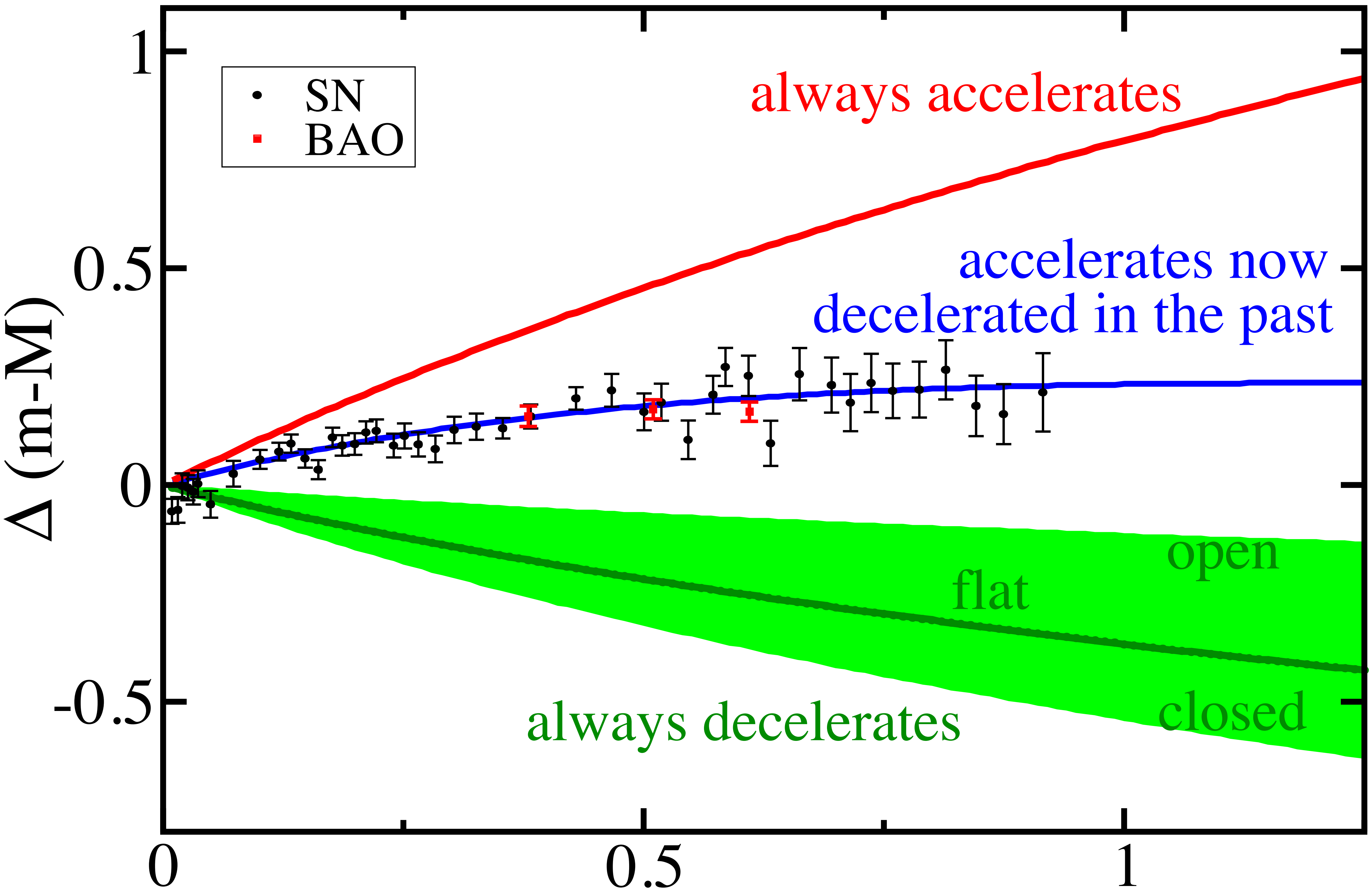
Probing the Universe with Dark Energy Survey

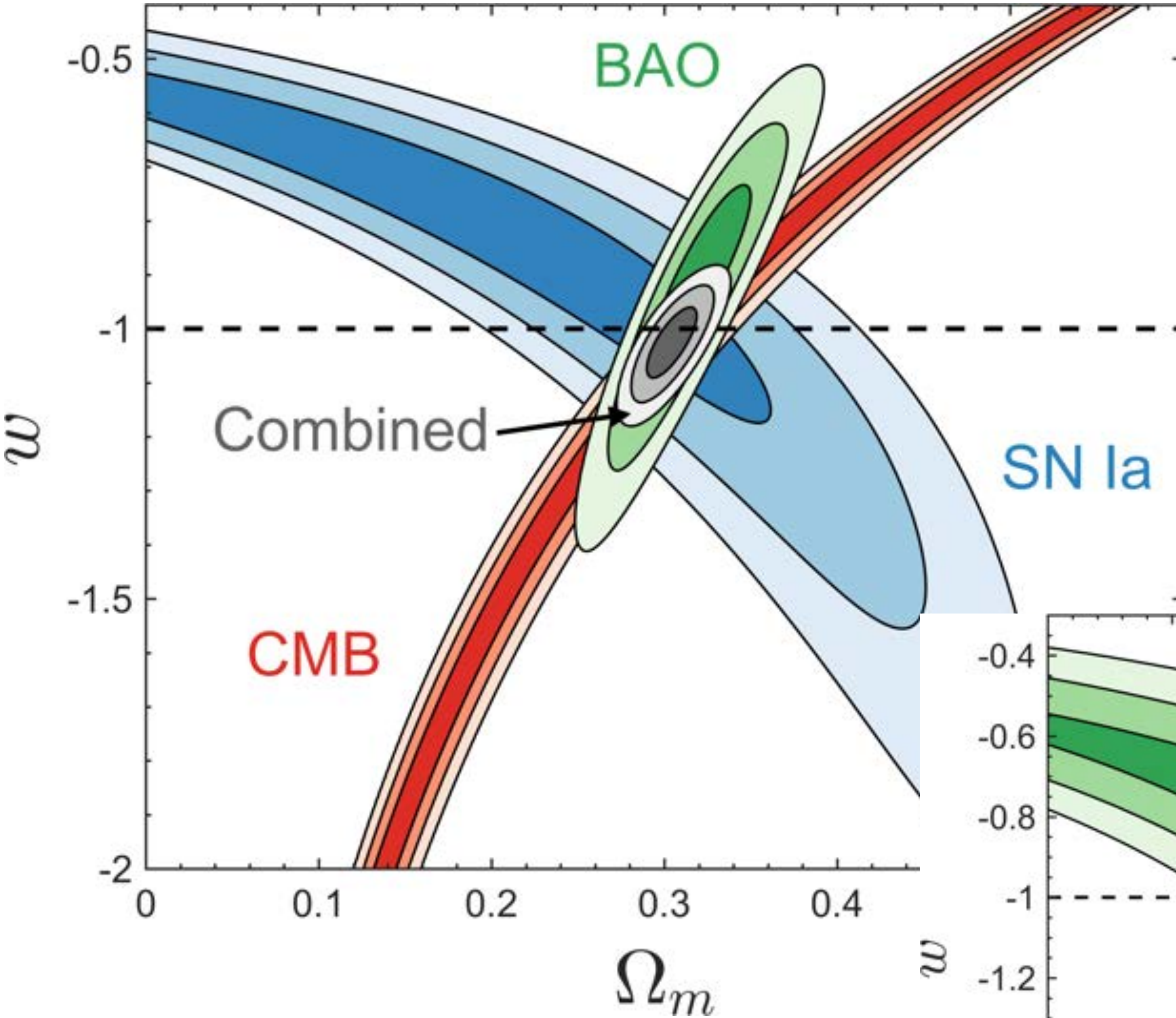
Dragan Huterer
Physics Department
University of Michigan

Blanco telescope at Cerro Tololo, Chile

Evidence for Dark energy from type Ia Supernovae



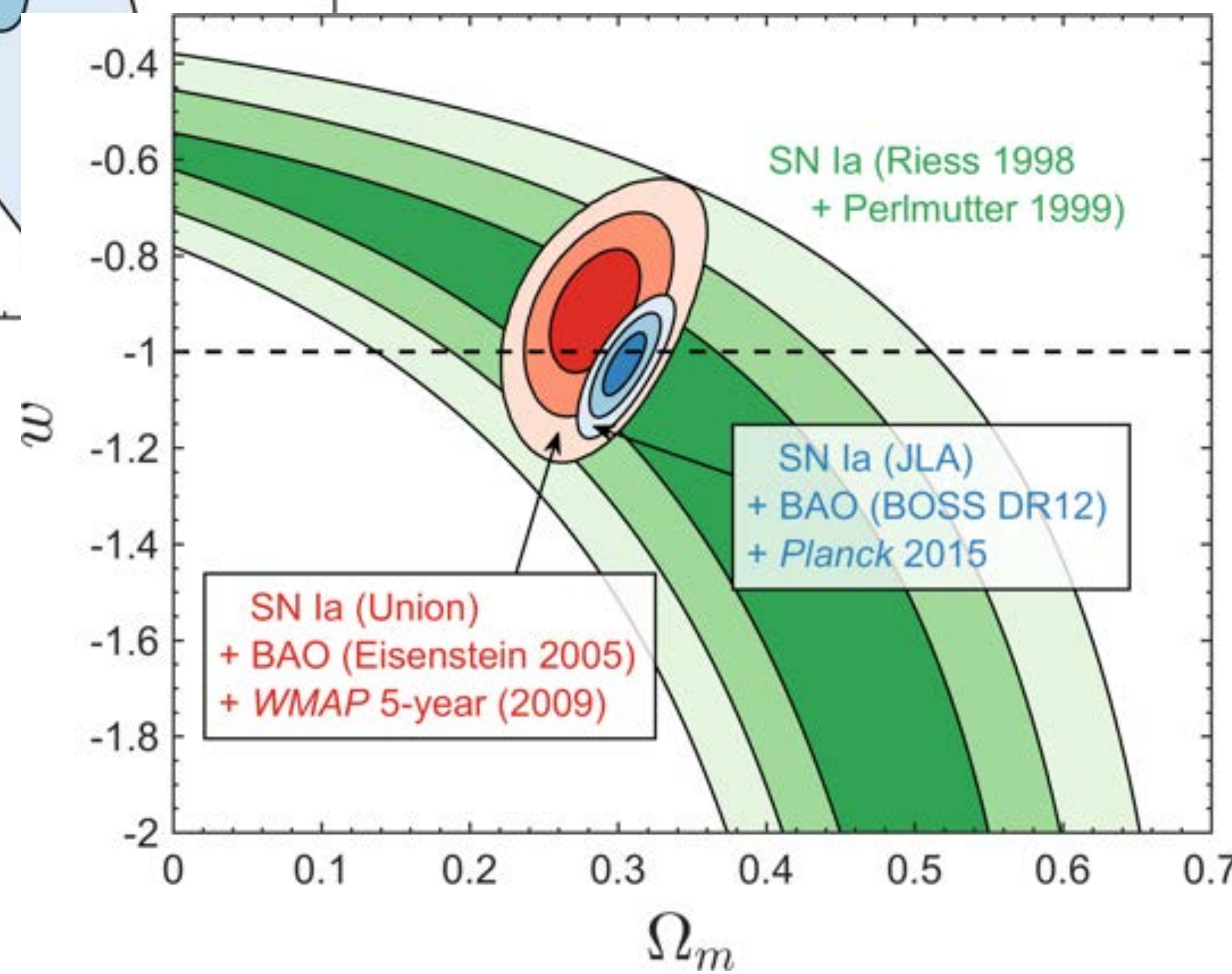
Huterer & Shafer,
Rep. Prog. Phys. 2018



$$\Omega_m = 1 - \Omega_{\rm DE}$$

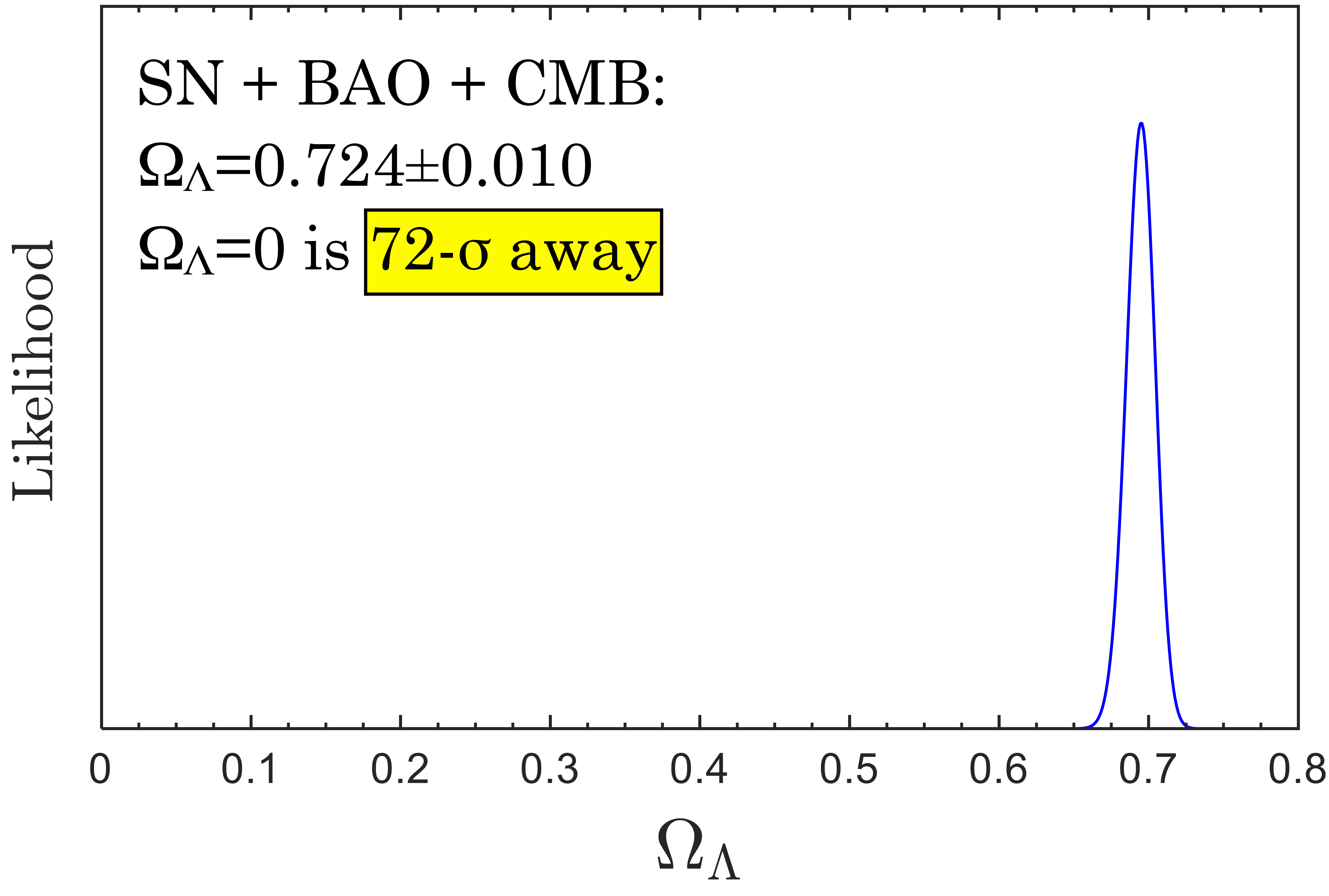
$$\Omega_{\rm DE} \equiv \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

$$w \equiv \frac{p_{\rm DE}}{\rho_{\rm DE}}$$



Huterer & Shafer,
Rep. Prog. Phys., 2018

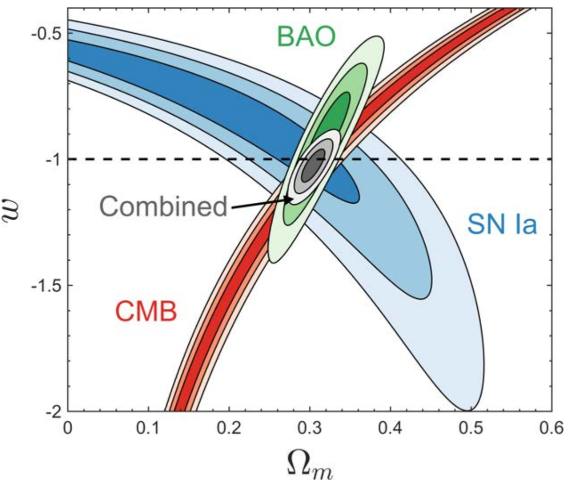
Current evidence for dark energy is impressively strong



Daniel Shafer, 2017

A difficulty:

DE theory target accuracy, in e.g. $w=p/\rho$, not known *a priori*



Contrast this situation with:

1. Neutrino masses:

$$(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ eV^2$$

$$(\Delta m^2)_{atm} \simeq 3\times10^{-3}\ eV^2$$

$$\sum m_i = 0.06\ eV^* \quad \text{(normal)}$$

vs.

$$\sum m_i = 0.11\ eV^* \quad \text{(inverted)}$$

*(assuming m_3=0)

2. Higgs Boson mass (before LHC 2012):

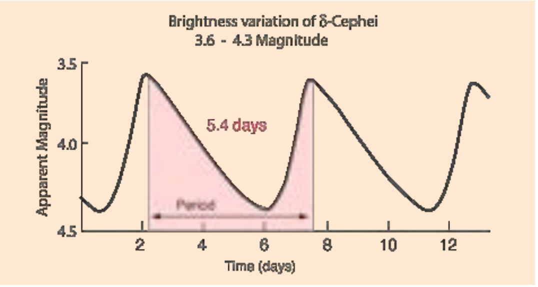
$$m_H \lesssim O(200)\ GeV$$

(assuming Standard Model Higgs)

Hubble tension

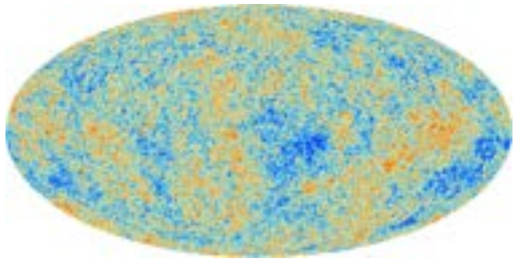
Type Ia supernovae + Cepheid distances give

$$H_0 = 74.0 \pm 1.4 \text{ (km/s/Mpc)}$$



Cosmic Microwave Anisotropies give

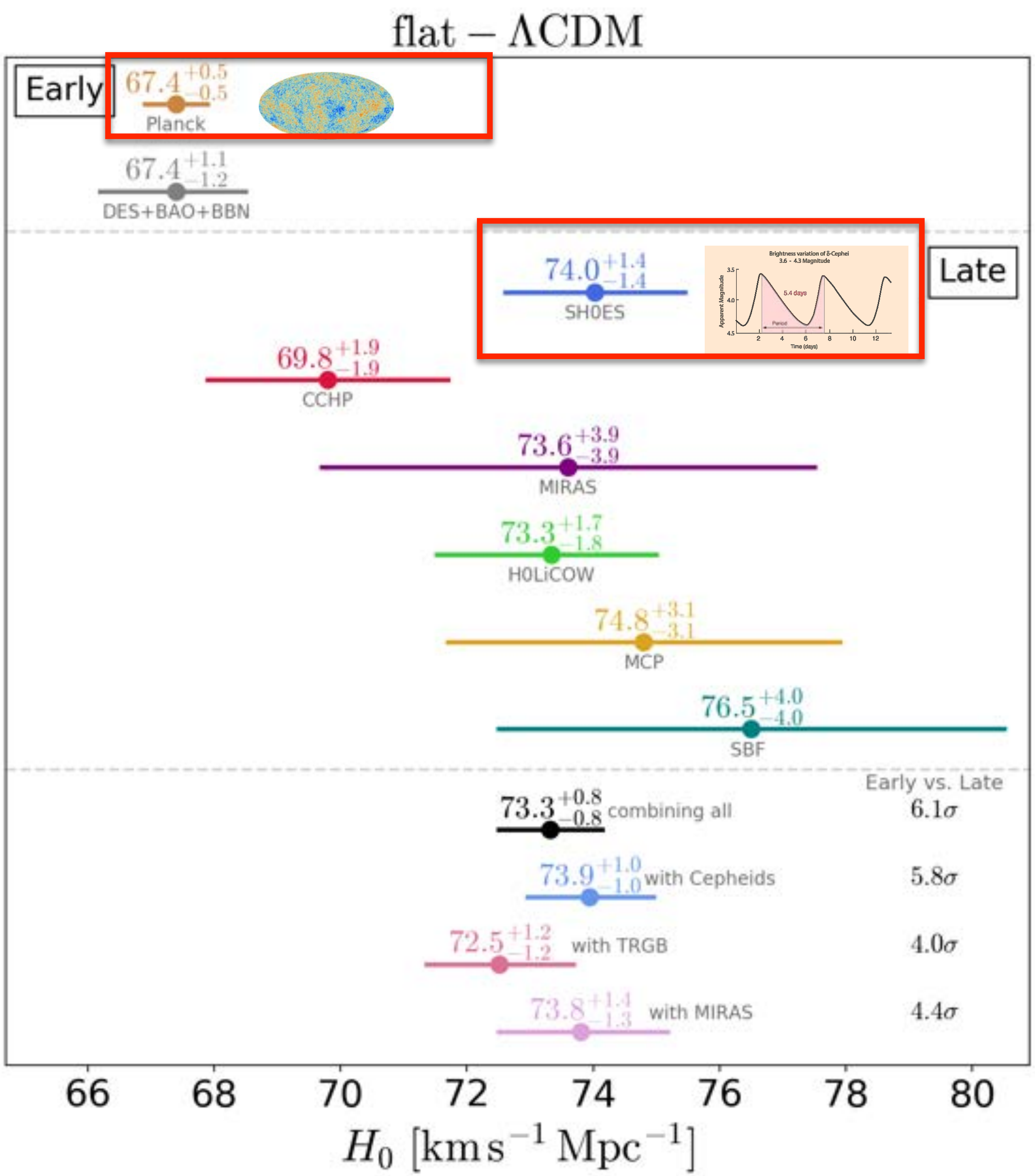
$$H_0 = 67.4 \pm 0.4 \text{ (km/s/Mpc)}$$



These two measurements are discrepant at about five sigma!*

* once strong-lensing constraints are added, which come out high ($H_0 \sim 73$)

Hubble tension - a gift to cosmology!



