Title: Testing the standard cosmological model with the Dark Energy Survey

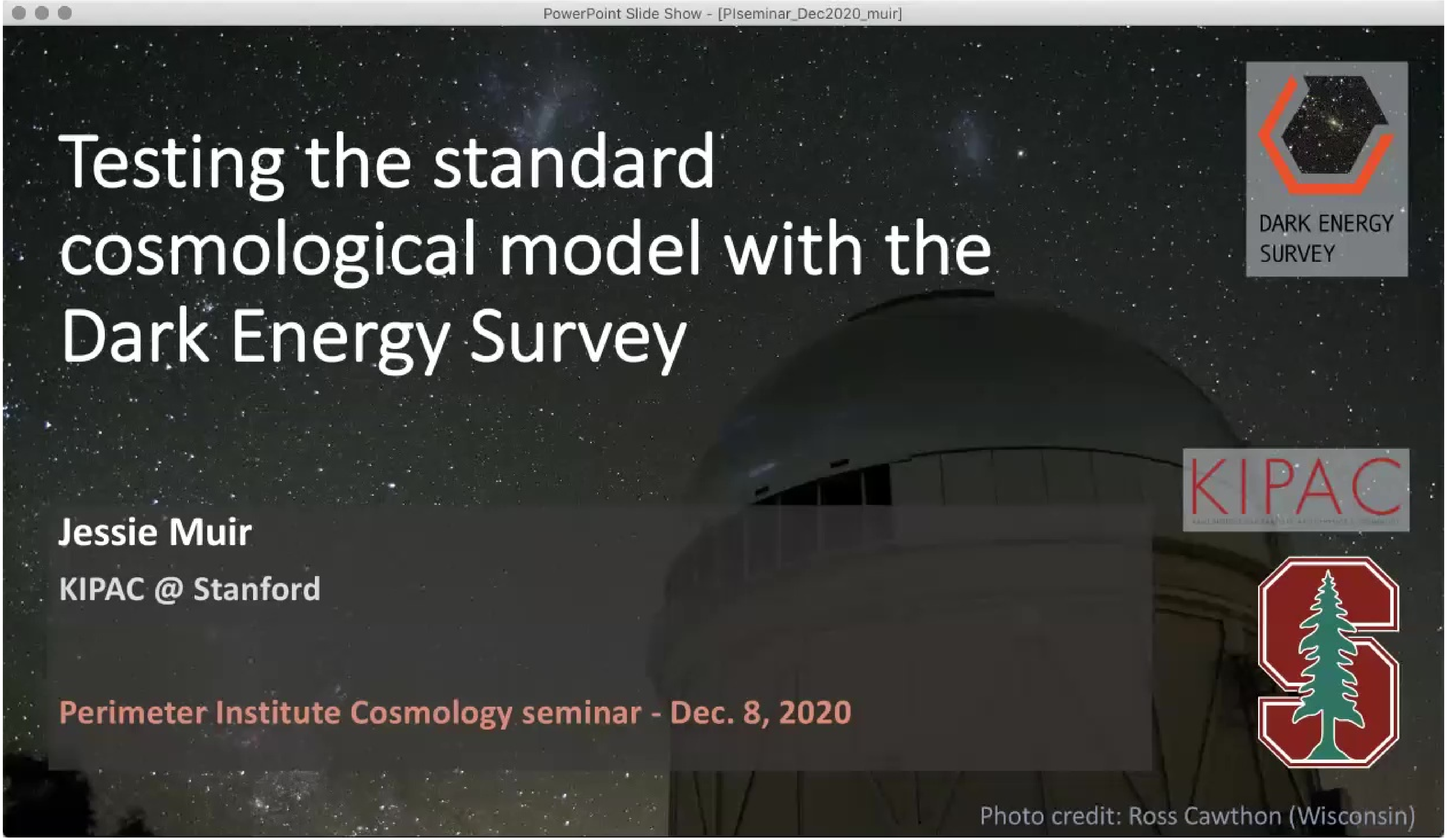
Speakers: Jessica Muir

Series: Cosmology & Gravitation

Date: December 08, 2020 - 3:00 PM

URL: http://pirsa.org/20120010

Abstract: The Dark Energy Survey (DES) is a photometric galaxy survey which, using measurements of distortions to galaxy shapes from weak gravitational lensing and other observables, we can use to test the validity of our standard cosmological model, LambdaCDM. As an example of this, I will motivate and discuss a recent analysis of the DES Year 1 data (described in https://arxiv.org/abs/2010.05924) in which we use a "growth-geometry split" parameterization to check the consistency of constraints from structure growth and expansion history. I will also highlight some of the ongoing work on the DES Year 3 analysis, as well as challenges we will face as we subject LambdaCDM to increasingly precise tests with future cosmological experiments.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Testing the standard cosmological model with the Dark Energy Survey
DARK ENERGY SURVEY
KIPAC
Jessie Muir
KIPAC @ Stanford
Perimeter Institute Cosmology seminar - Dec. 8, 2020
Photo credit: Ross Cawthon (Wisconsin)

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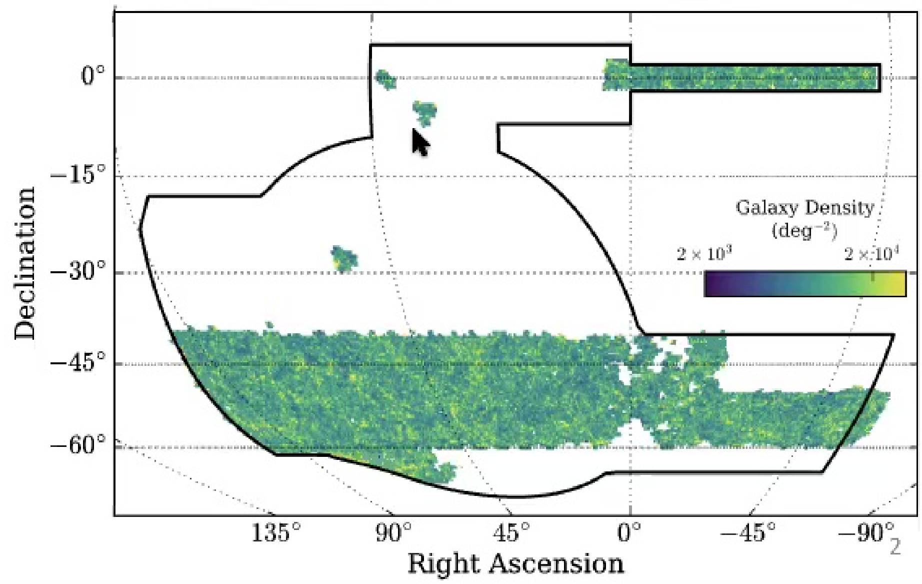
The Dark Energy Survey

Funded by U.S. DEPARTMENT OF ENERGY | Office of Science

NSF Finep GOBIERNO DE ESPAÑA MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

- 5000 sq. degree imaging survey using 4m Blanco telescope @CTIO in Chile
  - 6 years of observing ended Jan. 2019
- Probes: galaxy clustering, supernovae, galaxy cluster counts, weak gravitational lensing
- Y1: 1300 sq. deg, 40% depth
  - Many papers published of results starting in 2017
- Y3: 5000 sq. deg, 50% depth
  - Data processed, analysis almost done!
- International collaboration of ~700 participants



NCSA ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich LMU SLAC

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Outline

- Constraining cosmology with DES
- Growth-geometry split analysis of DES Y1 data (arXiv:2010.05924)
- DES Y3 and beyond

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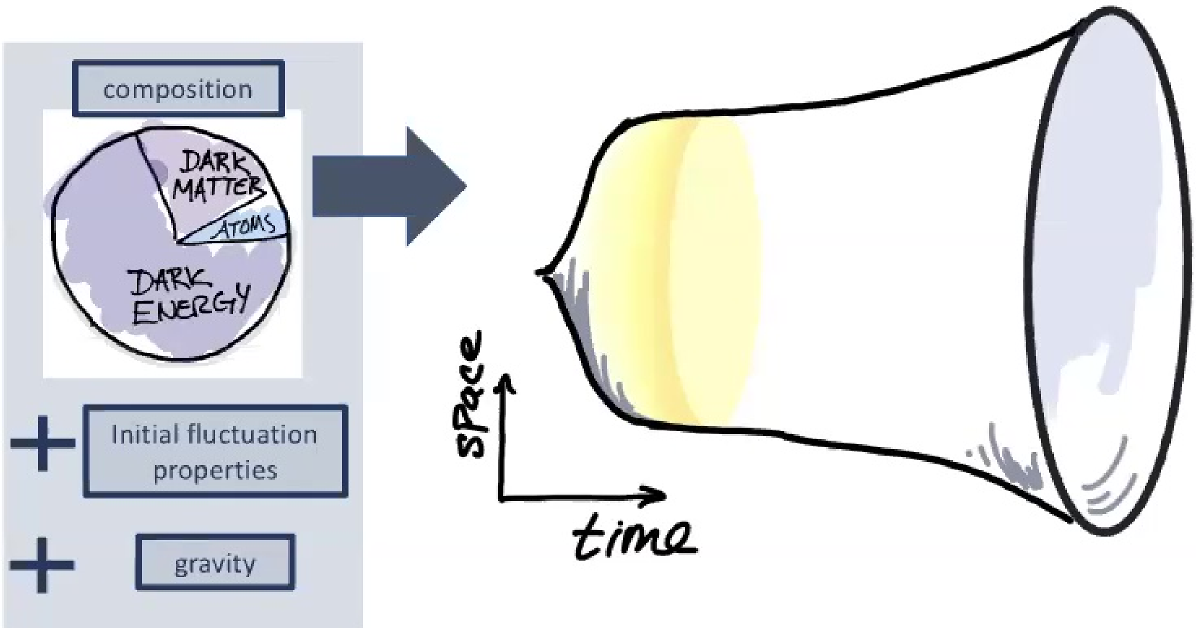
Our goal is to learn about fundamental physics by testing the predictions of ΛCDM.



ΛCDM:

- Dark energy as a cosmological constant (Λ)
- CDM: Cold dark matter
- Flat geometry: $\Omega_\Lambda + \Omega_m = 1$
- Gaussian initial fluctuations w. nearly scale-invariant power spectrum (A_s, n_s)
- Gravity described by General relativity

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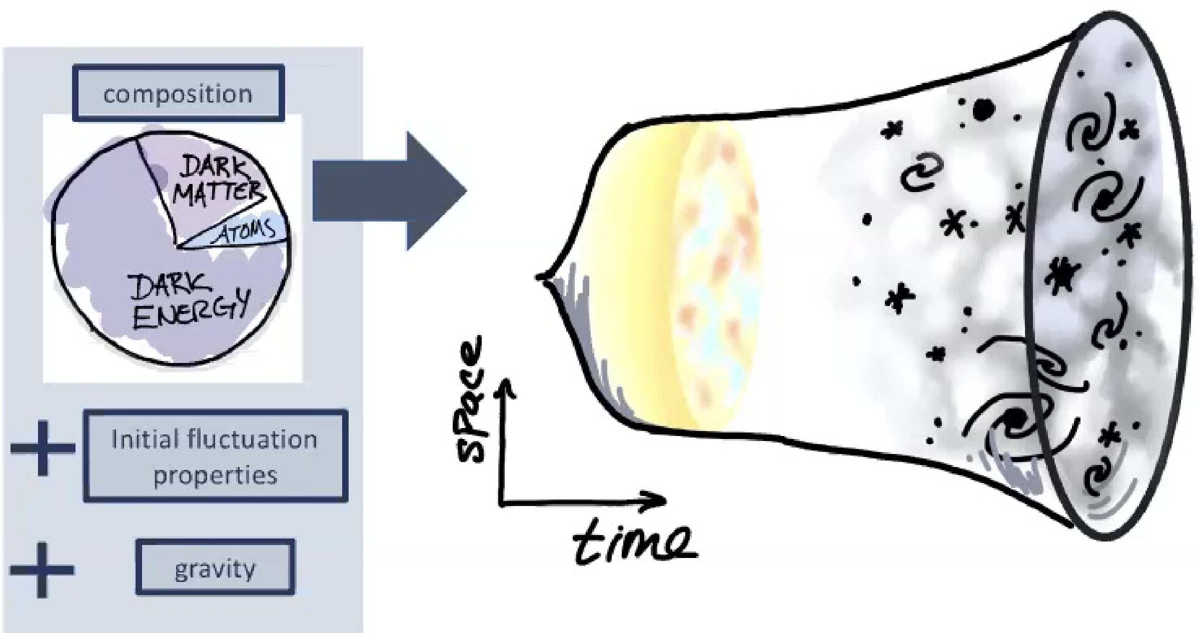

