SZ (and other "CMB" observations) as a Probe of Cosmic Structure and Baryonic Physics

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Towards the European Coordination of the CMB Programme
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"CMB" Observations

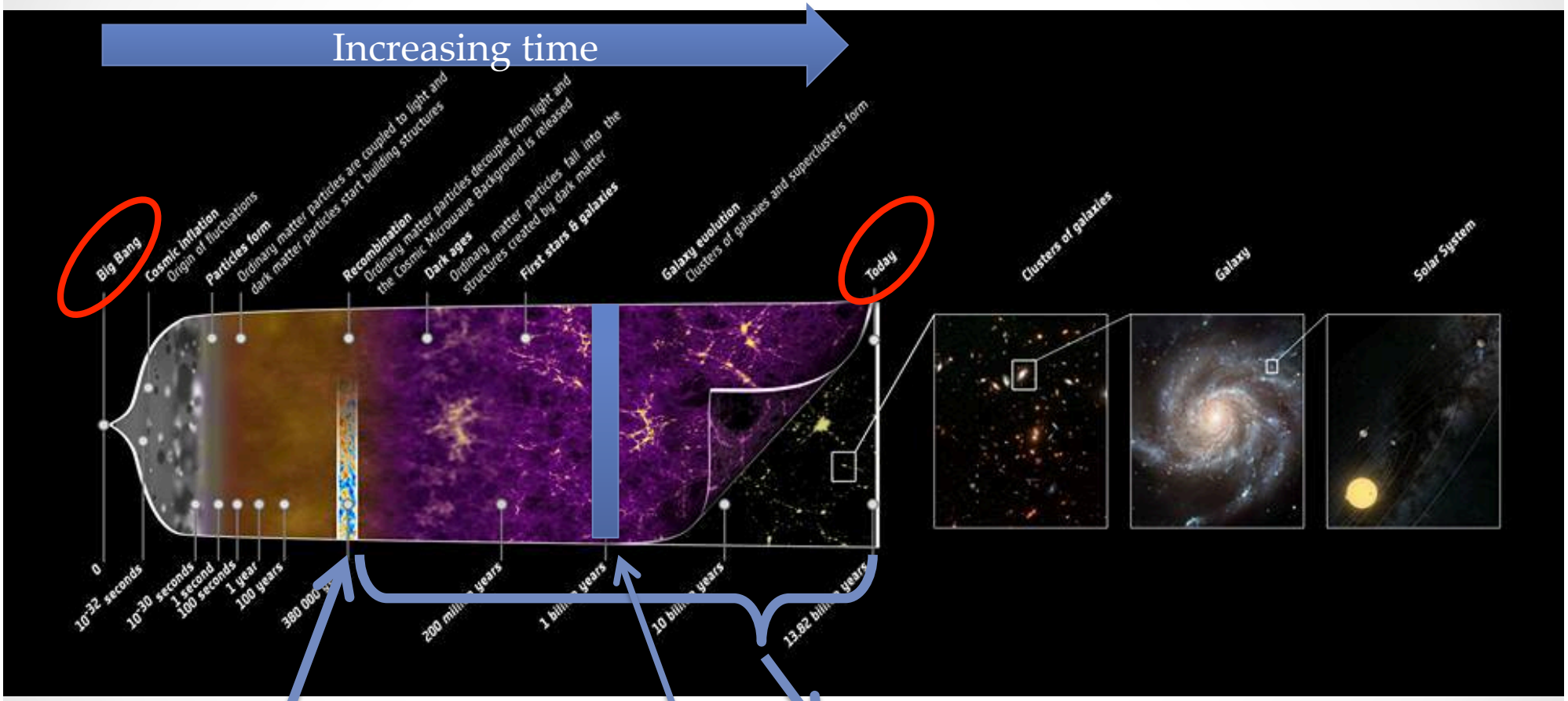
- Temperature & Polarization
- 10s-100s of GHz
- Order arcmin angular resolution
- Order microK-arcmin sensitivity
- Large sky coverage

Science Breakdown

- Cluster cosmology – SZ effect
  - Dark energy, neutrino mass, modified gravity
- Tracing the baryons – SZ effect & dust
  - Cluster Astrophysics
  - Galaxy formation
  - Impact on P(k) – important for Stage IV dark energy surveys
- Tracing the matter – CMB lensing
  - Tomographic reconstruction of P(k,z)
  - Object masses to high redshift
- Reionization – SZ effect

Context

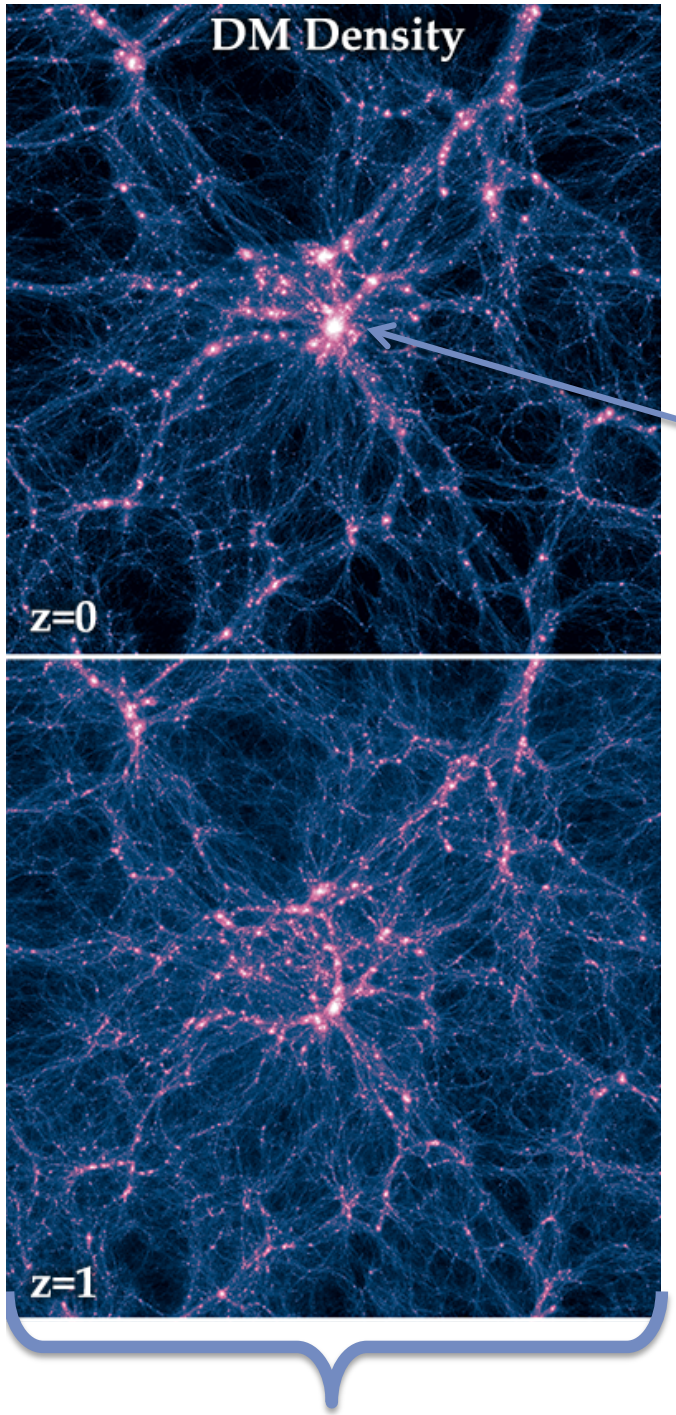
Vista Point



Recombination: "Emission" of cosmic microwave background (CMB)

