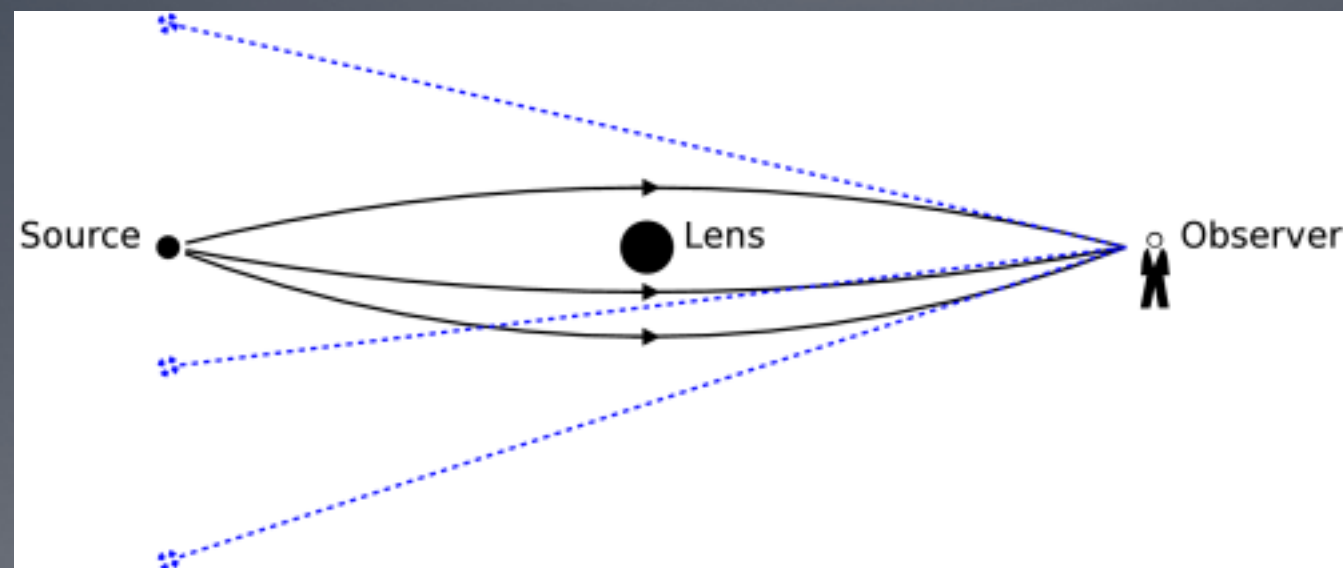# Instrumental systematics and weak lensing science

Rachel Mandelbaum (CMU)
PACCD, Dec. 4, 2014

Outline

- Weak gravitational lensing

    - What is it?

    - Why should you care?

- How lensing measurements work

- How systematics (including instrumental ones) affect weak lensing measurements

Gravitational lensing

Strong lensing

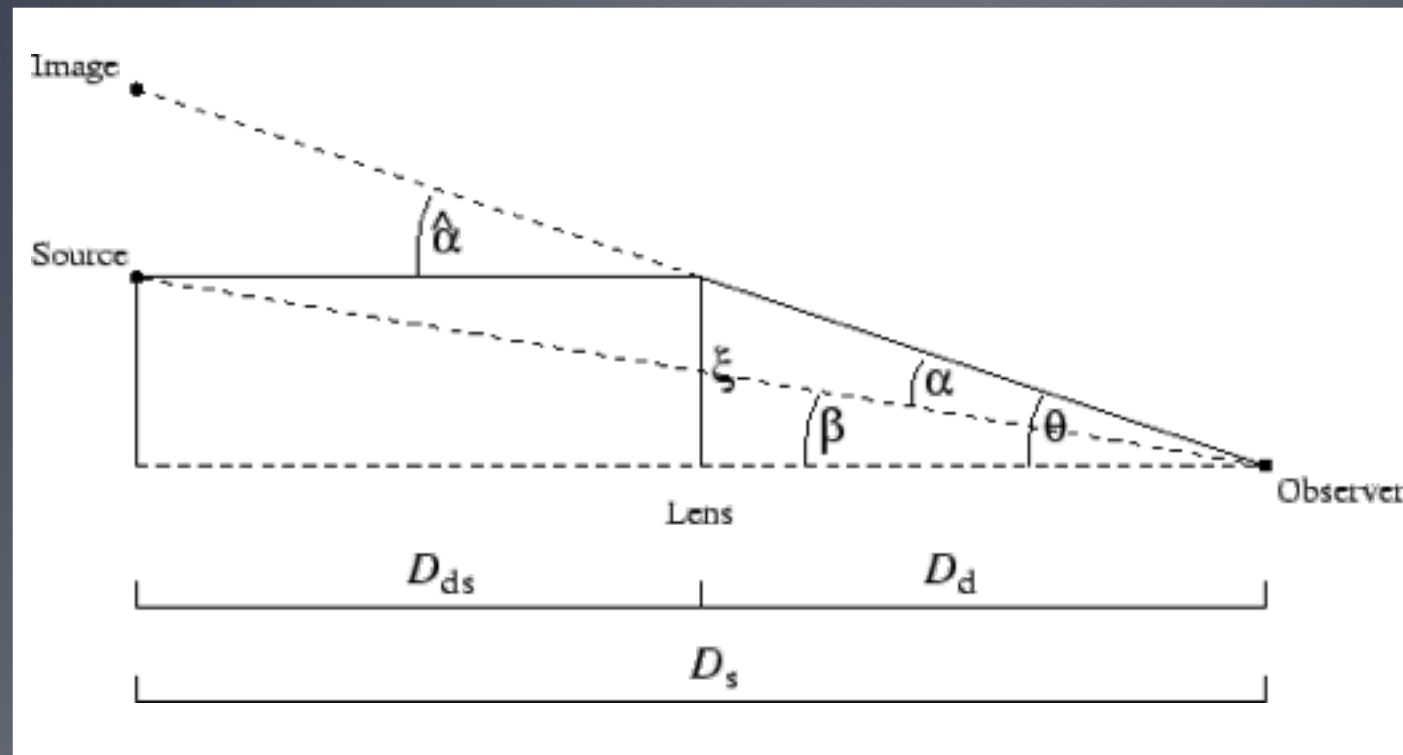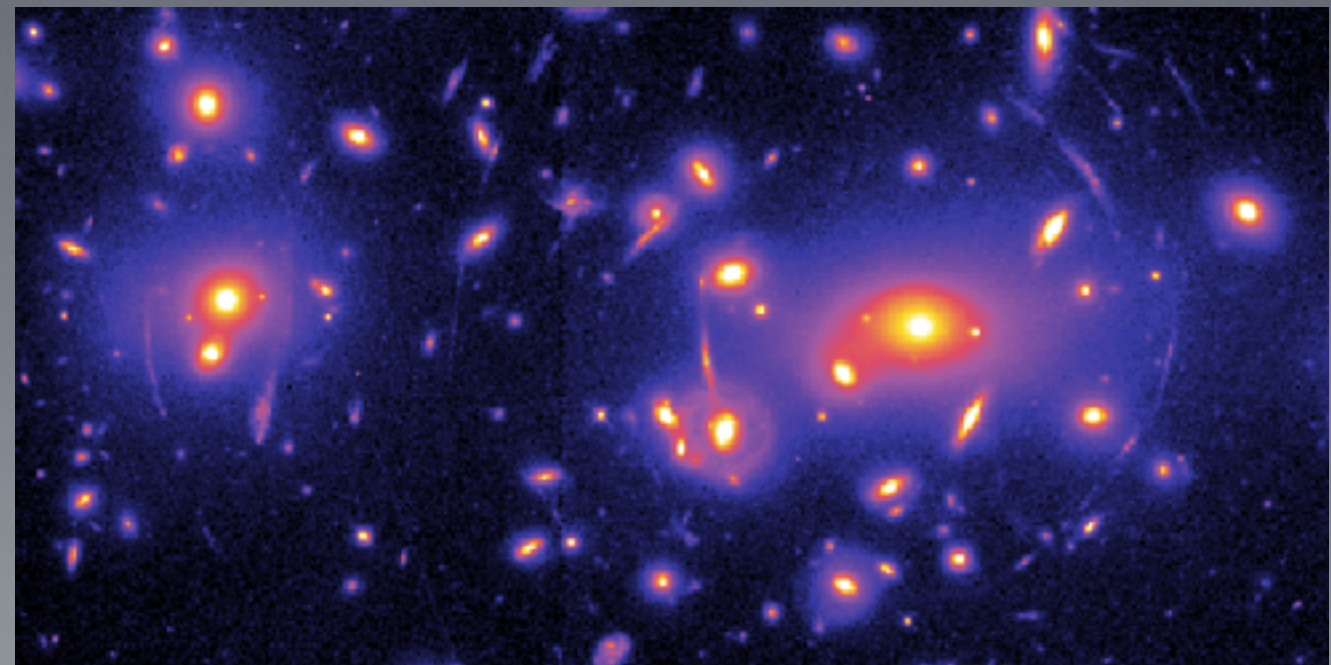Sensitive to all matter along line of sight, including dark matter!

