Title: Steps towards testing Î›CDM with the Dark Energy Survey

Date: Feb 13, 2018 11:00 AM

URL: http://pirsa.org/18020094

Abstract: <p>Large scale structure surveys are one of our primary tools for answering open questions in cosmology like: What is the physics behind dark energy? Is gravity well described by general relativity on cosmological scales, or does that description need to be extended? In order to take full advantage of the information contained in survey data, however, we must ensure that we understand our dataâ€™s sensitivity to new physics and that our analyses are not biased by systematics. In my talk Iâ€™ll describe work I have been doing in this aim for the Dark Energy Survey (DES). Iâ€™ll begin with an introduction to how we can use data from surveys like the DES to test LCDM, including approaches to constraining extensions to general relativity with cosmological data. Iâ€™ll use that discussion to motivate a so-called growth-geometry split analysis, a consistency test of LCDM that works by comparing constraints from probes of structure growth and expansion history, and will discuss the status of such an analysis applied to DES data. Iâ€™ll also give an overview of the blinding strategy planned for future multi-probe DES cosmology analyses.</p>

Steps towards testing ΛCDM with the Dark Energy Survey

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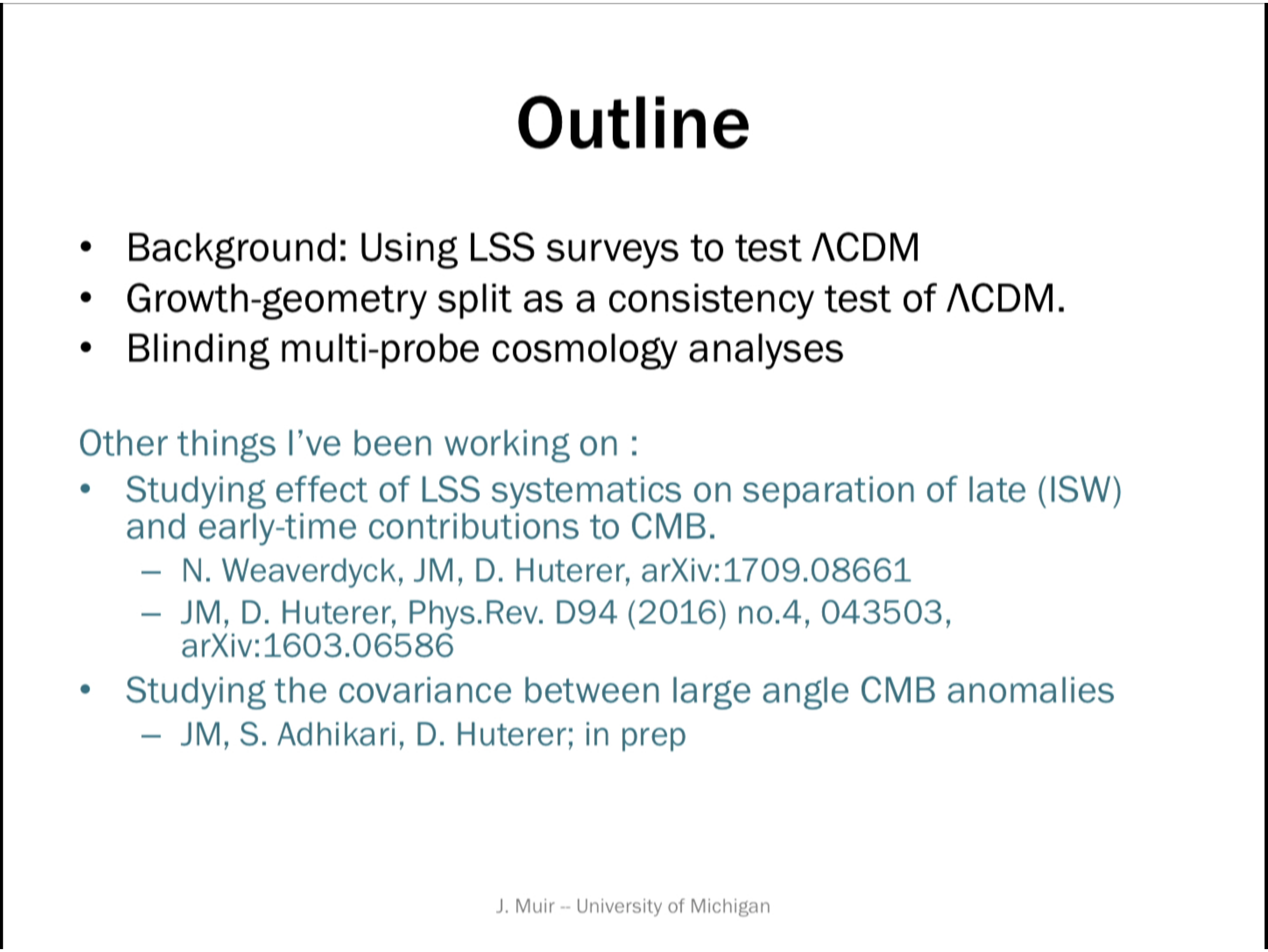
UNIVERSITY OF MICHIGAN

Perimeter Institute Cosmology and Gravitation Seminar 2/13/18



Outline

- Background: Using LSS surveys to test ΛCDM
- Growth-geometry split as a consistency test of ΛCDM.
- Blinding multi-probe cosmology analyses

Other things I've been working on :

- Studying effect of LSS systematics on separation of late (ISW) and early-time contributions to CMB.
  - N. Weaverdyck, JM, D. Huterer, arXiv:1709.08661
  - JM, D. Huterer, Phys.Rev. D94 (2016) no.4, 043503, arXiv:1603.06586
- Studying the covariance between large angle CMB anomalies
  - JM, S. Adhikari, D. Huterer; in prep

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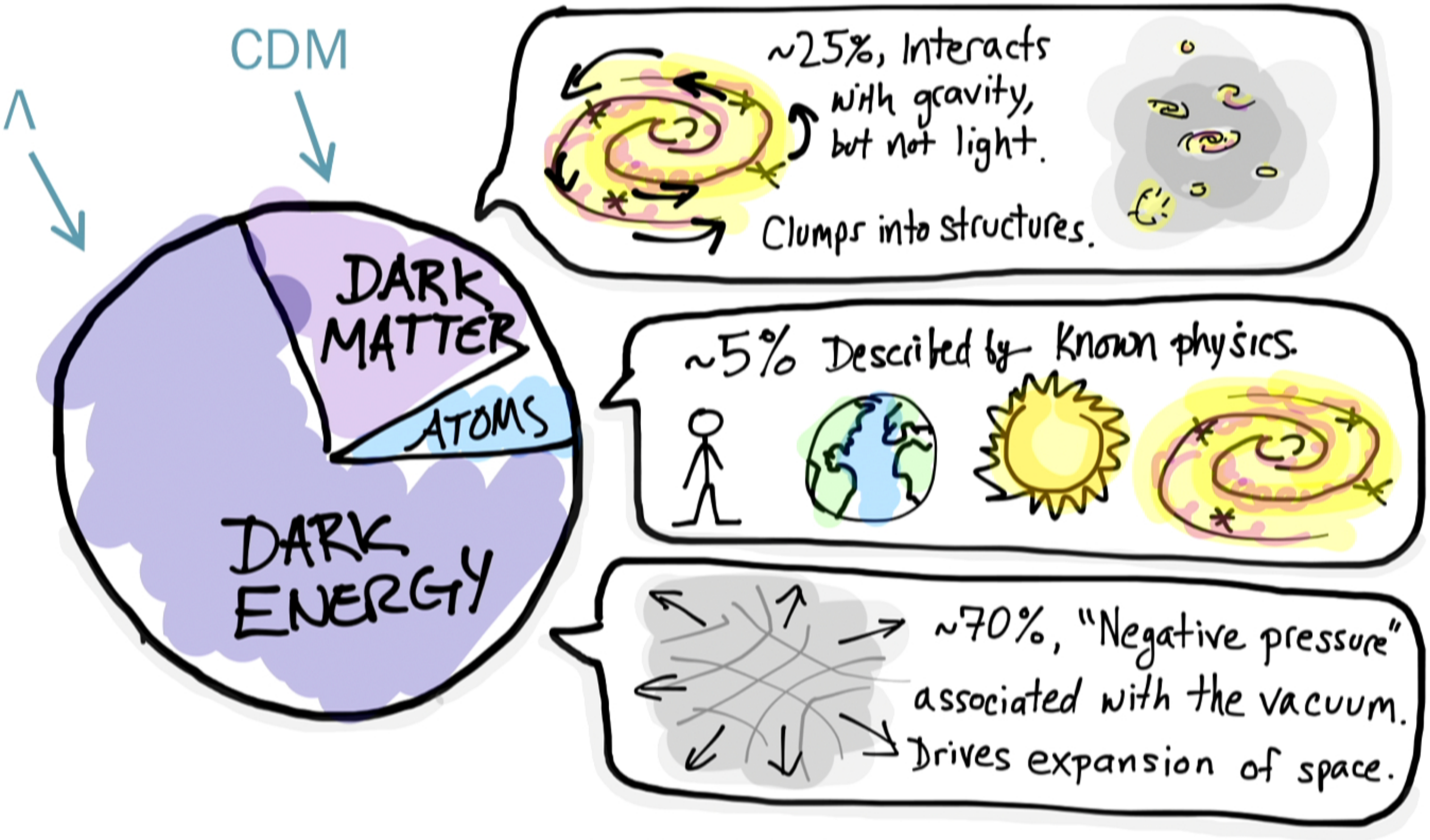
ΛCDM: Standard cosmological model



