Gravitational lensing: a cosmological test of gravity

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Cosmic acceleration: Dark energy, or modified gravity?

- Usual mode of analyzing large-scale structure data: assume GR + LCDM, constrain parameters of the theory
- Can we say anything about whether GR is really the effective theory of gravity on cosmological scales?
- Can this be done in a way that does not involve degeneracies with astrophysical parameters or nuisance systematic errors?

Observations

Galaxy clustering

Count excess galaxy pairs with respect to mean

$$\delta = \rho/\bar{\rho} - 1$$

$$\xi_{\rm gg}(\vec{r}) = \langle \delta_{\rm g}(\vec{x}) \delta_{\rm g}(\vec{x} + \vec{r}) \rangle$$

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Large scales: $\xi_{gg} = b^2\xi_{mm}$ (or $\delta_g = b\delta_m$)

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theory prediction: matter clustering due to gravitational attraction

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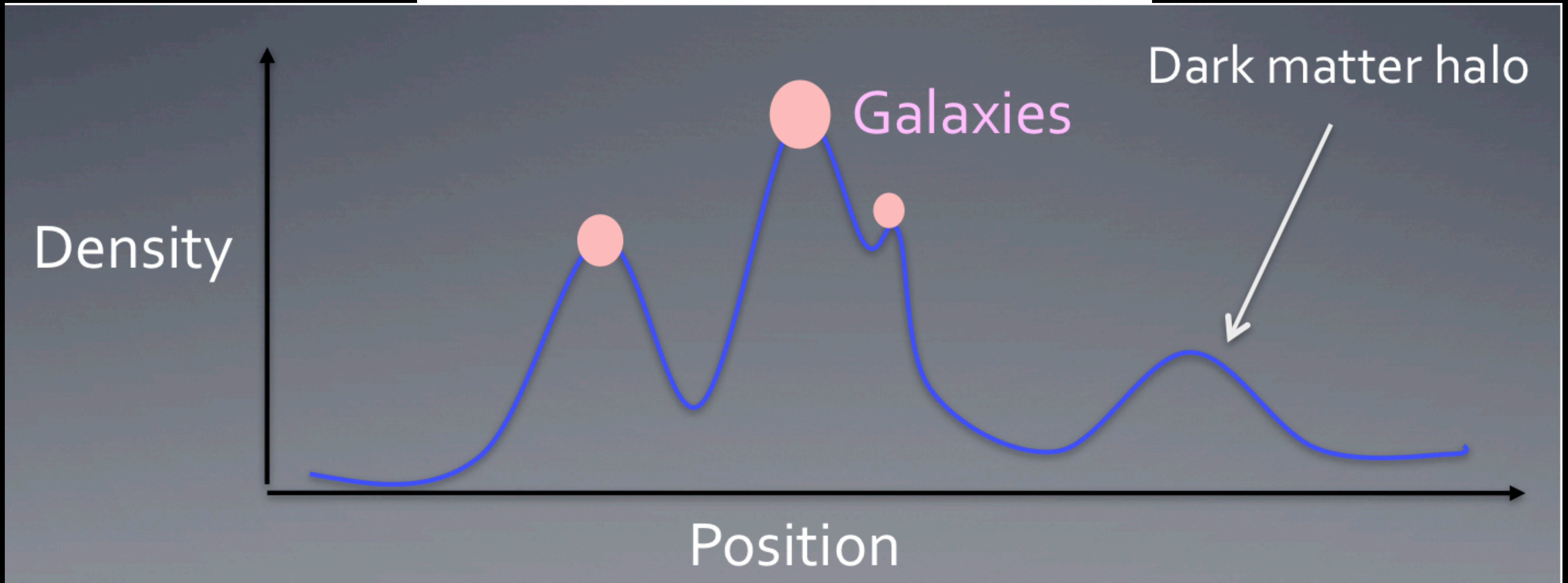
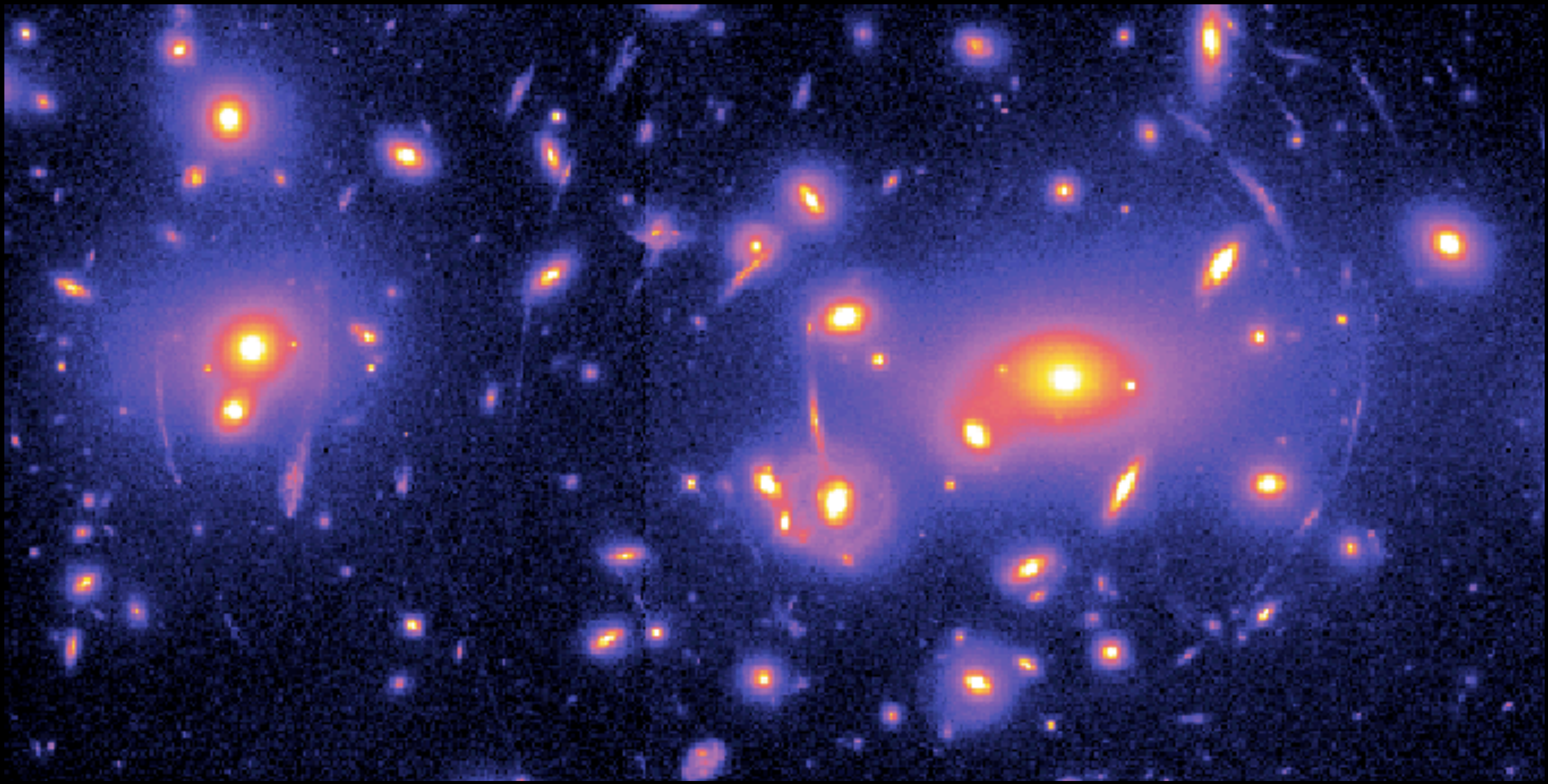