# More generally…

Diagram from Narayan & Bartelmann (1997)

$$\hat{\alpha} = \frac{4G}{c^2} \frac{M(<\xi)}{\xi}$$

Credit: Couch & Ellis / NASA

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Weak lensing

- Very small deflection angles

- Coherent statistical distortion (shear, γ) of galaxy shapes

- Does not require chance superposition like strong lensing

Picture credit:
LSST Science
Book

sheared image
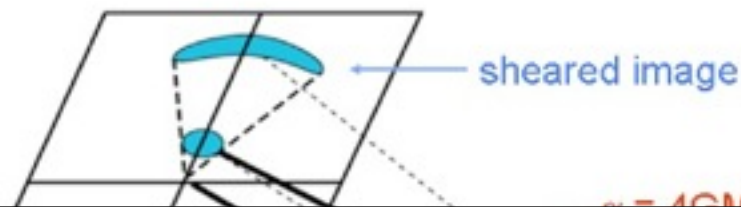
$\alpha = 4GM/bc^2$

D_S

D_{LS}

b

Weak lensing

- Very small deflection angles

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Picture credit:
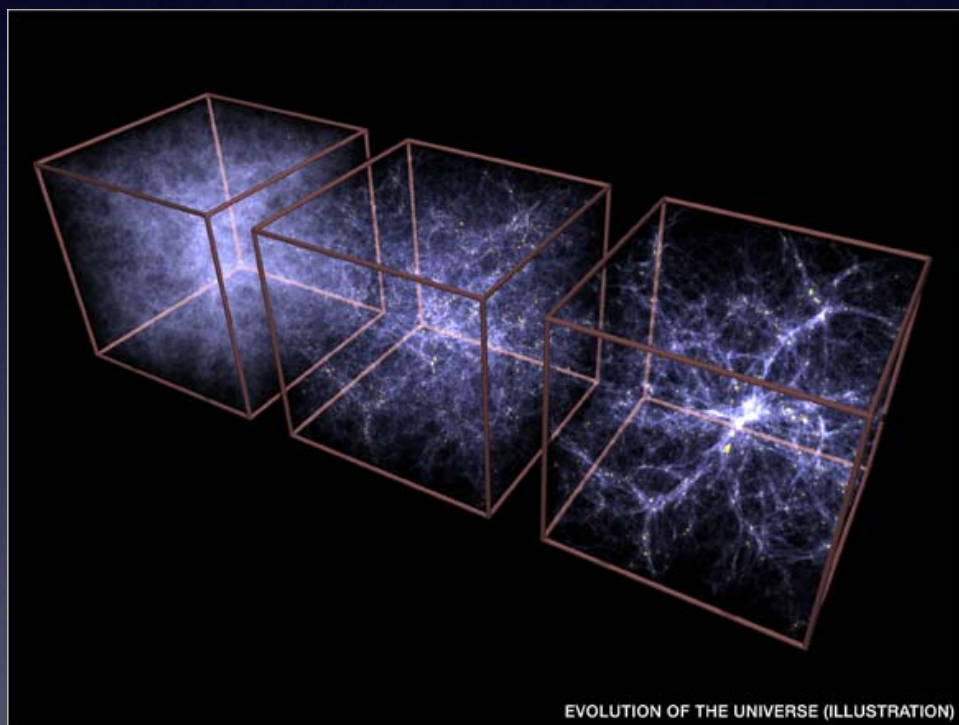LSST Science
Book

sheared image
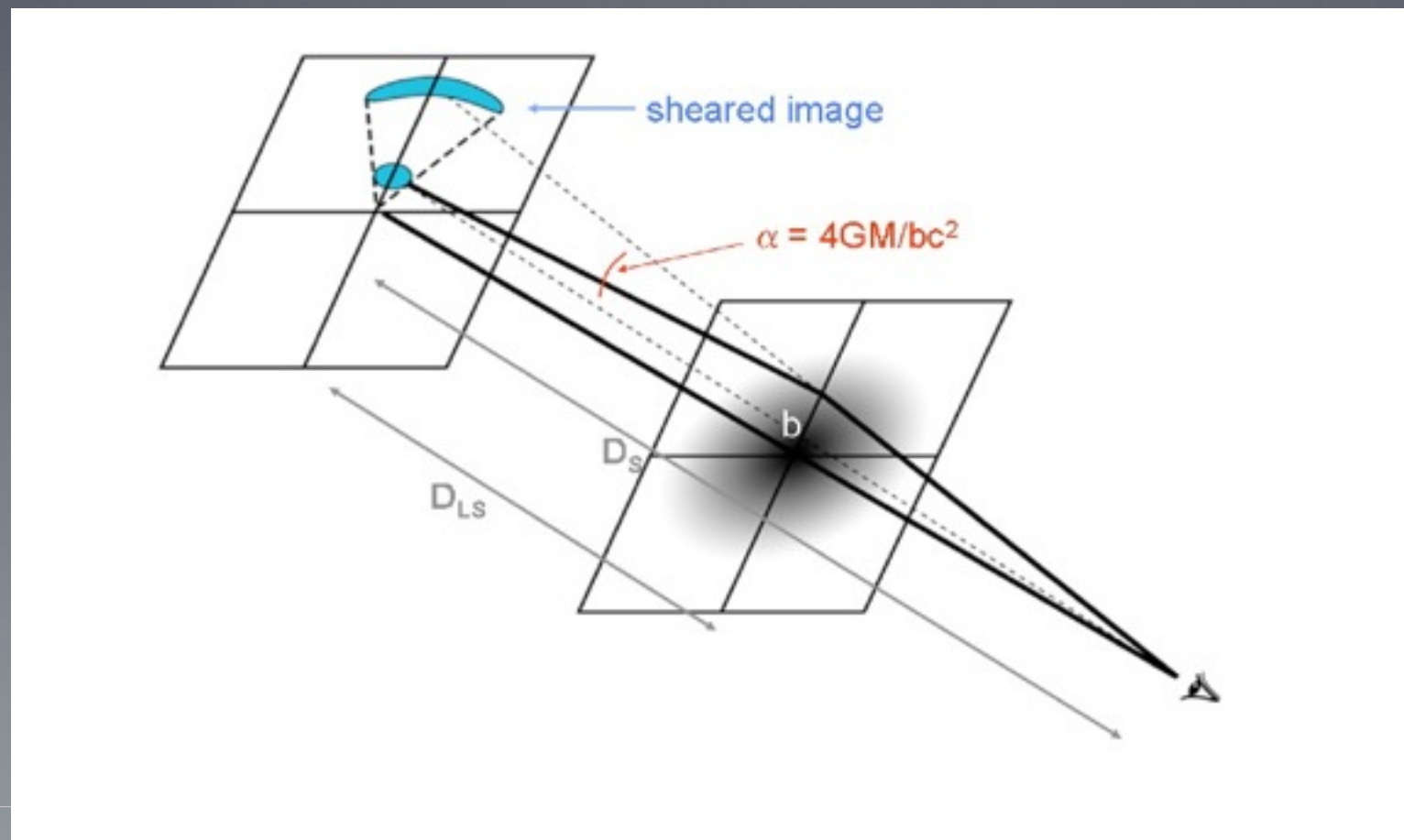
Lensing depends on:
- Enclosed mass
- Distance from that mass
- "Lensing kernel": distances to lens and source

R. Mandelbaum

Why should you care about weak lensing?