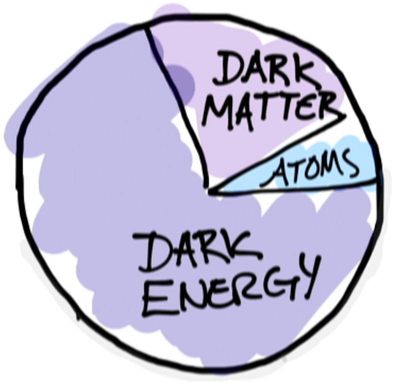
~25%, Interacts with gravity, but not light.

Clumps into structures.

~5% Described by known physics.

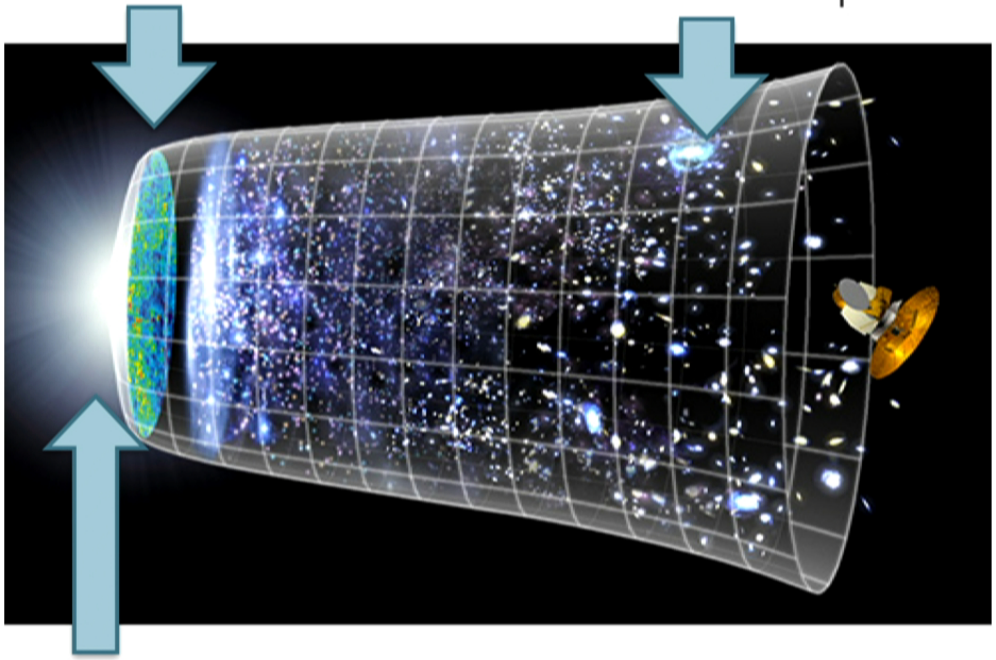
~70%, "Negative pressure" associated with the vacuum. Drives expansion of space.

Expansion history



\+ General relativity

=



CMB released

Dark energy causes accelerated expansion

Inflation

Credit: NASA WMAP Science team

Structure growth

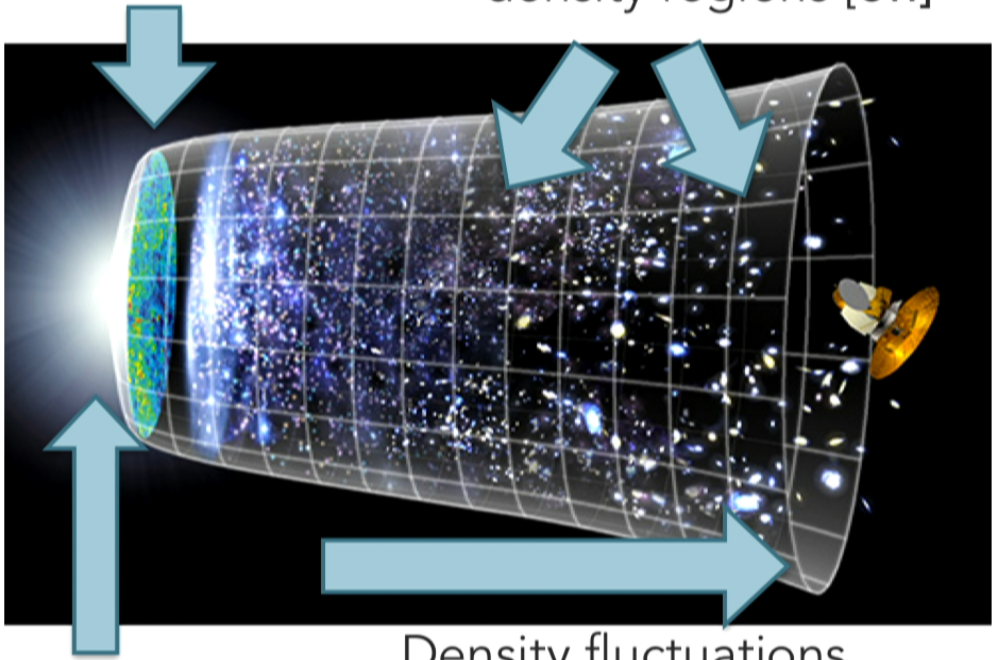
+ General relativity

+ Initial fluctuation properties

=

CMB released [δT]

Galaxies form in high density regions [δn]



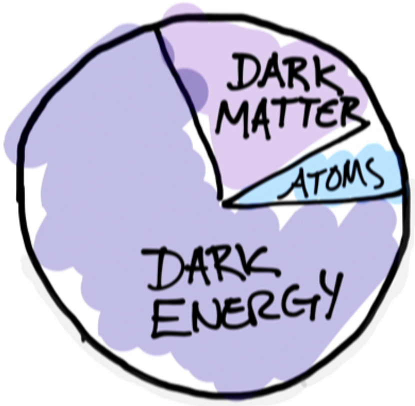
Inflation [δφ]

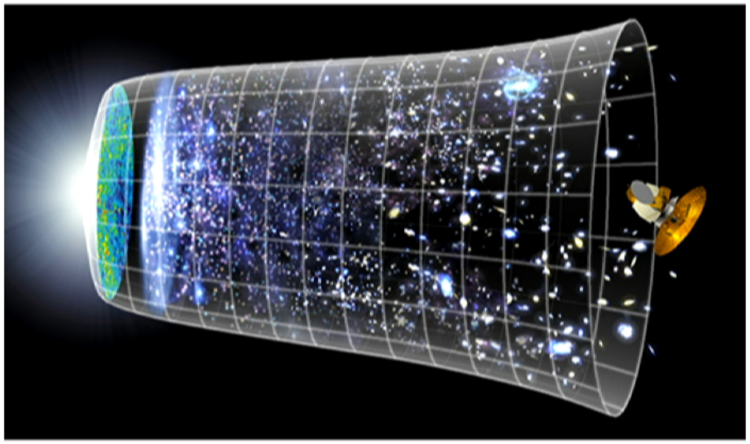
Density fluctuations grow [δρ]

Credit: NASA WMAP Science team

Open questions

- What physics governed inflation?
- What is dark matter?
- What is dark energy?
- Is general relativity a complete description of gravity?





