

Title: Observational Probes of Early Universe Cosmology - Lecture 4

Date: Jun 27, 2009 09:00 AM

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Abstract:

An Introduction to Observational Cosmology

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Lect 1: Dynamics of the Universe as probed by distance measurements (SNe)

Lect 2: Baryonic Acoustic Oscillations

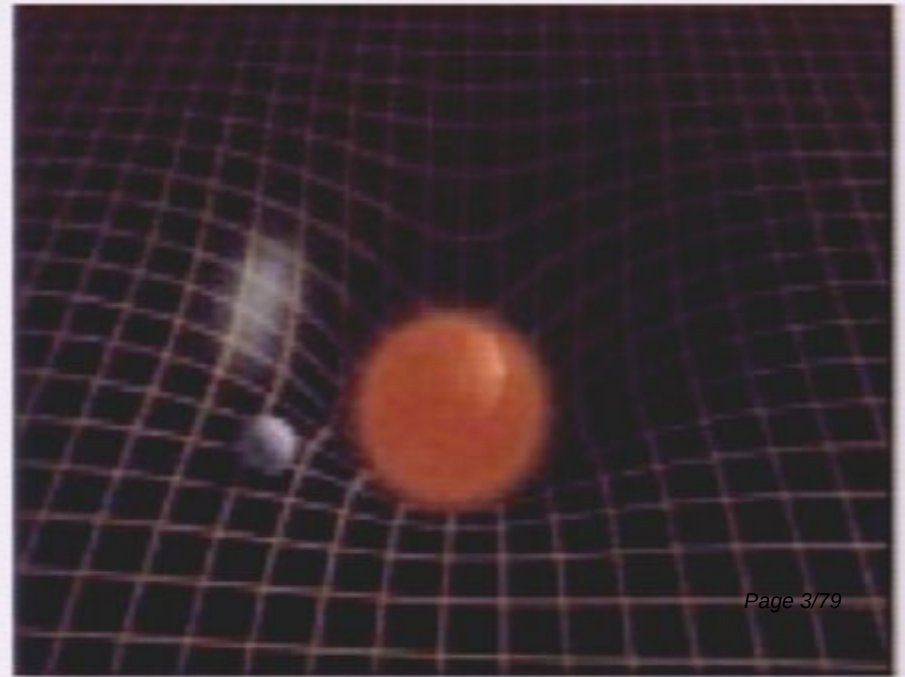
Lect 3: Dark matter clustering and galaxy surveys

Lect 4: Gravitational lensing

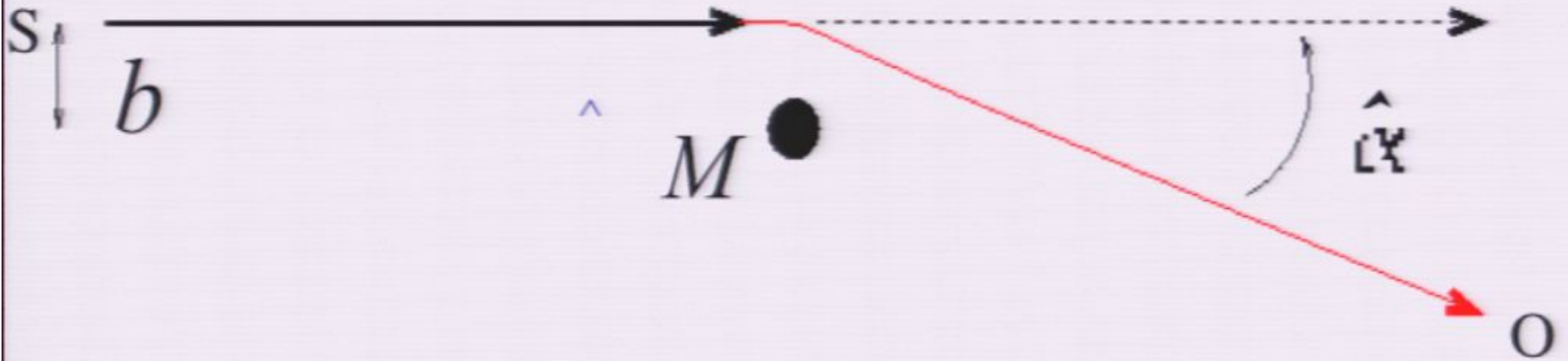
Lect 5: The cosmic microwave background radiation

Gravitational lensing in cosmology

1. History and basics
2. Lensing theory overview
3. Lensing by clusters of galaxies
4. Cosmic shear



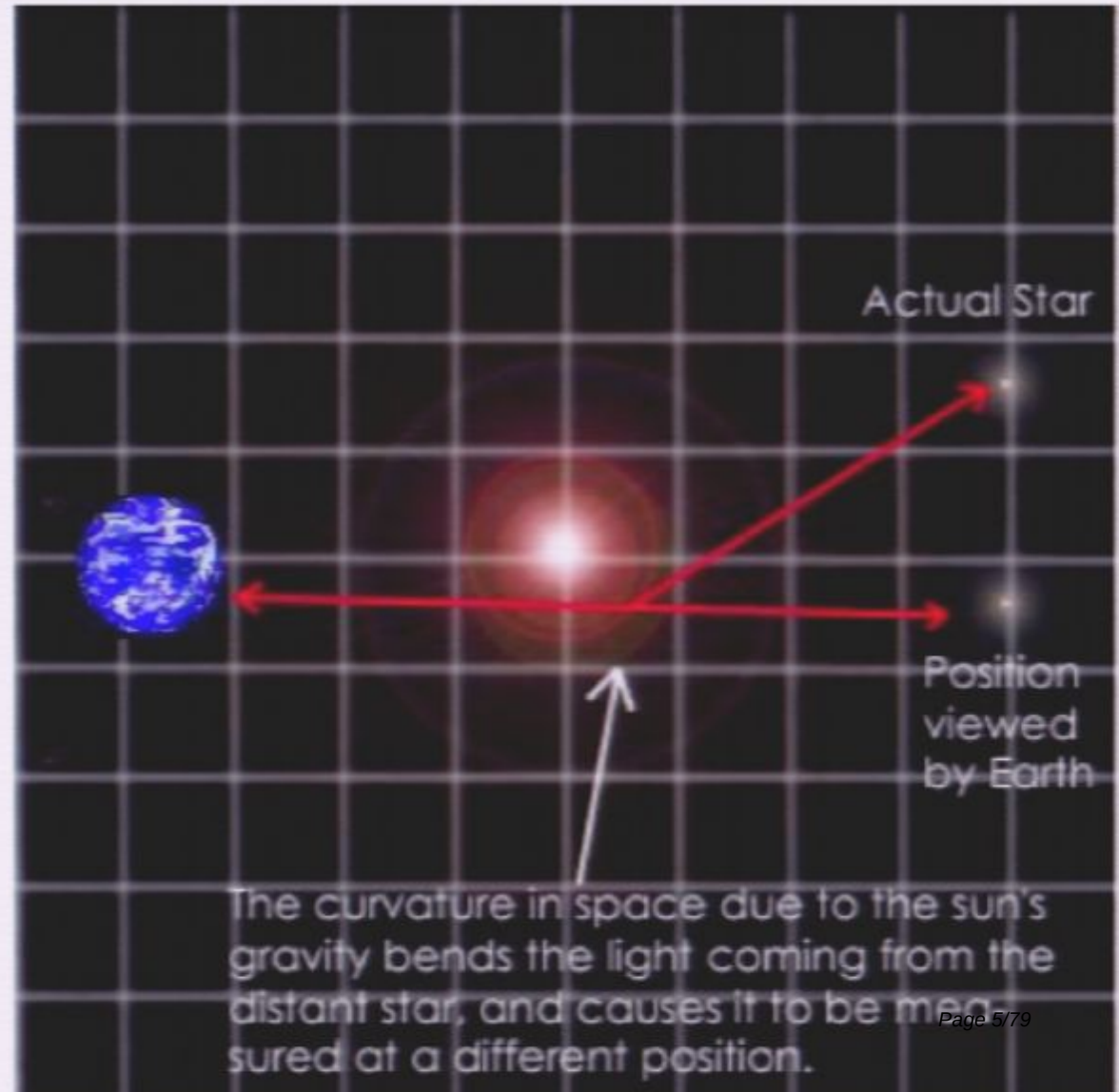
Just one equation from GR



- $\alpha = 4 G M / (c^2 b)$
- NB. Independent of light wavelength

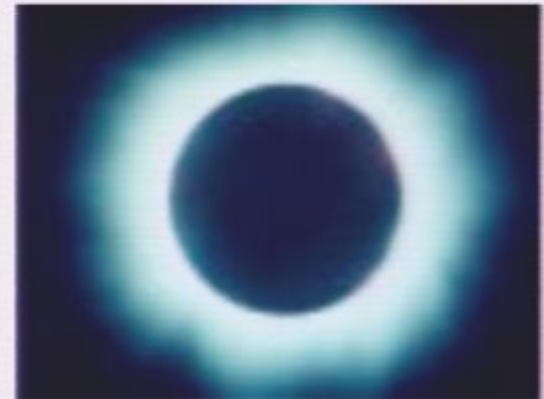
Deflection by the sun

$$\alpha = 1.75''$$

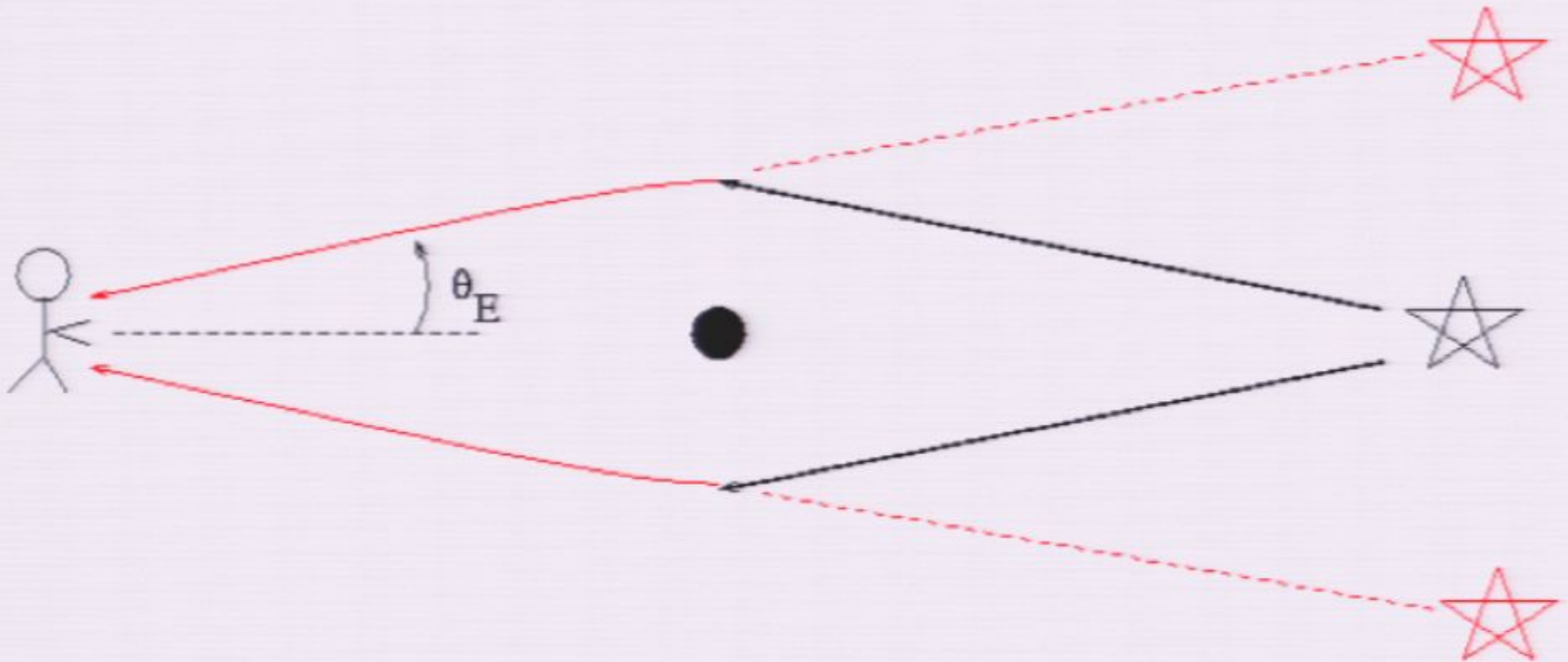


Eclipse Experiment

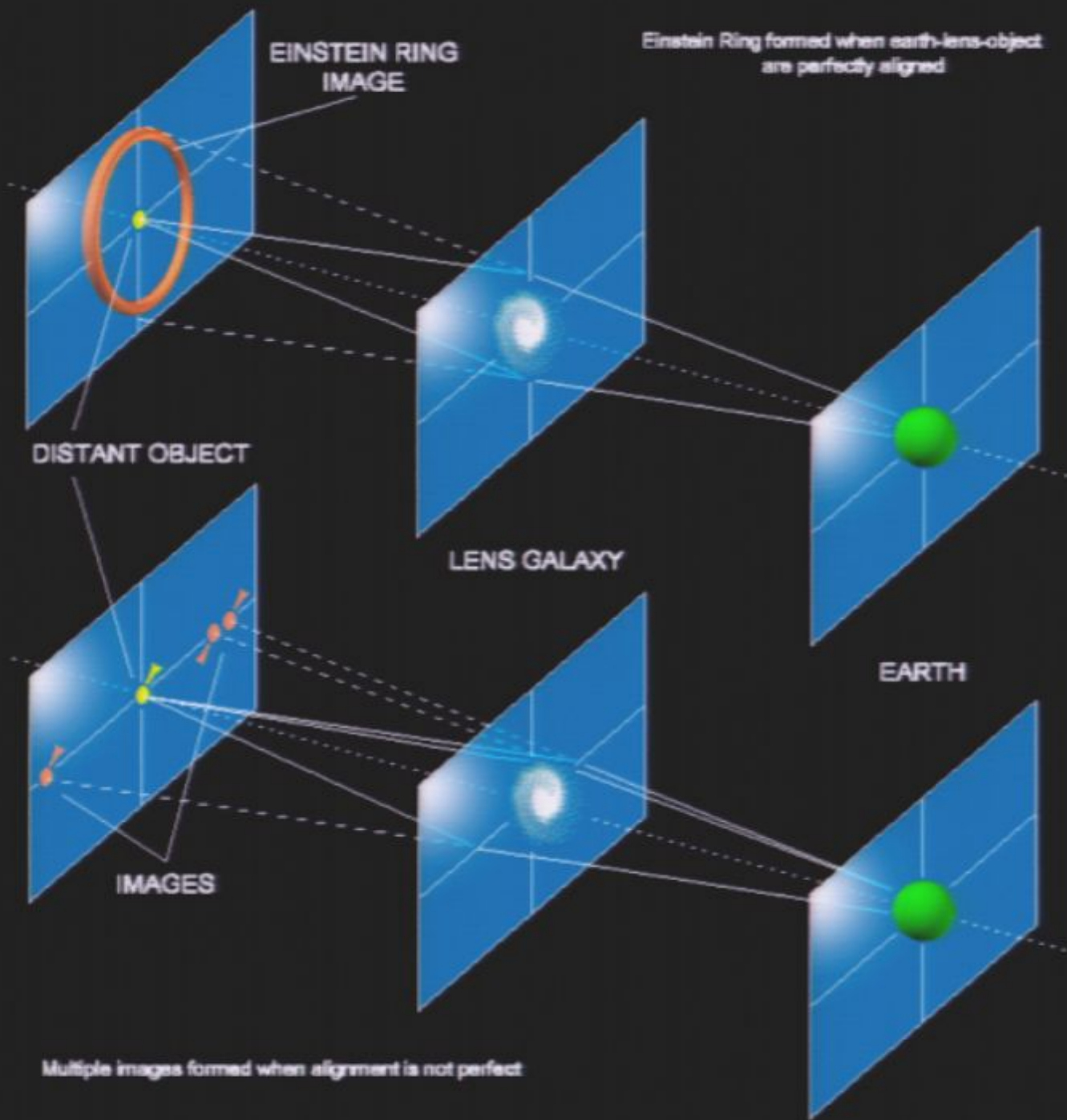
- Eddington et al.
 - 29 March 1919
 - Principe Island off west coast of Africa
- Agrees with Einstein
- Einstein becomes a celebrity
 - Within 1 year more than 100 books written on GR!



Einstein ring



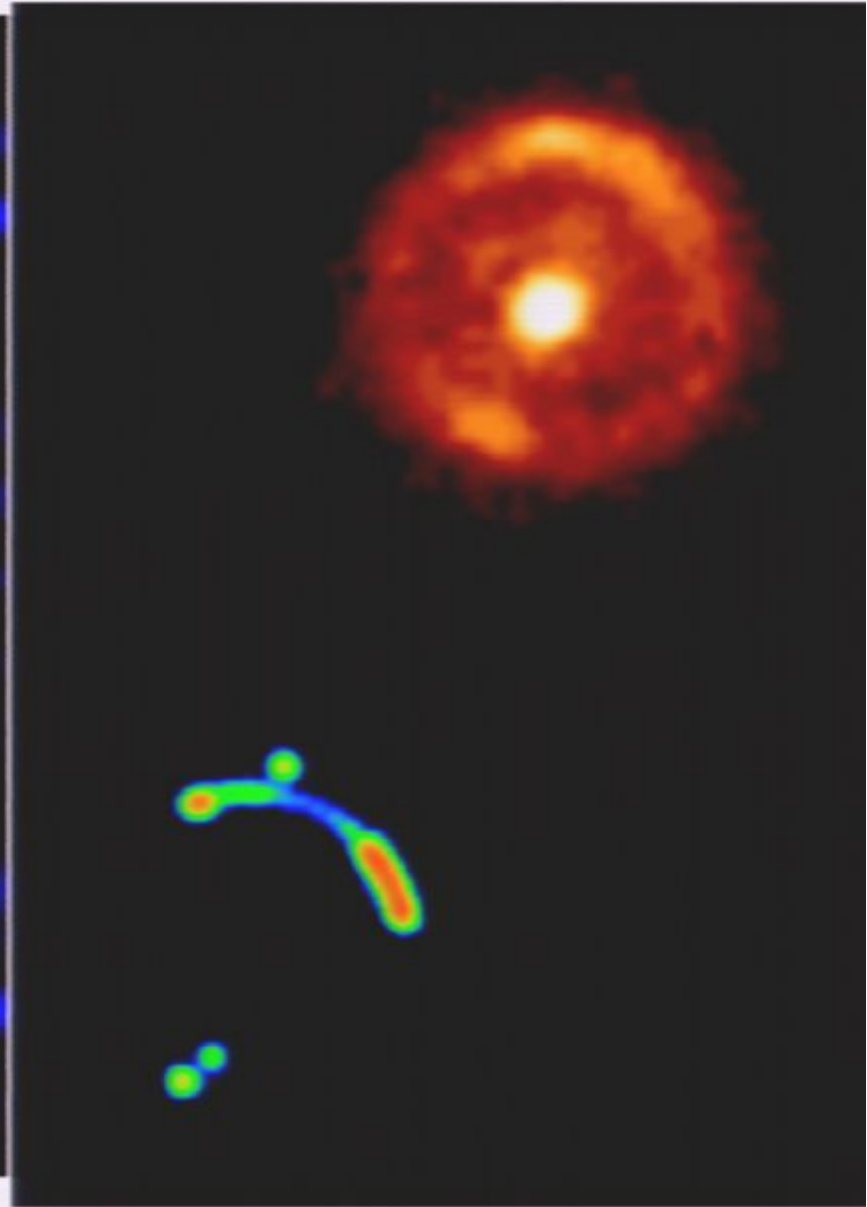
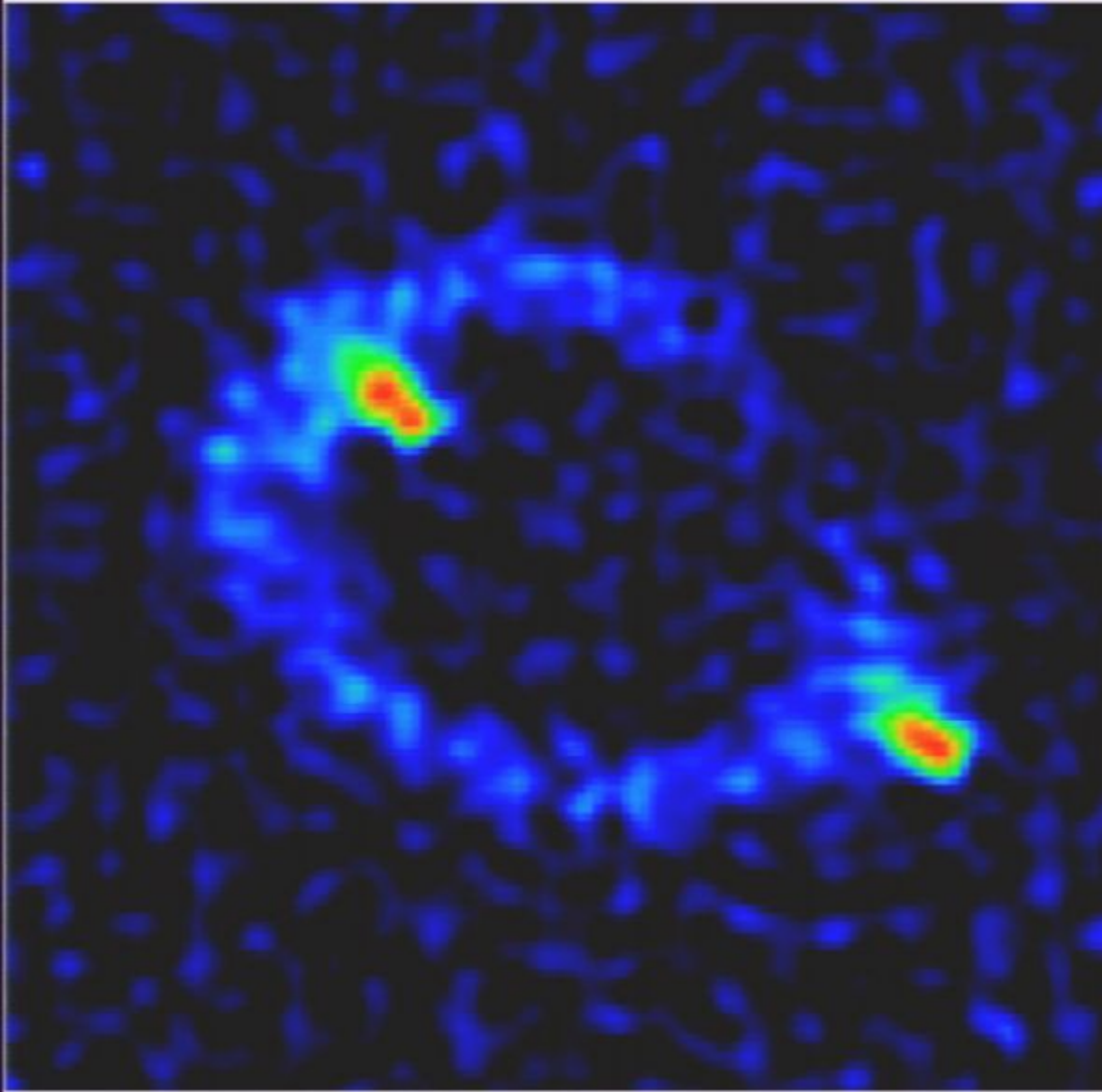
$$\theta_E^2 = 4GM/c^2 \ D_{ls} / (D_l D_s)$$



Einstein ring examples:

A galaxy at cosmological distance

- $M \sim 10^{11} M_{\odot}$, $D \sim 1 \text{ Gpc}$
- $\theta_E \sim 1'' (M / 10^{11} M_{\odot})^{1/2} (D / 1 \text{ Gpc})^{-1/2}$
- Comparable to 1" seeing, 0.5" Hubble
- If D is 100x smaller get $\theta_E \sim 10'' =$ possible
- ... Radio telescopes have the resolution



