Mapping the Universe in 3 dimensions with gravitational lensing

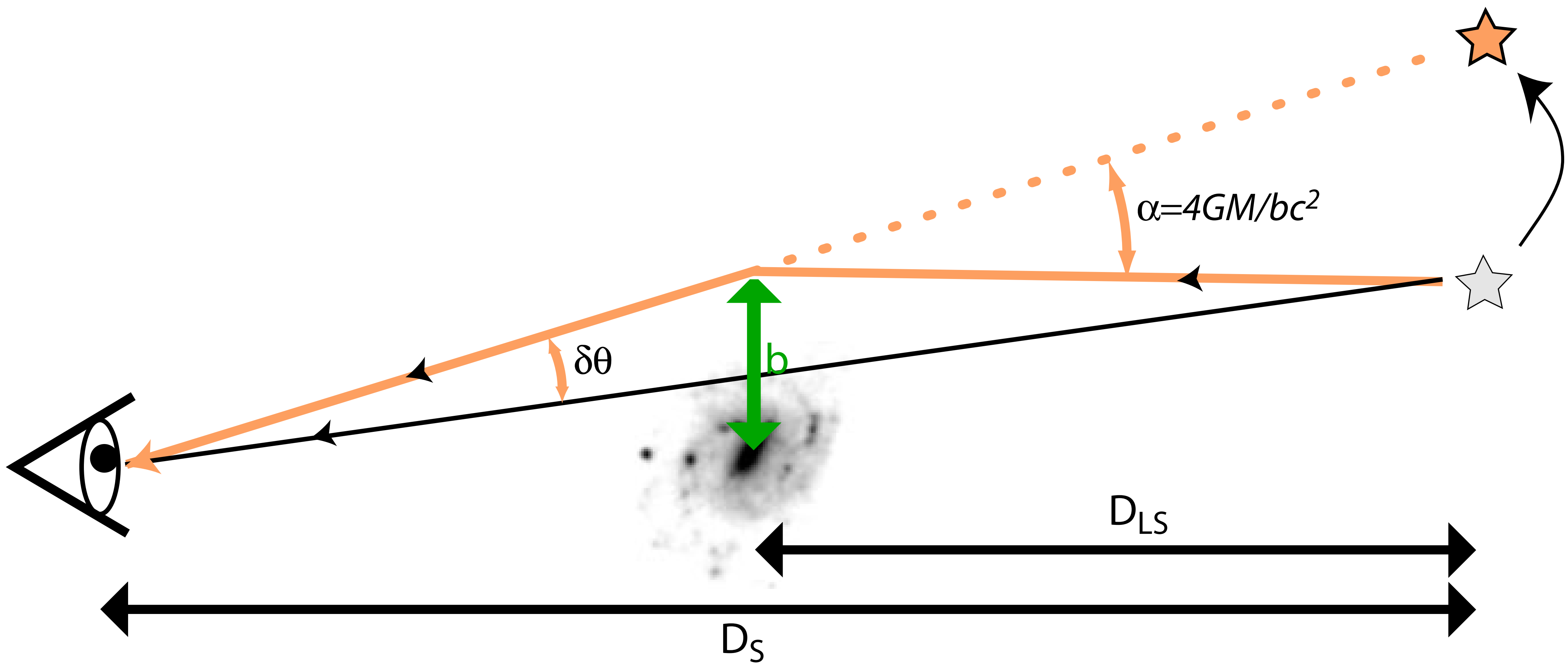
Gary Bernstein (U Penn)

Cosmic Cartography, 3 Dec 2007

Gravitational lensing maps

- How do we make the map?
- What is it a map *of*?
- Where is the treasure?
- Are there pirates or monsters??
- Has anyone found the treasure yet?

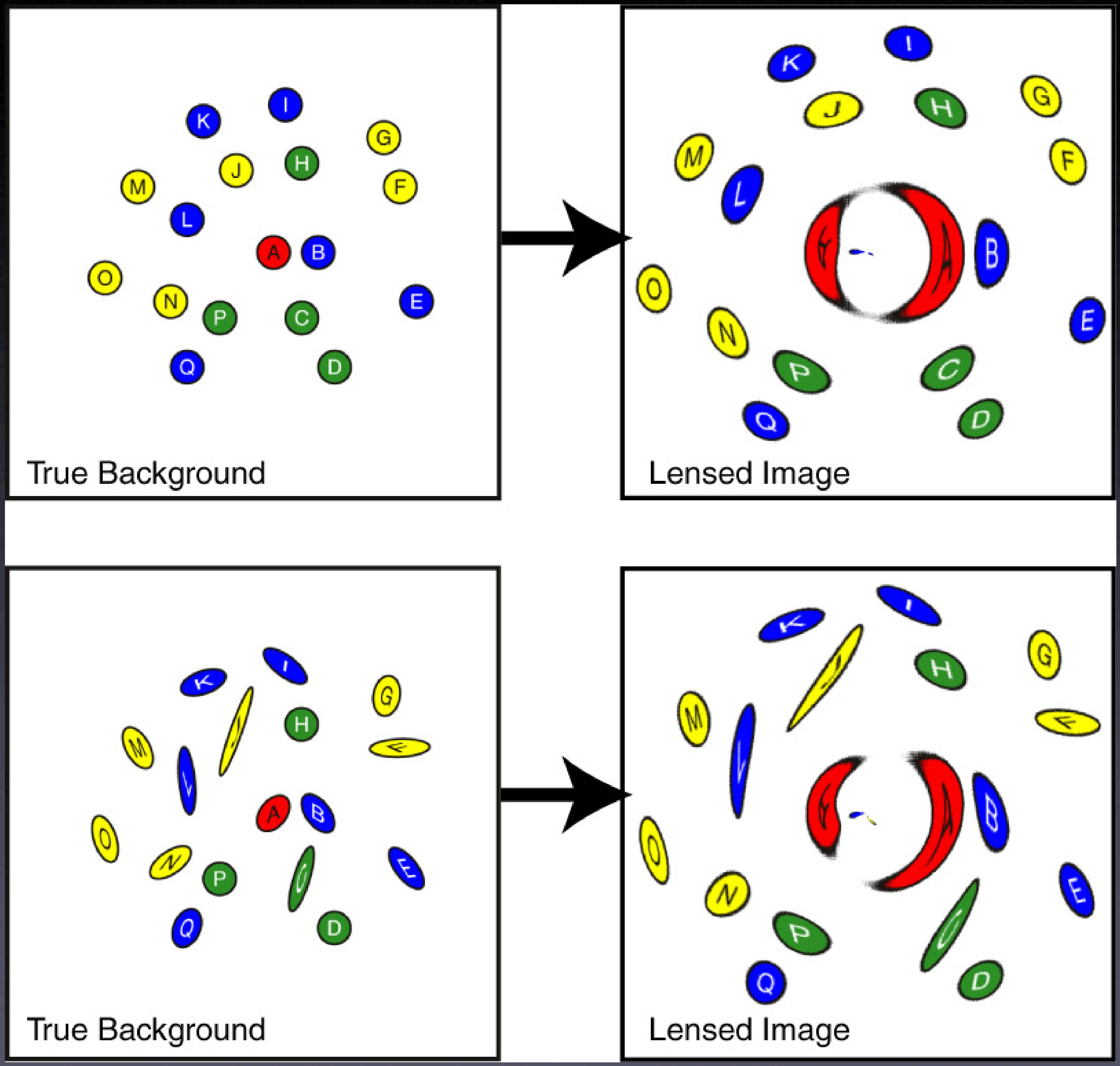
How do we make lensing maps?



$$\delta\theta = \frac{4GM}{bc^2} \frac{D_{LS}}{D_S}$$

We observe this deflection angle (more precisely, gradients of the deflection angle).

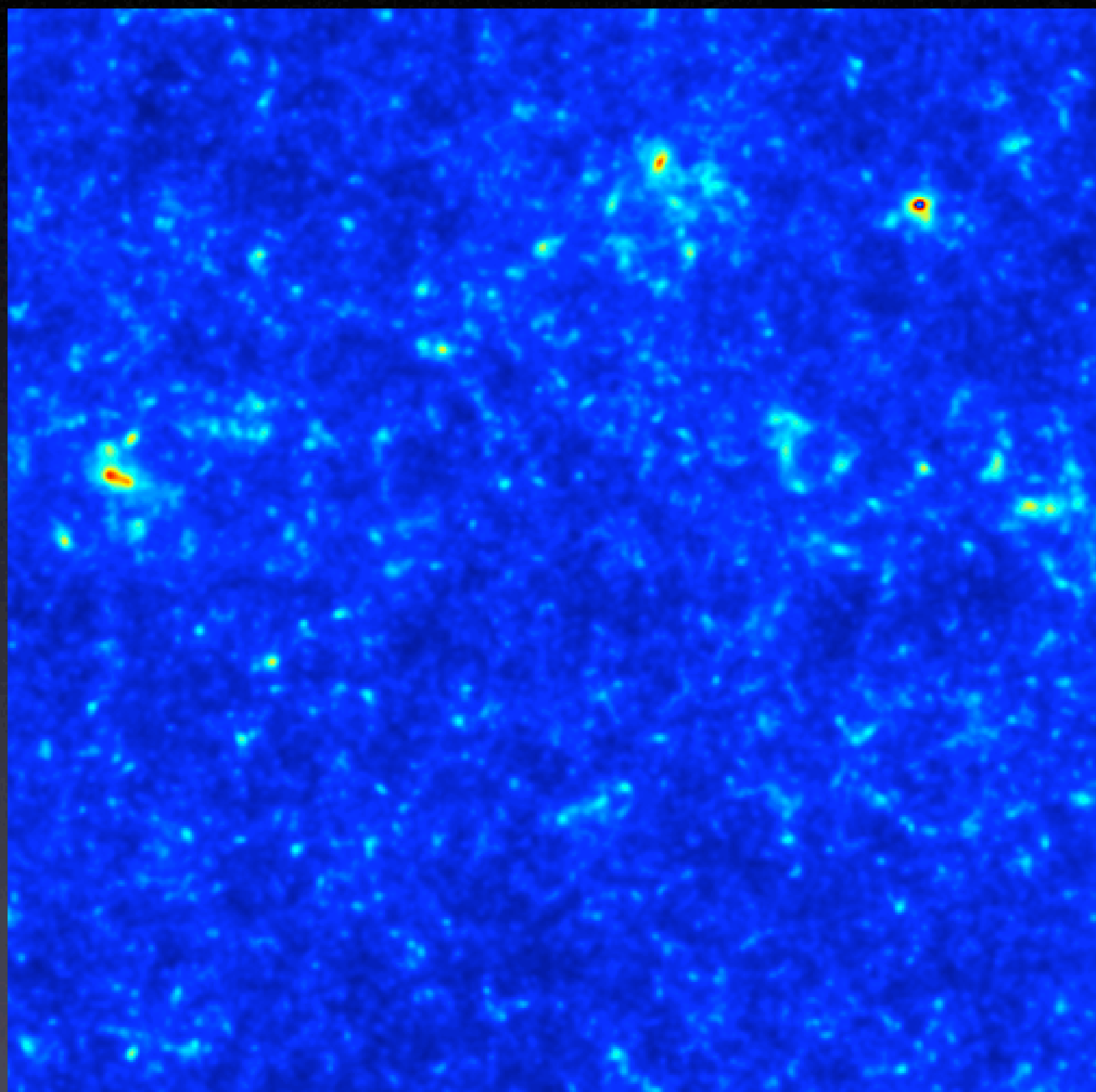
How do we make lensing maps?



