Statistical challenges for the future of weak lensing cosmology

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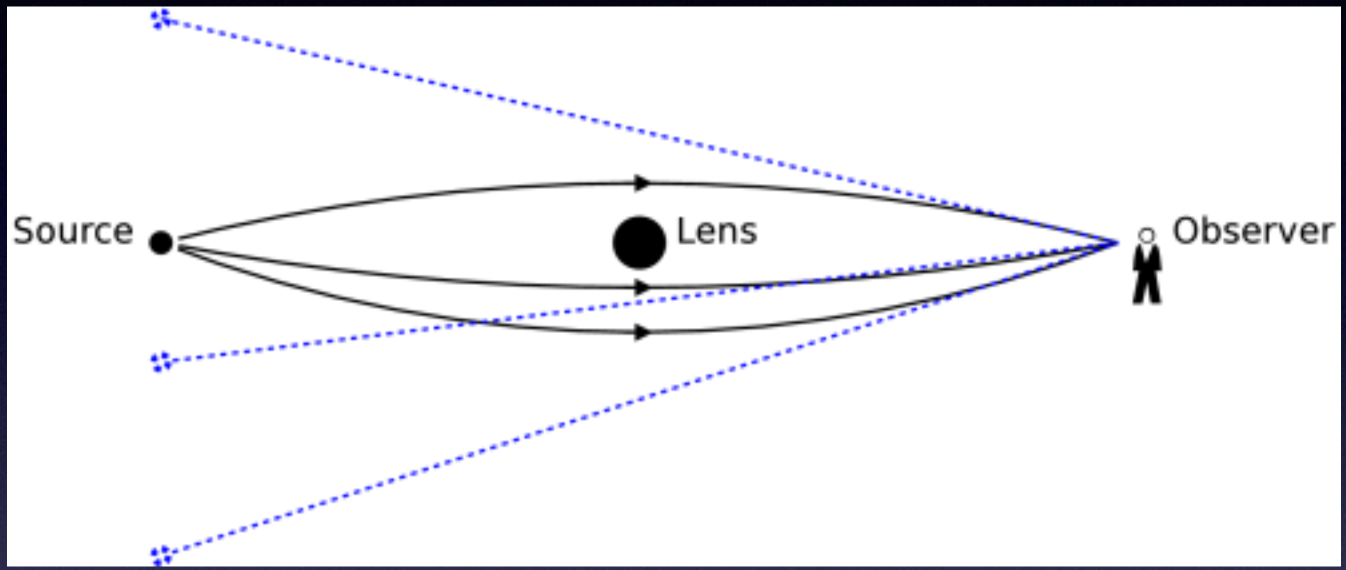
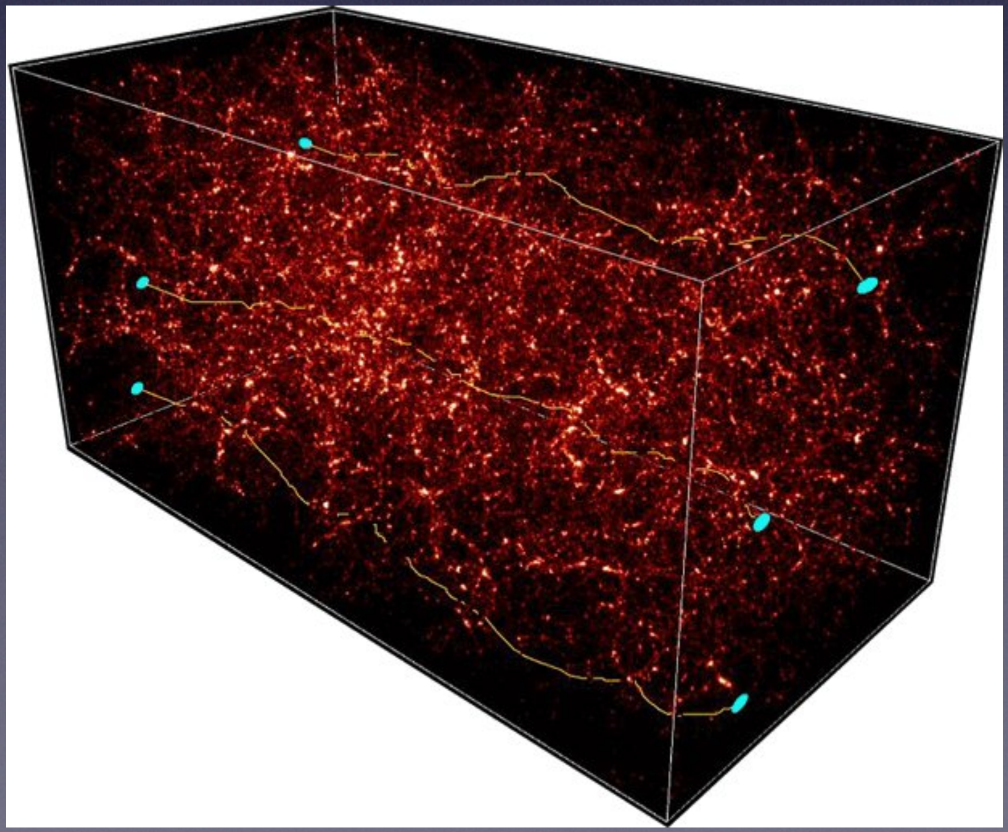
Gravitational lensing

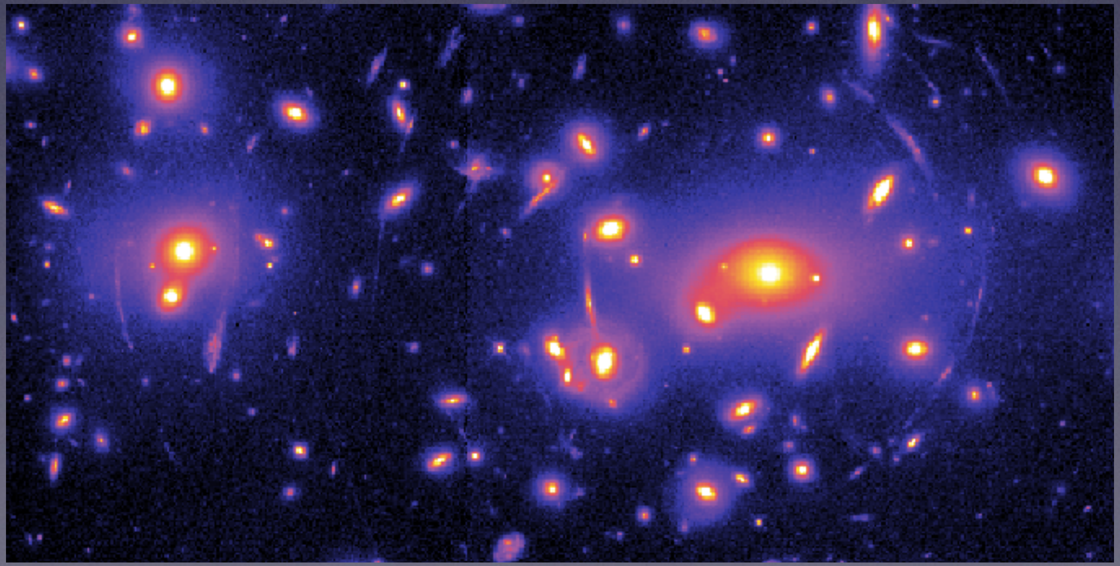


Deflection of light by all gravitational mass, including dark matter!

