FRONTIERS OF ASTRONOMY

Alexandria, March 2006

Richard Ellis, Caltech

1. Role of Observations in Cosmology & Galaxy Formation

   Key Results and the Standard Model (ΛCDM)

   Observational Probes of the Dark Matter Distribution

2. High Redshift Galaxies:

   Cosmic Star Formation History and Mass Assembly

   Cosmic Dawn: Searching for the Earliest Sources

3. Observational Probes of Dark Energy

   Supernovae, weak gravitational lensing and studies of large scale structure

Role of Observations

Many of the key features which define our current view of the Universe came through surprising observations:

1. Cosmic expansion (Slipher/Hubble): Einstein preferred a static Universe and disregarded the early observations
2. Big Bang (Penzias & Wilson): Hoyle and others considered the Steady State theory to be the `natural' solution
3. Dark Matter (Zwicky, Rubin & others): Dominant role in structure formation followed the observational evidence
4. Dark Energy (Perlmutter et al, Riess et al): Although Λ was invoked many times in the past, cosmic acceleration was an unpredicted result
5. More surprises in store??

The observational opportunities have advanced dramatically & many puzzles remain, so lots to do!

Key Result #1: Cosmic Expansion

Recession velocity V from the spectrum ↑

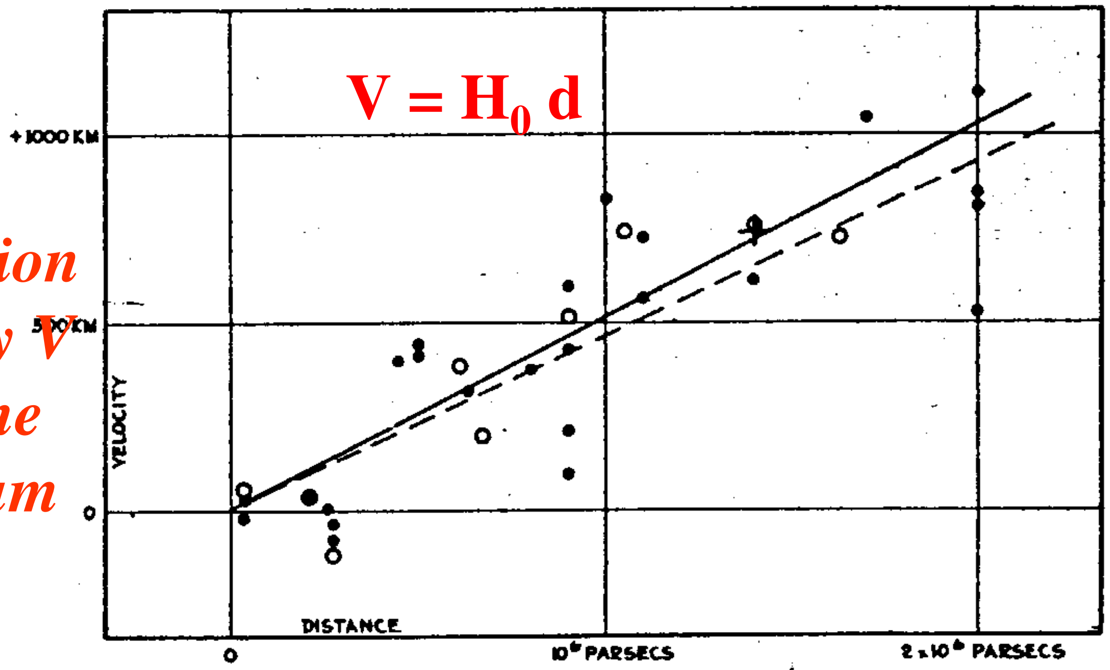
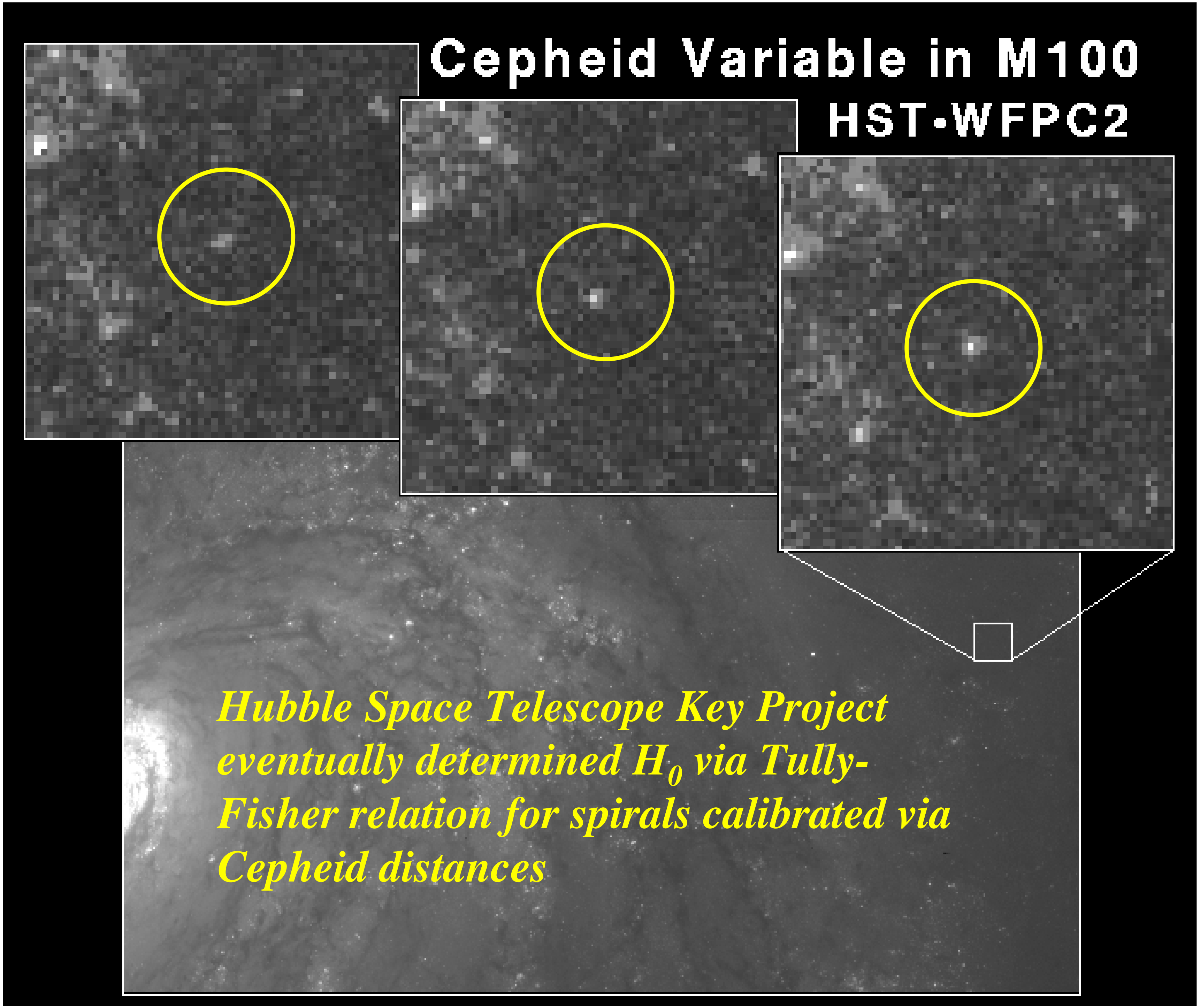


FIGURE 1

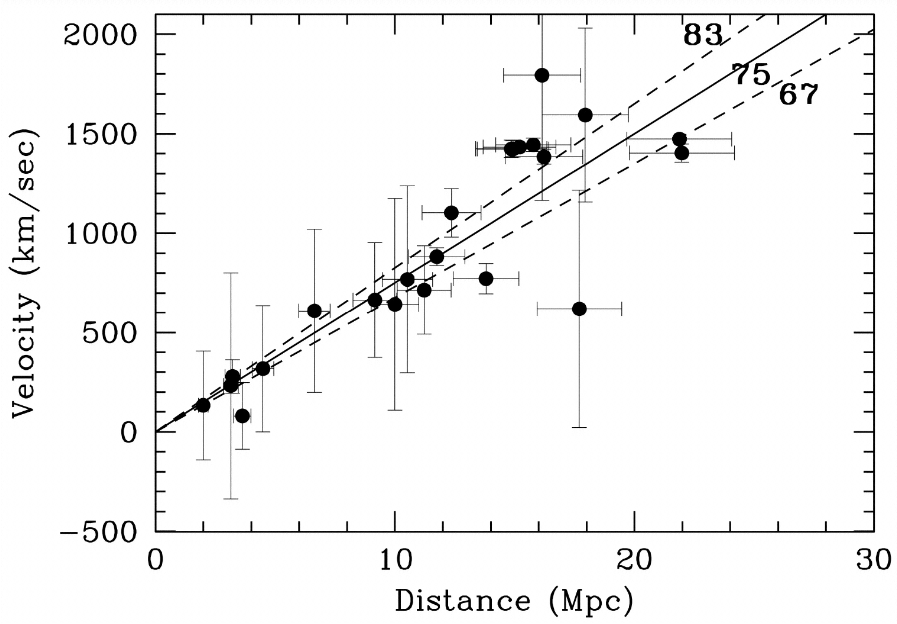
Distance to galaxy d (using luminous variable stars) →

Cosmic expansion (Hubble 1929):
Rate in km s^{-1} Mpc^{-1} is Hubble's constant H_0
H_0 governs physical scale and age of the cosmos


Cepheid Variable in M100
HST•WFPC2
Hubble Space Telescope Key Project eventually determined H_0 via Tully-Fisher relation for spirals calibrated via Cepheid distances

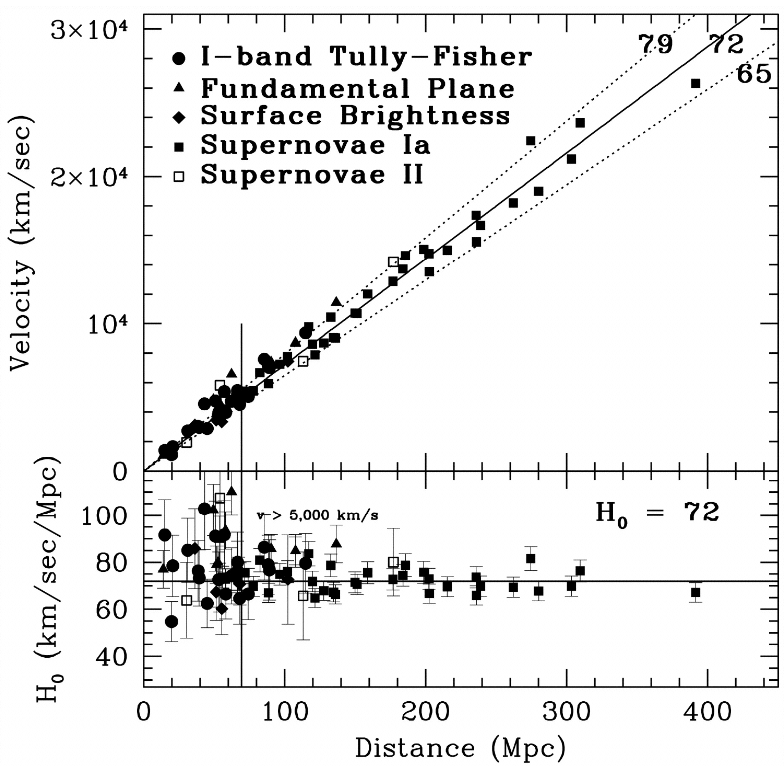
Two-stage determination of Hubble's Constant H_0

1. Period-luminosity relation



Primary Cepheid calibration of distances to nearby spirals (affected by galaxy pec. velocities)

2. Spiral rotation-luminosity relation

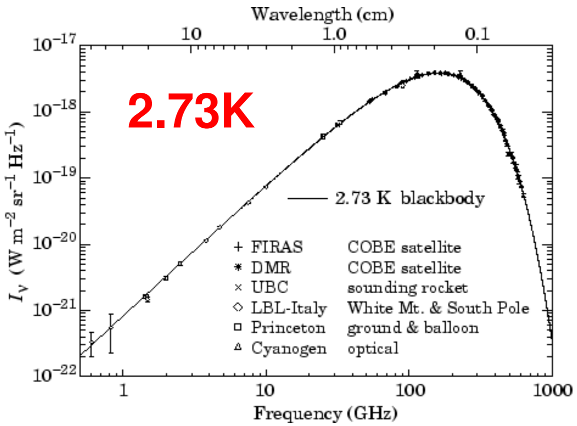


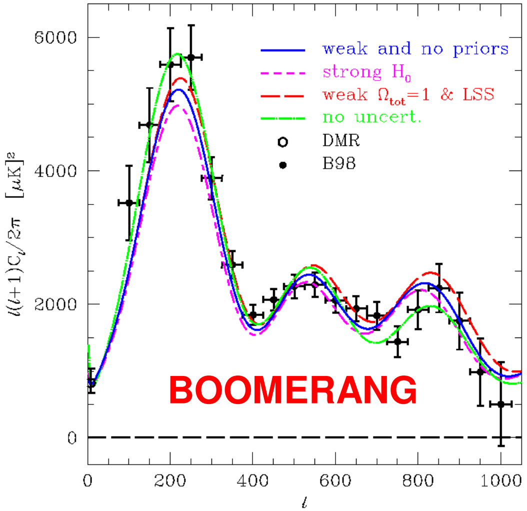
Secondary *Tully-Fisher* distances for distant spirals in the smooth Hubble flow

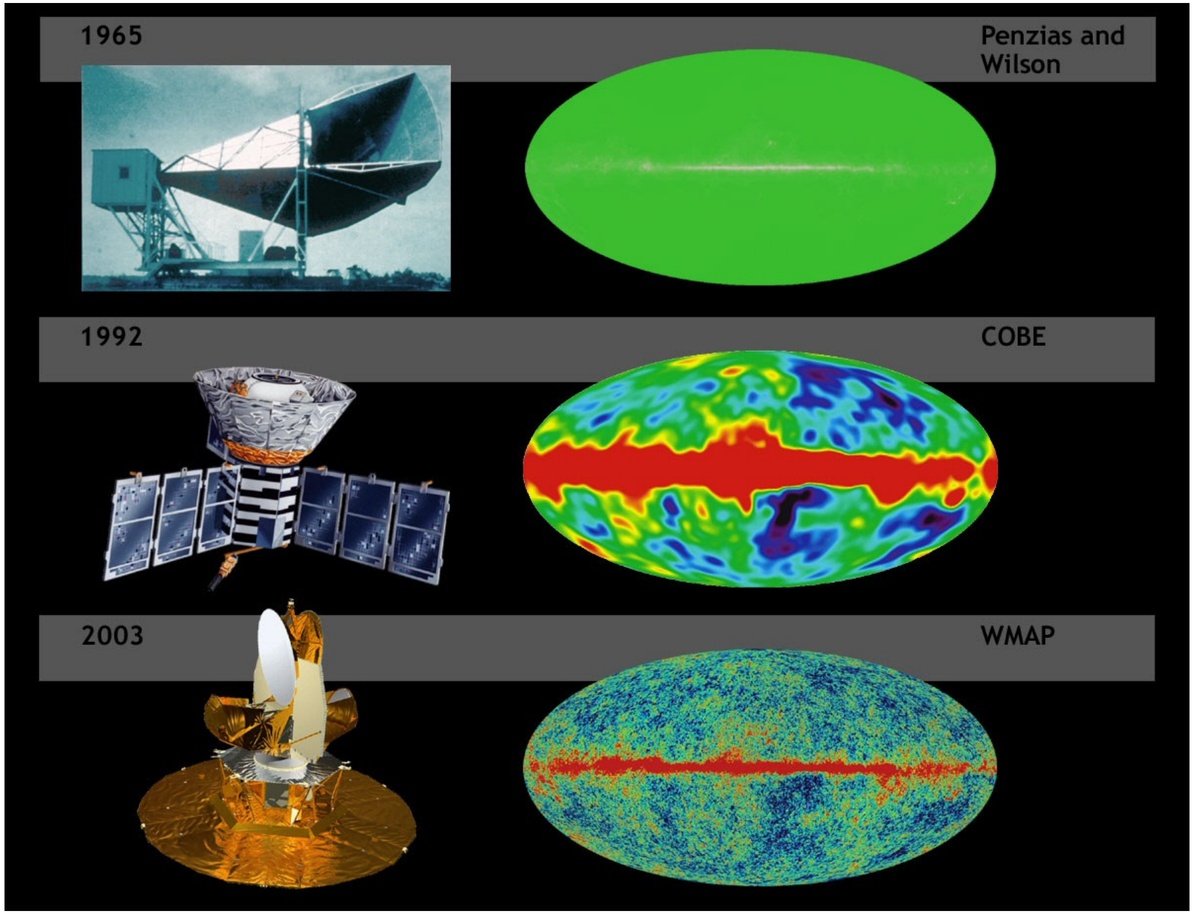
Final result (Freedman et al Ap J 553, 47, 2001):