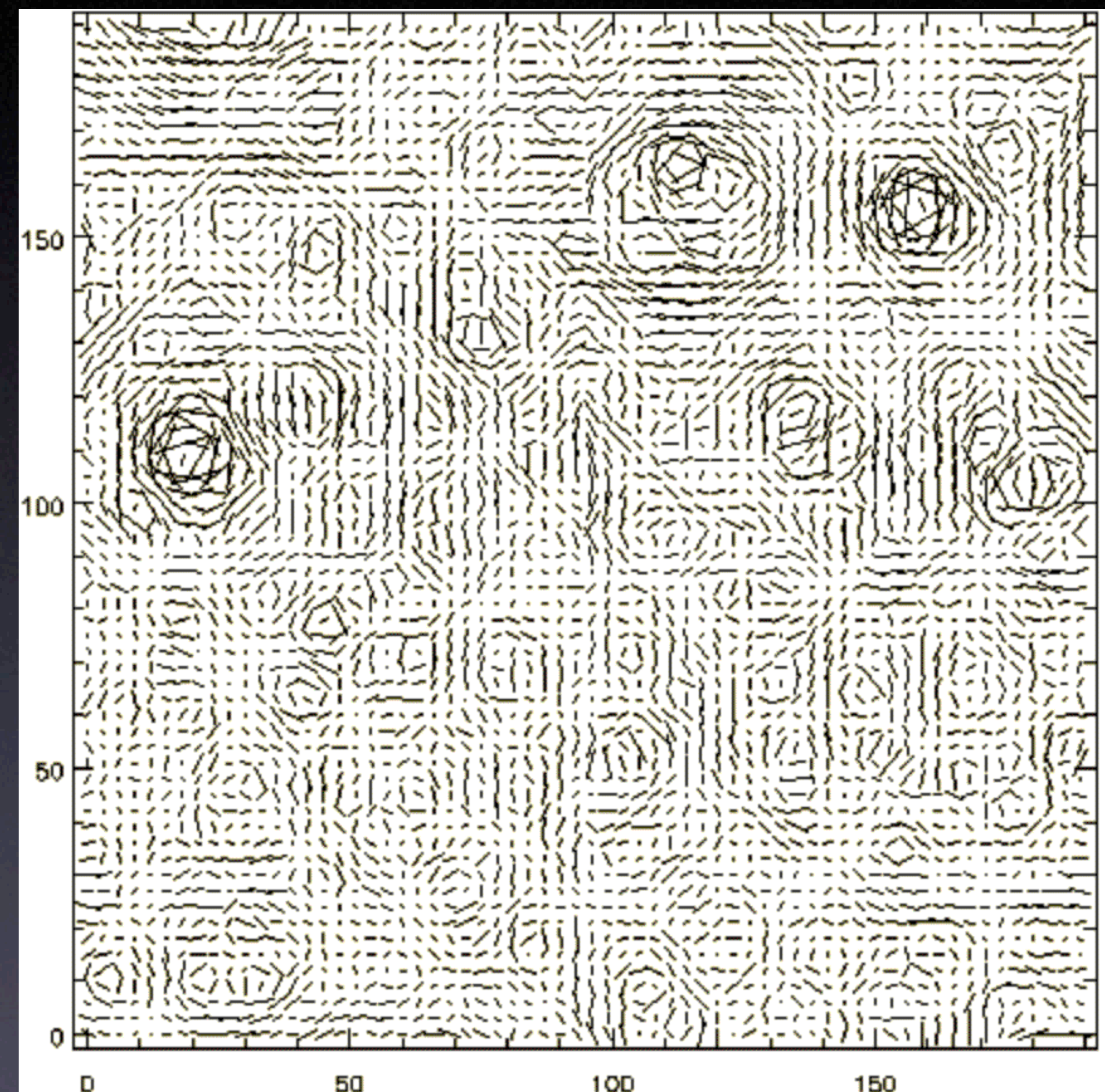
- Deflection angles are not generally observable since lensing mass cannot be removed!
- In weak gravitational lensing, we instead measure the gradients of the deflection angle as distortions to the shapes of galaxies.
- The intrinsic variation of galaxy shapes then becomes a source of noise which averages away as √N
- Cosmic signal is ~0.02; shape noise is 0.25/√N; N~1e9!

How do we make lensing maps?

(B. Jain)

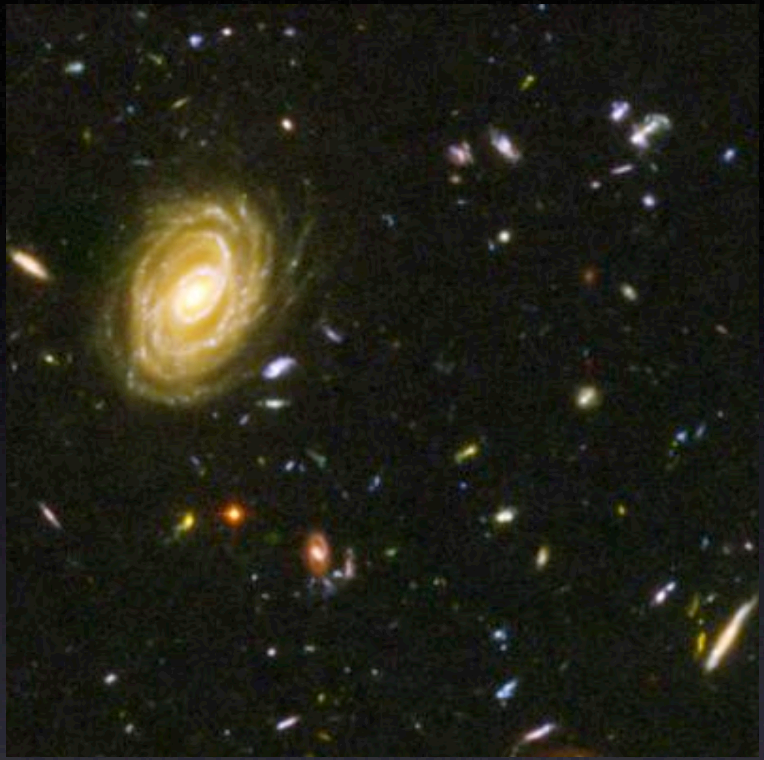


Projected mass map



Gravitational shear map

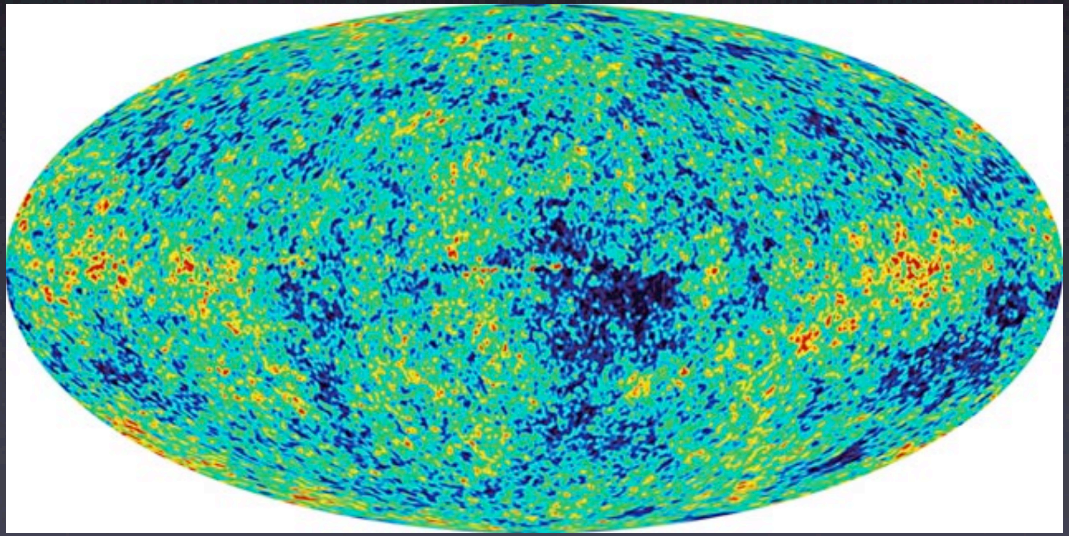
How do we make lensing maps?



Observe distortions of some background "wallpaper" with statistical isotropy.

Galaxies observed in visible, NIR, 21cm

The CMB radiation

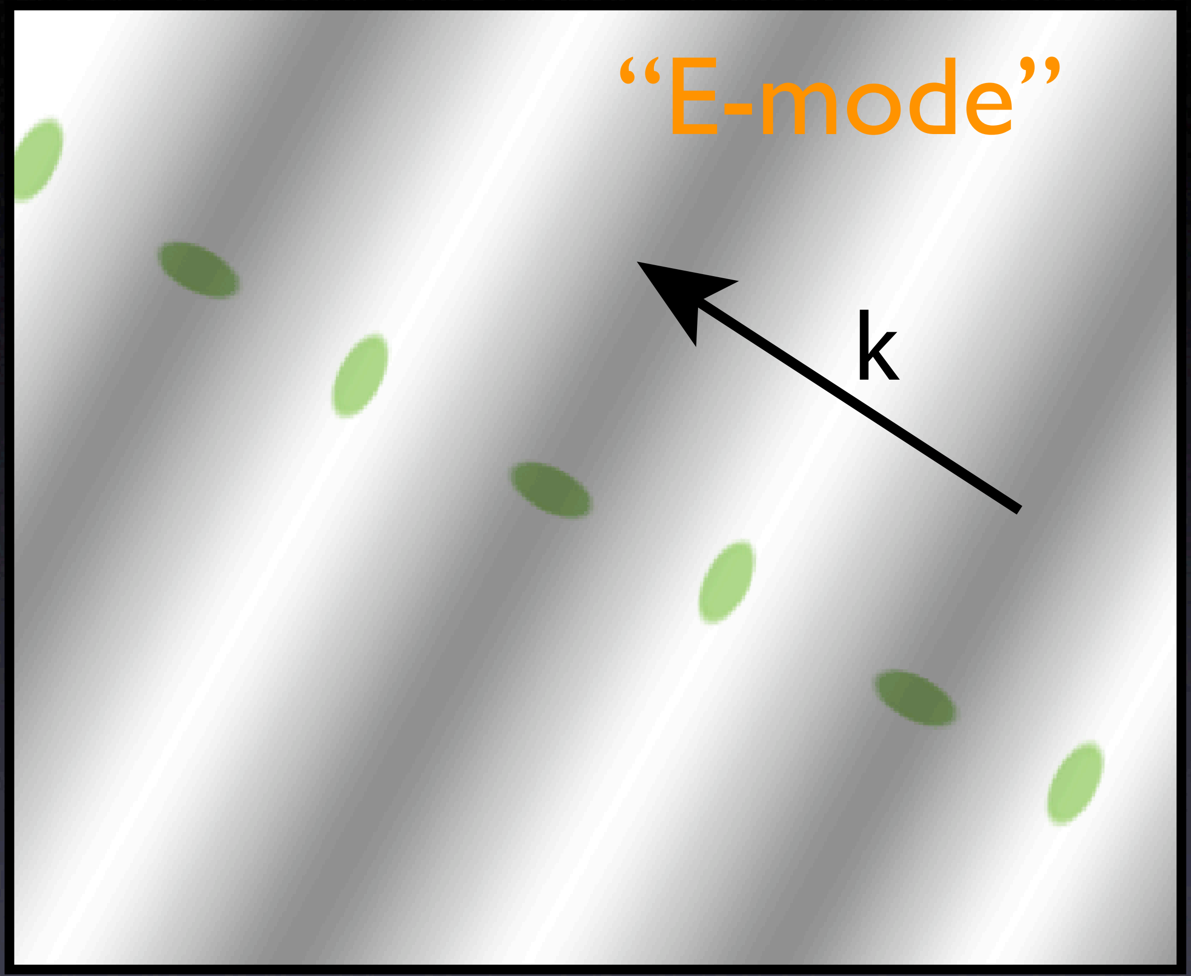


21 cm emission from reionization epoch

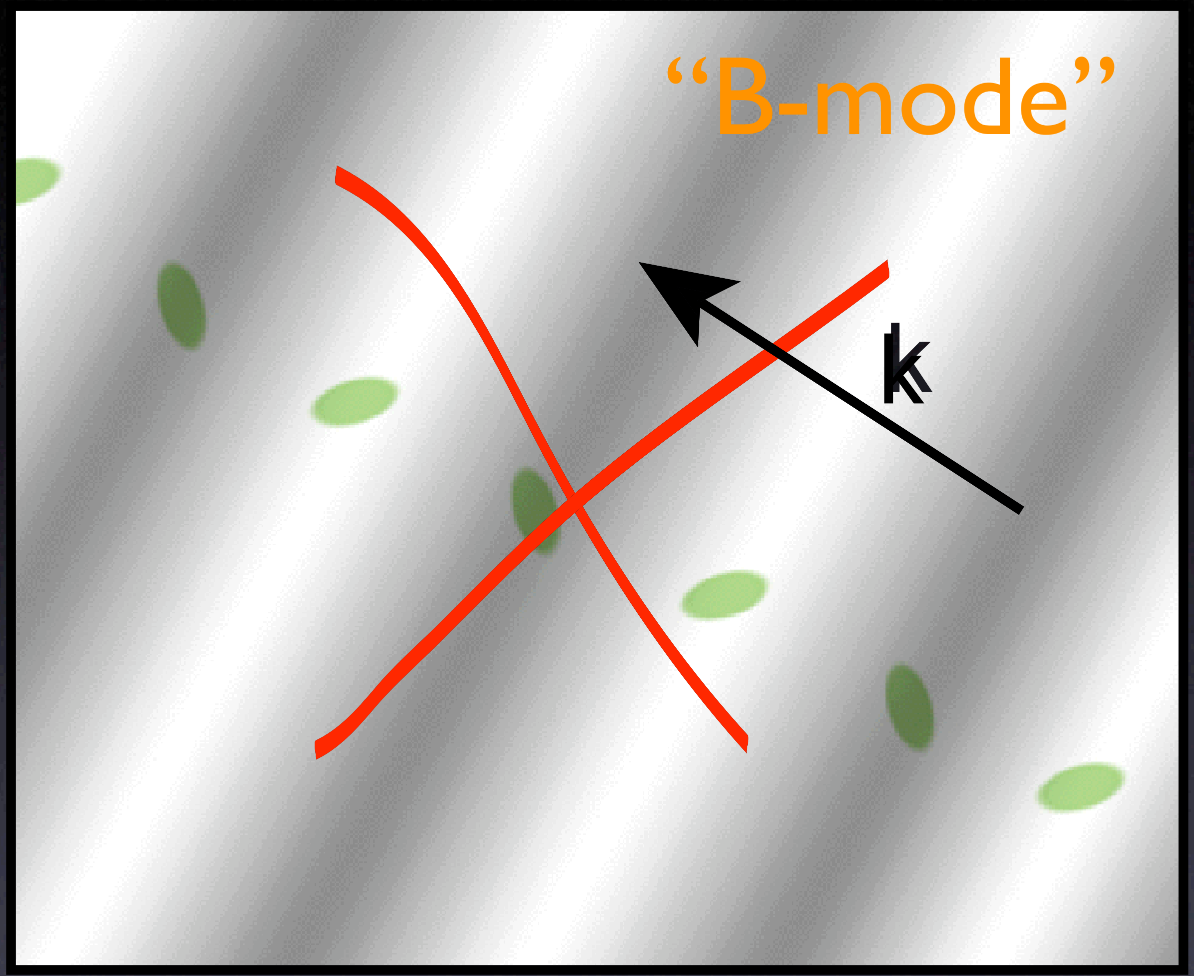
What does lensing map?