Structure growth!

EVOLUTION OF THE UNIVERSE (ILLUSTRATION)

Dark matter and dark energy!

Dark Matter 26.8%

Ordinary Matter 4.9%

Dark Energy 68.3%

ESA/Planck
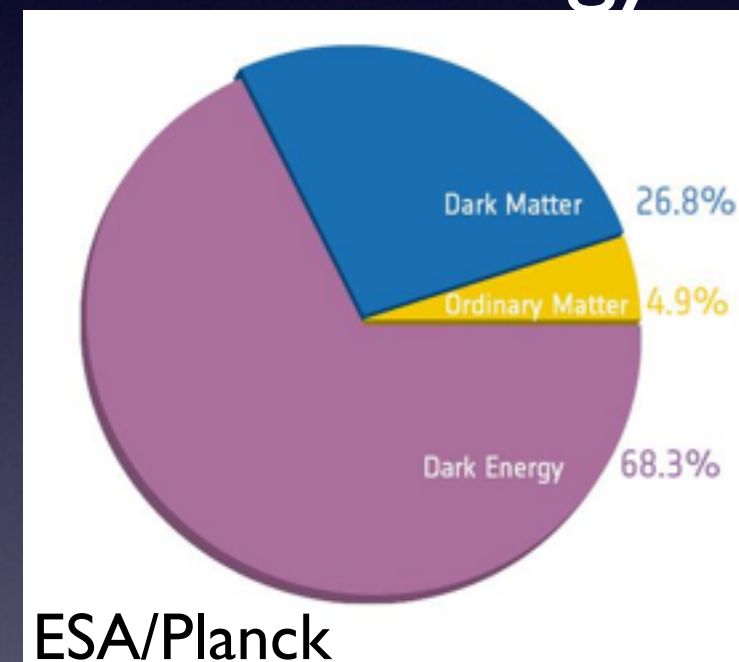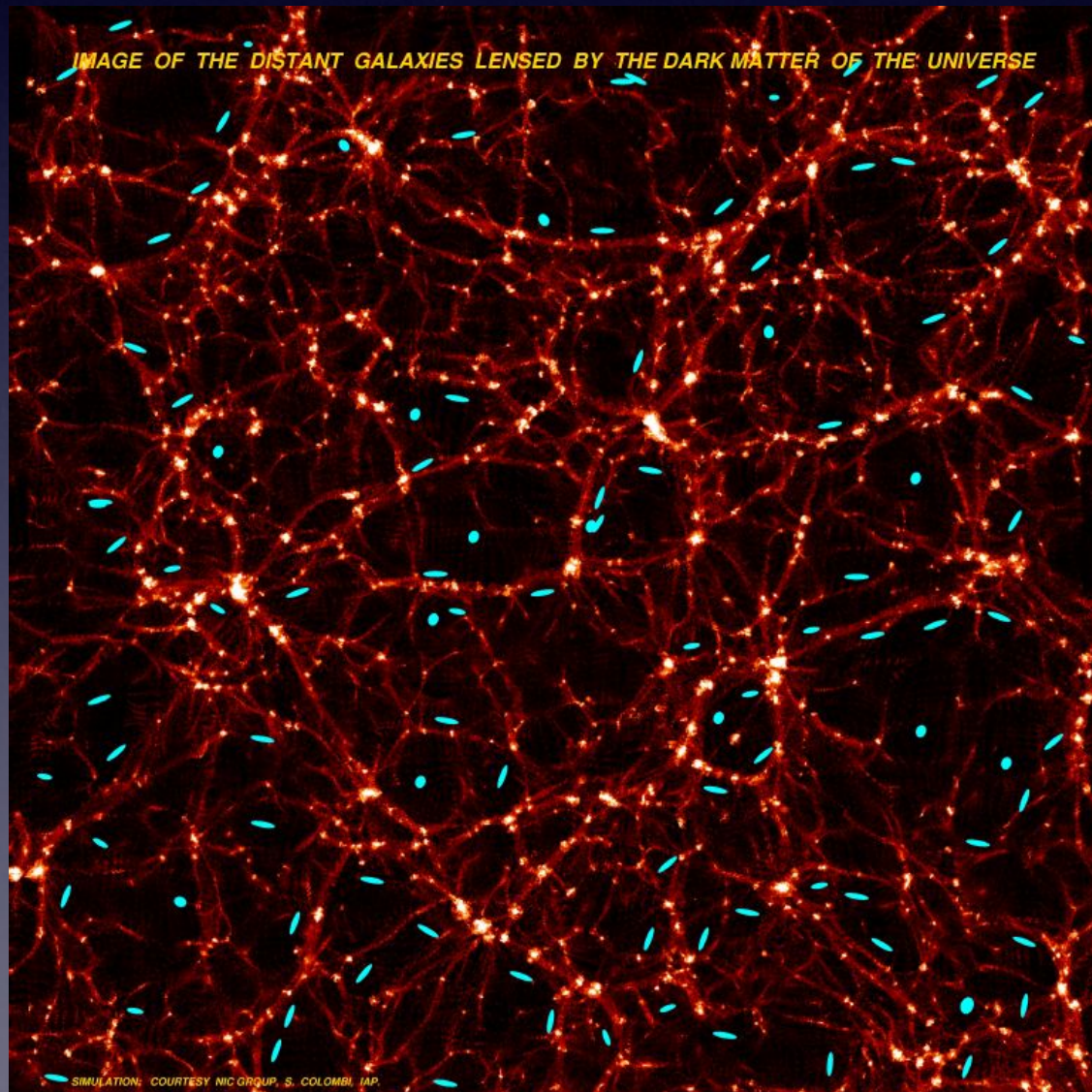
Theory of gravity!

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

Galaxy-dark matter connection!

So how does this work?

Cosmic shear:
weak lensing by large-scale structure

IMAGE OF THE DISTANT GALAXIES LENSED BY THE DARK MATTER OF THE UNIVERSE
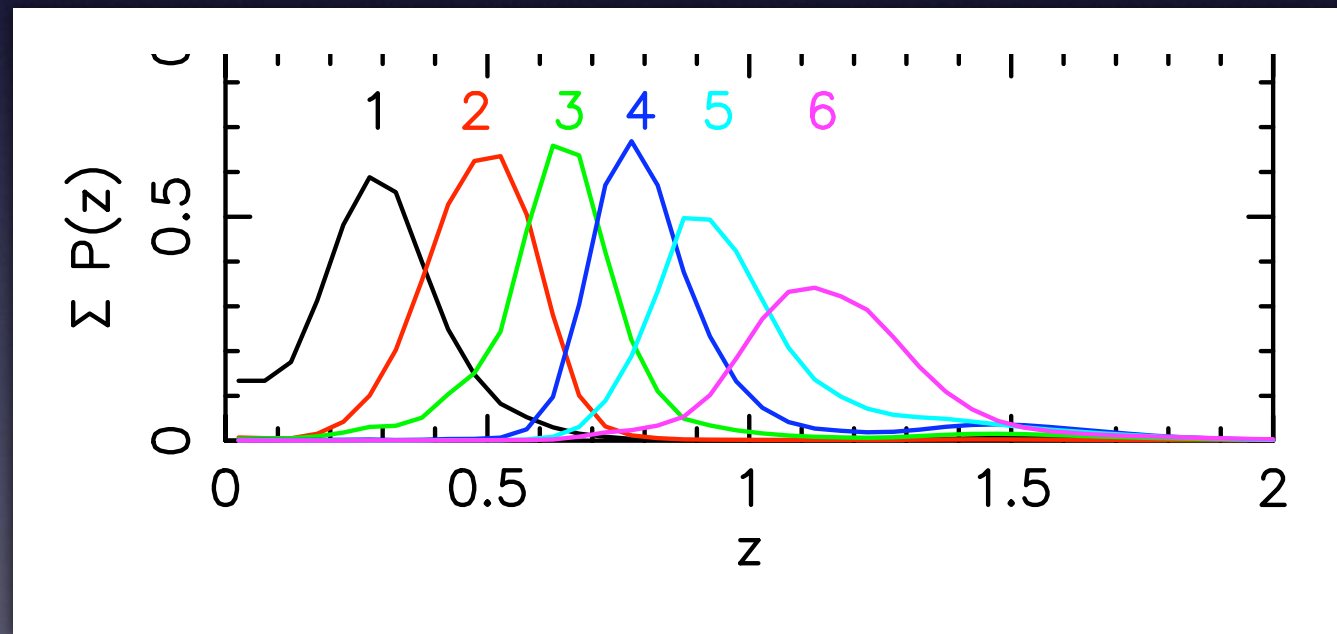SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Requires catalogs with:
1. Galaxy positions
2. Galaxy shear estimates (maybe?)

