DARK ENERGY SURVEY

PERIMETER INSTITUTE

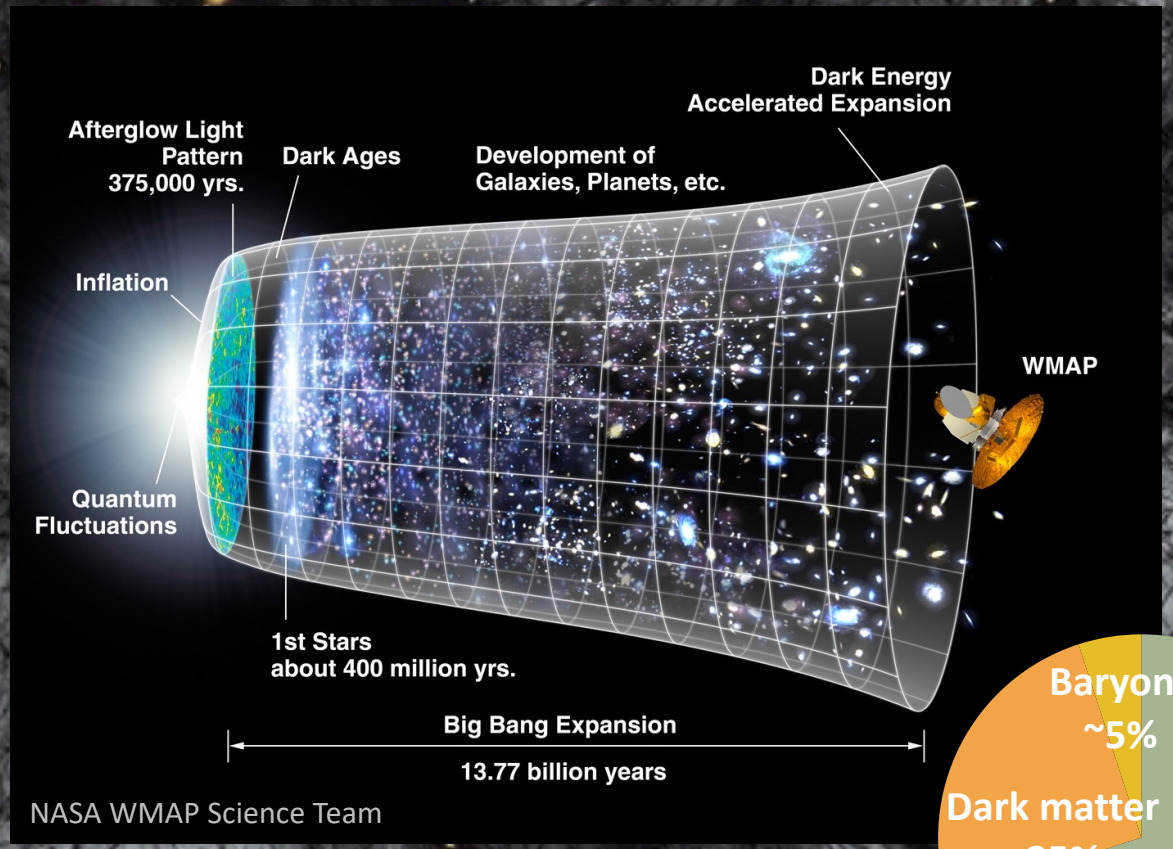
Cosmology Results from the Dark Energy Survey

Jessie Muir - Postdoctoral Fellow @ Perimeter Institute for Theoretical Physics

On behalf of the DES Collaboration

COSMO ’22 plenary session, August 2022

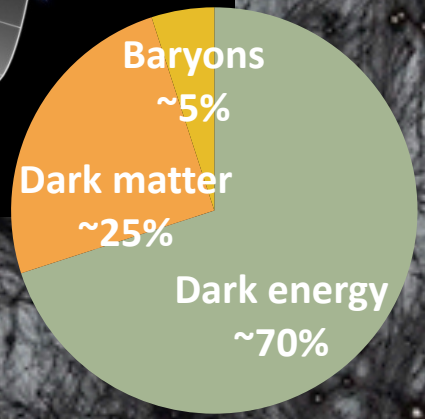
We want to use the large-scale structure (LSS) of the Universe to learn about fundamental physics.



NASA WMAP Science Team

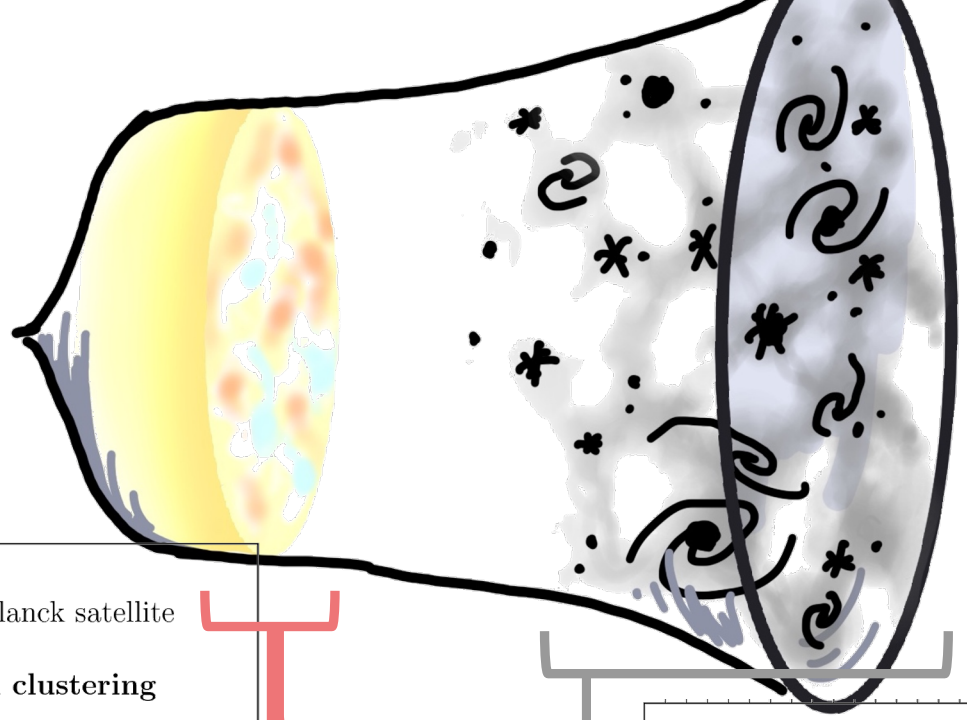
Properties of LSS depend on

- Properties of matter (dark matter, baryons, neutrinos)
- Expansion history (dark energy)
- Gravity (GR vs MG)
- Initial fluctuation properties (inflation)



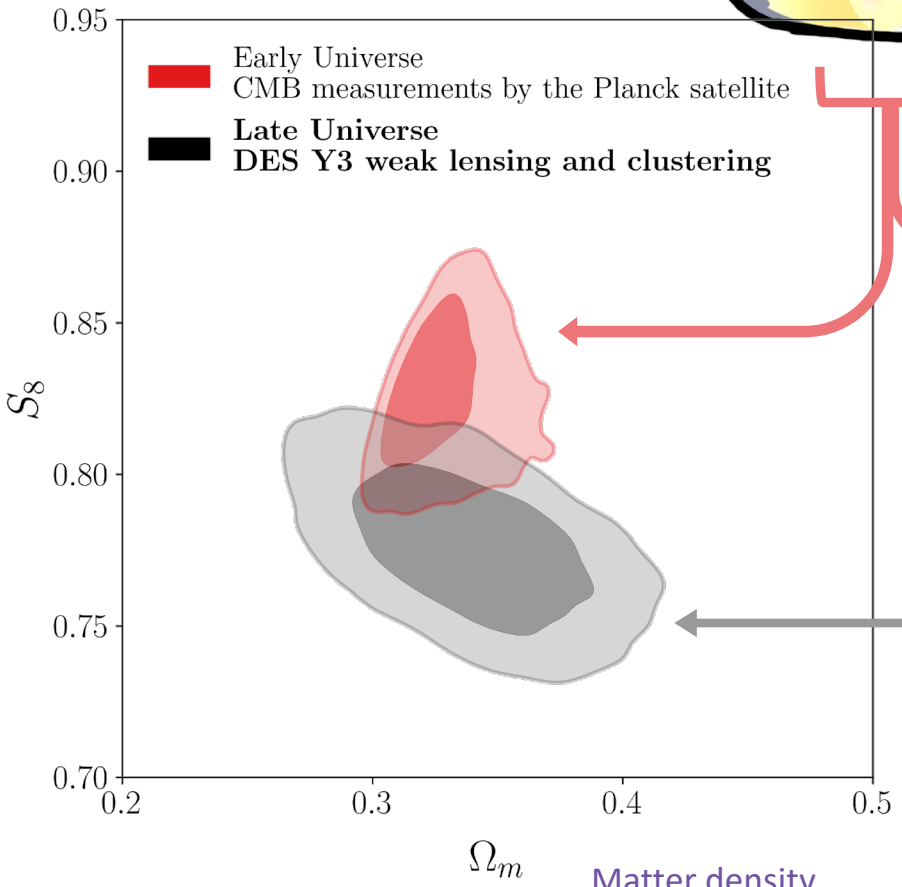
Background Image: Dark Universe planetarium show, via Science News

Comparing late- and early-time ΛCDM constraints tests predictions for 13.8Gyr of evolution.

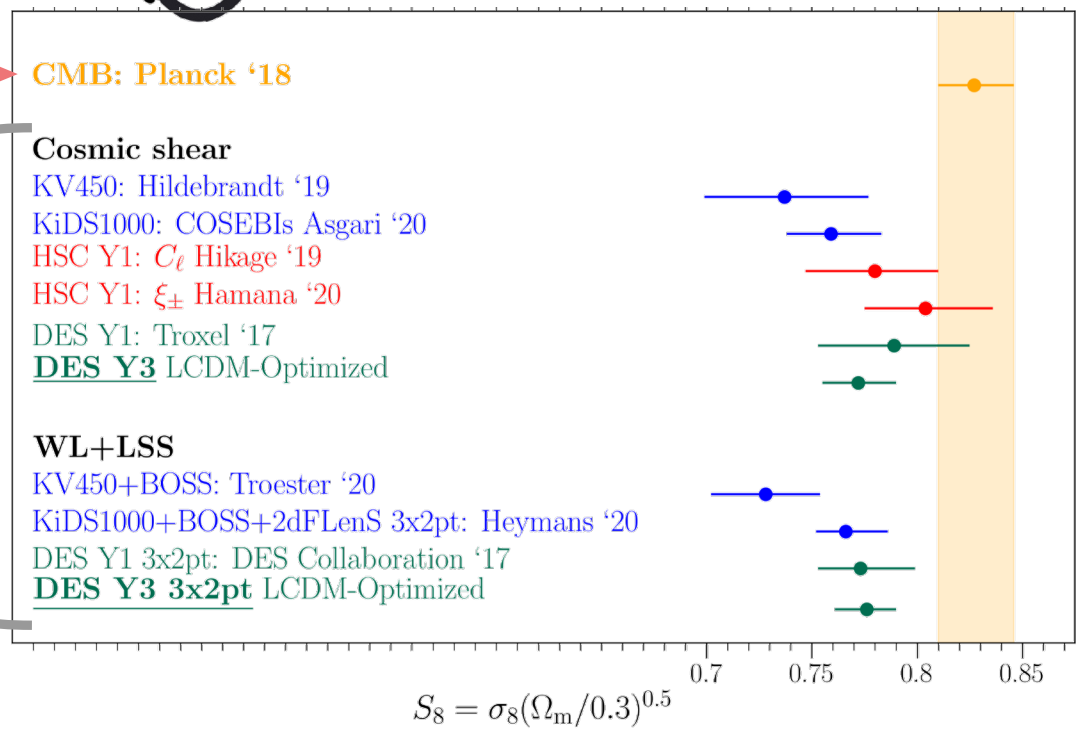


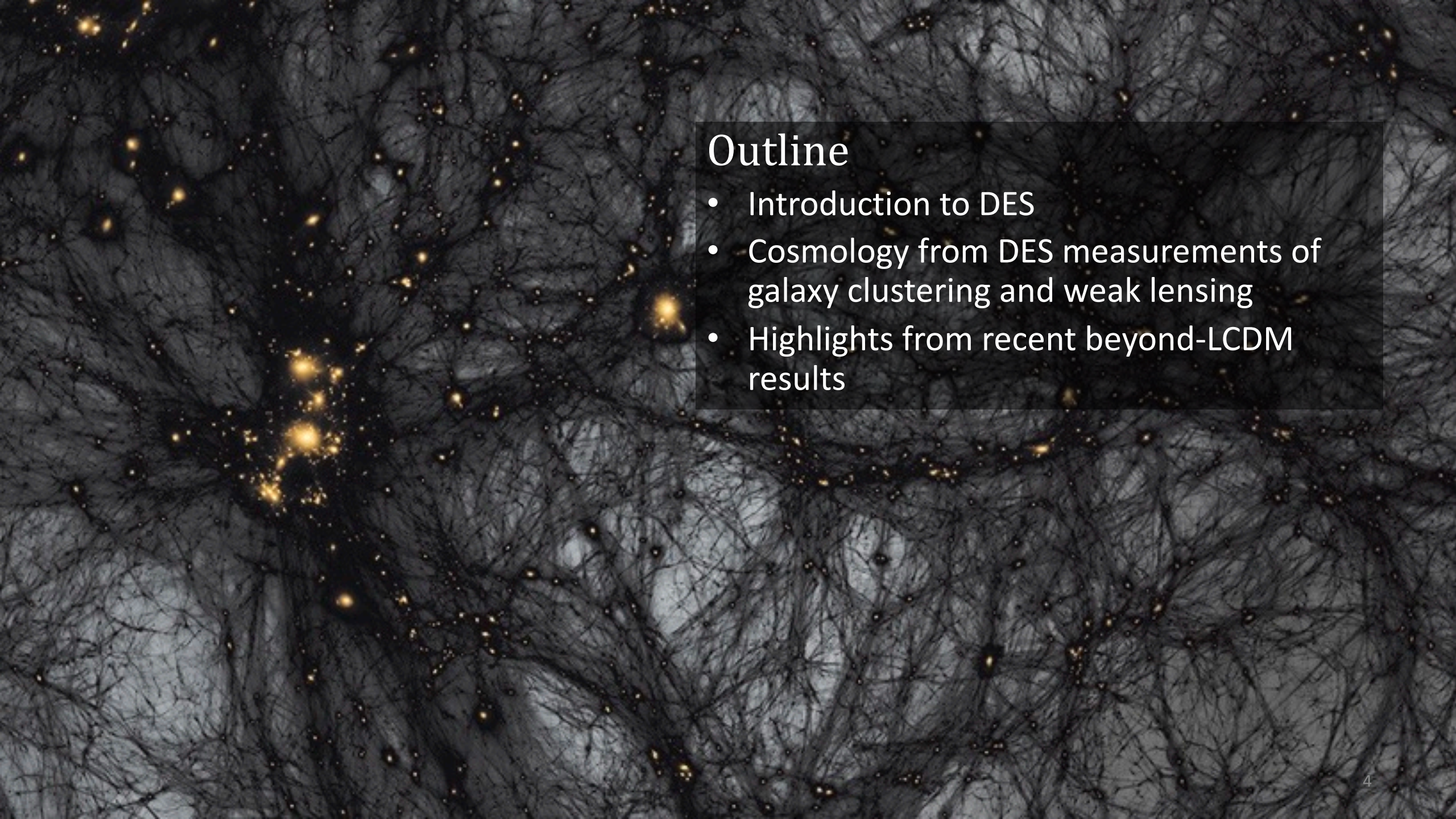
$$S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$$

Amplitude of density fluctuations



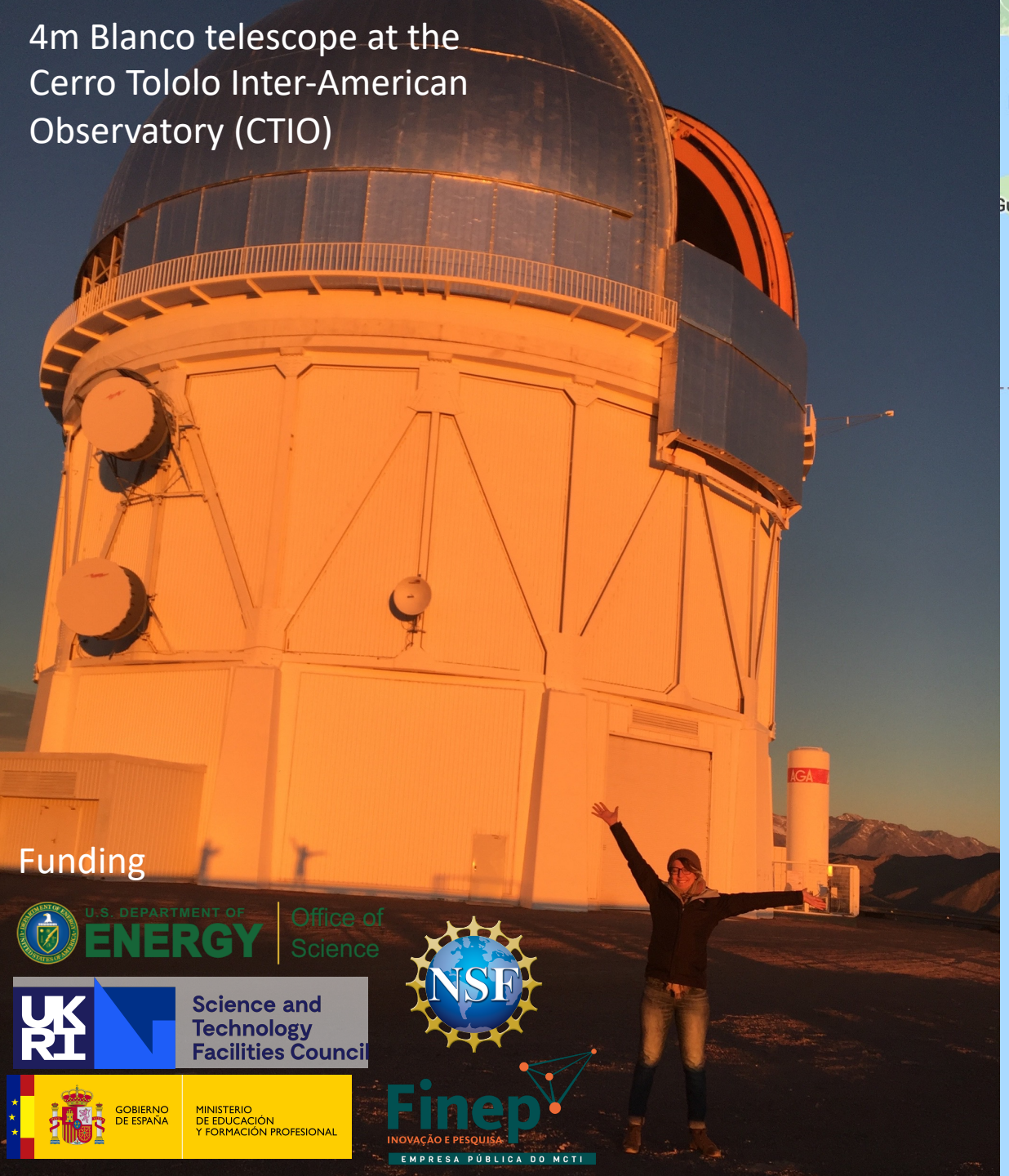
Matter density





Outline

- Introduction to DES
- Cosmology from DES measurements of galaxy clustering and weak lensing
- Highlights from recent beyond-LCDM results



4m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO)

The Dark Energy Survey (DES)

DARK ENERGY SURVEY

- Imaging survey
- 758 nights of observing, 2013-2019
- 700+ participants

Astronomical Observatory Cerro Tololo

Funding

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

UKRI Science and Technology Facilities Council

GOBIERNO DE ESPAÑA MINISTERIO DE EDUCACIÓN Y FORMACIÓN PROFESIONAL

Finep INOVAÇÃO E PESQUISA EMPRESA PÚBLICA DO MCTI

Member institutions

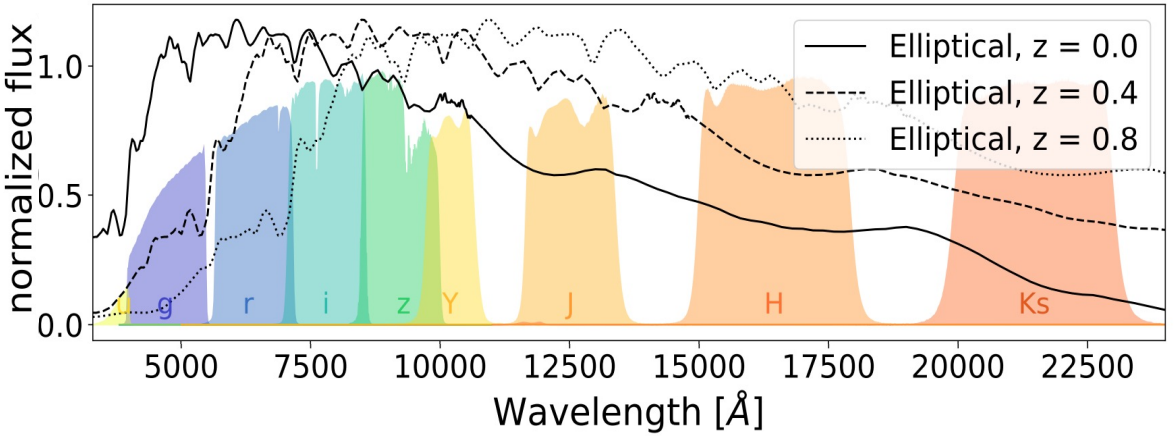
NCSA, The Ohio State University, Texas A&M, Stanford, Caltech, ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich, LMU, SLAC, Berkeley Lab, University of Michigan, University of Pennsylvania

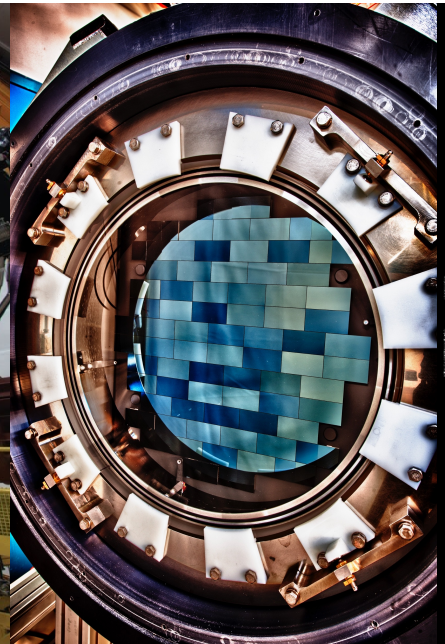
DARK ENERGY SURVEY

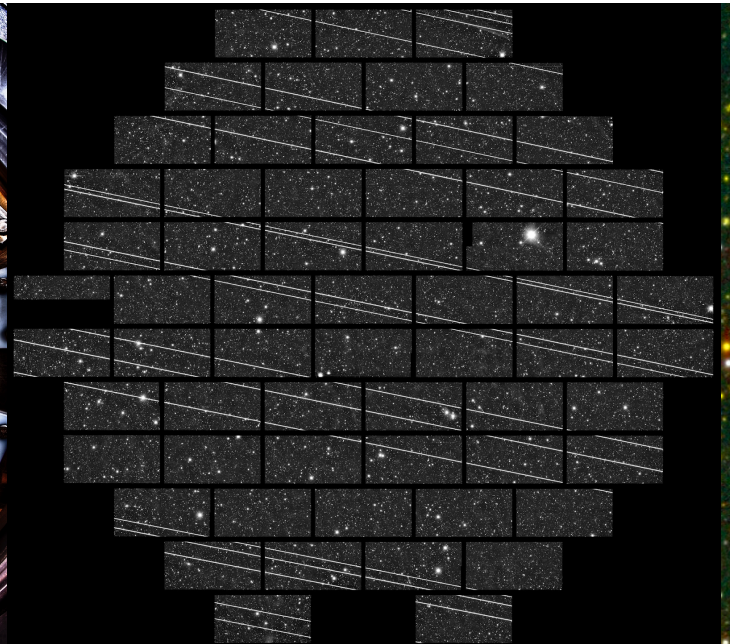
DES is an imaging (photometric) survey

- 540 Mpix DE Camera, 2.2 deg field of view
- 5 color filters used to estimate photo-zs
- 2 “surveys”:
  - **Wide survey**: 5000 sq degrees, ~23 magnitude
  - **Supernova type Ia**: repeated images of ten 2.7-square-degree fields
- Multi-purpose project! cosmology, galaxy clusters, SNe, milky way structure, galaxy evolution, QSOs, strong lensing, GW follow-up, solar system objects (TNO, comets)