$$H_0 = 72 \pm 8 \text{ kms s}^{-1} \text{ Mpc}^{-1}$$

Key Result #2: Thermal Origin





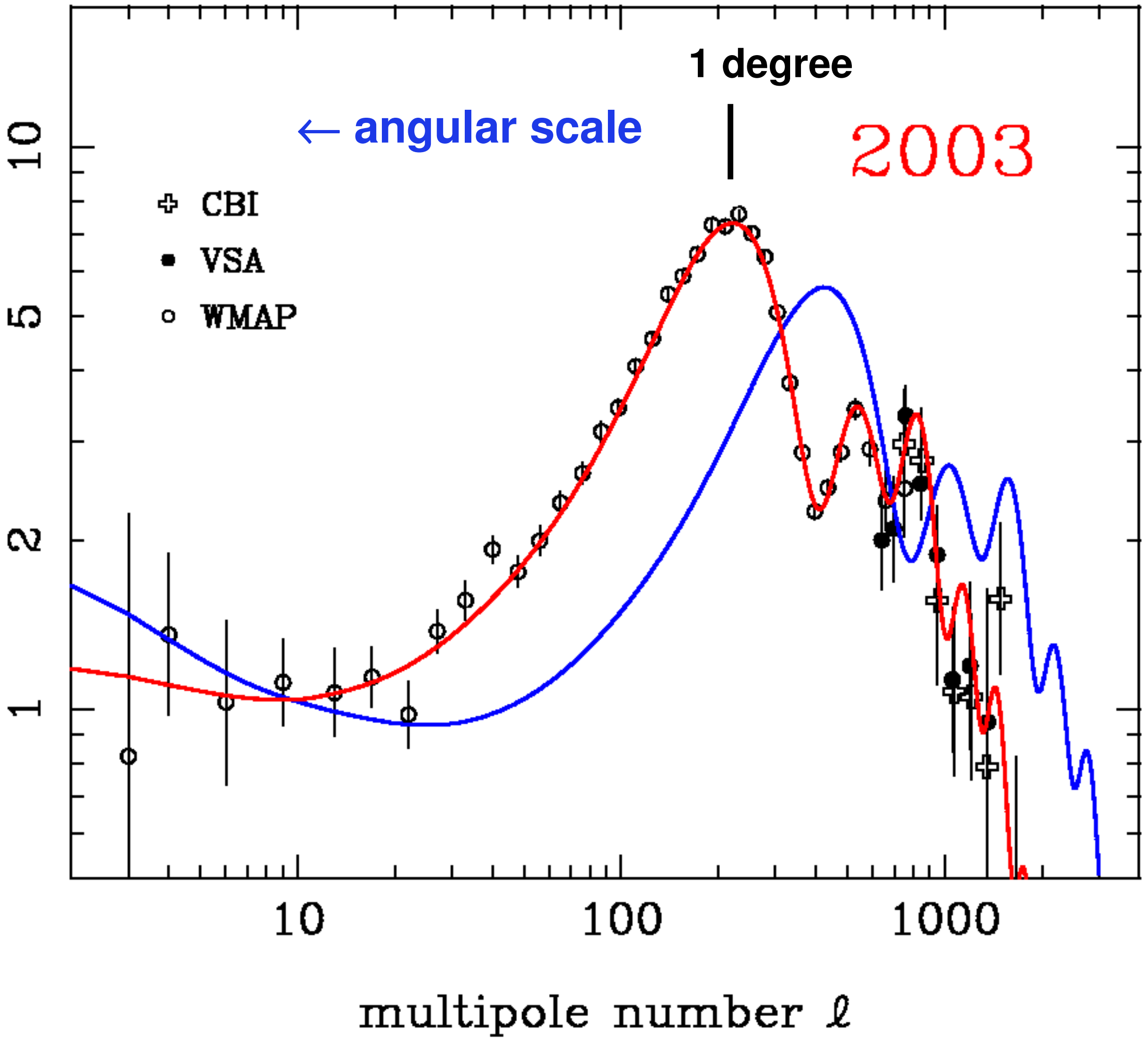


Blackbody spectrum of CMB corresponds to decoupling of matter & radiation at redshift z =1088 ±1 when t = 372 ± 14 kyr

Progress in measuring CMB Fluctuations

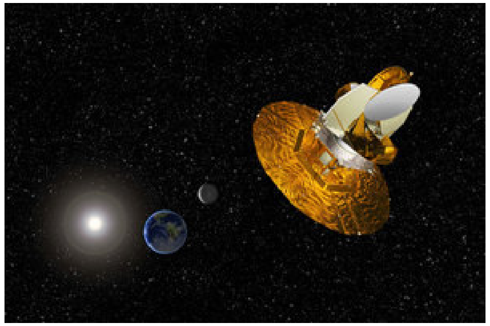
↑

Angular power spectrum

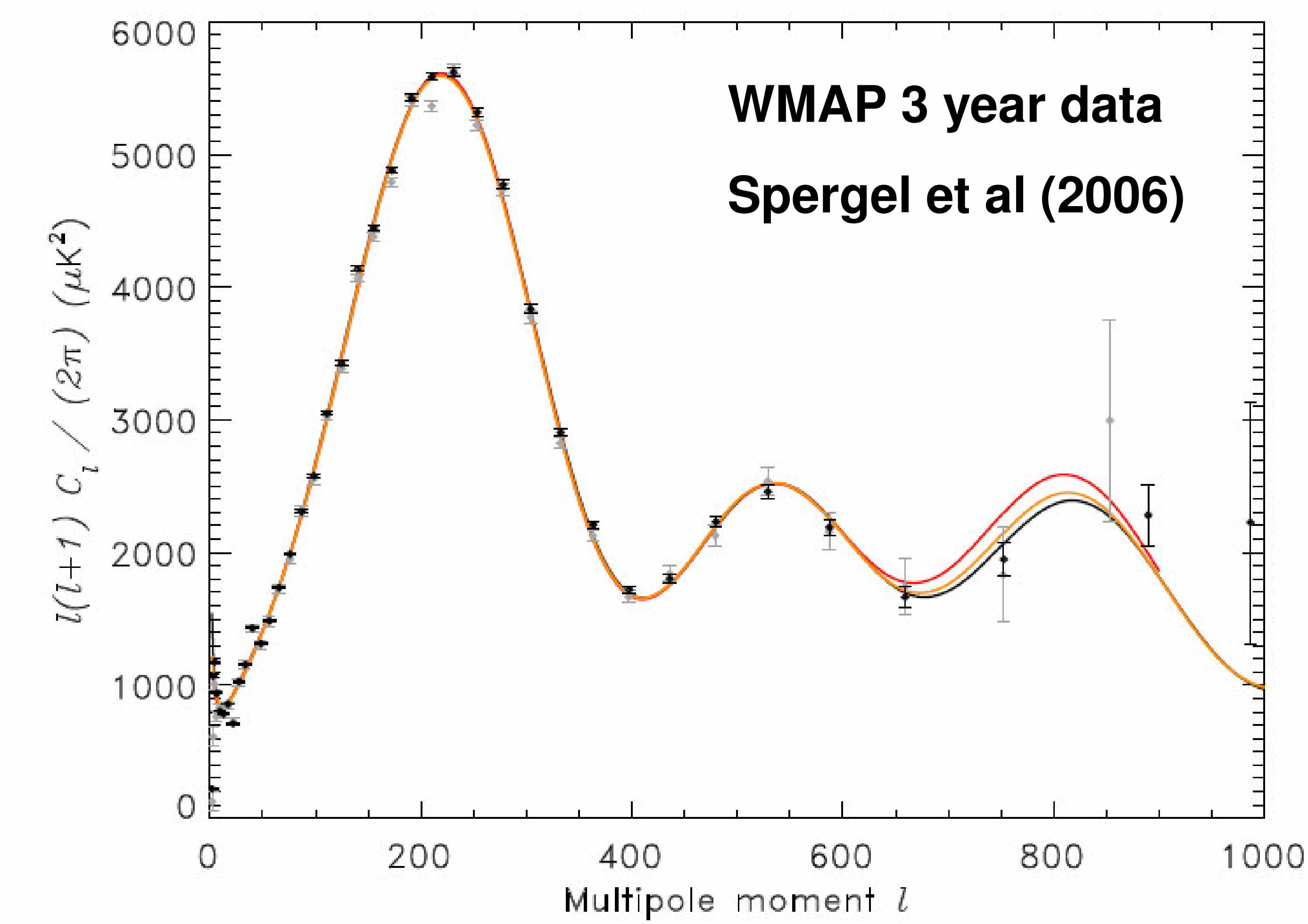


Flat $\Omega_m = 0.3$ (vacuum dominated)

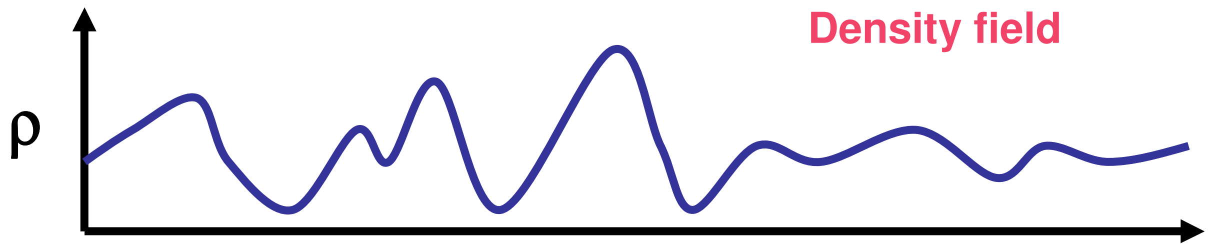
Open $\Omega_m = 0.3$ (no vacuum)



STOP PRESS!


WMAP 3 year data
Spergel et al (2006)
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
Multipole moment l
$l(l+1)\ C_l\ /\ (2\pi)\ (\mu K^2)$

Key Result #3: Clustering of Galaxies



Statistical description emerged in the 1970's (Peebles)

Angular and spatial correlation functions w(θ), ξ(r)

$$\boxed{\begin{aligned}\delta P &= N[1+w(\theta)]\delta\Omega \\ \delta P &= \rho[1+\xi(r)]\delta V\end{aligned}}$$

Excess probability of finding a pair with separation θ or r

Also will need power spectrum of density fluctuations

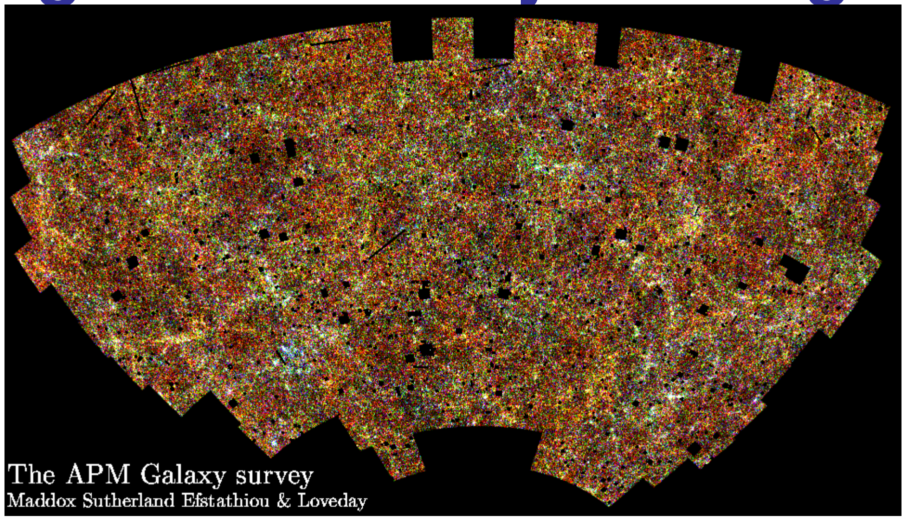
$$\boxed{P(k) = \langle\left|\delta_k{}^2\right|\rangle = \int \xi(r)\exp(ik.r)d^3r}$$

Formalism of gravitational instability developed via angular (2-D, w(θ)) and spectroscopic (3-D, ξ (r)) surveys

Angular Clustering: e.g. APM Galaxy Catalog

Peebles (Ap J 189, L51, 1974)

$$\delta P = N[1 + w(\theta)]\delta\Omega$$

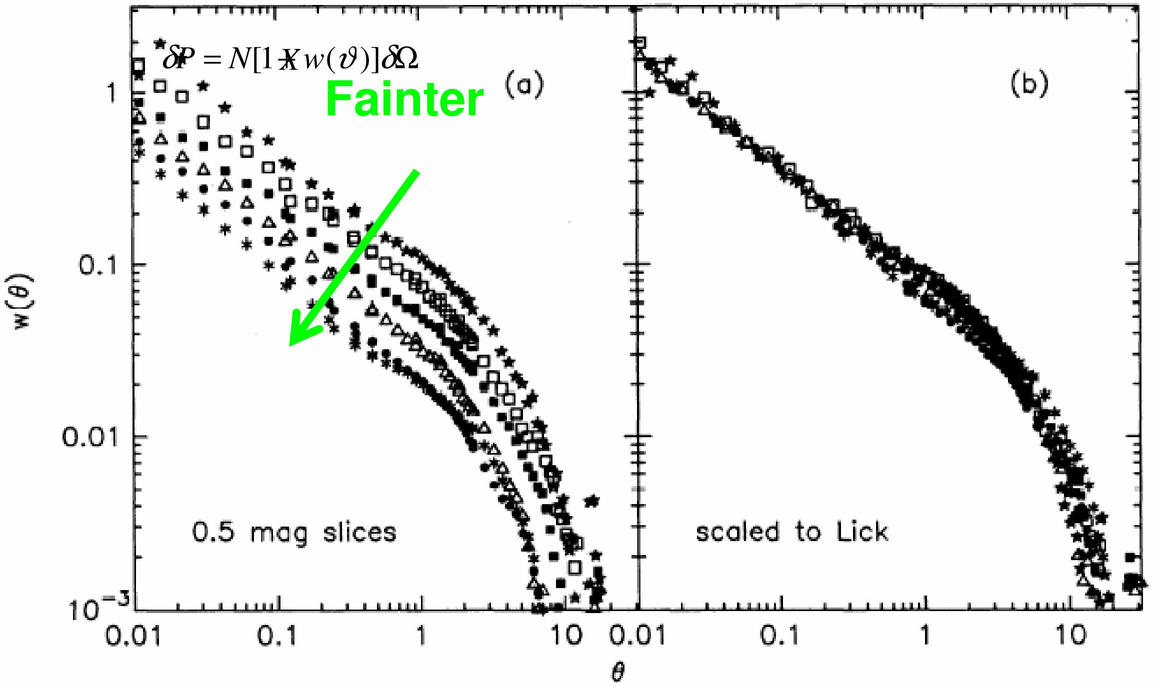


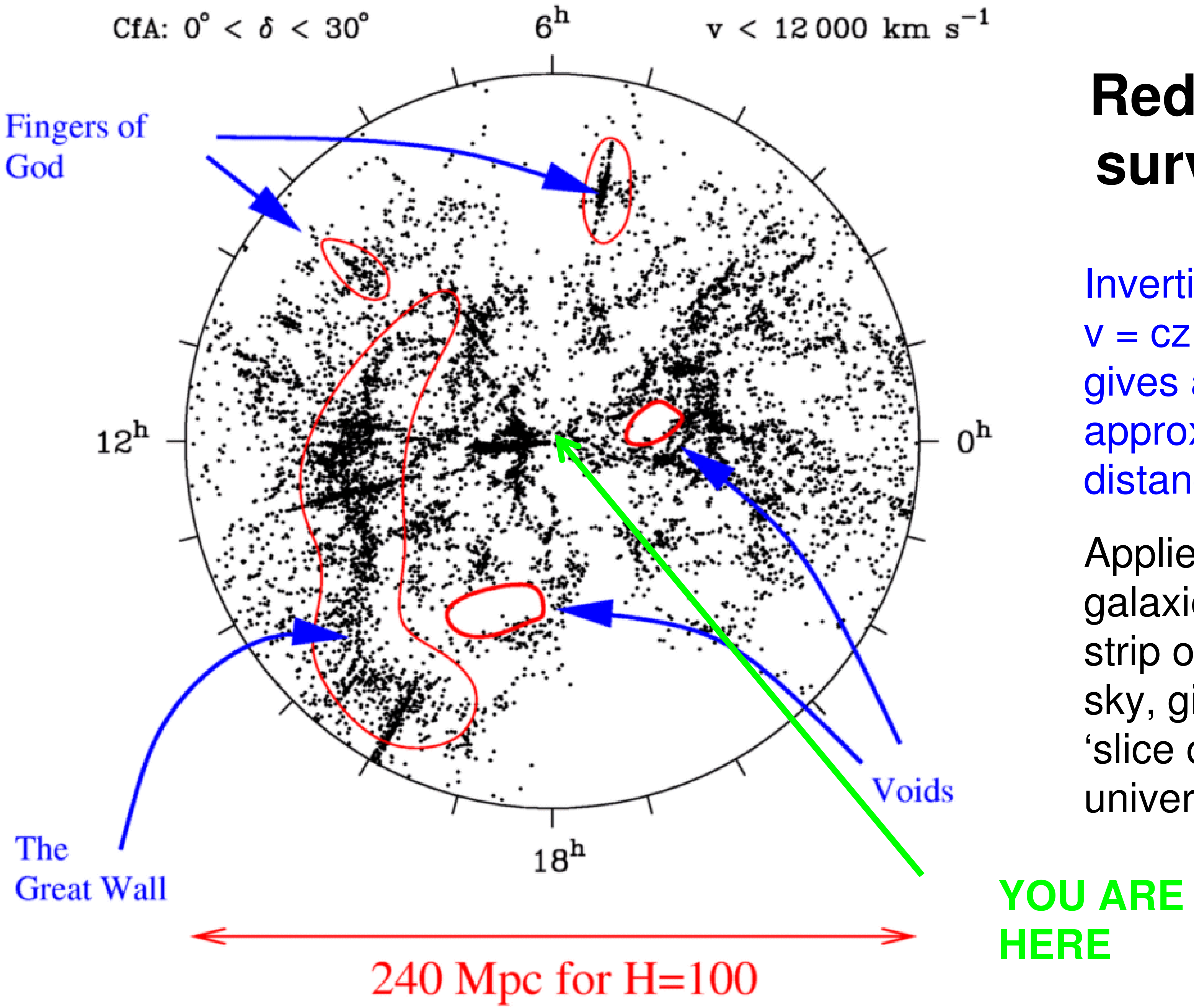
w(ϑ) measures excess probability of pairs on a given scale ϑ for mean surface density N in area $\delta\Omega$