Verde, Treu & Riess arXiv:1907.10625

- exciting, real tension in cosmology
- all major analysis very thorough
- no obvious systematics (as yet)
- theory models surprisingly hard to concoct (e.g. very finely tuned scalar field models that *also* don't really work)

Major ongoing or upcoming DE expt's:

- **Ground photometric:**
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES)
  - Hyper Supreme Cam (HSC)
  - Large Synoptic Survey Telescope (LSST)
- **Ground spectroscopic:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Prime Focus Spectrograph (PFS)
  - Dark Energy Spectroscopic Instrument (DESI)
- **Space:**
  - Euclid
  - Wide Field InfraRed Space Telescope (WFIRST)

The Dark Energy Survey (DES)

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey 2013-2019 (**Y3 2013-16**).
- Wide field: 5000 sq. deg. in 5 bands. ~23 magnitude.
- DES Y3: Positions and shapes of > 100M galaxies.

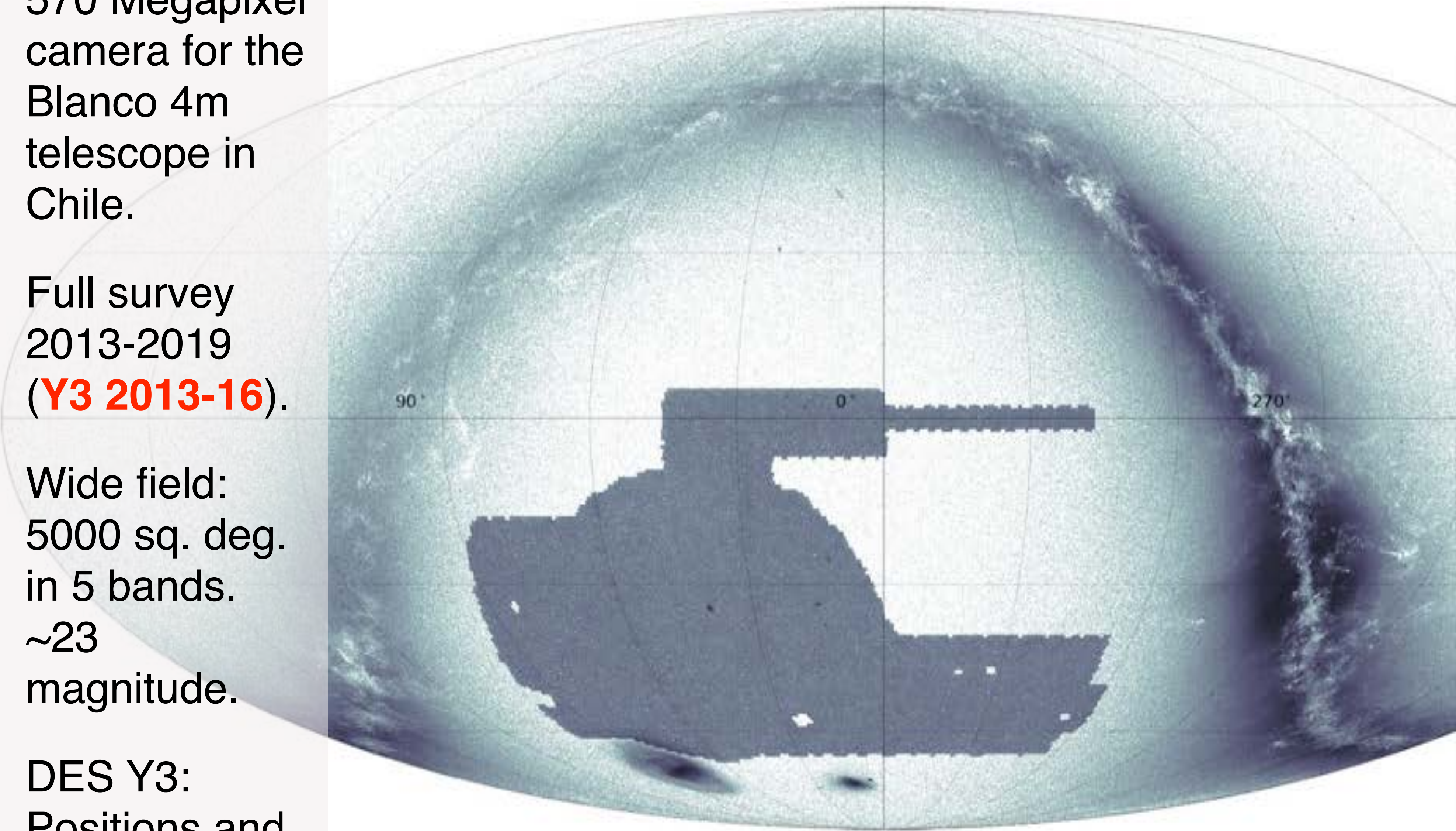


Image Credit: CosmoHub, Port d'Informació Científica (PIC)

Dark Energy Survey (DES)

Cerro Tololo, Chile

Blanco Telescope

List of participants

(Early Career Scientists in bold)

Beatrice Moser
Dan Scolnic
Robert Morgan
Nacho Sevilla
Paul Rogozenski
Elisabeth Krause
Joe DeRose
Richard Kron
H. Thomas Diehl
Ofer Lahav
Reese Wilkinson
Peter Melchior
David Weinberg
Anqi Chen
Dominik Zuercher
Niall Jeffrey
Mitch McNanna
Alexandre Refregier
Dylan Britt
Pablo Lemos
Alexandra Amon
Shantanu Desai

Adam Amara
Santiago Avila
Sunayana Bhargava
Antonella Palmese
Zhiyuan Zhou
Aaron Roodman
Matthew Becker
Risa Wechsler
Andrés Plazas
Rafael Gomes
Ian Harrison
Romain Buchs
Ami Choi
Maria Pereira
Alex Alarcon
Bhuvnesh Jain
Raphael Sgier
Albert Stebbins
Dragan Huterer
Justin Myles
Youngsoo Park
Marco Raveri

Ramon Miquel
Jenna Freudenberg
David Bacon
Tomasz Kacprzak
Giulia Giannini
Chihway Chang
Anderson Souza
Jacobo Asorey
David Burke
Isaac Tutusaus
Jamie McCullough
Paul Ricker
Eduardo Rozo
Noah Weaverdyck
Pauline Vielzeuf
Eusebio Sanchez
Boyan Yin
Robert Gruendl
Vivian Miranda
Xiao Fang
Marco Gatti
Heidi Wu

Alyssa Garcia
Dhayaa Anbajagane
Andresa Campos
Cyrille Doux
Jessie Muir
Georgios Zacharegkas
William Hartley
Nick Kokron
Michael Troxel
Judit Prat
Pablo Fosalba
Douglas Tucker
Eli Rykoff
Michael Johnson
Masaya Yamamoto
Dillon Brout
Matias Carrasco
Daniel Gomes
Nico Hamaus
Ismael Ferrero
Mike Wang
Andrew Liddle
Daniel Gruen
Keith Bechtol
Juan De Vicente
Anna Porredon

Felipe Andrade-Oliveira
Jack Elvin-Poole
Juan P. Cordero
Mike Jarvis
Eric Huff
Chris Conselice
Eric Neilsen
Javier Sanchez
Andres Navarro
Tae-hyeon Shin
Chun-Hao To
Tesla Jeltema
Kevin Wang
Niall MacCrann
Erin Sheldon
Agnes Ferte
Ross Cawthon
Manda Banerji
Yuuki Omori
Brenna Flaugher
Alfredo Zenteno
Mathew Smith
Otavio Alves
Eve Kovacs
Martin Rodriguez Monroy
Megan Tabbutt

Ken Herner
Danielle Leonard
Gaston Gutierrez
Federica Tarsitano
Juan Mena Fernández
David Sánchez Cid
Seshadri Nadathur
Gary Bernstein
Sujeong Lee
Prudhvi Varma
Oliver Friedrich
Simon Samuroff
Richard Kessler
Huan Lin
Rutuparna Das
Lorne Whiteway
Anushka Shrivastava
Tamara Davis
Jimena Gonzalez
Tim Eifler
Giorgia Pollina
Ashley Ross
Eleonora di Valentino
Lucas Secco
Ji Won Park
Andrew Pace

Alex Drlica-Wagner
Simon Birrer
Brian Yanny
Sahar Allam
Scott Dodelson
Jim Annis
Andras Kovacs
Hugo Camacho
Kai Hoffmann
Mandeep Gill
Jonathan Blazek
Lucas James Faga
Joe Zuntz
Steve Kent
Martin Crocce
Spencer Everett
Juan Estrada
Donald Petravick
Hung-Jin Huang
Yuanyuan Zhang
Georgios Zacharegka
Shivam Pandey
Helen Qu
Eric Baxter
Jack Odonnell
Sebastian Bocquet

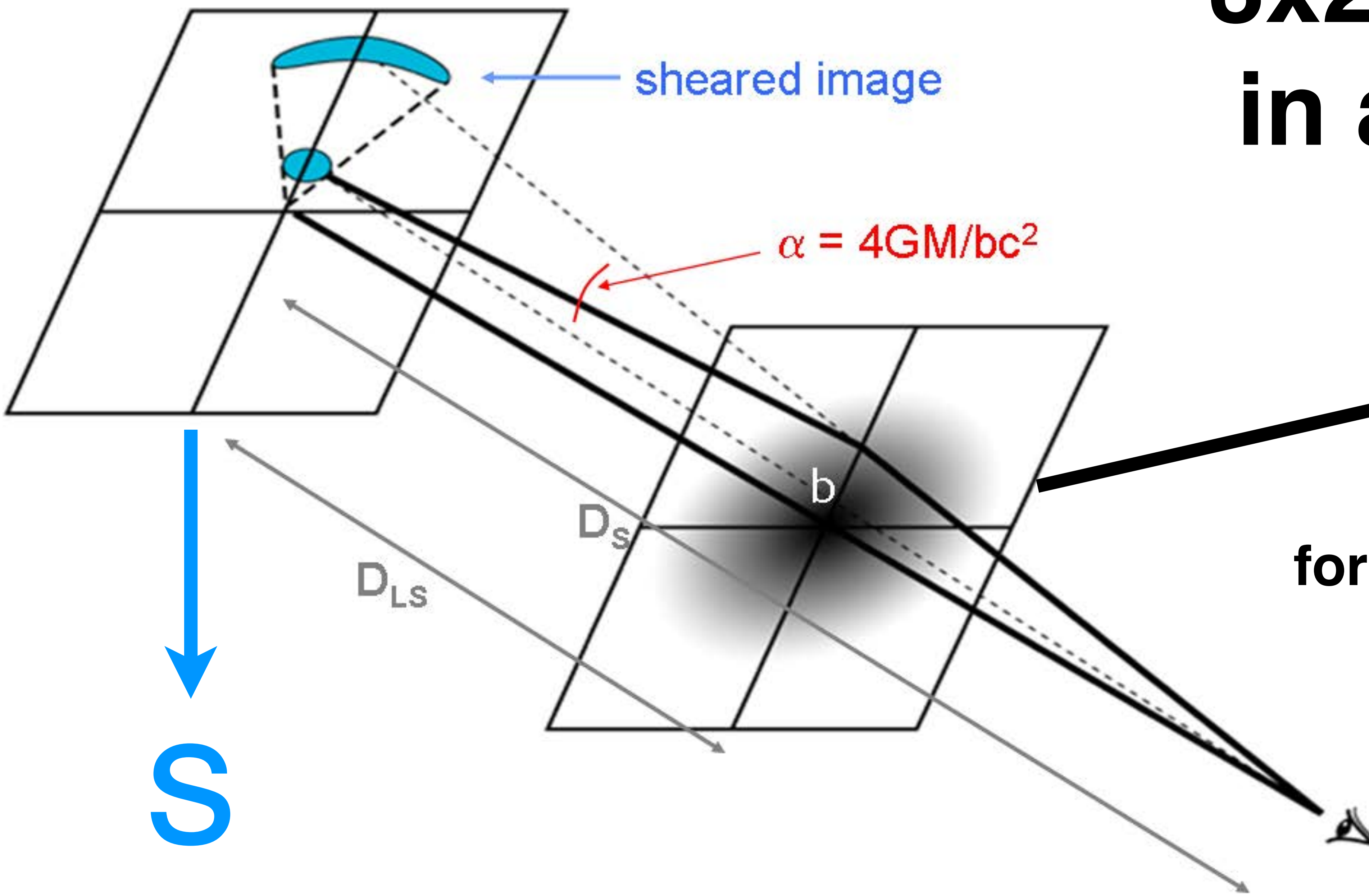
Dark Energy Survey Year 3 results. List of key and supporting papers

1. “Blinding Multi-probe Cosmological Experiments” J. Muir, G. M. Bernstein, D. Huterer et al., arXiv: 1911.05929, MNRAS **494** (2020) 4454
2. “Photometric Data Set for Cosmology”, I. Sevilla-Noarbe, K. Bechtol, M. Carrasco Kind et al., arXiv:2011.03407, ApJS **254** (2021) 24
3. “Weak Lensing Shape Catalogue”, M. Gatti, E. Sheldon, A. Amon et al., arXiv:2011.03408, MNRAS **504** (2021) 4312
4. “Point Spread Function Modelling”, M. Jarvis, G. M. Bernstein, A. Amon et al., arXiv:2011.03409, MNRAS **501** (2021) 1282
5. “Measuring the Survey Transfer Function with Balrog”, S. Everett, B. Yanny, N. Kuropatkin et al., arXiv:2012.12825
6. “Deep Field Optical + Near-Infrared Images and Catalogue”, W. Hartley, A. Choi, A. Amon et al., arXiv:2012.12824
7. “Blending Shear and Redshift Biases in Image Simulations”, N. MacCrann, M. R. Becker, J. McCullough et al., arXiv:2012.08567
8. “Redshift Calibration of the Weak Lensing Source Galaxies”, J. Myles, A. Alarcon, A. Amon et al., arXiv:2012.08566
9. “Redshift Calibration of the MagLim Lens Sample using Self-Organizing Maps and Clustering Redshifts”, G. Giannini et al., in prep.
10. “Clustering Redshifts – Calibration of the Weak Lensing Source Redshift Distributions with redMaGiC and BOSS/eBOSS”, M. Gatti, G. Giannini, et al., arXiv:2012.08569
11. “Calibration of Lens Sample Redshift Distributions using Clustering Redshifts with BOSS/eBOSS”, R. Cawthon et al. arXiv:2012.12826
12. “Phenotypic Redshifts with SOMs: a Novel Method to Characterize Redshift Distributions of Source Galaxies for Weak Lensing Analysis” R. Buchs, C.Davis, D. Gruen et al. arXiv:1901.05005, MNRAS **489** (2019) 820
13. “Marginalising over Redshift Distribution Uncertainty in Weak Lensing Experiments”, J. Cordero, I. Harrison et al., in prep.
14. “Exploiting Small-Scale Information using Lensing Ratios”, C. Sánchez, J. Prat et al., in prep.
15. “Cosmology from Combined Galaxy Clustering and Lensing - Validation on Cosmological Simulations”, J. de Rose et al., in prep.
16. “Unbiased fast sampling of cosmological posterior distributions”, P. Lemos et al., in prep.
17. “Assessing Tension Metrics with DES and Planck Data”, P. Lemos, M. Raveri, A. Campos et al., arXiv:2012.09554
18. “Dark Energy Survey Internal Consistency Tests of the Joint Cosmological Probe Analysis with Posterior Predictive Distributions”, C. Doux, E. Baxter, P. Lemos et al. arXiv:2011.03410, MNRAS **503** (2021) 2688
19. “Covariance Modelling and its Impact on Parameter Estimation and Quality of Fit”, O. Friedrich, F. Andrade-Oliveira, H. Camacho et al., arXiv:2012.08568
20. “Multi-Probe Modeling Strategy and Validation”, E. Krause et al., in prep.
21. “Curved-Sky Weak Lensing Map Reconstruction”, N. Jeffrey, M. Gatti, C. Chang et al., in prep.
22. “Galaxy Clustering and Systematics Treatment for Lens Galaxy Samples”, M.Rodríguez-Monroy, N. Weaverdyck, J. Elvin-Poole, M. Crocce et al., in prep.
23. “Optimizing the Lens Sample in Combined Galaxy Clustering and Galaxy-Galaxy Lensing Analysis”, A. Porredon, M. Crocce et al., arXiv:2011.03411 PhRvD **103** (2021) 043503
24. “High-Precision Measurement and Modeling of Galaxy-Galaxy Lensing”, J. Prat, J. Blazek, C. Sánchez et al., in prep.
25. “Constraints on Cosmological Parameters and Galaxy Bias Models from Galaxy Clustering and Galaxy-Galaxy Lensing using the redMaGiC Sample”, S. Pandey et al., in prep.
26. “Cosmological Constraints from Galaxy Clustering and Galaxy-Galaxy Lensing using the Maglim Lens Sample” A. Porredon, M. Crocce et al., in prep.
27. “Cosmology from Cosmic Shear and Robustness to Data Calibration”, A. Amon, D. Gruen, M. A. Troxel et al., in prep.
28. “Cosmology from Cosmic Shear and Robustness to Modeling Assumptions”, L. Secco, S. Samuroff et al., in prep.
29. “Magnification modeling and impact on cosmological constraints from galaxy clustering and galaxy-galaxy lensing”, J. Elvin-Poole, N. MacCrann et al., in prep.
30. “Cosmological Constraints from Galaxy Clustering and Weak Lensing” The DES Collaboration arXiv:2105.13549

(plus **hundreds** of other DES papers up to this point…)

3x2 analysis in a picture

image: LSST science book



g

(**positions** of **foreground** galaxies; 5 redshift bins)

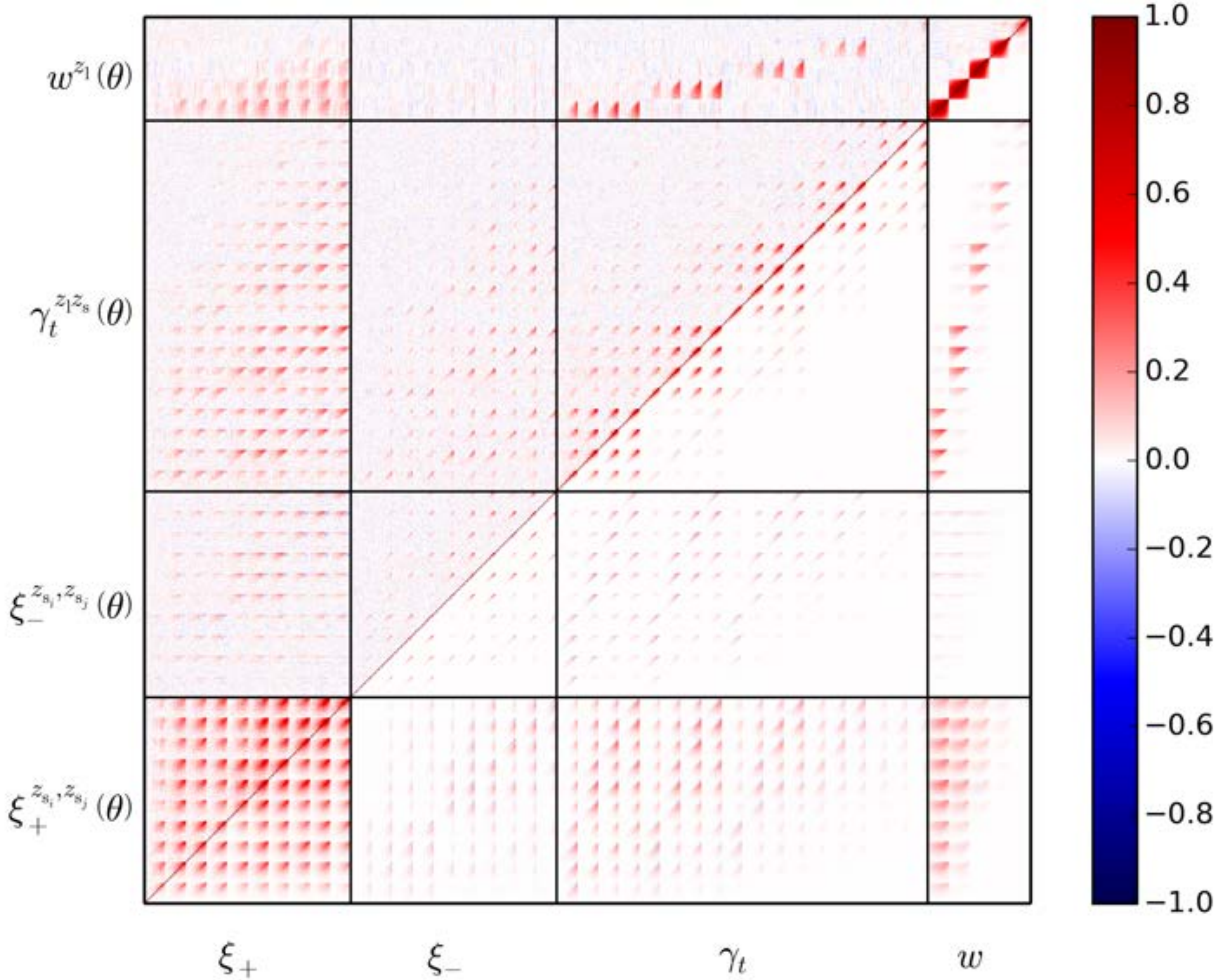
s

(**shear** of **background** galaxies; 5 redshift bins)

