weak lensing with CFHTLenS and future surveys

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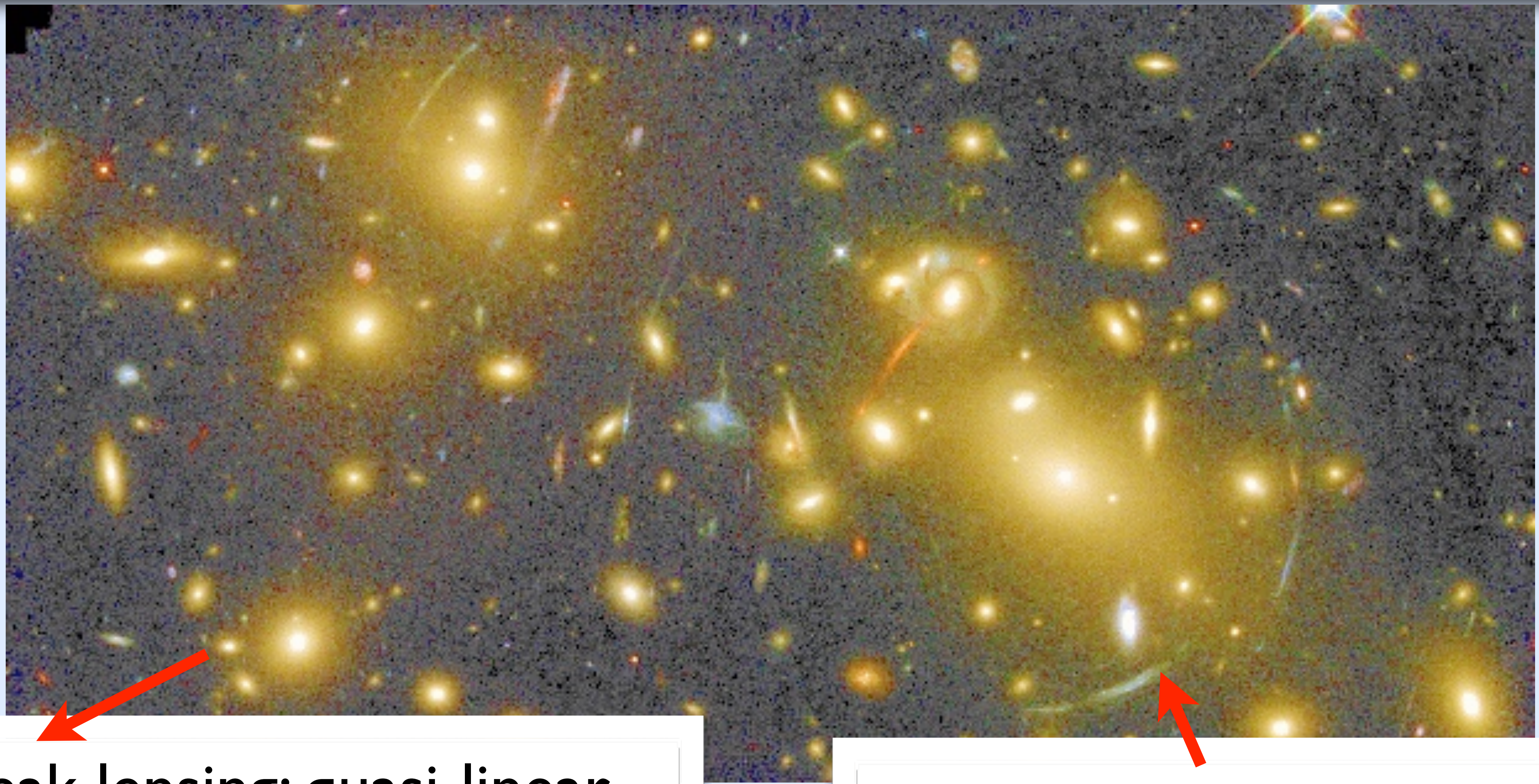
data and catalogue release at CADC

www.cfhtlens.org

1. ***Weak lensing shear measurement***
2. *Systematics*
3. *Results from CFHTLenS*
4. *Future surveys*

weak lensing and cosmic shear

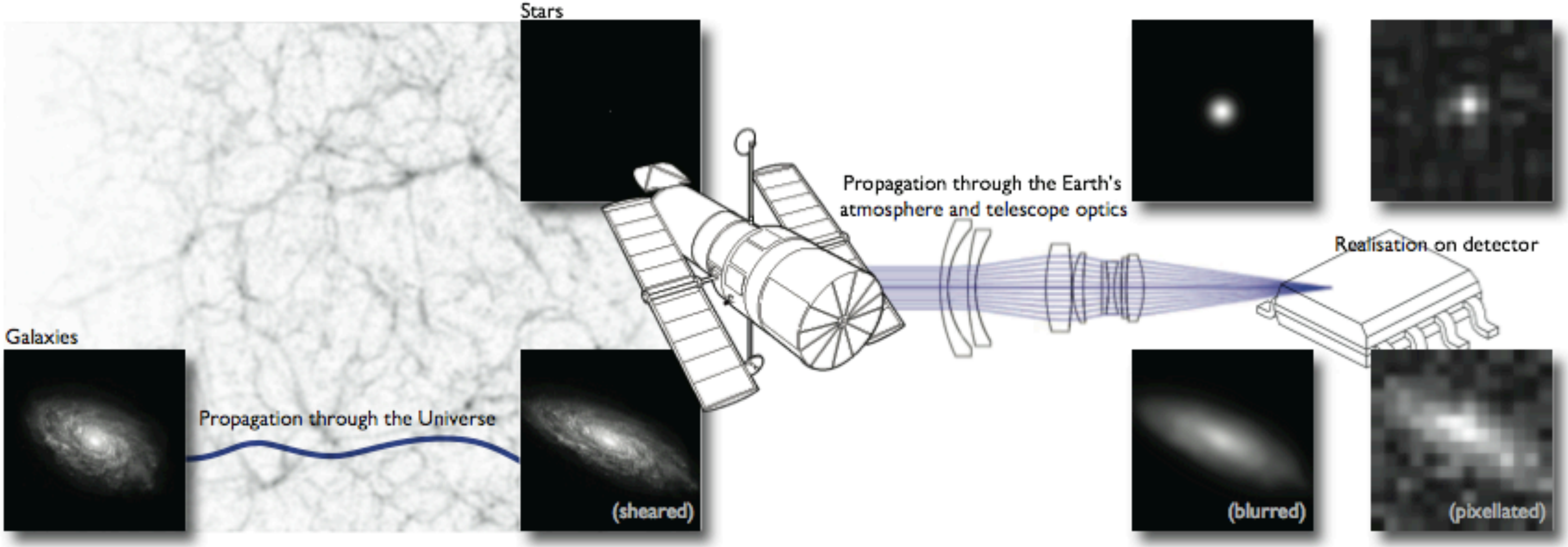


weak lensing: quasi-linear, single images

strong lensing: non-linear, multiple images

- “cosmic shear” is the statistical effect of cosmological large-scale structure: rms ellipticity distortion <1%
- although the shear is in the linear regime, we still sample modes in where the cosmological powerspectrum is non-linear

Shear measurement

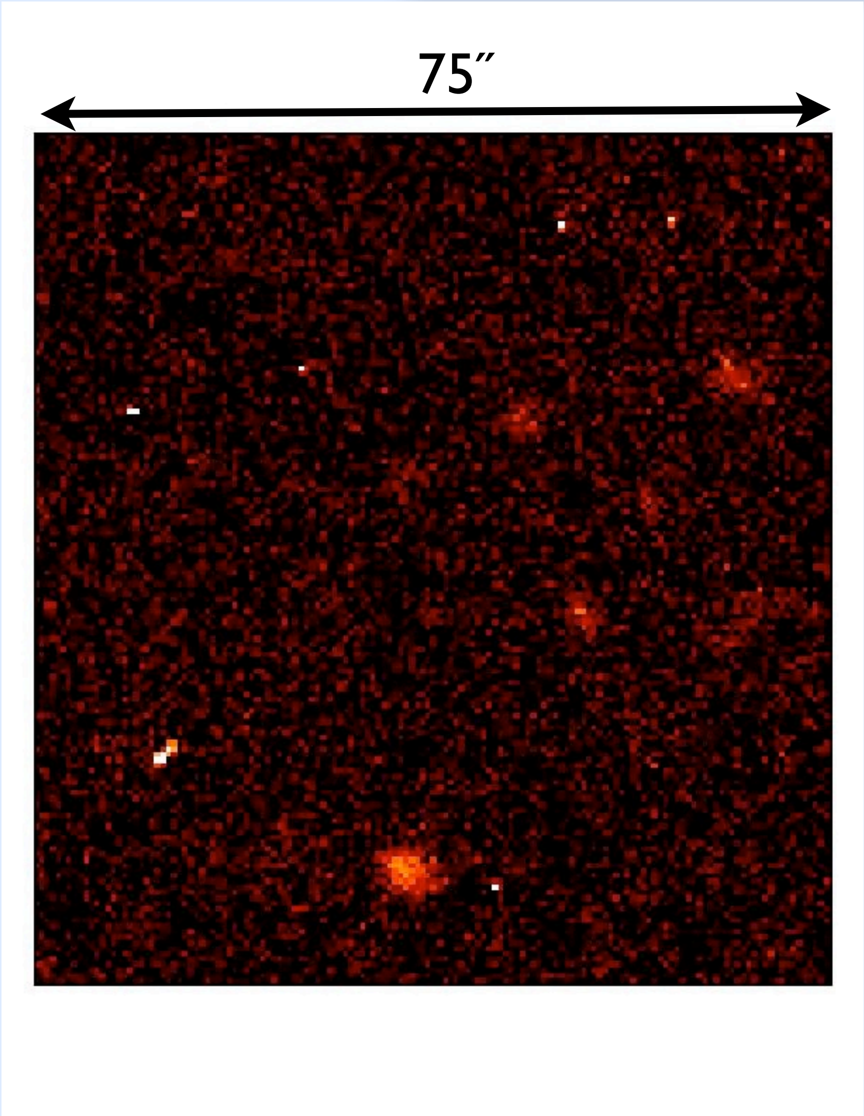


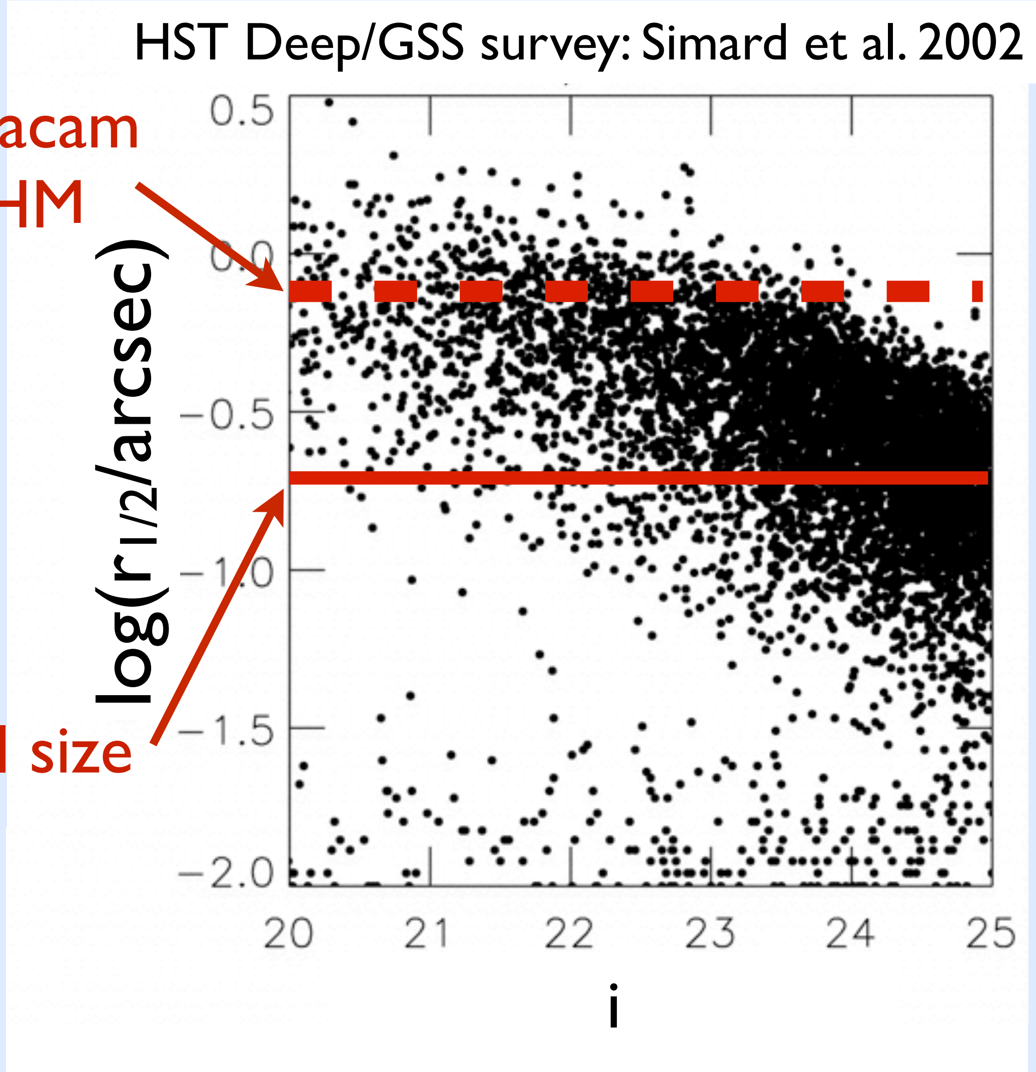
graphic from Great08, Bridle et al. 2009 (AnAp 3, 6)