First Einstein ring observed by VLA

Quasar lensed by galaxy

upper: Hubble

lower: Merlin

2. Theory overview

- General deflection angle
- Critical density
- Circularly symmetric lenses – images
- Non-circularly symmetric lenses

General deflection angle

- Thin screen approx: just **projected** mass
- Integrate deflection angle over masses
- Spherical/cylindrical lenses
 - $M \rightarrow$ mass enclosed by light ray
 - For a constant mass sheet of density Σ
 - $\alpha = 4 \pi G \Sigma \theta D_d D_{ds} / D_s / c^2$
- Convenient definition:

$$\Sigma_c = c^2 / 4 \pi G D_s / (D_s D_{ds})$$

Critical density

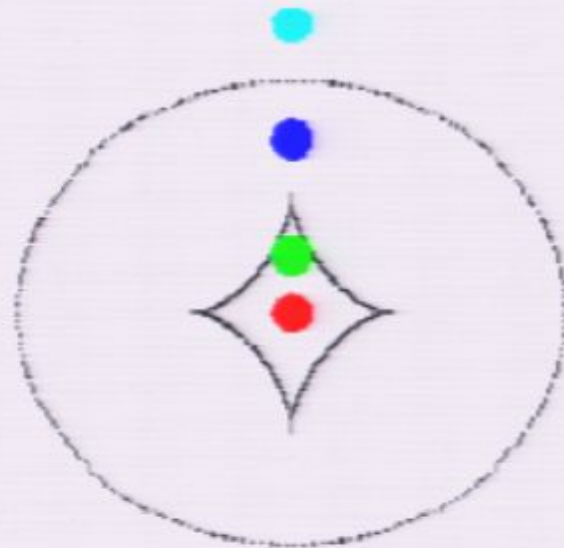
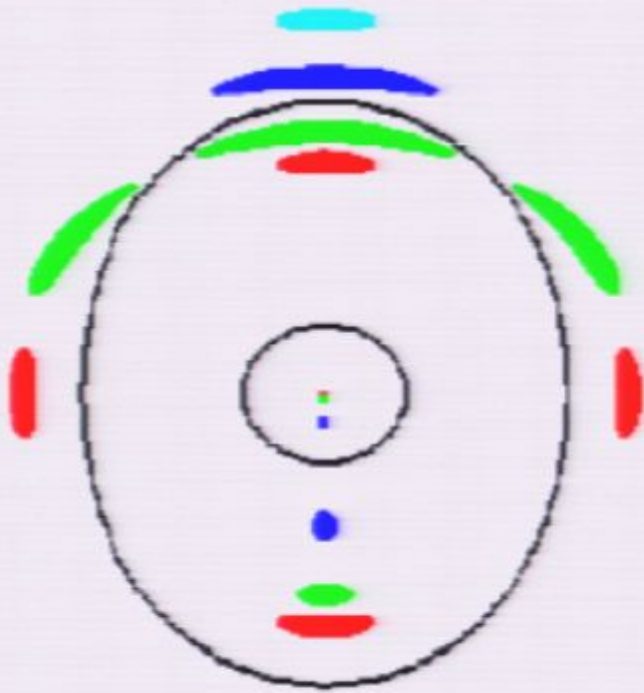
$$\Sigma_c = \frac{c^2}{4 \pi G} \frac{D_s}{D_d D_{ds}}$$

- Indicates 'strength of lensing'
 - Appears everywhere
- Lens is 'supercritical' if $\Sigma > \Sigma_c$ anywhere

Strong distortions and multiple images

- More complex images

http://www.mpa-garching.mpg.de/Lenses/museum.movies/GL_4.qt



Einstein cross



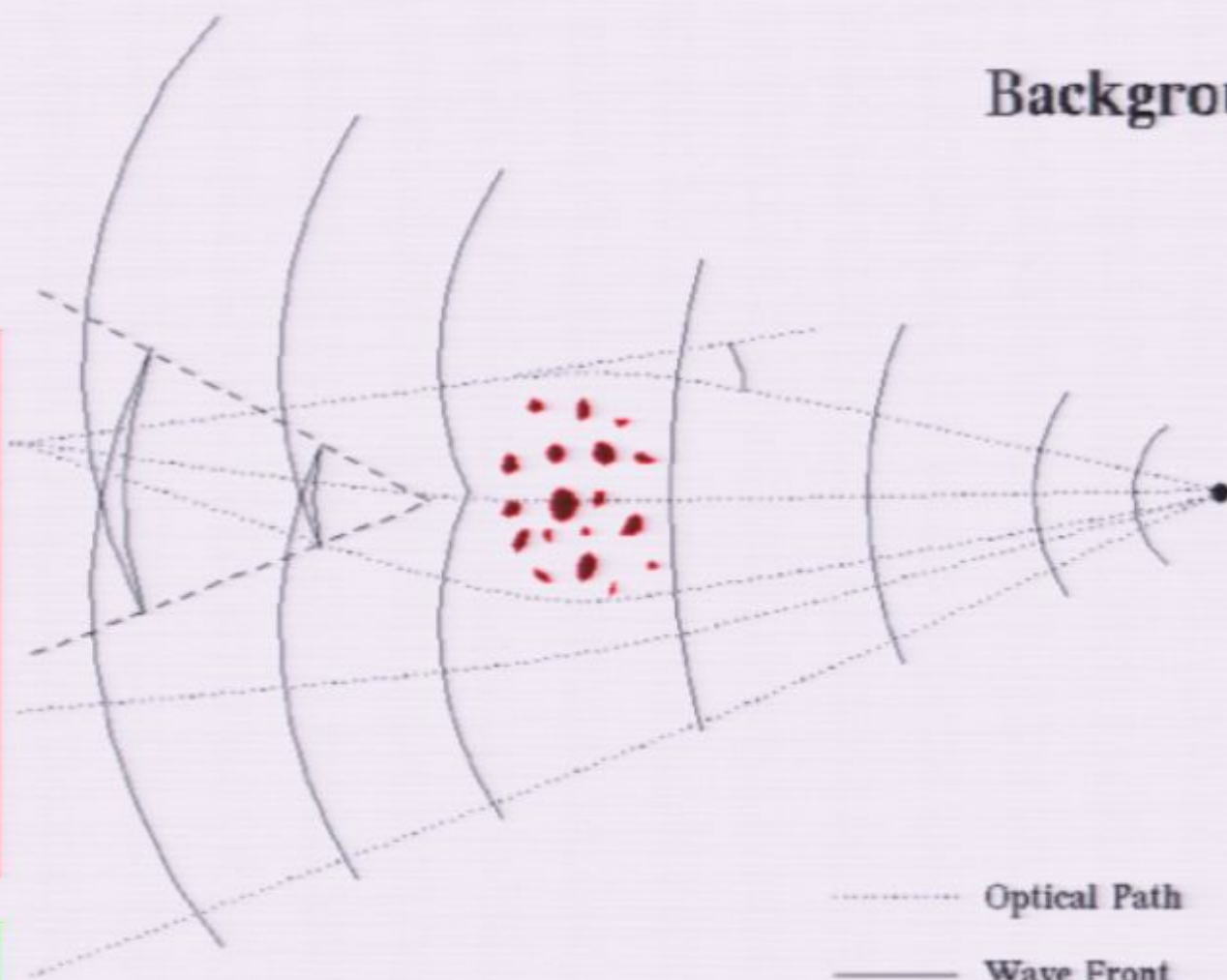
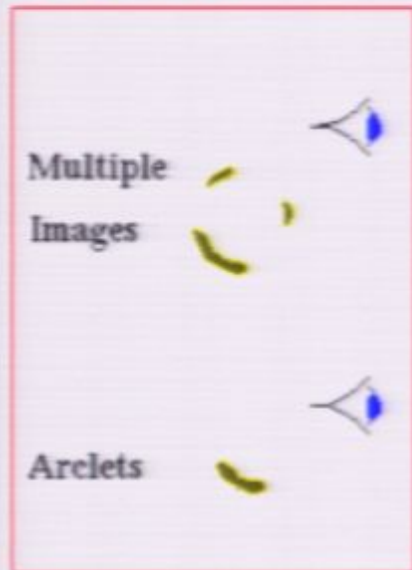
Fig. 1. The gravitational lens system 2237+0305 consists of a nearby spiral galaxy at redshift $z_g = 0.039$ and four images of a background quasar with redshift $z_s = 1.69$. It was discovered by Huchra et al. (1985). The image was taken by the *Hubble Space Telescope*

Observer

Cluster of Galaxies

Background Galaxy

Non-Linear

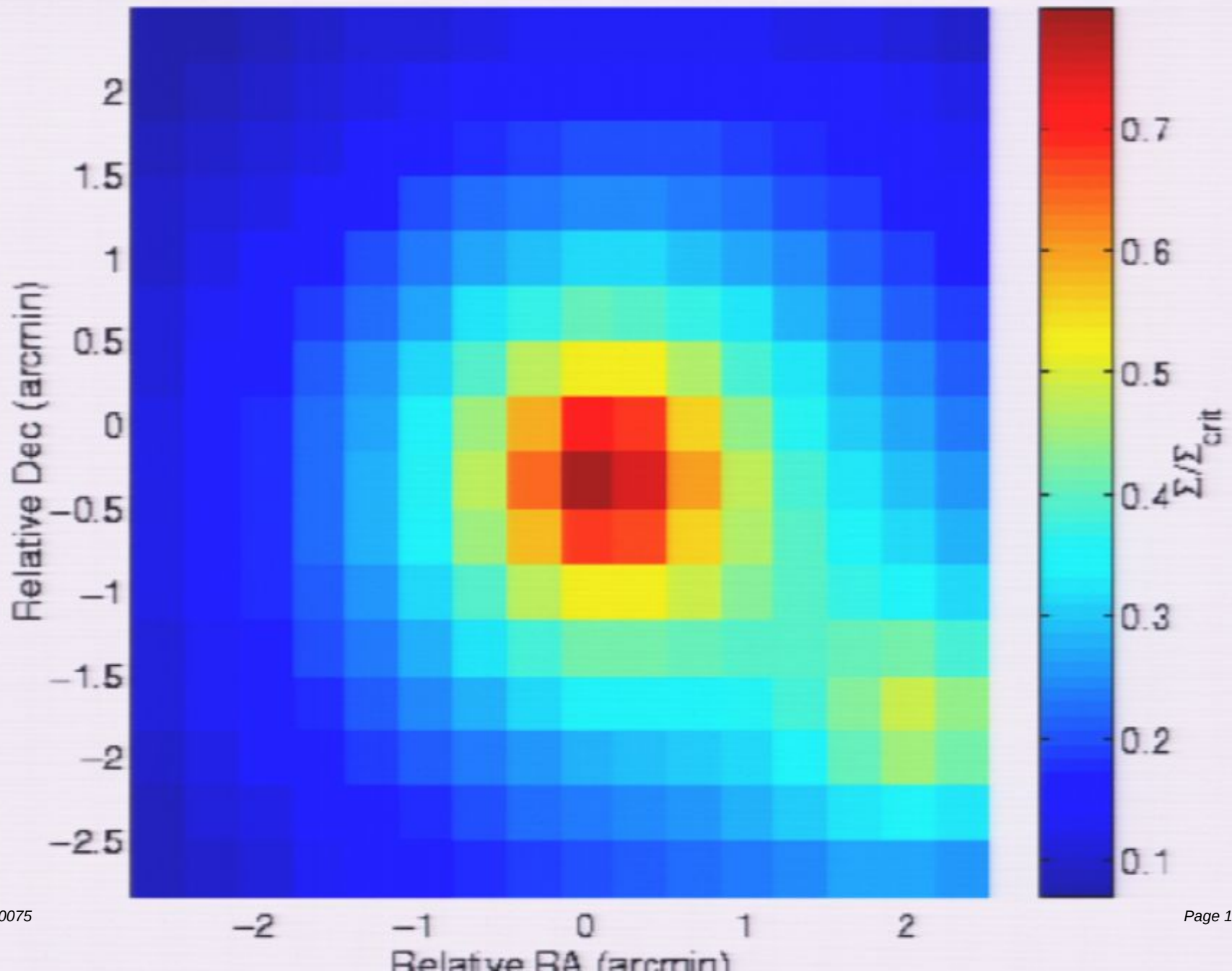


- Optical Path
- Wave Front
- Multiple Images Area

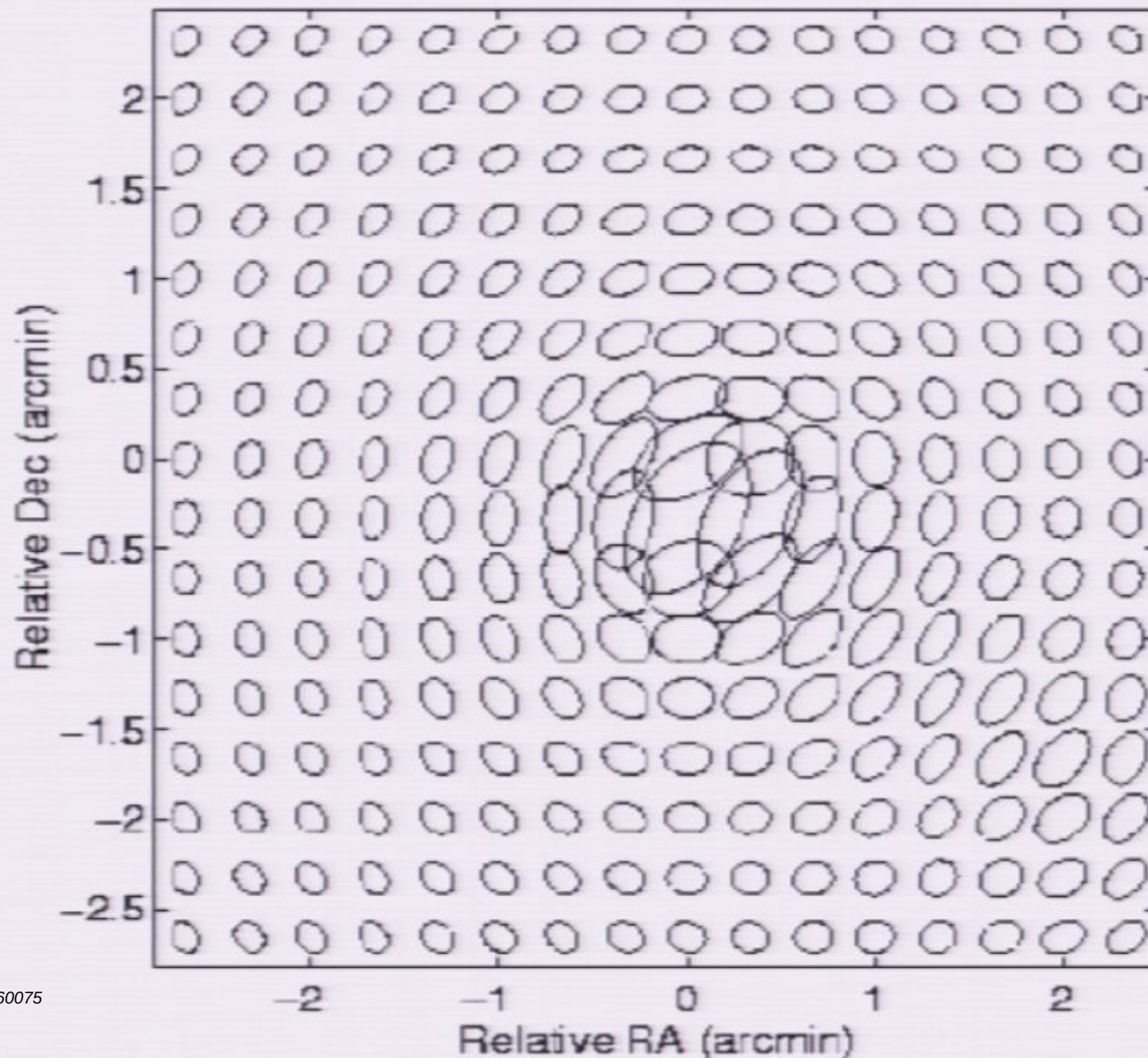
Weak versus strong lensing

- Strong lensing:
 - multiple images
 - banana shaped arcs
 - $\Sigma > \Sigma_c$
 - inner parts of massive clusters/ galaxies
- Weak lensing
 - ellipse orientation is changed
 - low-mass clusters, outer parts of massive c.