“3x2 (point-function)” clustering measurements:

$$\begin{bmatrix} gg & gs \\ gs & ss \end{bmatrix}$$

Covariance of 3x2 datavector



Krause, Eifler et al (2017)

tests in: Friedrich et al, arXiv:2012.08568

DES Y3 3x2 analysis highlights

A total of 32 parameters (in LCDM):
(7 cosmological, 25 astrophysical/systematic)

and a fanatical devotion to controlling the systematic errors:

Everything is validated

1. Two lens samples (redMaGiC and MagLim)
2. Two data-vector (theory) codes (cosmosis and cosmolike)
3. Two models for Intrinsic Alignments (in shear)
4. Many checks on shear measurements, data covariance, samplers, stat methods, bias modeling…..

and

All cosmology results are **blinded**

Blinding the DES analysis

Jessie Muir
(Stanford -> Perimeter))

Our requirements:

- Preserve inter-consistency of cosmological probes
- Preserve ability to test for systematic errors

Our choice is specifically:

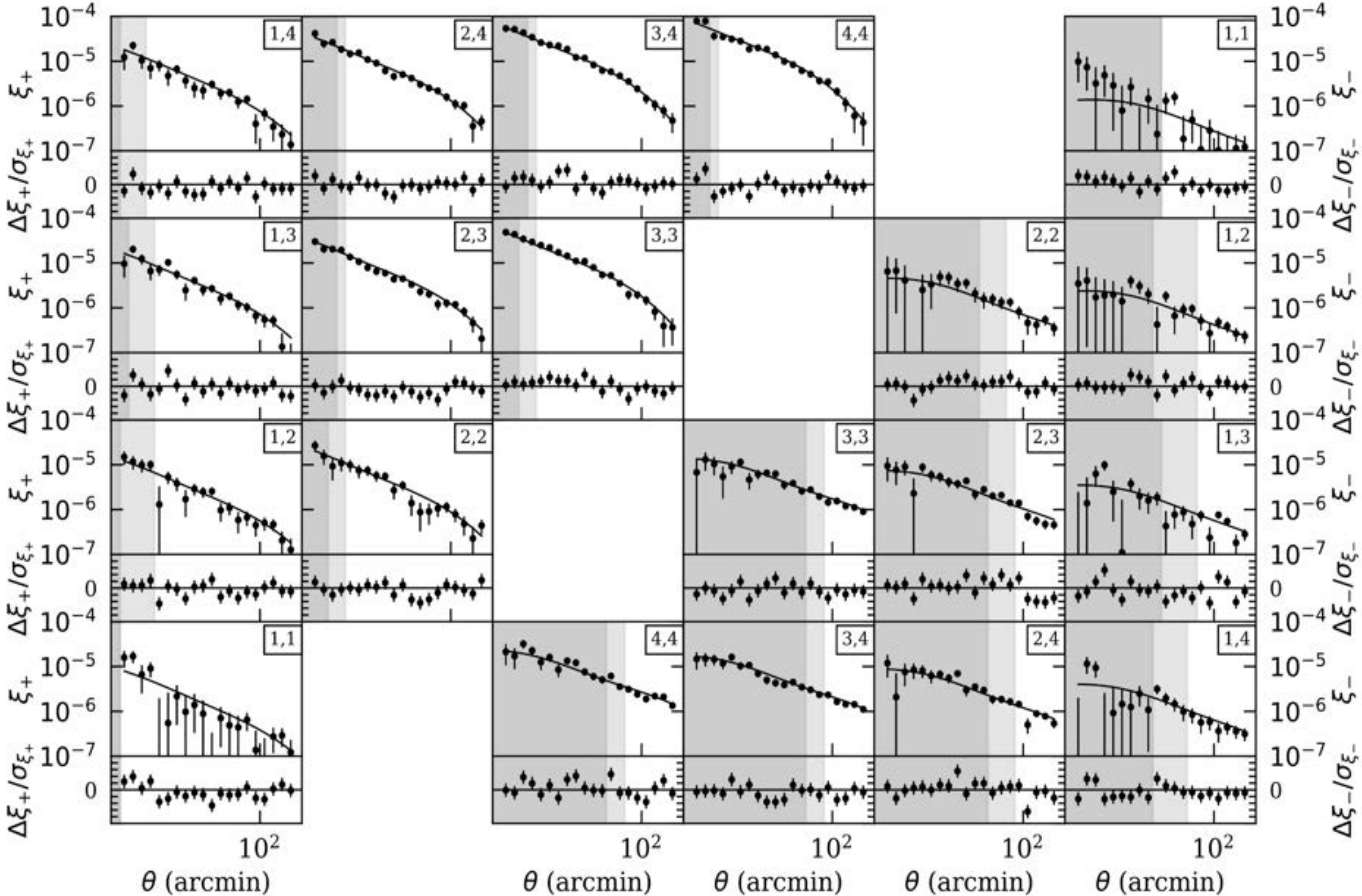
$$\xi_{ij}^{\mathrm{blinded}} = \xi_{ij}^{\mathrm{measured}} + [\xi_{ij}^{\mathrm{th\,model\,1}} - \xi_{ij}^{\mathrm{th\,model\,2}}]$$

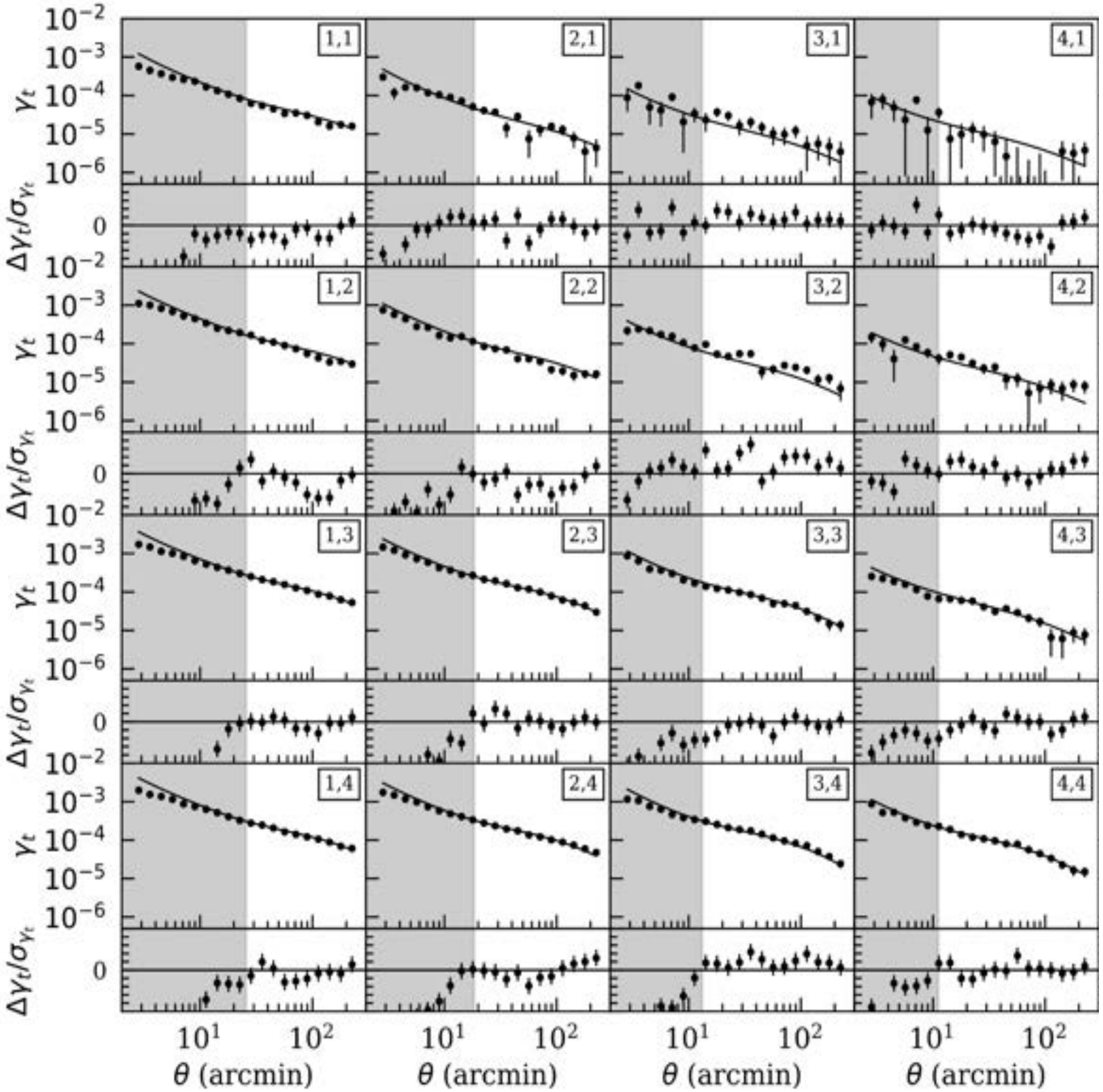
Applied to DES Y3!

Muir, Bernstein, Huterer, et al., arXiv:1911.05929

DES Y1 Measurements:
shear clustering, galaxy-galaxy lensing, gal clustering

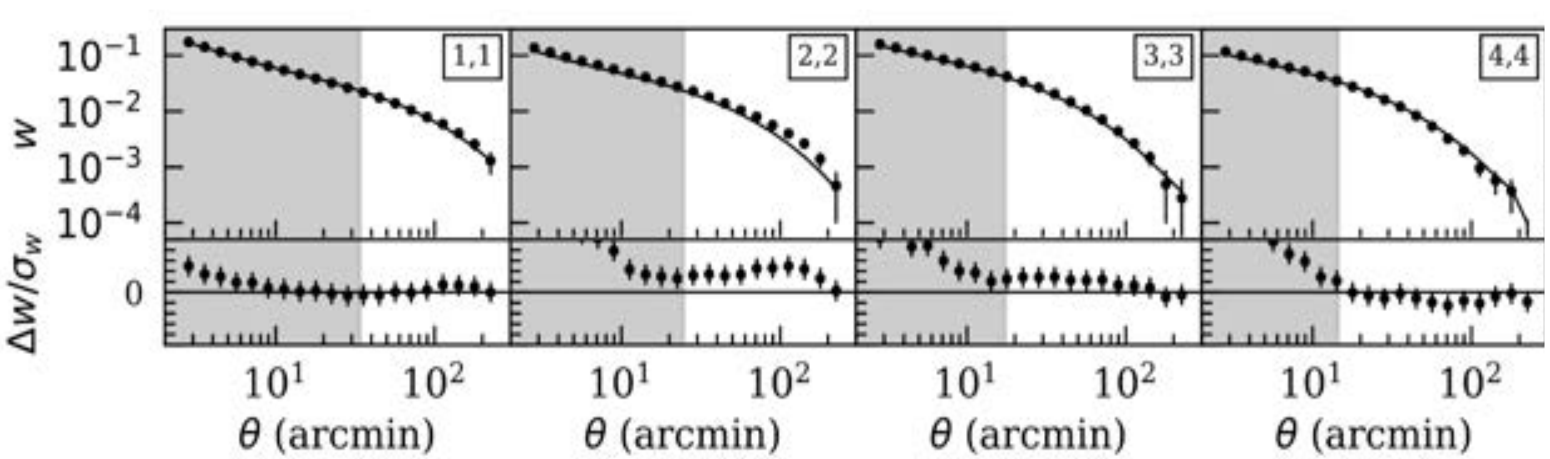
cosmic shear Amon+,Secco,Samuroff+





galaxy-galaxy lensing

Prat+



galaxy clustering

Rodriguez-Monroy+

Internal consistency

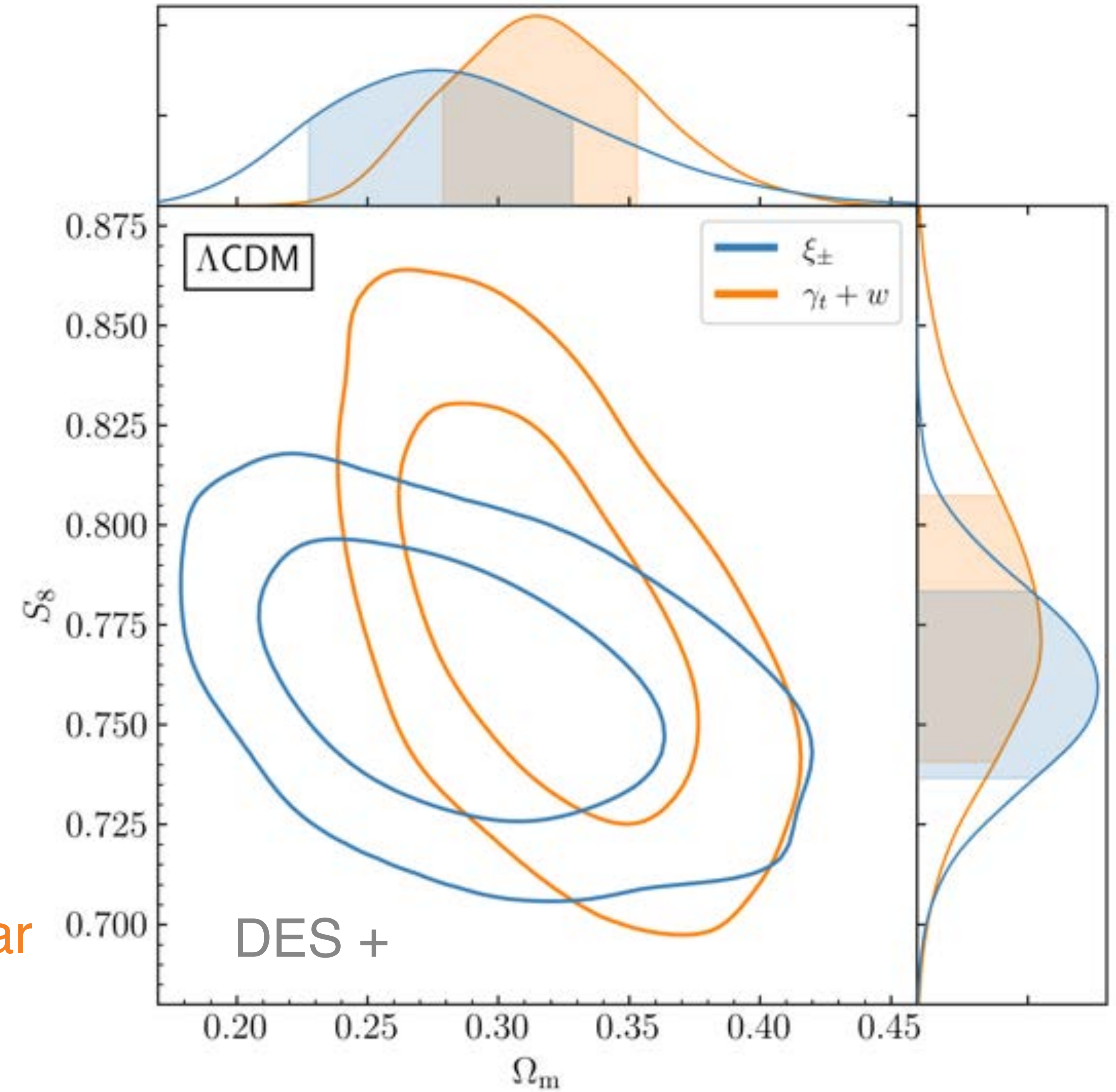
Two correlated cosmological probes:

1. **Cosmic shear** (blue)
2. **Galaxy clustering** and **tangential shear** (orange)

We find consistency between them.

Cosmic shear most sensitive to clustering amplitude.

Galaxy clustering and tangential shear more sensitive to total matter density.



$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3} \right)^{0.5}$$

3x2pt results

We combine these into the **3x2pt** probe of large-scale structure.

A factor of 2.1 improvement in signal-to-noise from DES Year 1.

In ΛCDM:

$$S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776)$$

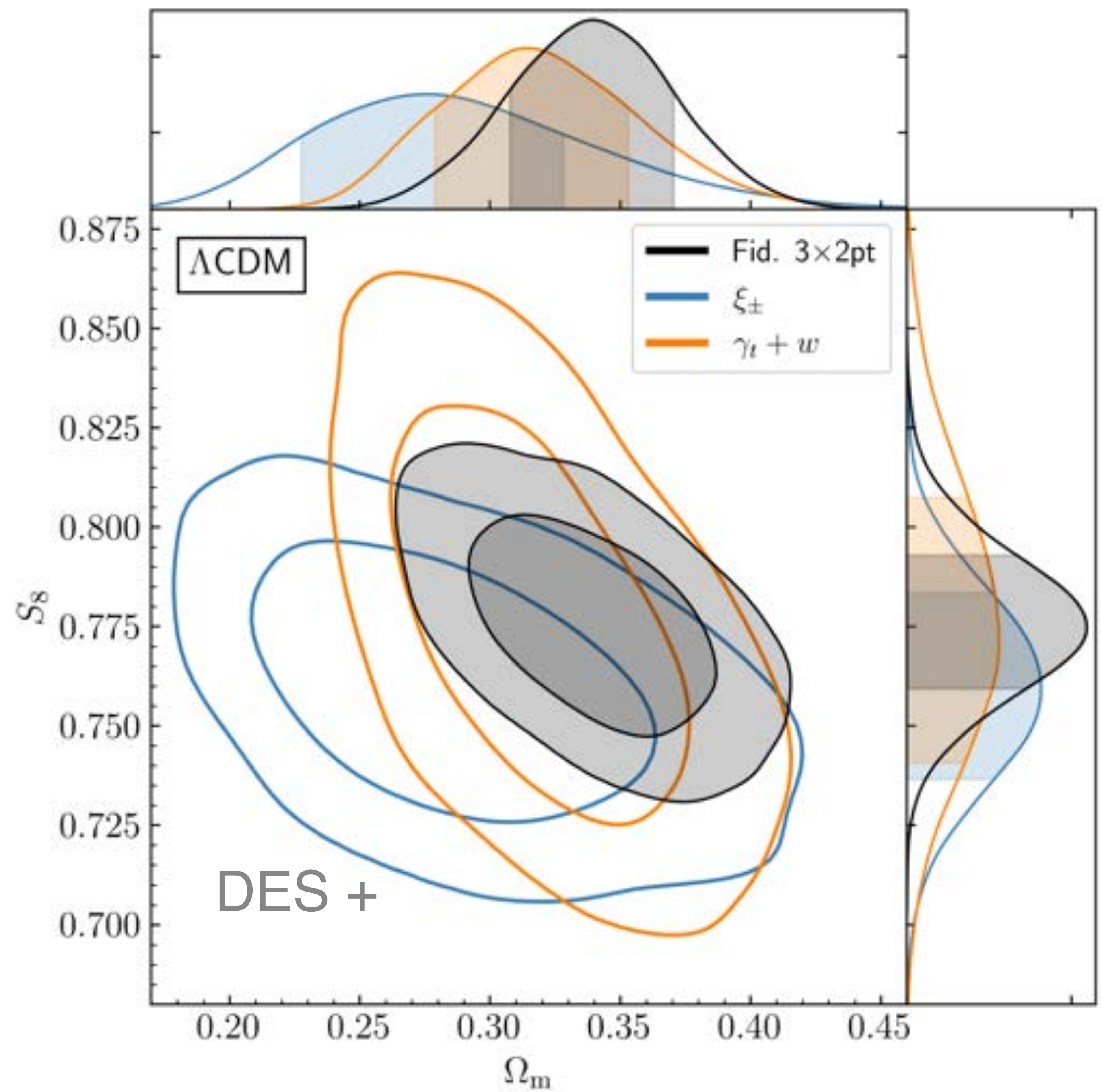
$$\Omega_m = 0.339^{+0.032}_{-0.031} \quad (0.372)$$