Need to measure galaxy shapes (ellipticity) given that images have been

- convolved with atmosphere and optics PSF
- sheared by atmosphere and optics
- sampled onto detector with finite pixels
- degraded by noise

shear measurement



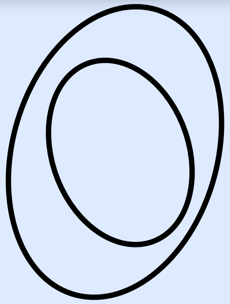


- The weak lensing signal is carried by the faintest galaxies with low S/N.
- Galaxy half-light radii are smaller than the PSF and comparable to the pixel scale!
- Although any individual galaxy cannot be well-measured, we must measure the ensemble free from systematic bias

methods: KSB

- Aim to correct for convolution with PSF by measuring second moments of image
- A round PSF reduces the measured ellipticity of the galaxy
- If we measure the sizes of galaxy and PSF we can correct for this
- We can also correct for an elliptical PSF

- Method only considers second moments, higher moments are ignored
- Hence cannot correct for complex PSFs, e.g. with twisted isophotes:



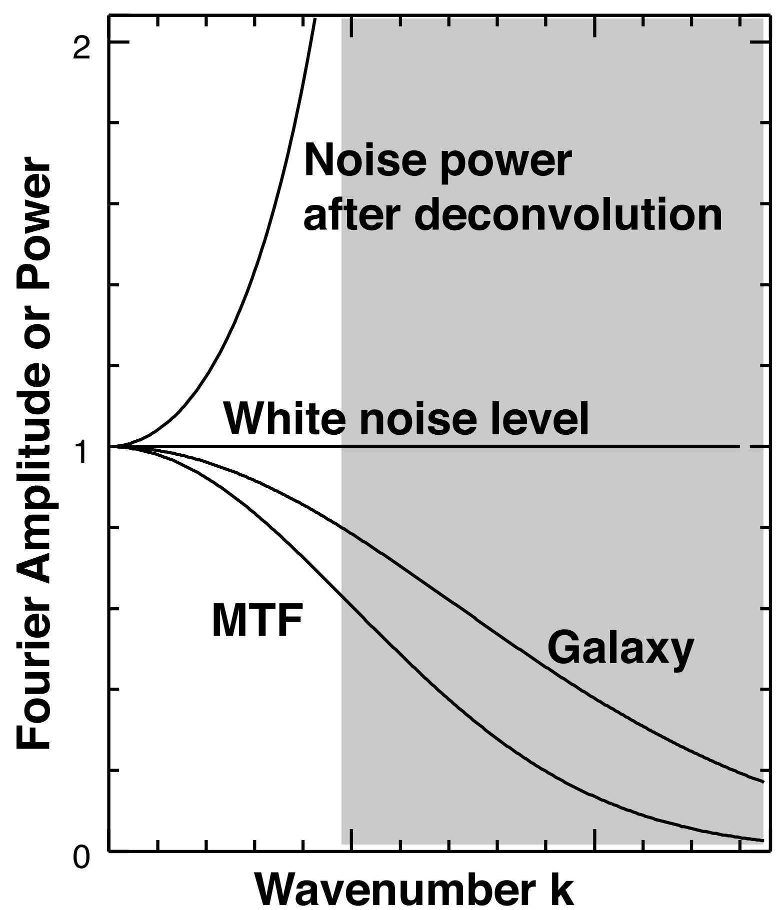
PSF with twisted isophotes

- Moments must be weighted because of noise: weighting biases the measurement towards the weight function
- Deconvolution of moments breaks down in limit of low signal-to-noise
- "Deimos" is better: applies some partial correction for higher moments

- You might think that because any one galaxy is very noisy we don't need an accurate method
- Wrong! we must avoid systematic bias at a level a factor >100 smaller than individual measurement accuracy!

The problem with deconvolution

Bernstein 2010



noise power blows up in deconvolved data

We should avoid trying to solve the deconvolution inverse problem and instead consider only the forward problem (model-fitting).

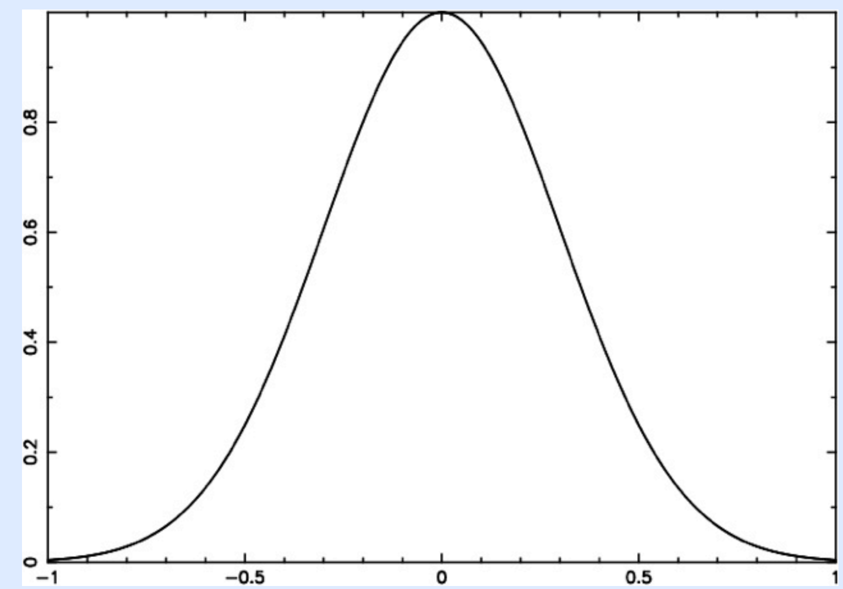
All methods require regularisation, and we need to understand the effect on measurement

Probabilistic model-fitting

model & priors

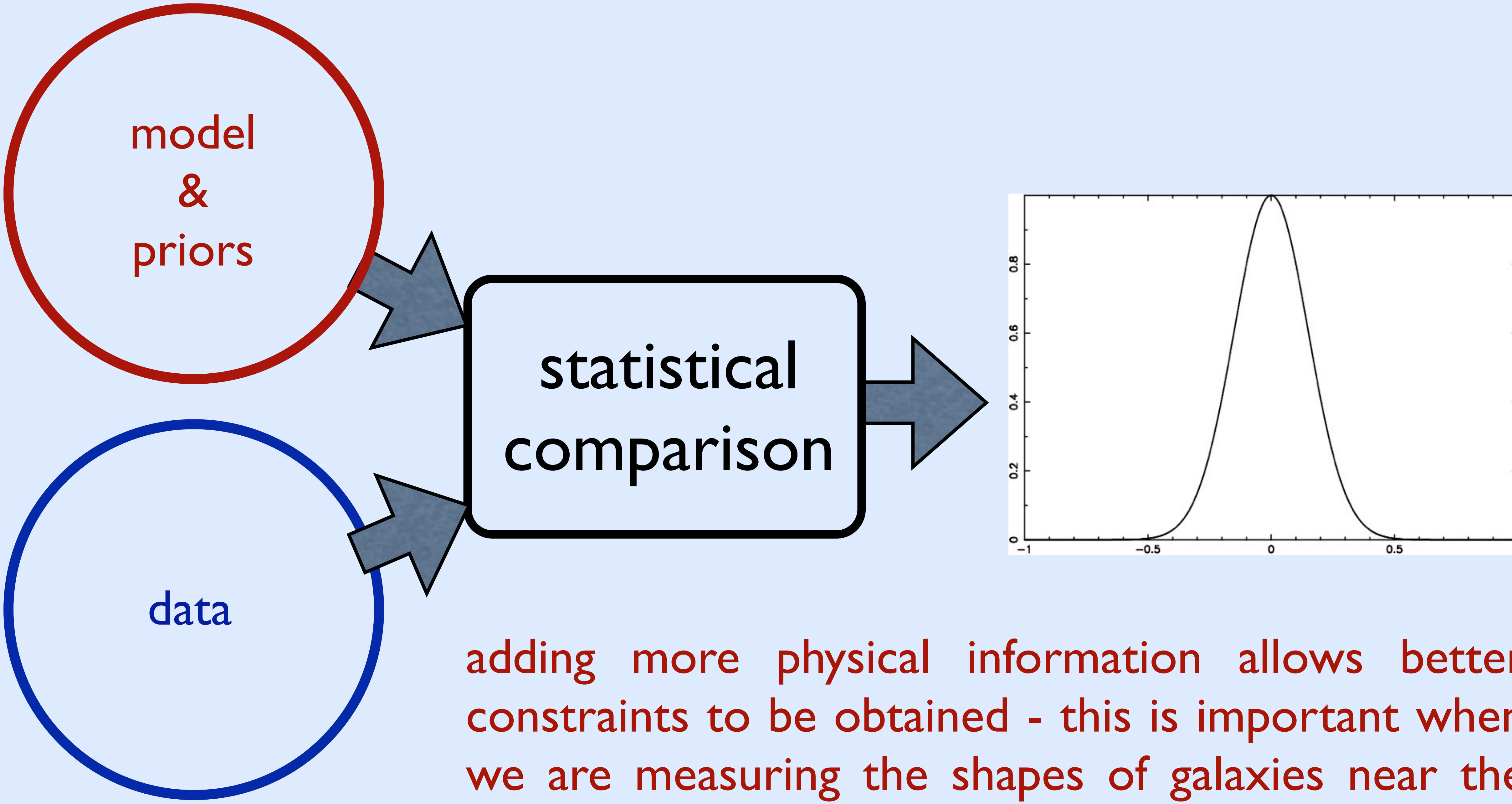
data

statistical comparison



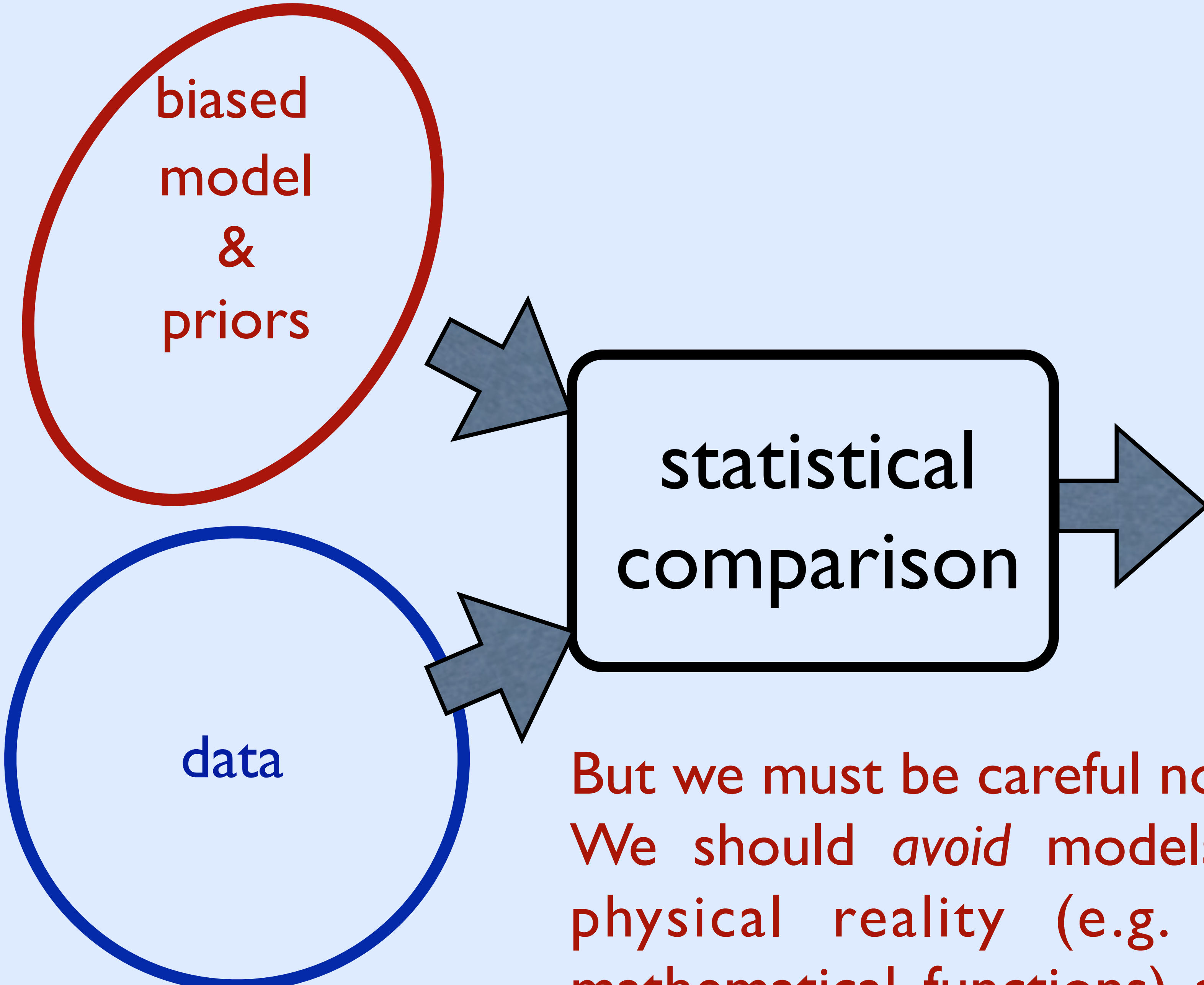
construction of a likelihood function based on a model (and its priors) allows a probabilistic interpretation of the data and hence the generation of PDFs for measured quantities

