Weak Gravitational Lensing

Michael D. Schneider

Lawrence Livermore National Laboratory

(also member of the Large Synoptic Survey Telescope Dark Energy Science Collaboration)

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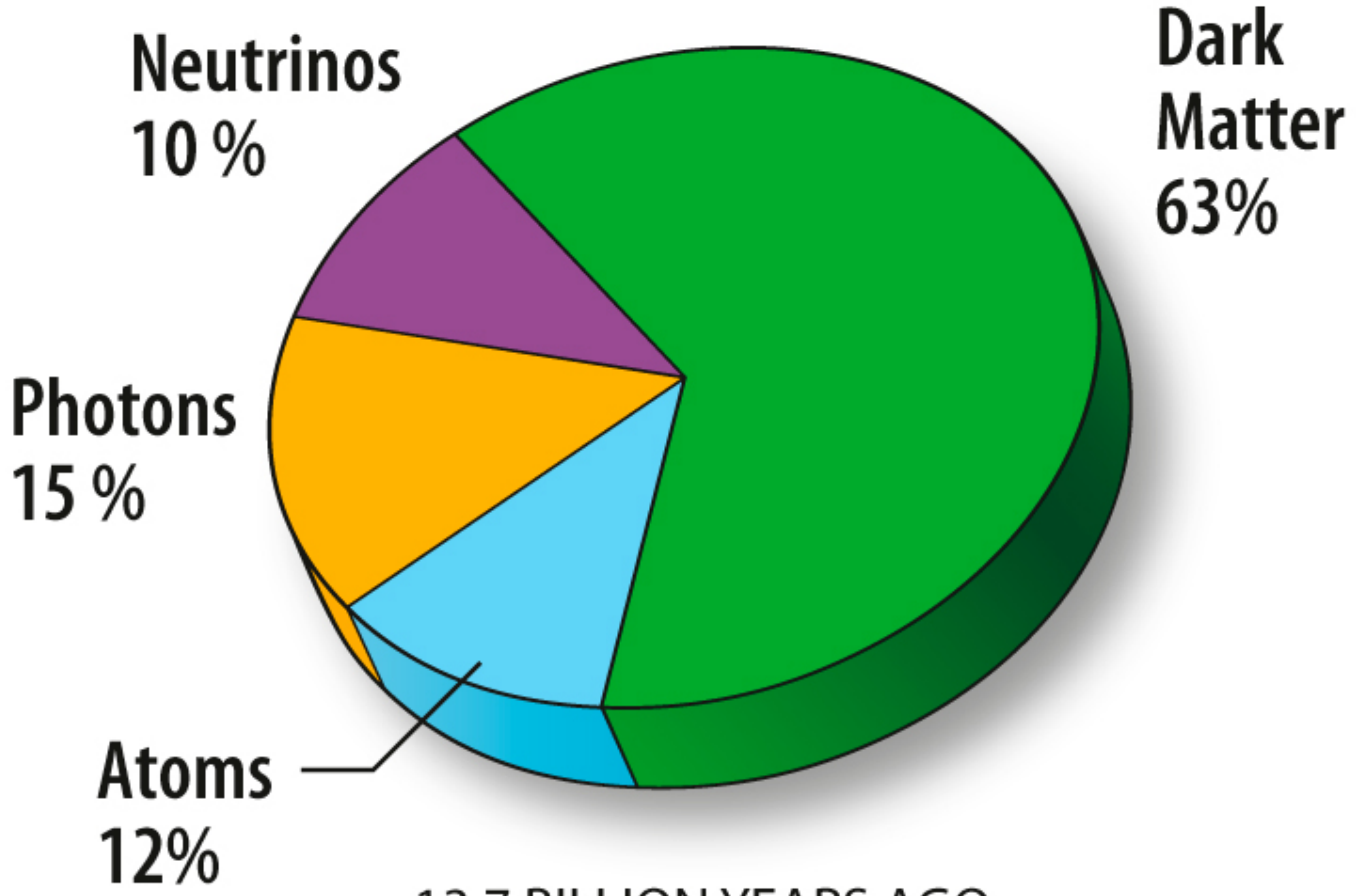
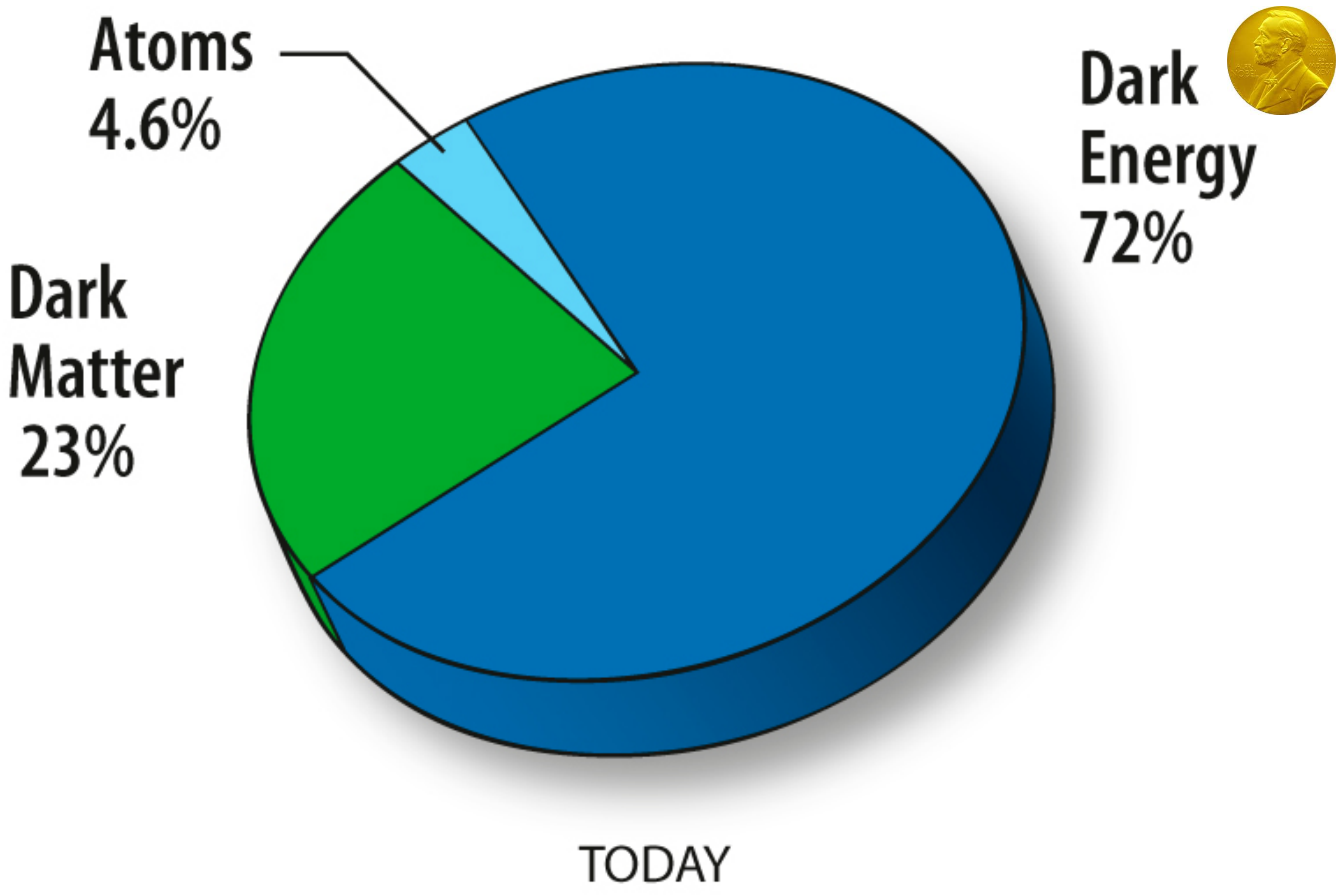
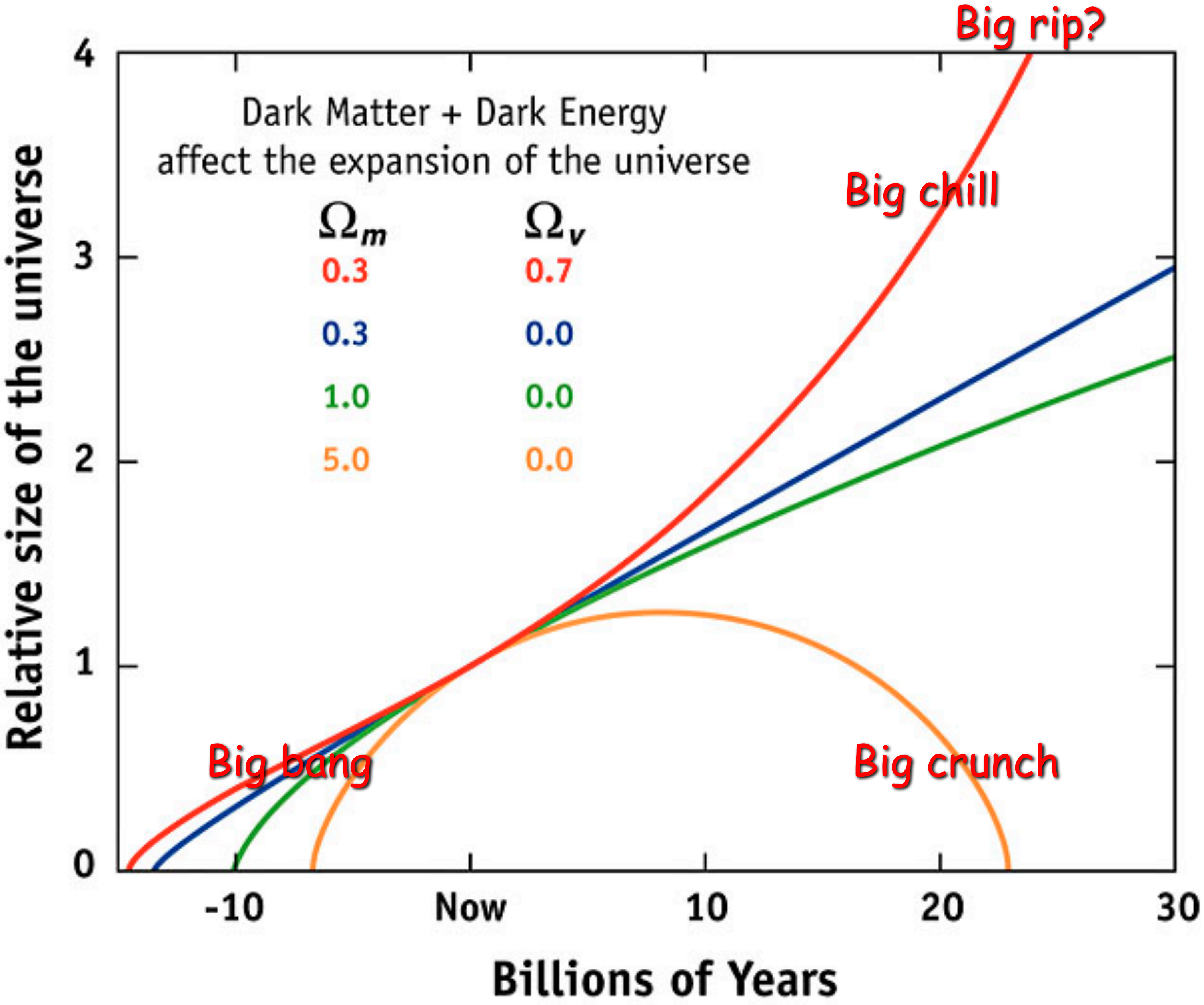


13.7 BILLION YEARS AGO

(Universe 380,000 years old)


Atoms
4.6%
Dark Energy
72%
Dark Matter
23%
TODAY

Expansion of the Universe



What causes Cosmic Acceleration?

Three possibilities:

1. **The Universe is filled with a negative-pressure component that gives rise to `gravitational repulsion': DARK ENERGY**

2. **Einstein's theory of General Relativity (gravity) is wrong on cosmic distance scales.**

3. **The Universe is inhomogeneous and only apparently accelerating, due to large-scale structure.**

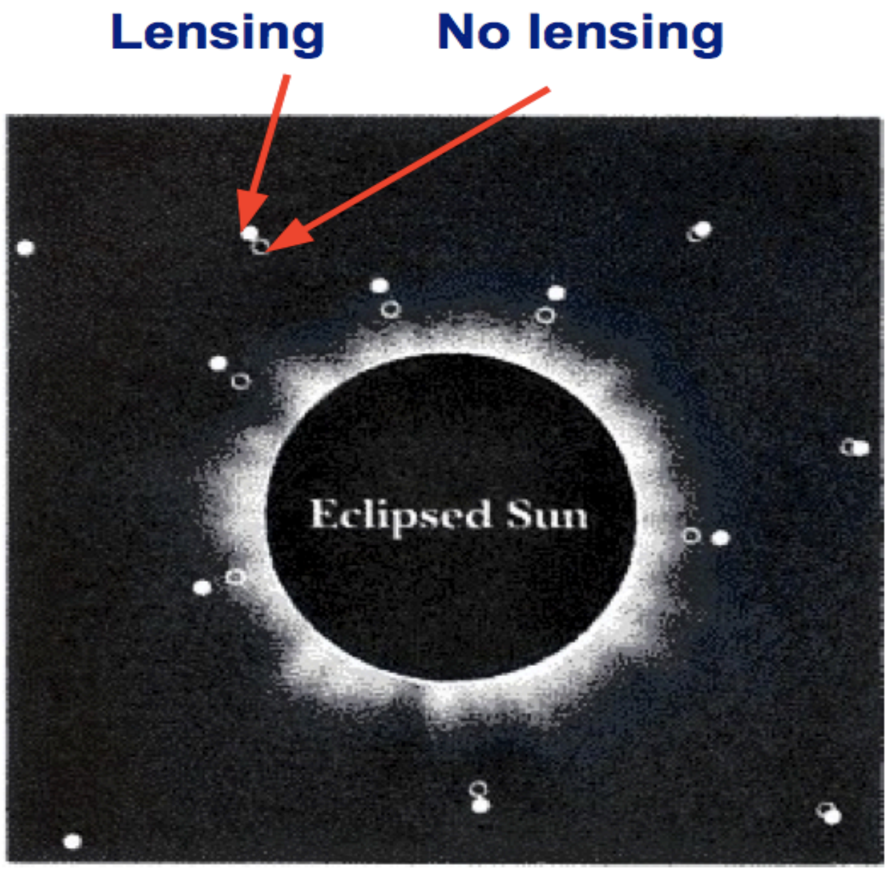
How can we probe dark energy?

Measure the history of the expansion of the universe and the growth of structure

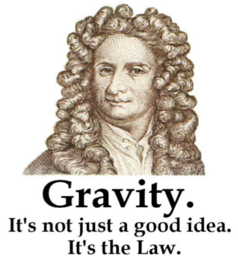
Requires mapping the distribution of all matter over cosmic time

Weak lensing basics

Gravitational lensing



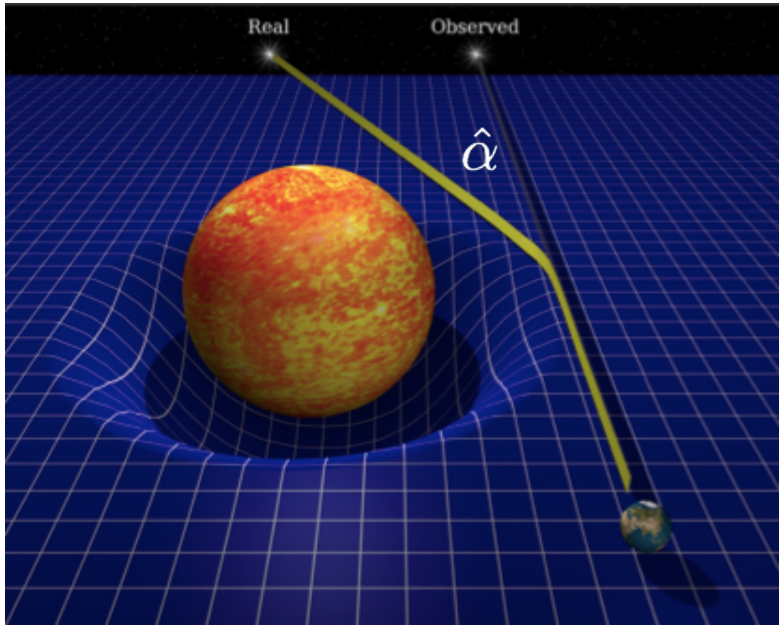
- ~1800: mass can bend light?
- 1911: Einstein predicts light deflection by gravity.
- 1919: Observation of light from a star deflected by the gravity of the Sun during an eclipse



Mass warps space-time and alters the path of light

Light ray travel time along null geodesic:

$$t = \frac{1}{c}\int \left(1 - \frac{2\Phi}{c^2}\right) dr$$



Light deflection angle from integrating Euler-Lagrange equations along light path:

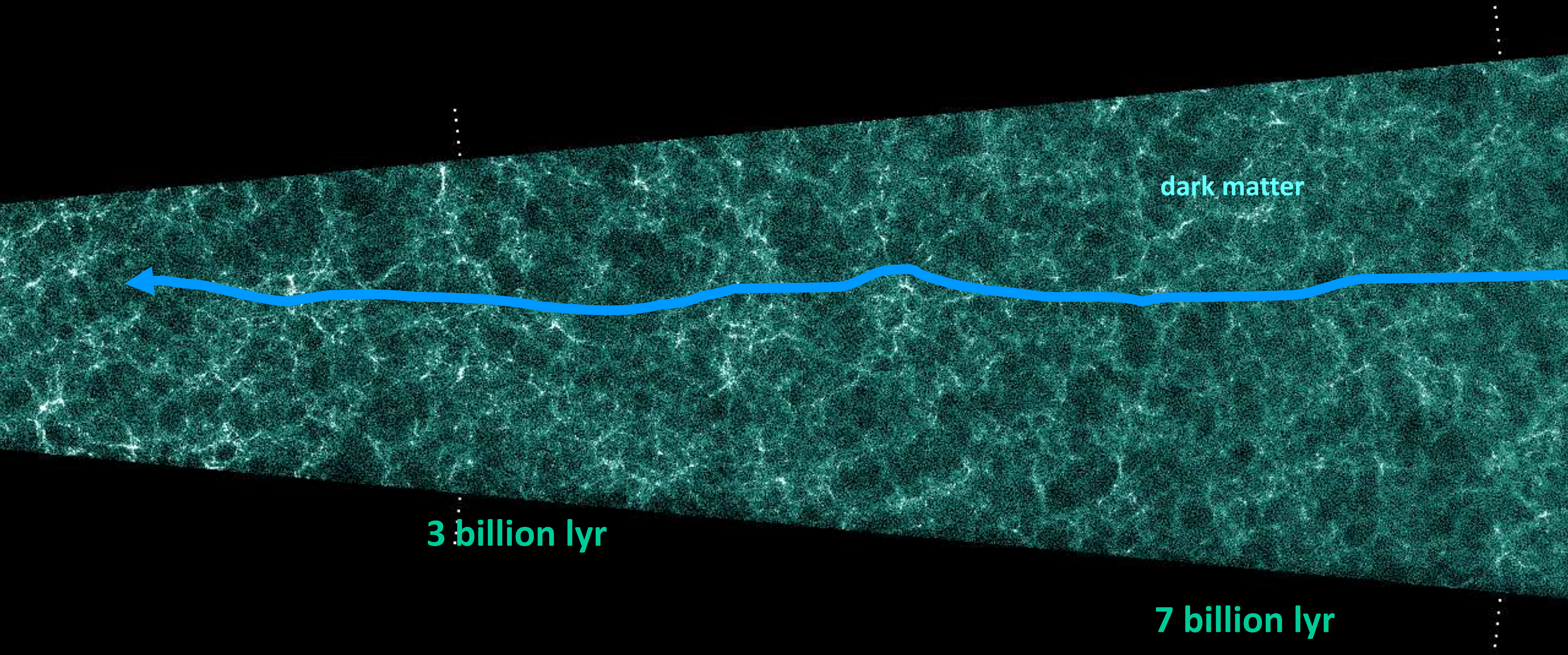
$$\hat{\alpha} = -\frac{2}{c^2}\int \nabla_\perp \Phi \, dr$$

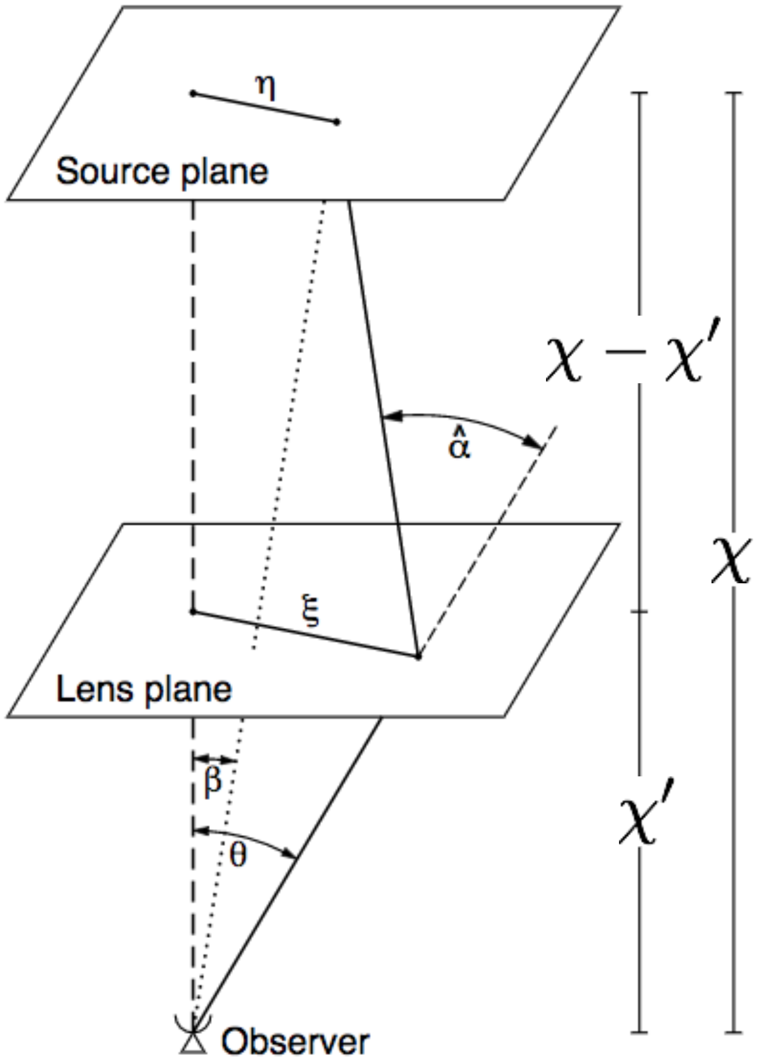
Not present in Newtonian gravity

Reference:
Cosmology with Cosmic Shear: A Review
Martin Kilbinger
https://arxiv.org/abs/1411.0115

Gravitational lensing today

mass structure vs cosmic time





Reference:
Weak Gravitational Lensing
Bartelmann & Schneider
https://arxiv.org/abs/astro-ph/9912508

Weak gravitational lensing

The **lens equation** relates the un-lensed angular sky position β of a source to the lensed position θ via the deflection angle α:

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

Infinitesimal light bundle approximation

In the **weak lensing approximation**, we consider only the first order linear dependence of the mapping from lens to source plane,

$$A_{ij} = \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial \alpha_i}{\partial \theta_j}$$

The deflection angle is the gradient of a scalar potential, which is an integral over the light travel path,

$$\alpha_i = \partial_i \psi(\vec{\theta}, \chi) = \partial_i \frac{2}{c^2} \int_0^{\chi} d\chi' \, \frac{\chi - \chi'}{\chi \chi'} \Phi(\chi' \vec{\theta}, \chi')$$