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

In *w*CDM:

$$\Omega_m = 0.352^{+0.035}_{-0.041} \quad (0.339)$$

$$w = -0.98^{+0.32}_{-0.20} \quad (-1.03)$$



$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

Galaxy clustering and Lens samples

Galaxy clustering measured in two foreground samples

redMaGiC

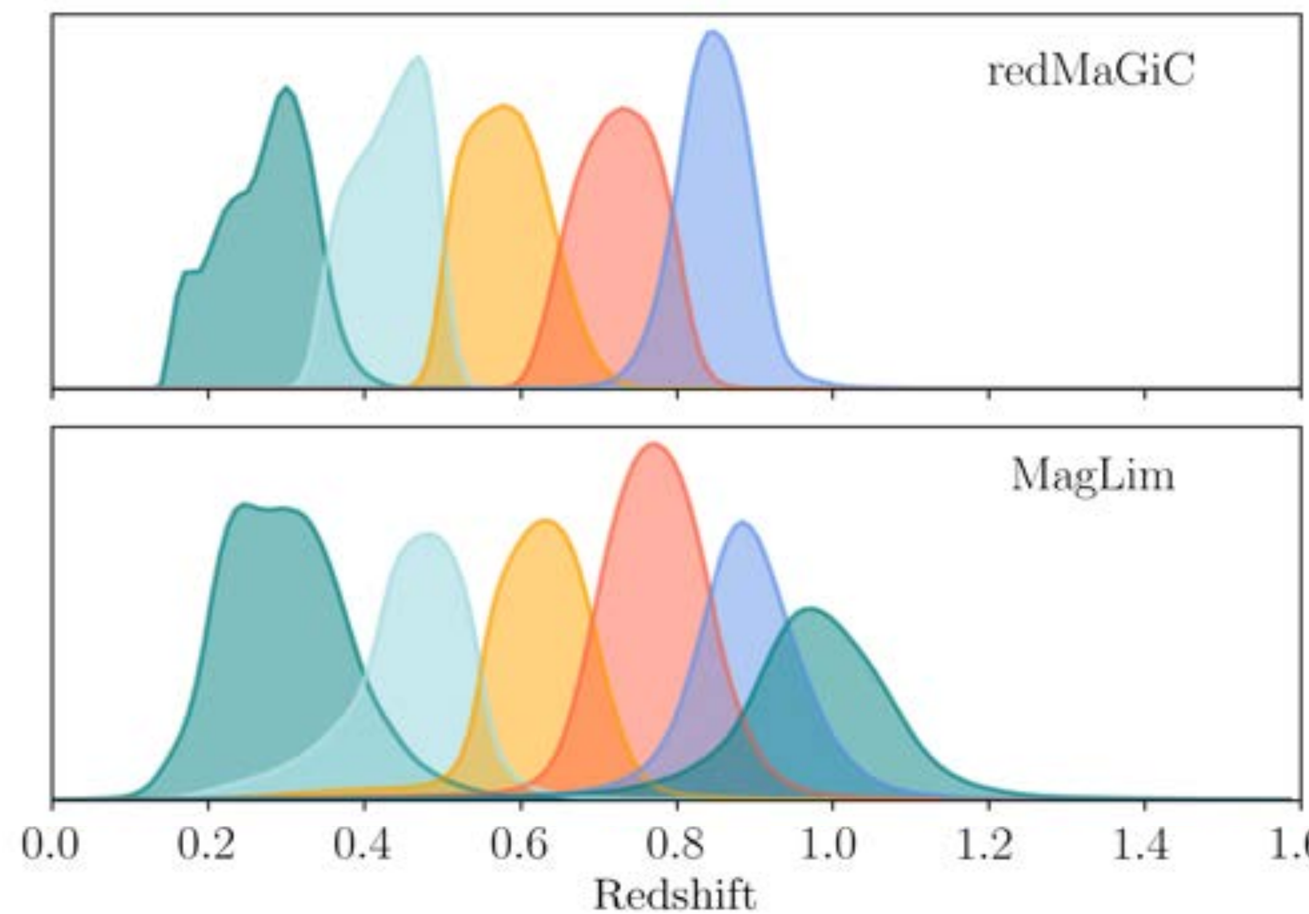
LRG selection also used in Y1 analysis

*p(z)*s are stacked, and then validated using WZ

MagLim

Bright selection $i_{\rm mag} < 4z + 18$

Defined using machine-learning photometric redshifts, and also validated using WZ



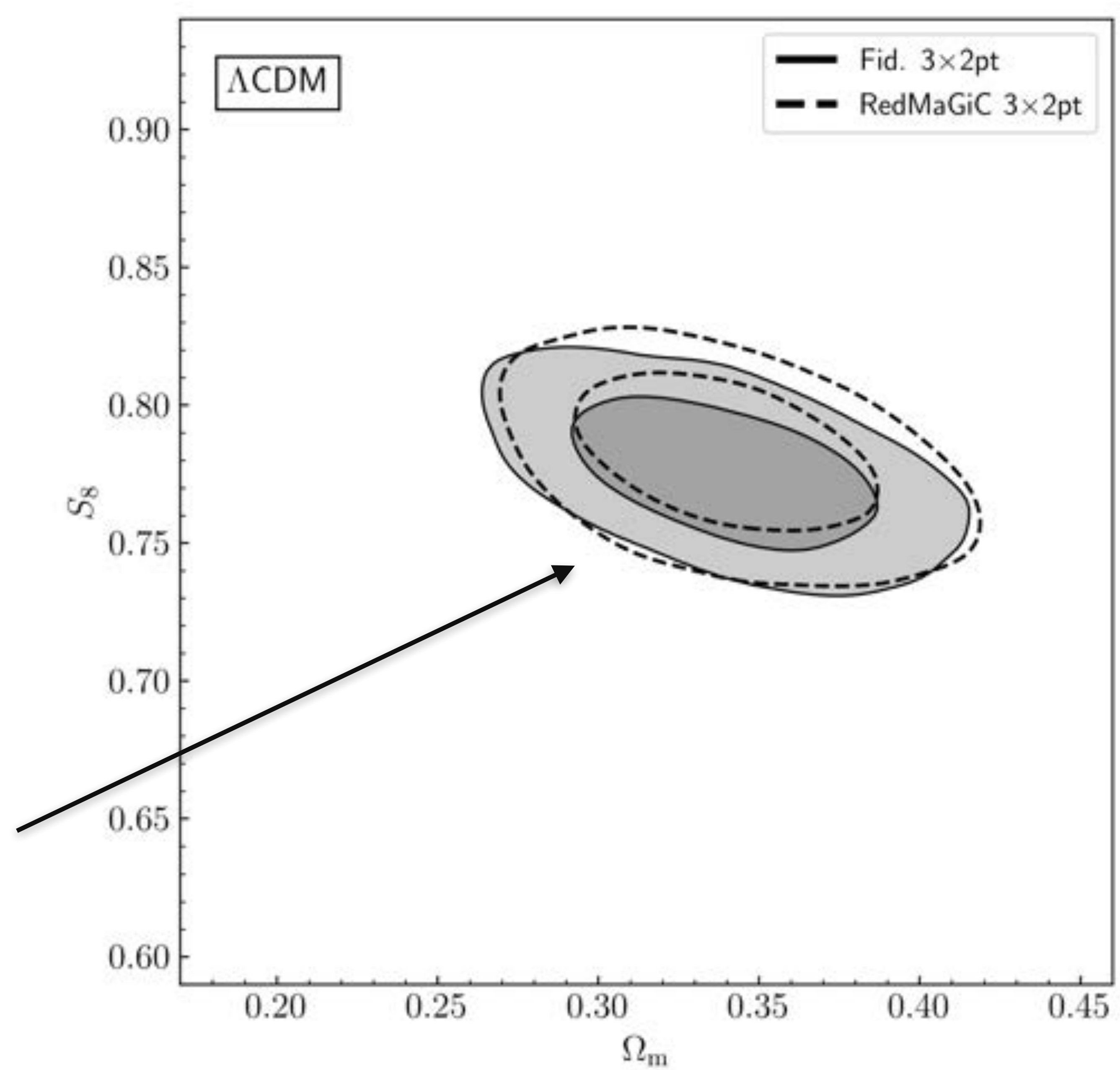
Lens WZ: **Cawthon** et al. (2021)
MagLim: **Porredon,** et al. (2020)
Clustering: **Rodriguez-Monroy** et al. (2021)
Lens SOMPZ (alt. method): **Giannini** et al. (in prep)
DNF: **de Vicente** et al (2015)

Lens sample comparison

We find consistent cosmological results between the fiducial MagLim lens sample and the redMaGiC lens samples

Almost perfect agreement for **3x2pt** in ΛCDM.

3x2 results are extremely robust



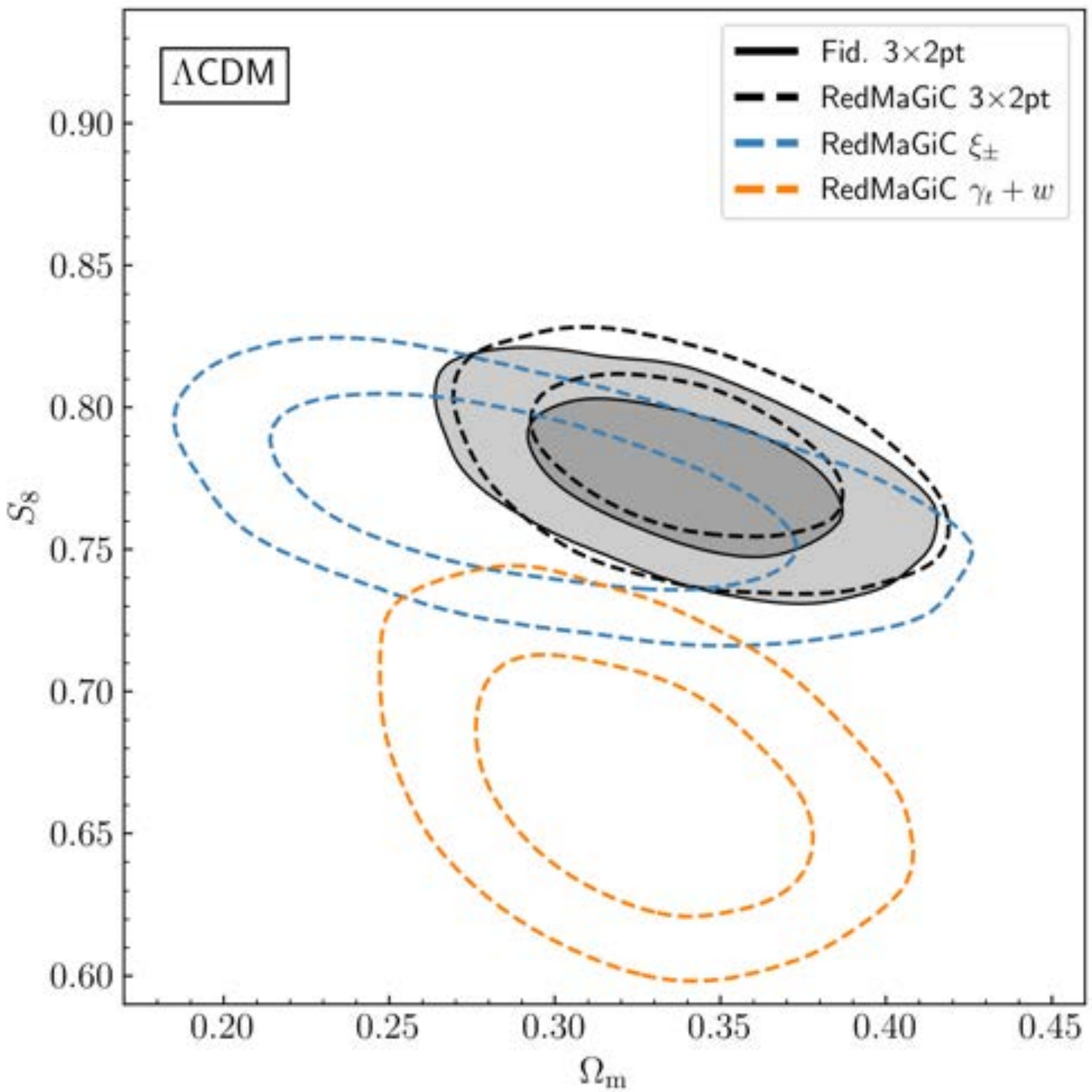
Lens sample comparison

Cosmic shear and galaxy clustering+tangential shear (2x2pt) for redMaGiC are also formally consistent and combine to give the **3x2pt** result.

2x2pt prefers lower S8 and higher galaxy bias. Combination with cosmic shear brings S8 up and bias down to agree with DES Y1.

Evidence for potential systematics in the redMaGiC clustering data vector at all redshifts and above the fiducial lens redshift range for MagLim.

Two highest-redshift bins removed in MagLim.



Lens sample comparison

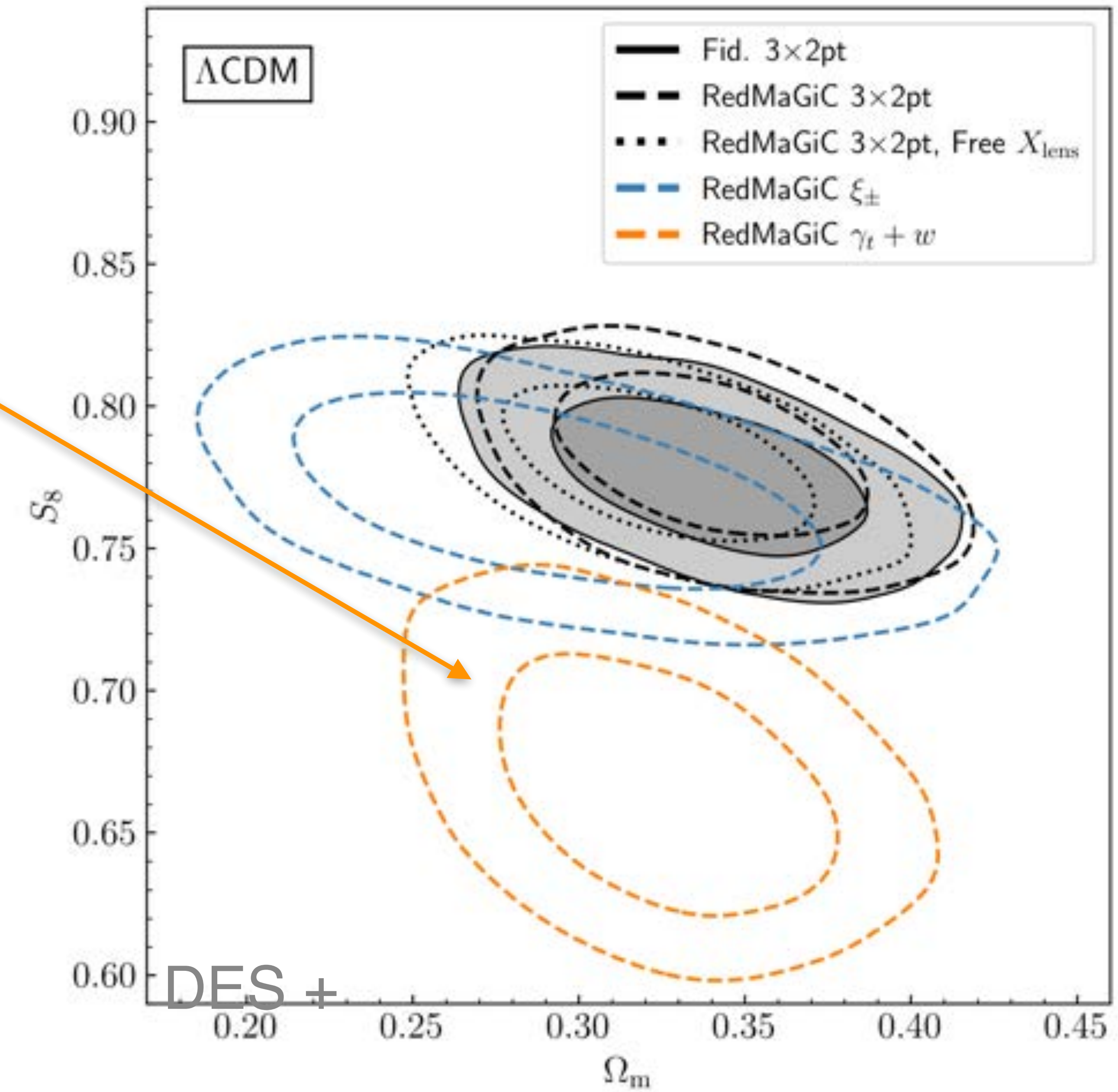
In RedMaGiC, γ_t+w (i.e. "2x2") appears inconsistent with 3x2

We introduce a parameter X_{lens} to model this, it decorrelates the clustering and lensing amplitude:

$$w^{ii}(\theta) = b_i^2 \xi_{\rm mm}^{ii}(\theta)$$
$$\gamma_t^{ij}(\theta) = X_{\rm lens} b_i \xi_{\rm mm}^{ij}(\theta)$$

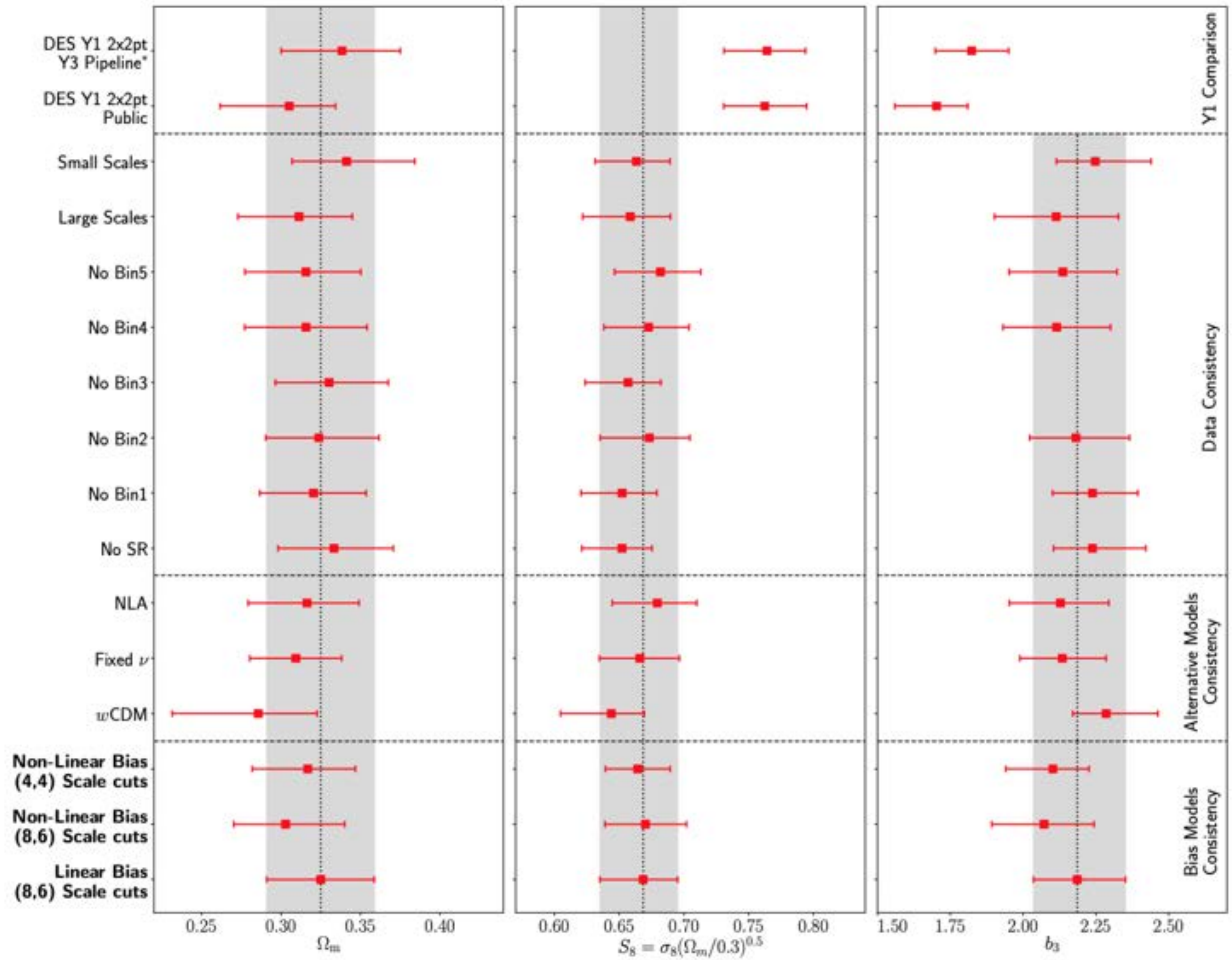
(expect X_{lens}=1)

$$X_{\rm lens} = 0.877^{+0.026}_{-0.019}$$



Lens sample comparison

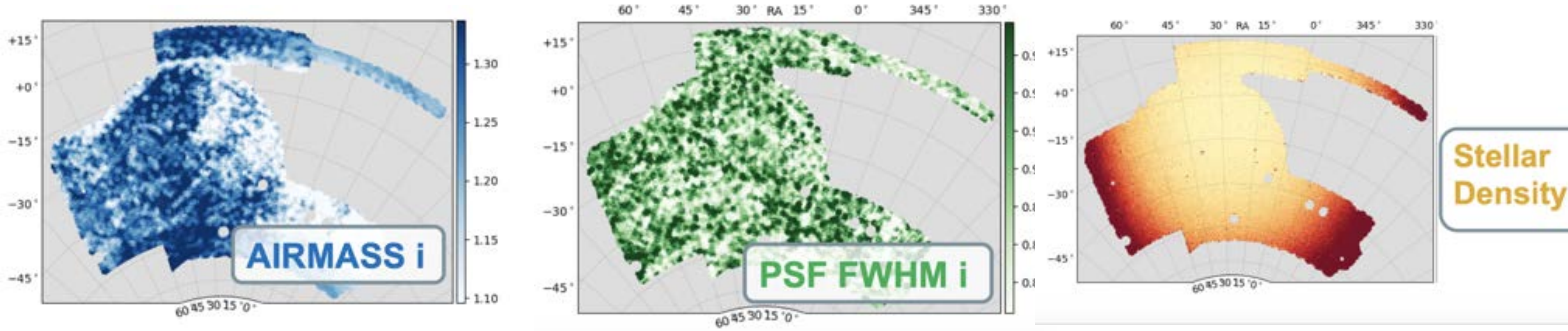
After extensive testing, we believe this to be largely a result of unaccounted for systematics in the *redMaGiC* sample



Pandey et al, arXiv:2105.13545

Important systematic: **Foregrounds** (survey properties etc)

- **Map contamination: a key systematic in LSS**
- due to variety of observ/astro/instrumental reasons
- visible "by eye" at large scales
- important for all galaxy-clustering, shear etc
- esp important for large-spatial-scale science (f_{NL})
- multiplicative, so small scales affected too

