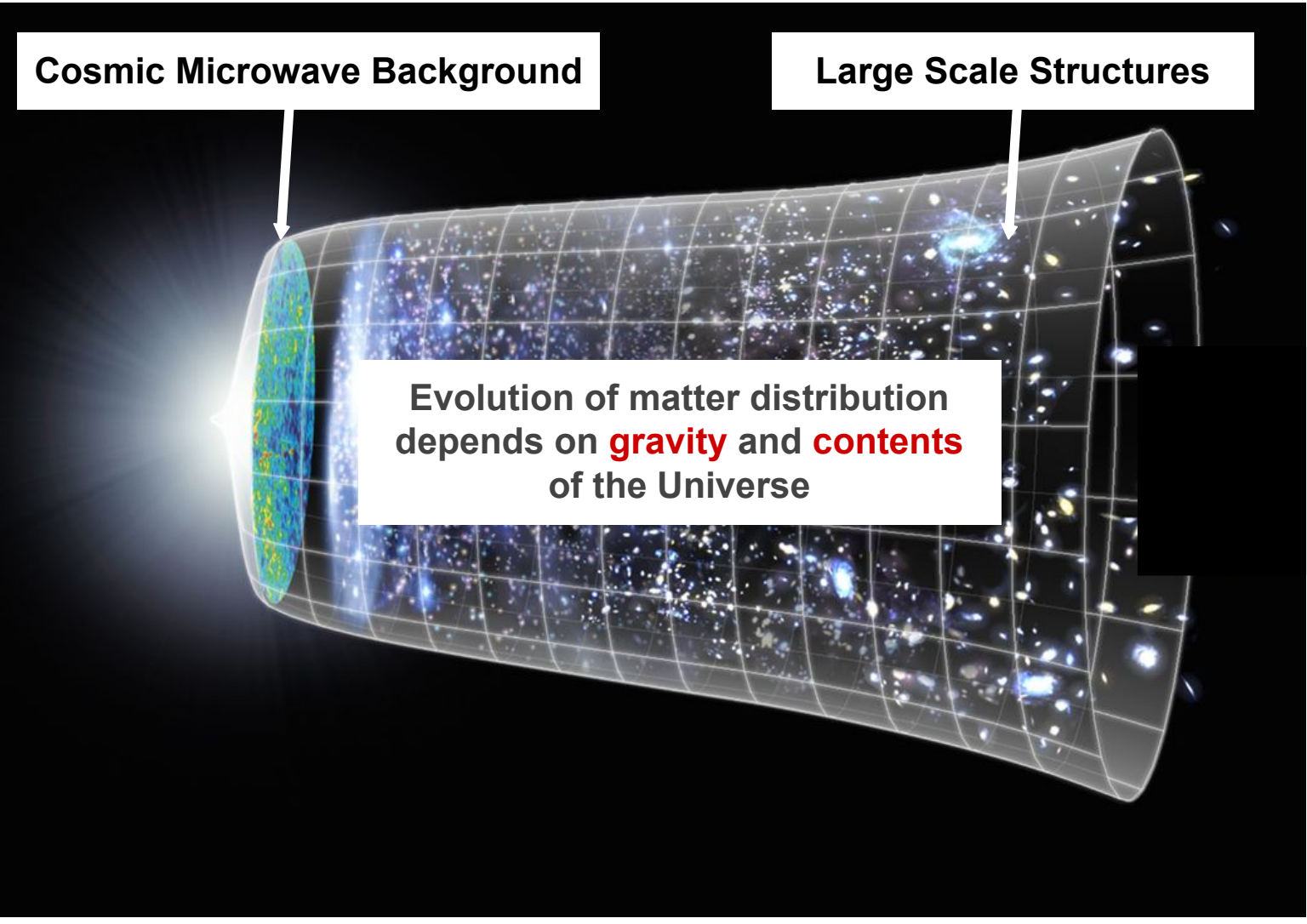
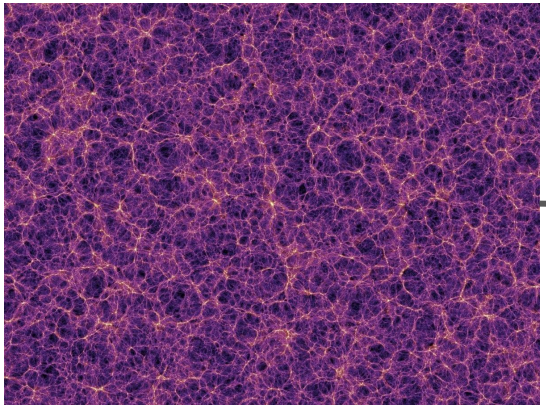
Why did we do this? Why now?

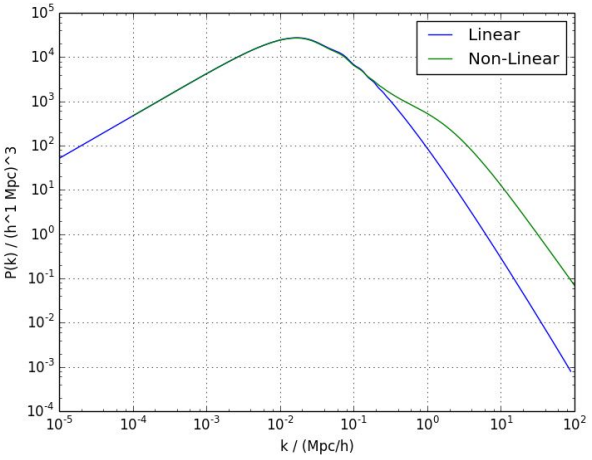
To leverage the most statistically powerful weak lensing dataset available to test ΛCDM.


Cosmic Microwave Background
Large Scale Structures
Evolution of matter distribution
depends on gravity and contents
of the Universe

Imaging galaxies to probe matter distribution

Millennium simulation

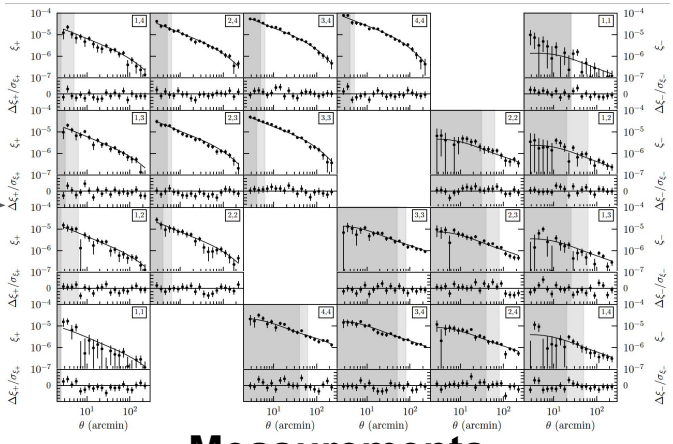




Model

Matter power spectrum

Dark Energy Survey



Measurements

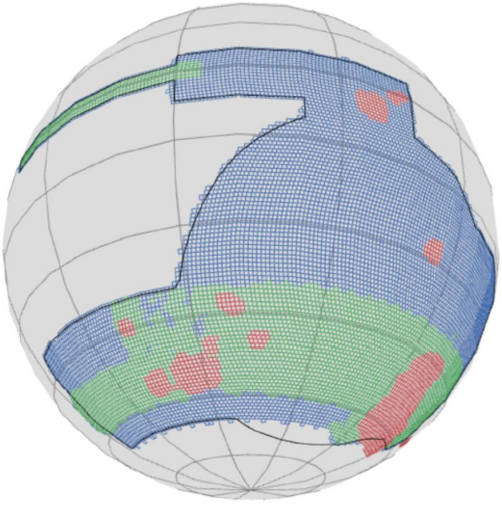
2-point correlation functions
in redshift bins