Buchs et al. 2019, arxiv:1901.05005



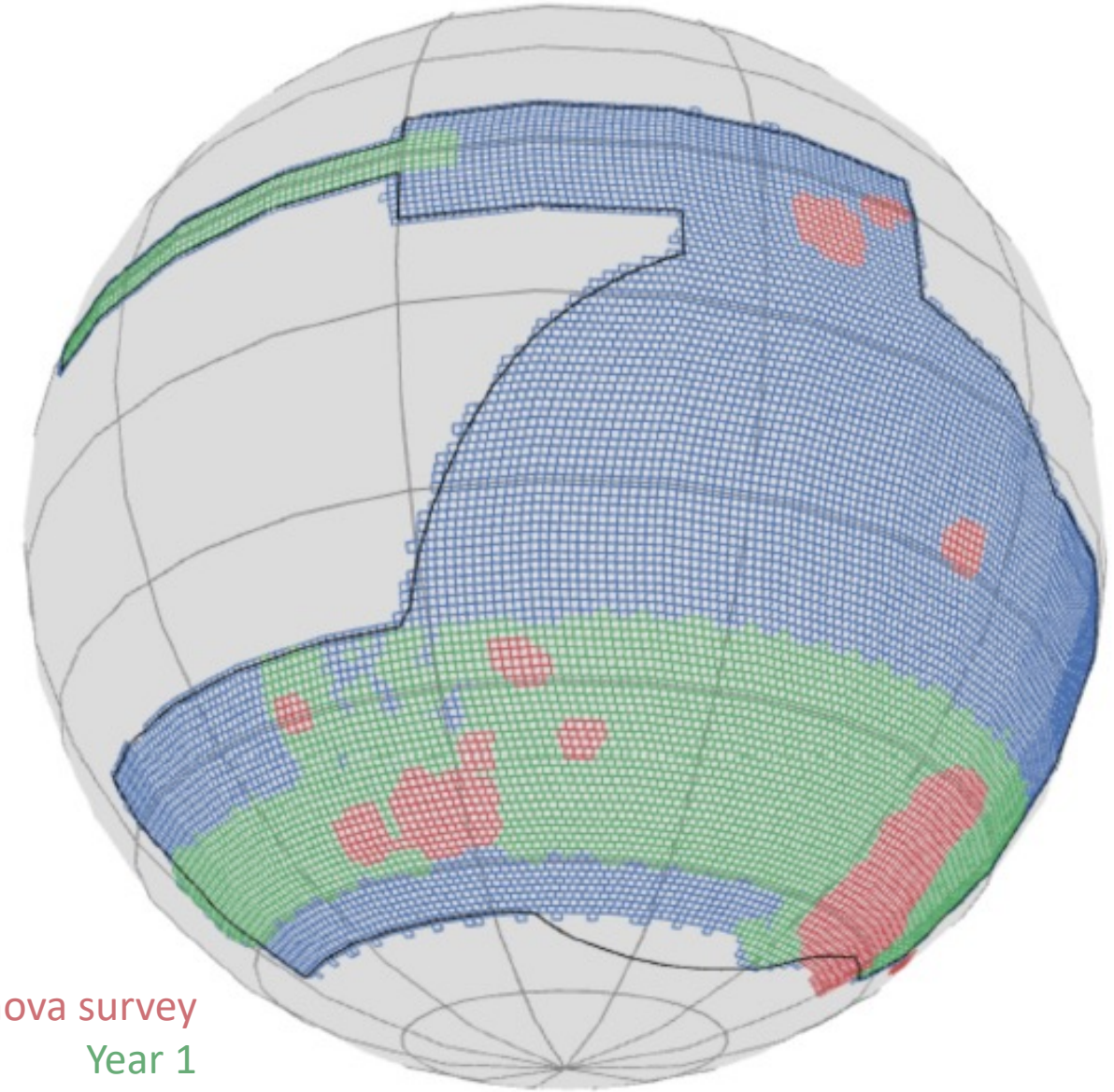




DARK ENERGY SURVEY

Status of DES

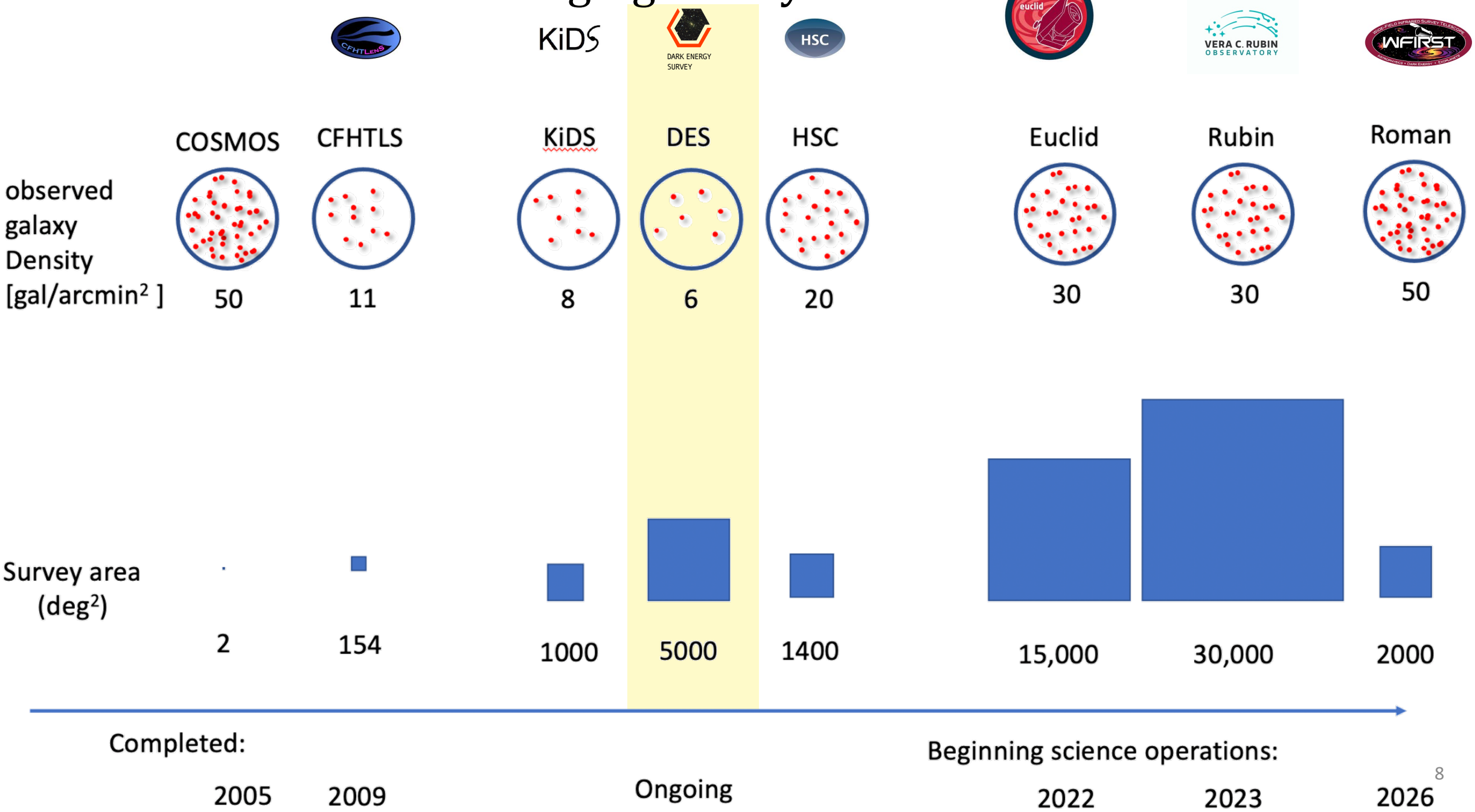
- Y1 Analysis:
  - ~1/3 survey area at ~50% depth
  - Cosmology results released 2017
- **Y3 Analysis:**
  - Full survey area at ~50% depth
  - >100M galaxies
  - Initial cosmology results released March 2021, extended model results July 2022
- Legacy Y6 Analysis:
  - In progress!

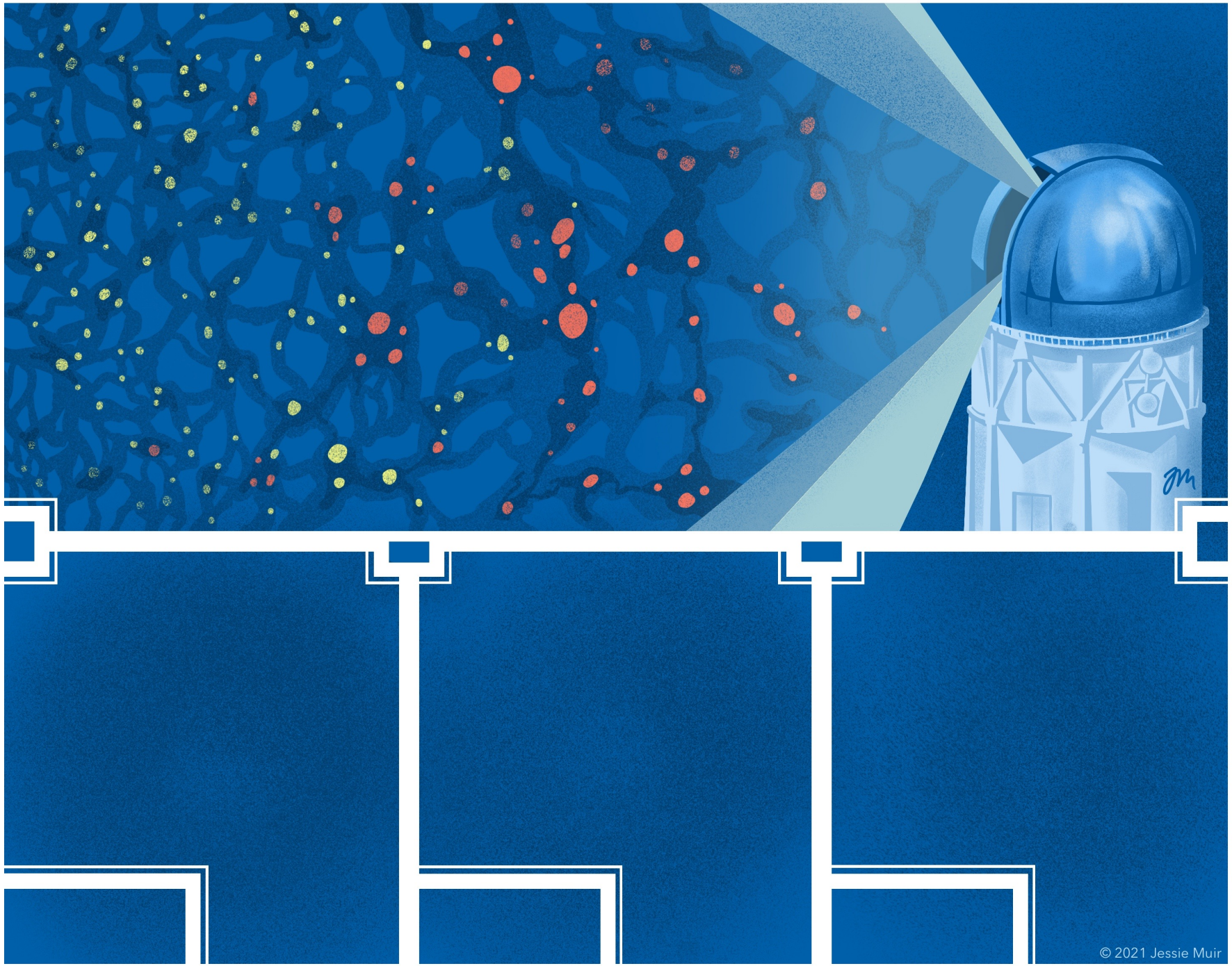


Science verification + supernova survey
Year 1
Year 3, Year 6

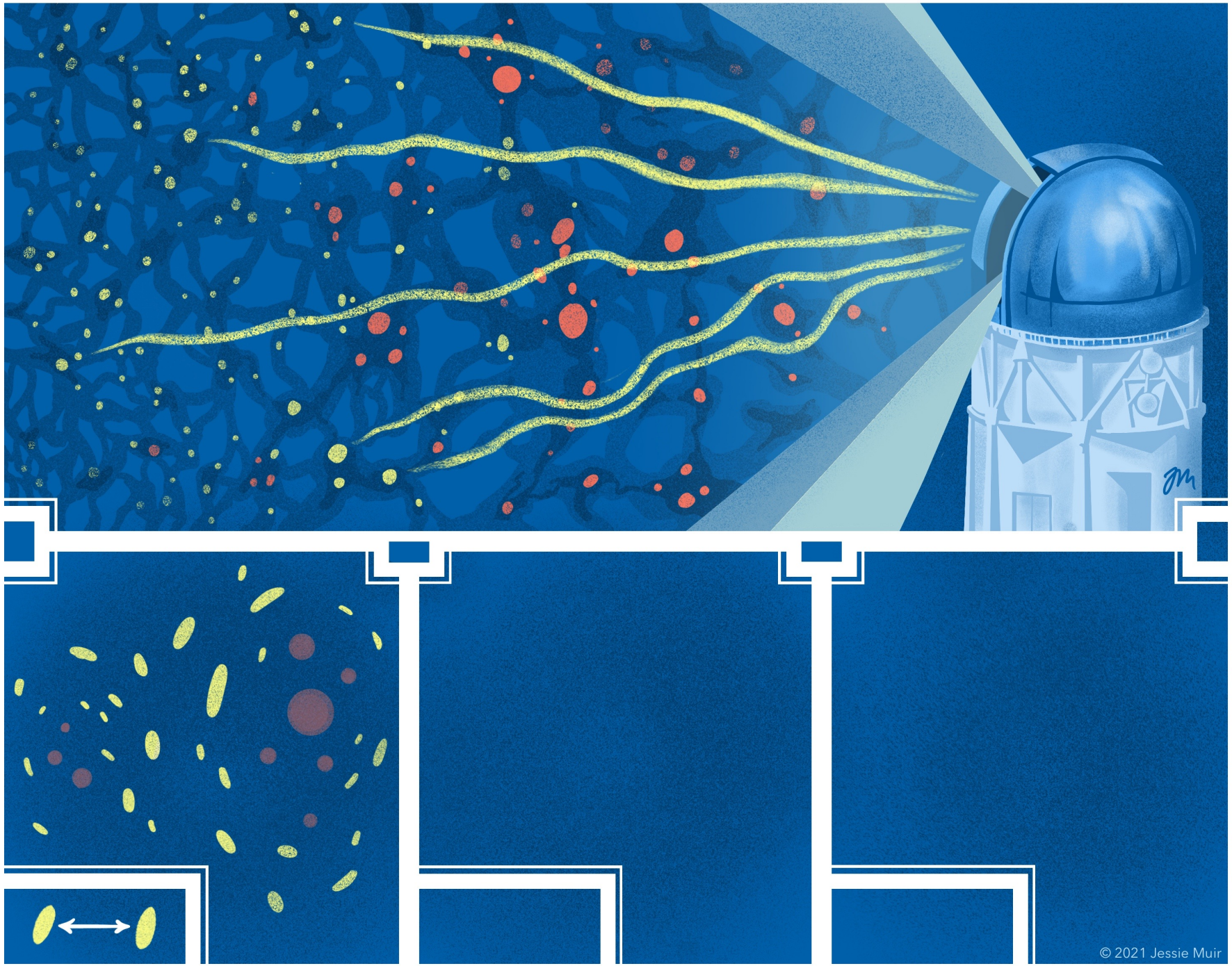
In context with other imaging surveys

Slide credit: Eric Huff




© 2021 Jessie Muir

Weak lensing:
0.1% distortions of apparent galaxy shapes due to line-of-sight structure



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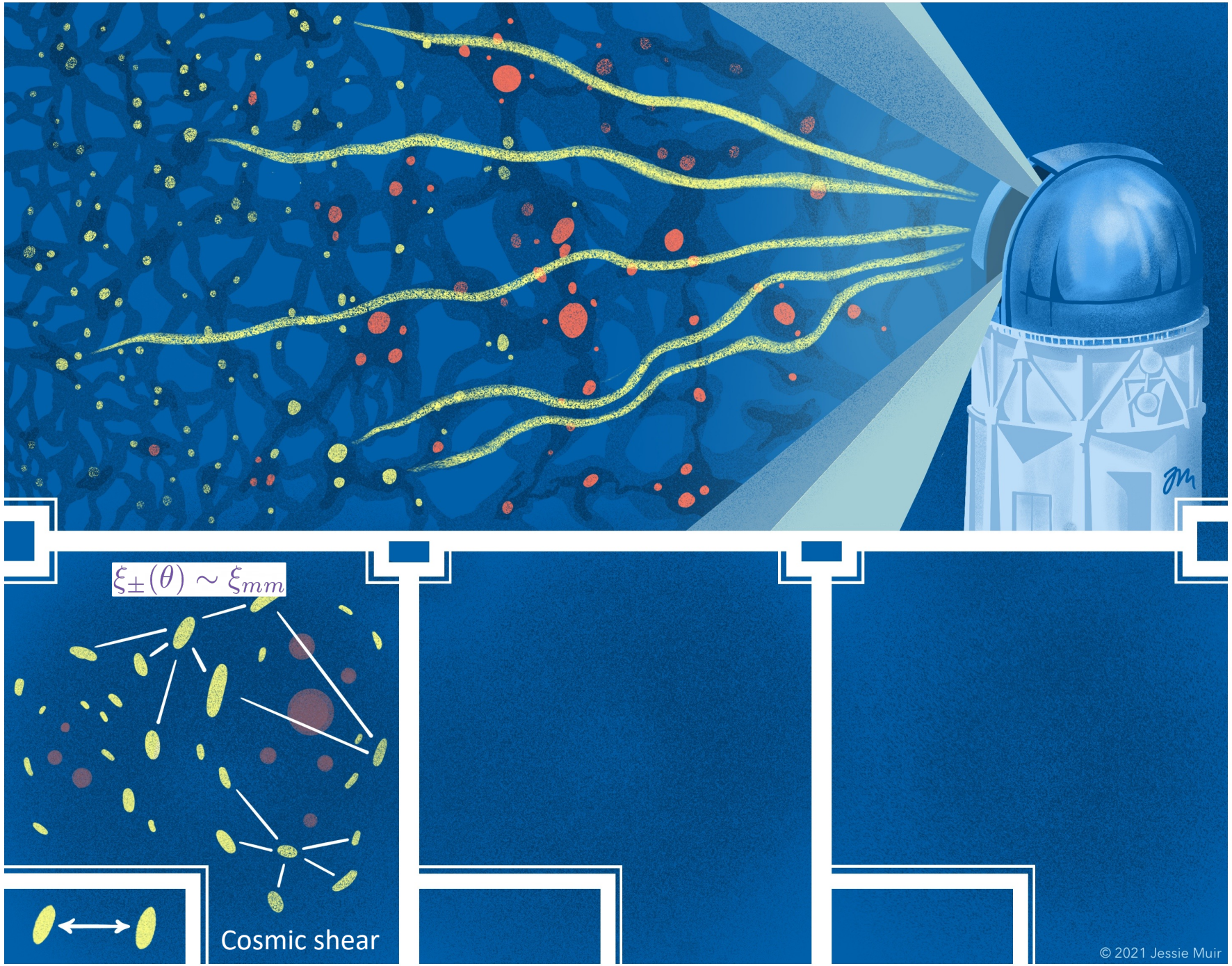

