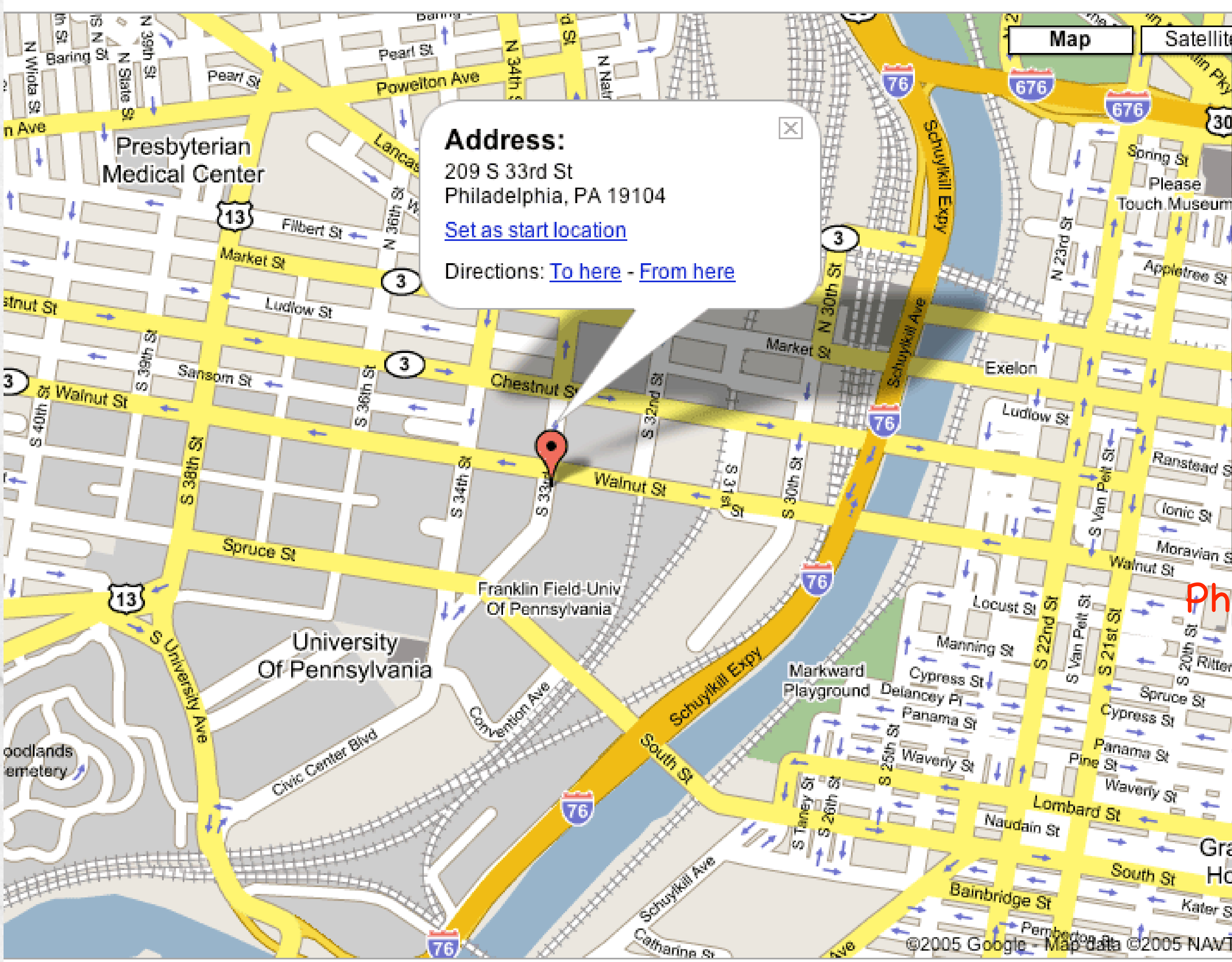
Weak Gravitational Lensing

Gary Bernstein, University of Pennsylvania

KICP Inaugural Symposium

December 10, 2005

astrophysics is on the 4th floor...

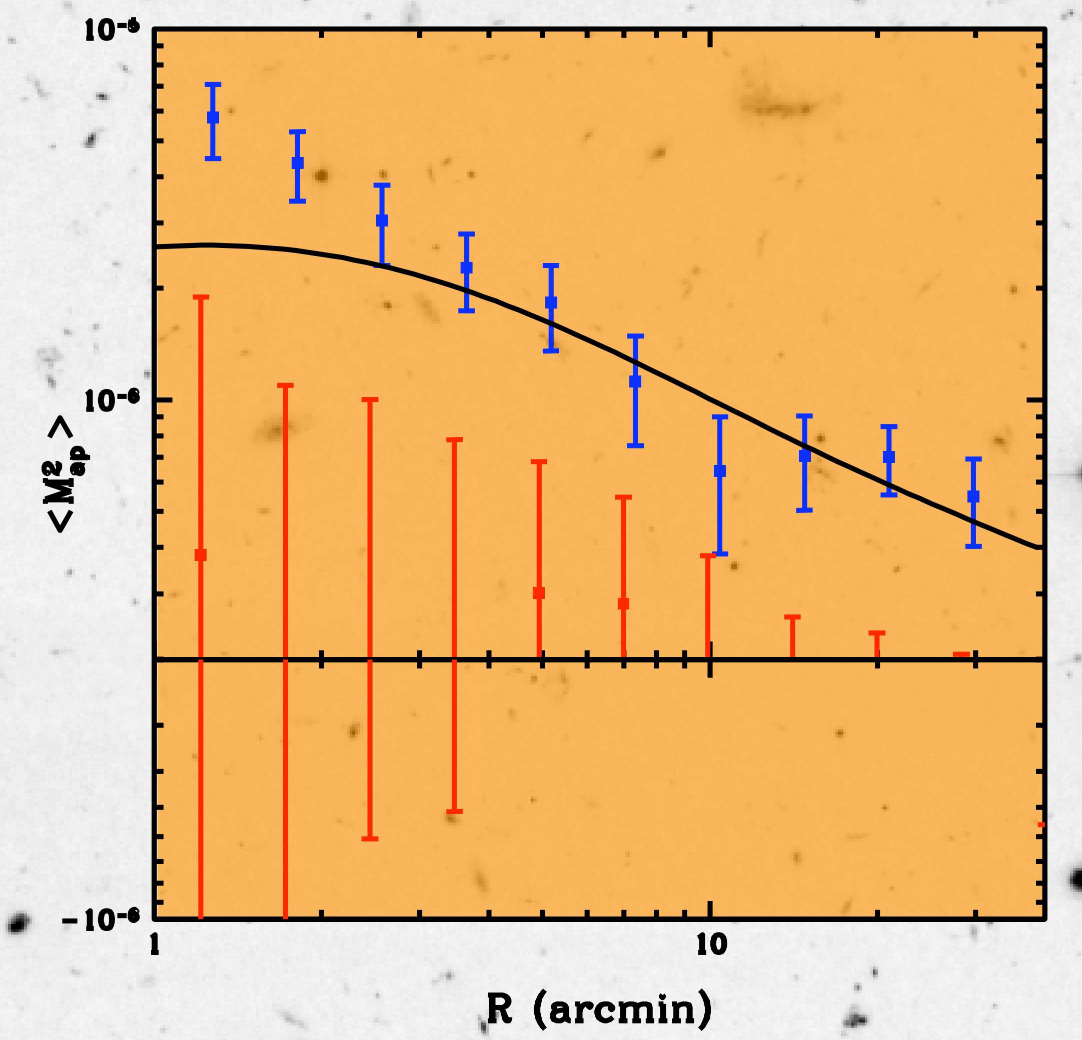


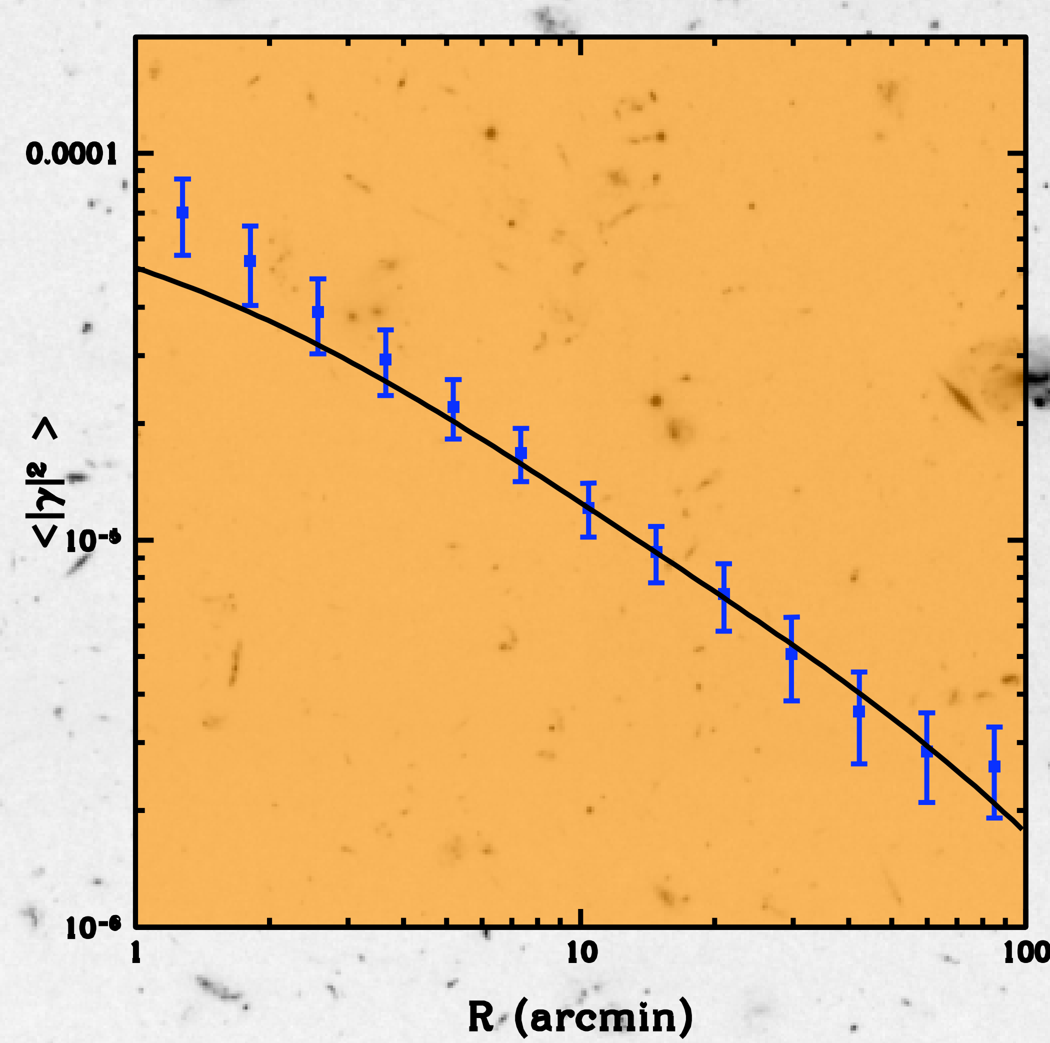
President Amy Gutmann
215 898 7221

Physics Chair Tom Lubensky
215 898 8152


Why am I in this session?

