Probing cosmological structure growth with the Dark Energy Survey

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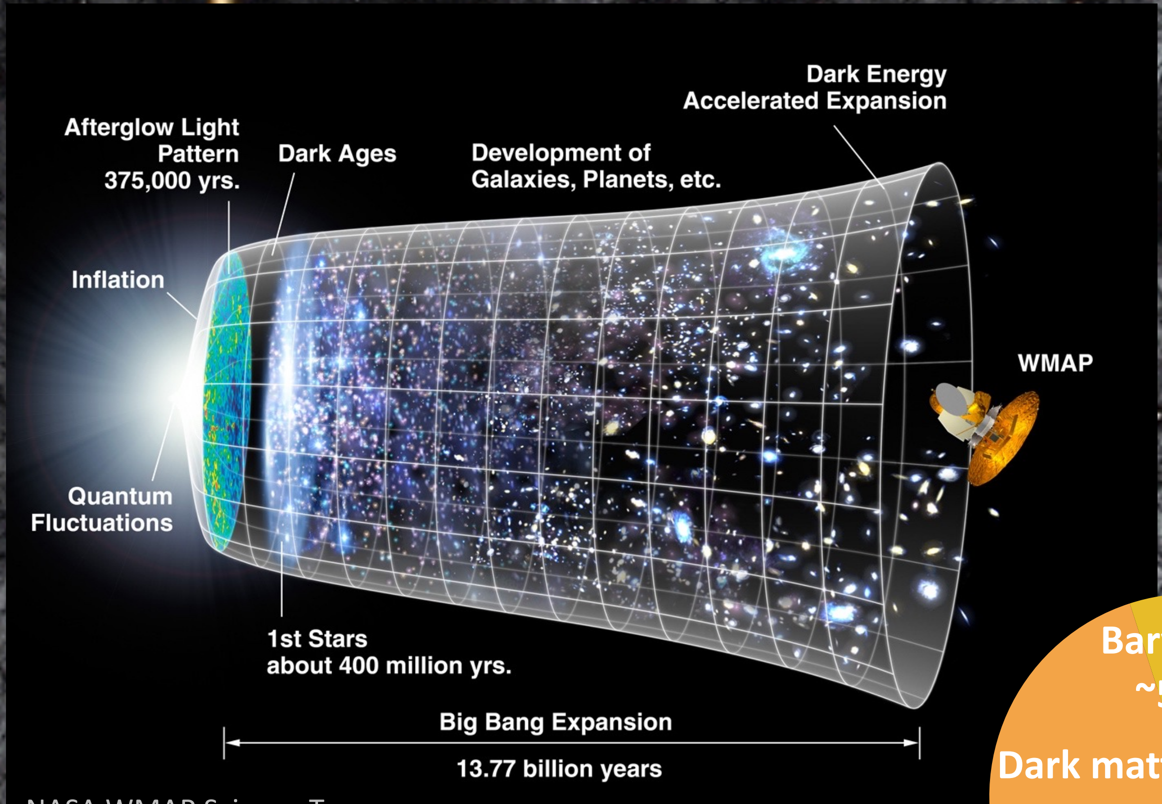
BCCP/Cosmology Seminar --- September 19, 2023

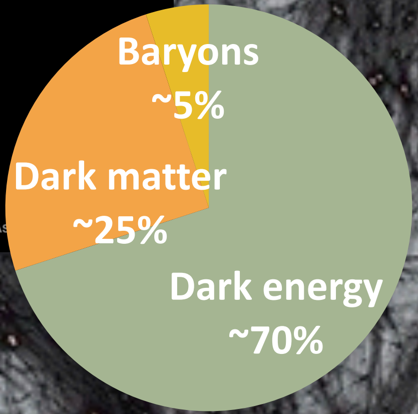
DARK ENERGY SURVEY

PERIMETER INSTITUTE

We can use the large-scale structure of the Universe to learn about fundamental physics.



NASA WMAP Science Team

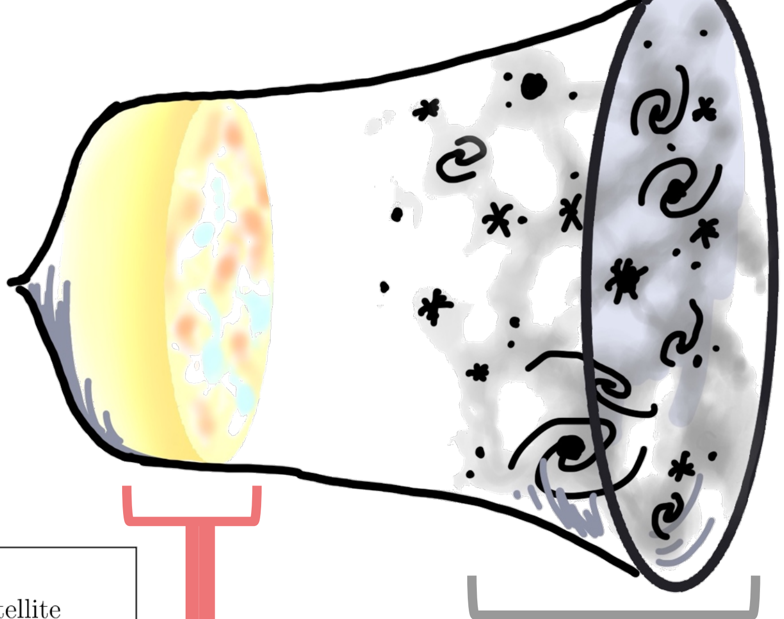


Properties of structure depend on

- Properties of matter (dark matter, baryons, neutrinos)
- Expansion history (dark energy)
- Gravity (general relativity)
- Initial fluctuation properties (inflation)

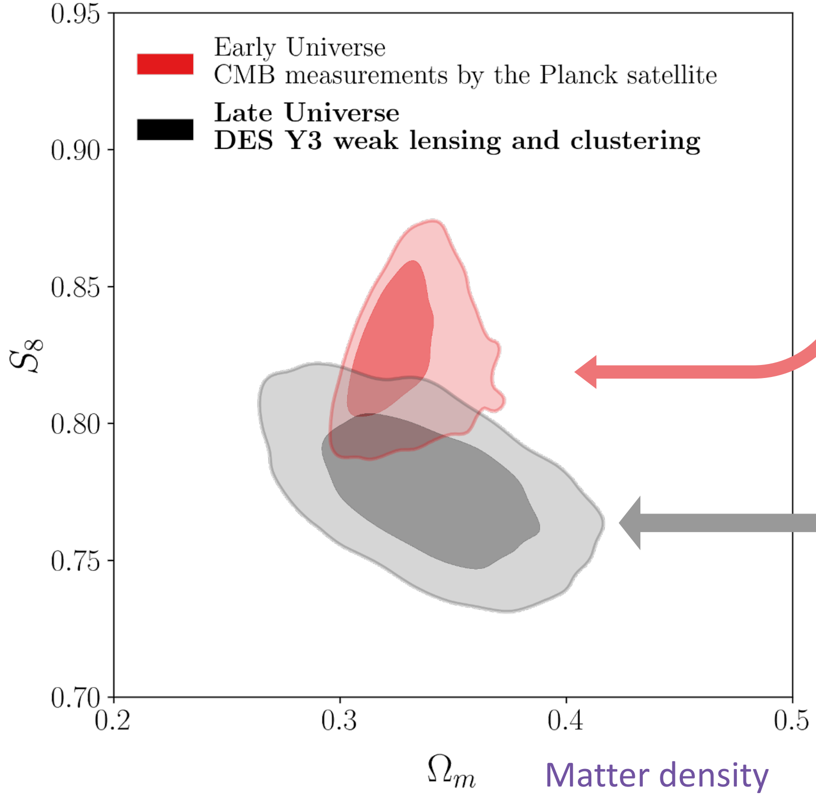
This is why it's interesting to compare late- and early-time constraints on the amplitude of density fluctuations:

"S_8 tension"

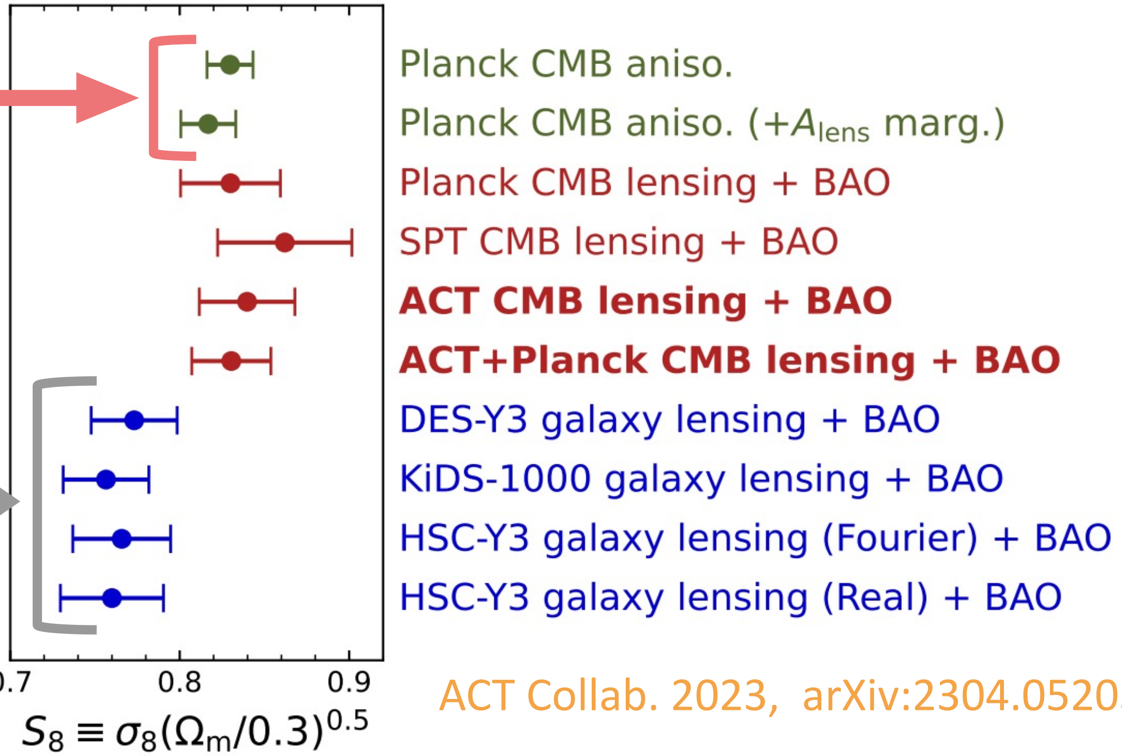


Amplitude of density fluctuations

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



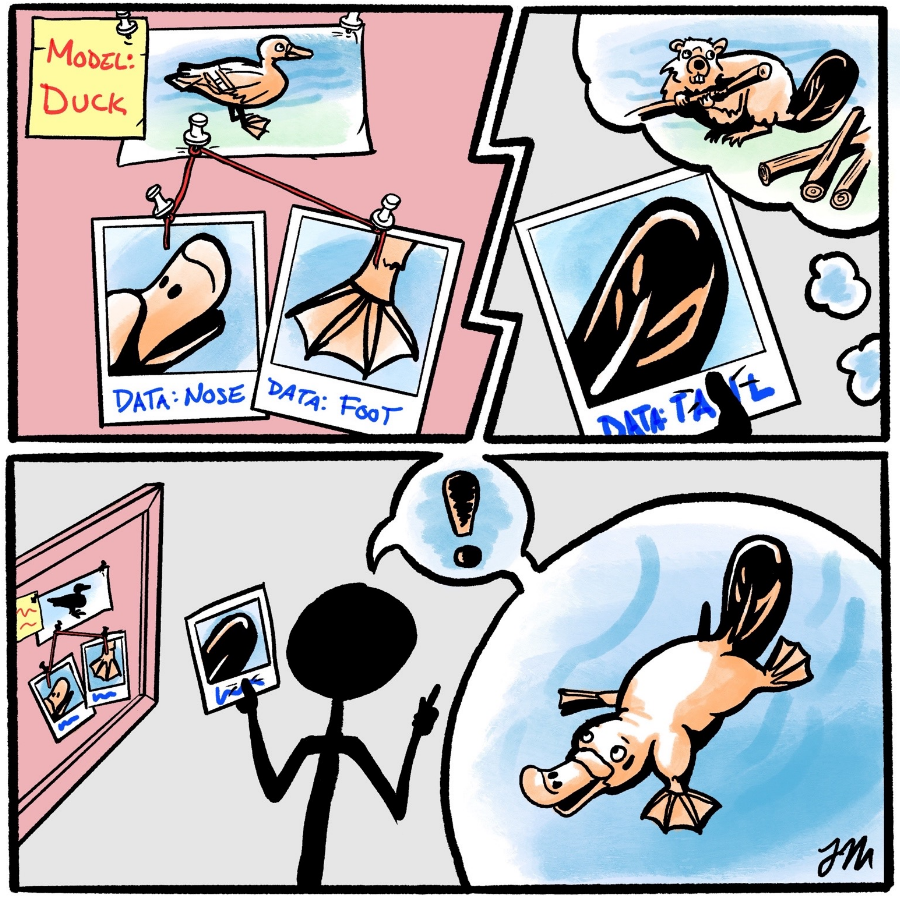
DES Collab. [inc. JM] 2021, PRD, arXiv:2105.13549



ACT Collab. 2023, arXiv:2304.05203

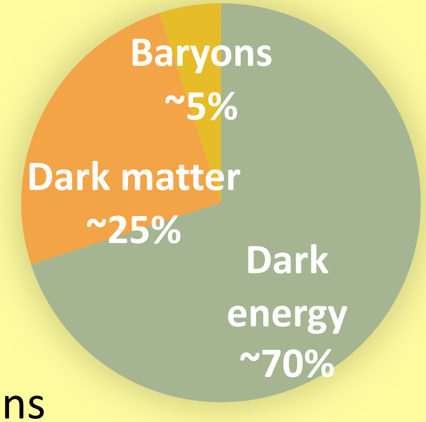
Testing models beyond ΛCDM

- Explore what kinds of physics could explain tensions
- Seek hints of new physics that don't yet show up as tensions

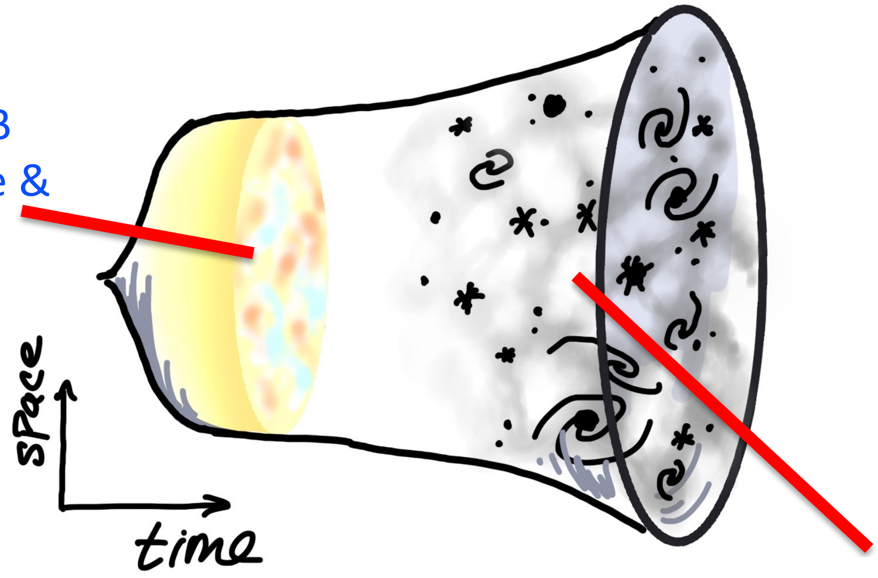


MODEL: ΛCDM

- Λ: cosmological constant dark energy
- CDM: cold dark matter
- General relativity
- Flat geometry
- Gaussian initial fluctuations

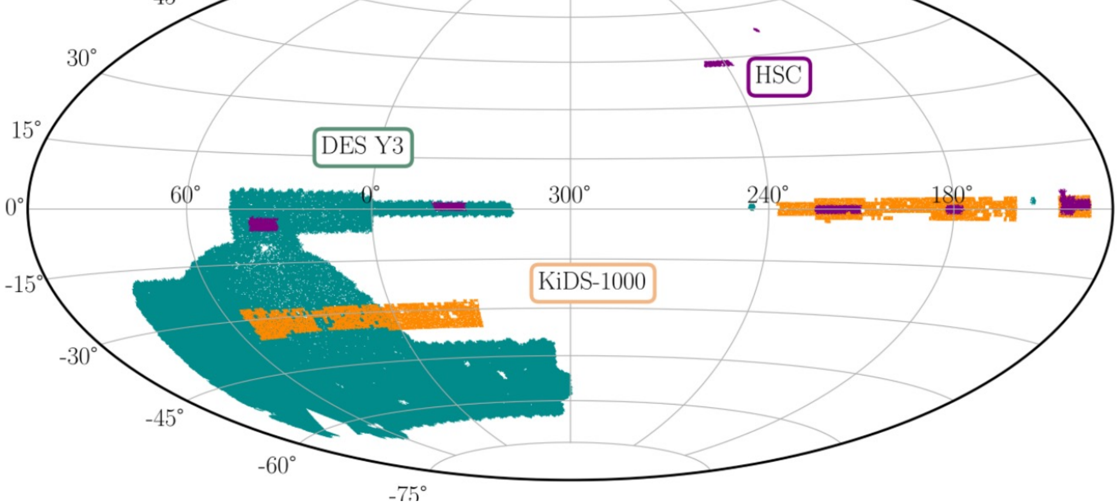


Data: CMB temperature & polarization fluctuations

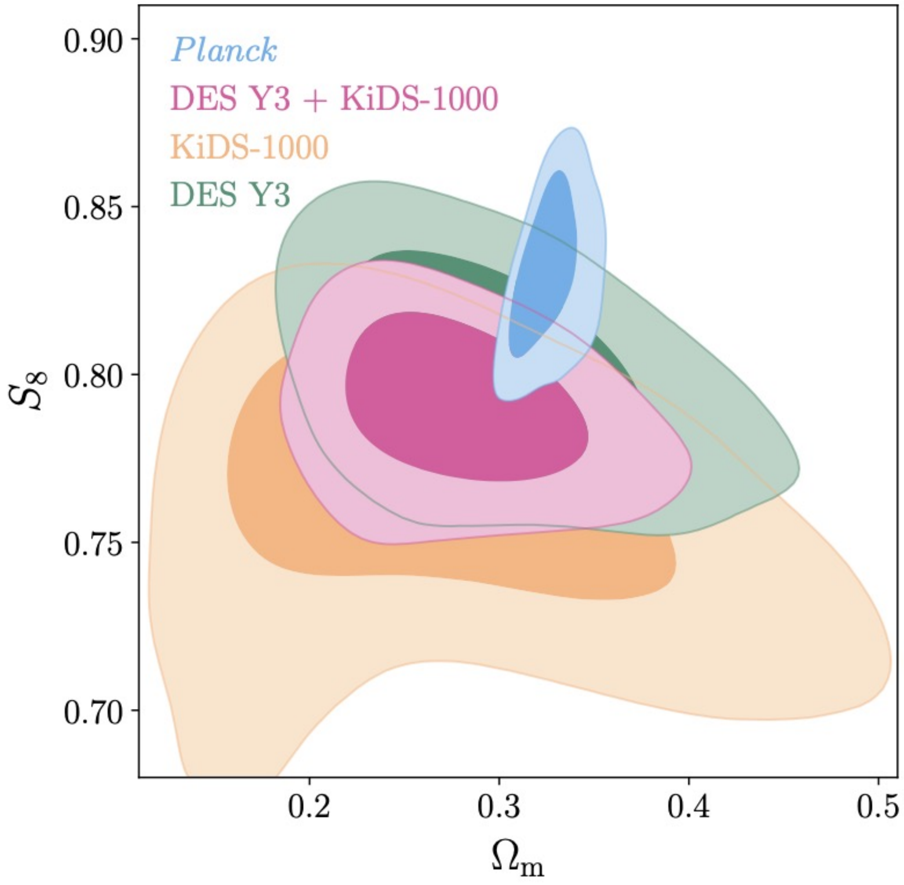


Data: The distribution of matter in the late Universe probed by galaxy surveys

Testing models beyond-ΛCDM is *not* a replacement for understanding data, improving precision & accuracy.



