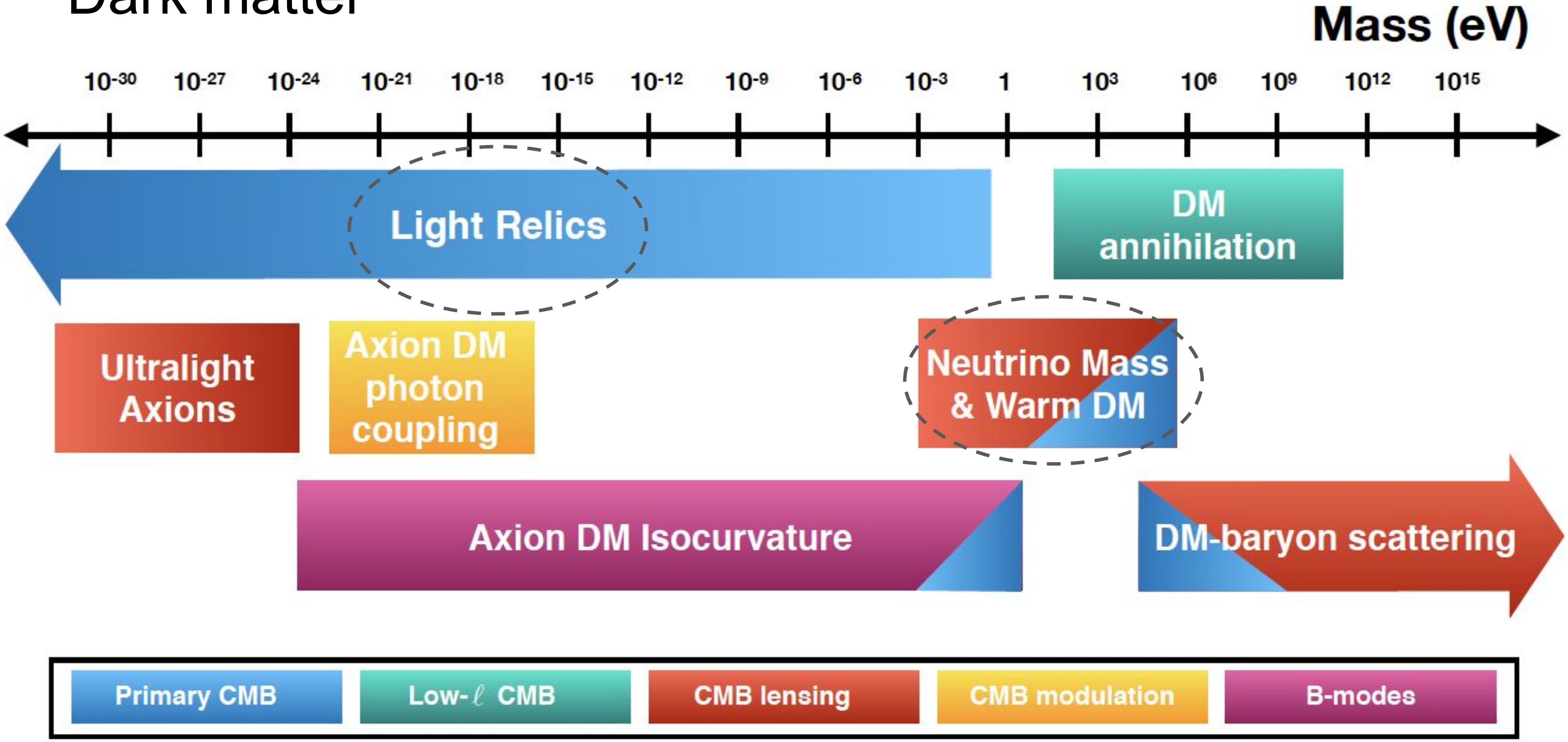
BK: BICEP&KECK, PR:Planck

$$V \sim (1\times10^{16}\ \mathrm{GeV})^4 (r/0.01)$$

r: tensor to scalar ratio

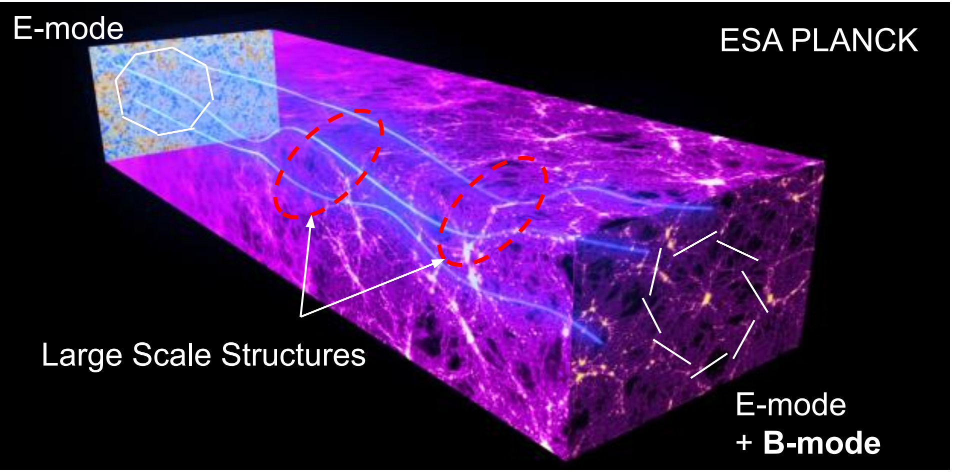
Combined result of BICEP&Keck 2018 and Planck PR4 tightened the constraint to r<0.032

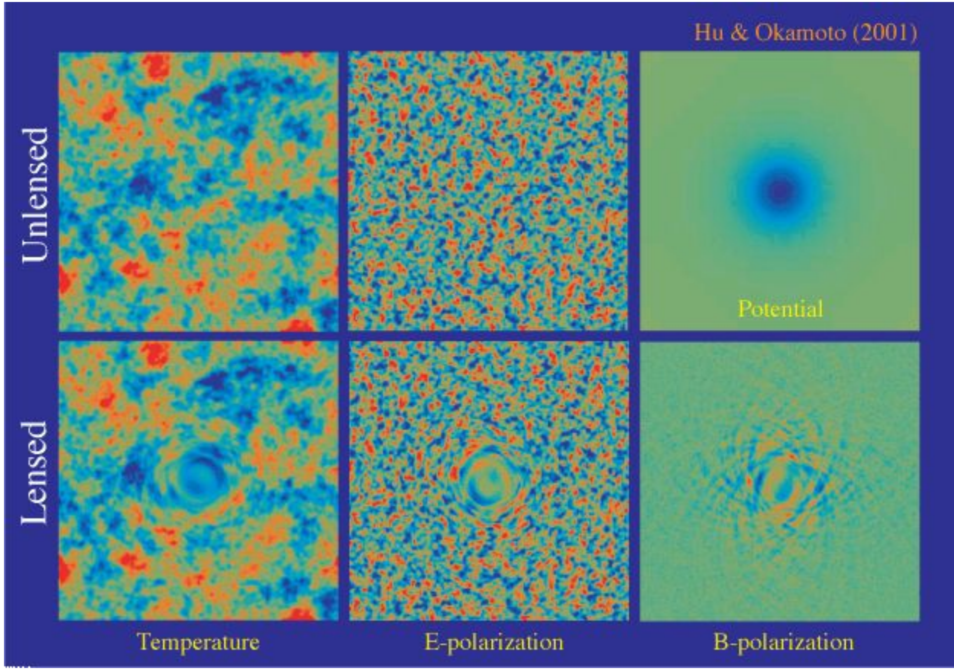
Dark matter



arXiv:1907.04473

Lensing B-mode (alternative source of B-modes)