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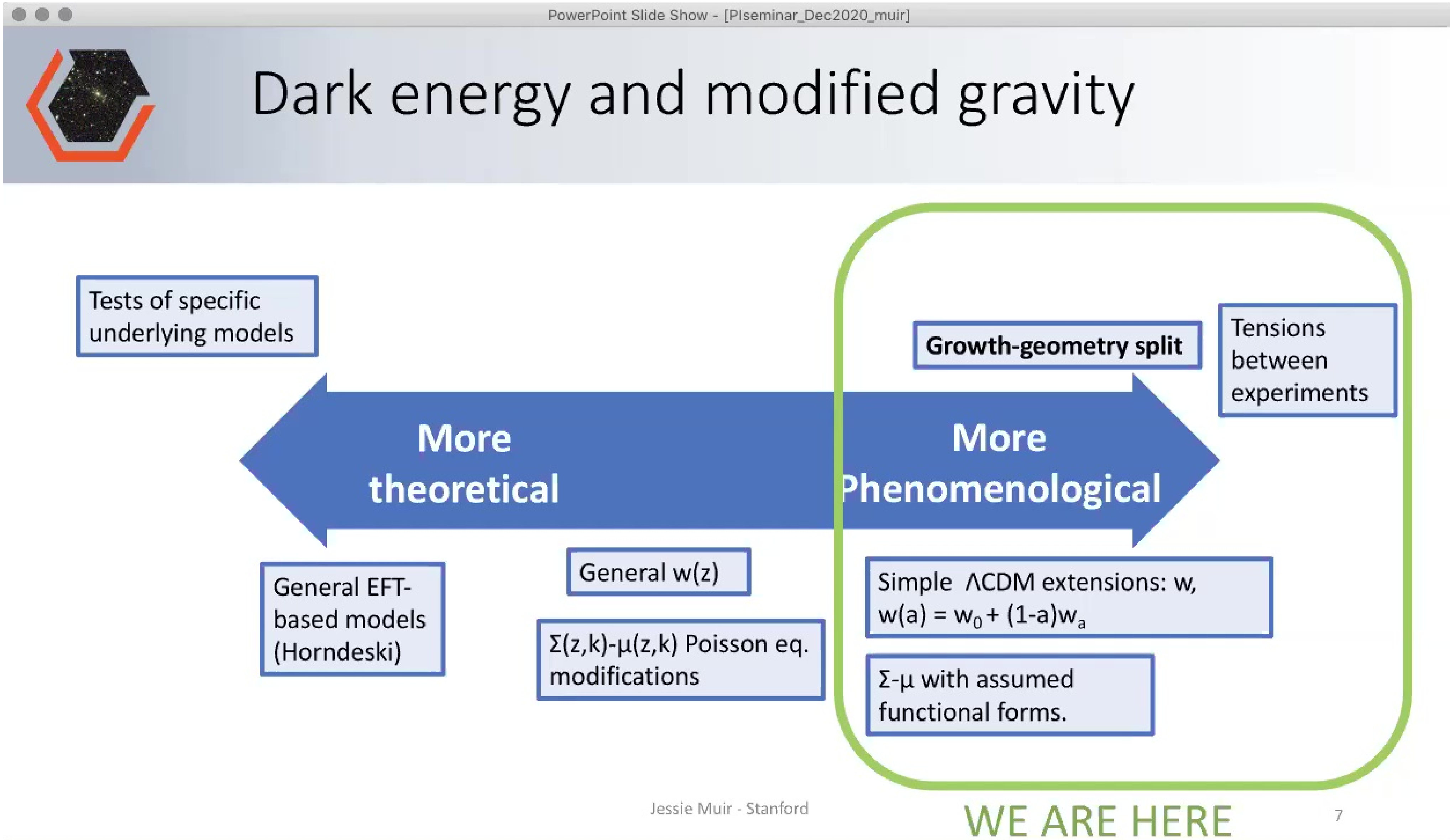
Dark Energy and Modified gravity

- Why is Λ so small?
- Could accelerating expansion be due to deviation from GR?
- More conservatively: is GR well tested on cosmological scales?

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Curvature of spacetime — Matter and energy

Einstein's equation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Dark energy and modified gravity
Tests of specific underlying models
Growth-geometry split
Tensions between experiments
More theoretical
More Phenomenological
General EFT-based models (Horndeski)
General w(z)
Σ(z,k)-μ(z,k) Poisson eq. modifications
Simple ΛCDM extensions: w, w(a) = w0 + (1-a)wa
Σ-μ with assumed functional forms.
Jessie Muir - Stanford
WE ARE HERE
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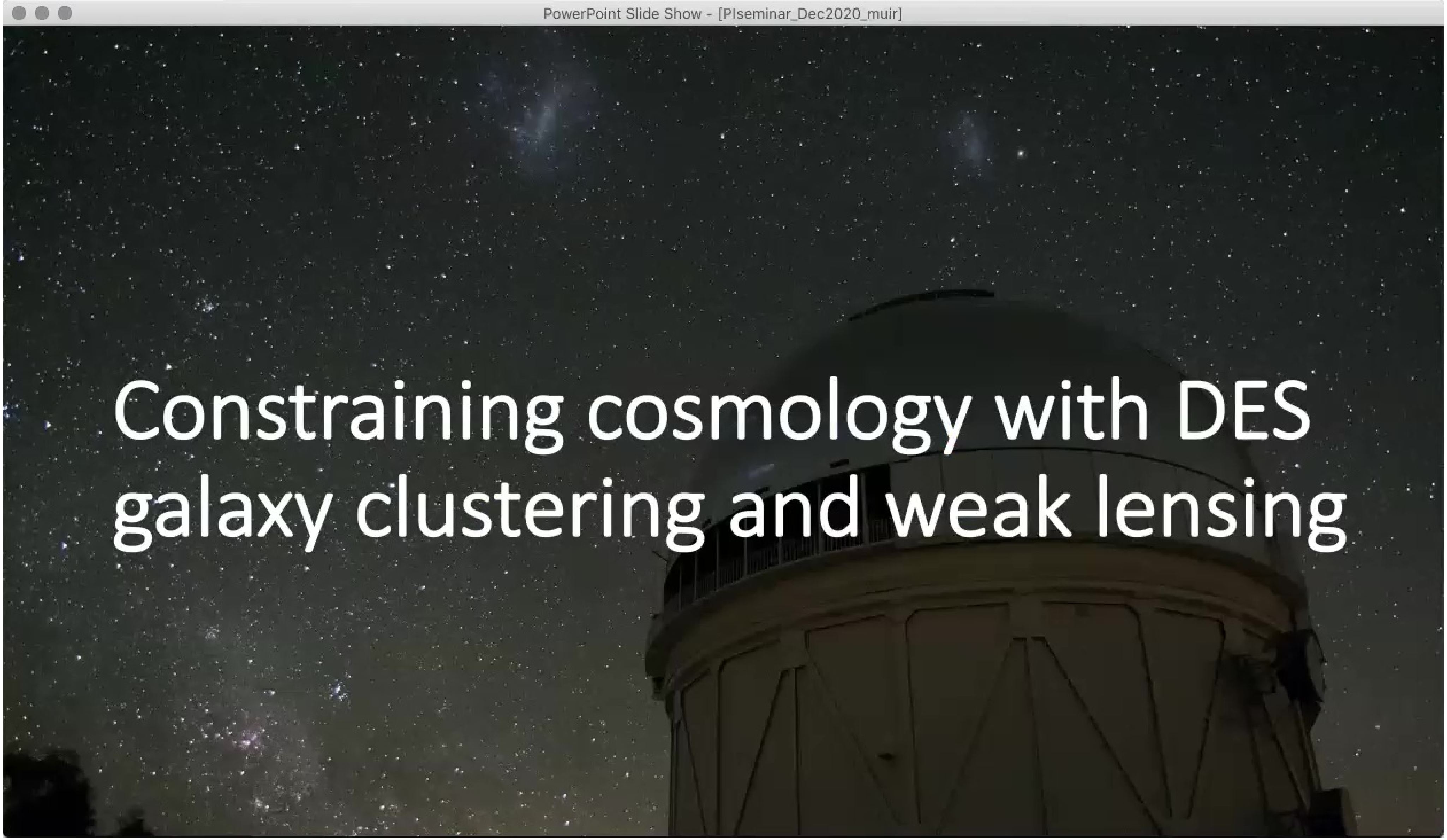
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Constraining cosmology with DES galaxy clustering and weak lensing

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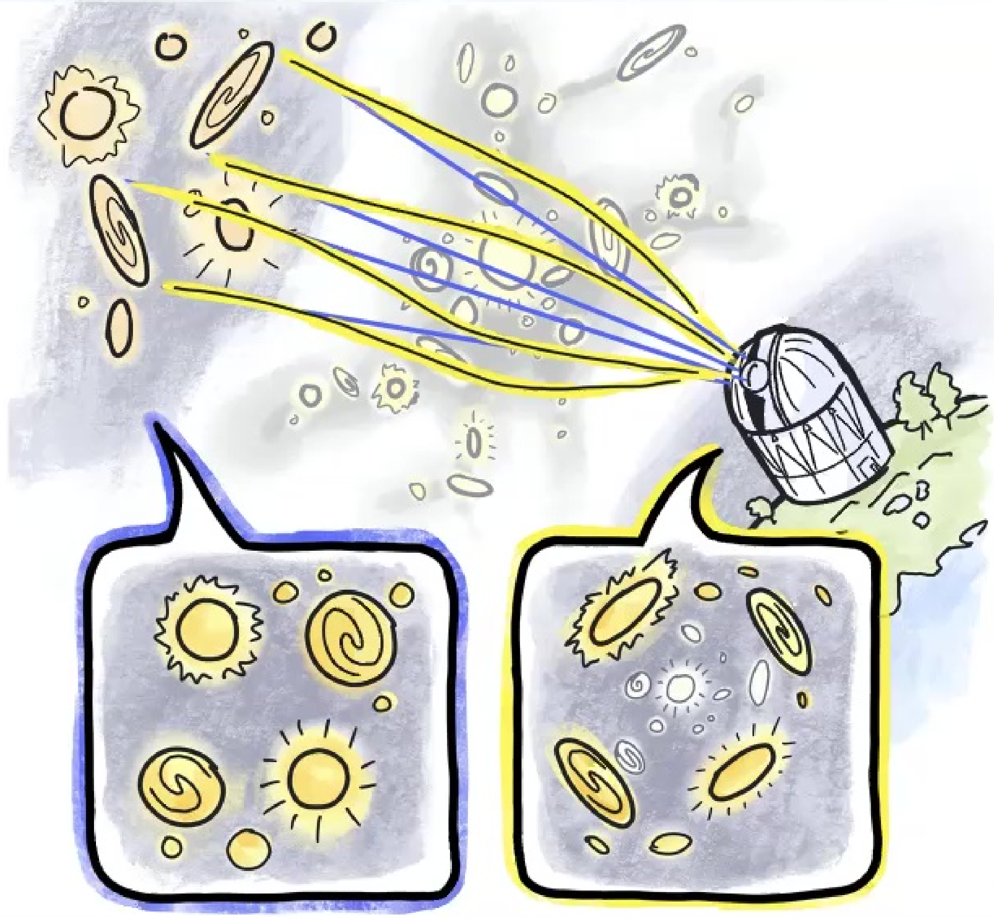
DES maps large scale structure

Large scale distribution of matter traced by

- Galaxy positions
  - Photometric redshifts: Galaxy line-of-sight distances from grizY color.
- Weak lensing shear



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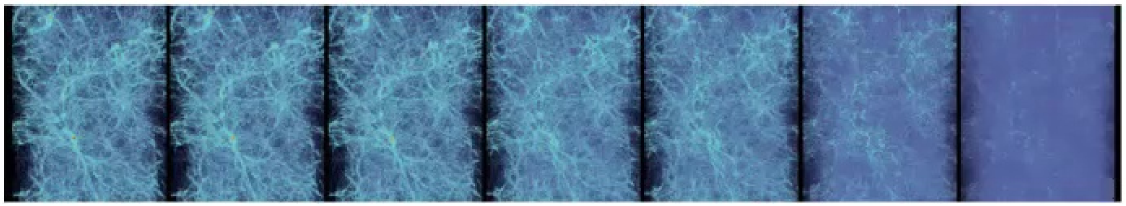
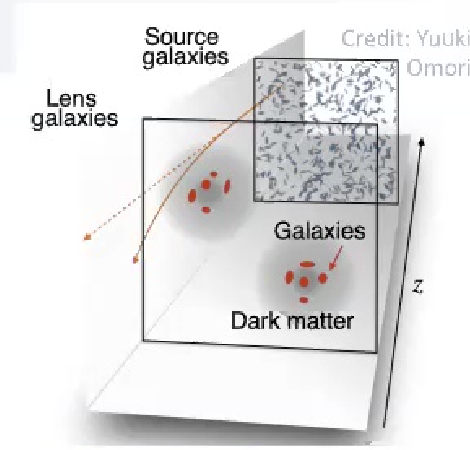
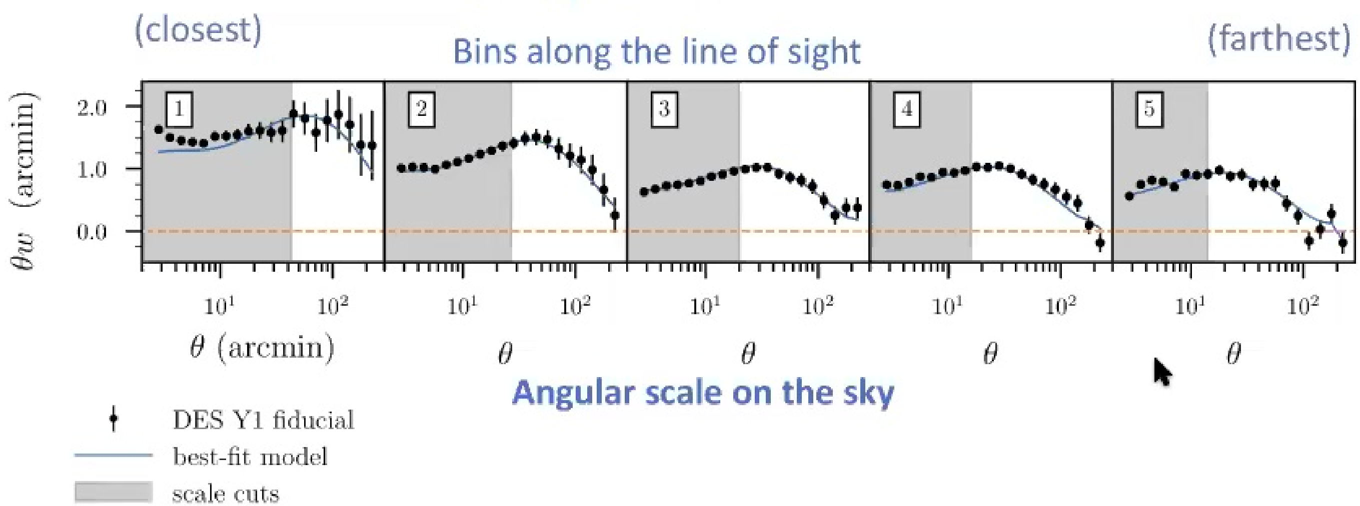
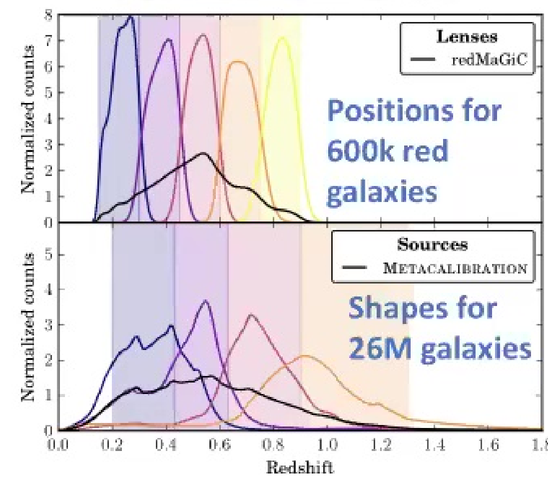
Summary statistic: 2pt angular correlations





