Title: The S8 tension in cosmology

Speakers: Mike Hudson

Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

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Abstract: In addition to the now-well known "Hubble tension", in recent years a second tension has emerged: the S_8 tension. This is a measure of the homogeneity of the Universe. Specifically, S_8 is defined as $(\Omega_{\mathrm matter}/0.3)^{0.5} \sigma_8$ where σ_8 is the standard deviation of the density fluctuation in an 8 h^{-1} Mpc radius sphere. As with the Hubble tension, there is disagreement, at greater than 4 σ significance between what is predicted by extrapolating the fluctuations in the Cosmic Microwave Background forward to the present day, and what is measured by multiple probes of the inhomogeneity in the nearby Universe. I will discuss the diverse lines of evidence for the tension, showing it is not restricted to one probe, but is seen in weak gravitational lensing, peculiar velocities and redshift-space distortions and cluster abundances. I will conclude by discussing prospects for future measurements.

Zoom Link: https://pitp.zoom.us/j/99946149565?pwd=M2puMy9nSEtBZTg1MnRmSllHeUE0UT09

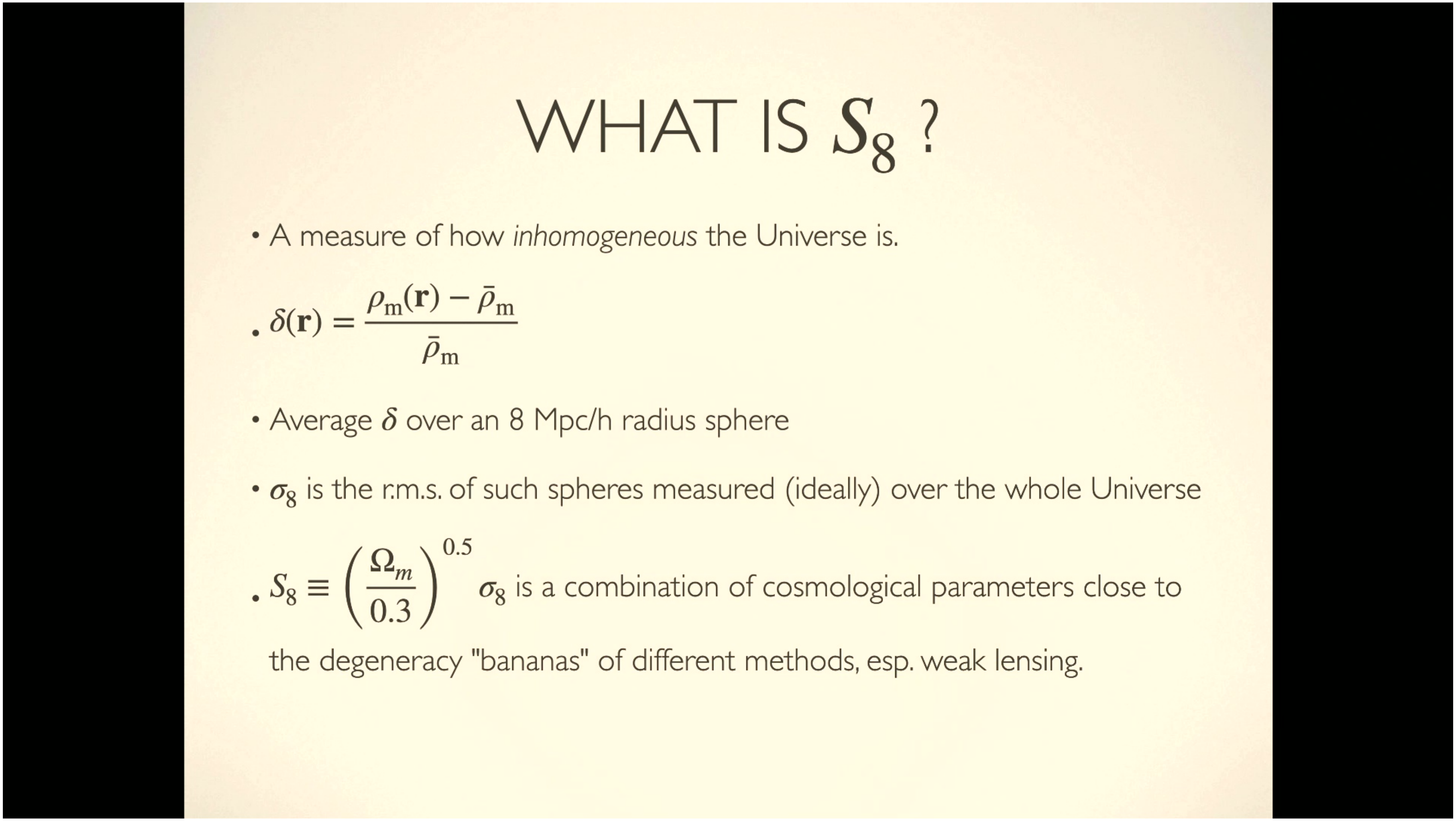
THE S_8 TENSION

MIKE HUDSON

UNIVERSITY OF WATERLOO | WATERLOO CENTRE FOR ASTROPHYSICS

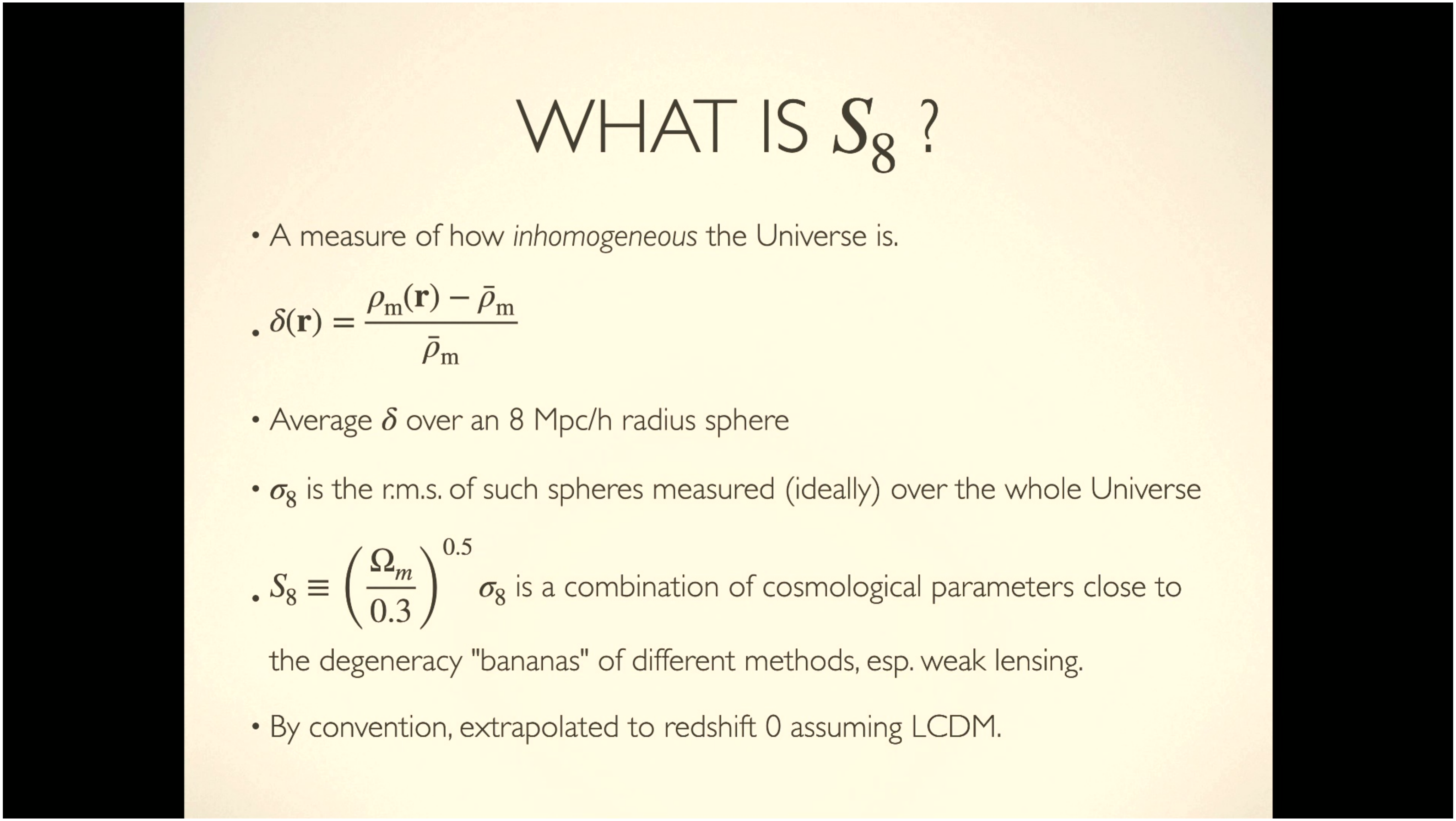
OUTLINE

- What is S_8 ?
- Ways to measure S_8
    - CMB
    - Weak lensing
    - Peculiar velocities and redshift-space distortions
    - Cluster abundances
- Solutions?



WHAT IS S_8 ?

- A measure of how *inhomogeneous* the Universe is.
- $\delta(\mathbf{r}) = \dfrac{\rho_{\rm m}(\mathbf{r}) - \bar{\rho}_{\rm m}}{\bar{\rho}_{\rm m}}$
- Average δ over an 8 Mpc/h radius sphere
- σ_8 is the r.m.s. of such spheres measured (ideally) over the whole Universe
- $S_8 \equiv \left(\dfrac{\Omega_m}{0.3}\right)^{0.5} \sigma_8$ is a combination of cosmological parameters close to the degeneracy "bananas" of different methods, esp. weak lensing.



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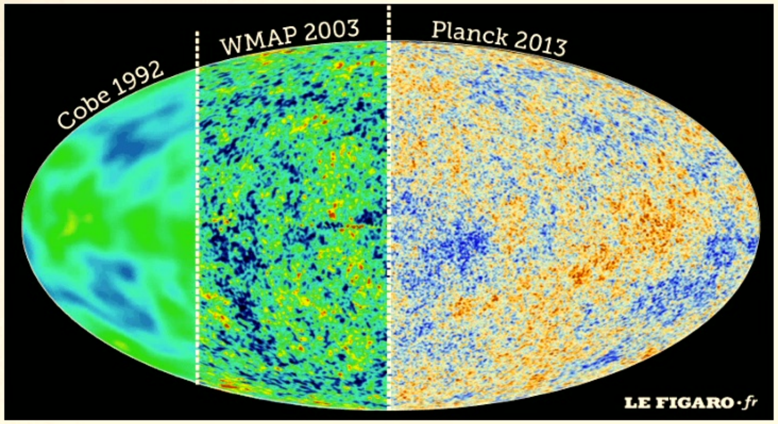
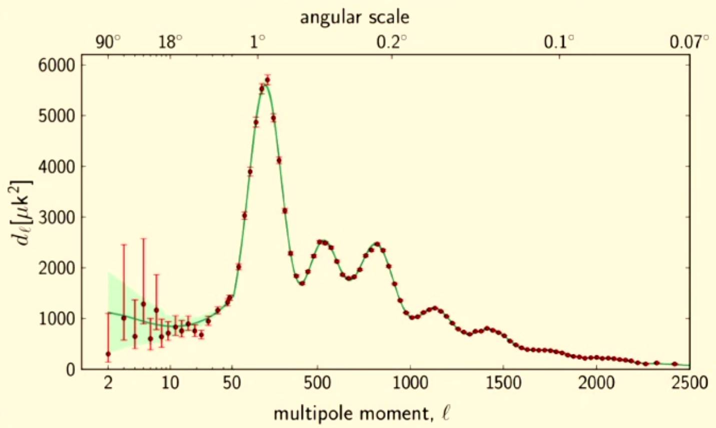
- By convention, extrapolated to redshift 0 assuming LCDM.