Data from Jarvis et al (2005), 75-square-degree CTIO Lensing survey



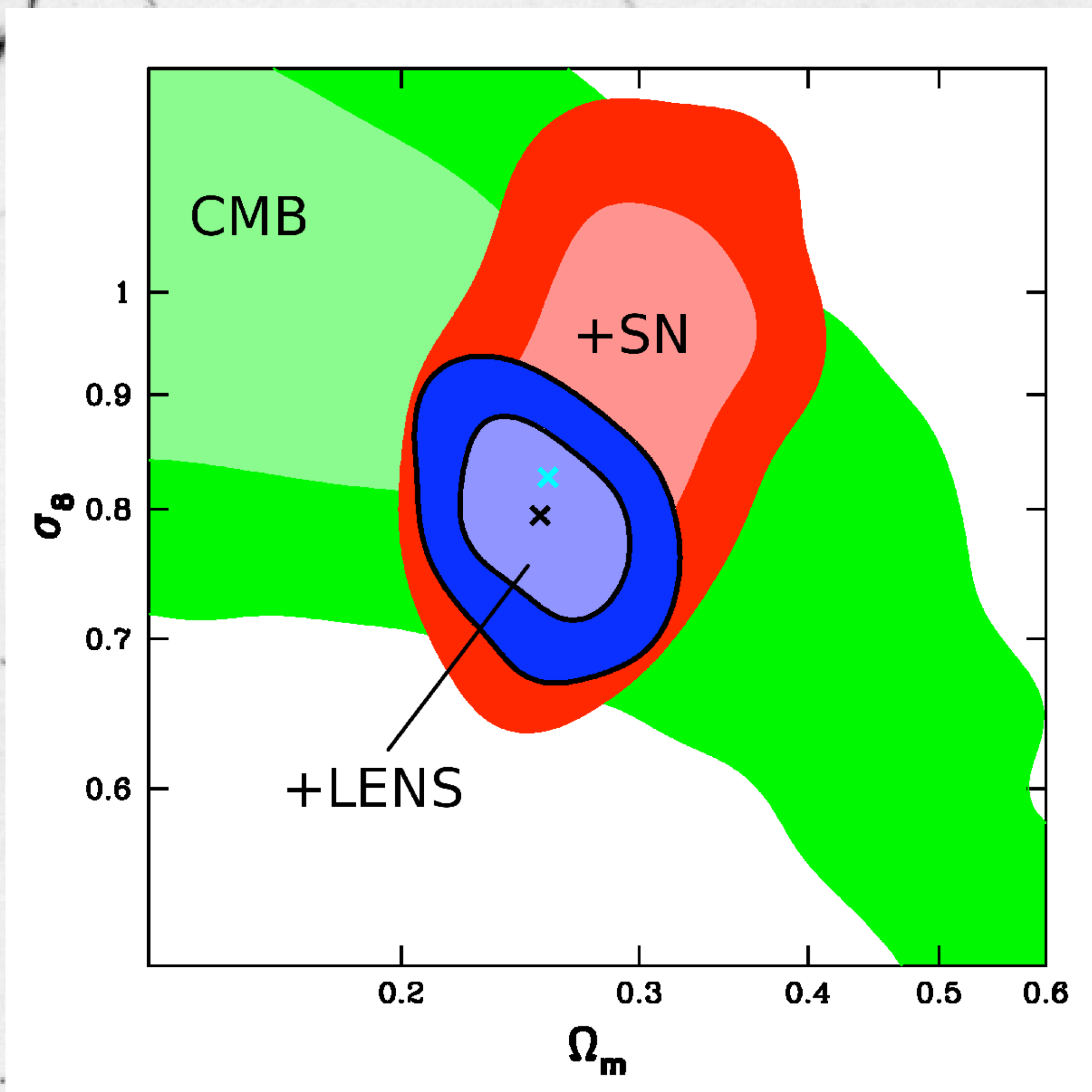


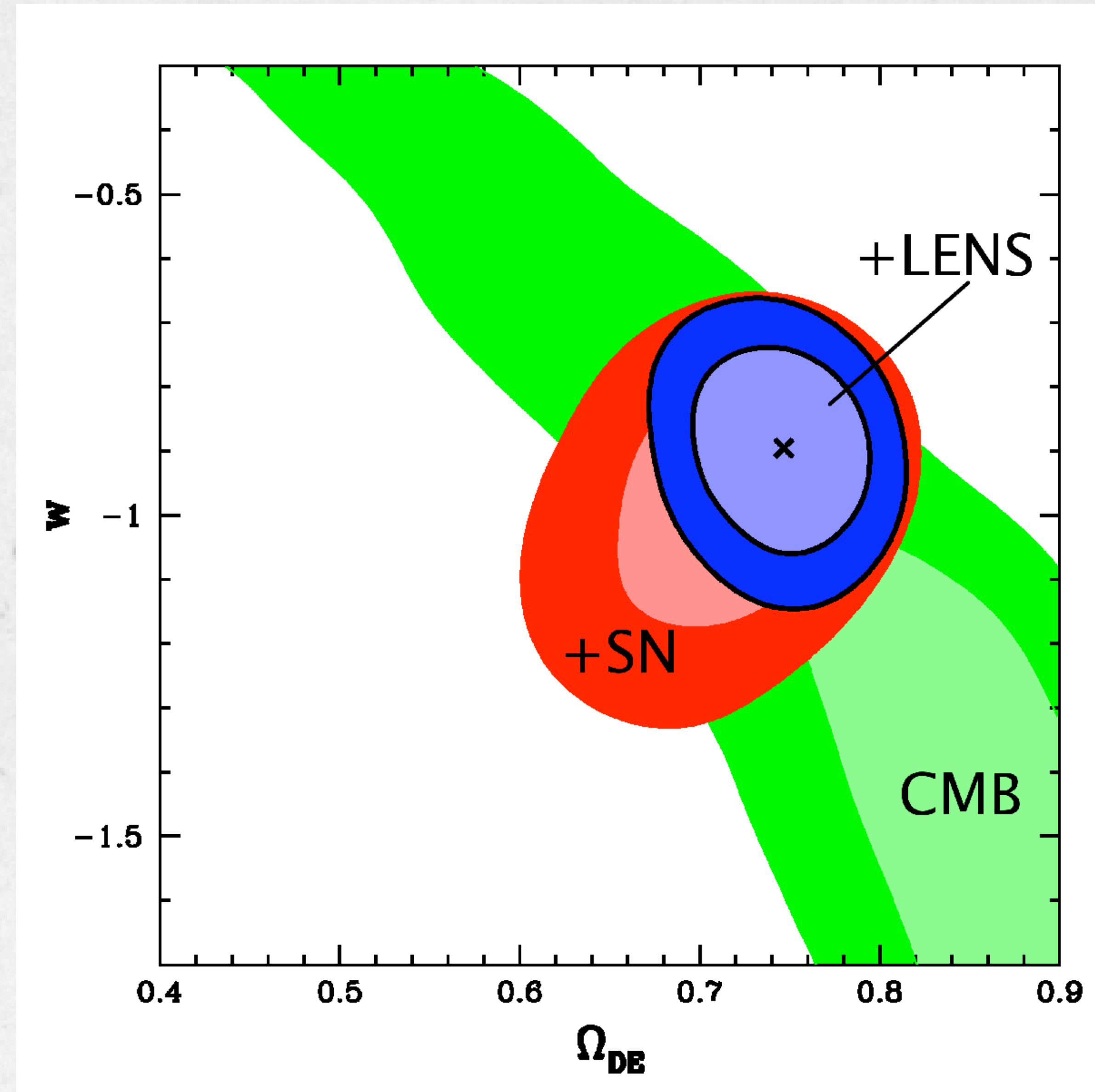
Shear "aperture mass" (=power spectrum)

Shear correlation function

(using ~2 million galaxies)

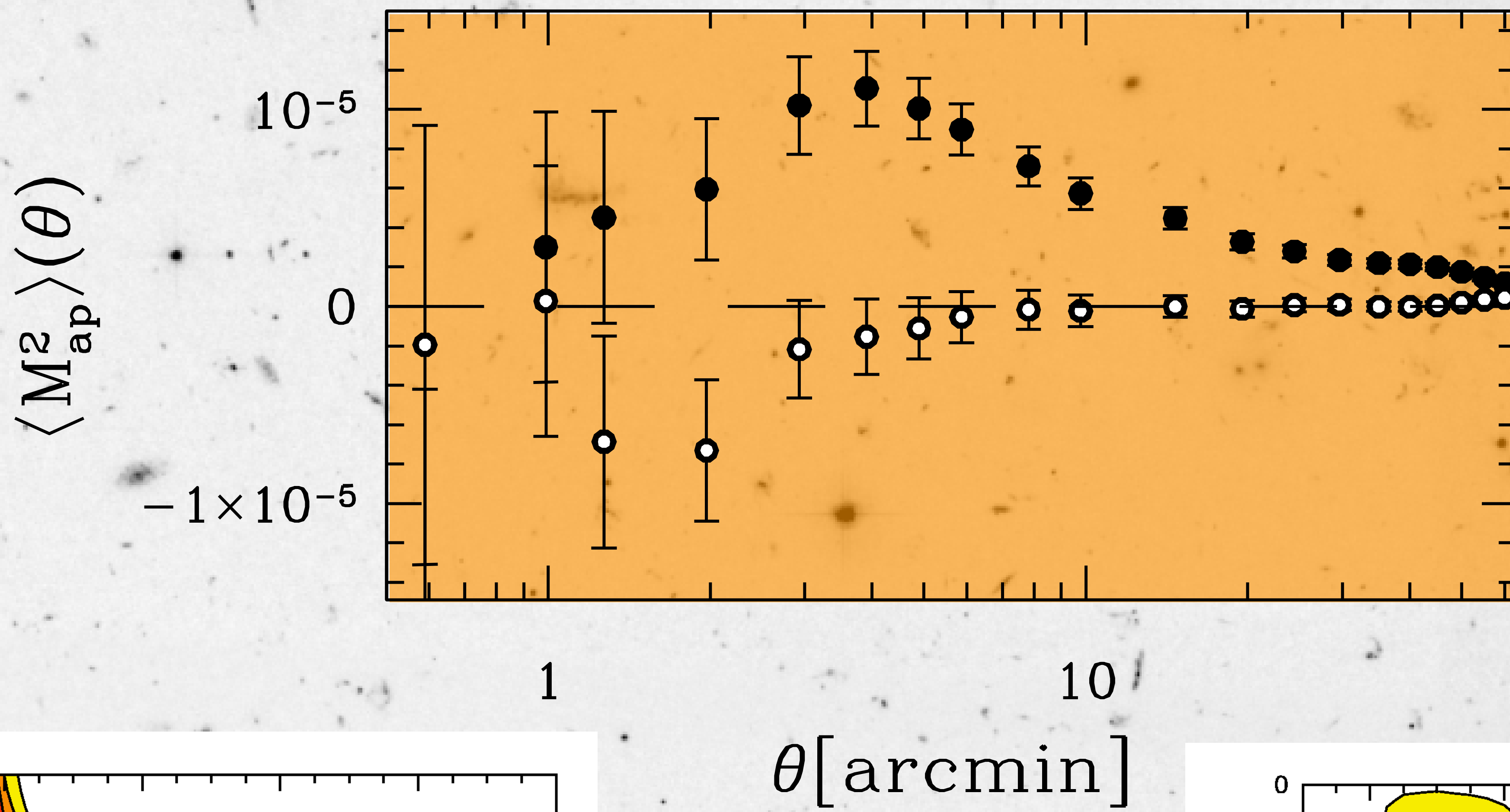
Measurements of dark energy!

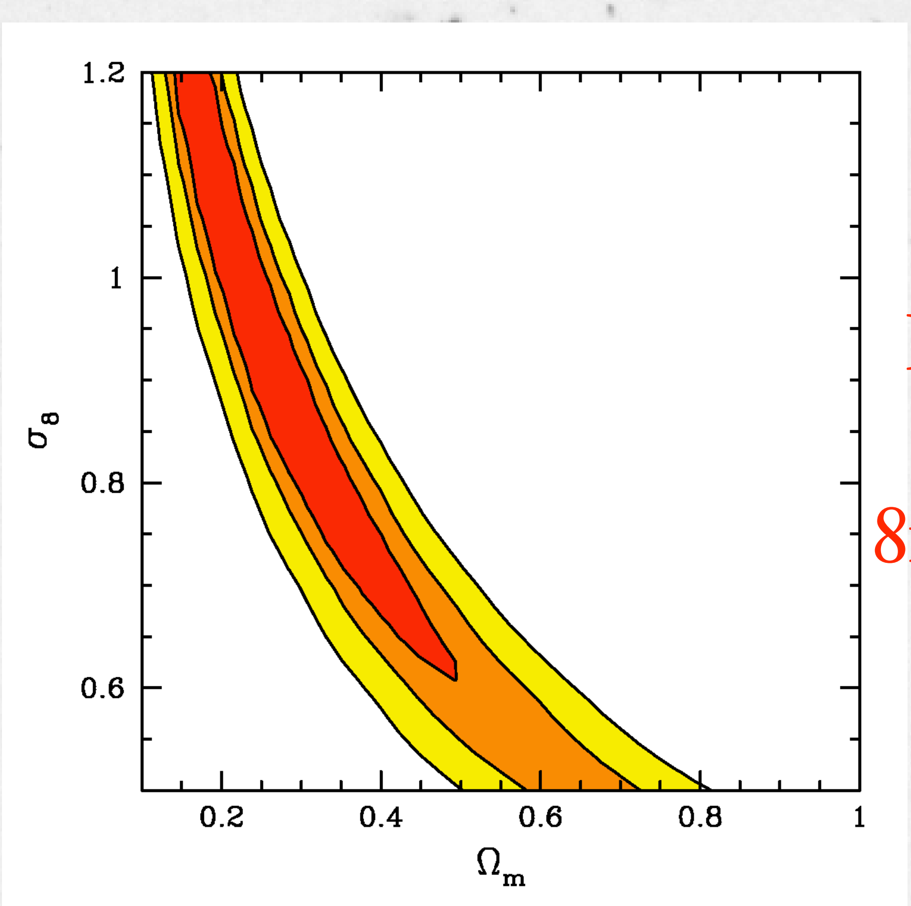




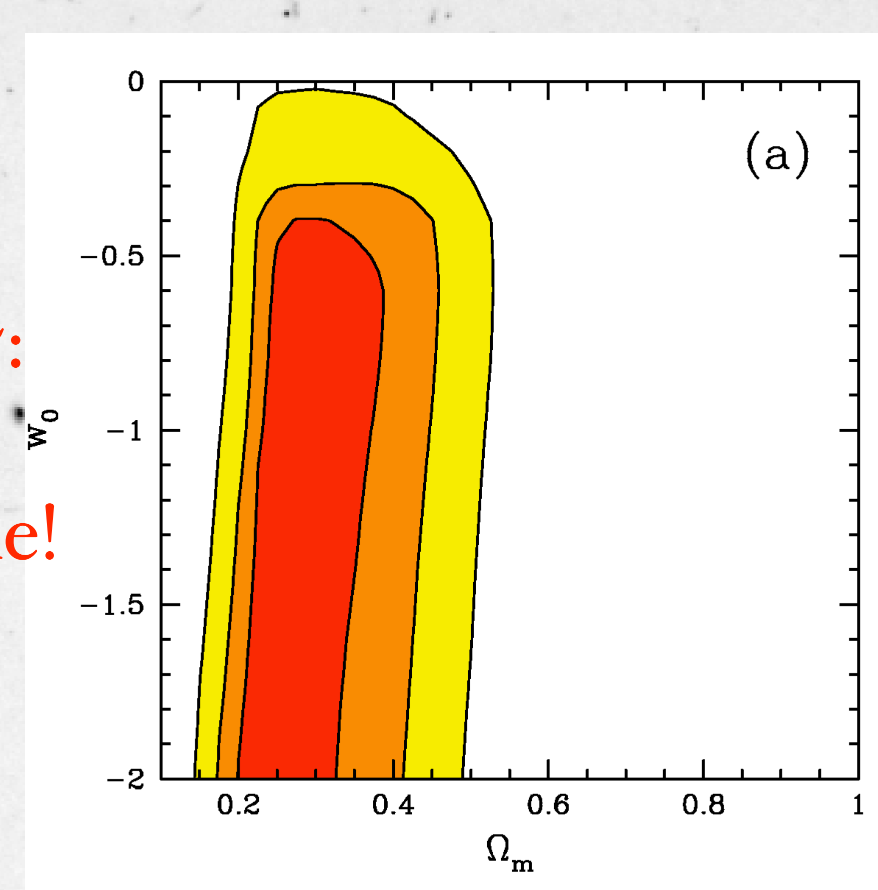
Results for flat, constant-w models from Jarvis et al (2005) from the 75-square-degree CTIO lensing survey

