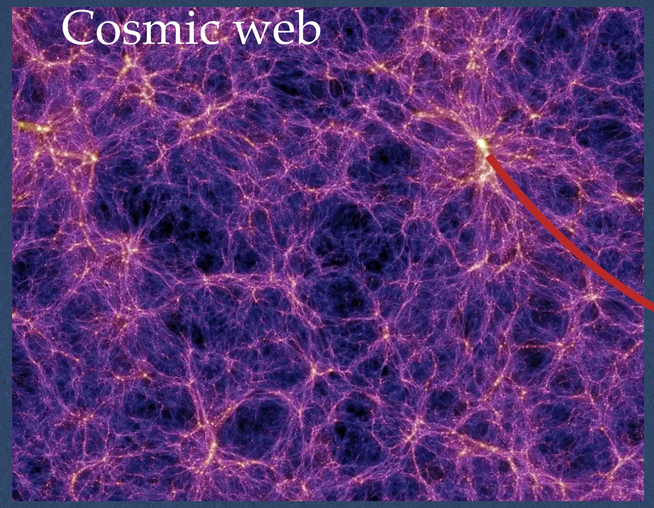
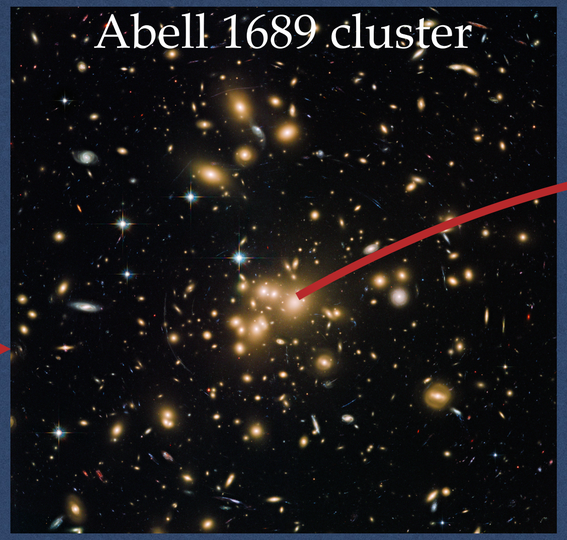
Are we missing systematic uncertainties in galaxy clusters cosmology ?

Narei Lorenzo Martinez (LAPP-CNRS)

Colloque National Dark Energy - November 4th 2026

Cosmology with optical galaxy clusters





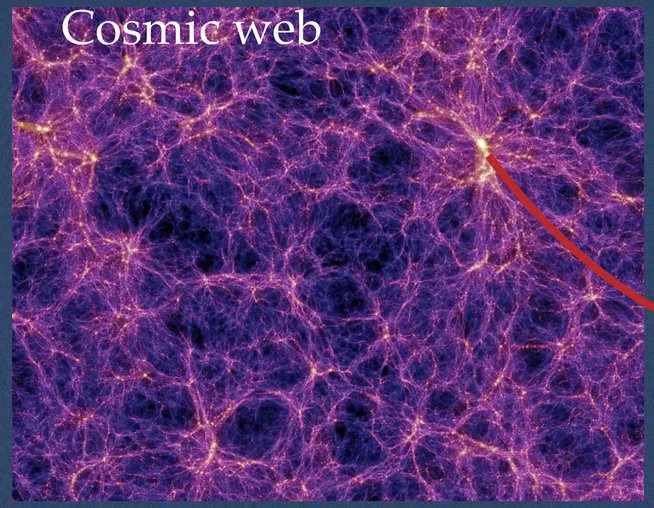


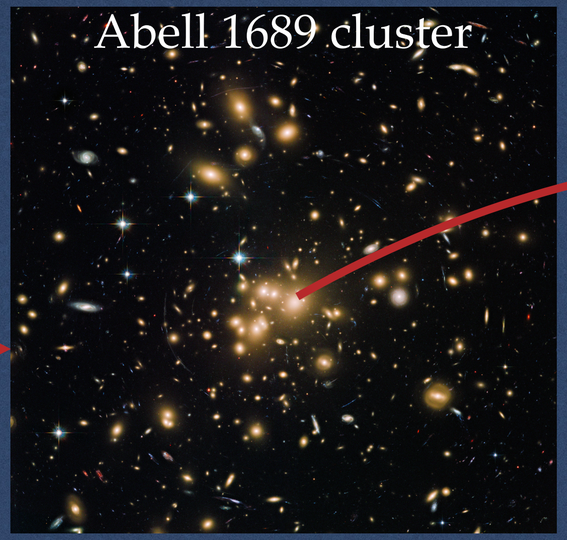
Most massive structures in the Universe

Extract cosmological parameters essentially from counting clusters at a given mass and redshift (Halo Mass Functions)

Need mass of the clusters !

Cosmology with optical galaxy clusters



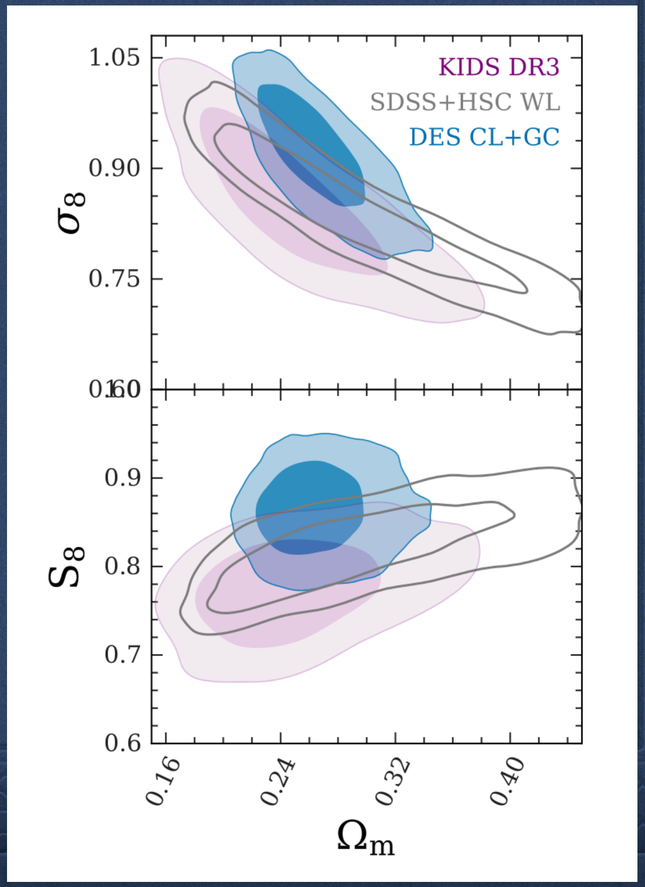




Most massive structures in the Universe

Extract cosmological parameters essentially from counting clusters at a given mass and redshift (Halo Mass Functions)

Need mass of the clusters !



https://arxiv.org/pdf/2503.13632

From image to mass

https://noirlab.edu/public/images/archive/search/?adv=&instrument=21



From image to mass

https://noirlab.edu/public/images/archive/search/?adv=&instrument=21



Cluster finder (density, color, …)

↓

Richness

From image to mass

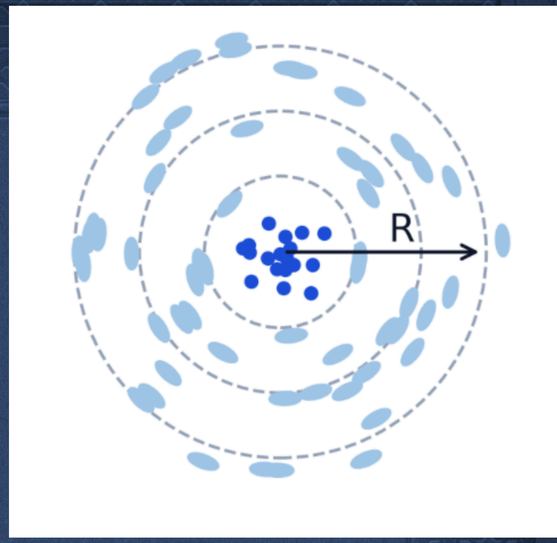
https://noirlab.edu/public/images/archive/search/?adv=&instrument=21



Cluster finder (density, color, …)

Richness Shear signal

Projected 2D mass



From image to mass

https://noirlab.edu/public/images/archive/search/?adv=&instrument=21

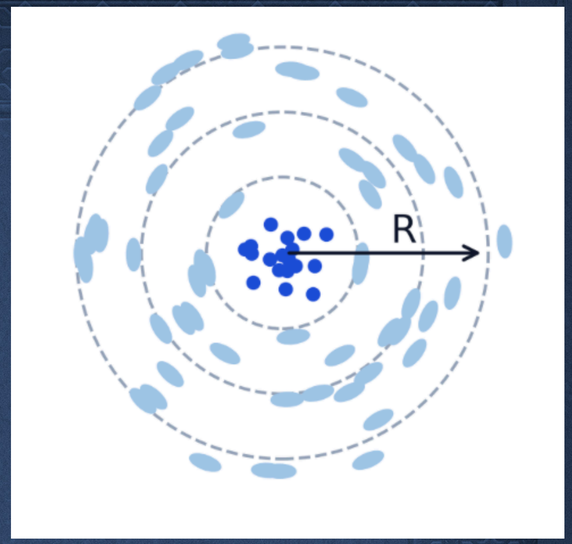


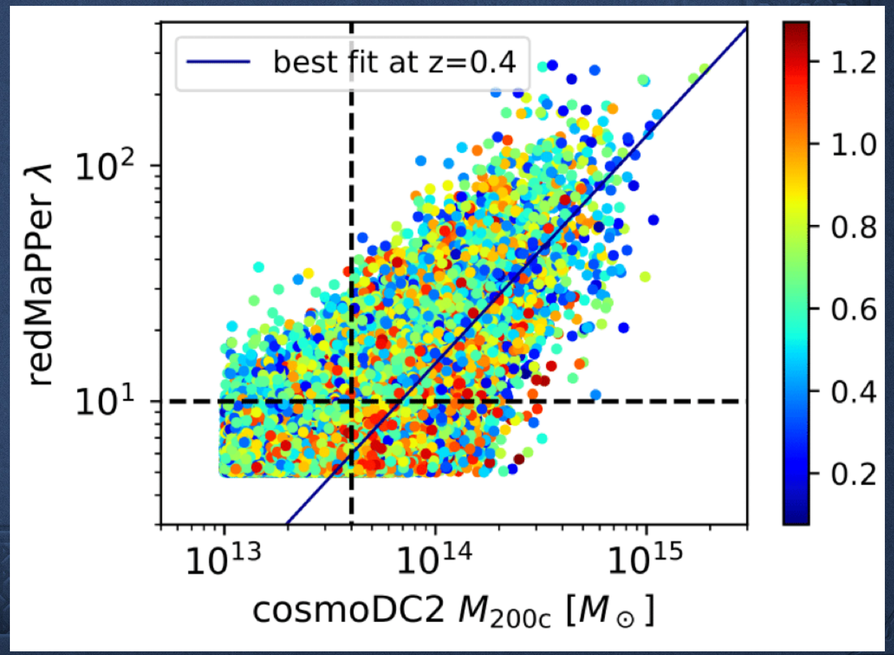
Cluster finder (density, color, …)

Richness Shear signal

Projected 2D mass

Mass-richness relation (simulation)





https://arxiv.org/pdf/2502.08444

From image to mass

https://noirlab.edu/public/images/archive/search/?adv=&instrument=21



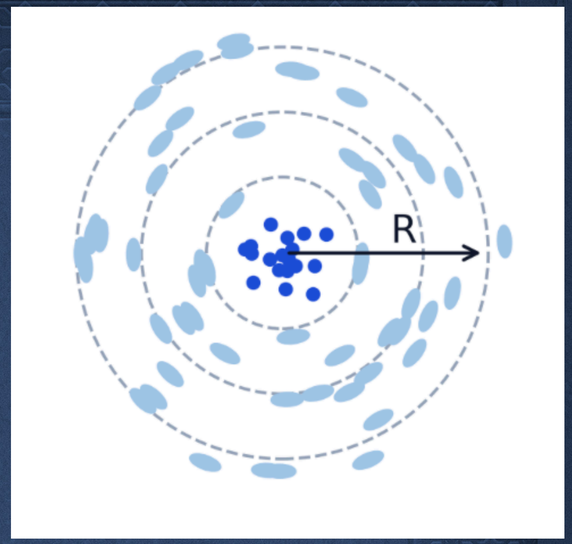
Cluster finder (density, color, …)

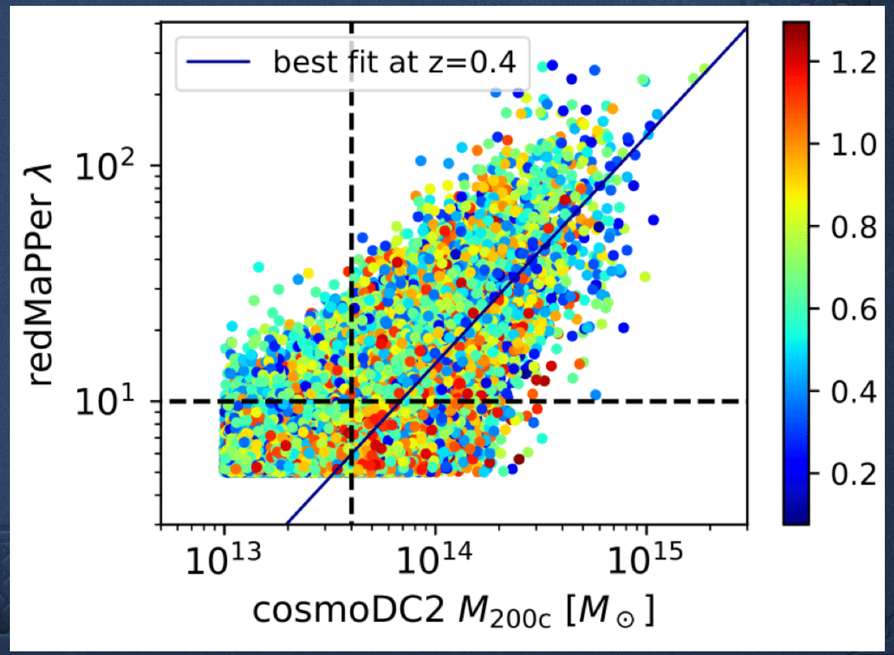
Richness Shear signal

Projected 2D mass

Mass-richness relation (simulation)

Cluster mass





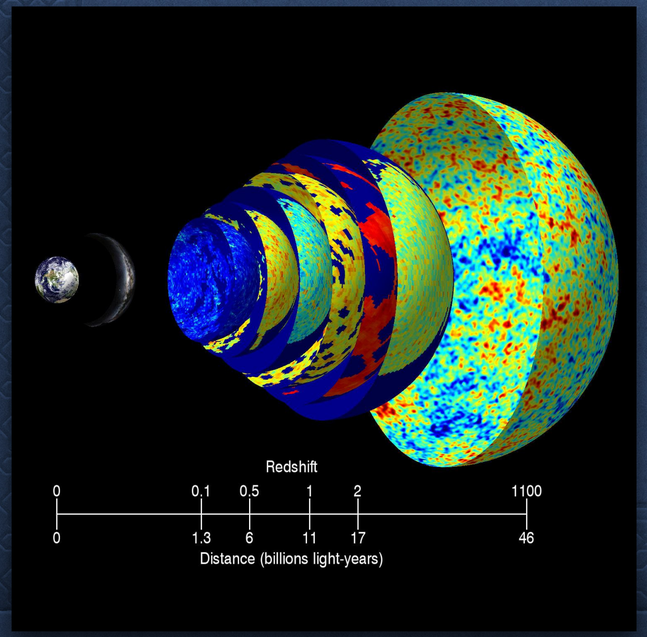
https://arxiv.org/pdf/2502.08444

Abundance as a cosmological probe

$$N_{ij} = \Omega_S \int_{z_i}^{z_{i+1}} dz \int_{\ln x_j}^{\ln x_{j+1}} d\ln x \int_{M_{\min}}^{M_{\max}} dM \times$$

$$\frac{d^2V(z)}{dz d\Omega} \frac{dn(M,z)}{dM} P\left(\ln x \mid M, z\right) \Phi(M, x, z),$$

Comoving volume

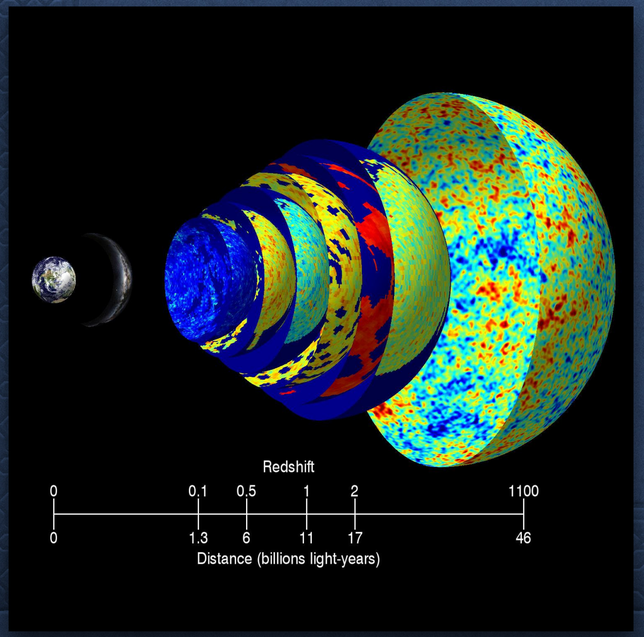


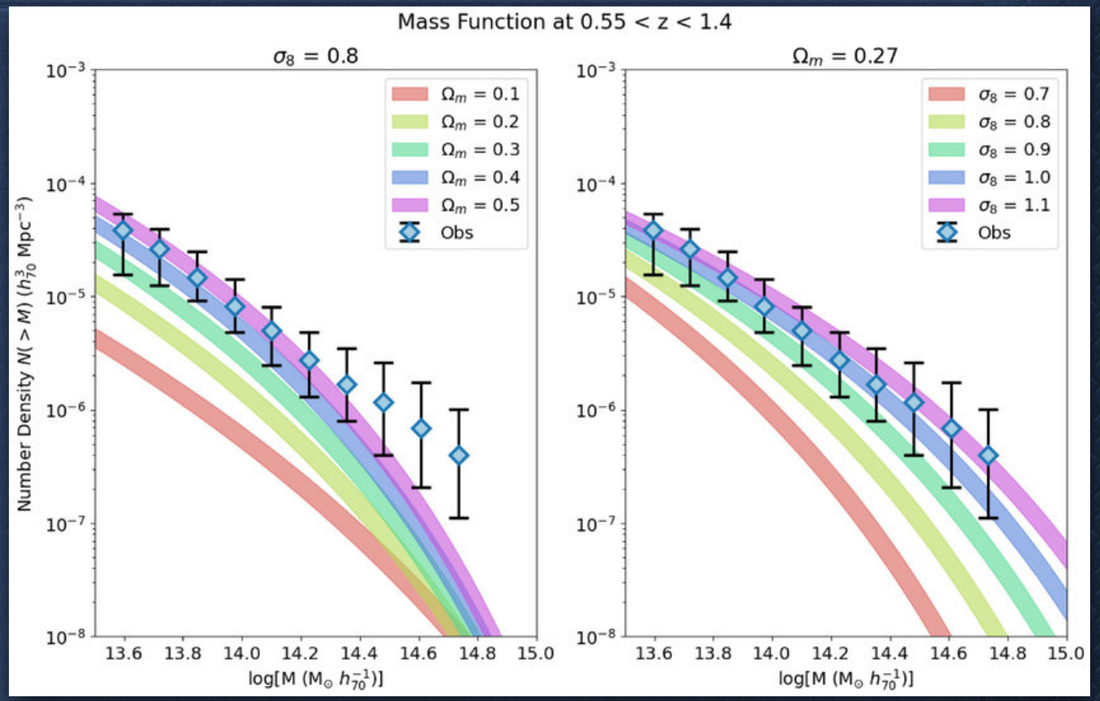
Abundance as a cosmological probe

$$N_{ij} = \Omega_S \int_{z_i}^{z_{i+1}} dz \int_{\ln x_j}^{\ln x_{j+1}} d\ln x \int_{M_{\min}}^{M_{\max}} dM \times \frac{d^2V(z)}{dz d\Omega} \frac{dn(M,z)}{dM} P\left(\ln x \mid M, z\right)\ \Phi(M, x, z),$$