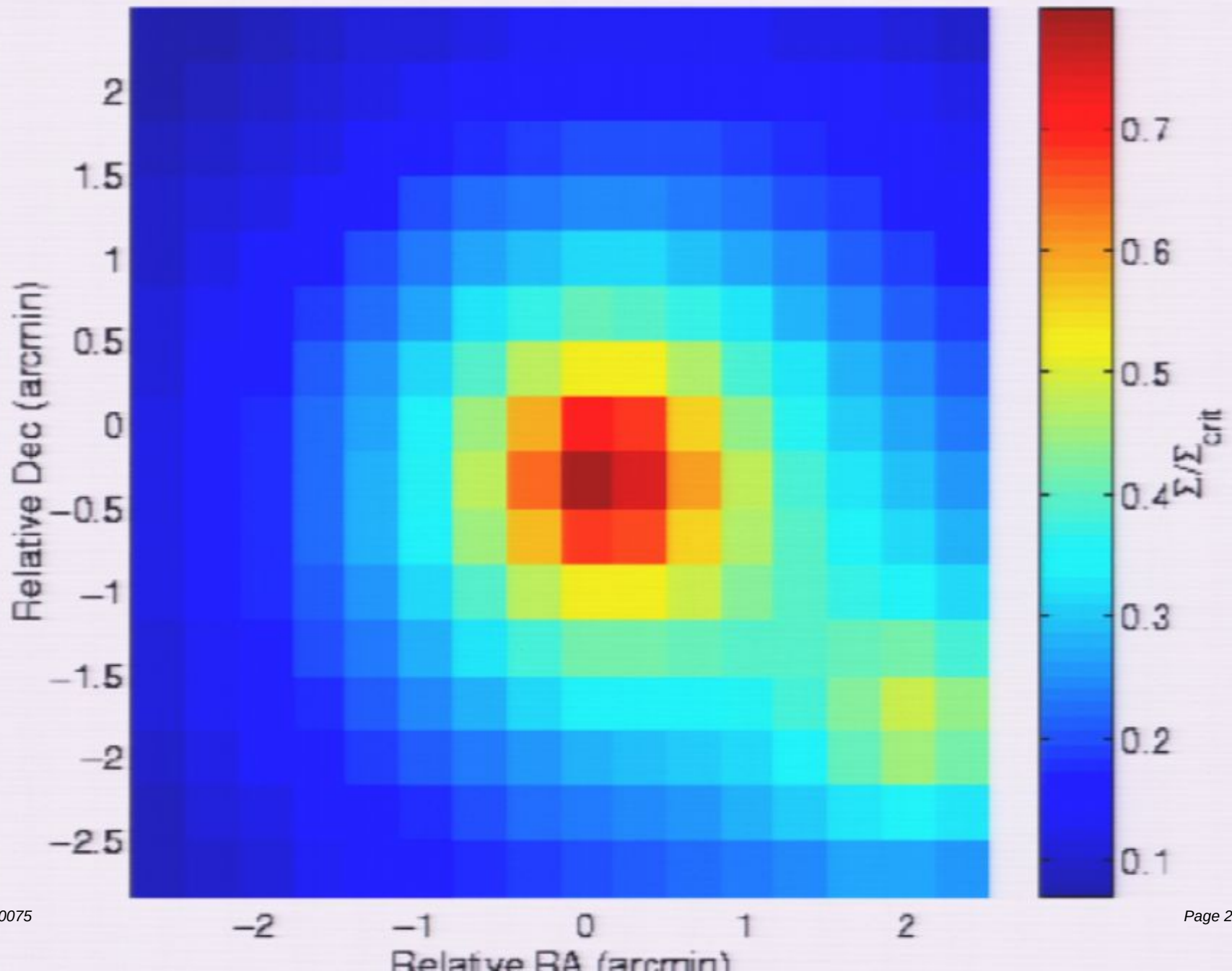
Mass Density Distribution



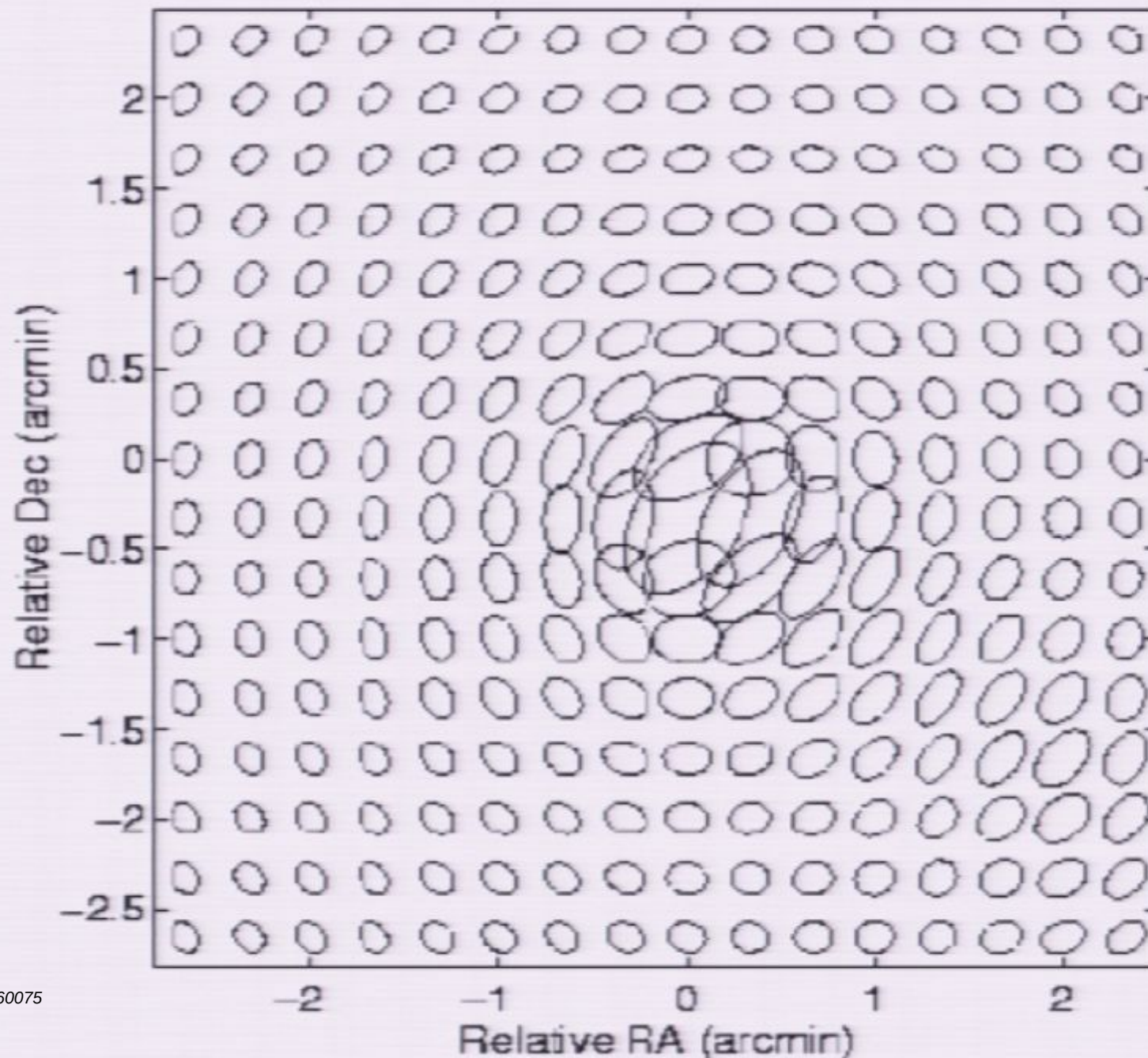
How Circles would be Distorted



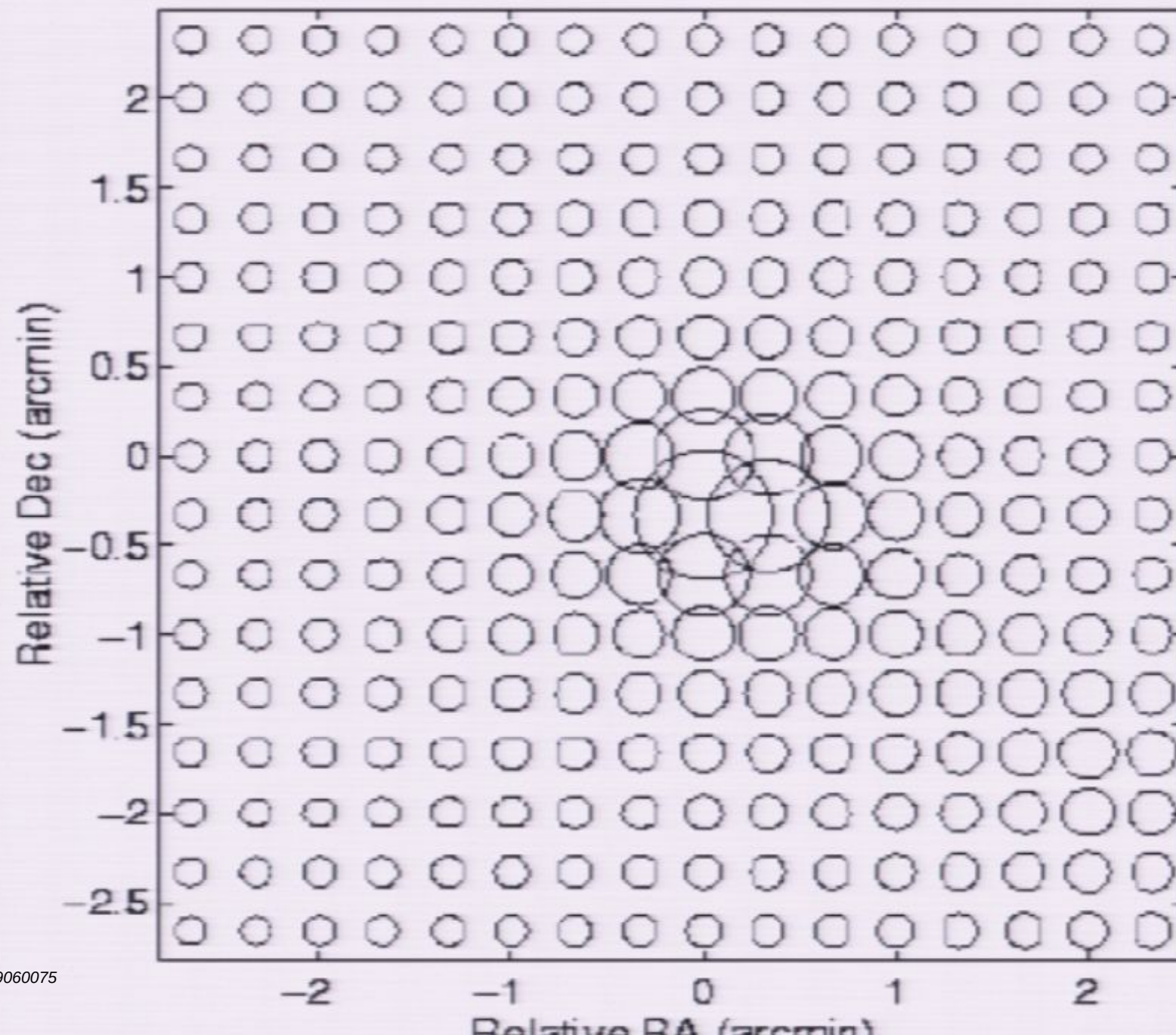
Mass Density Distribution



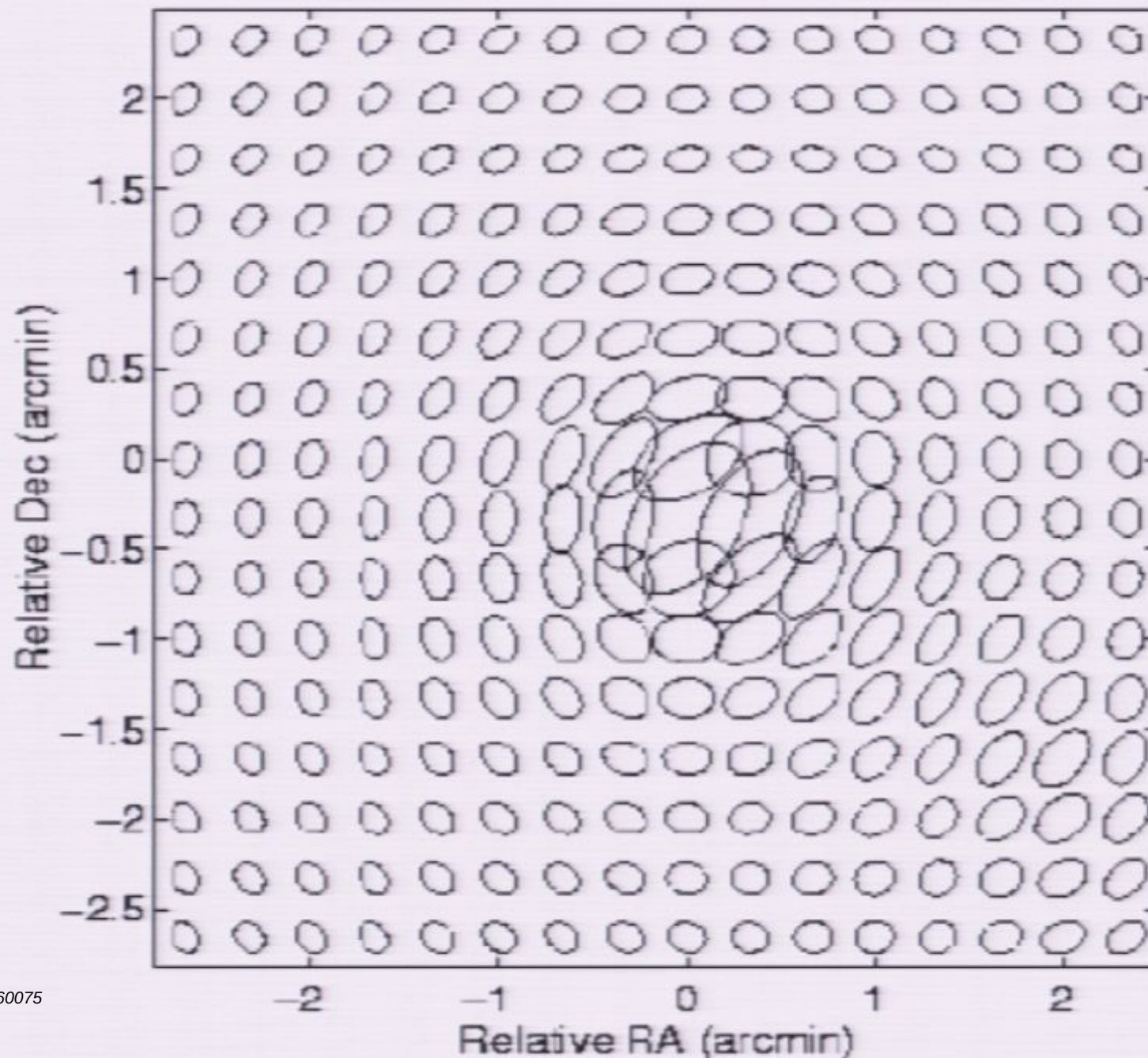
How Circles would be Distorted



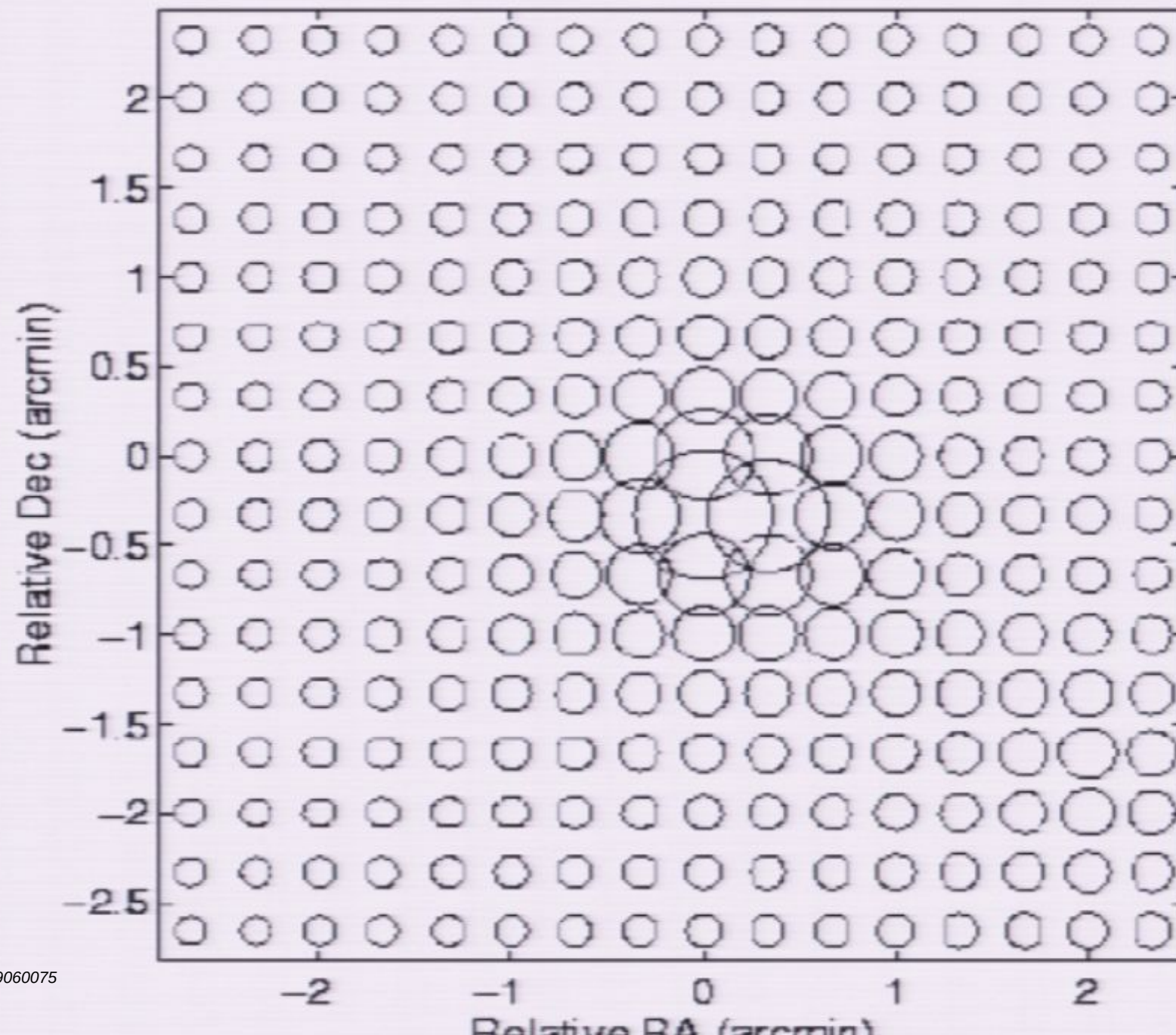
Magnification Alone



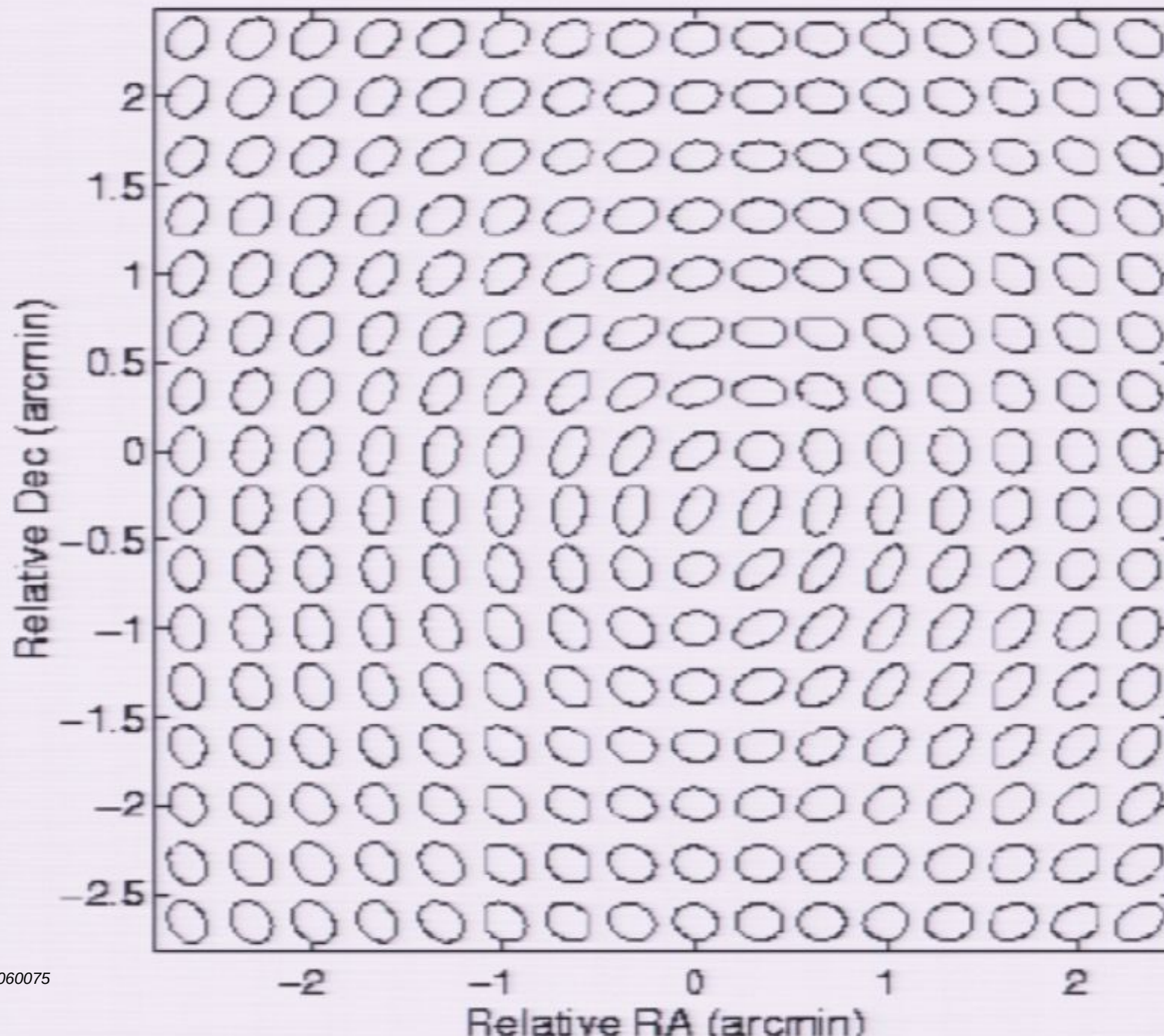
How Circles would be Distorted



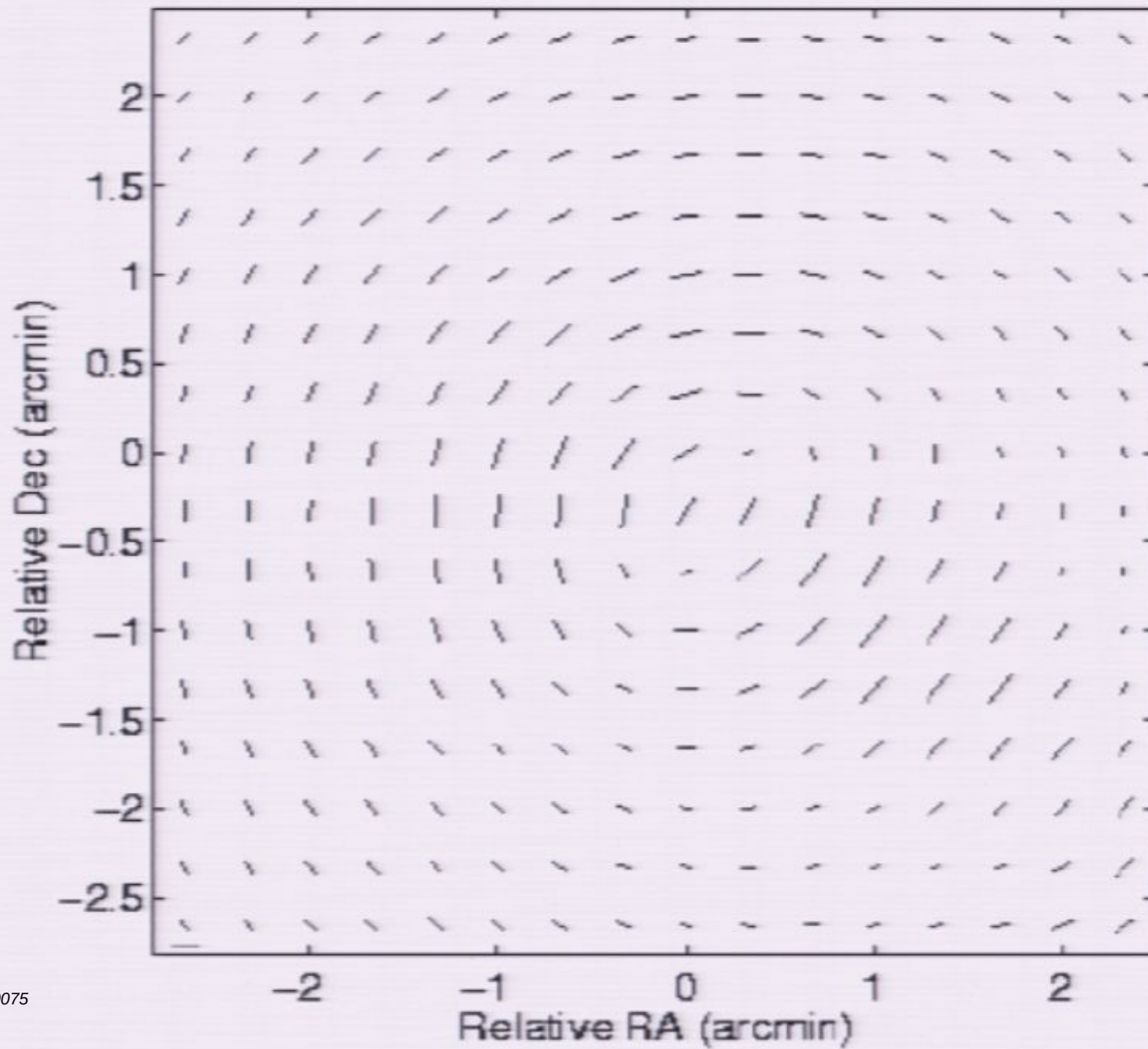
Magnification Alone



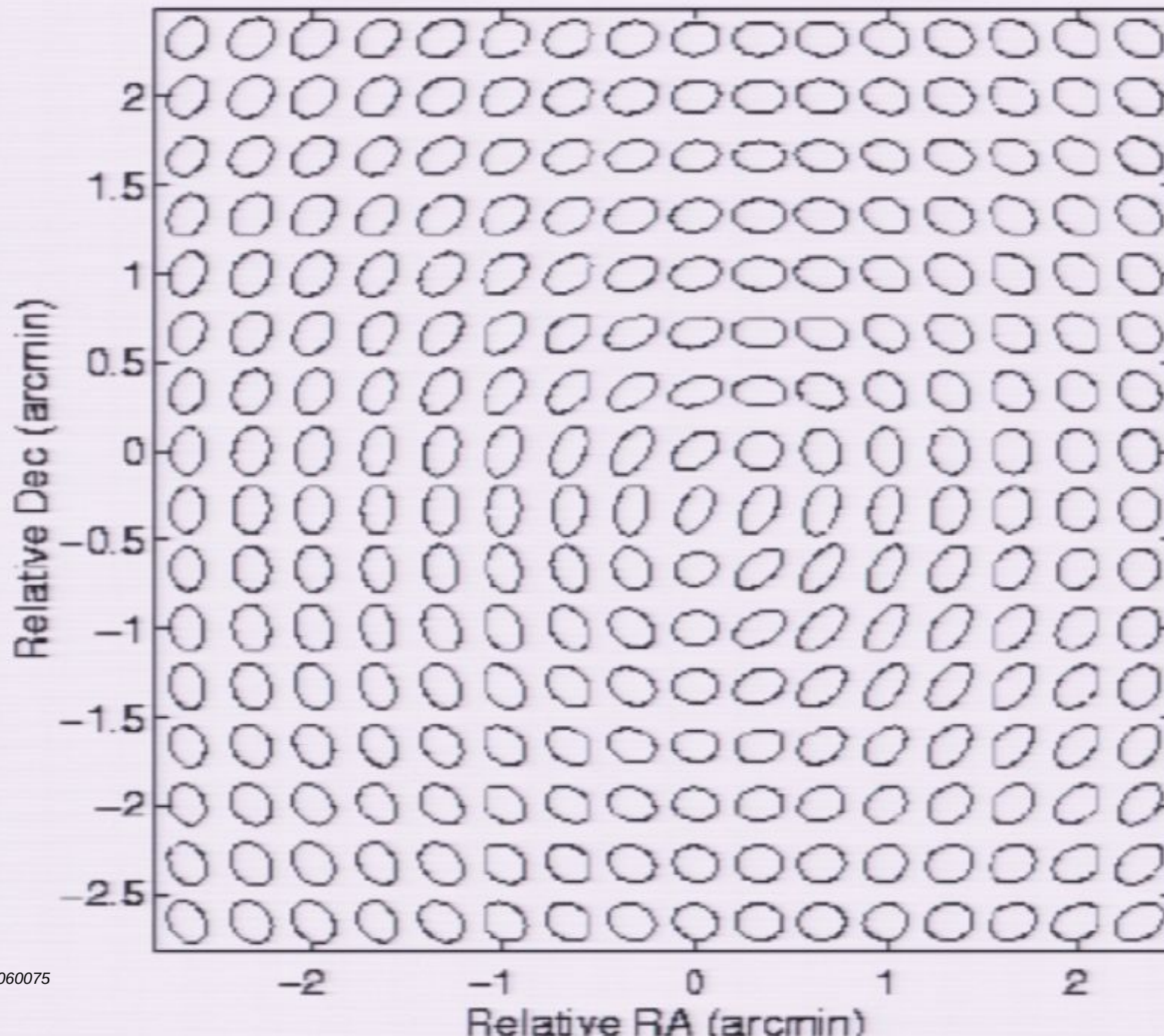
Shear Alone



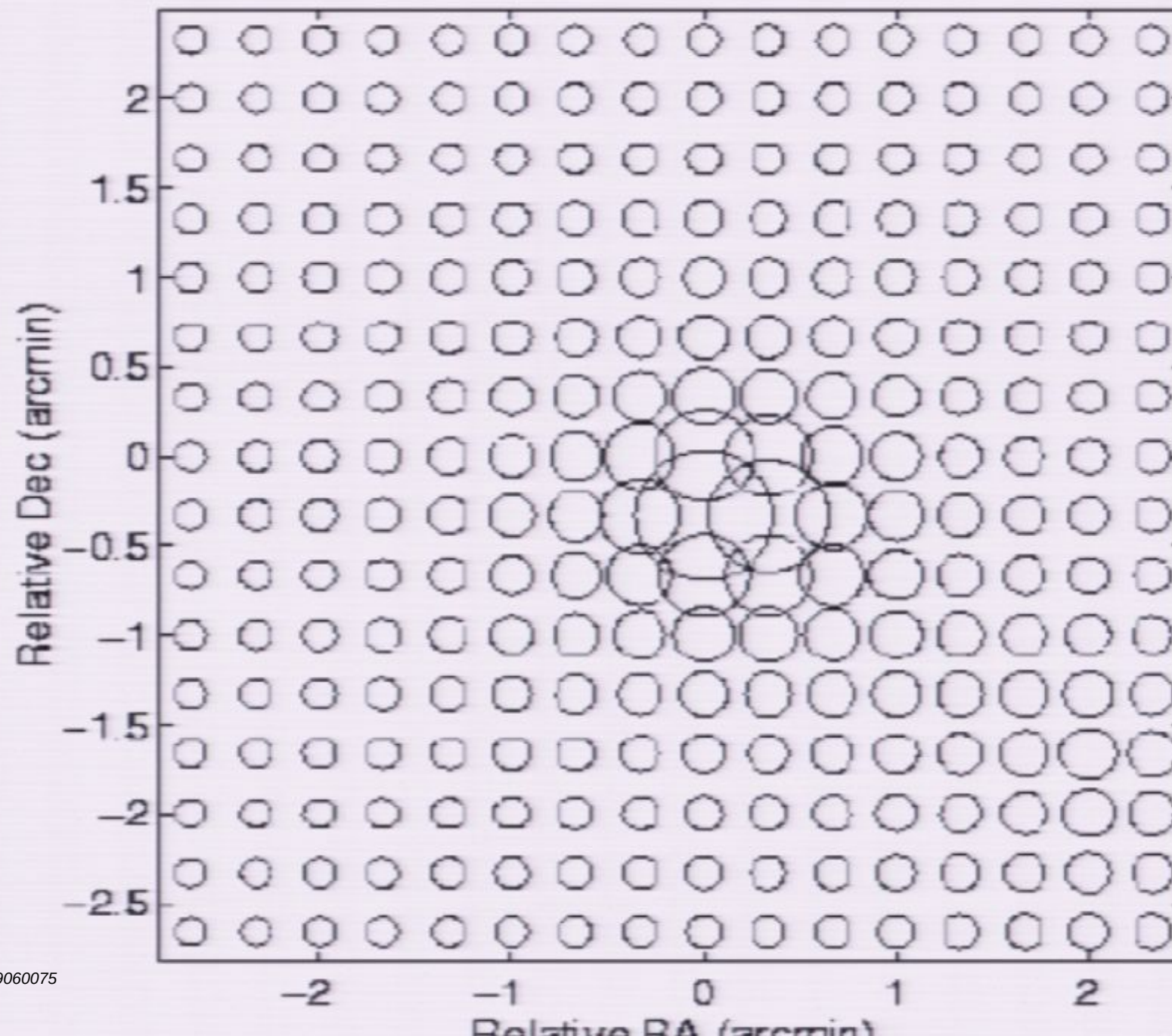
Shear Map



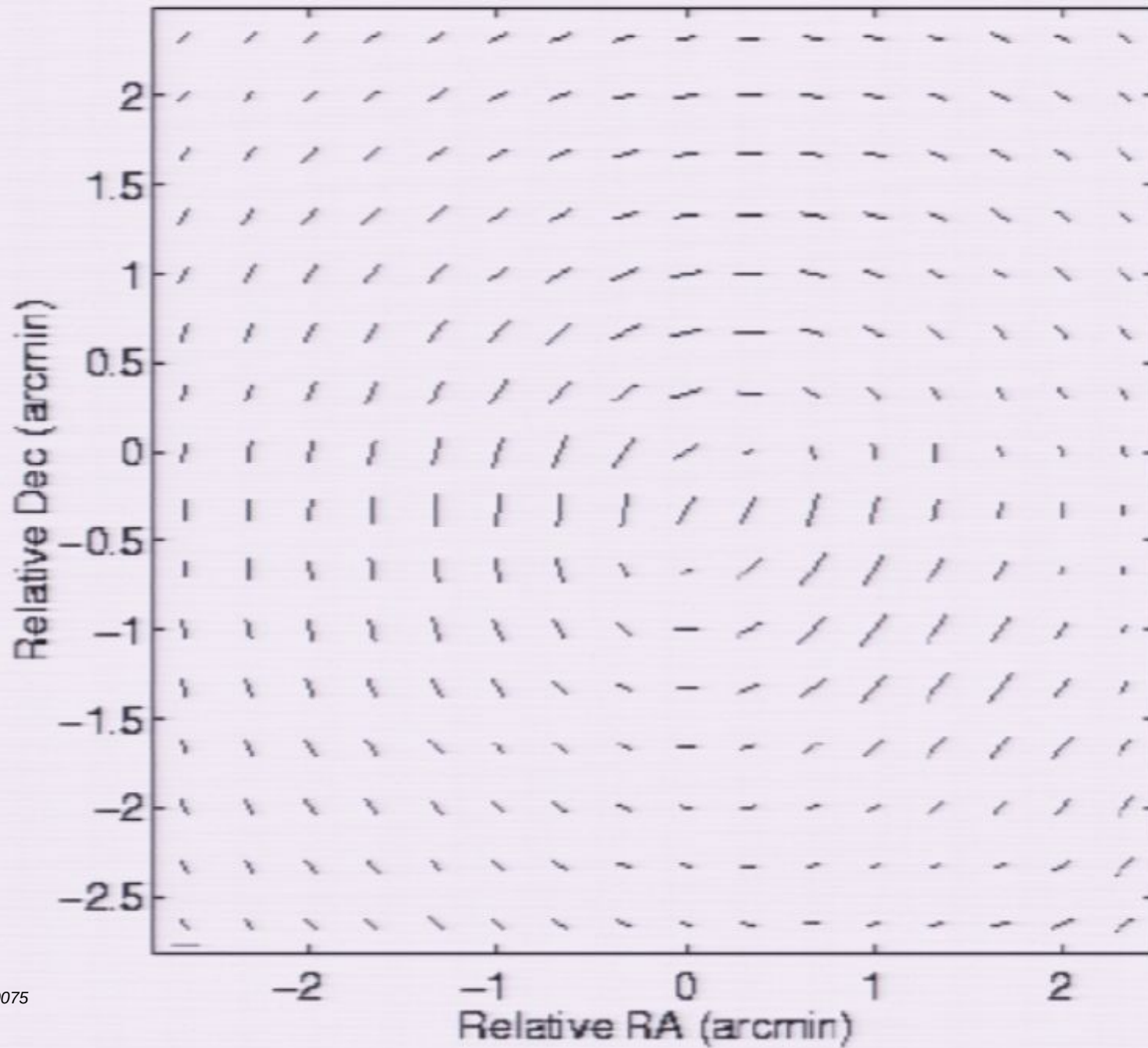
Shear Alone



Magnification Alone

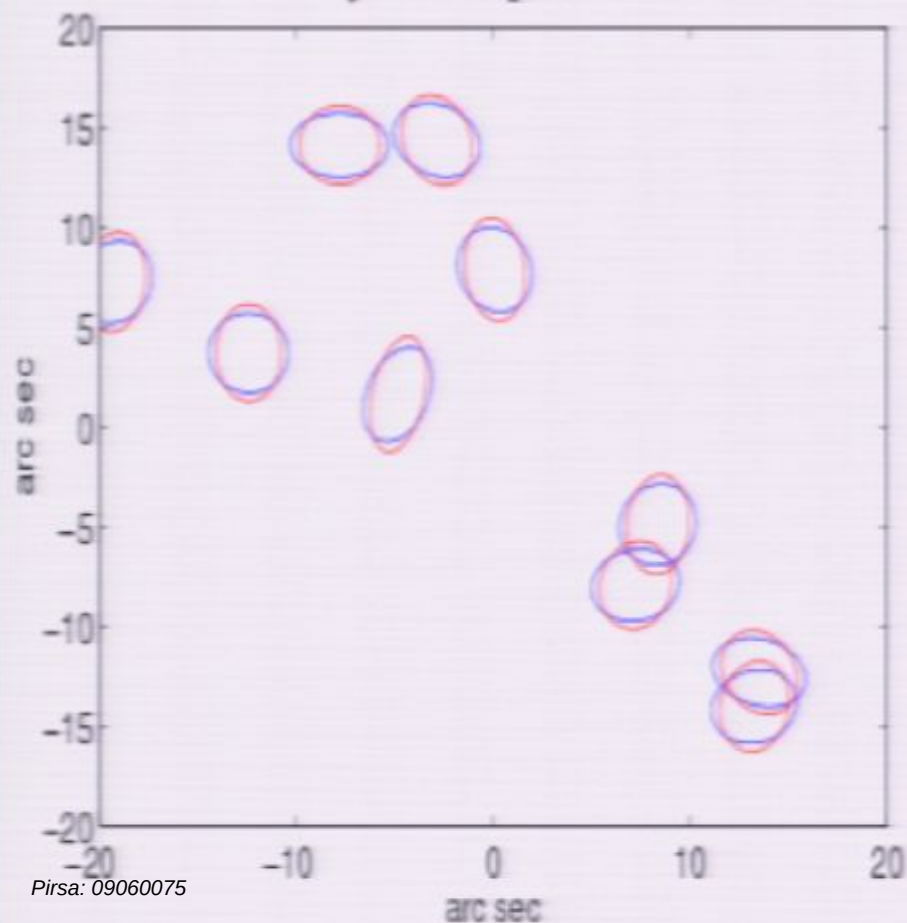


Shear Map

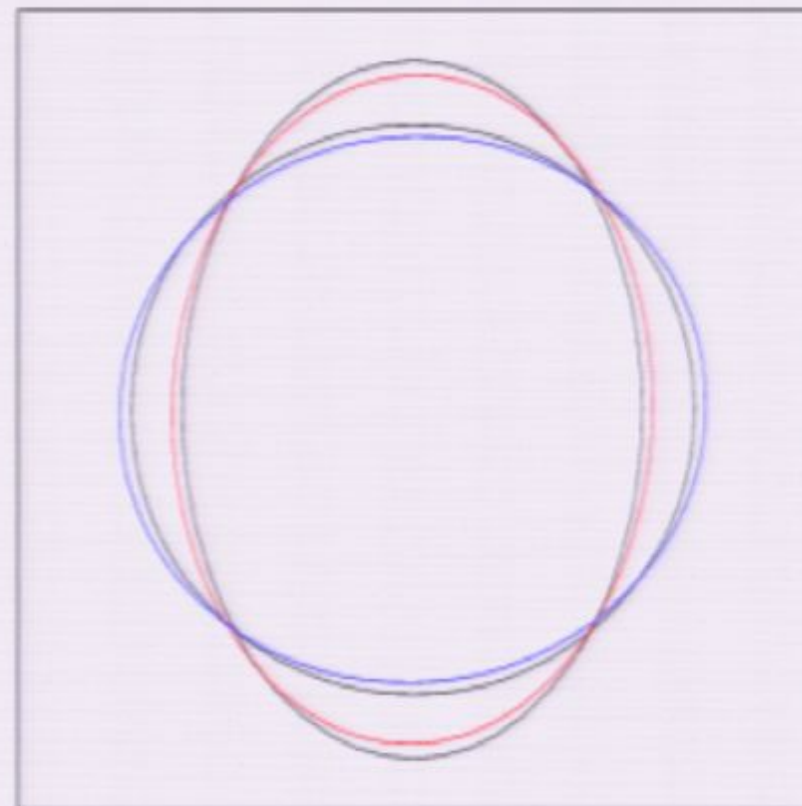