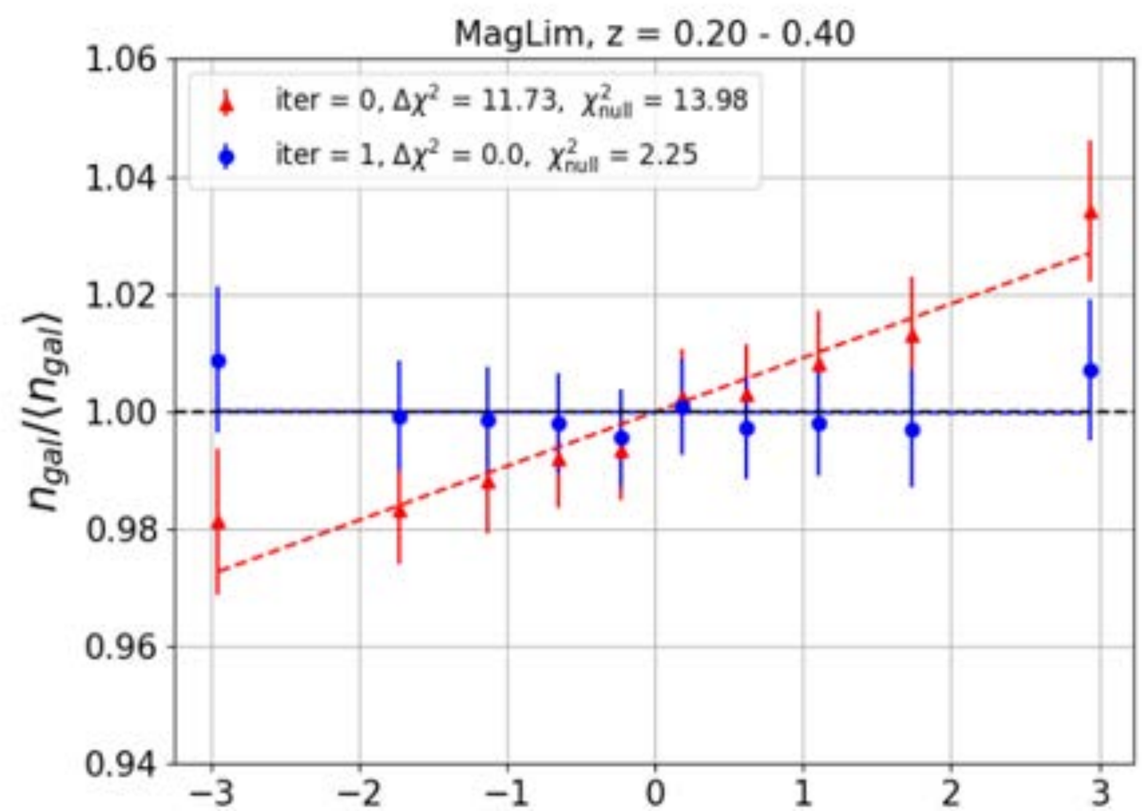


LSS systematics

Correlation with survey properties and astrophysical maps are removed by re-weighting galaxy sample by fitted relation

Accounts for correlation with: **airmass, seeing, exposure time, depth, stellar density, dust, sky brightness, calibration residuals**

Example (right): correlation with a PCA of the above survey property maps

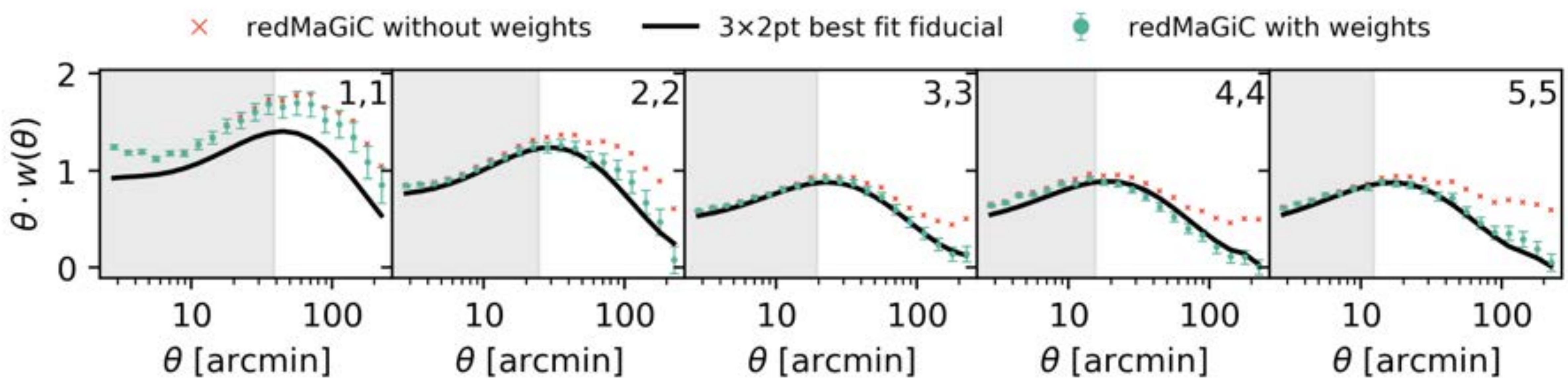


Linear combination of survey maps

Rodriguez-Monroy et al. (2021)

LSS systematics

Correlation with survey properties and astrophysical maps are removed by re-weighting galaxy sample by fitted relation

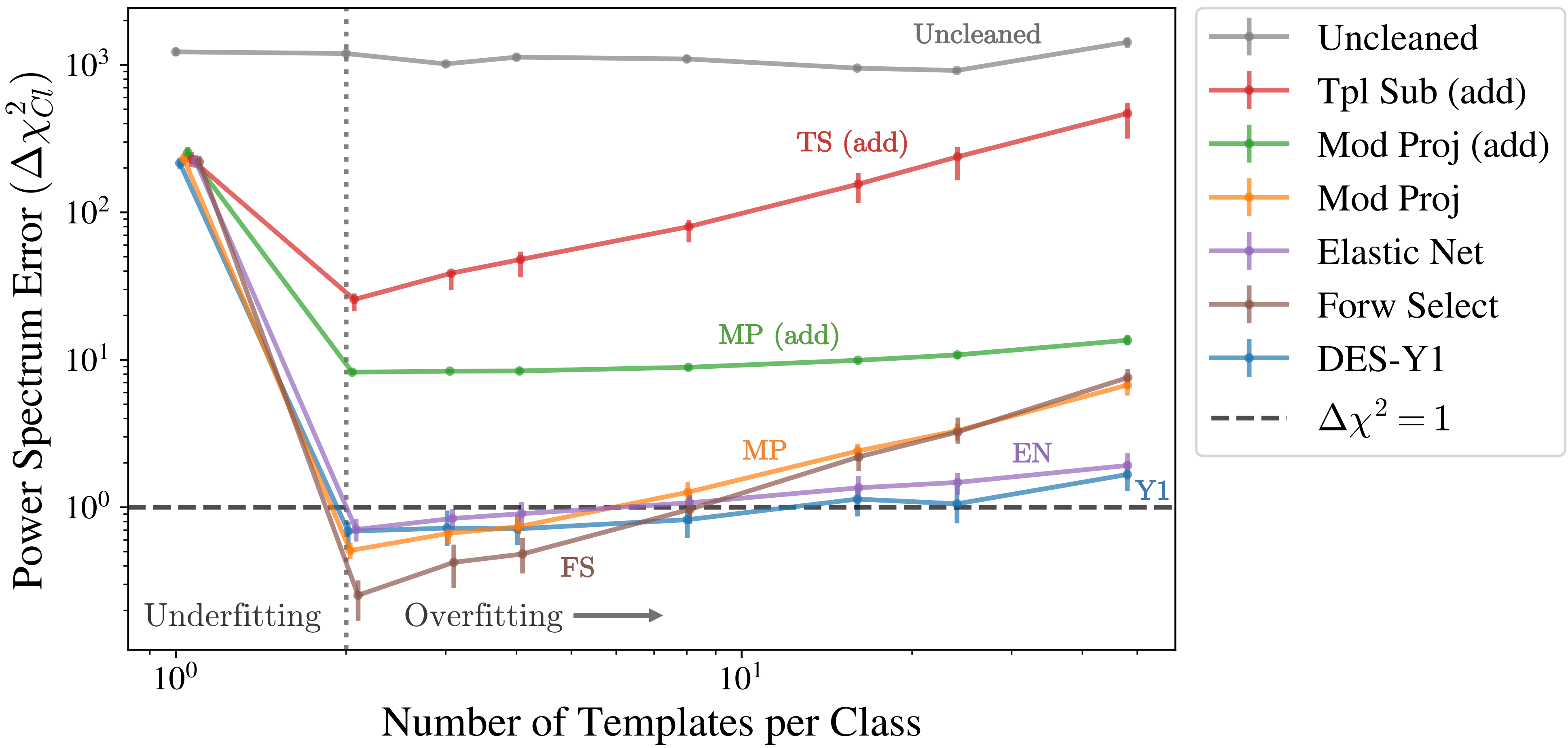


Rodriguez-Monroy et al. (2021)

Detailed analysis of LSS map cleaning methods

Noah Weaverdyck
(U. Michigan -> Berkeley)

$$\text{Loss} = \underbrace{\frac{1}{2N_{\text{pix}}}||d_{\text{obs}} - \sum_i^{N_{\text{tpl}}} t_i\alpha_i||_2^2}_{\text{Least Squares Loss}} + \lambda_1 \underbrace{\left(\sum_i^{N_{\text{tpl}}} |\alpha_i|\right)}_{\text{Prefer fewer templates}} + \frac{\lambda_2}{2}\underbrace{\left(\sum_i^{N_{\text{tpl}}} |\alpha_i^\dagger \alpha_i|\right)^2}_{\text{Shrink imprecise estimates}},$$



Weaverdyck & Huterer, 2021

DES Y3 (X_{lens}) results unchanged even after adopting these methods

DES Y3 analysis takeaways

- **Photometric LSS is… hard**. Lots of information, but (for a careful analysis), big pipeline needed, lots of validation
- Biggest systematics (my opinion): **map-level systematics** and **photometric redshifts**.
- **Nonlinear scales: difficult to model**, simulations exist but show a range of results. May be hard to exploit reliably even with fancy statistical algorithms.

On the other hand:

- A lot of **information** available in the density field: 3D galaxy positions plus their shapes (plus galaxy properties…) - for hundreds of millions of objects
- Information about both **geometry** (distances, volumes) and **growth** of structure (e.g. scaling of power spectrum in redshift) comes out automatically

What if gravity deviates from GR?

For example:

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \qquad \text{or} \qquad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

↓ Modified gravity

↓ Dark energy

Notice: there is no way to distinguish these two possibilities just by measuring expansion rate H(z)!

Growth of structure comes to the rescue: in standard GR, H(z) determines distances **and** growth of structure

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi\rho_M\delta = 0$$

⇒ measure geometry [D(z), Vol(z)] and growth [Pk(z)]

Specifically: compare geometry and growth in order to stress-test the LCDM model and see if it “breaks”

Our approach:

Double the standard DE parameter space

(Ω_M=1–Ω_{DE} and w):

$\Rightarrow \Omega_M^{geom}, w^{geom}$ $\Omega_M^{grow}, w^{grow}$

[In addition to other, usual parameters]

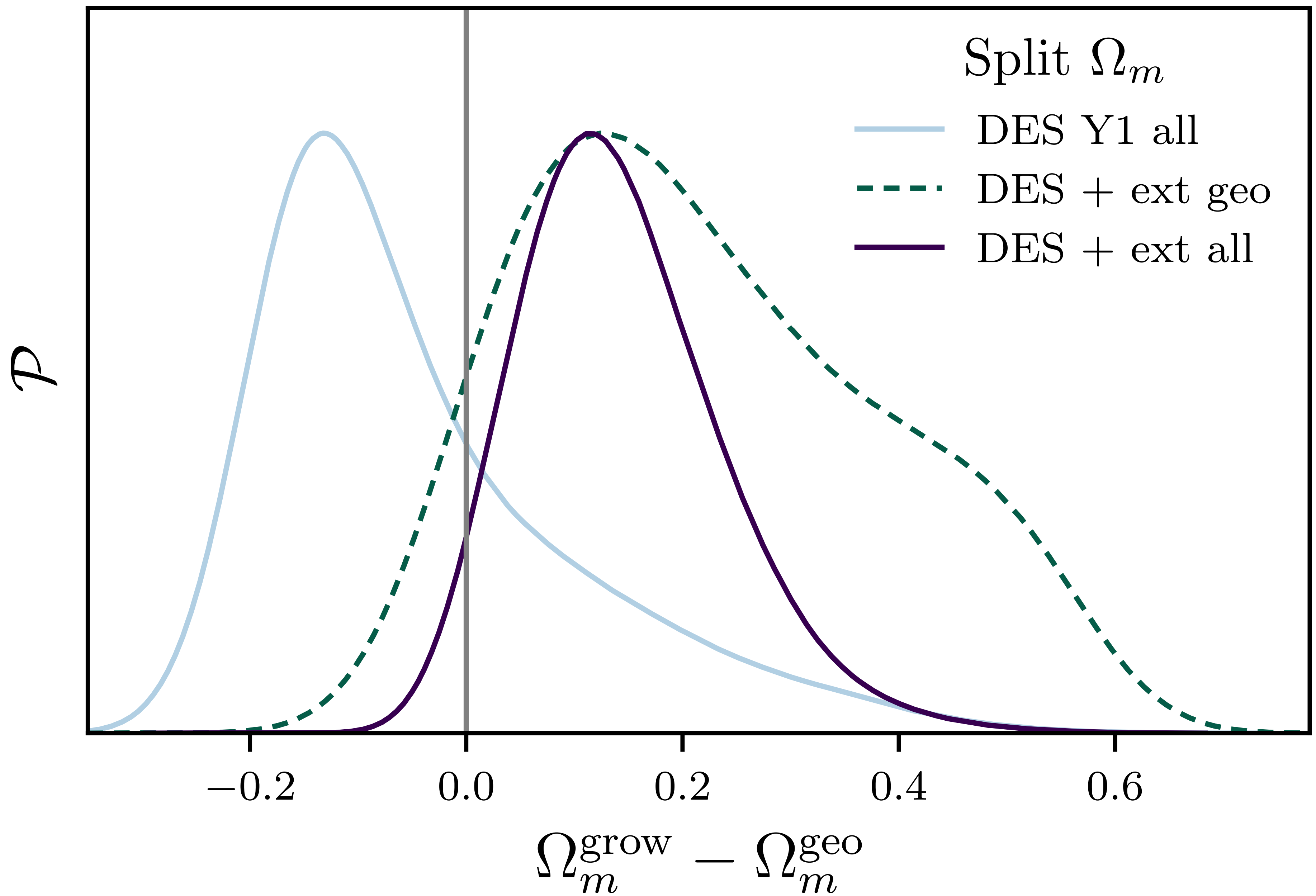
Zhang et al (2005); Wang et al (2007); Ruiz & Huterer (2015); Bernal et al (2016)

Sensitivity to geometry and growth

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$	—
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2}\, D_A(z_*)$	—
Cluster counts	$\frac{dV}{dz}$	$\frac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$	$P\left(k = \frac{\ell}{r(z)}\right)$
RSD	$F(z) \propto D_A(z) H(z)$	$f(z)\sigma_8(z)$

Ruiz & Huterer, 2015

Geometry-growth tests with DES Y1



Jessie Muir
(Stanford -> Perimeter)

Muir et al (DES collab.), arXiv:2010.05935

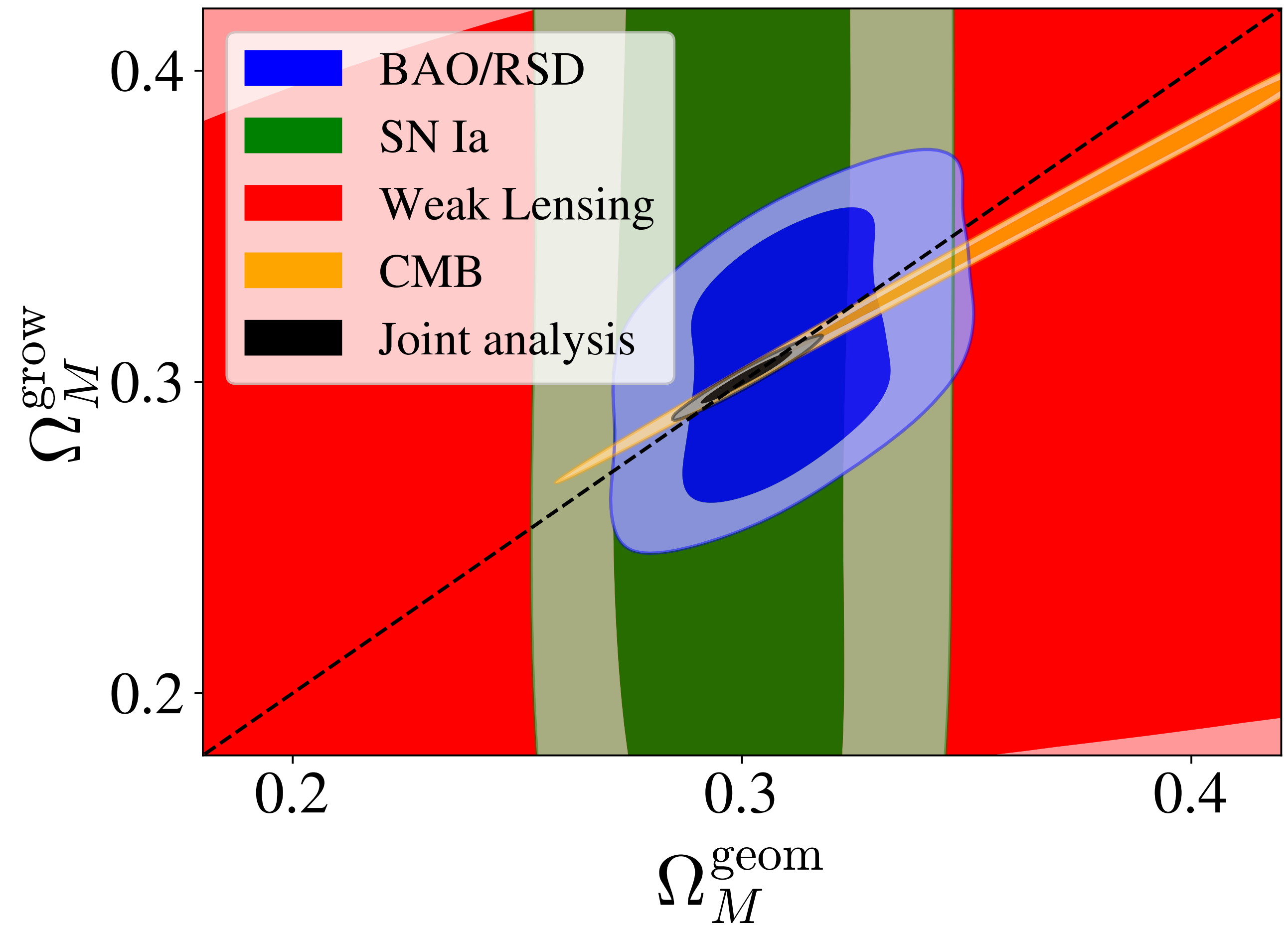
Geometry - growth split

$$\Delta\Omega_M = -0.0000^{+0.0026}_{-0.0027}$$
$$\Delta w = -0.041^{+0.099}_{-0.084}$$

(split wCDM)

where

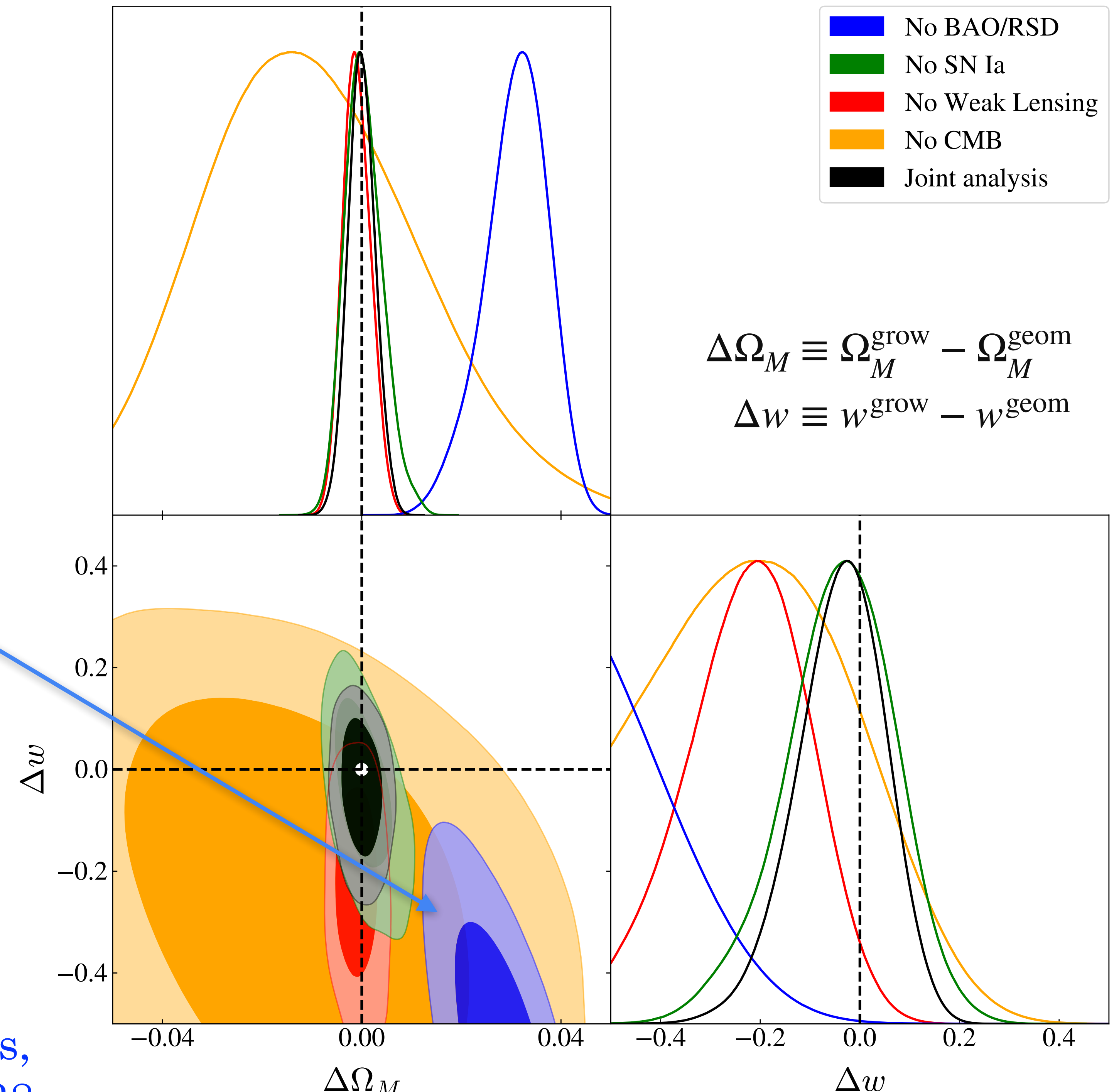
$$\Delta\Omega_M \equiv \Omega_M^{\rm grow} - \Omega_M^{\rm geom}$$
$$\Delta w \equiv w^{\rm grow} - w^{\rm geom}$$



Andrade, Anbajagane, van Marttens, Huterer & Alcaniz, arXiv:2107.07538

Joint analysis consistent, yet:

When BAO/RSD is dropped, results disagree with standard model



Andrade, Anbajagane, van Marttens, Huterer & Alcaniz, arXiv:2107.07538

Conclusions

- Dark Energy is a premier mystery in physics/cosmology; physical reason for accelerating universe still an open question

- Impressive variety of new data; forthcoming: DES Y6, HSC, Hetdex; DESI, LSST, Euclid, WFIRST. And new analyses! (geometry-growth split)

- Like particle physicists, we would really like to see some "bumps" in the data (e.g. Hubble tension!).

