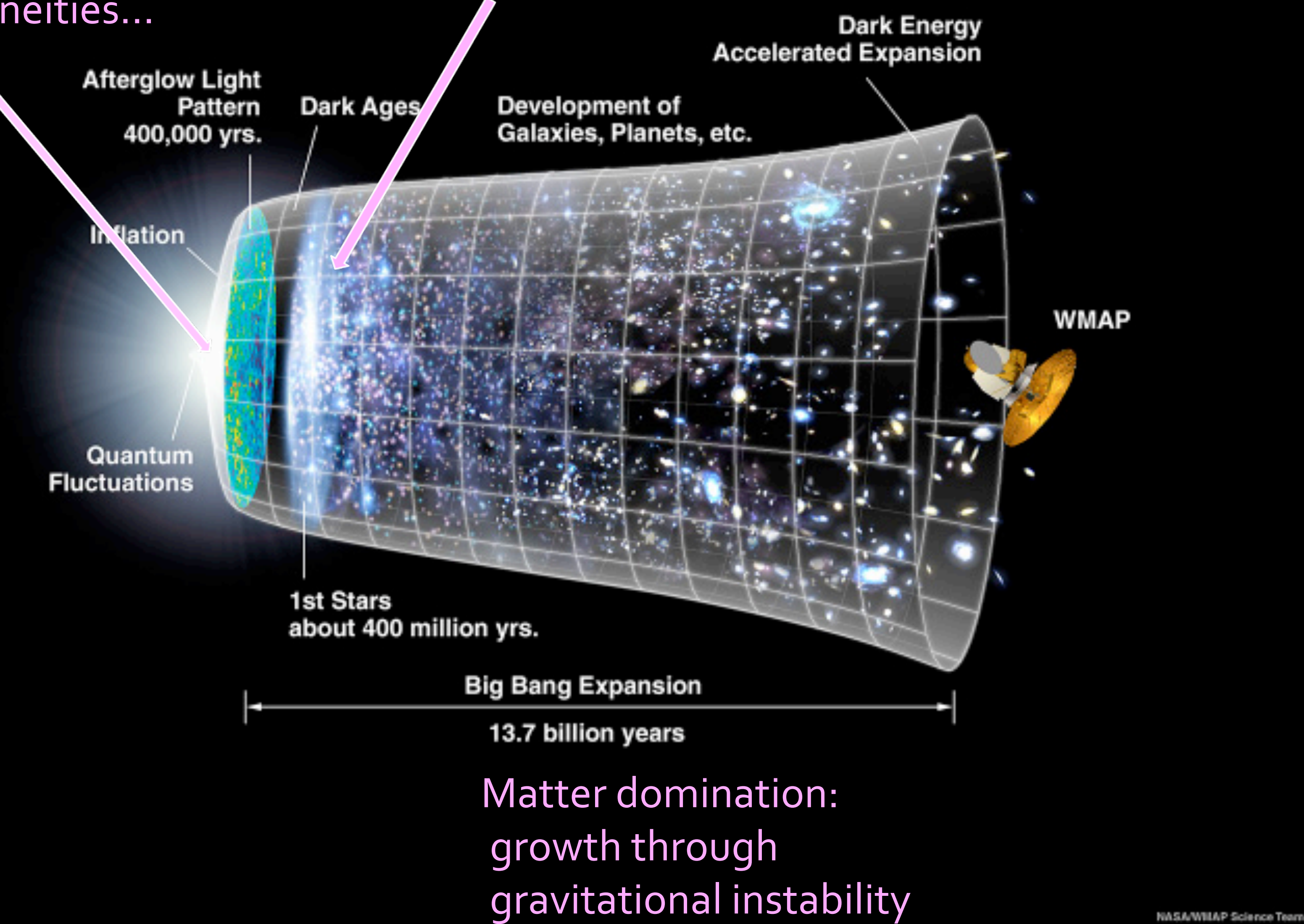
Uncovering the dark side of galaxies

Rachel Mandelbaum

Quantum fluctuations seed small ($\delta\rho/\rho \sim 10^{-5}$) inhomogeneities…

…which are imprinted in CMB…

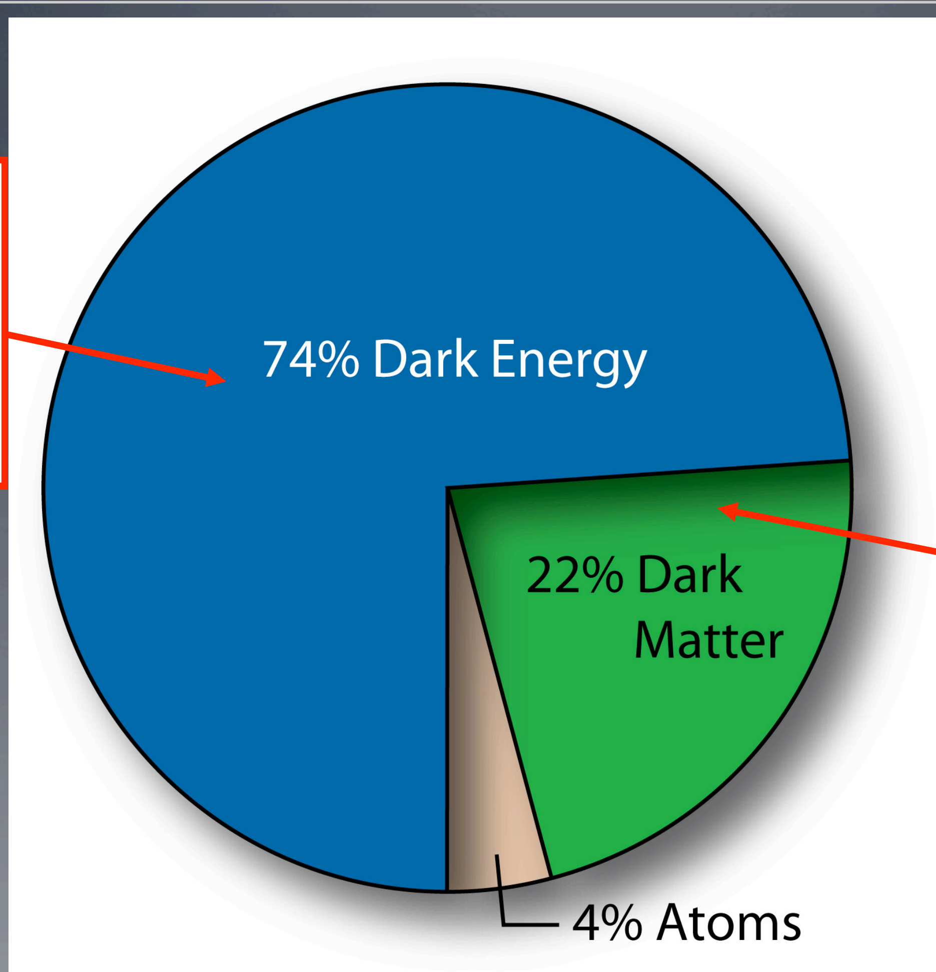


Matter domination: growth through gravitational instability

Picture courtesy of NASA/WMAP science team

Current cosmological picture

We don't know what this is! (but w≈-1, or p ≈ -ρ)



We don't know what this is, either! (but it's cold =non -relativistic)

Name for model: ΛCDM

Picture courtesy of NASA/WMAP science team

So, what is the dark side of these galaxies?

Pictures from Sloan Digital Sky Survey data release 6

What dark matter, if any, is associated with this galaxy?

What is the relationship between the visible and dark components?

What about special galaxy types, such as AGN?

What are the relevant processes in its formation and evolution?

The key problem:

- The universe is dominated by dark contents.
- But…we cannot directly observe those contents using a telescope.

Outline

Galaxy-dark matter connection

Gravitational lensing

- ✓ The basics
- ✓ How it helps

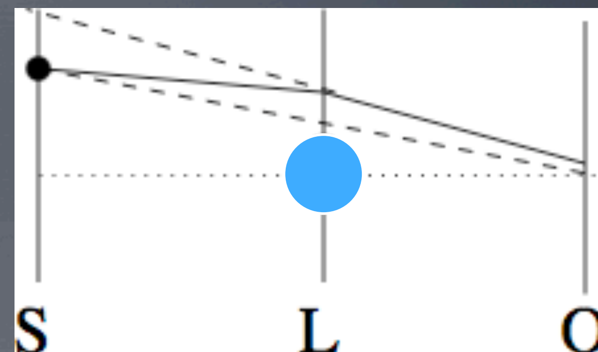
Applications

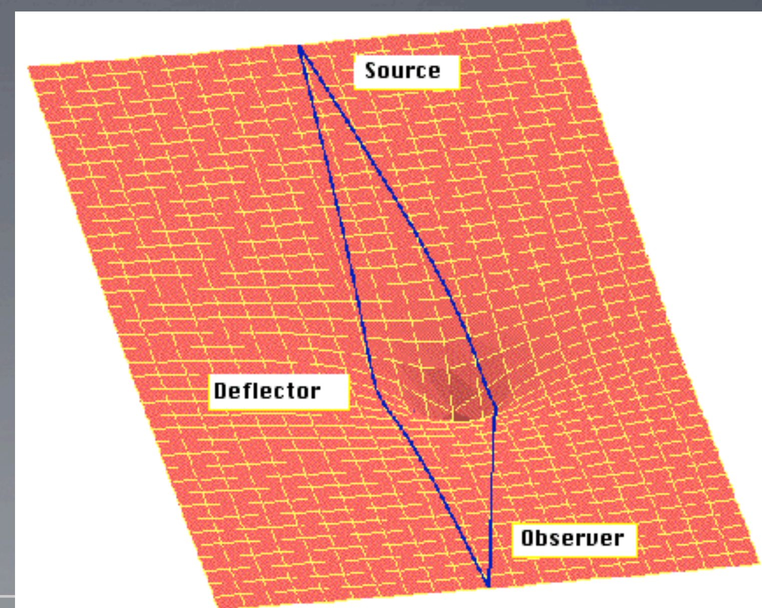
Future perspective

One important tool…

- Gravitational lensing:

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



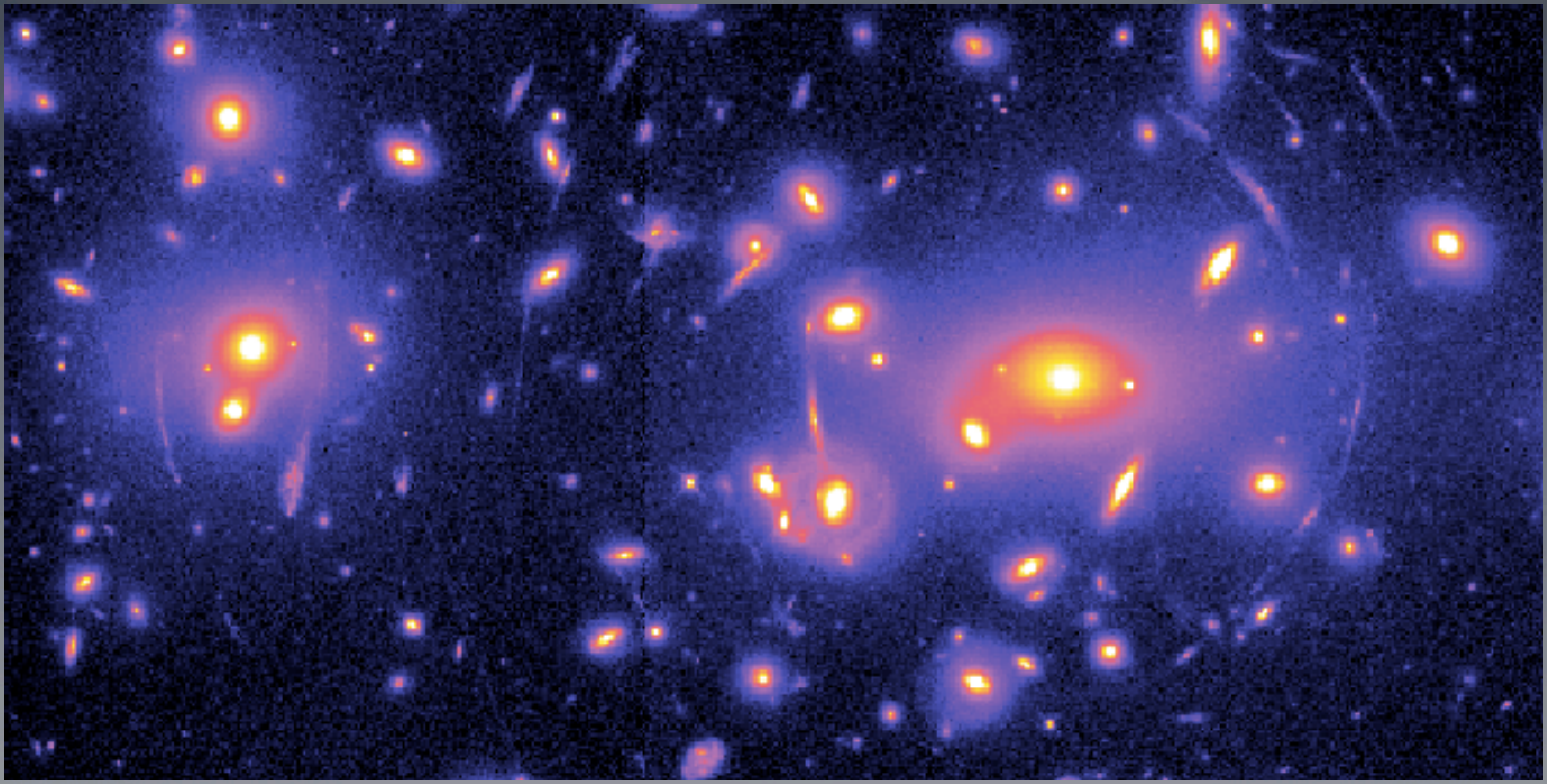


- Depends on projection along line of sight

Background

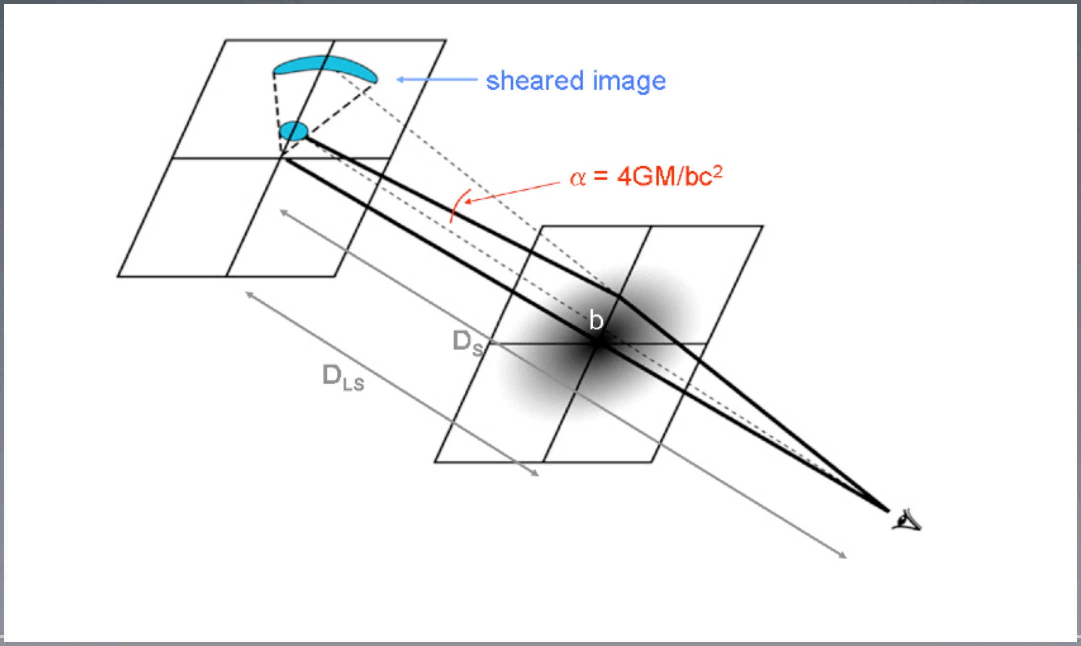
Lensing predicted by Newton, with modified predictions by Einstein:

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



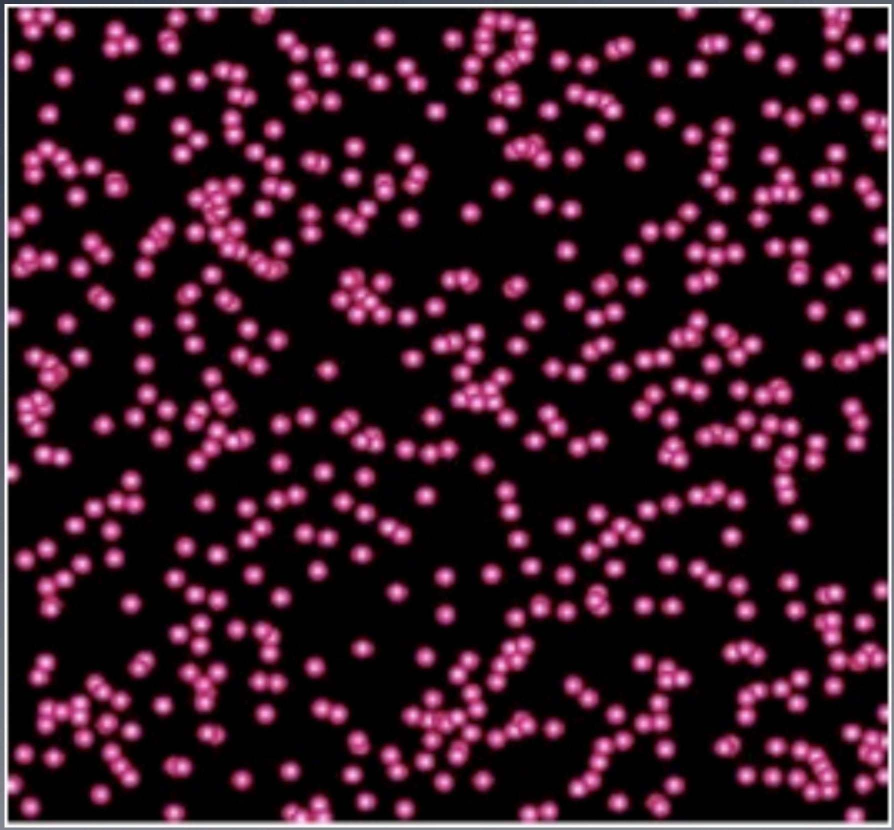
Weak lensing

- Deflection angle small enough to be treated perturbatively
- Focus on extended objects, and look for coherent statistical effect on their shapes

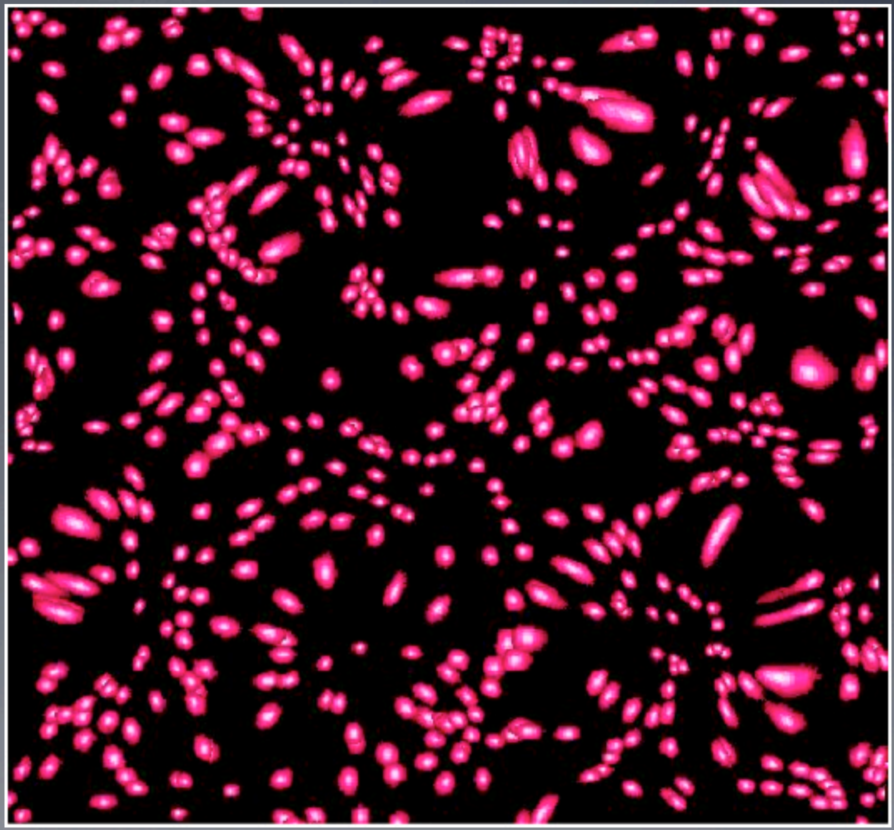


Picture credit: LSST Science Book

Weak lensing



Unlensed



Lensed

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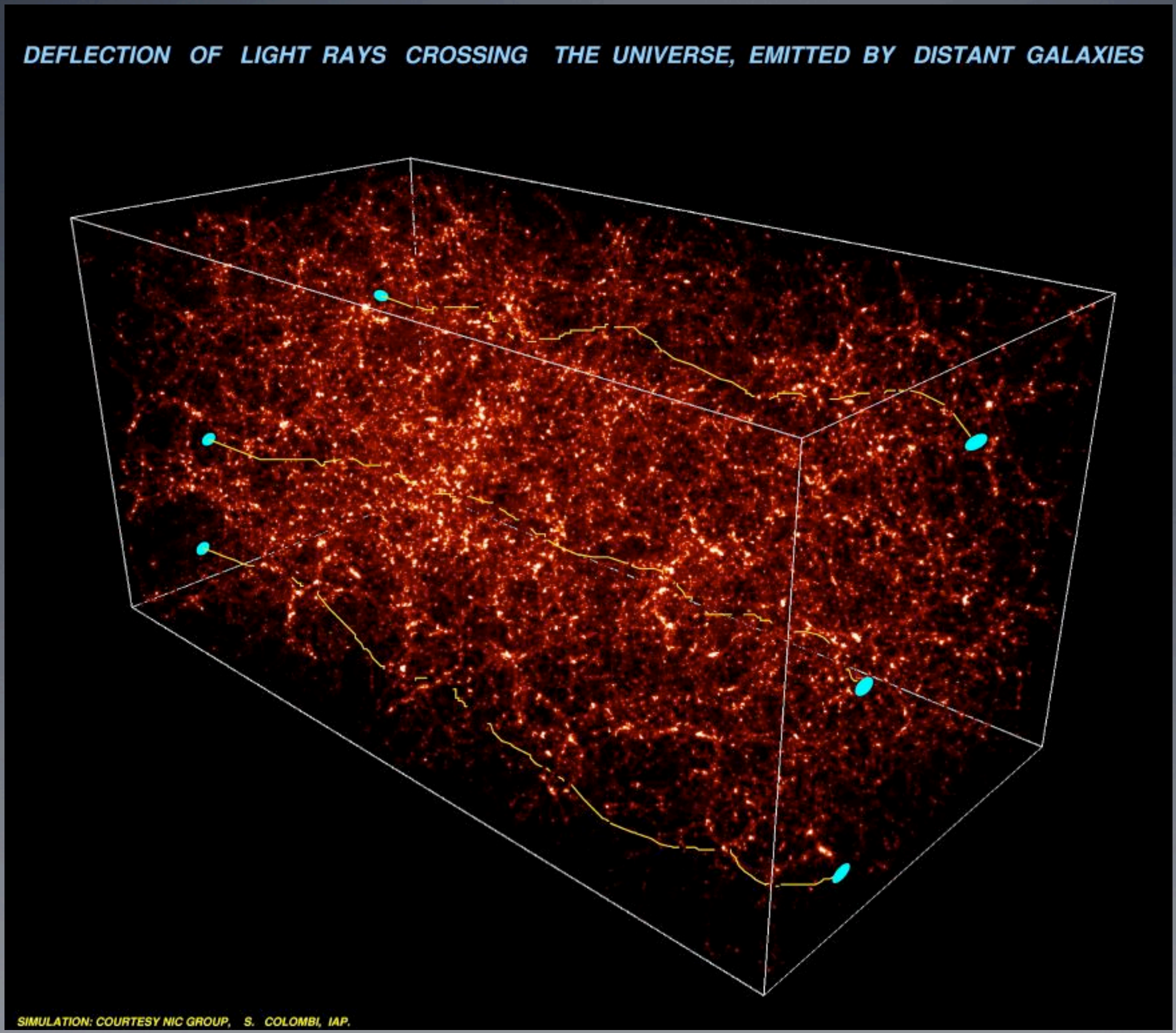
Cosmic shear

Shape autocorrelation → statistical map of large-scale structure

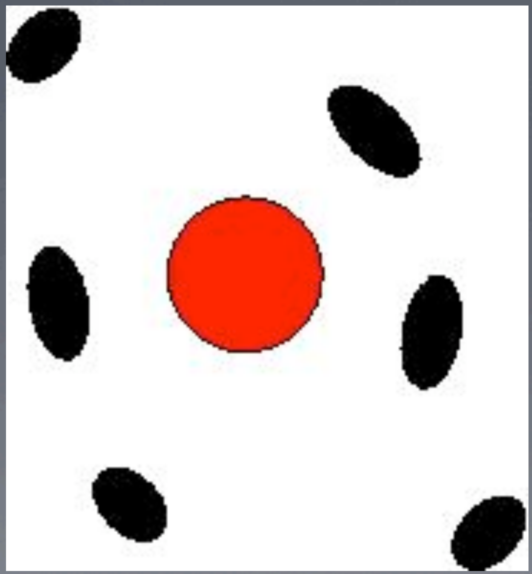


What does cosmic shear tell us?