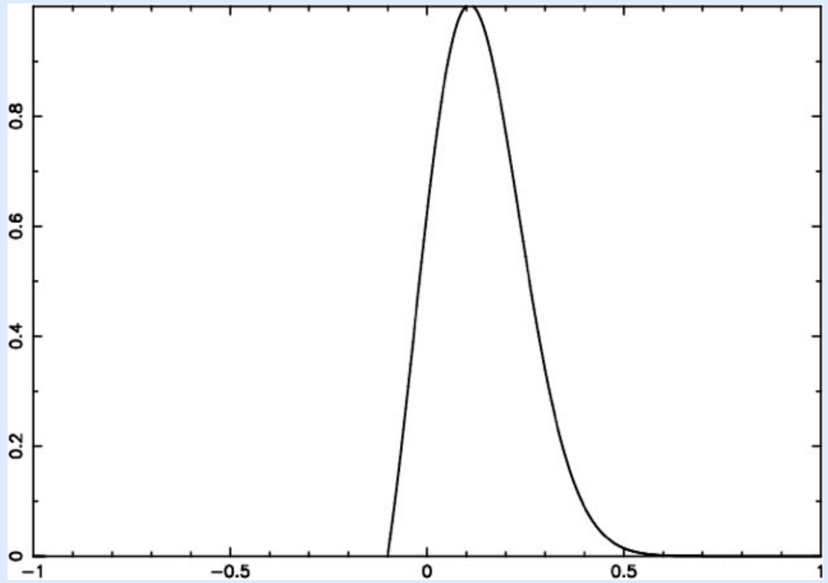
Probabilistic model-fitting



adding more physical information allows better constraints to be obtained - this is important when we are measuring the shapes of galaxies near the magnitude limit. We need to make use of our prior physical knowledge of the structures of galaxies from data with higher S/N

Probabilistic model-fitting

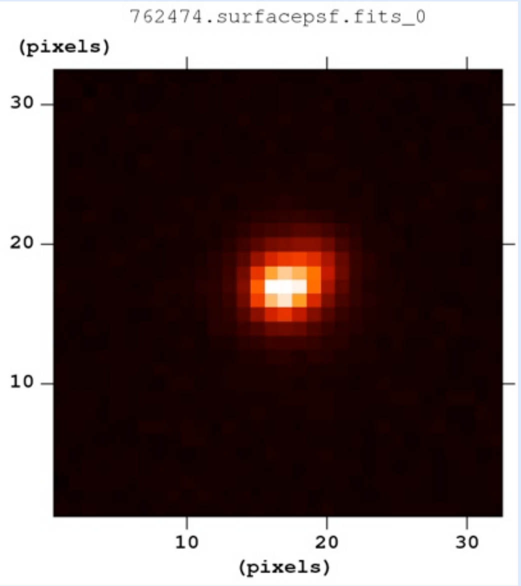




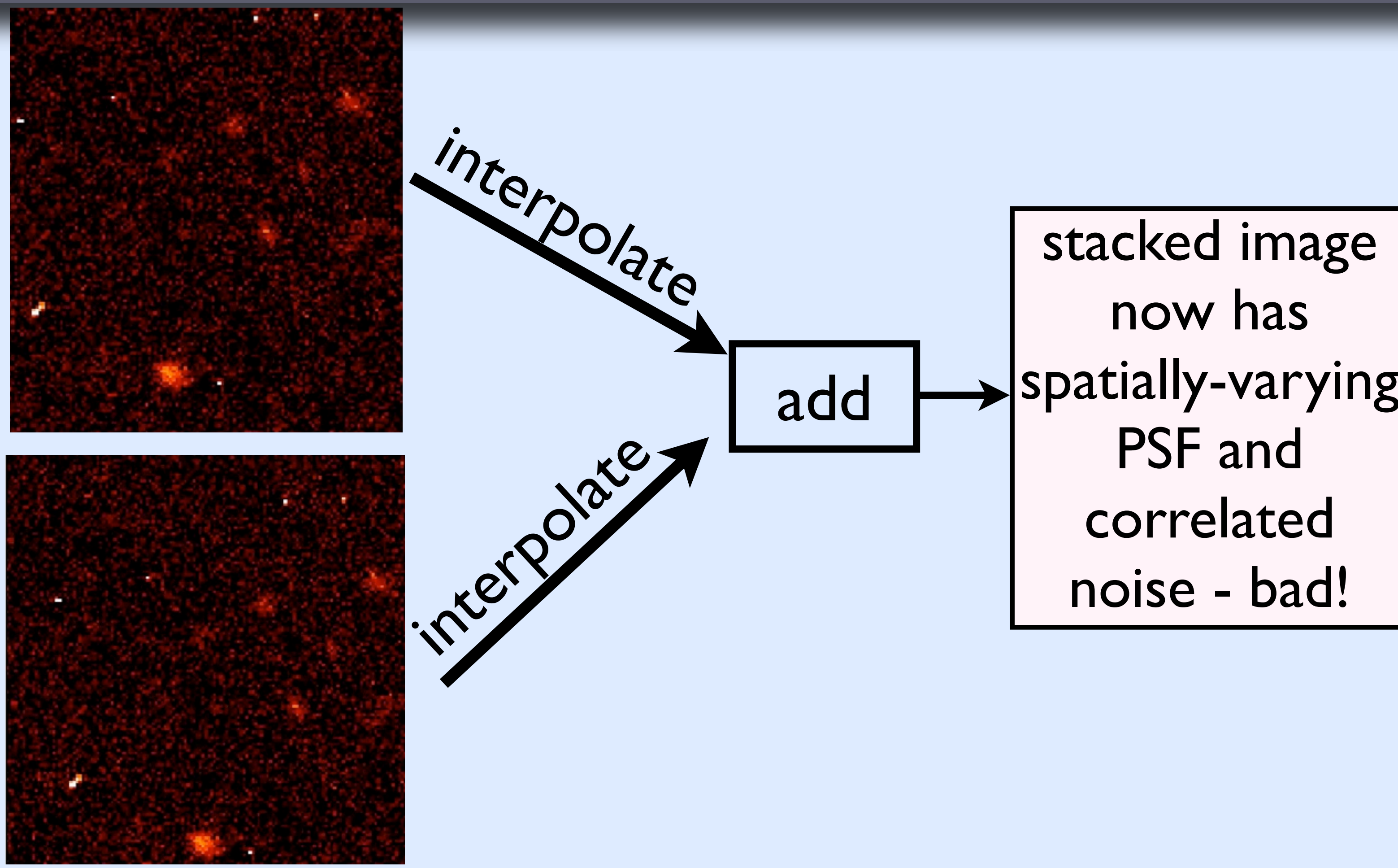
But we must be careful not to introduce bias!
We should *avoid* models that are not based on physical reality (e.g. convenient orthogonal mathematical functions) and instead prefer models based on our knowledge of galaxy structures (e.g. de Vaucouleurs, exponential, Sersic surface brightness profiles - although we may have trouble at z>1)

lensfit

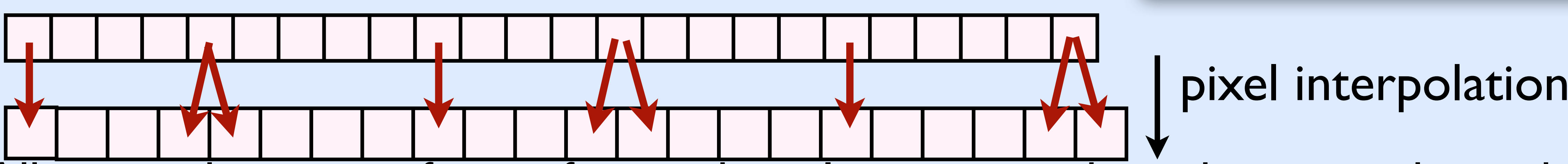
- make galaxy models with some free parameters (enough to allow the full range of galaxy types to be represented)
  - 2-component ellipticity
  - 2-component position
  - bulge + disk components with fixed relative scalelengths but variable flux ratio according to a bulge fraction prior
  - galaxy scalelength
- estimate priors from other data (e.g. distribution of disk ellipticity from SDSS, scalelength distribution from fits to HST data)
- measure the PSF from multiple star images, interpolating to galaxy position taking account of sub-pixel centroiding
- fit convolved galaxy models to multi-image data
- marginalise over "uninteresting" parameters
  - bulge and disk flux marginalisable with an assumed bulge fraction prior
  - position numerically marginalisable rapidly using FFT cross-correlation
  - scalelength numerically marginalised by sampling multiple values



Any method should use individual exposures, not stacked images!

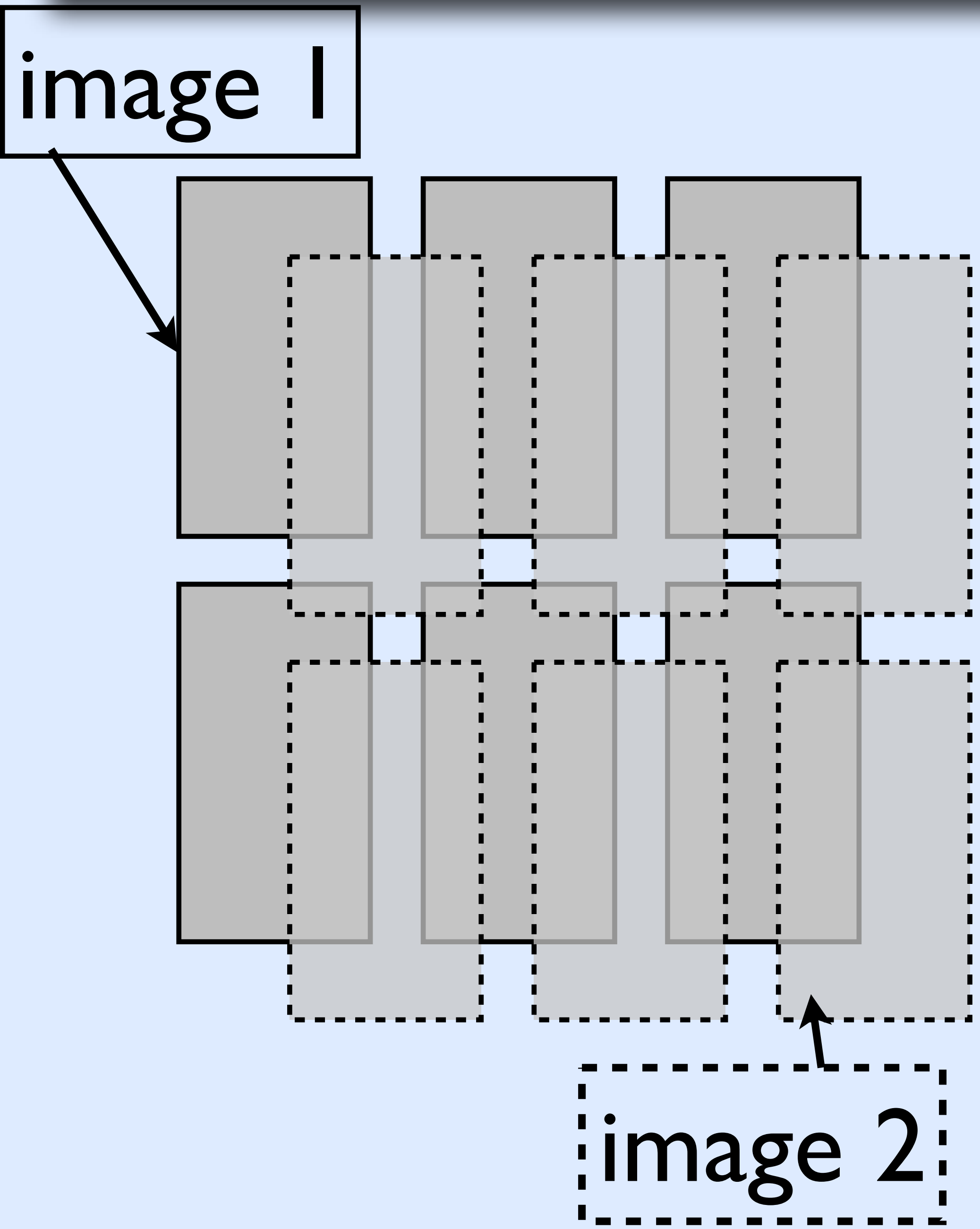


We need a method that measures individual exposures but optimally combines results from multiple measurements: easily done by adding log(likelihood) deduced from each exposure.



- All interpolation is a form of smoothing. In image stacking the interpolation kernel (and hence PSF) varies cyclically across image - very difficult to correct for!
- The noise is initially independent between pixels but after interpolation becomes correlated with spatially-dependent covariance.
- The "distorted multi-exposure" problem is crucial in real data (not included in "GREAT challenge" simulations, ***even in GREAT3 distortion is not included***).

Any method should use individual exposures, not stacked images!