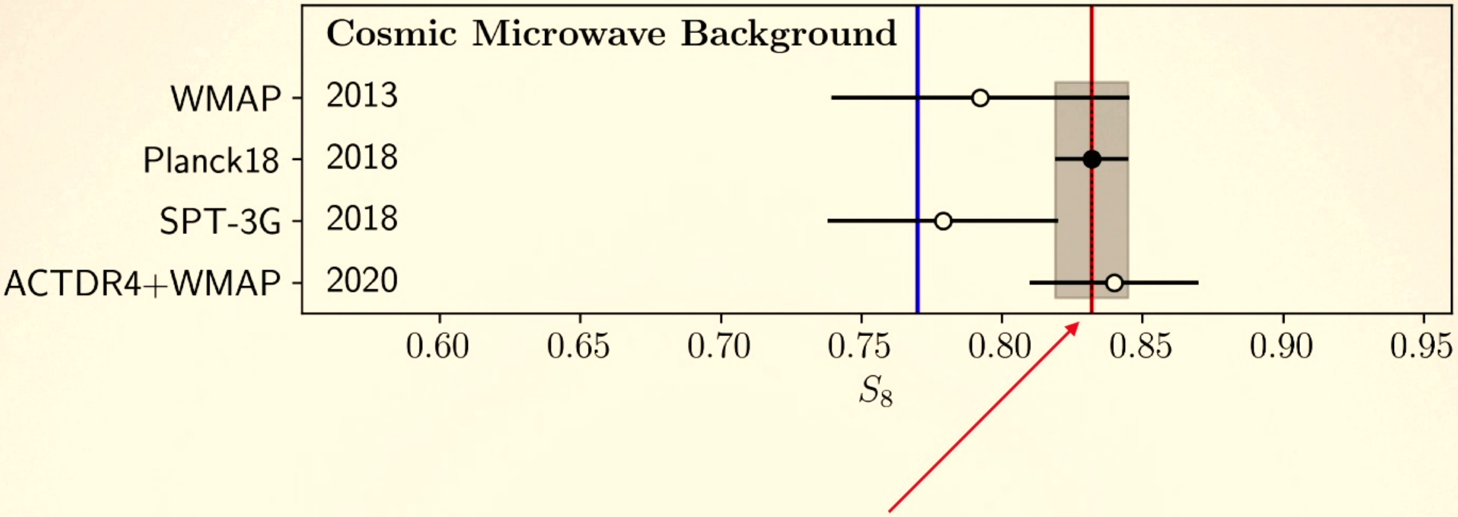
CMB





Fit the cosmological parameters at $z \sim 1100$
extrapolate to $z \sim 0$ assuming LCDM and linear perturbation theory

CMB



Not just Planck

COSMIC SHEAR

Correlations between the shapes of background galaxies (that are close to each other on the sky) due to foreground mass

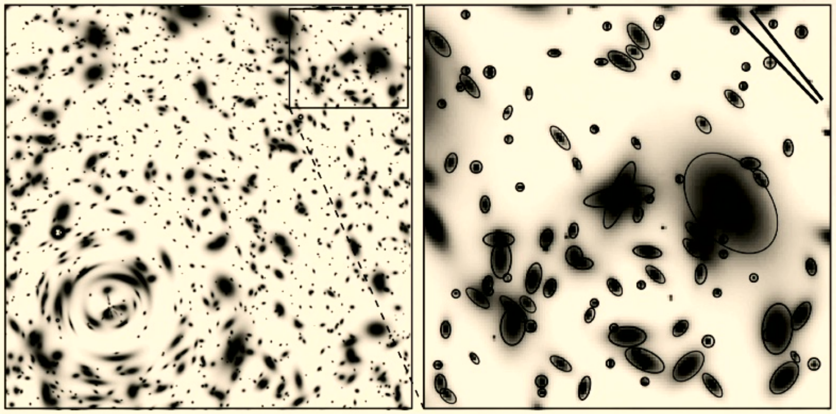
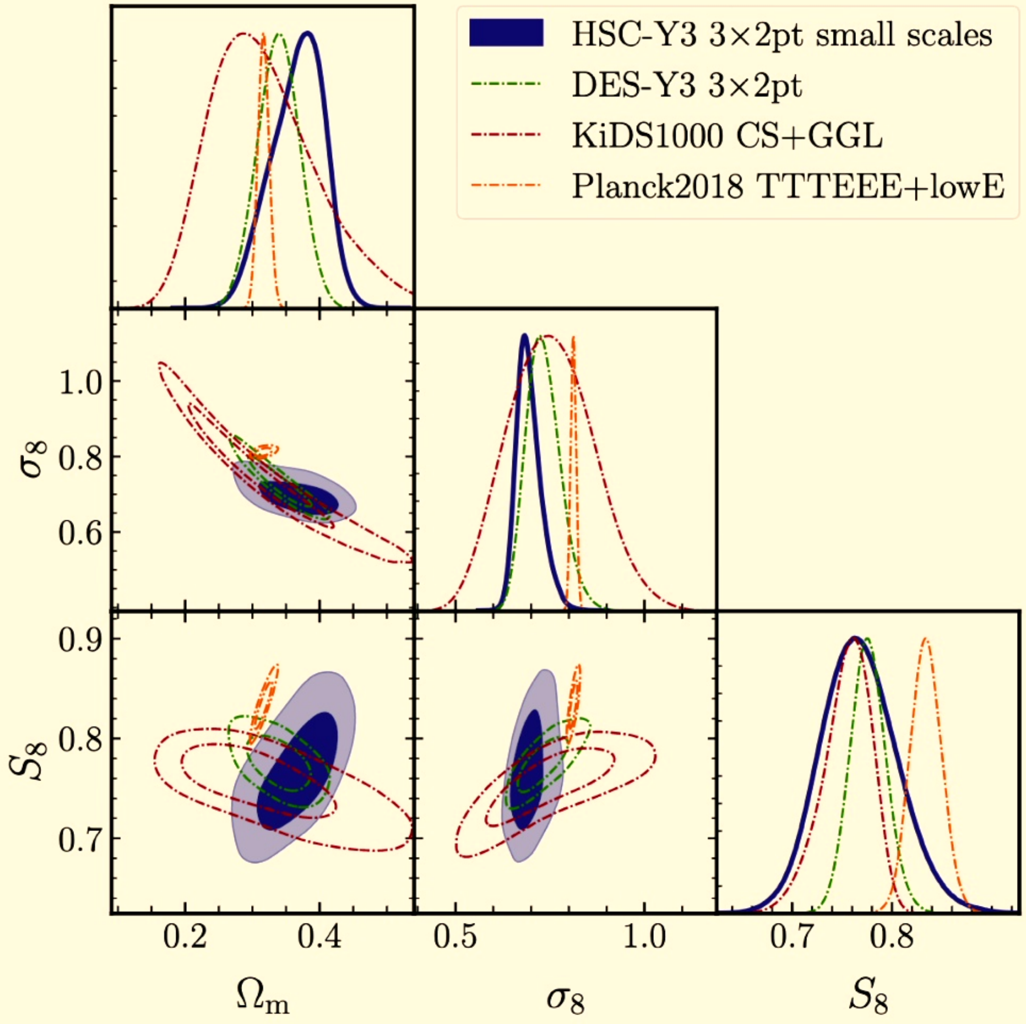


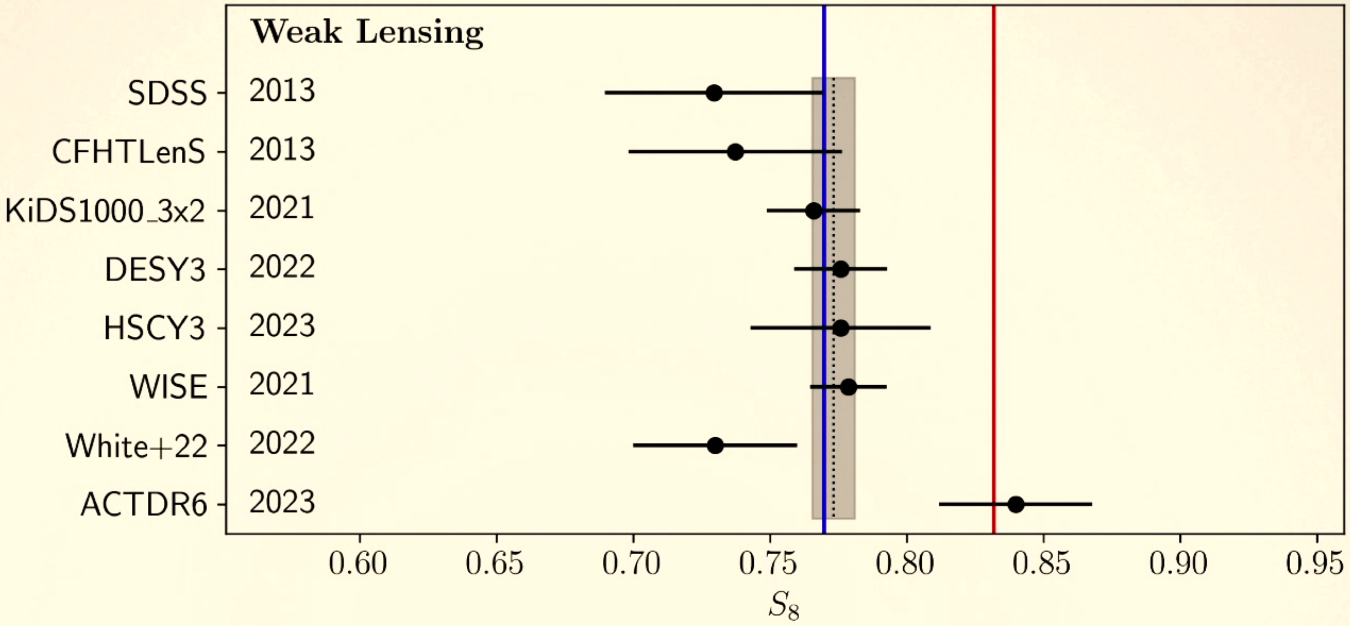
Image credit: Mellier 99

Technically challenging:

cosmic shear distortion ~ 0.001
atmospheric distortion ~ 0.1

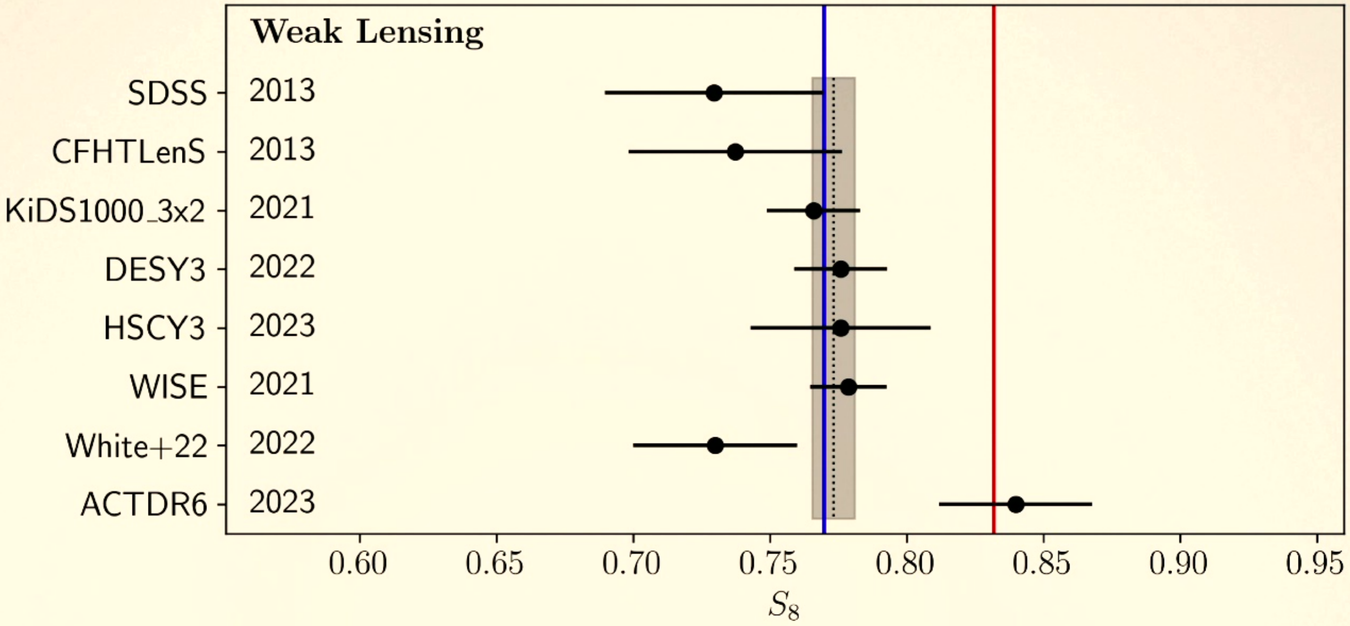

HSC-Y3 3×2pt small scales
DES-Y3 3×2pt
KiDS1000 CS+GGL
Planck2018 TTTEEE+lowE
σ_8
1.0
0.8
0.6
S_8
0.9
0.8
0.7
0.2
0.4
Ω_m
0.5
1.0
σ_8
0.7
0.8
S_8

Weak lensing S_8 measurements since 2010

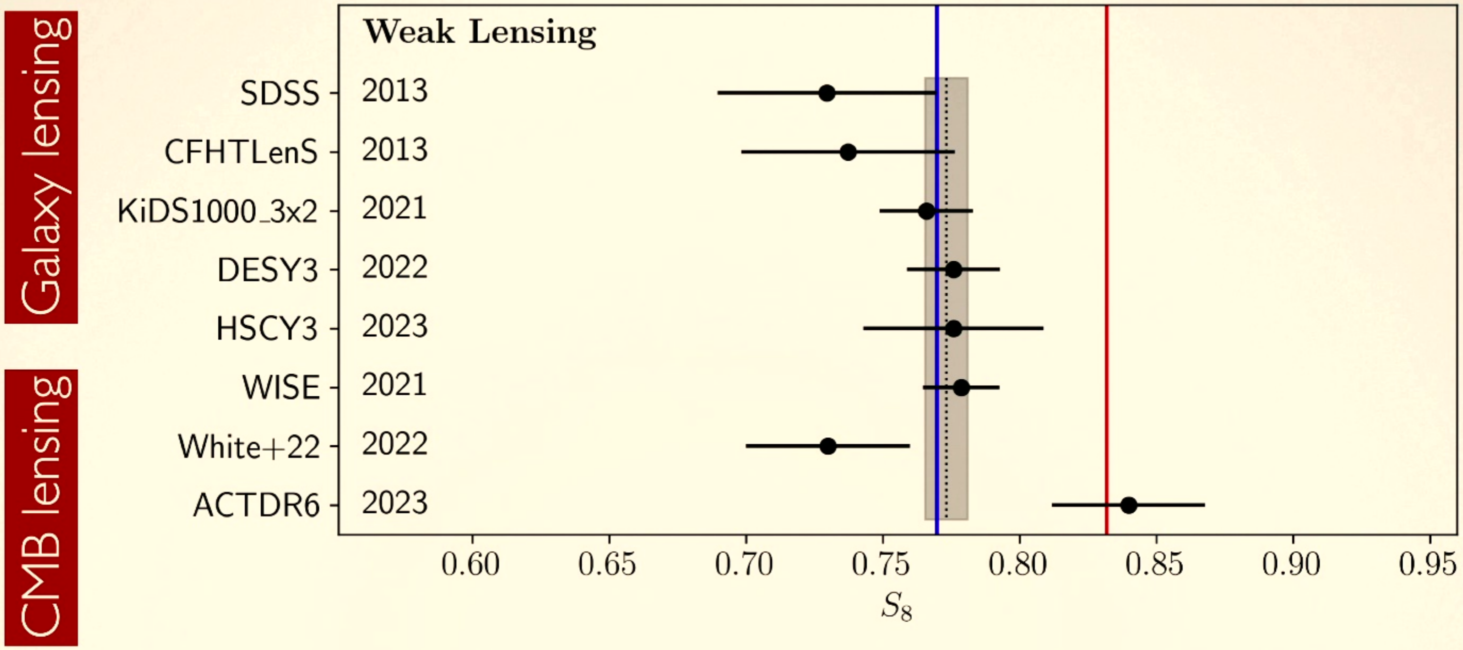


Weak lensing S_8 measurements since 2010

Galaxy lensing



Weak lensing S_8 measurements since 2010



OUTLINE

- What is S_8 ?
- Ways to measure S_8
  - CMB
  - Weak lensing
  - **Peculiar velocities and redshift-space distortions**
  - Cluster abundances
- Solutions?

MEASURING PECULIAR VELOCITIES

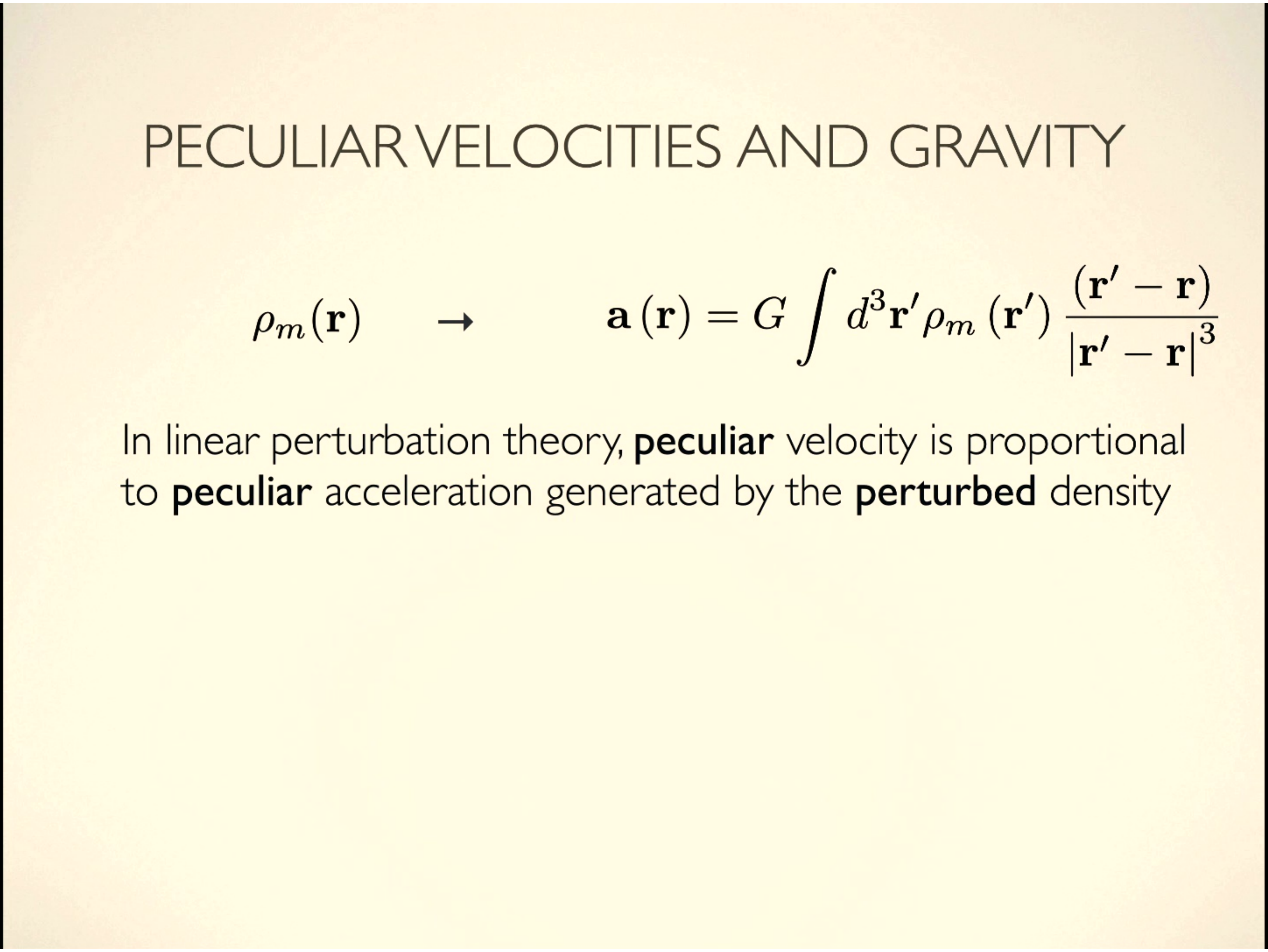
$$v \sim cz - H_0 r$$

1. Direct distance estimates
    - cz is easy to measure
    - $H_0\, r$ is difficult. Need a standard candle or rod:
        - Supernovae (5-10%), Tully-Fisher (20%), Fundamental Plane (20%)