Comoving volume

Halo Mass Function



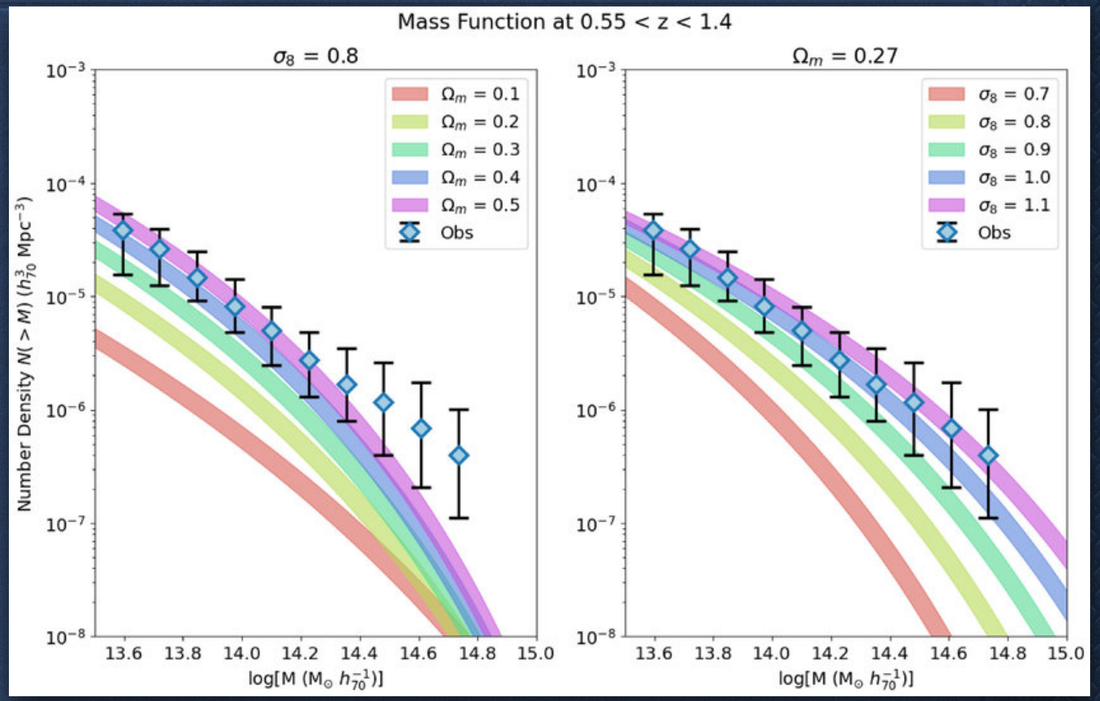


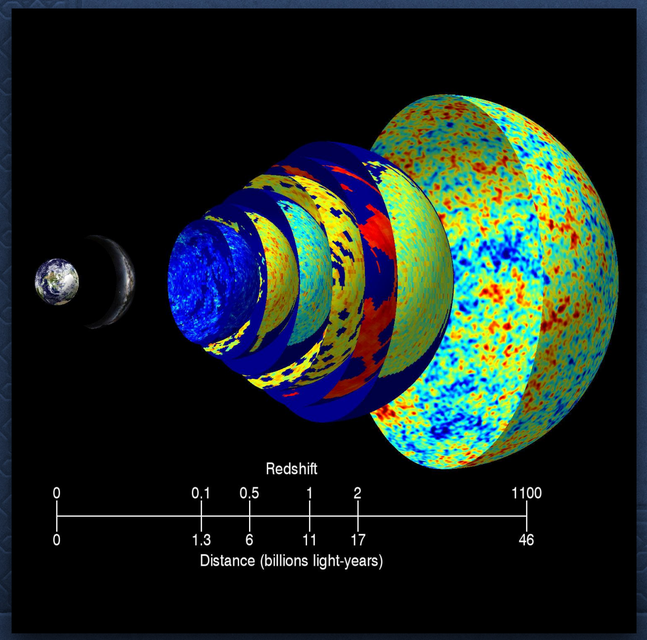
Abundance as a cosmological probe

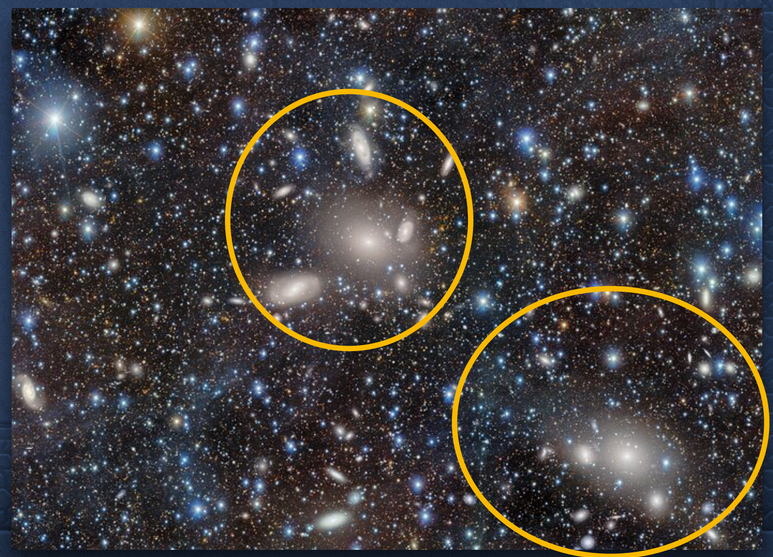
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$$\frac{d^2V(z)}{dz d\Omega} \quad \frac{dn(M,z)}{dM} \quad P\left(\ln x \mid M, z\right) \quad \Phi(M, x, z),$$

Comoving volume | Halo Mass Function | Mass/richness relation | Completeness/purity





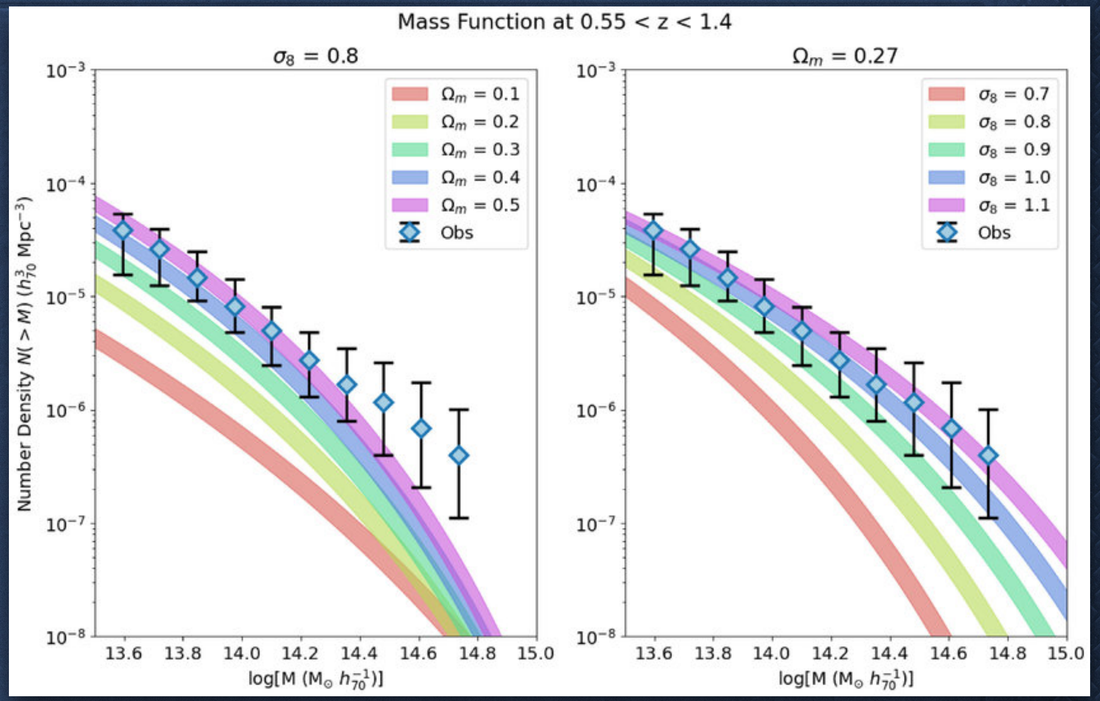


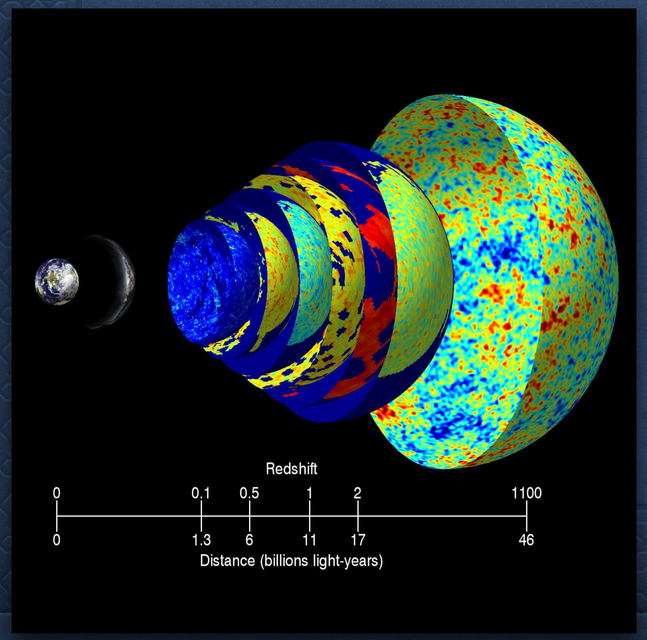
Abundance as a cosmological probe

$$N_{ij} = \Omega_S \int_{z_i}^{z_{i+1}} dz \int_{\ln x_j}^{\ln x_{j+1}} d\ln x \int_{M_{\rm min}}^{M_{\rm max}} dM \times$$

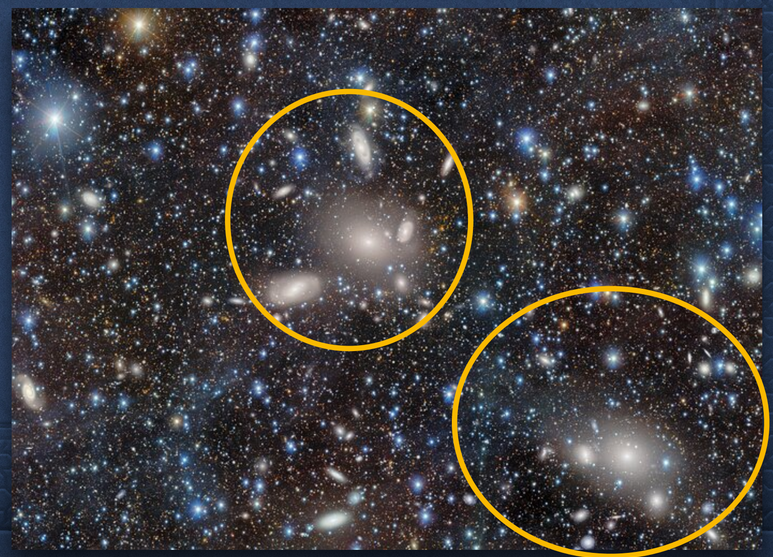
$$\frac{d^2V(z)}{dz d\Omega} \quad \frac{dn(M,z)}{dM} \quad P\left(\ln x \mid M, z\right) \quad \Phi(M, x, z),$$

Comoving volume | Halo Mass Function | Mass/richness relation | Completeness/purity





shear signal helps to break degeneracies



Several steps from image to cosmological constraints
Several hypotheses and models used

How does this translates in term of uncertainty on measurement on cosmo parameters ?

→ Review of publications

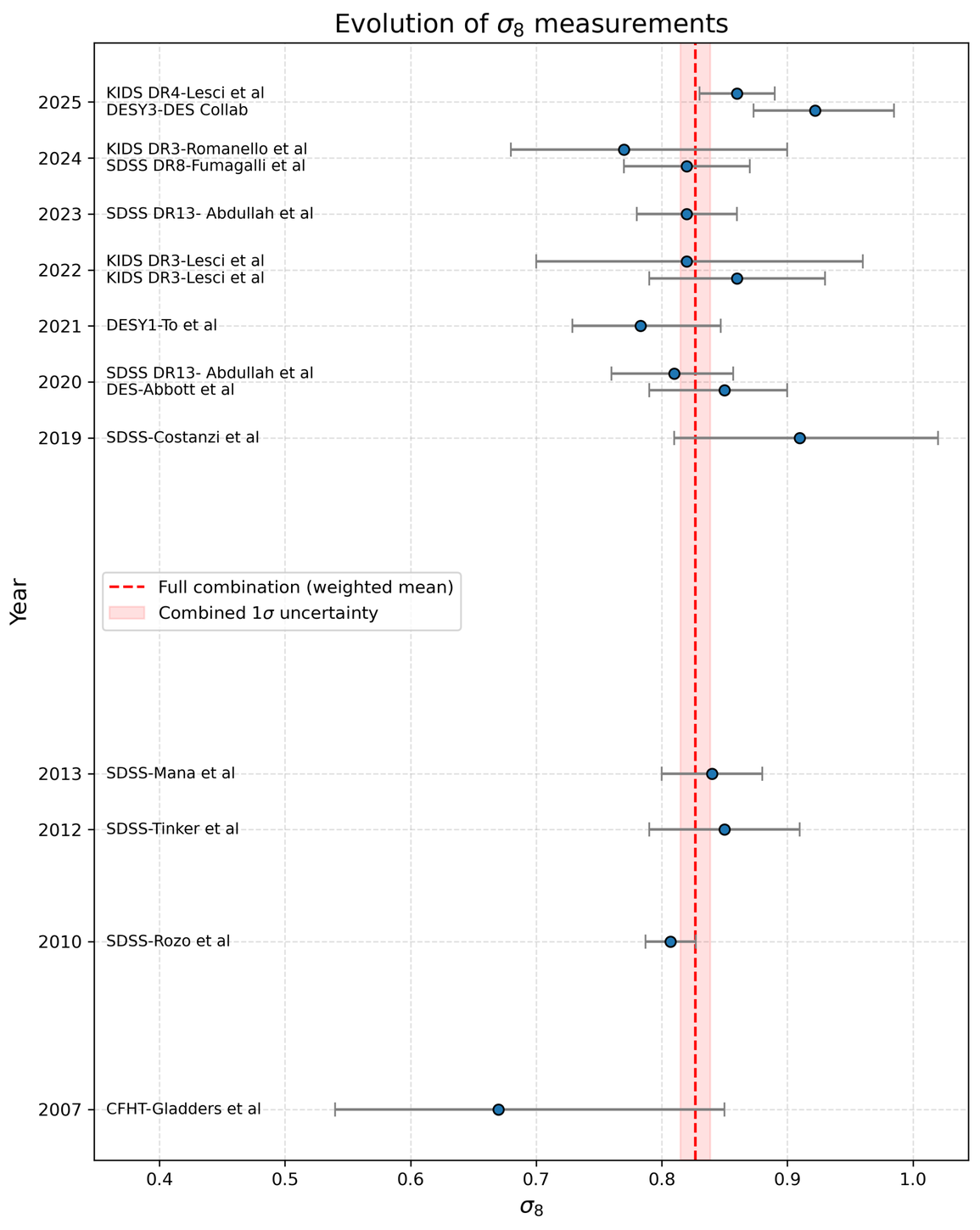
Summary of publications used

Using only papers on optical clusters and only those providing constraints on at least Ωm

-> 15 papers found between 2007 and 2026

Paper and authors	Year	Survey / telescope	Method	Number of clusters
Gladders et al.,	2007	RCS-1 / CFHT and CTIO	Abundance using RS cluster catalog; cosmo from mass–richness (MR) relation.	956
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Costanzi et al.,	2019	SDSS-DR8 / redMaPPer	Abundance and WL mass calibration; simult. fit of cosmo and MR relation.	6,964
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Abdullah et al.,	2020	SDSS-DR13 / GalWCat19	Abundance analysis using dynamical cluster masses and HMF;	756
To et al. (DES Collab.),	2021	DES Y1 / DECam / redMaPPer	Abundance and galaxy density, WL shear and cluster density correlations. Combines $4 \times 2{\rm pt} + N$ and $6 \times 2{\rm pt} + N$ statistics.	4794
Lesci et al.,	2022	KiDS-DR3 / VST (OmegaCAM)	Number counts and stacked WL profiles; simult. cosmo and calib. of MR relation.	3,652 (counts); 6,962 (lensing)
Lesci et al.,	2022	KiDS-DR3 / VST (OmegaCAM)	Redshift-space 2-point correlation function of clusters; constraints on cosmo and MR relation.	4,934
Abdullah et al.,	2023	SDSS-DR13 / GalWCat19	Calibration of MR relation with dynamical masses; construction of cluster mass function and abundance-based constraints on cosmo.	756
Fumagalli et al.,	2024	SDSS-DR8 / redMaPPer	Number counts, cluster clustering and WL mass measurements; comparison of combinations of the 3 probes.	6,964
Romanello et al.,	2024	KiDS-DR3 / VST (OmegaCAM)	Tomographic angular 2-point correlation function and angular power spectrum;	5,162
Abbott et al. (DES Collaboration),	2025	DES Y3 / DECam / redMaPPer	Joint analysis of abundance, galaxy clustering and WL measurements; comparison with DES Y3 3×2pt analysis.	$\sim 16,000$
Lesci et al.,	2025	KiDS-1000 / VST (OmegaCAM) and VIKING	Number counts and stacked WL profiles; simult. cosmo constraints and MR calibration.	7,789 (counts); 8,730 (lensing)