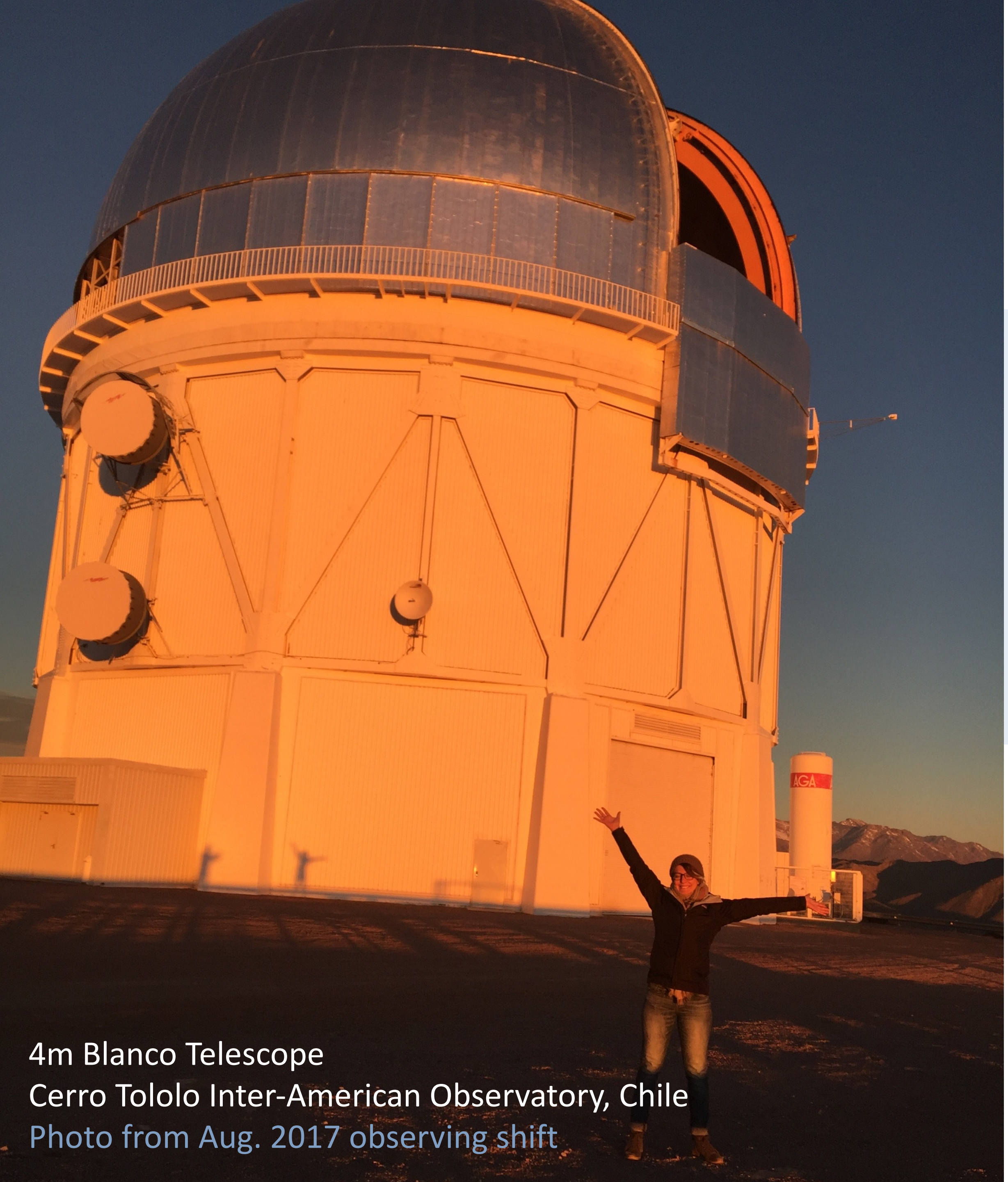
Increasing data precision → more stringent accuracy requirements



DES+KIDS cosmic shear combined analysis

- Methodology validated for each survey separately, but faced with combined-data constraining power, both KiDS and DES pipelines failed accuracy requirements.
- Team of members of both collab's developed "hybrid" model which was more robust in simulated analyses.
- Most impactful modeling choices:
  - Modeling of intrinsic alignments (astrophysical systematic)
  - Method for computing nonlinear matter power spectrum
- Final S_8 result 1.7σ from Planck

DES & KiDS Collabs. [inc. JM] 2023, arXiv:2305.17173



4m Blanco Telescope
Cerro Tololo Inter-American Observatory, Chile
Photo from Aug. 2017 observing shift

DARK ENERGY SURVEY

The Dark Energy Survey (DES)

- **Imaging survey 2013-2019**
  - 758 nights observing, 4M Blanco telescope @ CTIO
  - 5000 deg^2, ~10% of sky
  - 400+ participants
  - Probes include: Weak lensing, galaxy clustering, SNe, galaxy clusters, Milky Way satellites, …
- **Y3 galaxy clustering and weak lensing**
  - Full 5000 deg2 at ~50% depth
  - ΛCDM, wCDM cosmology: **DES Collab. 2022, PRD, arXiv:2105.13549**
- **Legacy Y6 analysis (full dataset) underway**

Funding

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Member institutions

NCSA · THE OHIO STATE UNIVERSITY · ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich · LMU · SLAC · BERKELEY LAB · UNIVERSITY OF MICHIGAN

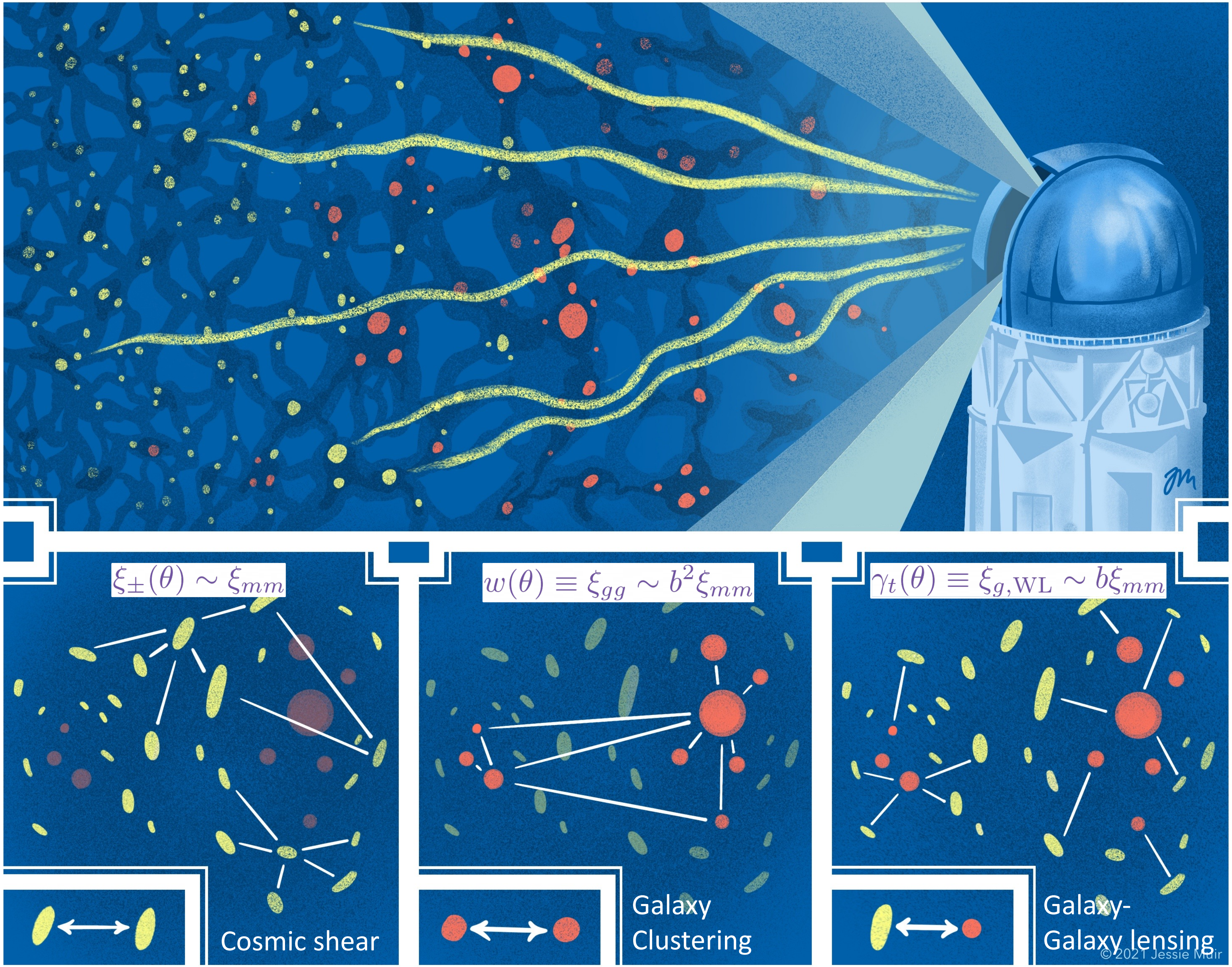
Weak lensing:
0.1% distortions of apparent galaxy shapes due to line-of-sight structure

Galaxy clustering:
Galaxy density traces matter density

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

b = galaxy bias

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



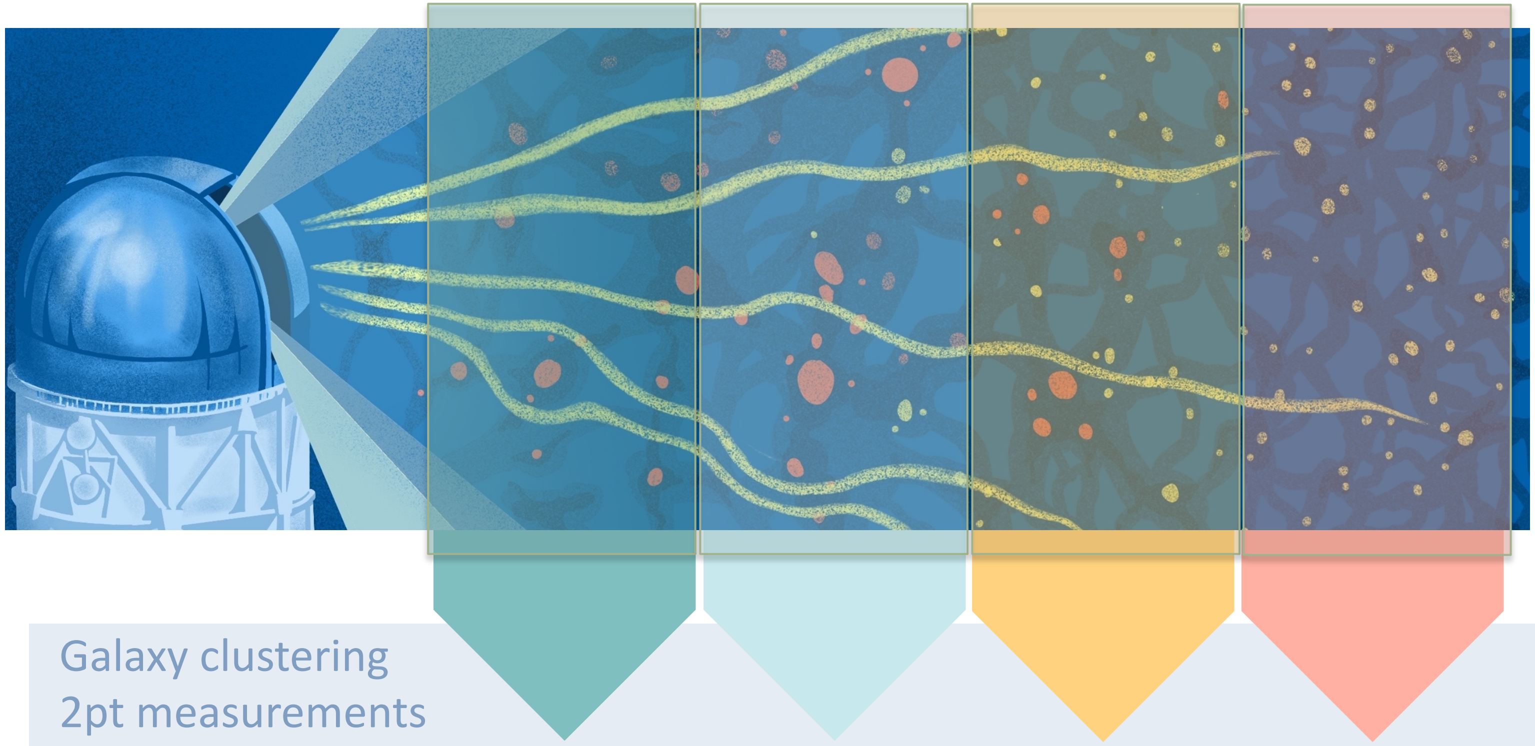
3x2pt analysis:
combined study of these three kinds of 2pt functions

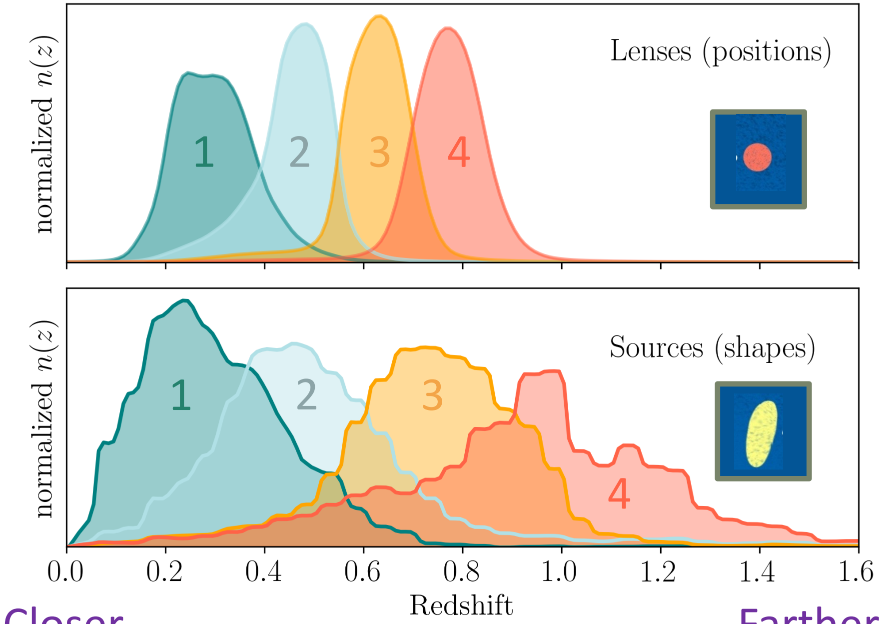
2pt functions:
correlation of signal (galaxy shapes, positions) vs separation on sky

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

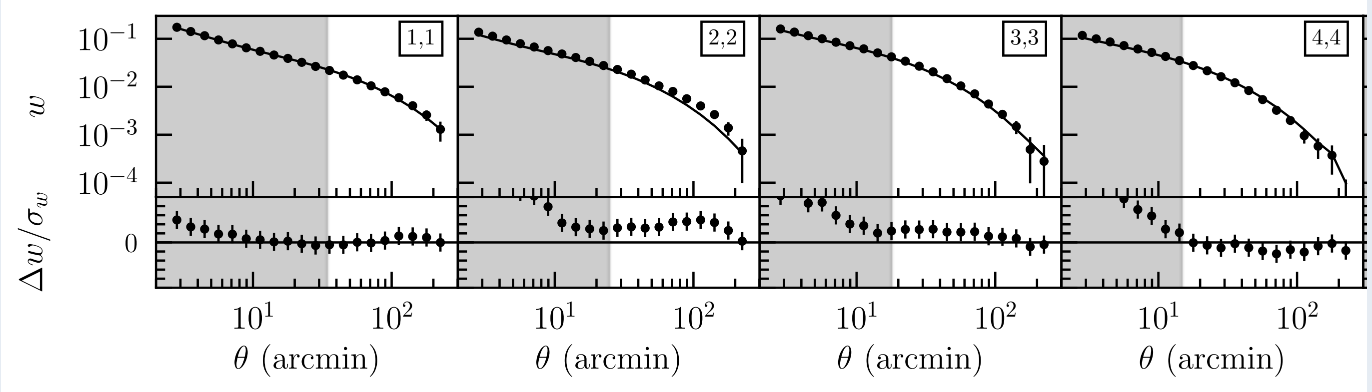
DES Y3 Measurements

- Lens sample
  - 7.6M galaxy positions
  - 4 redshift (line-of-sight) bins
- Weak lensing sources
  - 100M galaxy shapes
  - 4 redshift (line-of-sight) bins





Galaxy clustering
2pt measurements



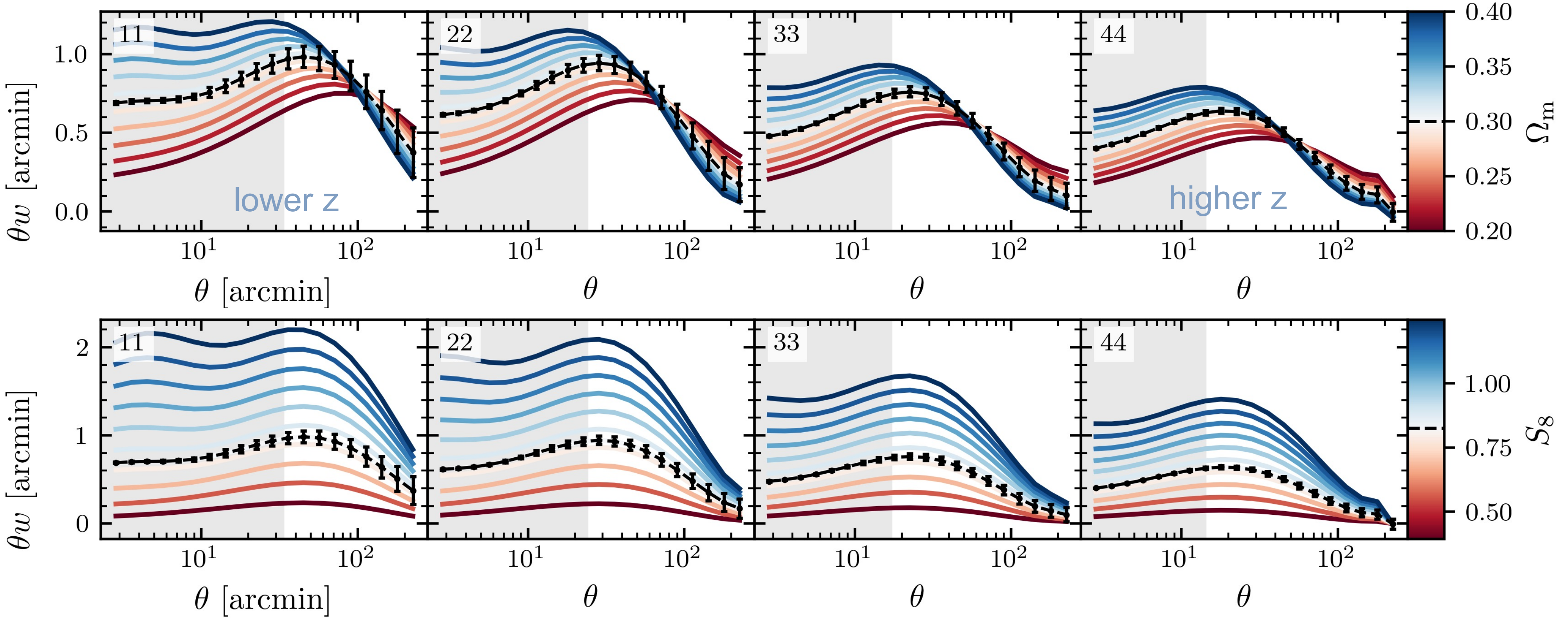
Closer

DES Collaboration 2022, arXiv:2105.13549

Farther

We constrain parameters by comparing predictions to 2pt measurements.