- Lensing *shear* is the derivative of lensing *deflection.*
- *Deflection* is the derivative of the gravitational *potential*
- The *potential* is formed by the *matter* according to Poisson equation.
- It is straightforward to construct a map of the *potential* or *matter* when given the *shear* map.
- Lensing makes maps of **(dark!)** matter.

What does weak lensing map?



Foreground mass sinusoid produces ellipticity pattern at the same k-vector



Lensing cannot produce ellipticity pattern at 45 degrees to k-vector

Straightforward to see that Fourier modes of shear are associated with same mode of mass, potential.

Note there is a “B-mode” shear pattern that cannot be created by gravity: systematic-error check!

Matter maps from weak lensing

The "Bullet Cluster" - Clowe et al

What does weak lensing map

(Projected) mass profiles of SDSS galaxy clusters vs luminosity (Sheldon et al 2007)

And of individual SDSS galaxies (Mandelbaum et al 2005)

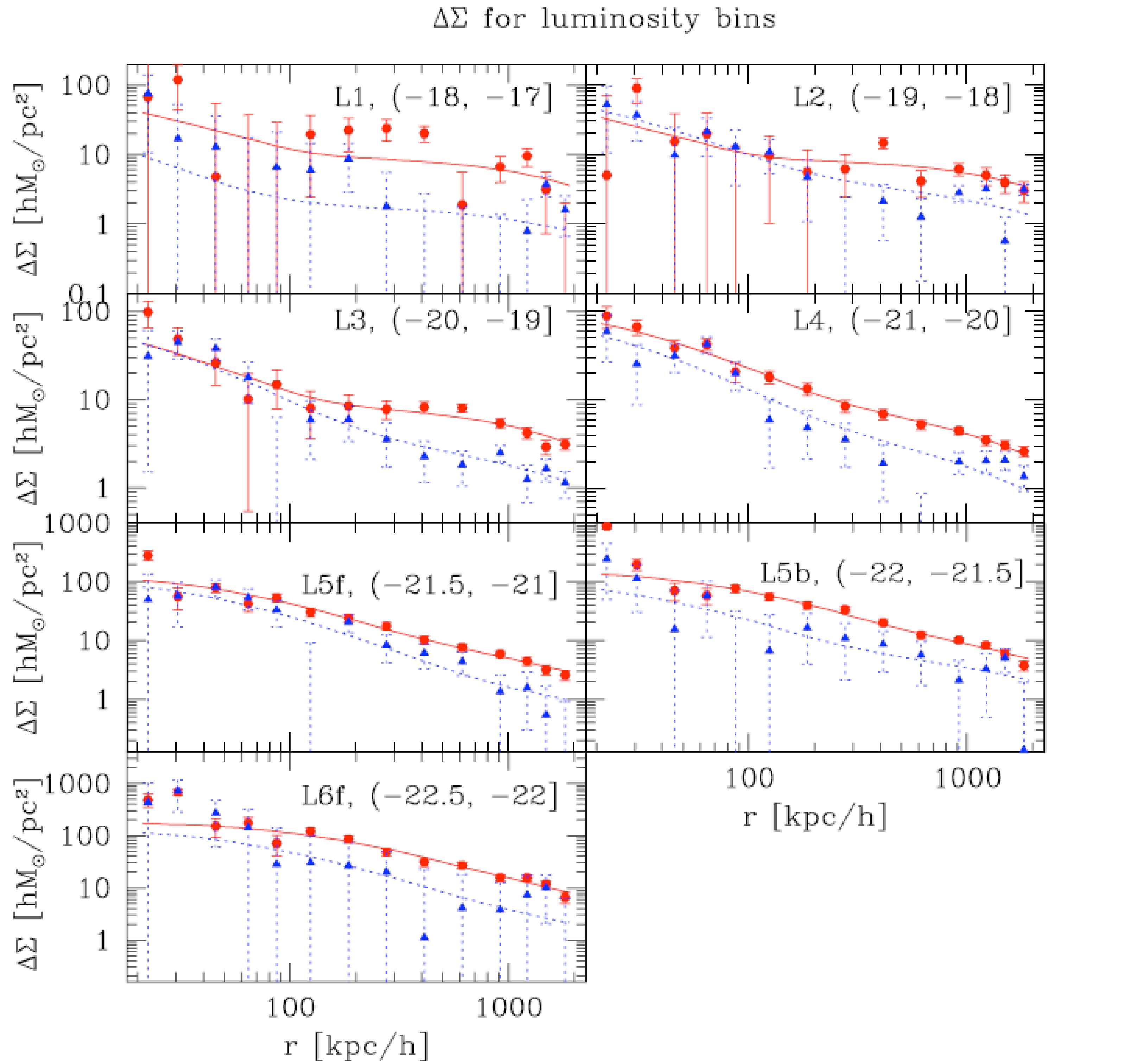
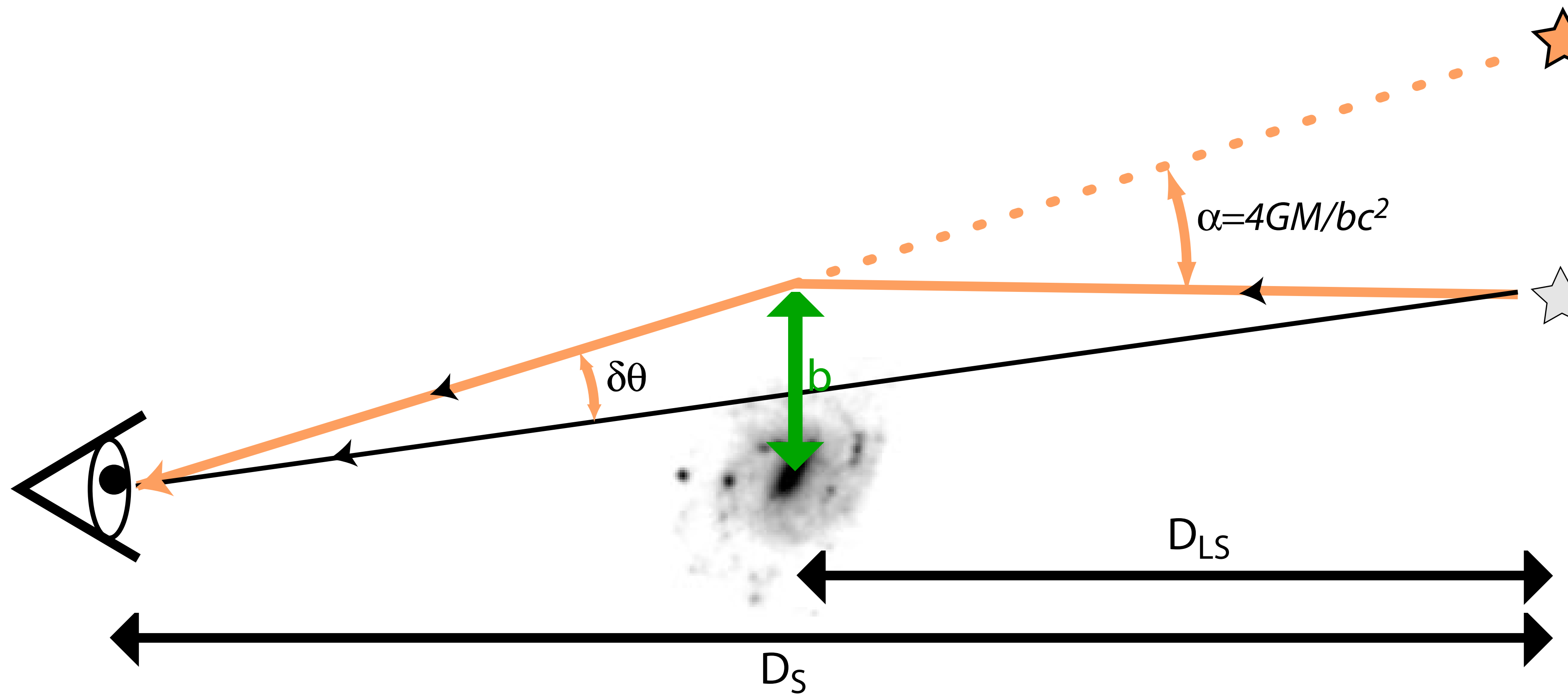


Figure 2. $\Delta\Sigma$ with best-fit halo model in luminosity bins for early (red hexagons, solid line) and late-type (blue triangles, dashed line) galaxies. All errors are 1σ.

What does weak lensing map?



$$\delta\theta = \frac{4GM}{bc^2} \frac{D_{LS}}{D_S}$$

More precisely, lensing measures the *projected* potential of mass along the line of sight, with a weighting for geometric distance factors:

$$\psi_{2d}(\vec{\theta}) = 2 \int_0^{r_s} dr \, \frac{D_{ls}}{D_l D_s} \phi_{3d}(r\vec{\theta}, r)$$

What does weak lensing map?

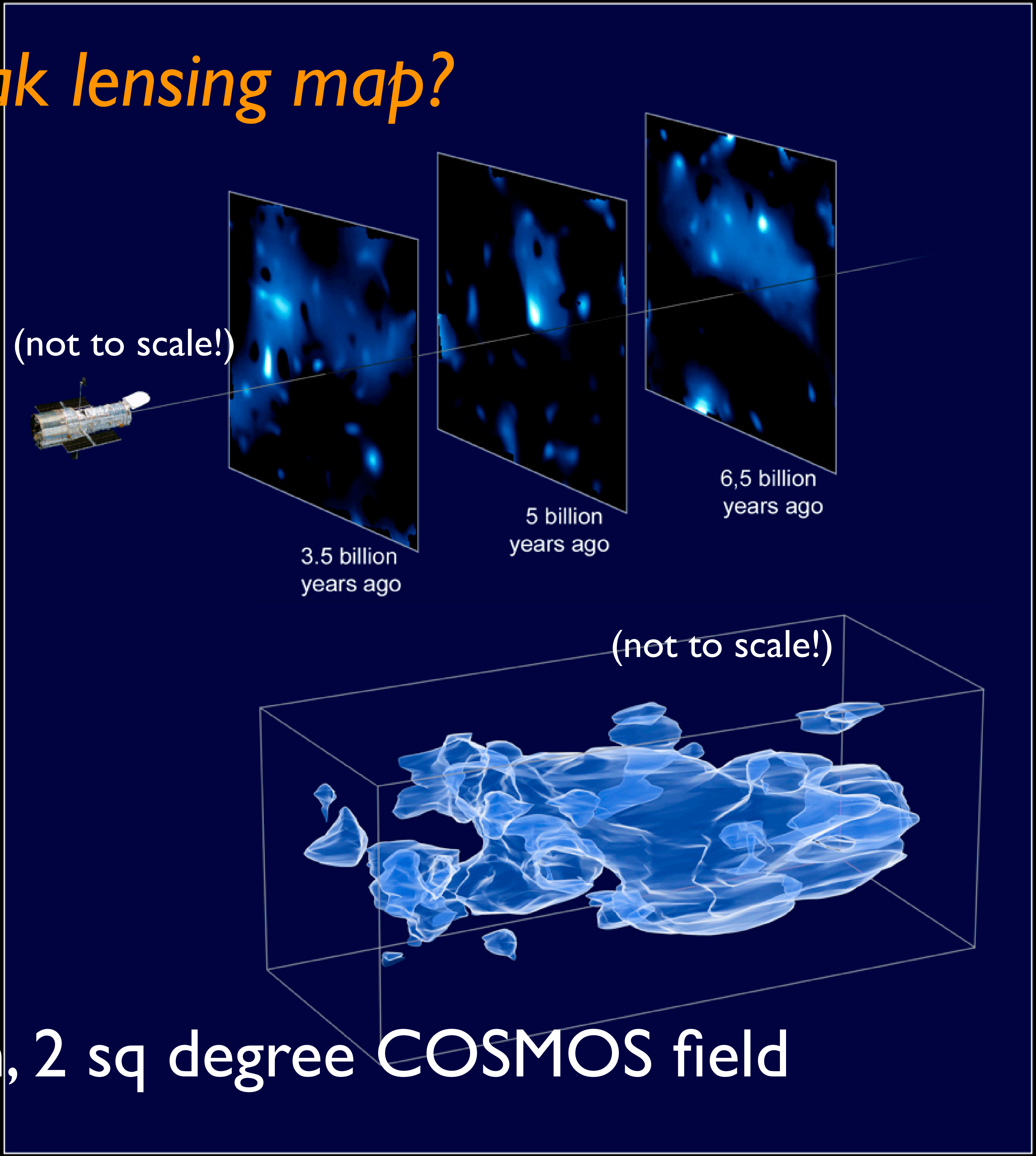
- Does lensing destroy all line-of-sight information?
- *Not if multiple source planes can be identified:*

$$\begin{pmatrix} \text{shear}_1 \\ \text{shear}_2 \\ \text{shear}_3 \\ \vdots \\ \text{shear}_n \end{pmatrix} = \begin{pmatrix} 0 & A_{12} & A_{13} & \cdots & A_{1n} \\ 0 & 0 & A_{23} & & A_{2n} \\ 0 & 0 & 0 & & A_{3n} \\ \vdots & & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{pmatrix} \times \begin{pmatrix} \text{mass}_1 \\ \text{mass}_2 \\ \text{mass}_3 \\ \vdots \\ \text{mass}_n \end{pmatrix}$$

$$A_{ij} = D_{ij}/D_j \qquad (i < j)$$

"Lensing tomography": invert this matrix on each line of sight to obtain **3d** potential or mass!