Reionization

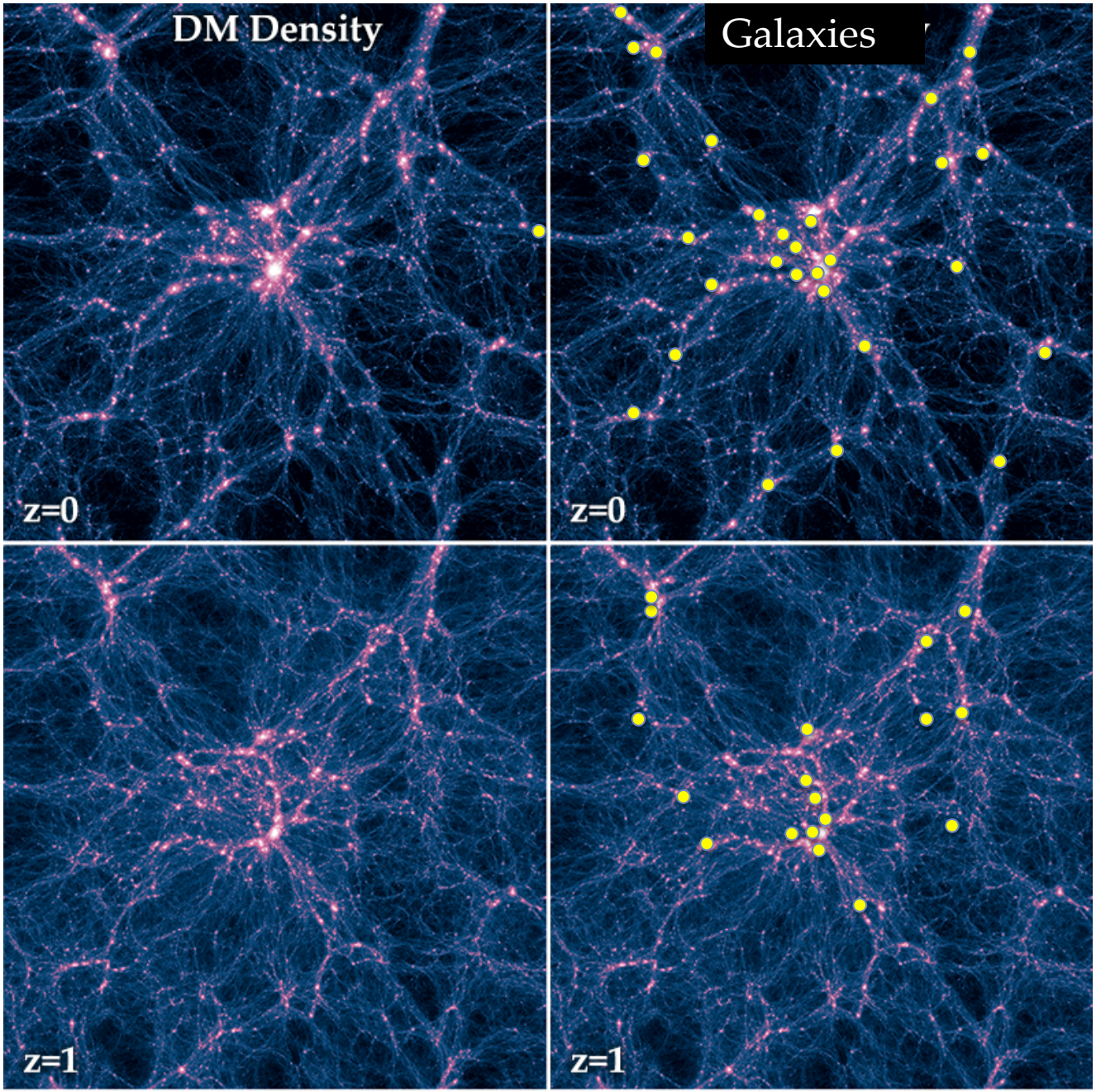
Large-scale structure (LSS): the cosmic web

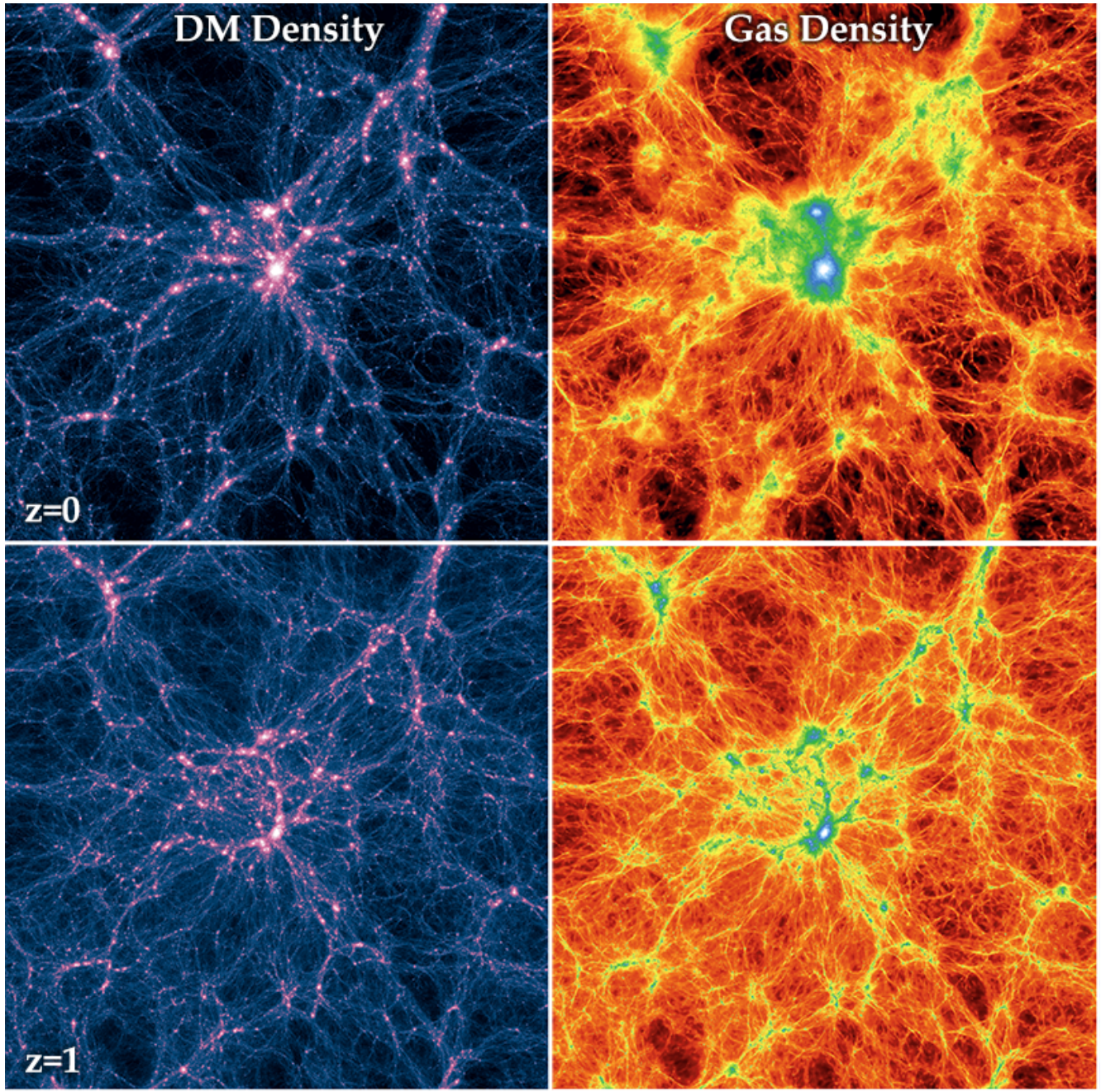


The cosmic web of LSS: Illustris Simulations

(http://www.illustris-project.org)