2pt functions:
correlation of signal (galaxy shapes, positions) vs separation on sky

$$\xi_{xy}(\theta) \propto \langle x(\hat{n}) y(\hat{n}+\theta) \rangle$$

Weak lensing:
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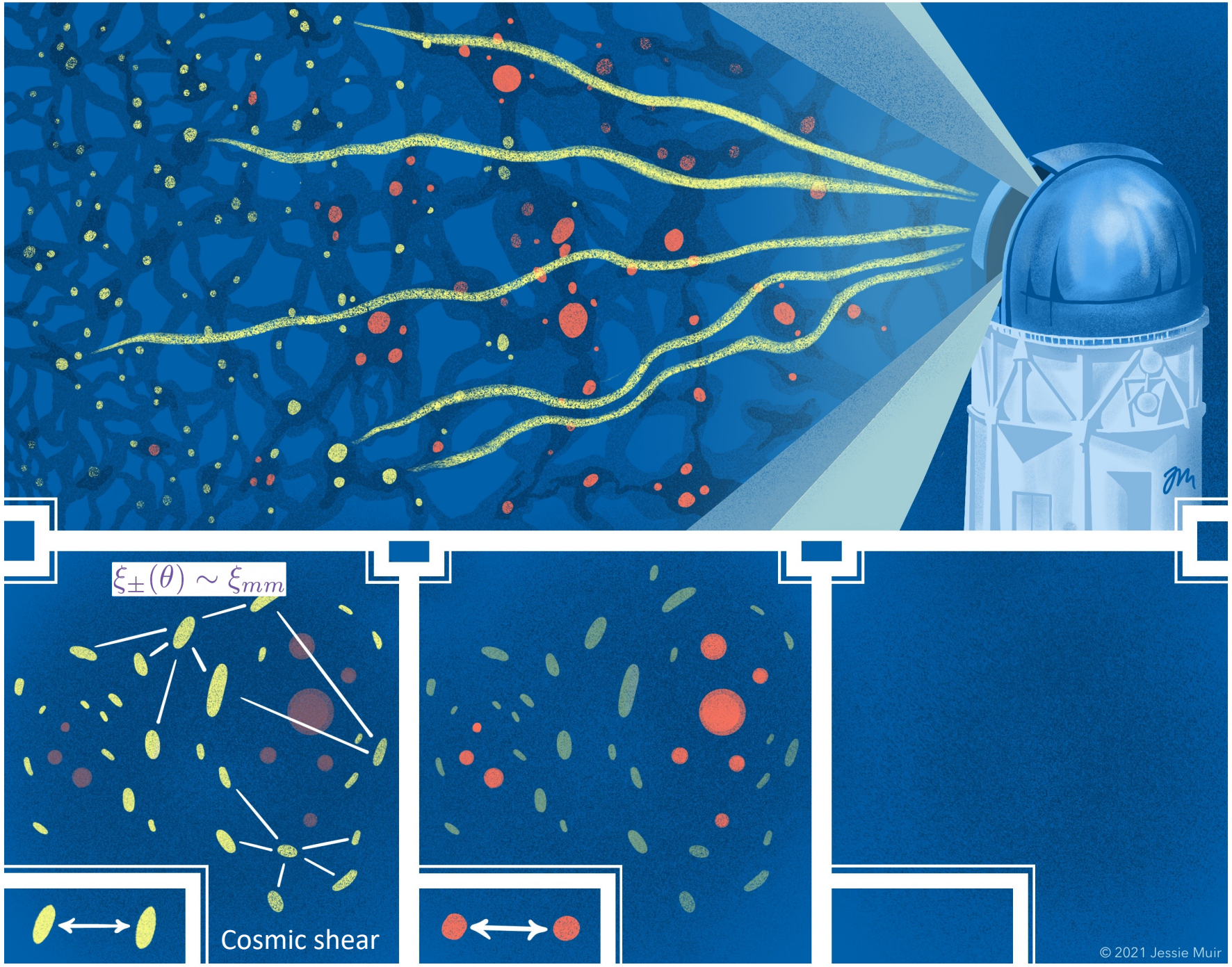
Galaxy clustering:
Galaxy density traces matter density

$$\delta_{\rm gal} = b\delta$$

b = galaxy bias



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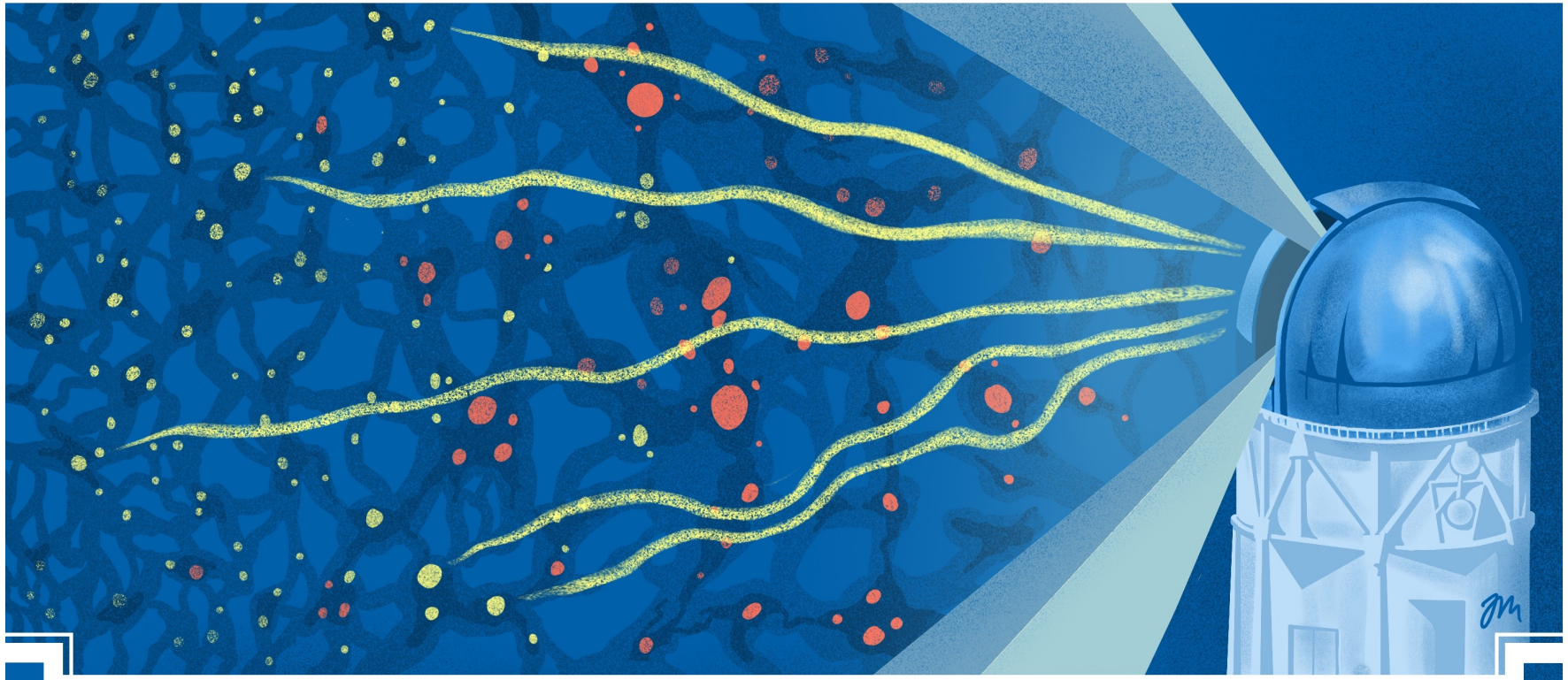

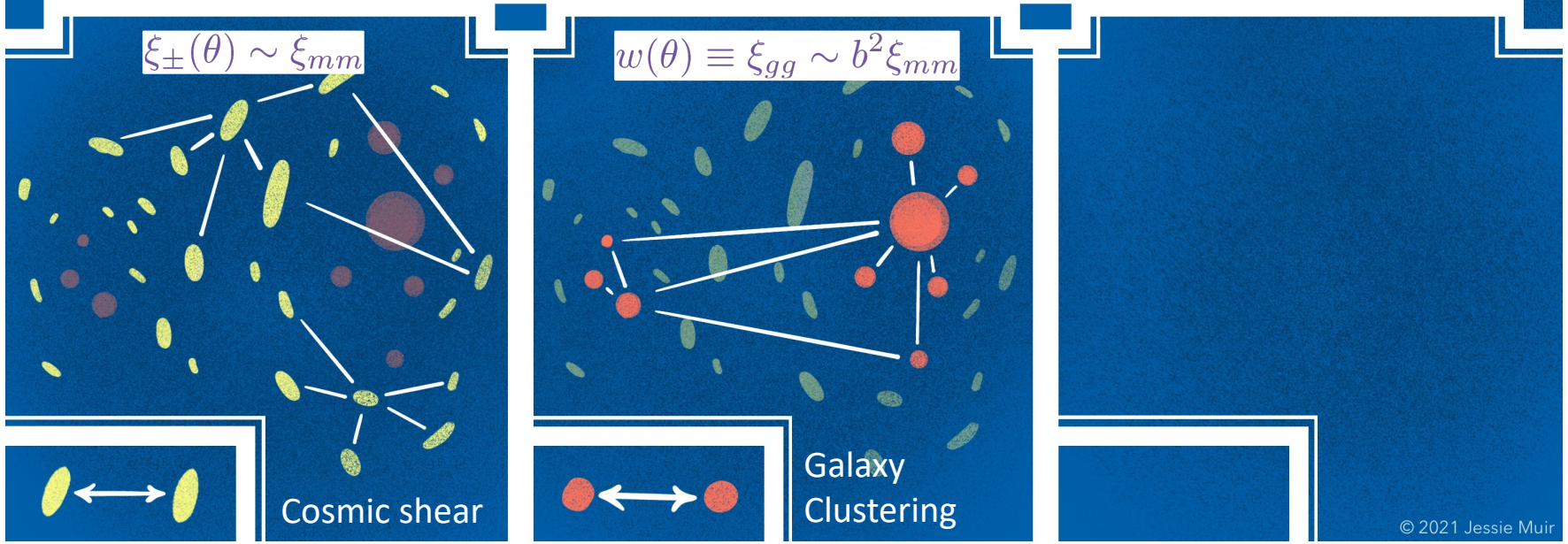

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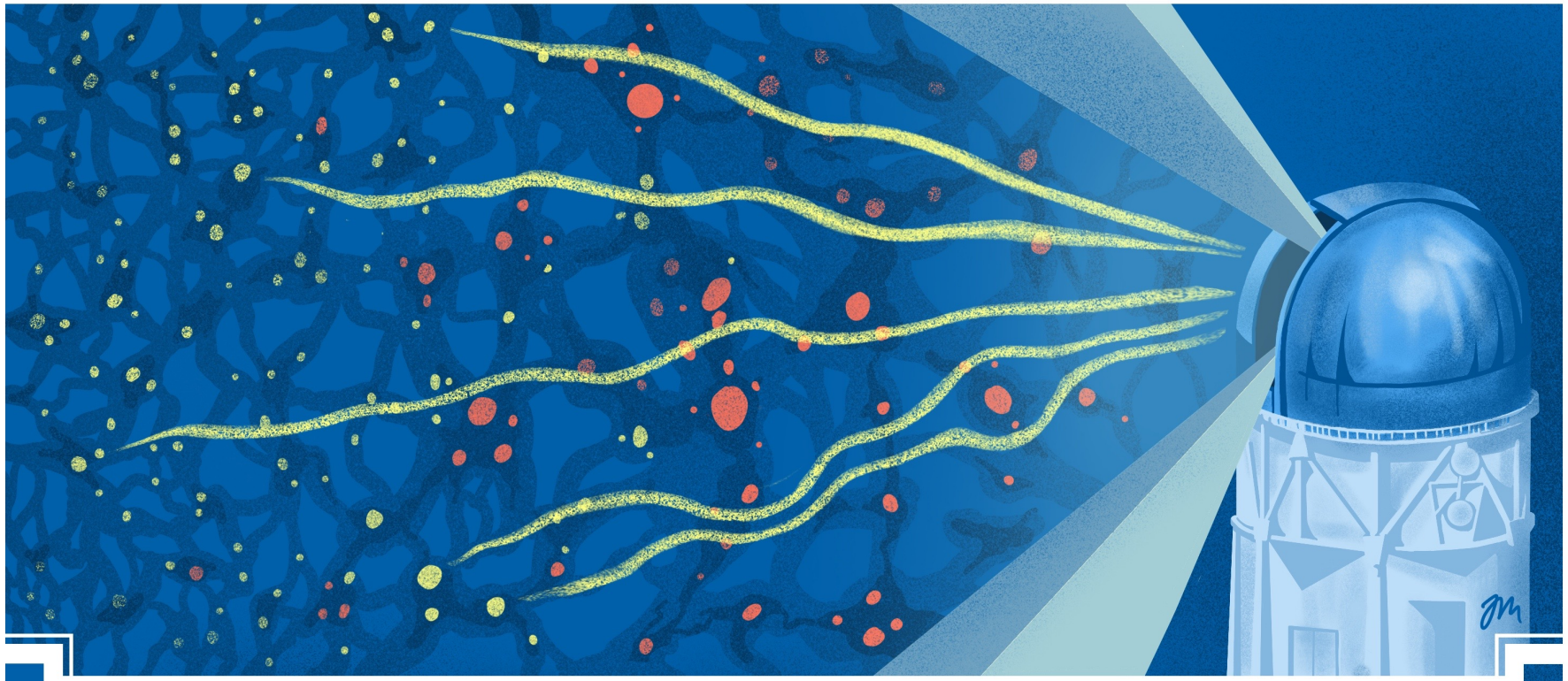
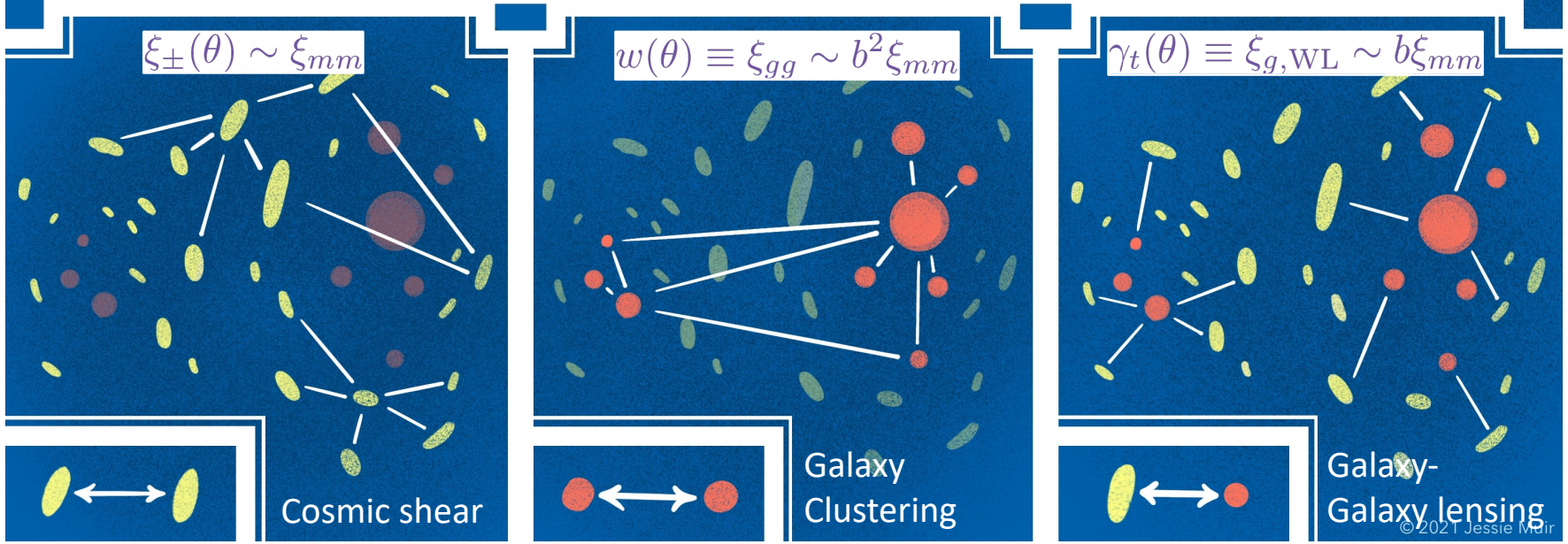
Galaxy – galaxy lensing:
Cross correlate foreground **lens** galaxies with shear of background **source** galaxies





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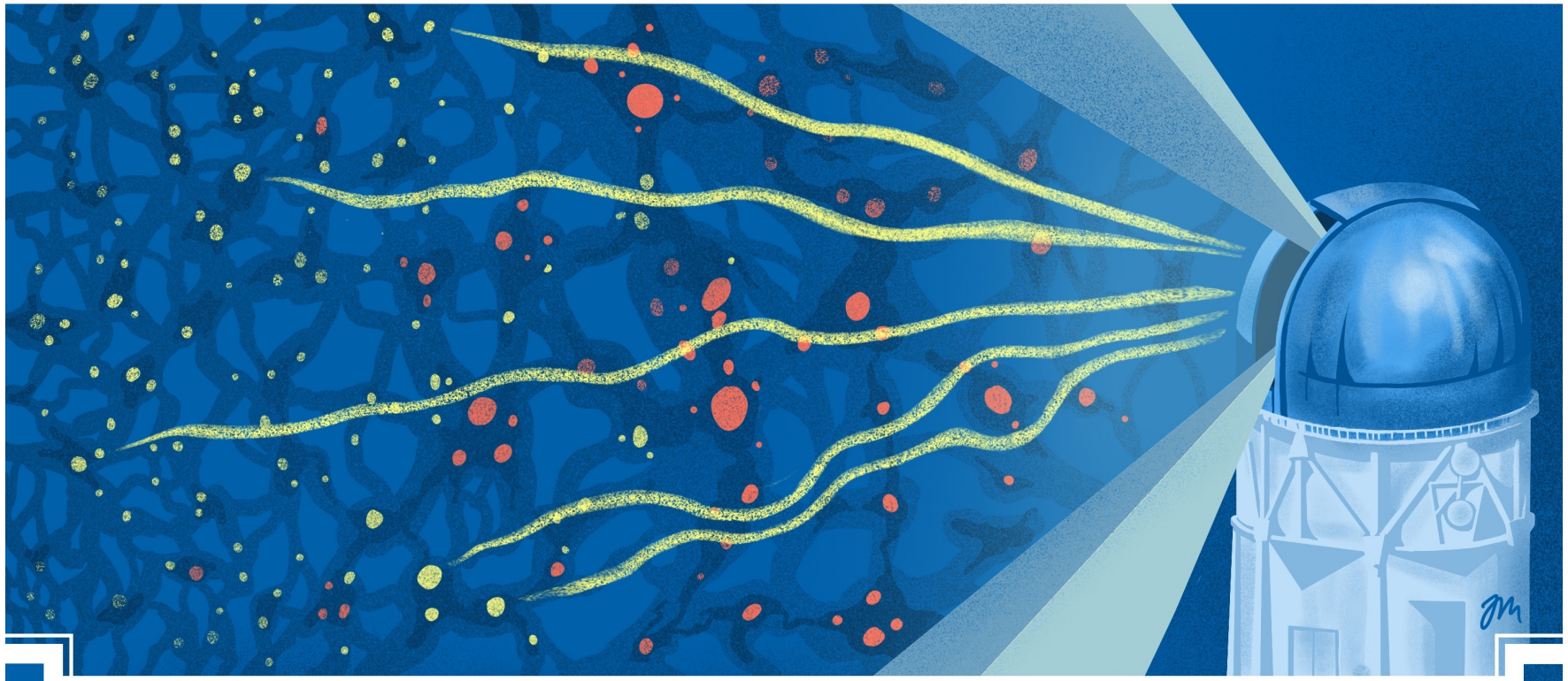
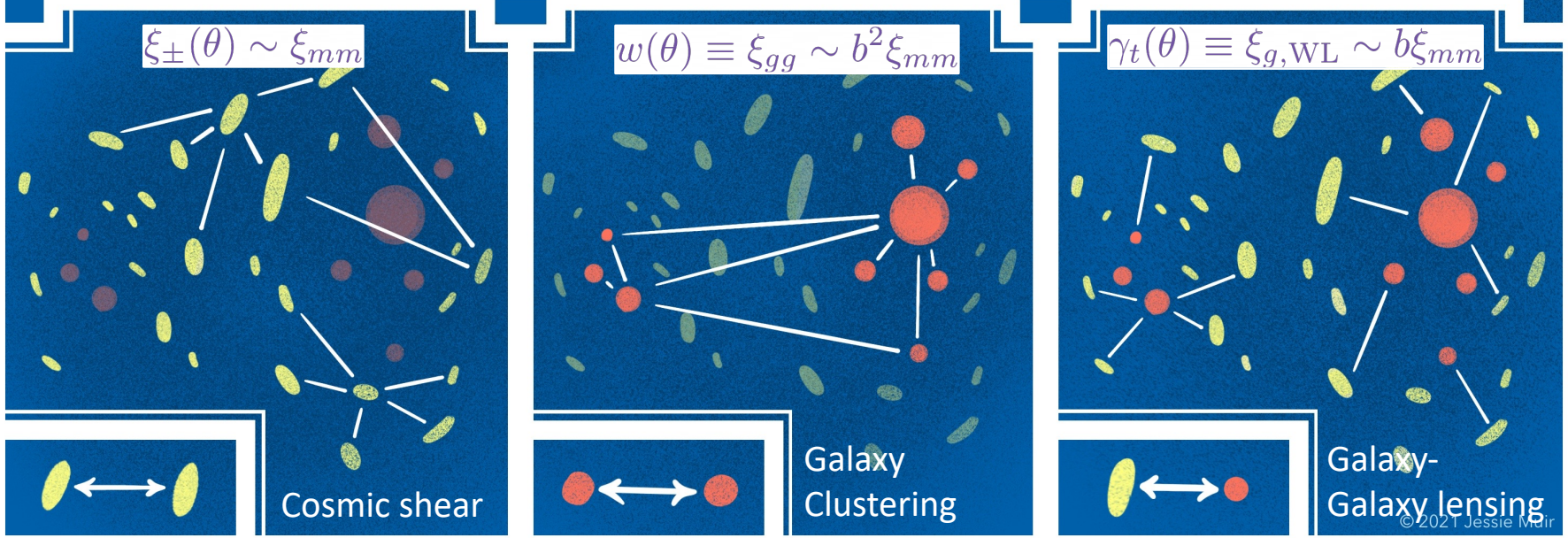
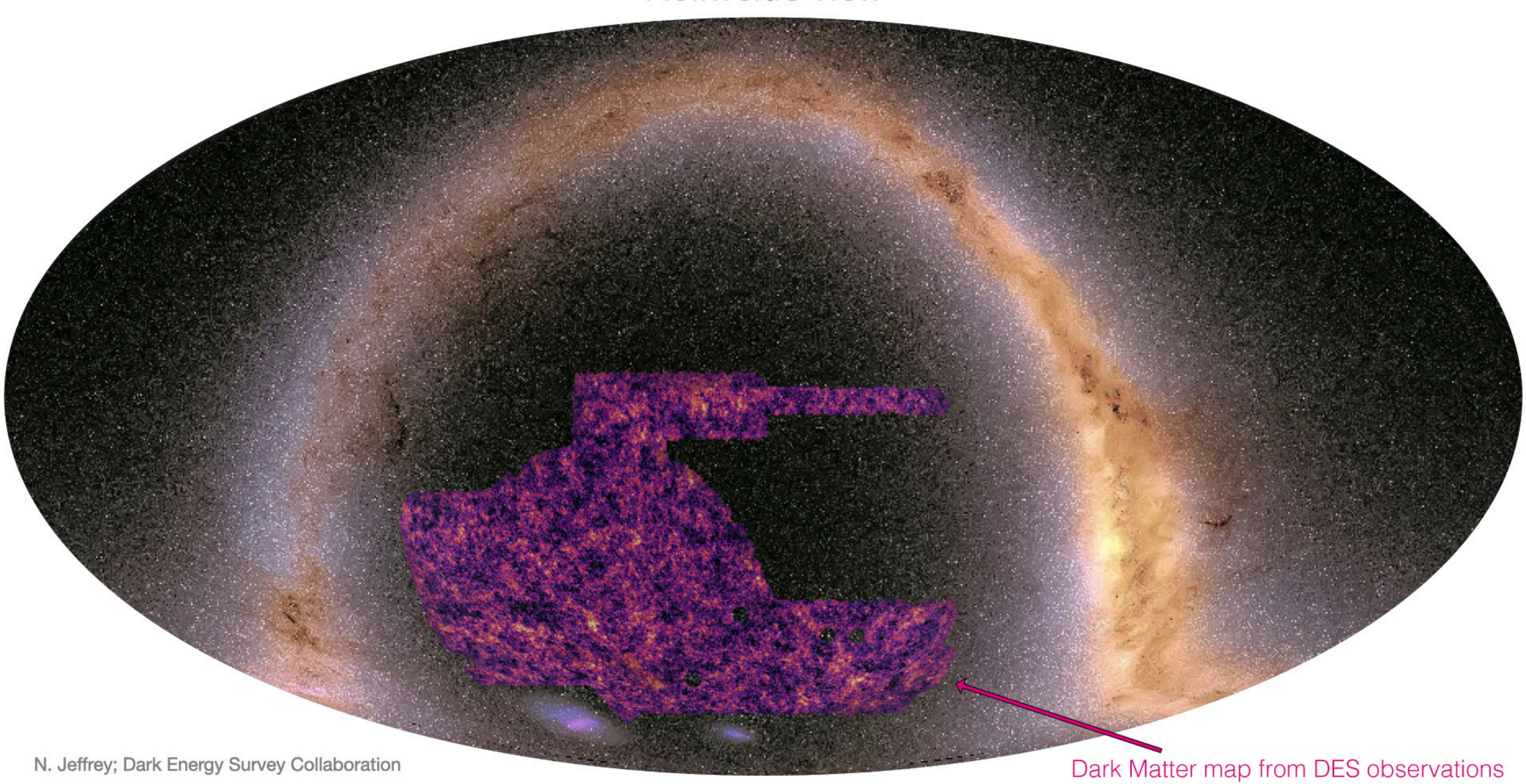