Observations

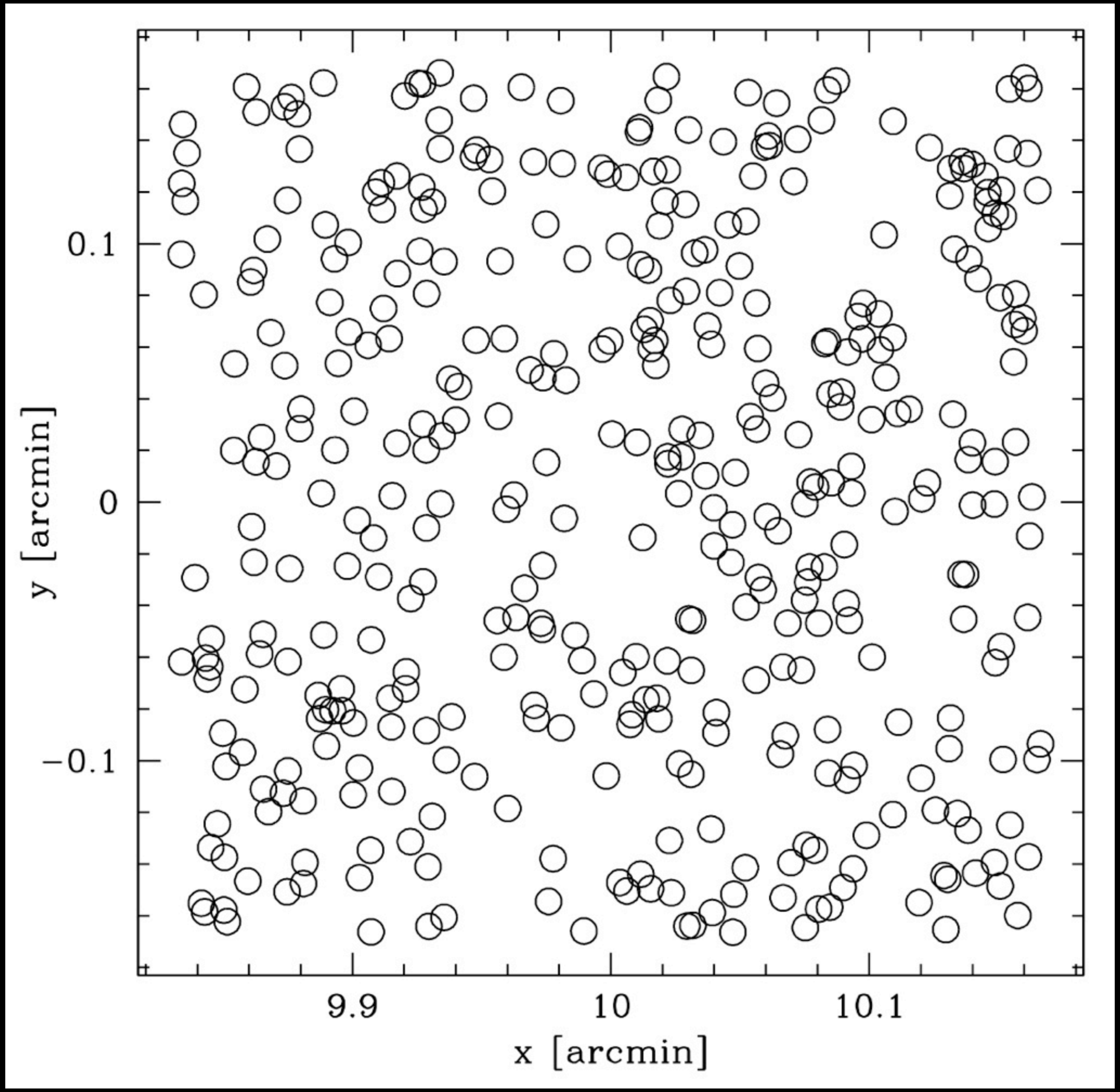
Gravitational lensing



Deflection of light due to mass along line-of-sight

Observations

weak lensing



Coherent shape distortion, detected statistically

Observations

weak lensing

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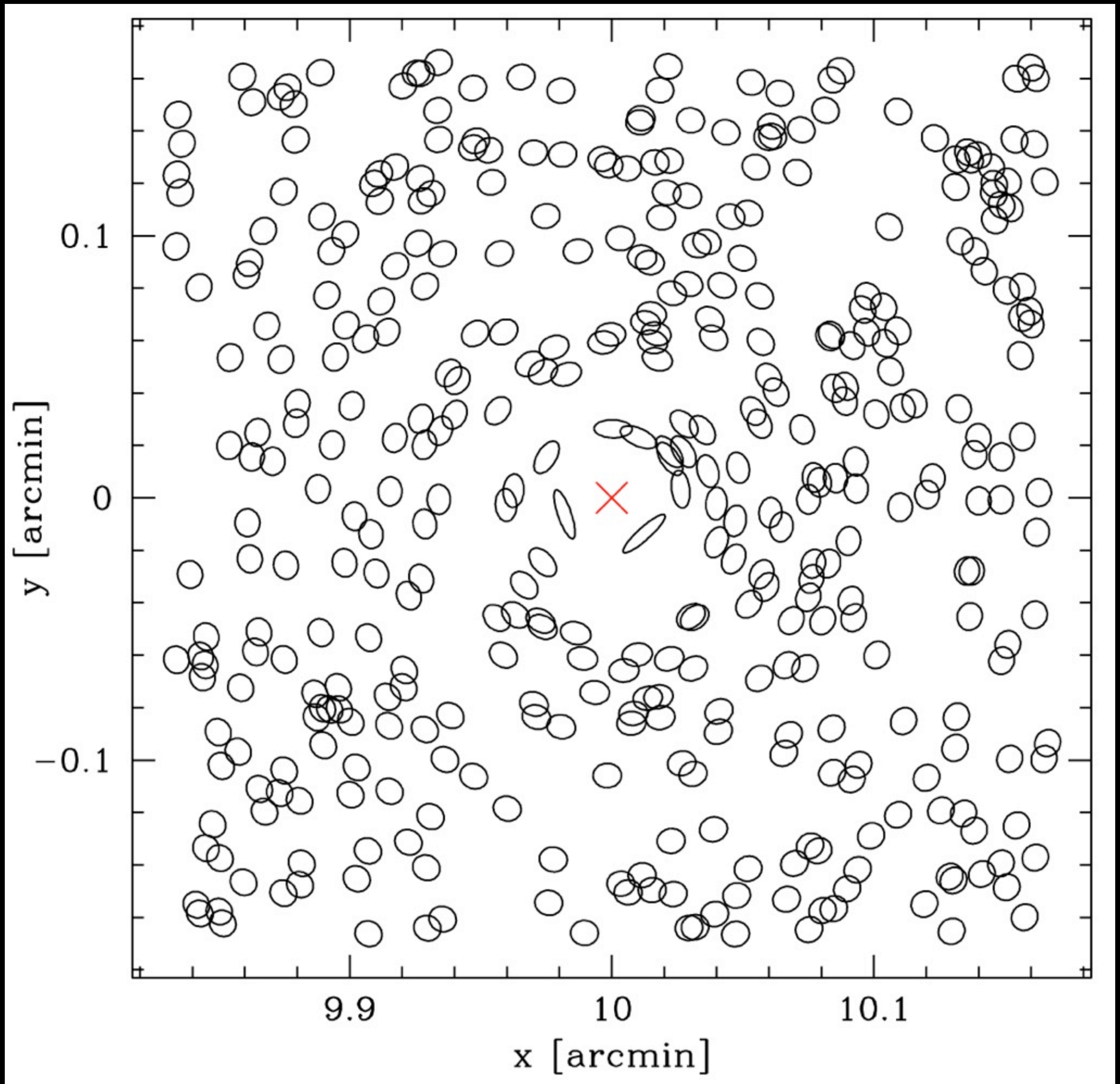
weak lensing



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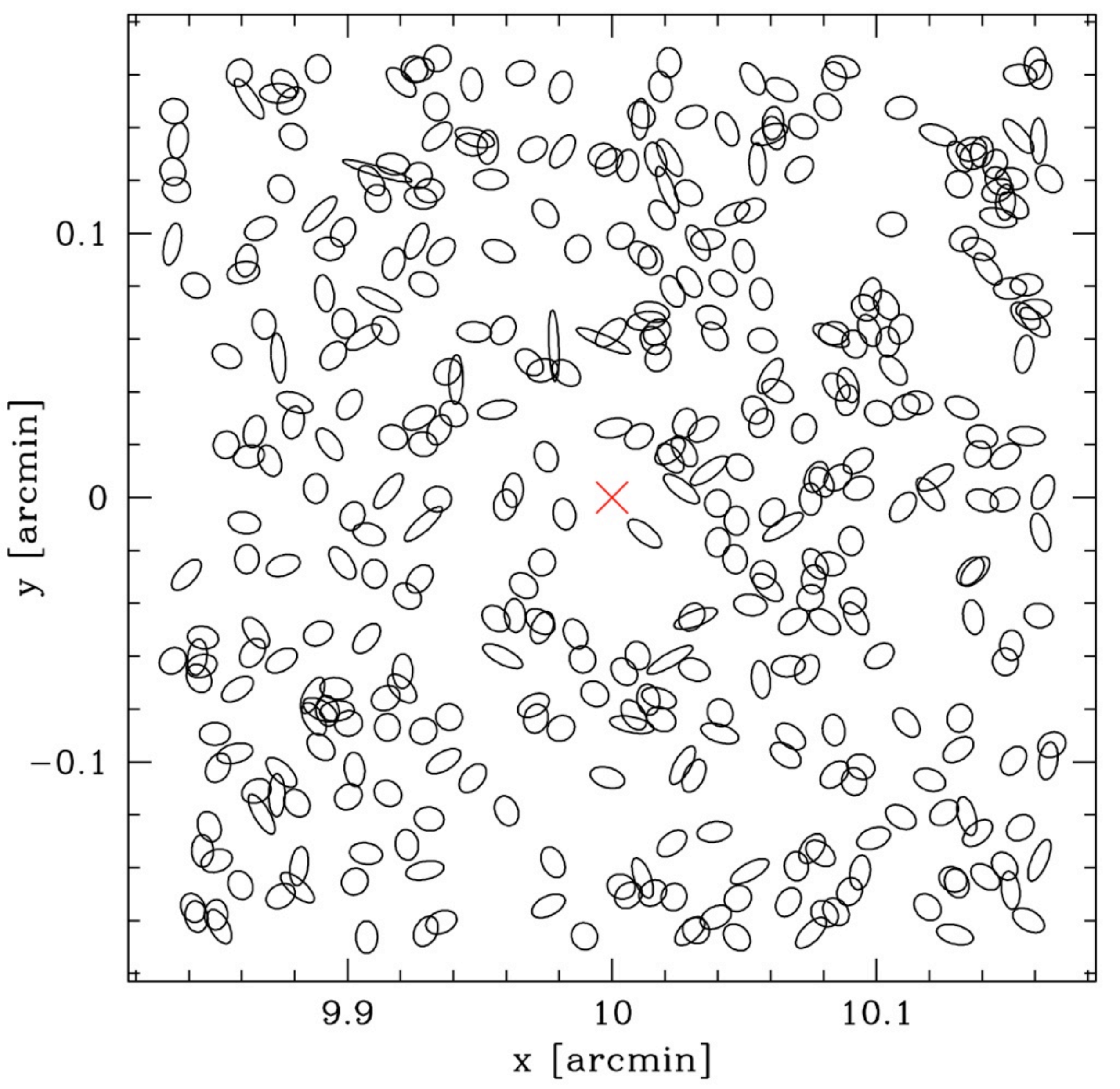
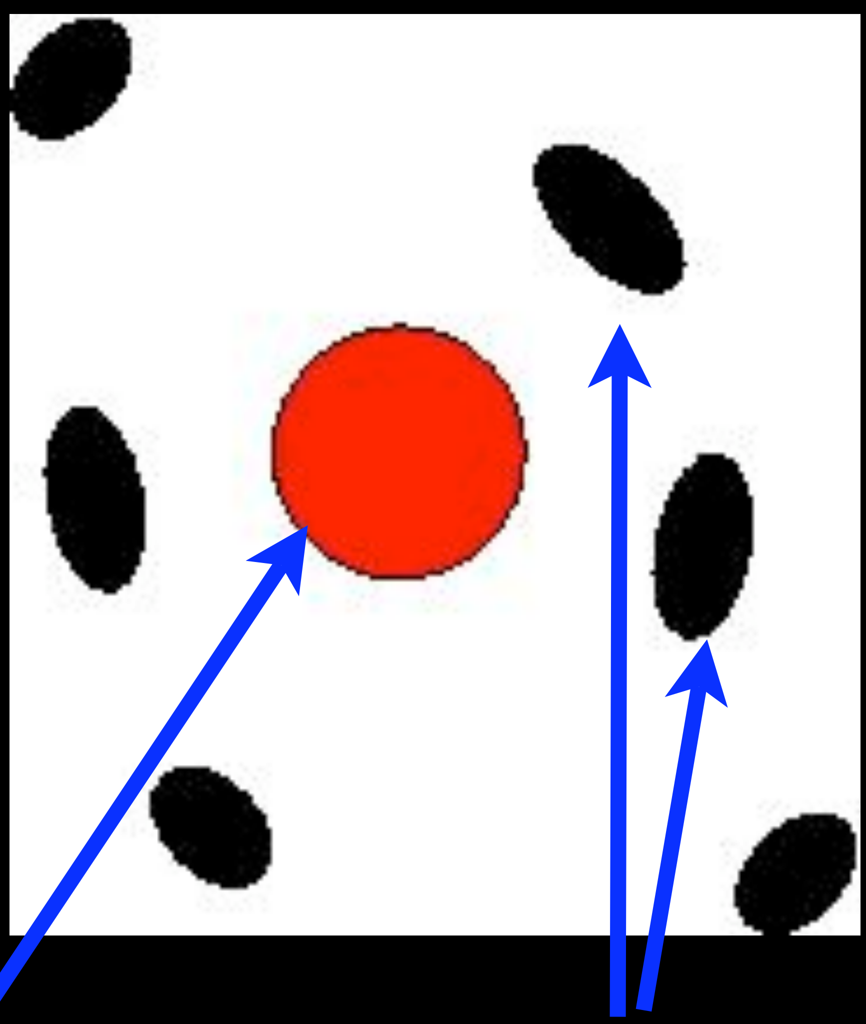


