The Cosmic Microwave Background: Secondary Anisotropies

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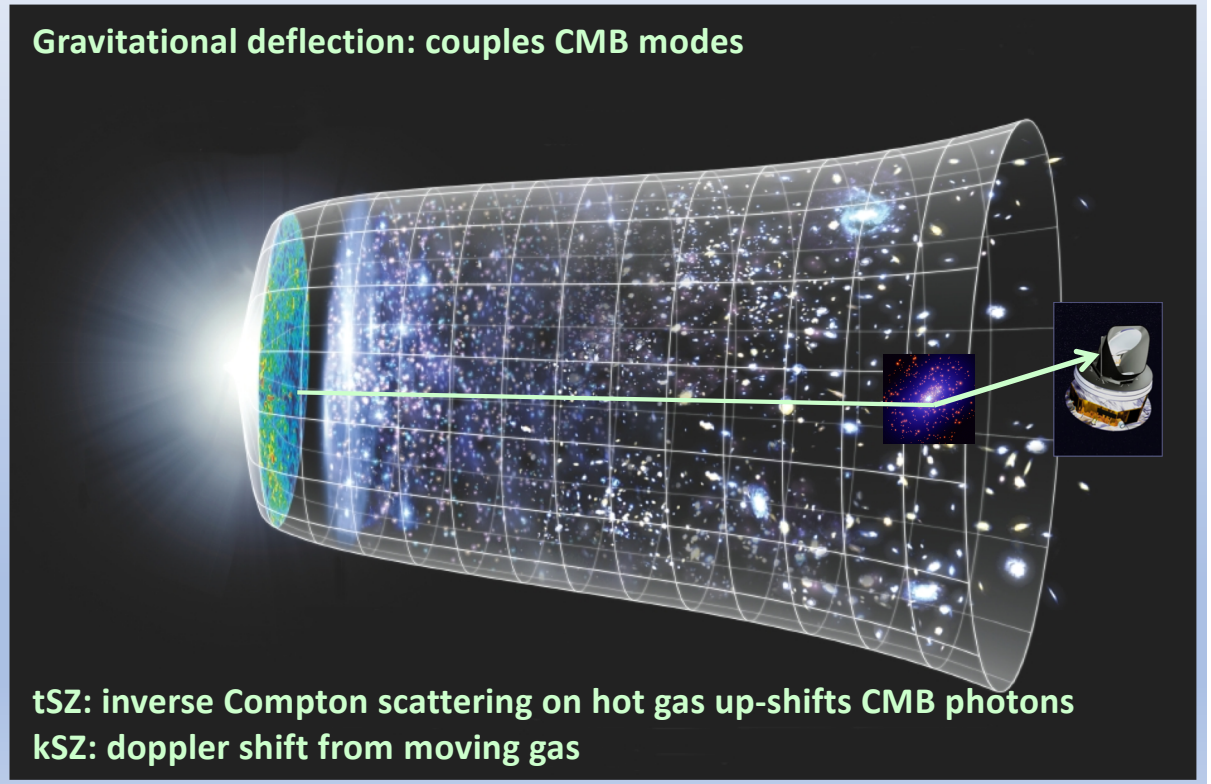
Secondary Anisotropies