The Dark Energy Survey

- DECam on Blanco-4m at CTIO in Chile
- Galaxy survey on **10%** of the sky in 5 optical bands for **6** years (2013-2019)
- DES international collaboration (700+ participants) to extract cosmology from DES data

1st year of observation:
Cosmology in ΛCDM *DES Collaboration, PRD, 2018* and beyond-ΛCDM *DES collaboration, PRD, 2019*

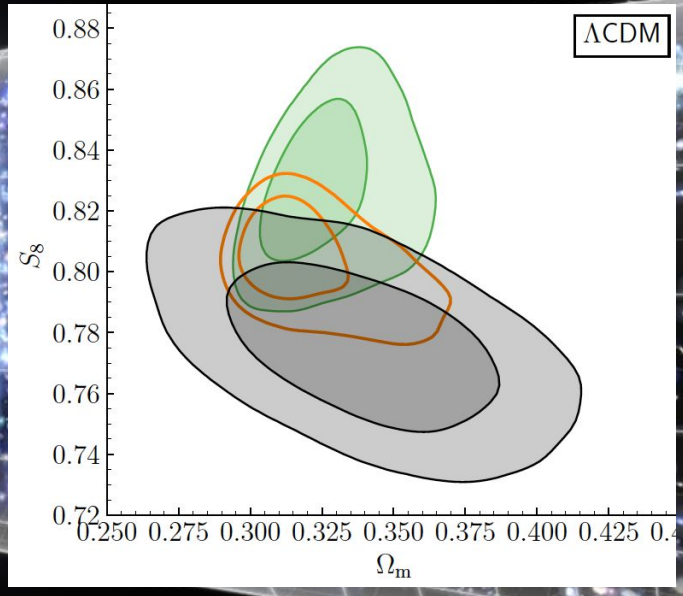
3 years of observation: 3 times **more sky coverage**, 12 times **more galaxies**
→ largest shape catalog to date with 100M galaxies
→ SNR of weak lensing and clustering between Y1 and Y3 **improved by a factor of 2**



From Gatti, Sheldon, et al, MNRAS, 2022

Planck satellite CMB measurements

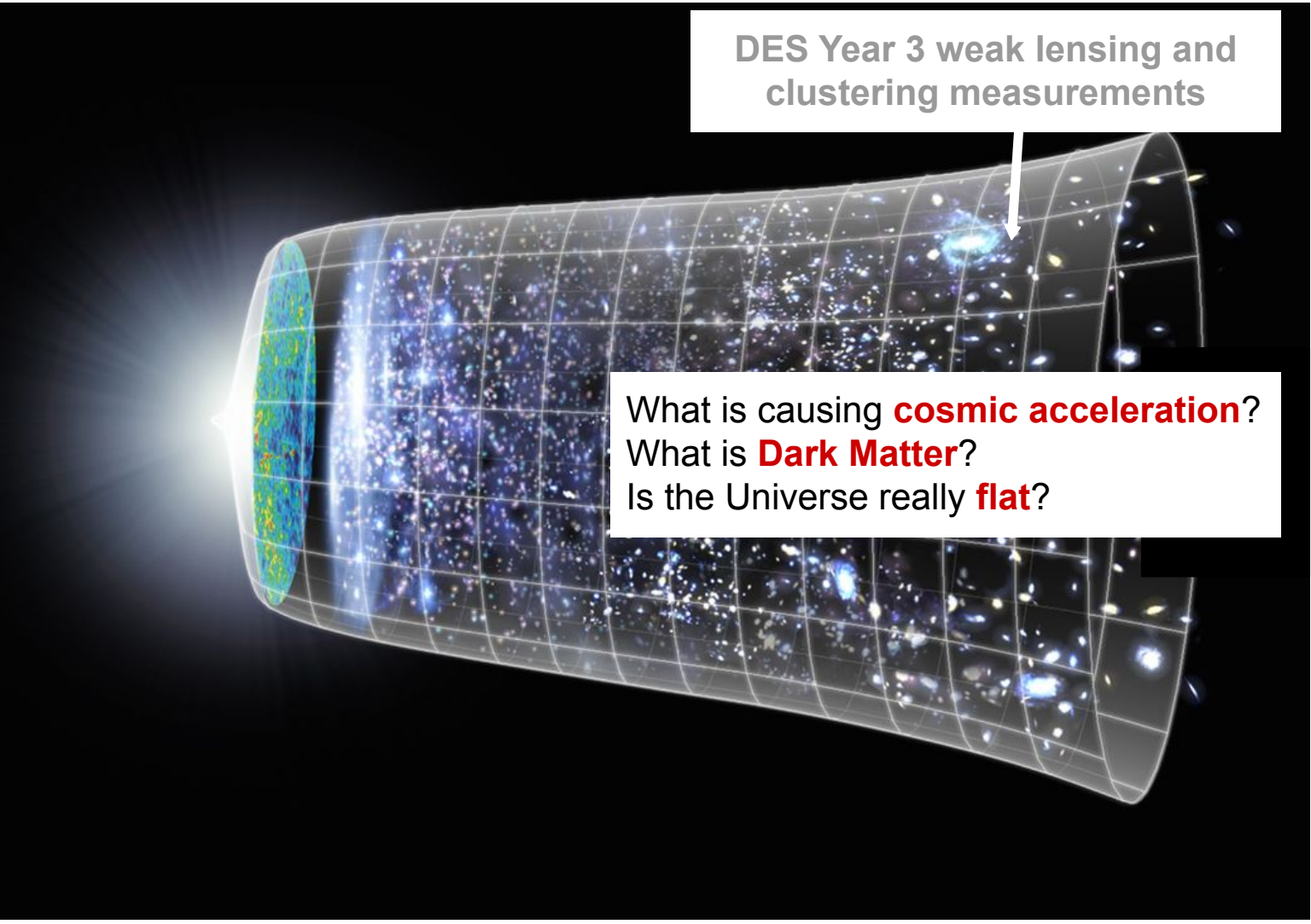
DES Year 3 weak lensing and clustering measurements