DES Y1: correlations between galaxy positions

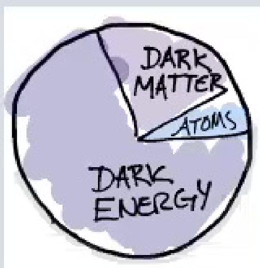




Plots from DES Collaboration 2017, arXiv:1708.01530

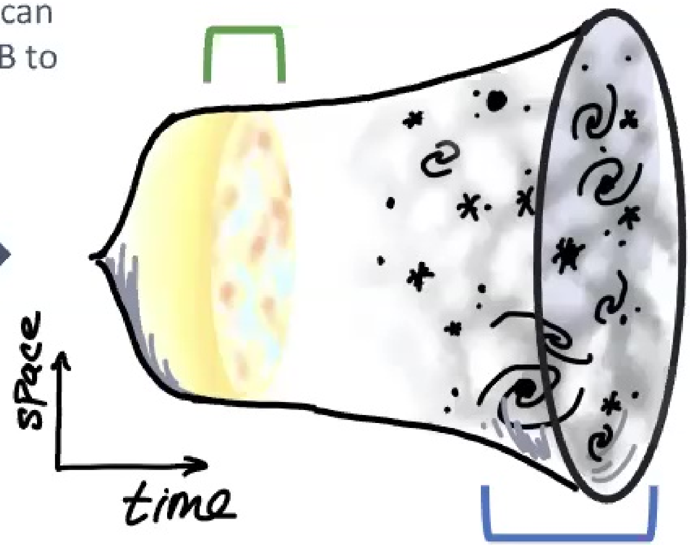
Testing ΛCDM via consistency with other probes

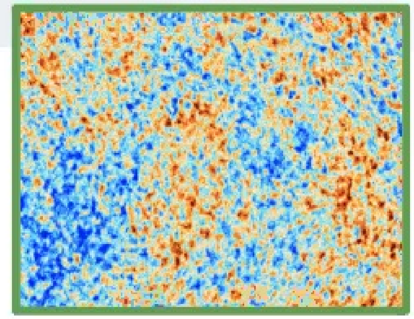
Given a cosmological model, we can extrapolate constraints from CMB to make predictions for LSS.



+ General relativity

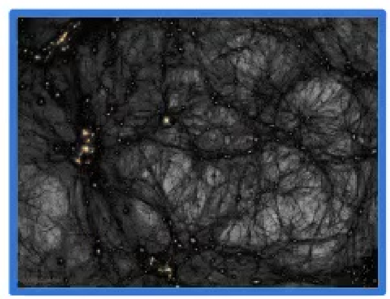
+ Initial fluctuation properties





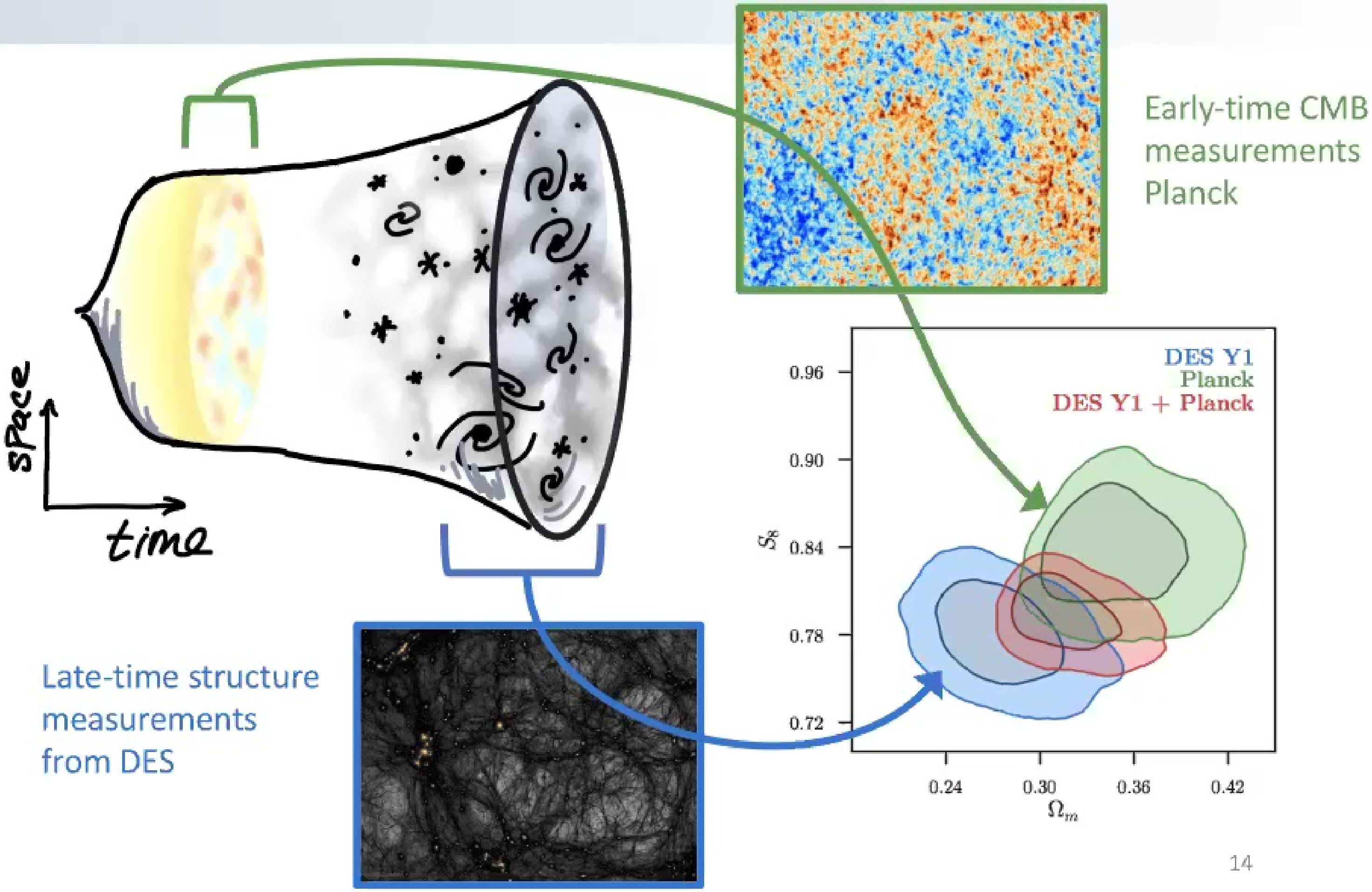
Early-time CMB measurements Planck

Late-time structure measurements from DES



Testing ΛCDM via consistency with other probes

- Plot from Abbott et al, arXiv:1708.01530
- DES & Planck constraints on Ω_m and S_8 are comparable.
- Central values different by 1-2σ, in same direction as prev. lensing results.
- Bayes factor 4.2; not statistically inconsistent
  - but see Handley & Lemos for discussion arXiv: /1902.04029



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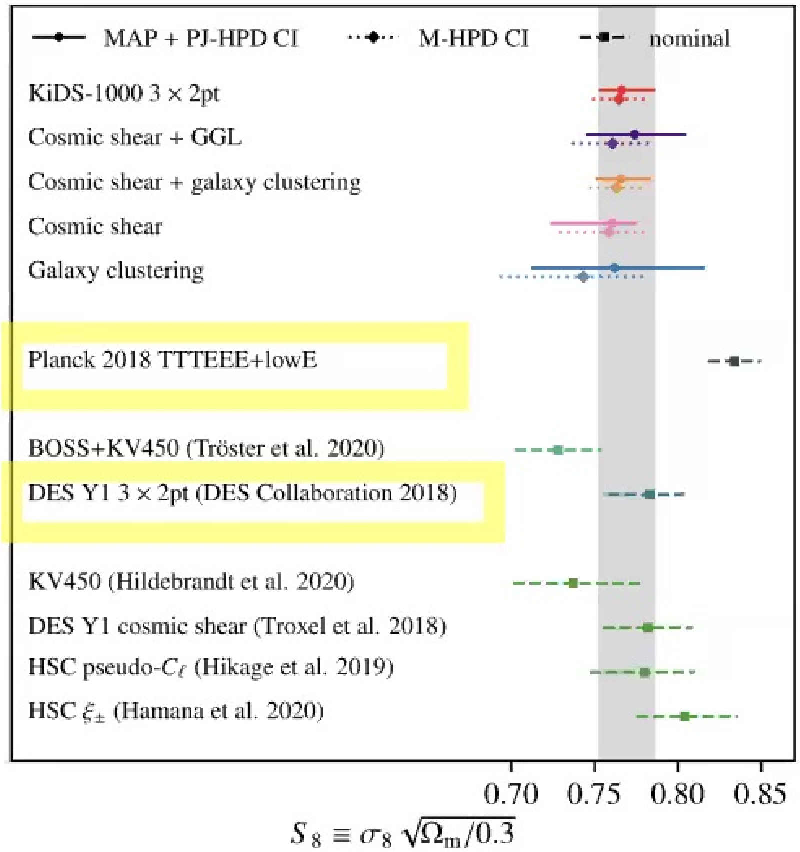
DES observes a S8 offset in the same direction as other weak lensing experiments.

- Summary plot from KiDS 1000 cosmology results paper Heymans et al 2020, arXiv:2007.15632



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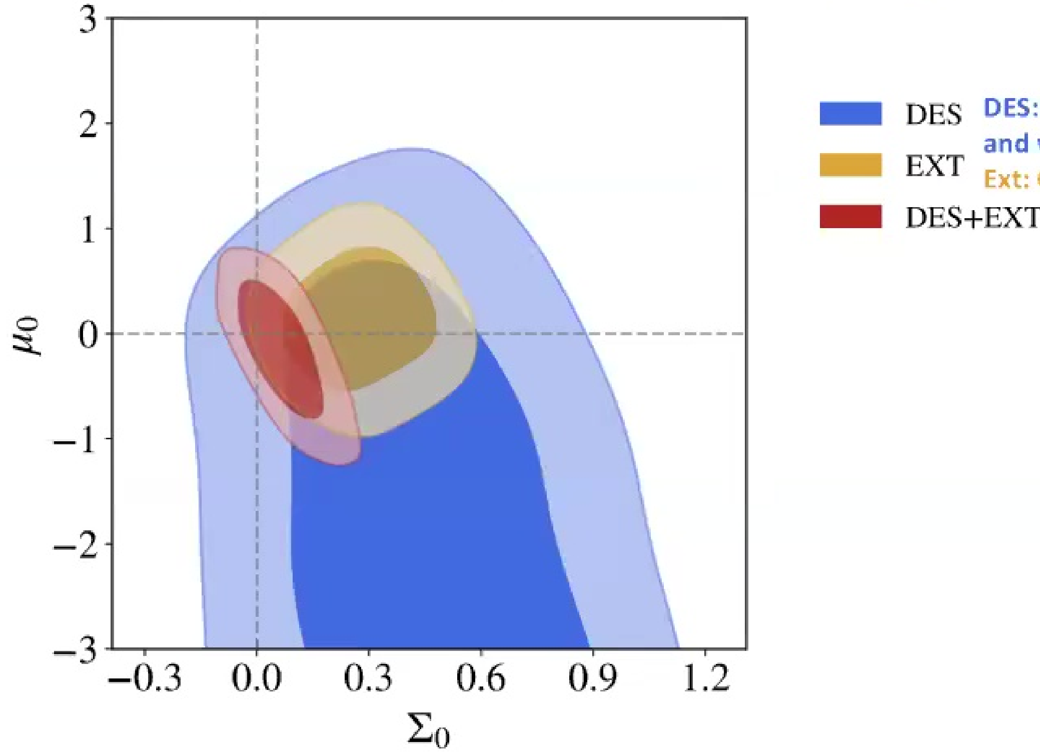
DES constraints on extended models test for phenomenological deviations from ΛCDM.

$$k^2\Psi = -4\pi G a^2(1+\mu(a))\rho\delta$$ <- matter

$$k^2(\Psi+\Phi) = -8\pi G a^2(1+\Sigma(a))\rho\delta$$ <- lensing

Results from DES Y1 Galaxy Clustering and Weak Lensing
DES Collaboration 2019
arXiv:1810.02499