Illuminating cosmic structures with the CMB

Fundamental Physics
- Dark energy
- Modified gravity
- Neutrino sector

Astrophysics
- Baryon history
- Galaxy evolution
- Reionization



Secondary Anisotropies: What & Why

- Gravitational lensing
- Sunyaev-Zeldovich (SZ) effects

Fundamental Physics
- Dark energy
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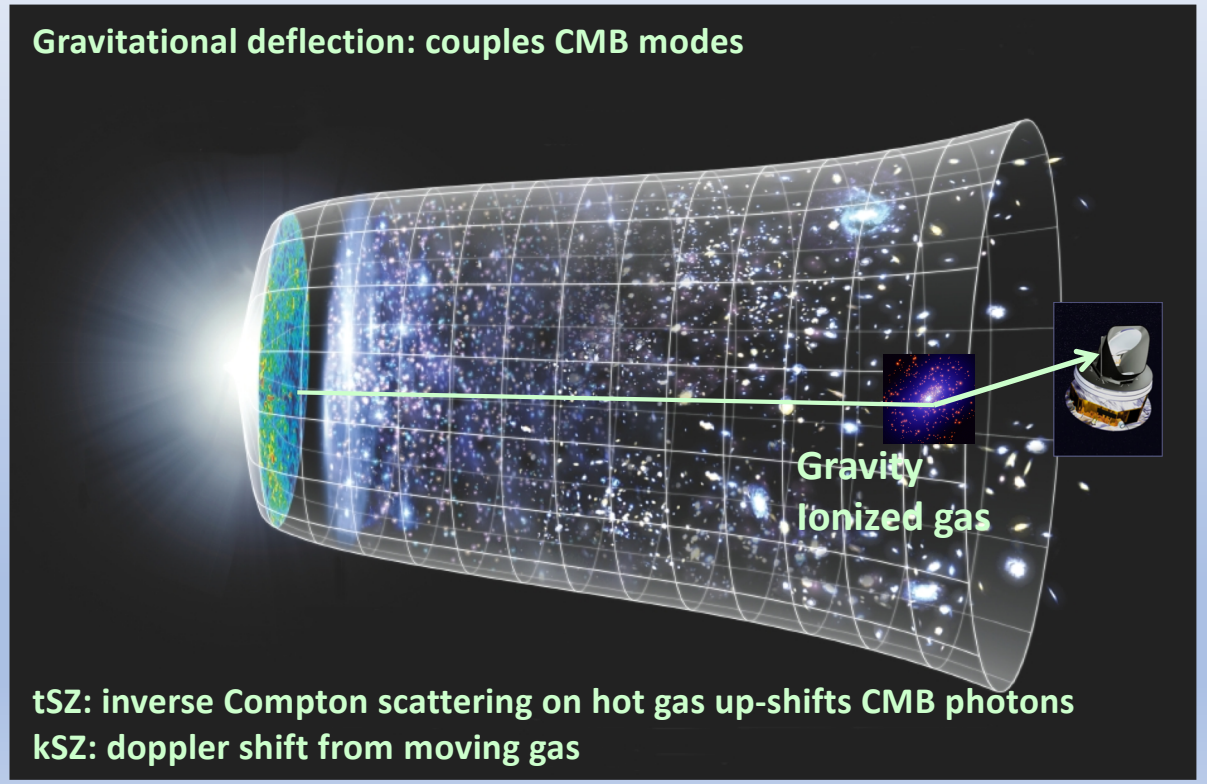
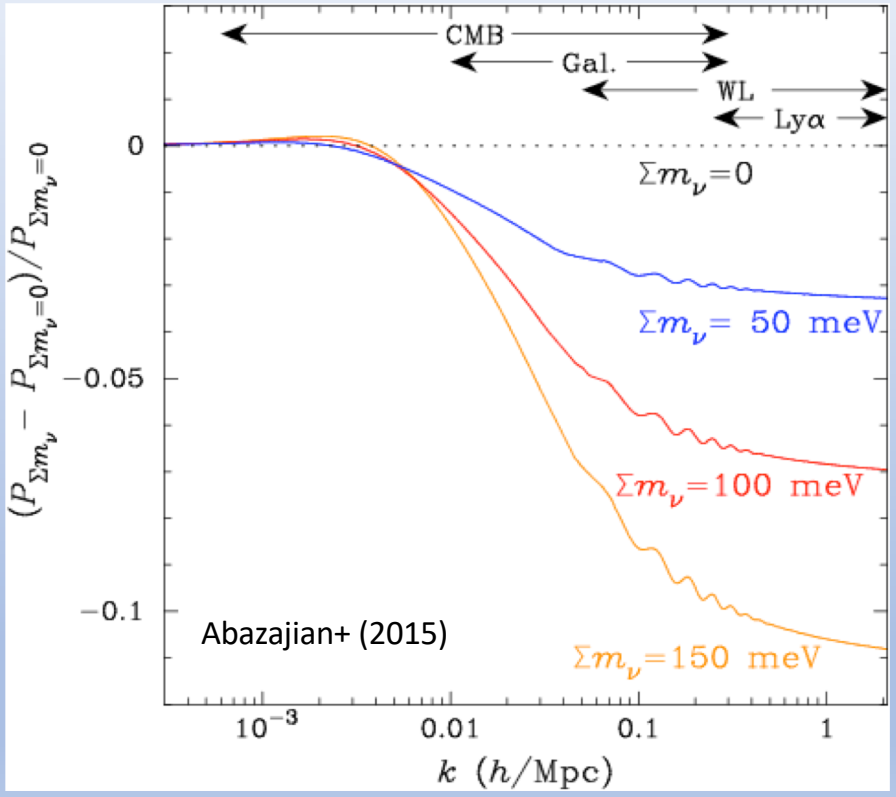