σ8 summary


Evolution of σ_8 measurements
2025
KIDS DR4-Lesci et al
DESY3-DES Collab
2024
KIDS DR3-Romanello et al
SDSS DR8-Fumagalli et al
2023
SDSS DR13- Abdullah et al
2022
KIDS DR3-Lesci et al
KIDS DR3-Lesci et al
2021
DESY1-To et al
2020
SDSS DR13- Abdullah et al
DES-Abbott et al
2019
SDSS-Costanzi et al
Full combination (weighted mean)
Combined 1σ uncertainty
Year
2013
SDSS-Mana et al
2012
SDSS-Tinker et al
2010
SDSS-Rozo et al
2007
CFHT-Gladders et al
0.4
0.5
0.6
0.7
0.8
0.9
1.0
σ_8

σ8 summary

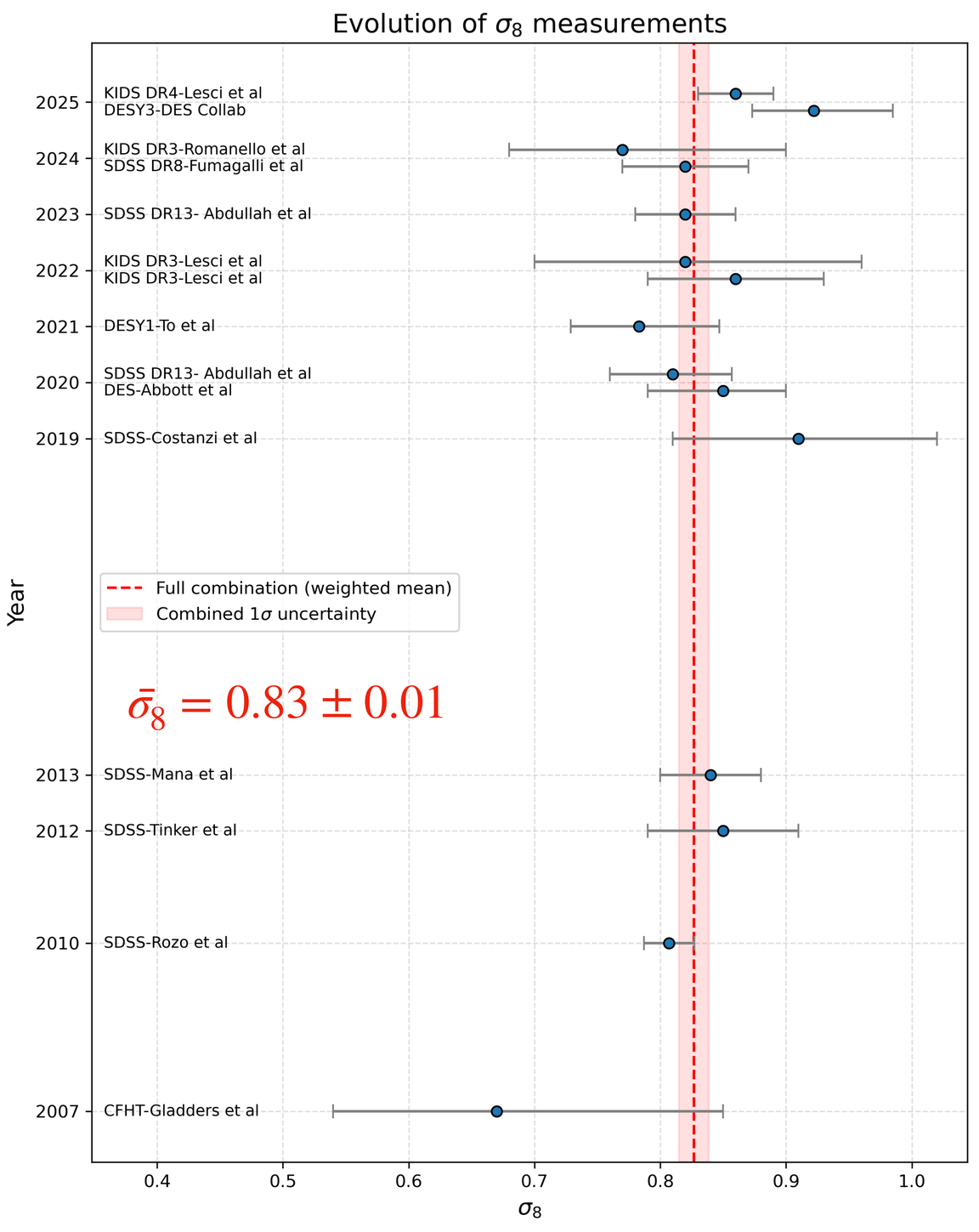
Combination and error computed as:

$$\bar{\sigma}_8 = \frac{\Sigma(w_i \cdot \sigma_{8,i})}{\Sigma w_i} \qquad \Delta\bar{\sigma}_8 = 1/\sqrt{\Sigma w_i}$$

with $w_i = 1/\Delta\sigma_{8,i}^2$

(assuming no correlation between measurements)

$$\bar{\sigma}_8 = 0.83 \pm 0.01$$



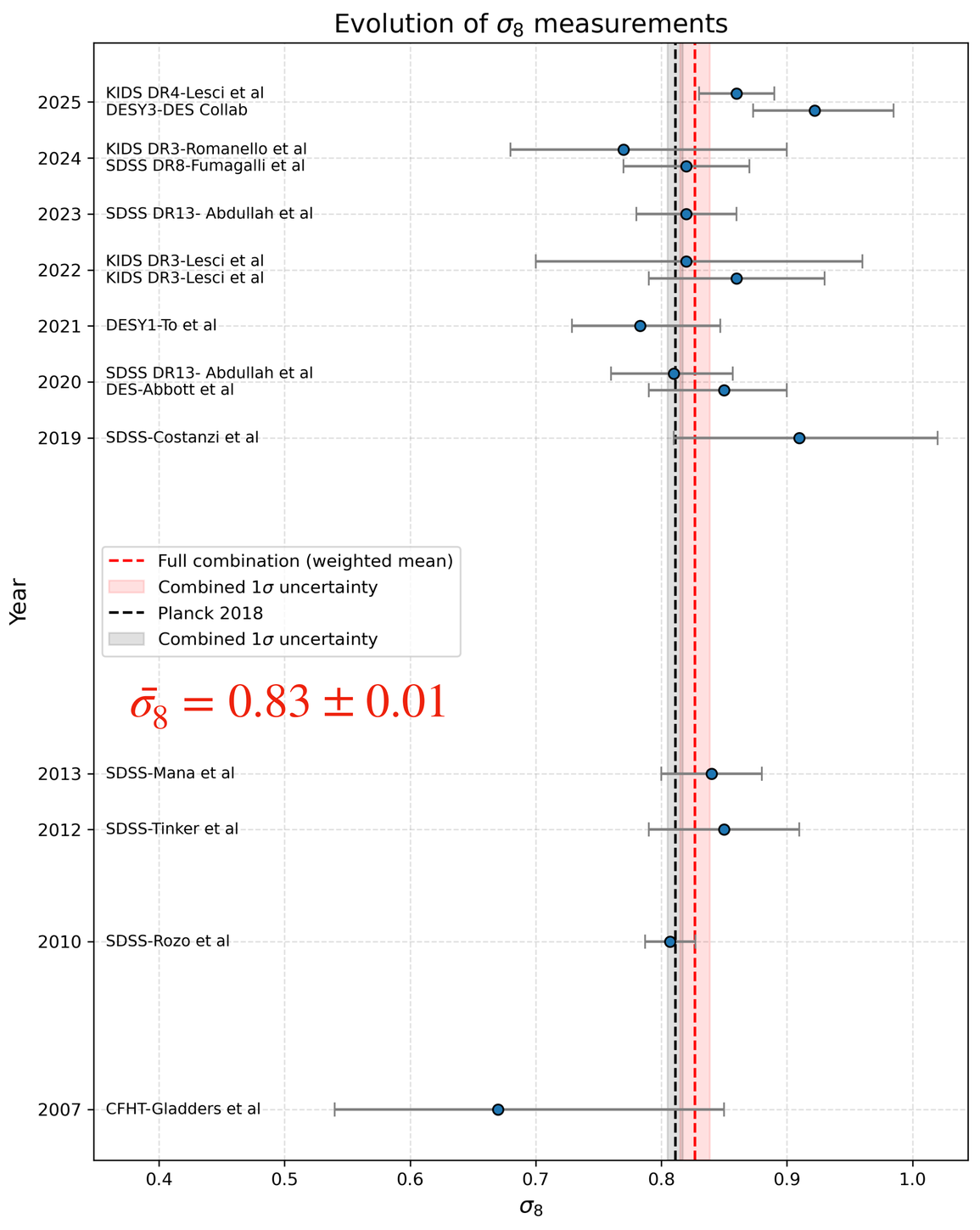
Comparison with Planck

$$\bar{\sigma}_8^{\,clusters} = 0.83 \pm 0.01$$

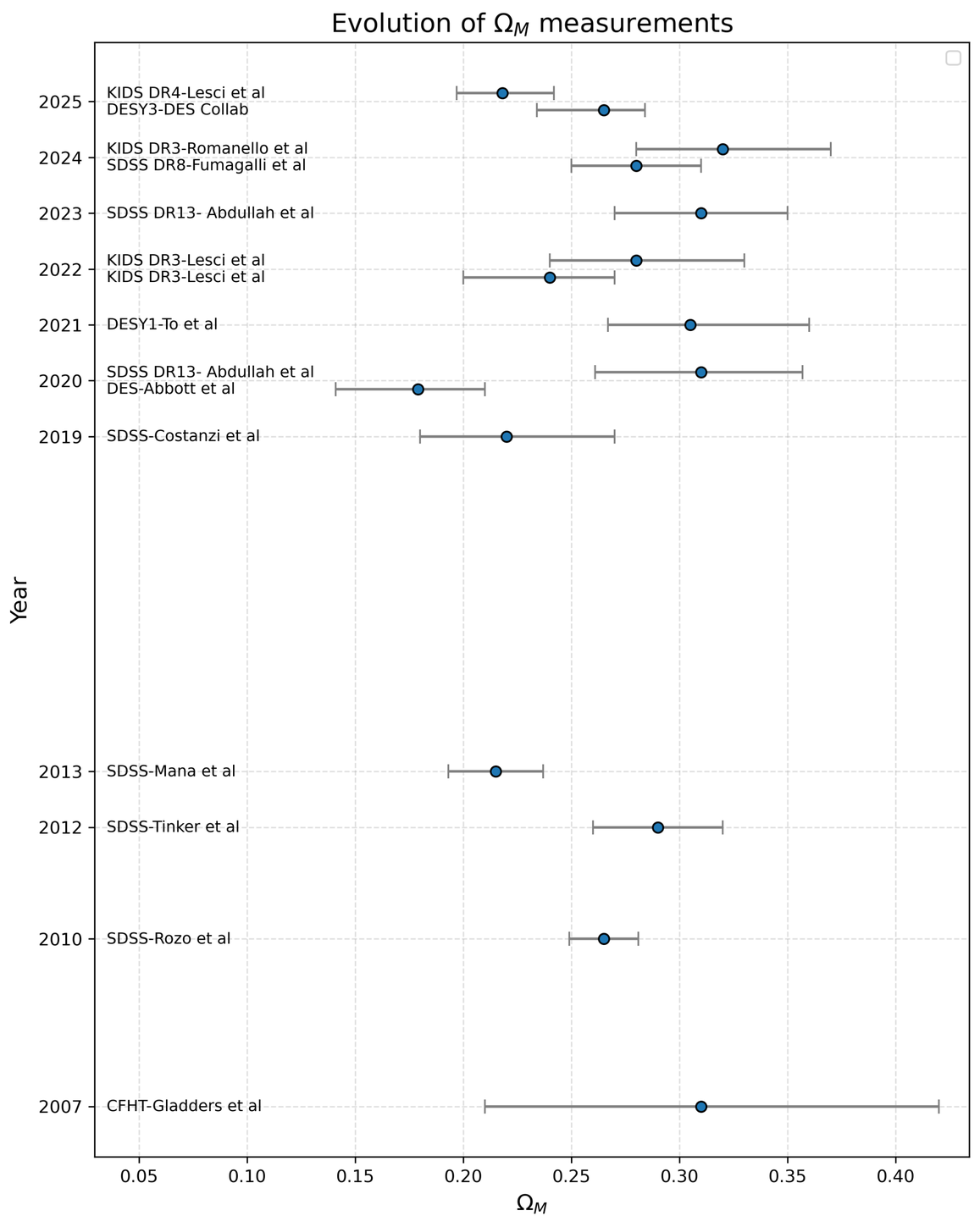
$$\sigma_8^{planck} = 0.811 \pm 0.006$$

Very good compatibility

Clusters provide less precise measurement



Ωm summary


Evolution of Ω_M measurements
KIDS DR4-Lesci et al
DESY3-DES Collab
KIDS DR3-Romanello et al
SDSS DR8-Fumagalli et al
SDSS DR13- Abdullah et al
KIDS DR3-Lesci et al
KIDS DR3-Lesci et al
DESY1-To et al
SDSS DR13- Abdullah et al
DES-Abbott et al
SDSS-Costanzi et al
SDSS-Mana et al
SDSS-Tinker et al
SDSS-Rozo et al
CFHT-Gladders et al
2025
2024
2023
2022
2021
2020
2019
2013
2012
2010
2007
Year
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Ω_M

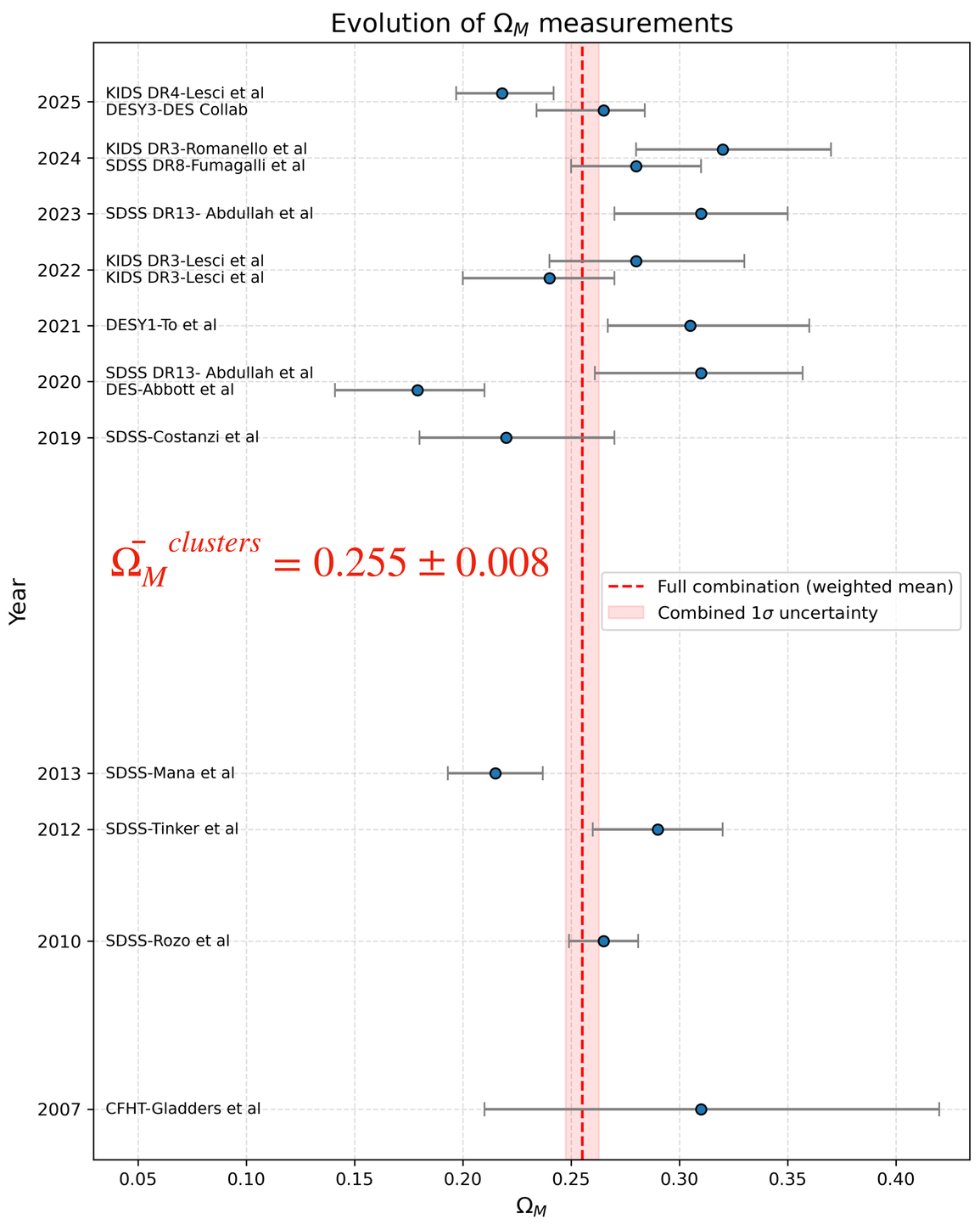
Ωm summary

Combination and error computed as:

$$\bar{\Omega}_M = \frac{\Sigma(w_i \,.\, \Omega_{M,i})}{\Sigma w_i} \qquad \Delta\bar{\Omega}_M = 1/\sqrt{\Sigma w_i}$$

with $w_i = 1/\Delta\Omega^2_{M,i}$

(assuming no correlation between measurements)



Ωm summary

Combination and error computed as:

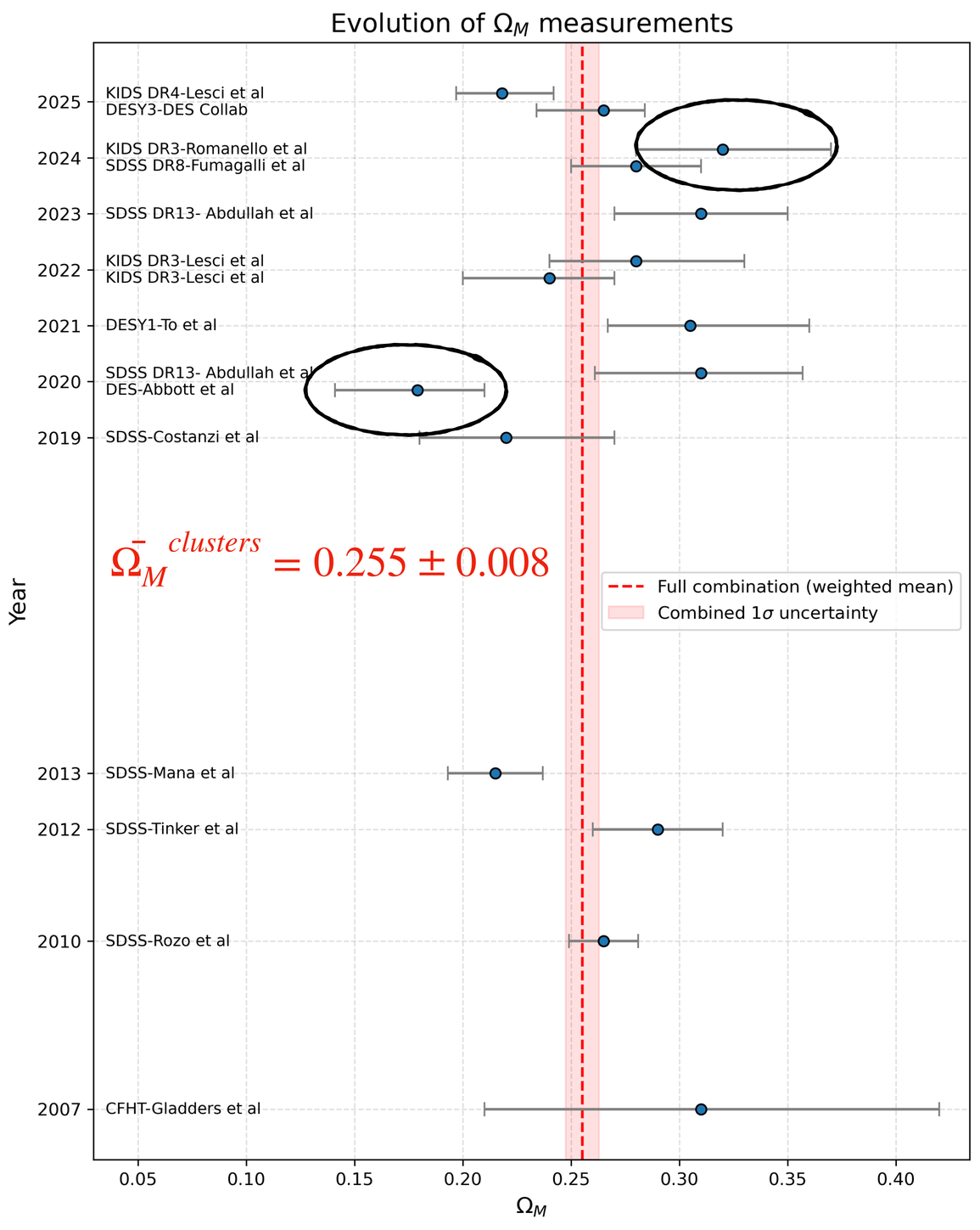
$$\bar{\Omega}_M = \frac{\Sigma(w_i \,.\, \Omega_{M,i})}{\Sigma w_i} \qquad \Delta\bar{\Omega}_M = 1/\sqrt{\Sigma w_i}$$

with $w_i = 1/\Delta\Omega^2_{M,i}$

(assuming no correlation between measurements)

Tension between two extremes values computed as:

$$T = \frac{\Omega_{M,1} - \Omega_{M,2}}{\sqrt{\Delta\Omega^2_{M,1} + \Delta\Omega^2_{M,2}}} = 2.7\sigma$$



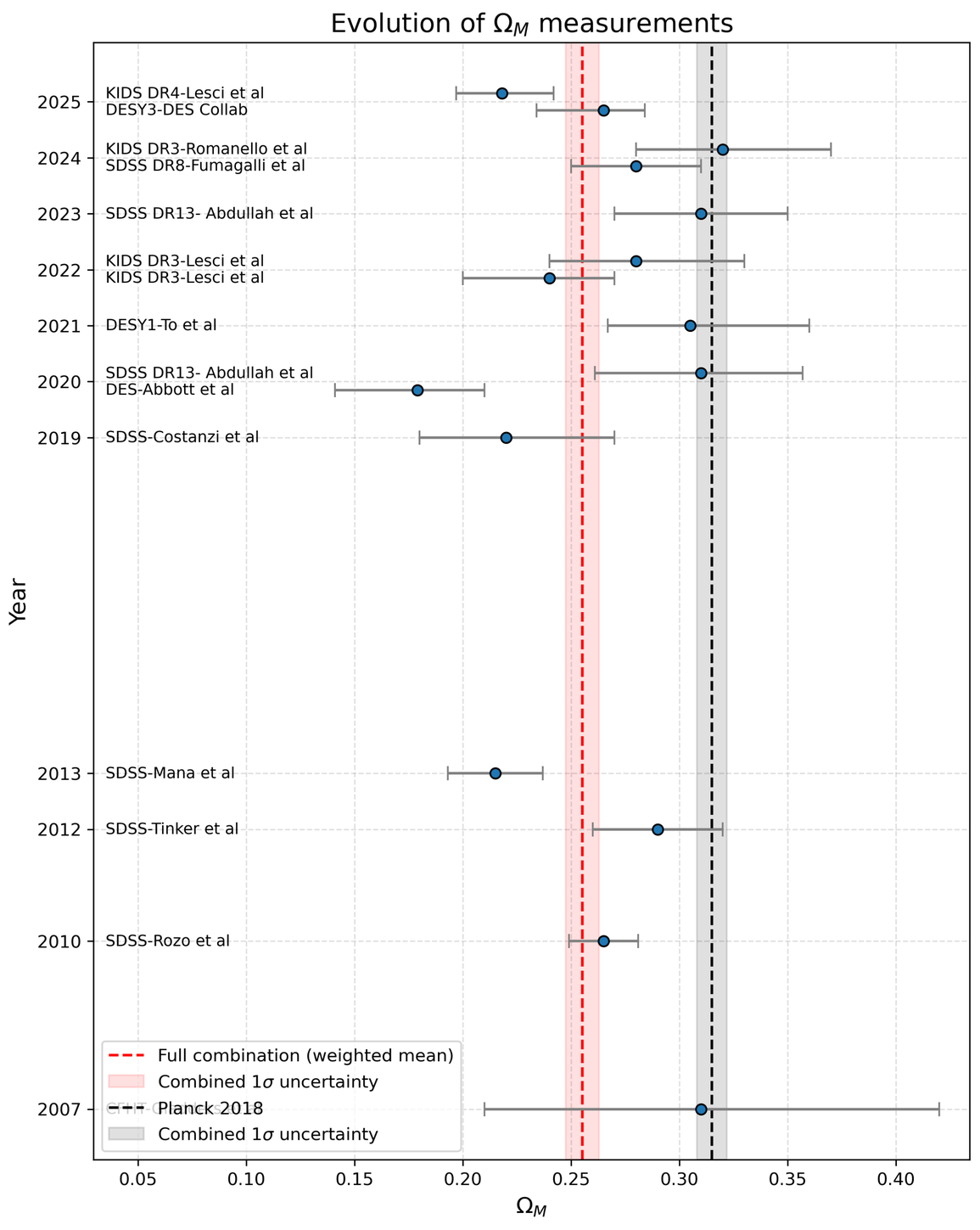
Comparison with Planck

$$\bar{\Omega}_M^{\,clusters} = 0.255 \pm 0.008$$

$$\bar{\Omega}_M^{\,Planck} = 0.315 \pm 0.007$$

Similar precision !

$\rightarrow T = 5.7\sigma$ with Planck



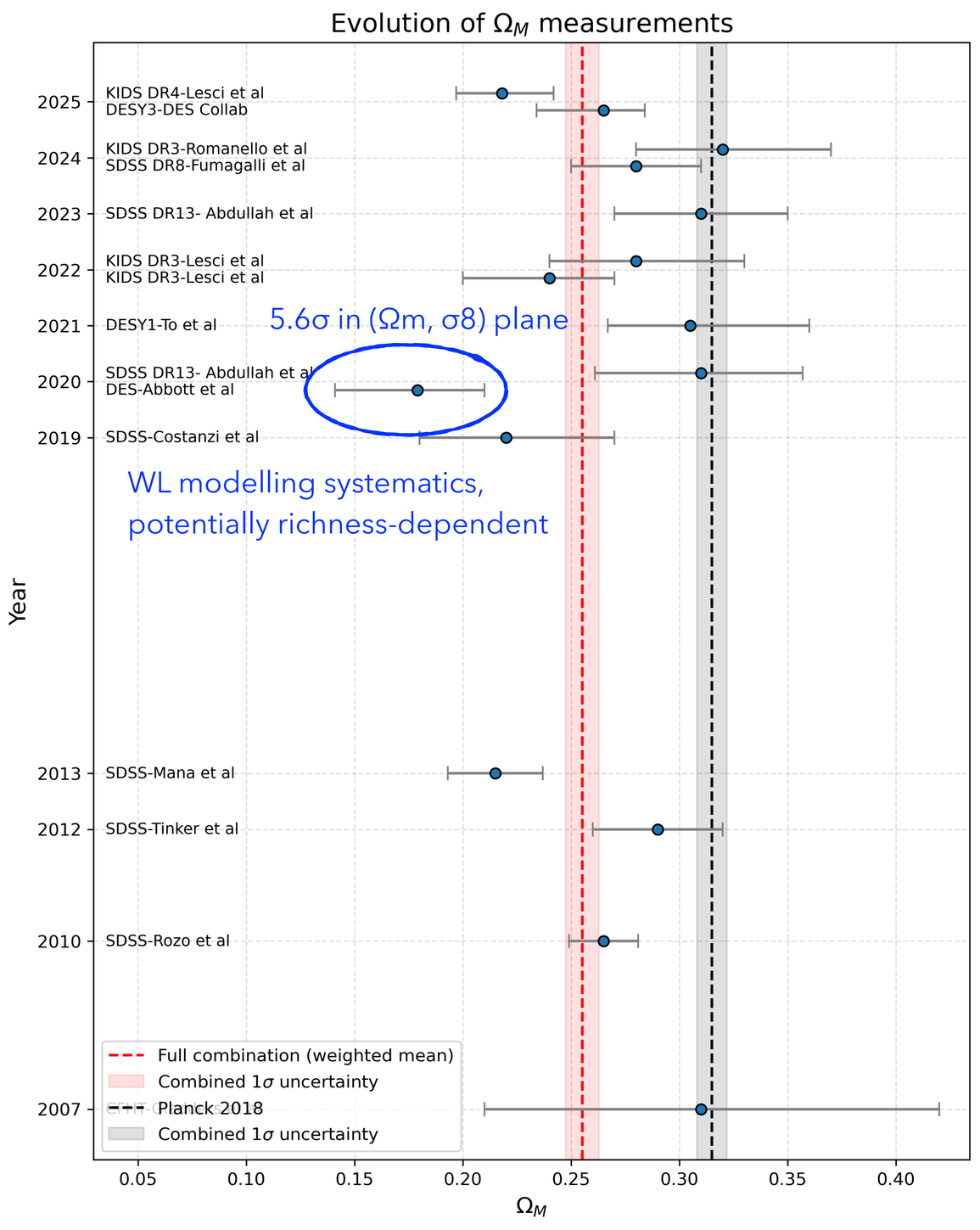
Comparison with Planck

$$\bar{\Omega}_M^{\,clusters} = 0.255 \pm 0.008$$

$$\bar{\Omega}_M^{\,Planck} = 0.315 \pm 0.007$$

Similar precision !

$\rightarrow T = 5.7\sigma$ with Planck



Global consistency test

What is the consistency between the individual Ωm measurements ?

If measurements are independent and their Gaussian uncertainties are correctly estimated, their scatter around a common value should be consistent with these uncertainties
-> χ^2 distribution with:

$$\chi^2 = \Sigma \frac{(\Omega_{M,i} - \bar{\Omega}_M)^2}{\Delta\Omega^2_{M,i}}$$

$$\chi^2_{red} = \frac{\chi^2}{N-1} \sim 1$$

N=15

In our case:

$$\chi^2_{red} = 1.52$$

Global consistency test

If χ_{red}^2>1, scatter is too large -> insufficient uncertainties ?

By how much should we inflate uncertainties to get χ_{red}^2~1 ?

Birge ratio:

$$f_{Birge} = max(1, \sqrt{\chi^2_{red}})$$

Global consistency test

If χ_{red}^2>1, scatter is too large -> insufficient uncertainties ?

By how much should we inflate uncertainties to get χ_{red}^2~1 ?

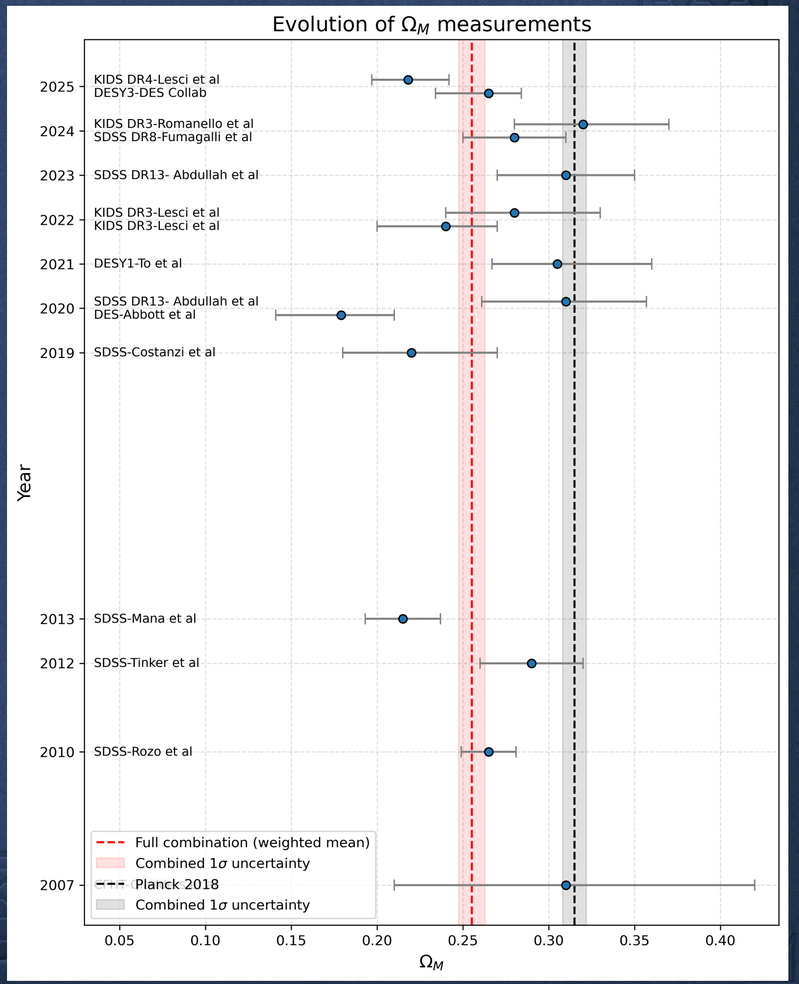
Birge ratio:

$$f_{Birge} = max(1, \sqrt{\chi^2_{red}})$$

In our case

$$f_{Birge} = 1.23$$

Uncertainties ~20% underestimated ?



Global consistency test

If χ_{red}^2>1, scatter is too large -> insufficient uncertainties ?

By how much should we inflate uncertainties to get χ_{red}^2~1 ?

Birge ratio:

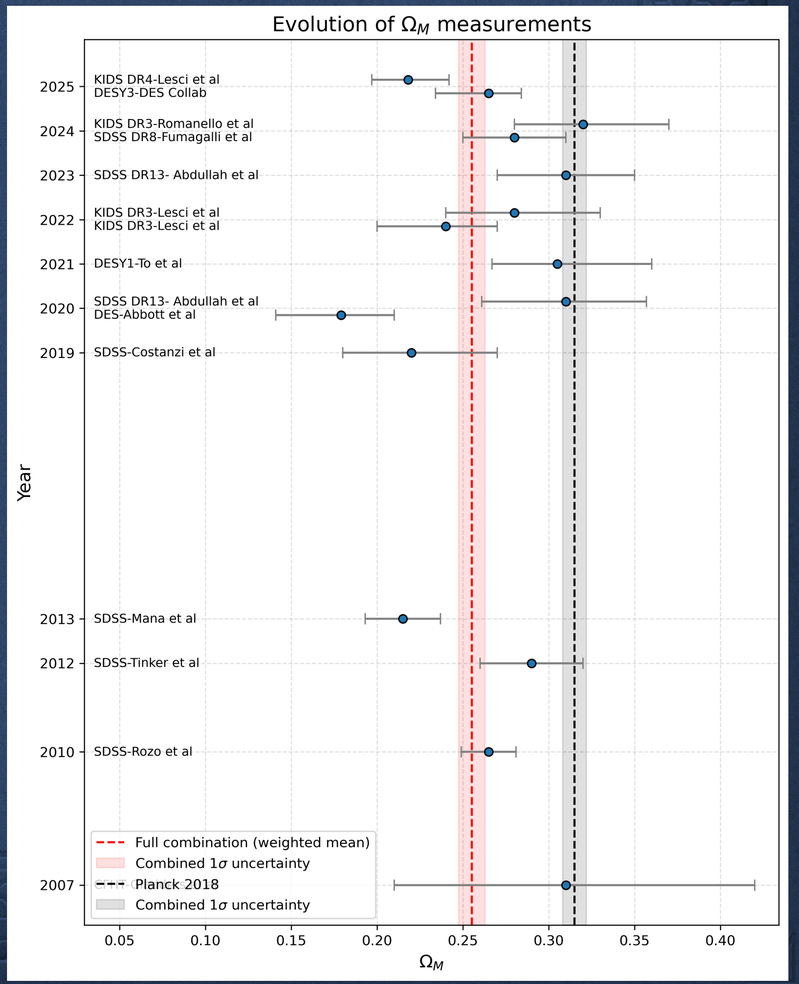
$$f_{Birge} = max(1, \sqrt{\chi^2_{red}})$$

In our case

$$f_{Birge} = 1.23$$

Uncertainties ~20% underestimated ?