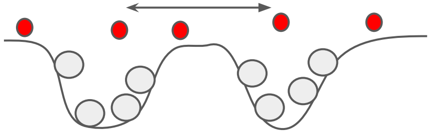




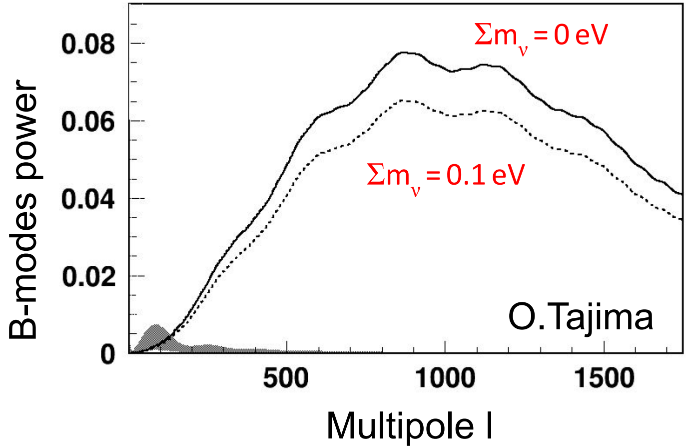
Gravity potential rotate the polarization angle
B-modes are produced from E-modes

We can see the large scale structure via
small angular scale B-modes

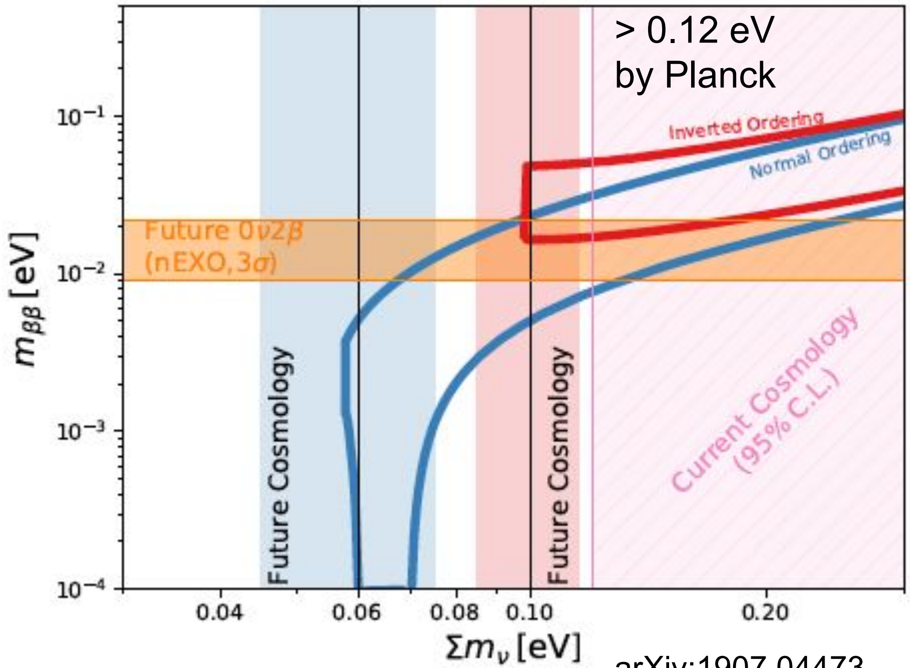
Sum of neutrino mass



Neutrinos are relativistic
Increasing neutrino mass
wash away small structures



Lensing B-mode is clean signal
and independent signal

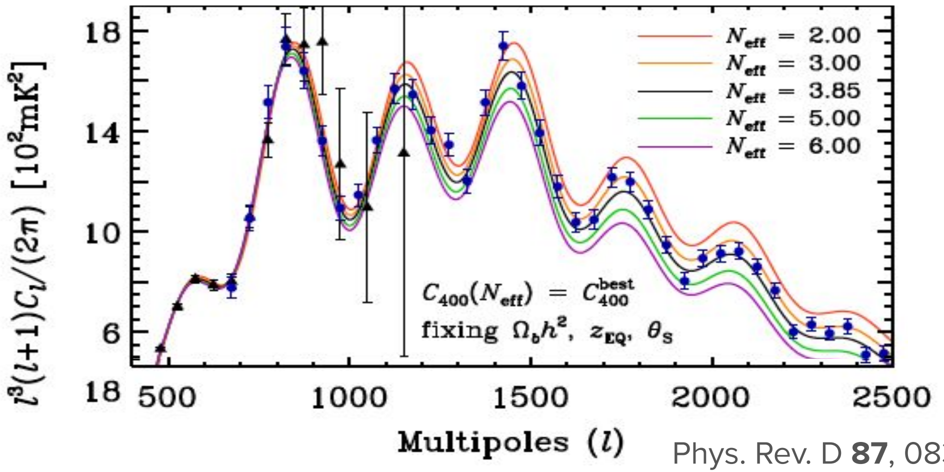


arXiv:1907.04473

Inverted case, combined with 0vββ
We can answer majorana or dirac

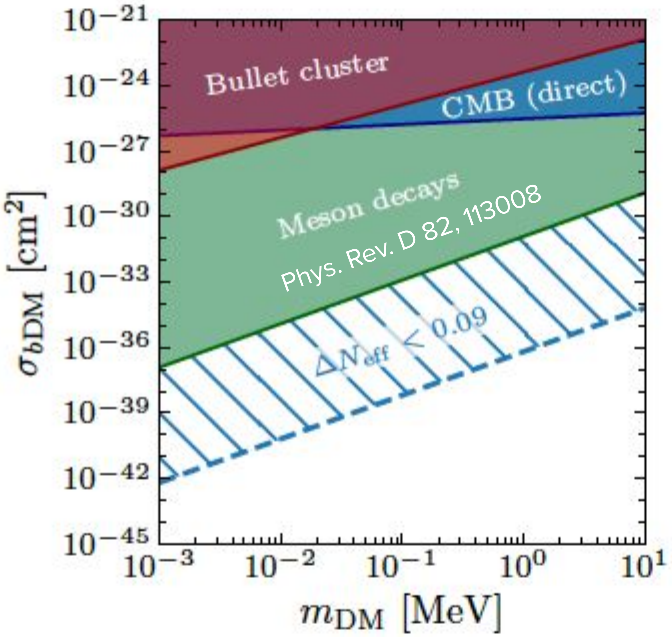
Light relic: Degree of freedom of relativistic particle

Temp. & E-mode cross spectra (Norm@l=400)