Effects of Neutrinos, DE, MoG on LSS

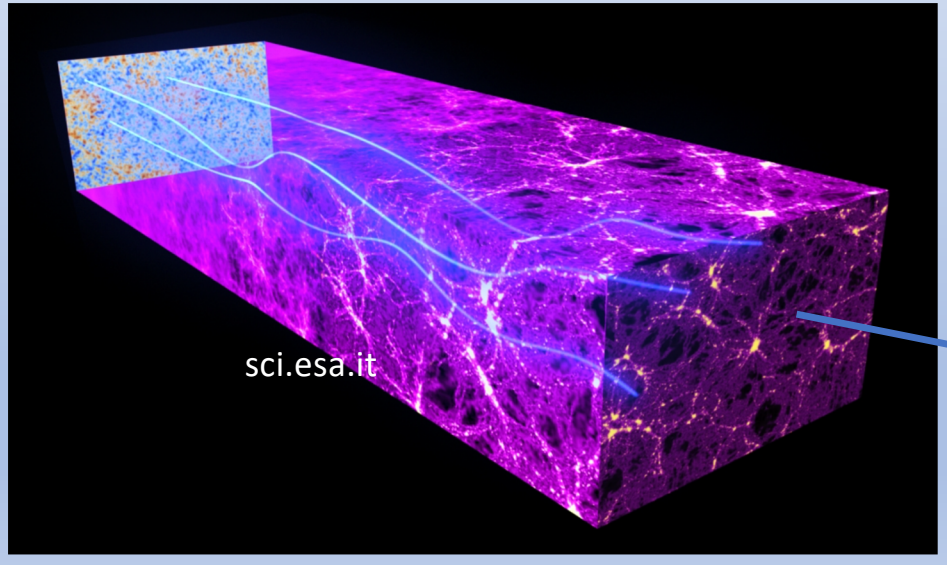
- Neutrinos: Shape of power spectrum
  - Damp small-scale power relative to CMB normalization on large scales
- DE/MoG: Growth rate
  - Change evolution rate of perturbation amplitude
- Goal: measure matter power spectrum and its evolution
  - Lensing
  - Galaxy clusters



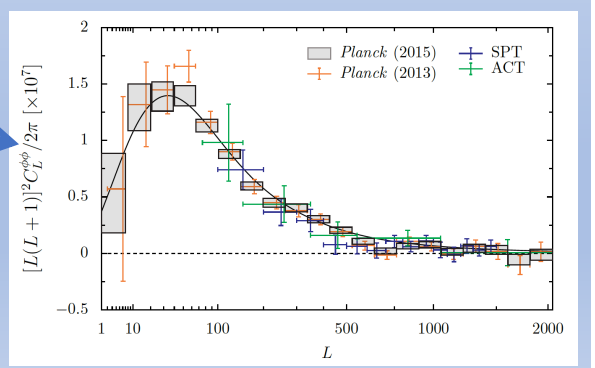
Abazajian+ (2015)

CMB Lensing

Deflections by gravitational lensing change the statistics of the CMB anisotropies in a characteristic way.



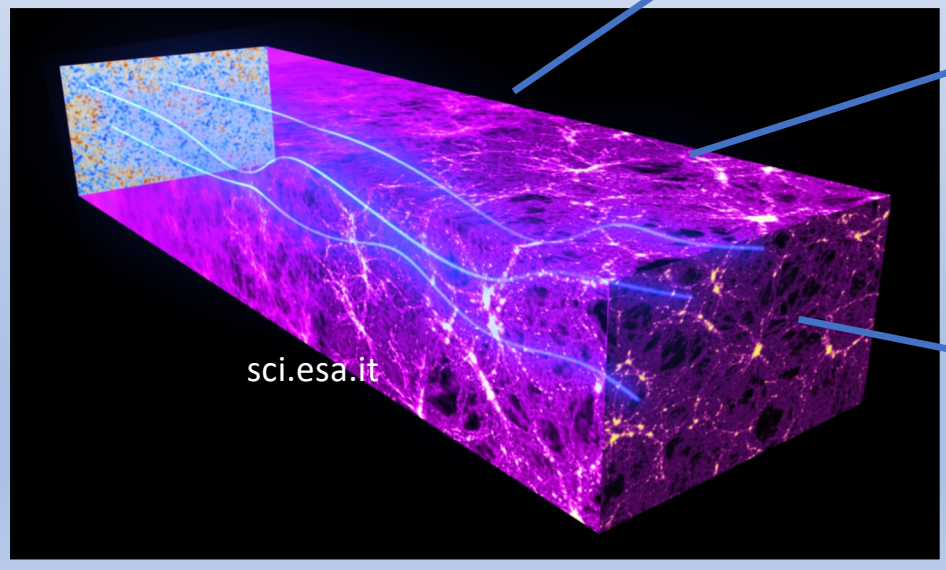
Mass density variations projected along the line-of-sight to z=1000!