Model predictions for galaxy clustering angular 2pt correlations



For precise *AND* accurate cosmology

Marginalize over
- Photo-z uncertainties
- Linear galaxy bias
- Intrinsic alignments
- Shear calibration

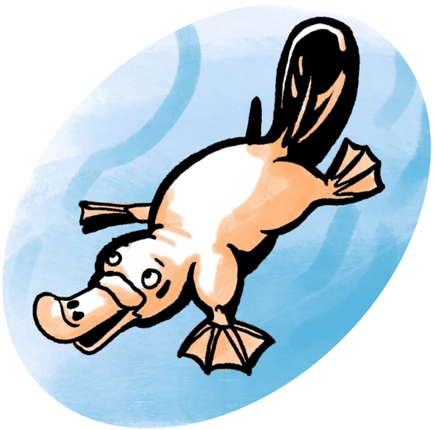
Scale cuts reduce sensitivity to
- Baryonic feedback
- Non-linear galaxy bias
- Uncertainties in nonlinear P(k)

Blind analysis @ multiple levels
- Shear catalog
- Summary statistics
- Cosmology parameters

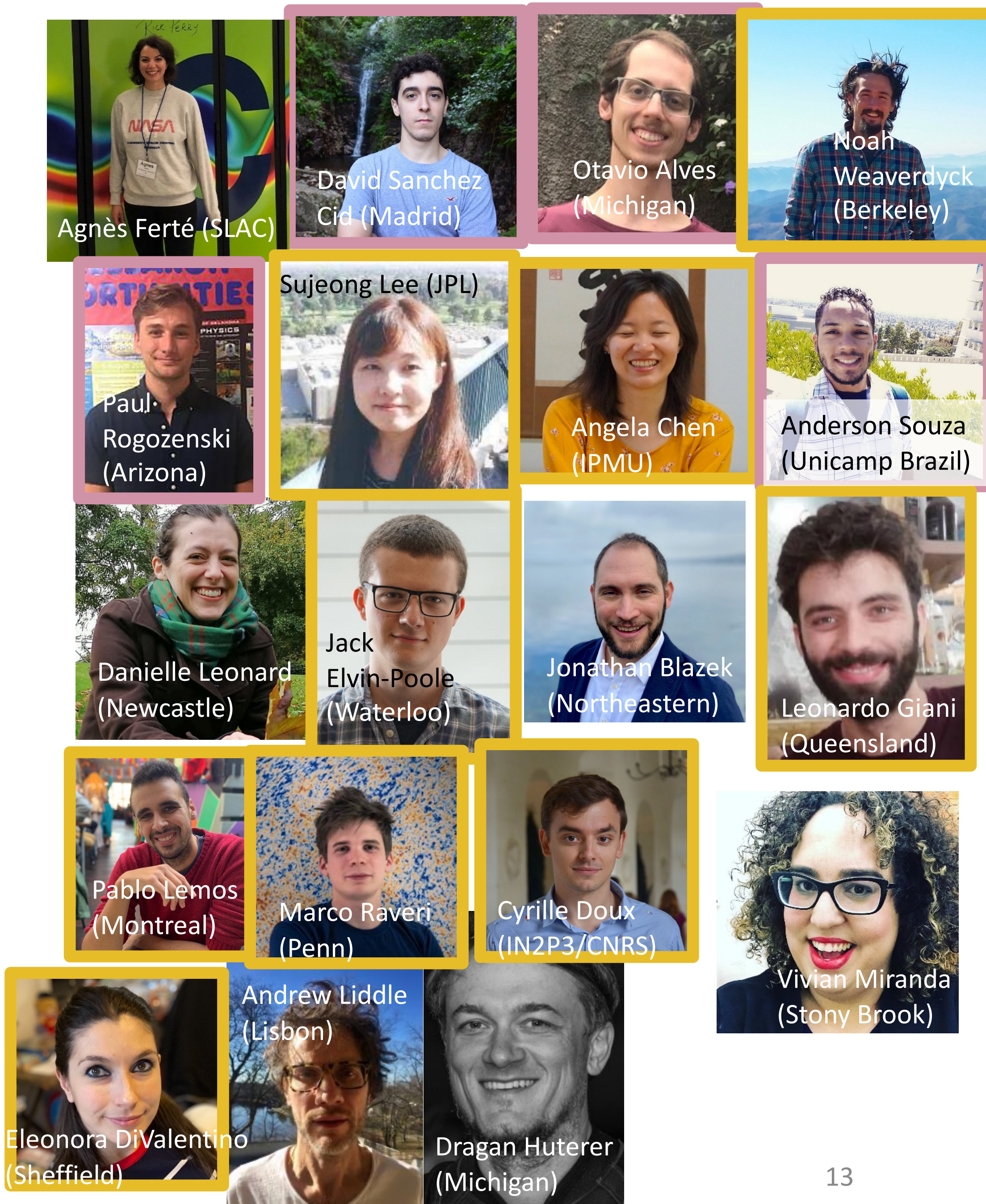
Bayesian analysis of 462 measurements, sampling 31 parameters (6 cosmology, 25 nuisance)

DES Y3 beyond-ΛCDM cosmology

- DES Collab. PRD April 2023, arXiv:2207.05766
  - No significant deviations from ΛCDM
  - Public data: https://dev.des.ncsa.illinois.edu/releases/y3a2/Y3key-extensions
- Analysis 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



Grad students postdocs



Modified gravity

Poisson Eq.

Newtonian potential → $$\Psi = -\frac{4\pi G \rho_m}{(1+z)^2 k^2}\,[1+\mu(z)]\,\delta$$

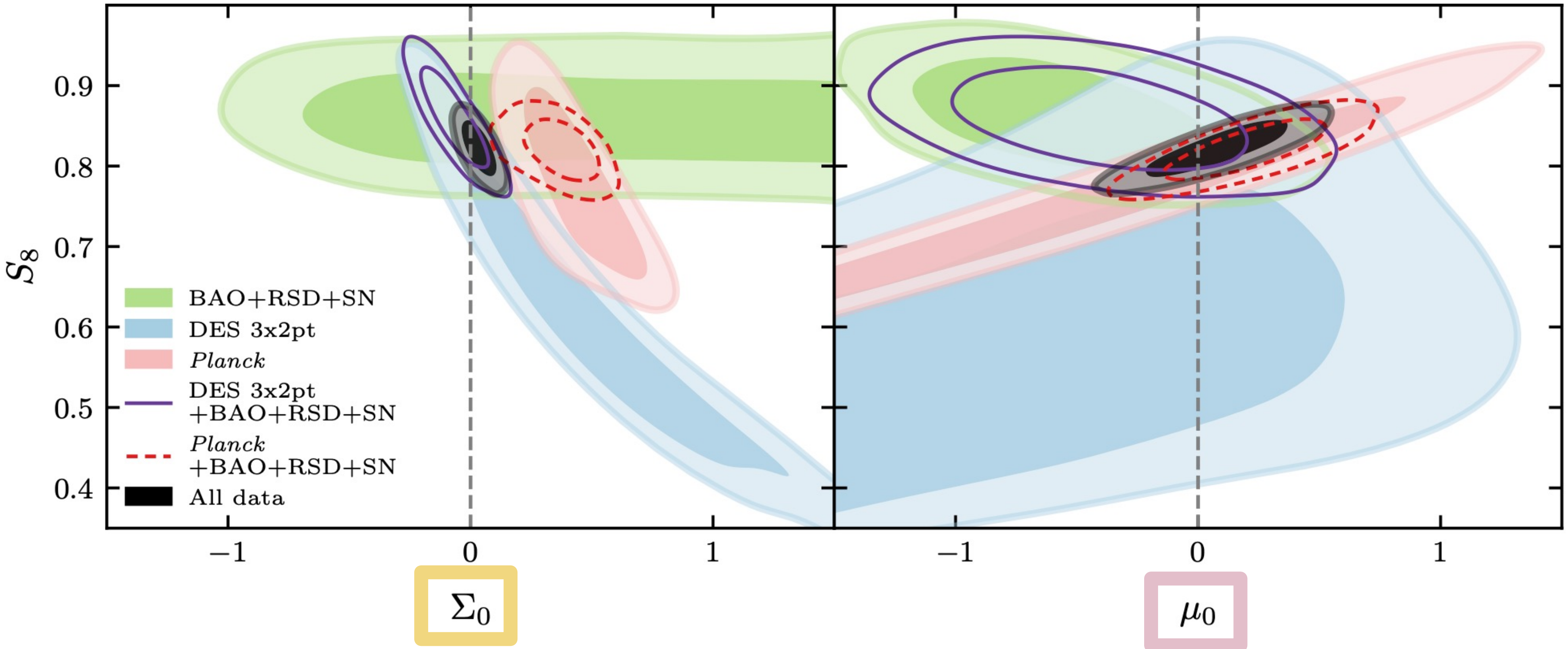
Lensing potential → $$\Phi = -\frac{8\pi G \rho_m}{(1+z)^2 k^2}\,[1+\Sigma(z)]\,\delta$$

Matter over-density (δ)

Assume modifications' time dependence follows accelerated expansion

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

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



DES Collaboration [inc. JM] 2023, PRD arXiv:2207.05766

Challenge: non-linear modeling

DES Y3 constraints don't improve on Y1 despite 3x more data. ***Why?***

Linear Scale cuts!

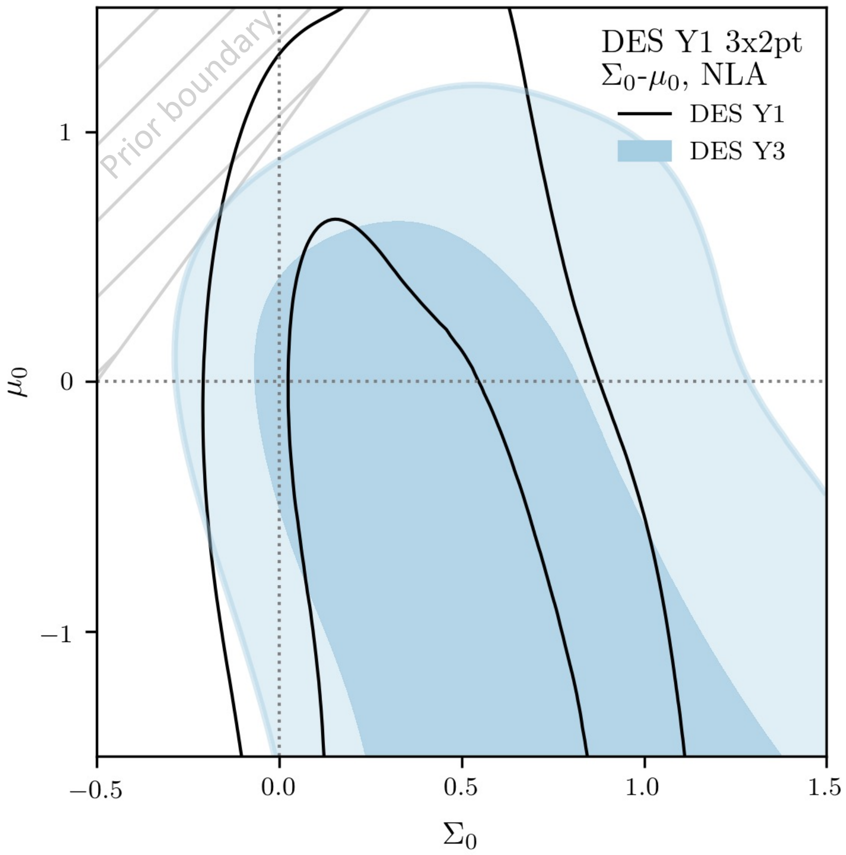
$$\text{DES Y3: } \Sigma_0 = 0.56^{+0.37}_{-0.48}$$

$$\text{DES Y1: } \Sigma_0 = 0.43^{+0.28}_{-0.29}$$

- DES ΛCDM analyses use halo-model-based tools that are not validated for many beyond-ΛCDM models
  - Halofit (Takahashi+Bird) – DES Y1, Y3
  - HMCode2020 – DES Y6
- So: We remove data sensitive to nonlinear modeling
  - Cuts defined by iteratively removing datapoints from 3x2pt measurements until $\Delta\chi^2<1$.

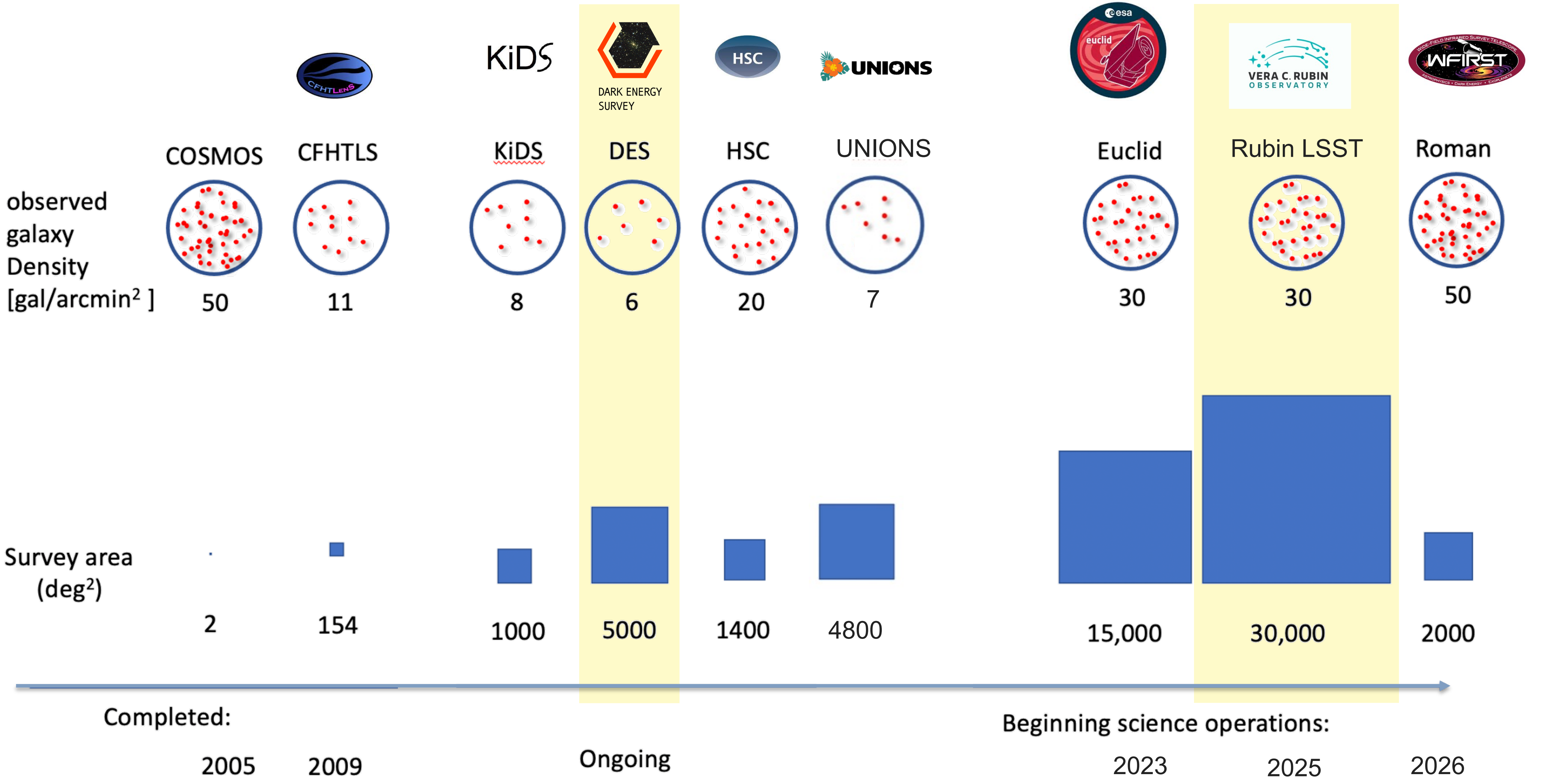
$$\Delta\chi^2 \equiv \left(\mathbf{D}_{\rm NL} - \mathbf{D}_{\rm lin}\right)^{\rm T} \mathbf{C}^{-1} \left(\mathbf{D}_{\rm NL} - \mathbf{D}_{\rm lin}\right)$$

  - Y3 uses 256/462 measurements
  - Y1 uses 334/457 measurements



Y3 - DES Collab. arXiv:2207.05766
Y1 - DES Collab. arXiv:1810.02499

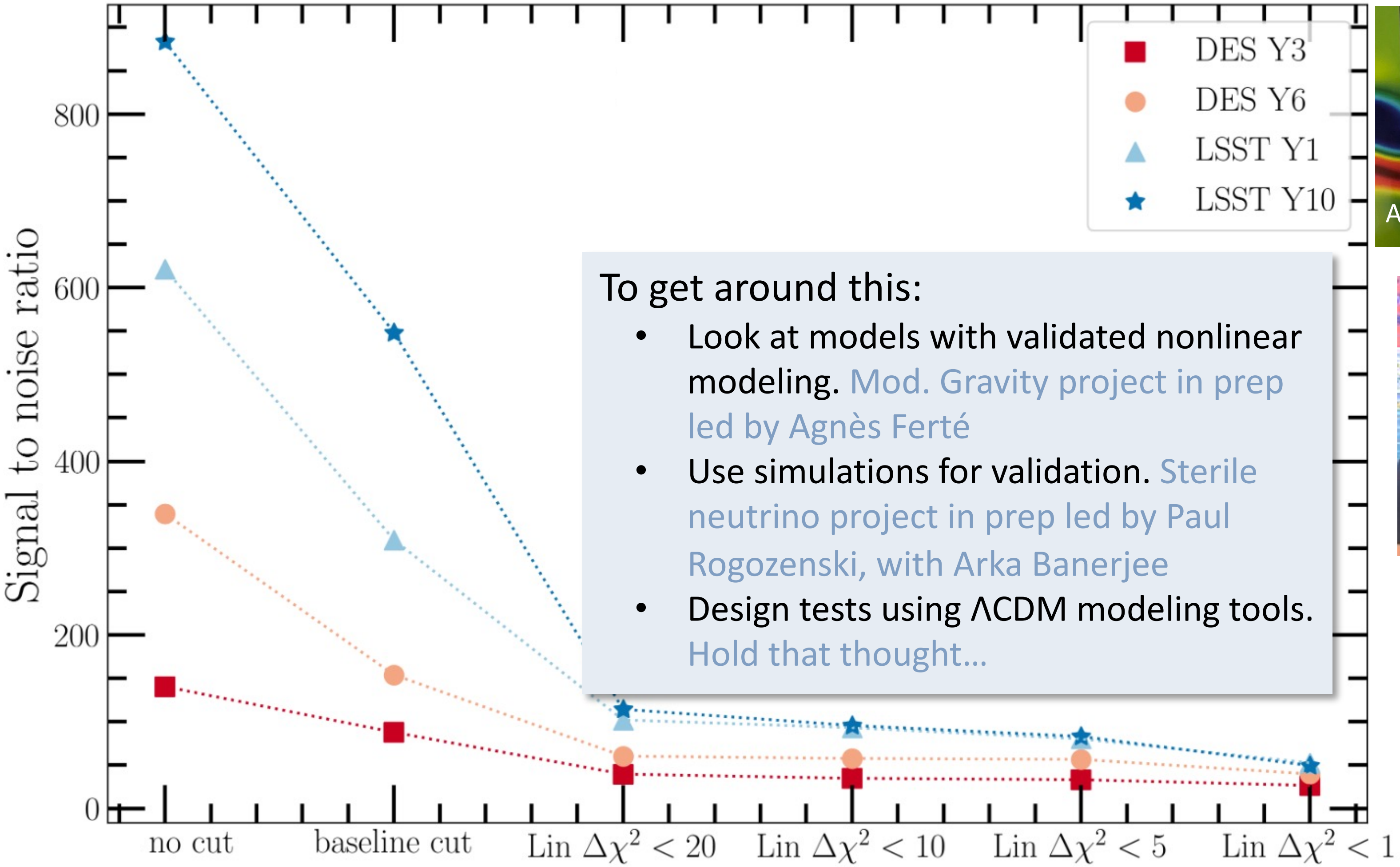
In context with other imaging surveys



Removing non-linear scales throws away a lot of information, and this will get worse with more precise data.

Forecasts for 3x2pt analyses

Plot by Yi Wang
(Undegrad @ Dalhousie
->PhD student @ Duke this fall)



different thresholds for defining linear cuts

To get around this:

- Look at models with validated nonlinear modeling. Mod. Gravity project in prep led by Agnès Ferté
- Use simulations for validation. Sterile neutrino project in prep led by Paul Rogozenski, with Arka Banerjee
- Design tests using ΛCDM modeling tools. Hold that thought…

Agnès Ferté (SLAC)

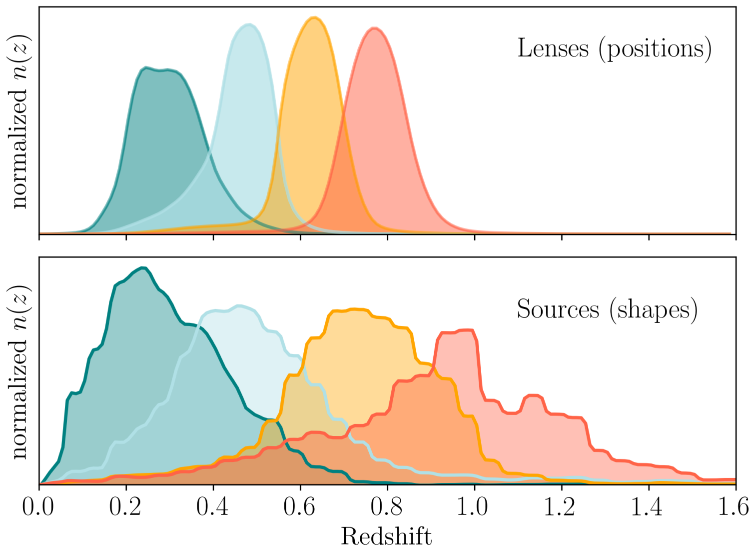
Paul Rogozenski (grad student @ Arizona)

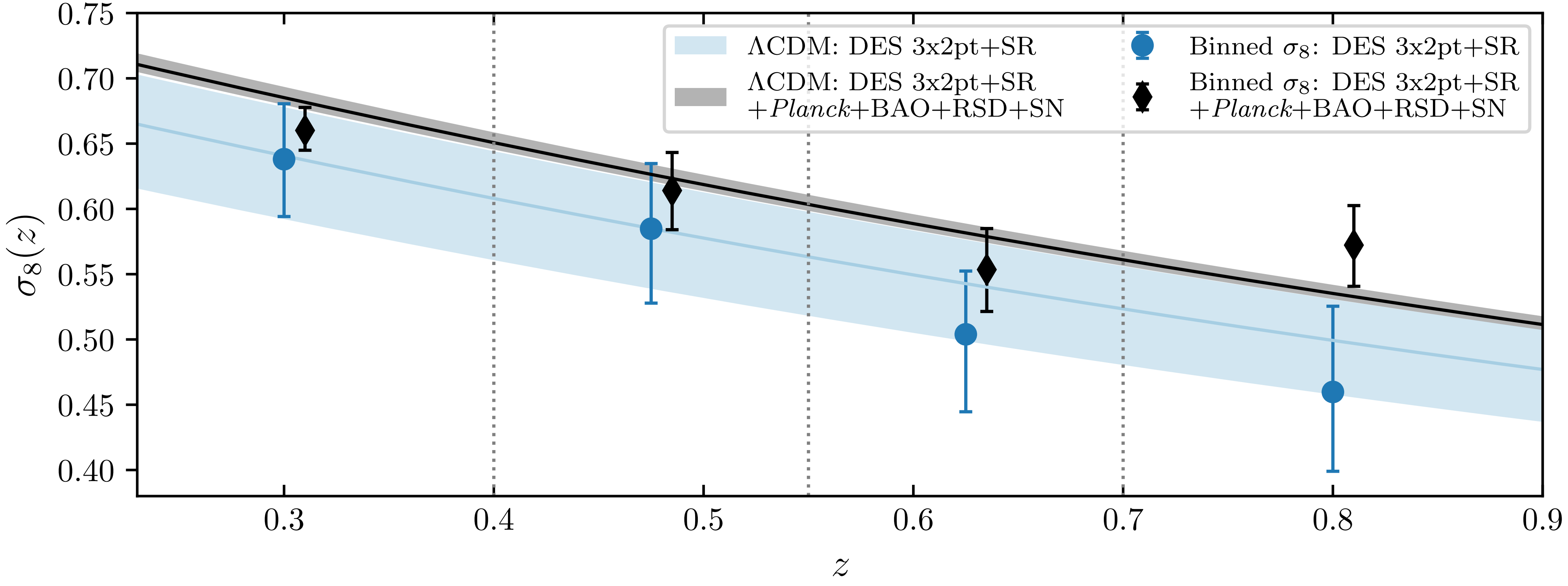
Arka Banerjee (IISER-Pune)

Binned $\sigma_8(z)$: Is large-scale structure growth over time consistent with ΛCDM?