Phys. Rev. D **87**, 083008

baryon-DM x-sec



arXiv:1907.04473

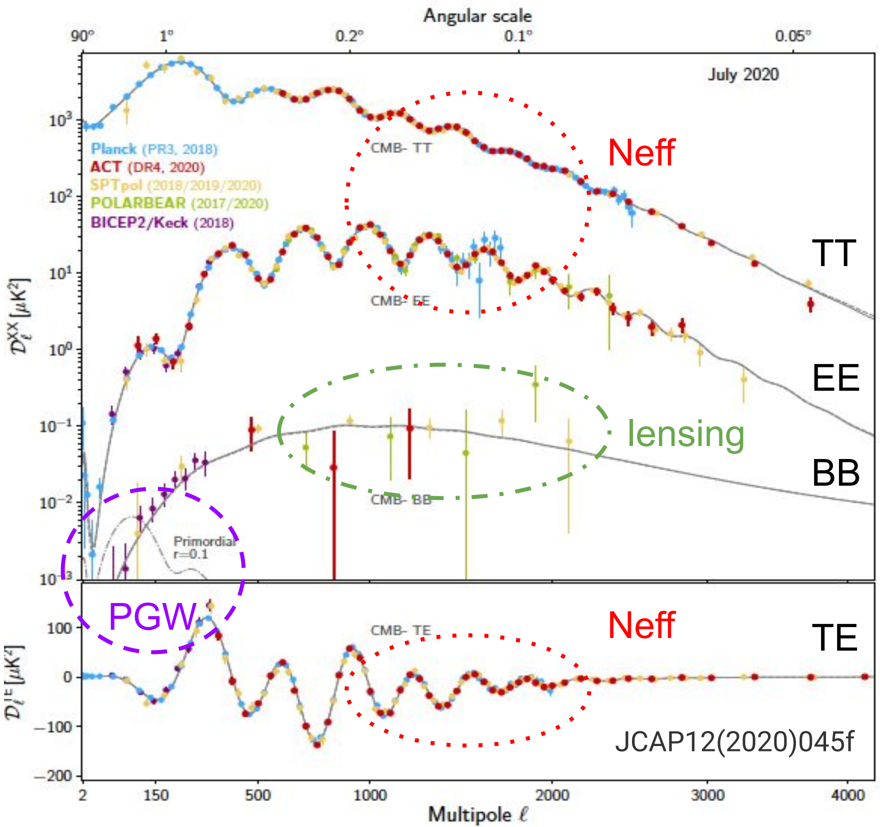
JHEP 2017, 13 (2017)

Neff: effective number of neutrino species

$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right]\rho_\gamma$$

↑Neff→↑Dark radiation → ↓Small scale baryon density fluctuation
Standard model expectation 3.046, current limit is 2.99 ± 0.17 by Planck

Current best limits



Current limits

- $r < 0.032$ (BK&Planck)
- $N_{\mathrm{eff}} = 2.99 \pm 0.17$ (Planck)
- $\Sigma m_\nu < 0.12$ eV (Planck)

A&A 641, A6 (2020), arXiv:2112.07961

Next target
$\sigma(r) = 0.003$, 3σ for $r = 0.01$

Current CMB Experiments (not all but…)

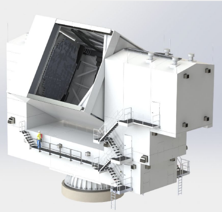
Atacama@Chile

ACT

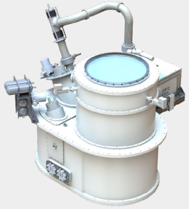
PB/SA

Simons Observatory

Large Aperture Telescope



Small Aperture Telescope



South Pole

SPT

BICEP/Keck

Tenerife@Spain

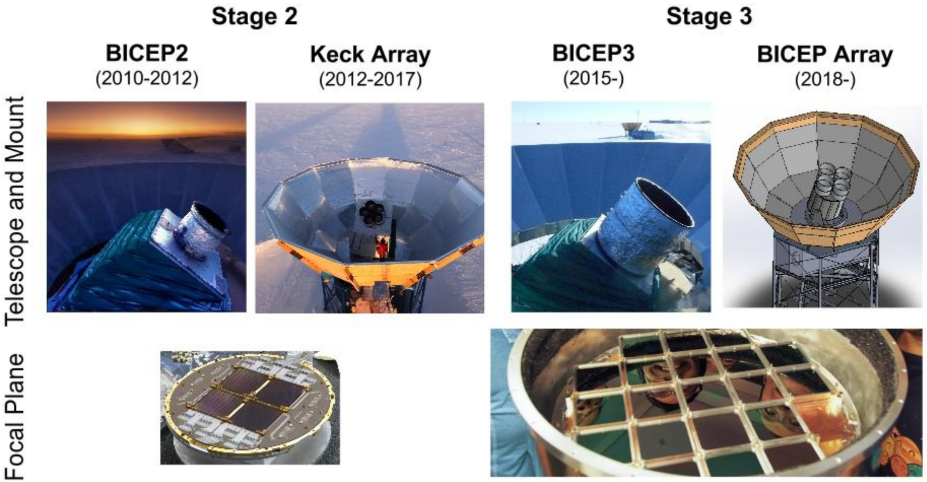
GroundBIRD

- this is just a part of full list

Evolution of the CMB experiments

SimonsArray

Polarbear



500 detectors

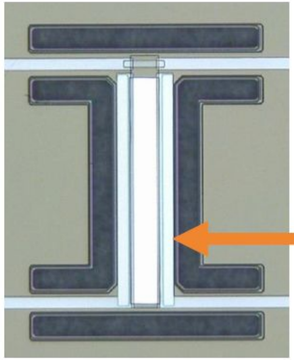
2500 detectors

total 30,000 detectors

Evolution of CMB experiments
= History of increasing detectors
Key is muitl-frequency observation

Transition-Edge Sensor (TES)

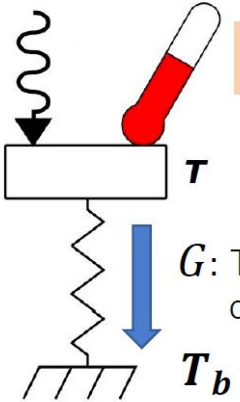
TES photo



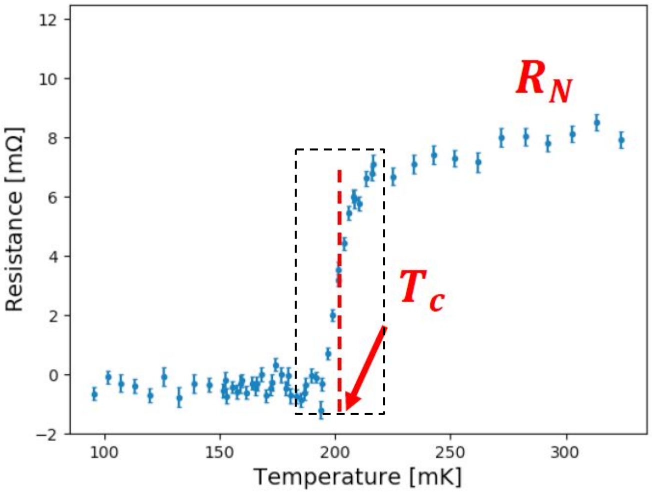
Made in SeeQC (provided by A. Suzuki (LBNL))