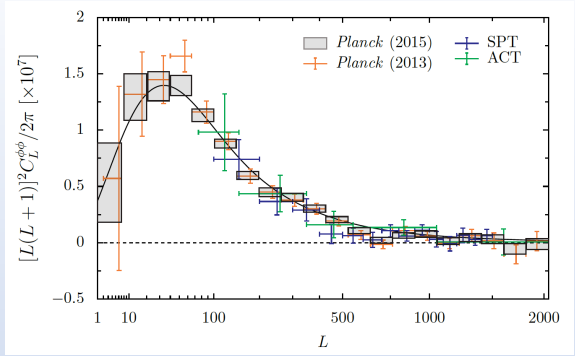


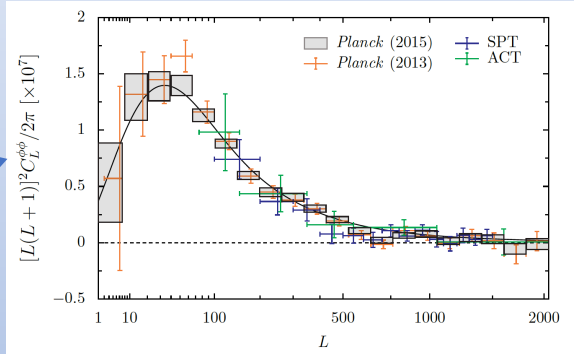
CMB Lensing Tomography

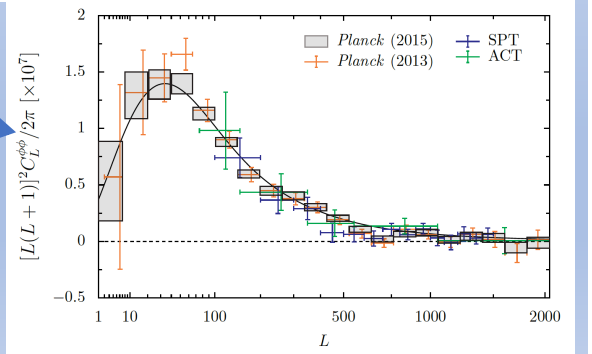
Slice up into redshift bins by correlating with a galaxy sample.