3x2pt analysis:
combined study of these three kinds of 2pt functions

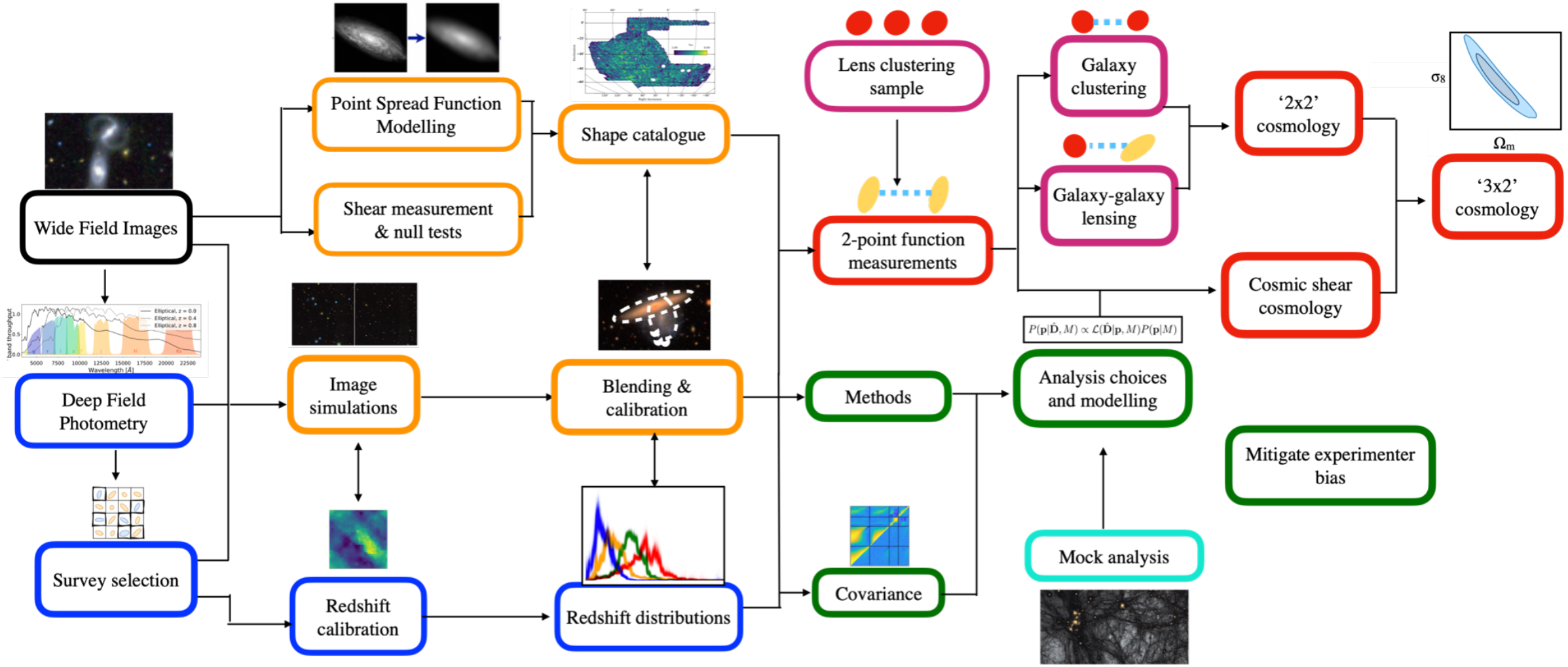
2pt functions:
correlation of signal (galaxy shapes, positions) vs separation on sky

$$\xi_{xy}(\theta) \propto \langle x(\hat{n})y(\hat{n}+\theta)\rangle$$



Mass map measurement: N. Jeffrey, M. Gatti, C. Chang et al., arXiv:2105.13539

Pixels to cosmology



Redshifts — Shears — Clustering — Simulations — Theory —> Results

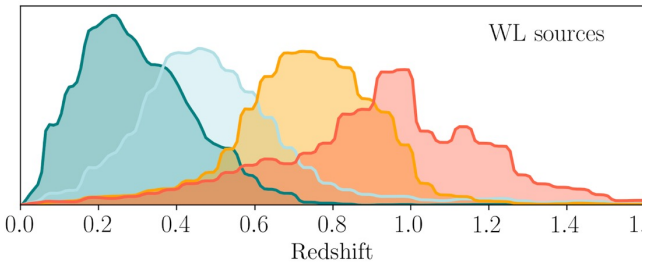
Flowchart credit: Alex Amon

DES Y3 papers on galaxy clustering and weak lensing

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., arXiv:2109.09636
14. “Exploiting Small-Scale Information using Lensing Ratios”, C. Sánchez, J. Prat et al., arXiv:2105.13542
15. “Cosmology from Combined Galaxy Clustering and Lensing - Validation on Cosmological Simulations”, J. de Rose et al., arXiv:2105.13547.
16. “Robust sampling of cosmological posterior distributions”, P. Lemos, N. Weaverdyck, R. Rollins, J. Muir, A. Ferté, A. Liddle 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, X. Fang et al., arXiv:2105.13548
21. “Curved-Sky Weak Lensing Map Reconstruction”, N. Jeffrey, M. Gatti, C. Chang et al., arXiv:2105.13539
22. “Galaxy Clustering and Systematics Treatment for Lens Galaxy Samples”, M.Rodríguez-Monroy, N. Weaverdyck, J. Elvin-Poole, M. Crocce et al., arXiv:2105.13540
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., arXiv:2105.13541
25. “Constraints on Cosmological Parameters and Galaxy Bias Models from Galaxy Clustering and Galaxy-Galaxy Lensing using the redMaGiC Sample”, S. Pandey et al., arXiv:2105.13545
26. “Cosmological Constraints from Galaxy Clustering and Galaxy-Galaxy Lensing using the Maglim Lens Sample” A. Porredon, M. Crocce et al., arXiv:2105.1354
27. “Cosmology from Cosmic Shear and Robustness to Data Calibration”, A. Amon, D. Gruen, M. A. Troxel et al., arXiv:2105.13543
28. “Cosmology from Cosmic Shear and Robustness to Modeling Assumptions”, L. Secco, S. Samuroff et al., arXiv:2105.13544
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, arXiv2105.13549

Cosmic shear measurements

Amon et al., arXiv:2105.13543
Secco, Samuroff et al., arXiv:2105.13544

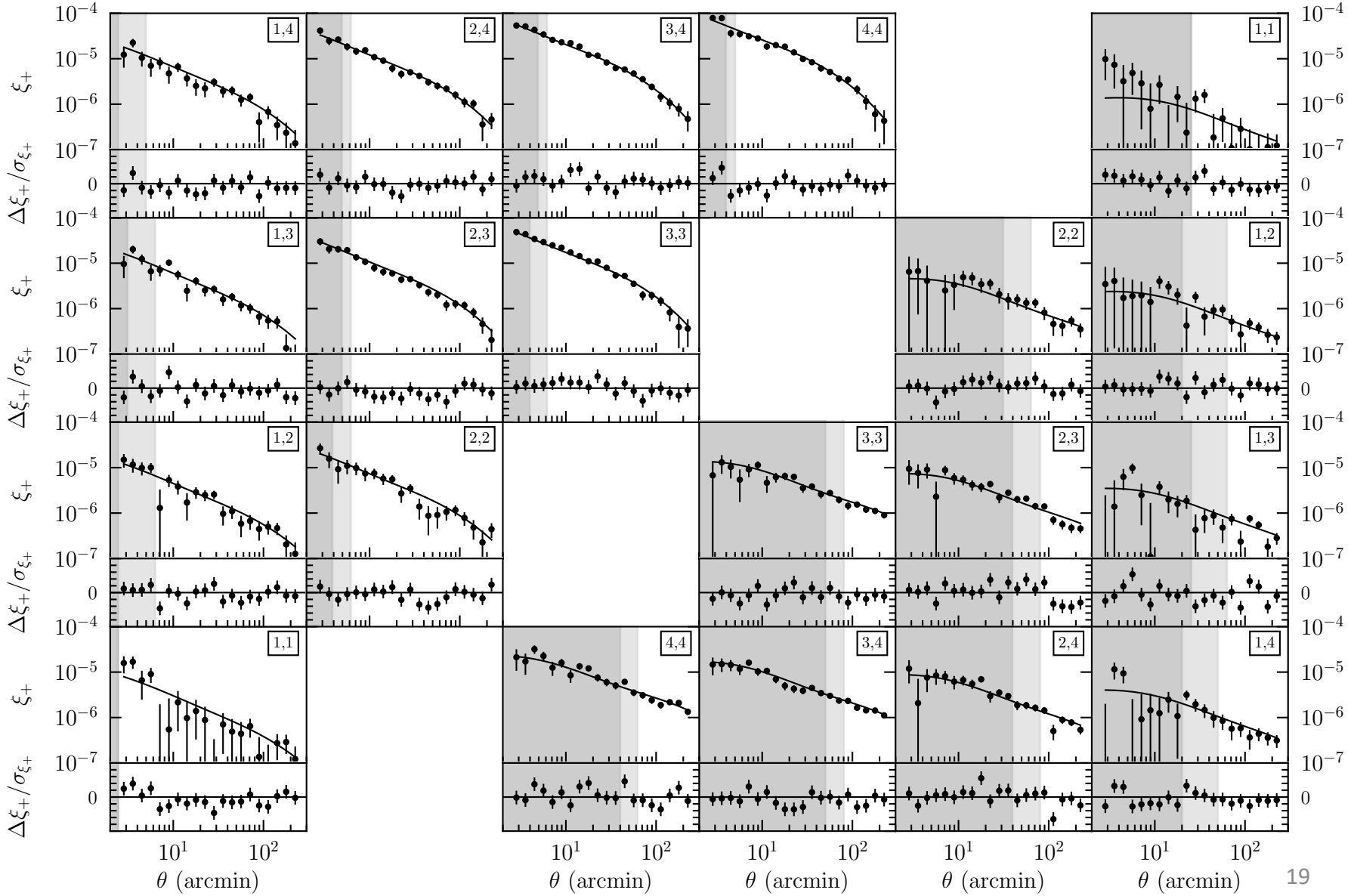


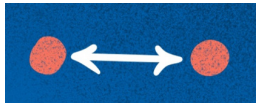
Subplots: different bins along the line-of-sight

Solid lines: best-fit model prediction

Shaded regions: scale cuts to avoid biases from modeling uncertainties

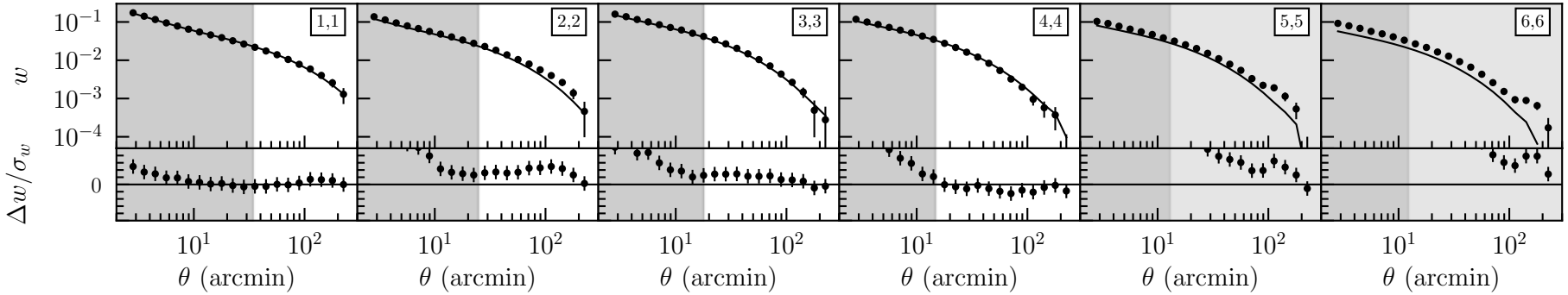
Darker shading: more aggressive “optimized” cuts





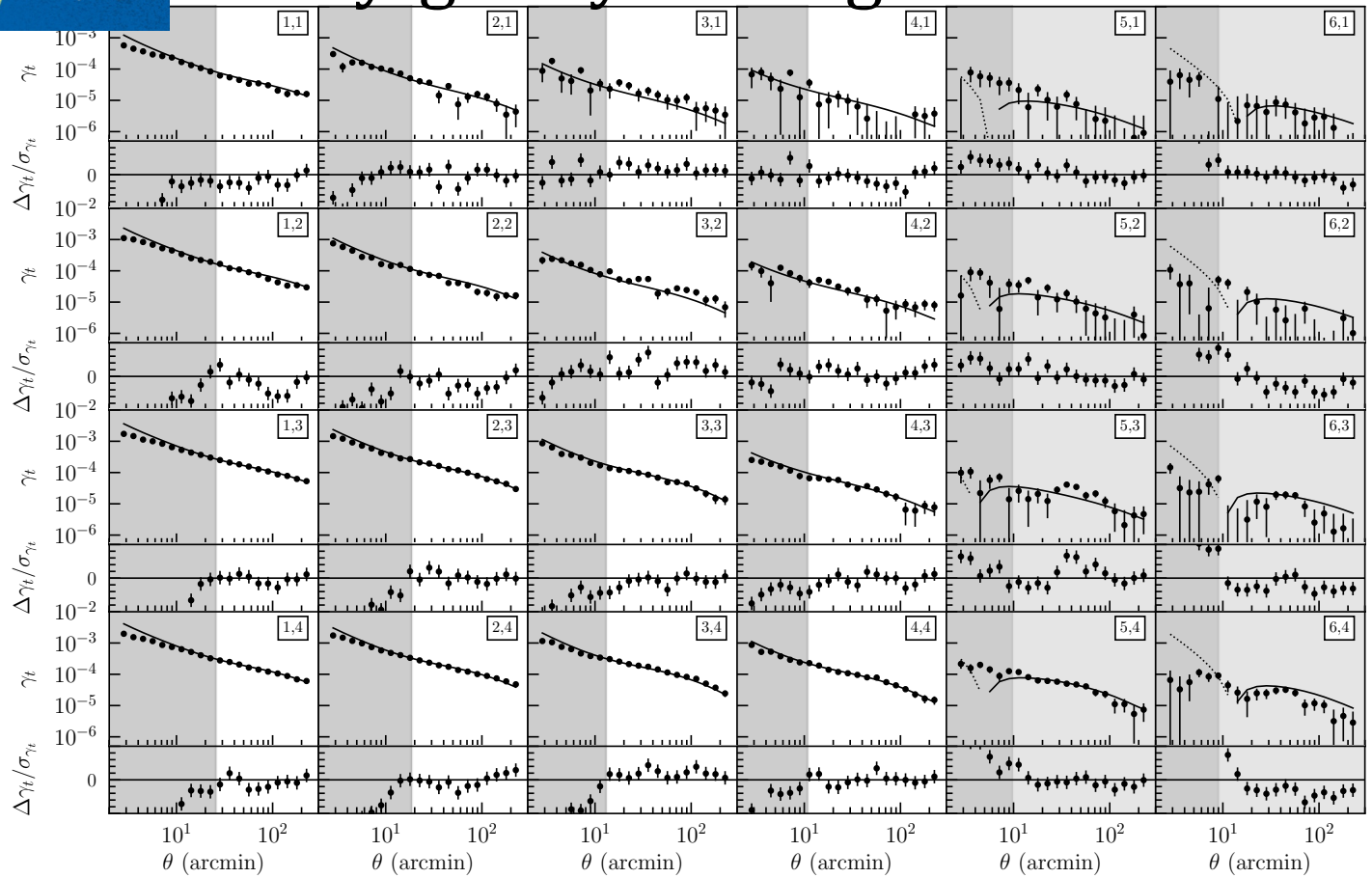
Galaxy clustering

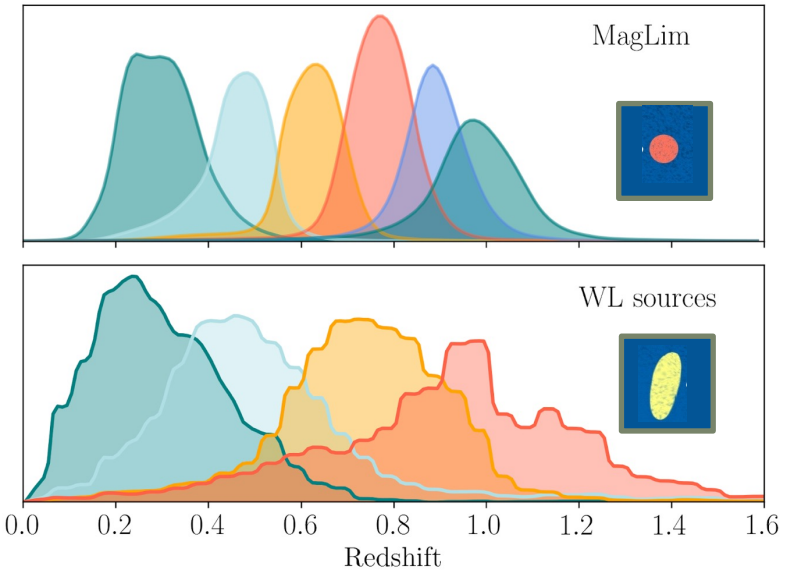
Rodríguez-Monroy, Weaverdyck, et al., arXiv:2105.13540



Galaxy-galaxy lensing

Prat et al. [DES], arXiv:2105.13541





Parameter inference using Bayesian statistical methods

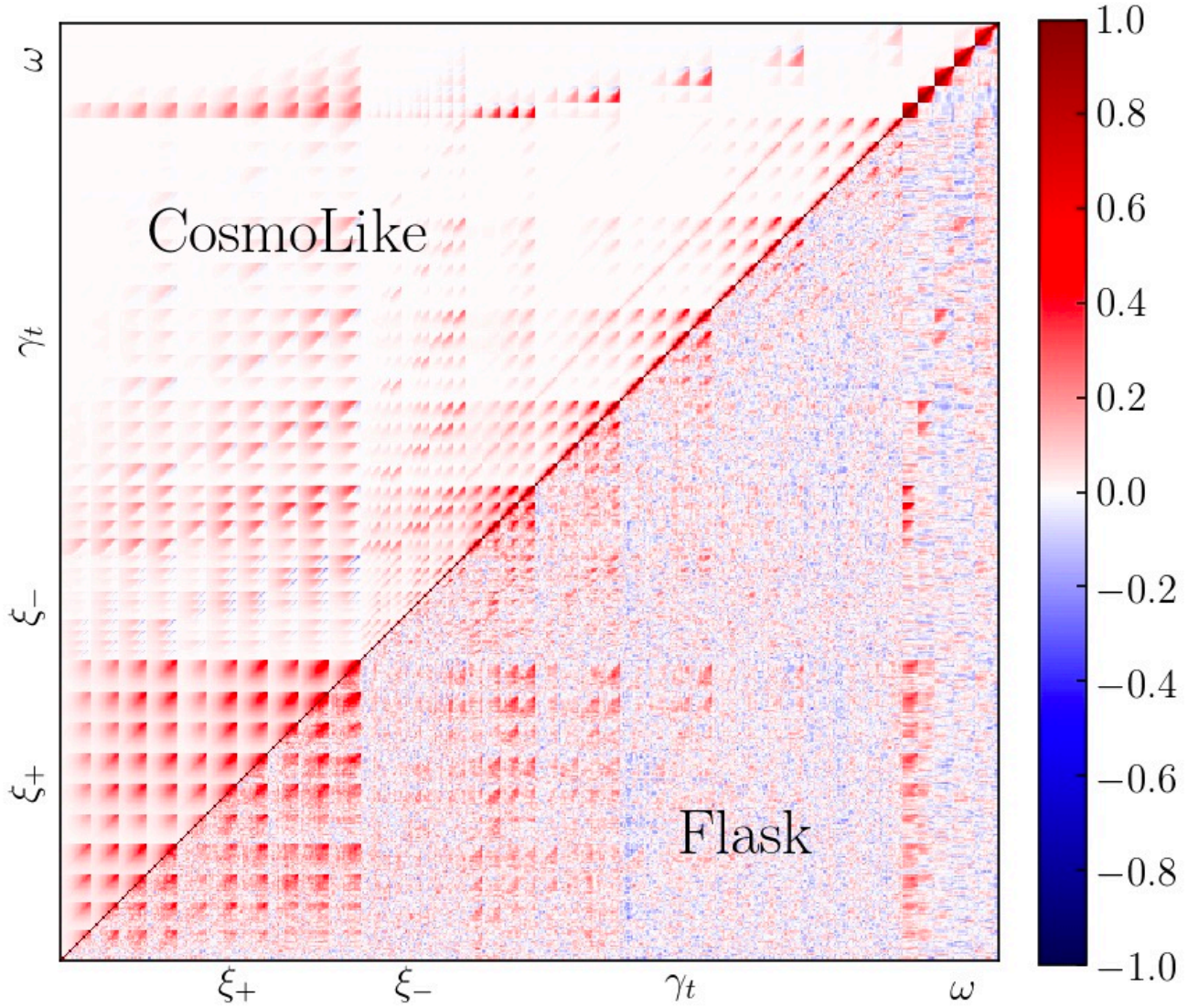
$$\mathcal{L}(\mathbf{D}|\mathbf{\Theta}) \propto [\mathbf{D} - \mathbf{M}(\mathbf{\Theta})]^T C^{-1} [\mathbf{D} - \mathbf{M}(\mathbf{\Theta})]$$

Gaussian likelihood

Measurements
- 462 data points

31 parameter model (LCDM)
- 6 cosmology parameters
  - Ω_m, Ω_b, h, n_s, A_s, m_ν
- 25 astrophysical/systematic

Covariance between 3x2pt datapoints.
Top: analytic calculations, bottom: simulations (used for validation)



E. Krause, X. Fang et al., arXiv:2105.13548, Friedrich et al., arXiv:2012.08568

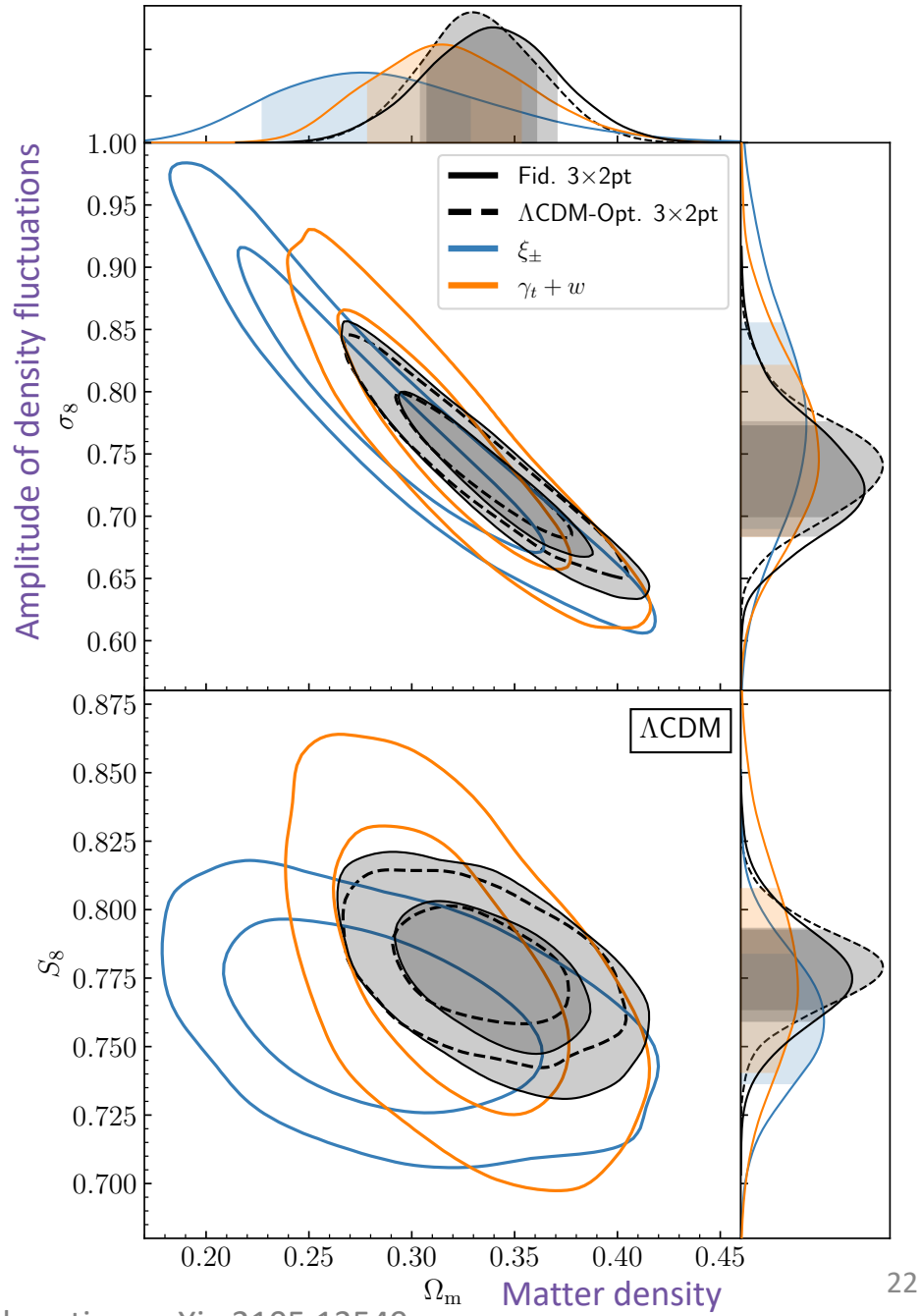
Combined DES Y3 galaxy clustering and weak lensing results