Galaxy cluster


DM Density
Galaxies
z=0
z=0
z=1
z=1


DM Density
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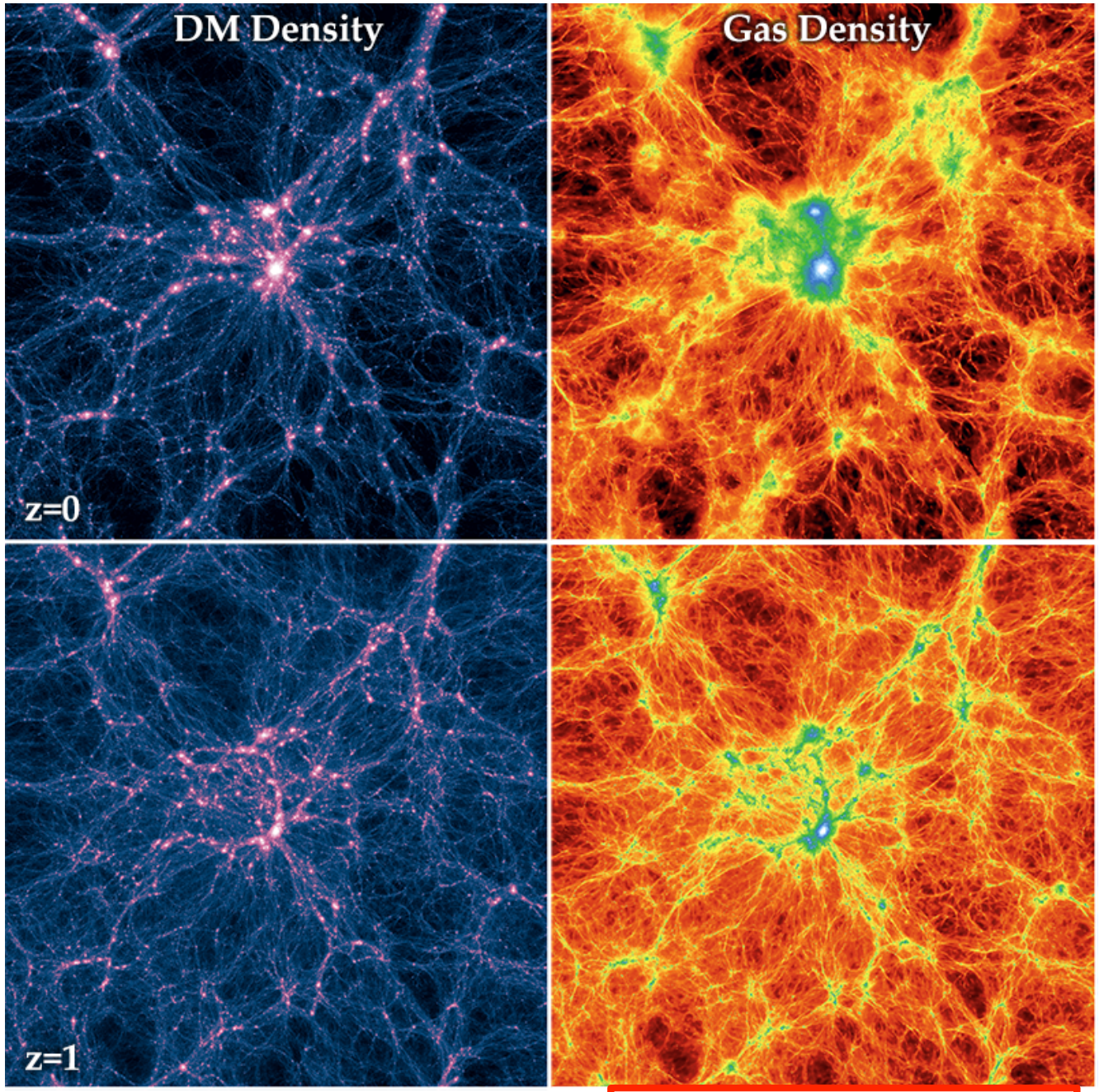
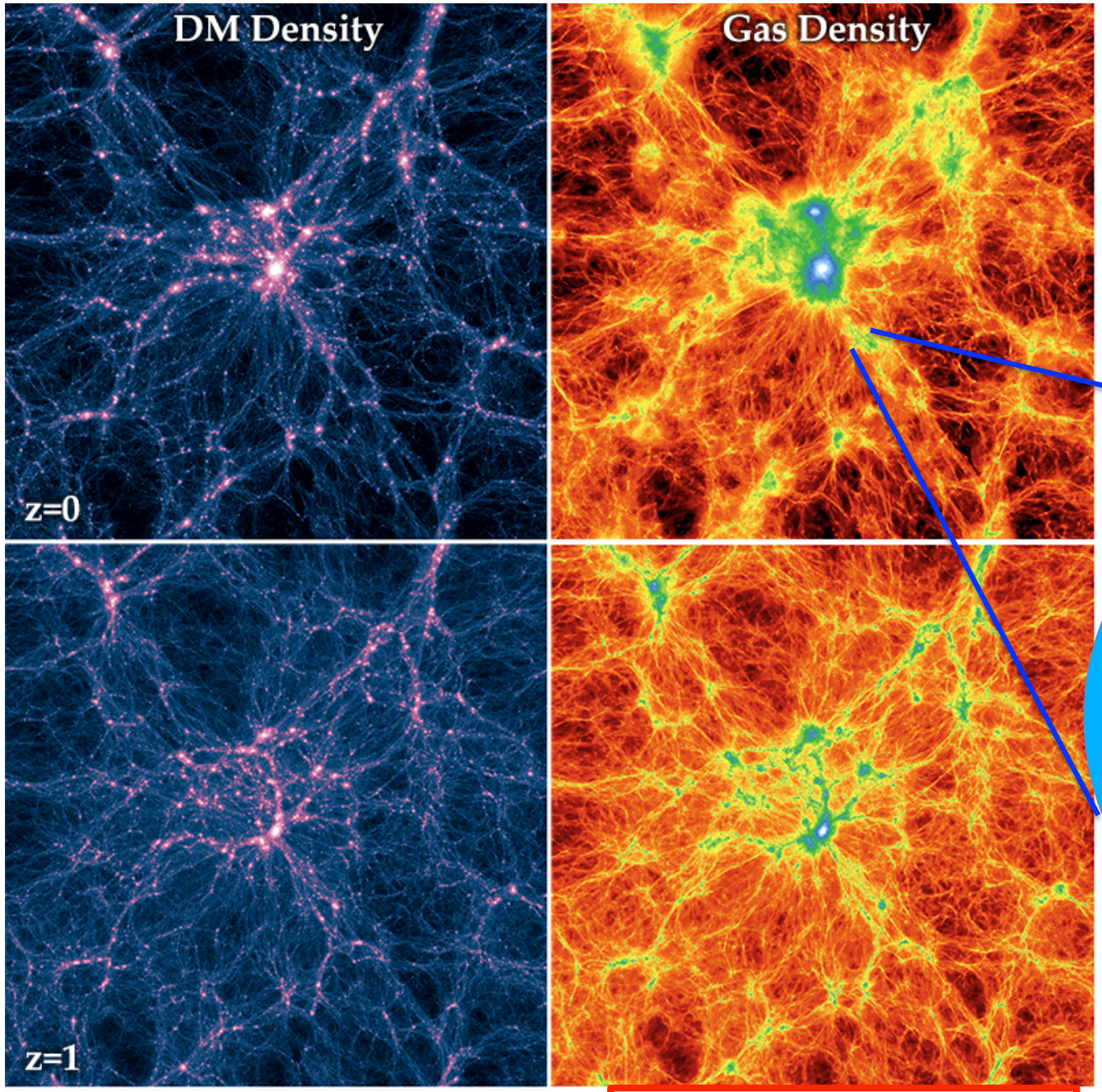
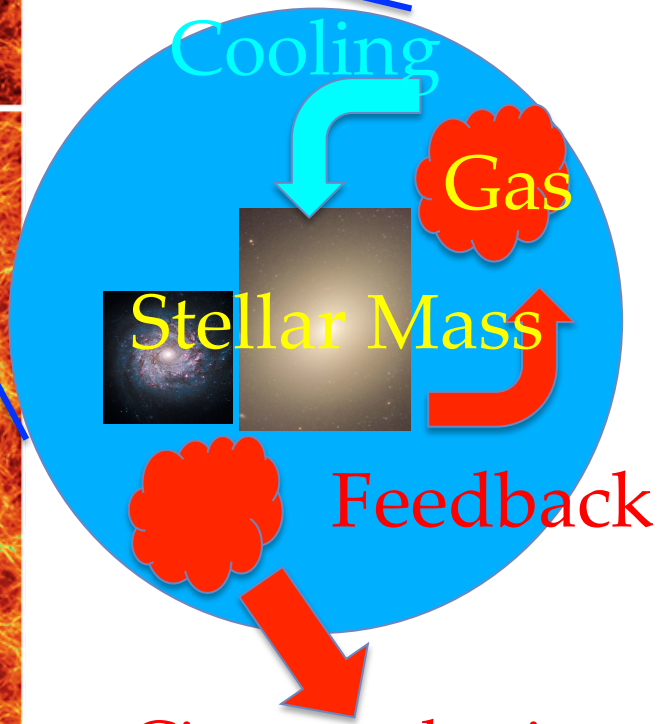


90% of the
Baryons are here!



Dark matter halos: building blocks of the cosmic web



90% of the Baryons are here!

Circumgalactic medium (CGM) and IGM

Most baryons are in the CGM/IGM and remain elusive!

• • •

Baryons make up ~15% of the total cosmic matter density

What are they doing?

