Constraints on primordial gravitational waves and cross-correlation between gravitational lensing from POLARBEAR data and optical / infrared survey by the Subaru HSC / the Herschel ATLAS

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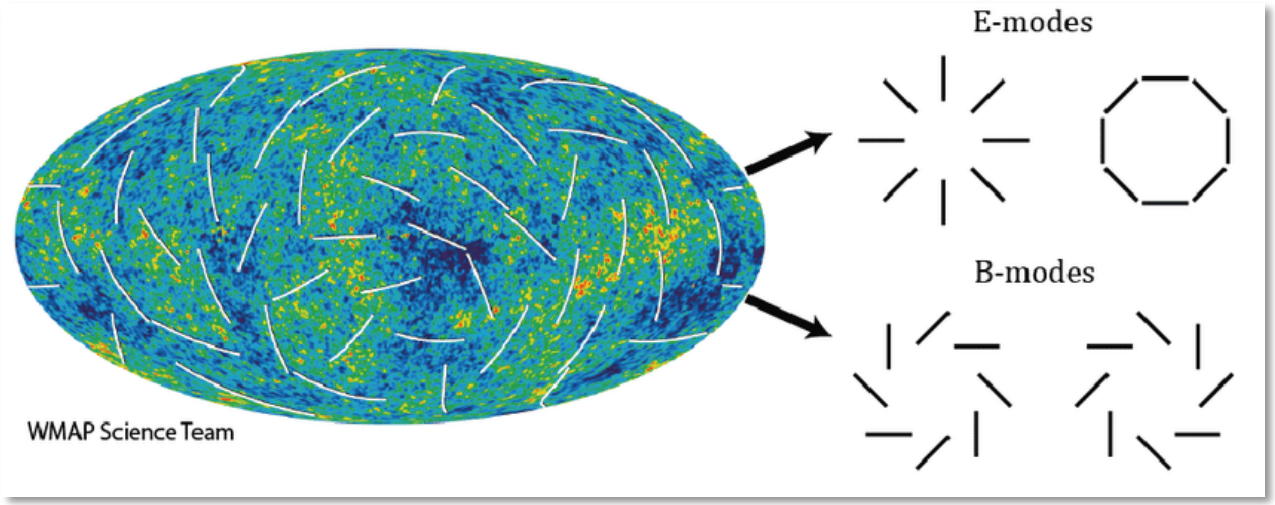
25'+5'; Tue, Aug 13, 2019

What I Want To Talk Today

- CMB Polarization & the **POLARBEAR** experiment
  - Measurement of CMB **B-mode** induced by Primordial gravitational waves (PWGs)="**Inflationary B-mode signal**"
  - Measurement of CMB **lensing B-mode signal**



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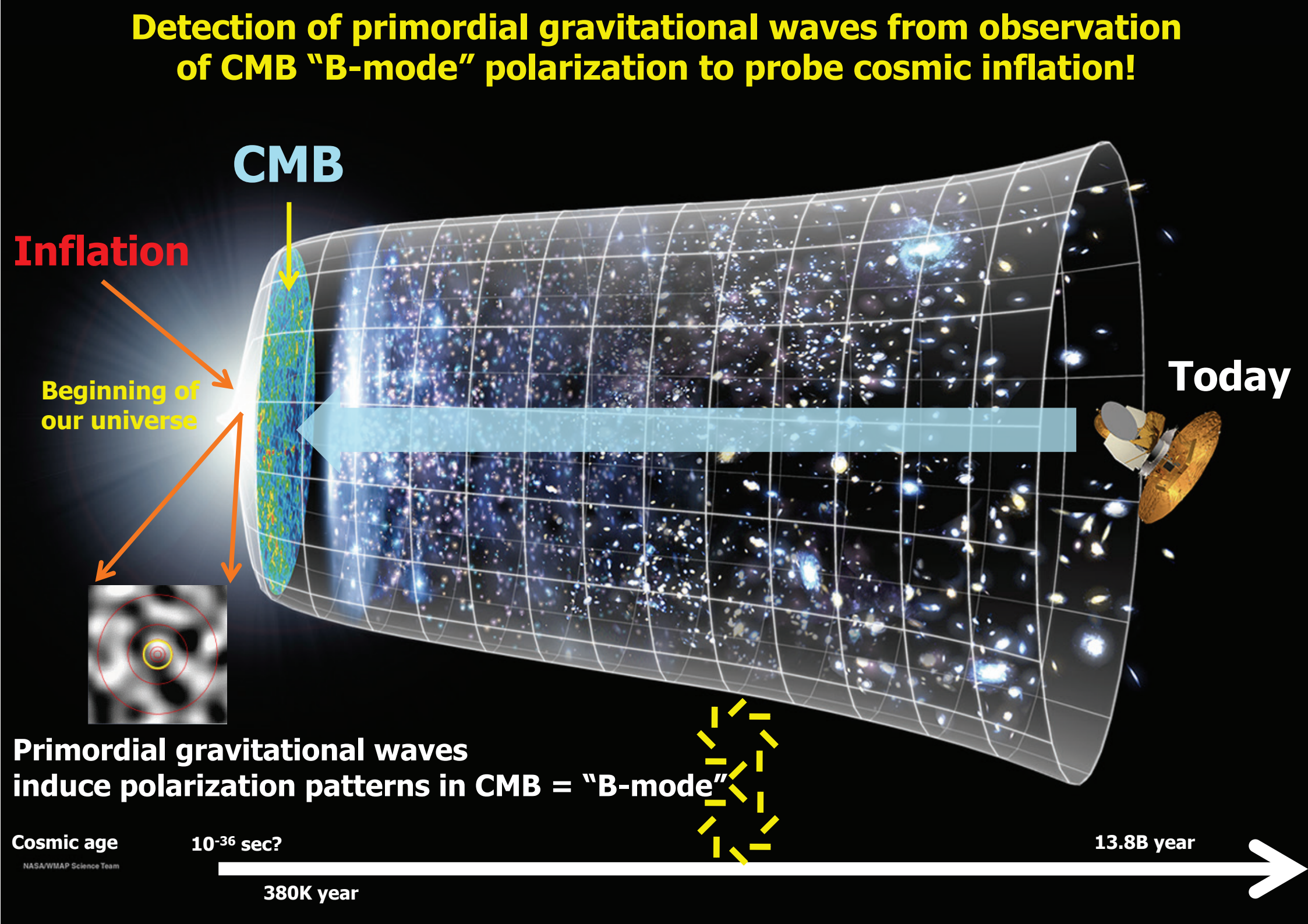
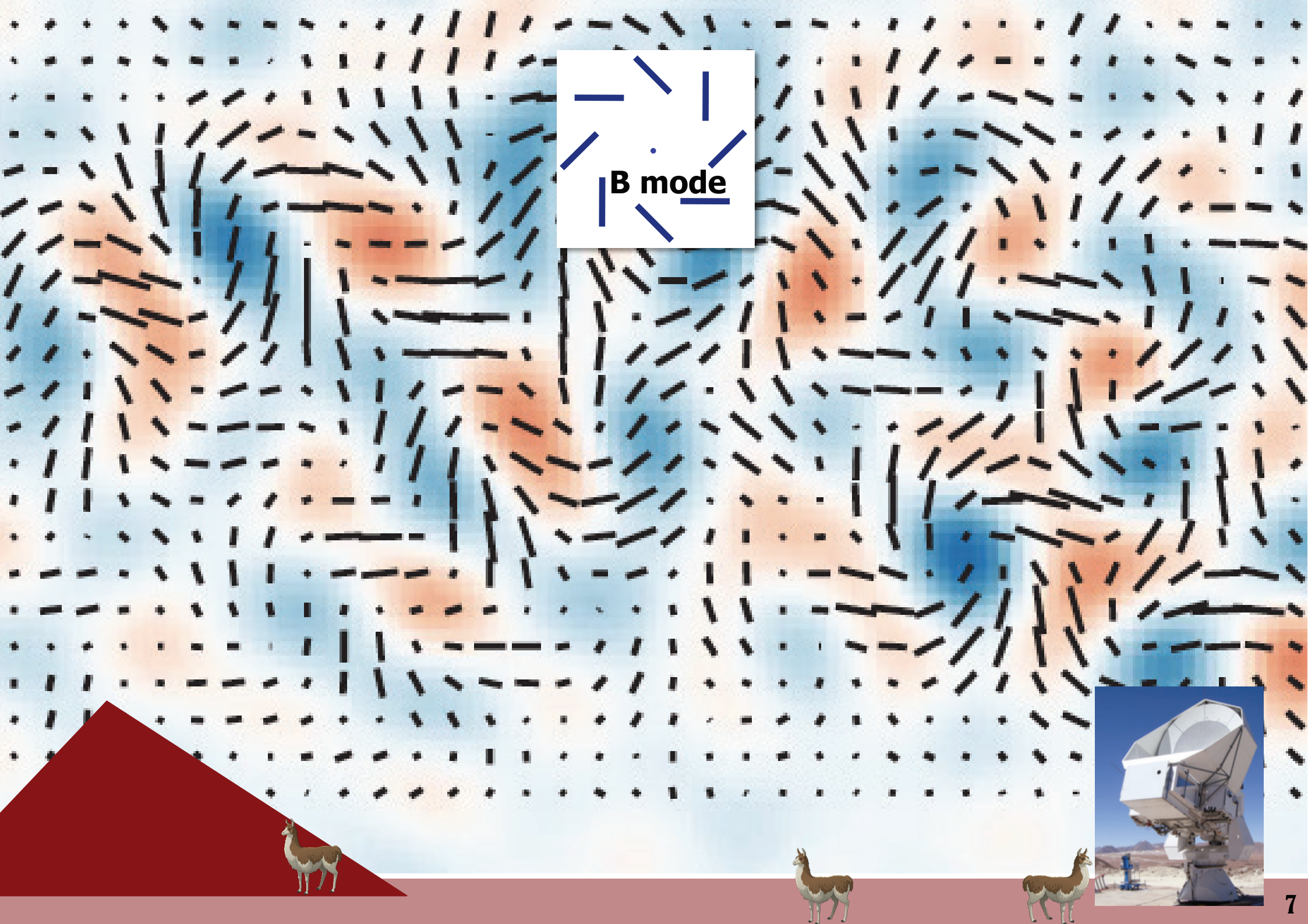
  - Measurement of CMB **lensing B-mode signal**
- Cross correlation w/ **Subaru Hyper Suprime-Cam** & **Herschel ATLAS (H-ATLAS)**
- On-going & future CMB experiments
  - **Simons Array** & **Simons Observatory**

Detection of primordial gravitational waves from observation of CMB "B-mode" polarization to probe cosmic inflation!

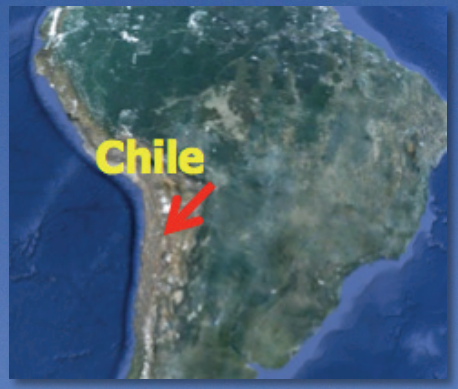


Measuring amp & angle of linear polarization on the sky


B mode

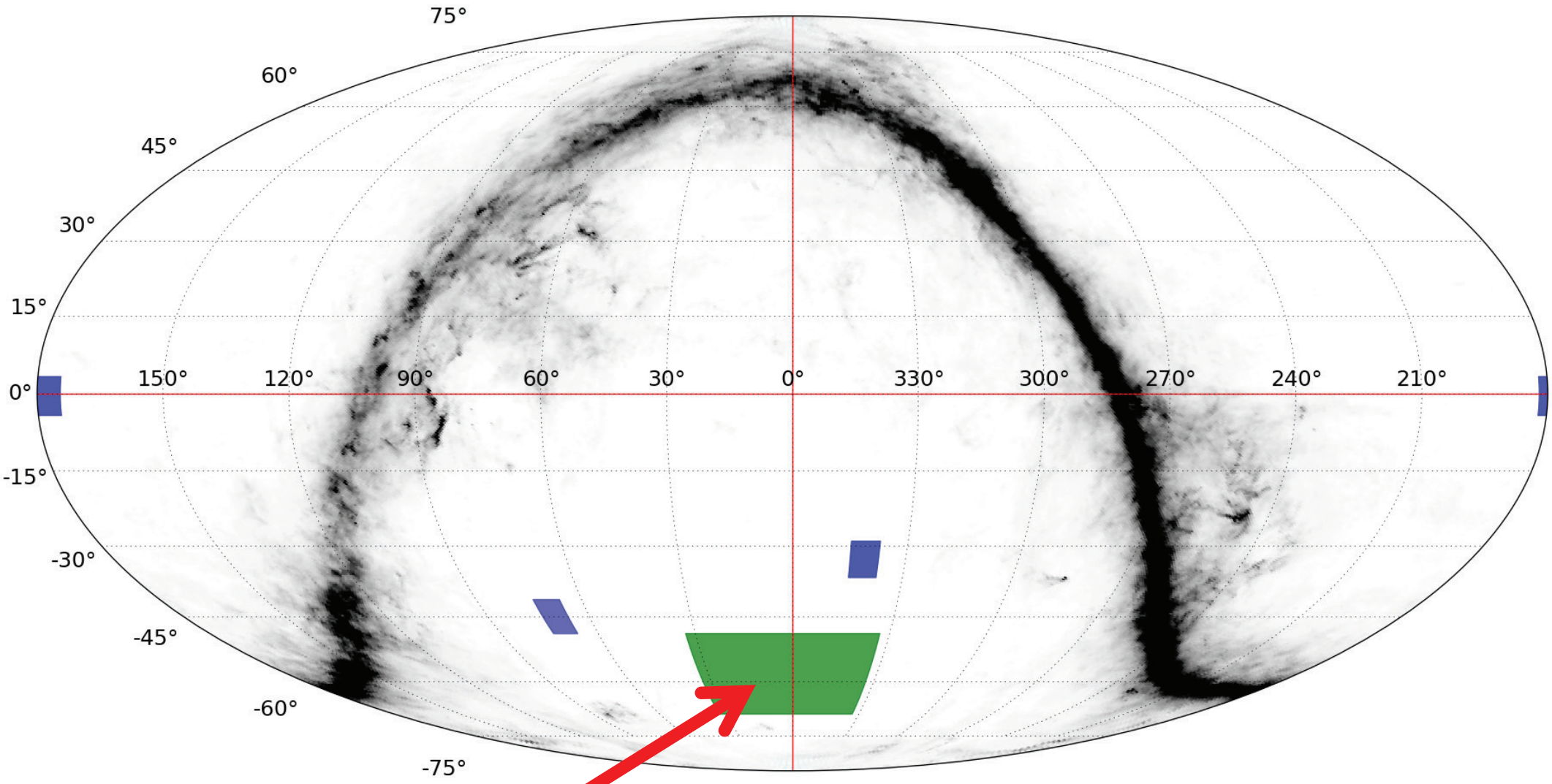
POLARBEAR since 2012 (deployed in 2011)