What does weak lensing map?



3d reconstruction, 2 sq degree COSMOS field
Massey et al 2007

What does weak lensing map?

- Relation between gravitational shear (deflection) and the matter assumed that General Relativity is correct.
- Is it?
- Can we think of lensing maps in a way that is independent of GR, or even tests GR?

Weak gravitational lensing maps the *metric of the Universe.*

What does weak lensing map?

- If the Universe is:
  - A 4d metric space
  - that is homogeneous and isotropic
  - with small scalar perturbations
- Then the metric can be expressed in Newtonian gauge as:

$$ds^2 = (1+2\Psi)dt^2 - (1-2\Phi)a^2(t)\left[dr^2 + S_k^2(r)(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

- And light travels on geodesics described by the functions $(\Psi+\Phi)$, a(t), and the curvature ω_k

What treasures does a lensing map reveal?

$$ds^2 = (1+2\Psi)dt^2 - (1-2\Phi)a^2(t)\left[dr^2 + S_k^2(r)(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

Treasure #1: The curvature of the Universe.

$$S_k(r) = \left\{ \begin{array}{c} r_0 \sin(r/r_0) \\ r \\ r_0 \sinh(r/r_0) \end{array} \right\} \approx r(1+\omega_k r^2/6)$$

The Universe is nearly flat ($\omega_k < 0.02$) - why?

Is curvature 1 part in 100? 1000? 10,000?

If inflation made us flat, what was inflation duration?

What treasures does a lensing map reveal?

$$ds^2 = (1+2\Psi)dt^2 - (1-2\Phi)a^2(t)\left[dr^2 + S_k^2(r)(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

Treasure #2: The expansion history of the Universe.

$$r(z) = \int \frac{dz}{H}, \quad H \equiv \dot{a}/a$$

$$D_A(z) \approx r(z)\left(1 + \omega_k r^2/6\right)$$

If GR is true, then Friedmann equation relates expansion history to contents of Universe:

$$H^2/H_{100} = \omega_m a^{-3} + \omega_r a^{-4} + \omega_k a^{-2} + \omega_X f_X(a)$$

Is there a "dark energy" substance X?

Is Friedmann/GR correct?

What treasures does a lensing map reveal?

$$ds^2 = (1+2\Psi)dt^2 - (1-2\Phi)a^2(t)\left[dr^2 + S_k^2(r)(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

Treasure #3: The potential fluctuations of the Universe.

If GR is true and there is no anisotropic stress, then these two potentials are equal. Cannot test this with light geodesics alone.

What treasures does a lensing map reveal?

$$ds^2 = (1+2\Psi)dt^2 - (1-2\Phi)a^2(t)\left[dr^2 + S_k^2(r)(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

Treasure #3: The potential fluctuations of the Universe.

CMB anisotropy observations tell us the power spectrum of potential fluctuations at z=1000.
Lensing can measure the spectrum more recently. In linear regime,

$$\Psi(\mathbf{k},t) = \Psi(\mathbf{k},t_0)G(k,t)$$

What is this growth function?

If GR's Poisson eqn is true and matter is the only clustering component, then growth obeys

$$\ddot{G} + 2h\dot{G} = \frac{3\omega_m}{2a^3}G$$

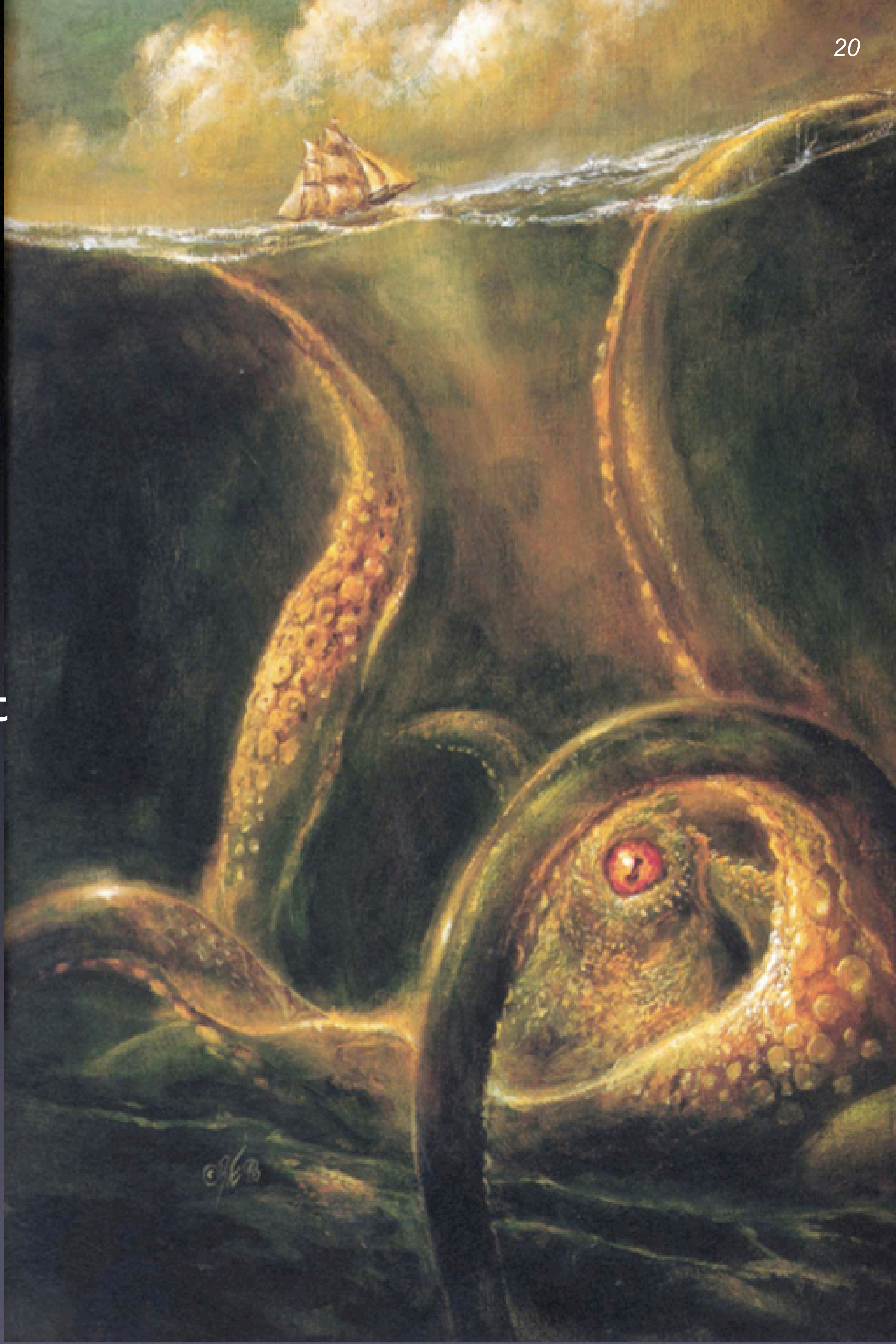
Is this equation correct? Is growth scale-independent?

Pirates and monsters

- Can we really extract all those different functions from one WL dataset, or are they hopelessly entangled?
- WL is *weak*: ~2% shear RMS. Optical and atmospheric distortions usually larger! Systematic effects in measurement if we want parts-per-thousand accuracy. Typically:

$$\gamma_{\rm obs}(\theta, z) = [1 + m(z)]\gamma_{\rm true} + c(\theta, z)$$

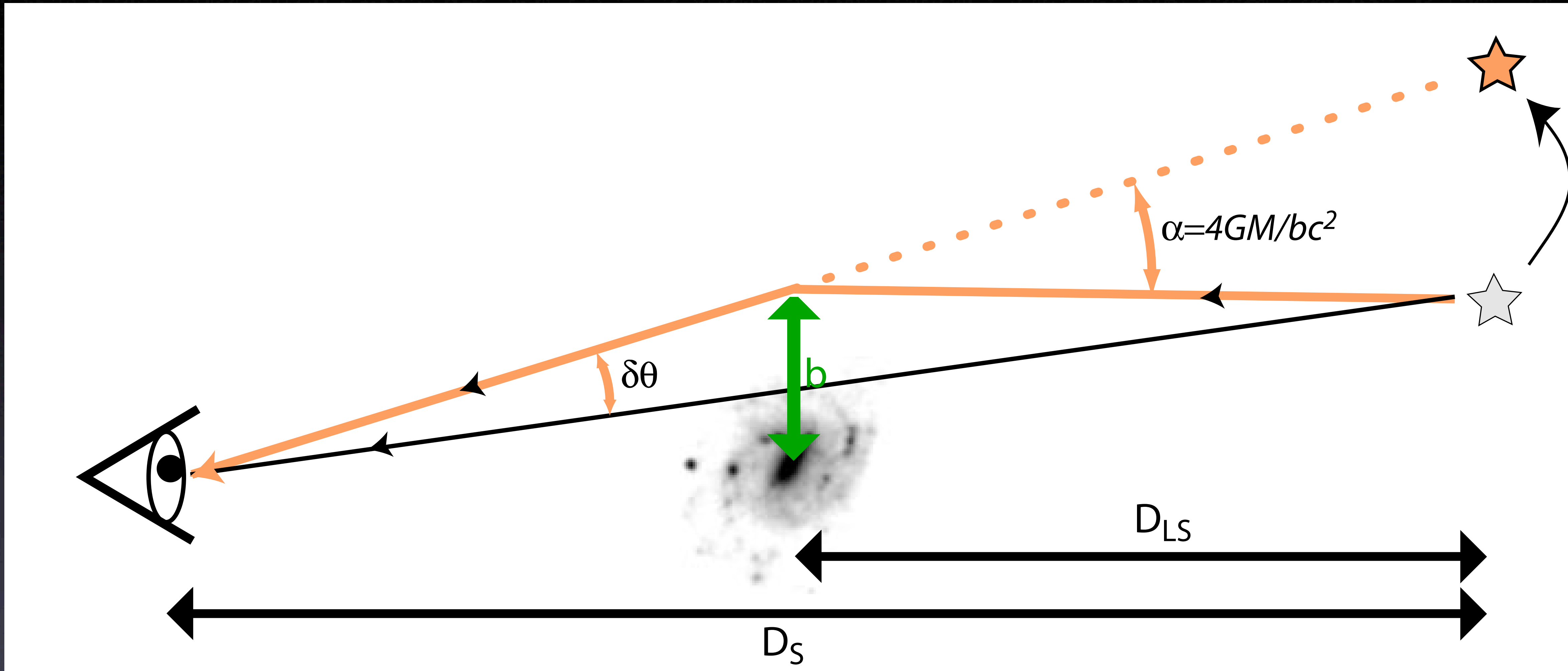
- Galaxies have *intrinsic alignments* with neighboring galaxy and mass, producing a spurious shear signal.
- Foreground galaxies are unreliable tracers of underlying matter.



Pirates and Monsters

- Lensing data are capable of distinguishing expansion history, curvature, growth-of-potential function, and most systematic errors! Why?
- From shear maps and galaxy maps, we can form 3 distinct 2-point functions (power spectra):
  - lensing-lensing
  - galaxy-lensing
  - galaxy-galaxy
- ...and *each* of these is function of three variables: angular multipole l and *two* redshifts.
- Each type of treasure (or nuisance) has different manifestation in this rich multivariate observable space.
- Then there are three-point and other non-Gaussian observable statistics too!