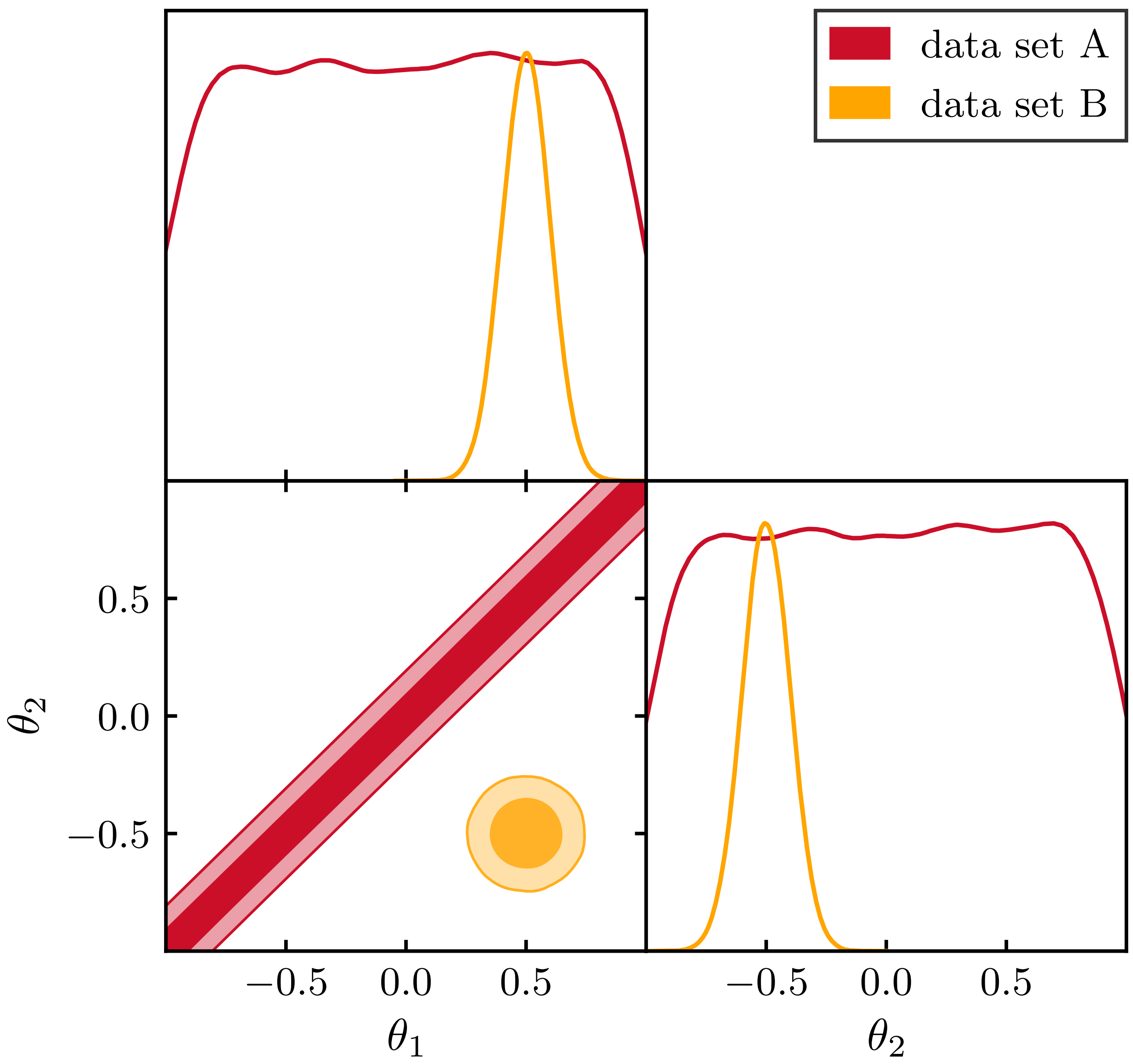
- DES Y3 results have established a new frontier in terms of quality of data, detail of analysis

- DES Y3 results largely consistent with LCDM model; confirm S8 tension; opened new mysteries as to (probably systematic?) feature in RedMaGiC lens galaxies

Extra slides

How do you measure (N-dim) tensions?

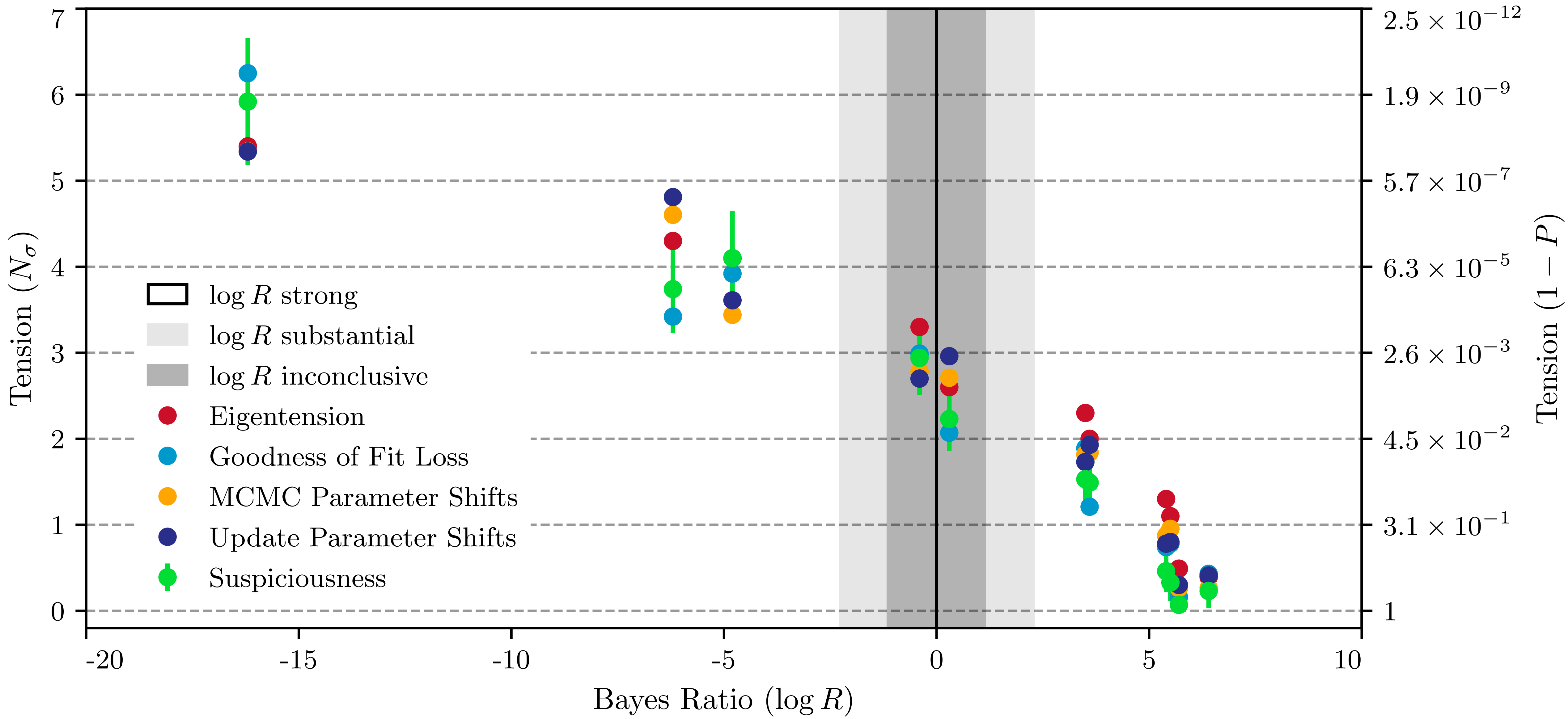
In 1D it's easy, but in ≥2D, ambiguous how to estimate



Lemos, Raveri et al (DES collab.),
in prep (arXiv in ~2 weeks)

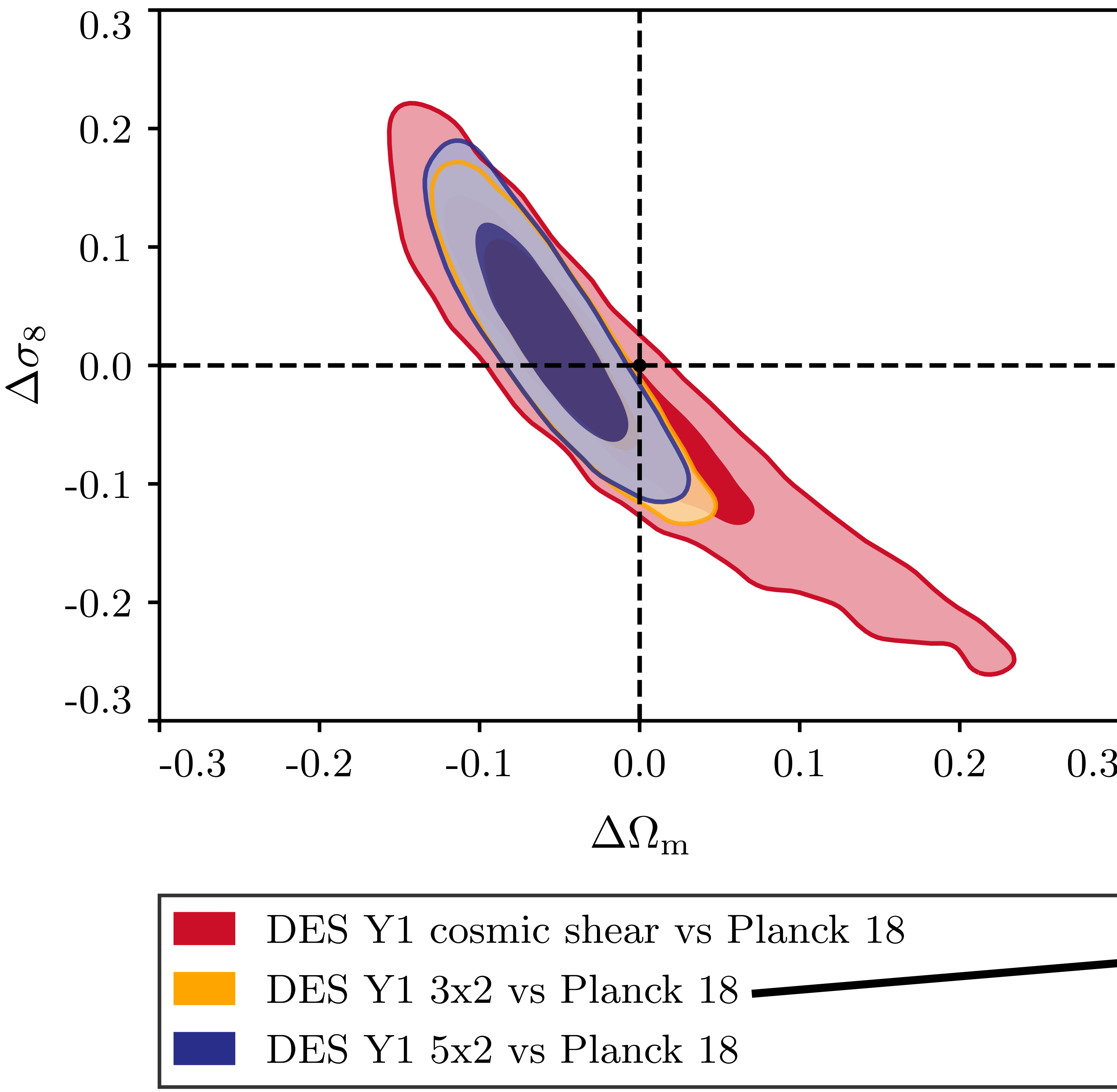
How do you measure (N-dim) tensions?

Principal result: tension metrics (roughly) agree



Lemos, Raveri et al (DES collab.),
in prep (arXiv in ~2 weeks)

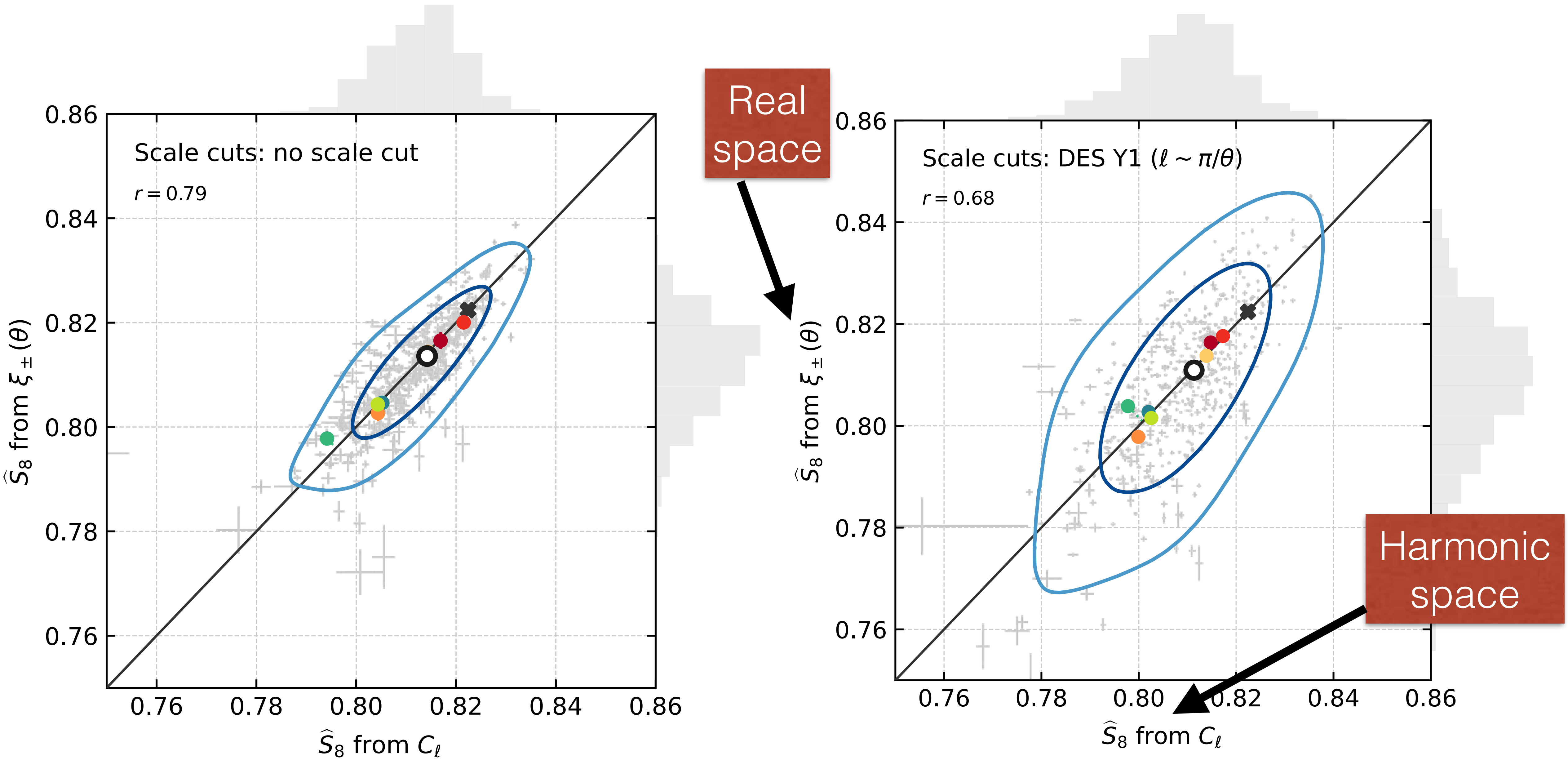
How do you measure (N-dim) tensions?

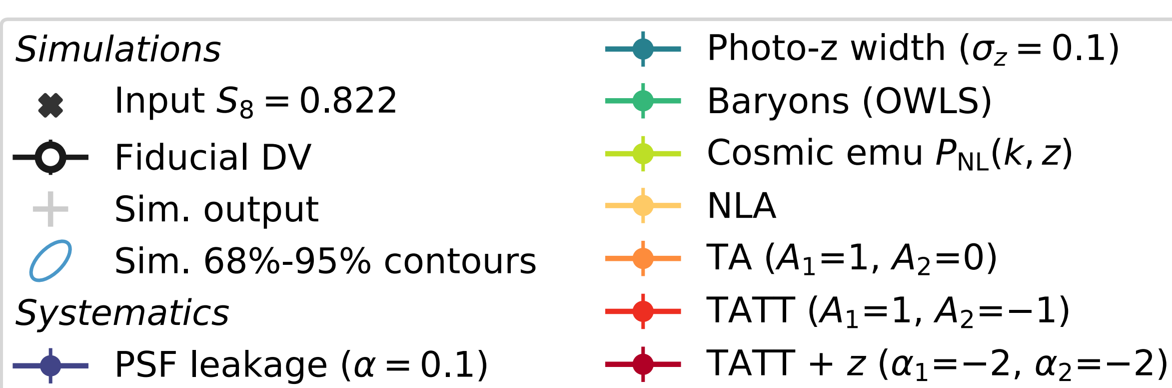


2-ish sigma tension

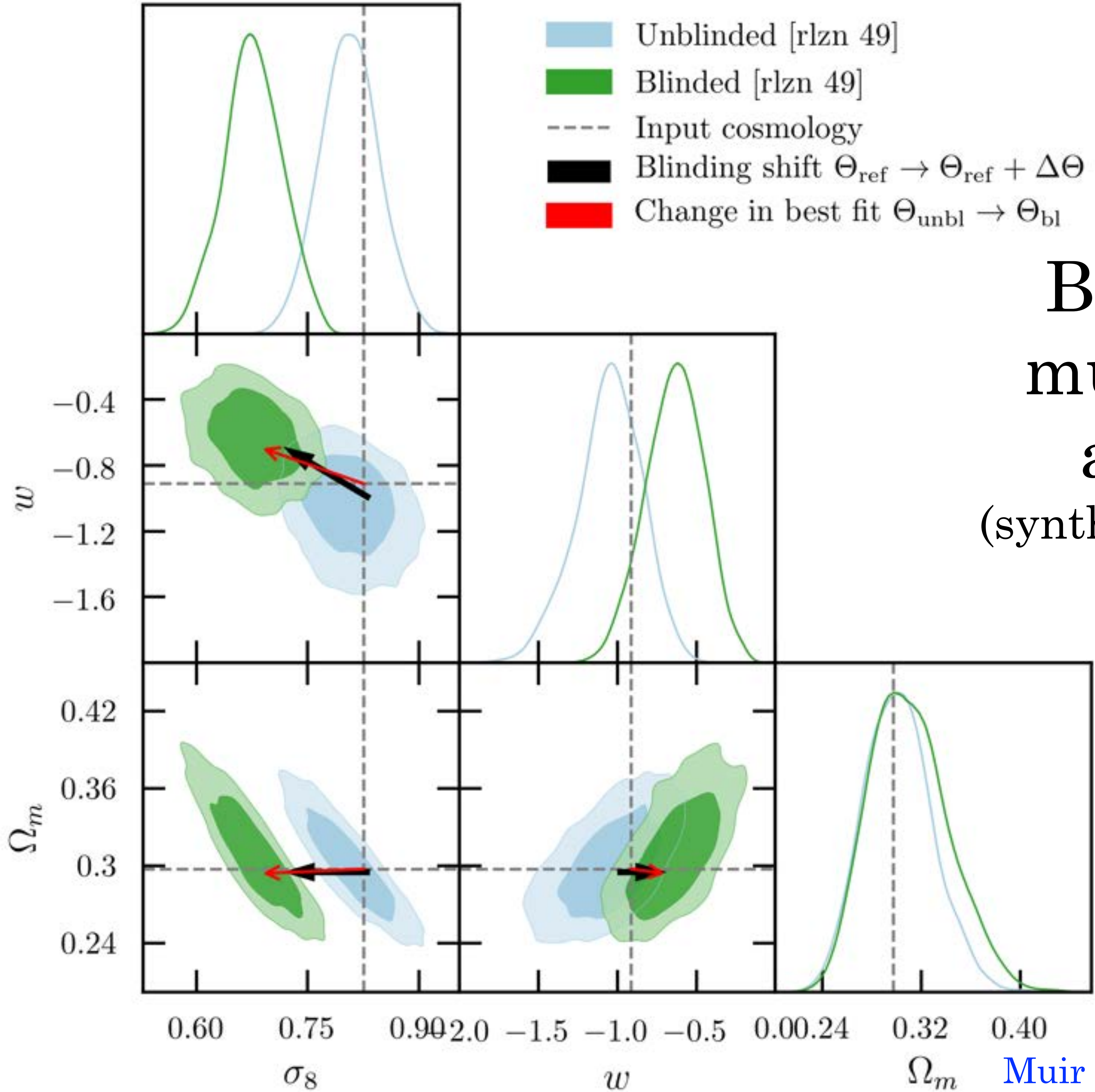
Lemos, Raveri et al (DES collab.), in prep (arXiv in ~2 weeks)

Harmonic vs real space analysis
- same information??





