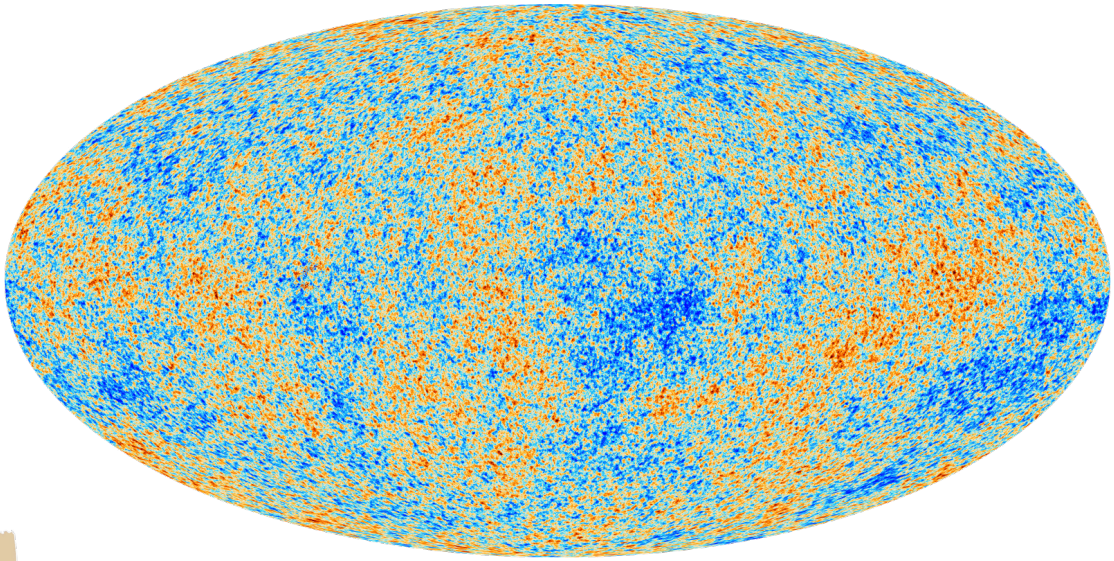
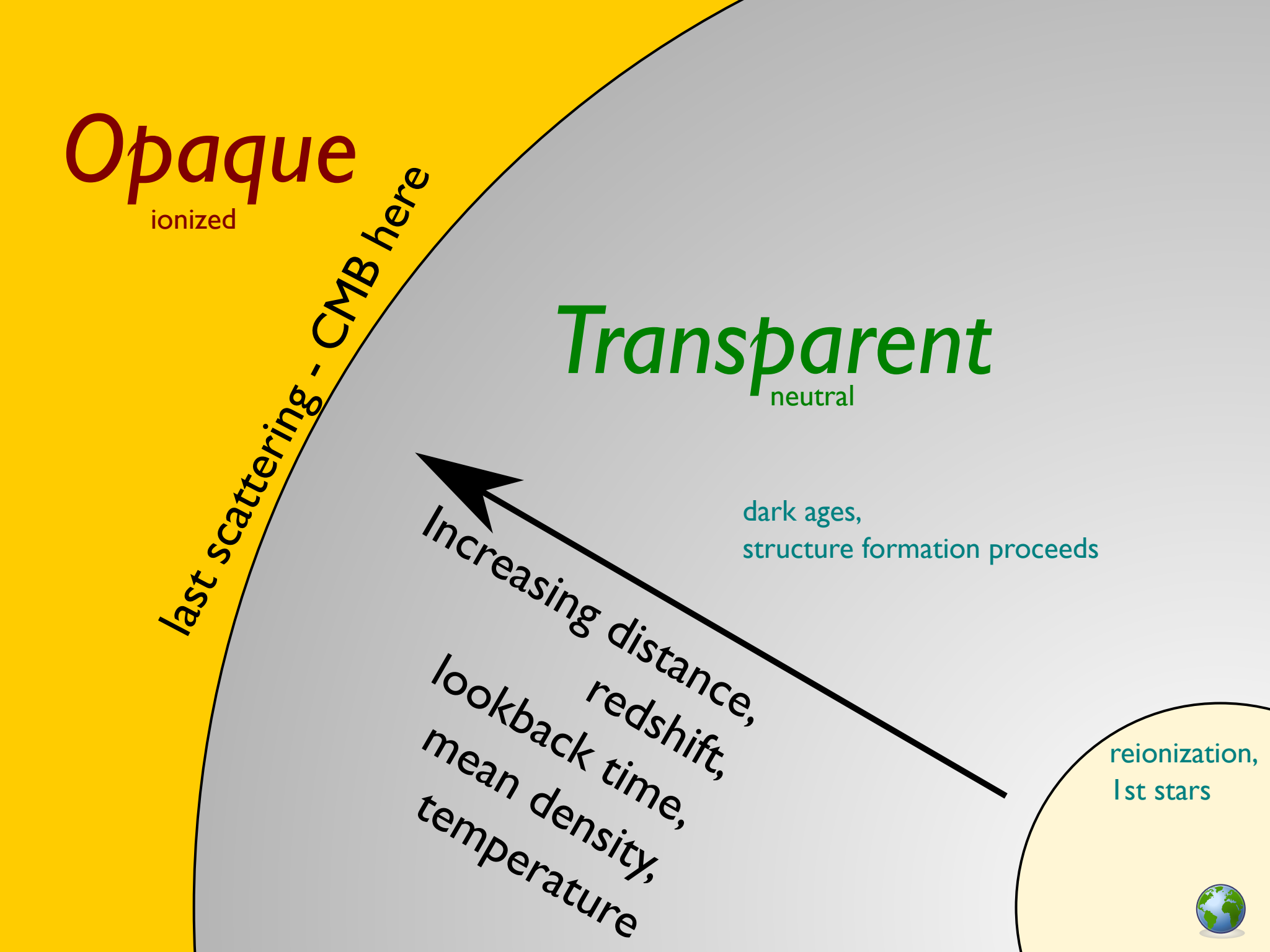
TACOS 2024

Cosmic Microwave Background foregrounds and other problems that might be opportunities

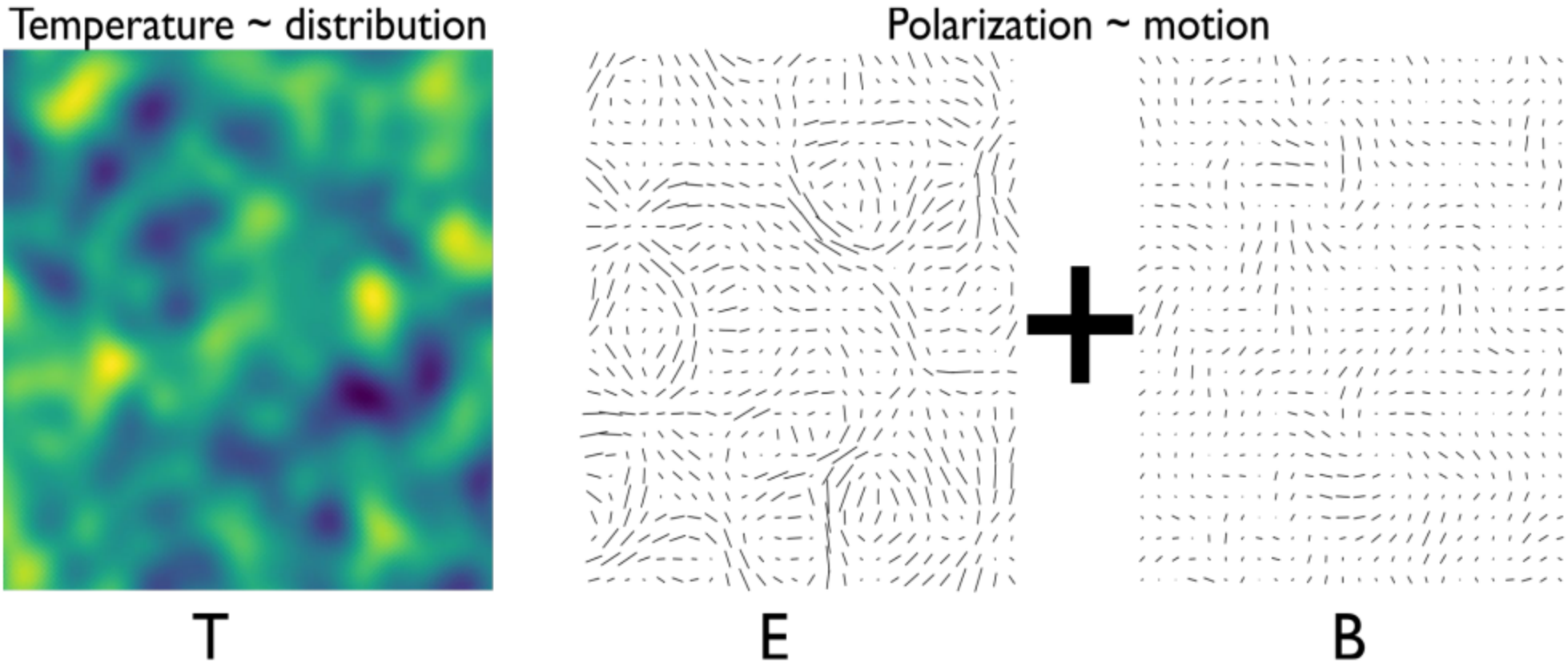


Kevin Huffenberger
Texas A&M University
(since Aug 2024)


Opaque
ionized
last scattering - CMB here
Transparent
neutral
dark ages,
structure formation proceeds
Increasing distance,
redshift,
lookback time,
mean density,
temperature
reionization,
1st stars

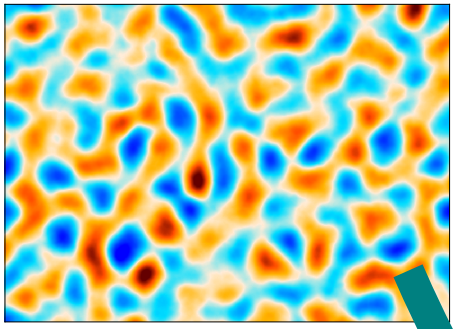
Information in CMB

Snapshot of the primordial plasma when the Universe became transparent



… plus the effects (lensing, scattering, emission) of everything in front.

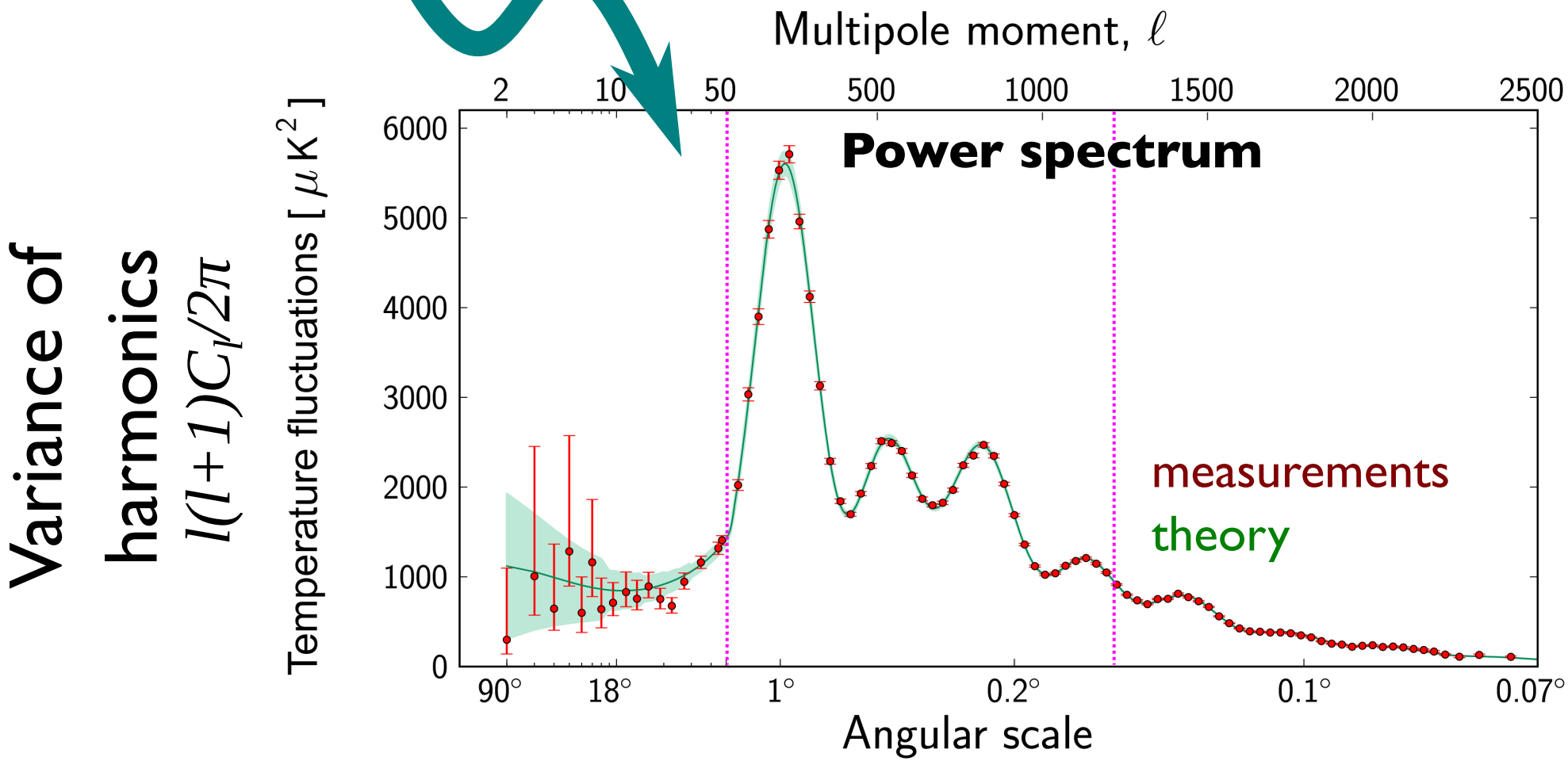
Comparing measurements to theory



$$a_{lm} = \int d\Omega\, T(\theta,\phi) Y^*_{lm}(\theta,\phi)$$

$$\langle a_{lm} a^*_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

Decompose to harmonic modes



Power spectra provide...

Big picture of ΛCDM cosmology:

5% baryons

27% dark matter

68% dark energy

Spatial flatness

Inflationary spectral tilt $n_s = 0.9649 \pm 0.0042$

... with ~ percent-level precision

What's next?

Primordial gravitational waves

Light relic particles beyond-the-standard-model

Neutrino mass

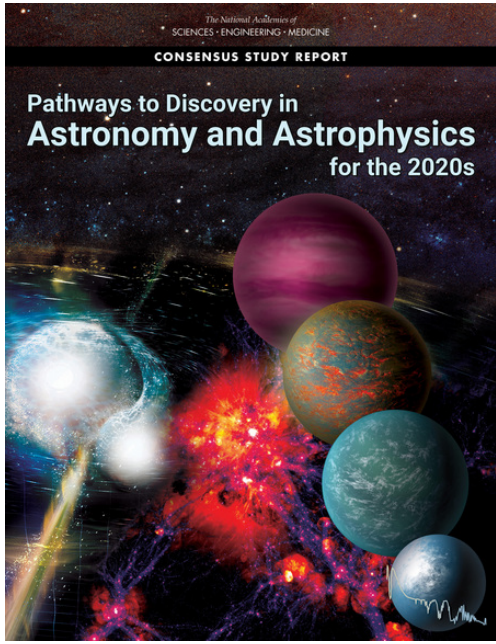
Integrated maps of gas pressure to high redshift (incl. galaxy clusters)

Integrated (lensing) maps of total mass to high redshift

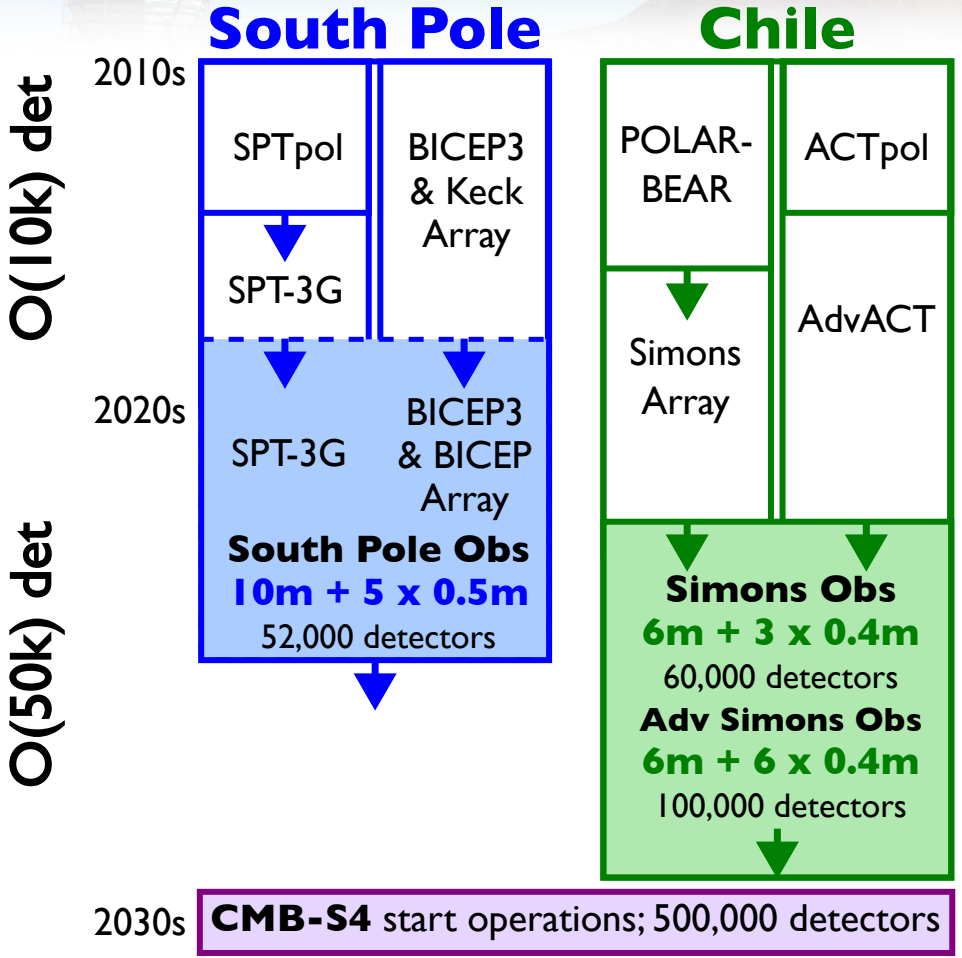
Time-domain millimeter-wave astronomy

Detailed images of Milky Way's turbulent ISM

... and more!



