

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

Speakers: Jessica Muir

Series: Cosmology & Gravitation

Date: December 08, 2020 - 3:00 PM

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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.

&nbsp;

# Testing the standard cosmological model with the Dark Energy Survey



Jessie Muir  
KIPAC @ Stanford



Perimeter Institute Cosmology seminar - Dec. 8, 2020



Photo credit: Ross Cawthon (Wisconsin)



# The Dark Energy Survey

Funded by



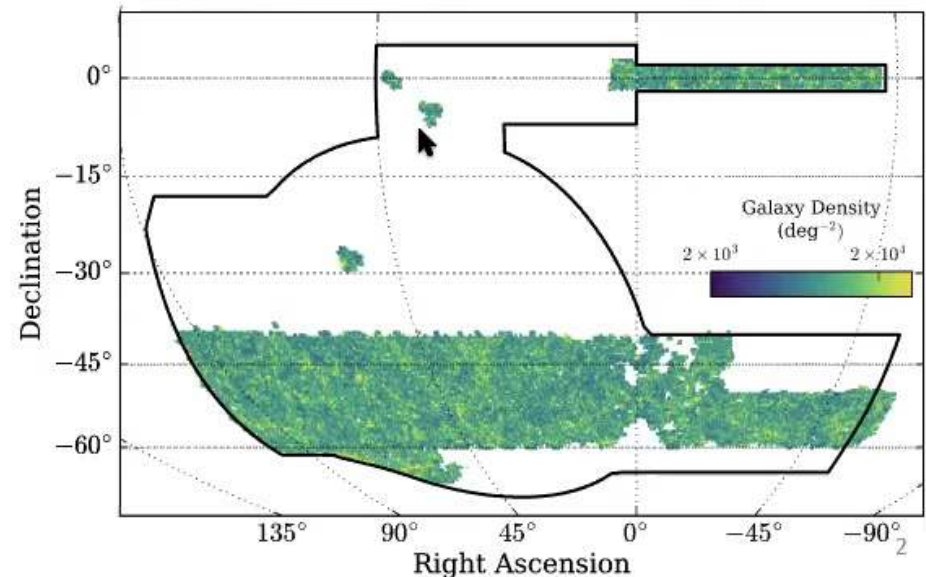
U.S. DEPARTMENT OF ENERGY

Office of Science



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



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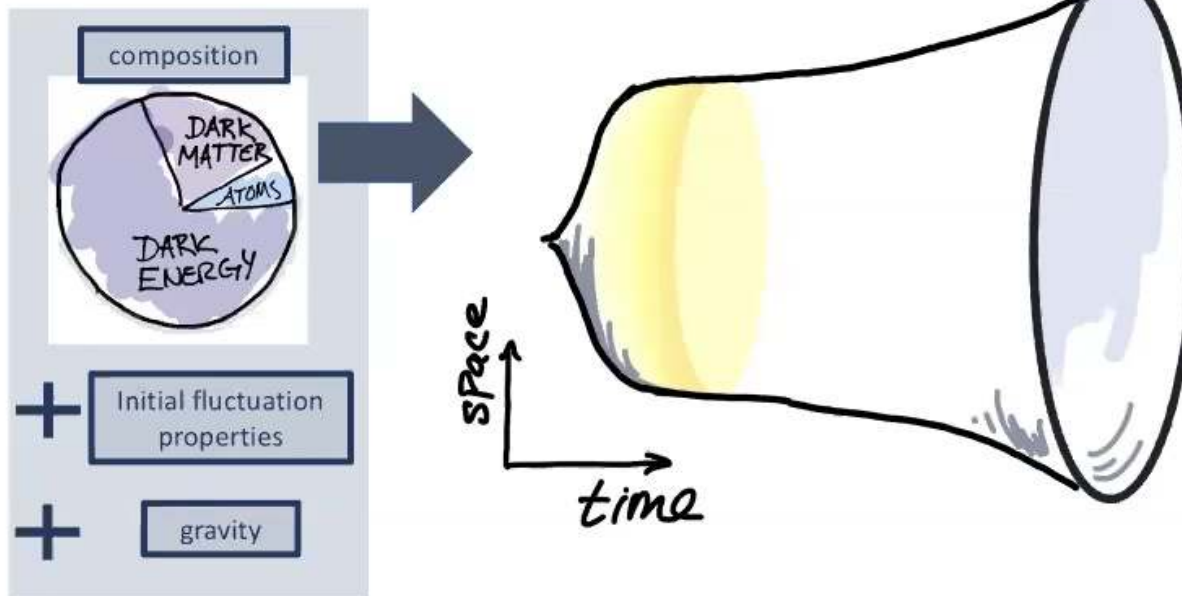


# Outline

- Constraining cosmology with DES
- Growth-geometry split analysis of DES Y1 data ([arXiv:2010.05924](https://arxiv.org/abs/2010.05924))
- DES Y3 and beyond



Our goal is to learn about fundamental physics by testing the predictions of  $\Lambda$ CDM.

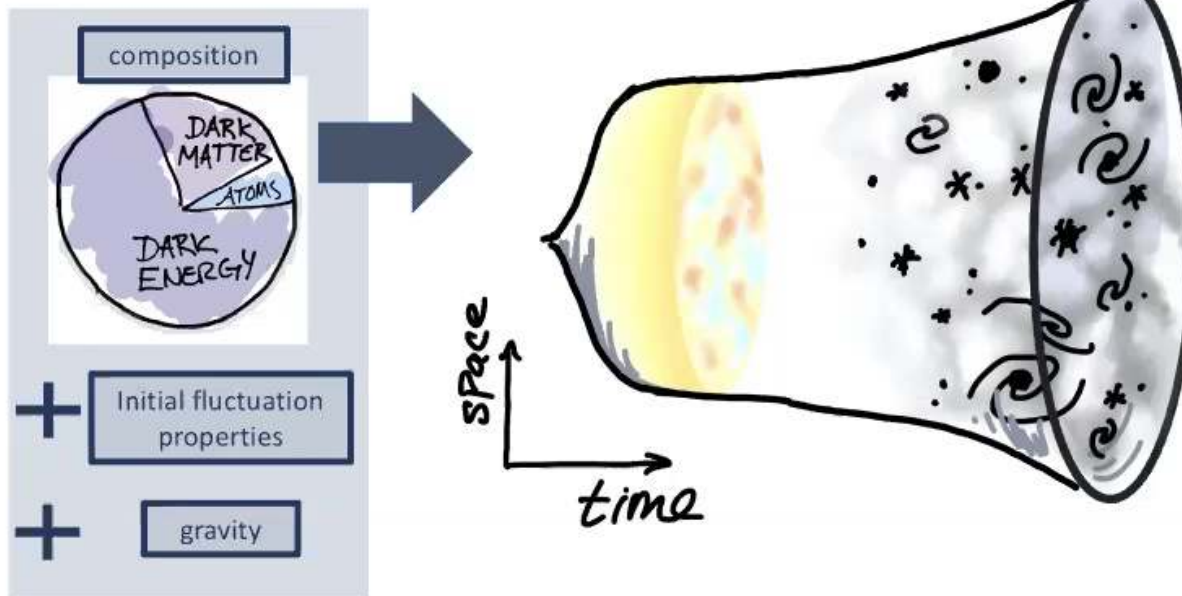


### $\Lambda$ CDM:

- Dark energy as a cosmological constant ( $\Lambda$ )
- 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



Our goal is to learn about fundamental physics by testing the predictions of  $\Lambda$ CDM.



### $\Lambda$ CDM:

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# Dark Energy and Modified gravity

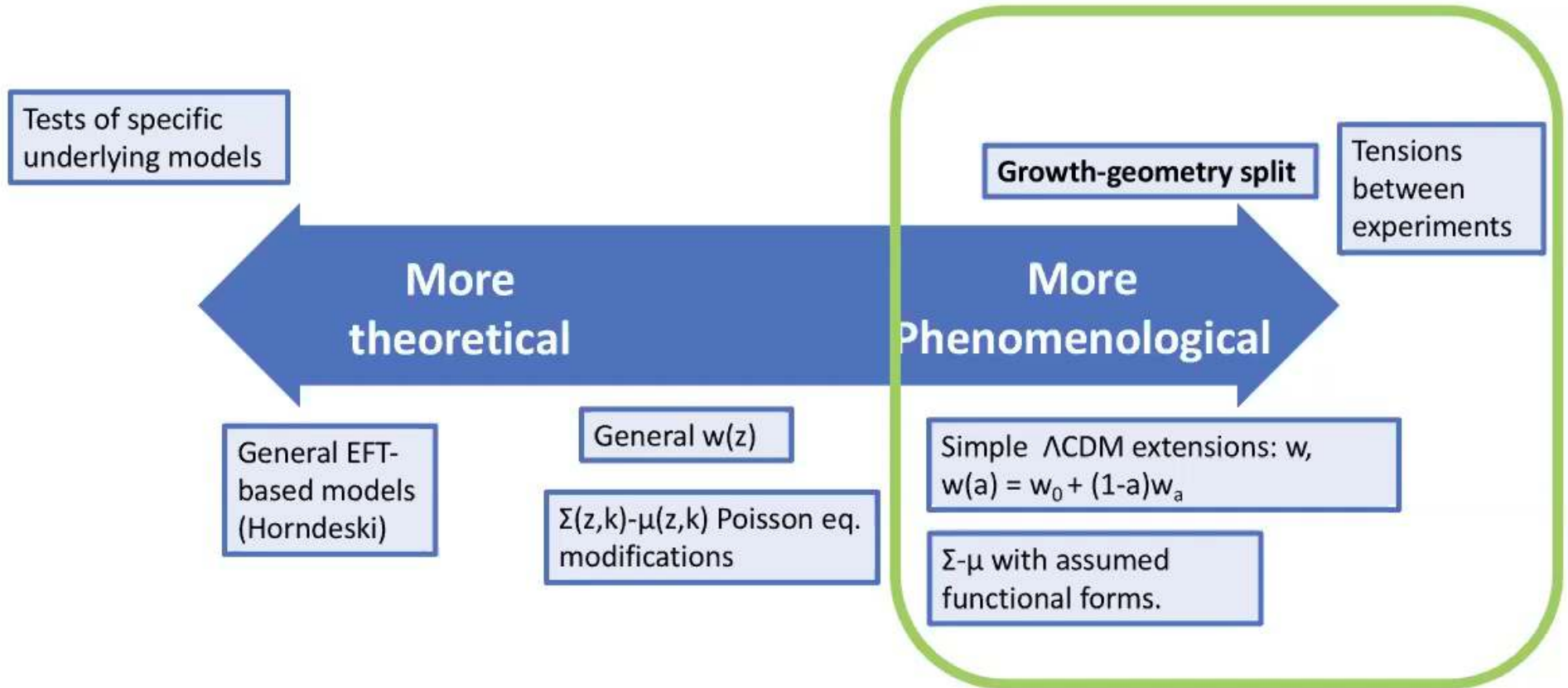
- Why is  $\Lambda$  so small?
- Could accelerating expansion be due to deviation from GR?
- More conservatively: is GR well tested on cosmological scales?