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

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





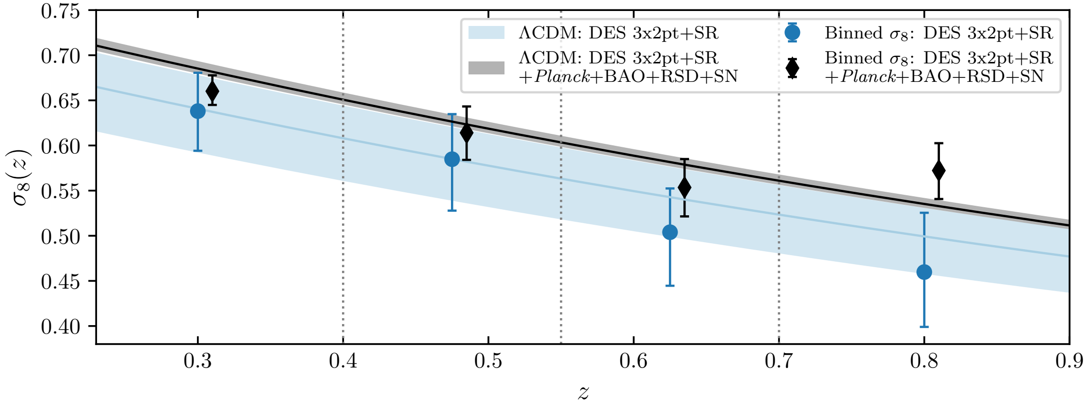
Developed with
Anderson Souza
PhD@Unicamp Brazil

DES Collaboration [inc. JM] 2023, PRD arXiv:2207.05766

Hints at slow growth at late times?

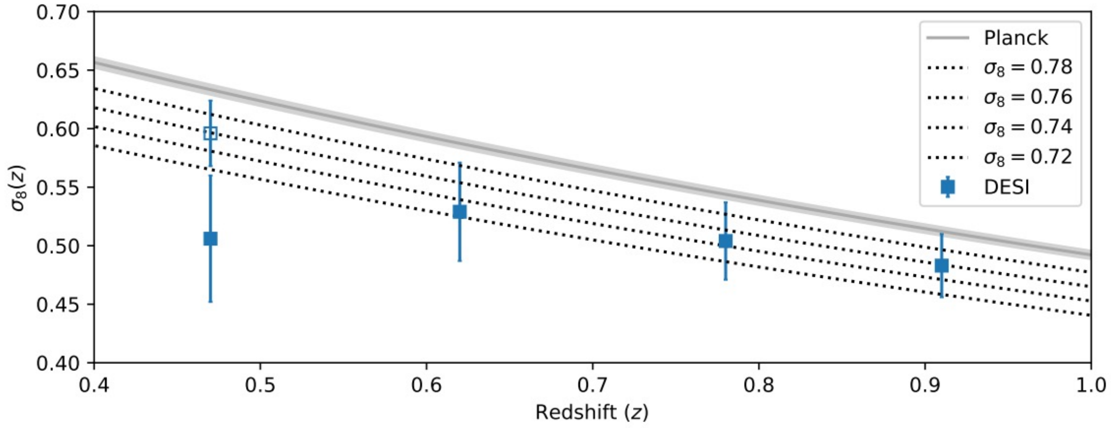
DES Collaboration [inc. JM] 2023, PRD arXiv:2207.05766

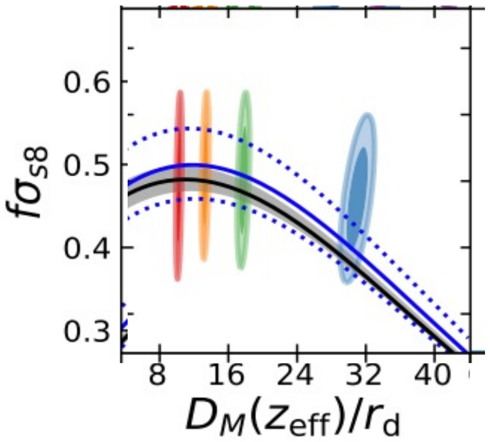
DES Y3, Planck 2018 primary CMB, BOSS/eBOSS BAO+RSD, Pantheon SNe



White et al, 2022, JCAP 2022 arXiv:2111.09898

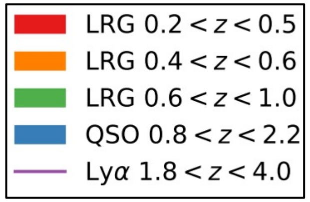
DESI LRG imaging data x CMB lensing





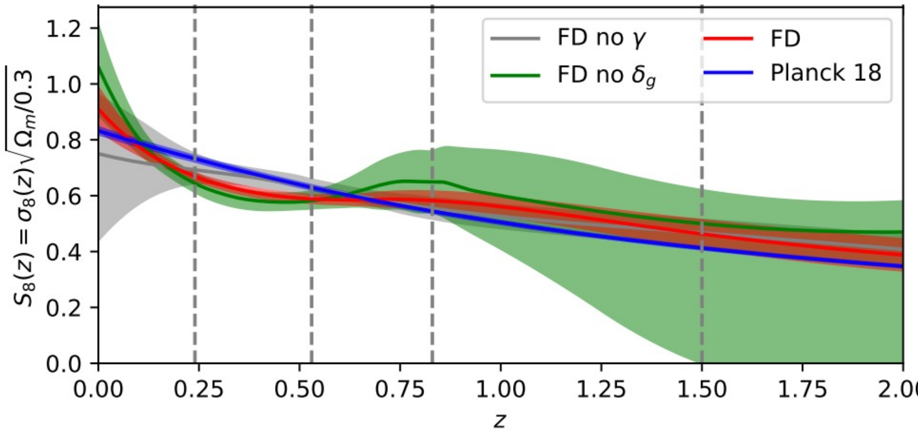
Brieden, Gil-marin, Verde 2022, JCAP arxiv:2204.11868

BOSS, eBOSS BAO+RSD



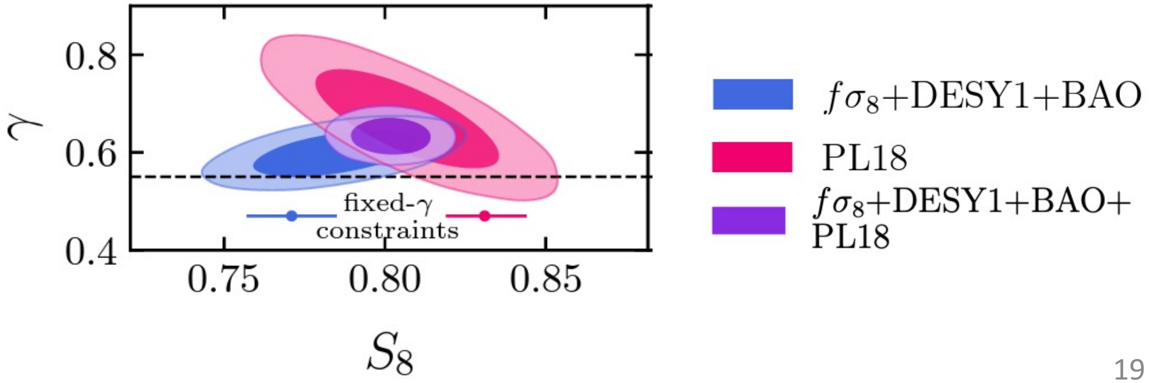
Garcia-Garcia et al, 2021, JCAP, arXiv:2105.12108

DES Y1, KiDS 450, CMB lensing, eBOSS QSO



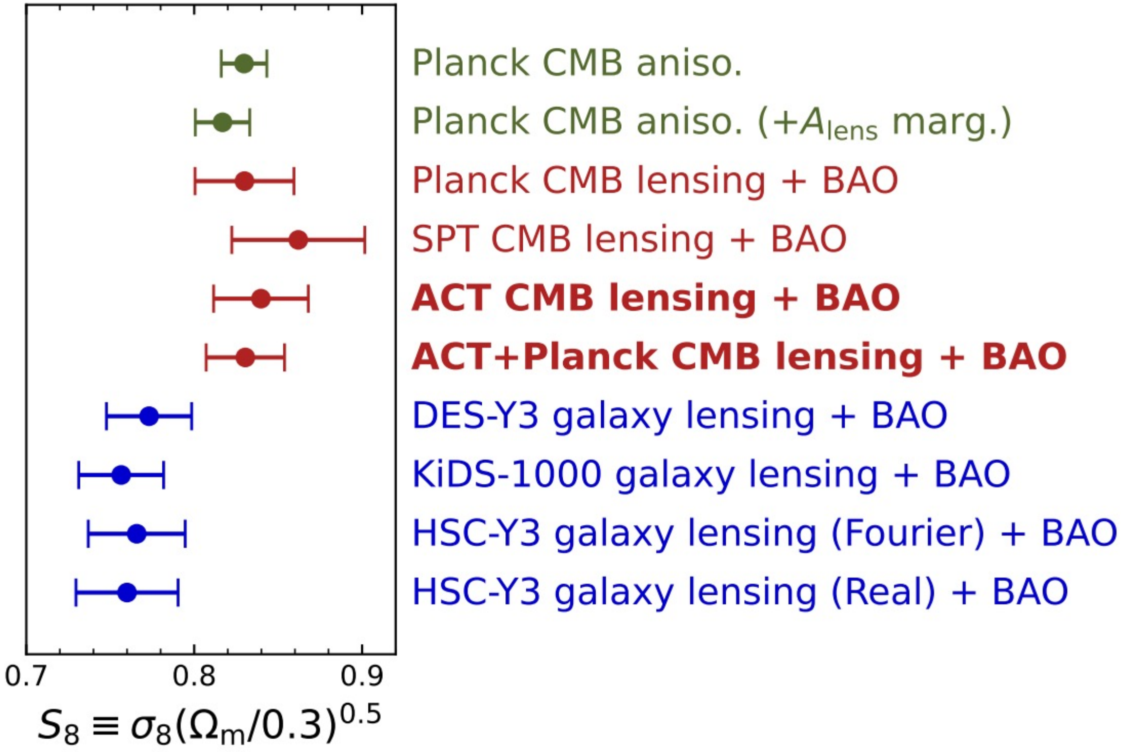
Nguyen, Huterer, & Wen, 2023 PRD, arXiv:2302.01331.

Planck 2018 primary CMB, DES Y1 3x2pt, 6DFGS+SDSS BAO, RSD & Pec. Vel.

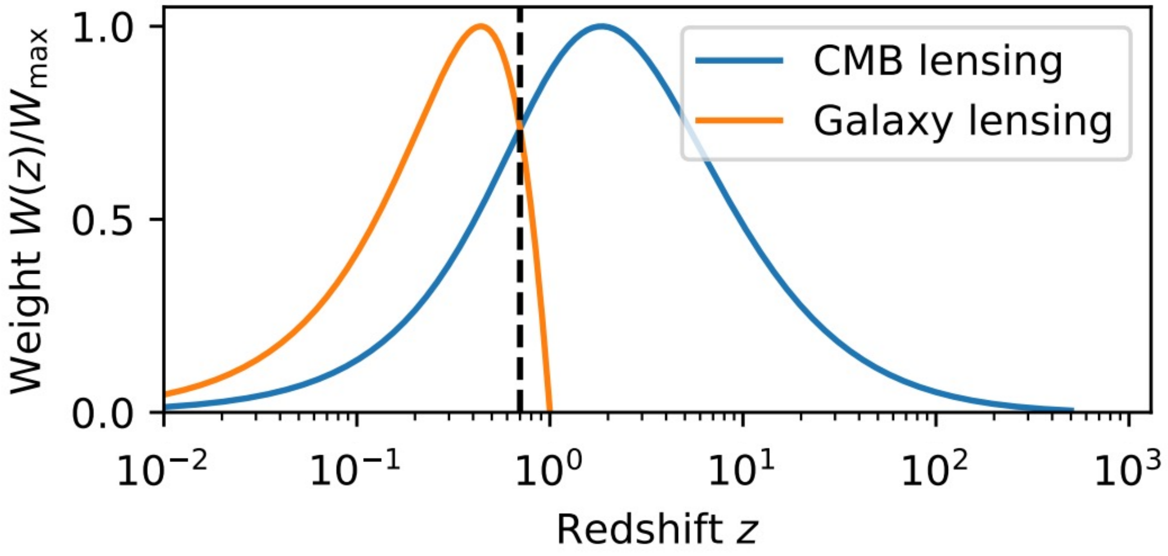


Designing a targeted phenomenological test, with CMB Lensing

ACT Collab. 2023, arXiv:2304.05203



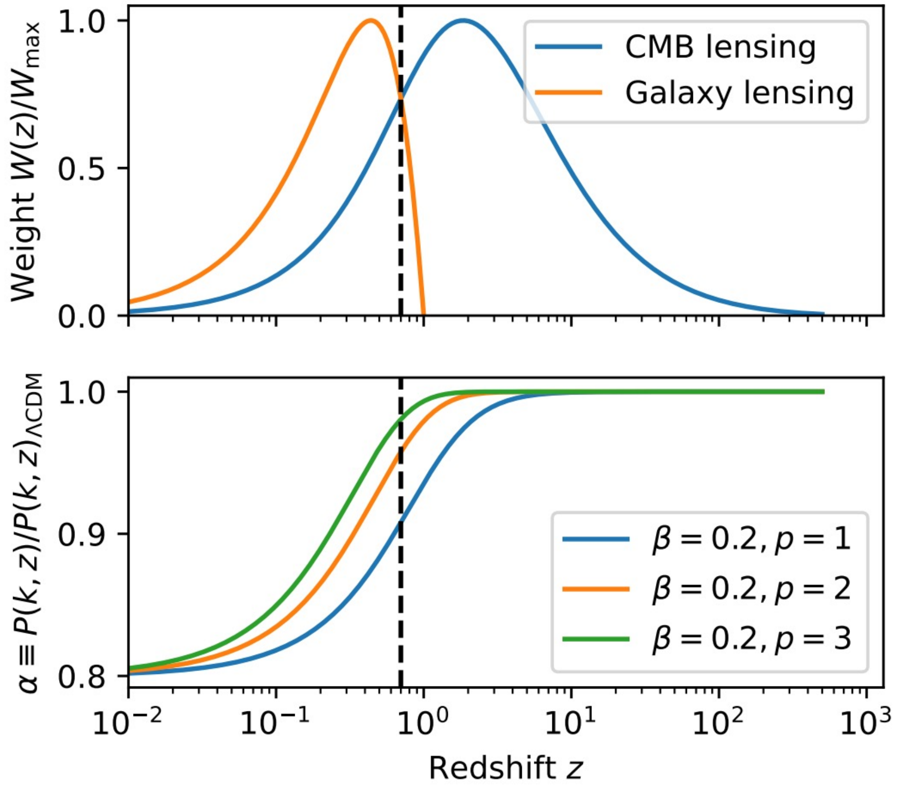
Lensing kernels:
Which redshifts contribute to lensing signals



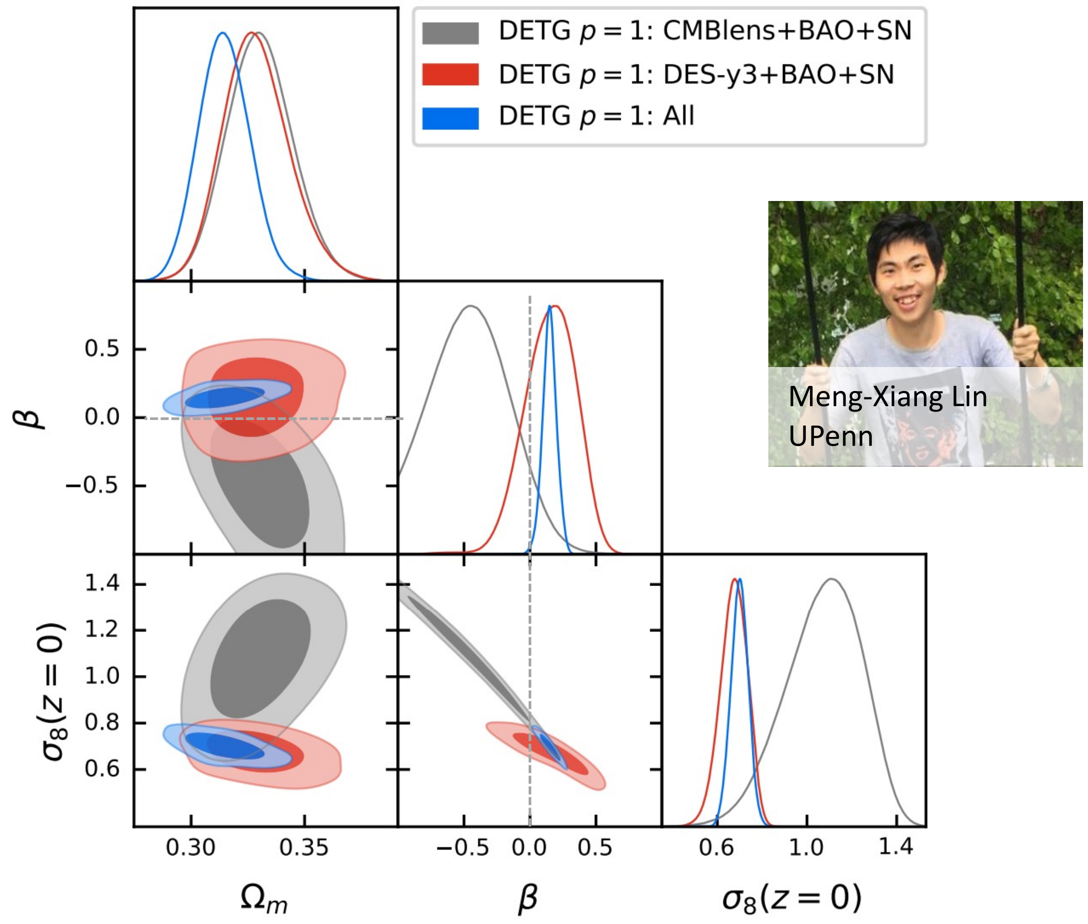
Lin et al [inc. JM] 2023, arXiv:2308.16183

Is growth suppressed in the dark energy dominated era relative to ΛCDM expectations?

$$\alpha(z) \equiv \frac{P(k,z)}{P(k,z)_{\Lambda\mathrm{CDM}}} = 1 - \beta \left(\frac{\Omega_{\mathrm{DE}}(z)}{\Omega_{\mathrm{DE}}^{0}} \right)^{p}$$



Lin et al [inc. JM] 2023, arXiv:2308.16183

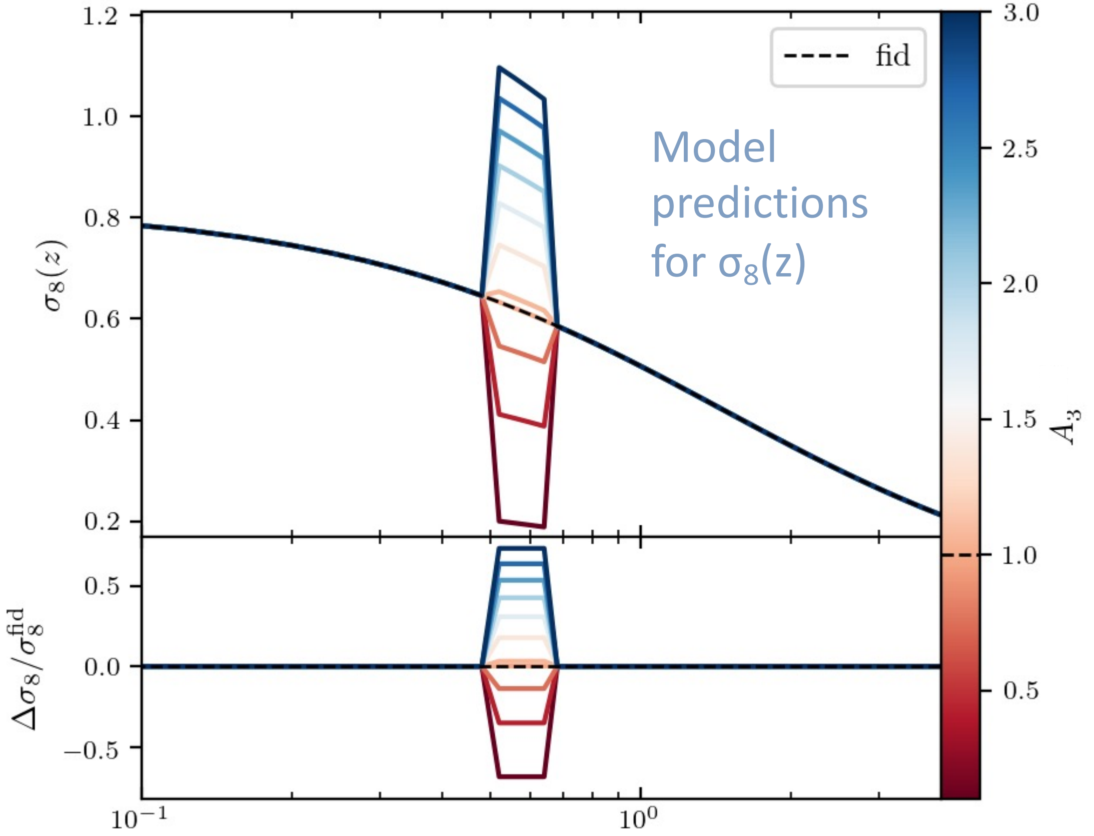


Maybe!