DES: Y1 galaxy clustering and weak lensing
Ext: CMB+Sne+BAO+RSD

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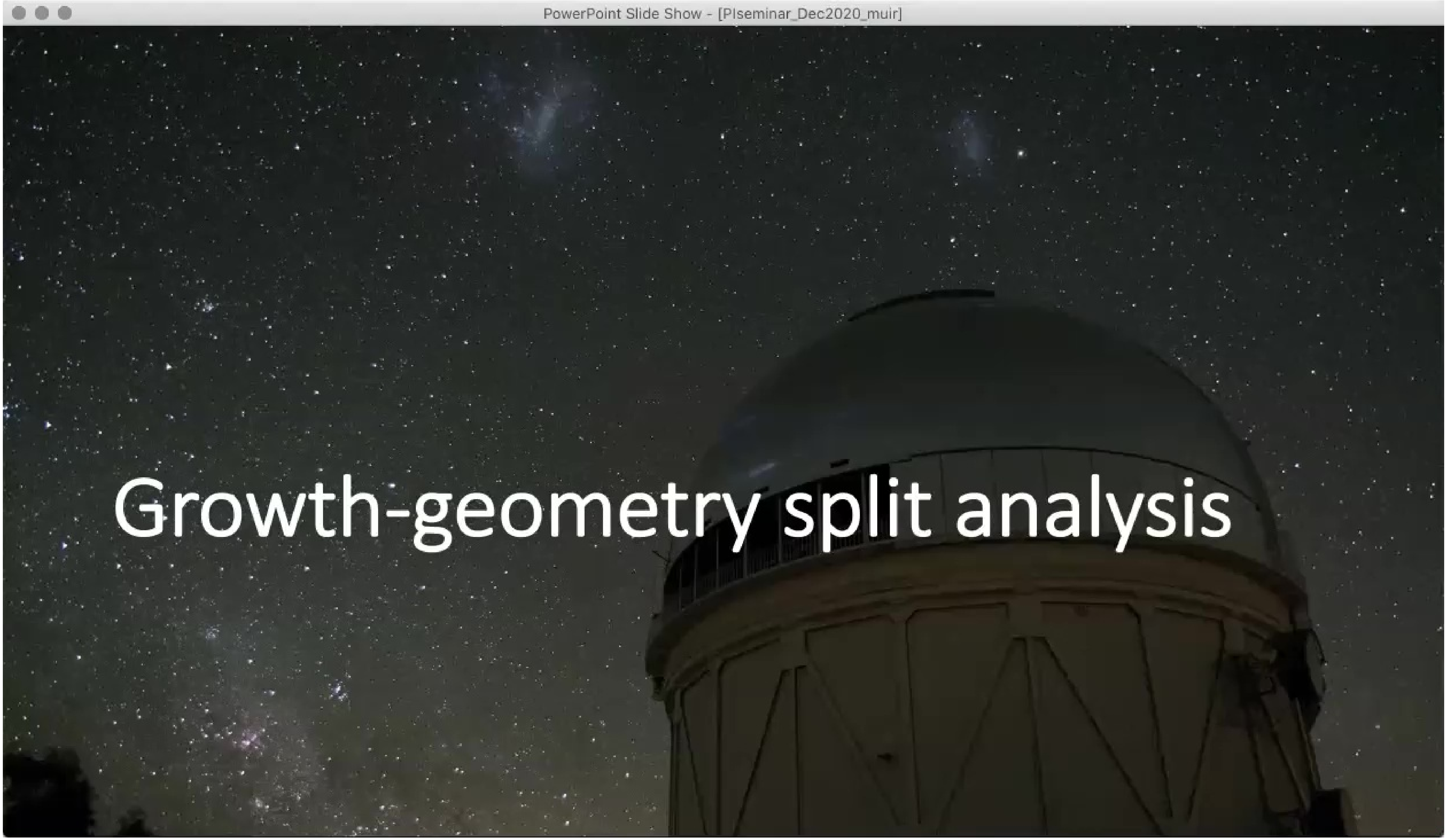
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Growth-geometry split analysis

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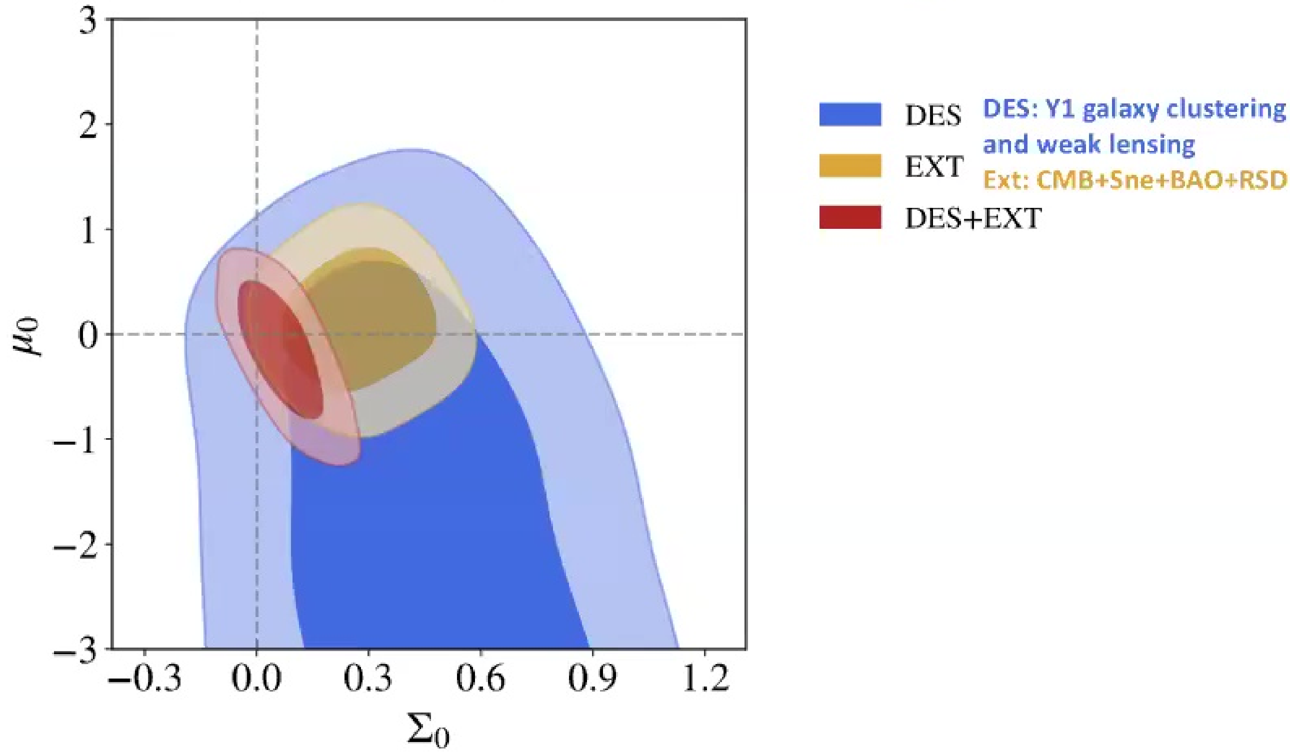

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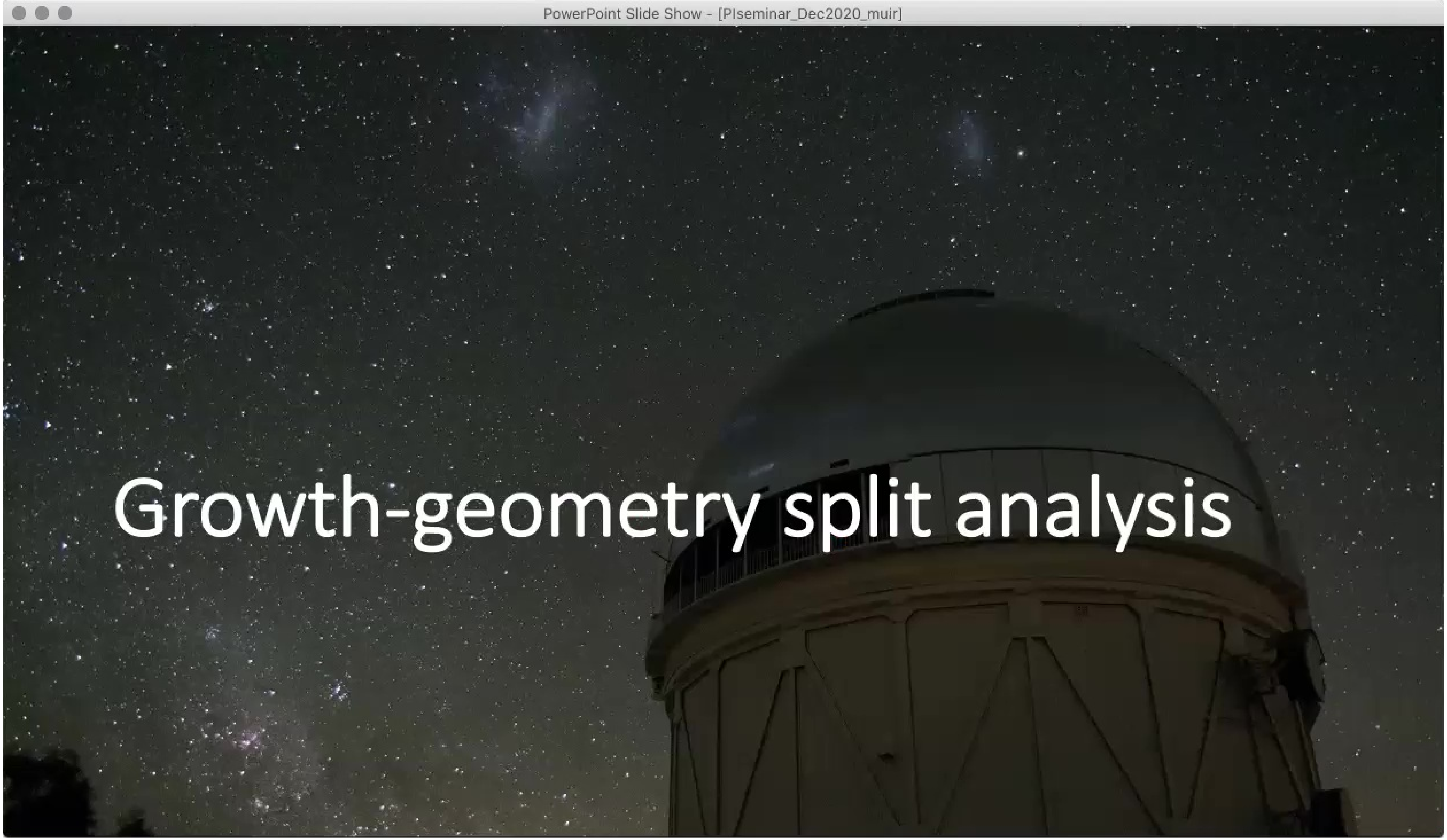
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Growth-geometry split analysis

Growth-geometry split

JM, Eric Baxter, Vivian Miranda, Cyrille Doux, Agnes Ferte, Danielle Leonard, Dragan Huterer, Bhuv Jain, et al (DES Collab) PRD 2020, arXiv:2010.05924

- **Goal:** Test consistency of cosmological constraints from expansion history (geometry) and structure growth.
- **Motivation:** Extensions to LCDM can break the expected relationship between structure growth and expansion history.
- **Method:**
  - Split cosmological parameters related to dark energy properties into "grow" and "geo" versions.
  - Constrain simultaneously, check consistency with grow = geo

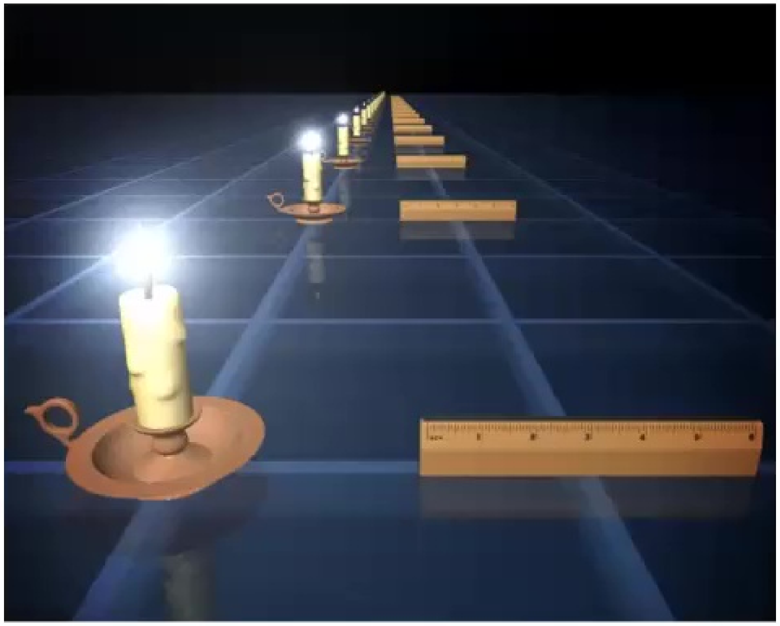
$$\Omega_m \quad \Rightarrow \quad \Omega_m^{\rm grow}, \ \Omega_m^{\rm geo}$$

See also: Wang et al 2007, arXiv:0705.0165
Ruiz and Huterer, 2014, arXiv:1410.5832
Bernal, Verde, and Cuesta 2016, arXiv: 1511.03049

Setting up split analysis for DES Y1

Some probes can be can be cleanly separated

- Geometry probes
  - Supernovae distances
  - BAO measurements
  - Angular scale of CMB power spectrum peak
- Growth probes
  - Redshift space distortions (RSD)



Credit: NASA/JPL-Caltech/R. Hurt (SSC).