Variable separation in lensing data

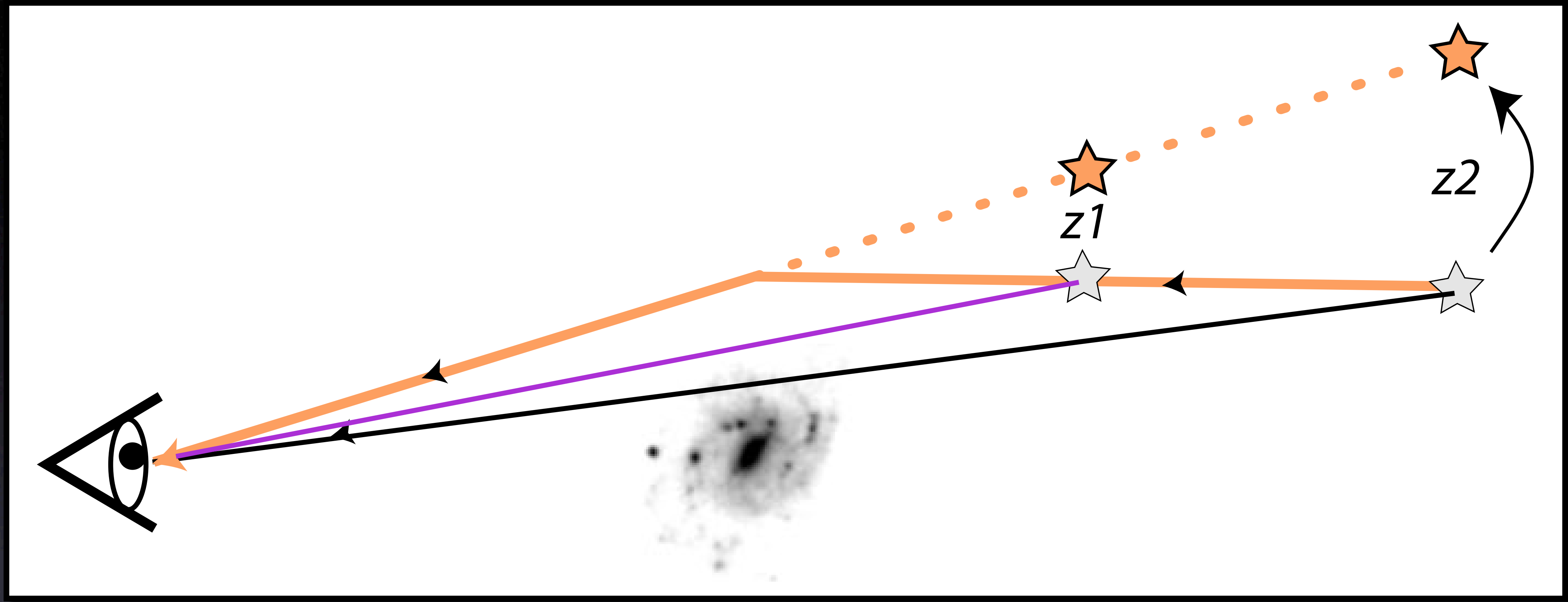


$$\delta\theta = \boxed{\frac{4GM}{bc^2}\;\frac{D_{LS}}{D_S}}$$

We observe this deflection angle (more precisely, gradients of the deflection angle).

The lensing observable appears to be a blend of growth factor (M) and expansion factors (D's)

Variable separation in lensing (Jain & Taylor)



But the ratio of deflection for two redshifts:

$$\frac{\delta\theta_1}{\delta\theta_2} = \frac{\left(\frac{D_{LS}}{D_S}\right)_1}{\left(\frac{D_{LS}}{D_S}\right)_2}$$

Is purely a expansion-history observable; potential cancels

Variable separation in weak lensing

Change in growth history at some z affects these

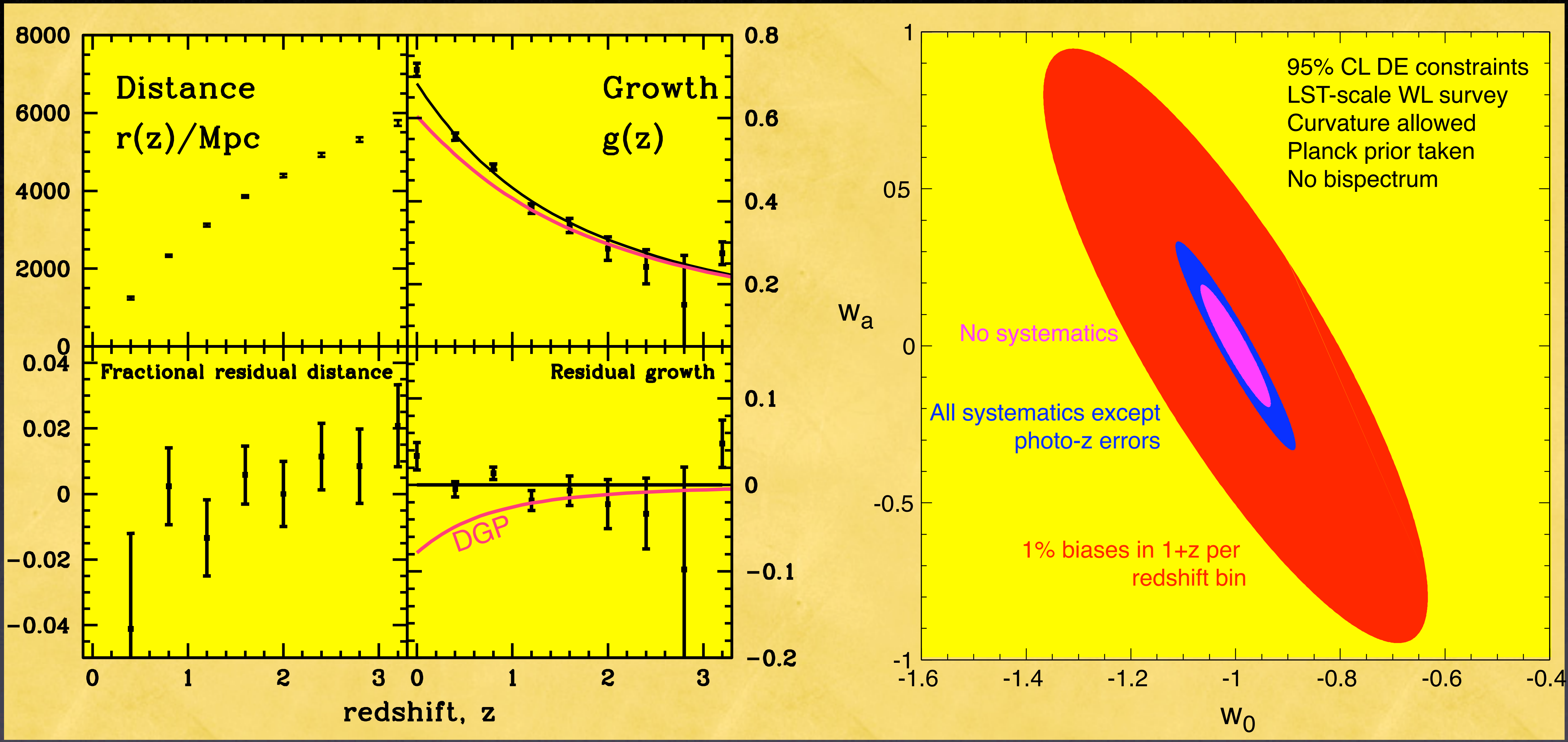
Intrinsic alignments appear here

Curvature affects

$$
\begin{pmatrix} \text{shear}_1 \\ \text{shear}_2 \\ \text{shear}_3 \\ \vdots \\ \text{shear}_n \end{pmatrix}
=
\begin{pmatrix}
0 & A_{12} & A_{13} & \cdots & A_{1n} \\
0 & 0 & A_{23} & & A_{2n} \\
0 & 0 & 0 & & A_{3n} \\
\vdots & & & \ddots & \vdots \\
0 & 0 & 0 & \cdots & 0
\end{pmatrix}
\times
\begin{pmatrix} \text{mass}_1 \\ \text{mass}_2 \\ \text{mass}_3 \\ \vdots \\ \text{mass}_n \end{pmatrix}
$$

$$A_{ij} = (1 - D_i/D_j)\,(1 - \omega_k D_i D_j/2) \qquad (i < j)$$

Variable separation: example forecasts



Power spectrum only,
no systematic errors.
20,000 square-degree ground survey

Knox, Song, & Tyson (2005)

Dark-energy parameter errors for 20,000 square-degree ground survey with/without systematic errors for shear measurement, intrinsic alignment, and redshift assignment (GMB)

Has anyone made the map (or found the treasure)?

Survey	Square deg	Multicolor/ Tomography?	Depth	Status	Telescope
COSMOS	2	yes-visible	i<~26	Massey et al (2007)	HST + Subaru
CTIO	75	no	R<23.5	Jarvis et al (2005)	Blanco 4m
CFH Legacy	140	yes-ugriz	i<24.5	published partial data	CFH 3.5m
KIDS	1500	yes-ugri + shallow NIR	r<25	about to begin	VST
DES	5000	yes-griz + shallow NIR	i<24.3	approved 2011-2016	Blanco 4m (new camera)
LSST	20,000	yes-ugrizy	i<25?	proposed 2014-2024?	Dedicated 6.5-meter
SNAP	4000	yes- 9 bands UV thru NIR	i<26.5?	proposed 2015-2020?	Dedicated space 2m
SKA	30000	yes-21 cm emission-lines	redshift < 1.5?	proposed 2017 ??	Square km Array

Progress in WL cartography

Google Earth presents
1 sq degree (COSMOS=2)

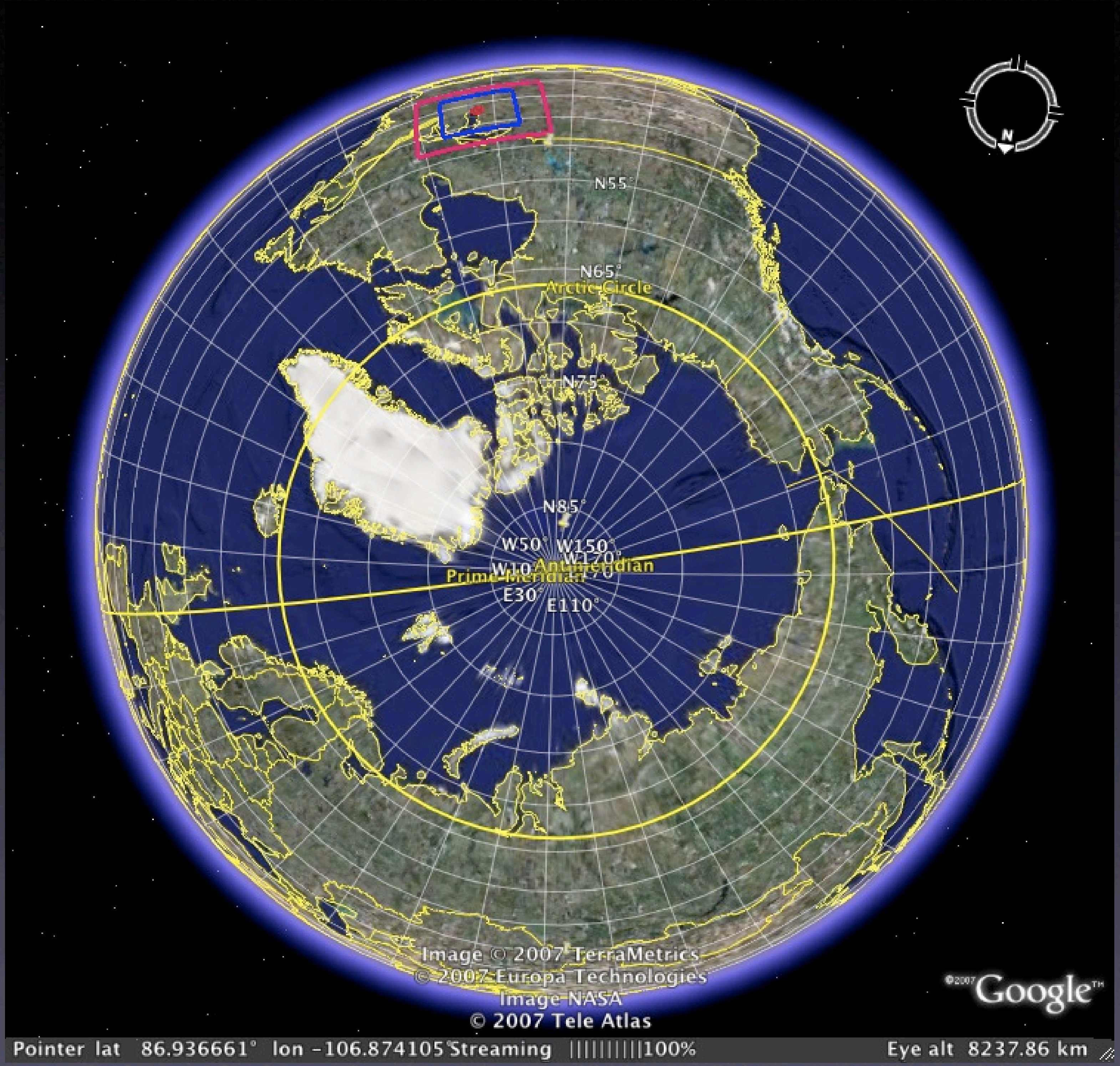
75 sq degree (CTIO Survey)

140 sq degree (CFHLS)

