Title: Cosmological Constraints from Gravitational Lensing

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Abstract:

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Perimeter Institute

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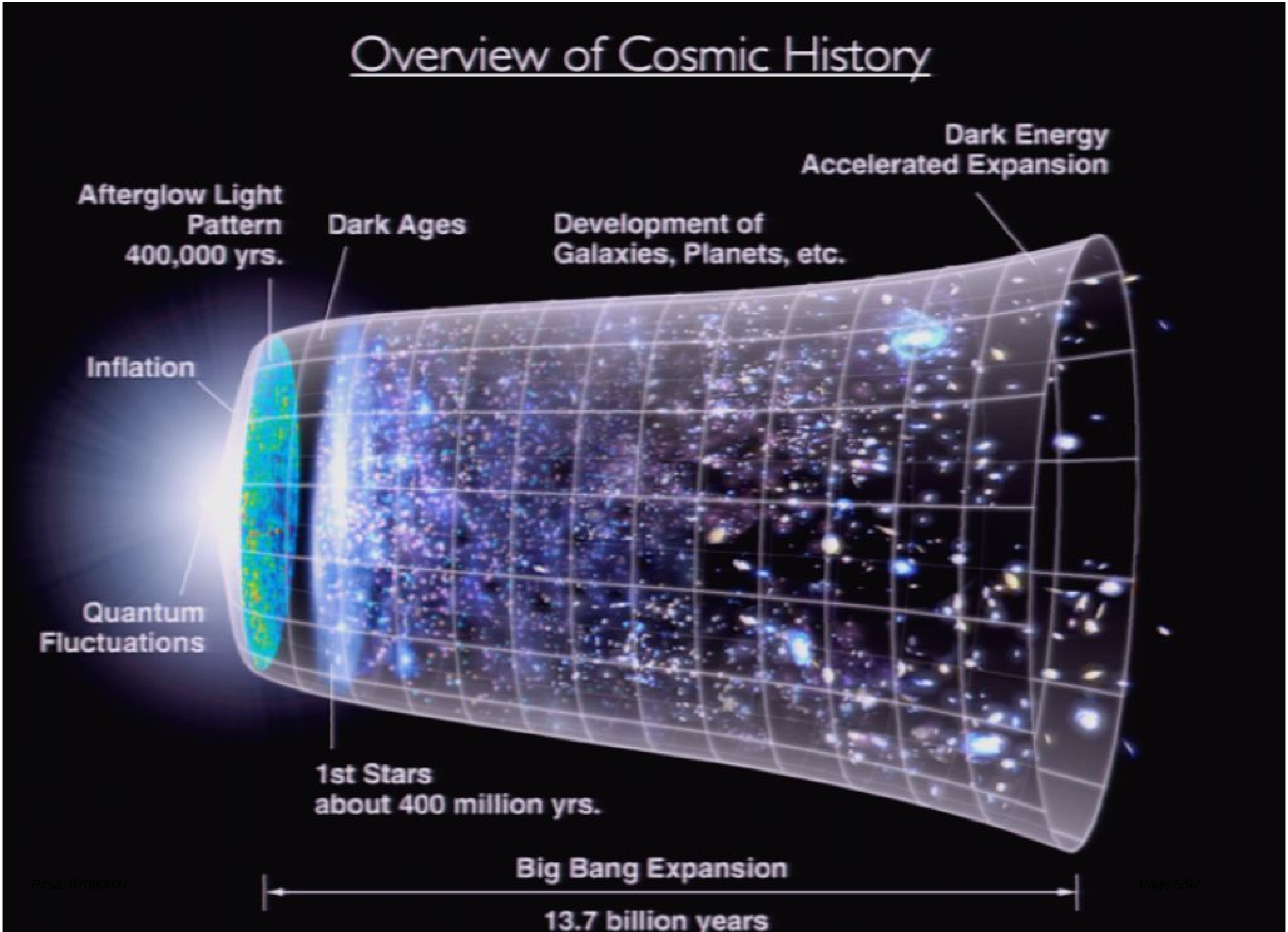
Outline

1) Introduction: what is observational cosmology and what does it tell us?

2) Lensing Basics, and forms of lensing

3) Weak Lensing results in cosmology

4) Results from a few recent surveys


Overview of Cosmic History
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Overview of Cosmic History

Era	Redshift	time	T (K)	E
Inflation, Topology		10^{-35} s	10^{27}	10^{14} GeV
The High-Energy Universe		10^{-6} s	10^{13}	1 GeV
Last Scattering	1100	3×10^{5} yr	3300	1 eV
The Dark Ages	1000-70	1 Myr	1000	
The First Stars	70-50	50 Myr	100	
Reionization	8-15	.2-.6 Gyr	30	
Formation of Massive Galaxies & AGN	2-5	1-3 Gyr		
Formation of Galaxy Clusters, end of Structure Formation	0-1	6-13.6 Gyr	2.79	

Overview of Cosmic History

"Cosmology"

"Observational Cosmology"

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What can we learn from observational cosmology?

Basically two things:

* Current expansion rate and expansion history of the smoothed background

⇐ net contents of the universe (matter, radiation, vacuum energy, etc.)

* Fluctuations in the smooth background

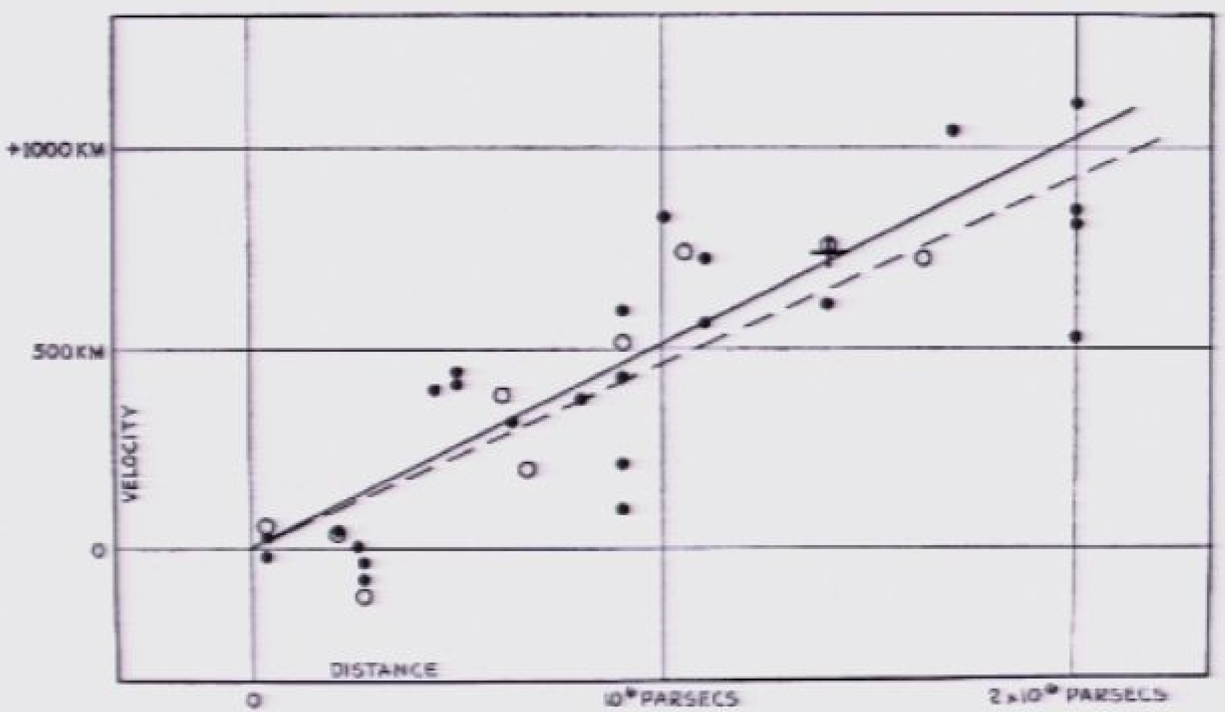
⇐ production method (inflation) and expansion history of the early universe

⇐ physical properties (velocity, temperature, pressure, interactions) of the different matter and energy components

What can we learn from observational cosmology?

a) The current expansion rate: the Hubble constant

$<v> \sim (\lambda - \lambda_0/\lambda_0) = H_0 d$; $H_0 \sim 73$ +/- 5 km/s/Mpc



all observed distances, densities etc. scale with this constant, often written as

H_0 = 100 h km/s/Mpc where h ~ 0.73

What can we learn from observational cosmology?

b) The past expansion rate at all times, $H(a) = \dot{a}/a$

N.B. easiest to measure the scale the expansion has reached:

scale factor $a = 1/(1+z)$

$$H^2(a) = H^2(0)\ [\ \Omega_R(0)\ a^{-4} + \Omega_m(0)a^{-3} + \Omega_k(0)a^{-2}\ + \Omega_\Lambda(0)a^0\ ]$$

(Friedmann equation)

here $\Omega_m(0)\ = \rho_m(0)/\ \rho_{crit}(0)$

for dark energy replace $\Omega_\Lambda a^0$ with $\Omega_X a^{-n}$ where $n = 3(1+w)$

$w = p/\rho$

equation of state parameter; can in principle be $w(a)$

What can we learn from observational cosmology?

c) Various integrals of the expansion and/or geometric terms:

"Luminosity distance" (+ in principle also time)

$$d_L = (1+z)\, S_k(r) = a \int_0^z dz/H(z)$$

$$\text{where } S_k(r) = \begin{cases} R_0 \sin(r/R_0) & k = +1 \\ r & k = 0 \\ R_0 \sinh(r/R_0) & k = -1 \end{cases}$$

all this ⇒ H(z)

⇒ equation of state

"Angular diameter distance"

$$d_A = 1/(1+z)\, S_k(r) = 1/a \int_0^z dz/H(z)$$

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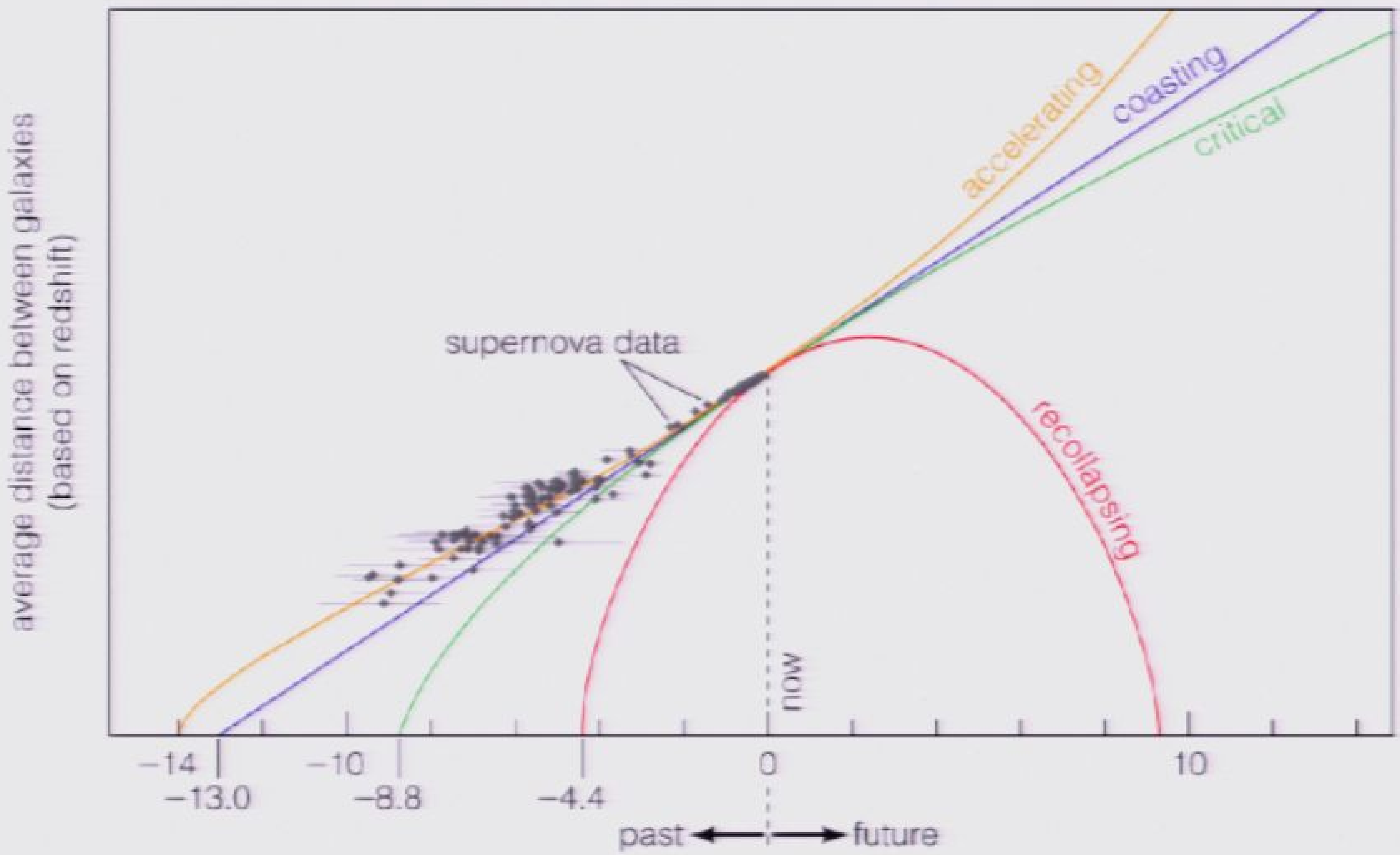

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$\Rightarrow$ equation of state

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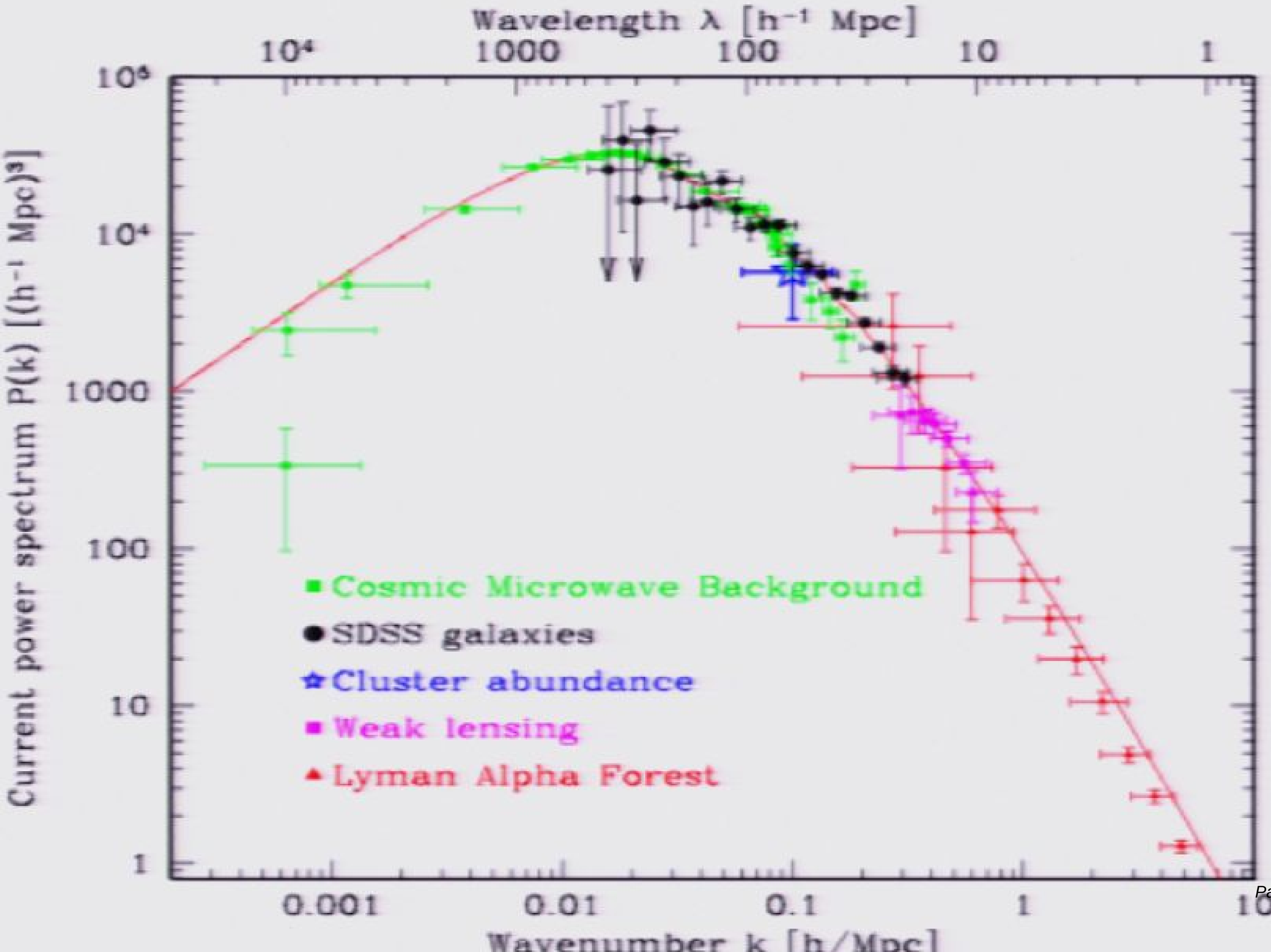

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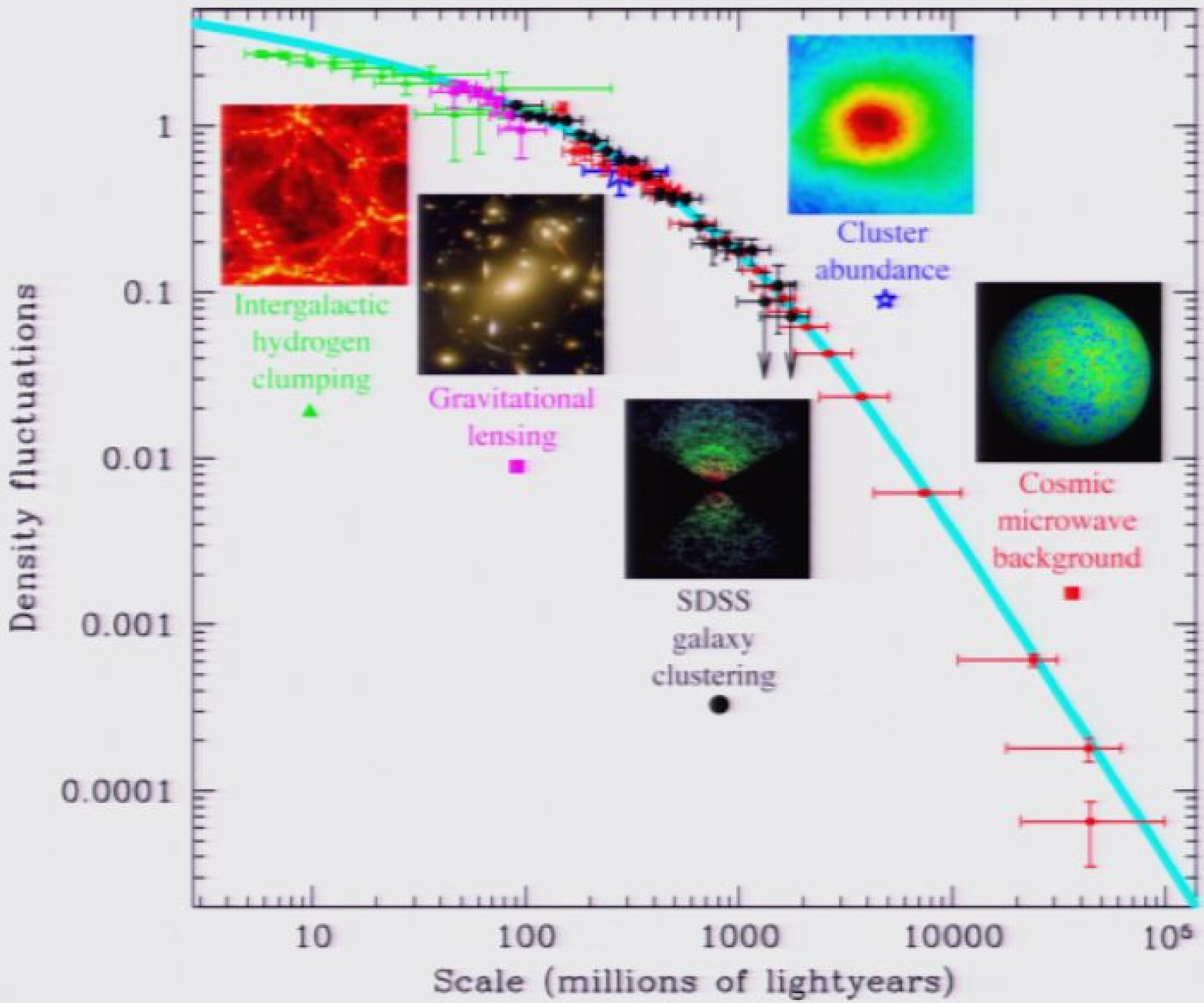

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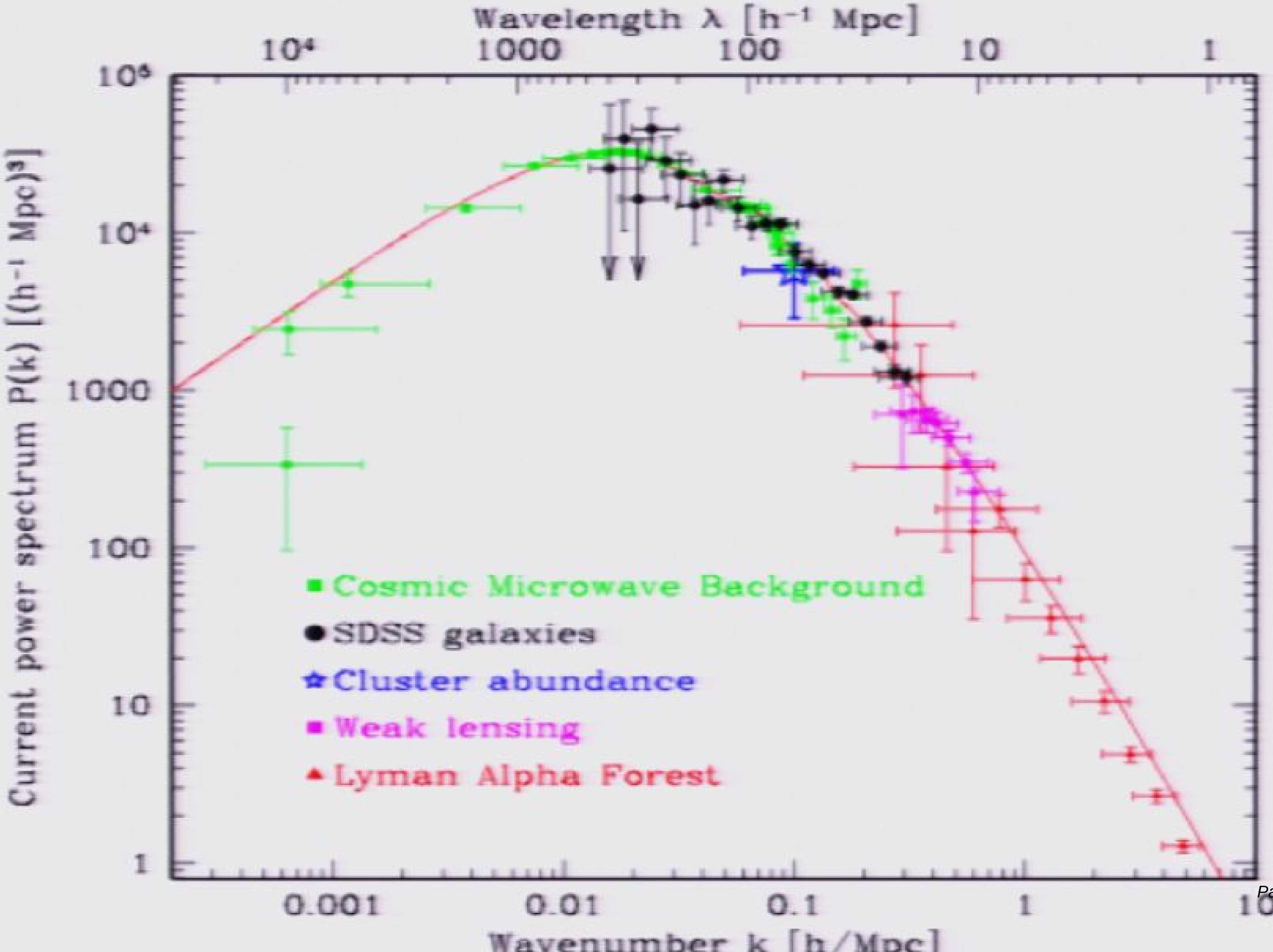