DES observables are sensitive to both growth and geometry.

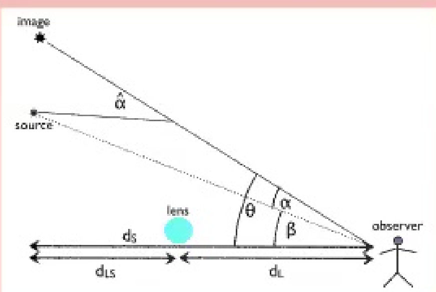
Angular correlation for z-bins i & j for A-B =

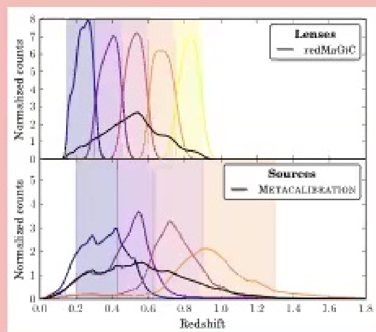
- Galaxy-galaxy
- Shear-shear
- Galaxy-shear

Redshift distribution of sources, lensing kernel

$$C^{ij}_{AB}(\ell) = \int d\chi \, \frac{q^i_A(\chi) q^j_B(\chi)}{\chi^2} \left[P\left(k, z(\chi)\right) \right]_{k=(\ell+\frac{1}{2})/\chi}$$

Projection onto the sky





Matter power spectrum

$$P(k,z) = \frac{P^{\mathrm{geo}}(k, z_i)}{P^{\mathrm{grow}}(k, z_i)} P^{\mathrm{grow}}(k, z)$$

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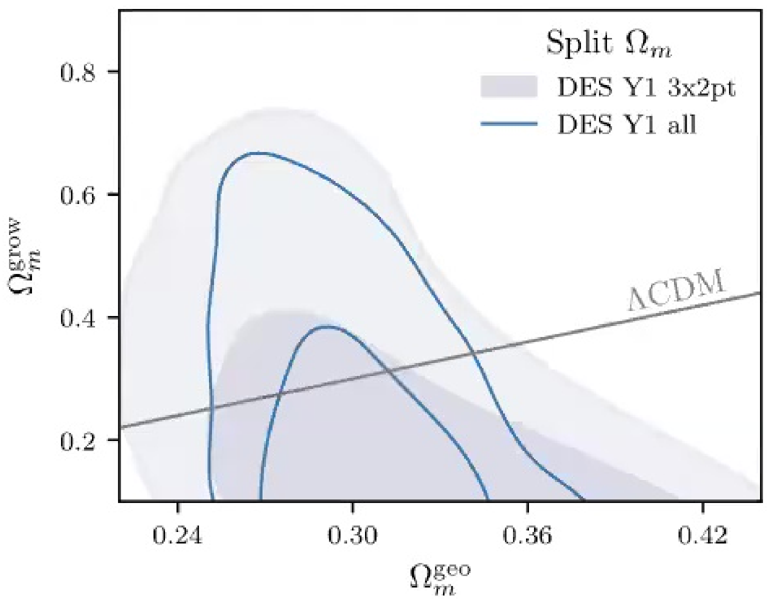
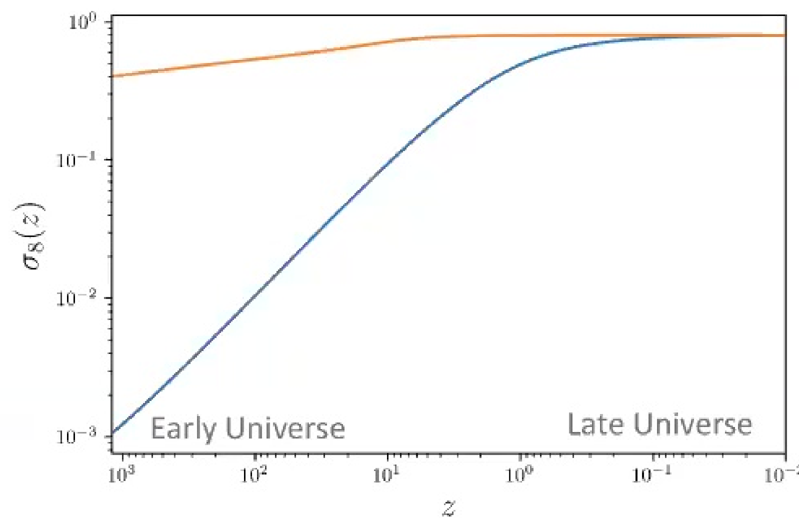
DES alone can only put upper bounds on Ω_m^{grow}.

DES "Year 1 all"

- Y1 galaxy clustering + WL [grow+geo]
- Y1 BAO [geo]
- Y3 SN + lowZ SN [geo]





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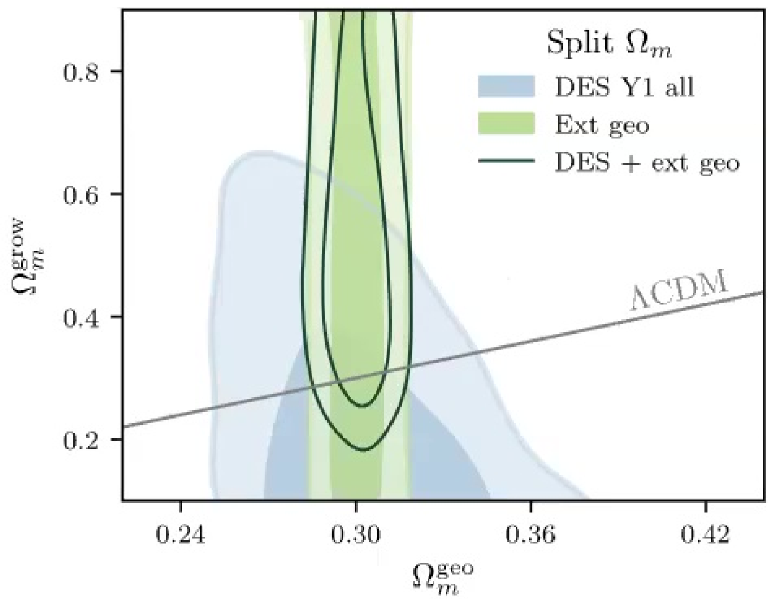
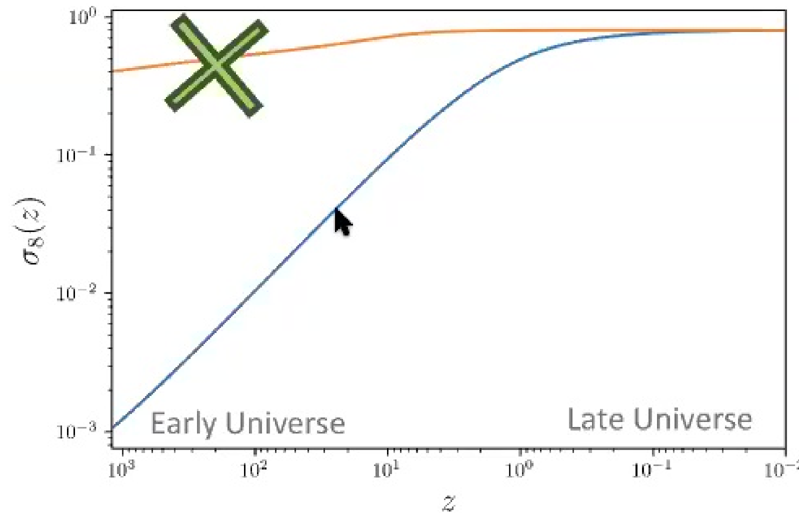
Adding external geometric data, Planck constraint on A_s helps break degeneracy.

DES "Year 1 all"
- Y1 galaxy clustering + WL [grow+geo]
- Y1 BAO [geo]
- Y3 SN + lowZ SN [geo]

"Ext geo" [geo]
- BOSS DR12 BAO
- Planck 2015 constraints on A_s, n_s, R_{shift}, $\Omega_b h^2$, l_A





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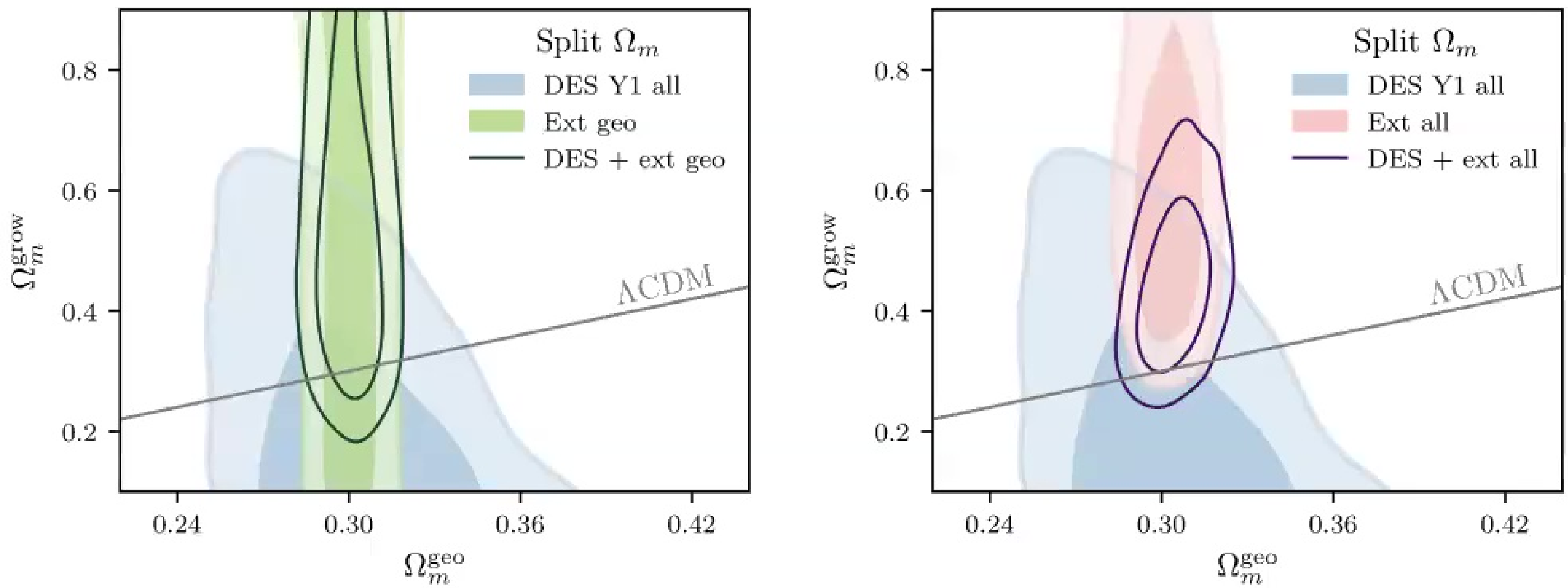
Adding RSD as additional growth probe allows two-sided constraints on Ω_m^{grow}.

DES "Year 1 all"
- Y1 galaxy clustering + WL [grow+geo]
- Y1 BAO [geo]
- Y3 SN + lowZ SN [geo]

"Ext geo" [geo]
- BOSS DR12 BAO
- Planck 2015 constraints on A_s, n_s, R_{shift}, $\Omega_b h^2$, l_A

"Ext all"
- Ext geo [geo]
- BOSS DR12 RSD [grow]