Find $w(\vartheta) = A\ \vartheta^{-0.8}$

Power law indicates growth by gravitational instability

Amplitude A decreases with increasing depth due to increase in no. of uncorrelated pairs, angular diameter distance and (ultimately) less developed structure



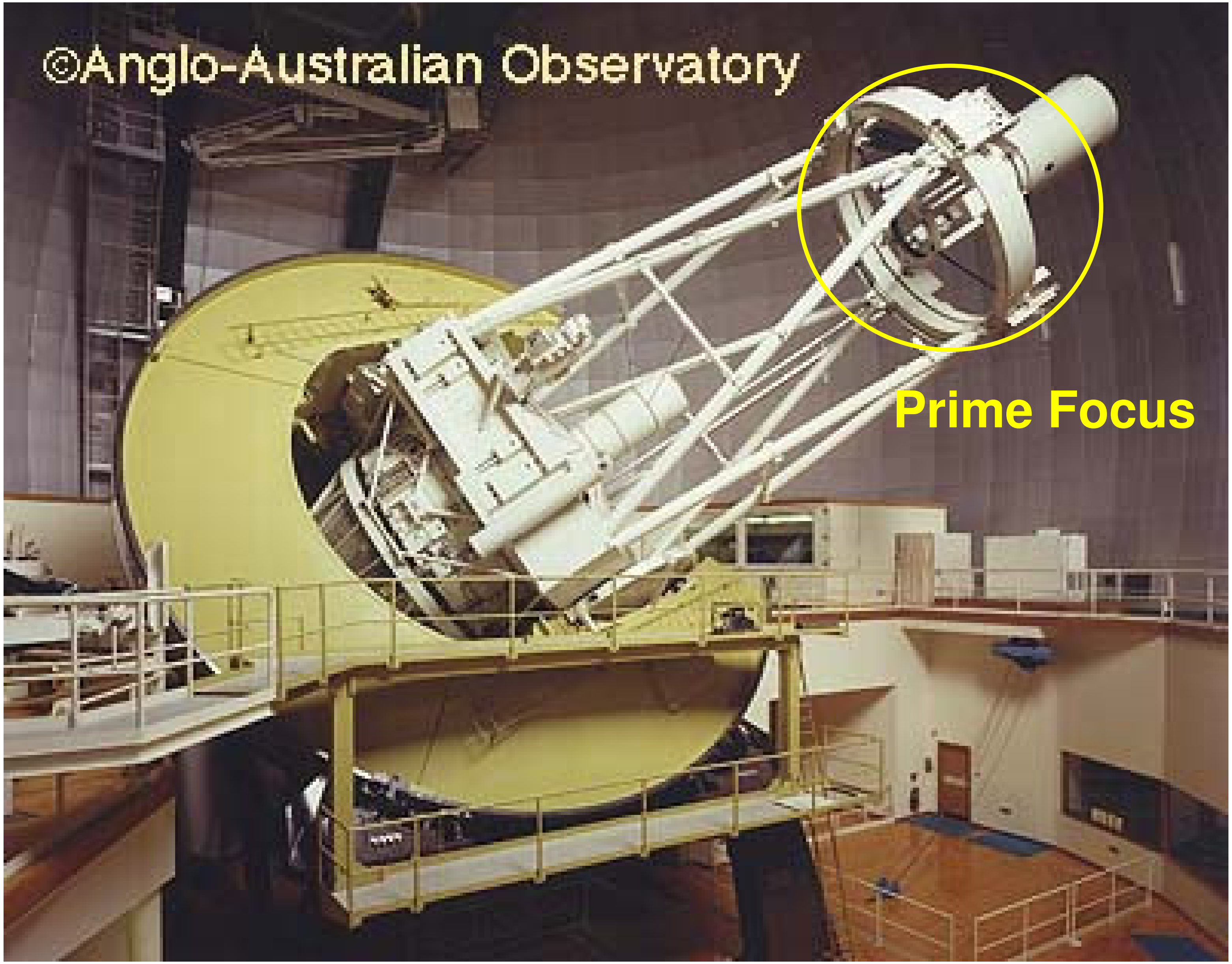


Redshift surveys

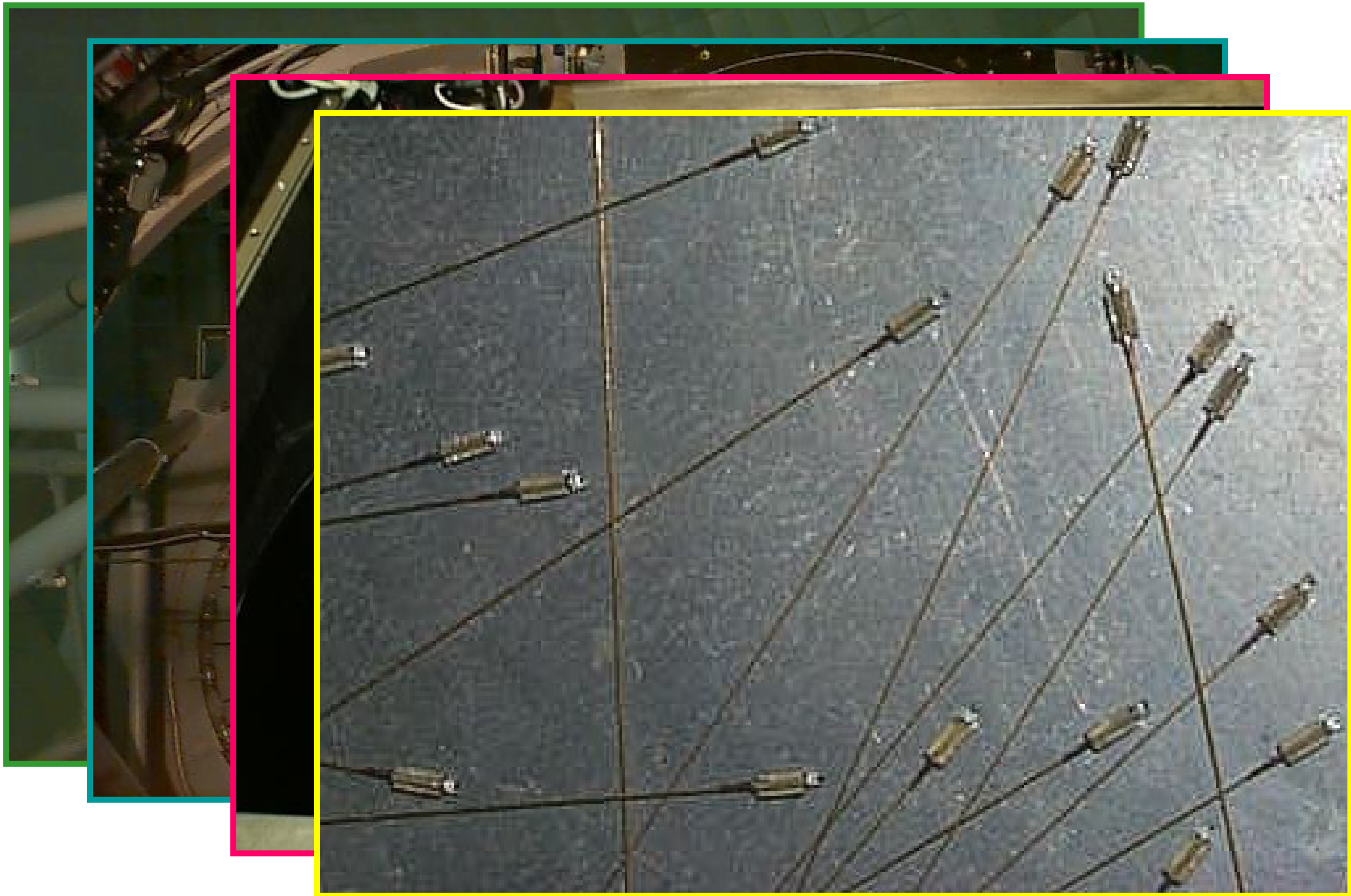
Inverting
$v = cz = H_0 d$
gives an approximate distance.

Applied to galaxies on a strip on the sky, gives a 'slice of the universe'