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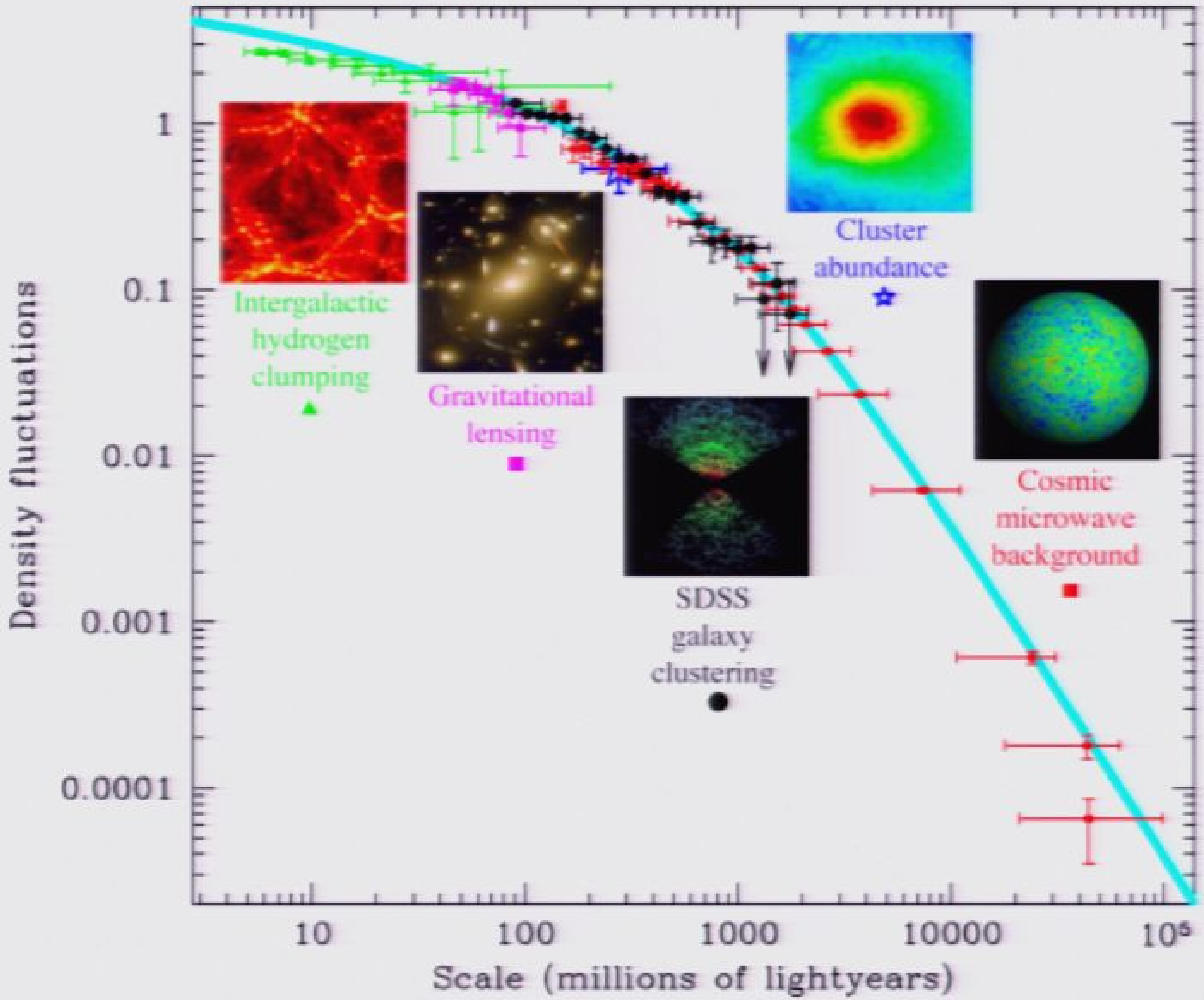

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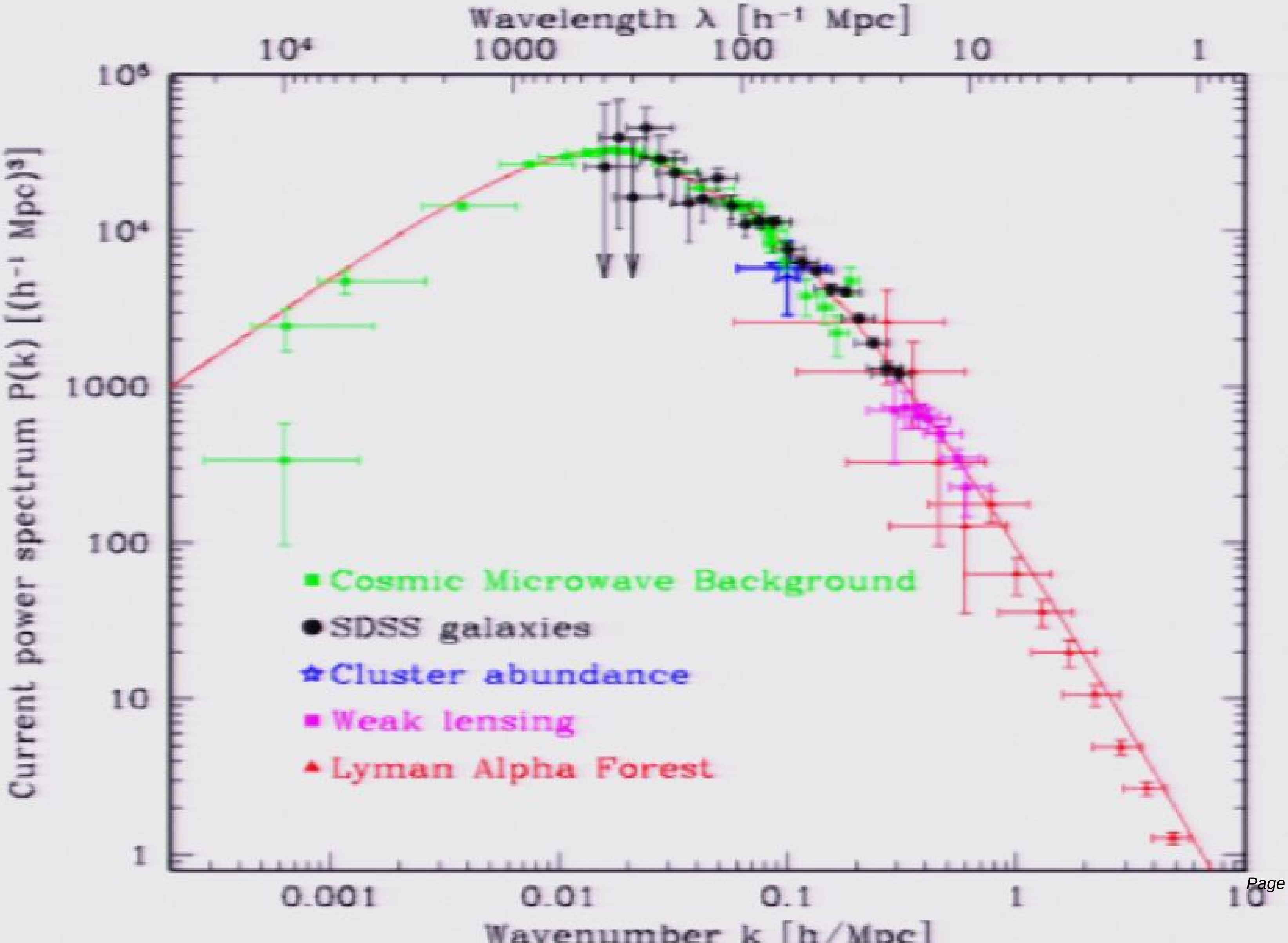

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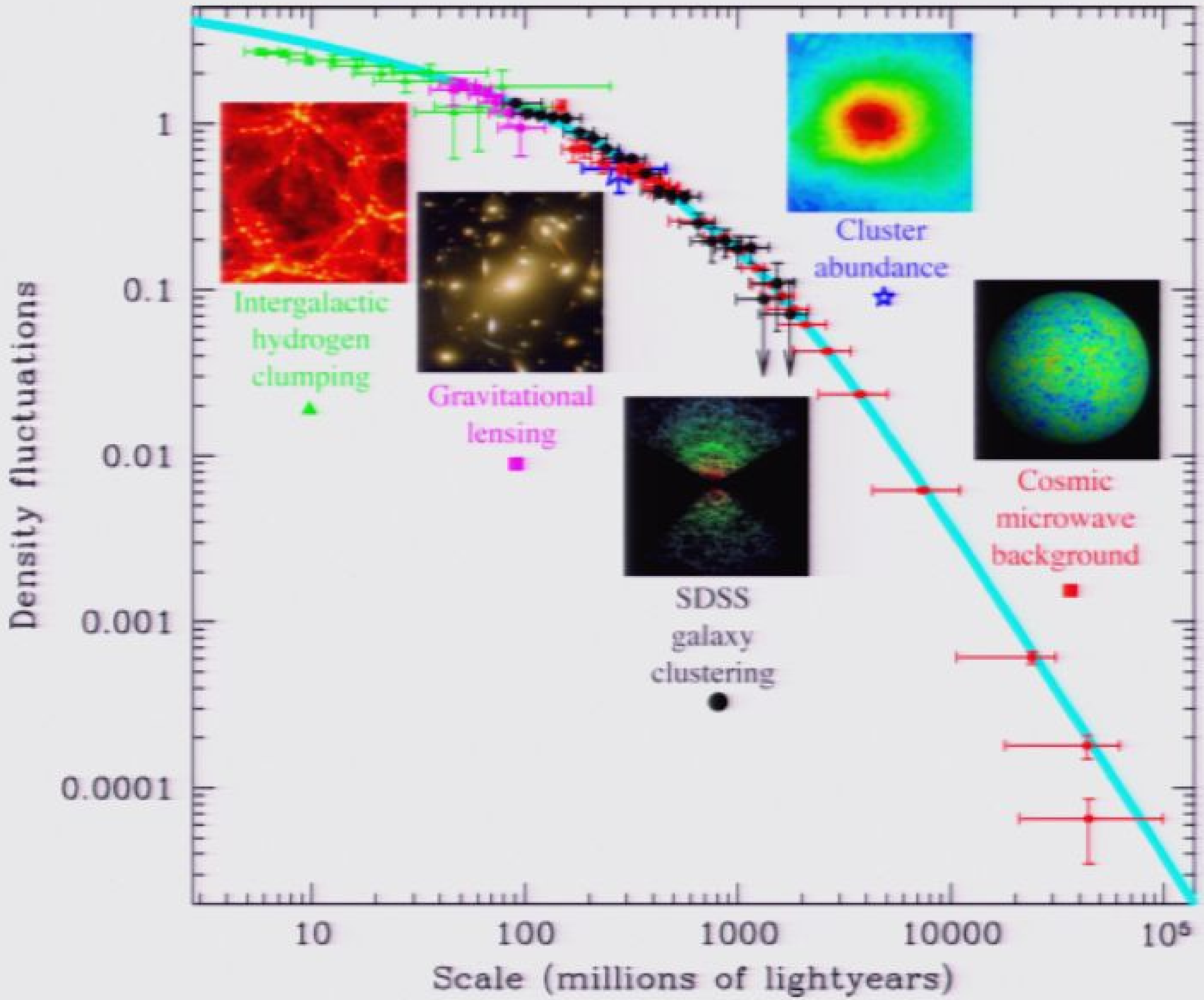


What can we learn from observational cosmology?

e) The physics of the main components, e.g. :

Dark Matter annihilation (e.g. Neutralino annihilation to photons/pions)
Dark Matter scattering cross-section
Dark Matter decays
other dark matter properties?

neutrino mass
neutrino oscillations

dark energy properties?

variations in the fundamental constants

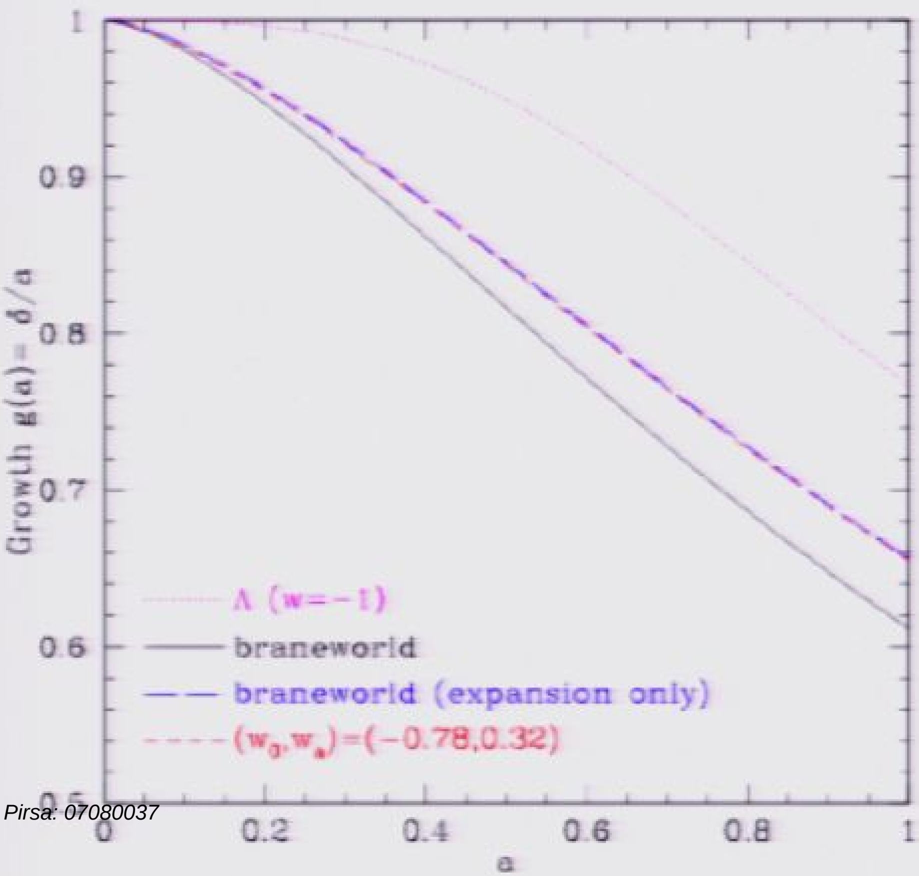
tests of strong and weak gravity

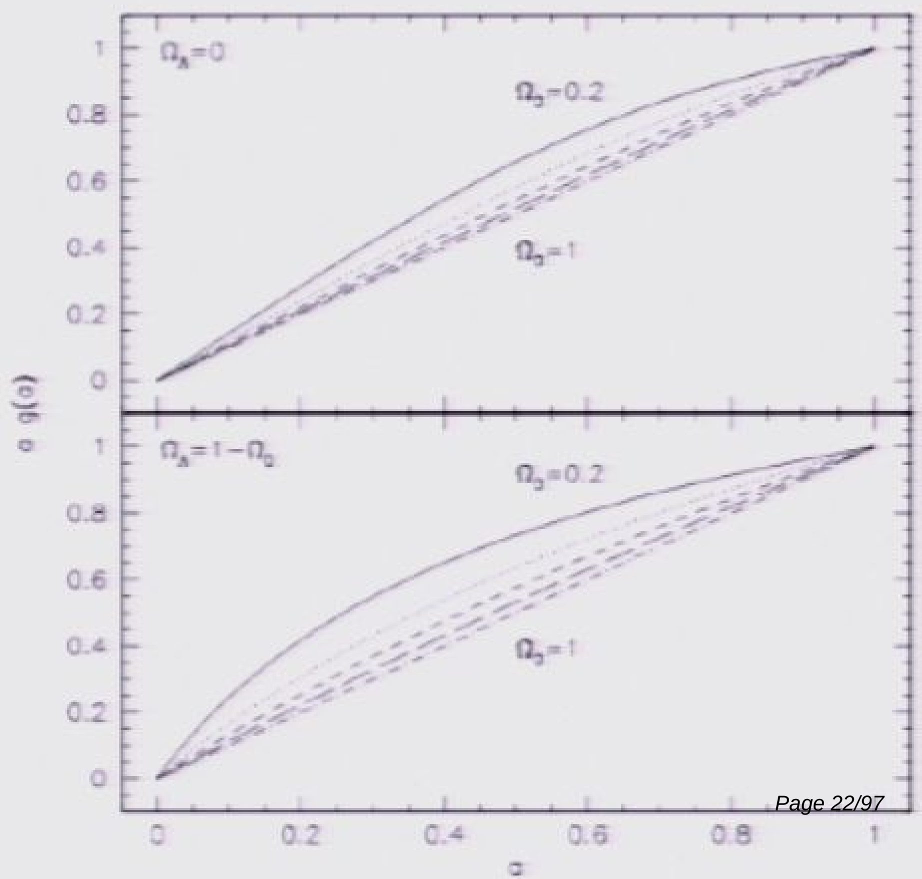
N.B. the value of multiple constraints (cf. Linder 2005)

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

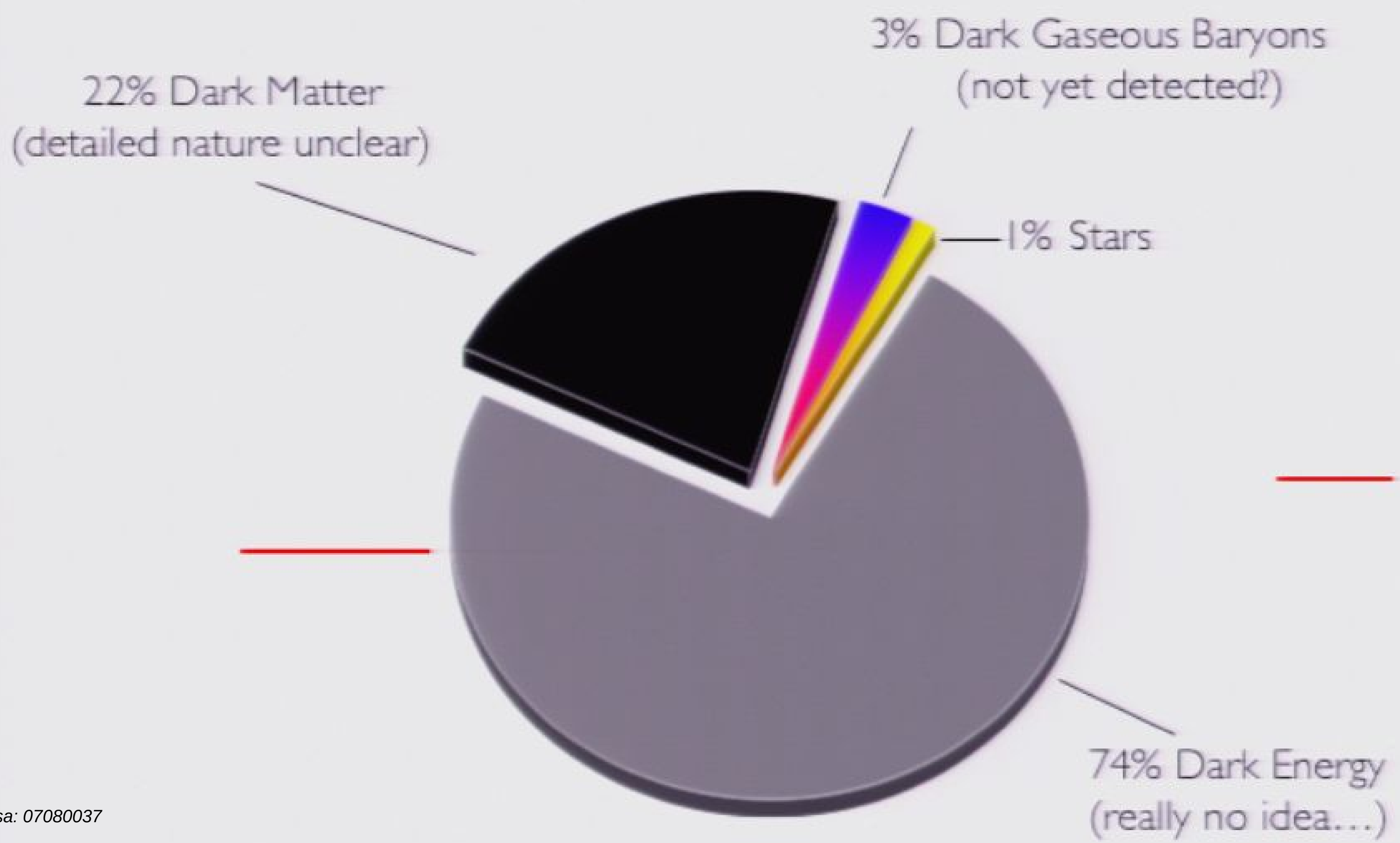
Linear growth factor describing the growth of perturbations can distinguish between the two (local vs. global effect), e.g. DGP braneworld gravity

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





Summary:
The Composition of the Universe (third quarter 2007)



Summary:
The Composition of the Universe (third quarter 2007)

22%
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So everything fits nicely into a model where almost all the energy in the universe is of some unknown and/or undetected form…

At a minimum, there is solid evidence for dark matter from redshift 1100 to the present, on spatial scales from 10^8 to 10^5 parsecs, dominating normal matter by a factor of 7:1

+ need c
scalar

(really no idea…)

Gravitational Lensing

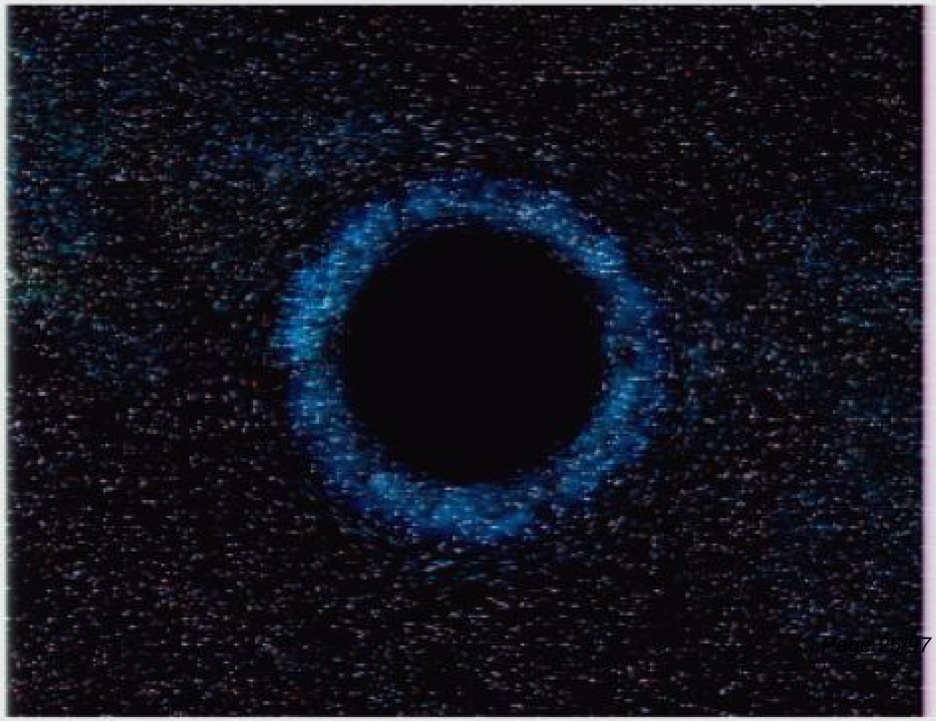
(cf. reviews by Schneider on astro-ph)

