Title: Structure Formation in Dark and Luminous Matter

Date: Sep 12, 2007 12:00 PM

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Abstract:

Outline

1: Mapping Structure on Large Scales

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II: Detecting Structure on Small Scales

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[III: Understanding the Dynamics of Non-linear Structure Formation]

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IV: CDM versus Modified Gravity

1: Mapping Structure on Large Scales: The Quest for Precision

Gravitational Lensing

For 2-D distribution of mass, deflection of ray from object at (2-D vector) position η should be at β, instead seen at θ:

$\theta = \alpha(\theta) + \beta$

where deflection angle α is given by:

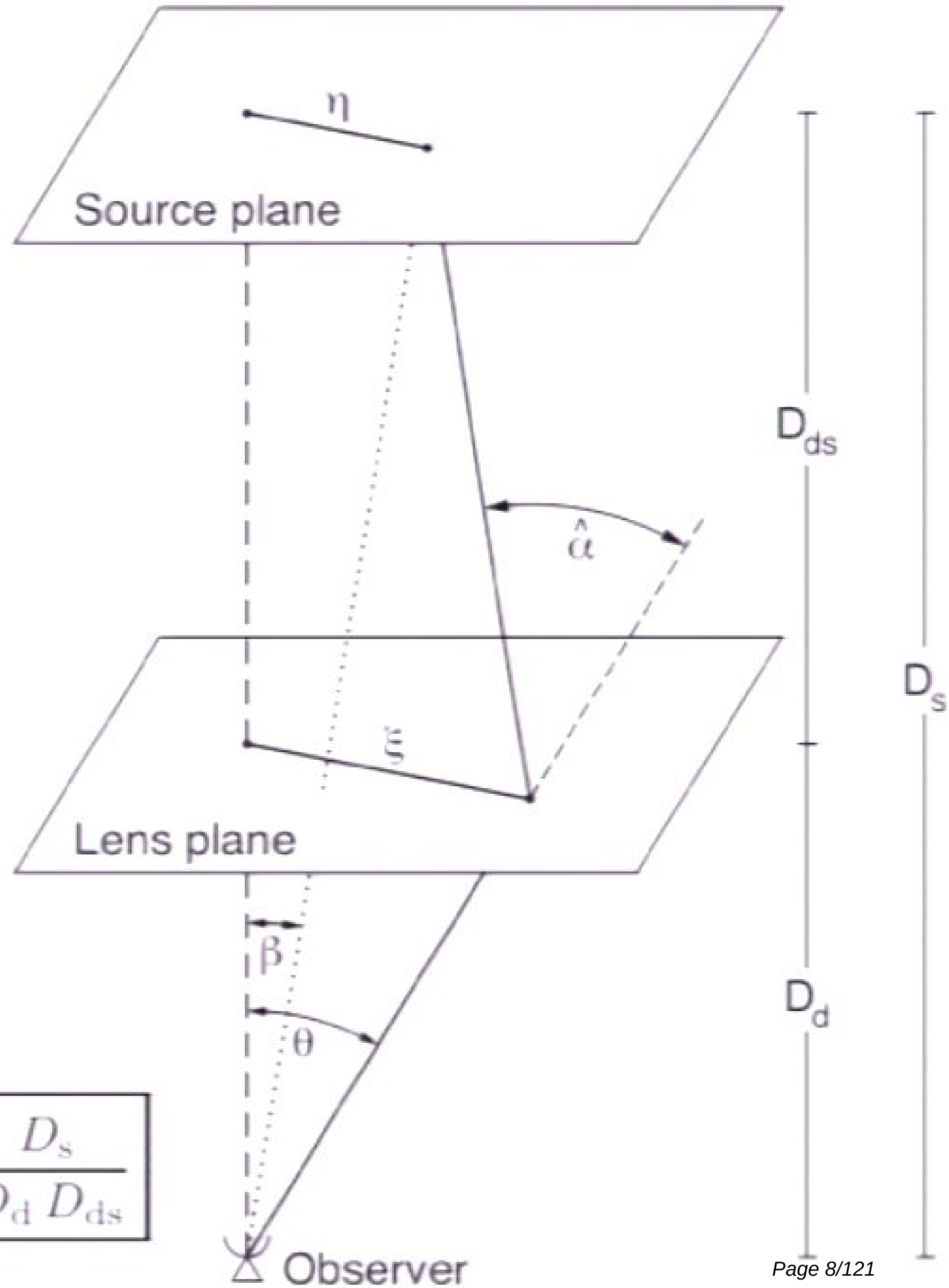
$$\hat{\alpha}(\boldsymbol{\xi}) = \frac{4G}{c^2} \int d^2\xi' \, \Sigma(\boldsymbol{\xi}') \, \frac{\boldsymbol{\xi} - \boldsymbol{\xi}'}{|\boldsymbol{\xi} - \boldsymbol{\xi}'|^2}$$

or:

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{1}{\pi} \int_{\mathbb{R}^2} d^2\theta' \, \kappa(\boldsymbol{\theta}') \, \frac{\boldsymbol{\theta} - \boldsymbol{\theta}'}{|\boldsymbol{\theta} - \boldsymbol{\theta}'|^2}$$

with <u>convergence</u>:

$$\kappa(\boldsymbol{\theta}) := \frac{\Sigma(D_d \boldsymbol{\theta})}{\Sigma_{cr}} \quad \text{with} \quad \Sigma_{cr} = \frac{c^2}{4\pi G} \frac{D_s}{D_d \, D_{ds}}$$



Cosmic Shear, etc.

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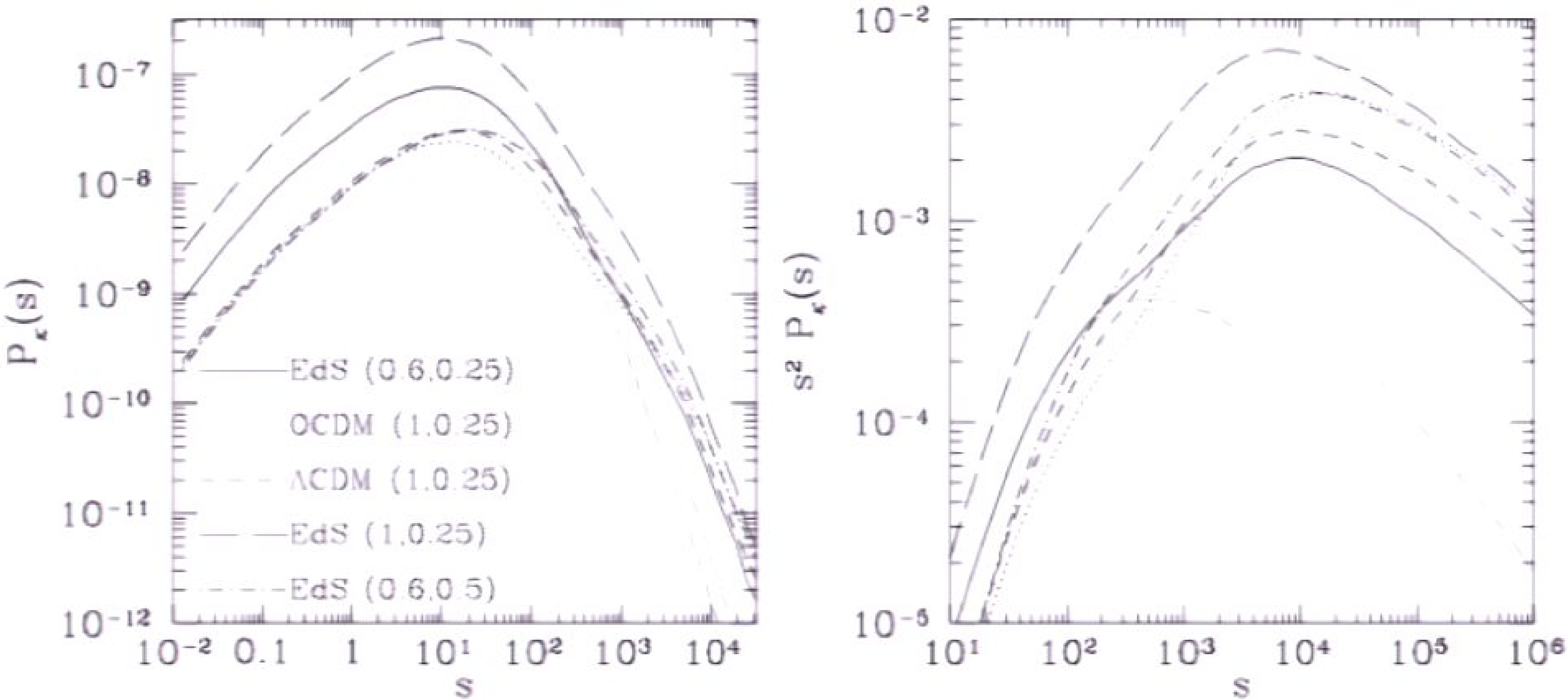
Redshift dependence of effect is very slow, producing a very broad kernel in redshift space:

$$\frac{4\pi G}{c^2}\int \frac{D_L D_{LS}}{D_S}\rho dl$$

Simple-minded Example of an Application:

Projected (Convergence/Surface Density) Power Spectrum

In principle, calculate kappa at each point, take Fourier transform and there you are:

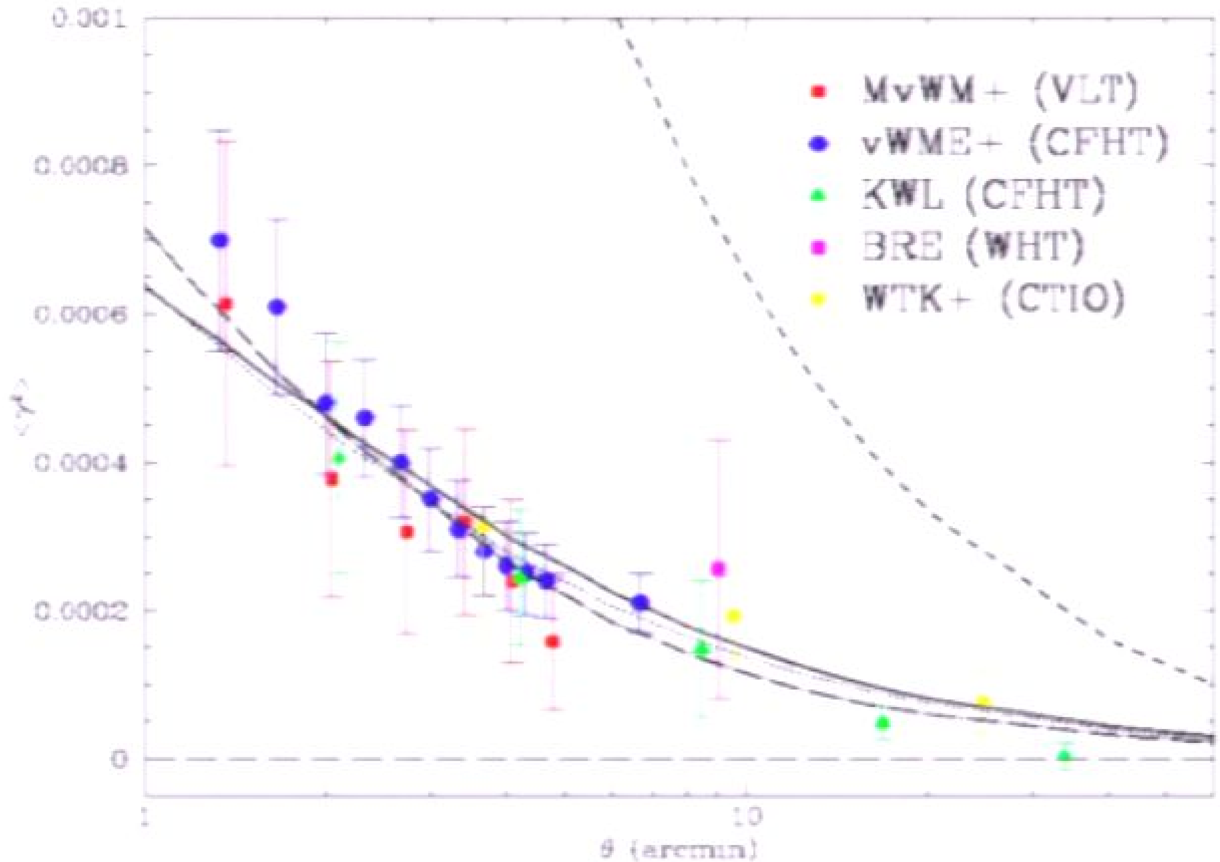


More Sophisticated Examples:

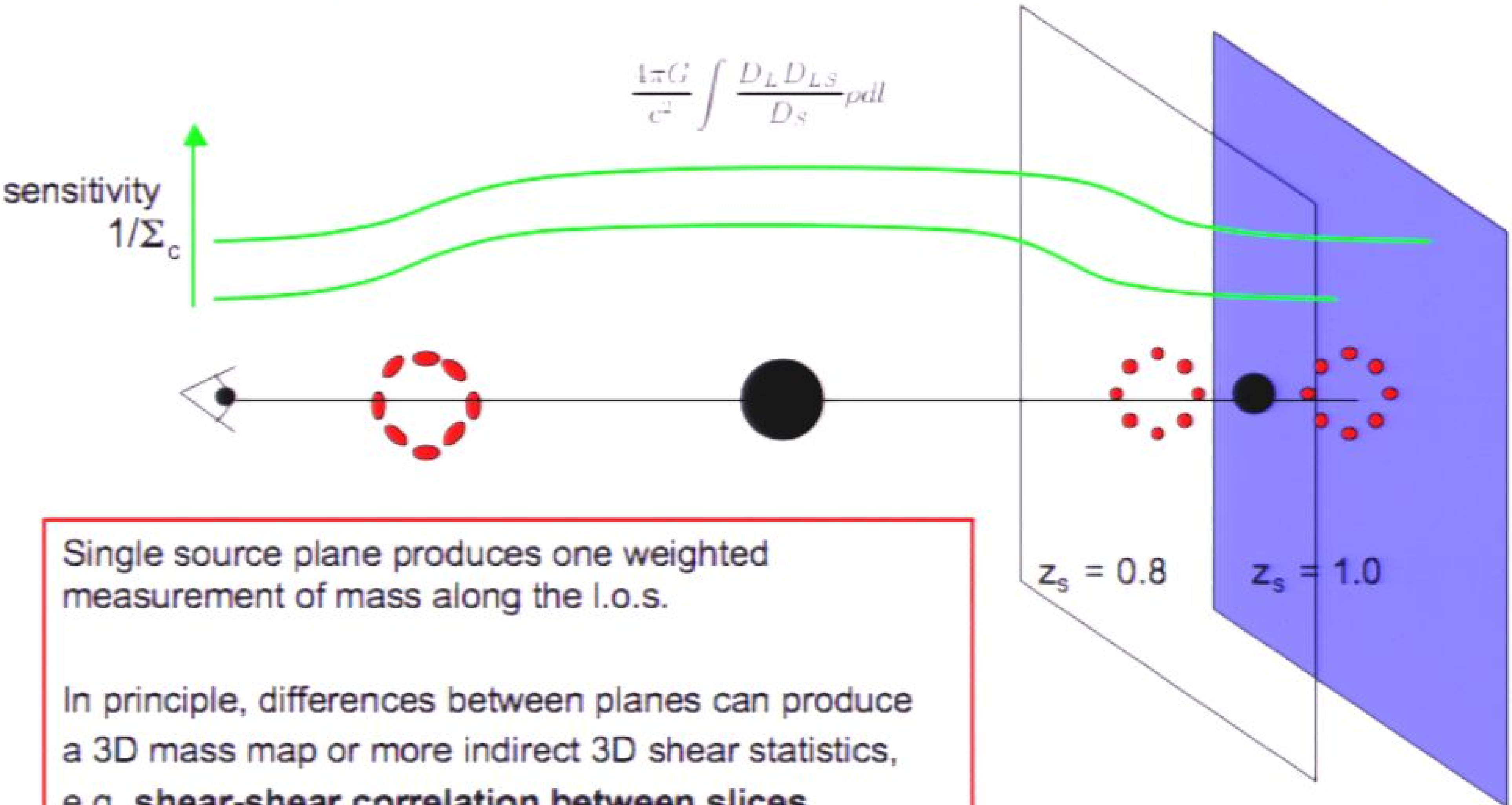
In practice, several other more practical measurements, e.g.

- 2-point shear correlation function
- mean shear dispersion
- aperture mass dispersion

which can be easier to measure and provide better sampling of the power spectrum



Measuring Growth: 3D Lensing Tomography

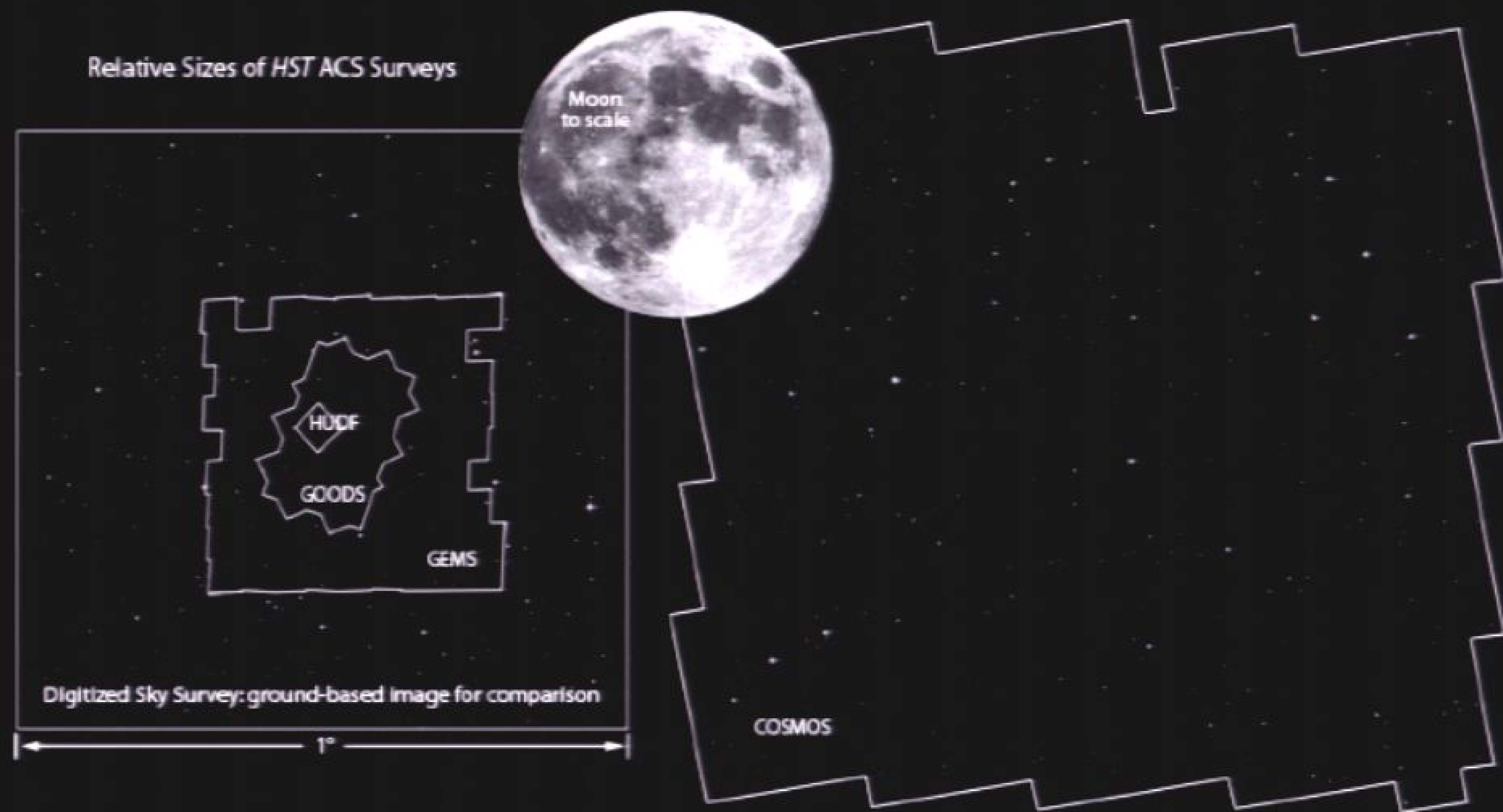


Single source plane produces one weighted measurement of mass along the l.o.s.

In principle, differences between planes can produce a 3D mass map or more indirect 3D shear statistics, e.g. **shear-shear correlation between slices**

Problems include extent of redshift kernel, inaccuracies in photo-zs

The COSMOS Survey P.I. Nick Scoville



The COSMOS Survey

- 2 square degree ACS mosaic
- current lensing results from 1.64 square degrees
- 2-3 million galaxies down to $F814W_{AB} = 26.6$
- 15-band photometry, photo-zs with $dz \sim 0.03(1+z)$ to $z = 1.4$ and $I_{F814W} = 24$
- follow-up in X-ray, radio, IR, UV

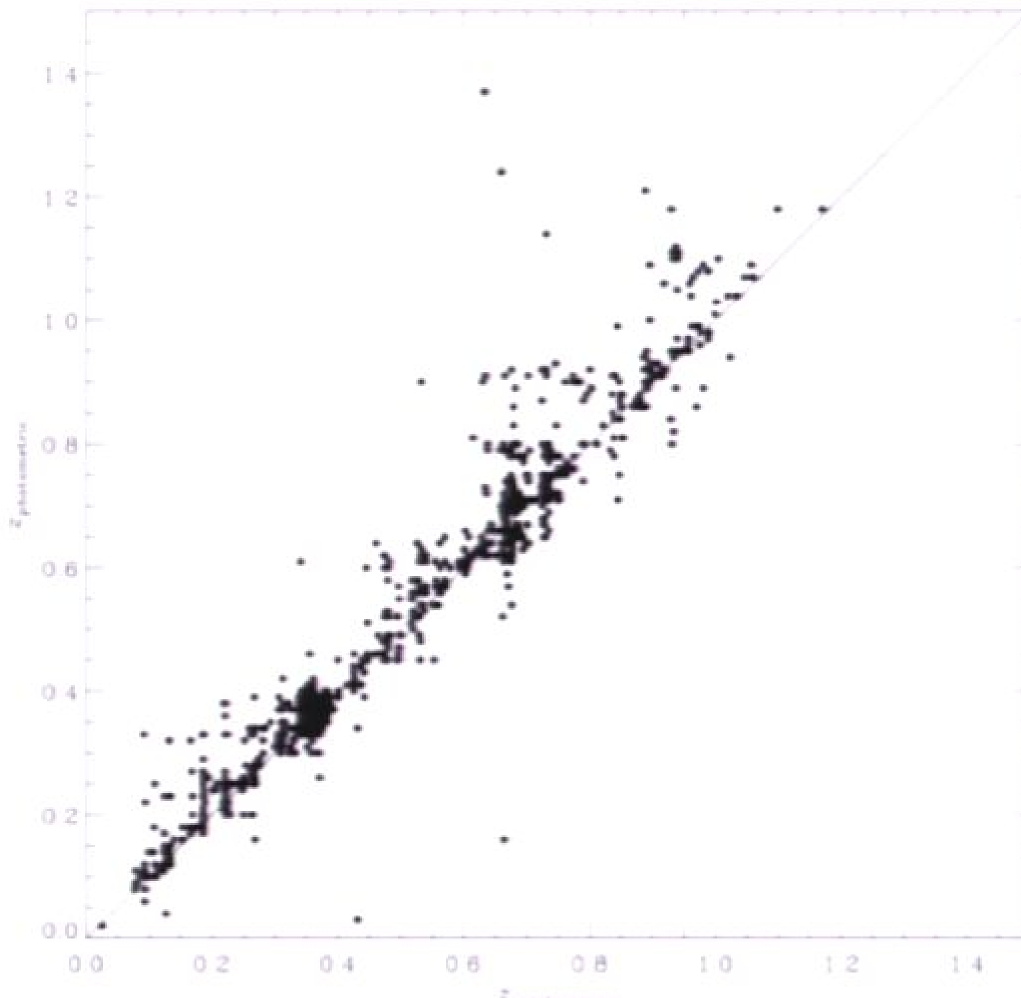
Getting the 3rd dimension

Spectra ~1000x more expensive than images

Get approximate spectrum with
multi-band photometry
(COSMOS now up to 18 bands)

Can get redshift errors down to
dz/(1+z) ~ 0.02

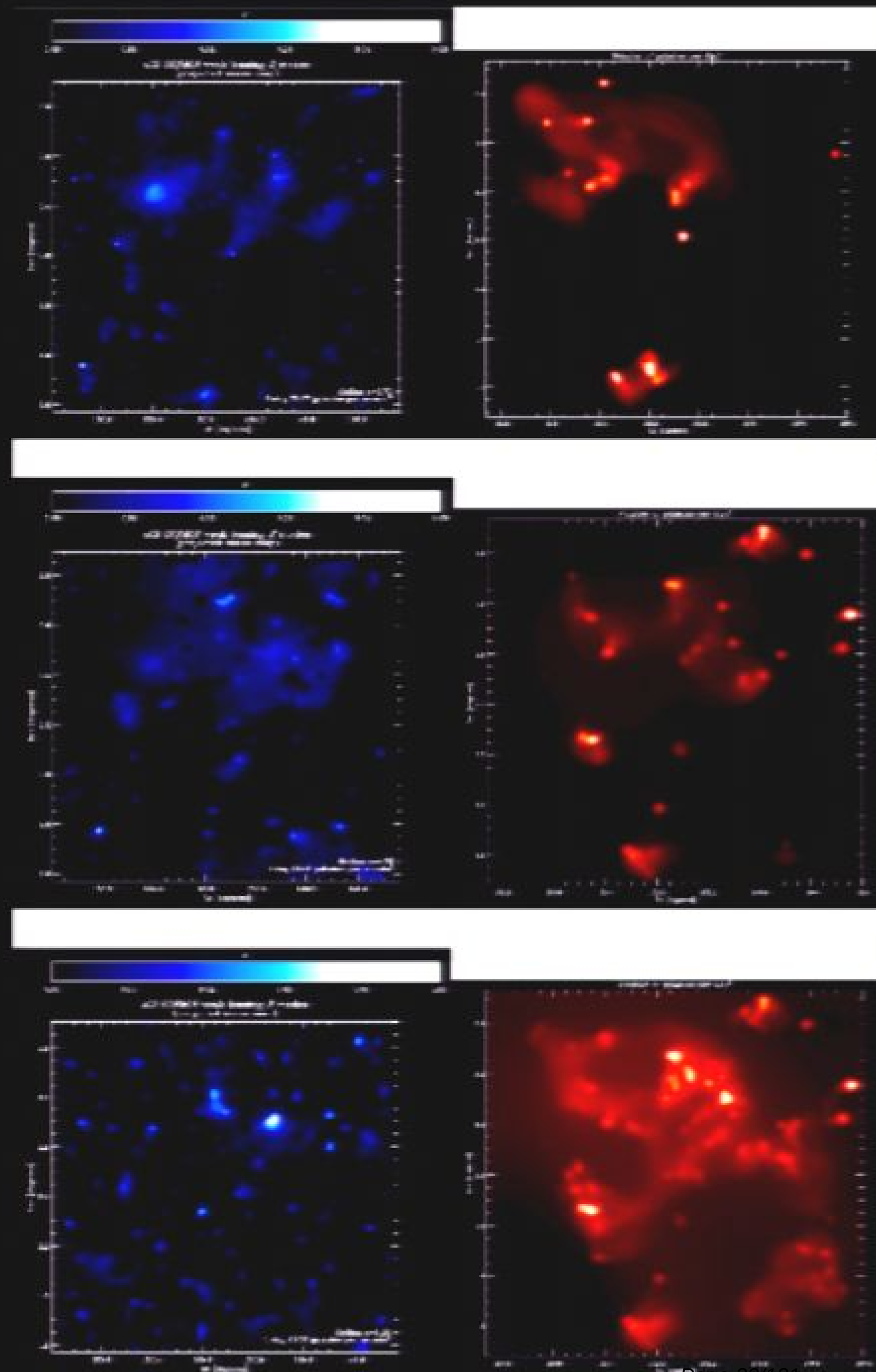
Lasting concern:
catastrophic errors



WL Convergence Maps

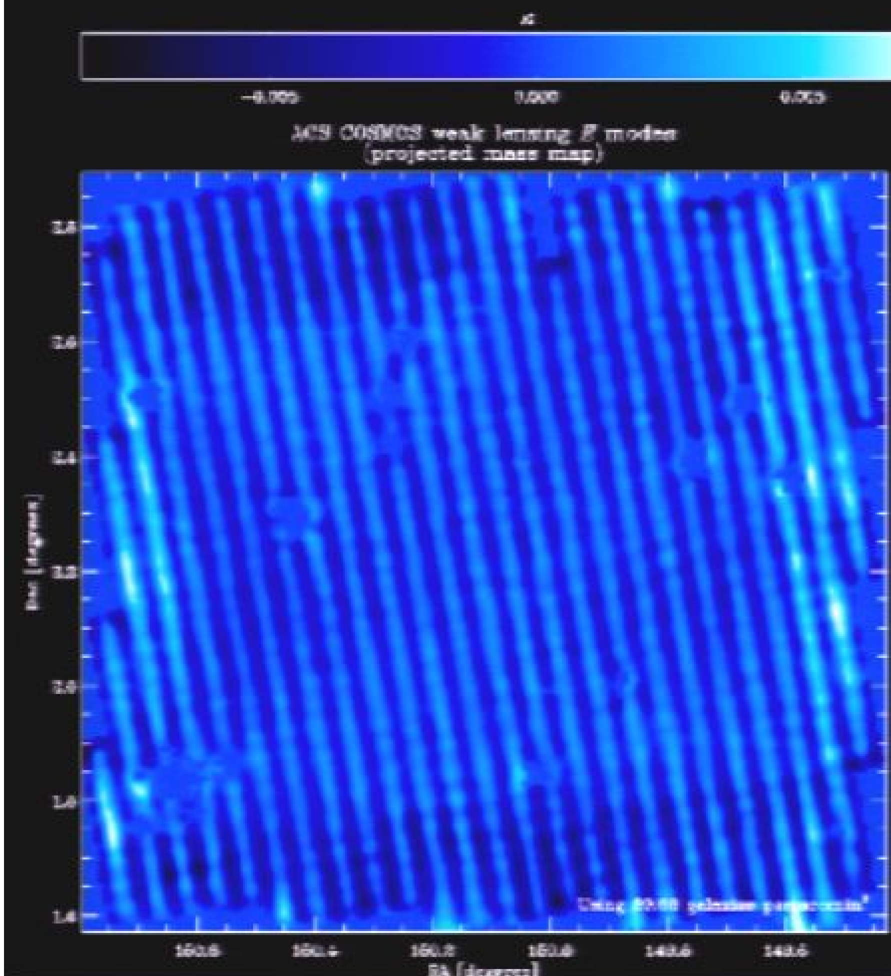
Massey, Rhodes, Leauthaud
Capak, Koekemoer, Scoville, Refregier

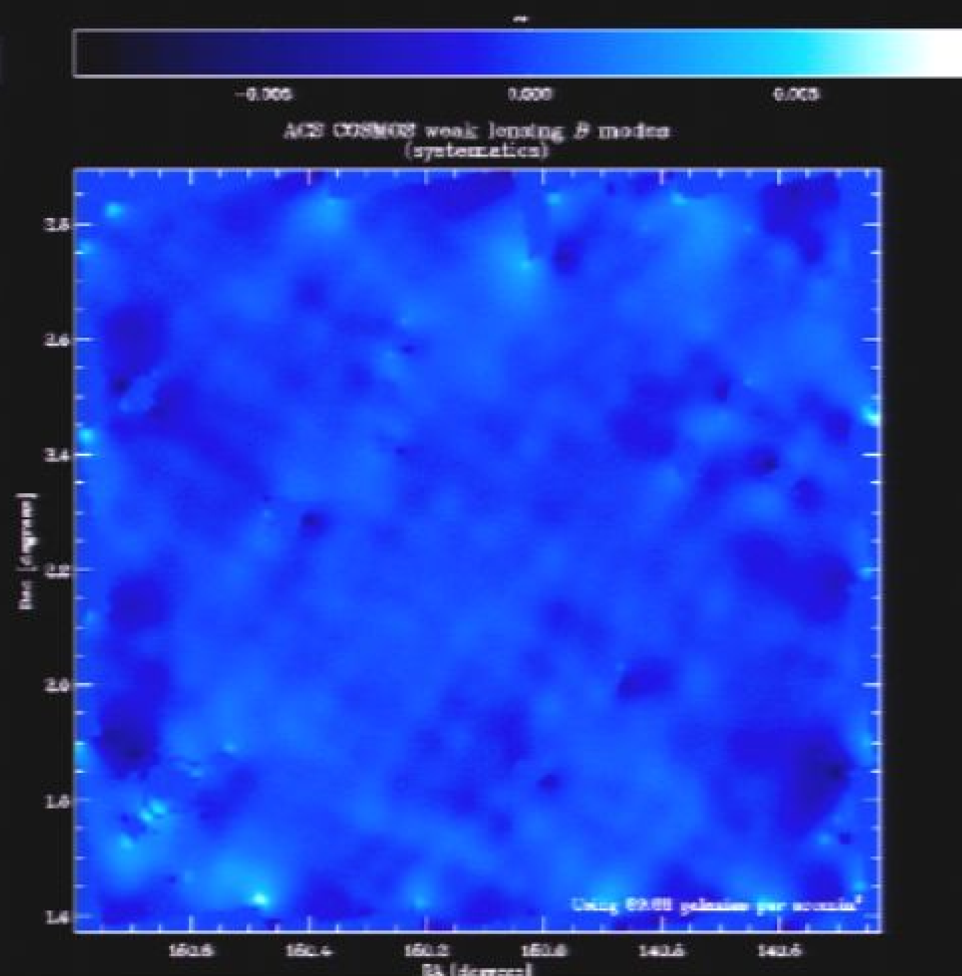
- cut catalogue down to 40 galaxies/arcmin^2 to remove bad zs
- correct for PSF variations, CTE
- Get lensing maps, low-resolution 3D maps, various measures of power in 2D and restricted 3D
- results compare well with baryonic distributions (e.g. galaxy distribution)