- For "all" data: Improvement of $\Delta\chi^2 \sim 7$, varying β, fixed p=1
- 2-3σ preference for β>0 based on 1D marginalized posteriors
- Worth further investigation: projection effects, S_8 behavior

Ongoing project highlight:

Motivation from odd results during $\sigma_8(z)$ validation

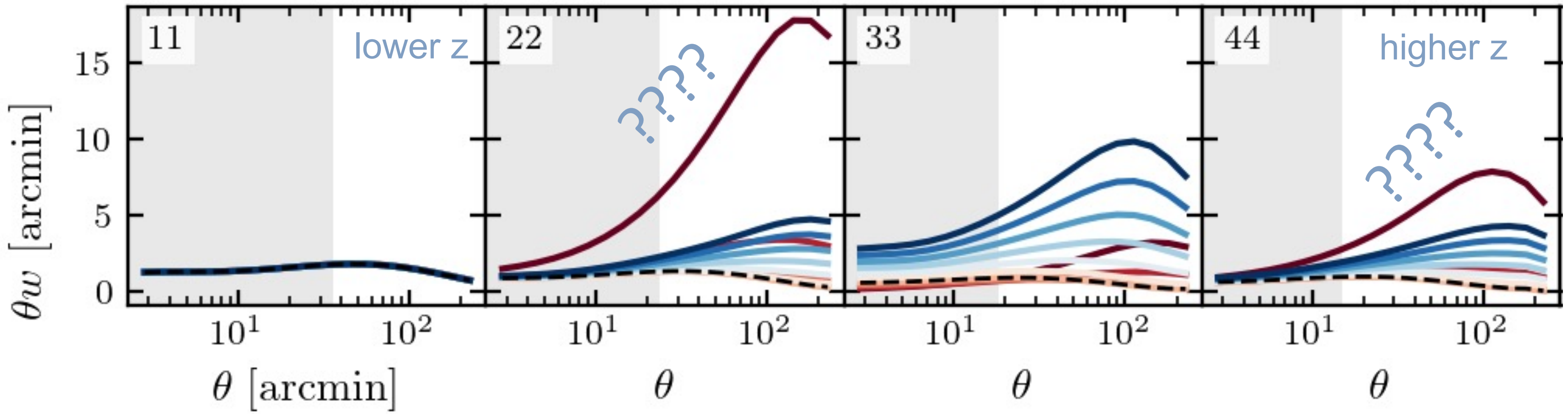


For each redshift bin i

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

$$\sigma_8^{[\mathrm{bin}\ i]} \equiv \sigma_8 \sqrt{A_i}$$

Model predictions for galaxy clustering



The culprit: RSD contributions to photometric clustering

Newly required by DES Y3 precision

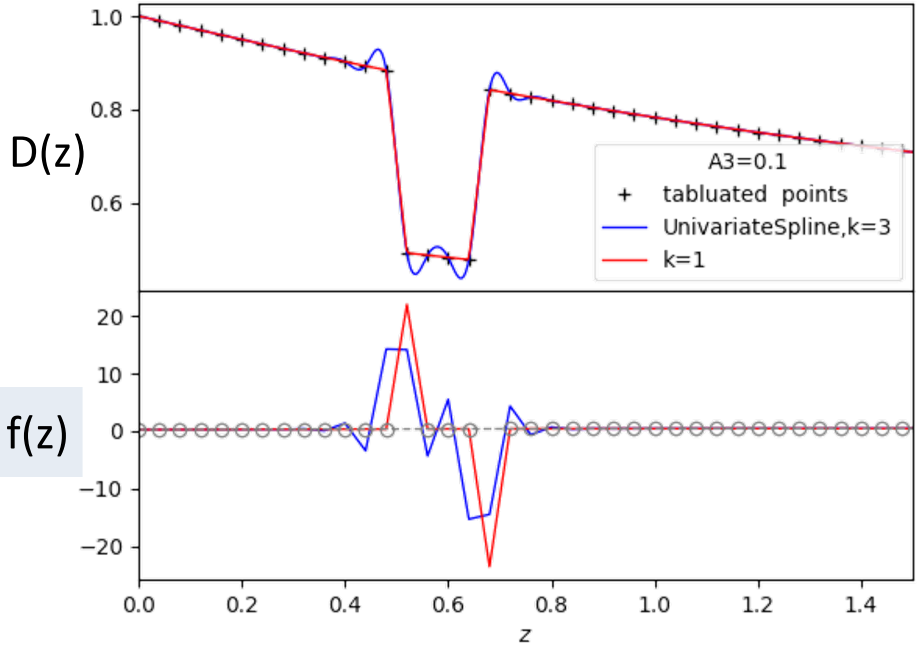
$$f = \frac{d\ \ln D}{d\ \ln a}$$

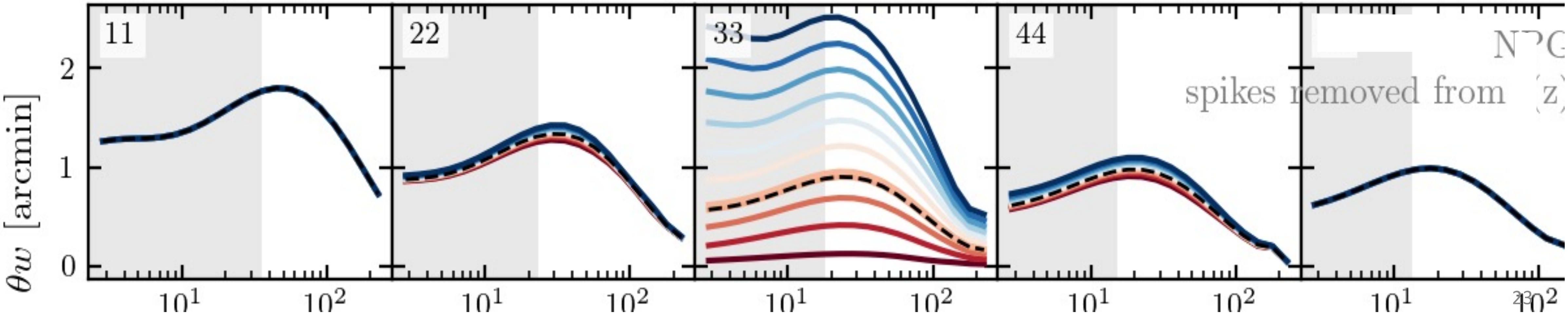
$$C_\ell^{gg} = \frac{2}{\pi}\int_0^\infty \frac{dk}{k} k^3 P_\Phi(k)\Delta_\ell^g(k, z_1)\Delta_\ell^g(k, z_2)$$

$$\Delta_\ell^g = \Delta_\ell^D + \Delta_\ell^{RSD} + \Delta_\ell^M$$

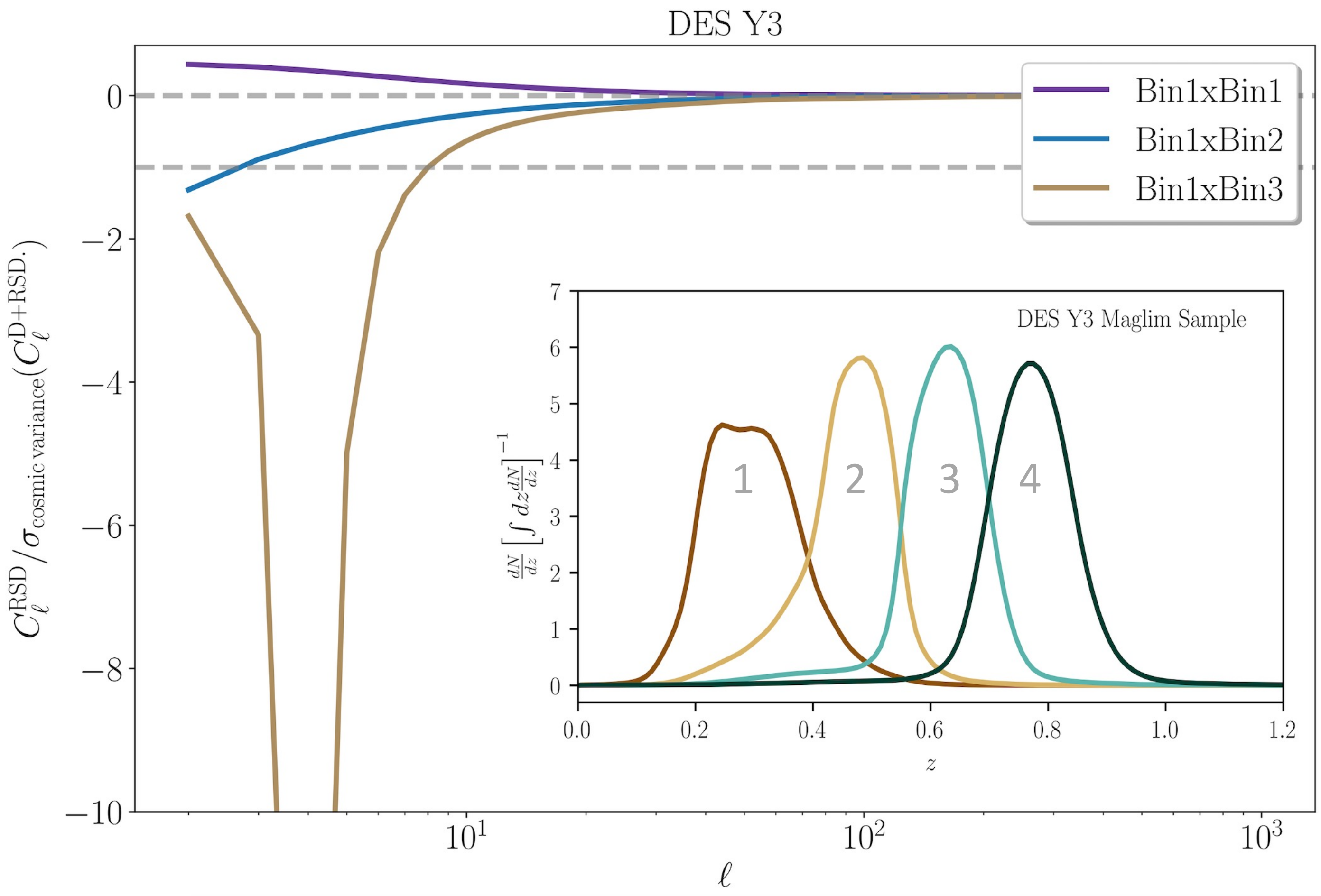
$$\Delta_\ell^{RSD}(k) = -\int dz\, n(z) f(z) T_\delta(k, z) j_\ell''(k\chi(z))$$

Fang et al 2020, JCAP arXiv:1911.11947





Accounting for RSD in photometric galaxy clustering: Can we extract additional growth information by adding cross-bin correlations?



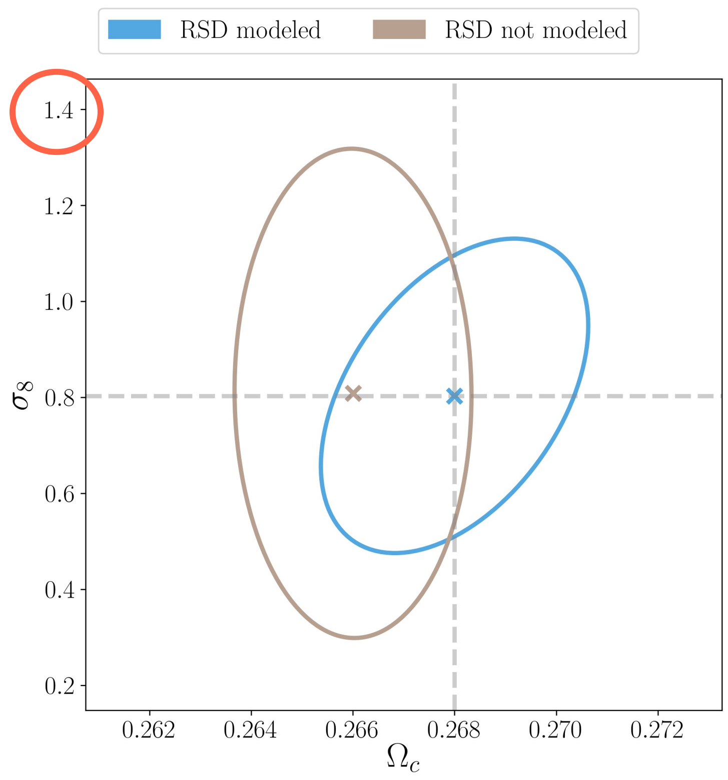
- DES analyses have only used auto-correlation measurements of galaxy (position) clustering.
- Most forecasts assessing value of cross-bin correlations haven't accounted for RSD contributions.

With Jordan Krywonos & Matt Johnson
York University / Perimeter

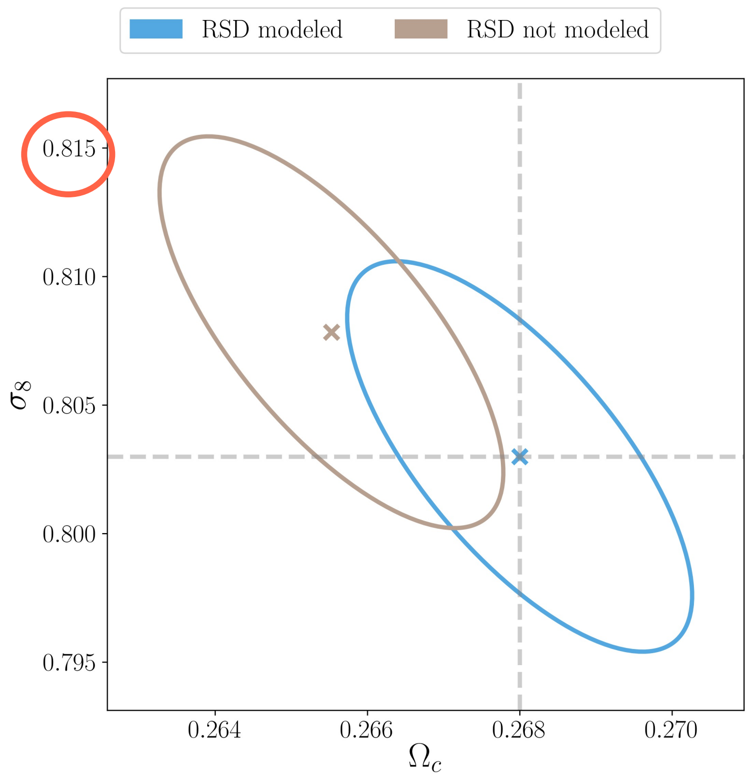
Preliminary results: Fisher forecasts for LSST Y1 galaxy clustering

Auto-correlations only

Note different scale ranges!



All cross-bin correlations



Plots by Jordan Krywonos, grad student @ York

- If analyzing photometric galaxy clustering alone, cross-bin correlations add a ton of information!
  - *(will be less impactful when combined with lensing)*
- Including RSD doesn’t significantly impact gains from “auto only” -> ”all cross”
- Either way, neglecting RSD in our model will bias cosmology results.

Next steps: impact of photo-z uncertainties

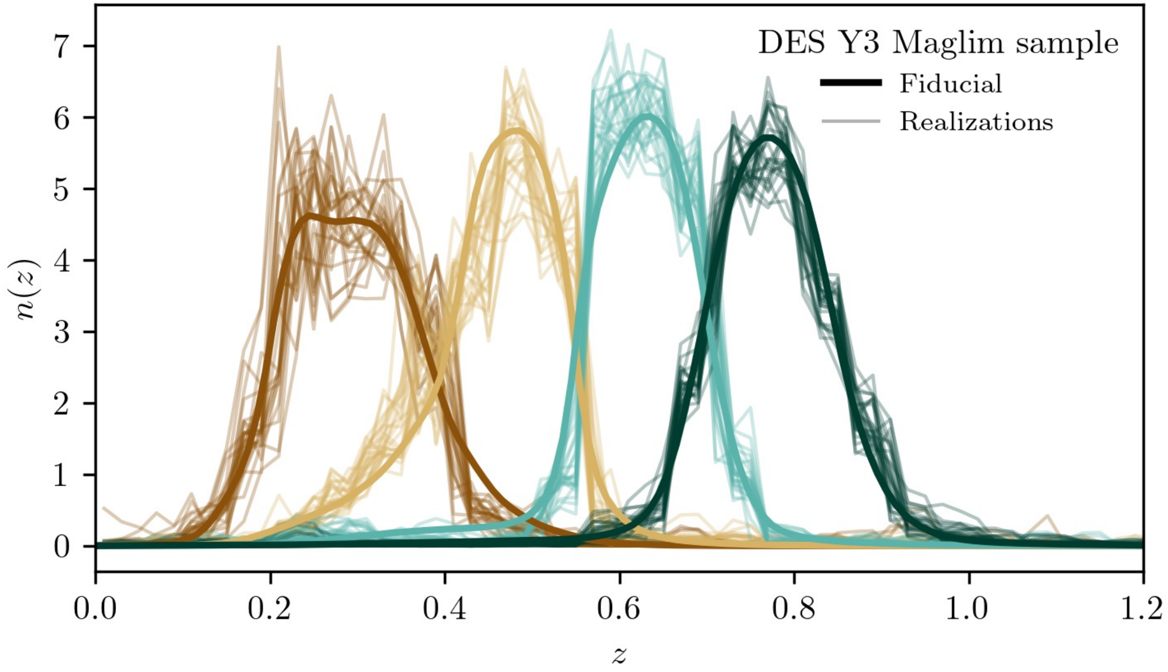
Very schematically,

$$C_\ell^{g_A g_B} \sim \int dz\, n_A(z)\, n_B(z) F(k,z)$$

- Fiducial (auto-only) DES Y3 analysis captures photo-z uncertainties via mean shift nuisance parameters:
  - Δz^A : $n^A(z) \rightarrow n^A(z-\Delta z^A)$
  - Tests show this is sufficient for robust cosmology with only auto correlations.

- Cross-bin correlations will have greater sensitivity to shape of n(z), especially distribution tails.