Inflating uncertainties by 20%, tension become 5σ



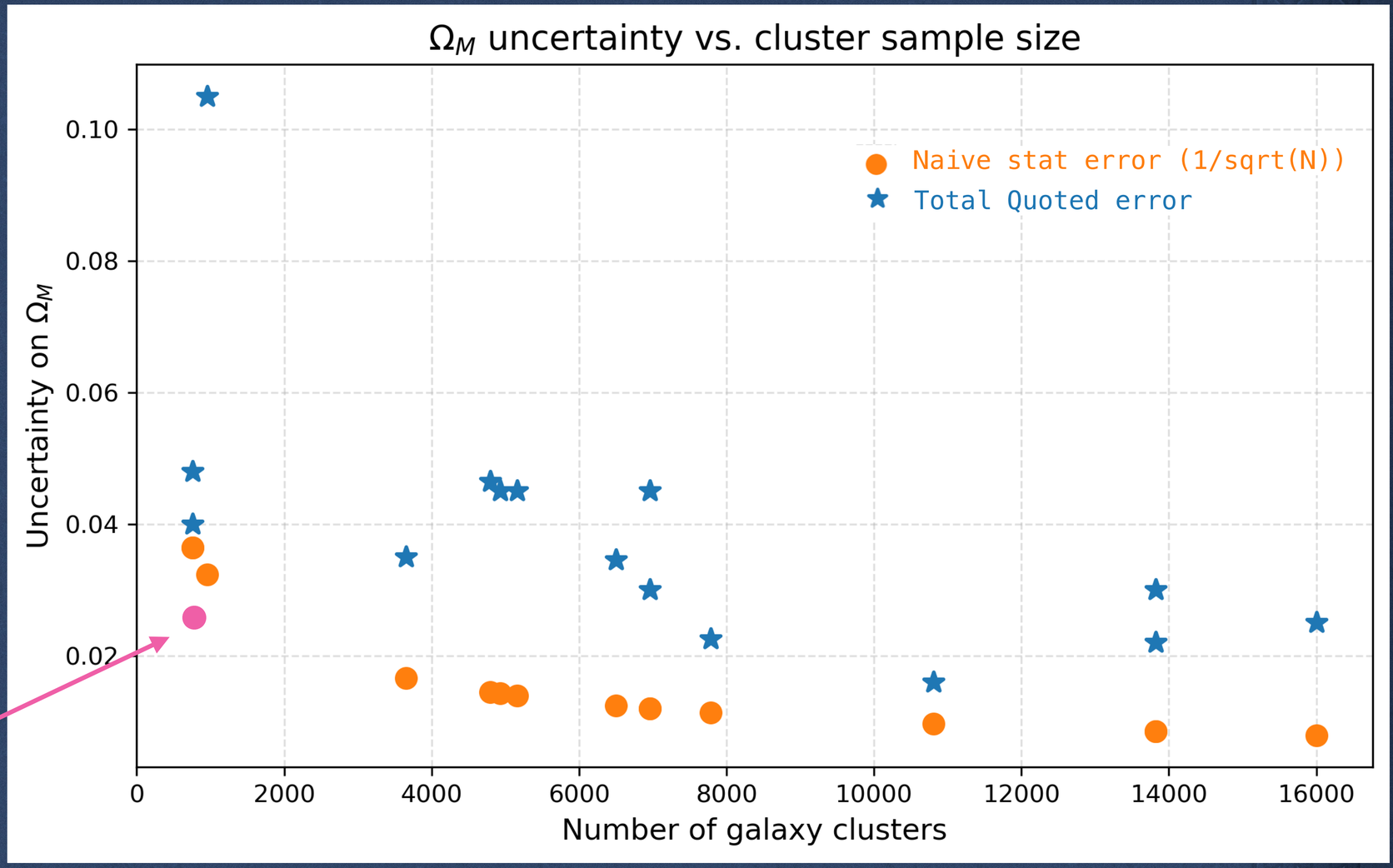
Systematic and statistical uncertainties

Systematic uncertainties clearly dominate almost everywhere

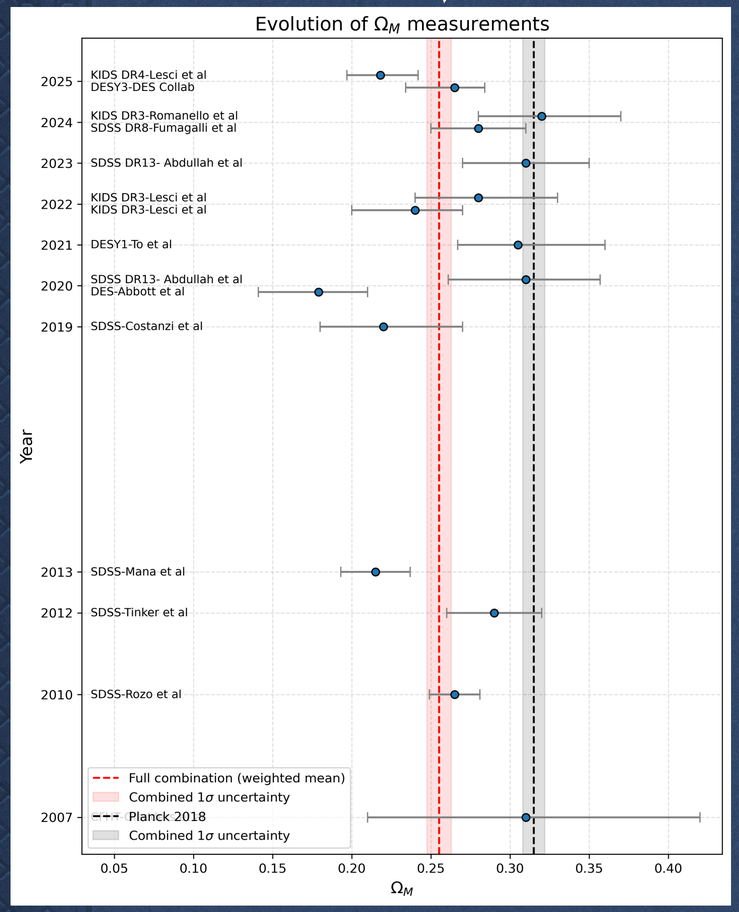
Only one paper provides a breakdown between the two:

Abdullah 2020

$\Omega_M = 0.310^{+0.023}_{-0.027}\ (\text{stat}) \ \pm 0.041\ (\text{syst})$

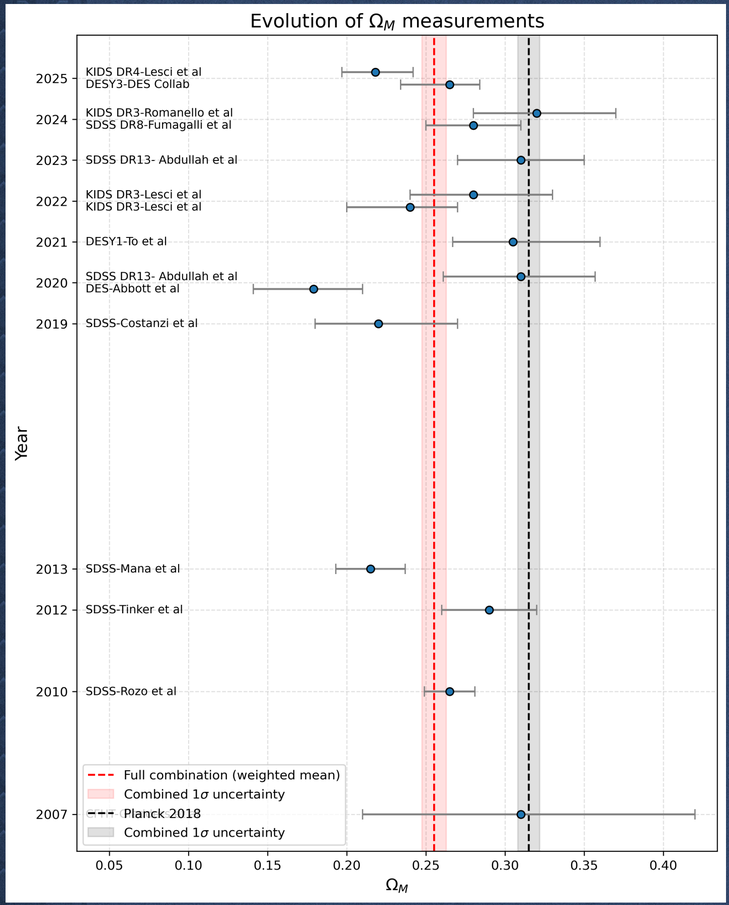


2+ categories of measurements ?



Measurement method

2+ categories of measurements ?

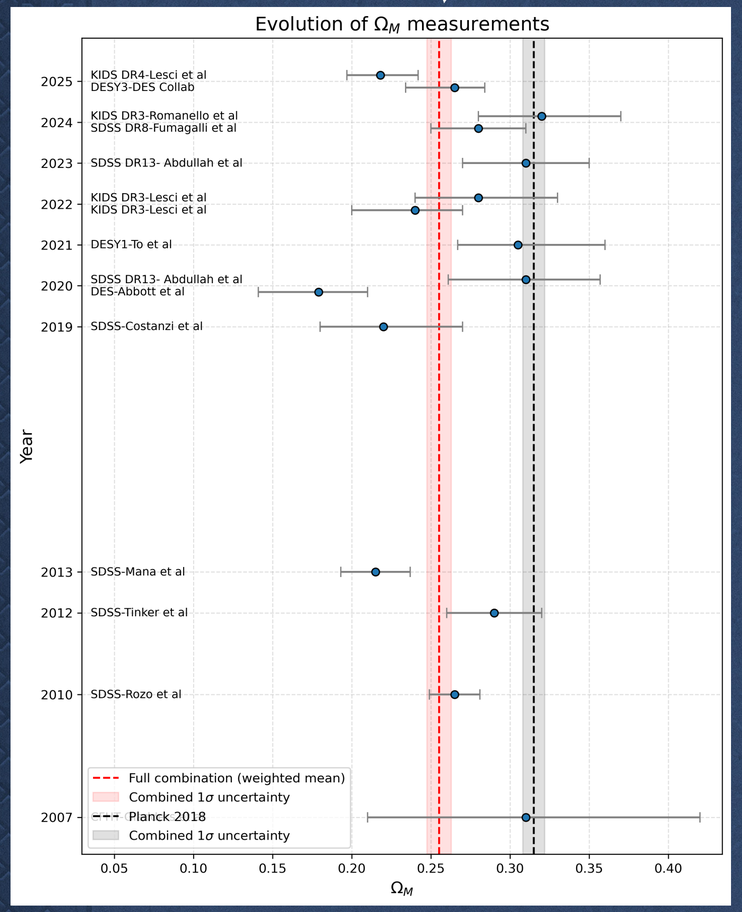


Count only

Paper and authors	Year	Survey / telescope	Method	Number of clusters
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Measurement method

2+ categories of measurements ?



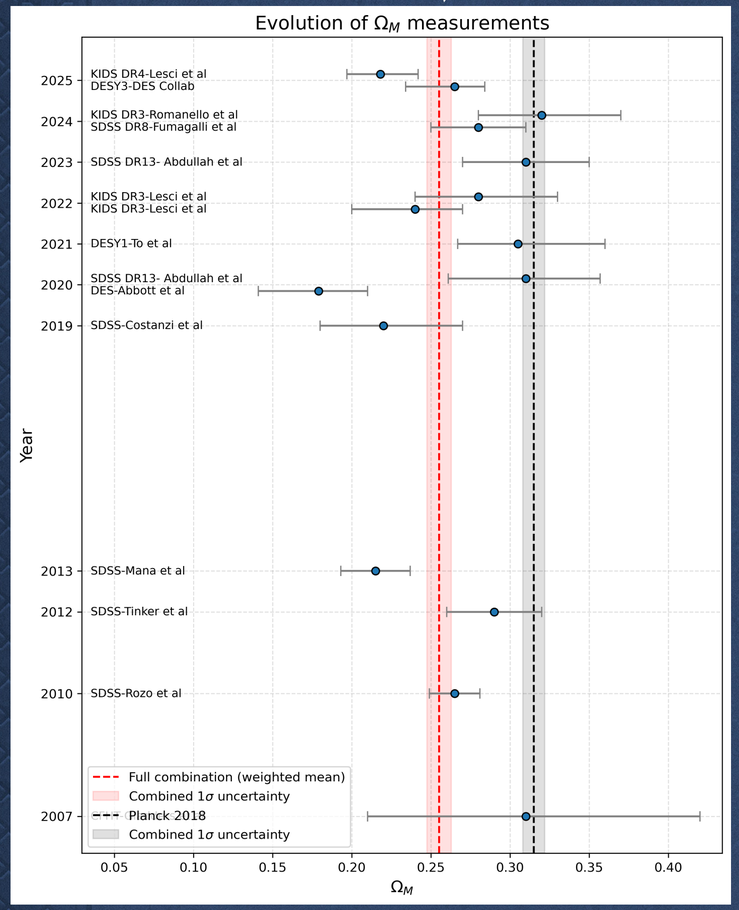
Count only

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Measurement method

2+ categories of measurements ?



Count only

Count +WL

Others (PS, CC, CMB, …)

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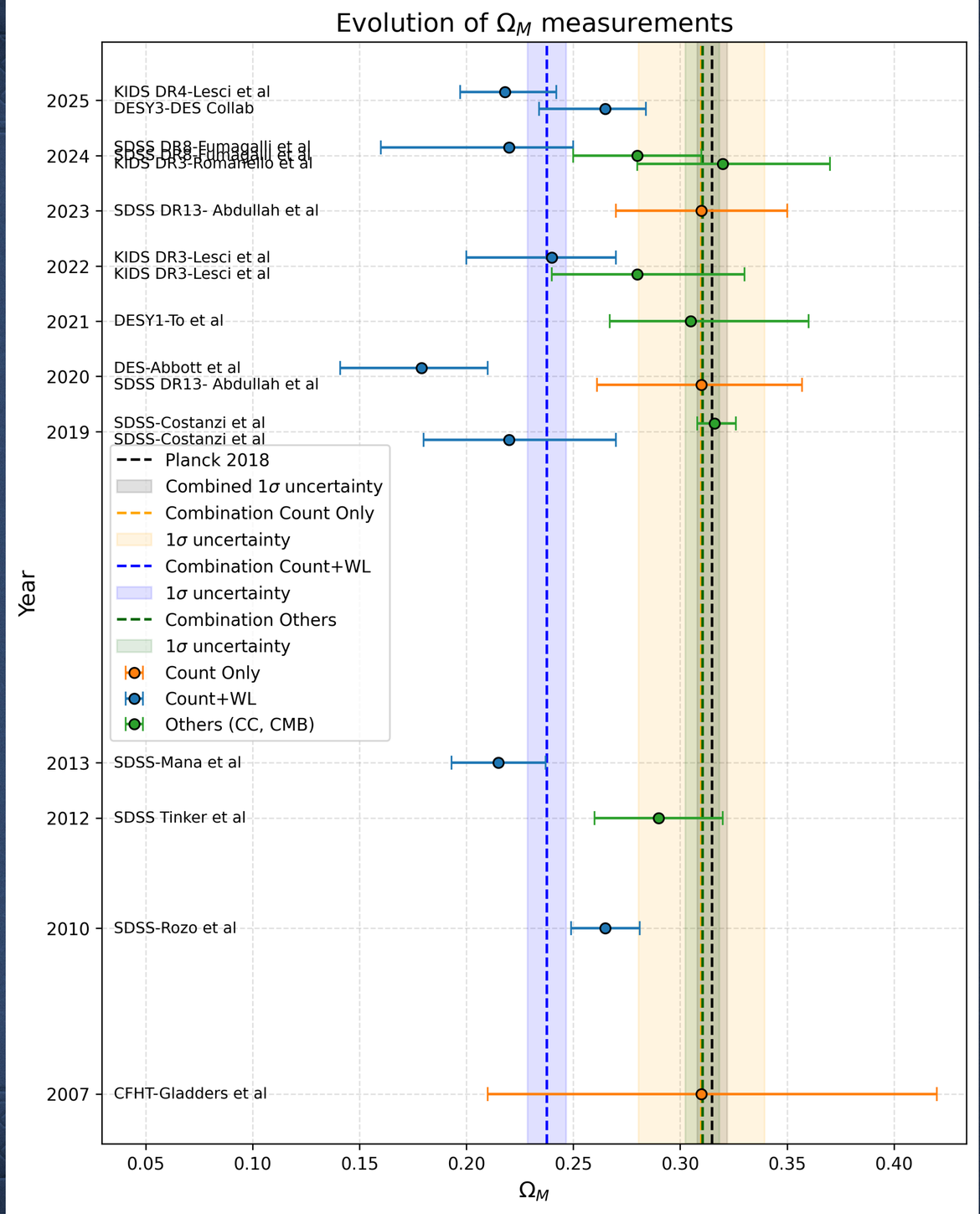
Combination by measurement method

Count only
Count +WL
Others (PS, CC, CMB, …)