- gaps between CCDs in mosaic cameras
- multiple images are "dithered"
- causes discontinuous variation in PSF!
- very difficult to measure PSF in gaps on stacked images
- can affect 20% of the area

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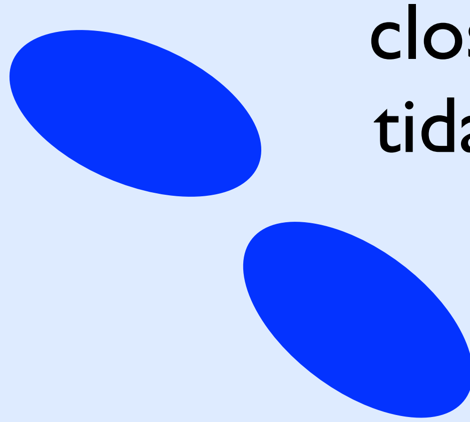
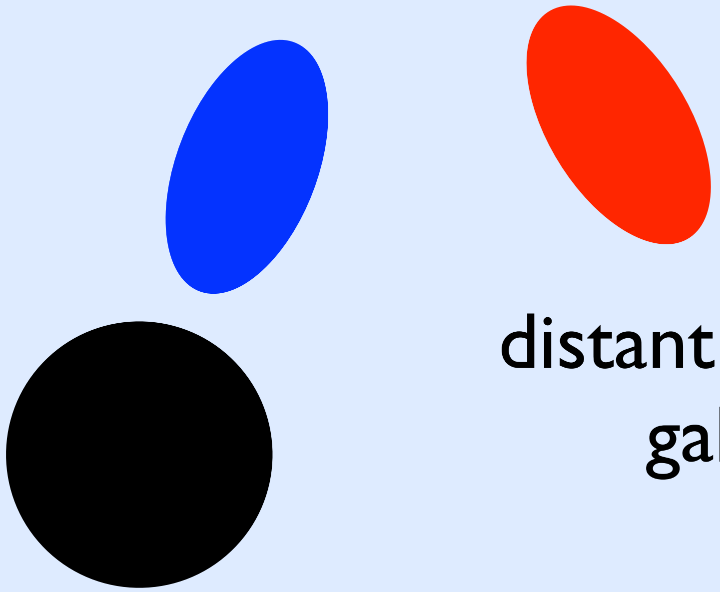
astrophysical systematics

close galaxies,
tidally aligned



Intrinsic alignments "II" term

galaxy near lens,
tidally aligned

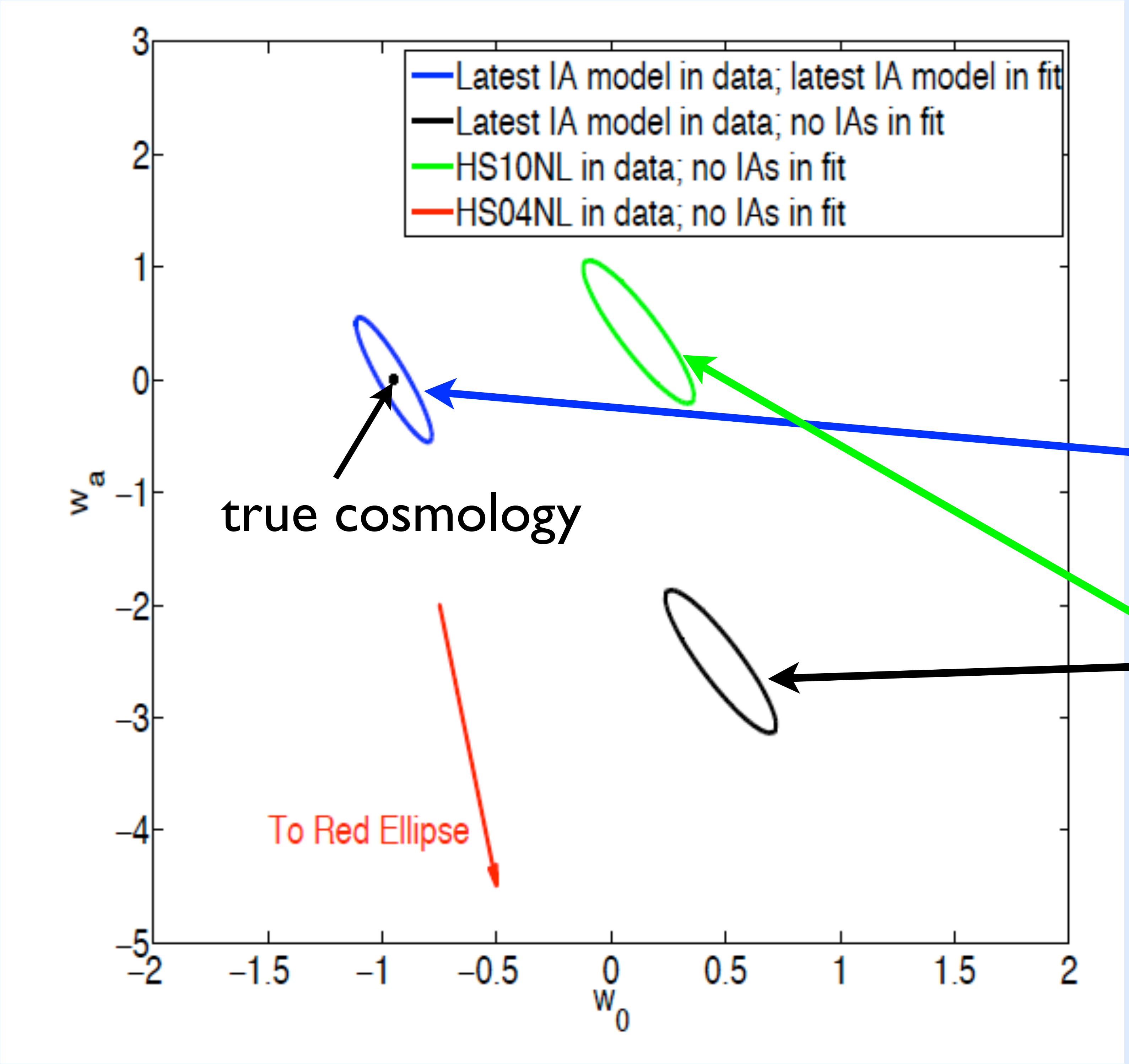


Intrinsic alignments "GI" term

distant sheared
galaxy

lens

astrophysical systematics



confidence contours on w0, wa for a Euclid-like survey, where $w(a) = w_0+(1-a)w_a$

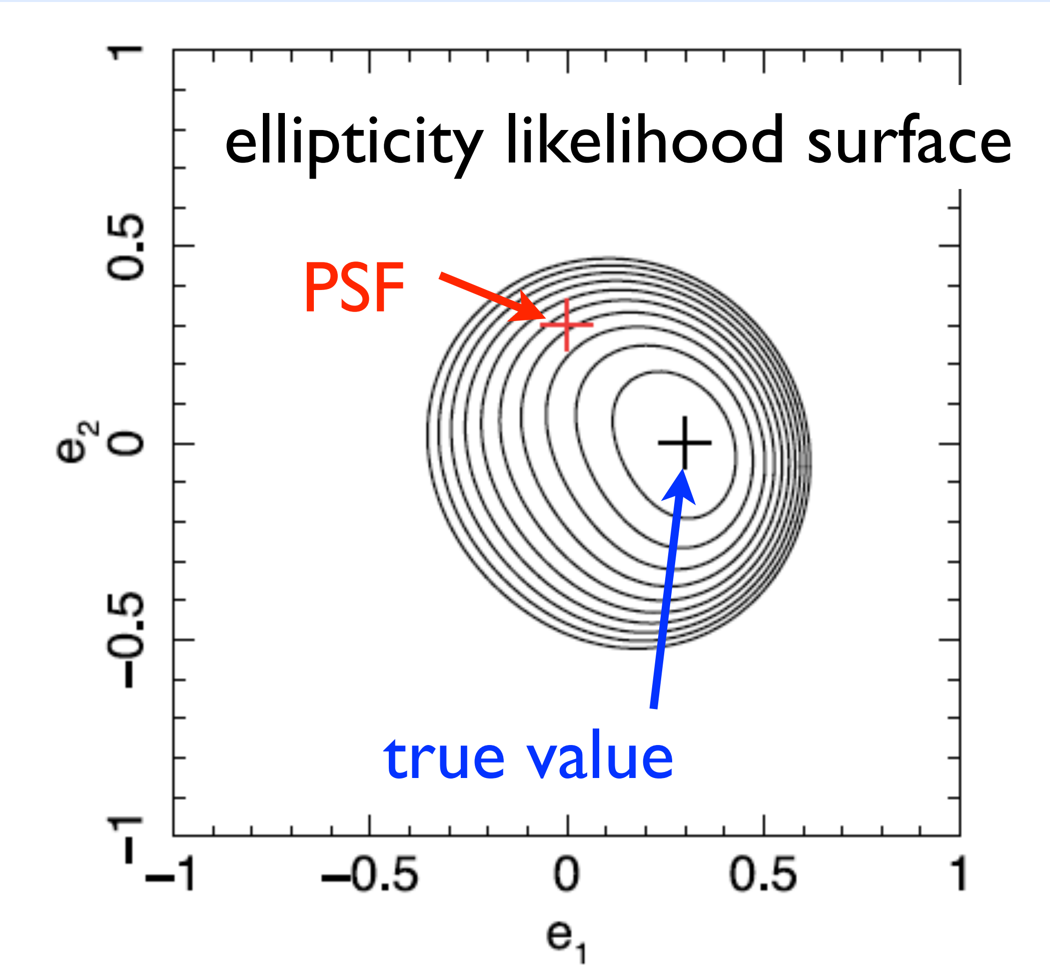
including model for intrinsic alignments

if intrinsic alignments are ignored, but really exist with various prescriptions

Kirk et al 2012

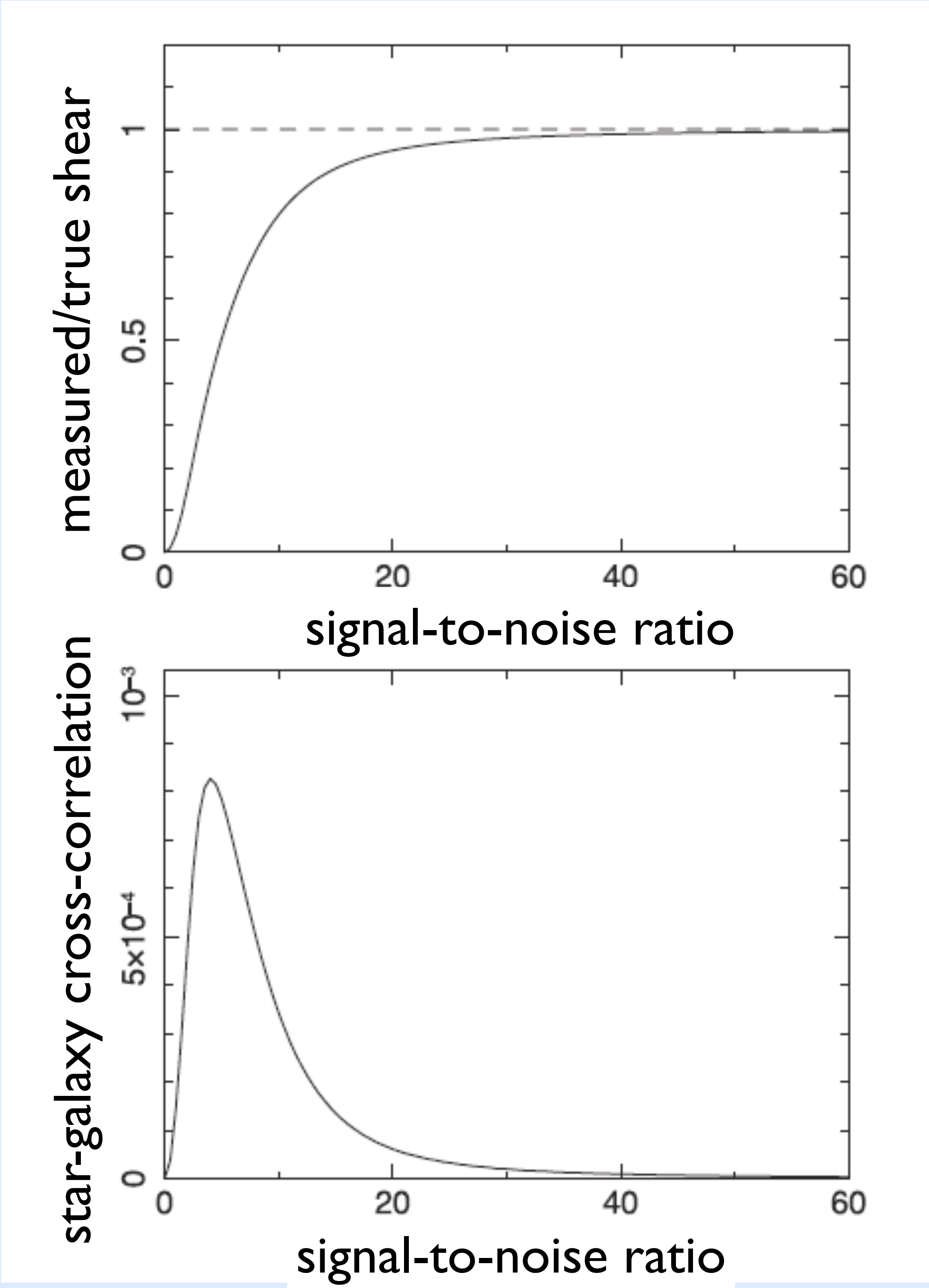
measurement systematics

- image combination errors
- PSF errors
- noise bias (Refregier et al 2012, Melchior & Viola 2012, Miller et al 2013)



- ellipticity and shear are non-linear transformations of the pixel values
- random pixel noise causes bias (likelihood function is distorted)
- bayesian method should be able to correct for this but we have not yet figured out how to calculate the likelihood bias

noise bias



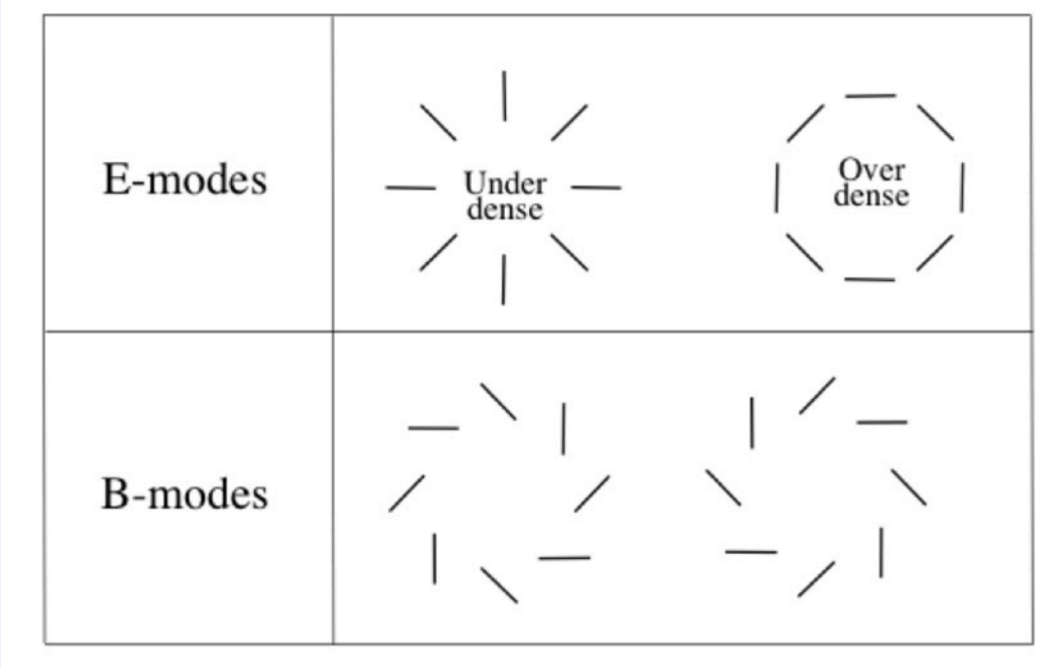
- causes measured shear to tend to zero at low signal-to-noise ratio
- effect is significant (few percent) even for bright galaxies
- also causes cross-correlation with PSF

model or weight bias

- if the wrong models are used, results may be biased
- galaxy morphology changes with redshift and rest-frame band of observation
- size of effect can only be determined from HST data
- same effect applies to all methods (moments, shapelets) because weight functions do not match true surface brightness distributions