5,200m @ Atacama Desert, Chile



@150 GHz

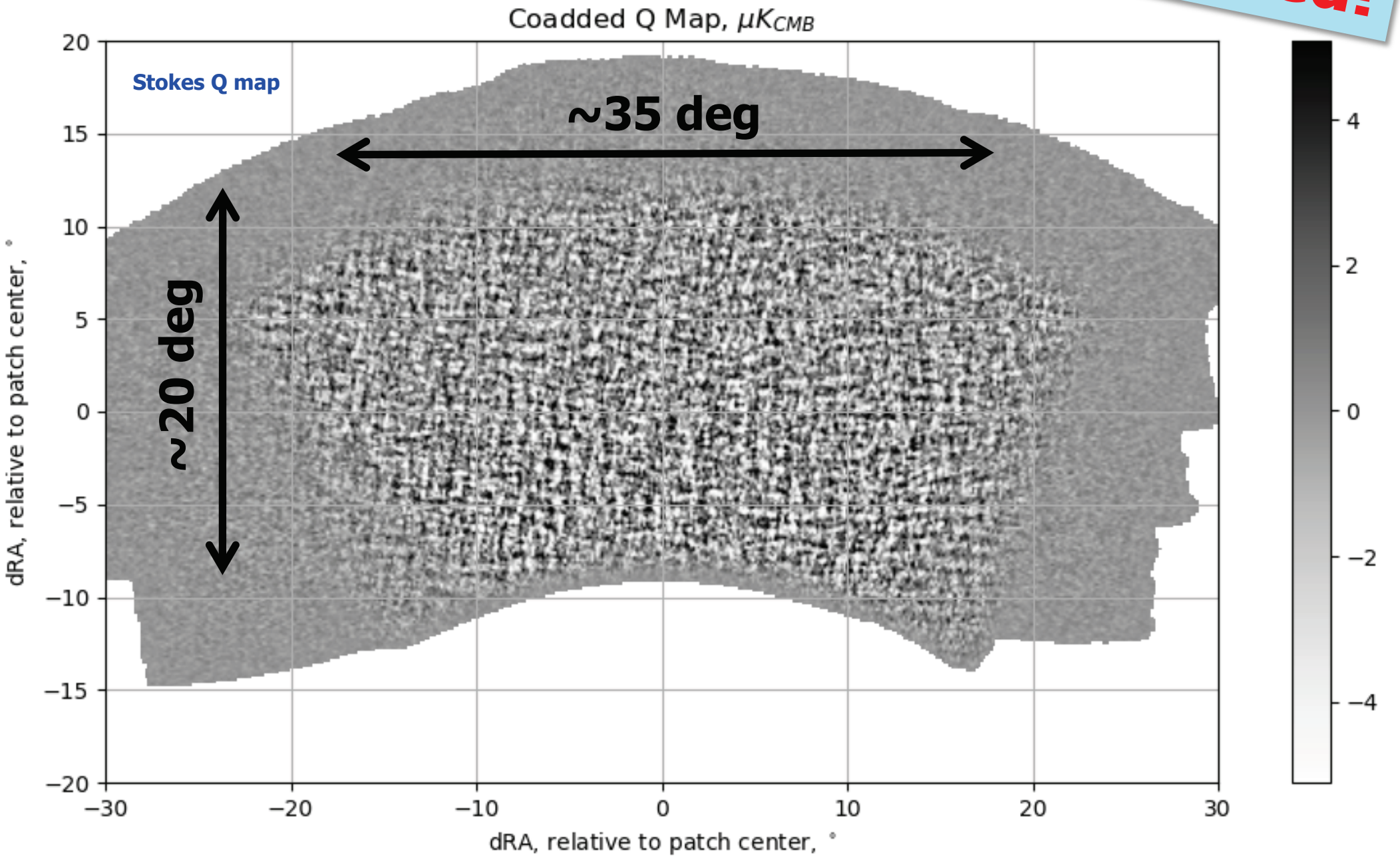
Wide Survey for Primordial Gravitational Waves (PGW)



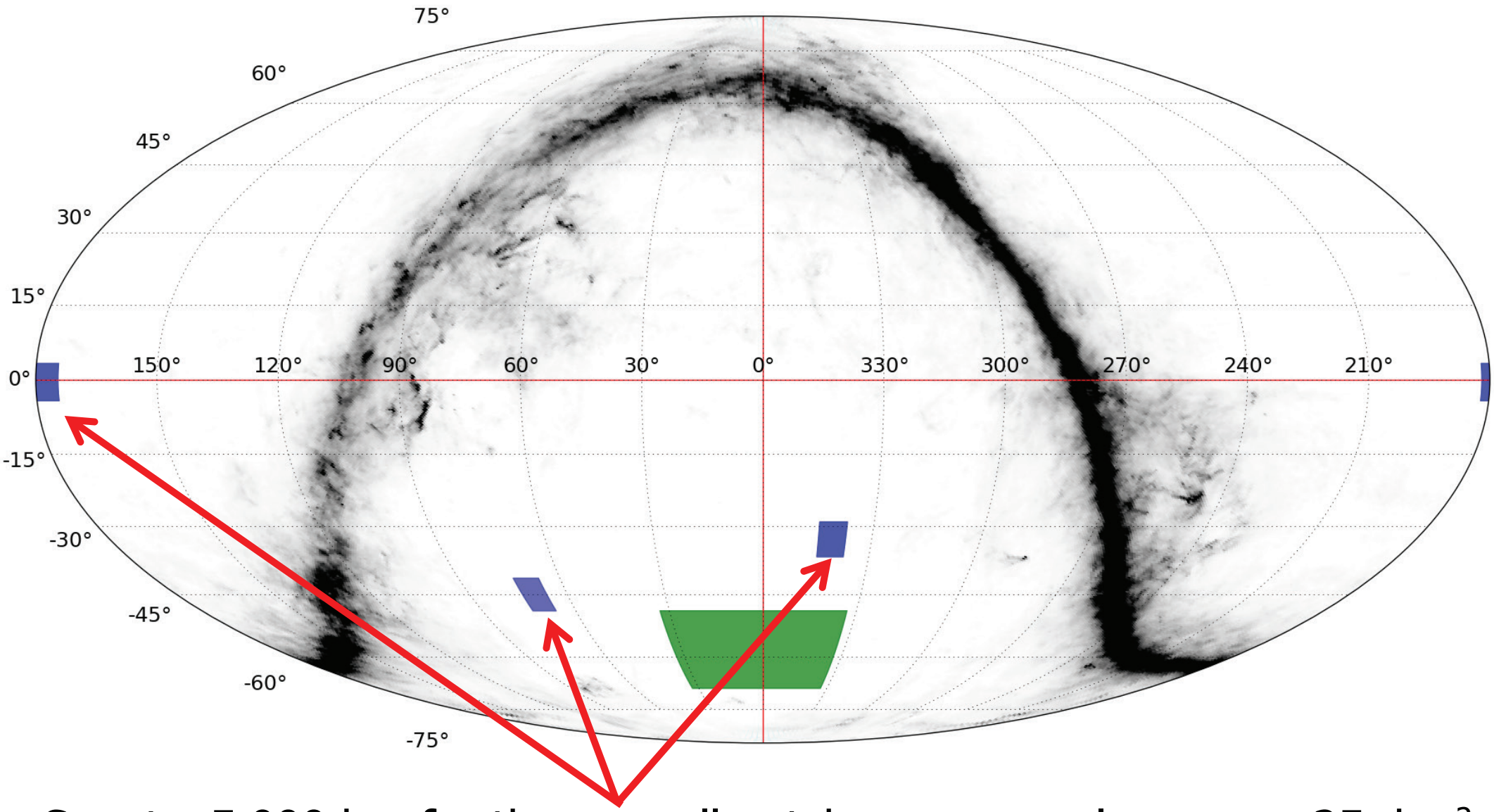
- Spent >7,000 hrs for the wide patch survey as large as a 700 deg^2 area @ the "BICEP" patch, targeting for **primordial gravitational waves**

Constraint on PGW?

Stay Tuned!



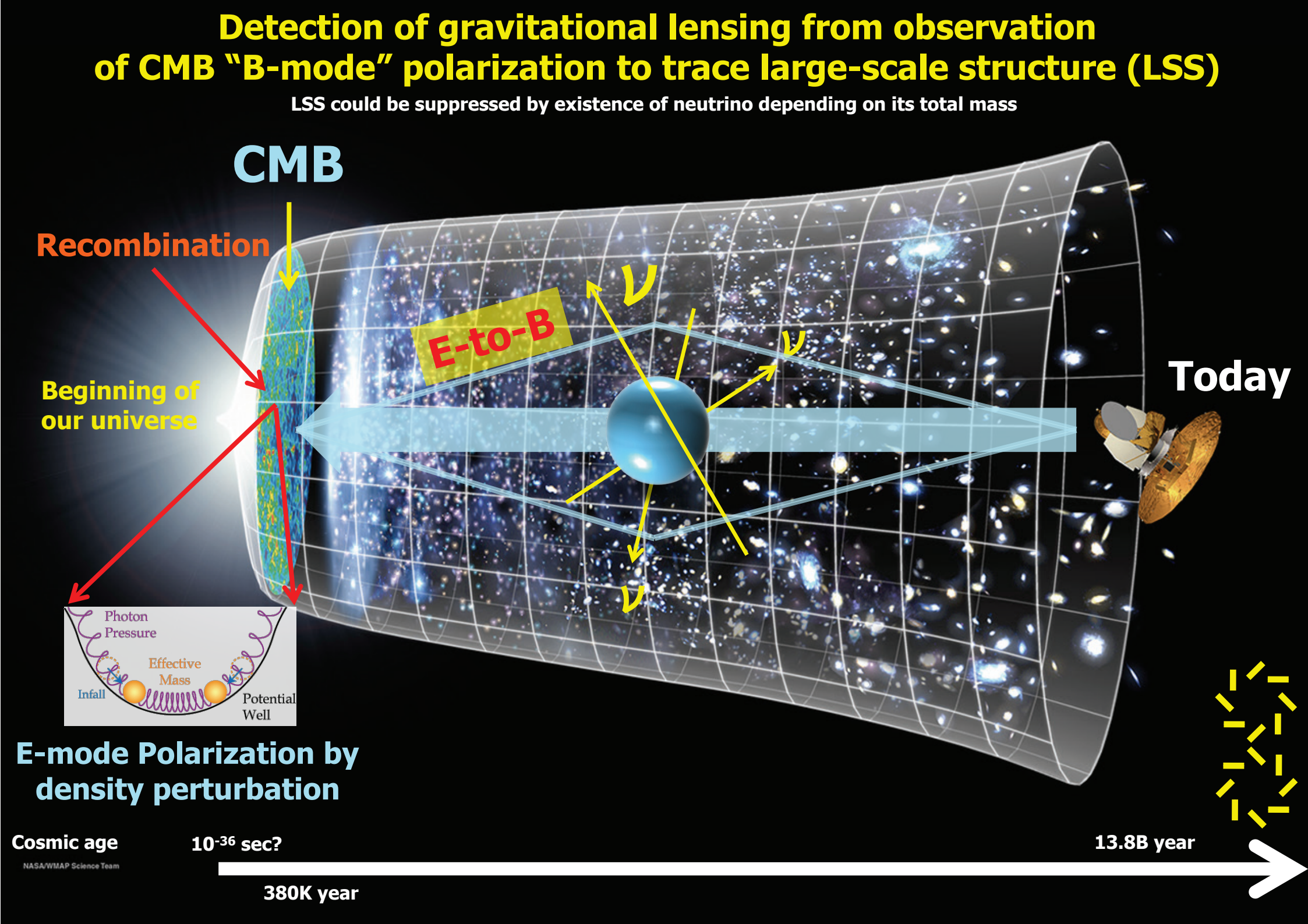
Small Patch Surveys for Gravitational Lensing



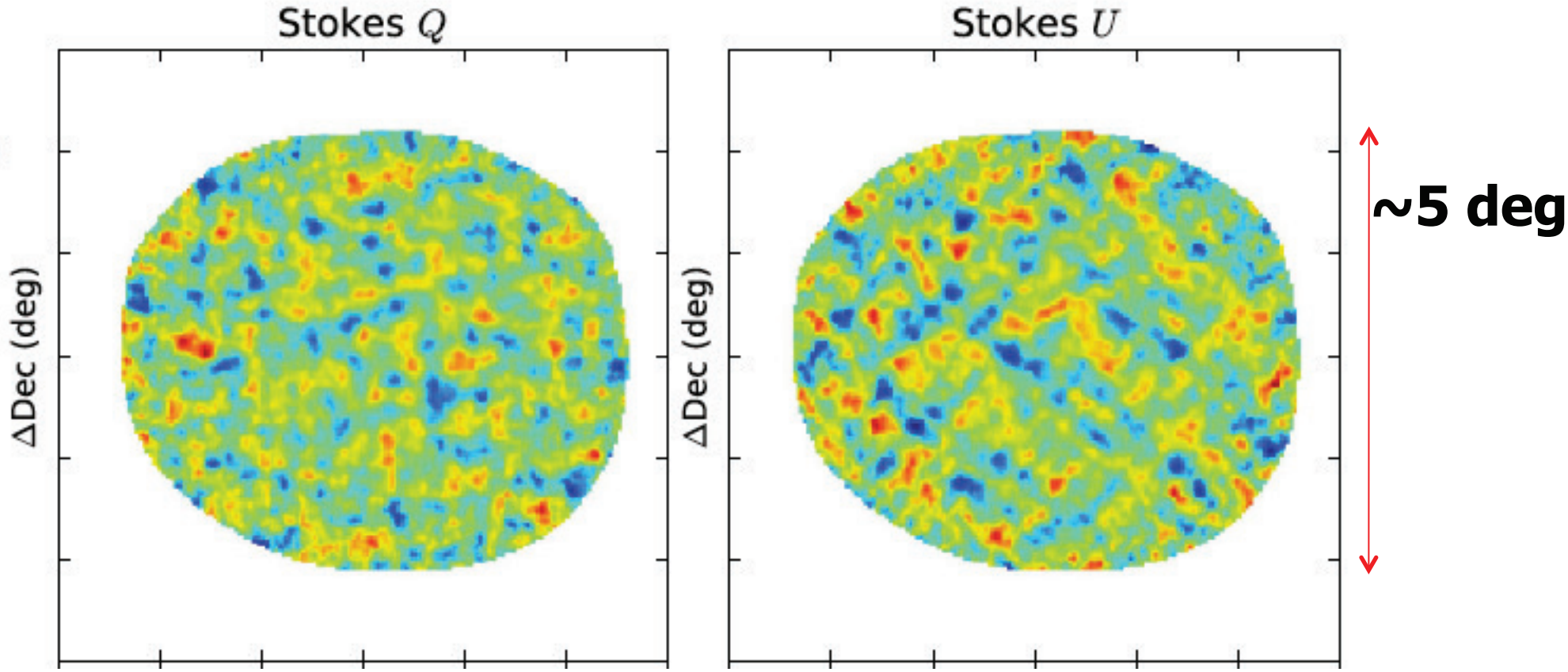
- Spent >5,000 hrs for three small patch surveys as large as a 25 deg^2 area, targeting for CMB lensing & cross-correlation w/ other surveys