Shear maps: average galaxy shapes

Blue: randomly oriented galaxies. Red: sheared



Blue, red: average galaxy shape. Black: true values



$1h_{100}^{-1}$ Mpc at $z=0.39$

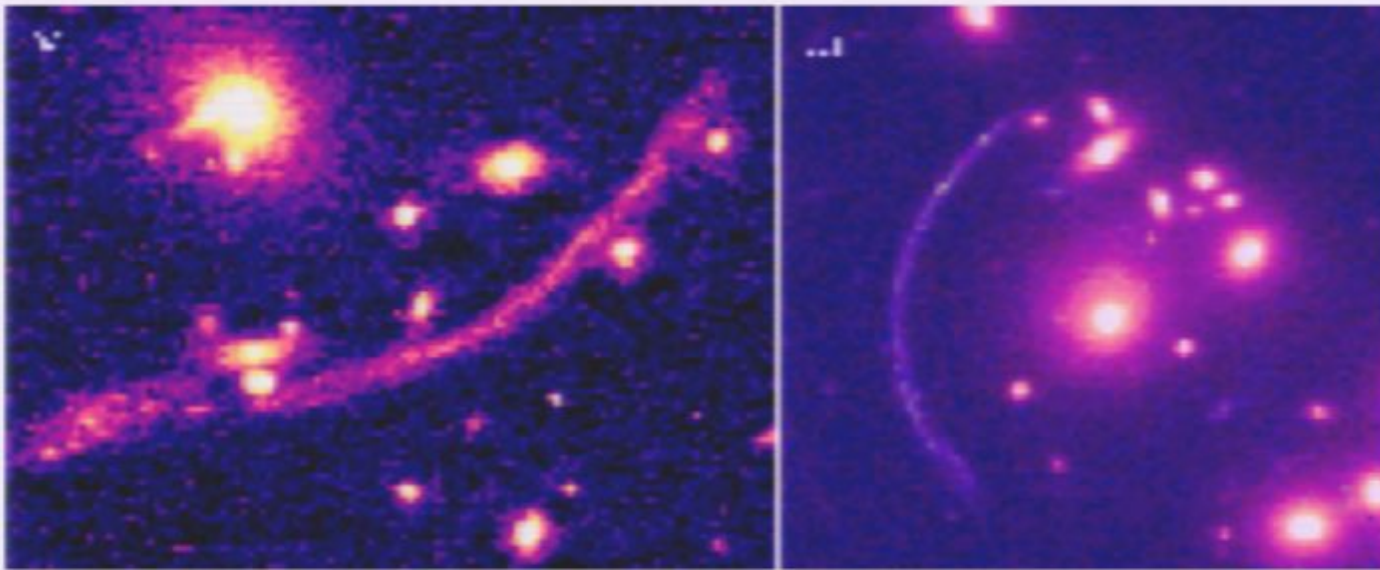
Perturbation

3. Clusters of galaxies: summary

- Composition: (not just galaxies!)
 - ~1 % of mass is in galaxies
 - ~10 % of mass is hot gas
 - the rest is dark matter
- Interesting questions
 - how much mass?
 - 'slope' of central profile
 - subclumps?

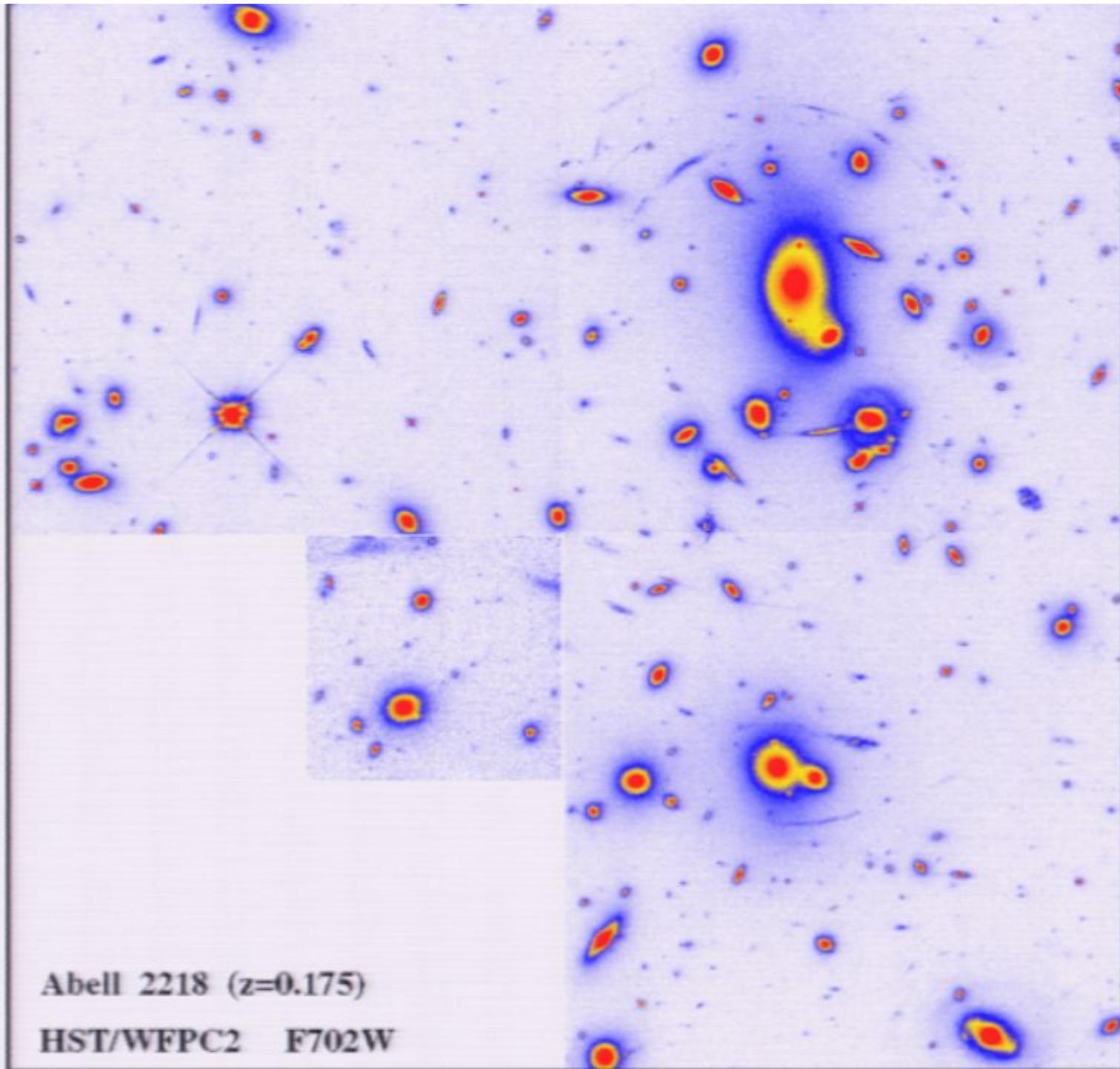
History

- Mysterious 'Giant arcs' in A370, Cl2244



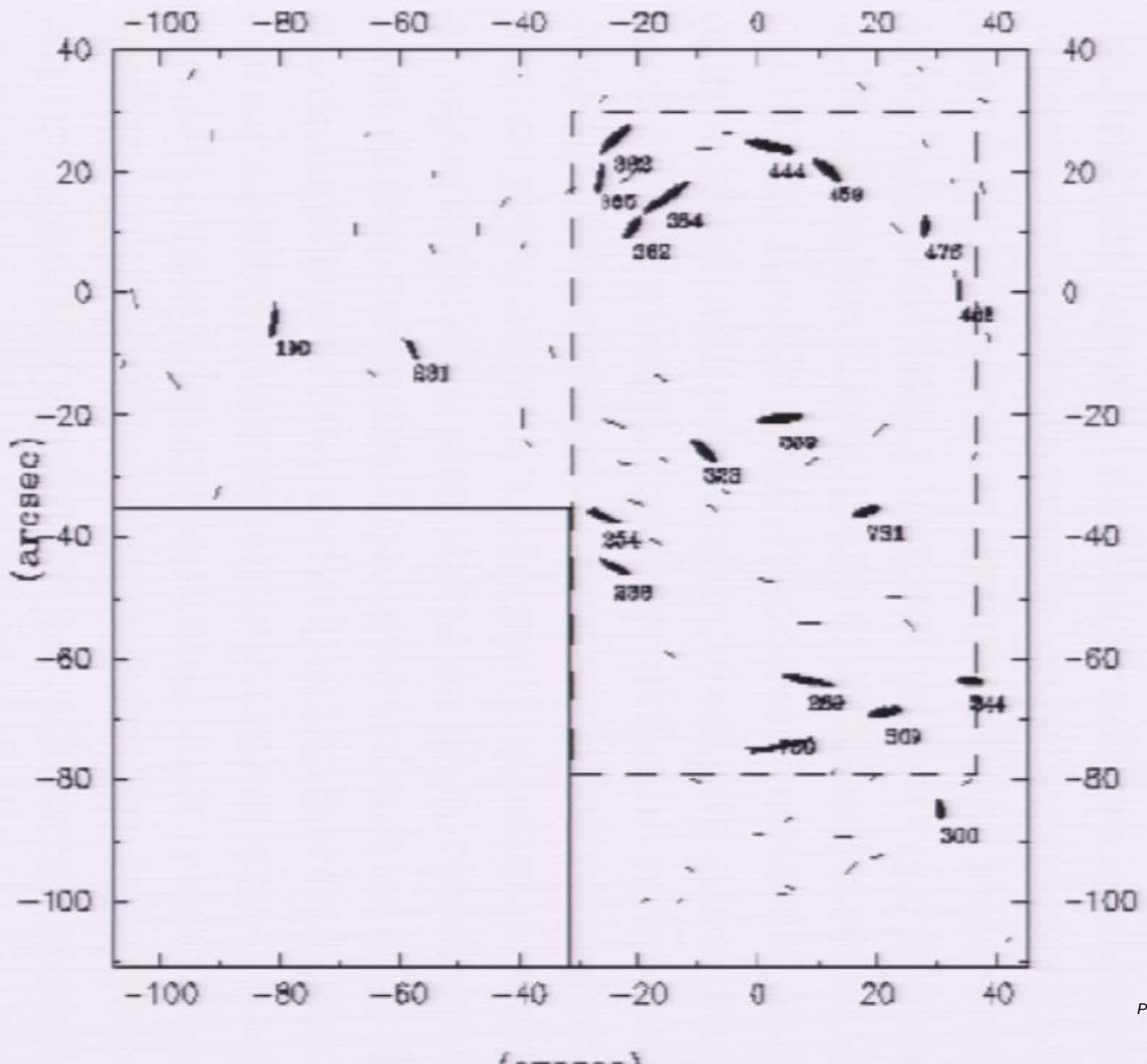
- Paczynski suggests lensing
- 1987 Fort et al. confirm. Spectroscopy.
- Clusters are more massive than expected

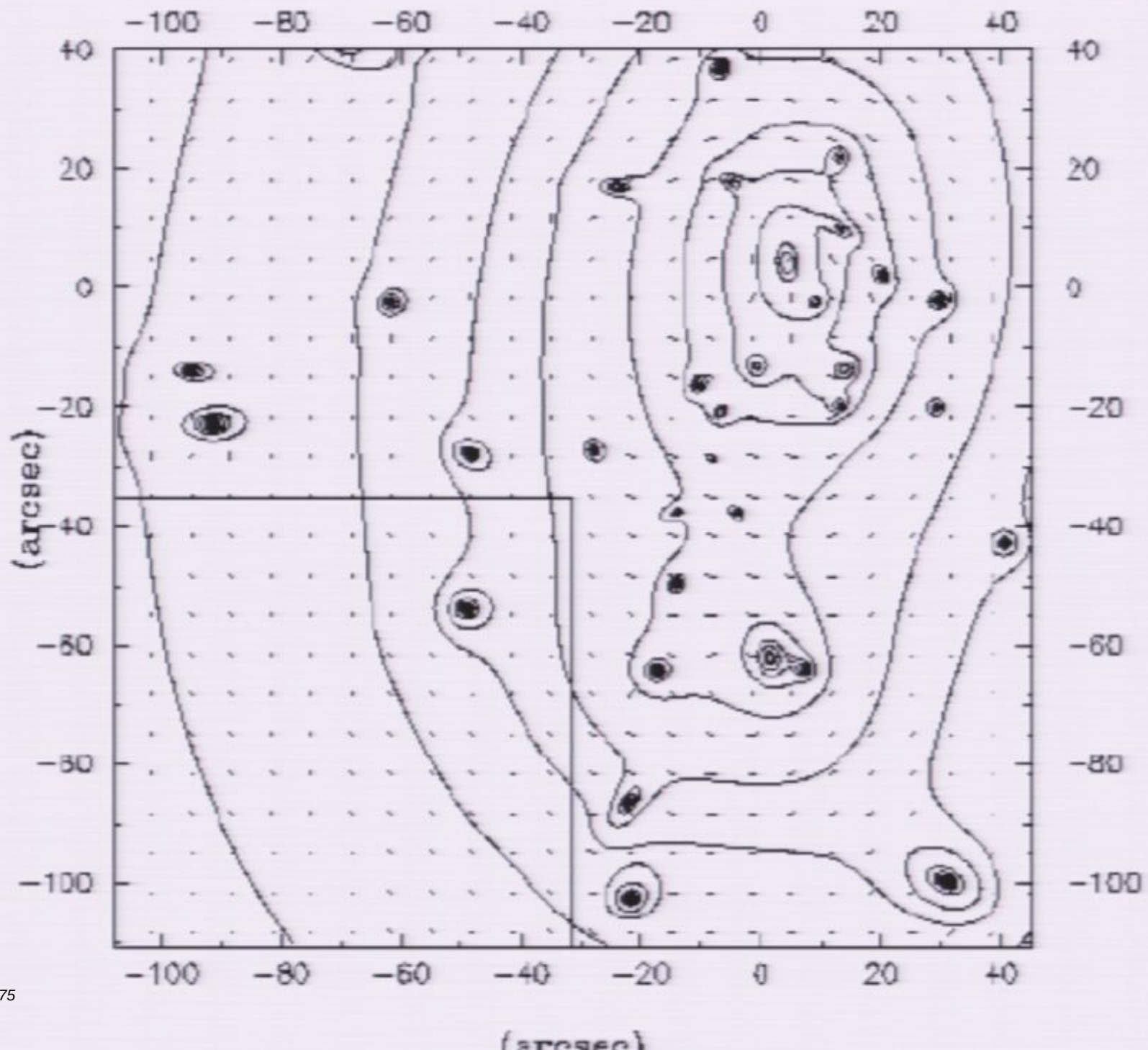




Abell 2218 ($z=0.175$)