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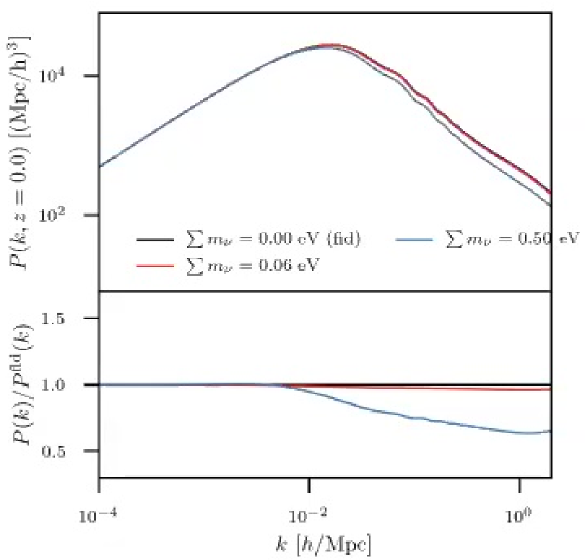
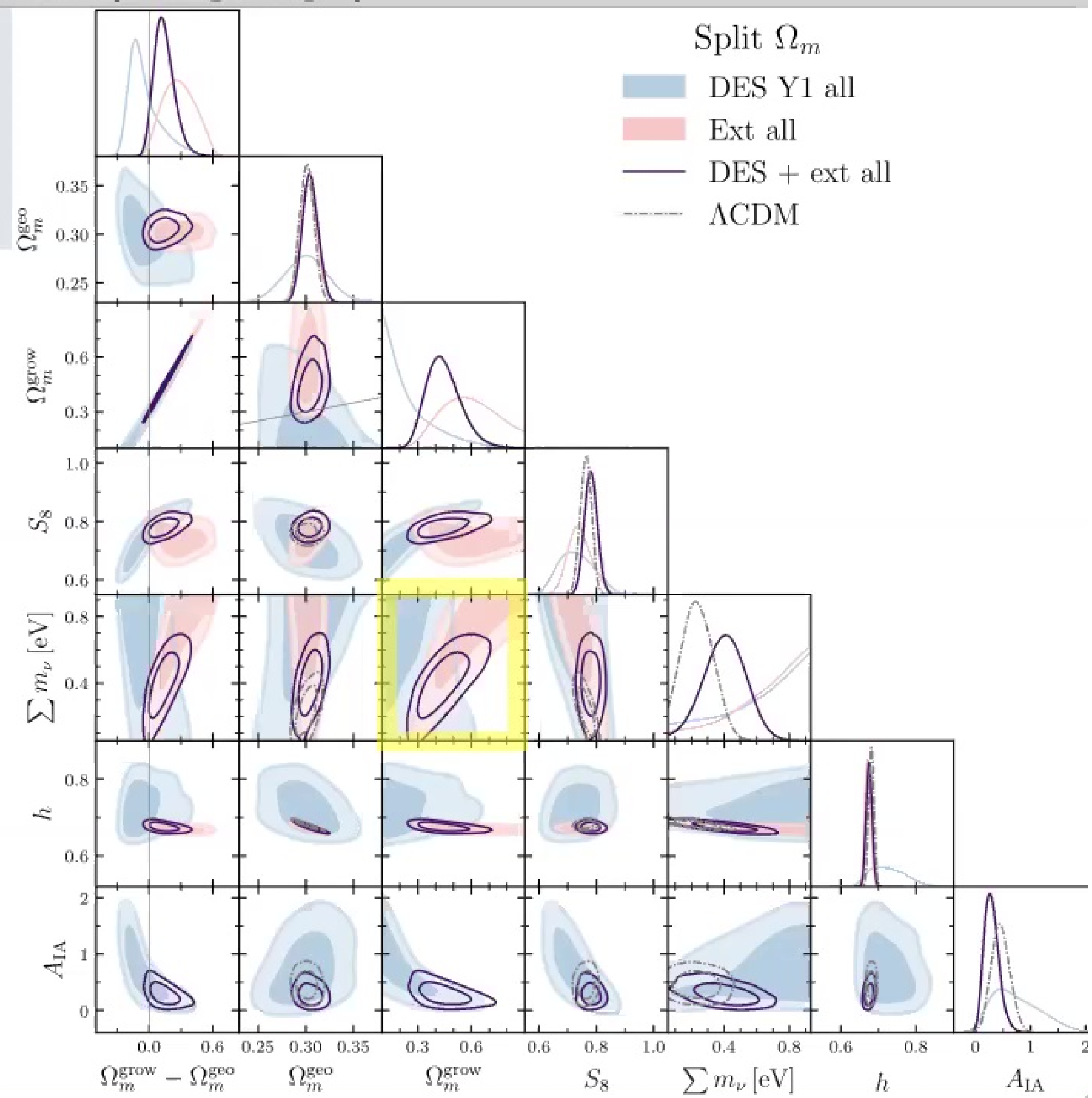
Growth and neutrino mass

Massive neutrinos suppress structure growth, can counteract increases in growth parameter.





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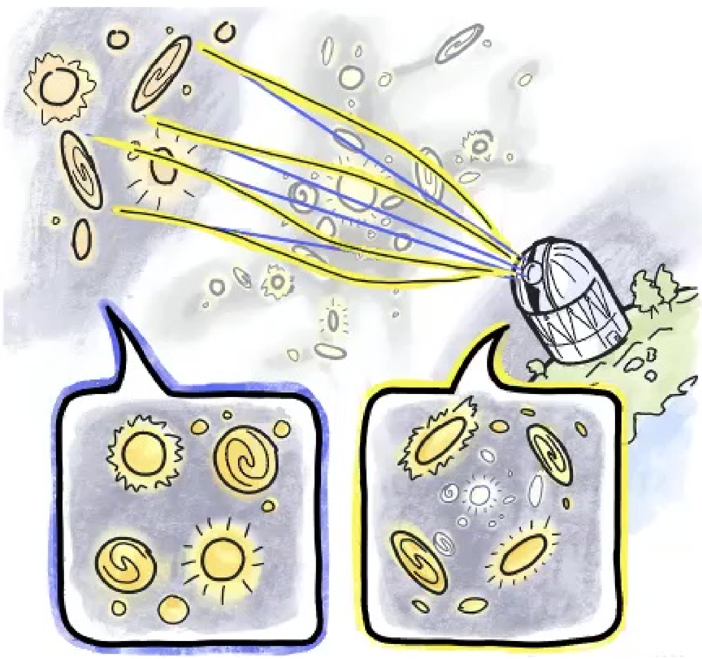
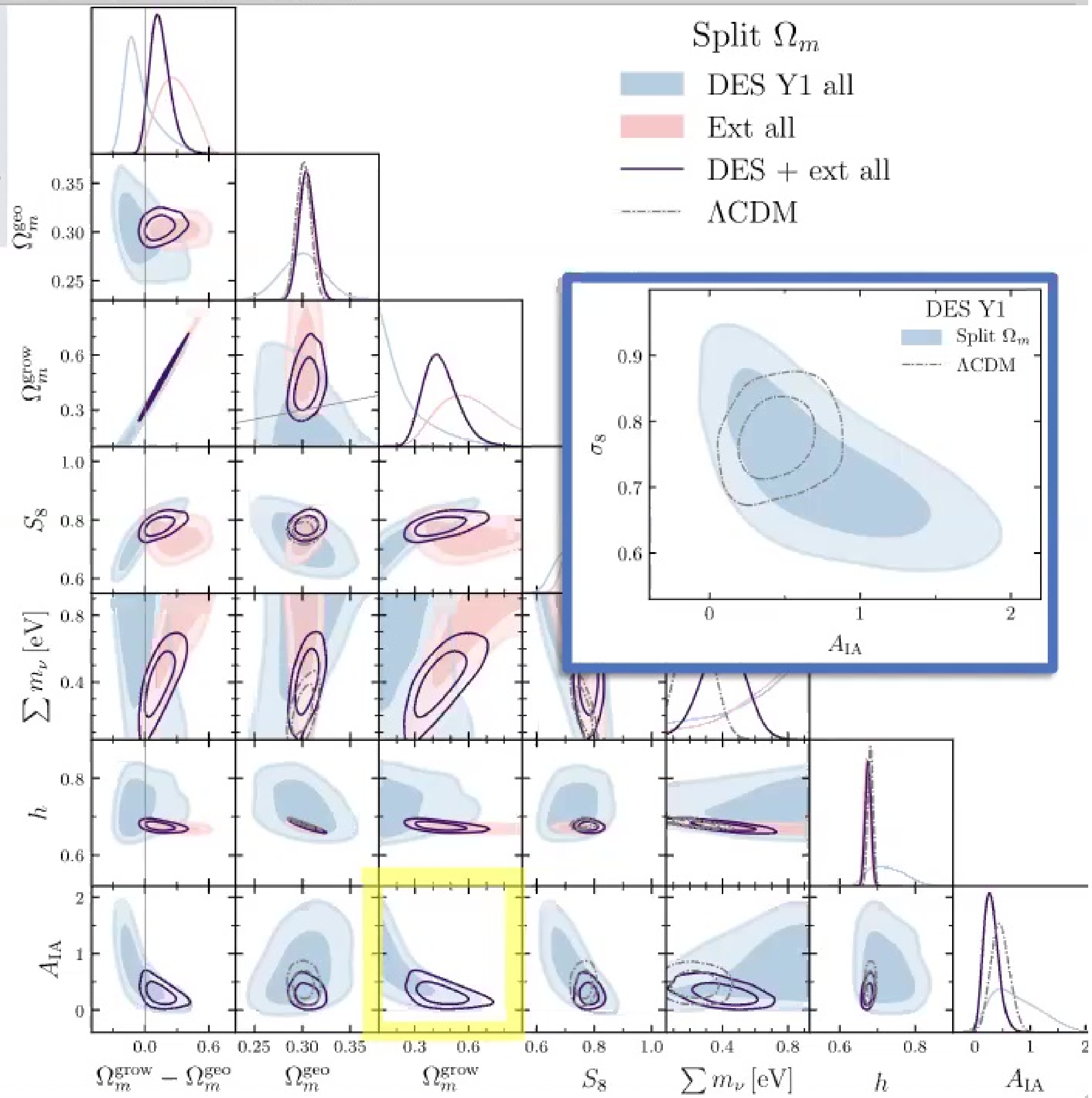
Growth and intrinsic alignments





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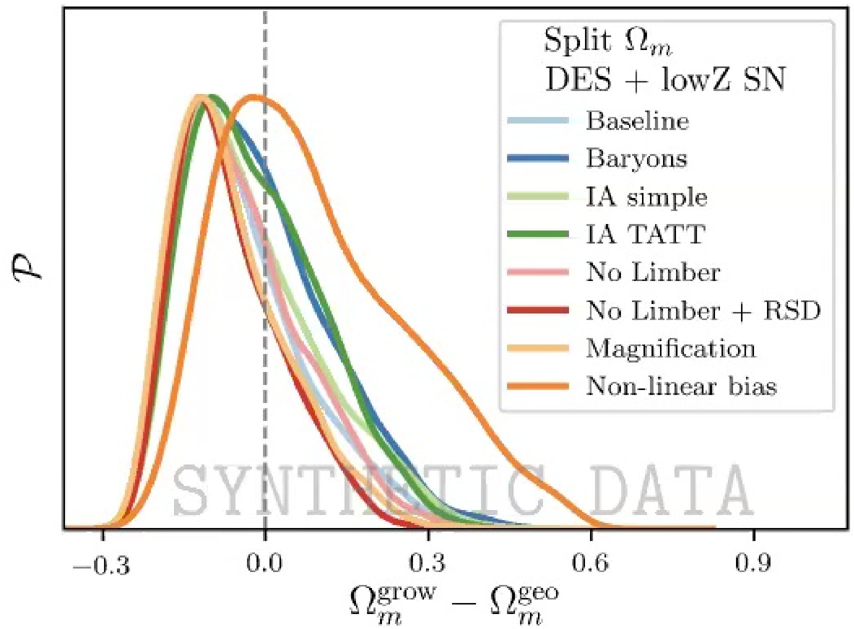
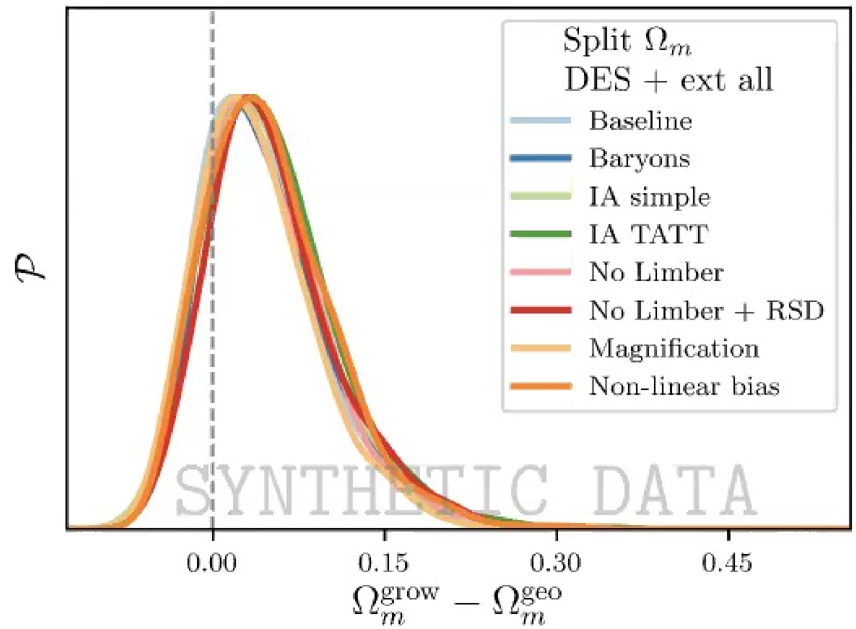
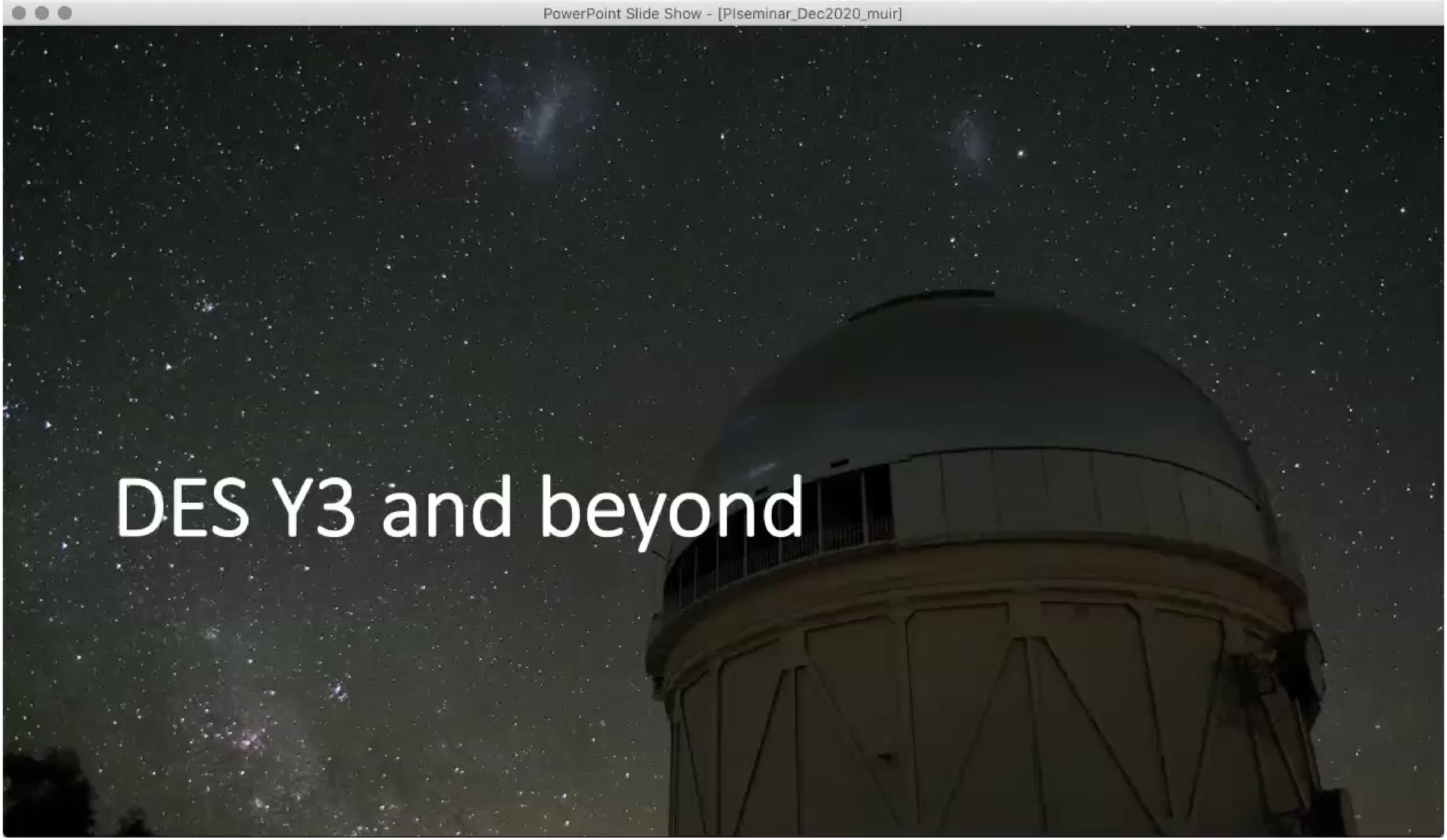
Results are more robust to systematics when combining complementary measurements.