Coherent shape distortion, detected statistically

Observations

Galaxy-galaxy lensing



$$\xi_{\rm gm}(\vec{r}) = \langle \delta_{\rm g}(\vec{x})\delta_{\rm m}(\vec{x}+\vec{r})\rangle$$

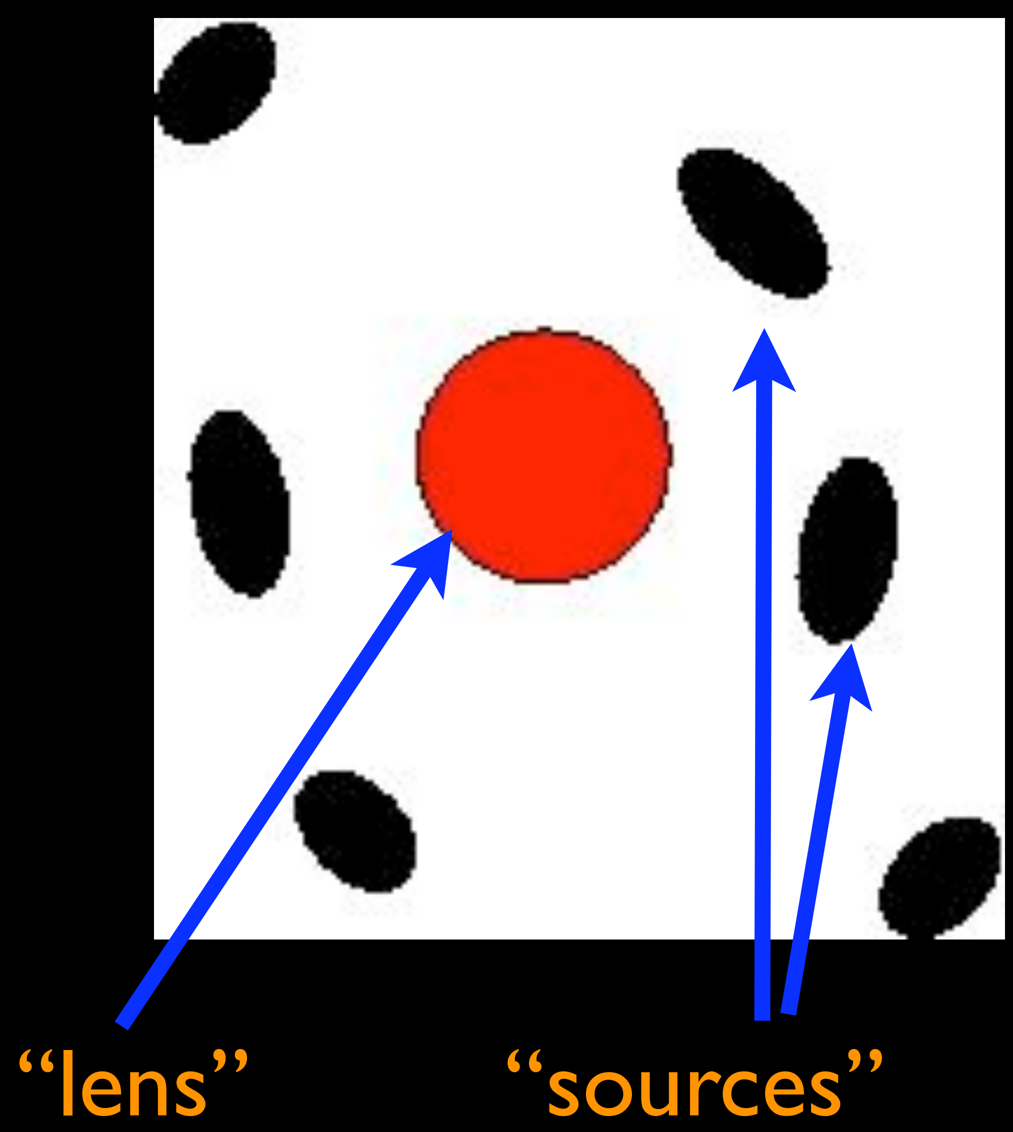
δ: density fluctuation with respect to mean

Large scales: $\delta_g = b\ \delta_m$

“lens” “sources”

Observations

Galaxy-galaxy lensing



$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$

Lensing deflection

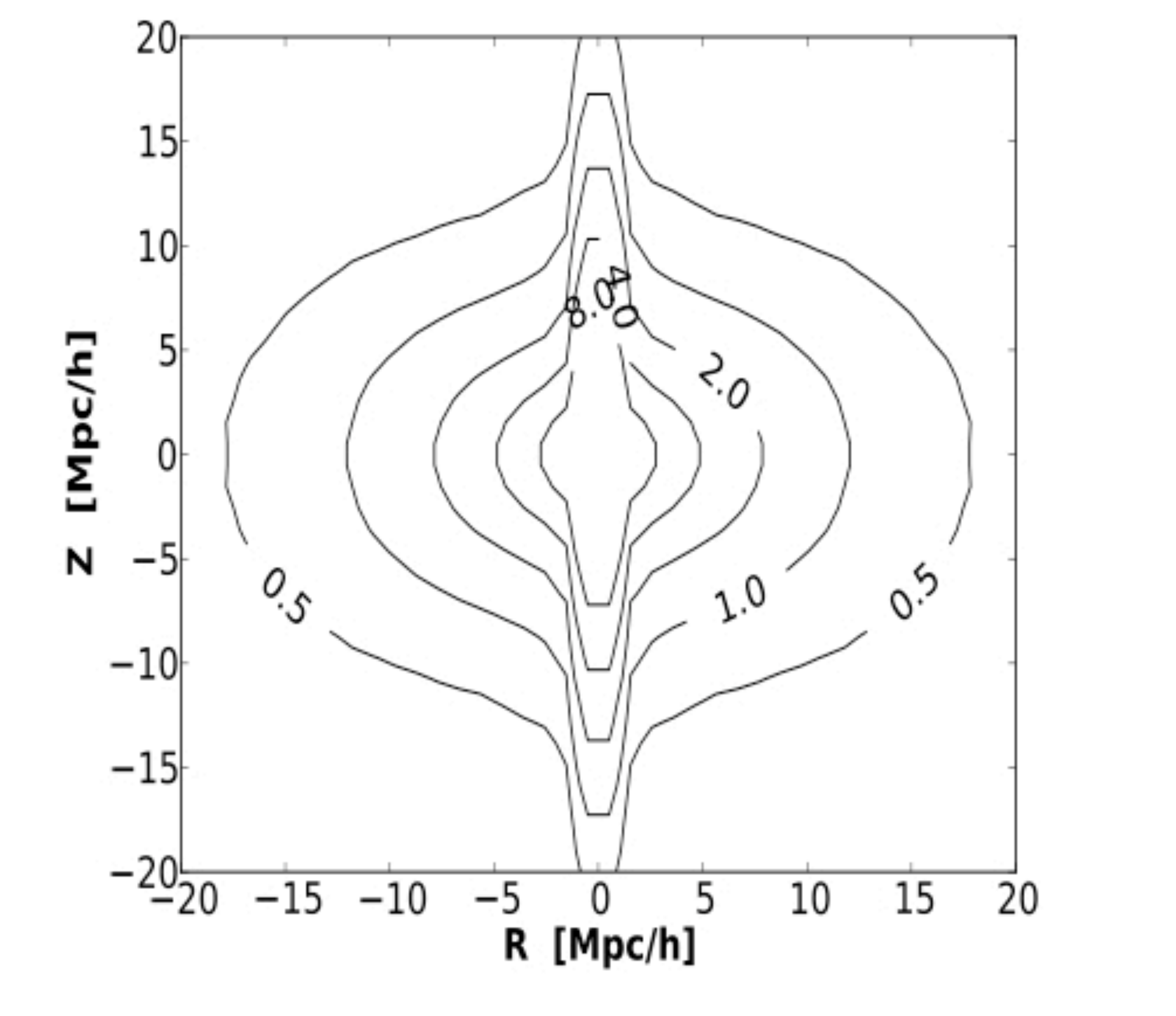
Observations

Redshift-space distortions

Redshift survey gives us 2d position on sky, plus redshift

$z_{obs} = z_{cos} + v_{pec}/c$

(White et al. 2011)