sparse and noisy, only works at low $z \lesssim 0.1$

2. Statistically, via "redshift-space distortions": cosmic variance limited

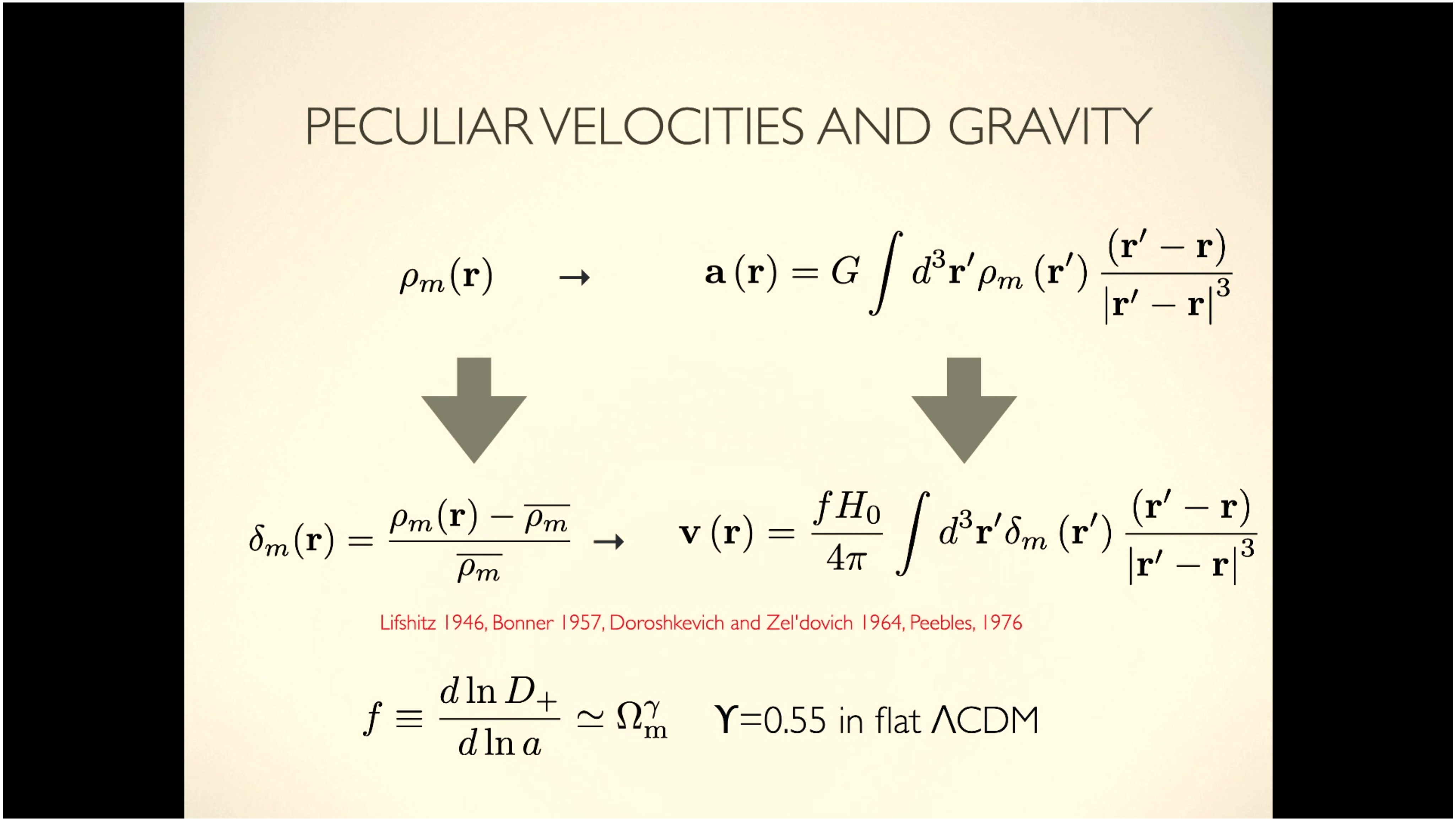
3. Kinetic Sunyaev-Zeldovich effect : very weak signal, but exciting prospects



PECULIAR VELOCITIES AND GRAVITY

$$\rho_m(\mathbf{r}) \quad \rightarrow \quad \mathbf{a}\left(\mathbf{r}\right) = G \int d^3\mathbf{r}' \rho_m\left(\mathbf{r}'\right) \frac{\left(\mathbf{r}' - \mathbf{r}\right)}{\left|\mathbf{r}' - \mathbf{r}\right|^3}$$

In linear perturbation theory, **peculiar** velocity is proportional to **peculiar** acceleration generated by the **perturbed** density



PECULIAR VELOCITIES AND GRAVITY

$$\begin{tikzcd}
\rho_m(\mathbf{r}) \arrow[r] \arrow[d] & \mathbf{a}\left(\mathbf{r}\right) = G\int d^3\mathbf{r}'\rho_m\left(\mathbf{r}'\right)\frac{\left(\mathbf{r}'-\mathbf{r}\right)}{\left|\mathbf{r}'-\mathbf{r}\right|^3} \arrow[d] \\
\delta_m(\mathbf{r}) = \frac{\rho_m(\mathbf{r}) - \overline{\rho_m}}{\overline{\rho_m}} \arrow[r] & \mathbf{v}\left(\mathbf{r}\right) = \frac{fH_0}{4\pi}\int d^3\mathbf{r}'\delta_m\left(\mathbf{r}'\right)\frac{\left(\mathbf{r}'-\mathbf{r}\right)}{\left|\mathbf{r}'-\mathbf{r}\right|^3}
\end{tikzcd}$$

Lifshitz 1946, Bonner 1957, Doroshkevich and Zel'dovich 1964, Peebles, 1976

$$f \equiv \frac{d\ln D_+}{d\ln a} \simeq \Omega_{\mathrm{m}}^{\gamma}$$ Υ=0.55 in flat ΛCDM

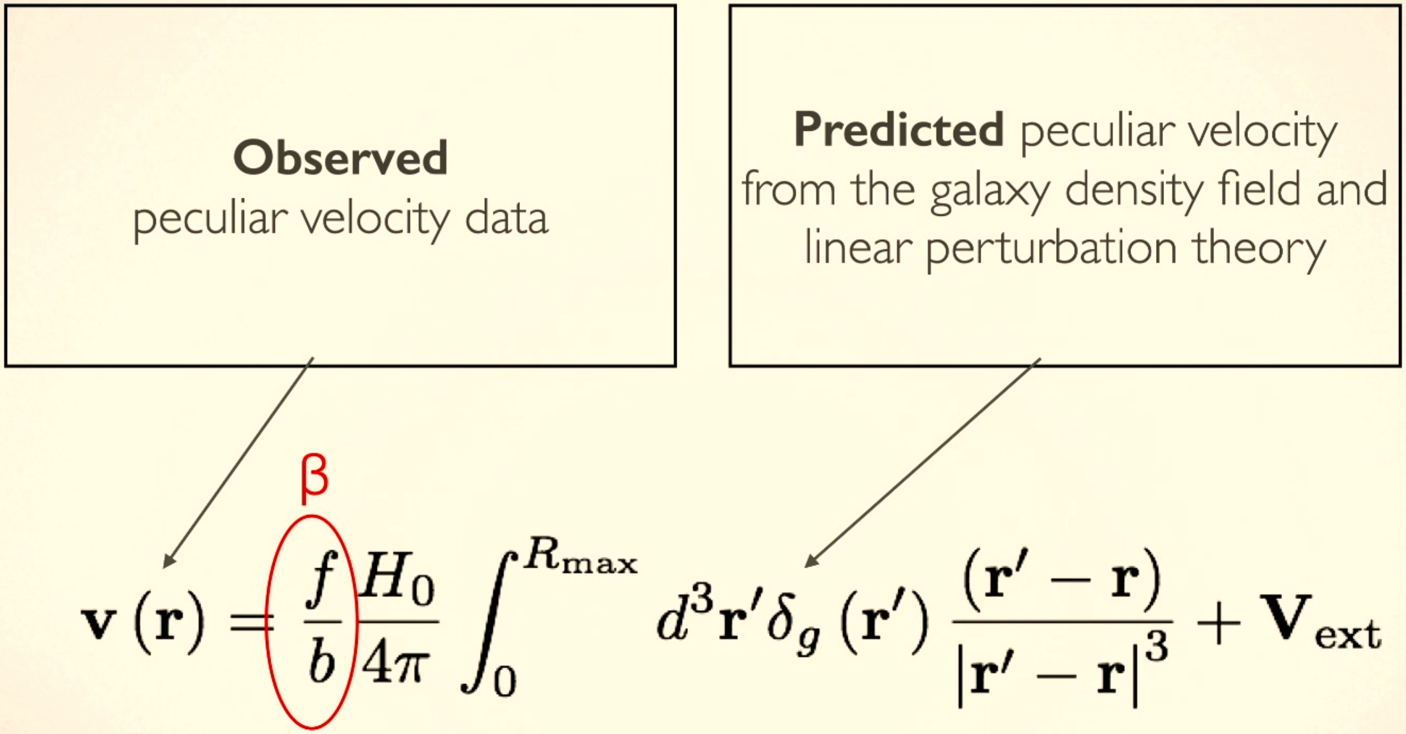
PECULIAR VELOCITIES TEAM

Supranta Boruah
Waterloo → Arizona

Guilhem Lavaux
Paris

Amber Hollinger
Waterloo→Technion

PECULIAR VELOCITY COMPARISONS



Observed
peculiar velocity data

Predicted peculiar velocity from the galaxy density field and linear perturbation theory

$$\mathbf{v}\left(\mathbf{r}\right) = \overset{\beta}{\frac{f}{b}} \frac{H_0}{4\pi} \int_0^{R_{\max}} d^3\mathbf{r}' \delta_g\left(\mathbf{r}'\right) \frac{\left(\mathbf{r}' - \mathbf{r}\right)}{\left|\mathbf{r}' - \mathbf{r}\right|^3} + \mathbf{V}_{\mathrm{ext}}$$

$$v(\boldsymbol{r}) = \overset{\beta}{\boxed{\frac{f(\Omega_m)}{b}}}\frac{H_0}{4\pi}\int_0^{R_{\max}} \delta_g(\boldsymbol{r}')\frac{(\boldsymbol{r}'-\boldsymbol{r})}{|\boldsymbol{r}'-\boldsymbol{r}|^3}d^3\boldsymbol{r}' + \boldsymbol{V}_{\text{ext}}$$

$$\delta_g = b\delta_m$$

$$\sigma_{8,g} = b\sigma_8$$

$$\underset{\downarrow}{\beta}\underset{\downarrow}{\sigma_{8,g}} = \left(\frac{f}{\cancel{b}}\right)\cancel{b}\sigma_8 = f\sigma_8$$