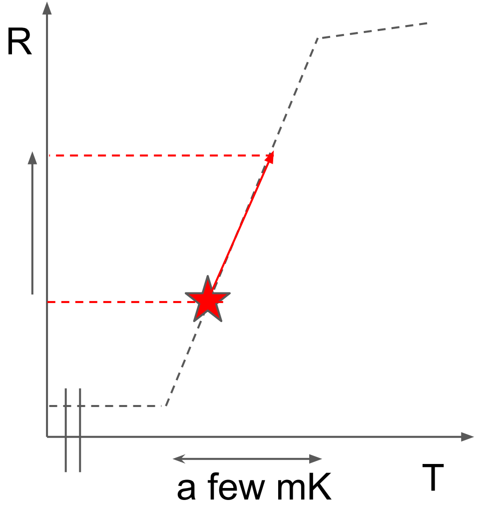
The sketch of a bolometer

M. J. Myers (2010)



TES resistance

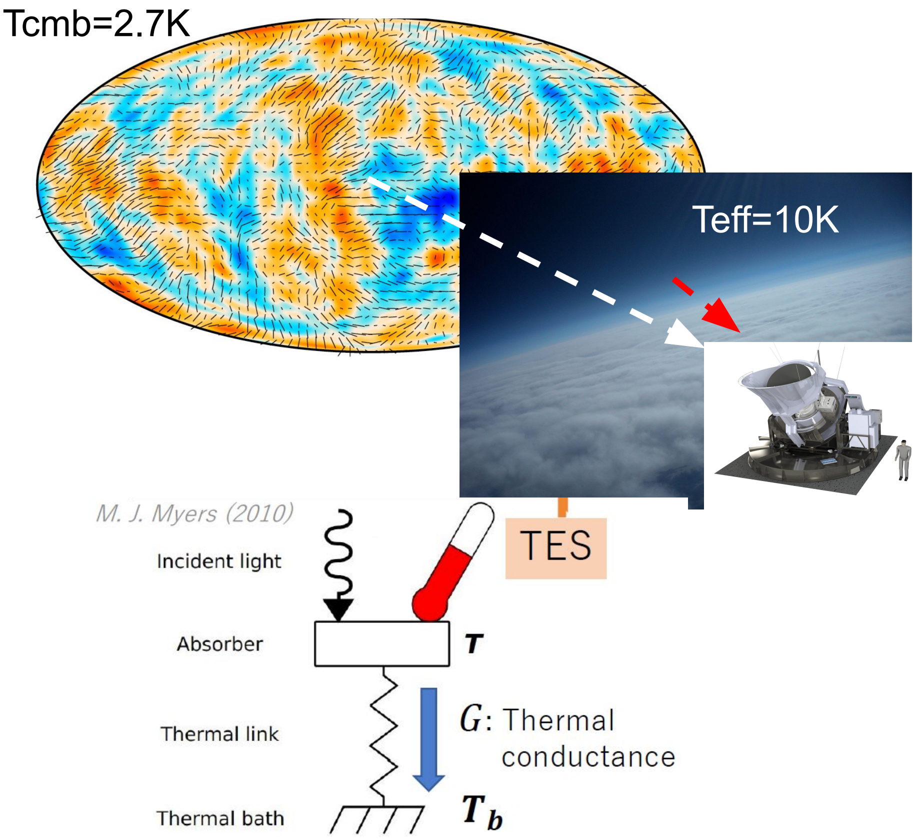




Around T_c, the resistance of TES varies **rapidly**.
→ TES is used as
a power meter of a bolometer.

Stable operation thermal feedback by constant voltage
↑T→↑R→ ↓P→↓T

Photon noise limit detectors of ground-based experiment



Photon noise

$$\mathrm{NEP}^2_{\mathrm{photon}} = \int_0^\infty 2\frac{\mathrm{d}P}{\mathrm{d}\nu} h\nu\Big(1 + \eta(\nu)m(\nu)\Big)\mathrm{d}\nu.$$

Intrinsic detector noise

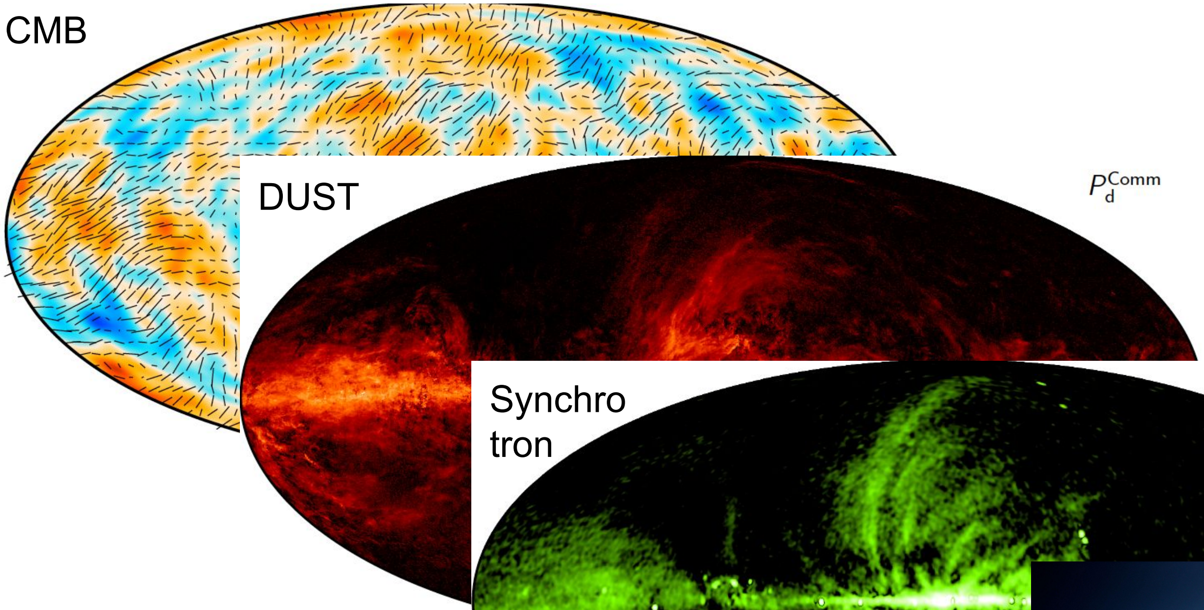
$$\mathrm{NEP}^2_G = F_{\mathrm{link}} 4k_{\mathrm{b}} T^2 G,$$

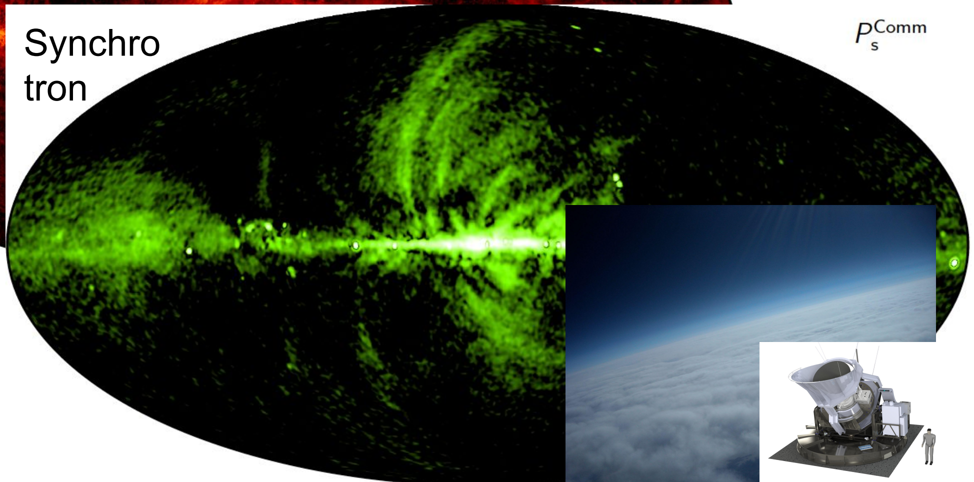
Typical photon noise 10^-17 W/sqrt(Hz)
>> Detector noise

Single detector performance is limited

Jonas Zmuidzinas, Appl. Opt. 42, 4989-5008 (2003)
Robert W. Boyd, Infrared Physics, 22, 3, 157-162, (1982)

Foregrounds = “Backgrounds?”