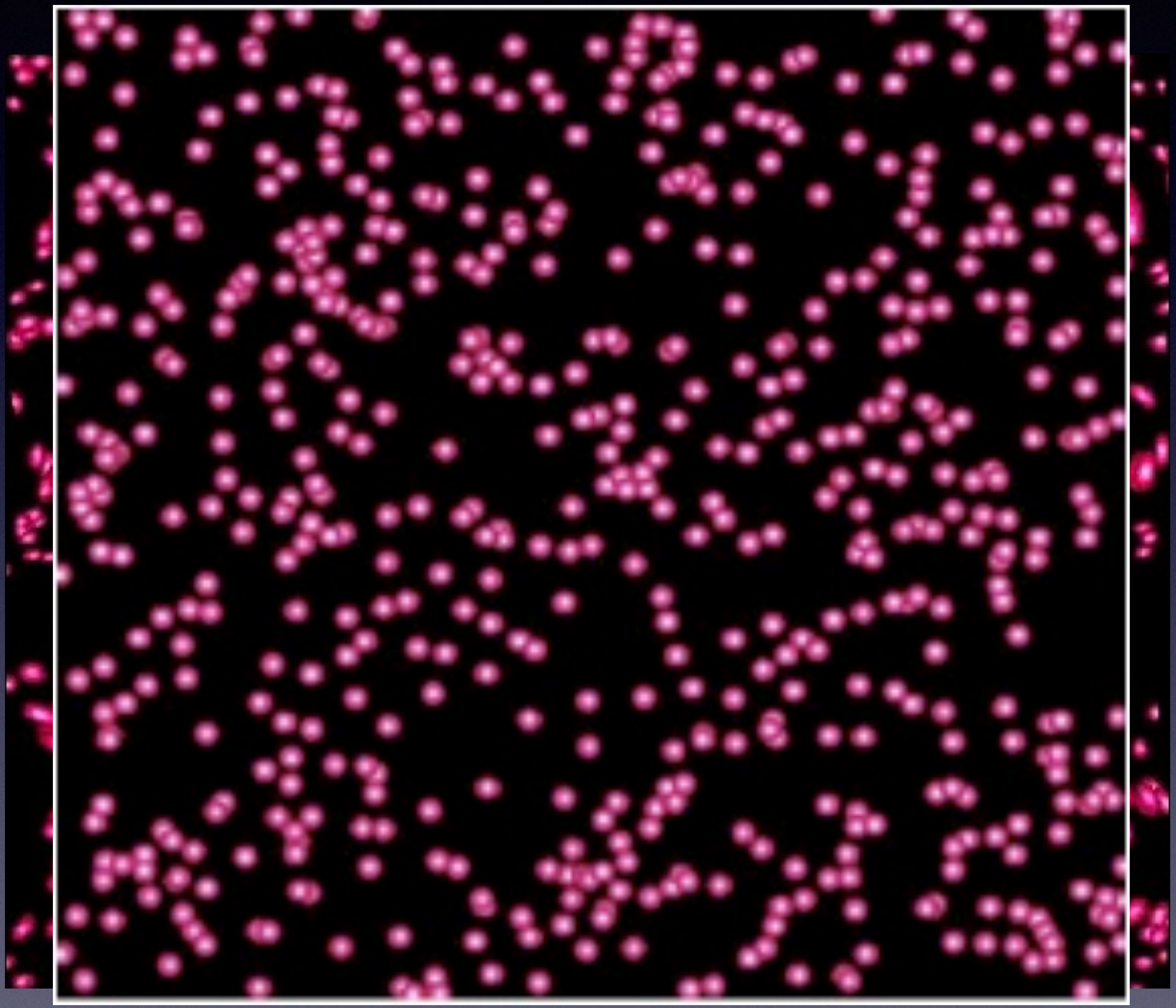
Weak: slight shape distortion and magnification



Strong: multiple images



Weak lensing (exaggerated)



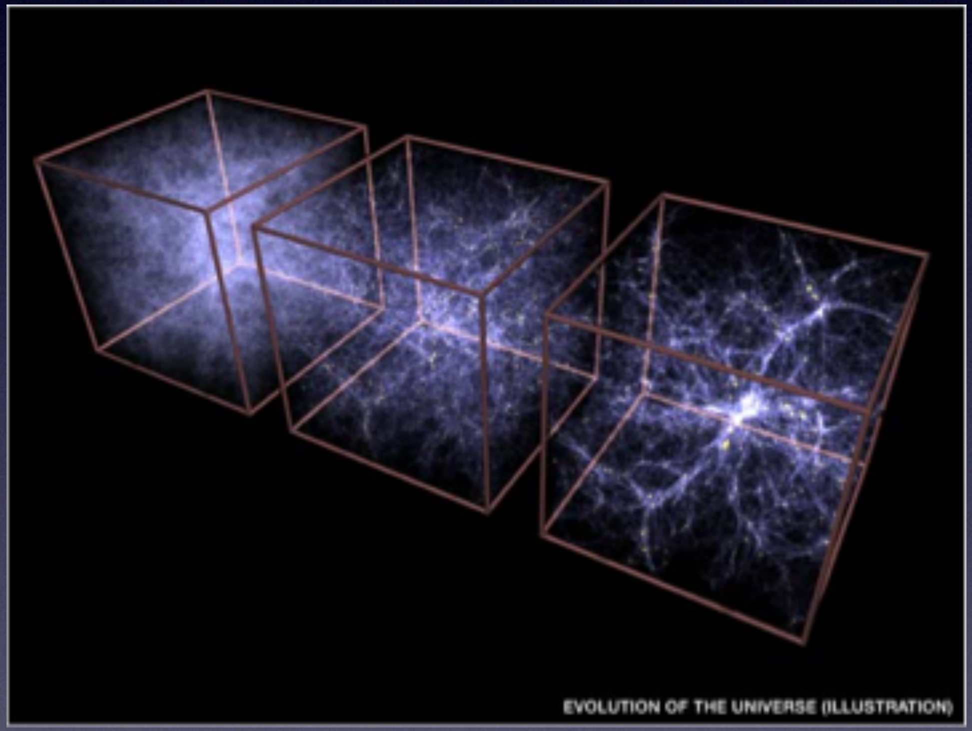
Coherent shape-shape (shear-shear) alignments

OR

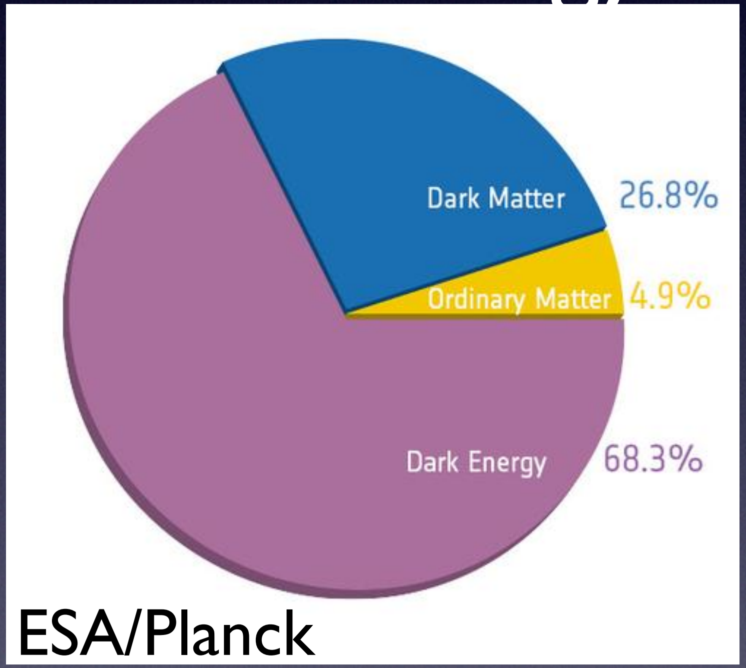
Coherent foreground position-background shape alignments

Why should you care about weak lensing?