$$\boxed{R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}} = \boxed{8\pi GT_{\mu\nu}} \quad \text{Einstein's equation}$$

Curvature of spacetime      Matter and energy



# Dark energy and modified gravity



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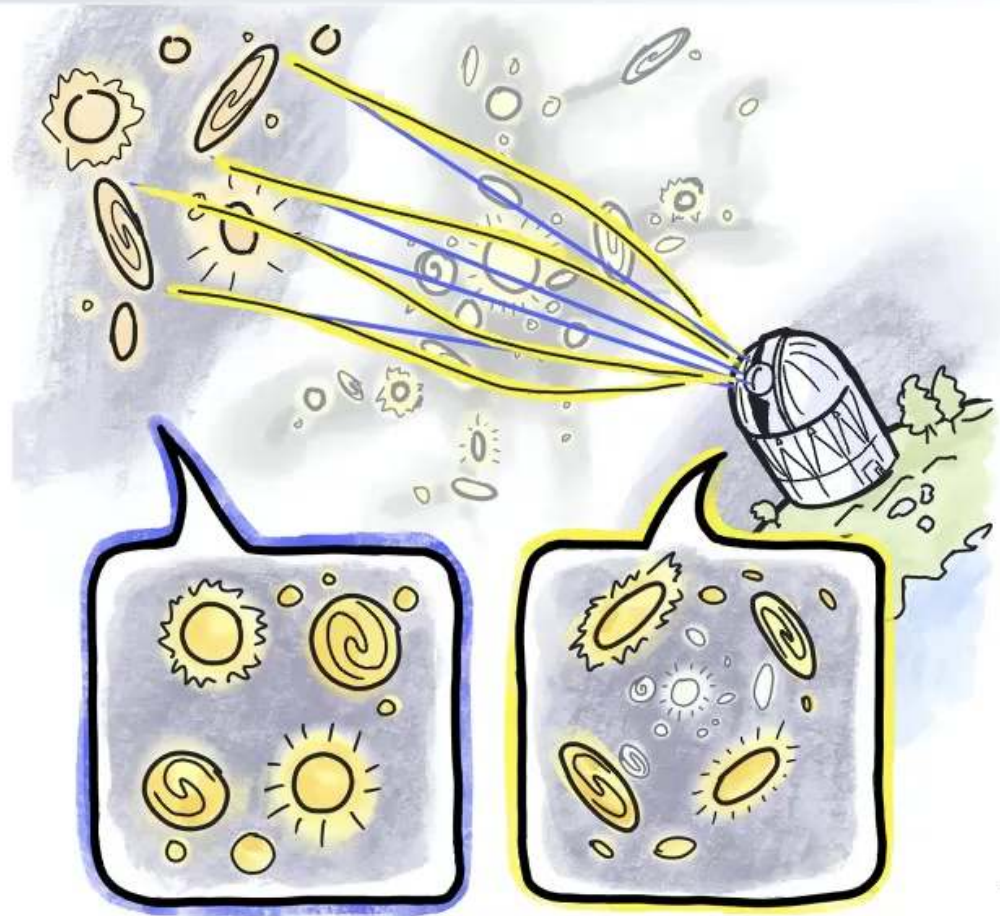
# Constraining cosmology with DES galaxy clustering and weak lensing



# 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

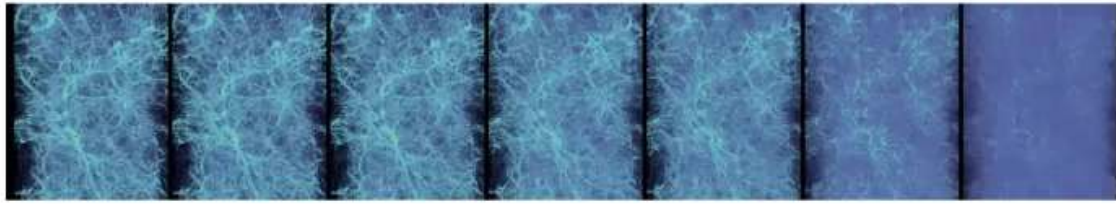


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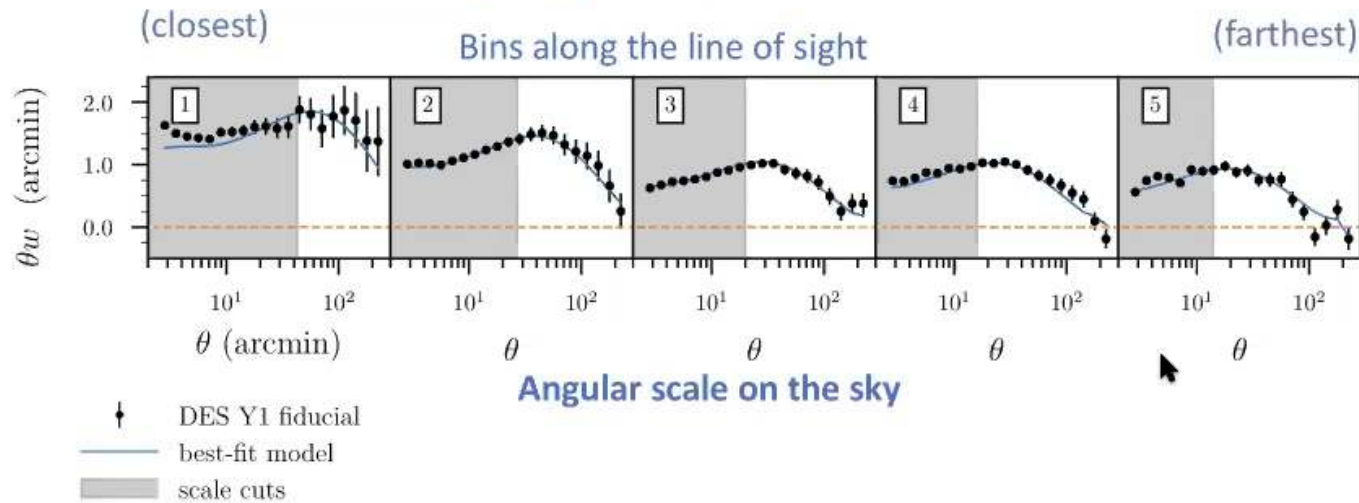
.1



# Summary statistic: 2pt angular correlations



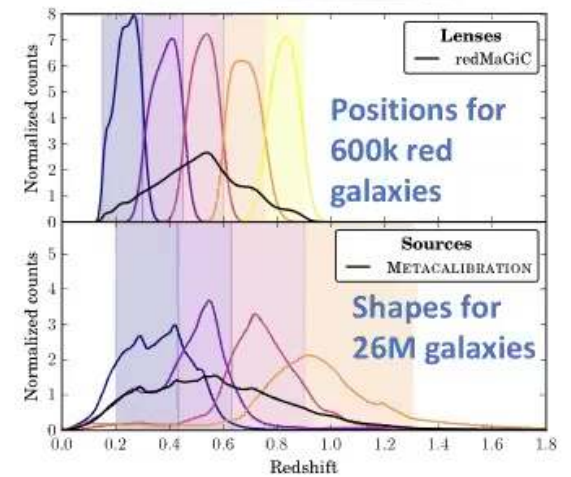
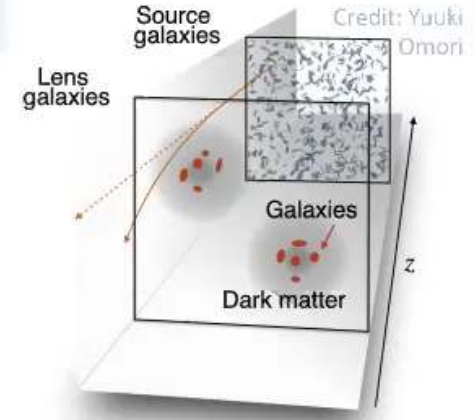
## DES Y1: correlations between galaxy positions



Plots from DES Collaboration 2017, arXiv:1708.01530

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Results from DES

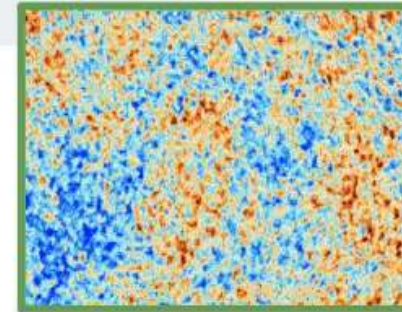
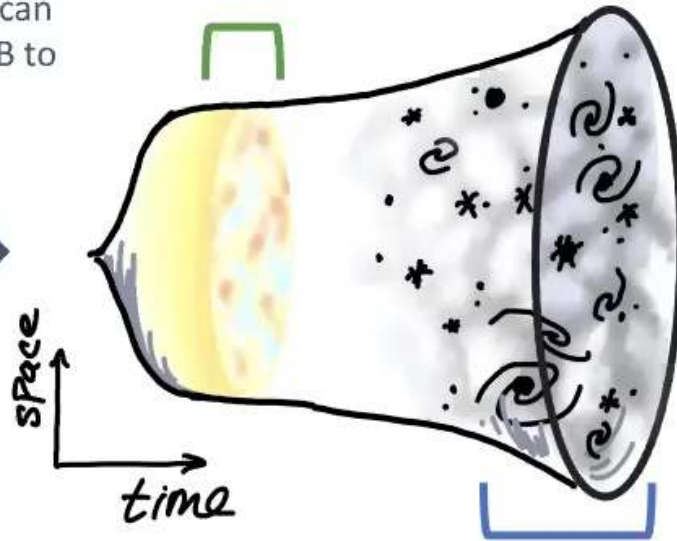
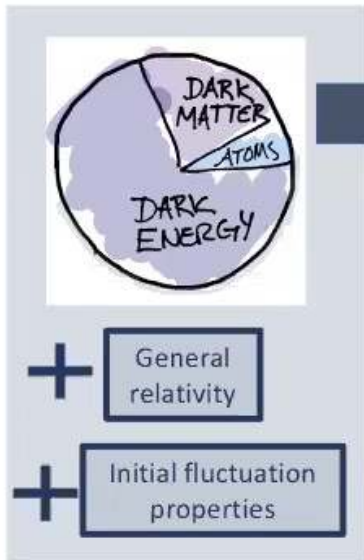


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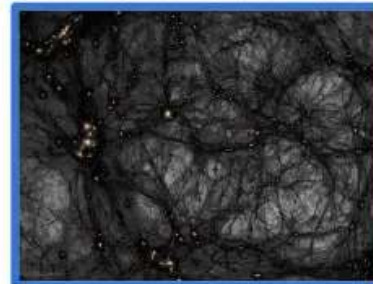
# Testing $\Lambda$ CDM via consistency with other probes