Detection of gravitational lensing from observation of CMB "B-mode" polarization to trace large-scale structure (LSS)

LSS could be suppressed by existence of neutrino depending on its total mass



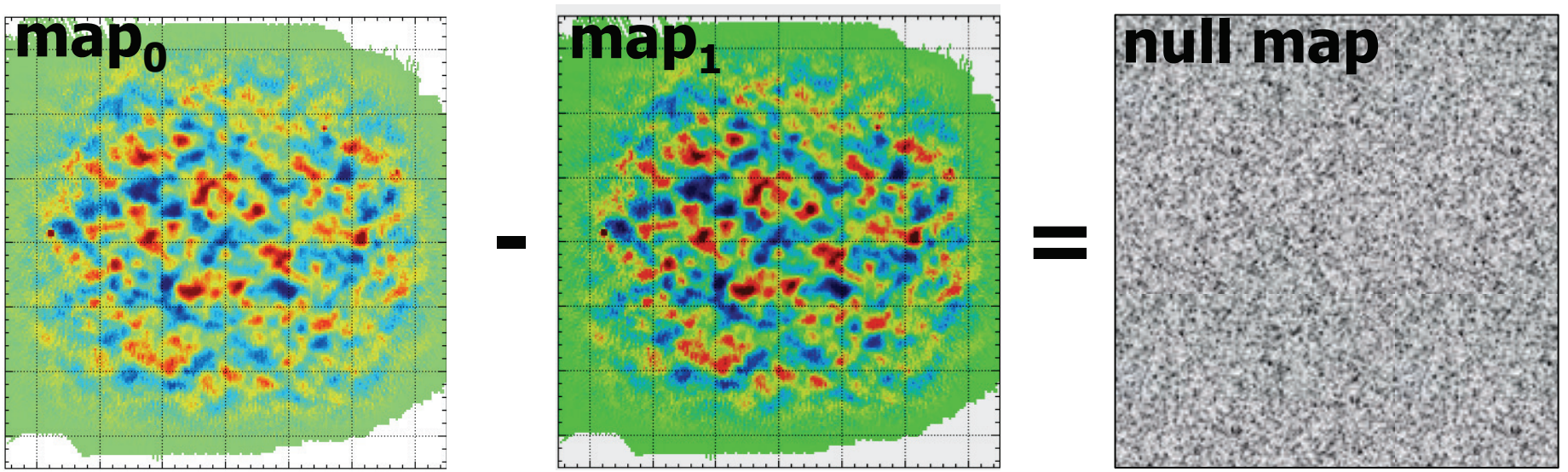
Deep Survey @ Sub-Degree Scale



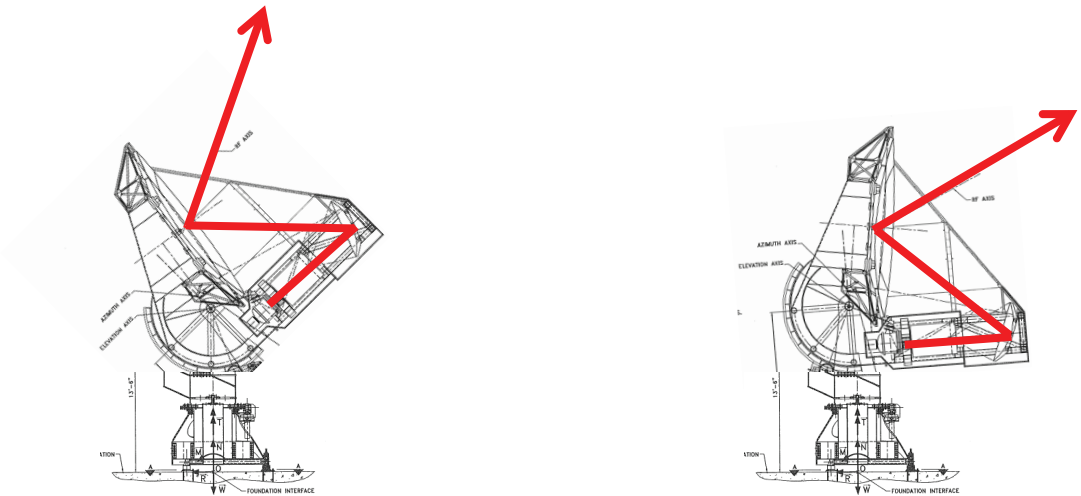
- One of the most "deepest" polarization maps
  - (deepest patch) ~5 μK-′ ~ lensing B-mode signal

Validation: "Null" Test

- Split data into two, then take the difference to check systematic
  - If no sys, it's just noise; but we would see corresponding sys if not



(CMB+$Noise_1$) - (CMB+$Noise_2$) = Noise



e.g. high elevation vs. low elevation

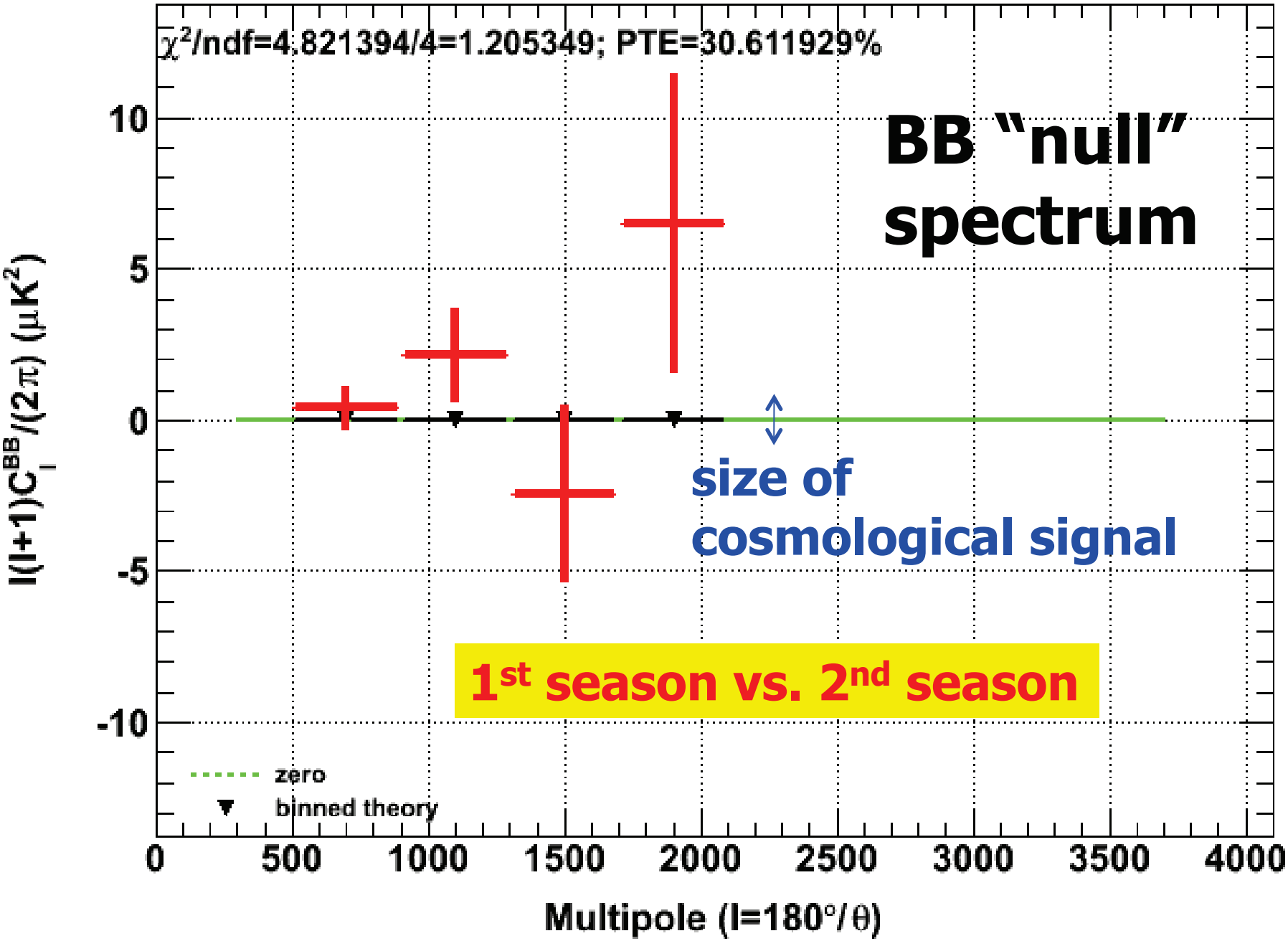
Validation: 12 “Null” Tests

- 1st_season_vs_2nd_season
- 1st_half_vs_2nd_half
- high_gain_ces_vs_low_gain_ces
- **high_elevation_vs_low_elevation**
- rising_vs_setting
- high_pwv_vs_low_pwv
- far_from_sun_vs_close_to_sun
- far_from_moon_vs_close_to_moon
- sun_above_horizon_vs_sun_below_horizon
- left_going_scan_vs_right_going_scan
- q_pixels_vs_u_pixels
- left_side_pixels_vs_right_side_pixels