Structure growth!



Dark matter and dark energy!



Theory of gravity!

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

Galaxy-dark matter connection!

Weak lensing with large surveys

Starting in 2003: shear-shear (cosmic shear) got lots of attention

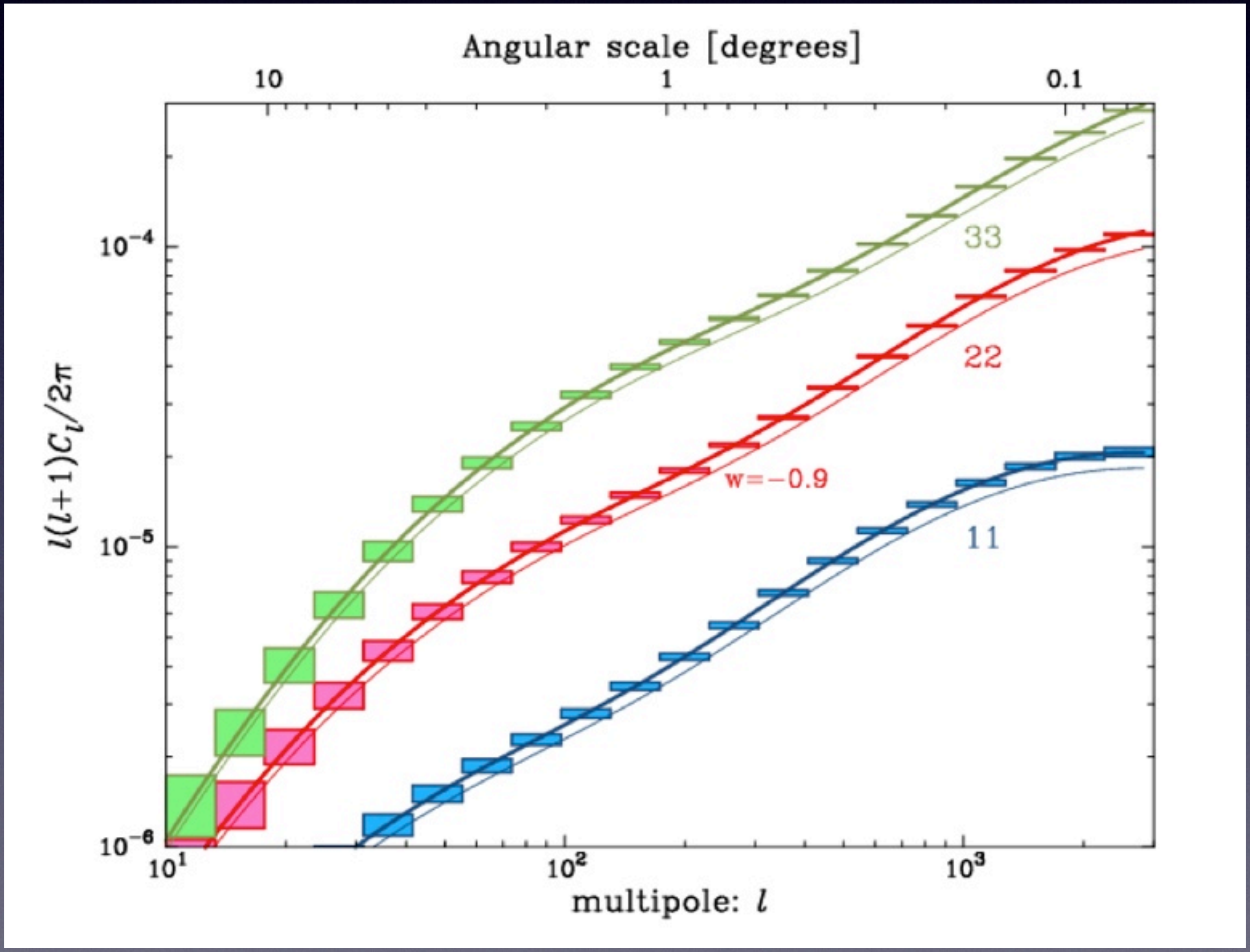
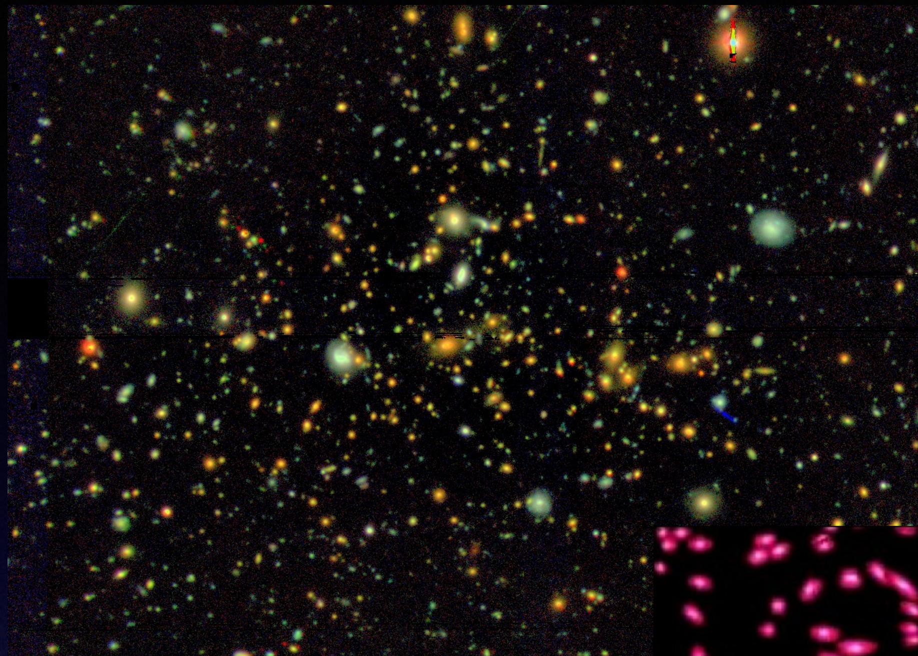
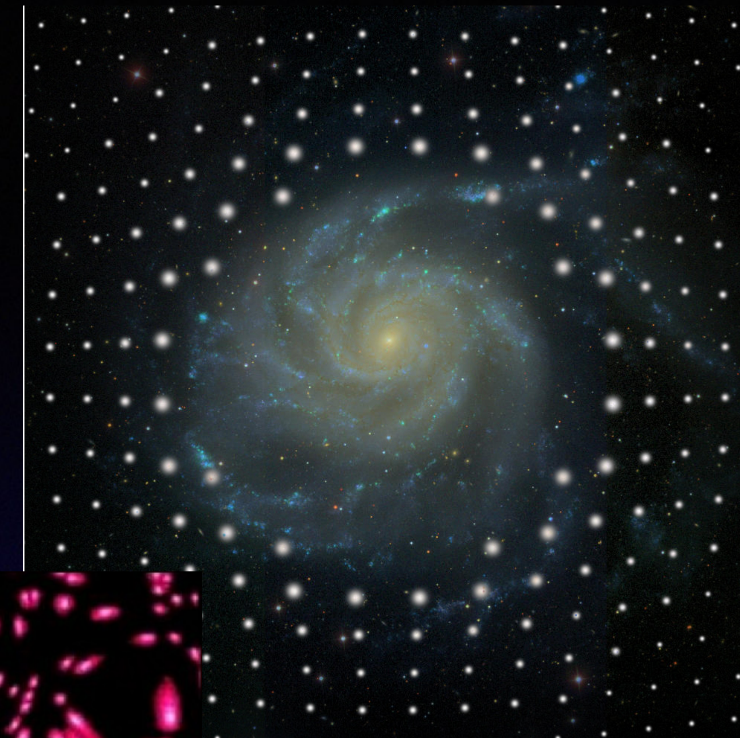