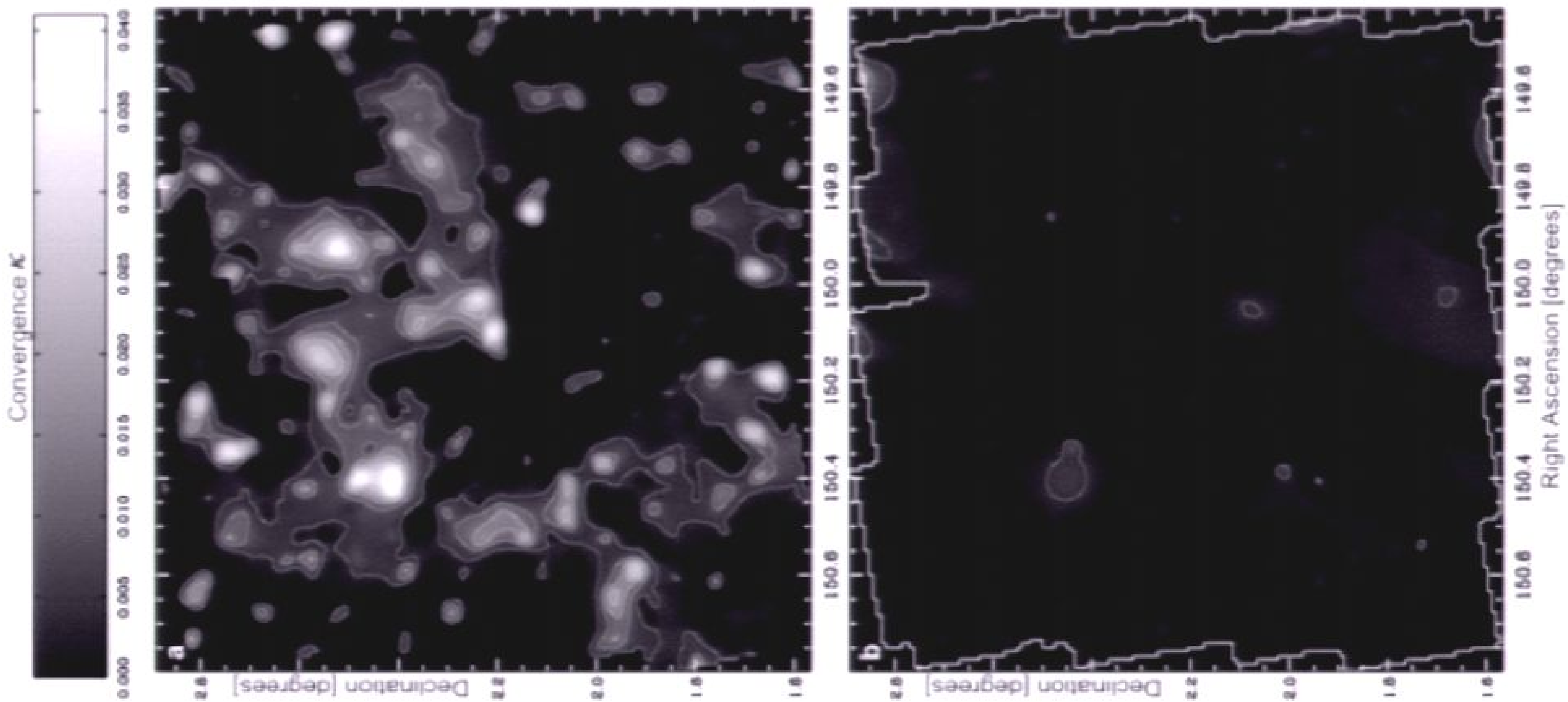
Systematics

instrumental systematics a major and unanticipated headache
(PSF variations, CTE)



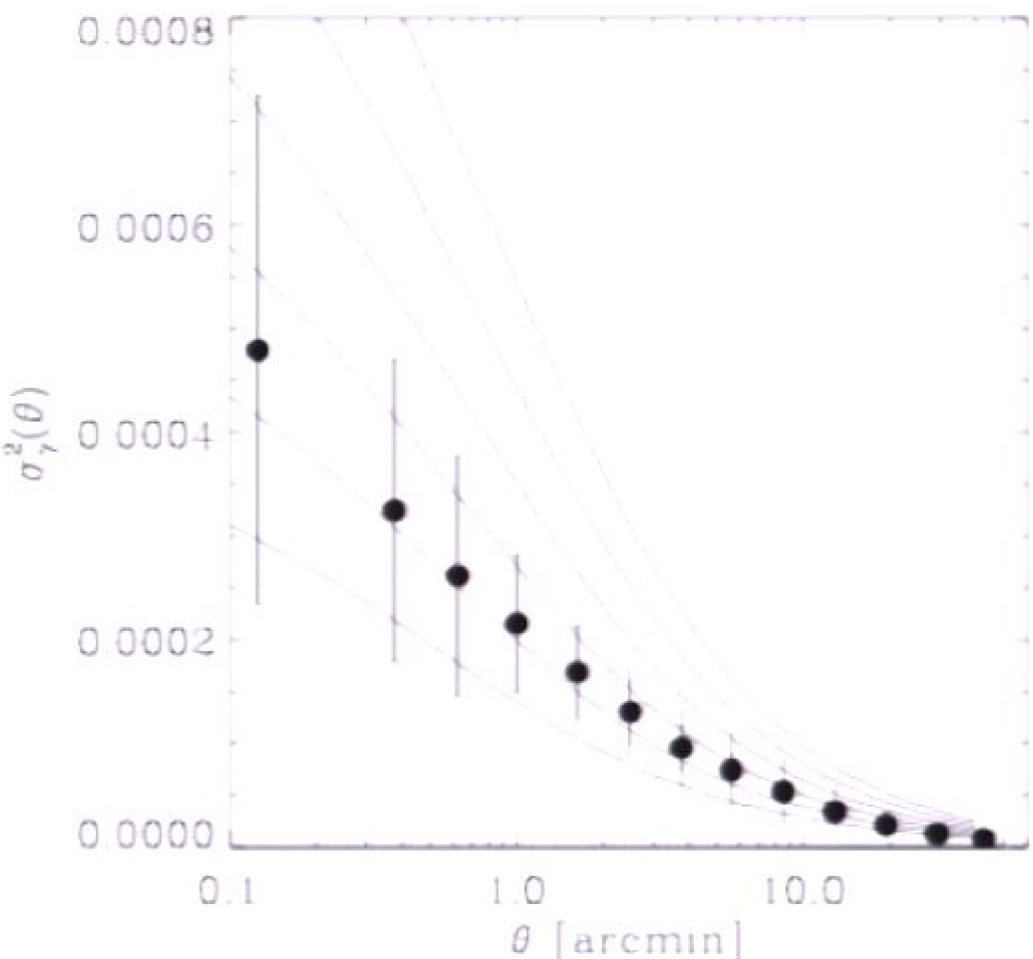


The Final Result



E-modes (left) versus B-modes (right)

The Final Result: Nice 2D signal

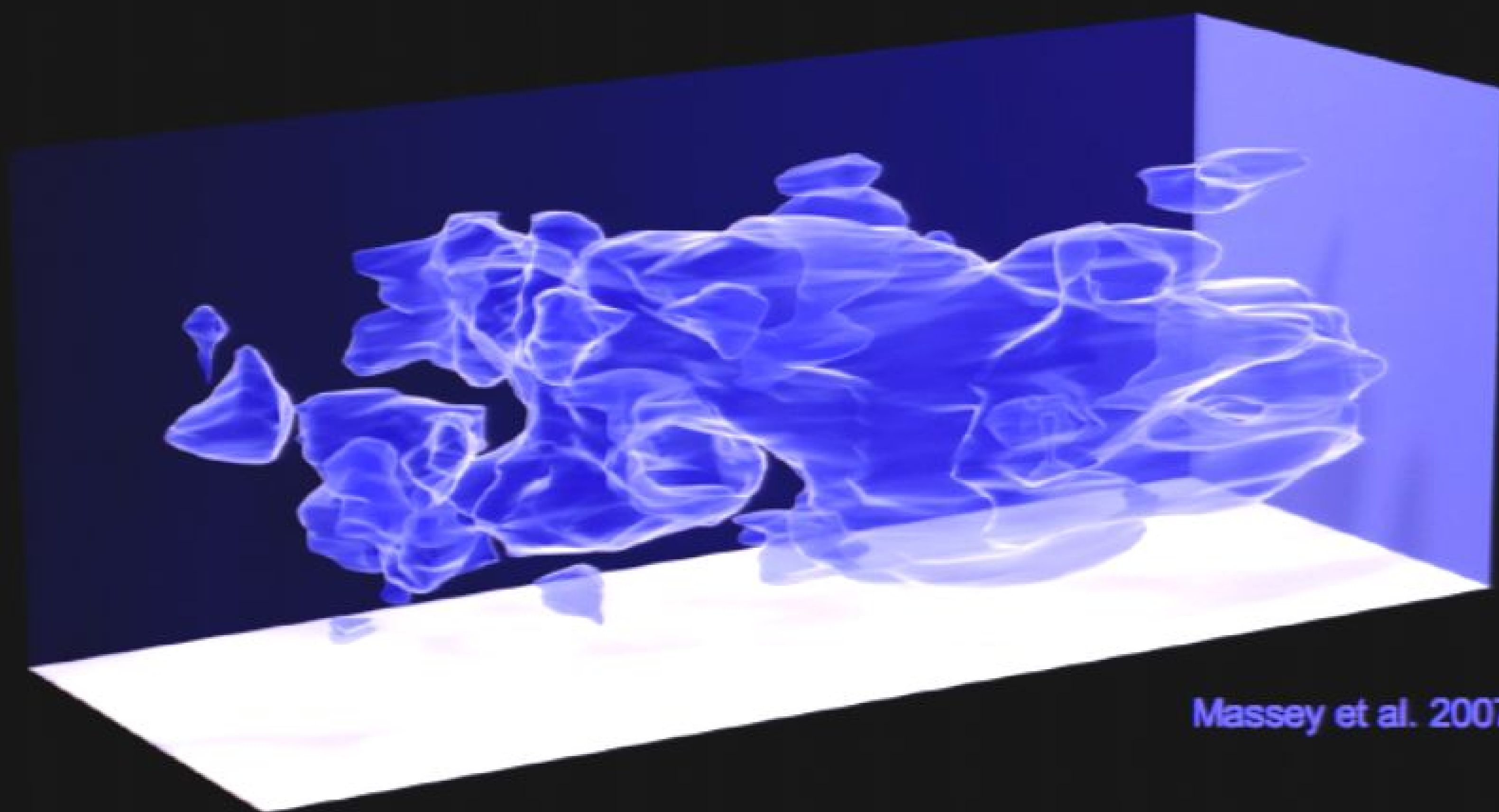


Shear variance in cells as a function of angular size.

Curves indicate prediction for σ_8 = 0.7,0.8,0.9,1.0,1.1,1.2

3D Mass Distribution

Final result: first 3D map of the <u>mass</u> (or potential) distribution in a large volume. Note this is only 1.6 square degrees on the sky.



Massey et al. 2007a

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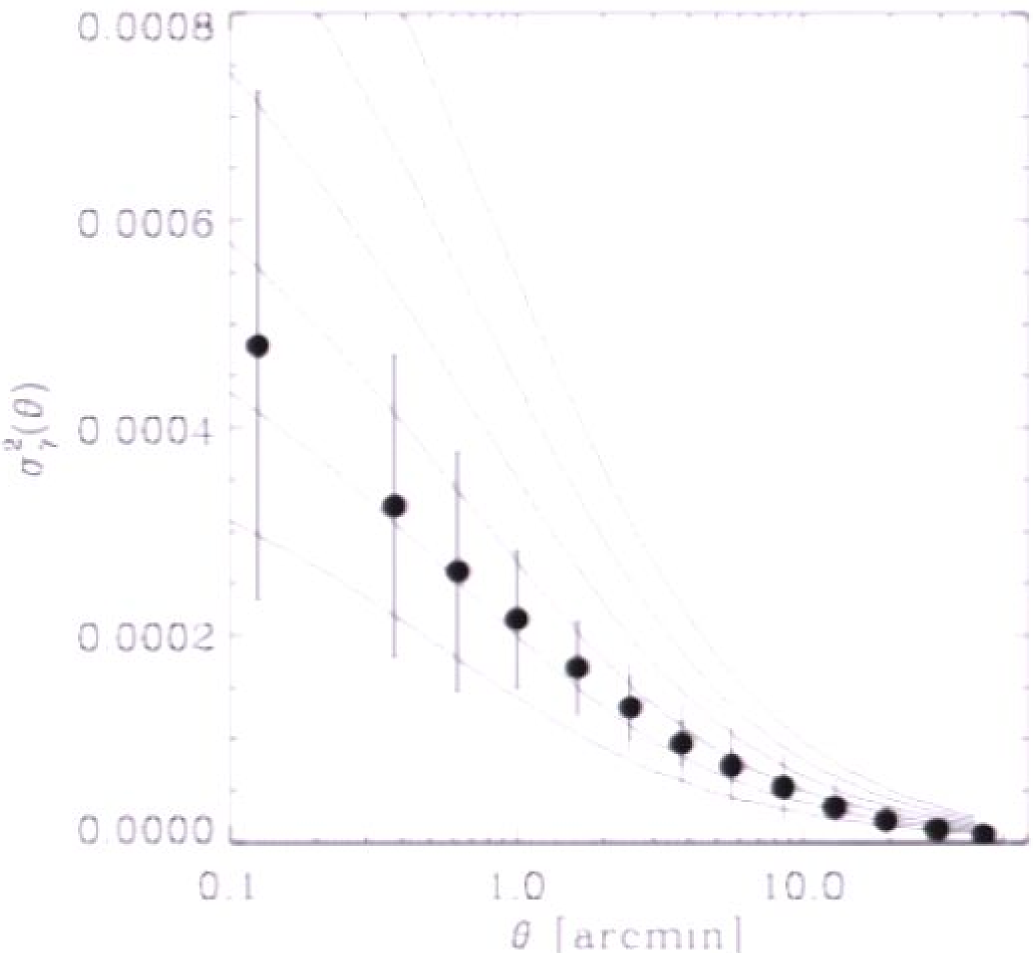

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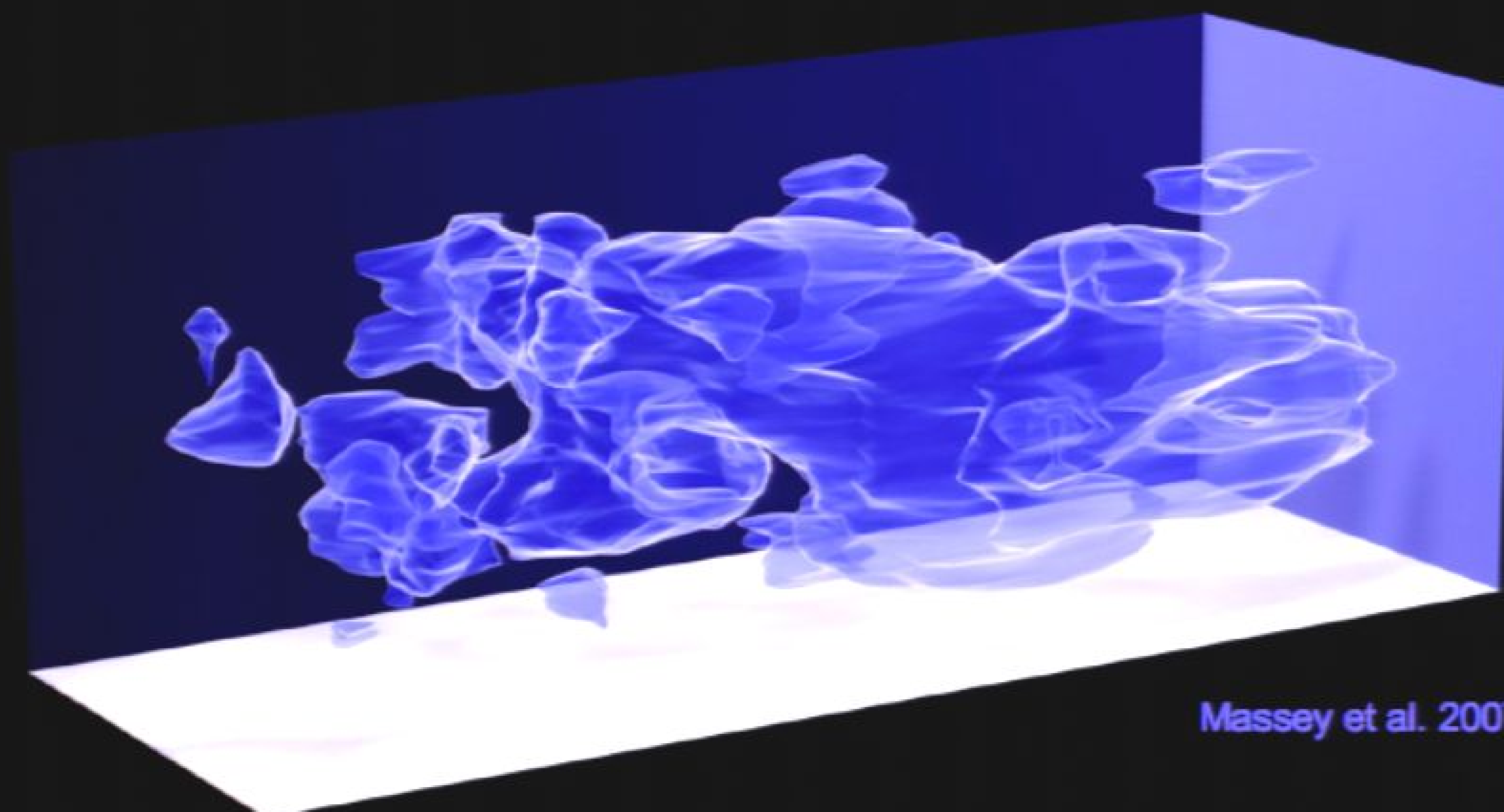
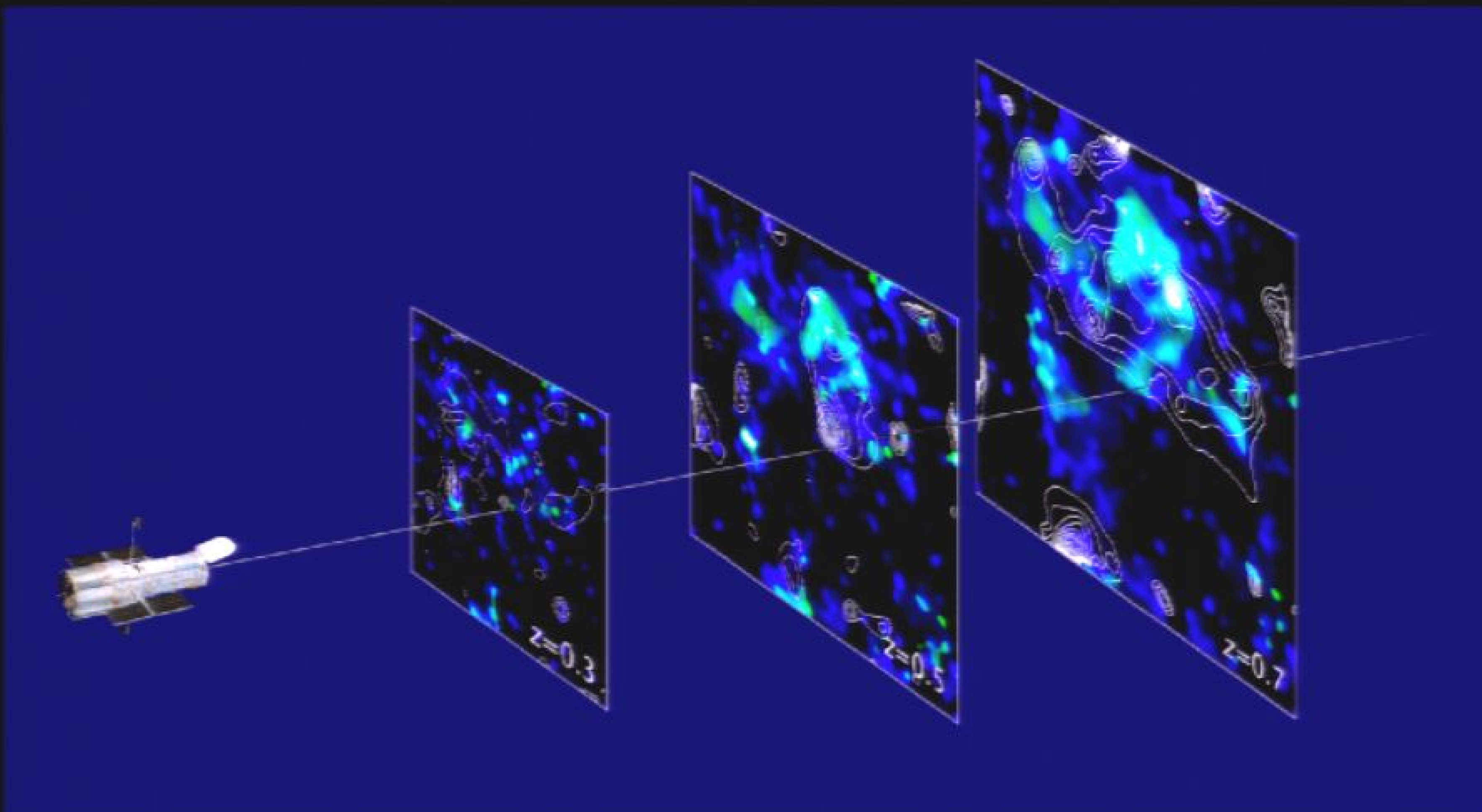


Massey et al. 2007a

Seeing the Growth of Structure Directly

actually quite complicated to show the
growth of structure going forward in time



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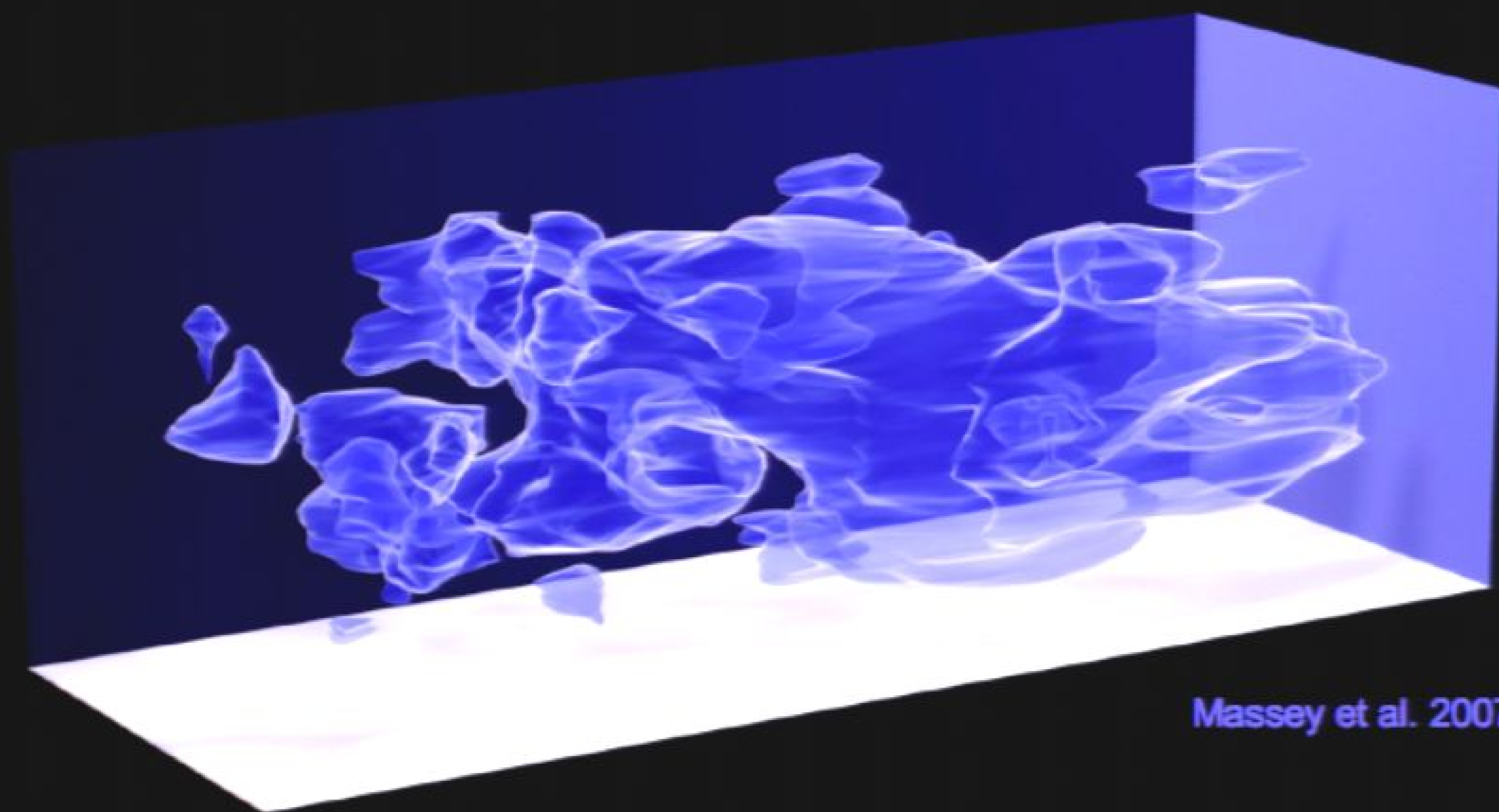

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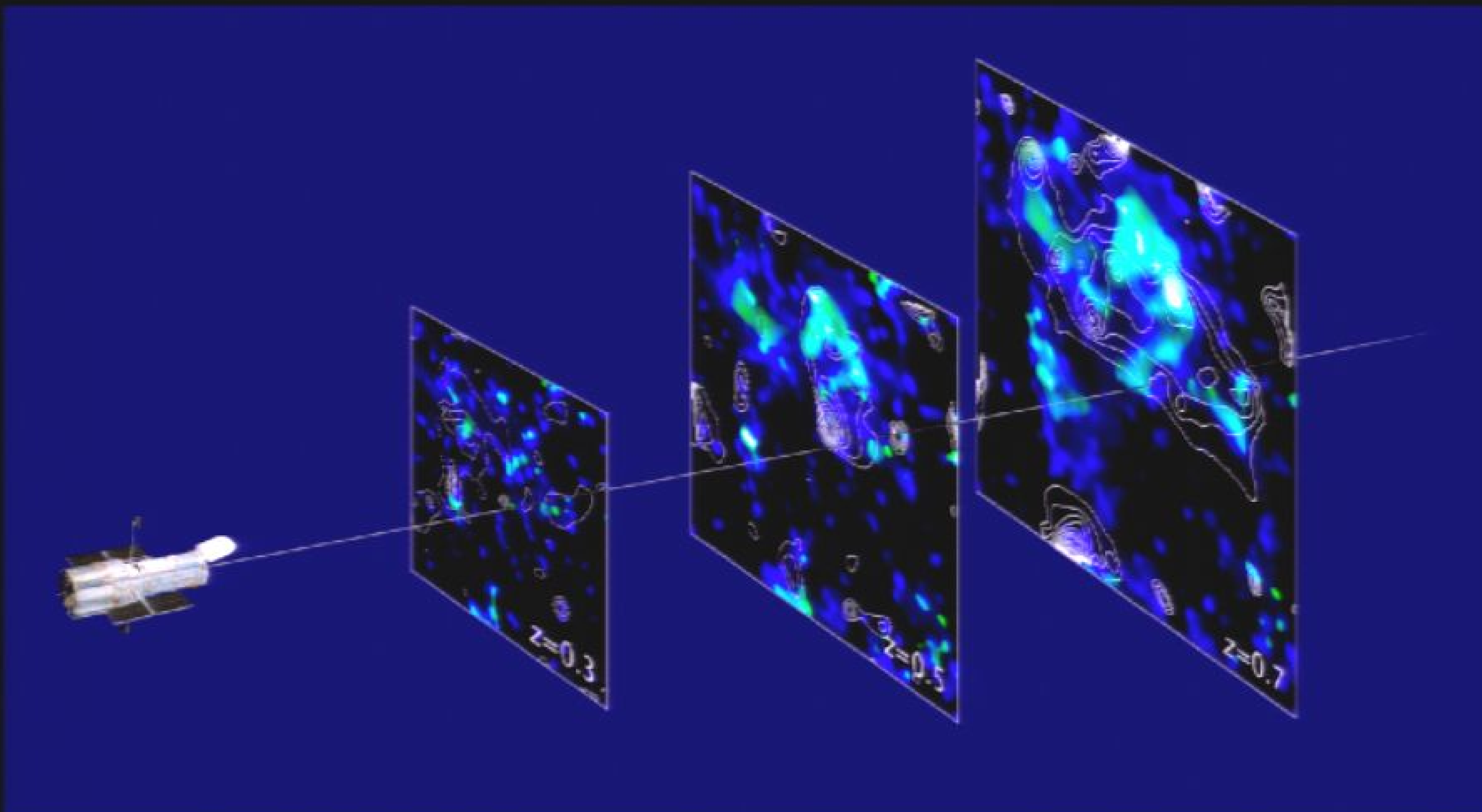

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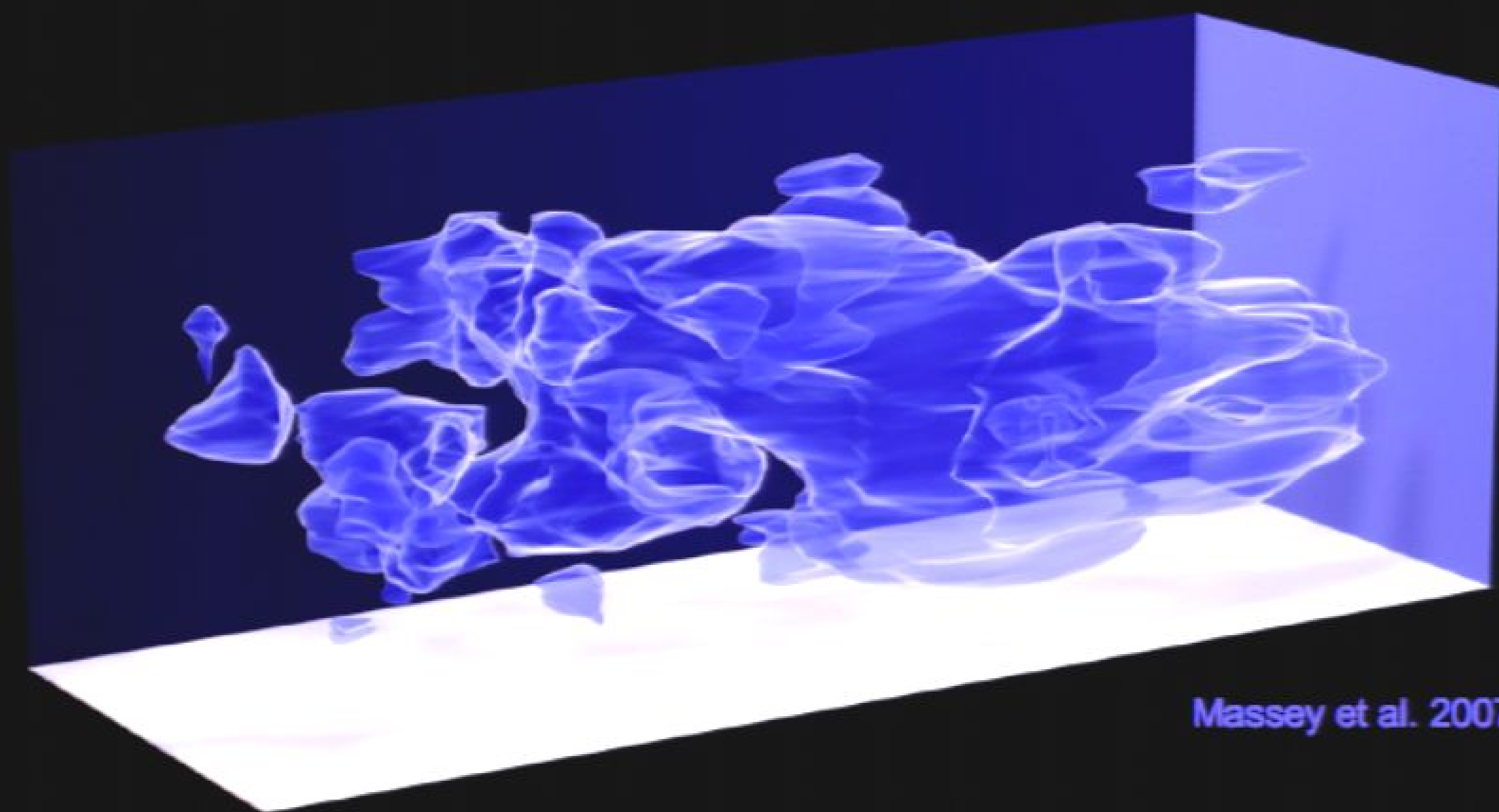

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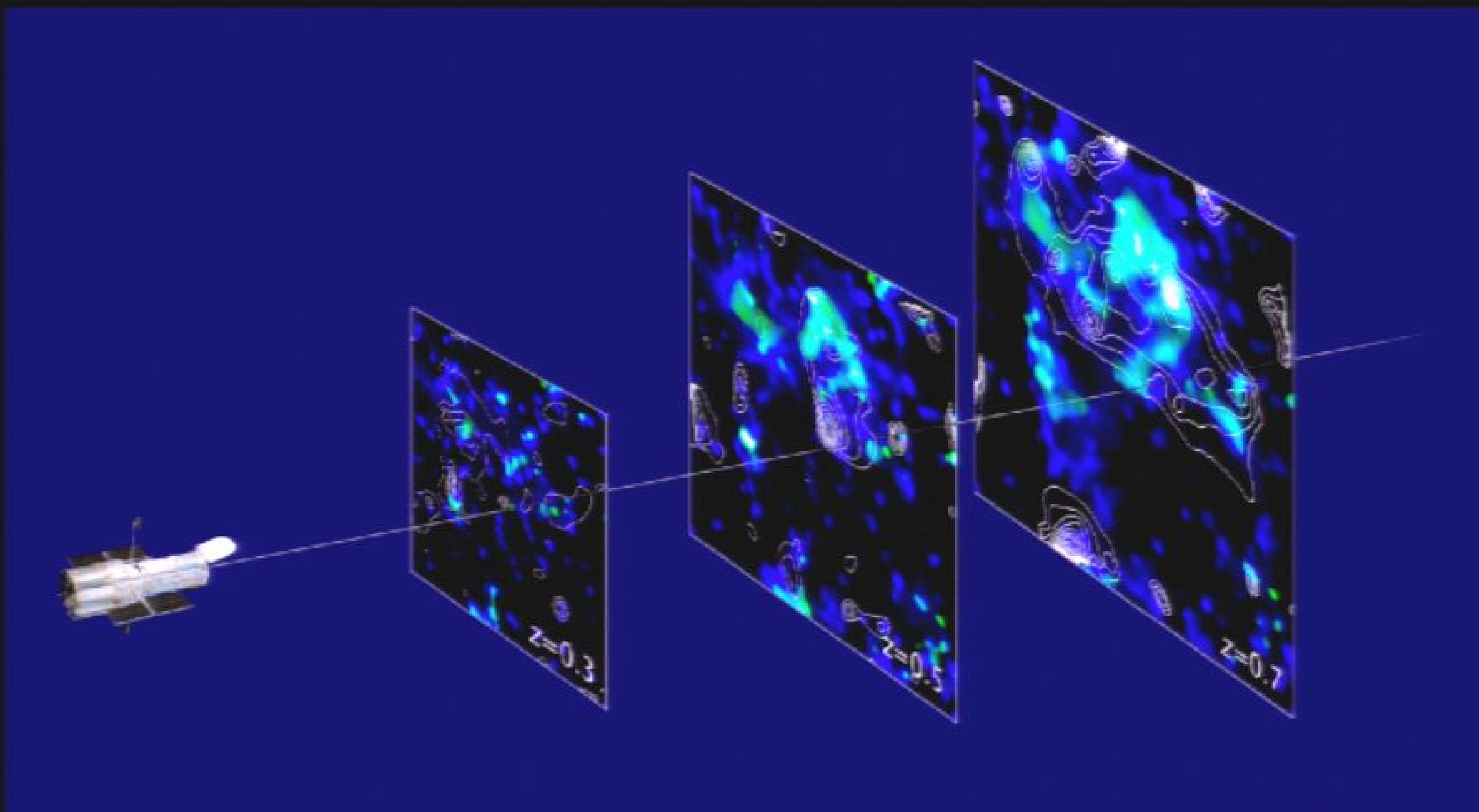