Evolution of Ground-Based CMB Experiments



Simons Observatory in 2024

LAT (mirror soon) SAT 1,2,3

6m 0.4 m

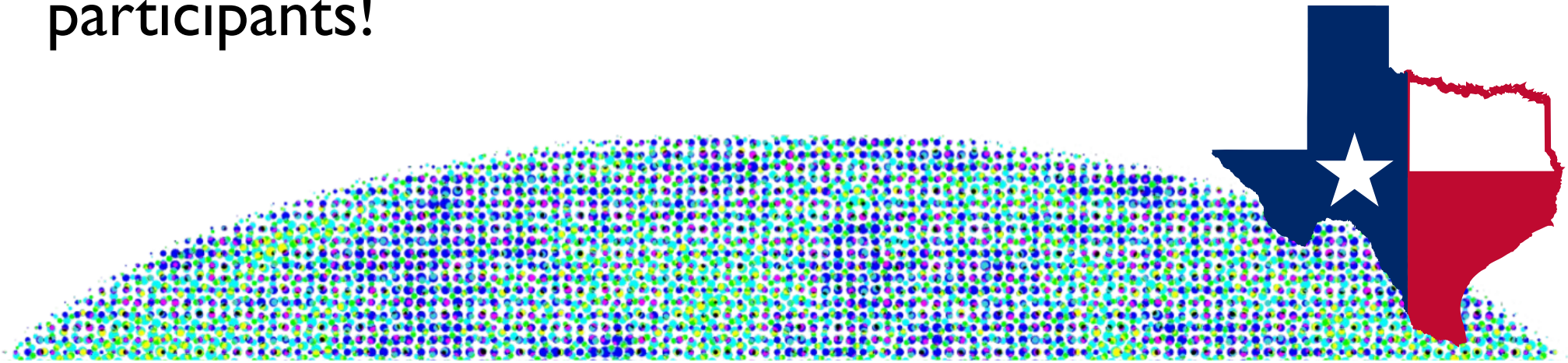
SATs now taking data, LAT in 2025

UT and TAMU are institutional members

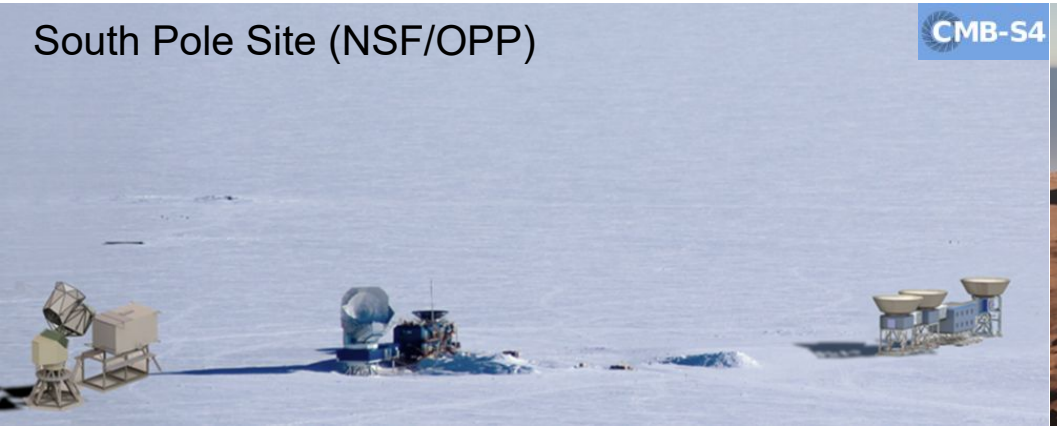
Texas Leadership in CMB-S4

Huffenberger (TAMU) - co-spokesperson
Boddy (UT) - analysis working group coordinator for power spectra
Maccarone (TTU) - analysis working group coordinator for sources and transients
Meyers (SMU) - former co-chair of science council

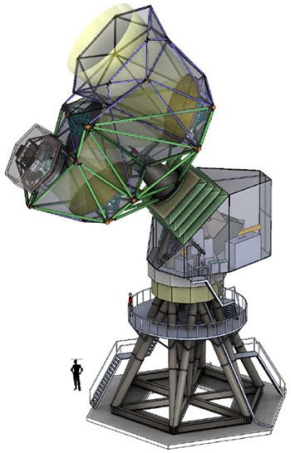
Many other collaboration members and committee participants!



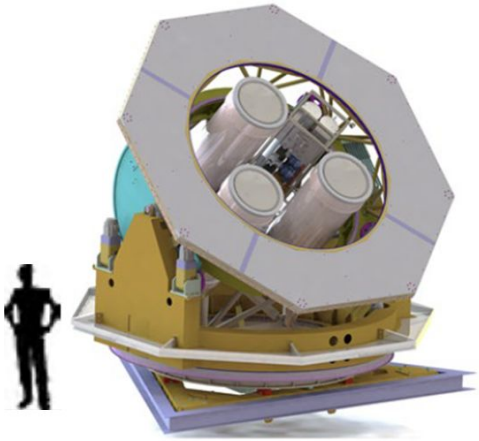
CMB-S4 prelim. design (for 2033)



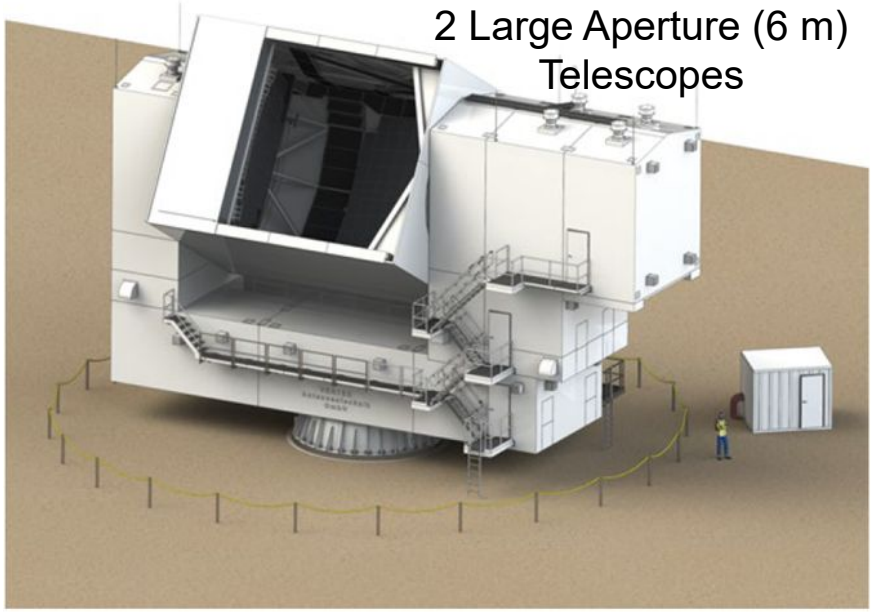
1 Large Aperture (5 m) Telescope



3 Small Aperture Telescopes (9 0.5-m aperture optics tubes)



2 Large Aperture (6 m) Telescopes



BUT... NSF said in May 2024 that the South Pole was not available!

CMB-S4 redesign

DOE & NSF are still supporting CMB-S4 at ~ $8M/year level.

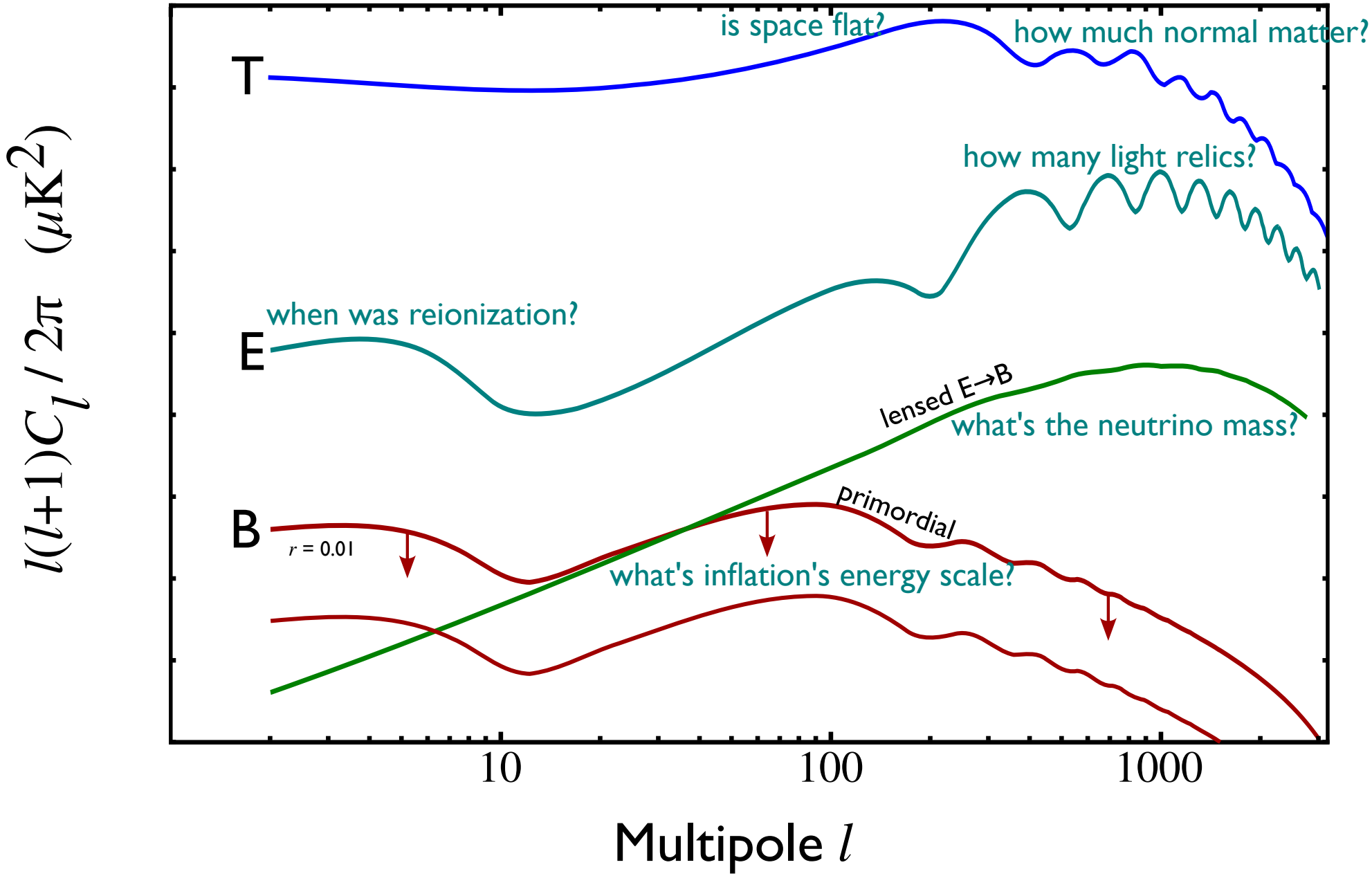
We have a focused action plan for reconfiguring CMB-S4 in Chile, which we are executing consistent with joint charge from agencies:

- (1) Developing and optimizing the all-Chile configuration, while (2) surveying the landscape of CMB experiments to determine CMB-S4's role in it. Reports due January 2025.

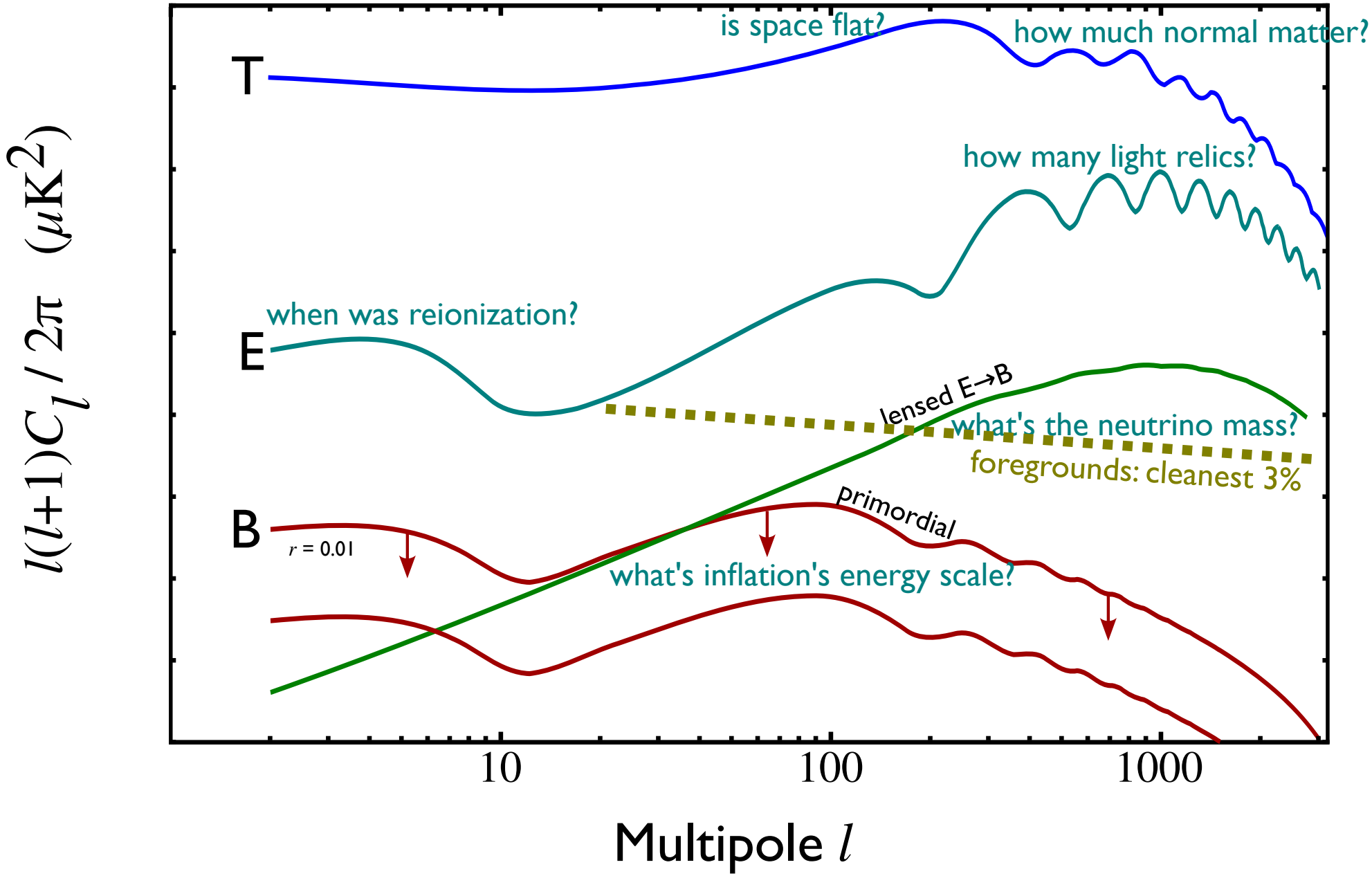
- Combining the two studies to determine a revised configuration that will form the basis for a complete conceptual design, in conjunction with expected capabilities other experiments.

- Moving toward readiness for CD-1 and CDR by the end of FY 2026, if funding permits.