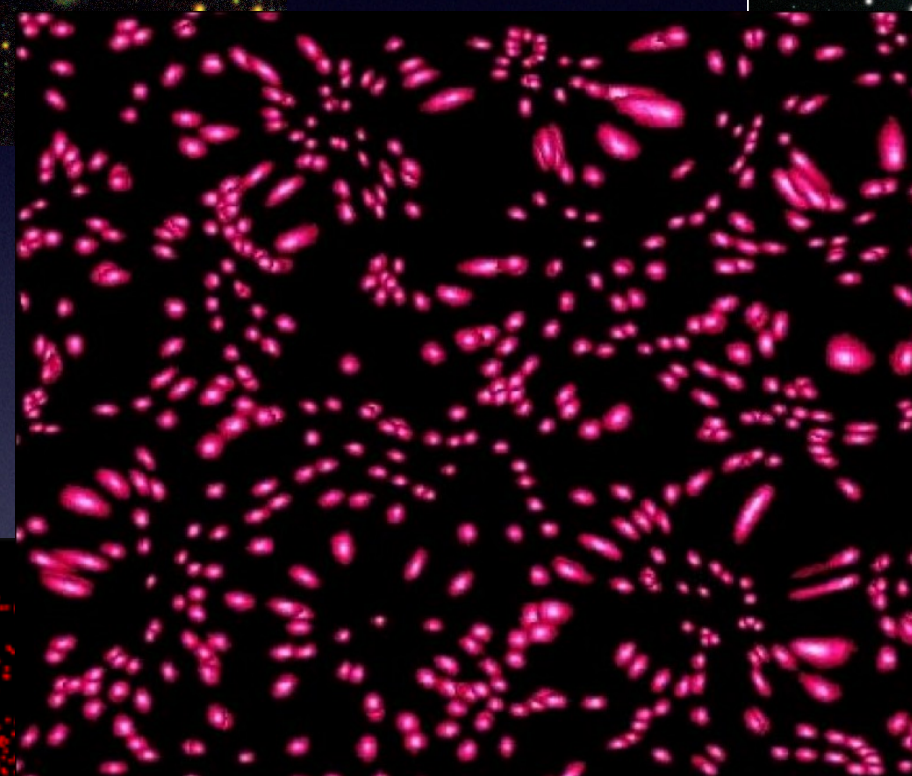
Image credit: LSST science book



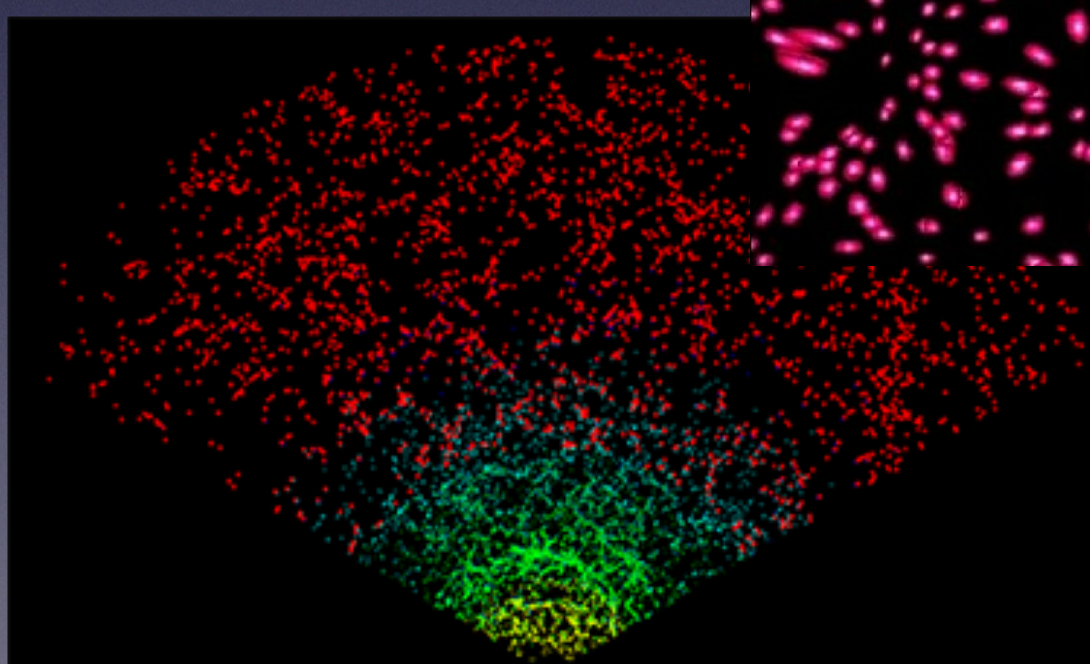
2d (2+1d?) galaxy density field



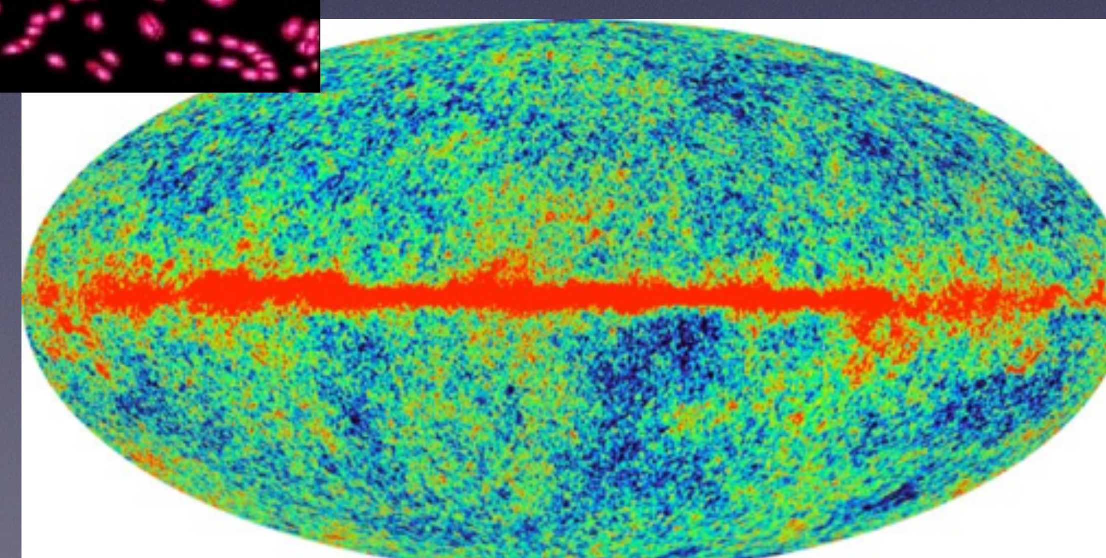
Lensing magnification



Lensing shear



3d galaxy density + peculiar velocity field



Cosmic microwave background

Why do we want that other stuff?