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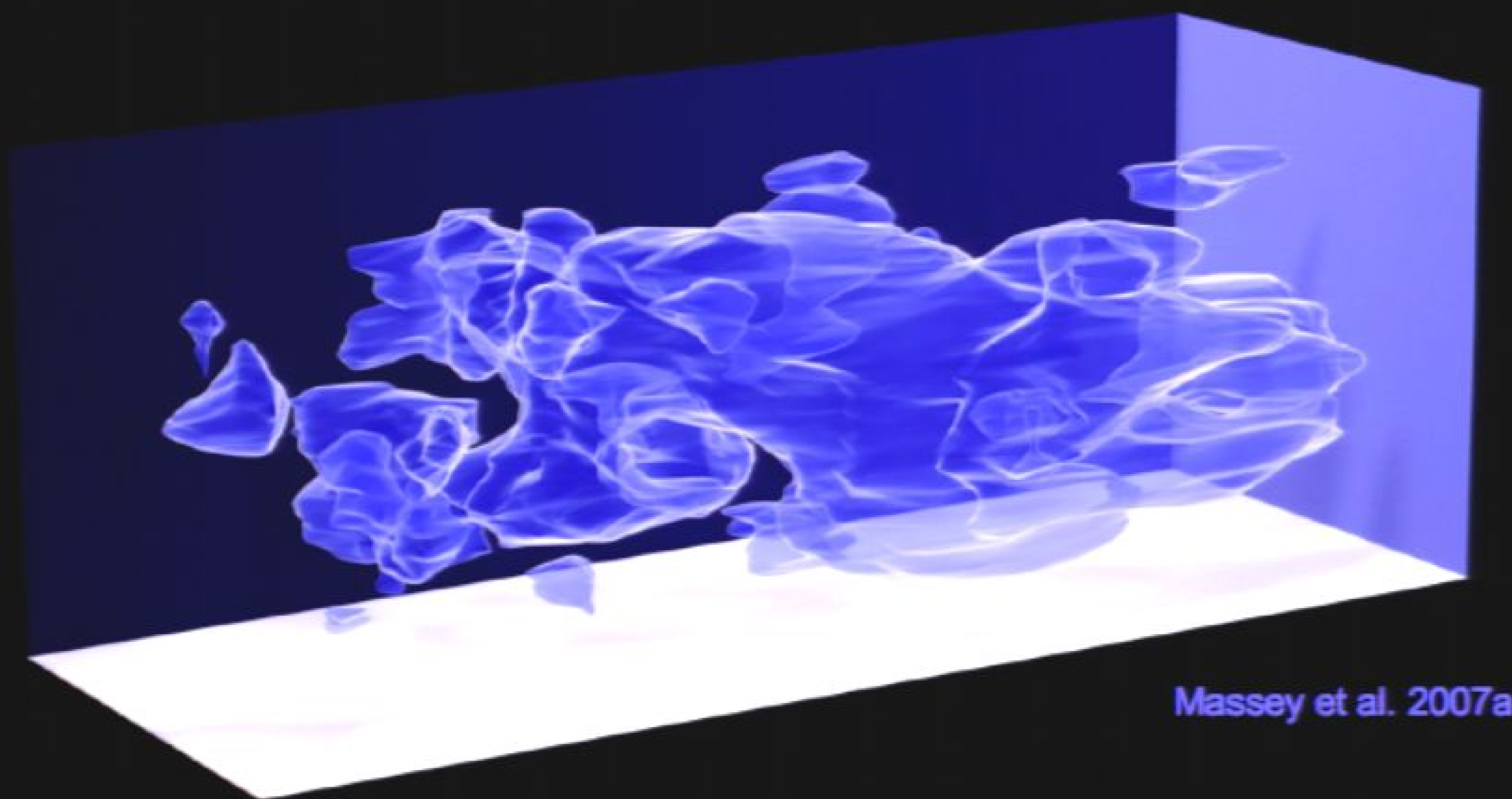

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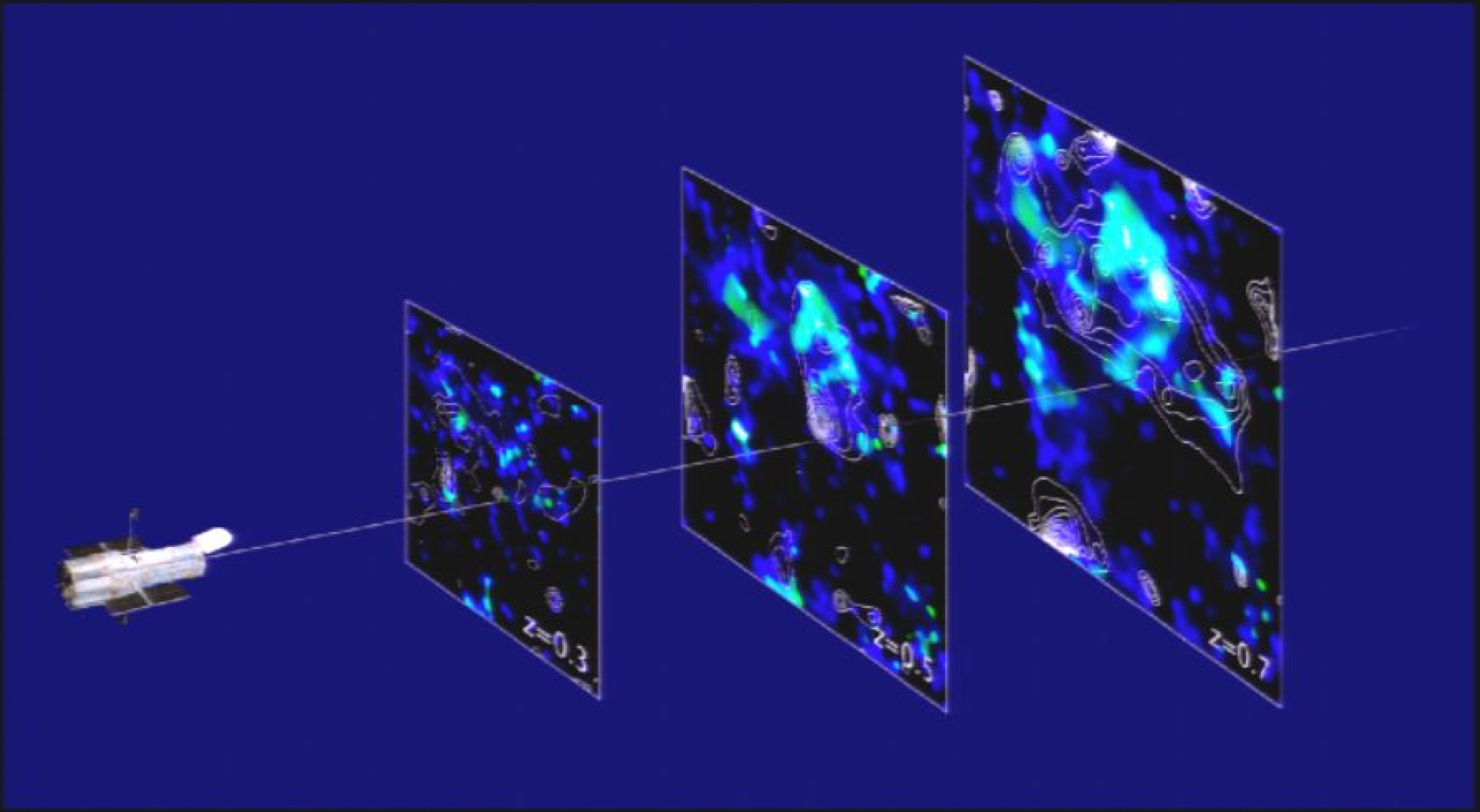
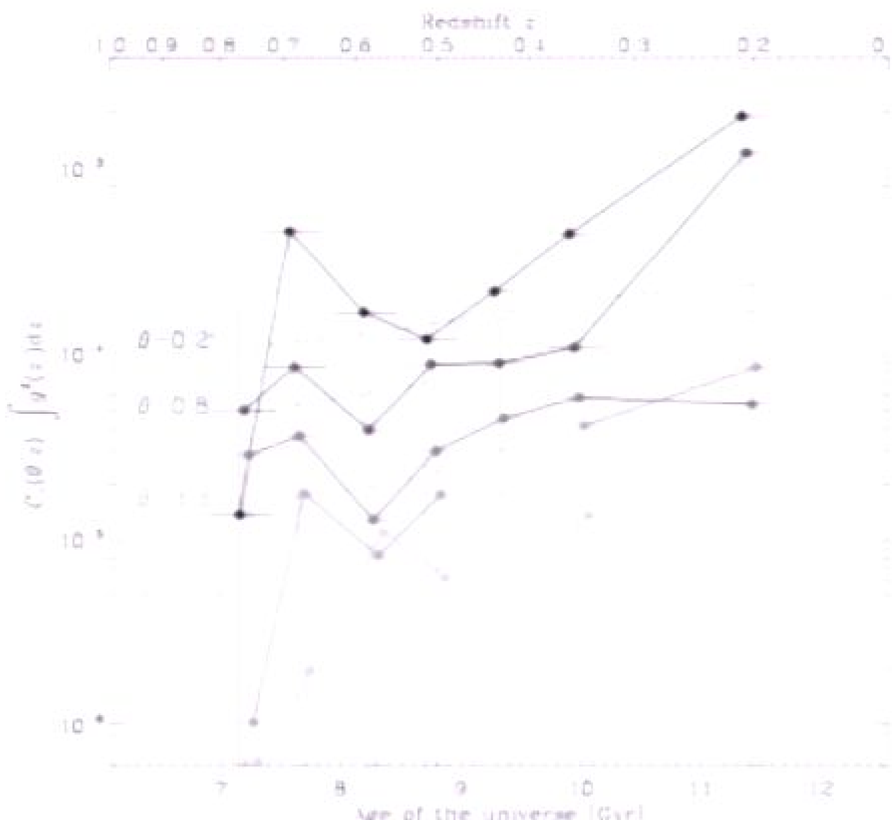


Measuring the Growth of Structure

Calculate the shear correlation function divided by the integrated lensing sensitivity to a given slice, and rescale to a fixed physical scale, assuming the signal is coming from the redshift of peak sensitivity.

Get (rather noisy) measure of the growth of structure:



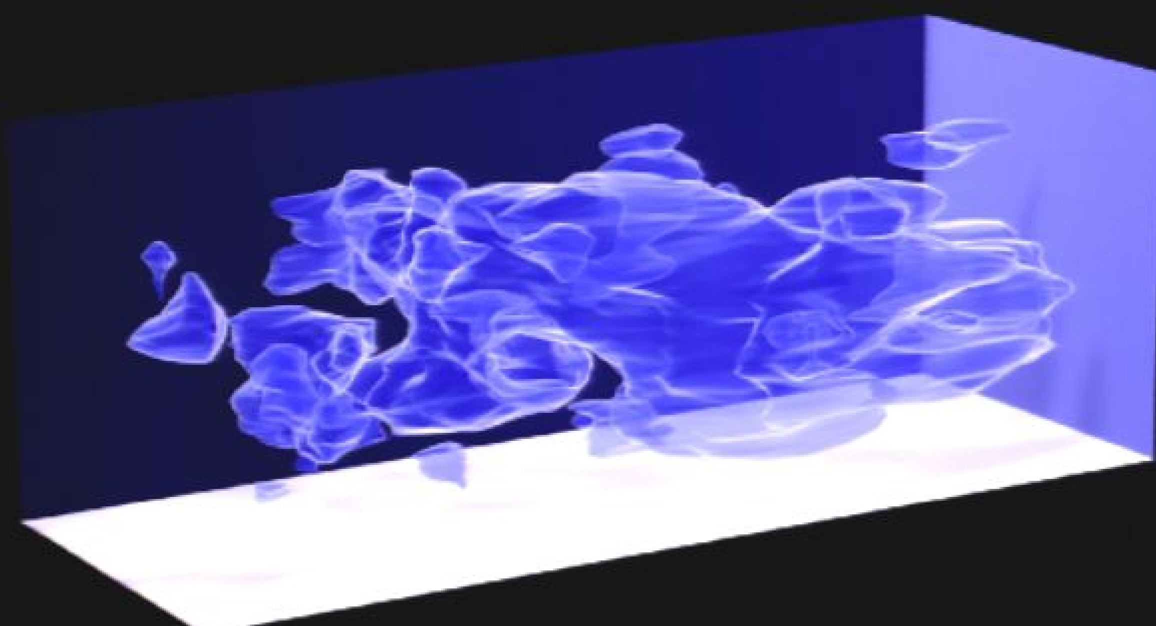
Massey et al. 2007b

The value of redshift information

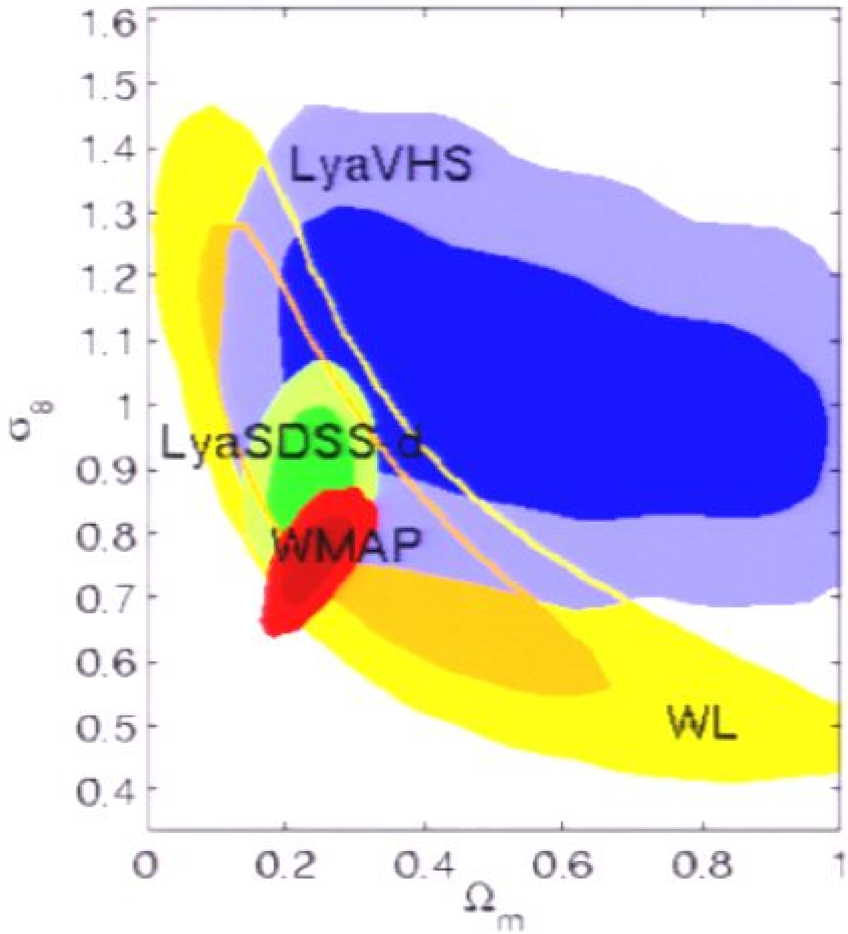
Even limited 3D information breaks some degeneracy, gives much tighter constraints (error bars 3x smaller)

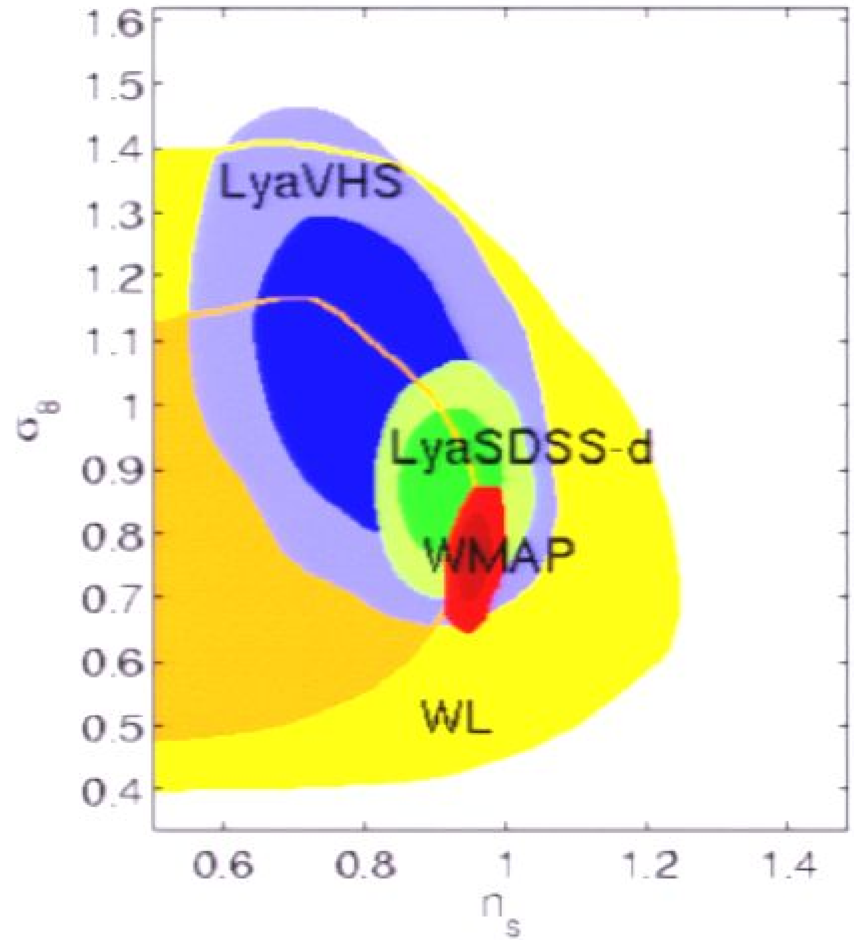
2D $$\sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.48} = 0.81 \pm 0.17$$

3D $$\sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.44} = 0.866^{+0.085}_{-0.068}$$



Combined constraints on power spectrum and cosmology





Lesgourgues et al. 2007: Lensing+ Lyman alpha results pull σ_8 higher (0.87 +/- 0.05); combining with CMB get very tight constraint: σ_8 = 0.8 +/- 0.02

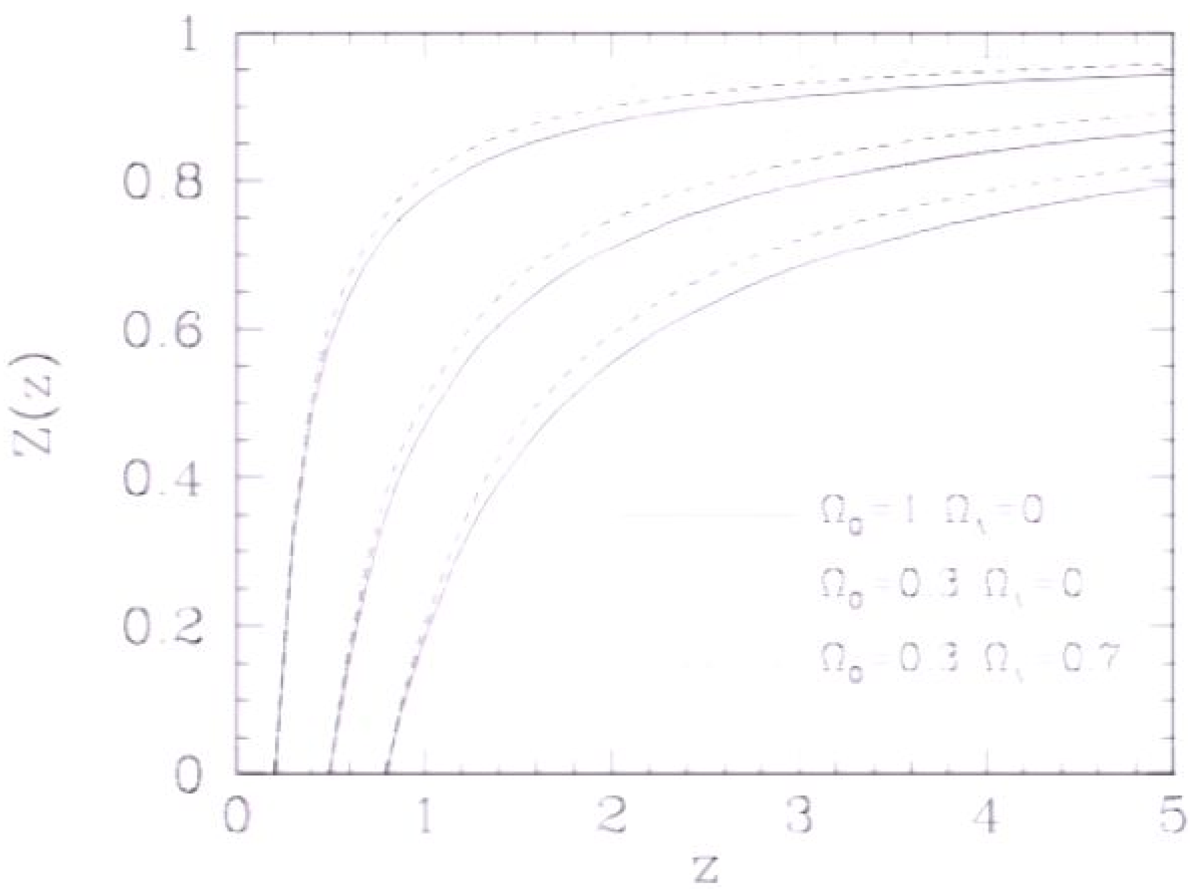
Measuring Geometry: The Shear Ratio Test

(Jain & Taylor 2003, Bernstein & Jain 2004, Taylor et al. 2007)

☺ Take ratio of shear of objects **behind** a particular mass, as a function of redshift

☺ Details of mass distribution, overall calibration cancel => clean geometric test

☺ Can extend this to continuous result by fitting to all redshifts $Z(z) \propto D_{LS}/D_S$



Bartelmann & Schneider 2001

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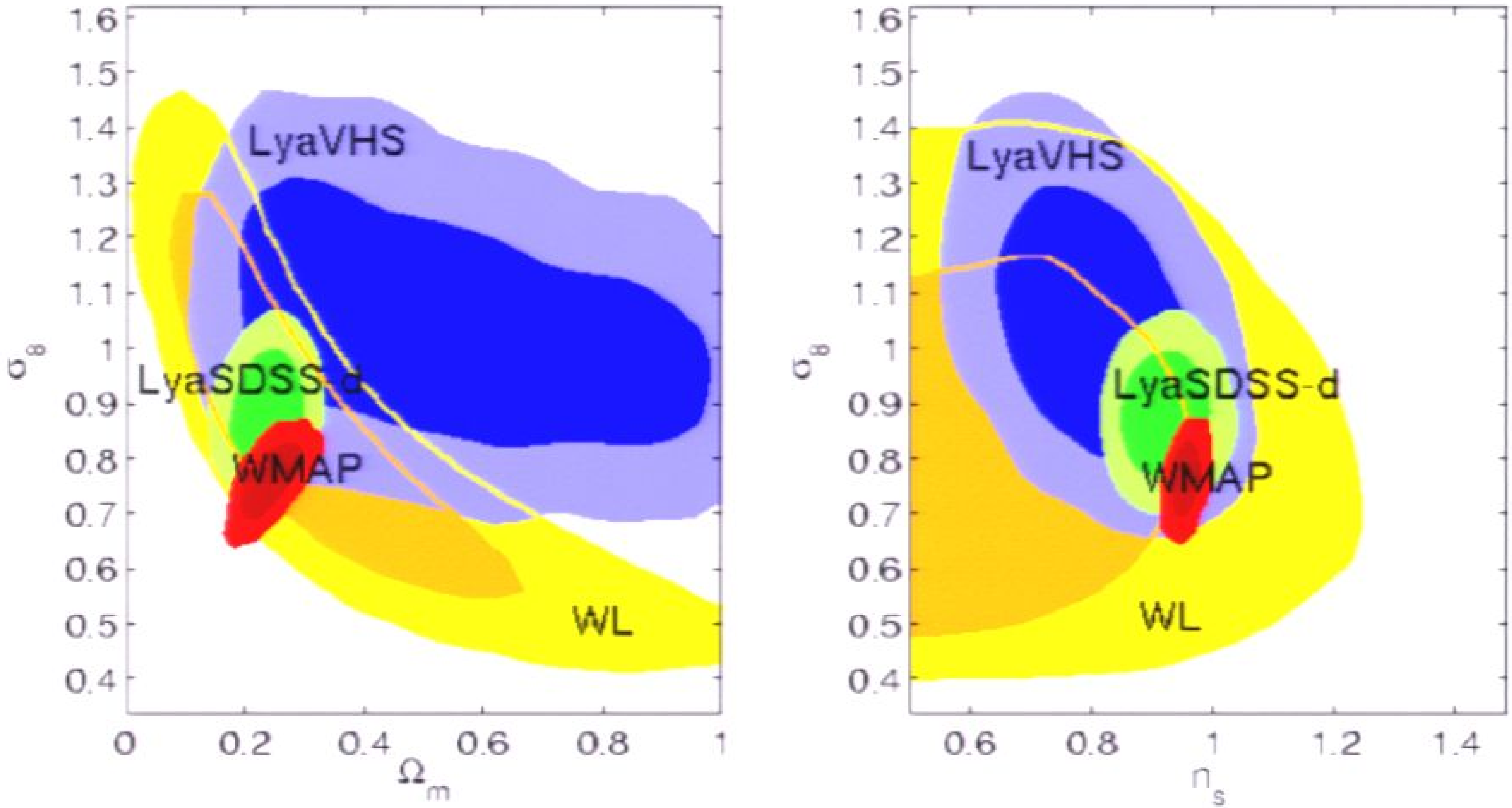

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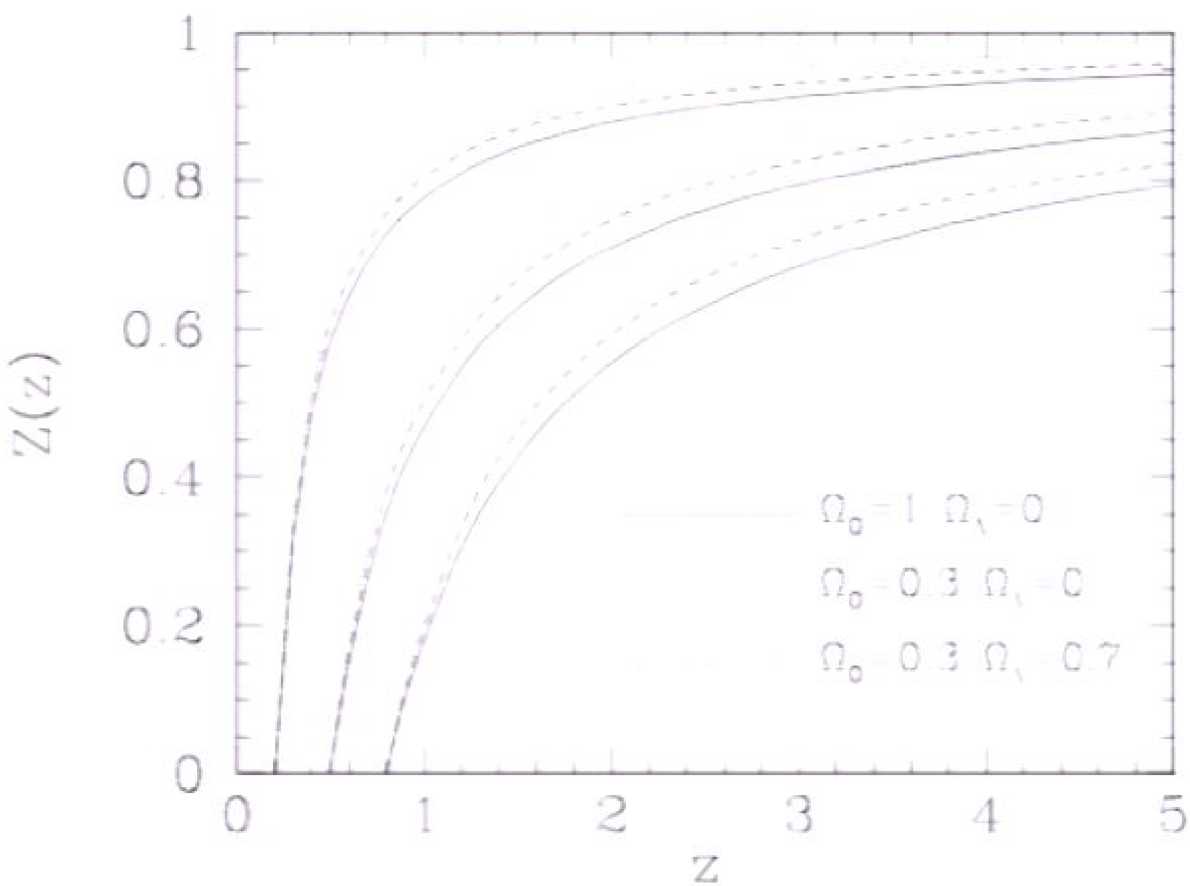
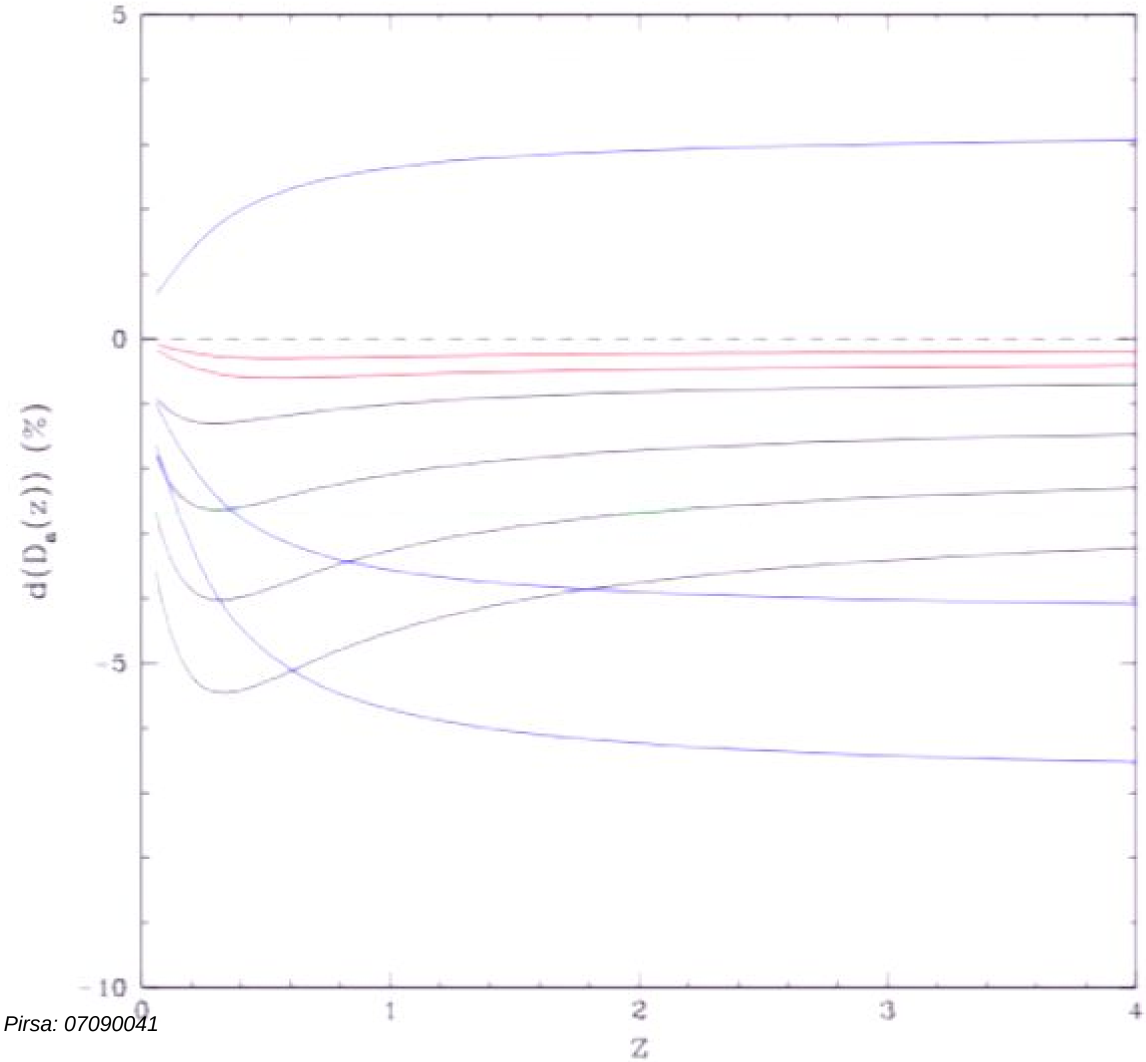


Bartelmann & Schnei

Lensing Behind Clusters

Use strength of signal behind cluster as a function of redshift to measure $D_A(z)$:



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$h = 0.73$, $\Omega_m = 0.27$
(Λ or $X = 1 - \Omega_m$)

Variants:
$\Omega_m = 0.25, 0.30, 0.32$

$w_0 = -1, -0.95, -0.9, -0.85, -0.8$

$w(z) = w_0 + w_a(1-a)$

$h = 0.7, 0.75$

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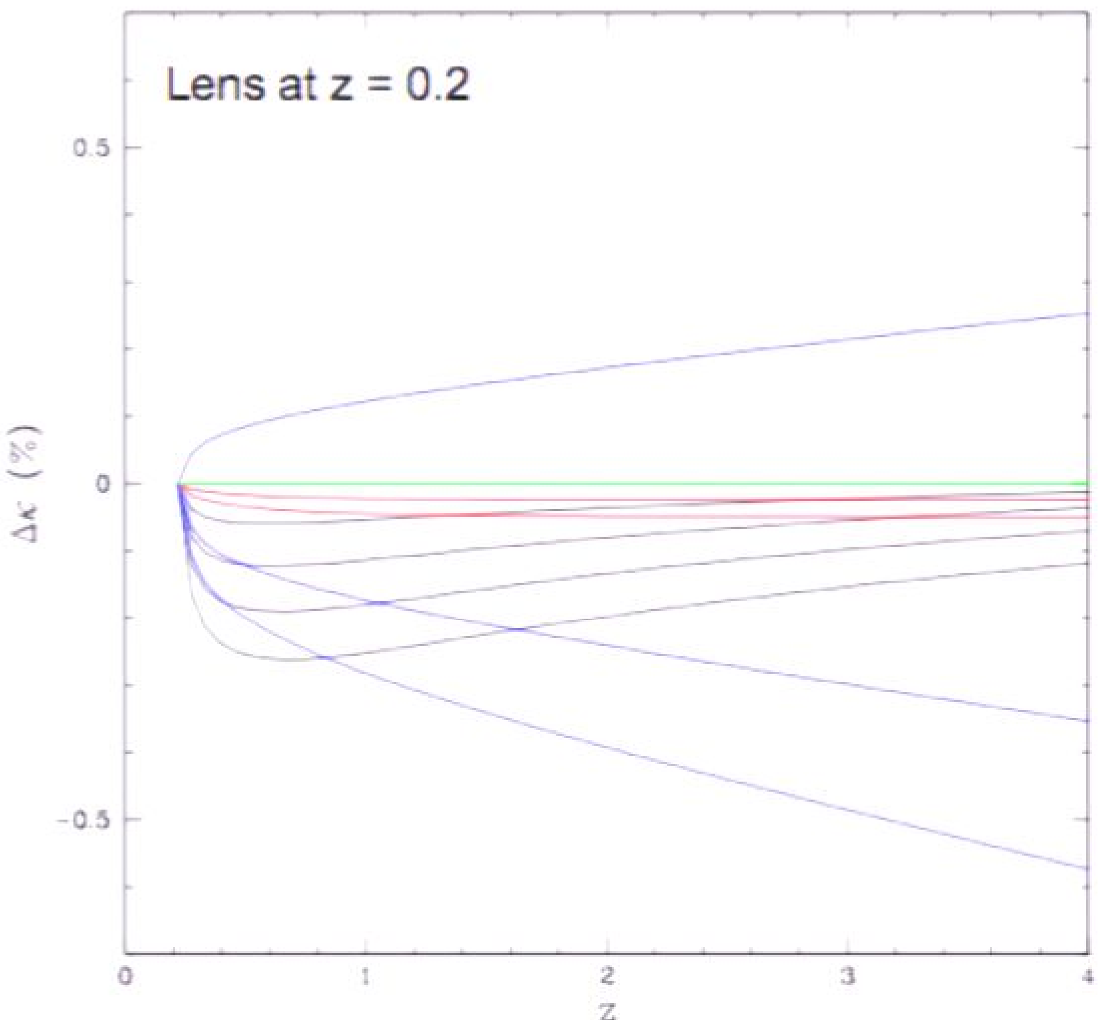

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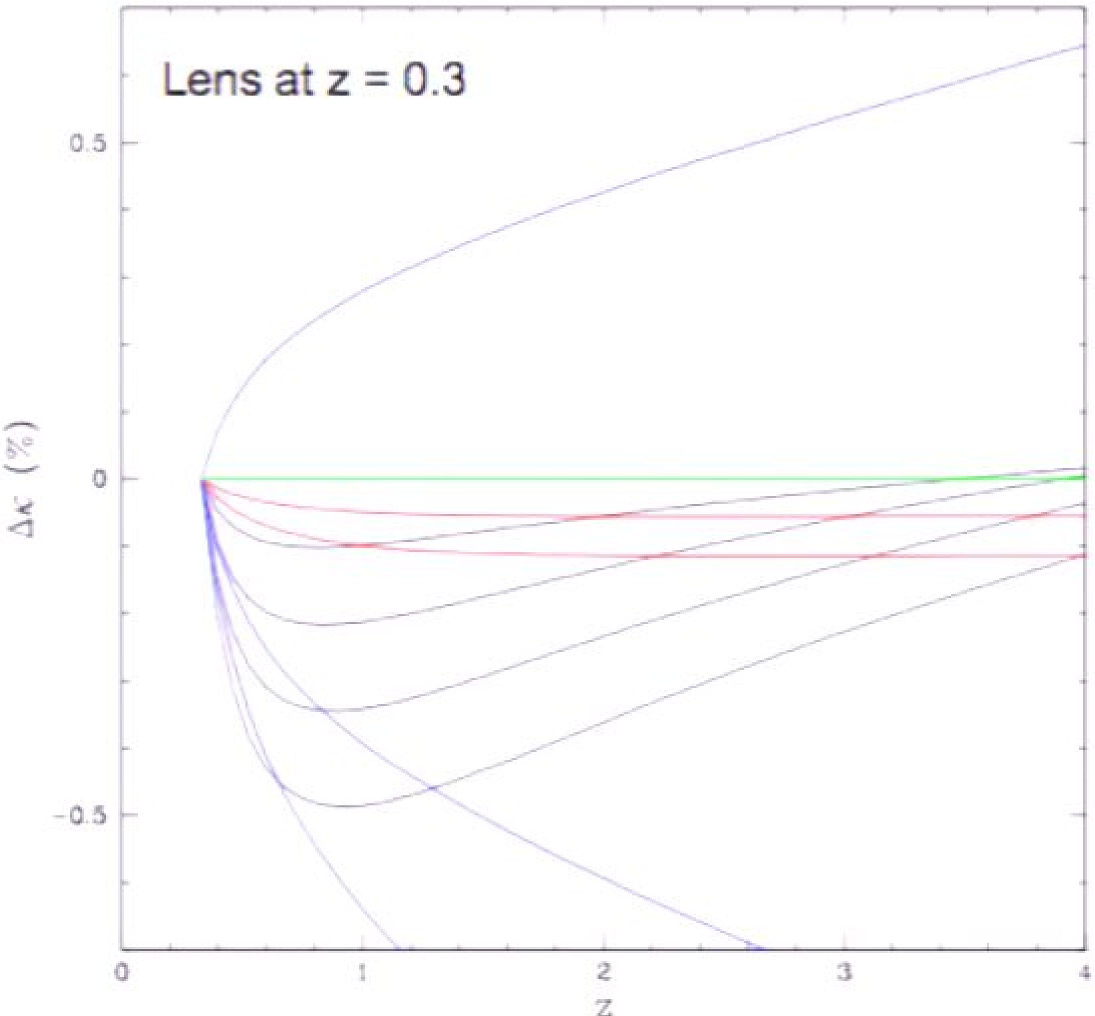

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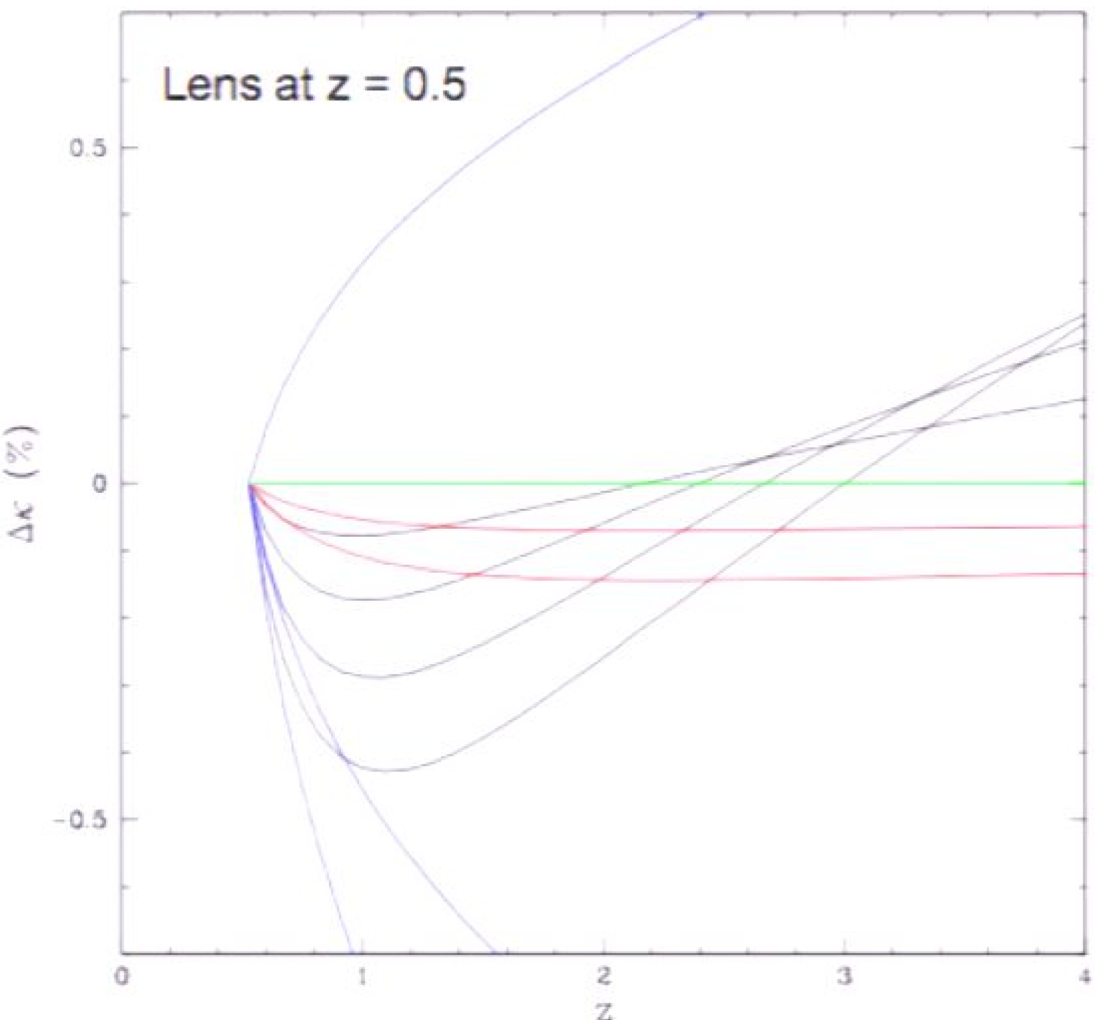

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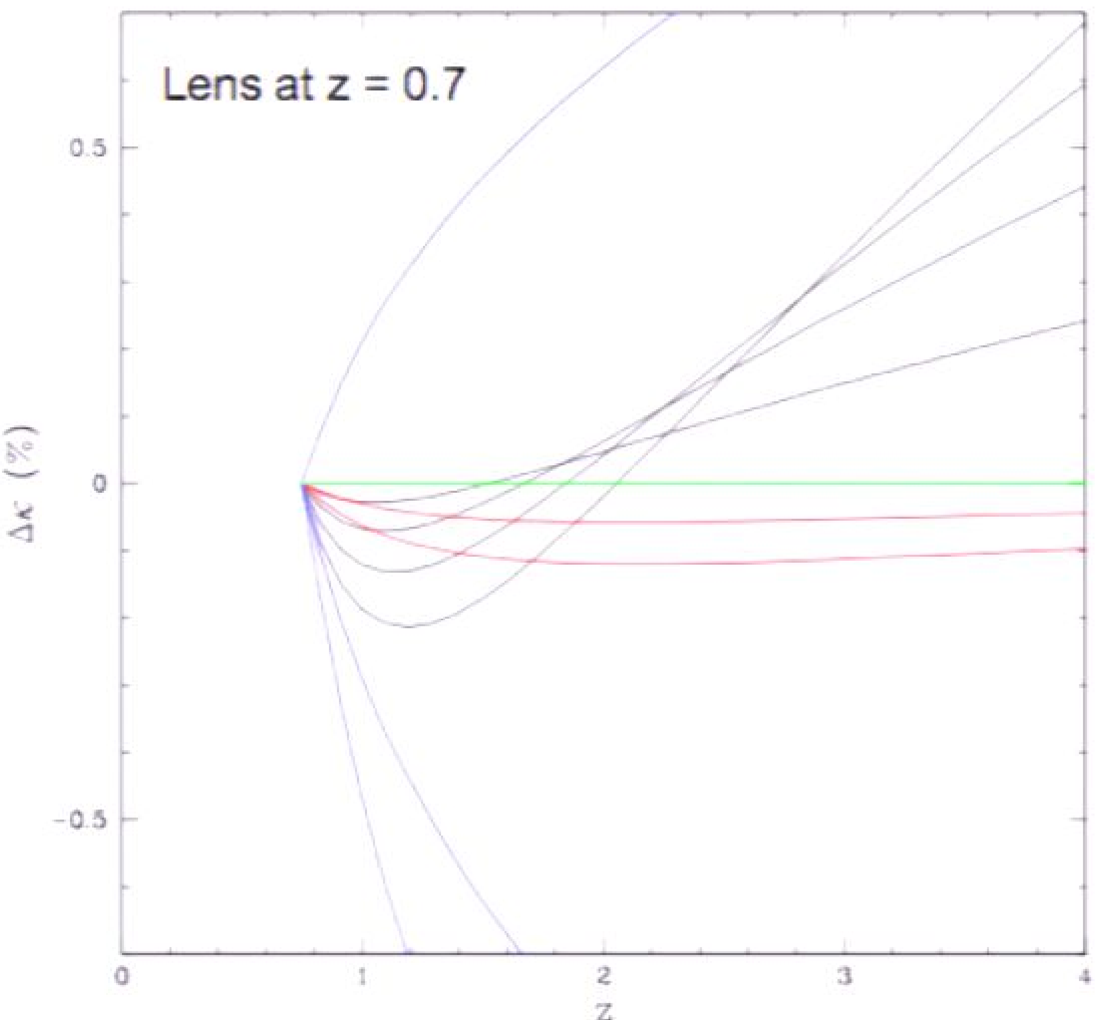

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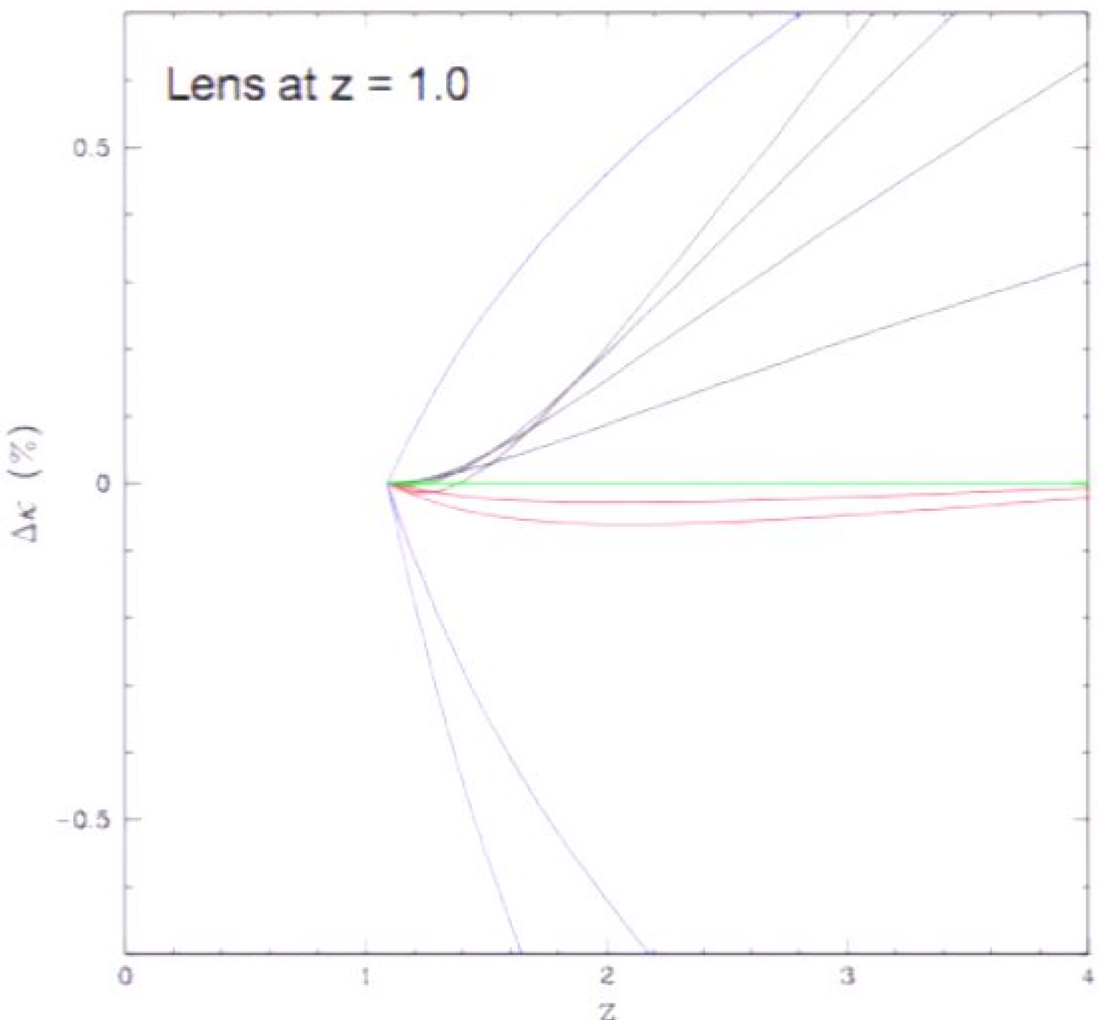

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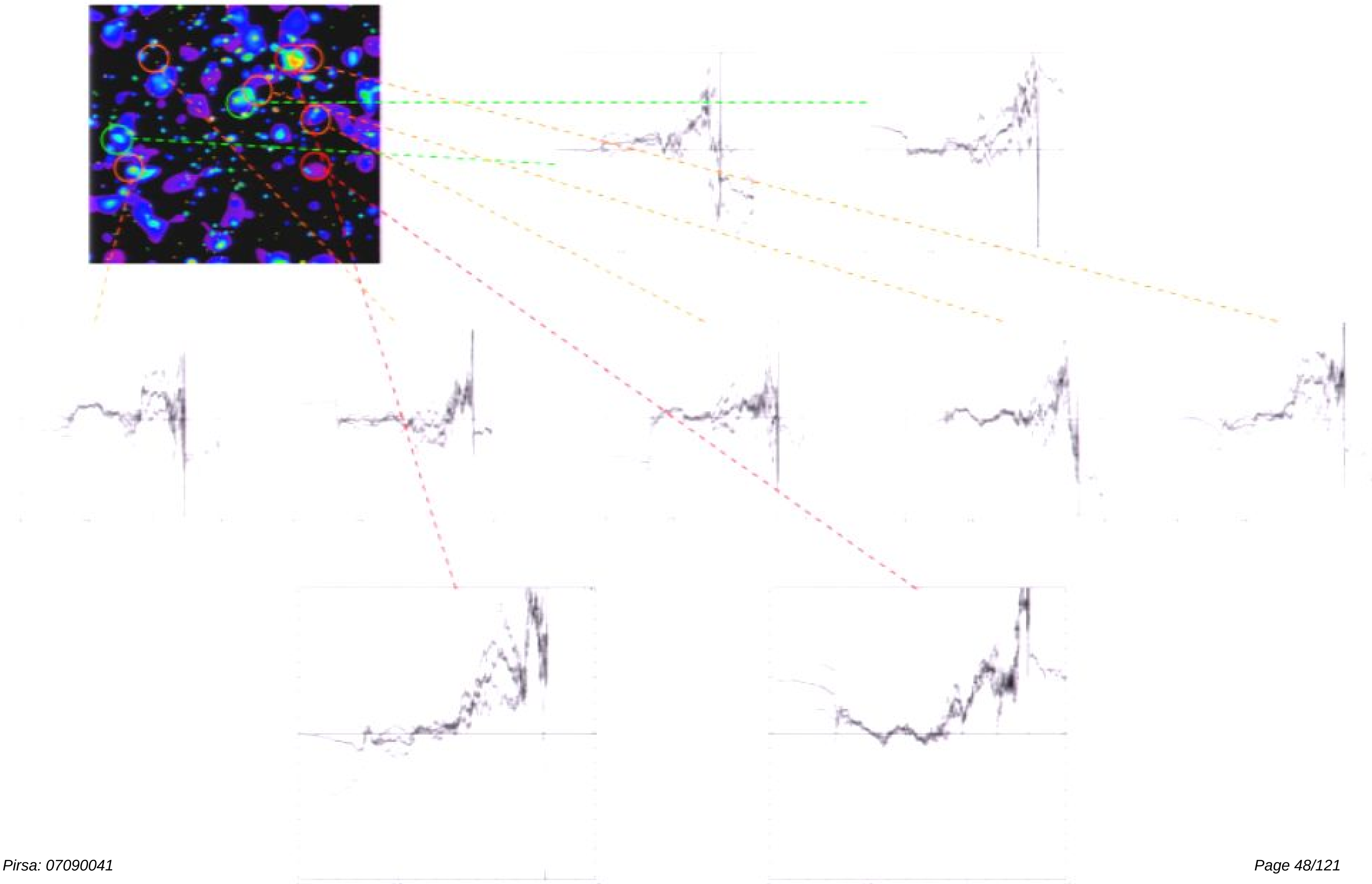
Signal weak but distinctive

Shear vs. photo-z around peaks, along promising lines of sight



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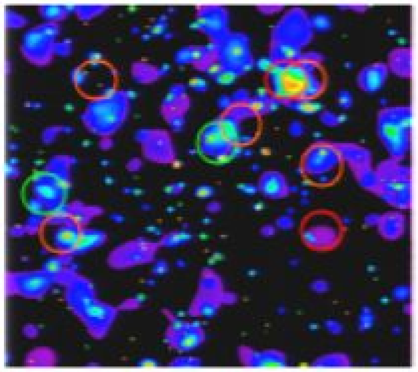
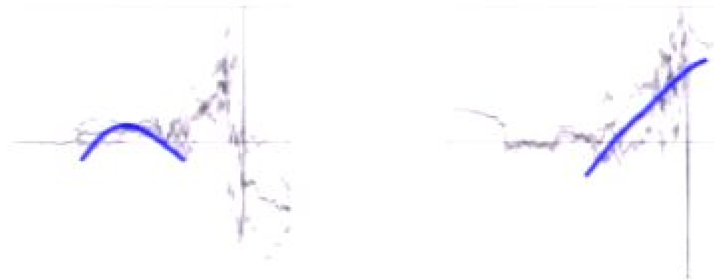
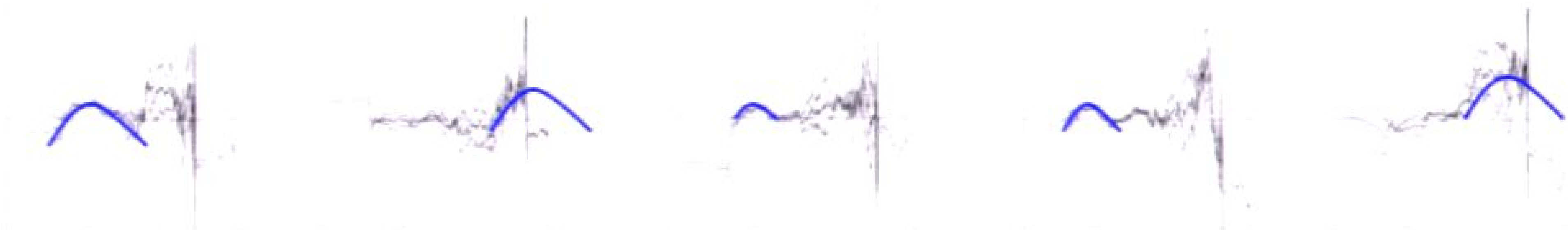
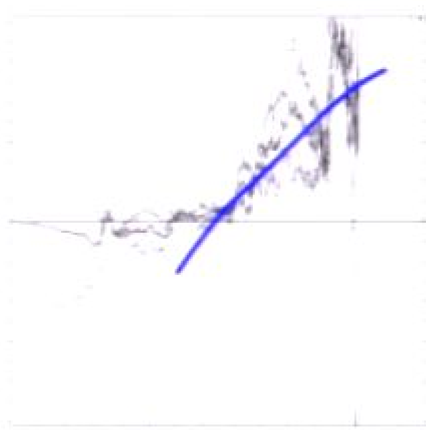
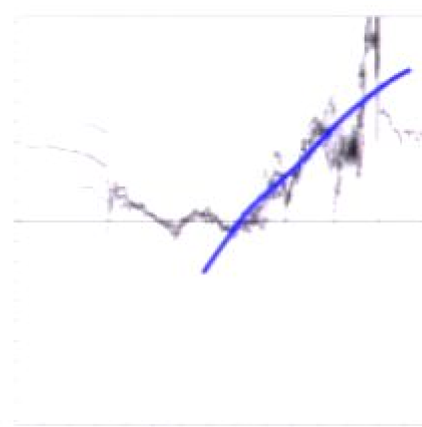




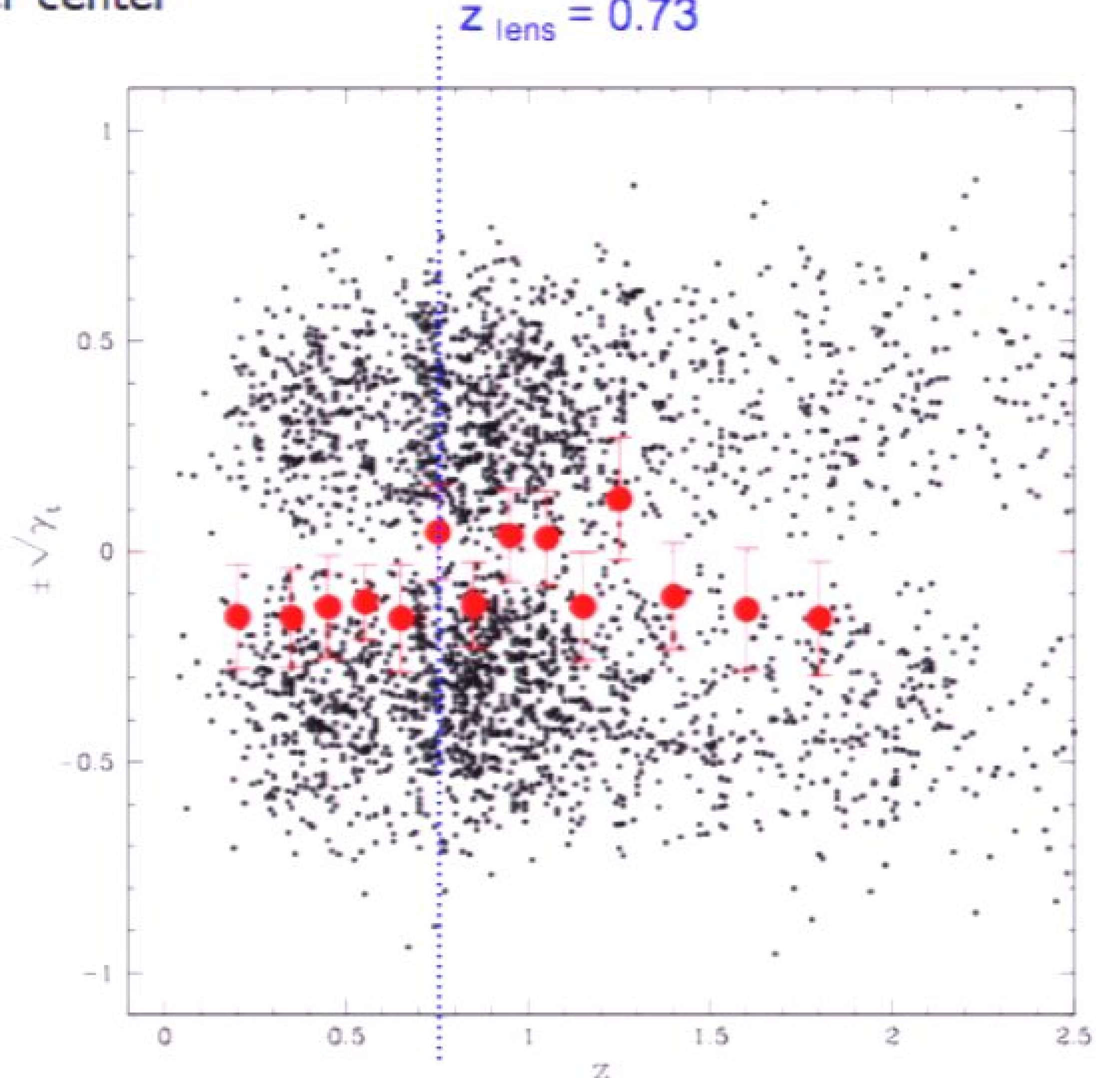






Preliminary Results

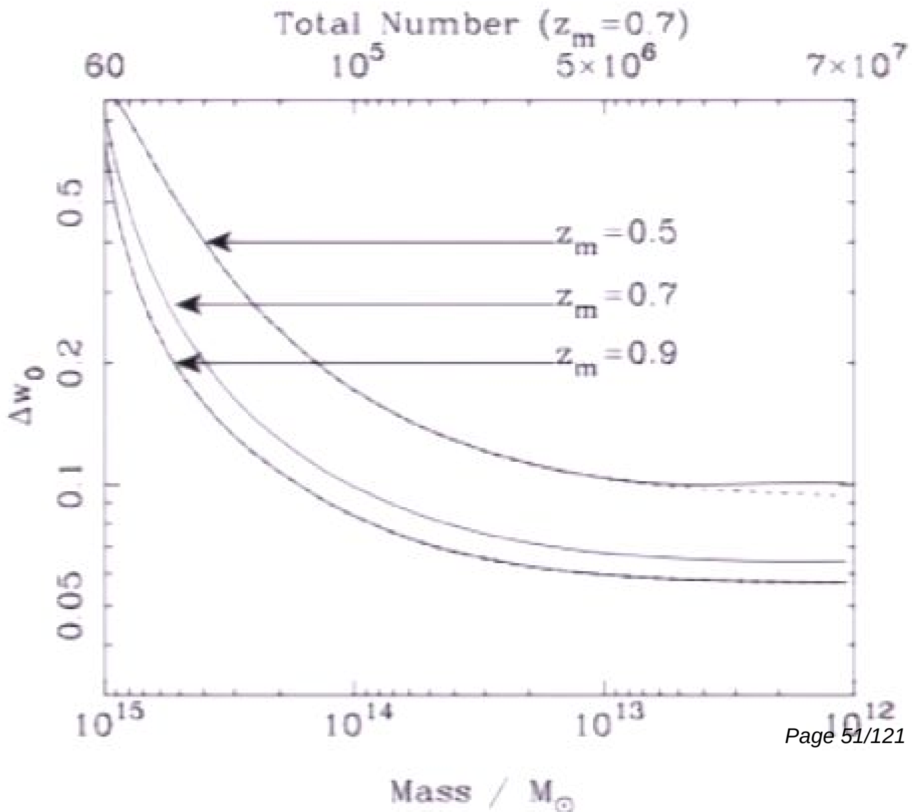
Signal detected in positive mean tangential shear within a given aperture behind cluster center



Preliminary Results

- Signal detected behind 6-7 clusters
- Still studying noise versus cylinder radius, catalogue cuts, path weighting
- Results consistent with $w_0 \sim -1.0$ +/- 1.0, but based on only a few objects
- Future predictions for large surveys + CMB + BAO (Taylor et al. 2007):

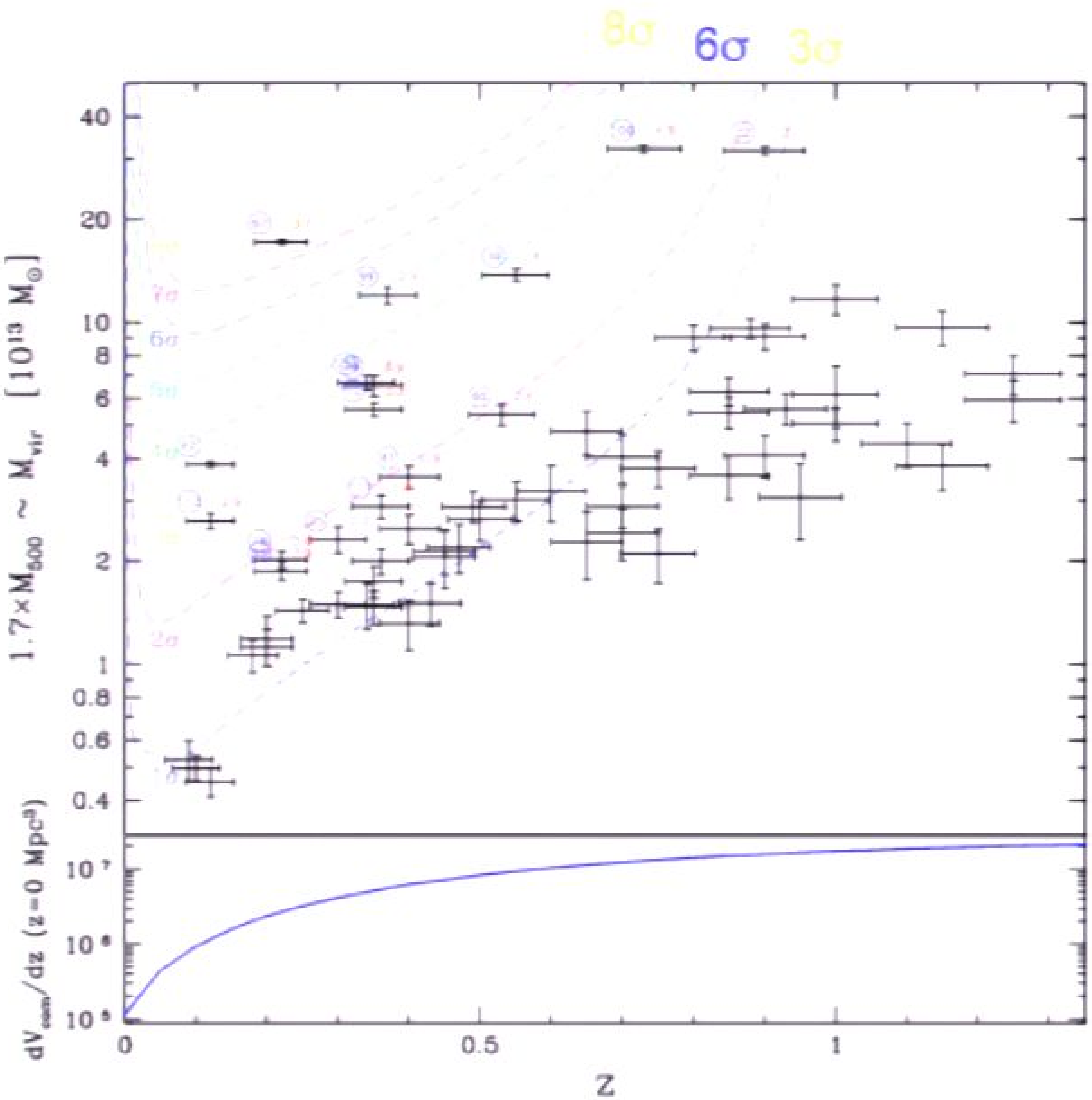
$\Delta w_0 = 0.047$, $\Delta w_a = 0.111$ and 2% measurement of dark energy at $z \sim 0.6$



error forecasts from 20,000 deg^2 survey (Taylor et al. 2007)

COSMOS Peaks: Xray-lensing comparison

(Finoguenov et al. 2006, Taylor et al in prep.)