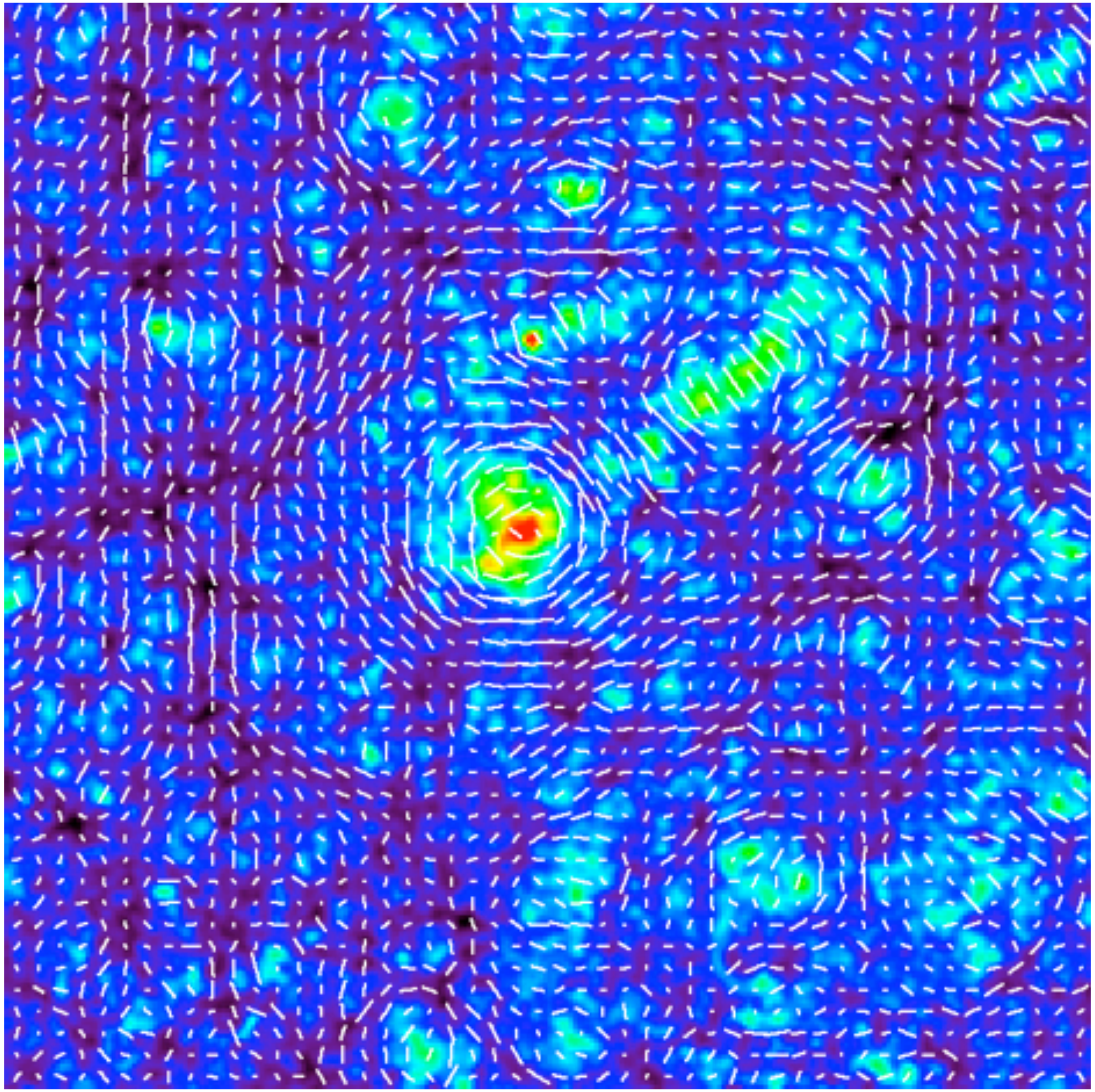
Born & flat-sky approximations

The linear **distortion matrix** is then,

$$A_{ij} = \delta_{ij} - \partial_i \partial_j \psi \qquad \mathsf{A} = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix}$$

A^{-1} gives the Jacobian for the local mapping between source plane and lens plane images

Reference:
Cosmology with Cosmic Shear: A Review
Martin Kilbinger
https://arxiv.org/abs/1411.0115



Weak lensing power spectrum

The lensing convergence is related to the projected Laplacian of the projected gravitational potential (note factor of 2 difference from 3D Poisson equation),

$$\kappa = \frac{1}{2}\nabla^2\psi \qquad \delta(\chi'\theta,\chi') \equiv \nabla_\perp^2\Phi(\chi'\theta,\chi')$$

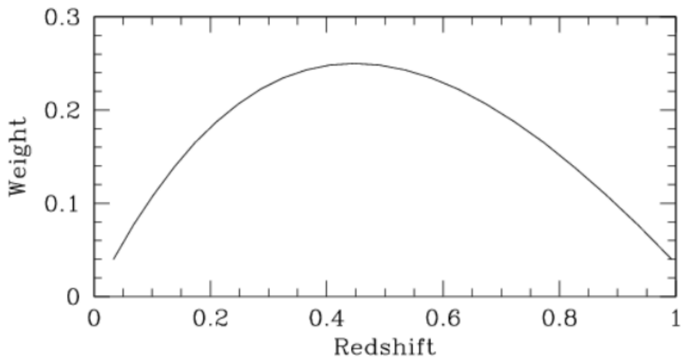
$$\kappa(\vec{\theta}) = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{\chi_\infty}\frac{\chi\,d\chi}{a(\chi)}g(\chi)\delta(\chi\vec{\theta},\chi)$$

The convergence is a weighted projection of the 3D cosmological mass density perturbations along the line-of-sight. We call the weighting function the **lensing efficiency**,

$$g(\chi) \equiv \int_\chi^{\chi_\infty} d\chi' \frac{\chi'-\chi}{\chi'} n(\chi')$$

Source redshift distribution

No source clustering



The lensing efficiency is very broad and most sensitive to mass mid-way between observer and source.

Credit: M. White

The convergence power spectrum is defined as,

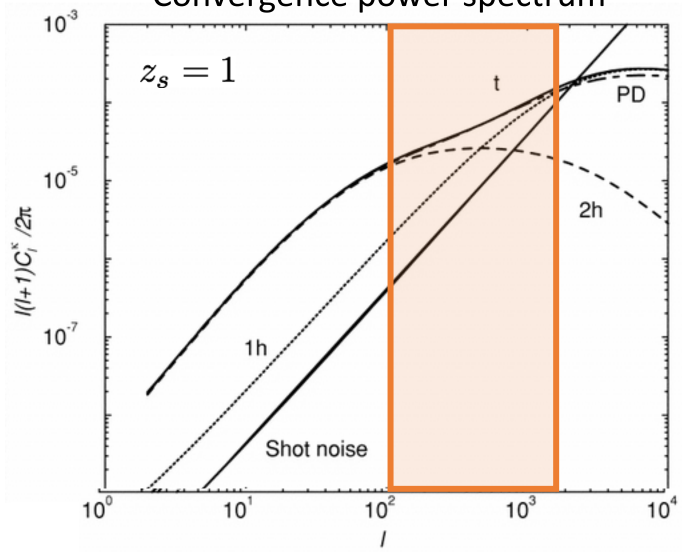
$$\langle\tilde{\kappa}(\ell)\tilde{\kappa}^*(\ell')\rangle = (2\pi)^2\delta_D(\ell-\ell')P_\kappa(\ell)$$

And is related to the 3D mass power spectrum as,

$$P_\kappa(\ell) = \frac{9}{4}\Omega_m^2\left(\frac{H_0}{c}\right)^4\int_0^{\chi_\infty} d\chi\,\frac{g^2(\chi)}{a^2(\chi)}P_\delta\left(k=\frac{\ell}{\chi},\chi\right)$$

Limber approximation

Convergence power spectrum

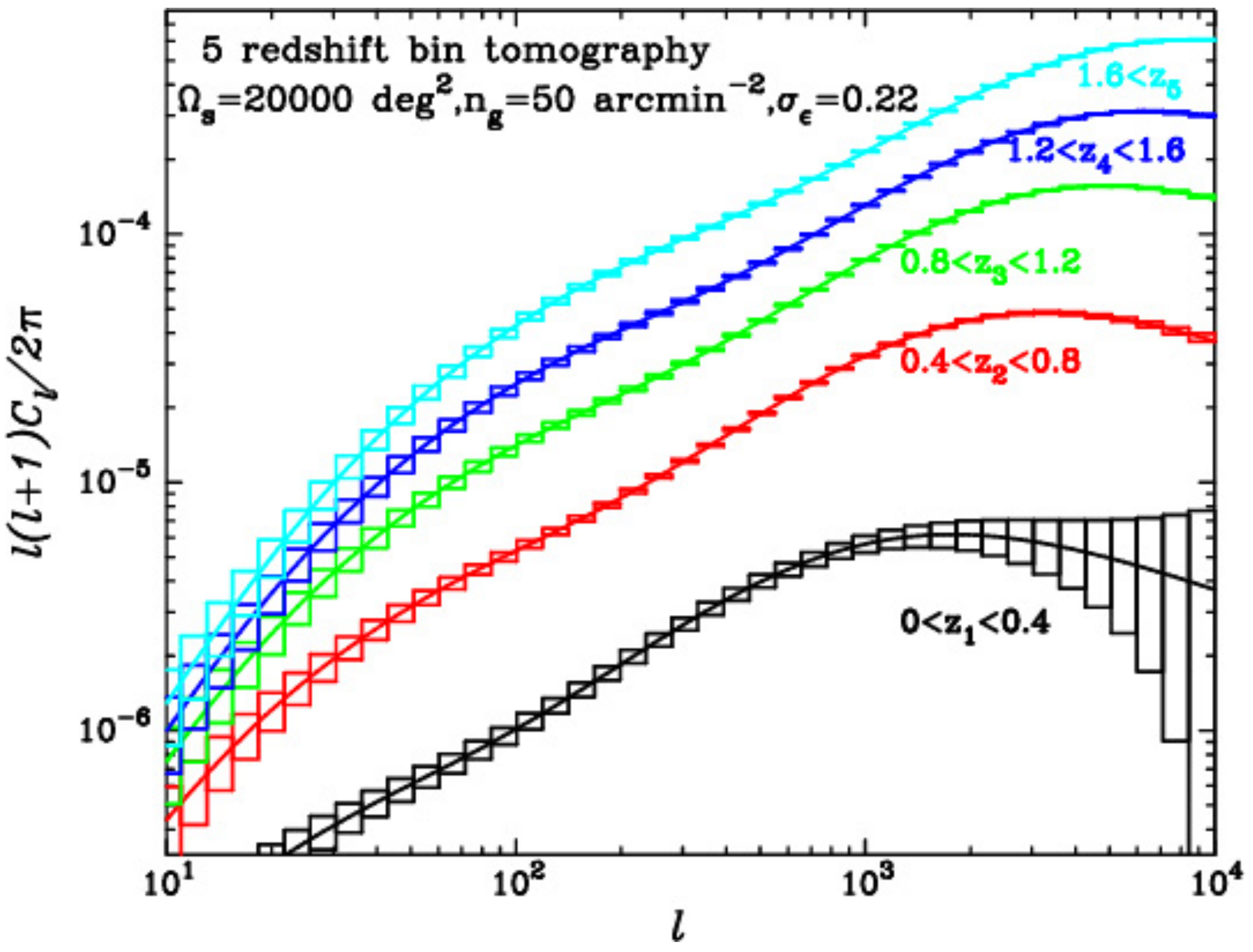


Cooray & Hu (2001)

Weak lensing tomography

By binning galaxies according to estimated redshift (i.e., line-of-sight distance), the change in the lensing amplitude over cosmic time can be measured with the angular power spectrum.

Figure credit: LSST



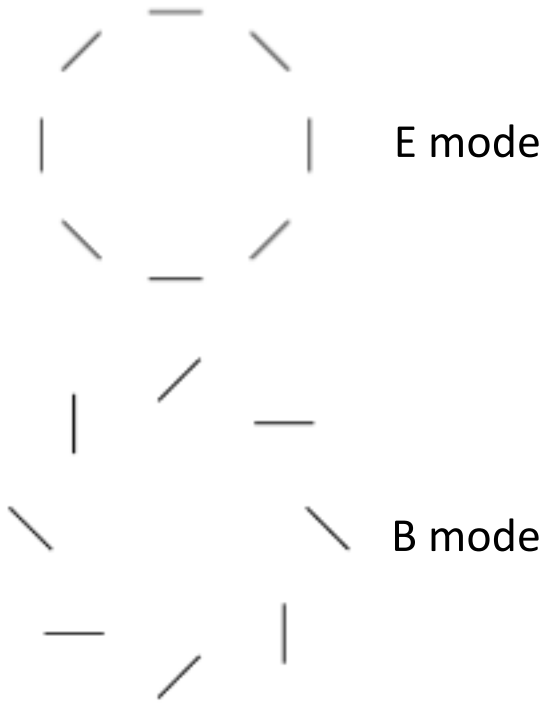
Shear correlation functions

The shear components are a related to the convergence by a phase shift in Fourier space.

$$\tilde{\gamma}(\ell) = e^{2i\beta}\tilde{\kappa}(\ell) \qquad\qquad P_\gamma = P_\kappa$$

The shear power spectrum is thus the same as the convergence.

The spin-2 shear field can be separated into 'E' and 'B' modes in Fourier space.



$$(\gamma_1 + i\gamma_2)(x) \equiv \int \frac{d^2k}{(2\pi)^2}\left[\epsilon(k) + i\beta(k)\right] e^{2i\phi_k} e^{i\vec{k}\cdot\vec{x}}$$

In configuration space, it's convenient to define the 'tangential' and 'cross' shear estimators,

$$\gamma_t \equiv -\mathrm{Re}\left(\gamma e^{-2i\phi}\right) \qquad \gamma_\times \equiv -\mathrm{Im}\left(\gamma e^{-2i\phi}\right)$$

We can then define two correlation functions of the shear,

$$\xi_+(\theta) = \langle\gamma_t\gamma_t\rangle(\theta) + \langle\gamma_\times\gamma_\times\rangle(\theta)$$

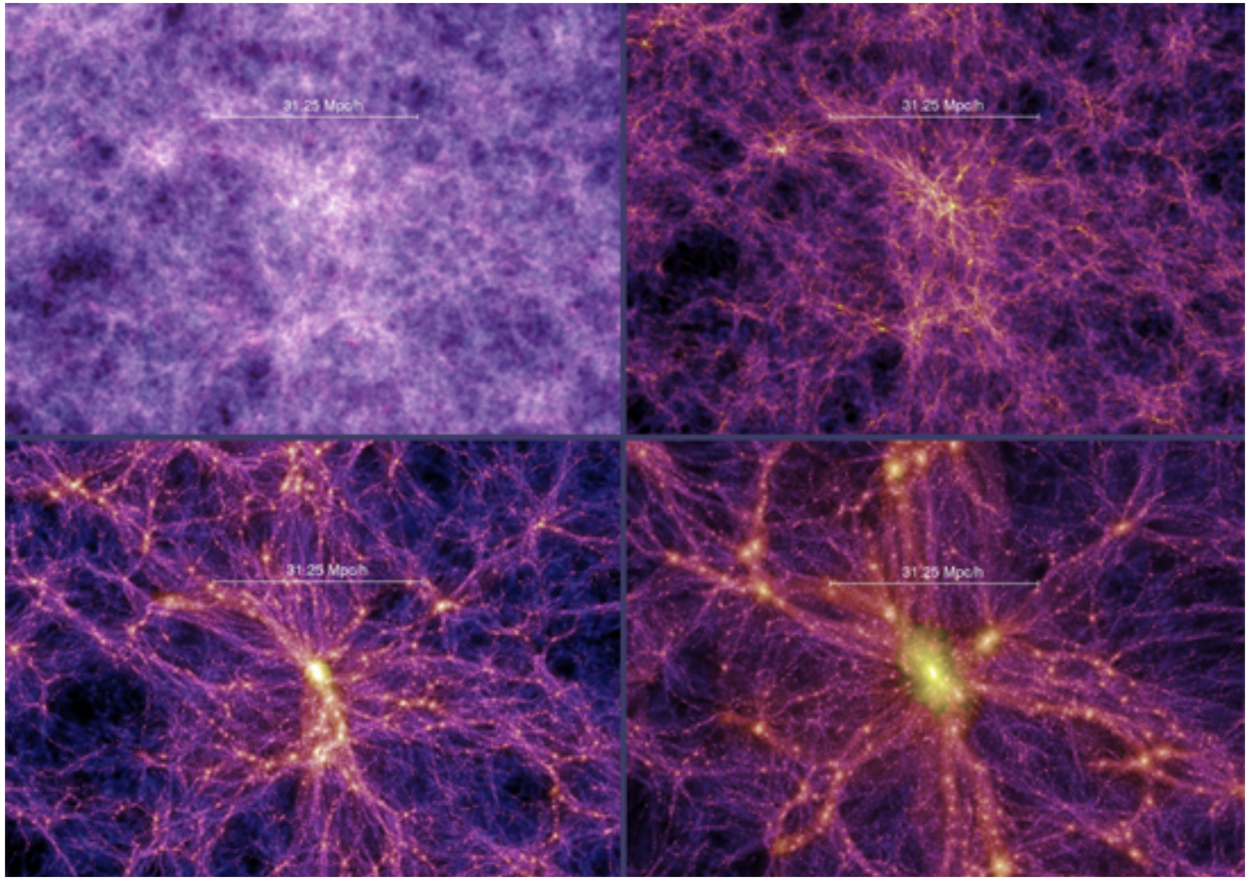
$$\xi_-(\theta) = \langle\gamma_t\gamma_t\rangle(\theta) - \langle\gamma_\times\gamma_\times\rangle(\theta)$$

An estimator of the shear correlations that is practical for real data analyses is,

$$\hat{\xi}_\pm(\theta) = \frac{\sum_{ij} w_i w_j (e_{t,i}e_{t,j} \pm e_{\times,i}e_{\times,j}}{\sum_{ij} w_i w_j}$$

Reference:
Cosmology with Cosmic Shear: A Review
Martin Kilbinger
https://arxiv.org/abs/1411.0115

Weak Gravitational Lensing (A Review)
M. White



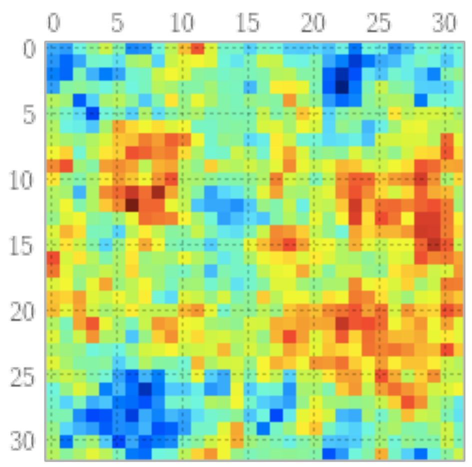
Describing gravitational growth of cosmological matter density perturbations

Predictions of the covariance of summary statistics of the late-time cosmological mass density

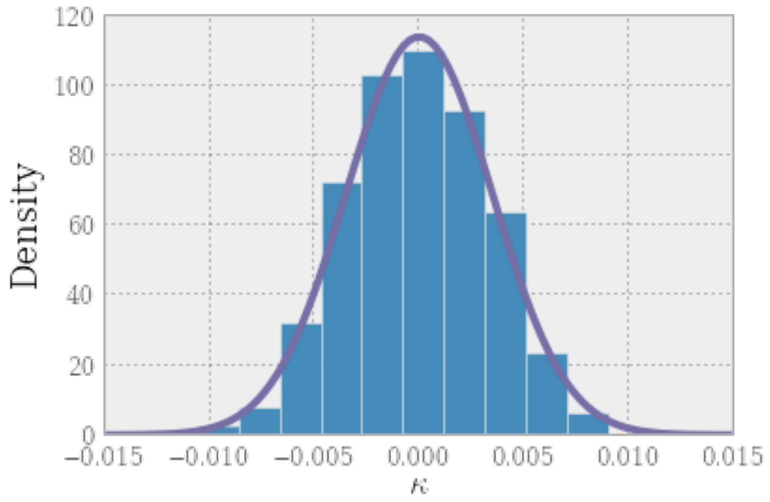
“Vanilla” inflation predicts the initial cosmological mass density perturbations are Gaussian distributed.

What does “Gaussian distributed” mean here?

Bin the mass density into cells



Histogram the cell values



The histogram of cell values is fit well by a Gaussian distribution.

The matter power spectrum covariance after inflation…

- Is diagonal
  - Every Fourier mode of the mass density and the mass density power spectrum is statistically independent.
  - Consequence of homogeneity
- Depends only on the power spectrum
  - General result for a Gaussian random field.

The power spectrum is the theorist's favorite summary statistic in part because of these properties.

The shell-averaged power spectrum estimator

- Assuming isotropy, power spectrum estimates with the same wave vector modulus but different phase are independent estimators of the same band power.

- Define the k “shell-averaged” estimator,

$$\hat{P}(k) \equiv \frac{1}{N_k} \sum_{i=1}^{N_k} \hat{P}(\vec{k}) \qquad N_k \equiv 4\pi k^2 \delta k V$$

- The covariance becomes,

$$\mathrm{Cov}(\hat{P}(k)) = \frac{2}{N_k} P^2(k)$$

Growth of mass density mode correlations…

…is caused by gravitational collapse, which breaks homogeneity

The covariance of the power spectrum depends on the 4-point expectation, $\left\langle \delta(\vec{k})\delta^*(\vec{k})\delta(\vec{k}')\delta^*(\vec{k}')\right\rangle$

If the joint probability distribution of the 4 δ terms does not factor, then there is a "connected" 4-point function that also contributes to the covariance,

$$\left\langle \delta(\vec{k})\delta^*(\vec{k})\delta(\vec{k}')\delta^*(\vec{k}')\right\rangle_c \equiv T(\vec{k}, -\vec{k}, \vec{k}', -\vec{k}')$$

The trispectrum T is nonzero only when the density field becomes non-Gaussian through gravitational evolution.

The nonlinear power spectrum covariance

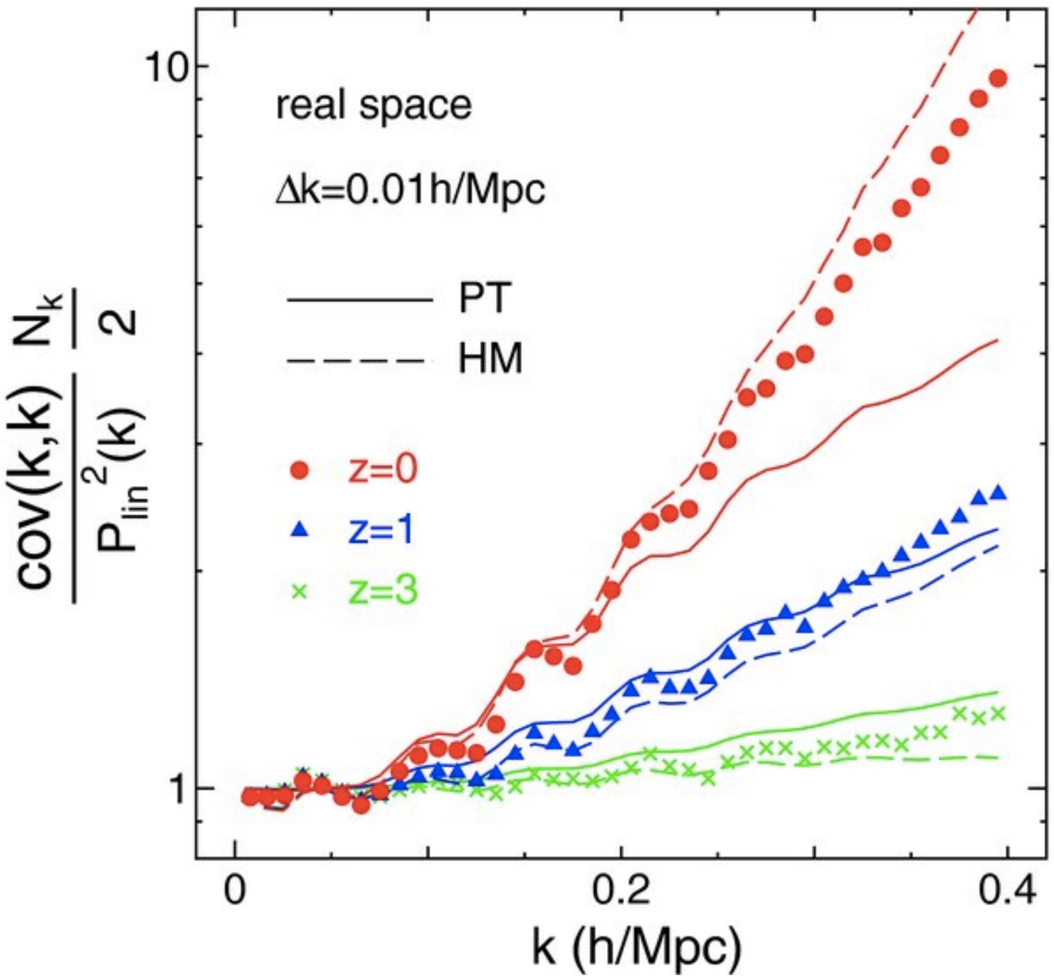
- The non-Gaussianity of the mass density field admits a non-zero trispectrum, which leads to off-diagonal terms in the power spectrum covariance.

$$C_{ij} = \frac{2}{N_k} P_i^2 \delta_{ij} + \frac{1}{V} \bar{T}(k_i, k_j) \qquad N_k \equiv 4\pi k^2 \delta k V$$

- Increasing survey volume reduces the power spectrum covariance. But, at fixed V, the trispectrum dominates for large k where there are many modes.