- Measures amplitude of matter density fluctuations *directly*
- Can use to constrain amplitude of power spectrum ➔cosmological model parameters

Galaxy-galaxy lensing

- Stacked lens galaxy position – source galaxy shape cross-correlation



- Reveals **total** average matter distribution around lens galaxies or cluster (galaxy-mass correlation)

Galaxy-galaxy lensing definitions

$\Delta\Sigma$ = projected surface density contrast

$$= \bar{\Sigma}(<R) - \Sigma(R) = \gamma(R)\Sigma_c$$ (axisymmetric)

γ = "shear"

$$\Sigma_c = \left(\frac{c^2}{4\pi G}\right)\frac{D_S}{D_L D_{LS}}$$

$$\Sigma(R) = \bar{\rho}\int[1 + \xi_{\rm gm}(\sqrt{R^2 + \chi^2})]W(\chi)\,{\rm d}\chi$$

Cosmic shear vs. g-g lensing

Shape autocorrelation: demanding systematics

But: it's the way to do lensing cosmology

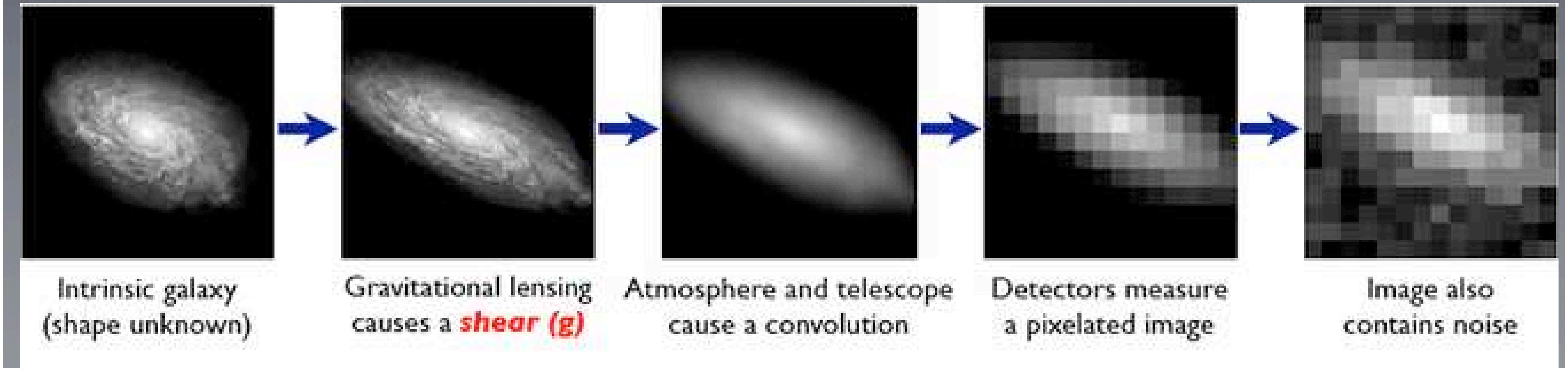
Enormous effort expended, future surveys planned

Shape cross-correlation: simpler systematics

A tool for galaxy/cluster studies

Challenges

- Galaxy shapes → shears
- Distances to sources
- Intrinsic shape alignments
- Note: more problematic for cosmic shear than for g-g lensing
- Summary: in the past 10 years, ~30% systematic errors reduced by a factor of **10**



Context

- Powerful lensing surveys planned for the next 10-20 years

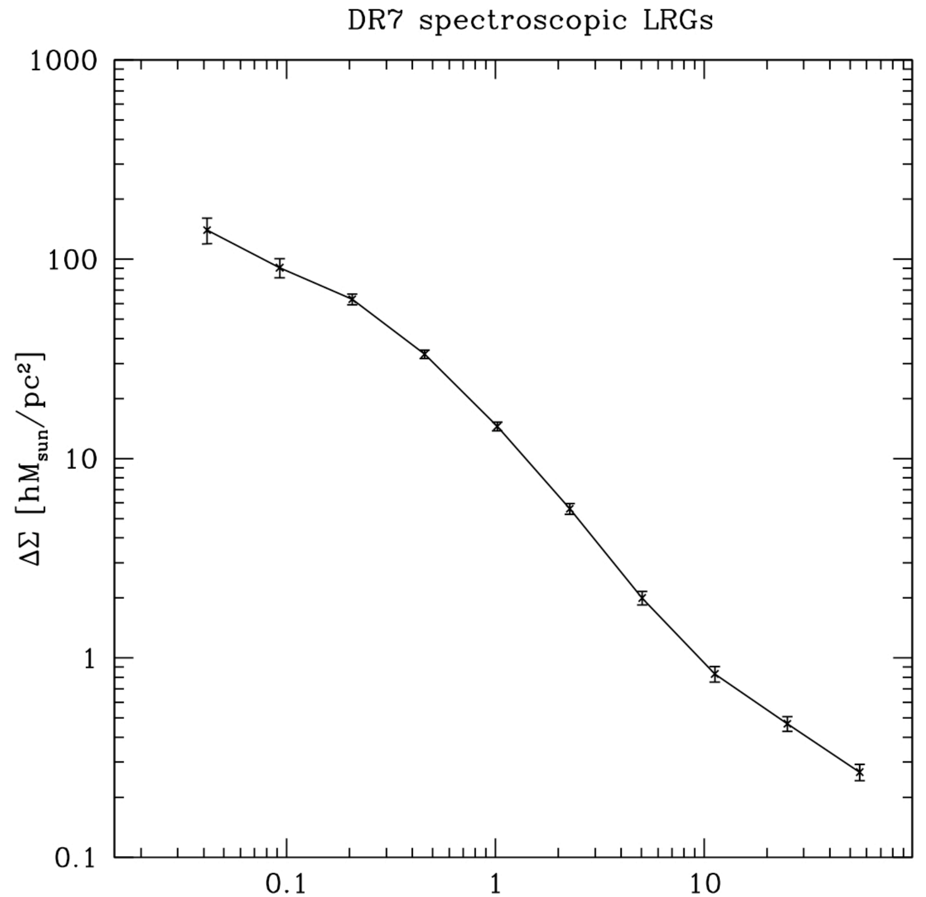
  → we must start preparing now!!

- Test new, robust methods of data analysis on simulations… and existing data such as SDSS:
  - ~10k square degrees
  - Imaging to r <~ 22
  - Typical seeing: ~1.2"

} 1 resolved source / $arcmin^2$

Example of current data

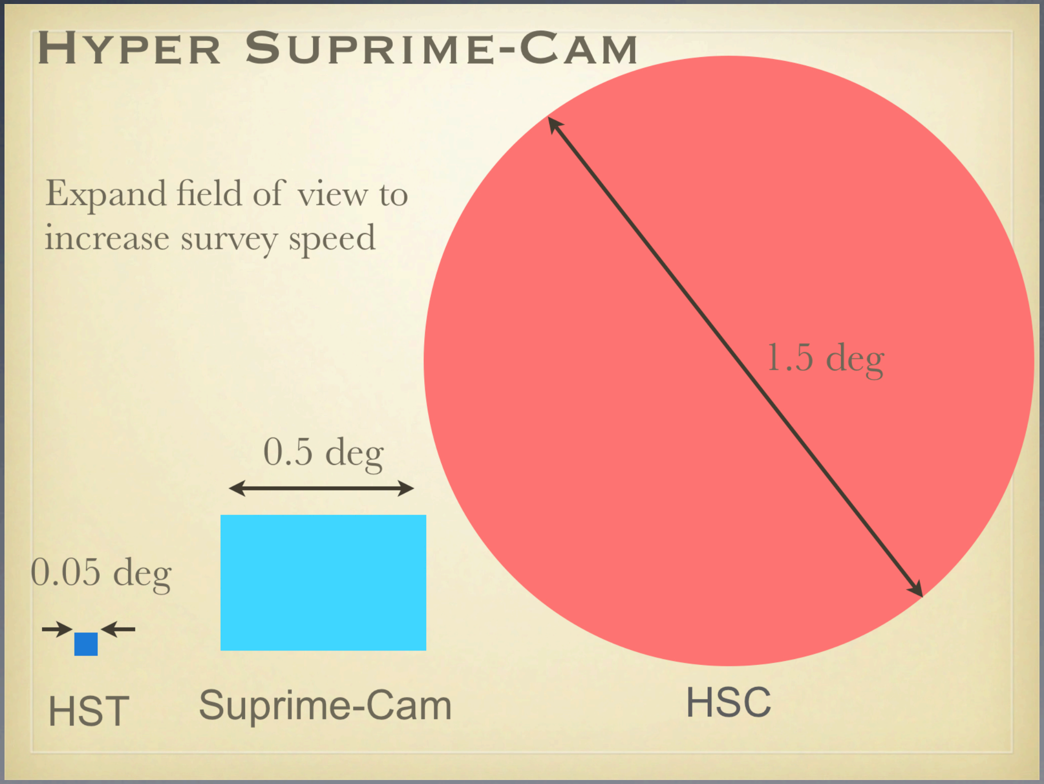
Galaxy -galaxy lensing signal



Transverse separation R (Mpc/h)

Stacked data: 10^5 LRGs (lenses), 70M sources

HSC: a weak lensing survey at the 8m Subaru telescope



Picture credit: S. Miyazaki

- Wide: 1500 deg^2
- r<~25
- Excellent seeing: ~0.7″
- 20-30 resolved galaxies / arcmin^2

DES: Dark Energy Survey

- CTIO (4m)
- 5000 deg^2
- $r < 24$
- Typical seeing ~ 0.8-0.9″

→ 10 resolved galaxies / $arcmin^2$

Dueling surveys?

NO!!

North vs. south

Wide vs. deep

Look towards LSST, WFIRST, Euclid!

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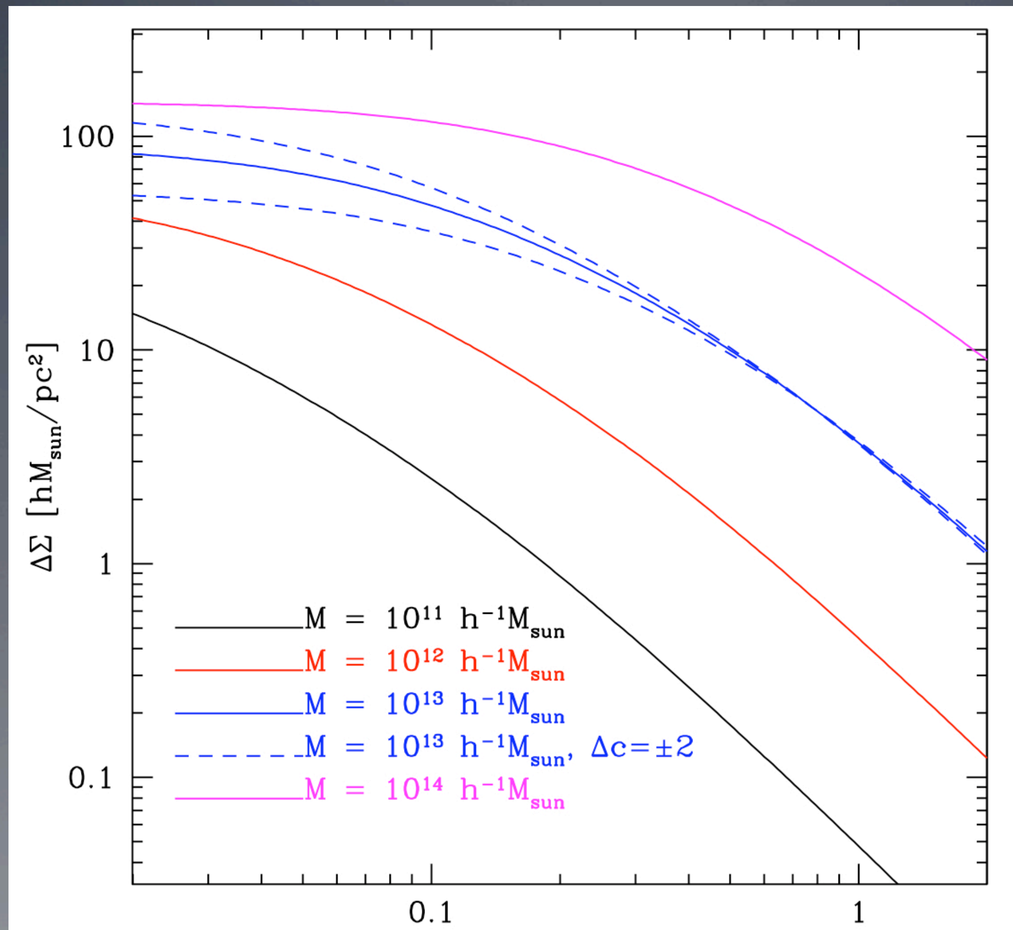
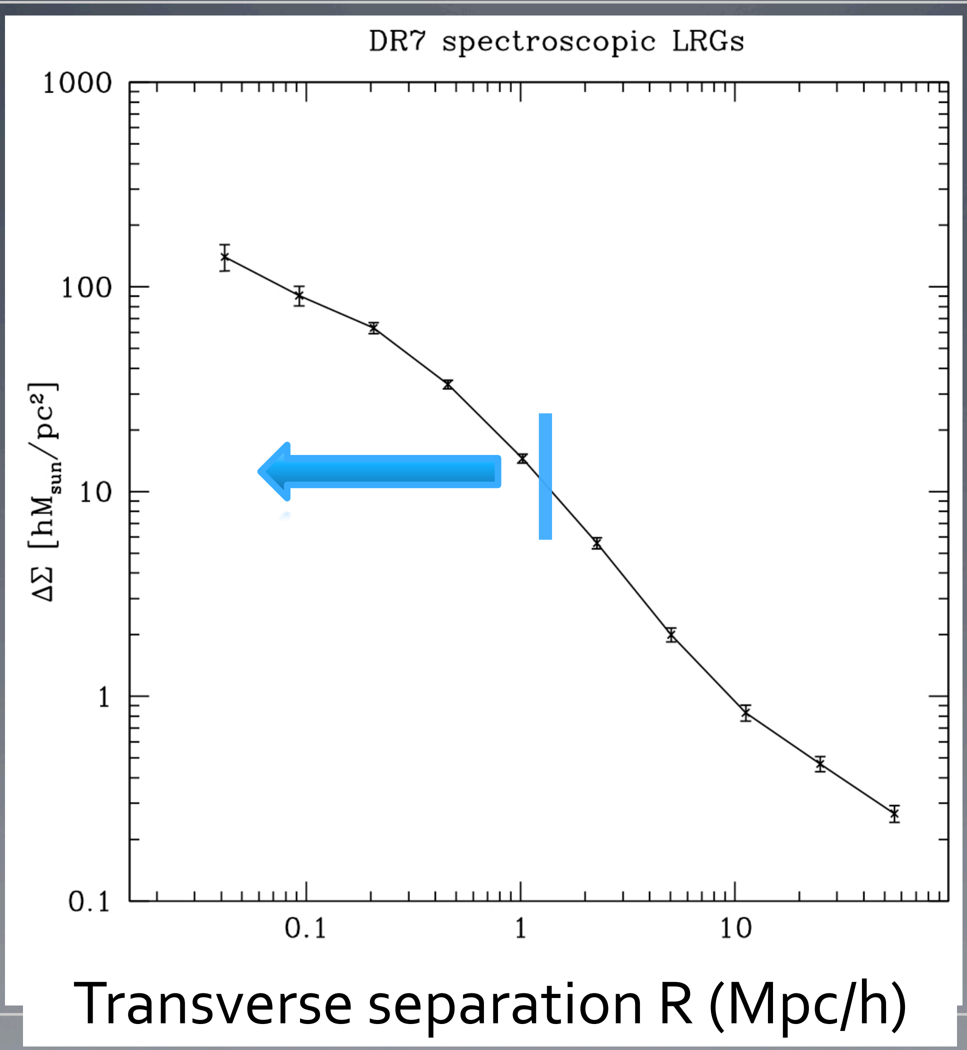
Small-scale lensing profiles reveal galaxy DM halos



