Title: Cosmic shadows and cosmic structures: the CMB as a Large-Scale Structure experiment

Speakers: Simone Ferraro

Series: Cosmology & Gravitation

Date: September 27, 2022 - 11:00 AM

URL: https://pirsa.org/22090095

Abstract: Information about the late-time Universe is imprinted on the small scale CMB as photons travel to us from the surface of last scattering. Several processes are at play and small scale fluctuations are very rich and non-Gaussian in nature. I will review some of the most important effects and I will focus on the Sunyaev-Zel'dovich (SZ) effect and gravitational lensing. I will discuss how a combination of measurements can probe velocity fields at cosmological distances and inform us on cluster energetics. I will also show recent measurements of weak lensing of the CMB and how they can help us interpret intriguing discrepancies in cosmological parameters between the high and low redshift Universe.

Zoom link: https://pitp.zoom.us/j/94451033605?pwd=Tkx4dHZTblMxUFJlZENyblJQVFo2dz09

Cosmic shadows and cosmic structures

the CMB as a Large-Scale Structure experiment

Simone Ferraro
(Lawrence Berkeley National Lab / UC Berkeley)

BERKELEY LAB

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

PI Cosmology seminar
September 27, 2022

Cosmology from the primary CMB

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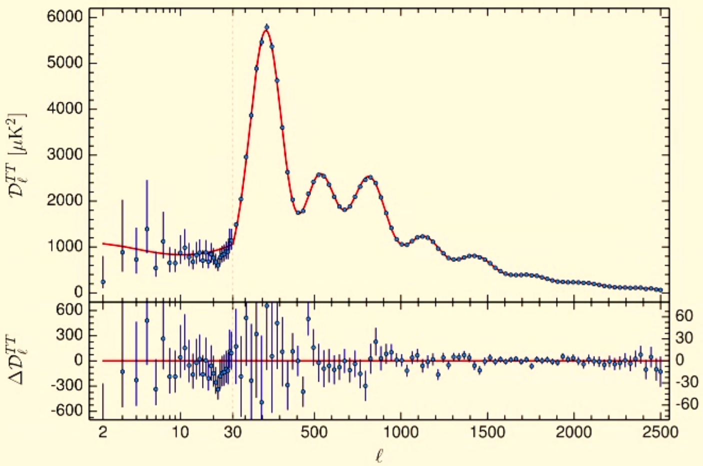
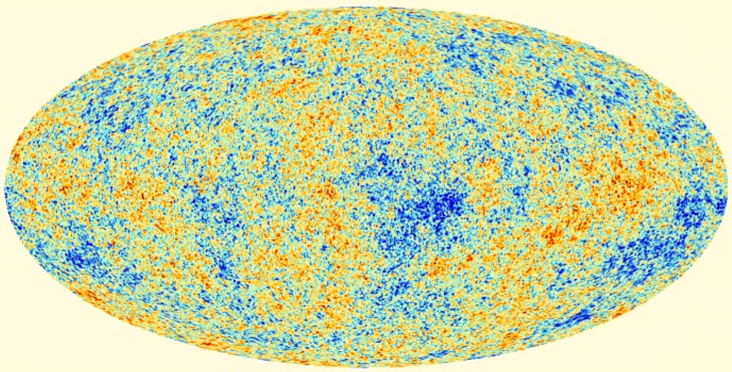
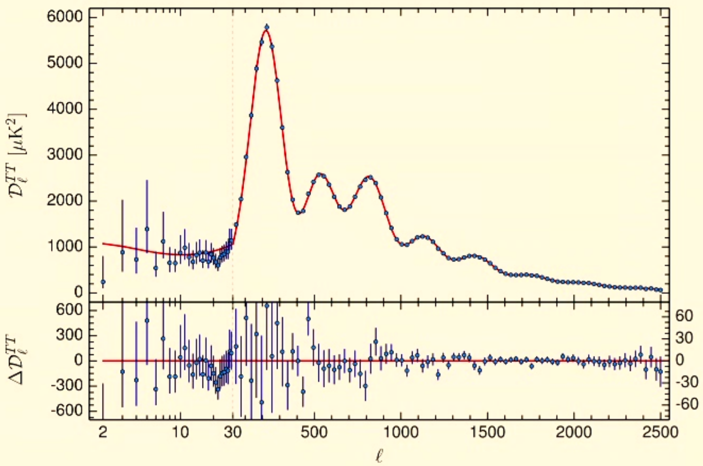
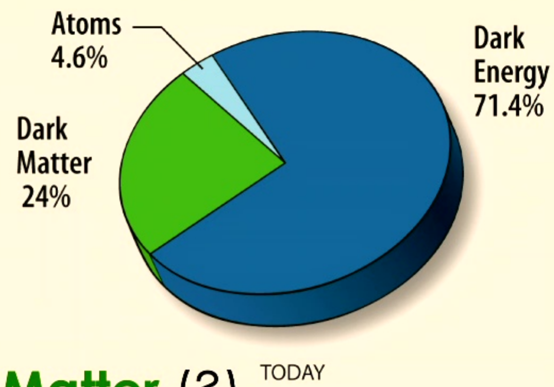




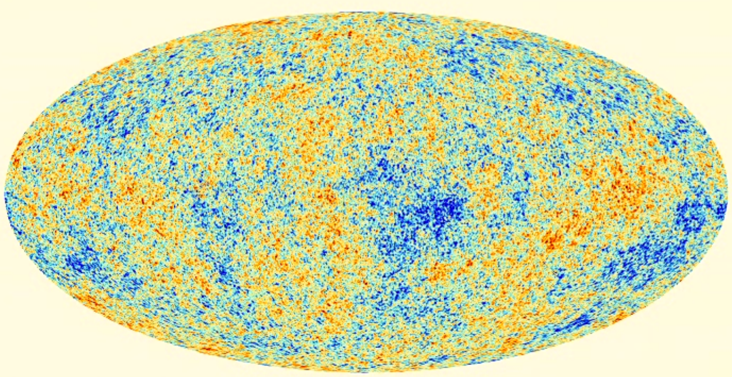
Planck 2018

Cosmology from the primary CMB



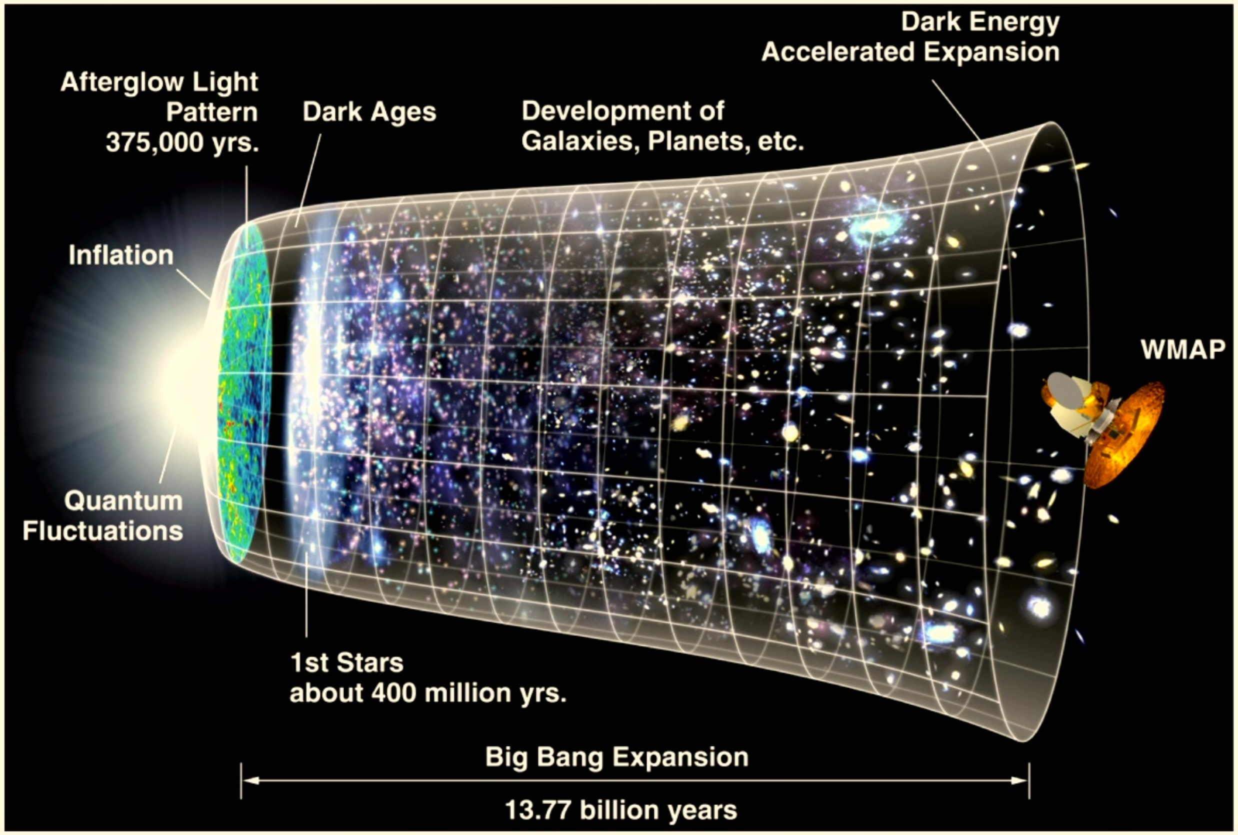


- Dark Matter (?)
- Dark Energy (?)
- Inflation (?):
  - (Approximately) Gaussian fluctuations
  - Adiabatic initial conditions
  - Small spatial curvature
  - Gravitational waves → search for B-modes



Planck 2018

The CMB is so much more!

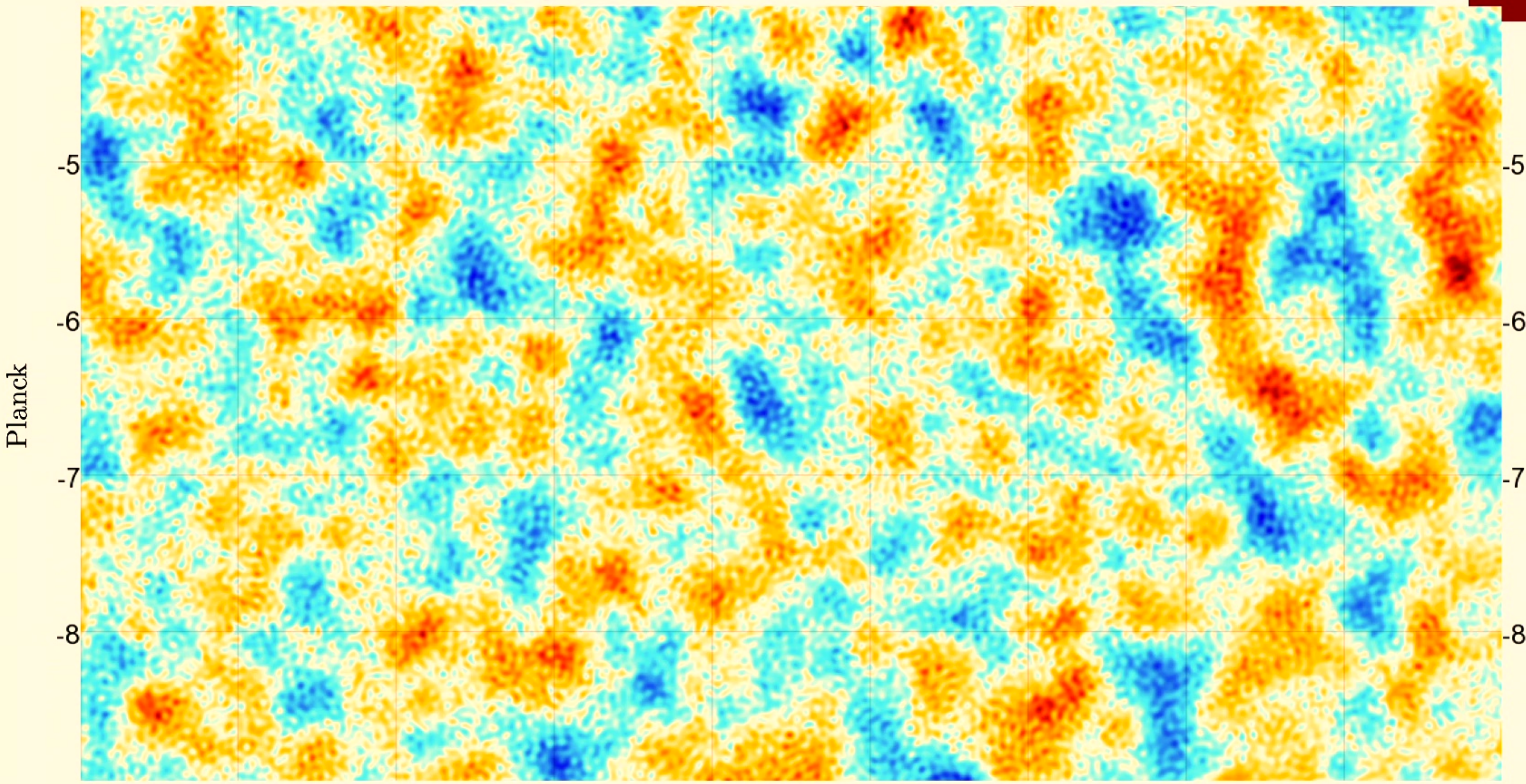


credit: WMAP

Thanks to scattering and lensing, it is a **map of the "whole" observable universe***

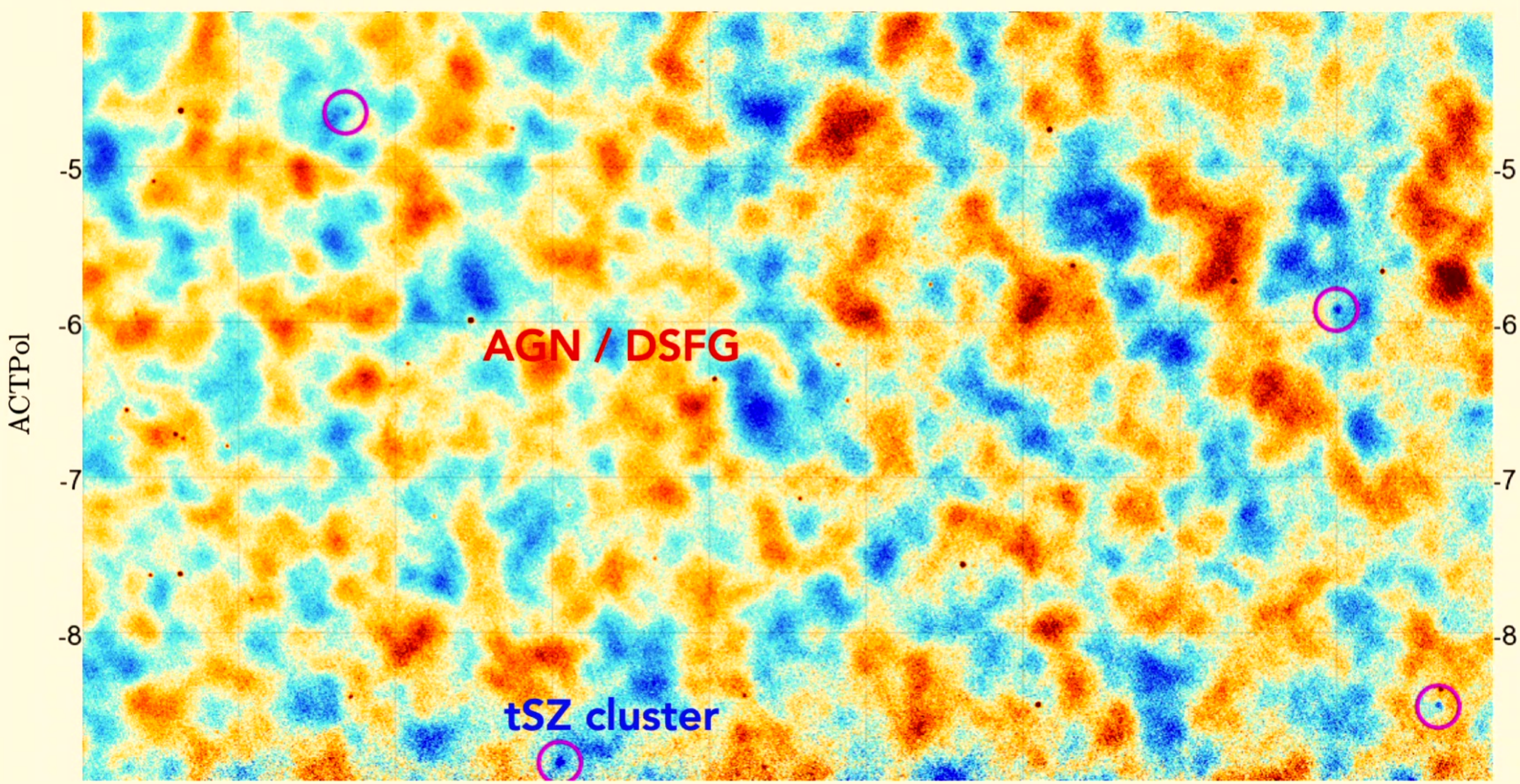
* If you have good enough resolution!