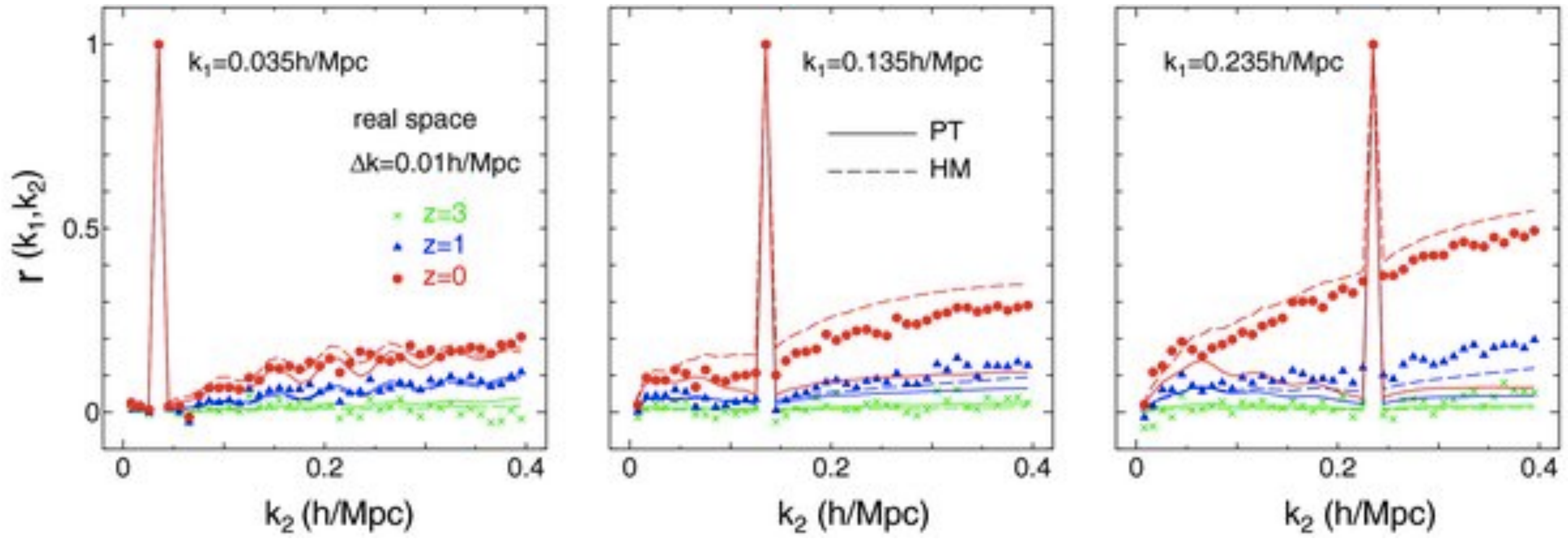
Warning: the shell-averaged trispectrum above neglects an important term - ‘super-sample covariance’.

Growth of P(k) correlations



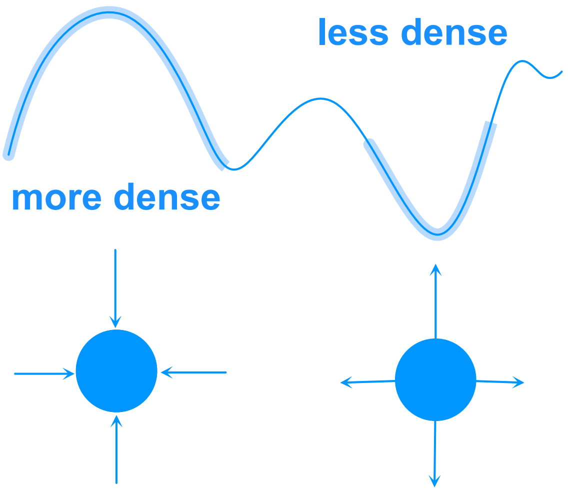
Takahashi et al. (2009)

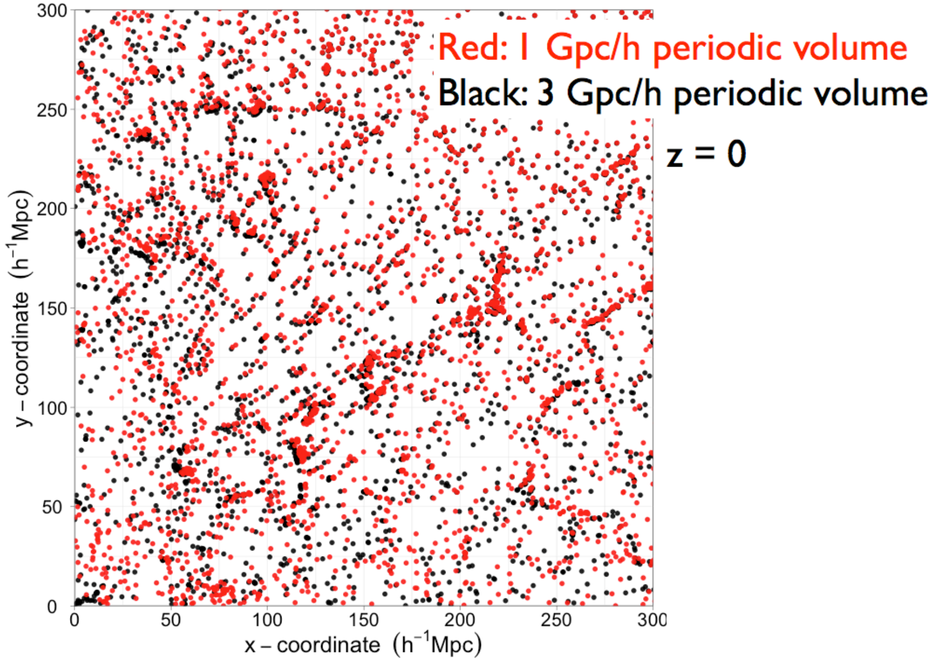
Growth of P(k) correlations



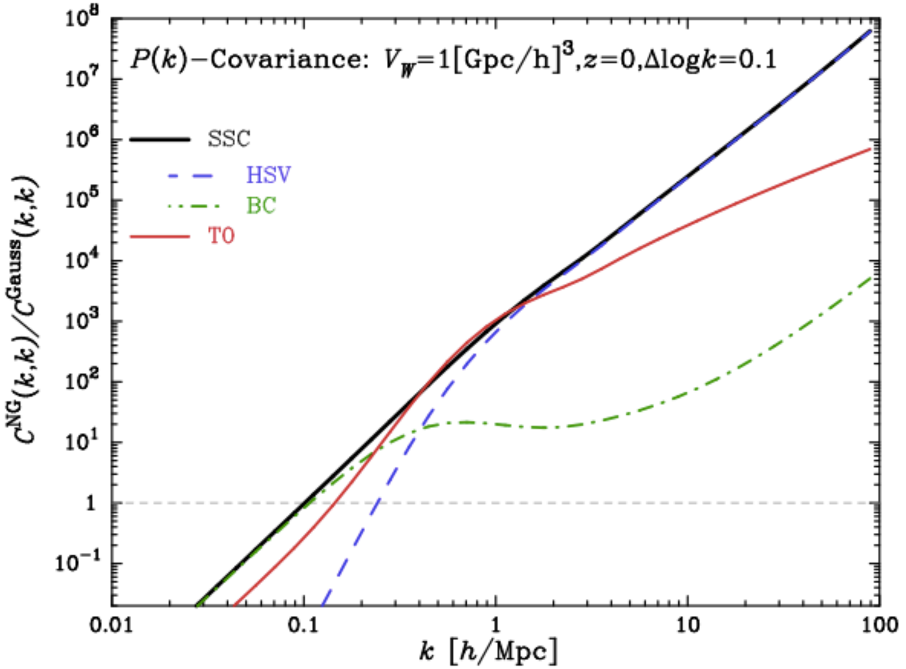
Takahashi et al. (2009)

Super-sample covariance



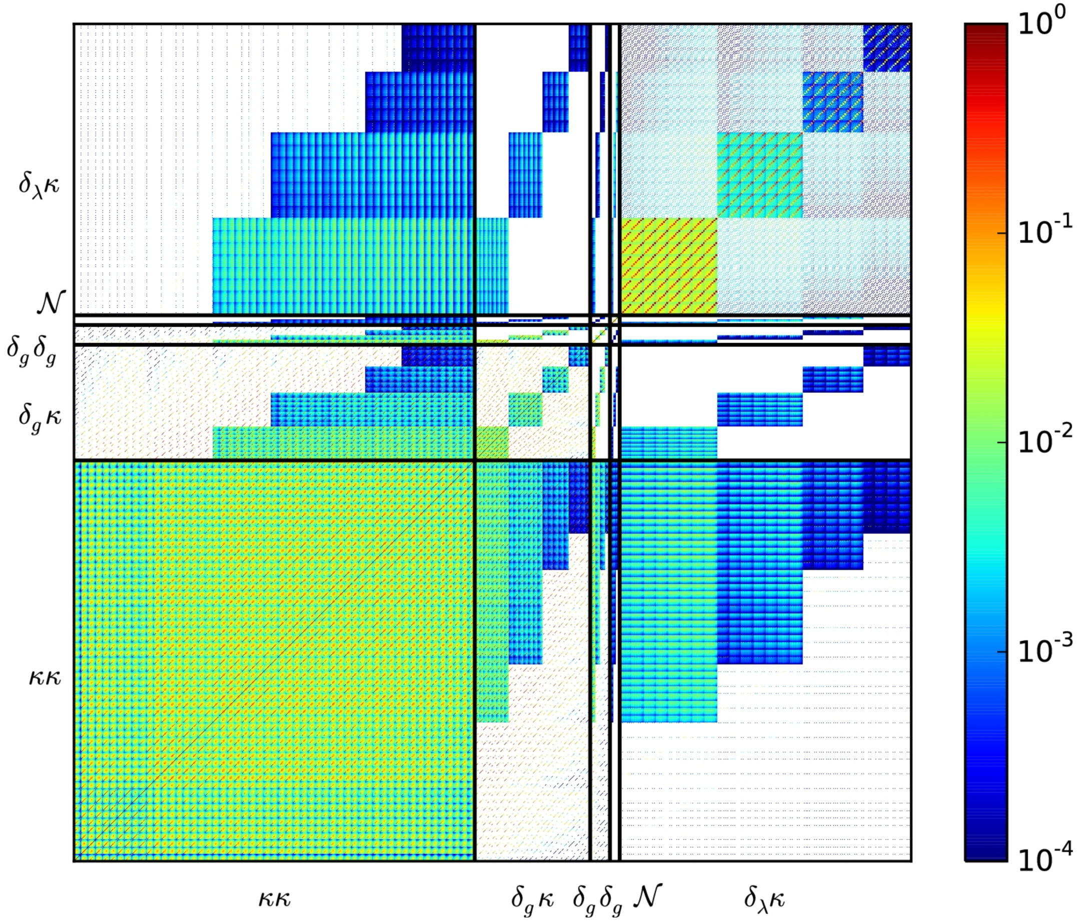


Takada & Hu (2013)



Different cosmological probes are correlated by common large-scale structure

The full covariance of the “joint probes” data vector is a challenge to model or estimate



Krause & Eifler (2017)
CosmoLike code
https://arxiv.org/abs/1601.05779

Galaxy shear estimation

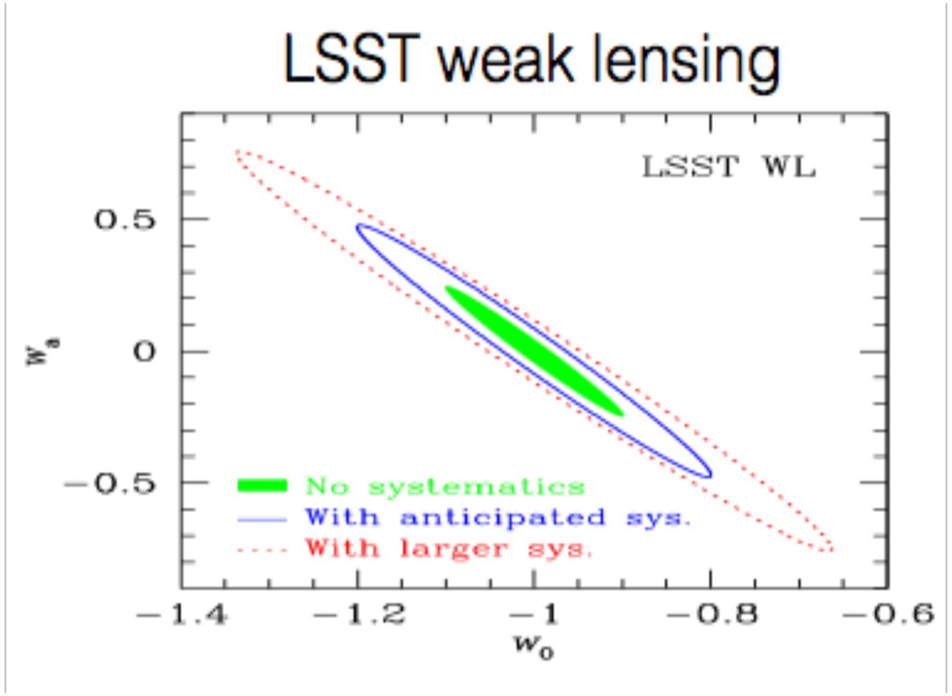
"Cosmic shear"

Cosmic shear measurement

- The lensing by large scale structure
- Looking for very small signal under very large amount of noise
- We **don't know "unsheared" shapes**, but can (roughly) assume they are isotropically distributed
- Cosmic shear distorts statistical isotropy; galaxy ellipticities become correlated
- Exquisite probe of DE, if systematics can be controlled
- LSST: will measure few billion galaxy ellipticities. Excellent sensitivity to both DE and systematics!

Cosmic shear signal is comparable to ellipticity of the Earth, ~0.3%

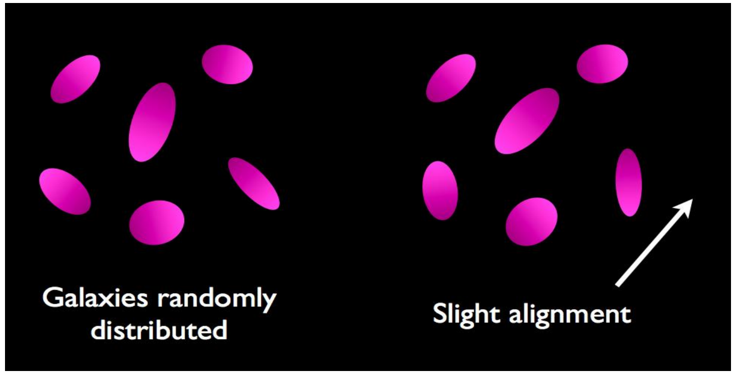
- D. Wittman



Gravitational lensing distorts the shapes of galaxies

The ellipticity estimator is defined by semi-major/minor axes,

$$e = \frac{a-b}{a+b}e^{2i\phi}$$



If the unlensed sizes of galaxies are unknown, lensing shear estimators are only sensitive to **reduced shear,**

$$g = \frac{\gamma}{1-\kappa}$$

$$< e > \approx g$$

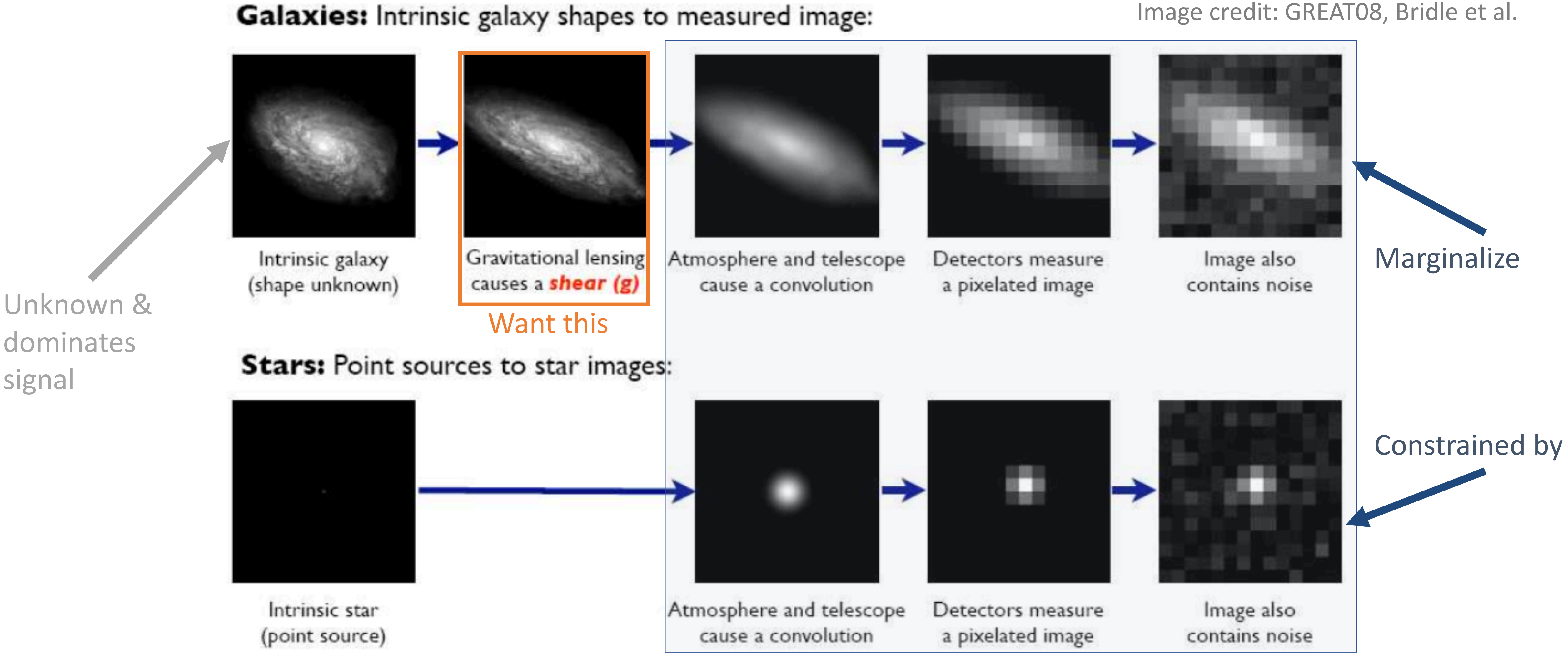
The ellipticity estimator transforms under shear as,

$$e = \frac{e^s + g}{1 + g^* e^s}$$

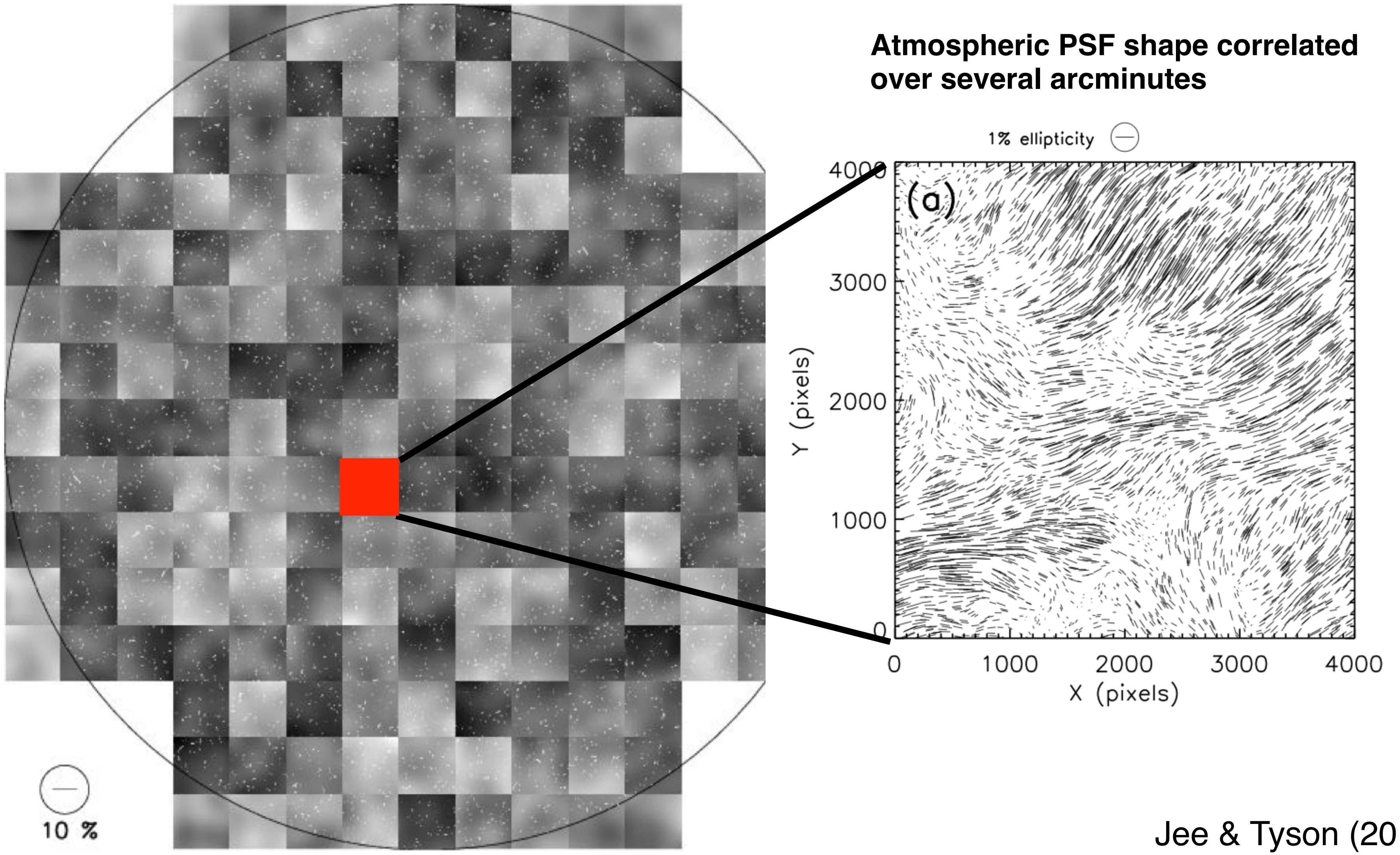
$$e \approx e^s + \gamma$$

Weak lensing of galaxies: the forward model

Image credit: GREAT08, Bridle et al.