Transverse separation R (Mpc/h)

Small-scale lensing profiles reveal galaxy DM halos



Relating mass to light

- Given galaxy light / stellar mass: what is relation to galaxy DM halo and large-scale environment?
- Use lensing to address this question, after dividing sample based on optical properties:
  - Age of stellar population
  - Luminosity
  - Stellar mass
  - Apparent environment

References

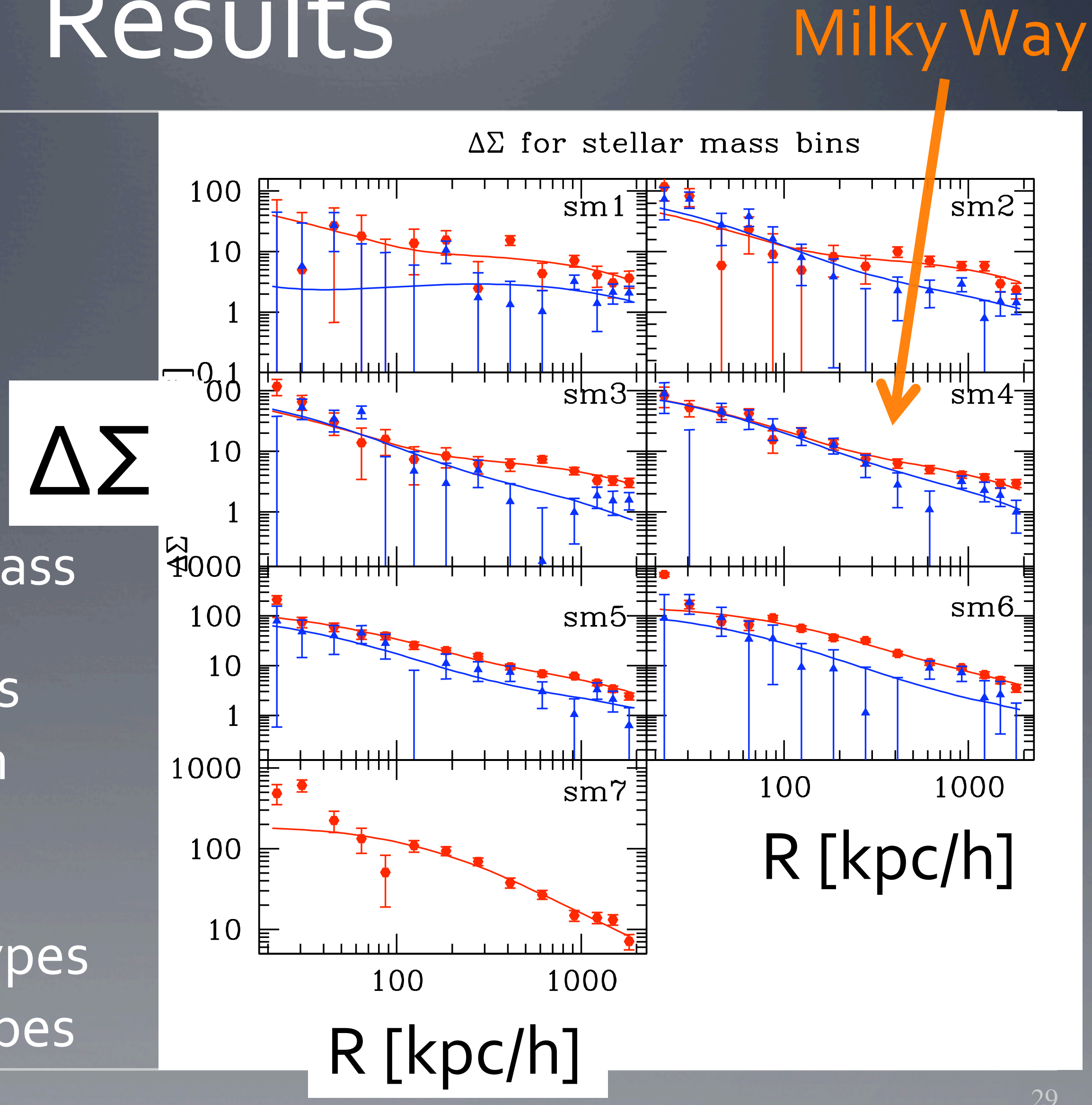
- SDSS: Sheldon et al. (2004),

  RM, U. Seljak, G. Kauffmann, C. Hirata, 2006, MNRAS 368, 715

- RCS: Hoekstra et al. (2005)
- GEMS: Heymans et al. (2006)
- CFHTLS: Parker et al. (2007)

Results

- Lensing signal vs. M_*
- Split by morphology
- Small scales: halo mass increases with stellar mass
- Large scales: early types preferentially located in denser environments



Implications

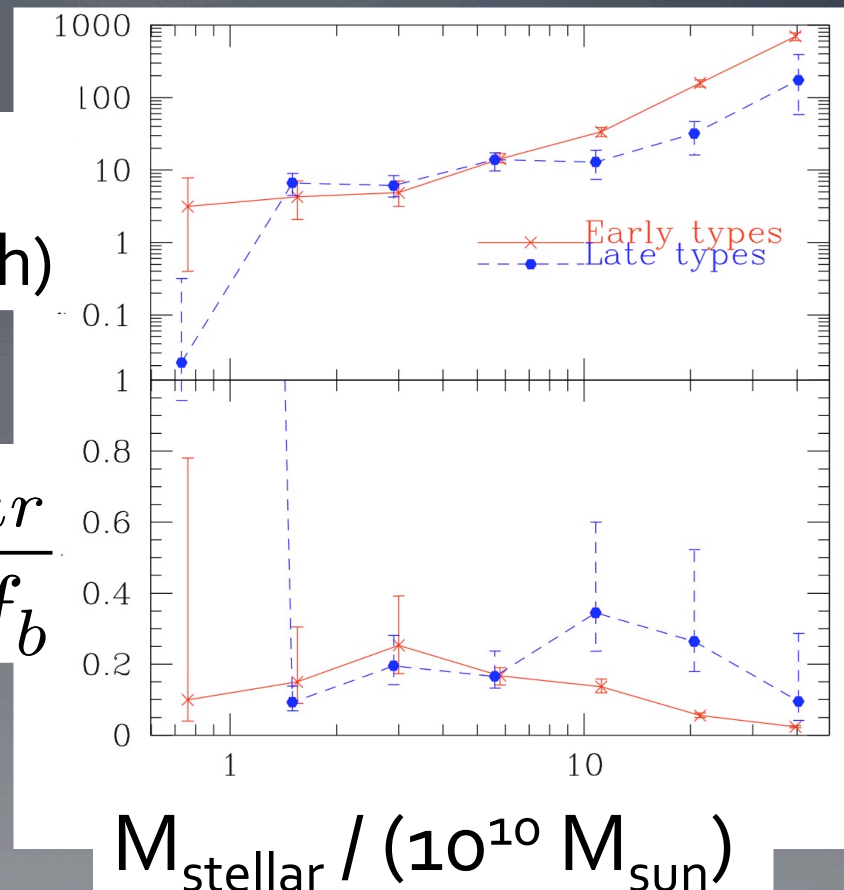
Errors: 68% CL

- Stellar mass traces halo mass for

  $M_* <\sim 10^{11} M_{sun}$

M_{halo} / (10^{11} M_{sun}/h)

$$\eta = \frac{M_{stellar}}{M_{halo} f_b}$$



- Baryon conversion efficiencies peak around 30-40%

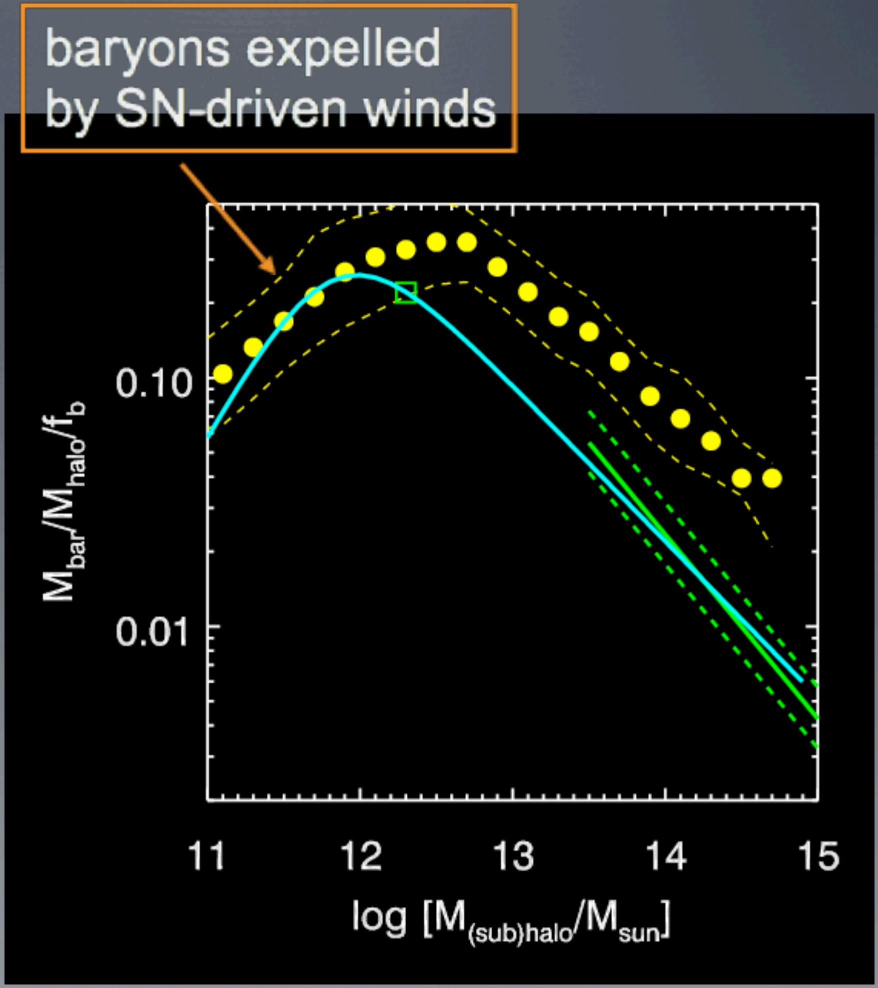
The galaxy overcooling problem

Somerville & Primack 1999; Cole et al 2001; Kauffmann et al 1999; Benson et al 2003; Croton et al 2006; also seen in hydro sims…