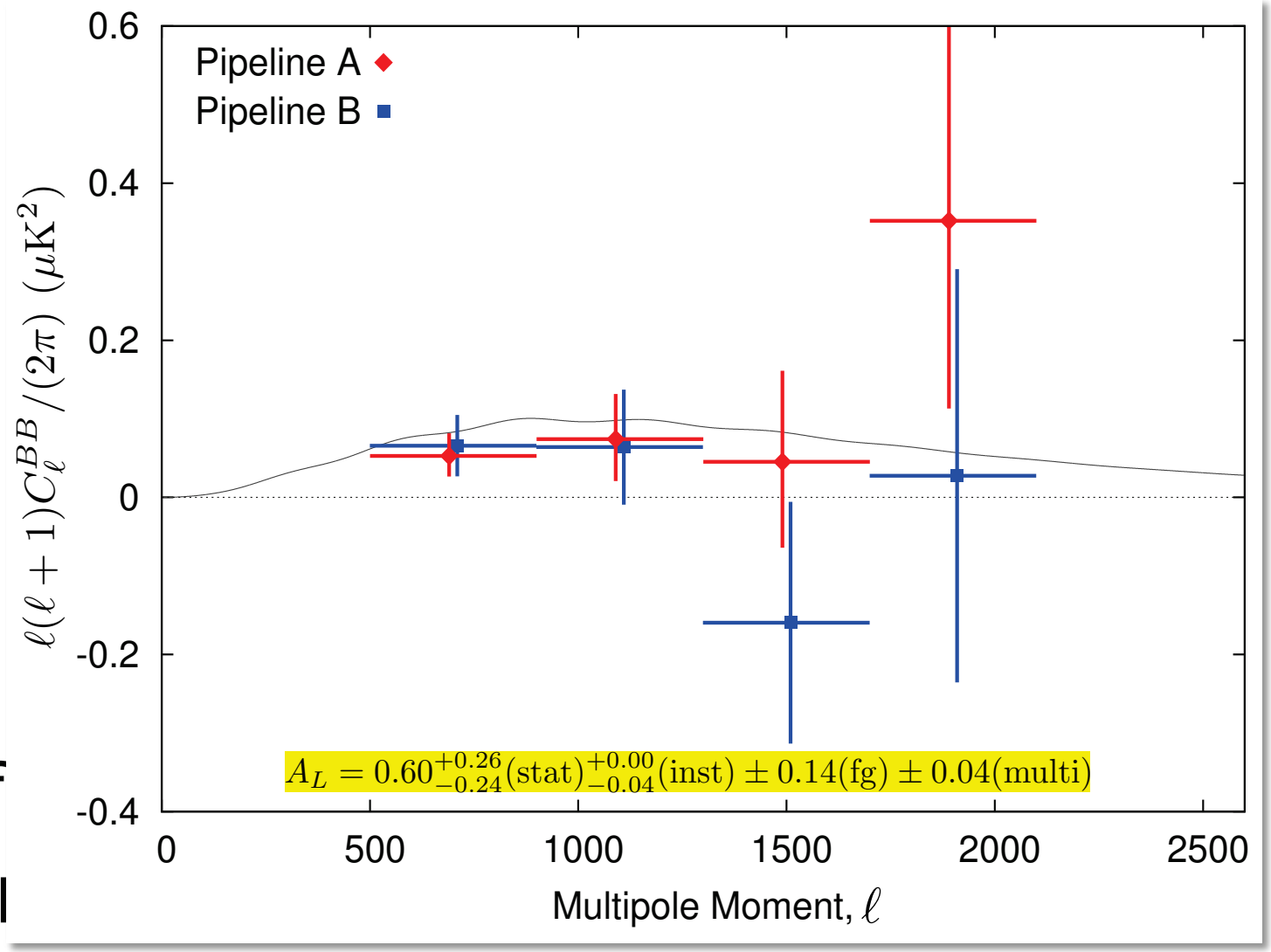
9 different combinations of CES’s

2 different splits of FP & L/R scans

Null Spectrum w/ No Problem



Deep Survey @ Sub-Degree Scale

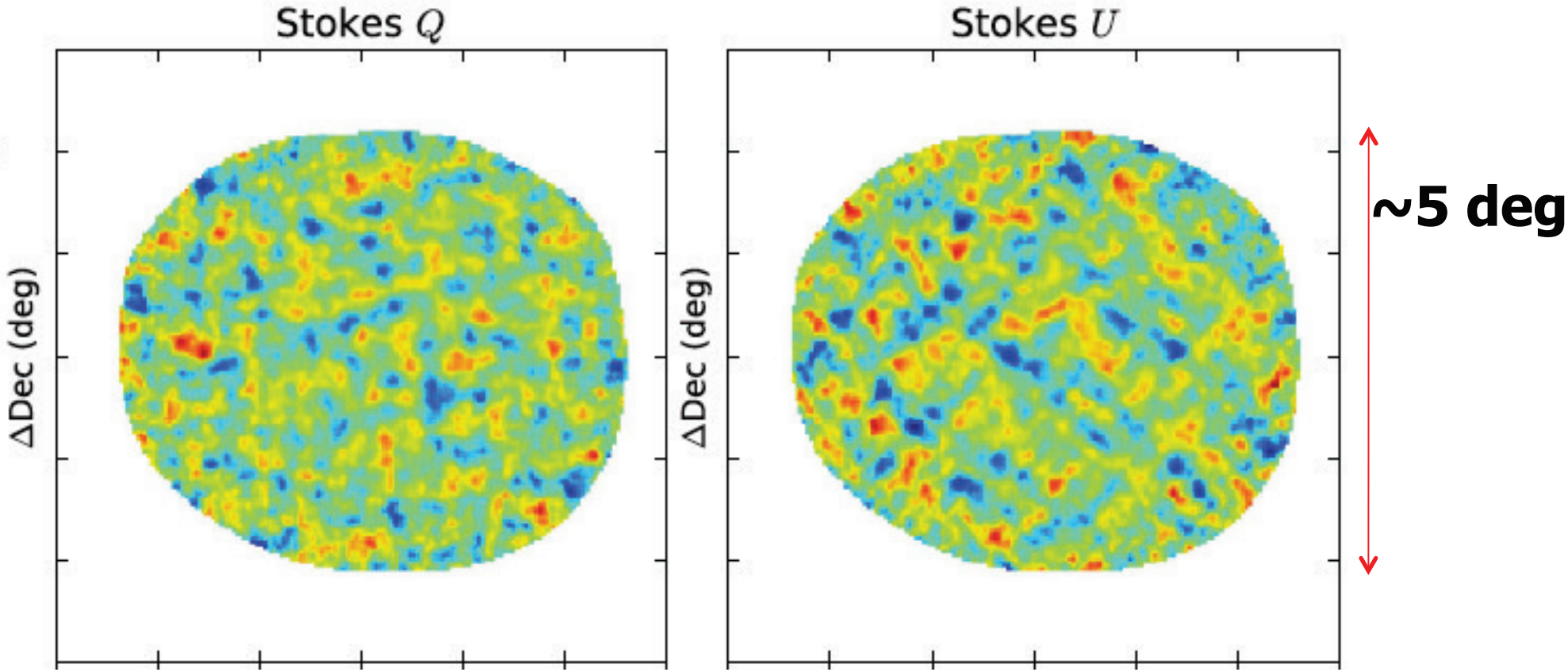


- One of
  - (deep

finally 3.1σ

- First measurement & improvement of BB (2014 & 2017)
  - Achieved dedicated systematic control by null test **before unblinding (blind analysis)**

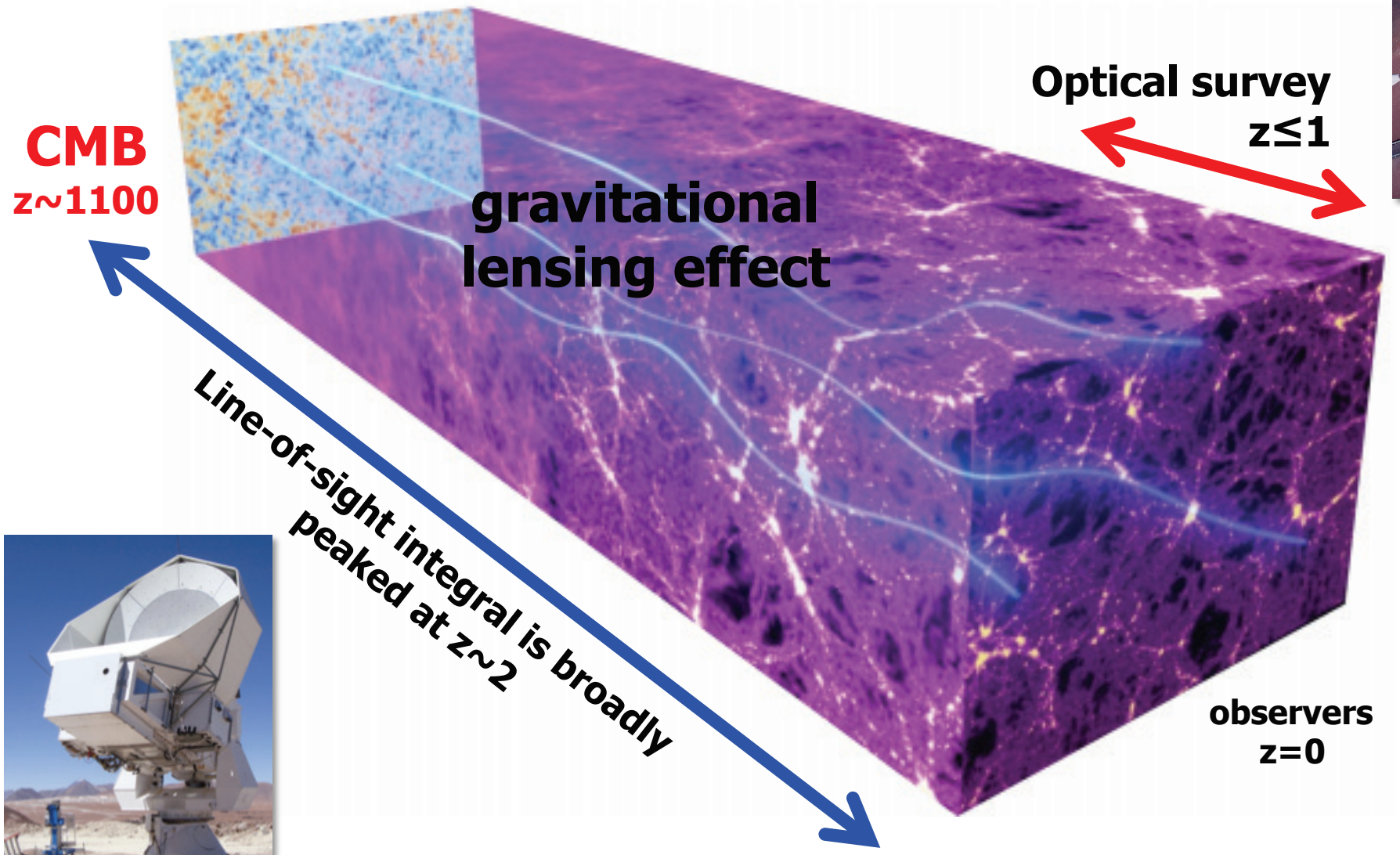
Deep Survey @ Sub-Degree Scale



- One of the most "deepest" polarization maps
  - (deepest patch) ~5 μK-′ ~ lensing B-mode signal

Already as sensitive as a future survey by next generation experiments, e.g. Simons Observatory →Important demonstration of "auto" & "cross" spectrum measurement for neutrino masses & dark energy

Cross Correlation BTW CMB & Optical Surv

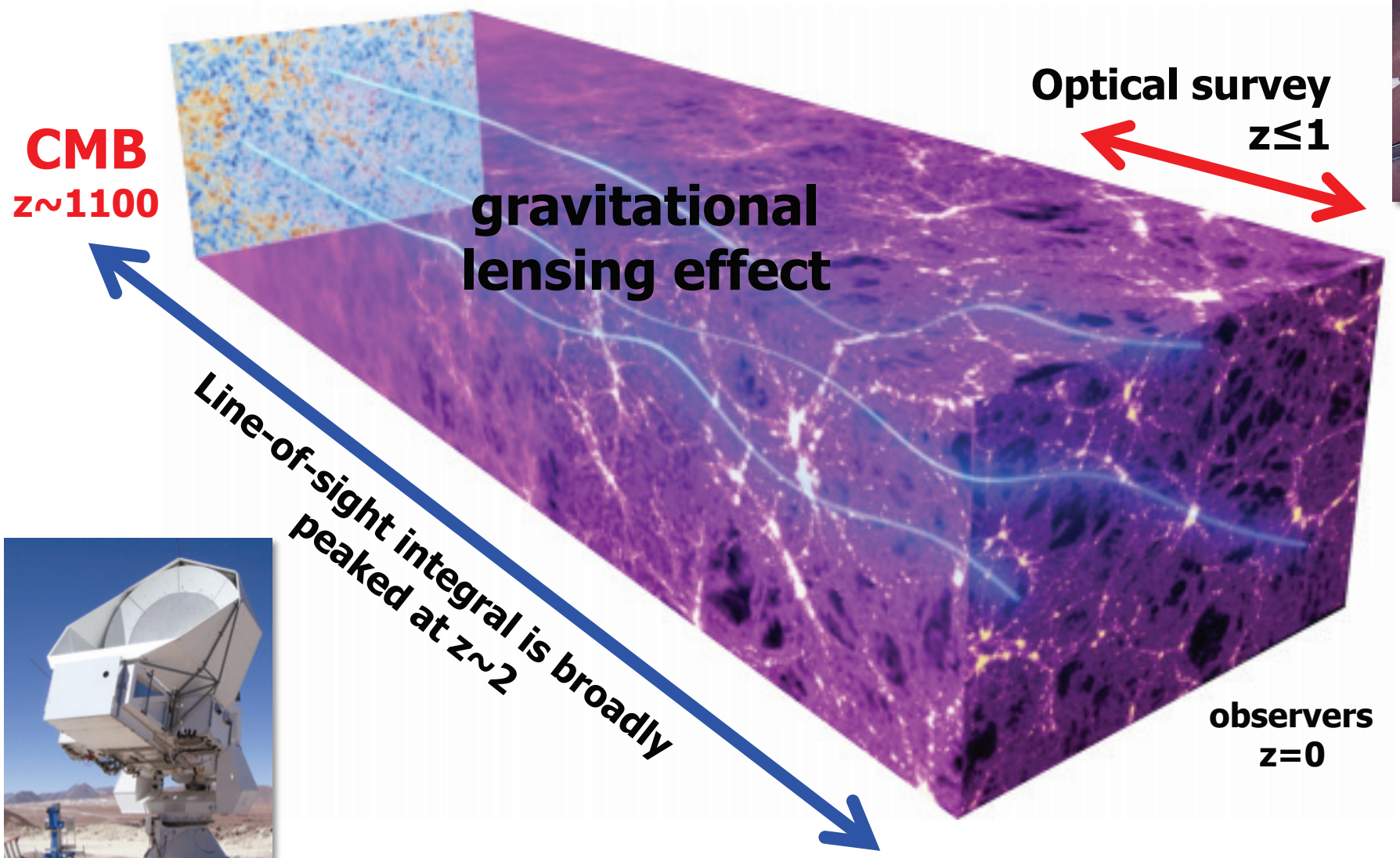


via lensing B mode

- CMB lensing traces large-scale structure (broadly peaked @ z~2)
- Optical survey traces it @ lower redshift (z≤1)

via lensing shear

Cross Correlation BTW CMB & Optical Surv

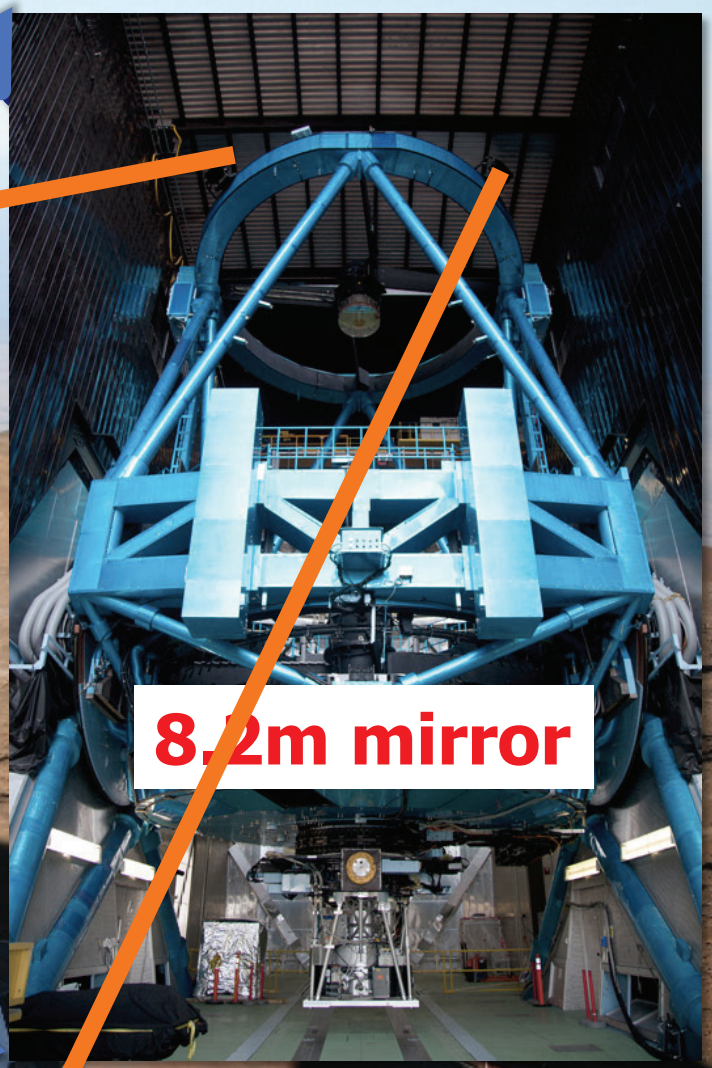


- Cross correlation can be cosmic **tomography**, which must be useful to understand properties of dark energy & gravity theory through cosmic evolution
- *Cross-correlation can be robust against instrumental & astronomical systematic*

Subaru Hyper Suprime-Cam (HSC)