Initial Data from the CFH Legacy Survey



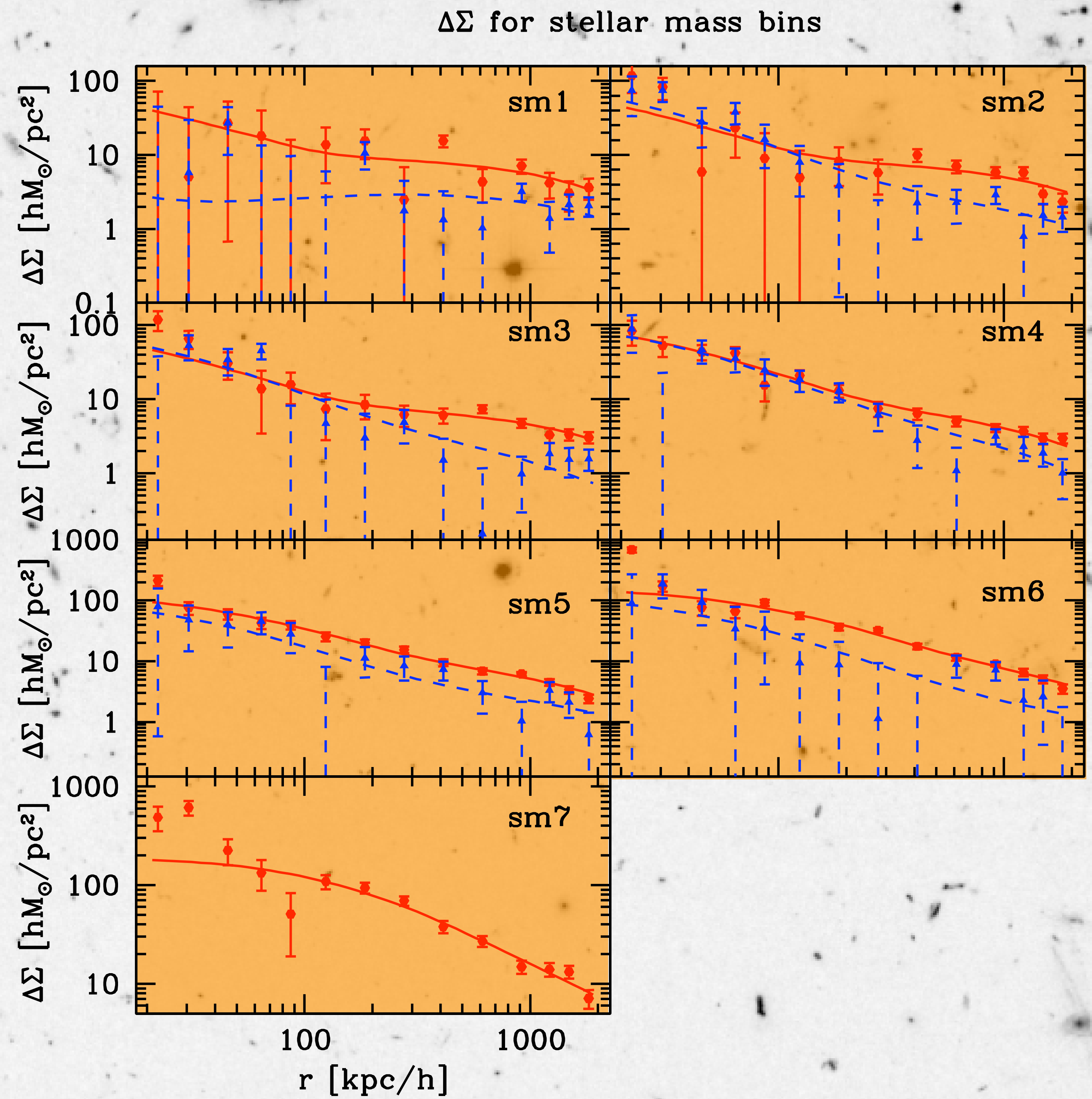


Hoekstra et al 2005:
22 square degrees,
8x more data to come!

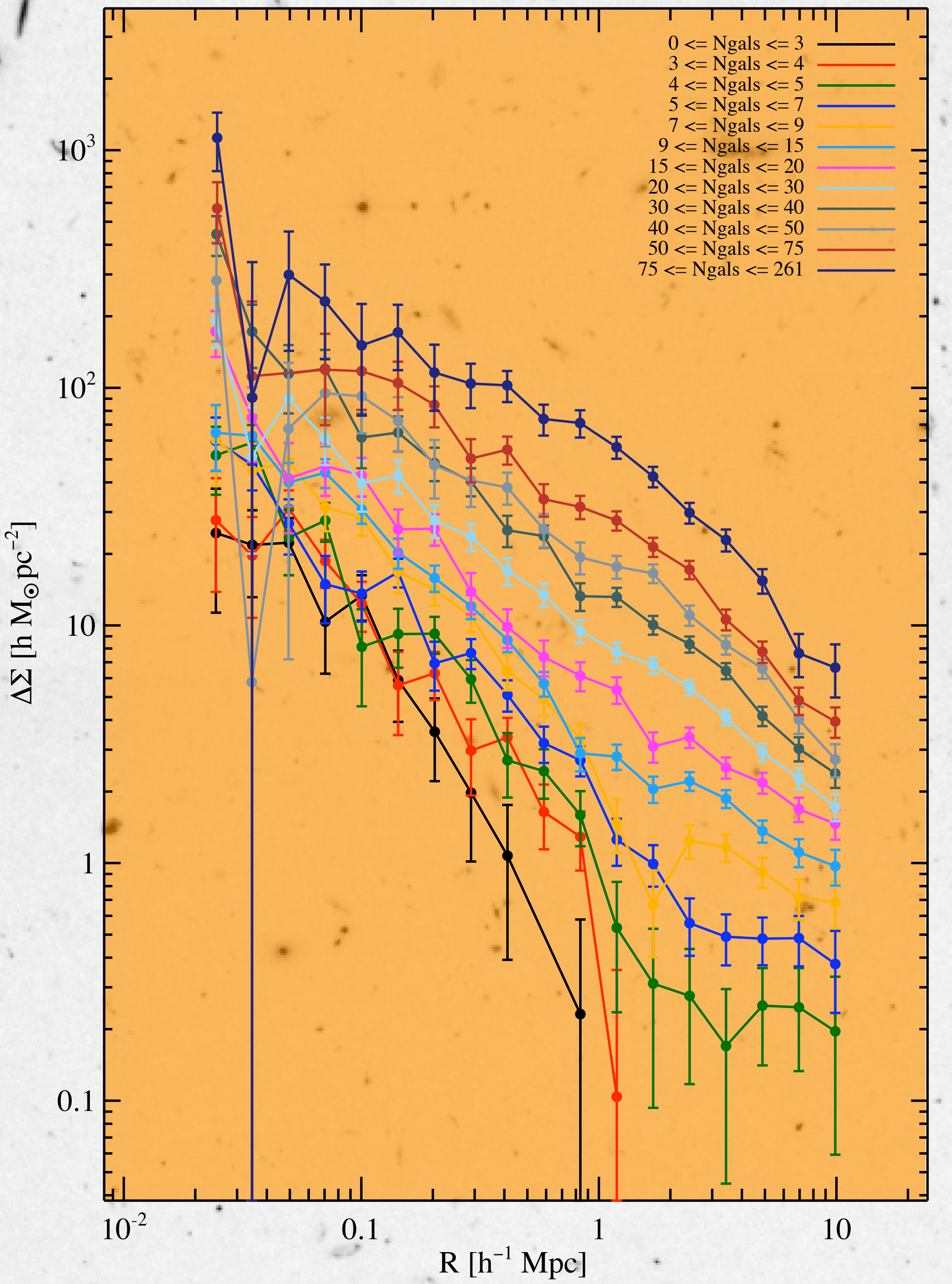


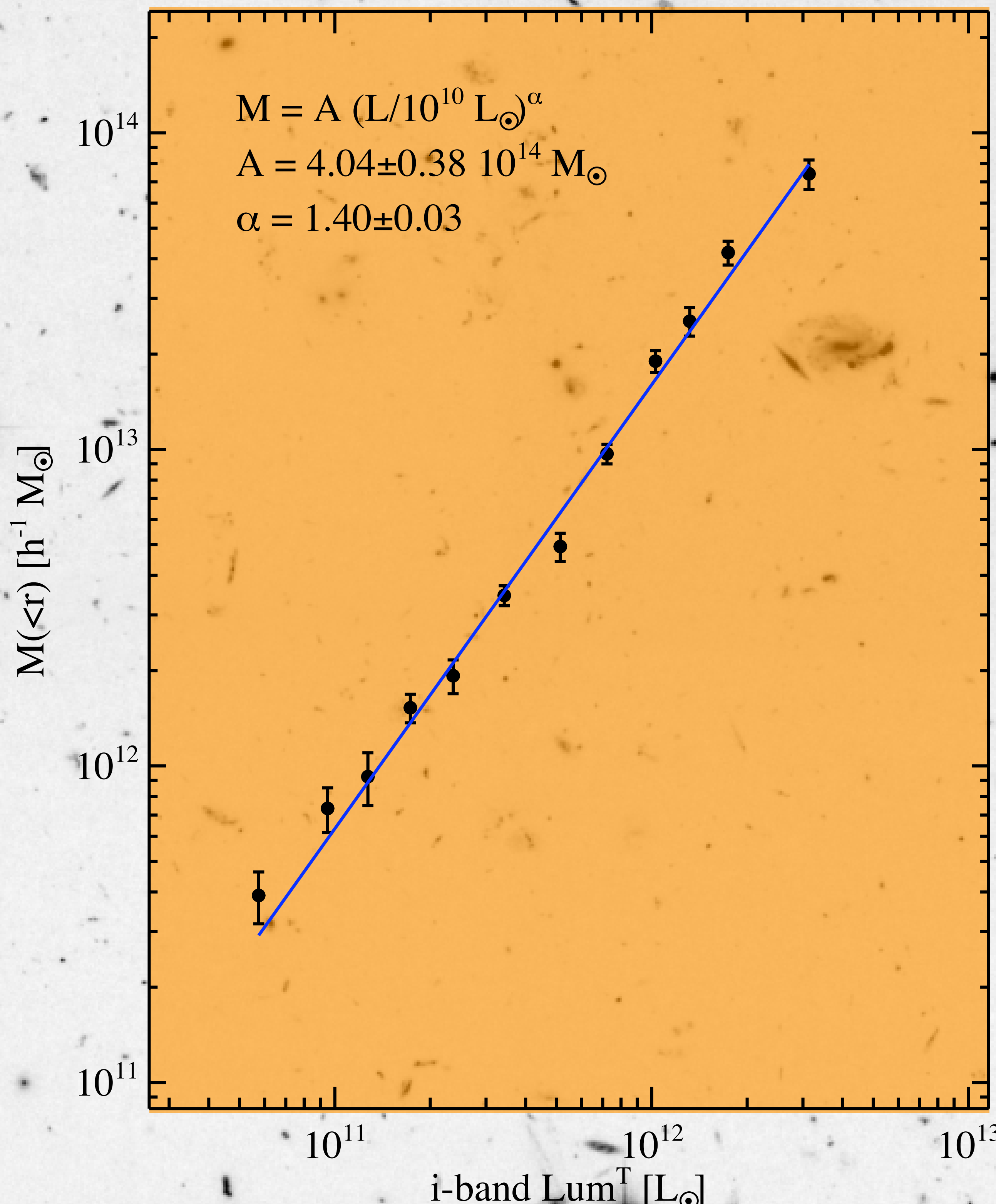
Testing the galaxy formation paradigm

Mandelbaum et al 2005:
Split SDSS galaxies into stellar-mass bins, early/late
Halo models overplotted



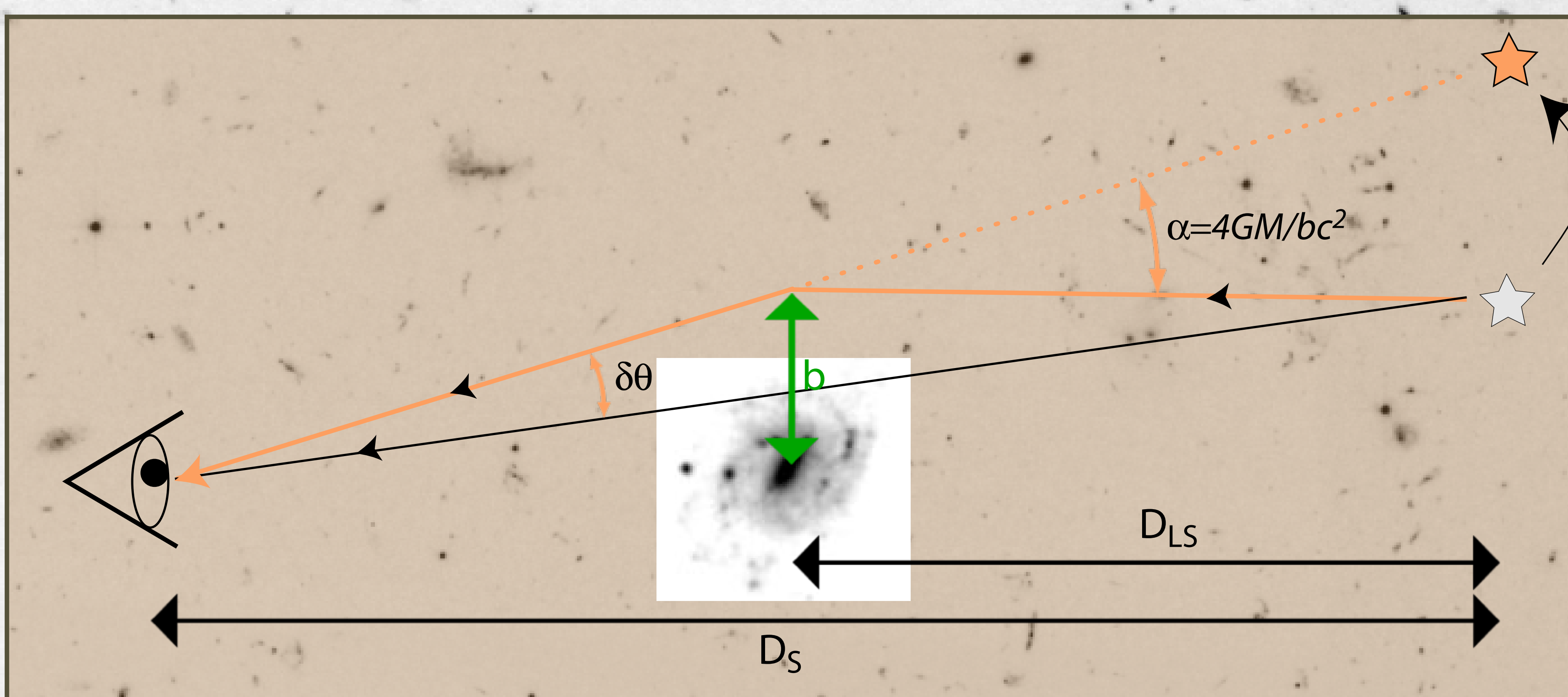
Calibrating galaxy clusters with WL





See Erin Sheldon's talk...

