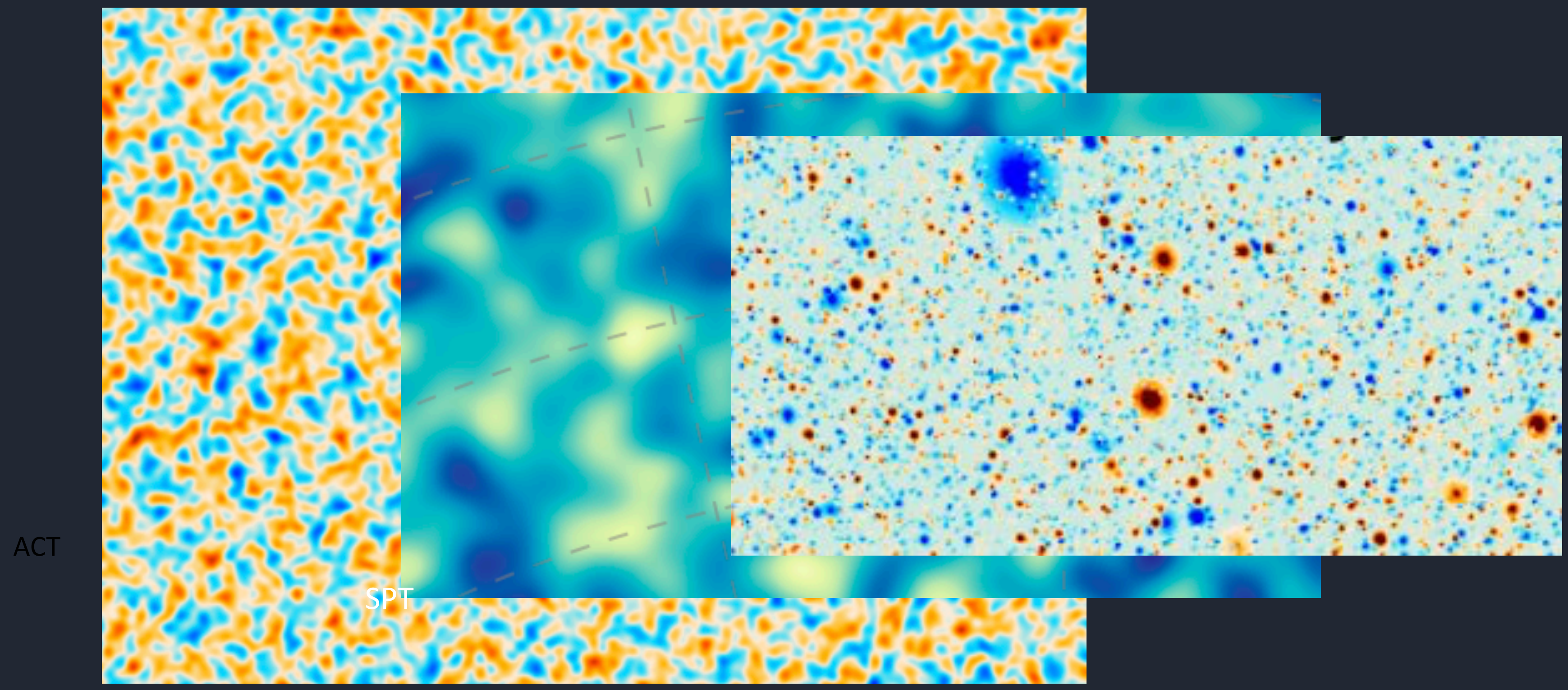
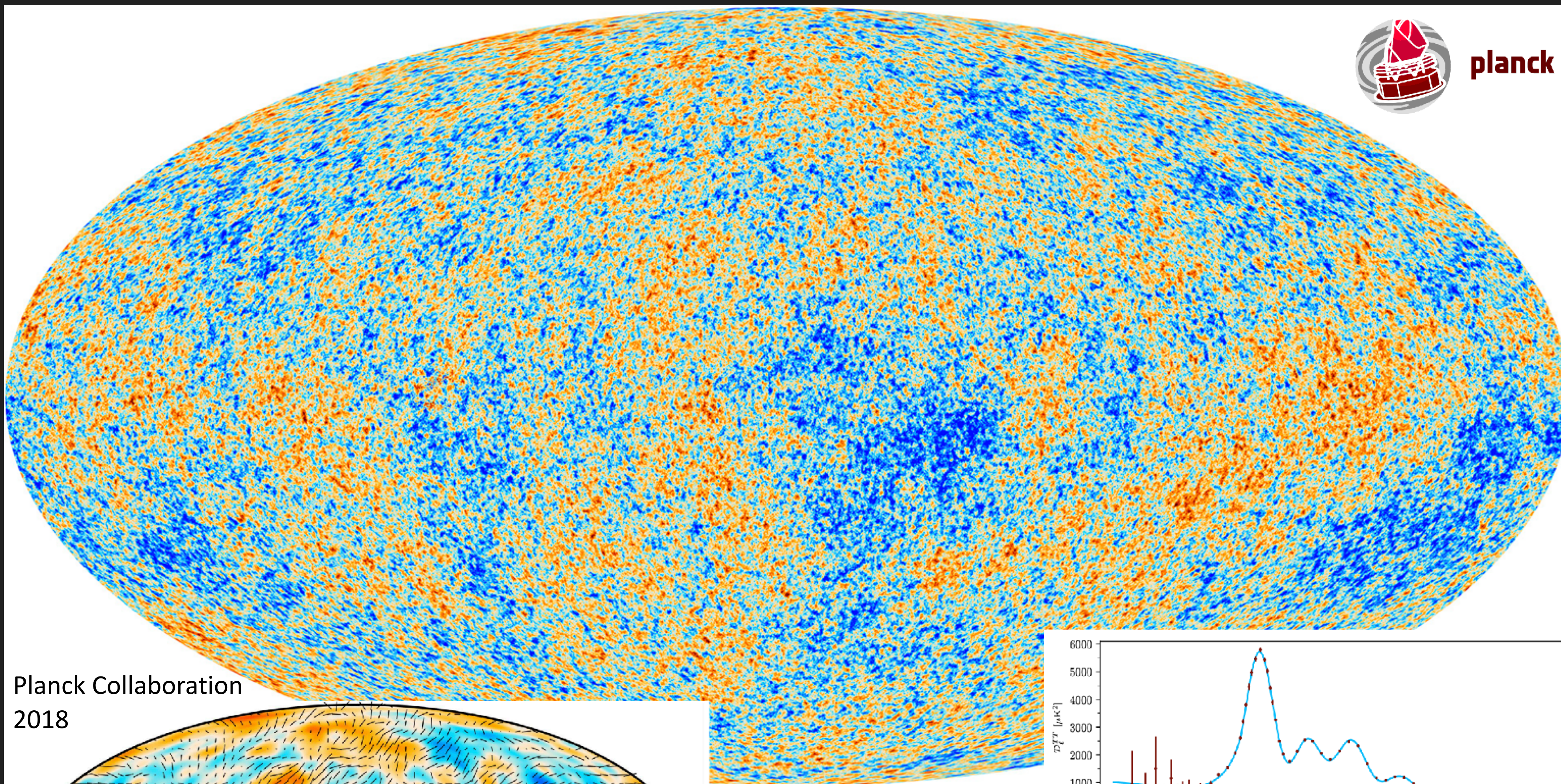
Key future science goals for the CMB