DES Y3 3x2pt results in LCDM

DES collaboration arxiv:2105.13549 + 29 accompanying papers

→ **Cosmology with 4% precision**

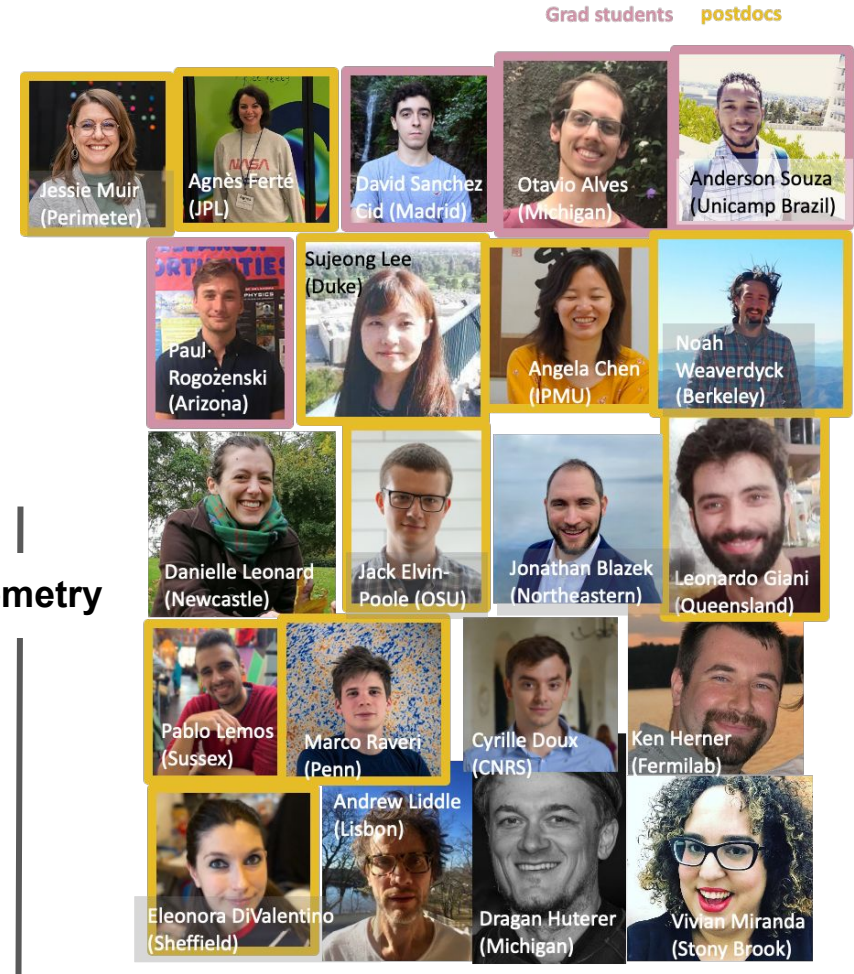

DES Year 3 weak lensing and clustering measurements
What is causing cosmic acceleration?
What is Dark Matter?
Is the Universe really flat?

What did we do in the paper?

DES Year 3 weak lensing and clustering to answer big questions of cosmology

Y3 *extensions* team:

- International team, including many early-career scientists
- Based on multi-year effort of the DES collaboration



Beyond ΛCDM-Models

- **w_0-w_a**: time-dependent dark energy equation of state
- **Ω_K**: non-zero spatial curvature
- **N_{eff}-m_{eff}**: massive sterile neutrino
- **Σ_0-μ_0**: test of gravity on cosmological scales
- **Binned $\sigma_8(z)$**: phenomenological test of LCDM growth predictions

geometry

growth

+ Lots of other contributing to broader DES 3x2pt measurement & analysis efforts!

Our approach: ΛCDM+extended parameters in a Bayesian analysis

$$L(\mathbf{D}|\boldsymbol{\theta}) \propto (\mathbf{D} - M(\boldsymbol{\theta}))^T C^{-1} (\mathbf{D} - M(\boldsymbol{\theta}))$$

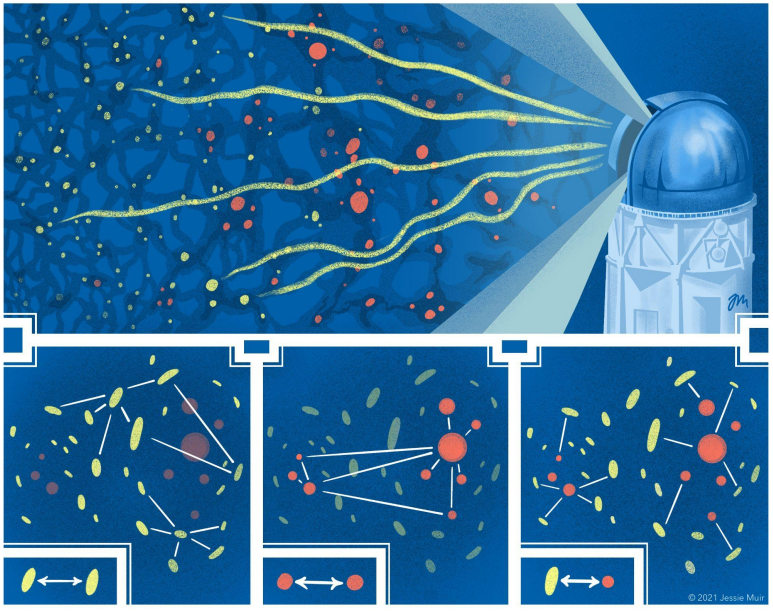
Beyond-ΛCDM parameters and tension metrics estimated by **sampling** the likelihood:

- 6 ΛCDM **cosmological** parameters +
  Beyond-ΛCDM parameters +
  22 **nuisance** parameters
- Analytic covariance, C
- **Polychord** sampler, Validation in *Lemos, Weaverdyck, et al. arxiv:2202.08233*
- 700+ MCMC!
- Use of external data
  - **CMB**: Planck TTTEEE+lowE
  - **Supernovae**: pantheon
  - **BAO/RSD**: eBOSS DR16 + MGS

Data: Dark Energy Survey Year 3 weak lensing and clustering data

$$L(\mathbf{D}|\boldsymbol{\theta}) \propto (\mathbf{D} - \mathbf{M}(\boldsymbol{\theta}))^T \mathbf{C}^{-1} (\mathbf{D} - \mathbf{M}(\boldsymbol{\theta}))$$

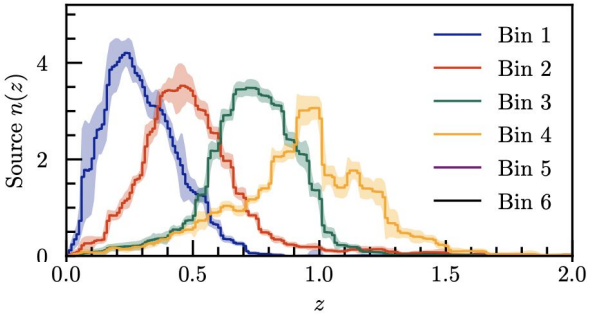
Shapes
Source galaxies
with metacalibration
4 redshift bins