Measurable from fit

Measurable from δ_g

REDSHIFT-SPACE DISTORTIONS

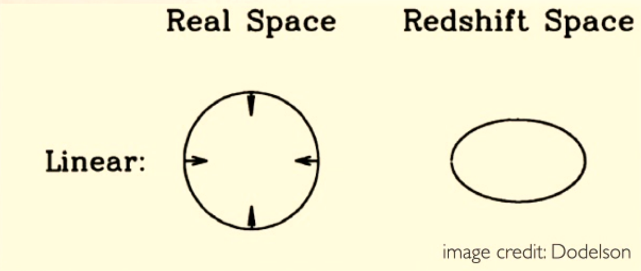
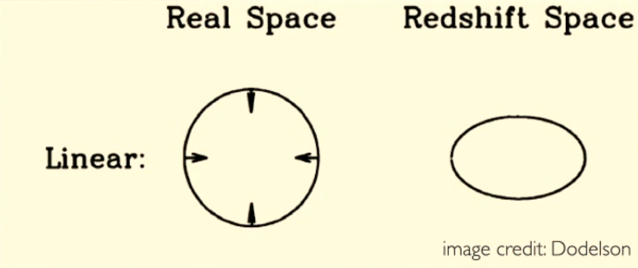


image credit: Dodelson

Kaiser 87

Line of sight

REDSHIFT-SPACE DISTORTIONS



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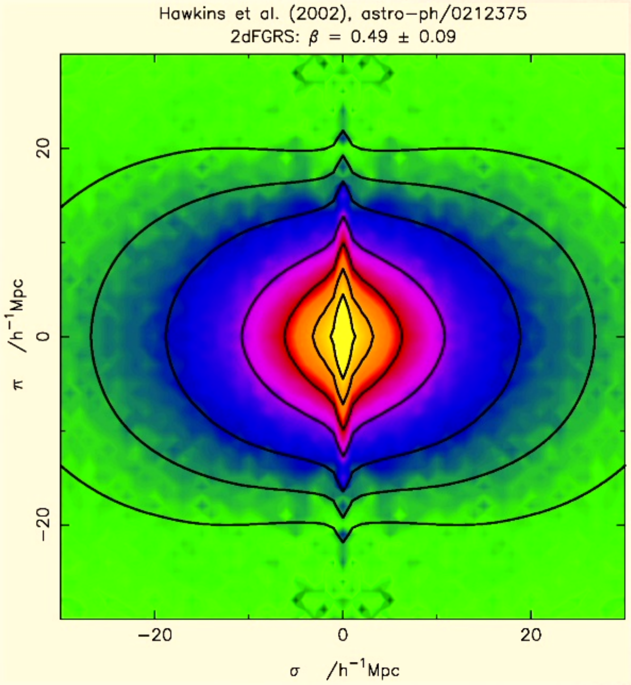
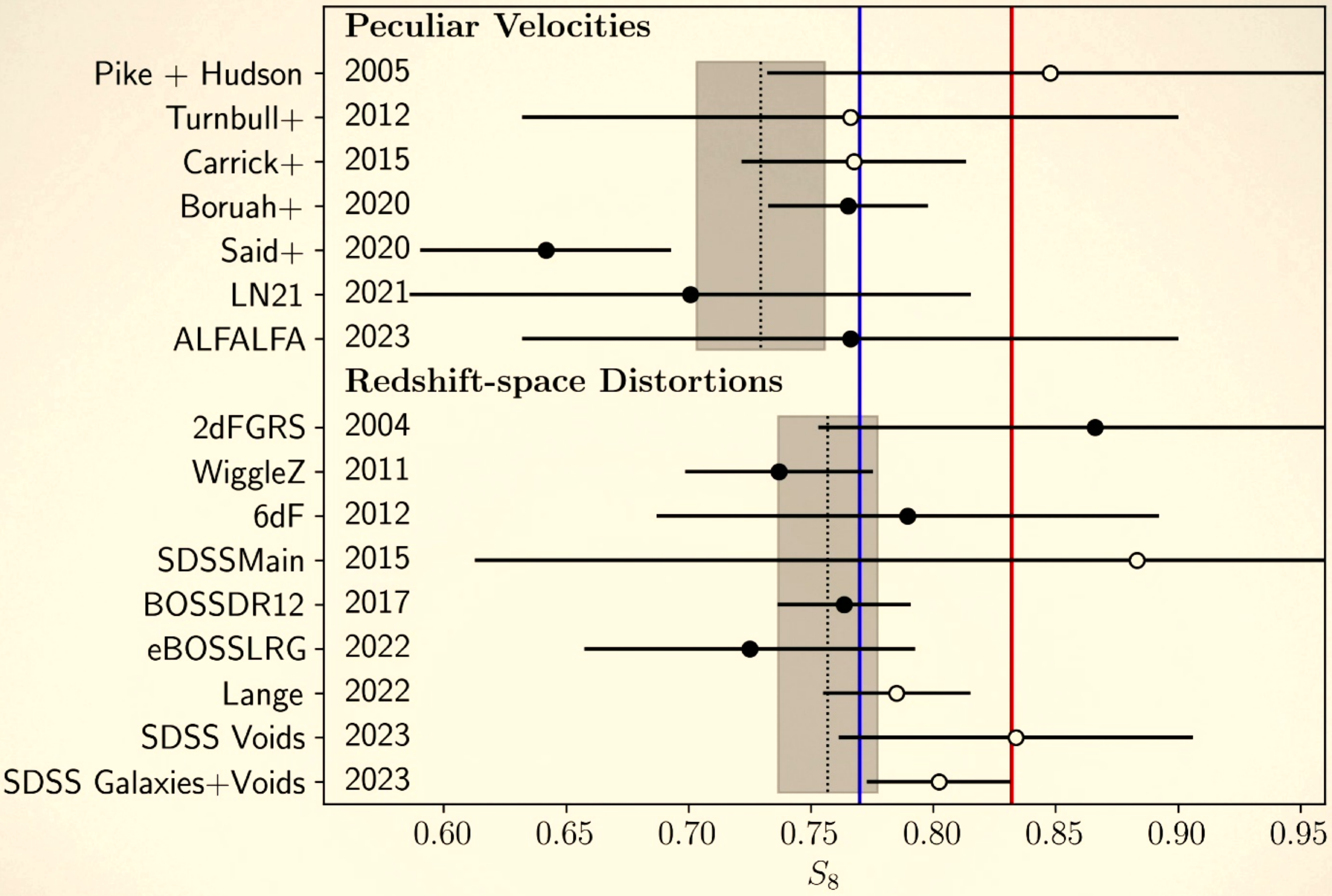
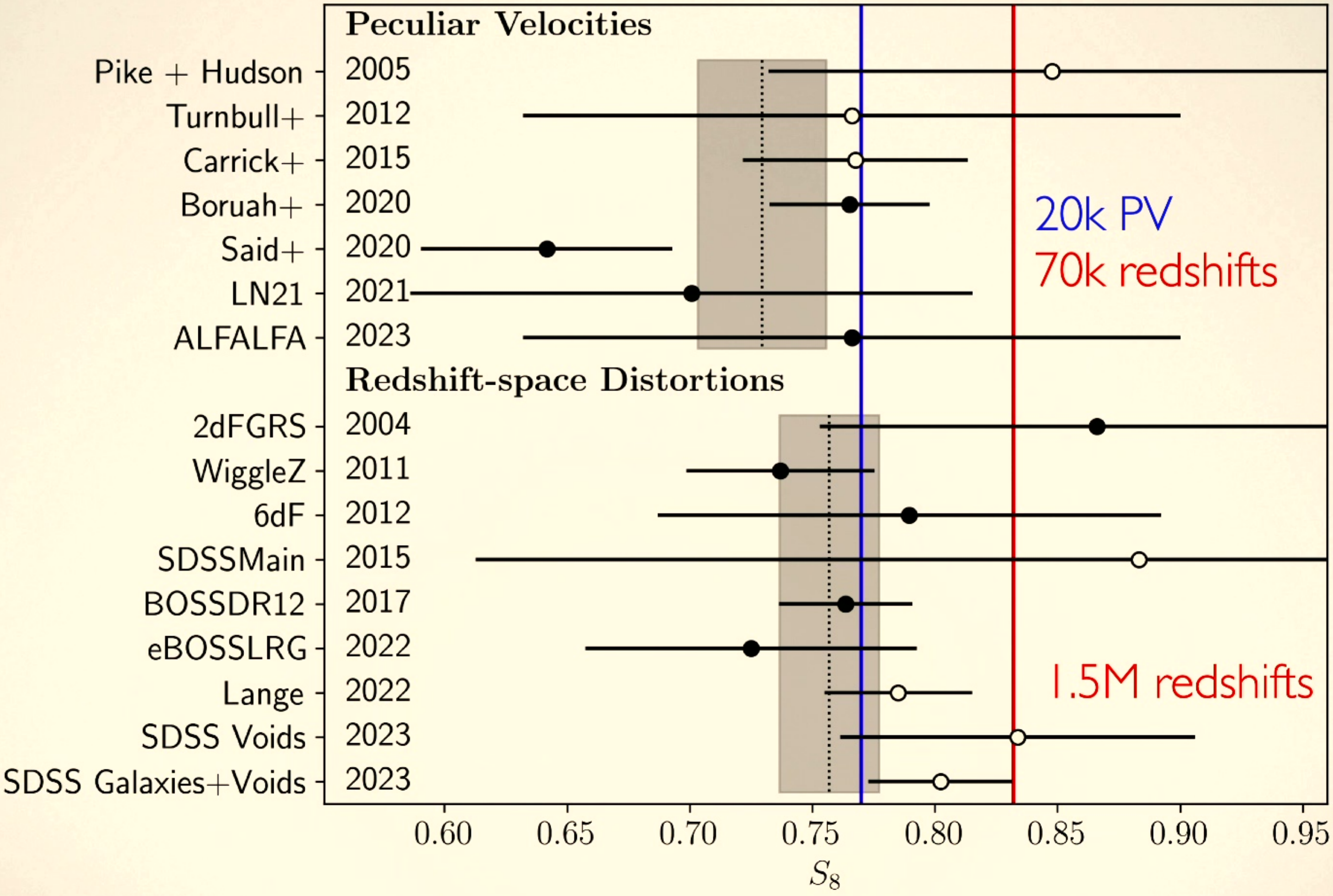



Peculiar Velocities
Pike + Hudson 2005
Turnbull+ 2012
Carrick+ 2015
Boruah+ 2020
Said+ 2020
LN21 2021
ALFALFA 2023
Redshift-space Distortions
2dFGRS 2004
WiggleZ 2011
6dF 2012
SDSSMain 2015
BOSSDR12 2017
eBOSSLRG 2022
Lange 2022
SDSS Voids 2023
SDSS Galaxies+Voids 2023
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
S_8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20k PV
70k redshifts
1.5M redshifts
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
S_8