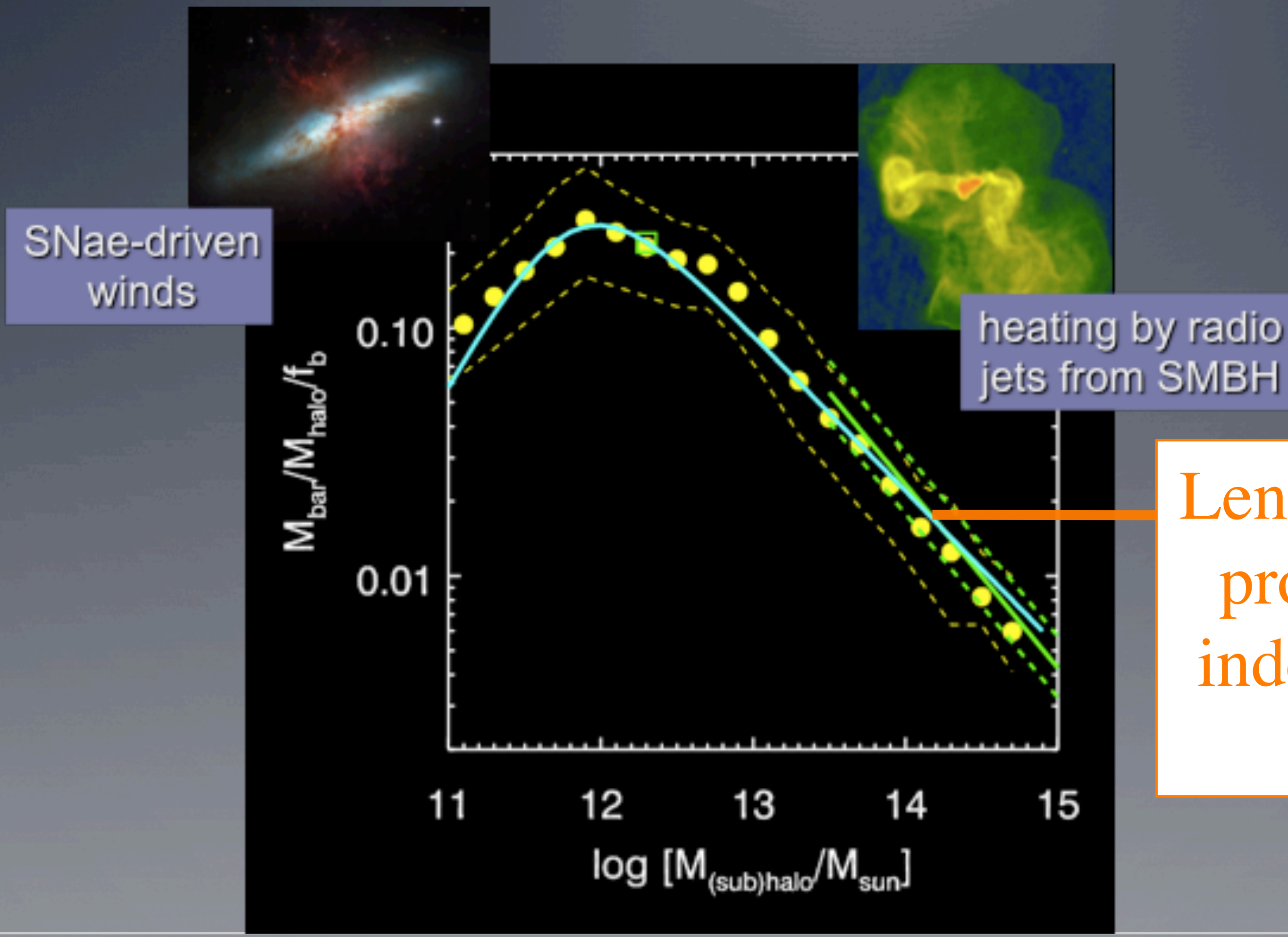
Yellow points: SAM

Blue line: Moster et al. stellar mass function constraints

Somerville et al. 2007



Include AGN feedback…



Lensing data provide an independent test

Somerville et al 2007, see also Croton et al 2006, Bower et al 2006

Room for future improvement

With surveys like HSC, DES, eventually LSST:

- High S/N lensing measurements at lower stellar masses
- Longer redshift baseline, to trace evolution from z~1

What are AGN?

- AGN = Active galactic nucleus
- Compact region at galaxy center with high luminosity in some ranges of wavelengths
- Believed to be associated with accretion disk around supermassive black hole
- May be associated with jets, detected at radio wavelengths

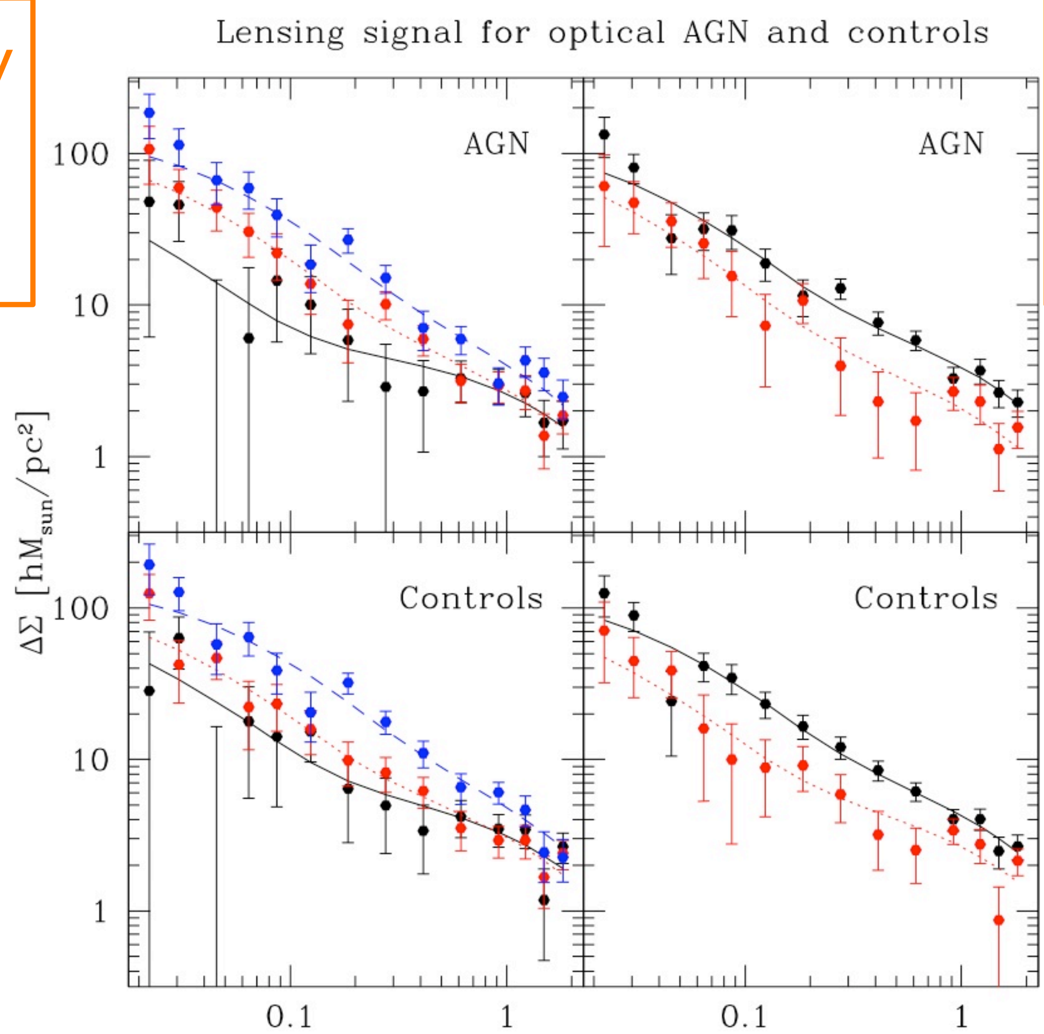
RM, C. Li, G. Kauffmann, S. D. M. White, 2009, MNRAS, 393, 377

Optical narrow-line AGN

- How does presence of accretion disk around SMBH relate to large-scale galaxy properties?
- Naïve answer: it doesn't.
- Test with their lensing signals
- Check using matched samples in redshift, morphology, stellar mass… (typically late type galaxies)

Naïve answer is basically correct!
(But see Li et al. 2006 for slight suggestion of reduced satellite fraction among optical narrow-line AGN.)

Split by stellar mass



Transverse separation R (Mpc/h)

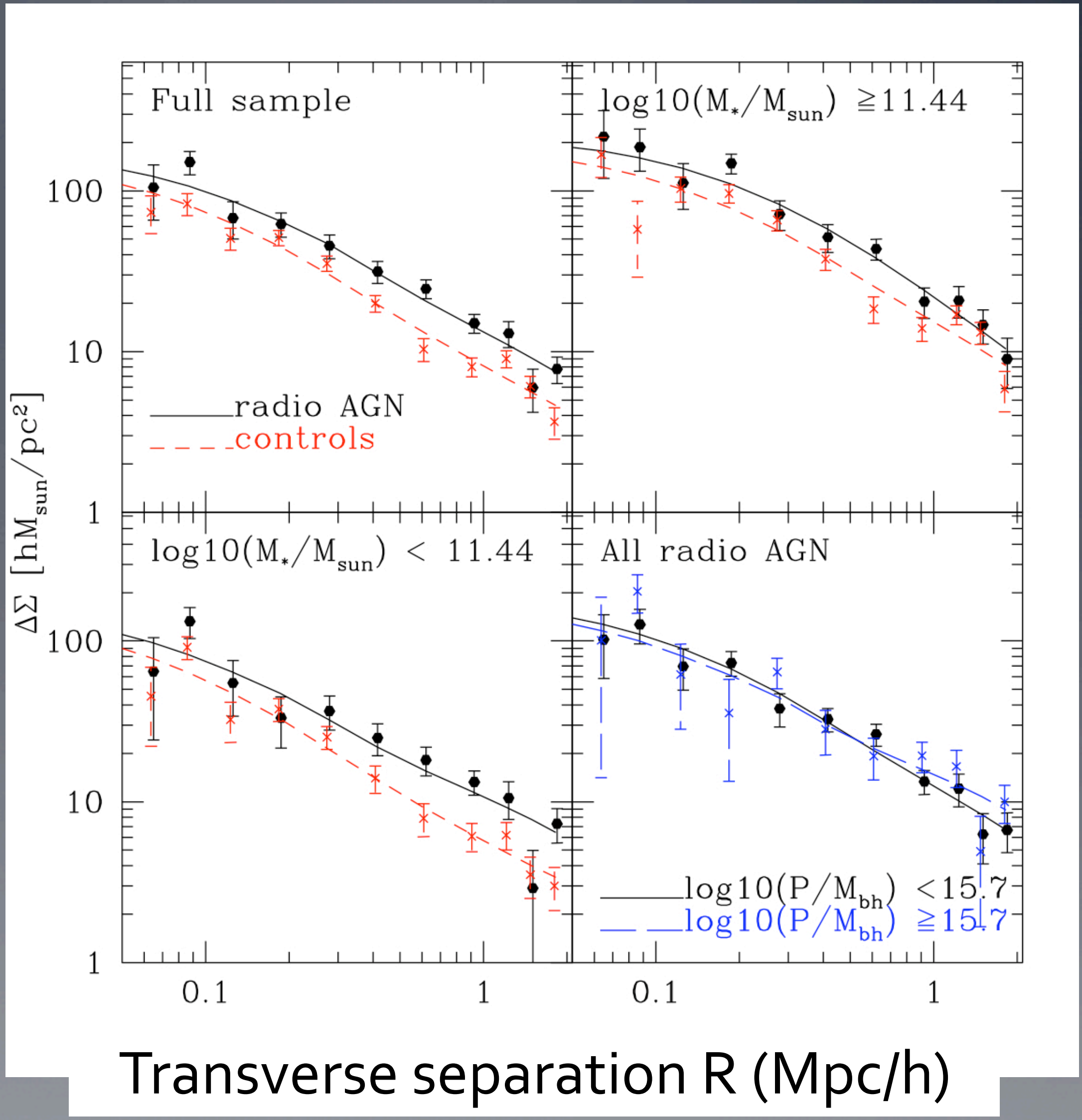
Split by line strength

Radio-loud AGN

- In what small- and large-scale environments do these galaxies live?
- Test with ~5500 in SDSS Main spectrosopic sample with matches in radio surveys, $0.1<z<0.3$
- Compare against matched samples (same z, M_*) containing ~20% radio AGN, typically massive early-type galaxies

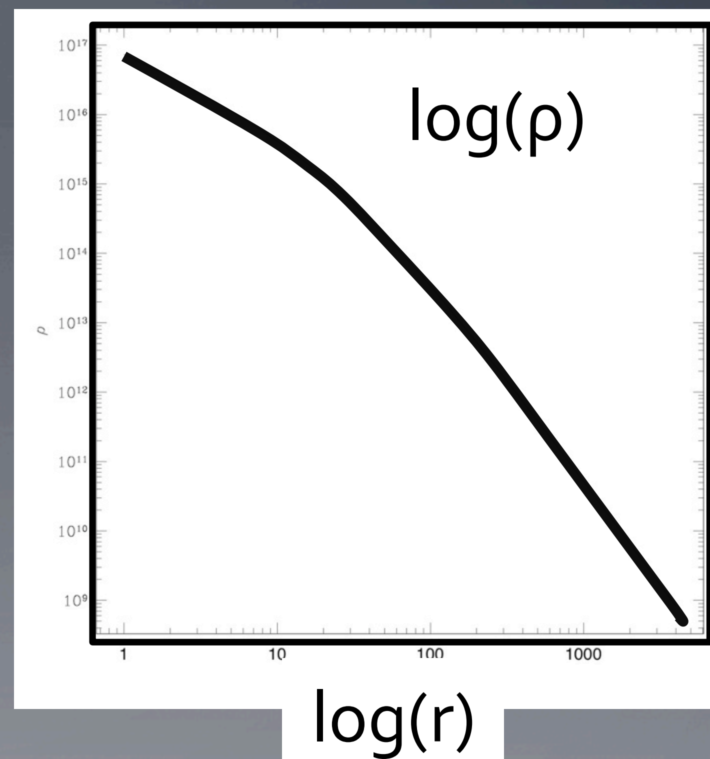
$M_{halo} \sim (2.5 \pm 0.6) \times 10^{13}\ M_{sun}/h$

- radio AGN vs. control samples: Mean halo masses differ by factor of ~2
- results can be used in modeling their formation / evolution
- some mysteries remain: duty cycle??