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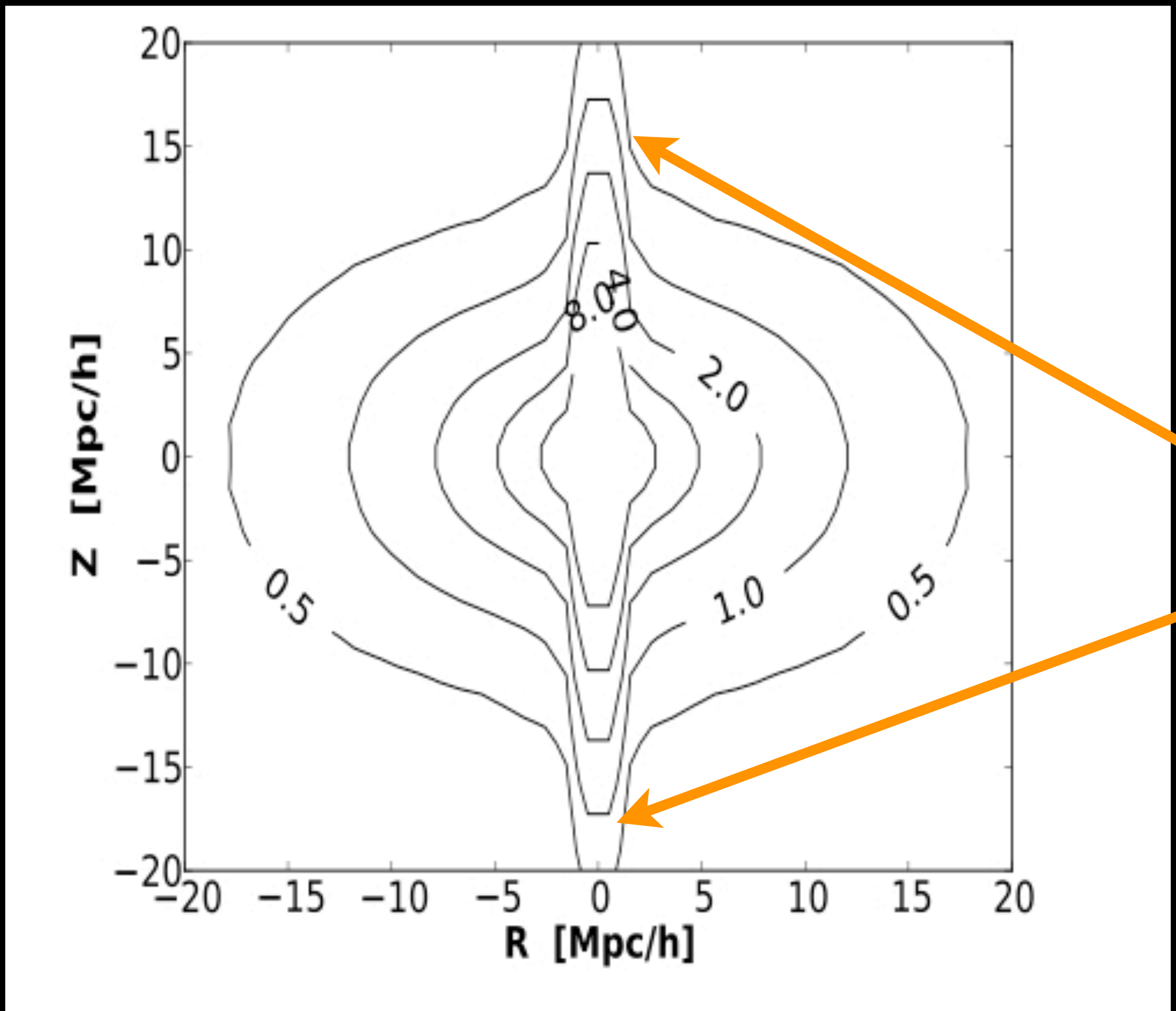

Small scales:
velocity dispersion within groups/clusters leads to line-of-sight smearing

NONLINEAR

Observations

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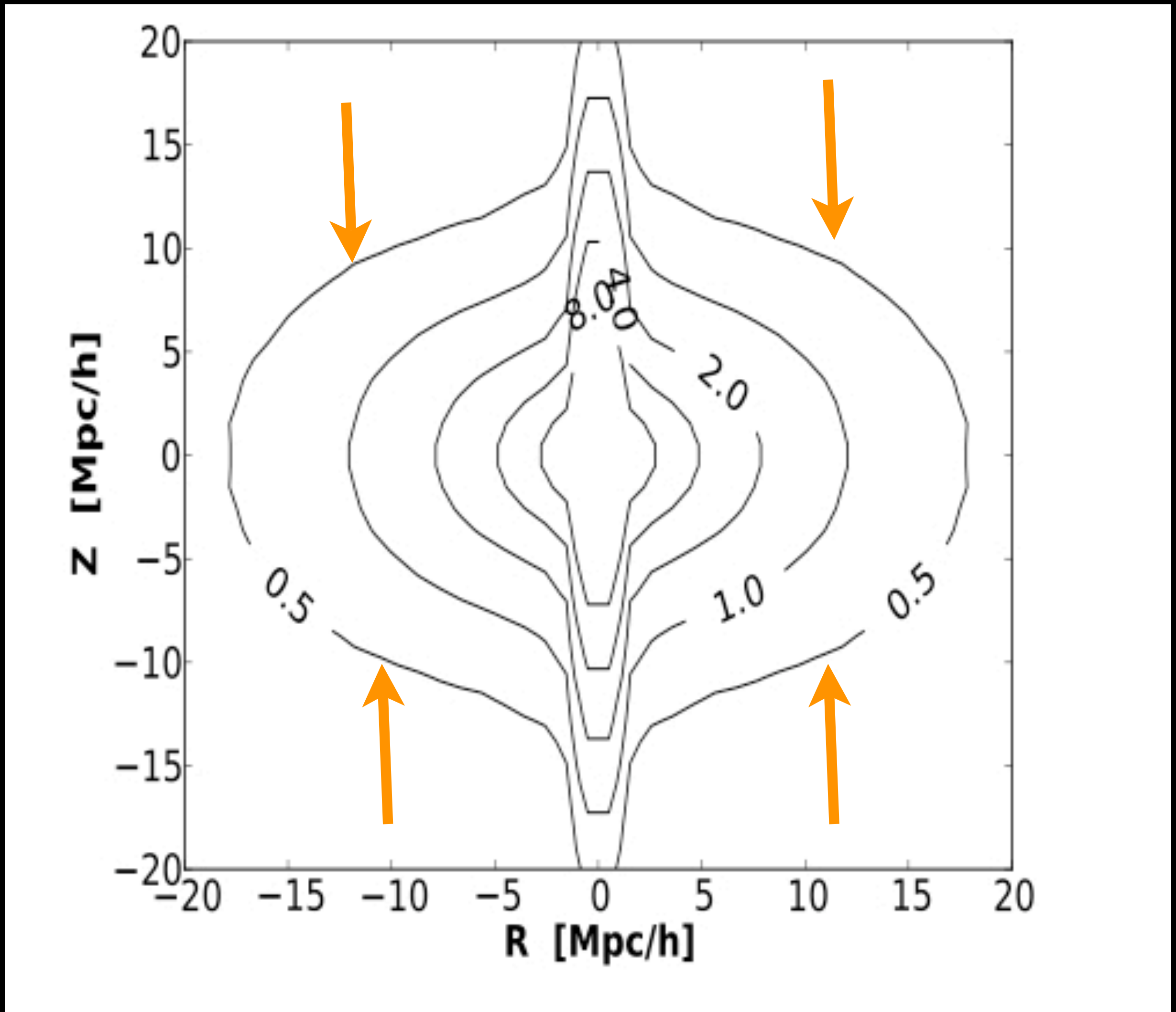

Large scales:
coherent infall leads to compression

Measure β ~ f / b

f: growth rate of structure
b: galaxy bias

Observations

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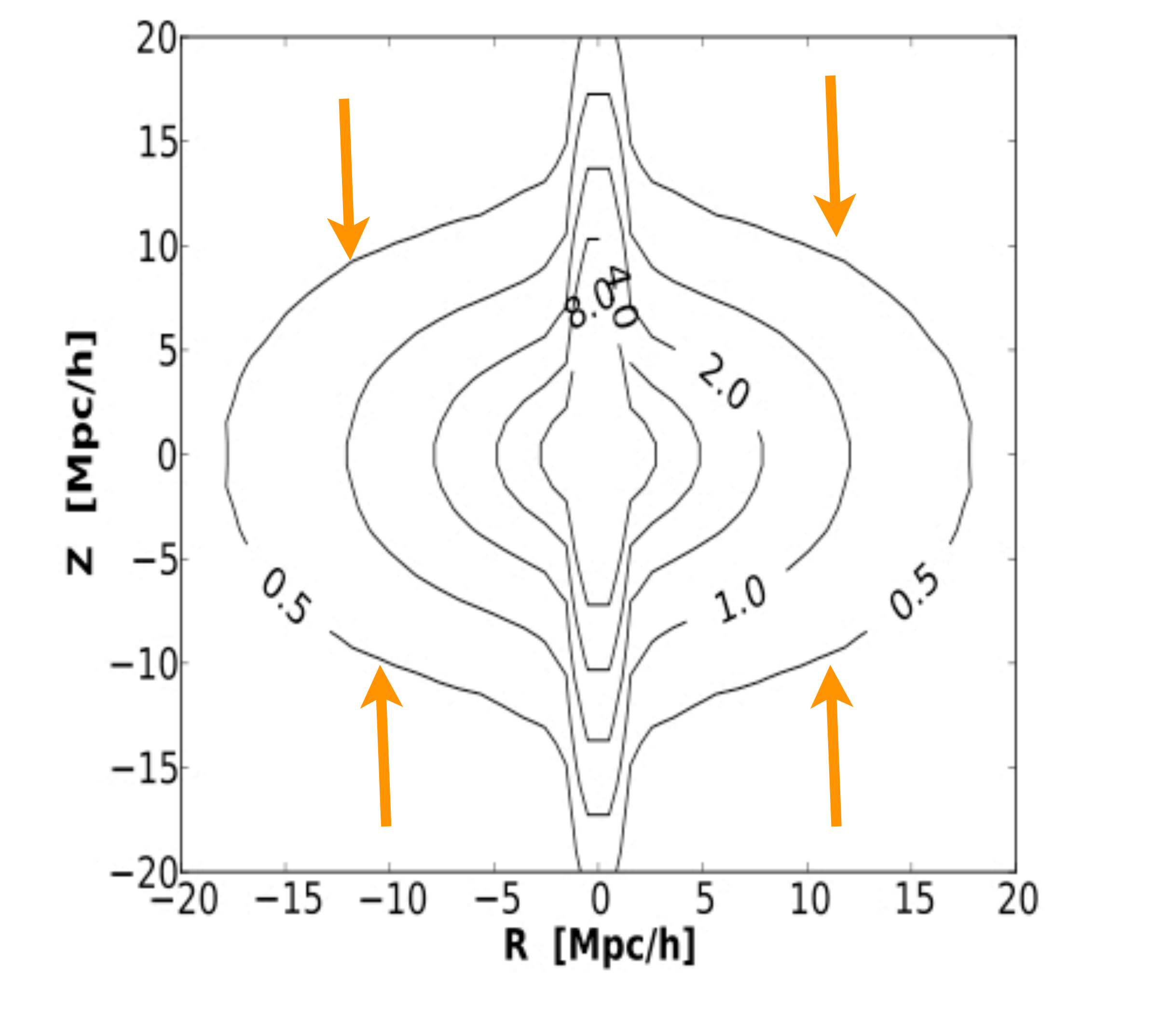

