From DESI to PFS

Cosmology with Spectroscopic Surveys and Connections to the CMB

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Challenges at CMB Frontiers · on behalf of the PFS SSP Cosmology WG

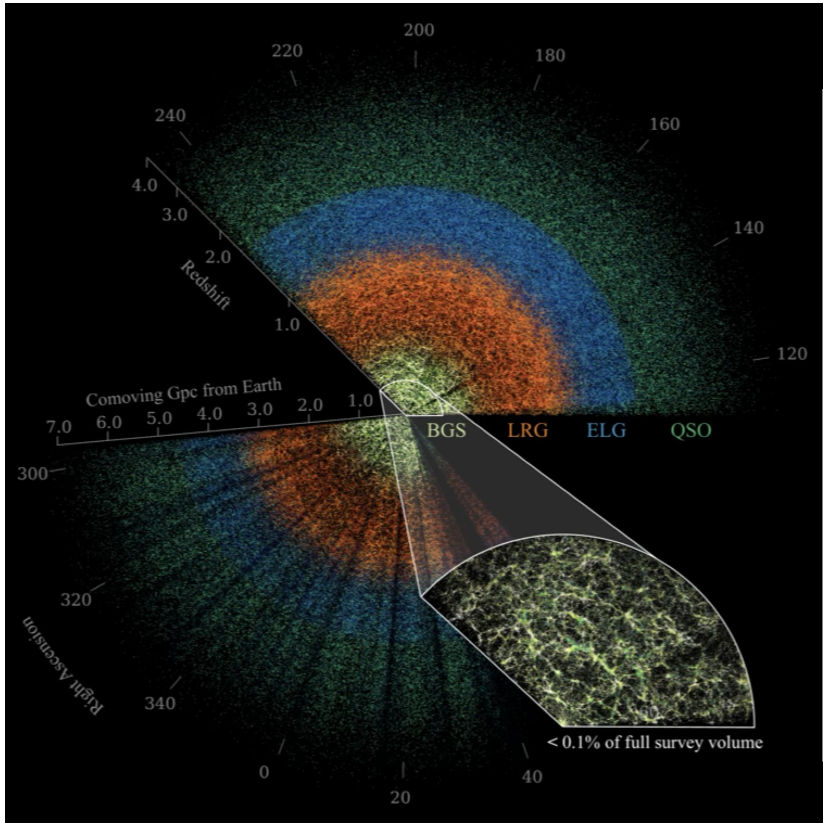
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
東京大学 THE UNIVERSITY OF TOKYO
wpi
CD3

Outline

1. Background: LSS & spectroscopic surveys — how they probe DE, gravity, neutrino mass, and PNG
2. DESI: BAO, neutrino mass & the dynamical dark-energy surprise
3. PFS Cosmology: independent and unique cross check
4. Synergy between LSS and CMB: lensing, kSZ & cross-correlations

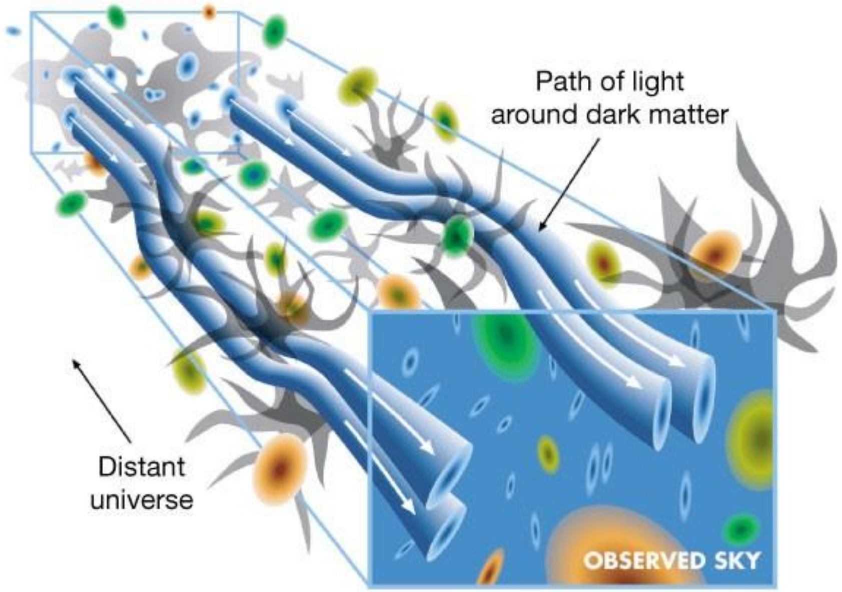
The large-scale-structure (LSS) survey landscape

Spectroscopic (3D)



SDSS, DESI, PFS, Euclid, Roman

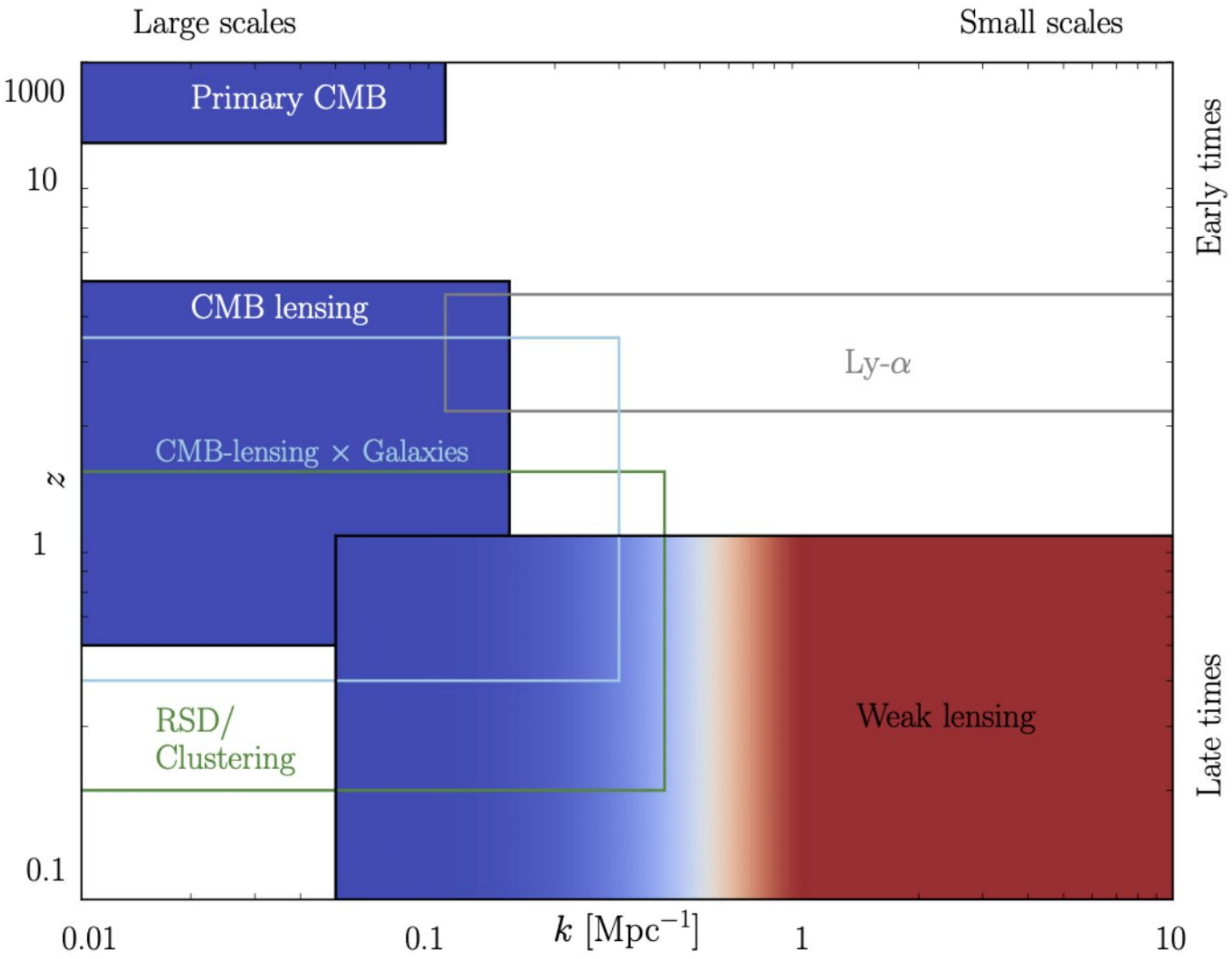
Imaging / weak lensing (2D)



HSC, KiDS, DES, LSST, Euclid, Roman

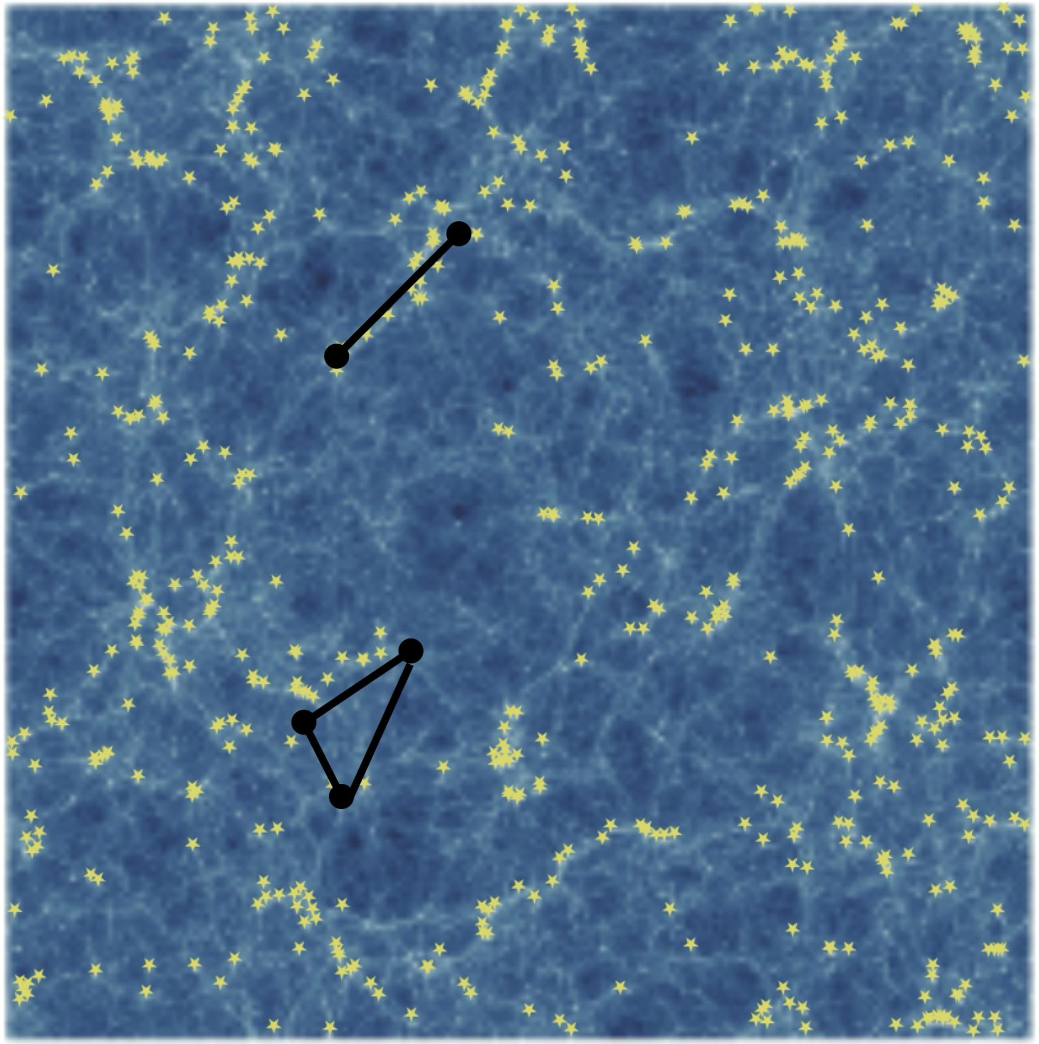
Other probes

- Clusters (SZ / optical / X-ray)
- Lyα forest (z > 2 IGM)
- 21cm
- X-ray maps
- Cosmic Infrared Background (CIB)
- Line Intensity Mapping (LIM) -- Kana's talk on Thursday
- SNae/GW/time delays
- CMB lensing κ (integrated matter)



Preston+ 2023

What do spectroscopic redshift surveys measure?



$$\delta_g = b_g \delta_m \qquad \delta_g(\mathbf{x}) = \frac{n_g(\mathbf{x}) - \bar{n}_g}{\bar{n}_g}$$

$$\xi(r) = \langle \delta_g(\mathbf{x})\, \delta_g(\mathbf{x} + \mathbf{r}) \rangle$$

Power Spectrum

$$\langle \delta(\vec{k}_1)\, \delta(\vec{k}_2) \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2)\, P(k)$$

Bispectrum

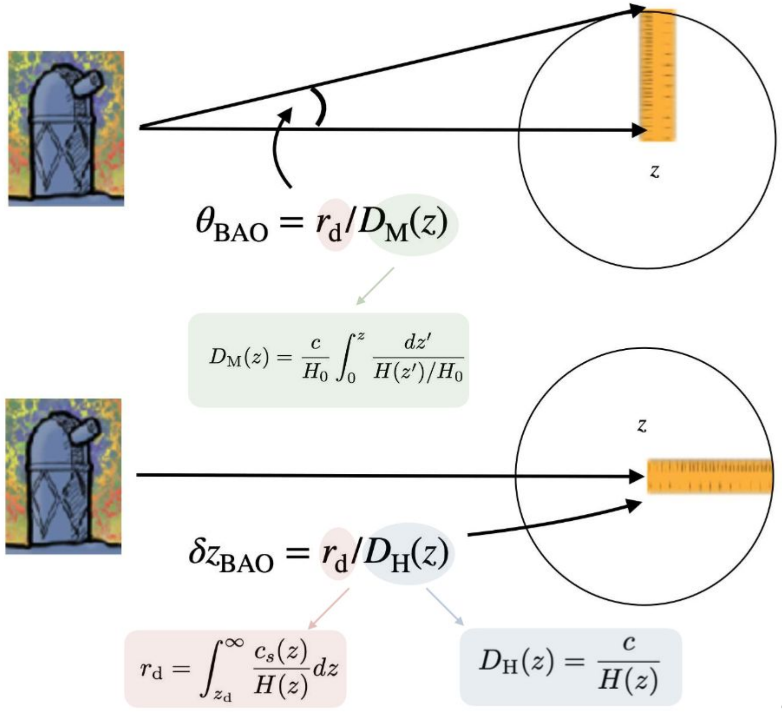
$$\langle \delta(\vec{k}_1)\, \delta(\vec{k}_2)\, \delta(\vec{k}_3) \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\, B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$

Precise redshifts → 3D galaxy positions → the full power spectrum P(k)

BAO – standard ruler

Elisa's talk slide

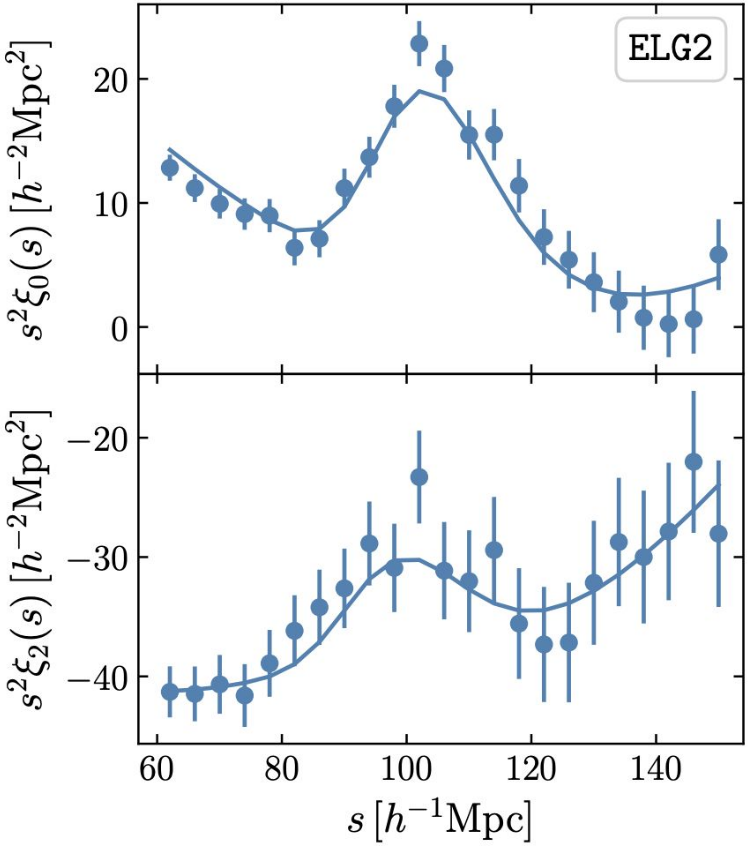
$$r_{\rm d} = 147.05\,\text{Mpc} \times \left(\frac{\omega_{\rm b}}{0.02236}\right)^{-0.13} \left(\frac{\omega_{\rm bc}}{0.1432}\right)^{-0.23} \left(\frac{N_{\rm eff}}{3.04}\right)^{-0.1}$$