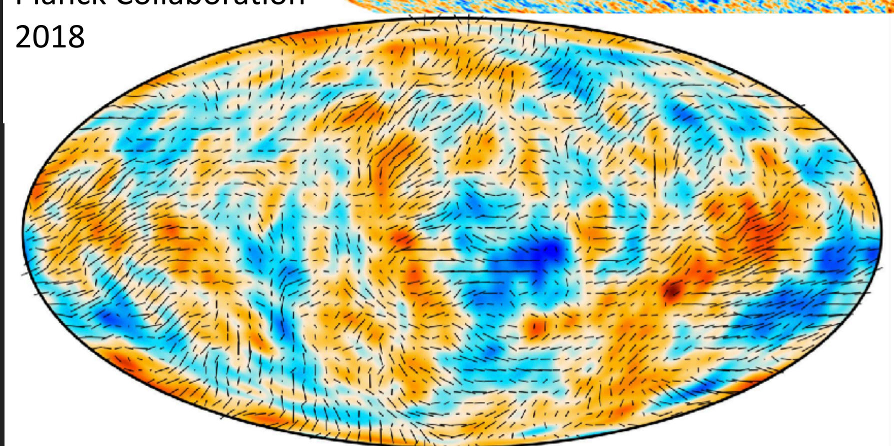
Jo Dunkley, Princeton University

Ferrara workshop May 2022

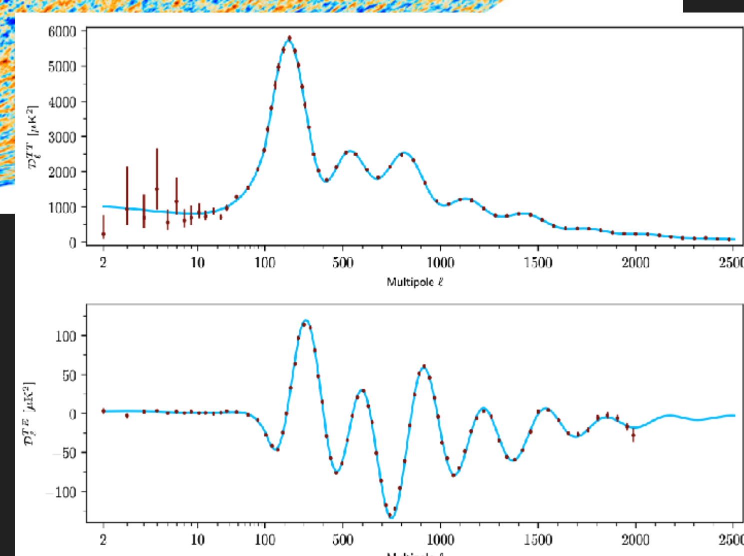
The Planck satellite



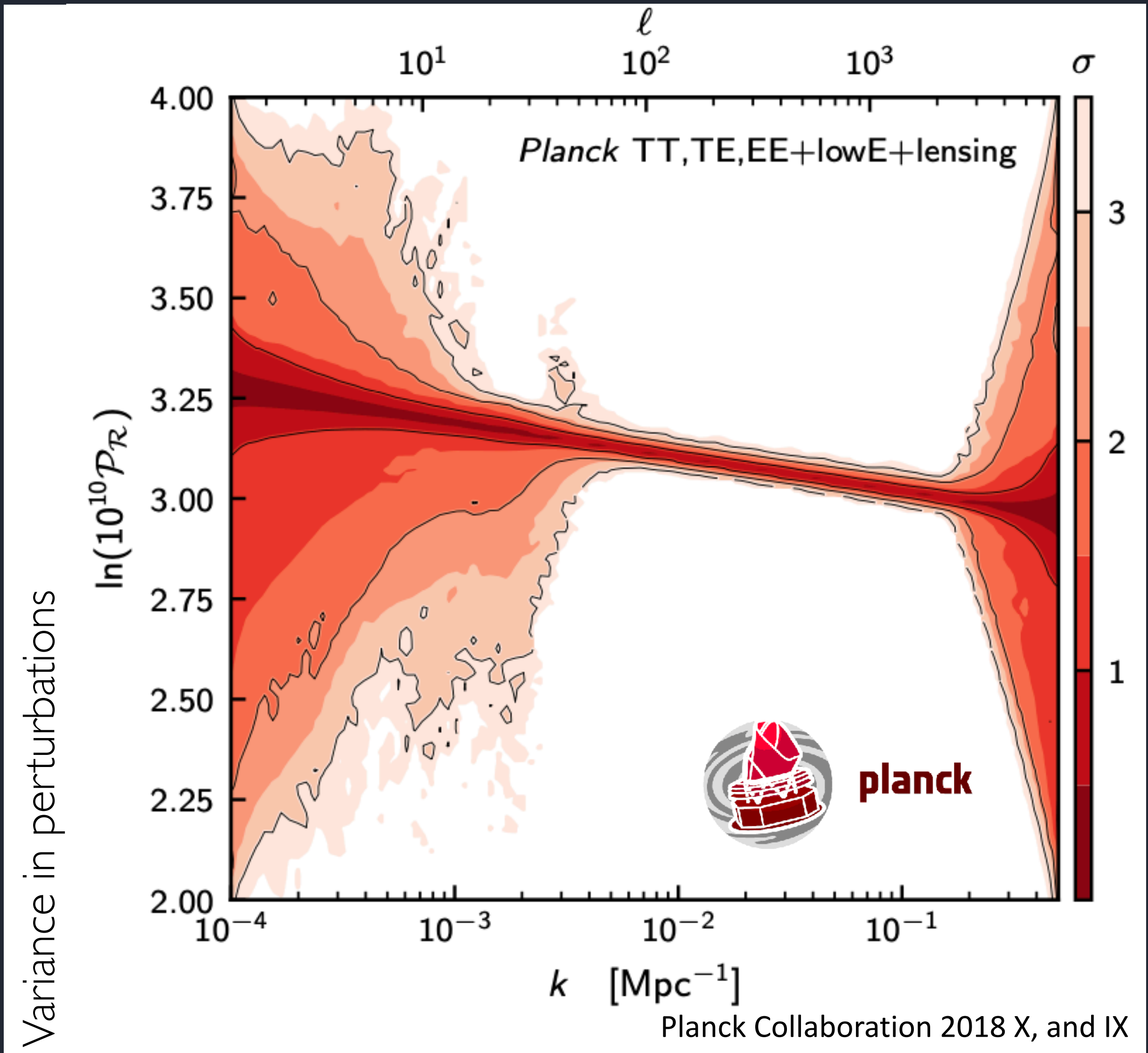
Planck Collaboration
2018



The model that best describes our universe is still ΛCDM



Initial conditions



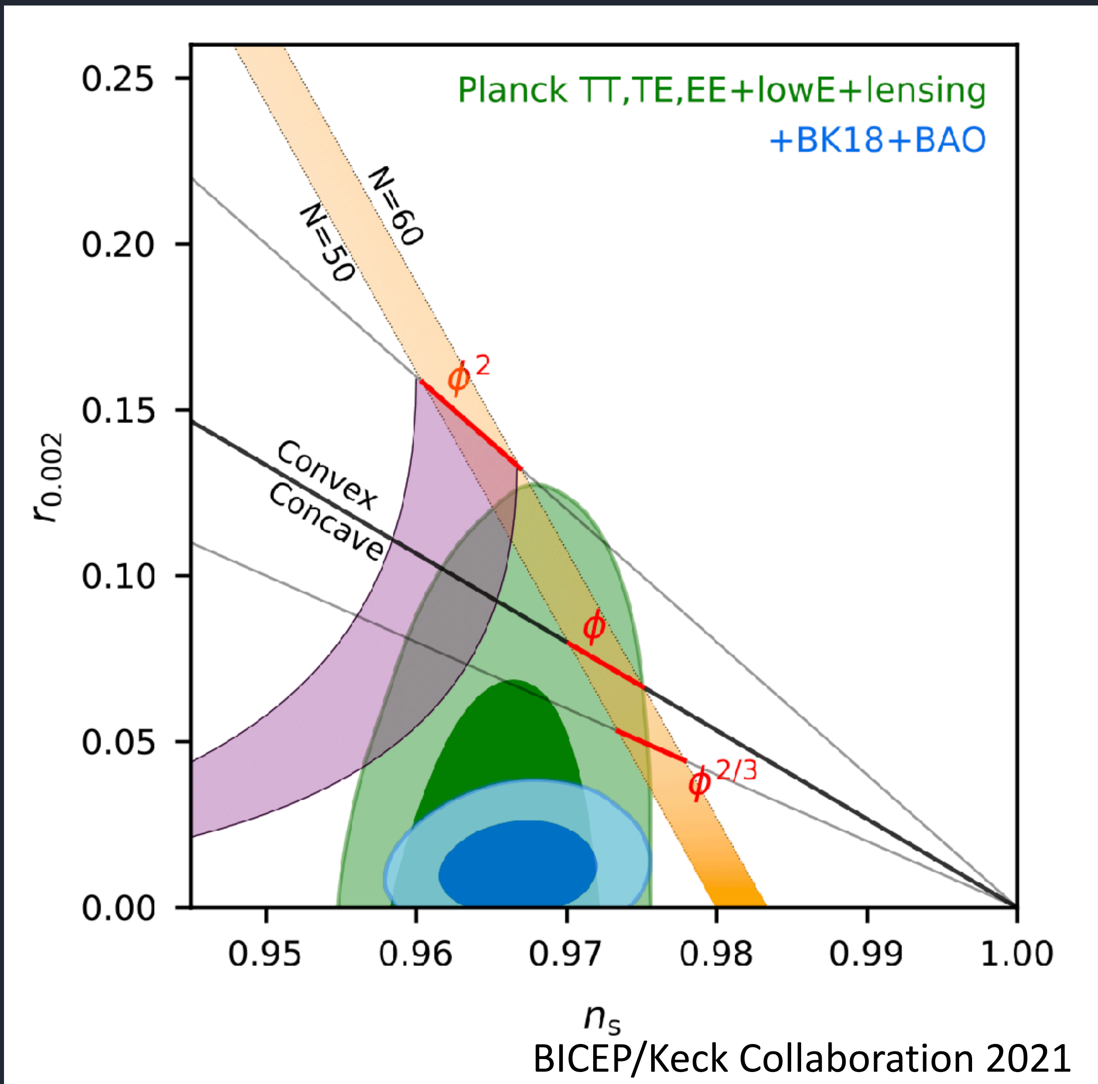
Planck Collaboration 2018 X, and IX

Scalars: described by two variables: amplitude and slope of power spectrum

- No departure from power law
  $dn/d\ln k = -0.005 \pm 0.007$, Planck
- No departure from adiabatic
  Variance in CMB < 2%, Planck
- No departure from Gaussian
  $f_{NL\text{-}Local} = -1 \pm 5$, Planck

—> compatible with single-field inflation

Initial conditions



Tensors: no sign yet of gravitational waves from ~10^{16} GeV scales, with rapidly improving limits

$r = P_T/P_S < 0.036$ (95% CL)
BICEP/Keck 2021
(<0.056 Planck PR4 Tristram et al)