Log(volume)

Caveat: Peak Height Systematics (e.g. Hamana et al. 2004)

With respect to shape noise, moderately massive clusters can be detected in ground based data at 4-σ significance at a rate of ~ 5/degree^2 or more (e.g. GaBoDs survey, Suprime survey)

Problem: many 0.3-1σ systematics, including:

☹ halo elongation
☹ halo concentration
☹ halo substructure

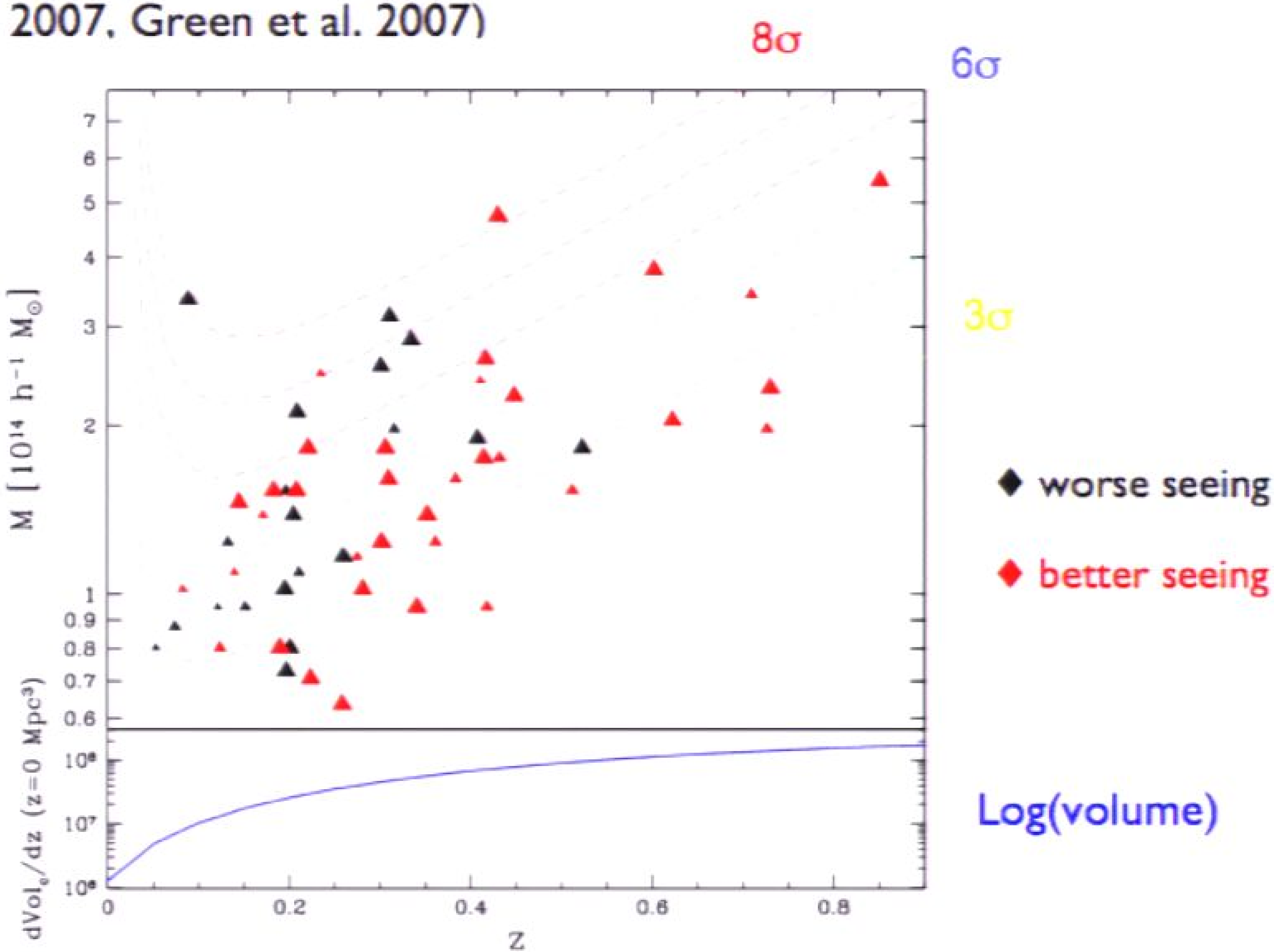
☹ chance projection
☹ correlated mass (i.e. non-chance projection)

☹ background source density fluctuations
☹ background mean-z_s fluctuations

☹ seeing
☹ other observational problems (field edges, stars, etc.)

Recent Subaru Suprime22 Survey Results

(Miyazaki et al. 2007, Green et al. 2007)

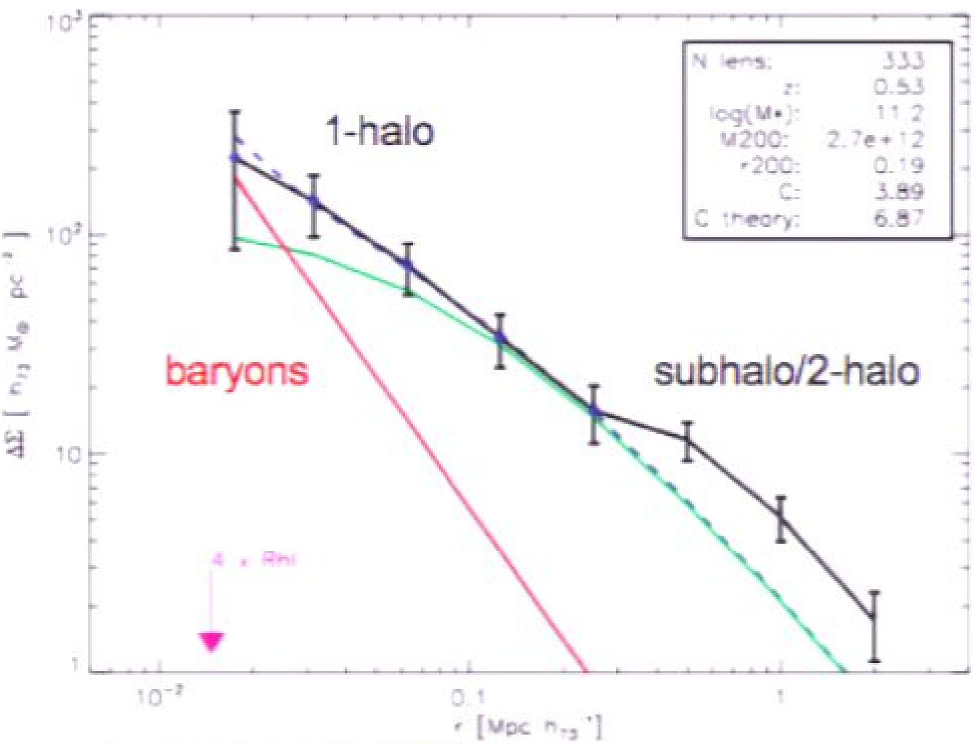


Other Lensing Results

Galaxy-galaxy lensing:
Stack lensing signal around groups and galaxies to get significant detection (have to decide how to bin galaxies)

Result: lensing detected at high significance over a range of radii

Future possibilities in this field include 1-halo/2-halo/baryonic decompostion of profile, concentration measurements, evolution etc.



Leauthaud et al. 2007

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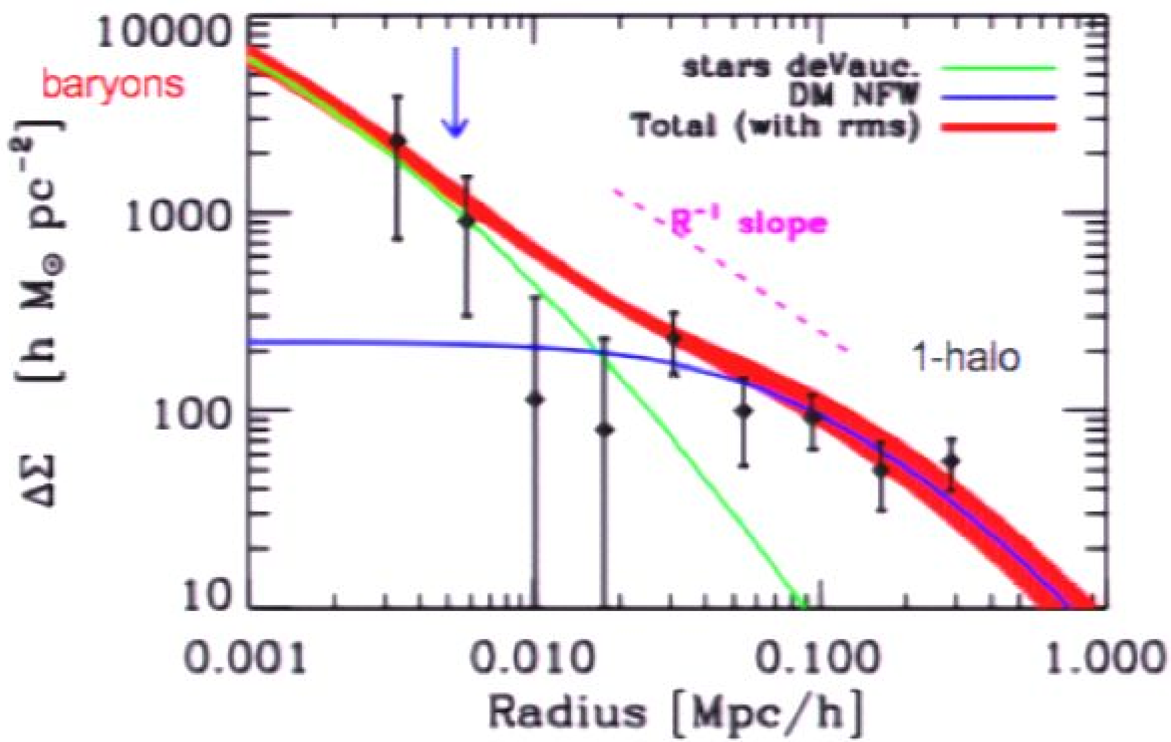

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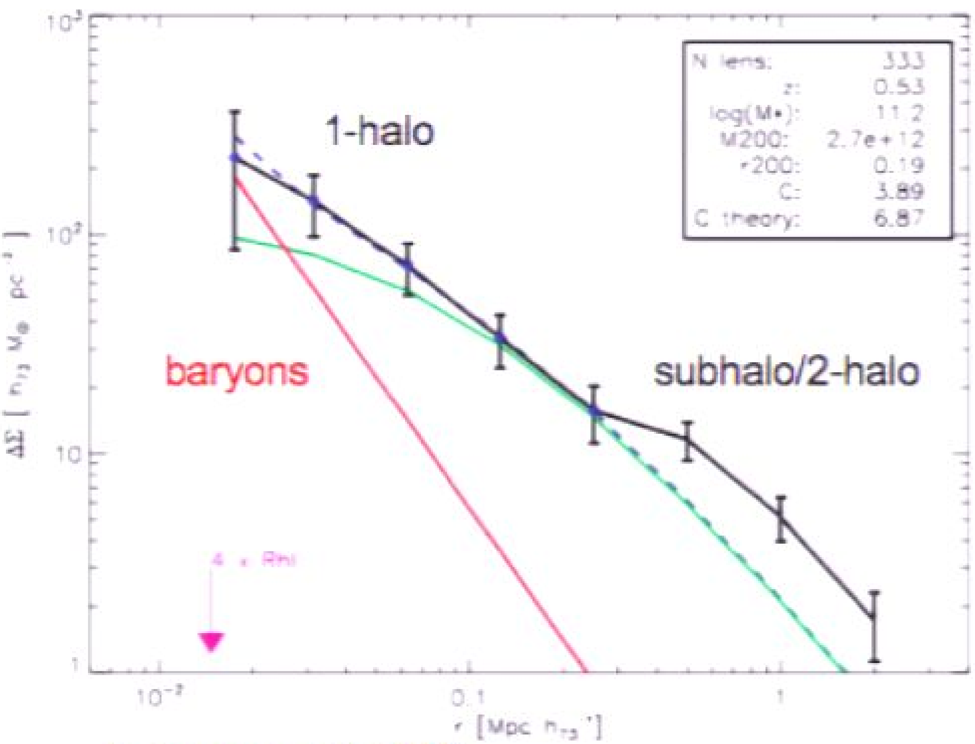

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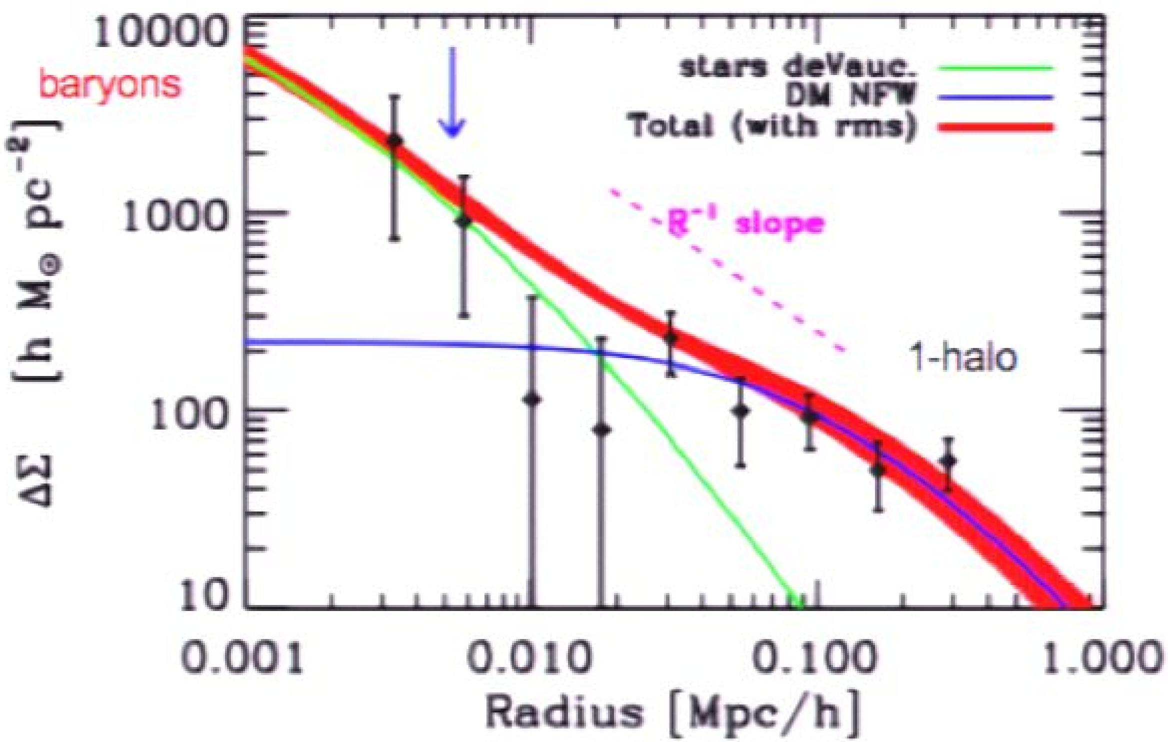

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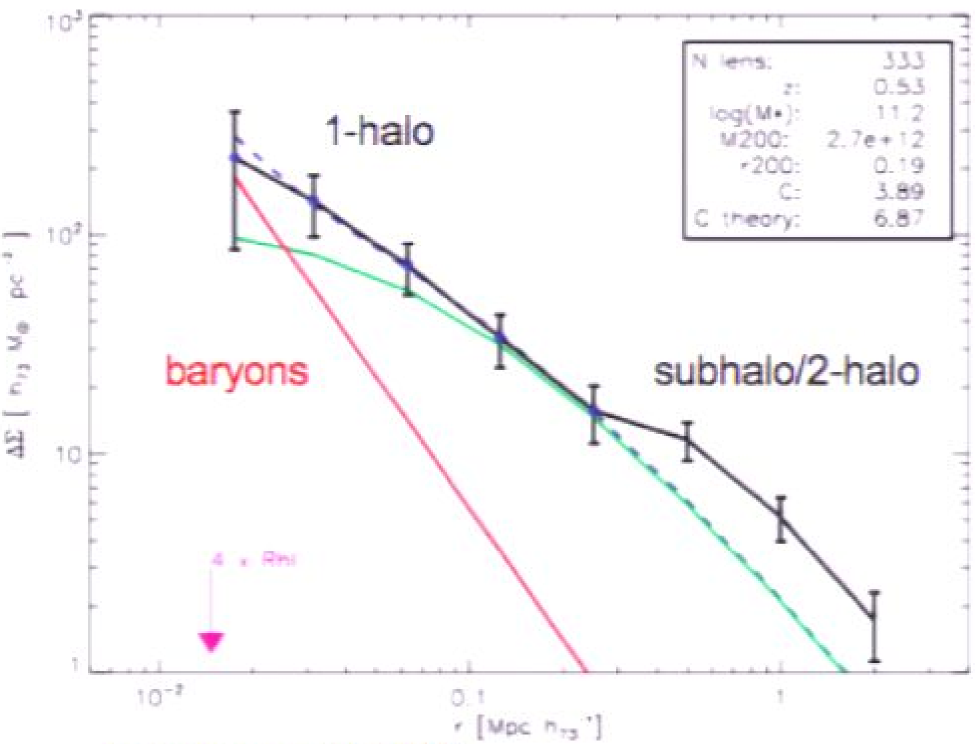

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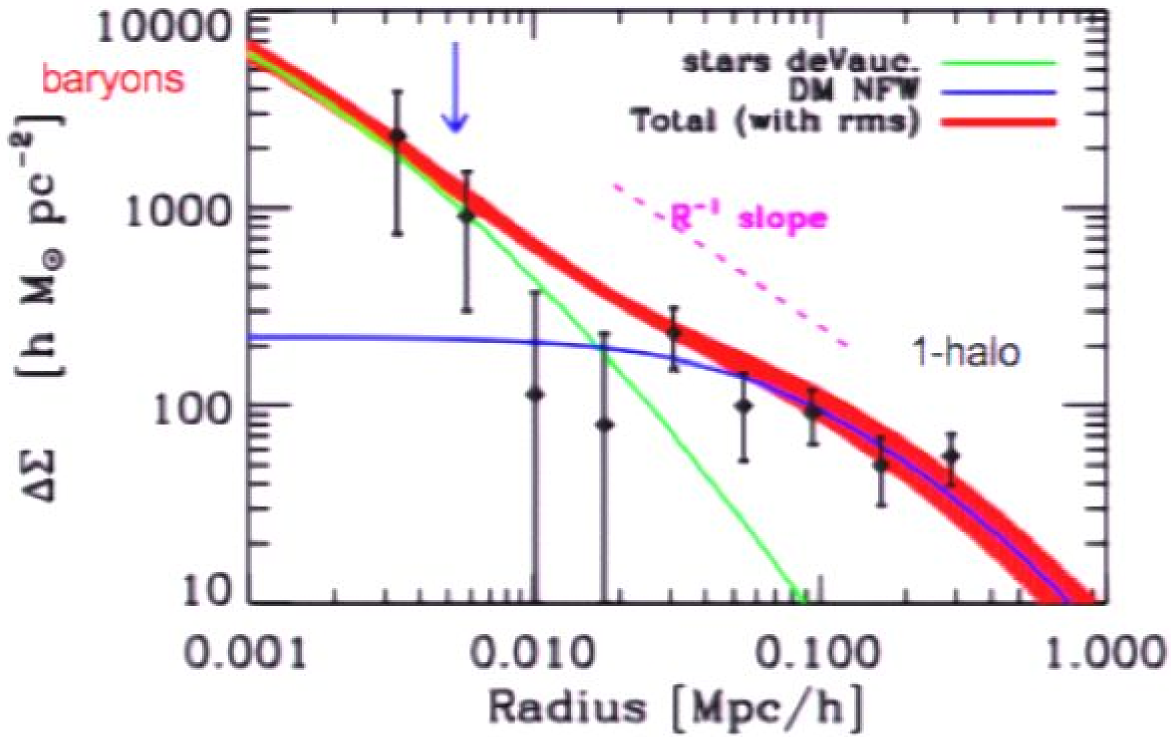

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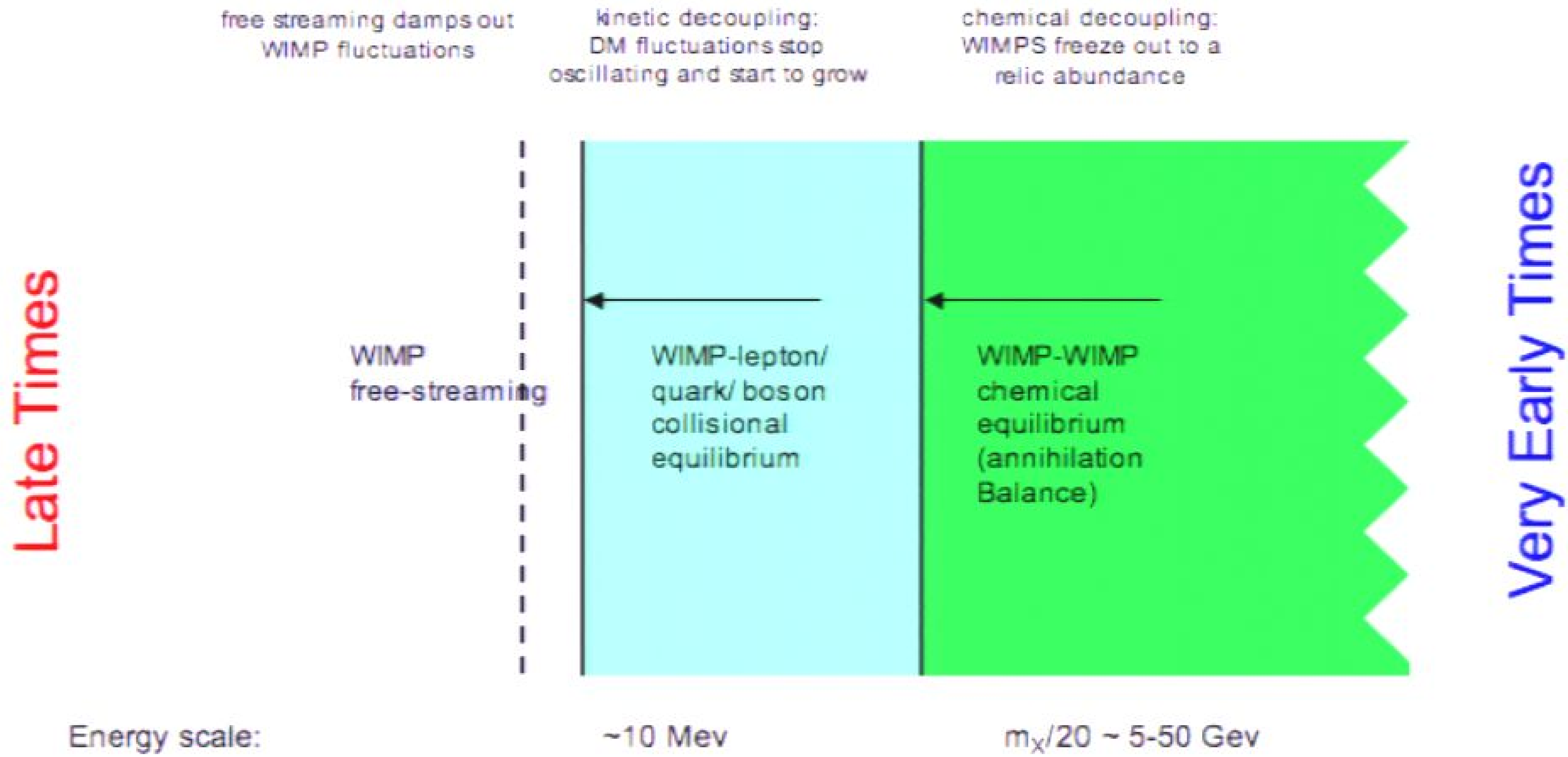
II: Detecting Structure on Small Scales

What are the initial conditions for structure formation?

Consider specific example: supersymmetric WIMP



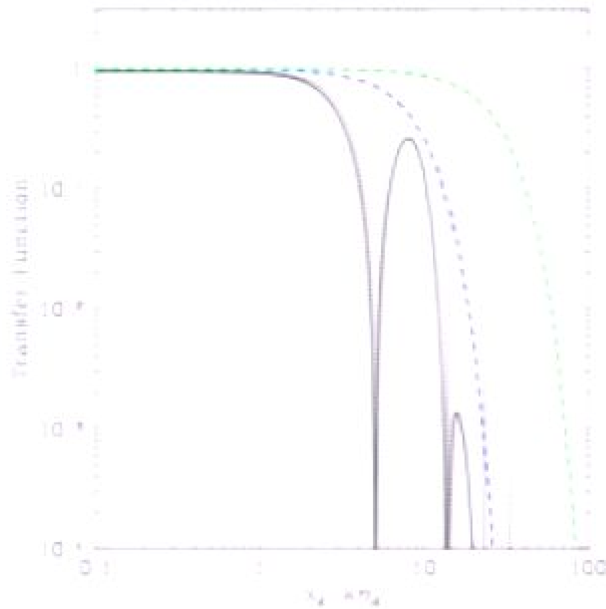
Basic answer: free streaming suppresses fluctuations below some scale, but acoustic oscillations also contribute ⇒ minimum halo mass M_c

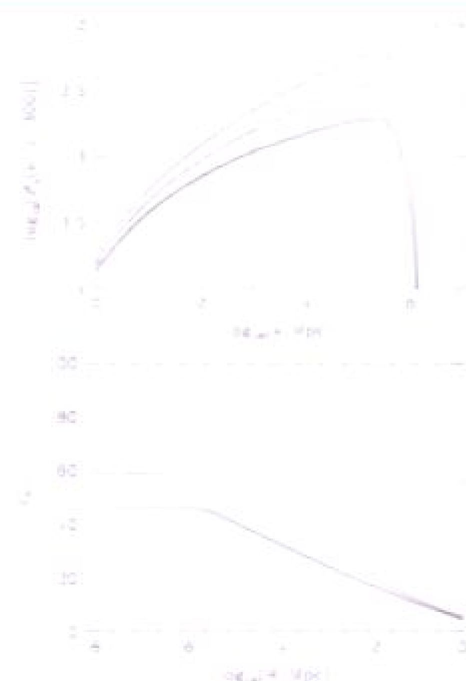
e.g. Loeb & Zaldarriaga (2005):

approximate calculation of transfer function due to collisional damping

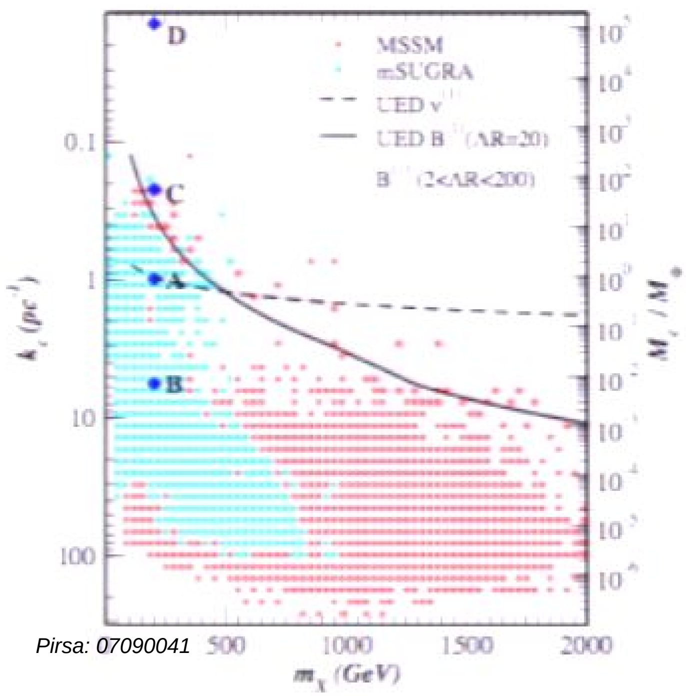
dominates over free streaming in case considered (100Gev WIMP w. T_d = 10Mev)

gives cutoff mass $M_c = 10^{-4} - 10^{-5}\ M_\odot$





Green, Hofmann & Schwarz 2005



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So smallest scale dark matter structure encapsulates DM particle properties (via M_c) and possibly also inflaton properties (via ρ or z_f) (e.g. Zentner & Bullock 2002, 2003)

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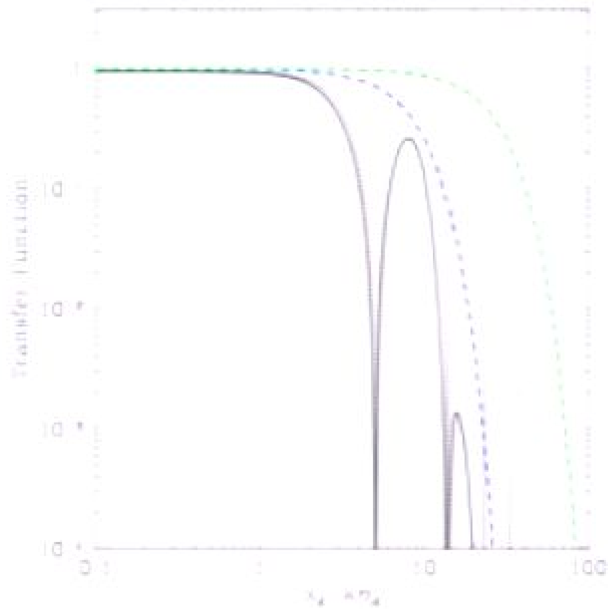

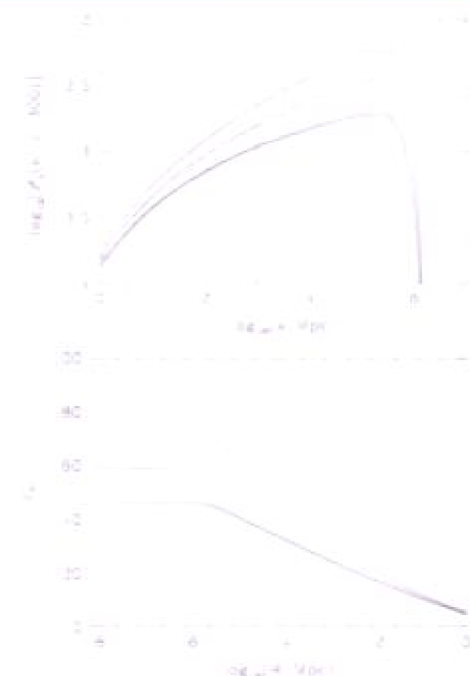

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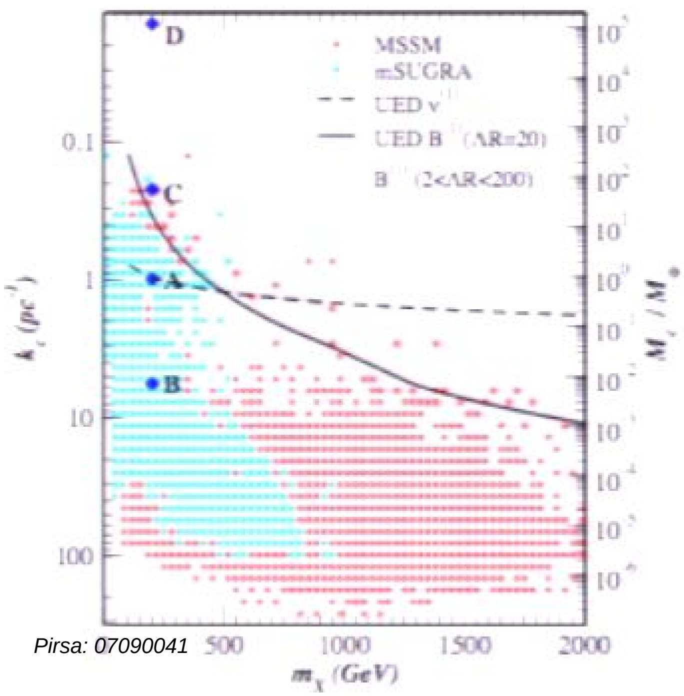

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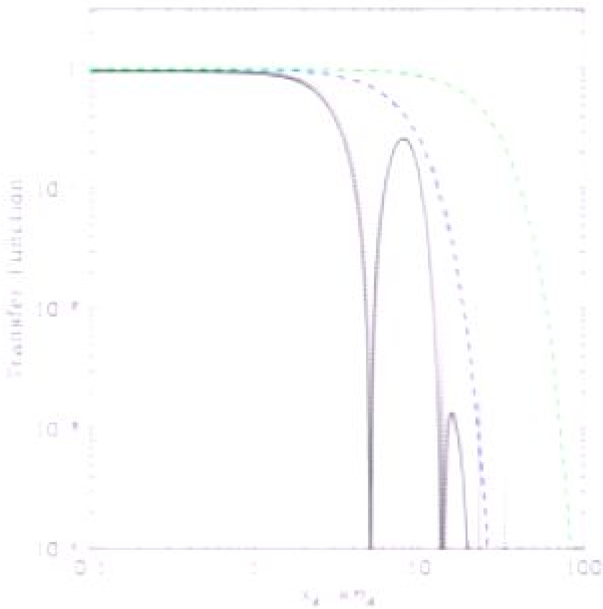