Planck CMB maps



Simone Ferraro (LBNL)

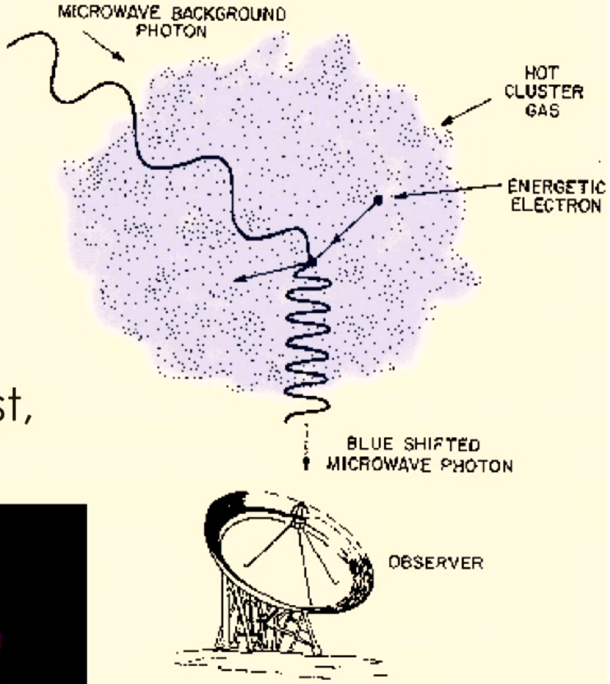
ACT maps (DR5)

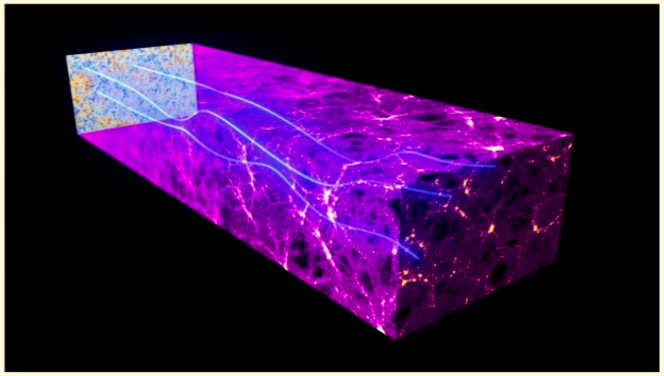


Louis+ACT collaboration 16

Photons interact with matter

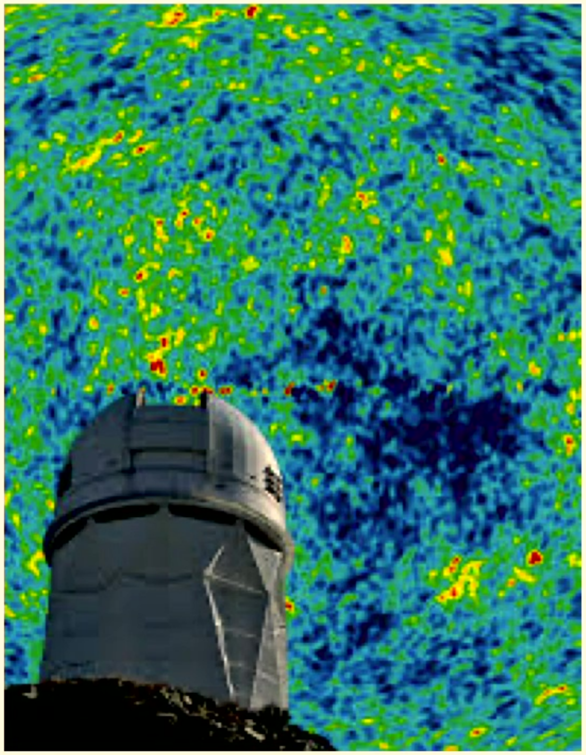
- Gravitational: CMB lensing, gravitational redshift, Integrated Sachs-Wolfe effect, "moving lens", time delay, …
- Scattering (Thomson/Compton scattering):
  - Thermal Sunyaev-Zeldovich (tSZ),
  - Kinematic Sunyaev-Zeldovich (kSZ),
  - Patchy screening and scattering, ...
- (Emission from late time matter): starlight, IR emission from dust, free-free, synchrotron, AME, …





Simone Ferraro (Berkeley)

This talk



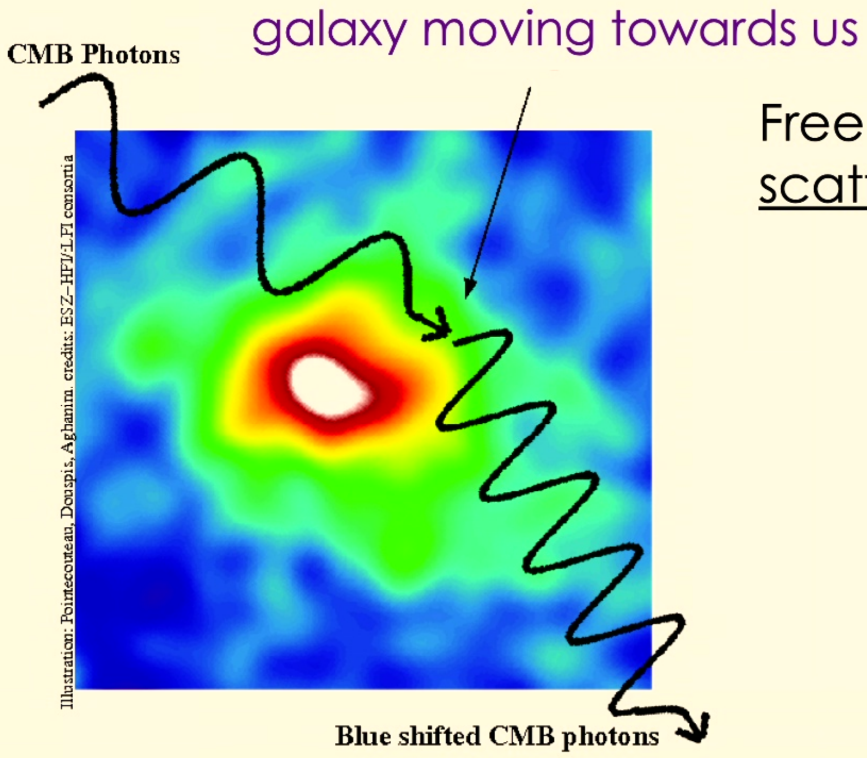
Part I: Imaging the gas with the CMB as a backlight

Part II: CMB lensing cross-correlations and high-redshift, low redshift discrepancies

Part I: Imaging the gas with the CMB as a backlight

With Emmanuel Schaan, Stefania Amodeo, Nick Battaglia + ACT team & Kendrick Smith

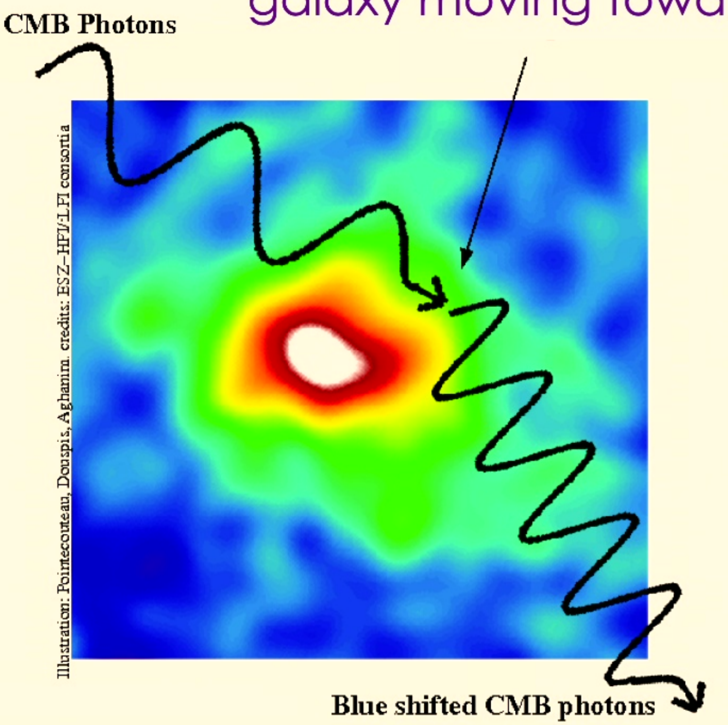
The kinematic SZ (kSZ) effect



Free electrons in galaxies → Thomson scattering of CMB photons

The kinematic SZ (kSZ) effect

galaxy moving towards us



Free electrons in galaxies → Thomson scattering of CMB photons

Galaxies move in cosmic velocity fields → Doppler shift due to motion

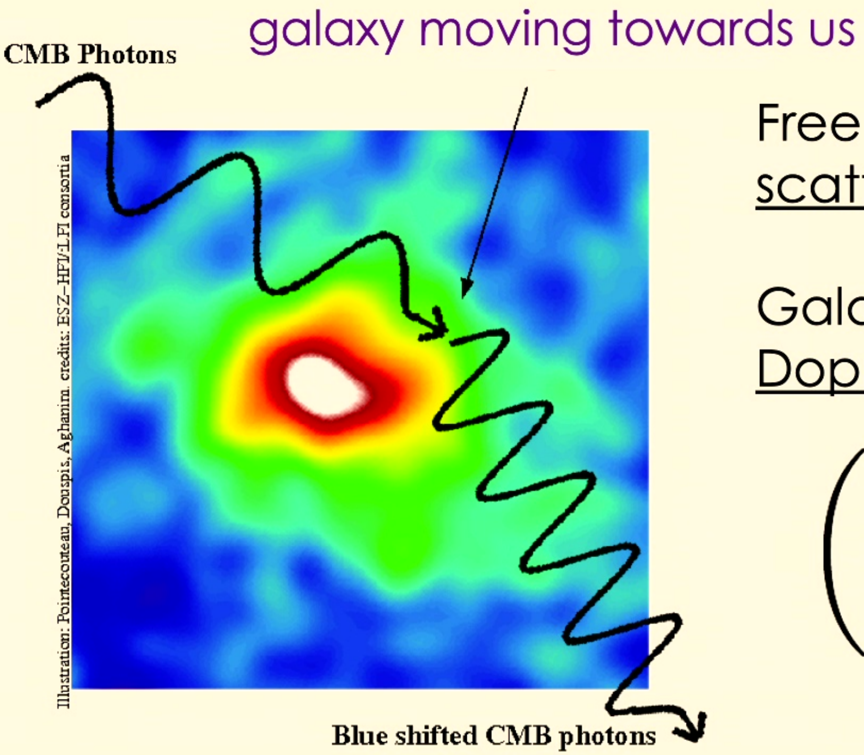
$$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} \approx \sigma_T \boxed{N_e(\boldsymbol{\theta})} \boxed{\frac{v_r}{c}}$$

column density of electrons

radial velocity

Simone Ferraro (LBNL)

The kinematic SZ (kSZ) effect



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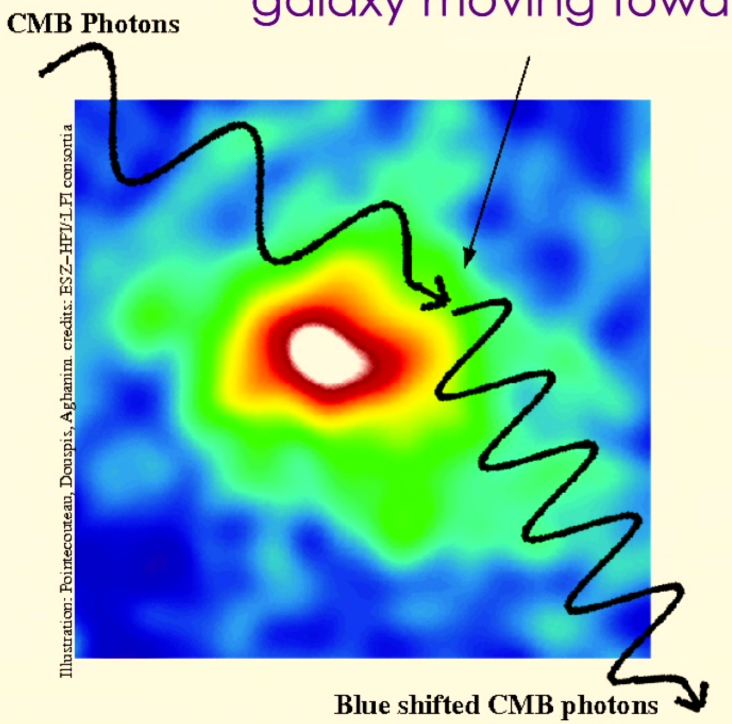
BARYON DISTRIBUTION x COSMOLOGY

Simone Ferraro (LBNL)