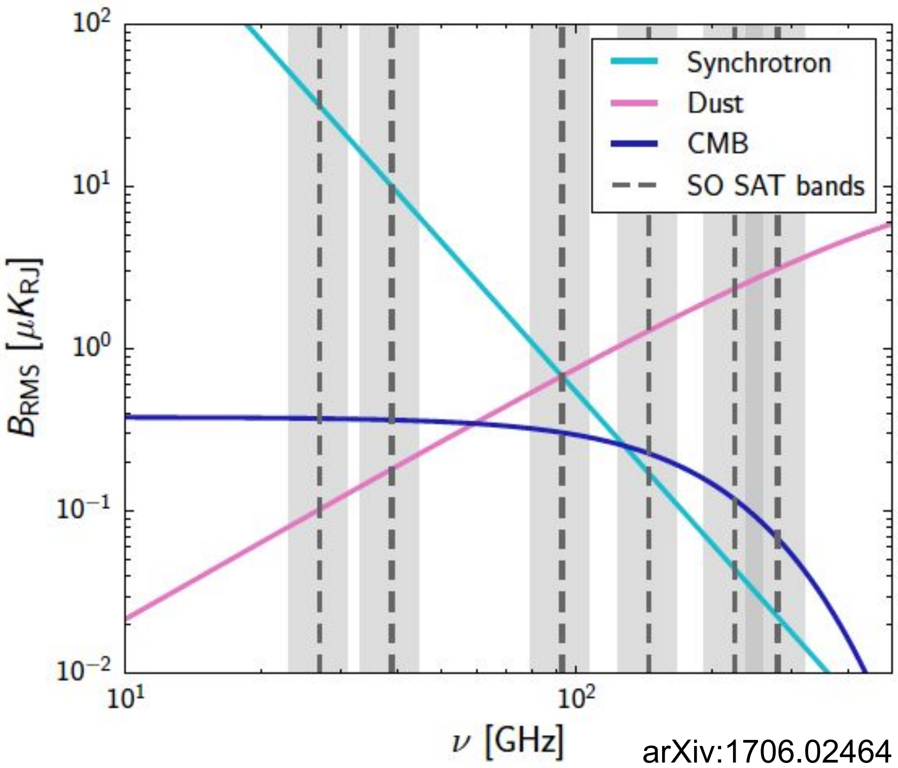


CMB + Dust + Synchrotron + Atmosphere

We need to subtract “foregrounds”

Planck ESA

Foreground estimation with multiband observation



arXiv:1706.02464

CMB + Two **foregrounds**

- Synchrotron
- Dust emission

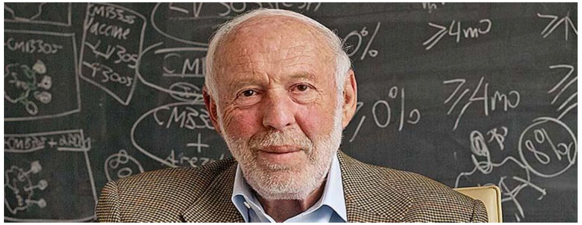
We need to estimate foregrounds to subtract them.

Next generation experiments will measure multi frequency bands

Simons Observatory (SO)

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION



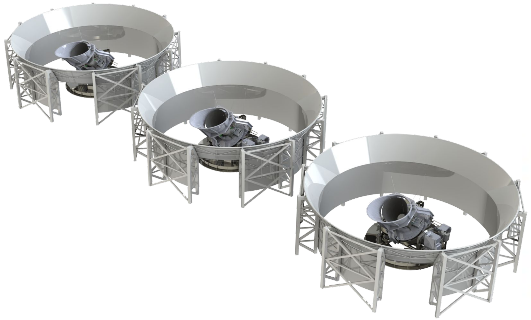
SIMONS OBSERVATORY
22°57'31" SOUTH, 67°47'15" WEST ELEVATION: 17,027.6' PARQUE ASTRONÓMICO ATACAMA, CHILE

Construction of nominal project is funded privately and has already begun. >200 collaborators

APC · BERKELEY LAB · CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD · CITA–ICAT · DUNLAP INSTITUTE FOR ASTRONOMY & ASTROPHYSICS · KAVLI IPMU · KEK-JAPAN · NASA · NIST · SISSA · SLAC · TEL AVIV UNIVERSITY · TOHOKU UNIVERSITY · UBC · UNIVERSITY OF KWAZULU-NATAL · MANCHESTER 1824 The University of Manchester · THE UNIVERSITY OF MELBOURNE · UNIVERSITY OF MICHIGAN · UNIVERSITY OF OXFORD · UNIVERSITY OF PITTSBURGH · UNIVERSITY OF SUSSEX · 東京大学 · WCU WEST CHESTER UNIVERSITY · STOCKHOLMS UNIVERSITET

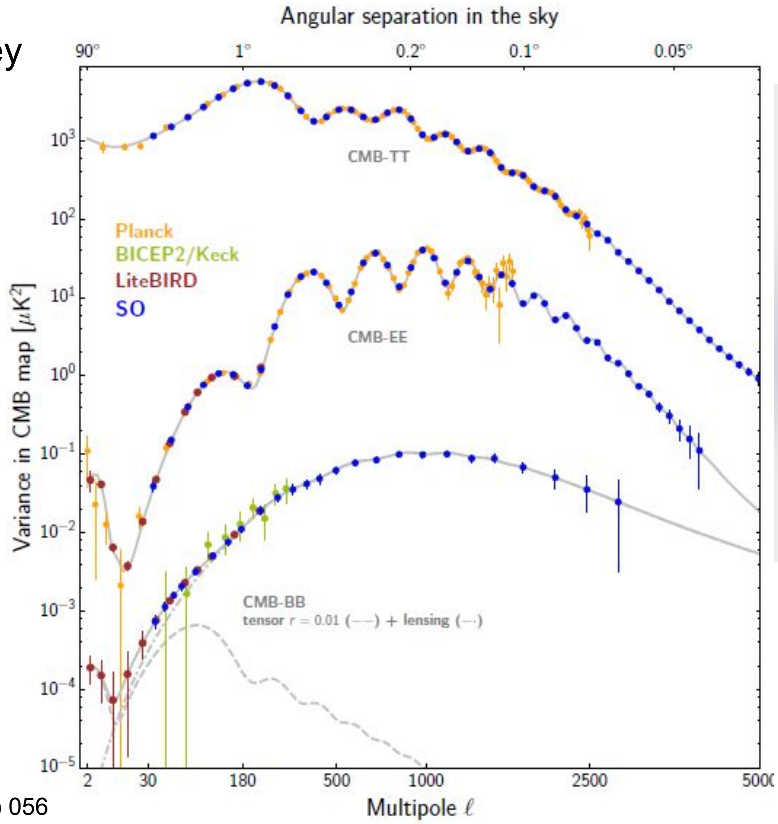
Small Aperture Telescope and Large Aperture Telescope