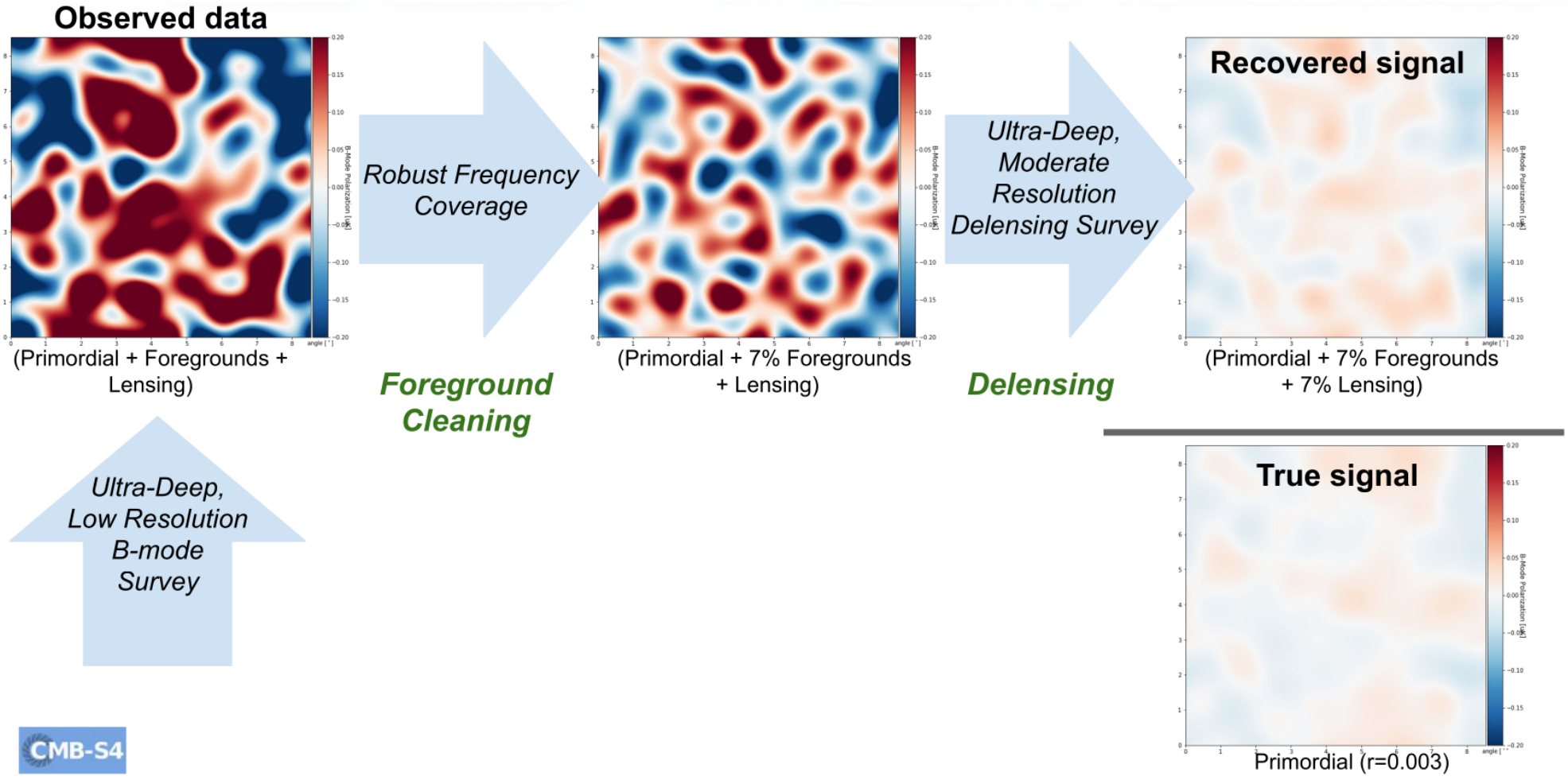
Polarization power spectra

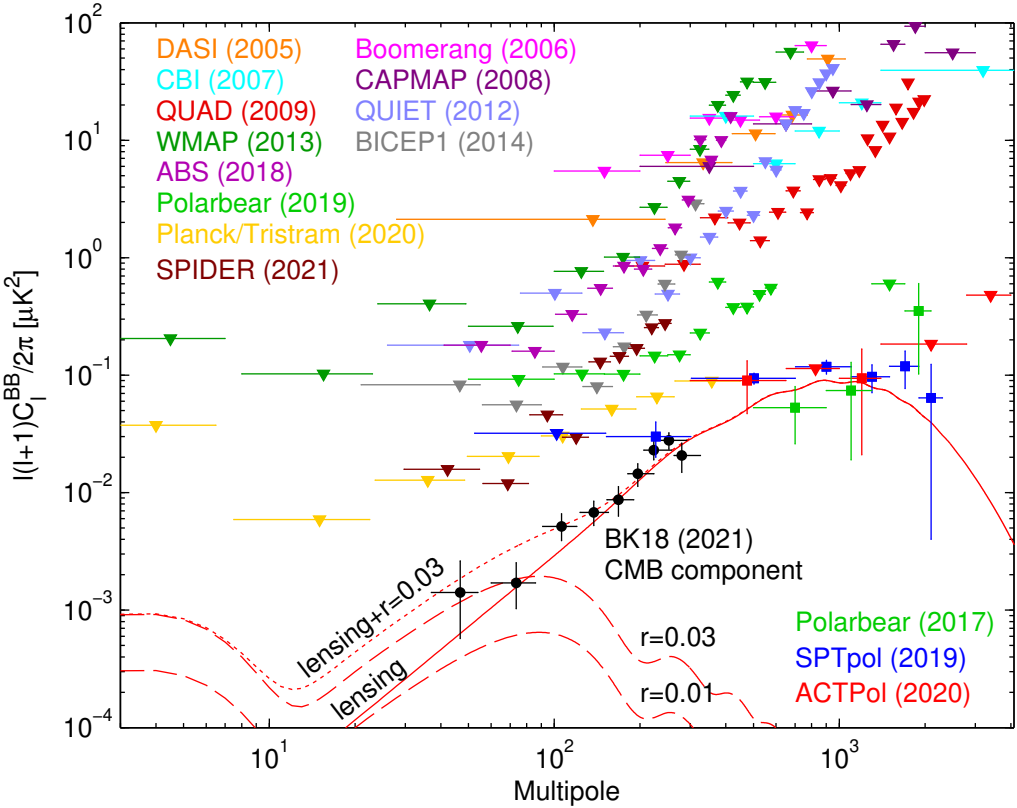


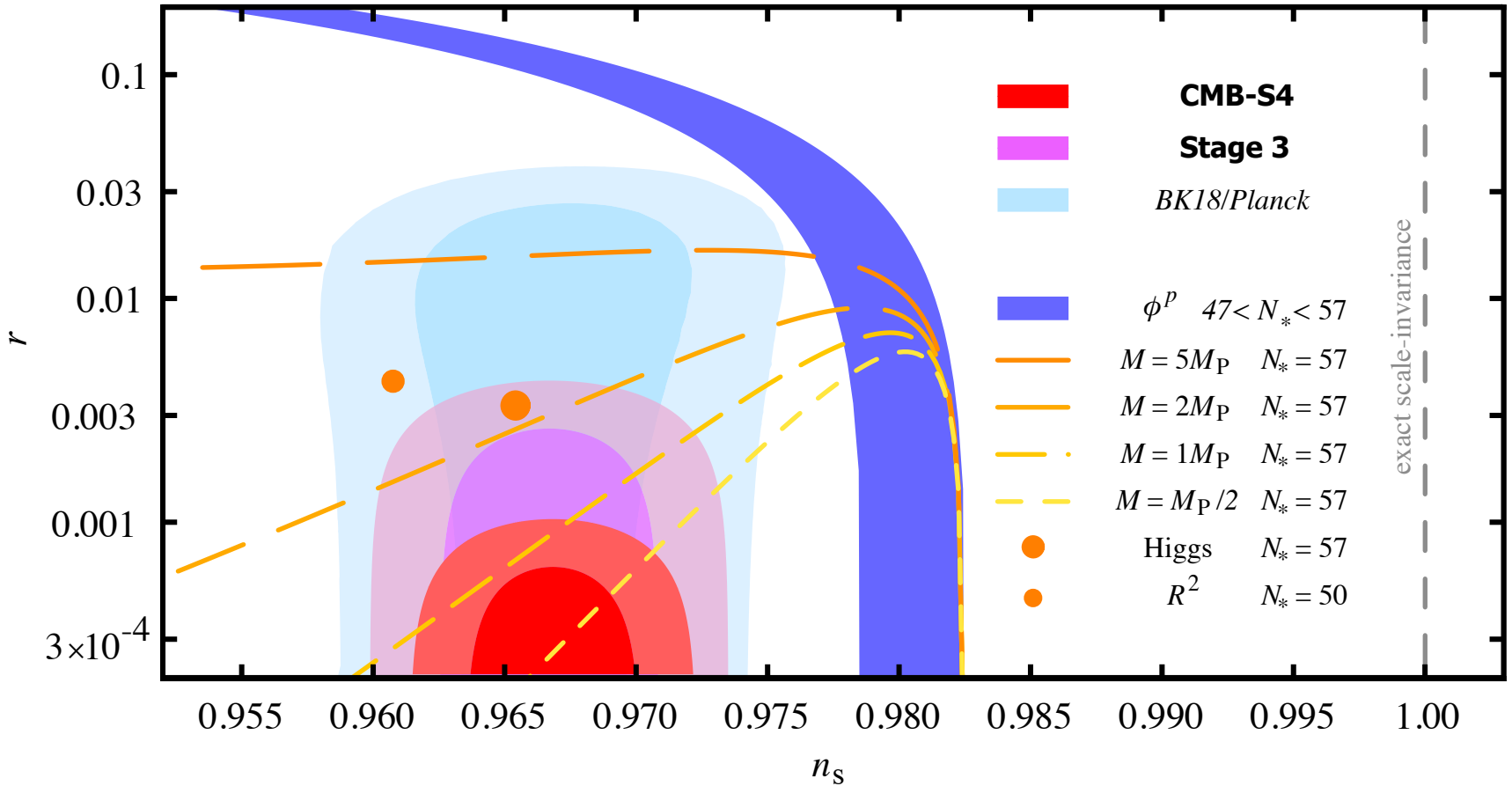
Polarization power spectra



Schematic B-mode pipeline



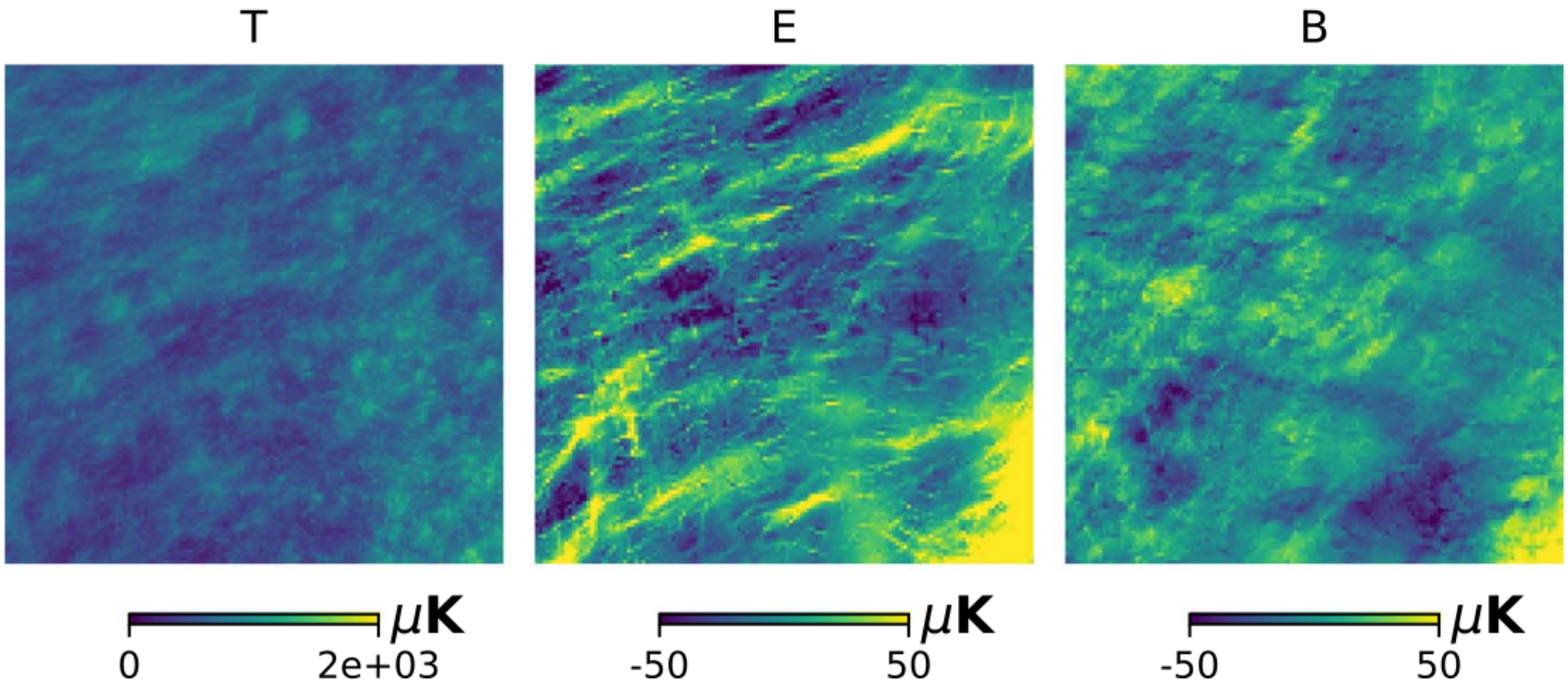

DASI (2005)
CBI (2007)
QUAD (2009)
WMAP (2013)
ABS (2018)
Polarbear (2019)
Planck/Tristram (2020)
SPIDER (2021)
Boomerang (2006)
CAPMAP (2008)
QUIET (2012)
BICEP1 (2014)
BK18 (2021)
CMB component
lensing+r=0.03
lensing
r=0.03
r=0.01
Polarbear (2017)
SPTpol (2019)
ACTPol (2020)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3


CMB-S4
Stage 3
BK18/Planck
ϕ^p $47 < N_* < 57$
$M = 5M_P$ $N_* = 57$
$M = 2M_P$ $N_* = 57$
$M = 1M_P$ $N_* = 57$
$M = M_P/2$ $N_* = 57$
Higgs $N_* = 57$
R^2 $N_* = 50$
exact scale-invariance
r
0.1
0.03
0.01
0.003
0.001
3×10^{-4}
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
1.00
n_S

Foreground challenge

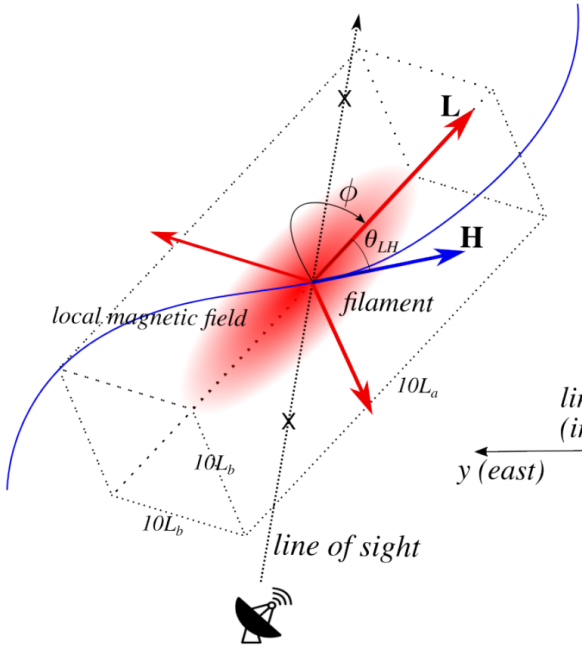
The primordial B-mode signal is smaller than Milky Way foregrounds and lensing

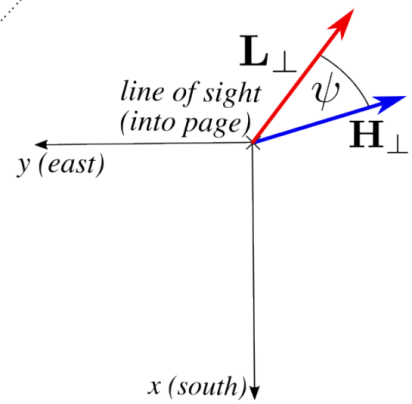
My group has made several studies of the relationships between the filamentary interstellar medium and the power spectral properties of the foreground polarization

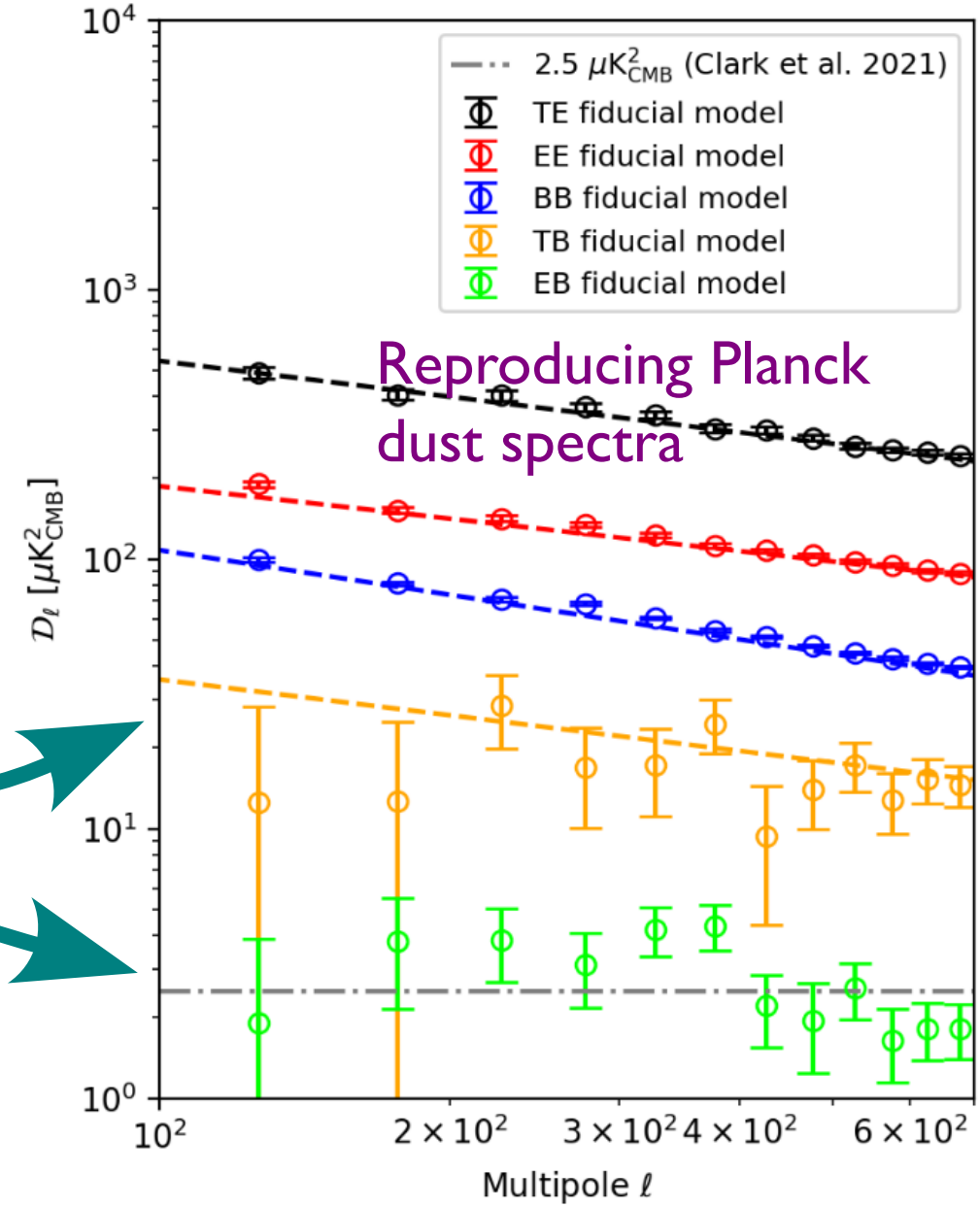


Rotti & Huffenberger 2019, Huffenberger et al 2020, **Hervias-Caimapo & Huffenberger 2022**