Baryon distribution in galaxies with kSZ

galaxy moving towards us



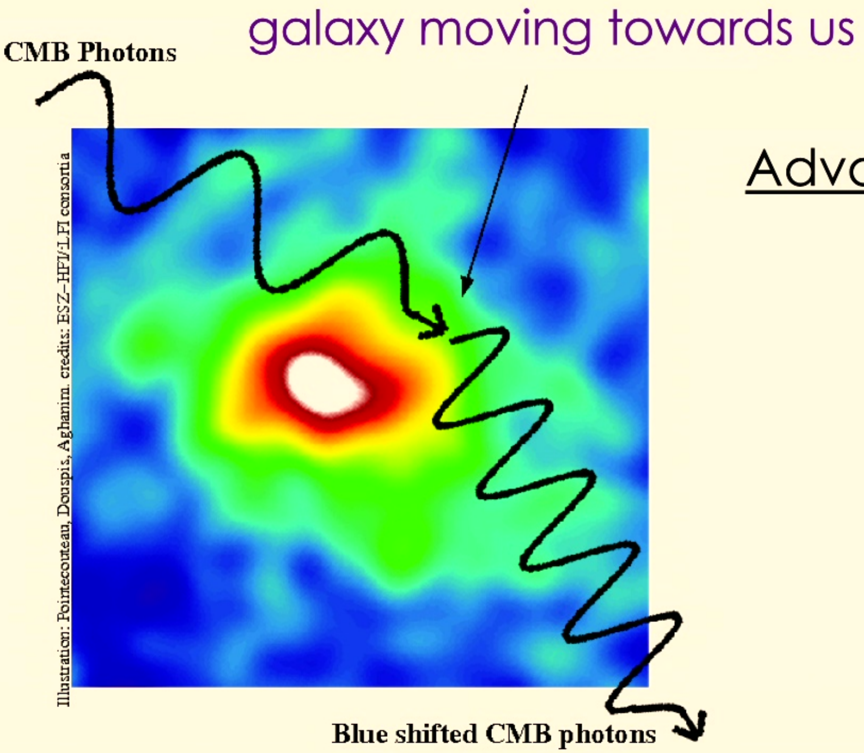
$$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} \approx \sigma_T \boxed{N_e(\boldsymbol{\theta})} \frac{v_r}{c}$$

column density of electrons

radial velocity

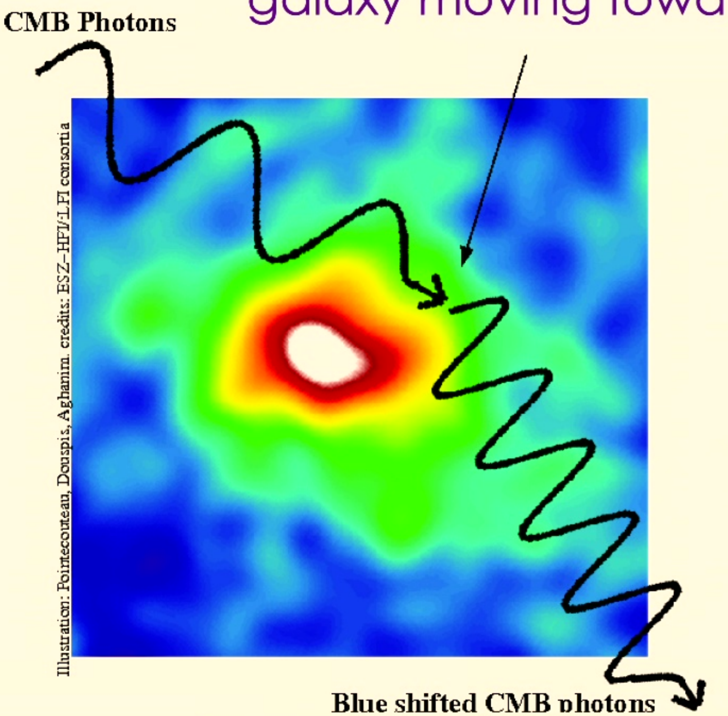
Distribution very uncertain → "**missing baryon problem**".

Baryon distribution in galaxies with kSZ



Advantages of kSZ:

Baryon distribution in galaxies with kSZ



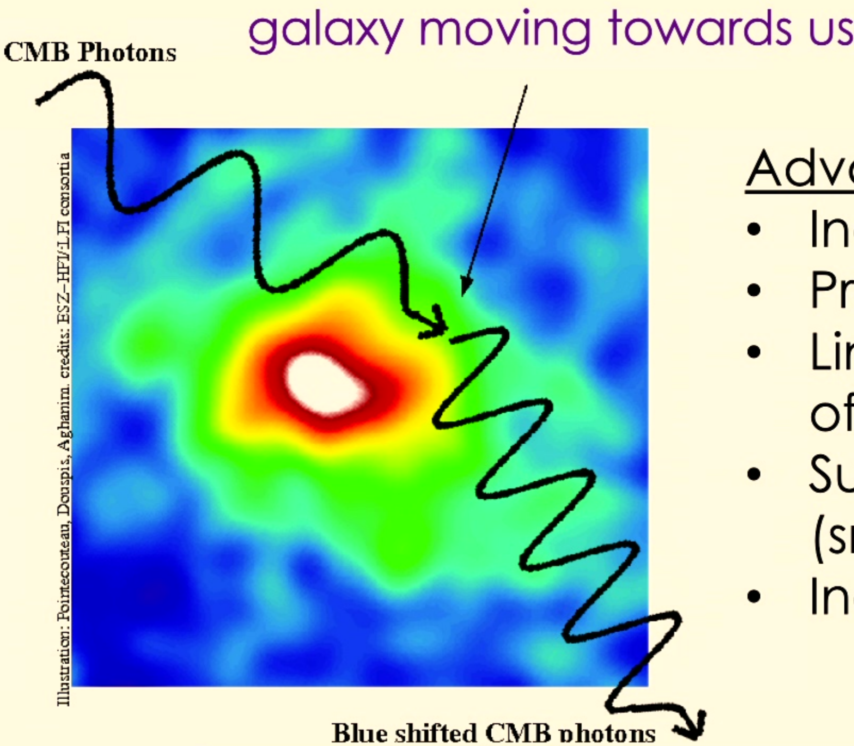
Advantages of kSZ:

- Independent of redshift
- Preserves black-body spectrum of CMB
- Linear dependence on the column density of electrons
- Suitable for “low density” environments (smaller halos, further out in the outskirts, etc.)
- Independent of temperature and metallicity.

$$\Delta T^{\rm kSZ} \approx -0.1\mu{\rm K} \quad \times \quad f_{\rm free}\left(M_{200}/10^{13}M_{\odot}\right)\left(\boldsymbol{v}_e\cdot\hat{\boldsymbol{n}}/300\ {\rm km\ s}^{-1}\right)$$

Simone Ferraro (LBNL)

Baryon distribution in galaxies with kSZ



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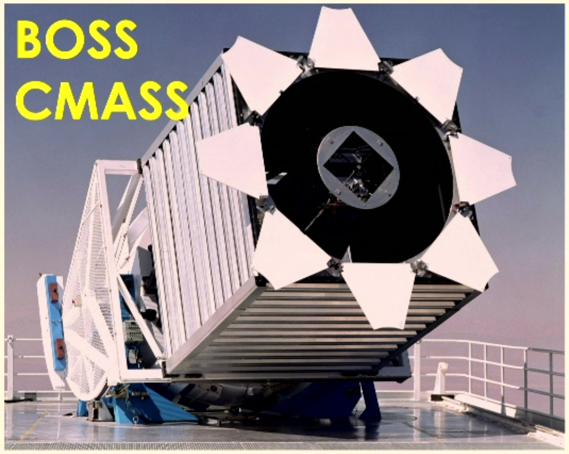
Simone Ferraro (LBNL)

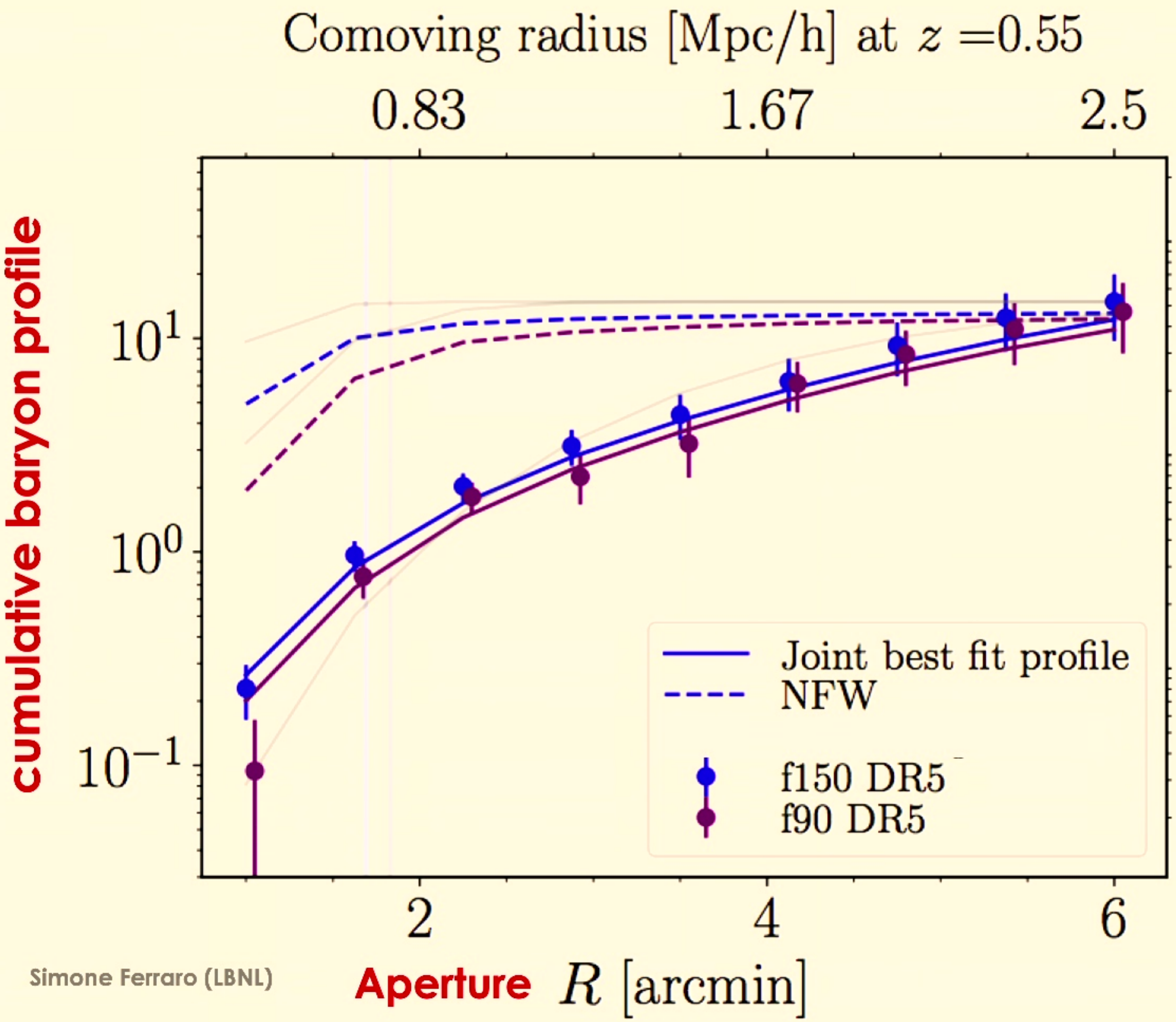
Baryon distribution in BOSS CMASS "galaxies"



BOSS CMASS galaxies:
- Number: 1M galaxies
- $0.4 < z < 0.7$
- Median mass: $2 \times 10^{13}\ M_{\odot}$ (galaxy groups)
- Well-understood spectroscopic sample

ACT CMB maps
- High resolution (beam ~ 1.4 arcmin)
- Low noise (factor of 4 smaller than Planck)
- Foreground reduced

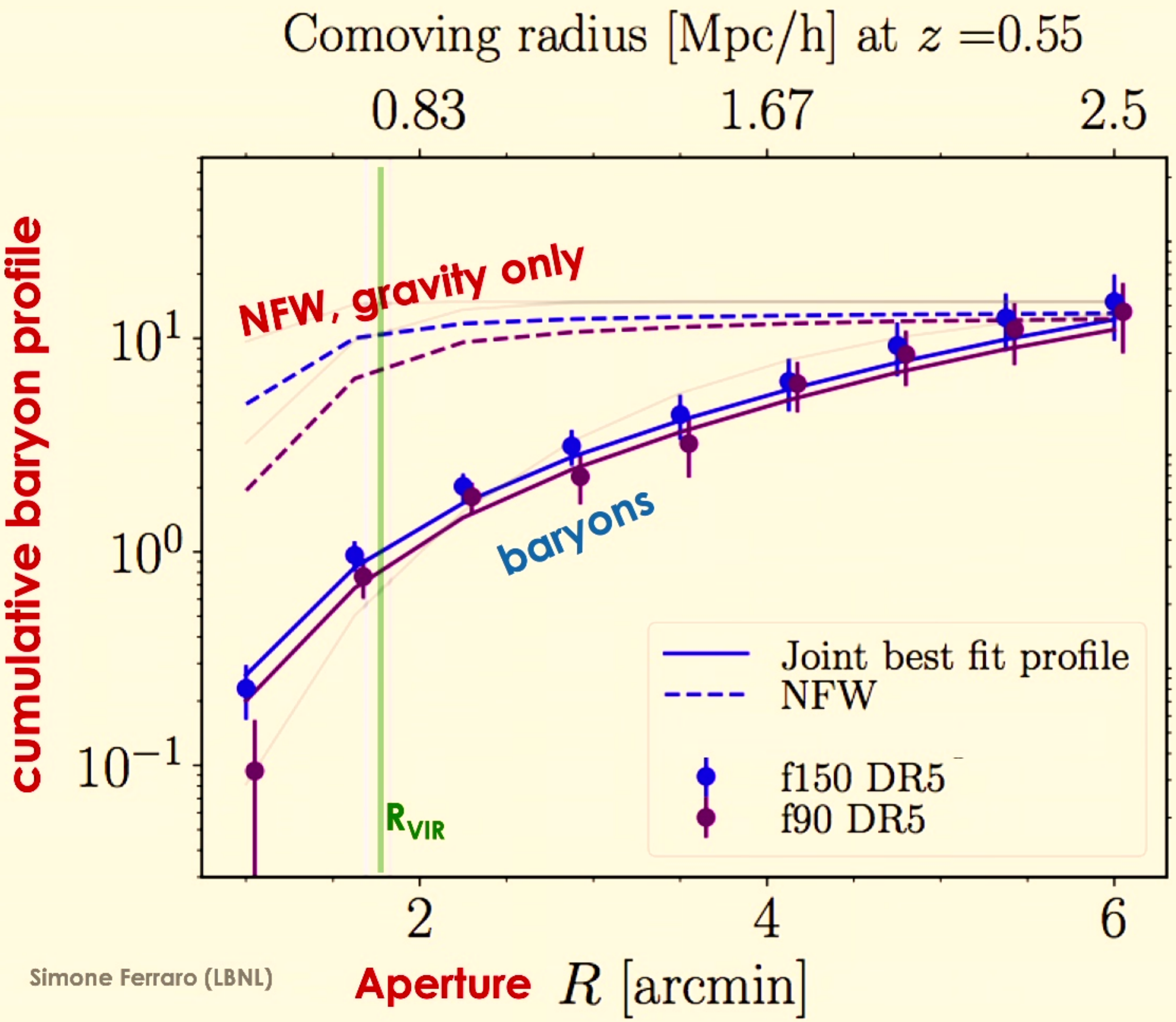
Gas density from kSZ



Simone Ferraro (LBNL)