Credit: NASA WMAP Science team

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CONSTRAINING COSMOLOGY WITH THE DARK ENERGY SURVEY (DES)

DES

- Photometric galaxy survey using 4-m Blanco telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile
- Mapping galaxy positions and shapes over 1/8 of the sky out to z~1
- Also measuring supernovae & galaxy clusters.

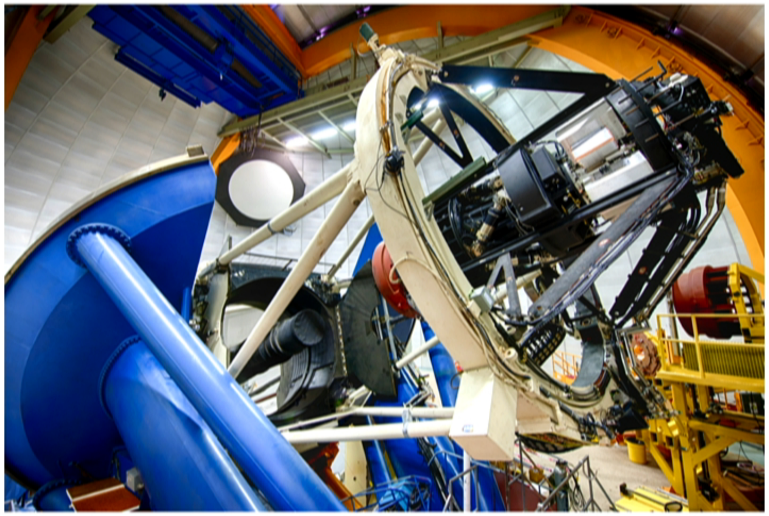
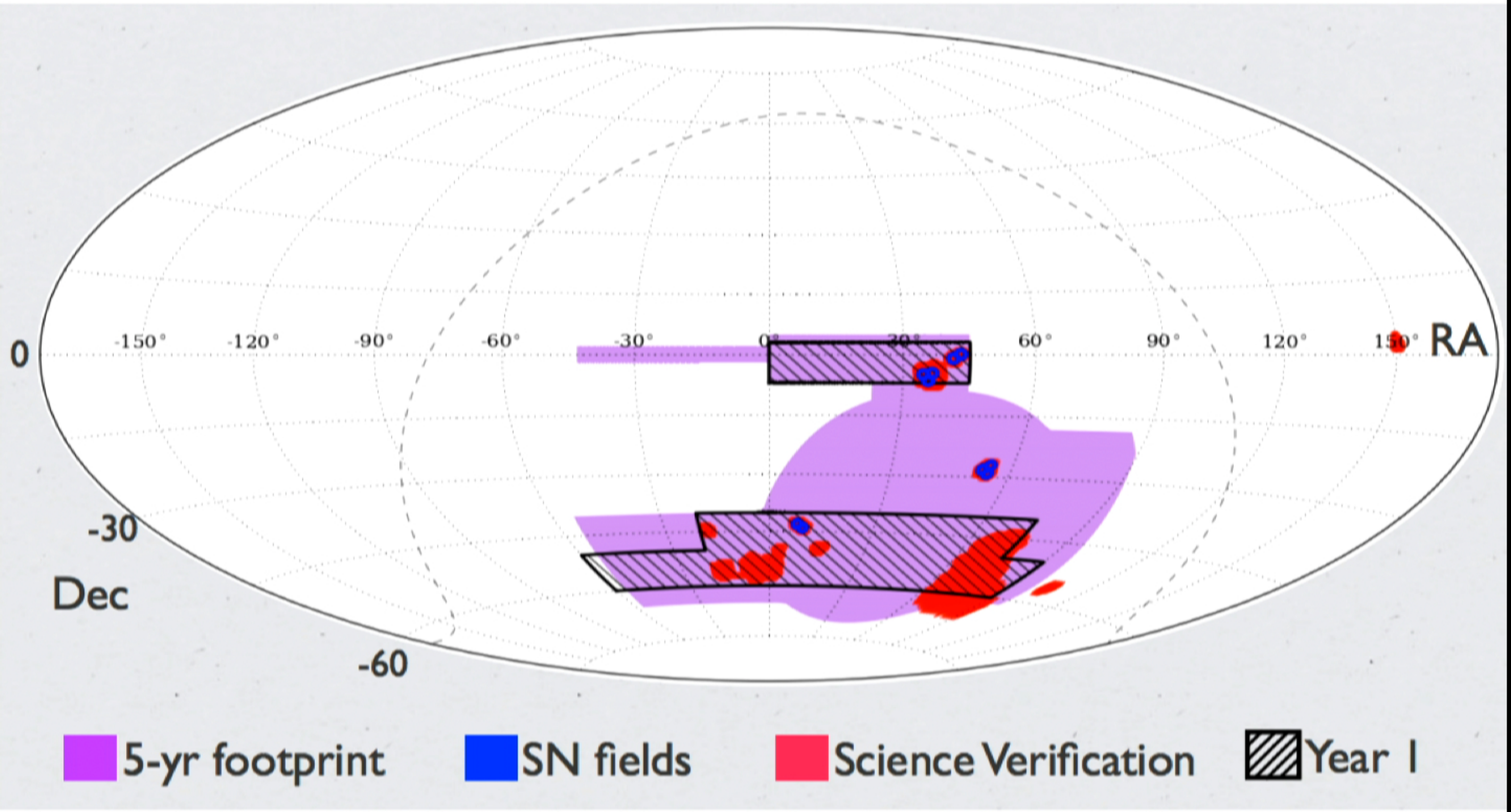
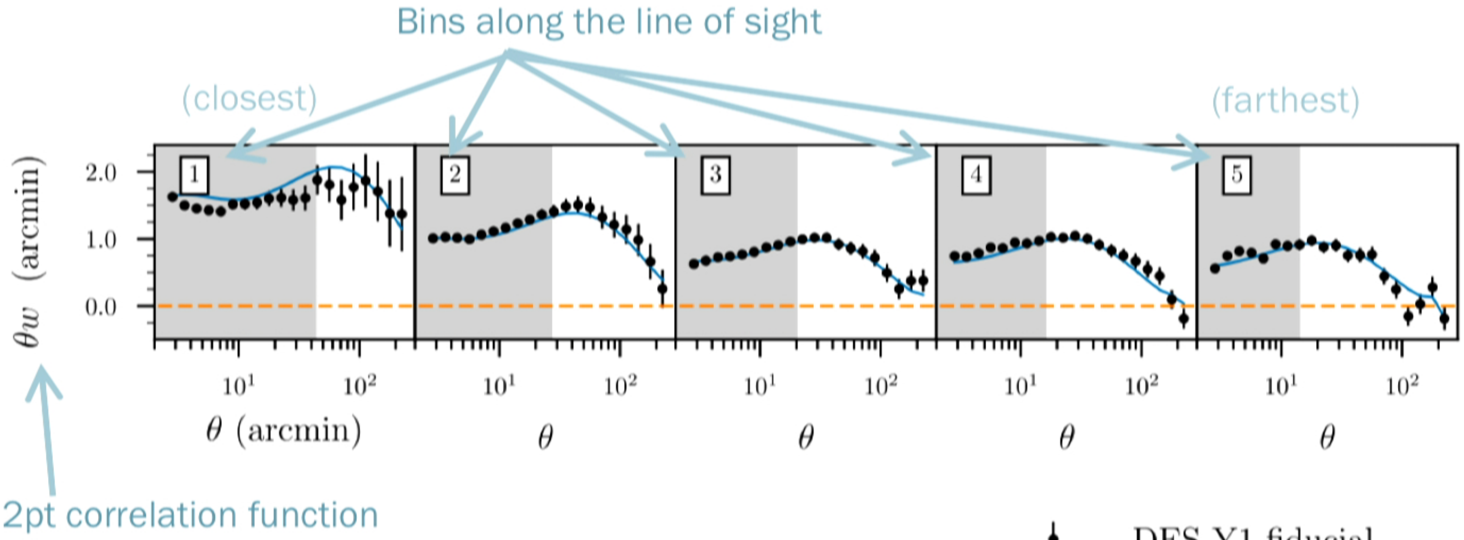