Cosmological Signals in Gravitational Lensing



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

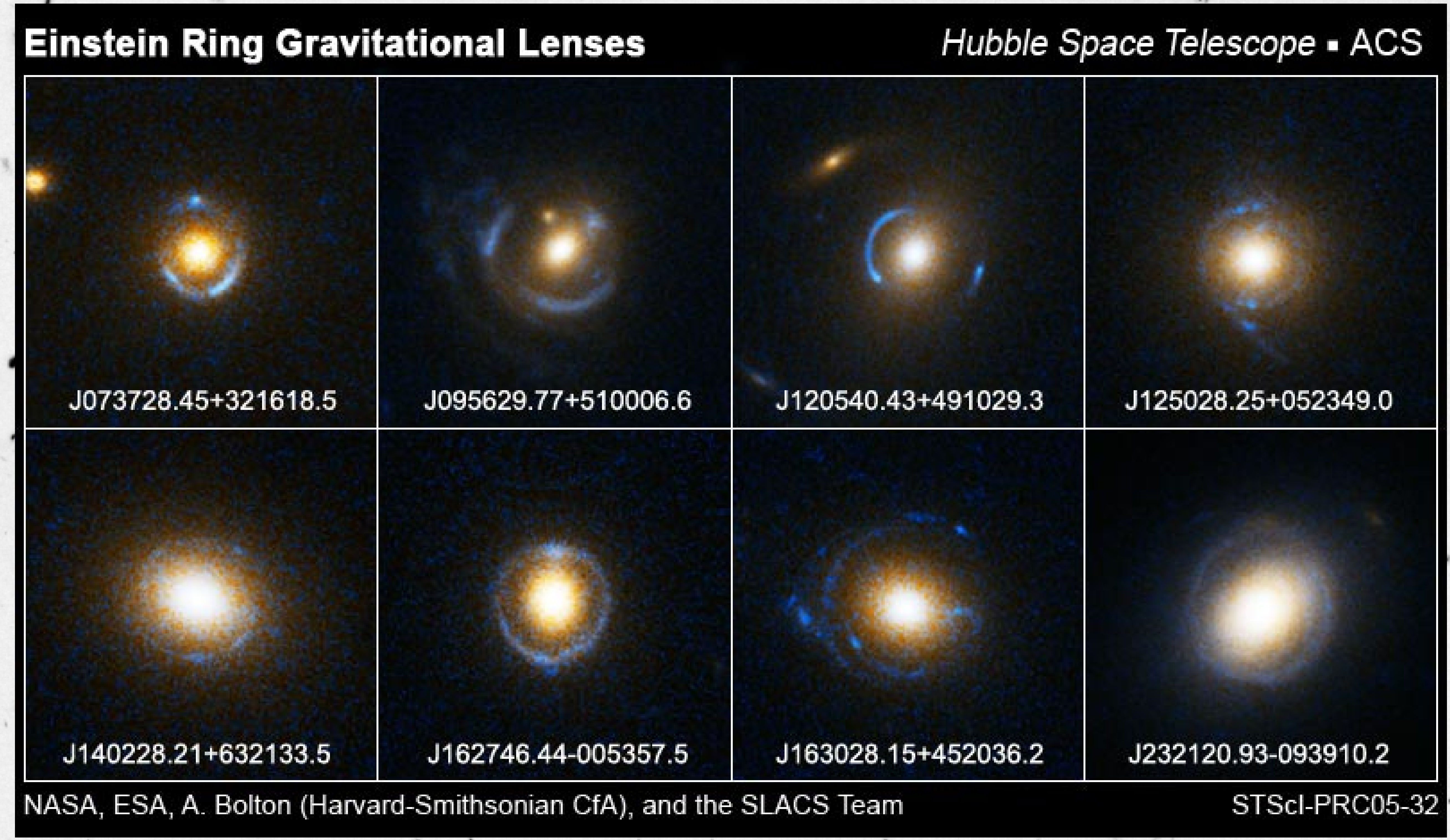
We observe this deflection angle (more precisely, gradients of the deflection angle).

Cosmology changes growth rate of mass structures in the Universe.

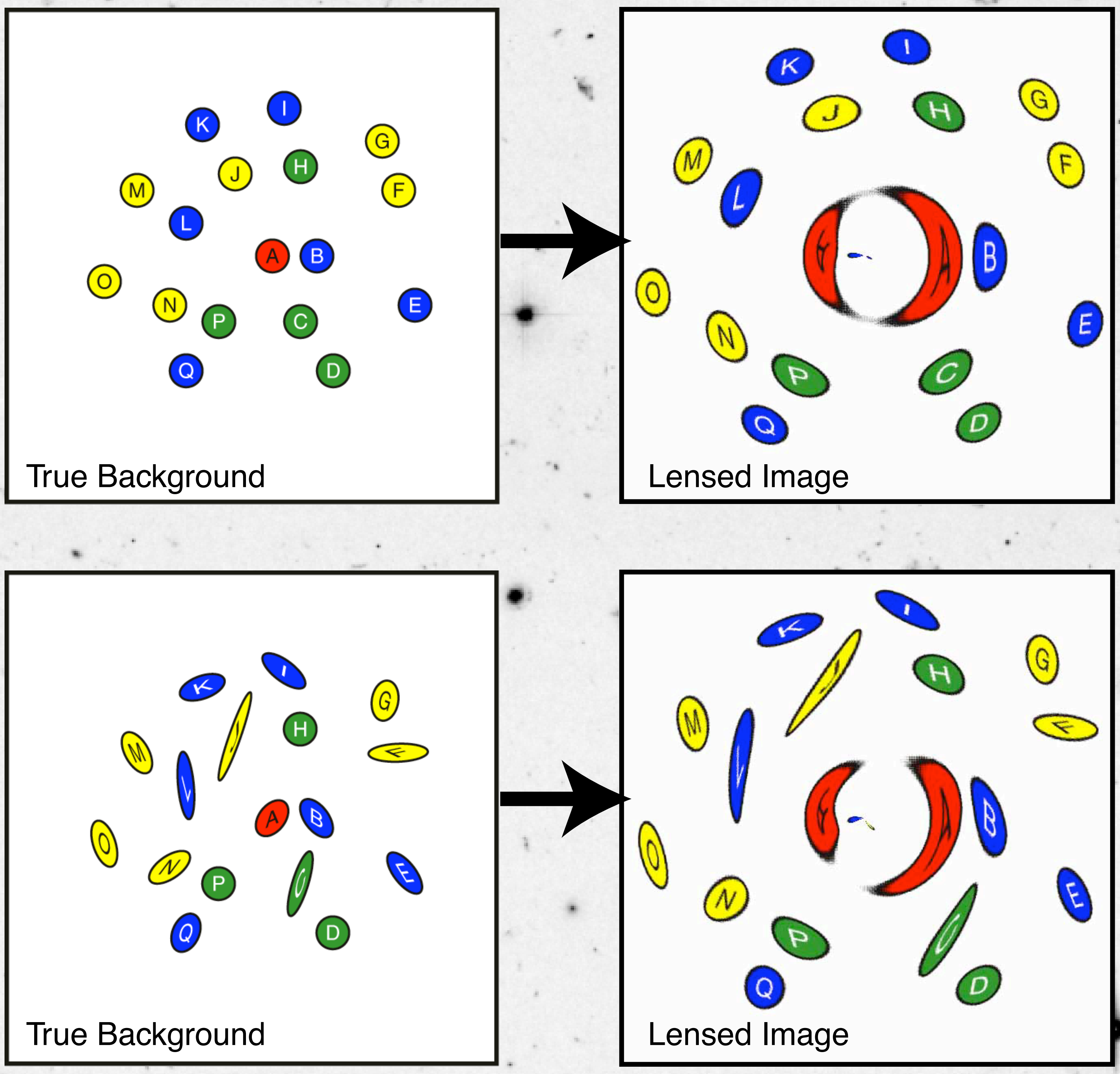
Cosmology changes the geometric distance factors.

Sensitive to both structure and geometry of Universe!

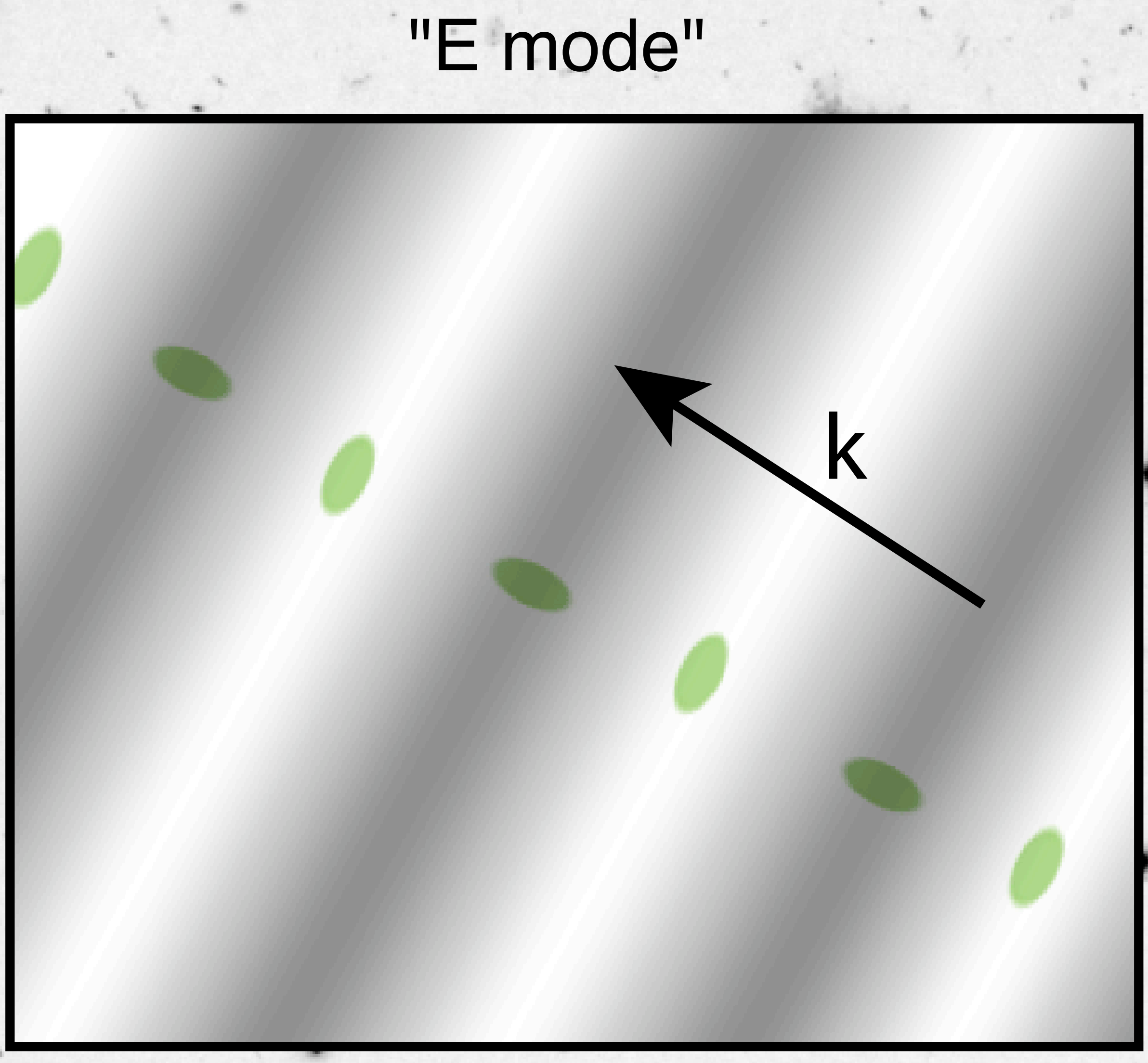
Strong lenses: obvious deflection angles