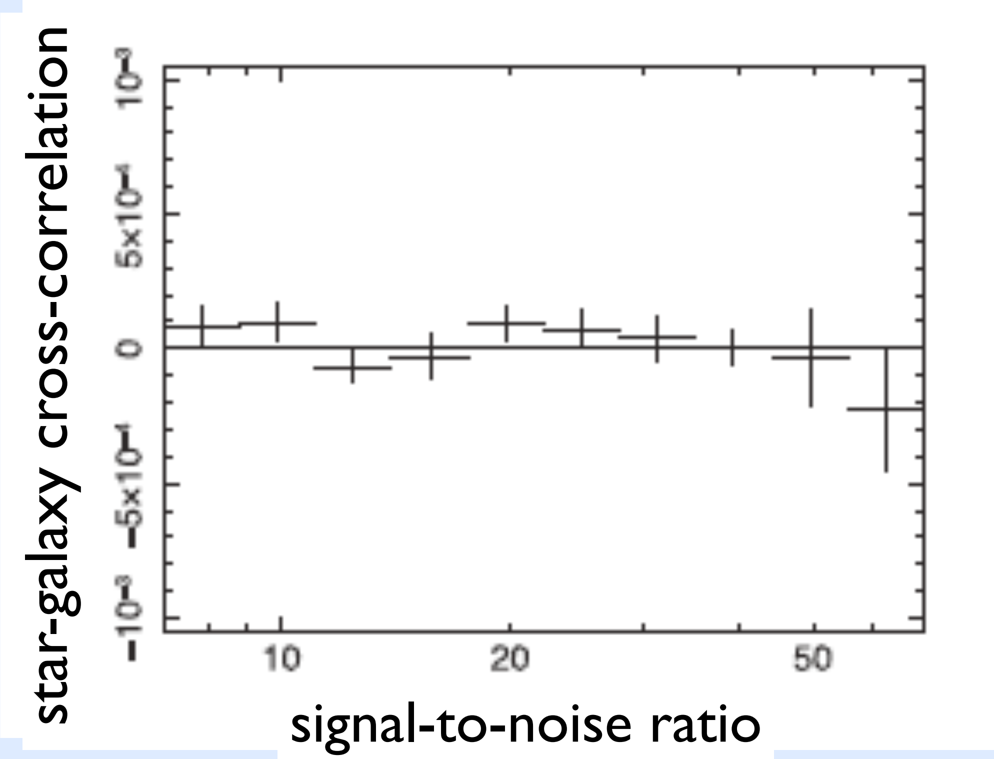
tests for measurement systematics

- E/B mode decomposition



- to first order, weak lensing should only make E modes (gradient of a scalar potential)
- need to account for survey boundaries
- measurement systematics may also create E modes
- in practice is not very sensitive test

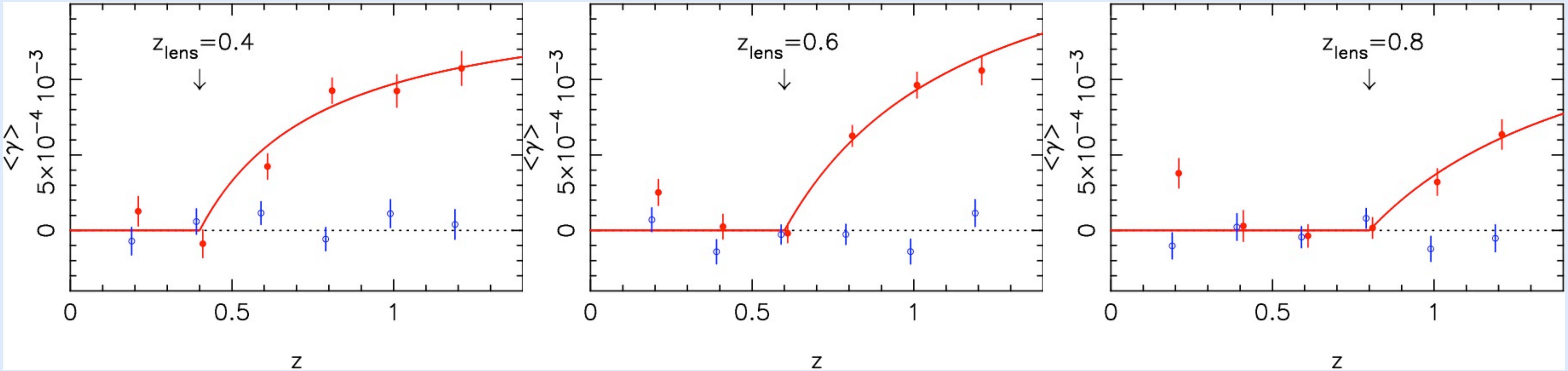
- star-galaxy cross-correlation



- many causes of systematics lead to PSF-galaxy cross-correlation and hence this is a powerful test
- we need to average over enough galaxies to detect an effect
- but the measure may vary on small length scales
- also need to allow that cosmological shear may randomly correlate with PSF

tests for measurement systematics

- redshift scaling



- signal should increase with redshift of source
- test either with cosmic shear or galaxy-galaxy lensing
- be careful not to create confirmation bias (i.e. do not require results to fit favourite cosmology, just check that signal increases with z)
- KSB in CFHTLenS failed this test!

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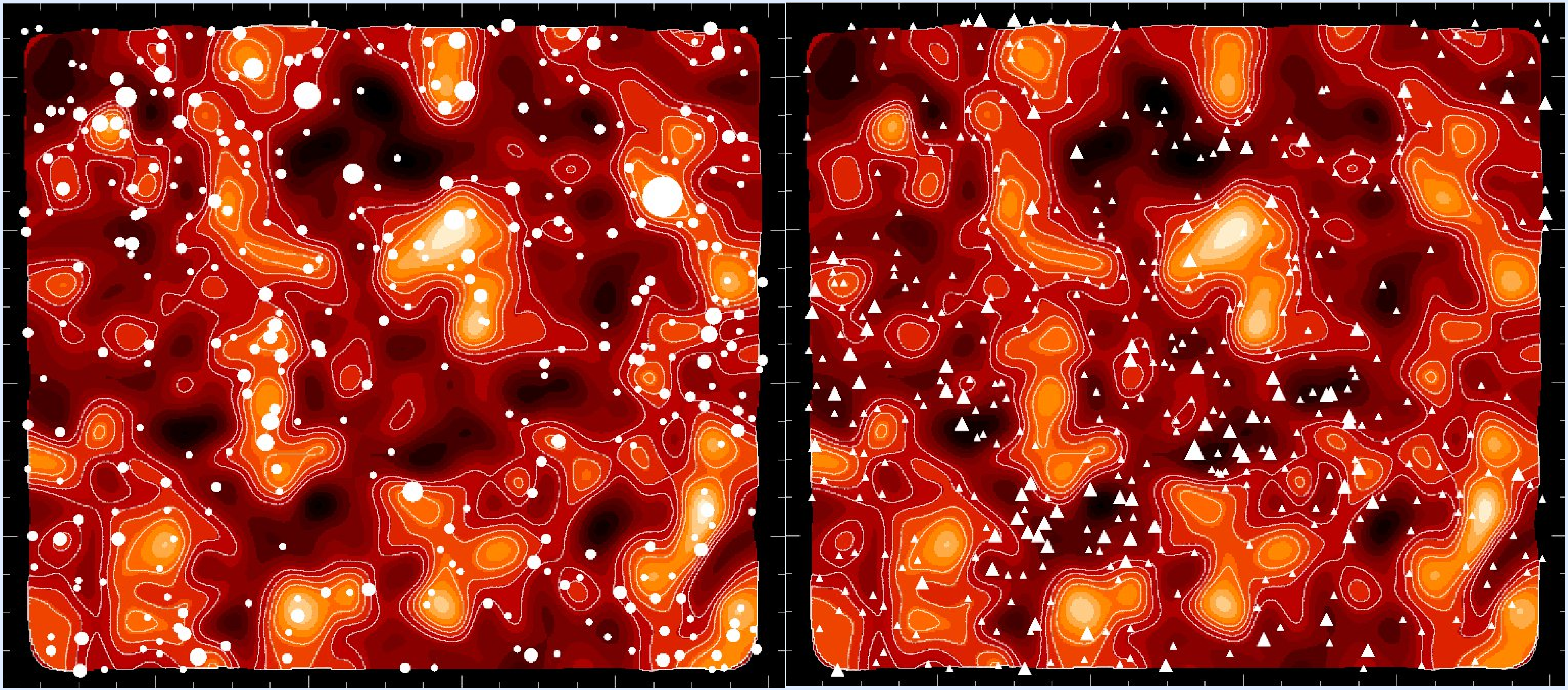
CFHTLenS: The CFHT Lensing Survey

- complete reanalysis of the CFHT Legacy Survey (CFHTLS) “Wide Survey”, data obtained 2003-9
- four years of work!
- 154 sq deg in five optical bands, ugriz
- lensing measurements of 8×10^6 galaxies in good seeing (FWHM < 0.8 arcsec) i band to depth i<24.7
- photometric redshifts from ugriz accurate to rms error $\sigma(z) \sim 0.04(1+z)$ with 4 percent outlier rate
  - crucial for lensing equation! also allows tomographic, 3D and GG lensing analyses
  - median redshift 0.7

direct mass maps



colours + contours: projected mass density inferred from shear (using Kaiser & Squires 93 reconstruction: shear -> convergence -> mass)

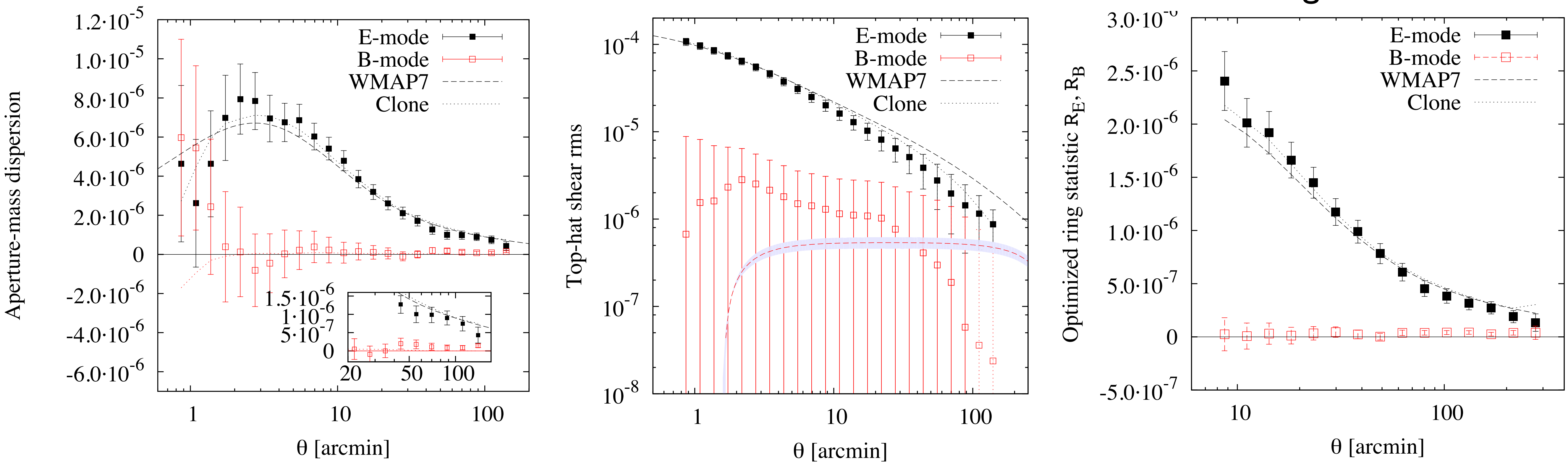
circles (left): convergence predicted from galaxy overdensity