Doux et al (DES collab.),
arXiv.2011.06469



Blinding a multi-probe analysis

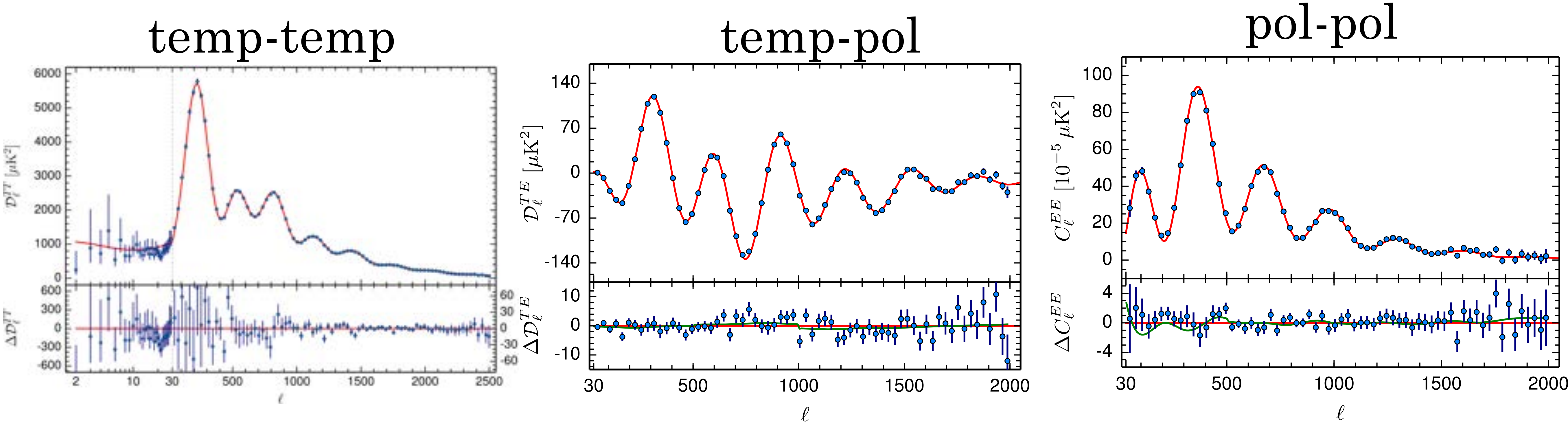
(synthetic test shown)

Muir et al, arXiv:1911:15929

Story so far:

- Cosmology definitely in the precision regime
- Impressive constraints on DM, DE and inflation…
- …but some big questions unanswered
- Lots of potential from upcoming surveys

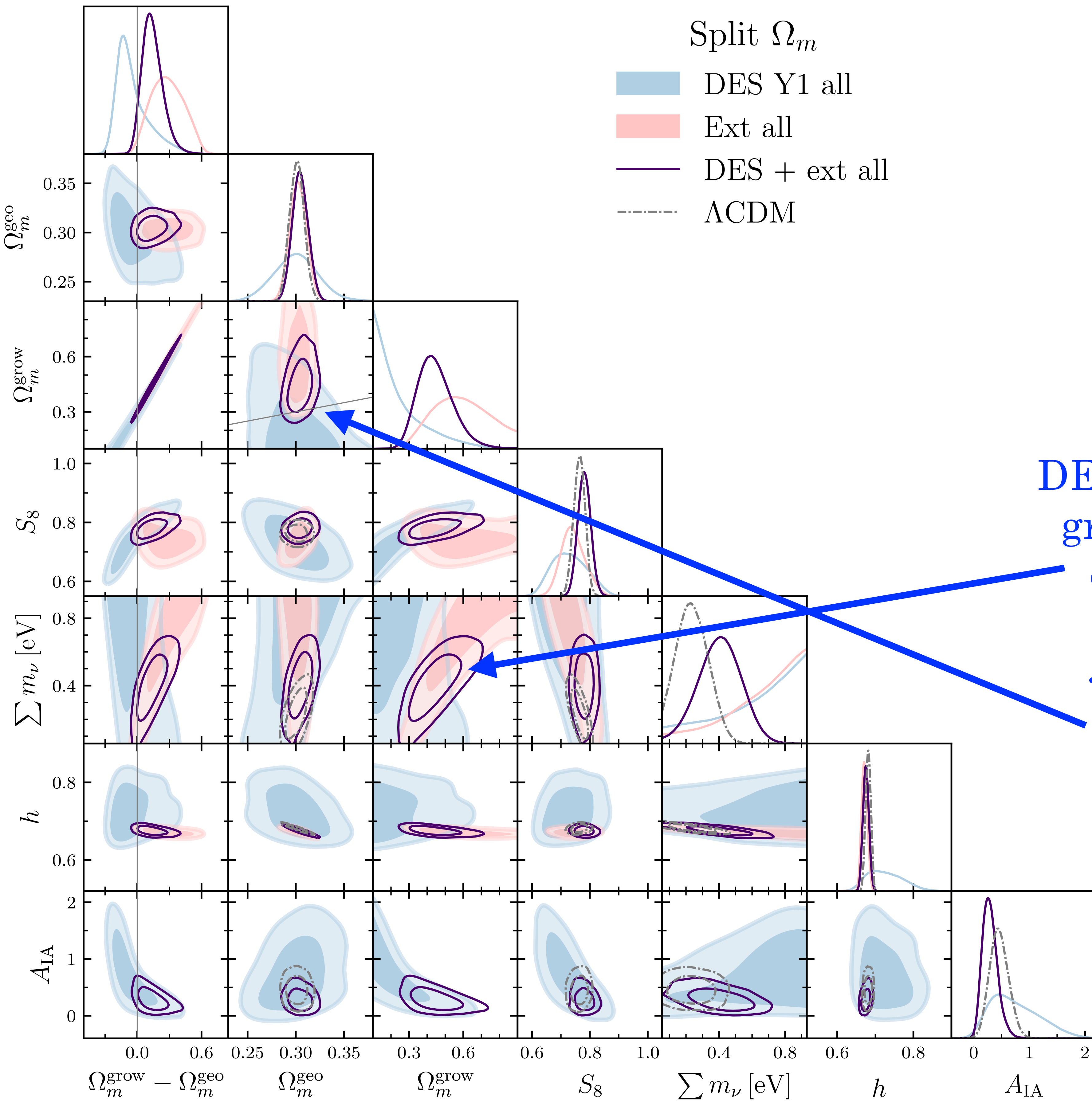
But are Planck++ constraints *so* good that they bias us?



Danger of declaring currently favored model to be the truth

$\Longrightarrow$ **blinding new data is key**

Geometry-growth tests with DES Y1



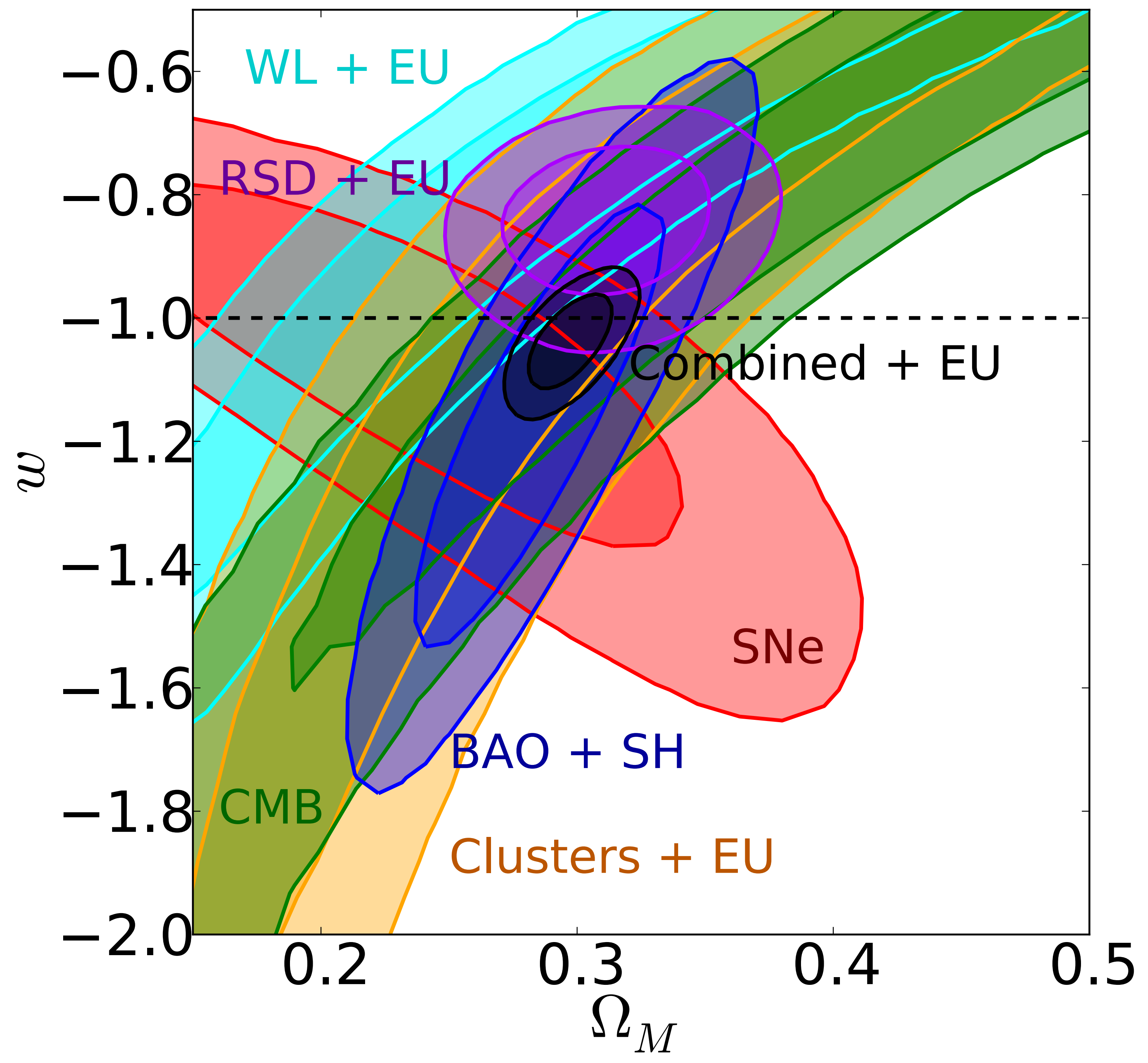
DES can break the growth-neutrino degeneracy…

…and get interesting constraints in geom-grow plane

Jessie Muir
(Stanford)

Muir et al (DES collab.), arXiv:2010.05935

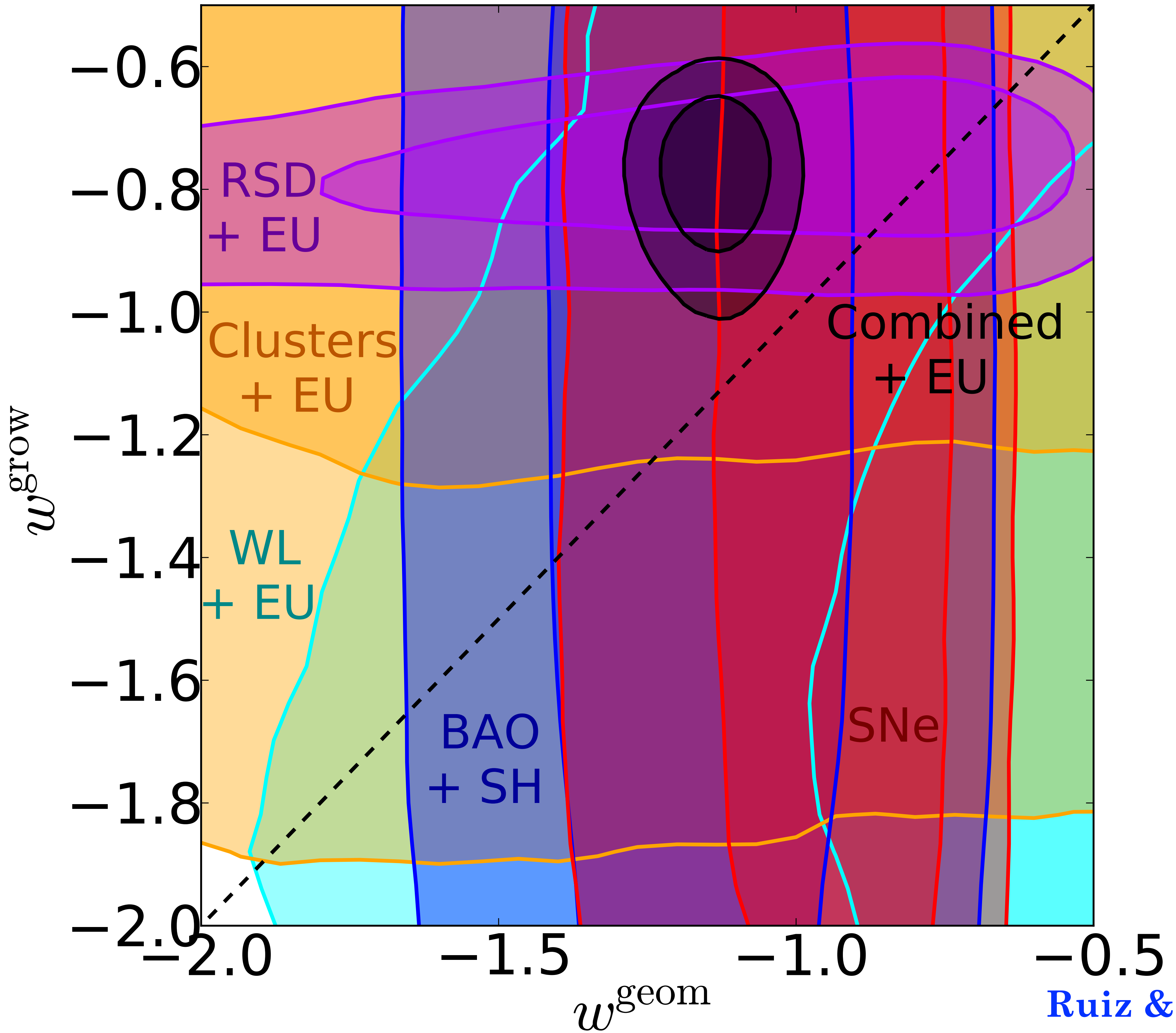
Standard parameter space



EU = Early Universe prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$, n_s, A)

SH = Sound Horizon prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$)

w (eq of state of DE): geometry vs. growth

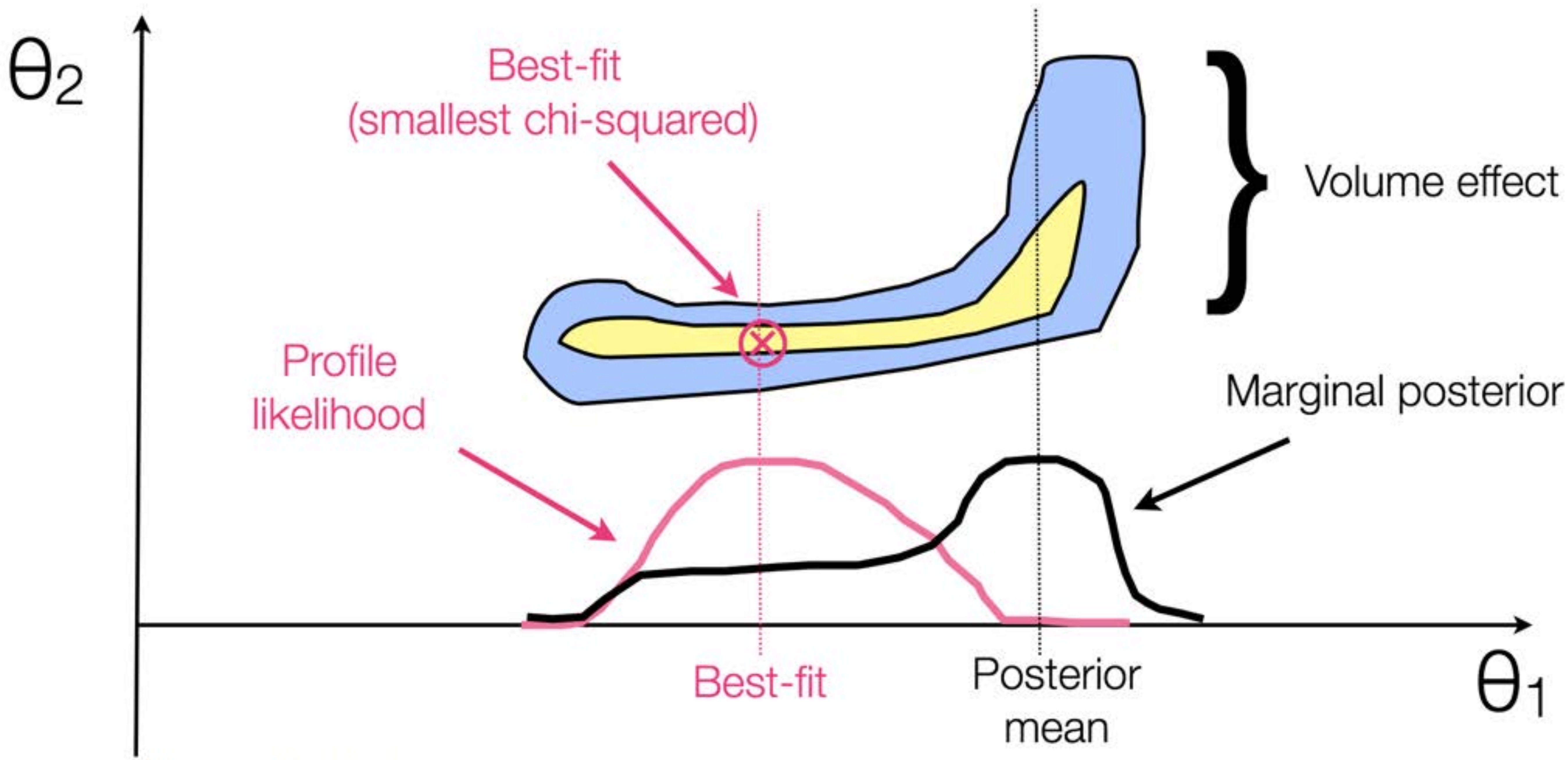


Evidence for $w^{\rm grow} > w^{\rm geom}$: 3.3-σ

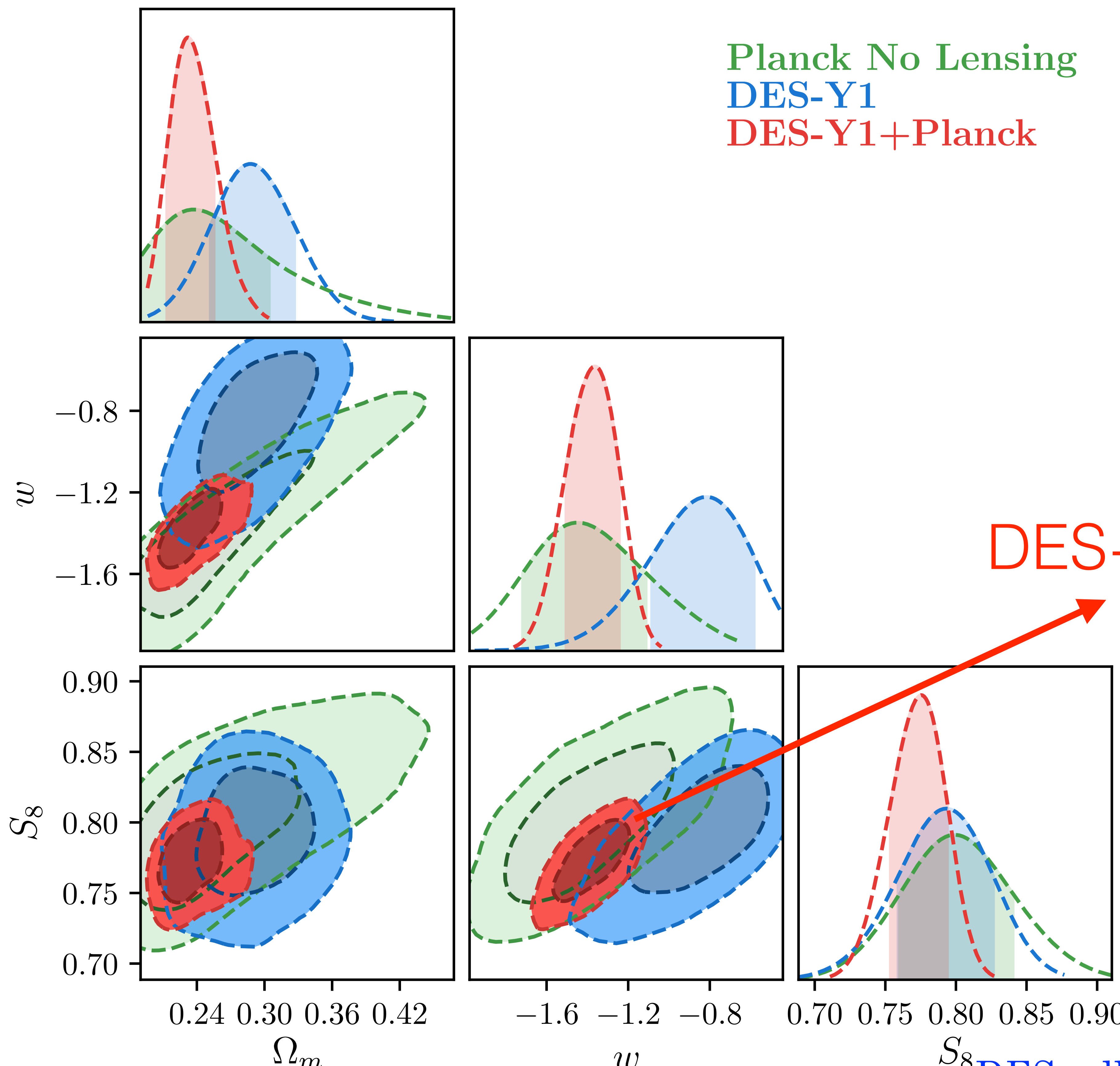
Method currently being applied to DES data