Basic Idea:

point mass M deflects light; using the Schwarzschild solution calculate deflection angle $\hat{\alpha}$:

$$\boxed{\hat{\alpha} = \frac{4GM}{c^2\,\xi} = \frac{2R_{\rm s}}{\xi}}$$

where ξ is the impact parameter



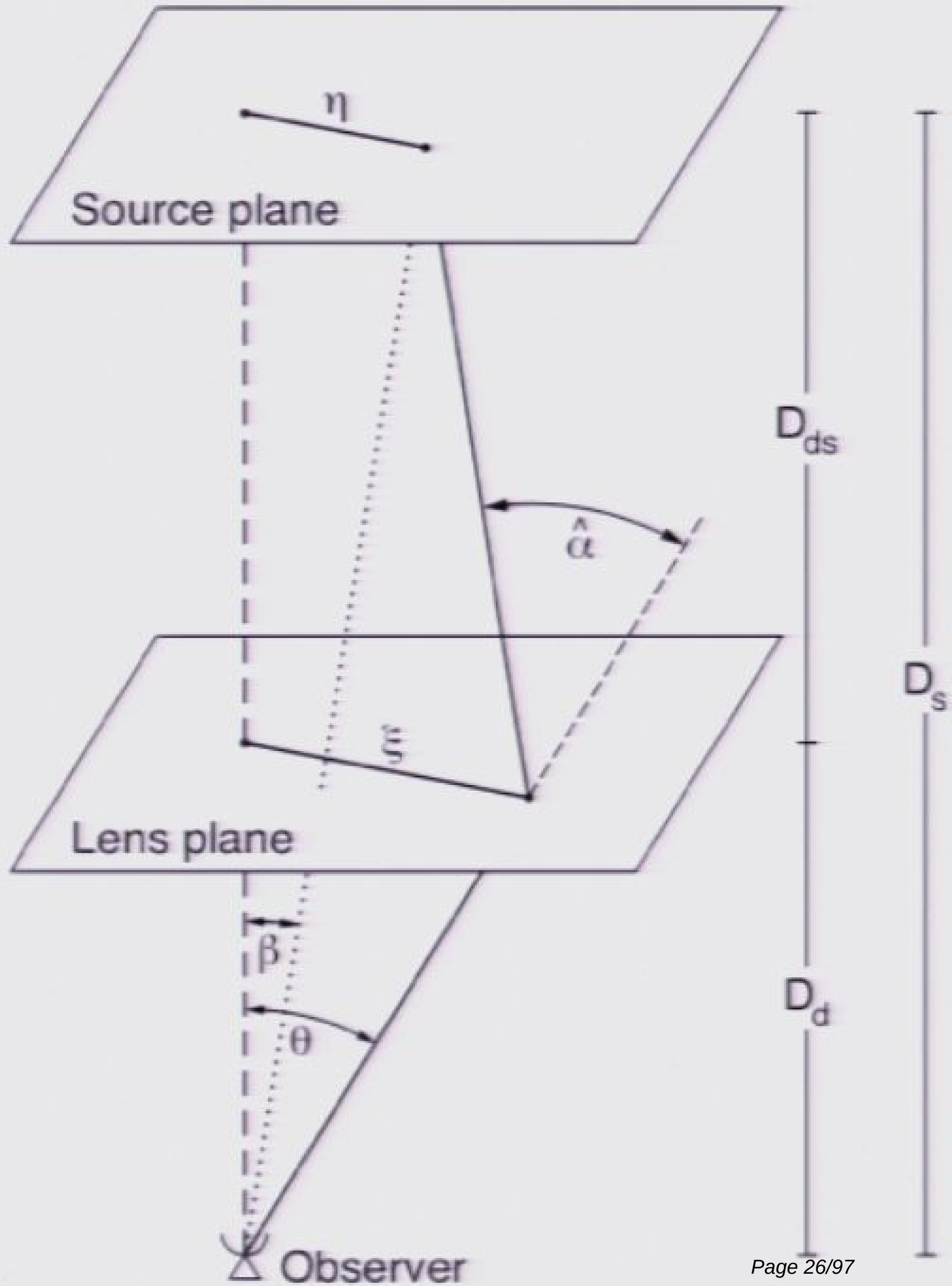
Gravitational Lensing

More generally, for 2-D distribution of m
deflection of ray from object at (2-D ve
position $\boldsymbol{\eta}$ should be at $\boldsymbol{\beta}$, instead seen

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

where deflection angle α is given by:

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



Gravitational Lensing

Deflection angle can be written in terms of the convergence kappa:

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

where:

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

also note that we can define a potential such that:

$$\boldsymbol{\alpha} = \nabla\psi, \quad \text{with} \quad \psi(\boldsymbol{\theta}) = \frac{1}{\pi} \int_{\mathbb{R}^2} \mathrm{d}^2\theta' \, \kappa(\boldsymbol{\theta}') \ln|\boldsymbol{\theta} - \boldsymbol{\theta}'|$$

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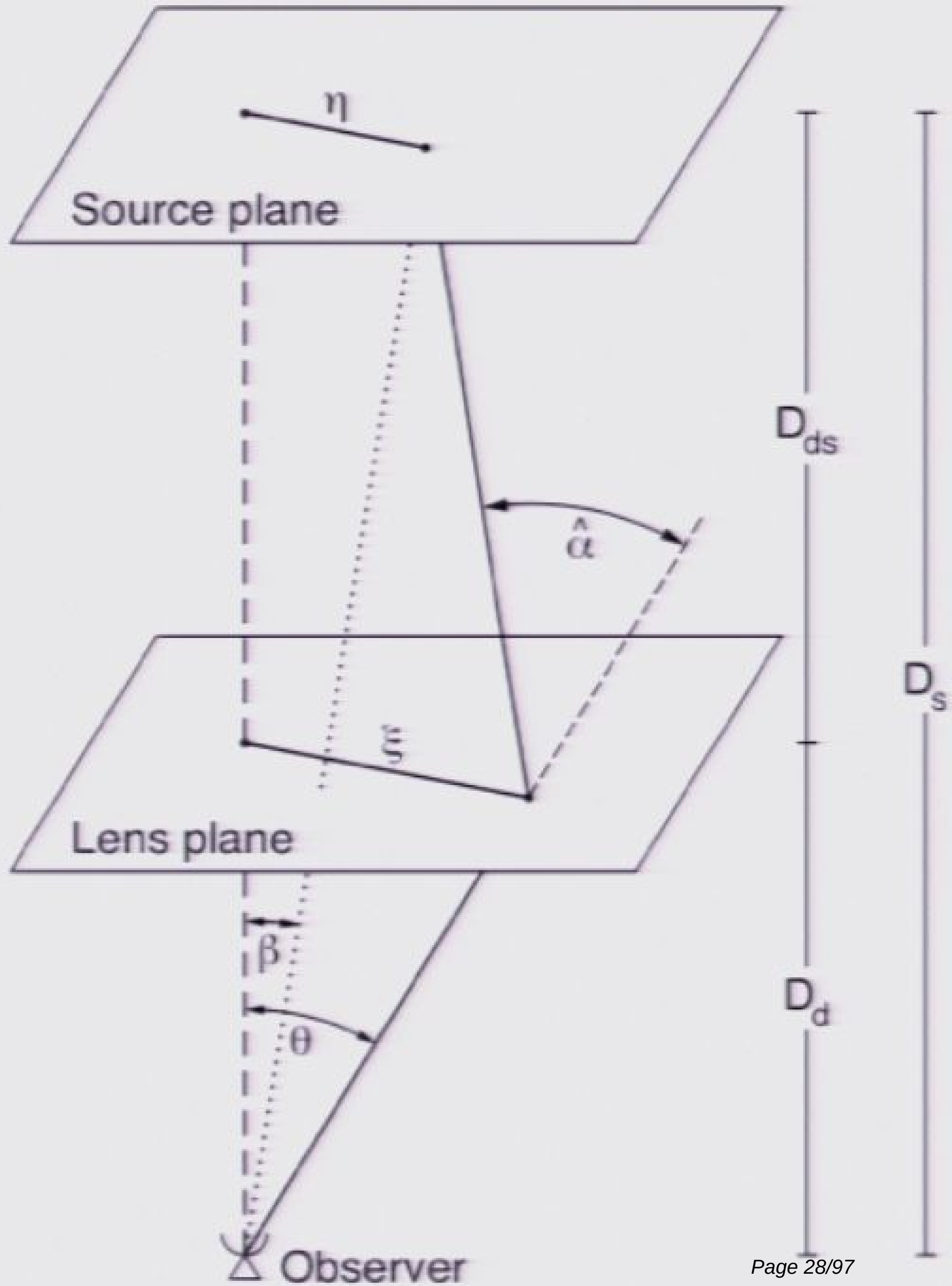

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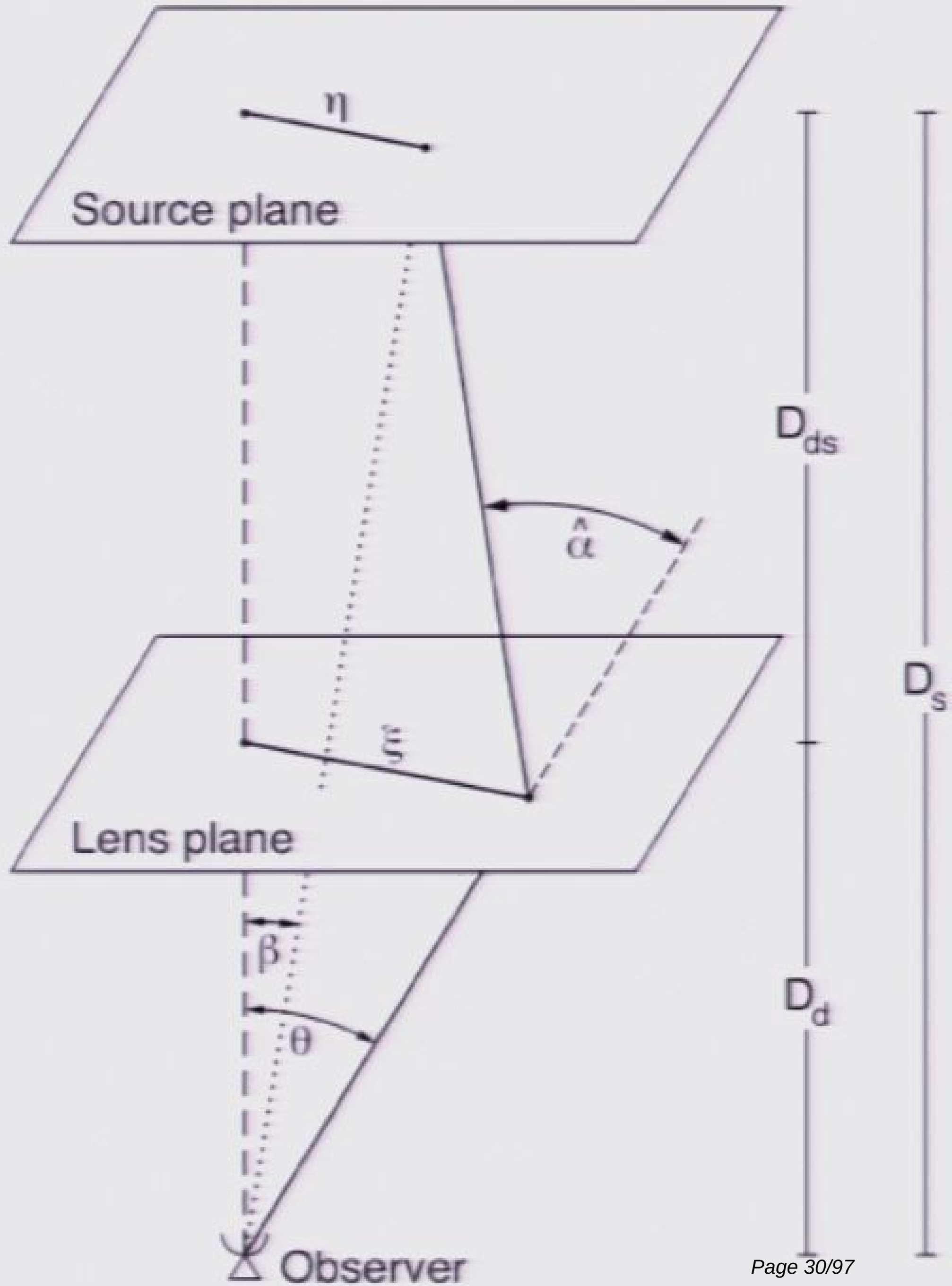

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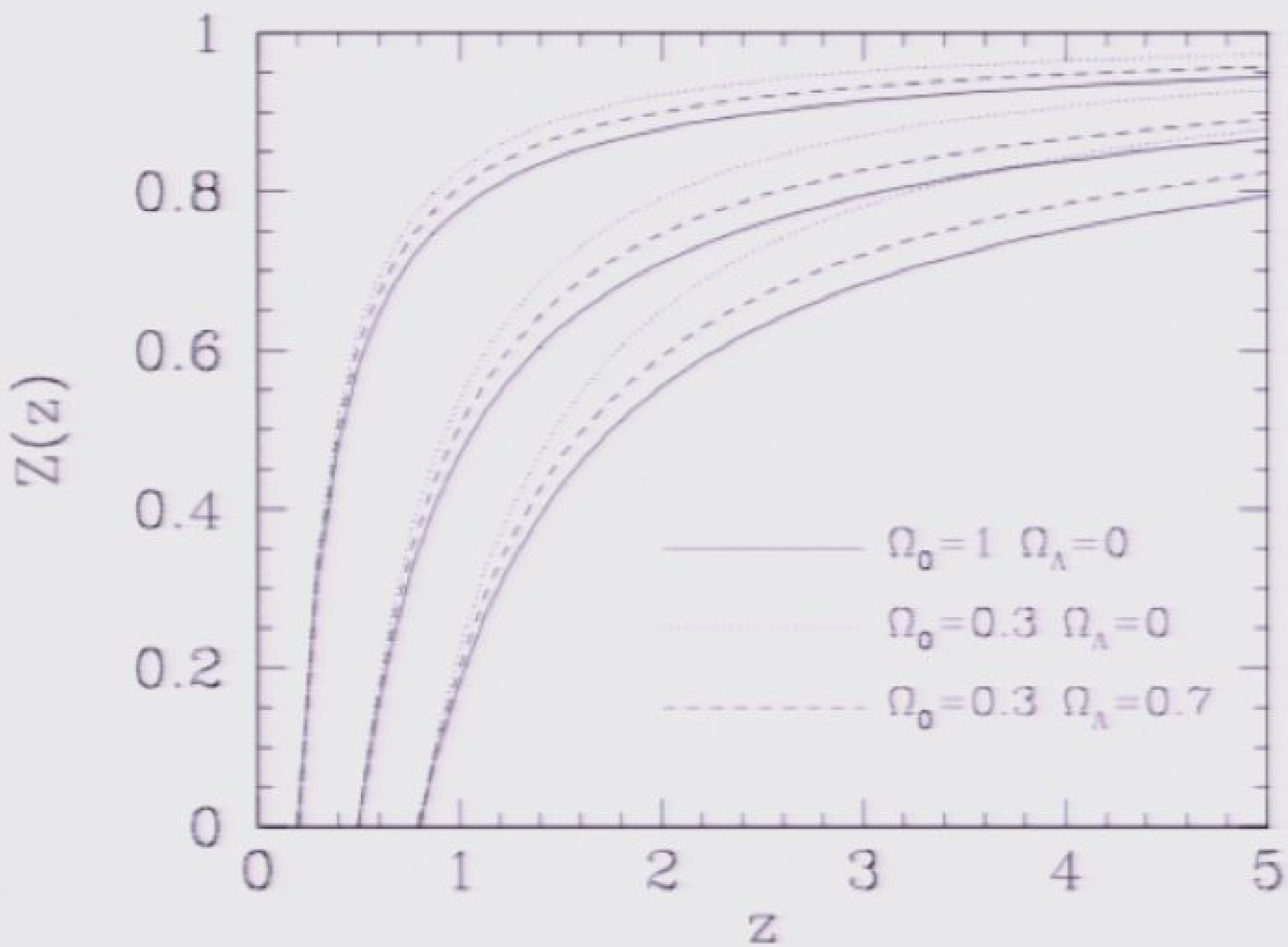
Gravitational Lensing

Effect of the geometric term is to make lenses most efficient when they are roughly halfway between the observer and the source:



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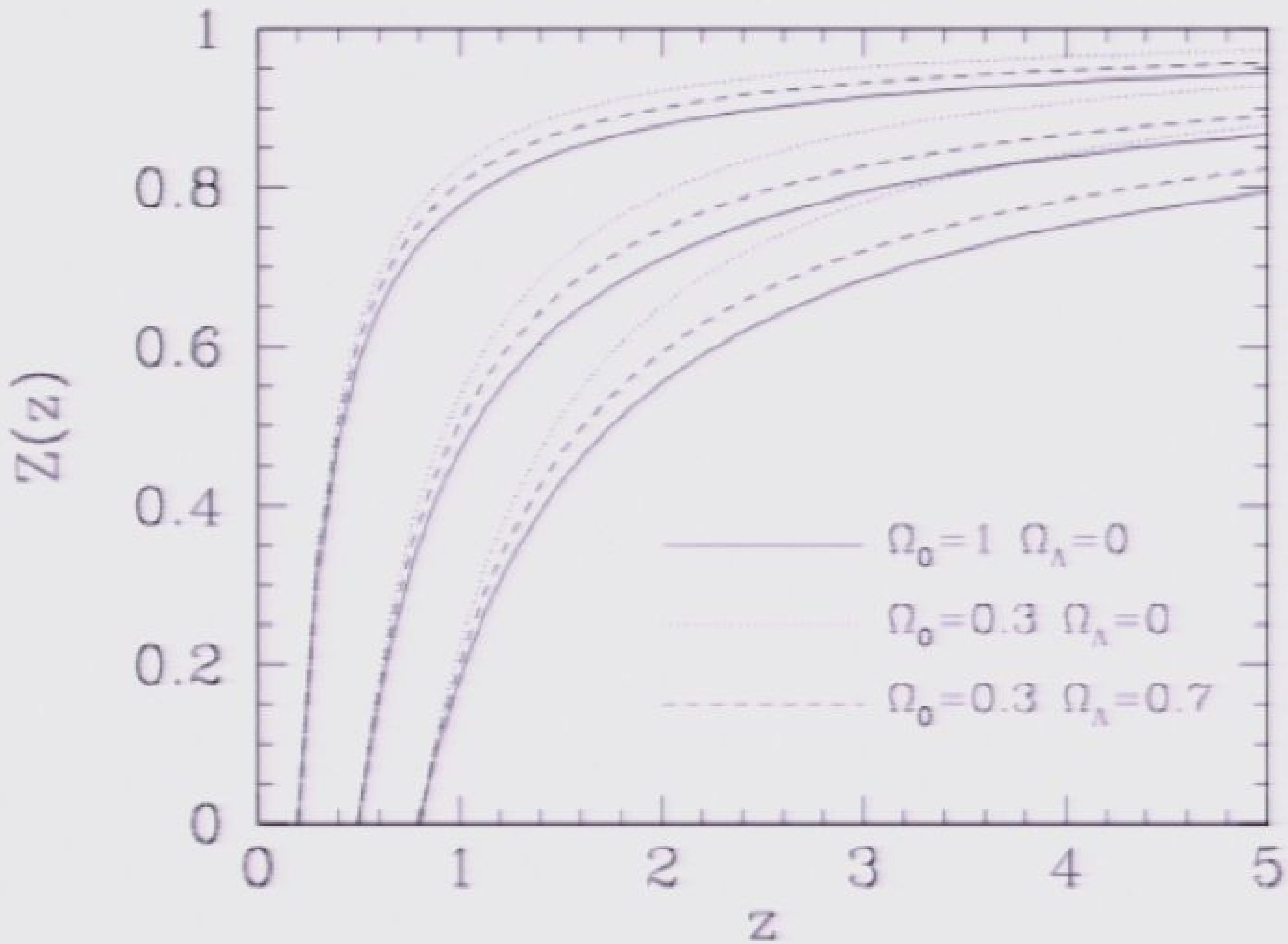


Shear and Weak Gravitational Lensing

Shear: consider a bundle of rays propagating from an extended source to the observer; if the mass distribution varies across the field different rays will be deflected by different amounts. Define a tensor describing the local deformation of objects:

$$\mathcal{A}(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} = \left(\delta_{ij} - \frac{\partial^2 \psi(\boldsymbol{\theta})}{\partial \theta_i \partial \theta_j}\right) = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix}$$

kappa: convergence (brightens/dims)

gamma: shear (distorts)

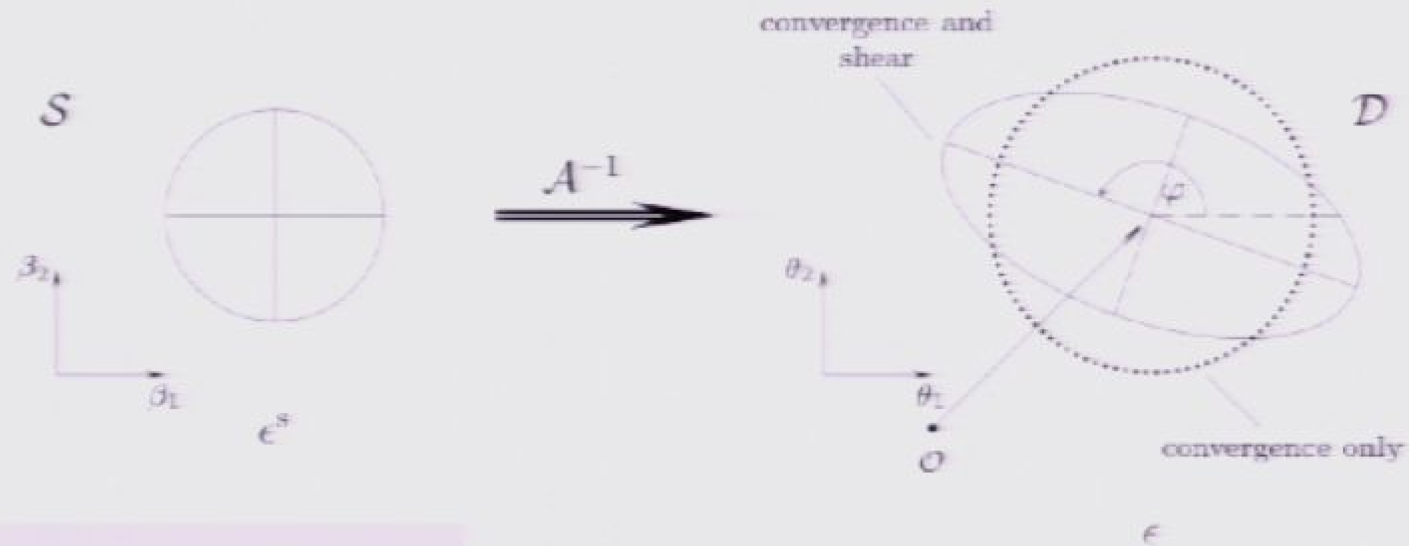
for kappa << 1, weak lensing regime; can make approximation:

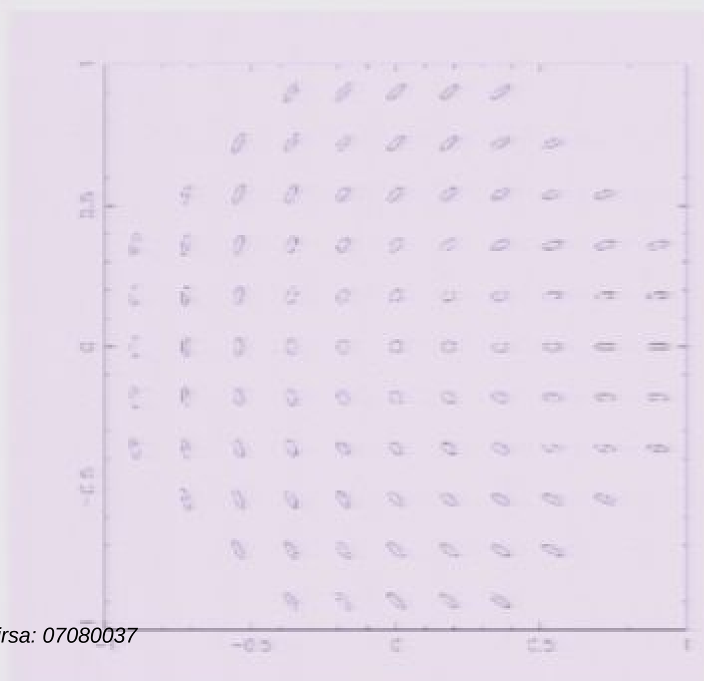
$$\boxed{\mathcal{A}(\boldsymbol{\theta}) = (1-\kappa)\begin{pmatrix} 1 - g_1 & -g_2 \\ -g_2 & 1 + g_1 \end{pmatrix}}, \quad \boxed{g_i = \frac{\gamma_i}{(1-\kappa)}} : \text{ reduced shear}$$

now distortion and amplification separated out

Shear and Weak Gravitational Lensing

Shear versus magnification:

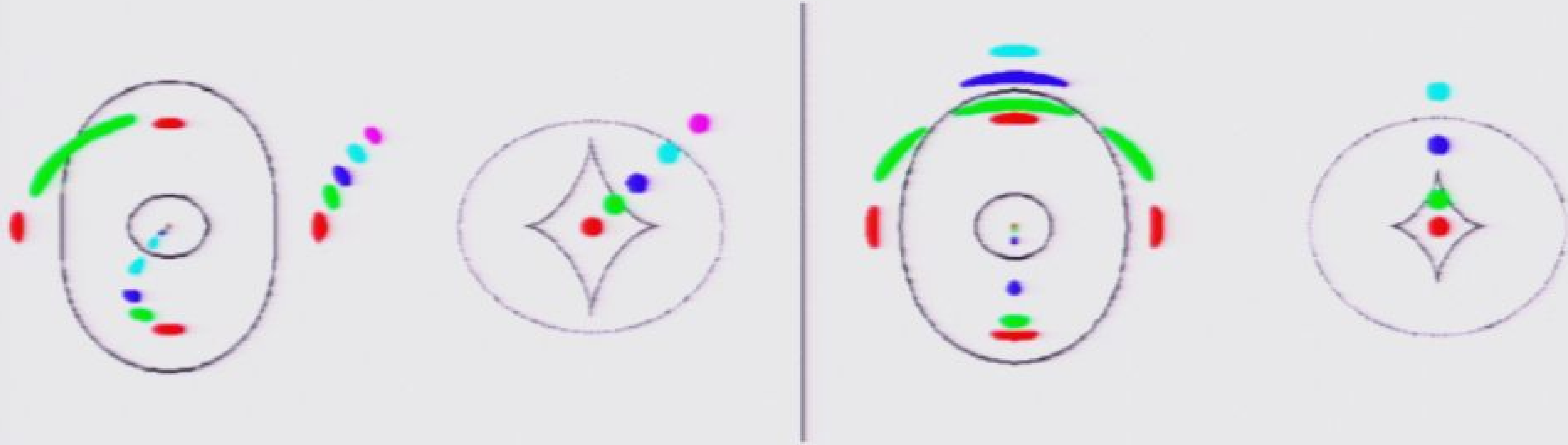




NB rather unintuitive description of shear in terms of two components, due to symmetry under 180 degree rotations

N.B.: Strong Gravitational Lensing

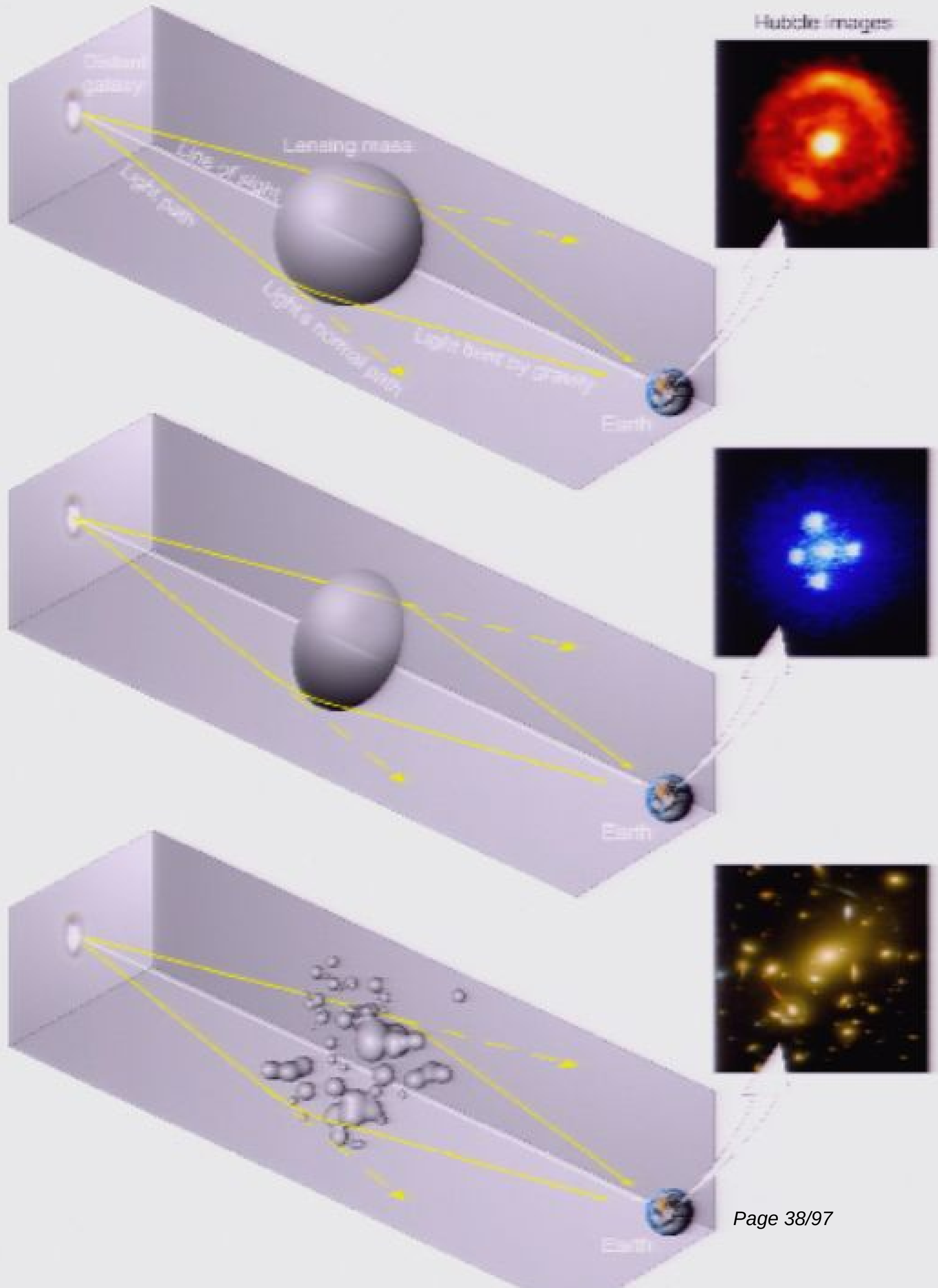
When kappa exceeds 1, can get multiple images, as rays passing around either side of an object are bent towards the observer:



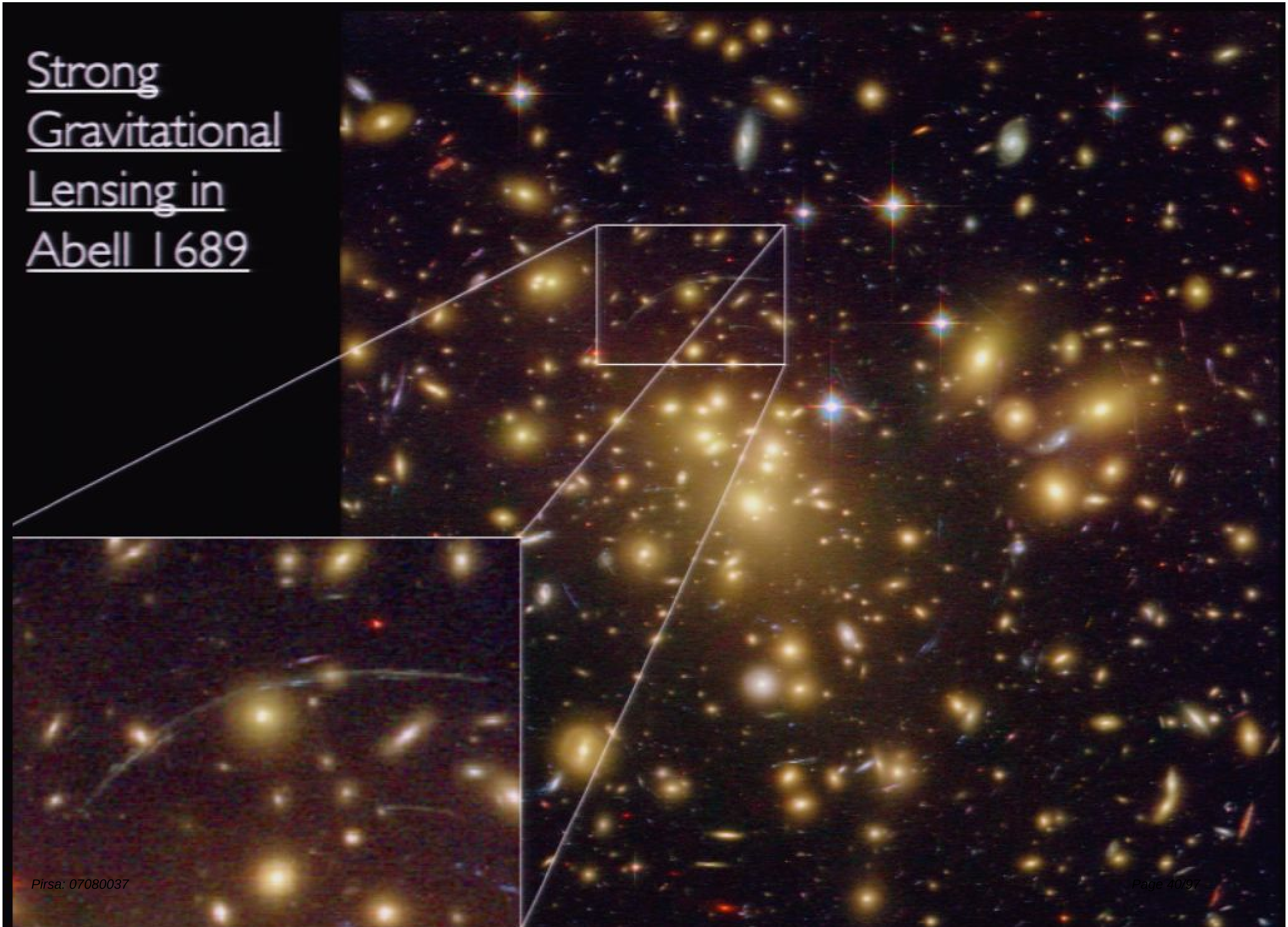
N.B.: Strong Gravitational Lensing

Useful probe of galaxies -> measure of mass profiles, Hubble constant, searches for small scale-dark matter structure

Also very useful probe of clusters -> internal structure, dark matter substructure, searches for distant source galaxies



Strong Gravitational Lensing in Abell 1689


Strong
Gravitational
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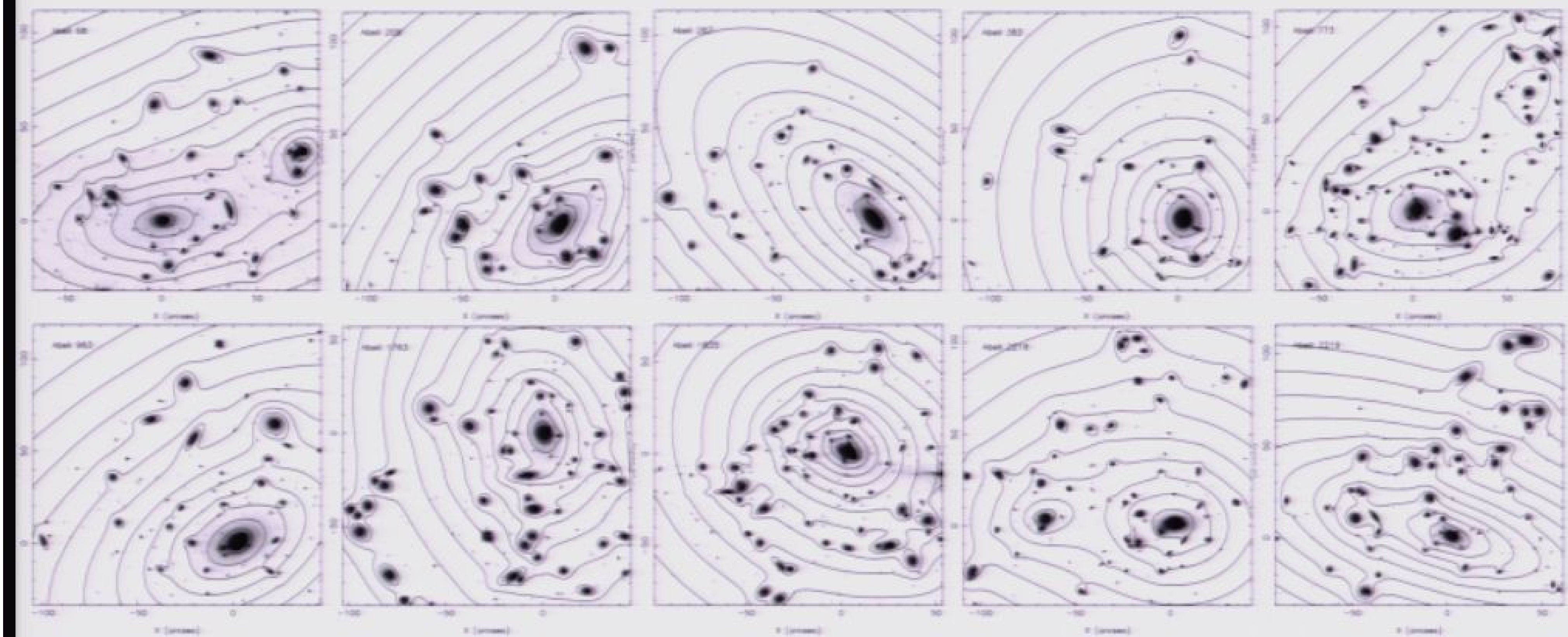
Abell 1689

Use strong + weak lensing to map cluster structure and substructure in detail

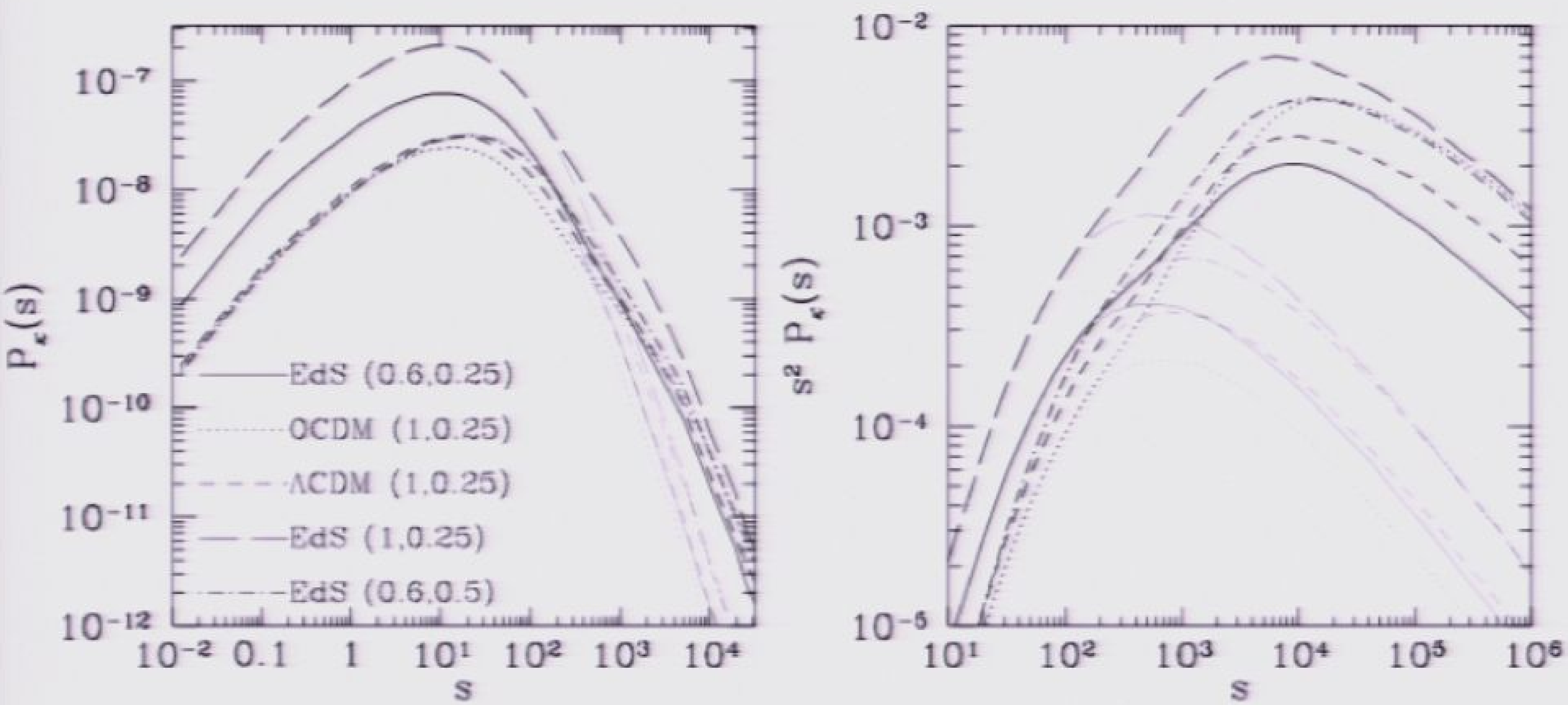
(Smith et al. 2005)



Applications of Weak Gravitational Lensing

Projected (Convergence/Surface Density) Power Spectrum:

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

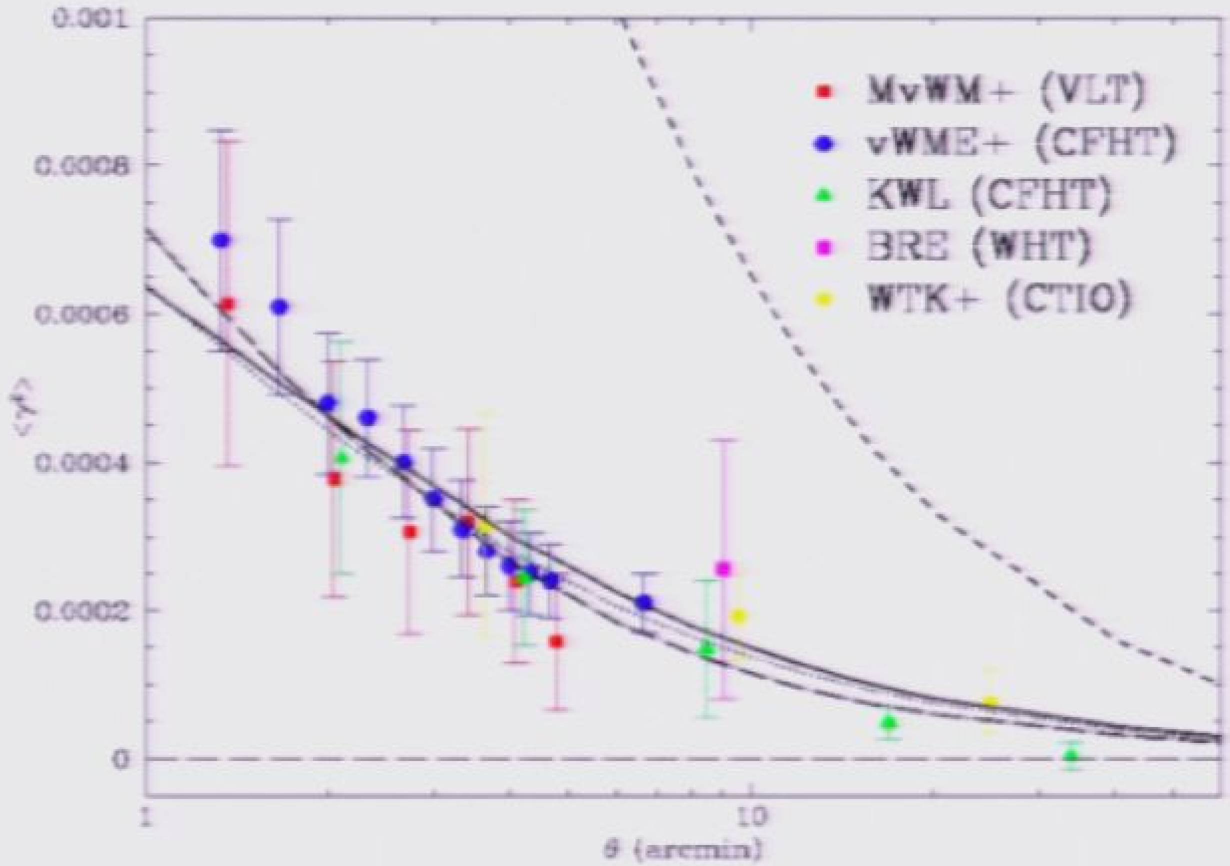


Applications of Weak Gravitational Lensing

In practice, several other more practical measurements:

- 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



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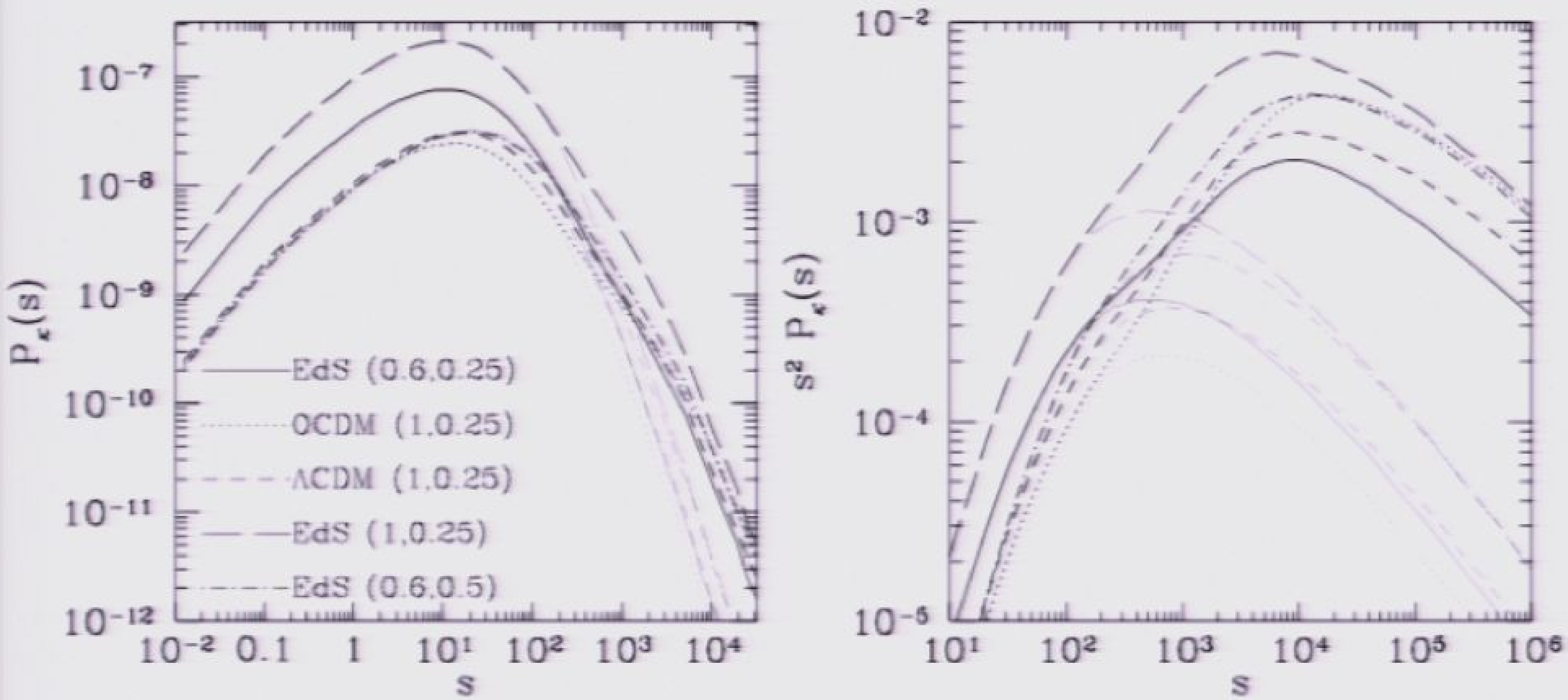