SATs: Large scale, deep survey



30,000 detectors
30 < ℓ < 300

σ(r)=0.003



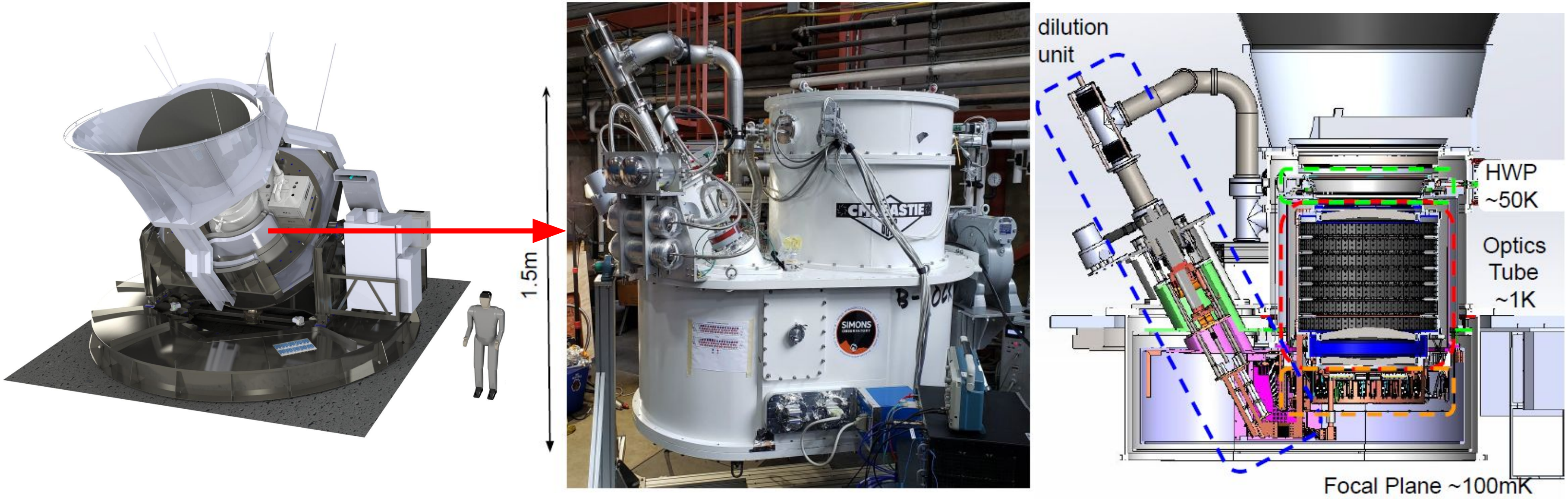
LAT: High resolution

30,000 detectors, ℓ < 3,000

σ(Σmν)=0.04 eV,
σ(Neff)=0.07 and etc.