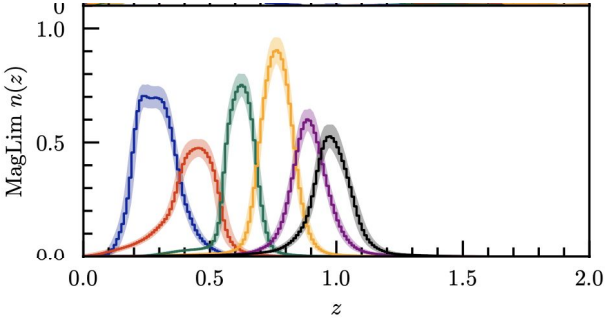


Positions
Lens galaxies:
Maglim sample
4 redshift bins

Cosmic shear | Clustering | Galaxy-galaxy lensing

$\xi_{+/-} \propto P(k)$ $\quad w \propto b^2 P(k)$ $\quad \gamma_t \propto b\,P(k)$





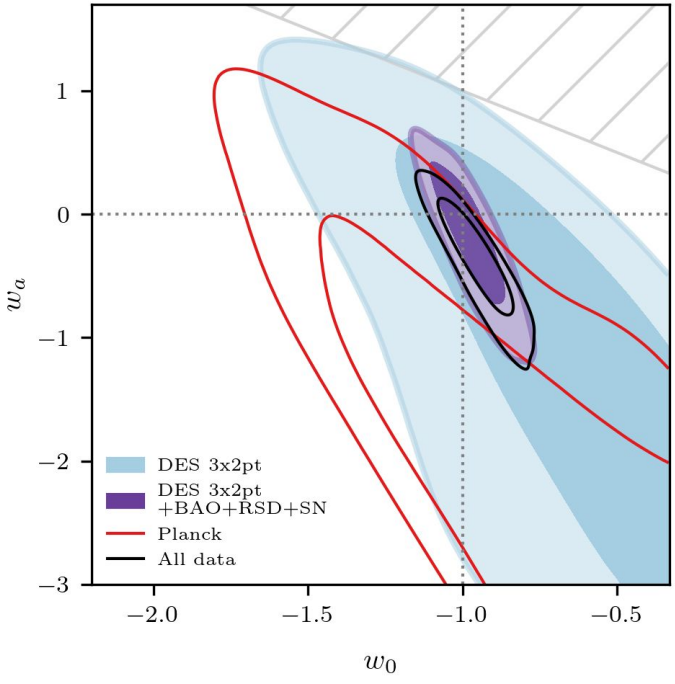
Modeling: accurate theoretical prediction of 3x2pt in beyond-ΛCDM models

$$L(\mathbf{D}|\boldsymbol{\theta}) \propto (\mathbf{D} - \mathbf{M}(\boldsymbol{\theta}))^T C^{-1} (\mathbf{D} - \mathbf{M}(\boldsymbol{\theta}))$$

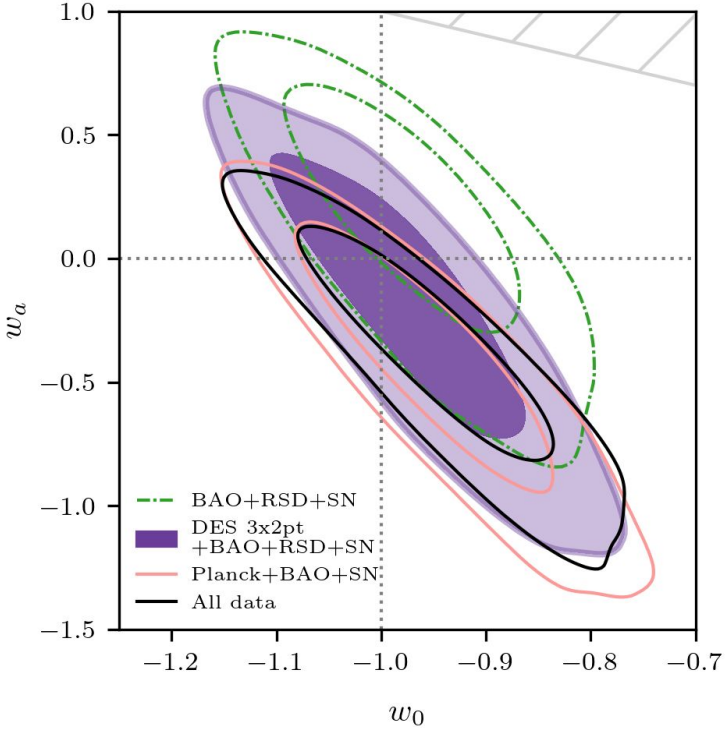
- **Matter** power spectrum:
  - CAMB
  - Non-linear with halofit
- **Intrinsic alignment**: non-linear alignment model (NLA)
- Galaxy **bias**: linear
- Impact of **magnification** included

!! Scale cuts:
Remove data points at small scales where we don't trust modeling of 3x2pt: driven by baryons, NL bias

Dynamical dark energy

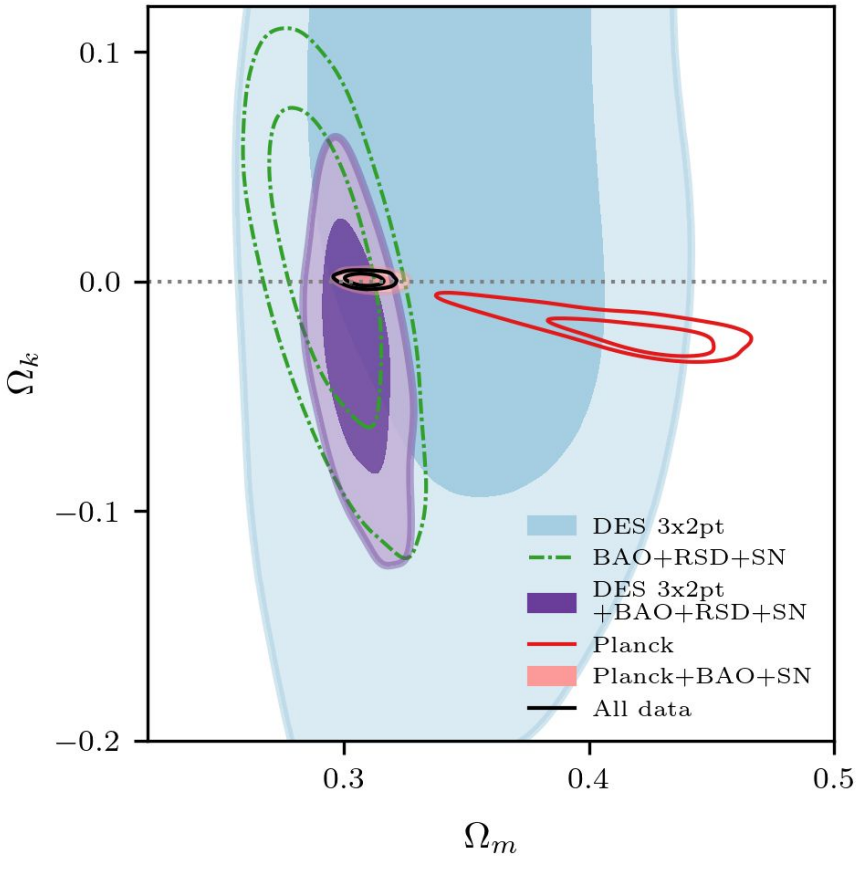


$$w(a) = w_0 + (1-a)w_a$$



Results consistent with ΛCDM (w_0,w_a)=(-1,0) for all data combinations considered.

