Unbiasing cosmology on the largest scales

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INPA Seminar, LBNL

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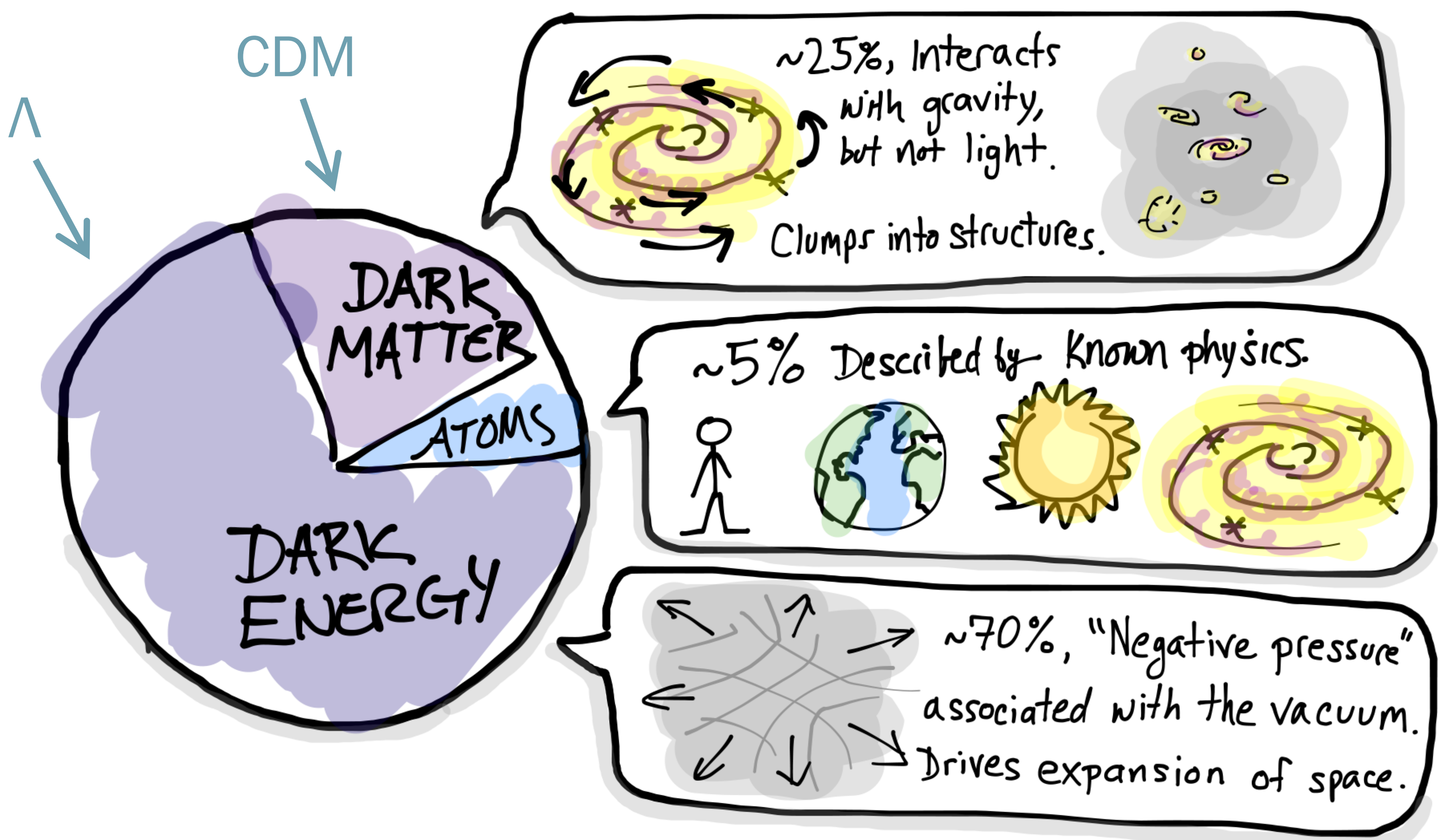
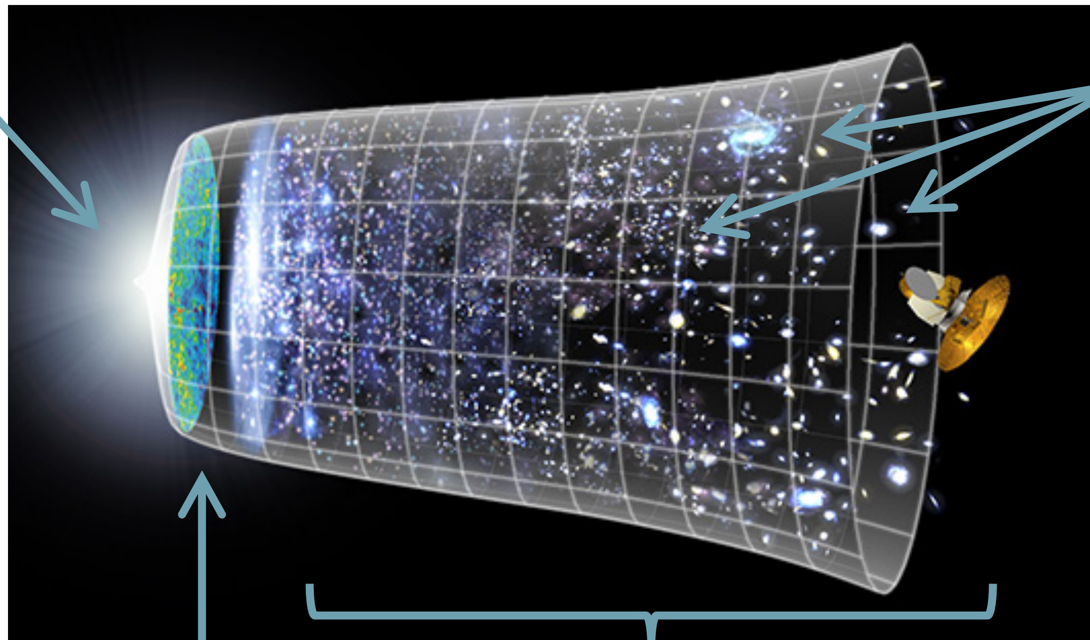
Concordance cosmology: ΛCDM



Concordance cosmology: ΛCDM

STANDARD MODEL

Inflation seeds initial density fluctuations



Structure formation: gravity causes density fluctuations to grow & form structures

Universe becomes neutral, cosmic microwave background (CMB) light released

Universe expands, at late times dark energy drives acceleration

Image credit: NASA, WMAP

Concordance cosmology: ΛCDM

STANDARD MODEL | **OPEN QUESTIONS**

Inflation seeds initial density fluctuations

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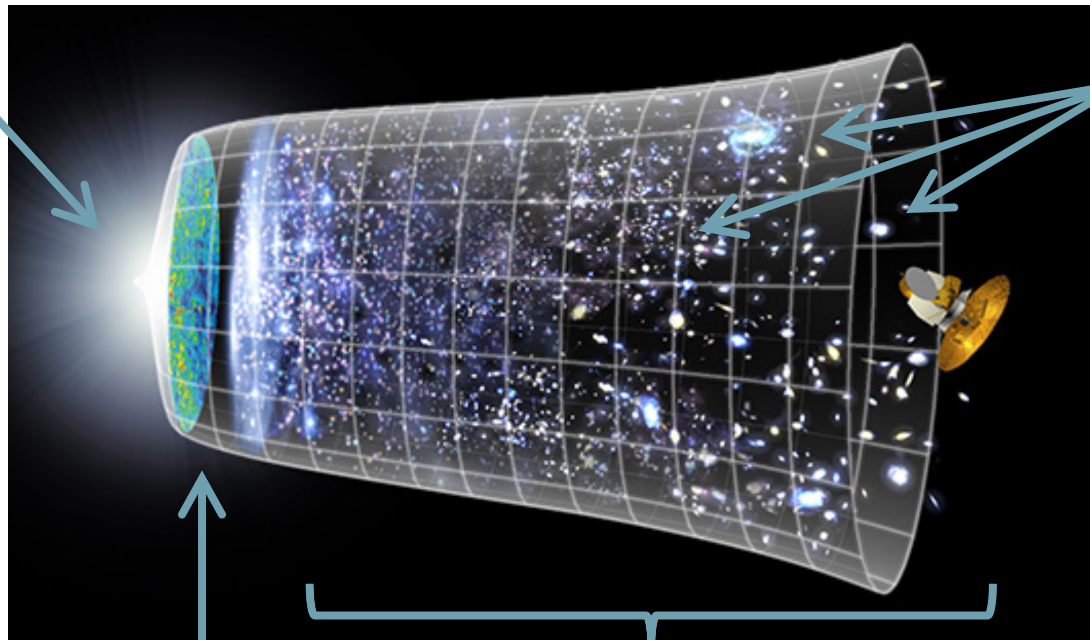


What physics governed inflation?

What is dark matter?

Universe becomes neutral, cosmic microwave background (CMB) light released

Universe expands, at late times dark energy drives acceleration

Is general relativity a good description of gravity?

What is dark energy?

Image credit: NASA, WMAP

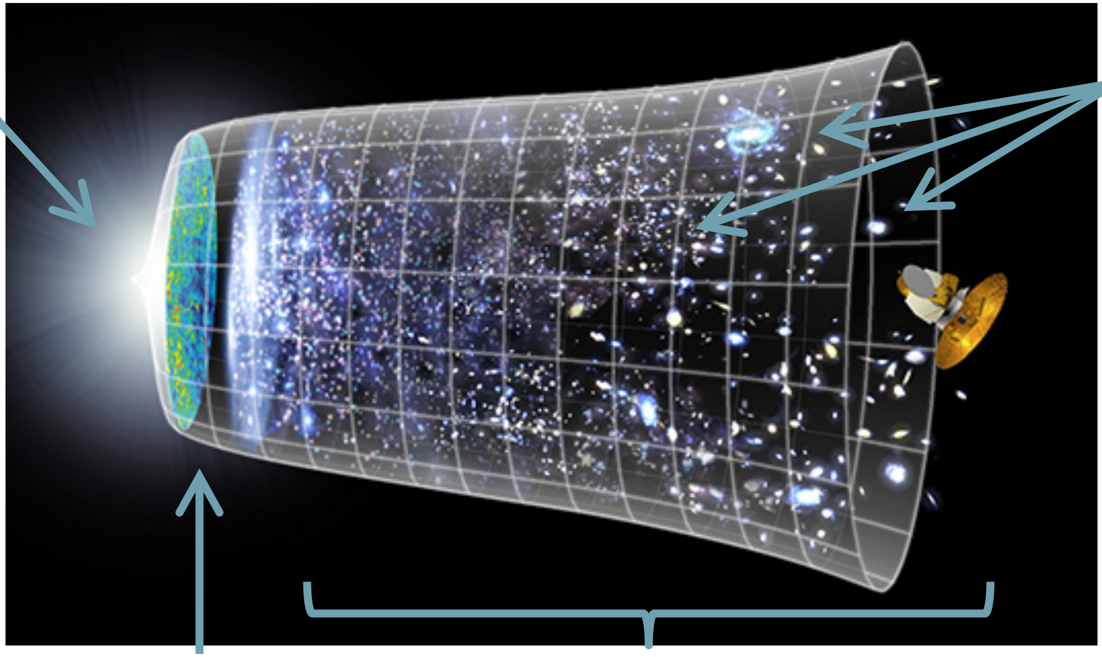
Concordance cosmology: ΛCDM

STANDARD MODEL OBSERVABLES OPEN QUESTIONS

Inflation seeds initial density fluctuations

What physics governed inflation?

CMB anisotropies



Structure formation: gravity causes density fluctuations to grow & form structures

Galaxy clustering
Weak lensing
Cluster counts

What is dark matter?

Universe becomes neutral, cosmic microwave background (CMB) light released

Universe expands, at late times dark energy causes acceleration

Type Ia supernovae, BAO

What is dark energy?

Is general relativity a good description of gravity?

Image credit: NASA, WMAP

Theme

We want to constrain fundamental physics with cosmological observations,

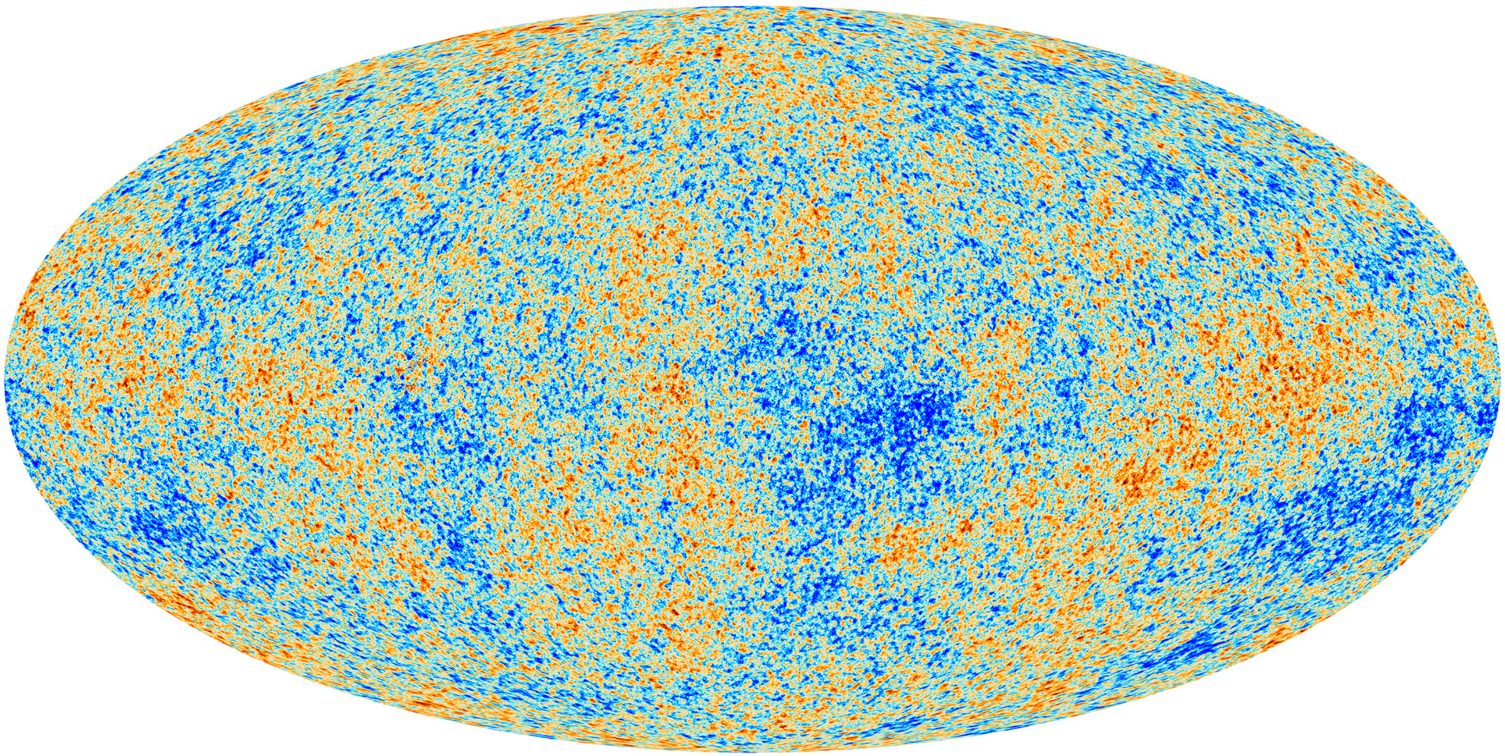
So we must understand and control systematics.