The Simons Observatory:
science goals and forecasts JCAP 1902 (2019) 056

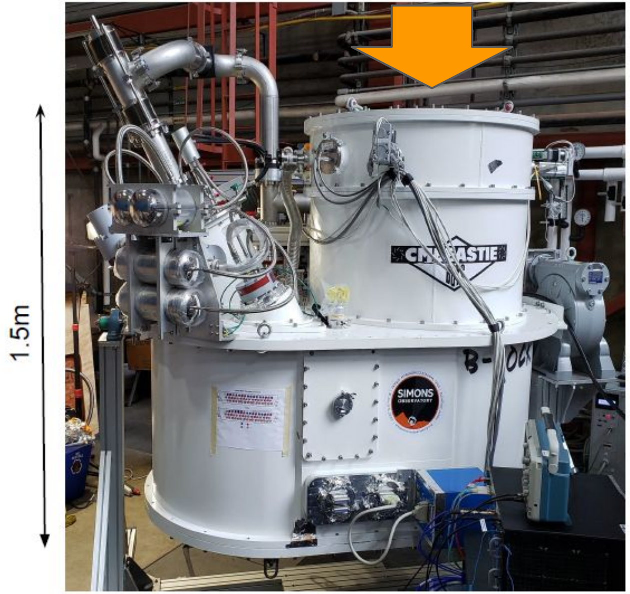
Small Aperture Telescopes

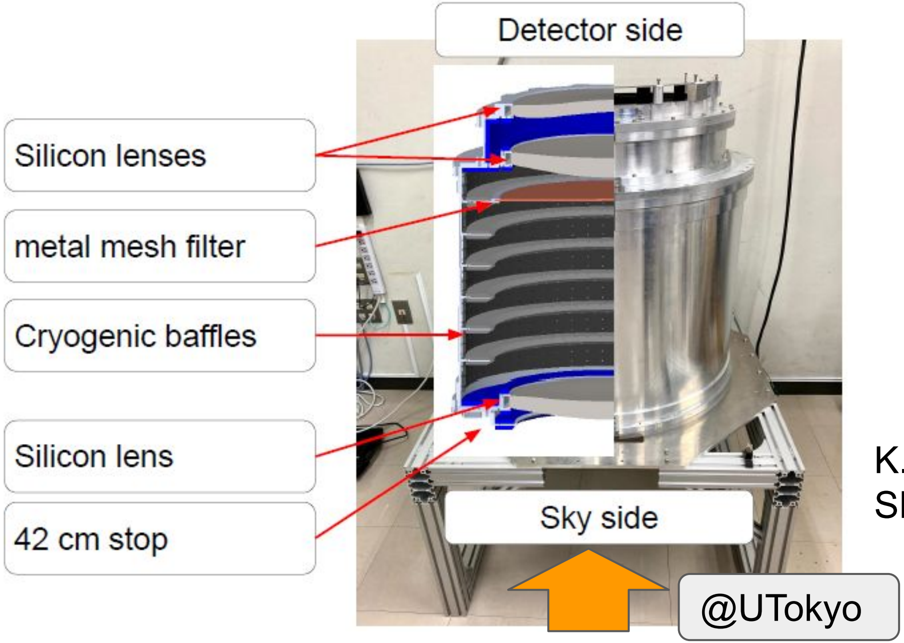


Robust design: Single optics tube in one cryostat with dilution unit

High statistics: Total 30,000 detectors, >10,000 detectors for one telescope

Optics Tube for SAT





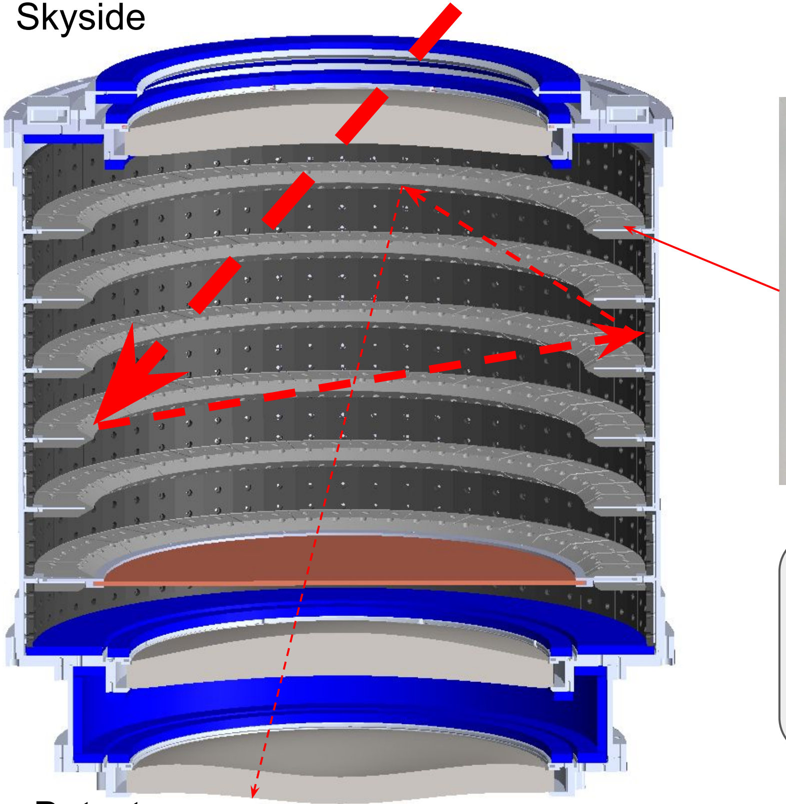
K.Kiuchi
SPIE 2020

High throughput optics: Refractive optics with 42 cm aperture

Stray light suppression: Refractive optics and cryogenic baffles are operated at 1K

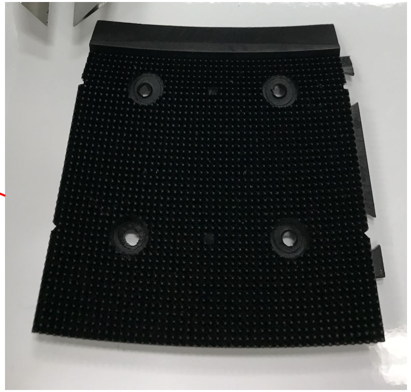
Cryogenic baffling for SATs

Skyside

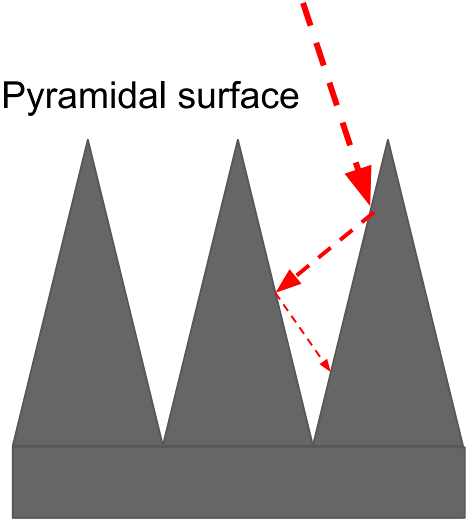


Detector

Blackbody



Pyramidal surface

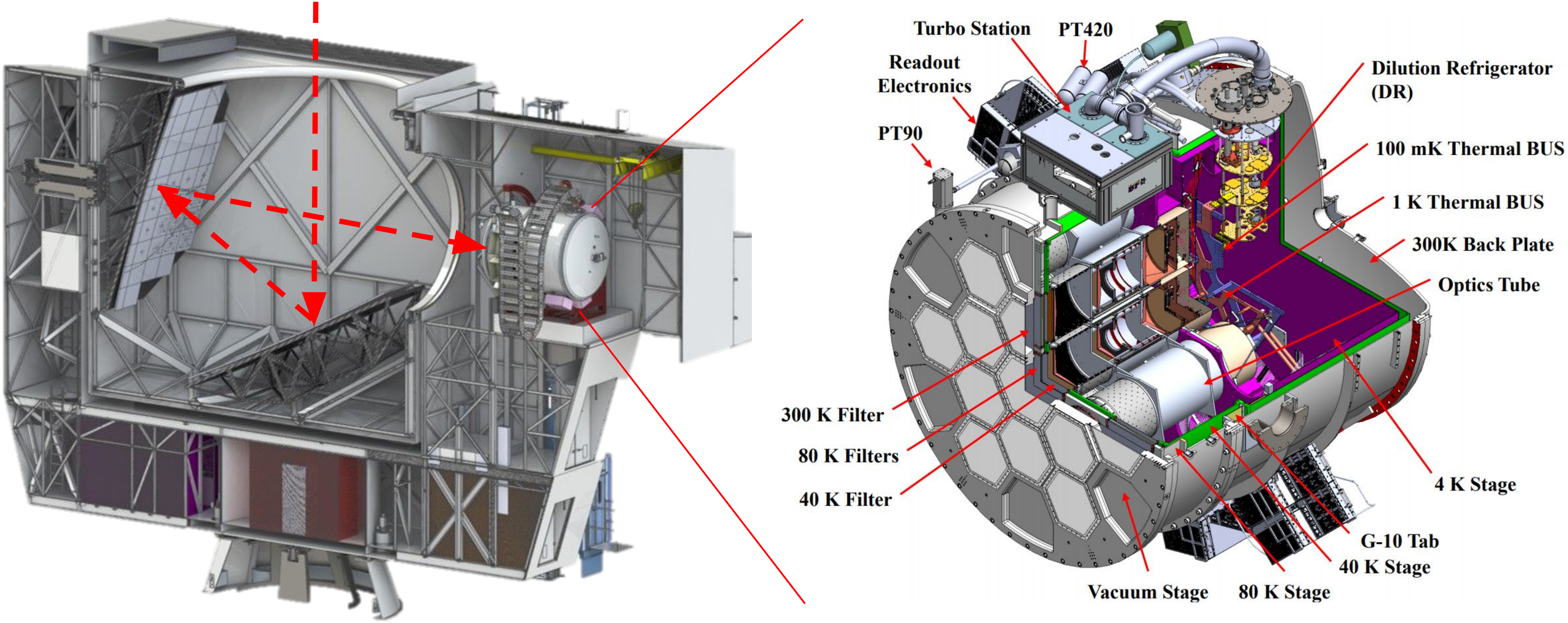


Suppress unexpected photons ”stray light”
Low reflective blackbody + baffling geometry
Realize photon noise limited telescoopes