Mixed-parity correlations require filaments w/ a twist

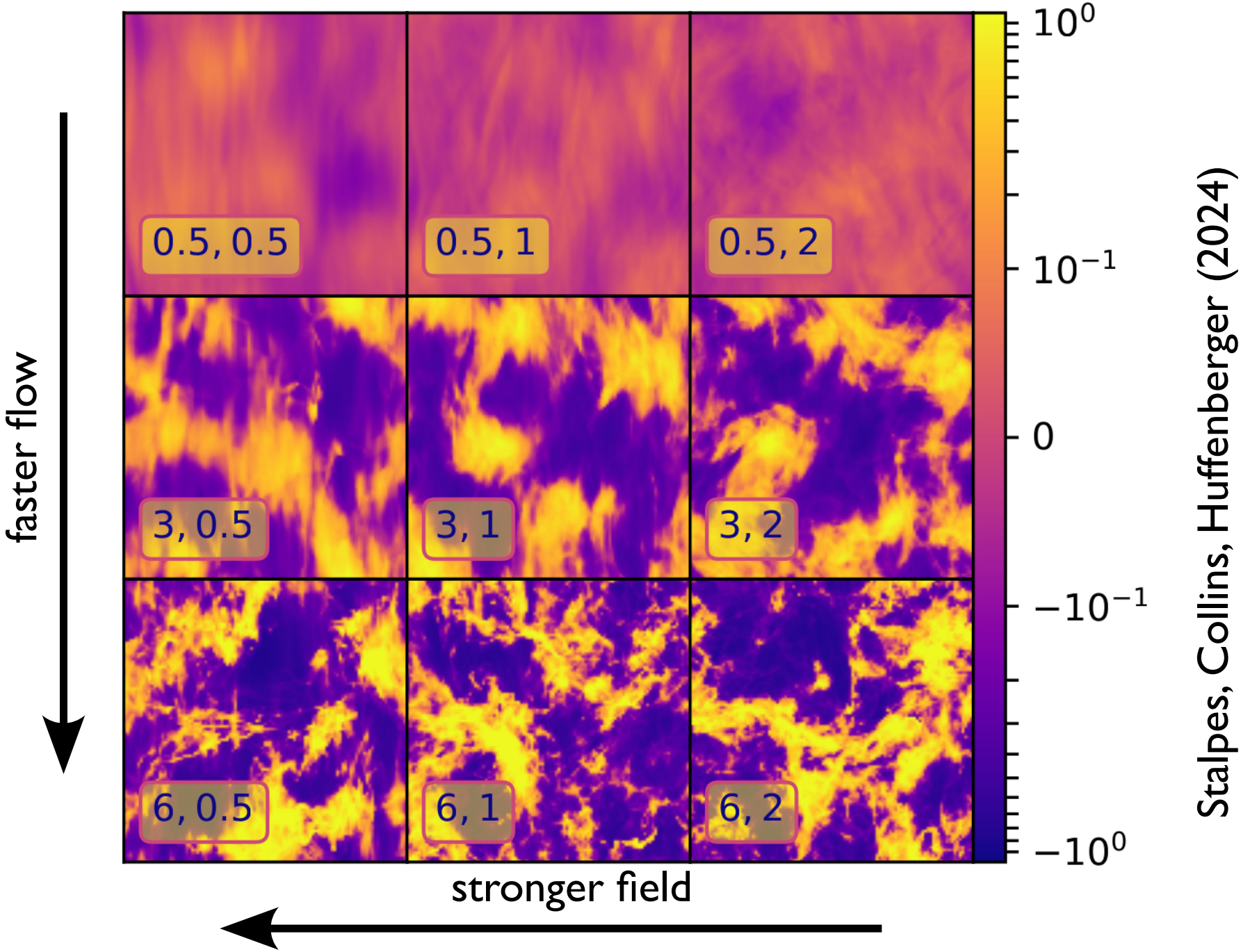




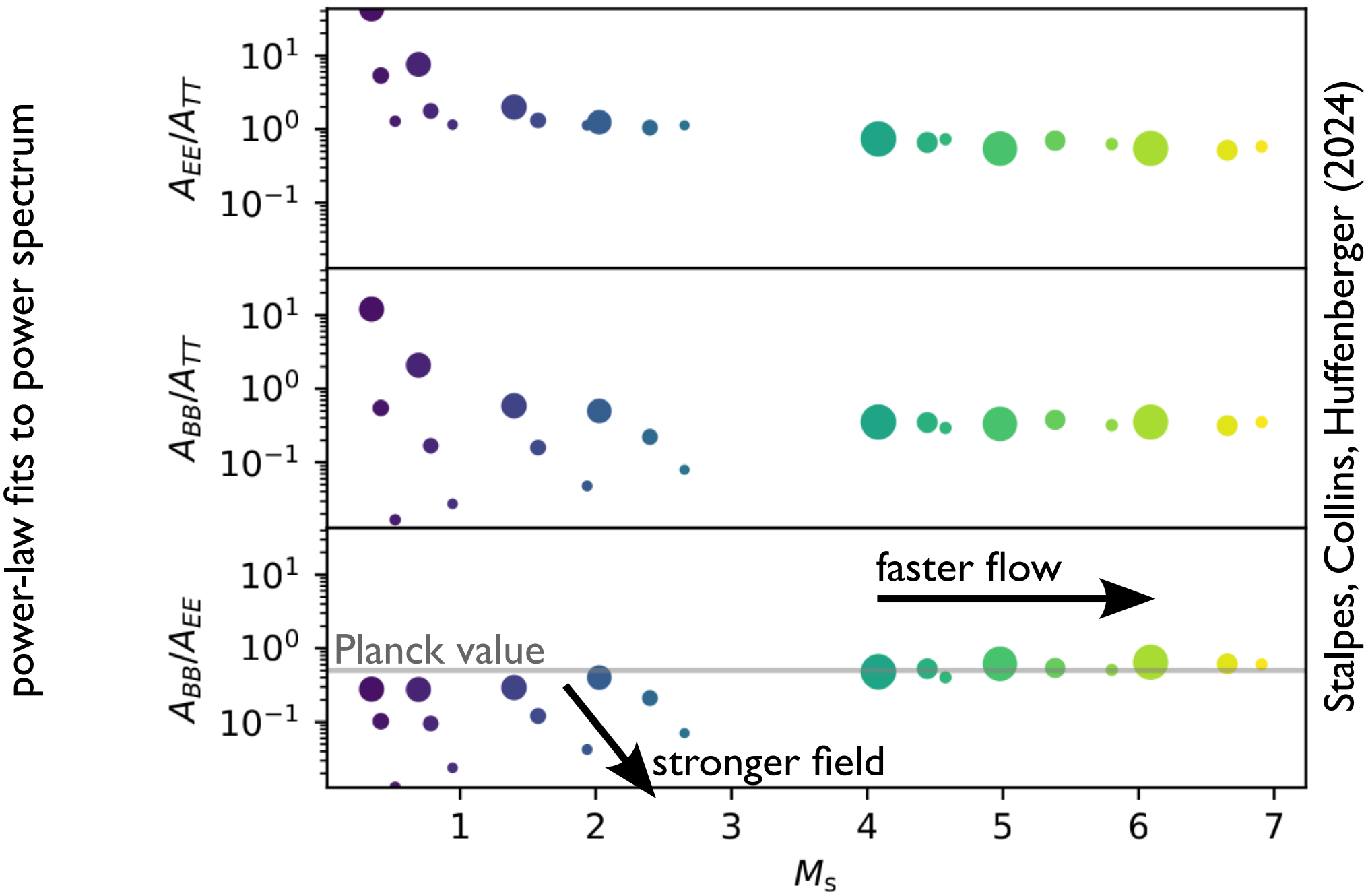


Hervias Caimapo++ (2024)

MHD turb. foreground suite

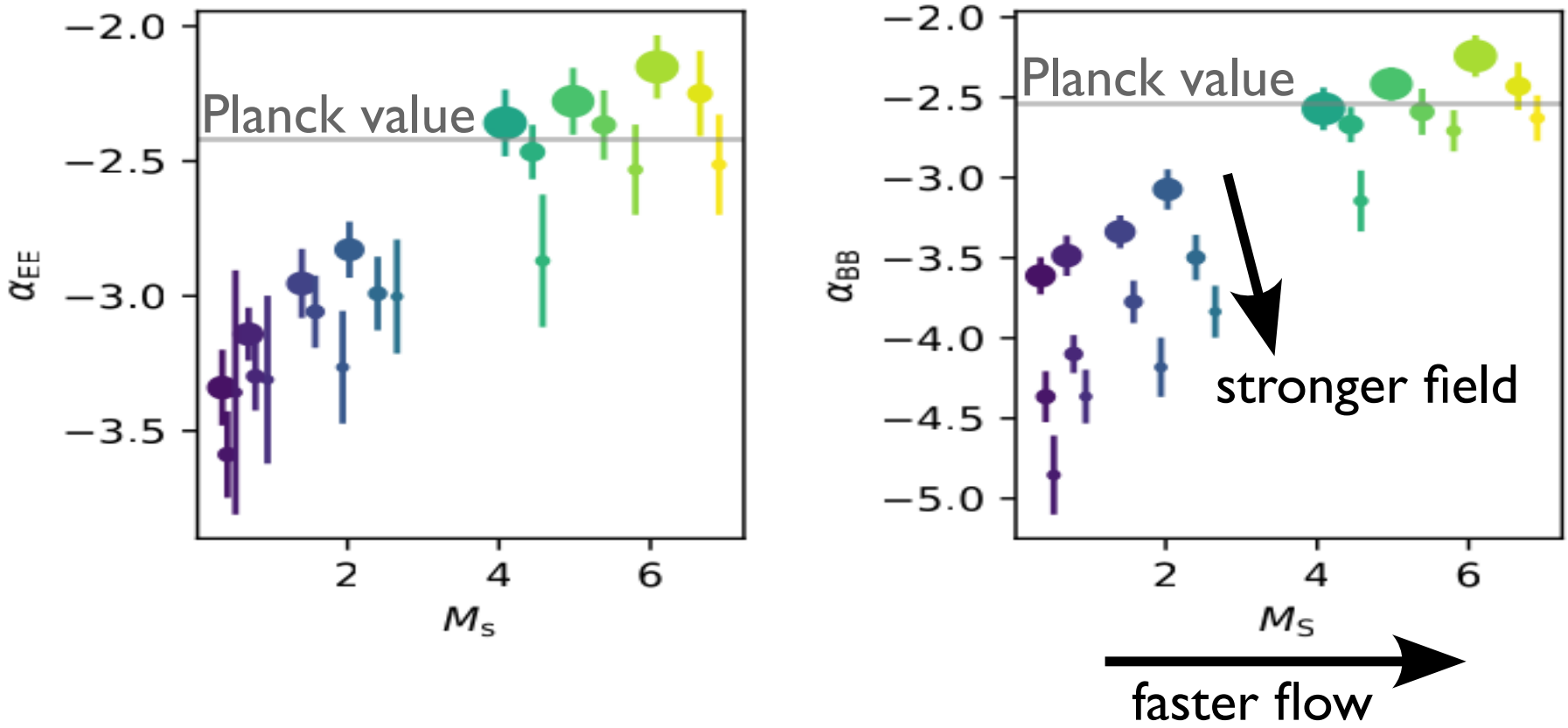


Power amplitudes from MHD sims



Power slopes from MHD sims

power-law fits to power spectrum

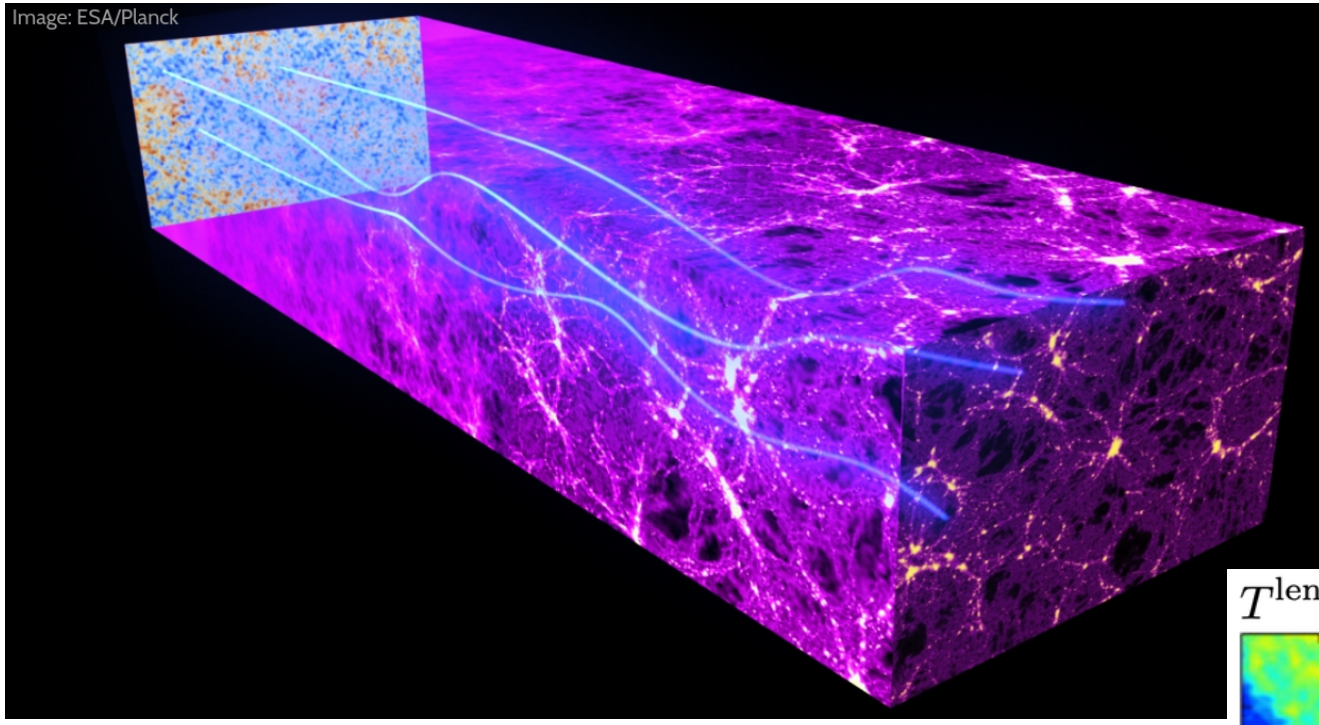


Stalpes, Collins, Huffenberger (2024)

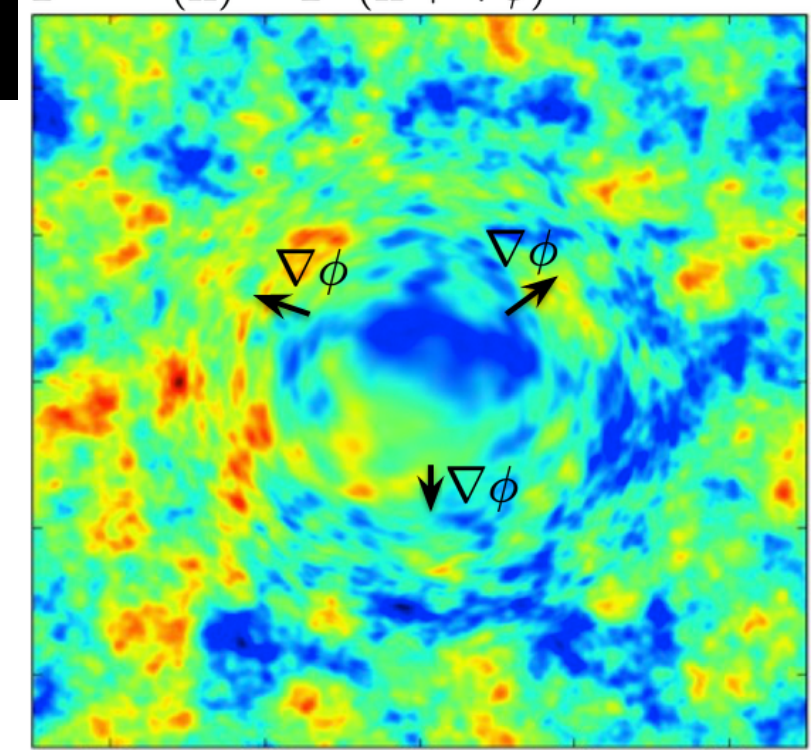
Characterizing FGs is teaching us about ISM

Next steps: verify with higher resolution, more realism (multiphase), whole-galaxy sims

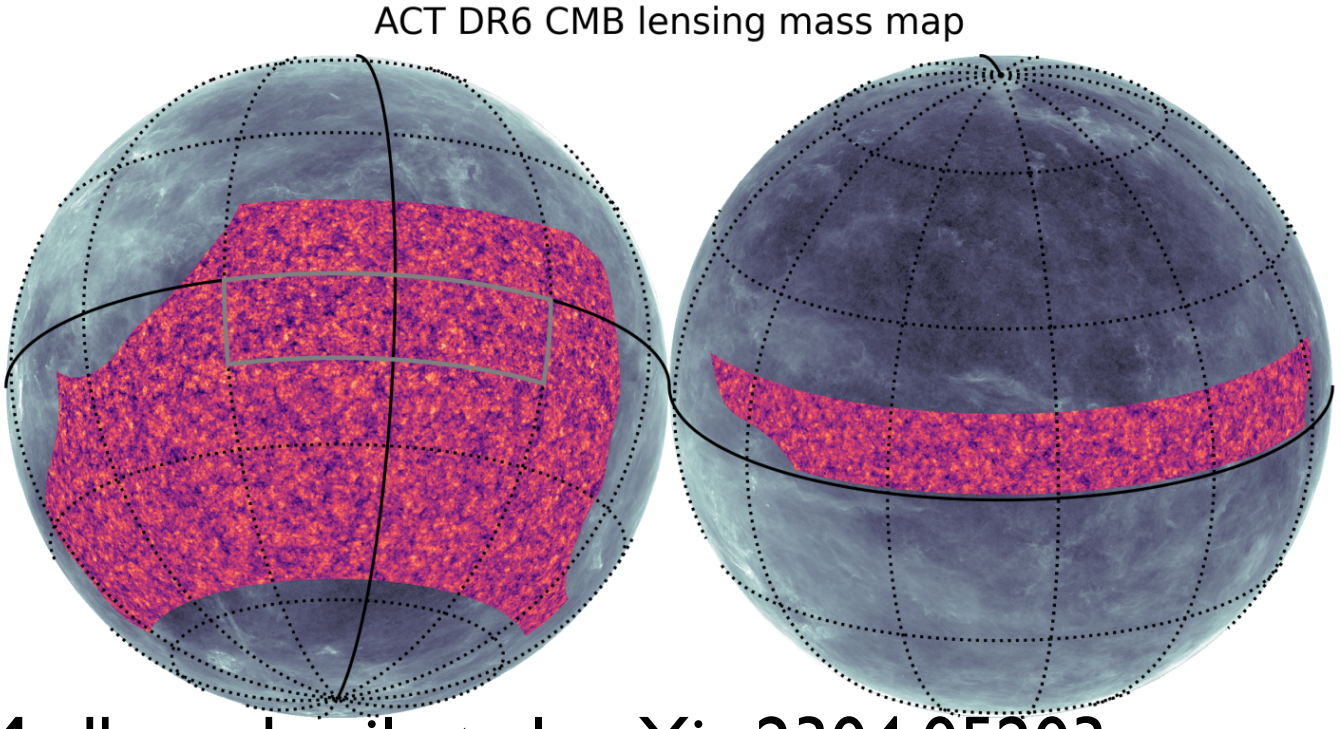
CMB gravitational lensing by large-scale structure



$$T^{\text{lensed}}(\hat{\mathbf{n}}) = T^0(\hat{\mathbf{n}} + \nabla\phi)$$



2023 ACT lensing results



>9000 sq deg

Madhavacheril et al. arXiv:2304.05203

Qu et al. arXiv:2304.05202

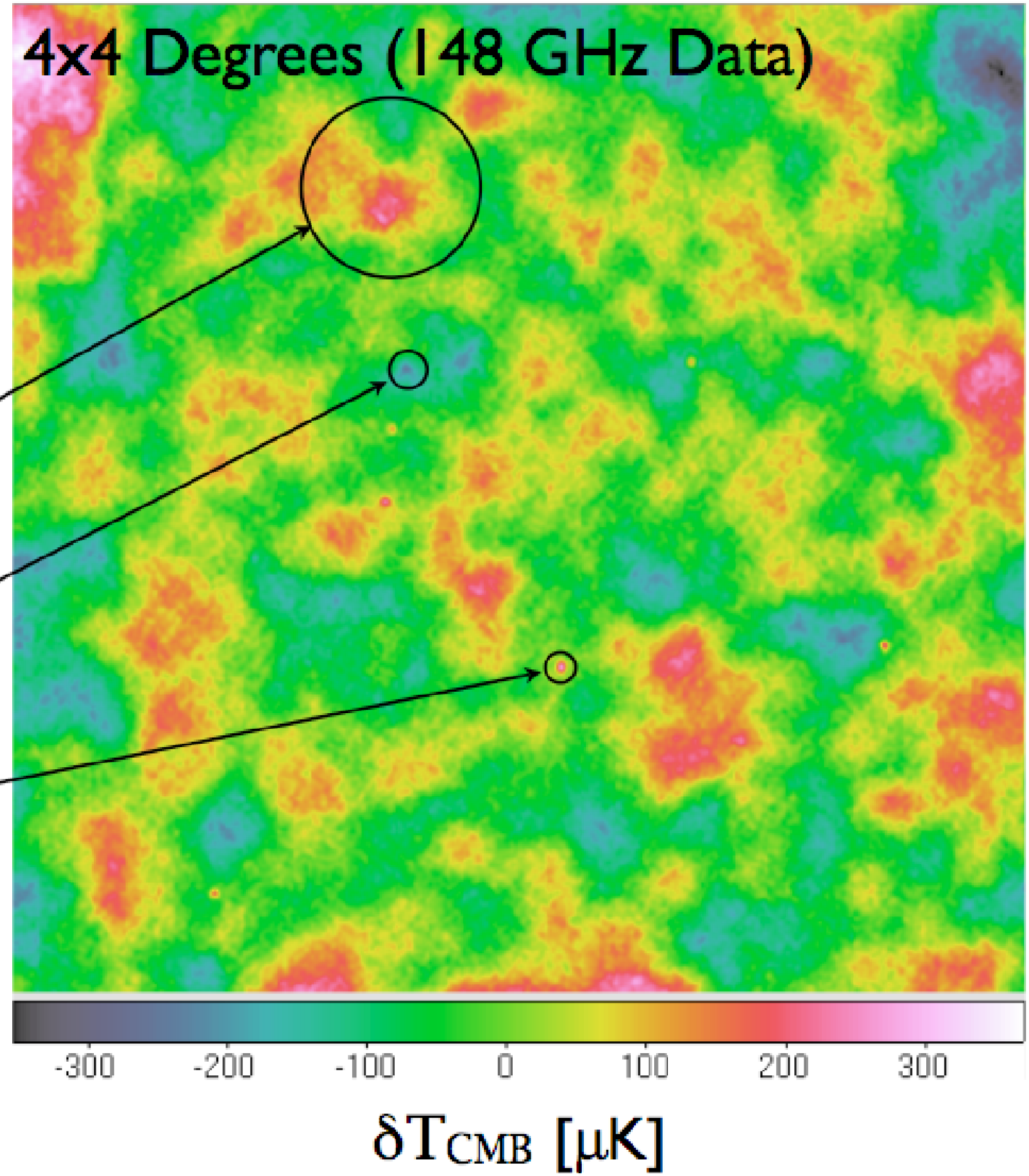
Cross-correlations w/ previous data set DR4

Marques et al. arXiv:2306.17268 (former FSU postdoc)

Shaikh, Harrison, van Engelen, Marques, et al. arXiv:2309.04412

Tests of structure growth in LCDM model!