- Ongoing work
  - forecast, study biases due to variations in n(z) shape.
  - Extend forecasts beyond ΛCDM

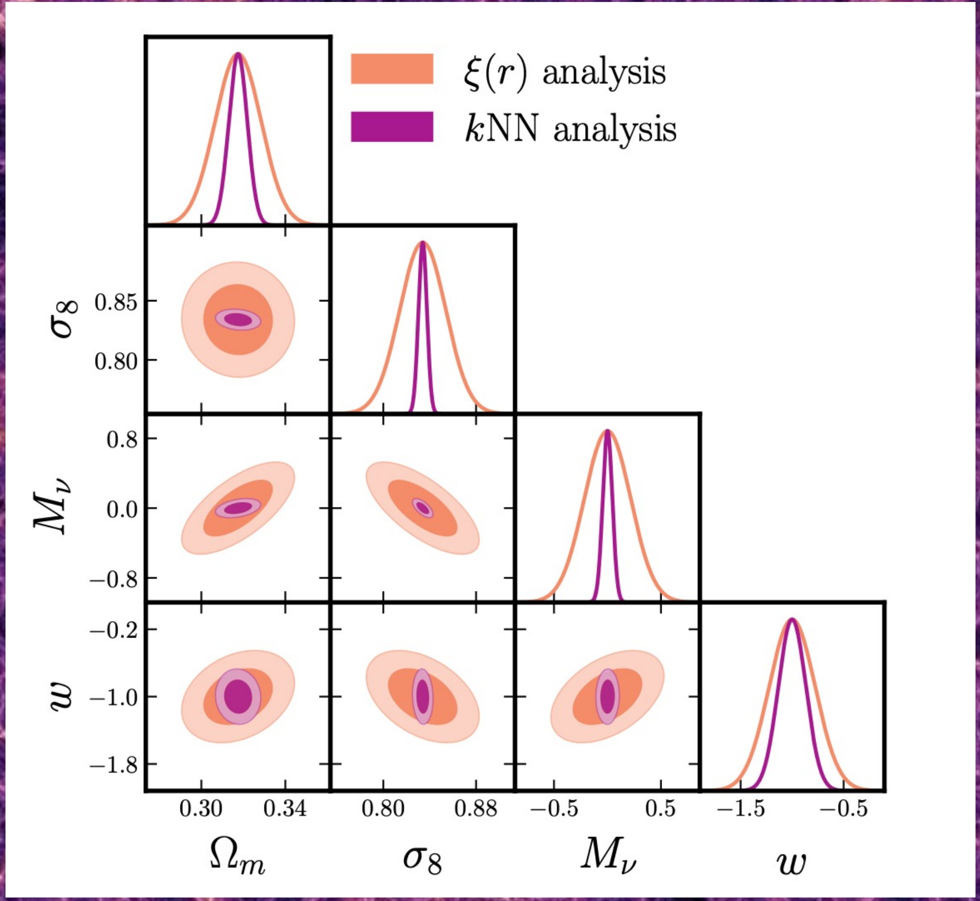


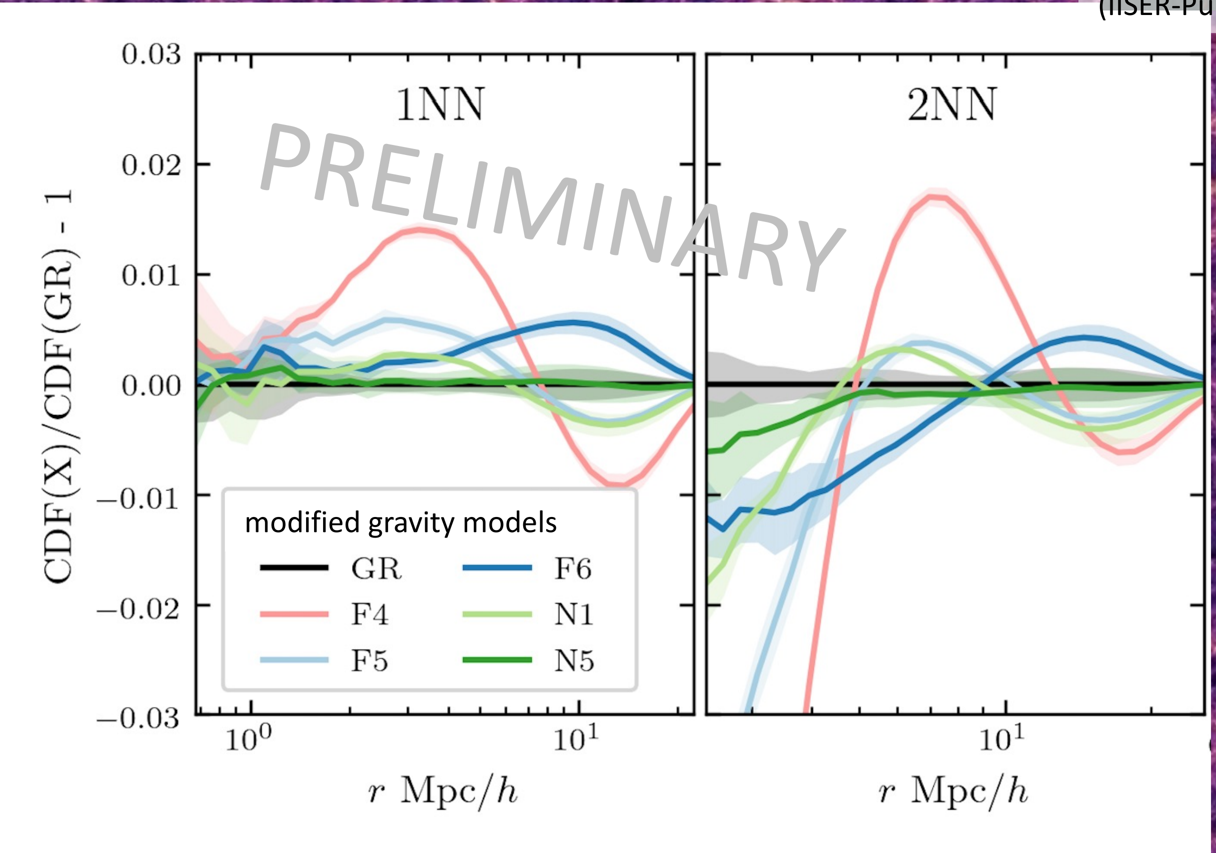
n(z) realizations used for redshift calibration study

Giannini et al 2022 [DES Collab], arXiv:2209.05853

Ongoing project highlight:
"k-Nearest Neighbor" summary statistics as a probe of modified gravity

with Arka Banerjee (IISER-Pune)





Forecast from
Banerjee & Abel 2021,
arXiv:2102.01184

Exploratory study of sensitivity to modified gravity effects in N-body simulations

Background image: Millennium simulation project

Conclusions

- Large scale structure (LSS) growth history and properties are sensitive to interesting cosmological physics, which is why mismatches between late- and early-Universe measurements of σ_8 have captured the field’s attention.

- With DES Y3 galaxy clustering and weak lensing, we’ve tested several beyond-ΛCDM models, including probes of LSS growth via modified gravity and binned $\sigma_8(z)$ parameterizations.

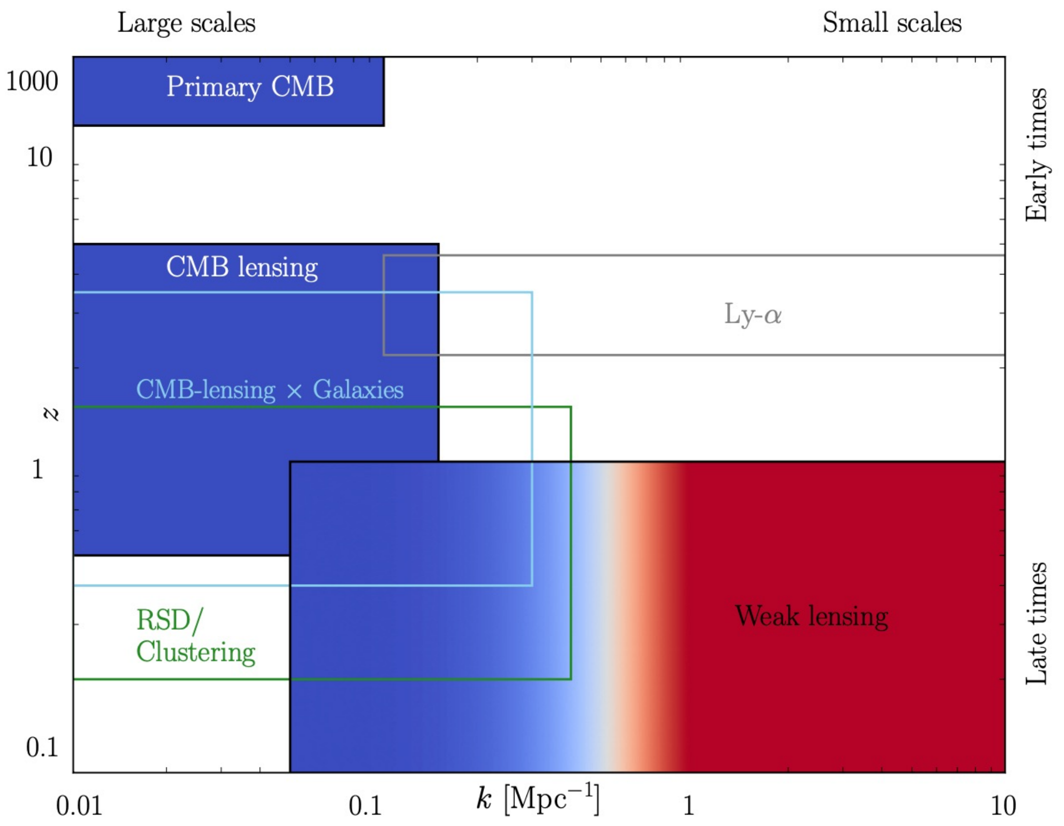
- There *may* be some hints of slower-than-ΛCDM growth at late times, but nothing conclusive yet.

- Learning more about growth motivates us to make the most of current & soon-to-be available data.
  - Improve non-linear modeling
  - Analyze additional observables: e.g. CMB lensing, cross-redshift-bin galaxy clustering
  - Go beyond 2-point summary statistics

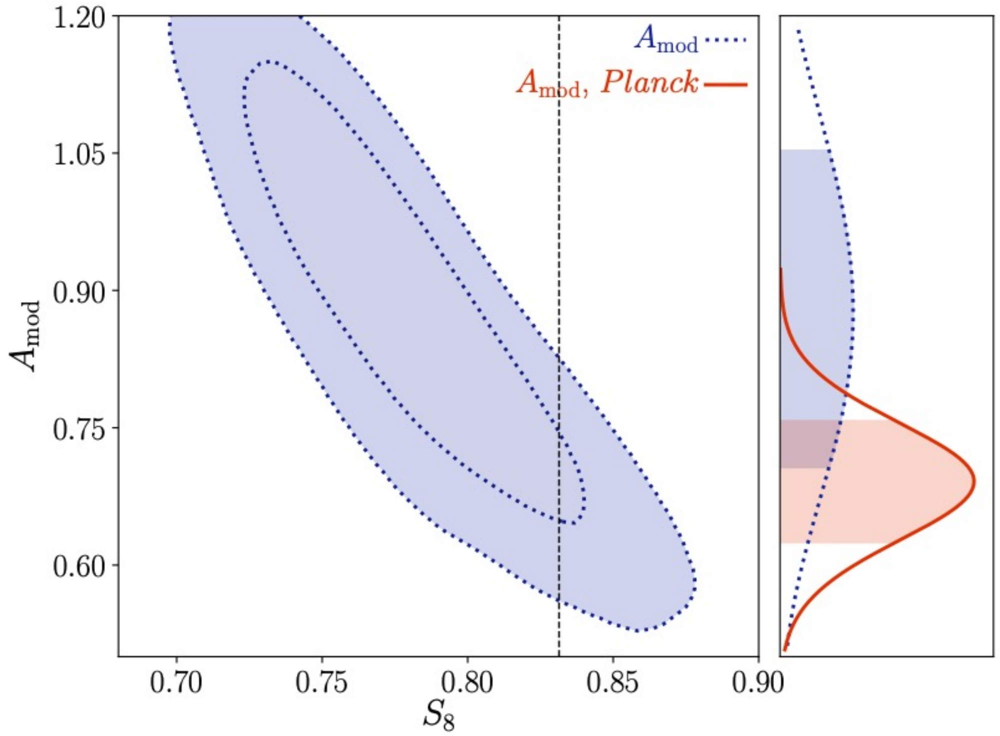
- Beyond-ΛCDM studies are complementary to work to understand how astrophysical, systematic uncertainties impact analyses --- and beware --- they may be particularly susceptible to modeling/analysis/systematics challenges!

BACKUP SLIDES

Differences could be driven by linear vs nonlinear scales, rather than (or in addition to!) redshift-dependent effects

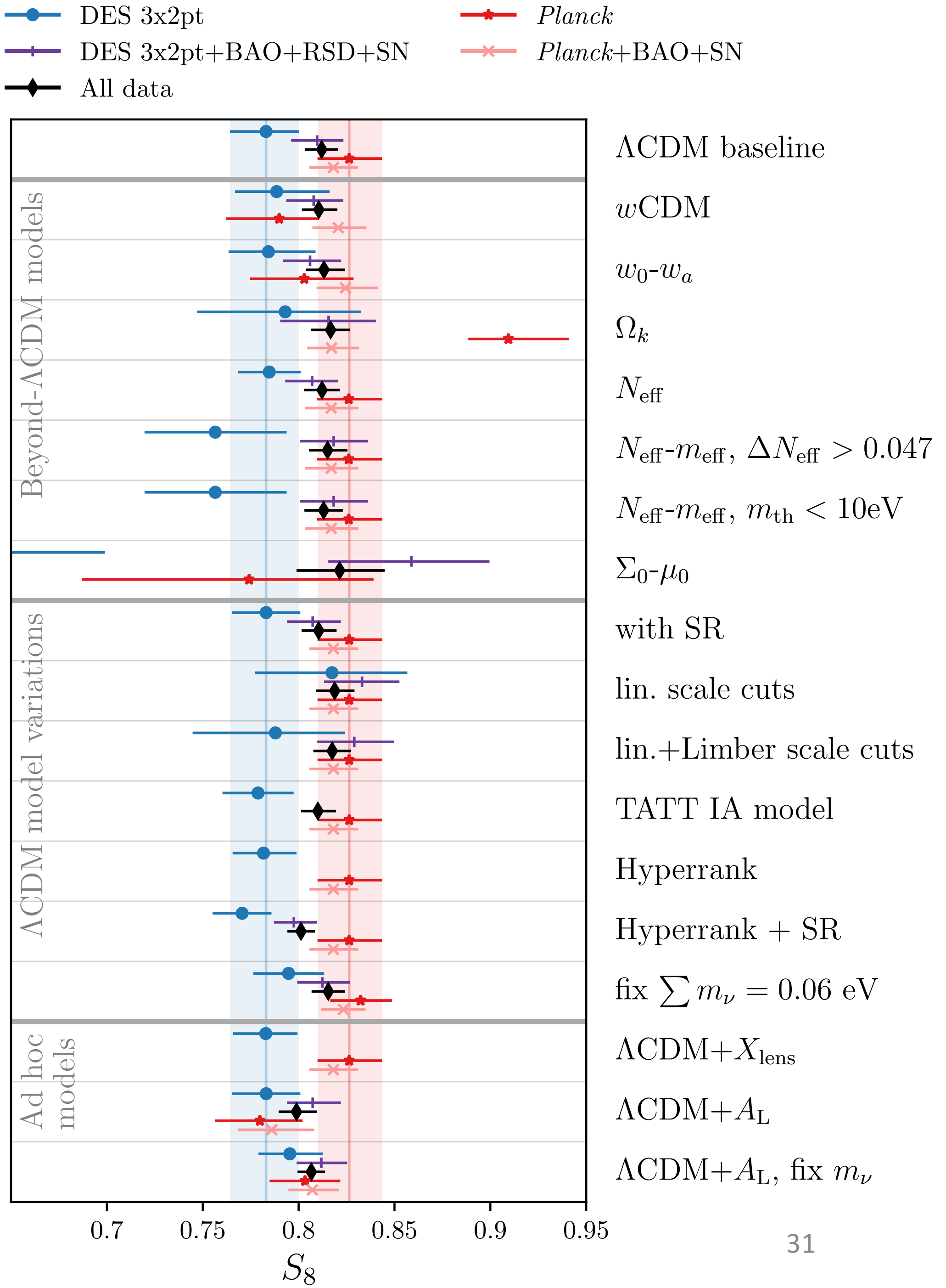


$$P_{\rm m}(k,z) = P_{\rm m}^{\rm L}(k,z) + A_{\rm mod}[P_{\rm m}^{\rm NL}(k,z) - P_{\rm m}^{\rm L}(k,z)]$$



Amon and Efstathiou, 2022, JCAP 2022 arXiv:2206.11794
Preston, Amon, and Efstathiou 2023, arXiv:2305.09827

Impact of model extensions on S_8



DES Collaboration [inc. JM] 2023, PRD arXiv:2207.05766

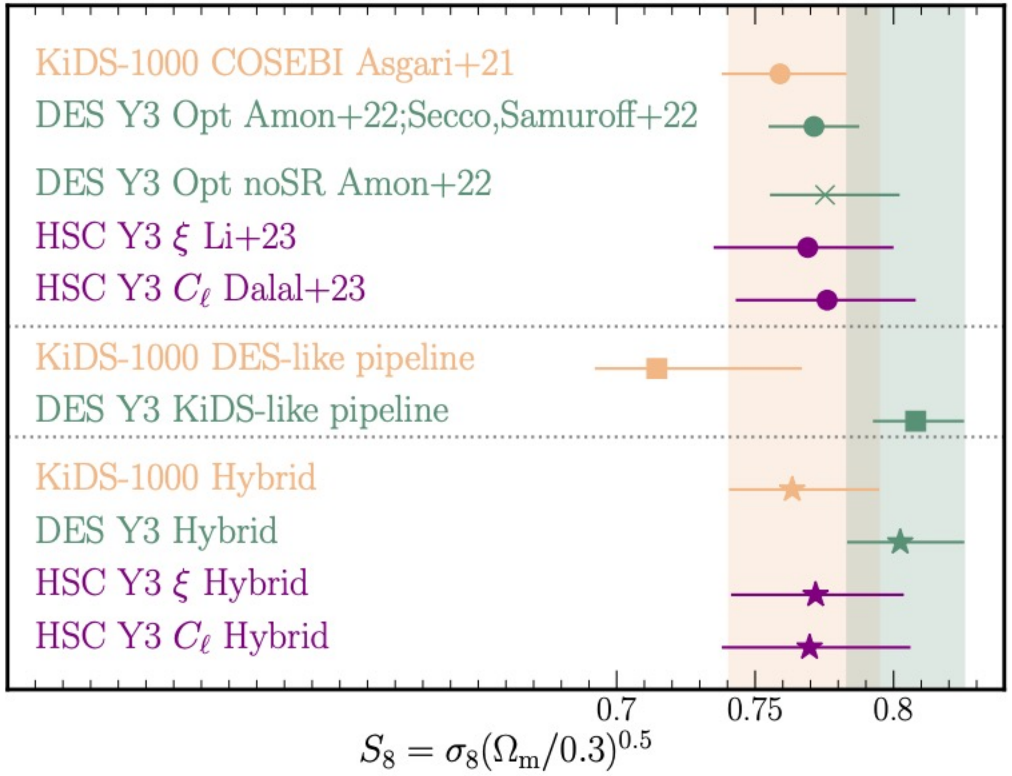
DES+KiDS details: Pipeline differences

	DES Y3	KiDS-1000	Hybrid
Cosmological parameter priors:			
Amplitude	A_s : [0.5, 5.0]	S_8 : [0.1, 1.3]	S_8 : [0.1, 1.3]
Hubble constant	h : [0.55, 0.91]	h : [0.64, 0.82]	h : [0.64, 0.82]
Matter density	Ω_m : [0.1, 0.9]	ω_c : [0.051, 0.255]	ω_c : [0.051, 0.255]
Baryon density	Ω_b : [0.03, 0.07]	ω_b : [0.019, 0.026]	ω_b : [0.019, 0.026]
Spectral index	n_s : [0.87, 1.07]	n_s : [0.84, 1.1]	n_s : [0.84, 1.1]
Neutrinos	$1000\,\Omega_\nu h^2$: [0.6, 6.44]	$\Sigma m_\nu = 0.06$eV	Σm_ν = [0.055, 0.6] eV
Astrophysical systematic models and priors:			
Intrinsic Alignments	TATT: b_{TA} : [0, 2]; a_1, a_2, η_1, η_2 : [−5, 5]	NLA: A_{IA} : [−6, 6]	NLA-z: A_{IA}, η_{IA} : [−5, 5]
Non-linear Model	HALOFIT	HMCODE2016	HMCODE2020
Baryon Feedback	Scale cuts	A_{bary} : [2, 3.13]	Scale cuts & $\log_{10}(T_{AGN}/K)$: [7.3, 8.0]
Neutrino Model	Bird et al. (2012)	HMCODE2016	HMCODE2020
Sampling Algorithm:			
	POLYCHORD	MULTINEST	POLYCHORD

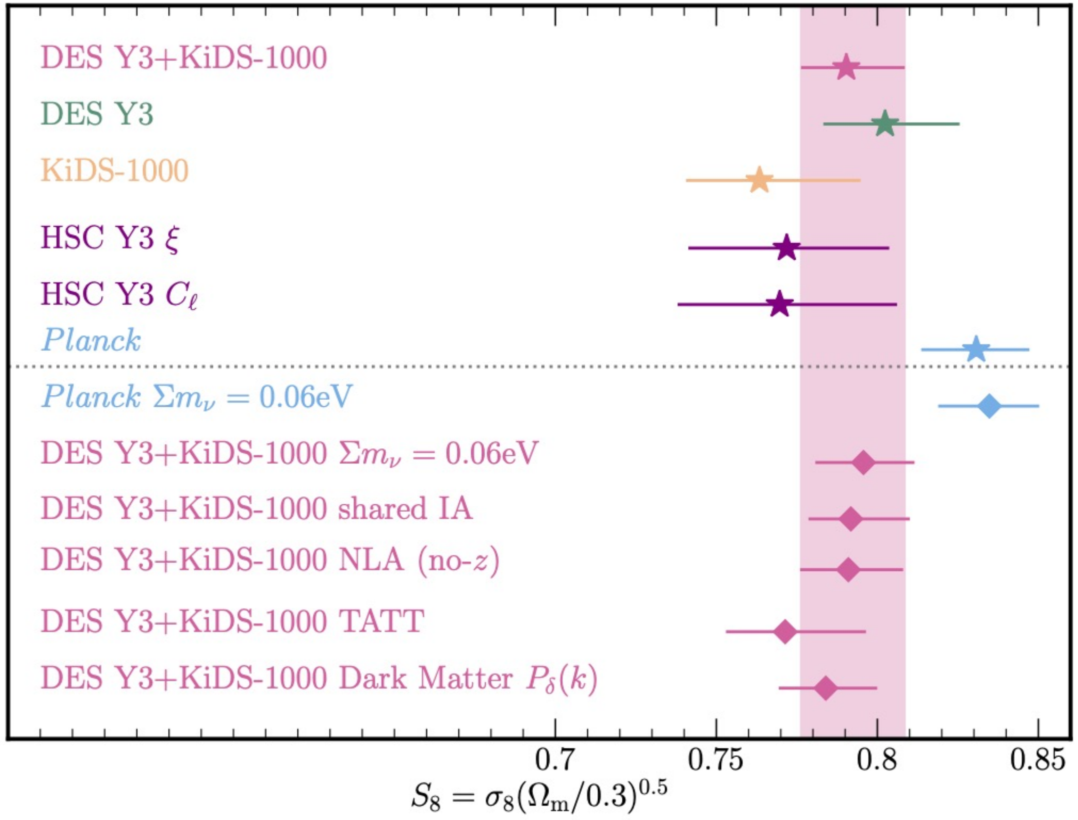
DES & KiDS Collabs. [inc. JM] 2023, arXiv:2305.17173