- Factor of 2 improvement in S/N vs DES Y1
- Most powerful available 3x2pt constraints from a single galaxy survey

Blue: [weak lensing] X [weak lensing]

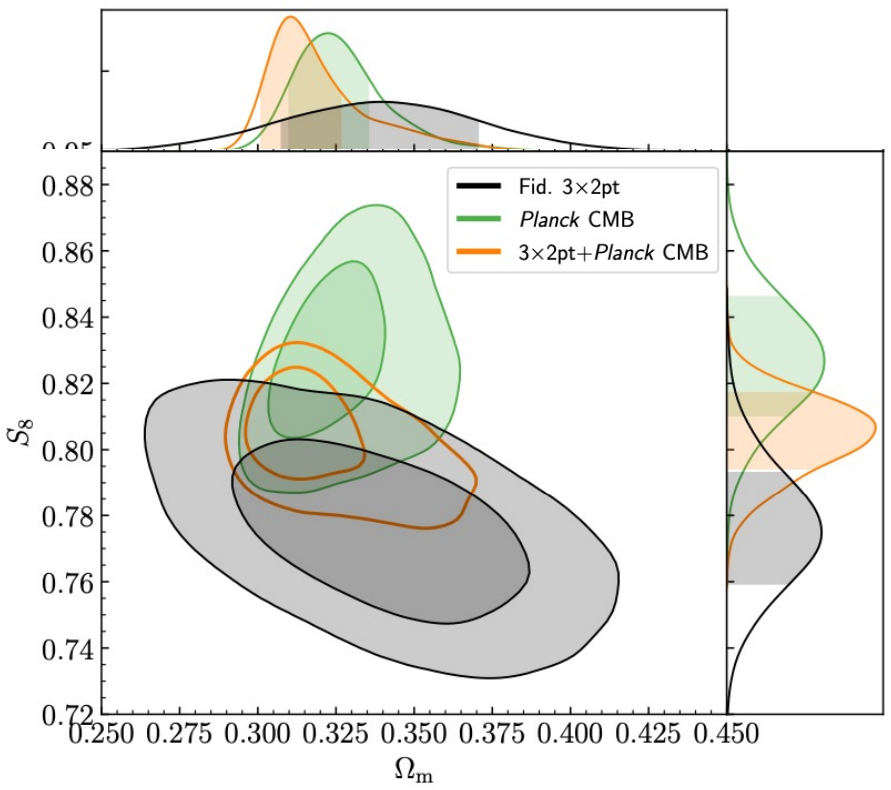
Orange: [galaxies] X [galaxies] +
[galaxies] X [weak lensing]

Black: 3x2pt = all three 2pt functions

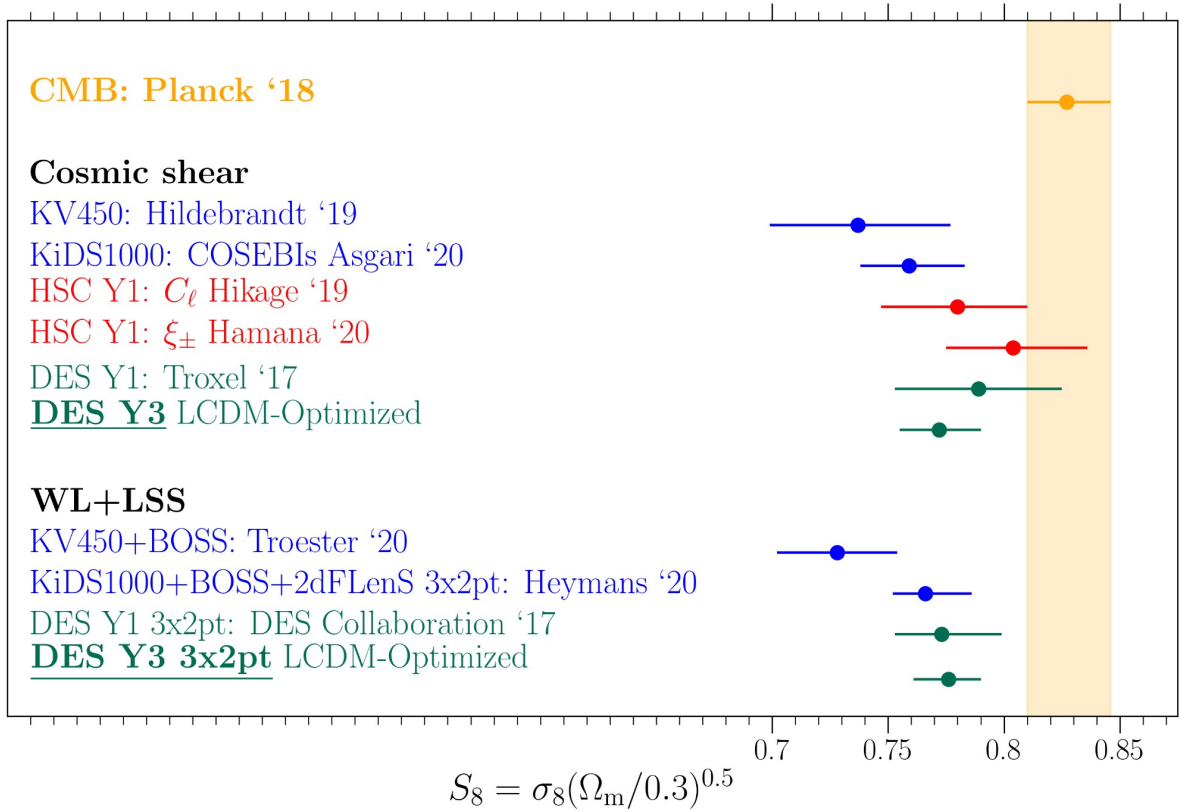


DES Collaboration, arXiv:2105.13549

3x2pt vs CMB in ΛCDM



DES Collaboration, arXiv:2105.13549



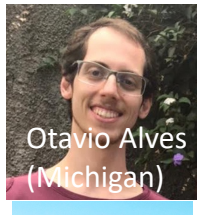
Tension between DES Y3 3x2pt and Planck isn't statistically significant:

- 1.5σ from S_8 parameter difference
- 0.7σ from Suspiciousness (Bayesian quantity assessing full parameter space)

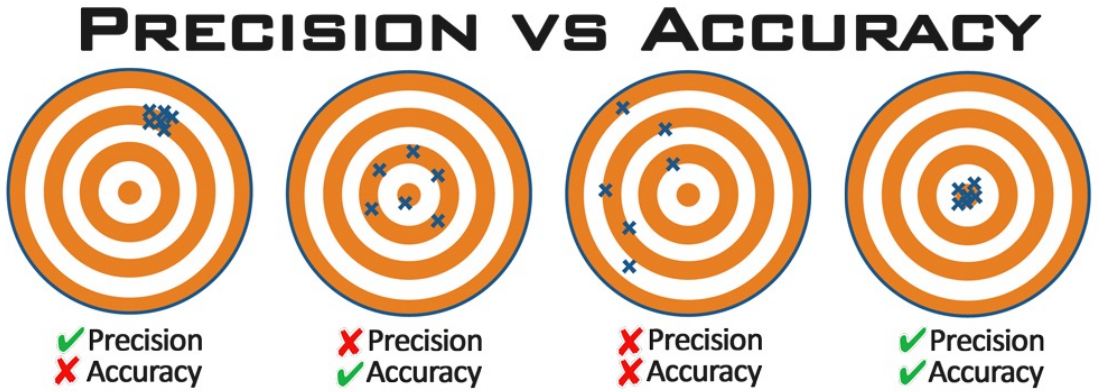
DES Y3 Paper comparing and calibrating different tension metrics: Lemos, Raveri et al [DES], MNRAS 2021, arXiv:2012.09554

Systematic uncertainties

- Some examples of how DES controls systematics
- Other modeled systematics: photo-z uncertainties, shear calibration, galaxy bias
- New fast importance sampling method used to test robustness against un-modeled systematics, developed by Otavio Alvez and Noah Weaverdyck



Noah Weaverdyck
(Berkeley)



Baryon feedback: Scale cuts

Our model doesn't capture how galactic process impact structure formation of small scales. We don't include datapoints likely to be affected by this is in our analysis.

E. Krause, X. Fang et al., arXiv:2105.13548

Intrinsic alignments: modeling

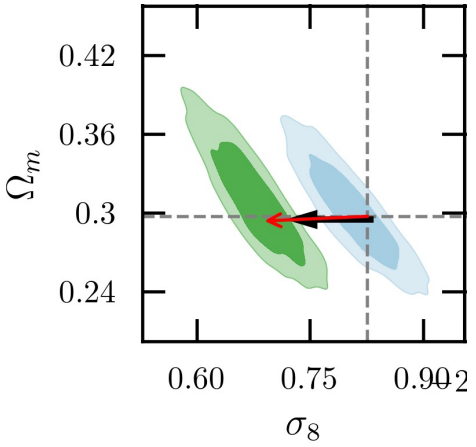
Tidal interactions contribute to measured alignments between galaxy shapes, contaminating lensing measurements. This is included in our model.

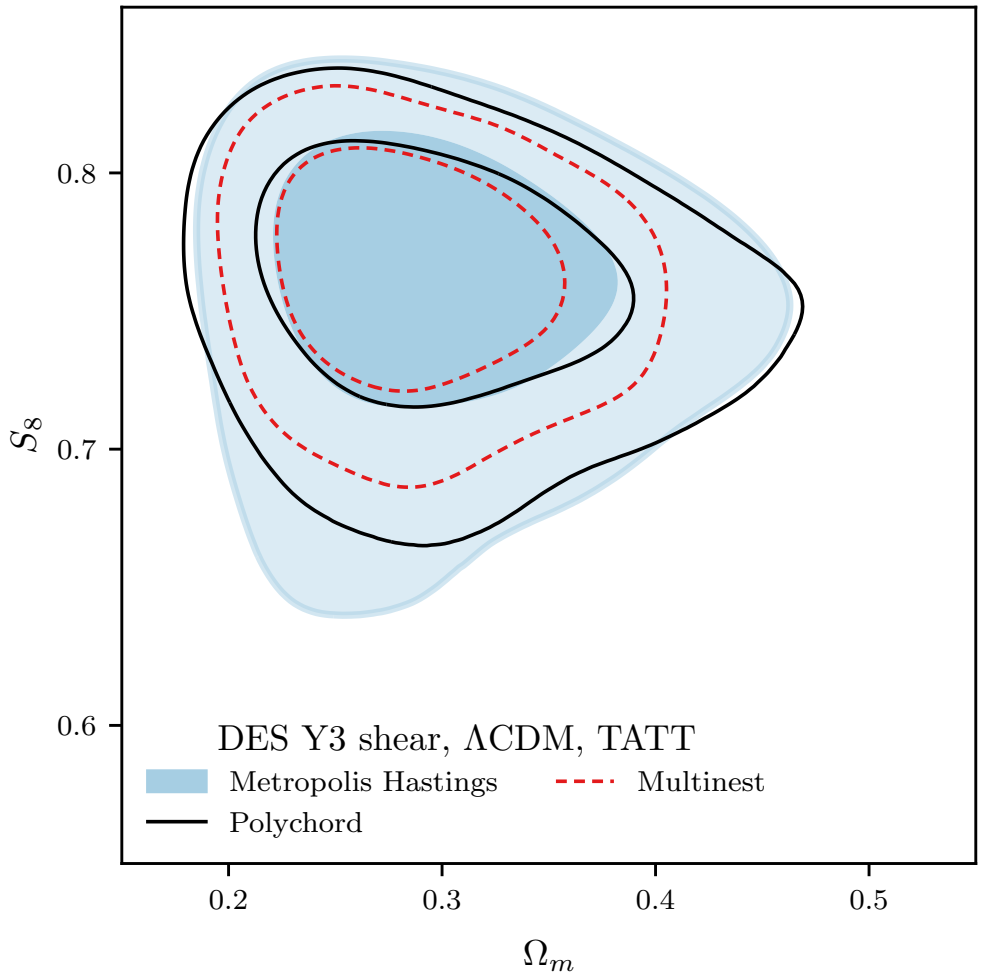
L. Secco, S. Samuroff et al., arXiv:2105.13544

Experimenter bias: Blinding

Make sure analysis decisions aren't influenced by how results compare to expectations. Procedure for "hiding results" until decisions, validation checks are finalized.

Muir et al. arXiv:1911.05929

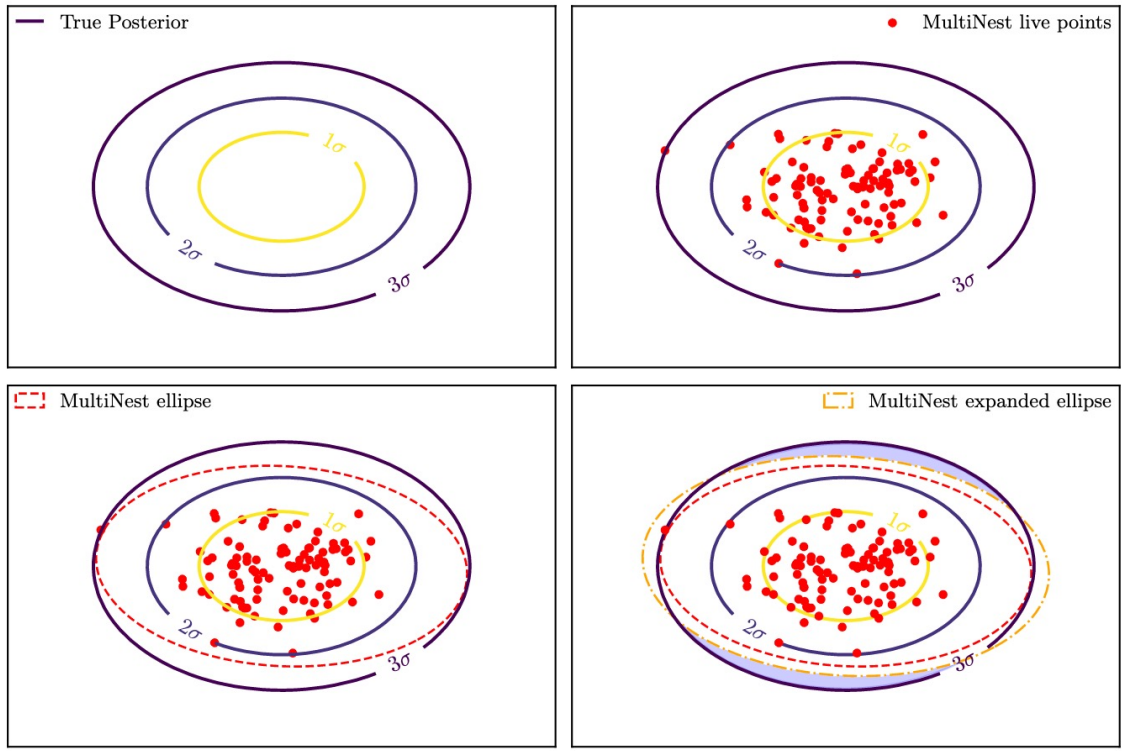




Findings motivated switch of nested sampling to Polychord sampler instead of Multinest (used in Y1).

Sampler validation

Goal: Recommend sampler settings for robust parameter estimation and model comparison.



Lemos, Weaverdyck, et al [DES]
arXiv:2202.08233


Noah Weaverdyck (Berkeley)


Pablo Lemos (Montreal)

Adding external data in ΛCDM

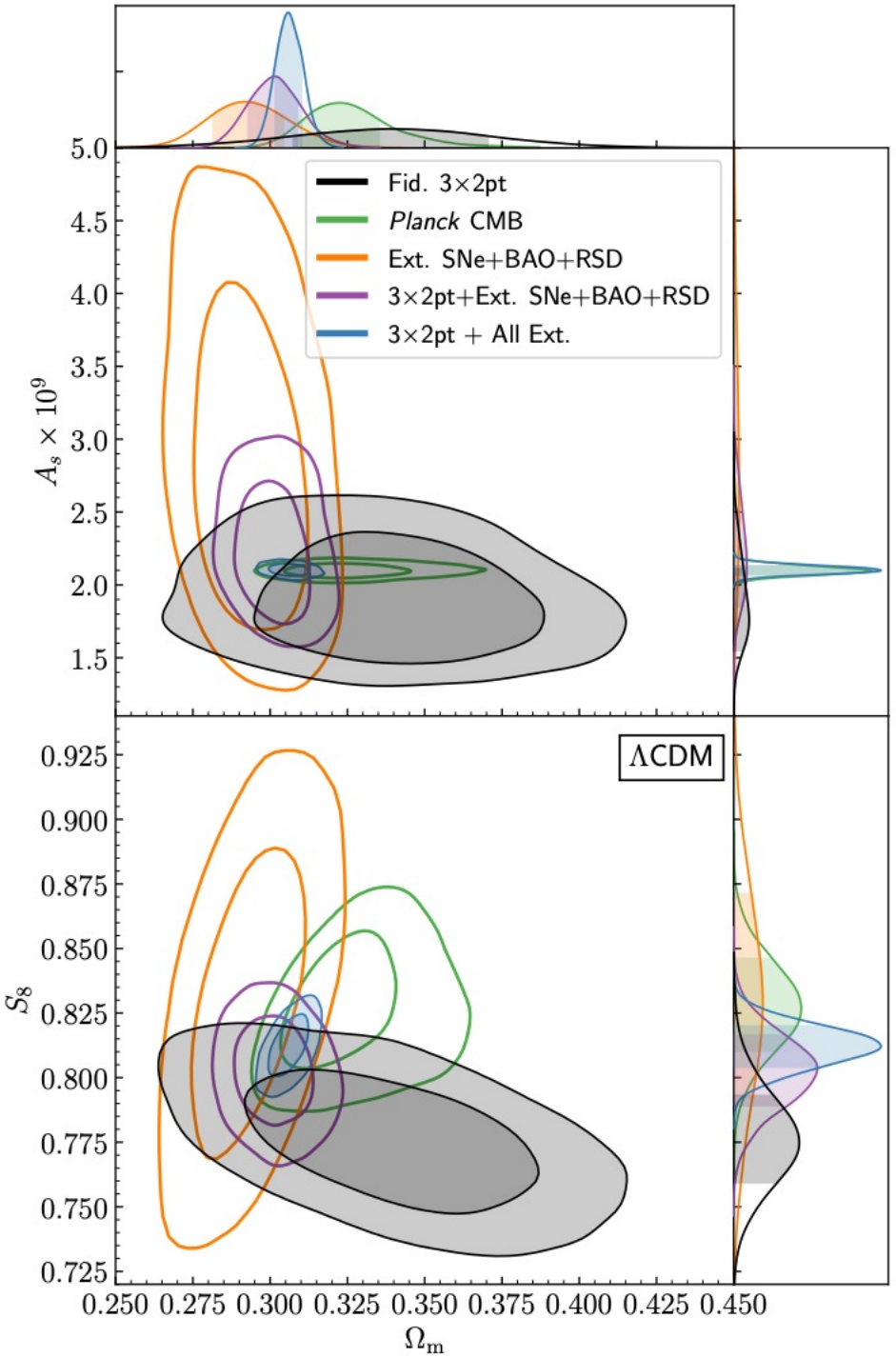
- Geometric probes tightly constraining expansion history
  - SNe: Pantheon supernovae
  - BAO+RSD: SDSS eBOSS DR16
    - (BAO is geometric, RSD adds growth info)
- Planck: 2018, TTTEEE+lowP (no lensing)

No tension between 3x2pt+SNe+BAO+RSD and Planck
- 0.9σ from S_8 parameter difference

$$S_8 = 0.812^{+0.008}_{-0.008}$$

$$\Omega_{\rm m} = 0.306^{+0.004}_{-0.005}$$

$$\sigma_8 = 0.804^{+0.008}_{-0.008}$$

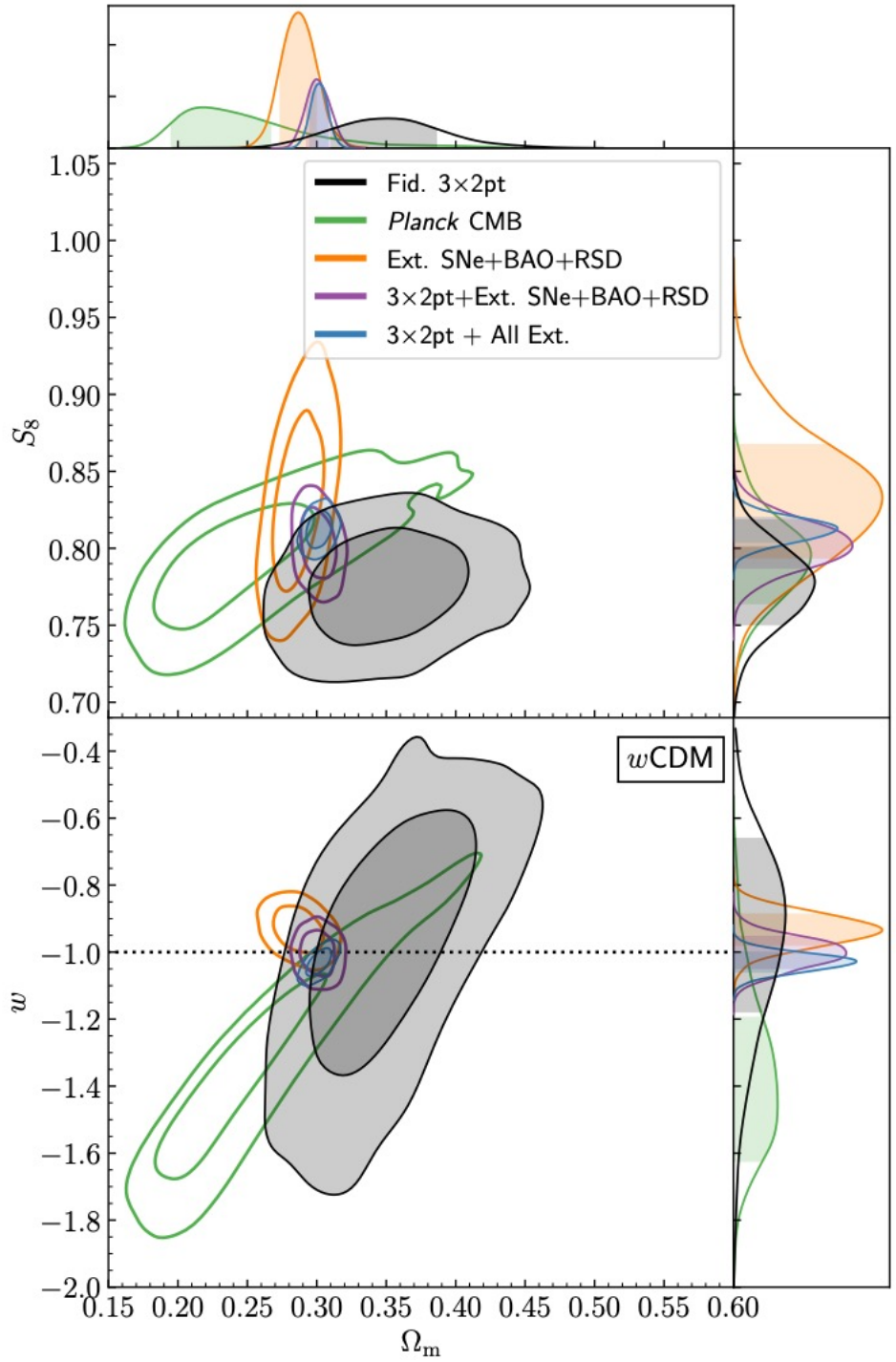


Adding external data in wCDM

Can introduce time-dependence in dark energy density via equation of state parameter:

$$w = \frac{p_{\rm DE}}{\rho_{\rm DE}} \qquad w = -1 \longleftrightarrow \Lambda$$

$$\sigma_8 = 0.810^{+0.010}_{-0.009}$$
$$\Omega_{\rm m} = 0.302^{+0.006}_{-0.006}$$
$$w = -1.031^{+0.030}_{-0.027}$$