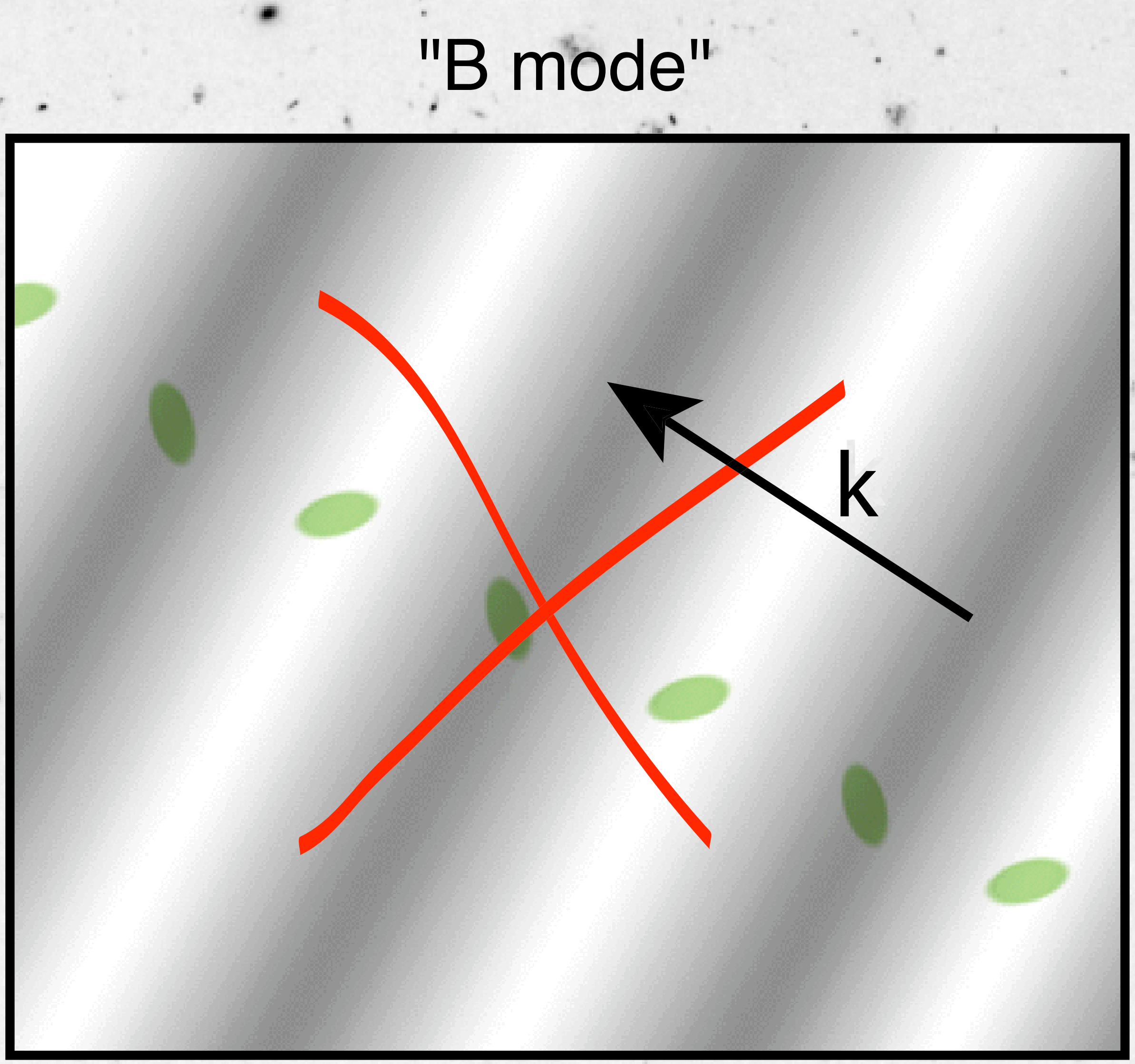
Weak lensing: deflection gradients



Weak lensing in Fourier space

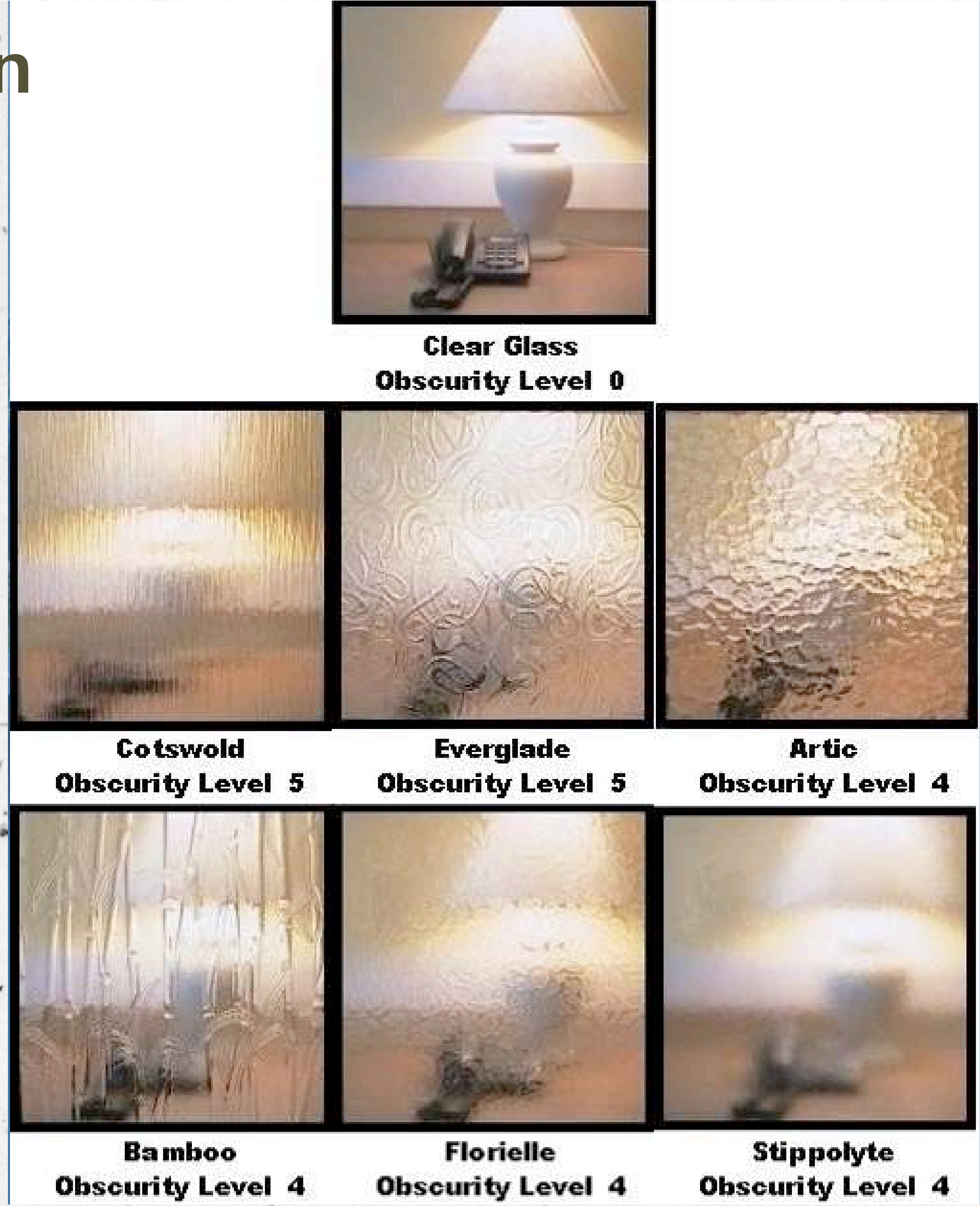


Foreground mass sinusoid produces ellipticity pattern at the same k-vector

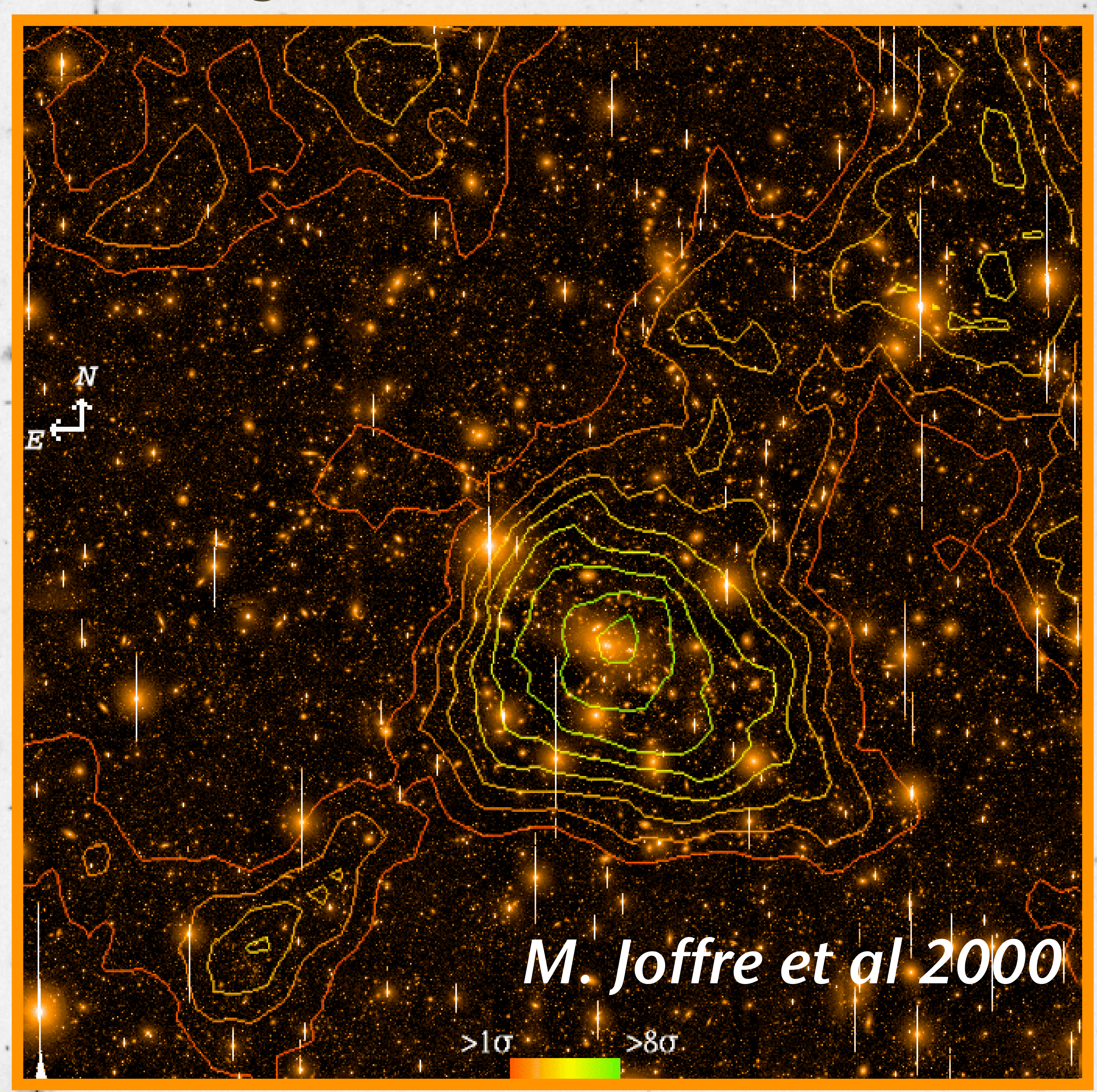


Lensing cannot produce ellipticity pattern at 45 degrees to k-vector

This is your brain on weak lensing

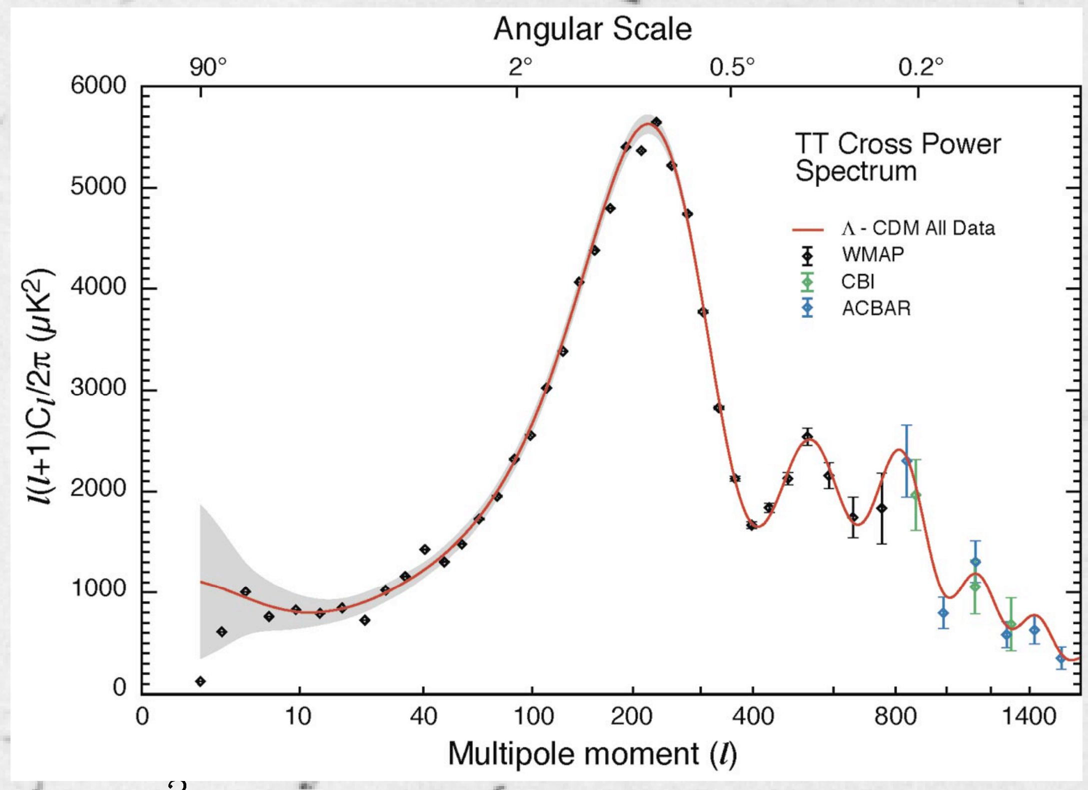


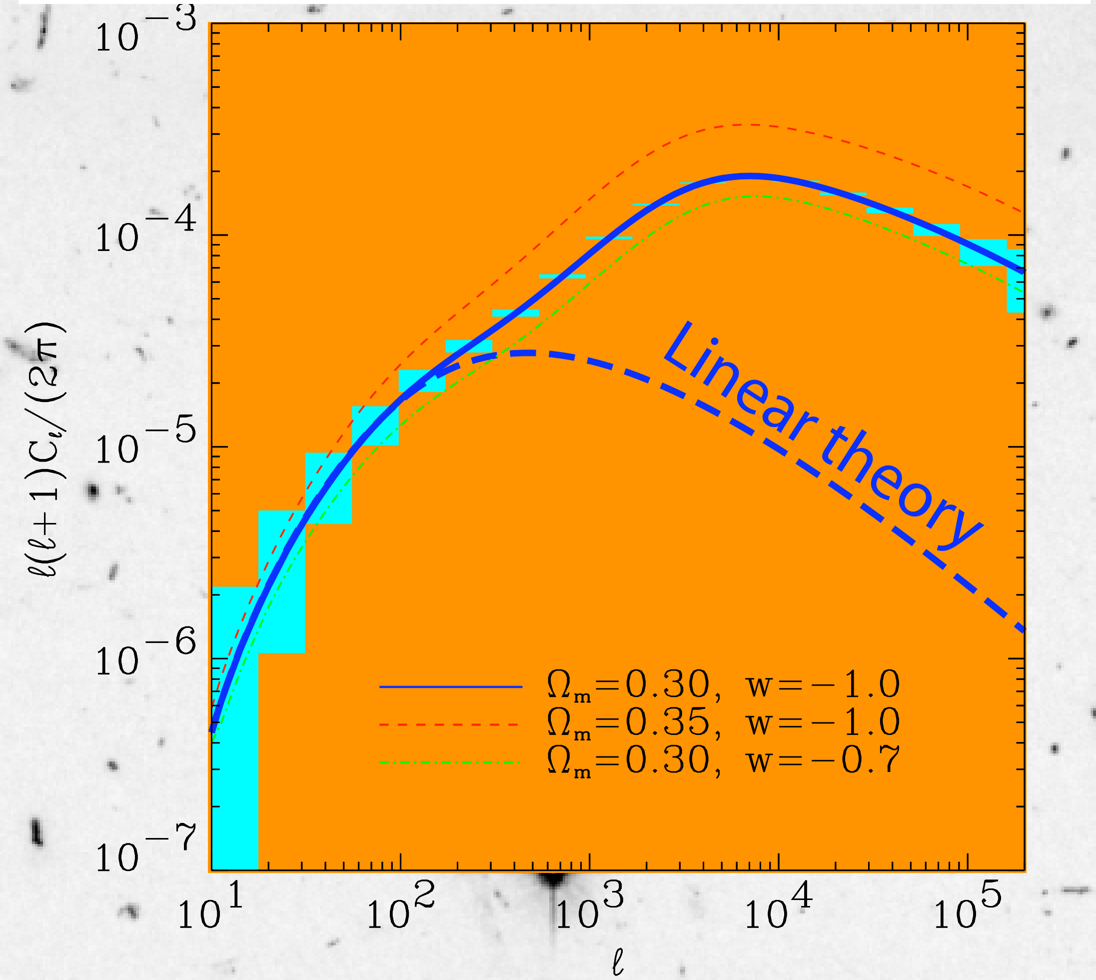
Weak lensing inversion to dark matter maps