ACT Map



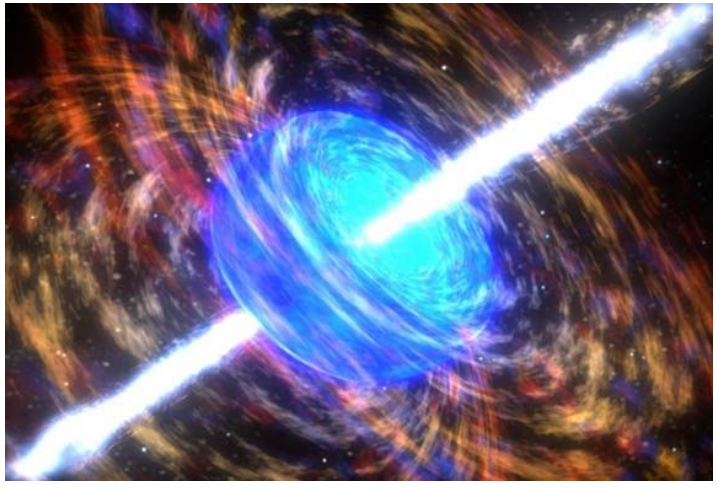
CMB fluctuation

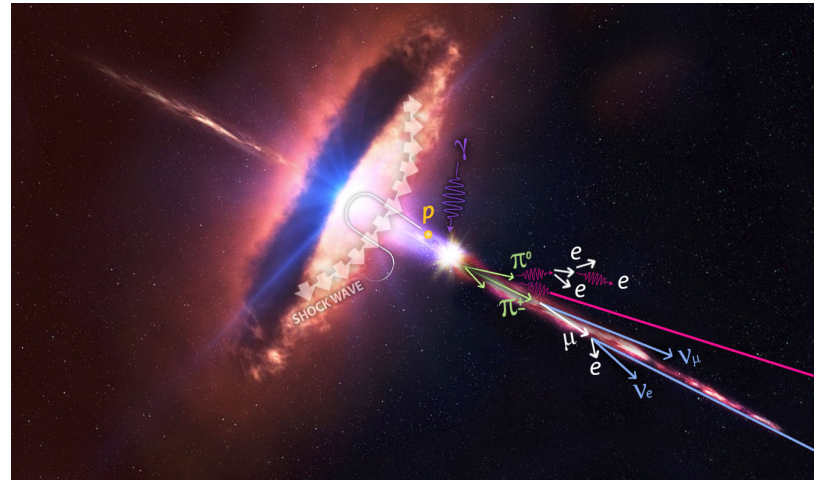
Cluster

Active Galactic Nucleus

Variable/transient millimeter band

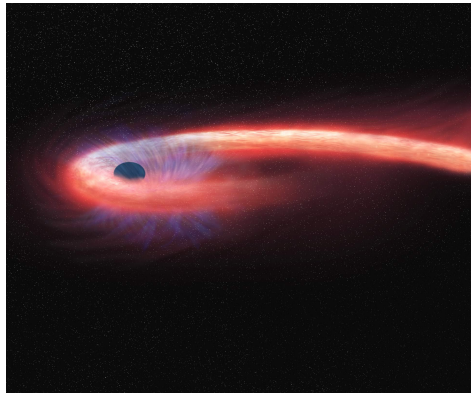
Gamma ray bursts

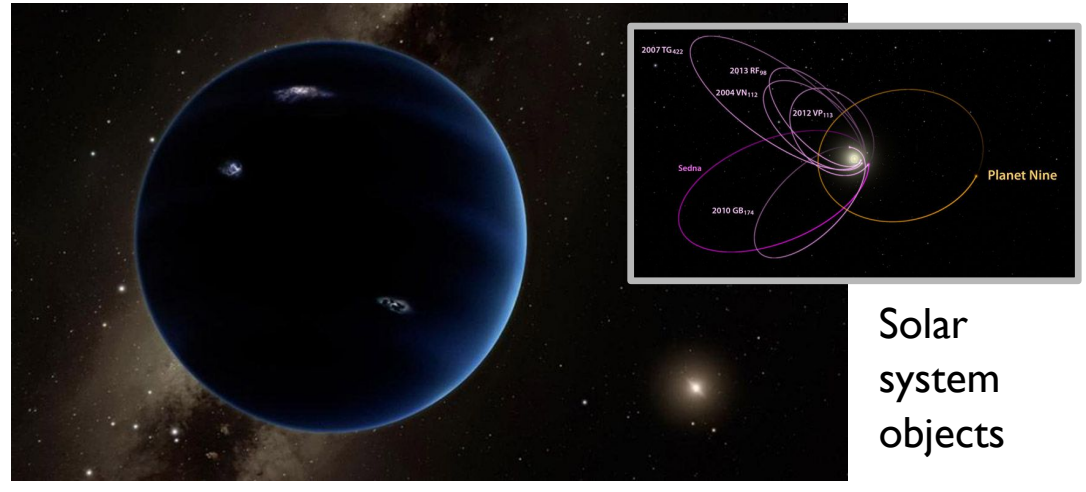




Active galactic nuclei

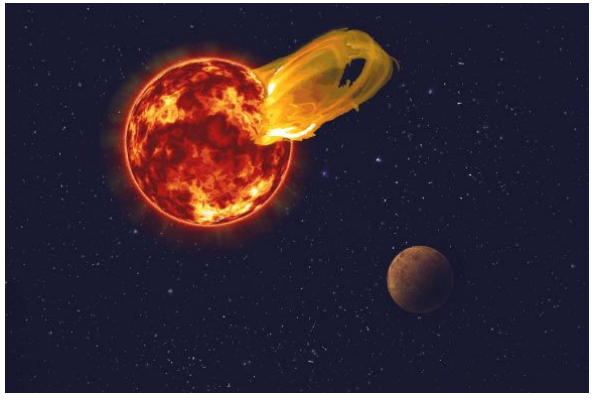
Tidal disruption events





Solar system objects

Stellar flares

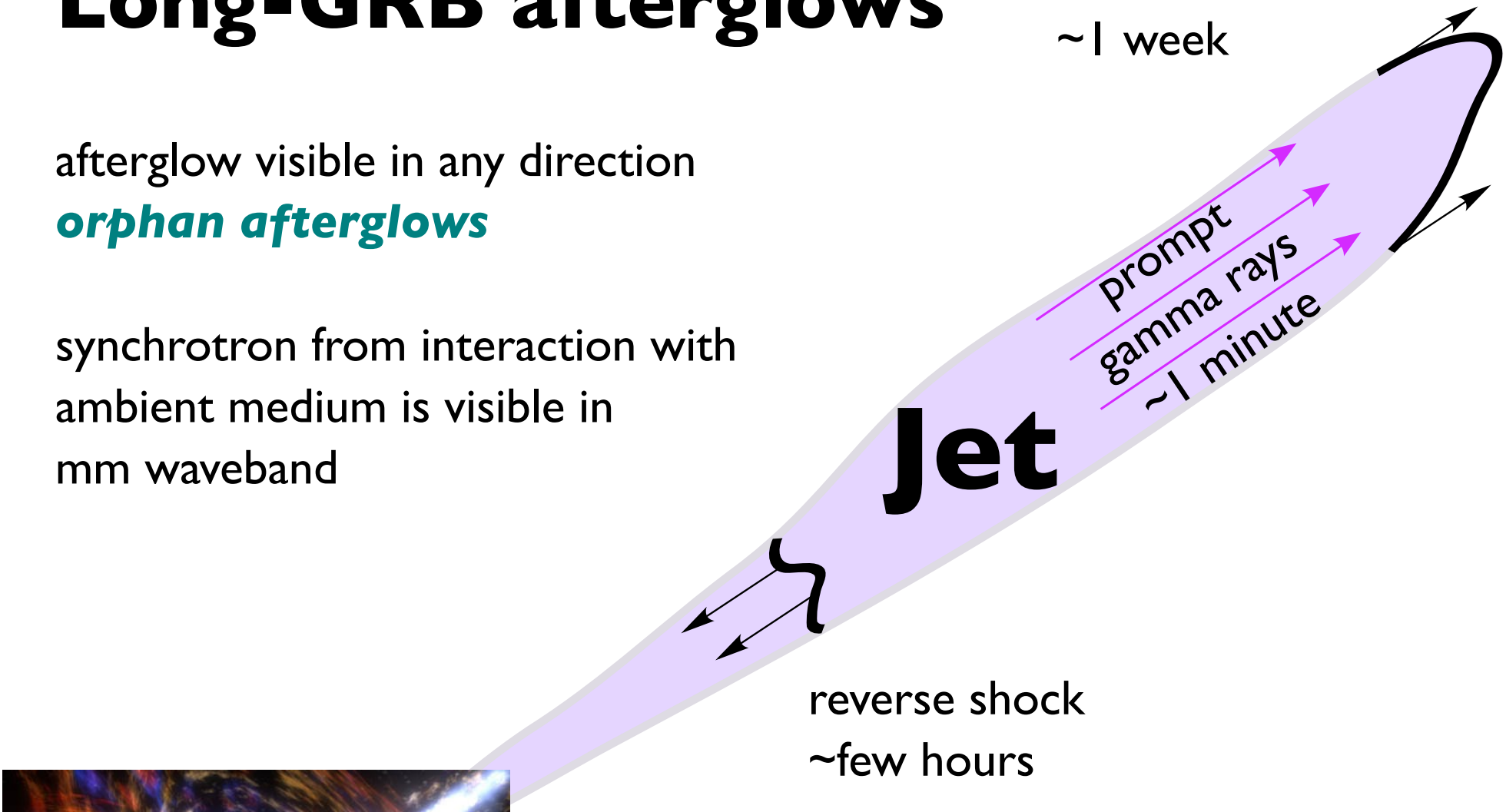


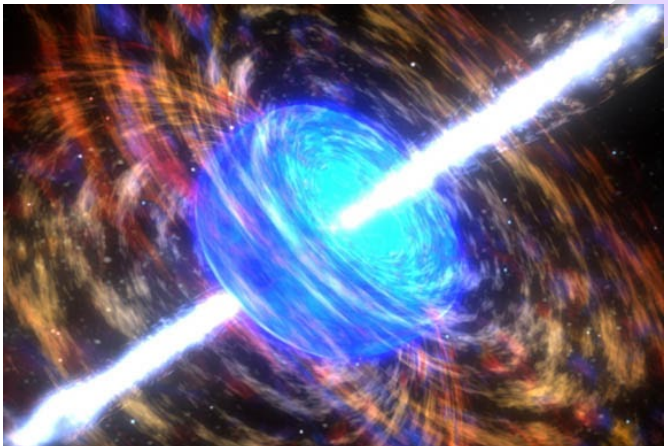
Long-GRB afterglows

afterglow visible in any direction

orphan afterglows

synchrotron from interaction with ambient medium is visible in mm waveband

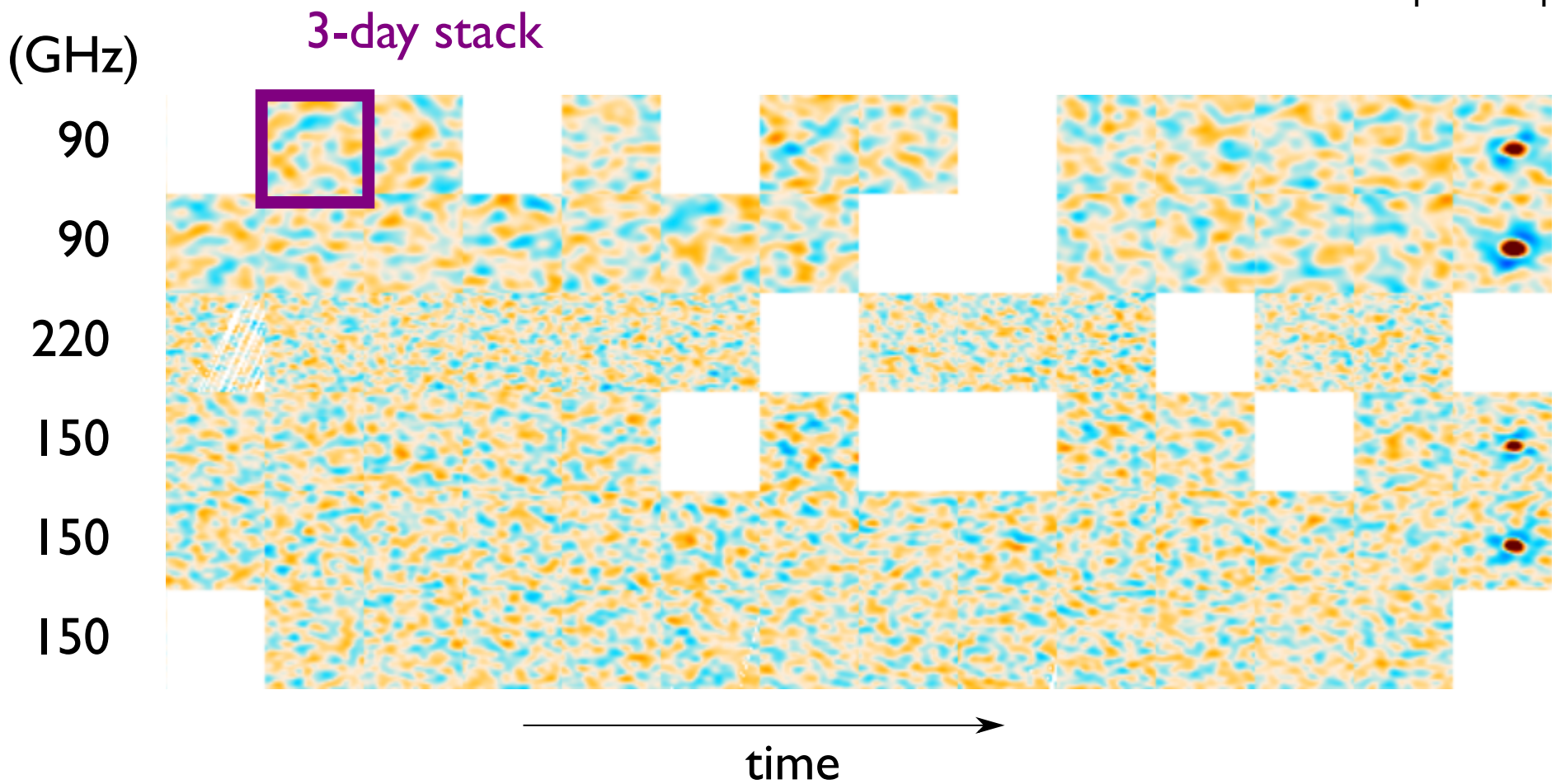




"collapsar/hypernova" direct collapse to black hole + accretion disk

ACT stellar transients

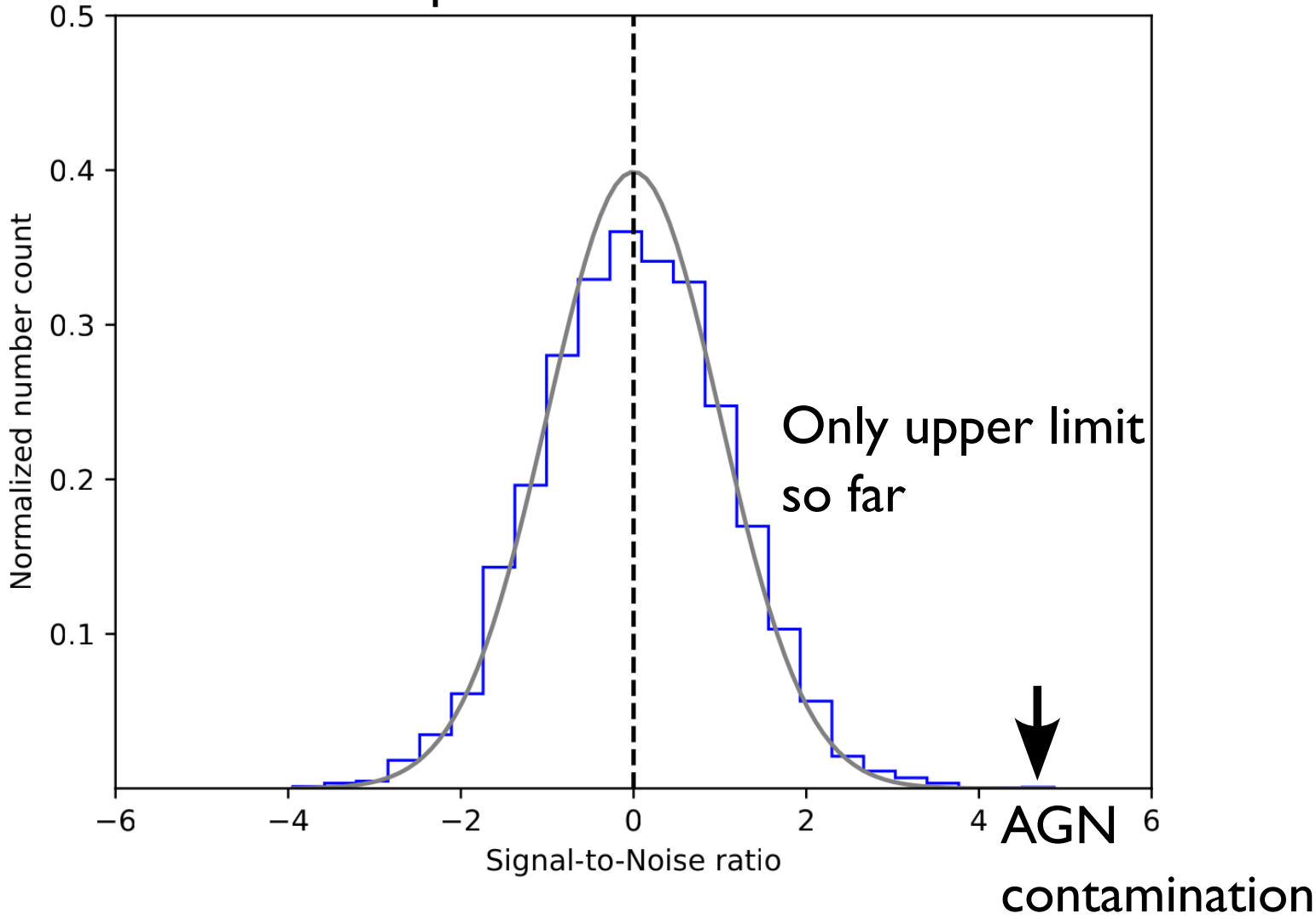
Naess++ 2021 (ACT)
Guns++ 2021 (SPT)
Li++ 2023 3-day search
Biermann++ 2024 Depth-1 maps