Ingredients & geometry

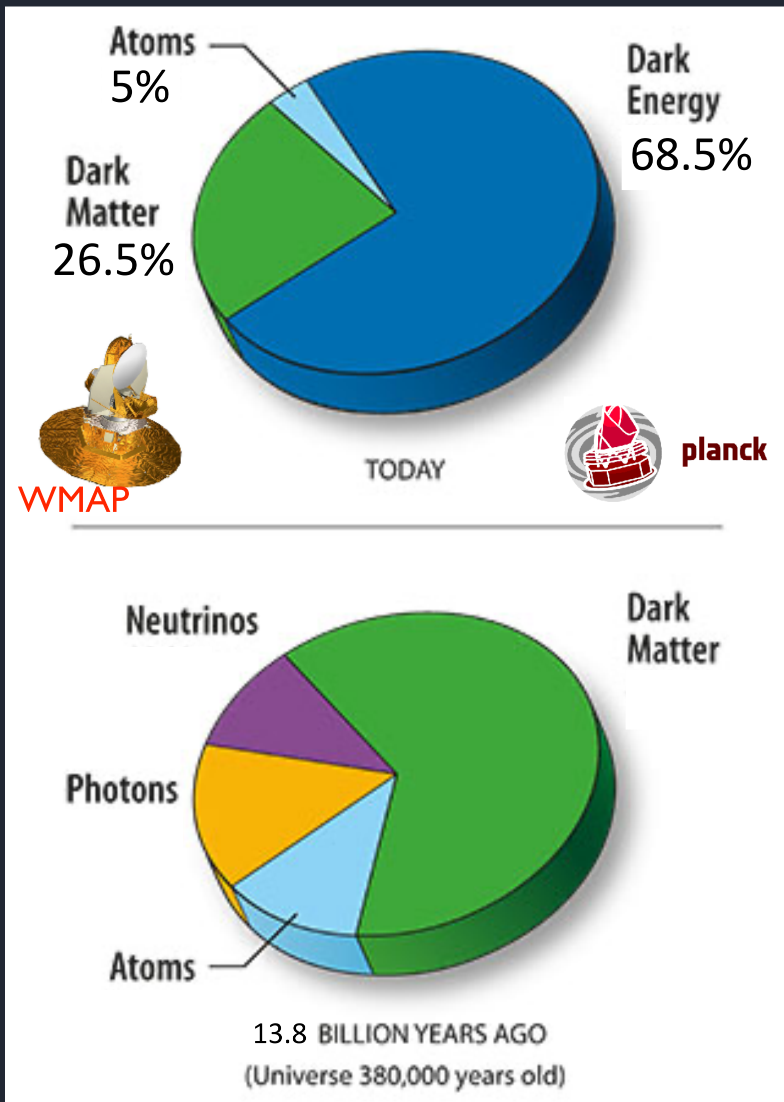
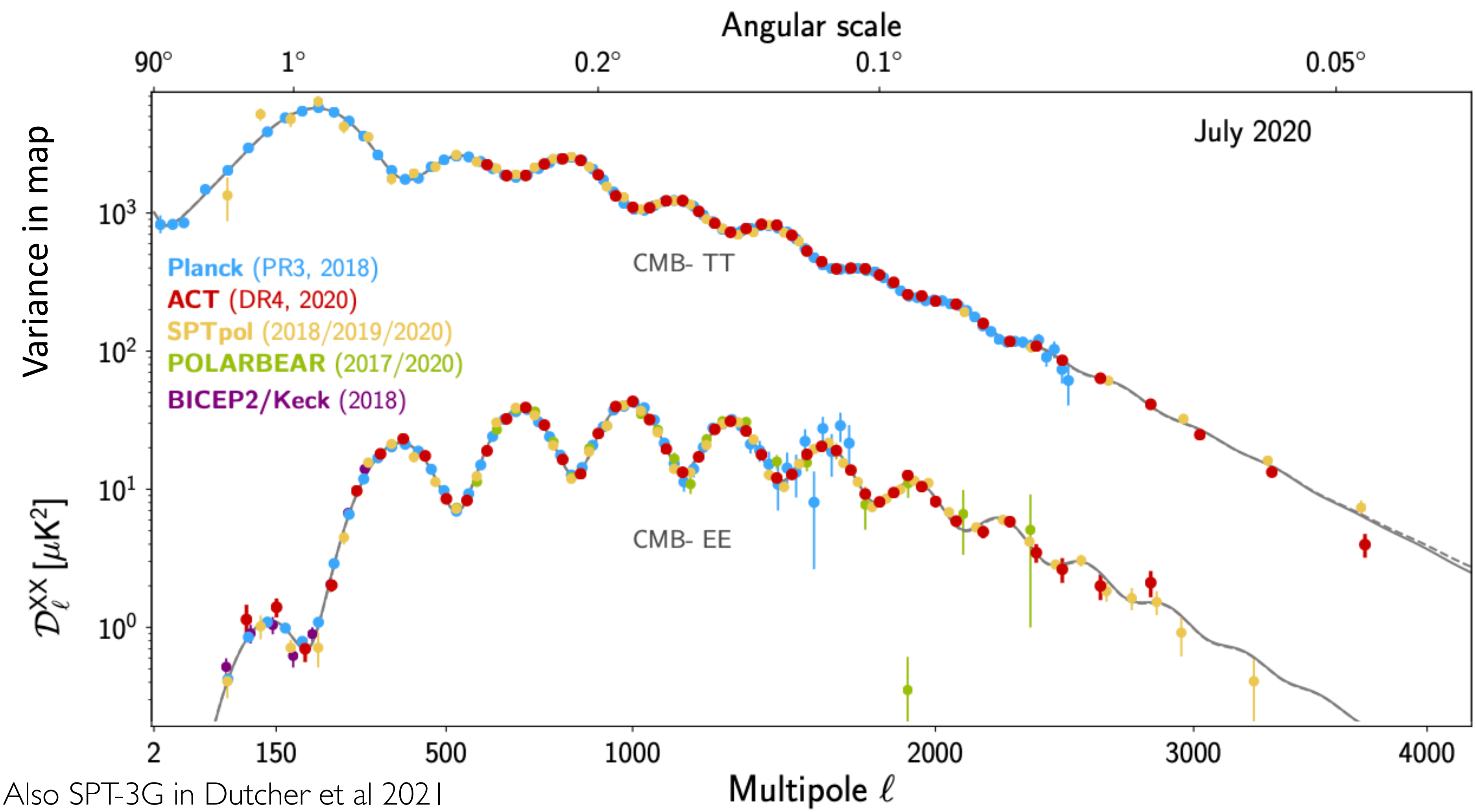


Fig from WMAP, updated with Planck estimates

Described by three variables: density in baryons, dark matter and cosmological constant.
Also includes: photons, 3 light neutrino species

- No sign of extra light particles $N_{eff} = 3.0 \pm 0.2$, Planck
- No non-zero neutrino mass $\Sigma m_\nu < 0.13$ eV (95%) Planck+BAO
- No departure from flatness
  $\Omega_K = 0.001 \pm 0.002$, Planck+BAO, Alam et al 2021
- No departure from cosmological constant
  $w_0 = -0.98 \pm 0.03$, SN+Planck, Pantheon+ Brout et al 2022



Also SPT-3G in Dutcher et al 2021

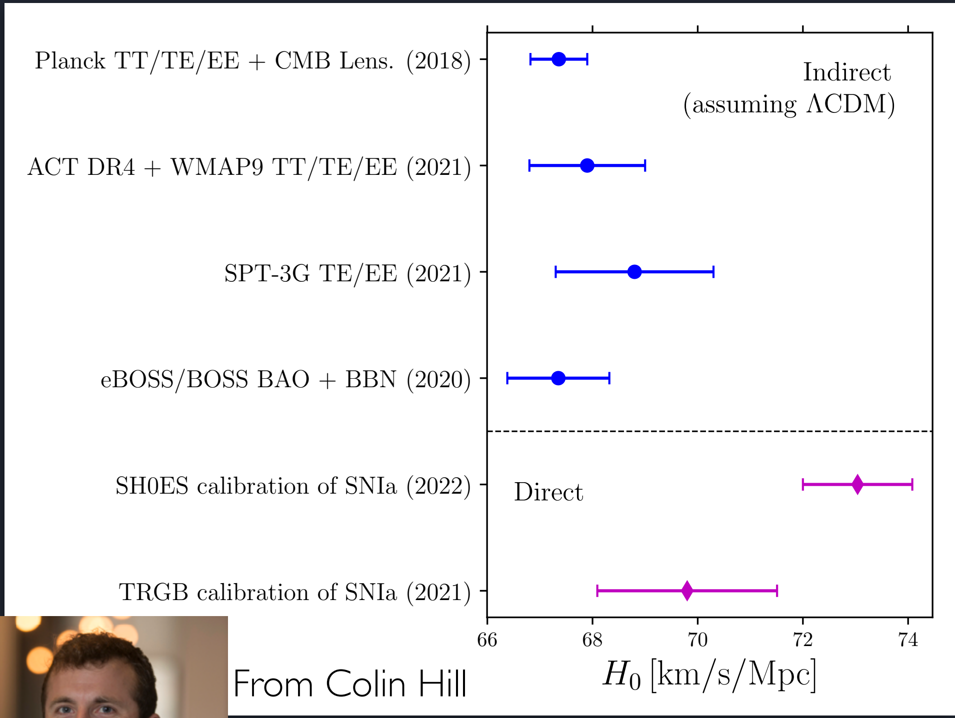
From Choi et al 2020

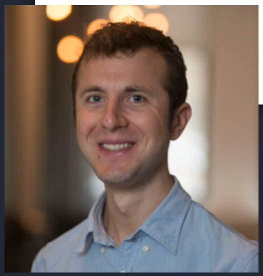
Ingredients & geometry

Consistent story without Planck, and even without primary CMB

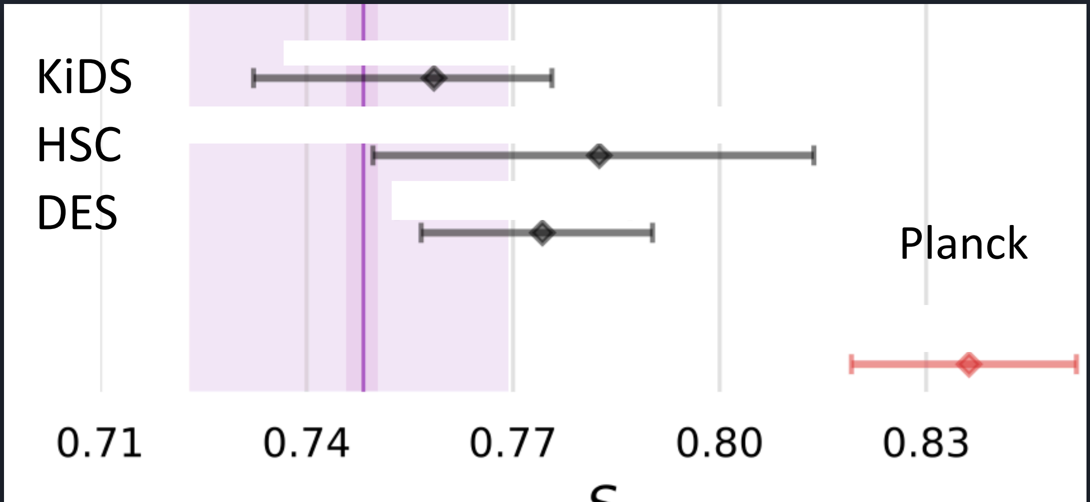
Curiosity 1: expected local expansion rate, H_0, is 5σ lower than Cepheid-derived estimate (Riess et al 2022)

Curiosity 2: expected amplitude of clustering of matter is 2-3σ higher than gravitationally lensed galaxies estimate





From Colin Hill



KiDS, van den Busch et al 2022

- If these differences persist, what part of ΛCDM is wrong?

- What physics describes the initial expansion of space ($\sim 10^{16}$ GeV)?

  Did inflation happen and how, and what about other scenarios?

- What is the physics of the dark sector?

  Are there new light relics/dark radiation?

  What are the masses of the neutrino particles; do they behave as expected?