Curvature



While **3x2pt alone** doesn't constrain Ω_k …

when combined with **BAO, SN, RSD**

it improves **constraints that can be placed without the CMB** by 20%.

(green dashed -> purple filled)

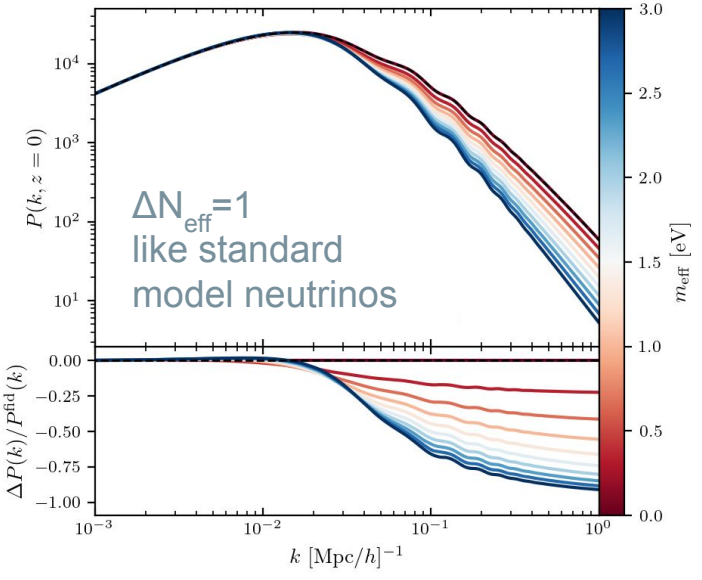
Lack of validated modeling for
- Nonlinear growth at small scales
- Non-limber projection effects for galaxy clustering @ large scales

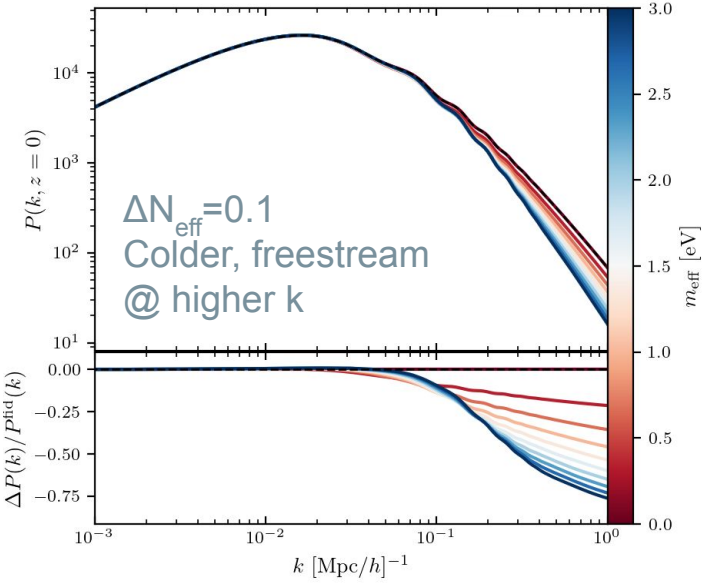
requires more conservative **scale cuts**, keeping only 221 of 462 datapoints

Planck offset reproduces previous results; tension metric just above 3σ threshold set pre-unblinding for combining datasets, but very noisy!

Massive sterile neutrinos N_{eff}, m_{eff}

$\Delta N_{eff} = N_{eff} - 3.044$





Massive sterile neutrinos N_{eff}, m_{eff}

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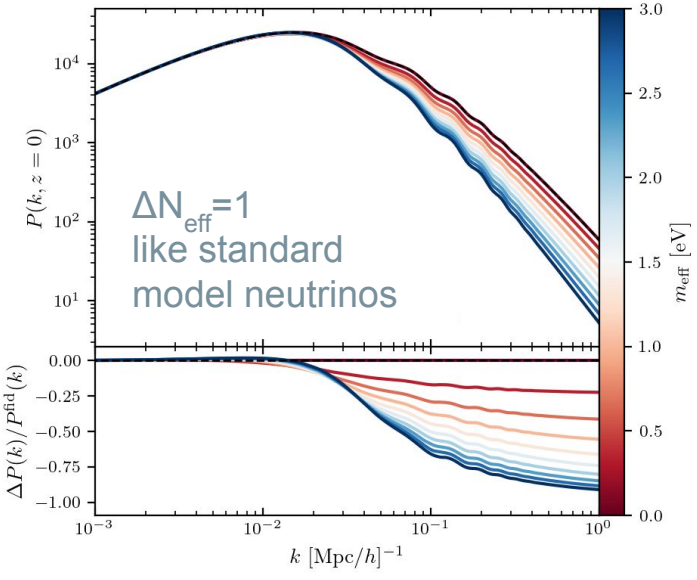
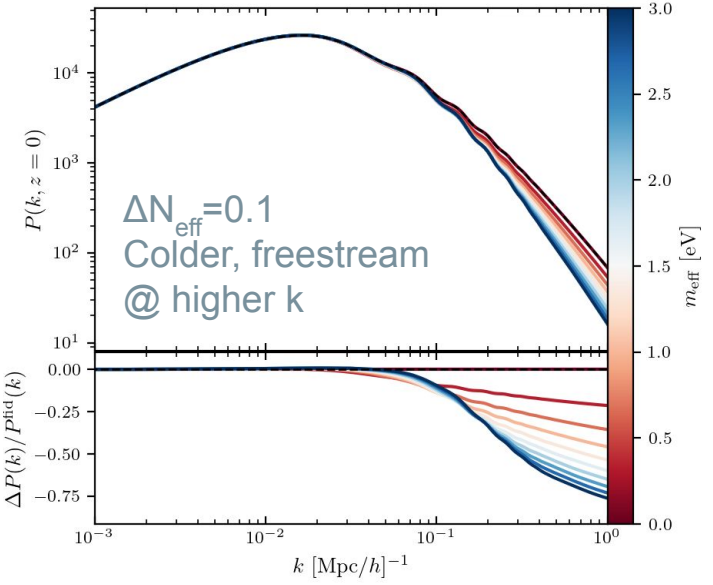
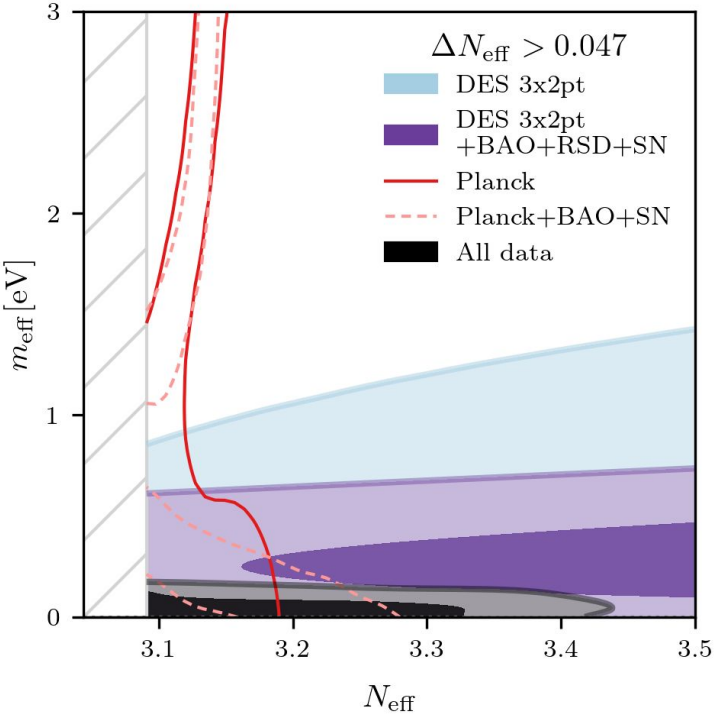