And an estimate of dN/dz.

So how does this work?

Cosmic shear:
weak lensing by large-scale structure

Heymans et al. (2013)
CFHTLenS

Tomography requires catalogs with:
1. Galaxy positions
2. Galaxy shear estimates
3. Galaxy redshift estimates (photo-z or p(z))

So how does this work?

Cosmic shear:
weak lensing by large-scale structure

$$\hat{\xi}^{ij}_{\pm}(\theta) = \frac{\sum w_a w_b \left[\epsilon^i_t(\boldsymbol{x_a})\epsilon^j_t(\boldsymbol{x_b}) \pm \epsilon^i_\times(\boldsymbol{x_a})\epsilon^j_\times(\boldsymbol{x_b})\right]}{\sum w_a w_b}$$

Tomography requires catalogs with:
1. Galaxy positions
2. Galaxy shear estimates
3. Galaxy redshift estimates (photo-z or p(z))

So how does this work?

Cosmic shear:
weak lensing by large-scale structure

Indices of z bins   Separation on
                         the sky

$$\hat{\xi}_{\pm}^{ij}(\theta) = \frac{\sum \mathrm{w}_a \mathrm{w}_b \left[\epsilon_t^i(\boldsymbol{x_a}) \epsilon_t^j(\boldsymbol{x_b}) \pm \epsilon_\times^i(\boldsymbol{x_a}) \epsilon_\times^j(\boldsymbol{x_b}) \right]}{\sum \mathrm{w}_a \mathrm{w}_b}$$

Shear correlation functions

Tomography requires catalogs with:
1. Galaxy positions
2. Galaxy shear estimates
3. Galaxy redshift estimates (photo-z or p(z))

So how does this work?

Cosmic shear:
weak lensing by large-scale structure

shears in coordinate system
aligned with vector connecting galaxy pair

$$\hat{\xi}_{\pm}^{ij}(\theta) = \frac{\sum w_a w_b \left[\epsilon_t^i(\boldsymbol{x_a}) \epsilon_t^j(\boldsymbol{x_b}) \pm \epsilon_\times^i(\boldsymbol{x_a}) \epsilon_\times^j(\boldsymbol{x_b}) \right]}{\sum w_a w_b}$$
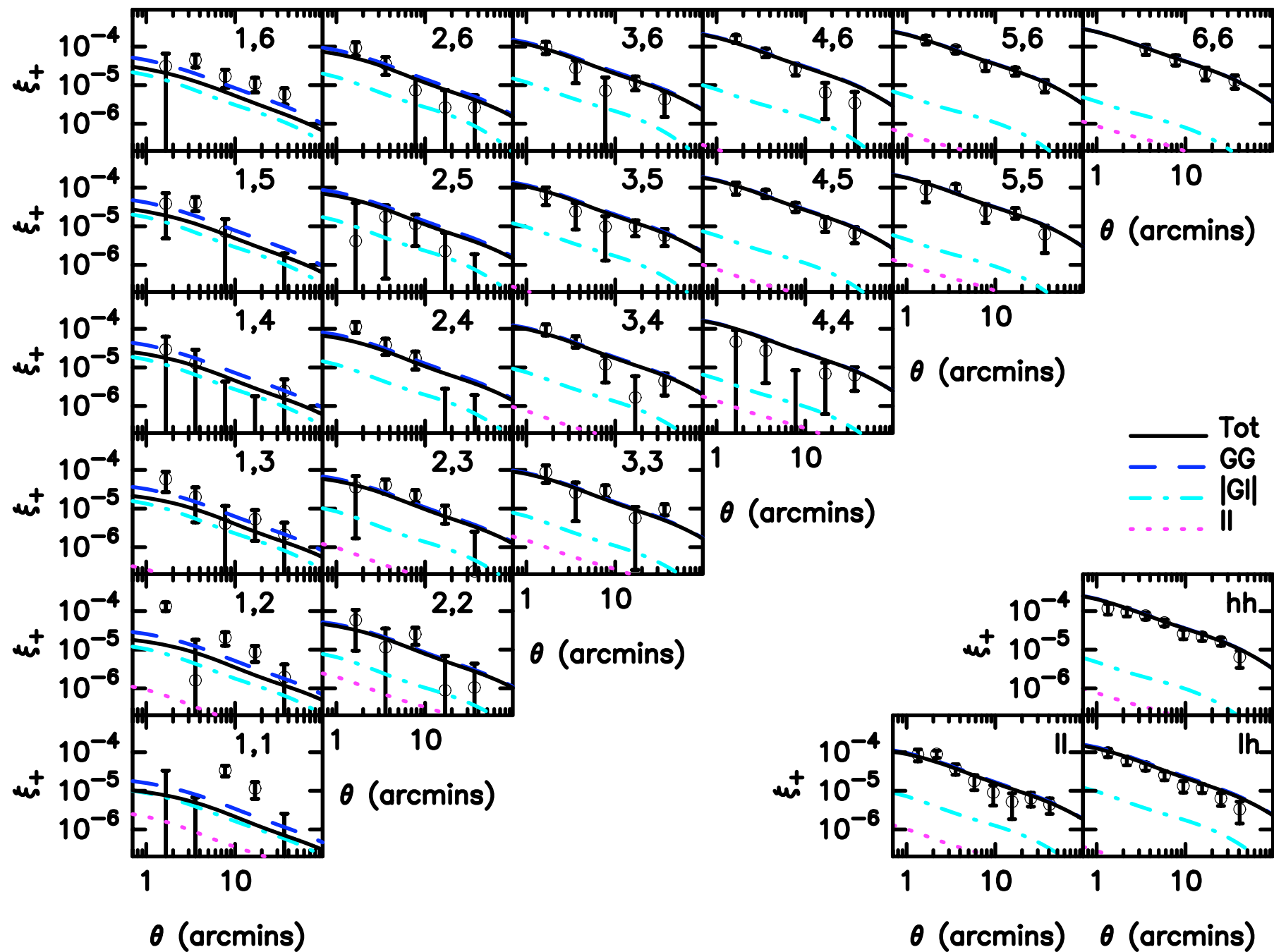
galaxy positions   weight factors