$r_d\,h$

Ω_M

$+\ D_V(z)/r_d$

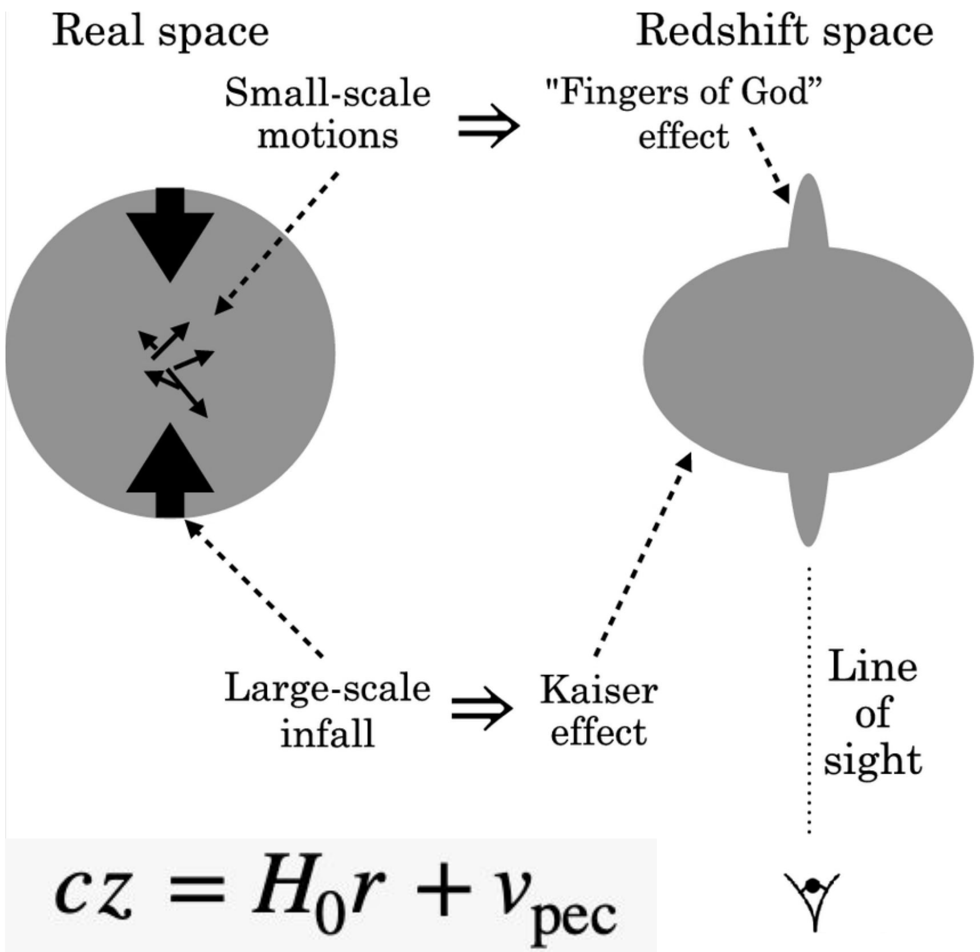


DESI DR2, 2025

Expansion history → the dark-energy equation of state w(z)

Redshift Space Distortion (RSD)

Fig. Credit: D. Huterer



$$cz = H_0 r + v_{pec}$$

Kaiser (1987)

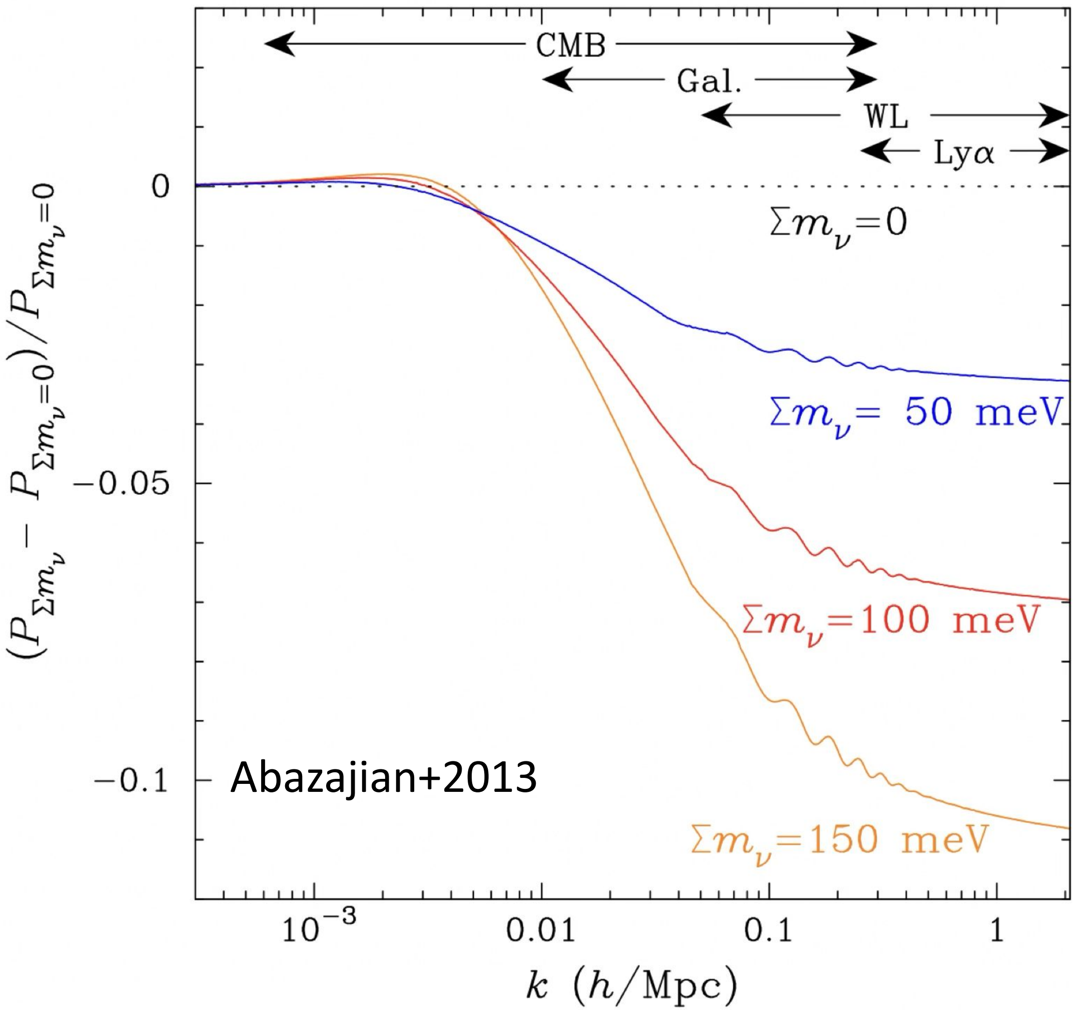
$$\boxed{P_s(k,\mu) = \left(1 + \beta\mu^2\right)^2 P_r(k)}$$

- $P_s(k,\mu)$: redshift space galaxy power spectrum
- $P_r(k)$: real space galaxy power spectrum
- $\mu = \cos\theta$: angle between wave vector and LOS
- $\beta = \dfrac{f(z)}{b_g}$: $f(z) \sim \Omega_m^\gamma$ with $\gamma \sim 0.55$ in GR + LCDM

Growth of Structure

→ growth rate $f\sigma_8(z)$ → tests gravity (GR vs modified)

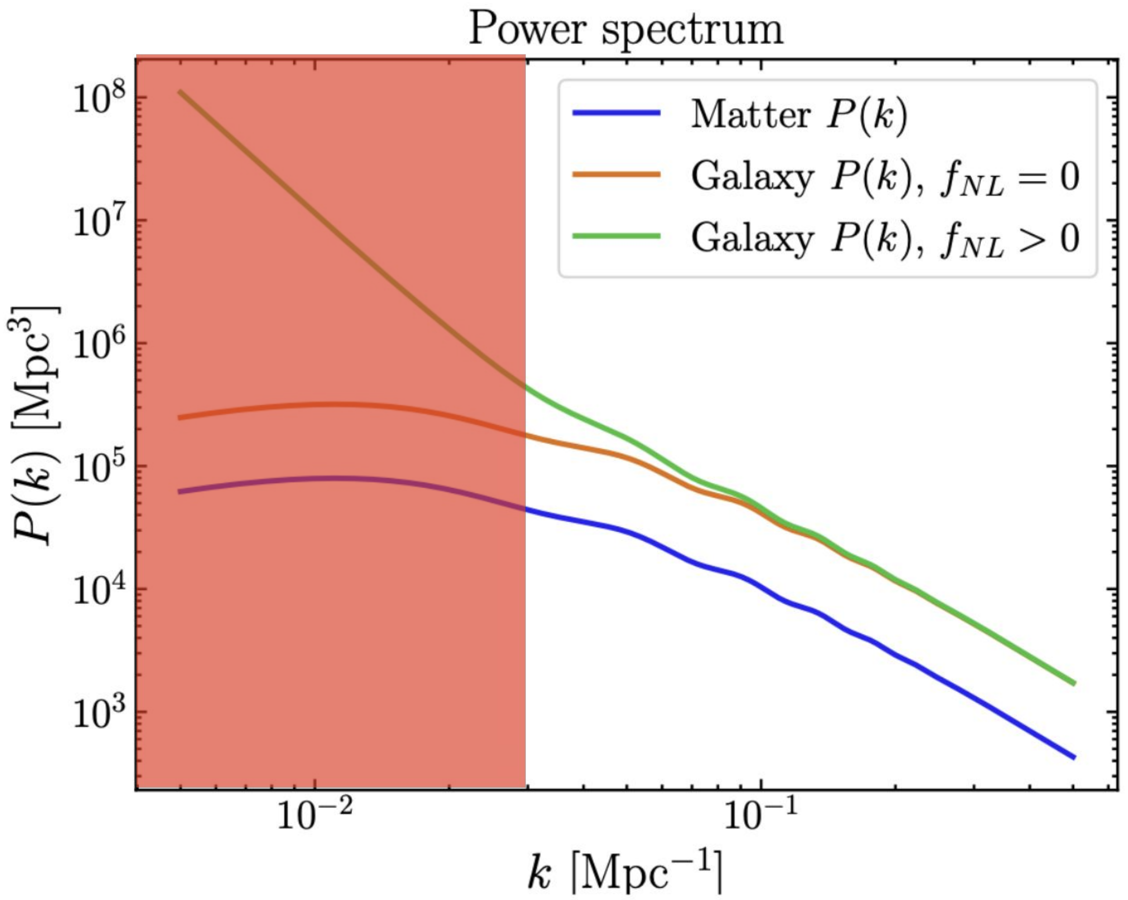
Neutrino Mass



Neutrino mass:

Suppressed matter power spectrum at large k (small scales)

Primordial Non-Gaussianity (PNG) – scale dependent bias



Dalal+ 2008

$$\Phi = \phi_{\rm G} + f_{\rm NL}\left(\phi_{\rm G}^2 - \langle\phi_{\rm G}^2\rangle\right)$$

$$\Delta b(k) \propto f_{\rm NL}\,\frac{(b-1)}{k^2}$$

Planck Bispectrum

$$f_{\rm NL}^{\rm loc} = 0.8 \pm 5.0$$

DESI DR1

$$f_{\rm NL}^{\rm loc} = -3.6^{+9.0}_{-9.1} \text{ at } 68\%$$

Elisa's talk on Monday

CMB – LSS Tension?

The S_8 tension

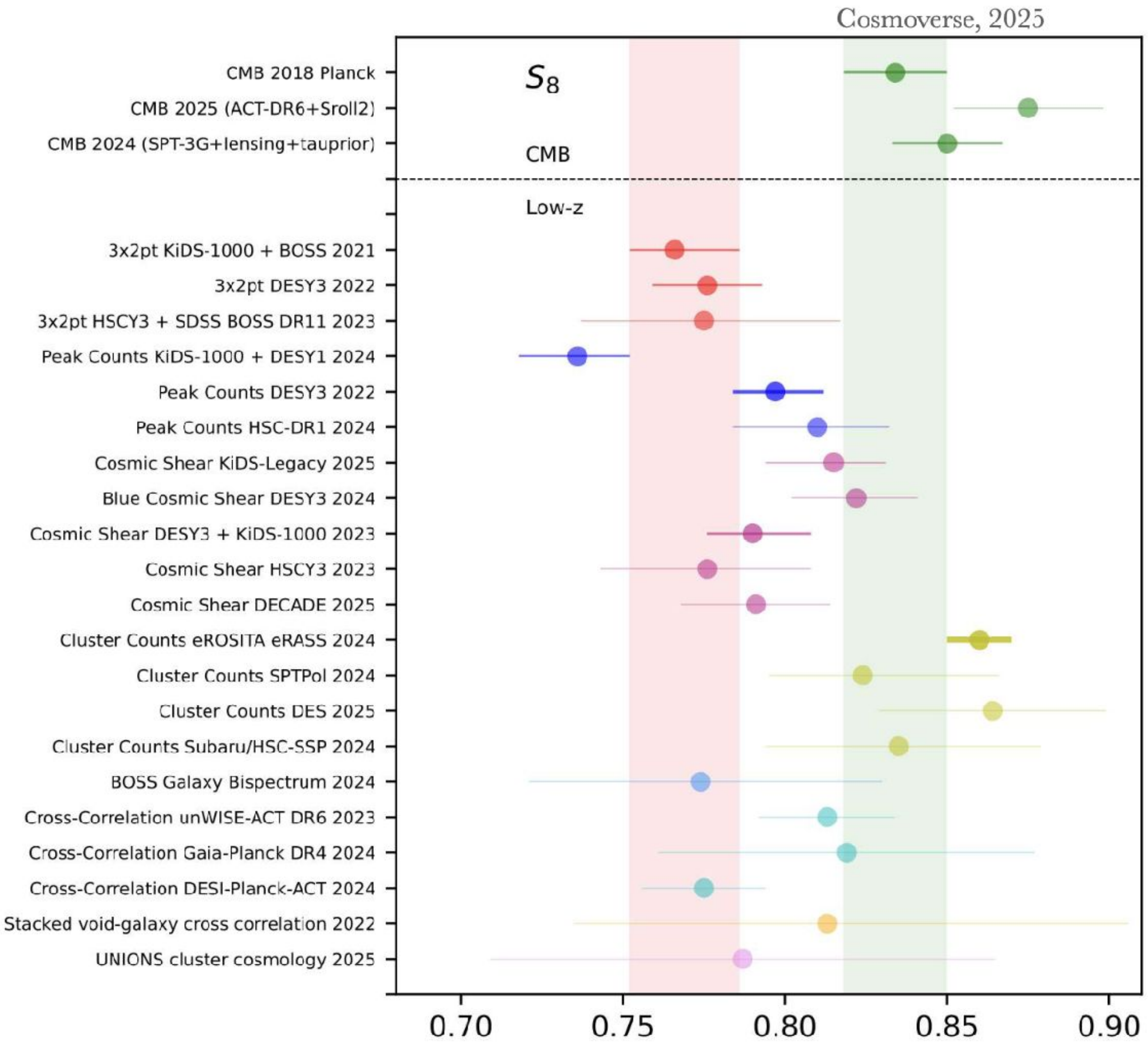
Discrepancy between the value of S_8 measure from weak lensing (WL) probes and Planck.

- While BAO/CMB are geometrical probes, WL measures the projected clustering of matter
- S8 describes the inhomogeneity of the matter distribution now; WL is sensitive to this quantity

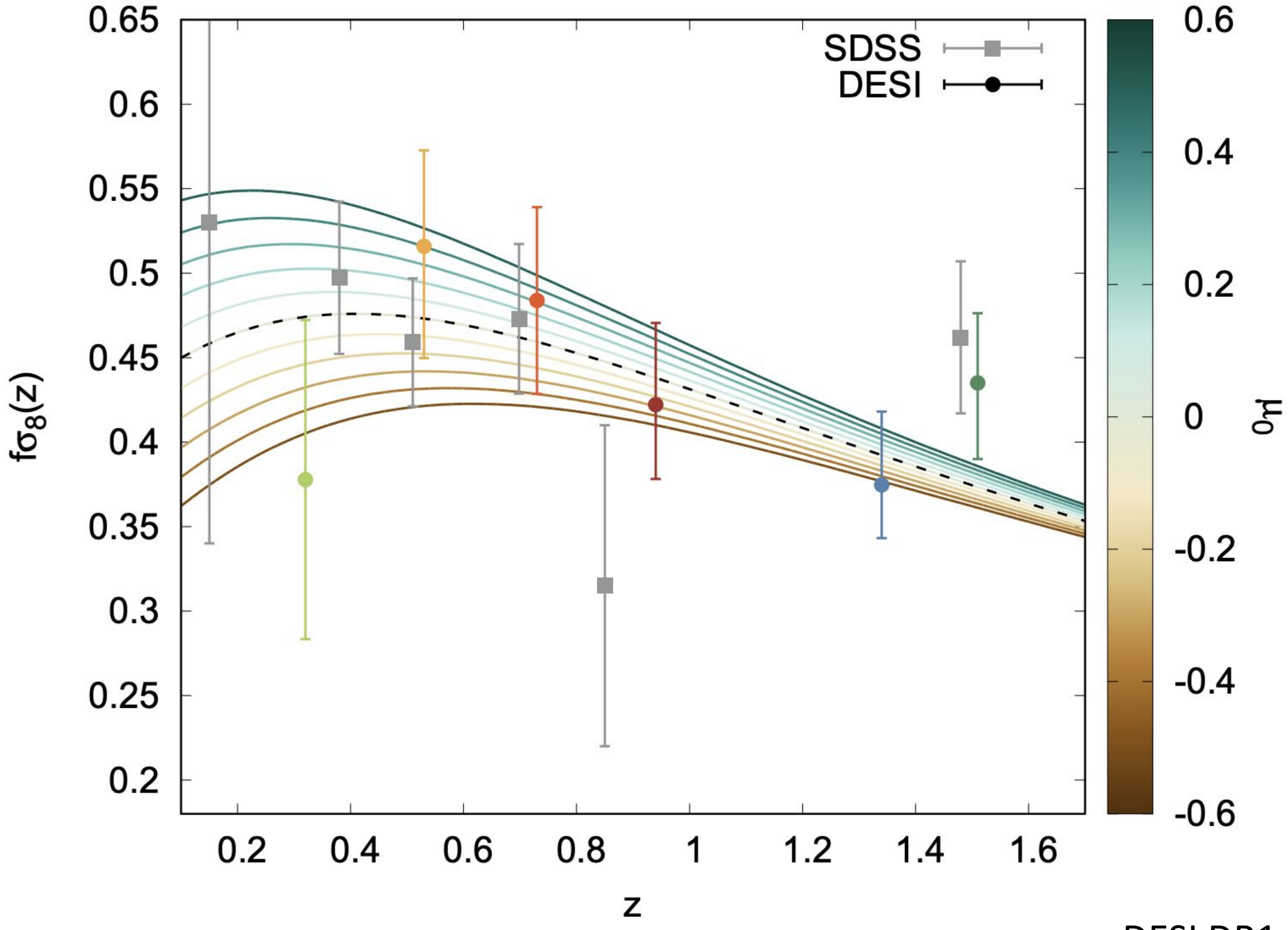
$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$$