Large scales:
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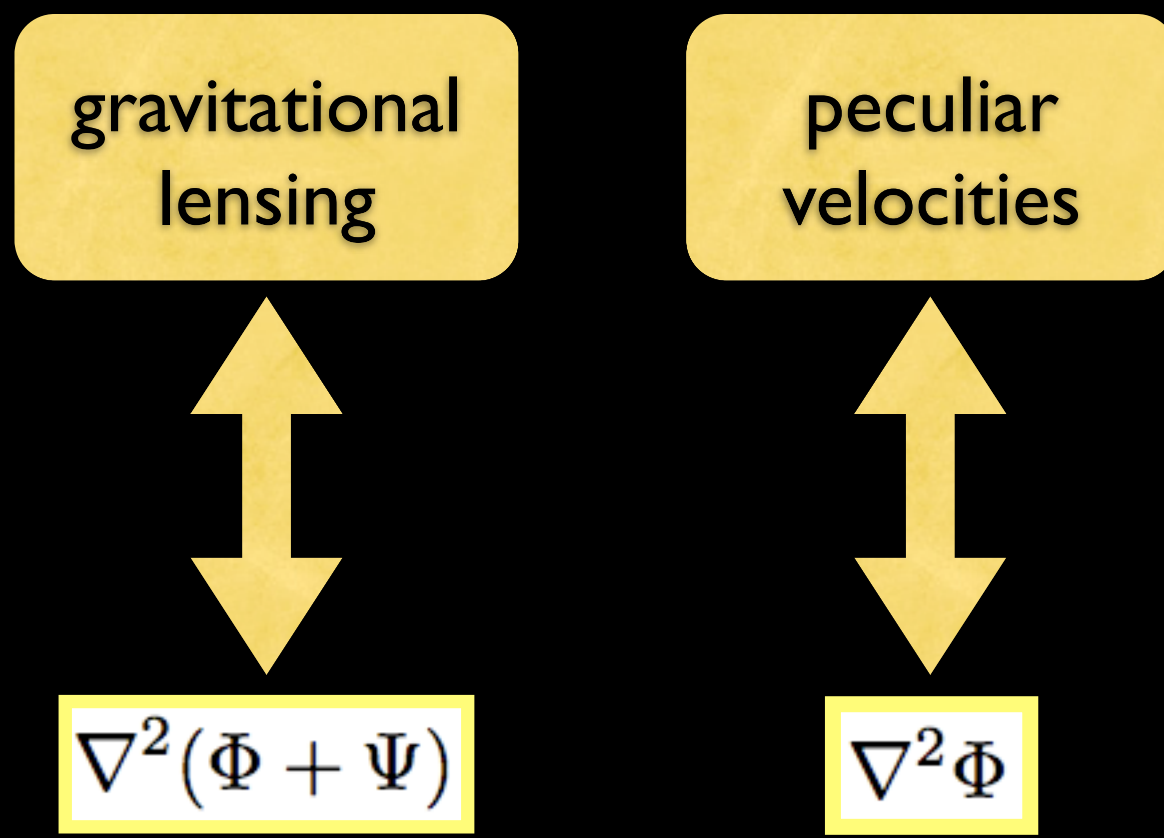
$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$

Method

dark energy or modified gravity?

(Zhang, et al. 2007, PRL 99, 141307)



$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$

Putting it all together

smoking gun of gravity

(Zhang et al. 2007, PRL 99, 141307)

$$E_G \sim \frac{\text{Galaxy-galaxy lensing}}{\text{(Galaxy clustering) x (z-space distortions)}}$$

dependence on theory of gravity:

$$\frac{\text{(1 + ratio of metric potentials)}}{\text{Logarithmic growth rate of structure}}$$

Putting it all together

smoking gun of gravity

(Zhang et al. 2007, PRL 99, 141307)

$$E_G \sim \frac{\text{Galaxy-galaxy lensing}}{(\text{Galaxy clustering}) \times (\text{z-space distortions})}$$

independent of bias and initial matter fluctuations

$$\frac{[b\,(\sigma_8)^2]}{[(b)^2\,(\sigma_8)^2]\,[b^{-1}]}$$

Note: can explicitly discard small scales

Other ways to use lensing to constrain gravity

- Cosmic shear to constrain matter power spectrum (e.g., Tereno, Semboloni, Schrabback 2011) as function of time
- Dark matter halo profiles $\rho(r)$, e.g., Lombriser et al. (2011)
- Non-lensing: RSD alone

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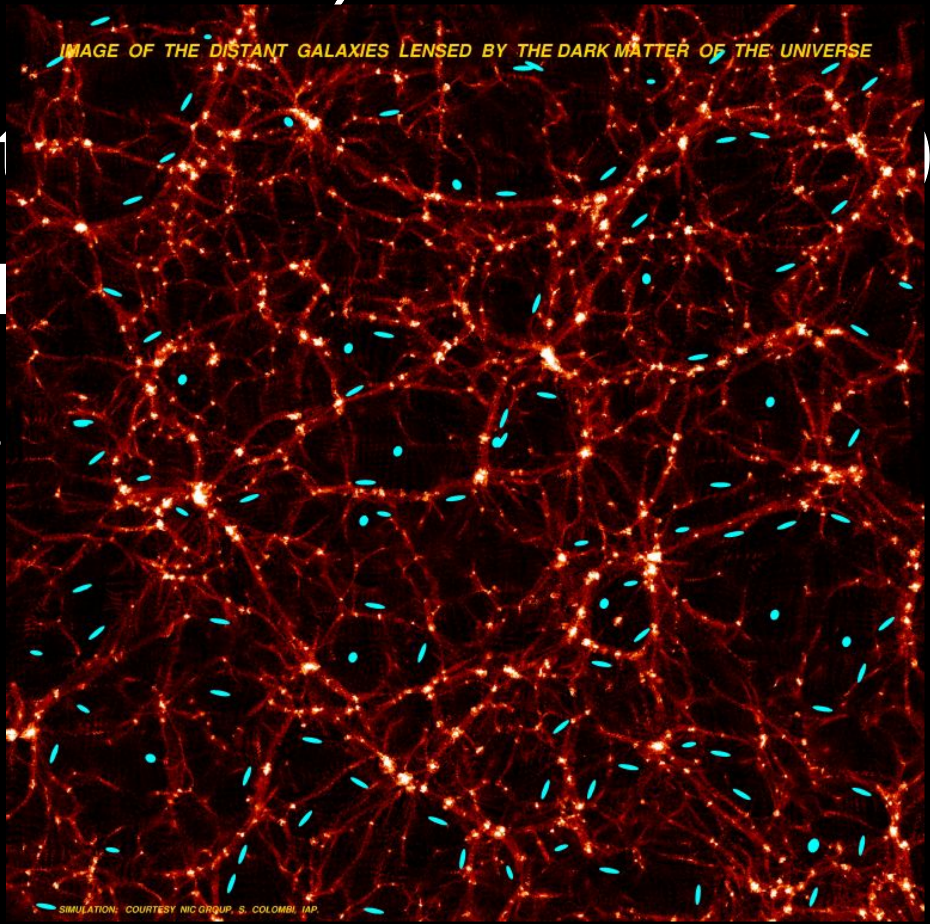

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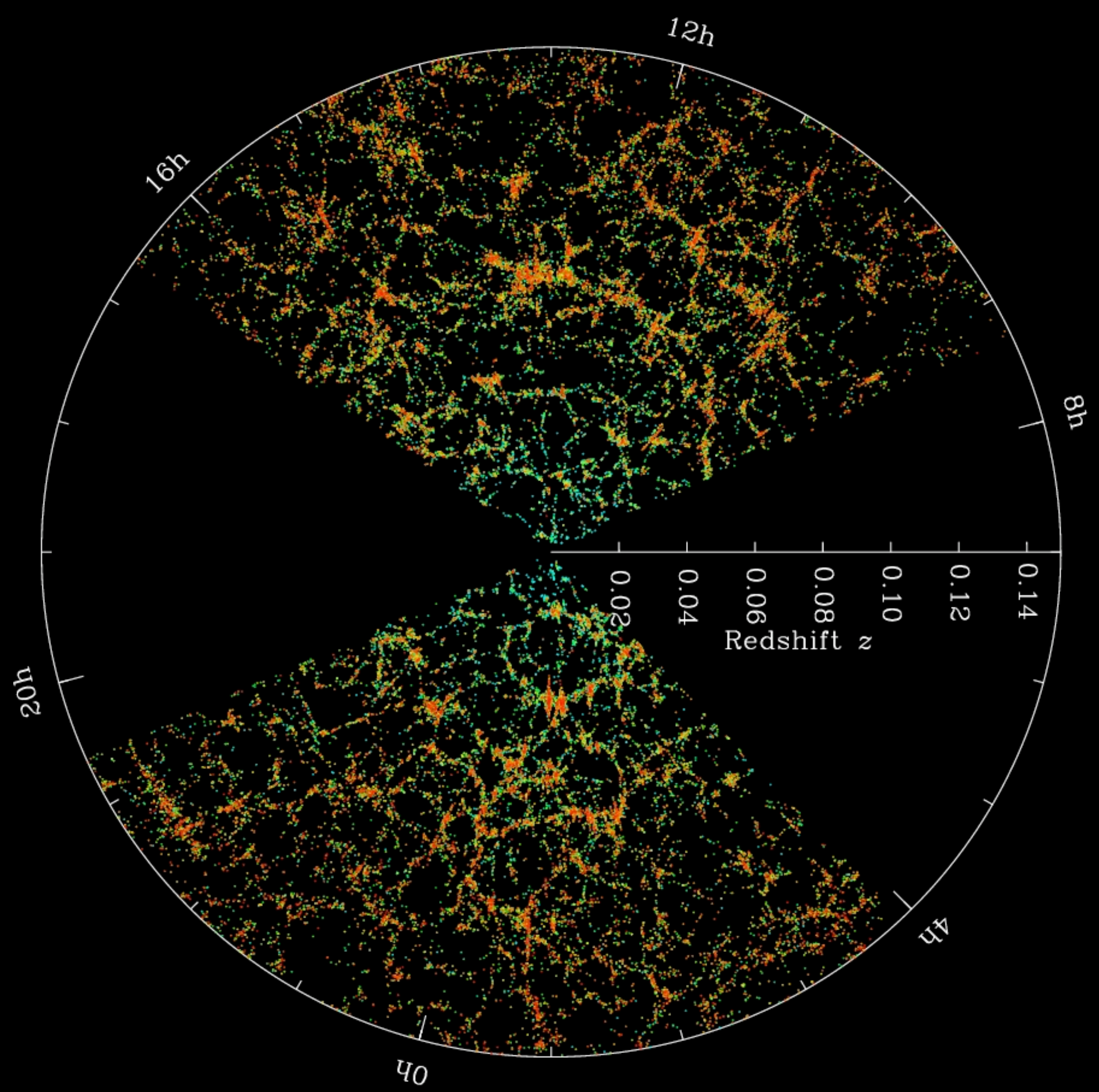
Sloan Digital Sky Survey (SDSS)