Image credit: Reider Hahn, Fermilab

The Dark Energy Survey



Galaxy clustering



DES Collaboration
arXiv: 1708.01530

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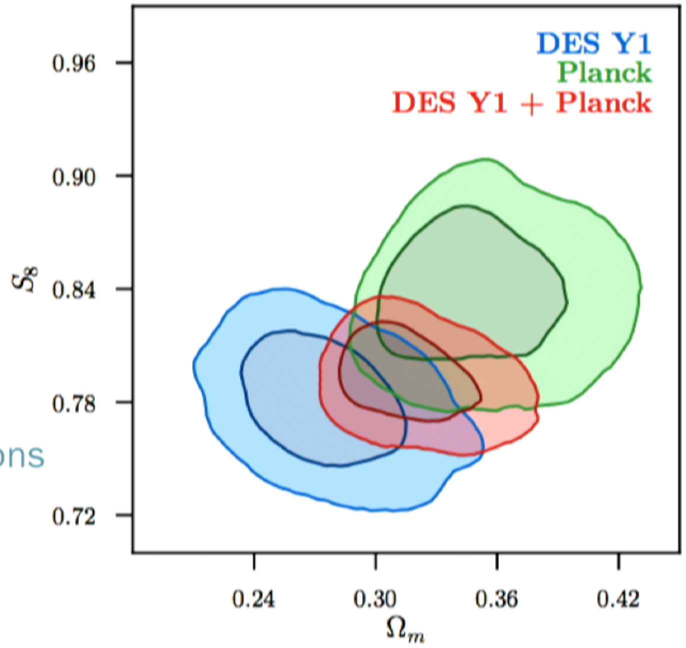
DES Y1 results for ΛCDM



Amplitude of density fluctuations

Matter fraction of mass-energy density

Cosmology analysis combines 2pt correlation functions:

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

DES Collaboration arXiv: 1708.01530

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GROWTH-GEOMETRY SPLIT

Going beyond ΛCDM

- Simplest model for dark energy: Cosmological constant
  - Λ in ΛCDM
- To test ΛCDM, can…
  - Check agreement between different probes
  - Constrain time dependence by measuring equation of state parameter w:
    - w = pressure/density
    - w=-1 ➔ Λ
    - w≠-1 ➔ time dependent energy density
  - Constrain parameters of other models
    - Dynamic DE, coupled DE, modified gravity…

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Modified gravity

- Could accelerating expansion be due to deviation from GR?
- Or more conservatively: is GR well tested on cosmological scales?

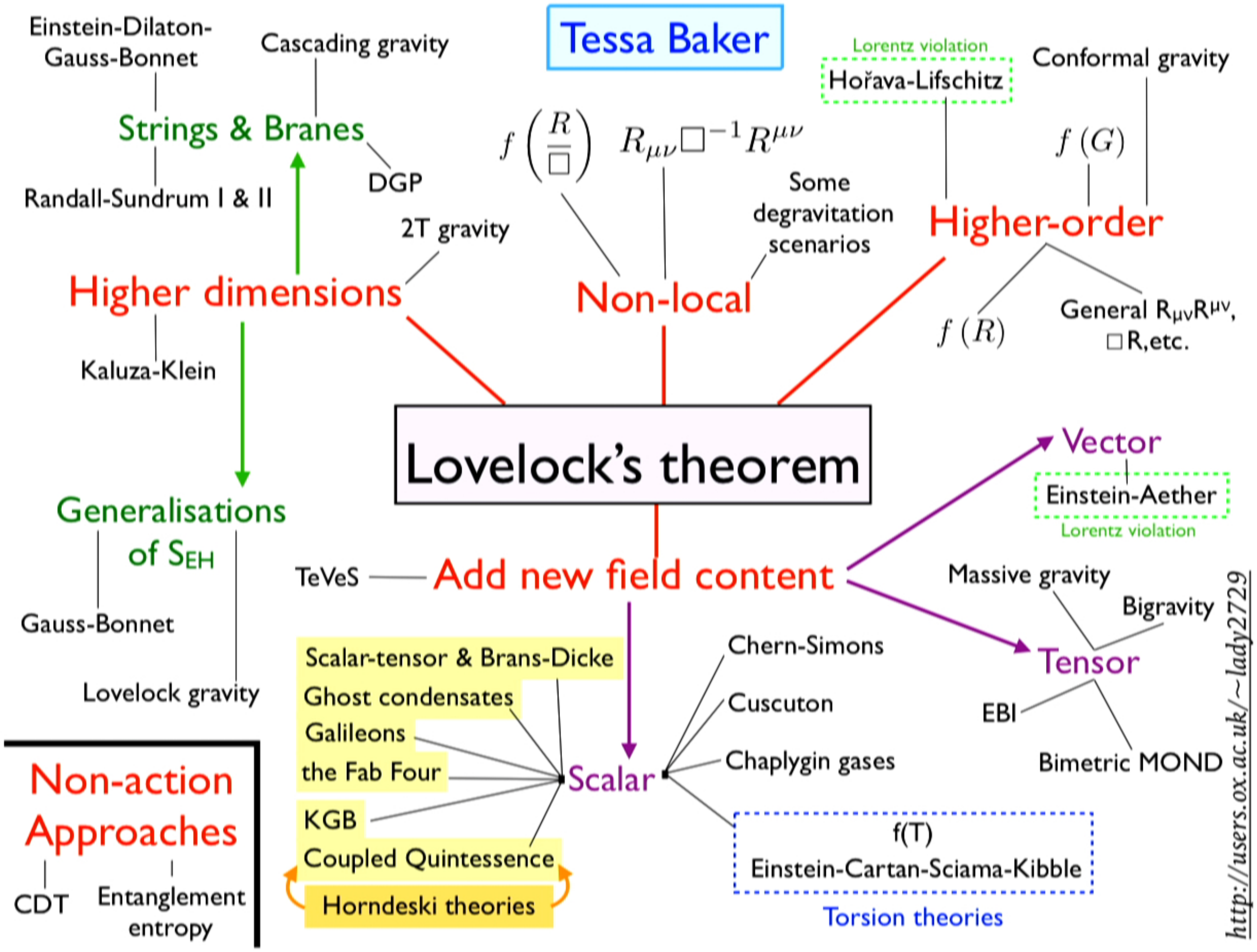
$$\boxed{R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}} = \boxed{8\pi G T_{\mu\nu}}$$

Curvature of spacetime

Matter and energy

Einstein's equation

Modified gravity models



Tessa Baker

Einstein-Dilaton-Gauss-Bonnet

Cascading gravity

Strings & Branes

Randall-Sundrum I & II

DGP

2T gravity

Higher dimensions

Kaluza-Klein

Generalisations of S_{EH}

Gauss-Bonnet

Lovelock gravity

$f\left(\frac{R}{\Box}\right)$

$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$

Some degravitation scenarios

Non-local

Lorentz violation

Hořava-Lifschitz

Conformal gravity

$f(G)$

Higher-order

$f(R)$

General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$,etc.

Lovelock's theorem

Vector

Einstein-Aether

Lorentz violation

TeVeS

Add new field content

Massive gravity

Bigravity

Tensor

EBI

Bimetric MOND

Scalar-tensor & Brans-Dicke

Ghost condensates

Galileons

the Fab Four

KGB

Coupled Quintessence

Horndeski theories

Scalar

Chern-Simons

Cuscuton

Chaplygin gases

f(T)

Einstein-Cartan-Sciama-Kibble

Torsion theories

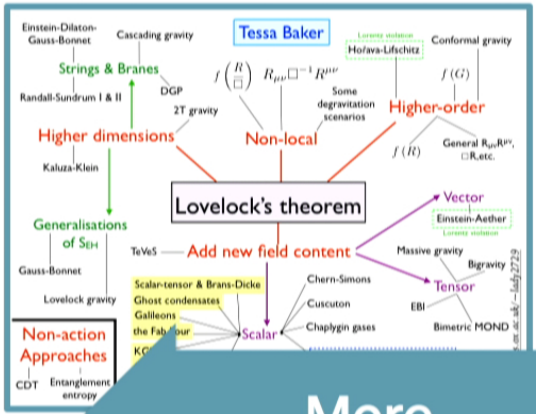
Non-action Approaches

CDT

Entanglement entropy

http://users.ox.ac.uk/~lady2729

Constraining MG models with LSS



More theoretical

More Phenomenological

Simple LCDM extensions:
w_0-w_a,
γ growth parameter

Tests of specific underlying models like f(R)

General EFT-based models

Growth-geometry split

Σ(z,k)-μ(z,k), aka G_{light}-G_{matter}
E_G – ratio between lensing and velocity power spectra

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Growth-geometry split parameterization

Test consistency of ΛCDM (or wCDM) by comparing constraints from geometry and growth-based probes.