The 2 degree field instrument

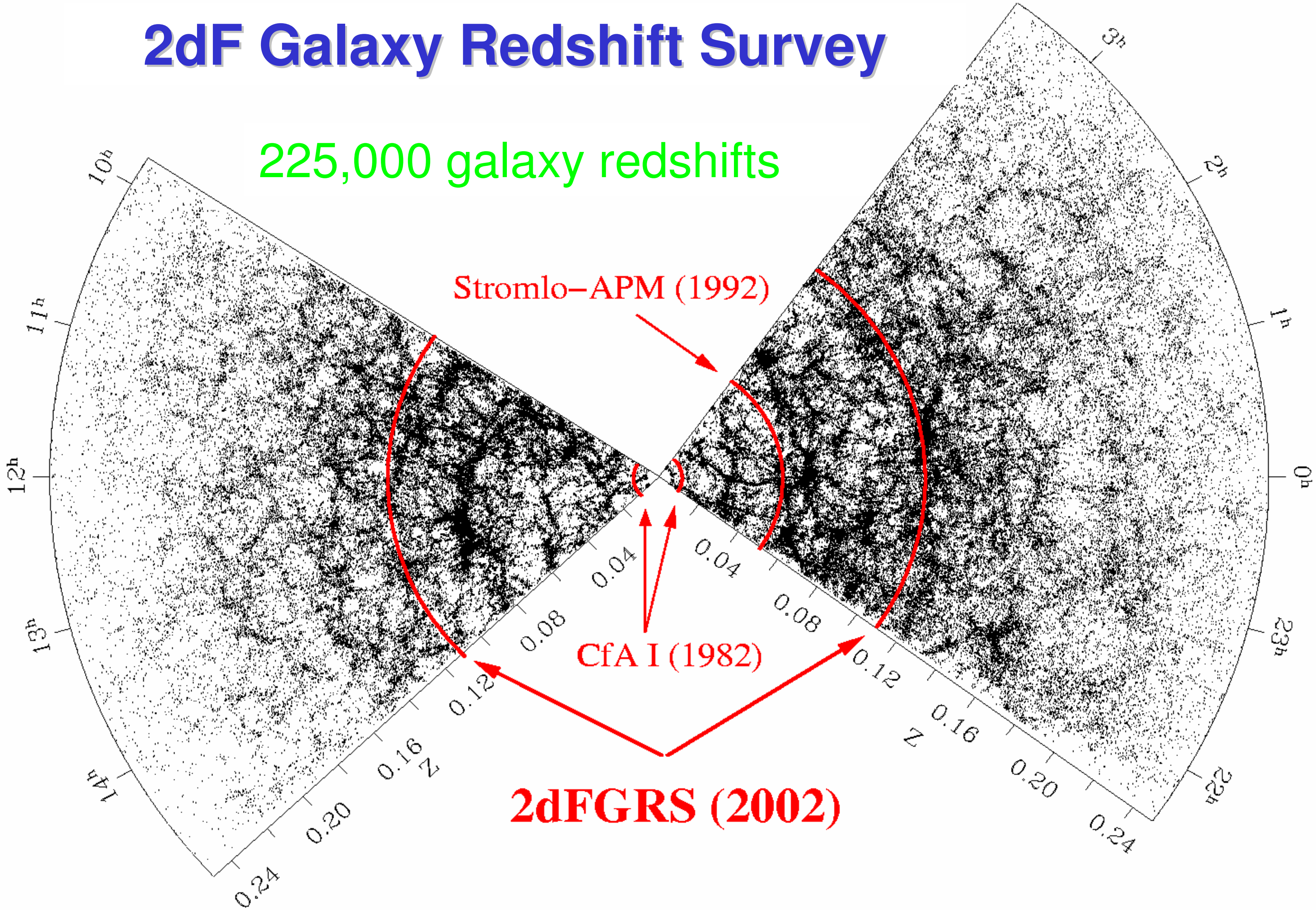


2dF on the AAT

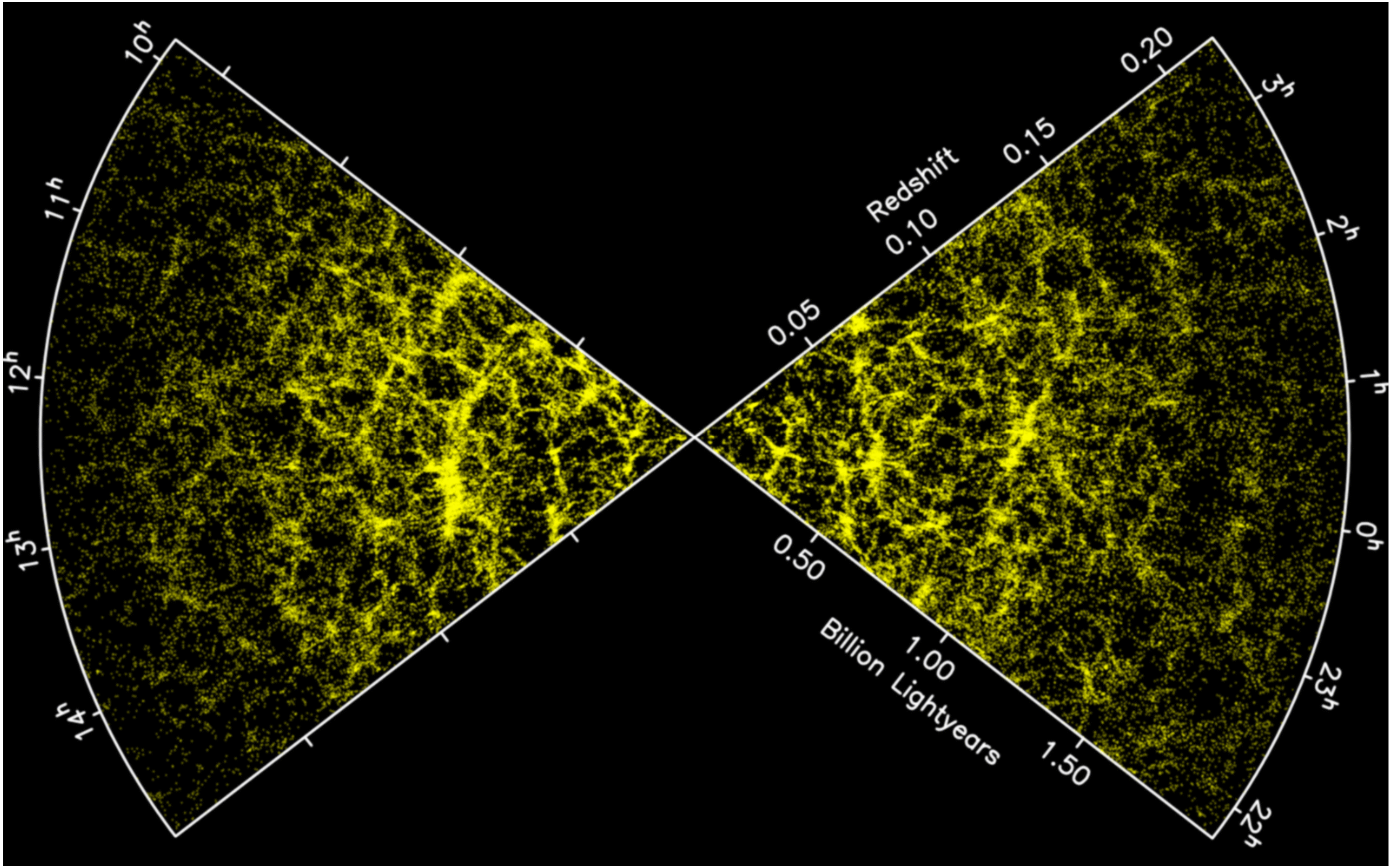


2dF Galaxy Redshift Survey

225,000 galaxy redshifts



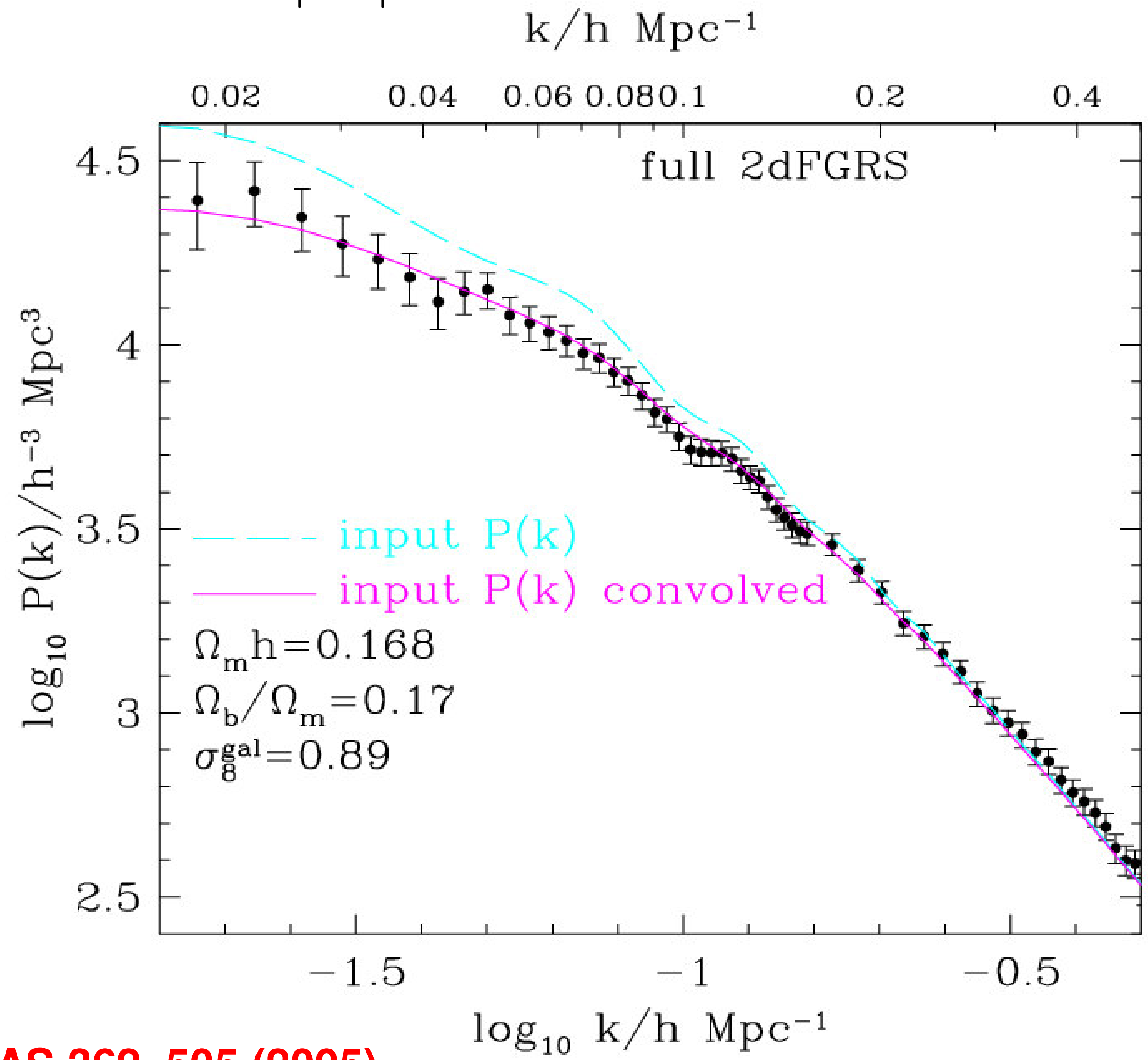
2dFGRS Galaxy Redshift Survey



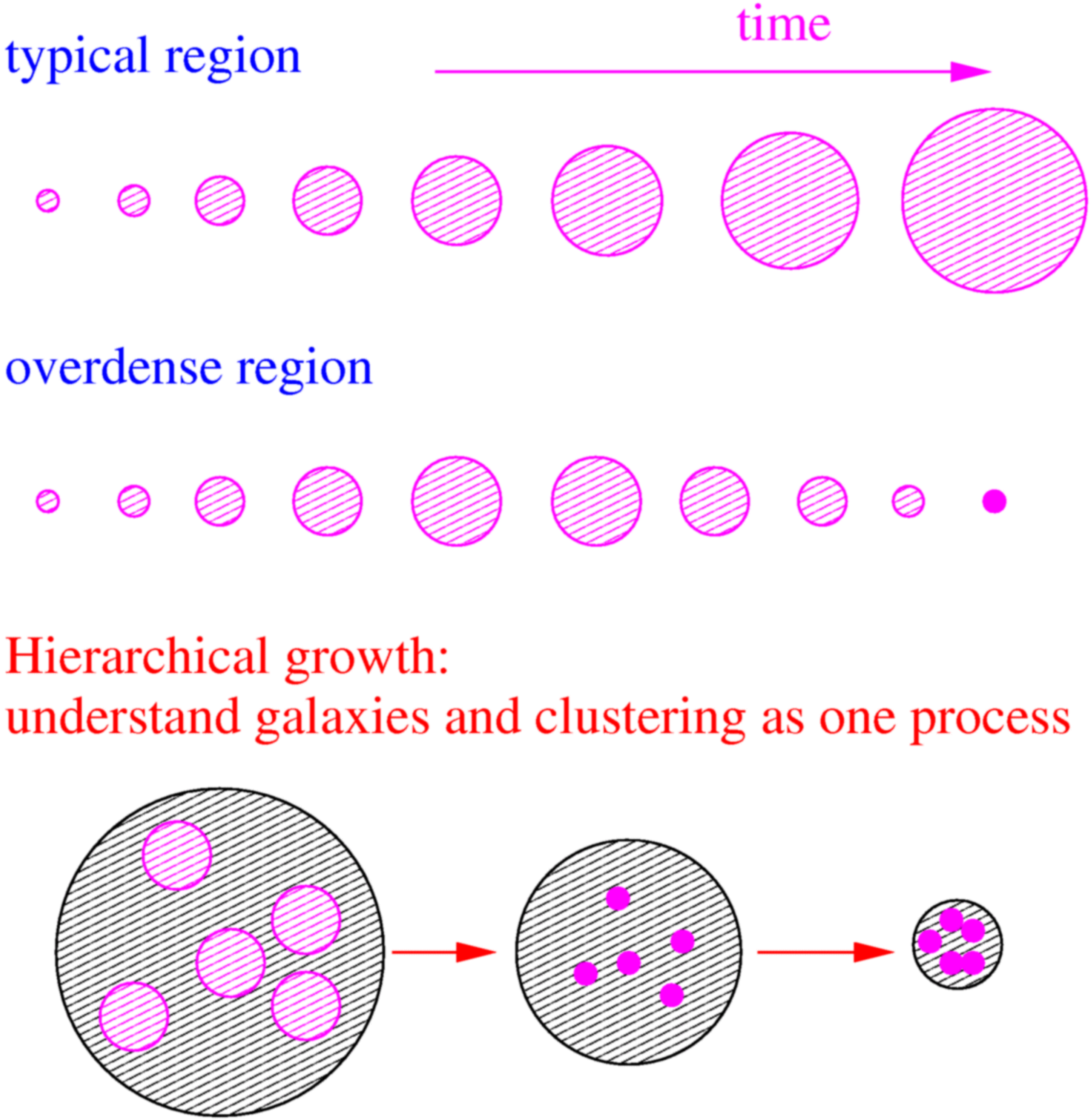
2dFGRS Power Spectrum

$$P(k) = \langle \left| \delta_k^{\ 2} \right| \rangle = \int \xi(r) \exp(ik.r) d^3 r$$

Power spectrum of local galaxy distribution can be reconciled with models of LSS that fit CMB angular fluctuations



Cole et al MNRAS 362, 505 (2005)



Gravitational instability:

hierarchical collapse generates ever larger structures

Key Result #4: Dark Matter

Cluster dynamics (Zwicky 1930's):
stability requires high mass/light ratio
via virial theorem

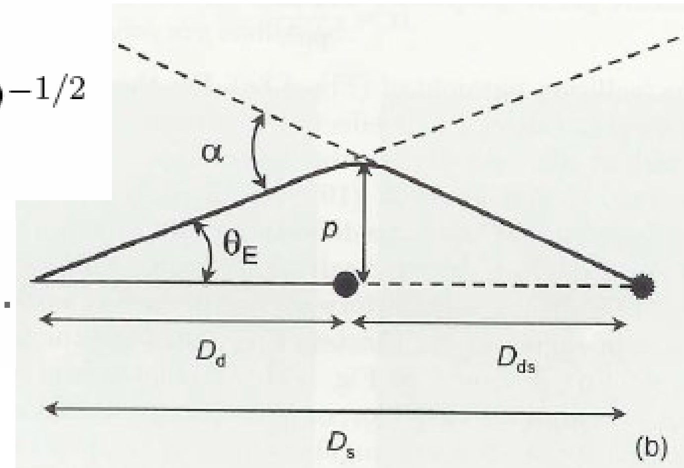
$$2T - U = 0$$

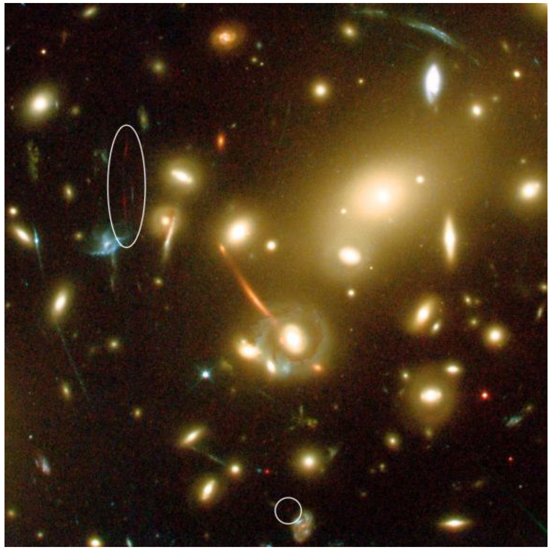
$$M = 3 < v_{los}^2 > \frac{R_{cl}}{G}$$

Gravitational lensing provides a clearer
geometric measure of mass:

$$\theta_E = (\frac{4GM}{c^2})^{1/2} D^{-1/2}$$

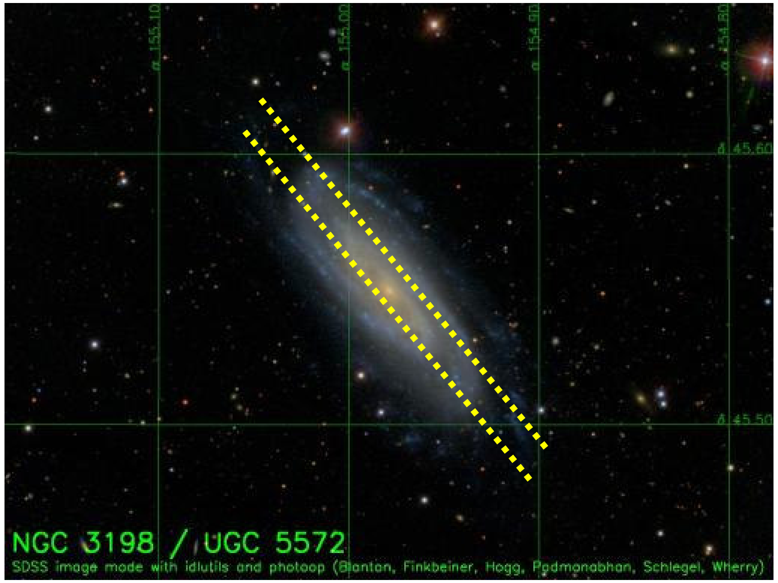
$$D = D_s \, D_d \, / \, D_{ds}.$$

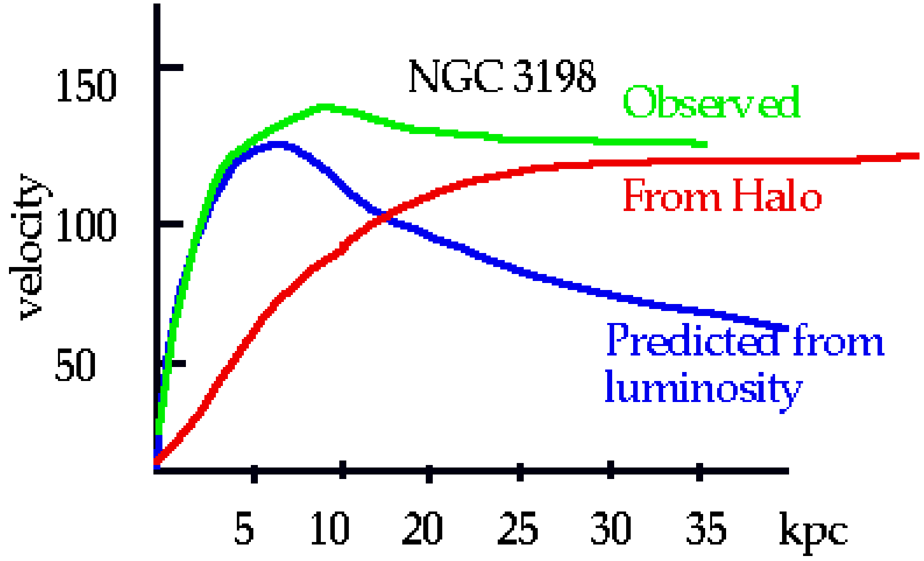




in several cases ***both methods*** can be applied and agree.

Dark Matter on Galactic Scales: Spirals





Circular orbits implies:

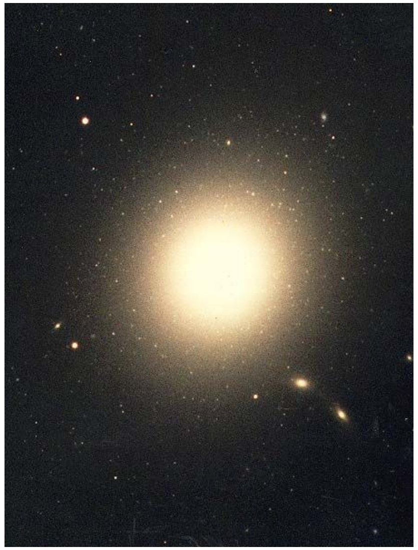
$$\frac{GM(<R)}{R^2} = \frac{V^2}{R}$$

Flat rotation curve, V~const, implies M(<R)∝ R

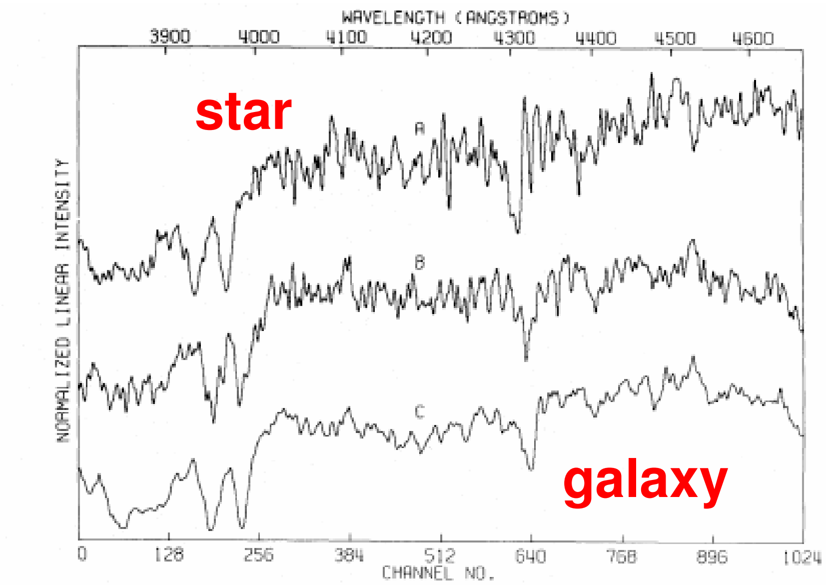
$$M \sim \frac{RV^2}{G}$$

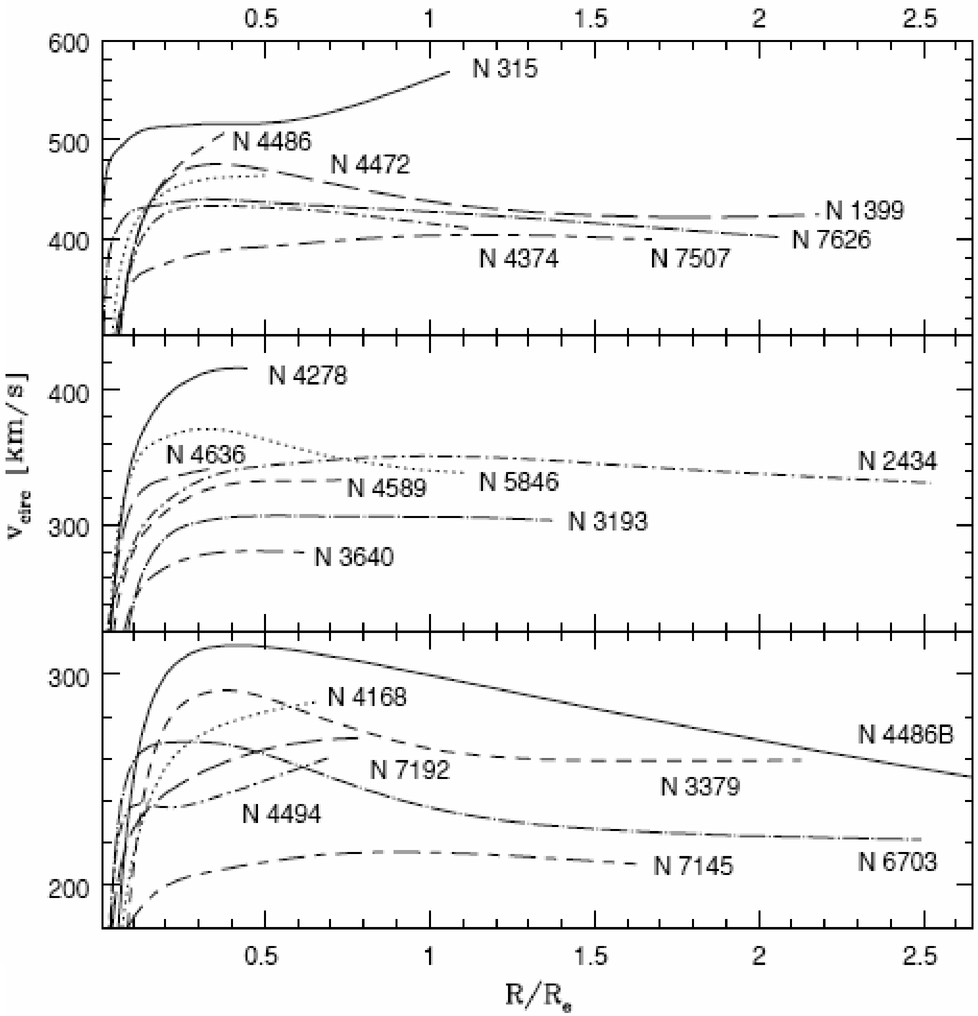
Spiral galaxy is embedded in dark, extensive halo