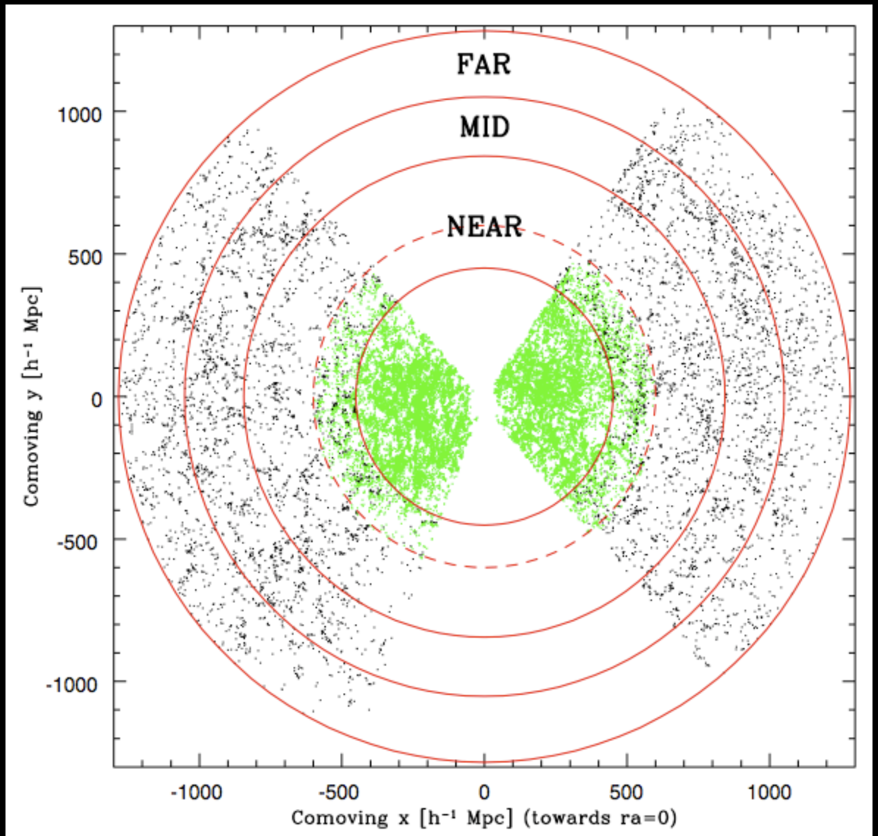


- 2.5m telescope
- 10^4 deg^2
- Imaging: 5 bands (ugriz), r<~22
- Spectroscopy of ~10^6 objects

Observations

SDSS LRG Sample

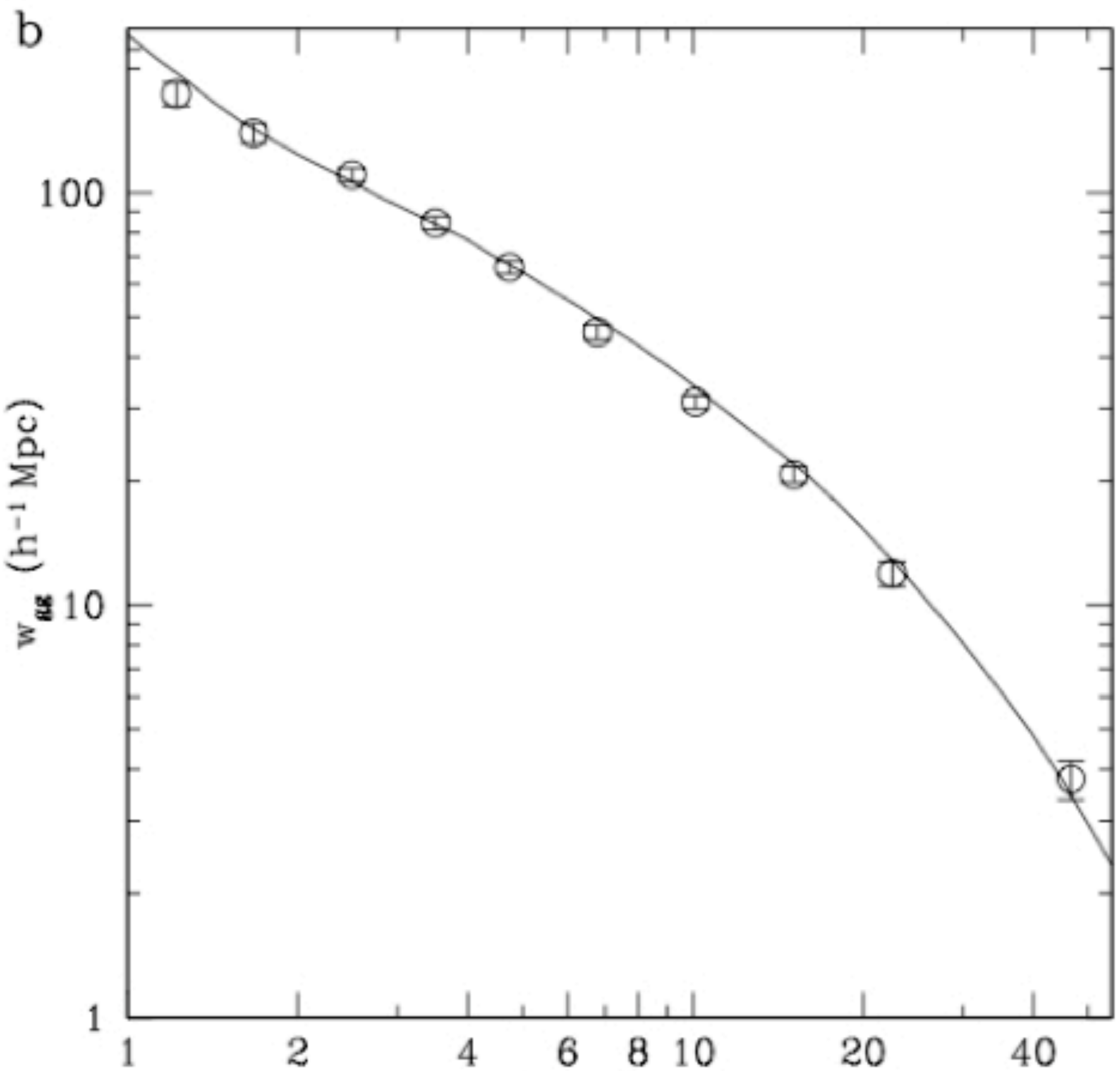
(Eisenstein, et al. 2001, 2005)



- 58,360 LRGs (SDSS DR4)
- uniform sample ($r < 19.1$, color cuts)
- $-23.2 < M_g < -21.2$
- $0.16 < z < 0.47$ (volume-limited for $z < 0.38$, $\langle z \rangle = 0.33$)

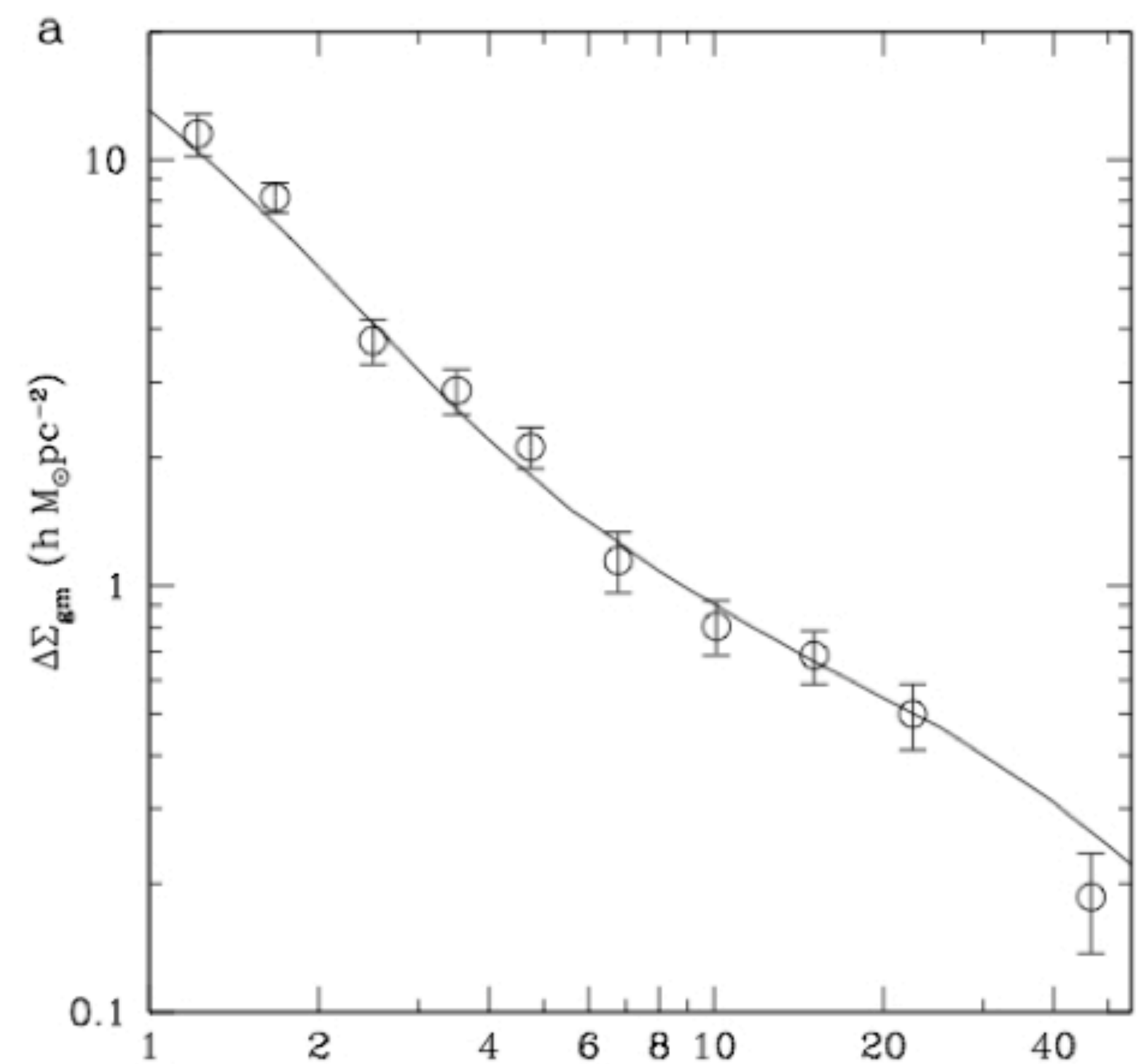
E_G measurement in SDSS

R. Reyes, RM et al (2010)



R [Mpc/h]