“Real” development

Tightening >2,000 screws by hand

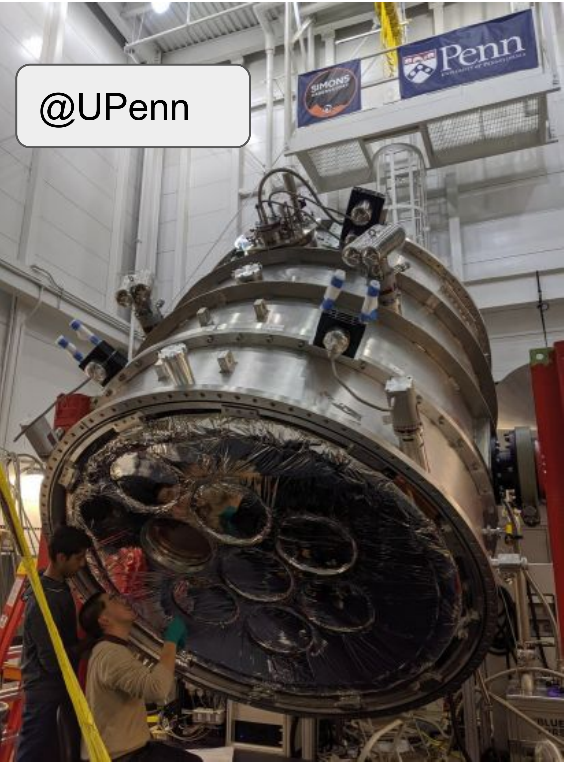
Large Aperture Telescope



High resolution: 6m aperture reflective optics with max 13 optics tubes
High statistics: 7 optics tube with total 30,000 sensors

Status of Simons Observatory

LAT reciever



@UPenn

SAT cryostat x 4

@UCSD

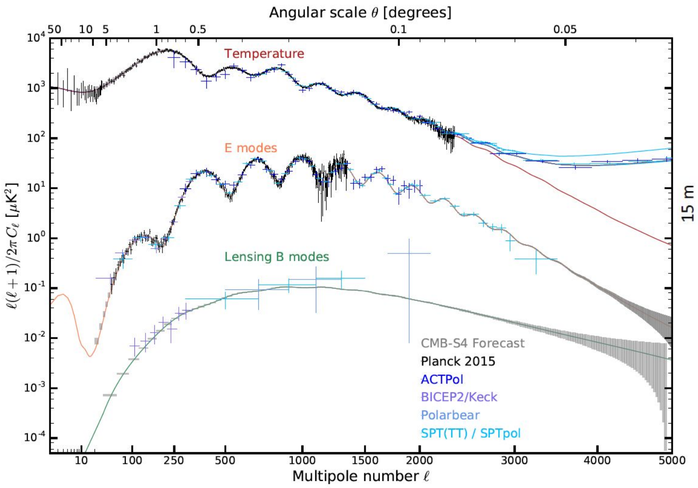
@Princeton

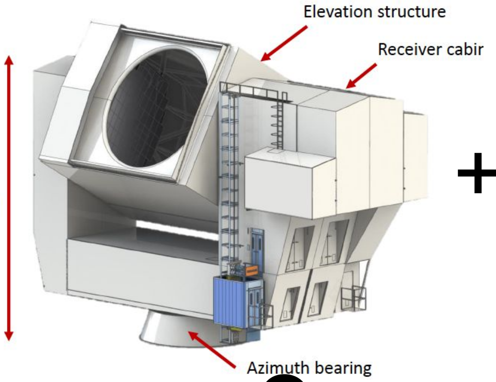
@Berkeley/LBNL

@Chicago

We are working hard for first light in early 2023!

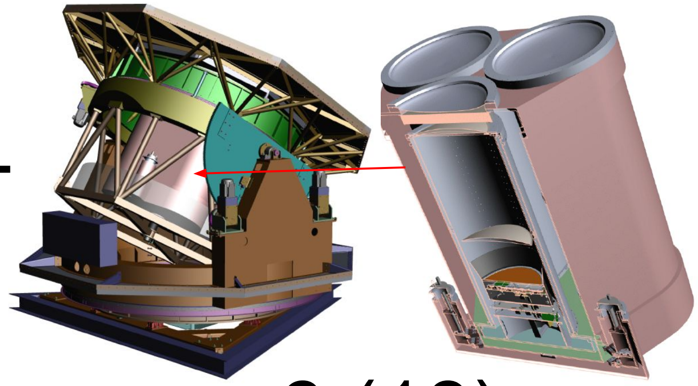
Future Prospects: CMB-S4





x 3

+



x 6 (18)

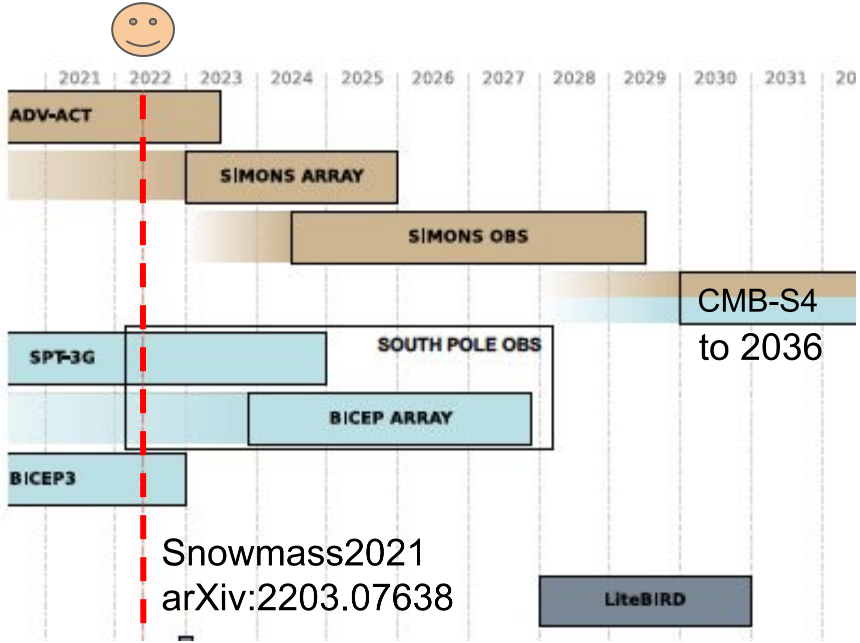
4th generation experiment by joint collaboration of SO team and BICEP/SPT team

Three SO-LAT like telescopes and 6 x 3 SAT telescopes at Pole and Chile

Total 511,302 sensors in 8 bands, l>30, σ(r)=0.0005

arXiv:1610.02743, arXiv:1706.02464, arXiv:1908.01062, arXiv:1907.04473, arXiv:2008.12619

Comparison Now and Future



	now 95% limit	BICEP 3&array	SO	CMB-S4	LB
r (=0)	<0.032	0.003	0.003	0.0005	0.001
N_{eff}	2.99±0.17	-	0.055	0.027	0.15
Σm_ν (meV)	<120	-	22	15	12

(*) Σm_ν are combined results with other experiments

arXiv:1907.08284
arXiv:1908.01062
arXiv:2203.08024
arXiv:2203.08024

CMB experiments are exponentially improved past and future

Summary

- Large angular scale B-modes are direct proof of inflation
- Neutrino mass and light relics are measured via CMB
- Latest results are given by Planck and BICEP
    - r=0.032, Neff consistent with SM, $\Sigma m_\nu < 0.12$eV
- Simons Observatory will start observation in 2023
    - target: r=0.003
- CMB-S4 and LB are planned in 202X
    - target: r=0.001
- Now and next 10 years are golden age of CMB experiments!