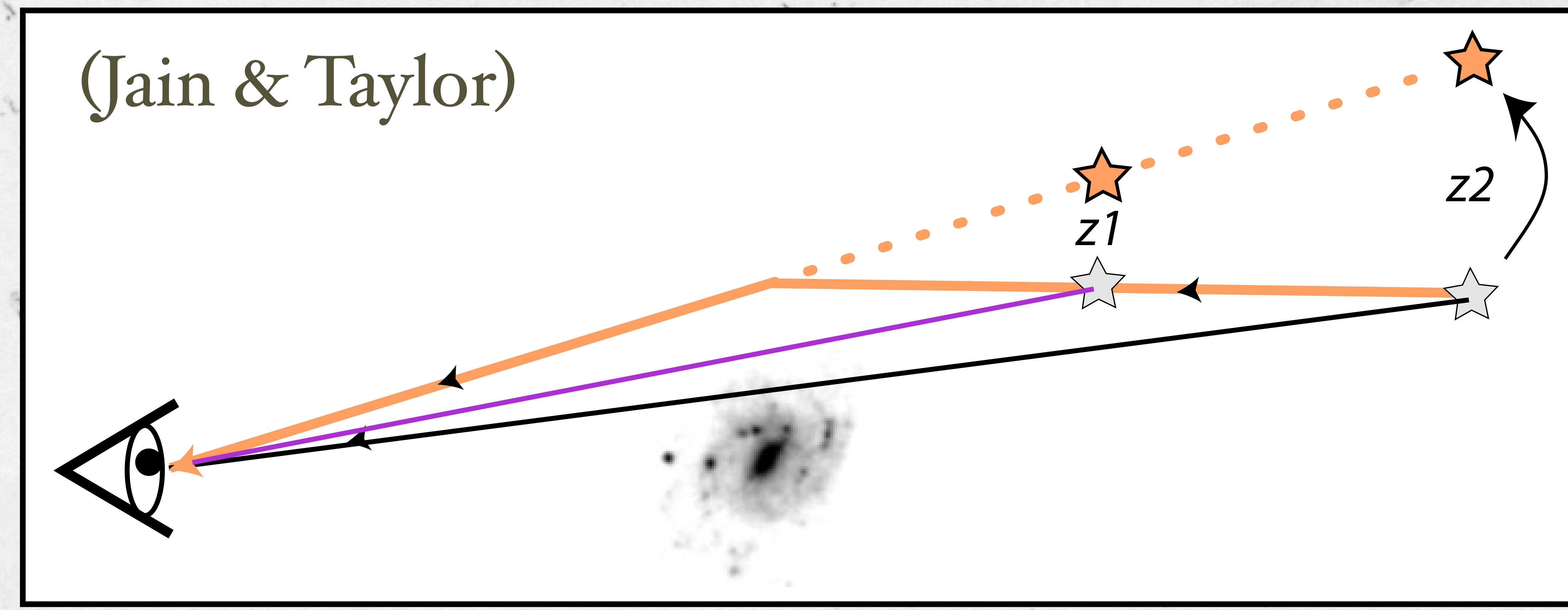
Weak lensing for CMB veterans

- Shear power spectrum has less information than CMB spectrum, but measures a more **recent** quantity.
- WL has **depth** information - “tomography”
- WL sees **non-linear** growth and collapse of mass structures.
- WL is **non-Gaussian** field, so bispectrum, etc., carry new information.
- WL can measure and use the relation between **visible matter** and dark matter - ***test galaxy evolution paradigm!***
- WL can distinguish the expansion history from and growth of structure within it. *This allows us to test whether GR is correct!*





WL as a pure distance measurement



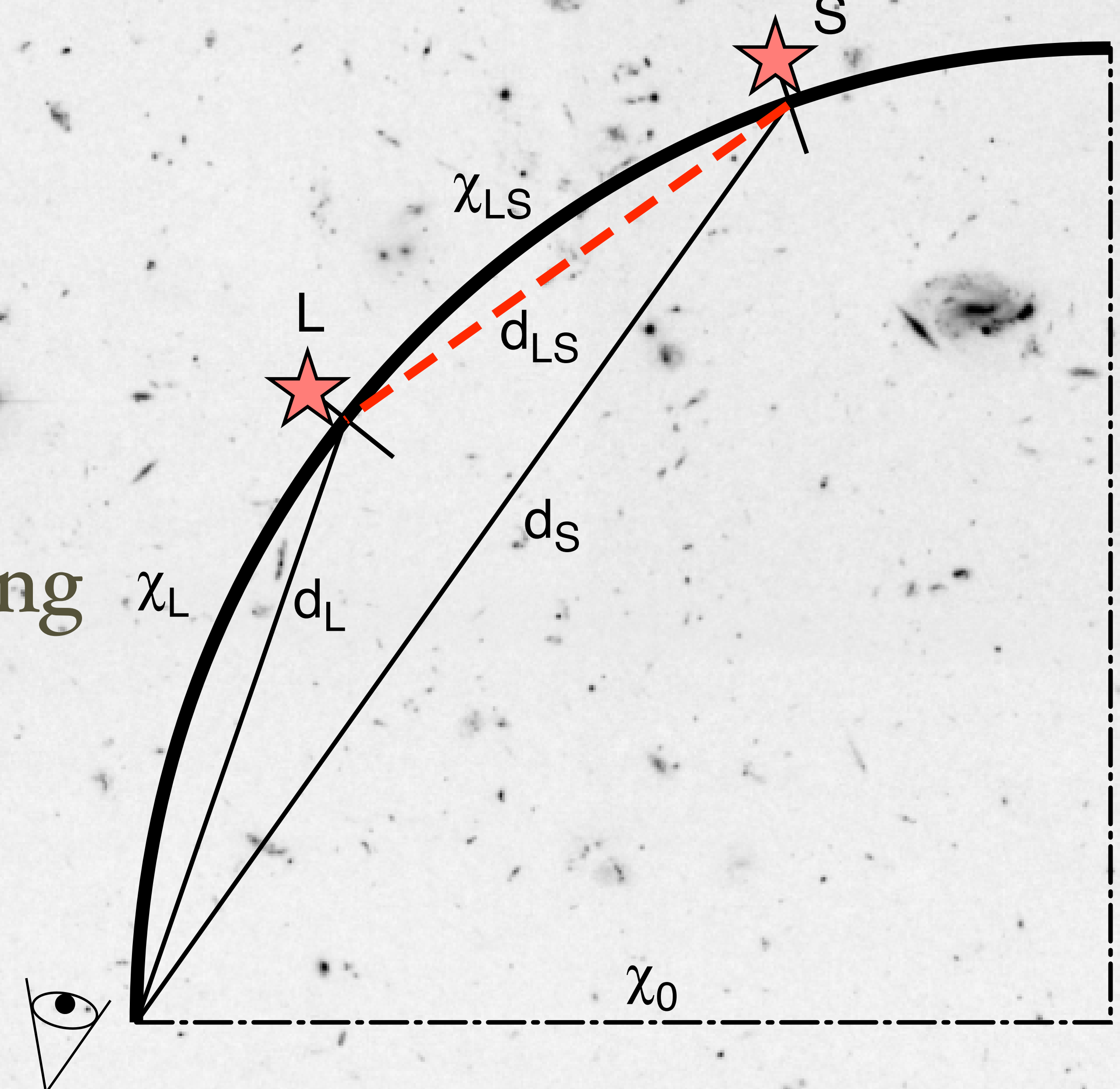
- Ratio of Deflection Angles:

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

No knowledge of foreground mass is required!

Weak lensing is a true geometric test for curvature

- Chord lengths are the observable angular-diameter distances
- Cannot constrain manifold curvature using only chords from observer
- Measure of d(LS) by lensing ties down curvature.



$$d_{LS} = (d_S - d_L)\,(1 - \Omega_k d_L d_S/2) + O(\Omega_k^2)$$

(GMB 2005)

Things WL analyses & forecasts should include

- Statistics:
  - Power spectrum tomography
  - Galaxy-shear cross correlations
  - Bispectrum tomography
  - Cluster counts/ PDF
- Systematic uncertainties:
  - Shear calibration errors
  - Additive shear errors (negligible?)
  - Photo-z biases
  - Photo-z scatter, catastrophic errors
  - Intrinsic shape correlations
  - Uncertainties in theoretical power spectrum

Things I've included:

- Statistics:
  - ☑ Power spectrum tomography
  - ☑ Galaxy-shear cross correlations
  - ☐ Bispectrum tomography
  - Cluster counts/ PDF
- Systematic uncertainties:
  - ☑ Shear calibration errors
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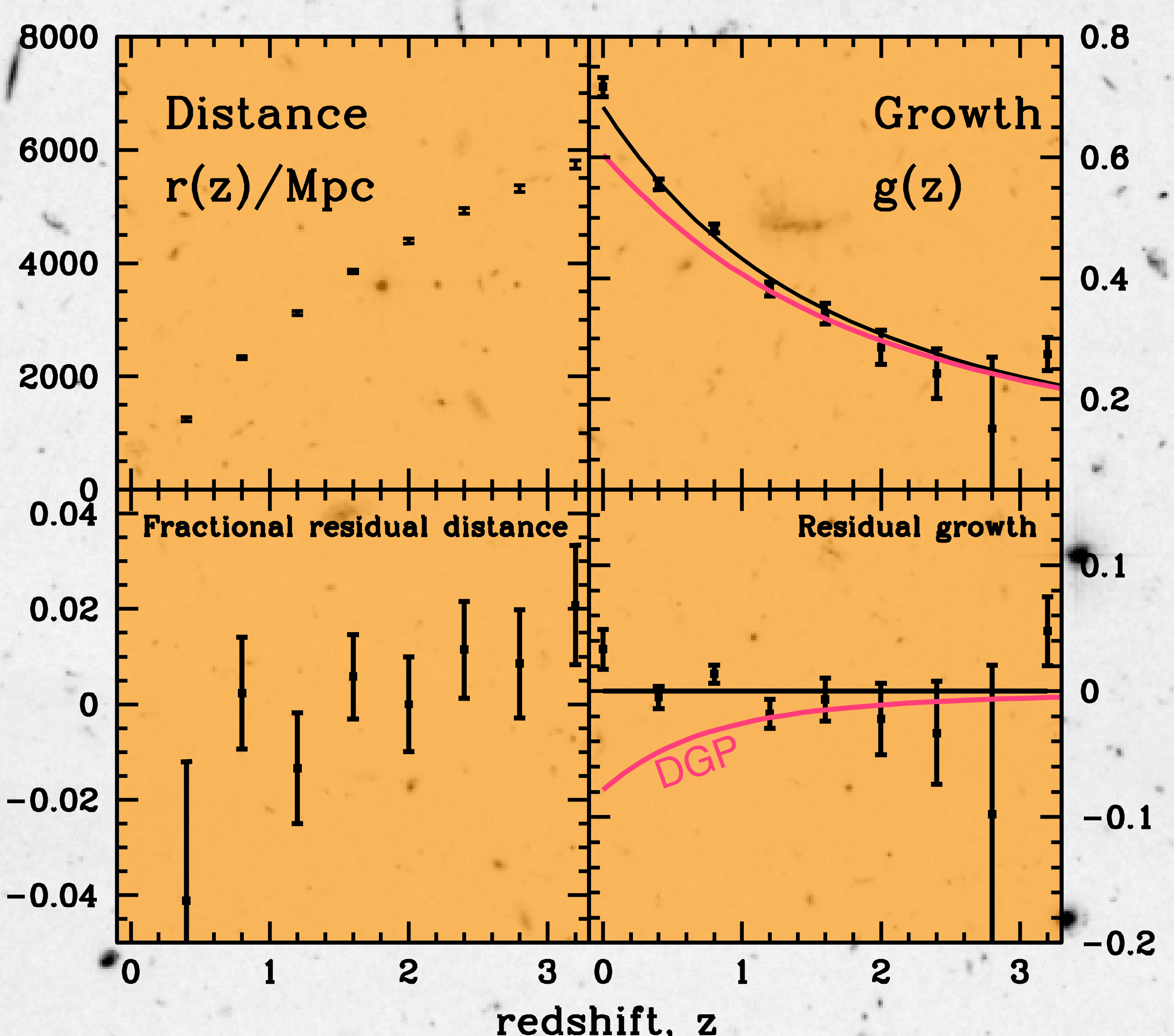
  - ☐ Photo-z scatter, catastrophic errors
  - ☑ Intrinsic shape correlations
  - ☑ Uncertainties in theoretical power spectrum

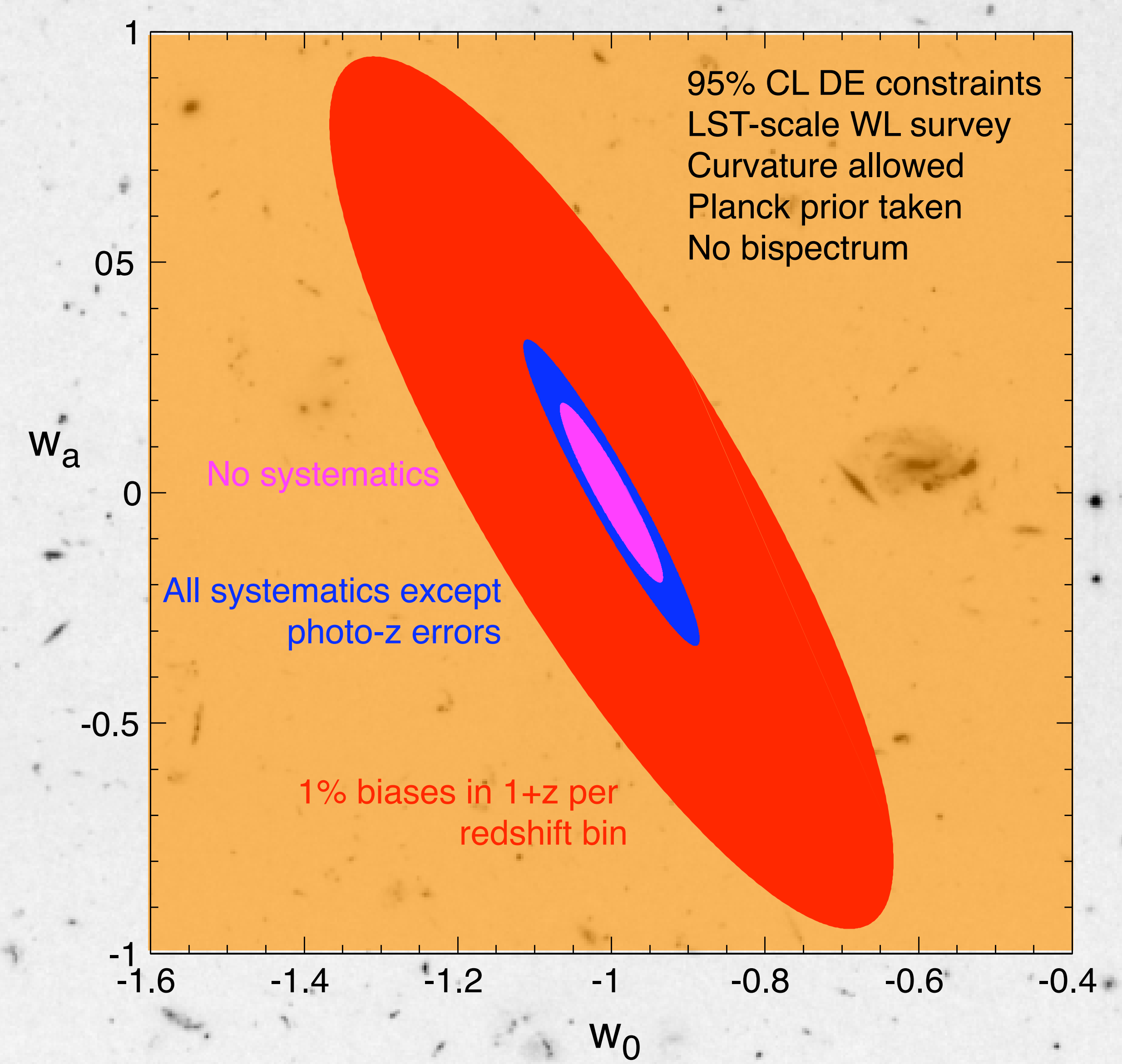
Ideally: posed without dependence on specific DE/MG model