It's all about the systematics

Theoretical:

- Intrinsic alignments
- Baryonic effects
- …

Observational:

- Shear estimation
- Photometric redshifts
- …

Example (schematically)

1. shear-shear
2. OTHER-shear
3. OTHER-OTHER

If a systematic is in shear,
but not OTHER ⇨
use the combination to
marginalize over the
systematic

Example (schematically)

1. shear-shear
2. OTHER-shear
3. OTHER-OTHER

If a systematic is in shear, but not OTHER ⇨ use the combination to marginalize over the systematic

- Systematics: theoretical or observational
- OTHER: galaxy position is a popular one

(the default WL cosmology analysis in future?)

A cosmic shear alternative / consistency check?

Connection to the matter field

- shear-shear $\longrightarrow$ Matter-matter correlations

- Galaxy-shear $\longrightarrow$ Galaxy-matter
- Galaxy-galaxy

$$\frac{(\bar{\rho}\,\xi_{\rm gm})^2}{\xi_{\rm gg}} = (\bar{\rho}\,r_{\rm cc}^{(\xi)})^2 \xi_{\rm mm}$$

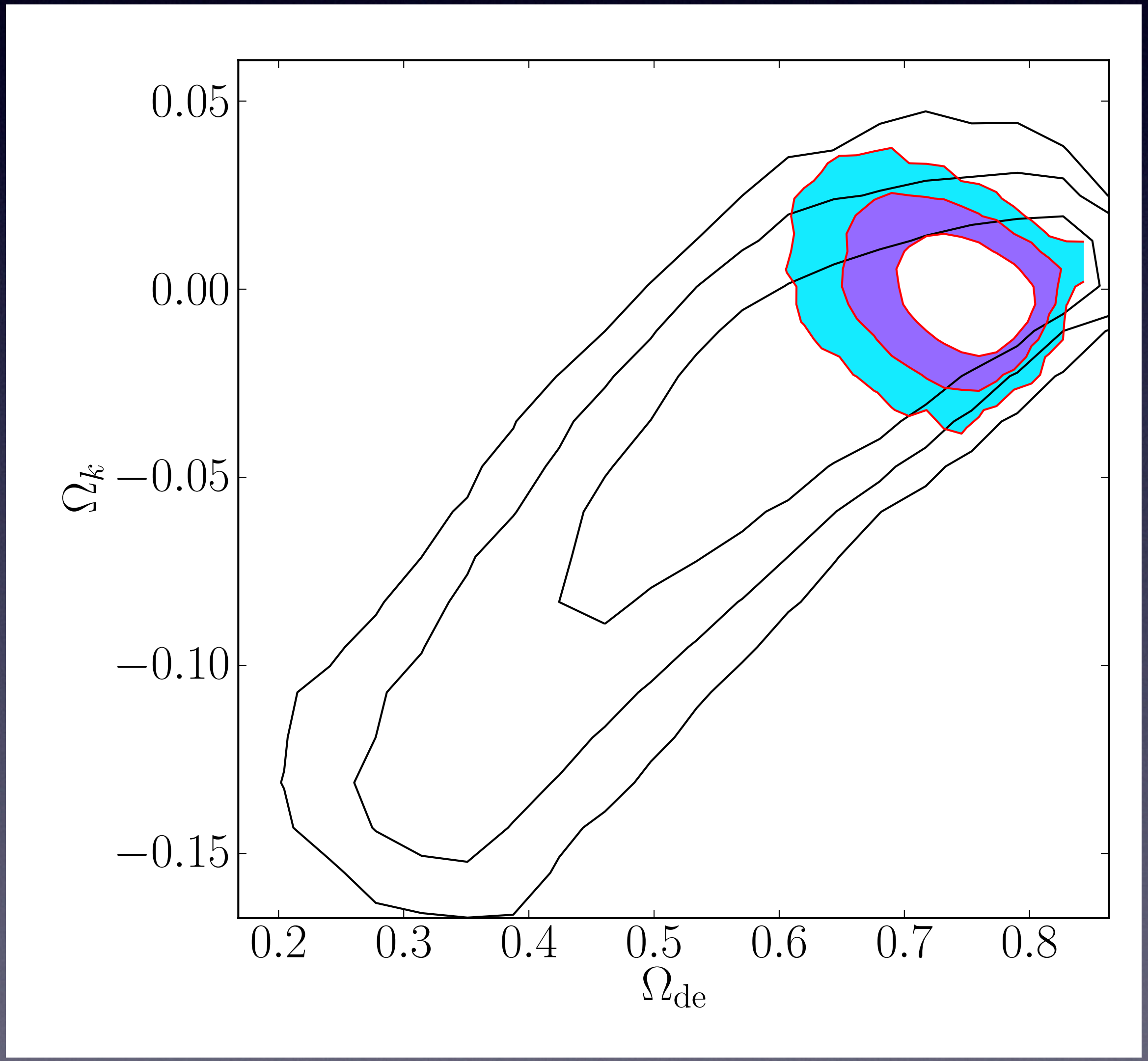
Cross-correlation coefficient between galaxies, matter: generically goes to 1 on large scales

Why?

- We often know lens redshifts quite well for massive objects (lots of cosmological info)
- Use of real-space separation (not angle) makes it easier to marginalize over small scales that we cannot easily model
- Some shear systematics vanish in cross-correlation, not auto-correlation

Proof of concept

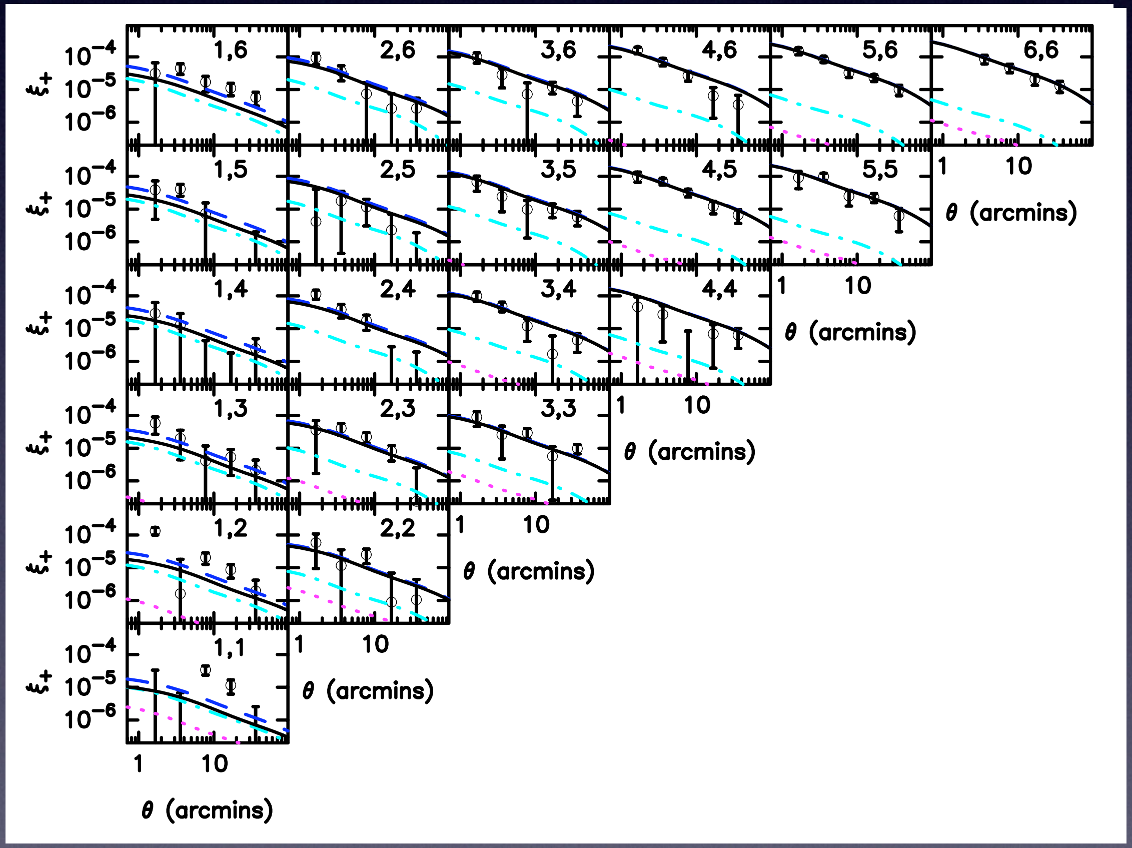
- RM+13 demonstrated method in SDSS (too shallow for cosmic shear)
- Constraints on dark energy were competitive with cosmic shear in other datasets
- Updated analysis in prep; Singh et al 2016