- Max. 3σ tension

σ_8: RMS fluctuation of the linear density field within a sphere of radius 8 Mpc/h



LCDM + GR (consistent with Planck)

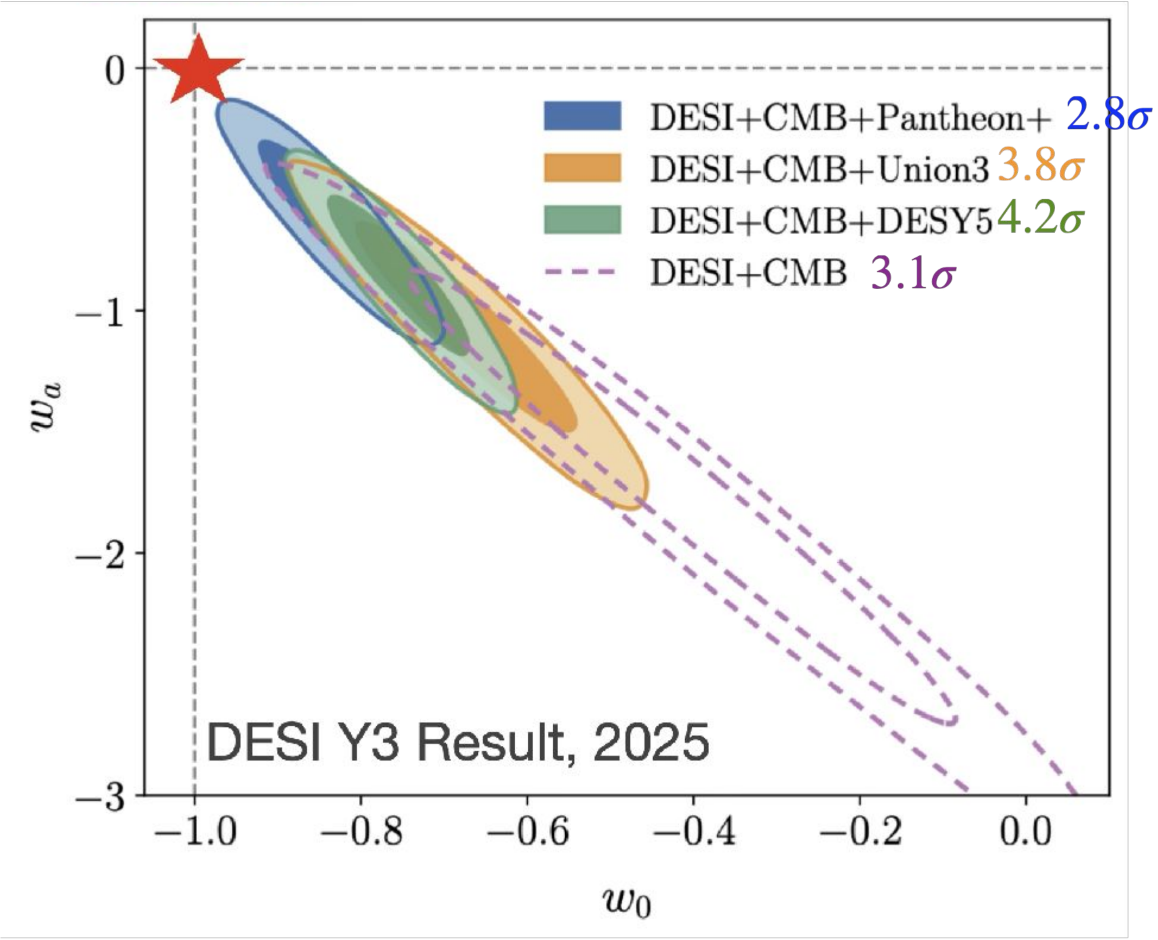


DESI DR1, full shape, 2024

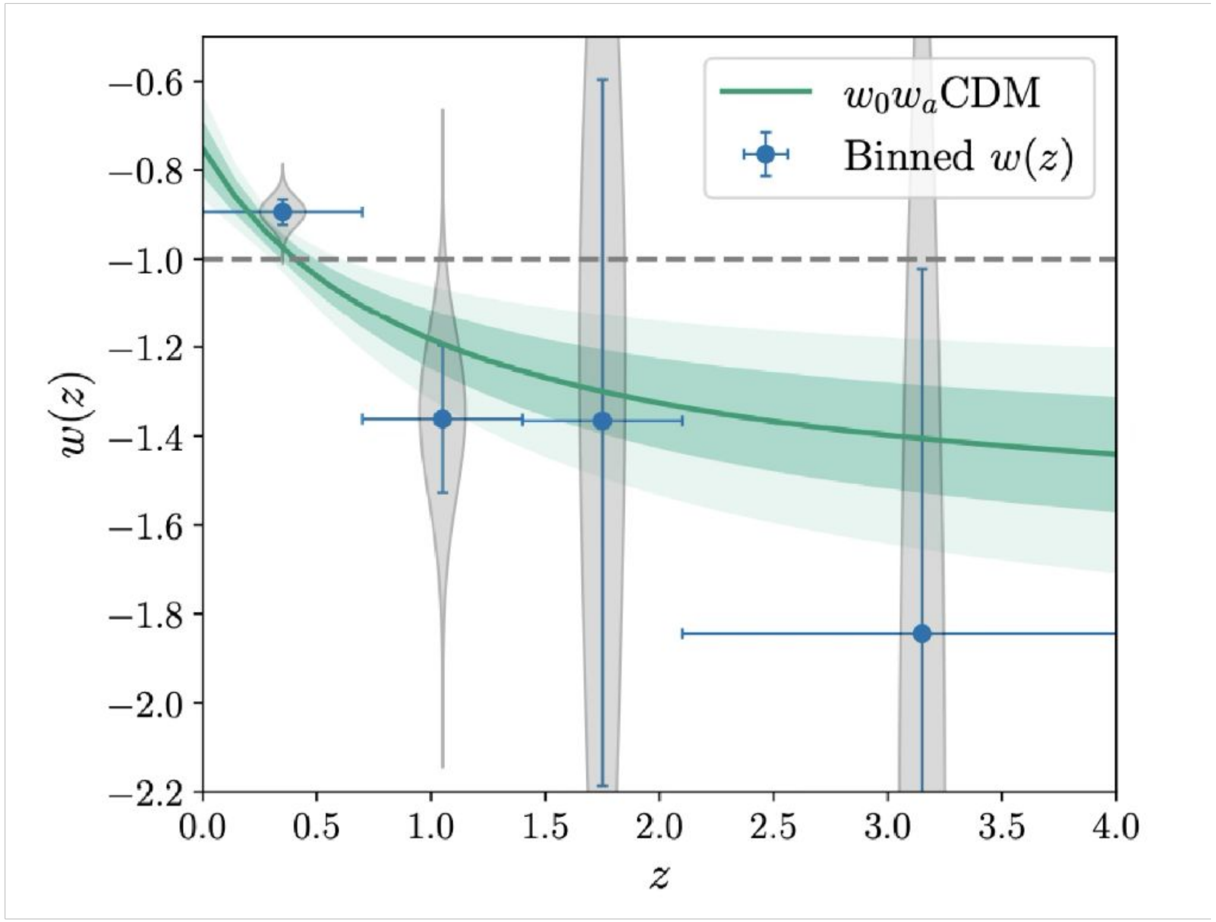
Check Elisa's talk also

Dynamical Dark Energy? — DESI DR2 (2025)

ΛCDM



$w(a) = w_0 + w_a(1-a)$



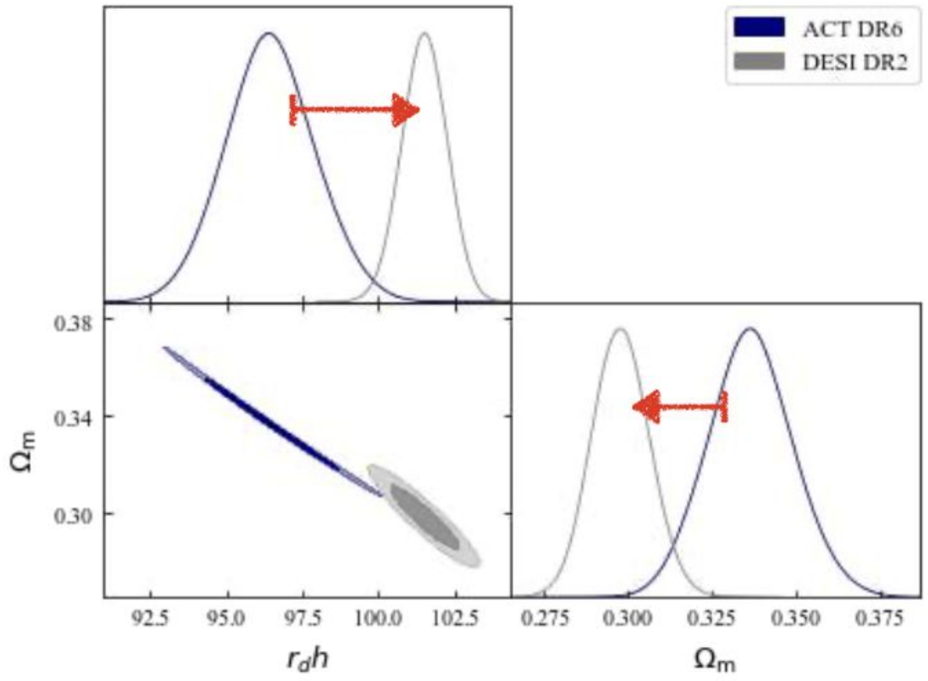
Elisa's talk on Monday

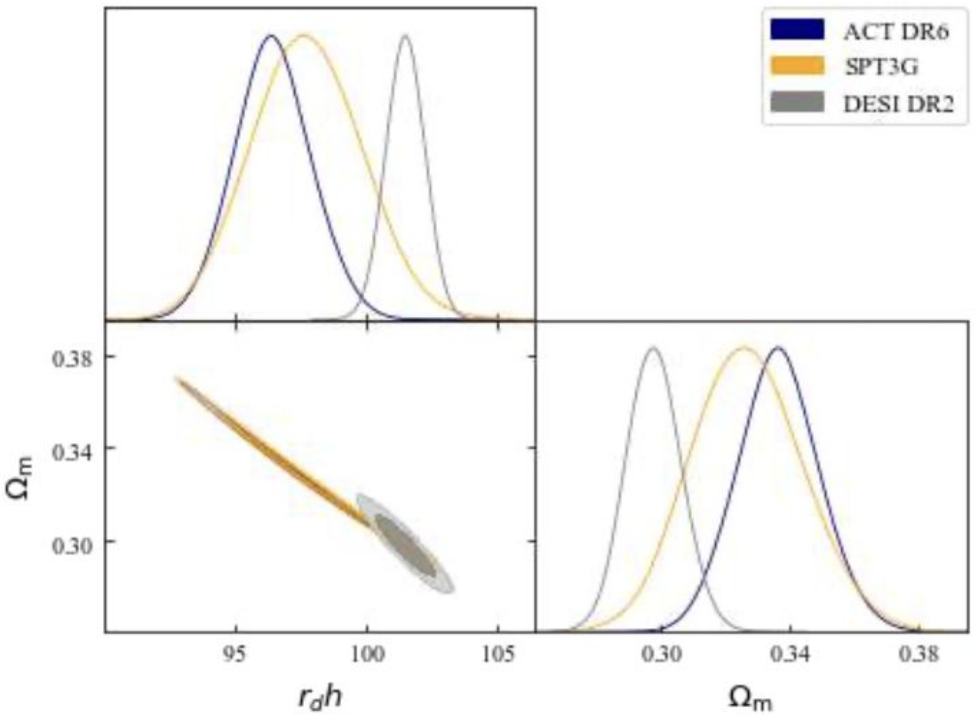
BAO - CMB tension

The BAO-CMB Tension and Implications for Inflation
***EF**, E McDonough, L Balkenhol, R Kallosh, L Knox, and A Linde,*
2507.12459

Are ACT and SPT compatible with DESI ?

(or BAO-CM tension or Ω_M tension)

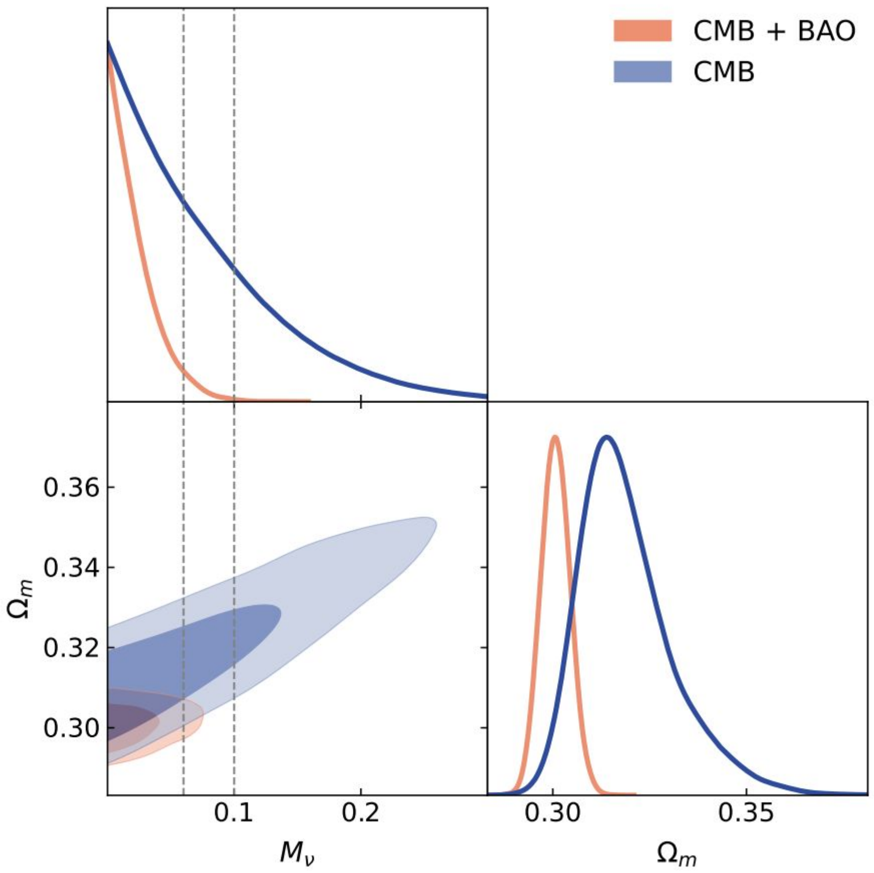


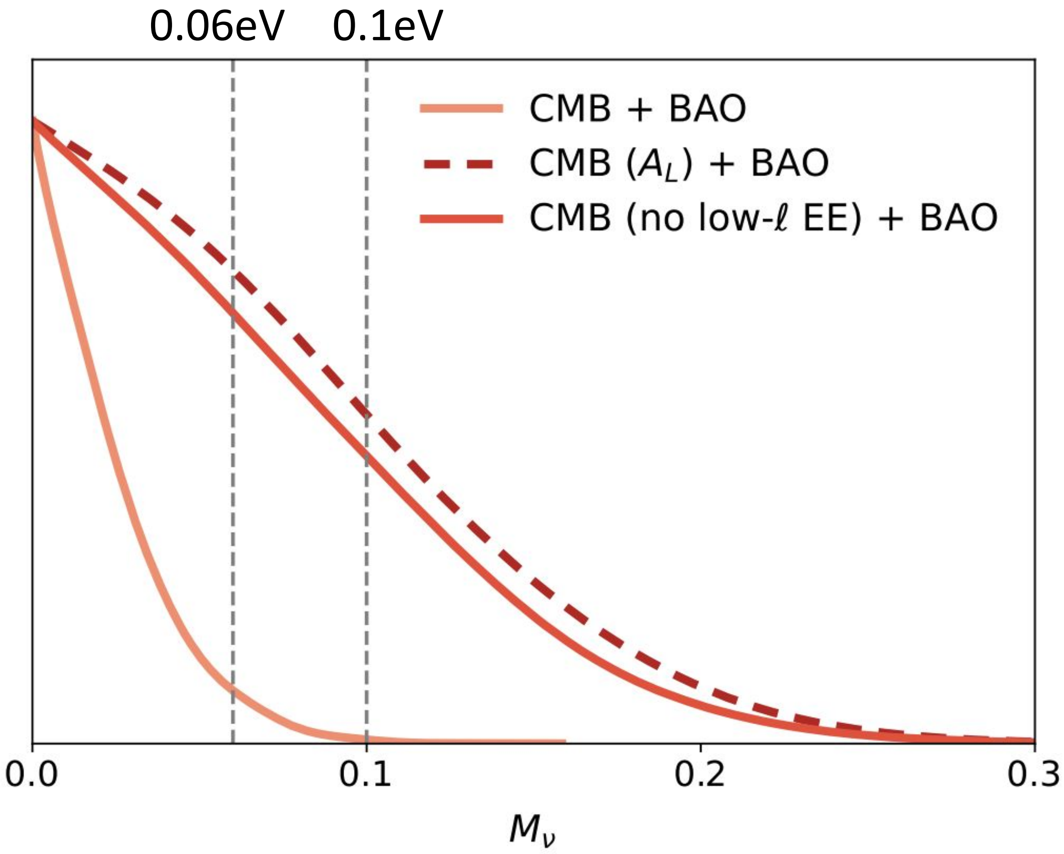


- 2d posteriors show small overlap
- 1d posterior shifted

Discrepancy (or tension) in the values of $r_d h$ and Ω_M measured from CMB and DESI BAO!