E. Schaan, **S. Ferraro**, ++ (ACTPol) 2020

Gas density from kSZ



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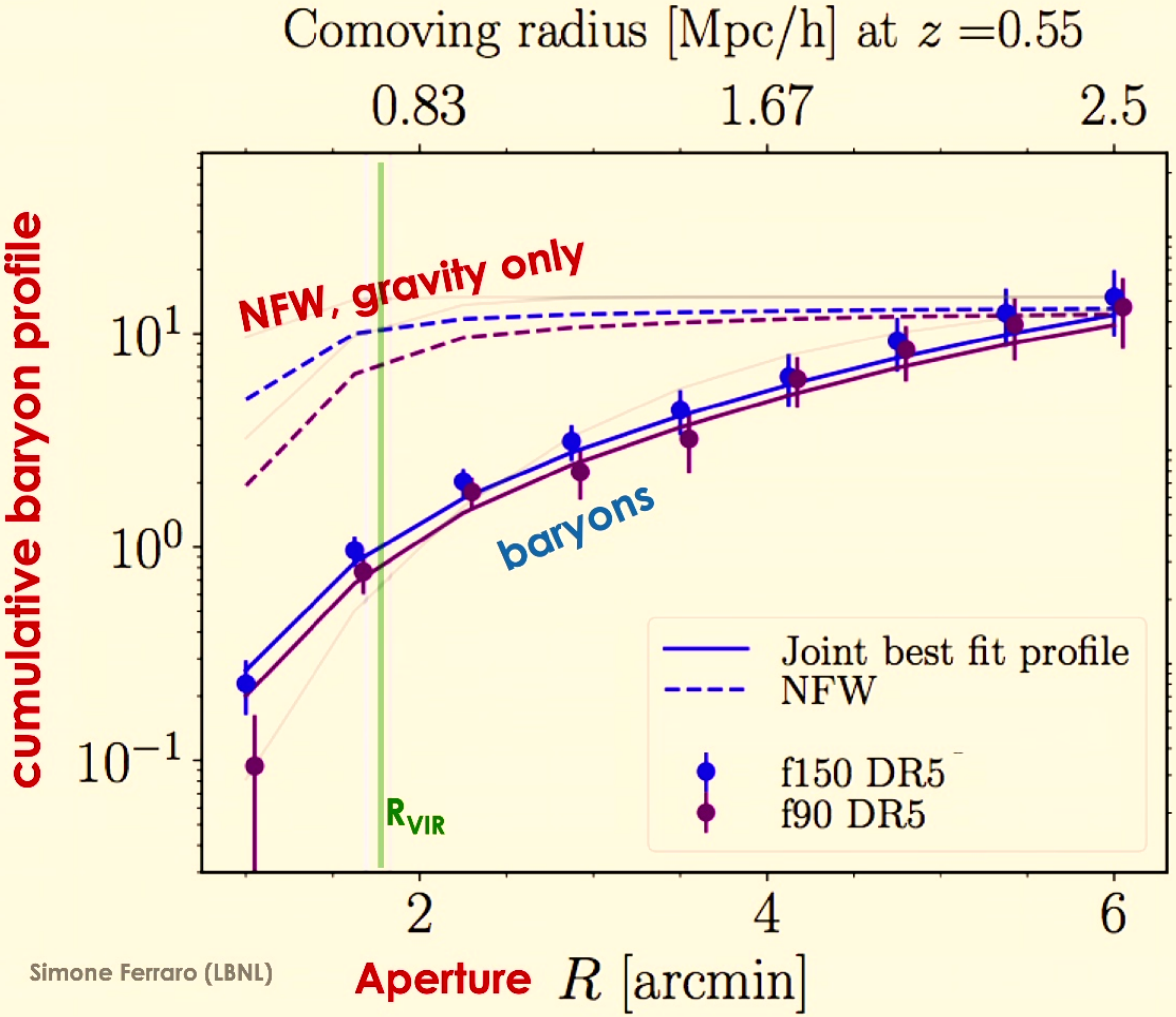
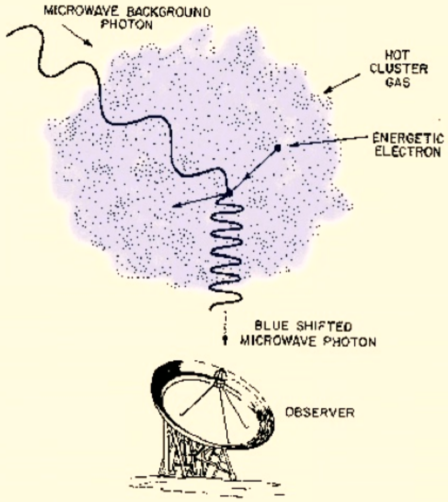


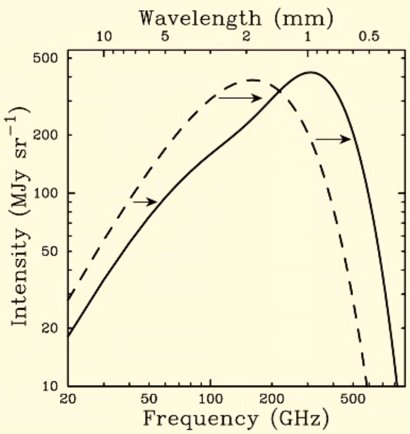
- Large deficit within the virial radius → **"missing baryons problem"**

Simone Ferraro (LBNL)

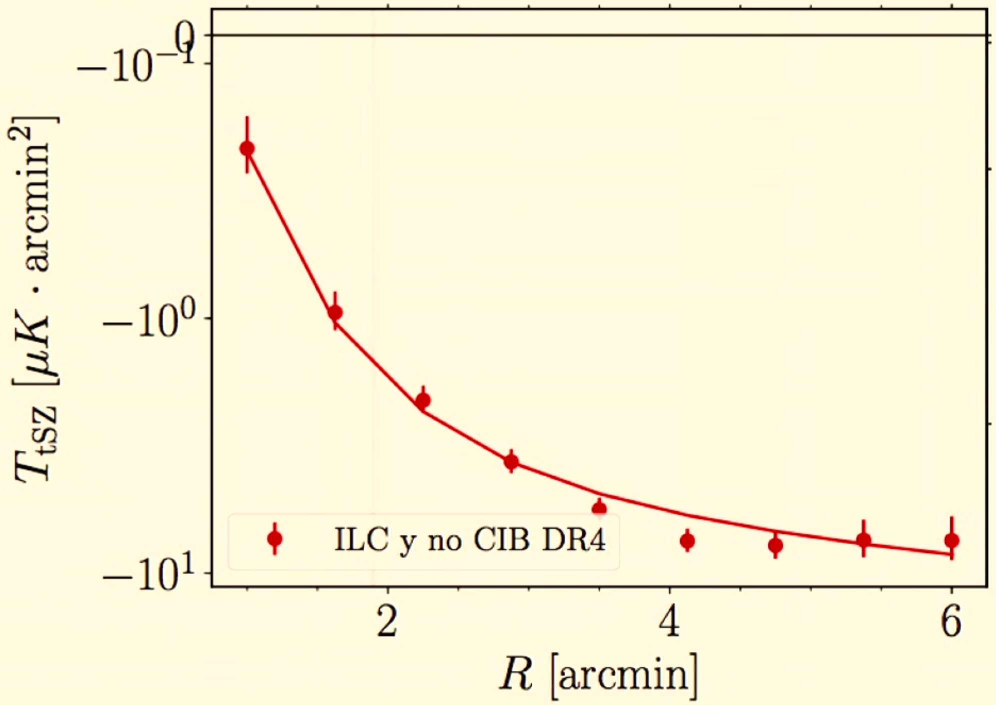
E. Schaan, **S. Ferraro,** ++ (ACTPol) 2020

The thermal SZ effect (tSZ)





tSZ = integrated pressure $\propto N_e \sigma_T T_e$



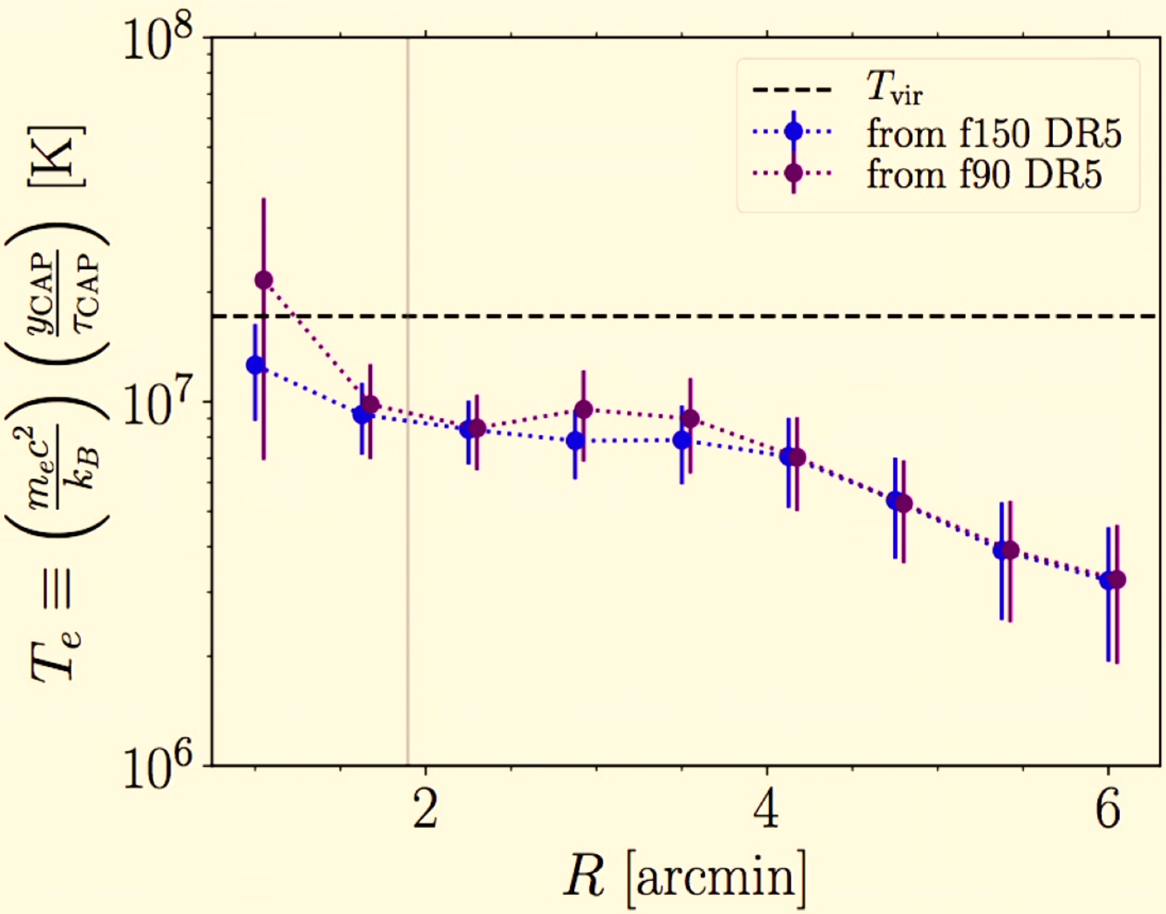
Schaan Ferraro Amodeo Battaglia & ACT 20

Temperature

$$\text{tSZ} \propto N_e \sigma_T T_e$$

$$\text{kSZ} \propto N_e \sigma_T$$

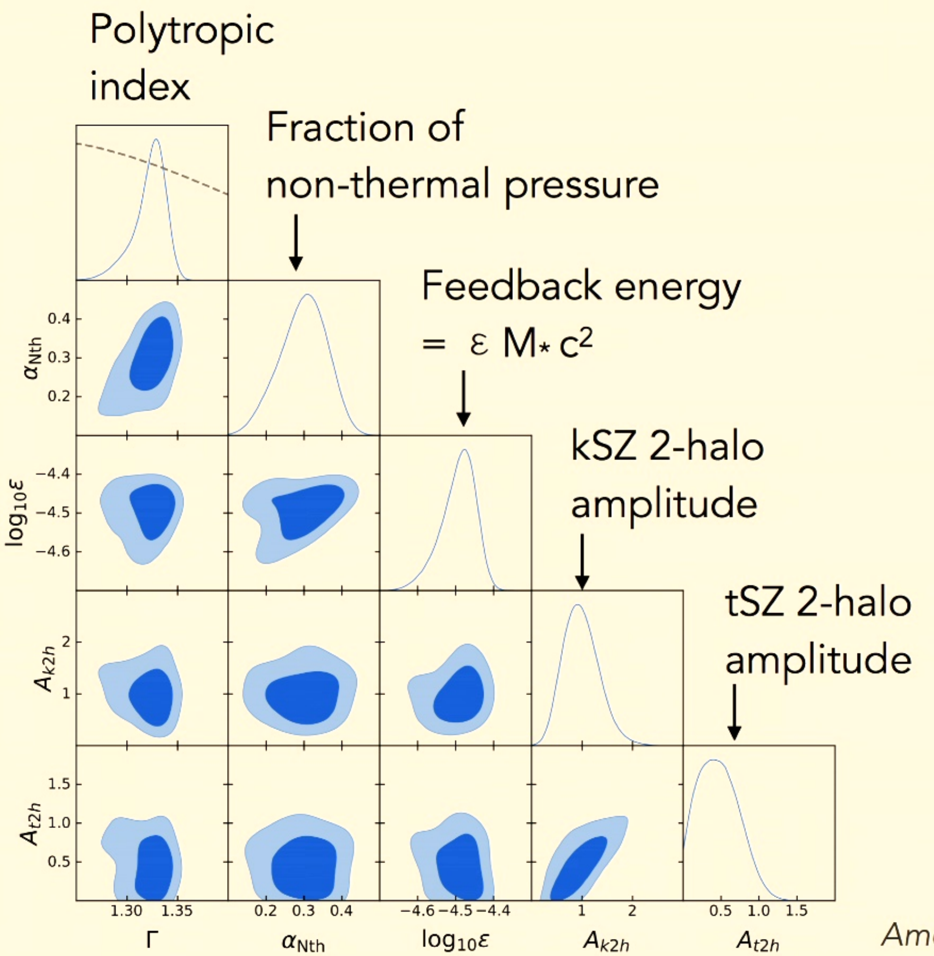
Ratio tSZ / kSZ $\propto T_e$



Schaan Ferraro Amodeo Battaglia & ACT 20

Simone Ferraro (LBNL)

Thermodynamic information



- ~30% **non-thermal pressure** support
- Energy injected **~ 30% of binding energy**

Amodeo Battaglia Schaan Ferraro & ACT 20
Ostriker Bode Babul 05

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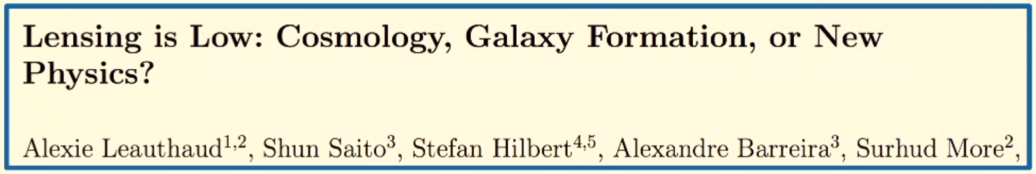
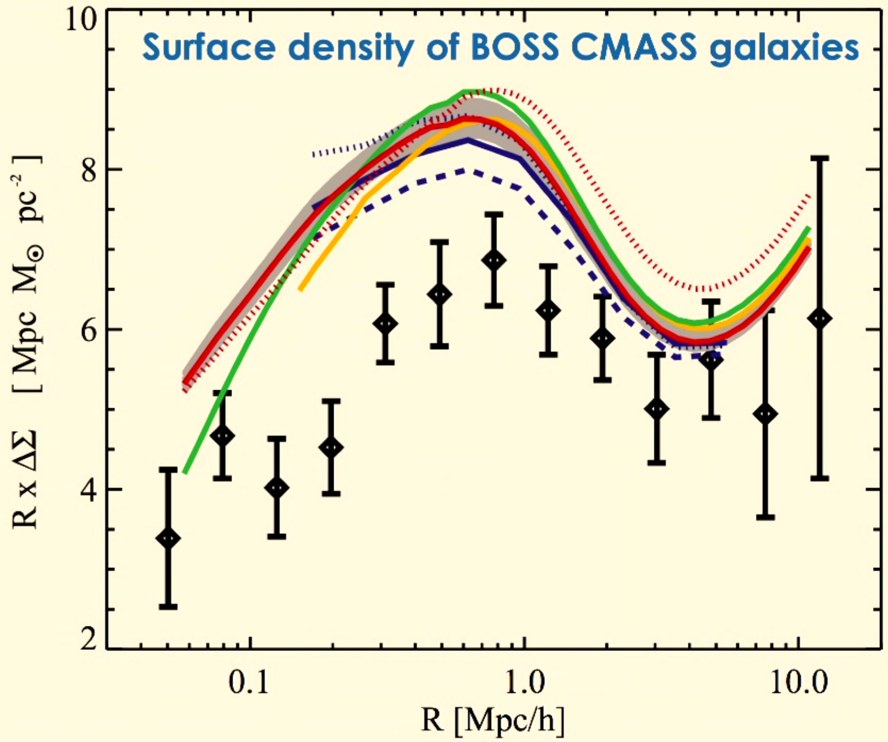
Baryon effects in weak lensing

Calibration of baryon effects in weak lensing:

- Baryons are ~16% of the mass: statistically "large" effect on weak lensing
- CMB lensing cross-correlations & galaxy lensing amplitude often "lower" than expected.
- Larger discrepancy on small scales, the most affected by baryons.