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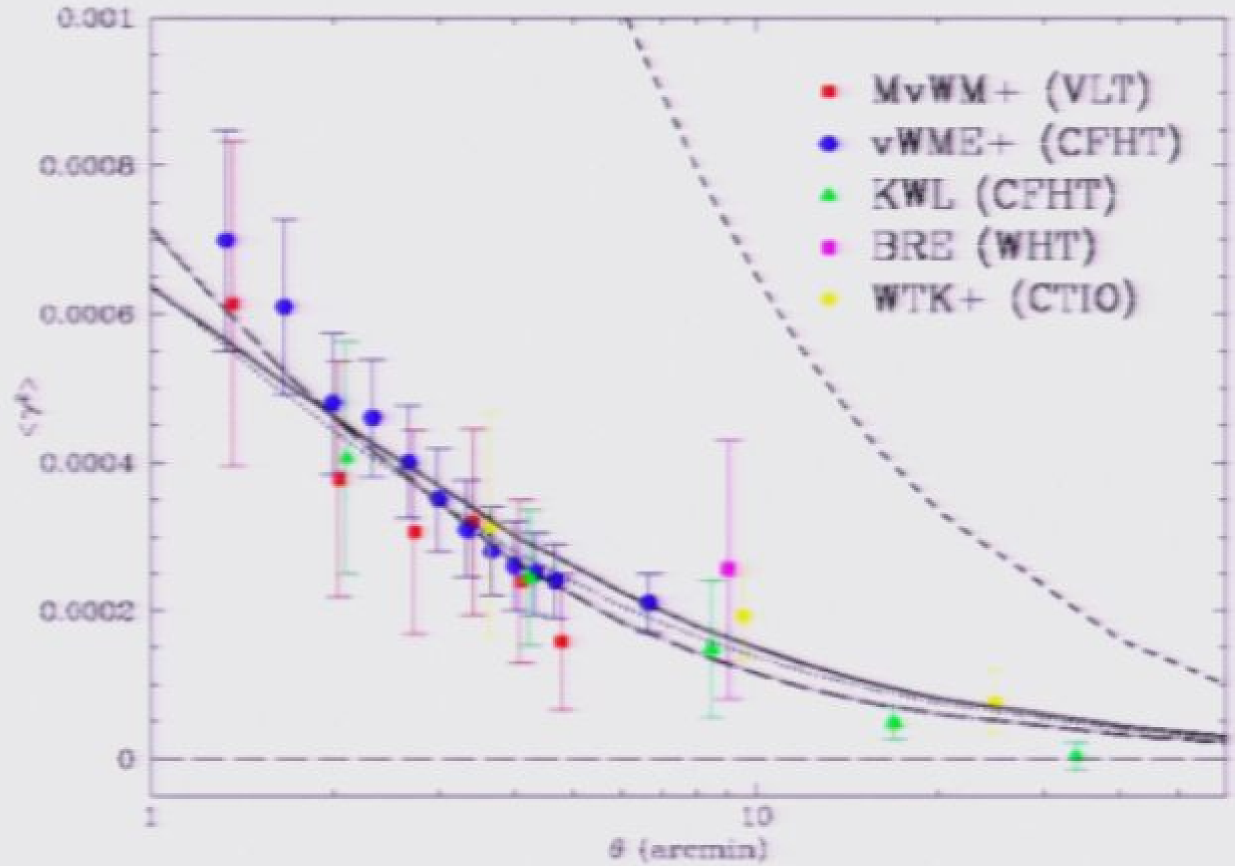

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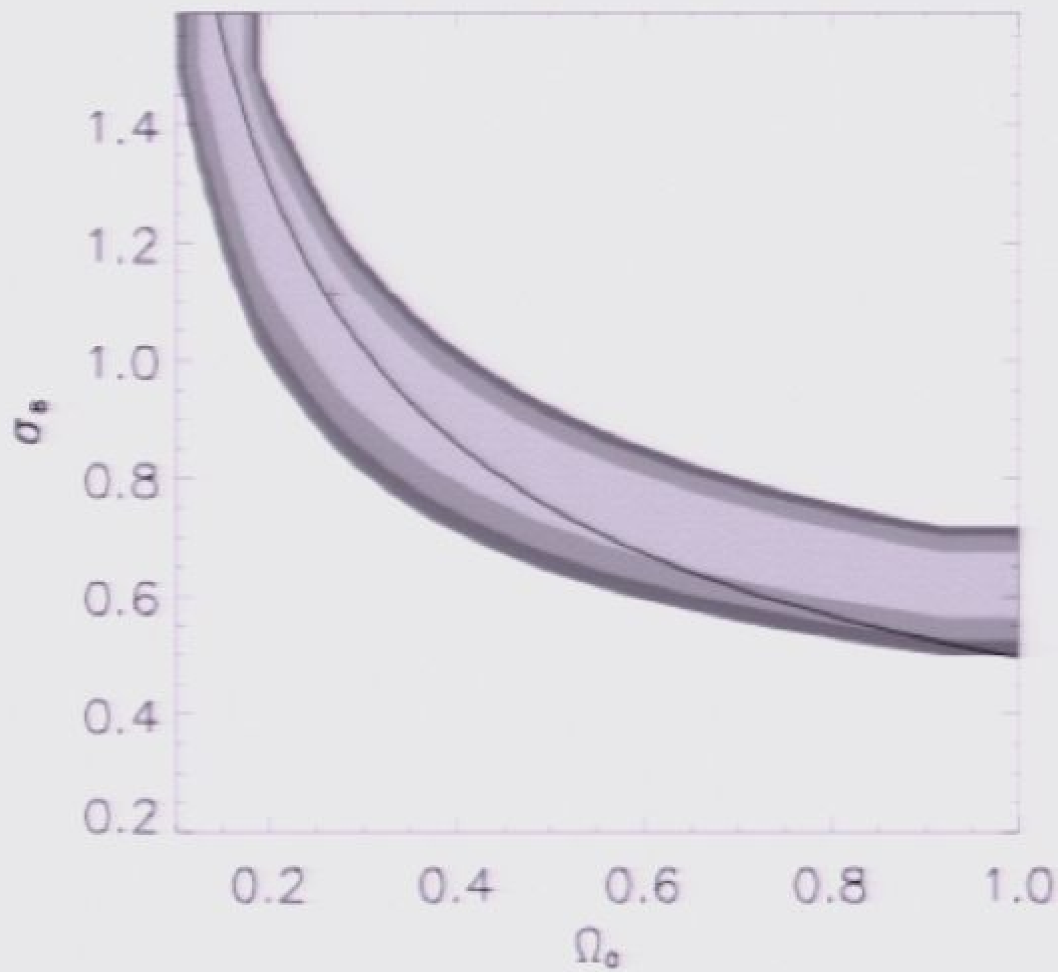
Results: Cosmological Parameter Constraints, mainly a combination of the amplitude of the power spectrum (via σ_8) and the growth factor (via Ω)



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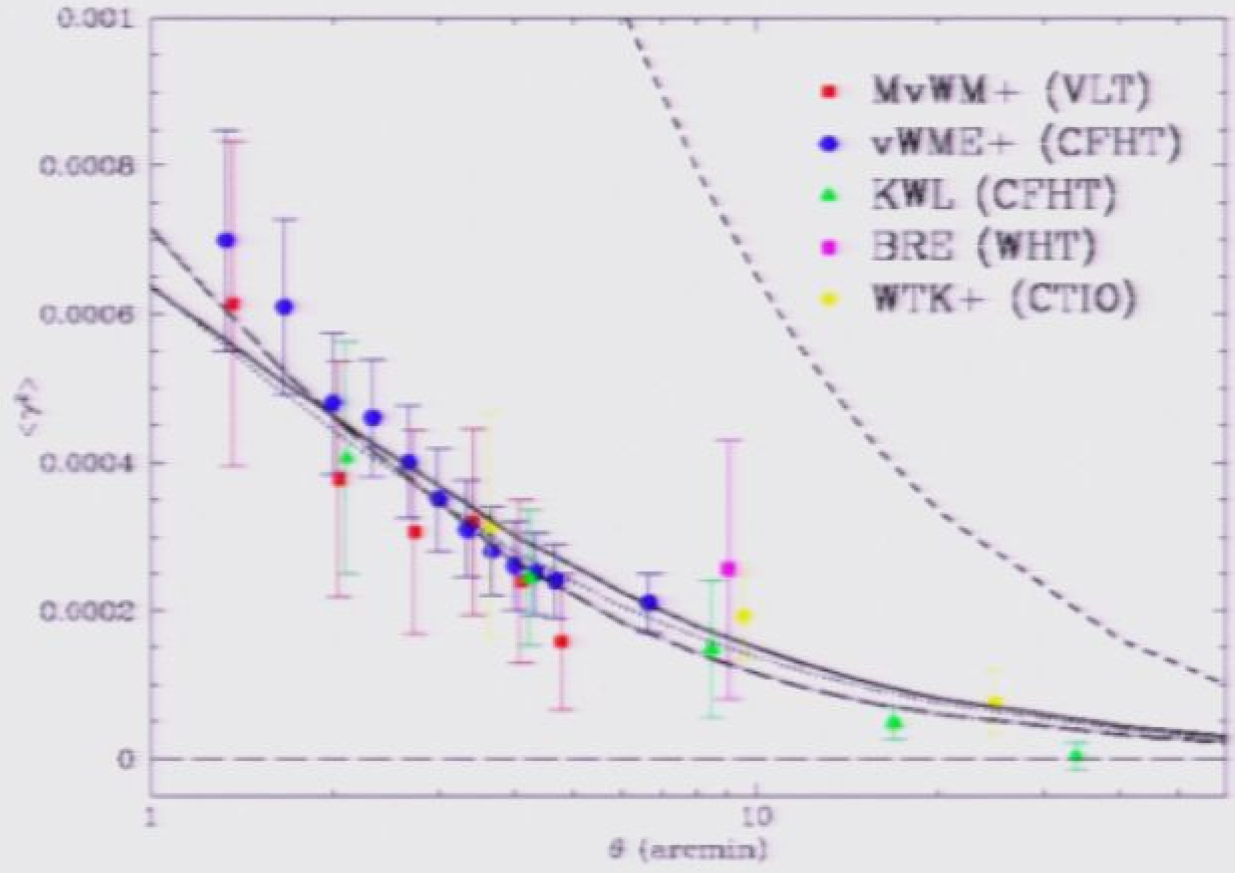

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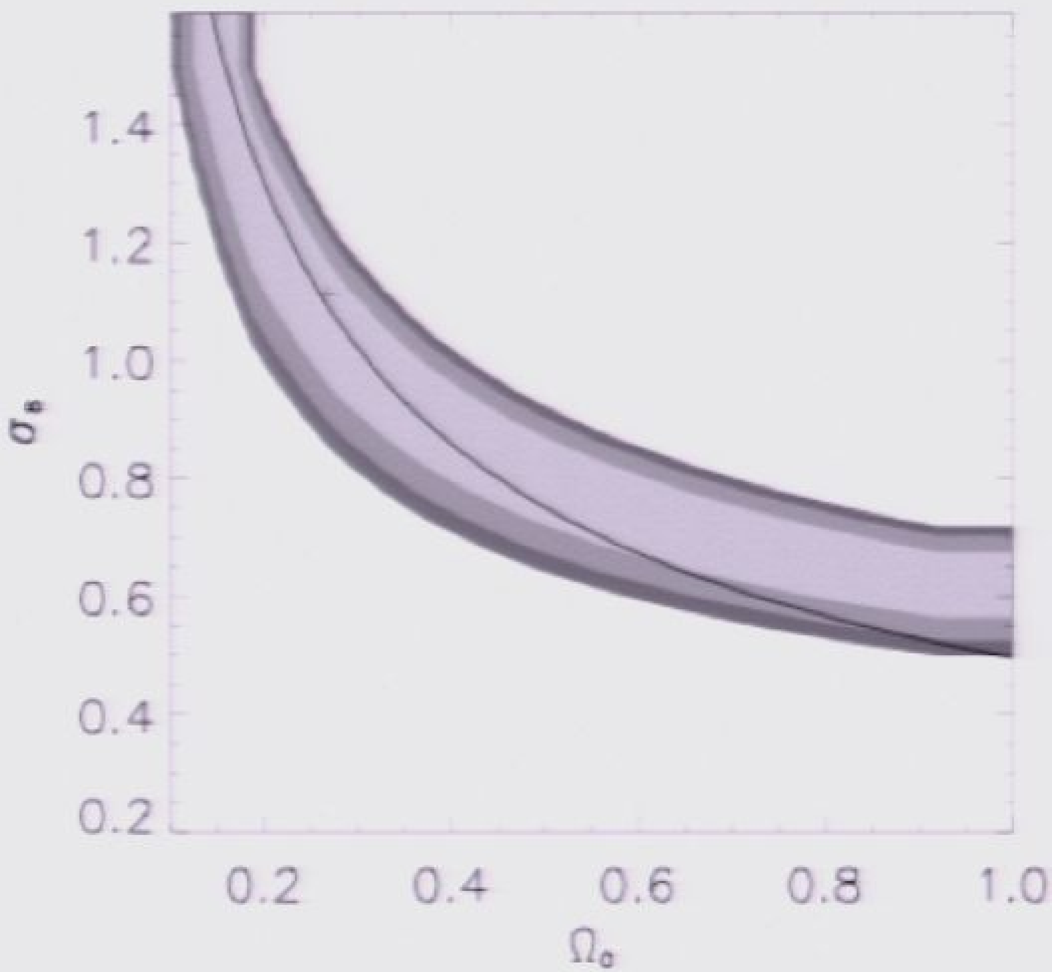


Applications of Weak Gravitational Lensing

Why not just use the CMB?

- weak lensing measure the power spectrum at low redshifts and on small scales, so very different from the CMB

- low redshifts => sensitivity to dark energy

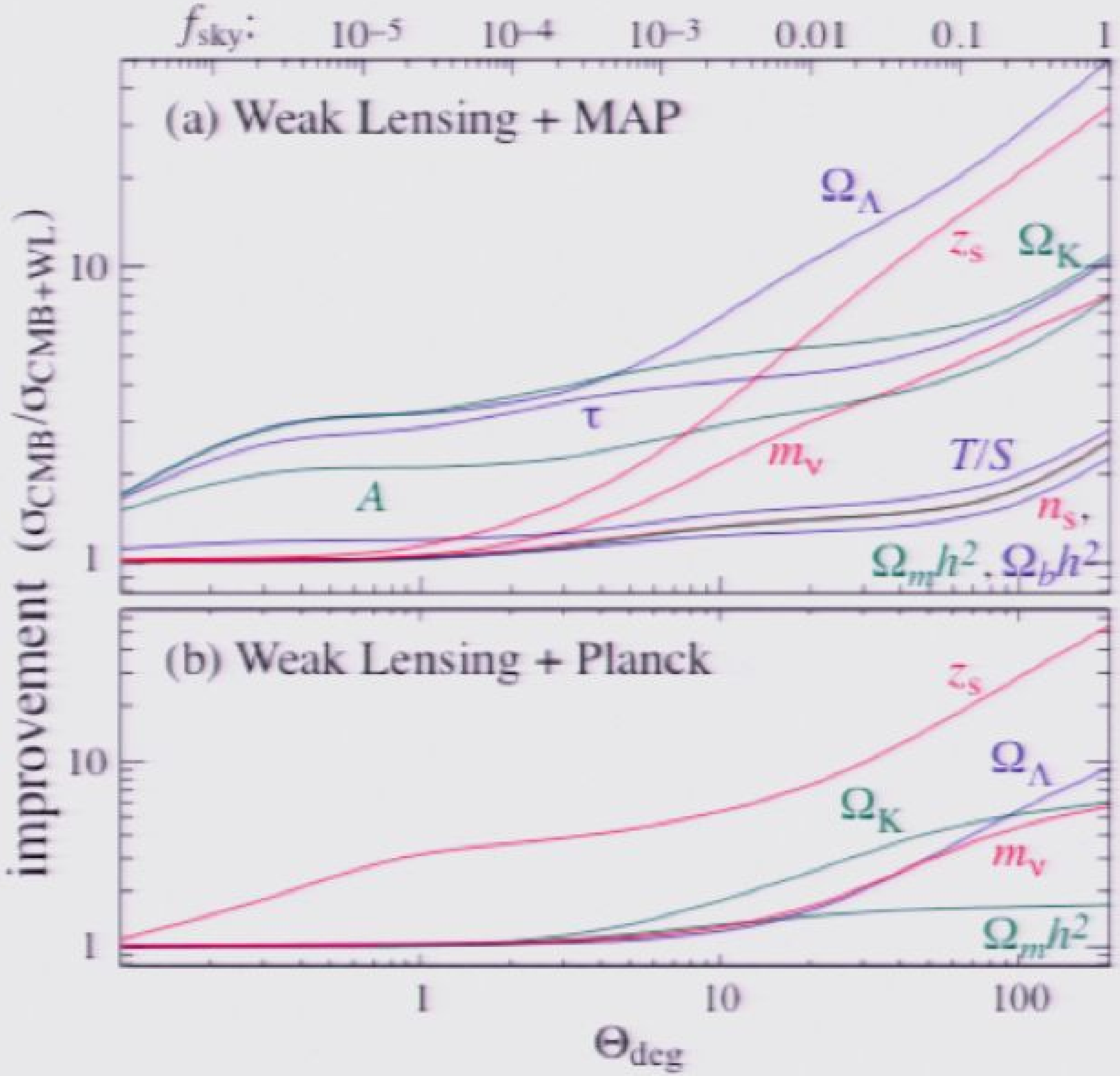
- small scales => (only) direct probe of dark matter distribution

- growth factor versus expansion history tests modifications to gravity

- even in conventional cosmologies, benefit of long lever arm

Applications of Weak Gravitational Lensing

Why not just use the CMB?



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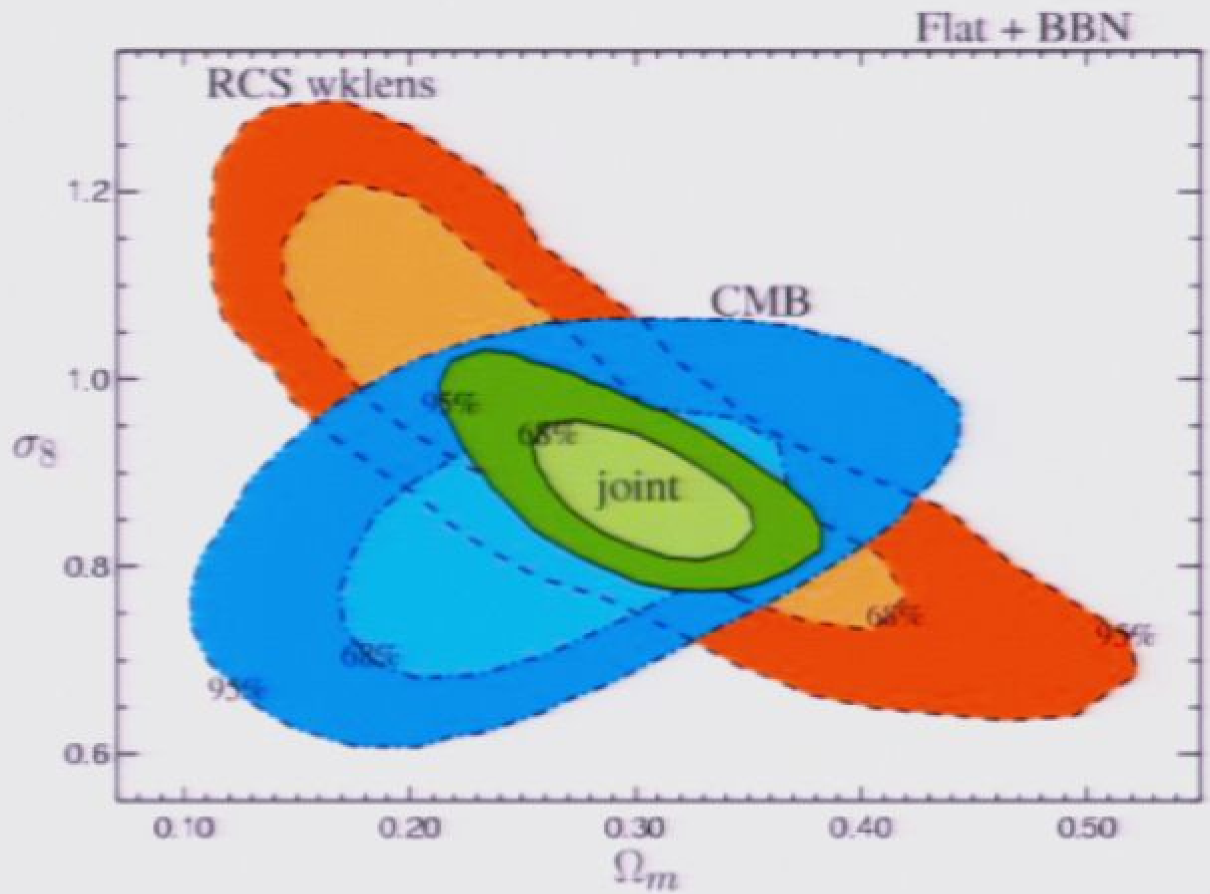

1E 0657-56 (The 'bullet' cluster) – a smoking gun?


But see Angus et al. 2007 (astro-ph/069125):
Brownstein & Moffat 2007 (astro-ph/072146)

Probes of structure growth using gravitational lensing:

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1) Cosmic shear from weak lensing

$\Leftarrow$ linear and non-linear fluctuations on a range of scales

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2) Cluster detection and characterization from weak and strong lensing

   ⇐ abundance of high peaks in the density field

   (degenerate in σ_8 and growth)

3) Differential growth of non-linear structure

   (interesting, but may be hard to calibrate?)