CMB constrains N_{eff} very well, while **DES 3x2pt** adds strong m_{eff} constraints.

All-data 95% upper bound on m_{eff} is 0.2eV

- factor of 3 tighter than comparable Planck 2018 analysis of CMB + BAO + CMB lensing
- Constraints depend on choice of prior handling low ΔN_{eff}

Linear scale cuts used due to lack of validated nonlinear modeling. (keeping 256 of 462 datapoints)

Tests of gravity on cosmological scales: Σ_0, μ_0

Newtonian potential

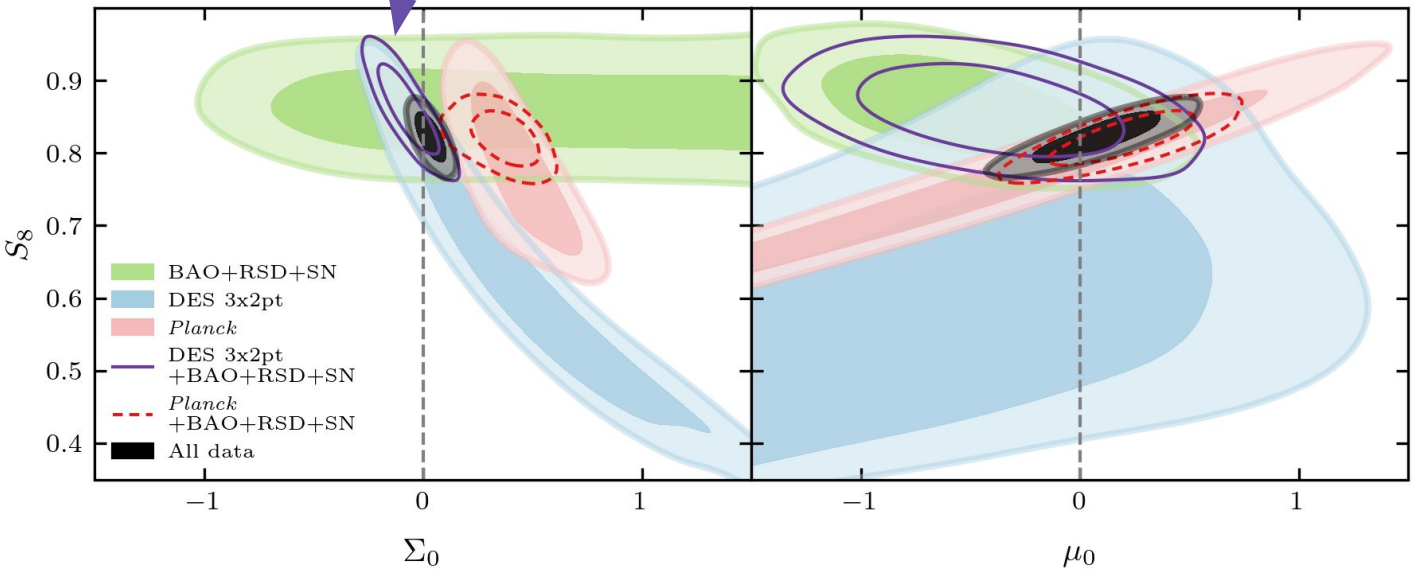
$$k^2\Psi = -4\pi G a^2 \left[1 + \mu(a,k)\right](\rho\delta + 3(\rho + P)\sigma),$$
$$k^2\Phi = -2\pi G a^2 \rho\delta \left[1 + \Sigma(a,k)\right](2\rho\delta + 3(\rho + P)\sigma)$$

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

Lensing potential

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

- Low-redshift measurements of Σ_0, μ_0
- Low-redshift vs Planck slight Σ_0 tension



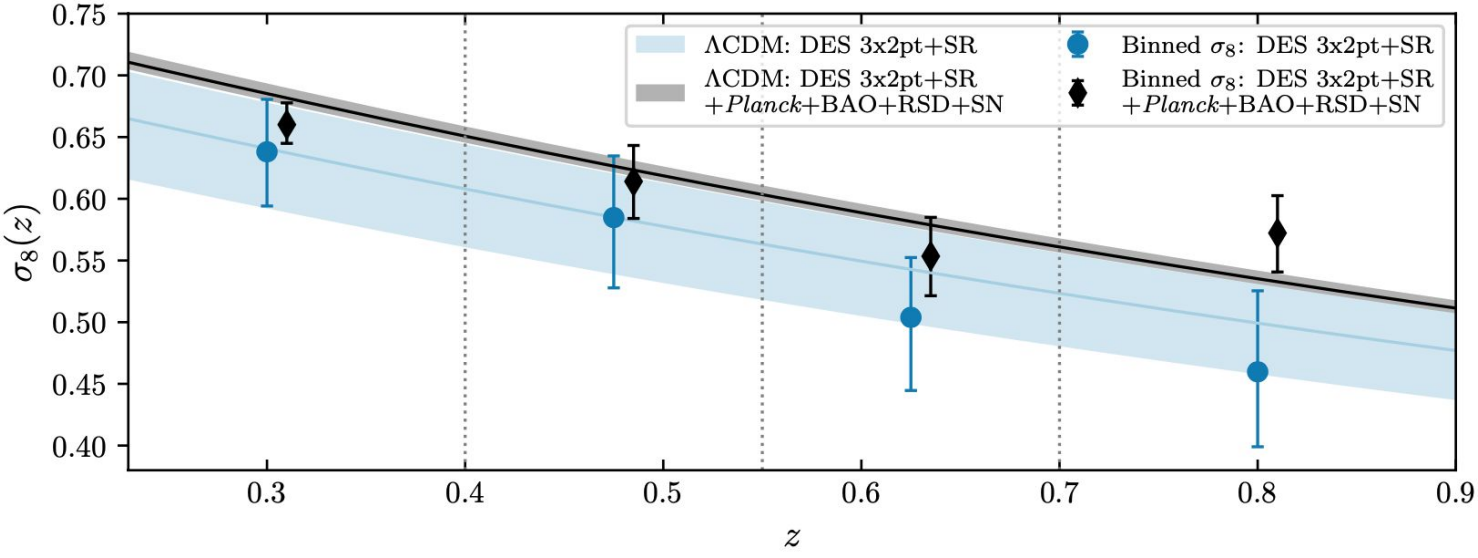
!! Scale cuts:
Limitation to DES 3x2pt precision on ∑0
Use only 20% of all data points