WL data is rich



Power spectrum only,
no systematic errors

Knox, Song, & Tyson (2005)

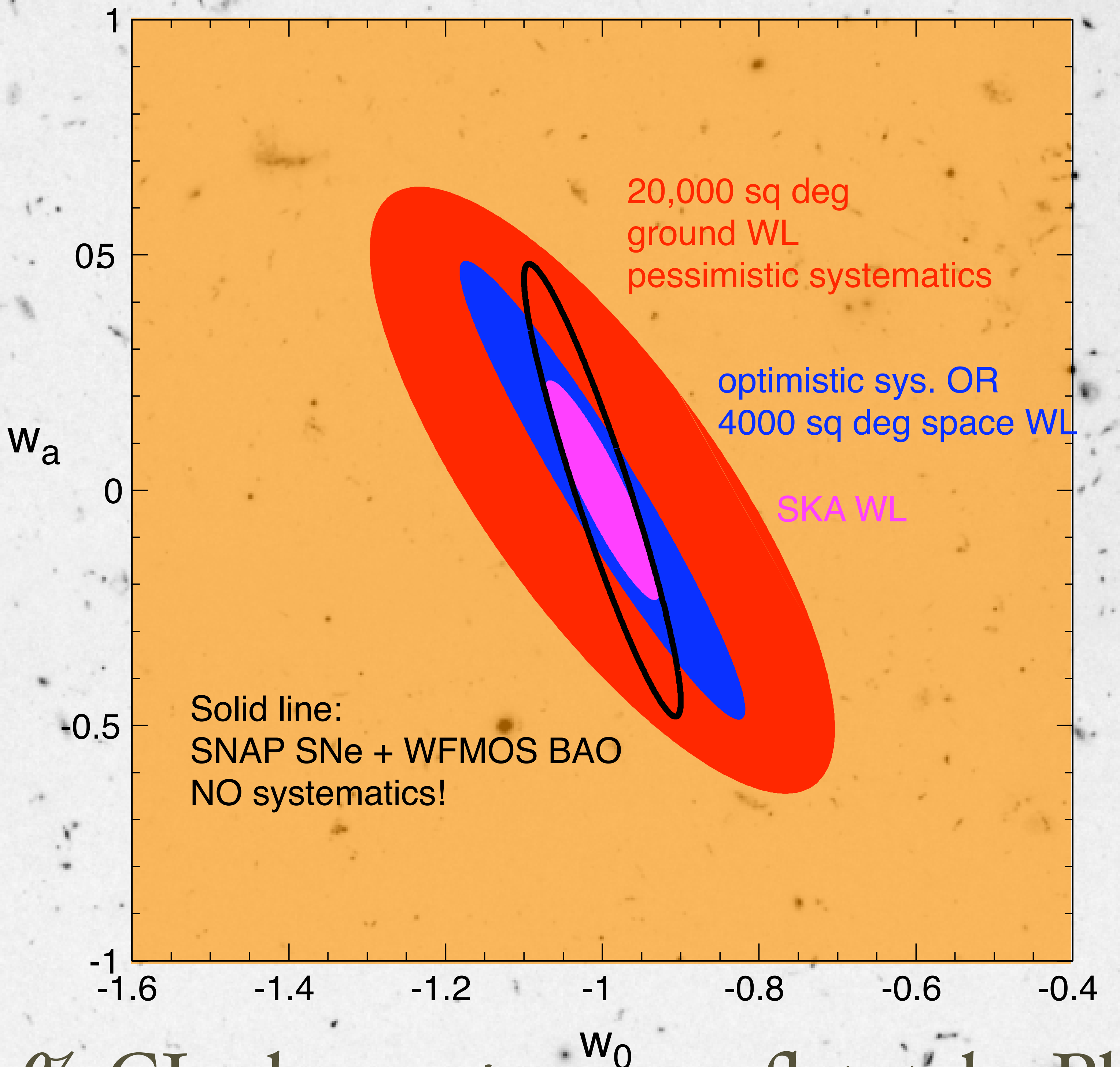


Plus: "gauranteed" neutrino-mass detection (Abazajian; Song & Knox)

The WL sky is very rich

- Reionization-era 21 cm and CMB can be source planes as well.
- Distinguish dark energy from modified GR:
-
$$\nabla^2\phi = 4\pi G\rho?$$
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\rho\delta?$$
-
- Wealth of observable statistics permits most posited systematic errors to be "self-calibrated" via internal solution.
- Is the dominant systematic going to be photo-z's?

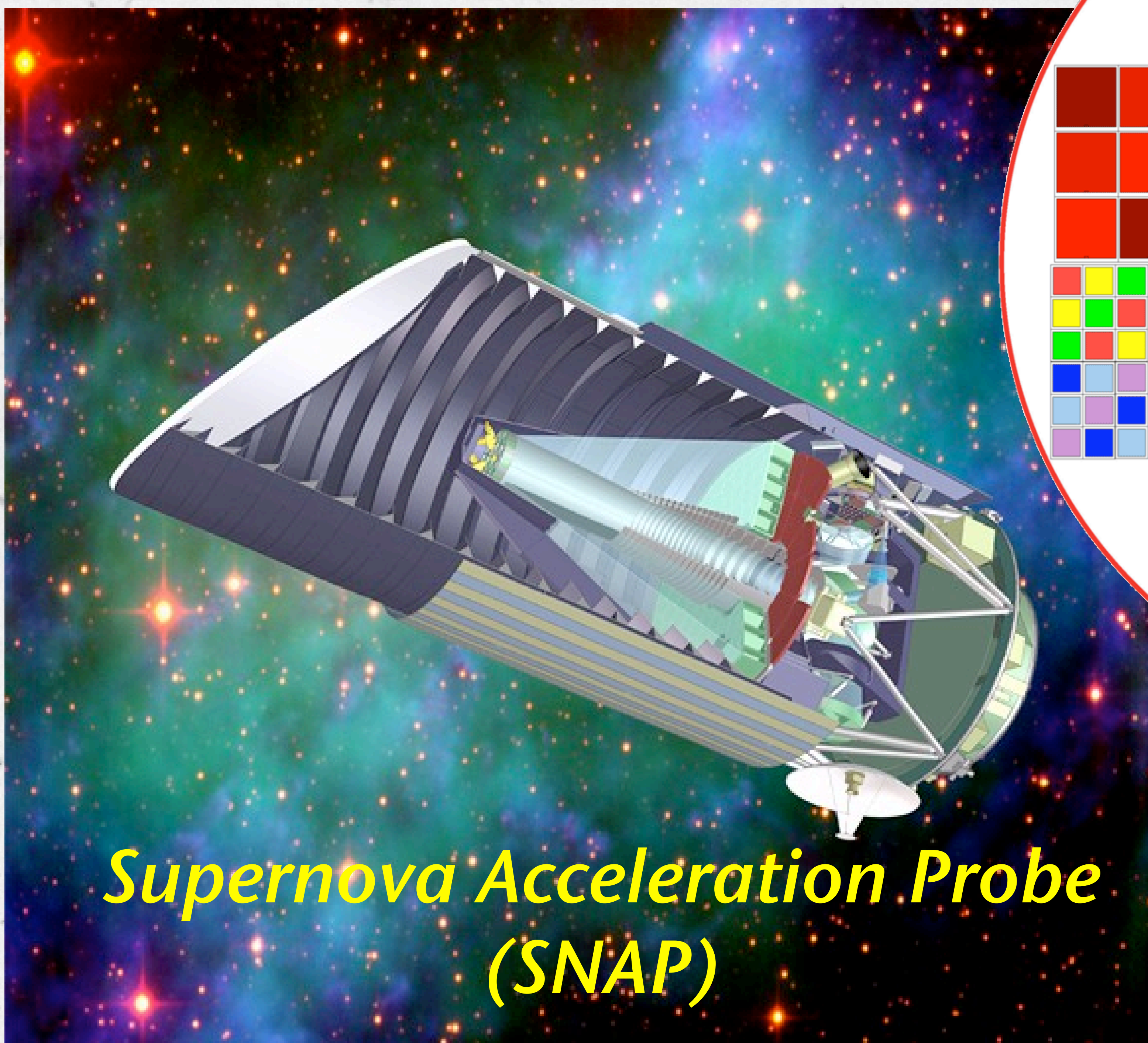
Dark-energy parameter forecasts

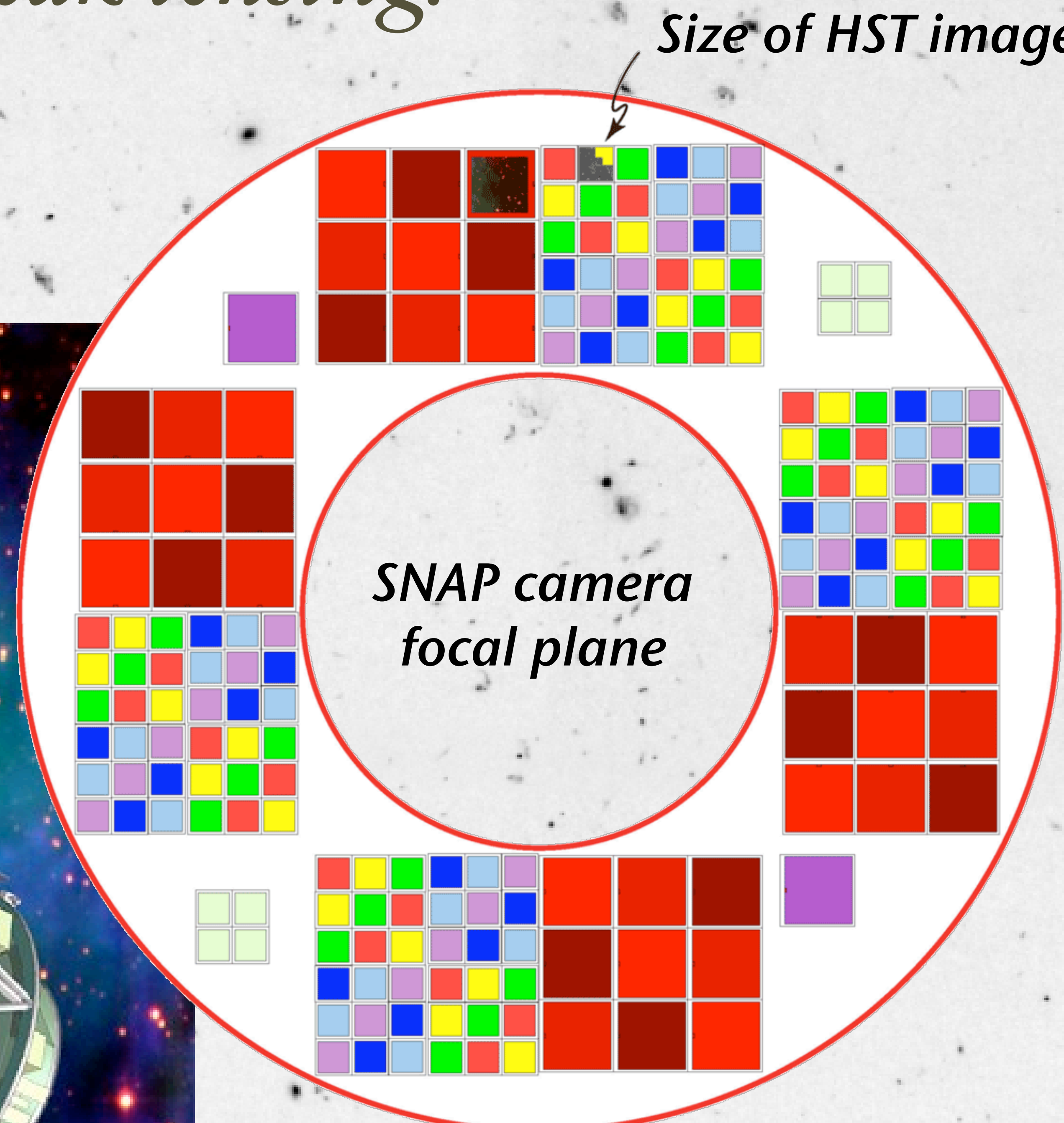


Details: 95% CL, does *not* assume flat, take Planck prior in each case, LCDM fiducial

An ideal instrument for weak lensing:

600 Megapixel Camera
on HST-sized Space Telescope

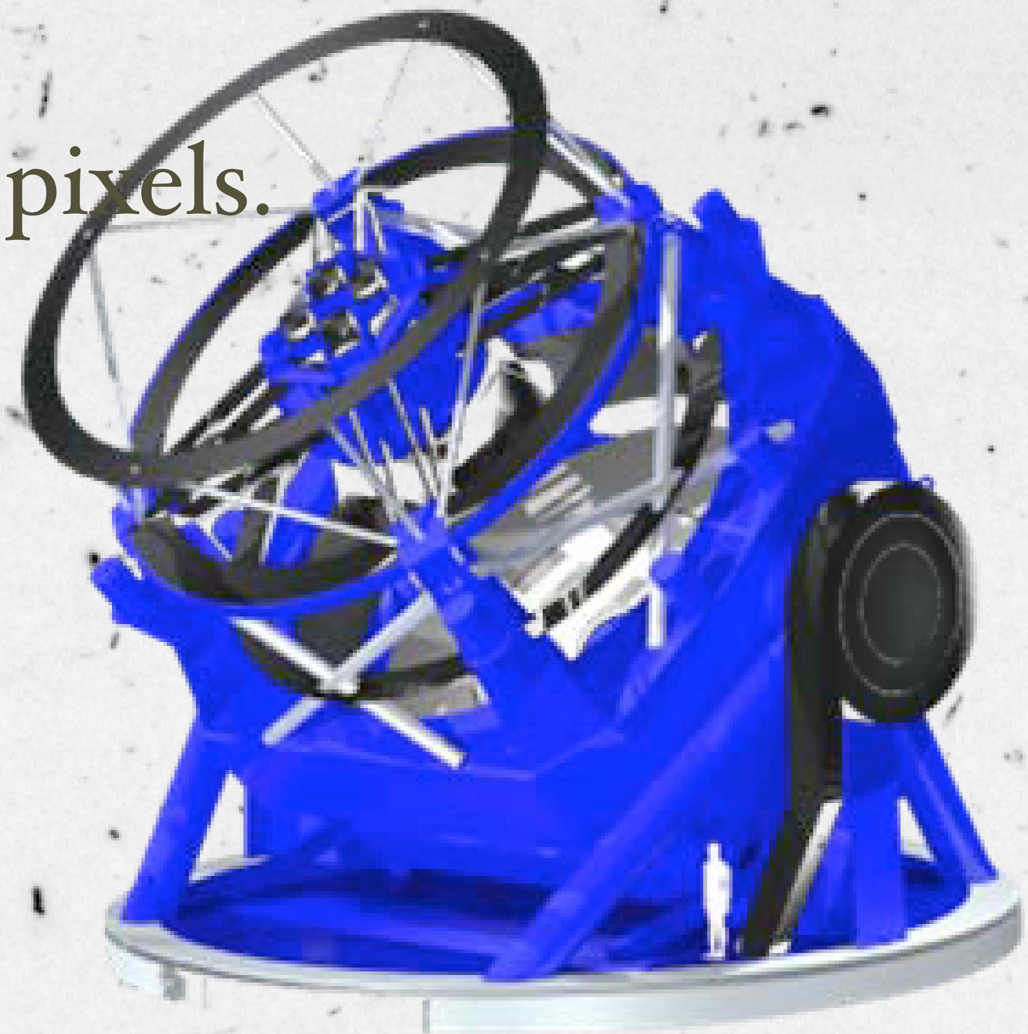




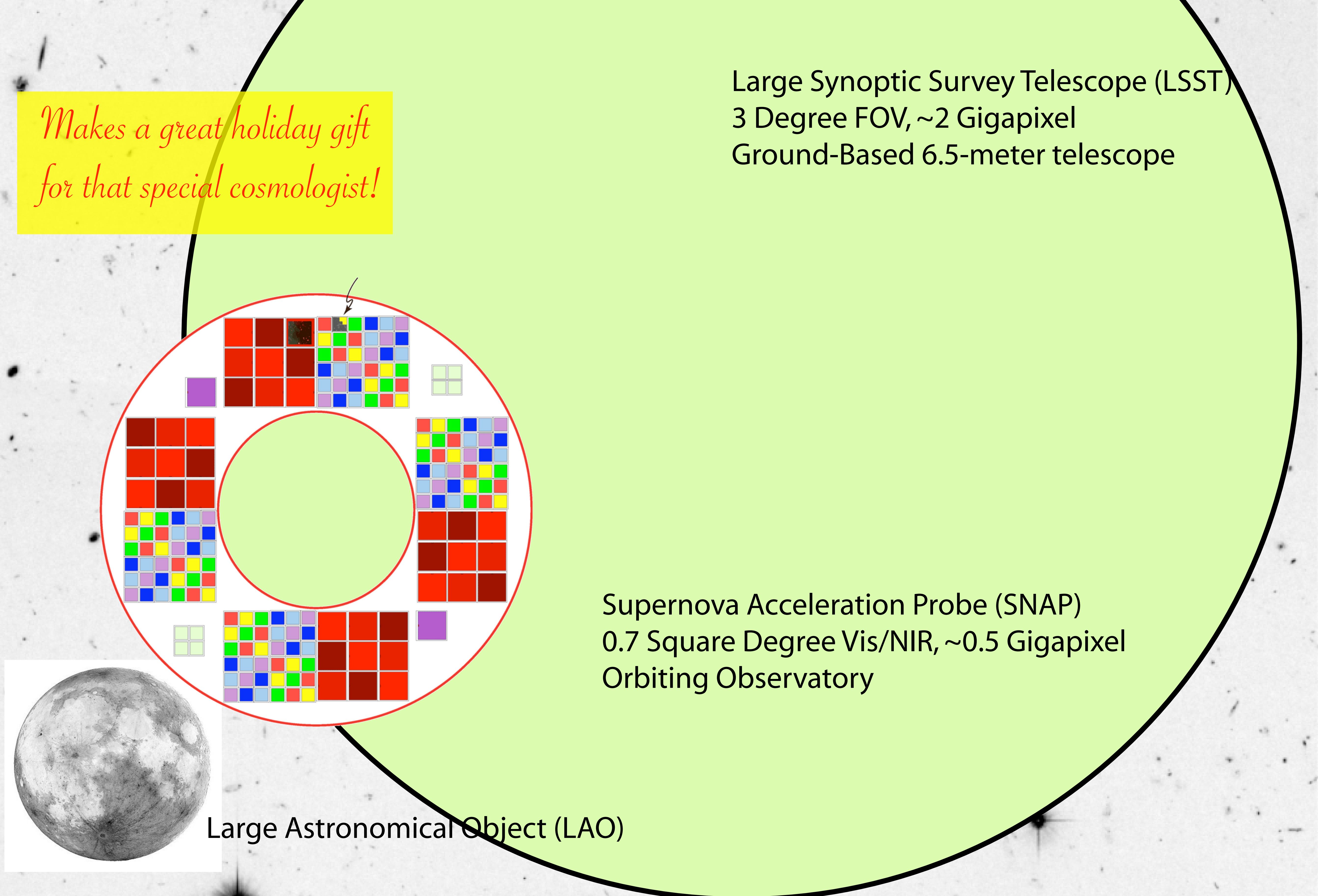
SNAP could harvest galaxy shapes hundreds of times faster than the HST or JWST

The LSST Project

- Ground-based 8-meter telescope to survey the entire visible sky every 4 days.
- Measure several billion galaxy shapes over a full hemisphere
- A single camera with >2 billion pixels.
- 4 GB image every 15 s
- 1 TB/hr, 8 TB/night, 2-3 PB/yr!
- Yours for only $300M!



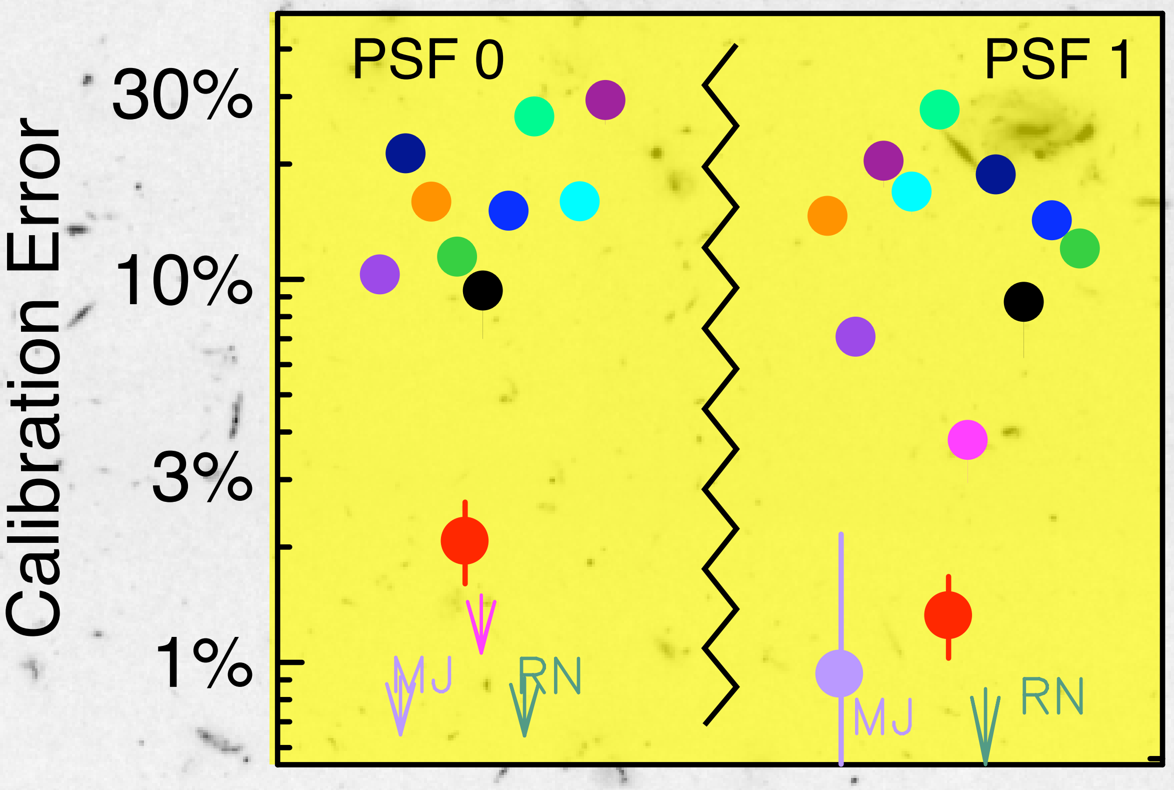
Digital cameras that Best Buy doesn't carry:



Shear Testing Program (STEP)

Will we really be able to measure weak lensing shear to parts per thousand of the already-weak signal?

- Collaborative testing of shear-measurement methodologies led by Catherine Heymans
- All groups produce blind estimates of the shear on artificial sky images
- Several methods look good to 1%, the limits of this round of tests (but most are worse).
- Much more stringent tests underway by R. Nakajima, also STEP round 2 to come.



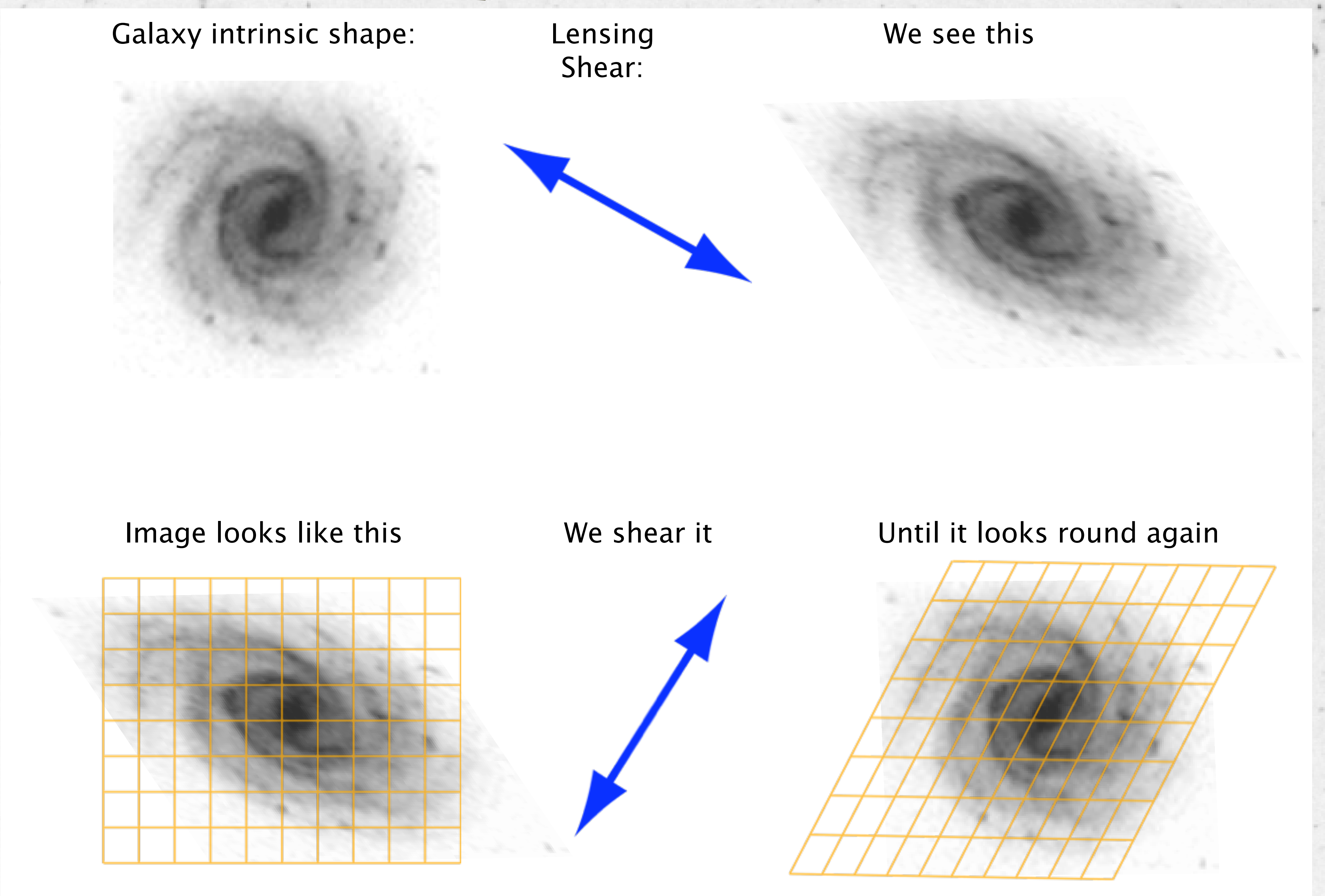
See Heymans talk, Nakajima poster

WL present and future

- Weak gravitational lensing is already constraining dark energy and galaxy formation models. Statistics-limited now at ~5% measures.
- WL offers a rich set of observables that complement other cosmological data.
- WL data of future will be capable of self-calibrating most systematic errors, and offer strongest dark energy constraints of any single test.
- WL can directly measure curvature and test GR on scales 100 kpc - 1 Gpc
- Work to be done:
  - Non-Gaussian theory
  - Theory of galaxy-mass joint evolution
  - Signatures of GR modifications
  - Build wide field instruments (no hardware unknowns)
  - Build software and algorithms to measure shear to very high accuracy
  - Huge advances in photometric redshifts.

Please attend the lensing and galaxy formation sessions to hear the real news from lensing.

Geometric Shapes



Applied shear to circularize is opposite of the lensing shear, independent of galaxy details