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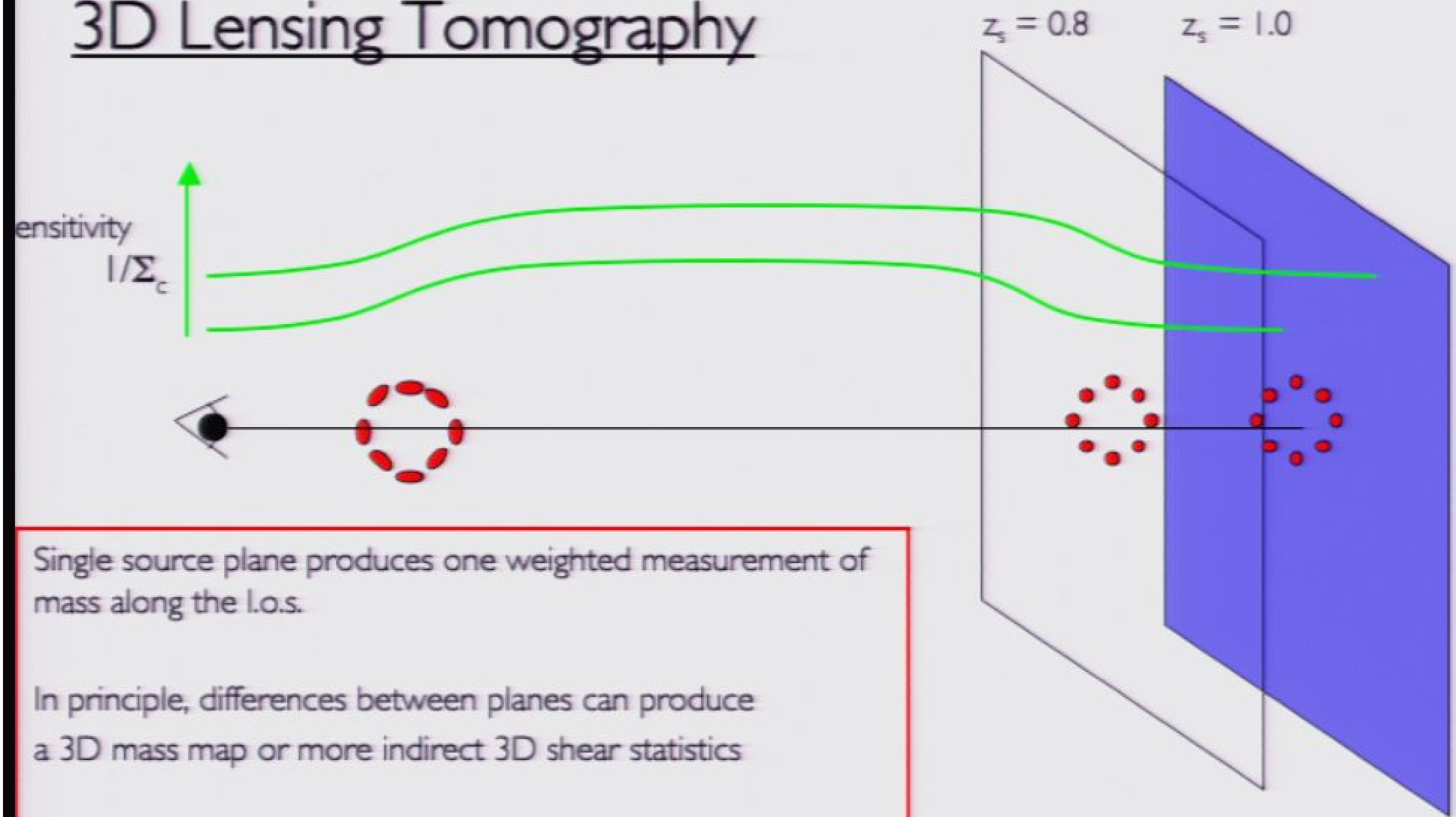
Redshift dependence of effect is very slow, producing a very broad kernel in redshift space:

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

3D Lensing Tomography

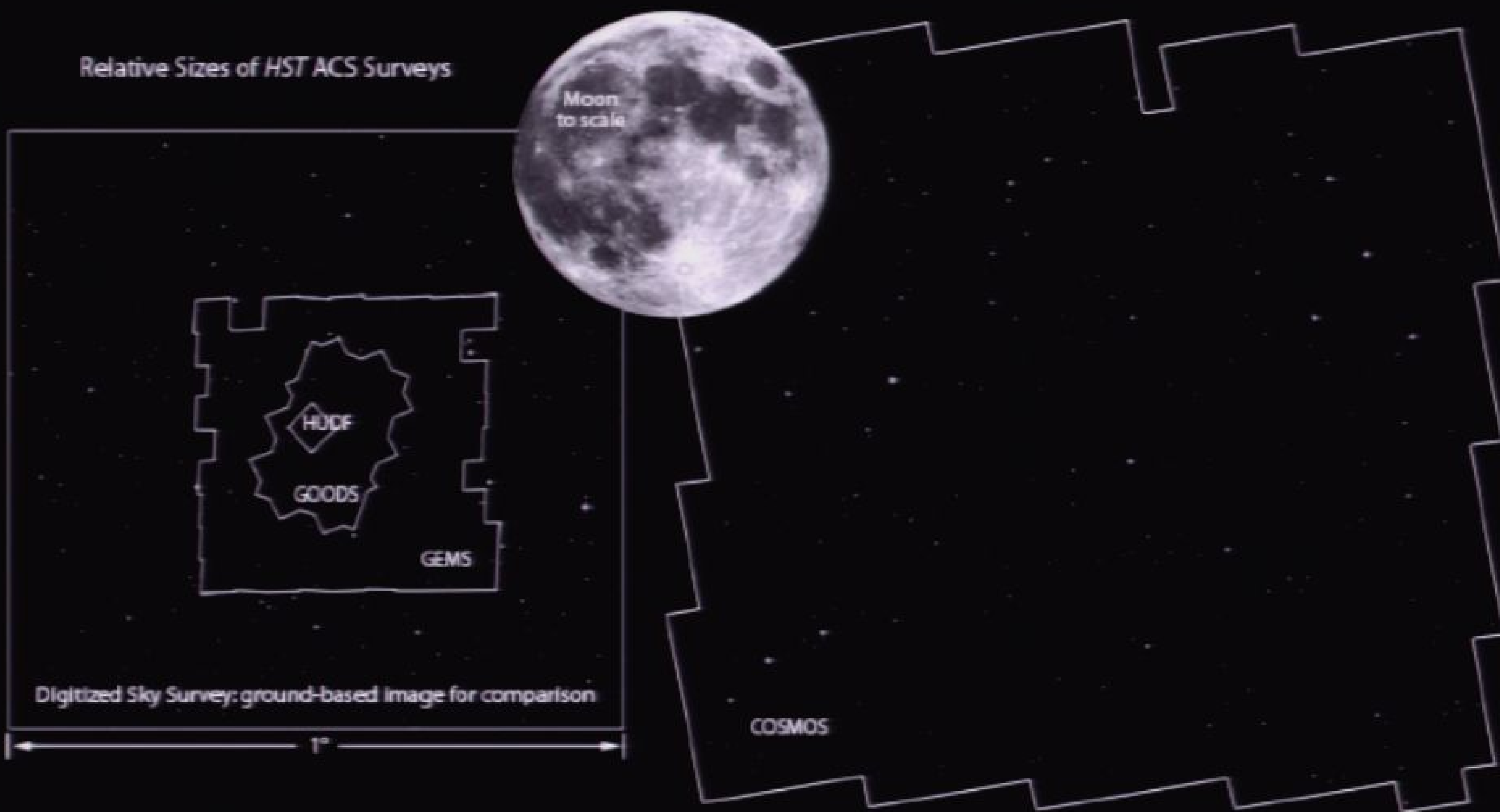


Single source plane produces one weighted measurement of mass along the l.o.s.

In principle, differences between planes can produce a 3D mass map or more indirect 3D shear statistics

Some problems from extent of redshift kernel, inaccuracies in photo-zs

The COSMOS Survey P.I. Nick Scoville



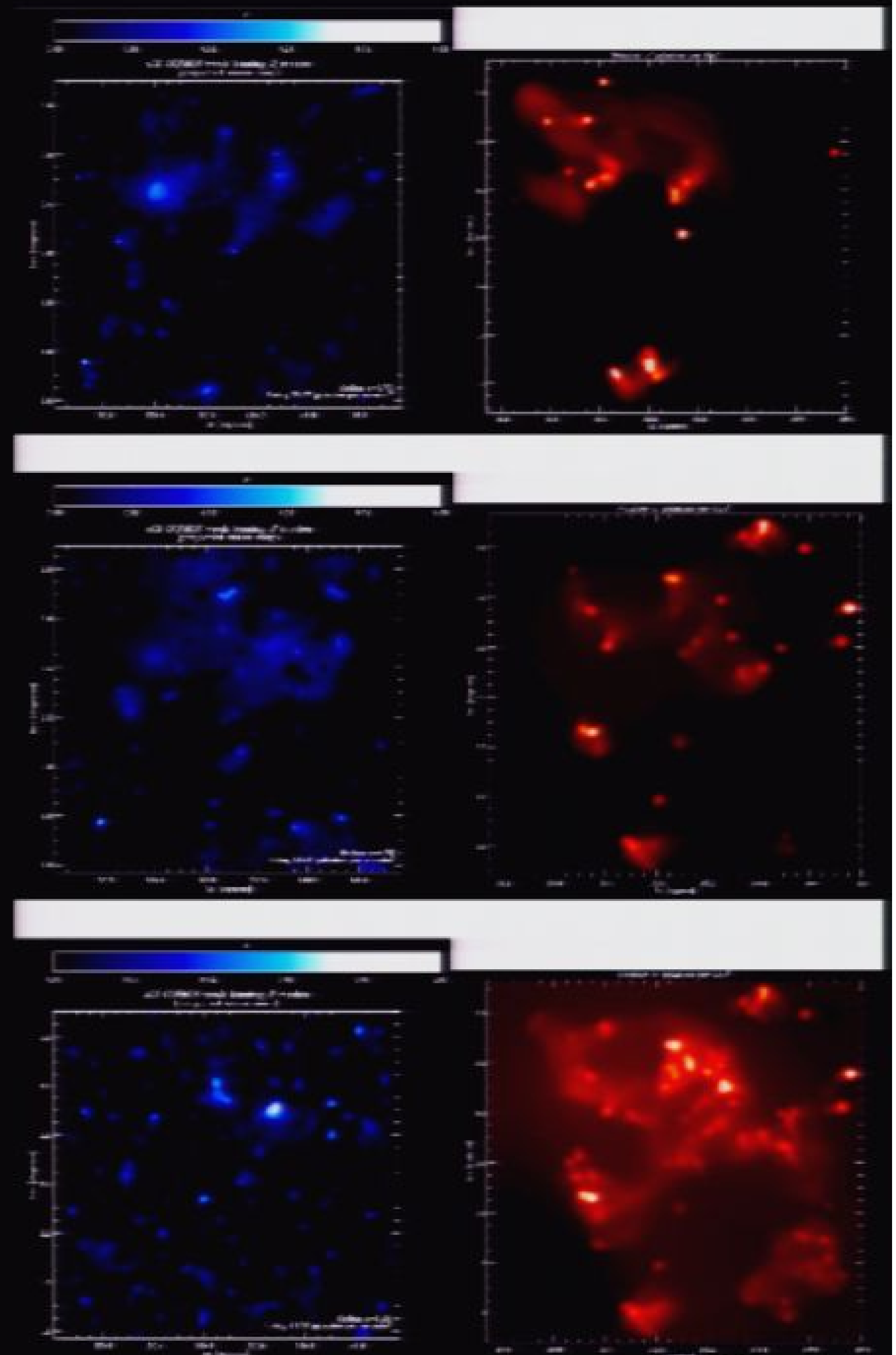
The COSMOS Survey

- 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

WL Convergence Maps

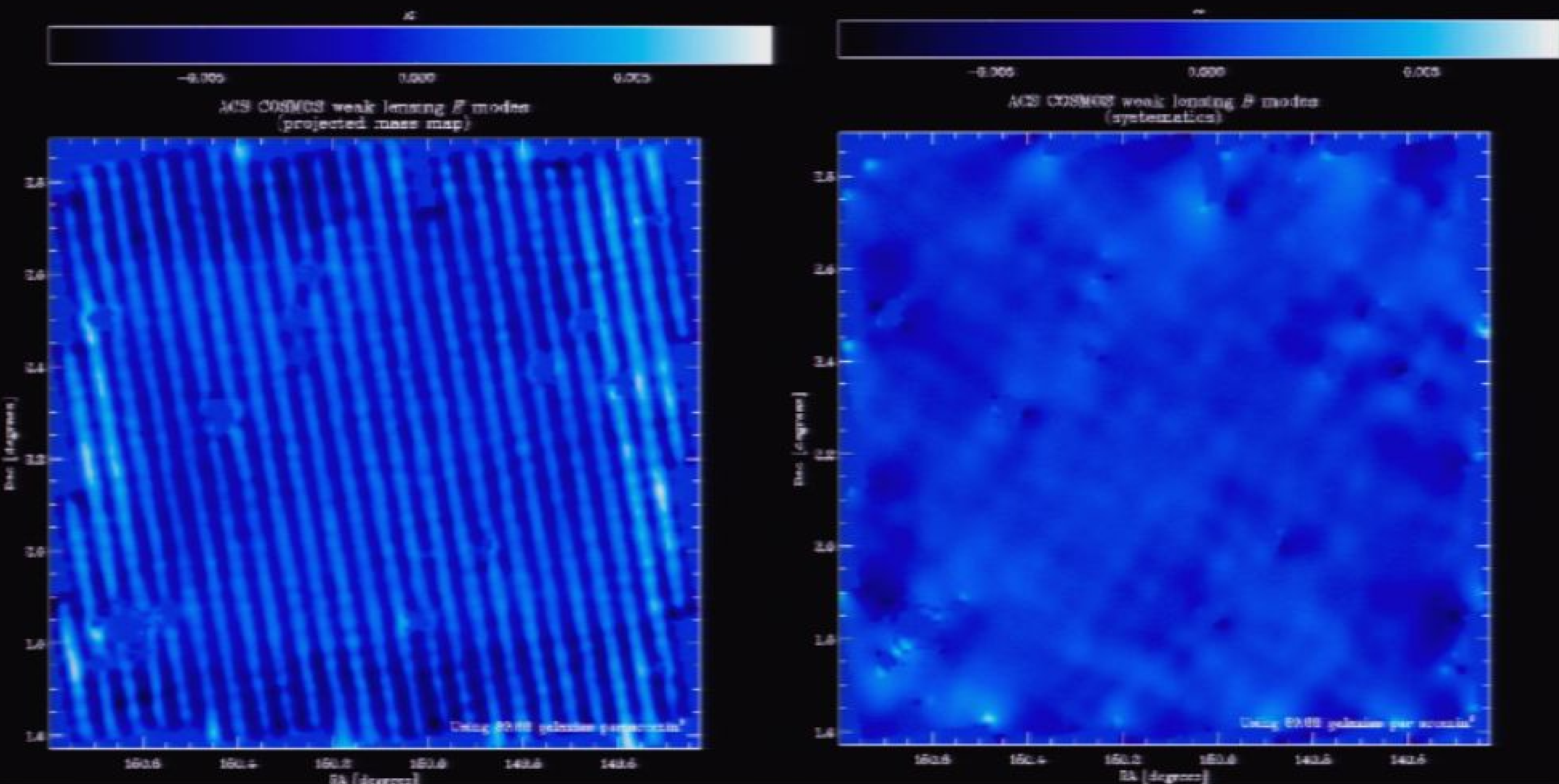
Massey, Rhodes, Leauthaud
Capak, Koekemoer, Scoville, Refregier

- 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)

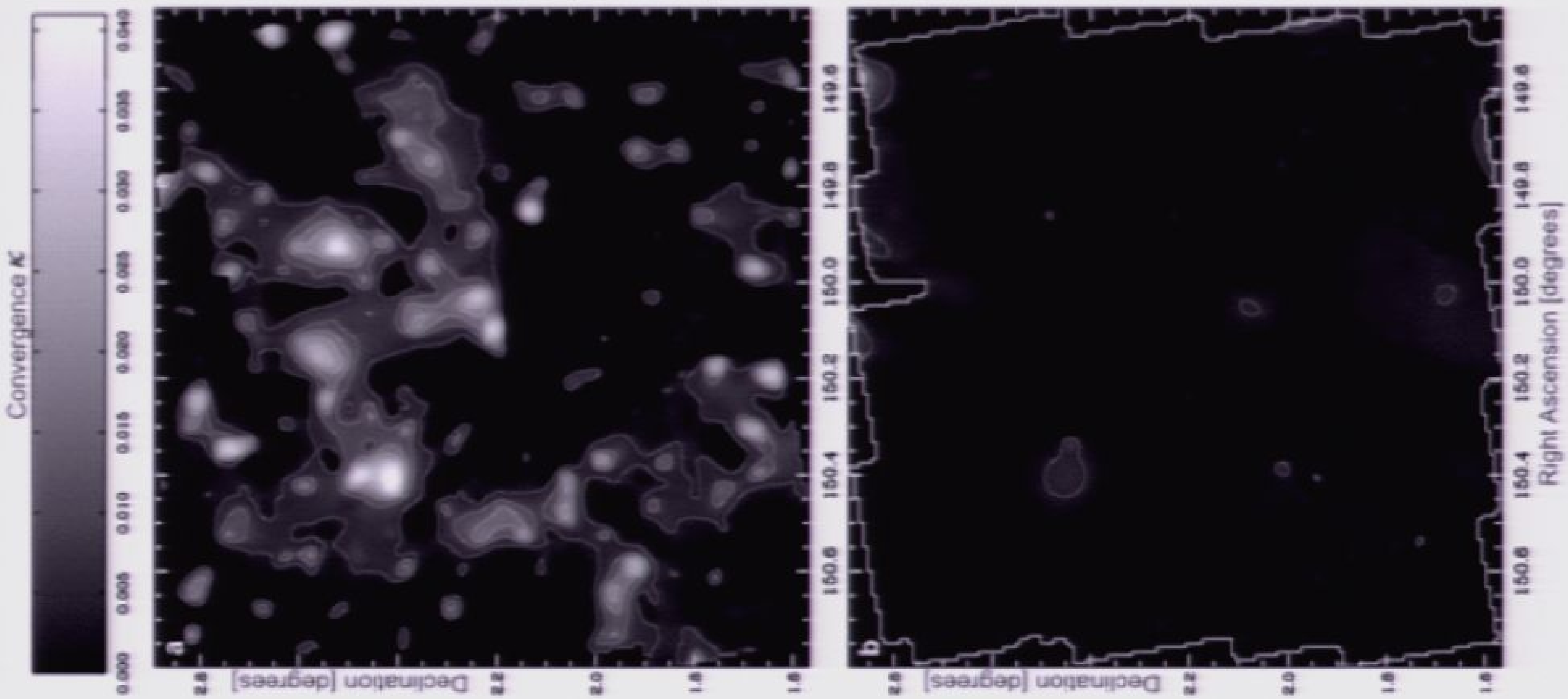


Systematics

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



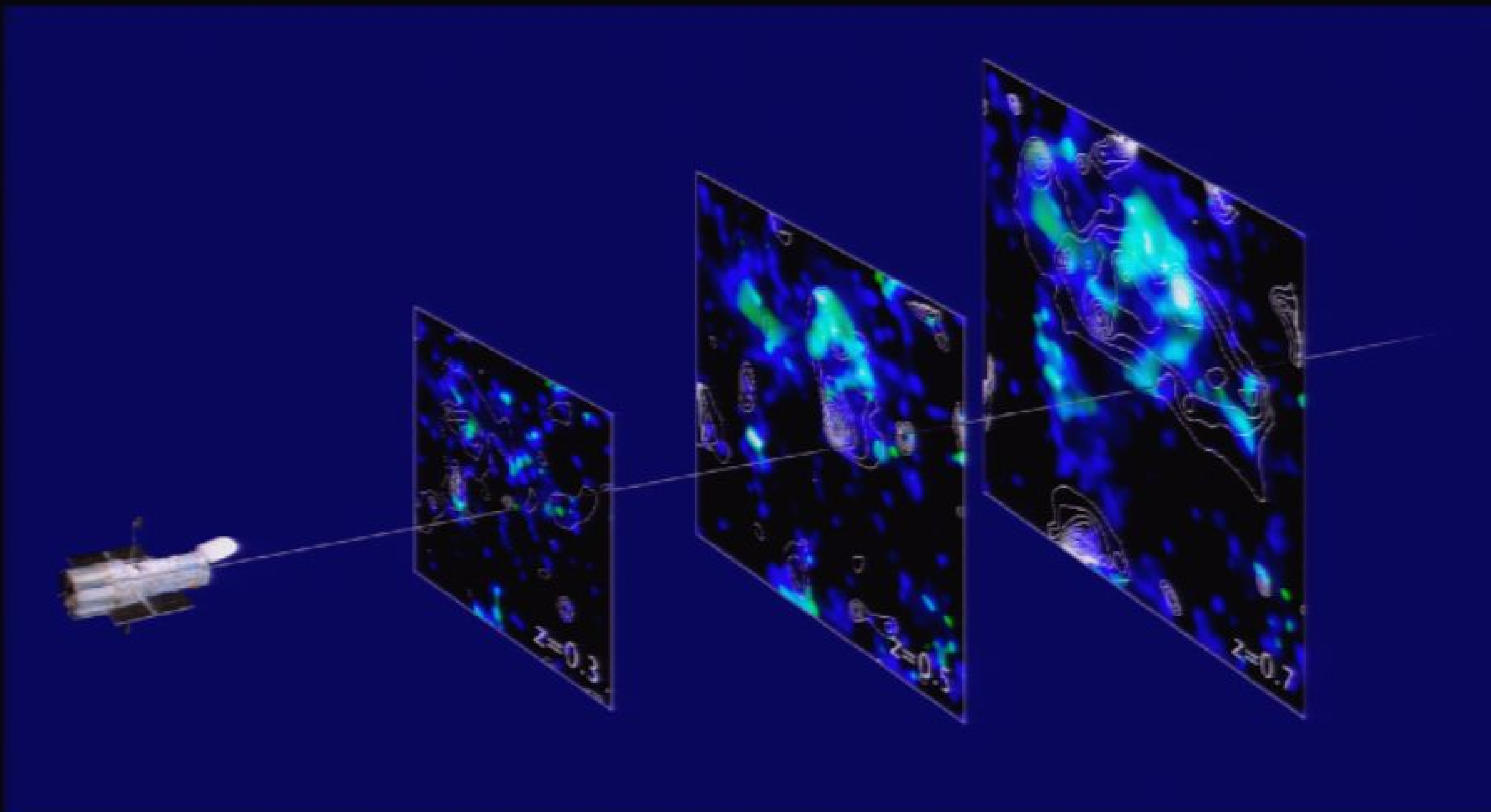
The Final Result



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

Seeing the Growth of Structure Directly

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



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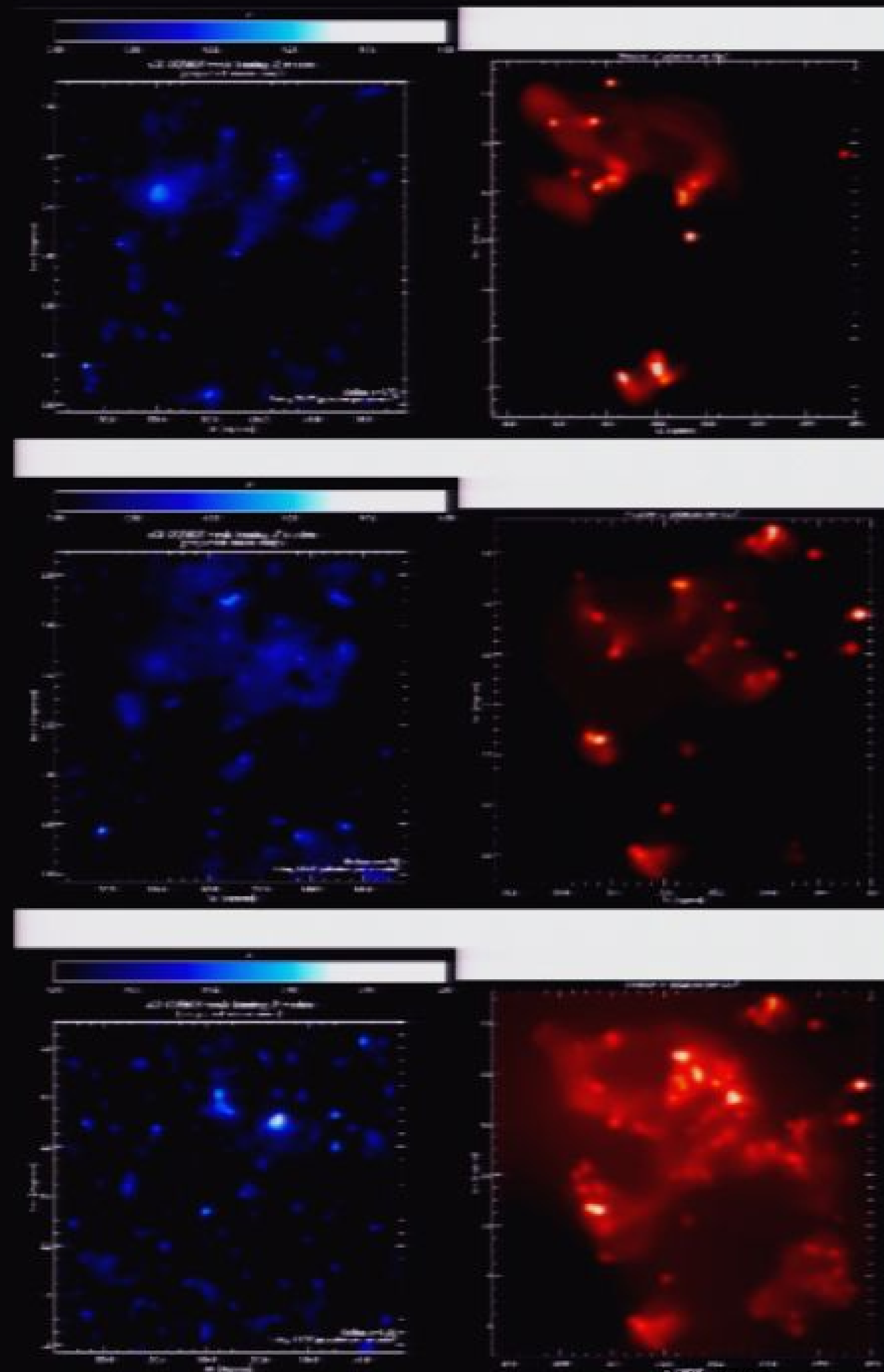