Evolution of matter perturbations

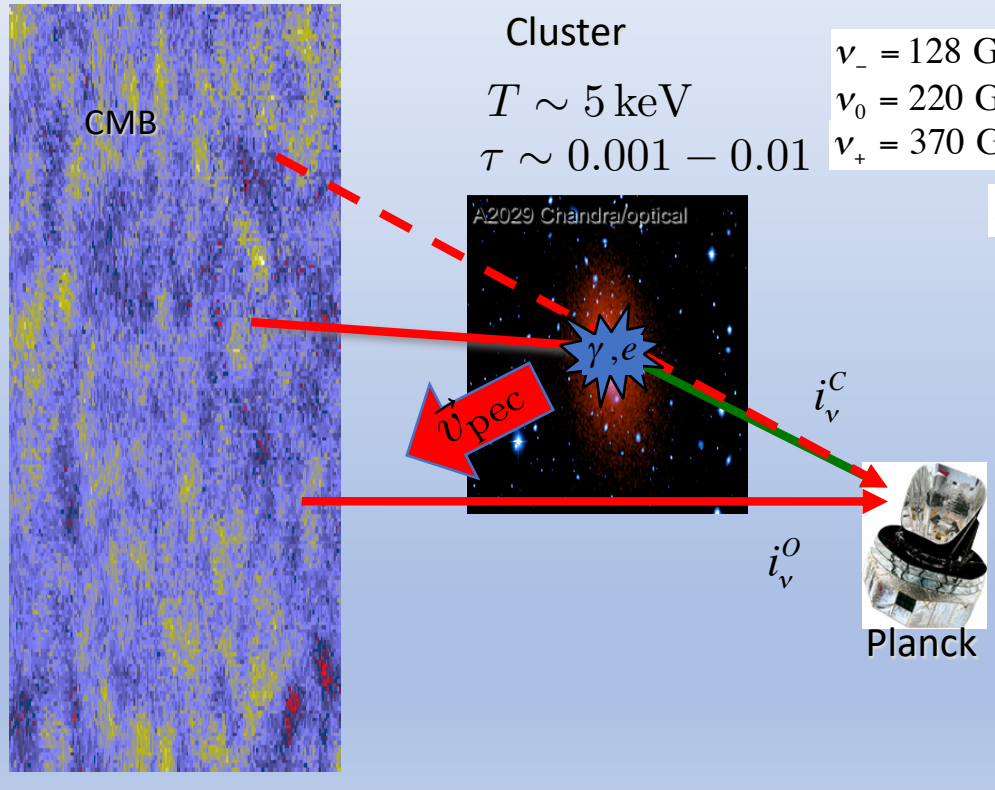


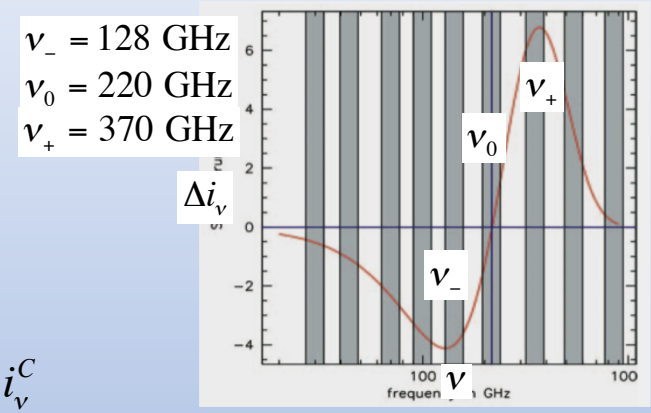






Sunyaev-Zeldovich (SZ) Effects



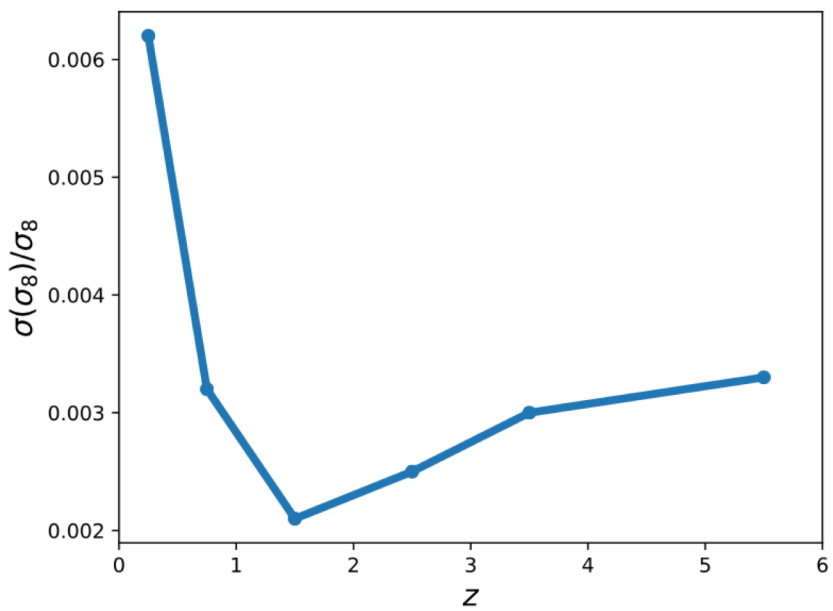


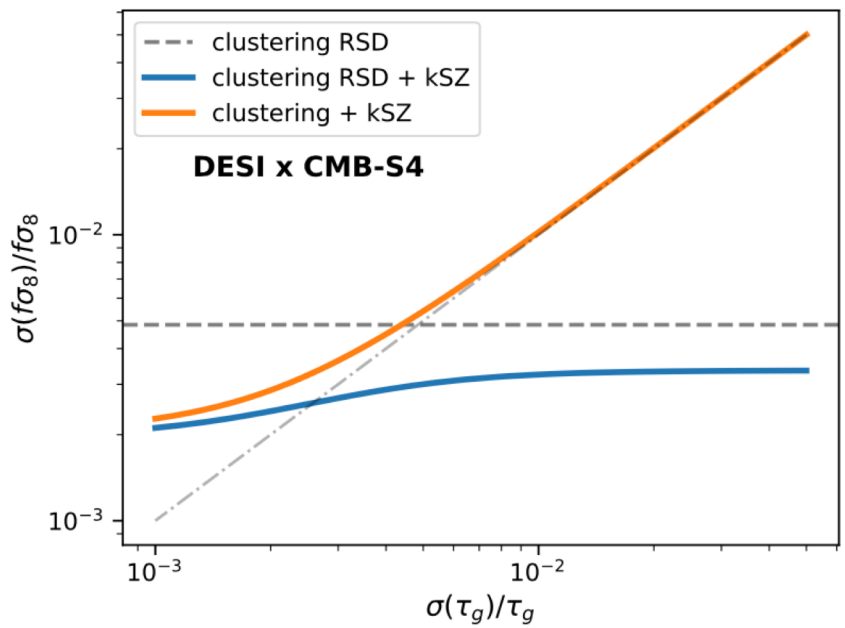
$$\frac{\Delta T}{T} = \frac{v}{c}\tau$$