- How did galaxies form and evolve?

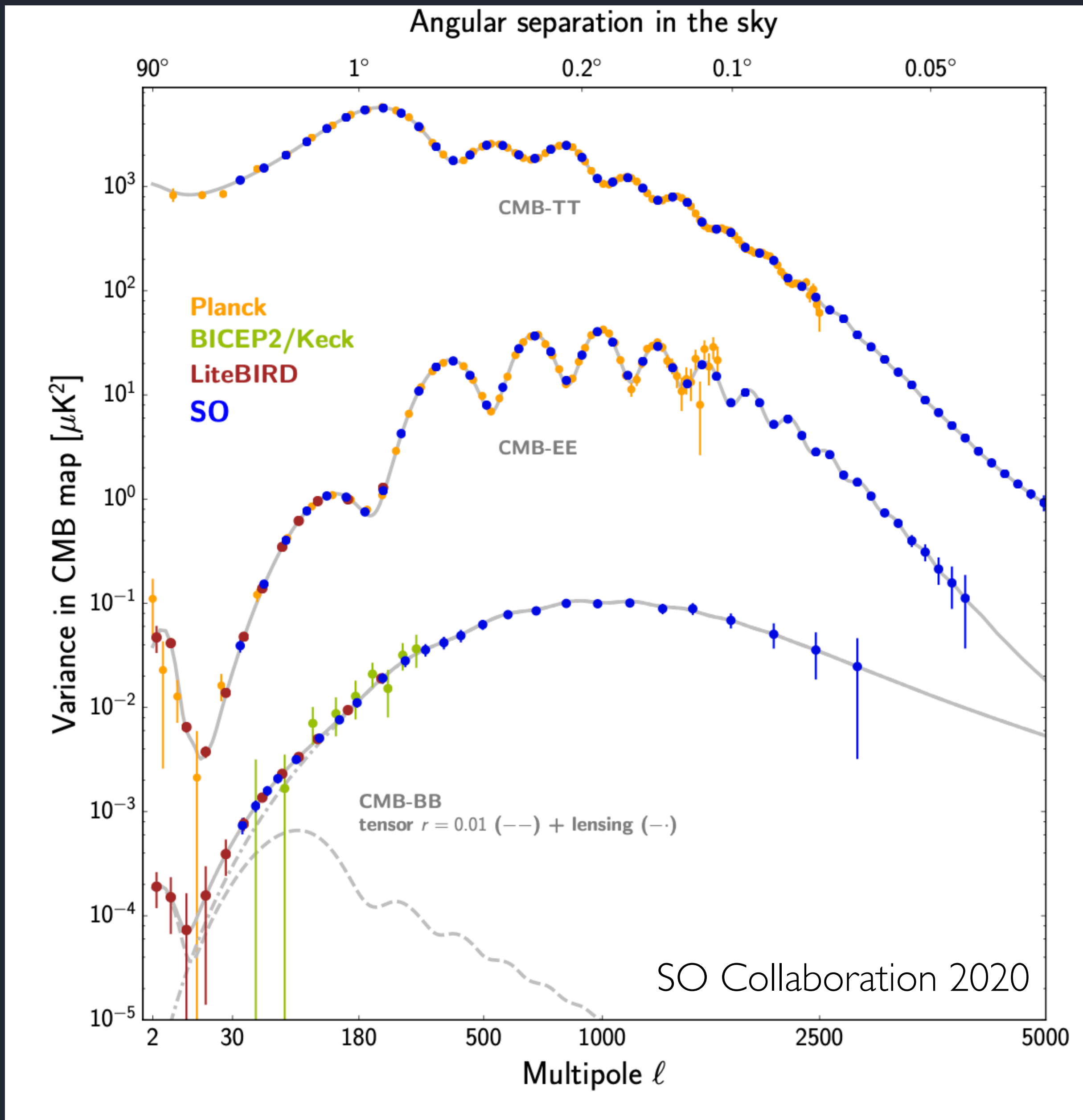
  Where is the gas? What role does feedback play?

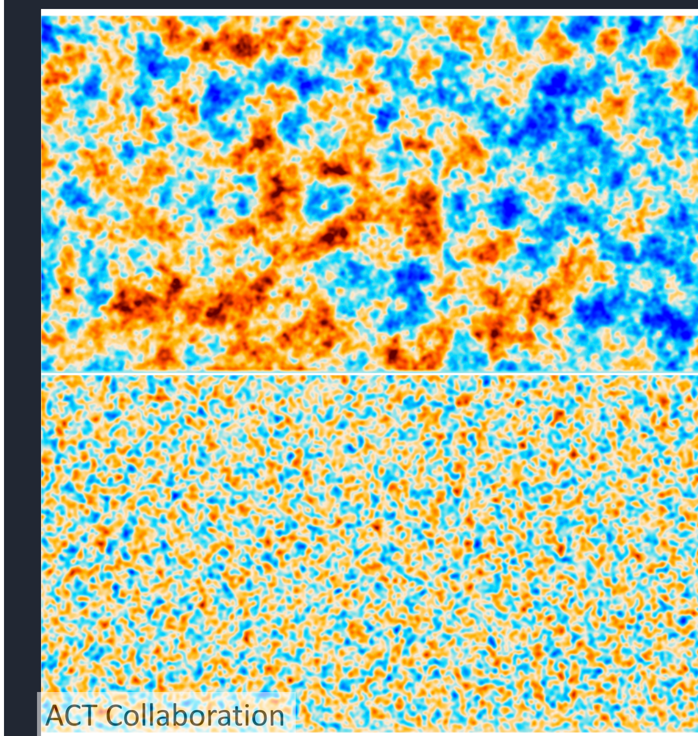
- How did the universe reionize?

  How long did the process take, and when?

Many of these use CMB secondaries: lensing, thermal and kinematic SZ effects

Early universe: primary spectrum and spectral distortions



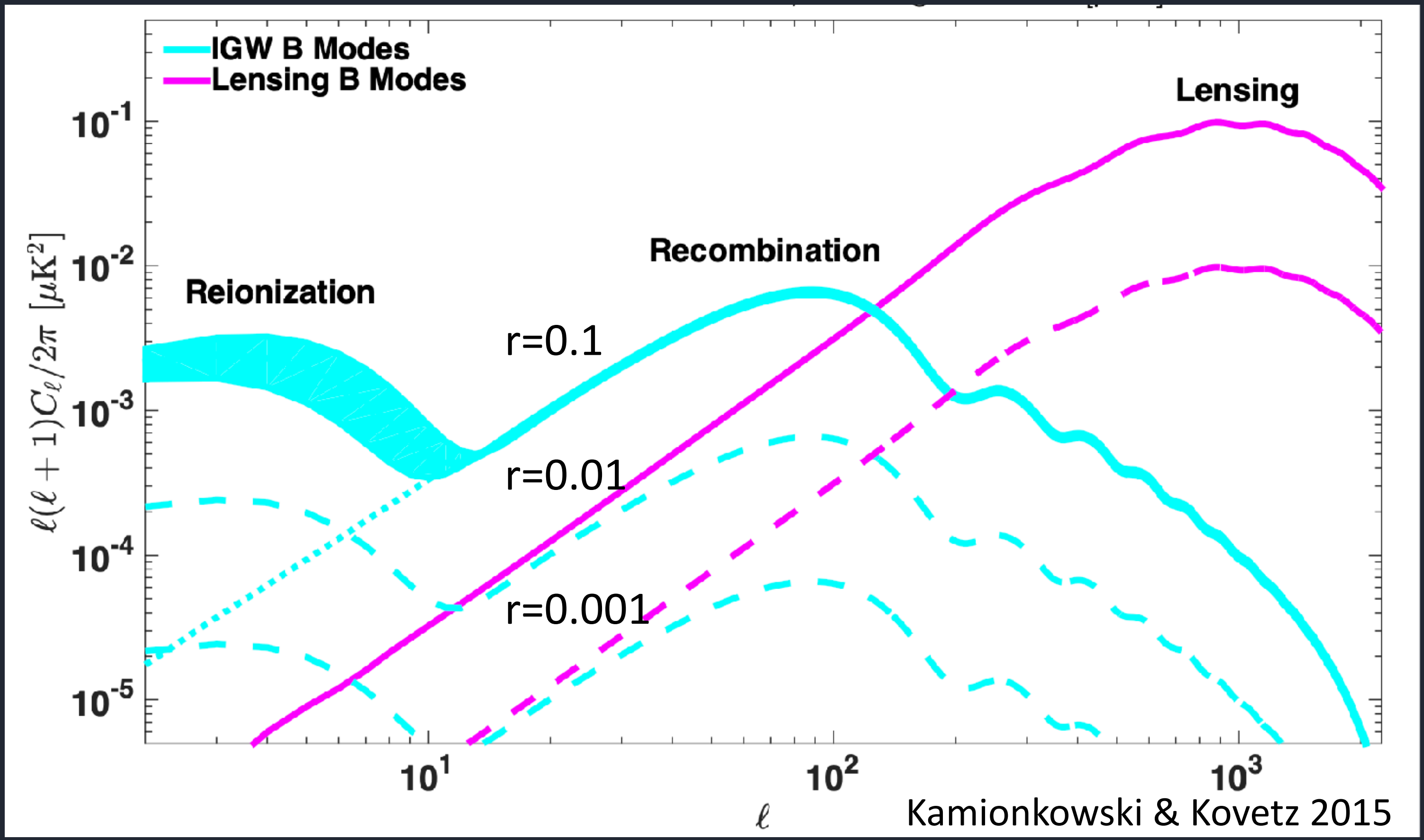


E-modes: CMB polarization tracks velocity of photon-baryon plasma.

B-modes: gravitational waves generate both E/B types.