Galaxy clustering



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Galaxy-galaxy lensing

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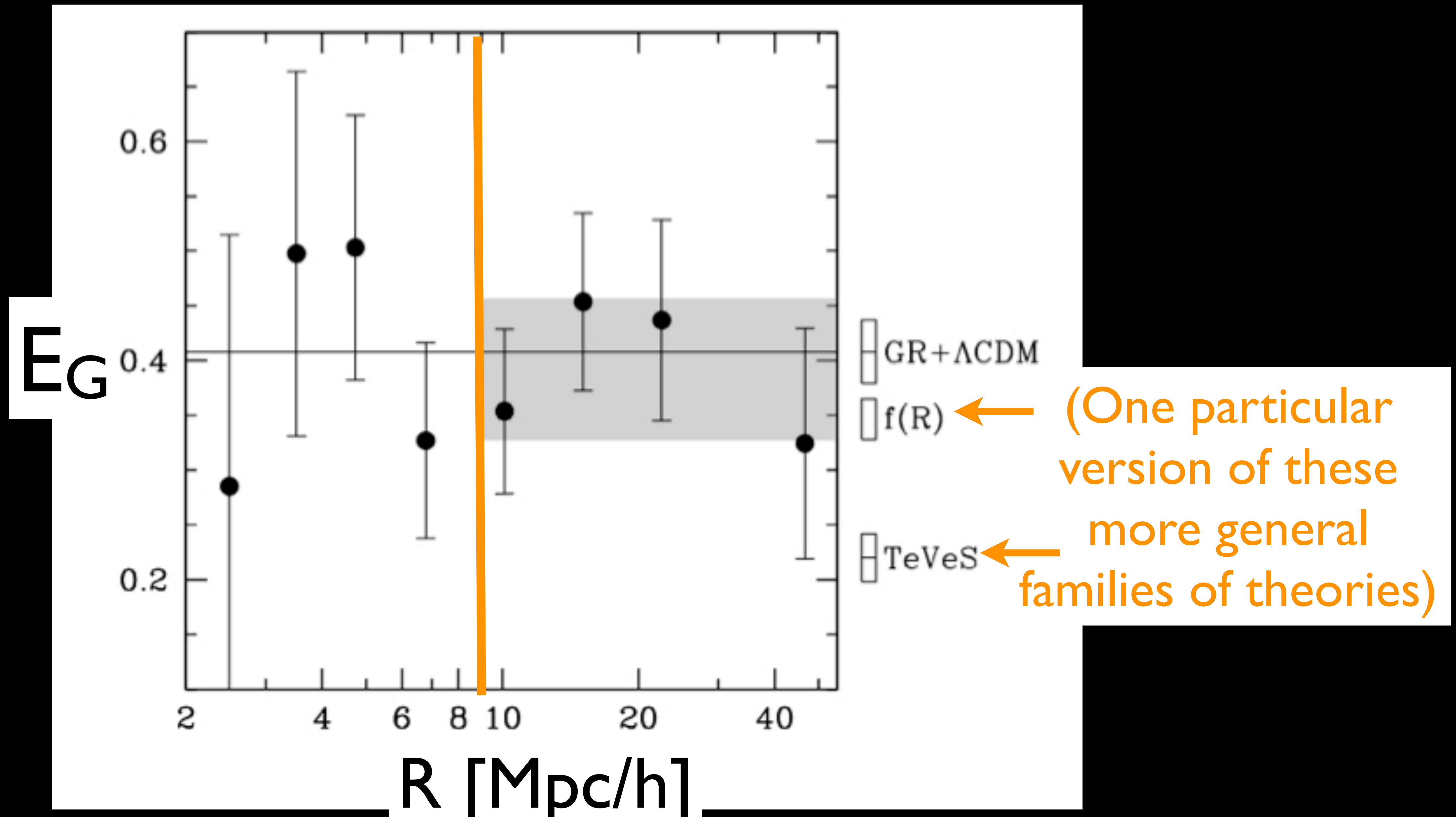


16% uncertainty: 11% from β, 12% from lensing noise

Future prospects

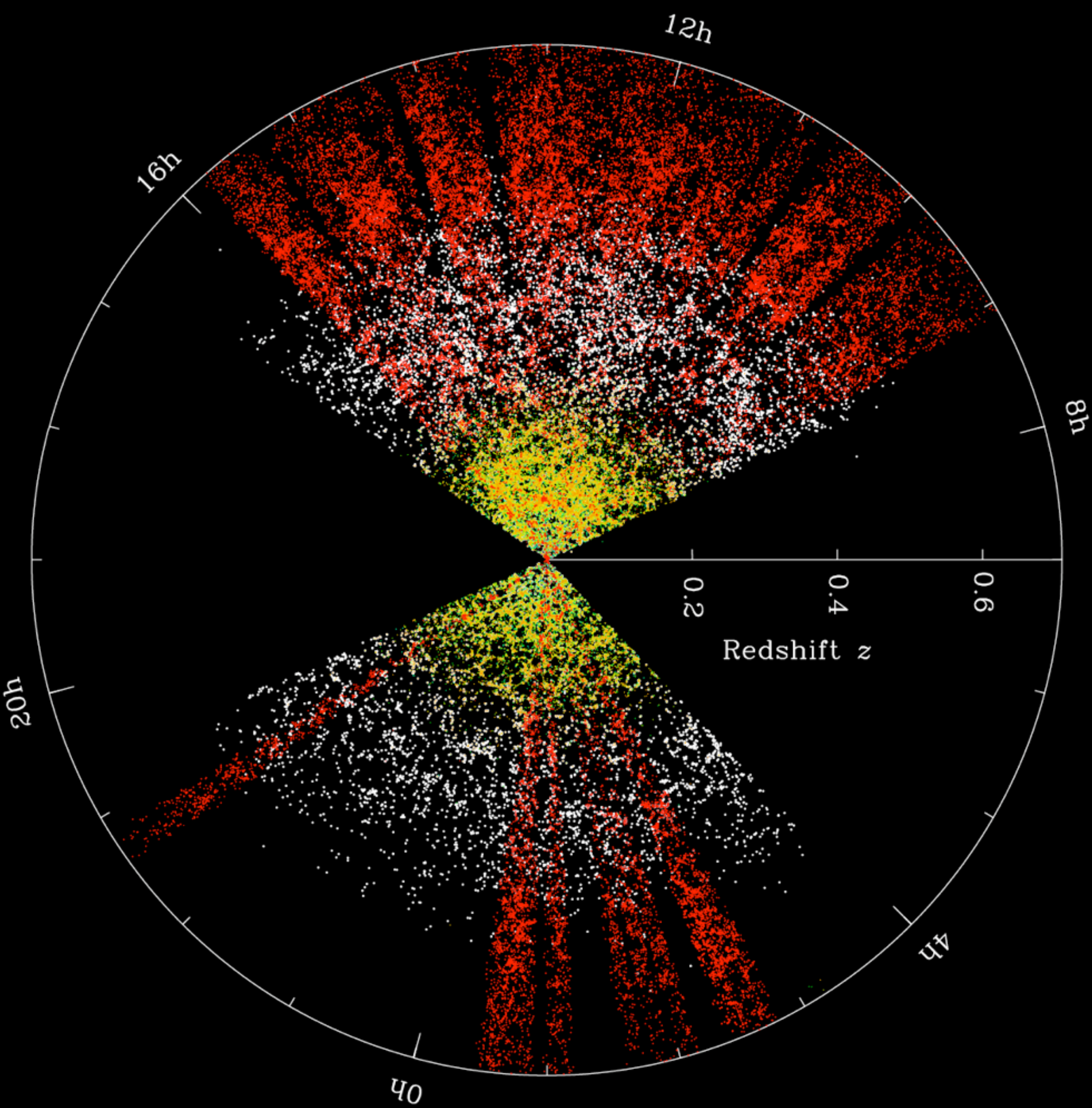
We need overlapping datasets with:

- spectroscopy to get redshift-space distortions, clustering
- galaxy shape measurements, photo-z for a sample of background galaxies to measure the g-g lensing

(and of course, adequate control of systematic errors)

Spectroscopic data: SDSS-III / BOSS

- Baryon Oscillation Spectroscopic Survey
- Ongoing survey: 2009-2014
- 10^4 deg^2
- LRGs, typically $0.4<z<0.7$
- Typical galaxy bias ~ 2