OUTLINE

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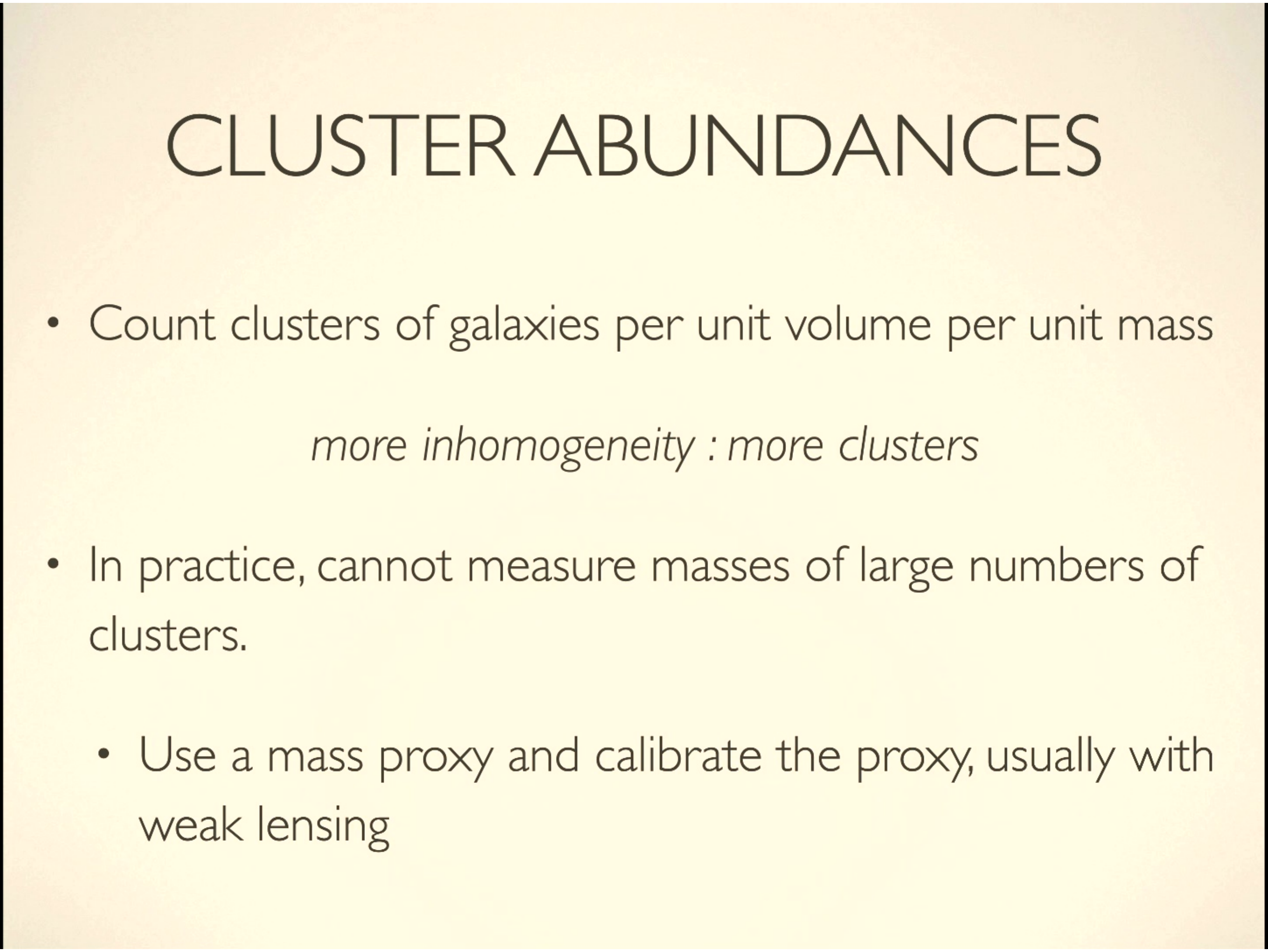


CLUSTER ABUNDANCES

- Count clusters of galaxies per unit volume per unit mass

more inhomogeneity : more clusters

- In practice, cannot measure masses of large numbers of clusters.
  - Use a mass proxy and calibrate the proxy, usually with weak lensing

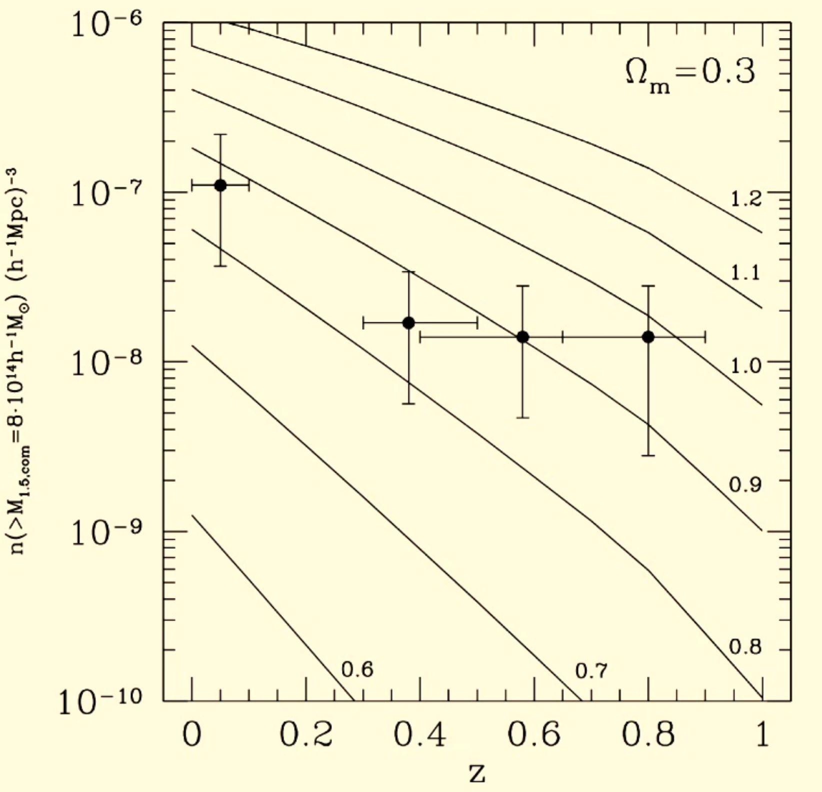
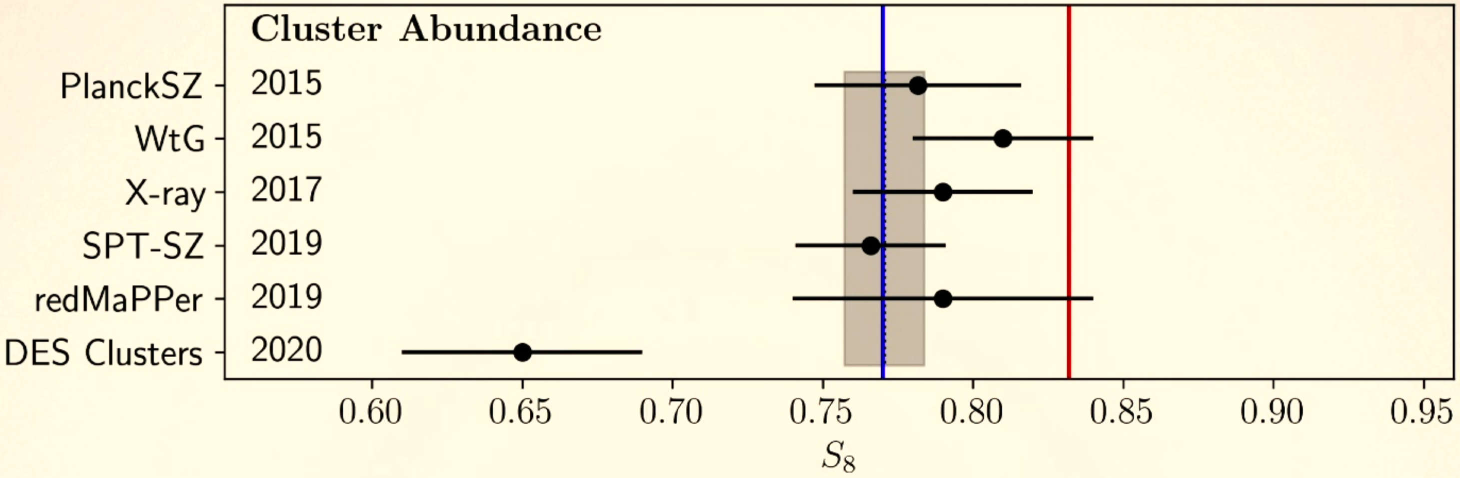
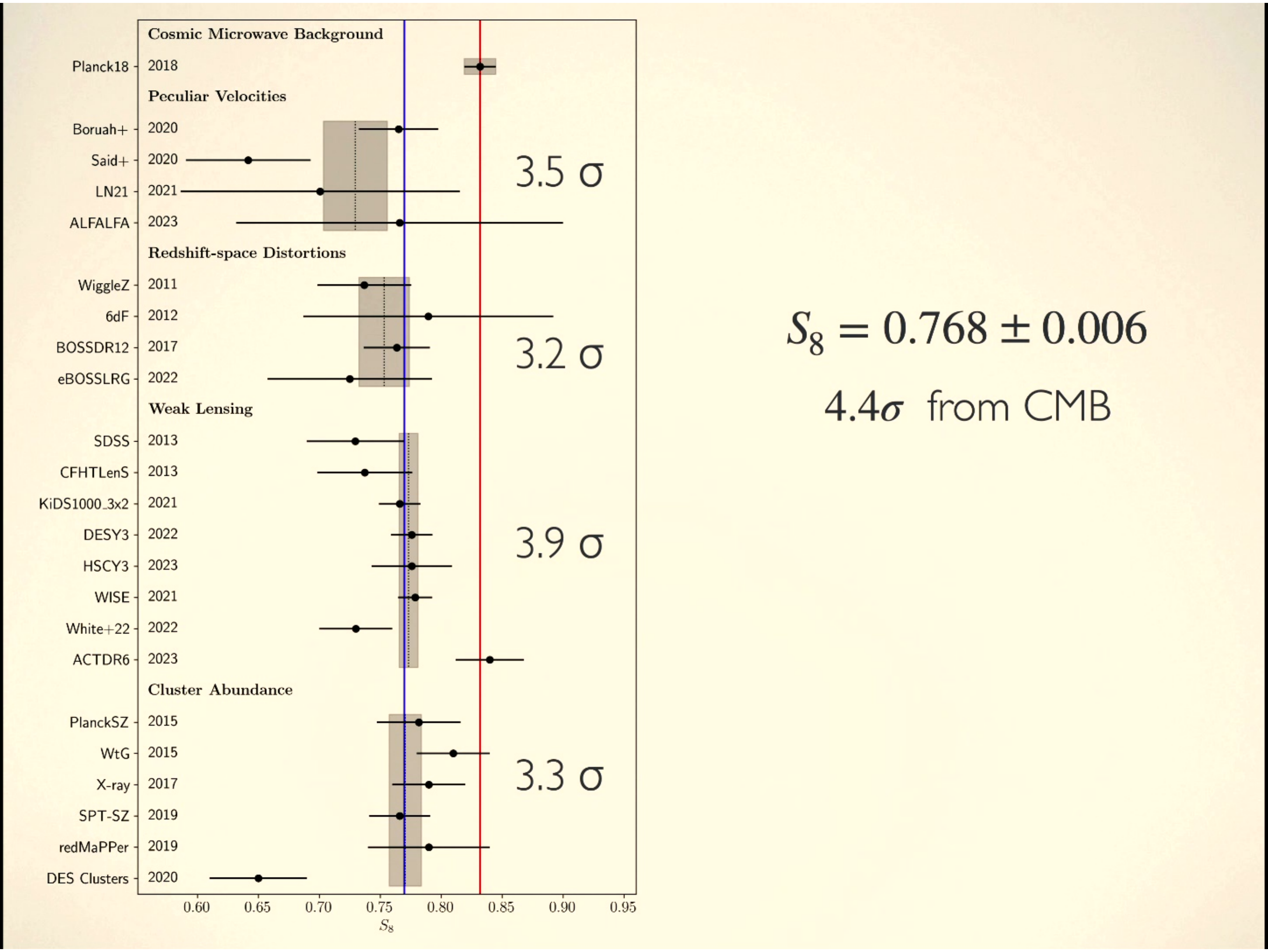


Fig. 1.— Evolution of cluster abundance with redshift, for clusters with mass $M_{1.5,com} \geq 8 \times 10^{14}h^{-1}M_\odot$ (within a comoving radius of $1.5h^{-1}$Mpc). Dots with error bars are the data as described in the text. The lines are the predicted number density assuming a flat $\Omega_m = 0.3$ cosmology; each line is labeled with the σ_8 used.