Dark Matter on Galactic Scales: Ellipticals

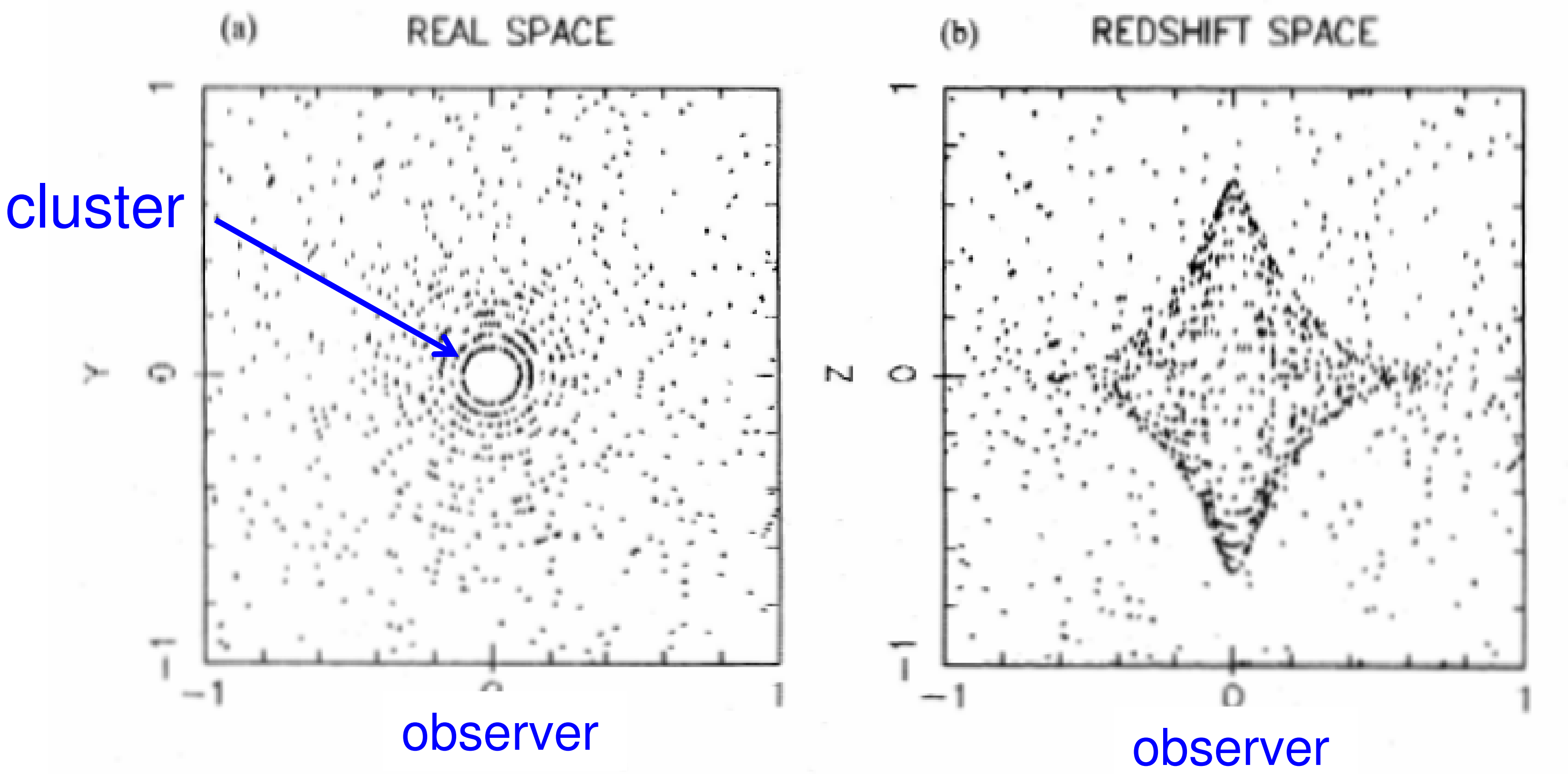


Stellar velocity dispersion σ determined from broadening of absorption lines and `converted' into an equivalent `rotation' curve (Gerhard et al 2001)



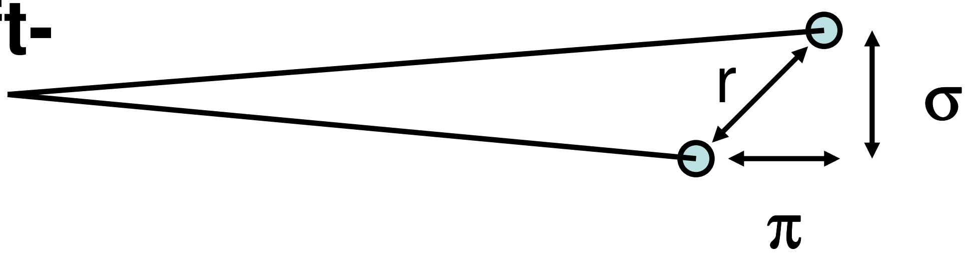


Galaxy distribution is distorted in redshift space

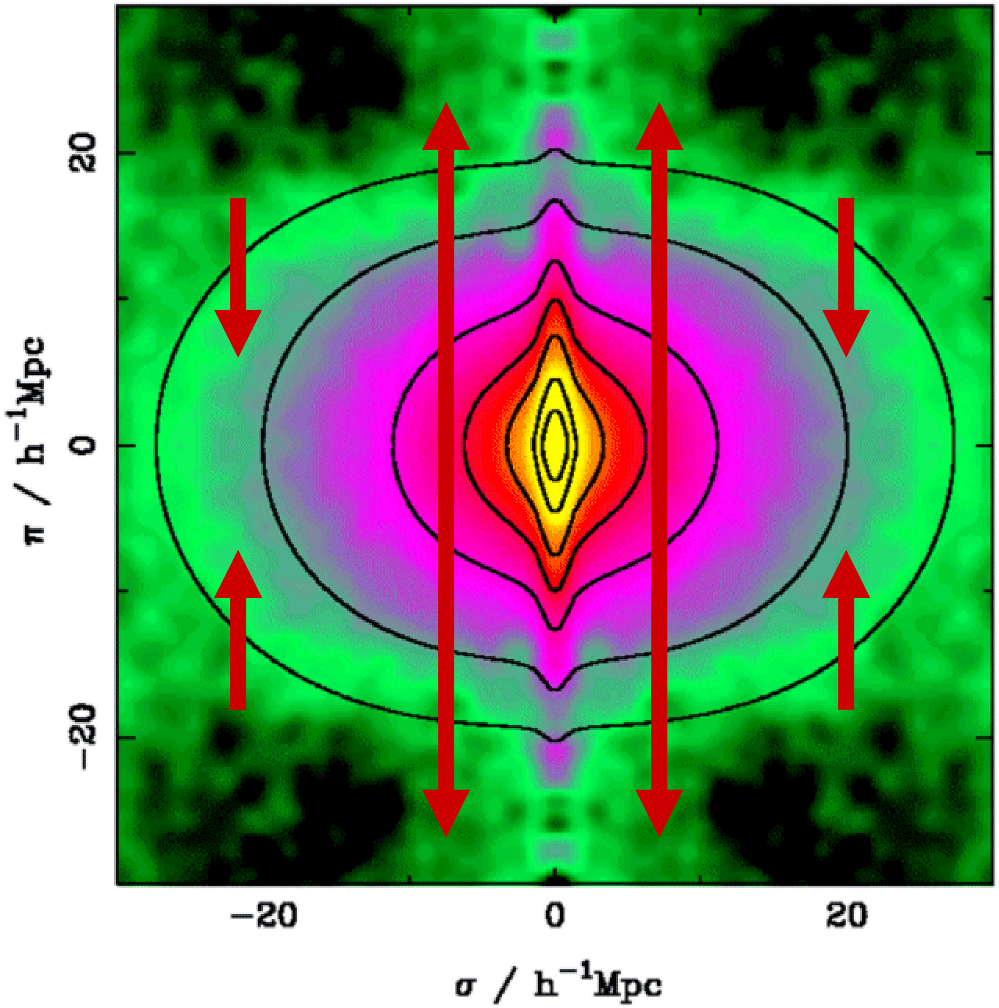


Kaiser (1987 MNRAS 227, 1) showed that peculiar velocities distort the distribution of galaxies in redshift space; this can provide a measure of the mass density of dark matter associated with galaxies on larger scales

Dark matter via redshift-space clustering



- Distortions due to peculiar velocities arising from mass probed by $\xi(\sigma,\pi)$.
- Two effects:
  - Small separations on sky: 'Finger-of God'
  - Large separations on sky: flattening along line of sight

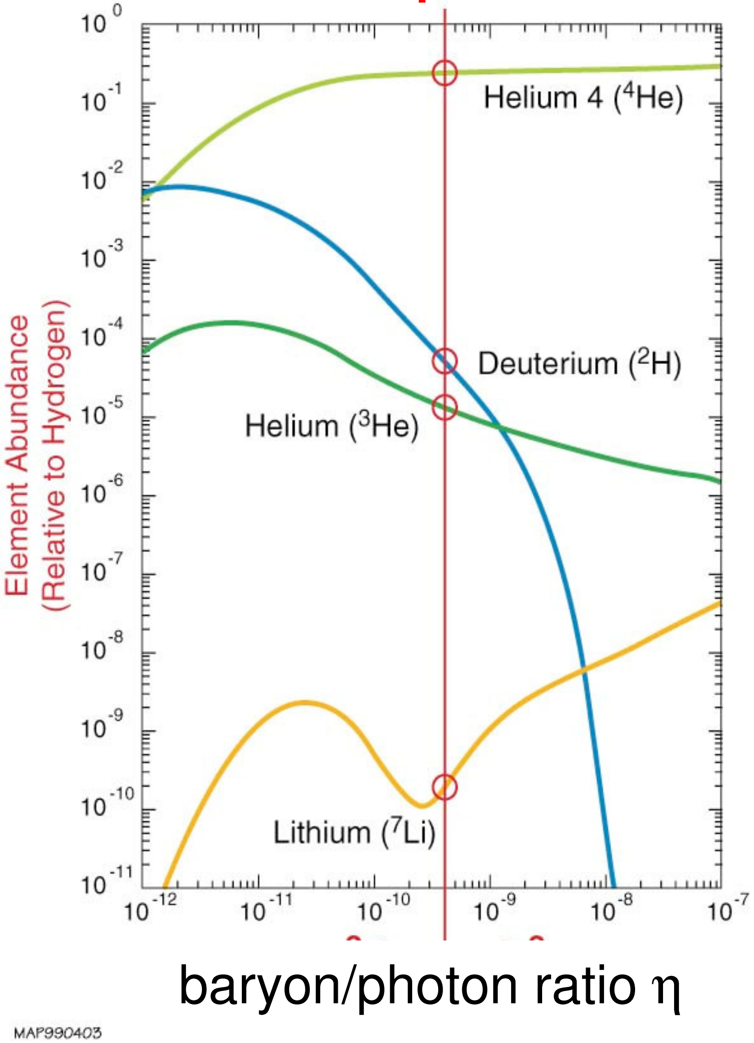


$$\sigma_p = 385 \pm 50 \ km/s$$
$$\Omega^{0.6}/b = 0.43 \pm 0.07$$

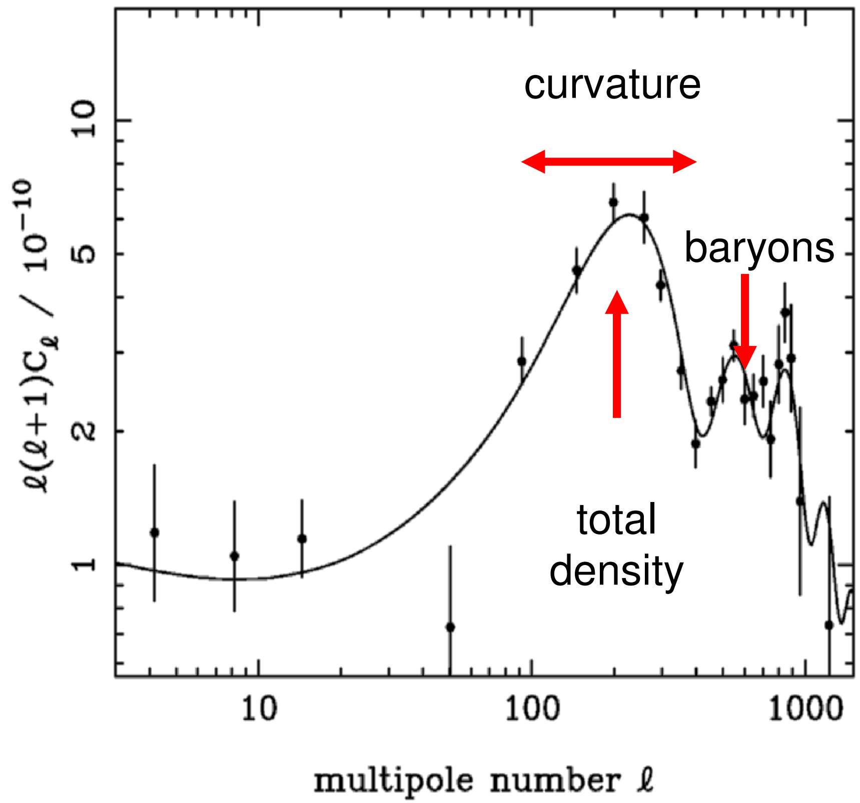
where ***b*** accounts for a possible ***bias*** between galaxy & DM distribution

Non-baryonic Dark Matter

Primordial isotope abundances



CMB Fluctuations (WMAP)



$$\Omega_b h^2 = 0.0237^{+0.0013}_{-0.0012}$$

$$\eta = (6.5^{+0.4}_{-0.3}) \times 10^{-10}.$$

Burles et al Ap J 552, L1 (2001)

Spergel et al Ap J S 148, 175 (2003)

Cosmic Expansion History

Prior to 1980 cosmologists attempted to measure two quantities:

- Hubble's constant: $H_0 = dR/dt\,/R(t);\ \tau \sim 1/\,H_0$ → scale & age
- Deceleration parameter $q_0 = -d^2R/dt^2/\,(dR/dt)^2$ → fate of expansion