triangles (right): negative convergence predicted from galaxy underdensity

van Waerbeke et al 2013

2D cosmic shear constraints

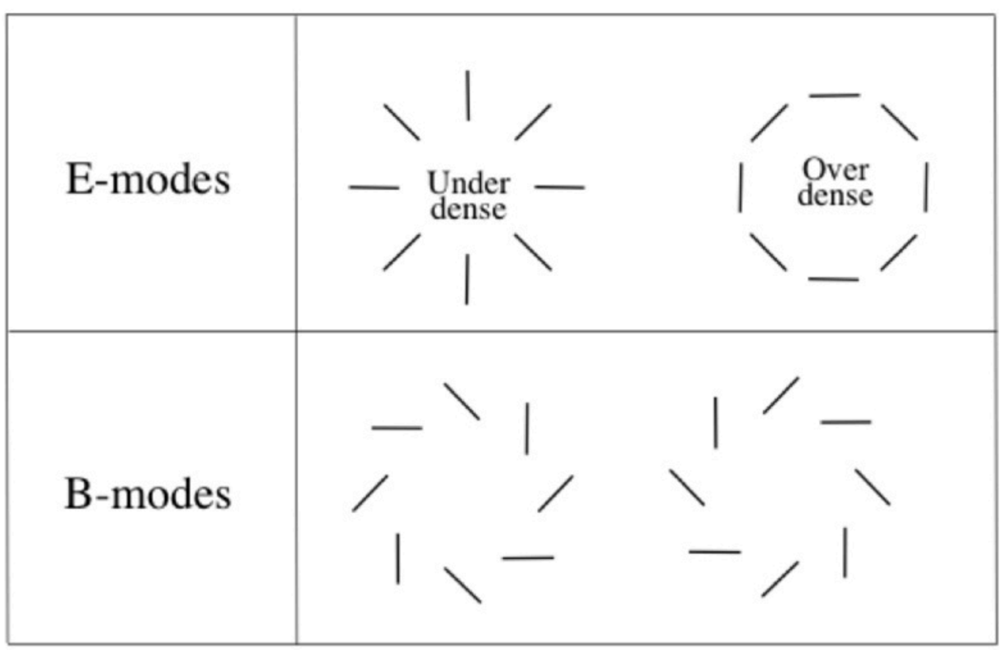
Kilbinger et al 2013



aperture mass dispersion

top-hat shear variance

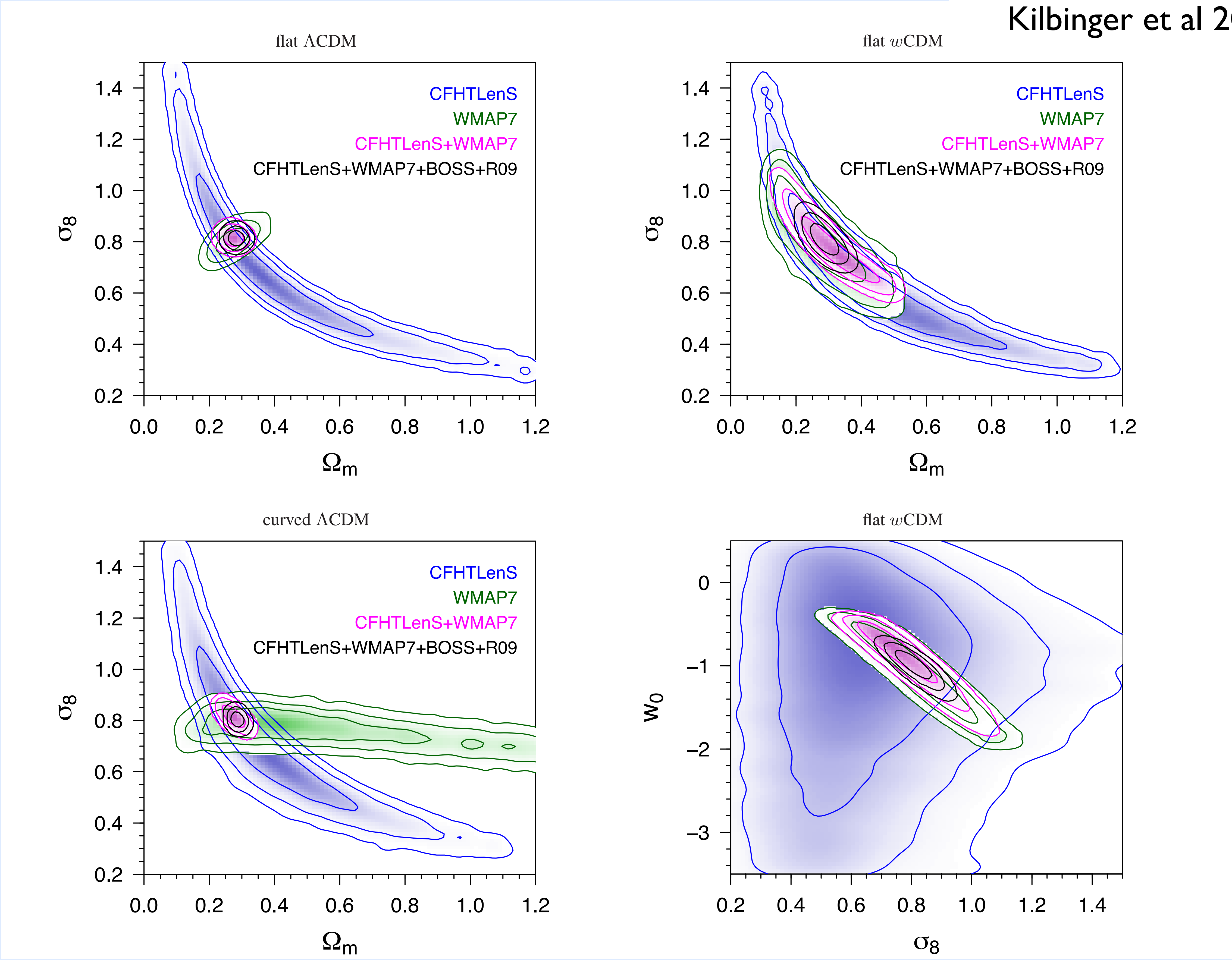
ring statistic



- to first order, weak lensing should only make E modes (gradient of a scalar potential)
- in CFHTLenS no significant B modes on any scale (red points)