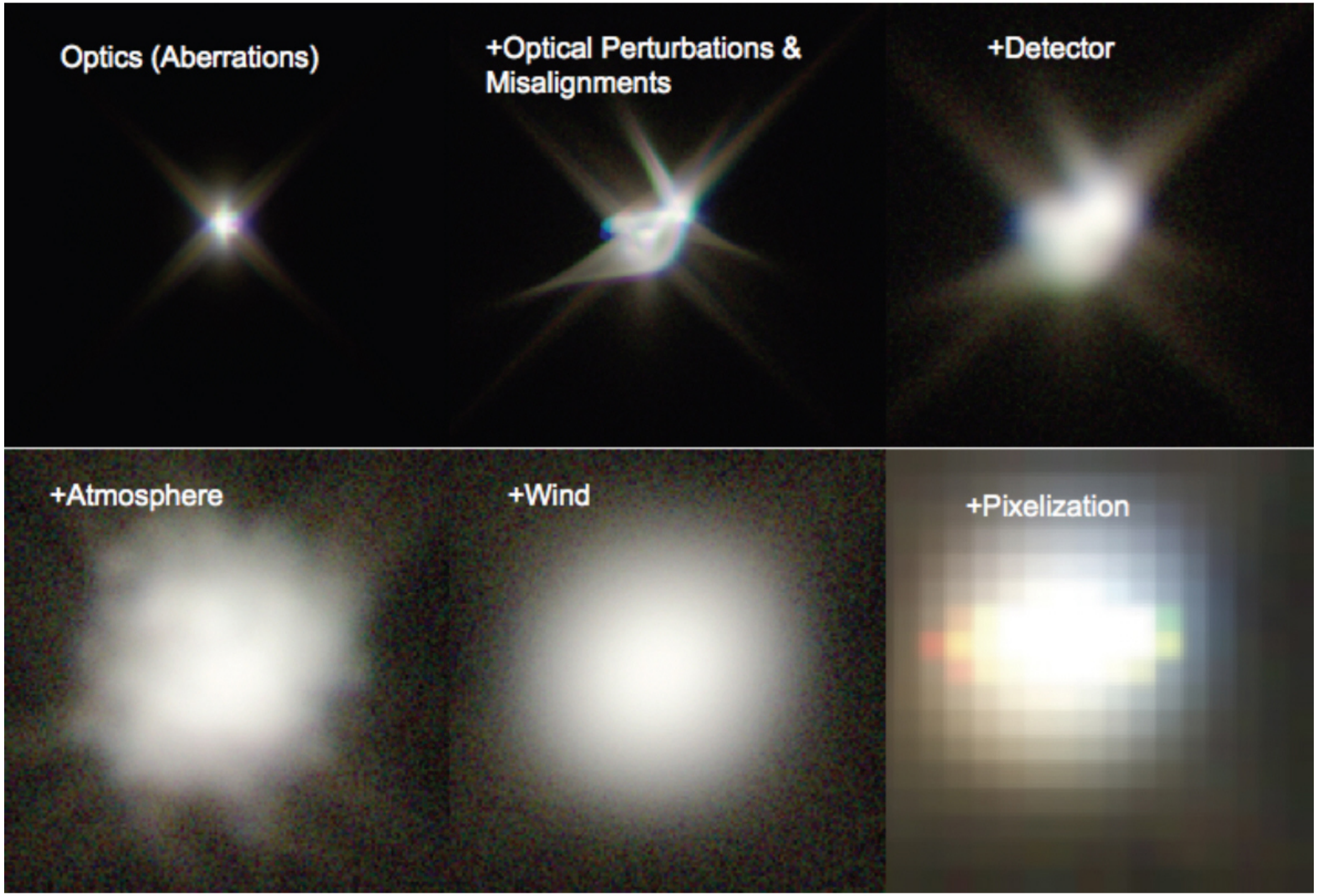


Atmospheric PSF shape correlated over several arcminutes



Jee & Tyson (2011)

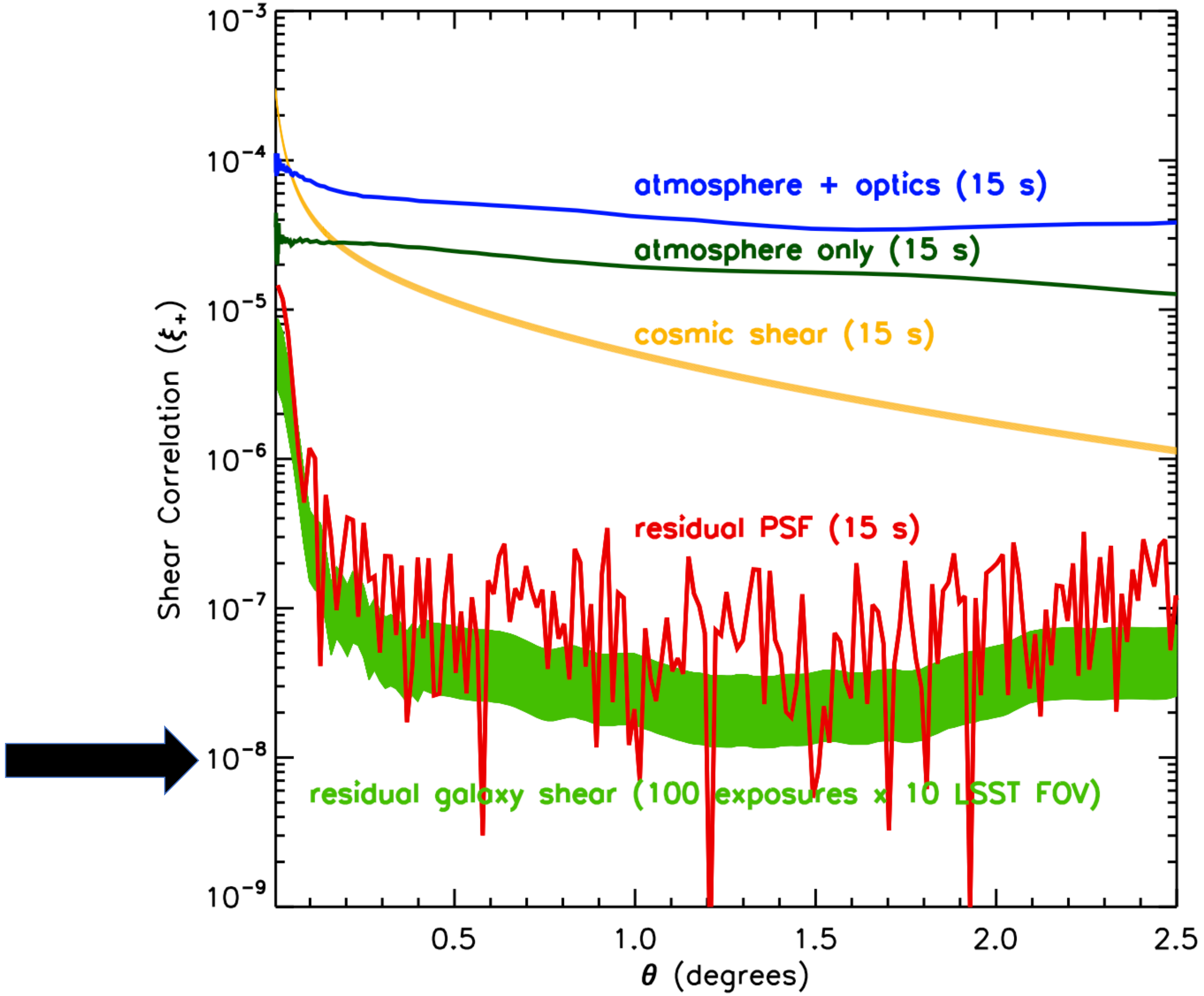
LSST Project image simulation (ImSim / PhoSim)



Correcting PSF systematics

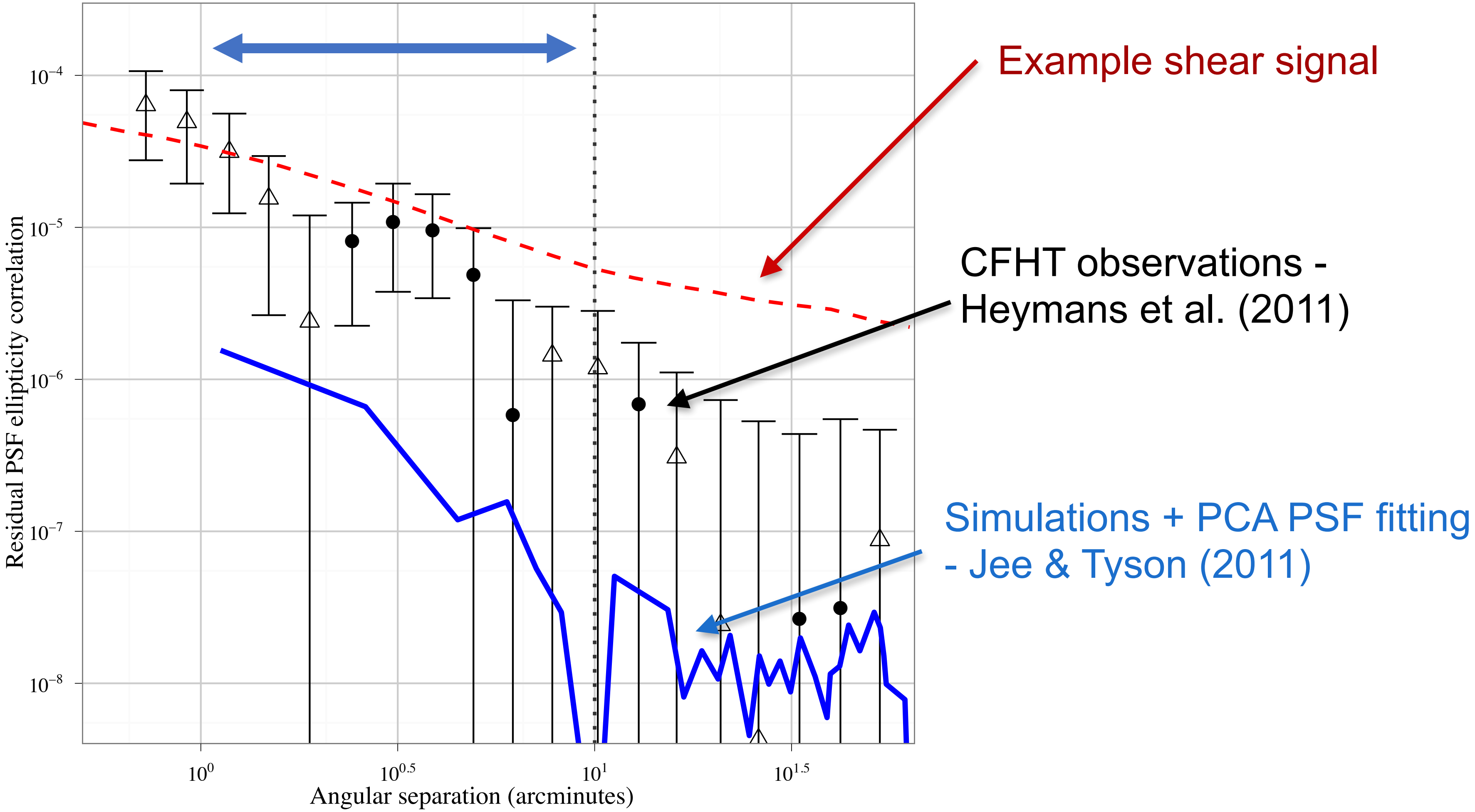
The shape of the PSF must be known (measureable and stable) to a part per ten thousand in each exposure at each position in the CCD. Software corrections to its effects on faint galaxies will be made: below are the shear-shear correlation residuals in a simulation of LSST observing.

Image systematics must be controlled at this level



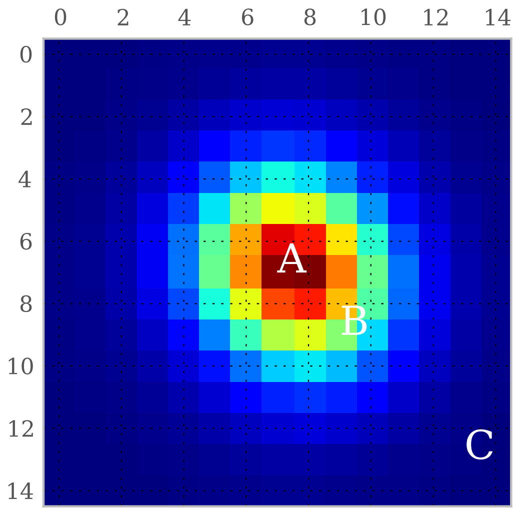
Simulated residual PSF correlations are not as small as we might like.

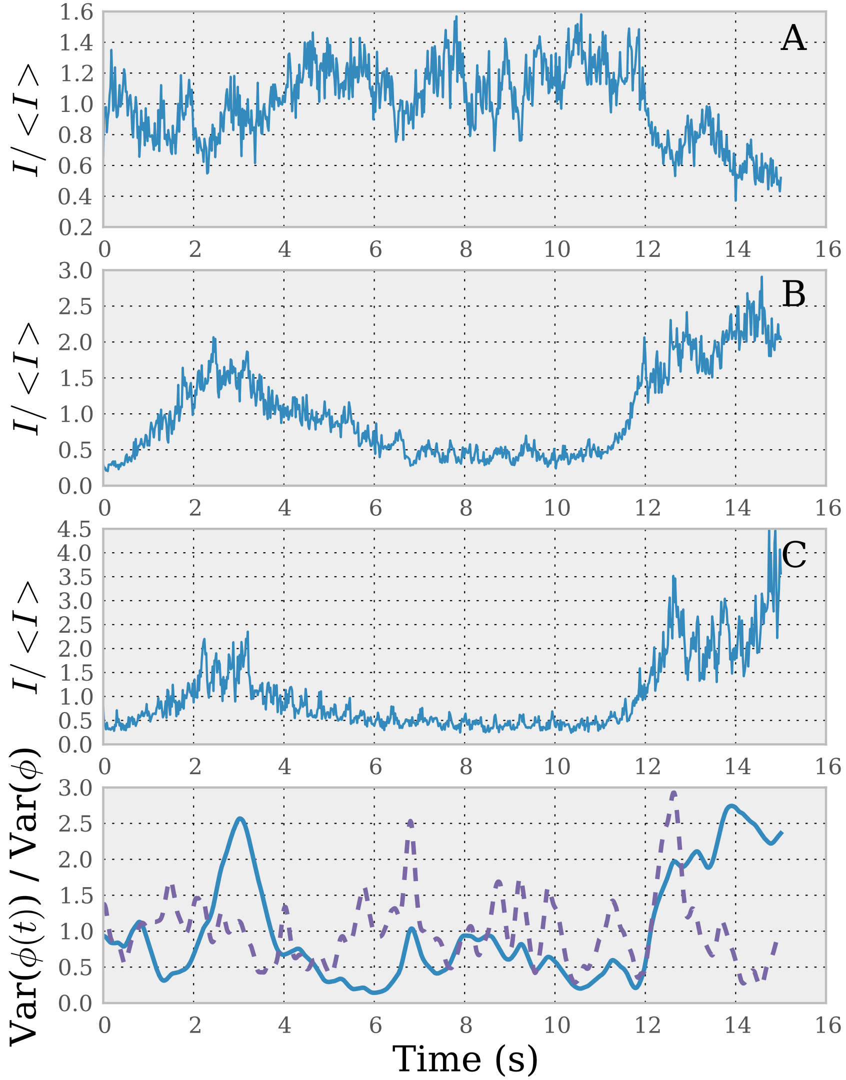
What minimum angular separation do we use between galaxies?



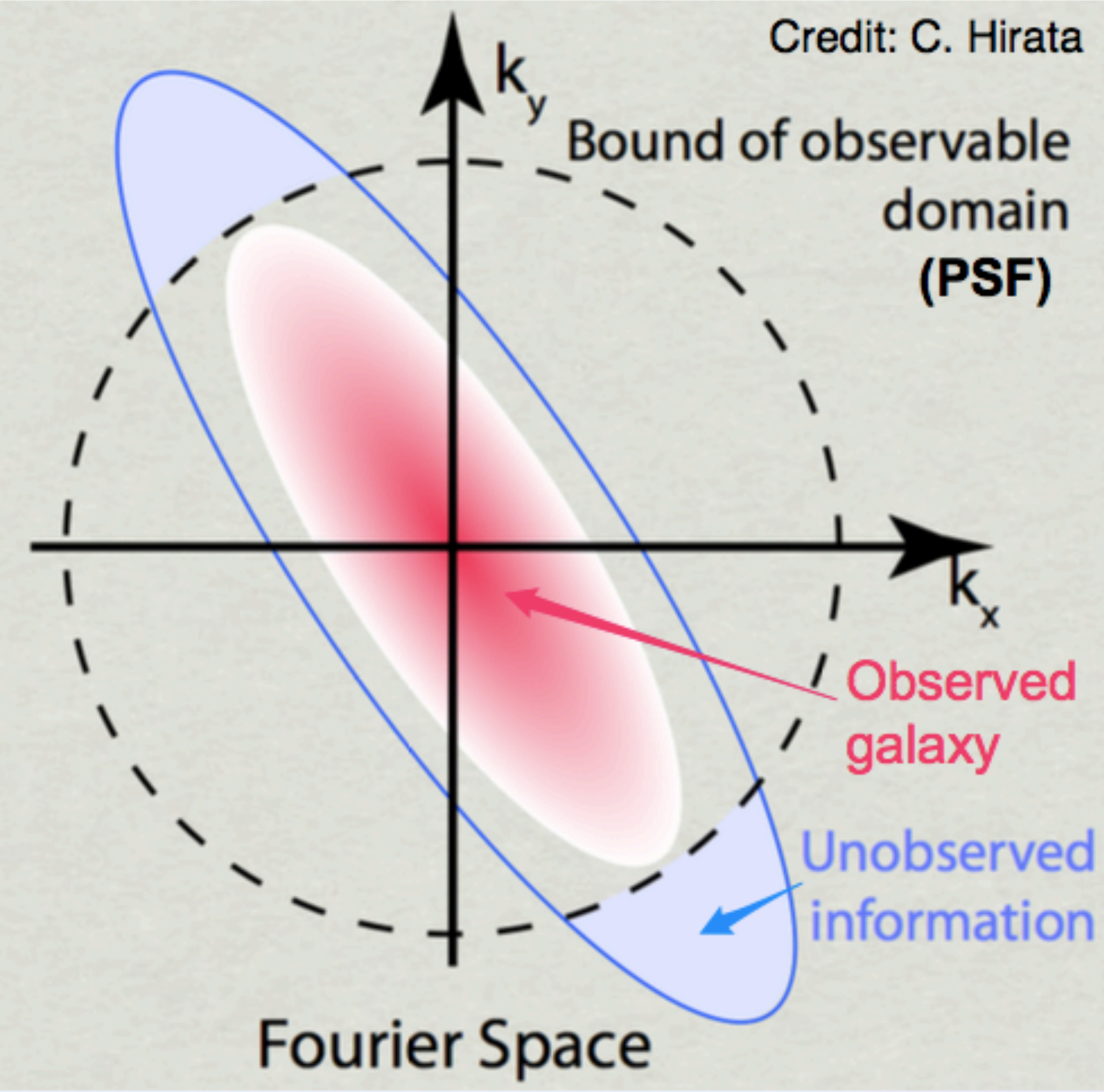
Speckle intensity vs time

How well do we need to understand the dynamics of atmospheric turbulence?





Long exposures may be preferred to "average out" the short timescale variations.

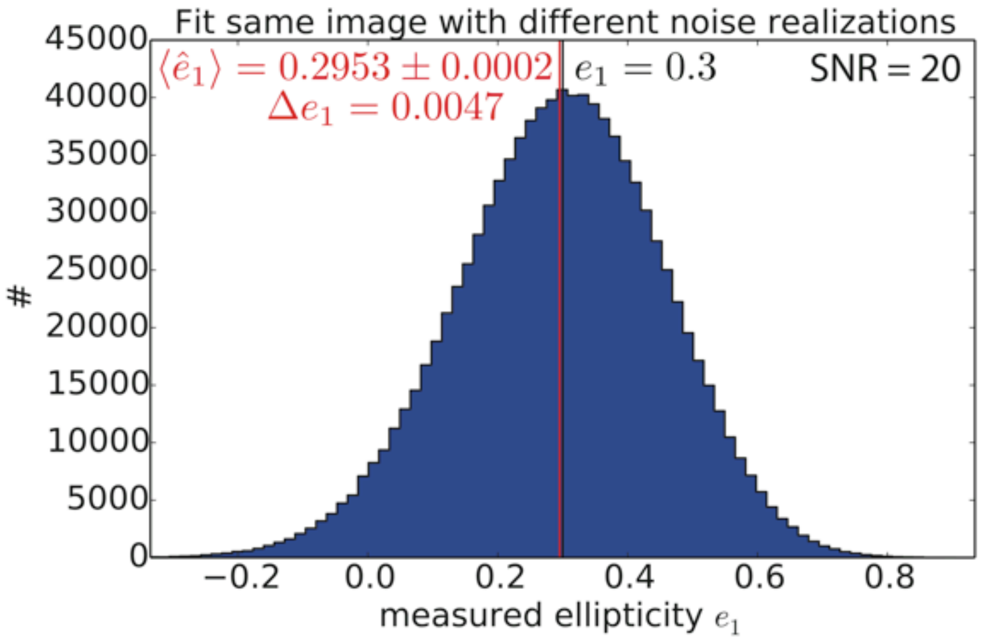


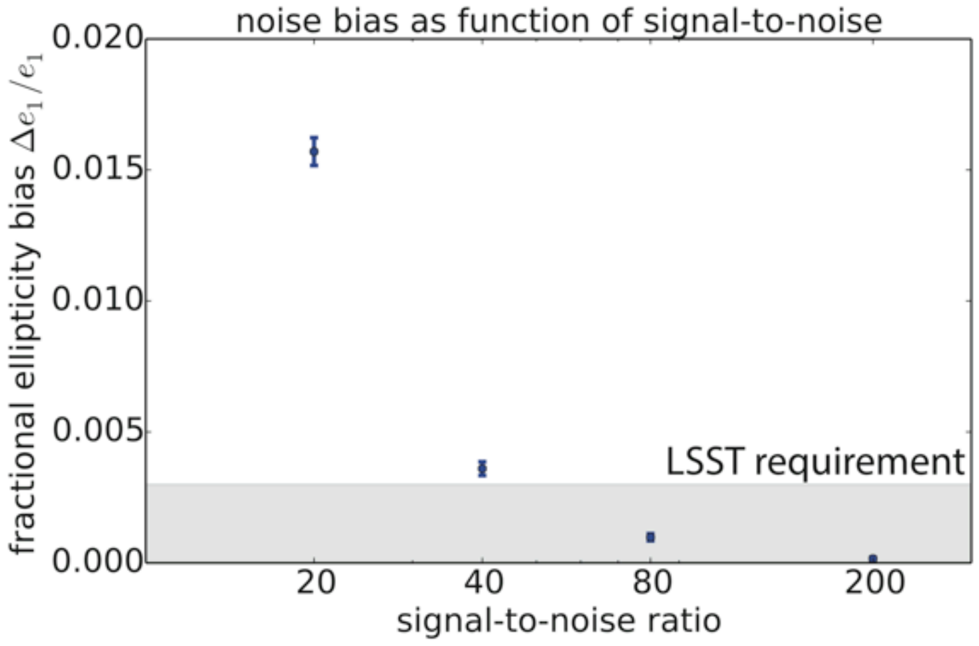
The PSF limits the observable Fourier modes of a galaxy image. So, if we try to 'unshear' an image we may require knowledge of galaxy image properties that are not observed.

That is, we need hyper-resolution information to precisely and accurately estimate shear from an image.

Shape to Shear: Noise Bias

- Ellipticity: $e = \dfrac{a-b}{a+b}\exp(2i\theta)$
- Ensemble average ellipticity is an unbiased estimator of shear.
- However, maximum likelihood ellipticity in a model fit is **not** unbiased.
- Ellipticity is a non-linear function of pixel values.