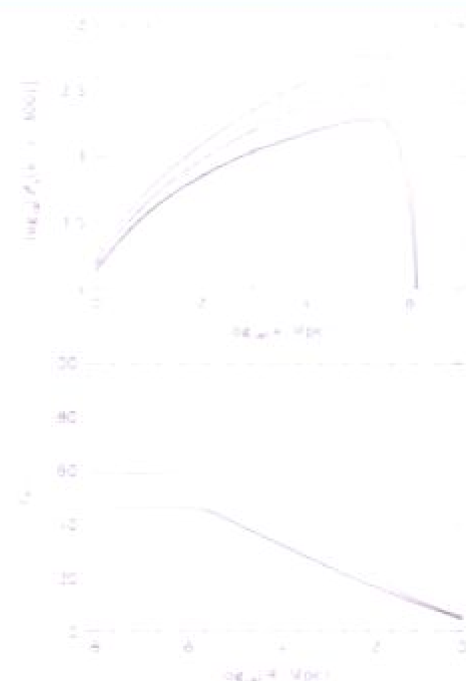

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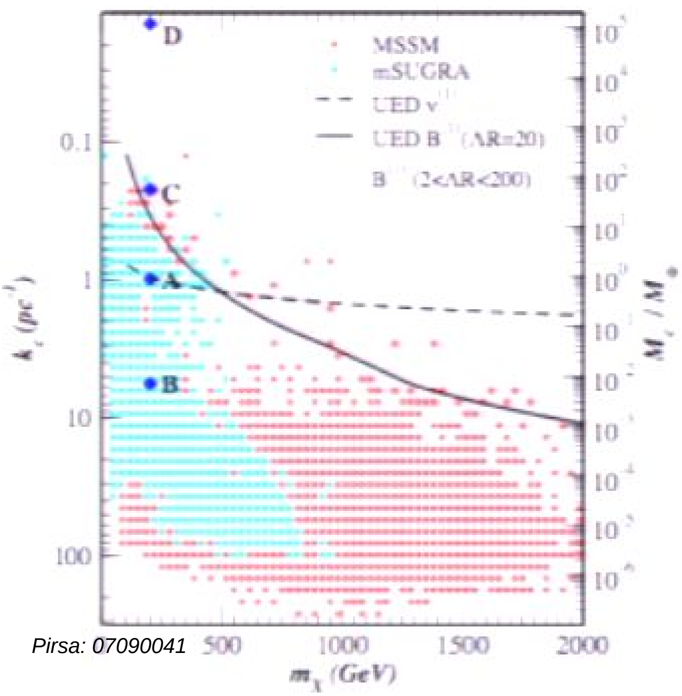

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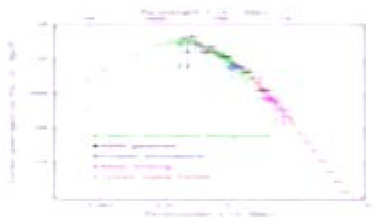
The Resulting Non-linear Power: Theoretical Expectations



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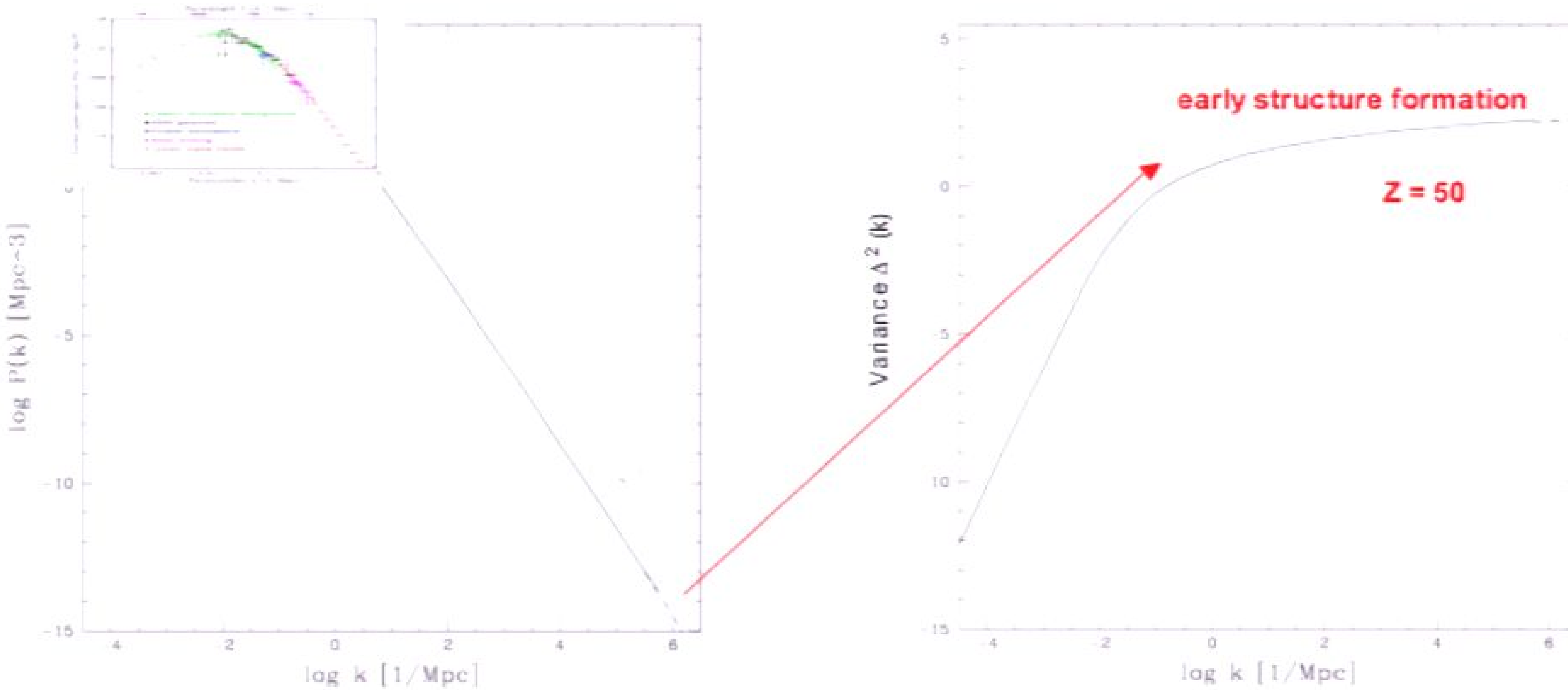

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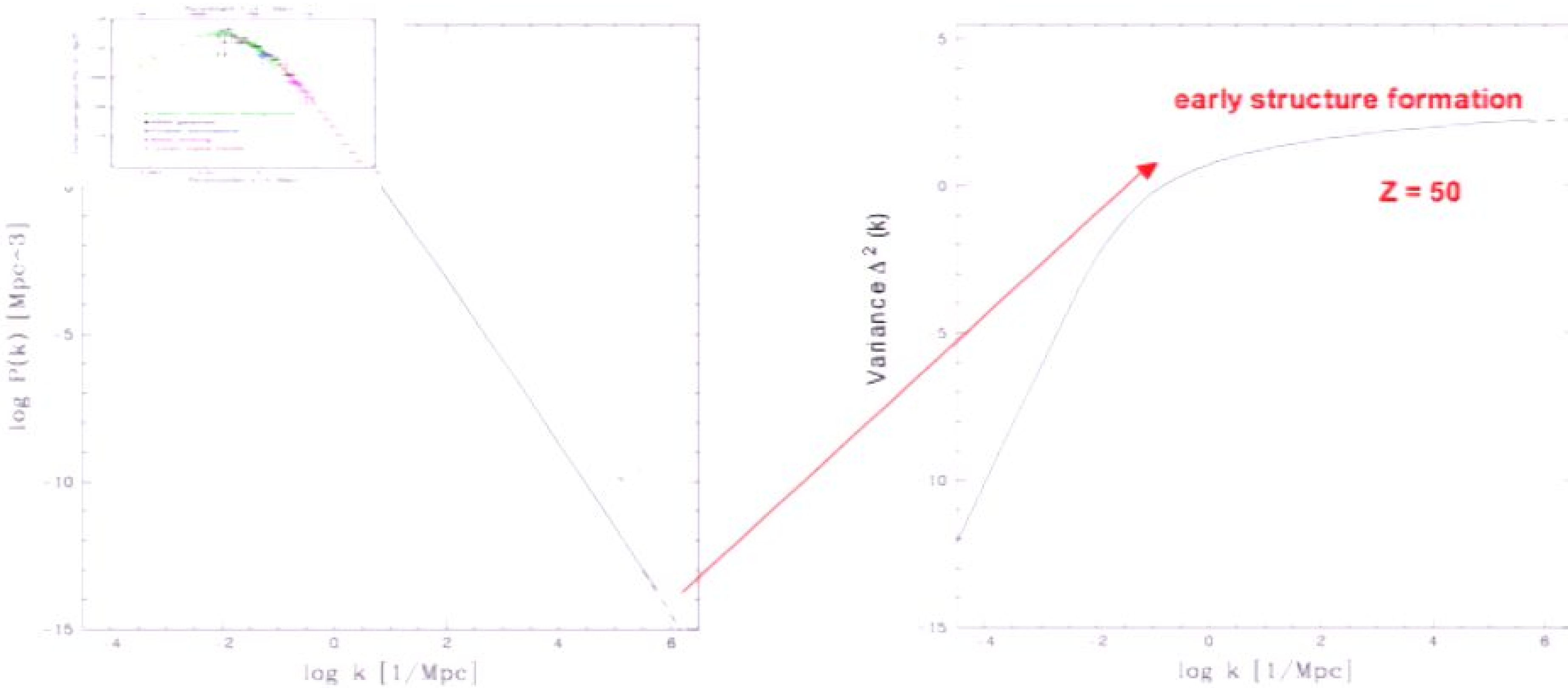


From linear power spectrum and subsequent growth history, expect scale invariance over ~20 orders of magnitude in mass

But effect of flattening of variance vs. mass?

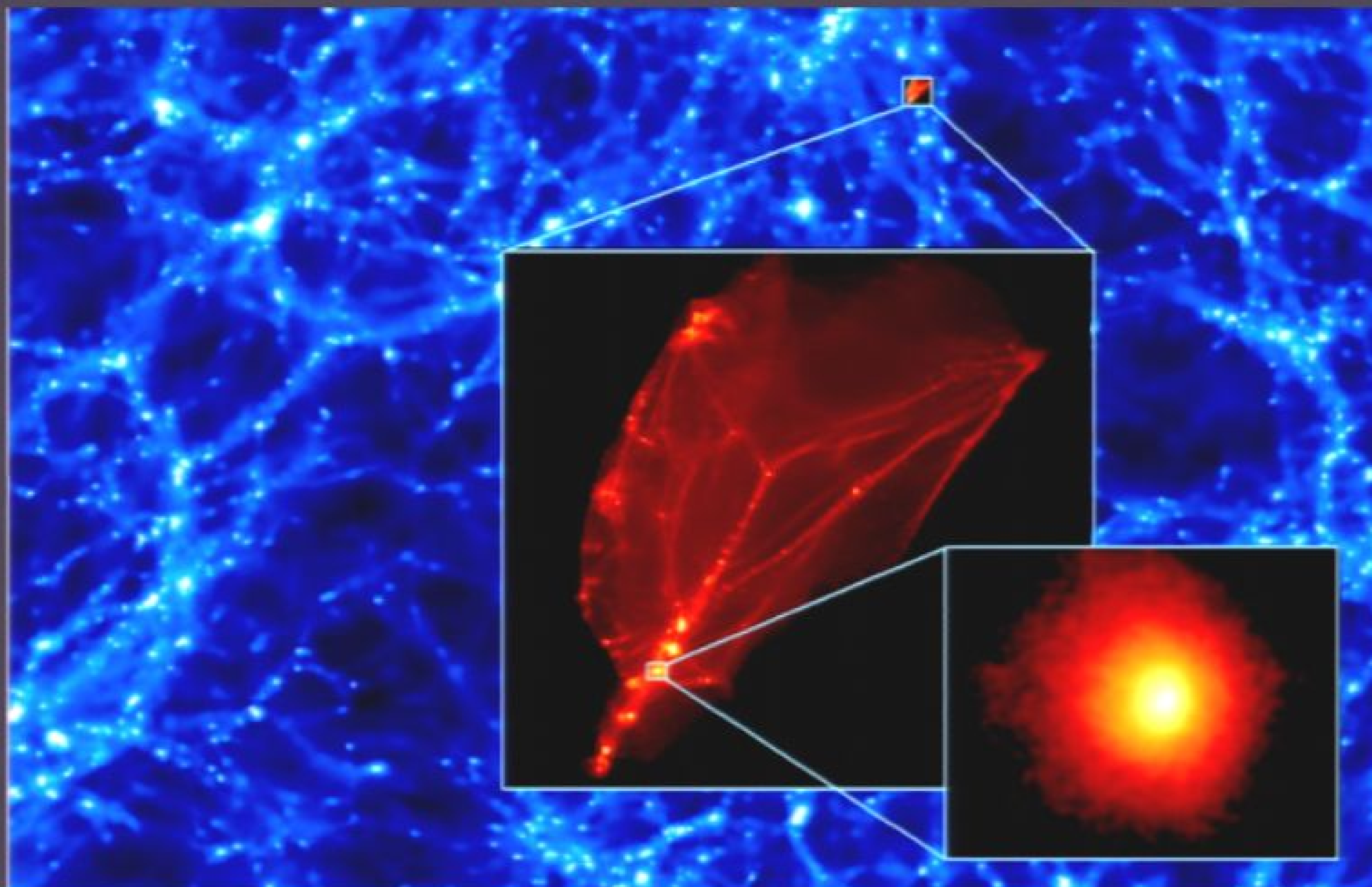
Diemand et al. (2005): first numerical attempt w. small box, stopping at high z

Consider linear power spectrum with $M_c = 10^{-6}\ M_o$

Start at z=350

Zoom in:
Simulate [3 kpc]^3 box, [60 pc]^3 sub-box and [0.024 pc]^3 sub-sub-box with 6×10^7 particles of mass $10^{-10}\ M_o$ each

Find $10^{-6}\ M_o$ `first' halo
With $M \sim M_c$



Profile, density as expected from theory

(Diemand et al. 2005)

Halo profile ~ universal;
Virial density ~ 200 mean,
even concentration ~ ok

Also abundance matches
lower redshift results

Implication: following scaling
for more massive substructure,
present-day MW halo should
contain 10^{15} mcirohalos, or
500/pc^3 locally, the nearest being
within ~0.15pc away

Further implications for direct and
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These objects move through solar
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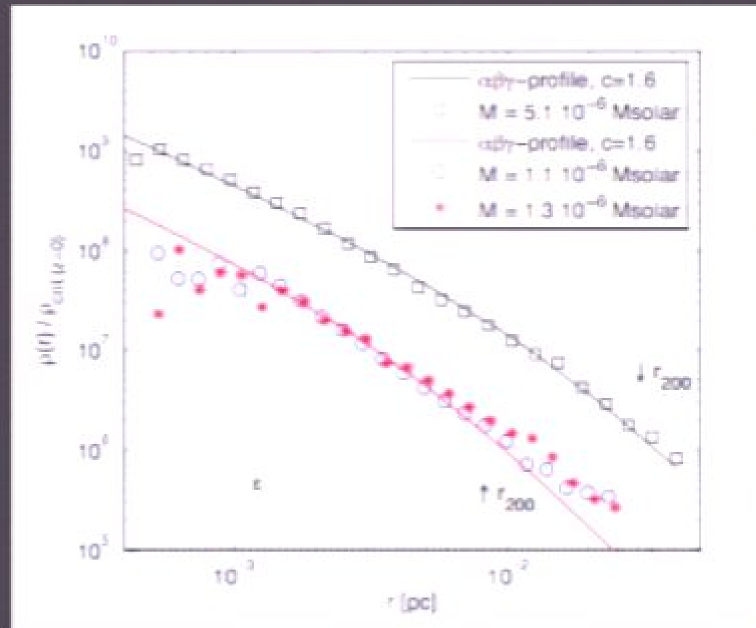
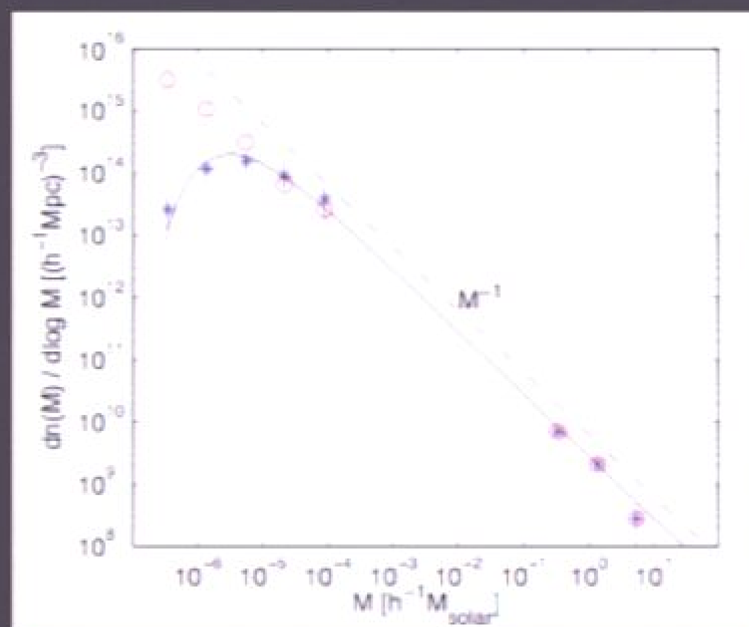
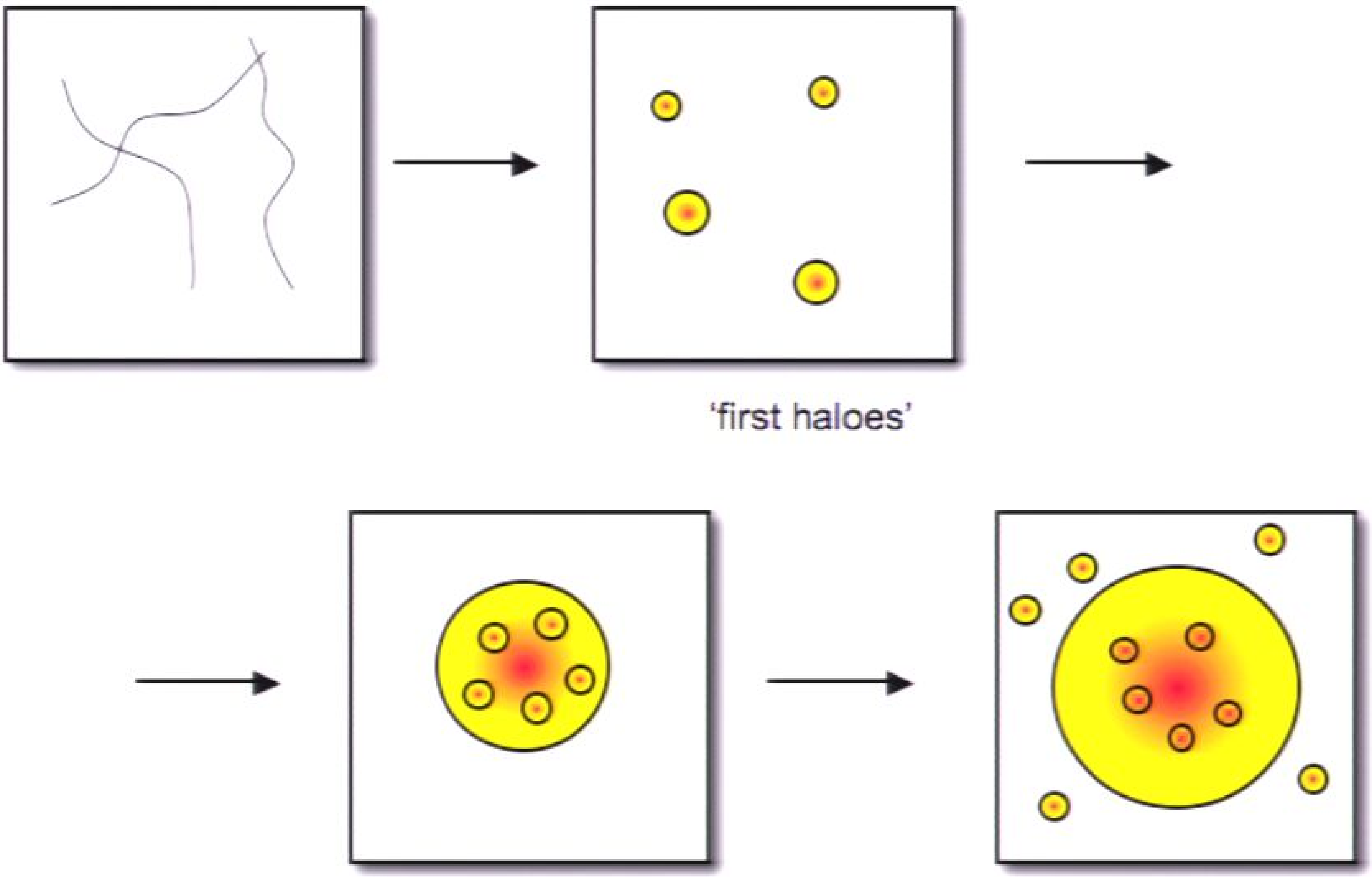
Motion on sky ~ 1 arcmin/yr





Given an initial spectrum, how does small-scale structure evolve subsequently?



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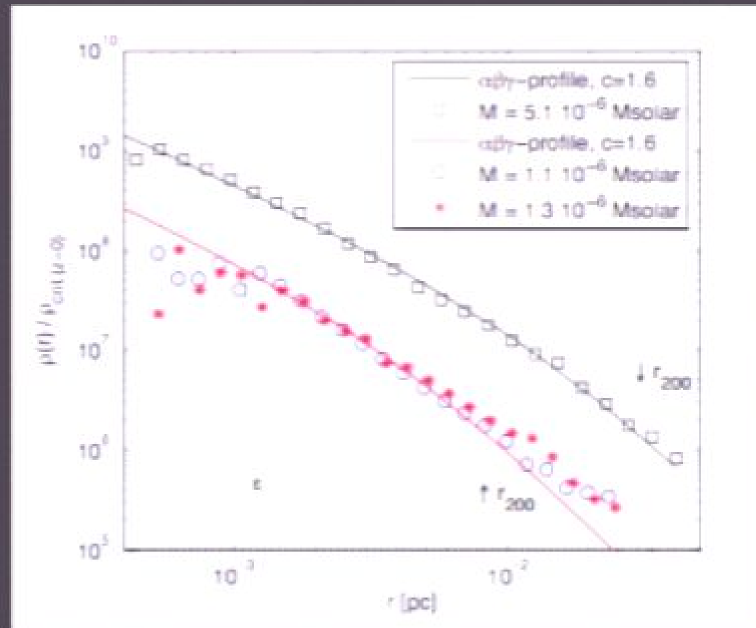

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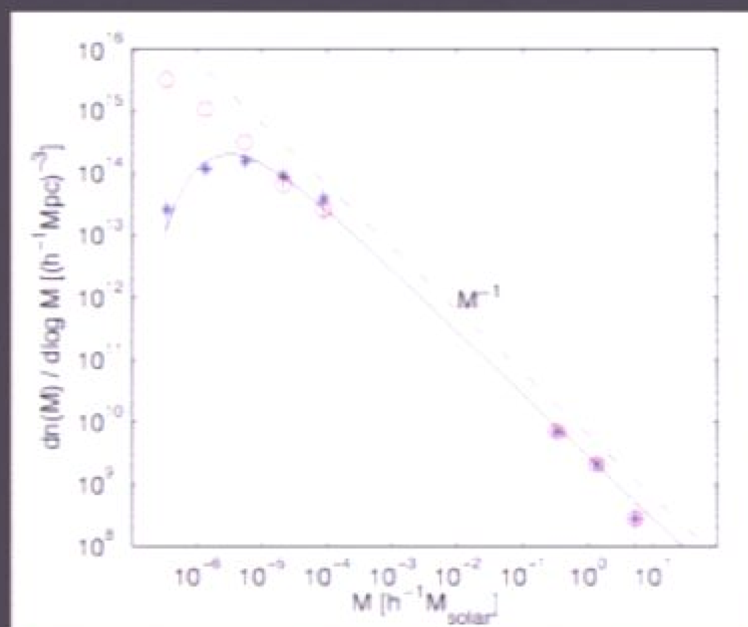

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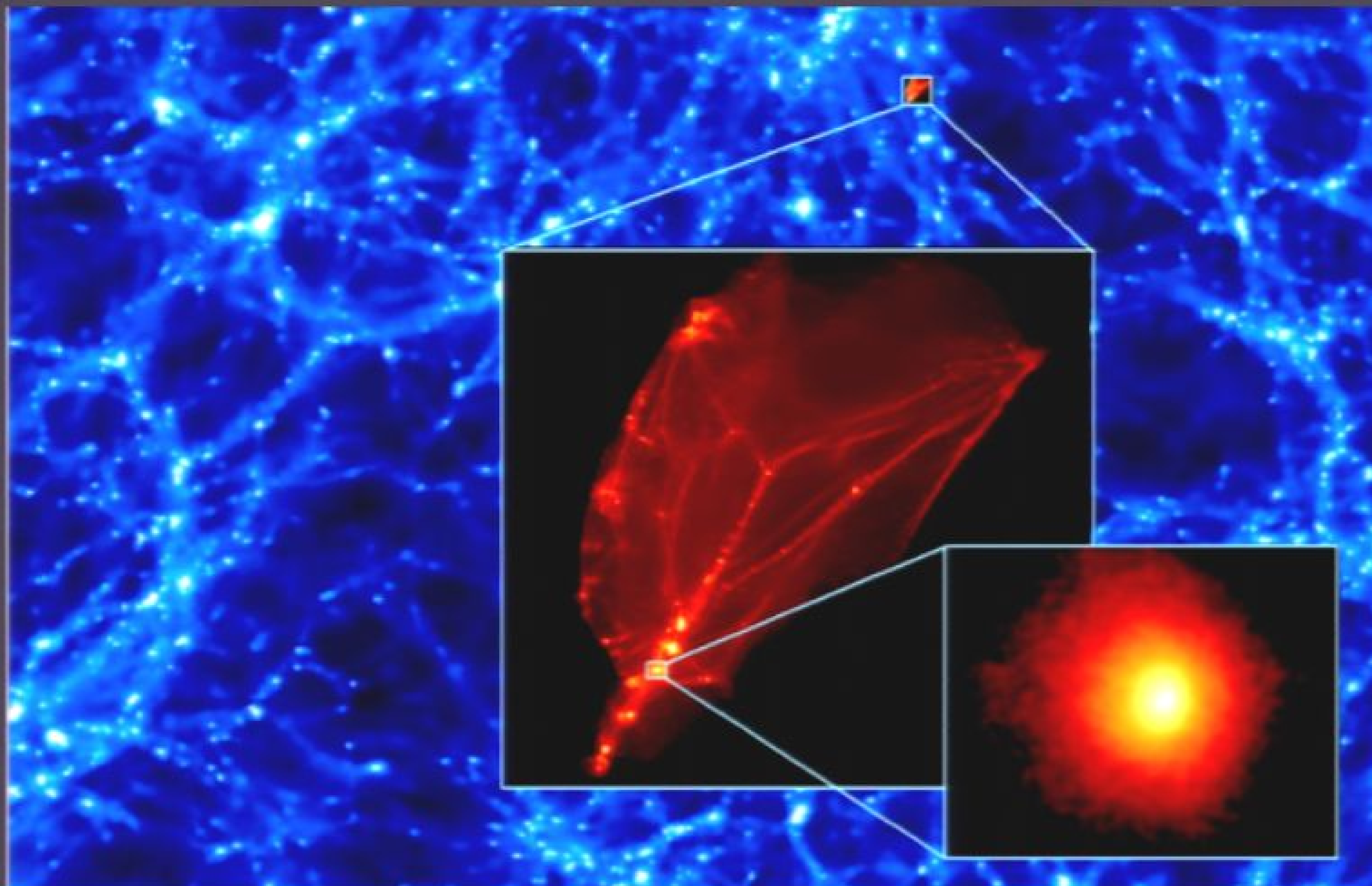

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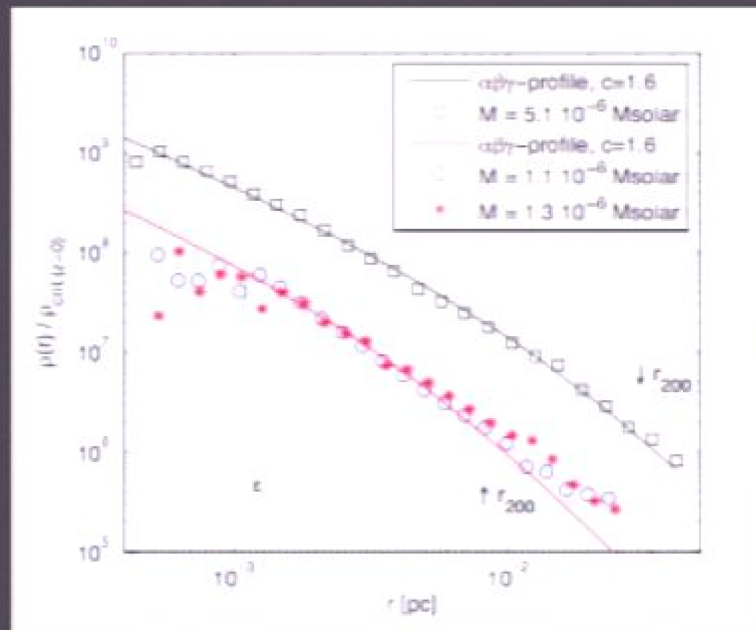

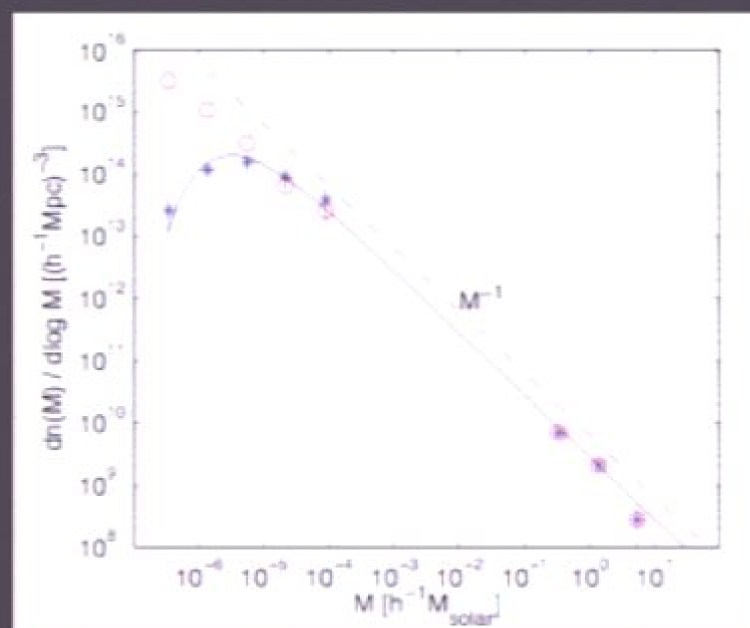

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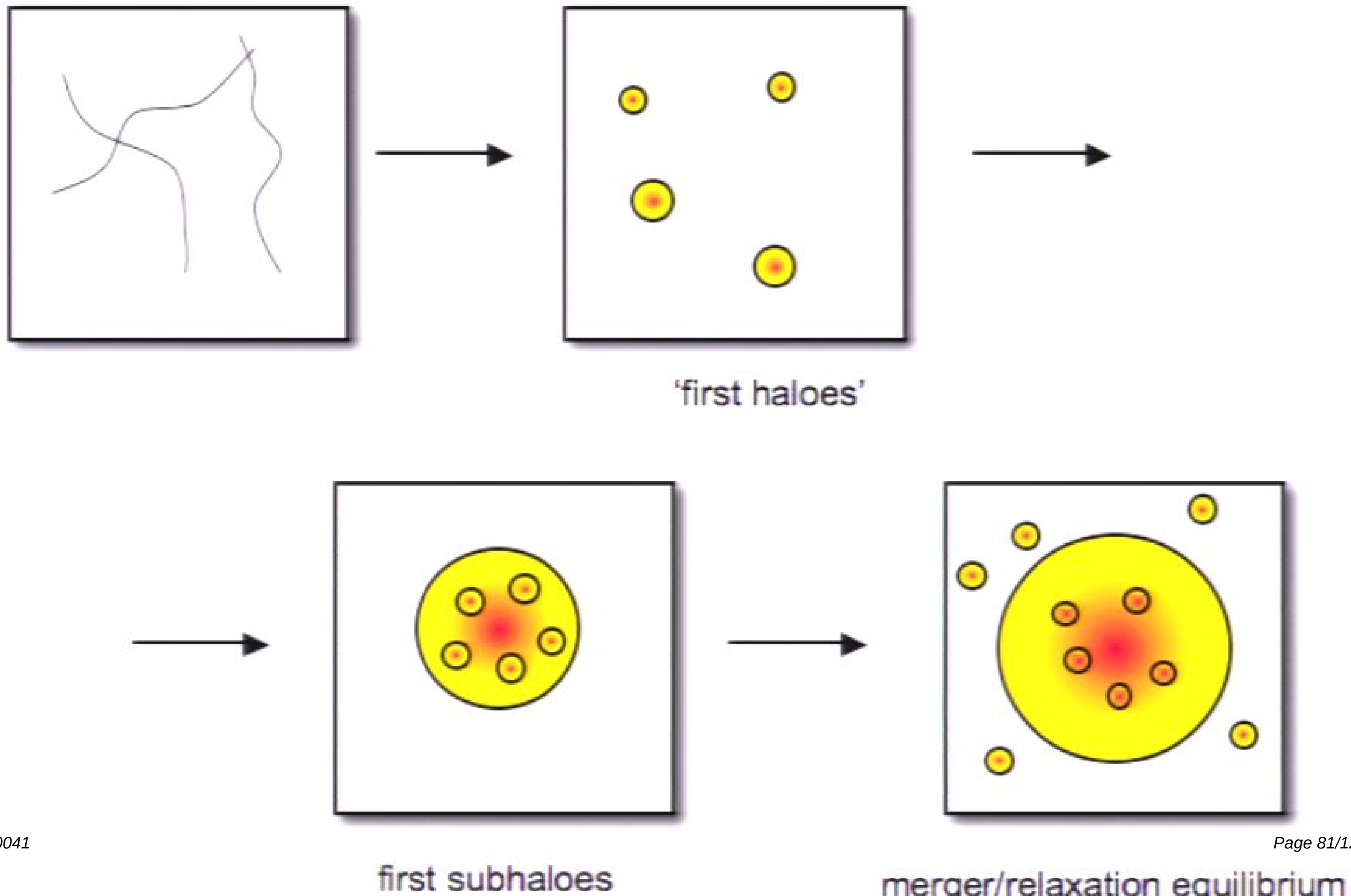
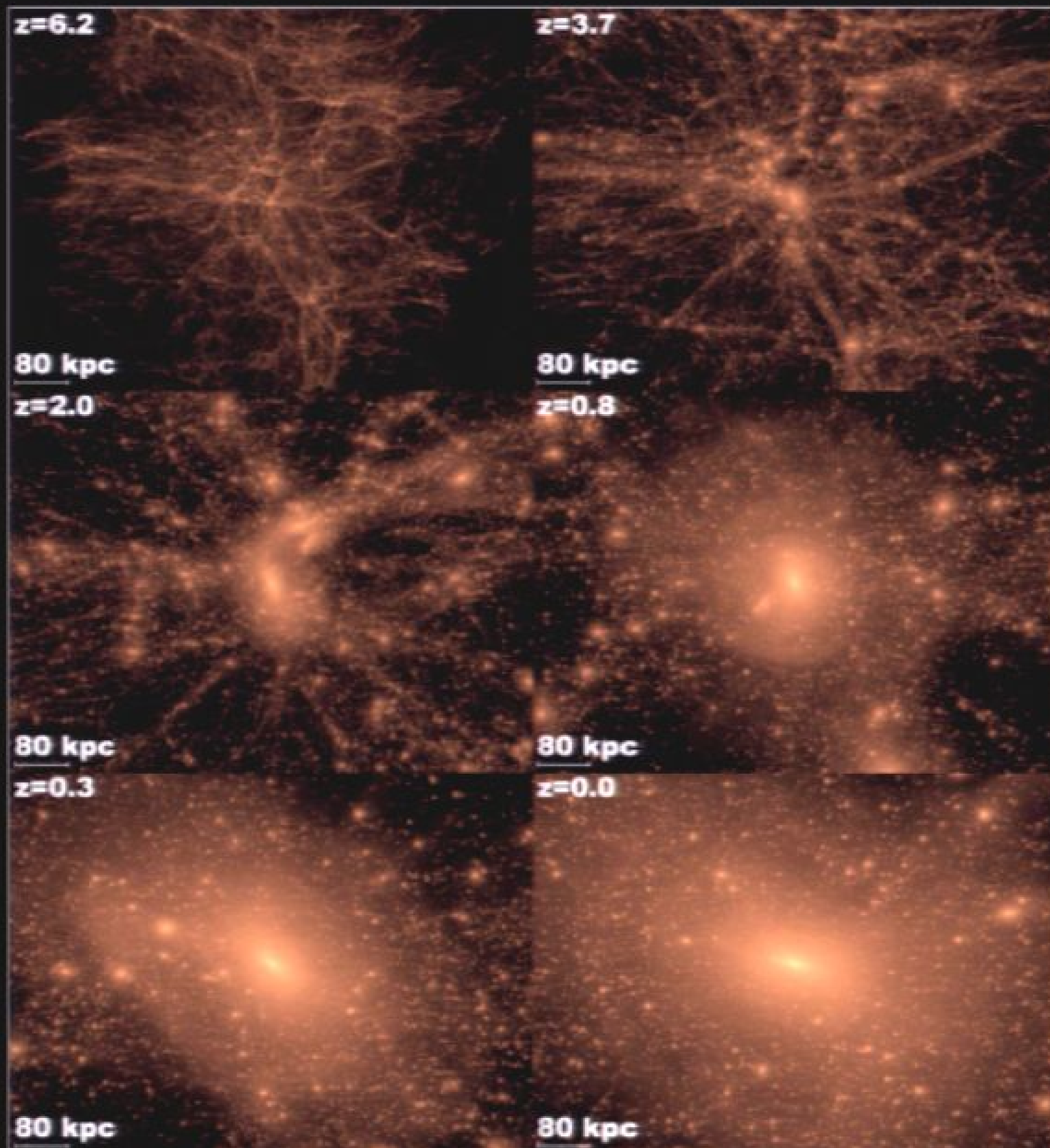