Diverse stars, young, main-sequence, magnetically active, binary

ACT archival multimessenger search

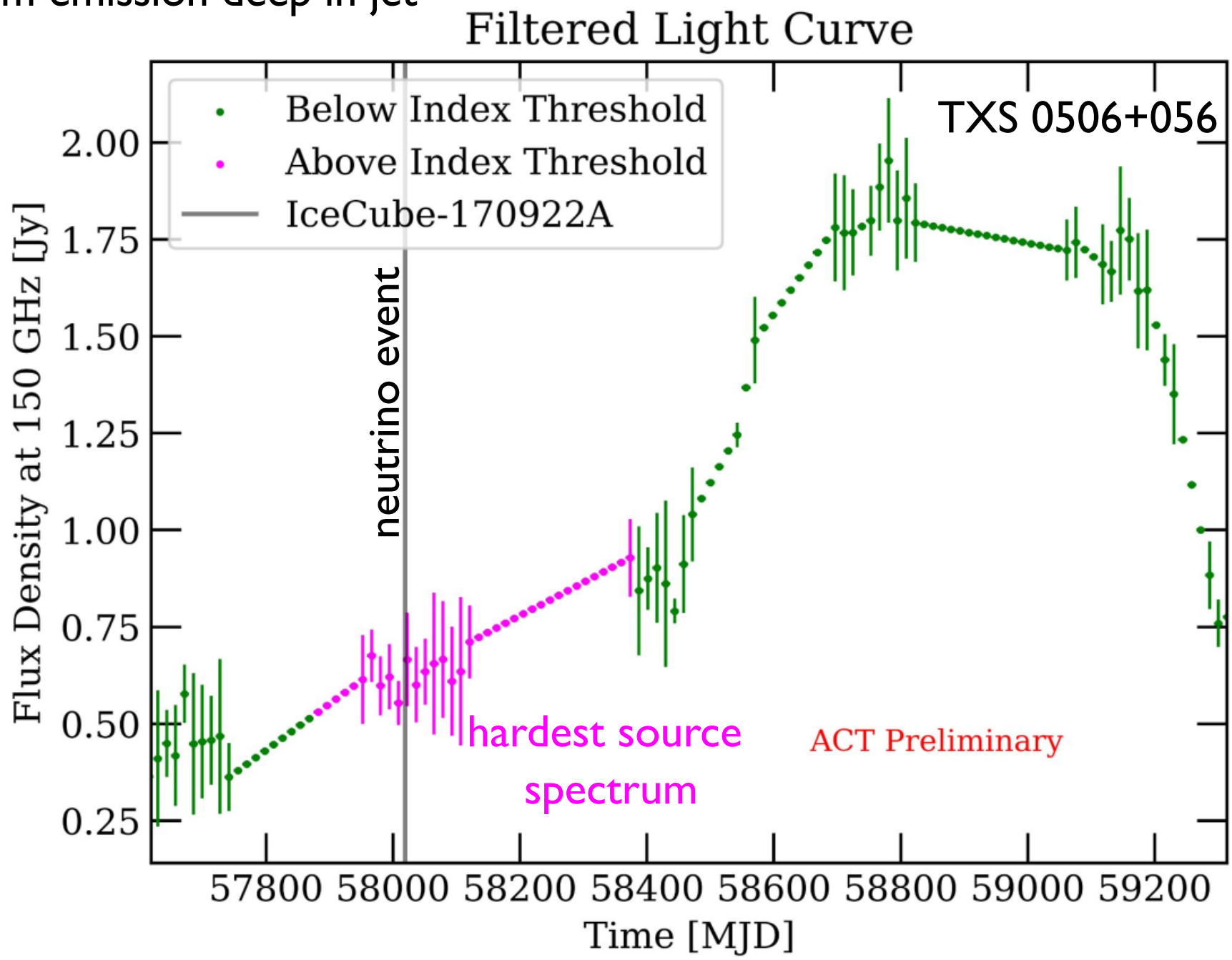
Hervias-Caimapo++ 2023 on known SNe/TDE/GRB



AGN variability

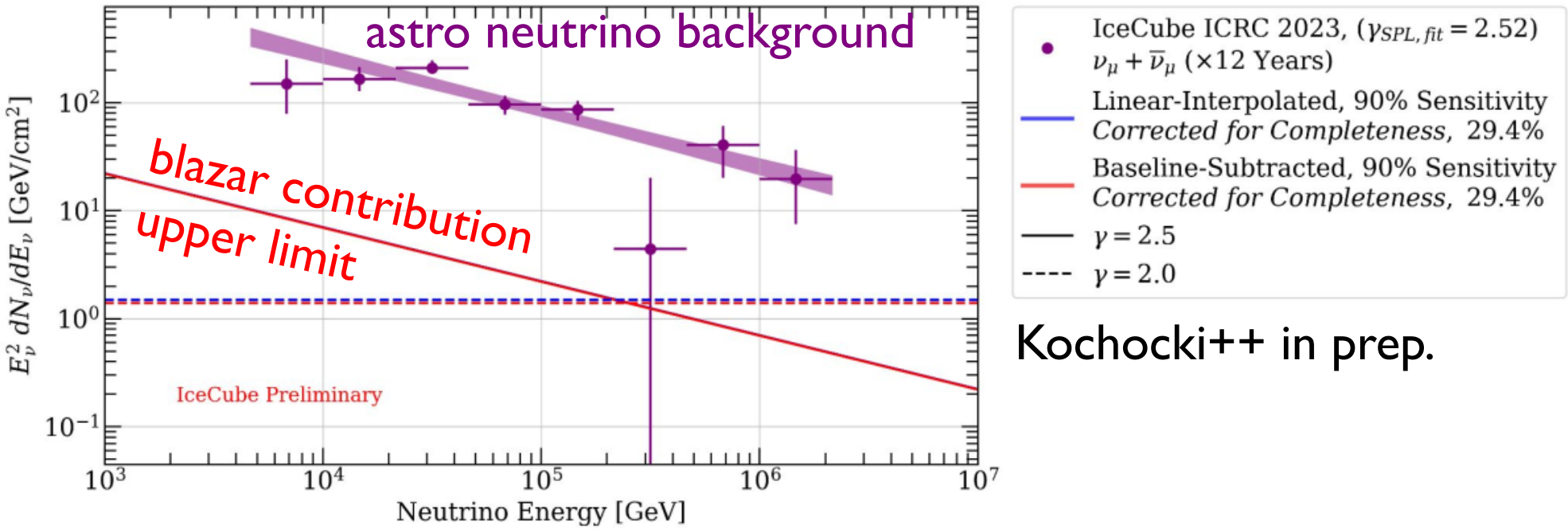
mm emission deep in jet

Kochocki++ in prep.



Limits on neutrino production

ACT: first catalog of ~200 brightest millimeter-blazar light curves (Hincks++ in prep.)



Kochocki++ in prep.

Preliminary: these blazars are not major contributors to the neutrino background. (Precise limit depends on the hypothesis for time-correlation.)

What are implications for leptonic vs. hadronic processes in jet?

Conclusions

CMB is rich in information about physics, astrophysics, and cosmology.

Multifrequency analysis, wide/deep coverage, high-/low-resolution all important (= ACT, SO, CMB-S4 for me)

Primordial B-modes, light relics are among several fundamental physics drivers, but there is also a bonzanza of astrophysics, including in the time domain.

Filament/MHD models for polarization foregrounds
Lensing growth of large-scale structure
Limits on targeted transients
AGN variability / neutrino correlations

Acknowledgments

Group members

Current postdocs: Fazlu Rahman Panam Parambil, Cristian Vargas (soon)

Current Graduate students: Bai-Chiang Chiang, Sophia Paulino Korte, Aaron Hughes

Past post-docs: Aditya Rotti (2015-2017, now Manchester), Gabriela Marques (2019-2022, now Fermilab), Carlos Hervias-Caimapo (2019-2022, now PUC, Santiago, Chile)

Past Graduate Students: Brittany Fuzia (2019, industry), Victoria Lakey (2020, now Lincoln University, PA), Felipe Maldonado (2021, museum education), S. Lucas Denny (2021, industry), John Waldroup (2023, further grad school)

Federal Funding

Sources & Transients: NSF AAG 2206344

B-mode foregrounds: DOE DE-SC0024462, NASA ADAP 80NSSC23K0466, NSF AAG 2009870, NASA ATP NNX17AF87G

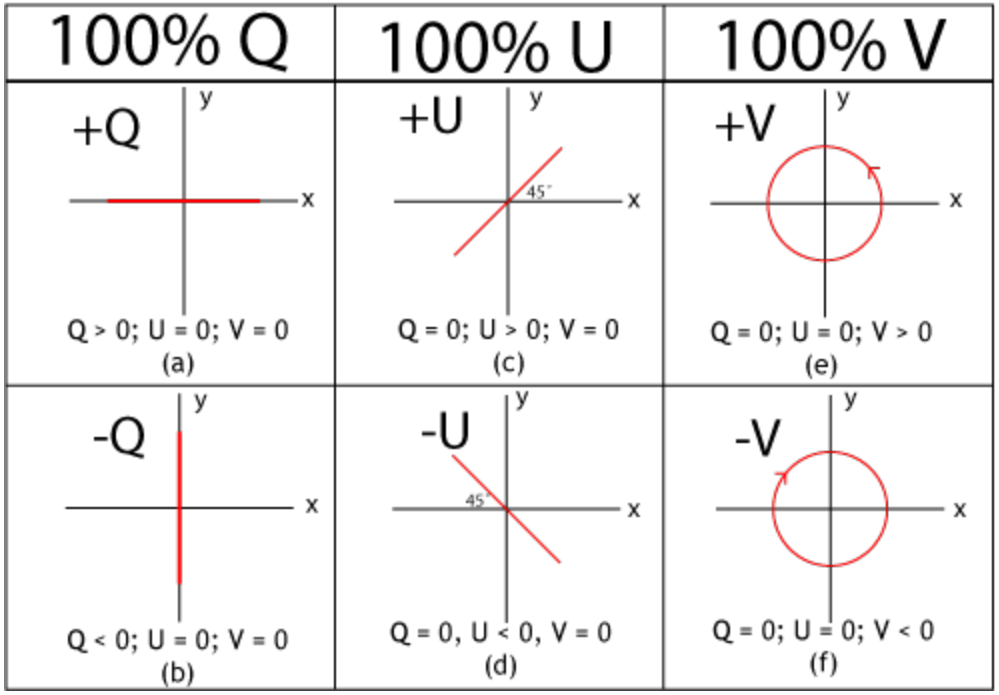
CMB data analysis techniques: NSF AAG 1815887

BACKUP SLIDES

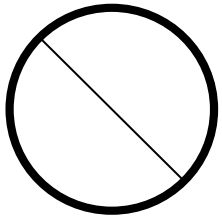
Polarization analysis

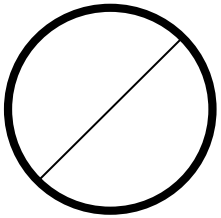
Step 1: decompose incoming E field into Stokes parameters:

T, Q, U, V



projected in polarized 3d

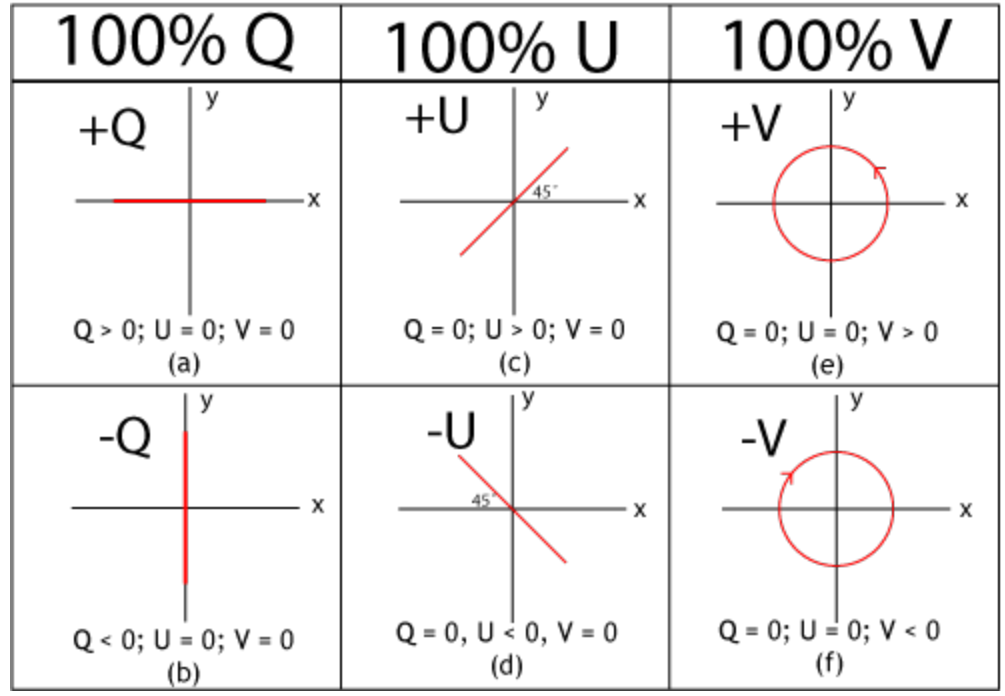




Polarization analysis

Step 1: decompose incoming E field into Stokes parameters:

T, Q, U, V



Step 2: rewrite in spin-0 and spin-2 sph. harm. basis:

$$
\begin{aligned}
T(\mathbf{n}) &= \sum_{lm} a_{T,lm} Y_{lm}(\mathbf{n}) \\
(Q+iU)(\mathbf{n}) &= \sum_{lm} a_{2,lm}\ {}_2Y_{lm}(\mathbf{n}) \\
(Q-iU)(\mathbf{n}) &= \sum_{lm} a_{-2,lm}\ {}_{-2}Y_{lm}(\mathbf{n})
\end{aligned}
$$

Polarization analysis

Step 3: Take even and odd parity combinations.