$$\Omega_M^{count} = 0.310 \pm 0.029$$

$$\Omega_M^{WL} = 0.238 \pm 0.009$$

$$\Omega_M^{Others} = 0.310 \pm 0.008$$



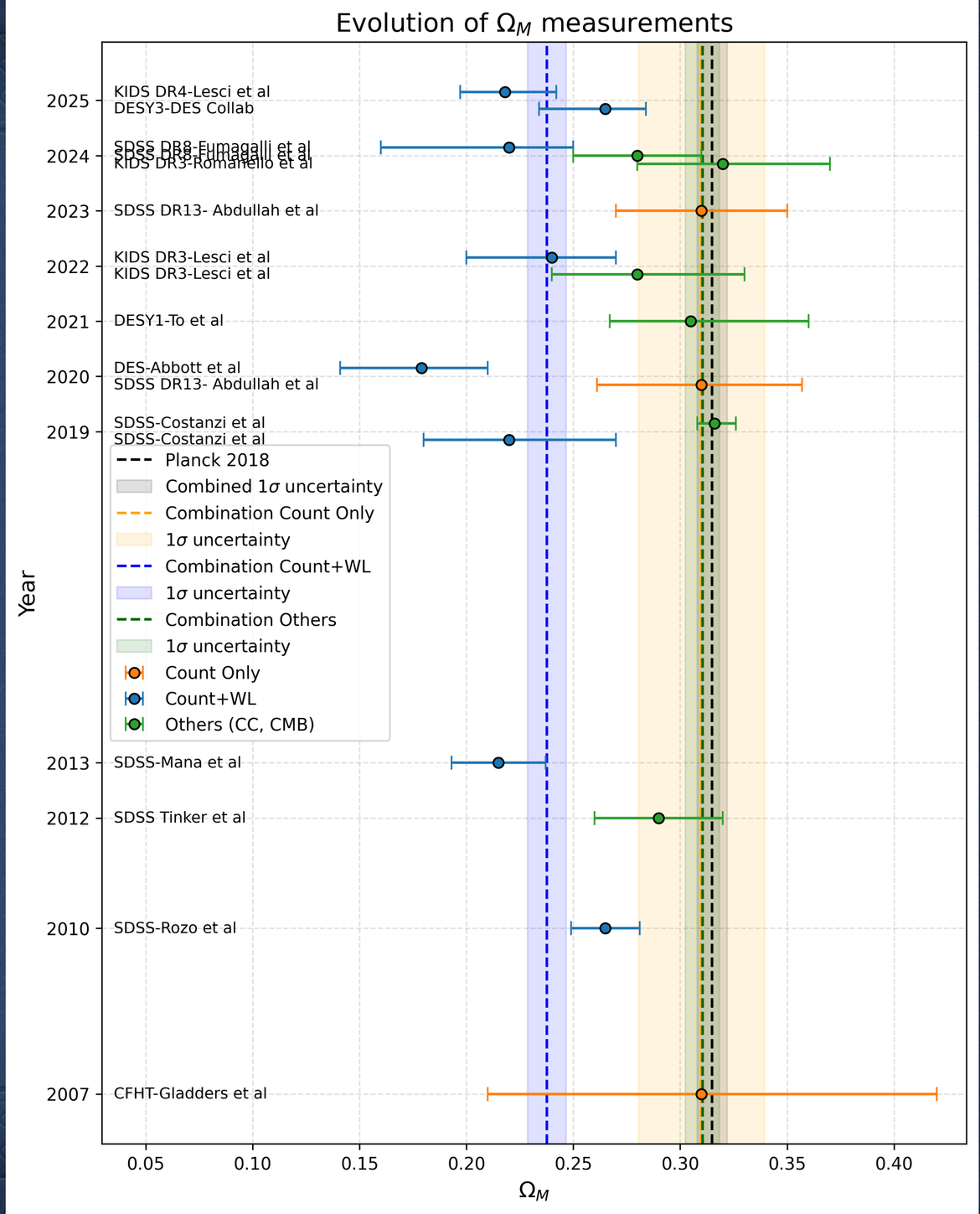
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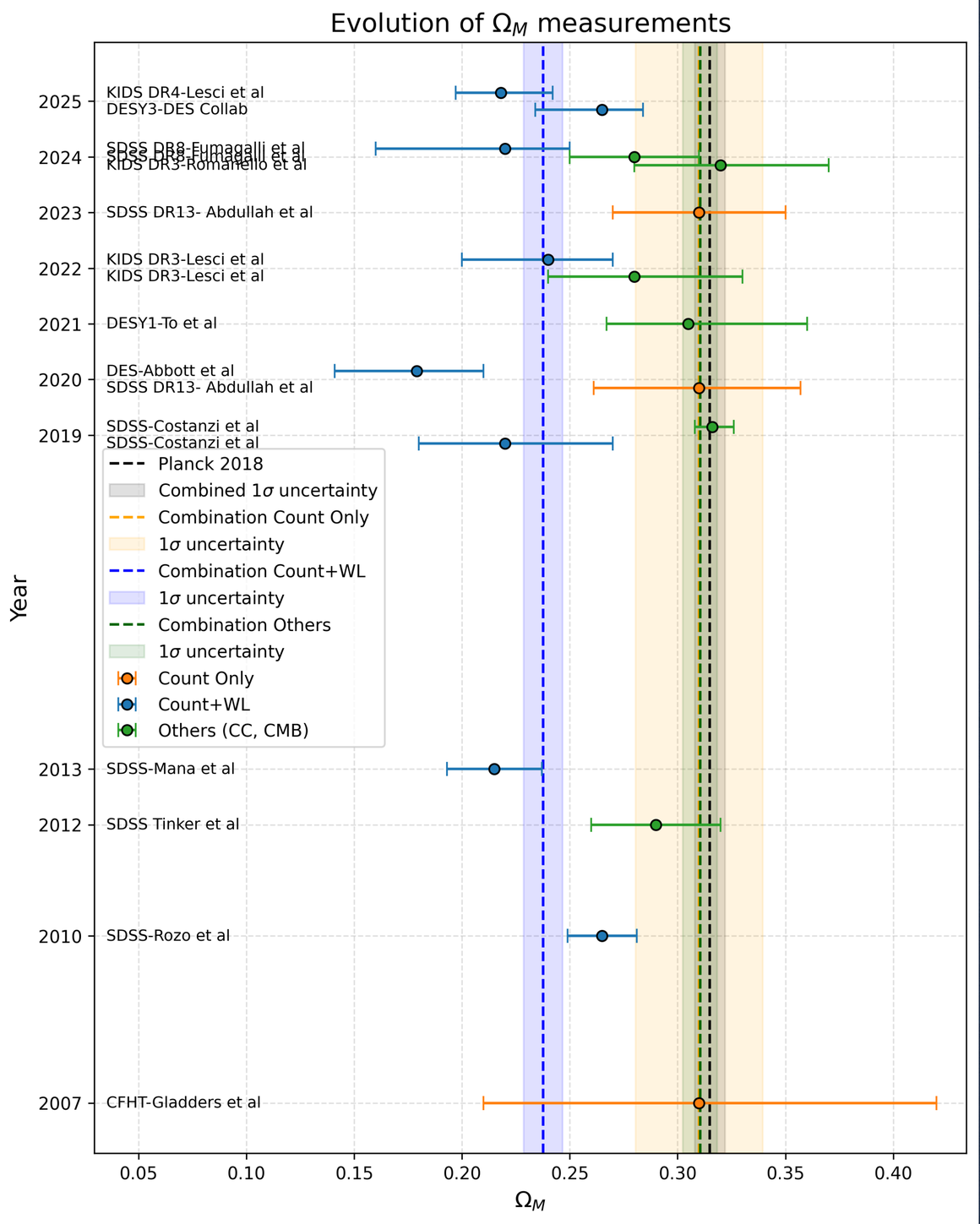
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Tensions:

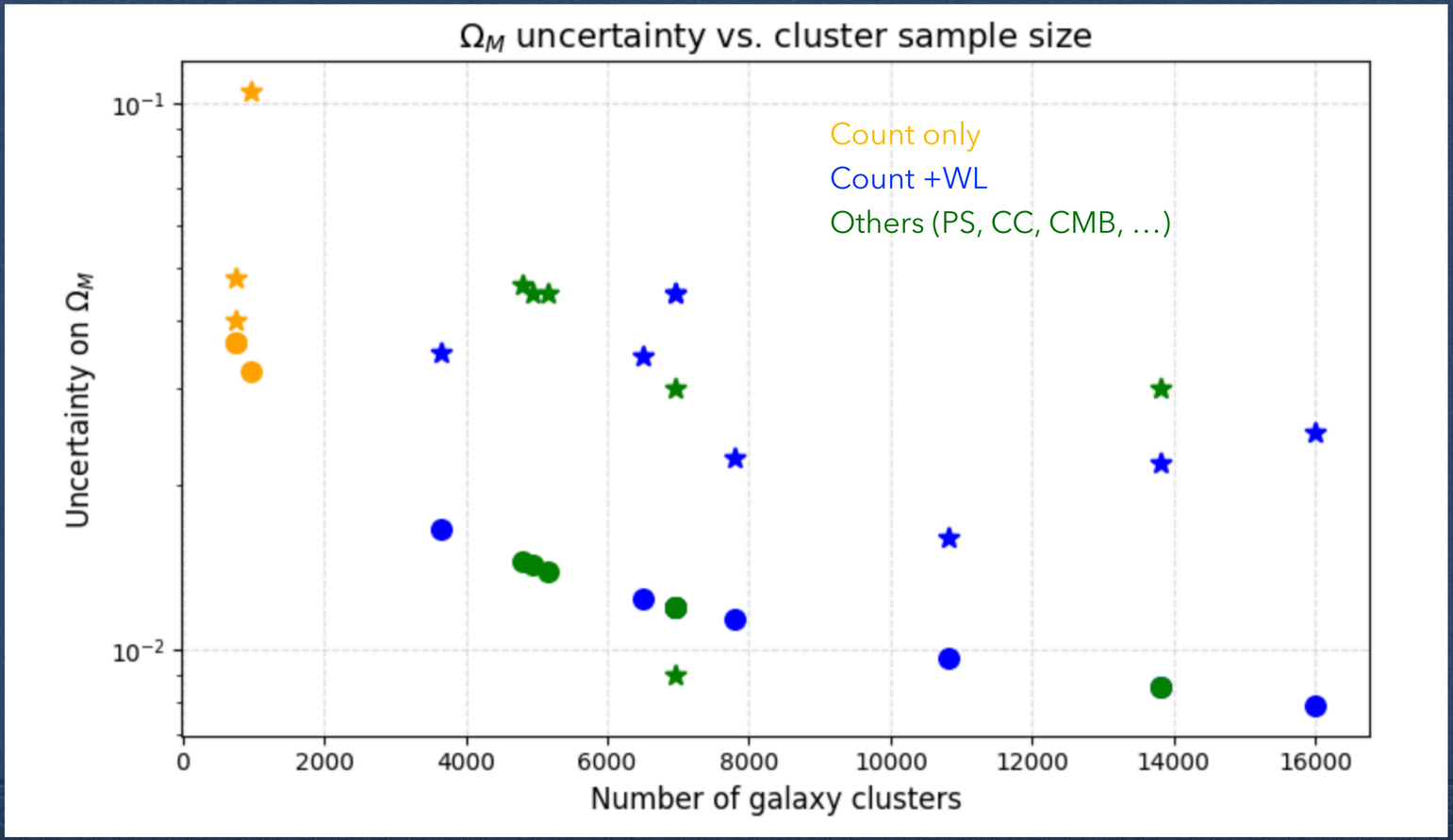
$$T(WL - Planck) = 6.8\sigma\ !$$

$$T(WL - Others) = 6.1\sigma$$



Systematic uncertainties by method

WL and Others method don’t show significant differences

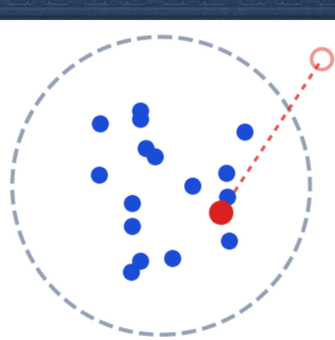


Tensions or missing uncertainties ?

Tensions or missing uncertainties ?

Detection :

- Cluster finder (Redmapper, WaZP, AMICO)
- Completeness/purity
- Projections effect

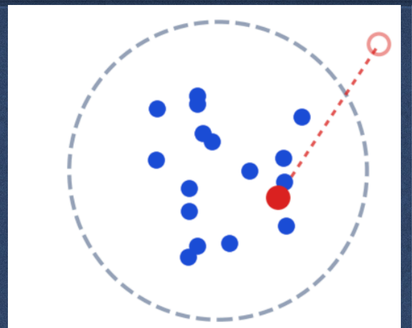


Projection effects
Foreground/background galaxy mistaken for a member

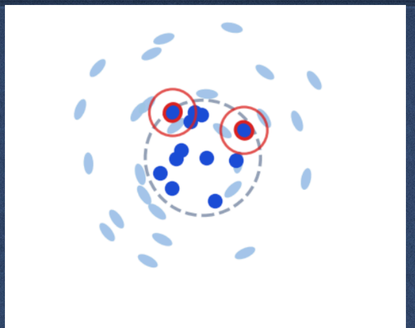
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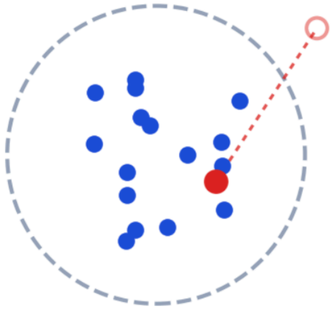
Member contamination
True member scattered into the source sample

Tensions or missing uncertainties ?

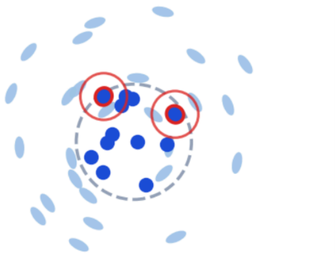
E. Barroso

Detection :

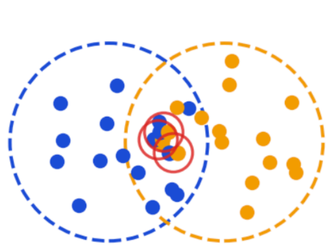
- Cluster finder (Redmapper, WaZP, AMICO)
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- Member contamination
- Shared members



Projection effects
Foreground/background galaxy mistaken for a member



Member contamination
True member scattered into the source sample



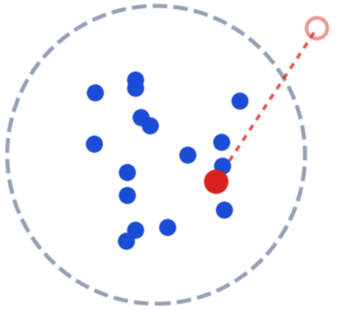
Shared Members
Overlapping clusters, ambiguous membership

Tensions or missing uncertainties ?

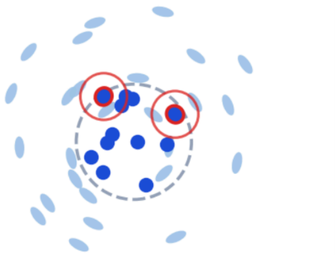
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Detection :

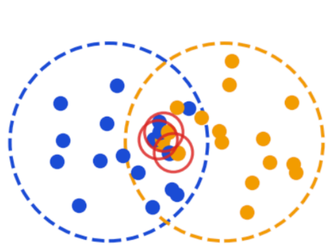
- Cluster finder (Redmapper, WaZP, AMICO)
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- Member contamination
- Shared members
- Photometric redshift



Projection effects
Foreground/background galaxy mistaken for a member

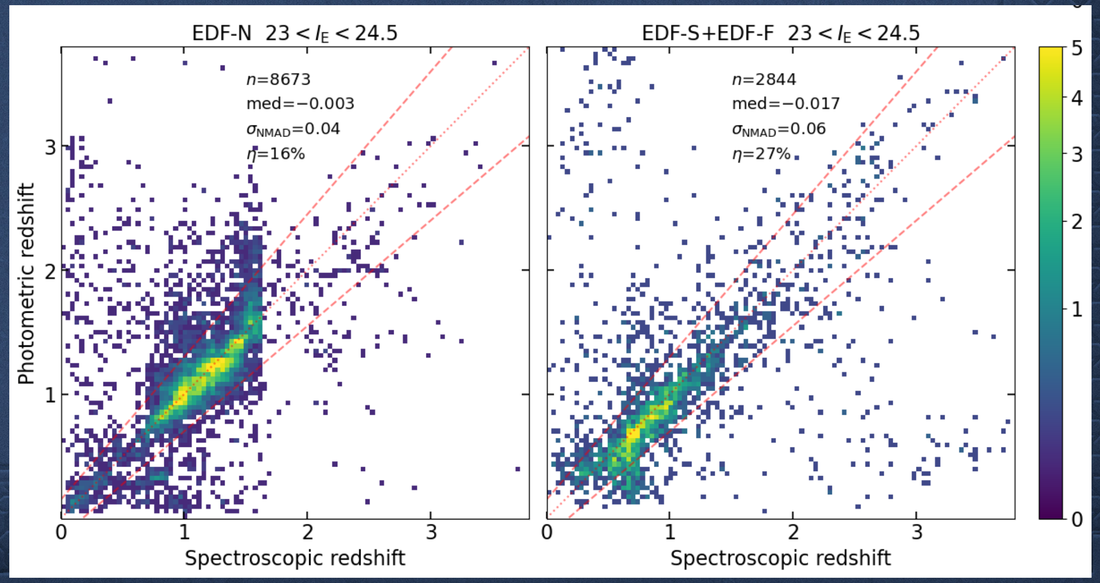


Member contamination
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Shared Members
Overlapping clusters, ambiguous membership

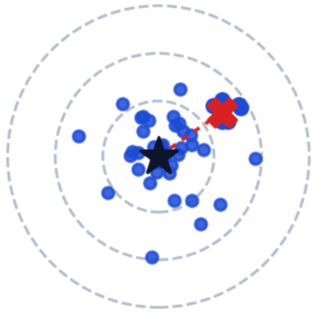
Euclid Quick Data Release (Q1) – V. Photometric redshifts and physical properties of galaxies through the PHZ processing function.



Tensions or missing uncertainties ?

Weak lensing

- Miscentering

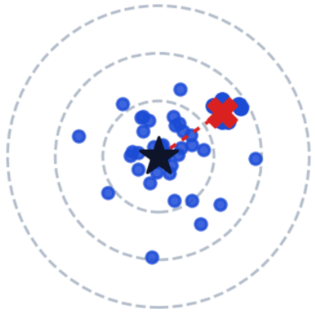


Miscentering
Assumed center offset from the true halo center

Tensions or missing uncertainties ?

Weak lensing

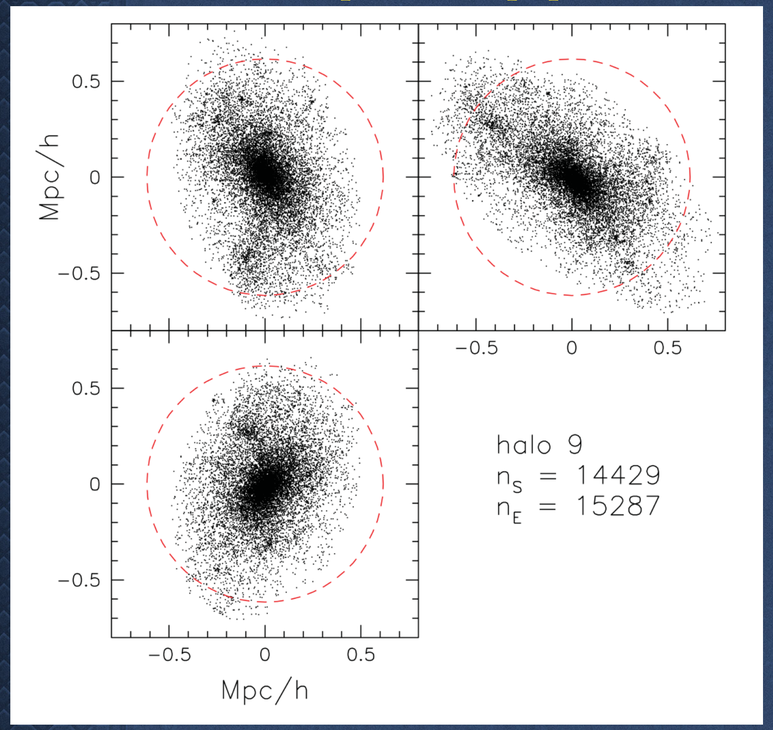
- Miscentering
- Triaxiality / Orientation

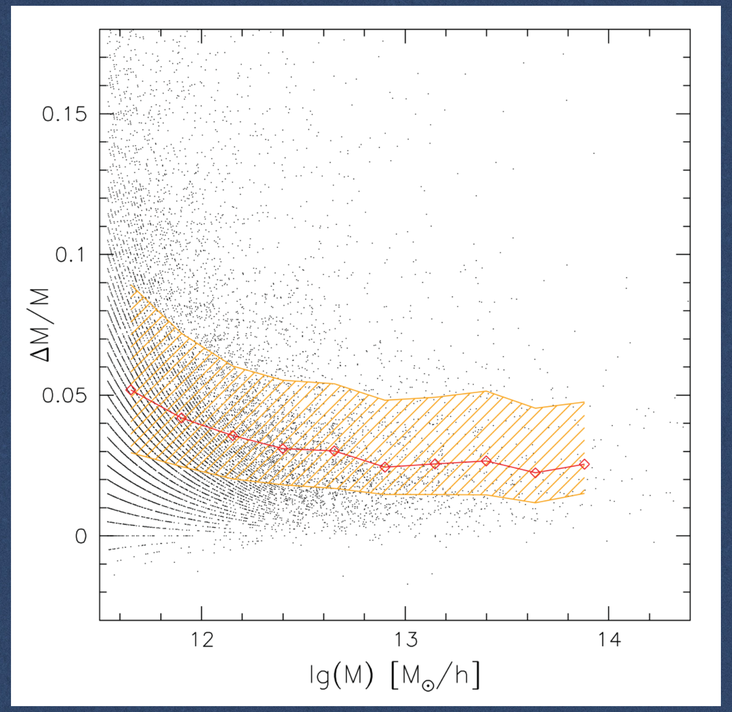


Miscentering
Assumed center offset from the true halo center

Triaxiality / Orientation

Despali 2013: paper





Biases due to spherical assumptions:

5-20% bias on cluster mass

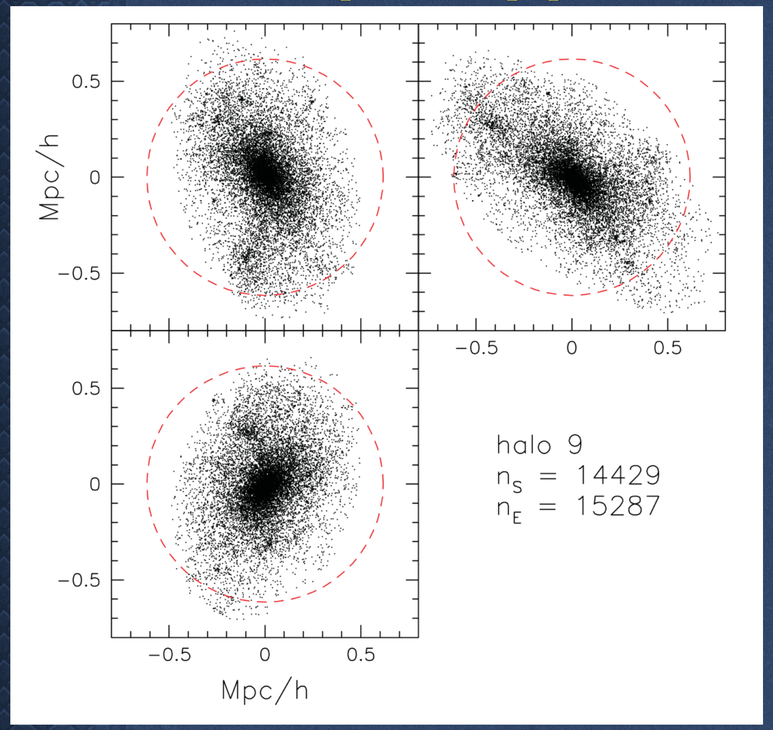
3-7% on σ_8,

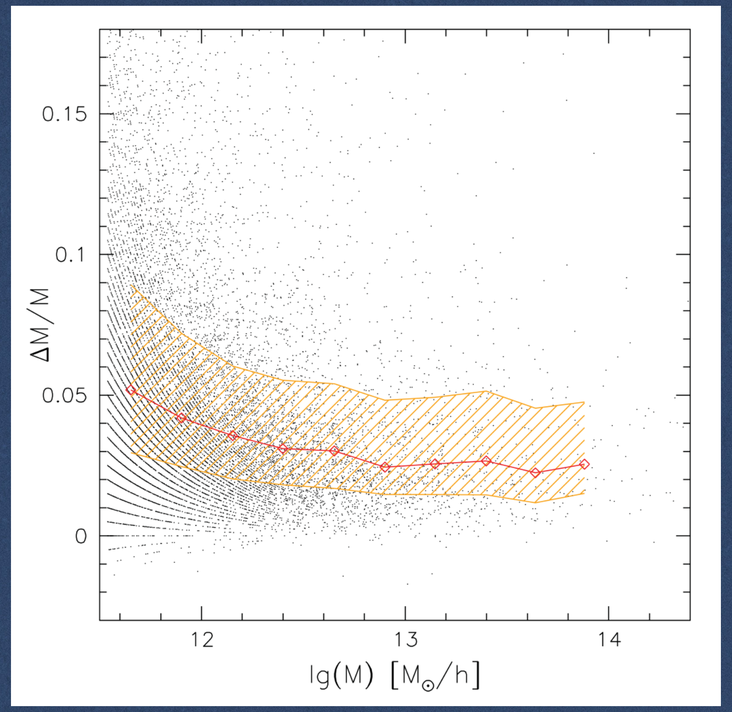
1-3% on Ωm

Shin et al. (2021), Dietrich et al. (2019)

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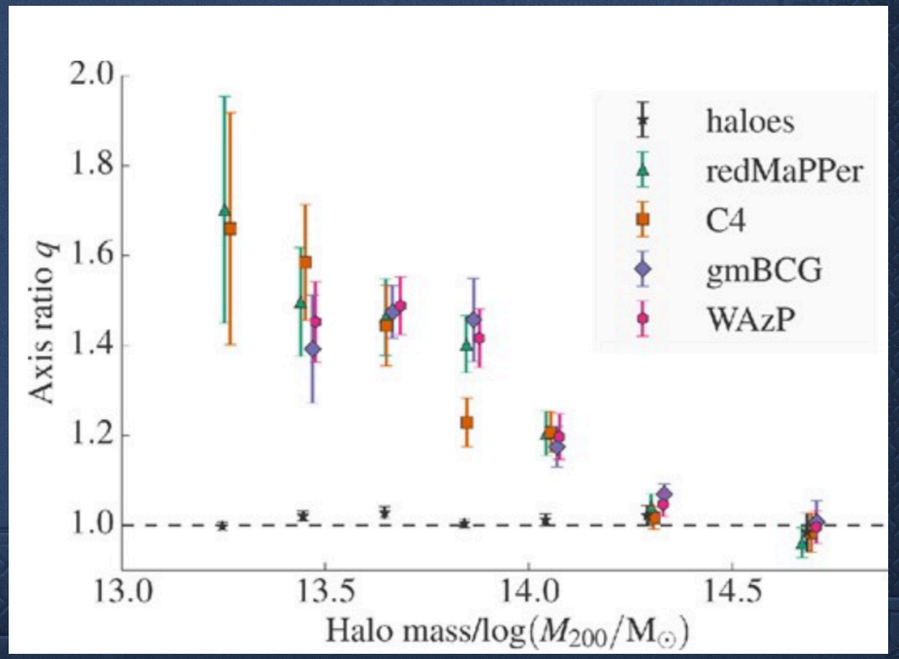
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1-3% on Ωm

Shin et al. (2021), Dietrich et al. (2019)

Tendency to select preferentially spherical clusters at large masses and elliptical clusters at smaller masses

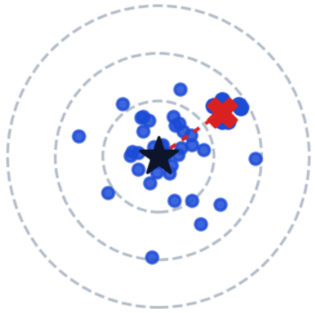
Dietrich et al « Orientation bias of optically selected galaxy clusters and its impact on stacked weak-lensing analyses » 2014



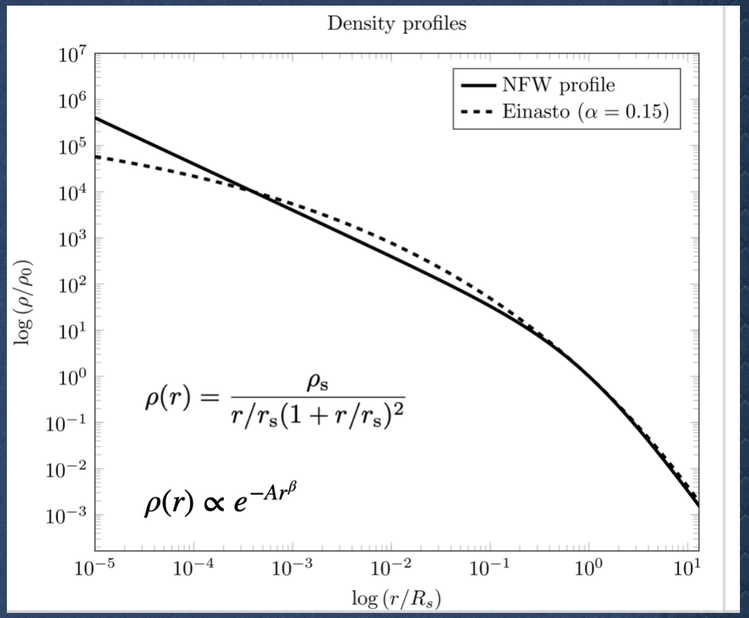
Tensions or missing uncertainties ?

Weak lensing

- Miscentering
- Triaxiality / Orientation
- Density profile (NFW, Einasto…)



Miscentering
Assumed center offset from the true halo center

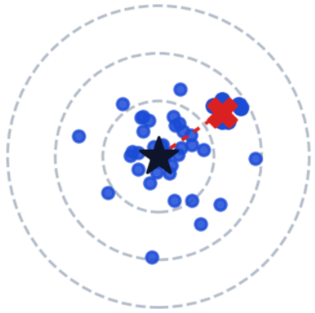


~7% uncertainty on cluster mass found by comparing these profiles in CLASH analysis (HST data) *https://arxiv.org/pdf/1507.04385*

Tensions or missing uncertainties ?

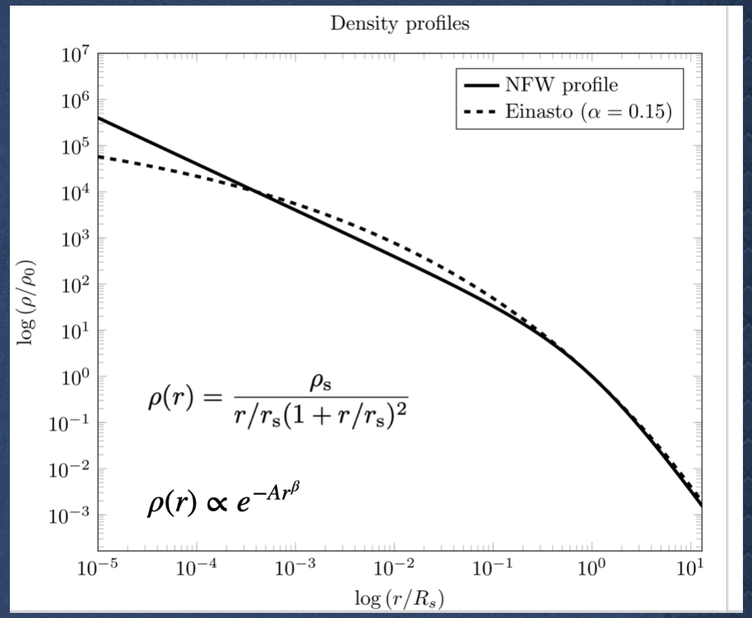
Weak lensing

- Miscentering
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- Density profile (NFW, Einasto…)
- Shear calibration
- Mass-concentration relation (see next talk !)



Miscentering

Assumed center offset from the true halo center

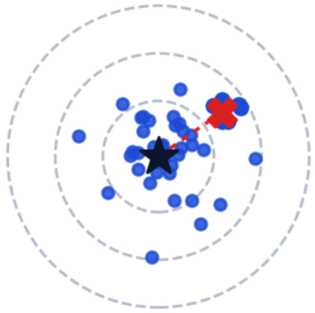


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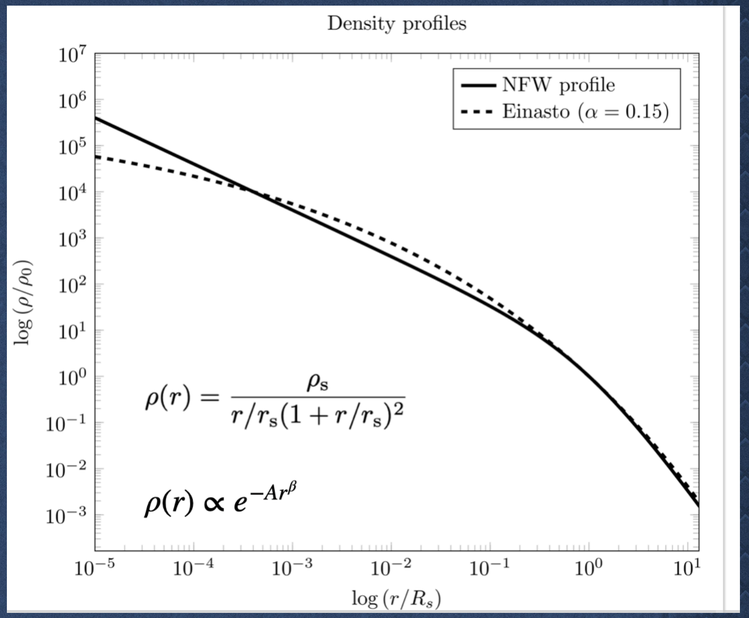
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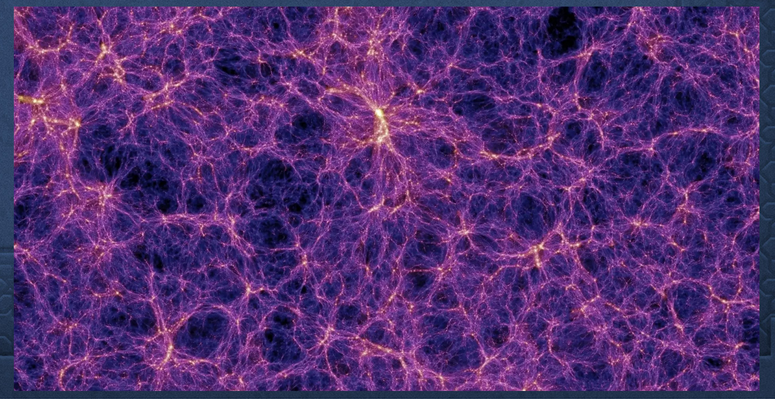
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- Density profile (NFW, Einasto…)
- Shear calibration
- Mass-concentration relation (see next talk !)
- Intrinsic alignement



Miscentering
Assumed center offset from the true halo center



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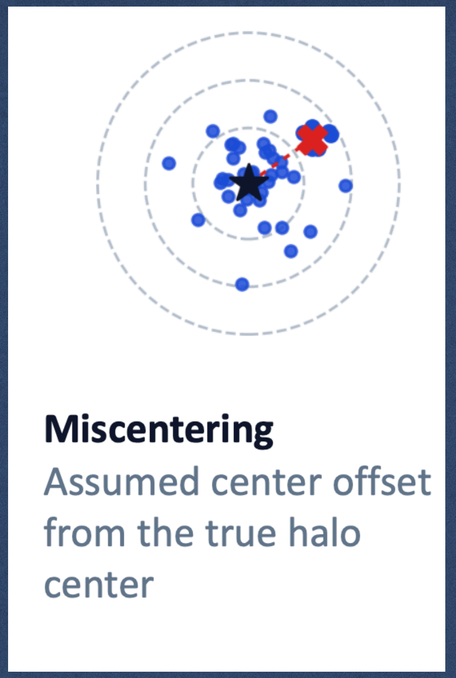
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Weak lensing

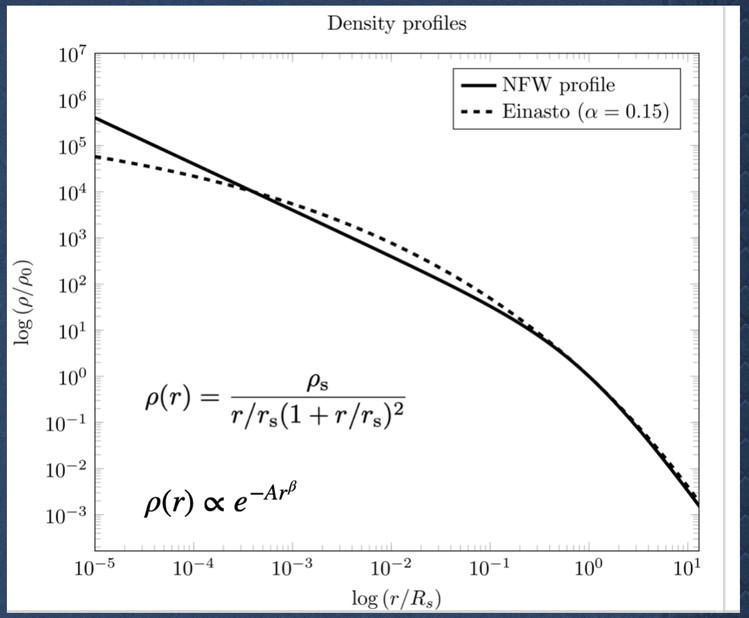
- Miscentering
- Triaxiality / Orientation
- Density profile (NFW, Einasto…)
- Shear calibration
- Mass-concentration relation (see next talk !)
- Intrinsic alignement
- Thin lens approximation
- Born approximation

+ other relativistic effects (next talk !)

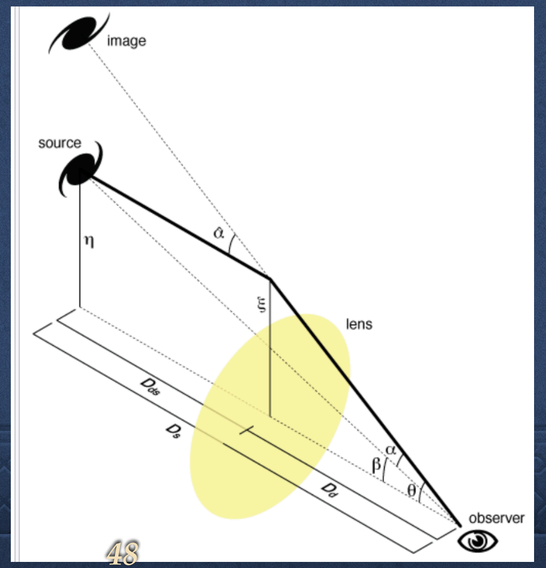
~5-15% effects

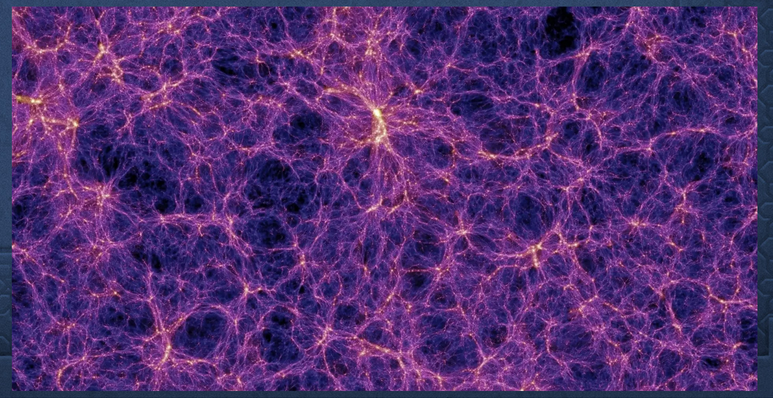


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Tensions or missing uncertainties ?

Modeling

- HMF

Halo Mass Function

σ = variance of matter density field

$$\frac{dn}{dM} = f(\sigma)\frac{\bar{\rho}_{\rm m}}{M}\frac{d\ln\sigma^{-1}}{dM},$$

$$\sigma^2(M,z) = \int \frac{1}{2\pi^2} P_{\rm lin}(k,z) W^2[kR(M)] k^2 {\rm d}k,$$

depends on which cosmo you assume !