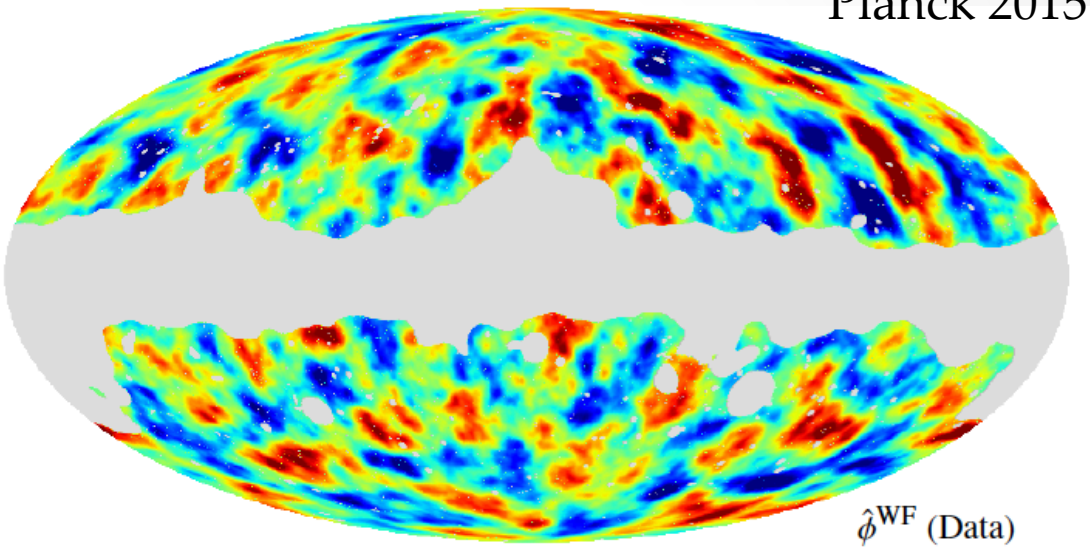
A Baryon Probe

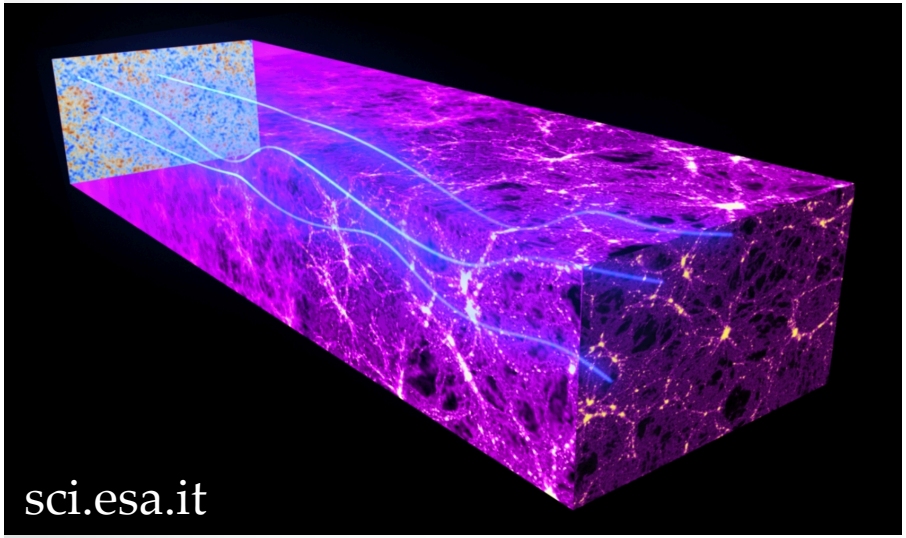
- Thermal Sunyaev-Zeldovich (SZ) Effect
  - Direct measure of gas thermal energy
- Kinetic SZ Effect
  - Gas density and velocity
- Dust Emission
  - Important at "CMB" observation frequencies
  - Tracer of star formation