Bahcall and Bode 02

CLUSTER ABUNDANCES





$$S_8 = 0.768 \pm 0.006$$

4.4σ from CMB

THEORETICAL EXPLANATIONS?

H0 tension

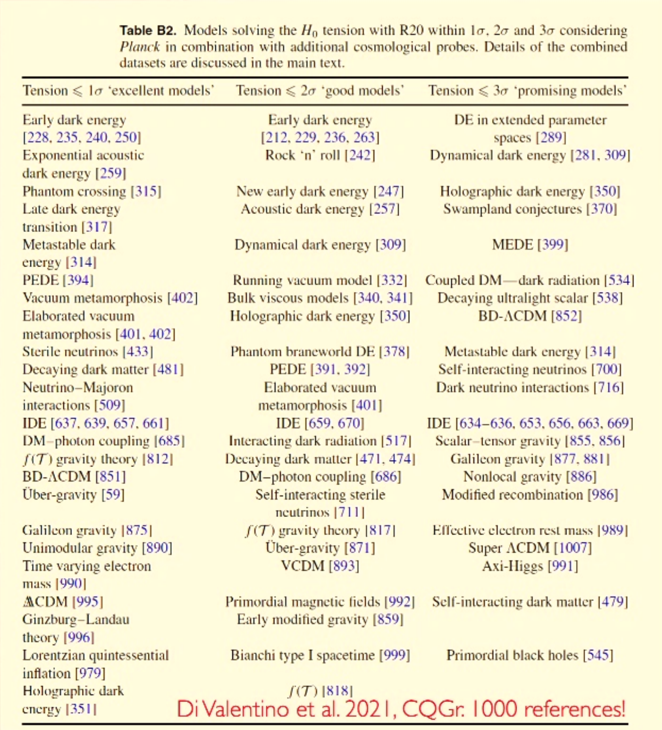


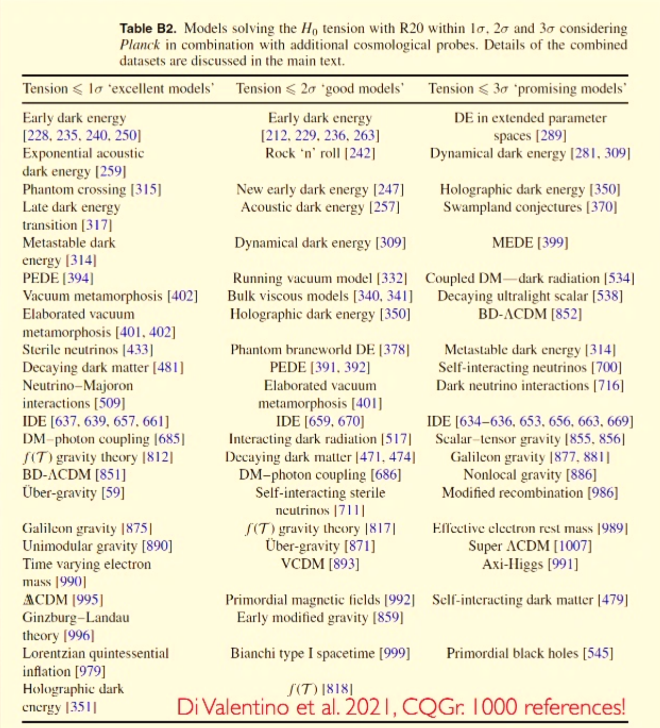
Table B2. Models solving the H_0 tension with R20 within 1σ, 2σ and 3σ considering *Planck* in combination with additional cosmological probes. Details of the combined datasets are discussed in the main text.

Tension $\leqslant 1\sigma$ 'excellent models'	Tension $\leqslant 2\sigma$ 'good models'	Tension $\leqslant 3\sigma$ 'promising models'
Early dark energy [228, 235, 240, 250]	Early dark energy [212, 229, 236, 263]	DE in extended parameter spaces [289]
Exponential acoustic dark energy [259]	Rock 'n' roll [242]	Dynamical dark energy [281, 309]
Phantom crossing [315]	New early dark energy [247]	Holographic dark energy [350]
Late dark energy transition [317]	Acoustic dark energy [257]	Swampland conjectures [370]
Metastable dark energy [314]	Dynamical dark energy [309]	MEDE [399]
PEDE [394]	Running vacuum model [332]	Coupled DM—dark radiation [534]
Vacuum metamorphosis [402]	Bulk viscous models [340, 341]	Decaying ultralight scalar [538]
Elaborated vacuum metamorphosis [401, 402]	Holographic dark energy [350]	BD-ΛCDM [852]
Sterile neutrinos [433]	Phantom braneworld DE [378]	Metastable dark energy [314]
Decaying dark matter [481]	PEDE [391, 392]	Self-interacting neutrinos [700]
Neutrino–Majoron interactions [509]	Elaborated vacuum metamorphosis [401]	Dark neutrino interactions [716]
IDE [637, 639, 657, 661]	IDE [659, 670]	IDE [634–636, 653, 656, 663, 669]
DM–photon coupling [685]	Interacting dark radiation [517]	Scalar–tensor gravity [855, 856]
$f(\mathcal{T})$ gravity theory [812]	Decaying dark matter [471, 474]	Galileon gravity [877, 881]
BD-ΛCDM [851]	DM–photon coupling [686]	Nonlocal gravity [886]
Über-gravity [59]	Self-interacting sterile neutrinos [711]	Modified recombination [986]
Galileon gravity [875]	$f(\mathcal{T})$ gravity theory [817]	Effective electron rest mass [989]
Unimodular gravity [890]	Über-gravity [871]	Super ΛCDM [1007]
Time varying electron mass [990]	VCDM [893]	Axi-Higgs [991]
ΛsCDM [995]	Primordial magnetic fields [992]	Self-interacting dark matter [479]
Ginzburg–Landau theory [996]	Early modified gravity [859]	
Lorentzian quintessential inflation [979]	Bianchi type I spacetime [999]	Primordial black holes [545]
Holographic dark energy [351]	$f(\mathcal{T})$ [818]	

Di Valentino et al. 2021, CQGr. 1000 references!

THEORETICAL EXPLANATIONS?

H0 tension



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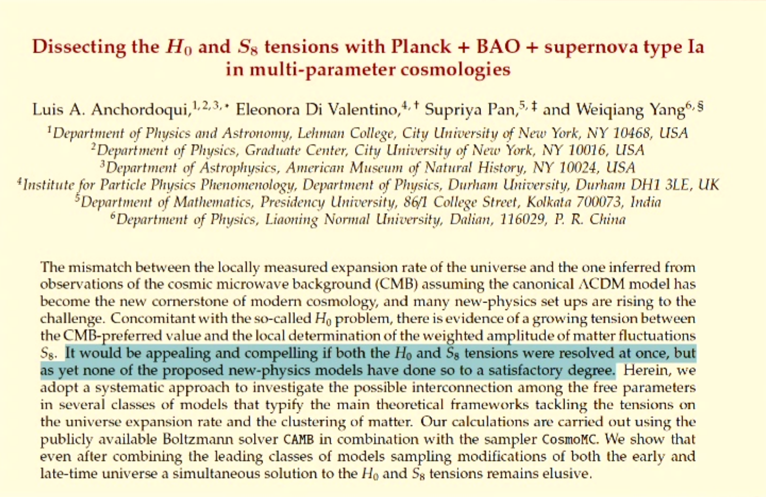
H0+S8 tension



Dissecting the H_0 and S_8 tensions with Planck + BAO + supernova type Ia in multi-parameter cosmologies

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[2] *Department of Physics, Graduate Center, City University of New York, NY 10016, USA*
[3] *Department of Astrophysics, American Museum of Natural History, NY 10024, USA*
[4] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, UK*
[5] *Department of Mathematics, Presidency University, 86/1 College Street, Kolkata 700073, India*
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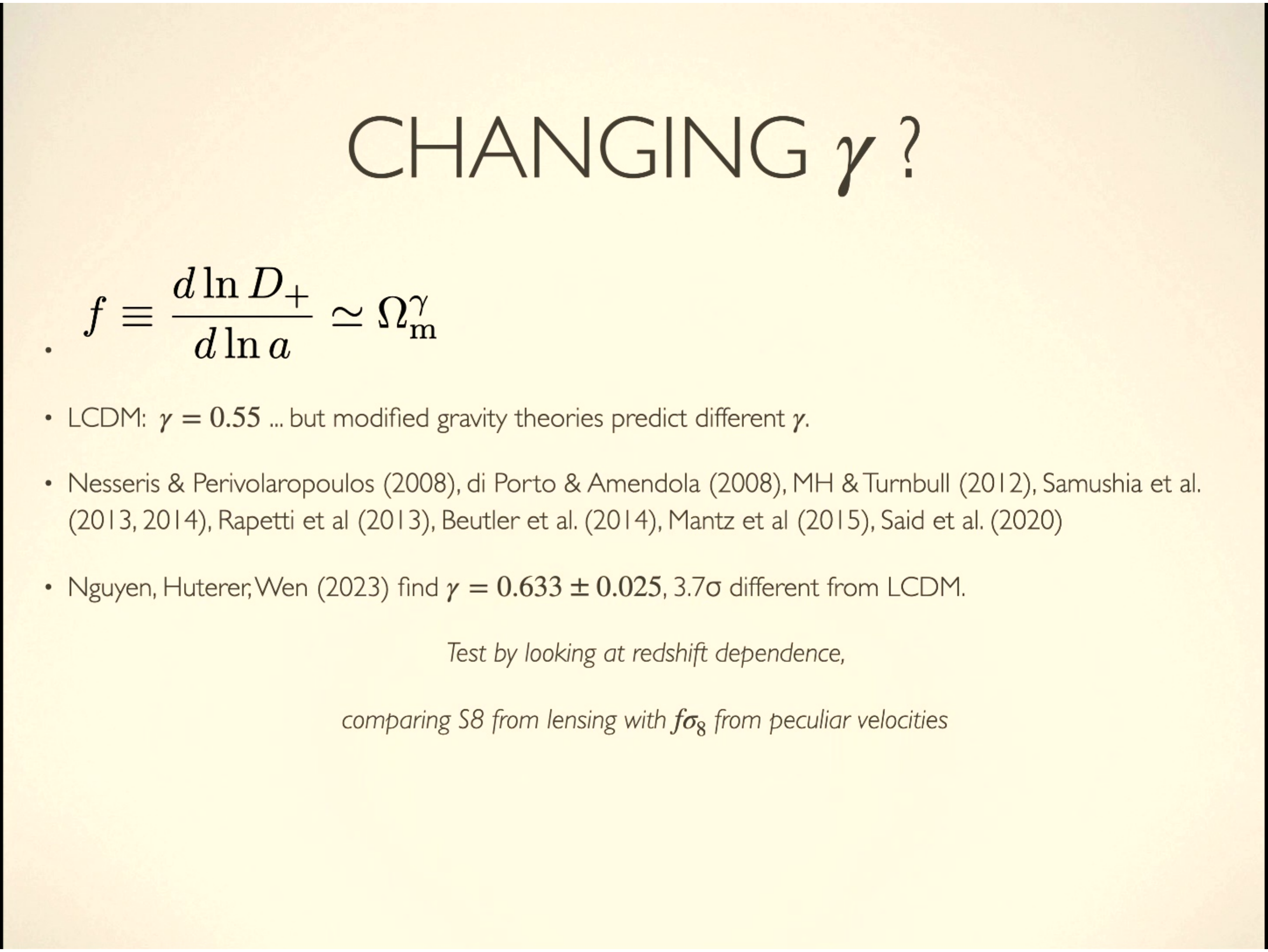
The mismatch between the locally measured expansion rate of the universe and the one inferred from observations of the cosmic microwave background (CMB) assuming the canonical ΛCDM model has become the new cornerstone of modern cosmology, and many new-physics set ups are rising to the challenge. Concomitant with the so-called H_0 problem, there is evidence of a growing tension between the CMB-preferred value and the local determination of the weighted amplitude of matter fluctuations S_8. It would be appealing and compelling if both the H_0 and S_8 tensions were resolved at once, but as yet none of the proposed new-physics models have done so to a satisfactory degree. Herein, we adopt a systematic approach to investigate the possible interconnection among the free parameters in several classes of models that typify the main theoretical frameworks tackling the tensions on the universe expansion rate and the clustering of matter. Our calculations are carried out using the publicly available Boltzmann solver `CAMB` in combination with the sampler `CosmoMC`. We show that even after combining the leading classes of models sampling modifications of both the early and late-time universe a simultaneous solution to the H_0 and S_8 tensions remains elusive.