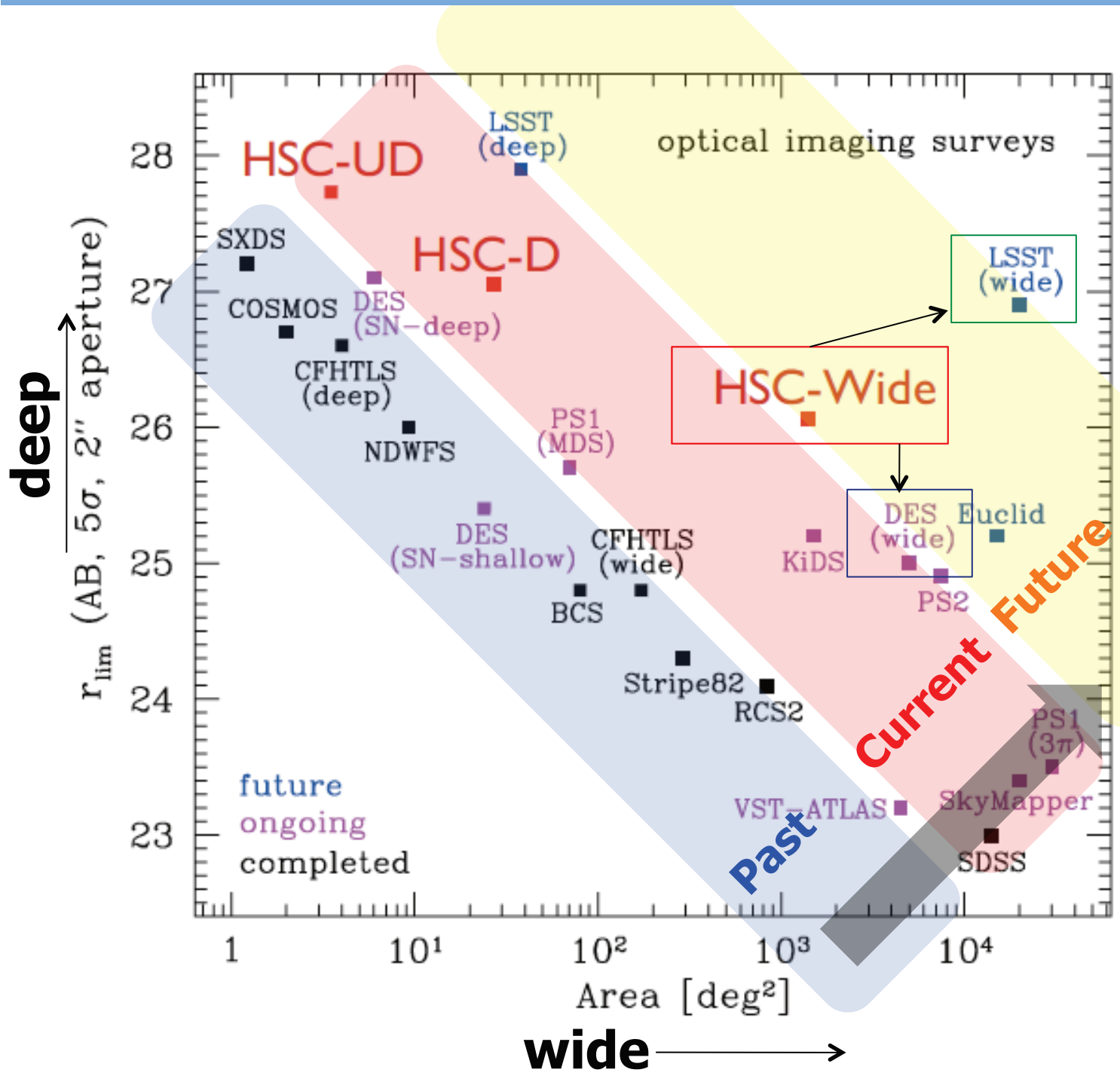
Subaru telescope (すばる望遠鏡) is located @
Summit of Mauna Kea, Hawaii Island (4200m) since 1999

Subaru Hyper Suprime-



Hyper Suprime-Cam (HSC) @ prime focus
w/ FoV~1.8 deg² since 2013

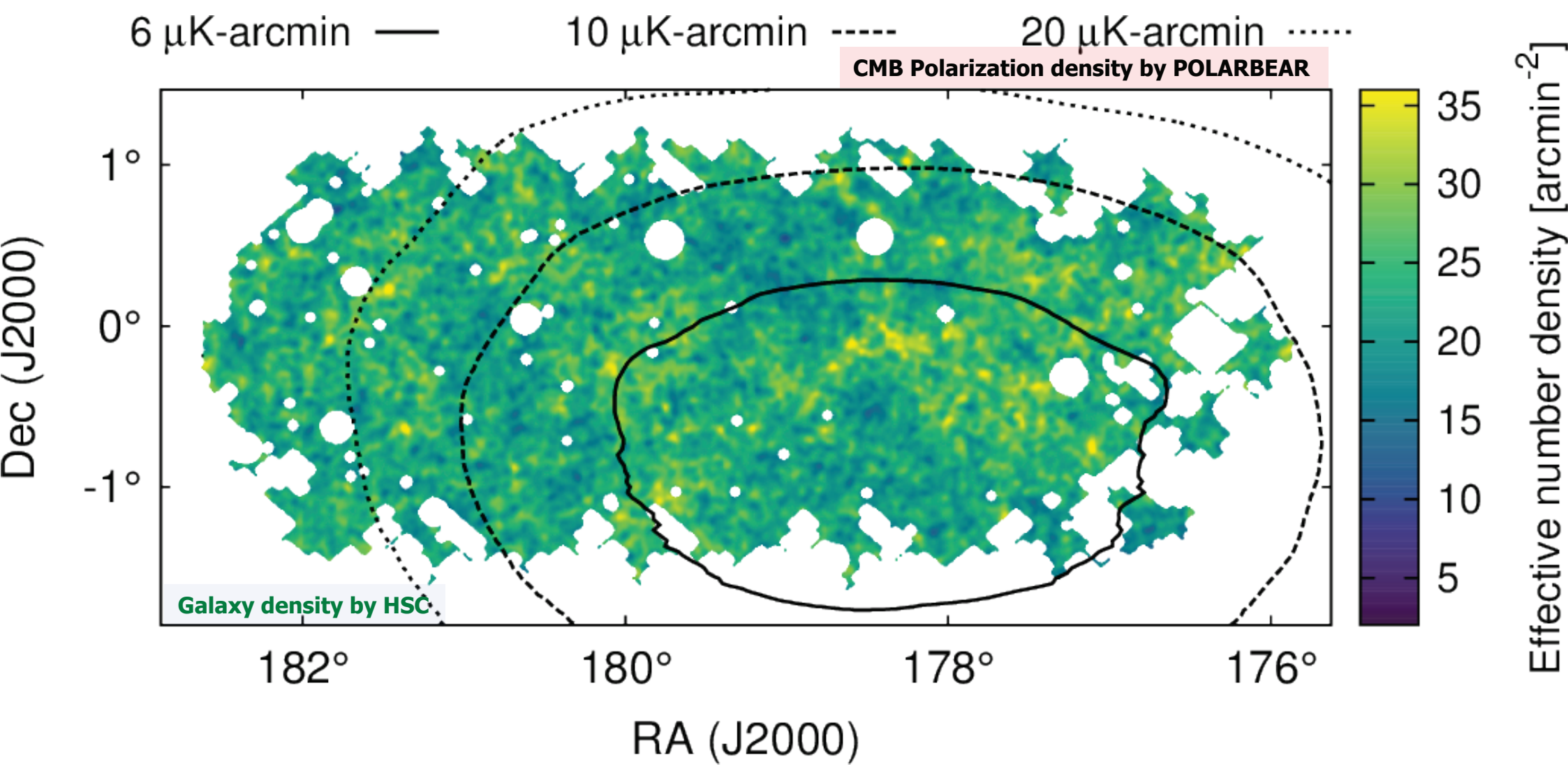
Performance of HSC-Wide Survey by Subaru Strategic Program



- **HSC-wide** survey is deeper than **DES-wide** survey, providing one of the deepest maps to date
- Can be seen as a **precursor** of the Large Synoptic Survey Telescope (**LSST**)
- PB is the deepest polarization CMB maps ever @ sub-degree scale

Must be an important demonstration for future (e.g. Simons Obs. x LSST)

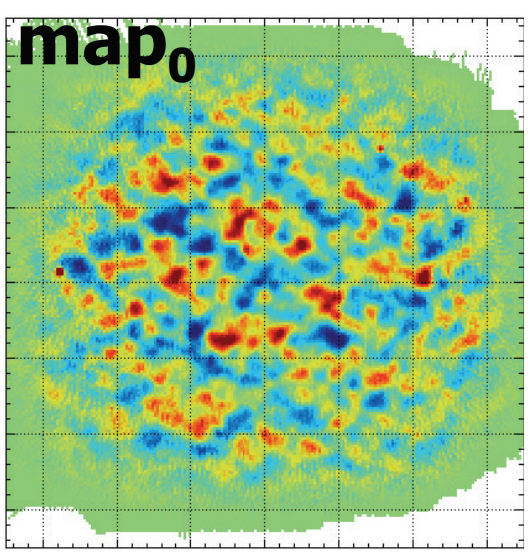
Overlap BTW POLARBEAR Survey & HSC Survey



- The overlepping area is 11 deg^2 (<11μK-′)
  - PB (RA12 field): ~6μK-′ & HSC (WIDE12H): ~23 amin^{-2} (z_{mean}=1)

Validation: CMB "Null" × HSC Test

- Split CMB data into two, take the difference to check systematic
  - If no sys, it's just noise; but we would see corresponding sys if not



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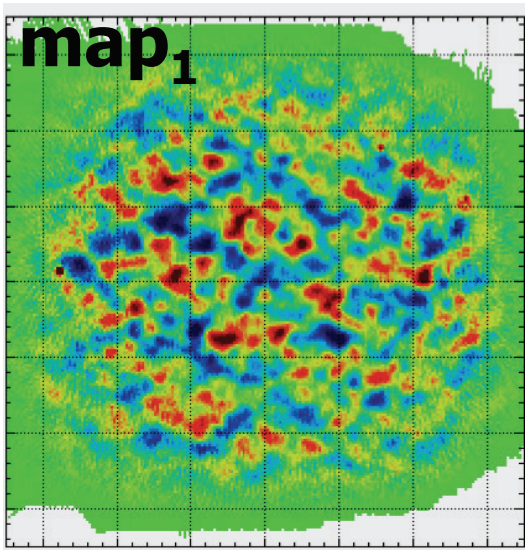
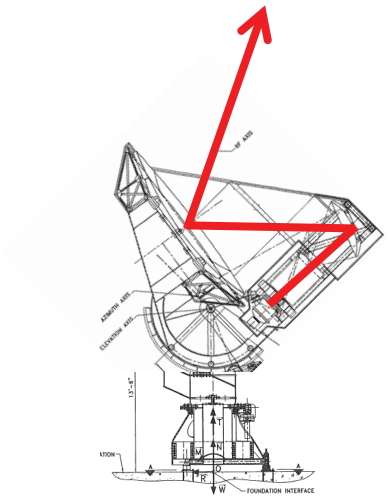
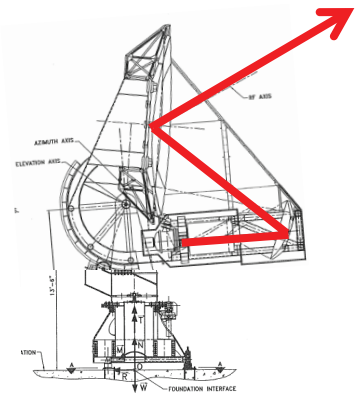