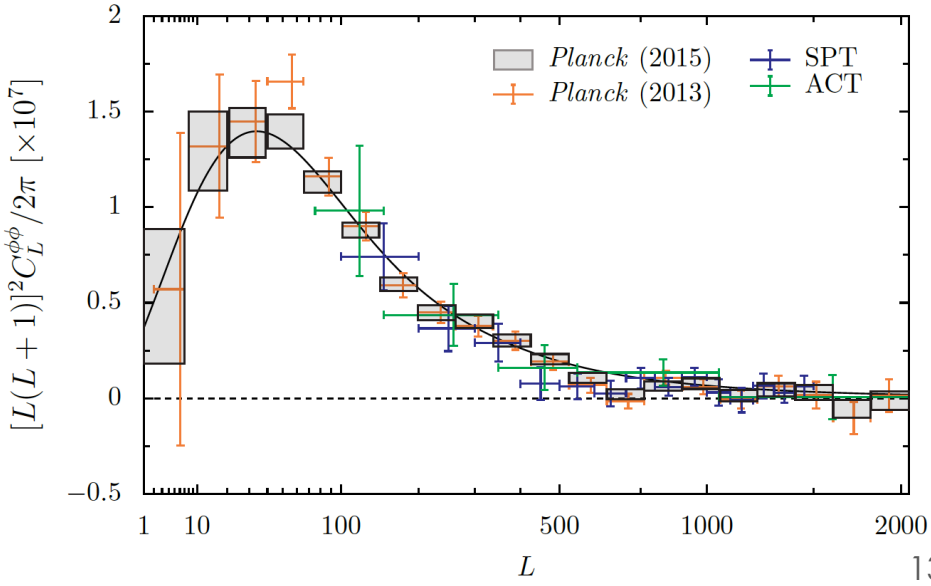
And a Matter Probe

- CMB lensing (see talk by A. Lewis)
- LSS matter distribution

Planck 2015

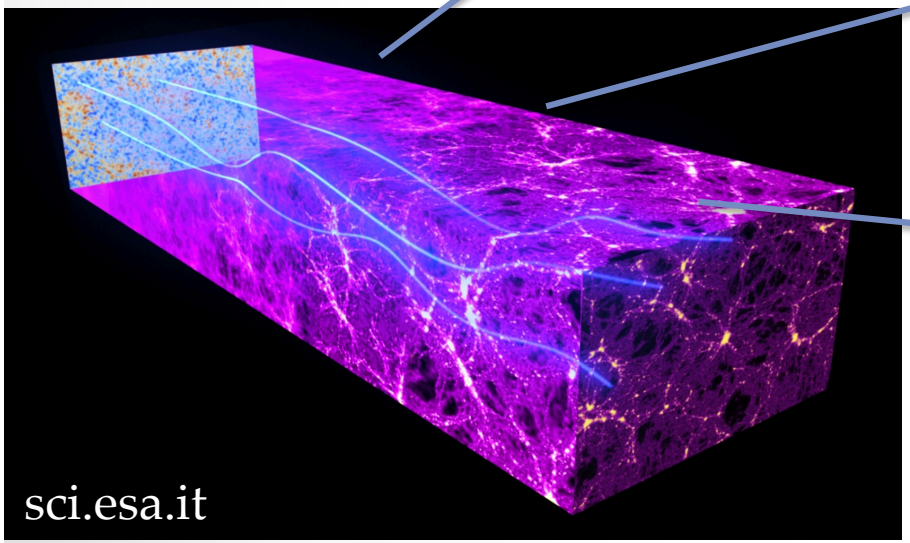


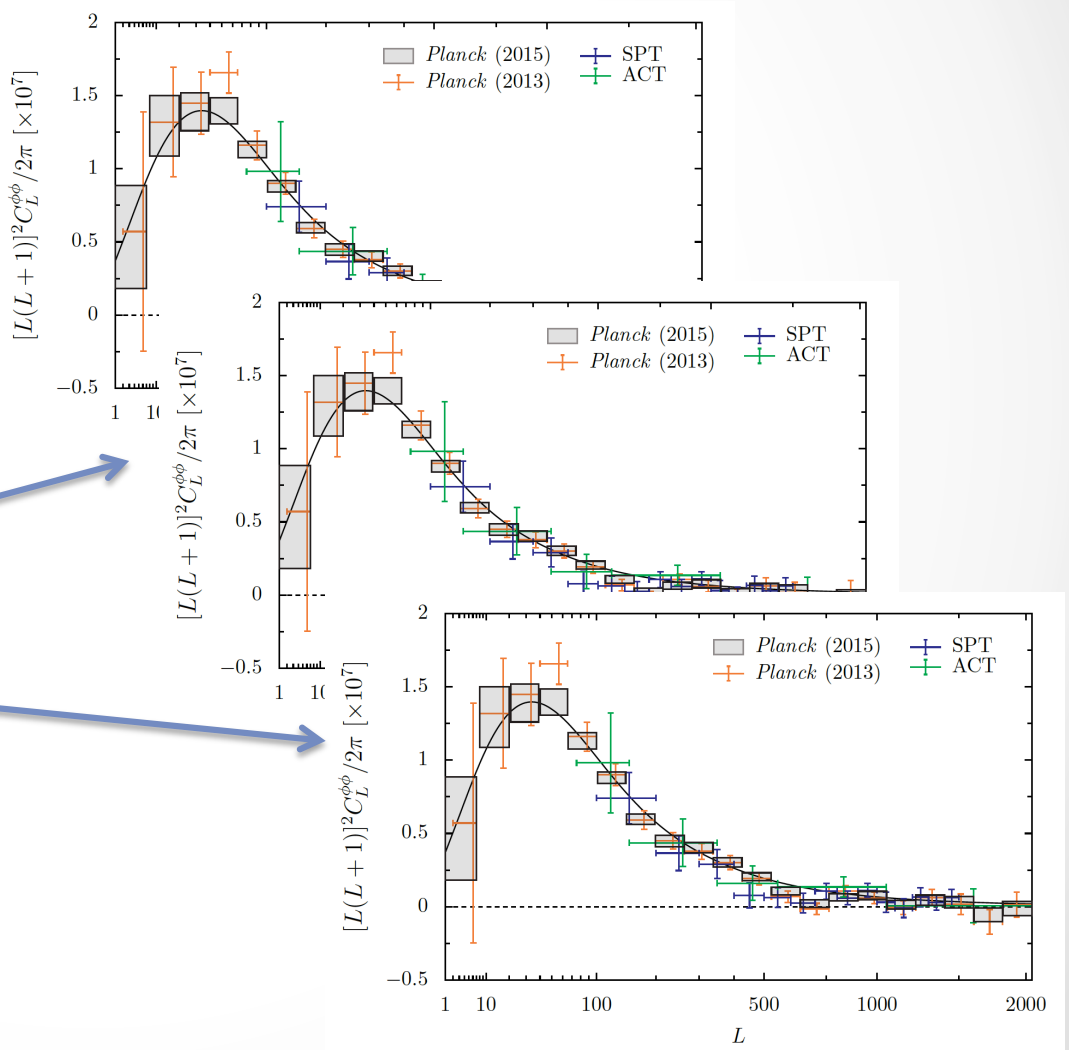




And a Matter Probe

- Tomography by cross-correlation with galaxies at different redshifts

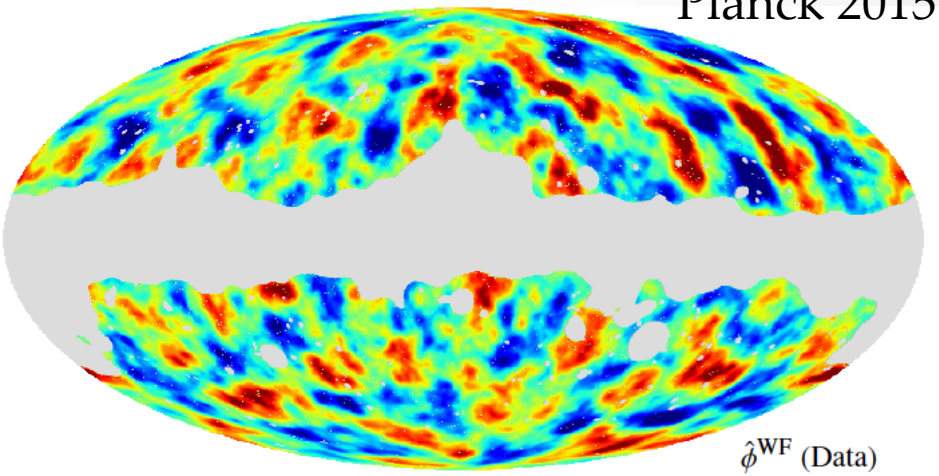




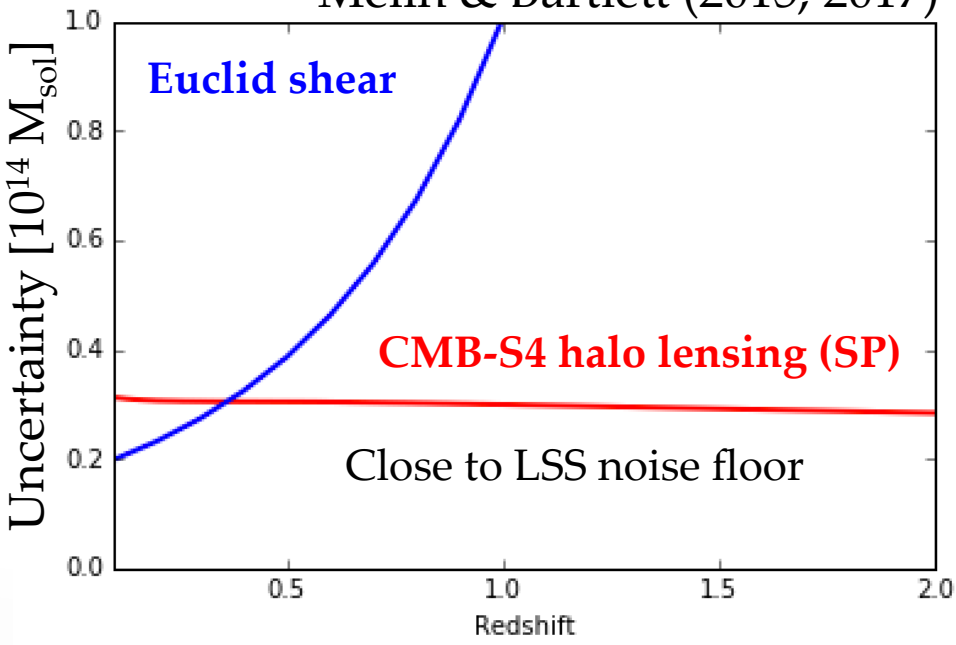
And a Matter Probe

- Measure object masses
- Reaches to much higher z than shear

Planck 2015

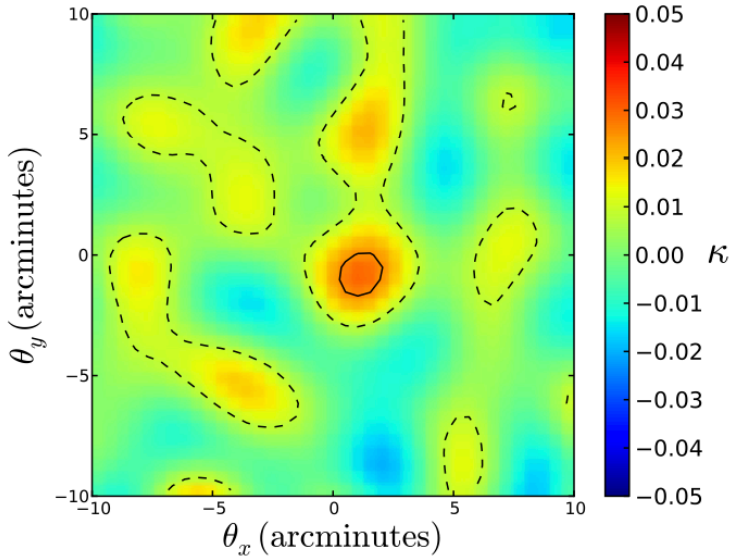


Melin & Bartlett (2015, 2017)