Unphysical neutrino mass or higher tau?





Jhaveri, Karwal, Hu 2025

Systematics or Physics?

PFS Cosmology: a unique spec-z survey

1

[OII] ELGs, $0.6 < z < 2.4$

Fills the missing high-z LSS-tracer gap (extends to $z = 1.6$–2.4)

2

High number density

8.2 m aperture → also a powerful neutrino-mass probe

3

Synergy with HSC / CMB

Shared deep fields → lensing & kSZ cross-correlations

Cross-checking the DESI–CMB tension

Independent geometry (BAO) + growth (RSD) probe over a wide redshift range


LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE
Max-Planck-Institut für Astrophysik
MPE
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
NORTHWESTERN UNIVERSITY
QUAECUMQUE SUNT VERA
1851
UNIVERSITY OF PITTSBURGH
PennState
University of Massachusetts Amherst
UCONN
UNIVERSITY OF CONNECTICUT
Tufts UNIVERSITY
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK
PEKING UNIVERSITY
1898
NAOC
TSINGHUA UNIVERSITY
1911
1958
PRINCETON UNIVERSITY
JOHNS HOPKINS UNIVERSITY
NASA
Jet Propulsion Laborato
California Institute of Technolo
Caltech
LNA LABORATÓRIO NACIONAL DE ASTROFÍSICA
SHANGHAI JIAO TONG UNIVERSITY
UNIVERSITAS AMOIENSIS
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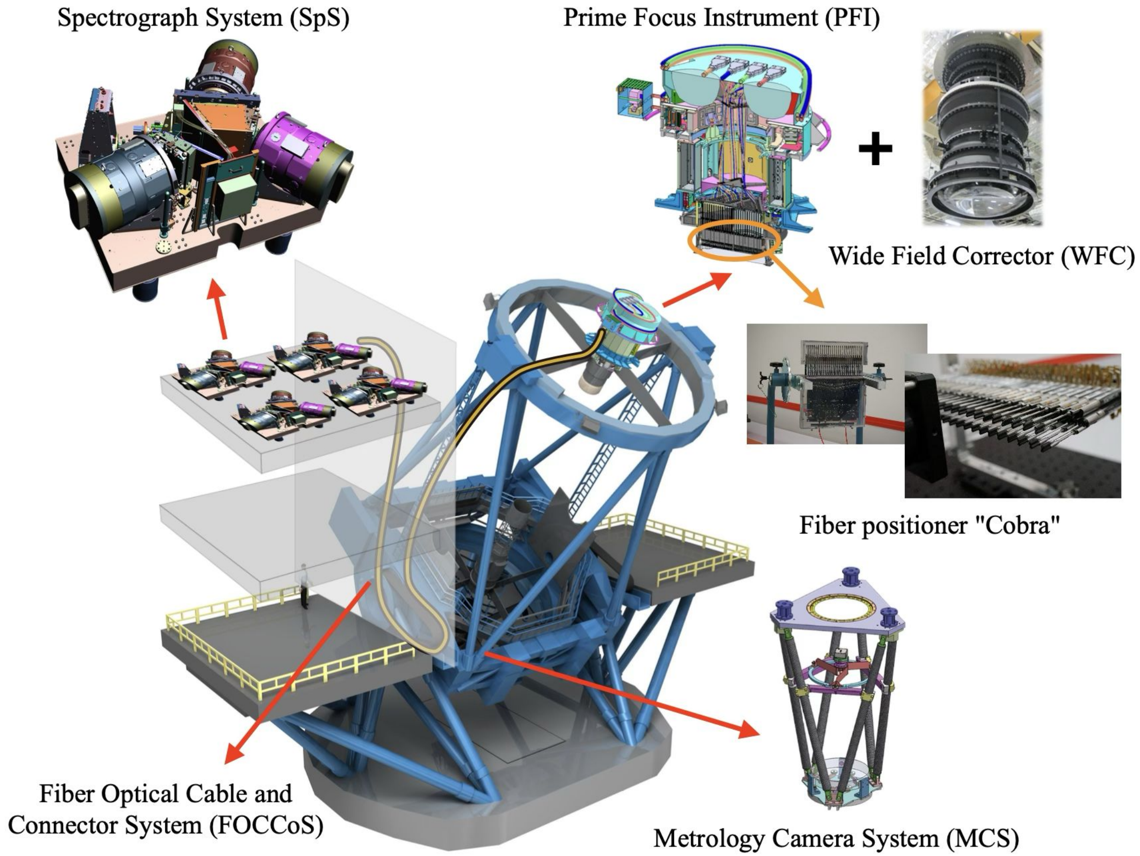
National Astronomical Observatory of Japan
OBSERVATÓRIO DE SÃO PAULO

PFS (Prime Focus Spectrograph): Instrument



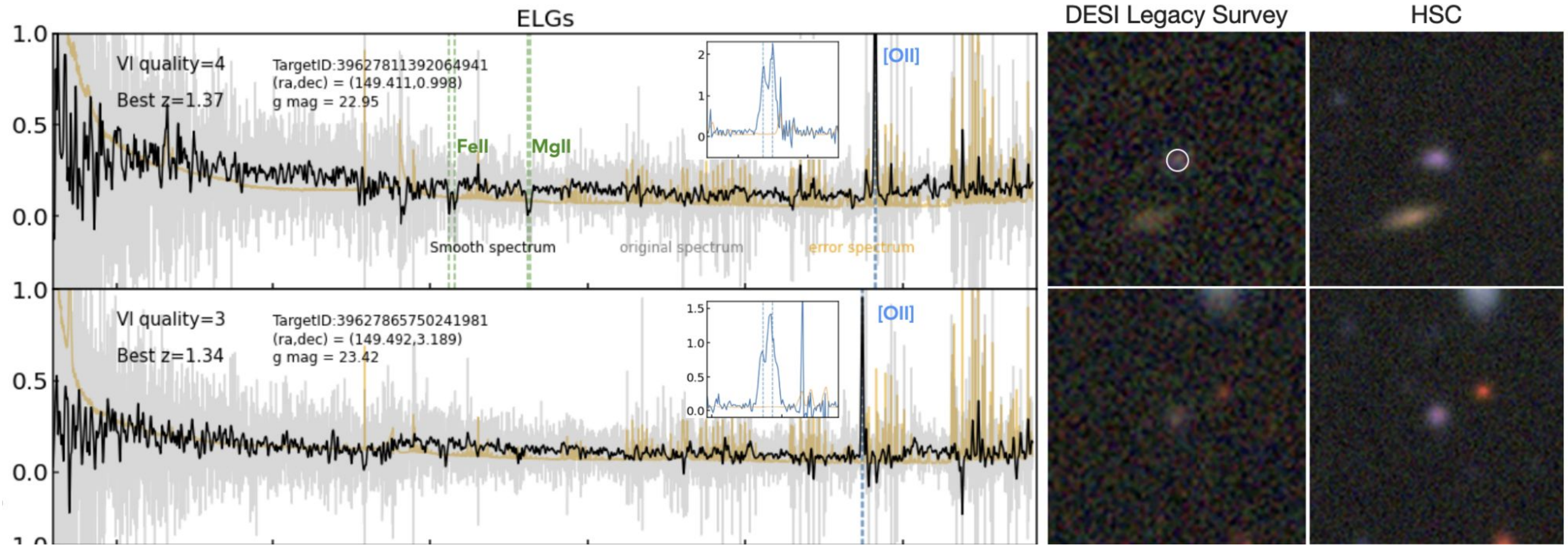
Prime Focus Instrument					
Field of view	~1.38 deg (hexagonal - diameter of circumscribed circle)				
Field of view area	~1.25 deg^2				
Input F number to fiber	2.8				
Fiber core diameter (1)	127 μm (1.12 arcsec at the FoV center, 1.02 arcsec at the edge)				
Positioner pitch	8 mm (90.4 arcsec at the FoV center, 82.4 arcsec at the edge)				
Positioner patrol field	9.5 mm diameter (107.4 arcsec at the FoV center, 97.9 arcsec at the edge)				
Fiber minimum separation (2)	~30 arcsec				
Fiber configuration time (3)	~130 sec				
Number of fibers(4)	Science fibers		Fixed fiducial fibers		
	2386 (2394)		92 (96)		
Fiber density	~2000 deg^{-2} / ~0.6 arcmin^{-2}				
Number of A&G camera (5)	6				
Field of view of A&G camera	~5.1 arcmin^2 per one camera				
Sensitivity of A&G camera (6)	gaia 21.7 AB mag for S/N~5 in 5 sec exposure				
Spectrograph System					
Number of Spectrograph	4				
Spectral arms	Blue	Red		NIR	
		Low Res.	Mid. Res.		
Spectral coverage	380 - 650 nm	630 - 970 nm	710 - 885 nm	940 - 1260 nm	
Dispersion	~0.7 Å/pix	~0.9 Å/pix	~0.4 Å/pix	~0.8 Å/pix	
Spectral resolution	~2.1 Å	~2.7 Å	~1.6 Å	~2.4 Å	
Resolving power (7)	~2500 (@500nm)	~3000 (@800nm)	~5500 (@800nm)	~4500 (@1100nm)	
Spectrograph throughput (8)	~49% (@500nm)	~52% (@800nm)	~48% (@800nm)	~39% (@1100nm)	

DESI
~ 625 deg^{-2}

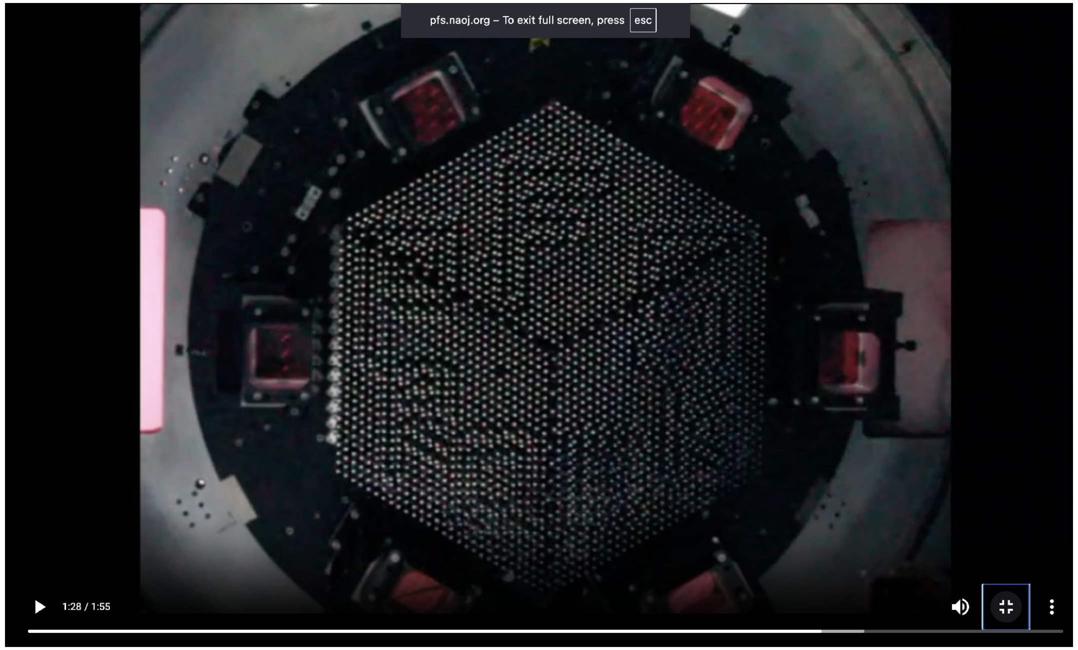
DESI
360–980 nm

Mounted on the 8.2 m Subaru Telescope, Maunakea

~2400 fibers · 1.3 deg² field · 380–1260 nm



DESI [OII] ELG spectrum
Lan+,2024



PFS Focal Plane,
Moving 2400 fiber positioner - cobra,
Credit: PFS project office

Cobra motion accuracy ~ 0.5arcsec (50um)

From survey to cosmology

Target selection from imaging surveys

↓

Observation (point fibers on targets)

↓

Raw data reduction → 1D spectrum

↓

Redshift fitting (obtain z)

↓

LSS catalog

↓

Measurement & cosmology analysis

PFS SSP Survey Science

	Testing ΛCDM	Assembly history of galaxies	Importance of IGM
CO	• Nature & role of neutrinos • Expansion rate via BAO up to z=2.4 • PFS+HSC tests of GR • Curvature of space: Ω_K • Primordial power spectrum	• PFS+HSC synergy • Absorption probes with PFS/SDSS QSOs around PFS/HSC host galaxies	• Search for emission from stacked spectra
GA	• Nature of DM (dSphs) • Structure of MW dark halo	• Stellar kinematics and chemical abundances – MW & M31 assembly history	• dSph as relic probe of reionization feedback • Past massive star IMF from element abundances
GE	• Small-scale tests of structure growth	• Halo-galaxy connection: $M_*/M_{\rm halo}$ • Outflows & inflows of gas • Environment-dependent evolution	• Physics of cosmic reionization via LAEs & 21cm studies • Tomography of gas & DM

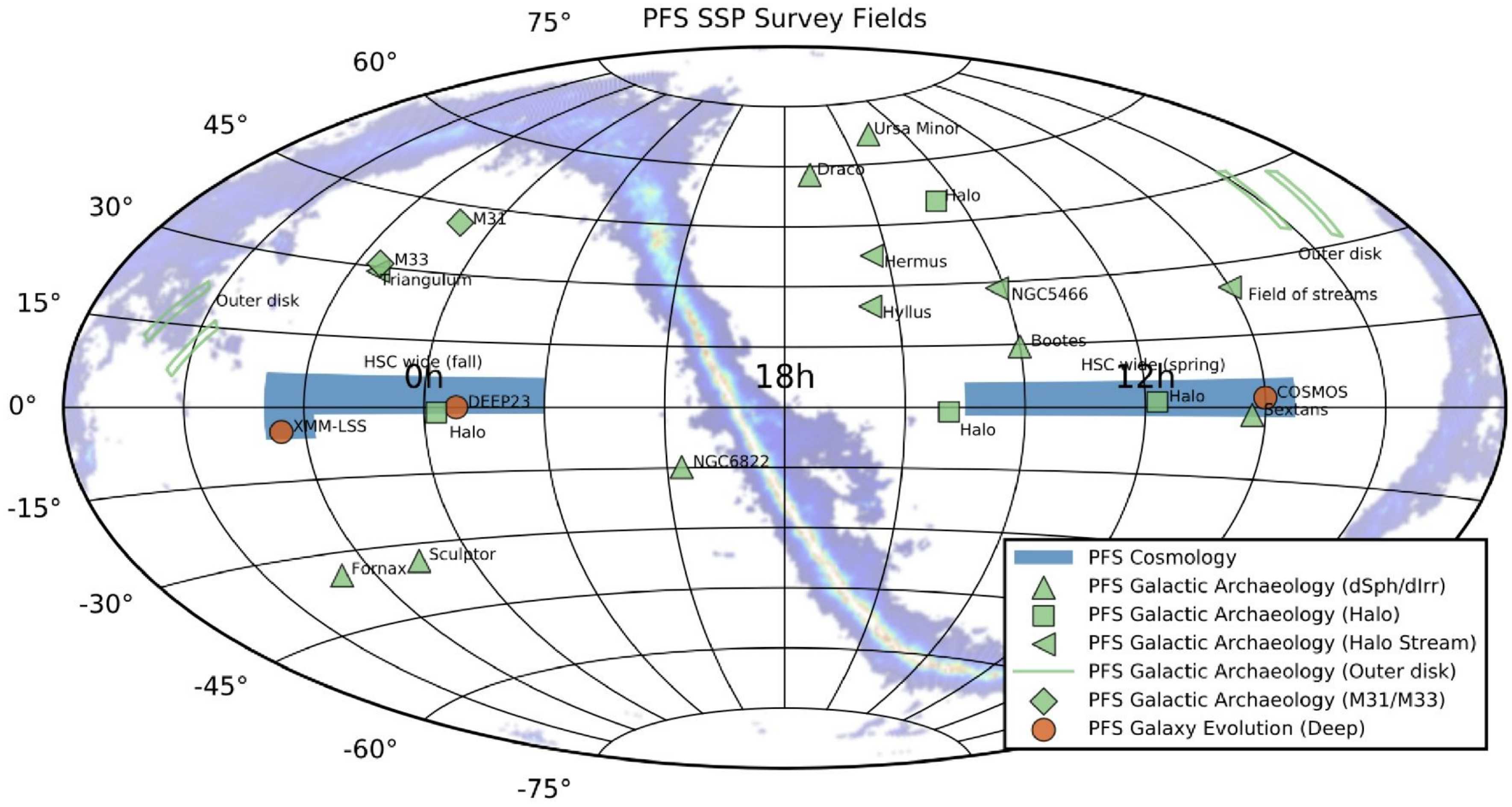
Cosmology (CO) (~1200 sq. degs.): ~4M emission-line galaxy spectra