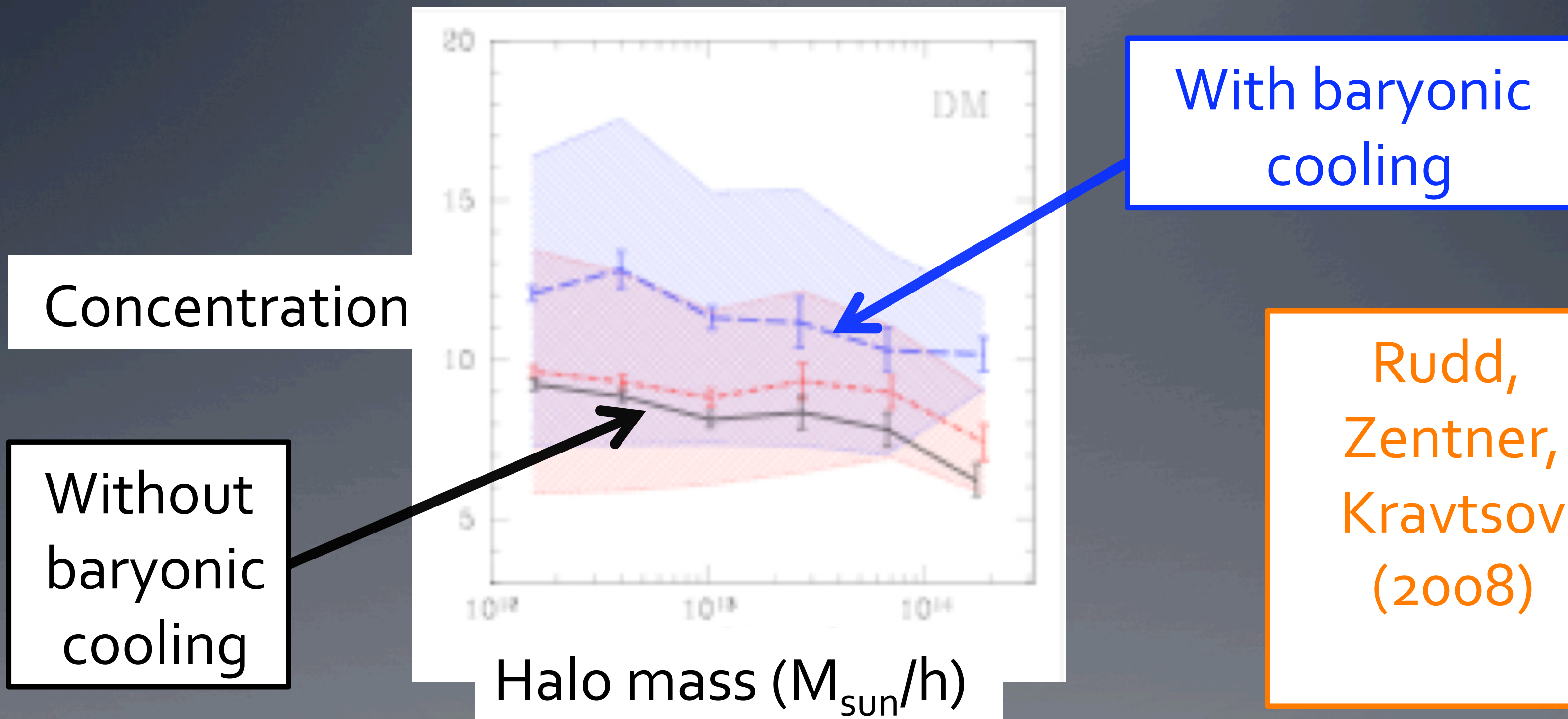


Now let's have more detail

- Not just halo masses, but full comparison with DM halo profiles
- Test of N-body simulations: predictions of DM profiles in non-linear regime ($\delta\rho/\rho$ unrestricted)
  - Broken power-law profile, characterized by r_s
  - Concentration (r_{vir}/r_s) prediction:
    - Amplitude depends on cosmology
    - Mass scaling $c \sim M^{-0.1}$



Effects of baryonic cooling



Rudd, Zentner, Kravtsov (2008)

- More concentrated DM, total matter relative to N-body simulations
- Caveat: known overcooling

Our mission, should we choose to accept it:

- Measure DM halo profiles using weak lensing, on >~ 50 kpc scales
- Test ΛCDM simulation predictions for radial profile
- Estimate halo concentrations, to check for signs of increase as predicted in hydro simulations
- Do this for a range of halo masses, from galaxies to galaxy clusters!

Modeling LRG density profiles

- Stellar Hernquist profile (mass known),

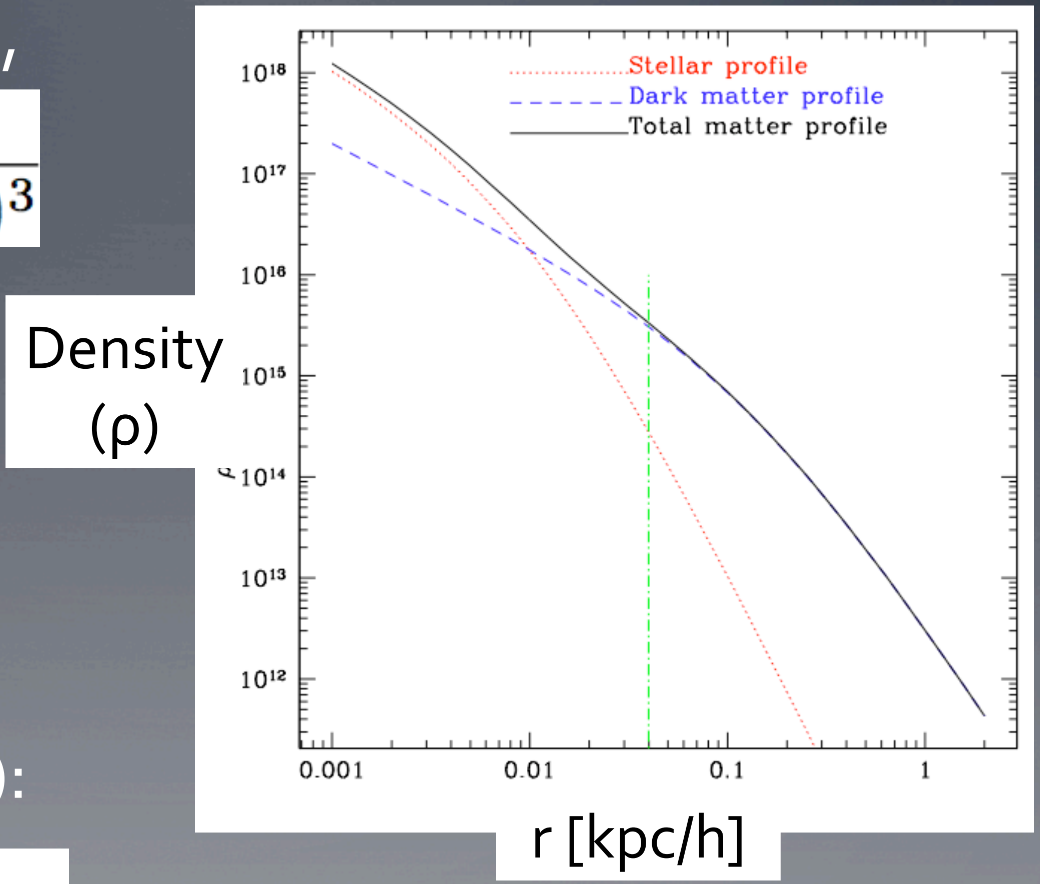
$$\rho(r) \propto \frac{1}{(r/r_s)(1+r/r_s)^3}$$

- Dark matter profile either power law:

$$\rho(r) \propto r^{-\alpha}$$

or NFW (Navarro, Frenk, & White 1996):

$$\rho(r) \propto \frac{1}{(r/r_s)(1+r/r_s)^2}$$

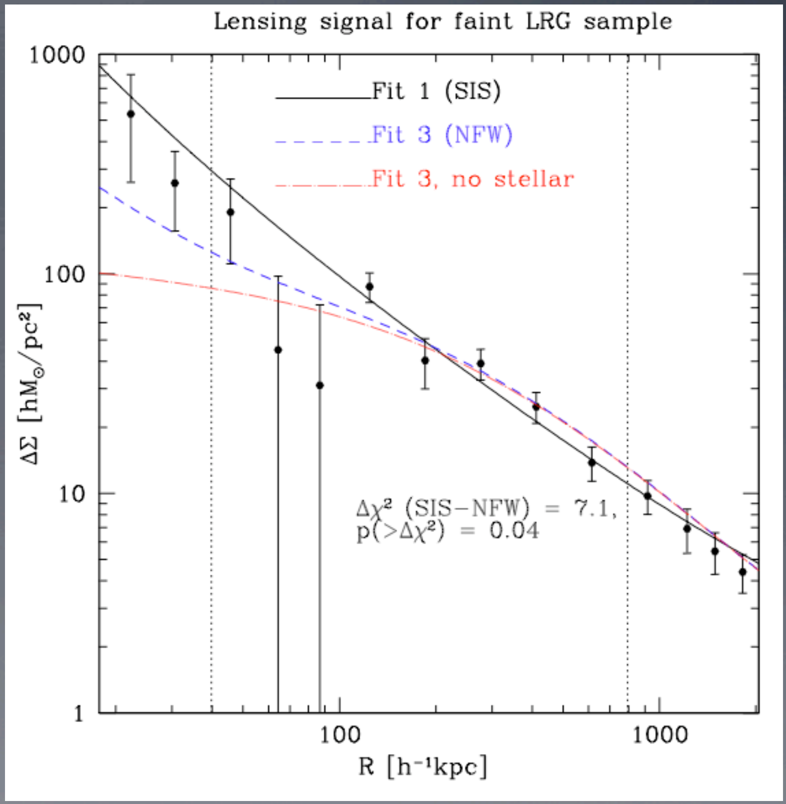


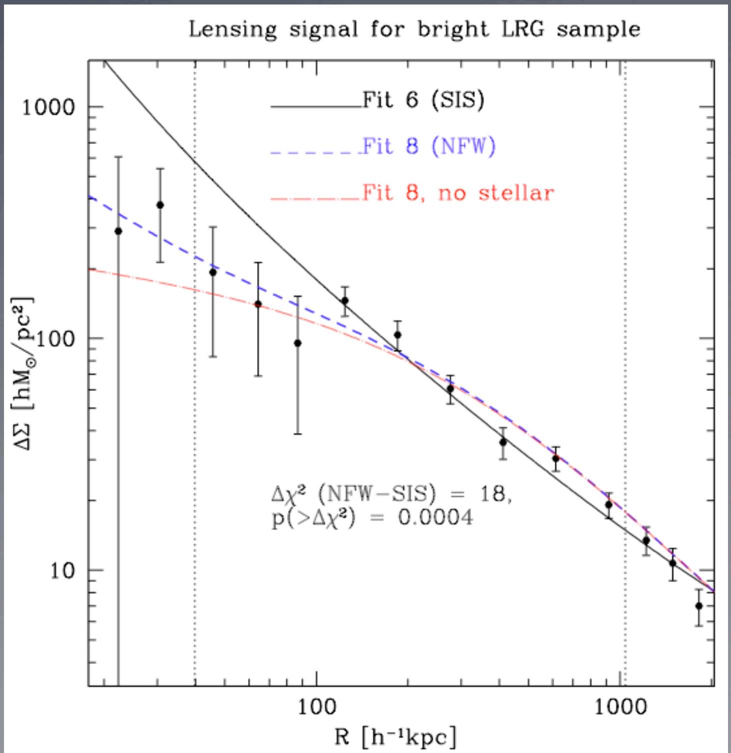
Host LRG halo profiles

RM, U. Seljak, et al. (2006)