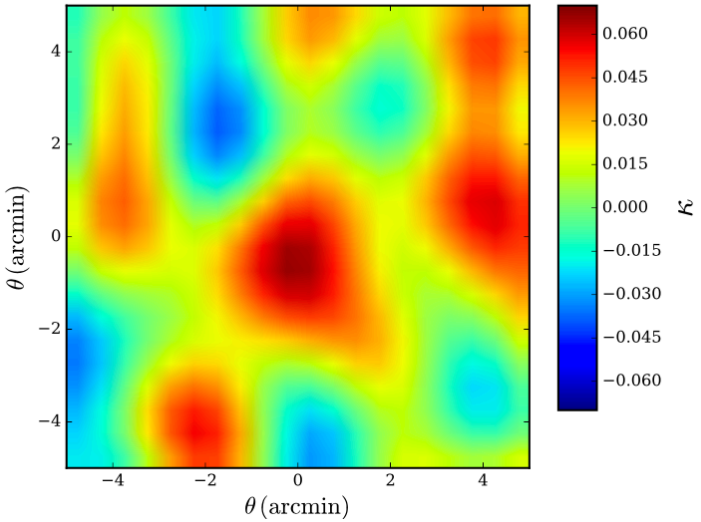


A Proven Concept

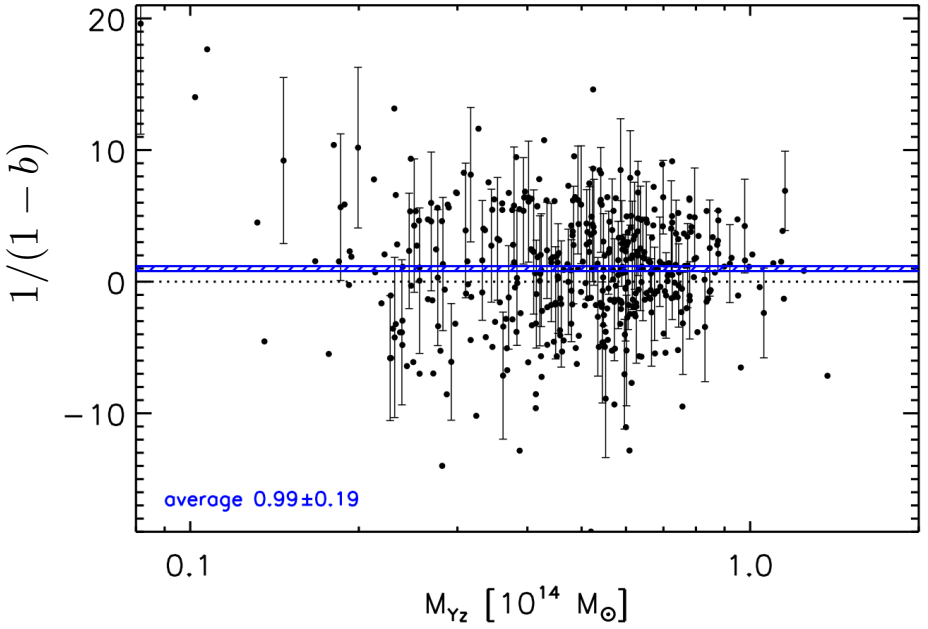
ACTPol: Madhavacheril et al. (2015)



SPT: Baxter et al. (2017)



Planck 2015



- ACTPol: 12,000 CMASS galaxies 3.2σ
- *Planck*: 439 SZ clusters 5σ
- SPT: 513 SZ clusters (2015) 3.1σ
- SPT: 3697 ReMaPPer clusters 6.5σ

"CMB" Observations

- Temperature & Polarization
- 10s-100s of GHz
- Order arcmin angular resolution
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Probe of CGM/IGM, stellar production and total mass

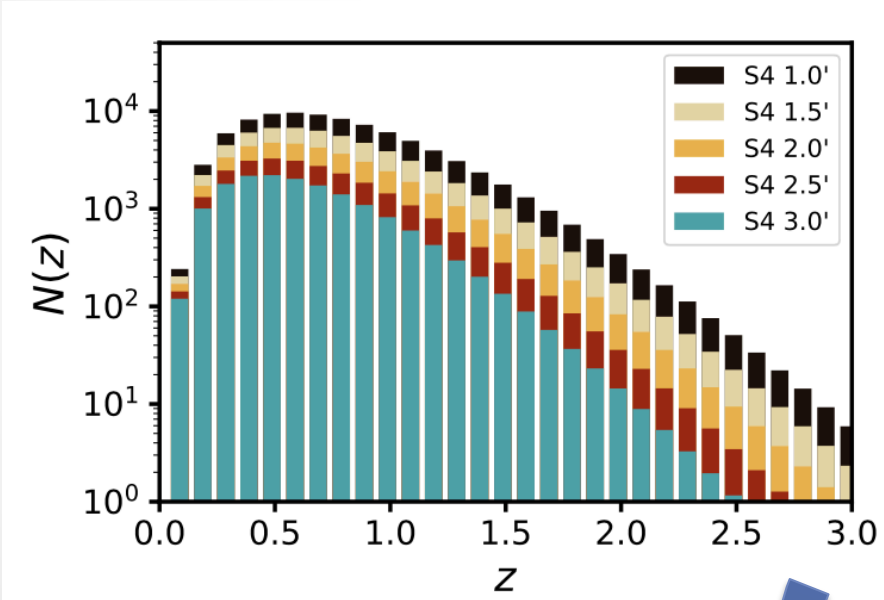
Example Applications …

Galaxy Clusters

- Find clusters with SZ out to high redshifts (z>2)
- Measure their mass with CMB lensing
  - ~1% mass calibration out to z>2
- Astrophysics
- Cosmology

Galaxy Clusters

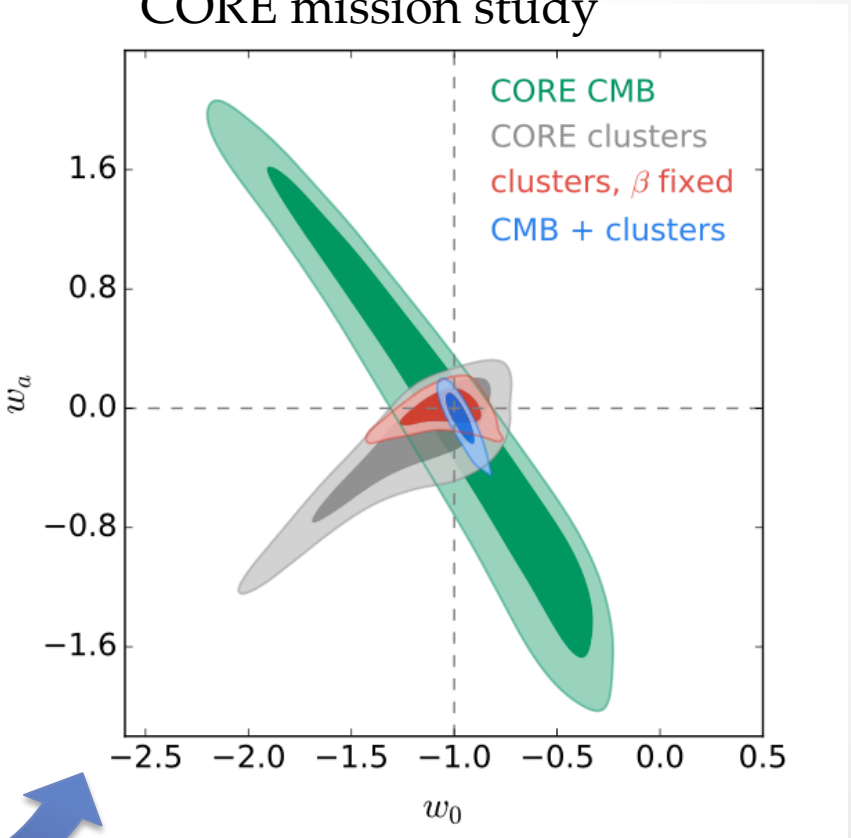
Madhavacheril et al. (2017)
CMB-S4 (see talk by J. Carlstrom)



Astrophysics: high-z clusters are active galaxy formation sites

- How do galaxies first form there?
- How are they quenched?