Galaxy Clusters

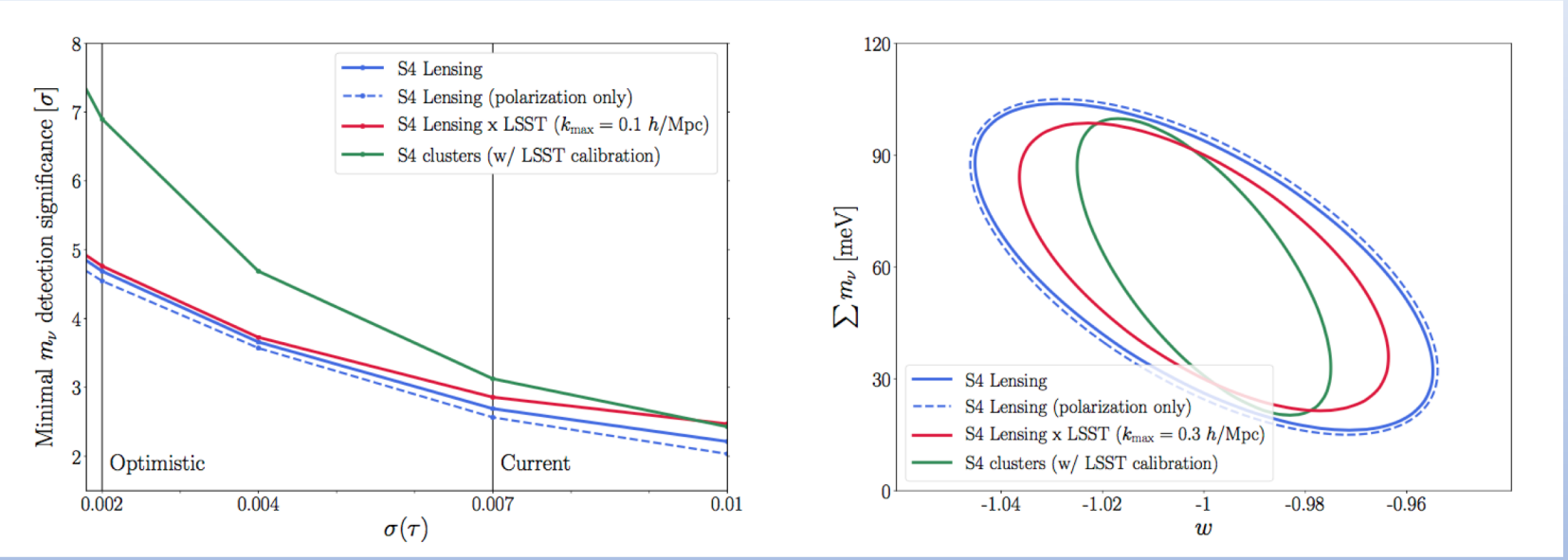
- Abundance is extremely sensitive to amplitude of density perturbations on $8h^{-1}$ Mpc scales
- They are an amplifier of the perturbation amplitude!

CMB-S4

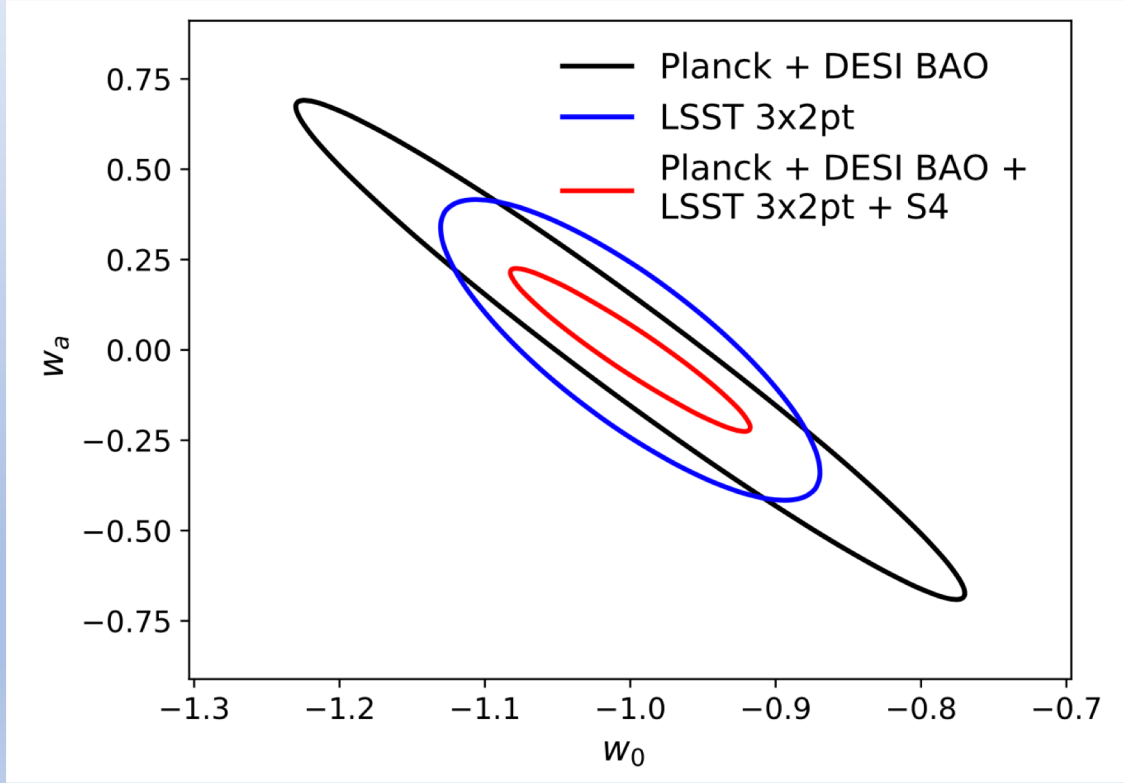

0.006
0.005
0.004
0.003
0.002
$\sigma(\sigma_8)/\sigma_8$
0
1
2
3
4
5
6
z


clustering RSD
clustering RSD + kSZ
clustering + kSZ
DESI x CMB-S4
10^{-2}
10^{-3}
$\sigma(f\sigma_8)/f\sigma_8$
10^{-3}
10^{-2}
$\sigma(\tau_g)/\tau_g$