Conclusions from Y1 Growth-geometry split analysis

- DES constraints come more from geometry than growth.
- Growth parameters are harder constrain than geometry, in large part because of degeneracies with astrophysical effects & systematics.
- Combined analyses of multiple growth probes can break those degeneracies.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DES Y3 and beyond

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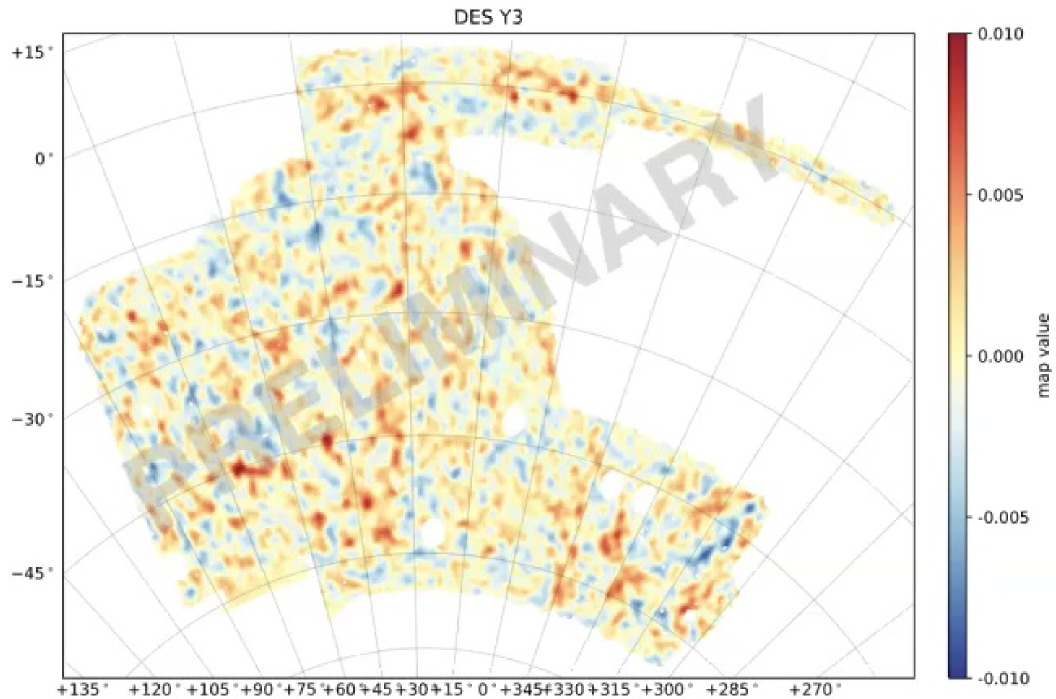
DES Y3 analysis underway

Weak Lensing Mass Map from DES data



credit: the Dark Energy Survey collaboration

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Mass map = weak lensing convergence map, or projected mass density

>100 million source galaxies

Improvements to methodology throughout measurement and analysis pipeline.

Slide by Marco Gatti

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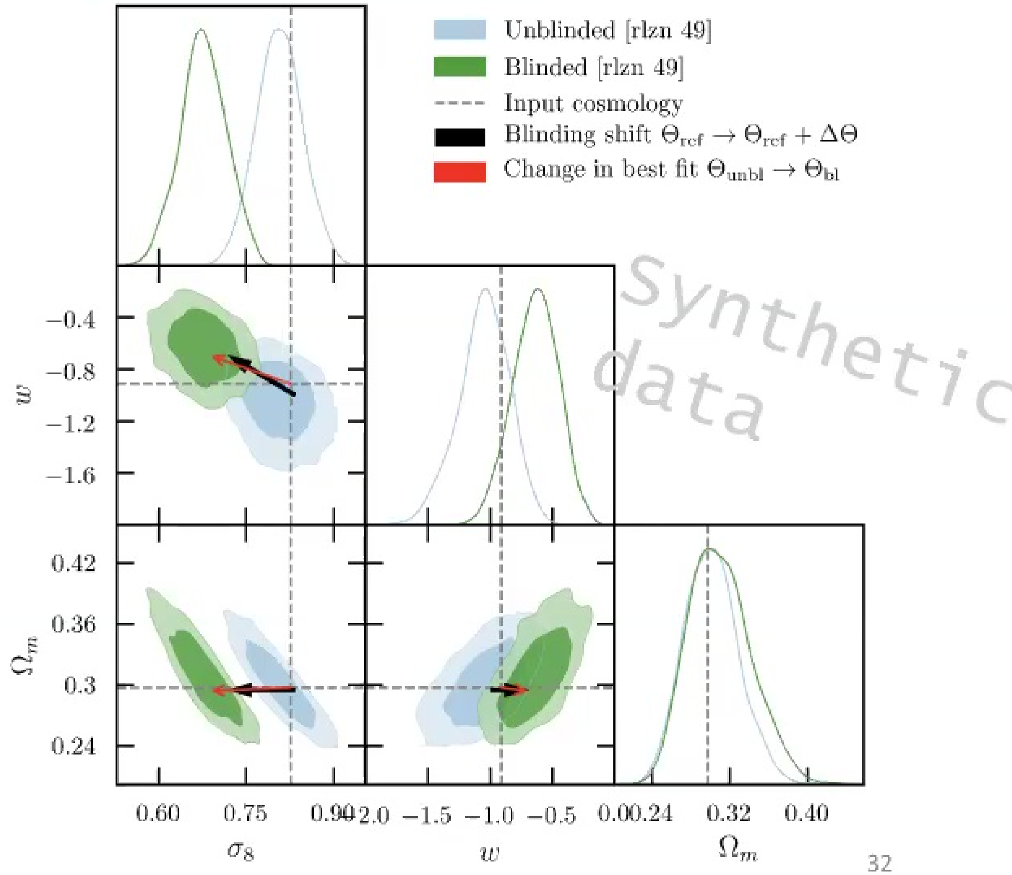
Preventing Experimenter Bias

- **DES Y1:** results shifted at parameter level until set of unblinding criteria are passed.
- **DES Y3:** new method of blinding by modifying summary statistics (2PCF).

JM, Gary Bernstein, Dragan Huterer, Franz Elsner, Elisabeth Krause, Aaron Roodman, et al [DES Collaboration]

*MNRAS **494**, no.3, 4454-4470 (2020)*

https://arxiv.org/abs/1911.05929



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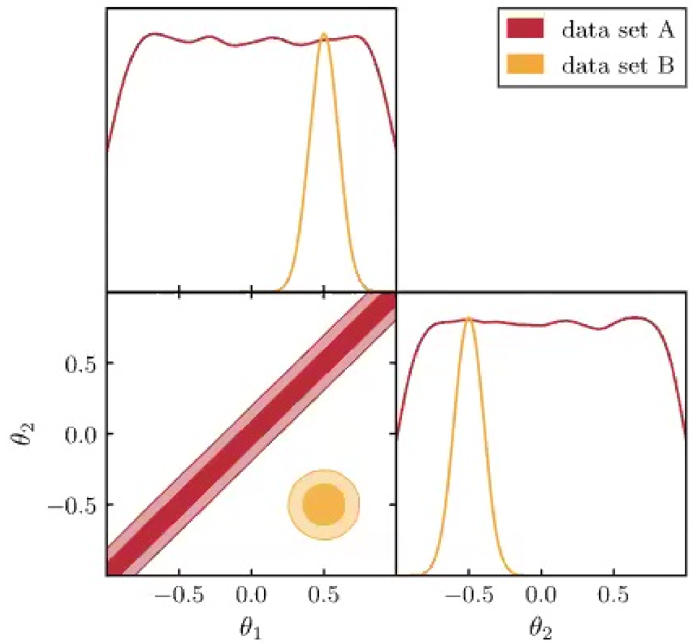
Calibrating tension metrics



- Evaluating tension can be ambiguous in >1D, for non-Gaussian posteriors

Pablo Lemos, Marco Raveri, Andresa Campos, Youngsoo Park, Chihway Chang, Noah Weaverdyck, et al [inc. JM] (DES Collaboration) -- on arXiv soon!

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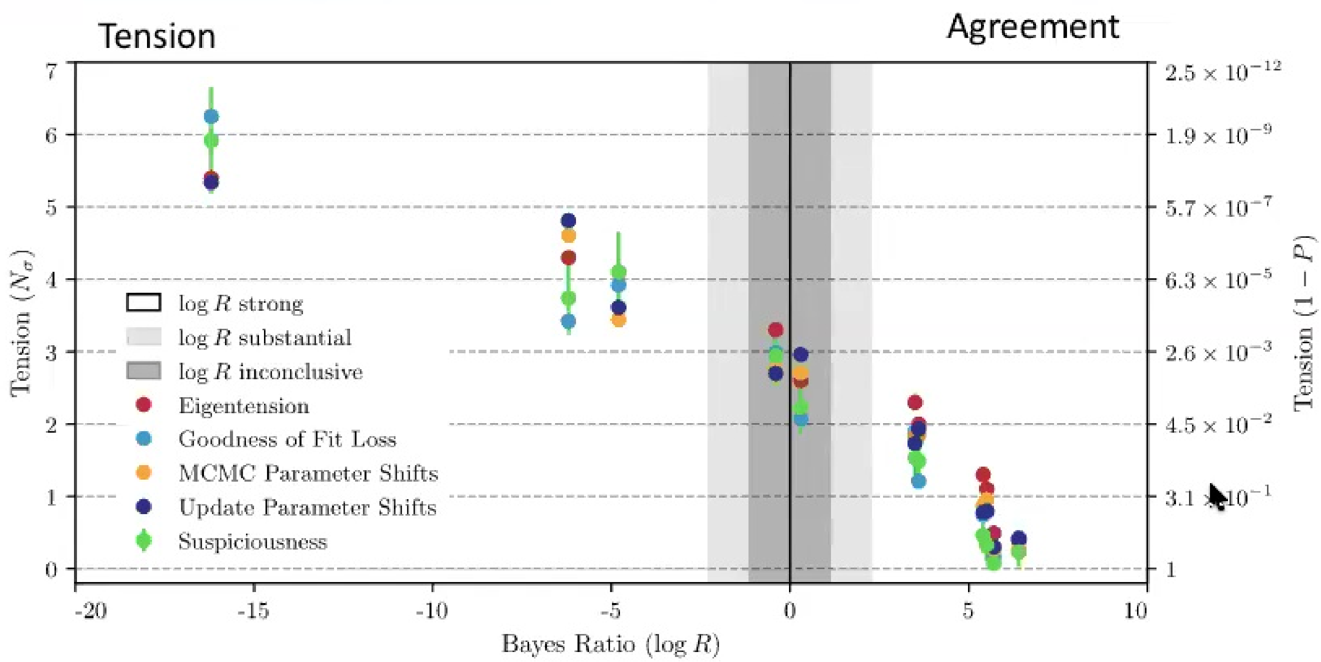
Calibrating tension metrics



Main result from Lemos, Raveri et al:

- Tension metrics agree
- Bayes ratio (aka Evidence ratio) shifts quickly from strong agreement to strong disagreement.