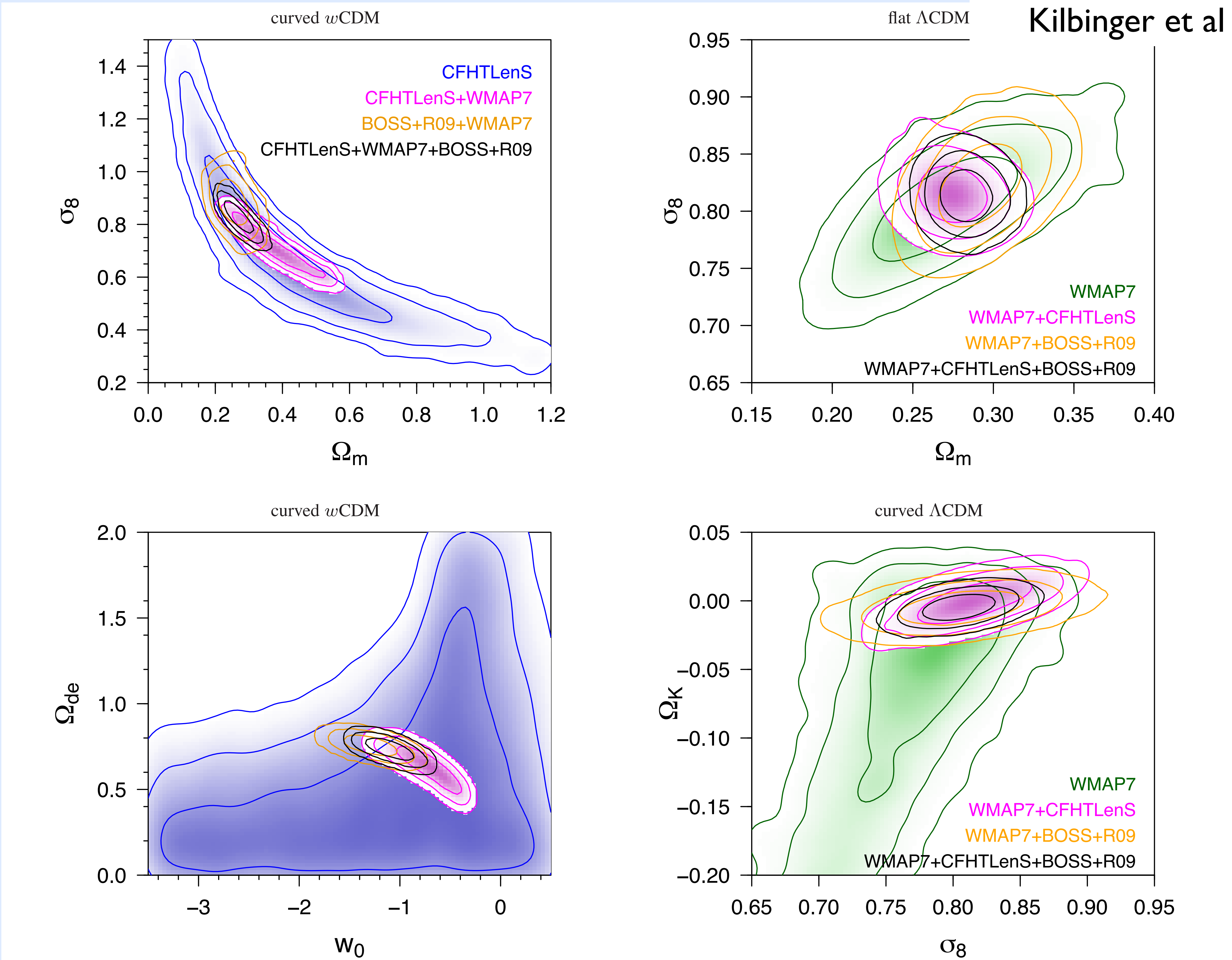
2D cosmic shear constraints

Kilbinger et al 2013



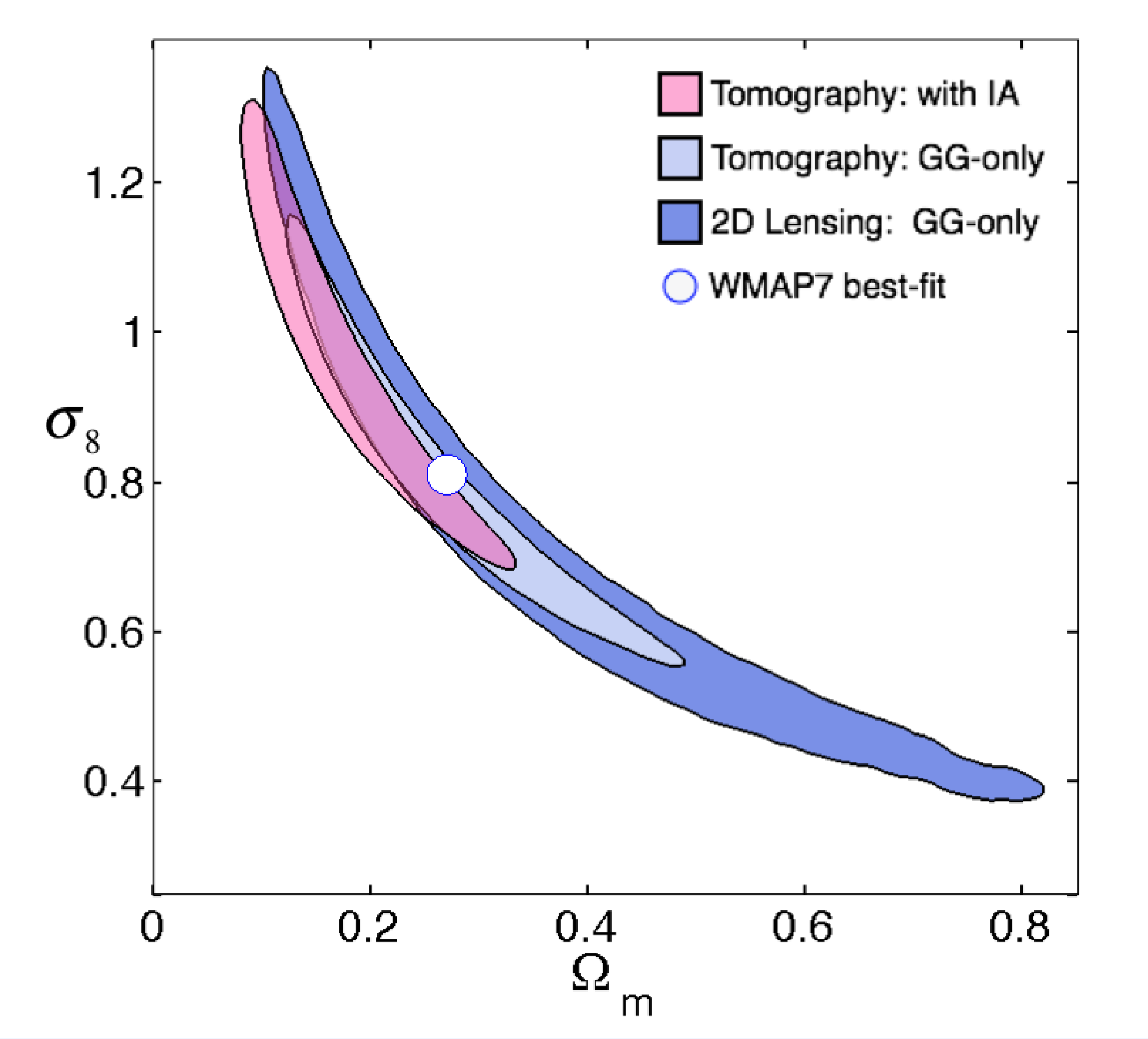
2D cosmic shear constraints

Kilbinger et al 2013

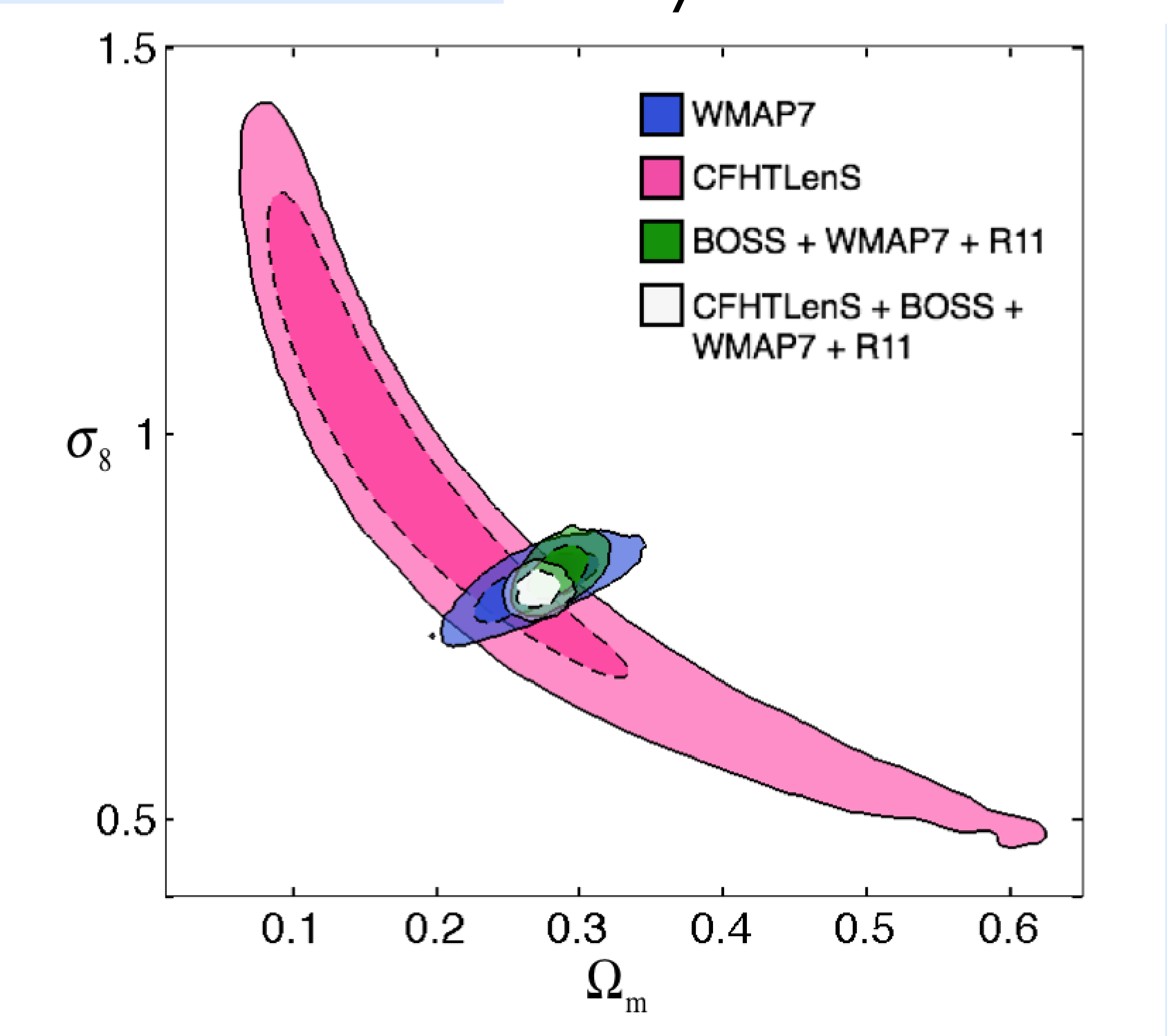


cosmic shear tomography and intrinsic alignments

Heymans et al 2013

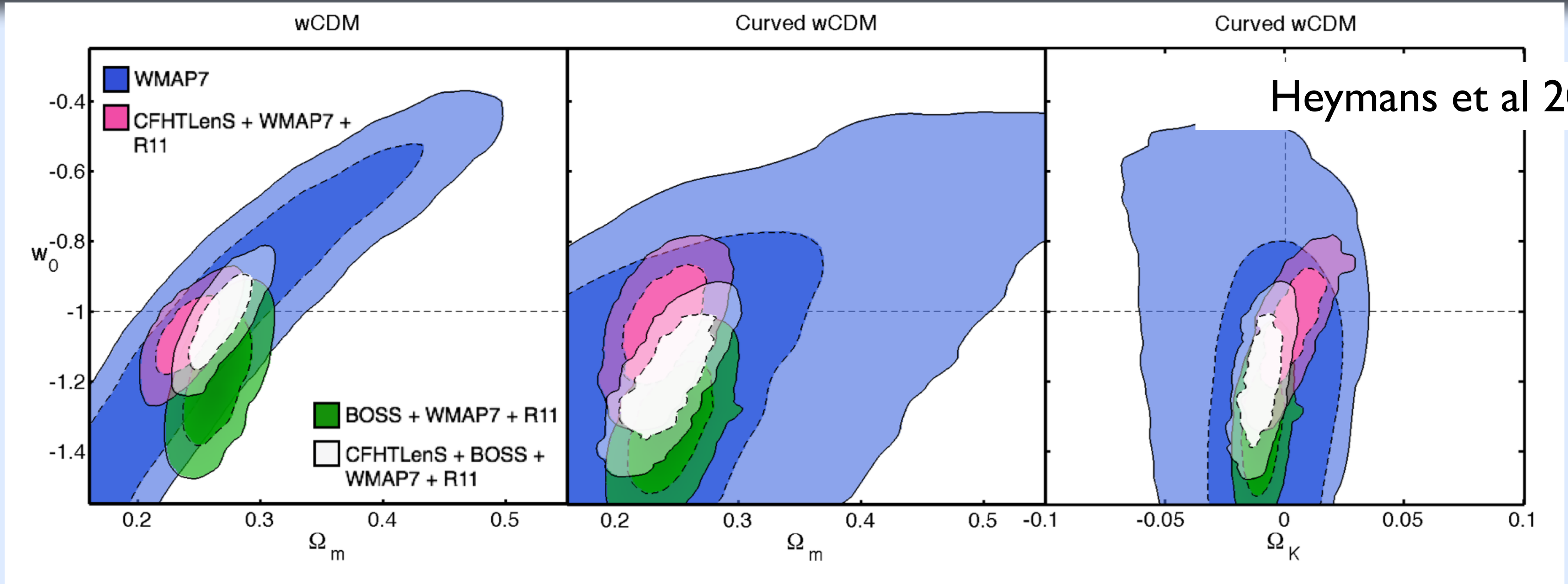


comparison of 2D lensing, 6-bin tomography and 6-bin tomography allowing for intrinsic alignments: 68% confidence intervals

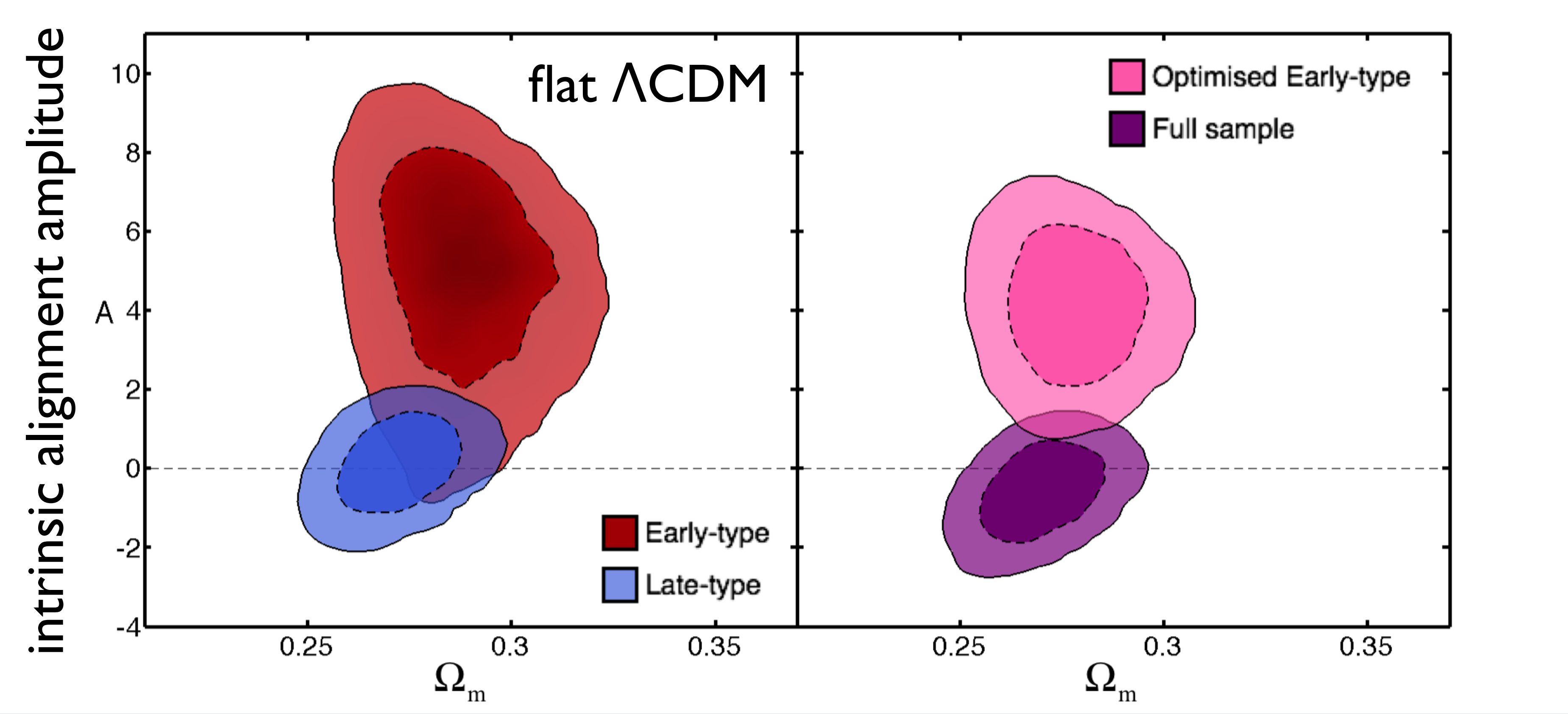


6-bin tomography allowing for intrinsic alignments, with other data (note axes zoomed-in)

cosmic shear tomography and intrinsic alignments



Heymans et al 2012



messing with gravity

$$ds^2 = (1 + 2\Psi)\, dt^2 - a^2(t)\, (1 - 2\Phi)\, d\boldsymbol{x}^2 \,.$$

Simpson et al 2013

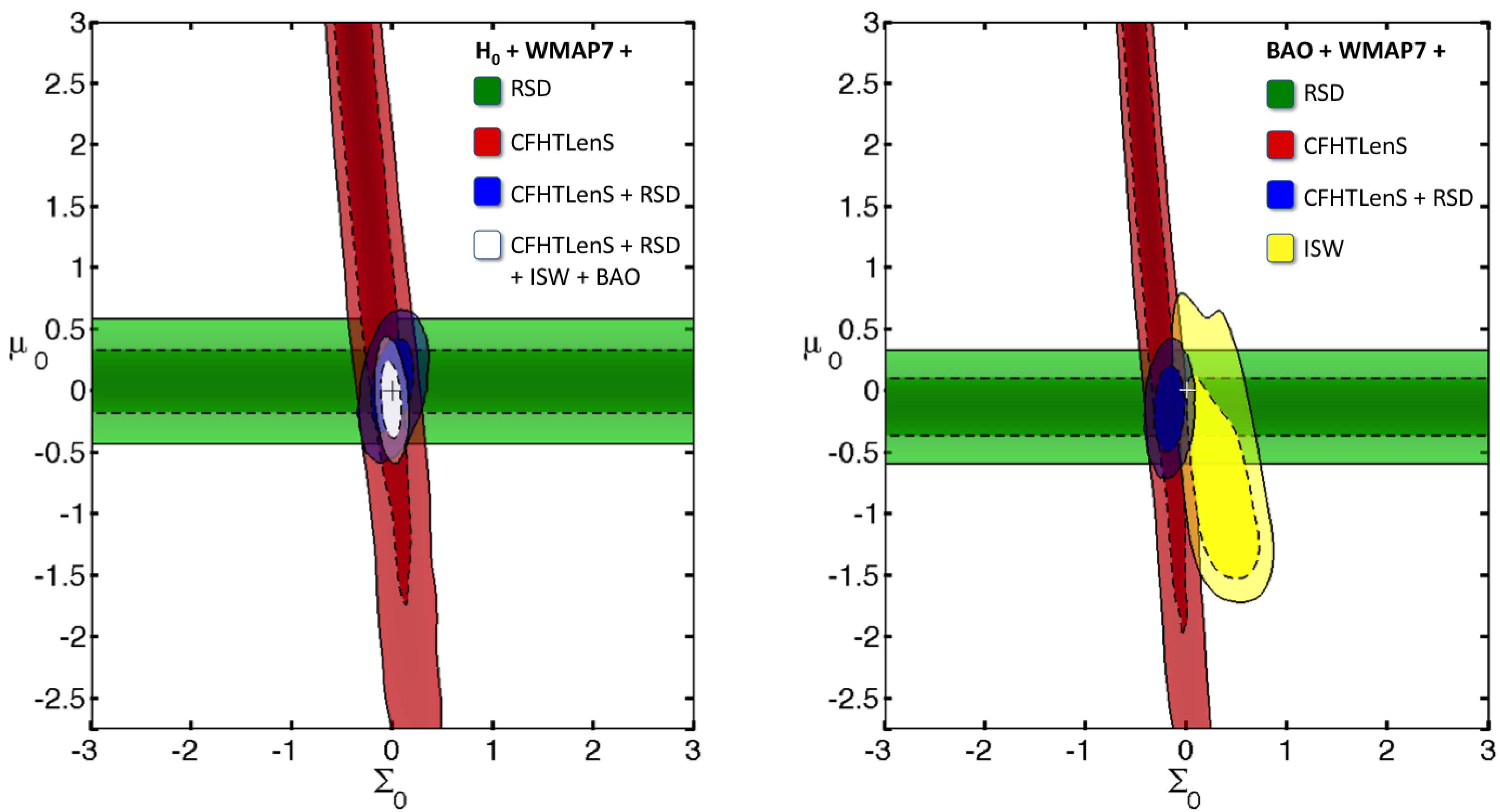
$$k^2 \left(\Psi_{\rm GR} + \Phi_{\rm GR}\right) = -8\pi G a^2 \bar{\rho}\delta \,.$$

$$\Psi(k,a) = [1 + \mu(k,a)]\, \Psi_{\rm GR}(k,a)$$

$$[\Psi(k,a) + \Phi(k,a)] = [1 + \Sigma(k,a)]\, [\Psi_{\rm GR}(k,a) + \Phi_{\rm GR}(k,a)]$$

$$\Sigma(a) = \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}\,, \quad \mu(a) = \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$$