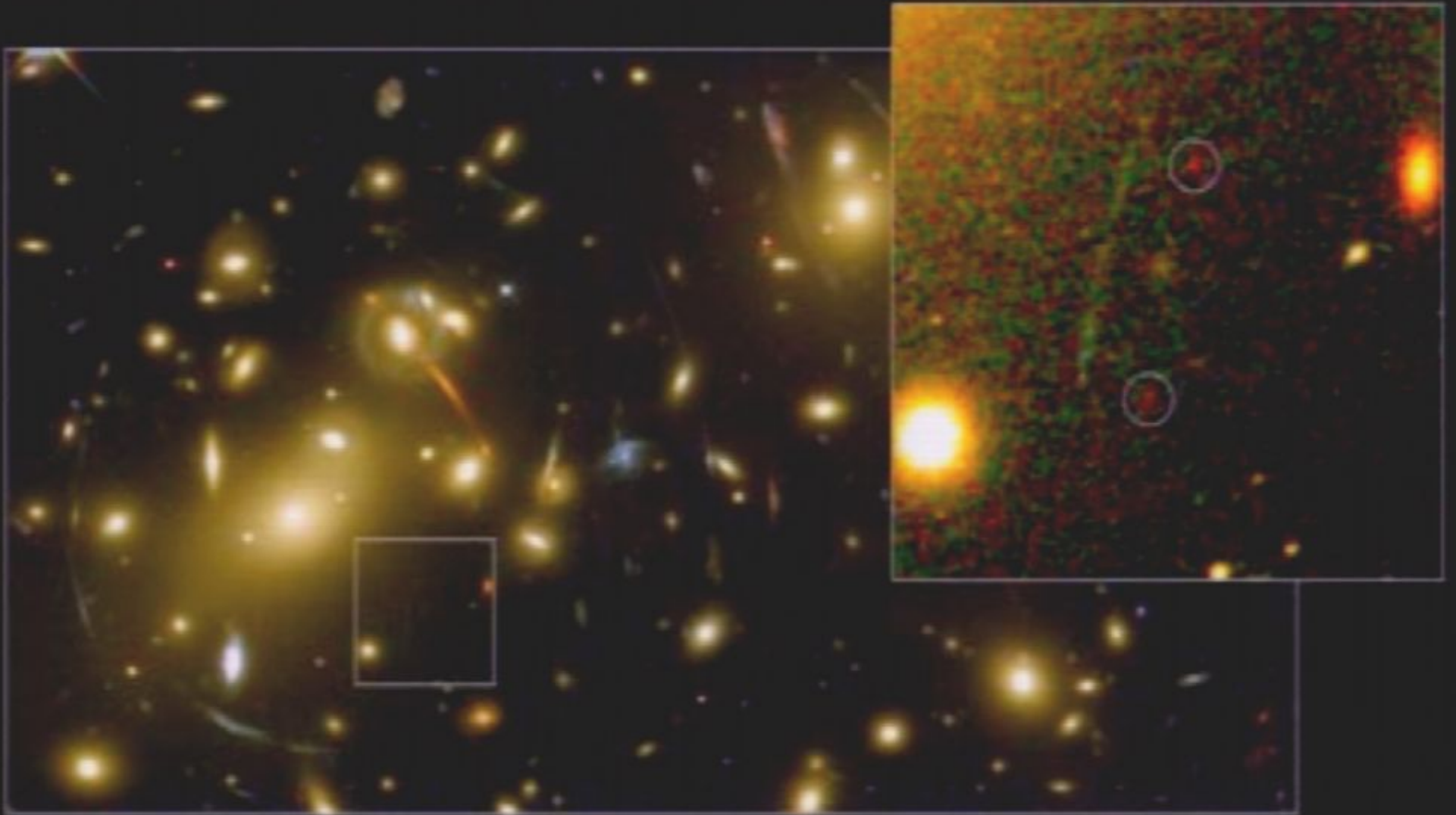
HST/WEPC2 F702W





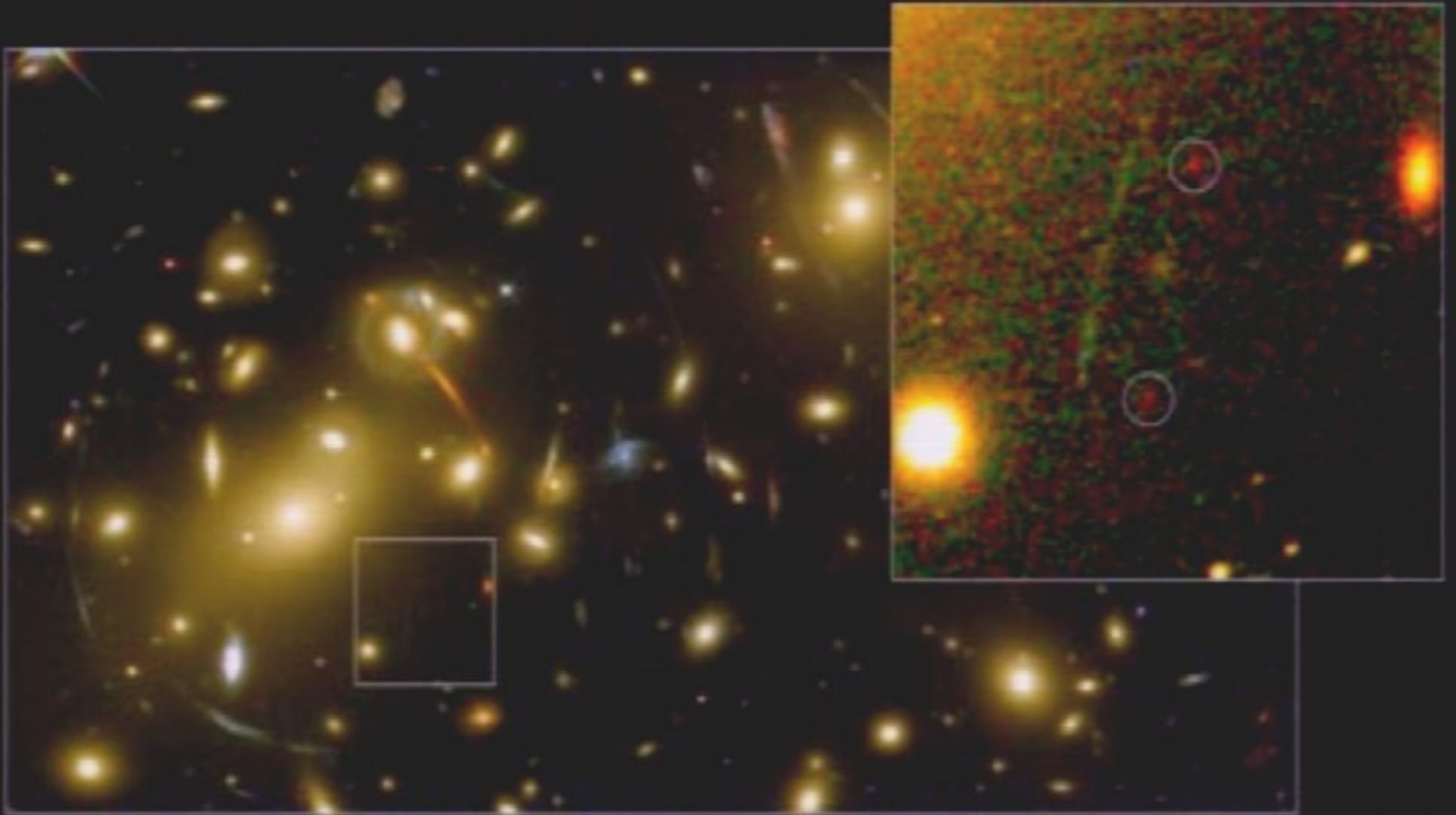
Gravitational telescope

- Systematic scan of high magnification regions for Lyman- α emission at $z > 5$
- A2218
 - 2 images, 1 source fits lens model well
 - only $10^6 M_{\odot}$ – first stars?
 - recently found $z \sim 10$ galaxy this way!



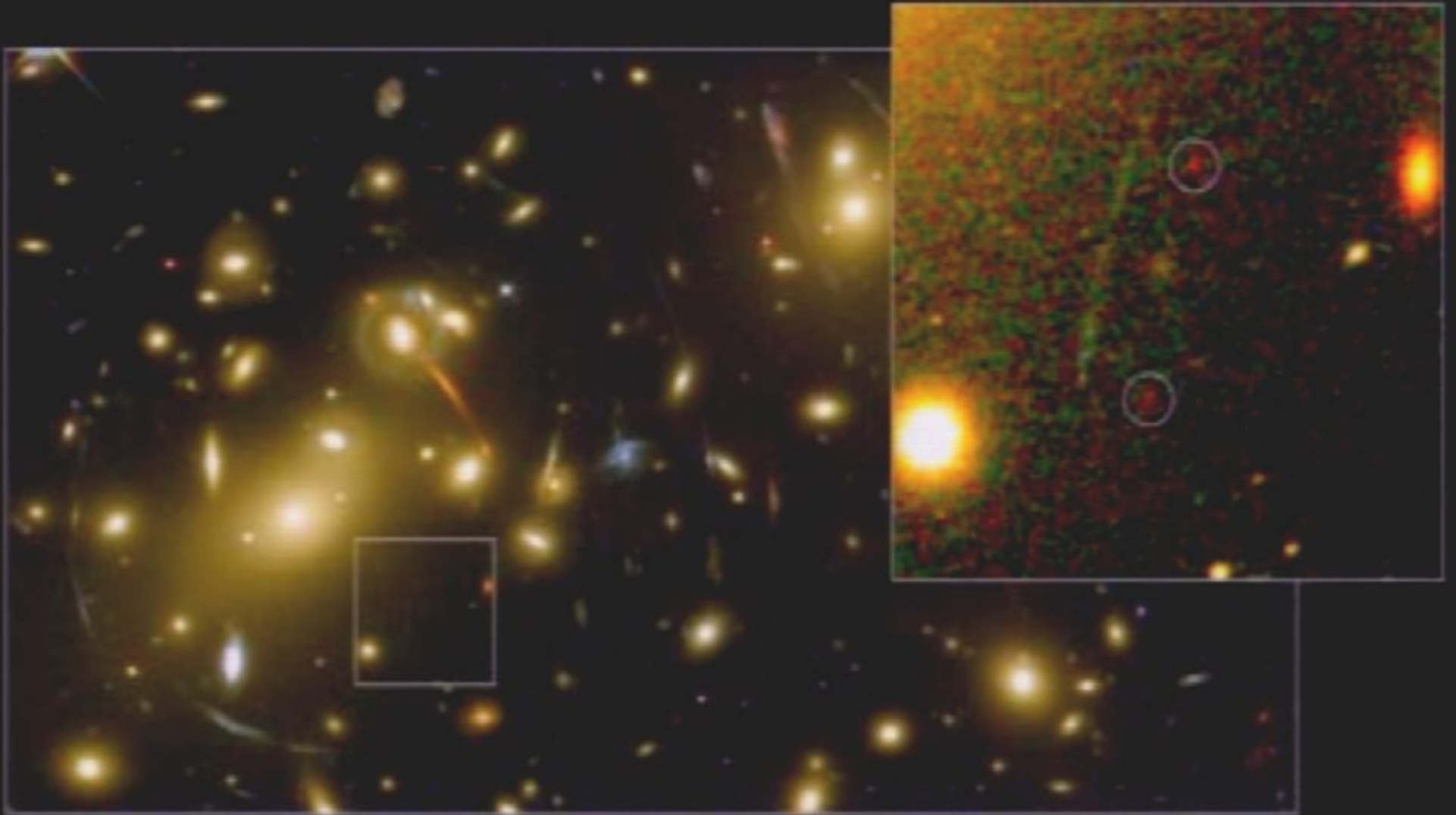
1E 0657-56 – The Bullet Cluster

Direct Observation of Dark Matter



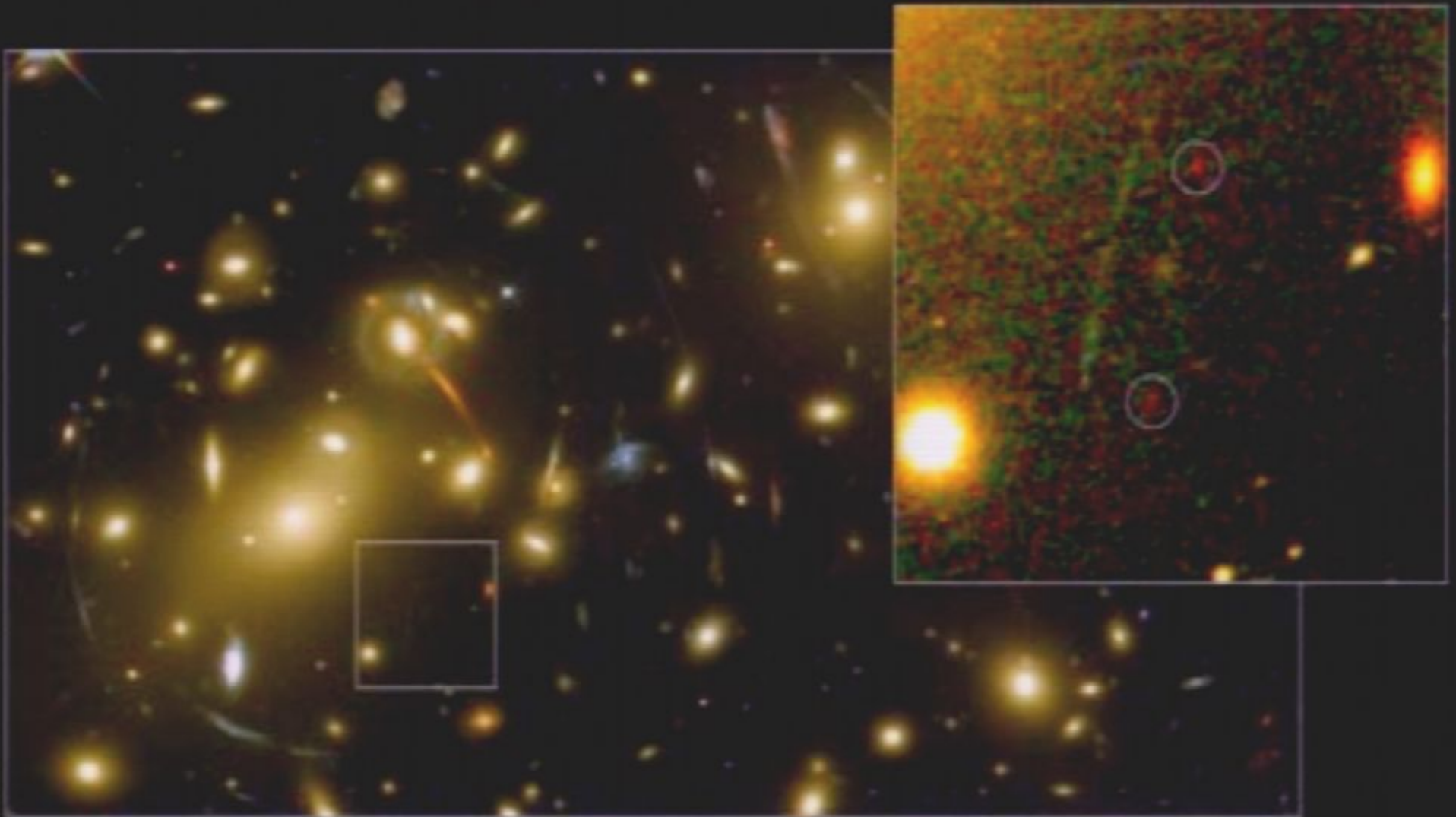
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1E 0657-56 — The Bullet Cluster

Direct Observation of Dark Matter

Proof that Dark Matter Exists

- 1E 0657-56 – A collision of galaxy clusters
- A cluster of galaxies consists of three components

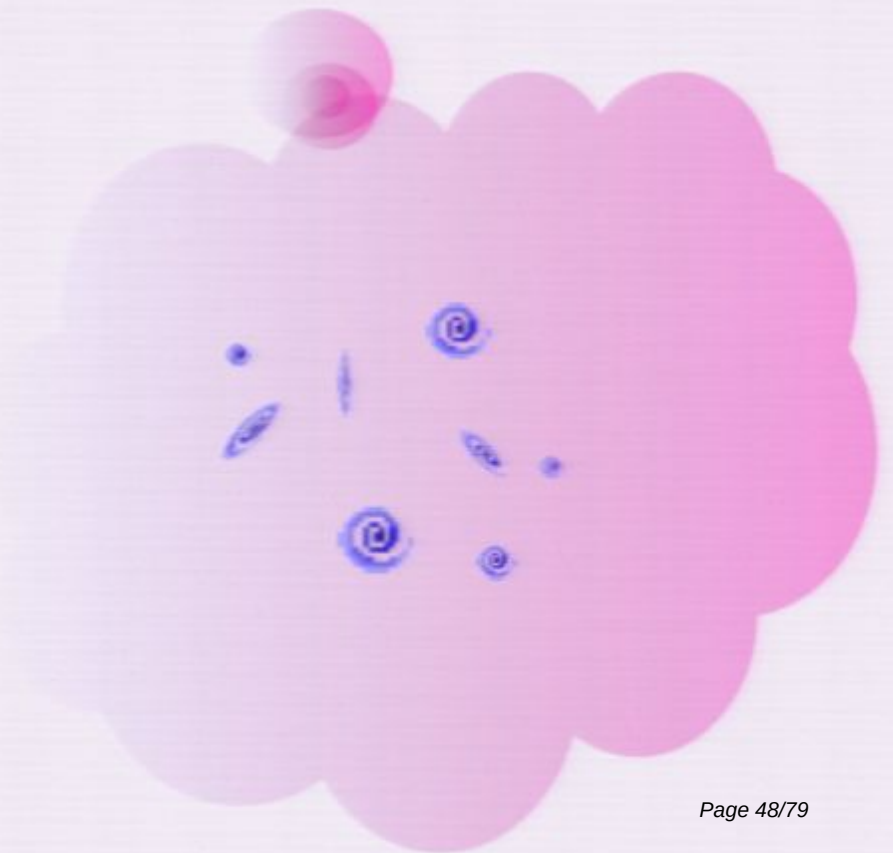
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1. Galaxies

2. Hot Gas

3. Dark Matter



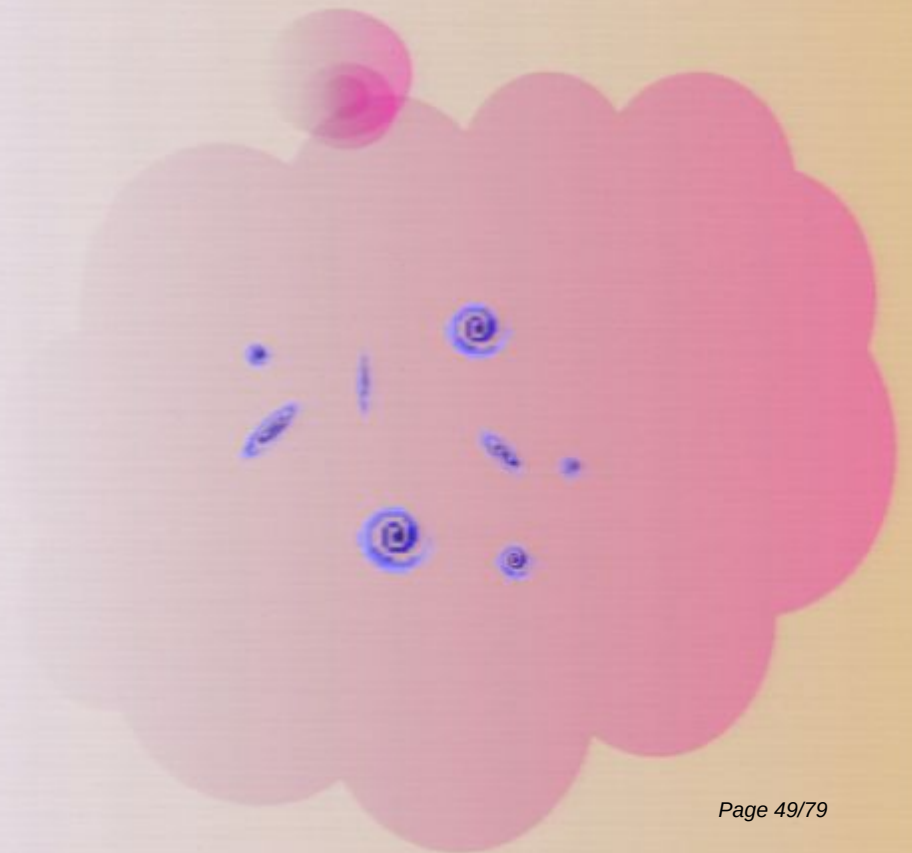
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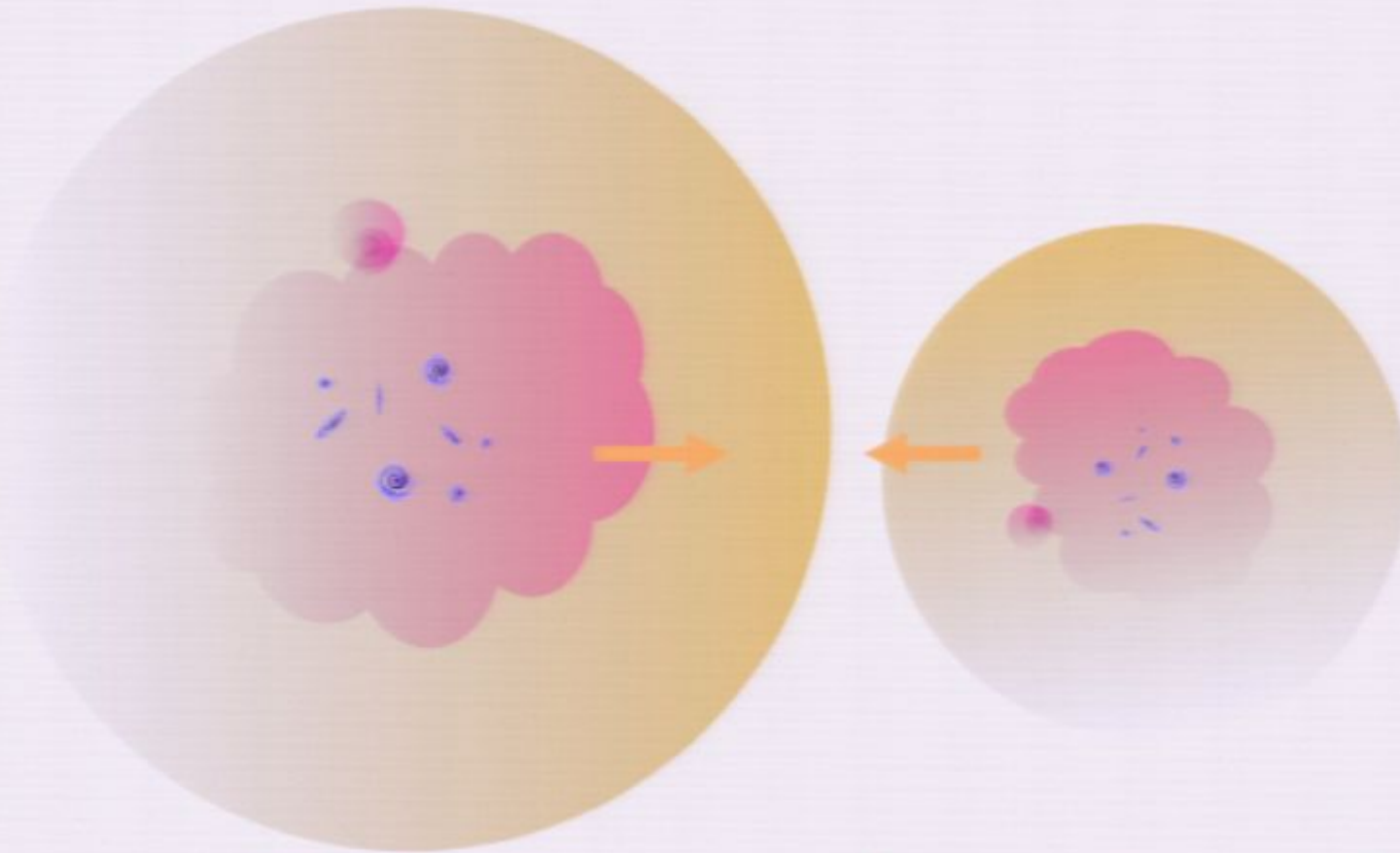
1. Galaxies

2. Hot Gas

3. Dark Matter



What's going on with 1E 0657-56?