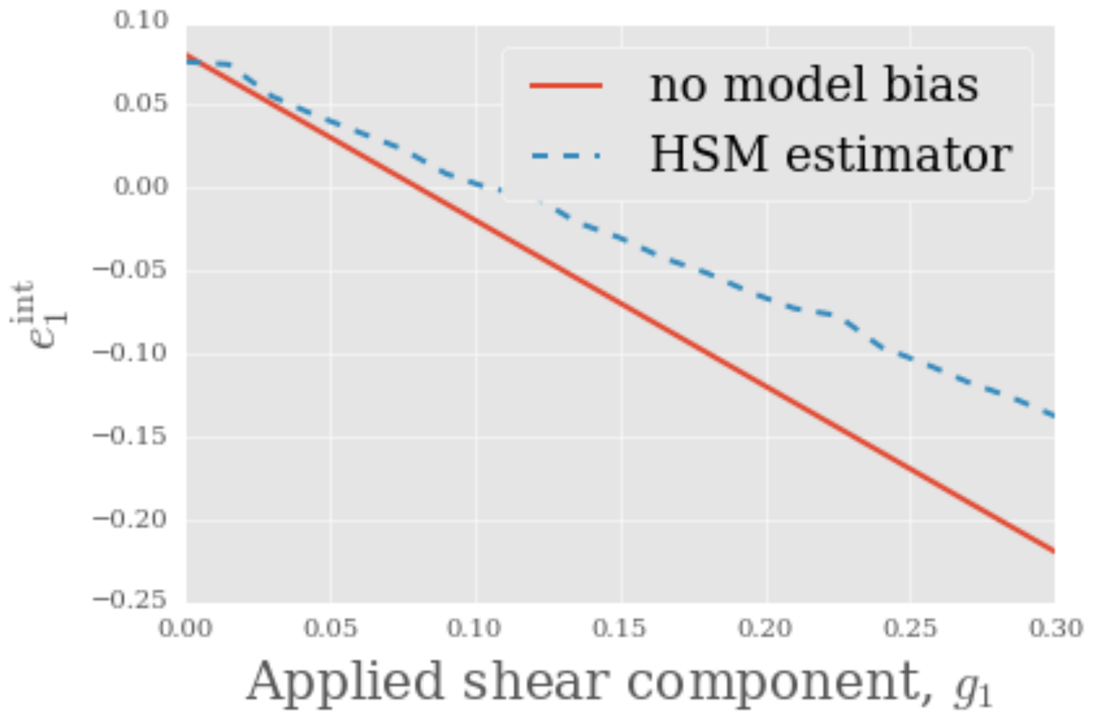


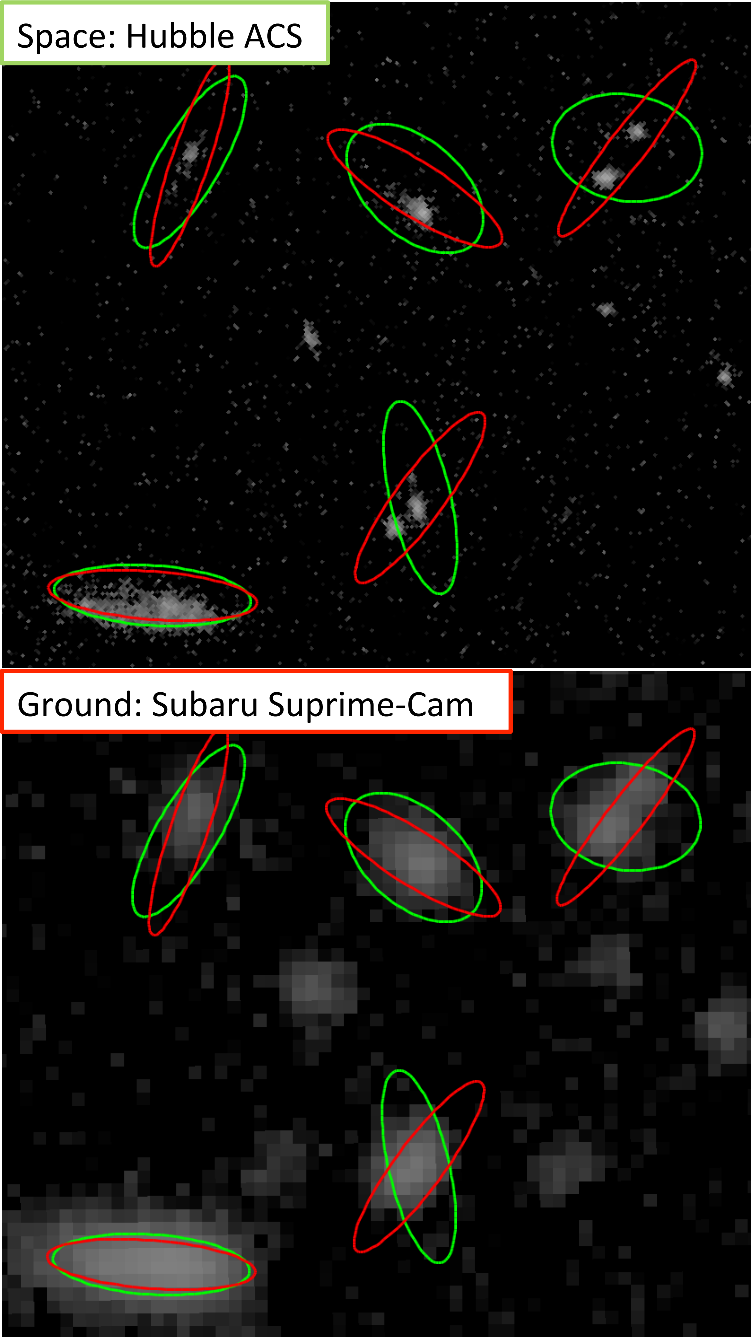
Mitigating Noise Bias – at least 2 strategies

1. Calibrate using simulations. (im3shape, sfit)
   - But corrections are up to 50x larger than expected sensitivity!
2. Propagate entire ellipticity distribution function P(ellip | data)
   - Use Bayes' theorem: P(ellip | data) $\propto$ P(data | ellip) P(ellip)
   - Measure P(ellip) in deep fields. (lensfit, ngmix, FDNT)
   - Infer simultaneously with shear in a hierarchical model. (MBI)

Understanding 'Model bias' – how accurate does a parametric model have to be?

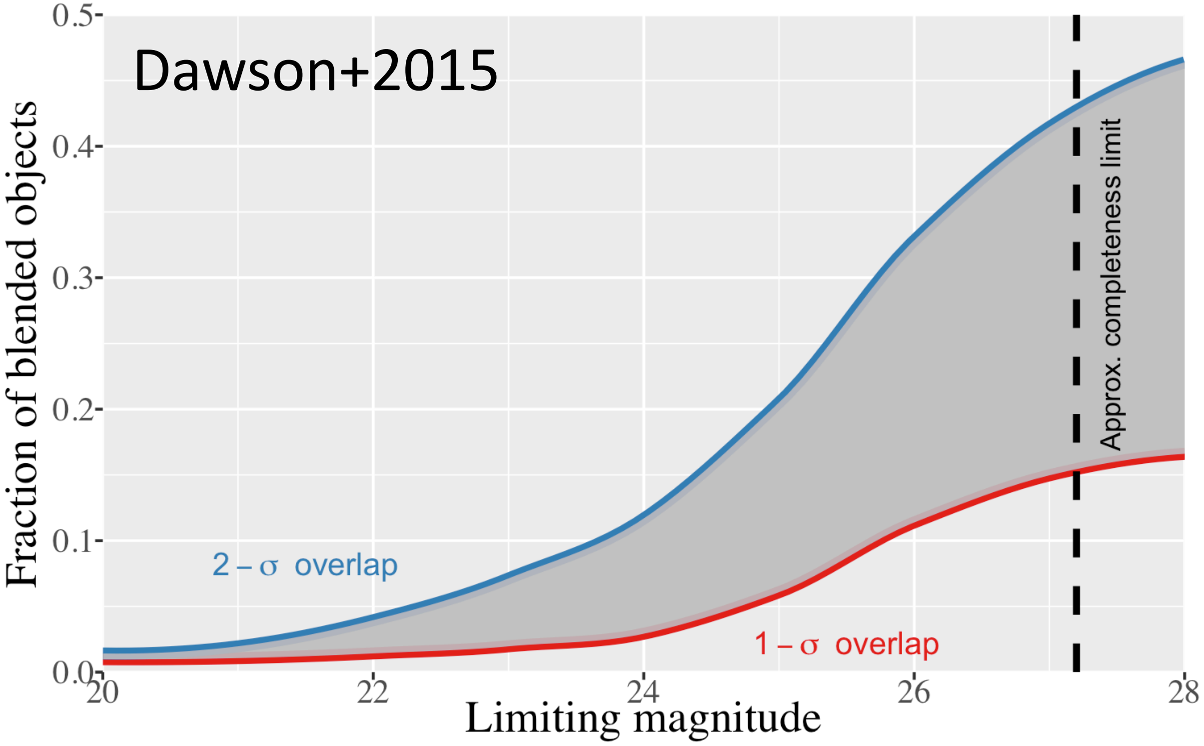
- Galaxy model ellipticity is perfectly degenerate with applied (reduced) shear, assuming:
    - Weak shear
    - Concentric ellipsoidal isophotes
- Deviations from this linear relationship indicate the effect of model bias on shear inference

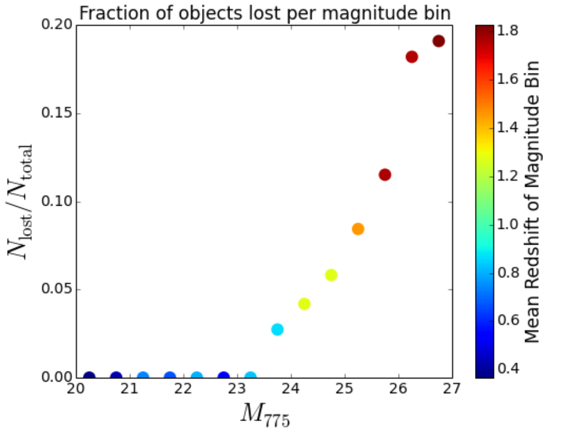




Blending of galaxy images by chance alignments in projection will become a major new systematic error for future deep surveys

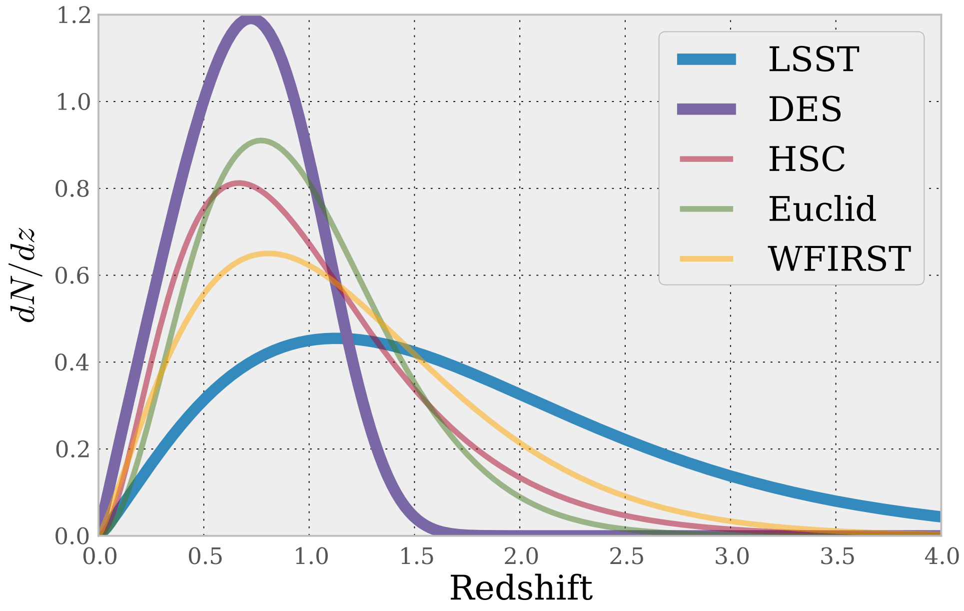
LSST blend fractions estimated from Subaru & HST overlapping imaging

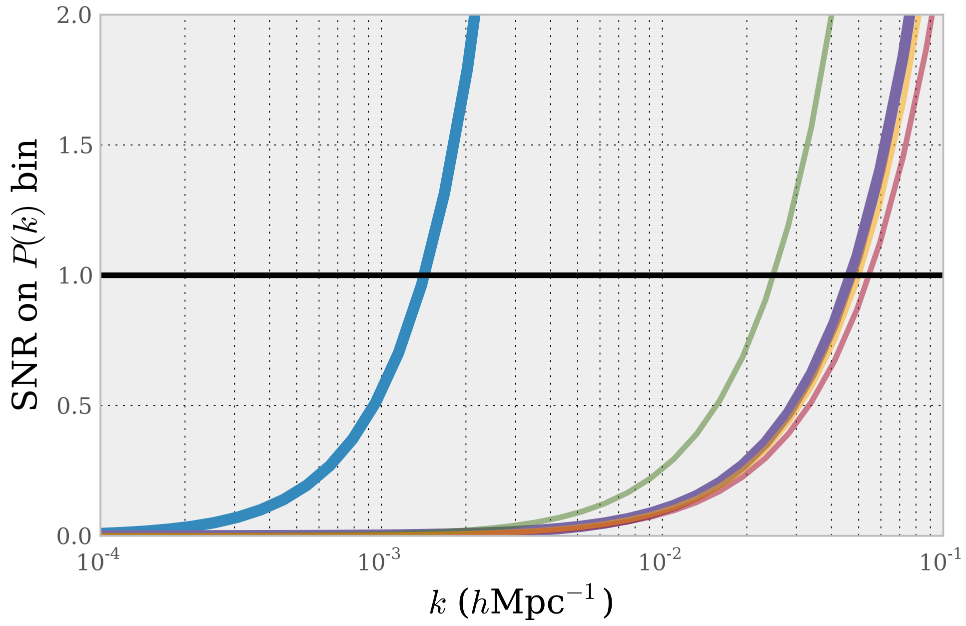




LSST: The next large weak lensing experiment

Survey comparisons



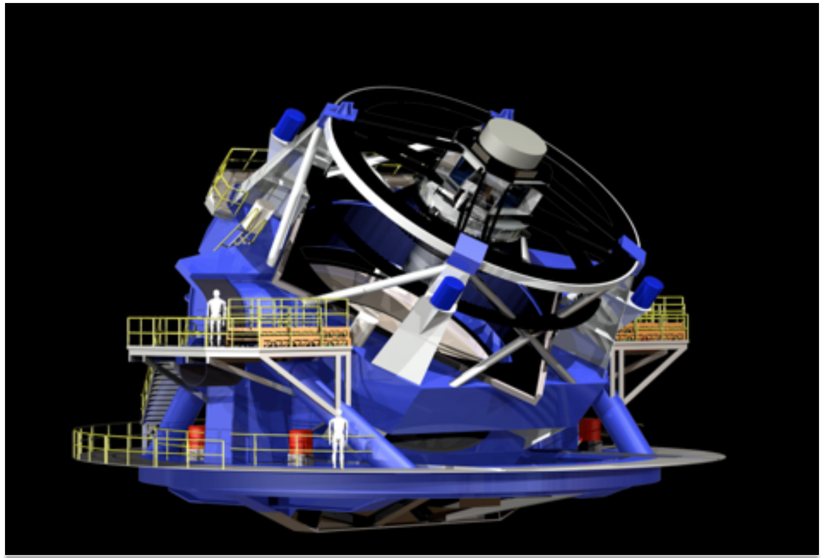


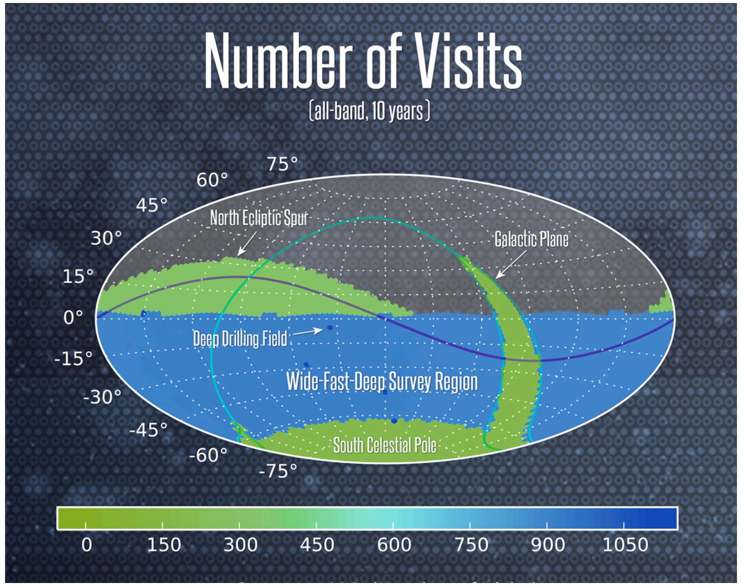
The Large Synoptic Survey Telescope (LSST) will be the premier cosmic shear survey for the next 20 years

Construction start: 2014 First light: 2021 Survey end: ~2031

8.4m telescope 18,000+ deg^2 10mas astrometry r<24.5 (<27.5@10yr)

6 broad optical bands (*ugrizy*) 0.5-1% photometry



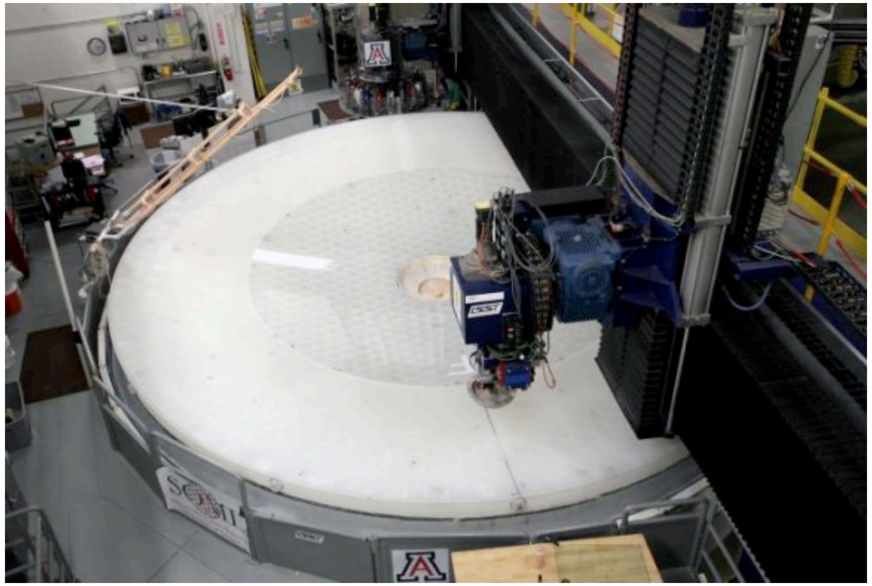


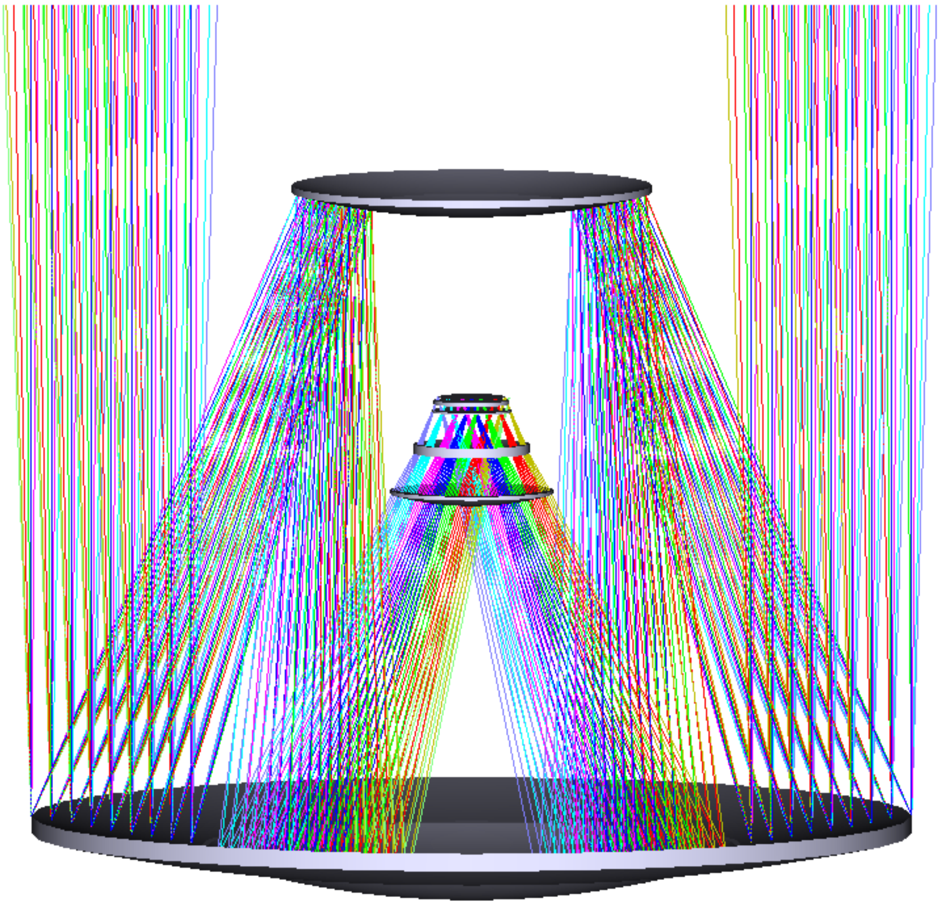
3.2Gpix camera 2x15sec exp/2sec read 15TB/night 20 B objects

Imaging the visible sky, once every 3 days, for 10 years (825 revisits)

LSST is a novel 3-mirror design to enable superb image quality over a 3.5 degree field of view

- The primary and tertiary mirrors were polished into single substrate. These mirrors were completed at the Univ. of Arizona Mirror Lab in January, 2015

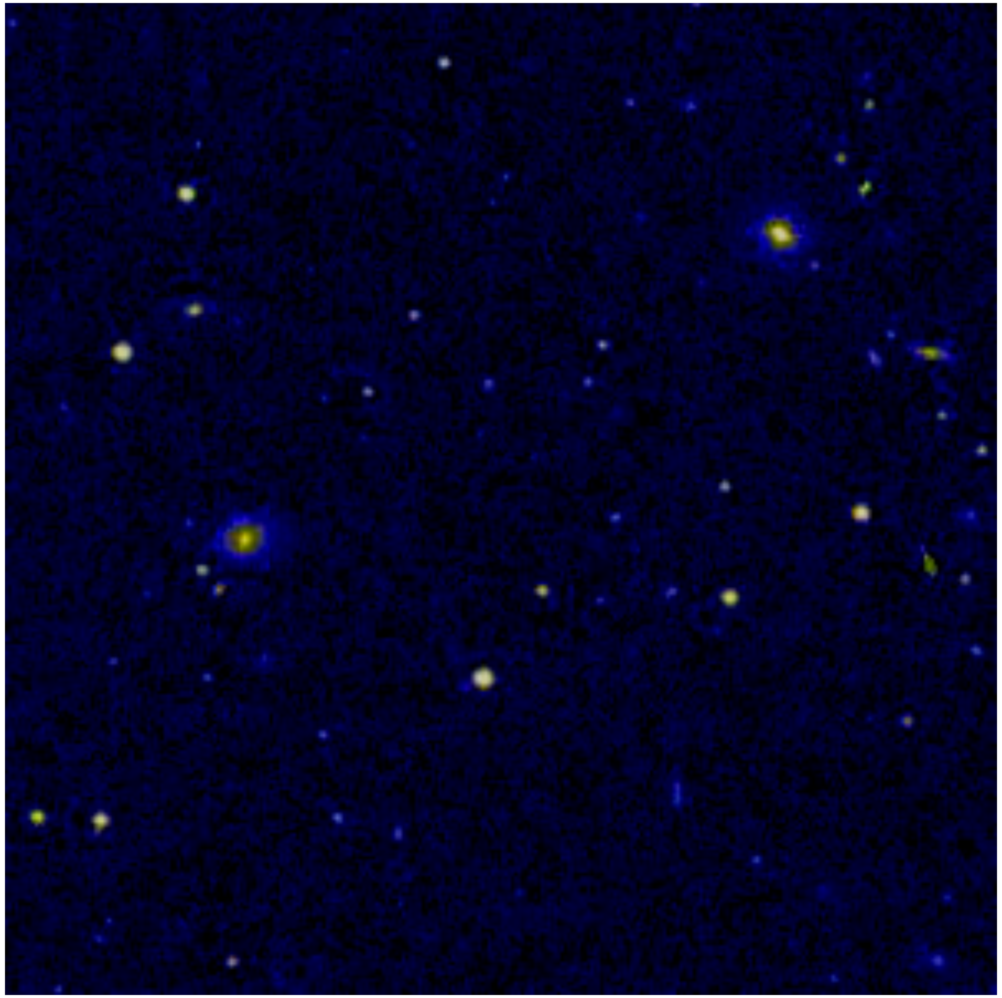




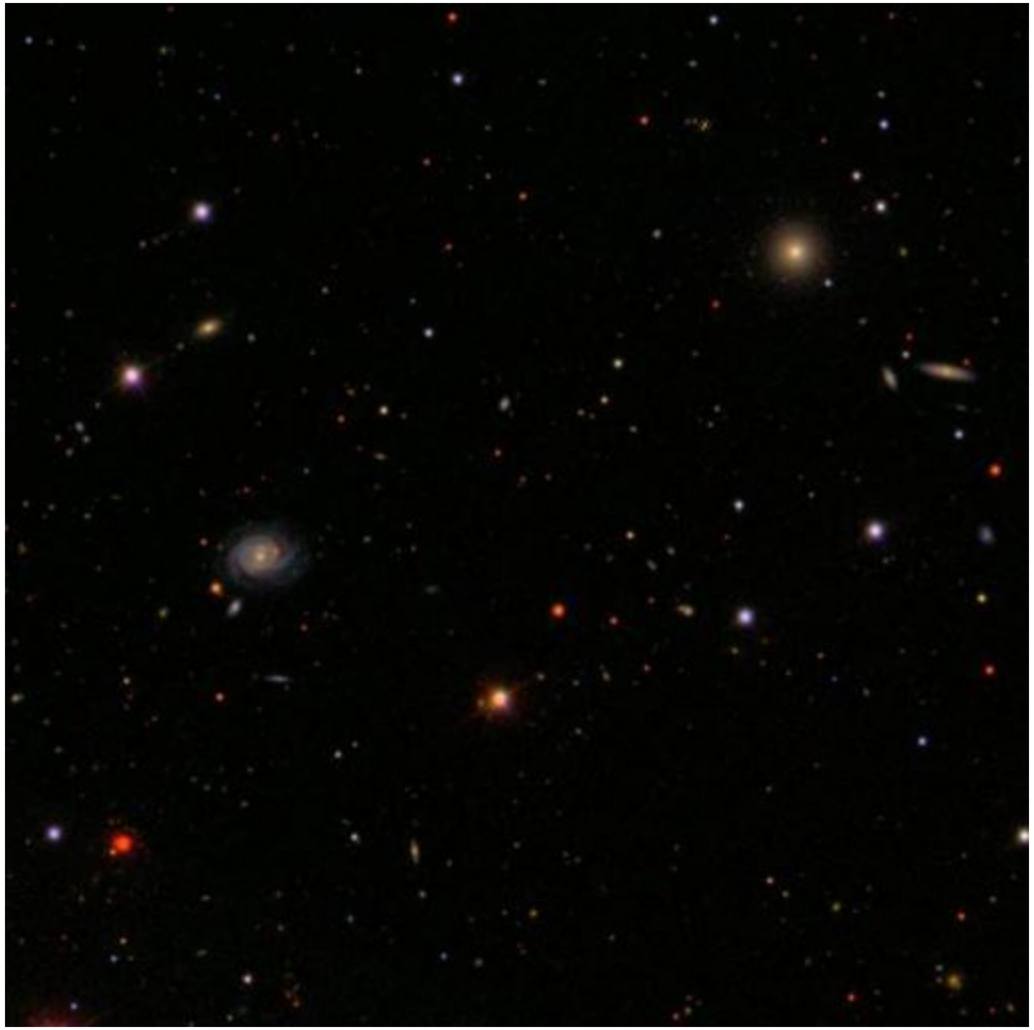
Seppala (2002, 2005, 2010)