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



Early-time CMB measurements  
Planck

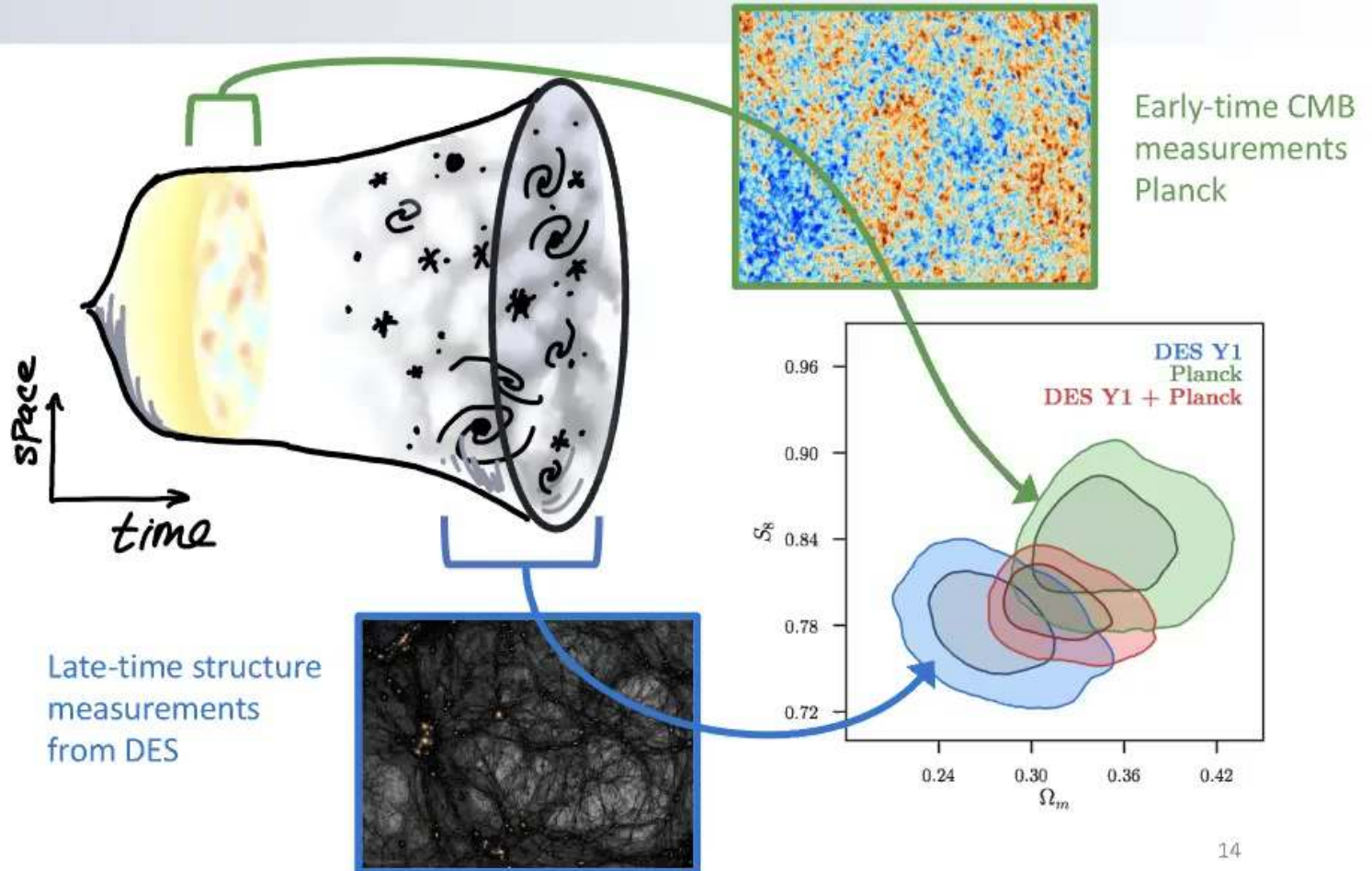
Late-time structure measurements  
from DES





# Testing $\Lambda$ CDM via consistency with other probes

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

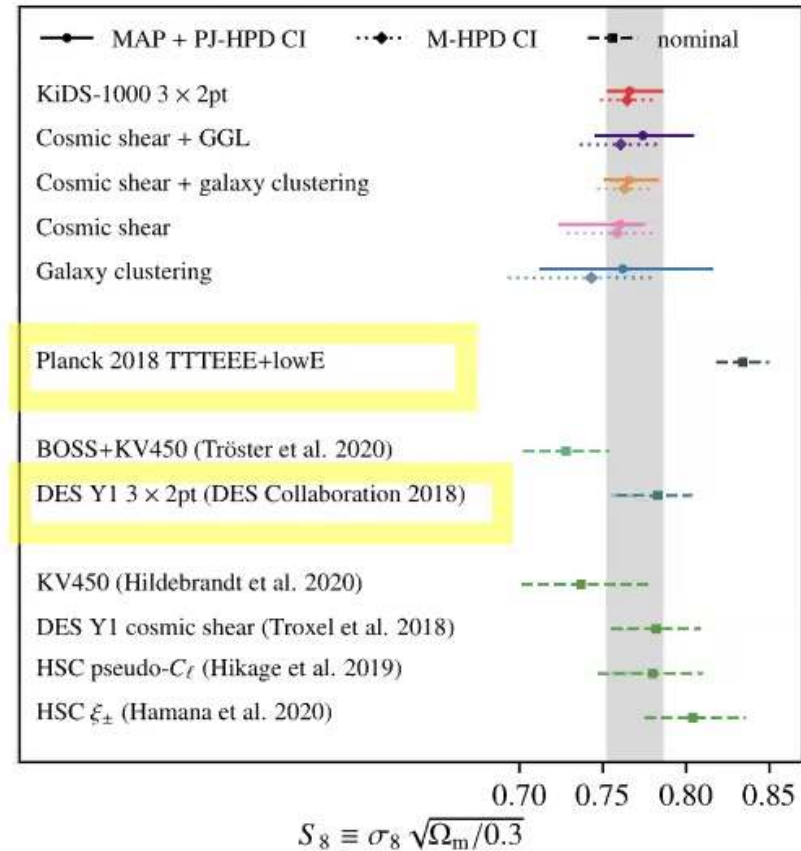


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# DES observes a $S_8$ offset in the same direction as other weak lensing experiments.

- Summary plot from KiDS 1000 cosmology results paper [Heymans et al 2020](#), [arXiv:2007.15632](#)



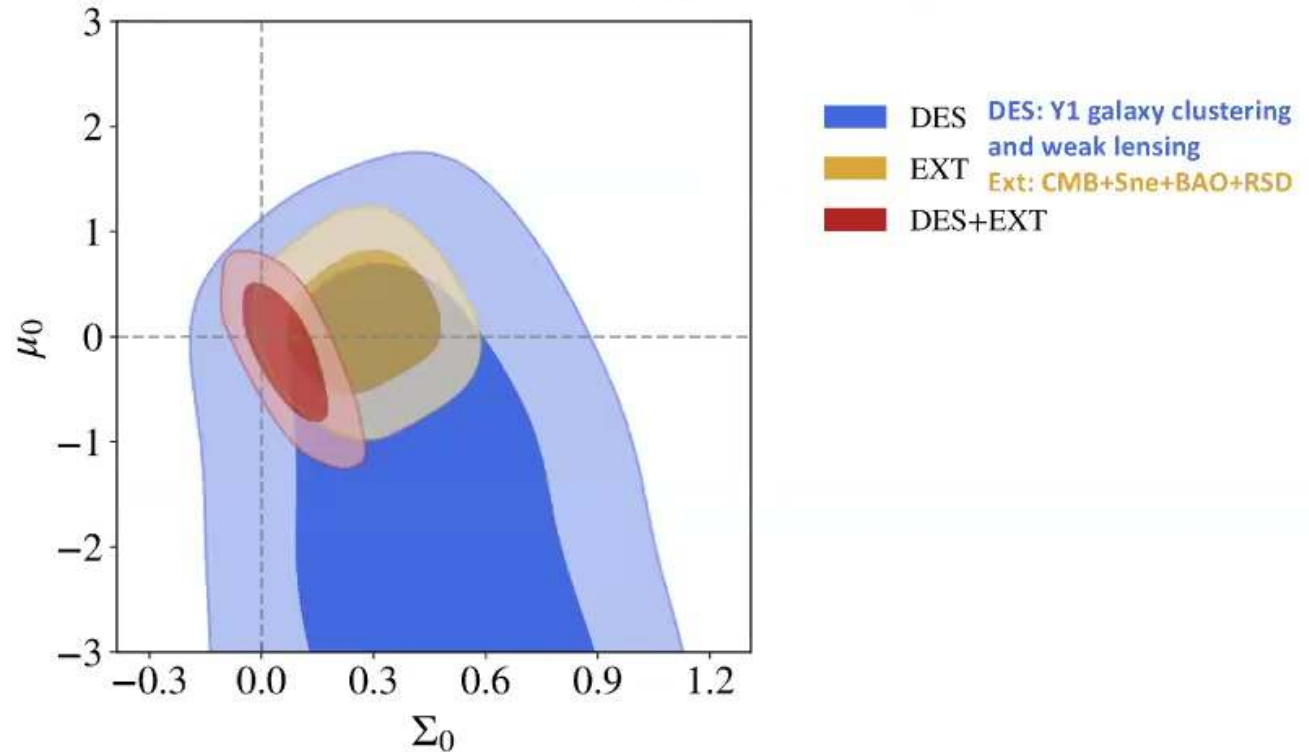


# DES constraints on extended models test for phenomenological deviations from $\Lambda$ CDM.

$$k^2\Psi = -4\pi G a^2(1 + \mu(a))\rho\delta \quad \leftarrow \text{matter}$$

$$k^2(\Psi + \Phi) = -8\pi G a^2(1 + \Sigma(a))\rho\delta \quad \leftarrow \text{lensing}$$