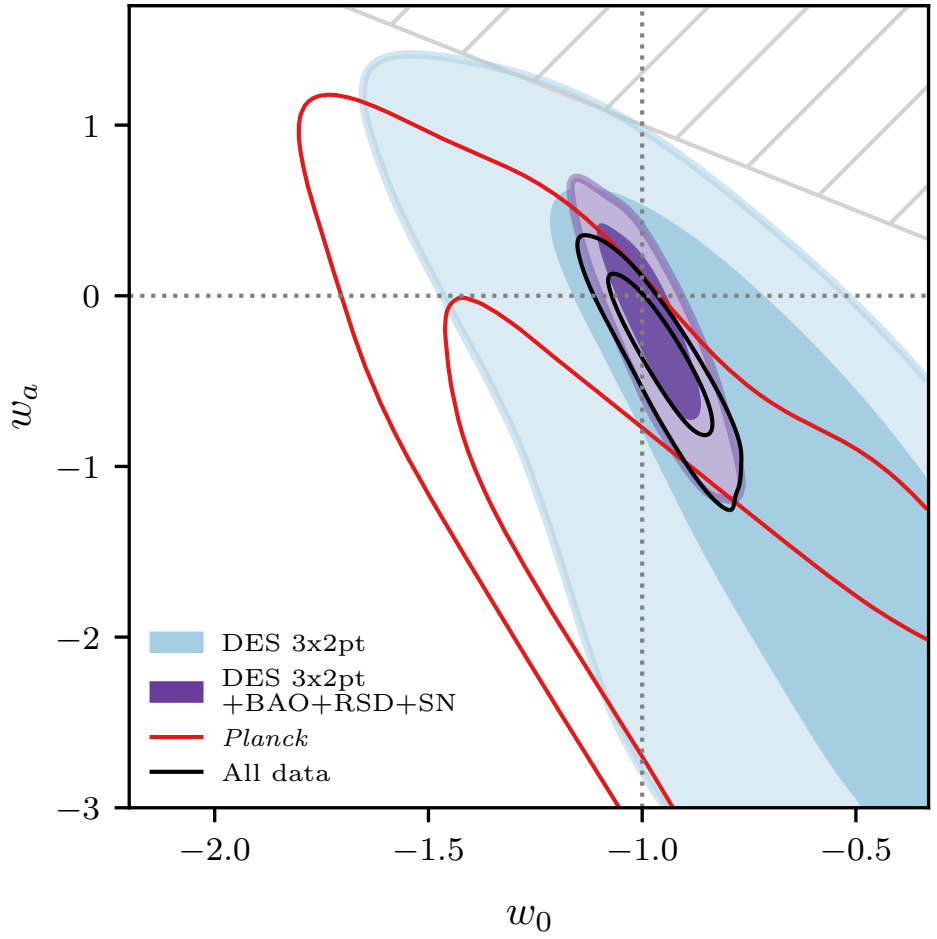
Dark energy time dependence

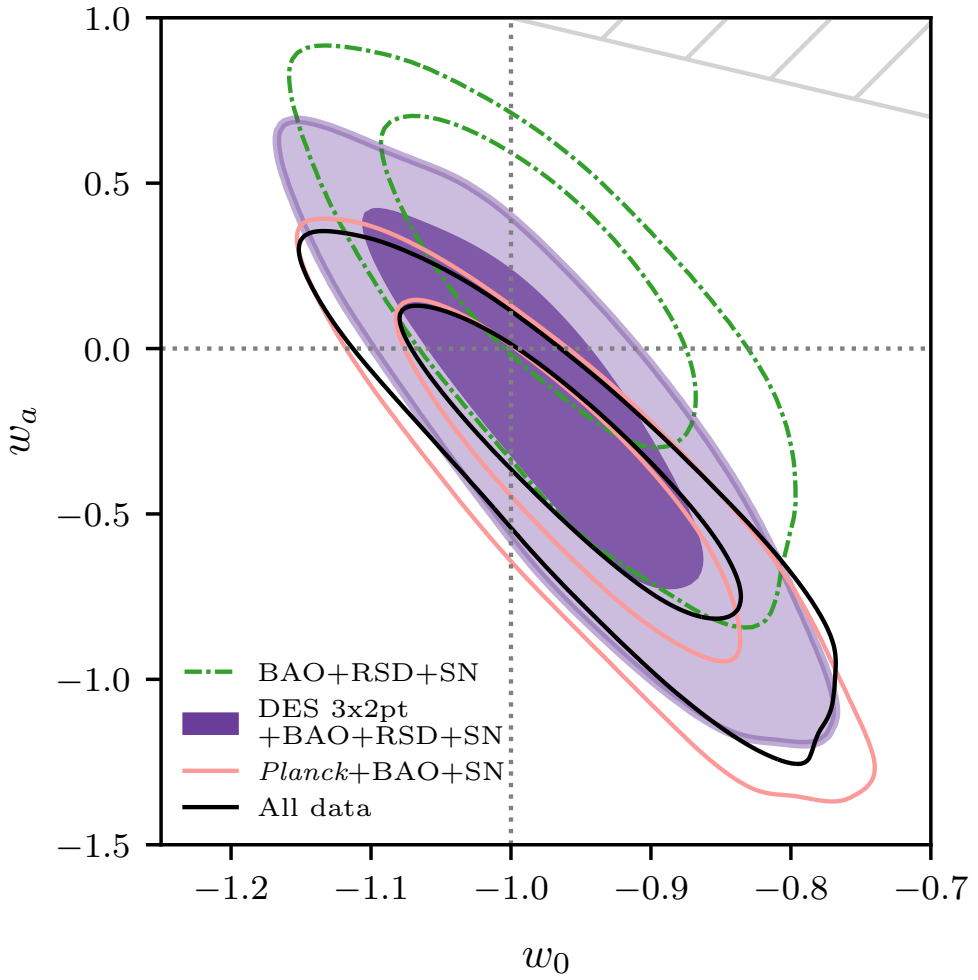
DES Collaboration arXiv: 2207.05766

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

Can introduce time-dependence in dark energy density via equation of state parameter:

$$w = \frac{p_{\rm DE}}{\rho_{\rm DE}} \qquad w = -1 \longleftrightarrow \Lambda$$



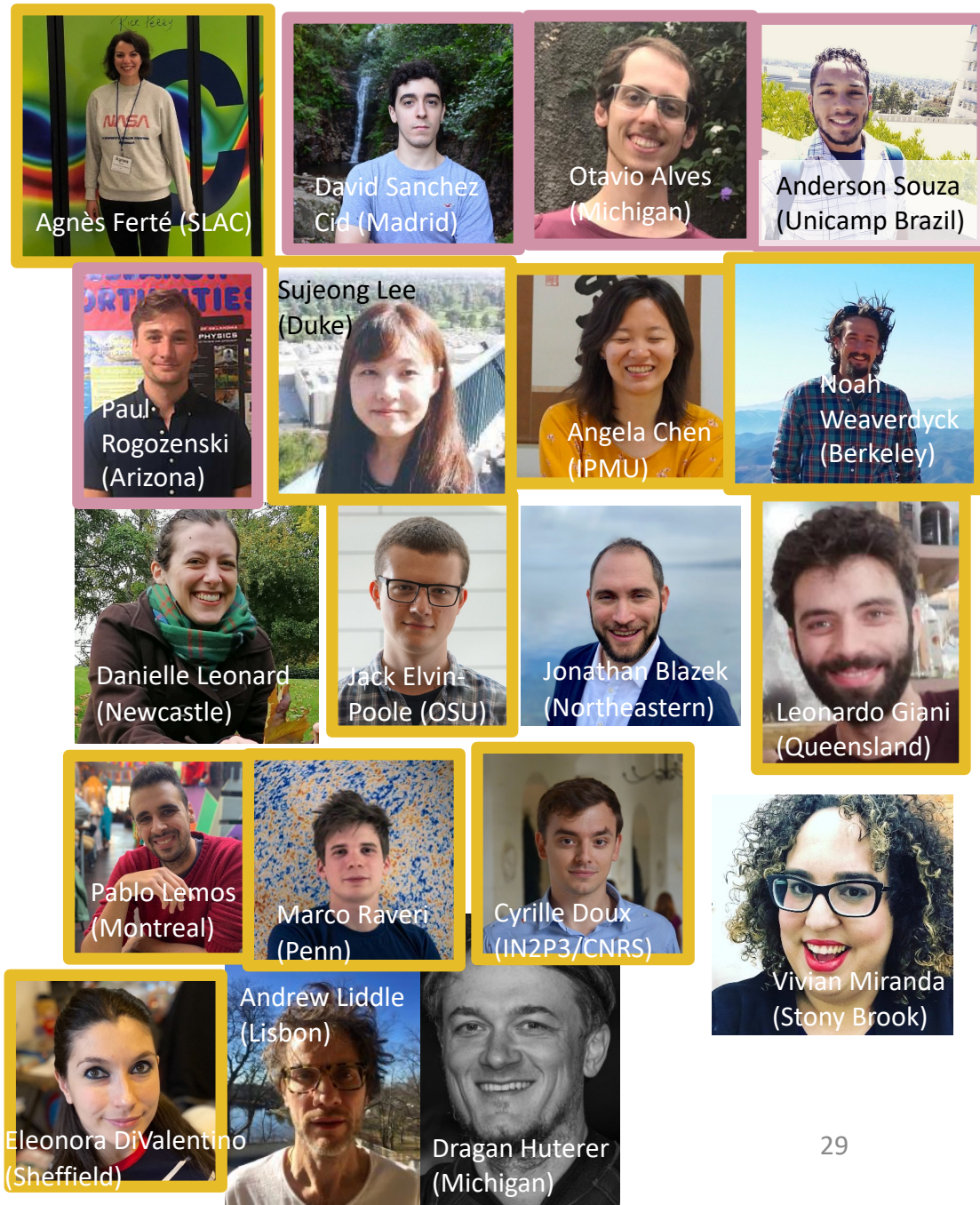


New beyond-ΛCDM results out in July!

- Goal: extend 3x2pt analysis to extended models beyond ΛCDM and wCDM
- Co-leads: JM and Agnès Ferté (SLAC)
- Models considered:
  - Time dependent dark energy equation of state
  - Non-zero spatial curvature
  - Modified gravity
  - Phenomenological $\sigma_8(z)$ test
  - Sterile neutrinos
- Results released July 2022
  - No significant deviations from ΛCDM
  - Paper: https://arxiv.org/abs/2207.05766
  - Public data: https://dev.des.ncsa.illinois.edu/releases/y3a2/Y3key-extensions

Main participants

Grad students postdocs



Modified gravity

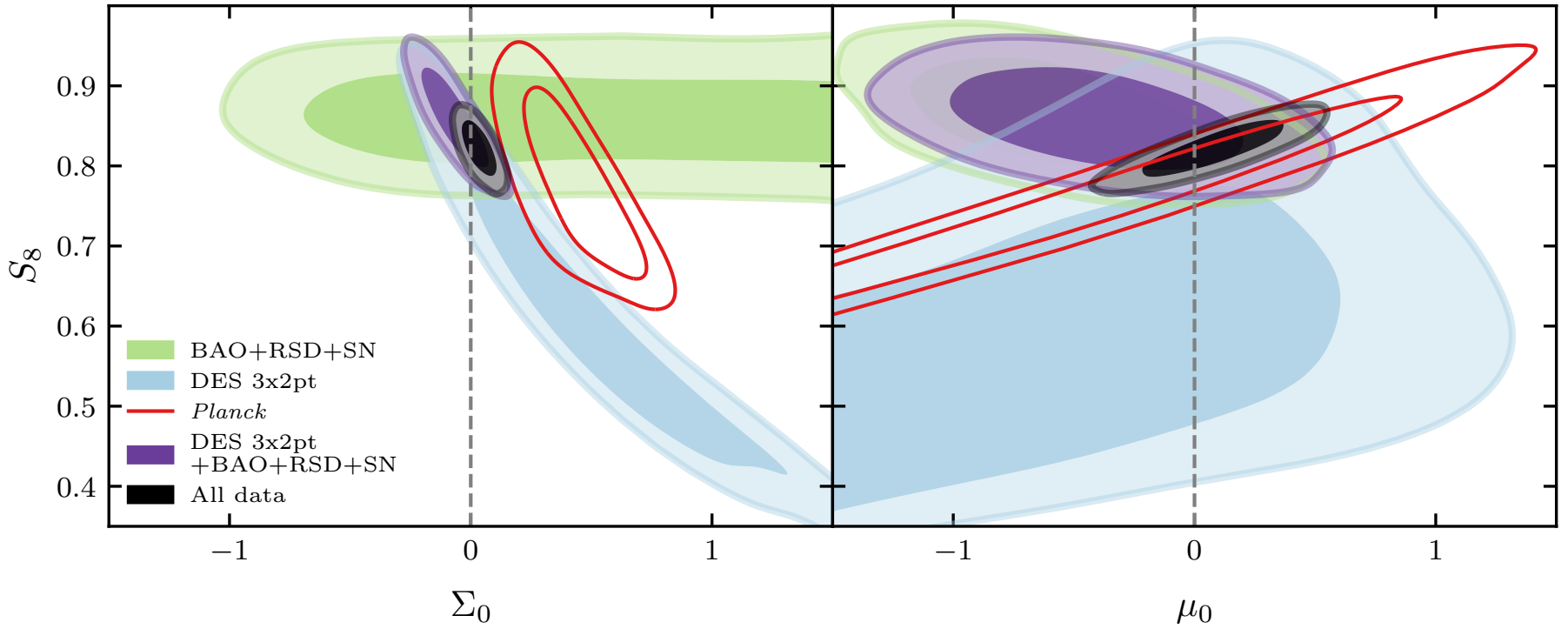
Assuming MG effects with no scale dependence, specific z evolution [more models currently under investigation in a project led by Agnès Ferté]

Newtonian potential $$k^2\Psi = -4\pi G a^2 \left[1 + \mu(a,k)\right](\rho\delta + 3(\rho+P)\sigma),$$

Lensing potential $$k^2\Phi = -2\pi G a^2 \rho\delta \left[1 + \Sigma(a,k)\right](2\rho\delta + 3(\rho+P)\sigma)$$

$$\mu(a,k) = \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda,0}}$$

$$\Sigma(a,k) = \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda,0}}$$



Only linear scales used due to lack of validated modeling.

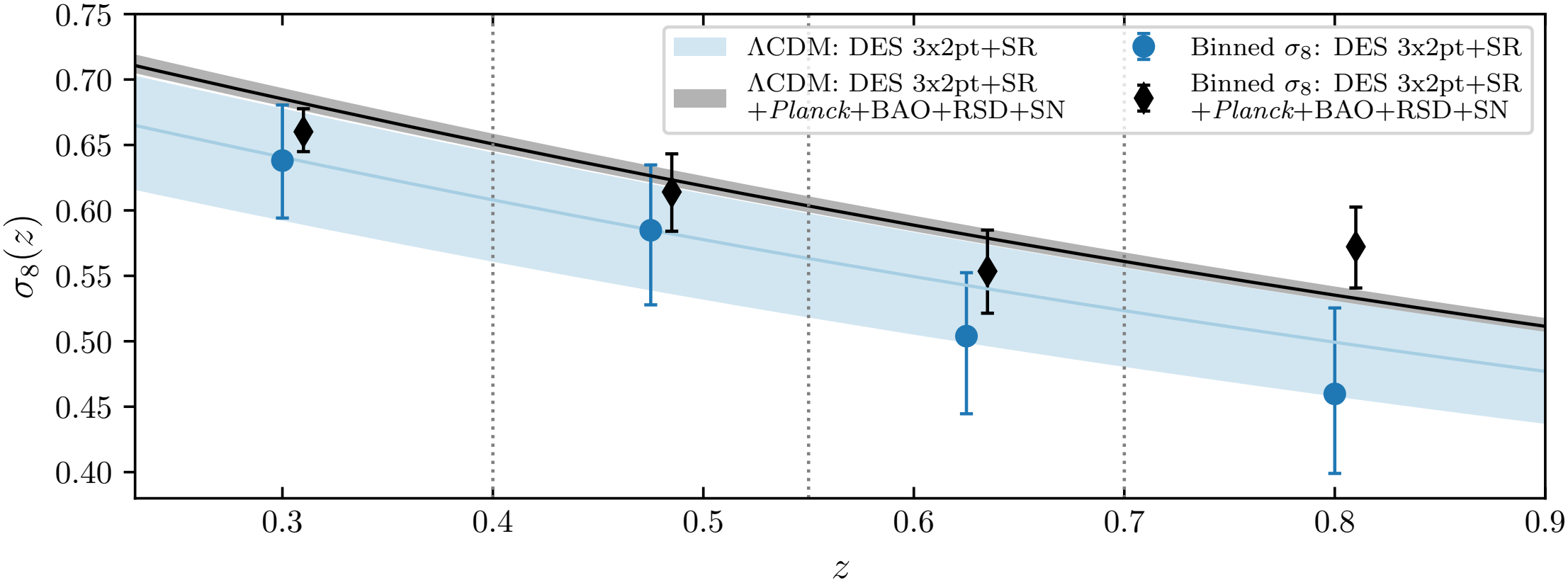
DES Collaboration arXiv: 2207.05766

Binned σ_8 -> inferred growth function

$$P_{\rm lin}(k,z) \;\rightarrow\; A_i P_{\rm lin}(k,z) \qquad \sigma_8^{[{\rm bin}\,i]} \equiv \sigma_8 \sqrt{A_i^{P_{\rm lin}}}$$

One A_i parameter per lens bin
Another (A_{CMB}) added for CMB when Planck included

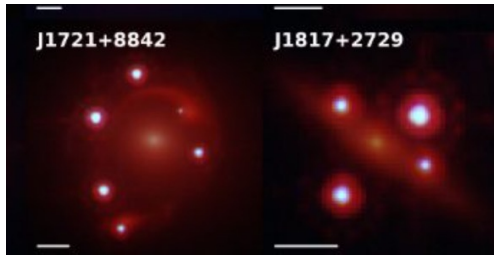
Warning!
DES-only constraints (blue points) are sensitive to how we account for redshift uncertainties.



DES Collaboration arXiv: 2207.05766

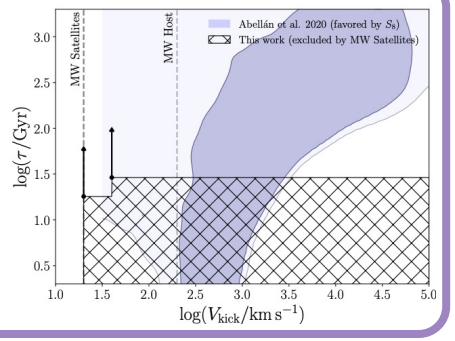
Some other DES highlights

STRIDES strong lensing analyses



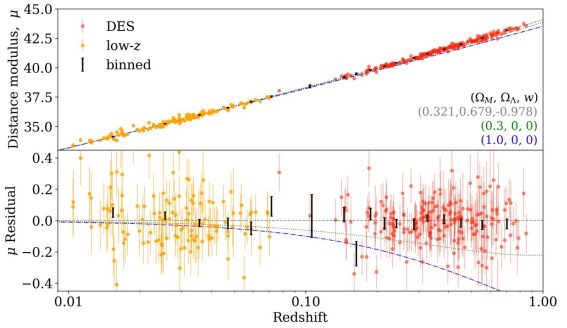
Dwarf galaxy constraints on dark matter

Mau, Nadler et al. arXiv:2201.11740



Supernova cosmology

DES Collab, arXiv:1811.02374

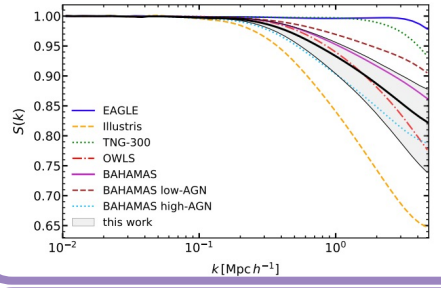


Discovery of Bernardinelli-Bernstein 'megacomet'

Bernardinelli, Bernstein et al arXiv:2109.09852

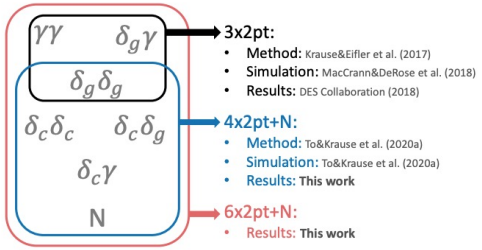
Constraints on baryonic feedback

Chen et al, arXiv:2206.08591



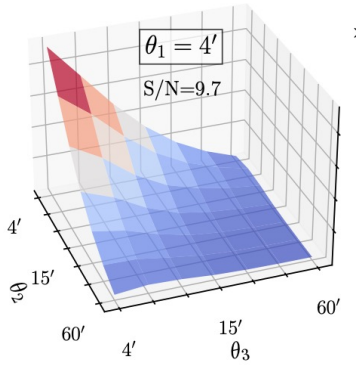
Cosmology with galaxy clusters

To et al, arXiv:2010.01138



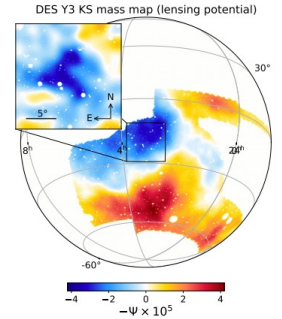
3pt shear measurements

Secco et al, arXiv: 2201.05227



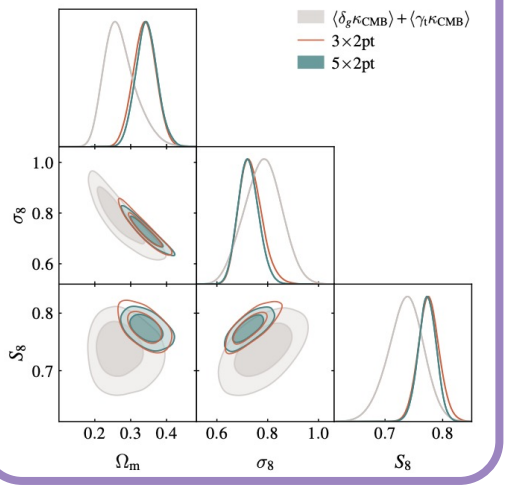
Eridanus Supervoid and the CMB cold spot

Kovacs et al, arXiv:2112.07699



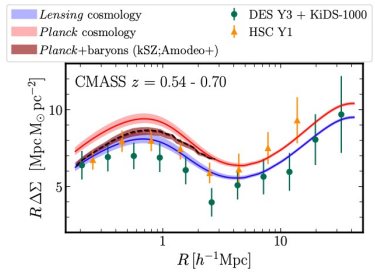
DES Y3 data x CMB lensing

DES & SPT, arXiv:2206.10824



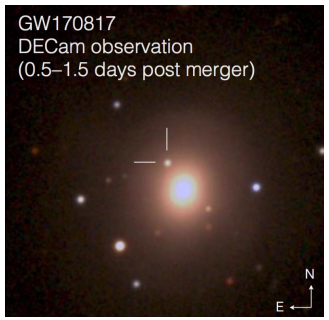
Consistent lensing measurements from DES, HSC, KiDS

Amon et al, arXiv:2202.07440



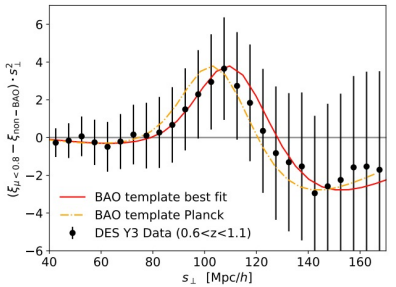
GW follow-up

Soares-Santos et al, arXiv:1710.05459



2.7% measurement of BAO scale at z=0.835

DES Collab., arXiv:2107.04646.