Lensing is Low: Cosmology, Galaxy Formation, or New Physics?

Alexie Leauthaud[1,2], Shun Saito[3], Stefan Hilbert[4,5], Alexandre Barreira[3], Surhud More[2],



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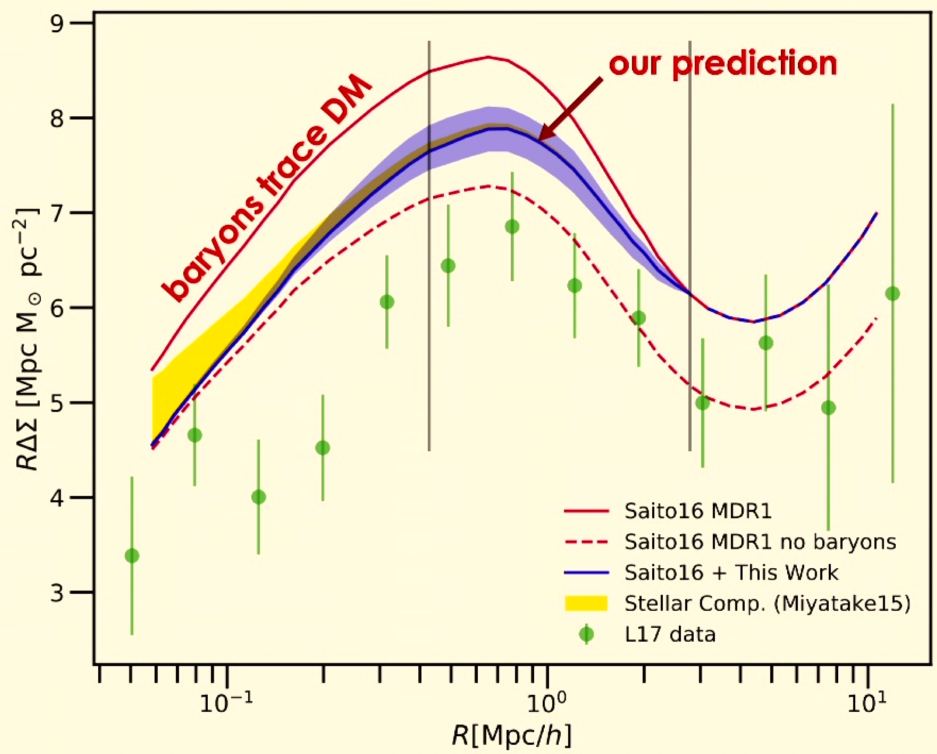
Baryon effects: first direct SZ calibration

Direct SZ calibration:
Use SZ measurements of gas on the same sample to directly calibrate

First example on BOSS CMASS with ACT data. Explains ~half of the discrepancy.

+ work in progress (Ferraro++, 2022)

Next milestone: ACT + DESI (thanks to ACT-DESI MoU)



Amodeo, Battaglia, Schaan, Ferraro, Moser + ACT (2021)

Simone Ferraro (LBNL)

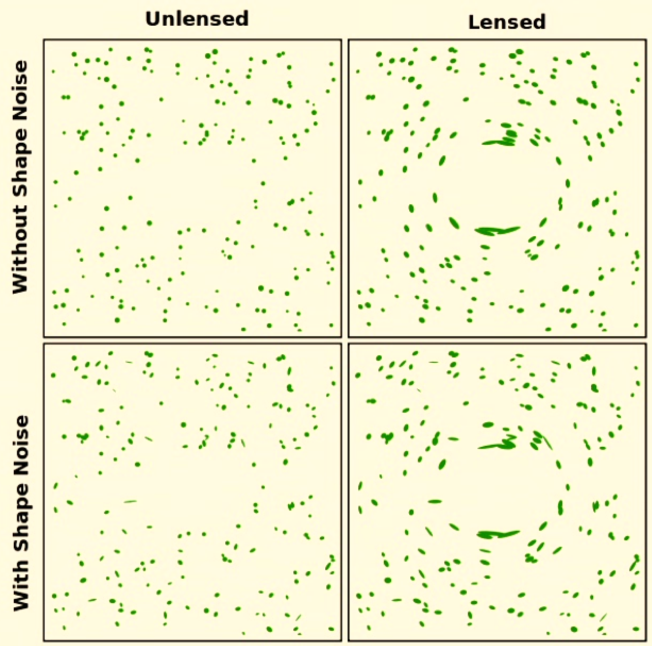
Cosmology from galaxy weak lensing (much simplified!)

- Galaxy shear γ
- Galaxy positions g

In a number of redshift bins.

- Can form 3 "2 point functions": $\langle\gamma\gamma\rangle, \langle\gamma g\rangle, \langle gg\rangle$
- Combined in **"3 x 2" analysis**

- Parameter sensitivity $\gamma \sim \Omega_m \sigma_8 \quad g \sim b_g \sigma_8$



Wikipedia

Simone Ferraro (LBNL)

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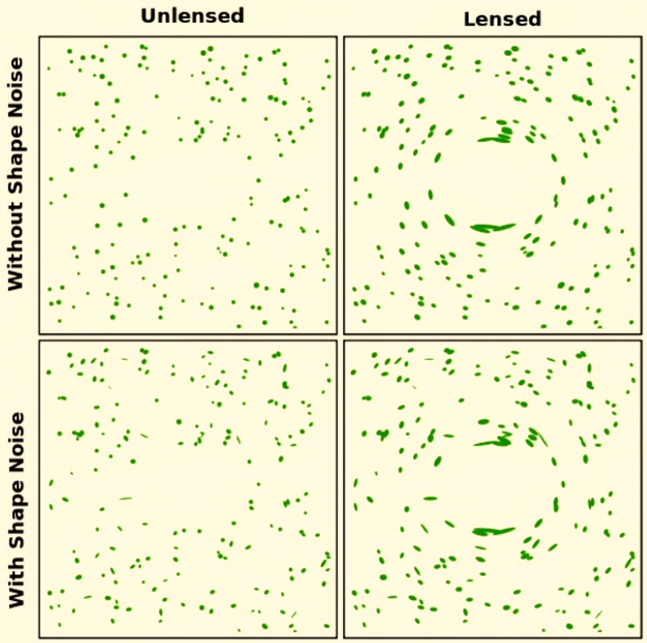


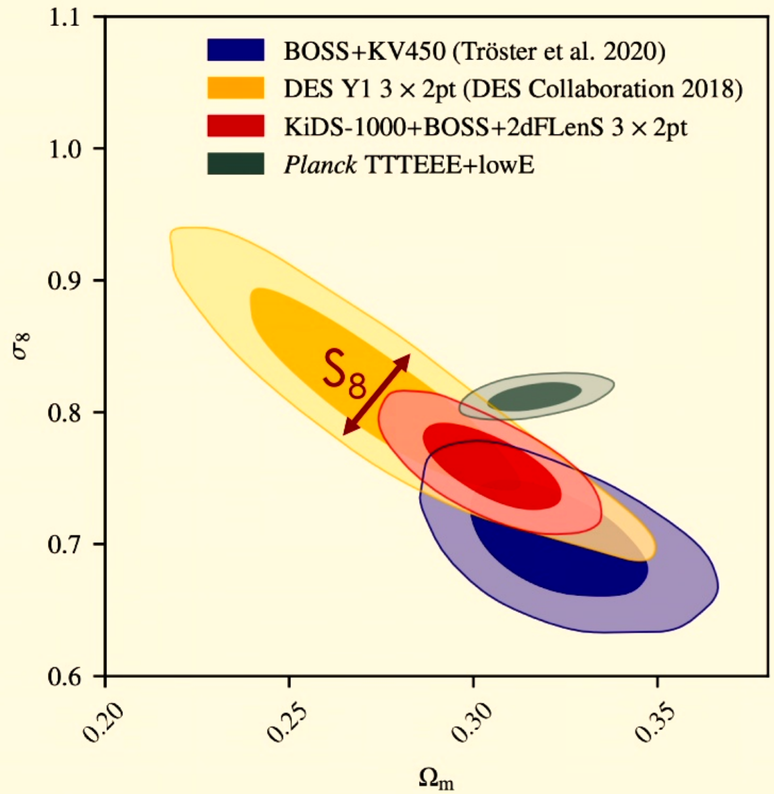
Wikipedia

Most sensitive "cosmology" quantity $S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$

Simone Ferraro (LBNL)

Some results ~1.5 years ago

$$S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$$



KiDS-1000 (Heymans et al, 2021)

Primary CMB

Planck:
$$S_8 = 0.832 \pm 0.013$$

WMAP + BAO:
$$S_8 = 0.8201 \pm 0.025$$

WMAP + ACT:
$$S_8 = 0.840 \pm 0.030$$

Galaxy lensing

KiDS-1000:
$$S_8 = 0.766^{+0.020}_{-0.014}$$

DES-Y1:
$$S_8 = 0.773^{+0.026}_{-0.020}$$

Can CMB lensing be used to test this?

From CMB lensing alone: $S_8 = 0.81 \pm 0.1$
Adding BAO: $S_8 = 0.83 \pm 0.03$

CMB lensing

What about cross-correlations? Wish list…

- Similar statistical power to galaxy lensing
- Ability to isolate redshift information
- Different systematics and techniques

}

Cross-correlations with unWISE galaxies

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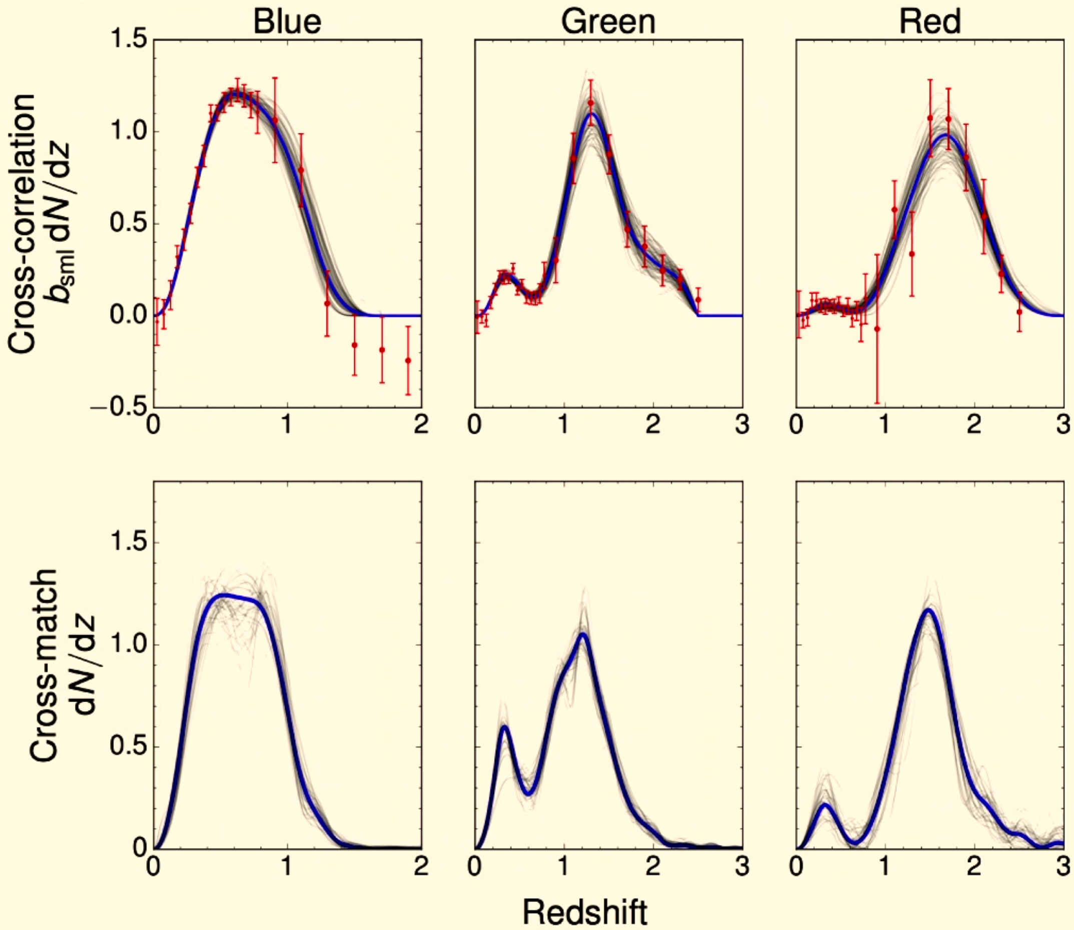
Redshift distribution