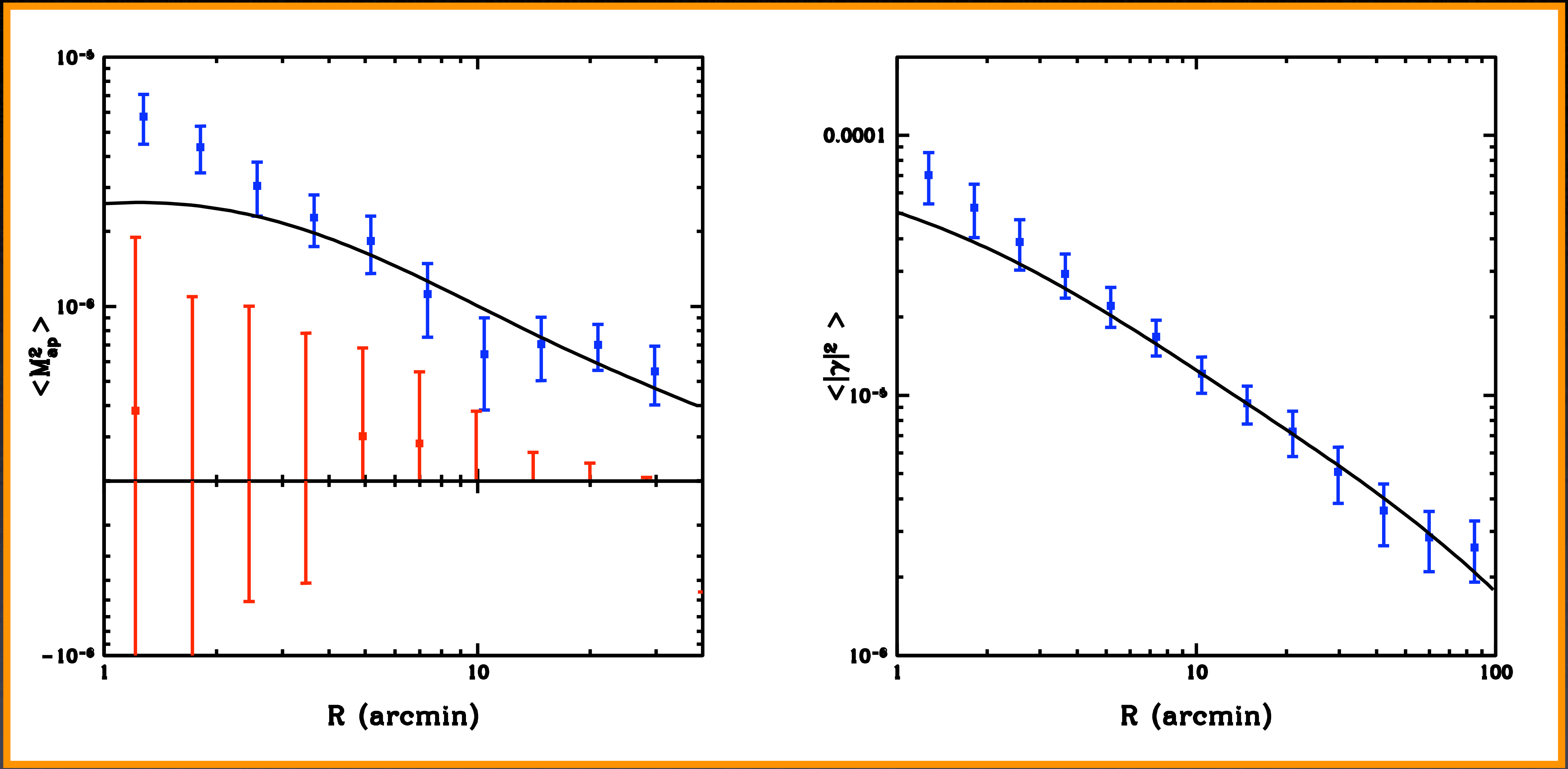
US+Canada=1500 sq deg (VISTA)

Asia~5000 sq deg (DES; SNAP)

Hemisphere=20,000 sq deg (LSST, SKA)



Science Results: CTIO Survey (Jarvis et al 2005)

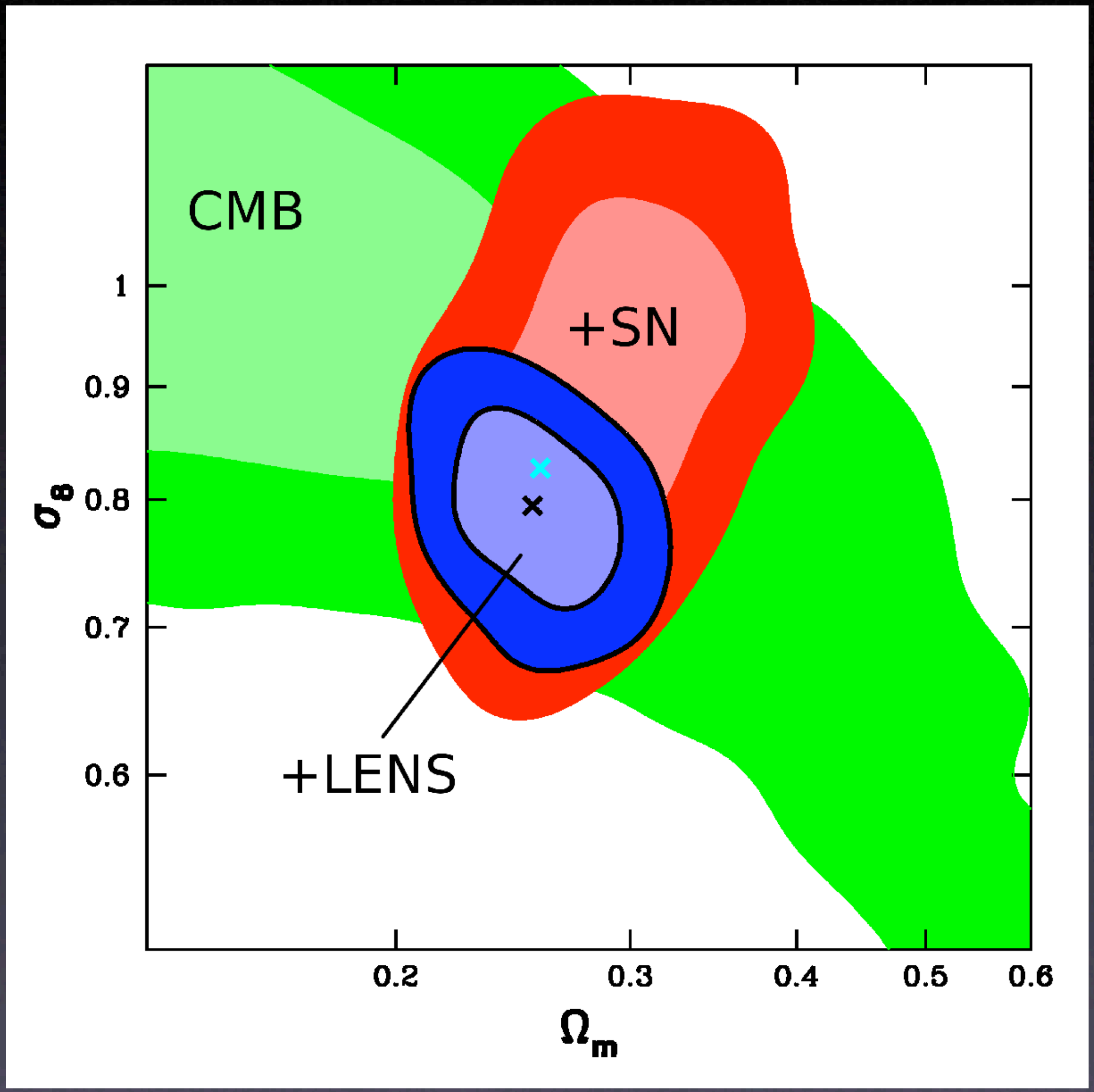


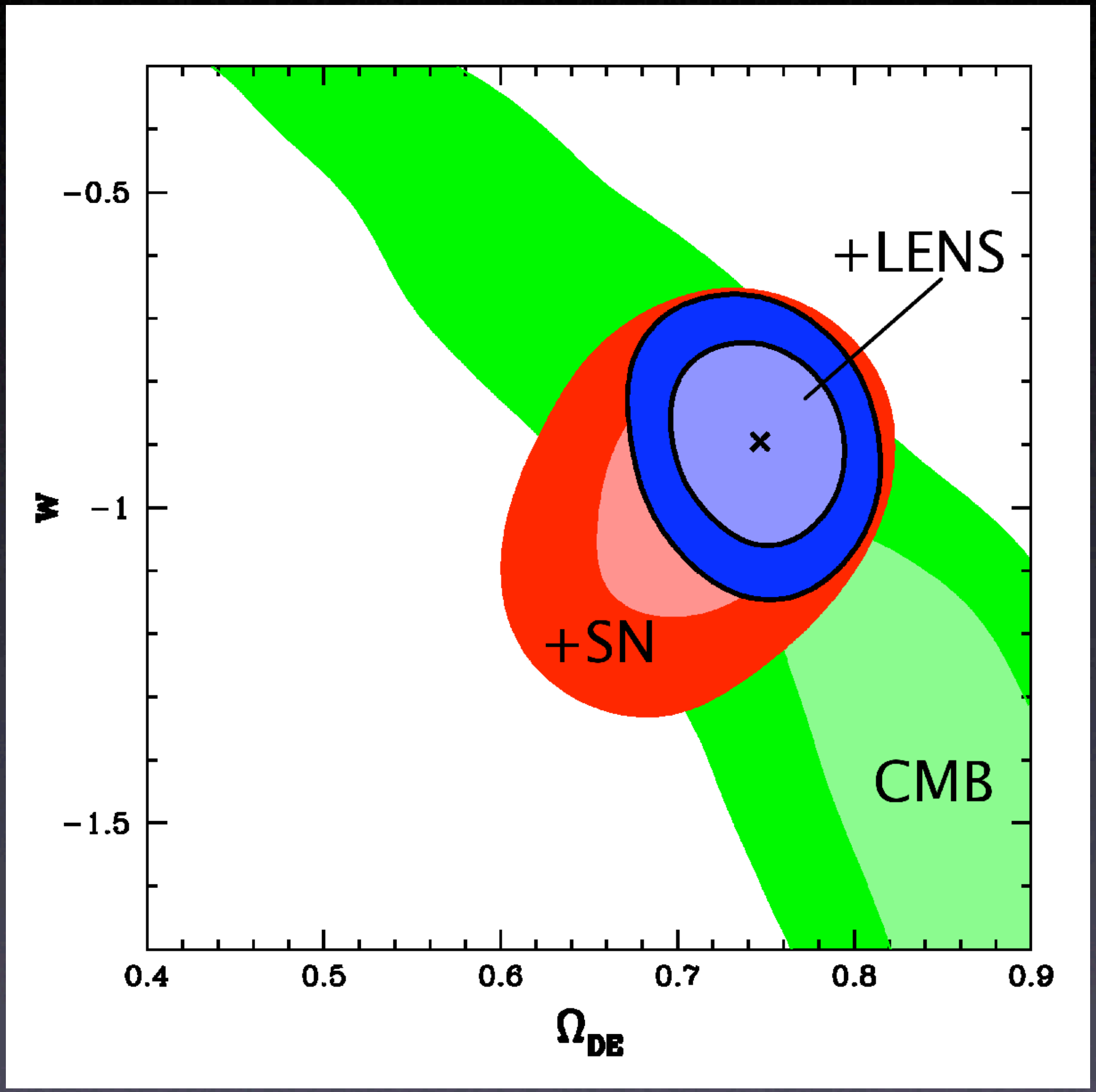
Shear "aperture mass" (=power spectrum)

Shear correlation function

(using ~2 million galaxies)

Science Results: CTIO Survey (Jarvis et al 2005)





Results for constant-w models from Jarvis, Jain, & Bernstein (2005) from the 75-square-degree CTIO lensing survey

Science Results: CFH Legacy Survey

- Complete 140 sq deg of ugriz imaging in 1 year
- Results from i-band in 57 sq degree just published: Fu et al (2008)
- Uses 1-sq-degree Megacam on CFH 3.5m

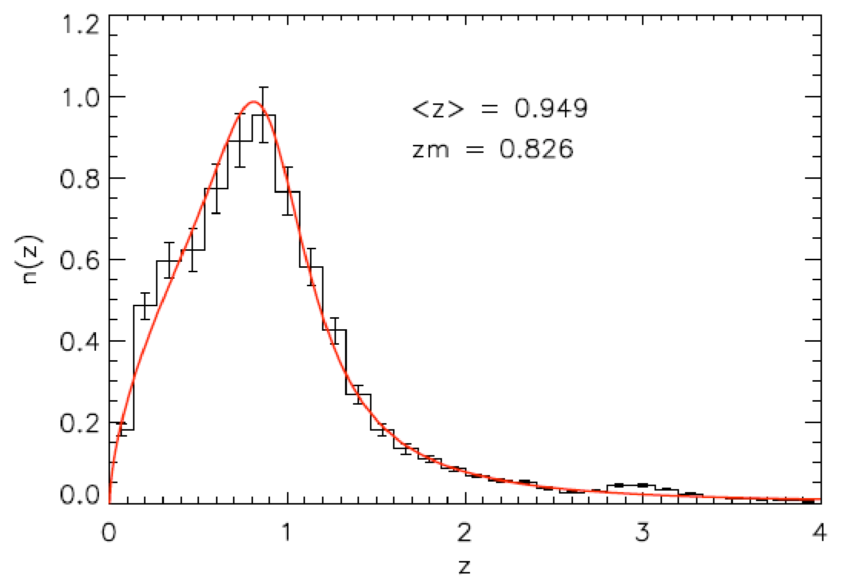


Fig. 9. Final normalised redshift distribution. Galaxies are selected in the range [0;4], and the best-fit is given for function given in Eq. (14). Note that the fit is only performed in the interval [0;2.5].