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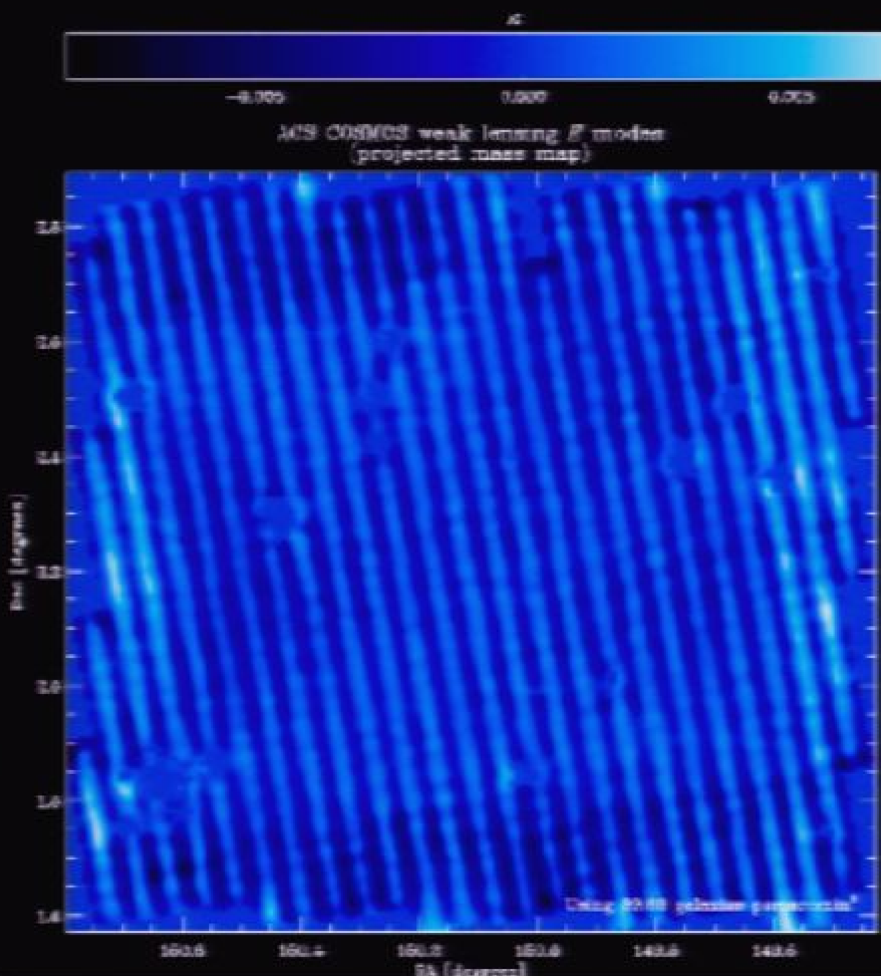

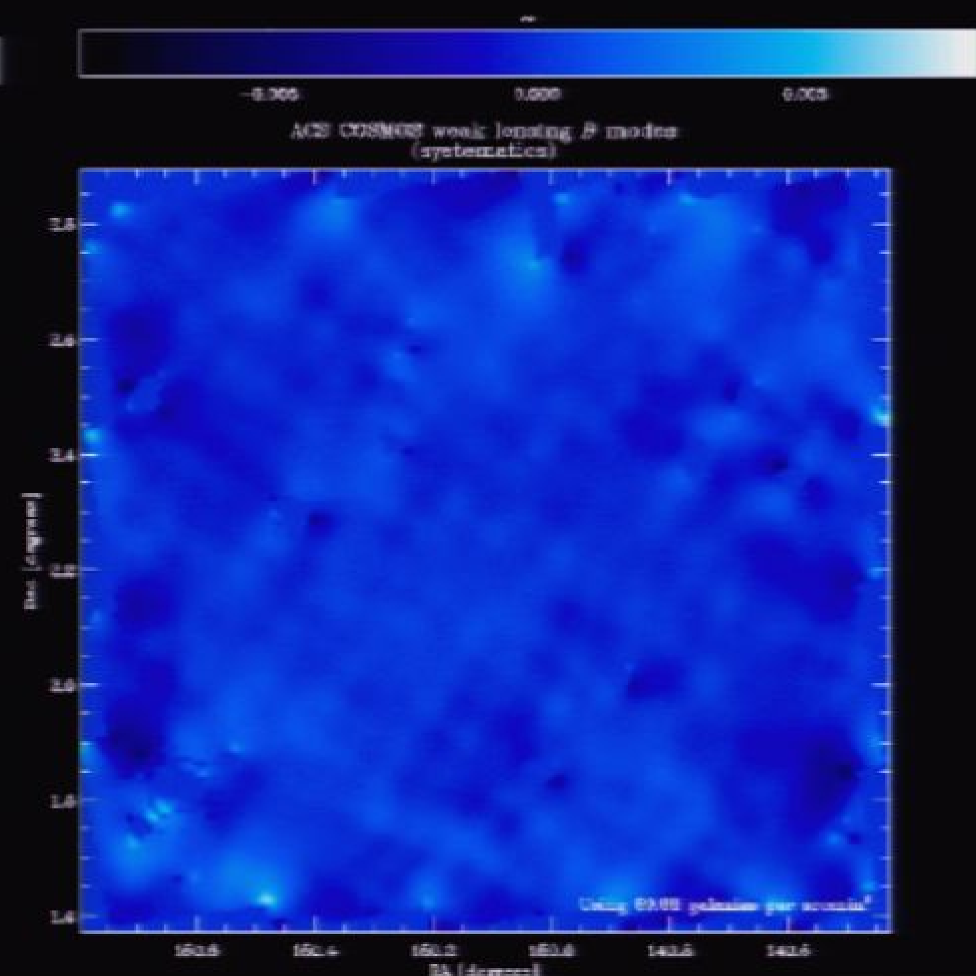

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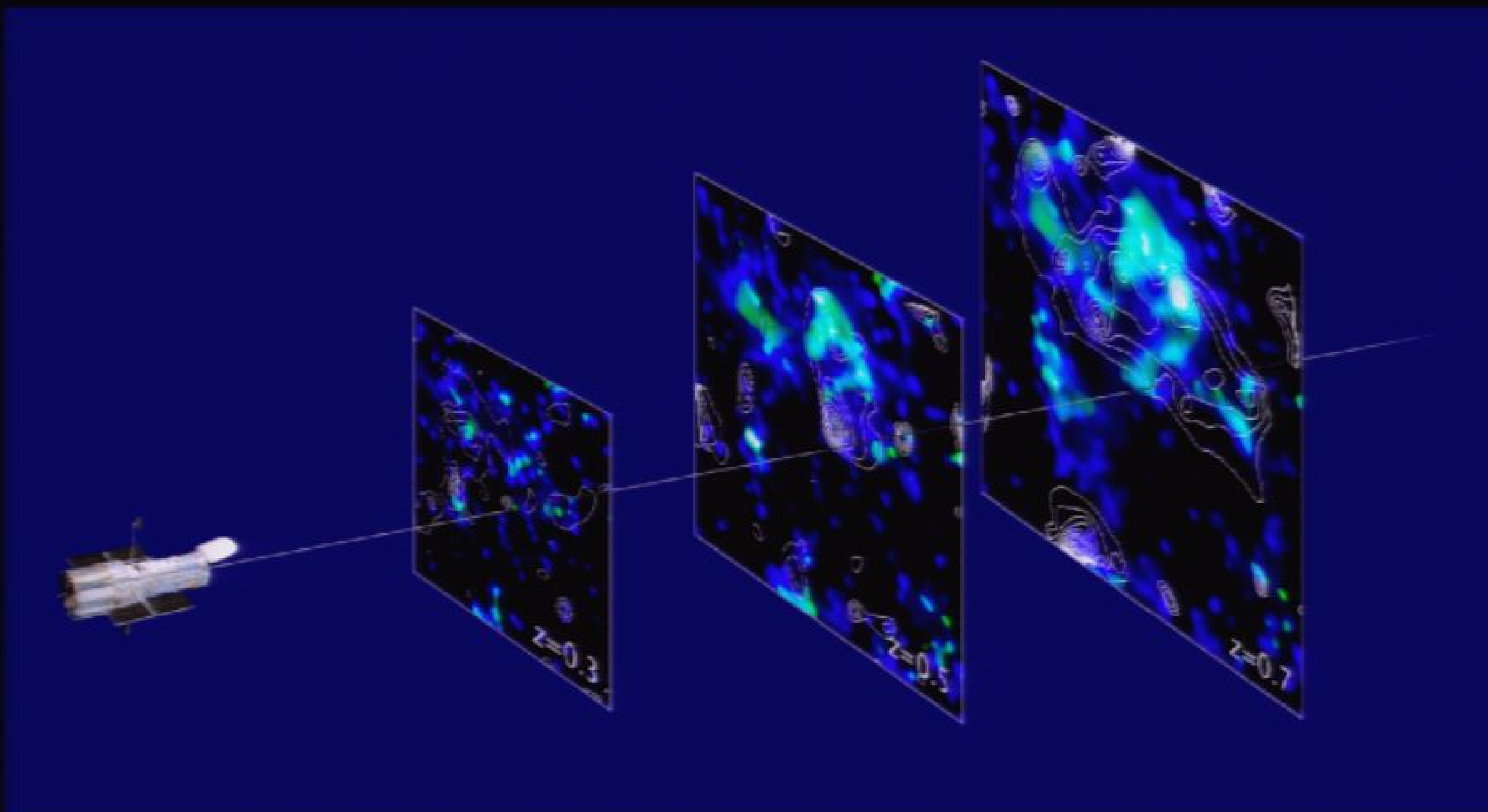
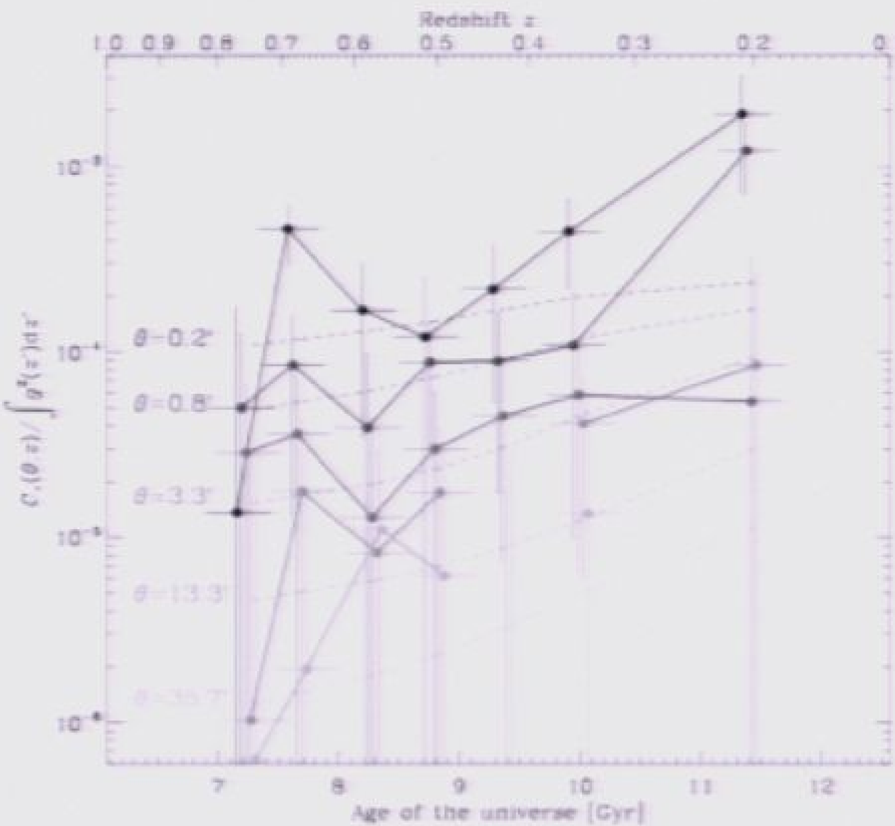


Measuring the Growth of Structure

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.

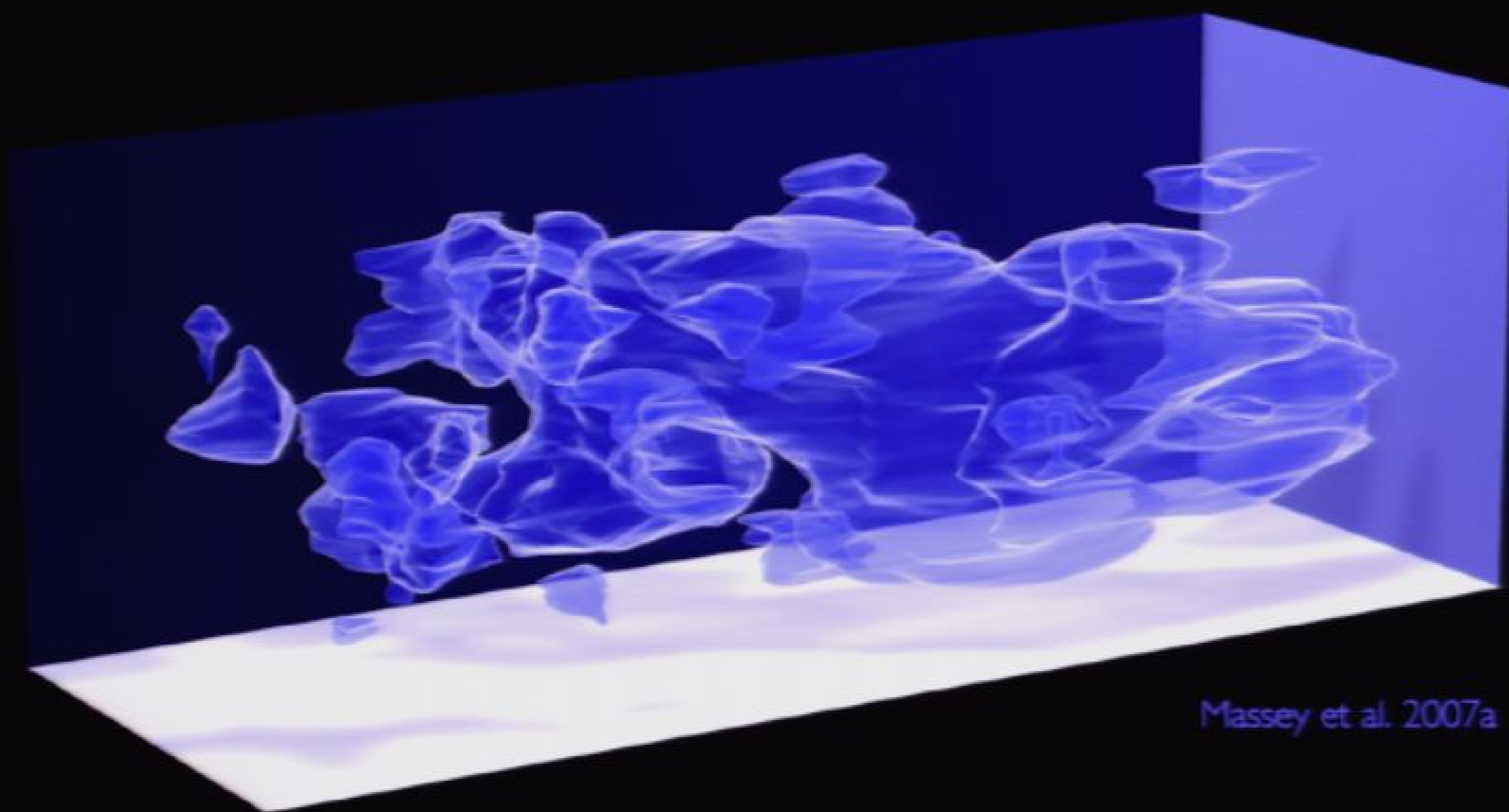
Get (rather noisy) measure of the growth of structure:



Massey et al. 2007b

3D Mass Distribution

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



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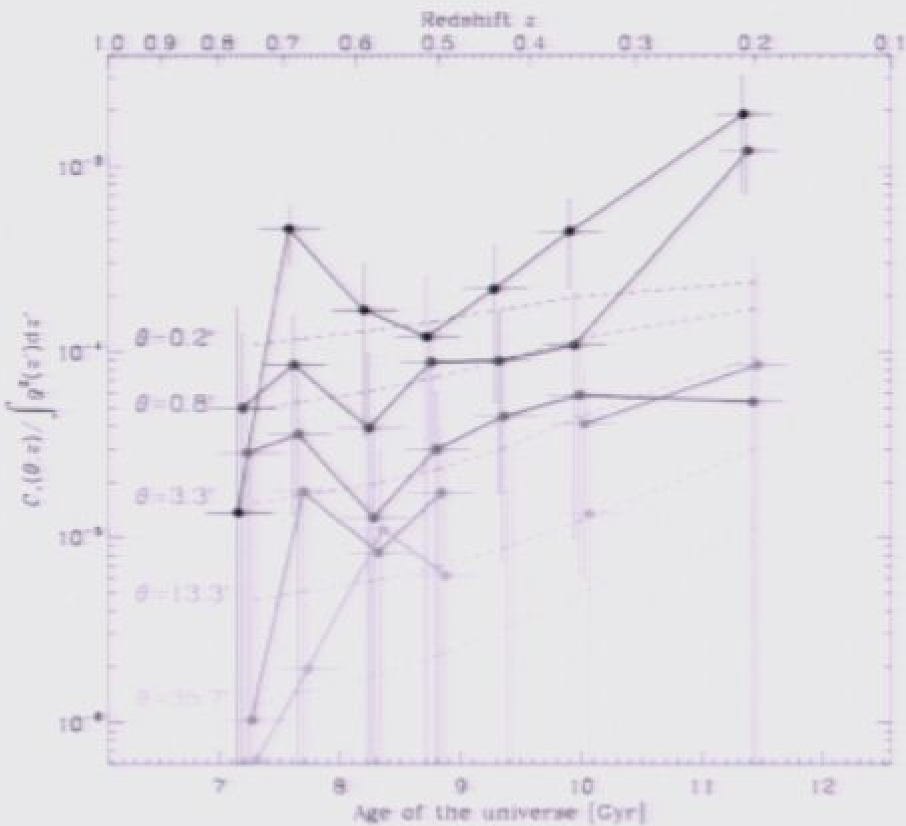

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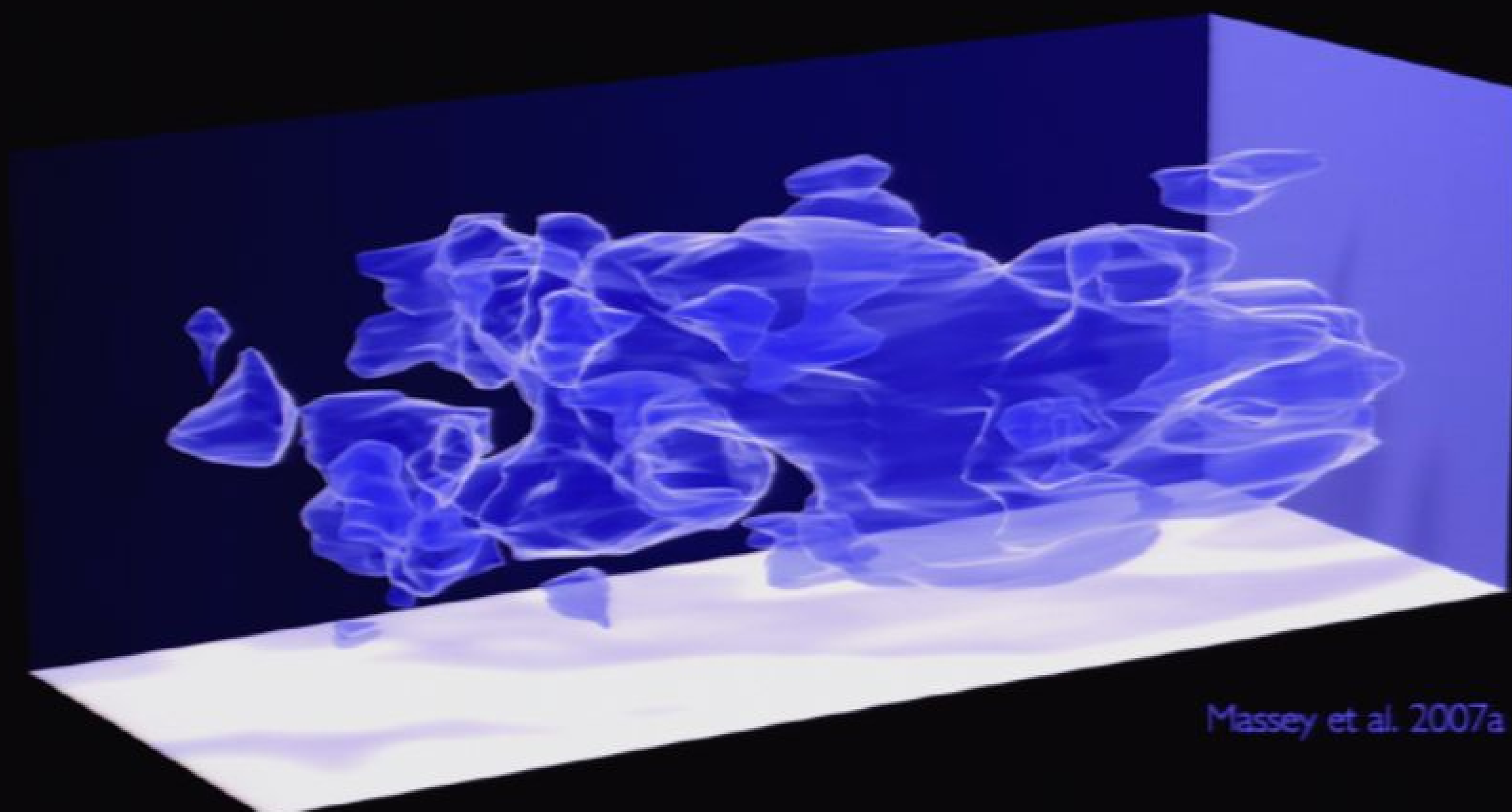
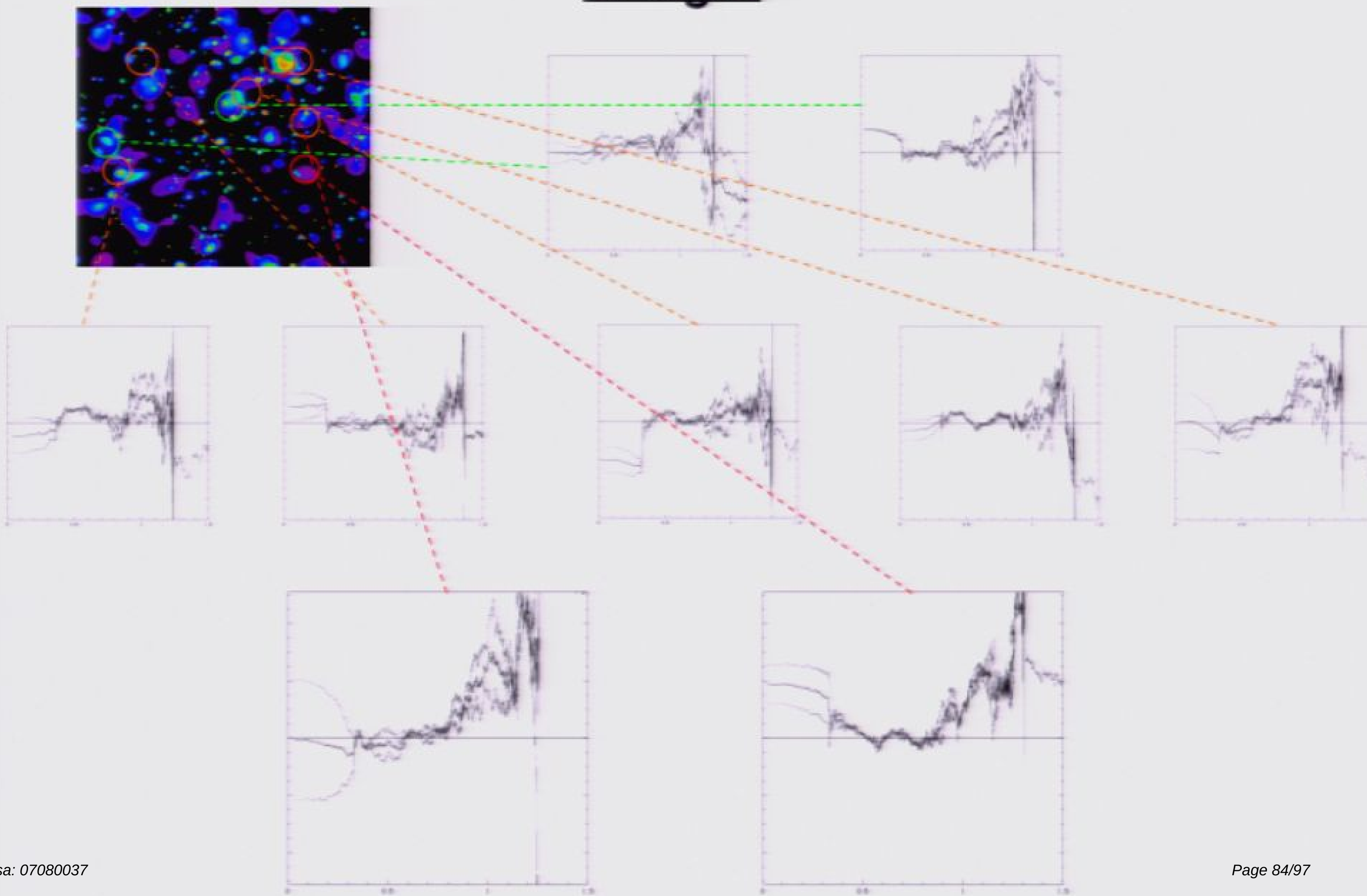