How to model small scales

Fundamental
resolution
limit
⇐ mixing

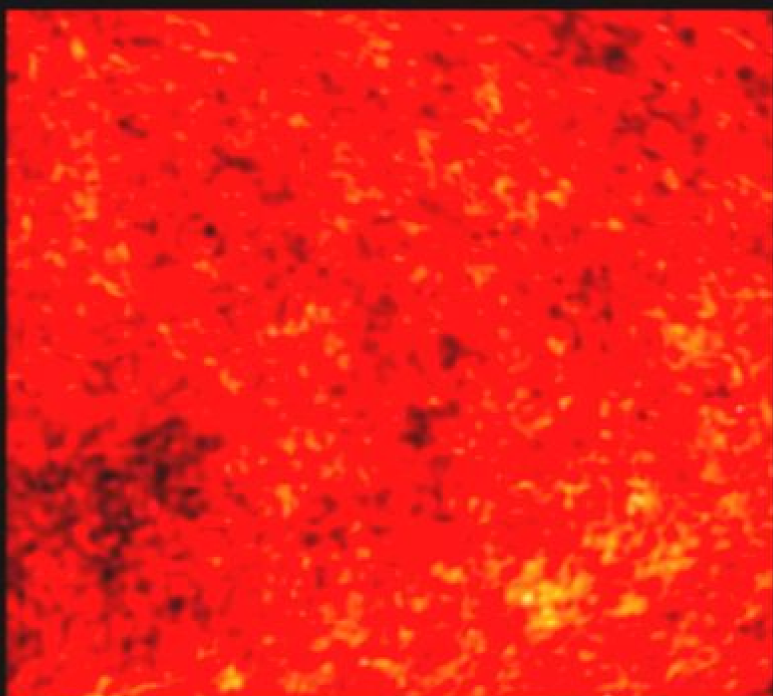


Via Lactea – Diemand, Kuhlen, Madau 2007

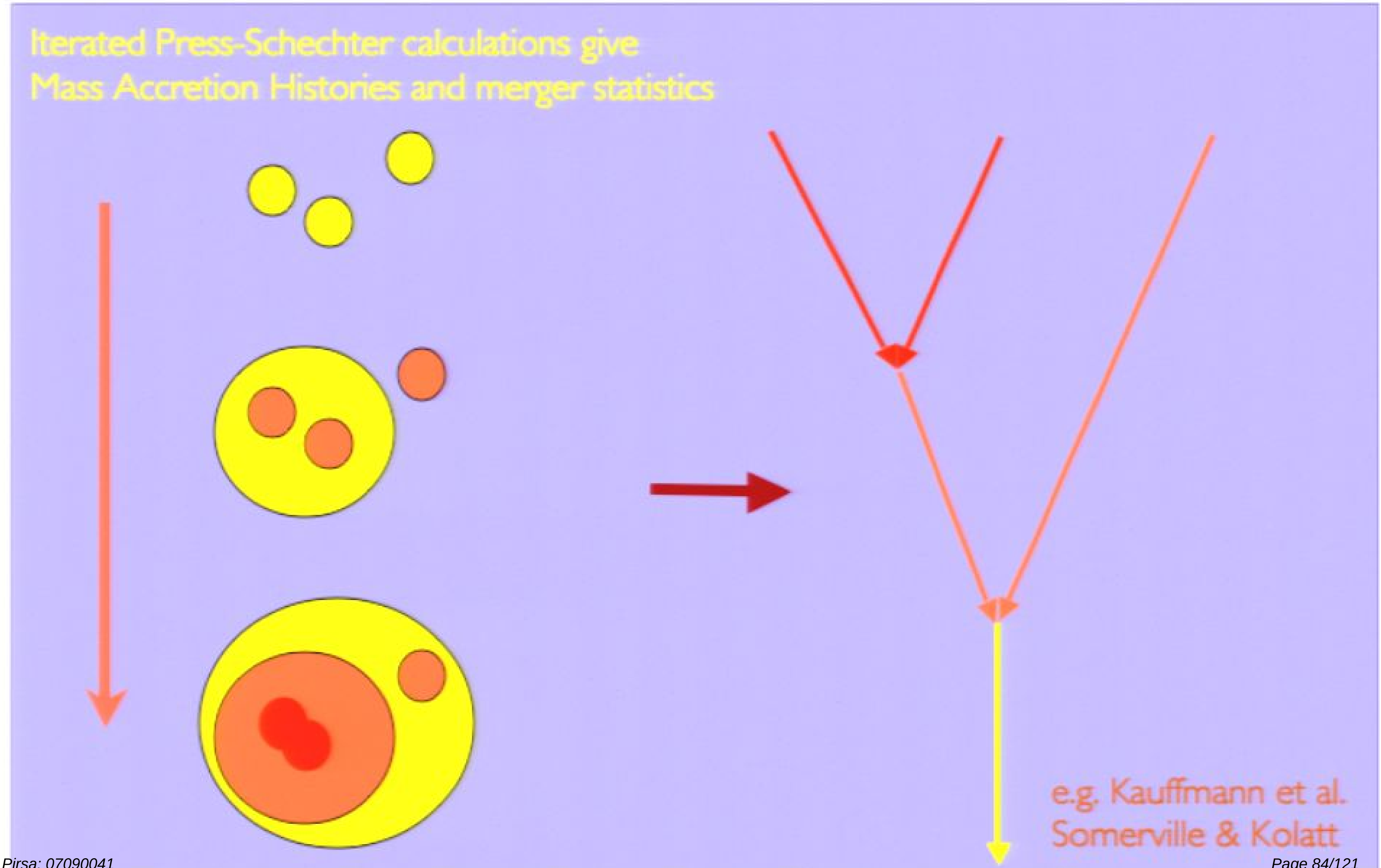
A statistical approach to the non-linear regime

Can't calculate full evolution of non-linear regime without N-body simulations, but can make statistical estimate of its extent: Press-Schechter theory

=> retain some of the power of linear theory to constrain parameters



Representing hierarchical non-linear growth: semi-analytic merger trees



Alternate Merger Tree Approach (w. Abel & Turk):

Basic resolution problem with trees:
Number of branches grows as ~Nlog(N), where $N = M/M_{res}$

Number of distinct redshift steps grows as N^2 or faster

So rather than following every branch, choose some preferentially, e.g. with declining probability at low mass

e.g. branching probability $= 1$ for $M > M1$

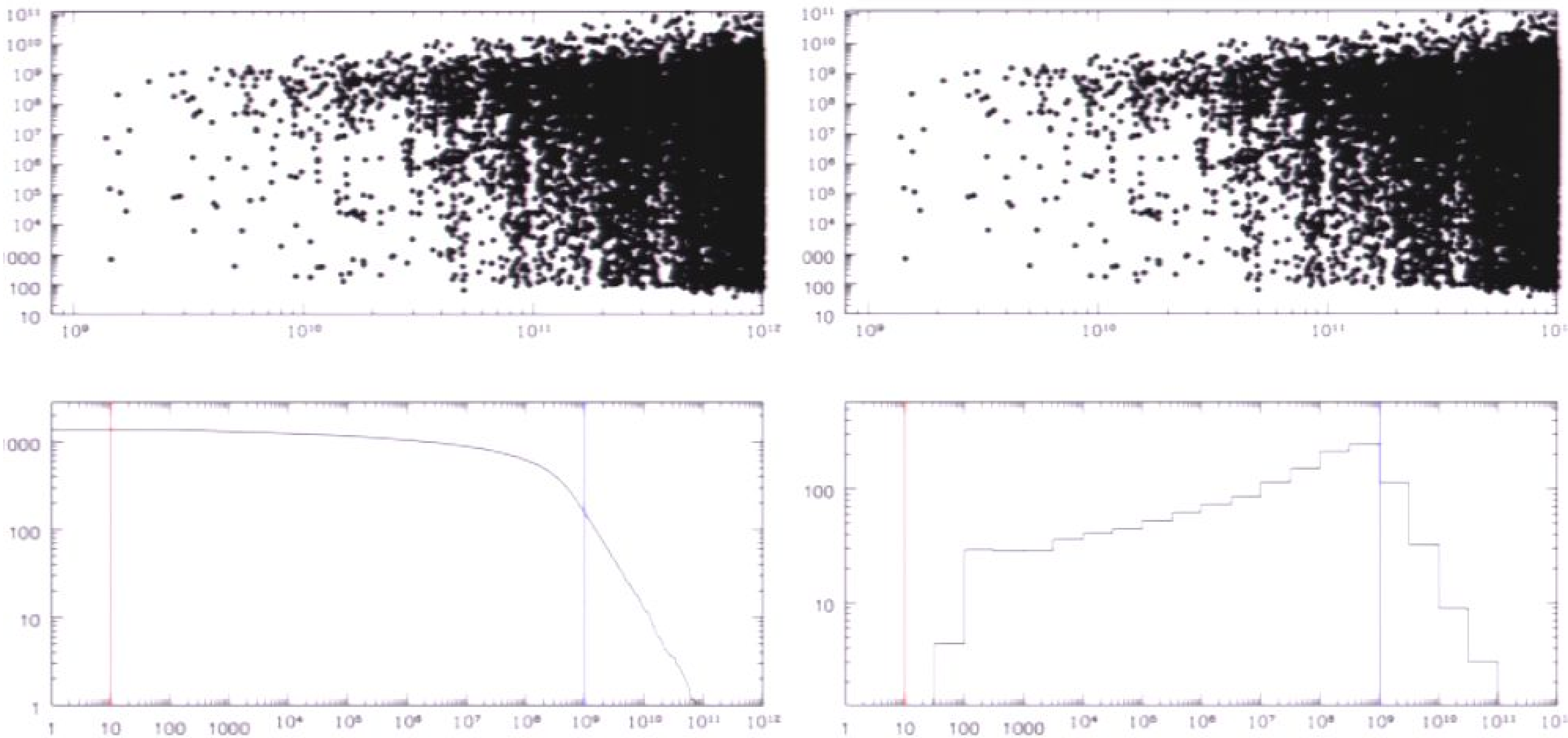
$= M/M1$ for $M2 > M > M1$

$= 0$ for $M < M2$

Get fast trees for $Mf/M1 \sim 10^3$, $M1/M2 \sim 10^8$

Use this as input to semi-analytic model of halo mergers and substructure evolution

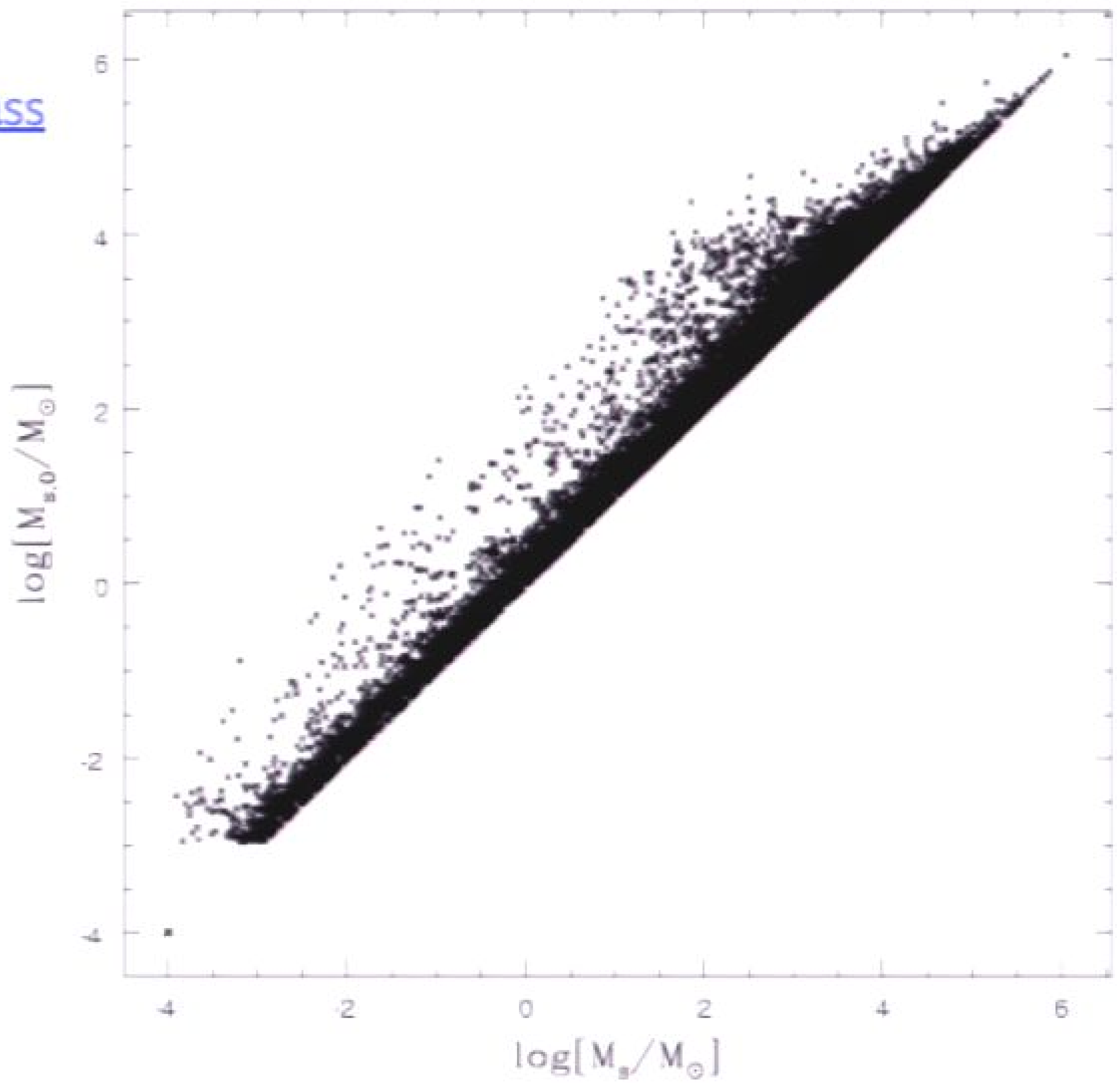
Sparsely-sampled Trees:



Some Results from Small Scales (~ R < R_{Sun})

I: Final mass versus initial mass

⇒two orders of magnitude range in mass loss



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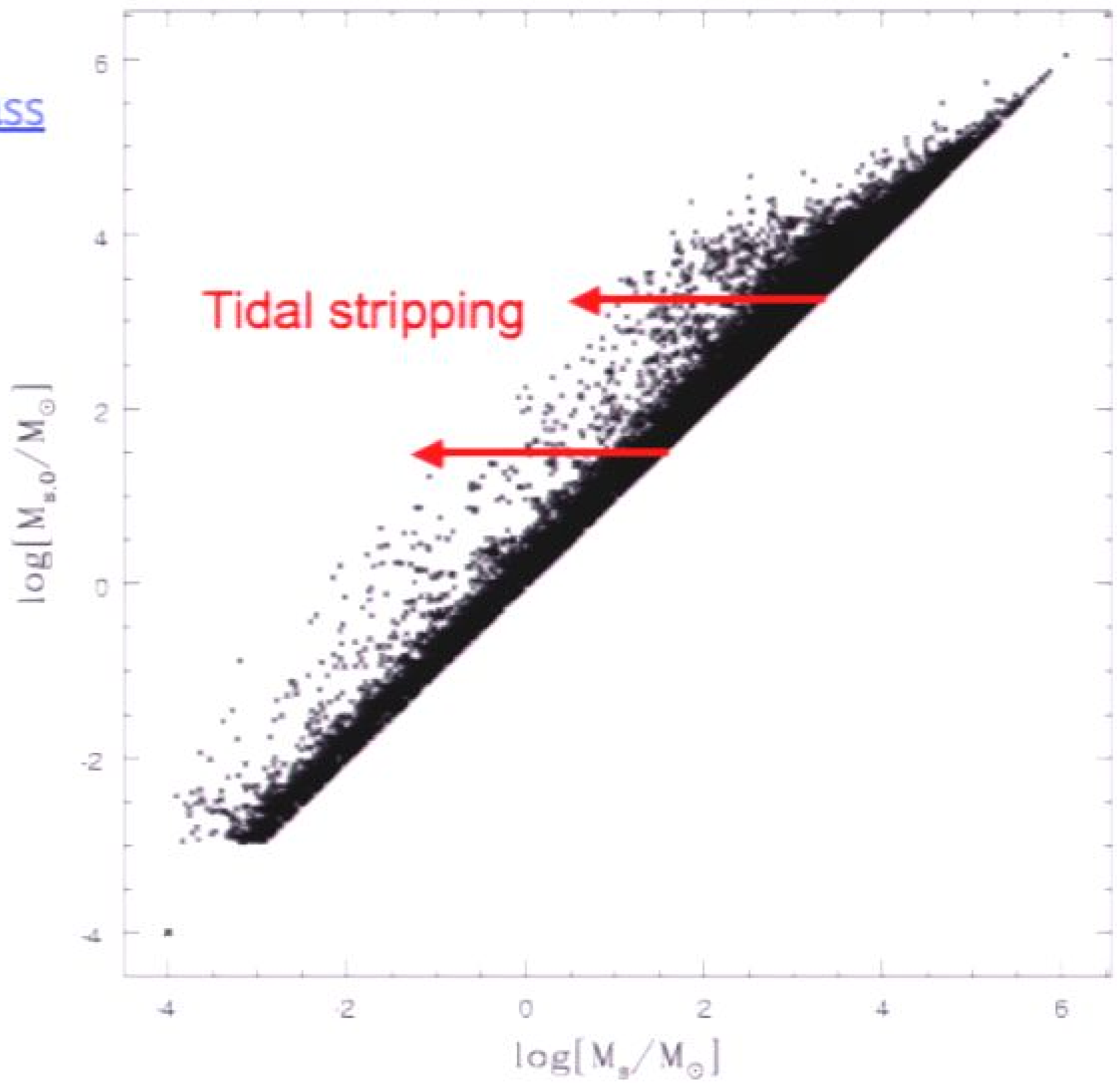
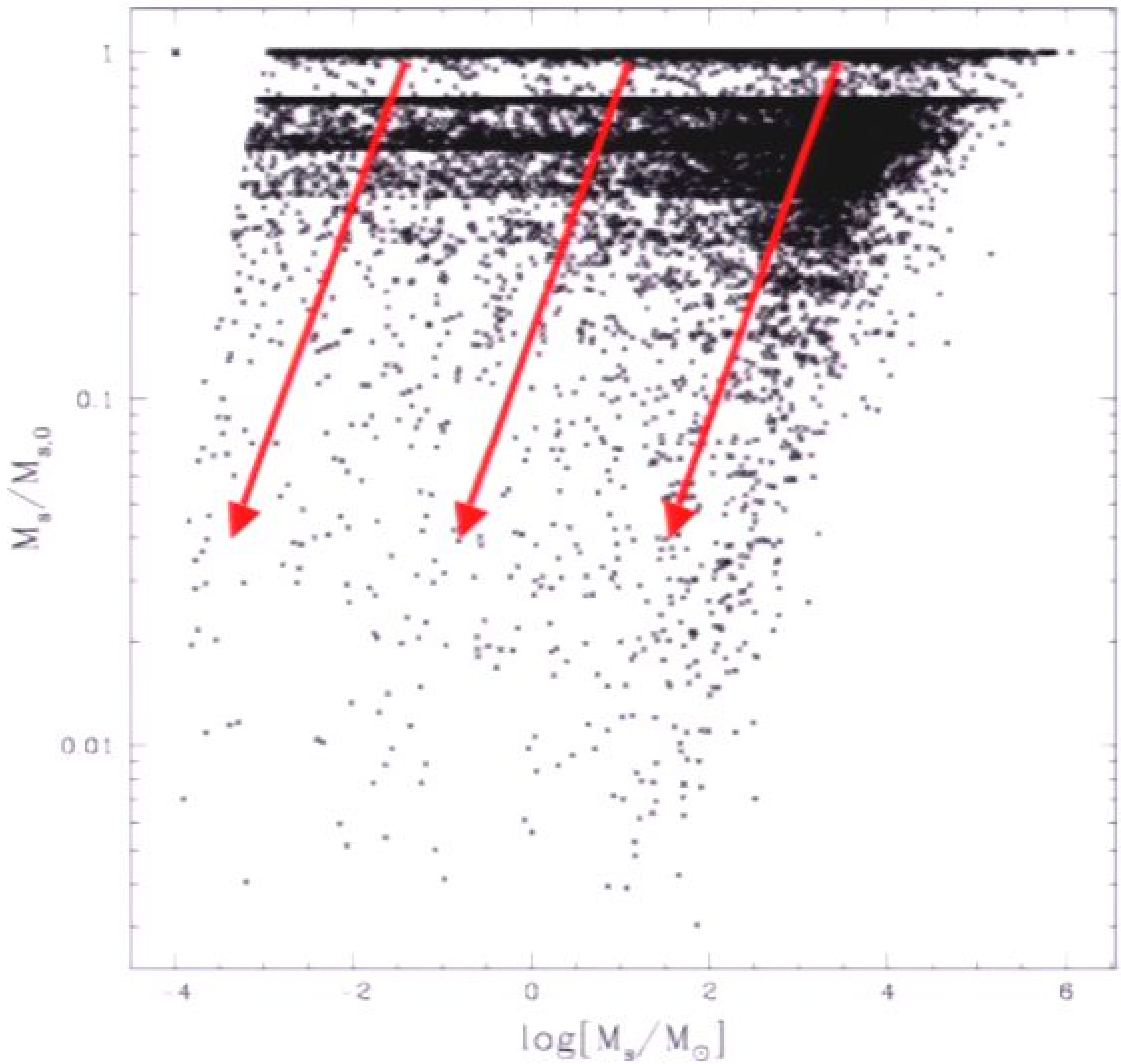


Some Results from Smaller Scales (~ $R < R_{Sun}$)

2: Mass loss vs. final mass

⇒ no major trend with mass

⇒ incompleteness in merger tree



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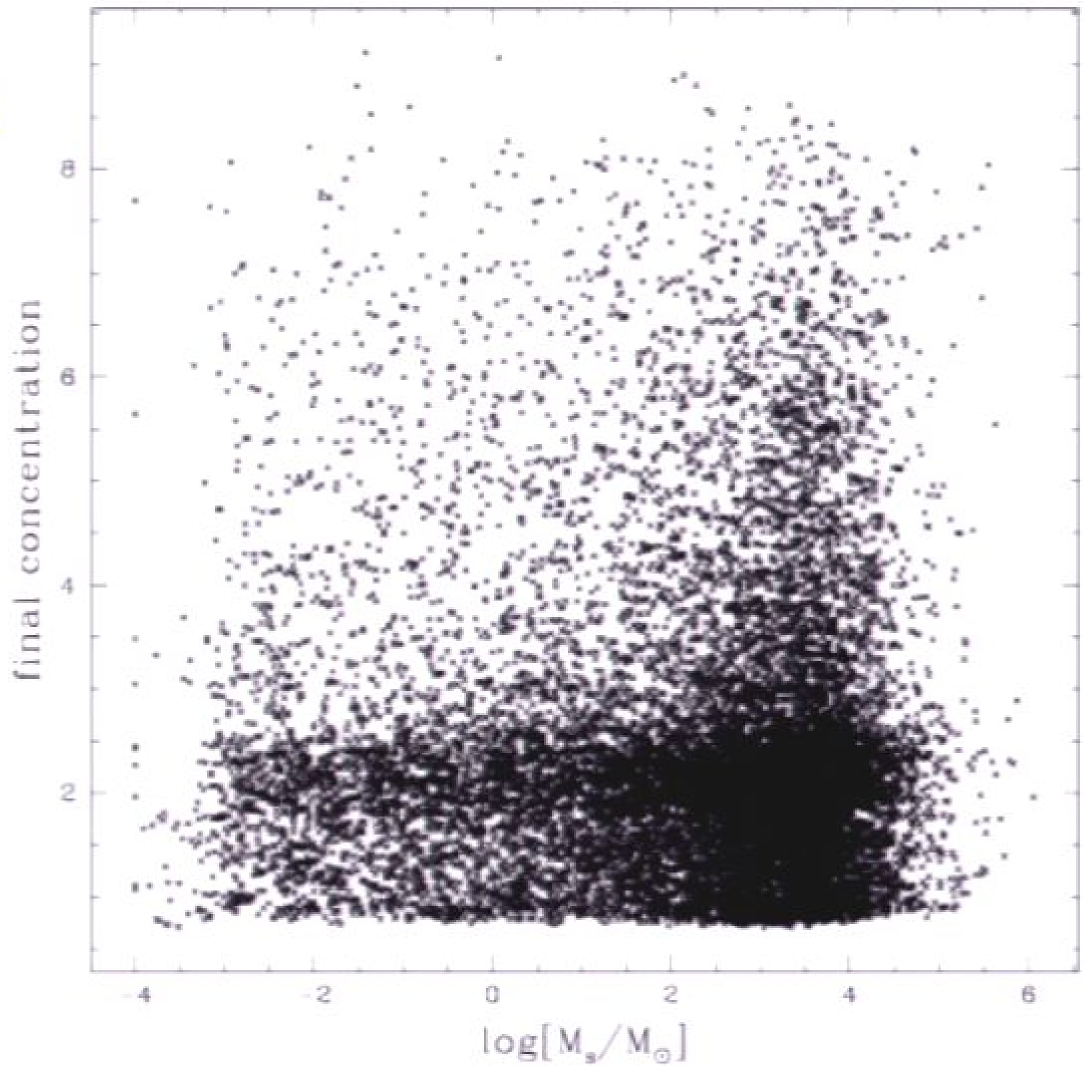
3: concentration vs. final mass

⇒ no major trend with mass

⇒ most systems heavily stripped



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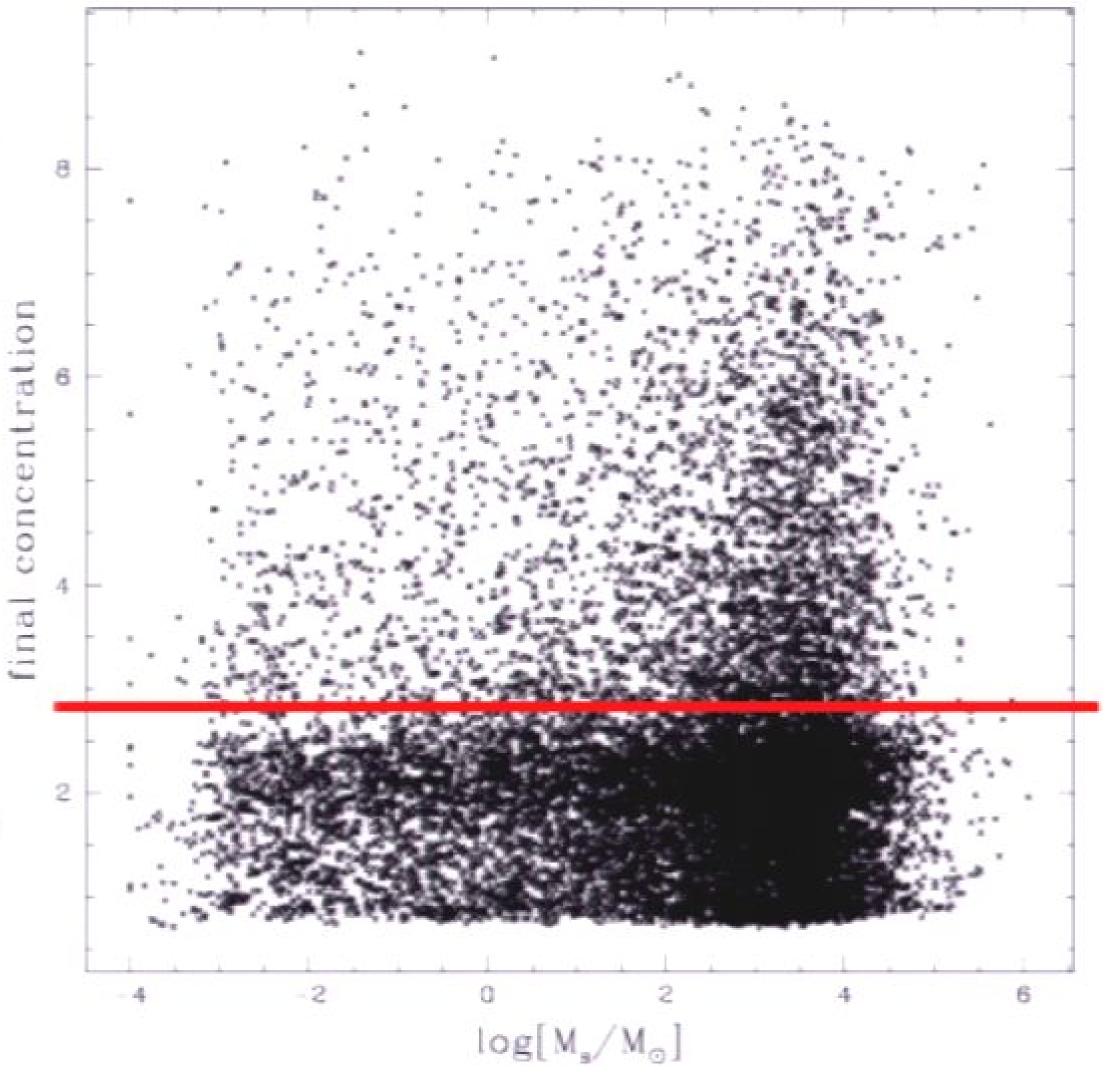