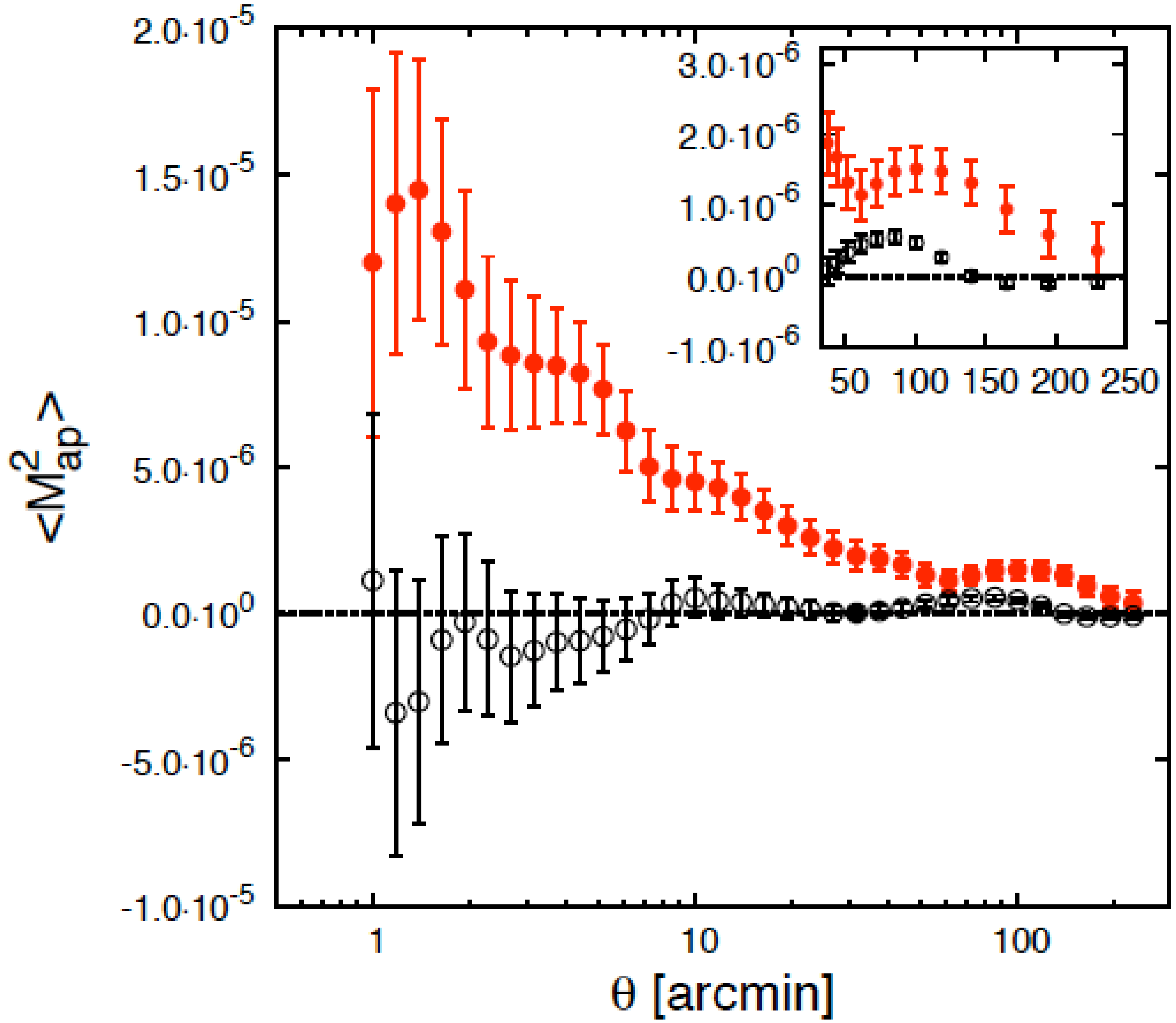


Fig. 4. Two-point statistics from the combined 57 pointings. The error bars of the E-mode include statistical noise added in quadrature to the non-Gaussian cosmic variance. Only statistical uncertainty contributes to the error budget for the B-mode. Red filled points show the E-mode, black open points the B-mode. The enlargements in each panel show the signal in the angular range 35′-230′.

Science Results: CFH Legacy Survey (Fu et al)

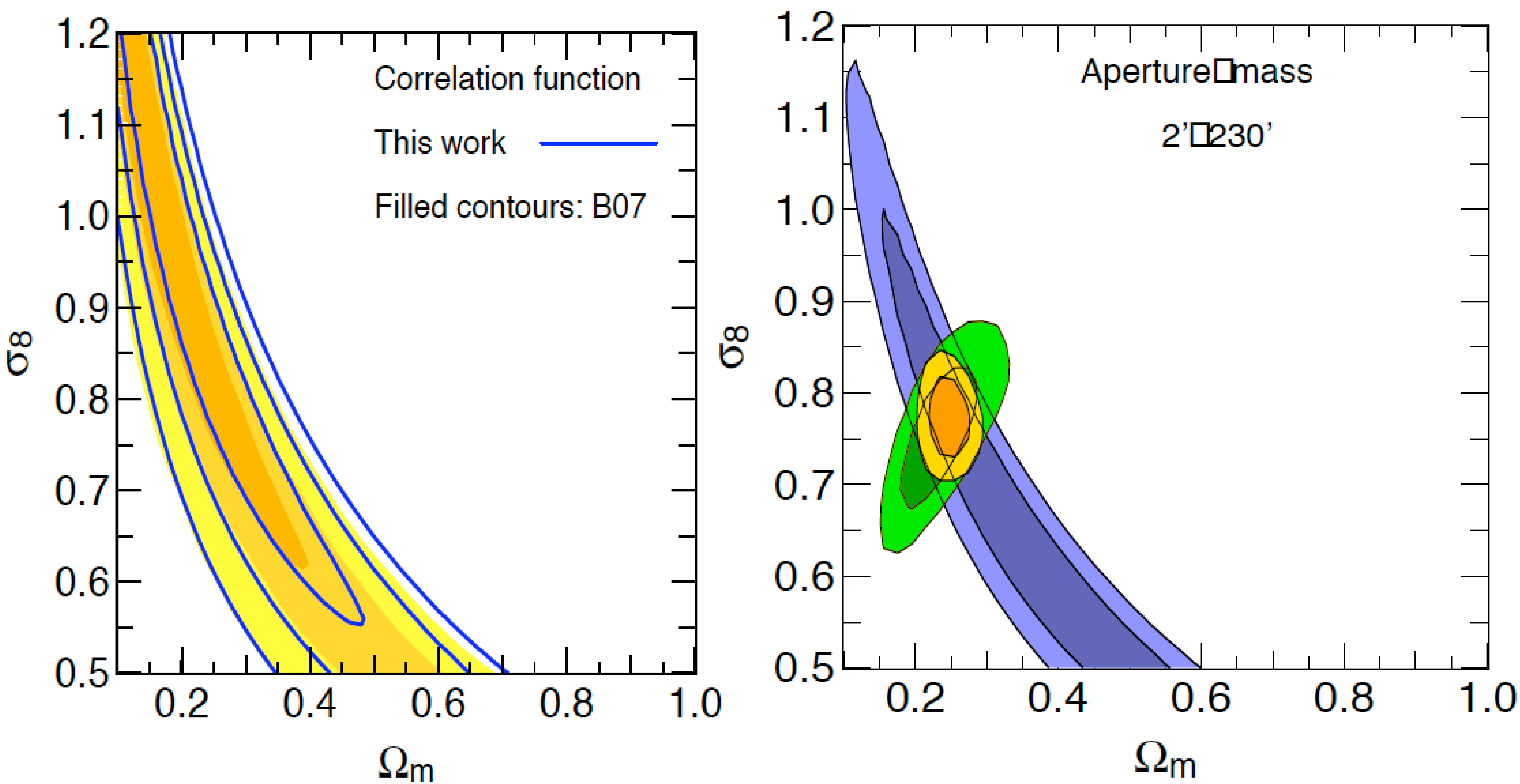
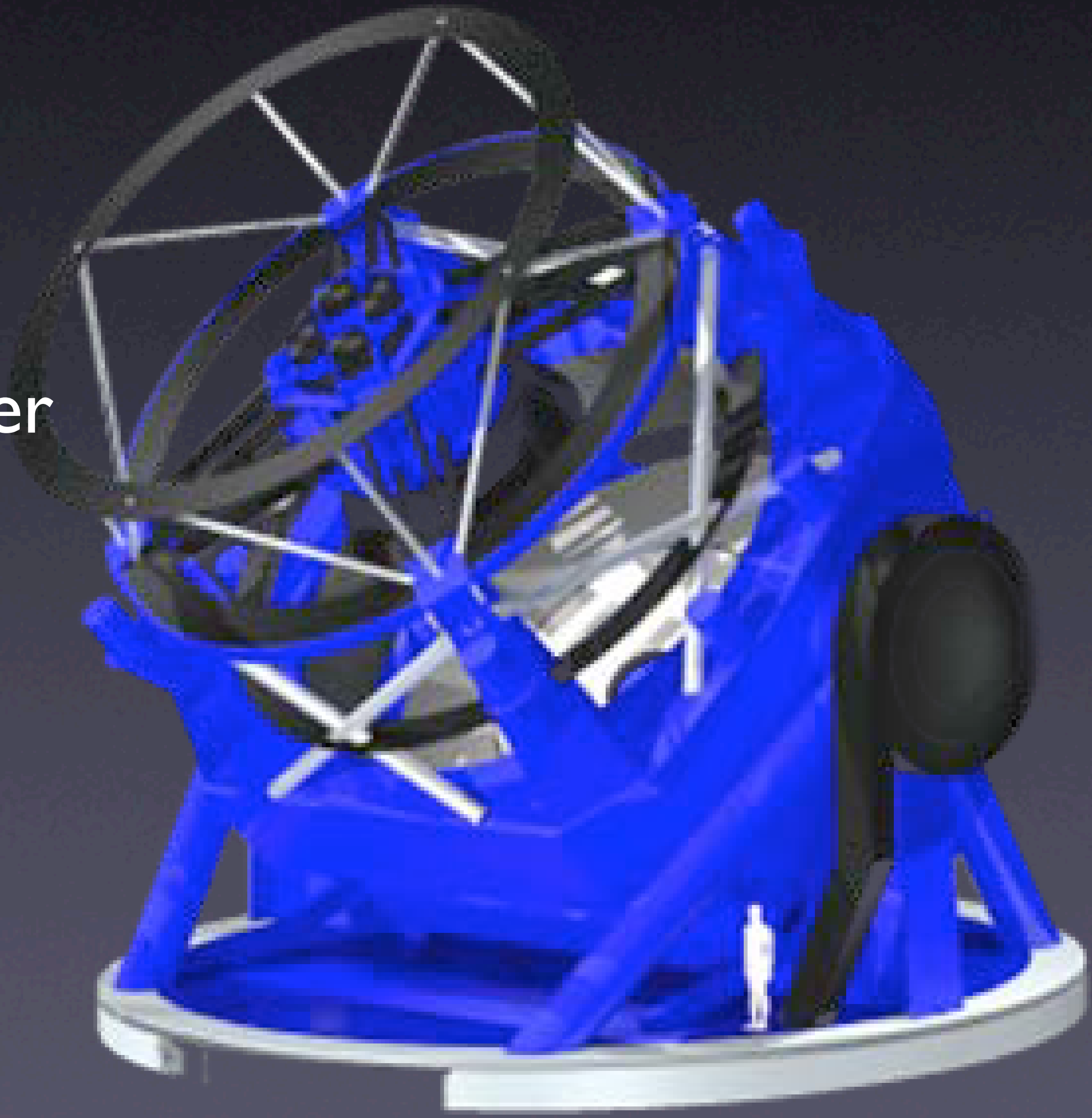


Fig. 12. *Left panel:* Comparison $(1, 2, 3\sigma)$ between our results (bold lines) and the 100 square degree survey (B07, filled contours), using ξ_E in both cases. The redshift distribution is fitted in the range of $[0.2; 1.5]$ to be consistent with B07. *Right panel:* Comparison $(1, 2\sigma)$ between WMAP3 (green contours, Spergel et al. 2007) and our $\langle M_{\rm ap}^2 \rangle$-results between 2 and 230 arc minutes (purple). The combined contours of WMAP3 and CFHTLS Wide are shown in orange.