Challenges

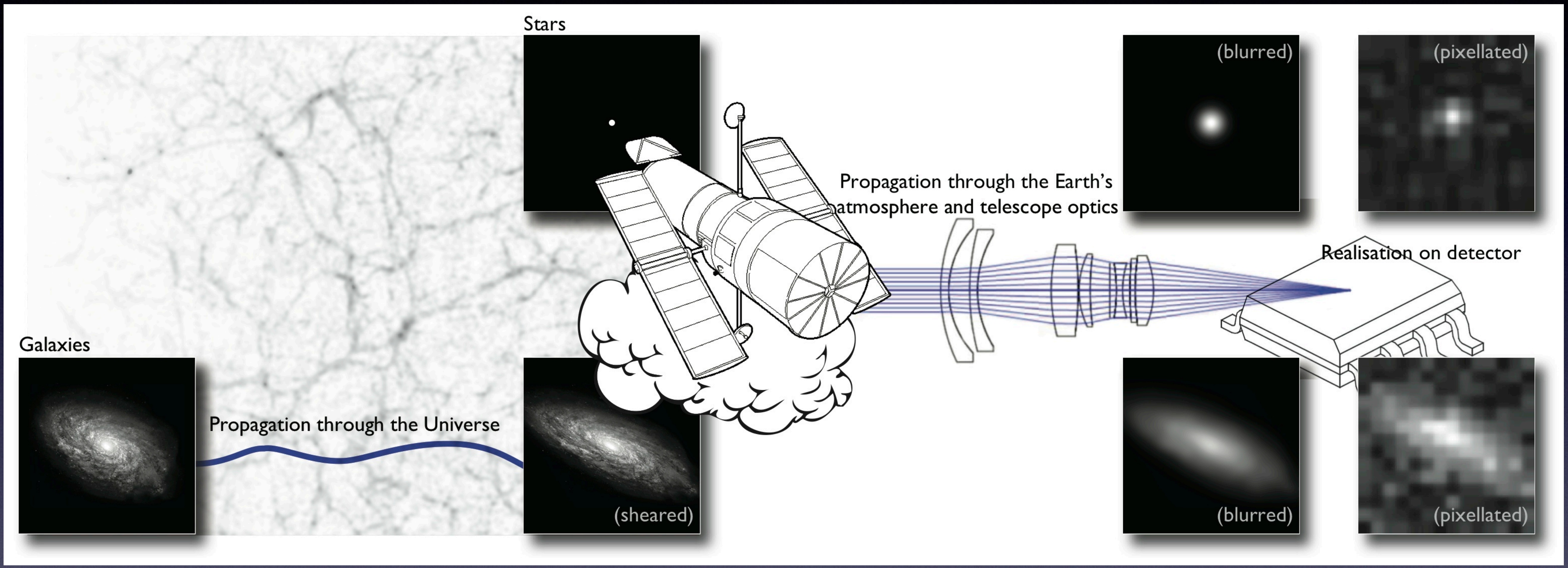
Challenge 1: analysis complexity

- ~6 z bins: 21 bin-bin correlations x 3 observables x 15 data points each = ~1000 data points
- 1000^2 (accurate) covariance matrix
- ~8 cosmological model parameters
- Of order 100 nuisance model parameters
- Do standard analysis methods work properly in this regime?
- 2pt WL + higher order stats or other probes is even worse



Heymans et al (2013)

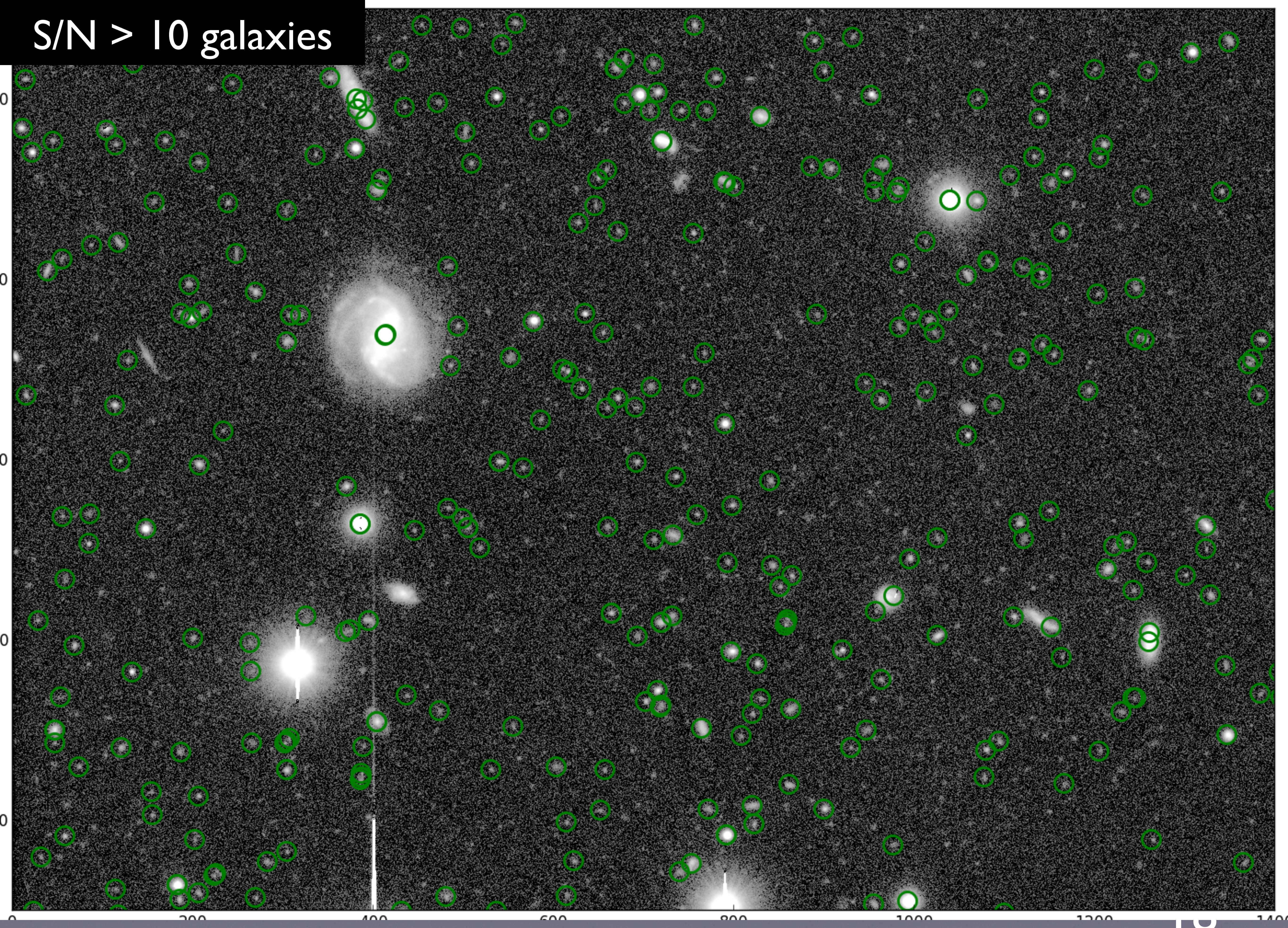
Challenge 2: a new era in shear estimation