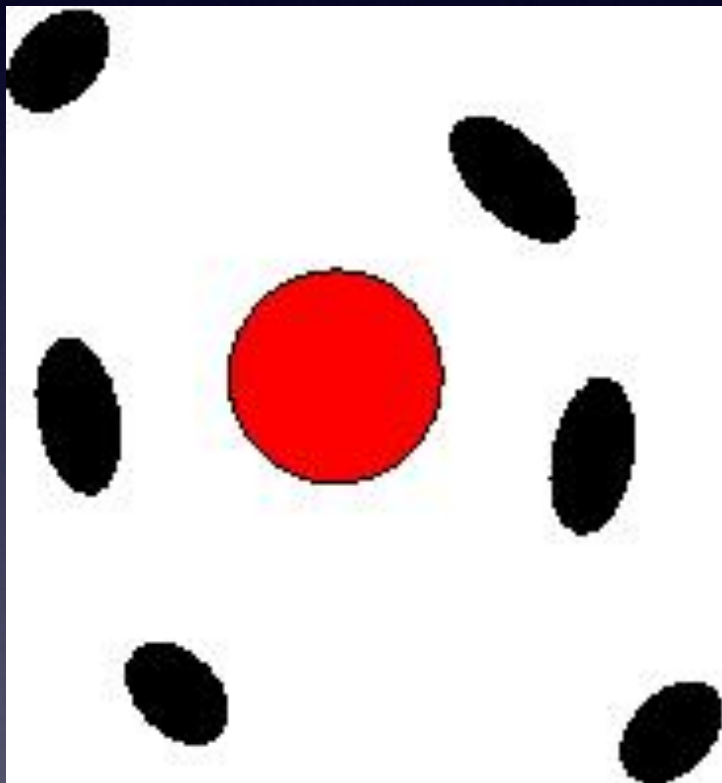Tomography requires catalogs with:
1. Galaxy positions
2. Galaxy shear estimates
3. Galaxy redshift estimates (photo-z or p(z))

e.g., in CFHTLenS

(Heymans et al. 2013)

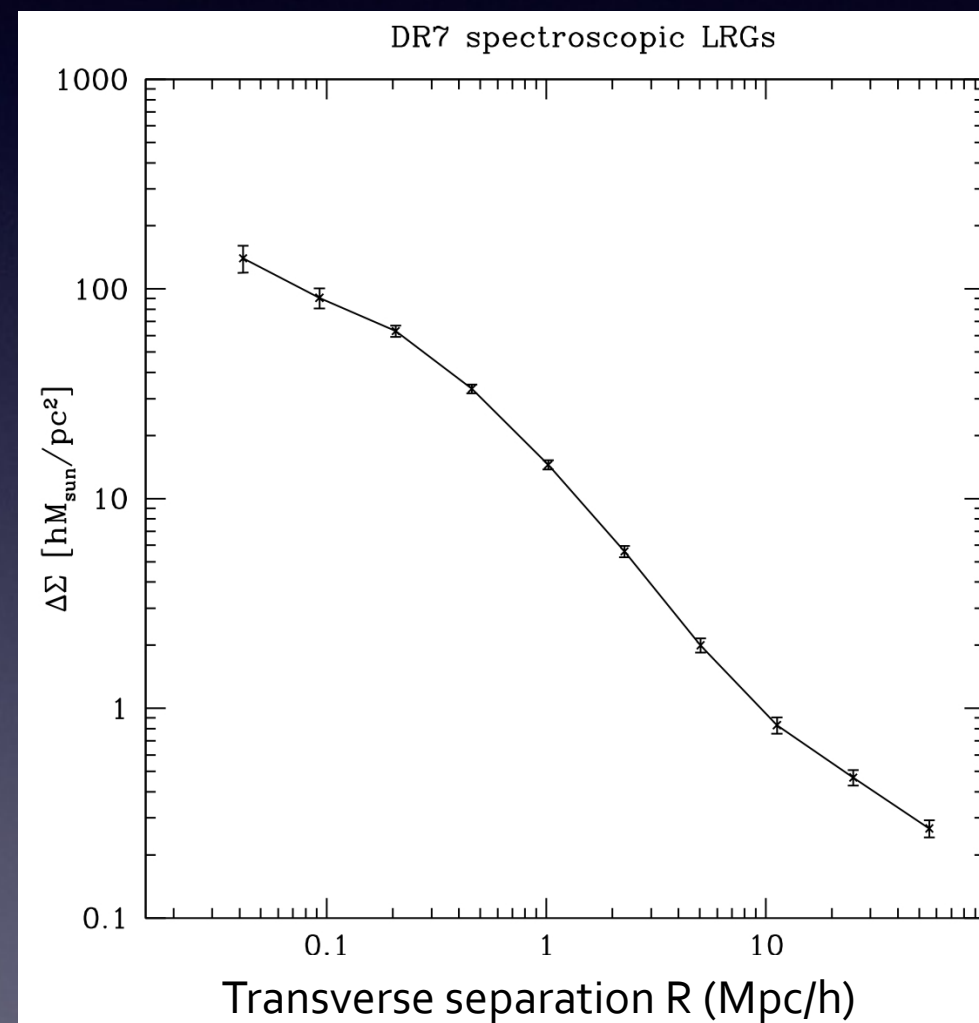# Another option:
galaxy-galaxy or cluster-galaxy lensing

Requires catalogs with:
1. Background galaxy positions, shear estimates, redshift estimates
2. A sample of foreground masses

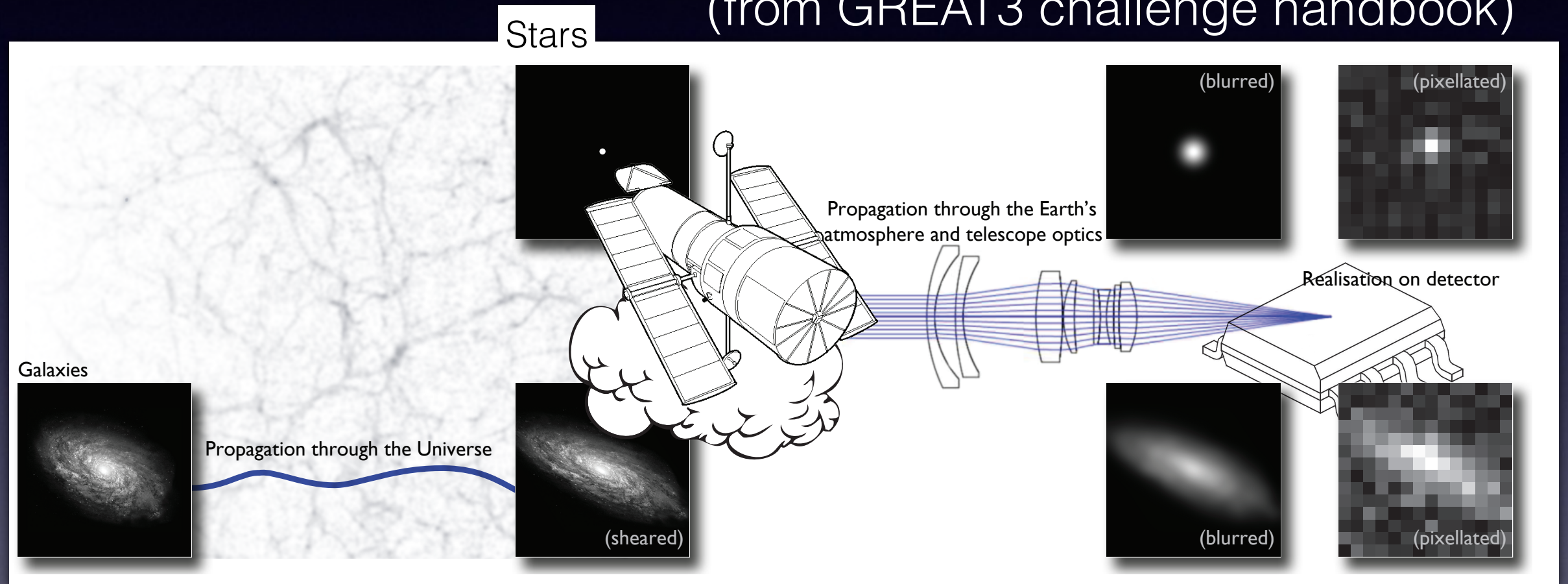# Another option:
galaxy-galaxy or cluster-galaxy lensing