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

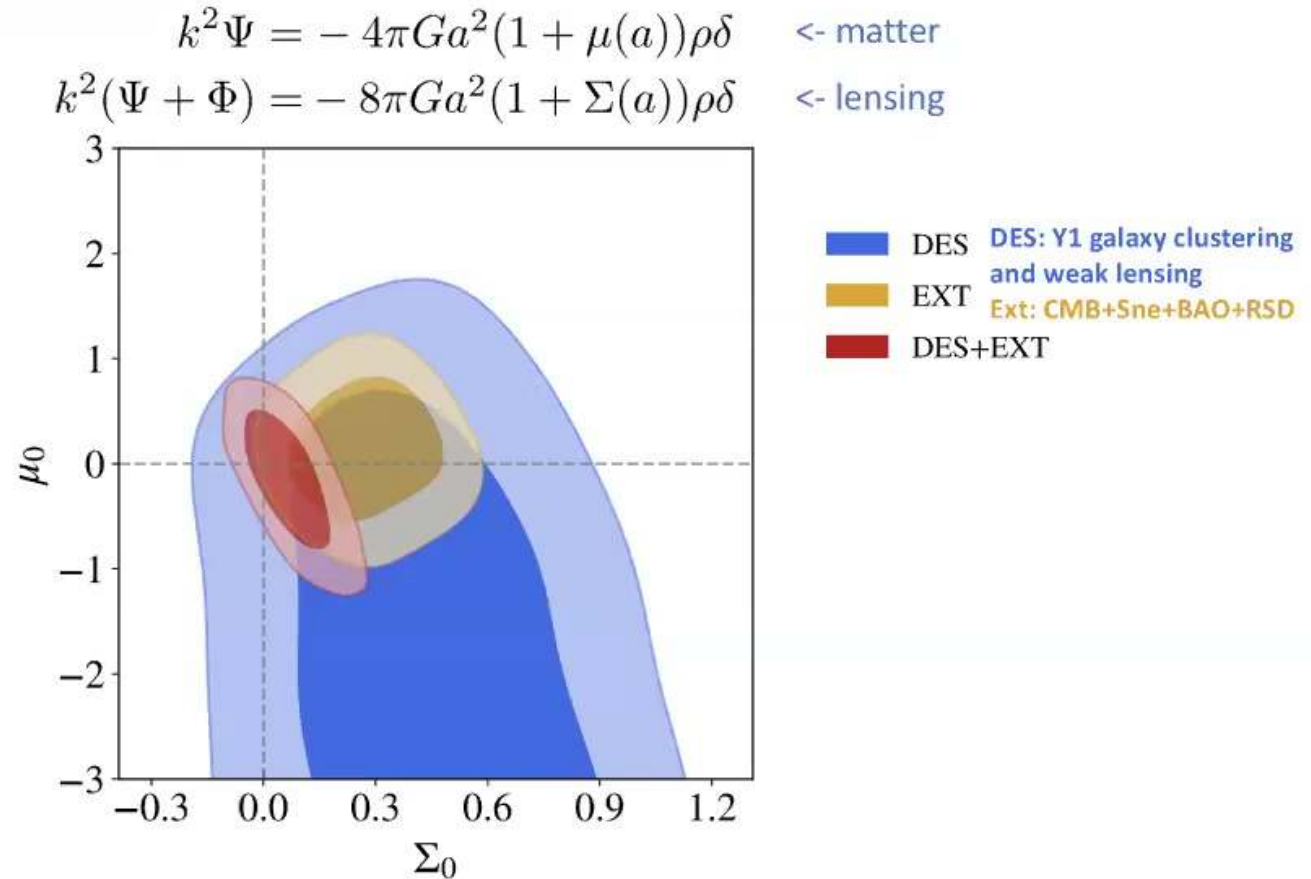


# Growth-geometry split analysis



# DES constraints on extended models test for phenomenological deviations from $\Lambda$ CDM.

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



# 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](https://arxiv.org/abs/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

$$\Omega_m \Rightarrow \Omega_m^{\text{grow}}, \Omega_m^{\text{geo}}$$

See also: Wang et al 2007, arXiv:0705.0165

Ruiz and Huterer, 2014, arXiv:1410.5832

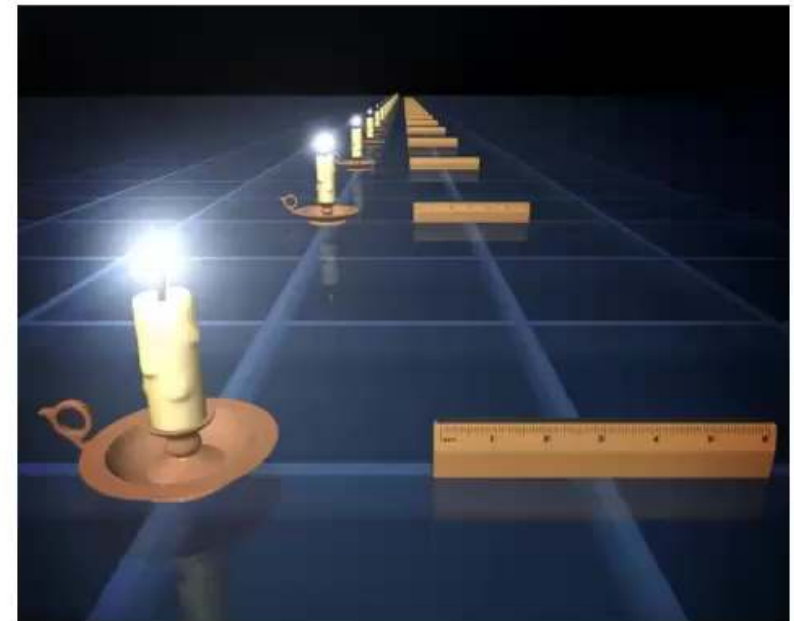
Bernal, Verde, and Cuesta 2016, arXiv: 1511.03049



# 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**.

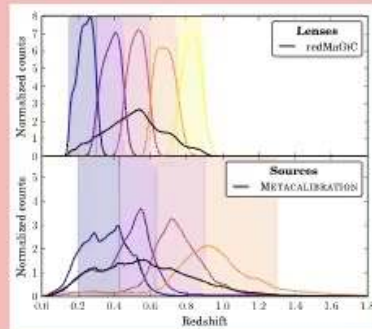
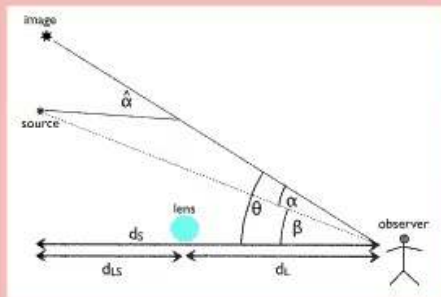
Angular correlation for z-bins i & j for A-B =

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

Redshift distribution of sources, lensing kernel

$$C_{AB}^{ij}(\ell) = \int d\chi \frac{q_A^i(\chi)q_B^j(\chi)}{\chi^2} [P(k, z(\chi))]_{k=(\ell+\frac{1}{2})/\chi}$$

### Projection onto the sky



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### Matter power spectrum

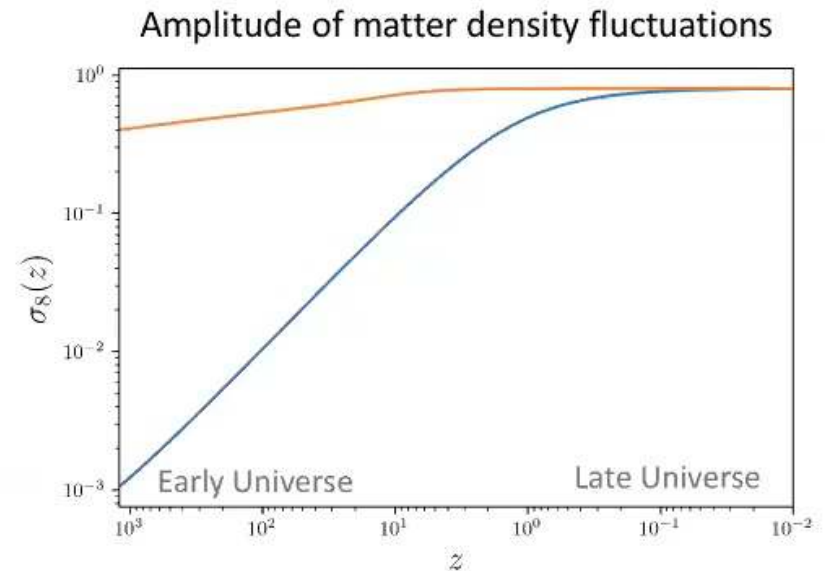
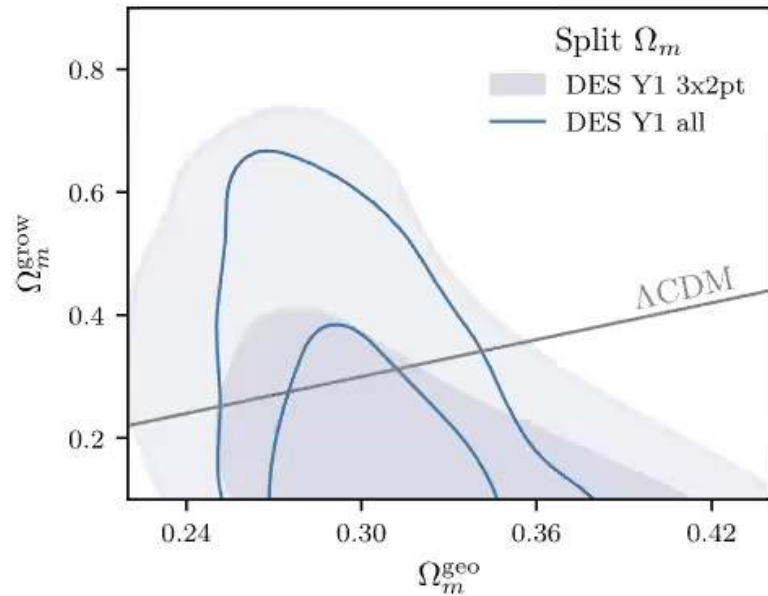
$$P(k, z) = \frac{P^{\text{geo}}(k, z_i)}{P^{\text{grow}}(k, z_i)} P^{\text{grow}}(k, z)$$