Outline

- Reconstructing late-time contributions to the CMB
- Blinding strategy for the Dark Energy Survey

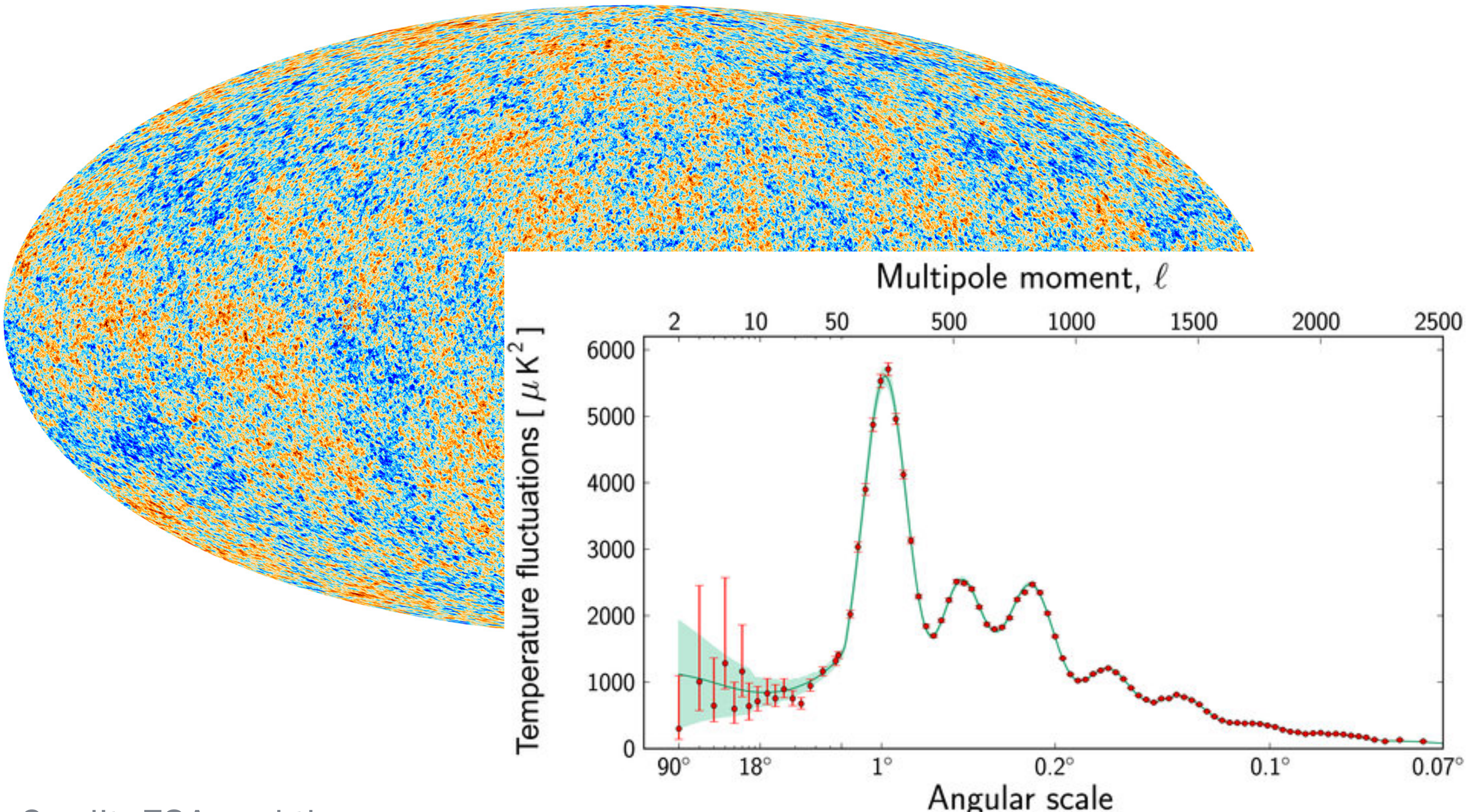
RECONSTRUCTING LATE-TIME CONTRIBUTIONS TO THE CMB

CMB temperature anisotropies



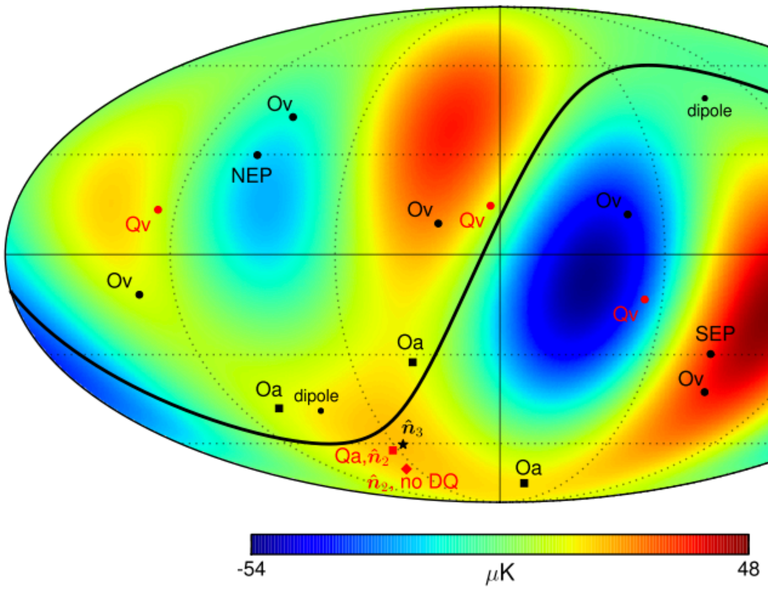
Credit: ESA and the
Planck Collaboration

CMB temperature anisotropies



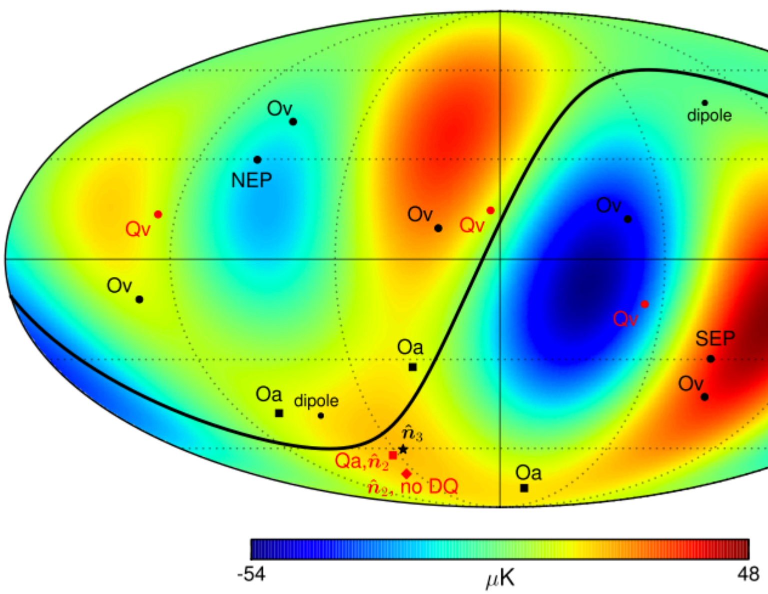
Credit: ESA and the Planck Collaboration

Large-angle anomalies



Copi et al., (1510.07929)
l=2,3 component of Planck 2013 map
Points show measure of directionality of modes

Large-angle anomalies



Possible explanations

- Statistical fluke
- New inflationary physics
- Instrumentation or analysis artifact
- Astrophysical foregrounds
- **Influence of low redshift LSS**

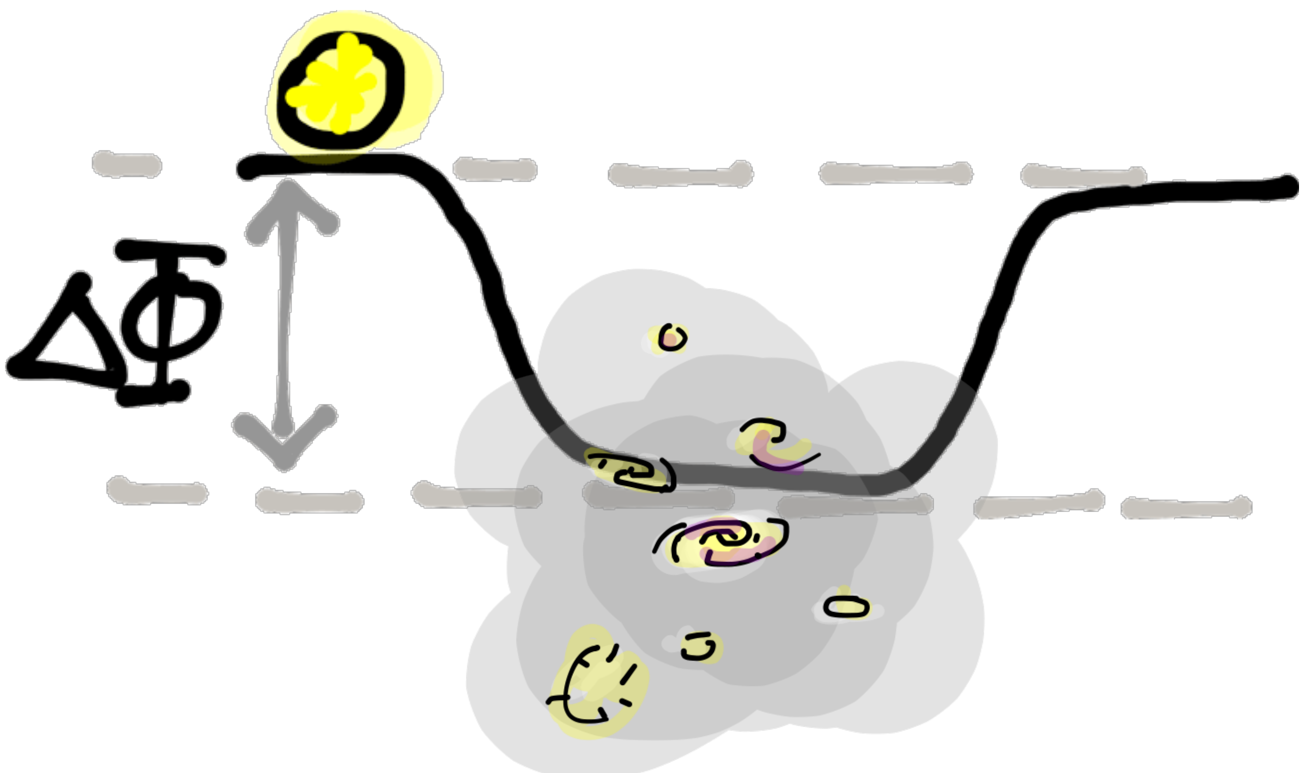
Copi et al., (1510.07929)
l=2,3 component of Planck 2013 map
Points show measure of directionality of modes

The integrated Sachs-Wolfe effect

- Induced when CMB photons cross evolving potential fluctuations:

Matter dominated era

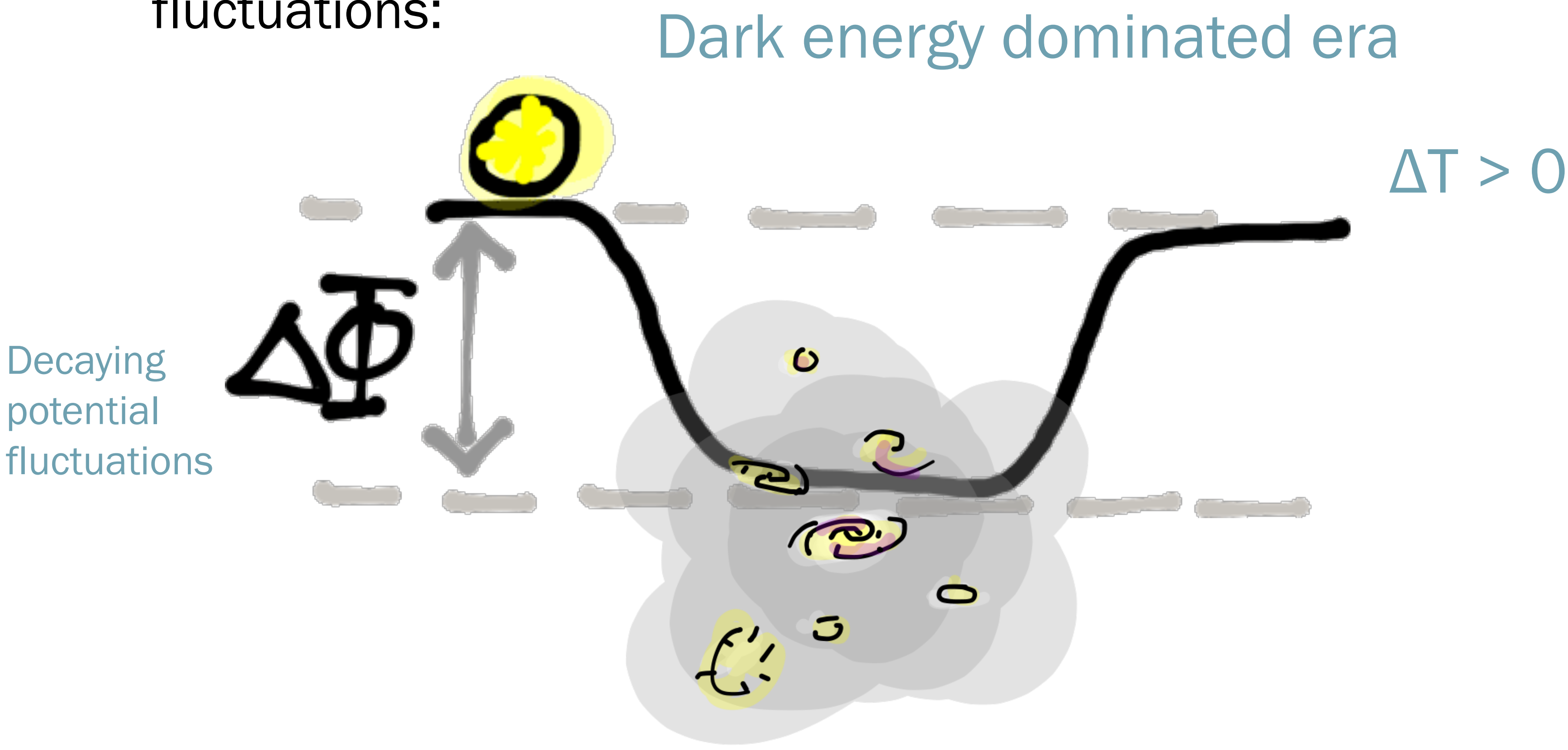
$\Delta T = 0$



Static potential fluctuations

The integrated Sachs-Wolfe effect

- Induced when CMB photons cross evolving potential fluctuations:



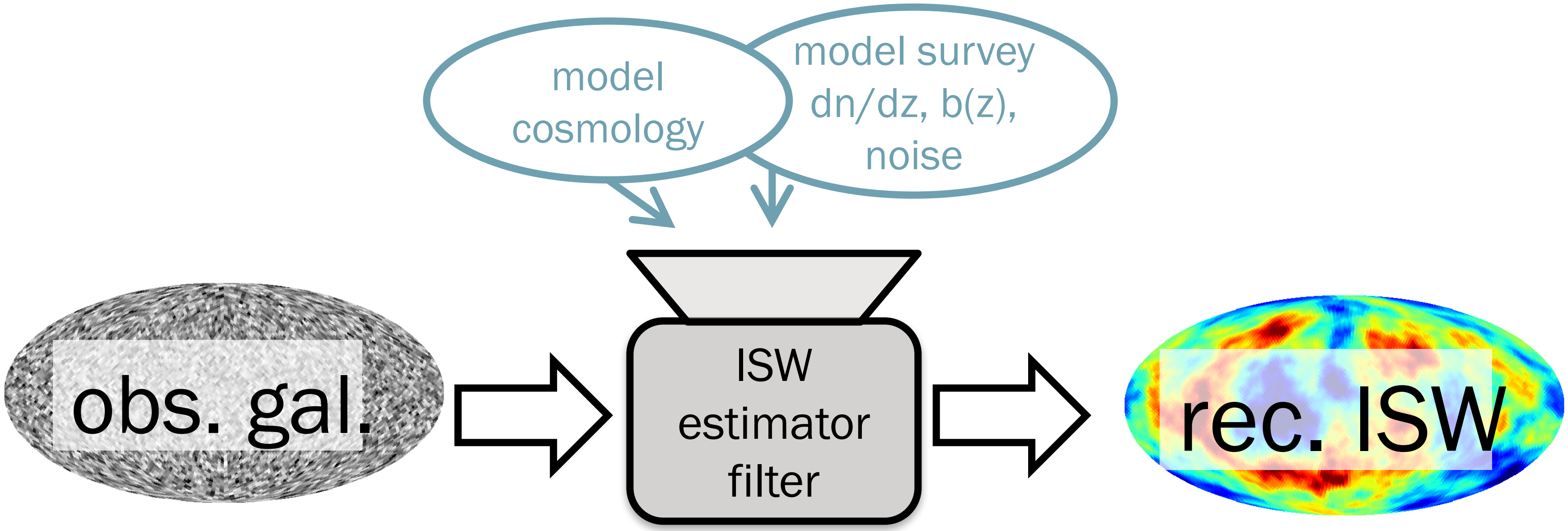
RECONSTRUCTING LATE-TIME CONTRIBUTIONS TO THE CMB

We want to know whether anomalous features in the CMB contain clues about the physics of inflation,

So we must determine how accurately we can separate primordial and late-time contributions to large-angle anisotropies.

ISW signal reconstruction

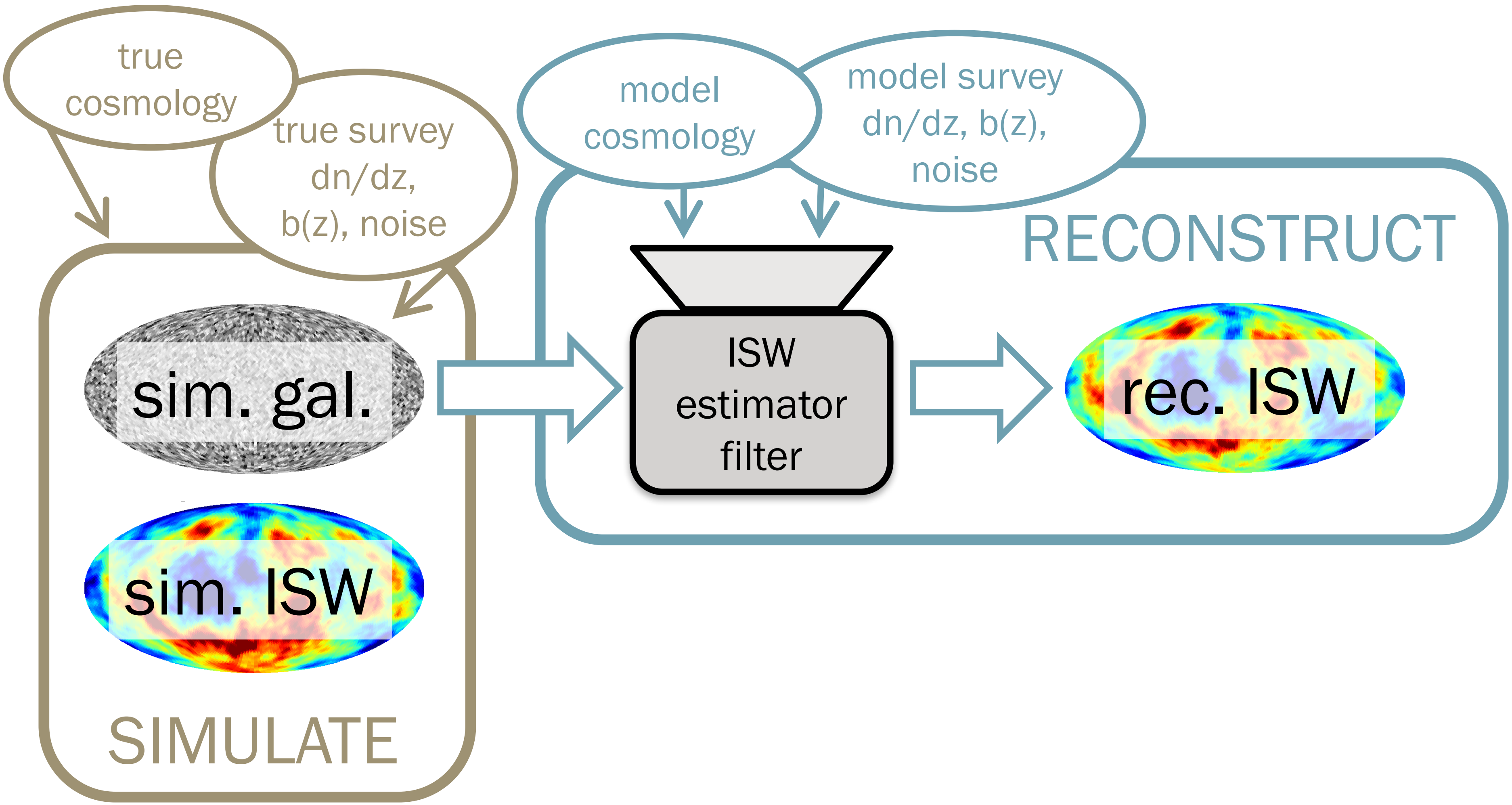
- Assume model for cosmology and survey properties, apply filter to LSS map to get optimal estimator for ISW.



See e.g.
Manzotti & Dodelson (1407.5623), Planck ISW paper (1502.01595), Bonavera et al. (1602.05893), Francis and Peacock (0909.2495), Rassat et al. (1303.4727)

Testing the impact of survey systematics

JM & Huterer (1603.06586)



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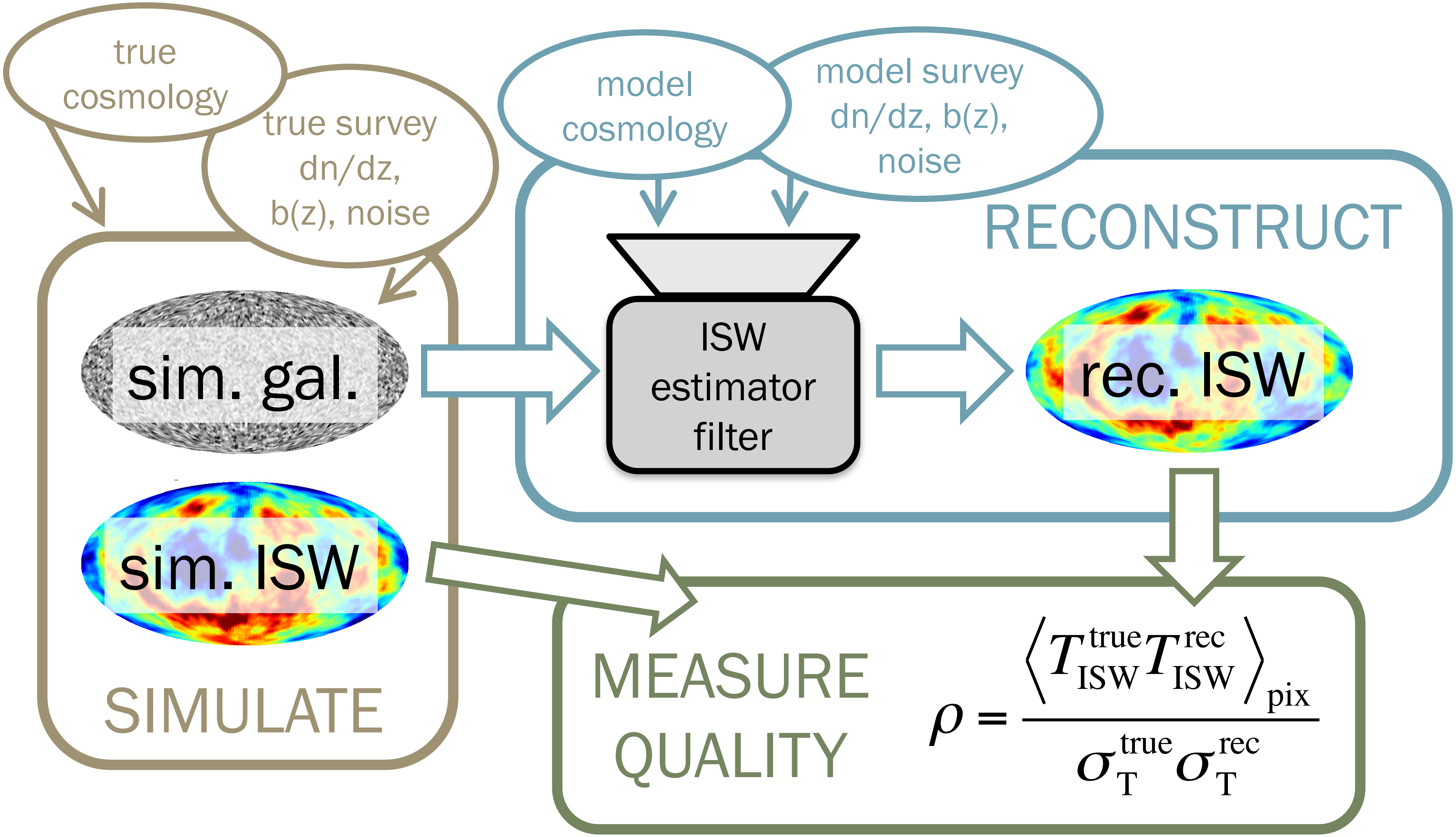
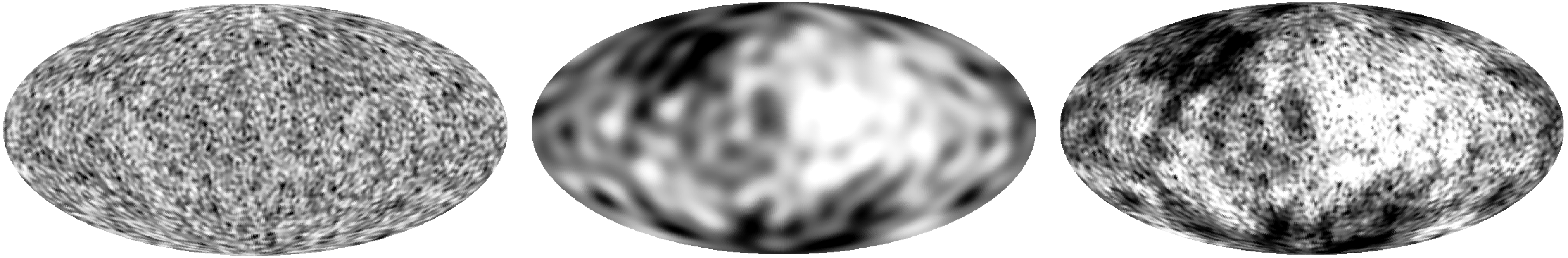


$$\rho = \frac{\left\langle T_{\mathrm{ISW}}^{\mathrm{true}} T_{\mathrm{ISW}}^{\mathrm{rec}} \right\rangle_{\mathrm{pix}}}{\sigma_{\mathrm{T}}^{\mathrm{true}} \sigma_{\mathrm{T}}^{\mathrm{rec}}}$$

Limiting systematic: Photometric calibration errors

- Any un-accounted for contribution to galaxy power
- Modeled as a “screen” applied to number density map

$$N^{\mathrm{obs}}(\hat{n}) = [1 + c(\hat{n})]N(\hat{n})$$



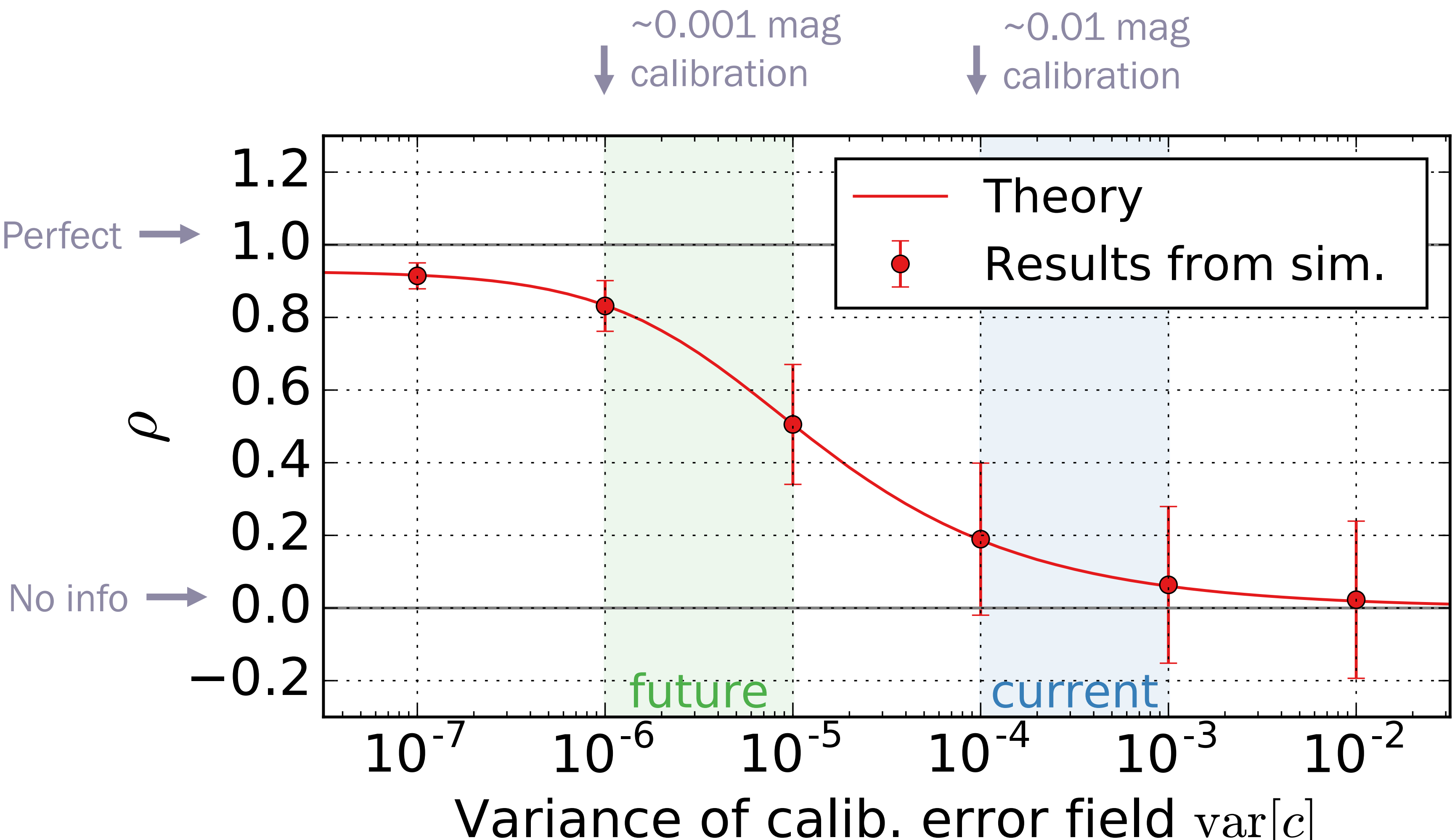
$N(\hat{n})$ $c(\hat{n})$ $N^{\mathrm{obs}}(\hat{n})$