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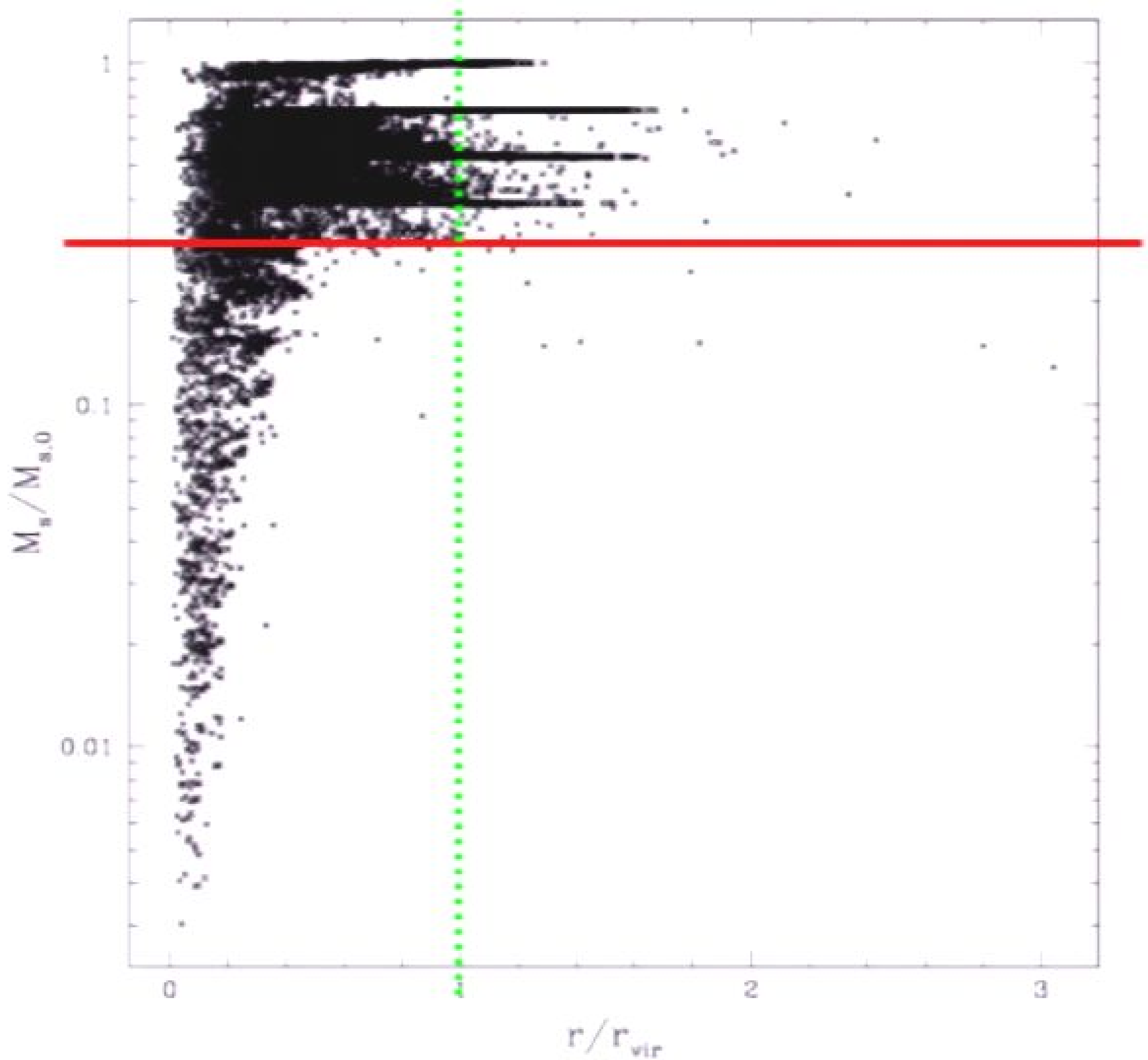
4: mass loss vs. location

⇒ heavily stripped systems are only found at small radii (but need to be careful about incompleteness of tree)



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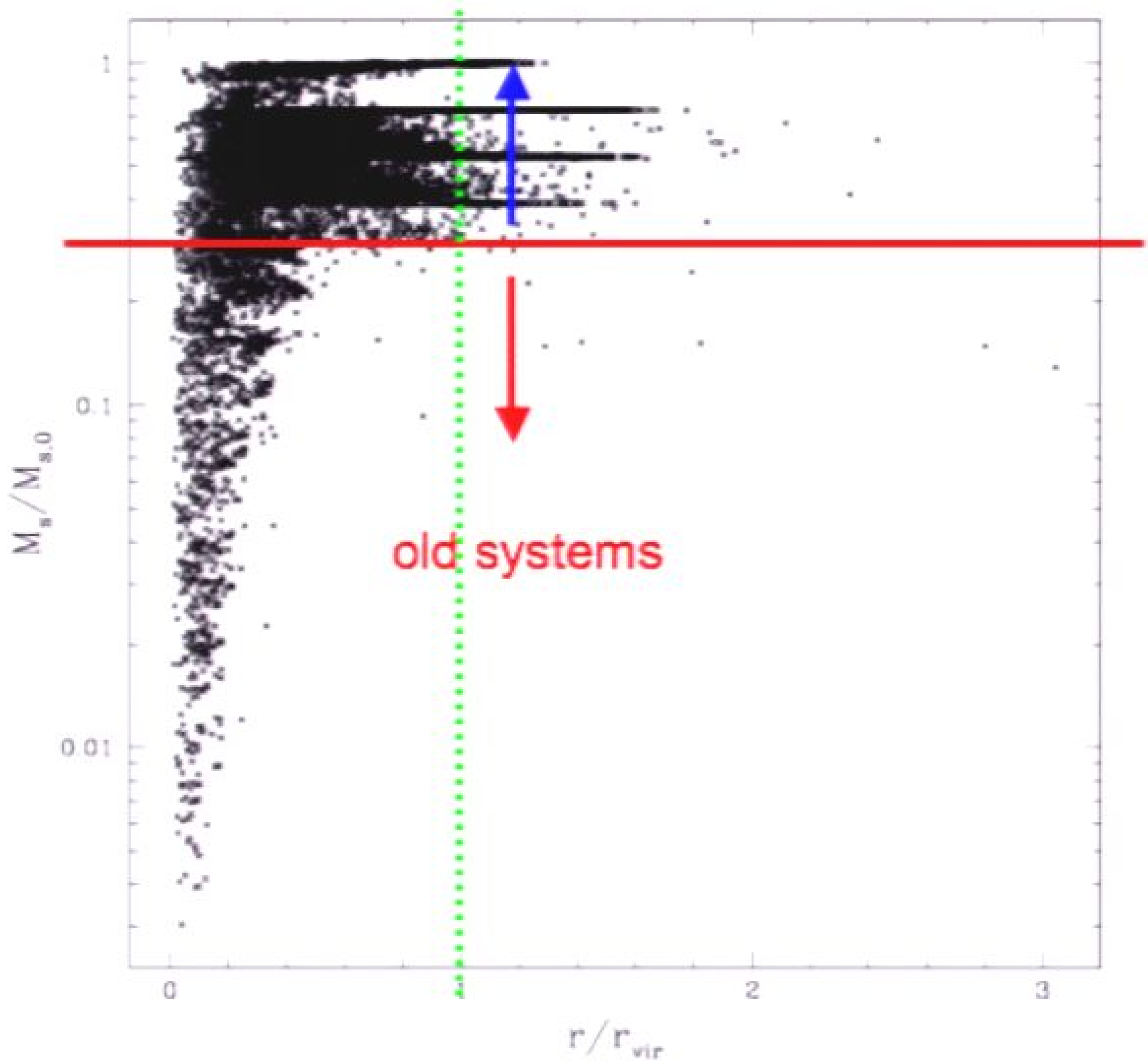


Some Results from Smaller Scales ($\sim R < R_{Sun}$)

5: luminosity vs. mass

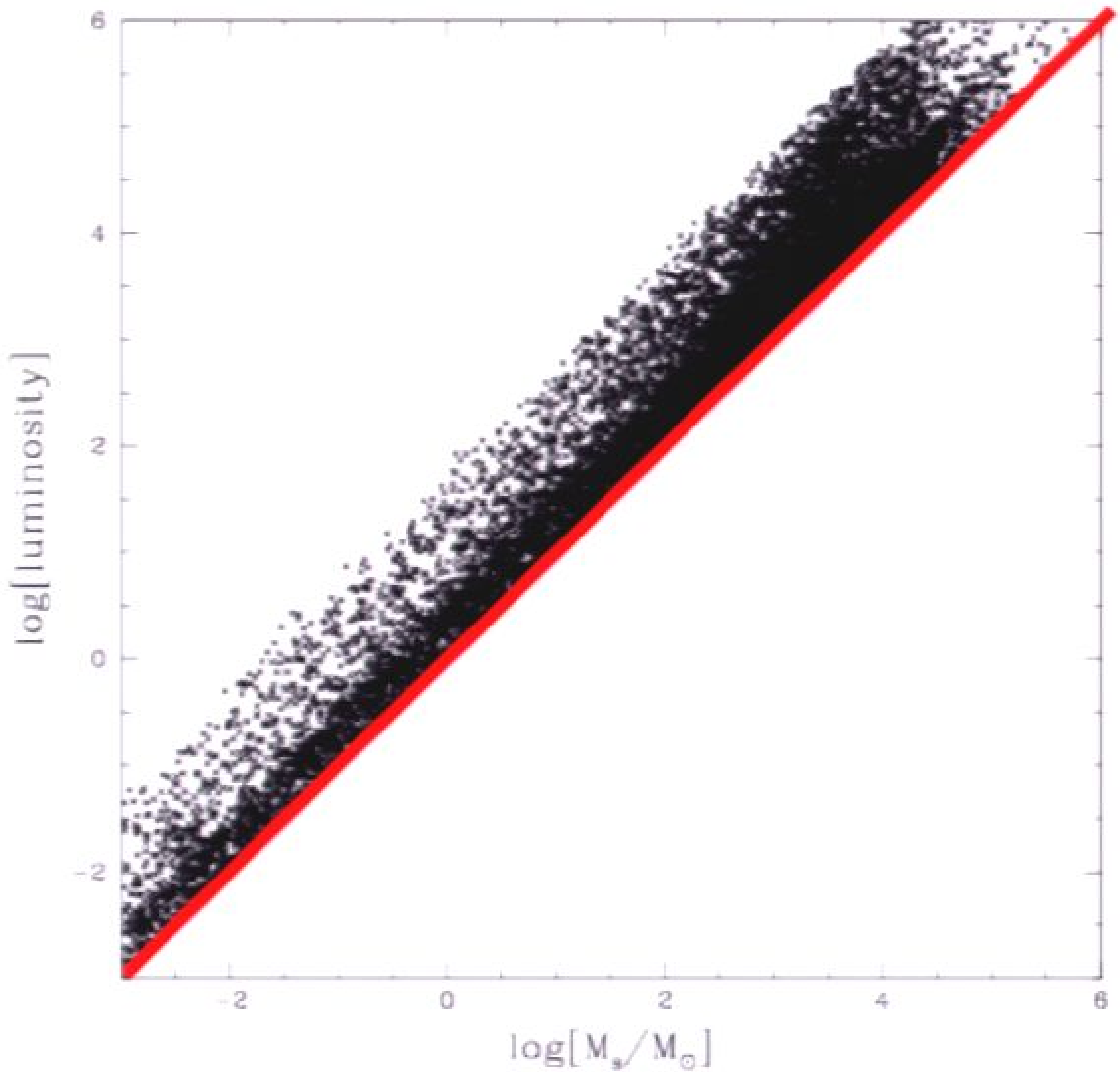
⇒ large scatter at fixed mass

⇒ massive systems dominate

however

(N.b. distance $\propto n^{-1/3}$

so apparent luminosity $\propto n^{2/3}$)



Small-scale Structure Summary

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Observational Paths to New Physics

- line-of-sight distances, e.g. $D_L(a)$ from SNe
- physical scales, e.g. the sound horizon from **Baryon Acoustic Oscillations**
- volumes, e.g. from **cluster number counts**?

- the growth of potential fluctuations (**ISW**)
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- physical scales, e.g. the sound horizon from **Baryon Acoustic Oscillations**
- volumes, e.g. from **cluster number counts**?

} geometry

- the growth of potential fluctuations (**ISW**)
- the growth of linear fluctuations (**cosmic shear**)
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Both ultimately measure H(a) or $\Sigma\Omega_i(a)$,

but with very different redshift weighting,

+ different relation to standard GR gravity.

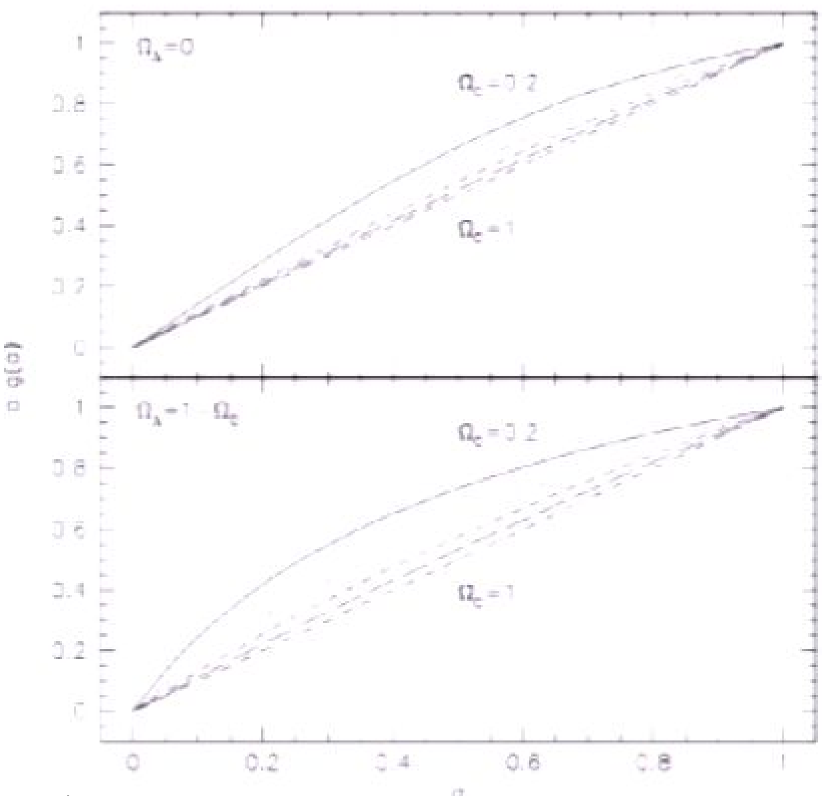
The value of multiple constraints (cf. Linder 2005)

Can modify the Friedman equation H(a) either by changing the *equation of state of dark energy* or by *modifying gravity*; either could produce exactly the same expansion history.

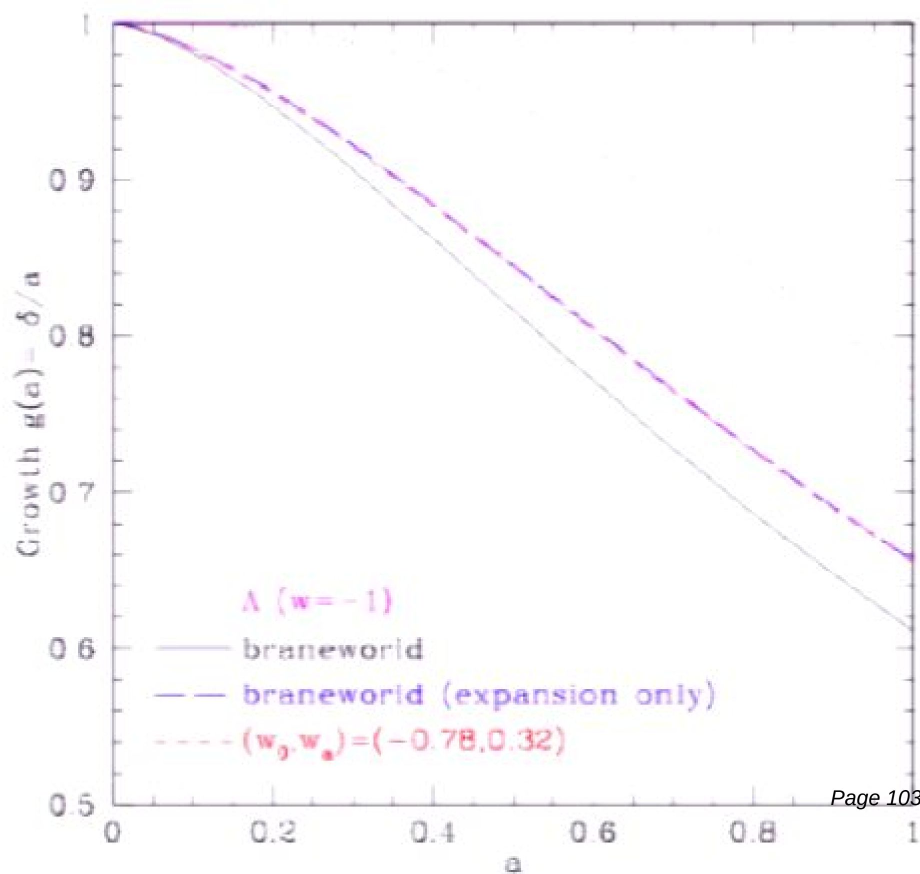
Linear growth factor describing the growth of perturbations can distinguish between the two (local vs. global effect)

e.g. DGP braneworld gravity

$$g \equiv \frac{D}{a} = \frac{5\Omega_m}{2}\frac{H(a)}{a}\int_0^a \frac{da'}{a'^3 H(a')^3}$$



Bartelmann & Schneider 1999



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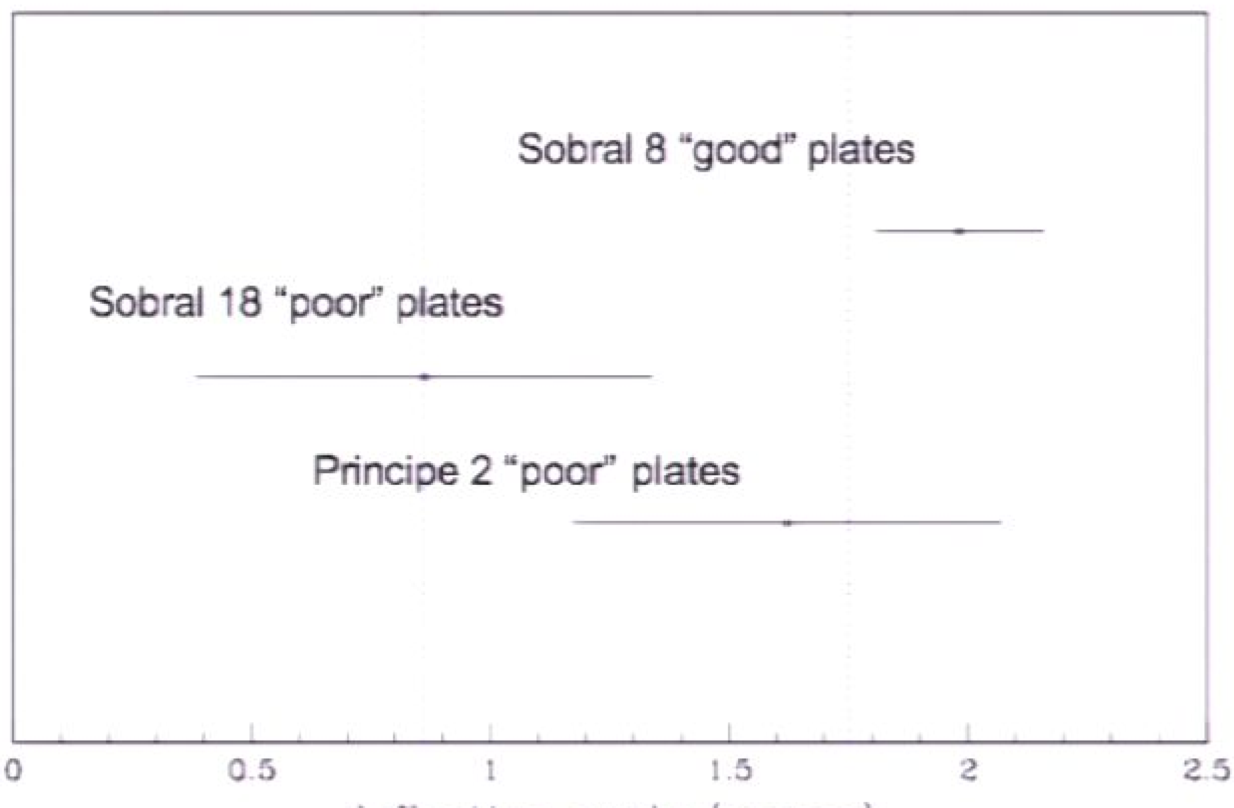

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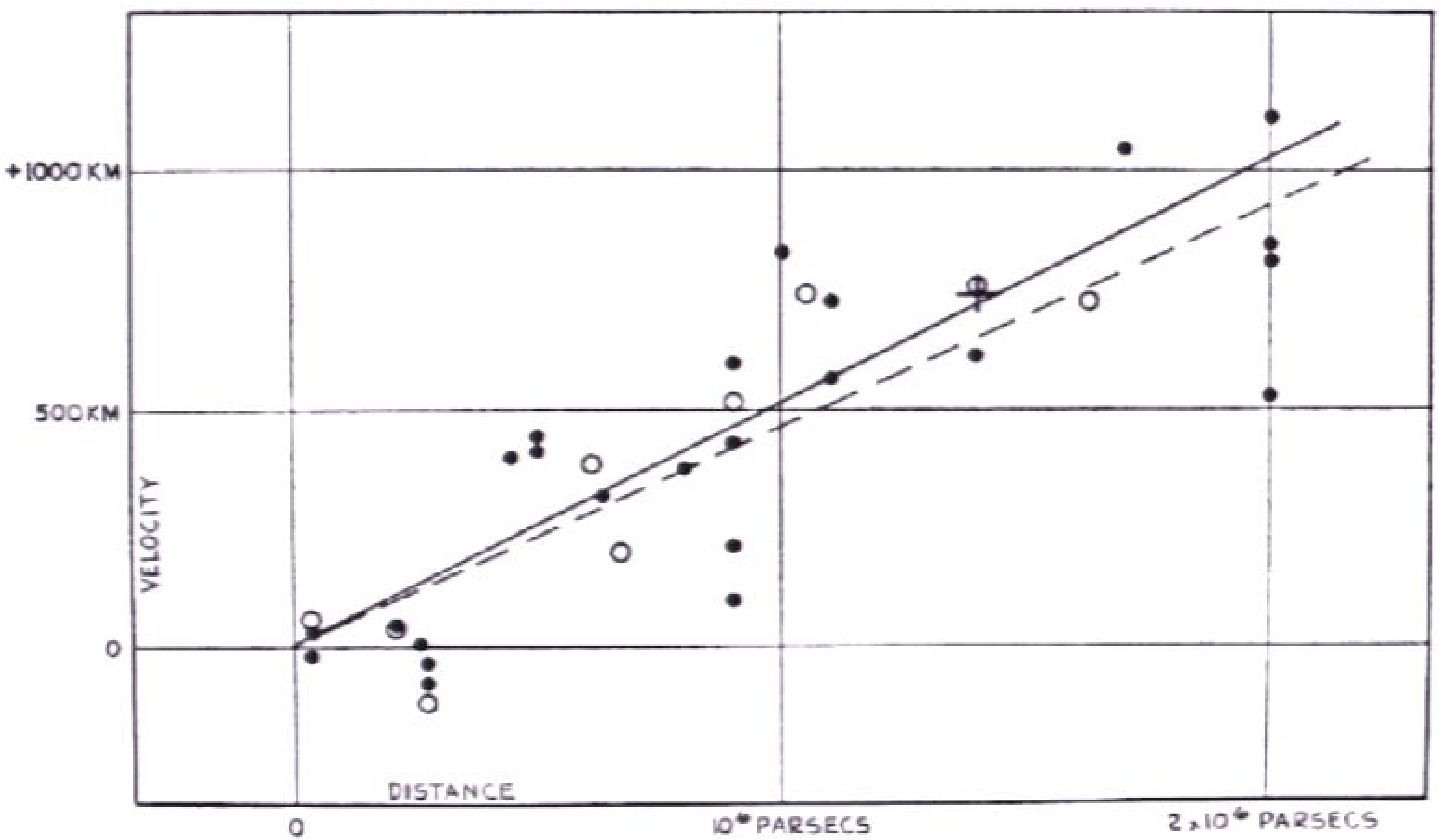
N.B. The original Hubble Law:



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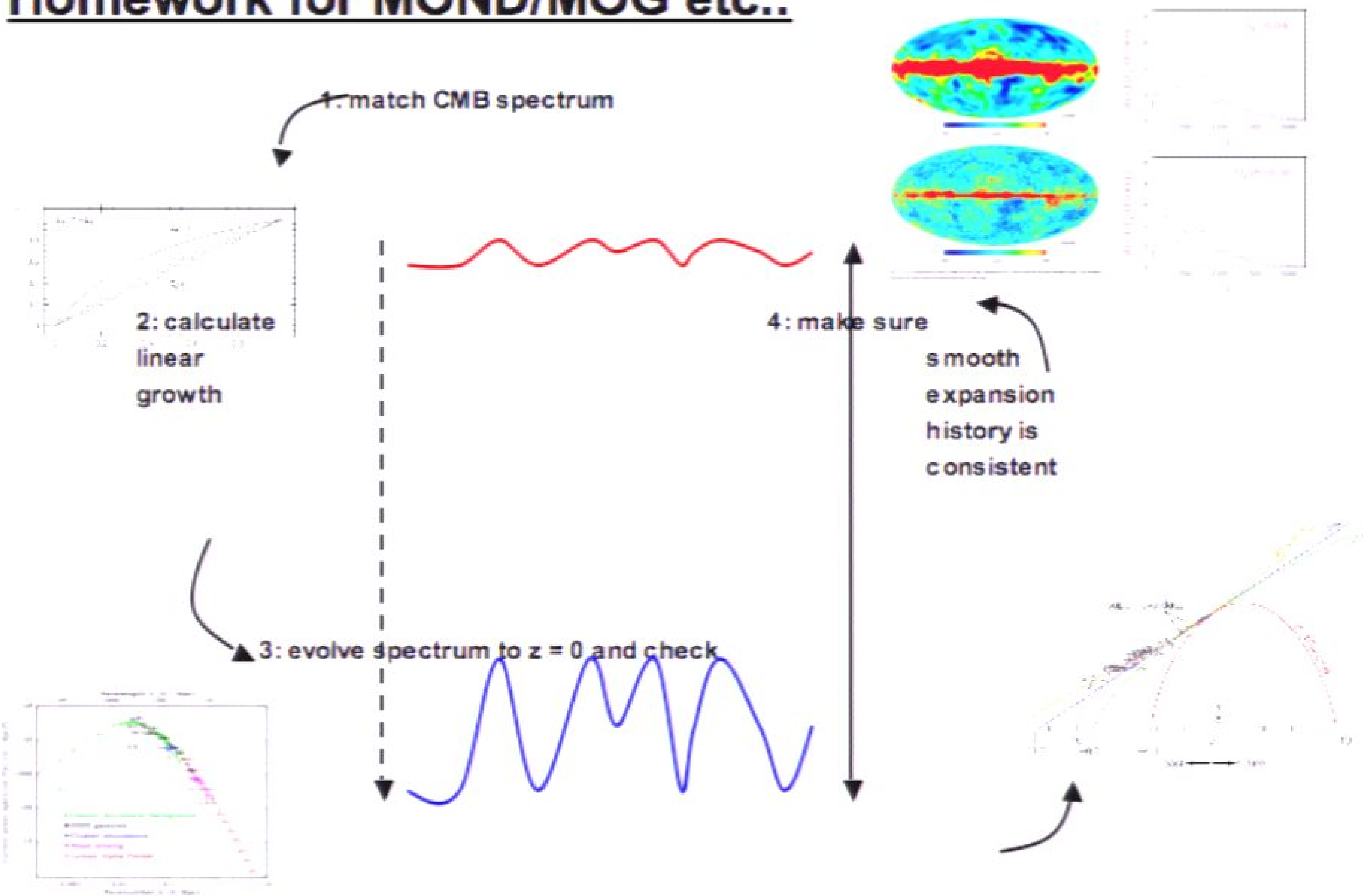
From this point of view, small scale structure and complex non-linear dynamics are attractive features of CDM, not crises or problems.

Also from this perspective, modifications to gravity need to focus on showing what else they can do, not on how well they can reproduce existing observations.

Homework for MOND/MOG etc.:



Note that: 1) none of these tests constitute a prediction

2) if it's too hard to figure out how to perform these tests properly that does not reflect well on the theory

Real Homework for MOND/MOG/etc.:

Where are the missing baryons? (i.e. the 50-70% of all baryons)
Can we ever detect them?
When do the "first" galaxies form? How do they form?
What are the masses of the first galaxies? Where do AGN come in?
What sets present-day galaxy masses, sizes, spins?
How is the IGM enriched?
How are baryons processed through galaxies?
What are the masses of the first stars?

and finally…

is there a solid theoretical motivation for the theory? e.g. is it some sort of "attractor" in theory space?

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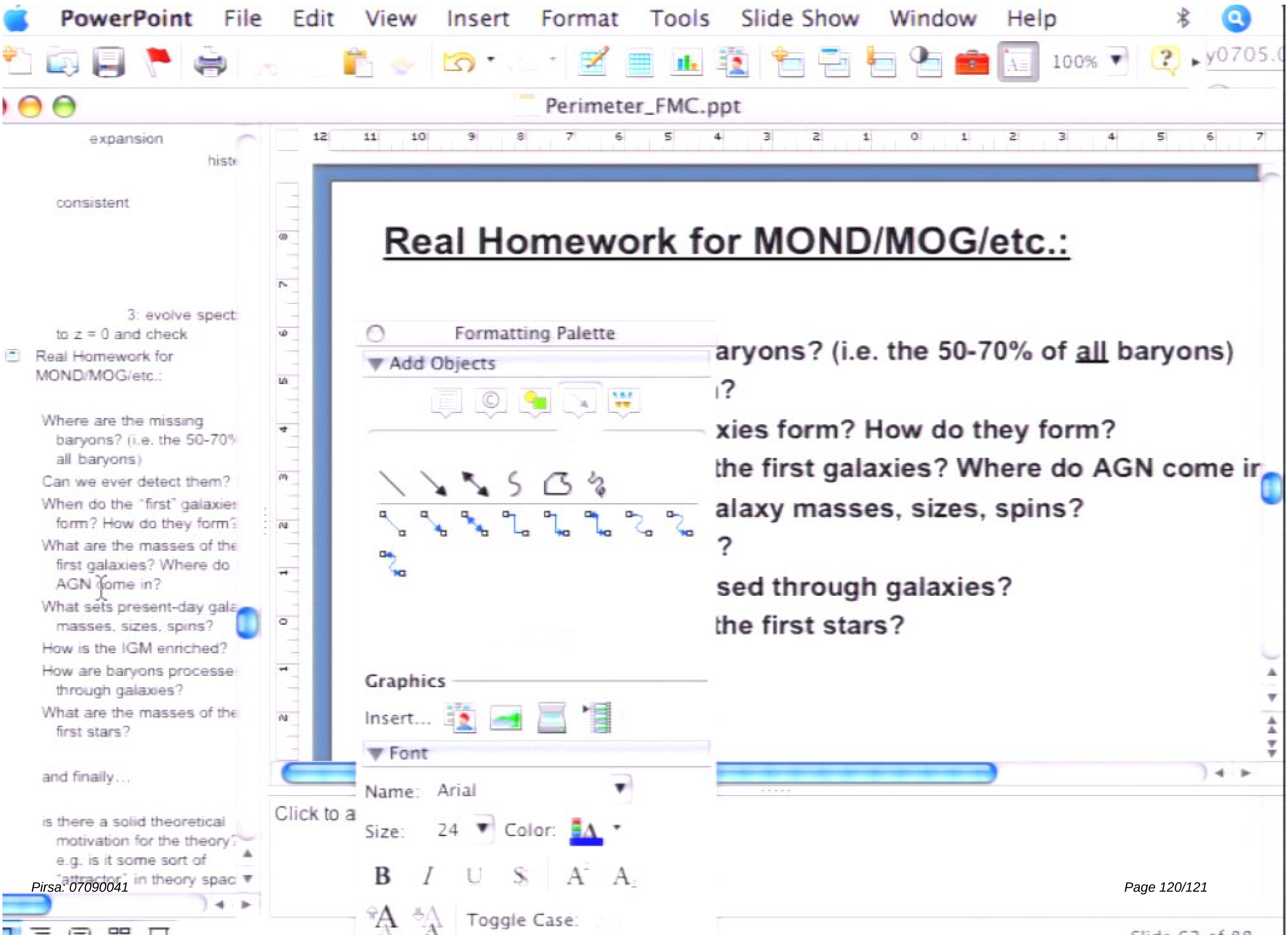
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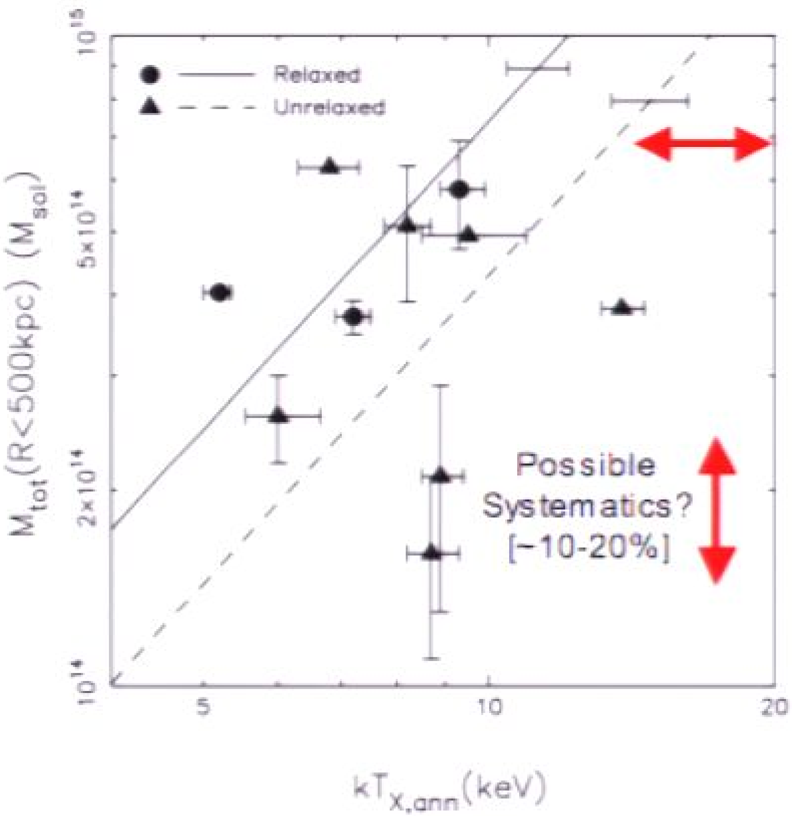
Structural segregation in the M-T relation?



Smith et al., 2005, MNRAS, 359, 417

- Mass measurement wrong for non-SL clusters?
- Core-related phenomena?
  - Pederson et al., 0603260
- Cluster-cluster mergers?
  - Ricker & Sarazin 2001, Randall et al. 2003
- What else?