DES+KiDS details

Separate, with pipeline variations



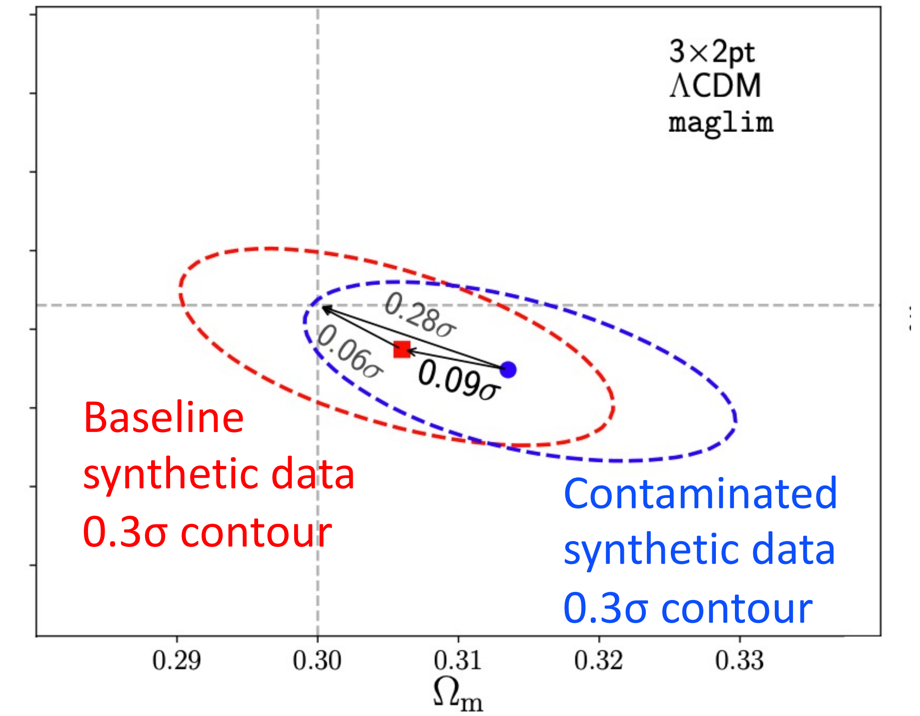
Using "hybrid" pipeline



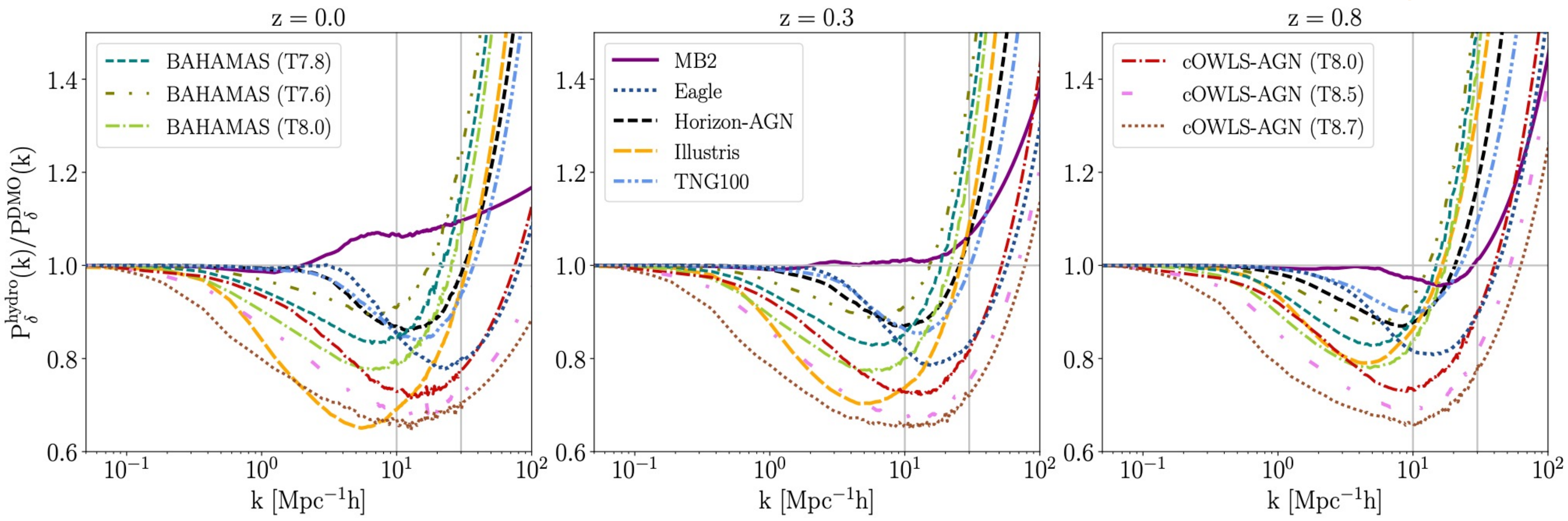
DES & KiDS Collabs. [inc. JM] 2023, arXiv:2305.17173

Systematics a challenge!
Example: baryon feedback

- Impact of baryonic physics on the matter power spectrum is one of our main modeling uncertainties.
- Size of effect estimated from hydrodynamic sims.
- In DES Y3 we cut scales, analyze synthetic data contaminated with OWLS-AGN baryon feedback to ensure cosmology results are robust.



Krause, Fang et al. arXiv:2105.13548



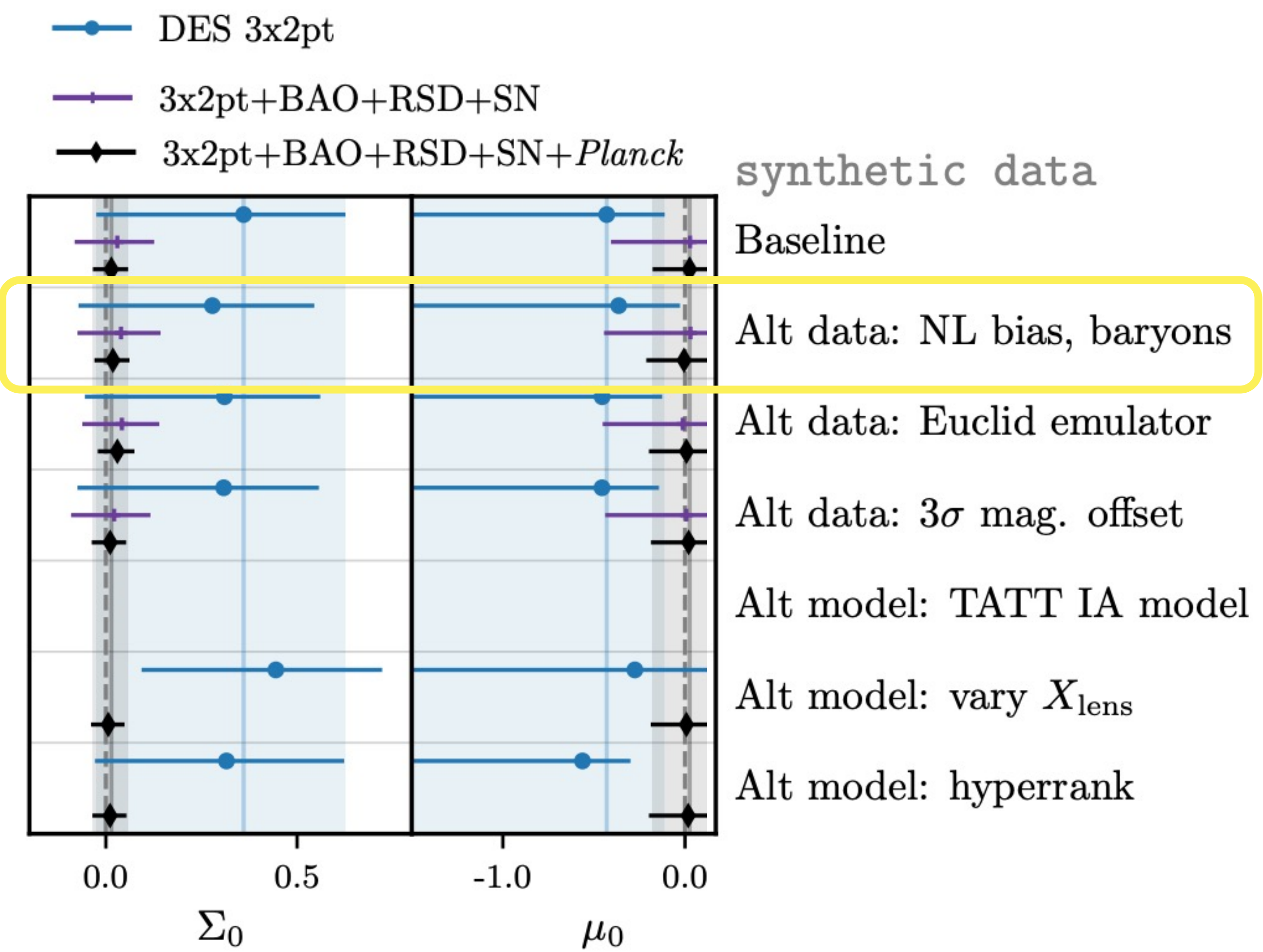
Huang et al. arXiv:2007.15026, see also Chen et al arXiv:2206.08591

Systematics are ***even more of*** a challenge ***beyond-ΛCDM***!

Example: baryon feedback

- Modified gravity could plausibly affect how baryonic process occur & impact structure.
- BUT Simulations used to estimate impact of baryons are done in LCDM, assuming GR.

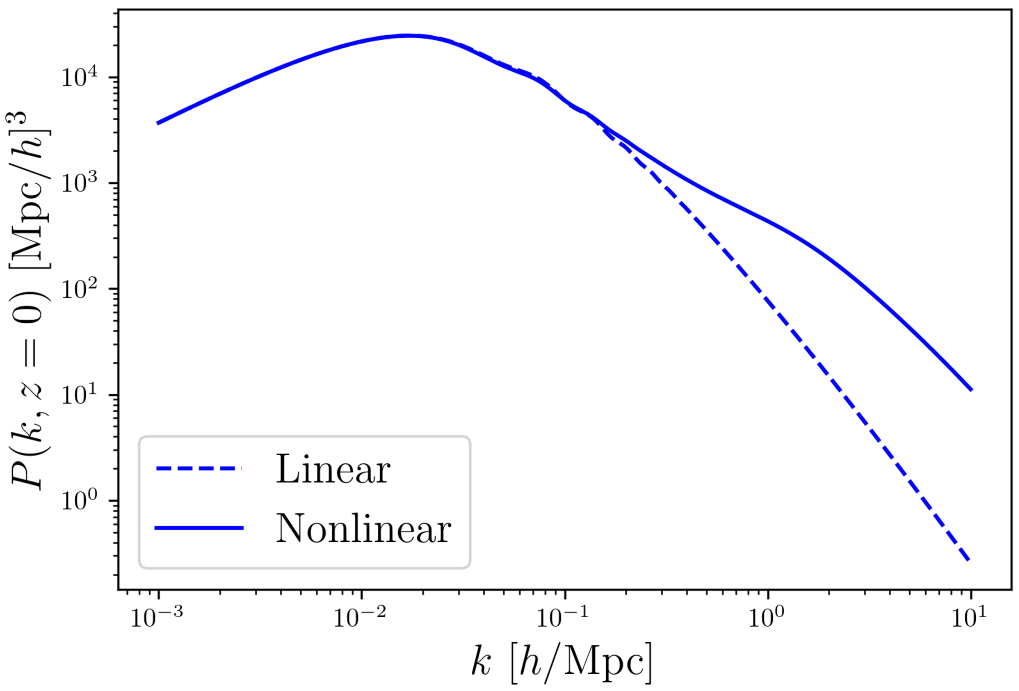
- **Ideally** would model baryons+MG, test robustness in that space.
- **In practice** we make sure LCDM+baryons won't give us a false detection of MG.



DES Collaboration [inc. JM] 2023, PRD arXiv:2207.05766

Similar issues for nonlinear matter power spectrum, intrinsic alignments, galaxy bias, higher order shear effects…

Challenge: Non-linear modeling is beyond ΛCDM



$$\Delta\chi^2 \equiv (\mathbf{D}_{\mathrm{NL}} - \mathbf{D}_{\mathrm{lin}})^{\mathrm{T}} \mathbf{C}^{-1} (\mathbf{D}_{\mathrm{NL}} - \mathbf{D}_{\mathrm{lin}})$$

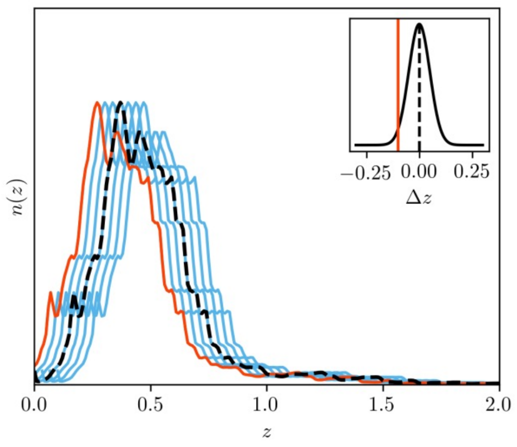
Cuts defined by iteratively removing datapoints from 3x2pt measurements until $\Delta\chi^2$<1.

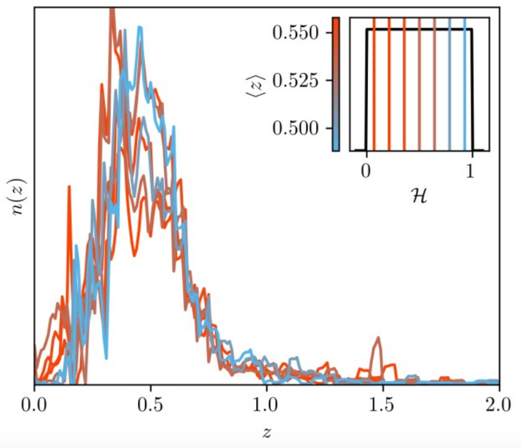
- DES ΛCDM analyses use halo-model-based tools calibrated on simulations
  - Halofit – Used in DES Y1, Y3
  - HMCode2020 – DES Y6

Other approaches

- Perturbation theory
- Emulators – (usually assume wCDM)
  - EuclidEmulator2, arXiv:2010.11288
  - Aemulus-nu, arXiv:2303.09762
- ReACT method
  - Cataneo 2019, arXiv:1812.05594
  - Available for certain dark energy, modified gravity models

Challenge: More freedom in the model can leads to greater sensitivity to photo-z uncertainties.





Fiducial: marginalize over mean-shift parameters:

- Δz^i_s : $n^i_s(z) \rightarrow n_s(z-\Delta z^i_s)$

Hyperrank:

- Sample over ensemble of possible $n^i_s(z)$ histograms

Cordero, Harrison et al. [DES] 2022, MNRAS
arXiv:2109.09636

Shear ΛCDM results unchanged between these methods.

3x2pt ΛCDM S_8 shifts by ~0.5σ.

Binned $\sigma_8(z)$ 3x2pt: some A_i shifts ~1σ. Add BAO+SN to help restore robustness.

In the binned $\sigma_8(z)$ model, changing to hyperrank produces larger shifts

DES 3x2pt alone

- $\sigma_8^{[\text{bin 2}]}$ ↑ 0.5σ
- $\sigma_8^{[\text{bin 3}]}$ ↑ 0.6σ

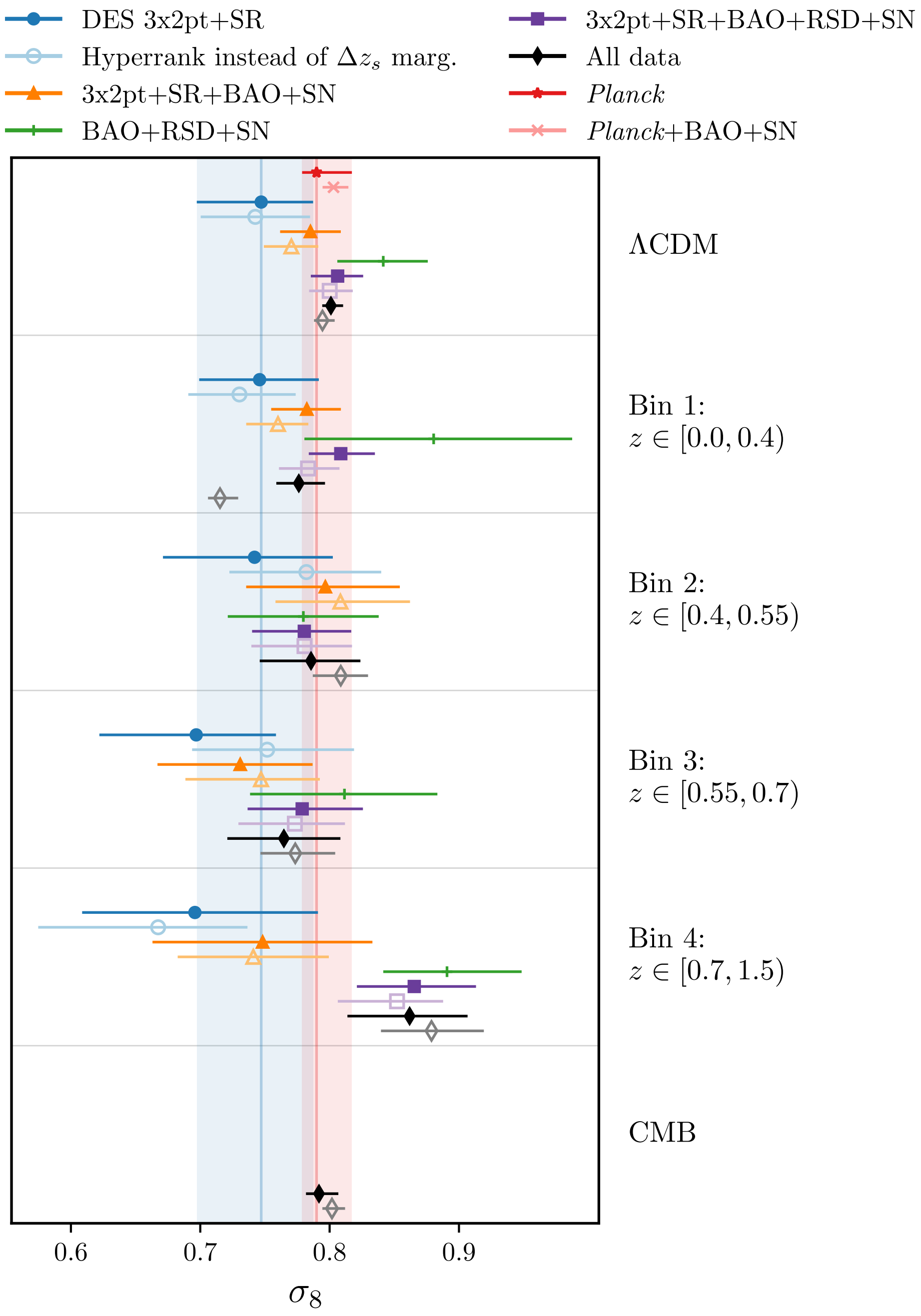
3x2pt +BAO+RSD+SN

- $\sigma_8^{[\text{bin 1}]}$ ↓ 0.7σ

3x2pt +BAO+RSD+SN + CMB

- $\sigma_8^{[\text{bin 1}]}$ ↓ 2.7σ
- $\sigma_8^{[\text{bin 2}]}$ ↑ 0.5σ
- $\sigma_8^{[\text{CMB}]}$ ↑ 0.6σ

More degrees of freedom in our model, more sensitivity to how certain systematics are handled.



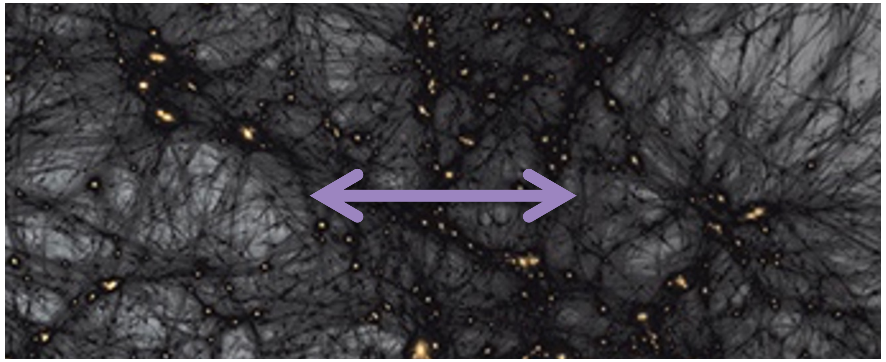
DES Collaboration [inc. JM] 2023, PRD arXiv:2207.05766

Challenge: More degrees of freedom in the model can lead to greater sensitivity to systematic uncertainty.