DSS: digitized photographic plates

7.5 arcminutes



Sloan Digital Sky Survey

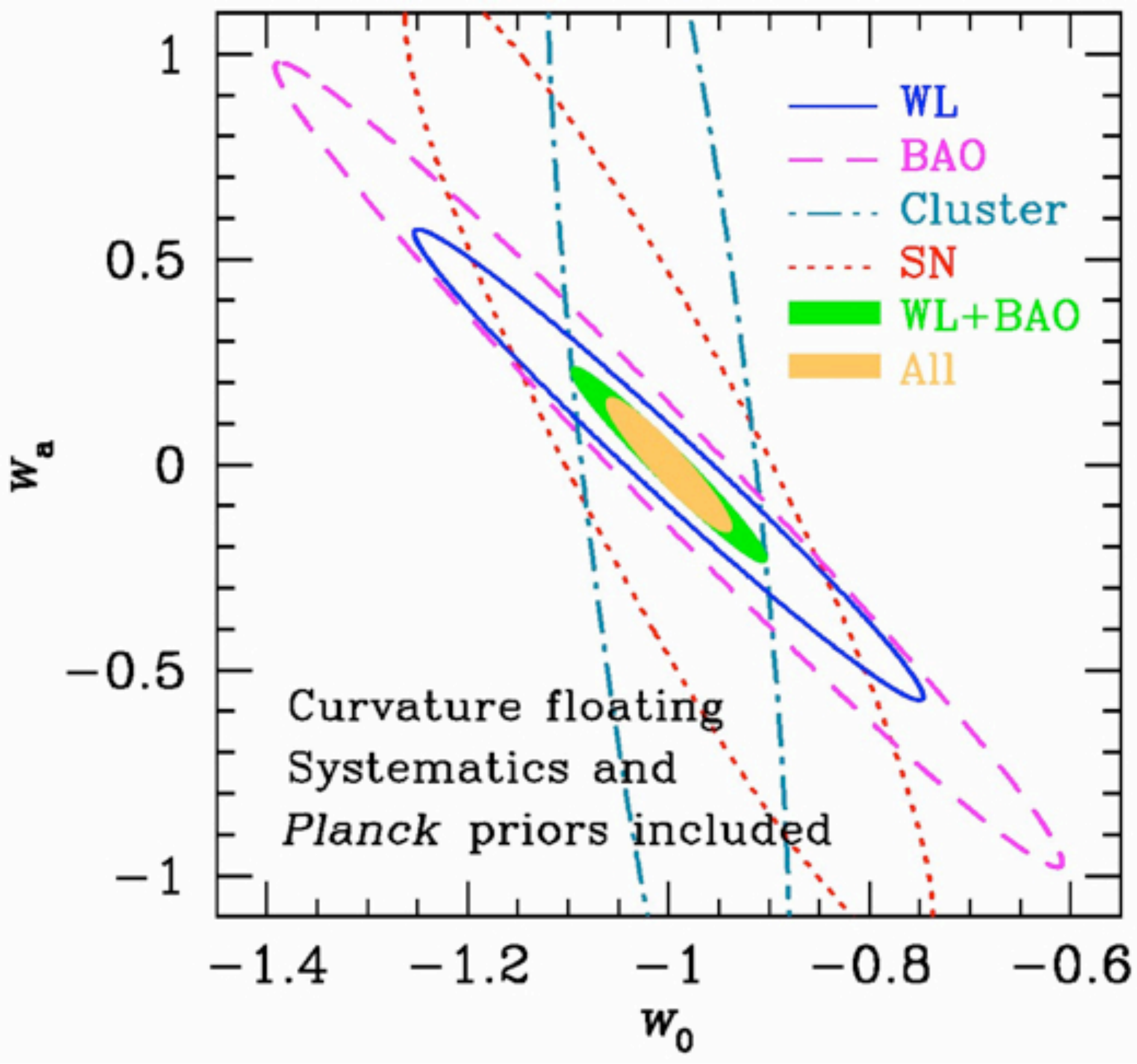


LSST -- almost

2800
galaxies
i<25 mag

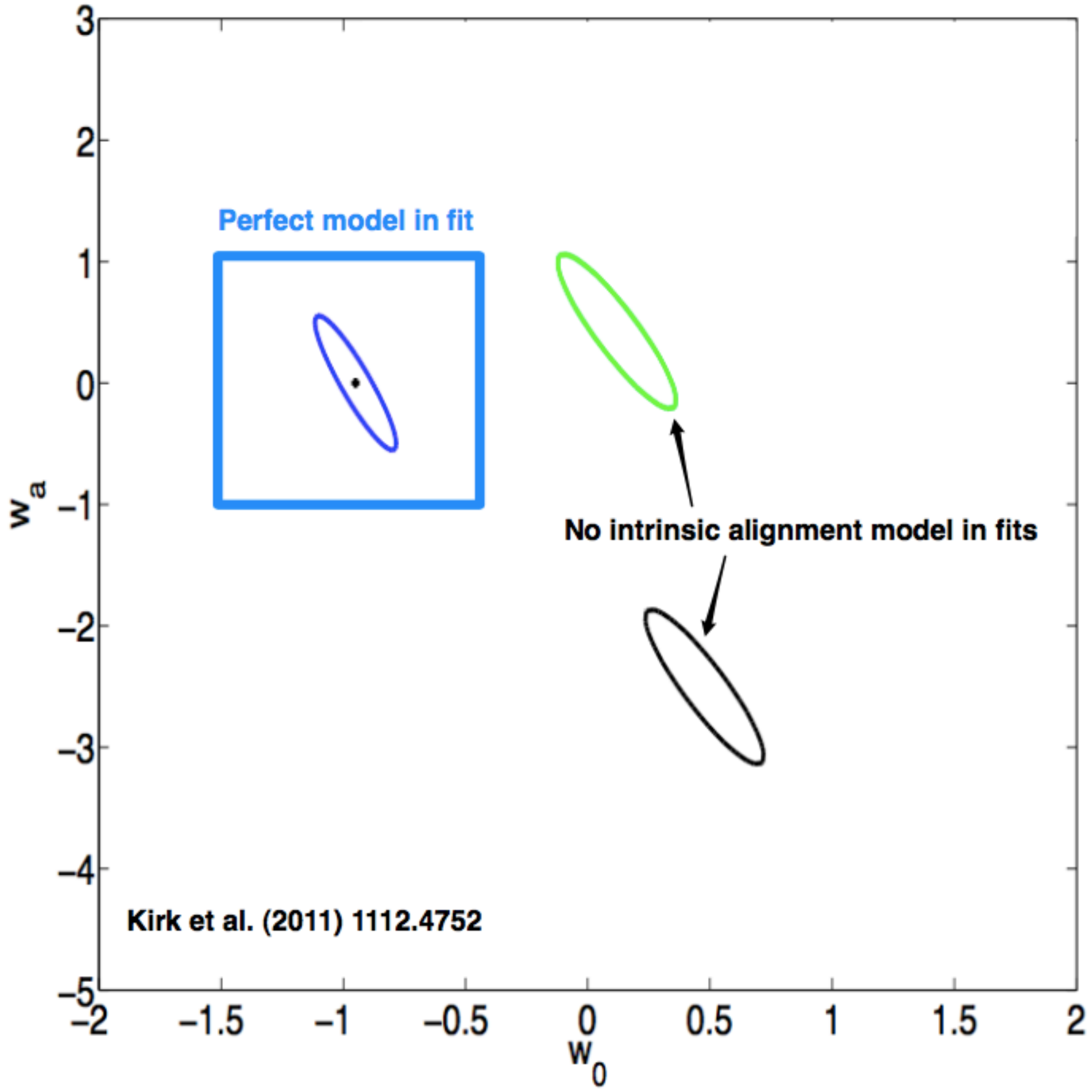
Astrophysical systematics

The promise of cosmic shear…

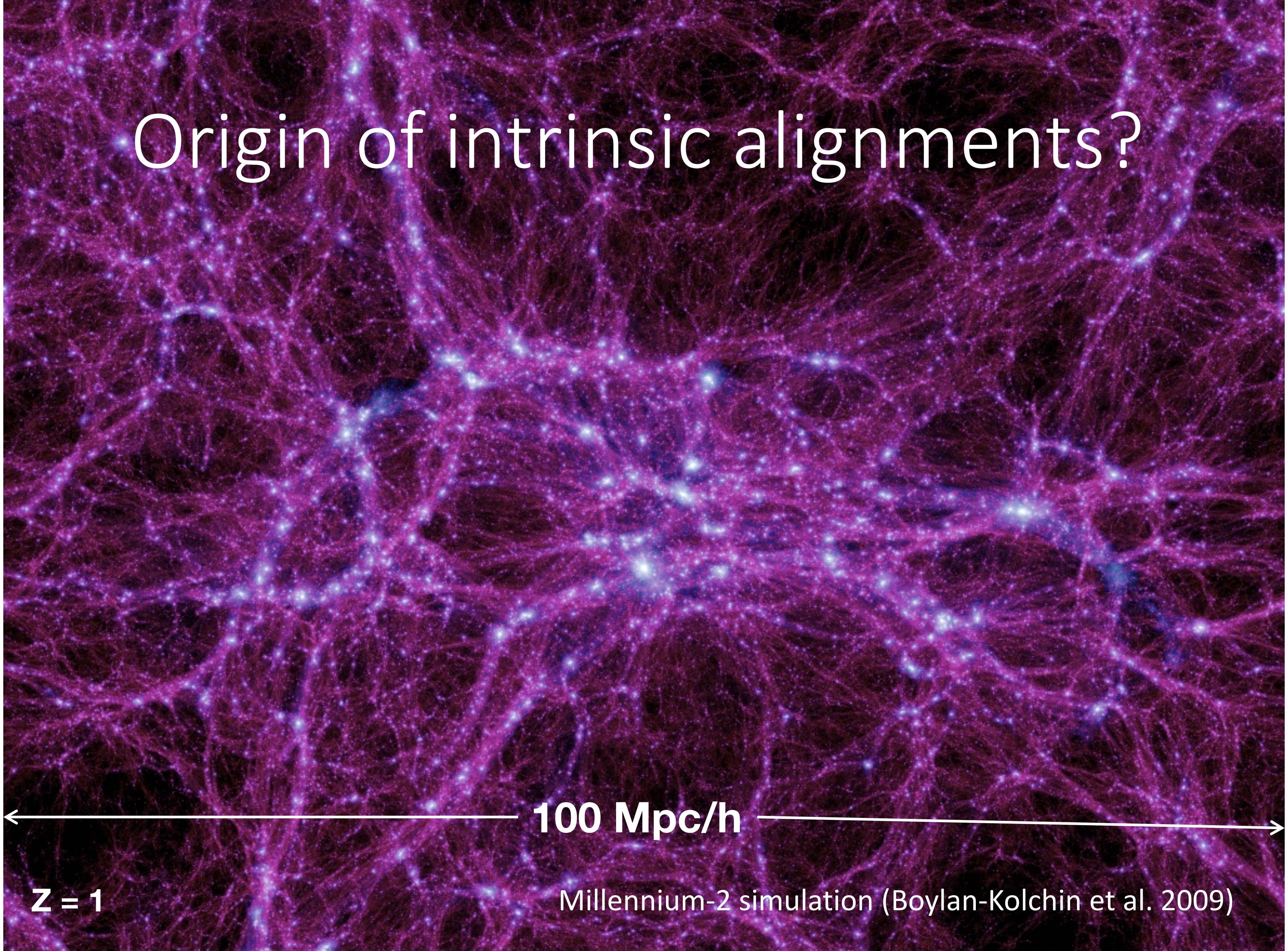


Hu Zhan

…is marred by (g)astrophysics!



Origin of intrinsic alignments?



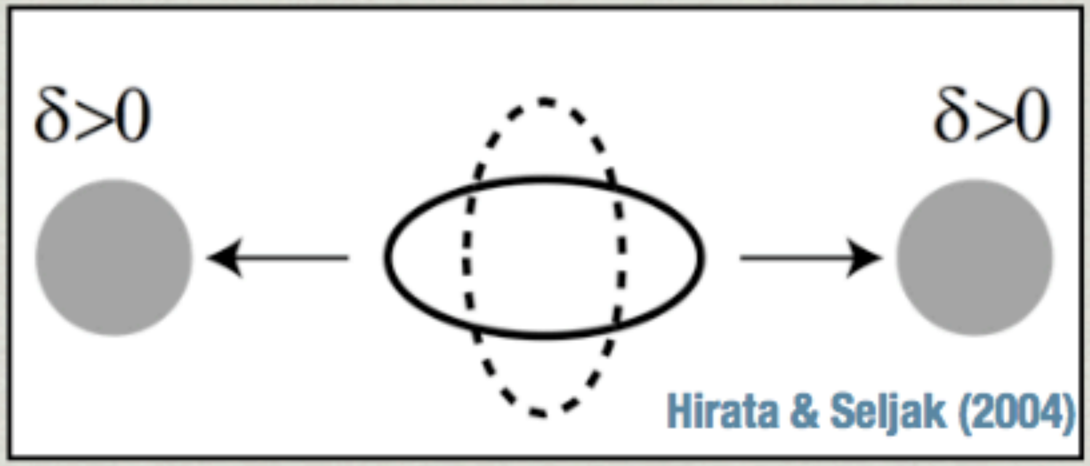
Intrinsic alignment contaminations to cosmic shear

$$\gamma^{\rm obs} = \gamma^G + \gamma^I$$

$$\langle \gamma^{\rm obs} \gamma^{\rm obs *} \rangle = \underbrace{\langle \gamma^G \gamma^{G*} \rangle}_{\xi^{GG}} + \underbrace{\langle \gamma^I \gamma^{I*} \rangle}_{\xi^{II}} + \underbrace{\langle \gamma^I \gamma^{G*} \rangle + \langle \gamma^G \gamma^{I*} \rangle}_{\xi^{GI}}$$

GI induces anticorrelation between lens and source galaxy ellipticities.

GI cartoon



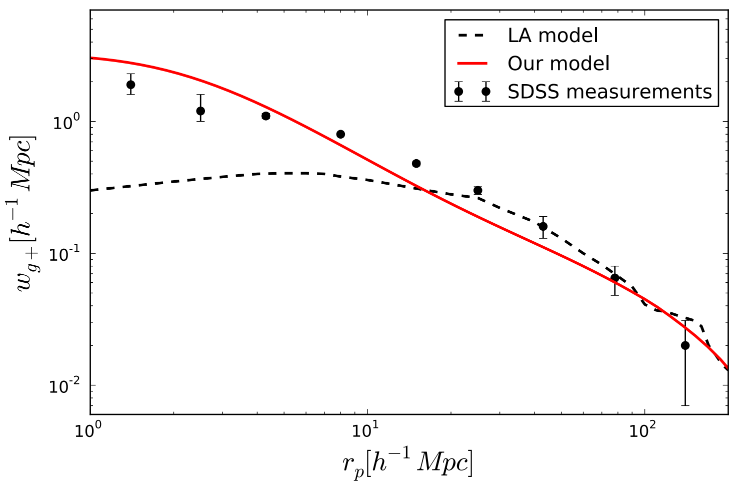
Origin of intrinsic alignments?

	"Blue galaxies"	"Red galaxies"
Shape	Rotationally supported	Prolate ellipsoid
Cause	Alignment of spin axes from initial tidal field	Anisotropic accretion along filaments
Effect	Localized correlations (predicted by linear tidal torque theory)	Long-range correlations (halos elongated with large-scale filamentary structure)

Heavens & Peacock (1988), Catelan et al. (2001), Crittenden et al. (2001, 2002), Auber et al. (2004), Schaefer (2009), Slosar & White (2009)

There are two approaches to intrinsic alignment mitigation

1. “Nulling”
   - Down-weight pairs close in redshift (King & Schneider 2002, Heymans & Heavans 2003, Takada & White 2004, Heymans et al. 2004)
   - Take linear combinations of tomographic power spectra (Joachimi & Schneider 2008, 2009, 2010)
2. Modeling
   - Fit parameterized models and marginalize over fit parameters (King Schneider 2003, Bernstein DETF, King & Bridle 2007, MDS & Bridle 2010)
   - Self calibration using density-shape cross-correlation (Zhang 2008)



State of weak lensing today

Weak lensing constraints on sigma8 over time

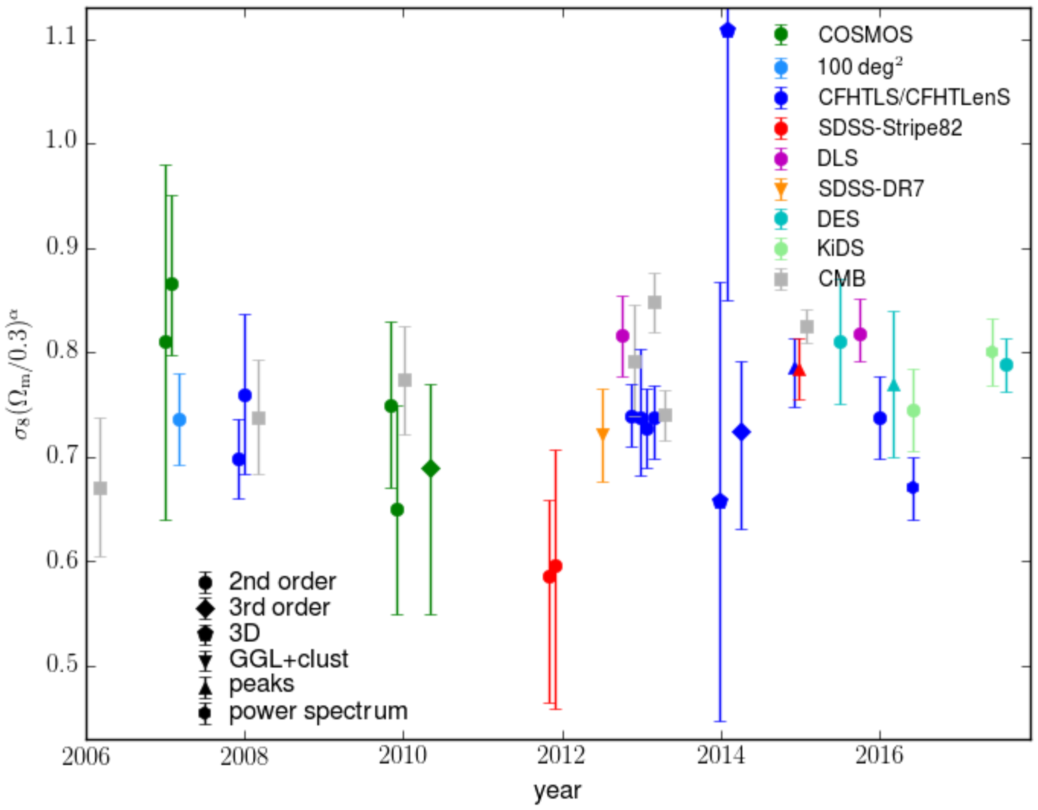


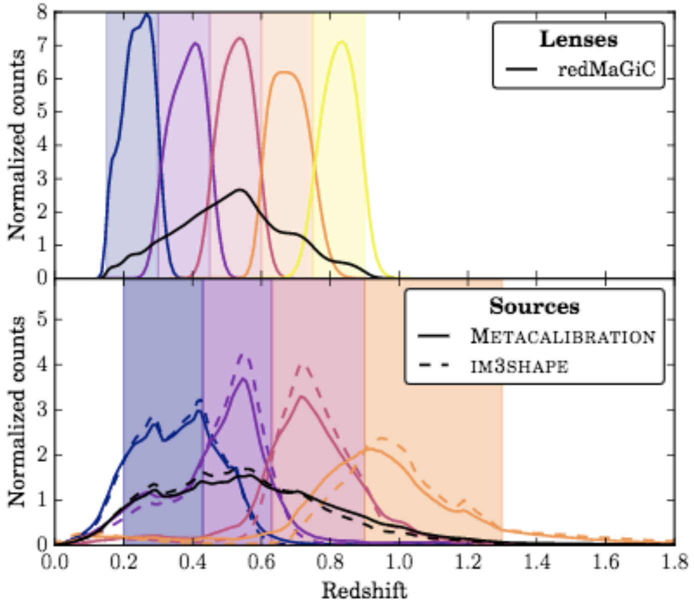
Figure credit: Martin Kilbinger

http://www.cosmostat.org/wp-content/uploads/2015/04/Sigma_0708.png

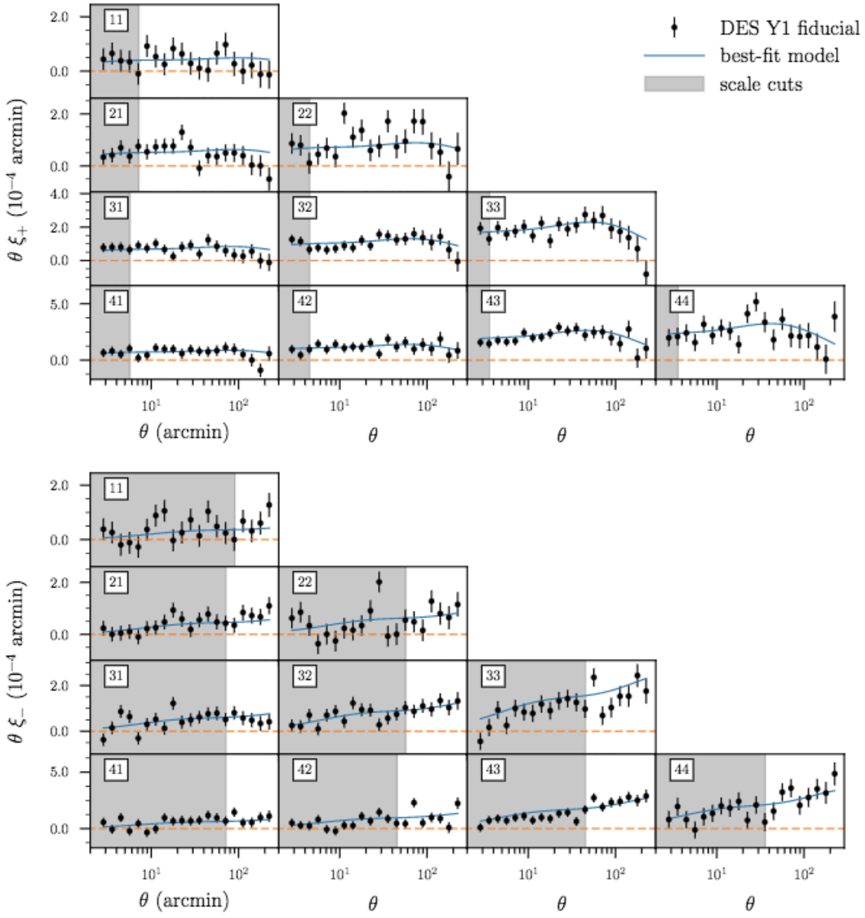
Dark Energy Survey

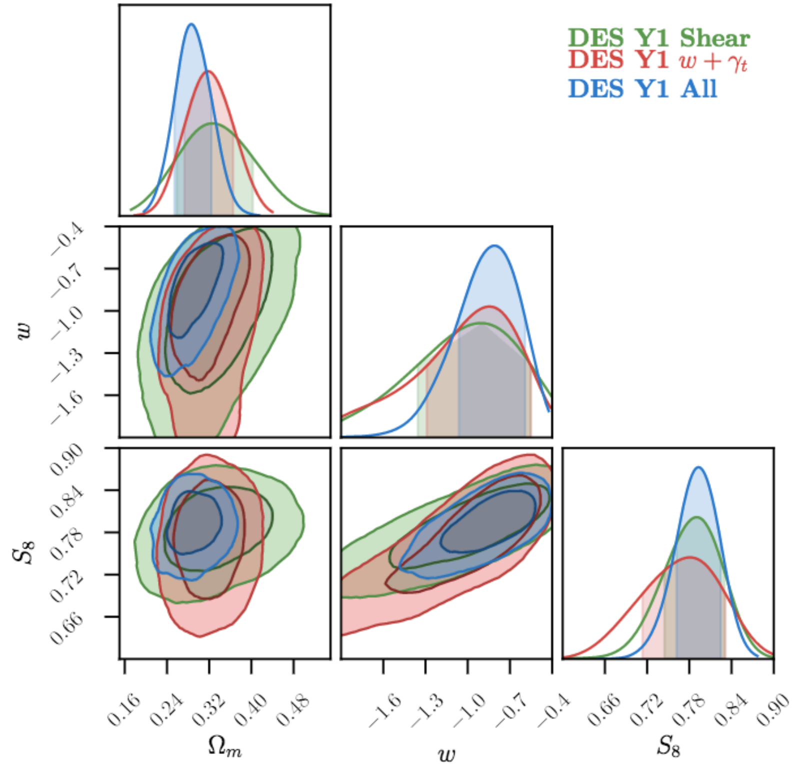
A new dedicated camera on a 4-meter telescope for a 5000 square degree lensing survey