Anchordoqui et al. 2021, JHEAP



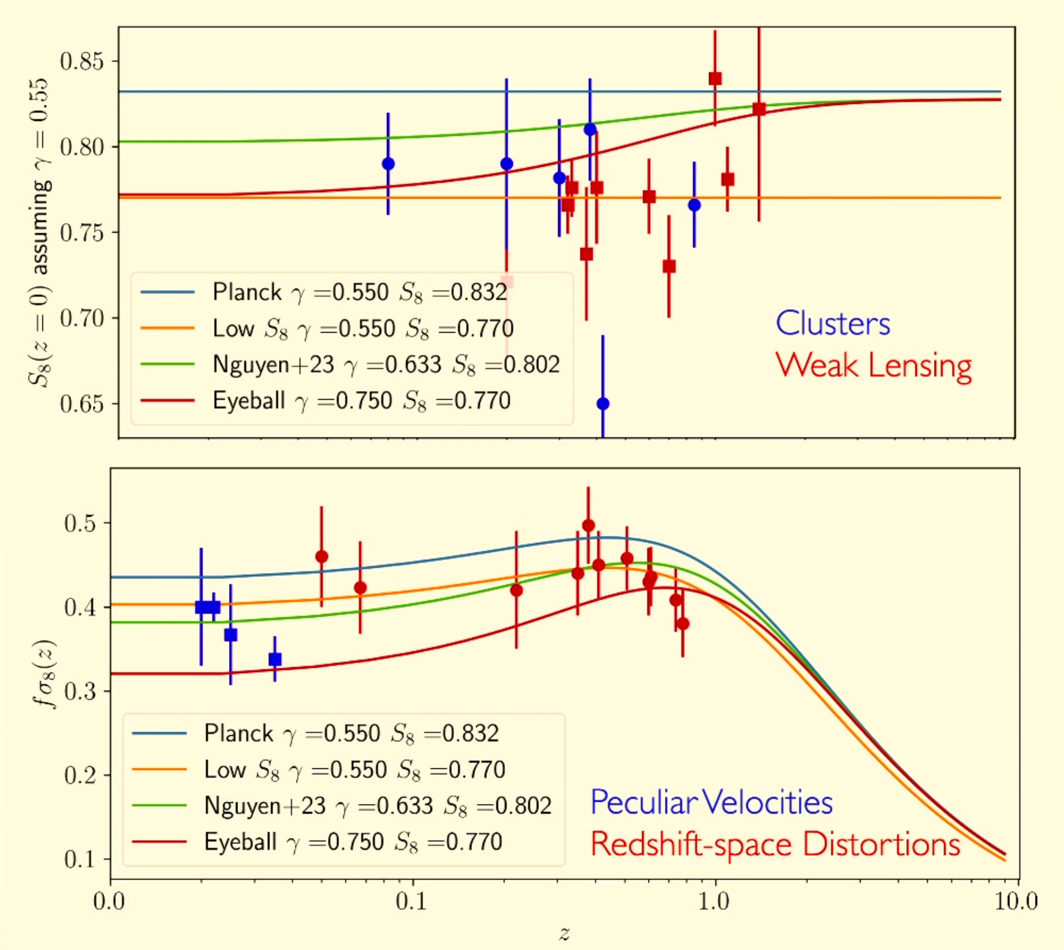
CHANGING γ ?

- $$f \equiv \frac{d \ln D_+}{d \ln a} \simeq \Omega_{\rm m}^{\gamma}$$
- LCDM: $\gamma = 0.55$ ... but modified gravity theories predict different γ.
- Nesseris & Perivolaropoulos (2008), di Porto & Amendola (2008), MH & Turnbull (2012), Samushia et al. (2013, 2014), Rapetti et al (2013), Beutler et al. (2014), Mantz et al (2015), Said et al. (2020)
- Nguyen, Huterer, Wen (2023) find $\gamma = 0.633 \pm 0.025$, 3.7σ different from LCDM.

Test by looking at redshift dependence,

comparing S8 from lensing with $f\sigma_8$ from peculiar velocities

REDSHIFT DEPENDENCE?



SCALE DEPENDENCE?

Another possibility is to look for a possible dependence on the comoving scales probed by each experiment

Weak lensing→Clusters→Peculiar velocities→RSD

UPCOMING SURVEYS/ MISSIONS

Weak Lensing

- UNIONS (ongoing), Euclid (launching in 7 weeks!), Rubin/LSST, Roman

Redshift-space Distortions

- DESI, Euclid, 4MOST

Peculiar Velocities

- DESI and 4MOST (Fundamental Plane, Tully-Fisher), Rubin/LSST (Supernovae), Euclid (Surface Brightness Fluctuations)

Clusters

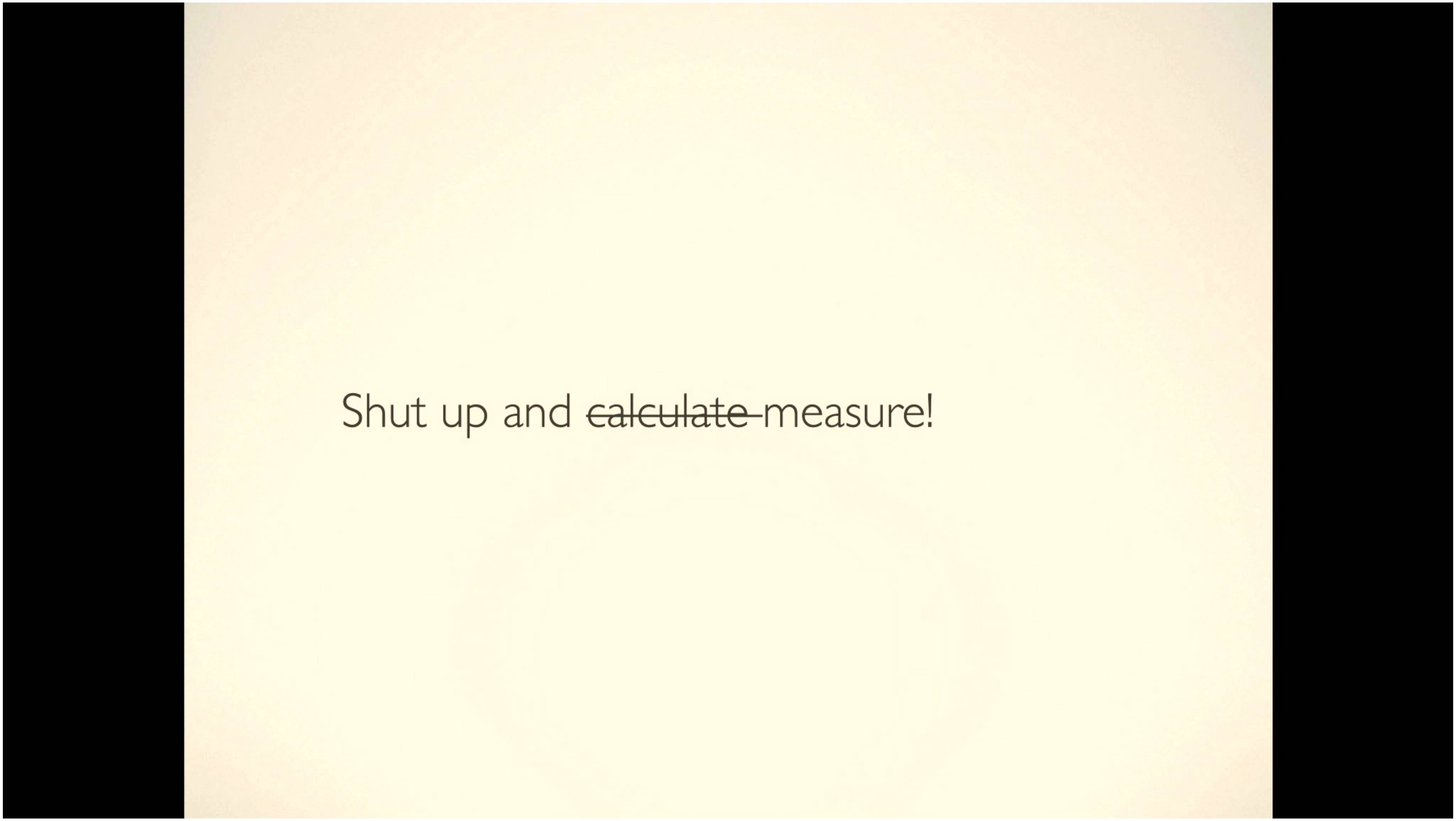
- Finding: X-ray (eROSITA), Sunyaev-Zel'dovich effect (ACT/SPT/Simons), Optical Surveys
- Weighing: Euclid, Rubin/LSST, Roman

ground

or

space

Shut up and calculate



Shut up and ~~calculate~~ measure!