- TWO clusters of galaxies collide

The gas interacts, the dark matter and galaxies don't



- The galaxies and dark matter pass through unimpeded, but the hot gas is separated from the clusters



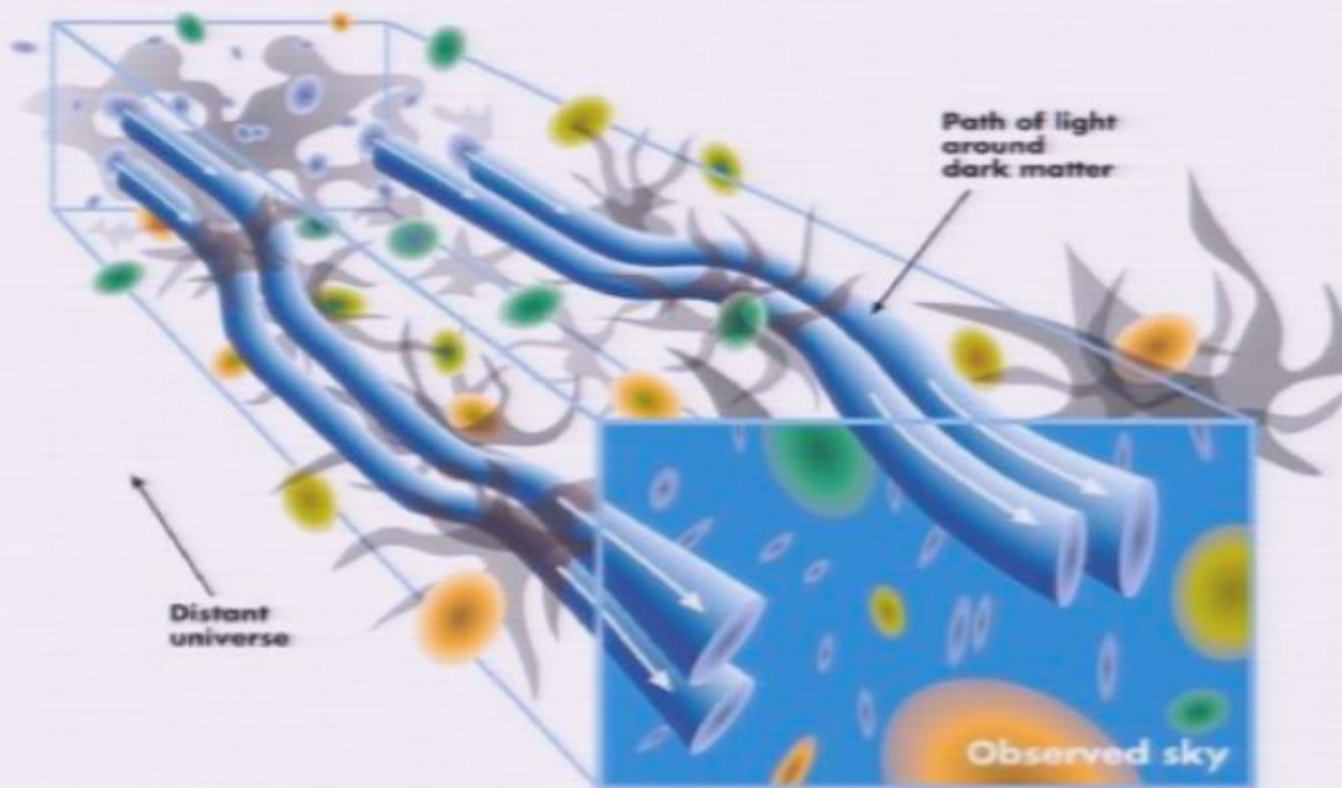
- Animation of 1E: 0657-56 http://chandra.harvard.edu/photo/2006/1e0657/1e0657_bullett_anim_lg.mpg



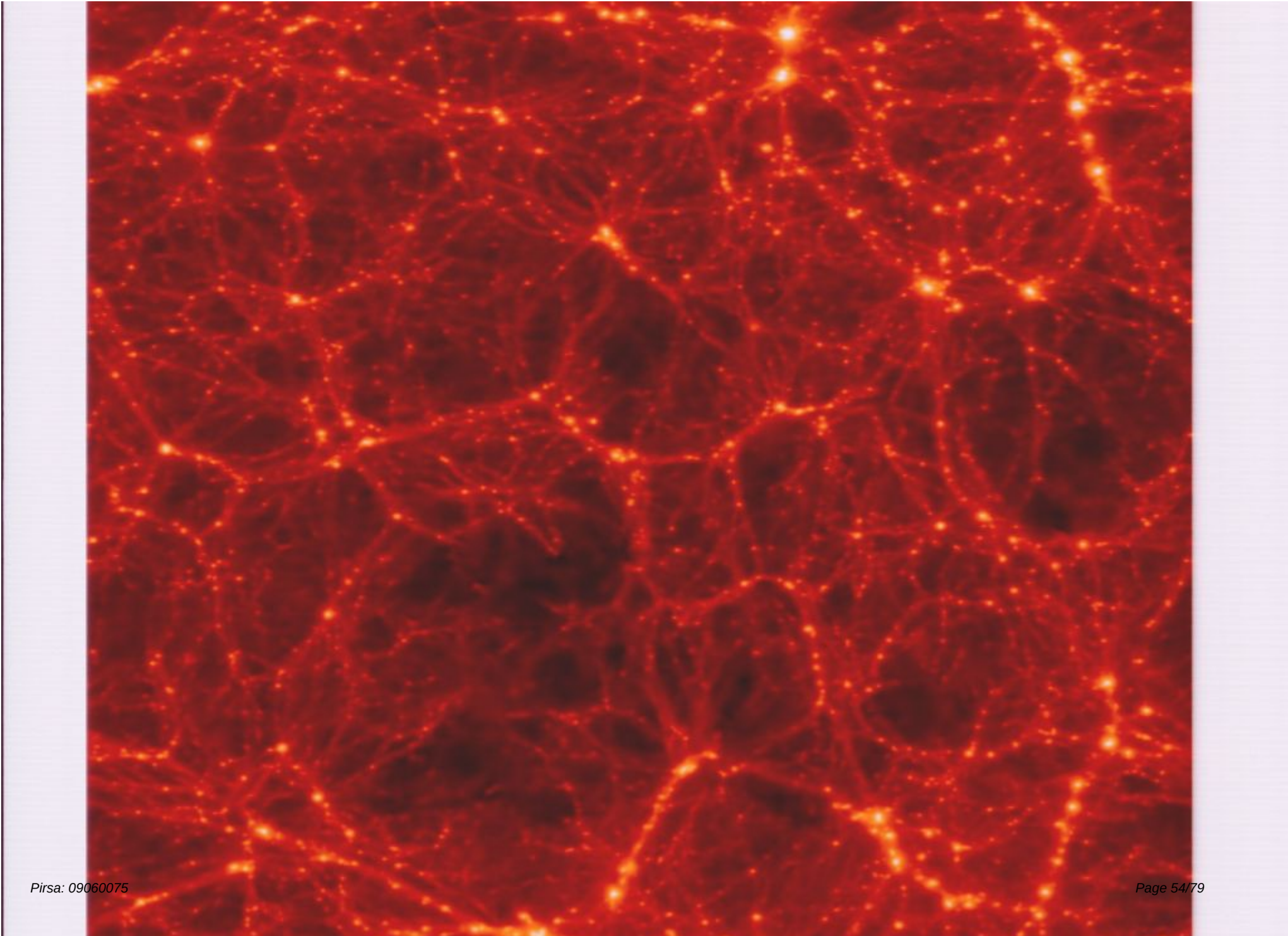
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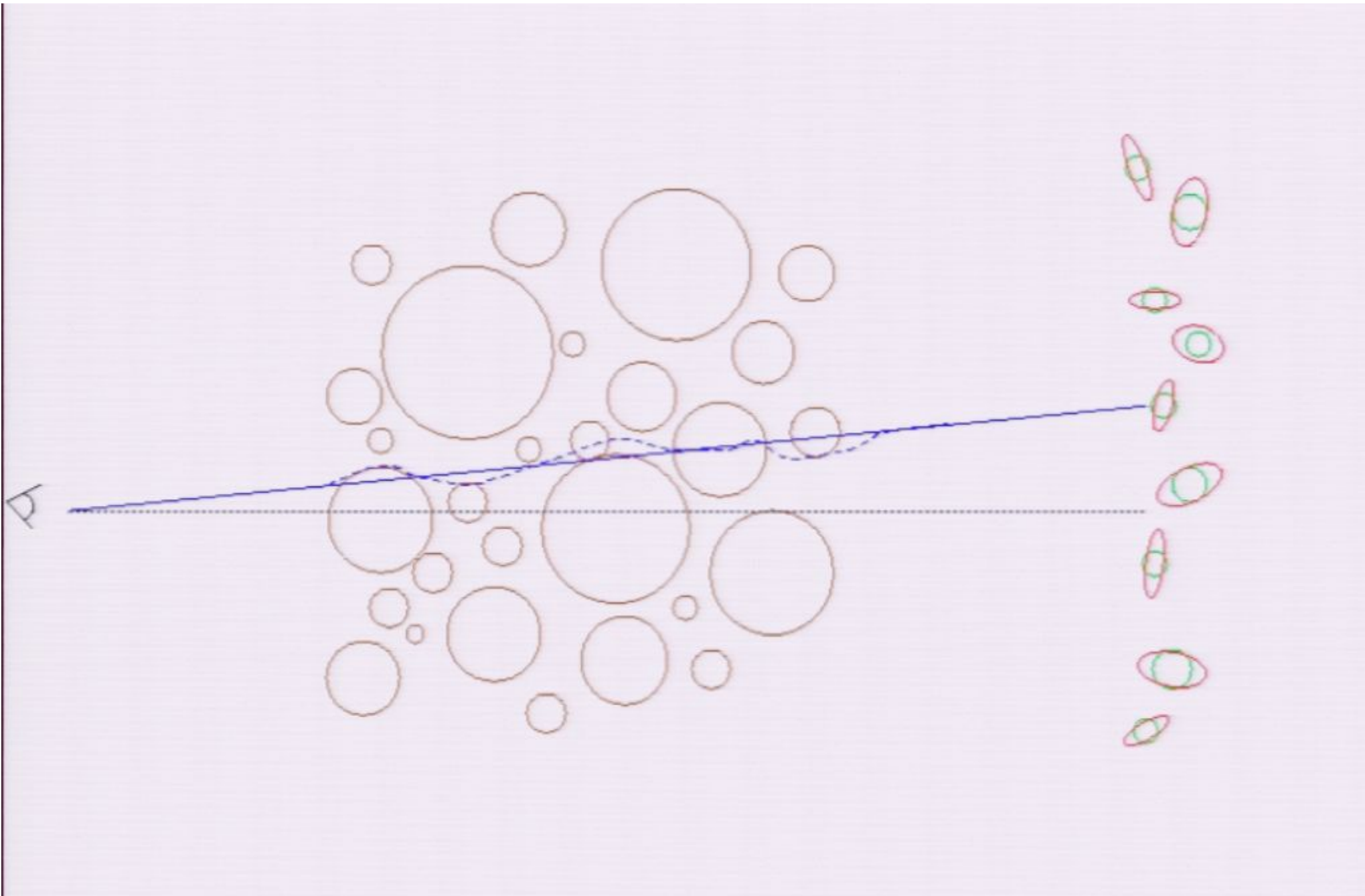
Direct Observation of Dark Matter

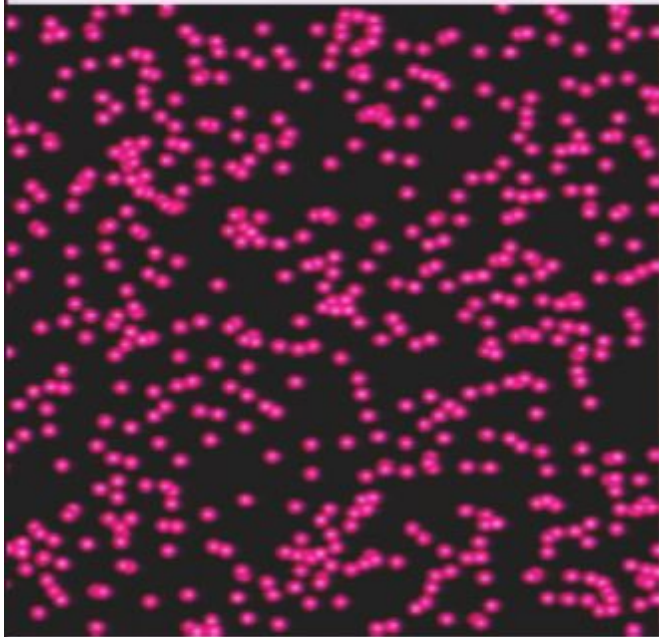
4. Cosmic shear



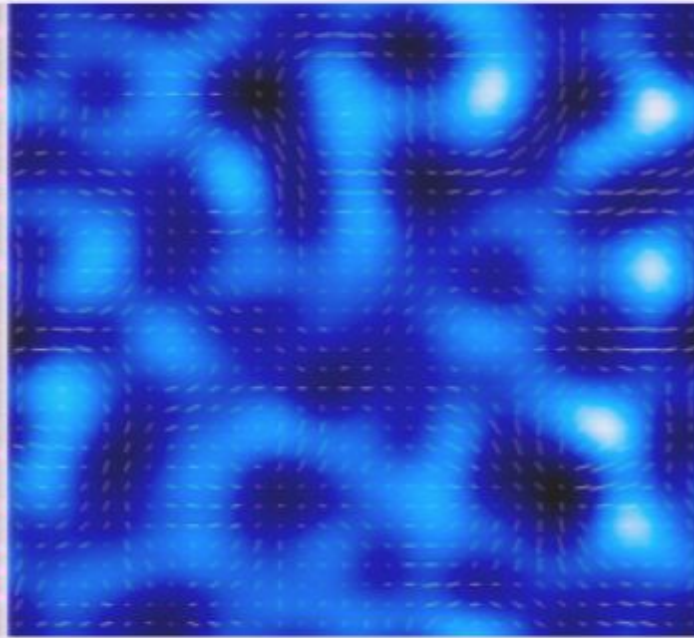
- Galaxies are more aligned than expected
- Intervening filamentary structure lenses



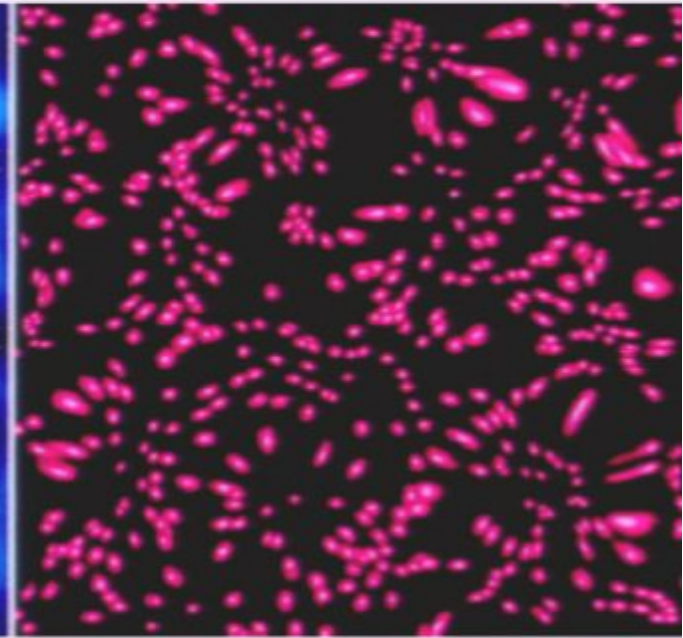




Unlensed galaxies



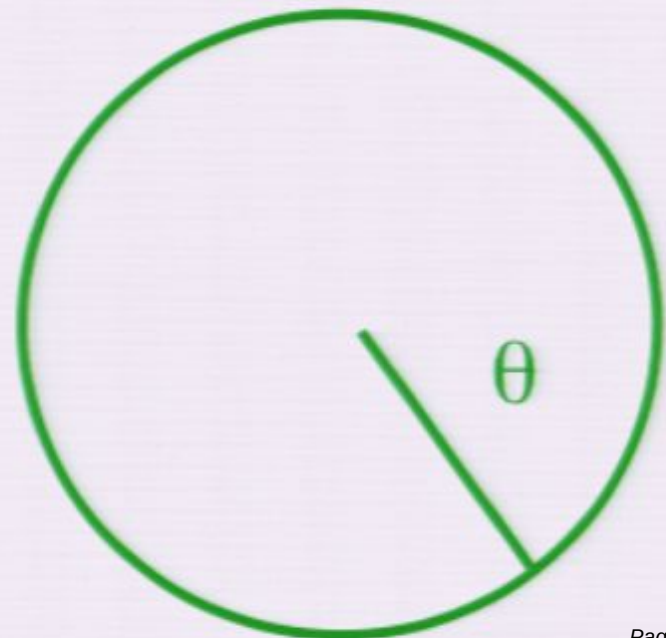
Projected mass
Shear map overlaid



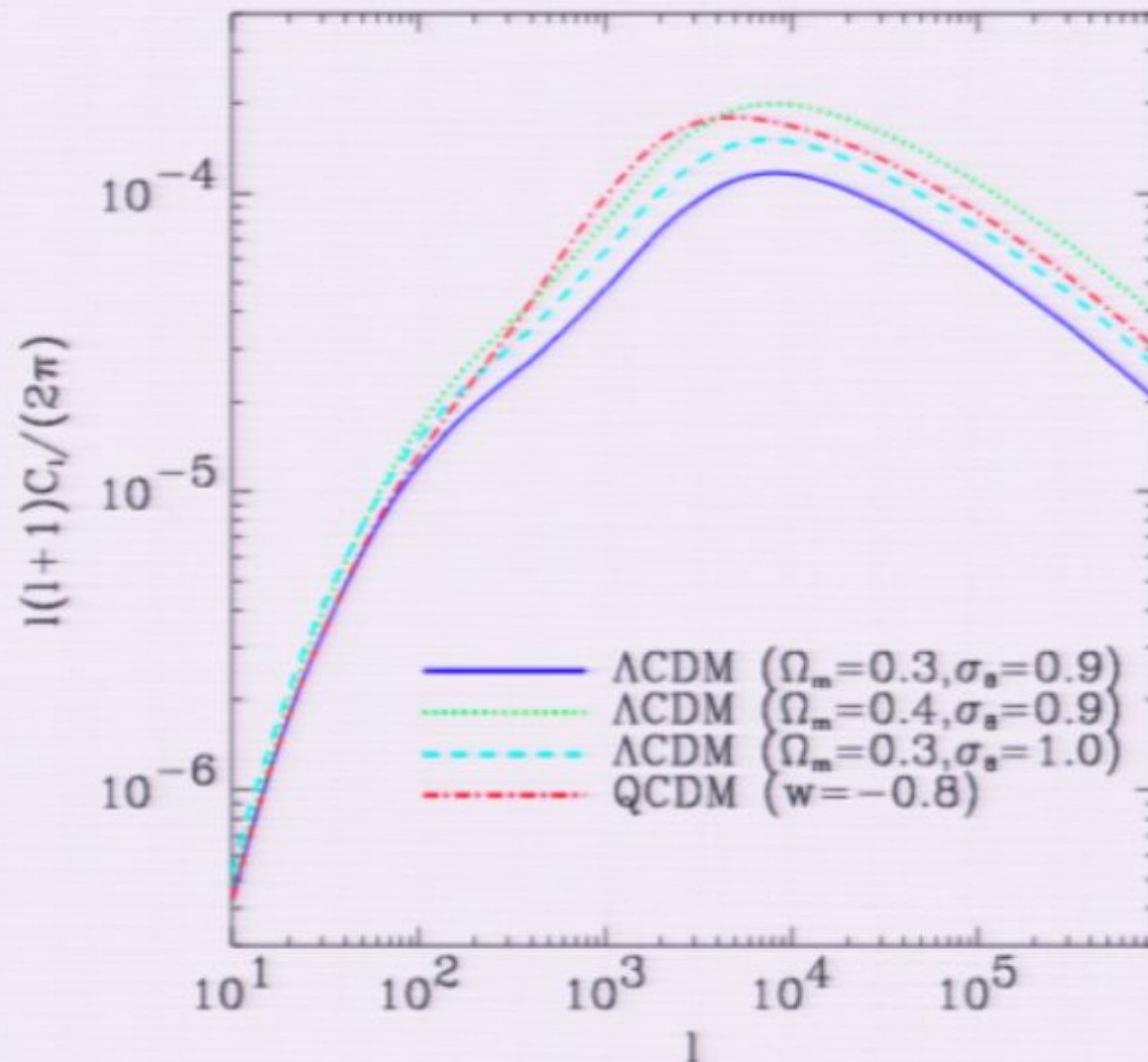
Lensed galaxies

Mean shear in cells

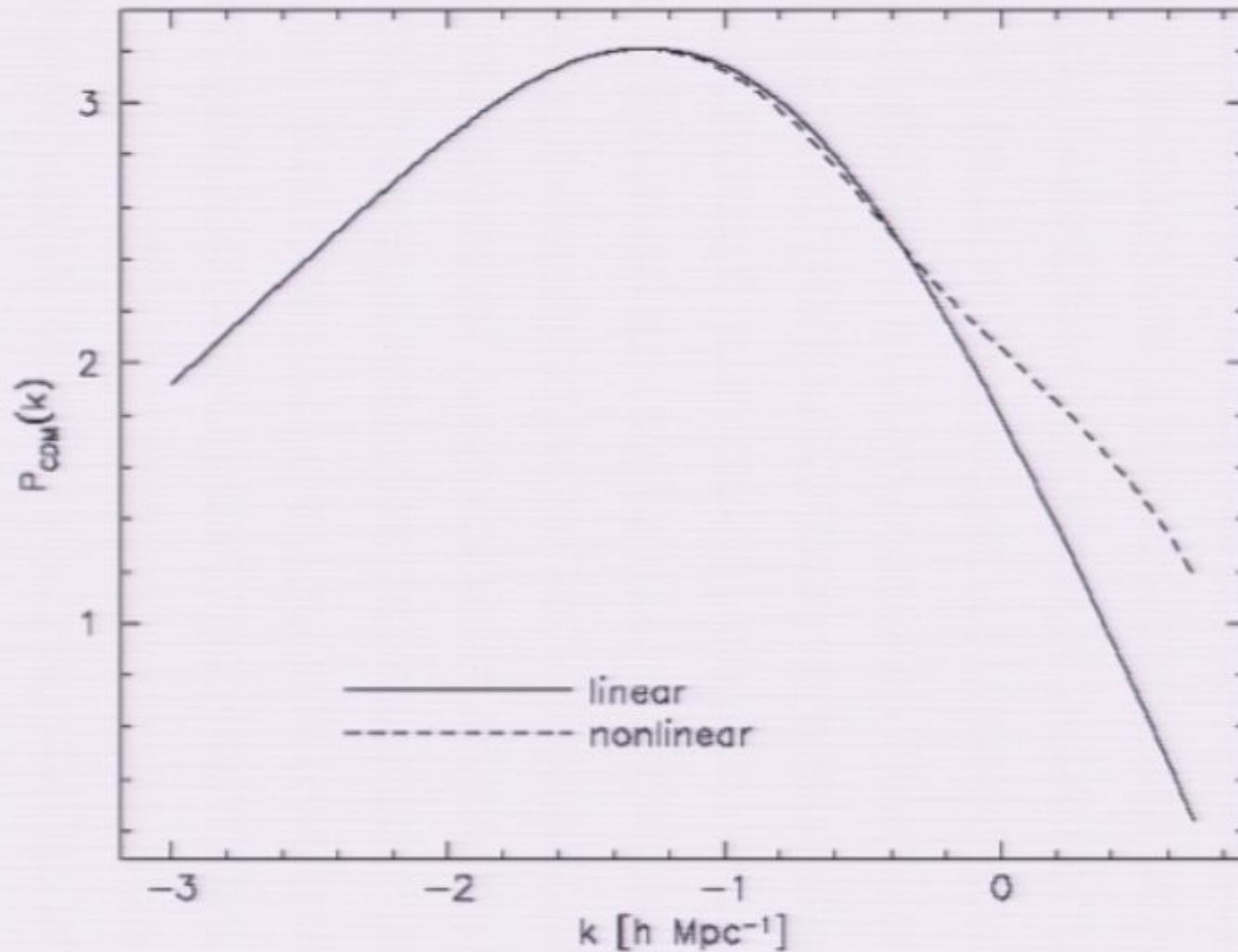
- Average $|\gamma|$ in circles of radius θ
- Move circles over image, find variance