- Related to variations in limiting magnitude

$$\delta N = \delta m_{\mathrm{lim}} \times \left.\frac{d \log N}{dm}\right|_{m_{\mathrm{lim}}}$$

~O(1) For COSMOS mock catalogues with z_{med}=0.75 (arXiv:0902.0625)

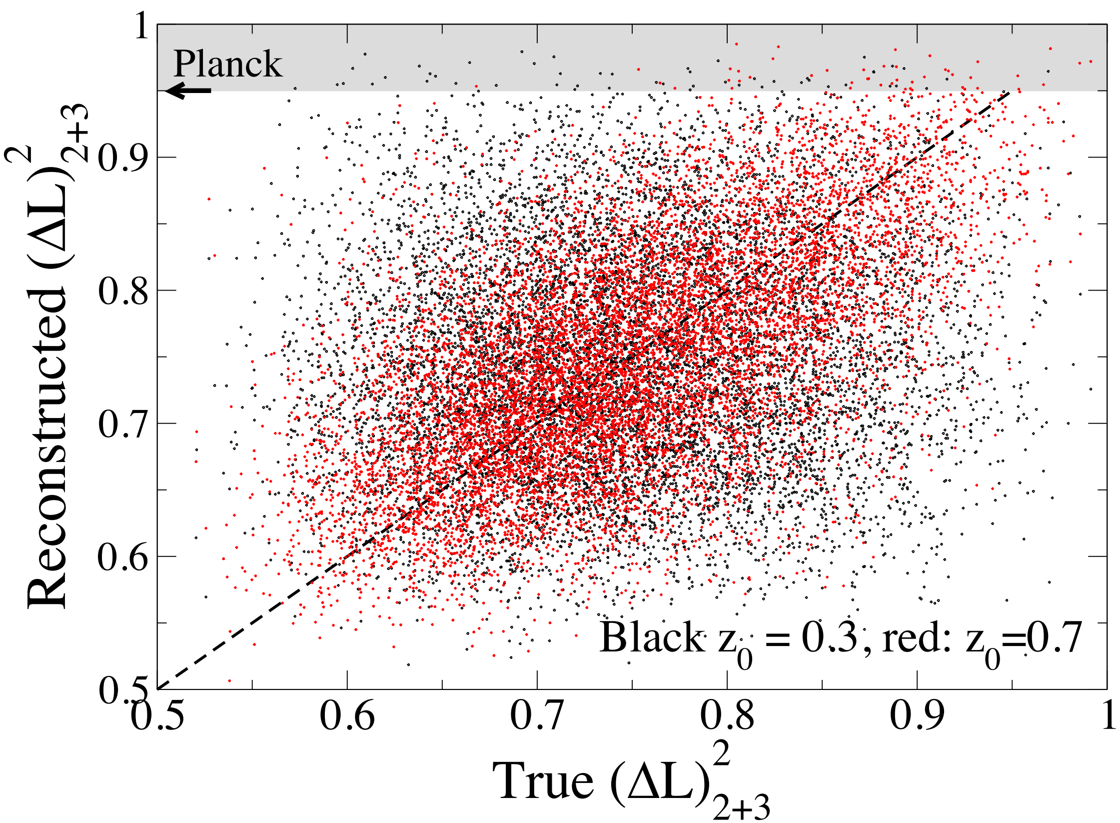
Calibration errors and reconstruction



roughly [calibration]^2

JM & Huterer (1603.06586), Ongoing work with Noah Weaverdyck (backup slide)

Large-angle CMB alignments generally not preserved



JM & Huterer (1603.06586)

- ΔL measures alignment of quadrupole and octupole
- z_0 ~ median redshift
- r=0.58 for z_0=0.7
- r=0.11 for z_0=0.3

SUMMARY
RECONSTRUCTING LATE-TIME CONTRIBUTIONS TO THE CMB

- We can filter observed LSS maps to reconstruct the ISW signal map.
- Photometric calibration errors are the limiting systematic for accurate ISW reconstruction.
- Even if reconstruction is good, individual features may not be accurately reproduced.

BLINDING STRATEGY FOR THE DARK ENERGY SURVEY

The Dark Energy Survey (DES)

- ~400 scientists from ~30 institutions, 7 countries
- 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

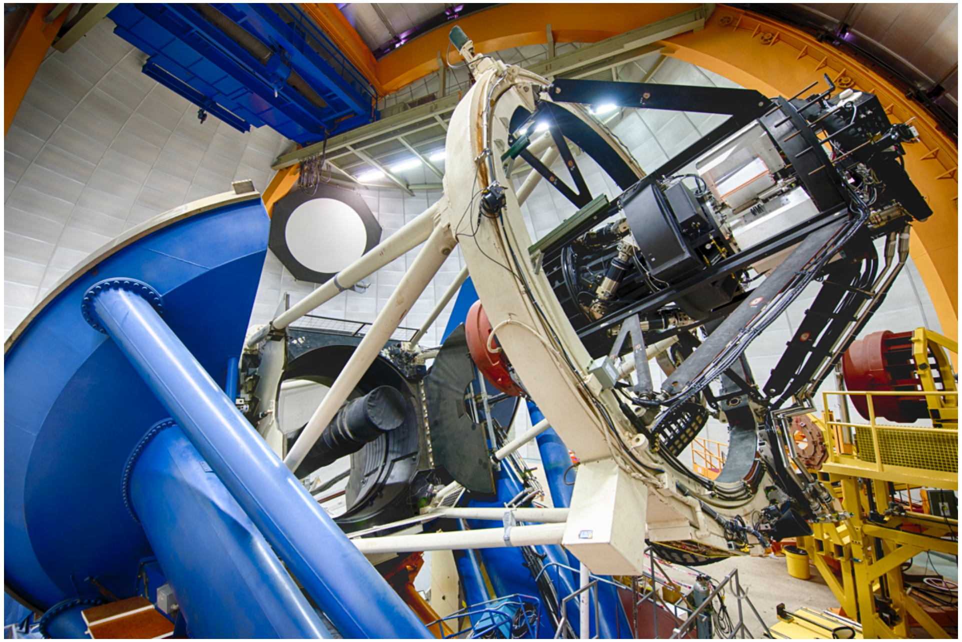


Image credit: Reider Hahn, Fermilab

Dark Energy

- Simplest model: Cosmological constant
  - Λ in ΛCDM
- To test ΛCDM, measure equation of state parameter w:
  - w = pressure/density
  - $w=-1 \rightarrow \Lambda$
  - $w\neq-1 \rightarrow$ time dependent energy density
  - Measured by studying expansion history and structure growth over time.

BLINDING STRATEGY FOR THE DARK ENERGY SURVEY

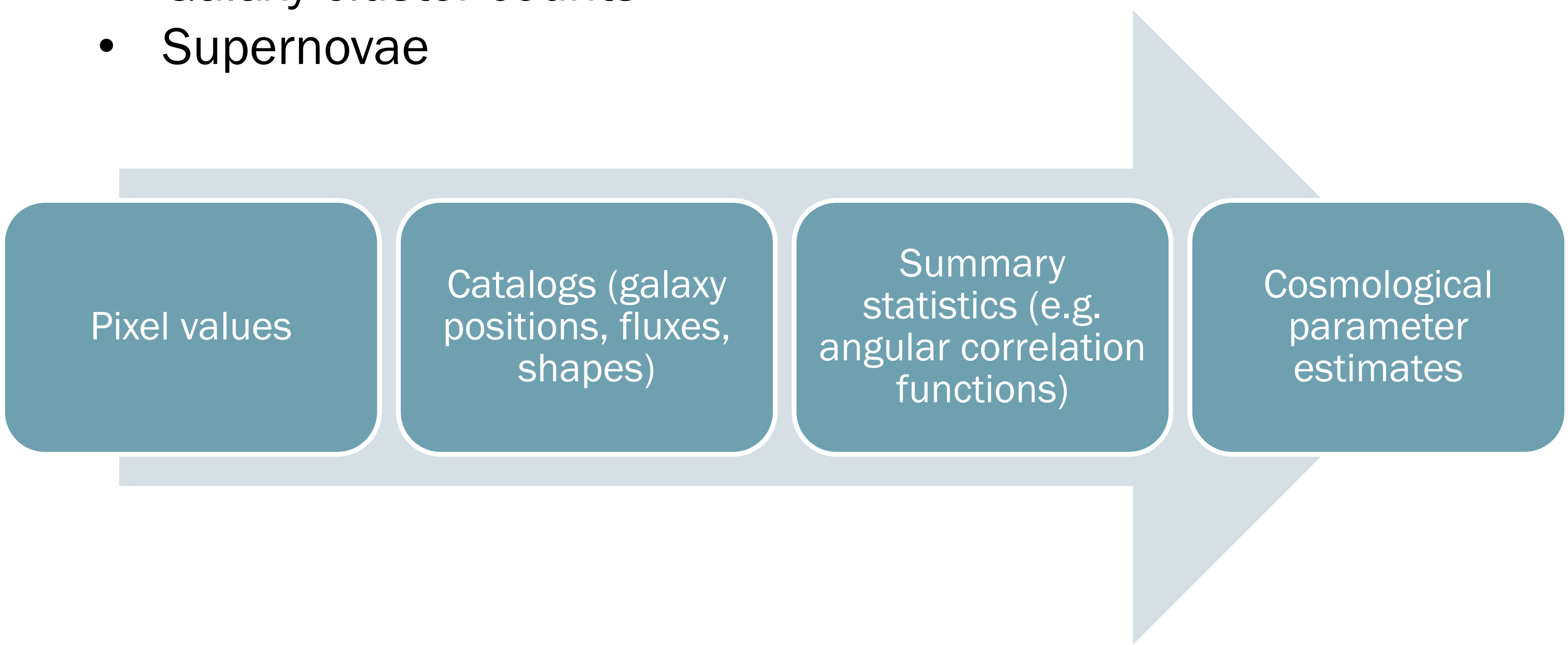
We want to measure to high precision whether dark energy behaves as cosmological constant,

So we must ensure that experimenters’ expectations don’t bias analyses of cosmological survey data.

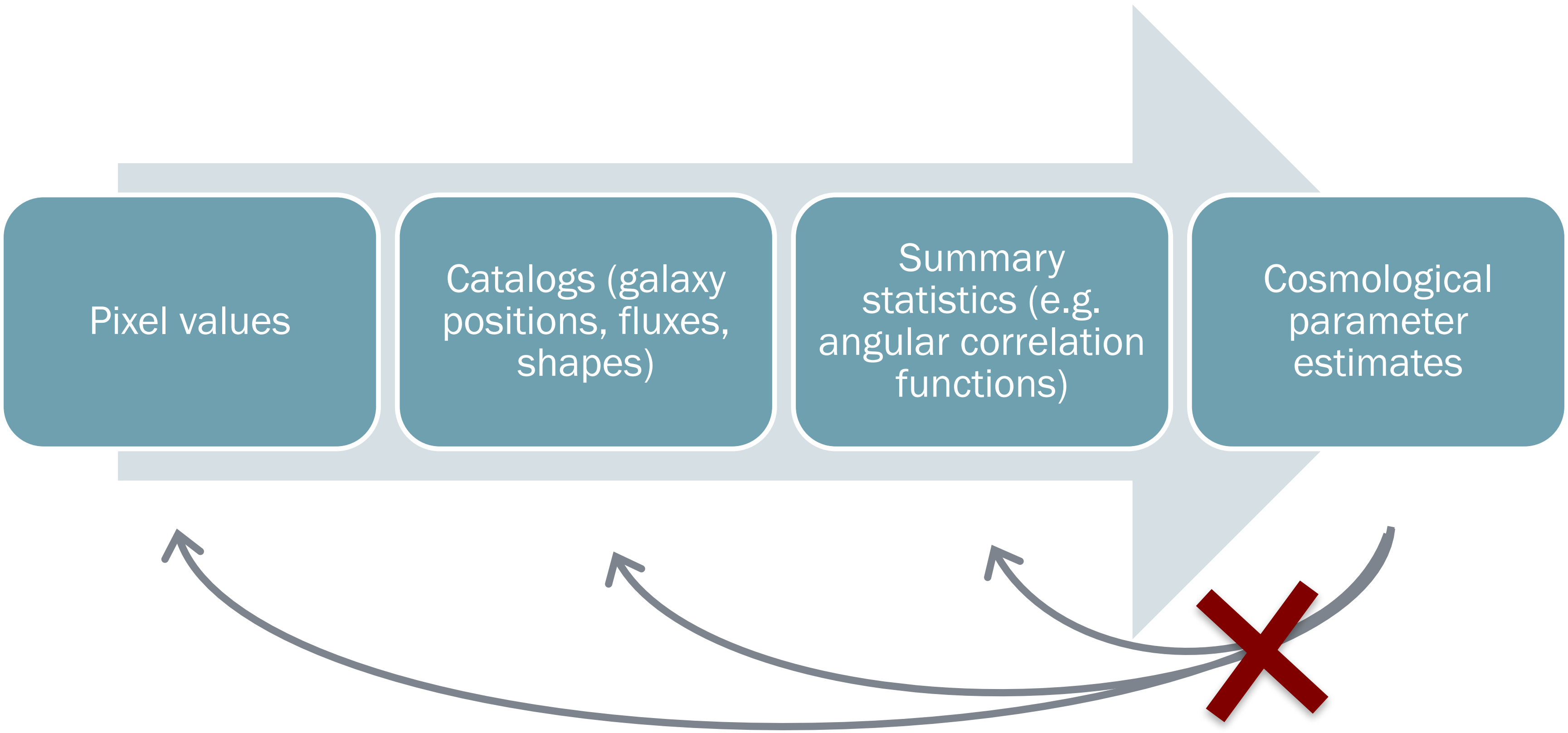
Sketch of DES pipeline

DES will constrain cosmology by looking at

- Galaxy clustering
- Weak gravitational lensing
- Galaxy cluster counts
- Supernovae