Redshift bins



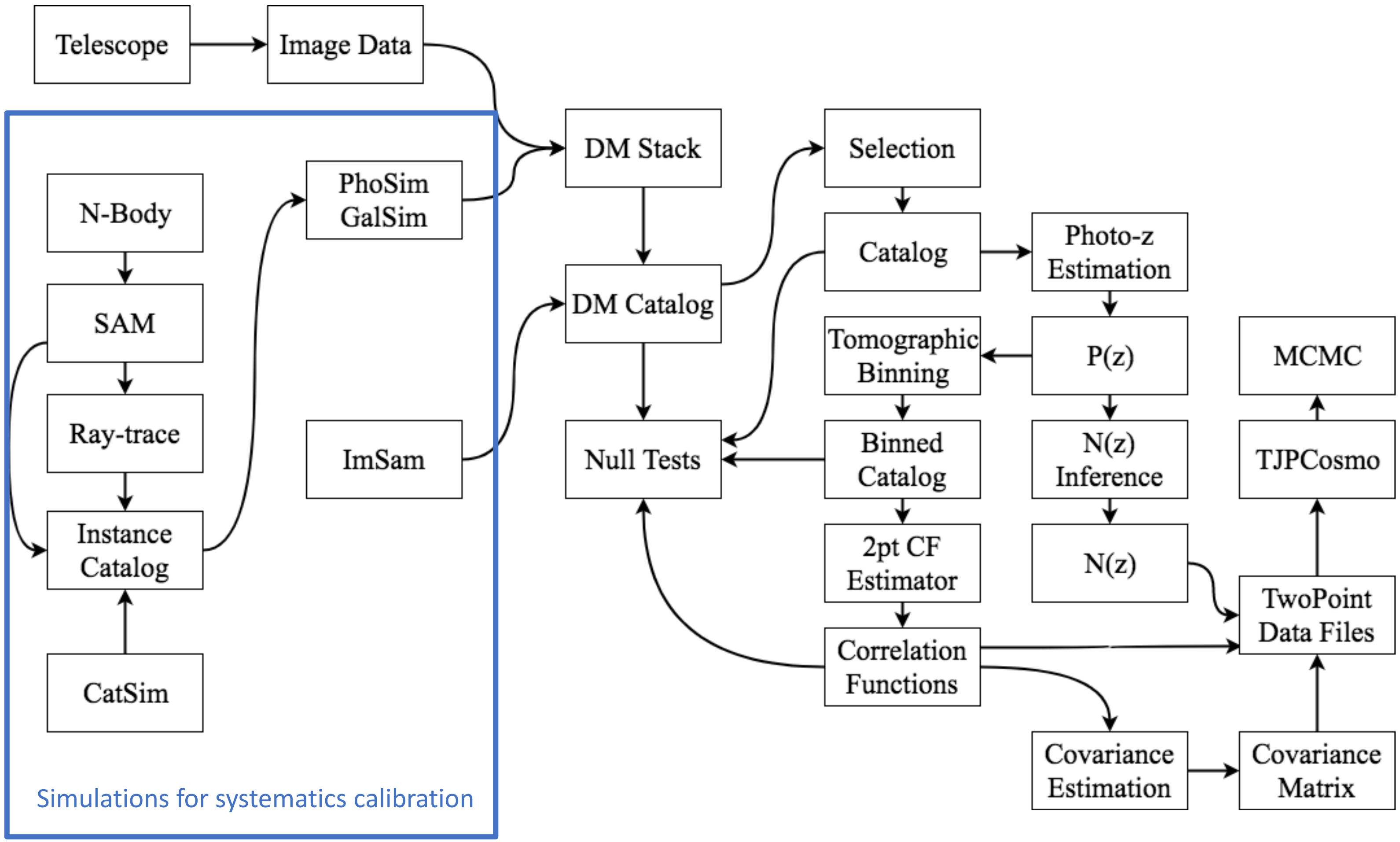
Tomographic shear correlations





[DES Year 1 cosmology](https://arxiv.org/pdf/1708.01530.pdf)
https://arxiv.org/pdf/1708.01530.pdf

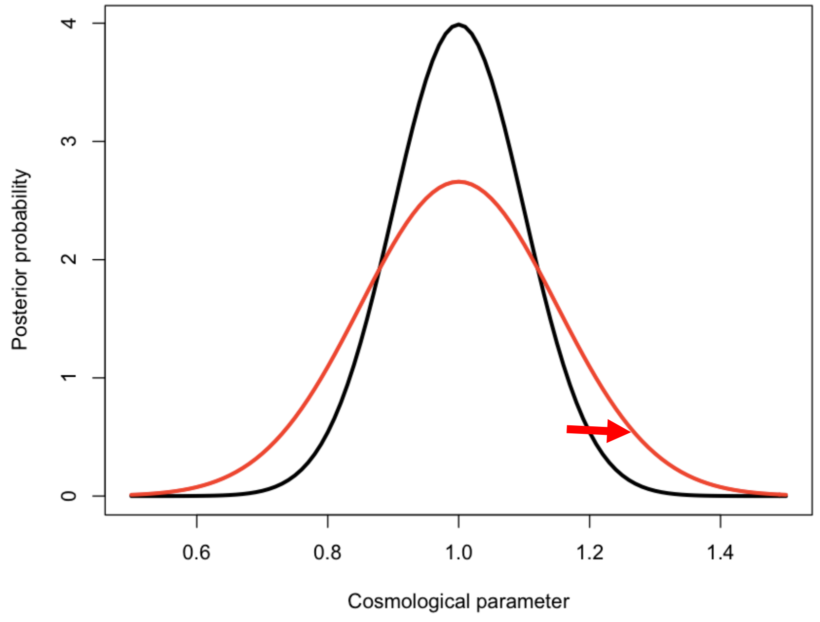
LSST Dark Energy Science Collaboration weak lensing pipeline

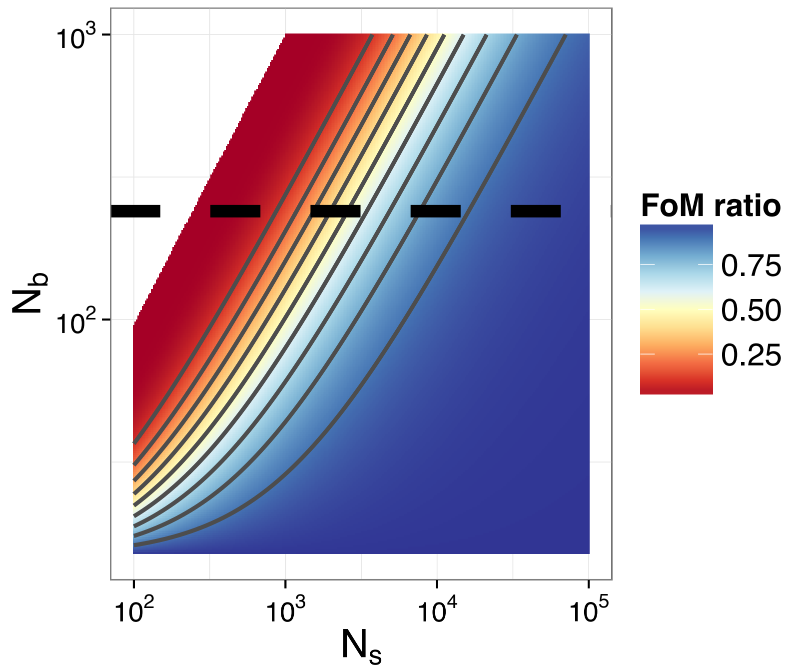


Current challenges: Covariances

Sample covariance error increases cosmological parameter errors

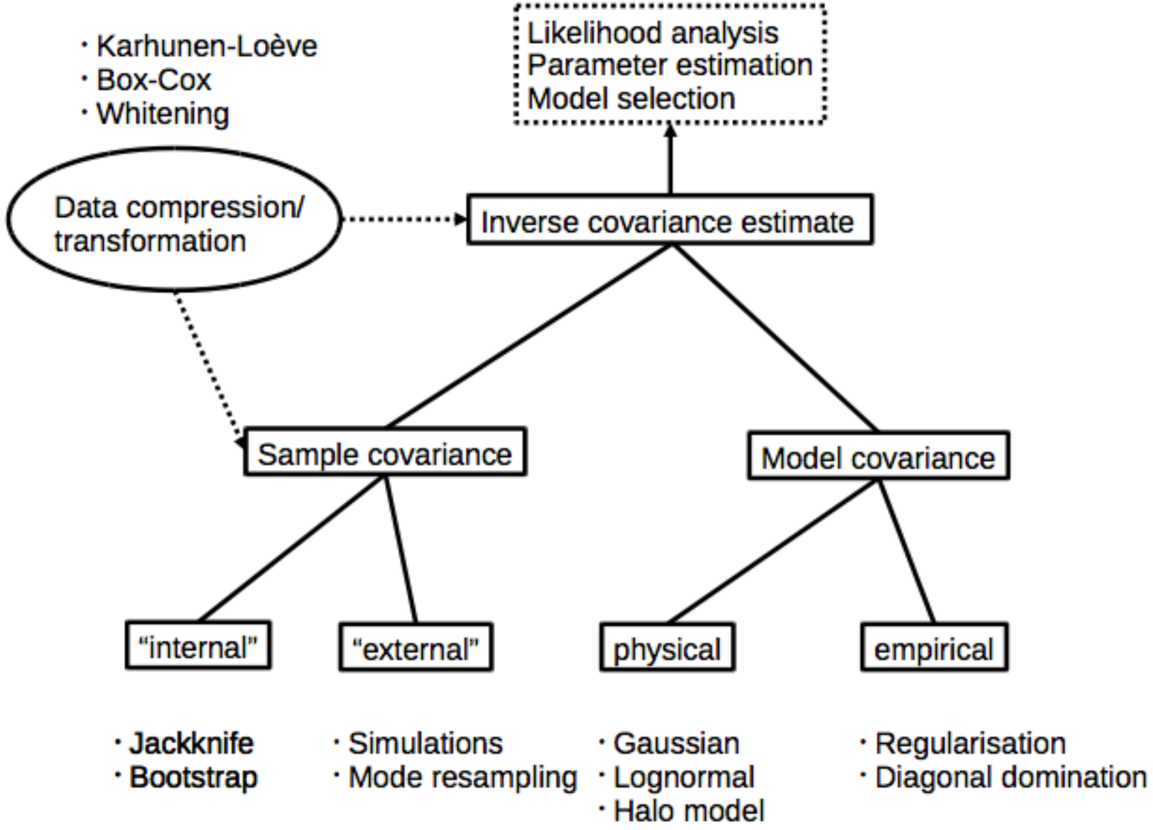
(Fixed cosmology)





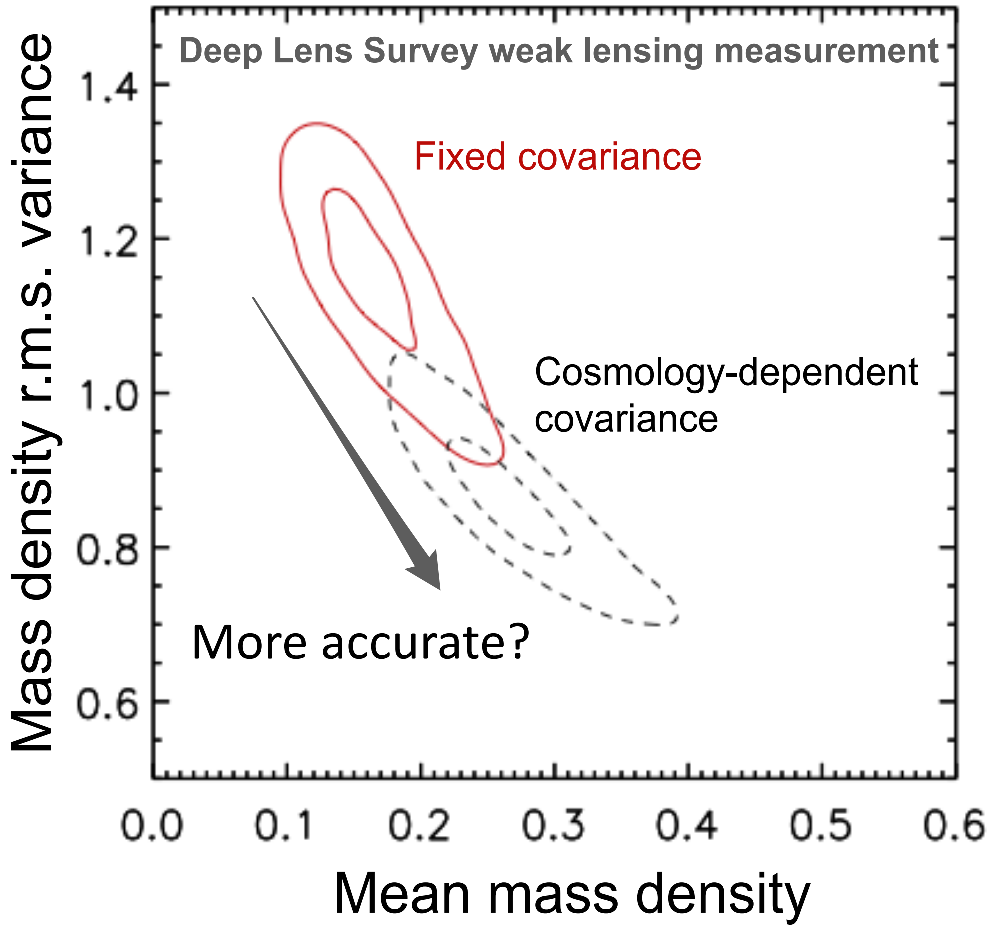
Dodelson & Schneider (2013)

Various approaches to covariance estimation



Taylor, Joachimi, Kitching (2013)

DLS cosmic shear:
Is the cosmology dependence of the covariance important?



Jee et al. (2013)

Super-sample covariance

Takada & Hu (2013)

The trispectrum term that governs the additional effects are so-called squeezed quadrilaterals where two pairs of sides are nearly equal and opposite. In Eq. (12), we can make the change of variables $\mathbf{k} + \mathbf{q}_1 \leftrightarrow \mathbf{k}$ and $\mathbf{q}_1 + \mathbf{q}_2 \leftrightarrow \mathbf{q}_{12}$ under the delta function condition $\mathbf{q}_{1234} = \mathbf{0}$ and the approximation that $q_{12} \ll k, k'$. The term of interest therefore is

$$\lim_{q_{12}\to 0} T(\mathbf{k}, -\mathbf{k} + \mathbf{q}_{12}, \mathbf{k}', -\mathbf{k}' - \mathbf{q}_{12}). \tag{17}$$

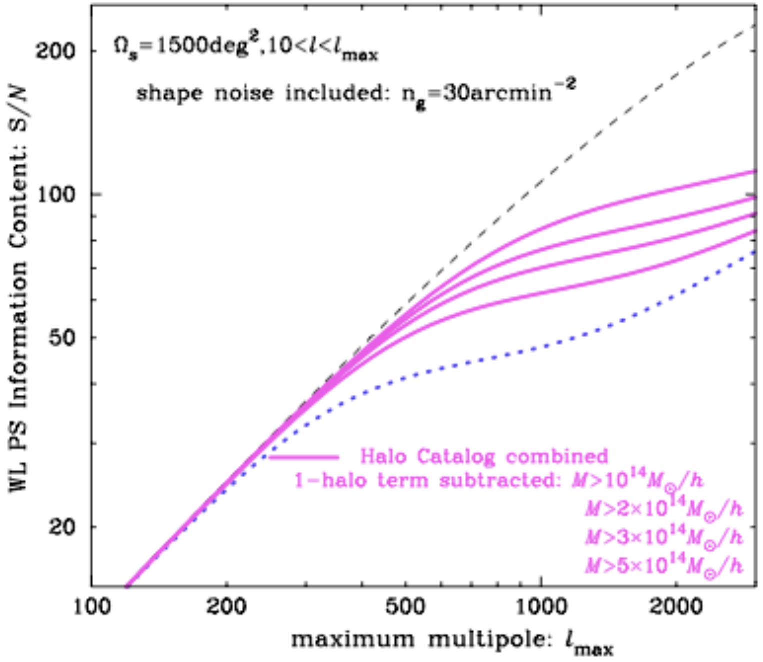
In this limit, the 4 point configuration describes the connection between $P(k)$ and $P(k')$ through a shared infinite wavelength mode $\mathbf{q}_{12}$. This mode acts like a background density or constant mode to the short wavelengths $\mathbf{k}$ and $\mathbf{k}'$. It follows therefore that the squeezed trispectrum can be characterized by the response of $P(k)$ to a fluctuation in the background density δ_b through

$$\bar{T}(\mathbf{k}, -\mathbf{k} + \mathbf{q}_{12}, \mathbf{k}', -\mathbf{k}' - \mathbf{q}_{12}) \approx T(\mathbf{k}, -\mathbf{k}, \mathbf{k}', -\mathbf{k}') + \frac{\partial P(k)}{\partial \delta_b}\frac{\partial P(k')}{\partial \delta_b} P^{\mathrm{L}}(q_{12}). \tag{18}$$

Takada & Spergel (2014)
Schann, Takada, & Spergel (2014)

Combine power spectrum and cluster number counts to correct for the sample-variance in the power spectrum due to super-survey density perturbations.

-> 30% improvements on cosmological parameter estimates.



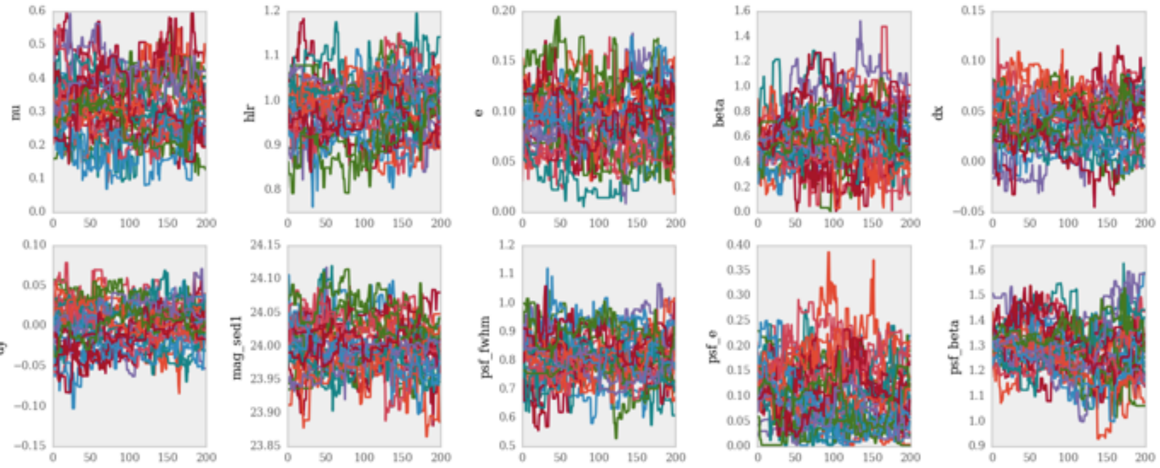
Future approaches

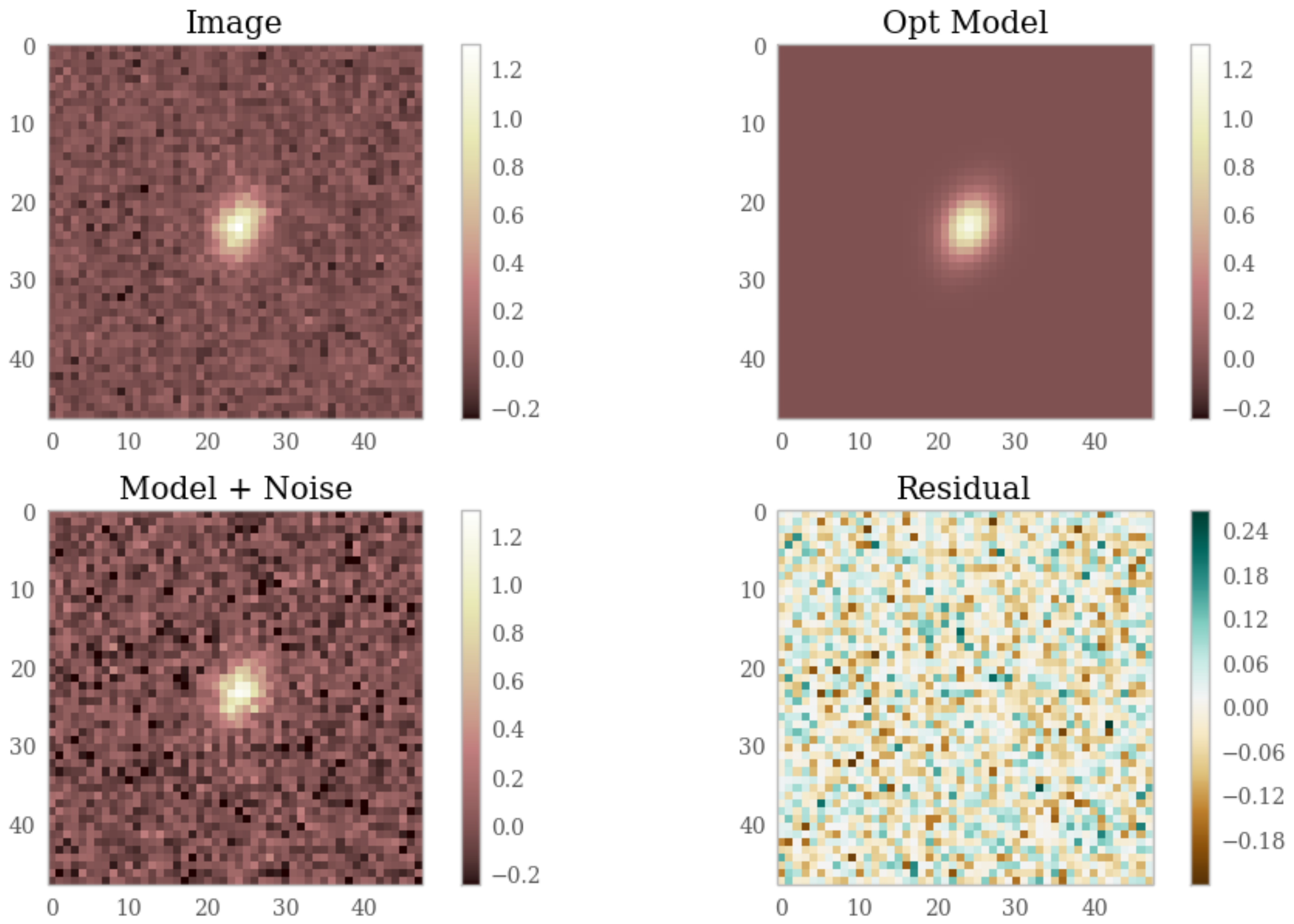
Shear inference via probabilistic image forward modeling

Infer image model parameters via MCMC under an interim prior distribution for the galaxy and PSF parameters.