- WL Photo-z uncertainty assessment; robust in LCDM, bigger changes in cosm than would be ideal when switching between these
  - For given redshift bin; things determining amplitude of lensing
    - Redshift distribution of lenses and sources
    - Amplitude of structure in redshift ranges
    - Expansion history, translating redshift distributions to distances in lensing geometry
  - More freedom in one of these can make us more susceptible to uncertainties in others: dropping assumption of smoothness of growth rate vs z means details of n(z) can matter more. Adding in external constraints of expansion from BAO can restore some robustness.

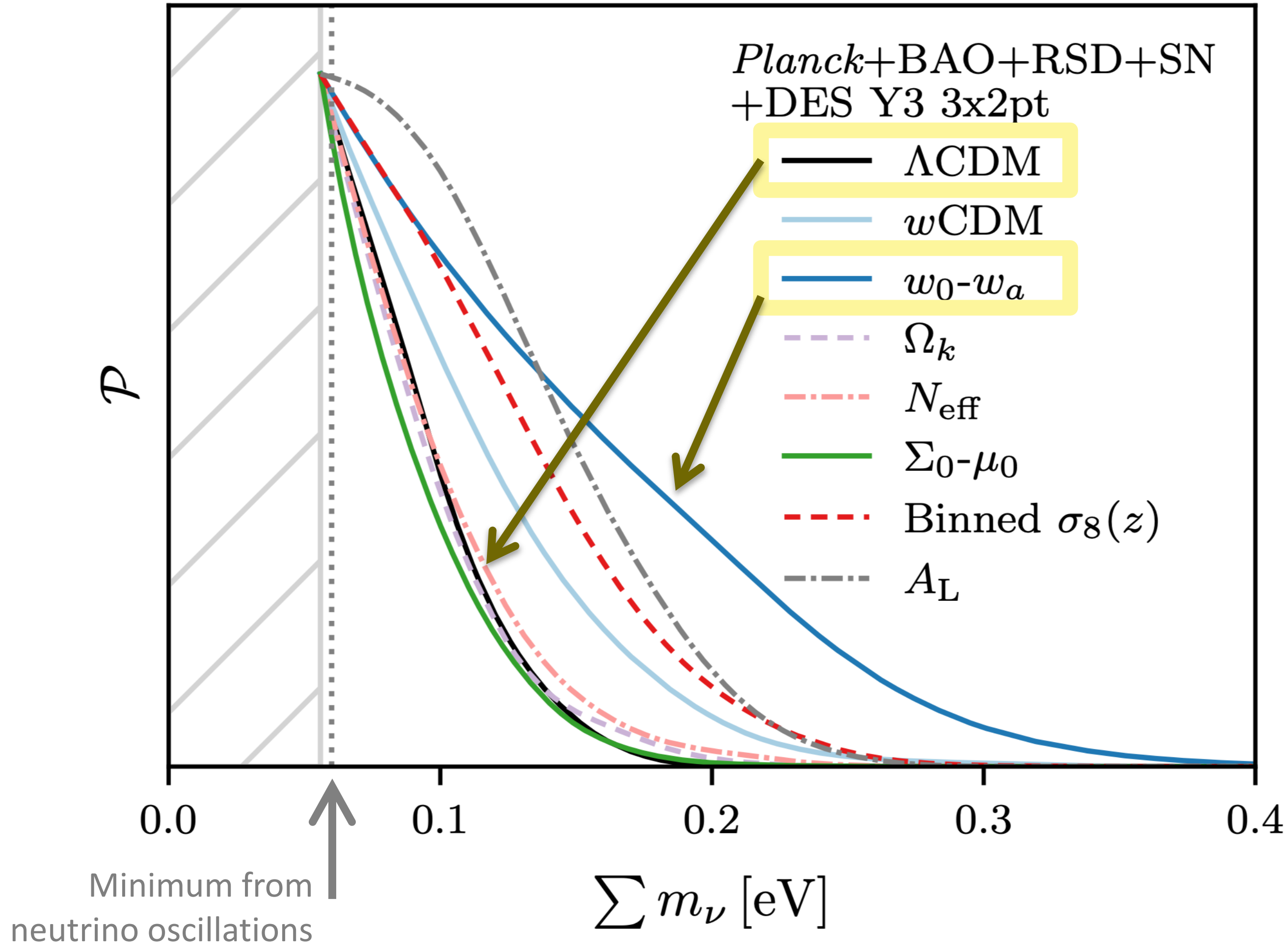
Neutrinos as (a small fraction of) dark matter

- Cosmological upper bounds on the sum of neutrino masses come from
  - Impact on expansion history
  - Structure growth suppressed on length-scales < free-streaming scale



- These constraints depend on the assumed cosmological model.

DES Collaboration 2022, arXiv:2207.05766

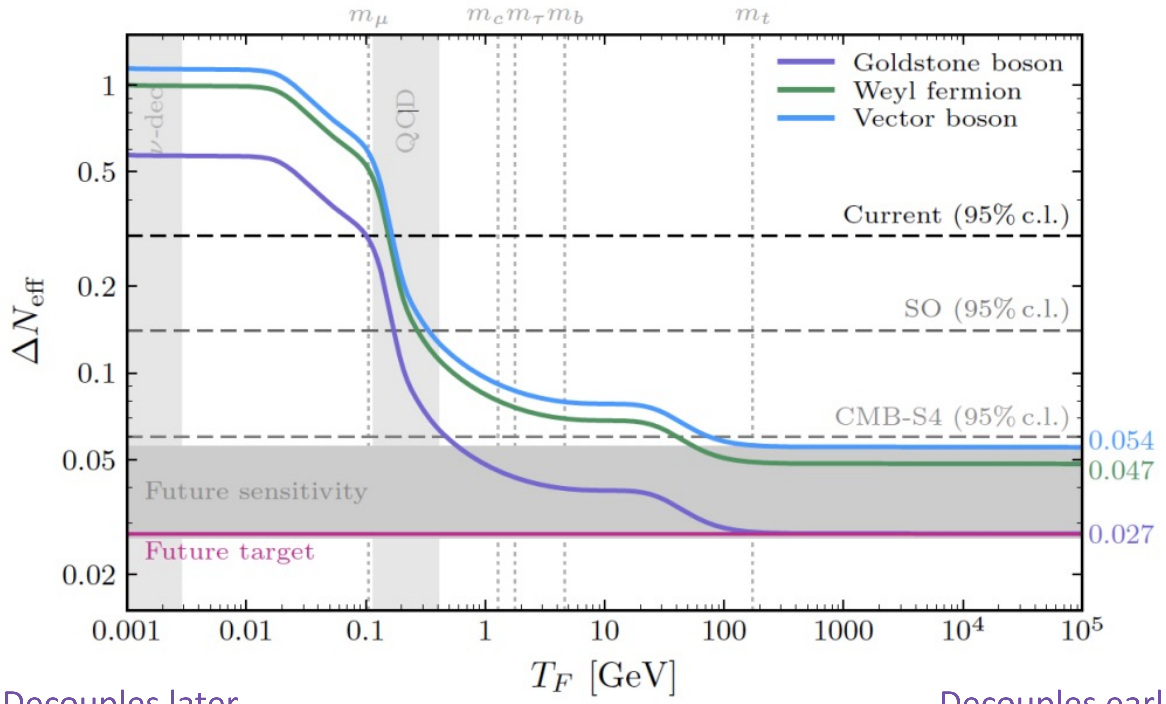


Searching for sterile neutrinos and other light relic particles

Radiation energy density @CMB emission

$$\rho_{\rm rad} = N_{\rm eff}\,\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_{\gamma}.$$

Excess effective degrees of freedom



Decouples later

Decouples earlier

Temp. when particle decouples from standard model species

- CMB observables are sensitive to the presence of new relativistic particles
  - Parameterized by $N_{\rm eff}$
  - $N_{\rm eff} \sim 3$ in standard model (3 neutrinos)
- Stable, massive particles may impact late-time structure growth.
- Relevant recent findings:
  - Constraining one species of light massive relic (e.g. sterile neutrino) provides general sensitivity to presence of others. DePorzio, Xu, Muñoz, and Dvorkin 2021, arXiv:2006.09380
  - Weak lensing data adds significant constraining power! Xu, Muñoz, and Dvorkin 2022, arXiv:2107.09664

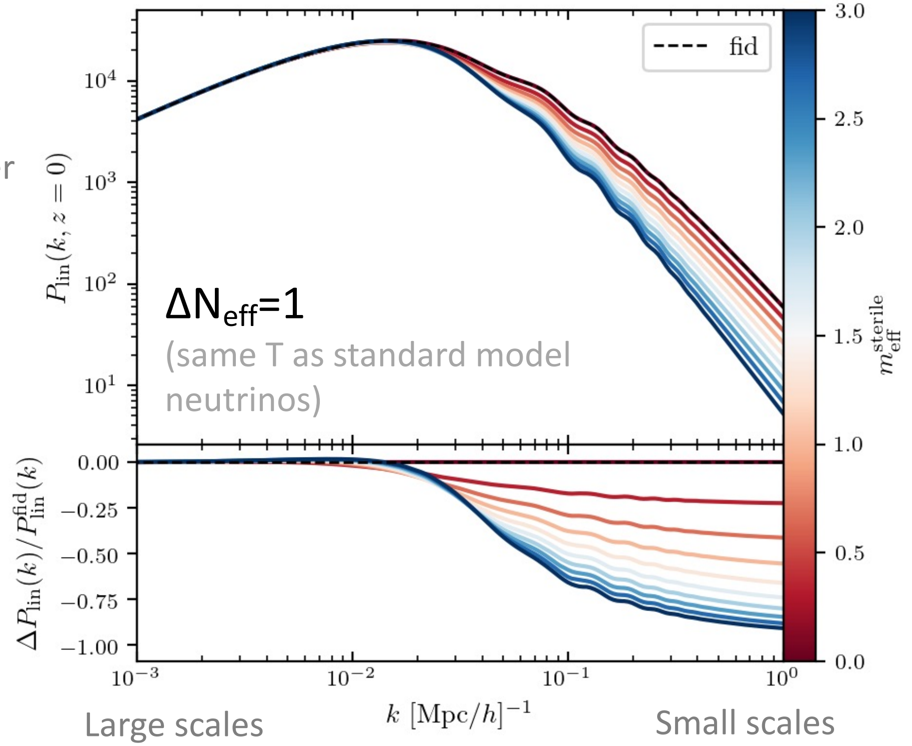
Dvorkin et al 2022, arXiv:2203.07943

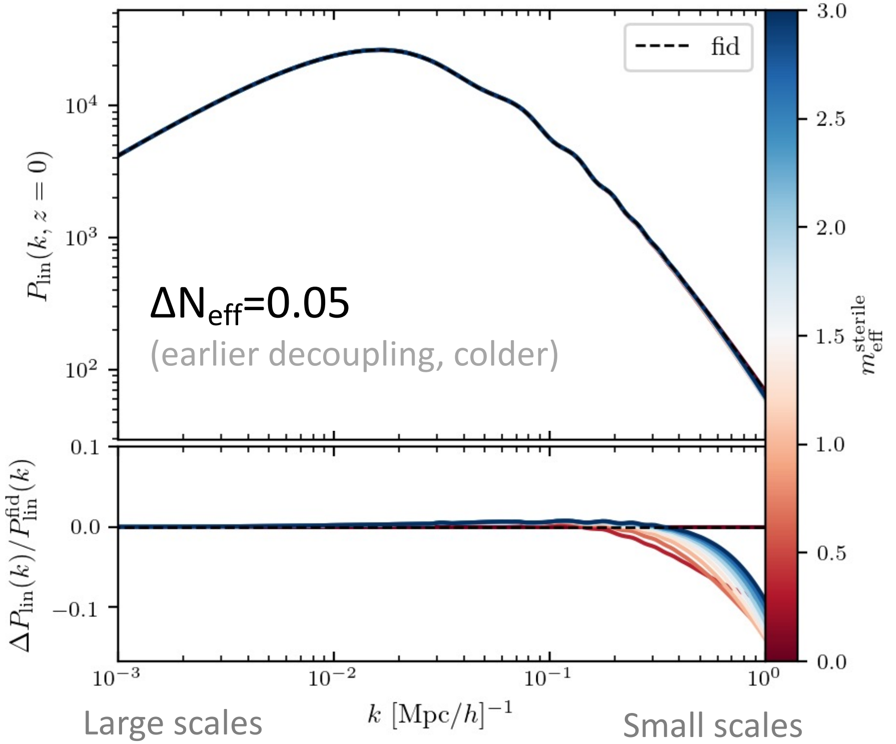
Sterile neutrinos

Generic search for light massive relic beyond-the-standard-model particles.

- m_{eff} - Mass of stable relic particle
  - controls fraction of dark matter made of relic
  - Higher m_{eff} → more growth suppression
- ΔN_{eff} – Early Universe energy-density contribution
  - Higher N_{eff} → hotter relic particles

Linear matter power spectrum





Large scales | Small scales

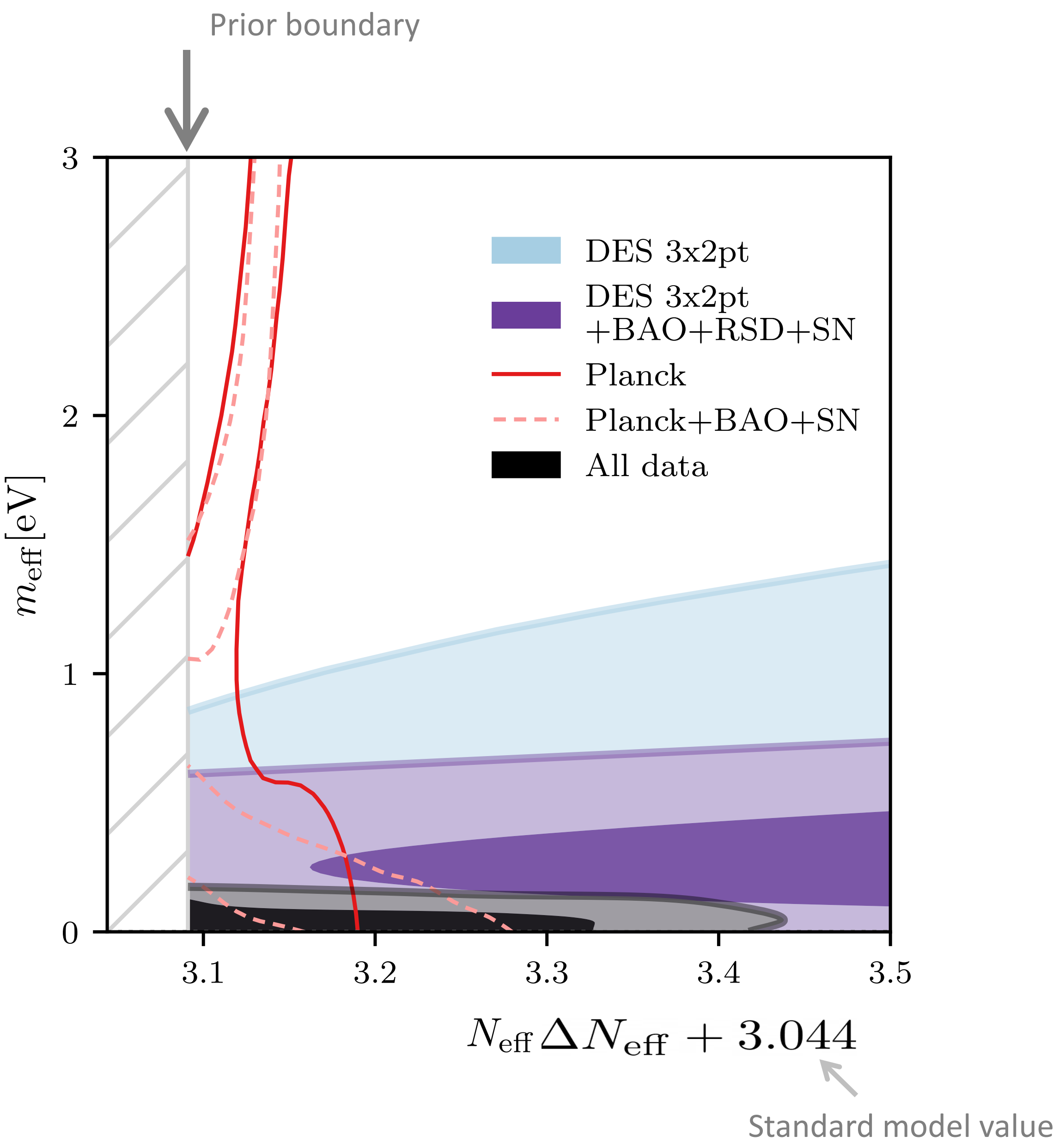
Large scales | Small scales

Sterile neutrino constraints

- DES Y3 analysis used linear only scales
  - Only 256 datapointss of 462 used in LCDM
- Even with linear cuts, m_{eff} bounds ~3x tighter than Planck 2018 results
- Ongoing project to update analysis:
  - validate nonlinear modeling using N-body simulations
  - Improving galaxy bias modeling

With Paul Rogozenski
(grad student @ Arizona)

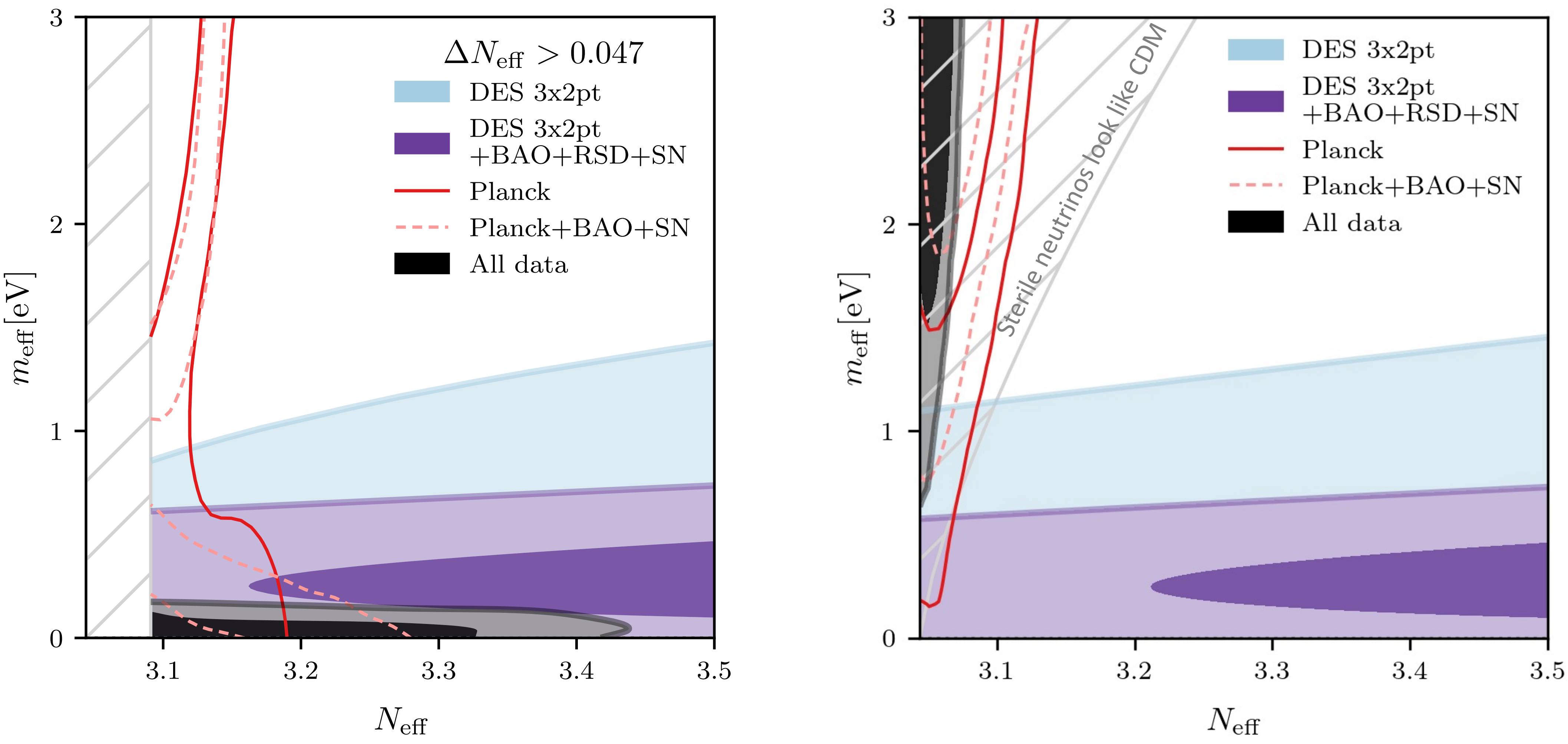
And Arka Banerjee
(IISER-Pune)



Challenge: Prior volume effects in unconstrained parameter space regions

Fiducial prior: $\Delta N_{eff} > 0.047$

Results with prior: $\Delta N_{eff} > 0$



Unconstrained small-N_{eff} region introduces sensitivity to noise realization, modeling choices, contaminations.
Robustness restored with fiducial prior.