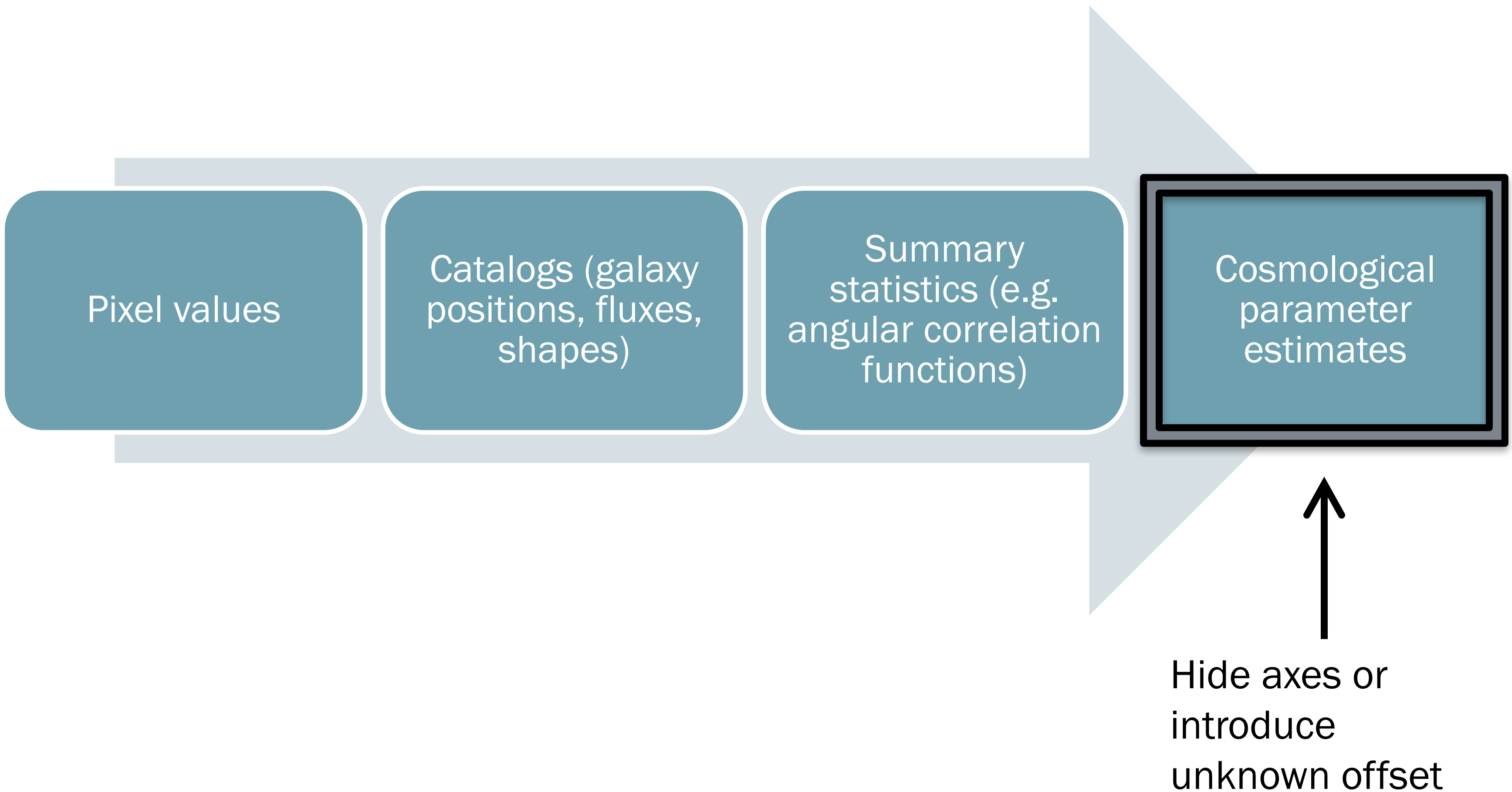
Multiprobe blinding



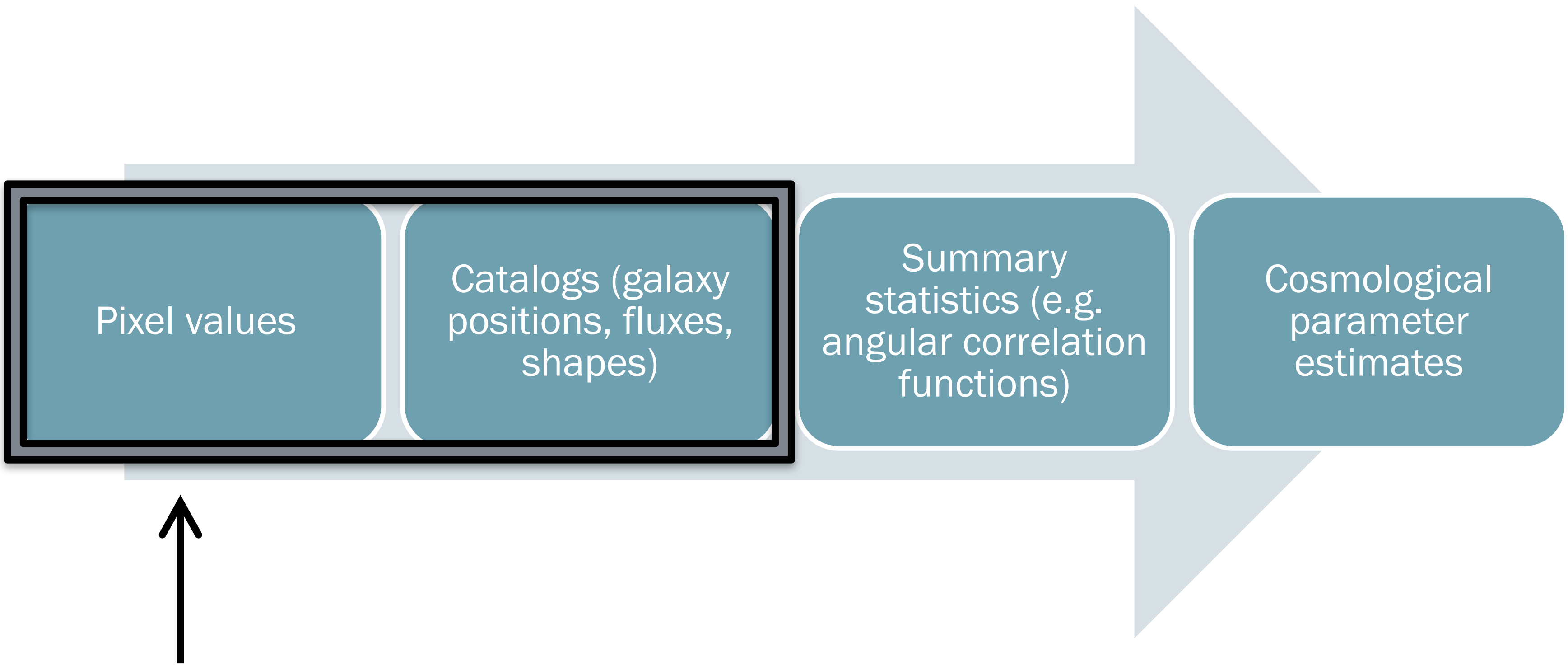
Requirements

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

For DES Year-1 analysis (ongoing)

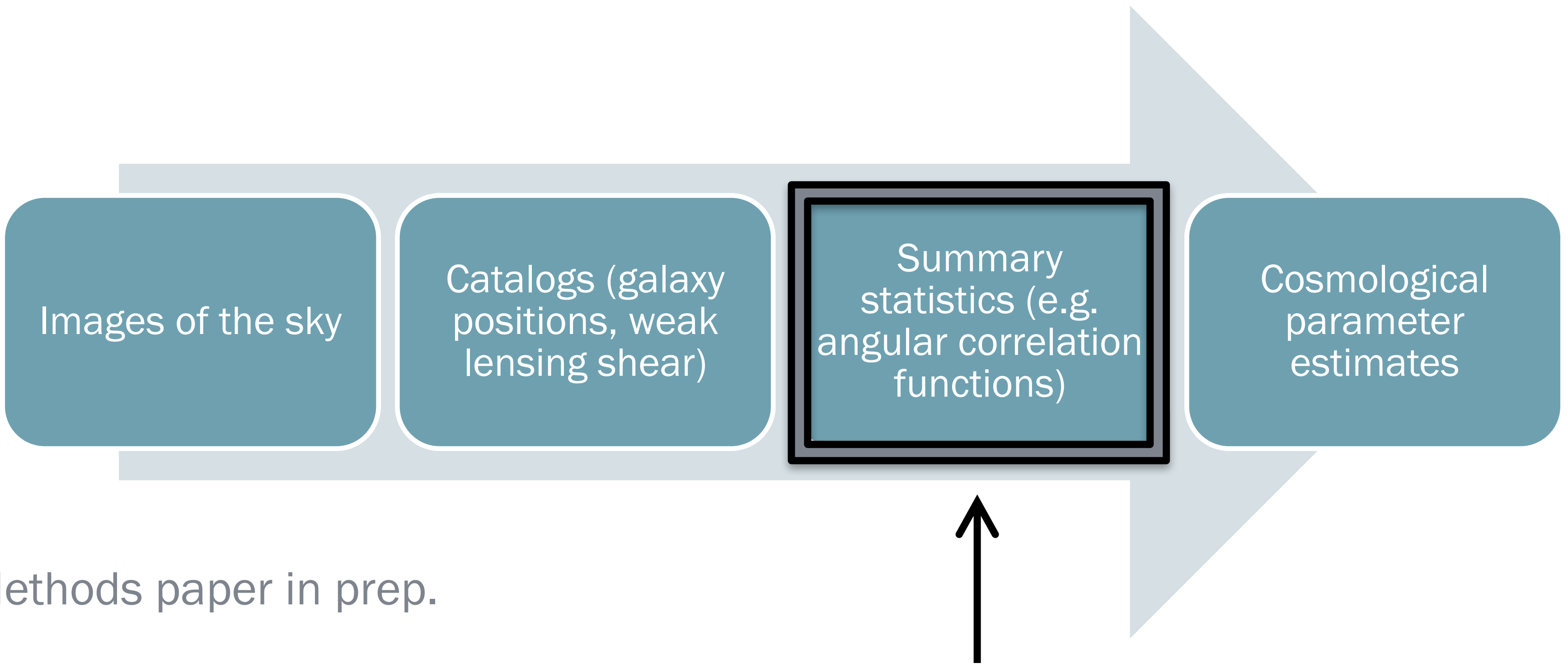


More robust scheme for Year-3 analysis



Making changes here is impossible (?) to do in a way that preserves consistency between probes

More robust scheme for Year-3 analysis



Methods paper in prep.

Working with Franz Elsner, Gary Bernstein, Dragan Huterer, Hiranya Peiris.

Strategy for Y3: Linearly scale summary statistics

d = any summary statistic
(component of data vector)

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

blinded
data vector

observed
data vector

Strategy for Y3: Linearly scale summary statistics

Θ = set of cosmological parameters

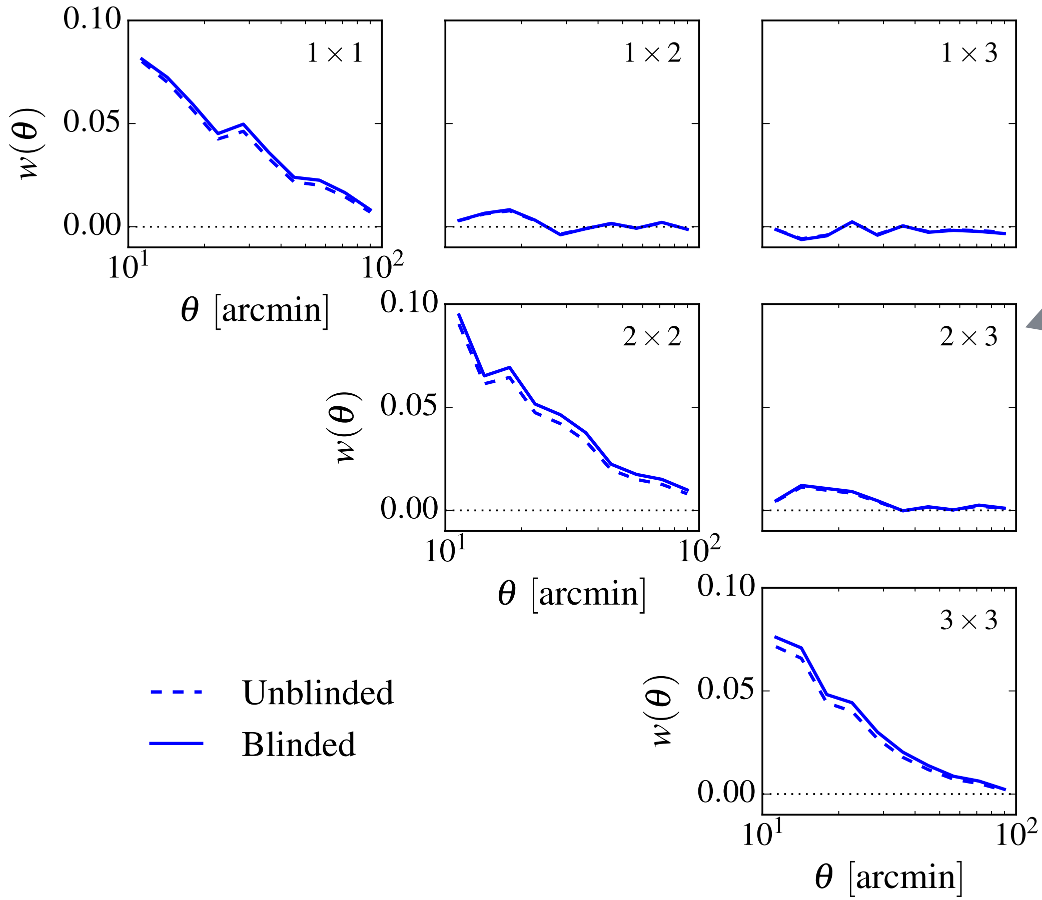
$$\Theta_{\mathrm{shift}} = \Theta_{\mathrm{ref}} + \Delta\Theta$$

d = any summary statistic (component of datavector)

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

Example on simulated data vector:

Galaxy-galaxy correlation function



Redshift bin labels

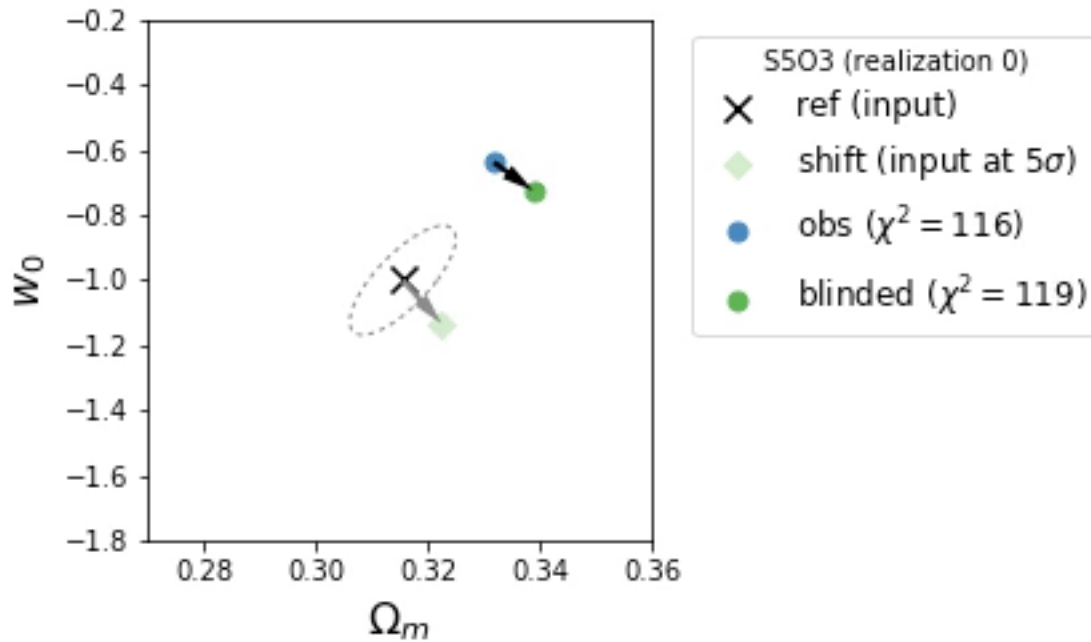
Credit: Franz Elsner

Test: How does blinding affect the best fit Θ?

$$\Theta_{\rm shift} = \Theta_{\rm ref} + \Delta\Theta \qquad d_{\rm obs} = \underbrace{\hat{d}(\Theta_{\rm obs})}_{\text{theory}} + \underbrace{n}_{\text{noise}}$$

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

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



In general:

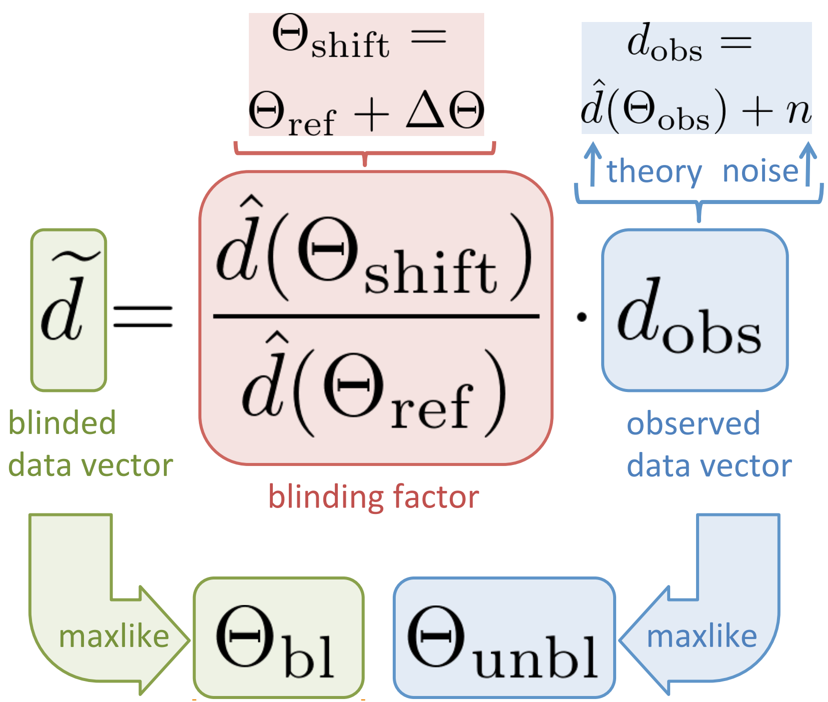
$$\boxed{\Theta_{\rm shift} - \Theta_{\rm ref} \approx \Theta_{\rm bl} - \Theta_{\rm unbl}}$$

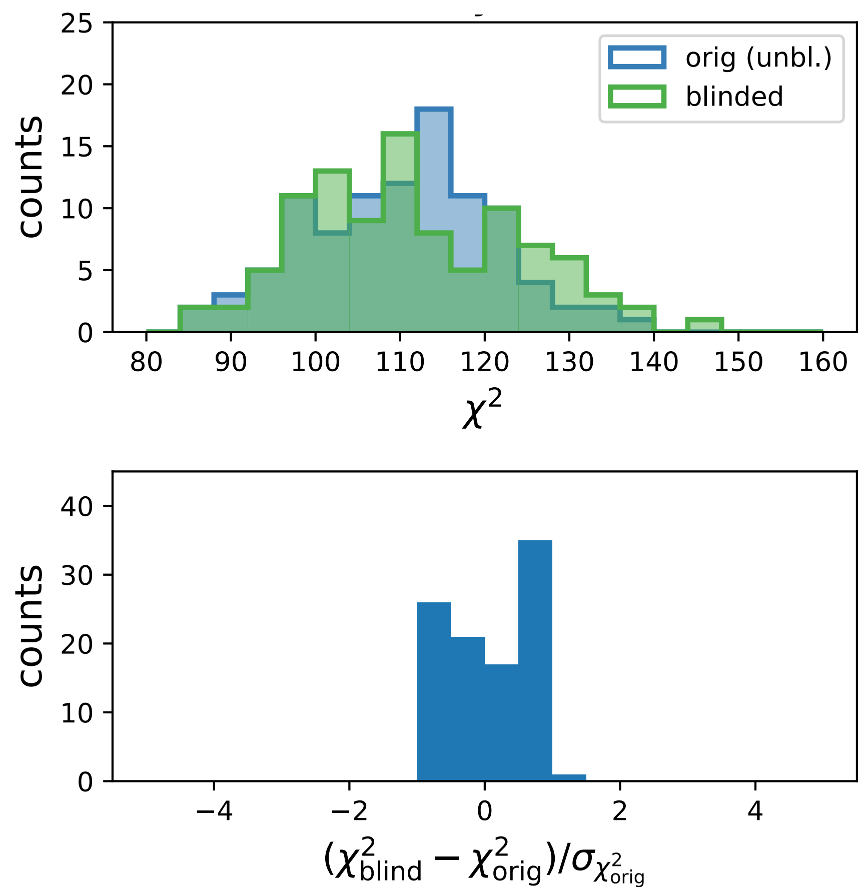
Test analysis run on simulated data vectors:

- 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?





Summary

To separate primordial and late-time contributions to large-angle CMB features:

ISW SIGNAL RECONSTRUCTION

- Current data don't allow us to reliably evaluate ISW contributions to large-angle CMB anomalies.
  - Need better control of photometric calibration errors
  - Need to study the fidelity of specific features in reconstructions

To prevent confirmation bias in precision measurements of dark energy:

BLINDING STRATEGY FOR THE DARK ENERGY SURVEY

- We can consistently shift the best-fit output cosmology of multiple cosmological probes by scaling 2pt correlation functions by specific scale-dependent factors.
  - This method will be used to blind the DES Year-3 combined probe analysis.

BACKUP SLIDES

The integrated Sachs-Wolfe effect

- Induced when CMB photons cross evolving potential fluctuations:

Temperature fluctuation due to ISW effect

Time derivative of gravitational potential

$$\left.\frac{\Delta T}{\bar{T}}\right|_{ISW}(\hat{\mathbf{n}}) = \frac{2}{c^2}\int_{t_*}^{t_0} dt\, \frac{\partial\Phi(r,t)}{\partial t}$$

Direction on sky

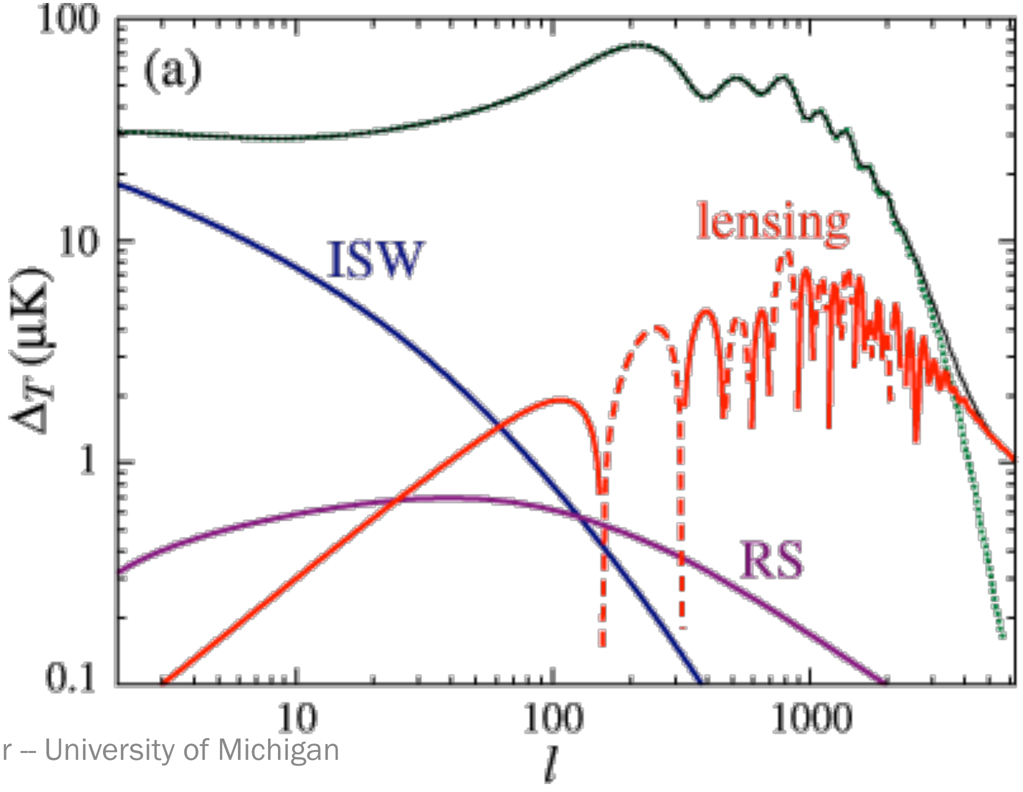
Line-of-sight integral from last scattering to now

The integrated Sachs-Wolfe effect

- Secondary CMB anisotropy, much weaker than primordial anisotropies except at very large angles.
- Detected with S/N ~ 4 using cross correlation of CMB with various LSS tracers.

See e.g. Planck ISW paper, arXiv:1502.01595, where Planck+NVSS+WISE+SDSS give S/N ~ 4

Image: Hu and Dodelson, astro-ph/0110414



Backup: ISW estimator

$$\boxed{\hat{a}_{\ell m}^{\mathrm{ISW}} = \sum_{i}^{n} R_\ell^i g_{\ell m}^i.}$$

$$R_\ell^i \equiv -N_\ell [D_\ell^{-1}]_{\mathrm{ISW}-i}$$

$$N_\ell^{-1} \equiv (D_\ell^{-1})_{11}$$

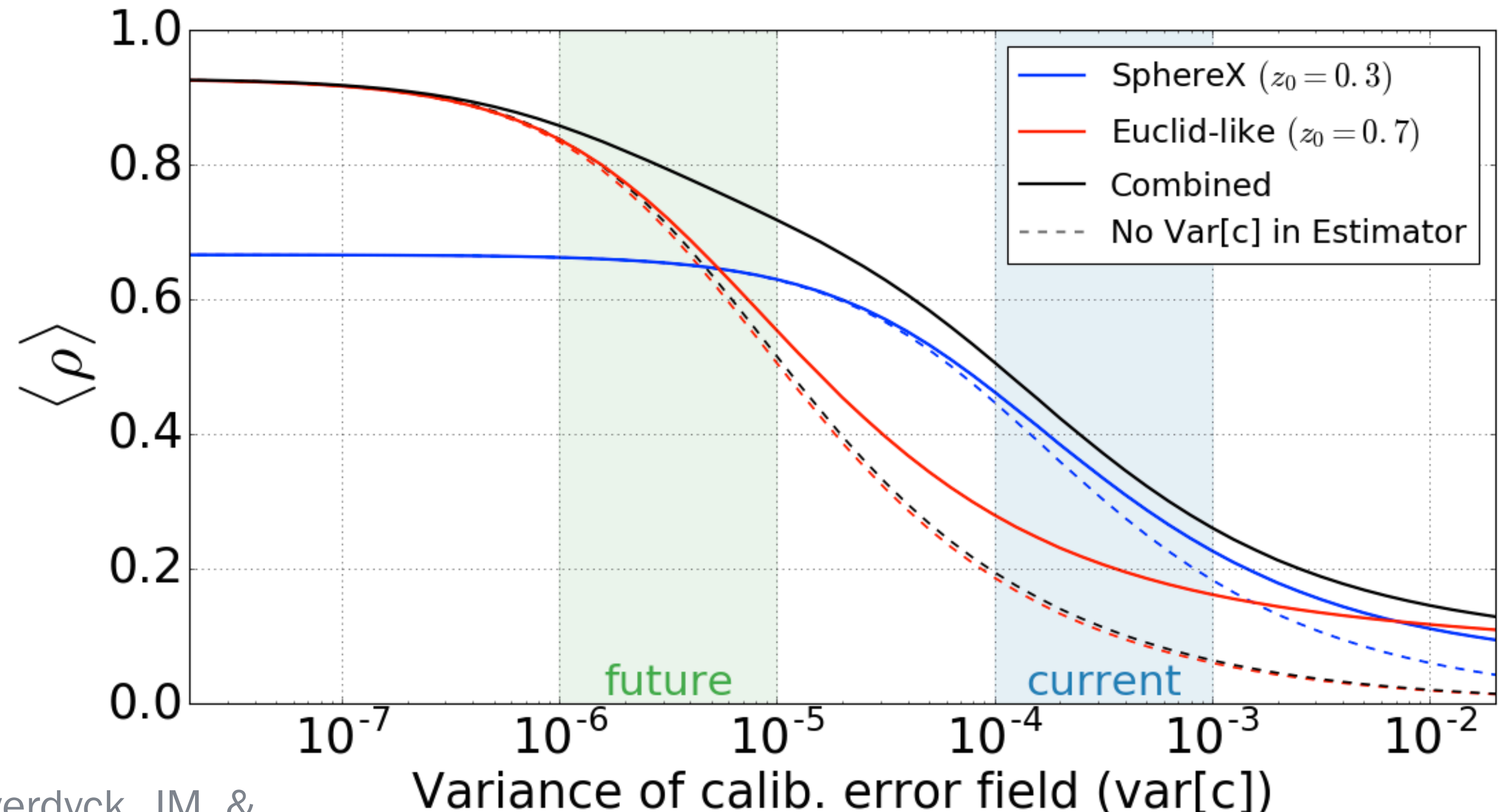
$$D_\ell = \begin{pmatrix} C_\ell^{\mathrm{ISW,ISW}} & C_\ell^{\mathrm{LSS_1,ISW}} & \cdots & C_\ell^{\mathrm{LSS_n,ISW}} \\ C_\ell^{\mathrm{LSS_1,ISW}} & C_\ell^{\mathrm{LSS_1,LSS_1}} & \cdots & C_\ell^{\mathrm{LSS_1,LSS_n}} \\ \vdots & \vdots & \ddots & \vdots \\ C_\ell^{\mathrm{LSS_n,ISW}} & C_\ell^{\mathrm{LSS_1,LSS_n}} & \cdots & C_\ell^{\mathrm{LSS_1,LSS_n}} \end{pmatrix}$$

$$\hat{a}_{\ell m}^{\mathrm{ISW}} \xrightarrow{\text{single LSS}} \frac{C_\ell^{\mathrm{ISW-gal}}}{C_\ell^{\mathrm{gal-gal}}} g_{\ell m}$$