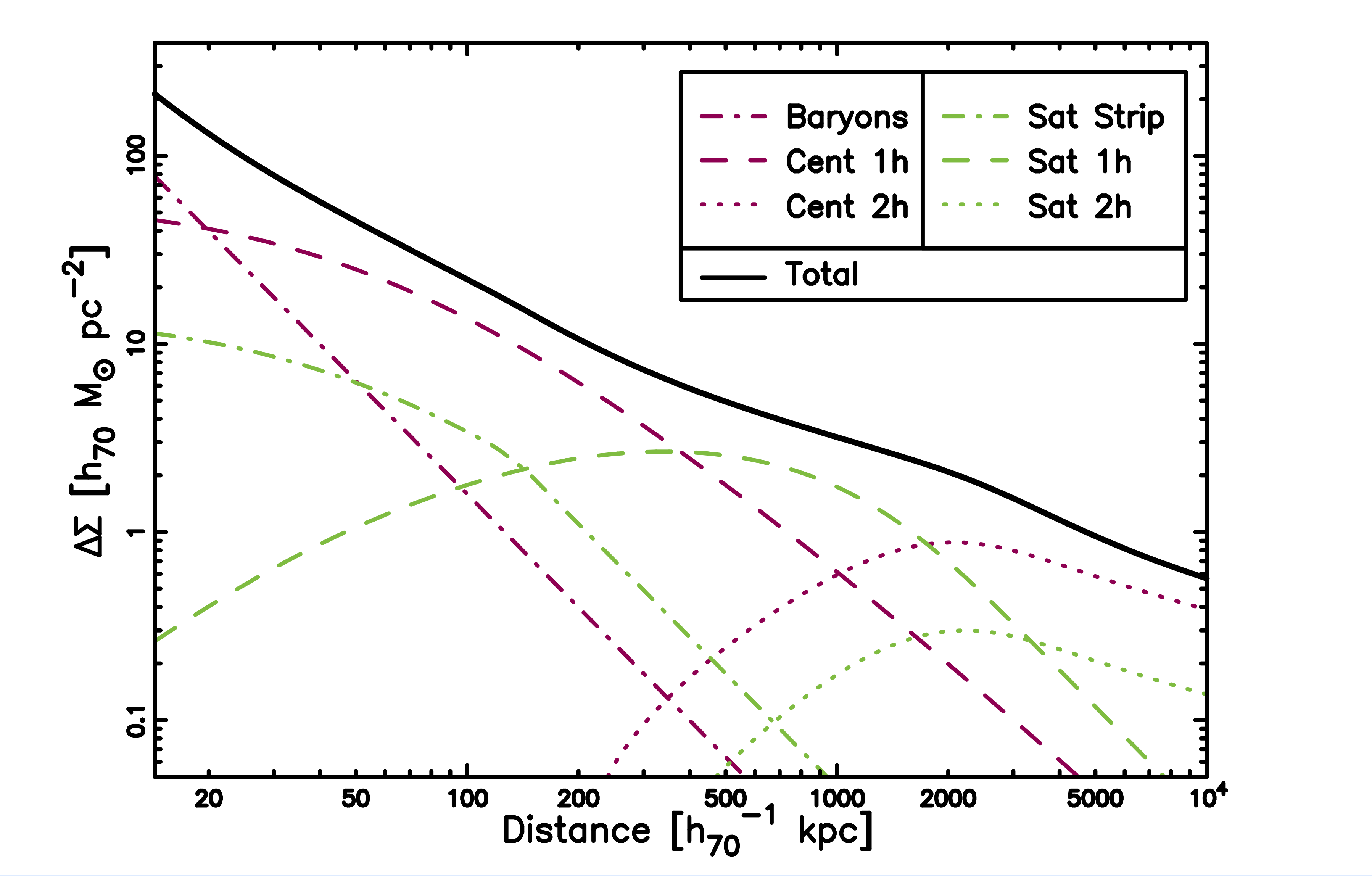
- flat LCDM background



galaxy-galaxy lensing

- halo modelling (dark matter halos populated by multiple galaxies with specified correlation functions between them)
- constrained by measuring shear around 10^6 identified galaxies, 0.2<z<0.4

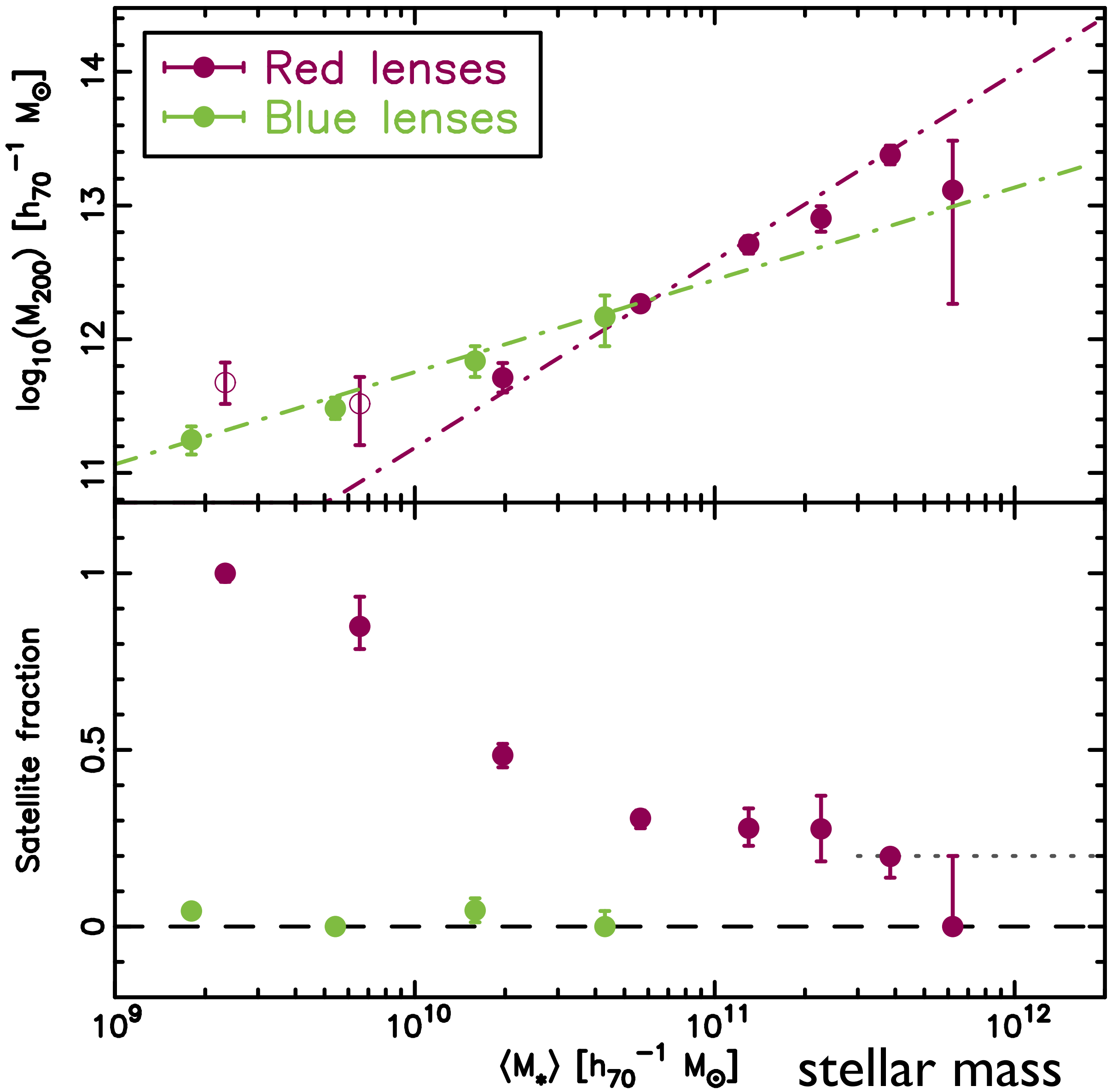
Velander et al 2013

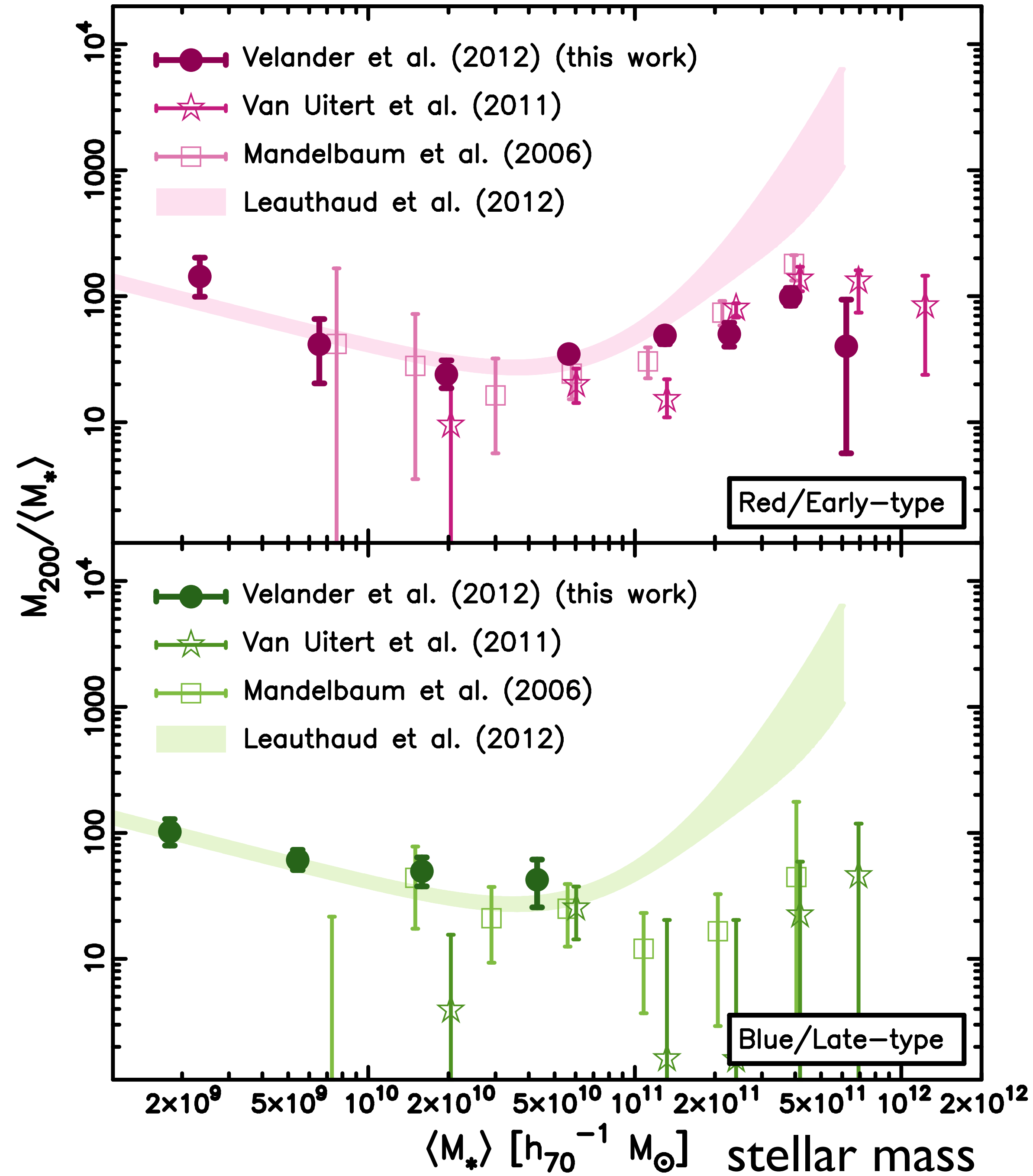


galaxy-galaxy lensing

Velander et al 2013

- measure relationship between dark halo mass and stellar mass as function of galaxy type





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future surveys

[CFHTLenS	154 deg^2	ugriz	i<24.7	2012	ground]
CS82	150 deg^2	ugriz	i<24	2013	ground
RCSLenS	1000 deg^2	gri	i<23.5	2013	ground]
KiDS+VISTA	1500 deg^2	ugrizyJHK	i<24	2017	ground
HSC	1400 deg^2	grizy	i<26	2018	ground
DES	5000 deg^2	griz	i<25	2018	ground
Euclid	15000 deg^2	"riz",YJH	i<24.5	2020-5	space
LSST	20000 deg^2	ugriz	i<27	2024?	ground

future surveys

- noise bias will dominate measurement accuracy
- PSF modelling must be much more accurate than now
- undersampling of images must be taken into account (even in ground-based data)
- cosmological evolution of galaxy morphology may introduce redshift-dependent bias
- wavelength-dependent PSF requires knowledge of star and galaxy SED
- intrinsic alignments cannot be ignored

summary

- CFHTLenS is currently the largest weak-lensing survey (SDSS has larger sky area but many fewer galaxies)
- Systematic biases that have plagued previous weak-lensing surveys have been eliminated at the level needed to meet the statistical accuracy
- Basic cosmological parameter measurements are competitive with other probes
- Can start to probe directly the relationship between dark matter and stellar mass - we can now measure things for which we don't have good theoretical/numerical models
- Highly constrained tests of gravity are possible but general constraints require orders of magnitude larger survey
- CFHTLenS will soon be eclipsed in area by KiDS, DES, HSC and eventually Euclid and LSST. Techniques we have developed will be useful for future surveys but are not yet good enough for those.