Galactic Archaeology (GA): stars in dSphs, streams and disk in MW and M31

Galaxy Evolution (GE) (~15 sq. degs.): ~a few 10^5 high S/N galaxy spectra

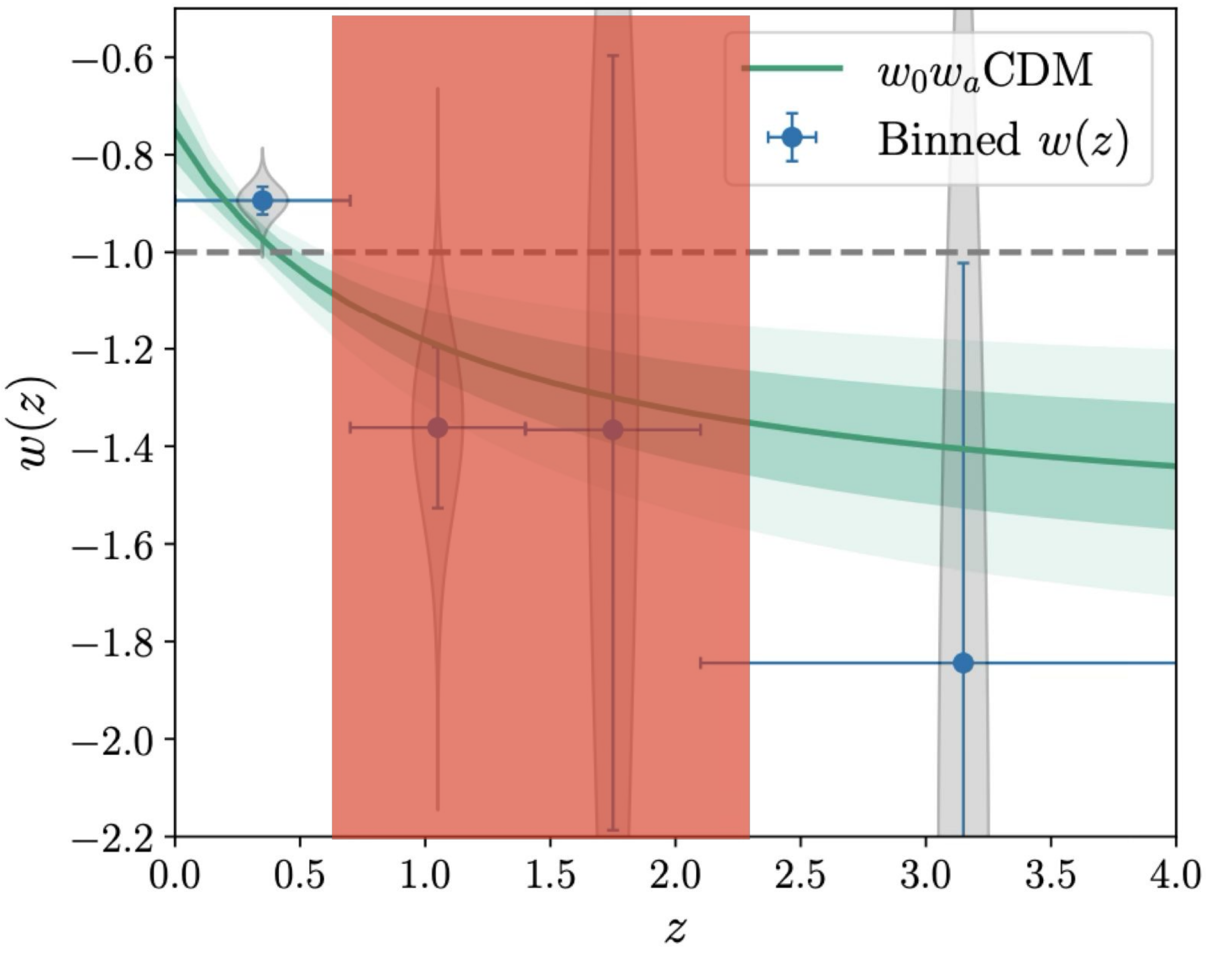
Target selection is based on the HSC data

PFS SSP Survey Footprint

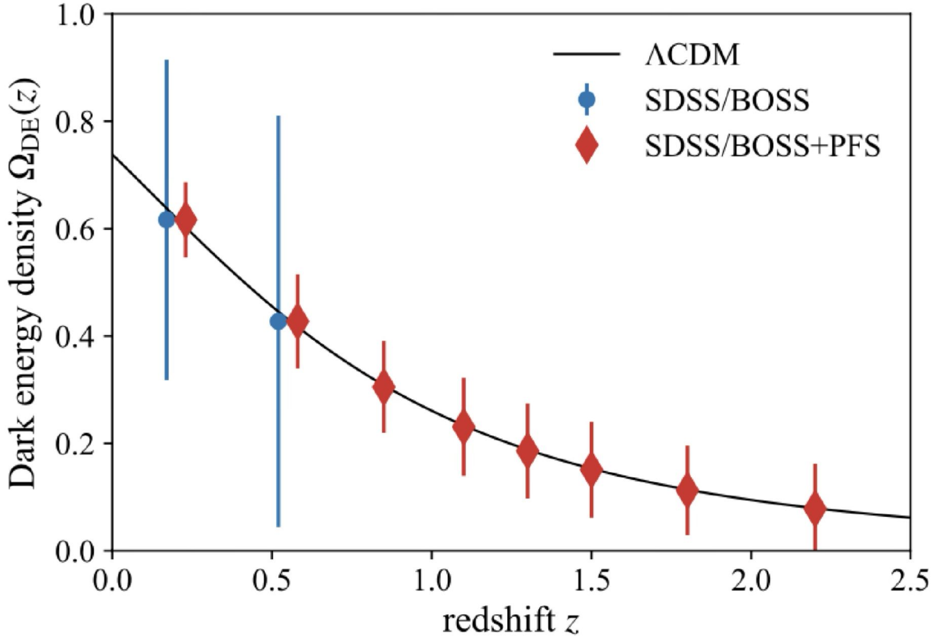


5-year Subaru Strategic Program · 360 nights · survey started March 2025
PFS Cosmology survey –> HSC wide survey footprint

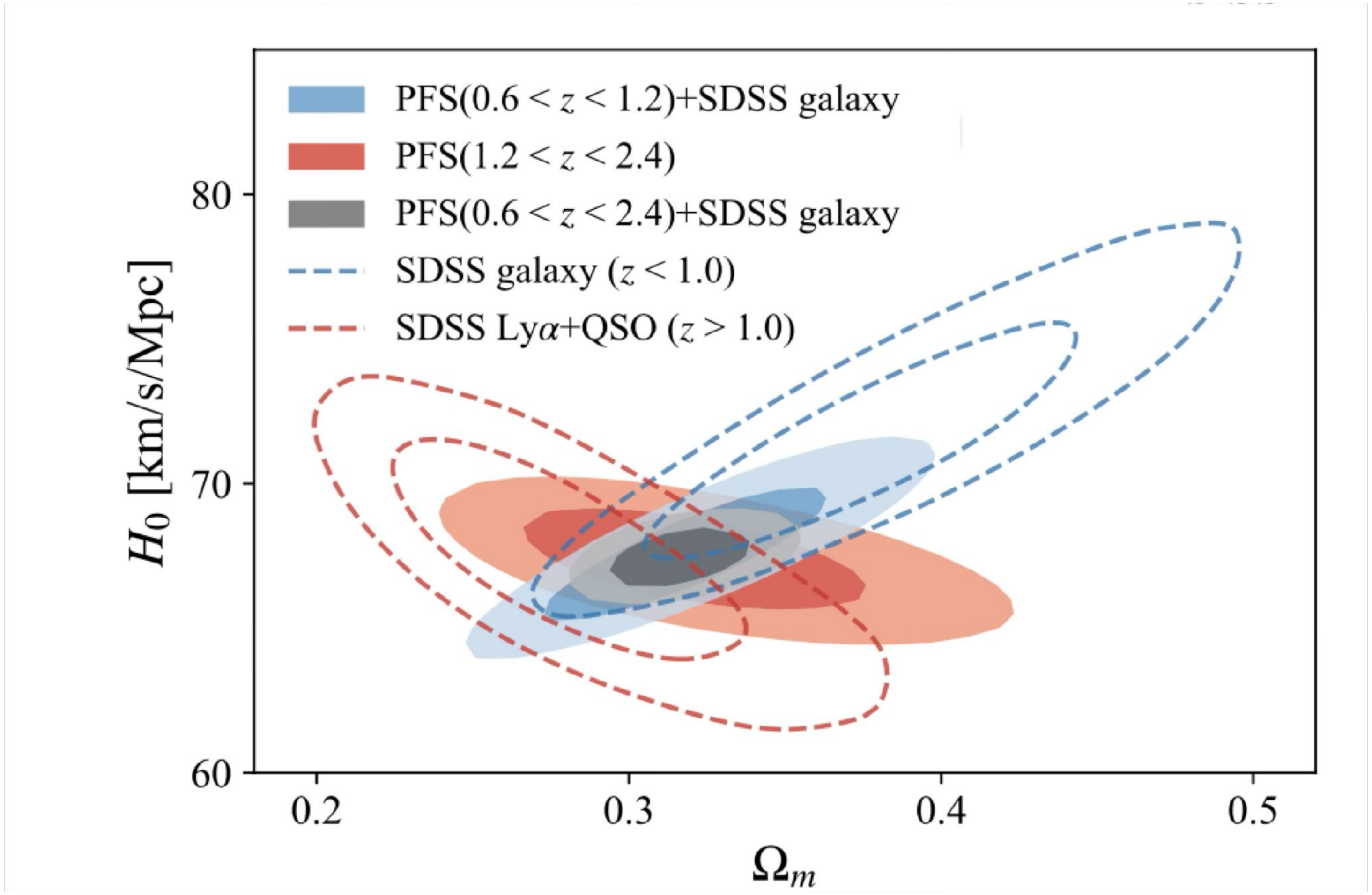
Dynamical Dark Energy: PFS as an independent cross check



Sunayama+, in prep

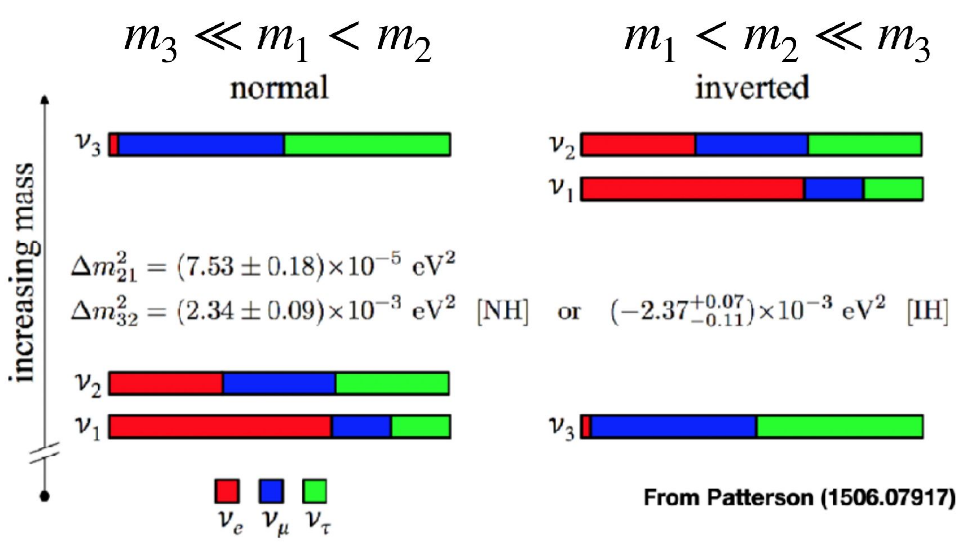


PFS SSP Cosmology: ~4M [OII] emission-line galaxies, ~7 (Gpc/h)³



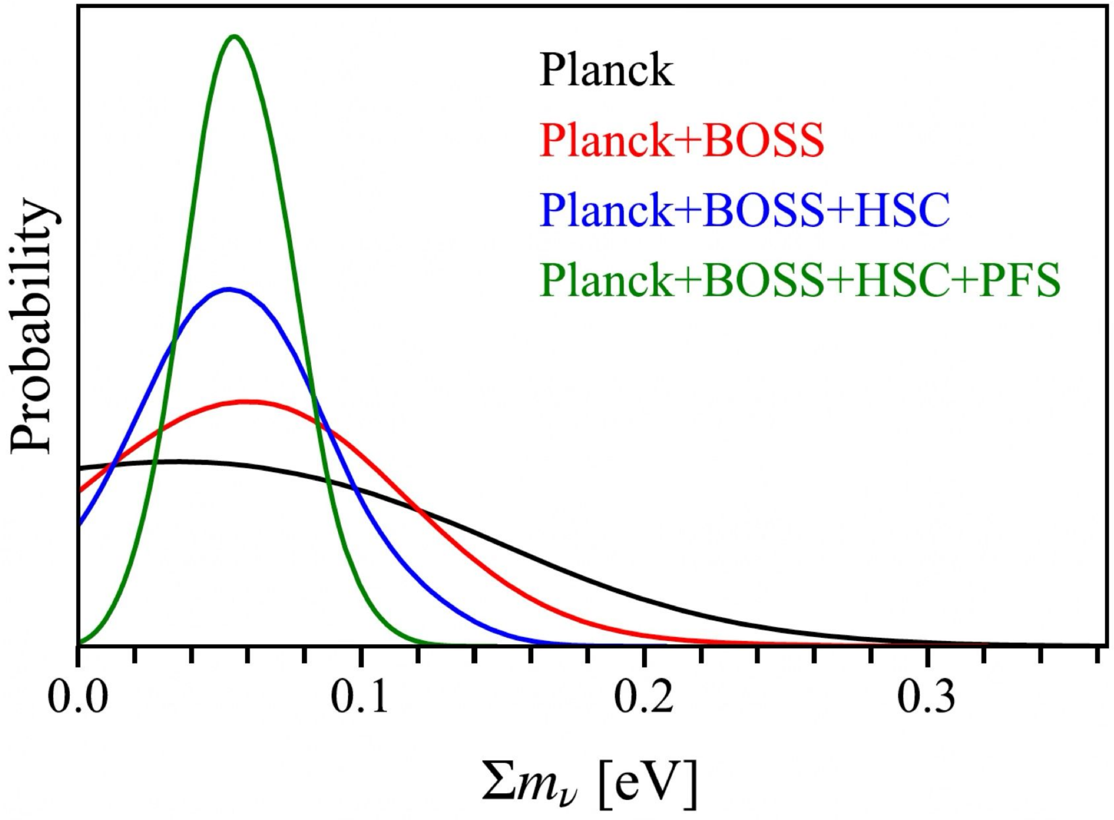
- Break the degeneragy on the Omega_m – H0 plane;
- independent check on the tension between SDSS galaxy and Lya+QSO; DESI BAO - CMB

Neutrino Mass



$\Sigma m_\nu = 0.06$eV

$\Sigma m_\nu = 0.1$eV



PFS forecast: σ(Σmv) = 0.02 eV (68% CL)

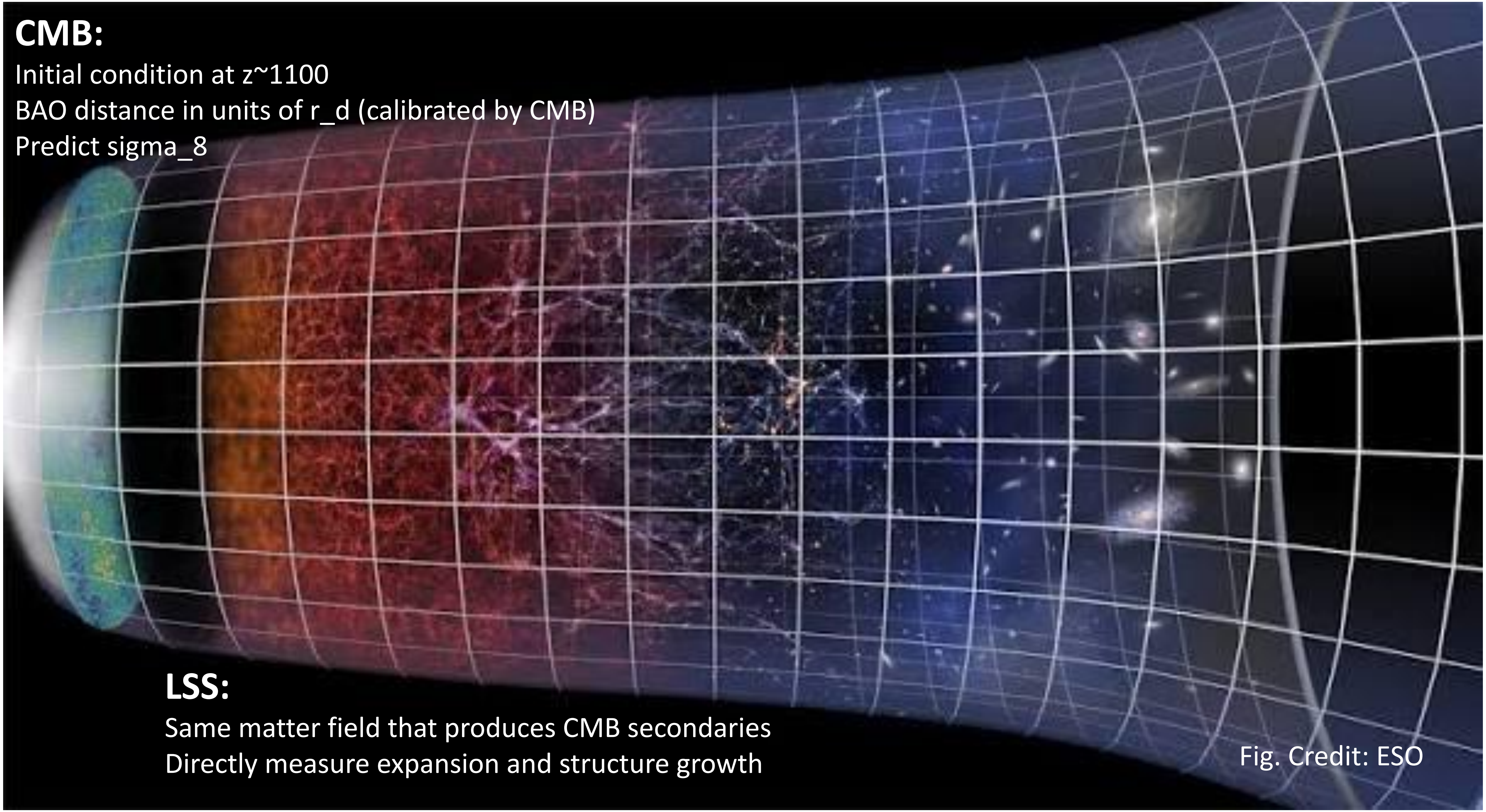
+30% from k_max = 0.2 → 0.5 h/Mpc

CMB:

Initial condition at z~1100

BAO distance in units of r_d (calibrated by CMB)

Predict sigma_8



LSS:

Same matter field that produces CMB secondaries

Directly measure expansion and structure growth

Fig. Credit: ESO

Slide credit:
Blake Sherwin

Possible CMB-LSS cross-correlations

- ✓ = standard / robust
- • = emerging
- — = futuristic or impossible

×	g	γ	cl	QSO	Lyα	CIB	X-ray	21/LIM
T/E/B	✓	—	•	•	—	•	•	—
κ	✓	✓	✓	✓	•	✓	✓	•
tSZ	✓	✓	✓	✓	•	✓	✓	•
kSZ	✓	•	•	•	—	—	—	—
SD	•	—	•	—	—	•	•	•

- High SNR: correlation among low redshift density tracers (matter/baryon tracers), but sometimes with significant systematic limitations (CIB contamination for y x X)
- New areas: correlations with velocity (kSZ), lines (21cm/LIM), ...