=

× Shear

(CMB+Noise$_1$) - (CMB+Noise$_2$) = Noise

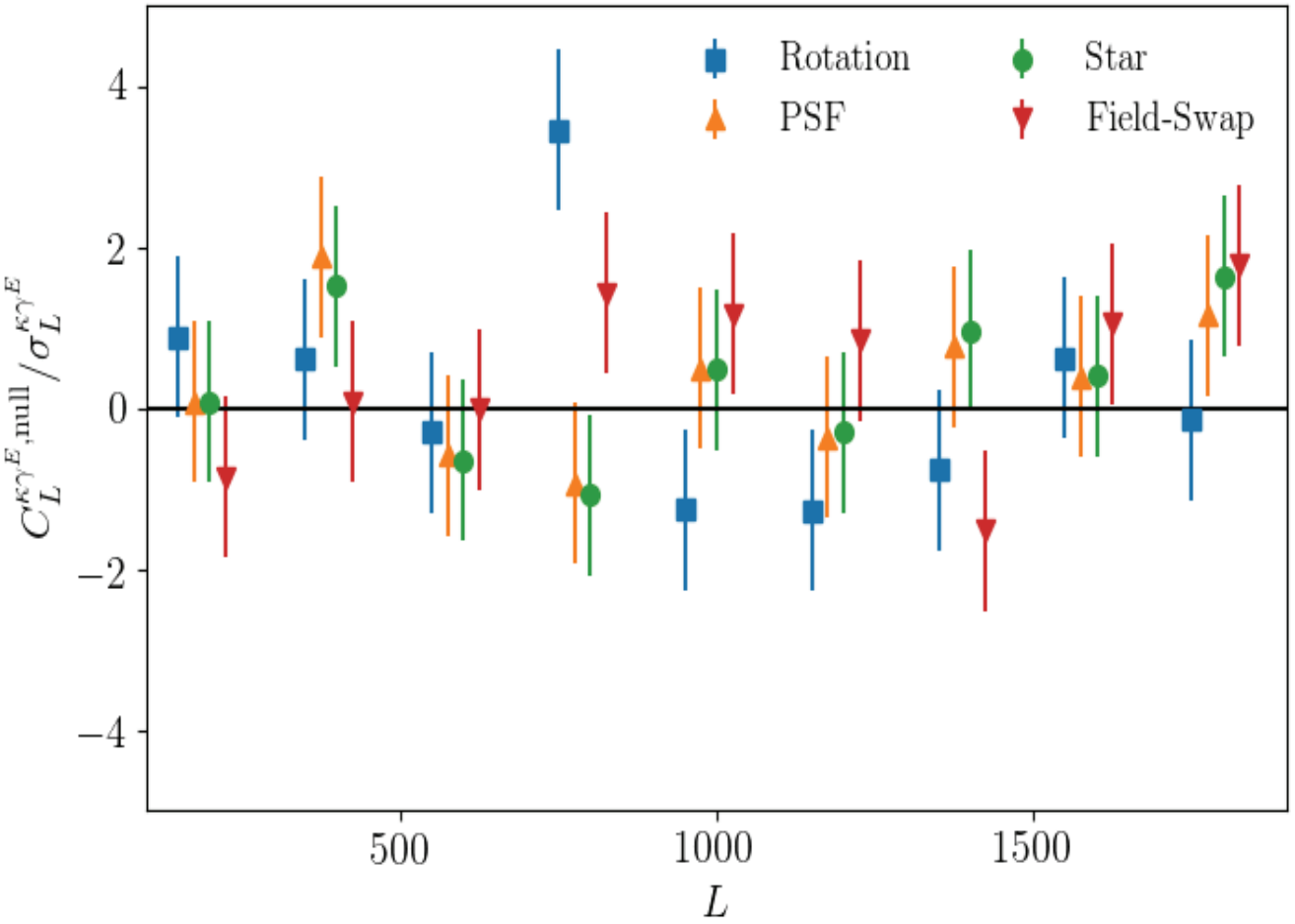




e.g. high elevation vs. low elevation

Validation: HSC Shear "Null" Test

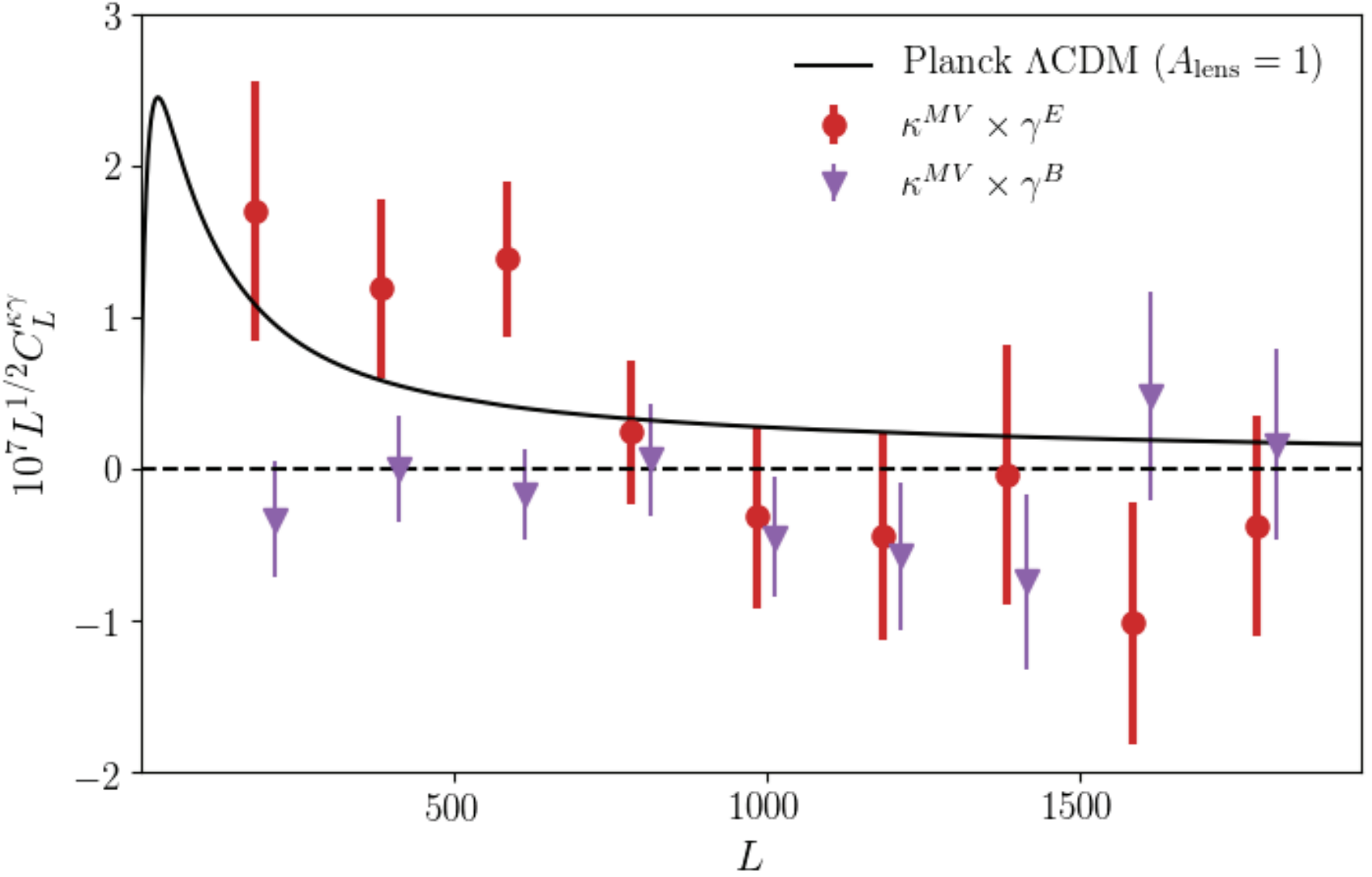
Correlation of CMB w/ following **shear null maps**



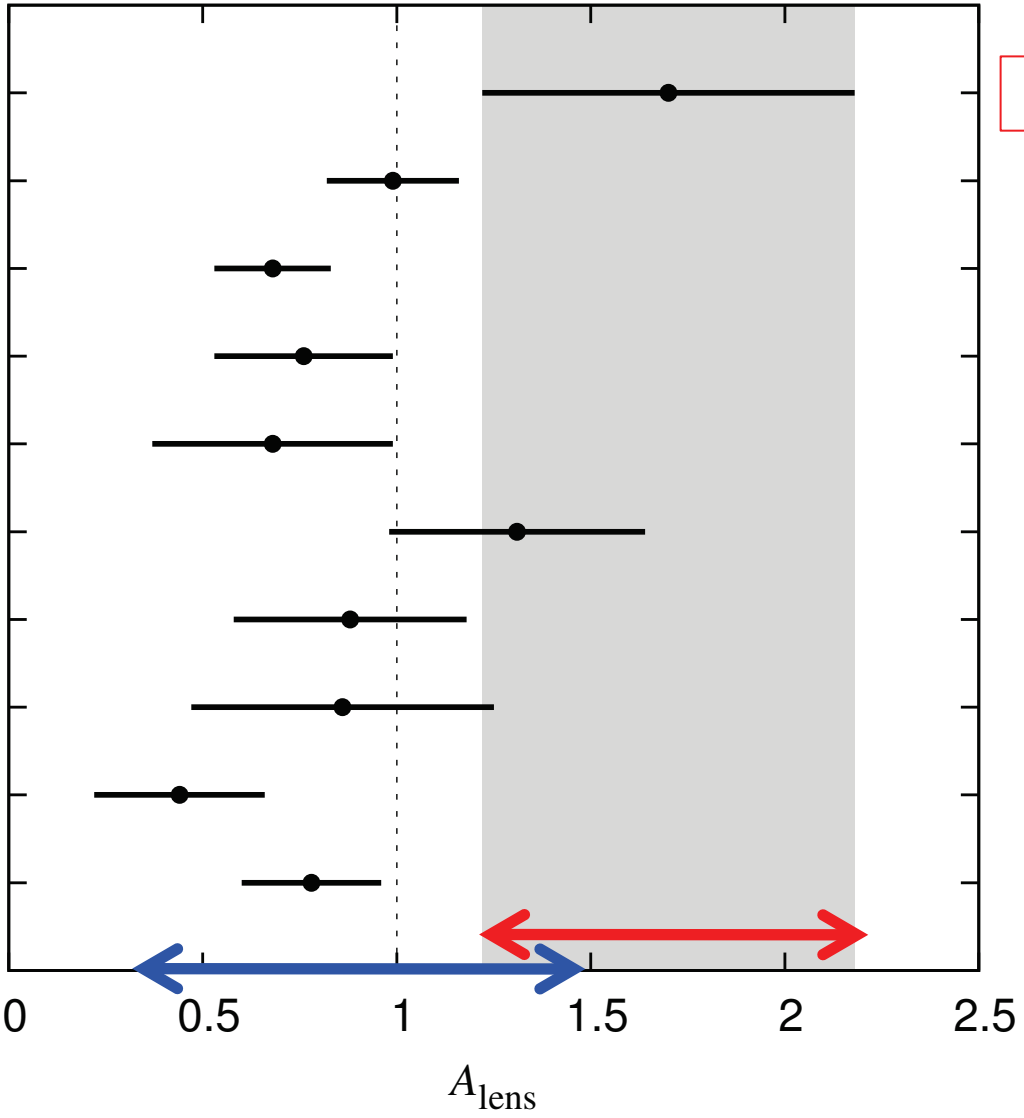
- a map randomly rotated ellipticities of galaxies (**Rotation**)
- a map from ellipticities of starts for reconstructing PSF (**PSF**)
- a map from PSF reconstructed at star position (**Star**)
- a shear map measured in another field (**Field-Swap**)

After several iterations,
finally found there is no systematic bias
Such "blind analysis" is useful/necessary to avoid "human bias"

Result



- Constraint amp. to $A_{\rm lens}$=**1.70±0.48**, rejecting the null hypothesis at **3.5σ** ($A_{\rm lens}$ is normalized to Planck 2018)
  - This is the first measurement achieved by polarization-dominated CMB lensing



pol

POLARBEAR Polarization × HSC (this work)

SPT & Planck × DES Y1 (Omori et al. 2018)

Planck × KiDS-450 (Harnois-Déraps et al. 2017)

Planck × SDSS (Singh et al. 2017)

Planck × CFHTLenS (Harnois-Déraps et al. 2016)

Planck × RCSLenS (Harnois-Déraps et al. 2016)

SPT × DES SV (Kirk et al. 2016)

Planck × DES SV (Kirk et al. 2016)

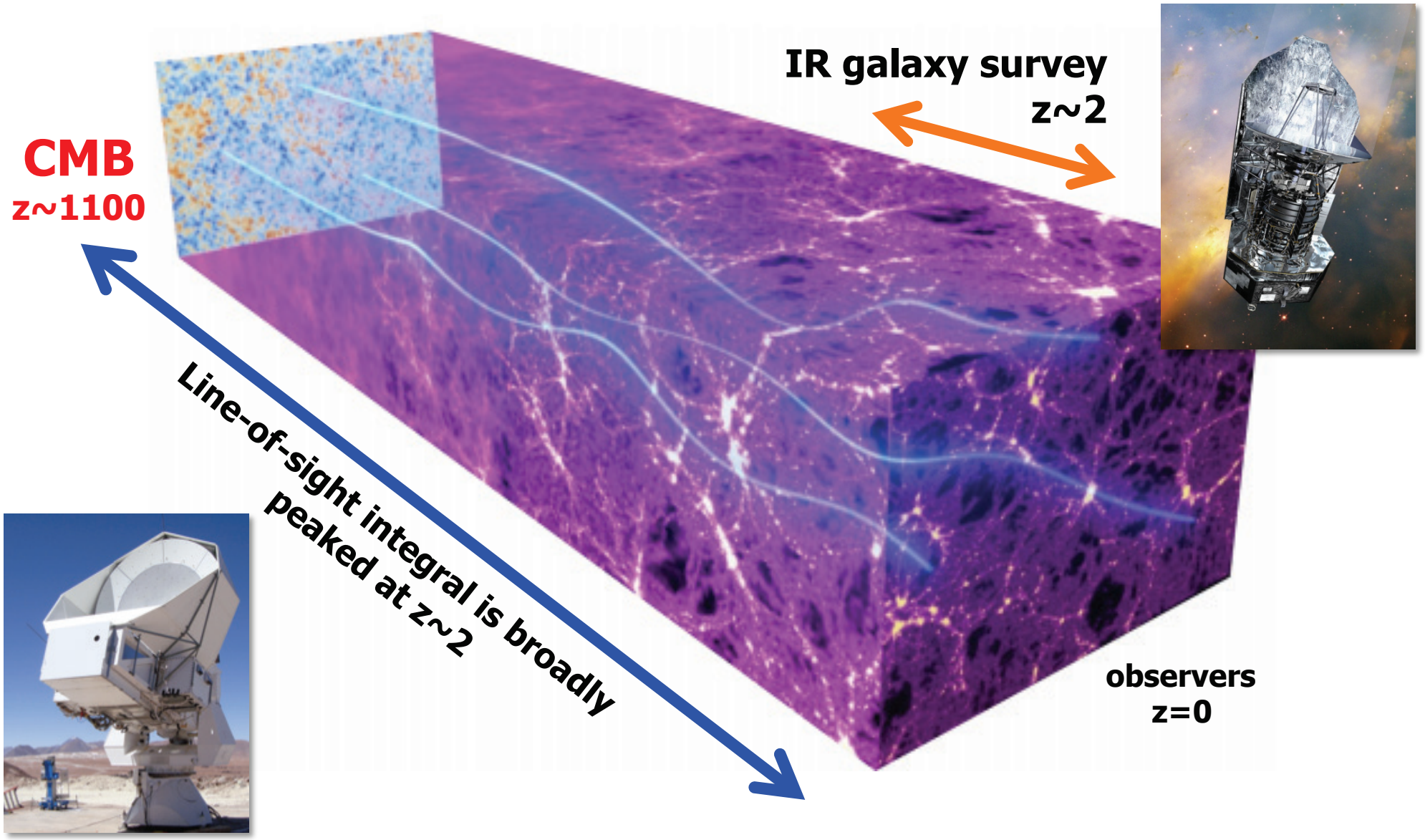
Planck × CFHTLenS (Liu & Hill 2015)