Summary, looking forward

- The Dark Energy Survey is the largest currently-generation imaging survey
  - Multi-purpose experiment
  - 5000 square degree footprint, ~200M galaxies
  - State-of-the-art precision and analysis methods
  - Cosmology results out from first three years of data, full legacy analysis is underway!
- New results released in July using DES Y3 data to constrain extensions to ΛCDM
  - No significant preference for beyond-ΛCDM physics, but some interesting modeling developments, things to investigate further.
- Modeling uncertainties are the limiting systematic for DES Y3.
  - Need to continue developing both theoretical & observational methods to take full advantage of future surveys' increasing precision. (DES Y6, Rubin, Euclid…)

EXTRA SLIDES

Binned σ_8

For lens redshift bin i:

$$P_{\rm lin}(k,z) \rightarrow A_i P_{\rm lin}(k,z)$$

One A_i parameter per lens bin
Another (A_{CMB}) added for CMB when Planck included

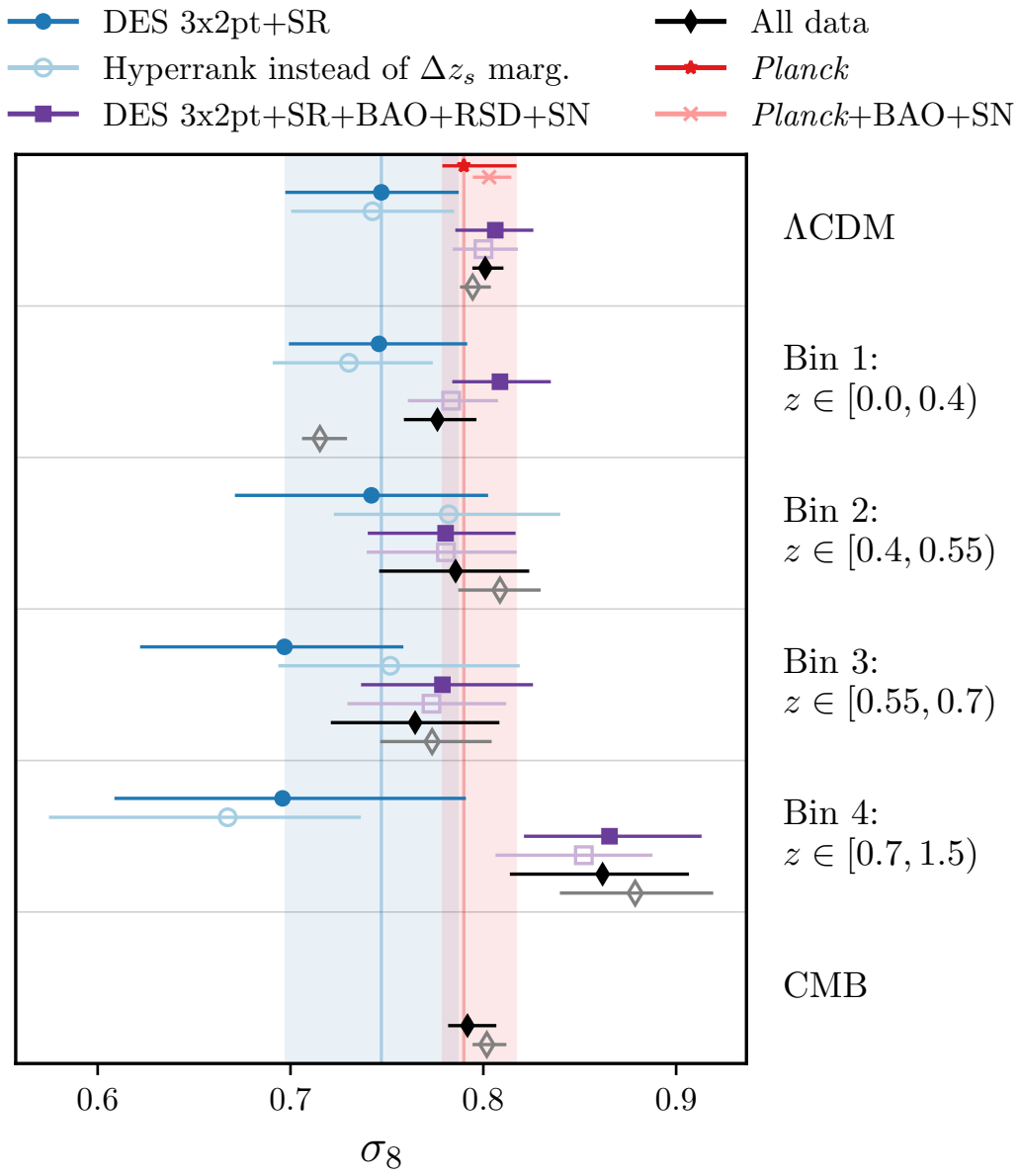
$$\sigma_8^{[\text{bin } i]} \equiv \sigma_8 \sqrt{A_i^{P_{\rm lin}}}$$

Warning!

- DES-only constraints lack robustness to changes in how we account for photo-z uncertainties (filled vs unfilled)
- With external data, bins 2-4 are more robust

Higher σ_8 in bin 4 → slower growth than LCDM?

- Model comparison; effect is less than 2σ
- But similar hint (?) seen at high z in other papers…
  - DESI x Planck lensing - White et al 2021 [2111.09898]
  - eBOSS QSO clustering – Brieden, Gil-Marin & Verde 2022 [2204.11868]
  - DES Y1, KiDS Cosmic shear, CMB lensing, eBOSS QSO, CMB lensing - García-García et al 2021 [2105.12108]



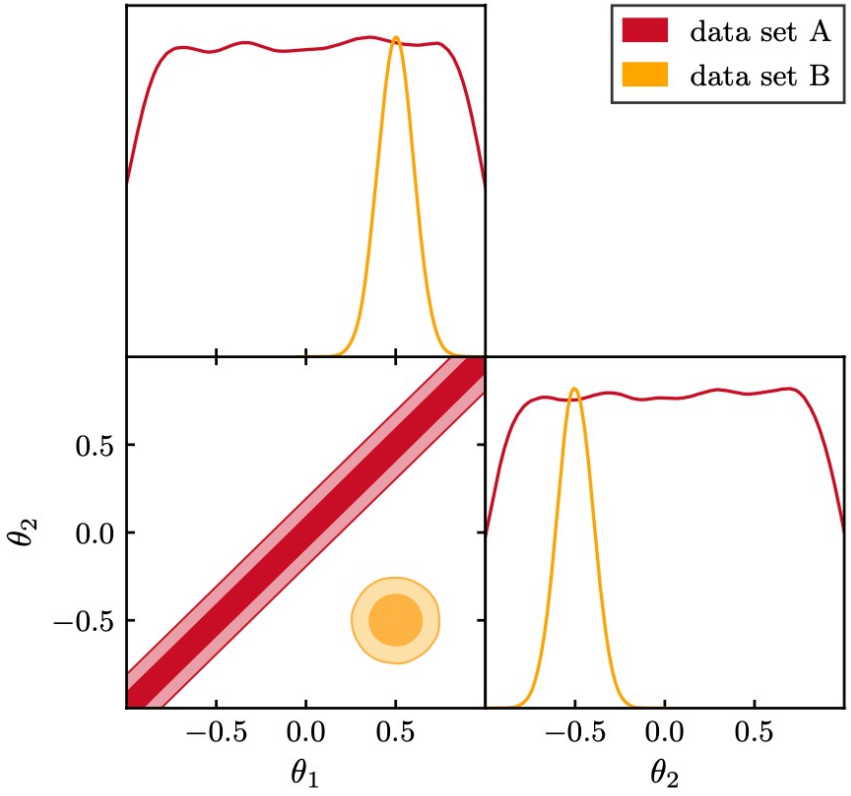
Calibrating tension metrics

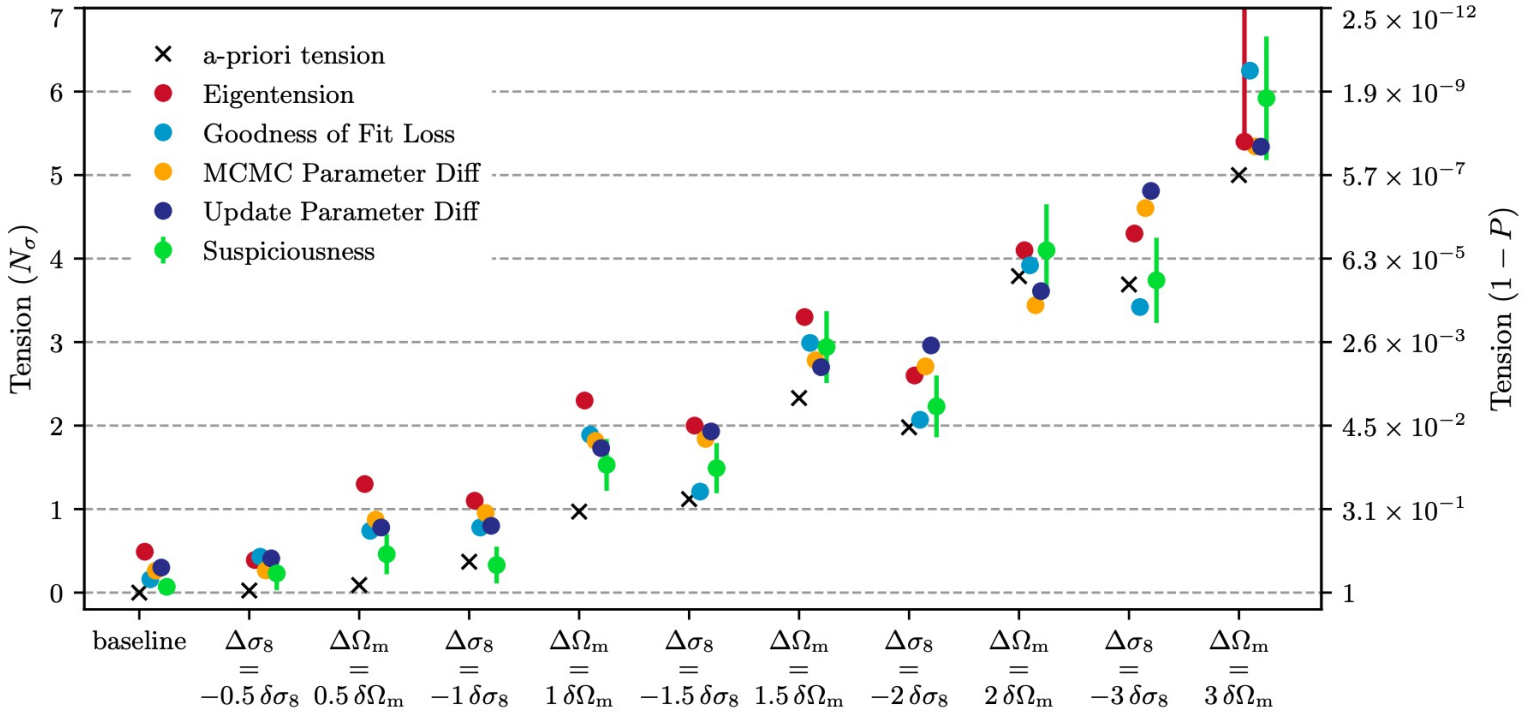
Goal: evaluate metrics for assessing tensions in high-dim parameter spaces. Found:

- Various tension metrics roughly agree
- DES Y1 and Planck were in ~2σ tension

Pablo Lemos (Montreal)

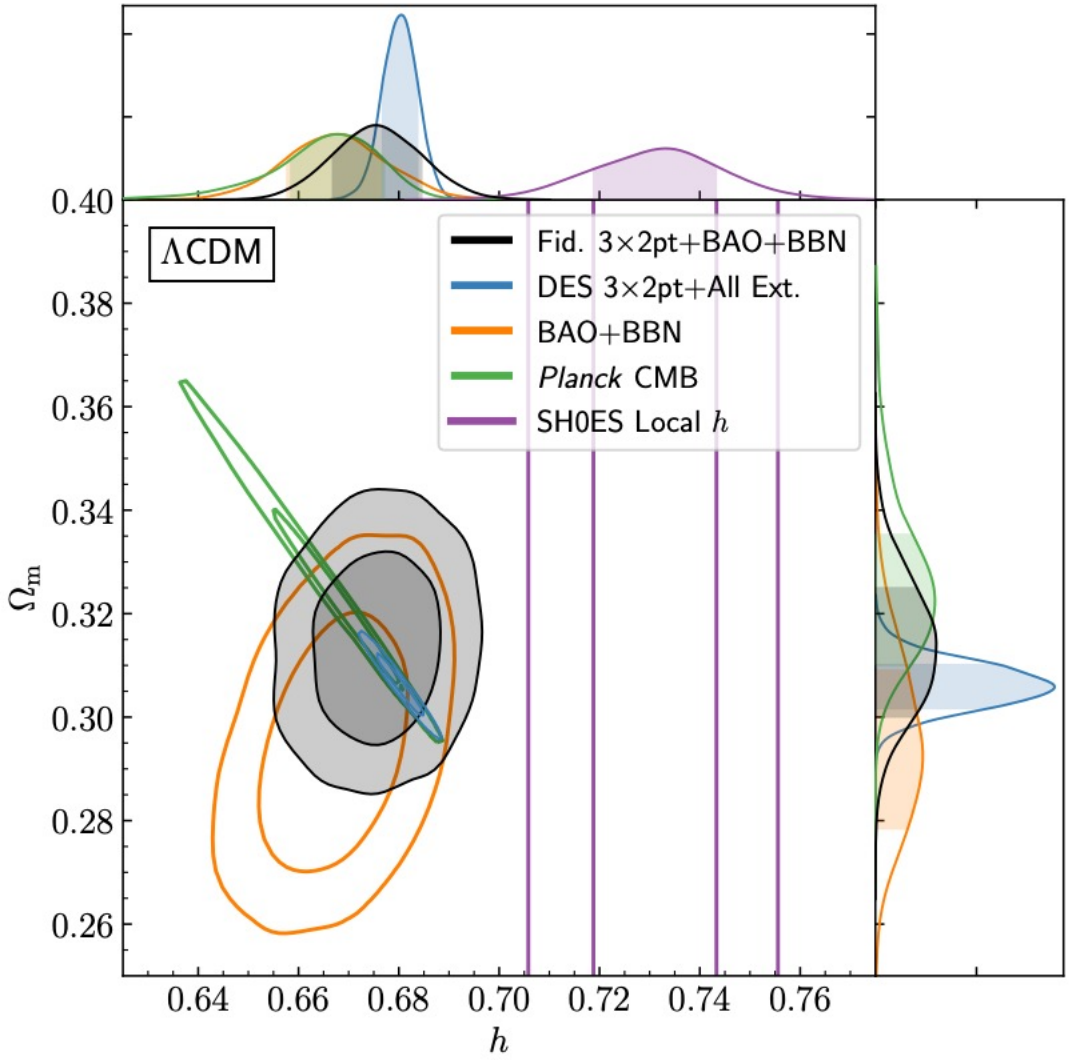
Marco Raveri (Penn)





Lemos, Raveri et al [DES], MNRAS 2021, arXiv:2012.09554

Hubble constant constraints



DES Collaboration 2105.13549

DATA

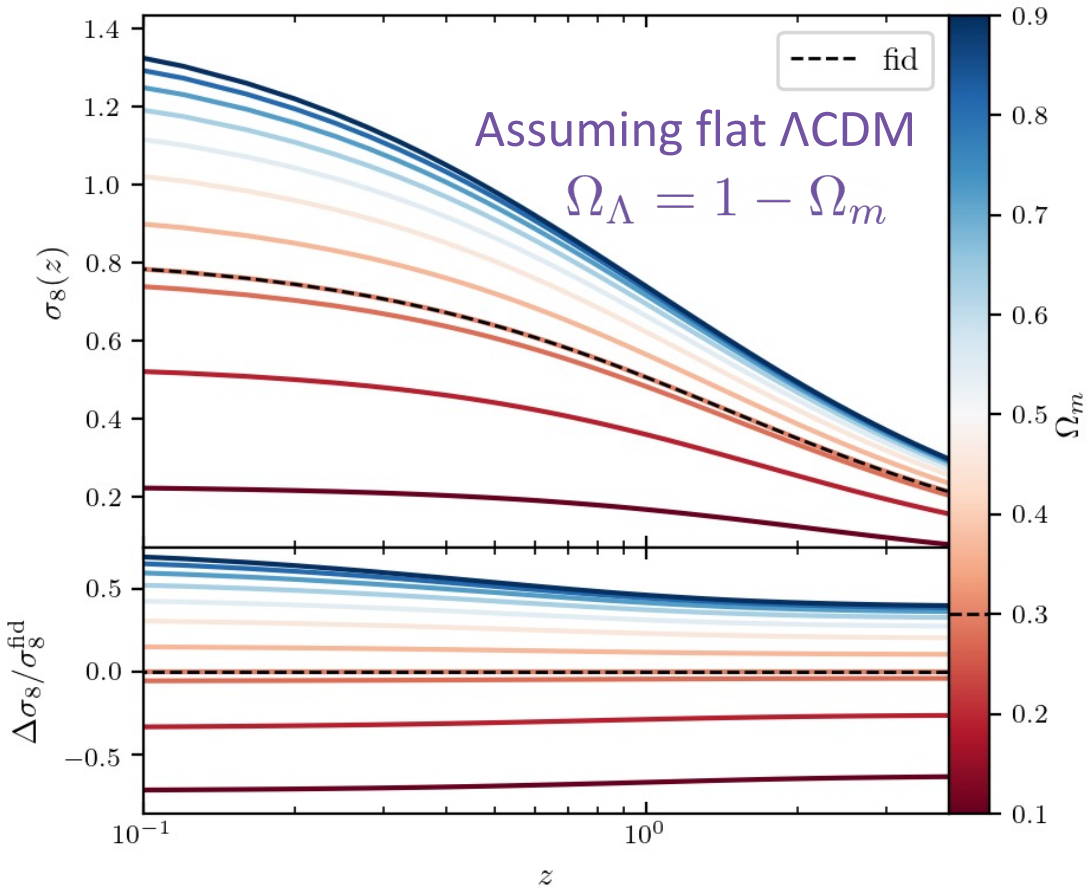
	Data points					
Scale cuts	ξ_+	ξ_-	γ_t	w	Total	Used for extended models
Fiducial	166	61	192	43	462	$w_0 - w_a$, $N_{\rm eff}$, binned $\sigma_8(z)$
Linear	105	3	105	43	256	$N_{\rm eff} - m_{\rm eff}$, $\Sigma_0 - \mu_0$
Linear+Limber	100	2	100	19	221	Ω_k

Observables	Data
CMB (*Planck* in text)	*Planck* 2018 TTTEEE-lowE (no lensing)
BAO	eBOSS DR16: LRGs, ELGs, QSOs, Lyman-α QSOs + 6dFGS + MGS
RSD	eBOSS DR16: LRGs, ELGs, QSOs + MGS
SN	Pantheon sample (2018)

Structure growth provides a complementary probe of DE properties.

More dark energy ⟶ more rapid acceleration ⟶ slower/less structure growth

amplitude of density fluctuations ~ $\langle\delta^2\rangle$



z= 0.1 ~1 Gyr ago

z=1 ~ 8 Gyr ago

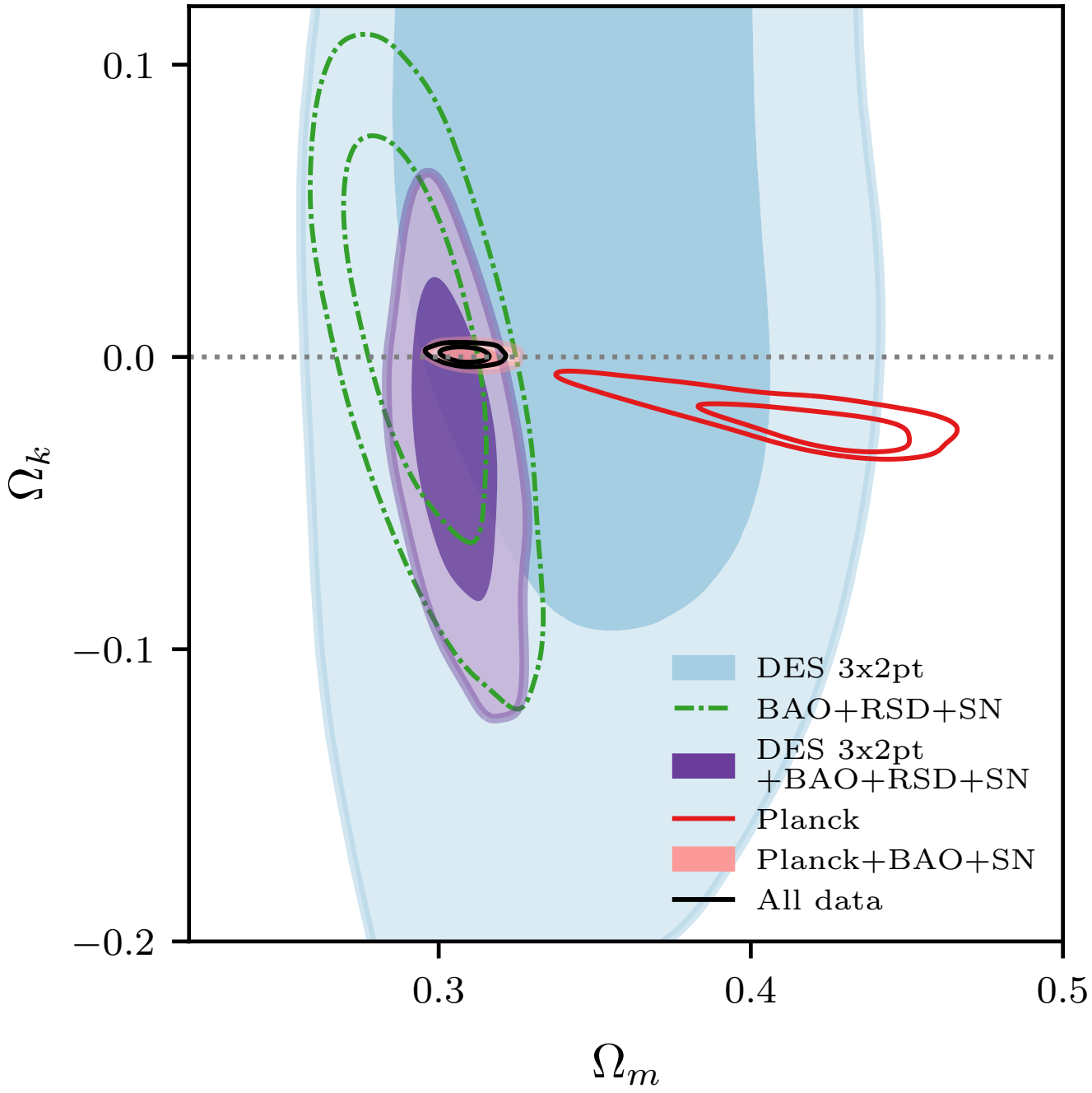
Density perturbations

$$\delta(\vec{x},t) = \frac{\delta\rho_m(\vec{x},t)}{\bar{\rho}_m}$$

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\bar{\rho}_m\delta = 0$$

Expansion rate = friction

Gravity



Curvature

- While 3x2pt doesn't constrain Ω_k alone, when combined with BAO, SN, RSD, it improves constraints that can be placed without the CMB by 20%.
- (green dashed -> purple filled)
- Suspiciousness tension measure between Planck (red) and DES+lowz (purple): 3σ, with 0-4 σ allowed by sampling uncertainty