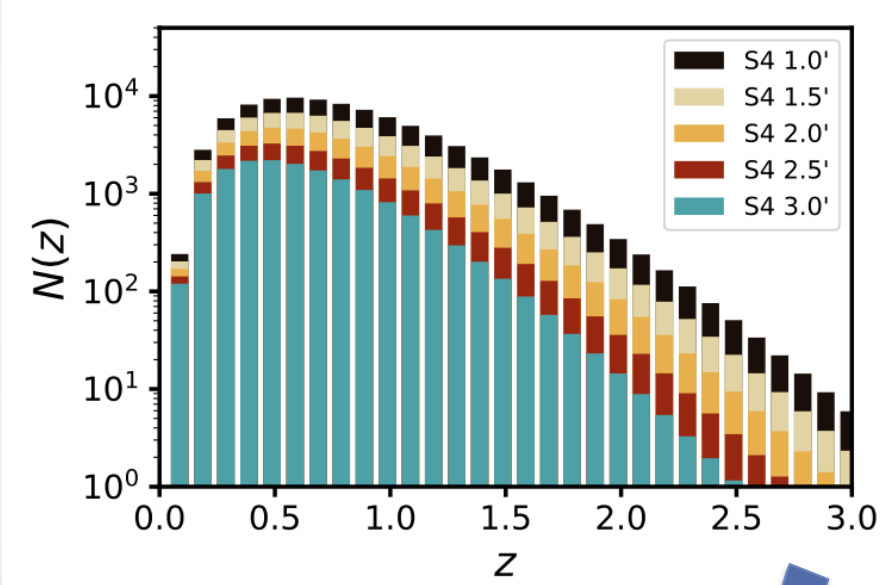
Melin et al. (2017)
CORE mission study



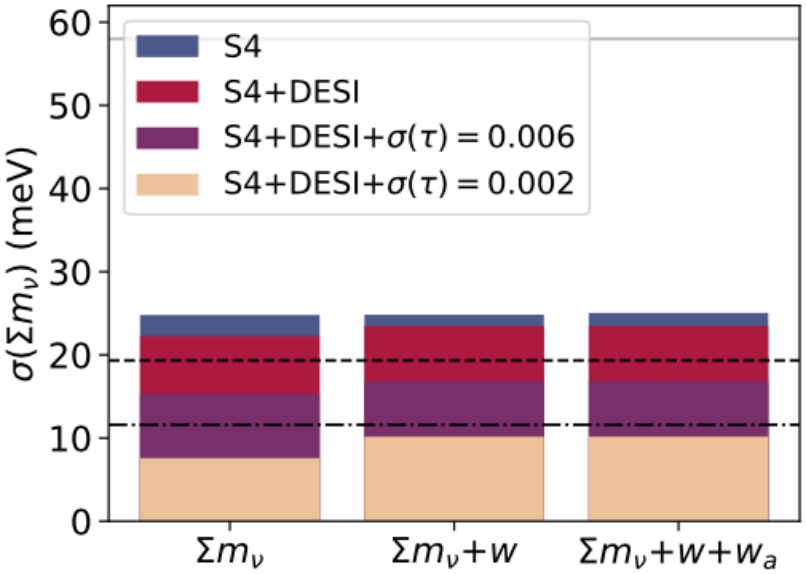
Cosmology: cluster z-distribution

Galaxy Clusters

Madhavacheril et al. (2017)
CMB-S4 (see talk by J. Carlstrom)



Madhavacheril et al. (2017)
CMB-S4



Astrophysics: high-z clusters are active galaxy formation sites

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- How are they quenched?

Cosmology: cluster z-distribution

Galaxy Formation

Galaxy Formation

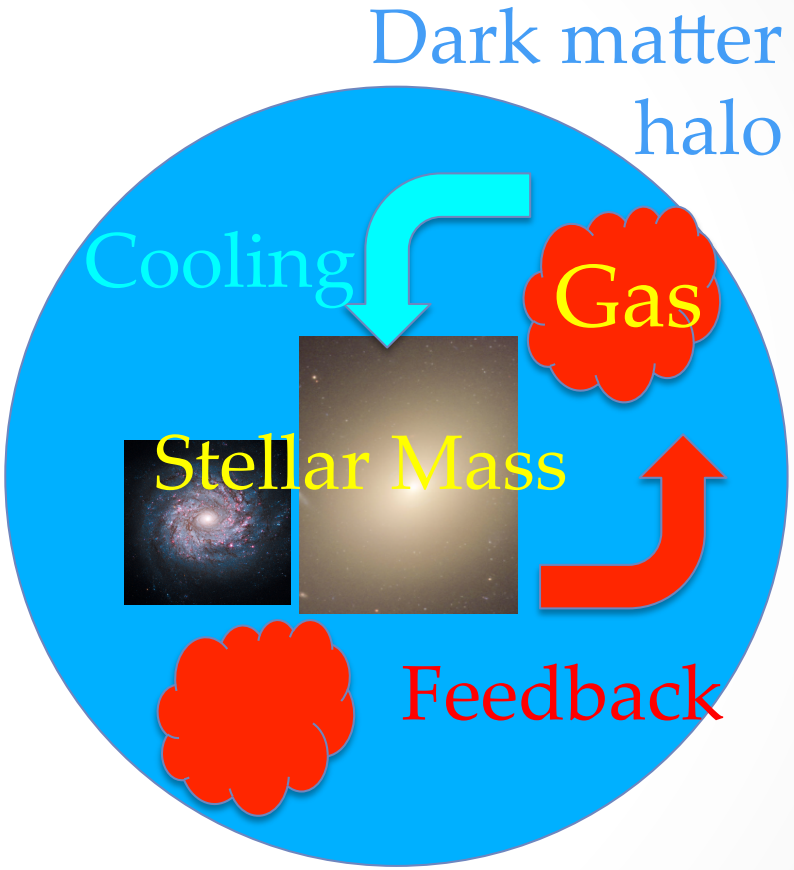
Is
shockingly inefficient:

< 10% of baryons make stars

Why?

The Circumgalactic Medium

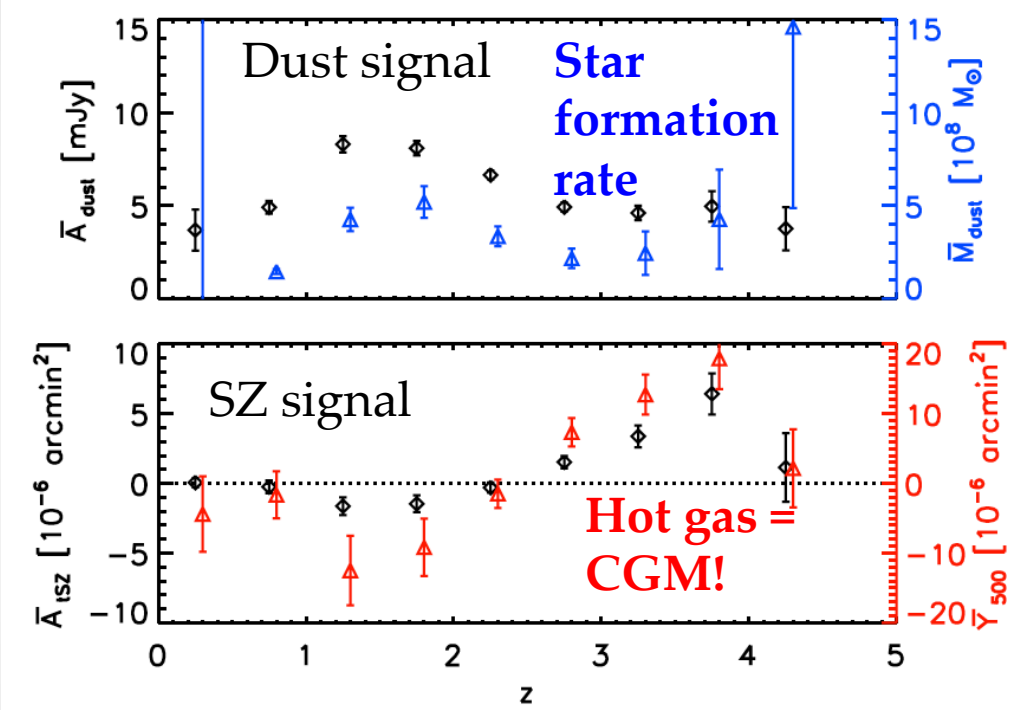
- Bulk of the baryons is in the CGM/IGM
- Keeping it there requires powerful feedback
- This central engine of galaxy formation is poorly understood