What we gain by combining CMB × LSS

Bias-clean growth

$C\_{\kappa g} \propto b \cdot \sigma_8^2$, $C\_{gg} \propto b^2 \cdot \sigma_8^2$ → the combination cancels galaxy bias, returning growth directly.

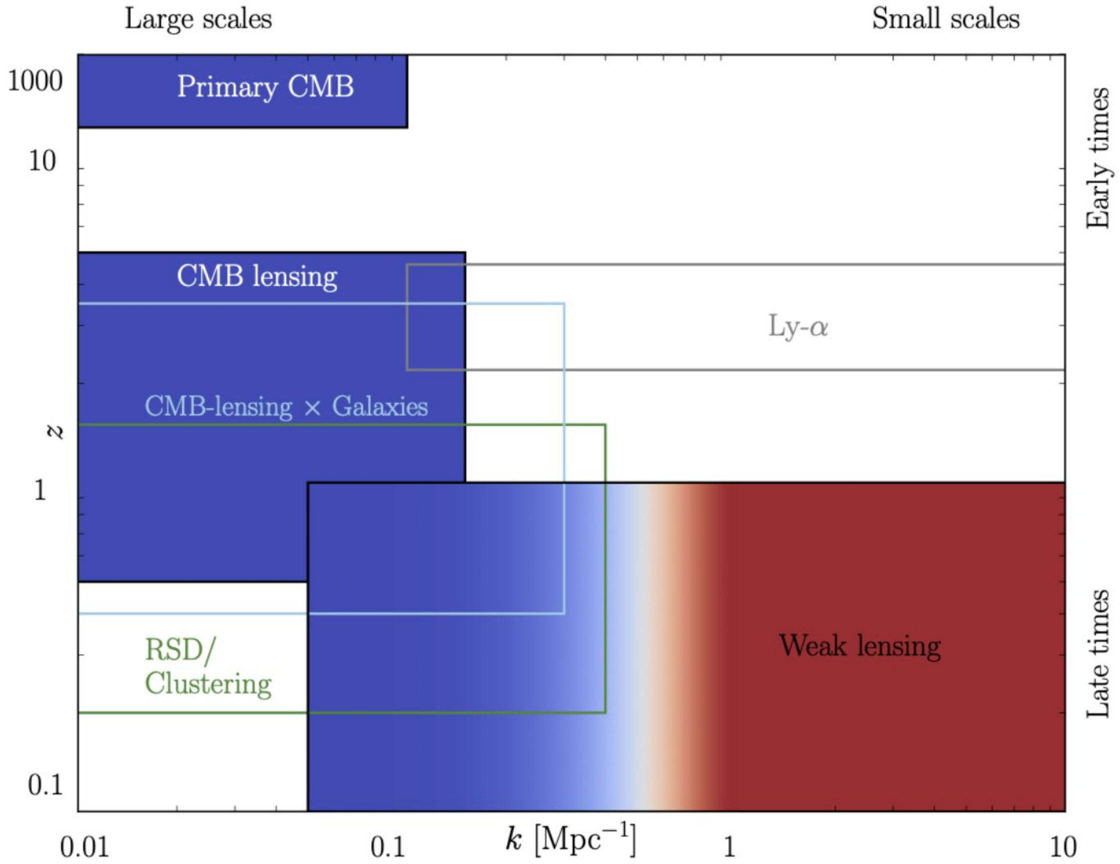
Robust to systematics

Cross-correlations are immune to systematics that don't correlate between two experiments.

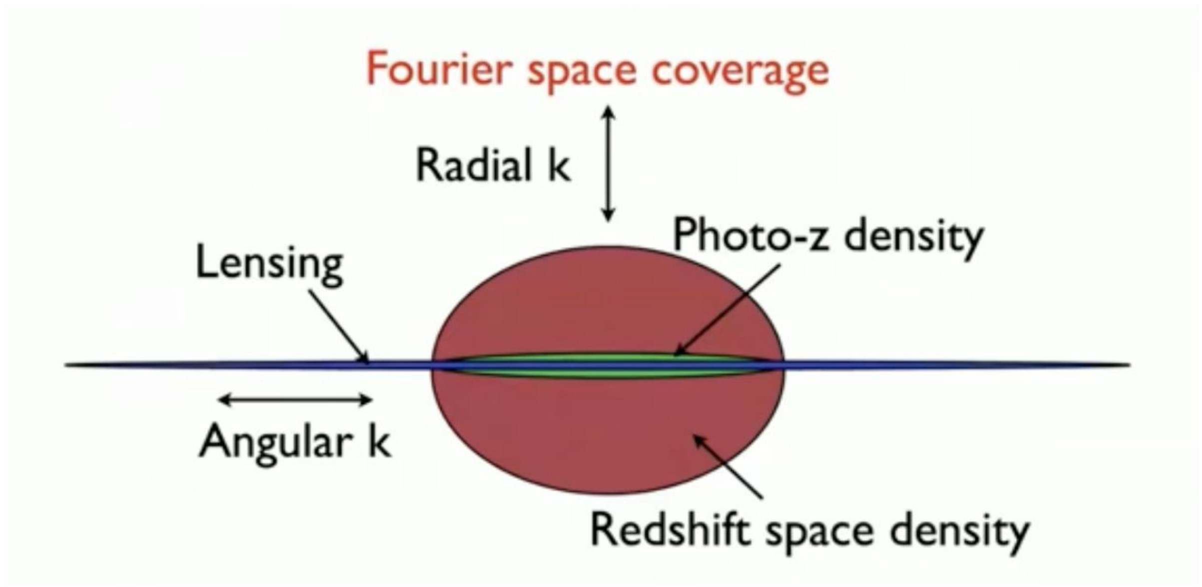
Break CMB degeneracy

Low-z distances break the Ωm–H_0–DE degeneracy → the long lever arm for w_0, w_a.

CMB × LSS: three overlaps that enable cross-correlation



Preston+ 2023



Credit: Andreu Font-Ribera & Patrick McDonald

Overlap in area + redshift + scale is what makes clean CMB × galaxy cross-correlations possible.

Case 1) A concrete CMB × LSS test of gravity: E_G

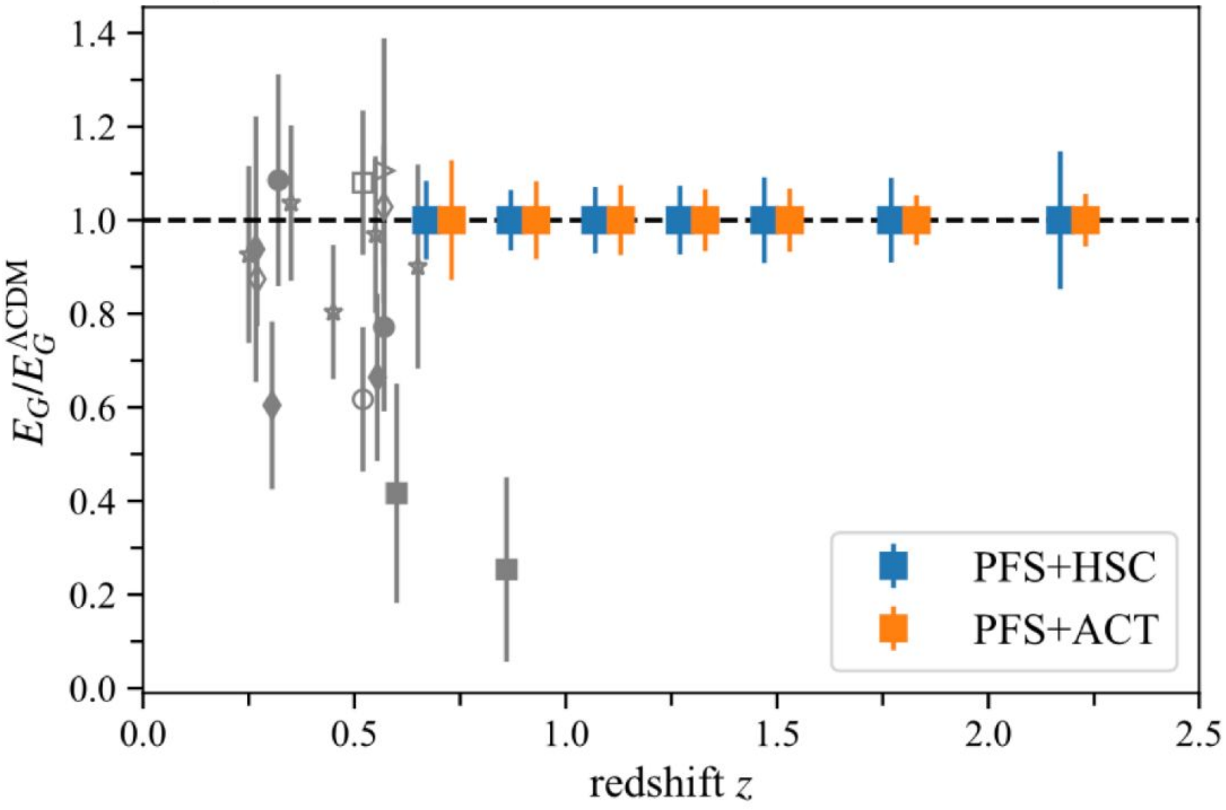
Lensing: how light is bent by gravity

$$E_G(z) = \frac{\nabla^2(\phi - \psi)}{f\delta_m}$$

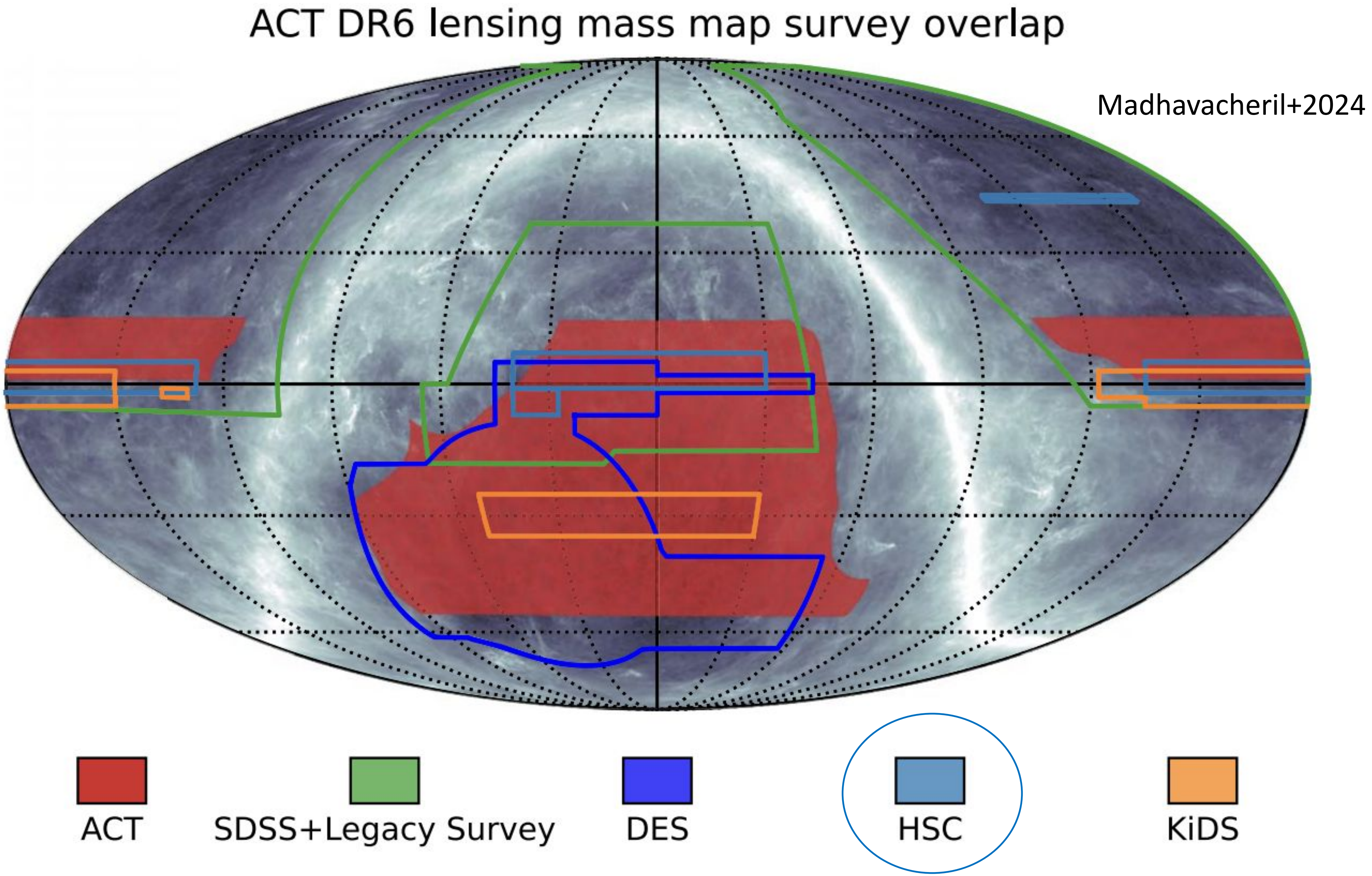
Clustering: how galaxy moves in gravitational potential

See: Zhang et al. (2007), Reyes et al. (2010)

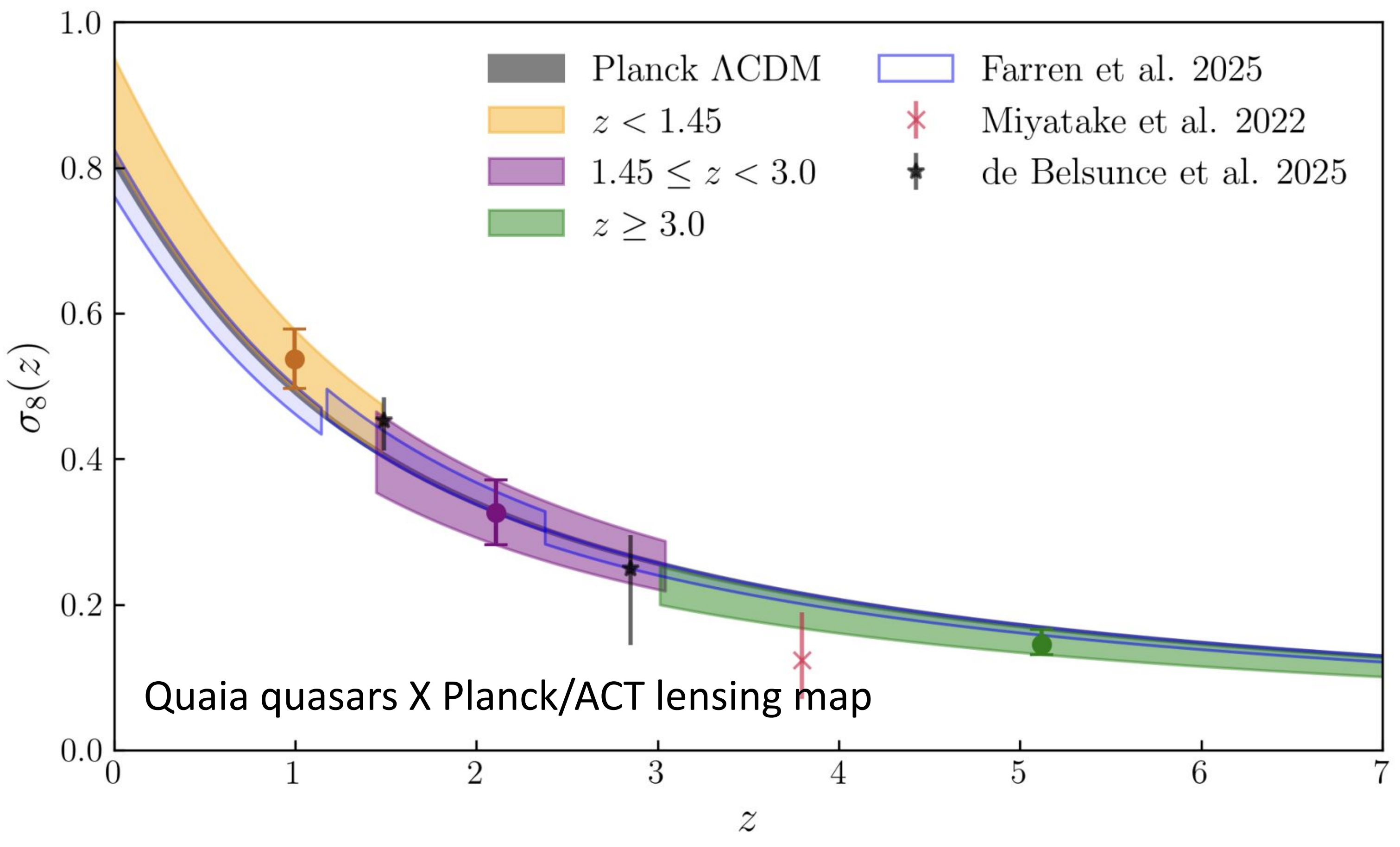
Reyes et al. 2010; Blake et al. 2016; Pullen et al. 2016a; Alam et al. 2017; de la Torre et al. 2017; Amon et al. 2018; Singh et al. 2019; Jullo et al. 2019; Blake et al. 2020