Massey et al. 2007a

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



Summary

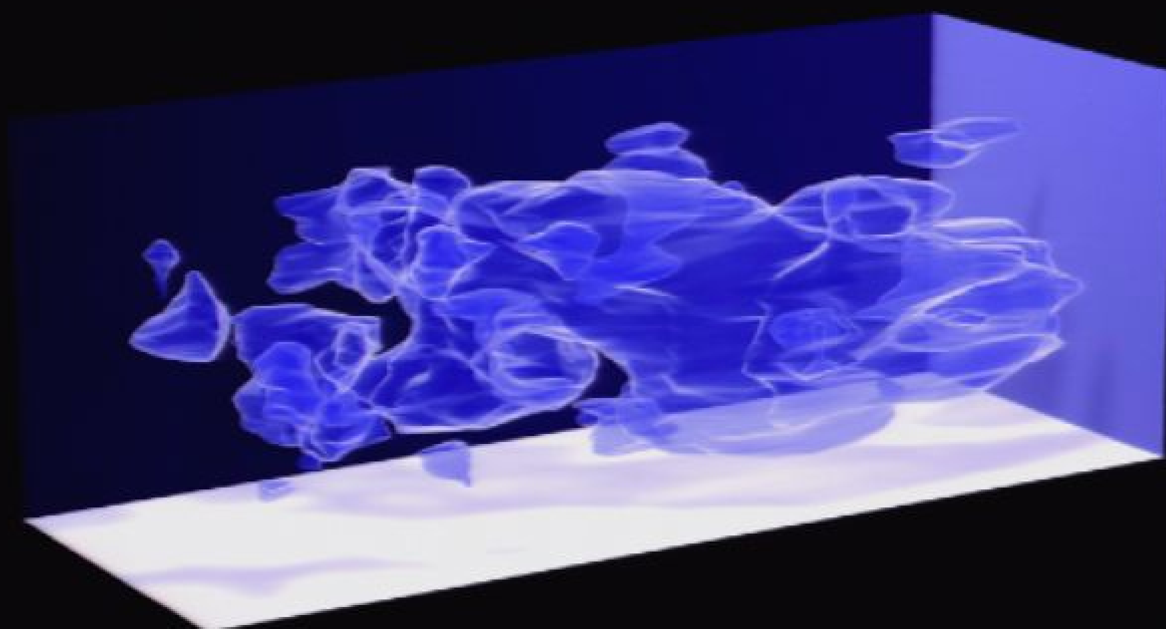
Can get constraints on the amplitude of fluctuations:

2D	$\sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.48} = 0.81 \pm 0.17$
3D	$\sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.44} = 0.866^{-0.085}_{-0.068}$

Need a larger volume to get constraints on the equation of state (current estimate: w = -1 ± 1 with this volume)

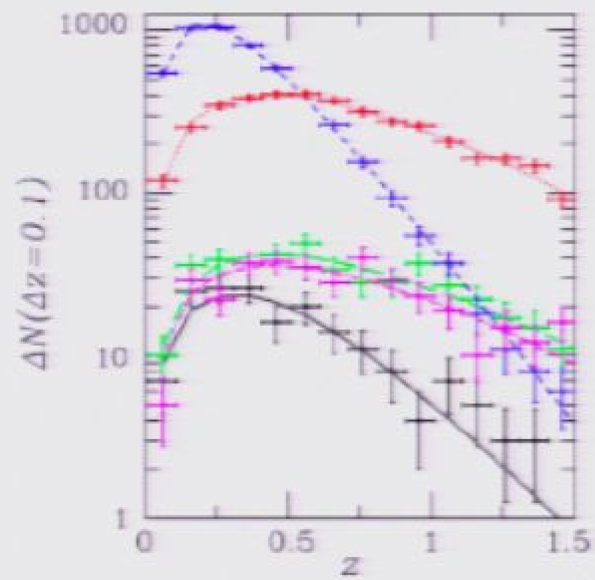
Working from space does not automatically make systematics vanish.

Physically, projection effects and photo-z errors a major issue.



Second Method: Cluster Number Counts

- Count the number of high peaks in the universe
- In principle a very sensitive measure
- In practice, mass calibrations a problem
- Also constrained to do this at fairly low redshift (esp. for x-ray) and fairly large mass



Weller & Battye 2003

N.B. Press-Schechter: $$\frac{dn}{dM}dM = \frac{\rho_0}{M}\exp\left[-\frac{\nu^2}{2}\right]\frac{d\nu}{dM}dM$$

where

$$\nu = \frac{\delta_c}{D\sigma}$$

How to break sigma-growth factor degeneracy?

Third Method: Differential Growth

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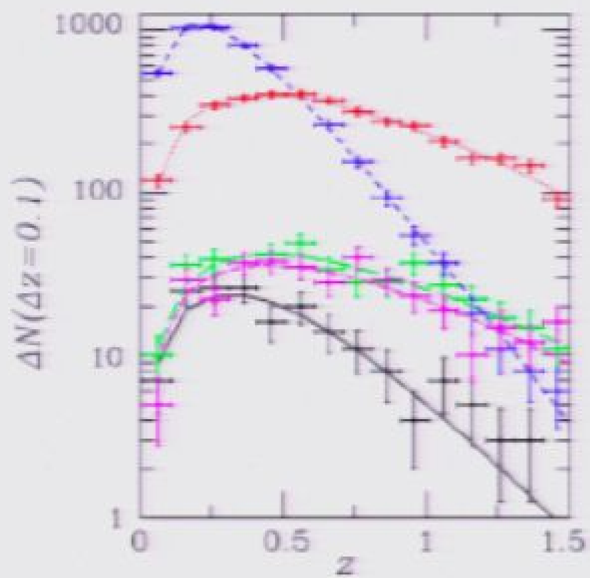

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- This is measured as halo concentration: $c \equiv r_s/r_{vir}$; r_s where slope is r^{-2}

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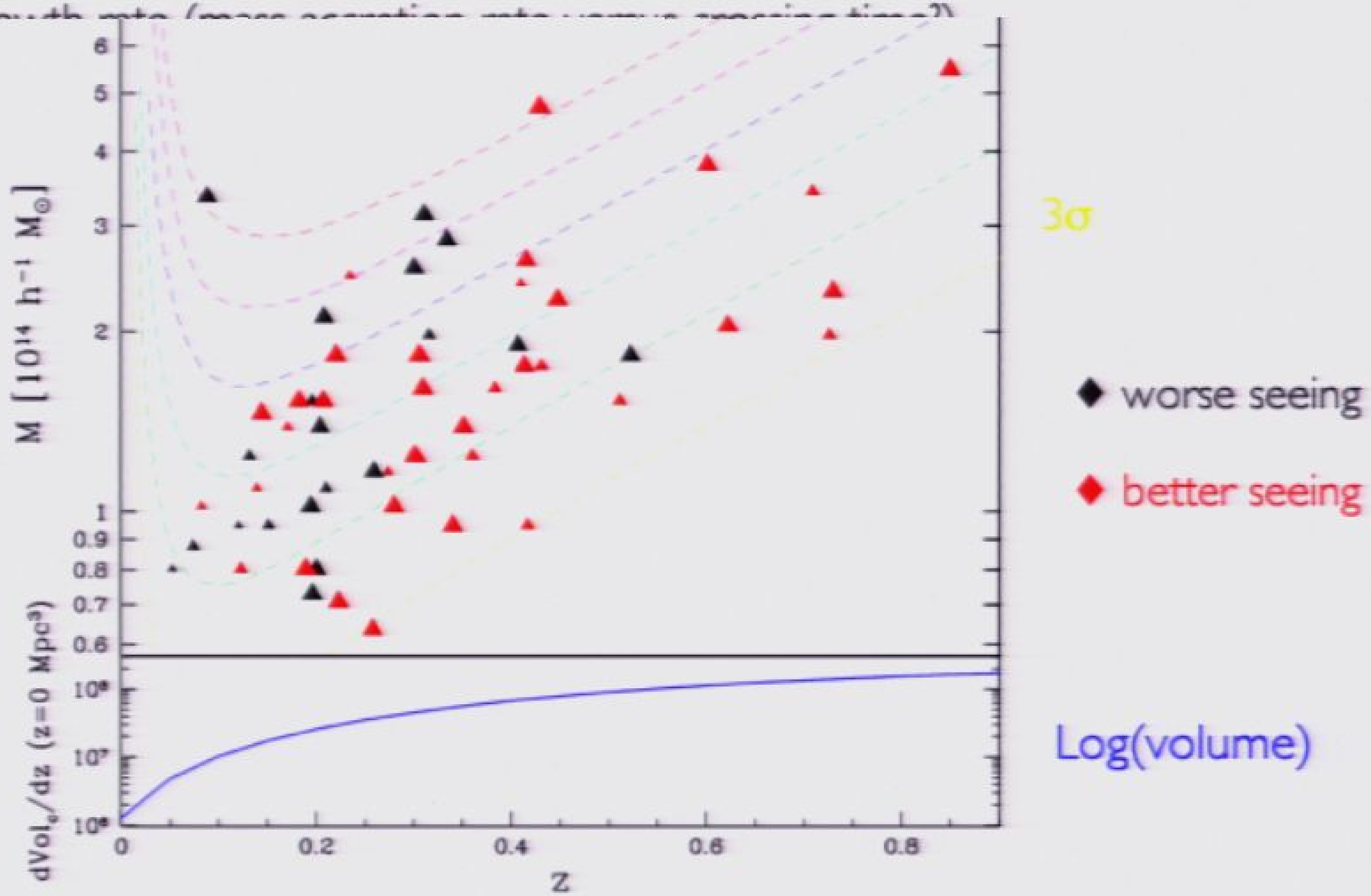
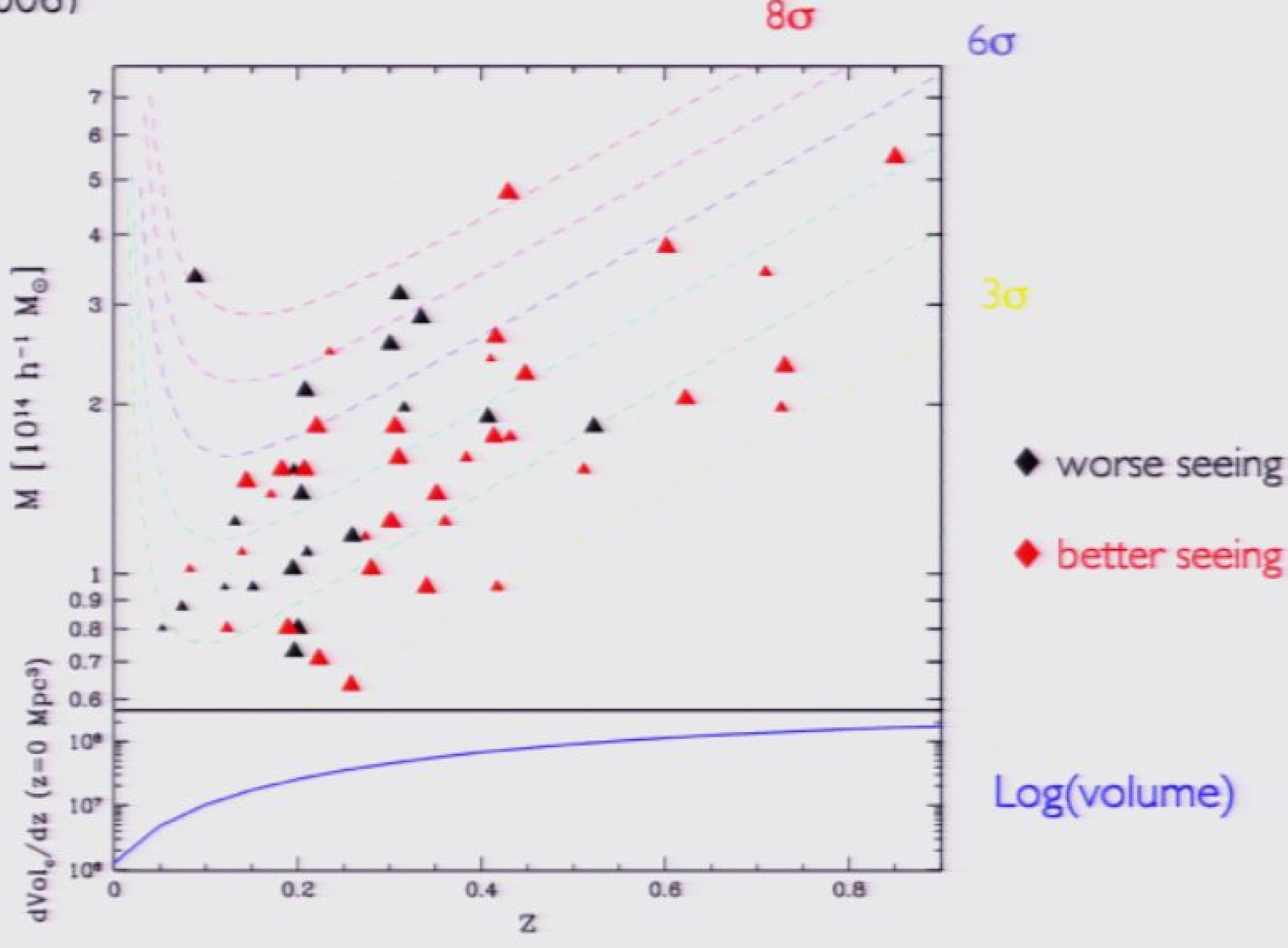


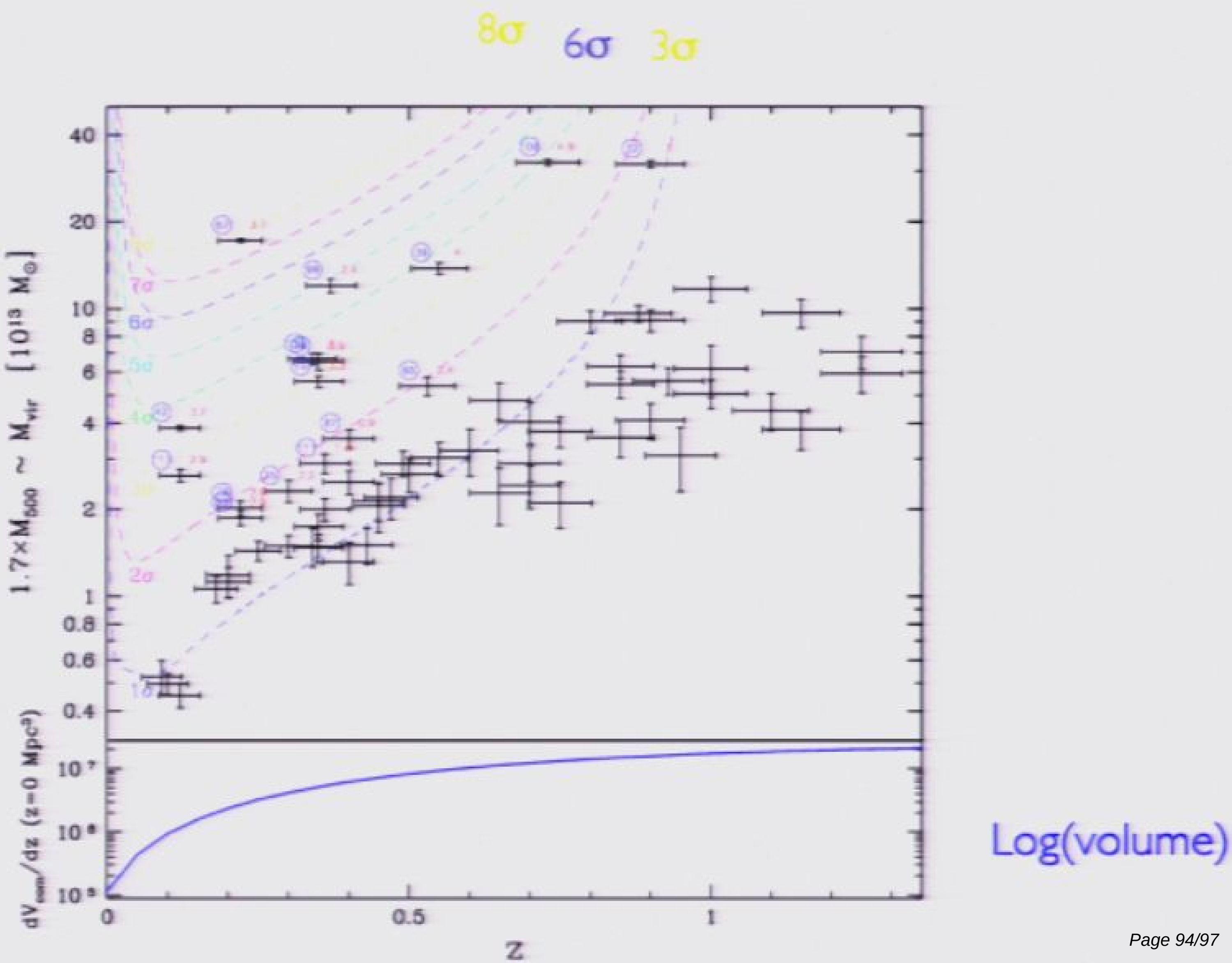
Recent Suprime22 Results

(Green et al. 2006)



COSMOS Xray-lensing comparison

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



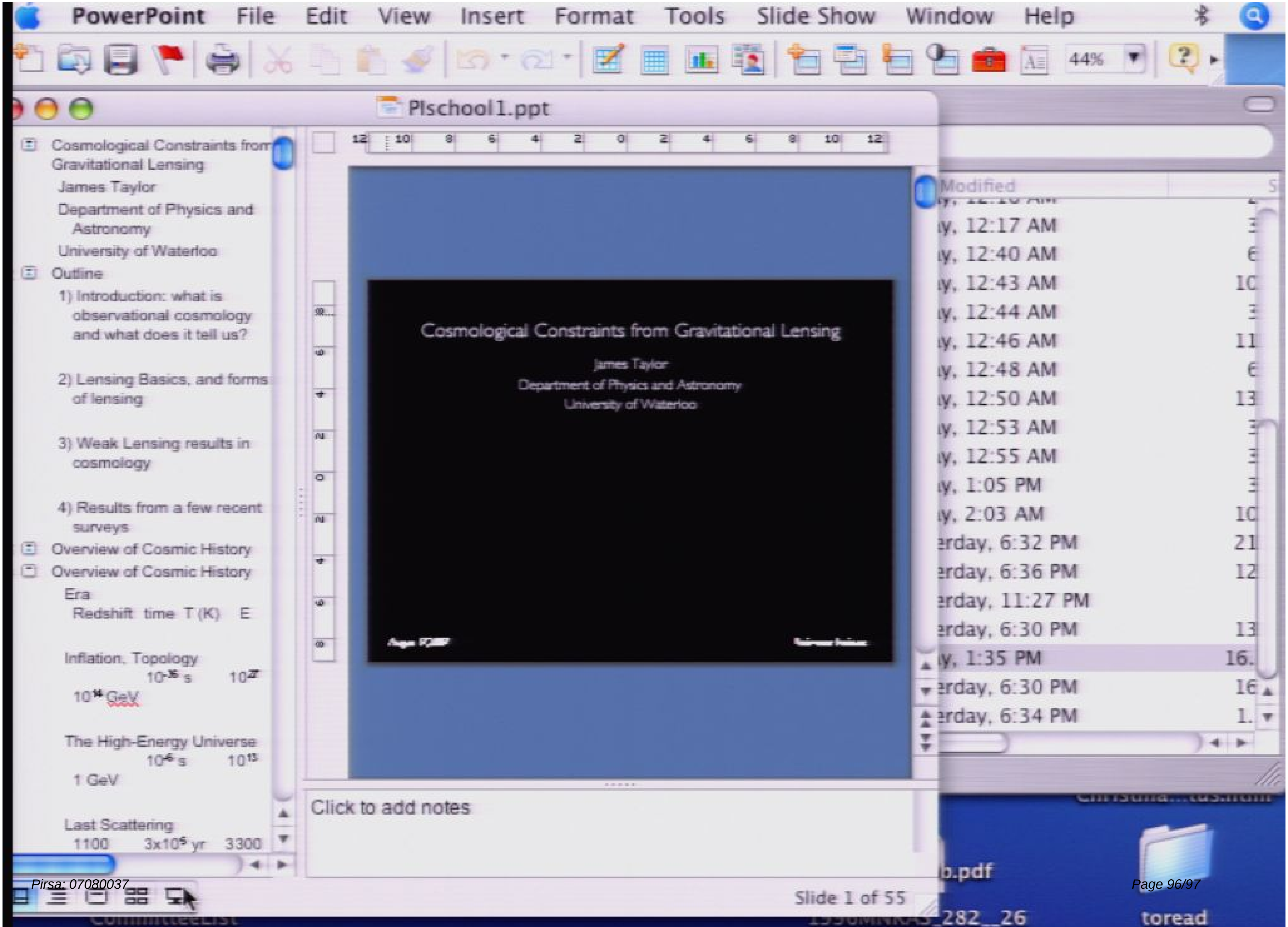
Summary

Gravitational lensing in general and weak gravitational lensing in particular provide the most direct route to measuring the mass distribution in the universe.

Most measurements boil down to the expansion history and the linear growth factor, although lensing also tests the physical properties of dark matter (thermal velocity, scattering cross-section).

These measurements are and will remain complementary too CMB measurements and results from other methods.

Field is currently limited by available facilities => hope of future space missions?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Cosmological Constraints from Gravitational Lensing
James Taylor
Department of Physics and Astronomy
University of Waterloo
Outline
1) Introduction: what is observational cosmology and what does it tell us?
2) Lensing Basics, and forms of lensing
3) Weak Lensing results in cosmology
4) Results from a few recent surveys
Overview of Cosmic History
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Era
Redshift time T (K) E
Inflation, Topology
10^-35 s 10^27
10^14 GeV
The High-Energy Universe
10^-6 s 10^13
1 GeV
Last Scattering
1100 3x10^5 yr 3300
Cosmological Constraints from Gravitational Lensing
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