Continued search for tensor fluctuations

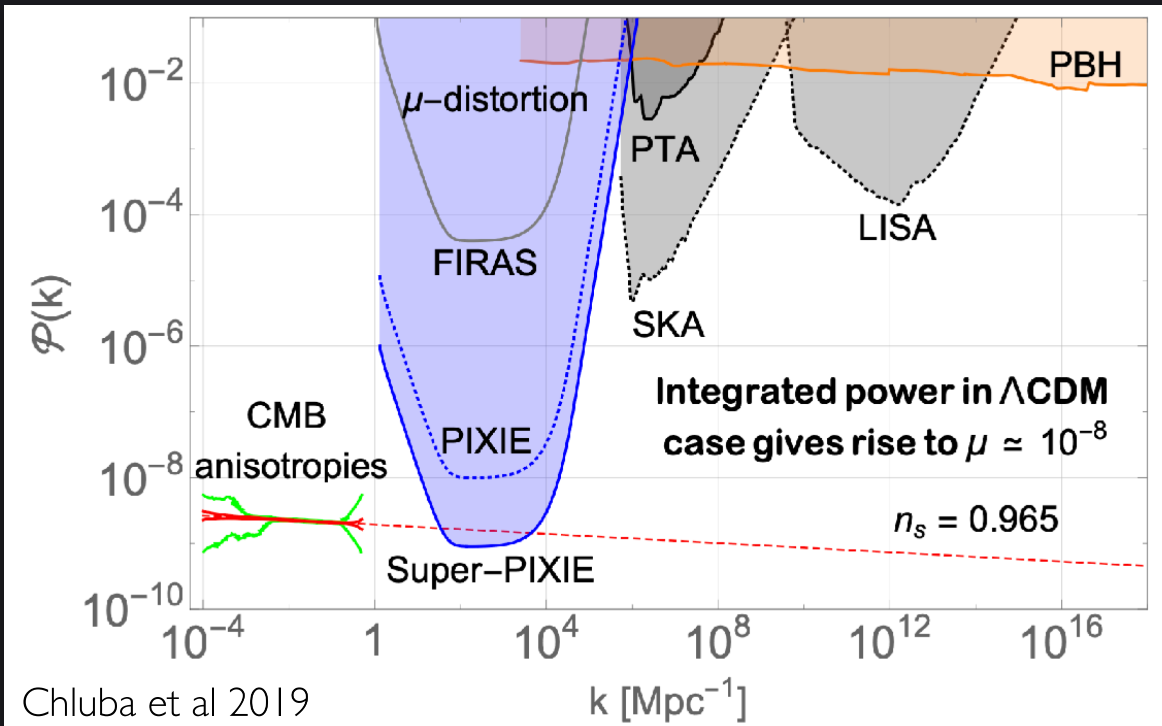
(And see Anthony Challinor's talk)



Now σ(r)~0.01, many inflationary models are ruled out; leaving various models with r>0.01.
Other non-inflation models don't predict observable tensors (Ijjas & Steinhardt 2019).

Current projects targeting σ(r) ~ 0.002-0.004
Future projects target σ(r) ~ 0.0005

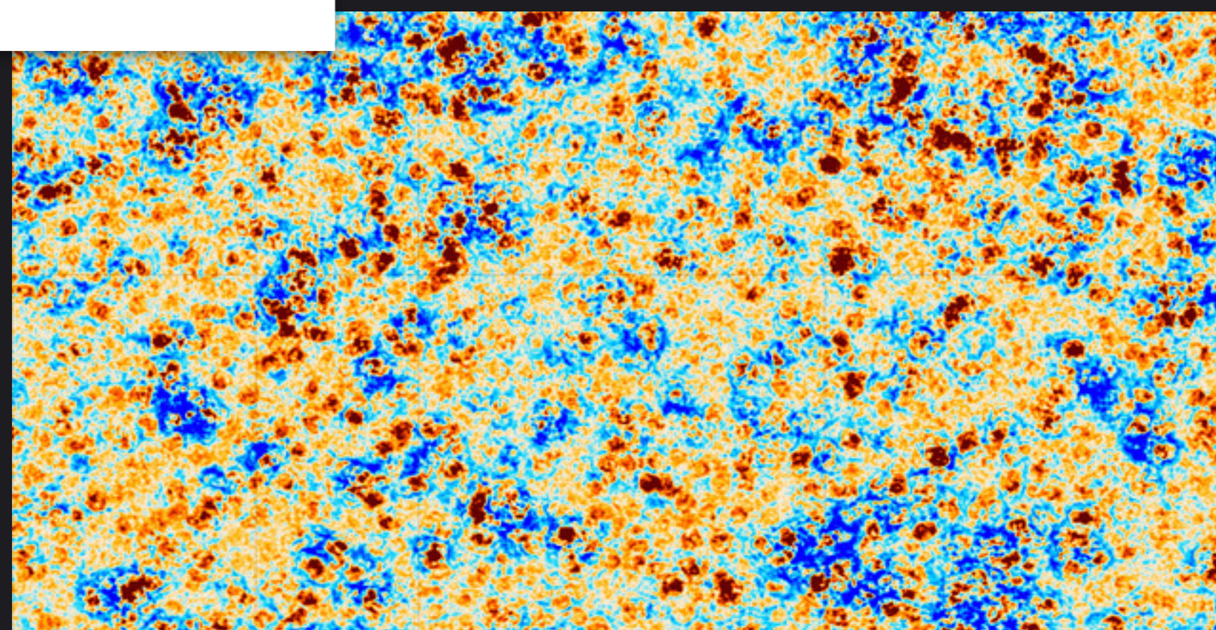
Continued characterization of scalar fluctuations



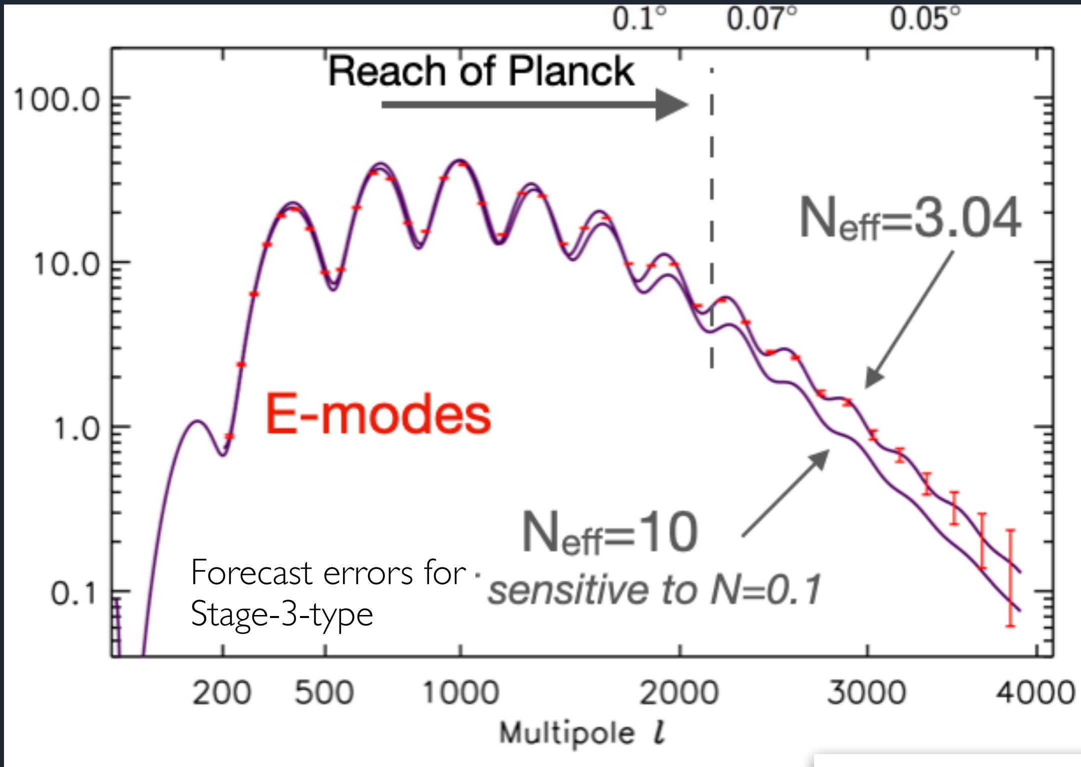
Chluba et al 2019

Power-law behavior can be pushed to smaller scales with anisotropy, but bigger lever arm with *spectral distortions* *(see Aditya Rotti's talk)*

Higher-resolution anisotropy measurements can better constrain non-Gaussianity (local and other shapes, e.g. SO Collaboration 2018)



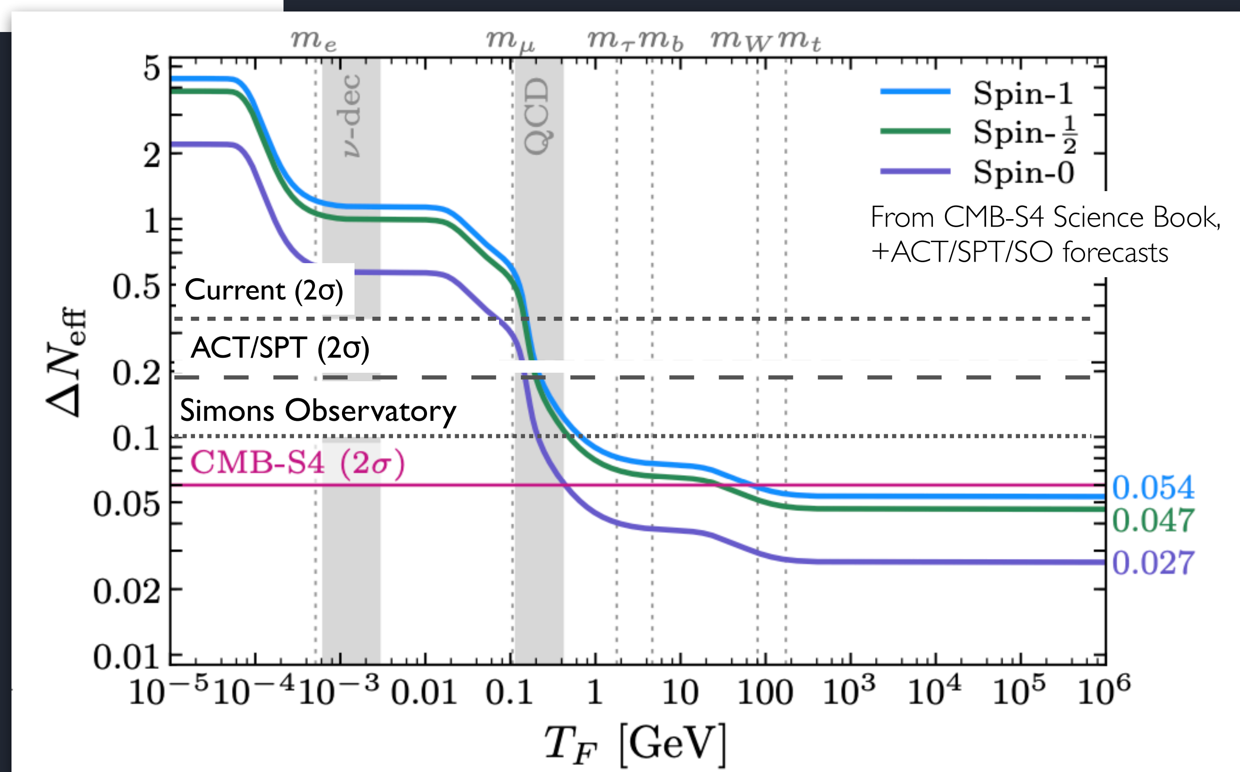
From Will Coulton, Adri Duivenvoorden



Searching for light relics/dark radiation

The earlier a particle froze-out, the smaller a contribution it makes to the radiation density.