Krolewski, **Ferraro**, Schlafly, White (2020), JCAP

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Redshift distribution

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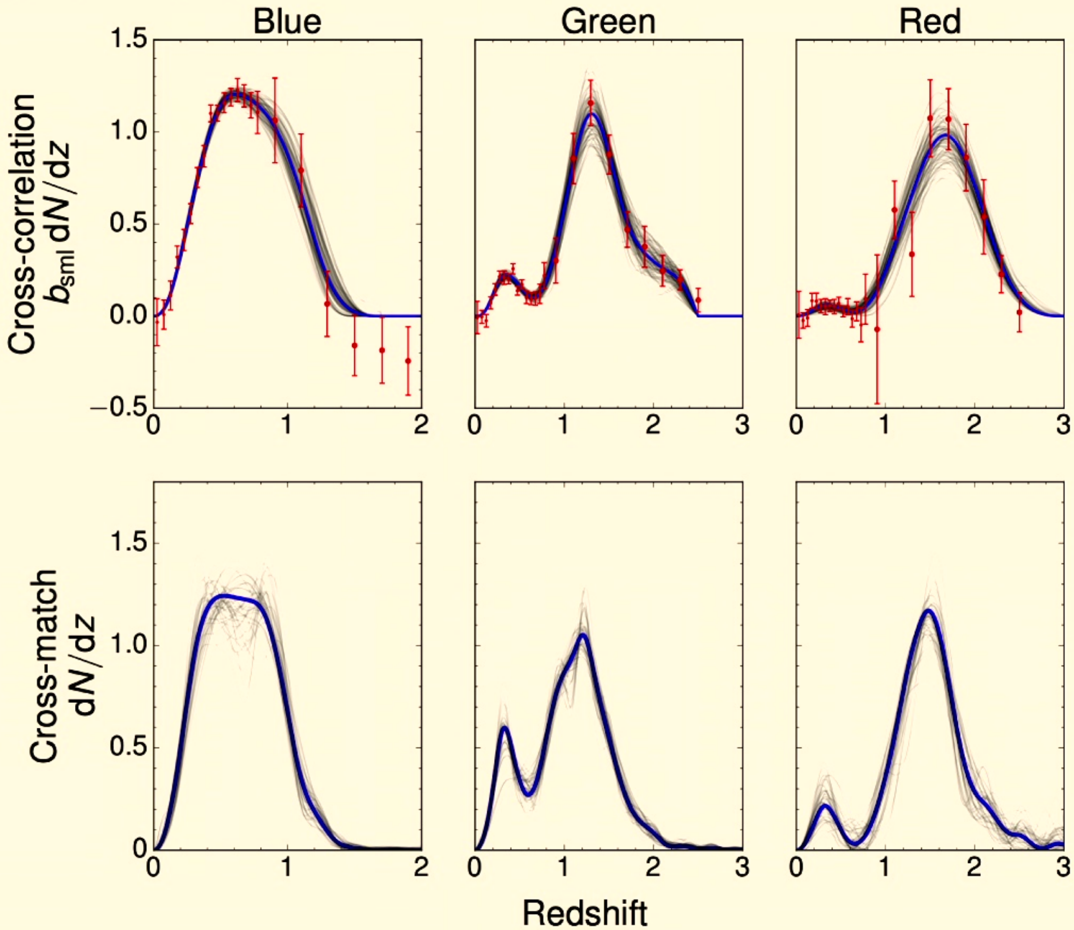

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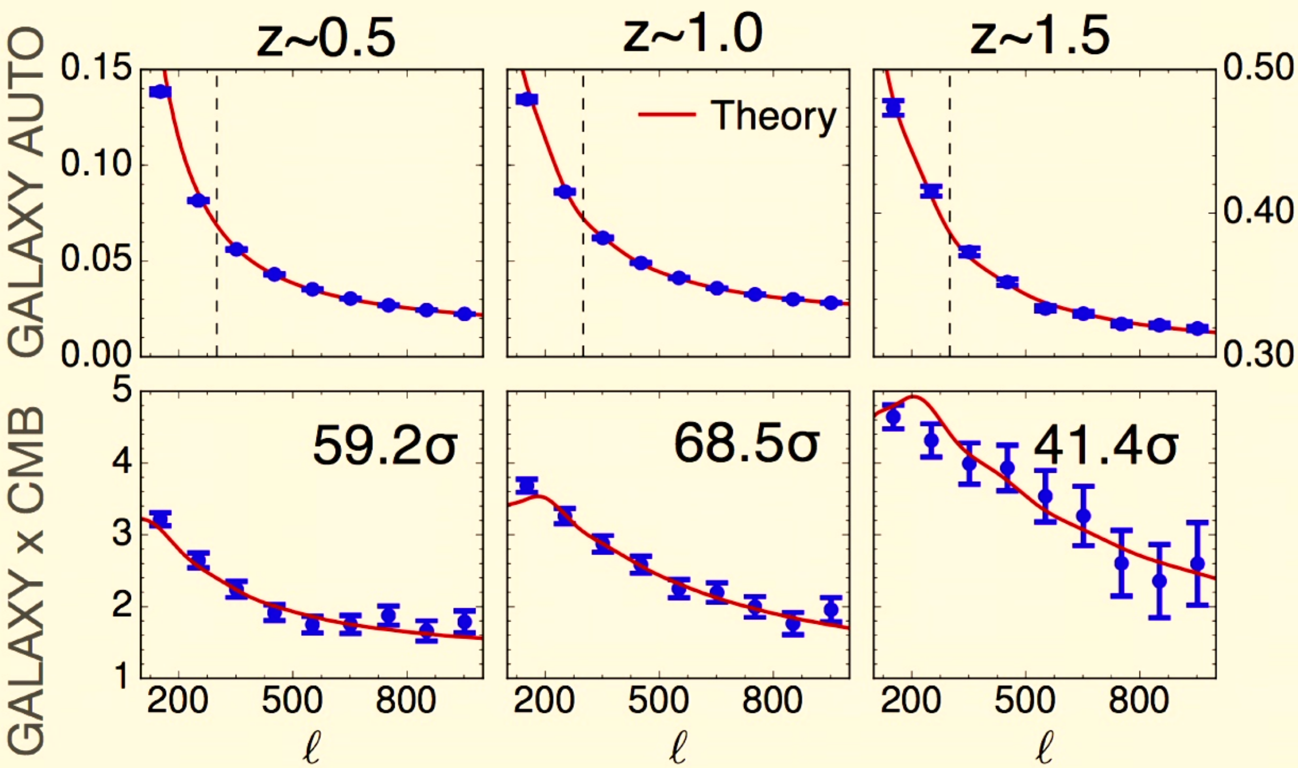
Krolewski, **Ferraro**, Schlafly, White (2020), JCAP

unWISE x Planck CMB lensing



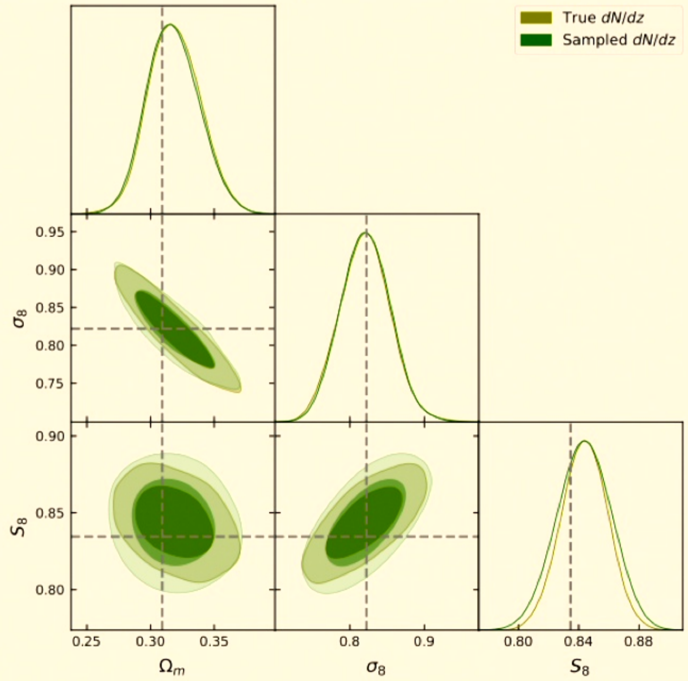
Total SNR in lensing
~ 100

Krolewski, **Ferraro**, Schlafly, White (2020), JCAP

Simone Ferraro (LBNL)

Cosmological analysis: brief summary

- Large number of systematic checks
- Theory: Convolution Lagrangian Effective Field Theory (CLEFT) + magnification bias
- Analysis is blinded to cosmology
- Tests on mocks
- Marginalize over redshift uncertainty
- Subtract "noise bias"
- Full covariance matrix
- Check consistency between samples



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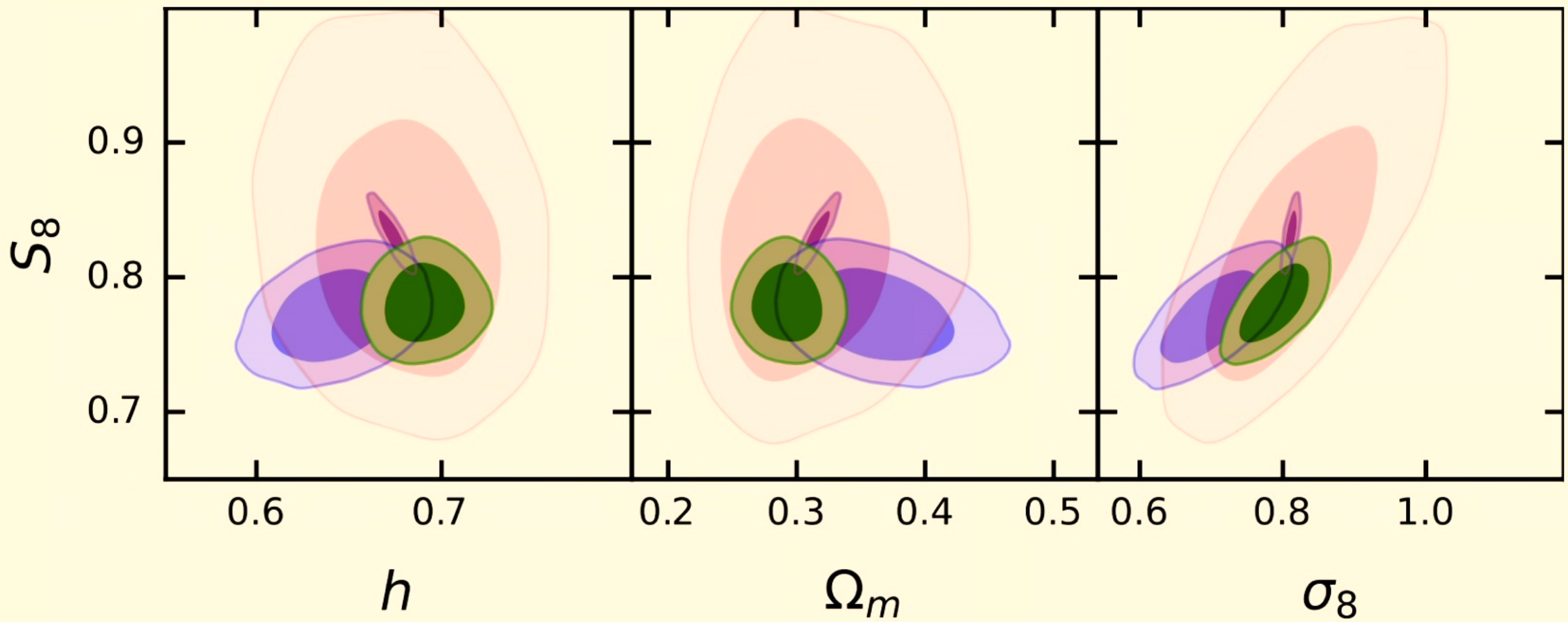
Cosmological results



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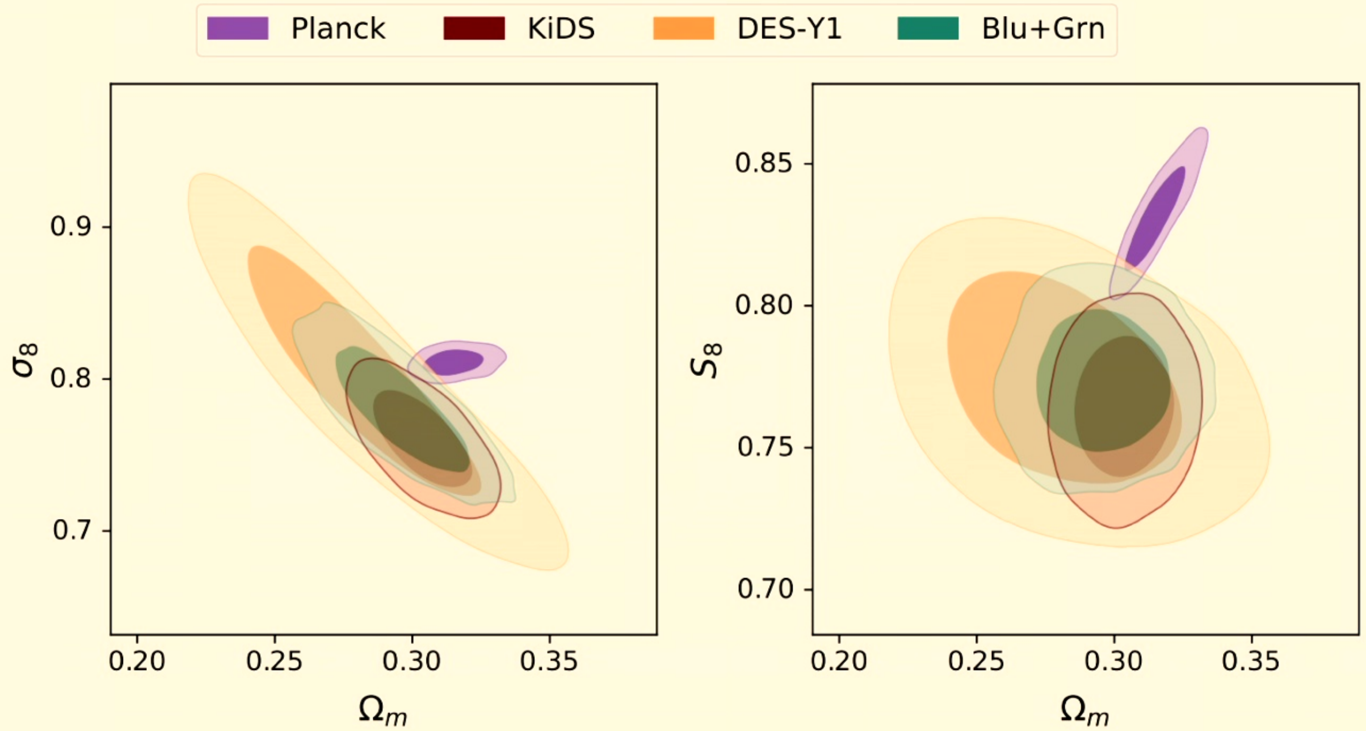
Comparison with galaxy weak lensing



<u>Very good agreement with galaxy lensing!</u>

Simone Ferraro (LBNL)

DES-Y3

Cosmological constraints from unWISE and Planck CMB lensing tomography

Alex Krolewski[a,c,d,e] Simone Ferraro[b,a] Martin White[a,b,c]

infer the amplitude of low-redshift fluctuations, σ_8; the fraction of matter in the Universe, Ω_m; and the combination $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ to which these low-redshift lensing measurements are most sensitive. The combination of blue and green samples gives a value $S_8 = 0.776 \pm 0.017$, that is fully consistent with other low-redshift lensing measurements and in 2.6σ tension with the CMB predictions from Planck. This is noteworthy, because CMB lensing probes the same

$$S_8 = 0.776 \pm 0.017$$

A few weeks later

Dark Energy Survey Year 3 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing