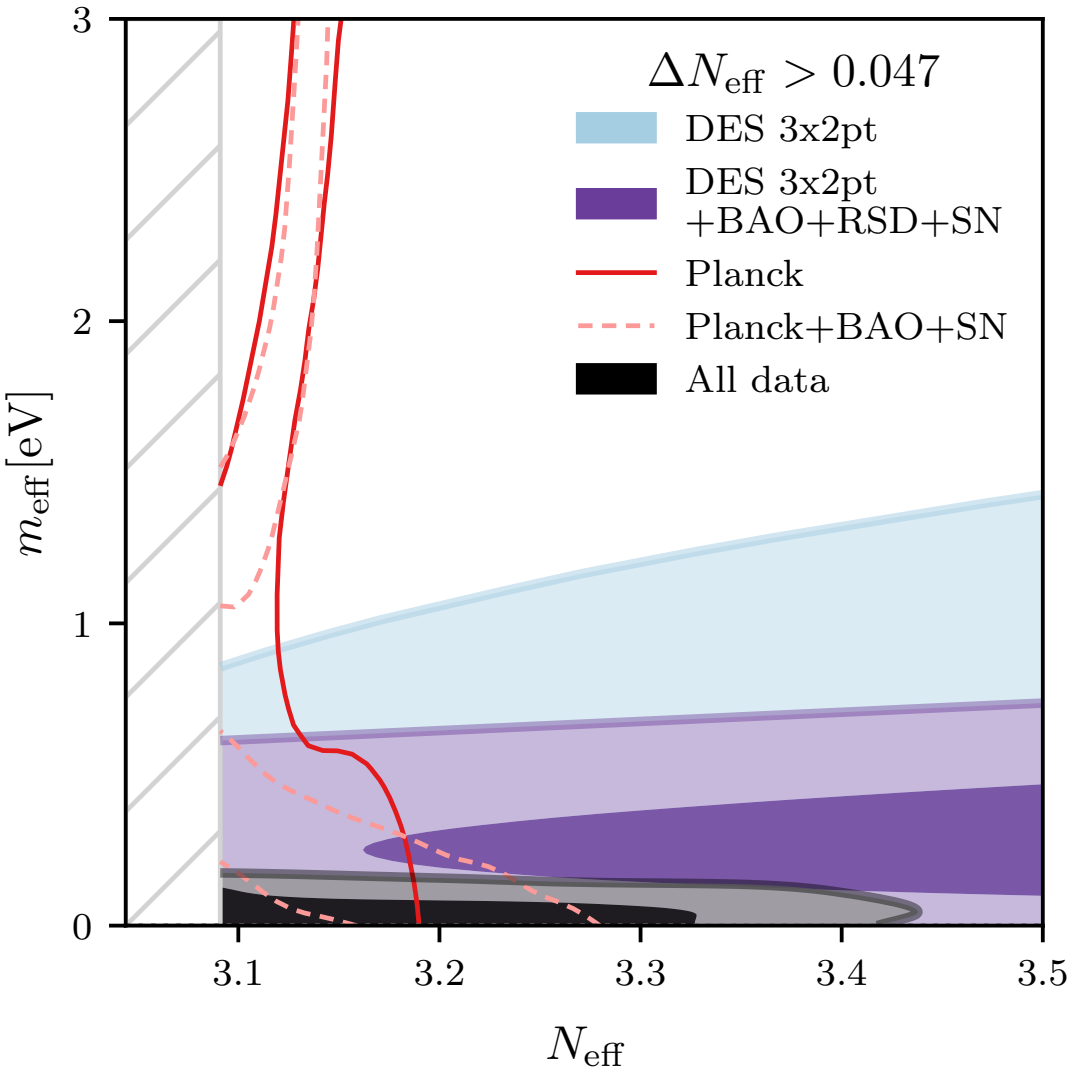
Pipeline dev notes:

- Linear scale cuts due to lack of validated NL modeling
- Limber scale cuts removing large-angle galaxy clustering as fast non-Limber calculations aren't validated for non-flat cosm

Massive sterile neutrinos (and/or other light massive relics [LiMRs])

- CMB constrains Neff very well
  - $\Delta N_{eff} = N_{eff} - 3.044$
- 3x2pt adds strong constraints on m_{eff}
  - P(k,z) suppression like standard model neutrinos, but with free-streaming scale set by both mass and N_{eff} (temperature)
  - Upper bound on m_{eff} from all data combined tightened by factor of 3 compared to similar Planck 2018 analysis

$$k_{\rm fs} = \frac{0.8h{\rm Mpc}^{-1}}{\sqrt{1+z}}\left(\frac{m_{\rm eff}}{(1{\rm eV})\Delta N_{\rm eff}}\right)$$

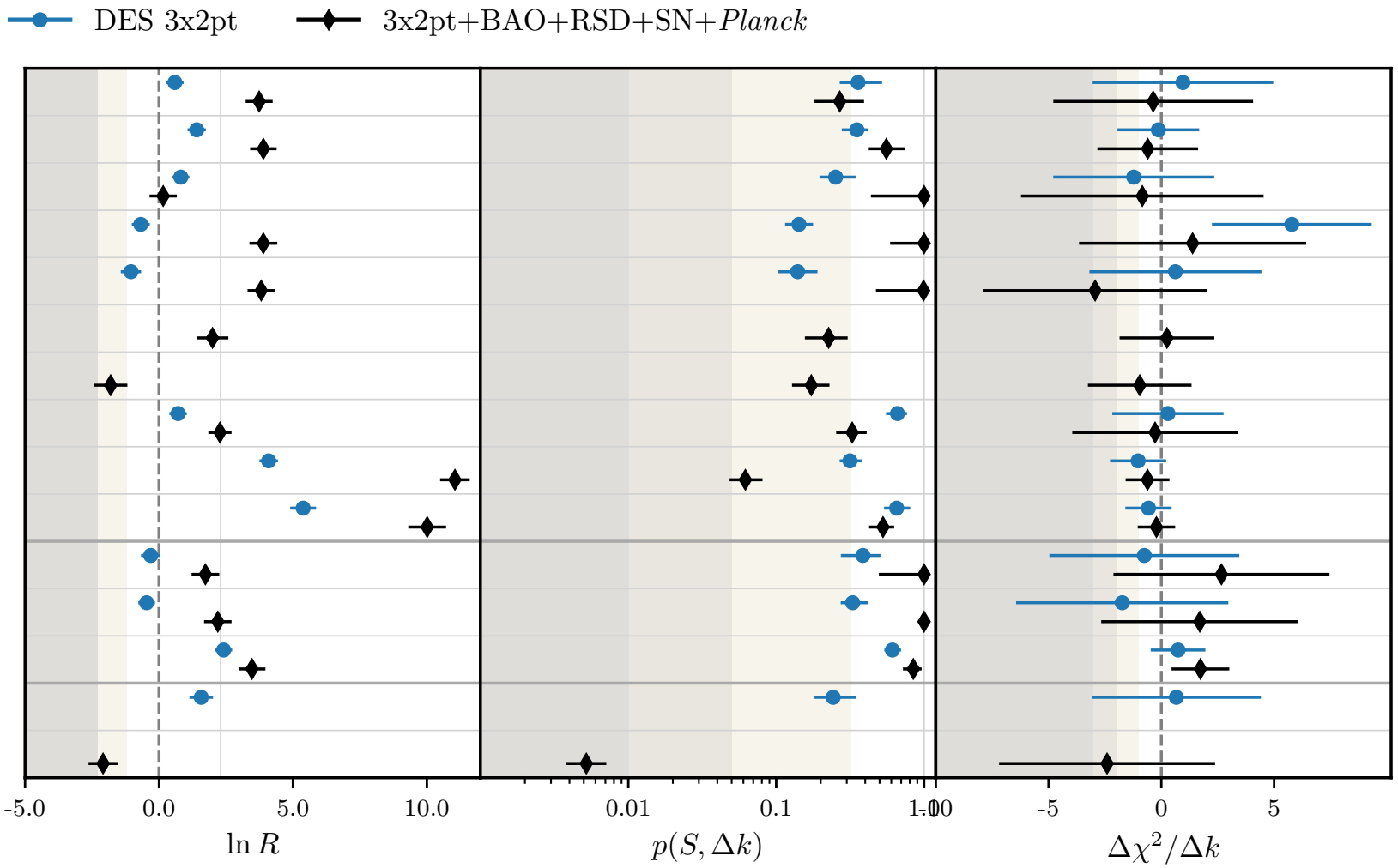


Pipeline dev notes:

- Only linear modeling, linear scale cuts; nonlinear modeling with LiMRS is an active area of research!

Model comparison

Preference for extended model



Model Comparisons

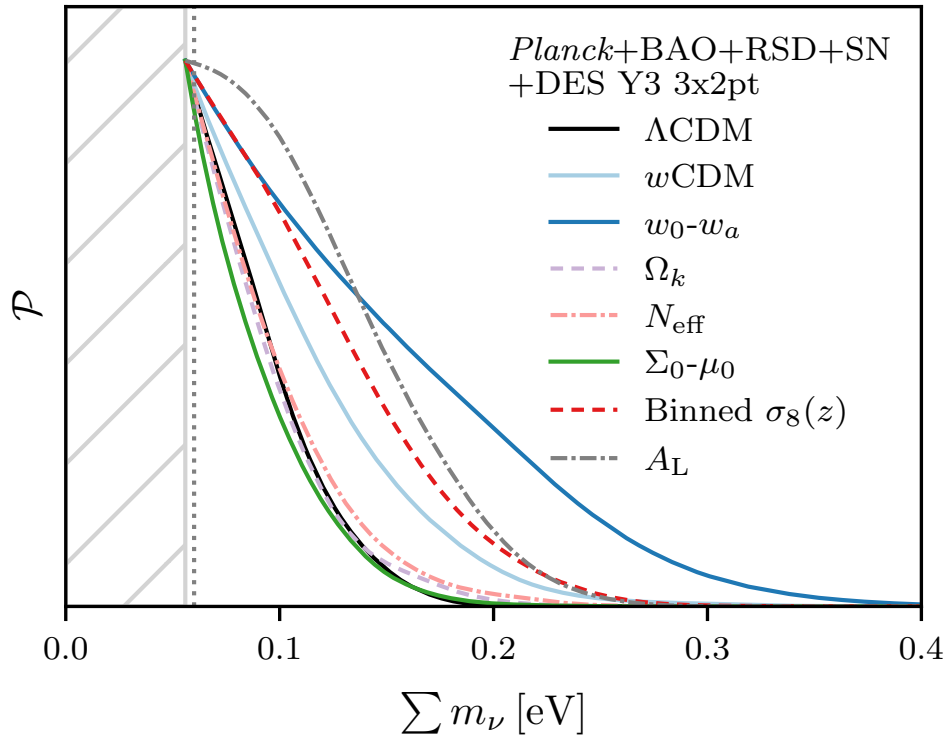
- [wCDM] vs. [ΛCDM]
- [w_0-w_a] vs. [ΛCDM]
- [w_0-w_a] vs. [wCDM]
- [Ω_k] vs. [ΛCDM]
- [$N_{\rm eff}$] vs. [ΛCDM]
- [$N_{\rm eff}$-$m_{\rm eff}$, $\Delta N_{\rm eff} > 0.047$] vs. [ΛCDM, fix m_ν]
- [$N_{\rm eff}$-$m_{\rm eff}$, $m_{\rm th} < 10$ eV] vs. [ΛCDM, fix m_ν]
- [Σ_0-μ_0] vs. [ΛCDM]
- [Binned $\sigma_8(z)$] vs. [ΛCDM]
- [Binned $\sigma_8(z)$, hyp] vs. [ΛCDM, hyp]
- [ΛCDM] vs. [ΛCDM, fix m_ν]
- [ΛCDM, lin. $P(k)$+cuts] vs. [ΛCDM, fix m_ν]
- [TATT IA model] vs. [ΛCDM]
- [$X_{\rm Lens}$] vs. [ΛCDM]
- [$A_{\rm L}$] vs. [ΛCDM]

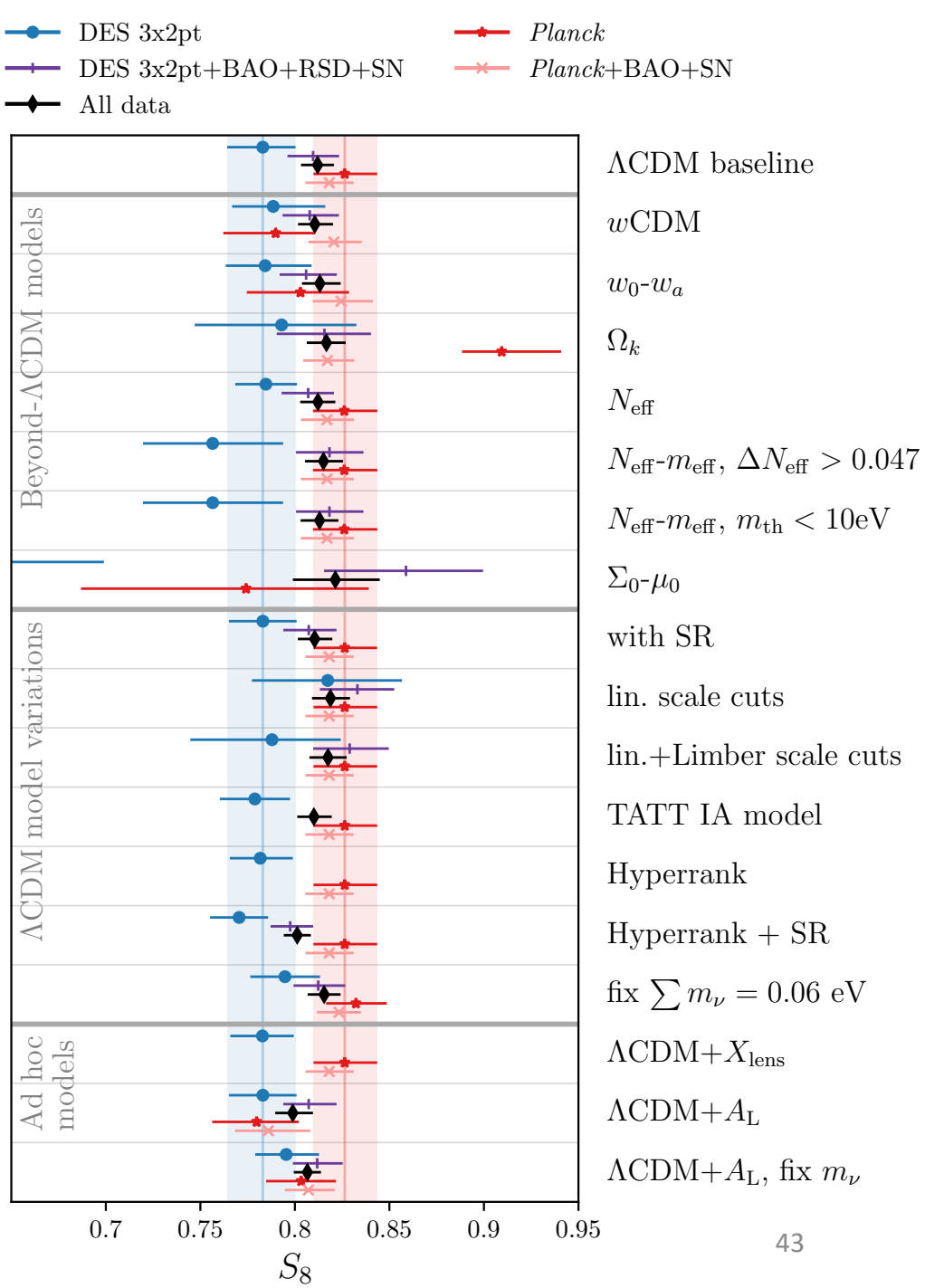
Bayes Evidence ratio

Suspiciousness p-value: Bayesian analog of $\Delta\chi^2/\Delta k$

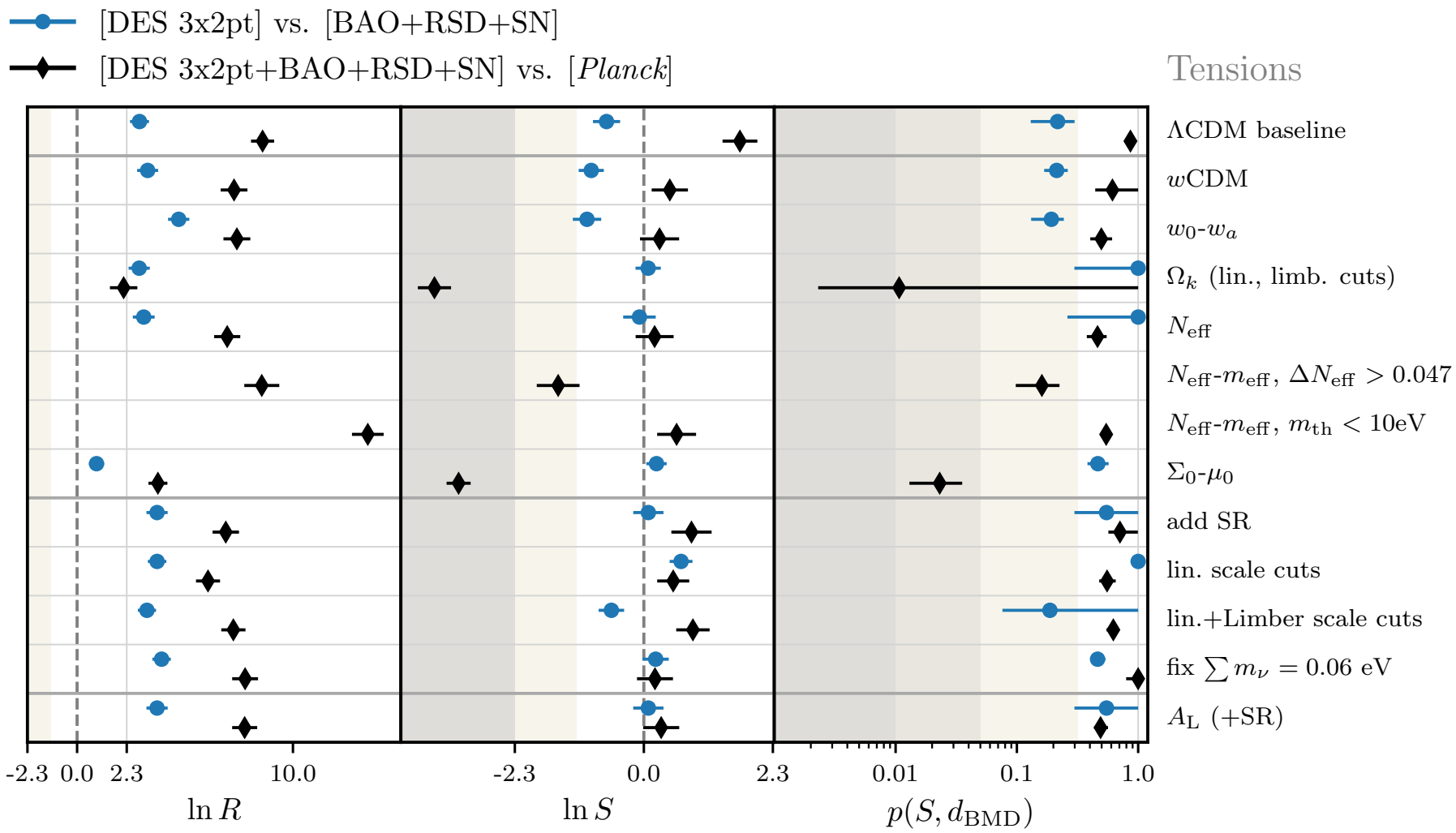
Change in goodness-of-fit per added parameter

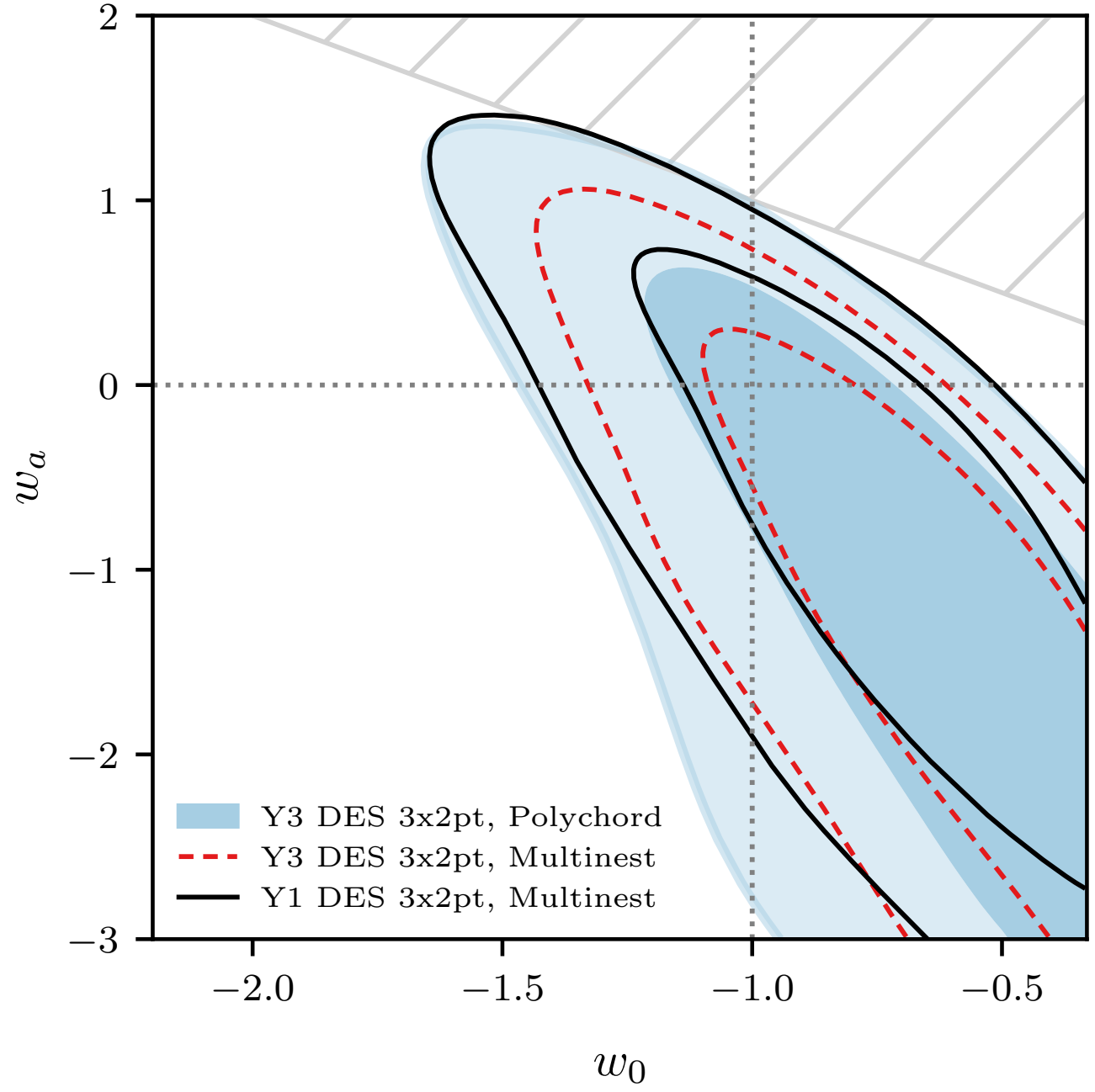
Impact of model extensions on S8, m_ν





Tensions between datasets




2
1
0
−1
−2
−3
w_a
−2.0
−1.5
−1.0
−0.5
w_0
Y3 DES 3x2pt, Polychord
Y3 DES 3x2pt, Multinest
Y1 DES 3x2pt, Multinest