# DES alone can only put upper bounds on $\Omega_m^{\text{grow}}$ .

## DES "Year 1 all"

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





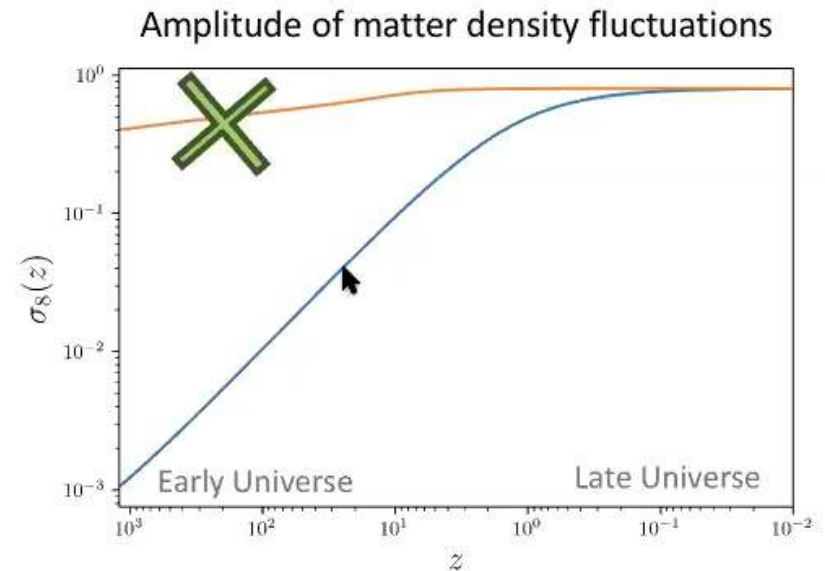
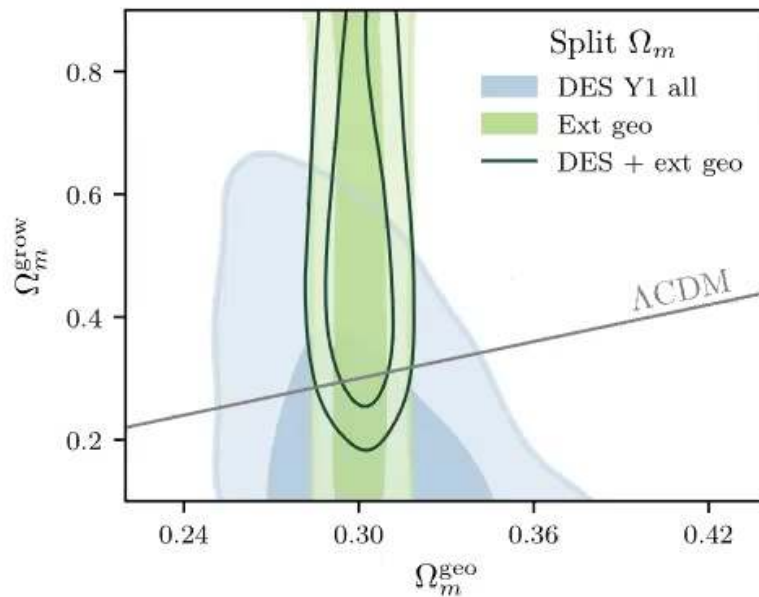
# Adding external geometric data, Planck constraint on $A_s$ helps break degeneracy.

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  $A_s, n_s, R_{shift}, \Omega_b h^2, I_A$





# Adding RSD as additional growth probe allows two-sided constraints on $\Omega_m^{\text{grow}}$ .

## DES "Year 1 all"

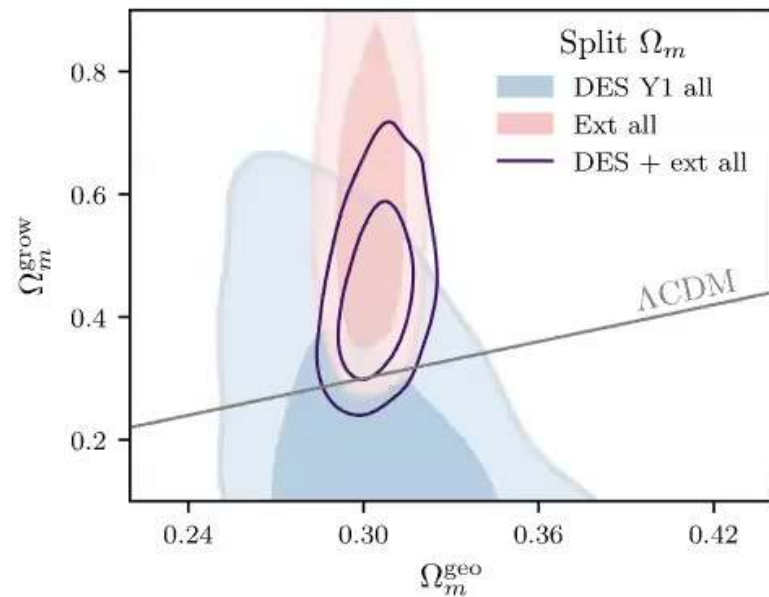
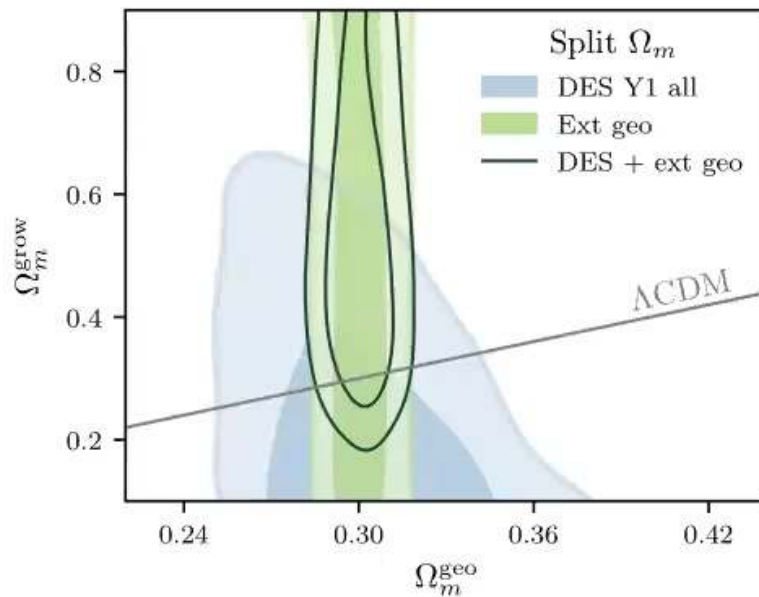
- Y1 galaxy clustering + WL [grow+geo]
- Y1 BAO [geo]
- Y3 SN + lowZ SN [geo]

## "Ext geo" [geo]

- BOSS DR12 BAO
- Planck 2015 constraints on  $A_s, n_s, R_{\text{shift}}, \Omega_b h^2, I_A$

## "Ext all"

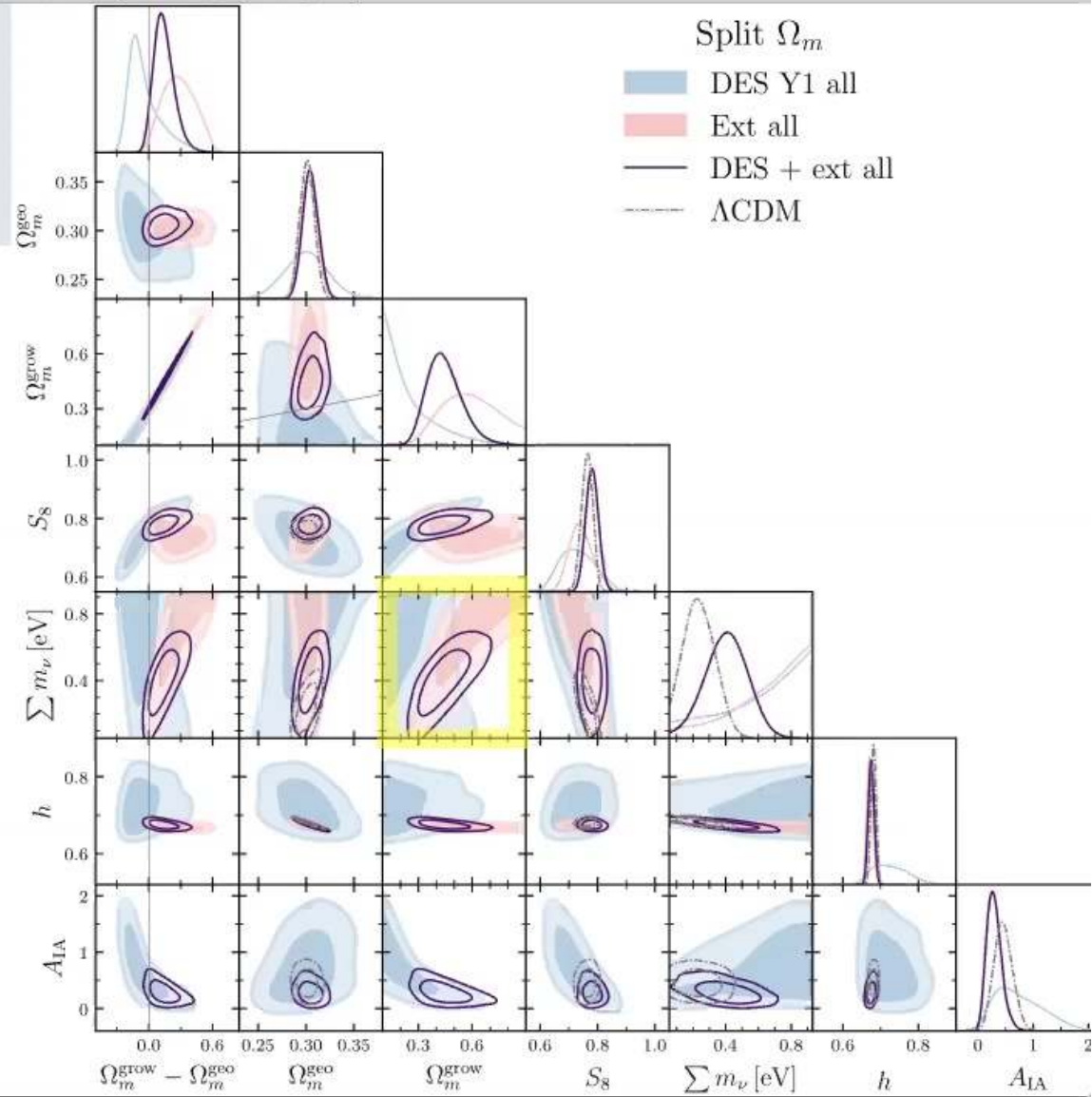
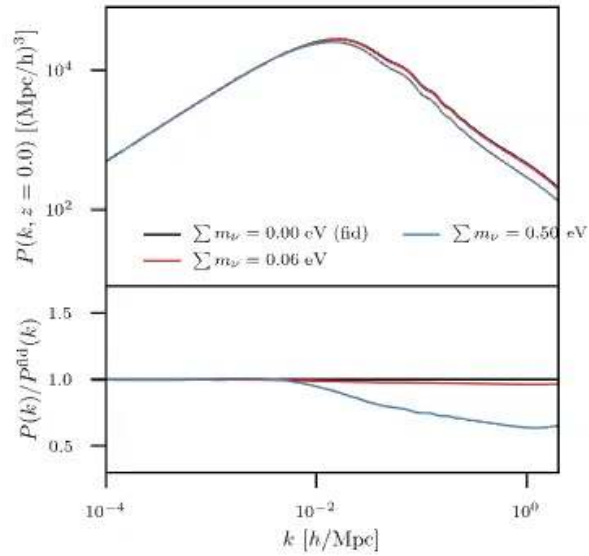
- Ext geo [geo]
- BOSS DR12 RSD [grow]