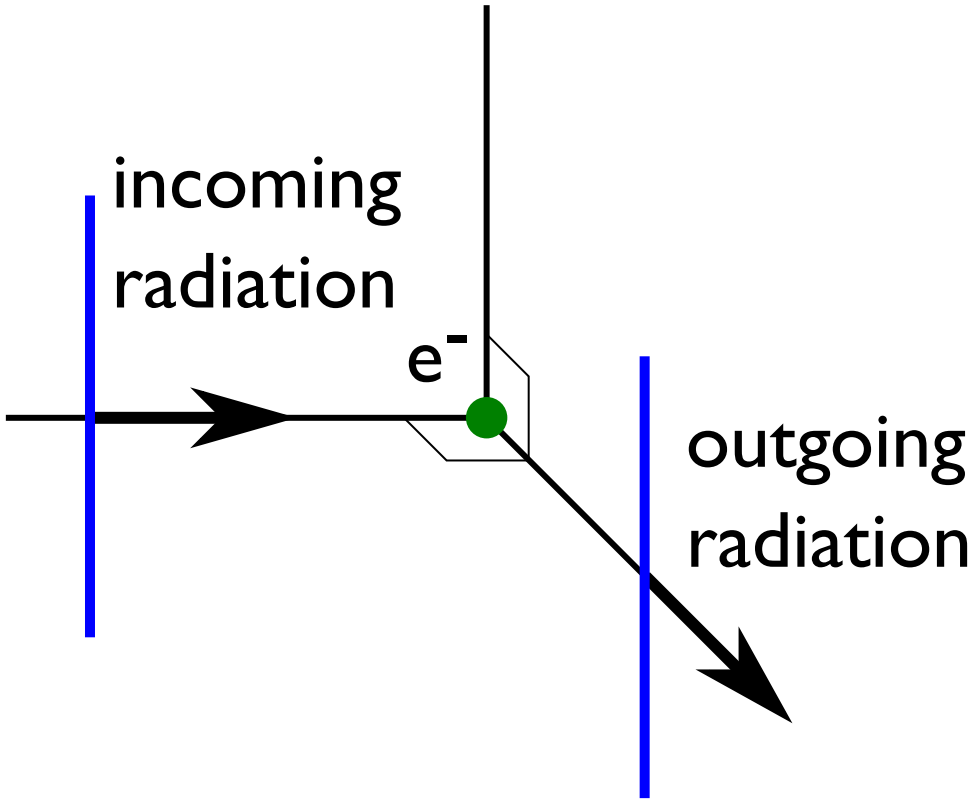
$$a_{E,lm} = -(a_{2,lm} + a_{-2,lm})/2 \qquad \text{even}$$
$$a_{B,lm} = -(a_{2,lm} - a_{-2,lm})/2i, \qquad \text{odd}$$

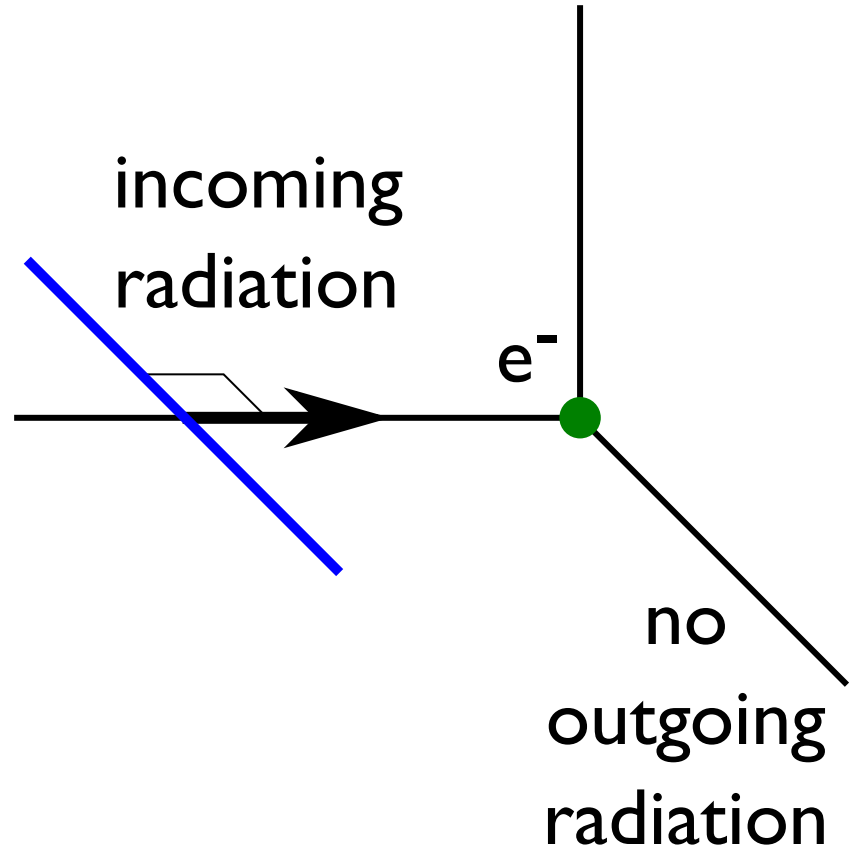
Variance of a_{lm}s are "easy" to compute from theory for T, E, B.

e.g.
$$\langle a^B_{lm} a^{B*}_{lm} \rangle = \delta_{mm'} C_l^{BB}$$

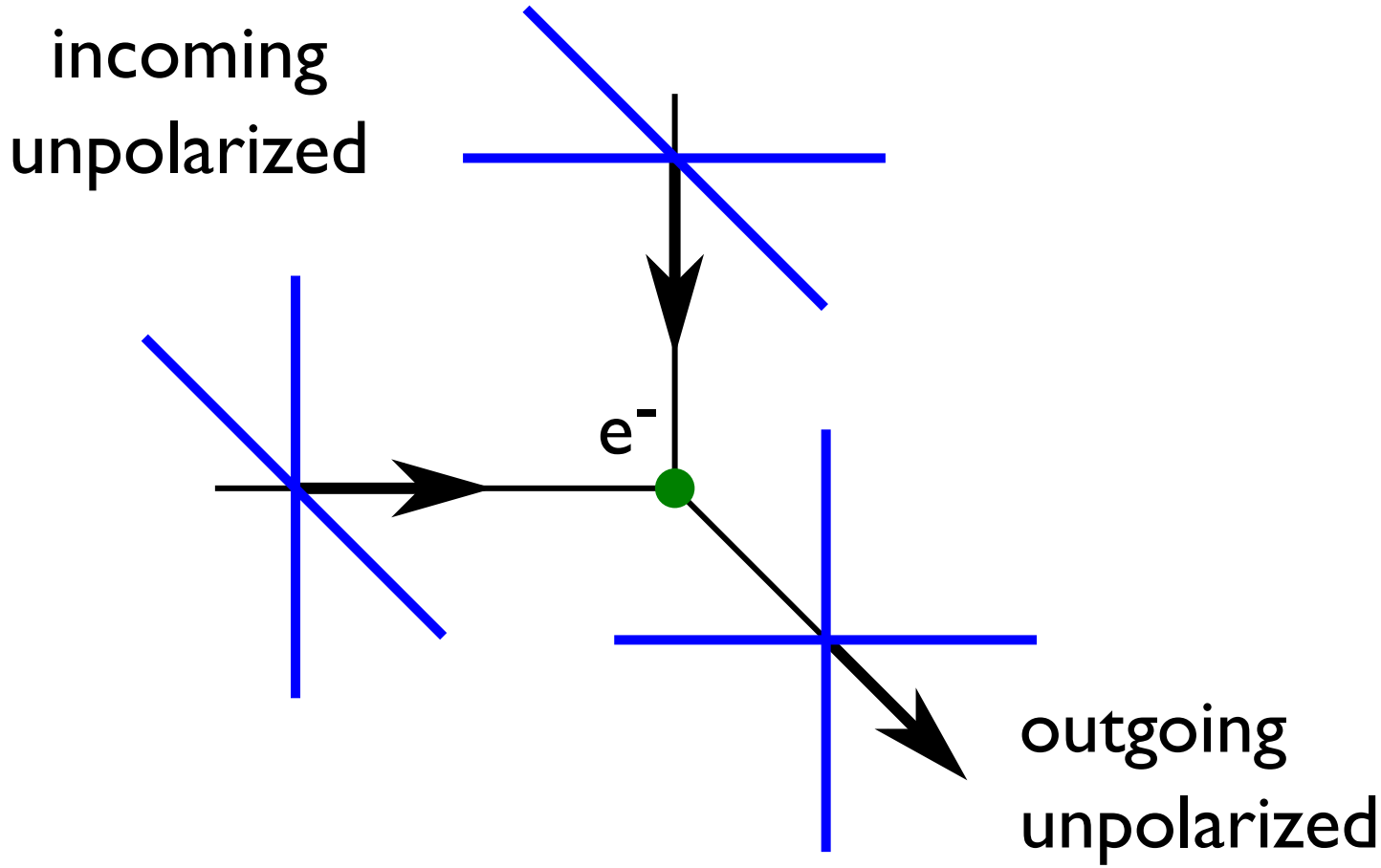
Theory: init'l 3d P(k) for fluct. from infl. (scal., tens.)
composition (gives expansion history and growth)

Polarization in Thomson Scattering

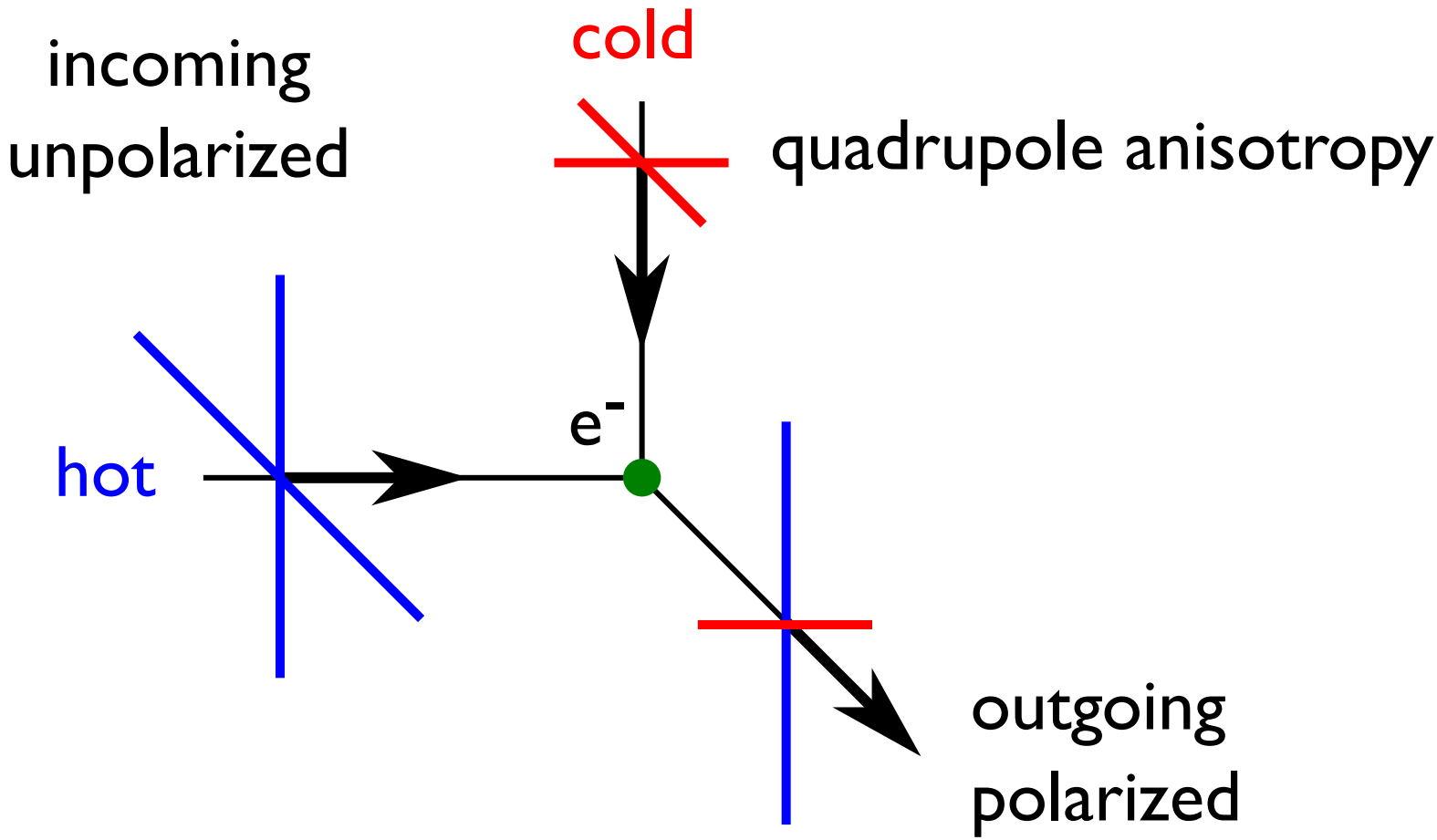


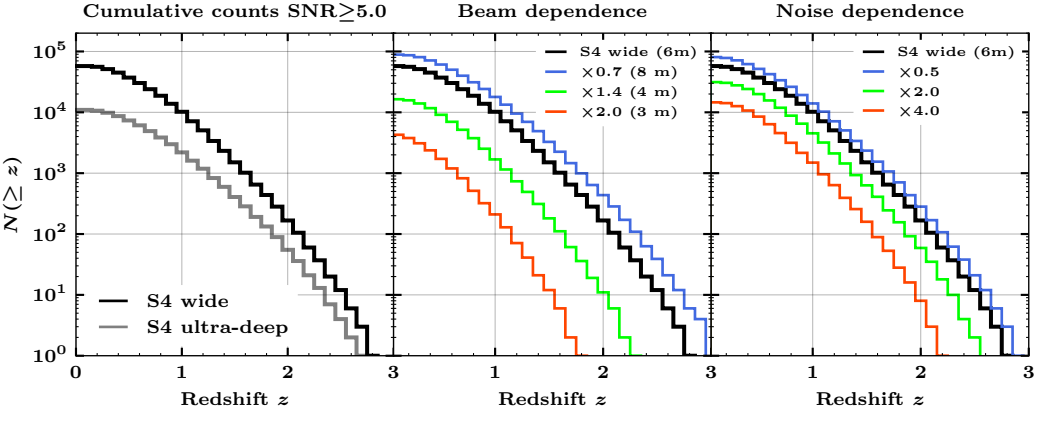


Polarization in Thomson Scattering



Polarization in Thomson Scattering

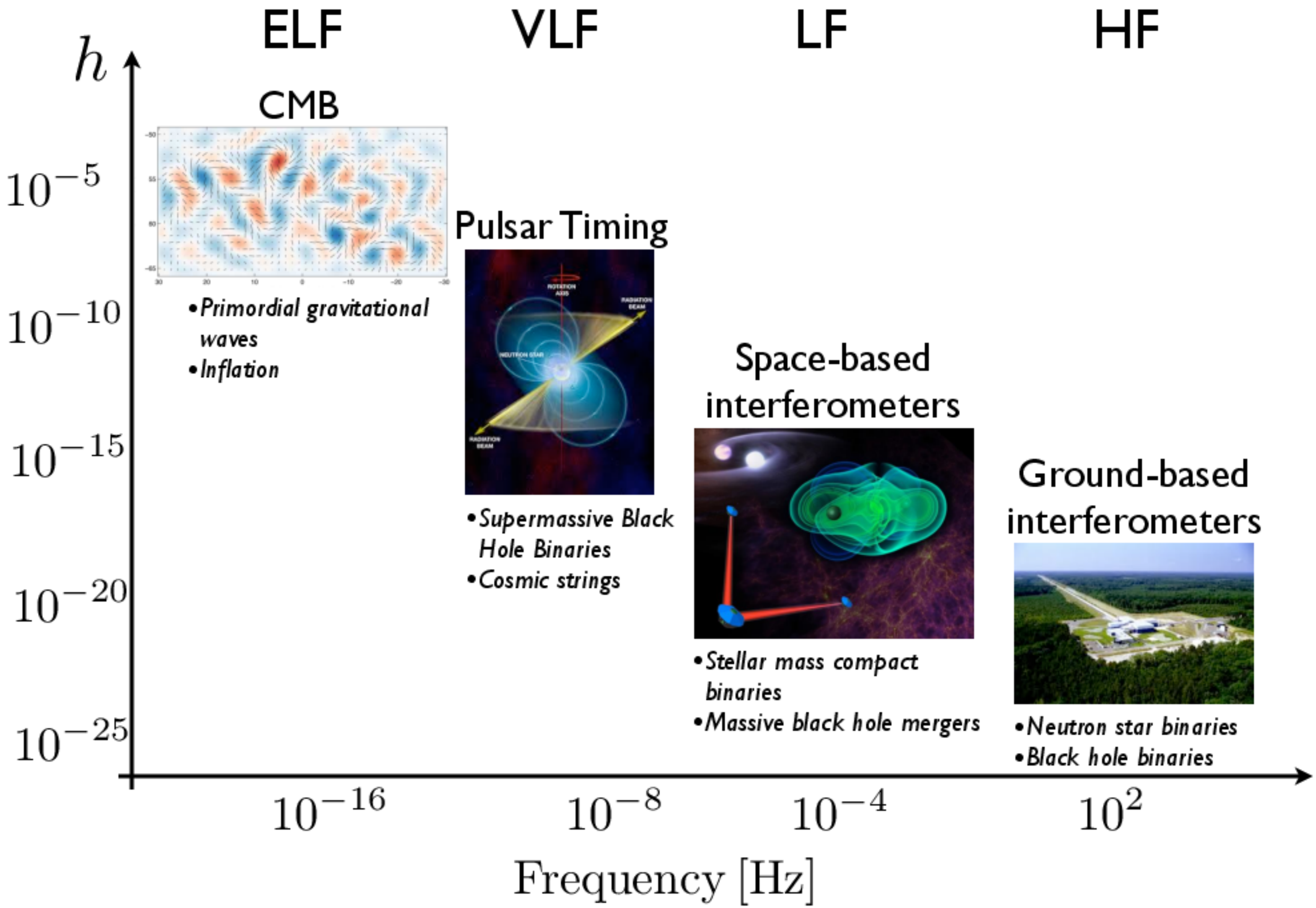



Cumulative counts SNR≥5.0
Beam dependence
Noise dependence
N(≥ z)
Redshift z
S4 wide
S4 ultra-deep
S4 wide (6m)
×0.7 (8 m)
×1.4 (4 m)
×2.0 (3 m)
S4 wide (6m)
×0.5
×2.0
×4.0