Ongoing work with Noah Weaverdyck:

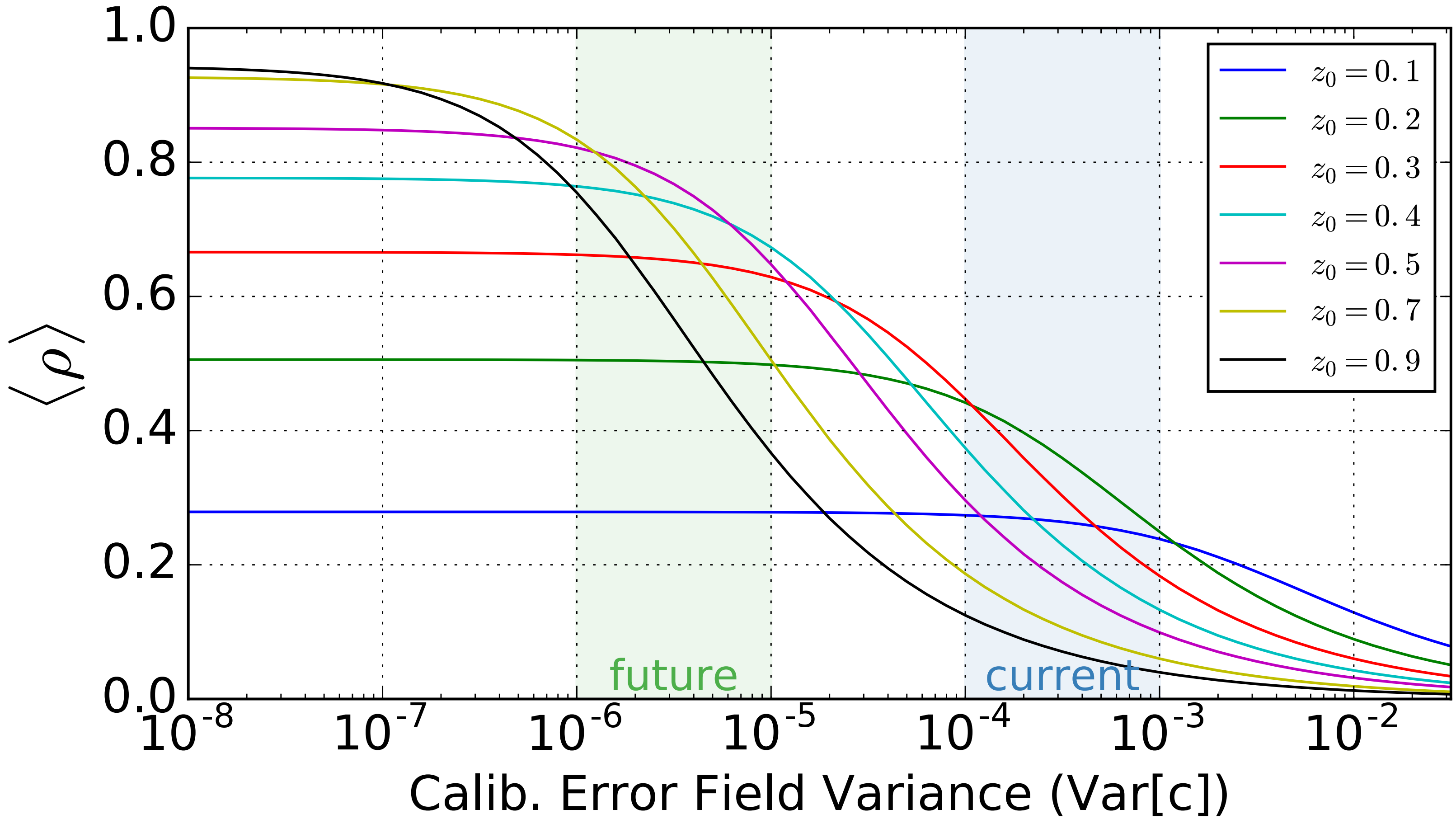
How to mitigate the effect of calibration errors?

- Calibration errors change optimal survey depth.
- Must include calibration error in noise model to gain from using multiple input LSS maps.



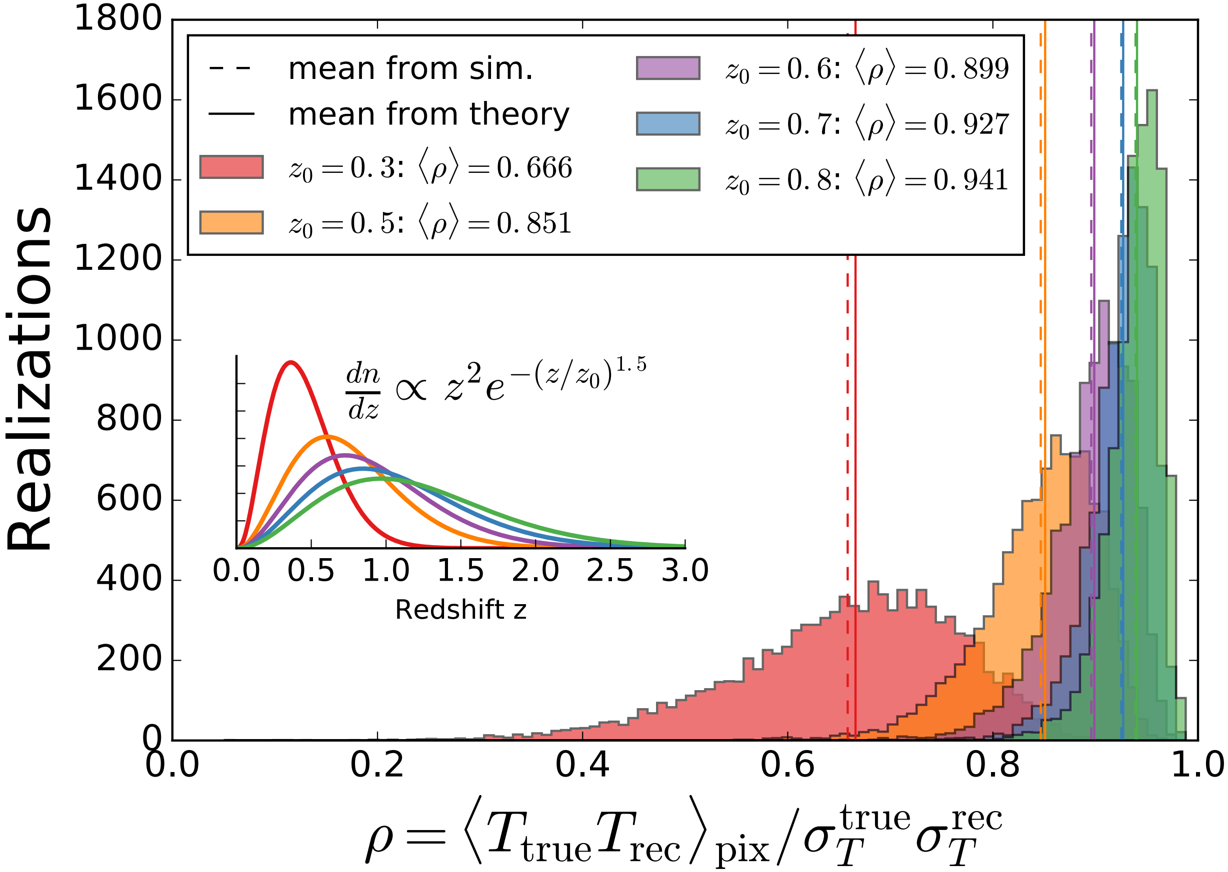
Weaverdyck, JM, & Huterer (in prep)

Depth and calibration errors



Weaverdyck, JM, & Huterer (in prep)

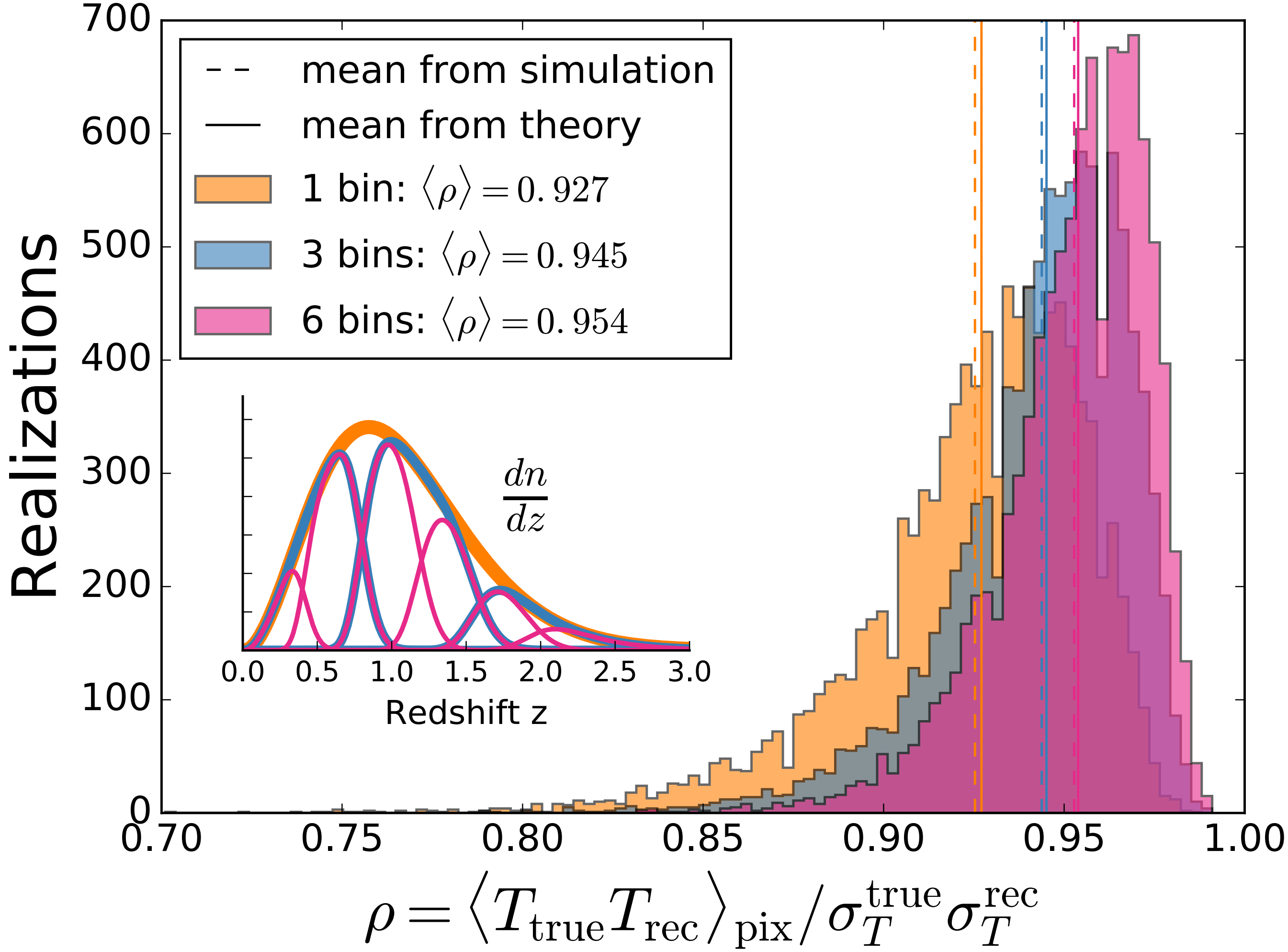
ISW rec. and changing survey depth



z_0 ~ median redshift

JM & Huterer (1603.06586)

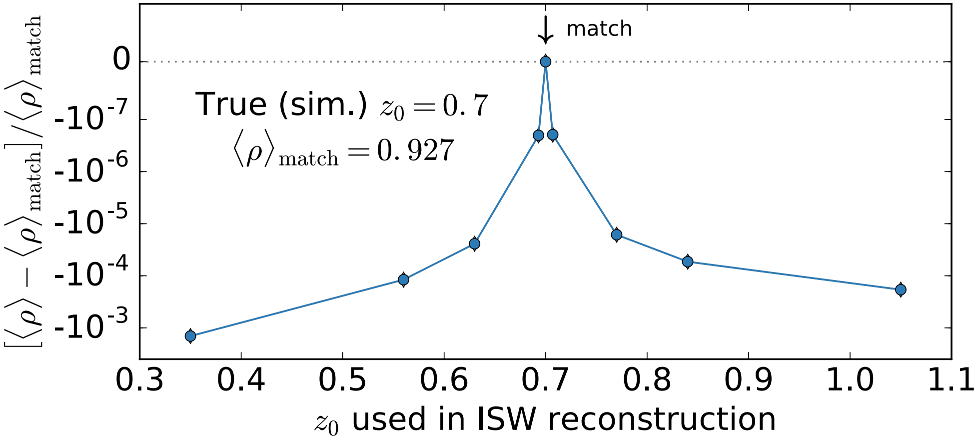
ISW rec. and adding redshift bins

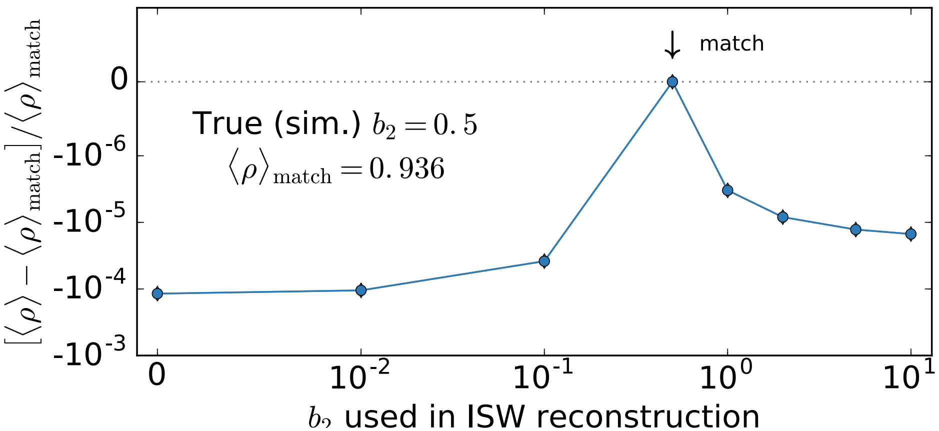


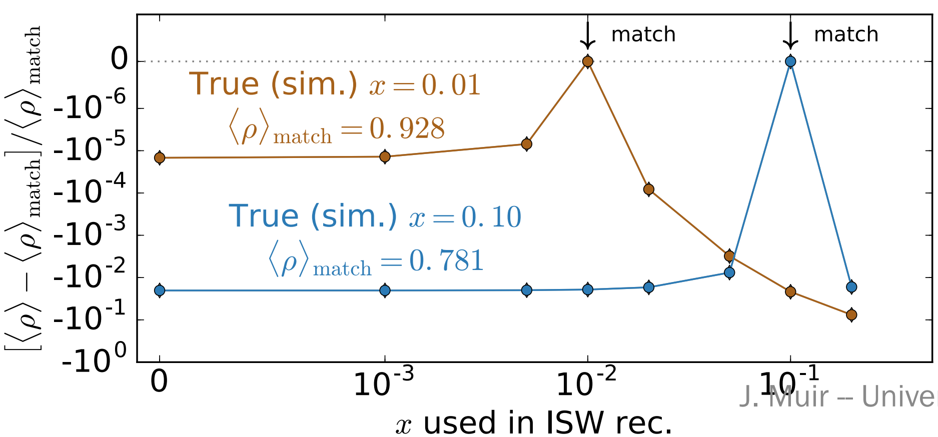
J. Muir -- University of Michigan

JM & Huterer (1603.06586)