Shear power spectrum



Related to matter power spectrum



5. Non-linear theory

- Non-linear v linear theory
 - linear theory matter power spectrum
- n-body simulations result
- What about other cosmological models?
 - the halo model
 - effect of Ω_m

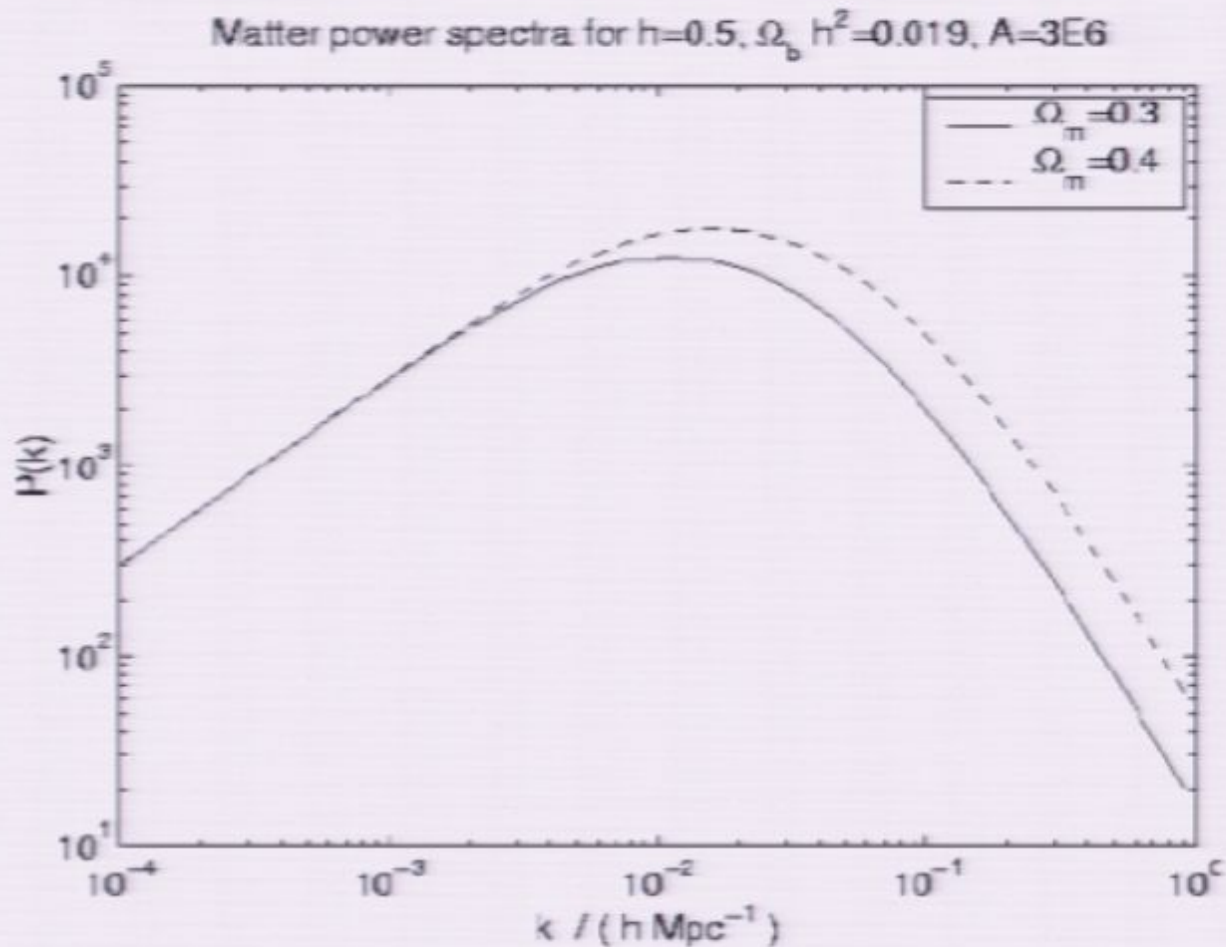
Motivation

- What is the matter power spectrum today?
- Needed for comparison with observations
 - cosmic shear
 - velocities
 - number of dwarf galaxies
- Other non-linear quantities:
 - number of clusters of galaxies (Press Schechter)
 - velocities of galaxies (L7)

Non-linear v linear theory

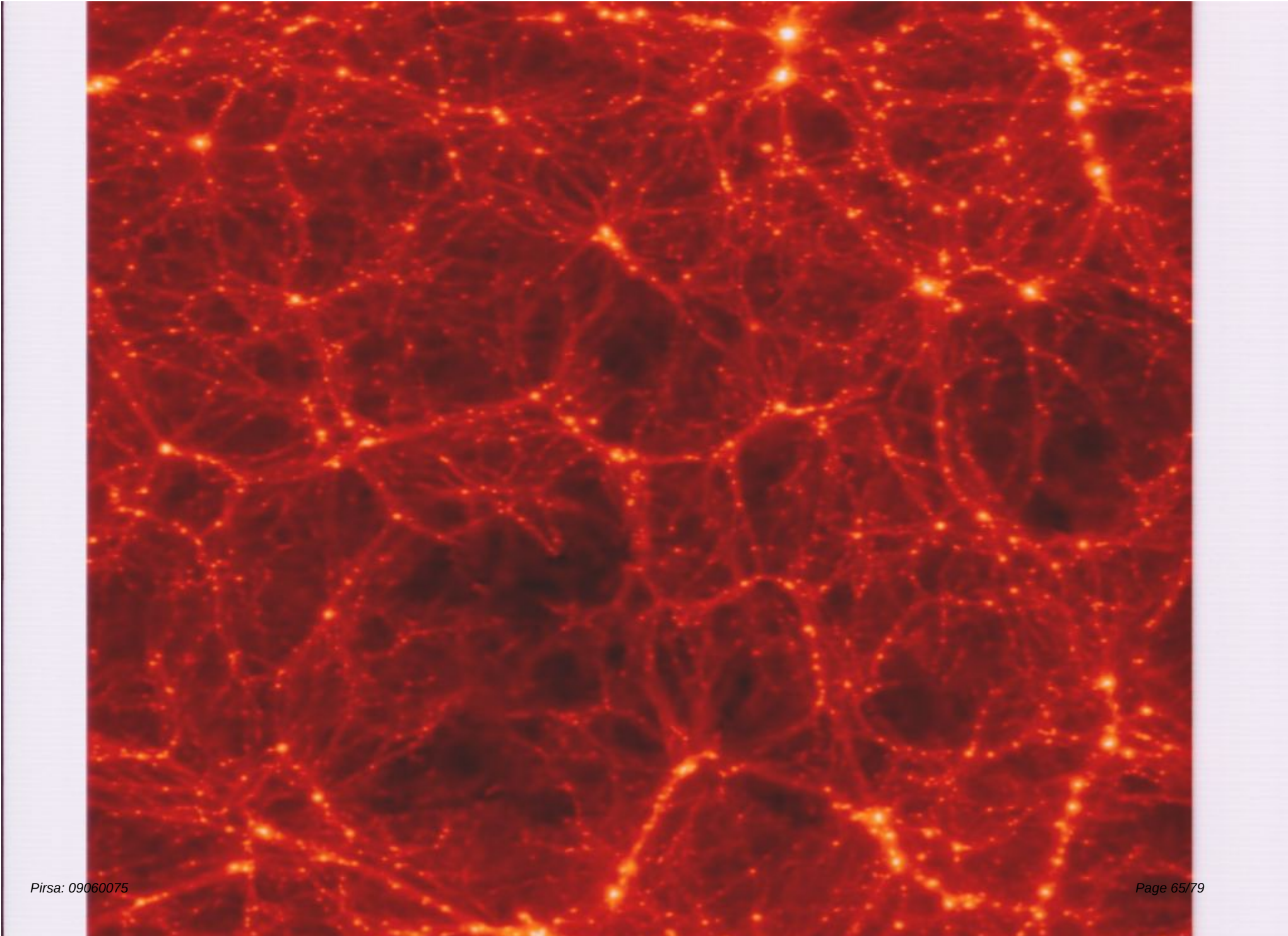
- Linear theory
 - assume all k modes are independent
 - applies when fluctuations are small
 - much faster to calculate (eg. CMBFAST)
- Non-linear theory
 - do the full GM/r^2 calculation
 - can't expect k modes to be indep in general

Linear theory matter power spectrum



N-body simulations

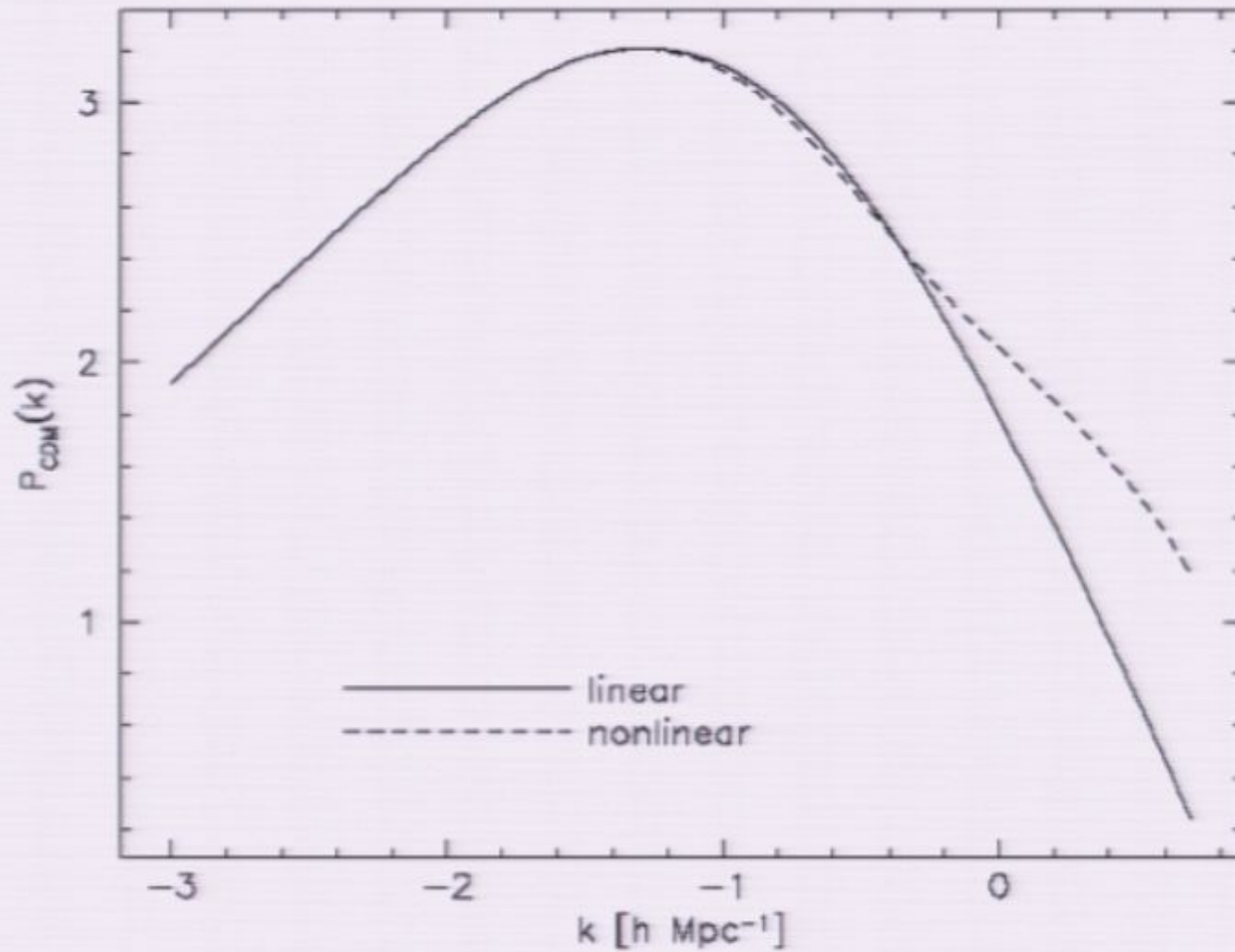
- Take into account full gravity eqns GMm/r^2
- In practice use tricks to speed up
 - eg. PPM, TPM...
- Questions to ask:
 - box size / longest wavelength mode?
 - spatial resolution?
 - mass resolution?
 - with baryons?



Departures from linearity

- Occur on small scales, largest fluctuations
 - where variance of linear density field $\sigma > 1$
- Increases the power over linear result
- Power from large scales cascades down
- 'Non-linear' scale increases with time

Modification to linear-theory $P(k)$



Cosmic Shear Observations

- Observational difficulties
 - Galaxy shape measurement methods
 - Removal of psf
- Latest results
- Cosmological parameter constraints

Deep optical images

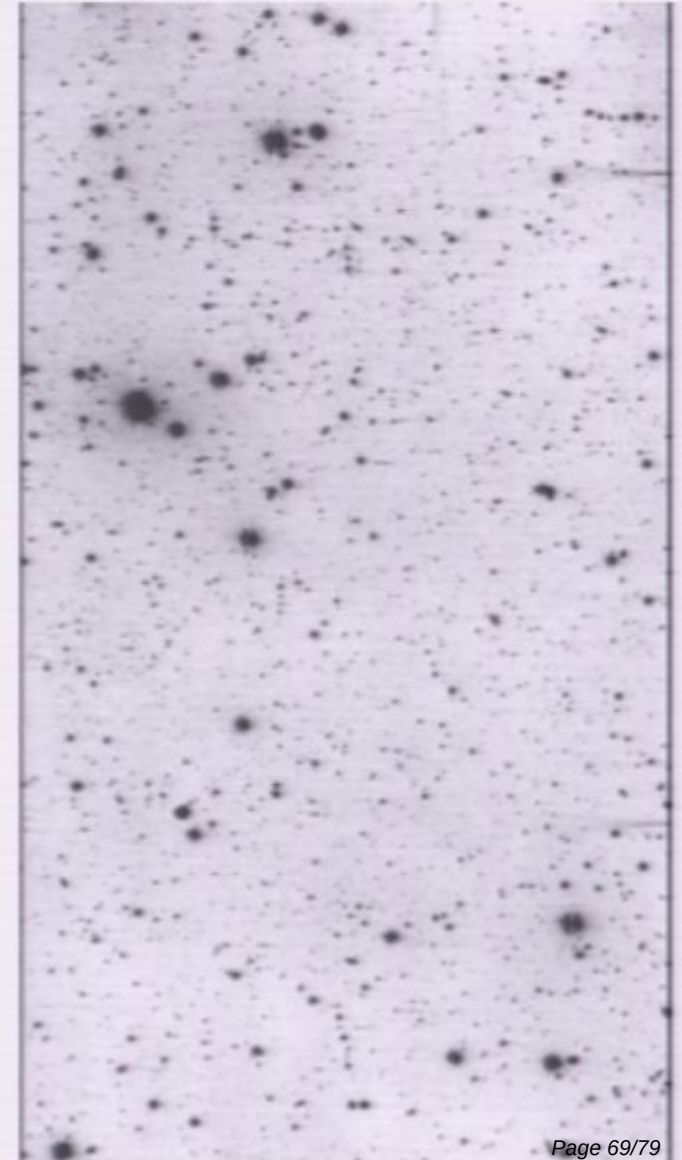


William Herschel Telescope
La Palma, Canaries

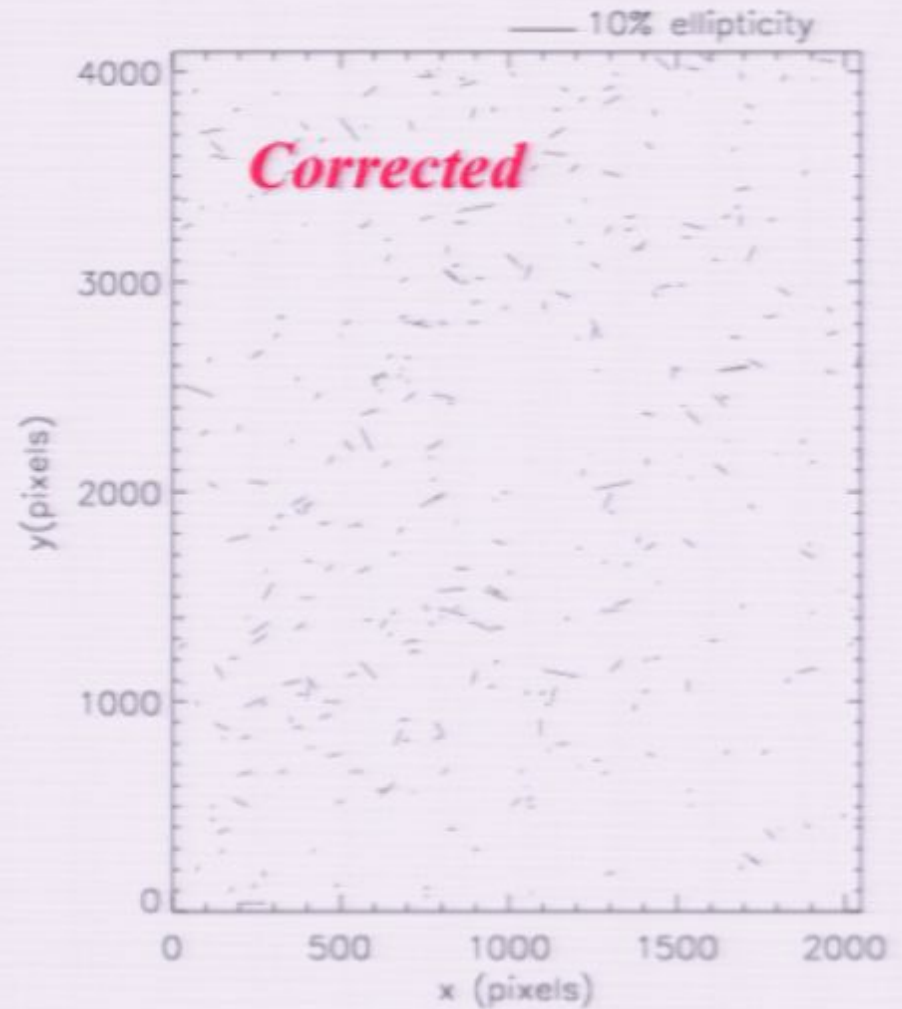
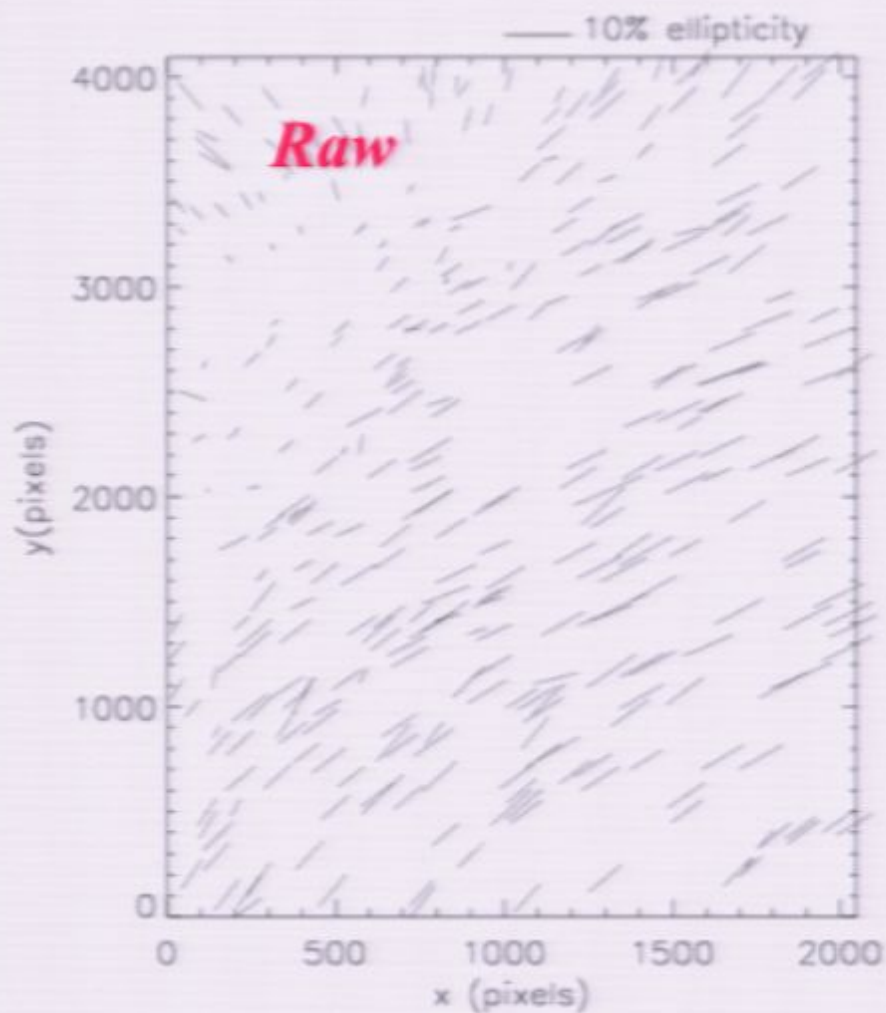
16'x8' arcmin