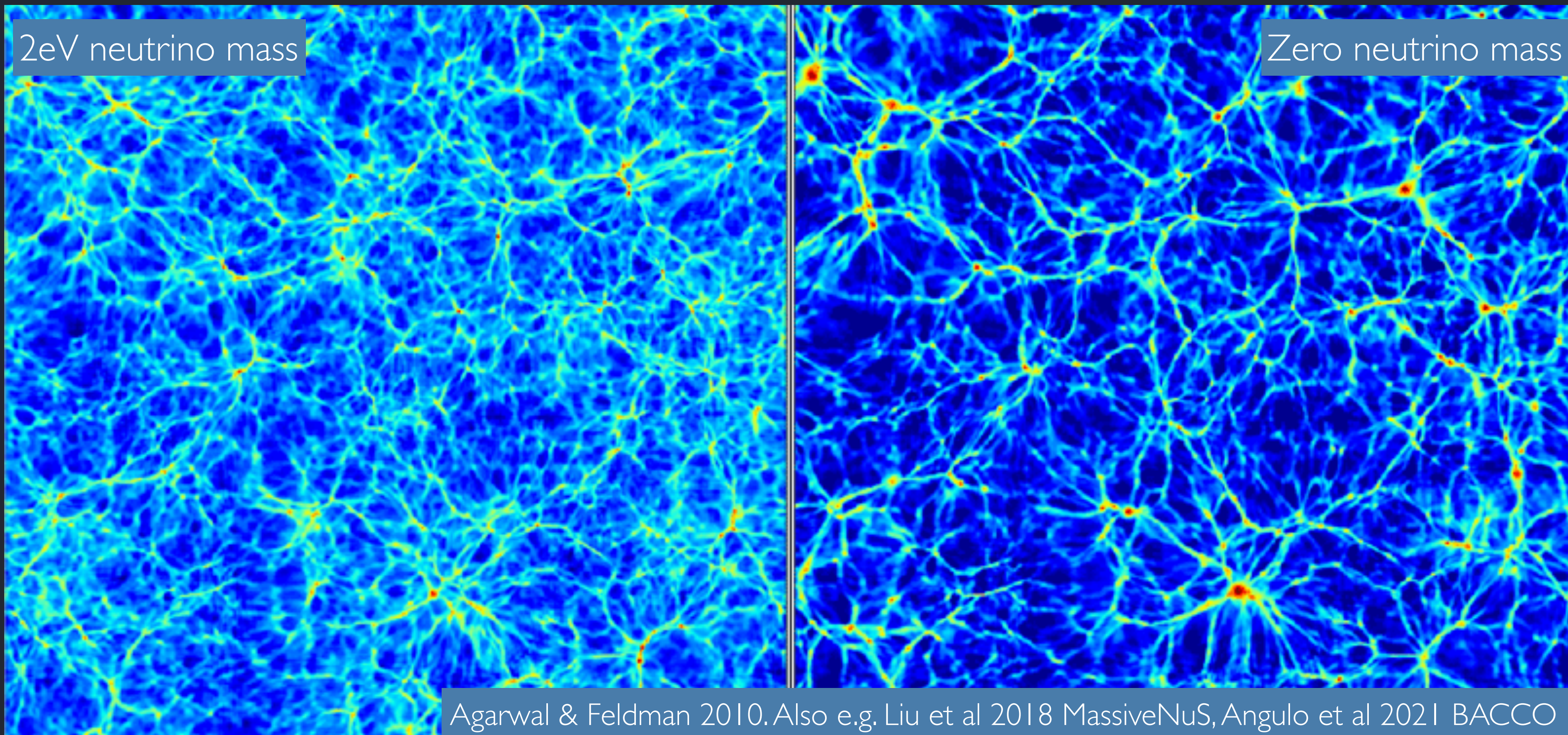
E-modes can also be used to search for models that could increase H0 (e.g Early Dark Energy, self-interacting neutrinos, other dark radiation models)



(And see Massimiliano Lattanzi's talk)

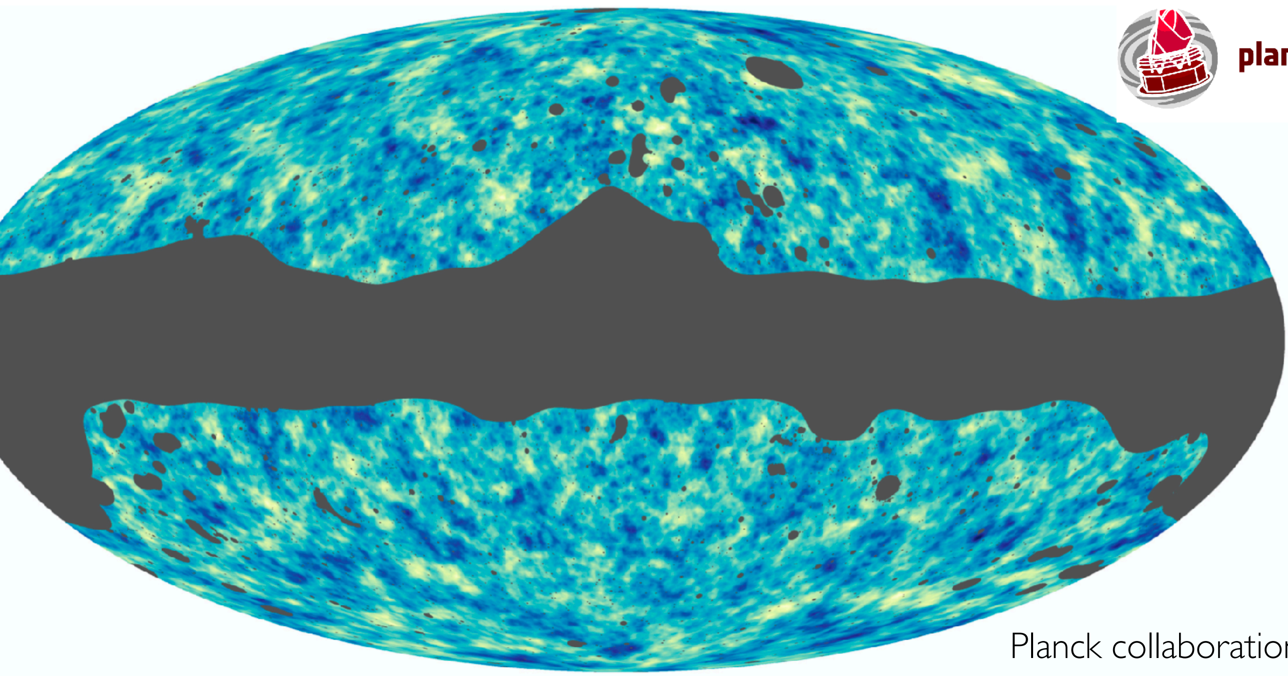
From CMB lensing and cluster counts: *mass of neutrinos*

Part of the web of dark matter is made of neutrinos; fraction scales with neutrino mass sum.
Must be at least 0.5% of total dark matter from oscillation expts (current limits are <2%)

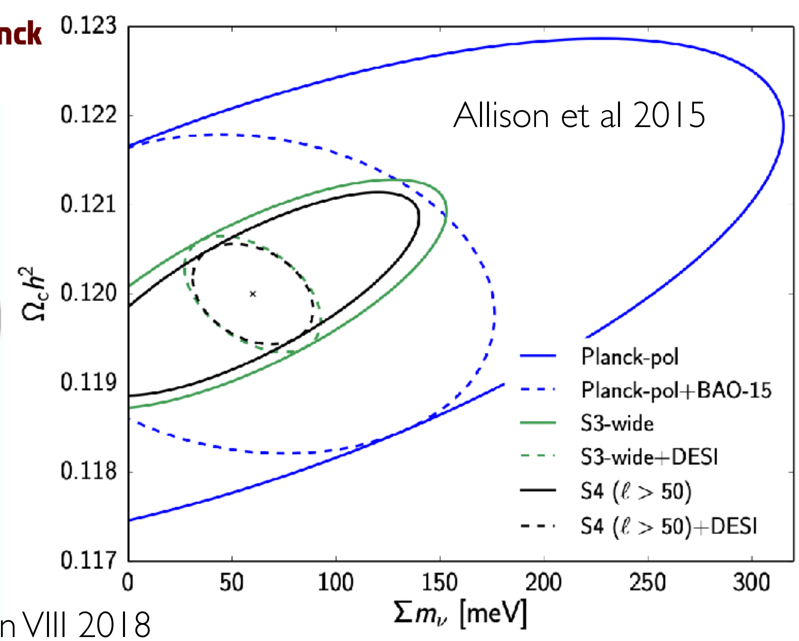


(see *Jia Liu's talk*)

Lower contrast in high-neutrino-mass universe.
Need to measure total amount of dark matter, and suppression of growth due to neutrinos