Mass profiles of massive galaxies, including large-scale structure
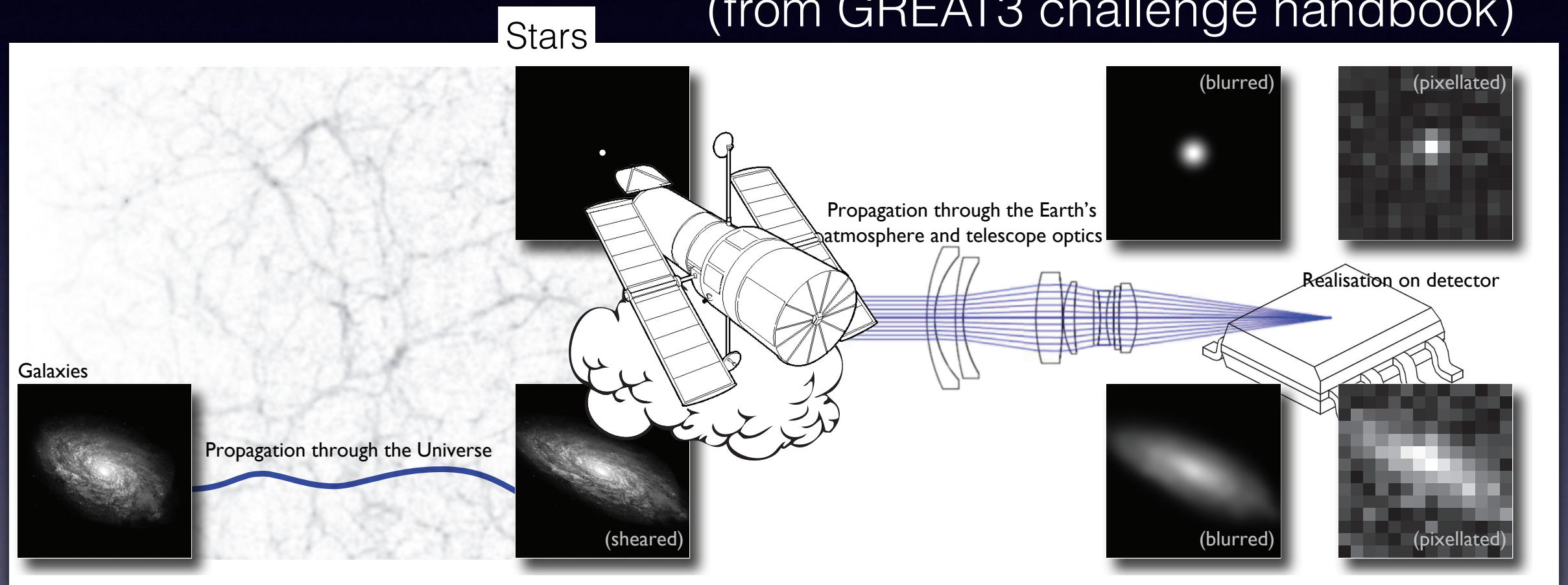
(RM et al. 2013)

Where do systematics come in?

(from GREAT3 challenge handbook)

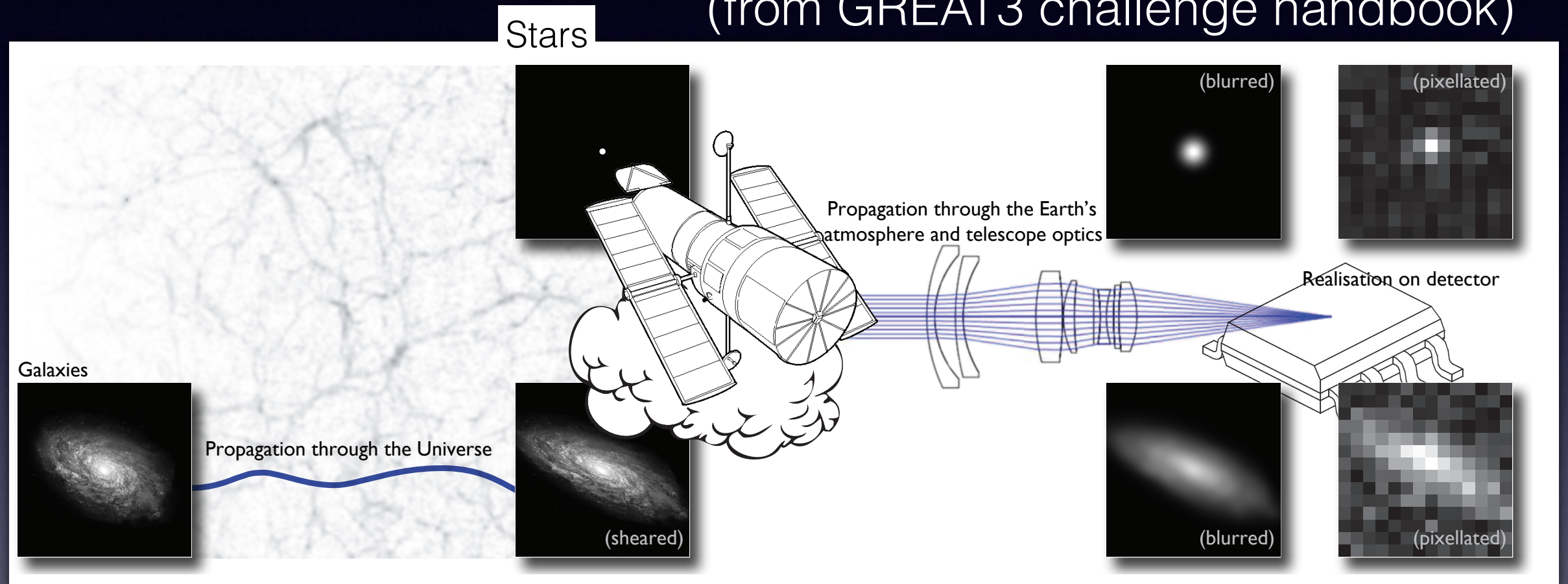# Where do systematics come in?

(from GREAT3 challenge handbook)

To estimate the shear, we have to measure galaxy image properties, and *estimate* and *remove* the PSF

Where do systematics come in?

(from GREAT3 challenge handbook)

To estimate the shear, we have to measure galaxy image properties, and *estimate* and ~~remove~~ the PSF

Examples of where systematics come in

- Chromatic effects: PSF for stars is different from that for galaxies, or even within different parts of the same galaxy.

- Brighter-fatter effect: PSF for bright stars is fatter than that for the galaxies.

- Tree rings, edge distortion: astrometry (a remapping that isn't a convolution)

- Cosmic rays: basic measurement issue

- Defects can lead to coherent selection effects

The connection to science

Model errors in shapes as a multiplicative bias, additive term:

$$\gamma_{meas} = (1+m)\, \gamma_{true} + c$$

(Ideally m=c=0)

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Model errors in shapes as a multiplicative bias, additive term:

$$\gamma_{meas} = (1+m)\, \gamma_{true} + c$$

(Ideally m=c=0)

Galaxy-galaxy lensing (shear-position correlation):

$$\langle g\, \gamma_{meas}\rangle = (1+m)\, \langle g\, \gamma_{true}\rangle + \langle g\, c\rangle$$

Calibration bias

Additive term (often removable)

The connection to science

Model errors in shapes as a multiplicative bias, additive term:

$$\gamma_{meas} = (1+m)\, \gamma_{true} + c$$

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The connection to science

Model errors in shapes as a multiplicative bias, additive term:

$$\gamma_{meas} = (1+m)\ \gamma_{true} + c$$

(Ideally m=c=0)

Cosmic shear (shear-shear correlation):

$$\langle\gamma_{meas}\ \gamma_{meas}\rangle = (1+m)^2\ \langle\gamma_{true}\ \gamma_{true}\rangle + 2\ (1+m)\ \langle c\ \gamma_{true}\rangle + \langle c\ c\rangle$$