Model-independent test of GR at cosmological scale; free of galaxy bais uncertainty


ACT DR6 lensing mass map survey overlap
Madhavacheril+2024
ACT
SDSS+Legacy Survey
DES
HSC
KiDS

Case 2) z dependent growth from CMB lensing 3x2pt



Embil-Villagra+2025

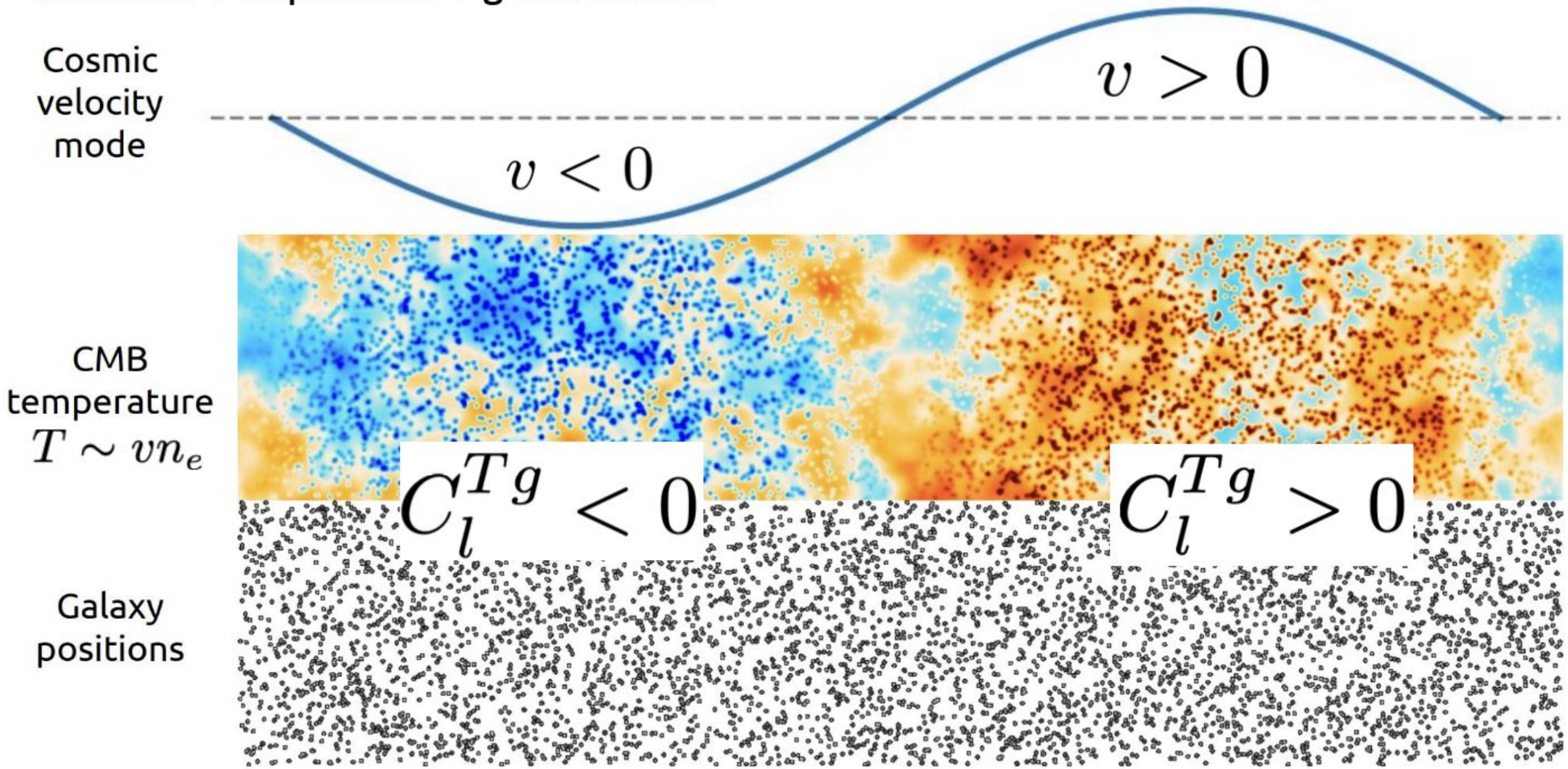
See also Farren+ 2023, 2024; Sailer+2024;

Case 3) kSZ: probe primordial non-Gaussianity

kSZ velocity reconstruction using CMB and galaxy density

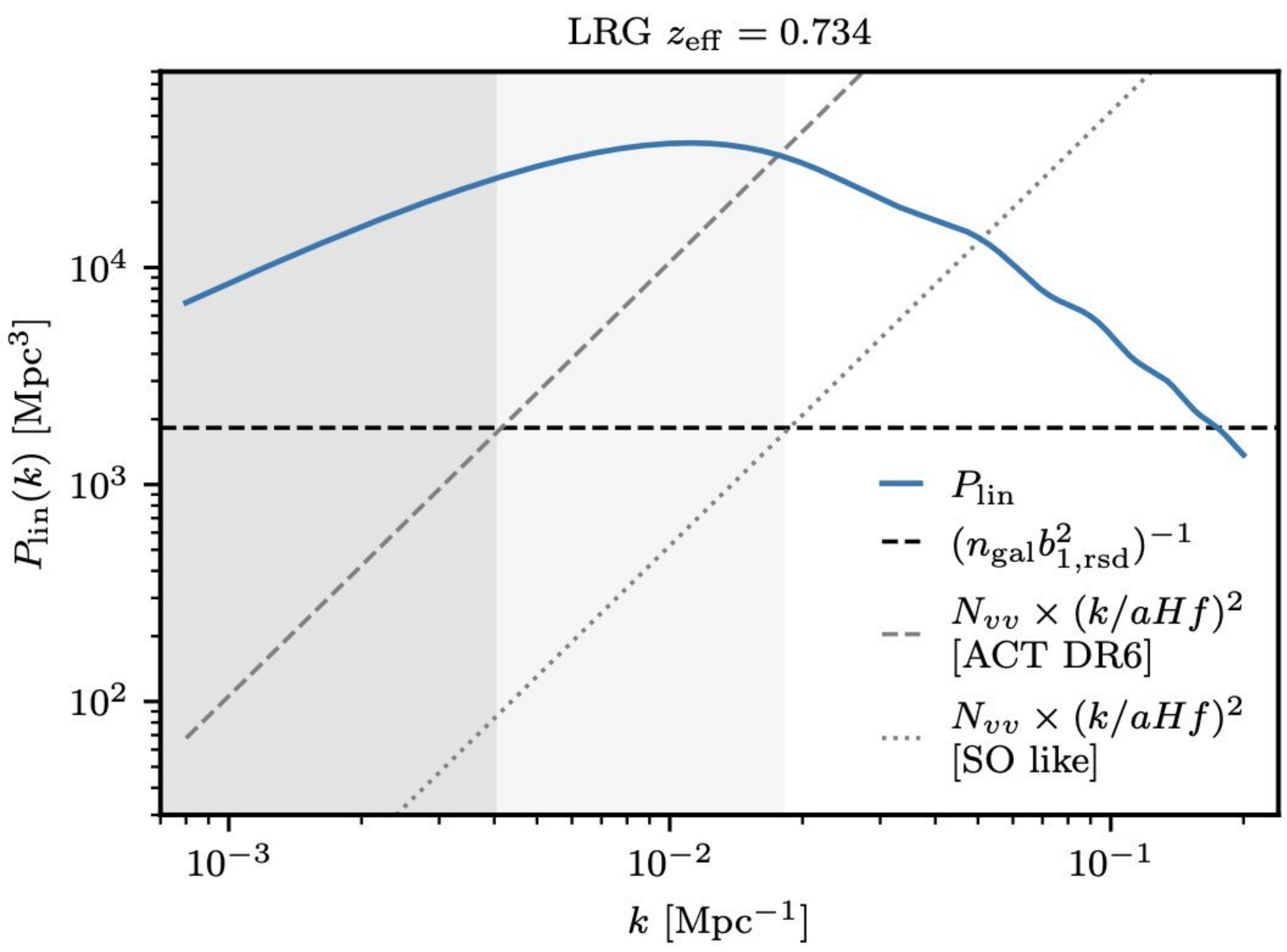
- Reconstruct by measuring v-induced T-g mode coupling
- Intuition: v-dependent T-g correlation

$$\hat{v}(\mathbf{L}) \sim \int dl \; T(\mathbf{l}) g^*(\mathbf{l} - \mathbf{L})$$



Slide credit:
A. Challinor

Case 3) kSZ: probe primordial non-Gaussianity



Edmond Chaussidon+2026, DESI DR2 X ACT DR6s

	~DESI X SO baseline 1	~LSST X CMB S4 baseline 2
survey volume V	100 Gpc^3	100 Gpc^3
central redshift z	1.0	1.0
galaxy density n_g	2×10^{-4} Mpc^{-3}	10^{-2} Mpc^{-3}
halo bias b_h	1.6	1.6
photo-z error σ_z	-	0.06
CMB sensitivity	5μK-arcmin	1μK-arcmin
CMB resolution	1.5’	1.5’
$\sigma^{\rm gal}_{f_{NL}}$	6.0	5.3
$\sigma^{\rm kSZ+gal}_{f_{NL}}$	3.3	0.7
$\sigma^{\rm gal}_{f_{NL}}/\sigma^{\rm kSZ+gal}_{f_{NL}}$	1.8	7.8

Muenchmeyer++ 2018

P_gv + P_gg provides an even tighter constraints, because of the sample variance cancellation.

Summary

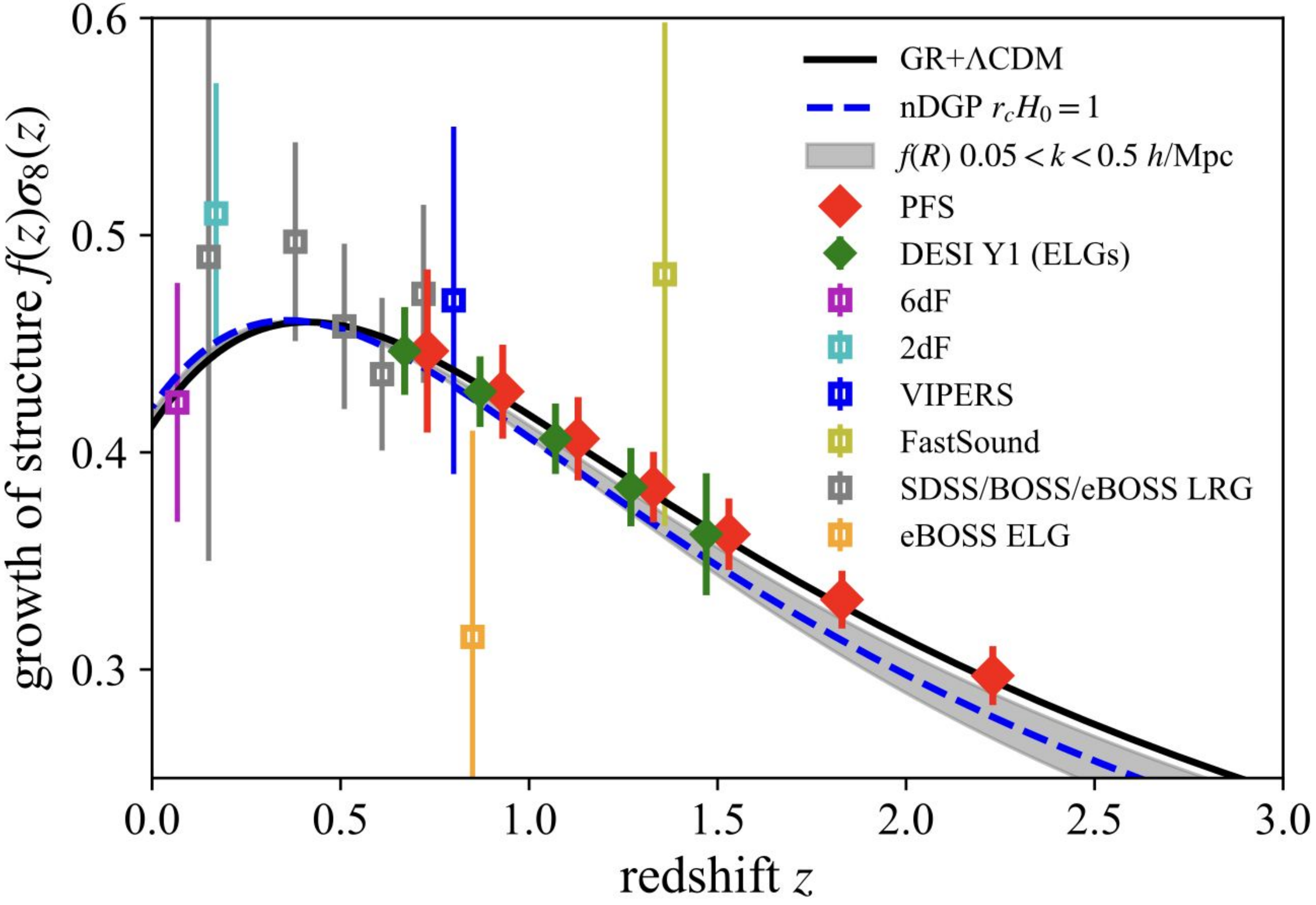
1. LSS spectroscopic surveys provide a powerful probe of DE, growth rate, neutrino mass and PNG.

2. DESI hints a dynamical dark energy, however, the BAO x CMB tension should not be ignored.

3. PFS delivers the independent measurement of expansion and growth of the late time Universe over wide redshift range ($0.6<z<2.4$) and probes much smaller scales.

4. CMB × LSS — especially lensing cross-correlation, and tomographic kSZ provides a bias-clean, systematics-robust way to constrain gravity, structure growth, and inflation.

Thanks!



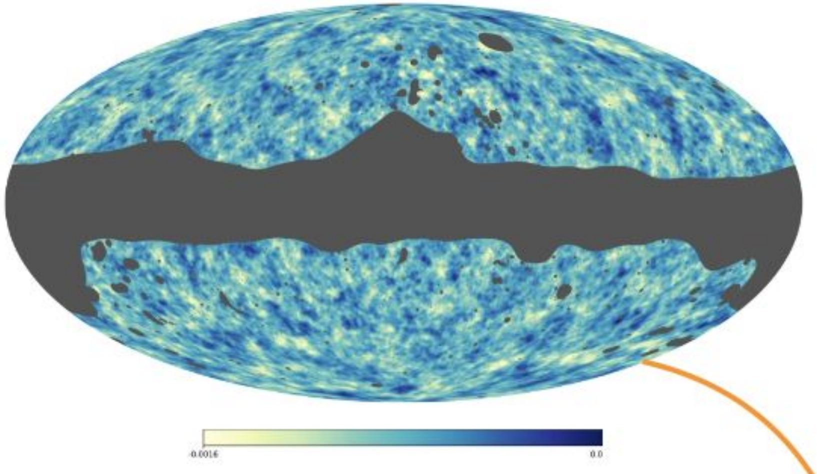
0.6
0.5
0.4
0.3
growth of structure $f(z)\sigma_8(z)$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
redshift z
GR+ΛCDM
nDGP $r_c H_0 = 1$
$f(R)$ $0.05 < k < 0.5$ h/Mpc
PFS
DESI Y1 (ELGs)
6dF
2dF
VIPERS
FastSound
SDSS/BOSS/eBOSS LRG
eBOSS ELG

Secondary	Coupling	Variables	BB?	T or Pol	Detectability	Cosmo info
Linear ISW	G_N	$\dot{\Phi}$	Y	T	Planck x LSS	DE, MG, IN
Nonlinear ISW (RS & Moving Lens)	G_N	$\dot{\Phi},\ \mathbf{v}_\perp,\ \nabla_\perp\Phi$	Y	T	SO x LSS	DE, MG, DM
Weak Lensing	G_N	$\nabla_\perp\Phi,\ \nabla_\perp T$	Y	T & Pol	Planck	NU, DM
tSZ	α	$T_e,\ n_e$	N	T	Planck	B
kSZ	α	$v_\parallel, \Phi, \dot{\Phi}, n_e$	Y	T	ACT/SPT-SO (x LSS)	B, DE, MG, DM, NU, IN, RI
tkSZ	α	$v_\parallel, \Phi, \dot{\Phi}, n_e, T_e$	N	T	SO-S4 x LSS	B, DE, MG, DM, IN, RI
Patchy Screening	α	n_e, T	Y	T & Pol	ACT x LSS	B, RI
pSZ	α	$q^{E,B}, n_e$	Y	Pol	SO-S4 x LSS	B, DE, MG, IN, BSM, RI
kpSZ	α	$\mathbf{v}_\perp, n_e$	N	Pol	SO-S4 x LSS	B, BSM, DE, MG, RI
Dark photon screening	$\frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu}$	n_e	N	T & Pol	Planck x LSS	BSM, DM
Axion screening	$\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$	$n_e, \mathbf{B}$	N	T & Pol	Planck x LSS	BSM, DM
Rolling birefringence	$\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$	ρ_{DE}, E, B	Y	Pol	Planck	BSM, DE
Oscillating birefringence	$\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$	ρ_{DM}, E, B	Y	Pol	ACT-SO-S4	BSM, DM
Cosmic strings	μ or $\mathcal{A}\alpha$	E, B	Y	Pol	Planck	BSM, DE, DM, IN