Planck collaboration VIII 2018

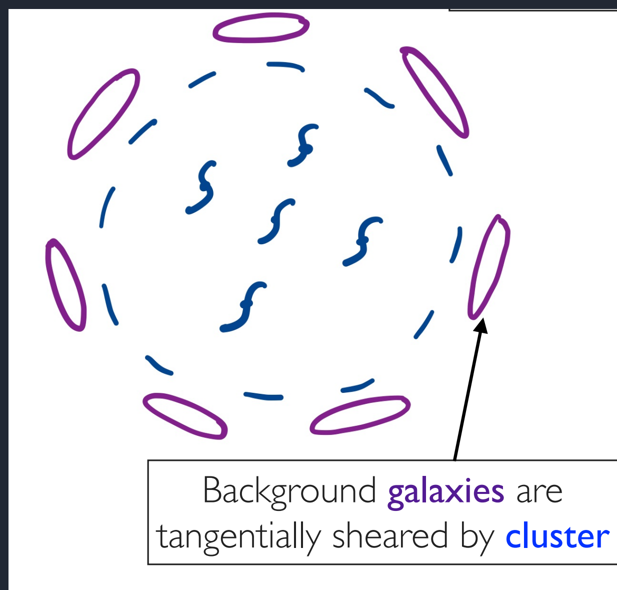


Less pronounced features in CMB lensing —> higher neutrino mass sum. Combined with SDSS galaxy positions gives current limit:

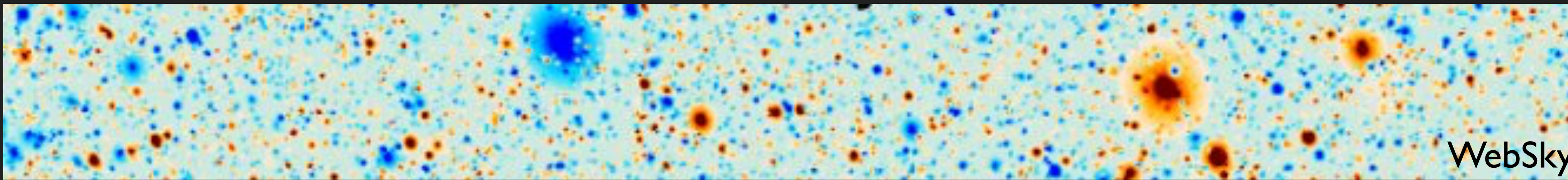
$\Sigma m_\nu < 0.13$ eV (95% CL, Planck + eBOSS)

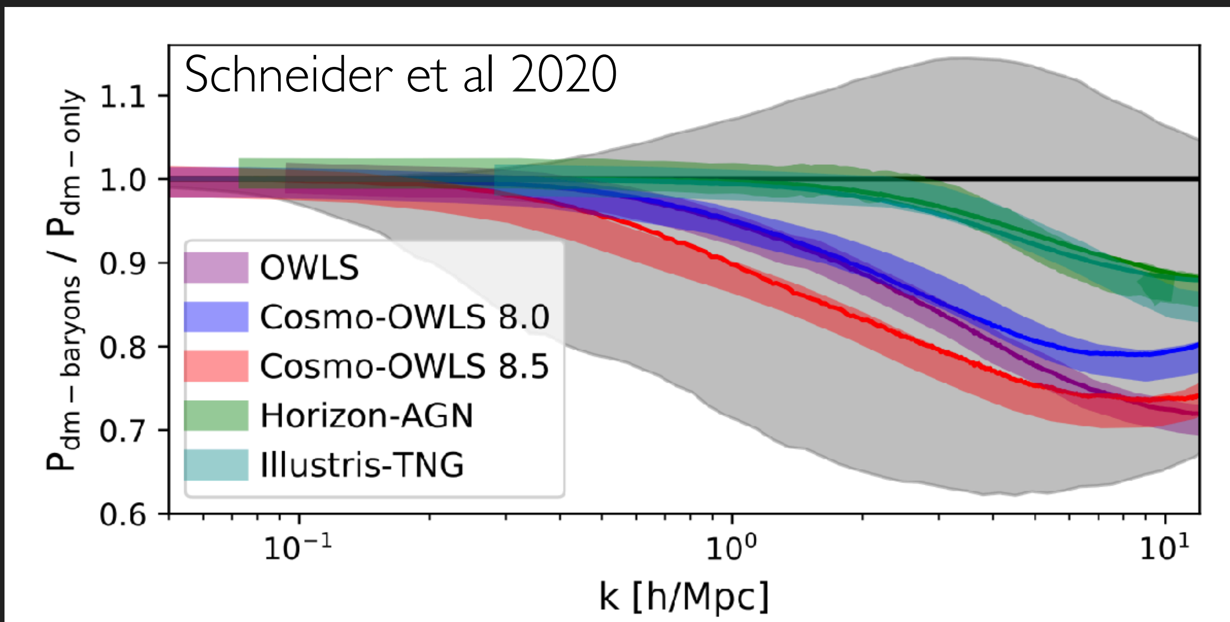
Future CMB+DESI: σ=0.03 eV (0.015eV with CV-limited τ).

Or, N(M,z) for clusters also comparable prospects; with estimation of masses using optical shear.

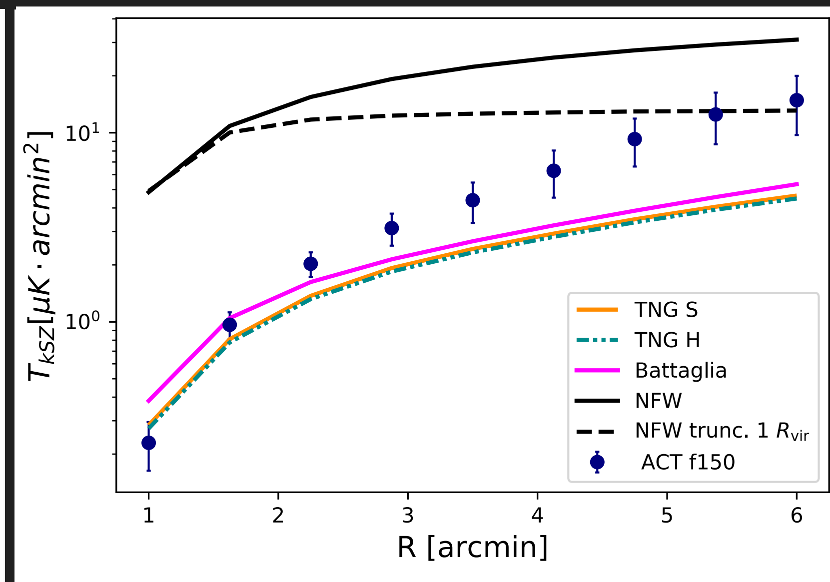


From kinematic and thermal Sunyaev Zel'dovich effects: *measuring the baryon distribution*





Doing cosmology from shear requires understanding baryonic effects at small-scale. kSZ/tSZ is unique way to probe the baryons.



Amodeo Battaglia Schaan Ferraro & ACT 20

Current: gas profile is more extended than dark matter profile; hotter gas in outskirts

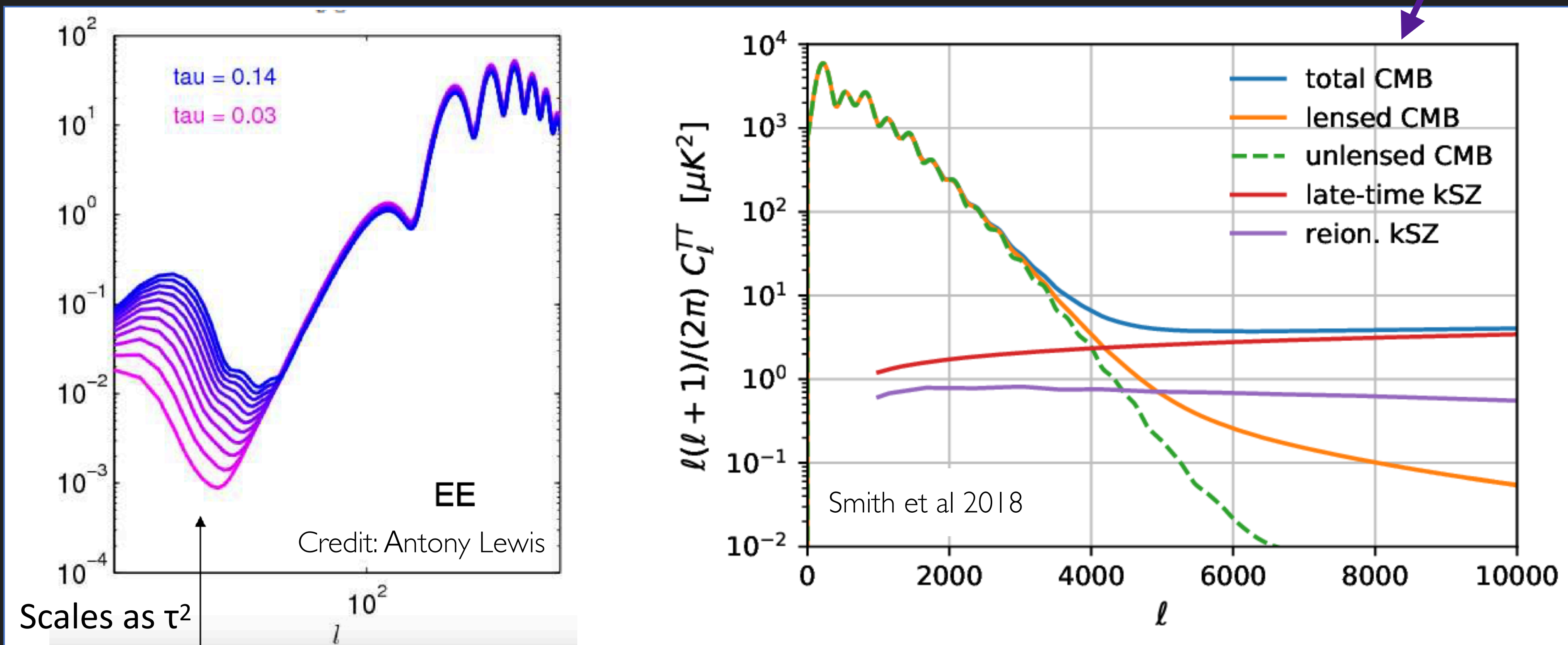
Detection now at 6-8σ

New CMB measurements - and DESI - expected at 100s σ

From large-scale EE and kSZ: *global reionization properties*

(And see Stephan Ilic's talk)

$$\frac{\Delta T_{\mathrm{kSZ}}(\vec{\mathbf{n}})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} v_r \delta_e(\vec{\mathbf{n}}, \chi)$$