- *Geometry: expansion rate H(z), distance measures*
- *Growth: growth rate in linear & nonlinear regimes*

Following Ruiz & Huterer, Phys. Rev. D 91, 063009 (2015) arXiv:1410.5832:

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

See also:
Sheng Wang et al, Phys. Rev. D 76, 063503 (2007);
Bernal, José Luis and Verde, Licia and Cuesta, Antonio J., astro-ph/1511.03049;

Growth-geometry split

Pros

- MG models break ΛCDM relationship between expansion history and structure growth. Sensitive to this.
- Fairly model independent.
- Simple to implement – e.g. can reuse ΛCDM modeling of non-linear physics.

Cons

- If $\Omega_m^{geo} \neq \Omega_m^{grow}$ physical interpretation is not clear.

Following Ruiz & Huterer, Phys. Rev. D 91, 063009 (2015) arXiv:1410.5832:

$$\Omega_m \rightarrow \Omega_m^{grow},\ \Omega_m^{geo}$$

Implementing in DES pipeline

- Power spectrum mixes growth and geometry. For z_i=3.5, linear P(k) is

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

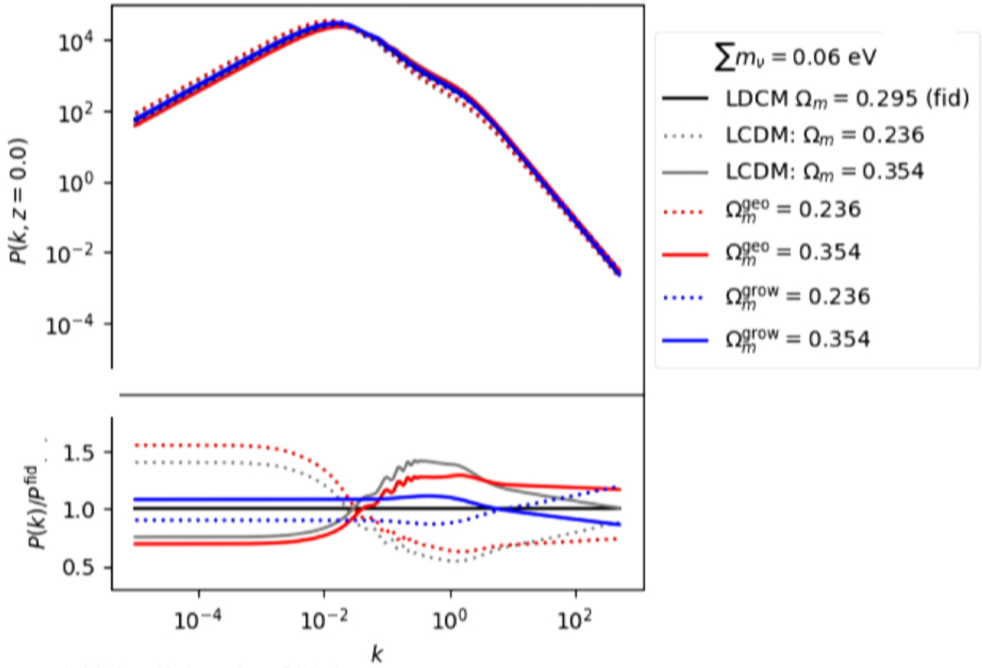
- Projection effects are geometry

Solid lines: Ω_m ↑20%

Dotted lines: Ω_m ↓20%

Grey: ΛCDM
Red: change Ω_m^{geo} only
Blue: change Ω_m^{grow} only

Working with: Eric Baxter, Vinicius Miranda, Dragan Huterer, Bhuvnesh Jain



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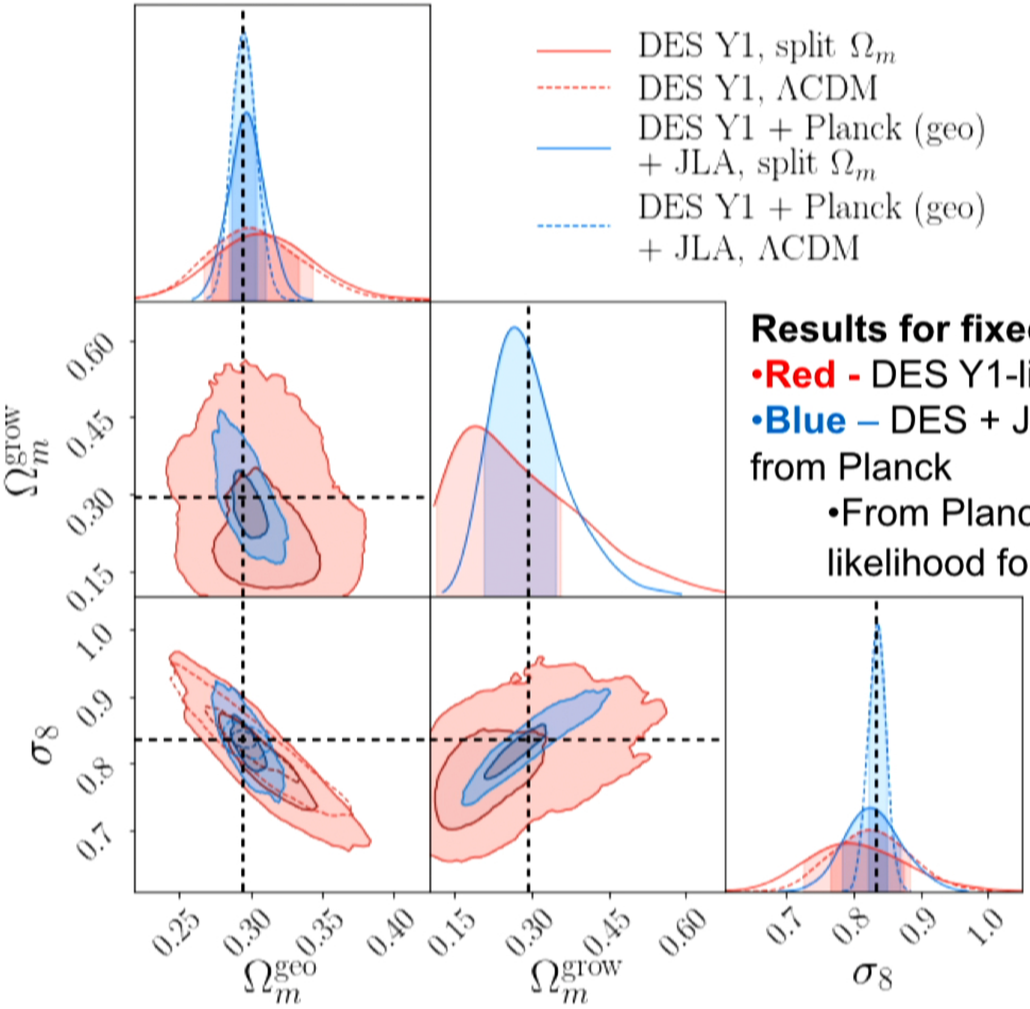
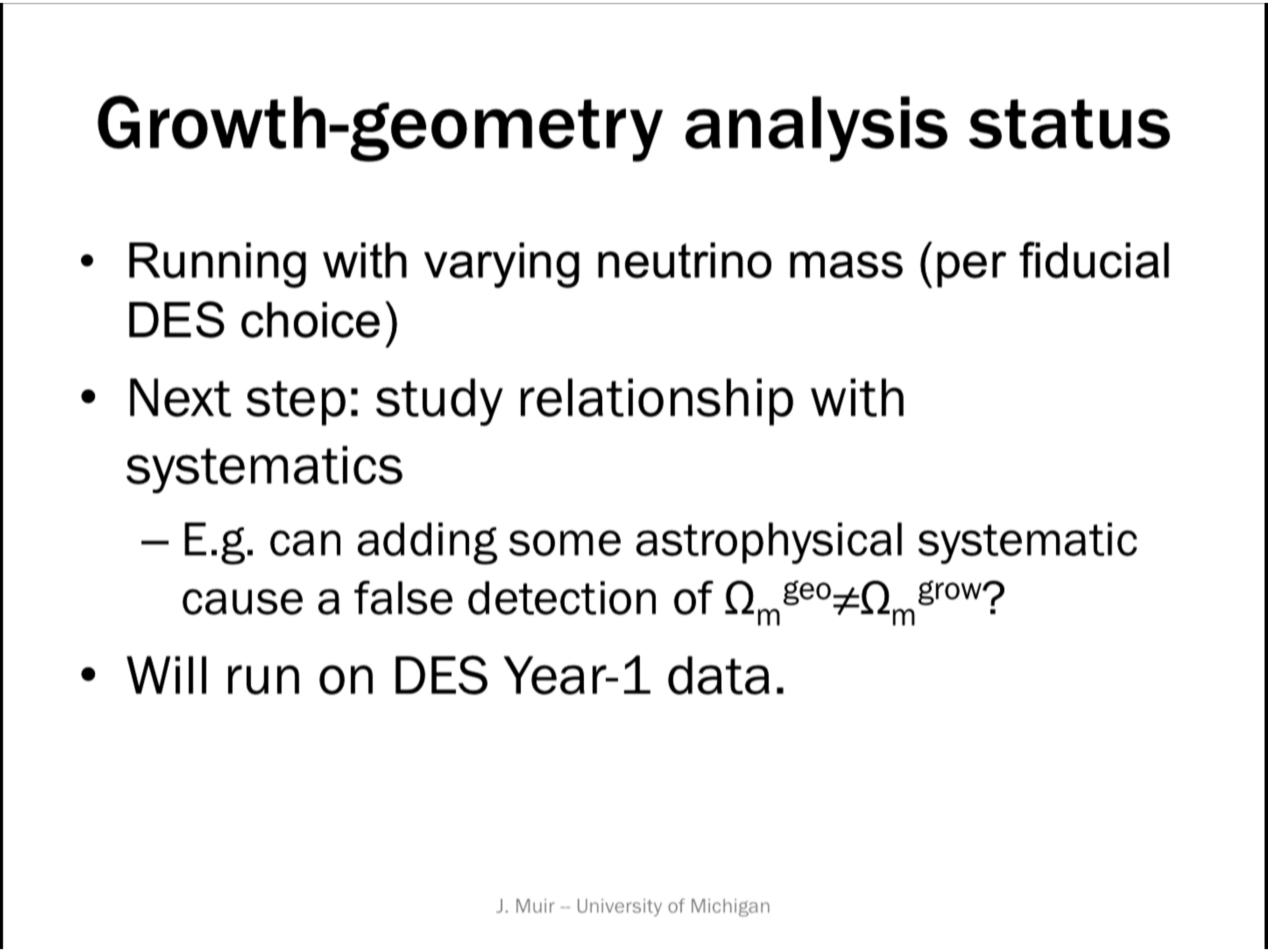
Testing on DES Y1-like simulated data