Modeling codes:

- The Tractor (Lang & Hogg)
- GalSim





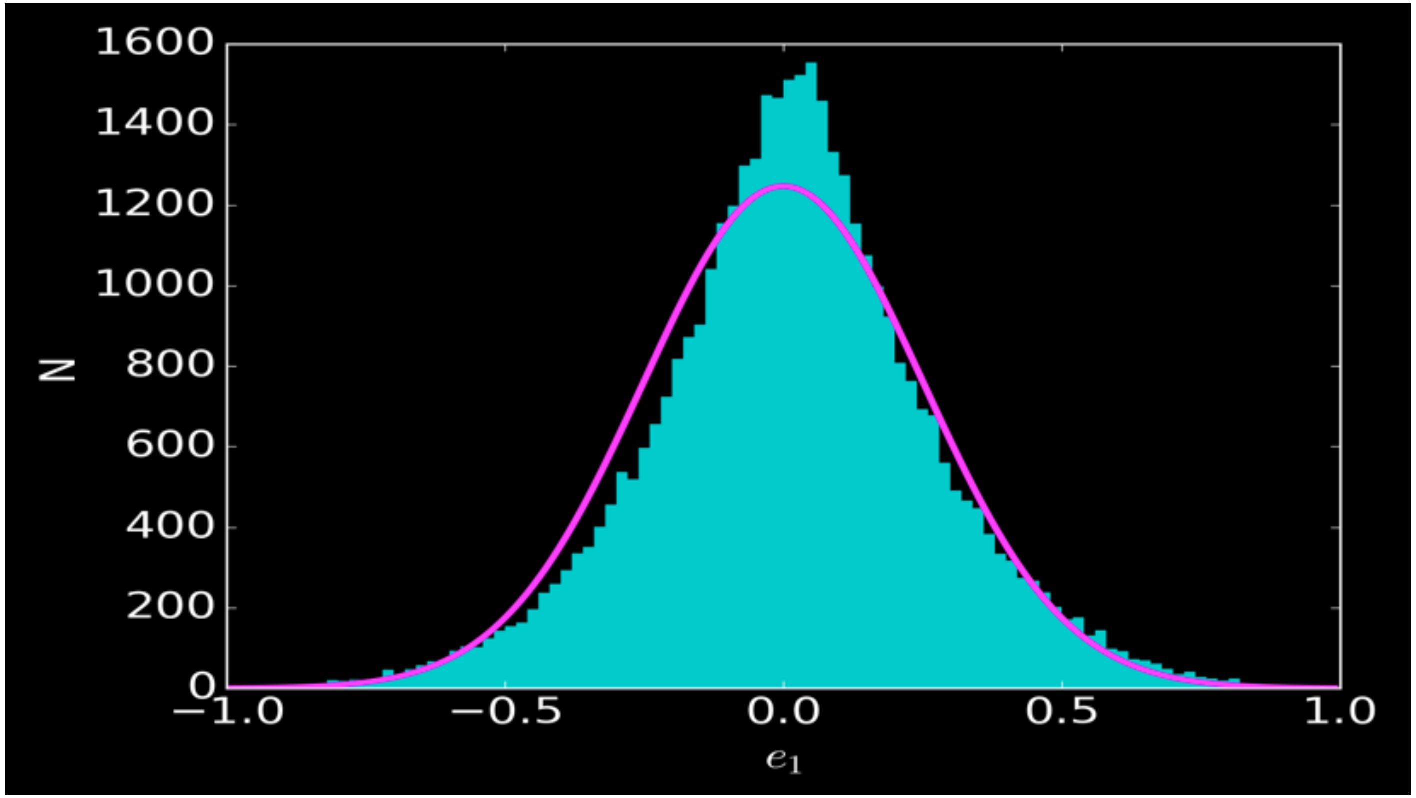
GalSim models inside an MCMC chain – **Can it be made fast enough?**

Pr(e^{int}) is not Gaussian!

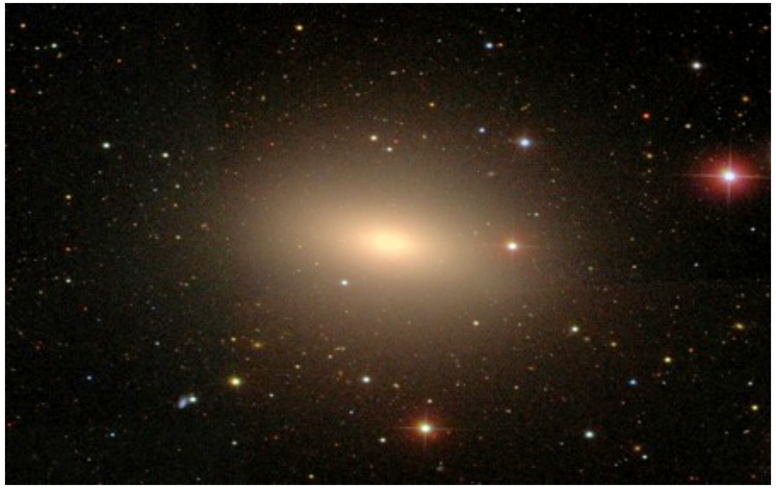
This affects the accuracy of shear calibration

- Would rather not assert a particular parametric form for P(e^{int}).
  - Learn from deep imaging data
  - Use a "non-parametric" distribution: a Dirichlet Process Mixture Model

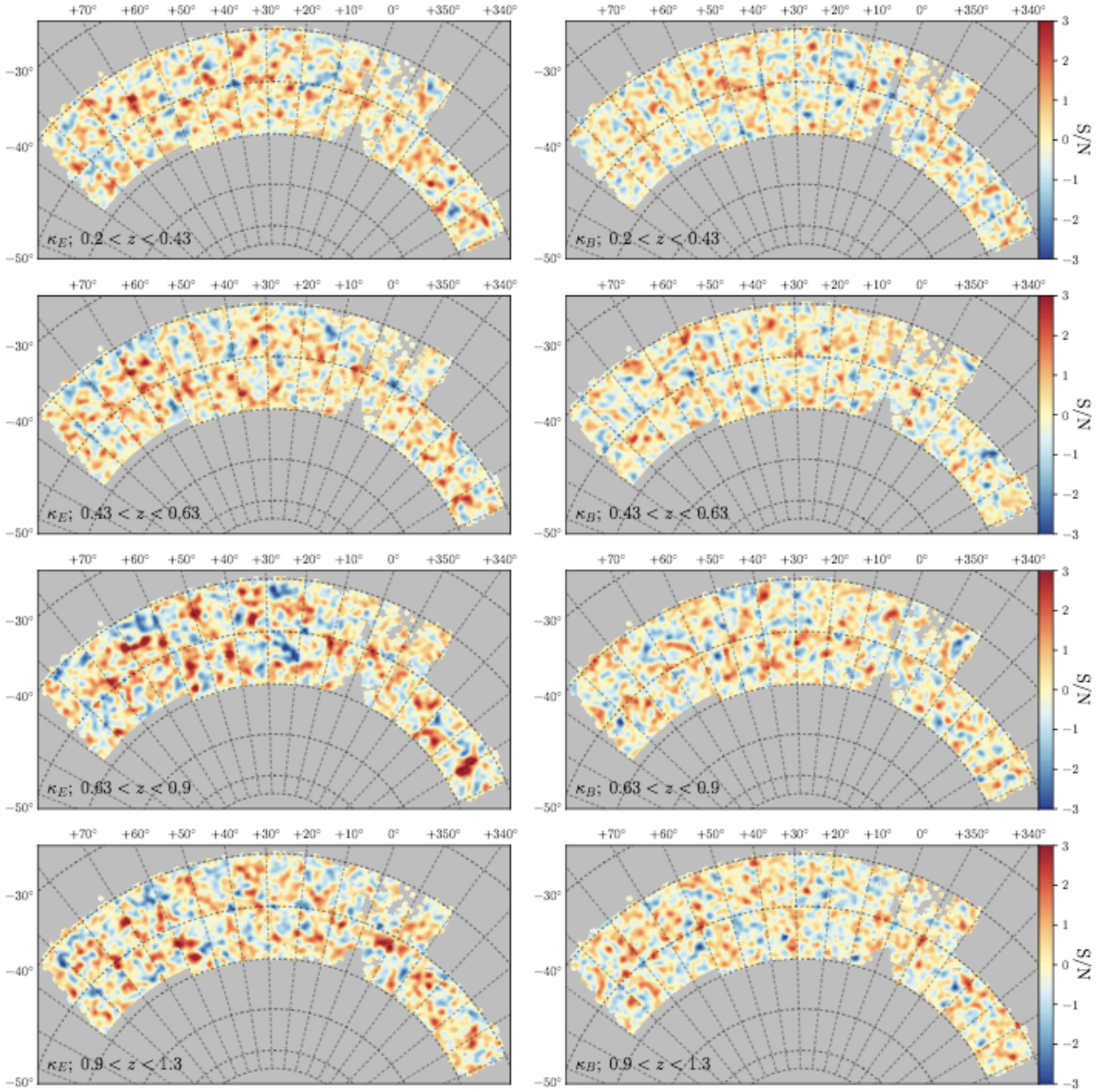
Ellipticities from COSMOS



Multi-variate galaxy image properties: "standardizable" ellipticities?



- Elliptical galaxies have a narrower intrinsic ellipticity distribution than late-type. Higher sensitivity to shear!
- Ellipticals/spirals also distinguishable by color and morphology (e.g., Sersic index, Gini coefficient, asymmetry), potentially providing additional variables with which to cluster.
- Other correlations to exploit?



3-D Mass Tomography

Chang et al. 2017
https://arxiv.org/pdf/1708.01535.pdf

arXiv:1610.06673

Probabilistic cosmological mass mapping

Objective: infer the 3D gravitational potential of the initial conditions

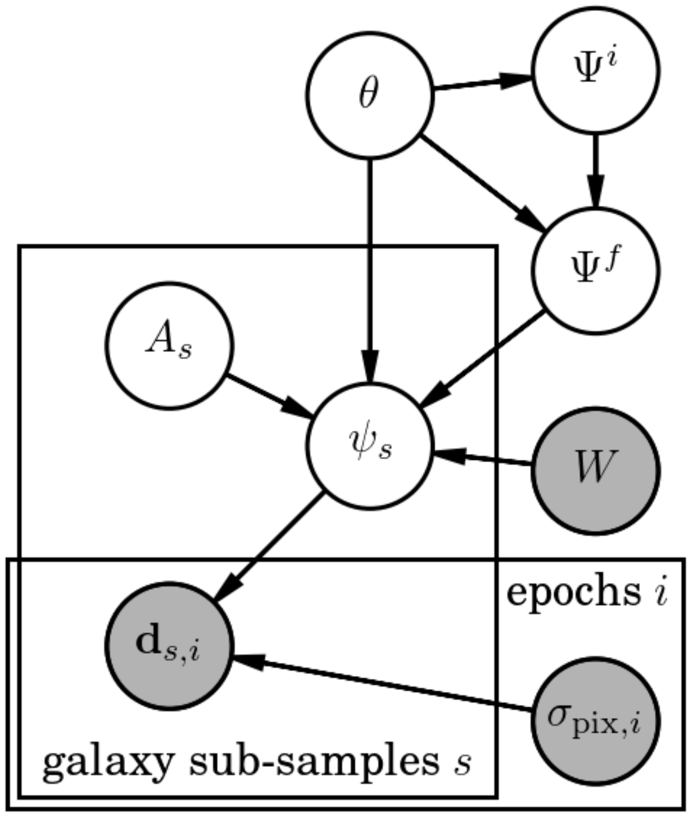
Interpolate the unobserved lensing potential with GP

$$\psi_s \sim GP(0, \Sigma),$$

$\kappa, \gamma_1, \gamma_2$ are the second (spatial) derivatives of ψ_s

$$\mathrm{Cov}(\psi_{,ij}(\vec{x}), \psi_{,k\ell}(\vec{y})) = \Sigma_{,x_i x_j y_k y_\ell}(\vec{x}, \vec{y}).$$

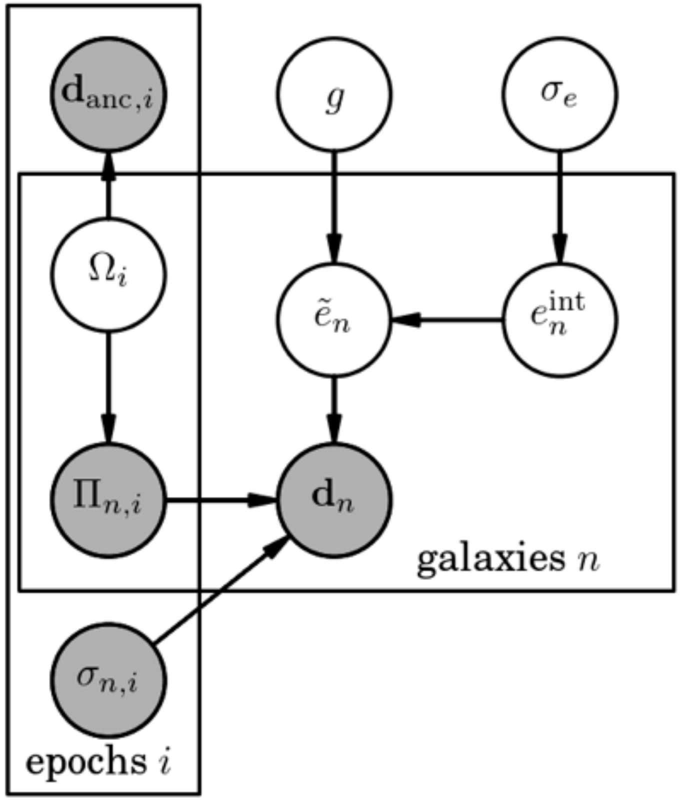
GP kernels of $\kappa, \gamma_1, \gamma_2$ are linear combinations of the 4th (spatial) derivatives of the kernel of ψ_s



Zero E/B mode mixing by construction

Marginalizing PSFs: An ambitious goal to optimally use all available star images for PSF inference while propagating measurement and modeling uncertainties

- LSST will have ~200 epochs per object per filter
    - We aim to marginalize the PSF $\prod_{n,i}$ in every epoch
    - The marginalization is constrained by:
        - Consistency of PSF realizations over the focal plane for each epoch
        - Consistency of the underlying source model across epochs
- Simplest approach (statistically, not computationally): Infer galaxy models given all epoch imaging simultaneously
    - "Interim" samples are of size: ~10 galaxy params + 200 * ~4 PSF params = ~1k parameters!



The pipeline for PSF marginalization

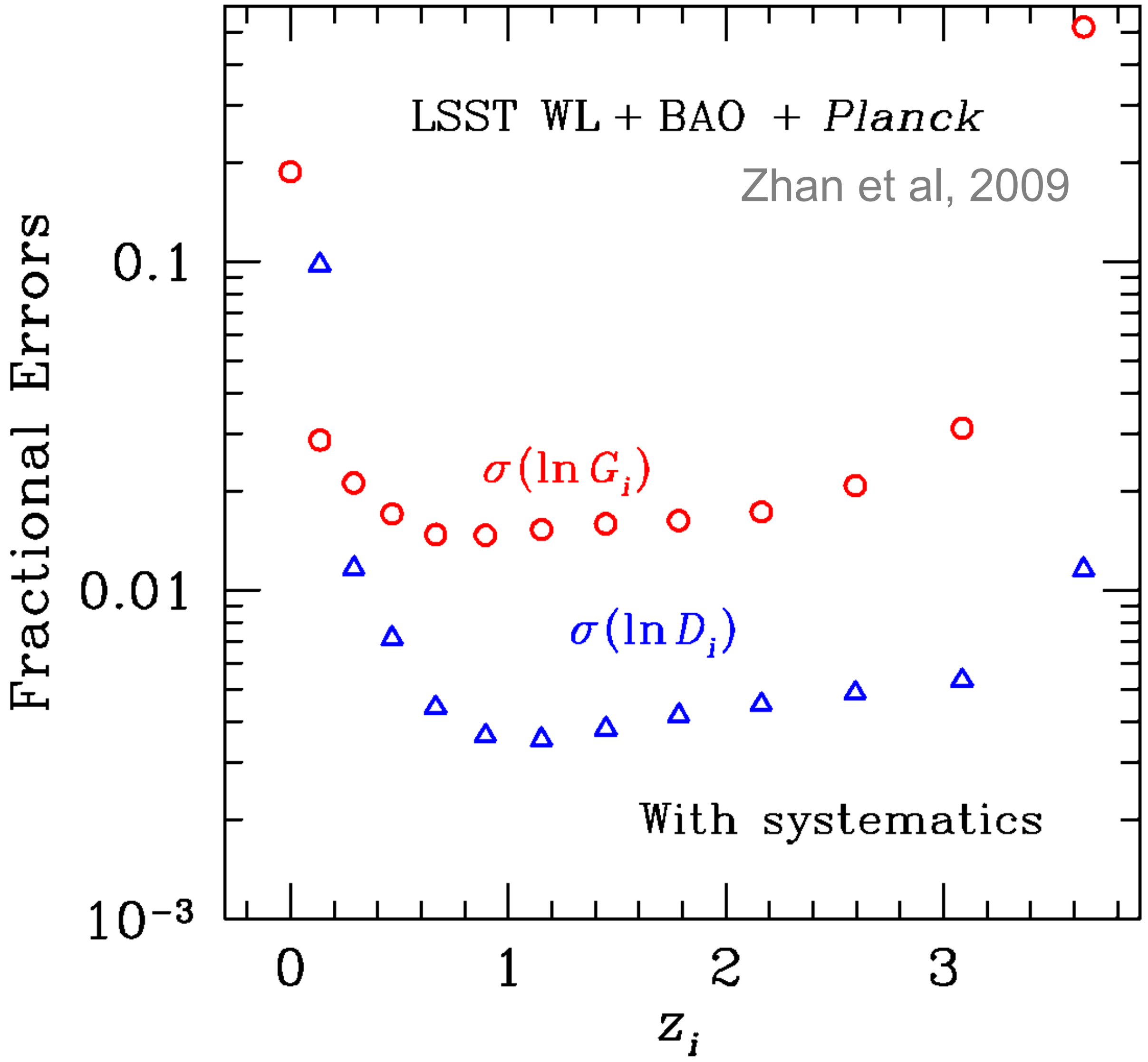
1. Fit star footprints in all epochs via probabilistic forward models
2. Marginalize star image parameters to constrain the global field PSF model for each epoch
   - State of the optics aberrations, and
   - Distribution of atmosphere turbulence statistics
3. Fit all galaxy footprints in each epoch via forward models
   - Use PSF models drawn from the marginal posterior given the star images
4. Run Thresher on the interim galaxy samples for all epochs (via ‘cross-pollinator’)

One approximation needed:

Marginalize PSF model independently for each field location

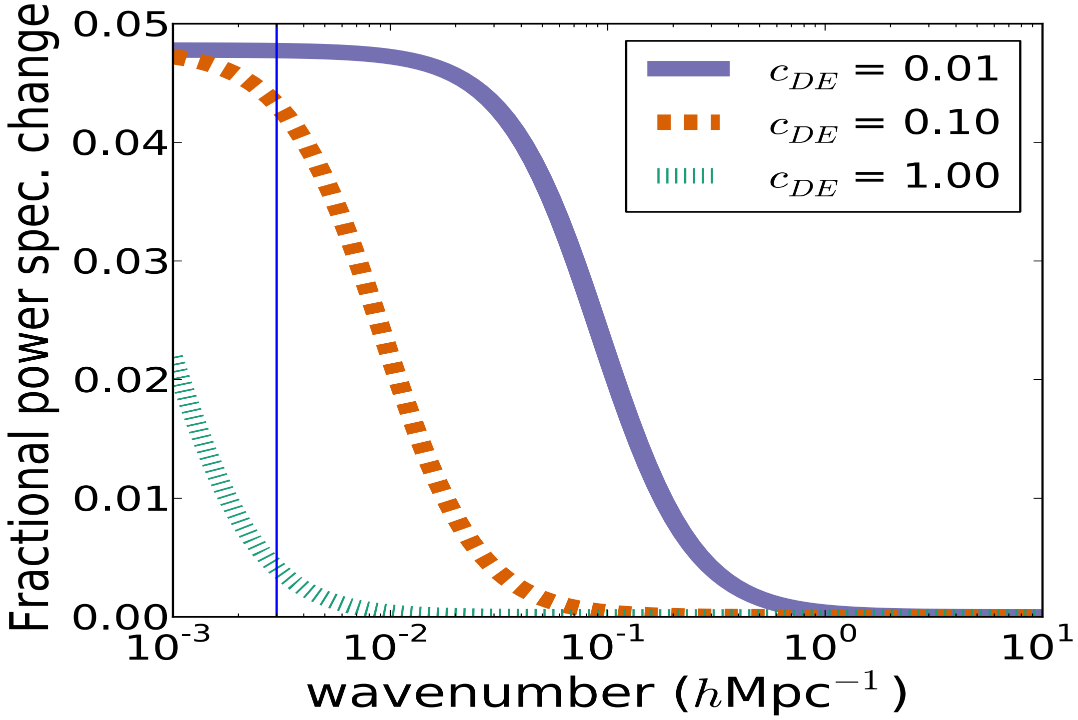
Dark energy in 2027

Testing general models of dark energy

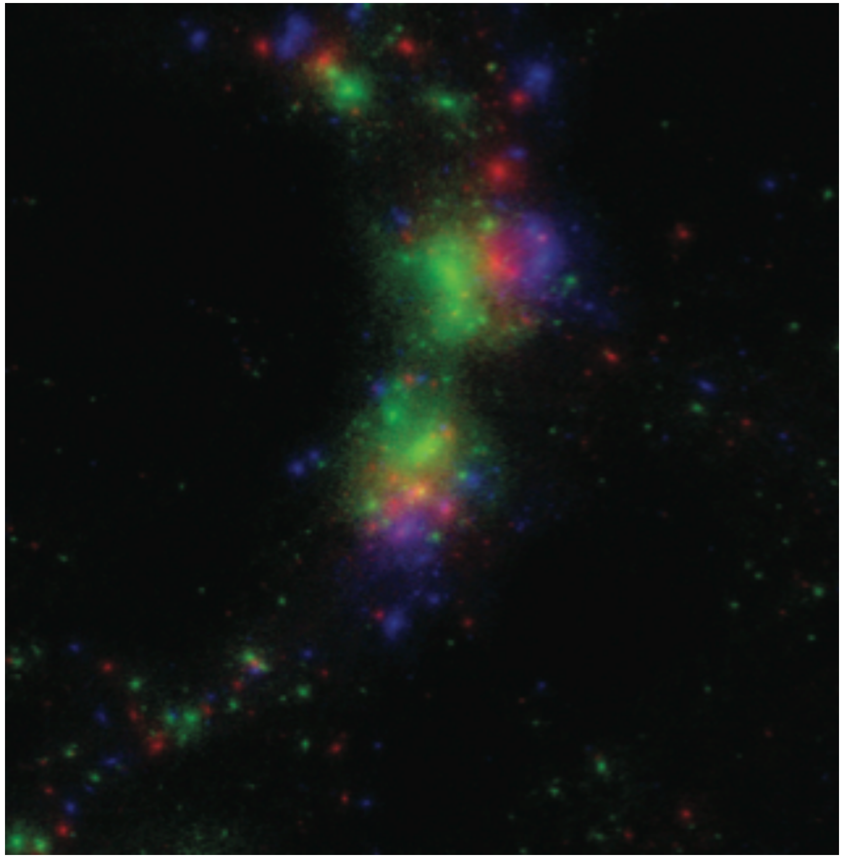


Dynamical dark energy leaves observable imprints on the cosmological mass distribution

Clustering dark energy parametrized by a sound speed, c_DE



N-body simulations of a galaxy cluster region with different 'quintessence' models



Some things I didn’t cover

- Weak lensing by galaxy clusters
  - Mass, concentration, profiles, substructure
- ”galaxy-galaxy lensing” – the weak shear from single galaxies (stacked)
  - Mass-to-light ratios and biasing for galaxy formation
- Lensing magnification
  - Changes to the galaxy angular number density from magnification effects
  - (Can we measure in the presence of blending?)
- Weak lensing of the CMB
- Specific tests of modified gravity from lensing and velocity based measures of large-scale structure
- Key systematics:
  - Photometric redshifts
  - Baryonic contributions to the matter power spectrum
  - Source clustering