CMB-S4

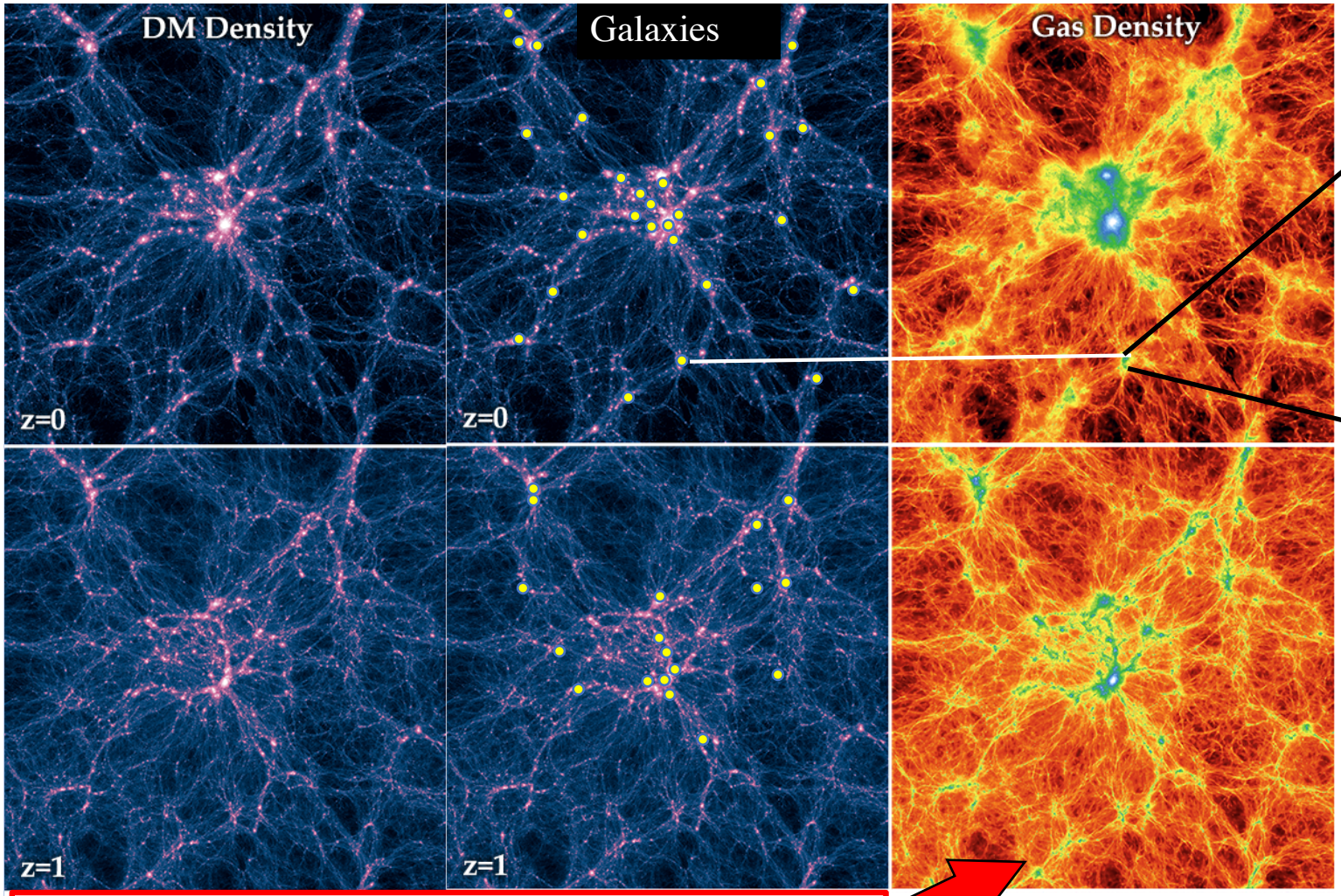

S4 Lensing
S4 Lensing (polarization only)
S4 Lensing x LSST ($k_{max} = 0.1\ h$/Mpc)
S4 clusters (w/ LSST calibration)
Minimal m_ν detection significance [σ]
Optimistic
Current
$\sigma(\tau)$
S4 Lensing
S4 Lensing (polarization only)
S4 Lensing x LSST ($k_{max} = 0.3\ h$/Mpc)
S4 clusters (w/ LSST calibration)
$\sum m_\nu$ [meV]
w

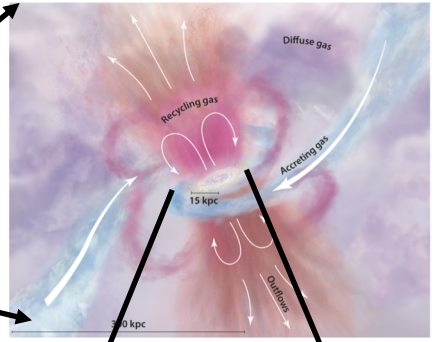
CMB-S4


Planck + DESI BAO
LSST 3x2pt
Planck + DESI BAO +
LSST 3x2pt + S4
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
w_a
−1.3
−1.2
−1.1
−1.0
−0.9
−0.8
−0.7
w_0