Polarization

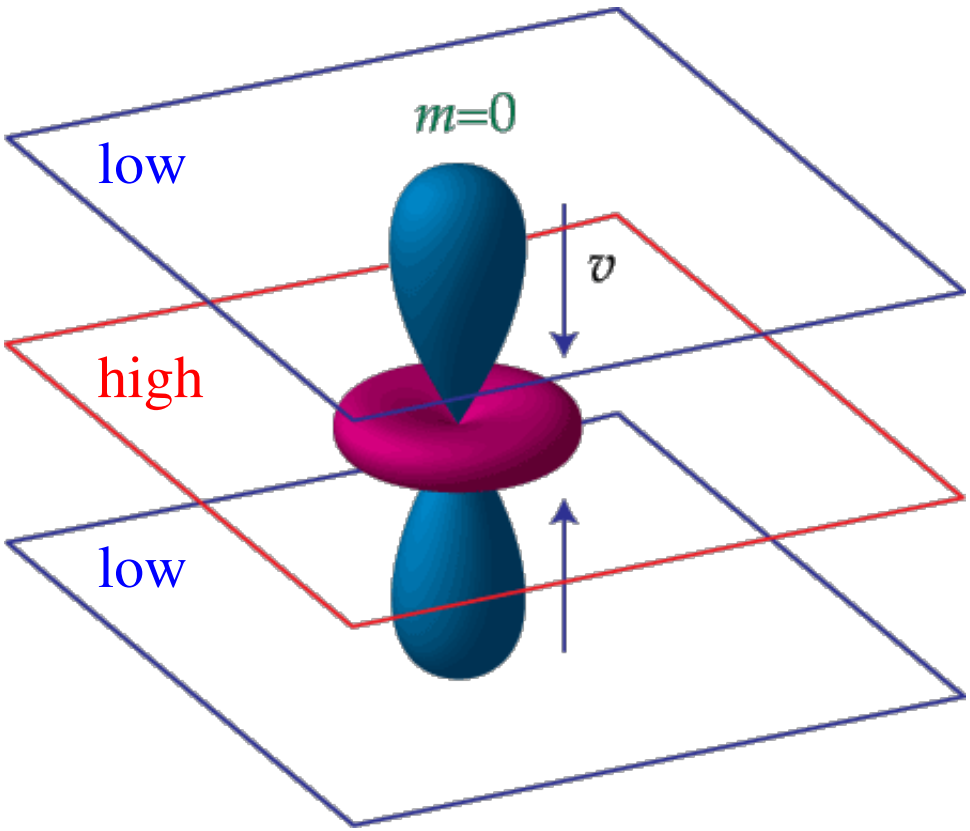
B modes

The big picture of gravitational wave astronomy

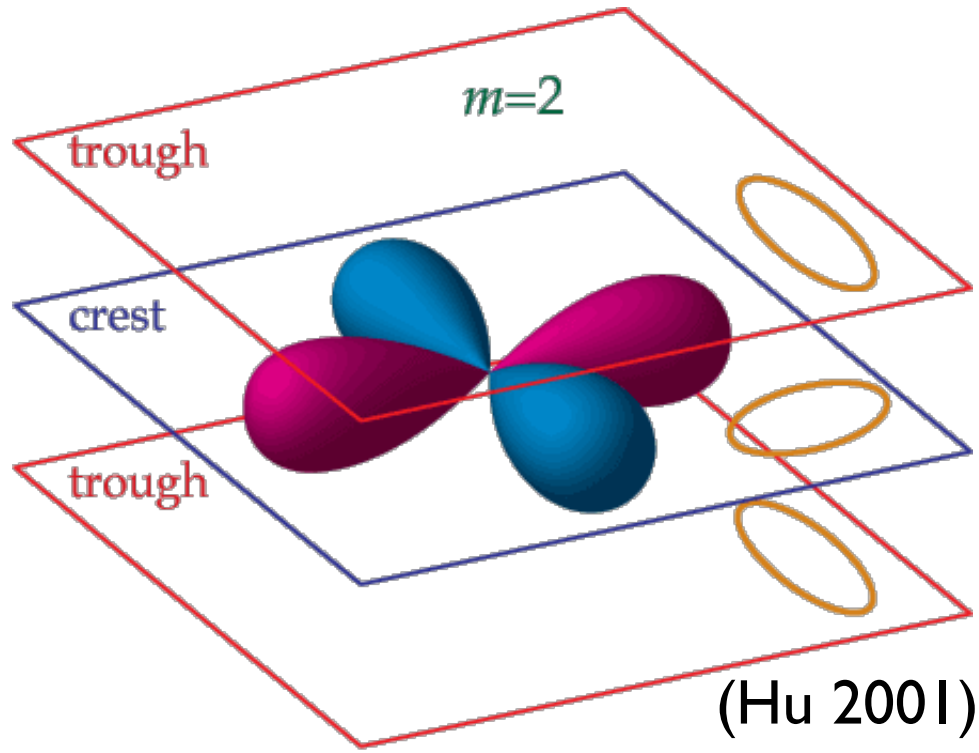


Perturbations generating quadrupoles

Scalar



Tensor



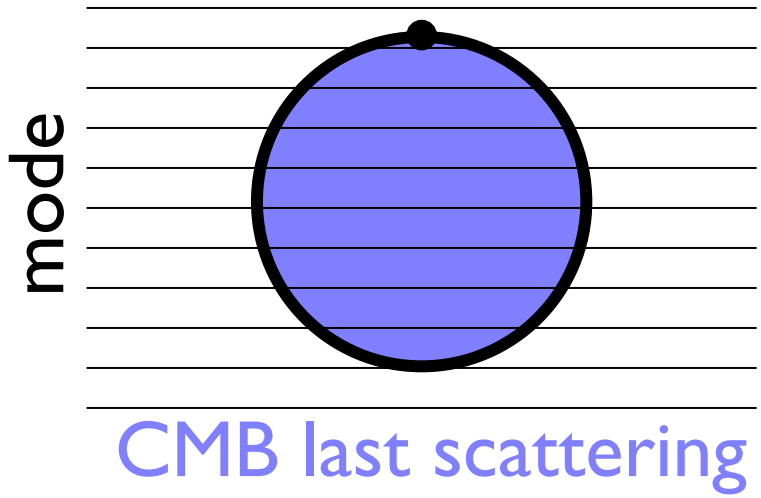
(Hu 2001)

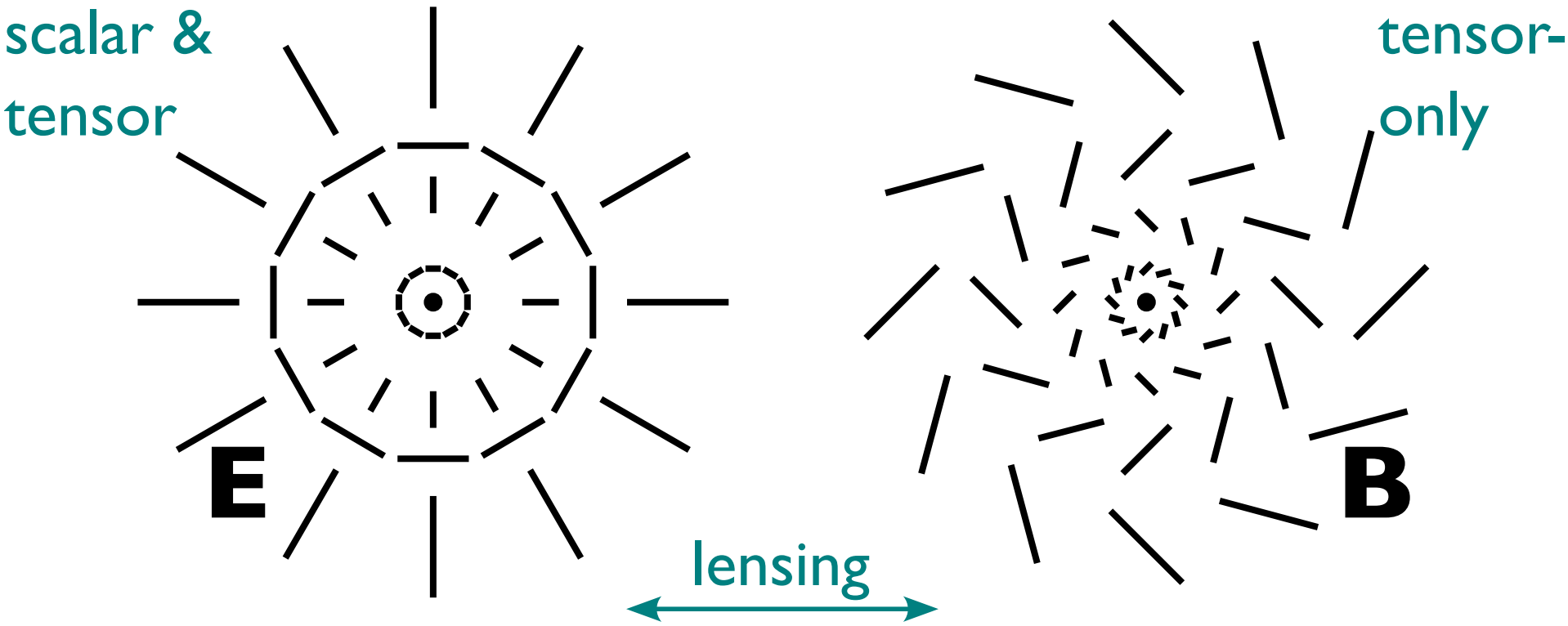
density

gravity wave

inflation

Types of polarization patterns

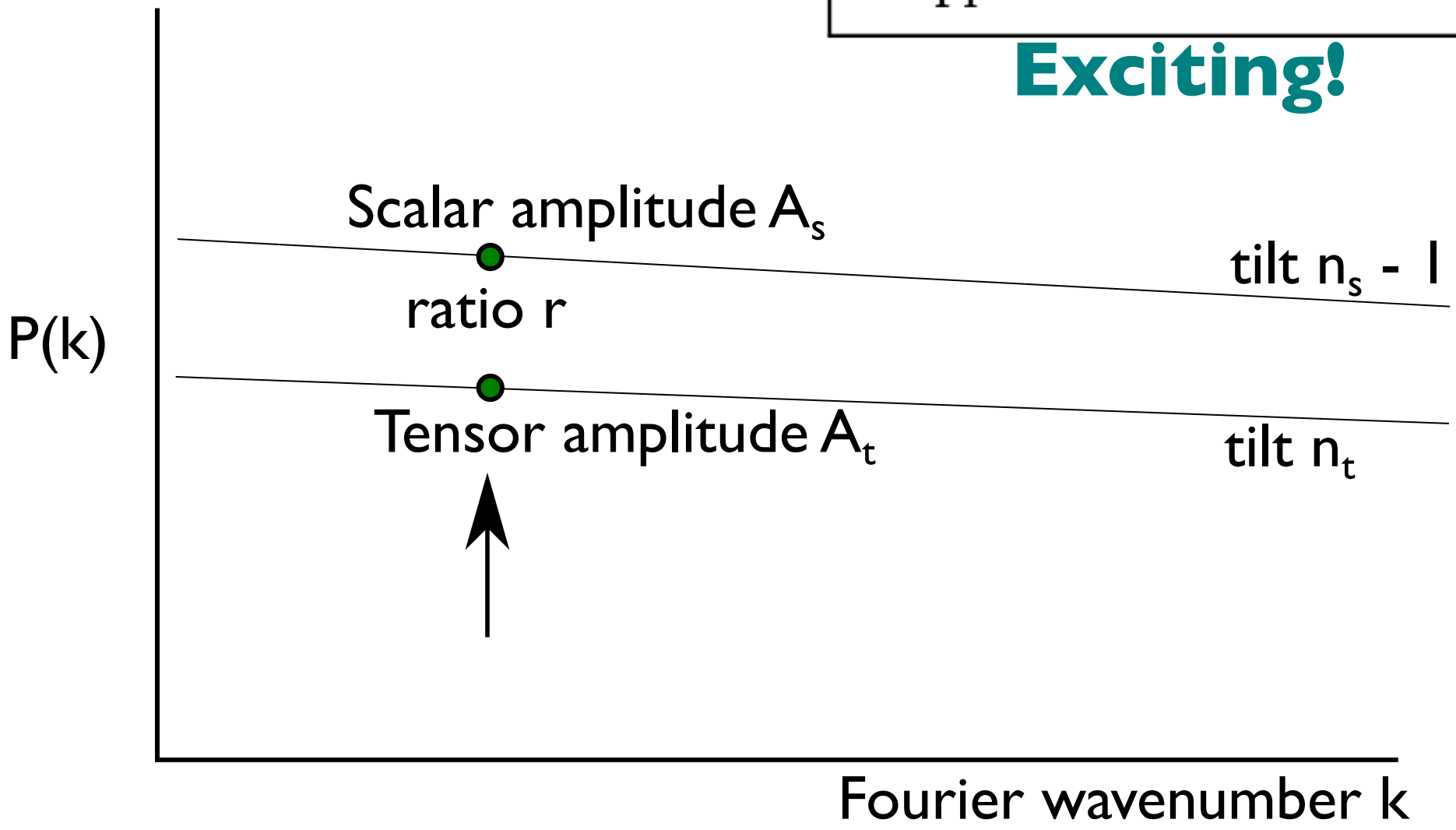




inflaton potential

$$r = \frac{8}{M_{\rm Pl}^2}\left(\frac{d\phi}{dN}\right)^2 \longrightarrow \boxed{\frac{\Delta\phi}{M_{\rm Pl}} = \mathcal{O}(1)\sqrt{\frac{r}{0.01}}.}$$

Exciting!



Light Relic Particles

Light relic particles

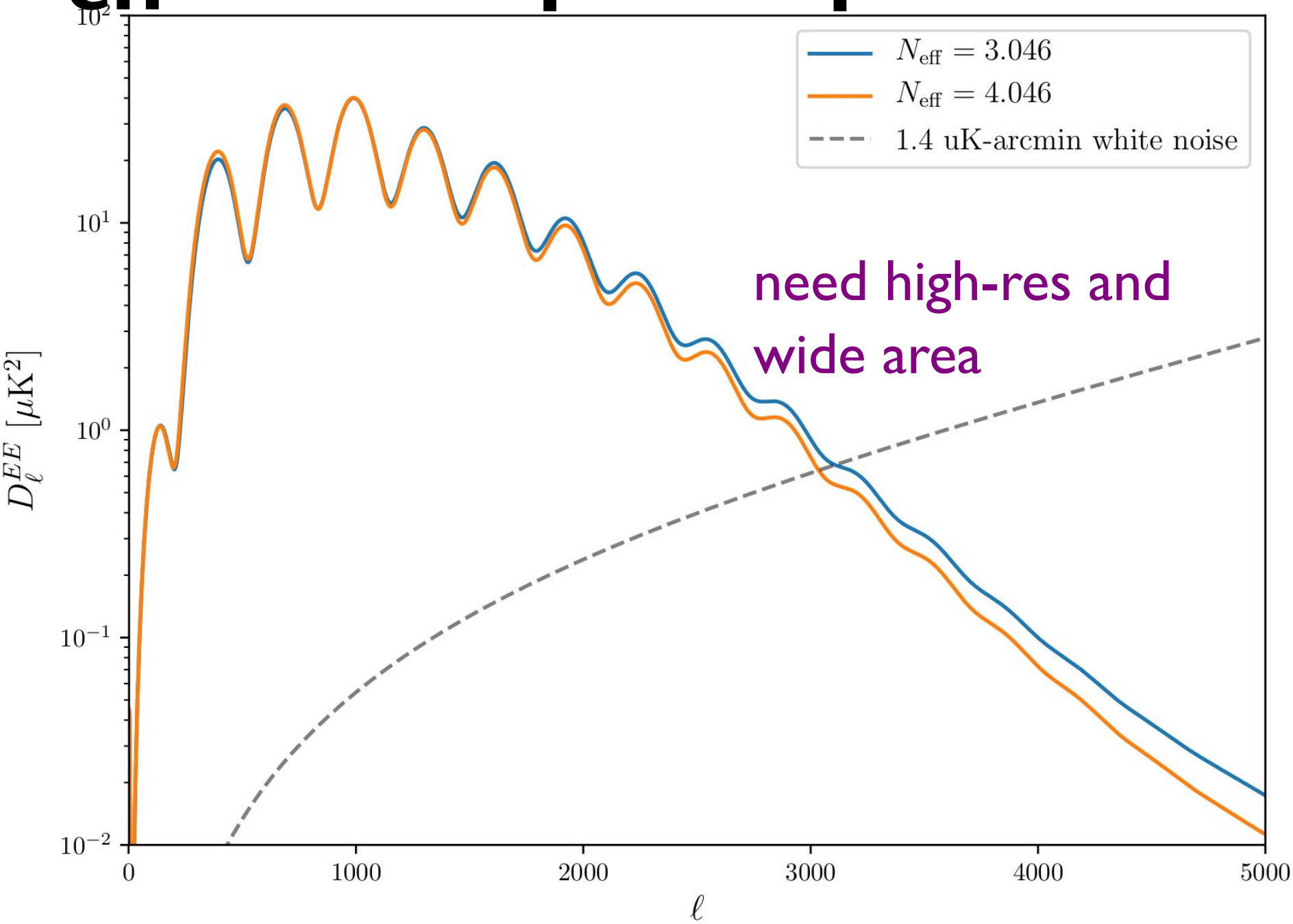
Once they decouple/freeze out, relativistic, free-streaming particles move mass-energy density out of overdensities

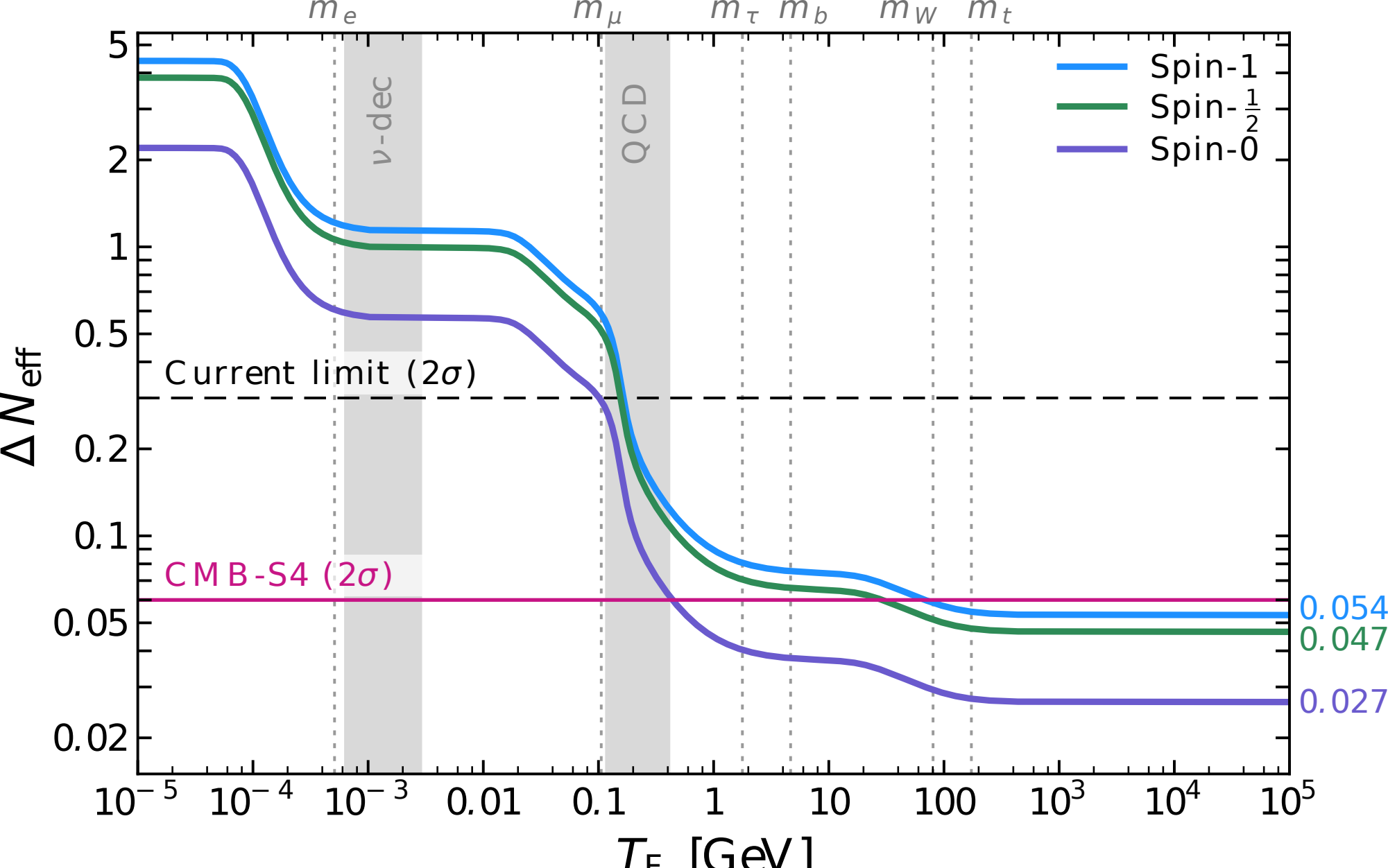
SM has only ν, but any BSM light thermal particle is similar: axion, sterile neutrinos, etc.

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma} \qquad N_{\rm eff}^{\rm SM} = 3.044$$

*would be exactly 3 for instant ν decoupling

N_{eff} effect on power spectrum




m_e
m_μ
m_τ
m_b
m_W
m_t
ν-dec
QCD
Spin-1
Spin-$\frac{1}{2}$
Spin-0
Current limit (2σ)
CMB-S4 (2σ)
0.054
0.047
0.027
$\Delta N_{\rm eff}$
$T_{\rm F}$ [GeV]