Ruiz & Huterer 2015; see also Bernal, Verde and Cuesta 2016

Prior-volume effect illustrated



DES Y1 3x2 results: constraints on w



DES+Planck:

$$w = -1.47^{+0.31}_{-0.22}$$

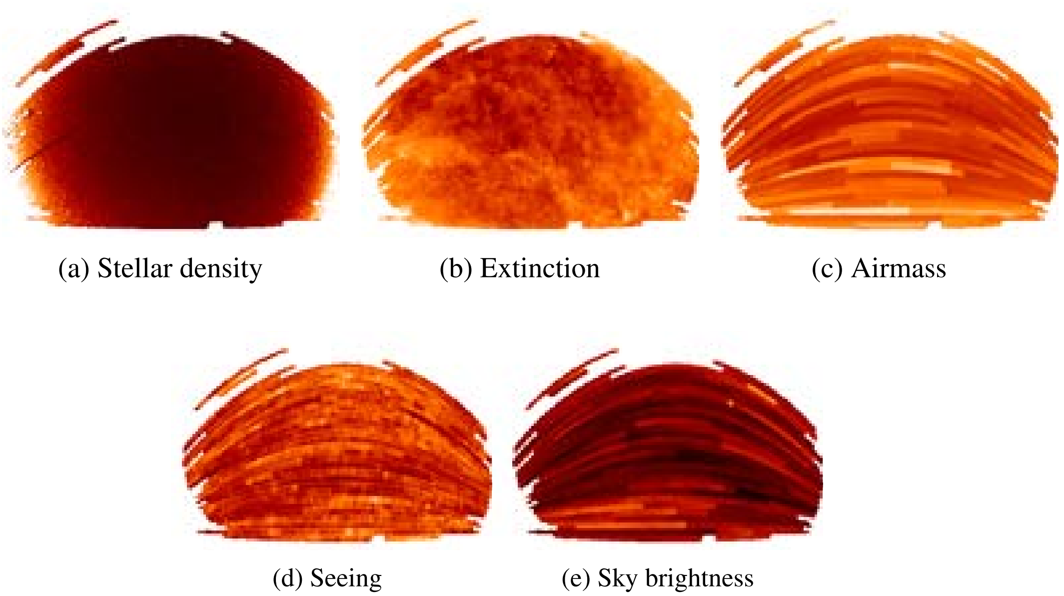
DES+Planck+
SN+BAO:

$$w = -1.00^{+0.05}_{-0.04}$$

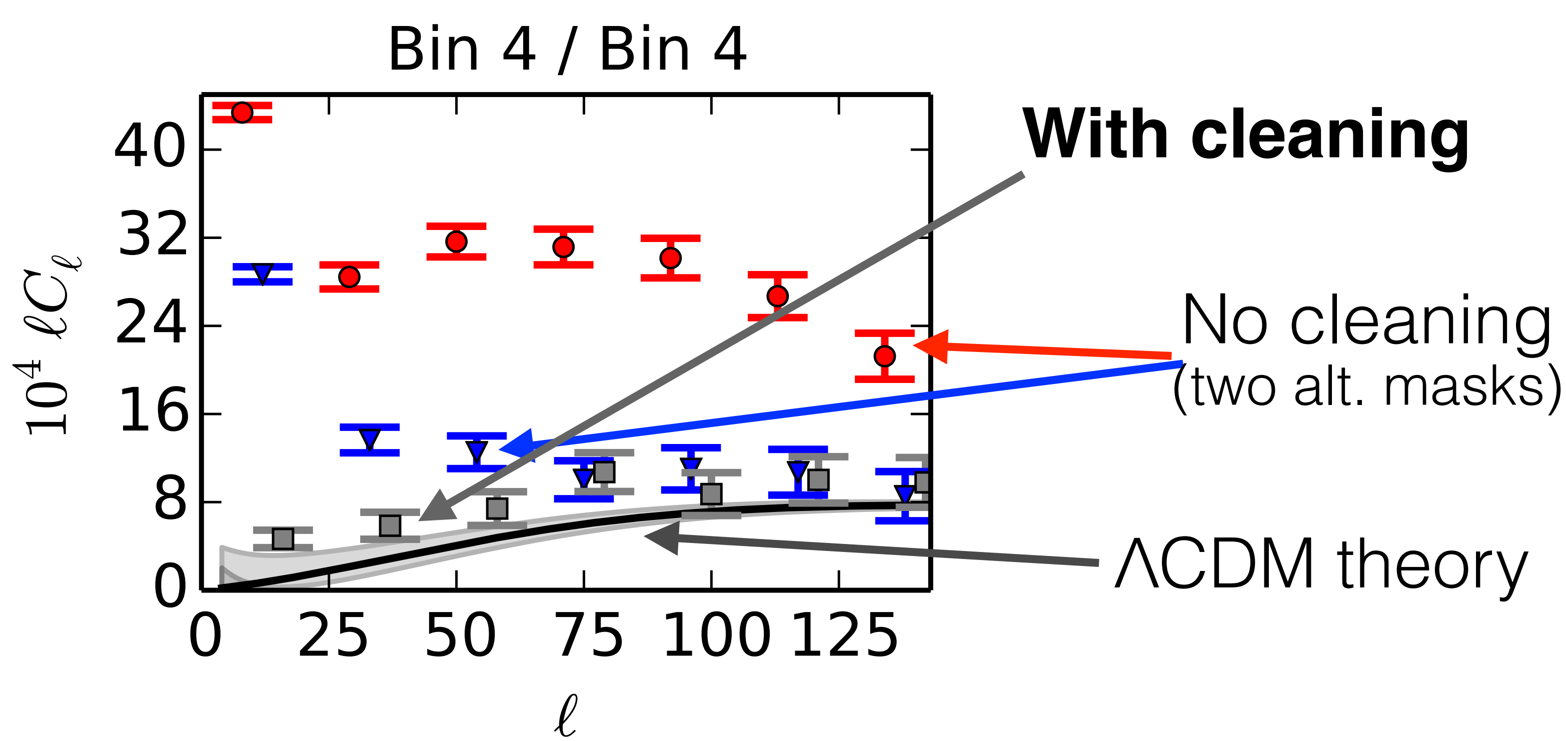
DES collaboration, arXiv:1708.01530

Systematics cleaning (of LSS maps)

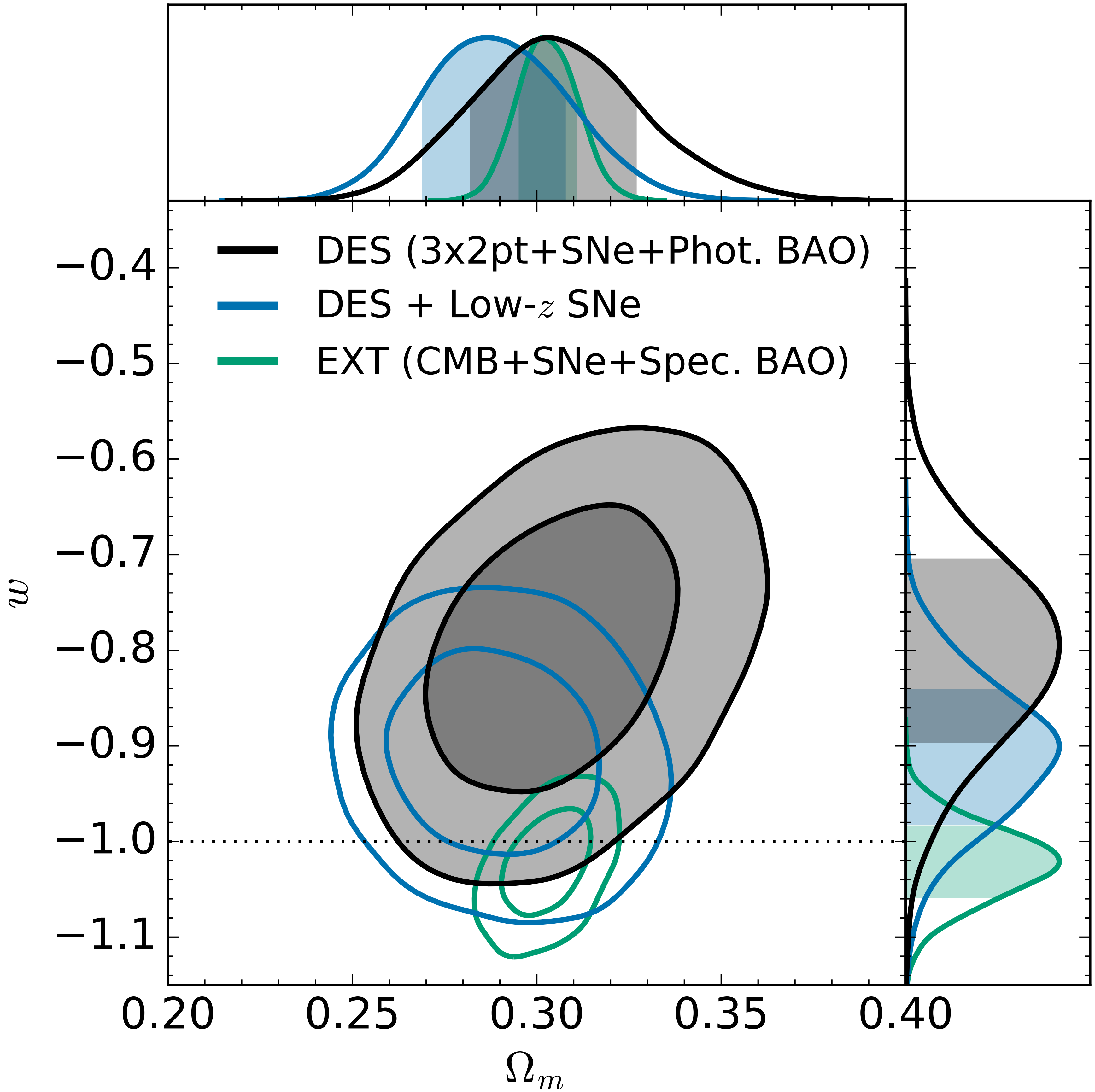
- **Map contamination: a key systematic in LSS**
- due to variety of observ/astro/instrumental reasons
- visible “by eye” at large scales
- important for all galaxy-clustering, shear etc
- esp important for large-spatial-scale science (f_{NL})
- multiplicative, so small scales affected too



Leistedt & Peiris 2015



DES-only Y1 constraints on DE



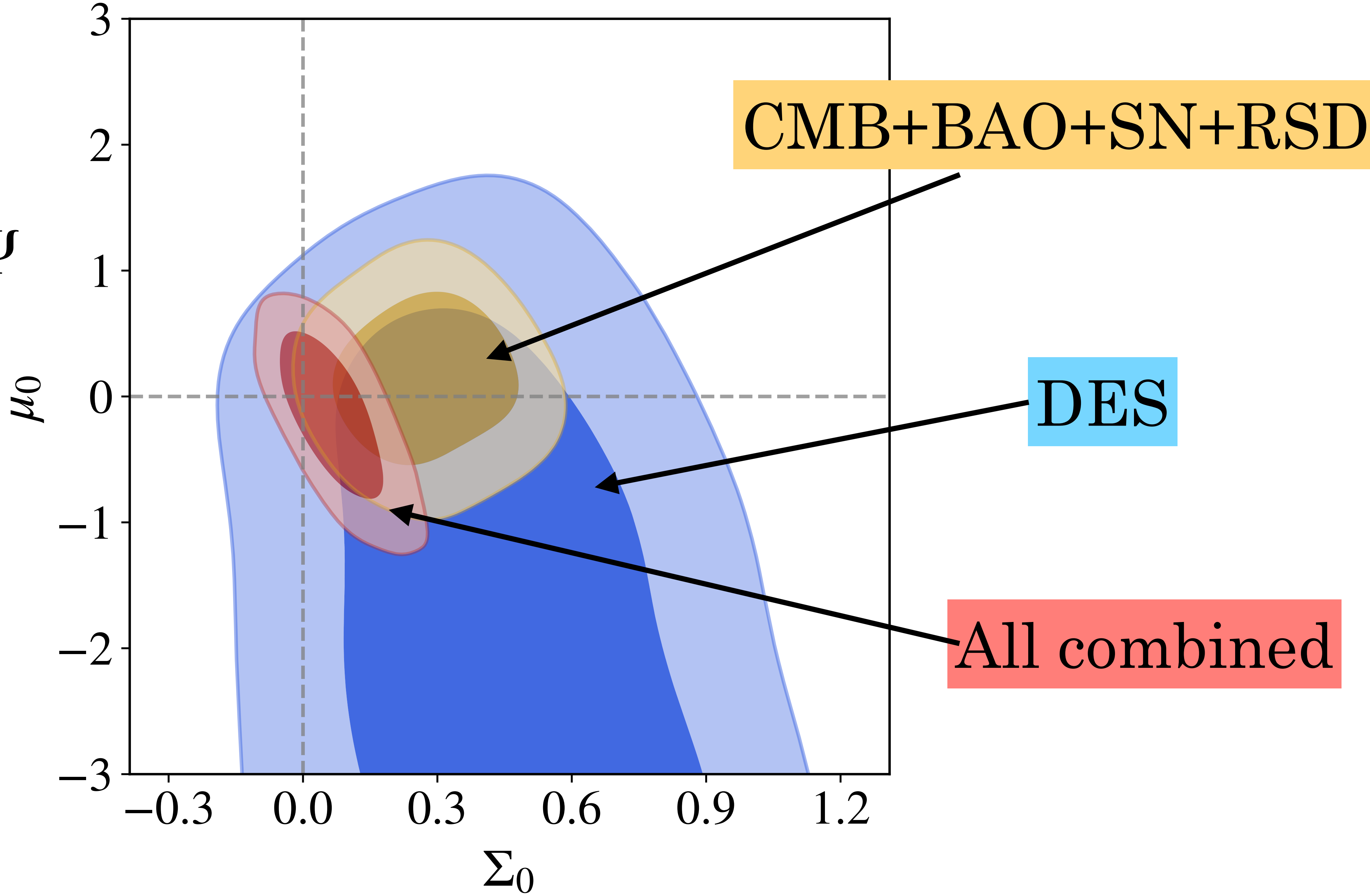
"This is the first time a low-redshift survey has been capable of independently constraining these properties of dark energy to this level of precision"

DES collaboration, arXiv:1811,02375 PRL 2019

DES Year1 results:
extensions to ΛCDM, incl. modified gravity

$1+\mu \sim \Psi$

$1+\Sigma \sim \Phi+\Psi$



DES collaboration, arXiv:1810.02499;
PRD Editor's suggestion

Current notable tensions in cosmology

1. The amplitude of mass fluctuations (σ_8) is higher in the CMB (σ_8=0.83) than in cluster abundance / weak lens (σ_8=0.80)

2. Hubble constant measured by the Planck collaboration (H_0=67.4±0.5) disagrees with that from the distance ladder measurements (H_0=74.02±1.42); the two are 4-5 **sigma** apart

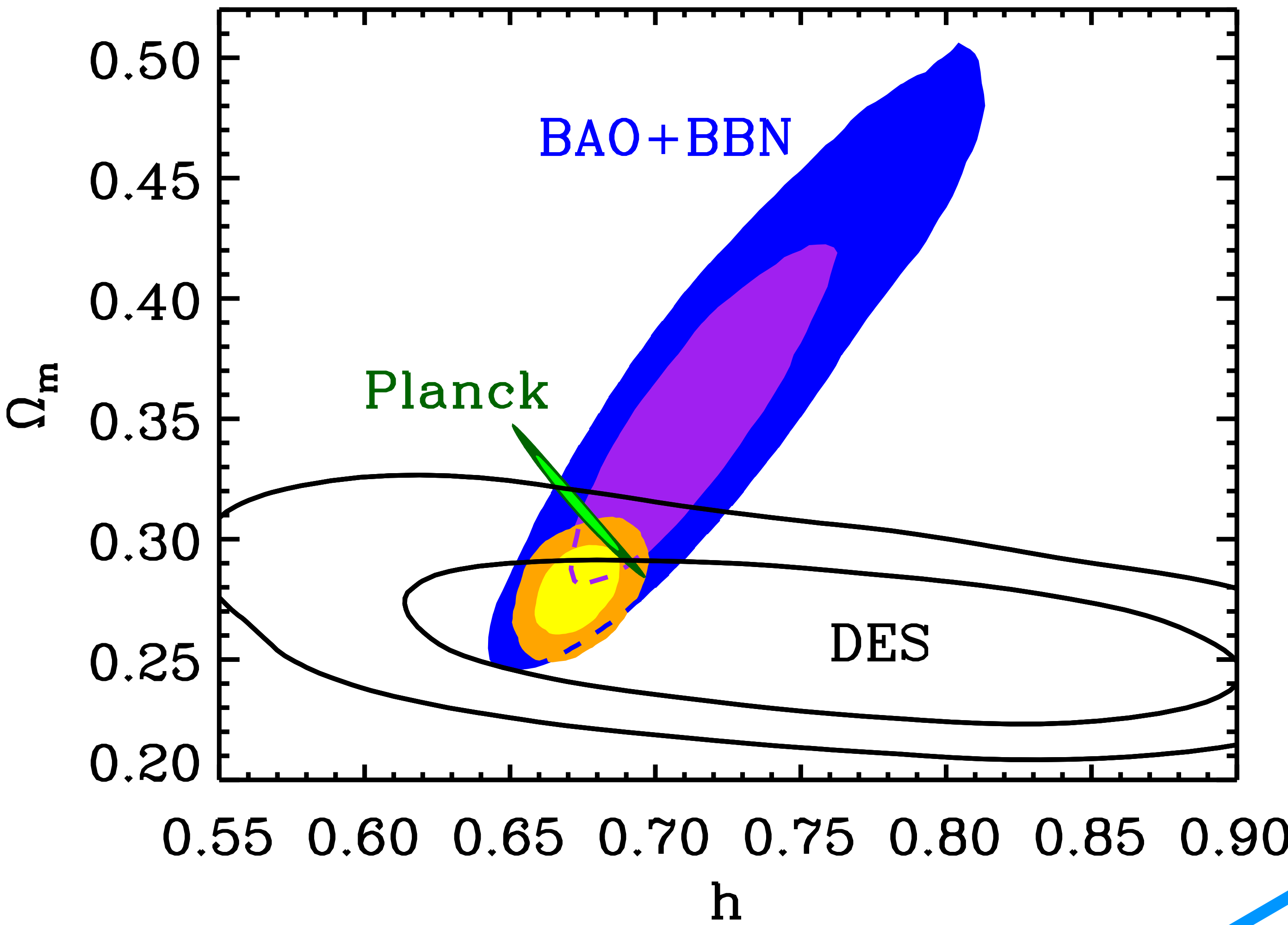
My totally personal view of these:

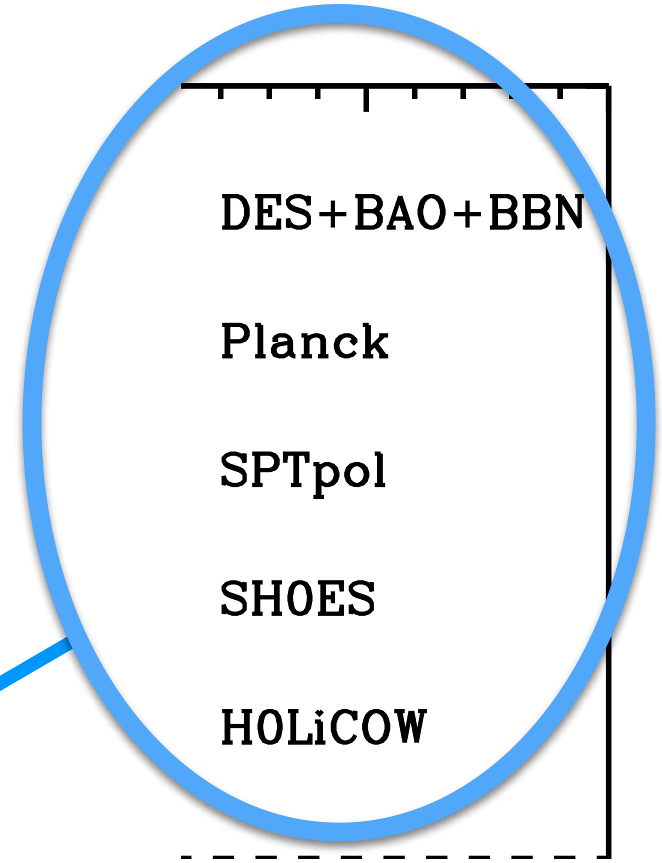
1. is an accidental "scattering around central value" and will go away basically

2. is much more serious, because of excellent, rigorous analyses by CMB **and** distance ladder teams, and may be pointing toward new physics (or non-trivial systematics). Moreover, cosmic variance (fact we live in a "high local H_0" part of universe) contributes negligibly to the (H_0^{local} $-H_0^{CMB}$) difference (Wu & Huterer 2017)

DES H_0 constraints

DES collaboration, arXiv:1711.00403





$$H_0 = 67.2^{+1.2}_{-1.0}$$

Interesting fact:
these 5 measurements of H0 are basically independent

All 5 combined give: $H_0 = 69.1^{+0.4}_{-0.6}$