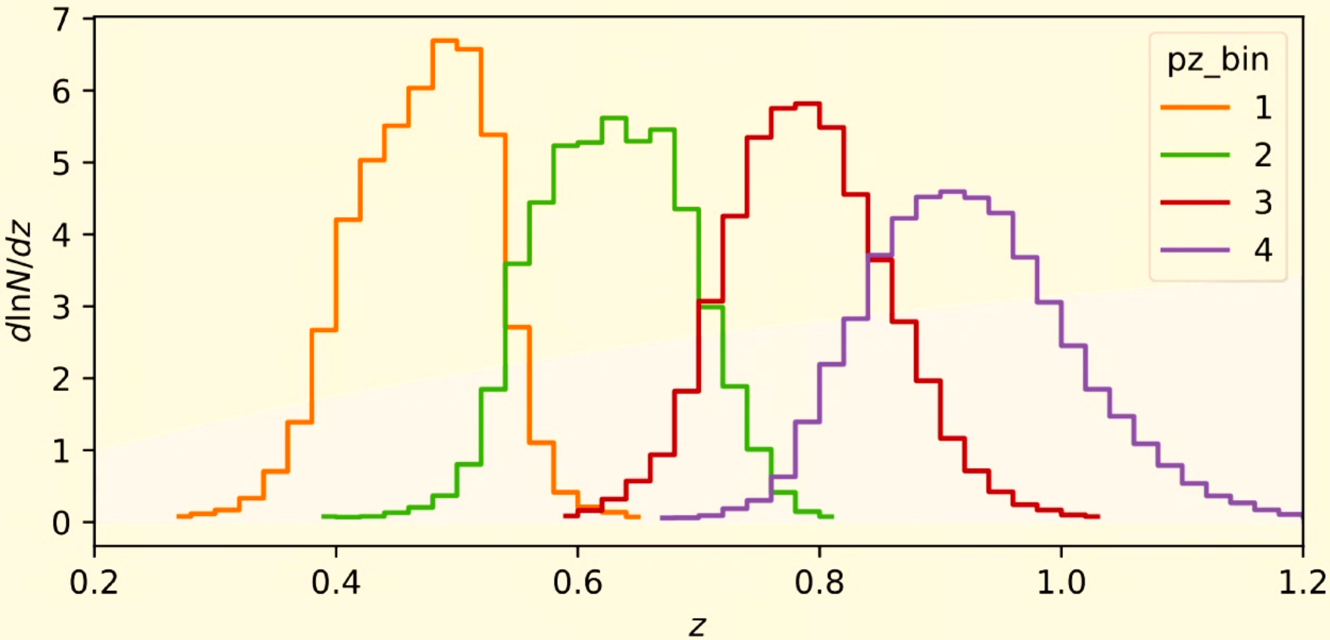
DES Y3 3x2 analysis

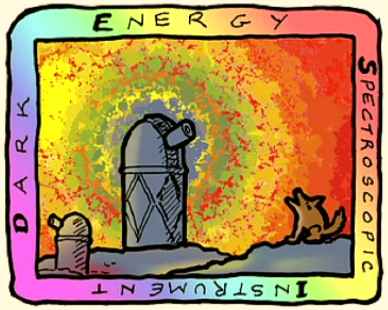
$$\text{In } \Lambda\text{CDM:} \quad S_8 = 0.776^{+0.017}_{-0.017} \; (0.776)$$
$$\Omega_m = 0.339^{+0.032}_{-0.031} \; (0.372)$$
$$\sigma_8 = 0.733^{+0.039}_{-0.049} \; (0.696)$$

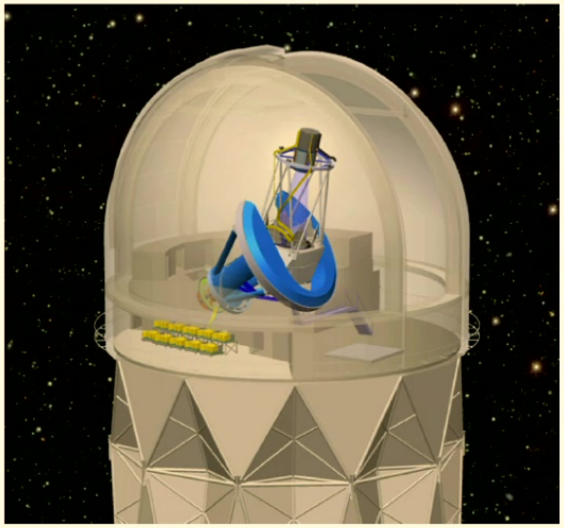
Similar numerical constraints, but different interpretation!

What about photo-z? DESI spectroscopy

- Divide the LRG sample into 4 photometric bins







Zhou, **SF**, et al (DESI, in prep)

Simone Ferraro (LBNL)

Cosmological results

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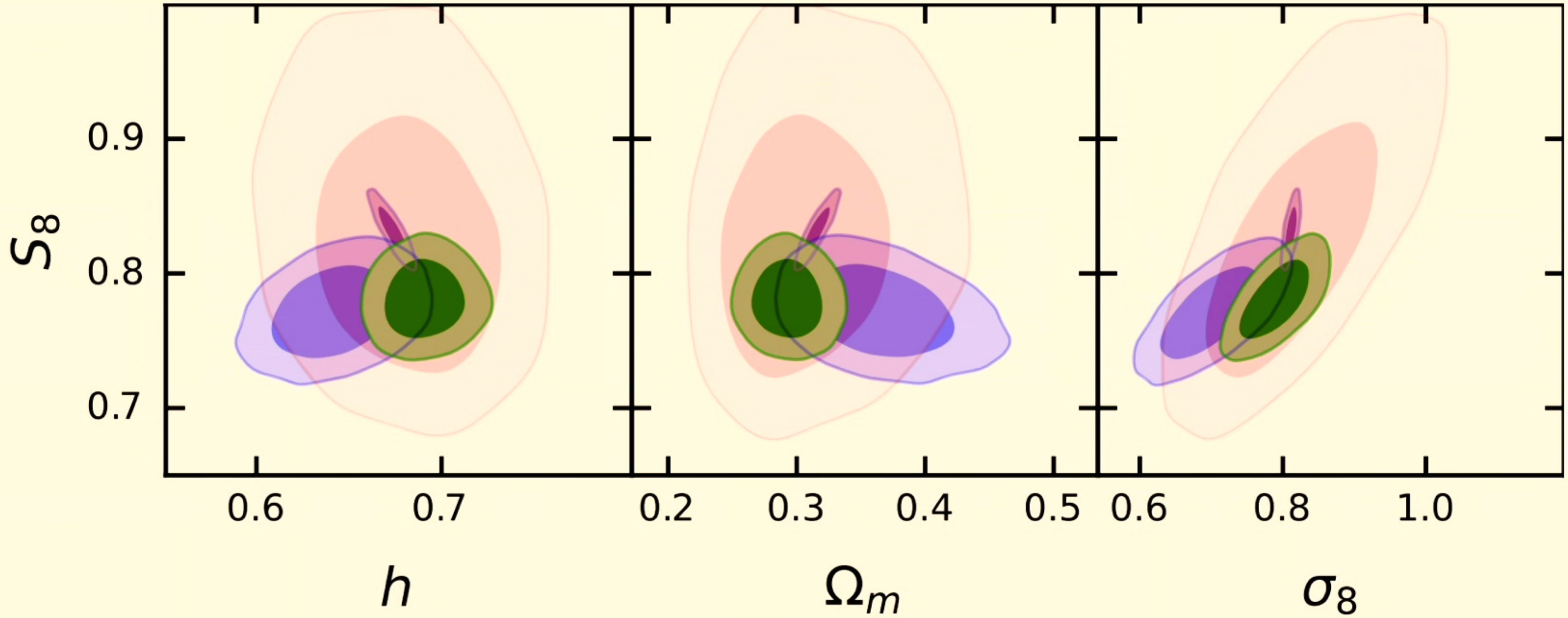

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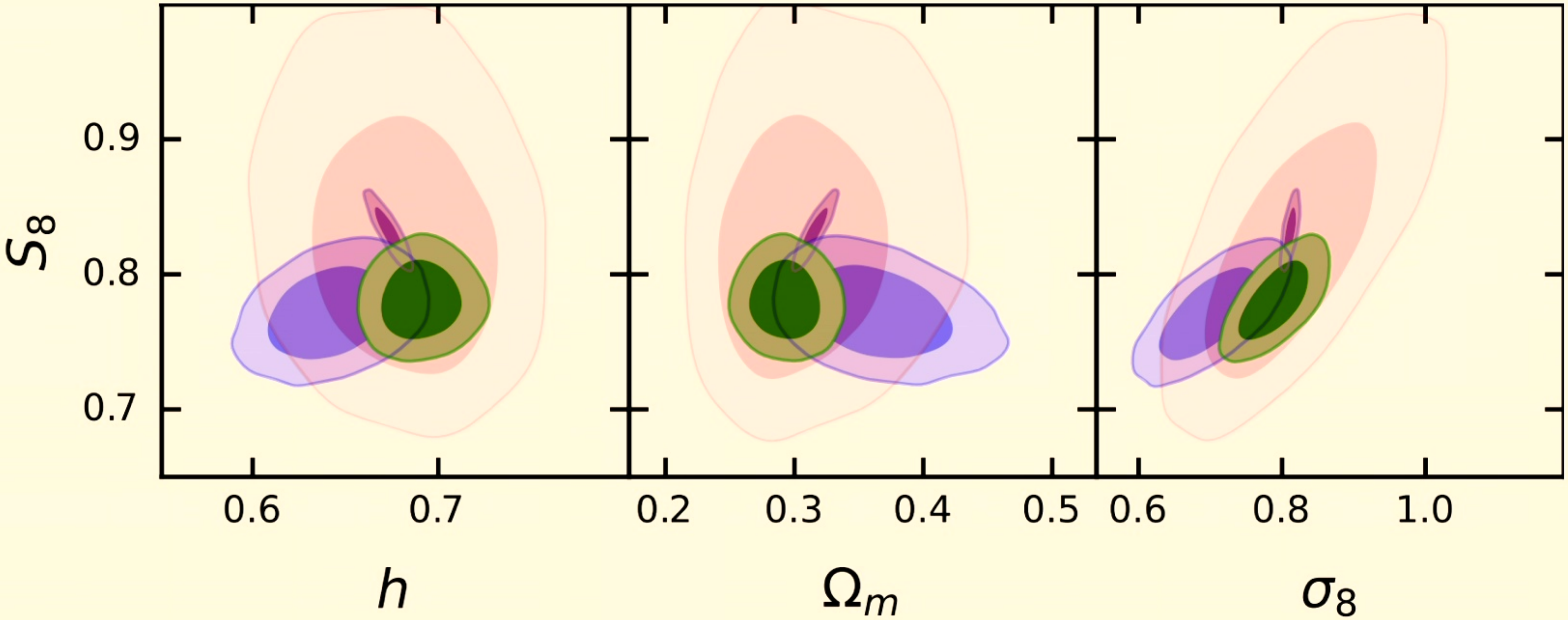
Cosmological results



Combined: $S_8 = 0.776 \pm 0.017$ vs Planck: $S_8 = 0.832 \pm 0.013$

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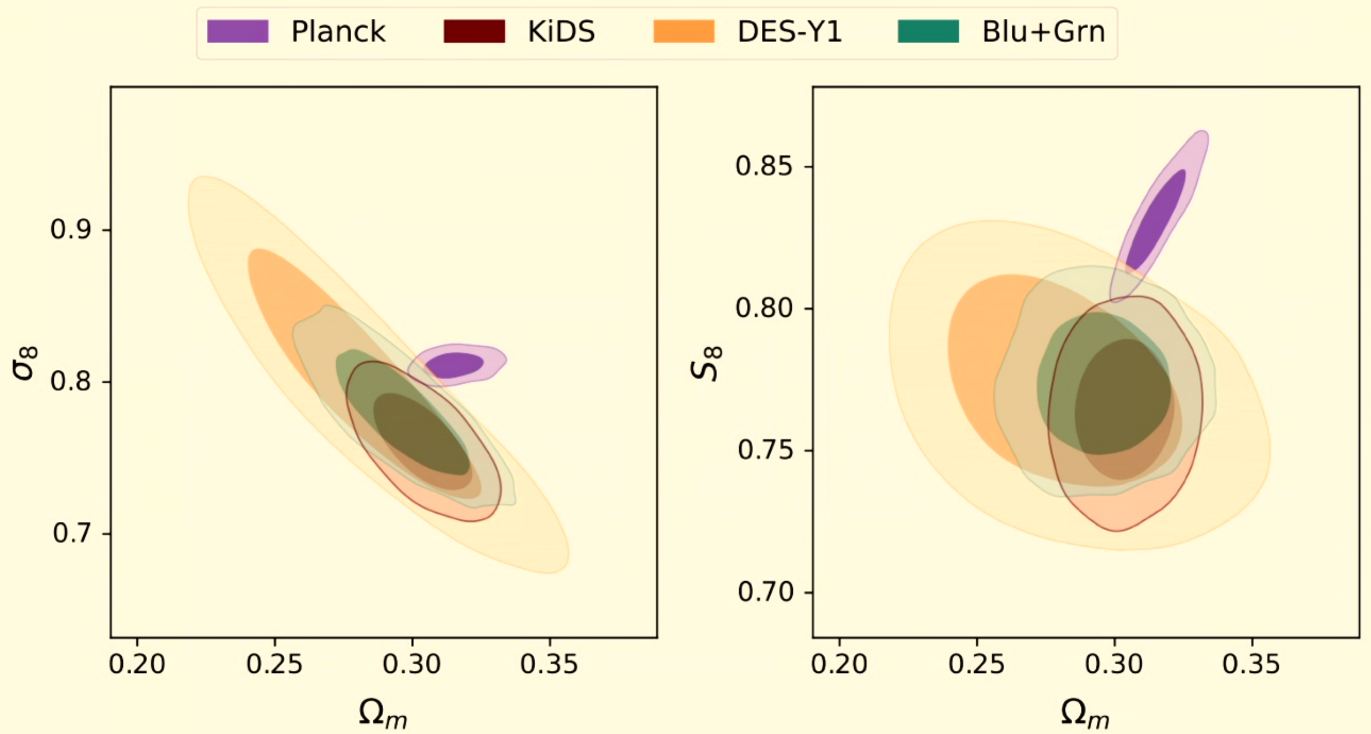
Comparison with galaxy weak lensing



Very good agreement with galaxy lensing!