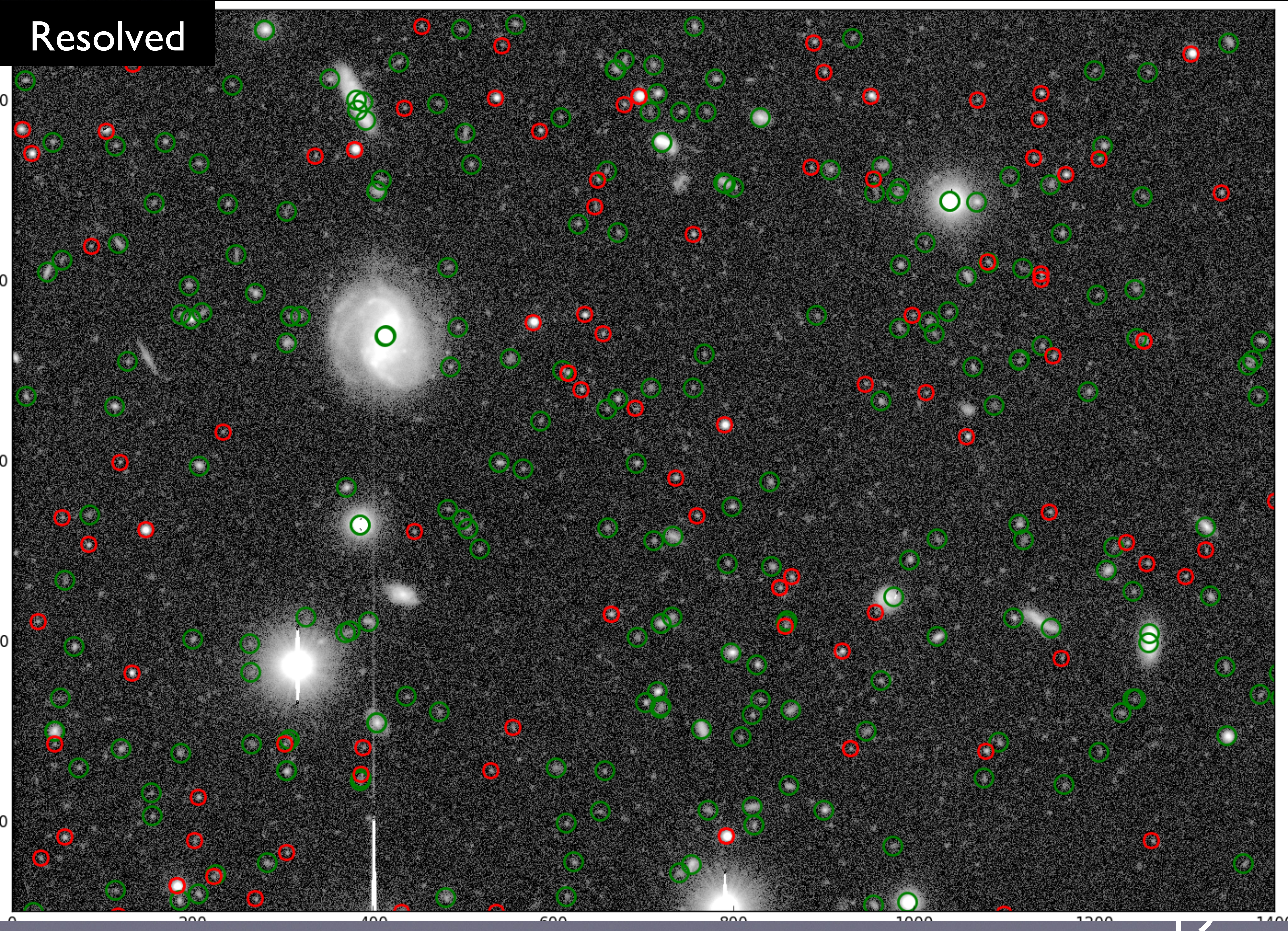
This is a challenging statistical measurement:
a non-linear inverse problem
...that we must reliably solve for galaxies
that are near our S/N and resolution limits!

Some perspective: what do the galaxies we are measuring look like?