In the simplest Friedmann cosmologies containing gravitating matter:

$$\Omega_M = \rho_M\,/\,\rho_{crit} = 2q_0$$

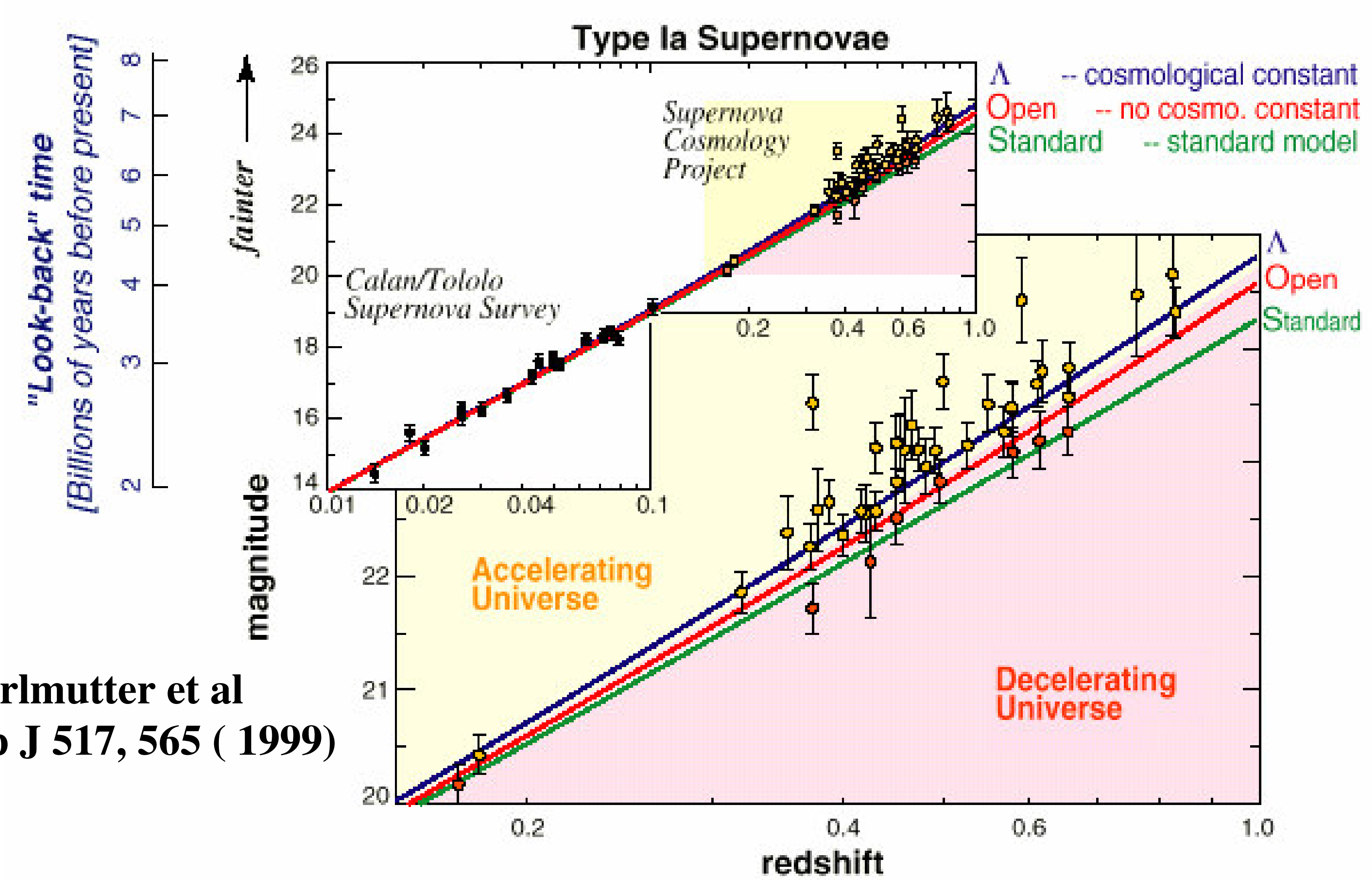
Two ways to determine the fate of expansion:

- Census of gravitating matter ρ_M (redshift surveys): $\Omega_M < 0.3$
- Distance-redshift relation over significant look-back times

$$d_L(z,q_0) = cz/H_0q_0^2\ [\ zq_0 + (q_0-1)\{(2q_0z+1)^{1/2}-1\}$$

Inflation (horizon and flatness) suggested $\Omega_M = 2q_0 = 1$

Key Result #5: Cosmic acceleration



Perlmutter et al
Ap J 517, 565 (1999)

In generalized Friedmann models $q_0 = \Omega_M/2 - 3\Omega_\Lambda/2$
Negative q_0 is acceleration and implies $\Lambda \neq 0$

"Concordance Cosmology"

"Precision Cosmology?"

- $\Omega_{DM} \approx 0.24 \pm 0.03$ (dark matter)
- $\Omega_B \approx 0.042 \pm 0.004$ (baryons)
- $\Omega_\Lambda \approx 0.73 \pm 0.04$ (dark energy)

(Bennett et al 2003, Spergel et al 2006)

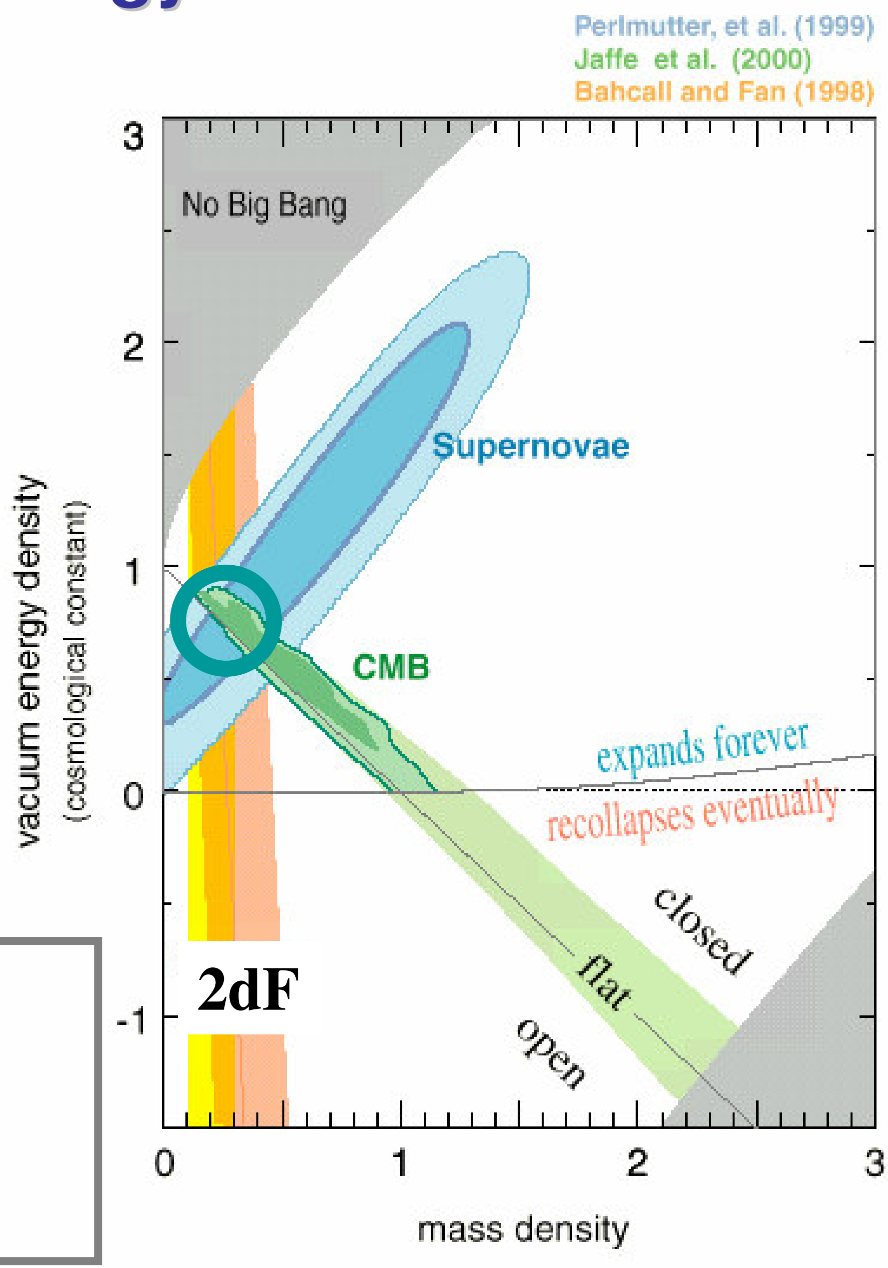
All 3 ingredients comparable in magnitude but only one component physically understood!

Dark Energy equation of state:

$$p / \rho = w = -0.97 \pm 0.08$$

$w = -1$ corresponds to Einstein Λ

$w < -1/3$ required for acceleration

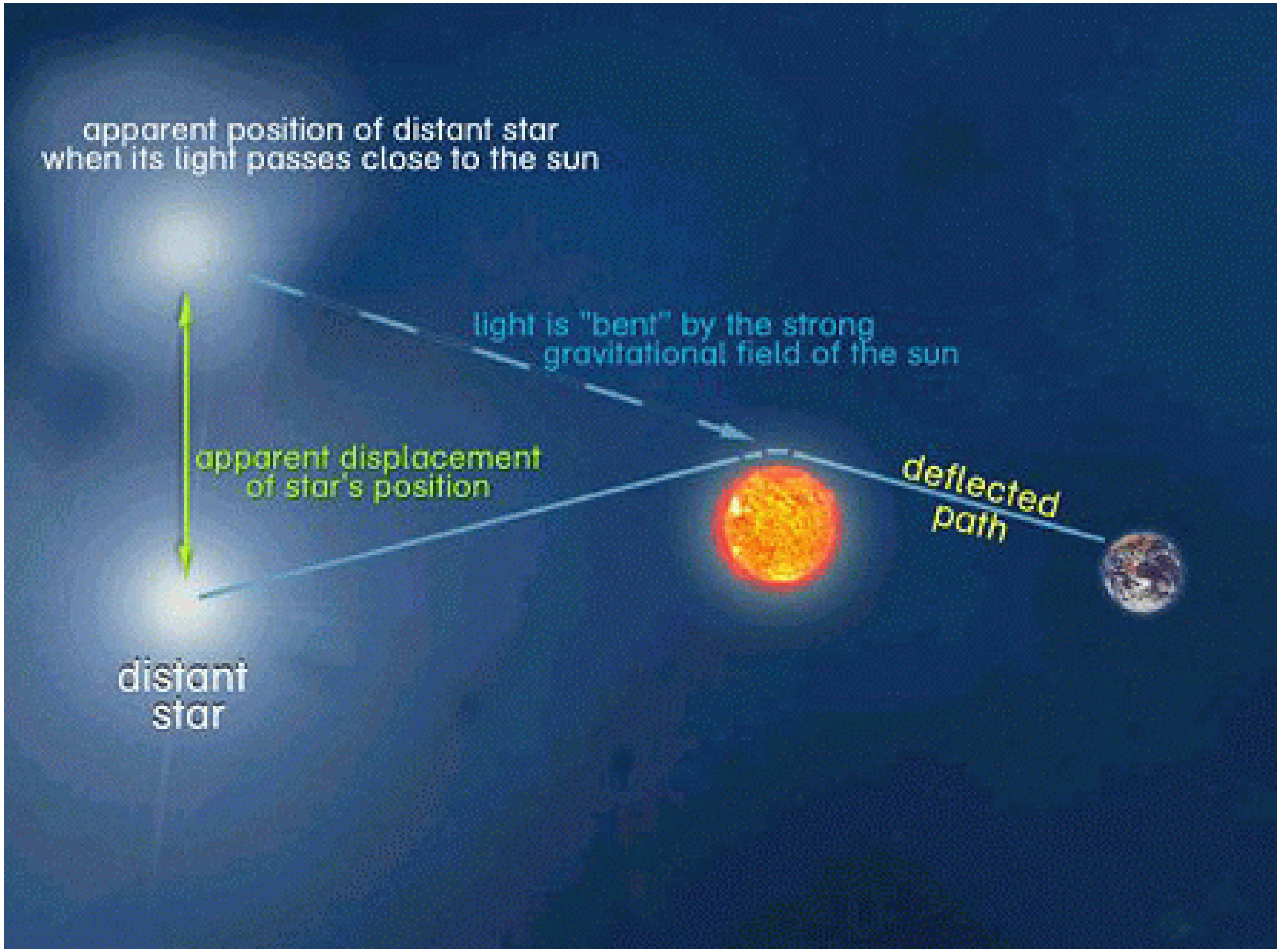


Observing the Distribution of Dark Matter

Gravitational Lensing:

- Rapidly developing area with ground and space-based telescopes
- Enables mapping of the distribution of matter in the foreground `lens' regardless of whether that mass is radiating.
- Aim here to illustrate a few examples

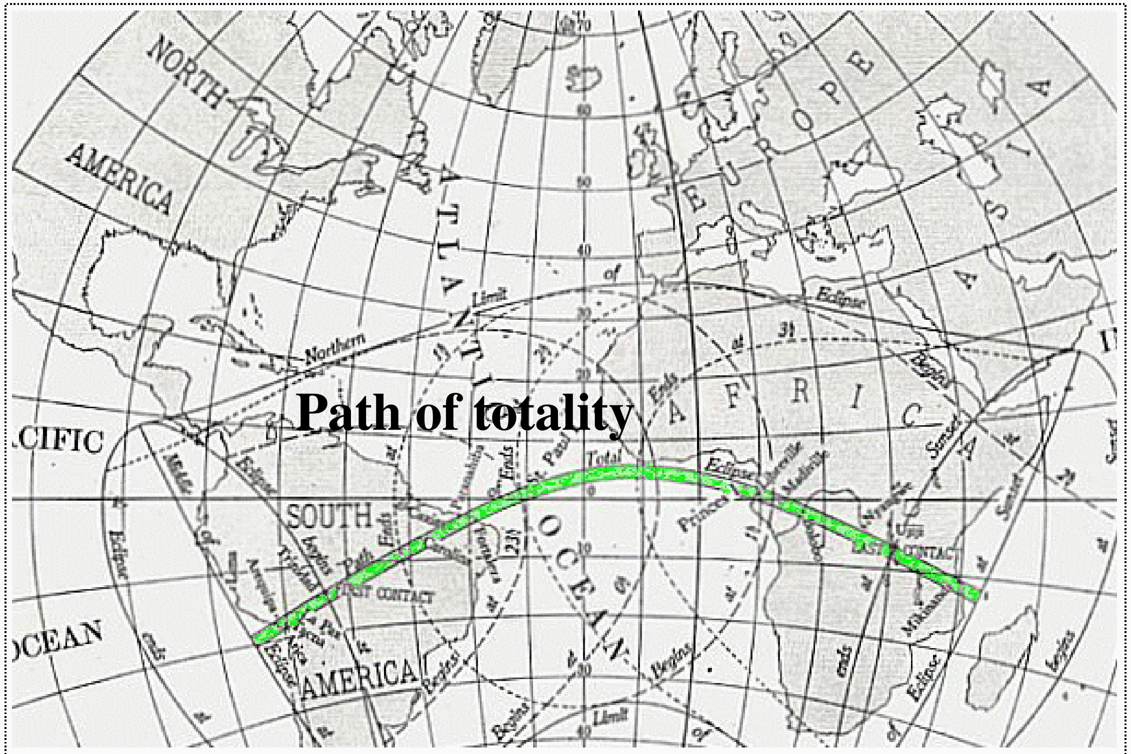
Verifying Einstein's prediction: deflection of starlight by Sun



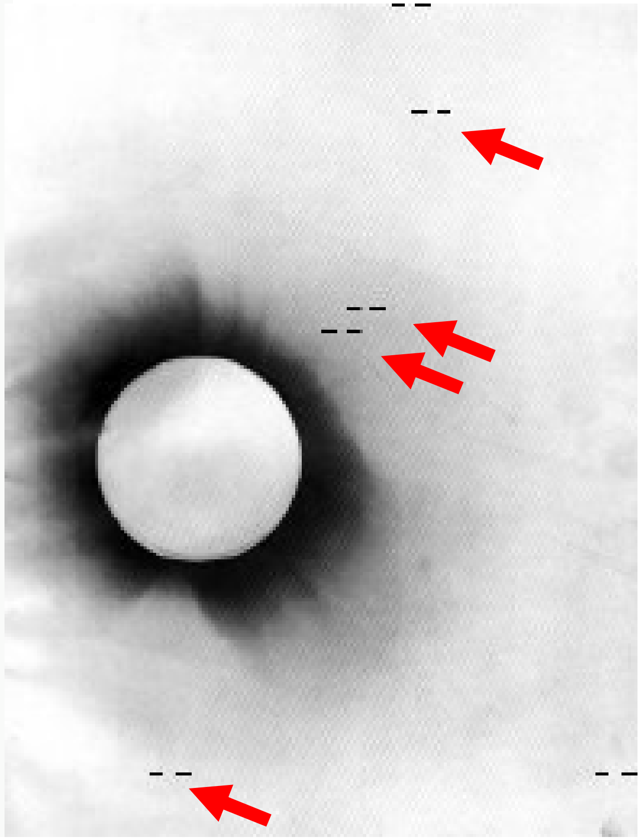
The predicted deflection at the limb is only $4GM/Rc^2$ = 1.7 seconds of arc

The Solar Eclipse of 1919

British expeditions: to Sobral, Brazil and Principe, W Africa



The path of the 1919 eclipse.