Simone Ferraro (LBNL)

DES-Y3

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Cosmological constraints from unWISE and Planck CMB lensing tomography

Alex Krolewski[a,c,d,e] Simone Ferraro[b,a] Martin White[a,b,c]

infer the amplitude of low-redshift fluctuations, σ_8; the fraction of matter in the Universe, Ω_m; and the combination $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ to which these low-redshift lensing measurements are most sensitive. The combination of blue and green samples gives a value $S_8 = 0.776 \pm 0.017$, that is fully consistent with other low-redshift lensing measurements and in 2.6σ tension with the CMB predictions from Planck. This is noteworthy, because CMB lensing probes the same

$$S_8 = 0.776 \pm 0.017$$

A few weeks later

Simone Ferraro (LBNL)

DES-Y3

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A few weeks later

Dark Energy Survey Year 3 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing

DES Y3 3x2 analysis

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$$\text{In } \Lambda\text{CDM:} \quad \Omega_m = 0.339^{+0.032}_{-0.031} \; (0.372)$$

$$\sigma_8 = 0.733^{+0.039}_{-0.049} \; (0.696)$$

DES-Y3

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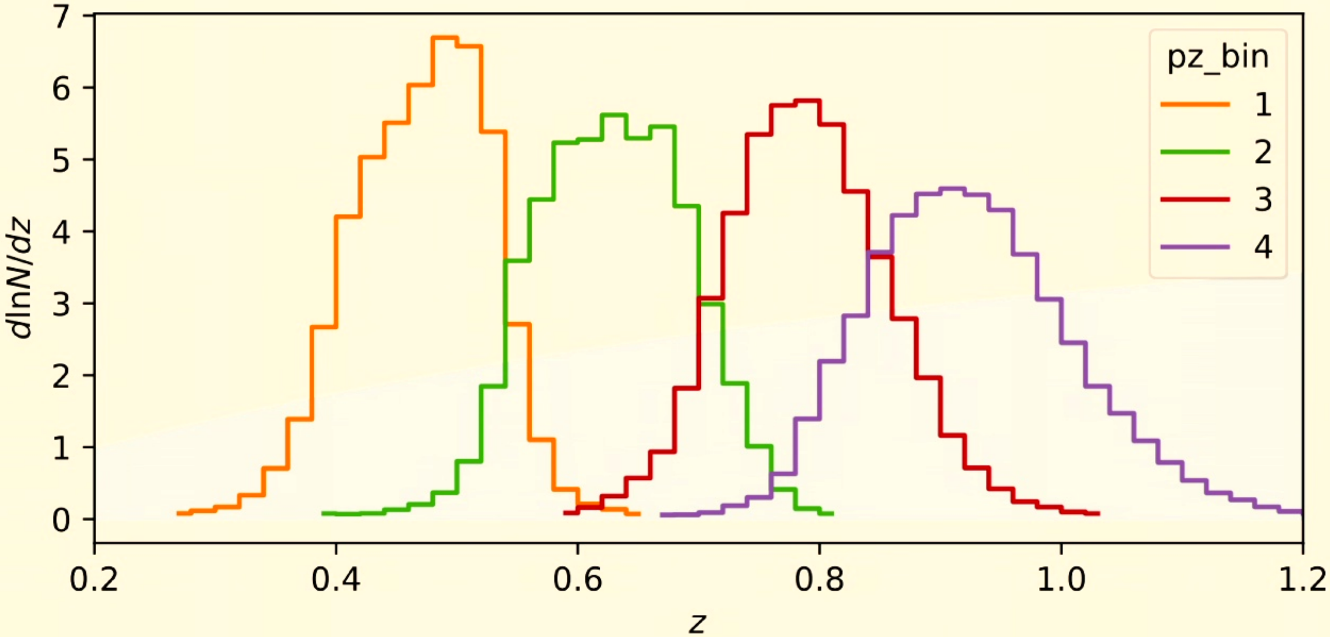
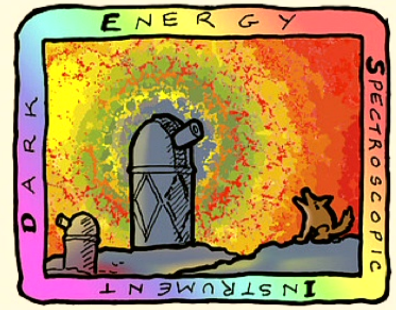
Similar numerical constraints, but different interpretation!

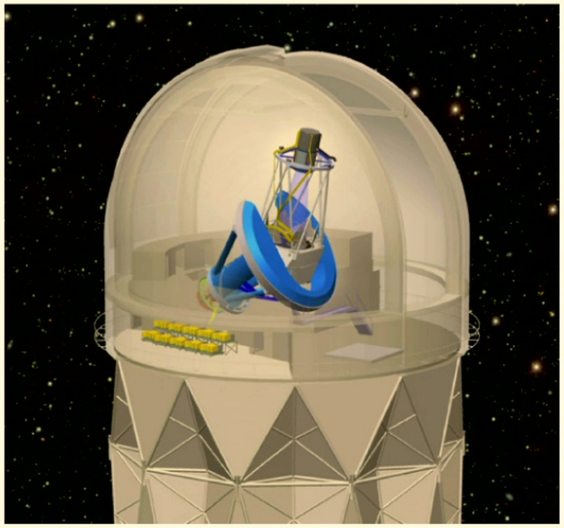
Simone Ferraro (LBNL)

What about photo-z? DESI spectroscopy

- Divide the LRG sample into 4 photometric bins







Zhou, **SF**, et al (DESI, in prep)

Simone Ferraro (LBNL)

DESI LRG x Planck lensing tomography

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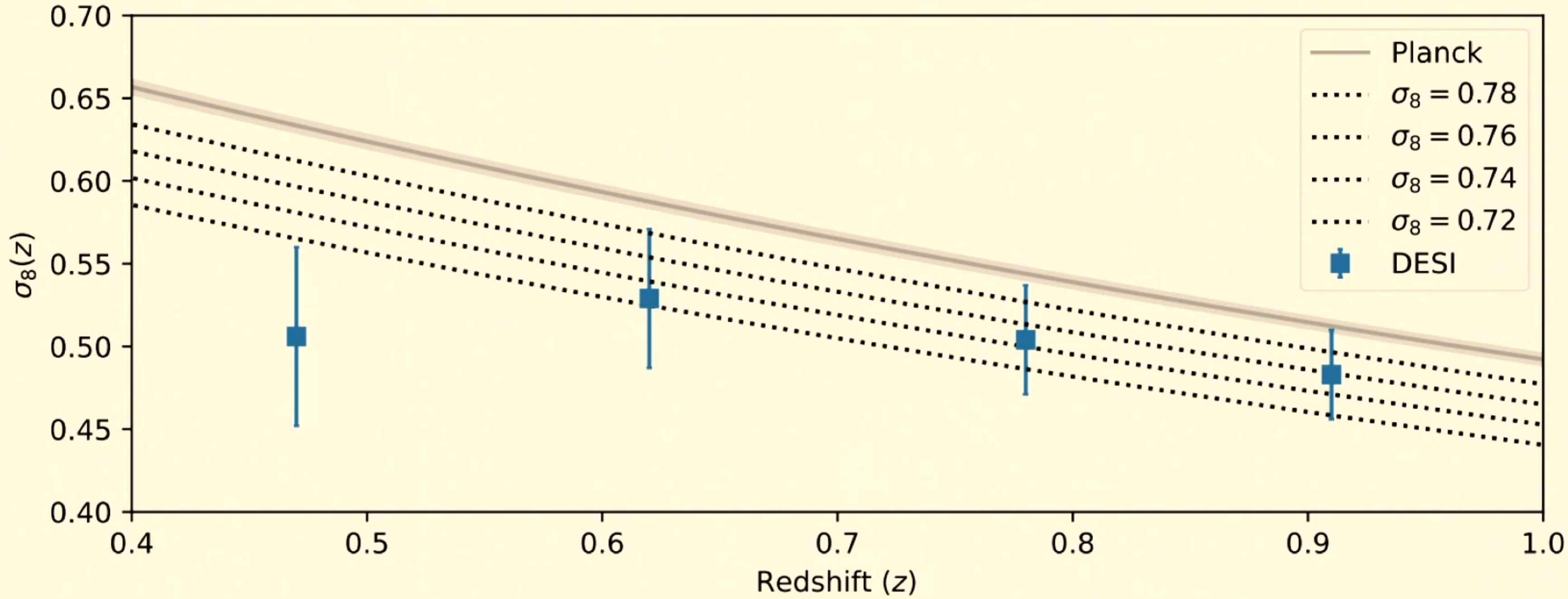
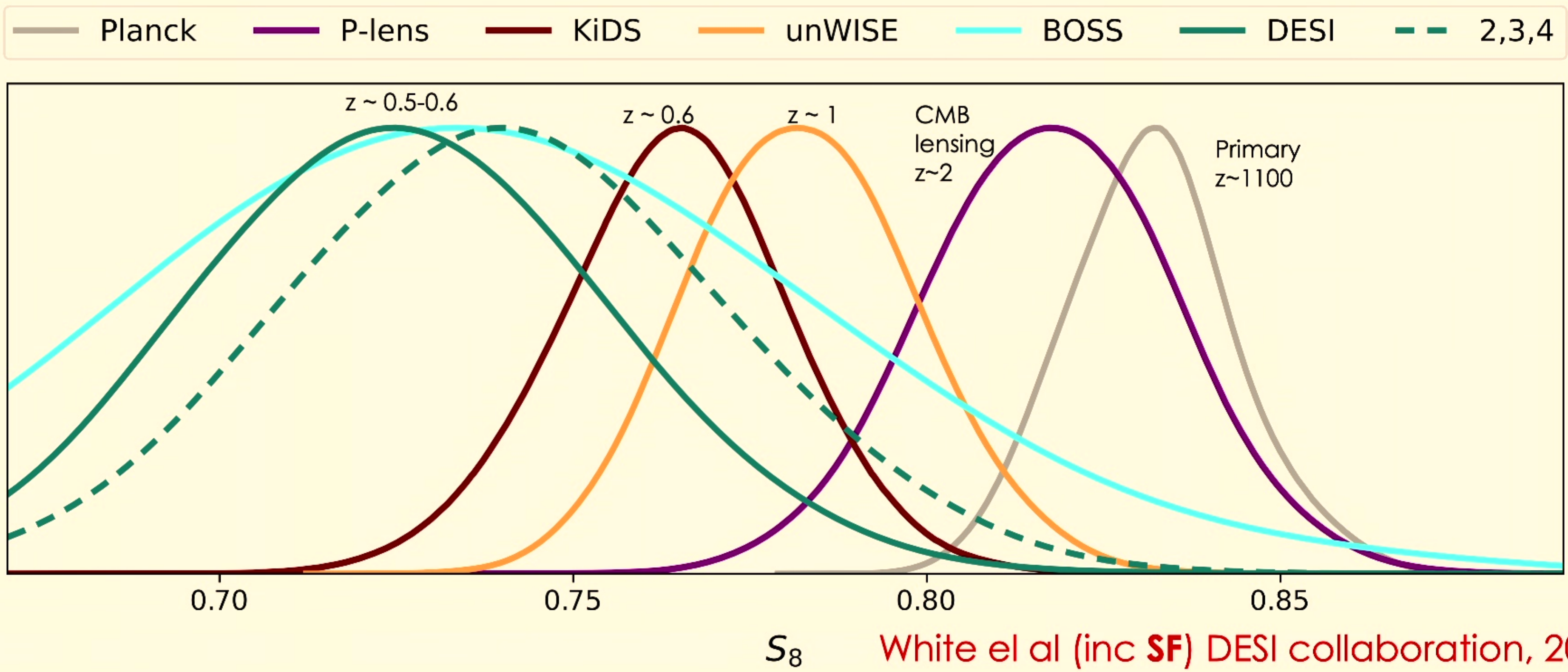


[see also Kitanidis & White, 2020
Hang, Alam, Peacock, Cai, 2020
García-García et al, 2021]

White el al (inc **SF**) DESI collaboration, 2022

In summary



White el al (inc **SF**) DESI collaboration, 2022

Some of the results so far…

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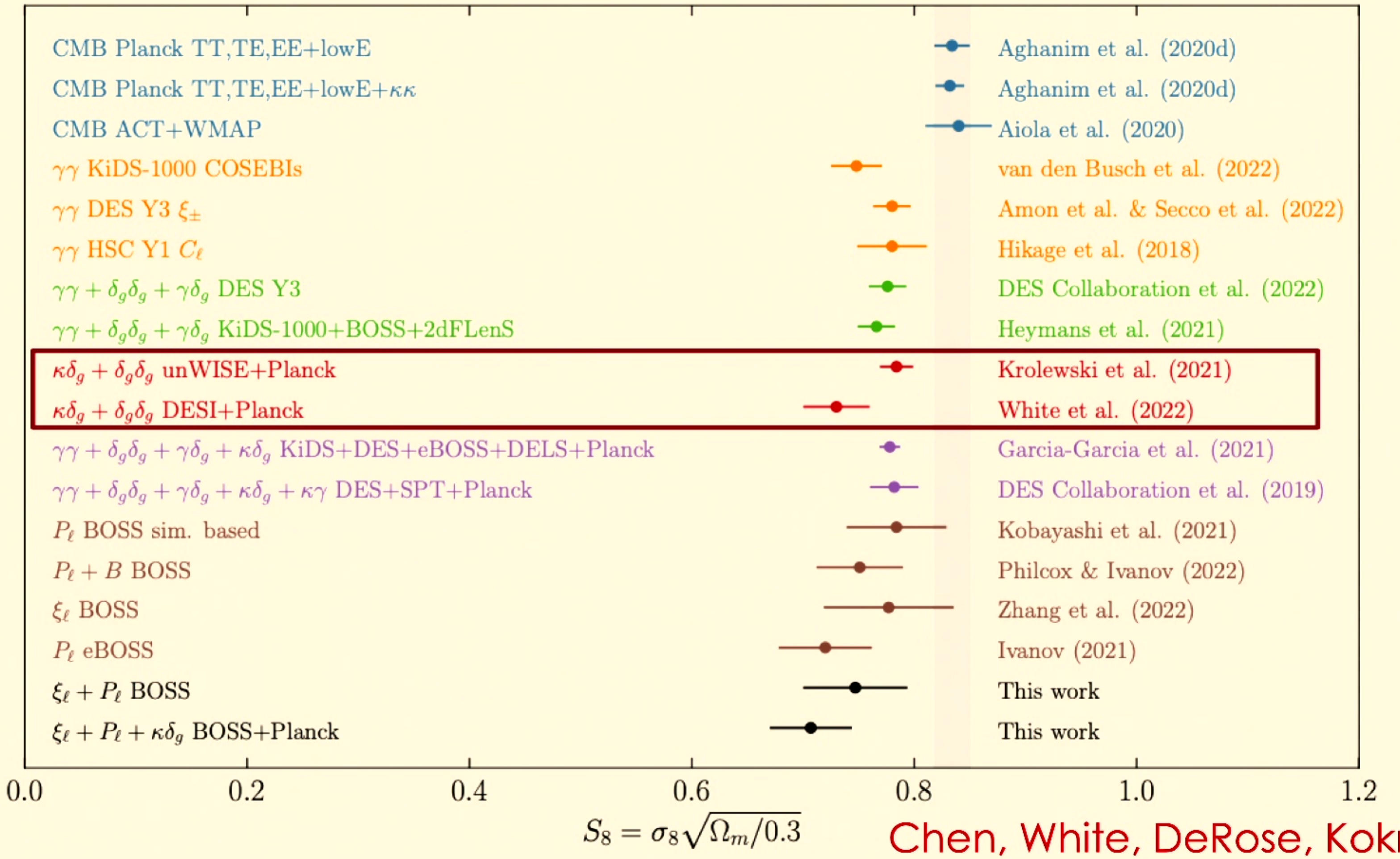

Chen, White, DeRose, Kokron (2022)

My 2 cents…

- I think we may have a serious problem, worth paying attention to it!
- No obvious common systematic. Perhaps galaxies are harder to model than we thought? Most of the information coming from rather large scales.
- Photo-z are (likely) not the cause.
- Projection/volume effects are tricky but (likely) not the cause here.
- Neutrino induced suppression is ~3% (for minimum mass). Discrepancy is too large.
- Just a statistical fluctuation is very unlikely.
- Hard to find compelling new "fundamental" physics that can explain this.
- Problem is worse on smaller scales (galaxy formation, baryons?).
- I'm excited about combination of RSD + lensing and SZ calibration of baryon effects
- Stay tuned!