ACT × CFHT Stripe 82 (Hand et al. 2015)

temp

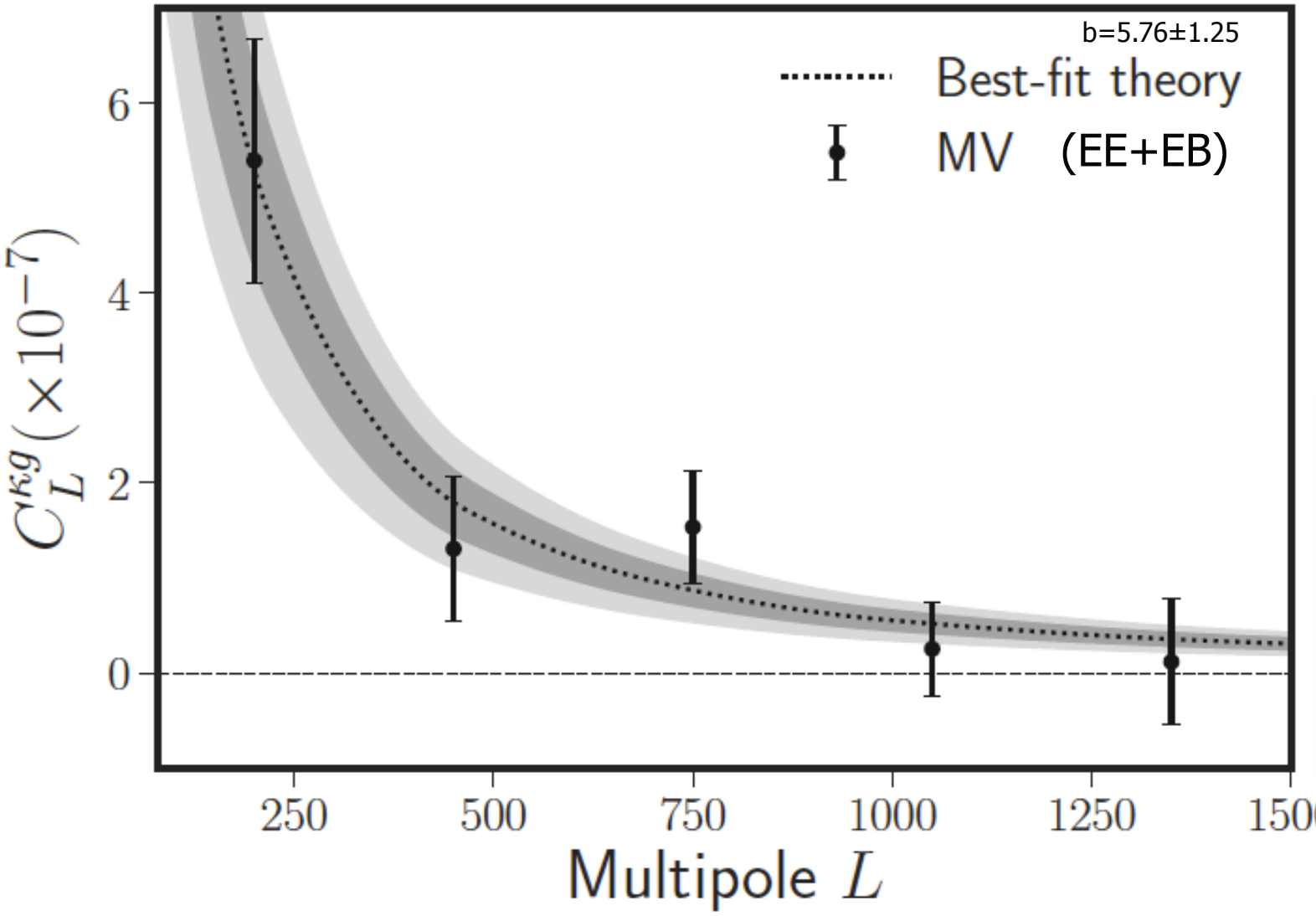
- Our lensing amplitude is slightly higher than unity, but is consistent with the Planck prediction within **2σ (PTE=66%)**
- It agrees with the previous cross-correlation analyses, although their best-fit values still have a large variation **$A_{\rm lens}$=0.4-1.3**

Cross Correlation BTW CMB & IR Galaxy Survey



- Cross-correlation w/ IR-selected galaxies by **Herschel ATLAS** survey; Well-matched w/ CMB lensing peak

Result



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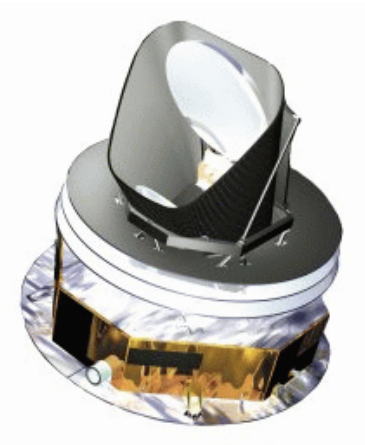
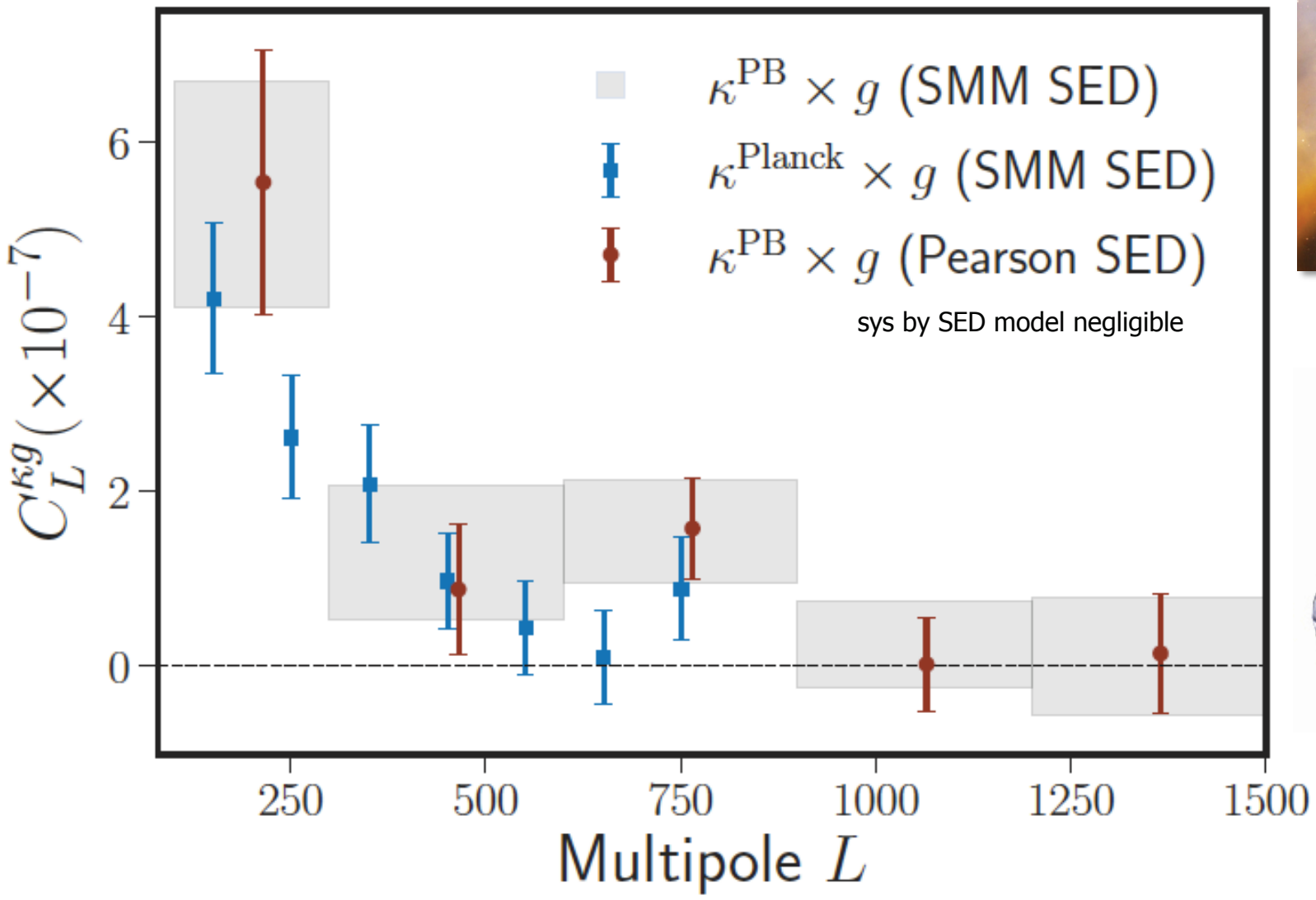
- A **4.8σ** measurement of cross-correlation BTW CMB polarization lens & IR-selected galaxies by Herschel-ATLAS
  - This is the first measurement of its kind

Comparison w/ Planck

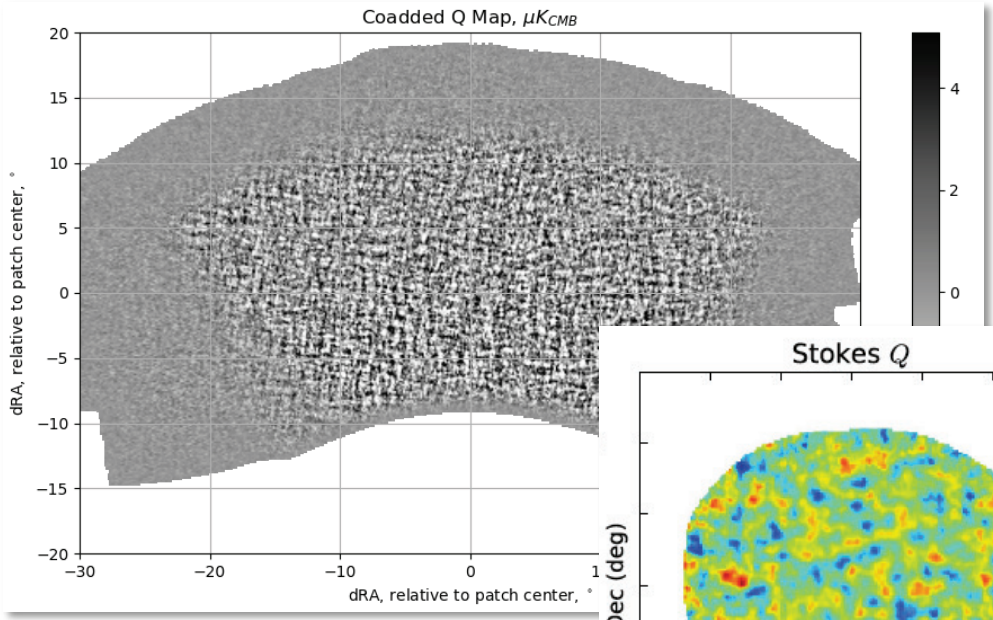


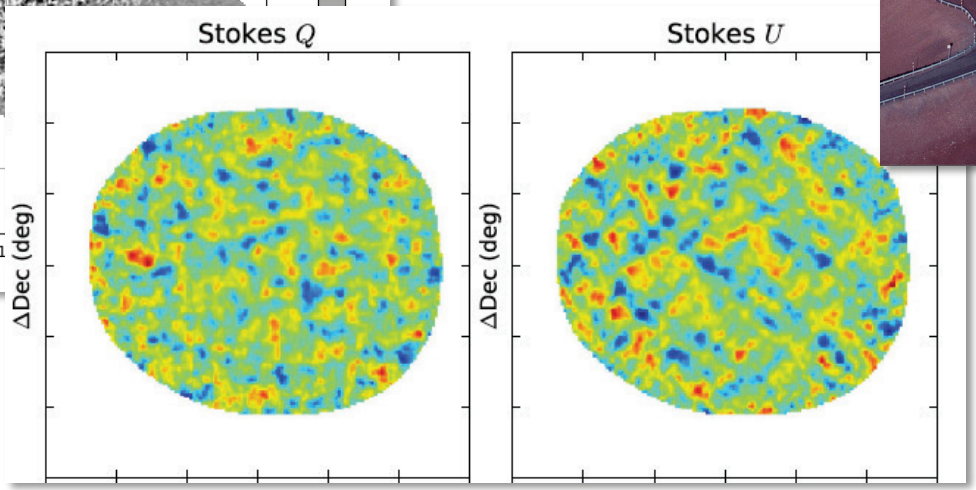


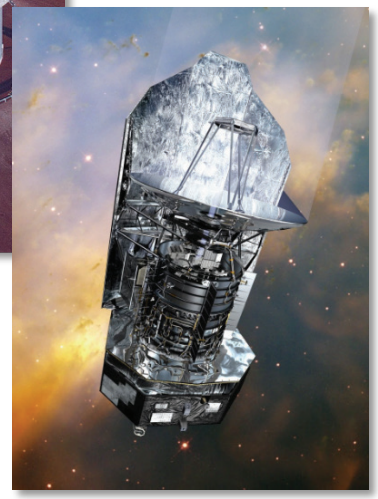
- Consistent w/ Planck within **2σ**, despite the sky coverage being **~30x smaller** than **Planck × Herschel-ATLAS**
  - b=5.76±1.25 (x PB) vs. 3.43±0.51 (x Planck)

What's Next?

- **POLARBEAR** achieving to put an upper limit on primordial gravitational waves as well as have detected lensing auto & cross-correlation w/ **HSC & H-ATLAS**
- Want to do "science" w/ them!?



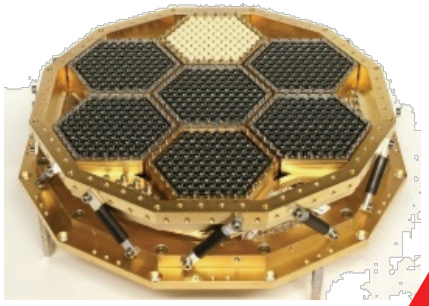




Simons Array

190mm

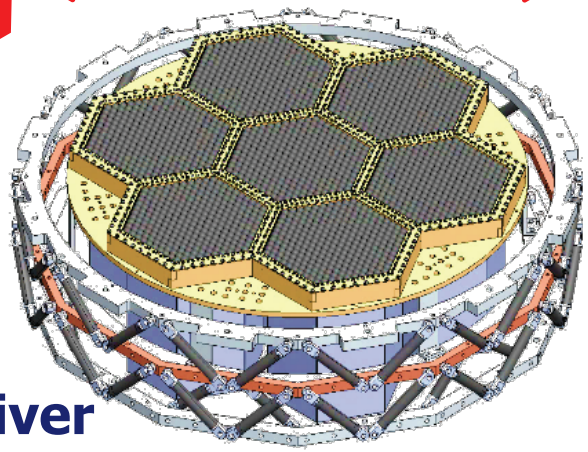
POLARBEAR receiver



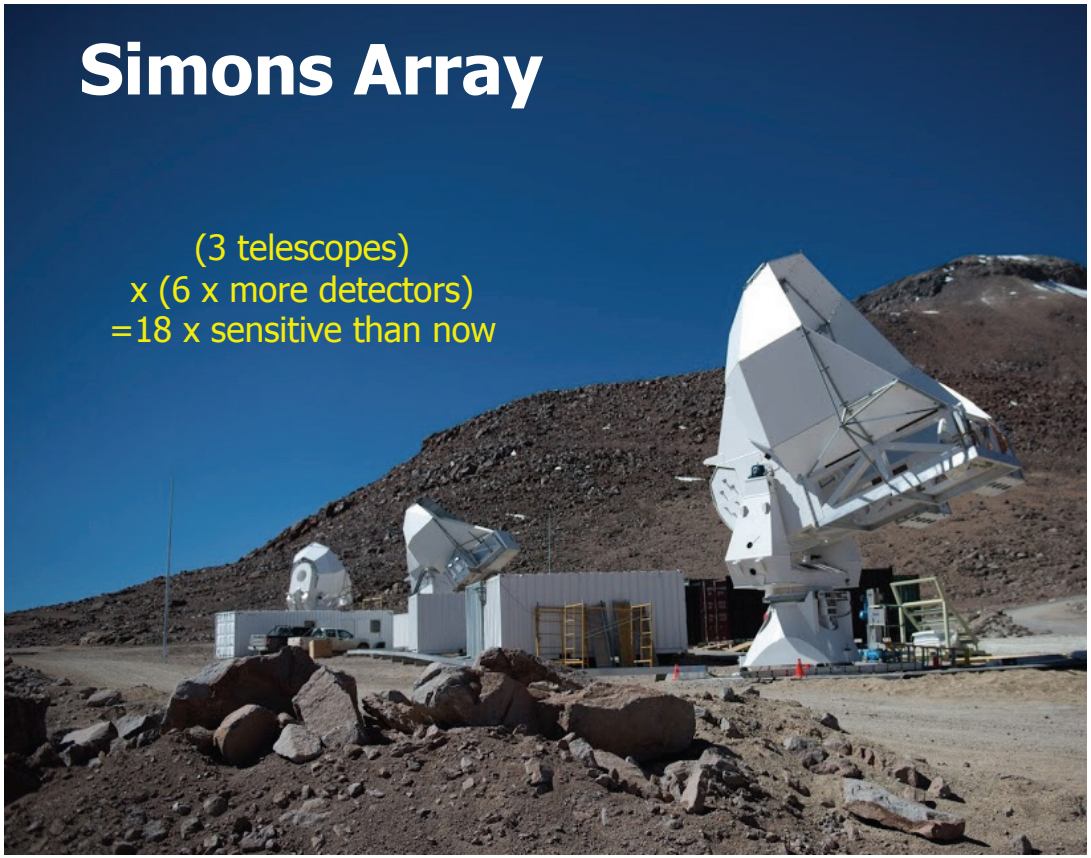
x6 more detectors

365mm

dual freq.