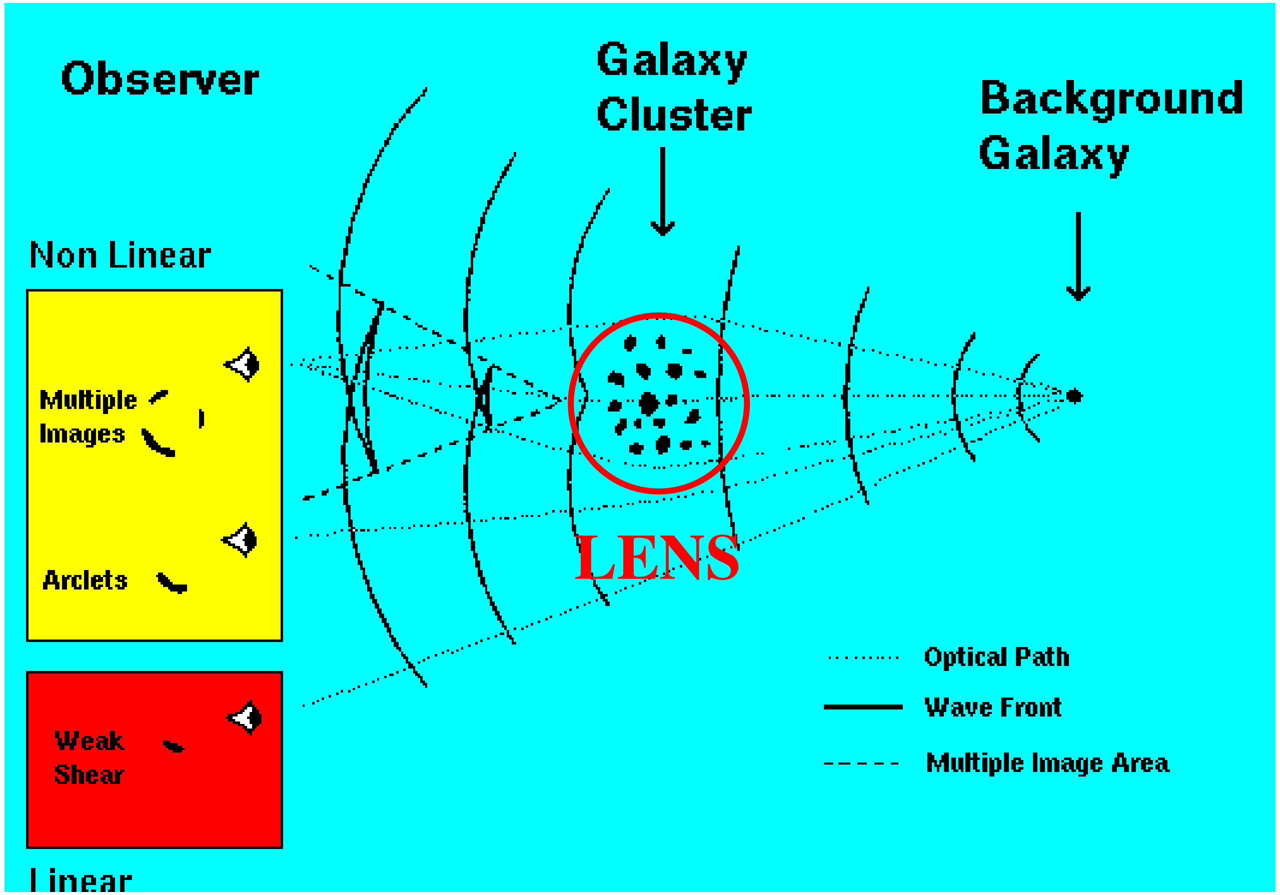
The observed positions of stars in the Hyades cluster are carefully compared with those taken earlier in the year when the sun is not in the light path to test theory

Gravitational lensing: three regimes

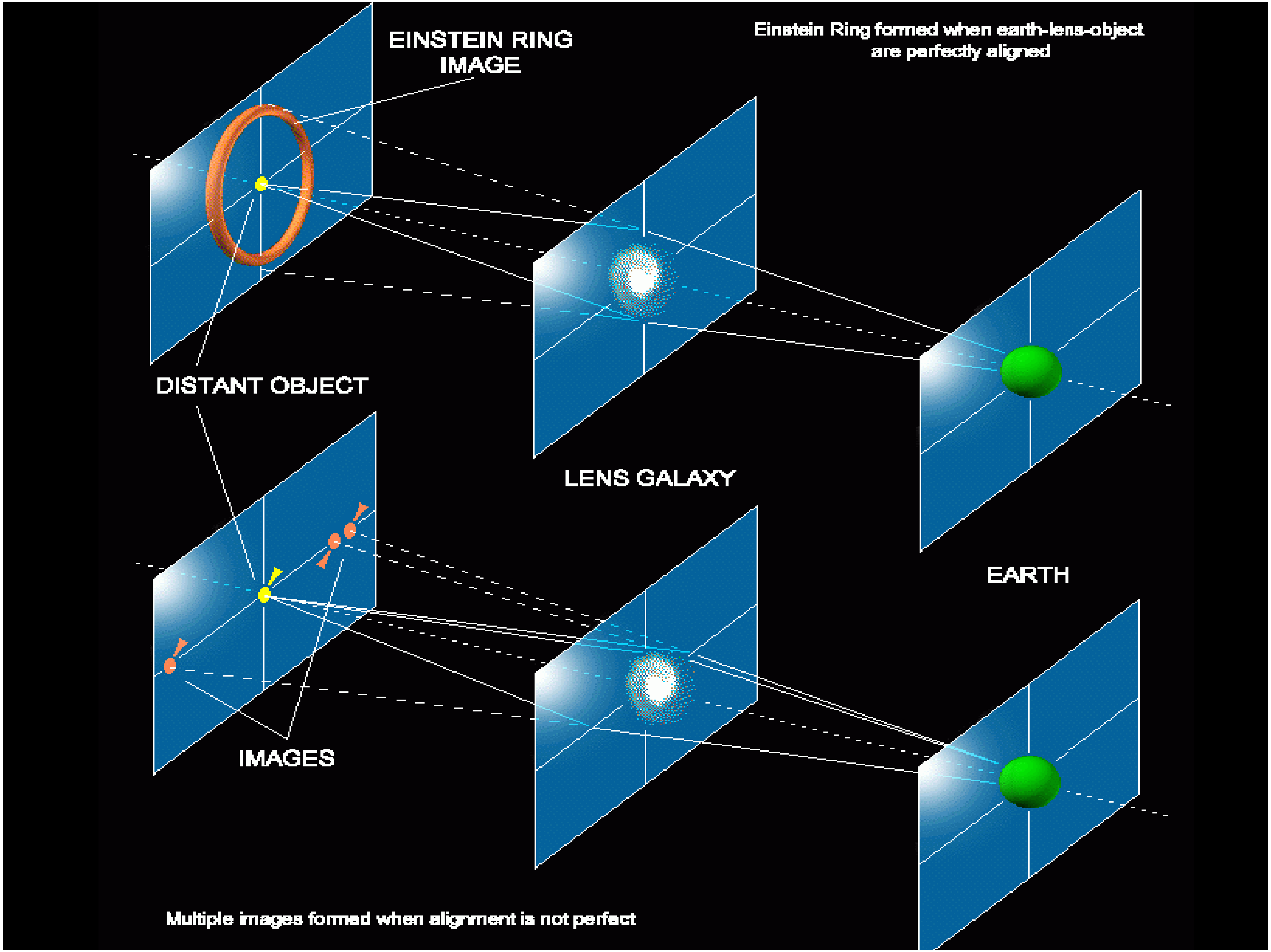
• rings & arcs

•arclets

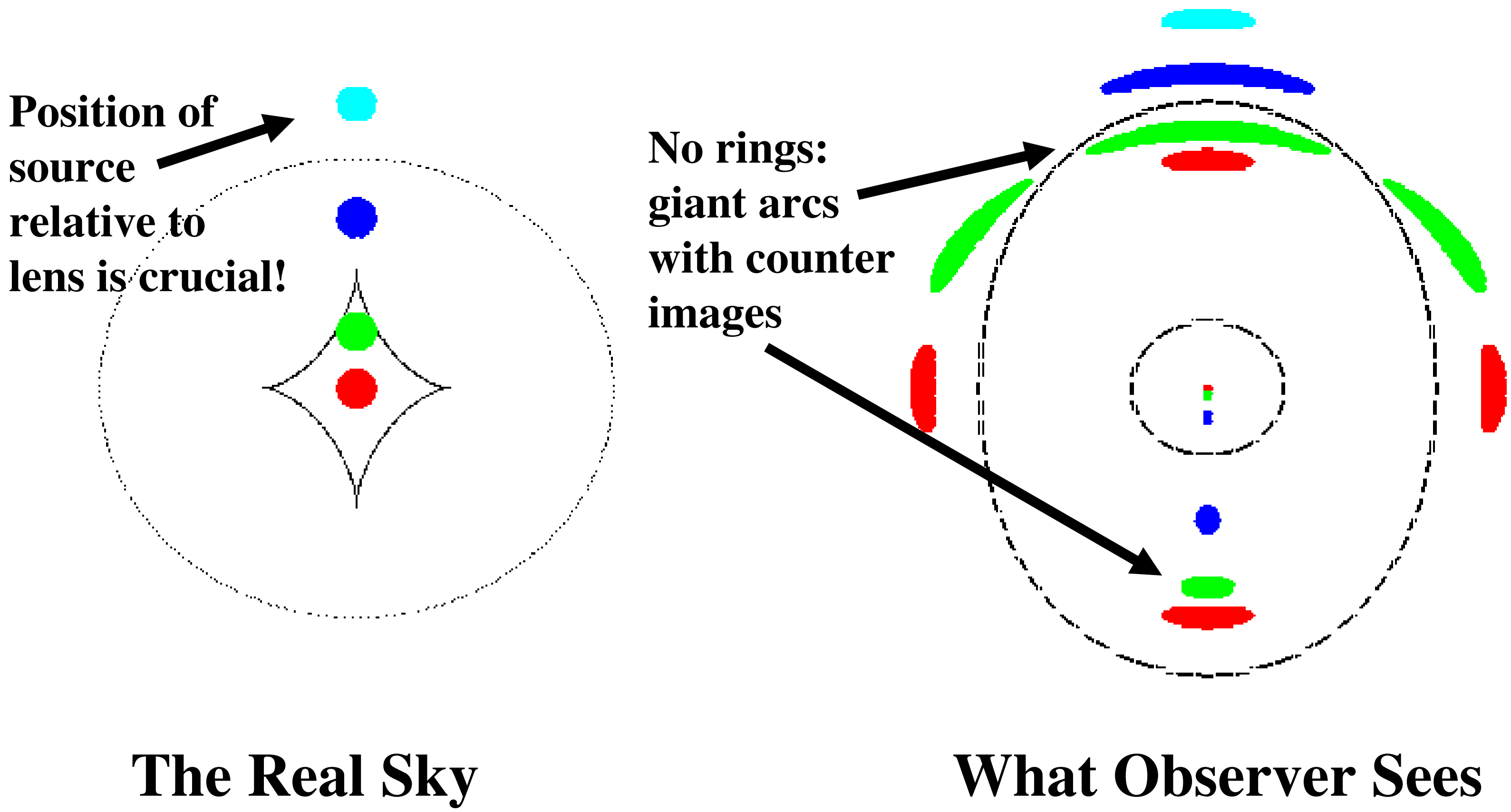
• weak distortion



The image, viewed through the lens, depends on the focusing power of the lens (its mass), the relative distances of lens & source and the degree of alignment

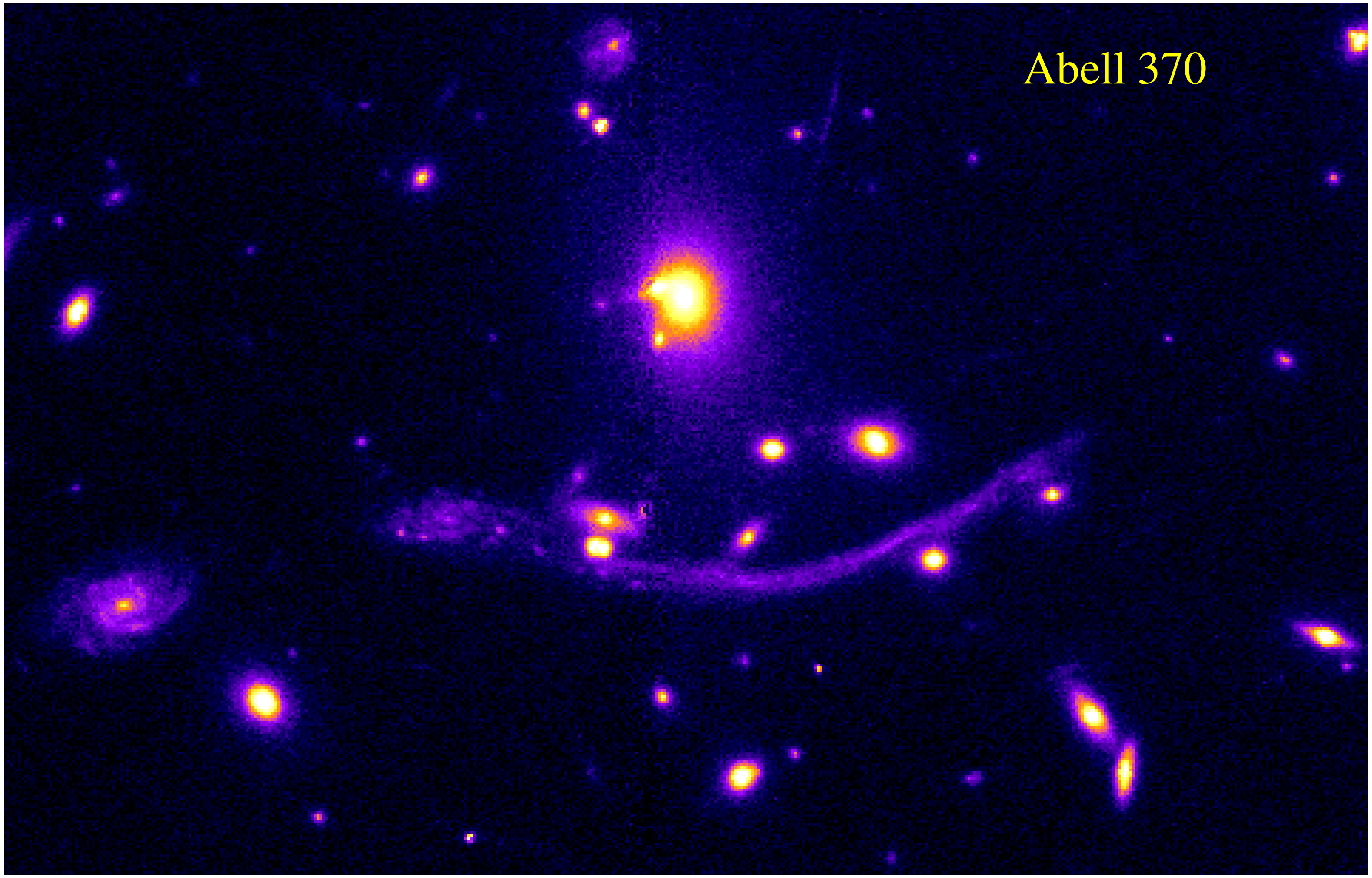

EINSTEIN RING IMAGE
Einstein Ring formed when earth-lens-object are perfectly aligned
DISTANT OBJECT
LENS GALAXY
EARTH
IMAGES
Multiple images formed when alignment is not perfect

More Complicated Strong Lenses

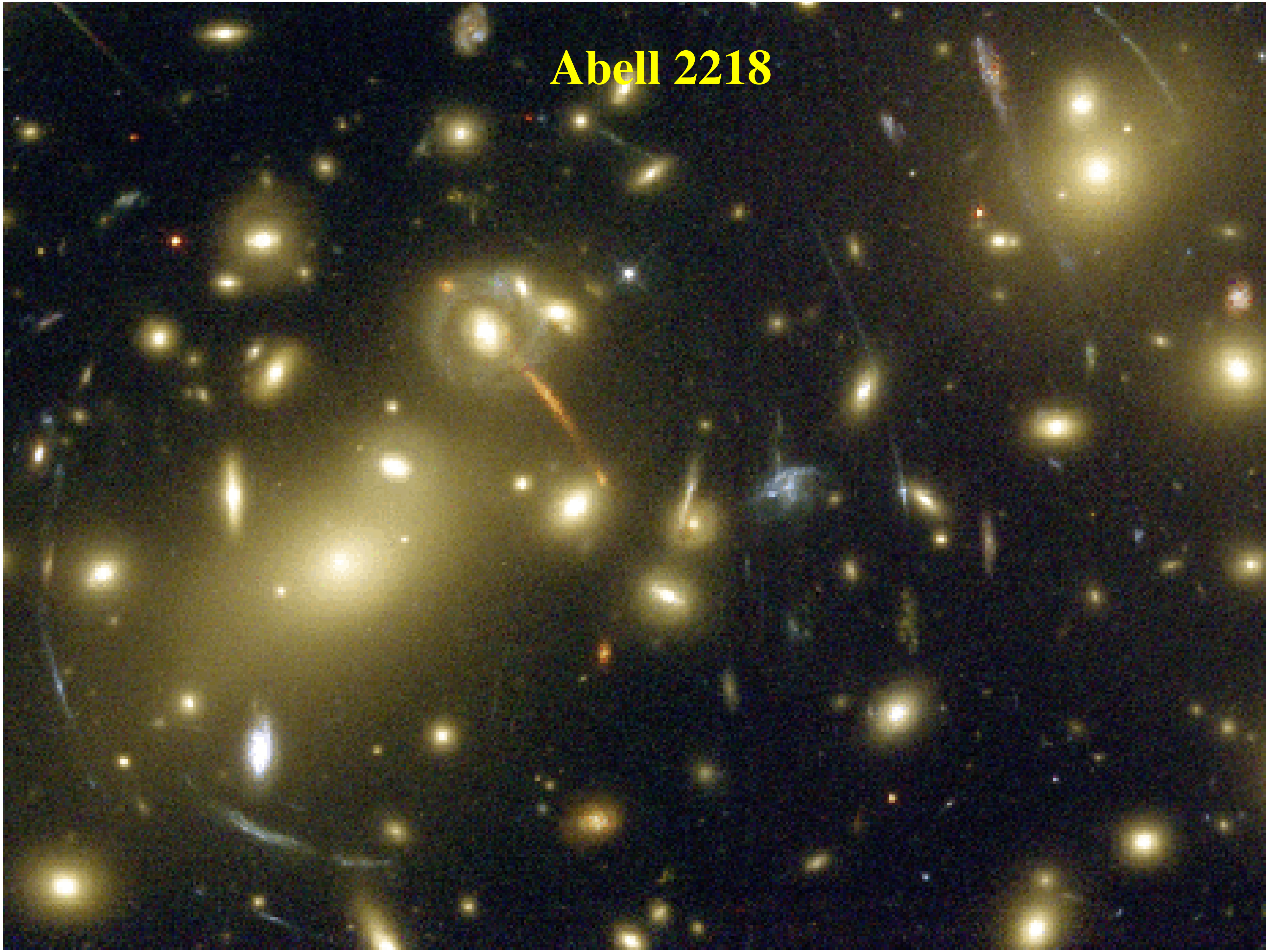


In case of elliptical lens, no ring is produced, but as background source moves closer in alignment, multiple images, some highly magnified appear – these are known as “giant arcs”