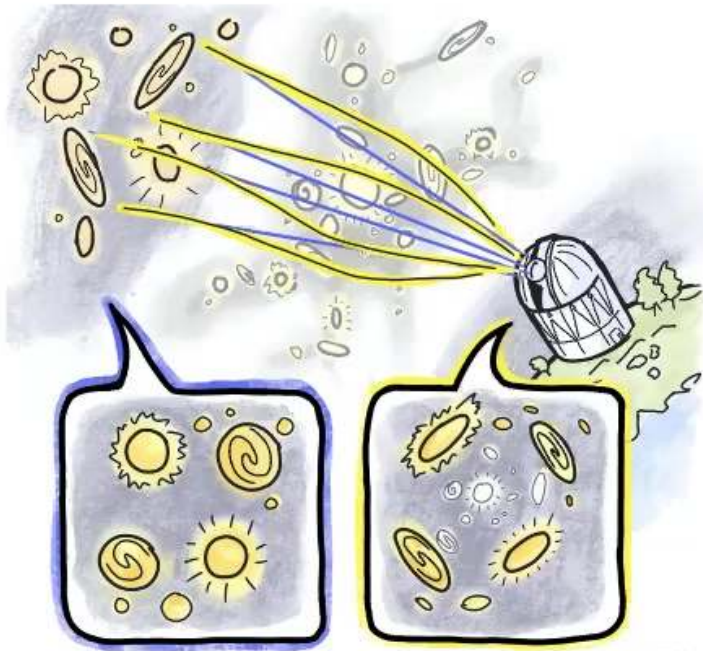
# Growth and neutrino mass

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



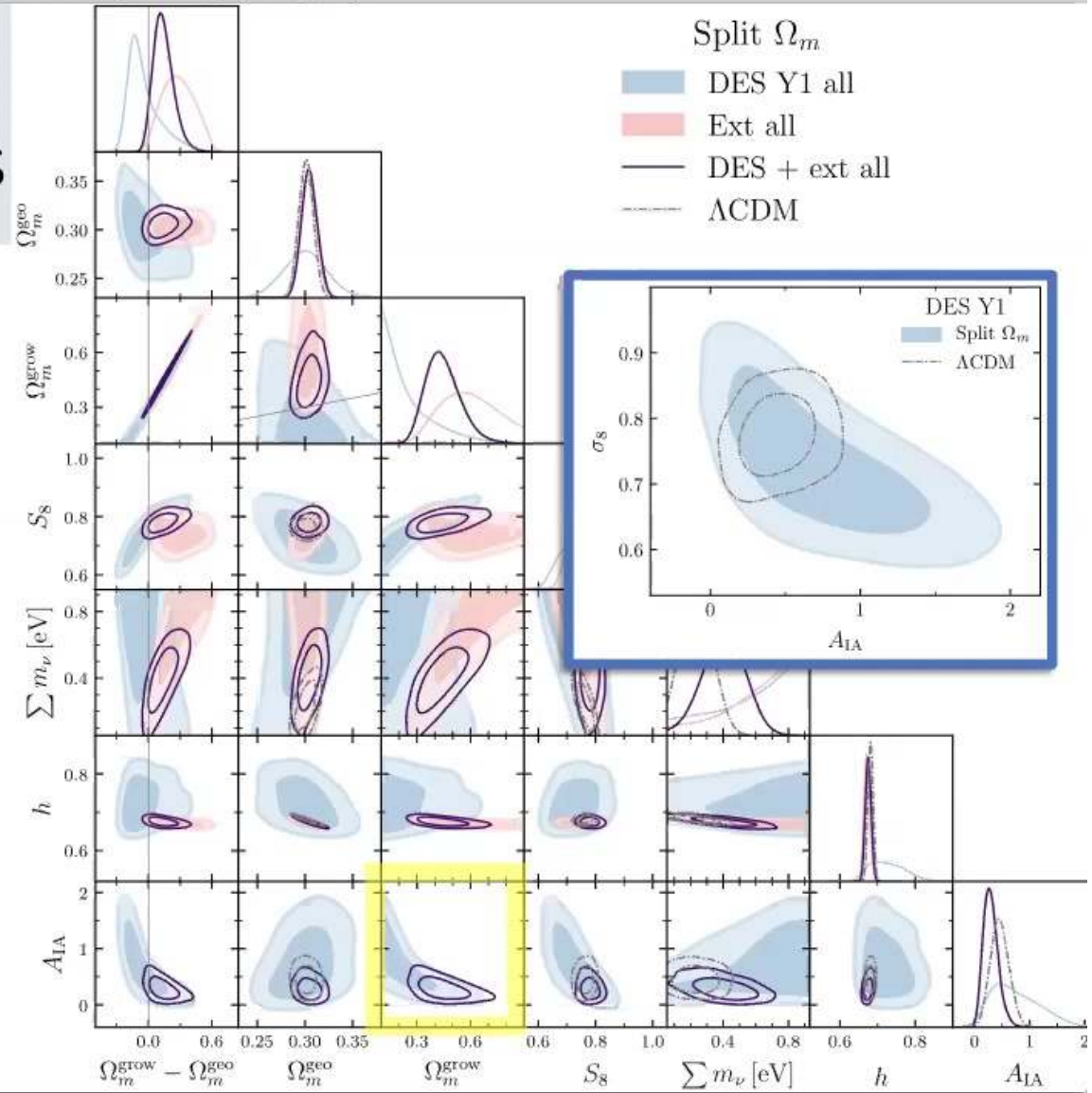


# Growth and intrinsic alignments



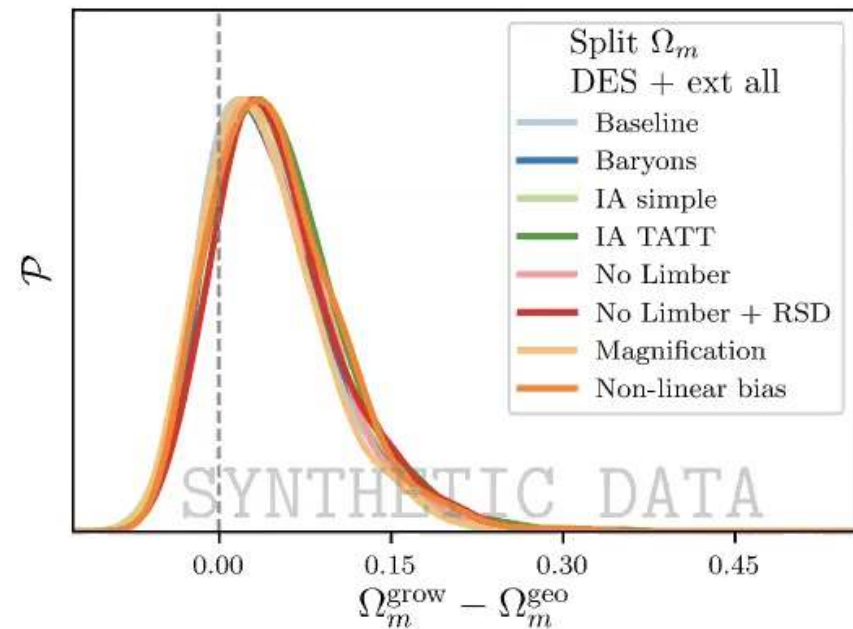
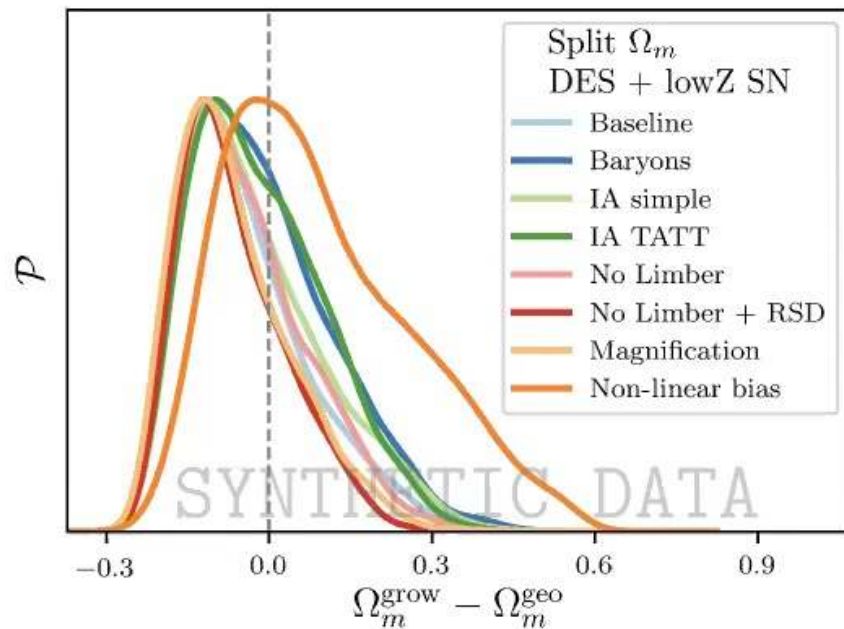
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Results are more robust to systematics when combining complementary measurements.





# Conclusions from Y1 Growth-geometry split analysis

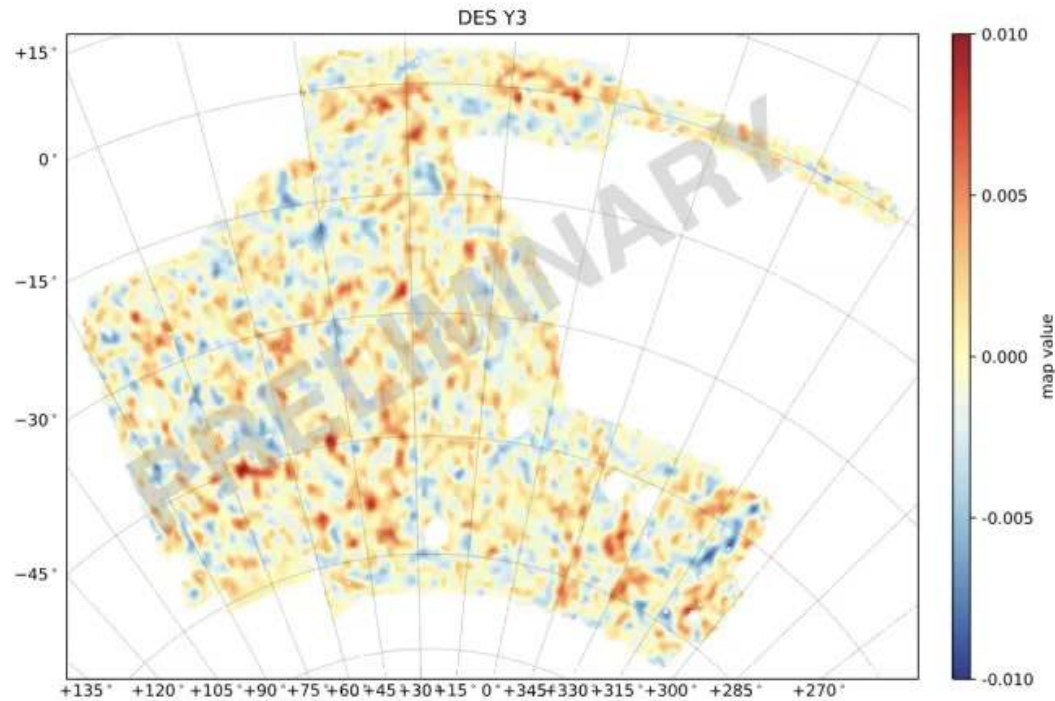
- DES constraints come more from geometry than growth.
- Growth parameters are harder constrain than geometry, in large part because of degeneracies with astrophysical effects & systematics.
- Combined analyses of multiple growth probes can break those degeneracies.