SIS dark matter profile strongly excluded relative to NFW

Fainter 2/3





Brighter 1/3 ←

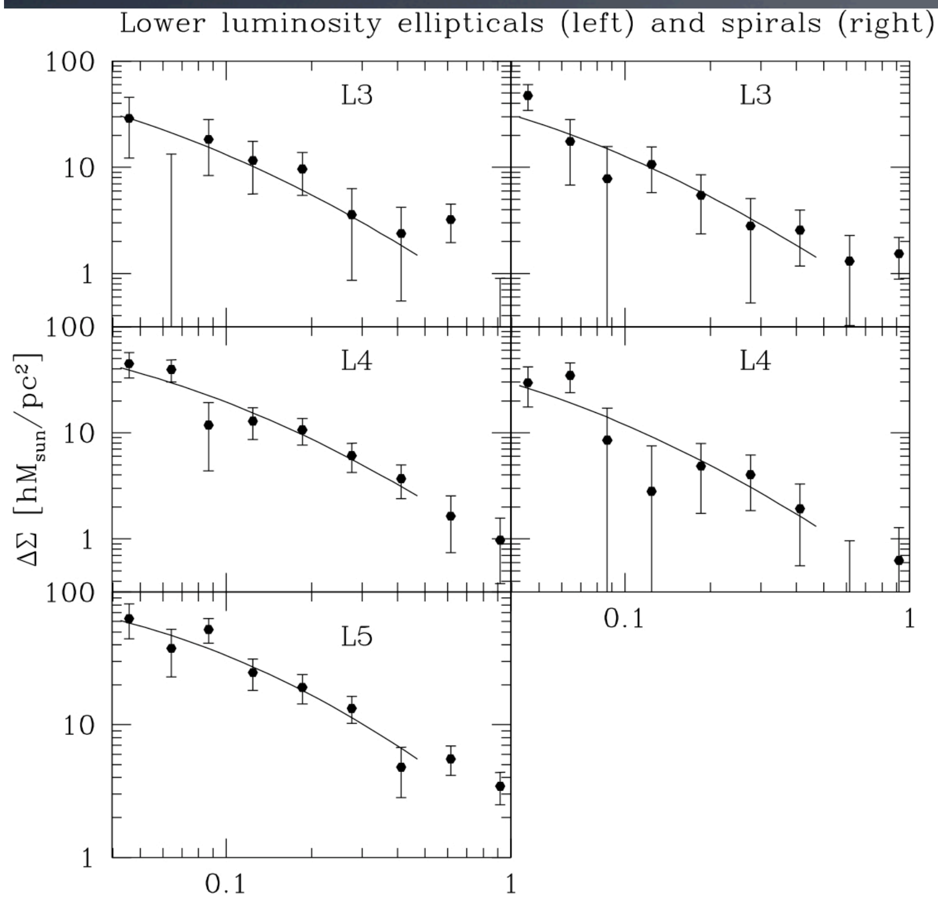
Full DM concentration analysis

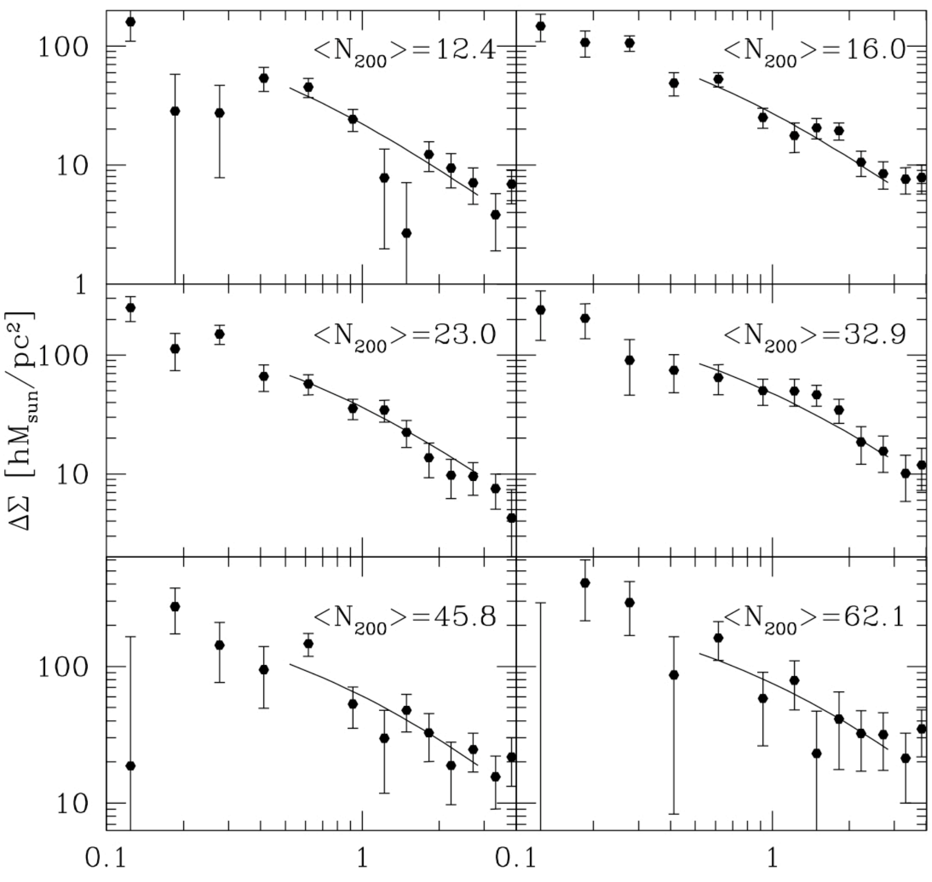
- Measure lensing for samples spanning a factor of 1000 in mass
- Avoid scales with significant baryonic contribution: we want to check if larger scale DM profiles are modified relative to N-body
- Fit simultaneously:
  - Mass in each bin
  - Concentration-mass relation

Observed lensing signals

Galaxies

Clusters





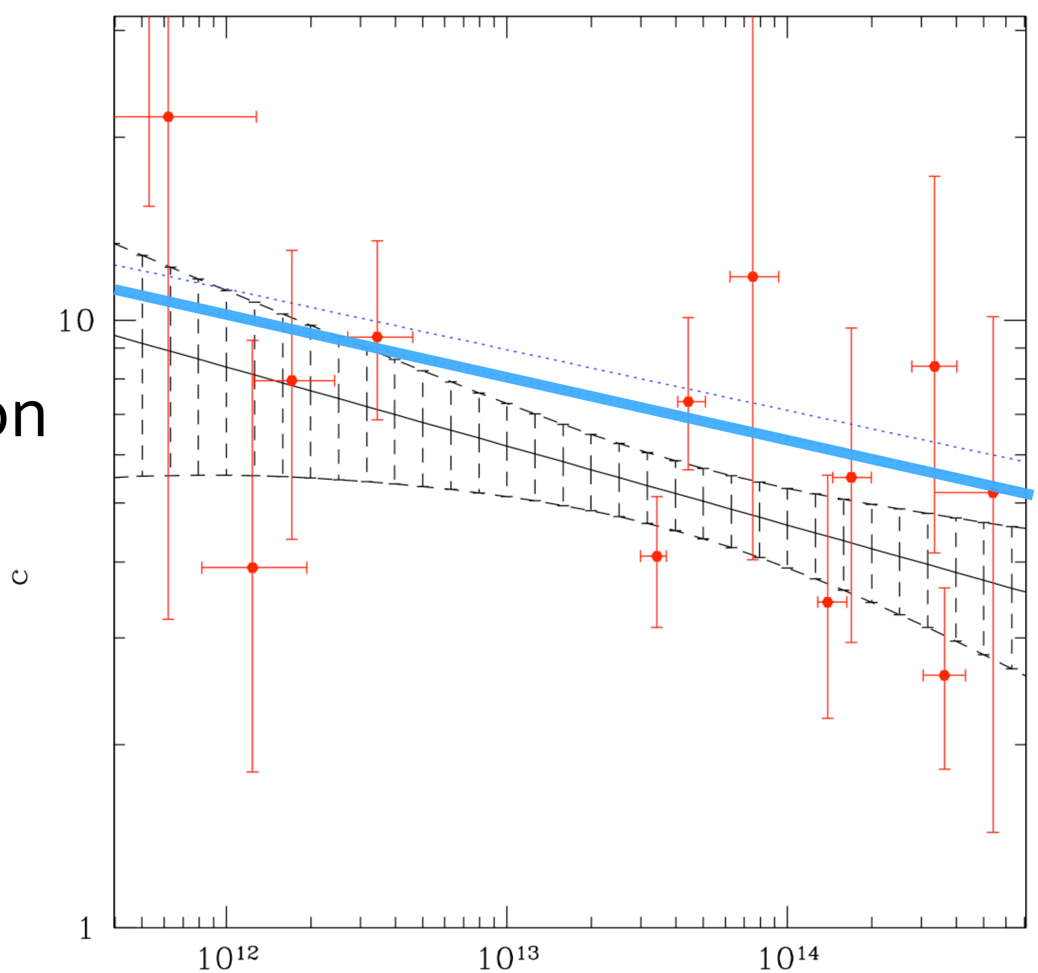
R [Mpc/h]

R [Mpc/h]

Best-fitting c(M) relation

Concentration

(z = 0.22)



Halo mass [M_{sun}/h]

Implications

- Results are consistent with ΛCDM prediction for the radial profiles of dark matter halos, from a few $\times 10^{11}$ to a few $\times 10^{14}$ M_{sun}/h
- Concentrations from WL are on the low side, but still in allowed range
- Significant modifications of halo profiles on scales >~ $r_{vir}/3$ are unlikely

Elliptical galaxy density profiles

Question: how do density profiles of ellipticals from lensing (>~40 kpc) match up to small-scale profiles from dynamical information (<3 kpc)?

A. Schulz, RM,
N. Padmanabhan

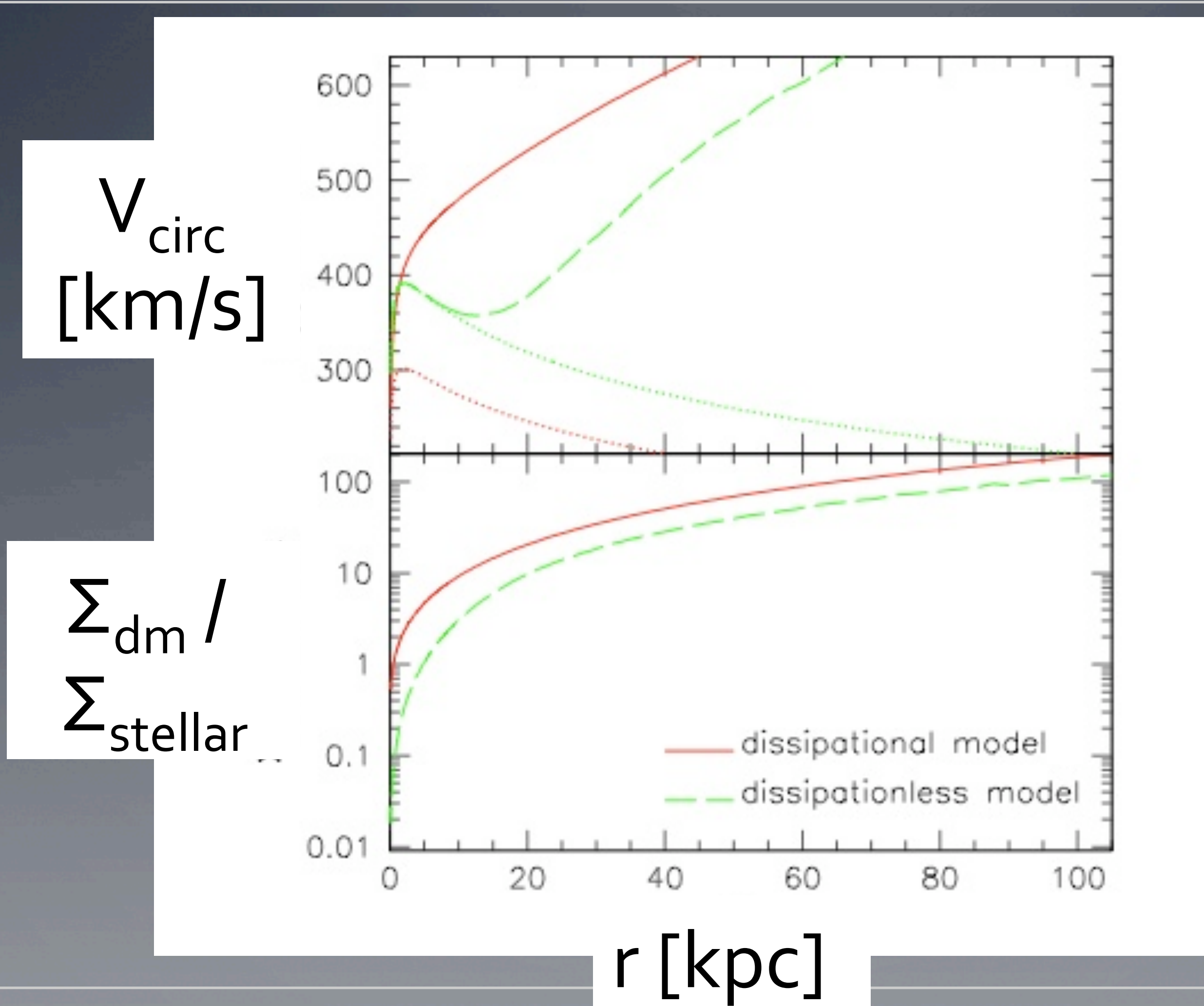
Elliptical galaxy density profiles

Question: how do density profiles of ellipticals from lensing (>~40 kpc) match up to small-scale profiles from dynamical information (<3 kpc)?