Calibration bias
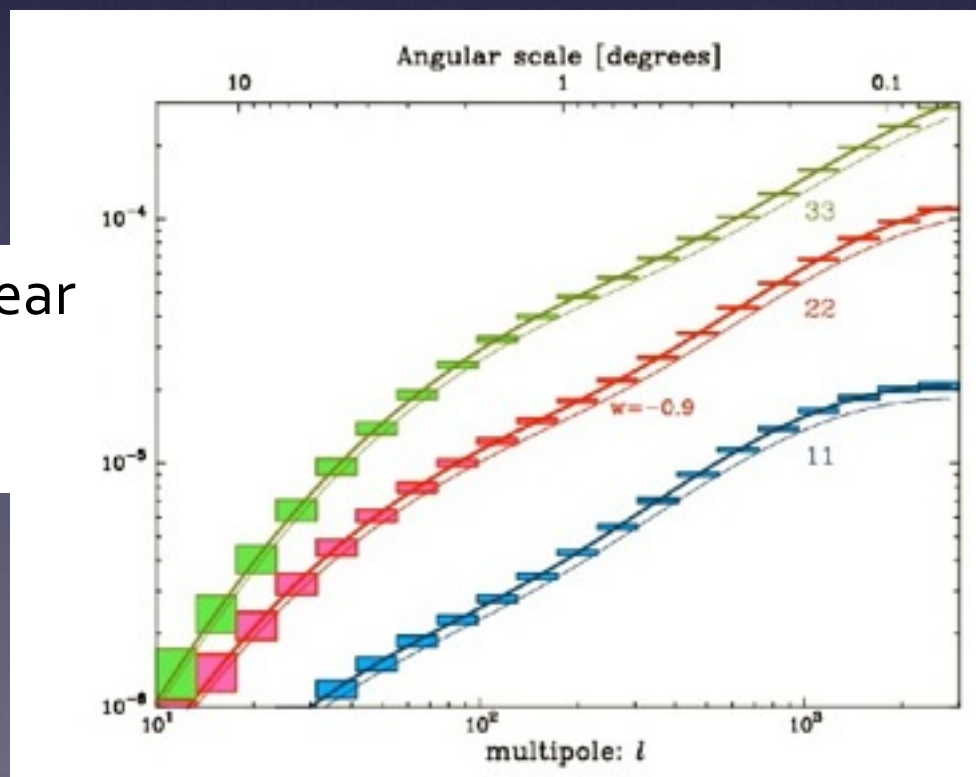
Additive term
(diagnosable with star-galaxy cross-correlations)

The connection to science

Model errors in shapes as a multiplicative bias, additive term:

$$\gamma_{meas} = (1+m)\,\gamma_{true} + c$$
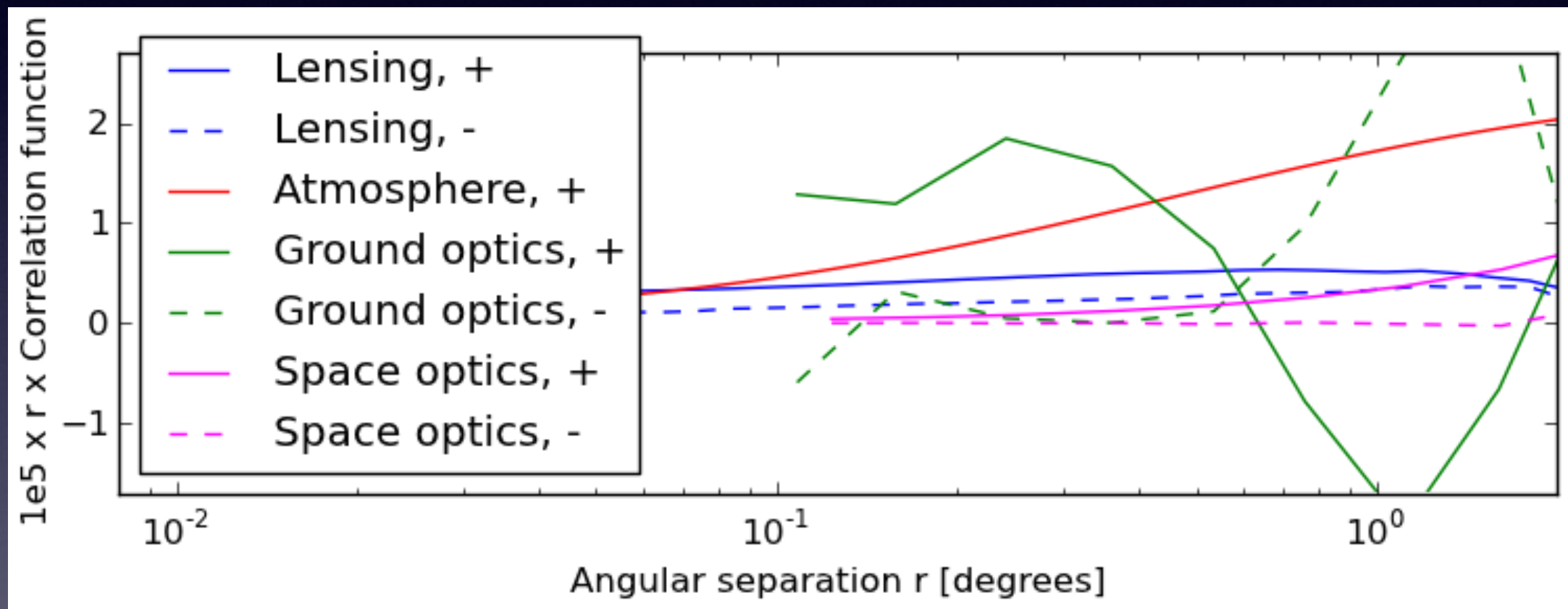
(Ideally m=c=0)

Cosmic shear power spectrum

Important note:
usually m = m(S/N, size, …) = m(z), effectively

and same for c

Picture credit: LSST science book

The connection to science

(from GREAT3 handbook)

Examples of instrumental effects

Brighter-fatter effect:

- If PSF size is wrong by 1%…

- For typical shear estimation methods and moderately-resolved galaxies, shear estimates will be wrong by 1%
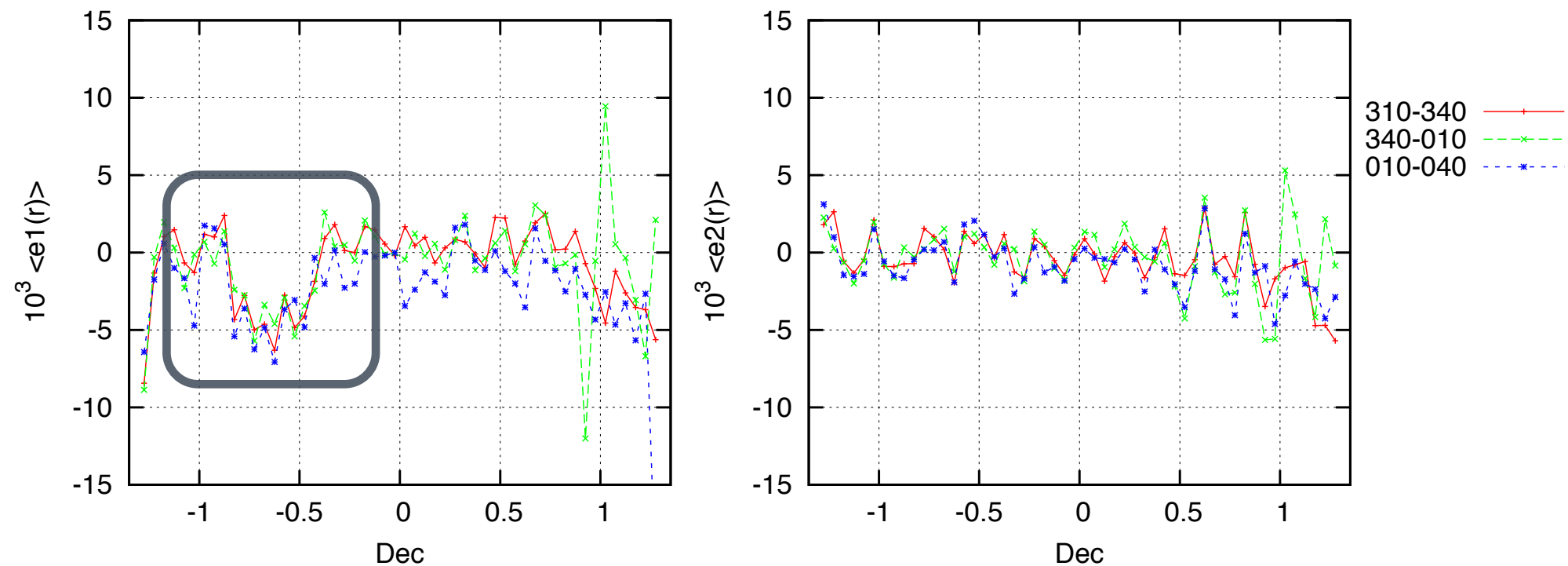
- Worse for smaller galaxies