The LSST Project

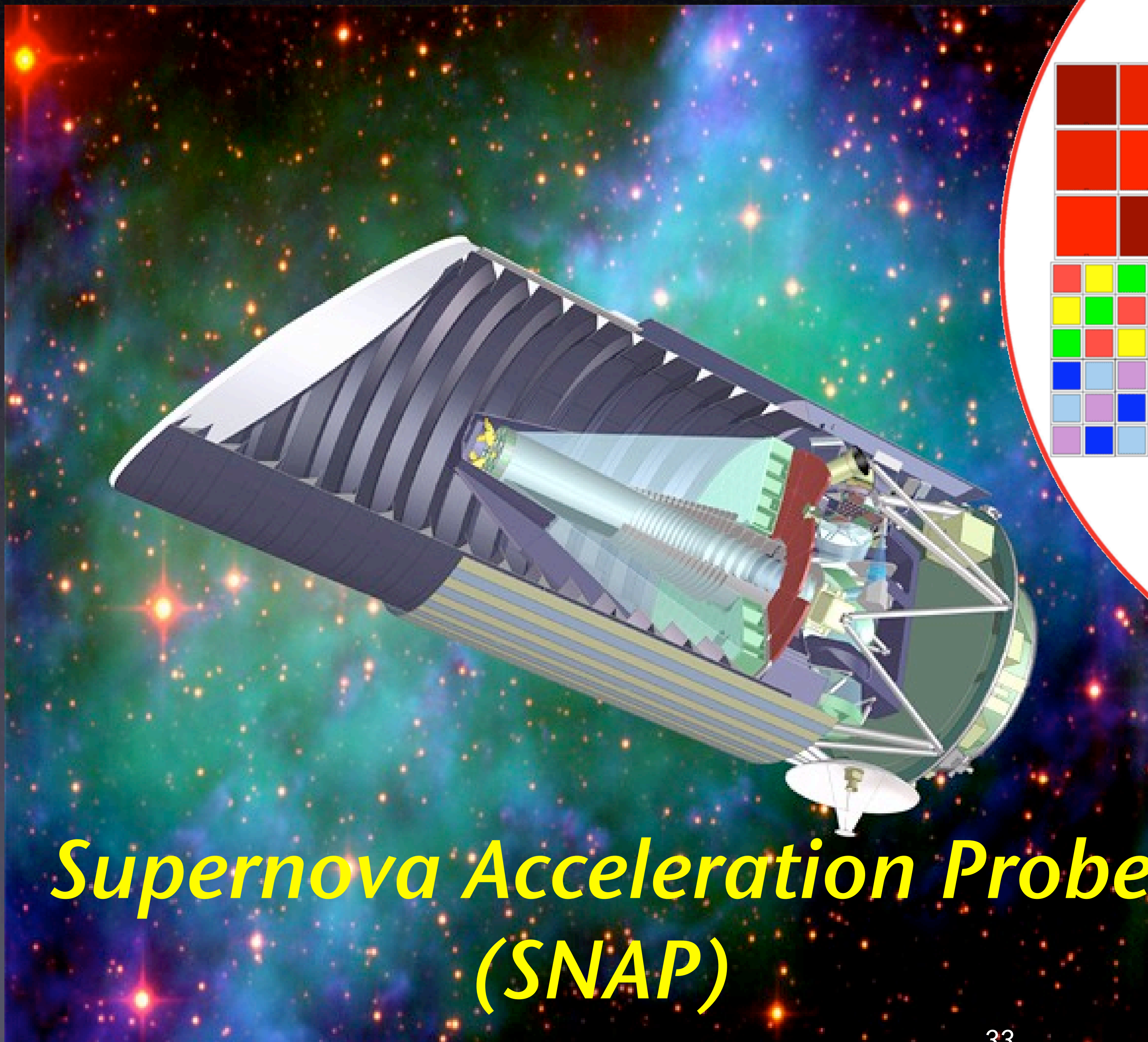
- The ultimate ground-based visible sky imaging project.
- Dedicated 8-meter, 3-mirror telescope (6.5-m equivalent aperture)
- A single camera with >2 billion pixels.
- Survey the entire visible hemisphere every 4 days.
- Several hundred visits, 6 filters 0.35-1 um, for each accessible sky location over 10 years.
- Measure several billion galaxy shapes over a full hemisphere
- 4 GB image every 15 s
- 1 TB/hr, 8 TB/night, 2-3 PB/yr!
- 10-year operation.

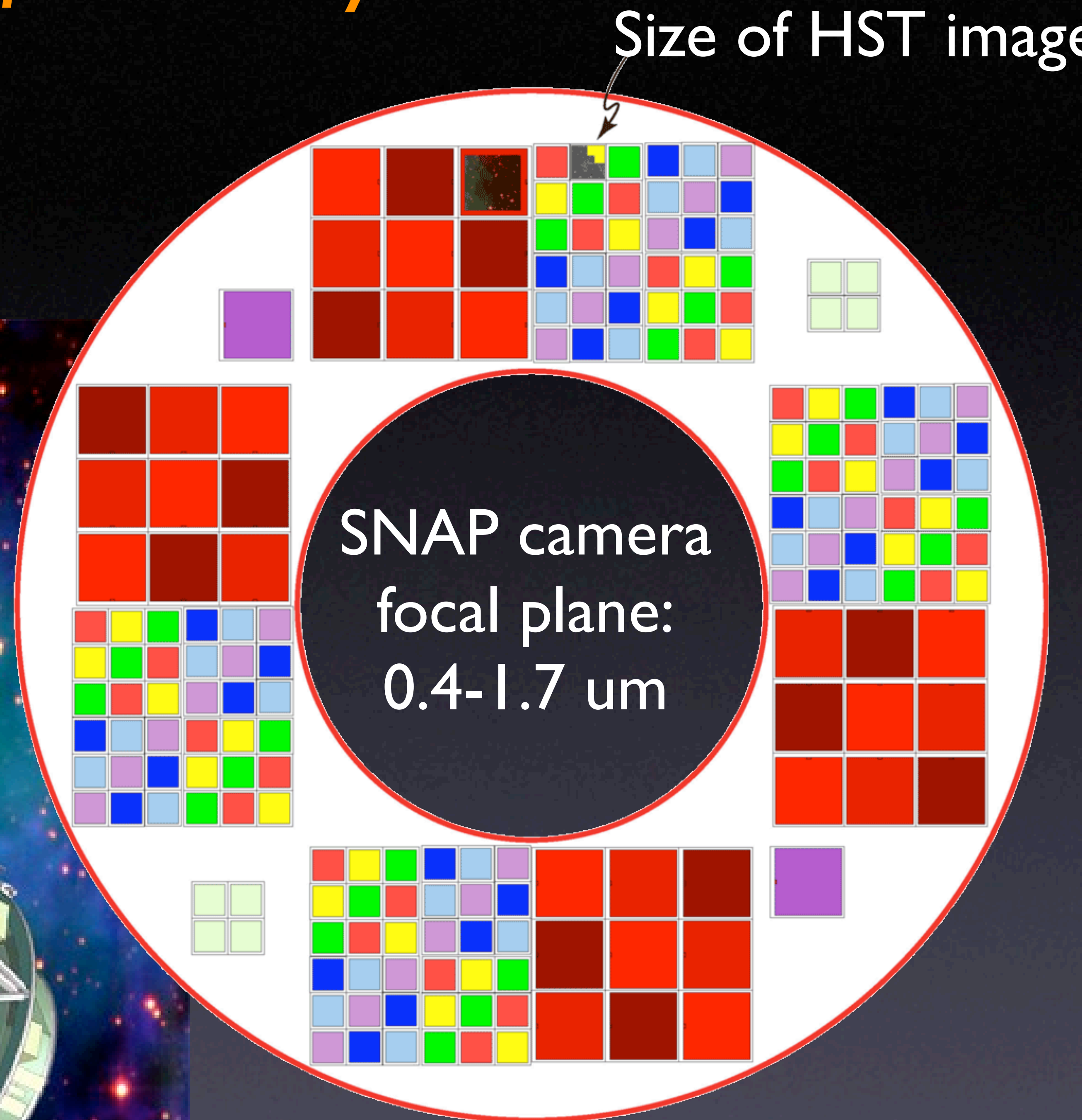


Bernstein

SNAP: a space telescope for surveys

600 Megapixel Camera
on 2-meter Space Telescope

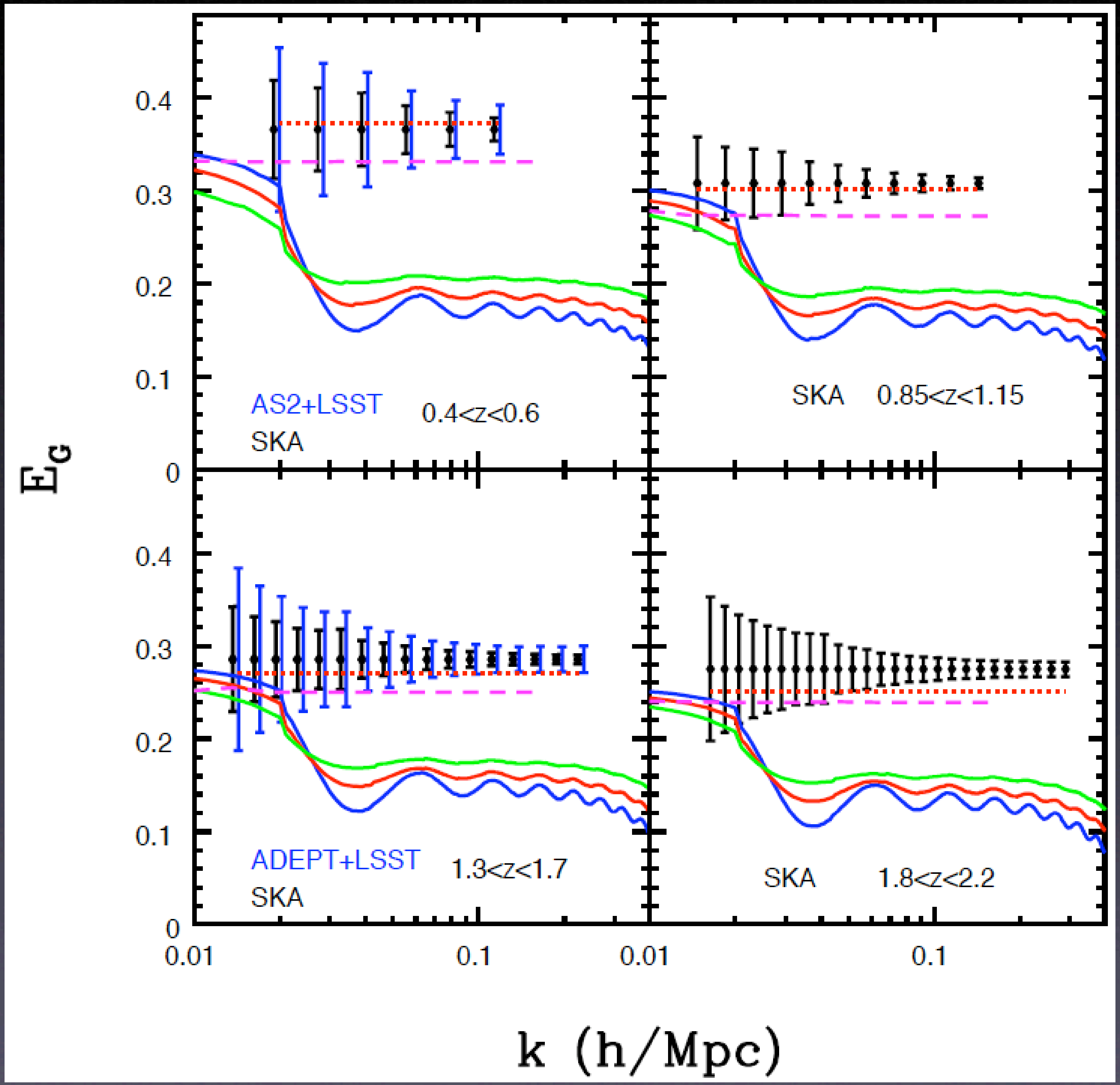




SNAP will harvest galaxy shapes hundreds of times faster than the HST or JWST

Weak lensing cartography + spectroscopic survey?

- Lensing data (=massless geodesics) are only sensitive to sum ($\Psi+\Phi$)
- Non-relativistic flows are sensitive only to Ψ.
- Zhang et al (2007) propose that ratio of *galaxy-lensing* correlation to the *galaxy-velocity* correlation is a clean test of the equivalence of Ψ to Φ.
- Lensing survey + spectroscopic survey in linear regime.



Summary

- Weak lensing observations produce maps of the *metric of the Universe* from shearing of geodesic bundles.
- Present data constrain power in the *projected gravitational potential:* sigma8
- Future tomographic data produce 3d data, capable of simultaneously constraining growth of potential fluctuations, expansion of Universe, and curvature.
- Self-diagnostic for most systematic errors due to rich data set.
- Scientific treasure:
  - Tests of GR (anisotropic stress, growth eqn)
  - Curvature data point for inflation
  - Dark energy or other contributors to Friedmann eqn?
  - Potential well associated with every kind of galaxy, group, and cluster.
- Inspire and exploit huge surveying projects from ground & space: visible/NIR/21-cm galaxies, CMB imaging, recombination era.