Binned $\sigma_8(z)$

For each redshift bin i:

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

One A_i parameter four each of the four lens bins
A_{CMB} added for CMB when Planck included

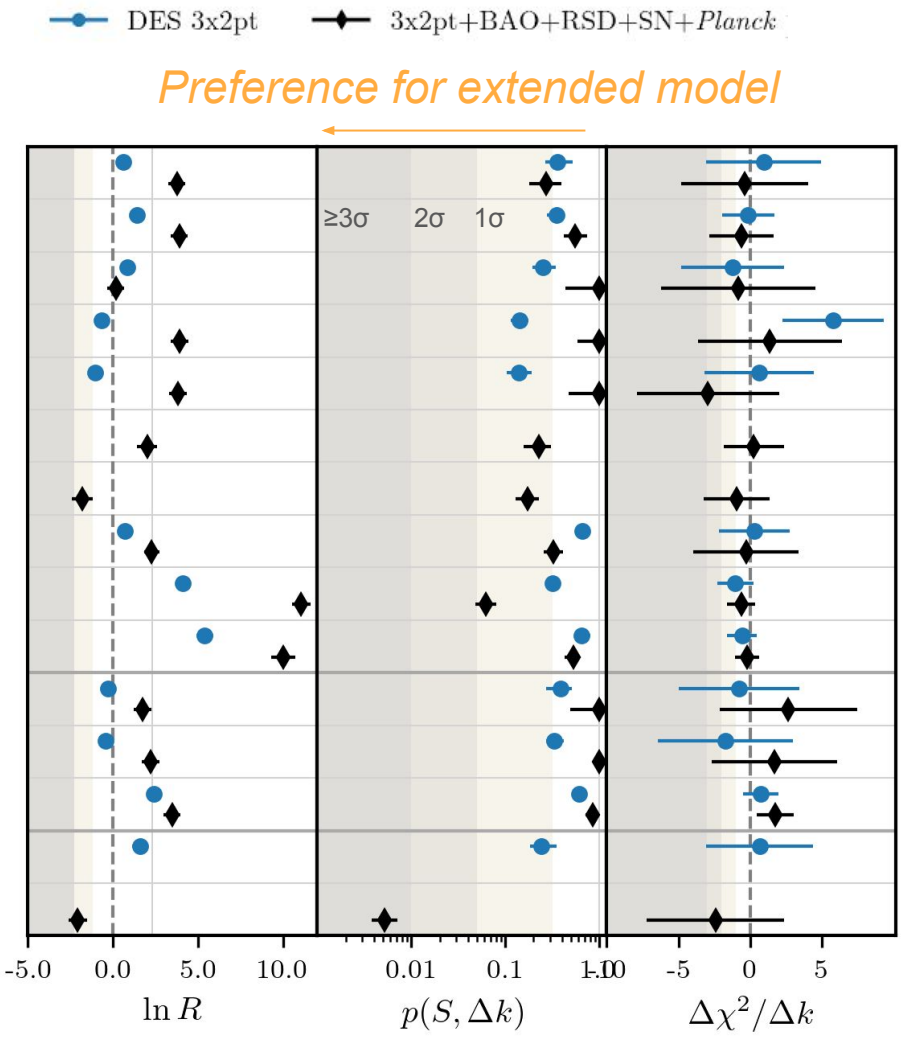


Warning!

DES-only constraints lack robustness to changes in how we account for source photo-z uncertainties.

Constraints are more robust when we combine with external data.

Model comparison tests show no significant detection of beyond-ΛCDM physics.