Baryonic Majority

- Galaxy formation is remarkably INEFFICIENT:
  - >~90% of all baryons do not make stars – they remain “hidden” in the circumgalactic medium (CGM) and the intergalactic medium (IGM)
  - Demands strong feedback to keep the gas there
- Very difficult to observe, especially over wide areas/many objects
- tSZ & kSZ powerful new probes
  - Survey wide areas: general distribution + object stacks

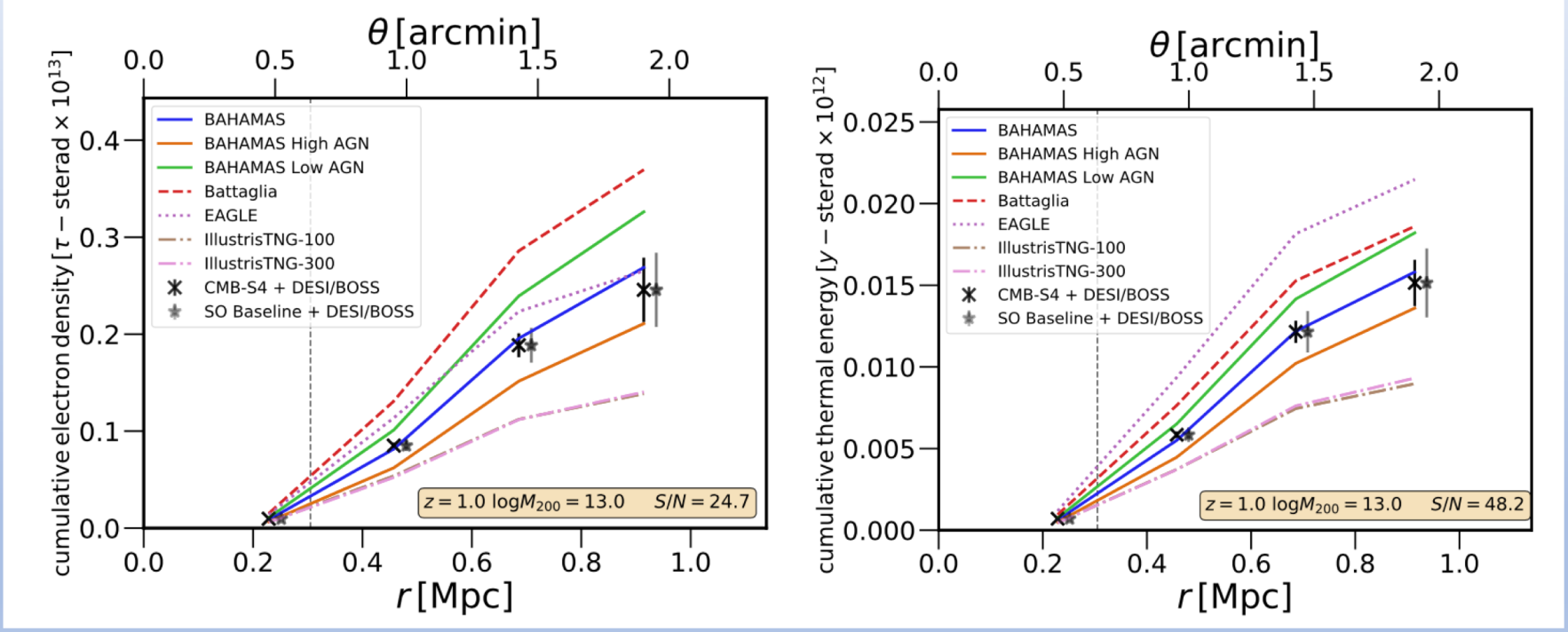




"Tip of the iceberg"

90% are in the CGM/IGM that we know little about.

CMB-S4: Measure properties of the gas



New & Very Rich Observational Field

- Basic idea: use CMB as probe of large-scale structure
  - Total matter distribution
  - Baryon distribution
  - Velocities and flows
- Fundamental Physics
  - Neutrino sector
  - Dark energy & dark matter
  - Modified gravity
- Astrophysics
  - Mystery of feedback and the baryonic majority in the CGM/IGM
  - Reionization

The Experimental Program

- For this science, especially need
  - angular resolution ~arcmin
  - Sensitivity ~1uK-arcmin
  - broad frequency coverage
  - Large survey area
- Experimental program
  - Atacama Cosmology Telescope (AdvACT) * SPT-3G (now)
  - CCATprime
  - Simons Observatory (2022)
  - CMB-S4 (2027)
- The LSS surveys
  - DESI, LSST, *Euclid*, WFIRST