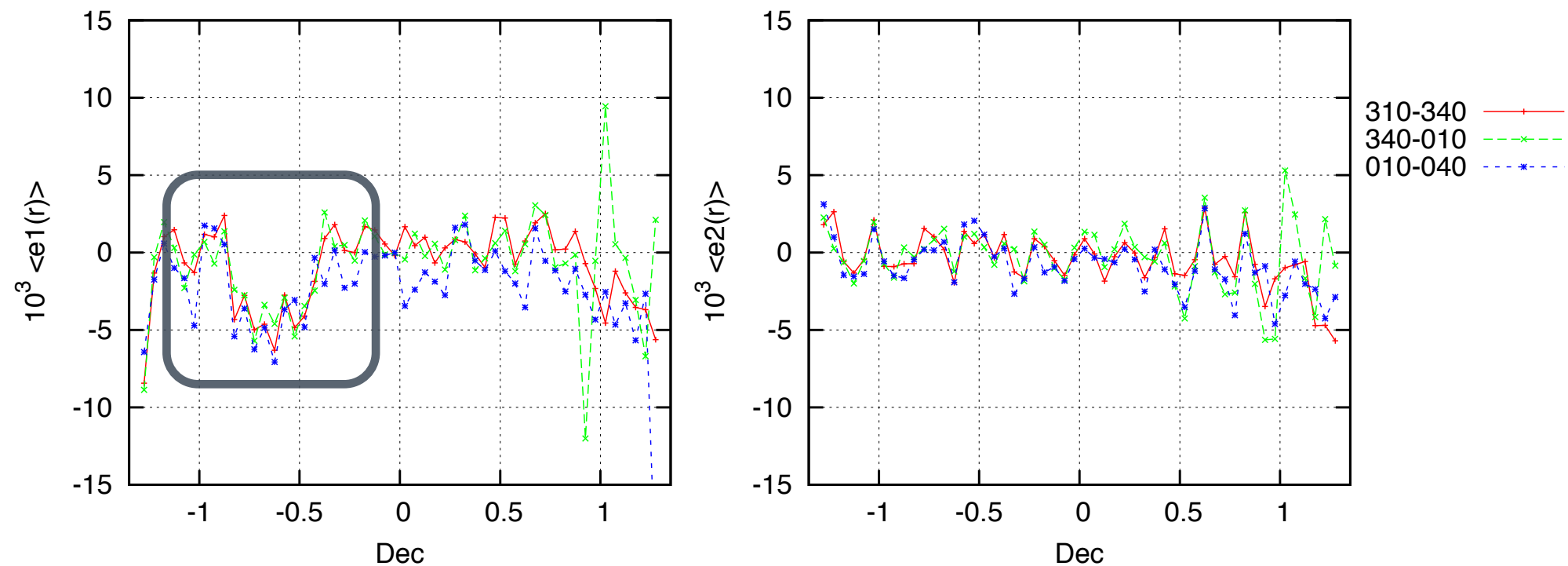# Examples of instrumental effects

Brighter-fatter effect:

- If PSF ellipticity is wrong by 0.01 (coherently)…

- For typical shear estimation methods, ~a few % of this will leak into the galaxy shapes, giving coherent shear of few x 10^{-4}

- Worse for smaller galaxies

Examples of instrumental effects

Huff et al. (2014)
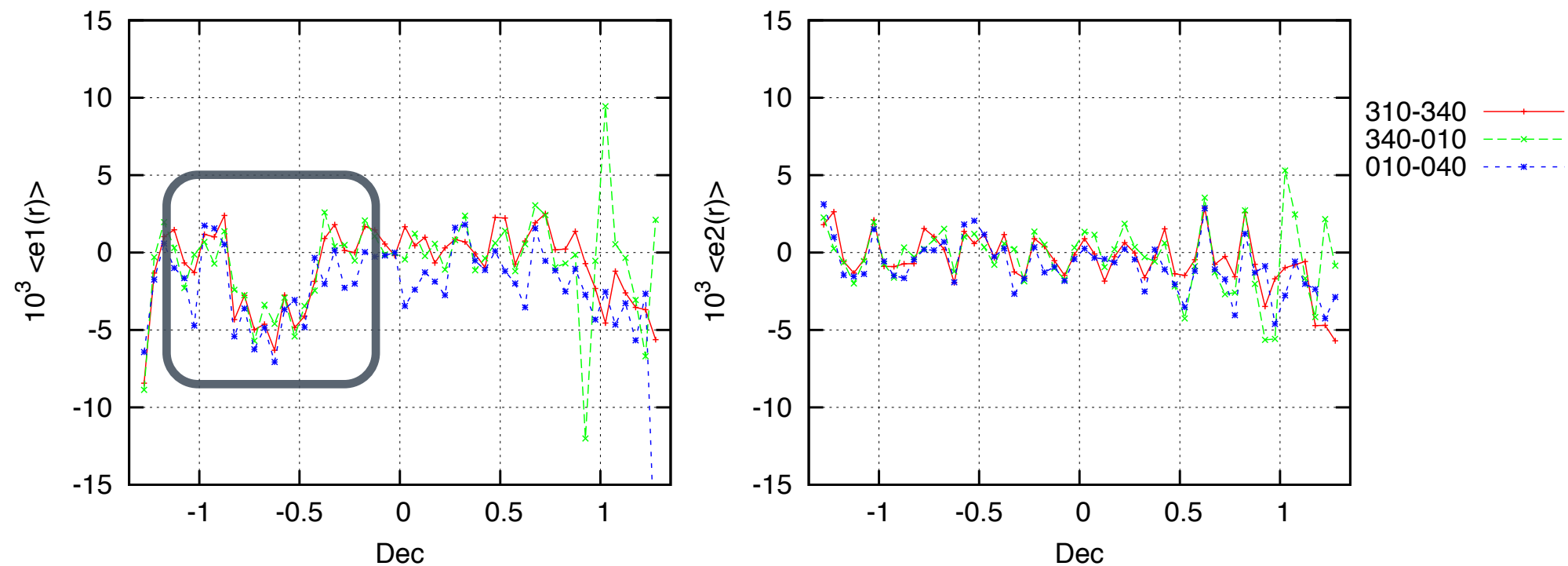
Examples of instrumental effects

Huff et al. (2014)

Best explanation for this: nonlinearity correction in SDSS r2 CCD is wrong.

Examples of instrumental effects

Huff et al. (2014)

Responsible for 2/3 of additive shear systematics in SDSS lensing analyses!

In the context of other analysis issues…

- PSF correction / shear estimation: many methods, lots of effort (incl. ongoing, based on 2 decades)

- Astrophysical and theoretical uncertainties: lots of work for the past 2 decades

- Instrumental systematics: less well-explored than these in WL context. Lots to do!

Conclusions

- Weak lensing science can do amazing things (dark energy, gravity, dark matter-galaxy connection)

- More work is needed on characterizing the impact of instrumental systematics!