Results for fixed neutrino mass

- **Red -** DES Y1-like data only
- **Blue –** DES + JLA + geometric info from Planck
  - From Planck 5D Gaussian likelihood for n_s, R_{shift}, l_A, $\Omega_b h^2$, A_s



Growth-geometry analysis status

- Running with varying neutrino mass (per fiducial DES choice)
- Next step: study relationship with systematics
  - E.g. can adding some astrophysical systematic cause a false detection of $\Omega_m^{geo} \neq \Omega_m^{grow}$?
- Will run on DES Year-1 data.

MULTI-PROBE BLINDING FOR DES

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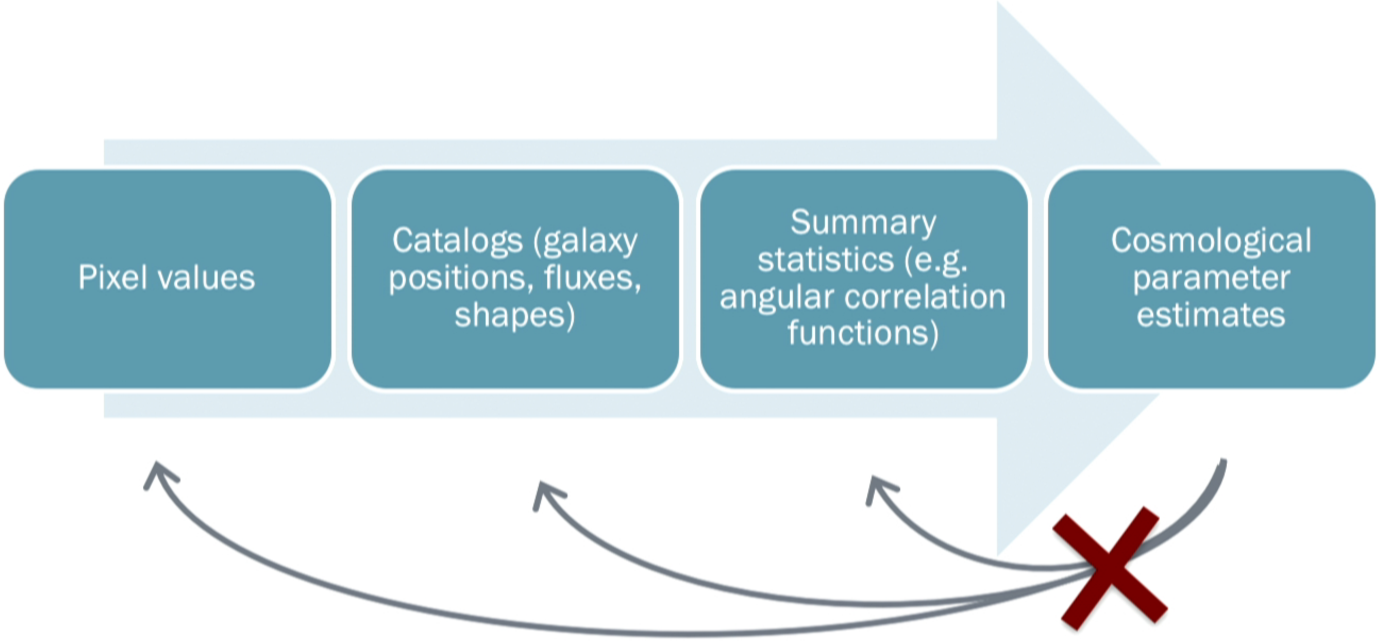
Multiprobe blinding


Pixel values

Catalogs (galaxy positions, fluxes, shapes)

Summary statistics (e.g. angular correlation functions)

Cosmological parameter estimates

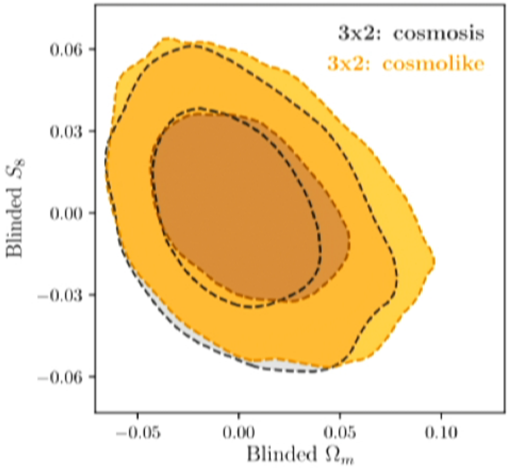
Requirements

- Shift output cosmological parameters
- Preserve inter-probe consistency
- Preserve ability to test for systematic errors

For DES Year-1 analysis

Shears blinded with
multiplicative factor
(unblinded to combine) ↓

- Pixel values
- Catalogs (galaxy positions, fluxes, shapes)
- Summary statistics (e.g. angular correlation functions)
- **Cosmological parameter estimates**