$R < 25.5$

30 (15) gals/sq. arcmin



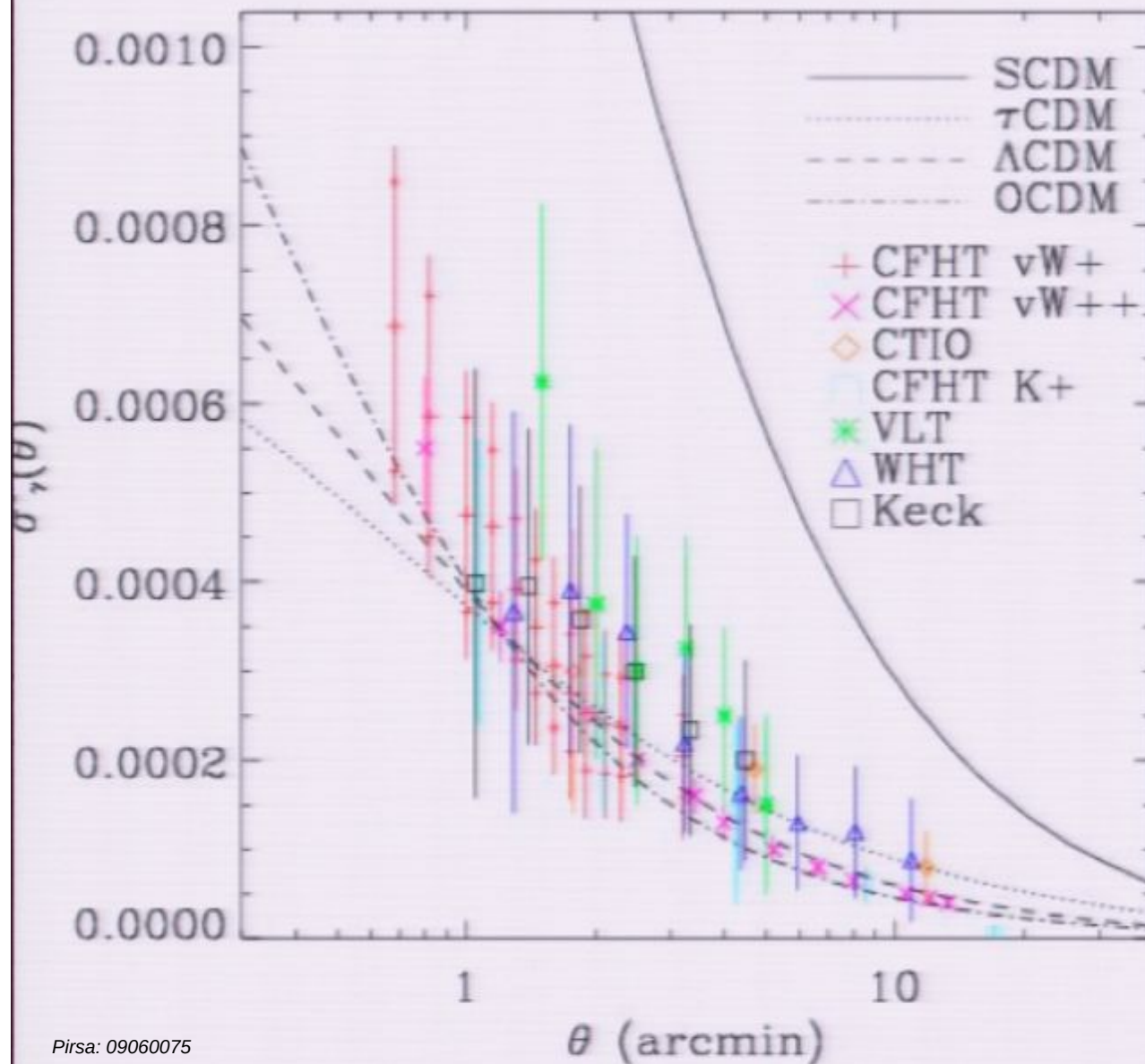
PSF anisotropy ε swirl patterns



Ground based limits: 3-10% rms reduced to $\approx 0.1\%$

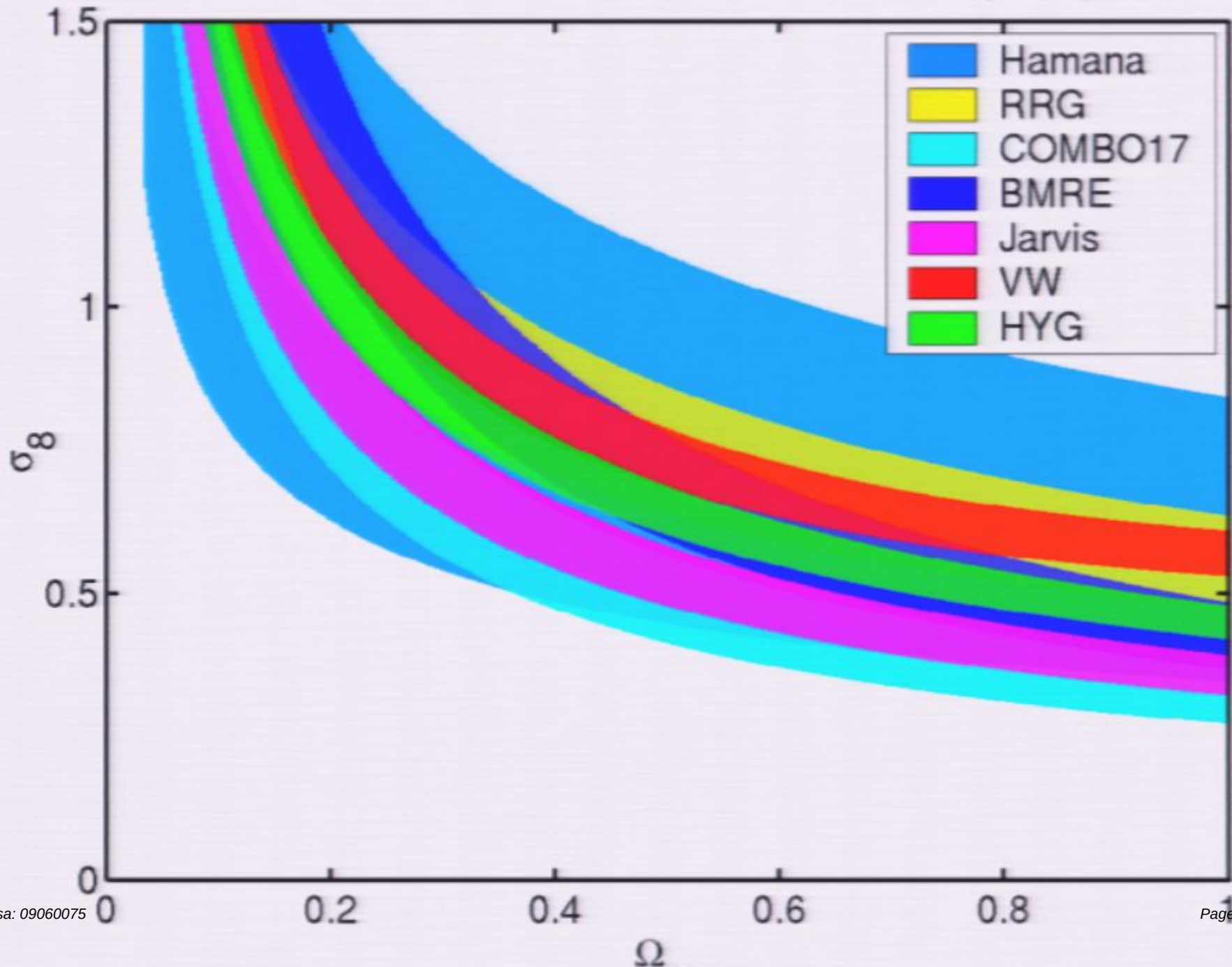
The most serious systematic: inherent in tracking

Results

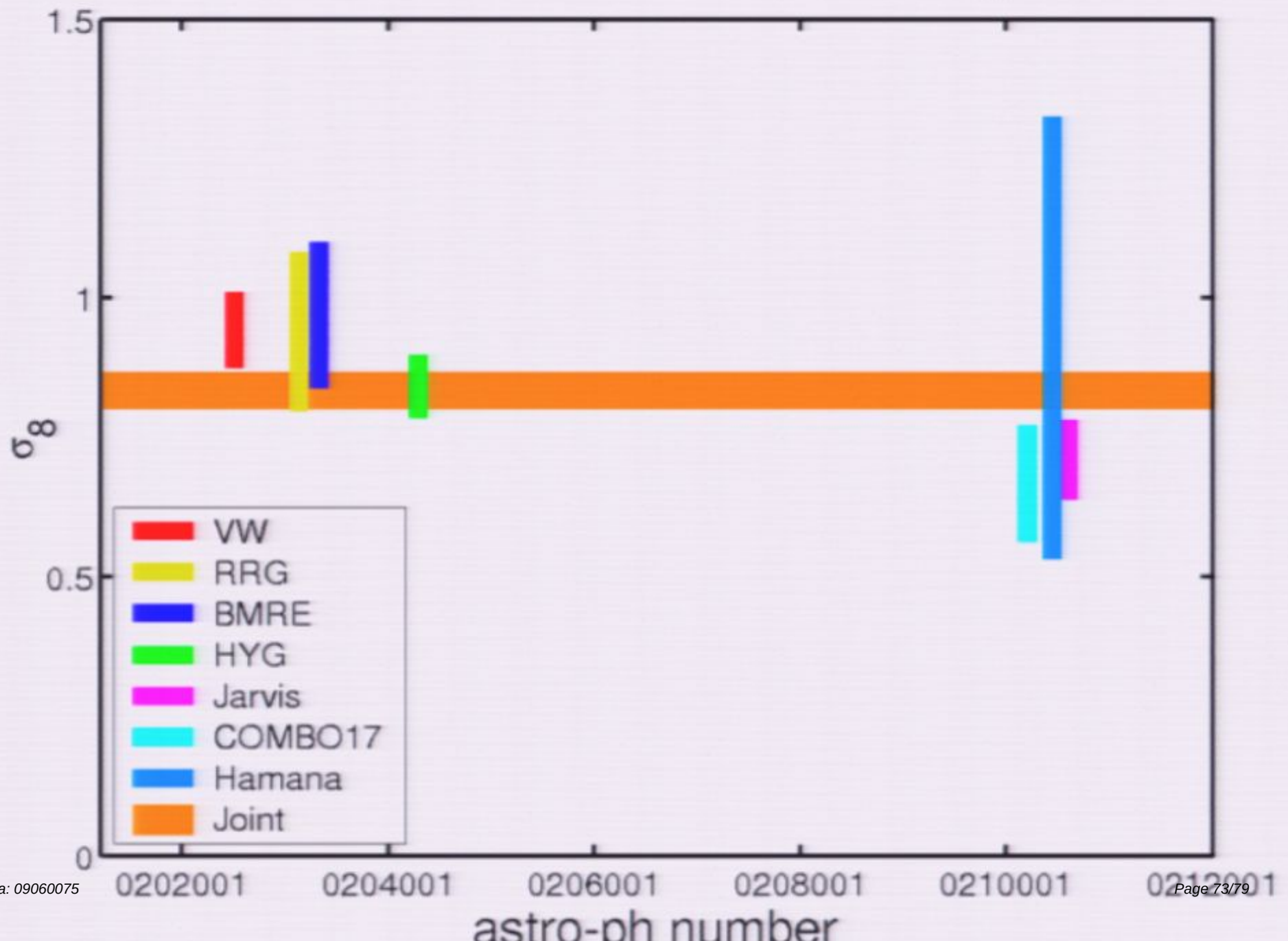


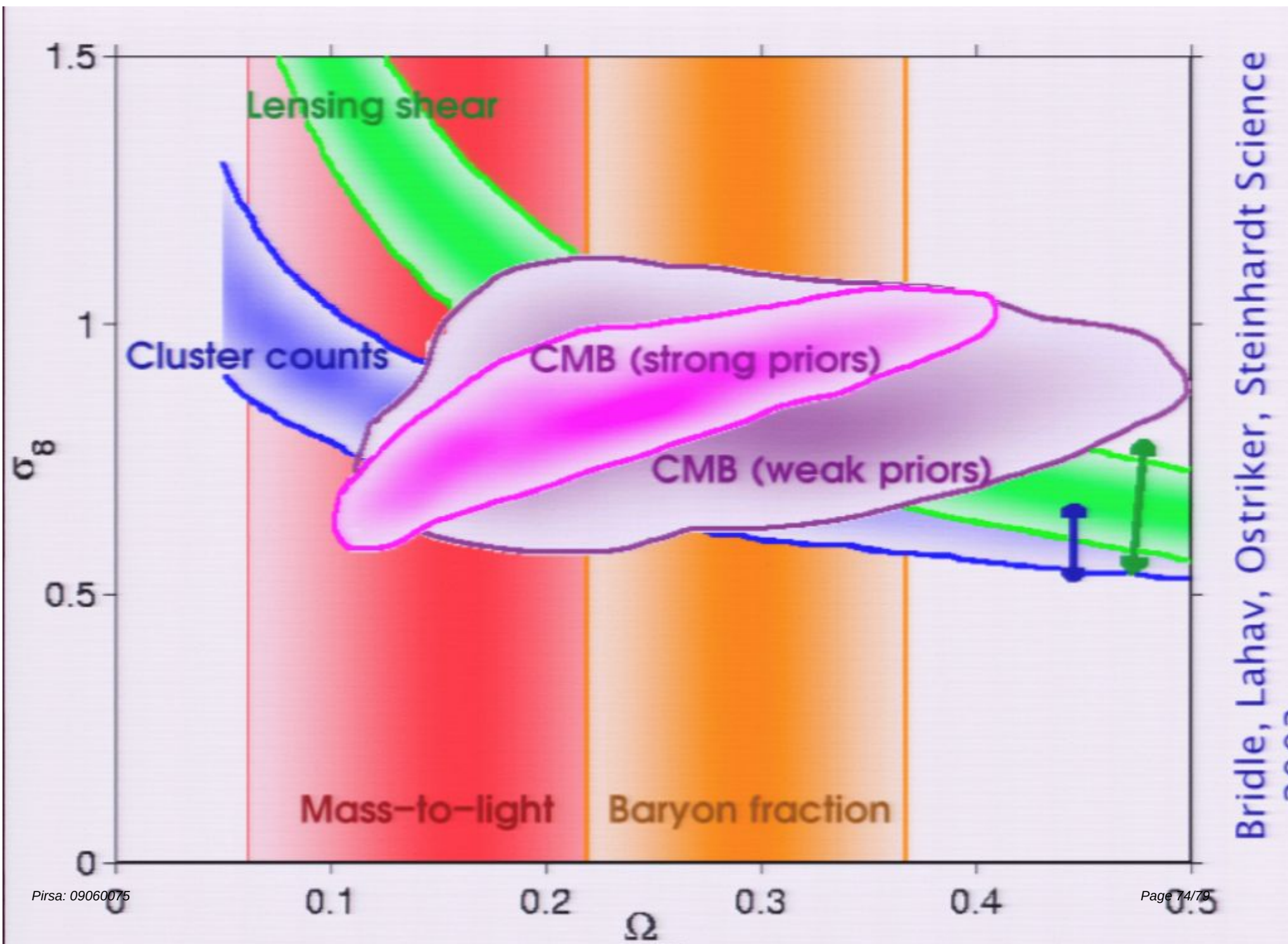
Bacon, Refregier & Ellis 2000
 Bacon, Massey, Refregier & Ellis 2001
 Kaiser *et al.* 2000
 Rhodes, Refregier & Groth 2001
 Van Waerbeke *et al.* 2000
 Van Waerbeke *et al.* 2001
 Wittman *et al.* 2000

Cosmic Shear Constraints Nov 2003 (68%)



Cosmic Shear Constraints Nov 2003 ($\Omega_m=0.3$)

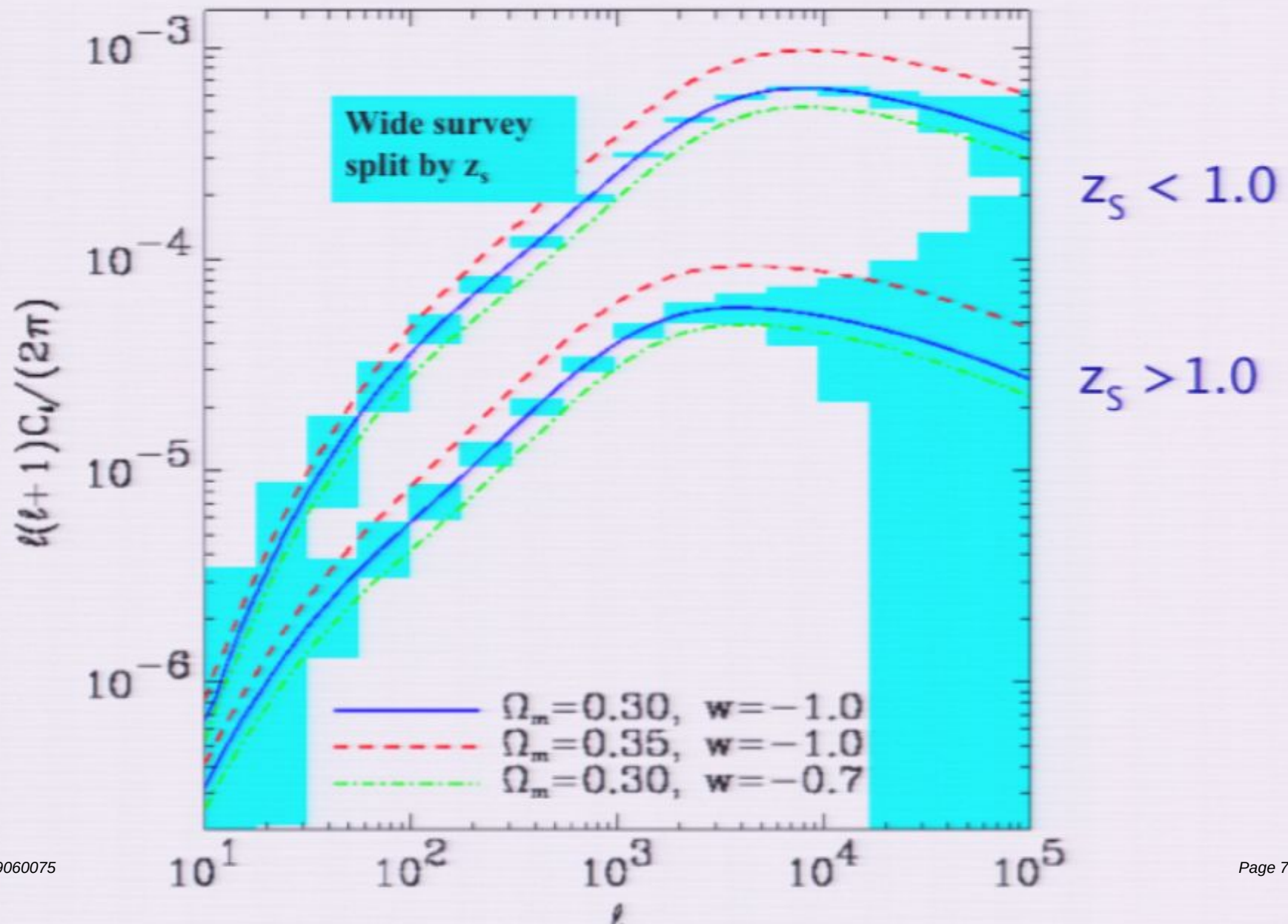




Long term aims of cosmic shear

- Probes the matter power spectrum directly
 - cf galaxy z surveys, unknown light $\rightarrow$ mass
- Measures evolution of matter pk with time
- Combine with CMB
 - primordial power spectrum
 - cosmological parameters
- Combine with galaxy distribution
 - constrain galaxy formation models

Evolution of Large Scale Structure



Supernova Cosmology Project
Perlmutter *et al.* (1998)

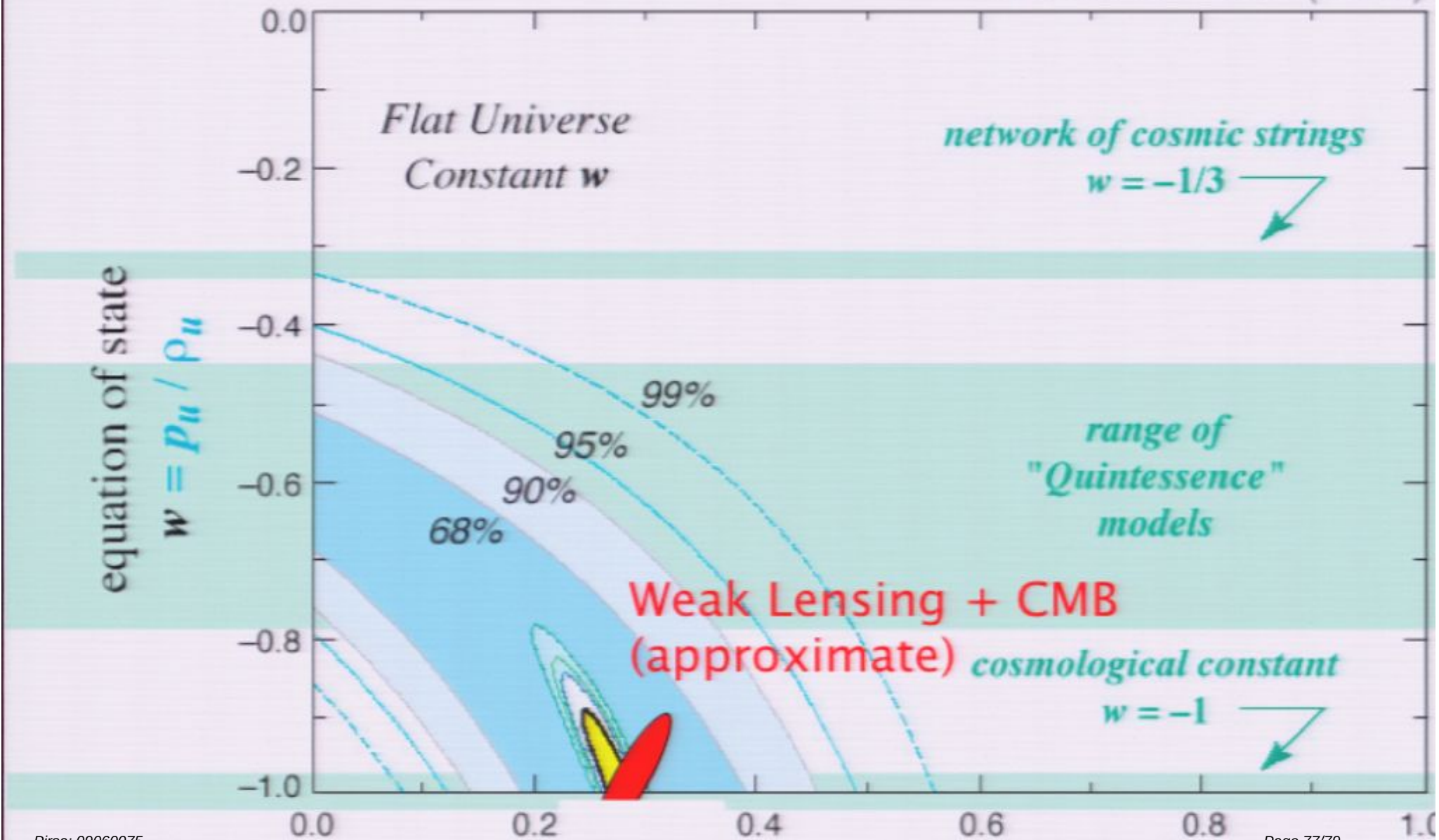


Table 2: Future cosmic-shear surveys

Telescope/Survey	Ground/Space	Diameter (m)	FOV (deg ²)	Area (deg ²)	Start ^a	Ref. ^b
DLS	ground	2 × 4	2 × 0.3	28	1999 ^c	1
CFHTLS	ground	3.6	1	172	2003	2
VST	ground	2.6	1	$\times 100^d$	2004	3
VISTA ^e	ground	4	2	10000	2007	4
Pan-STARRS	ground	4 × 1.8	4 × 4	31000	2008	5
LSST	ground	8.4	7	30000	2012	6
SNAP	space	2	0.7	300	2011	7

^a planned start date of the cosmic shear surveys

^b references: 1: Wittman et al. 2002; 2: Mellier et al. 2000; 3: Kuijken et al. 2002; 4: Taylor et al. 2003; 5: Kaiser et al. 2000; 6: Tyson et al. 2002a,b; 7: Perlmutter et al. 2003, Rhodes et al. 2003, Massey et al. 2003, Refregier et al. 2003

^c the survey will be complete in 2003

^d a survey of several 100 deg² is planned

^e assuming the availability of the optical camera

Conclusions

- Lensing is a chromatic, bends by $4GM / (c^2 b)$
- Critical mass $\Sigma_c = c^2 / 4 \pi G D_s / (D_s D_{ds})$
- Einstein radius measures mass enclosed
- Cosmic shear probes non-linear matter power spectrum
- Cosmic shear currently gives $\sigma_8 \sim 0.9$