Central engine of galaxy formation

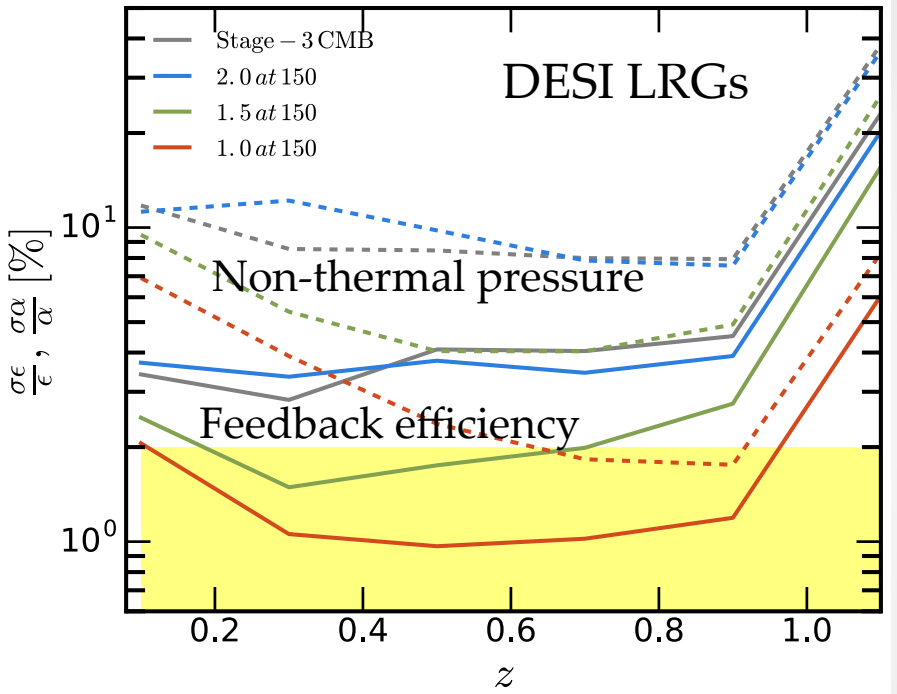
Probing Galaxy Formation

Planck observations of quasars



Verdier et al. (2015)

CMB-S4 Simulations

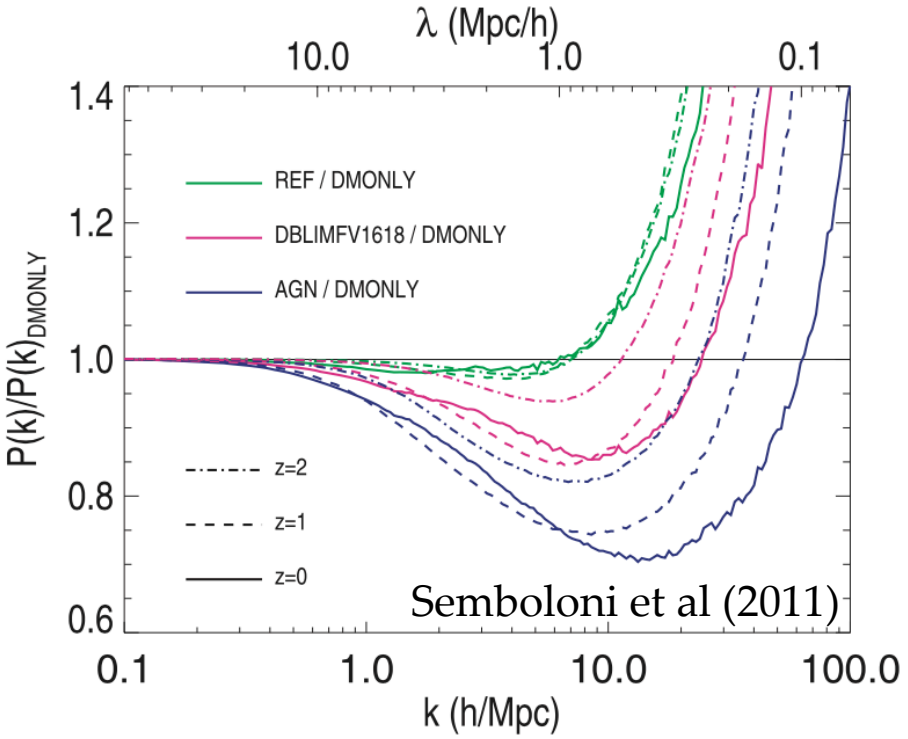


Battaglia et al. (2017)

Measure CGM and star formation rate out to high redshifts
Constrain feedback efficiency to % level

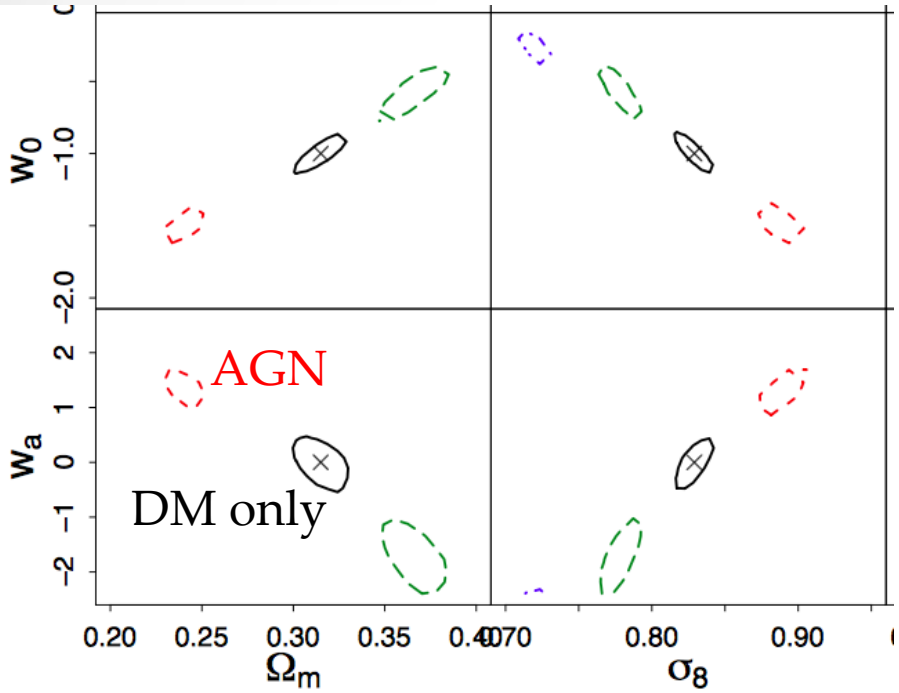
Impact of Baryons on Dark Energy

- Stage IV cosmic shear surveys (e.g., *Euclid*, LSST, WFIRST) use measurements of the matter power spectrum, P(k), as precision probe of dark energy
- Baryonic physics (e.g., feedback) impact P(k) up to 10s of %!
- Order of mag. larger than LSST specs!

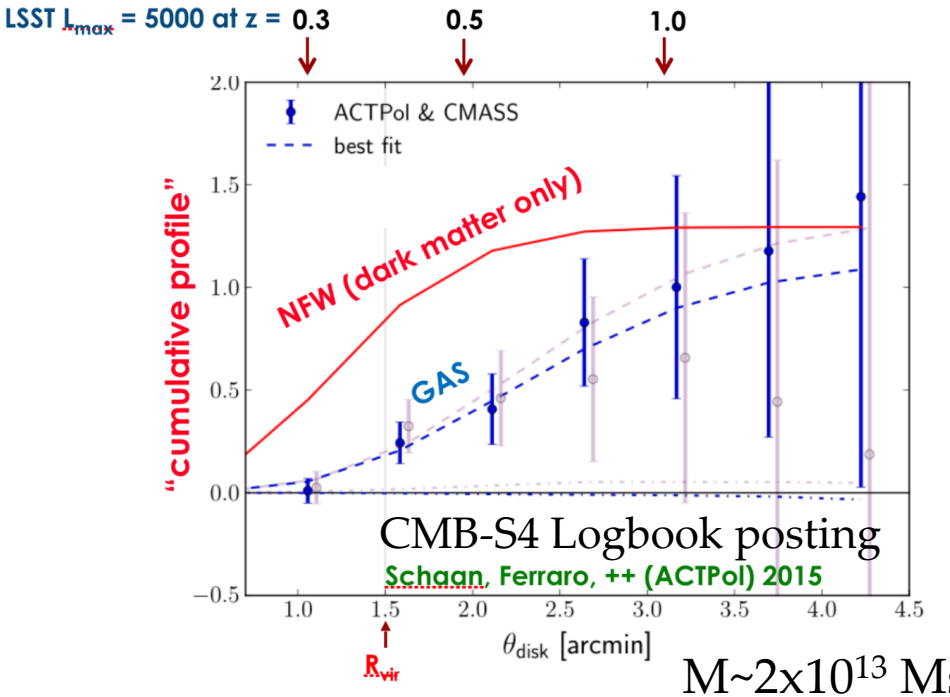


Baryonic Effects on P(k)

LSST/*Euclid*-like shear survey



Eifler et al. (2014)



M~2x10^{13} Msol
z~0.6

SZ determination of baryon distribution can directly measure the baryon impact for Stage IV

Conclusions

- "CMB" observations open a new window onto LSS and galaxy formation
- Probe baryons, matter & stellar formation
  - Current generation (ACT, SPT, *Planck*) has discovered new territory
  - Vast science area under expansion/exploration
- Novel tools for
  - Astrophysics
  - Cosmology