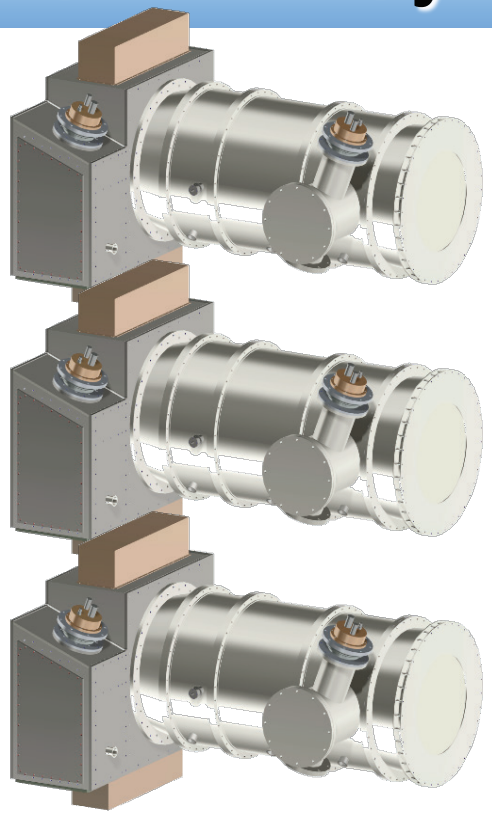


SA receiver



- A new receiver has **6x** more detectors than POLARBEAR
- **3 telescopes** (two new telescopes + one current one)
- → **(3 telescopes) x (6 x more detectors) = 18 x sensitive than now**

Simons Array



@KEK

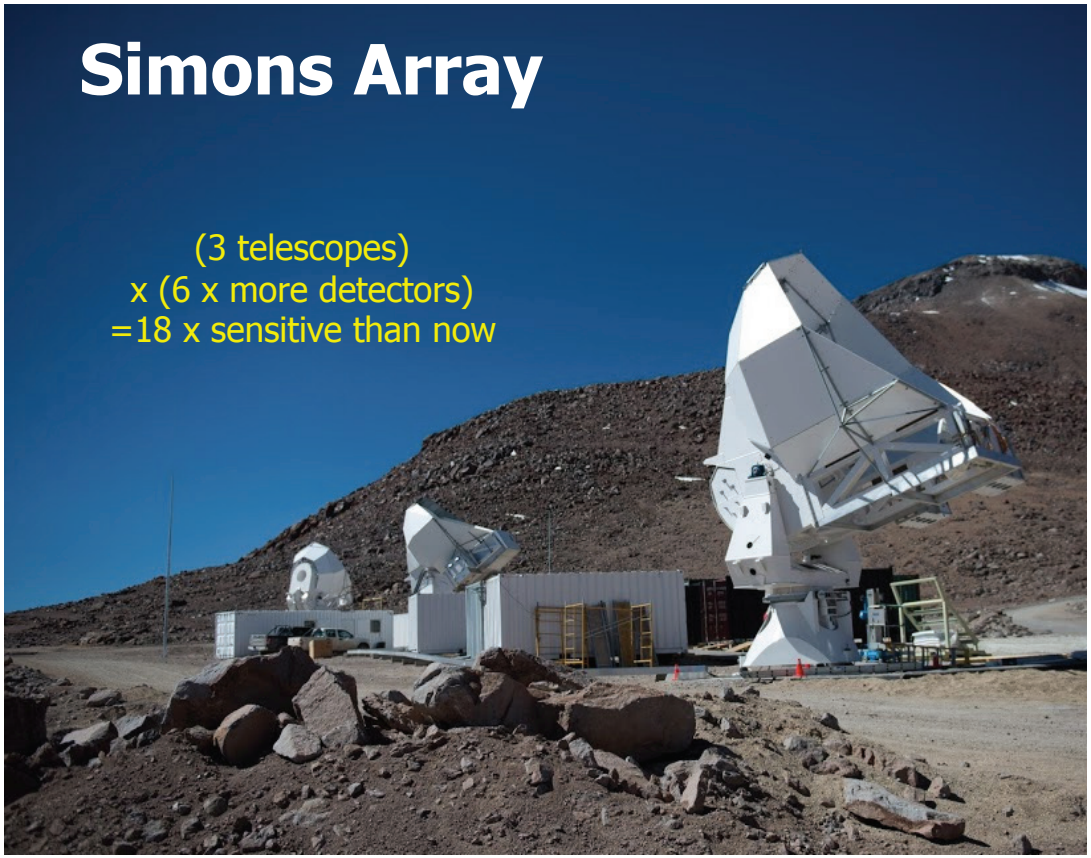
@UCB
& UCSD

POLARBEAR-2A
95/150 GHz

POLARBEAR-2B
95/150 GHz

POLARBEAR-2C
220/270 GHz

POLARBEAR-2 Receiver Frequency Plan

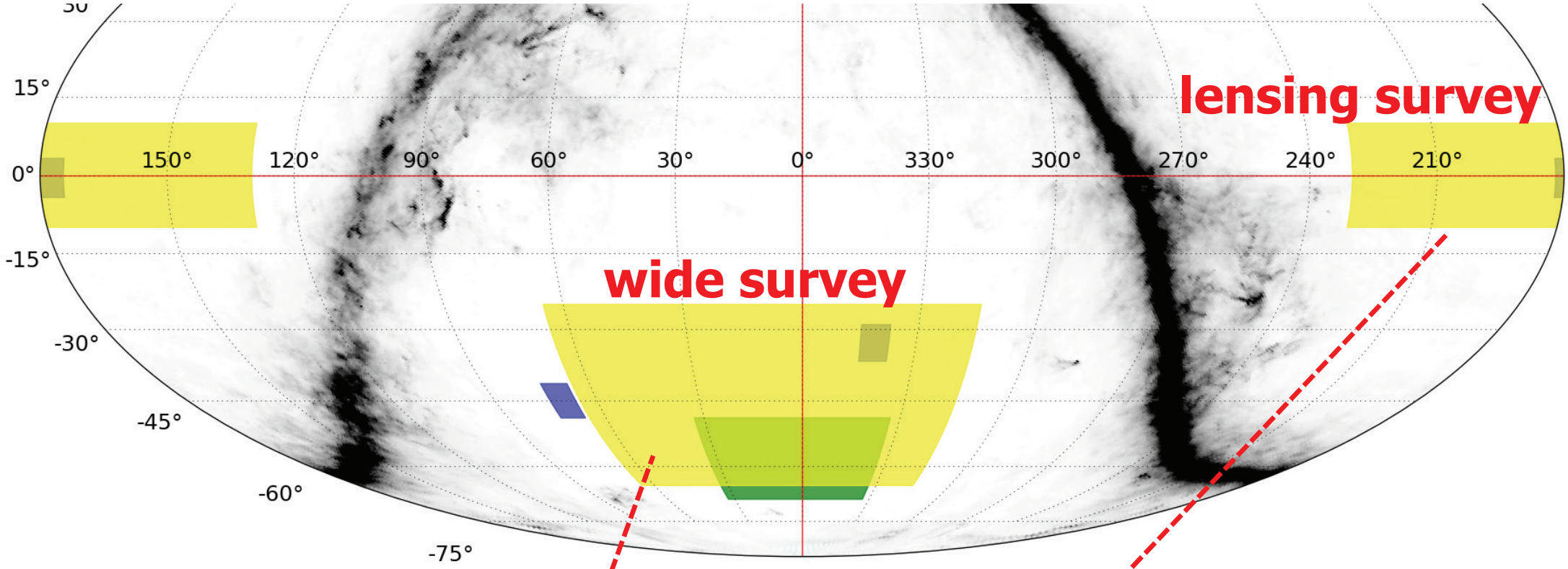


- A new receiver has **6x** more detectors than POLARBEAR
- **3 telescopes** (two new telescopes + one current one)
- **→ (3 telescopes) x (6 x more detectors) = 18 x sensitive than now**
- Expand frequency coverage for foreground removal (**95/150/220/270 GHz**)

Deploying Simons Array

- **Deployed 1st receiver & deploying 2nd & 3rd ones by 2020**

Deploying Simons Array



- Deployed 1st receiver & deploying 2nd & 3rd ones by 2020
- On early 2020's,
  - PGWs: $\sigma(r) = 6\times10^{-3}$ (4×10^{-3} stat.)
  - Neutrino masses: $\sigma(\Sigma m_\nu) = 40$ meV (19 meV stat.) w/ BAO from DESI
    - ✓ Overlap w/ HSC & PFS as well as DES & LSST

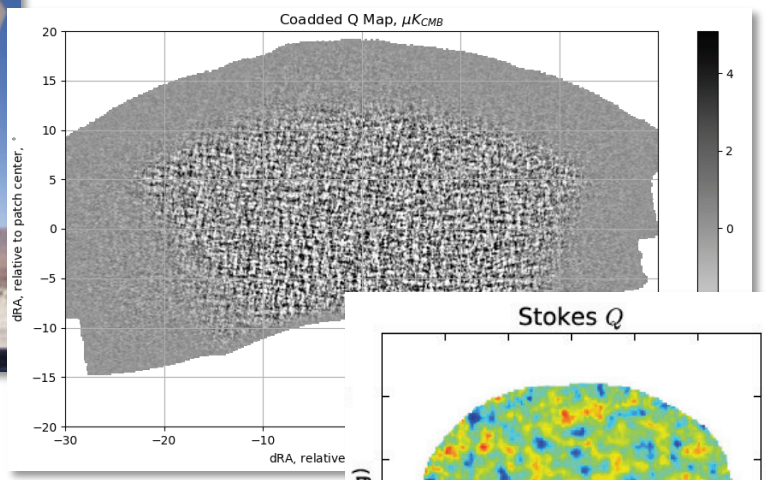
Simons Array to Simons Observator

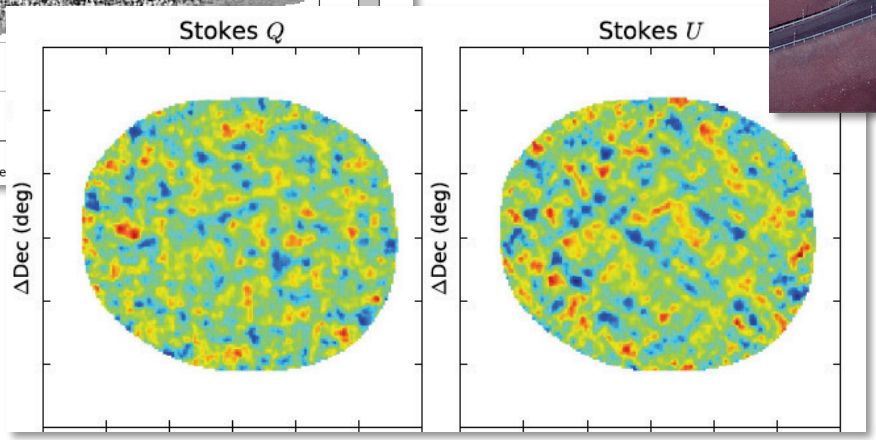
Stay Tuned!

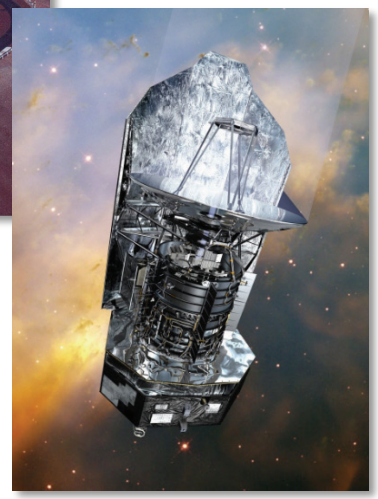
- Simons Array & ACT will be combined to "Simons Observatory" (SO)
  - The Simons Foundation is providing $80M in support for the Simons Observatory
  - Building a new large aperture telescope & three small aperture telescopes (x60)
- SO is targeting to achieve **$\sigma(r)<2\times10^{-3}$**; **$\sigma(\Sigma m_\nu)\sim30$ meV**
  - ***developing and will start science observation in 2021!***

Summary

- **POLARBEAR** is a successful experiment
  - putting an upper limit on primordial gravitational waves
  - have achieved the first measurement of B-mode lensing auto spectrum & cross-correlation w/ HSC & H-ATLAS thanks to the excellent systematic control







Summary

- **POLARBE**
  - putting a onal waves
  - have achi ode lensing
    auto spec H-ATLAS
    thanks to
- To move forward & accomplish *our science targets*, developing & starting new experiments:

  Simons Array & Simons Observatory
  - *i.e. detecting primordial gravitational waves, determining neutrino masses & tomography science*