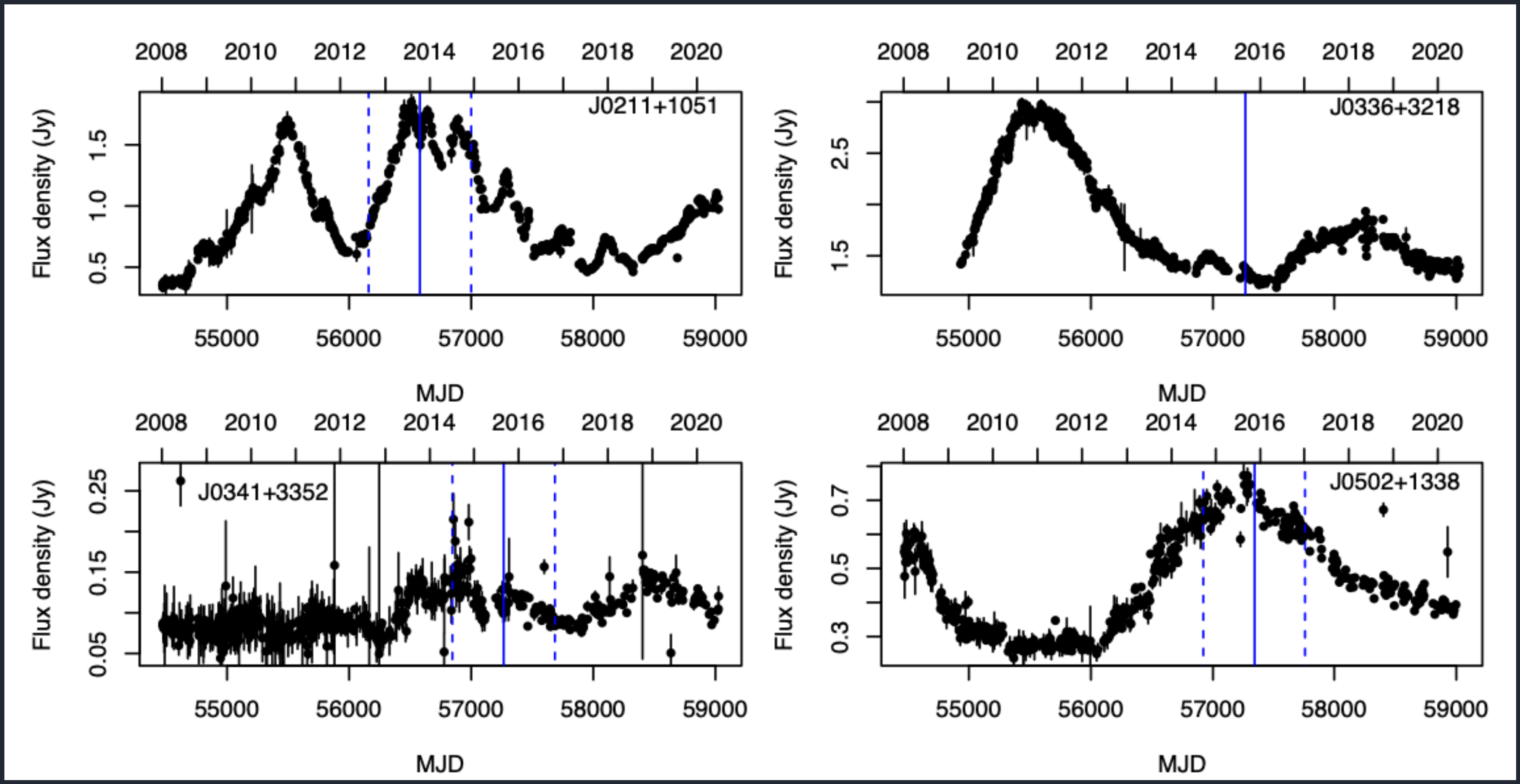
Planck: τ=0.051-0.063 ± 0006 (SRoll/NPIPE maps)
Mid-point at z~8
Goal: cosmic variance limit σ(τ)= 0.002

Reichardt et al 2021 (SPT), Δz < 3-5 (95% CL)
Future goal: σ(Δz) ~ 0.25

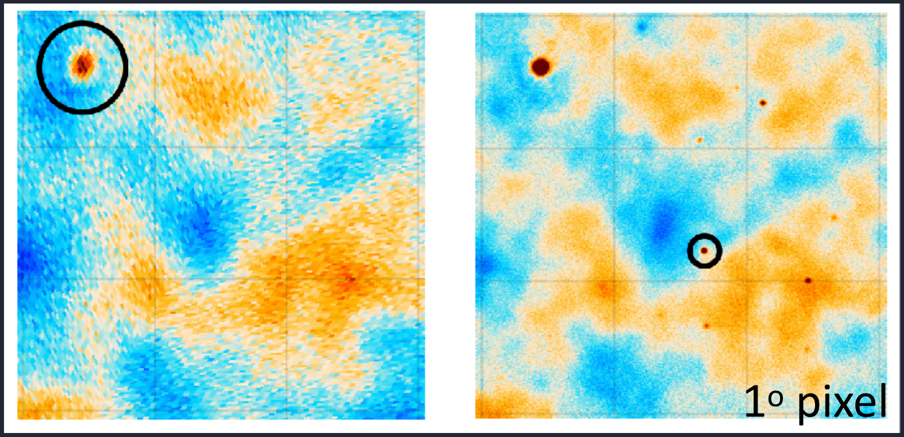
The mm sky seen by CMB experiments is also very interesting!

- Variable AGN
- Transient mm sources
- Search for Solar System bodies
  Is there a Planet 9?
- Dusty star-forming galaxies
- Galactic science ***[see Brandon Hensley's talk]***
  What is composition of dust?
  What is distribution of magnetic fields in the Galaxy?

Variable AGN: are they source of high-energy neutrinos



Hovatta et al 2021, OVRO + Metsahovi w IceCube

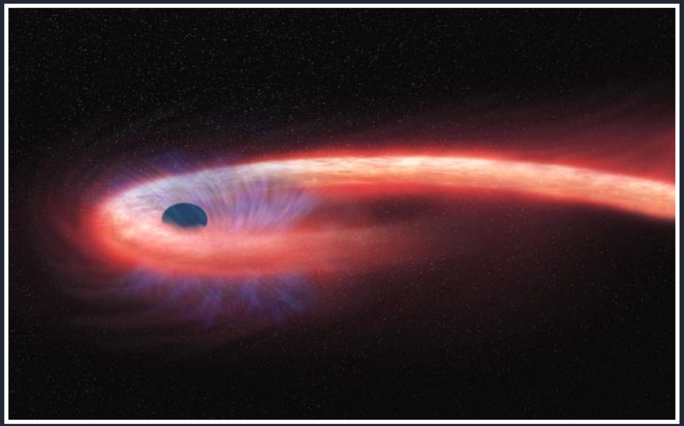


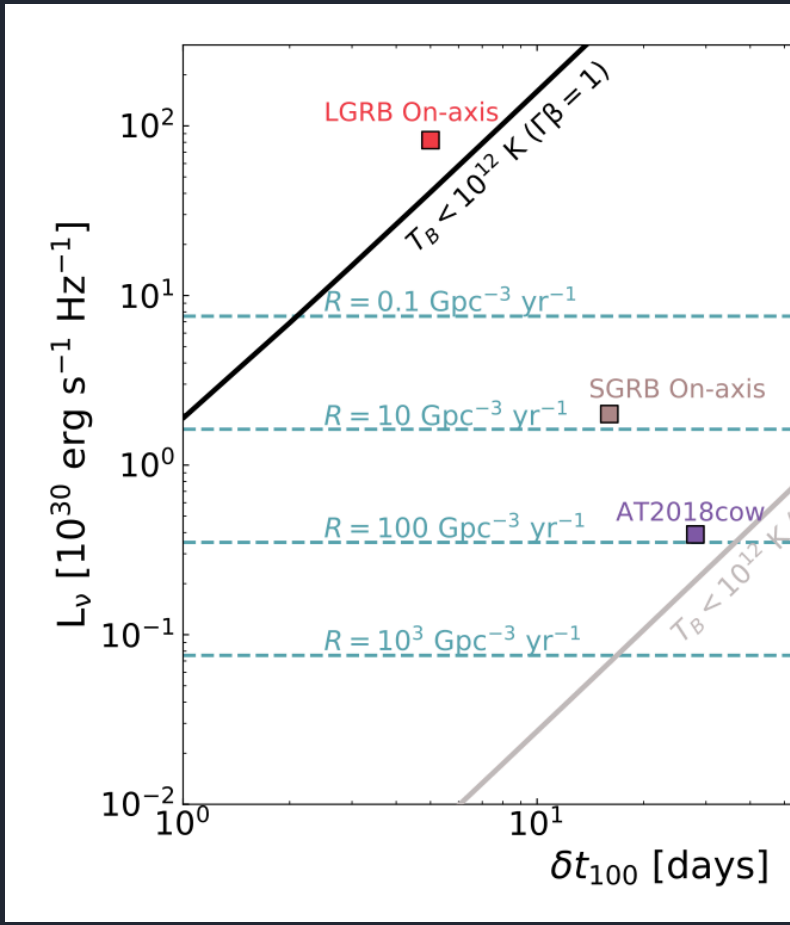
Planck v ACT, Naess et al 2020

New wide-field high-resolution 'CMB' data (with regular cadence) will be able to track 1000s - 10000s of AGN on day/week/month timescales; can correlate with neutrino expts.

Transient mm sources: new discovery space

Transient sources now seen by ACT & SPT (Naess et al 2021, Guns et al 2021)





Eftekhari et al 2021

Gamma-ray burst afterglows with and without triggers

Tidal disruption events

Stellar flares + more

So much still to learn from the CMB, and its mm sky-maps

Using CMB primary polarization we hope to shed light on the inflation/early universe mechanism, the dark sector, or reveal something new.

Using CMB lensing, tSZ & kSZ we know that a non-zero neutrino mass is a concrete target, as well as measuring baryons and reionization.

We can do a wealth of new science from the mm maps (‘for free’): time domain astrophysics, Galactic science, planet hunting…