# DES Y3 and beyond



# DES Y3 analysis underway

Weak Lensing Mass Map from DES data



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

credit: the Dark Energy Survey collaboration

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Results from DES

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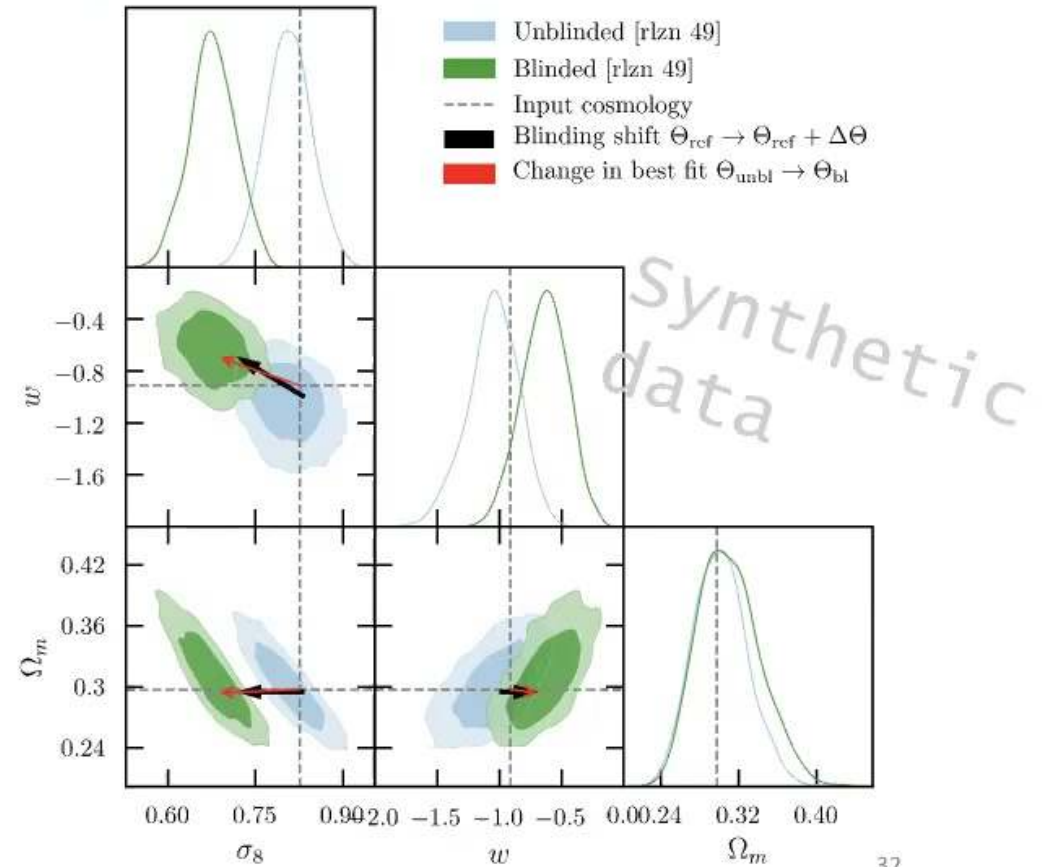


# Preventing Experimenter Bias

- **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).

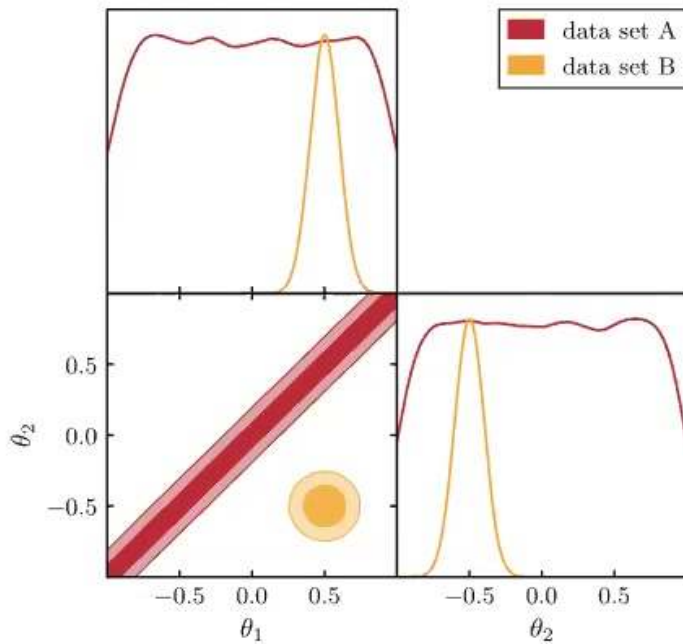
*JM, Gary Bernstein, Dragan Huterer, Franz Elsner, Elisabeth Krause, Aaron Roodman, et al [DES Collaboration]*  
*MNRAS 494, no.3, 4454-4470 (2020)*  
<https://arxiv.org/abs/1911.05929>

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# Calibrating tension metrics

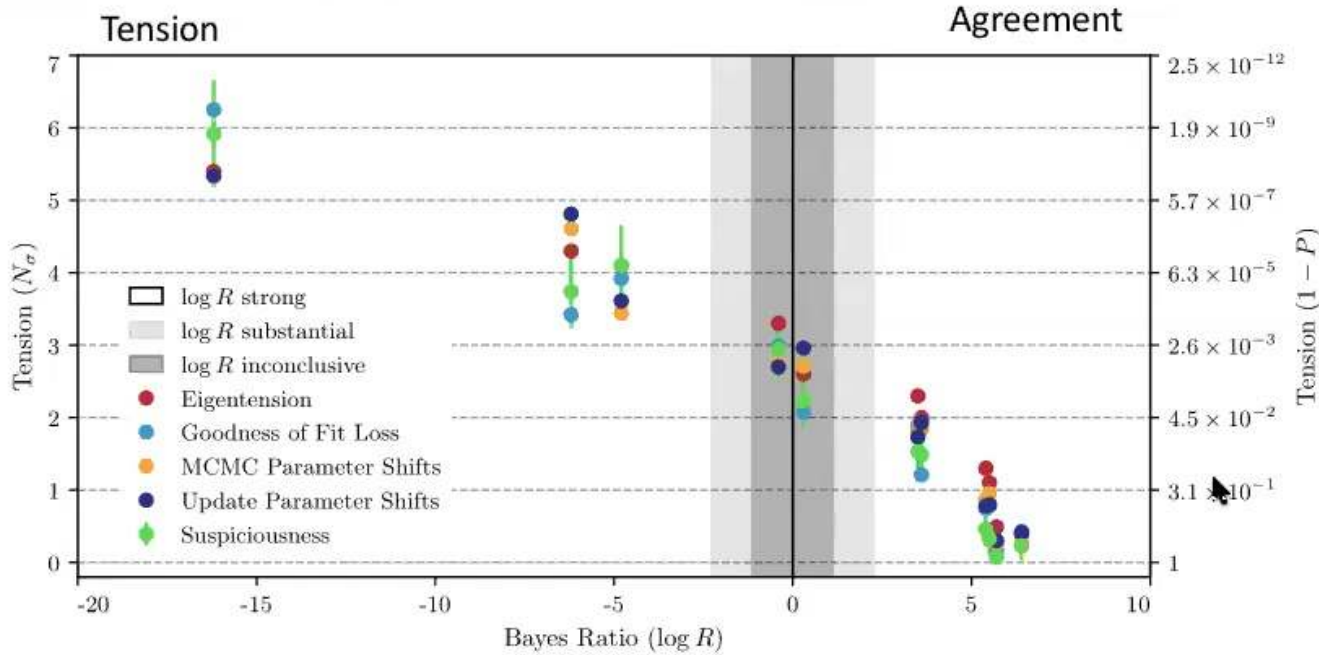


- Evaluating tension can be ambiguous in  $>1D$ , for non-Gaussian posteriors

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



# Calibrating tension metrics



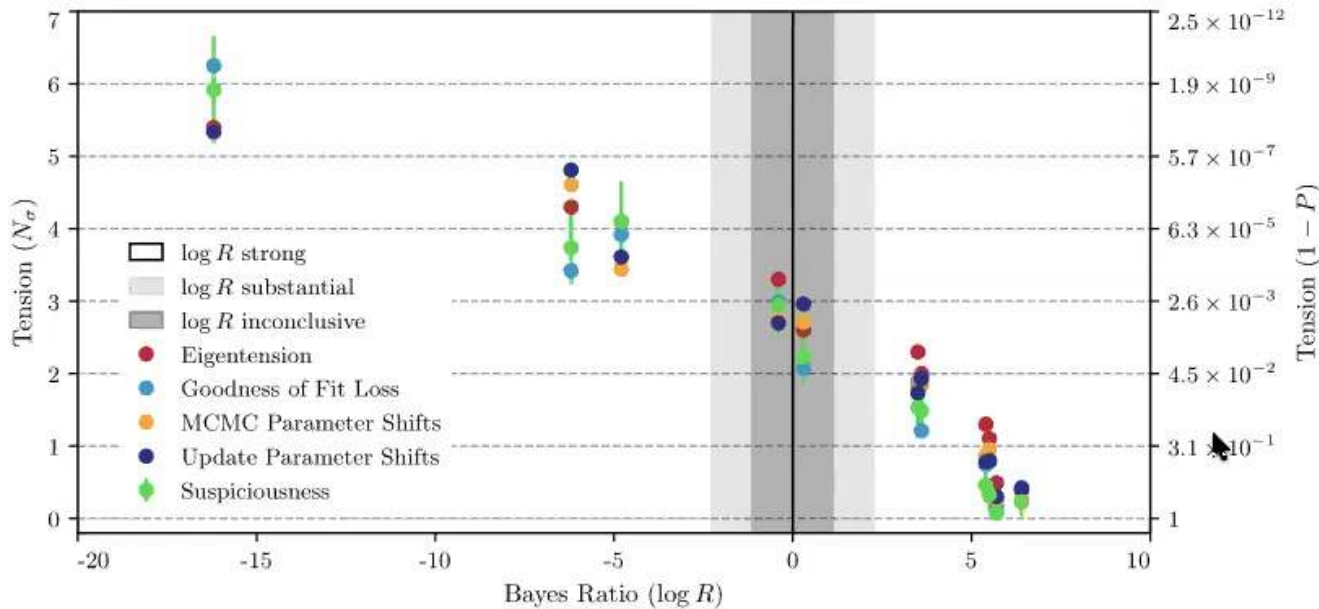
Main result from Lemos, Raveri et al:

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

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



# Calibrating tension metrics AND evaluating sampler accuracy



Main result from Lemos, Raveri et al:

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

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

## 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

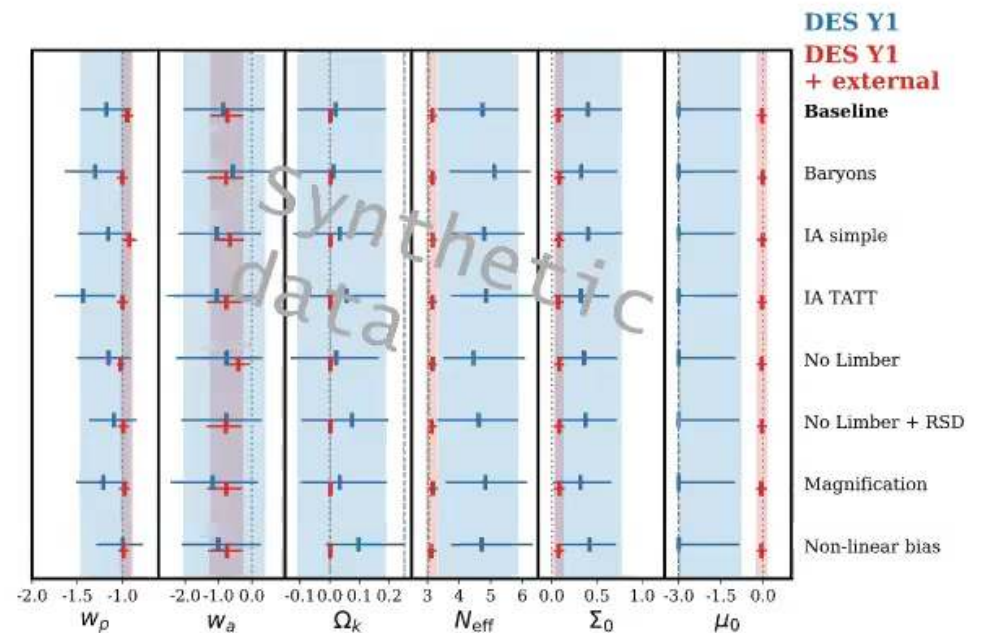
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# Y3 extended model analysis in prep

- 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**





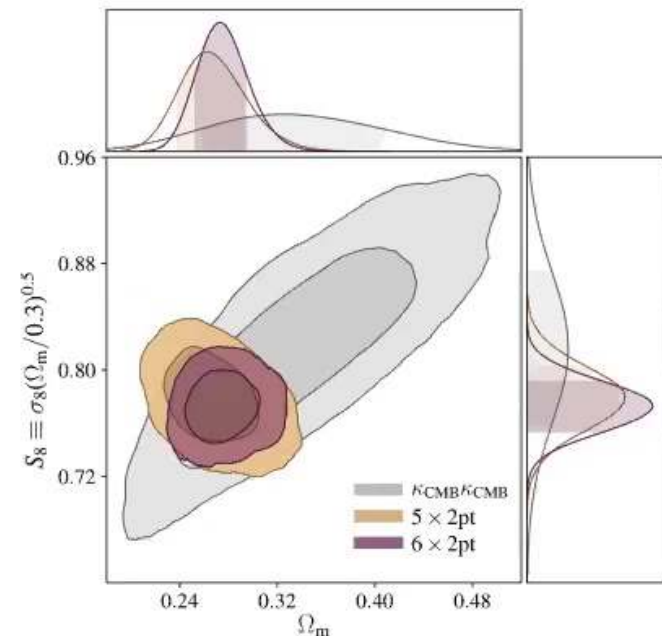
# Further tests of LSS growth history

- DES Y3 planned extended model projects:
  - Key project will include a non-parametric 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>

## Beyond DES Y3:

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

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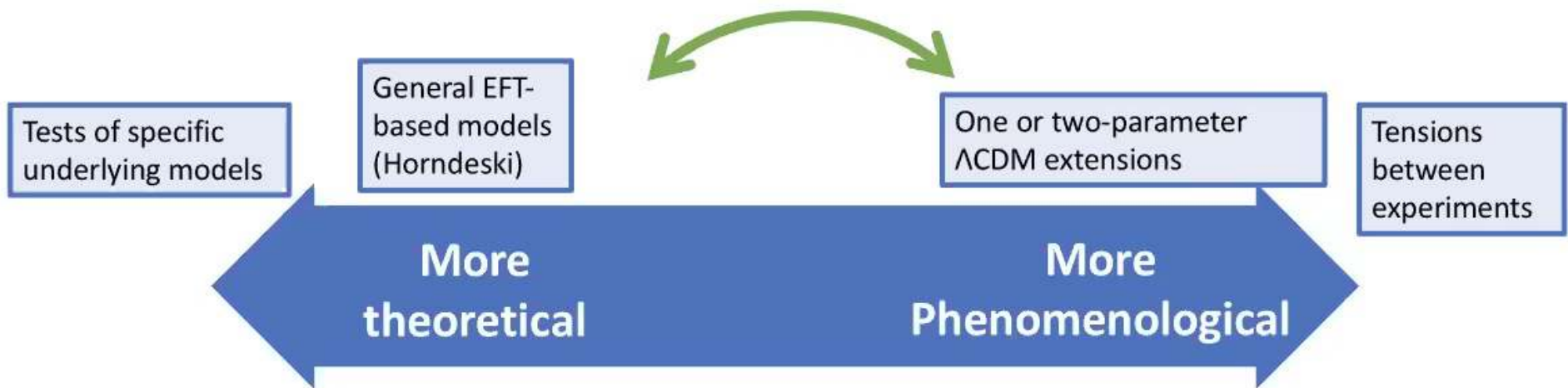
DES x CMB Lensing Y1 joint analysis:  
 DES Collab, PRD 2019, [arXiv:1810.02322](https://arxiv.org/abs/1810.02322)

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# 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](https://arxiv.org/abs/1809.01121)



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# There's theory work to do!

Understanding degeneracies between beyond- $\Lambda$ CDM signals, astrophysical effects or systematics.

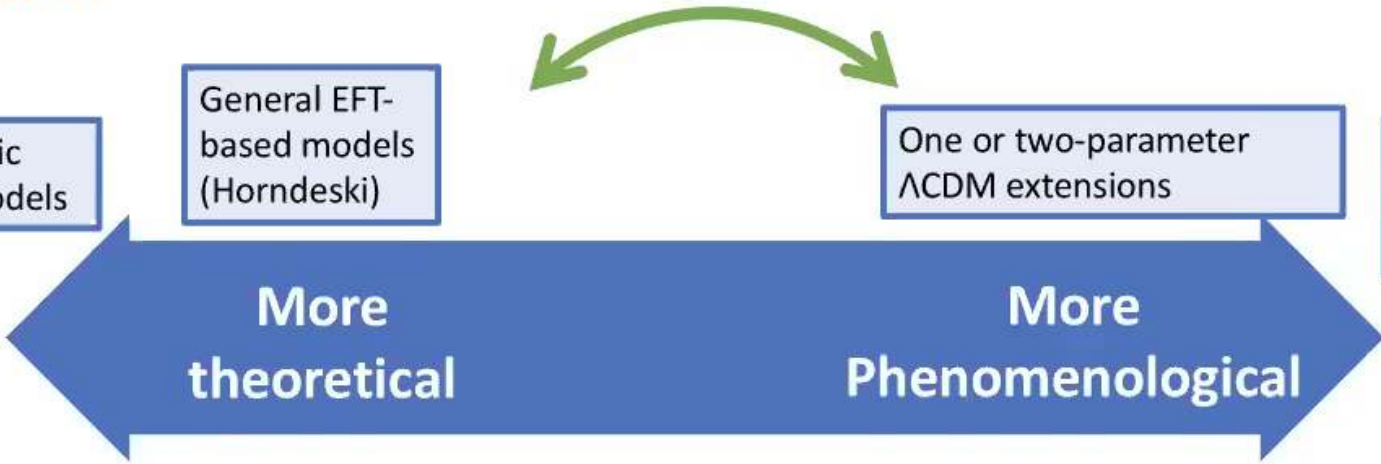
Mapping between more fundamental models and **constrainable model extensions**. See e.g. Espejo et al 2018 [arXiv:1809.01121](https://arxiv.org/abs/1809.01121)

Tests of specific underlying models

General EFT-based models (Horndeski)

One or two-parameter  $\Lambda$ CDM extensions

Tensions between experiments





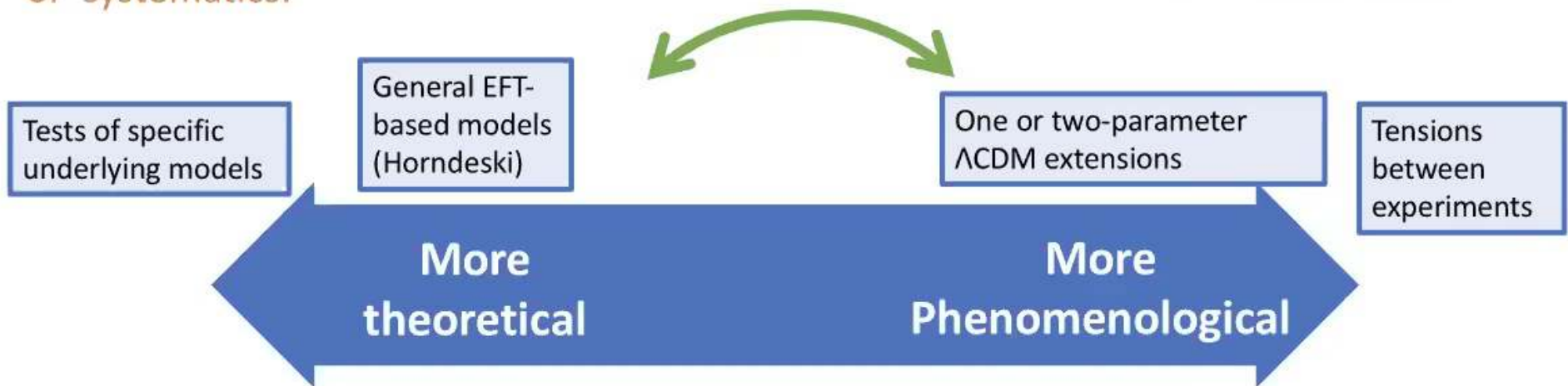
# There's theory work to do!

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Mapping between more fundamental models and **constrainable model extensions**.  
See e.g. Espejo et al 2018  
[arXiv:1809.01121](https://arxiv.org/abs/1809.01121)

## LSS measurements beyond 2PCF.

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



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# 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.

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## # Darkbites

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

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