$$R = \frac{P(D_A, D_B|M)}{P(D_A|M)P(D_B|M)}$$

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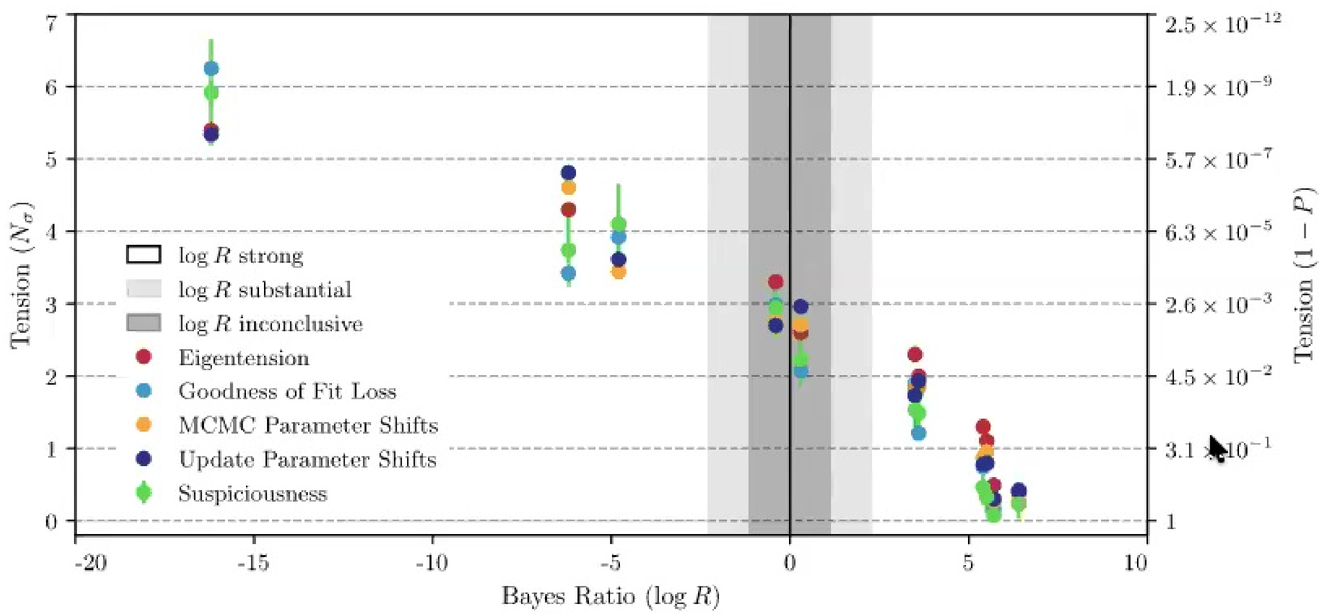
Calibrating tension metrics AND evaluating sampler accuracy



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DES Samplers project

- Richard Rollins, Noah Weaverdyck, Pablo Lemos, Marco Raveri, Agnes Ferte, and more [inc JM], (DES Collab) – paper in earlier stages of prep.
- Main result: Polychord is more reliable than Multinest for calculating Evidence

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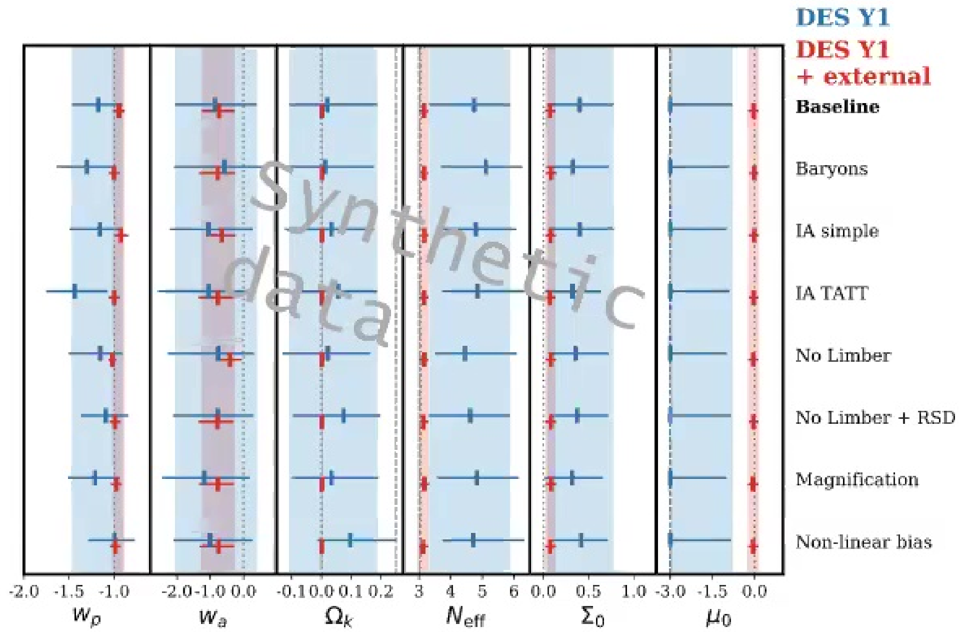
Y3 extended model analysis in prep

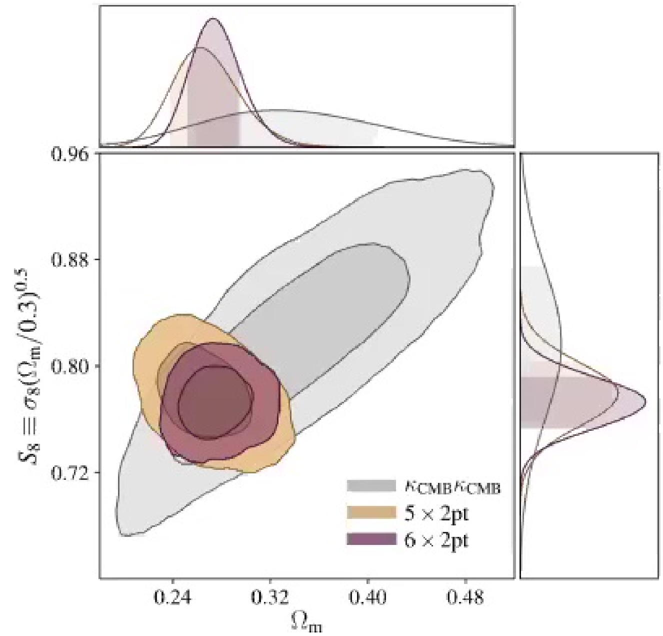
- Extended model key paper will be a few months behind the main cosmology paper
- Co-leading analysis team with Agnes Ferte
- Contributors: **Angela Chen***, **Anderson Souza**, **Paul Rogozenski**, **Noah Weaverdyck**, **Otavio Alves**, Jack Elvin-Poole, Marco Raveri, Pablo Lemos, Sujeong Lee, Cyrille Doux, Ian Harrison, Vivian Miranda, Eric Baxter, Danielle Leonard, Andrew Liddle, Eleonora DiValentino, Dragan Huterer, Tim Eifler, Scott Dodelson, and more

Bold names = grad students



Further tests of LSS growth history

- DES Y3 planned extended model projects:
  - Key project will include a non-parameteric growth model similar in spirit to growth-geometry split. Implemented by Anderson Souza, advised by JM
  - Modified gravity follow-up study, led by Agnes Ferte
  - "Extensions after dark" exotic DE model study, led by Vivian Miranda
- SPT CMB lensing cross correlations with DES galaxy clustering and weak lensing
  - Non-parametric growth analysis led by Cyrille Doux
- Combined analysis with galaxy cluster counts x WL x galaxy clustering
  - Y1 results – Chun-hao To et al (DES Collab.) https://arxiv.org/abs/2010.01138

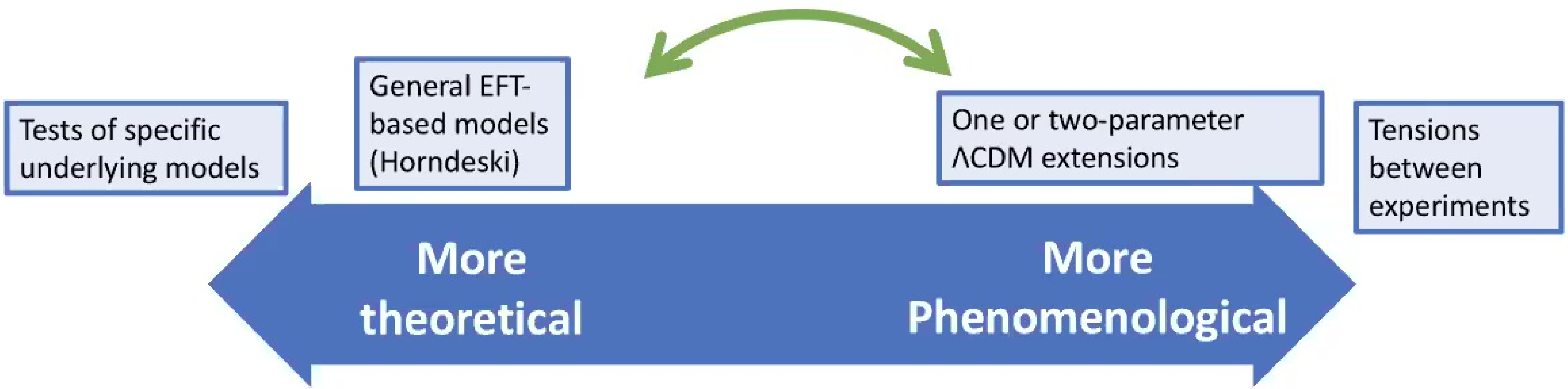


DES x CMB Lensing Y1 joint analysis:
DES Collab, PRD 2019, arXiv:1810.02322

Beyond DES Y3:
- DES Y6
- Stage IV surveys: Rubin LSST, Roman (WFIRST), Euclid, CMB-S4, DESI …

There's theory work to do!

Mapping between more fundamental models and **constrainable model extensions**. See e.g. Espejo et al 2018 arXiv:1809.01121



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Understanding degeneracies between beyond-LCDM signals astrophysical effects or systematics.

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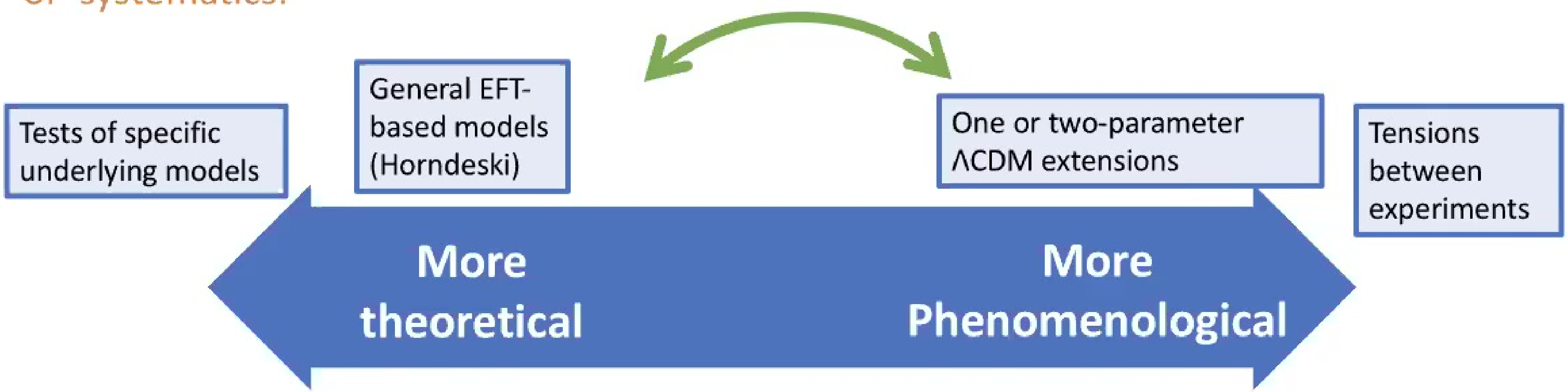

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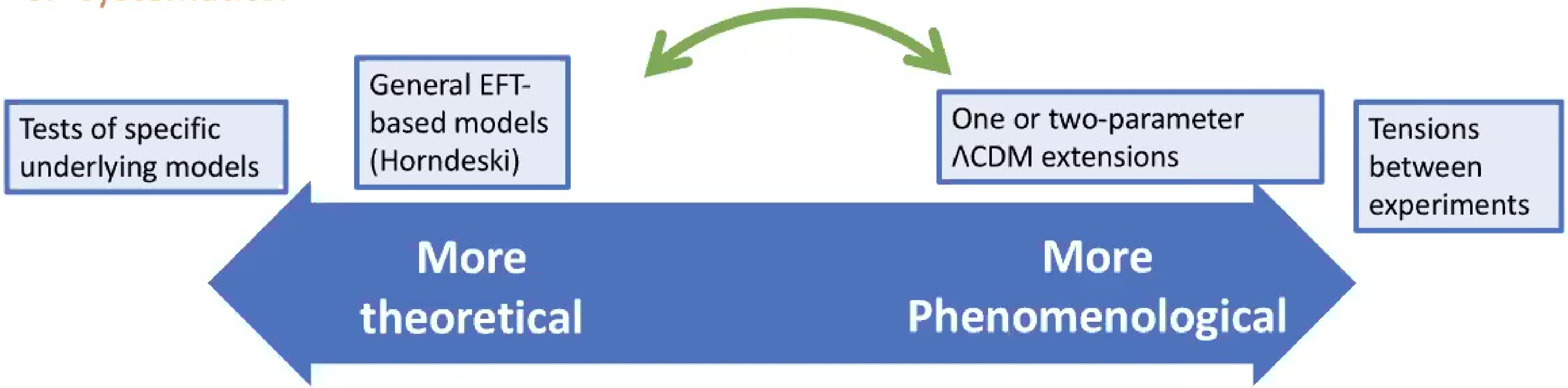
LSS measurements beyond 2PCF.

- Higher order correlations
- Marked correlation functions –See e.g. DES MG paper - Alam et al arXiv:2011.05771
- Peaks and voids
- **kNN statistics – Banerjee & Abel arXiv:2007.13342 – working with Arka on preliminary test of use for modified gravity searches**



Summary

- Dark energy is a significant open question in cosmology!
- Tensions with LCDM's predictions may hint at something new – clues for new physics, or systematics.
- DES Y3 results (coming soon!), future experiments will provide even more powerful tests.
- When searching for possible signals of new physics, it is important to:
  - Account for degeneracies with astrophysical effects, systematics
  - Combine measurements of complementary observables.

Darkbites

^ Cartoon from DES outreach project with Chihway Chang, Ross Cawthon, and others.