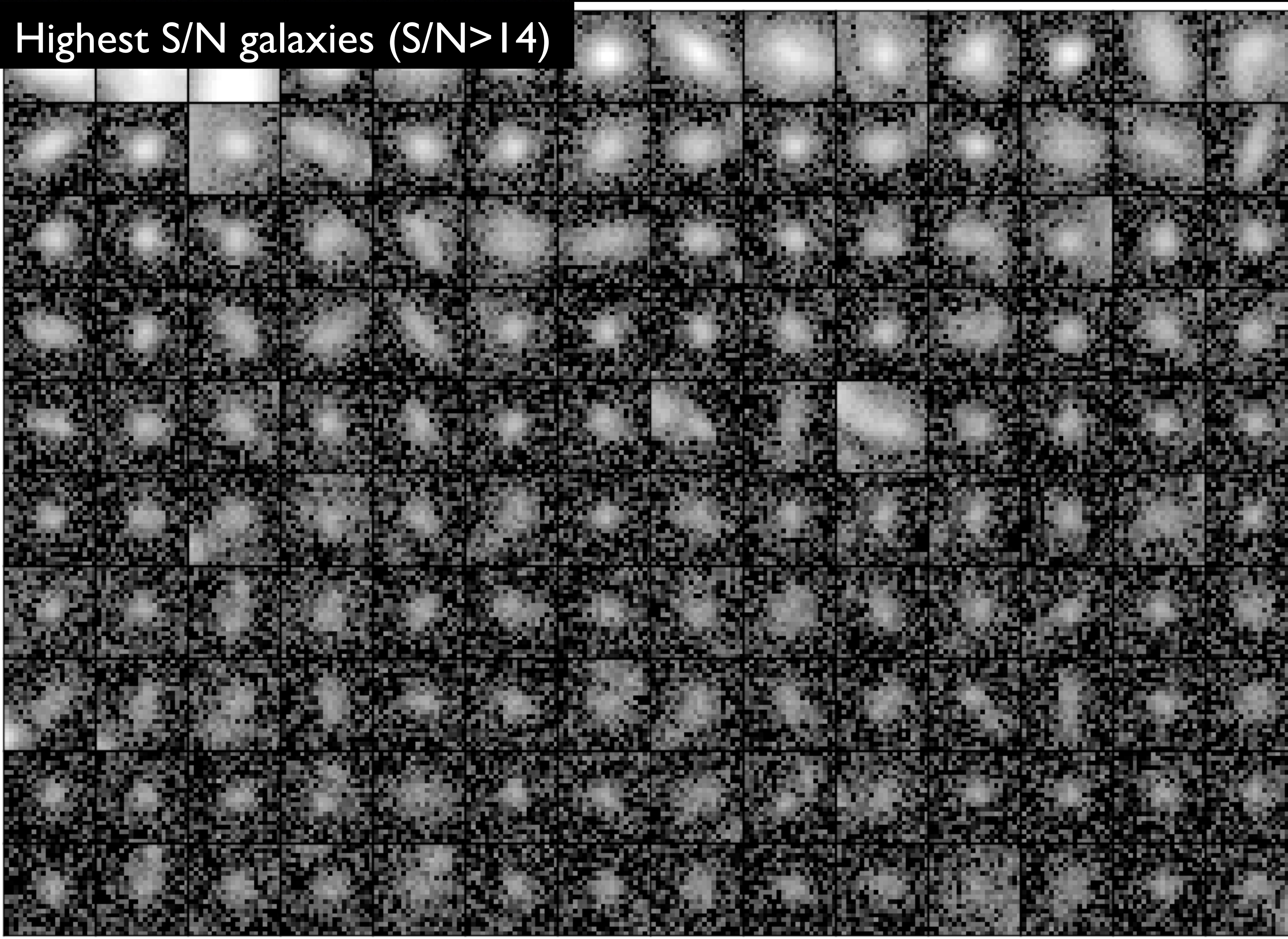
S/N > 10 galaxies



Resolved



Highest S/N galaxies (S/N>14)



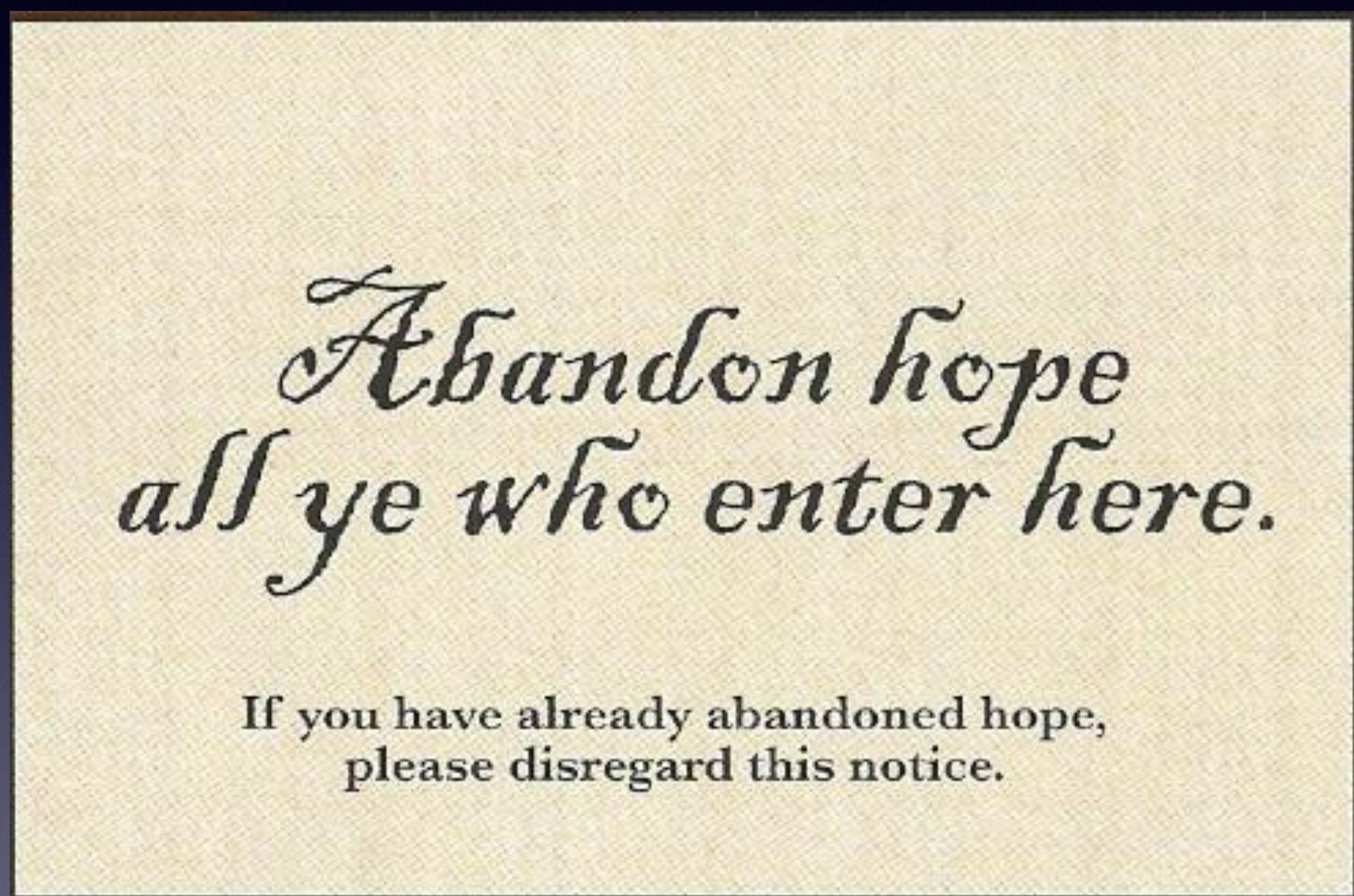
The standard paradigm (until recently)

- Select galaxies for which shapes seem measurable
- Estimate a shape for each galaxy
- Take some kind of weighted average, $\gamma \sim \langle e \rangle$
- ~~As these methods improve, they will eventually become unbiased~~

We know there are basic mathematical reasons why this won't work.

The new paradigm

Now what?


Abandon hope
all ye who enter here.
If you have already abandoned hope,
please disregard this notice.

Now what?

Must include a fully realistic galaxy population, PSF, ...

1. Calibrate with simulations

2. Calibrate with fake objects inserted in real data

3. Estimate ensemble shears, not galaxy shapes (Bernstein & Armstrong 2014; Schneider+15)

4. External calibration: CMB lensing

Or… MetaCalibrate

Huff, RM, Sheldon, Hirata (in prep)

d 

d(shear)

d 

d(systematic)

Use these derivatives to measure the response of the entire measurement pipeline with the correct galaxy population!

Where's the challenge?

- These all sound good *in principle*
- Have not been demonstrated to the level of accuracy needed for e.g. LSST
- Some come with major computational or statistical challenges, particularly when trying to carry through to the full shear analysis

Conclusion

- Upcoming surveys will provide a flood of beautiful data the likes of which we have never seen before
- More work is needed to ensure that we have methods in place for
  - Believable shear estimation
  - Robust joint analysis and systematics marginalization