Multiplicity function :

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right]\exp\left(-\frac{c}{\sigma^2}\right)$$

(Exemple from Bocquet16)

Arbitrary function fitted on simulations (universality idea)

Halo Mass Function

σ = variance of matter density field

$$\frac{dn}{dM} = f(\sigma)\frac{\bar{\rho}_{\rm m}}{M}\frac{d\ln\sigma^{-1}}{dM},$$

$$\sigma^2(M,z) = \int \frac{1}{2\pi^2} P_{\rm lin}(k,z) W^2[kR(M)] k^2 {\rm d}k,$$

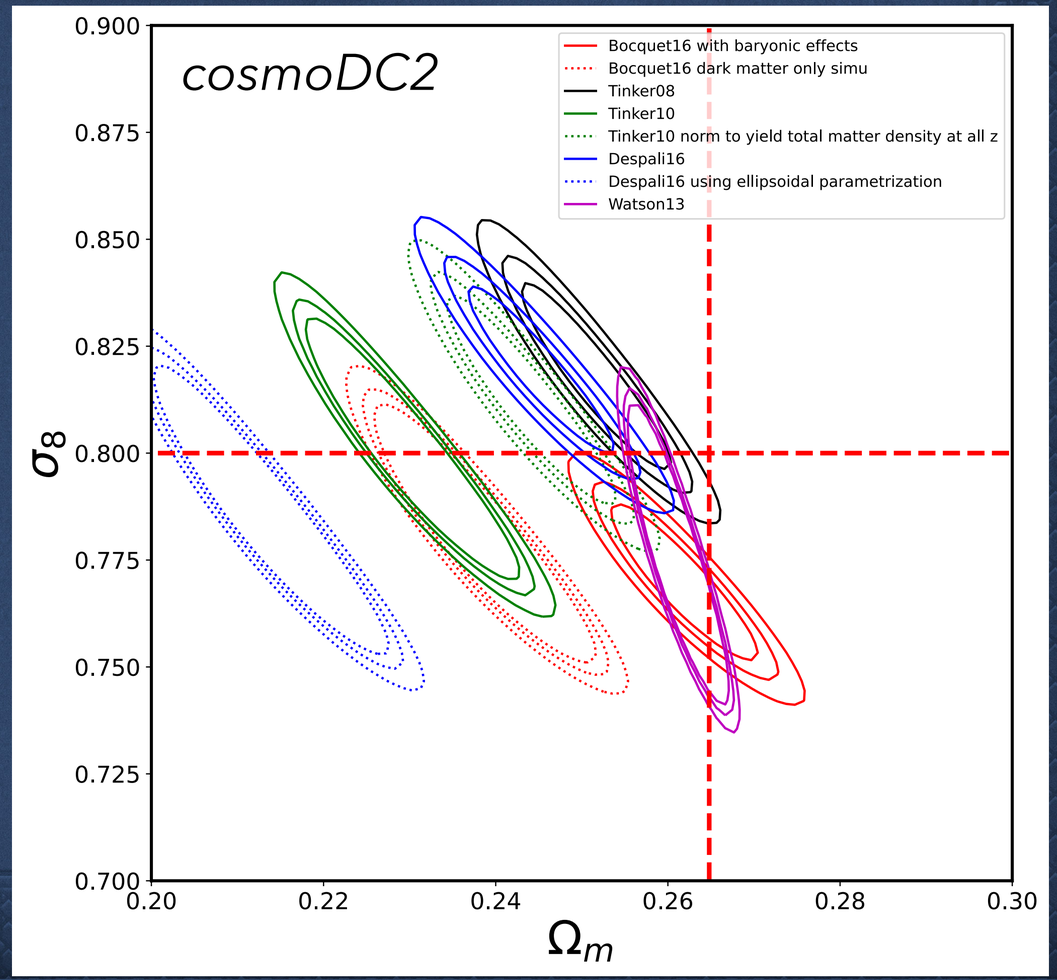
depends on which cosmo you assume !

Multiplicity function :

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right]\exp\left(-\frac{c}{\sigma^2}\right)$$

(Exemple from Bocquet16)

Arbitrary function fitted on simulations (universality idea)



Halo Mass Function

σ = variance of matter density field

$$\frac{dn}{dM} = f(\sigma)\frac{\bar{\rho}_{\rm m}}{M}\frac{d\ln\sigma^{-1}}{dM},$$

$$\sigma^2(M,z) = \int \frac{1}{2\pi^2} P_{\rm lin}(k,z) W^2[kR(M)] k^2 {\rm d}k,$$

depends on which cosmo you assume !

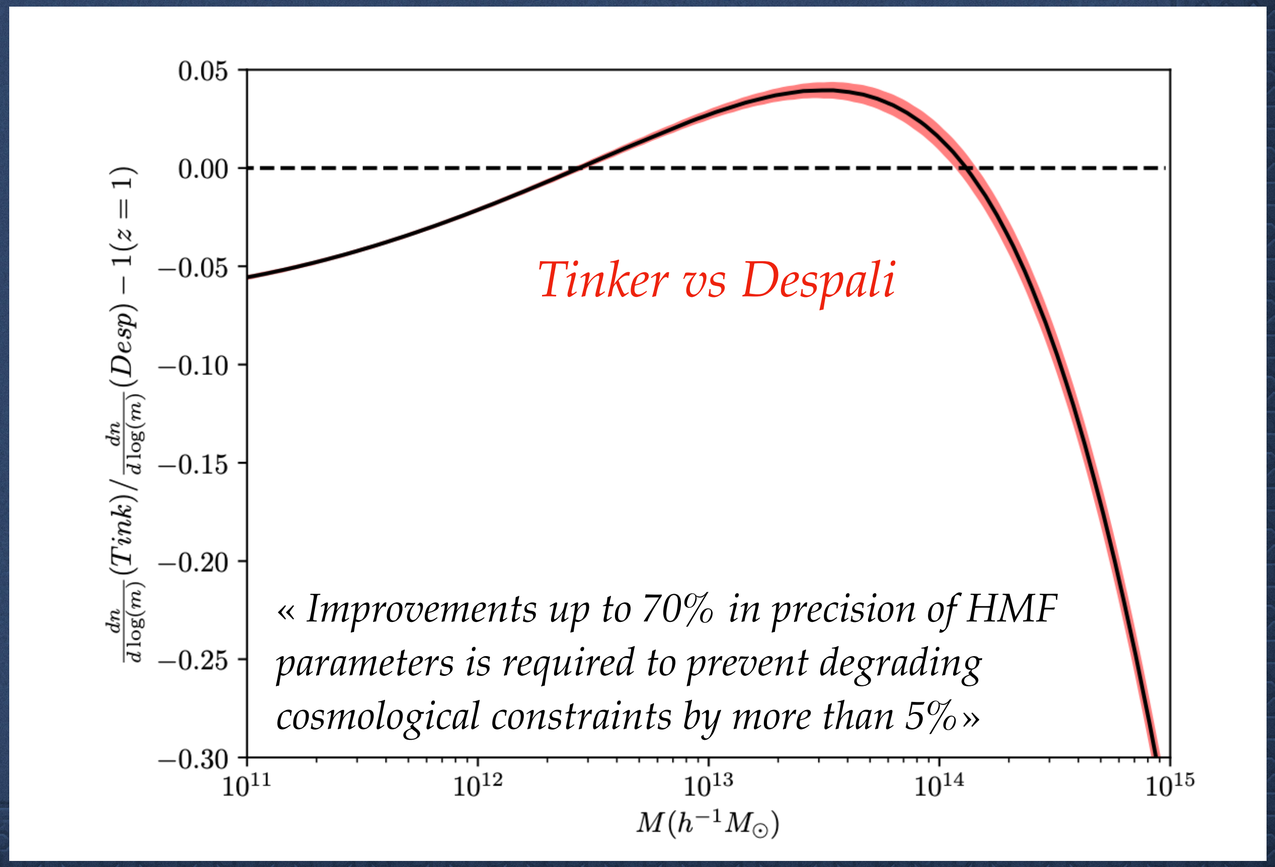
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Arbitrary function fitted on simulations (universality idea)

https://www.aanda.org/articles/aa/pdf/2021/05/aa40293-21.pdf



Tensions or missing uncertainties ?

Modeling

- HMF
- Mass/richness relation

$$P(\ln\lambda|m,z) = \frac{1}{\sqrt{2\pi}\sigma_{\ln\lambda|m,z}} \exp\left\{-\frac{[\ln\lambda - \langle\ln\lambda|m,z\rangle]^2}{2\sigma^2_{\ln\lambda|m,z}}\right\},$$

where

redshift dependence — mass dependence

$$\langle\ln\lambda|m,z\rangle = \ln\lambda_0 + \mu_z \ln\left(\frac{1+z}{1+z_0}\right) + \mu_m \log_{10}\left(\frac{m}{m_0}\right),$$

offset richness

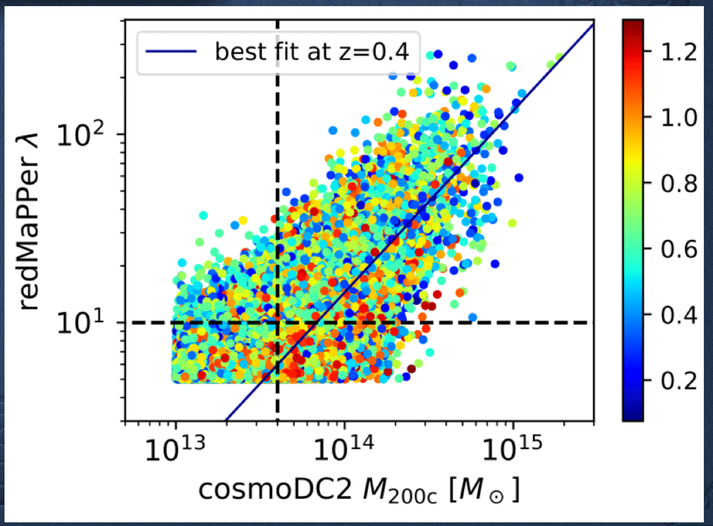
and

mass dependencie of variance

offset variance

$$\sigma_{\ln\lambda|m,z} = \sigma_{\ln\lambda_0} + \sigma_z \ln\left(\frac{1+z}{1+z_0}\right) + \sigma_m \log_{10}\left(\frac{m}{m_0}\right).$$

redshift dependencie of variance



Tensions or missing uncertainties ?

Modeling

- HMF
- Mass/richness relation
- Halo bias model
- Baryonic physics

$$P(\ln\lambda|m,z) = \frac{1}{\sqrt{2\pi}\sigma_{\ln\lambda|m,z}} \exp\left\{-\frac{[\ln\lambda - \langle\ln\lambda|m,z\rangle]^2}{2\sigma^2_{\ln\lambda|m,z}}\right\},$$

where

redshift dependence — mass dependence

$$\langle\ln\lambda|m,z\rangle = \ln\lambda_0 + \mu_z \ln\left(\frac{1+z}{1+z_0}\right) + \mu_m \log_{10}\left(\frac{m}{m_0}\right),$$

offset richness

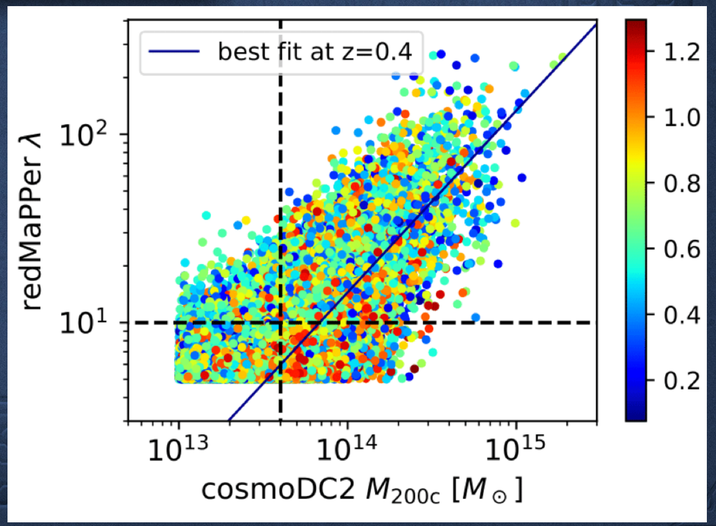
and

mass dependencie of variance

offset variance

$$\sigma_{\ln\lambda|m,z} = \sigma_{\ln\lambda_0} + \sigma_z \ln\left(\frac{1+z}{1+z_0}\right) + \sigma_m \log_{10}\left(\frac{m}{m_0}\right).$$

redshift dependencie of variance



Summary of treated/discussed uncertainties

Paper	P/C	Proj	Sel-WL	Shear	z-src	z-cl	Miscent	Prof	Orient.
Gladders 2007	▲	▲	–	–	–	▲	–	–	–
Rozo 2010	✓	▲	✗	✓	✓	▲	▲	▲	▲
Tinker 2012	–	–	–	✓	✓	▲	▲	▲	▲
Mana 2013	▲	▲	▲	✓	✓	✓	▲	▲	▲
Costanzi 2019	▲	✓	▲	✓	✓	✓	✓	✓	✓
DES Y1 2020	▲	▲	▲	✓	✓	✓	✓	✓	✓
Abdullah 2020	▲	–	–	–	–	–	–	–	–
To 2021	▲	✓	✓	✓	✓	✓	✓	▲	▲
Lesci 2022a	▲	▲	▲	✓	✓	✓	✓	✓	▲
Lesci 2022b	▲	–	–	–	–	✓	–	–	–
Abdullah 2023	▲	–	–	–	–	▲	–	–	–
Fumagalli 2024	▲	▲	▲	✓	✓	✓	✓	✓	▲
Romanello 2024	▲	–	–	–	–	✓	–	–	–
DES Y3 2025	▲	✓	✓	✓	✓	✓	✓	✓	▲
Lesci 2025	▲	▲	▲	✓	✓	✓	✓	✓	✓

Abbreviations: P/C = purity/completeness; Proj = optical projection/richness contamination; Sel-WL = selection-induced weak-lensing bias; Shear = shear calibration; z-src = source redshifts; z-cl = cluster/lens redshifts; Miscent = miscentering; Prof = halo profile/concentration/truncation; Orient. = halo triaxiality/orientation.

✓ Included in fit
▲ Discussed but not included
✗ Not considered
– Not relevant

Summary of treated/discussed uncertainties

Paper	HMF	h-bias	NL/RSD	IA	Baryon	Cosmo-par
Gladders 2007	▲	–	–	–	✗	✓
Rozo 2010	▲	–	–	✗	✗	✓
Tinker 2012	✓	✓	✓	✗	▲	✓
Mana 2013	▲	✓	✓	✗	✗	✓
Costanzi 2019	✓	–	–	▲	▲	✓
DES Y1 2020	✓	–	–	▲	▲	✓
Abdullah 2020	▲	–	–	–	✗	✓
To 2021	✓	✓	✓	▲	▲	✓
Lesci 2022a	✓	–	–	✗	▲	✓
Lesci 2022b	–	▲	▲	–	–	✓
Abdullah 2023	▲	–	–	–	✗	✓
Fumagalli 2024	▲	▲	▲	✗	▲	✓
Romanello 2024	–	▲	▲	–	–	✓
DES Y3 2025	✓	✓	✓	▲	▲	✓
Lesci 2025	✓	–	▲	▲	▲	✓

Abbreviations: HMF = halo mass-function calibration; h-bias = halo-bias model; NL/RSD = nonlinear clustering/redshift-space distortions; IA = intrinsic alignments; Baryon = baryonic physics; Cosmo-par = priors/marginalization on additional cosmological parameters.

✓ Included in fit
▲ Discussed but not included
✗ Not considered
– Not relevant

Summary

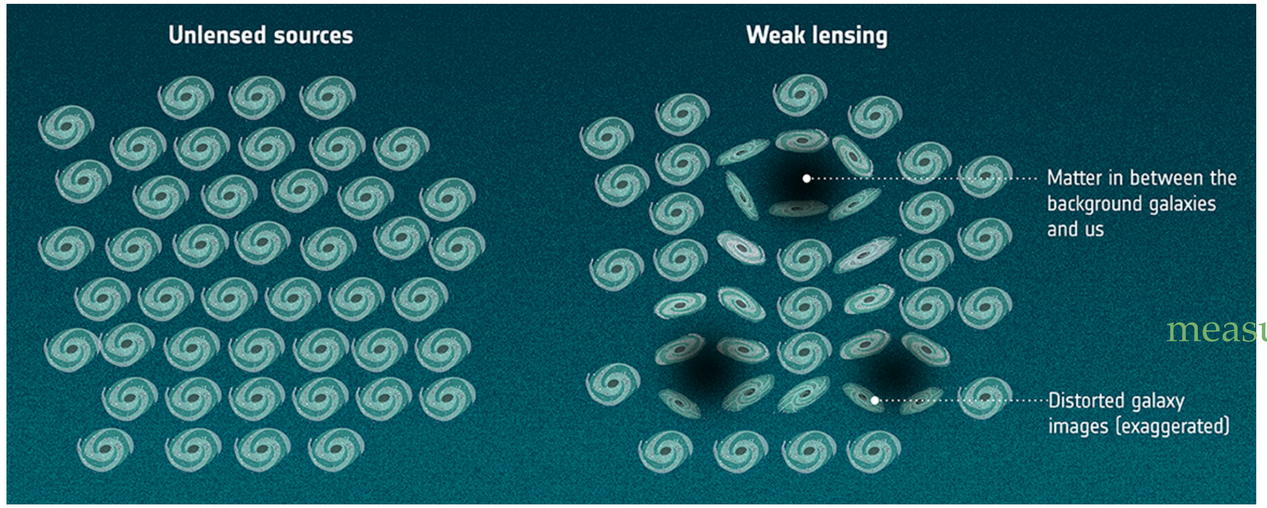
- Performed a simplistic combination study of optical cluster analyses
  - did not account for correlations, non-gaussian errors, etc…
- 5.6σ tension in Ωm between optical clusters measurements and Planck.
- The set of 15 measurements has a too large spread, maybe sign of at least 20% underestimated total uncertainties
- Abundance+WL measurements are the ones most deviating from Planck, with a tension of 6.8σ
- Some important uncertainties are not included in most measurements. Most recent analyses (like DES Y3) start to include them

Conclusion

- Given current treatment of uncertainties, it's becoming easy to find >5σ tensions
- Need now to have a standardized treatment of uncertainties !
- Need information about size of uncertainties and breakdown of total error to allow future combinations / comparisons

Thank you !

Mass measurement with gravitational lensing



k : convergence / γ : shear

$$A = \begin{bmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{bmatrix}$$

measured

$$\gamma_t = -\gamma_1 cos(2\phi) - \gamma_2 sin(2\phi)$$

>0 if shear signal

$$\gamma_\times = \gamma_1 sin(2\phi) - \gamma_2 cos(2\phi)$$

~0 if spherical lens

projected mass density

$$\gamma_t(R) = \bar{\kappa}(<R) - \kappa(R) = \frac{\Delta\Sigma(R)}{\Sigma_{crit}}$$

$$\Delta\Sigma(R) = \bar{\Sigma}(<R) - \Sigma(R)$$

density profile hypothesis

$$M_{proj}(<R) = \pi R^2 \bar{\Sigma}(<R)$$

Very small effect, average on several sources to reduce the noise