ISW rec. and line-of-sight modeling systematics



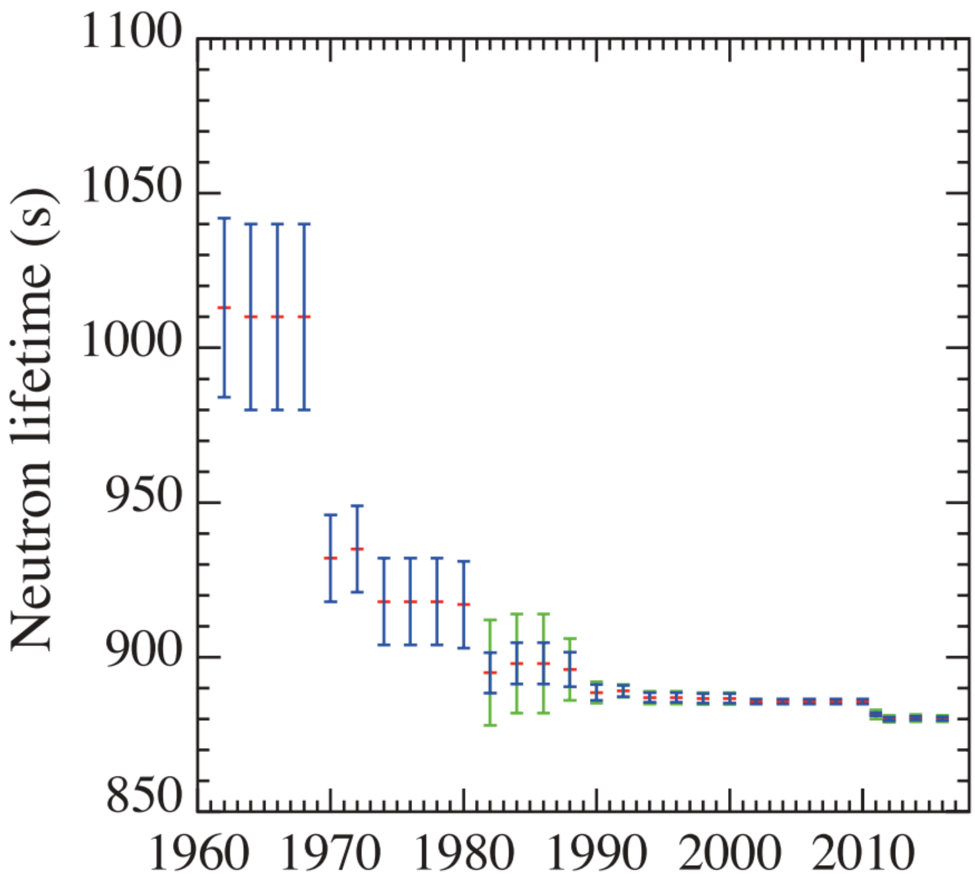




- z_0 ~ median redshift
- b_2 = parameter describing shape of redshift-dependent bias $b(z) = b_0 + b_2(1+z)^2$
- x = fraction of galaxies subject to catastrophic photo-z errors

JM & Huterer (1603.06586)

Motivation for blinding

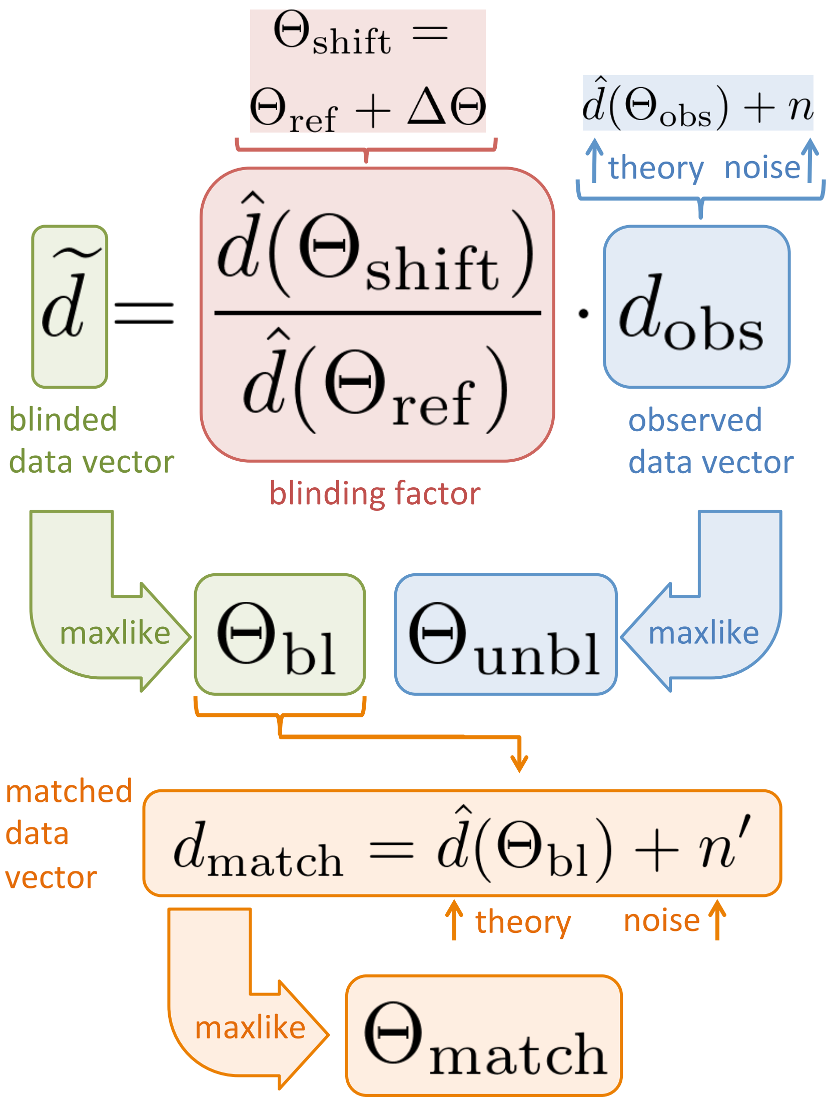


Confirmation bias introduced if results of influence

- Choice of analysis parameters
- Choice of data cuts
- Stopping criterion
- Etc.

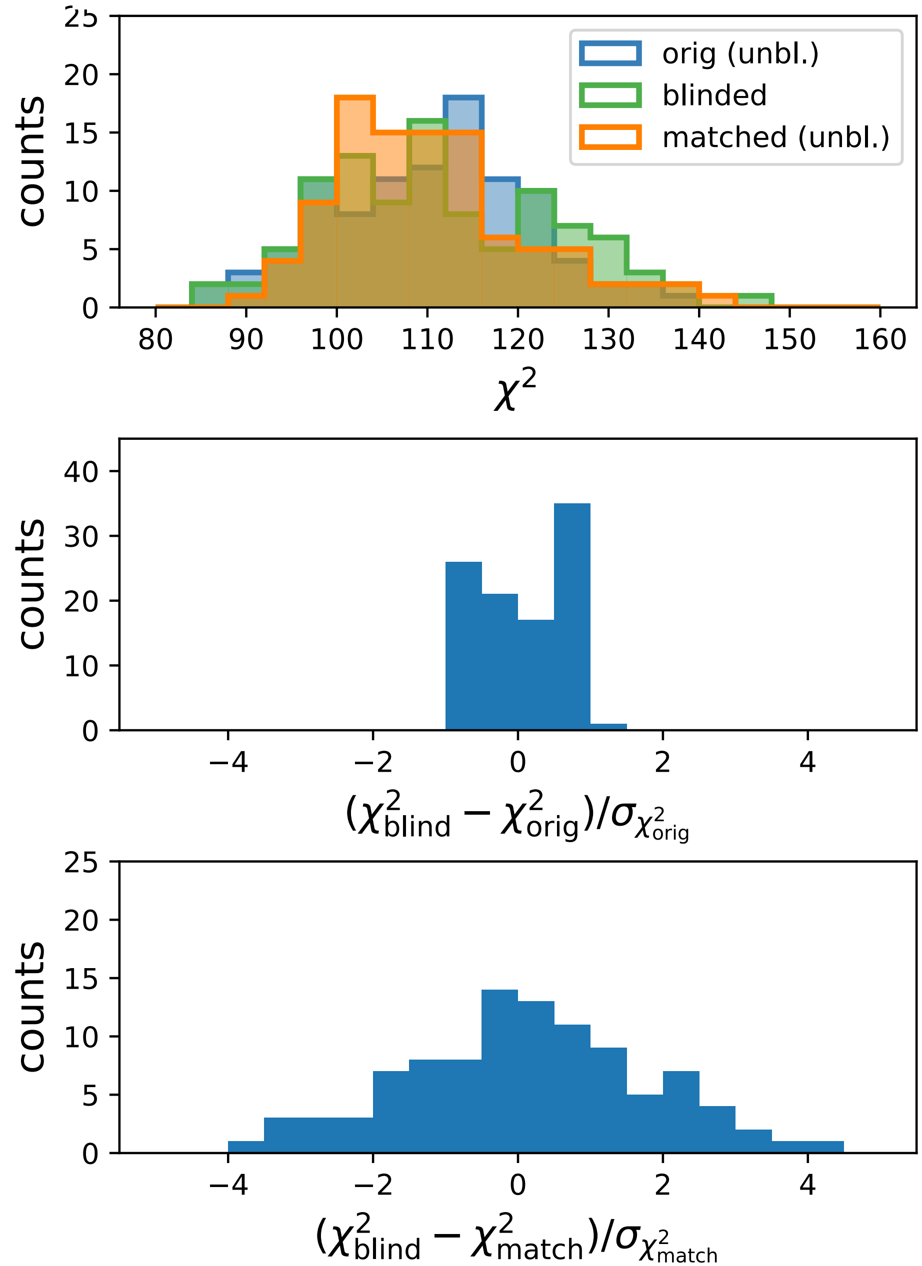
C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

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

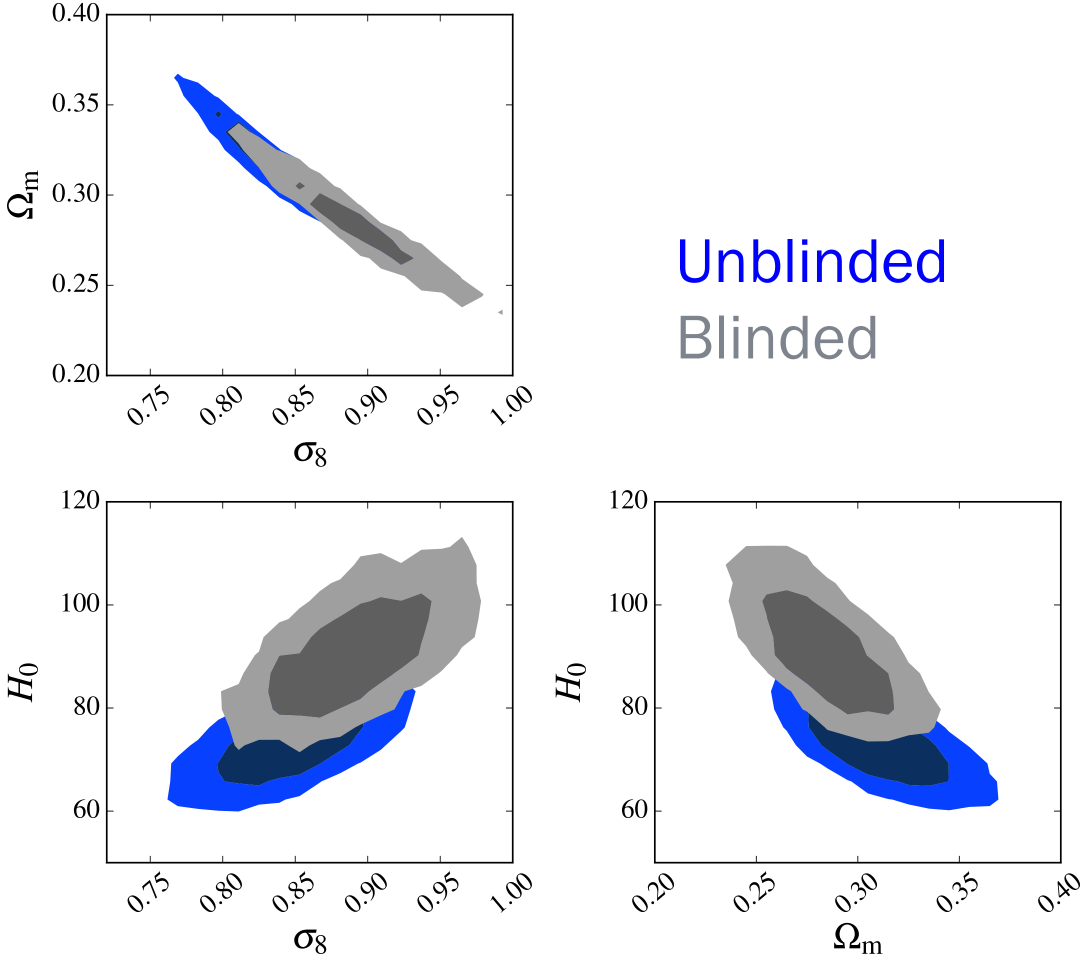


Varying only w and Ω_m

$\Theta_{\rm obs}$ at ~3σ from $\Theta_{\rm ref}$, $\Theta_{\rm shift}$ at ~5σ from $\Theta_{\rm ref}$



Effect of blinding on MCMC output



Credit: Franz Elsner

Plans for implementation

Blinding factors computed and applied by software module which can be inserted into pipeline.

- Comes with file containing ~100 draws of Θ_{shift}
- Using string seed, pseudo-randomly select one.
- Generate blinding factors using settings already in pipeline.
- To unblind, just remove blinding module and rerun

$$\underbrace{\tilde{d}}_{\text{blinded data vector}} = \underbrace{\frac{\hat{d}(\overbrace{\Theta_{\text{shift}}}^{\Theta_{\text{shift}} = \Theta_{\text{ref}} + \Delta\Theta})}{\hat{d}(\Theta_{\text{ref}})}}_{\text{blinding factor}} \cdot \underbrace{\overbrace{d_{\text{obs}}}^{d_{\text{obs}} = \underbrace{\hat{d}(\Theta_{\text{obs}})}_{\text{theory}} + \underbrace{n}_{\text{noise}}}}_{\text{observed data vector}}$$