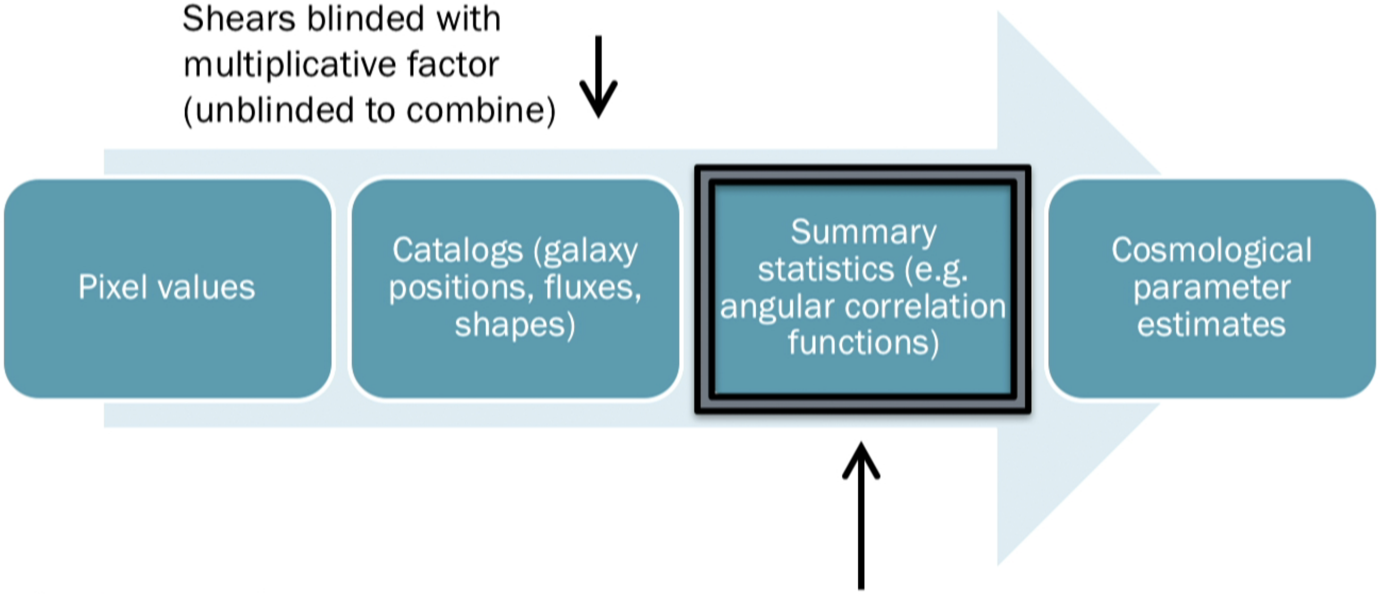


↑

Hide axes or
introduce
unknown offset

More robust scheme for Year-3 analysis

Shears blinded with
multiplicative factor
(unblinded to combine)

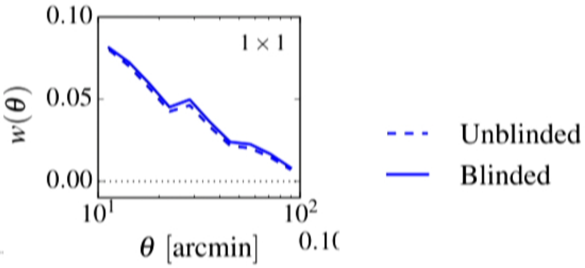


Pixel values

Catalogs (galaxy positions, fluxes, shapes)

Summary statistics (e.g. angular correlation functions)

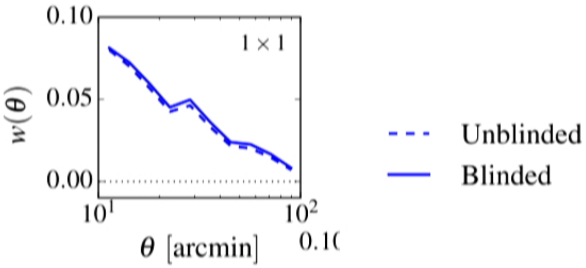
Cosmological parameter estimates



Methods paper in prep.

Working with Franz Elsner, Gary Bernstein, Dragan Huterer

Strategy for Y3: Linearly scale summary statistics



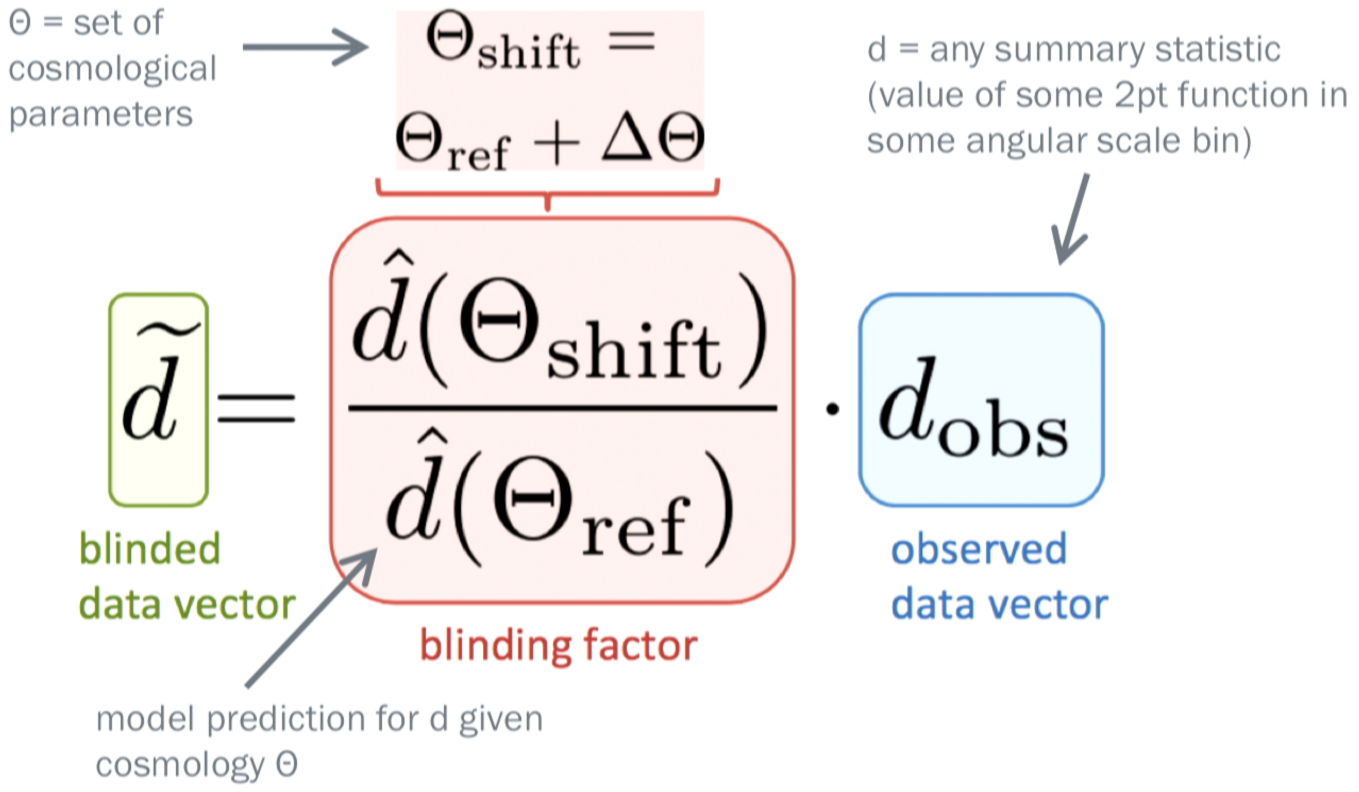
d = any summary statistic (value of some 2pt function in some angular scale bin)

$$\tilde{d} = \mathbf{f} \cdot d_{\mathrm{obs}}$$

blinded
data vector

observed
data vector

Strategy for Y3: Linearly scale summary statistics



Θ = set of cosmological parameters

$$\Theta_{\rm shift} = \Theta_{\rm ref} + \Delta\Theta$$

d = any summary statistic (value of some 2pt function in some angular scale bin)

$$\boxed{\tilde{d}} = \boxed{\frac{\hat{d}(\Theta_{\rm shift})}{\hat{d}(\Theta_{\rm ref})}} \cdot \boxed{d_{\rm obs}}$$