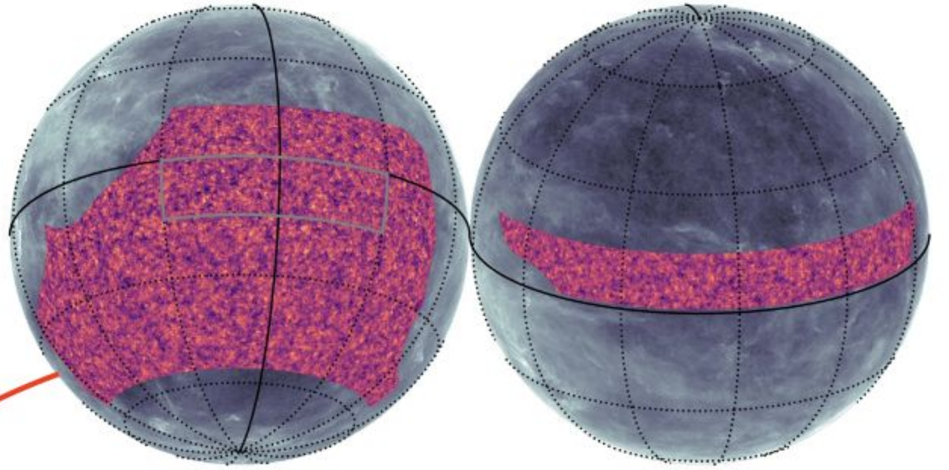
Slide credit:
Selim Hotinli
Matthew Johnson
Sophia Singh
KITP, CMBxLSS, 2026

DE - Dark Energy
MG - Modified GR
IN - INitial conditions
DM - Dark Matter
Nu - Neutrinos
B - Baryonic physics
RI - ReIonization
BSM - Beyond-SM

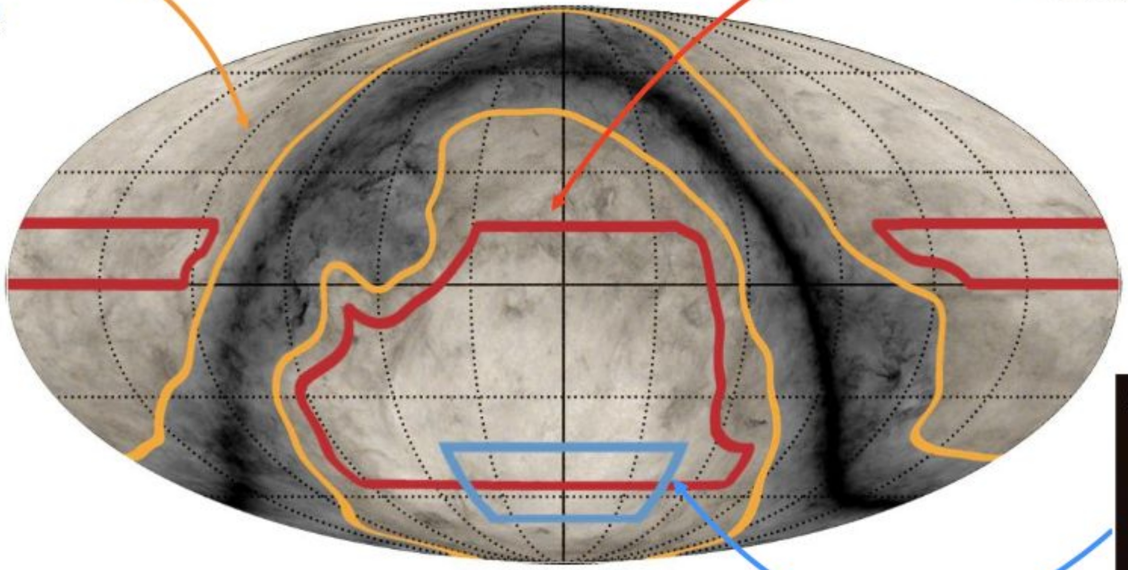
Reconstructed CMB lensing maps

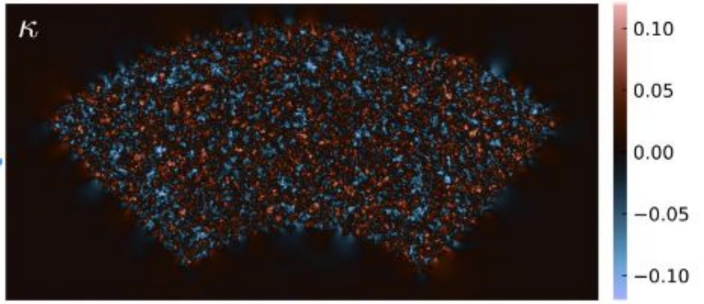


Planck 2018



ACT – Madhavacheril+ 2024





SPT-3G – Ge+ 2024

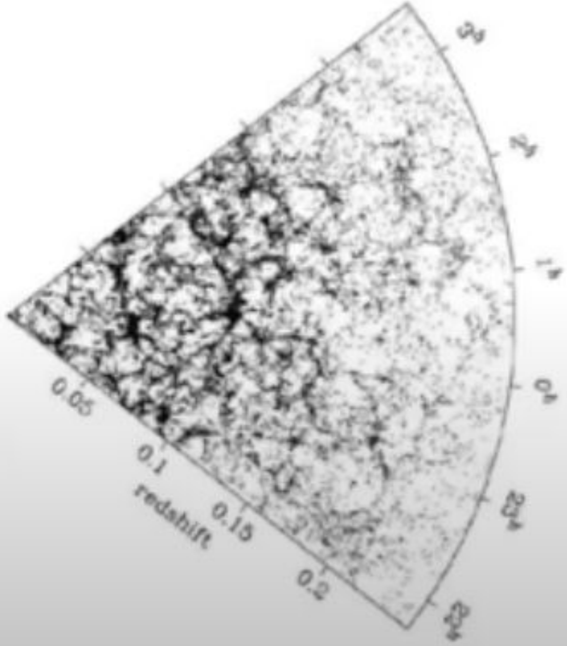
A quadratic estimator for kSZ: "velocity reconstruction"

Suppose we observe two fields: the CMB $T(\mathbf{l})$ and a 3-d galaxy field $\delta_g(\mathbf{k})$.

$$\big(\text{kSZ velocity reconstruction estimator } \hat{v}_r(\mathbf{k}_L)\big)$$
$$= \big(\text{a noisy reconstruction of the large-scale 3-d radial velocity field } v_r(\mathbf{k}_L)\big)$$

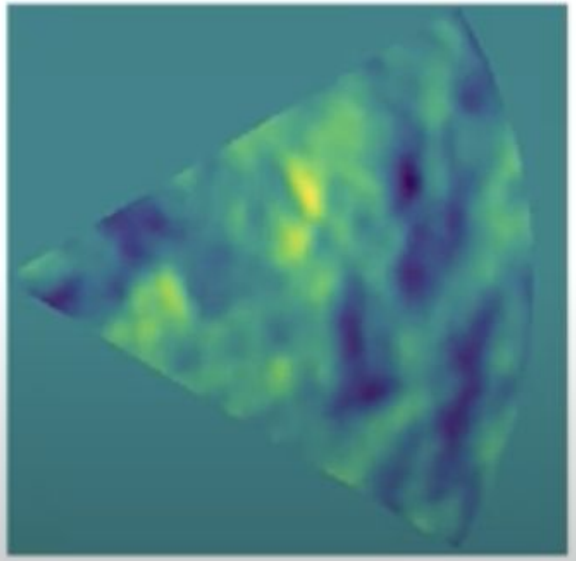
CMB temperature $T(\mathbf{l})$

+



Galaxy survey with redshifts

Velocity reconstruction estimator $\hat{v}_r(\mathbf{k})$ $\longrightarrow$



Noisy reconstruction $\hat{v}_r(\mathbf{k}_L)$ of large-scale **radial** velocities

Goal of talk: explain this picture

"Landscape" of kSZ statistics

$\langle Tgg \rangle$ type

Reconstructs modes on largest cosmological scales. One application: f_{NL}.

Also measures galaxy-electron power spectrum $P_{ge}(k, z)$.

$\langle TTg \rangle$ type

Measures small-scale modes (astrophysics, neutrino mass).

$\langle T^4 \rangle$ type

Can constrain reionization.

$\langle T^2 g^2 \rangle$ type

Can measure total electron power spectrum $P_{ee}(k, z)$

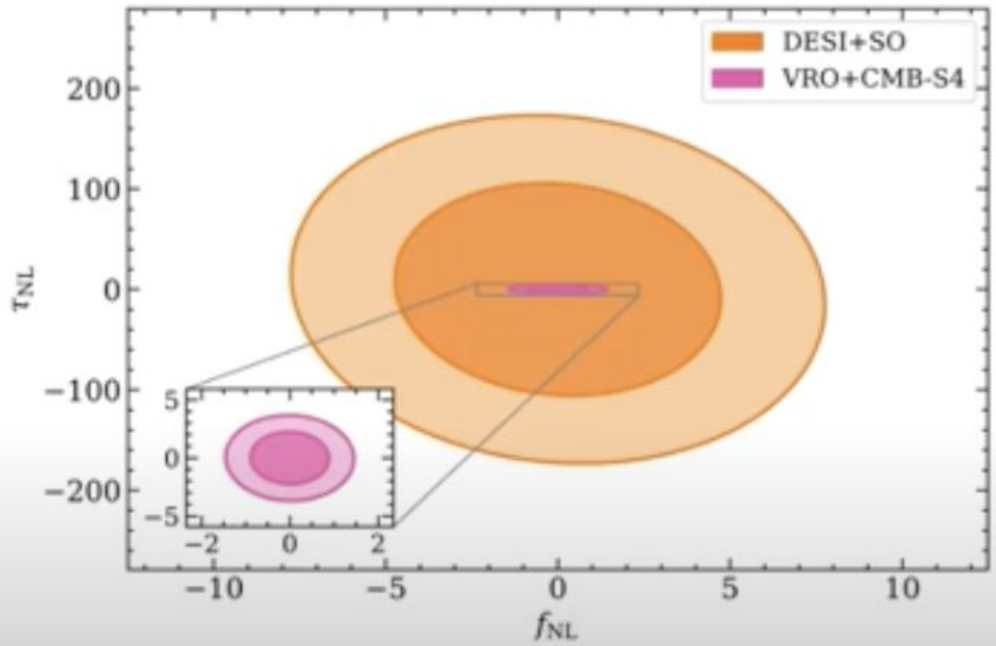
Primordial non-Gaussianity forecasts

"Baseline 1" (~DESI x SO): $\sigma(f_{NL}) = 3.3$

"Baseline 2" (~LSST x CMB-S4): $\sigma(f_{NL}) = 0.7$

	baseline 1	baseline 2
survey volume V	100 Gpc^3	100 Gpc^3
central redshift z	1.0	1.0
galaxy density n_g	$2 \times 10^{-4}\ \mathrm{Mpc}^{-3}$	$10^{-2}\ \mathrm{Mpc}^{-3}$
halo bias b_h	1.6	1.6
photo-z error σ_z	-	0.06
CMB sensitivity	5μK-arcmin	1μK-arcmin
CMB resolution	1.5'	1.5'
$\sigma_{f_{NL}}^{\mathrm{gal}}$	6.0	5.3
$\sigma_{f_{NL}}^{\mathrm{kSZ+gal}}$	3.3	0.7
$\sigma_{f_{NL}}^{\mathrm{gal}} / \sigma_{f_{NL}}^{\mathrm{kSZ+gal}}$	1.8	7.8

	$\sigma(f_{NL})$	$\sigma(\tau_{NL})$
Forecasted (DESI x SO)	3.1	69
Forecasted (VRO x CMB-S4)	0.59	1.5
Current Planck constraint	5.1	6.5×10^4



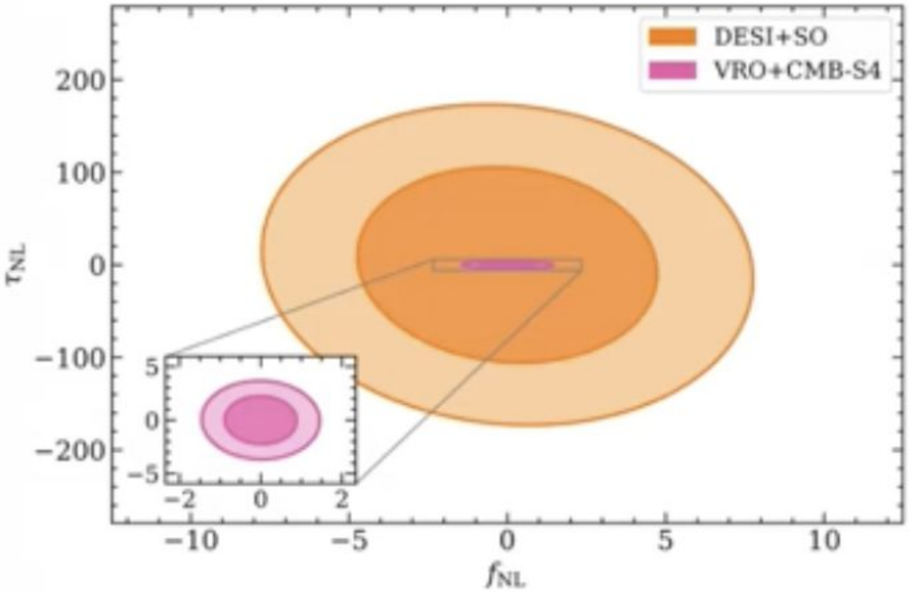
Münchmeyer, Madhavacheril, Ferraro, Johnson, Smith 1810.13424

Anil Kumar, Sato-Polito, Kamionkowski, Hotinli, 2205.03423

Some qualitative differences between $\langle Tgg \rangle$ and $\langle TTg \rangle$

$\langle Tgg \rangle$ ("kSZ tomography")

Constrains "large scale" cosmology (e.g. f_{NL}) + astrophysics



Anil Kumar, Sato-Polito, Kamionkowski, Hotinli (2205.03423)

$\langle TTg \rangle$ ("projected fields")

Constrains "small scale" cosmology (e.g. m_ν) + astrophysics

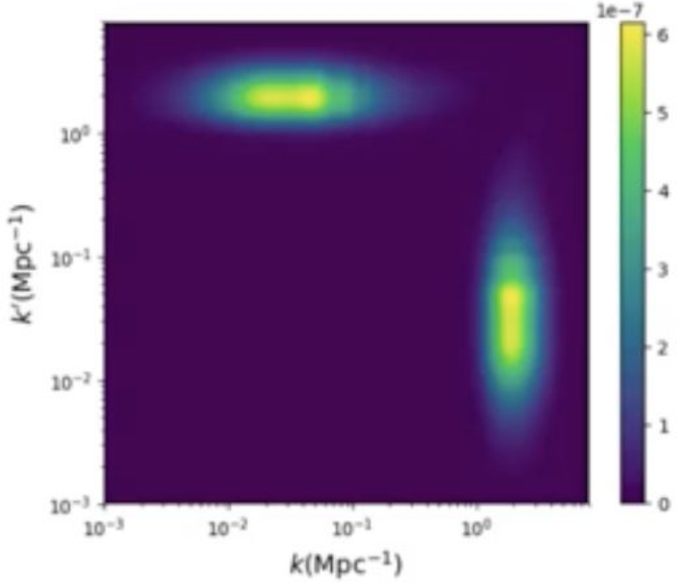
Parameter	1σ errors on parameters		
	Planck prior	CMB-S4(Det)×WISE kSZ-only	CMB-S4(Det)×WISE kSZ + *Planck*
H_0 [km/s/Mpc]	0.57	3.20	0.34
$\Omega_b h^2$	0.00013	0.00430	0.00010
$\Omega_c h^2$	0.0013	0.0131	0.0008
$10^9 A_s$	0.031	0.366	0.023
n_s	0.003	0.030	0.003
Σm_ν [meV]	-	136	38
A_{kSZ^2}	-	0.411	0.025
b_g	-	0.011	0.007

Patki, Battaglia, Ferraro (2306.03127)

Some qualitative differences between $\langle Tgg \rangle$ and $\langle TTg \rangle$

$\langle Tgg \rangle$ ("kSZ tomography")

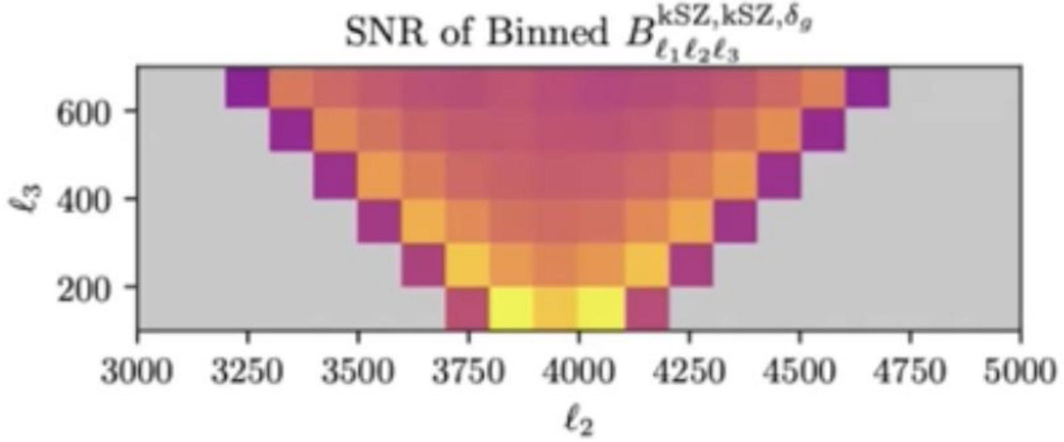
Dominated by squeezed limit



Smith, Madhavacheril, Münchmeyer, Ferraro, Giri, Johnson (1810.13423)

$\langle TTg \rangle$ ("projected fields")

Signal comes from all scales



Patki, Battaglia, Hill (2411.11974)

Some qualitative differences between $\langle Tgg \rangle$ and $\langle TTg \rangle$

$\langle Tgg \rangle$ ("kSZ tomography")	$\langle TTg \rangle$ ("projected fields")
Dominated by squeezed limit	Signal comes from all scales
Constrains "large scale" cosmology (e.g. f_{NL}) + astrophysics	Constrains "small scale" cosmology (e.g. m_ν) + astrophysics
Bispectrum has simple form $\propto P_{gv}(k_L) P_{ge}(k_S)$	Bispectrum is a heroic halo model calculation
Symmetry-protected from foreground/lensing biases	Relies on modelling to mitigate foreground/lensing biases