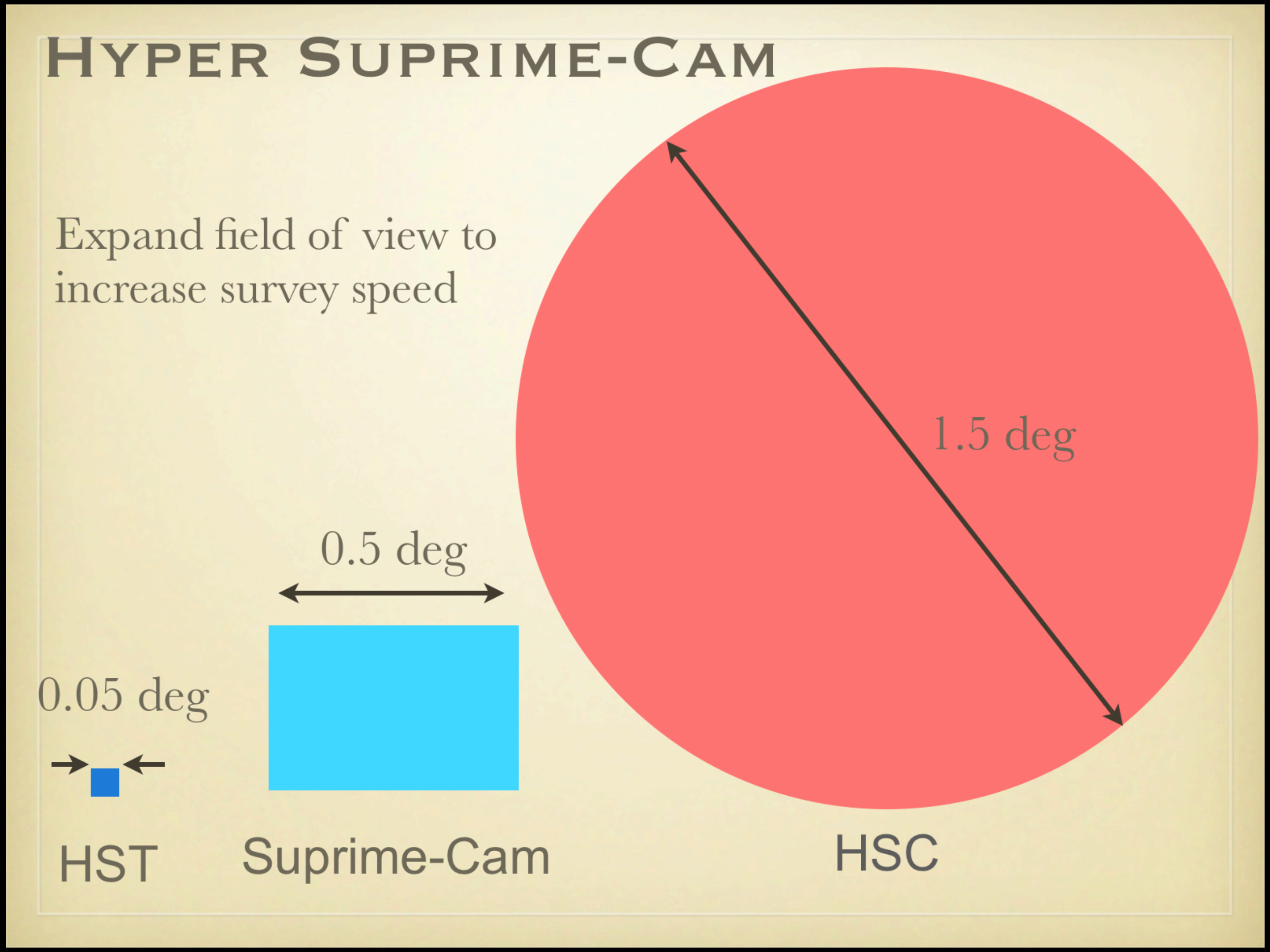


Contrast old vs. new spectroscopic data

- Increase in <z> from 0.3 to 0.5
- Increase in cosmological volume: factor of 7

➡ Statistical error on β decreases from 11% to 3% (averaged over redshifts) - White, Song, & Percival (2009)

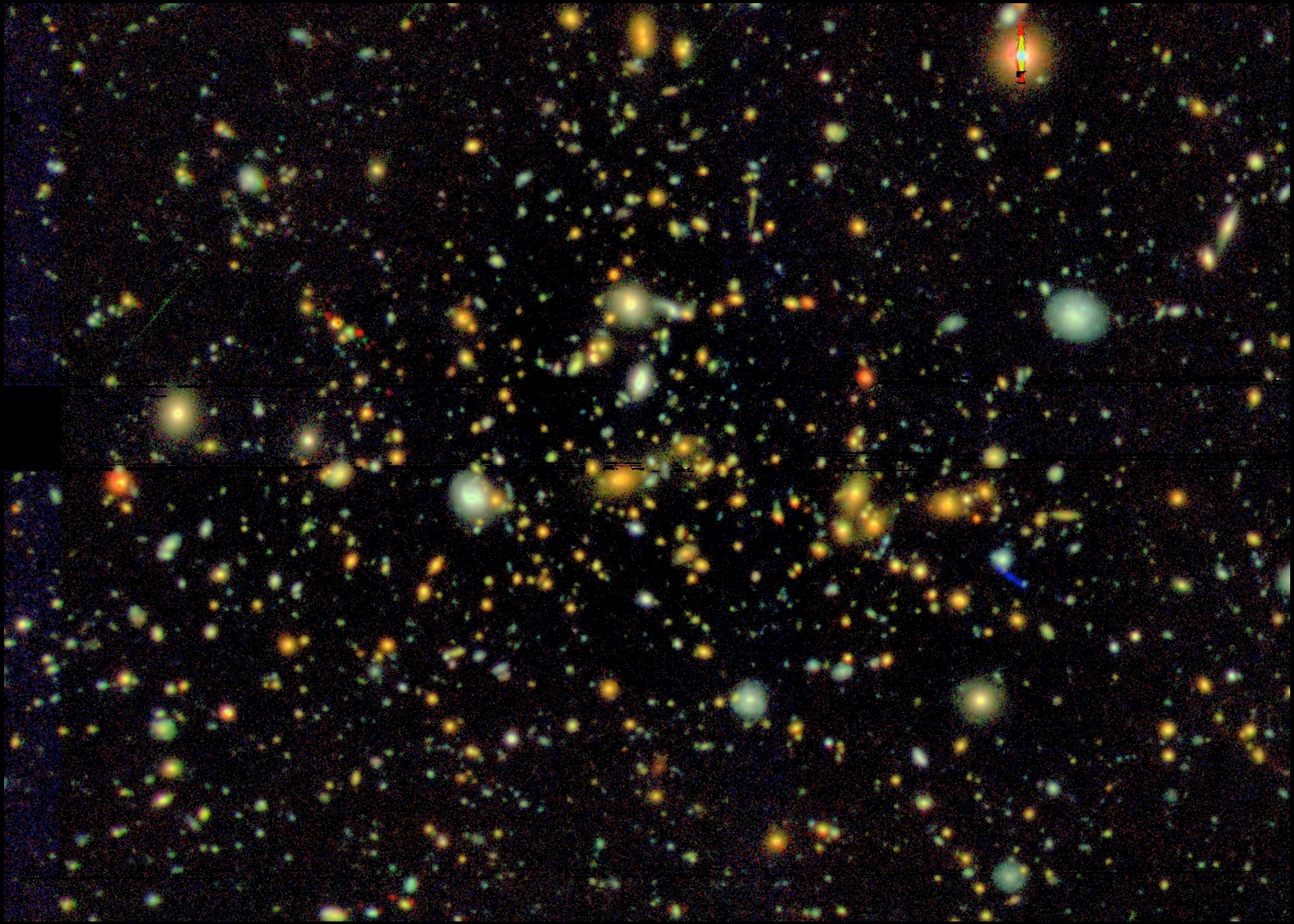
Imaging data: HSC



Picture credit: S. Miyazaki

- 8m Subaru telescope
- Very large FOV
- Red-sensitive CCDs
- Wide survey: 1500 deg^2
- Excellent image quality
- ~late 2013-2017

Example from Suprime-Cam

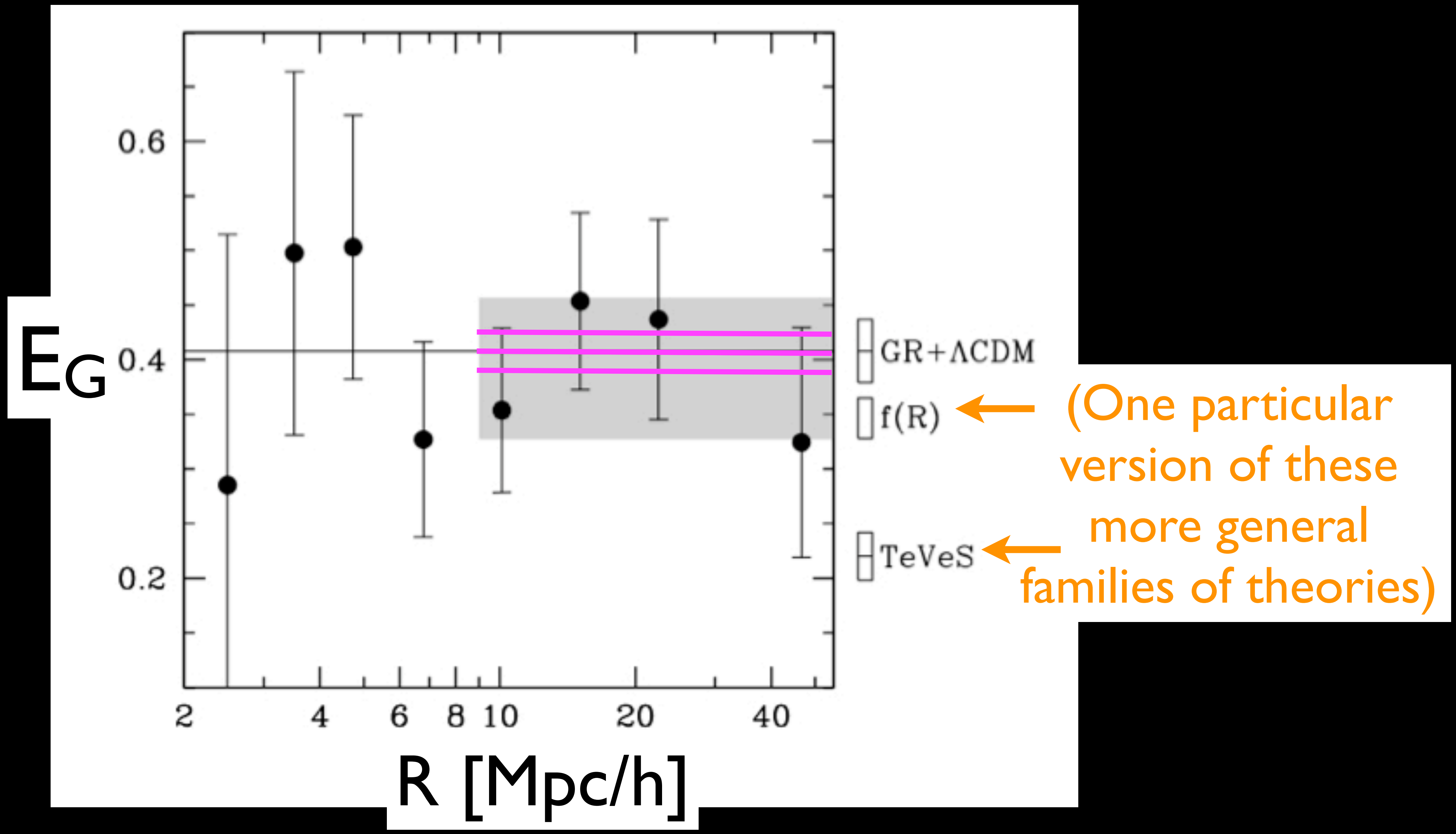


Expected E_G constraints

- β: 3% error (was 11%)
- Lensing signal: 2.5% error (was 12%)

➡ Total statistical error on E_G: 4% (1σ), a factor of 4 decrease from SDSS analysis!

So what do we gain?



15-year timescale
(Stage IV dark energy experiments)

- Spectroscopy: BigBOSS, PFS, Euclid, ...
- Imaging: LSST, Euclid, WFIRST
- 1% level constraints, or better

Summary

- Data intended to constrain cosmology in current and upcoming surveys can be used to constrain gravity
- Model-independent constraints come from combining different types of observations
- In the next ~5 years, we can expect to discriminate between competing theories at the few % level