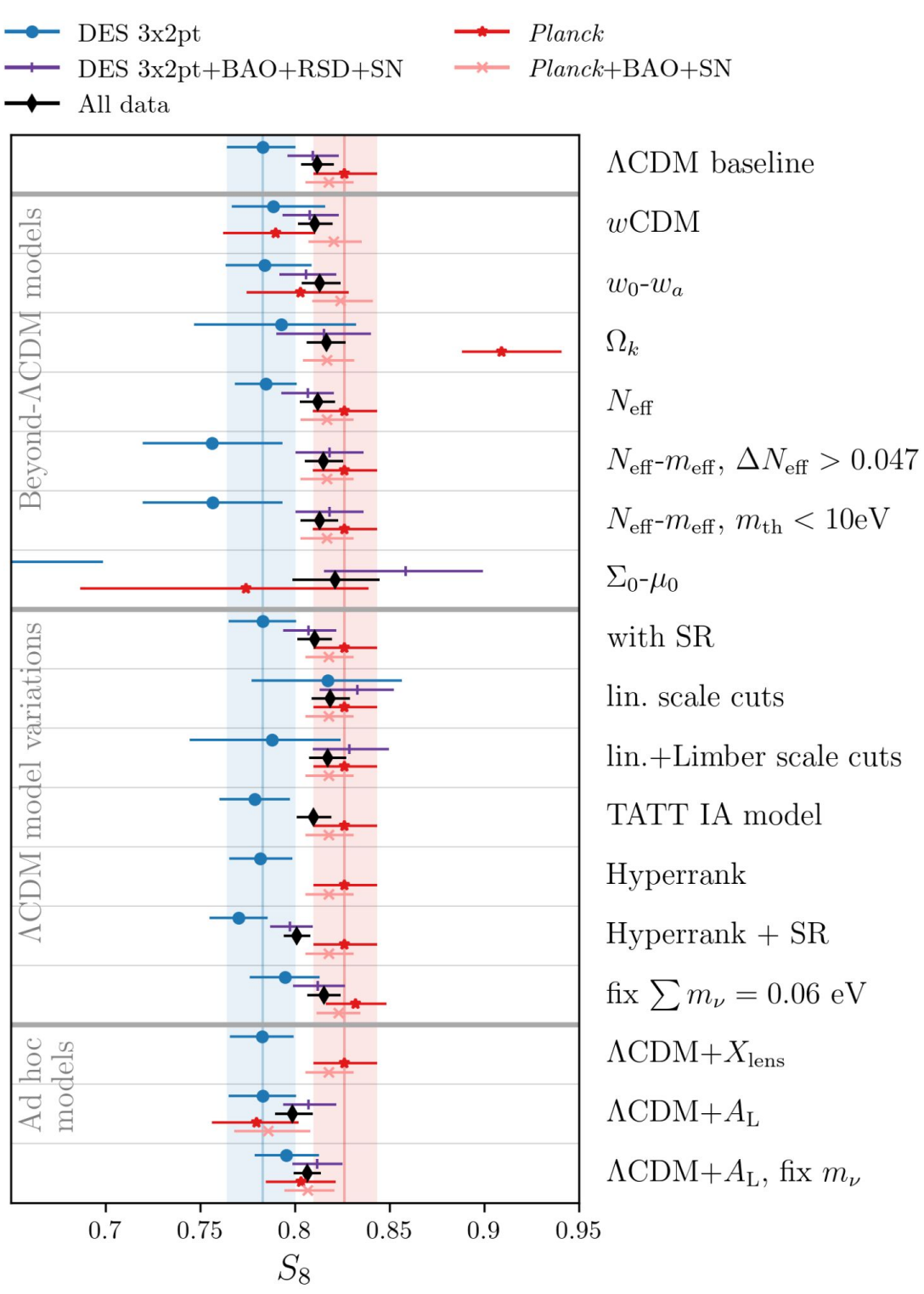
Model Comparisons

- [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

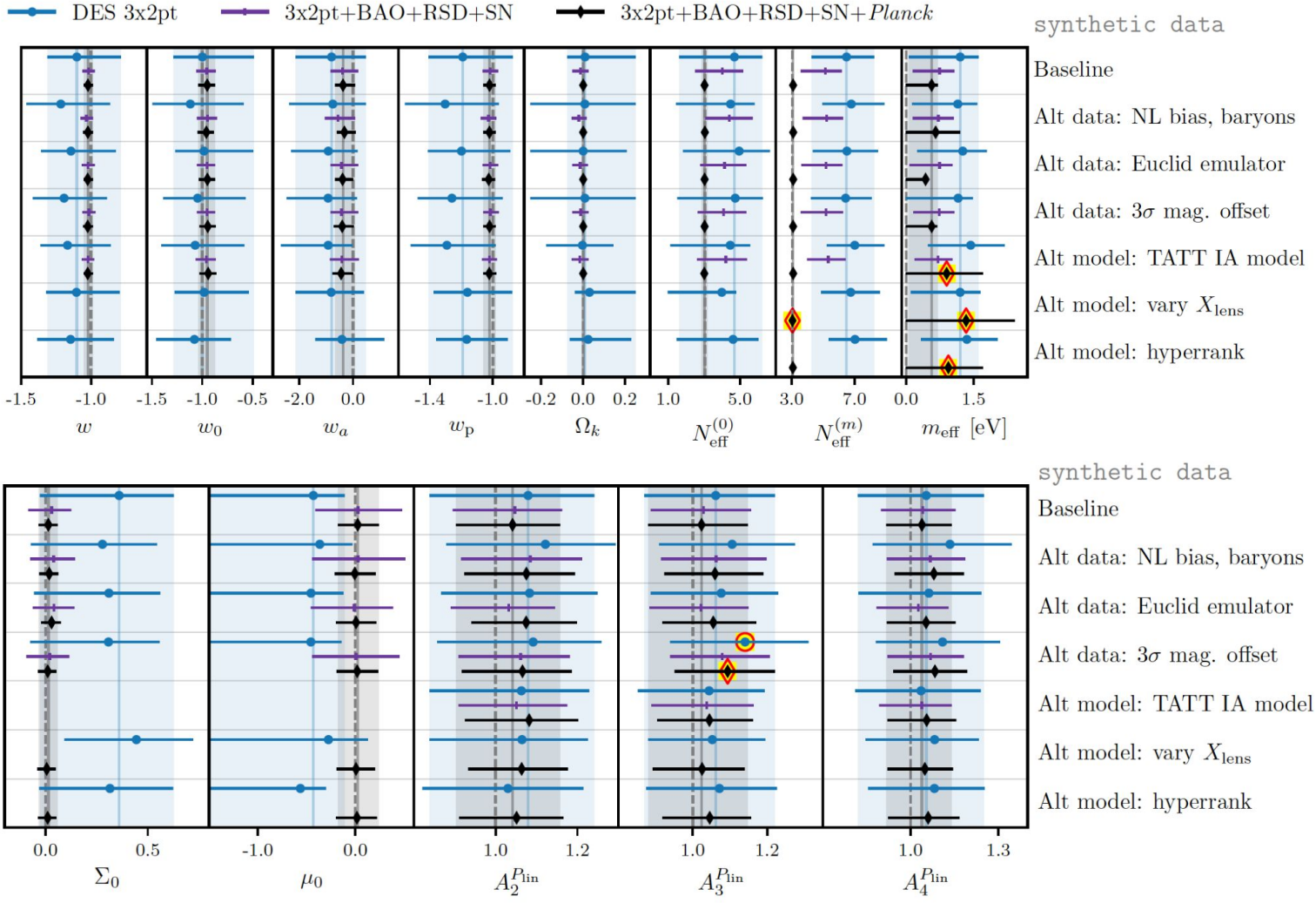
Suspiciousness p-value: Bayesian analog of $\Delta\chi^2/\Delta k$

Change in goodness-of-fit per added parameter


DES 3x2pt
DES 3x2pt+BAO+RSD+SN
All data
Planck
Planck+BAO+SN
Beyond-ΛCDM models
ΛCDM model variations
Ad hoc models
ΛCDM baseline
wCDM
w0-wa
Ωk
Neff
Neff-meff, ΔNeff > 0.047
Neff-meff, mth < 10eV
Σ0-μ0
with SR
lin. scale cuts
lin.+Limber scale cuts
TATT IA model
Hyperrank
Hyperrank + SR
fix ∑mν = 0.06 eV
ΛCDM+Xlens
ΛCDM+AL
ΛCDM+AL, fix mν
0.7
0.75
0.8
0.85
0.9
0.95
S8

Validating modeling and analysis choices

- Made analysis choices based on **simulated** data:
  - Can unmodeled systematics or changes in modeling pipeline lead to a **>0.3σ shifts** of beyond-ΛCDM parameters?
- **Didn't look** at parameter estimates or model comparison statistics until after collaboration-wide review of analysis plan



(Cartoon from #darkbites outreach project highlighting DES Y3 papers)