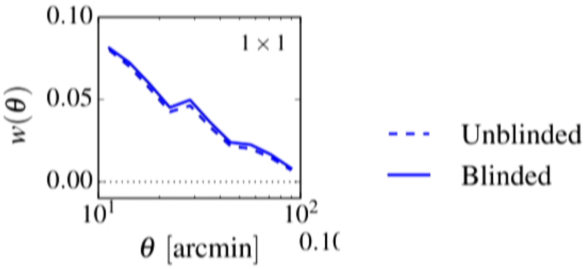
blinded data vector

blinding factor

observed data vector

model prediction for d given cosmology Θ

Strategy for Y3: Linearly scale summary statistics



d = any summary statistic (value of some 2pt function in some angular scale bin)

$$\boxed{\tilde{d}} = \boxed{\mathbf{f}} \cdot \boxed{d_{\mathrm{obs}}}$$

blinded
data vector

observed
data vector

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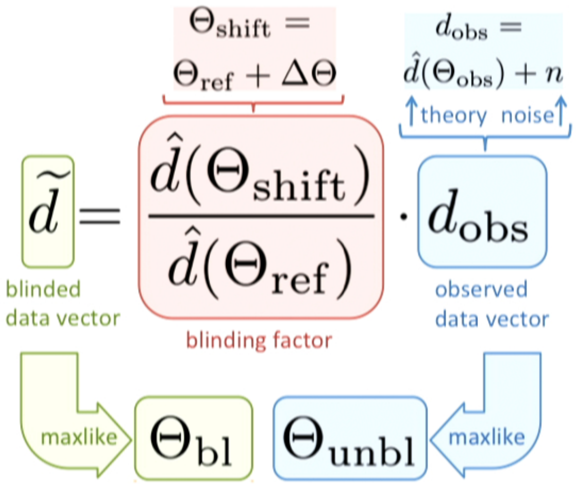
Test: How does blinding affect the best fit Θ?

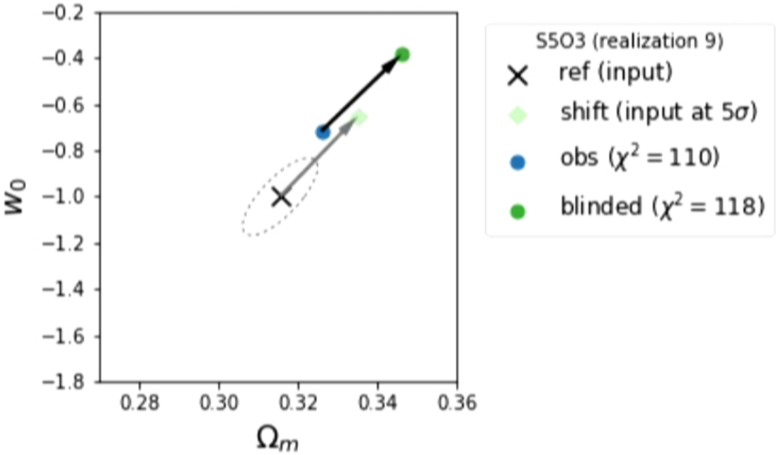


$\Theta_{\text{shift}} = \Theta_{\text{ref}} + \Delta\Theta$

$d_{\text{obs}} = \underbrace{\hat{d}(\Theta_{\text{obs}})}_{\text{theory}} + \underbrace{n}_{\text{noise}}$

$$\underbrace{\tilde{d}}_{\text{blinded data vector}} = \underbrace{\frac{\hat{d}(\Theta_{\text{shift}})}{\hat{d}(\Theta_{\text{ref}})}}_{\text{blinding factor}} \cdot \underbrace{d_{\text{obs}}}_{\text{observed data vector}}$$

$$\tilde{d} \xrightarrow{\text{maxlike}} \Theta_{\text{bl}} \qquad \Theta_{\text{unbl}} \xleftarrow{\text{maxlike}} d_{\text{obs}}$$



In general:

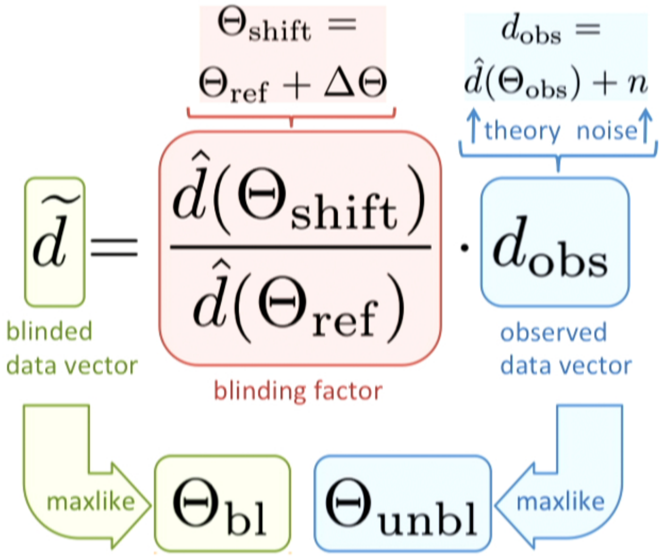
$$\boxed{\begin{aligned} &\Theta_{\text{shift}} - \Theta_{\text{ref}} \\ &\qquad \approx \Theta_{\text{bl}} - \Theta_{\text{unbl}} \end{aligned}}$$

Test analysis run on simulated data vectors:

- Galaxy-galaxy corr
- shear-shear corr
- Galaxy – shear corr

Ellipse: 1σ for DES Y1

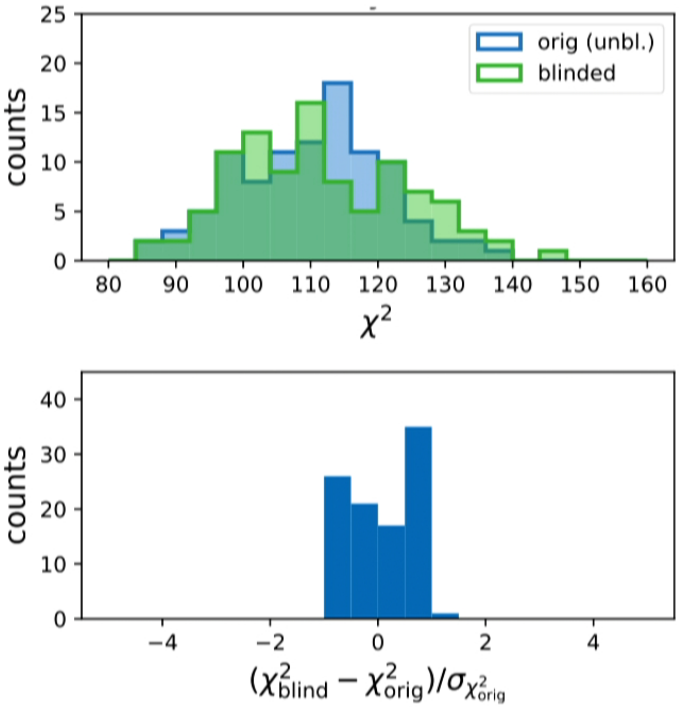
Test: Is the blinded data vector consistent with a valid cosmology?



$$\Theta_{\rm shift} = \Theta_{\rm ref} + \Delta\Theta$$

$$d_{\rm obs} = \hat{d}(\Theta_{\rm obs}) + n$$

$$\tilde{d} = \frac{\hat{d}(\Theta_{\rm shift})}{\hat{d}(\Theta_{\rm ref})} \cdot d_{\rm obs}$$



Summary

- LSS surveys give us an opportunity to test ΛCDM by comparing results against other probes or testing extended models.

- Growth-geometry split parameterization is:
  - A phenomenological consistency test of ΛCDM motivated by modified gravity models.
  - One of the extended analyses that will be run on DES Year 1 data.
- Multi-probe blinding is:
  - A tool to prevent experimenters' bias from influencing analyses, one among many tools to protect against systematics.
  - Able to shift output parameters without influence treatment of other systematics by multiplying summary statistics (2pt functions) by specific scale-dependent factors.

- Both of these will implemented in near-future DES analyses, which can serve as a test-bed for future LSS analyses.