Answer relates to how they assembled their stars: e.g. Lackner & Ostriker (2010):

- Dissipational buildup of stars: gas radiates away energy outside of galaxy+halo system→ DM undergoes adiabatic contraction (AC) = **steepening**
- Dissipationless mergers of existing stars: dynamical friction heats central DM = **smoothing**

Profiles for toy models

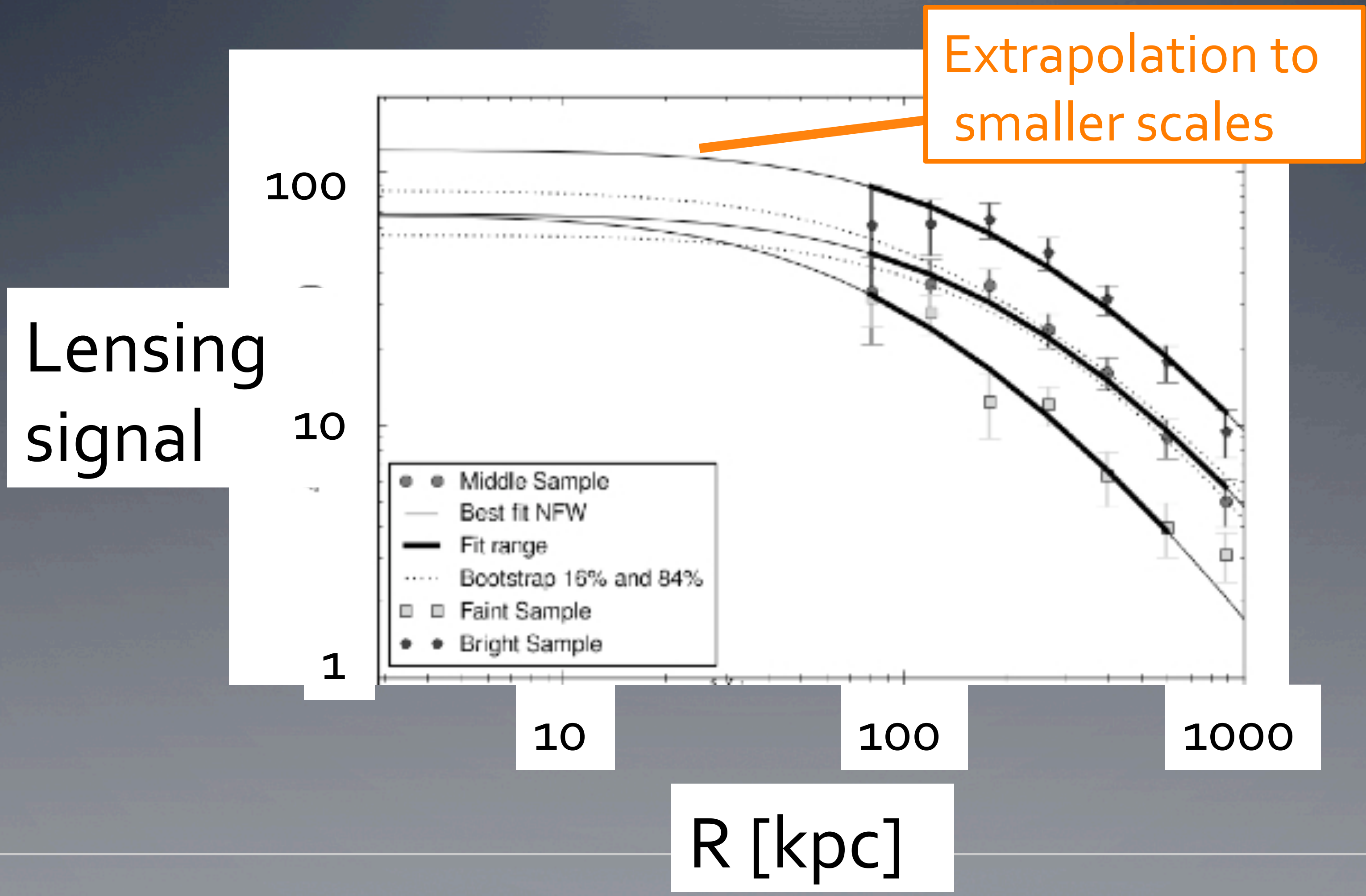


Observational approach

Combine three SDSS observations:

- Stacked weak lensing: surface density on large scales
- Fiber velocity dispersions + Jeans analysis = typical dynamical mass (enclosed 3d mass within some small scale)
- Stellar masses inferred from photometry: 2d, 3d stellar mass profiles

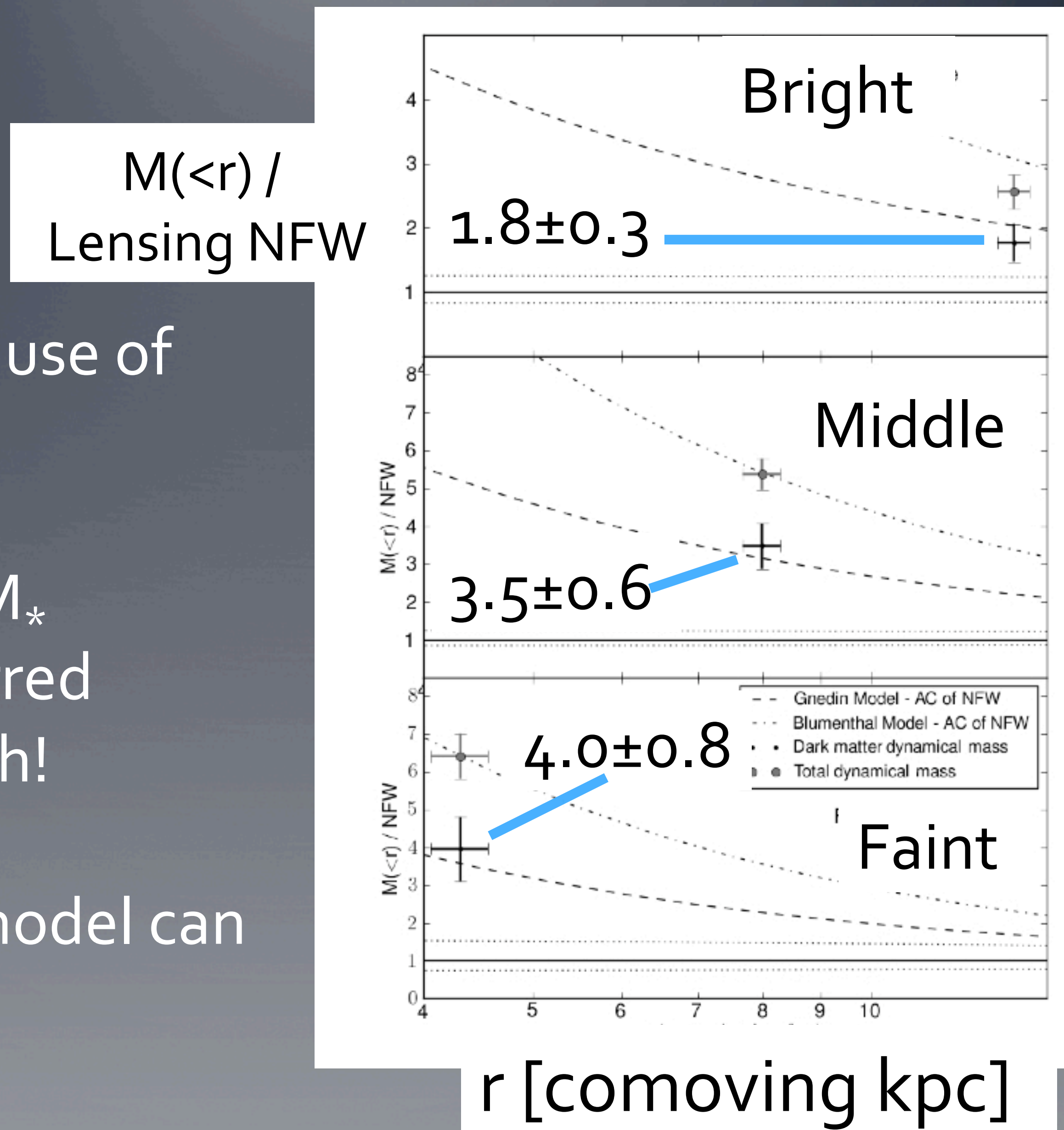
Lensing observations, fits



- Total M_{dyn}>1, because of stars

- After removal of M_* (Kroupa IMF), inferred $M_{dyn,dm}$ still too high!

- Gnedin et al. AC model can explain the excess.



Some intriguing conclusions

We have options:

- Accept Kroupa IMF for ellipticals → **AC required** → dissipational star formation history
- Require pure NFW / reject AC →**need a new IMF**:
  - M_* must increase by factor of 1.9 to 2.3 (for low to high L samples): Salpeter?
  - Also: **IMF is not universal!**
- Life is complicated: some combination of the above?
- Tension is worse if we want a dissipationless star formation history

More galaxy studies

- Disk galaxies and the TF relation: see (upcoming) thesis of Reina Reyes, Princeton.
- Halo concentration versus mass for stacked galaxy samples in HSC

And much, much more…

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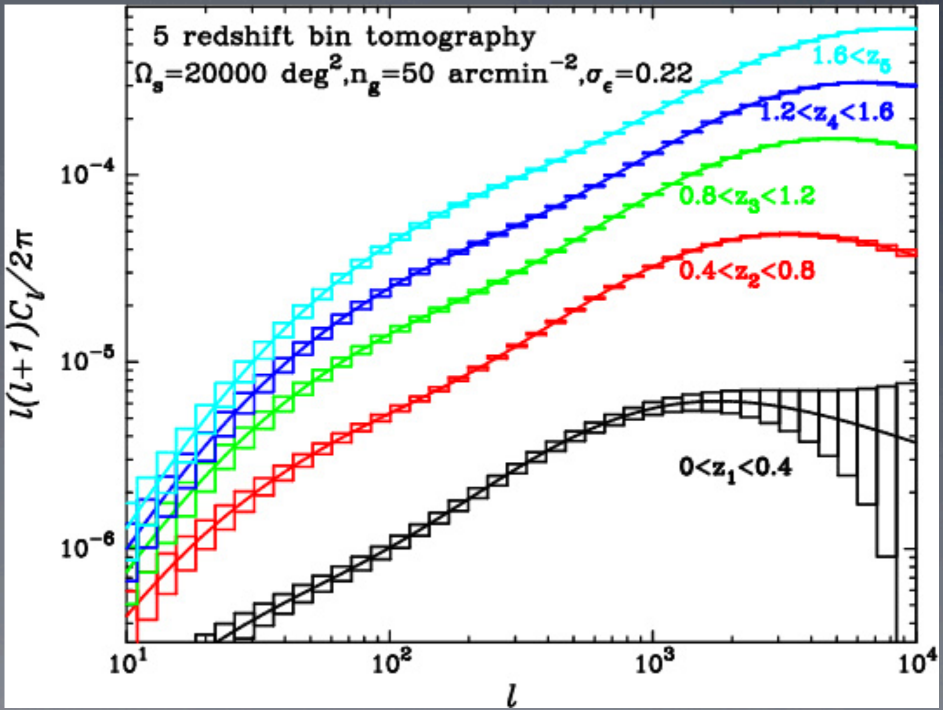
What about the next ~10 years?

Many large surveys with weak lensing as a major science application

From ground, e.g. DES, HSC, LSST, and space, e.g. Euclid and WFIRST

Unprecedented statistical precision (<1%)!



From lsstcorp.org

A common future survey design

Let's do a deep wide-field lensing survey.
This means we will study…

Cosmic shear = $\langle\gamma\gamma\rangle$

→ ξ_{mm} → σ_8, Ω_m, w_{de}

(typically with other probes, such as supernovae or BAO, which constrain geometry)

But…

Constrain astrophysical uncertainties, galaxy-DM connection

Note: survey requirements are not more stringent, but science payoff is much larger!

Cosmic shear = $\langle\gamma\gamma\rangle$

$\rightarrow \xi_{mm} \rightarrow \sigma_8, \Omega_m, w_{de}$

G-g lensing = $\langle g\gamma\rangle$

$\rightarrow \xi_{gm}$

Galaxy clustering = $\langle gg\rangle$

$\rightarrow \xi_{gg}$

Conclusions

- Lensing is the ONLY technique that directly probes the total matter distribution!
- Current g-g lensing measurements already let us test theory predictions for galaxy-DM relationship
- Future datasets: better S/N →more powerful constraints on galaxy-DM connection