The First Giant Arc



In 1987 Genevieve Soucail at Observatoire de Midi Pyrenees (Toulouse) demonstrated the arc in the galaxy cluster Abell 370 represents light of a single background galaxy distorted by the foreground cluster lens

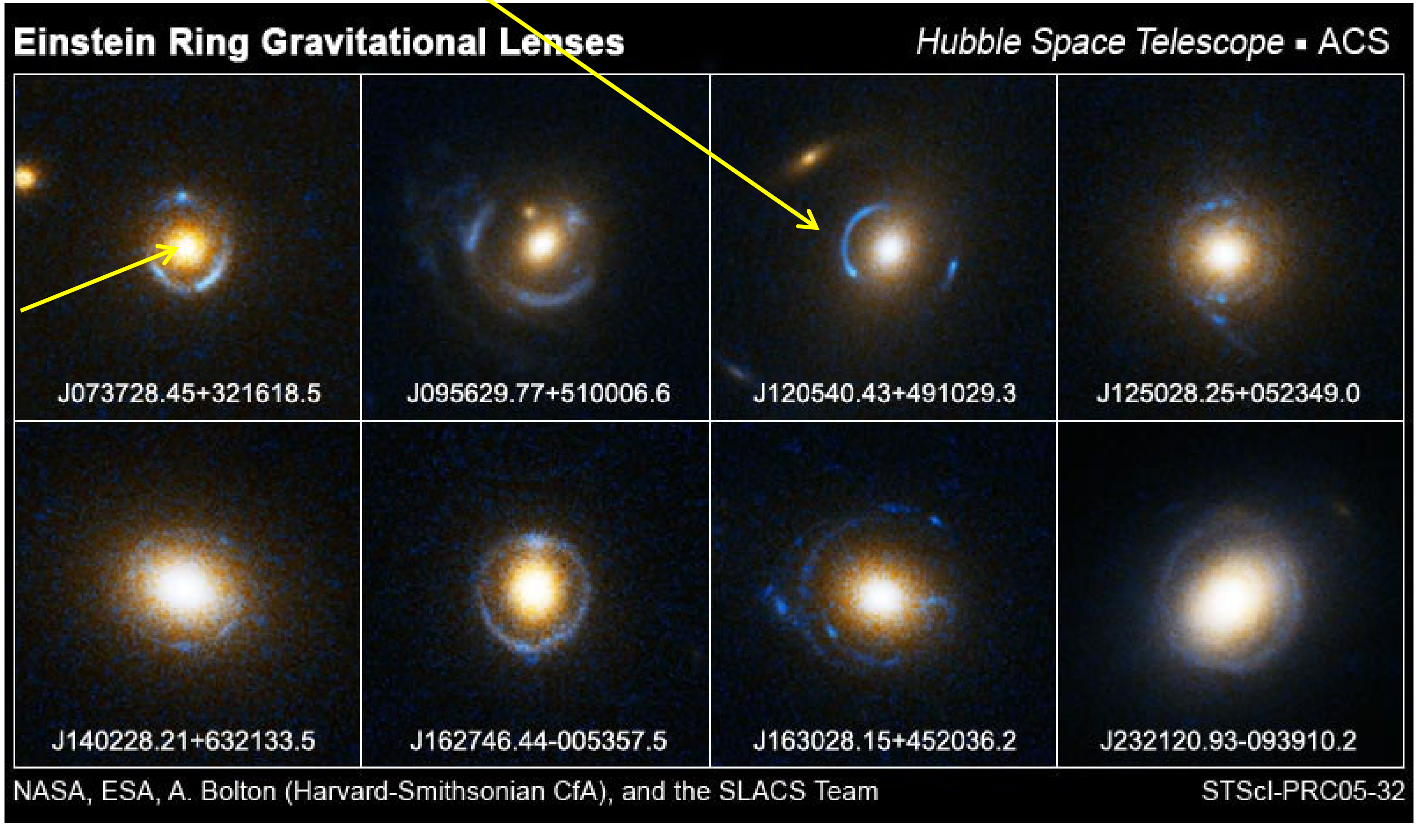

Abell 2218

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Einstein Rings Observed

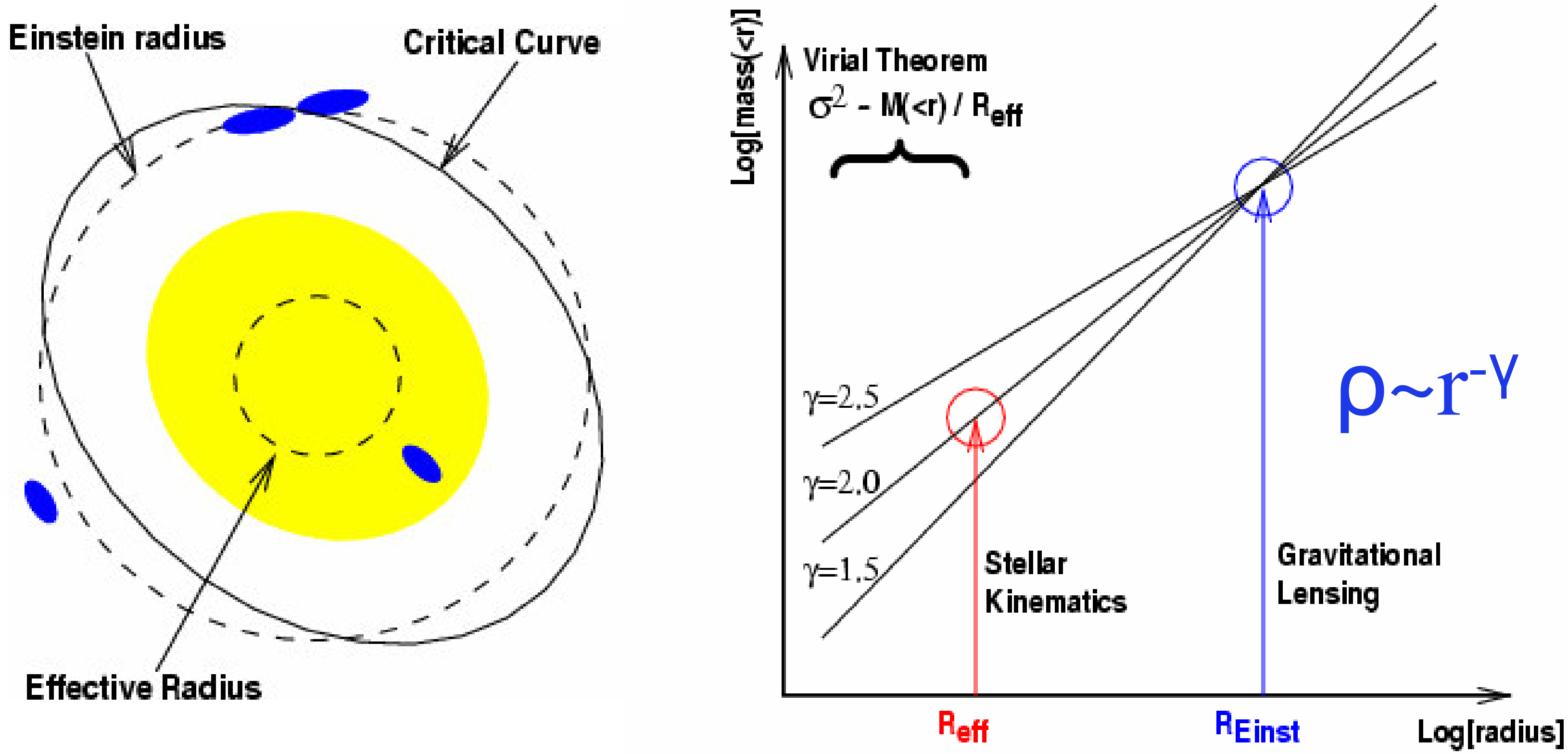
ring arising from single background source

lensing galaxy



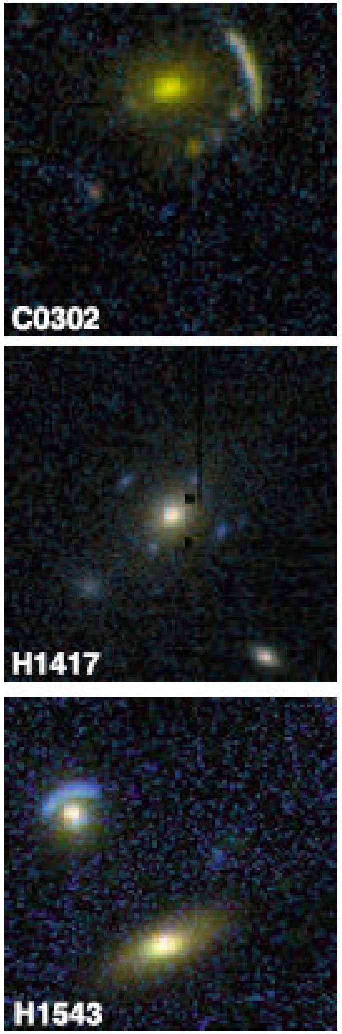
For a compact strong lens aligned with a background source, a ring of light is seen at a radius depending on the geometry and the lens mass, i.e. this allows us to measure the mass of the lens

Combining Lensing & Stellar Dynamics



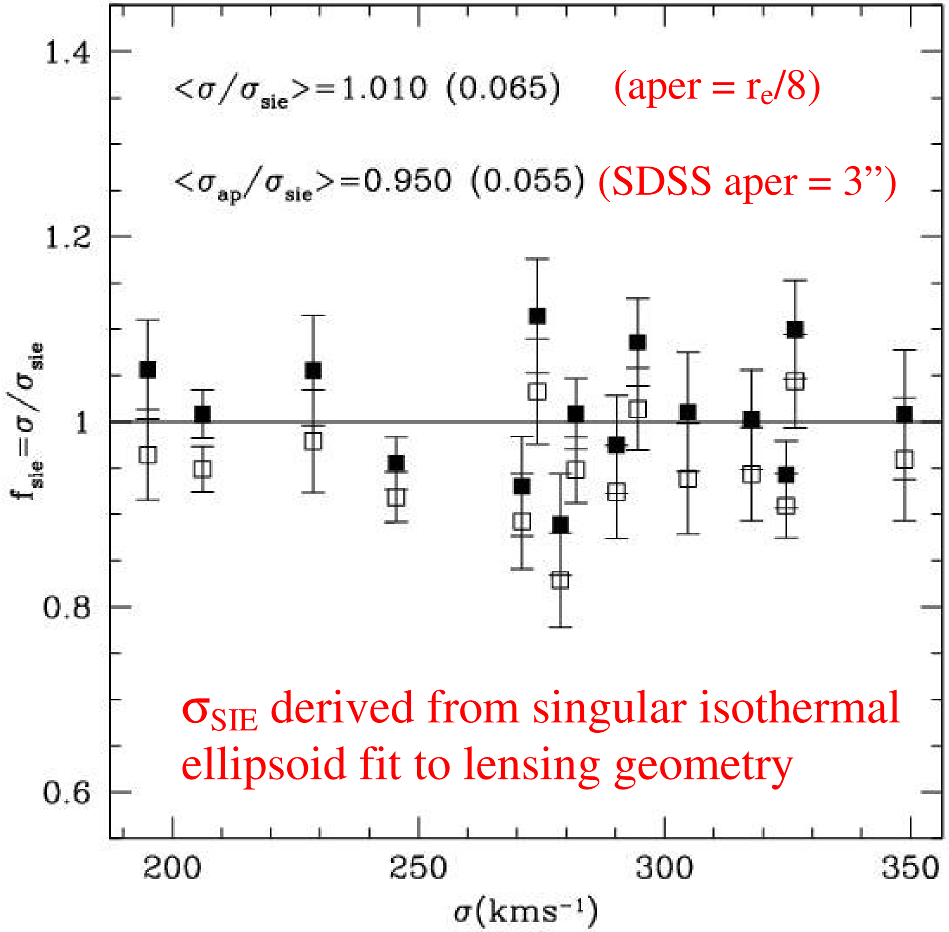
In elliptical galaxies, lensing and stellar dynamics provide constraints on the mass distribution on complementary scales. In combination, therefore, they constrain the outer slope, γ , of the total mass distribution (i.e. in the halo)

Lensing vs Dynamical Masses



Singular Isothermal Ellipsoid

$$\rho(r) = \frac{\sigma_{SIE}^2}{2\pi G}\frac{1}{r^2}$$

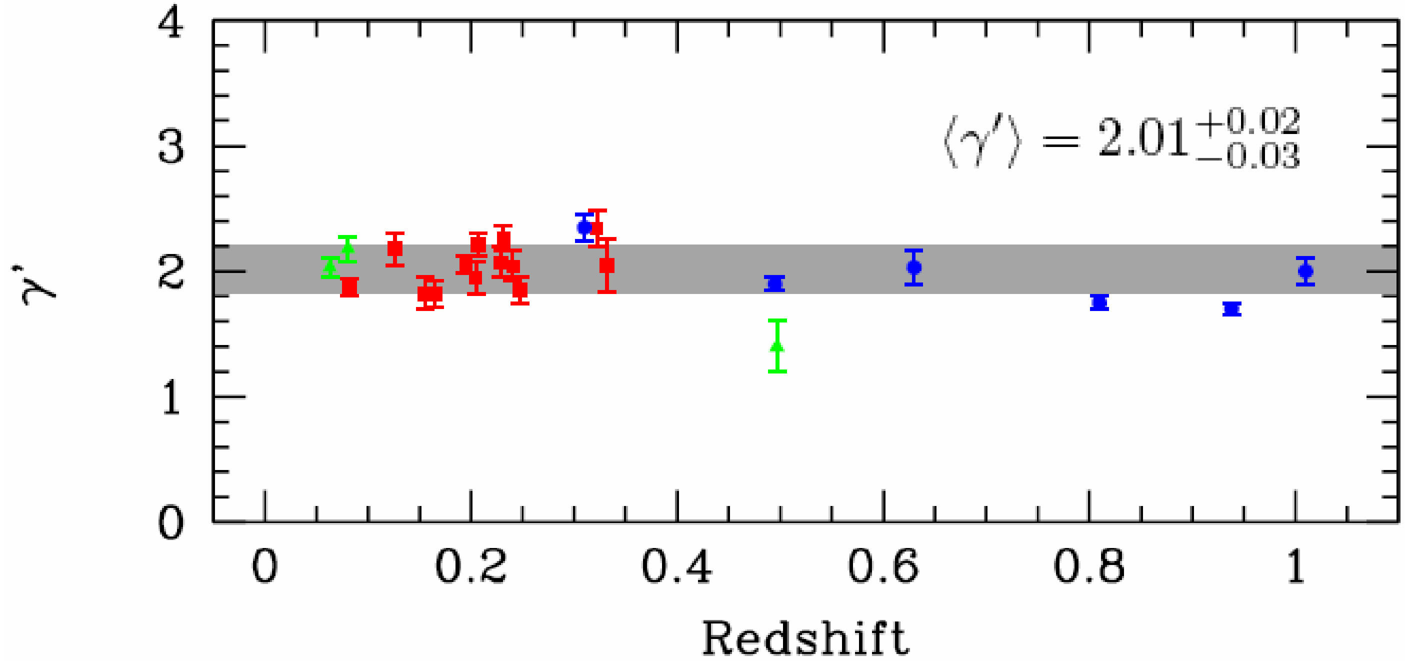


Koopmans & Treu Ap J 611, 739 (2004); Treu et al (astro-ph/0512044)

Total Mass Density Profile

$$\rho_{\rm tot}(r) = \rho_0 \, (r/r_0)^{-\gamma'}$$

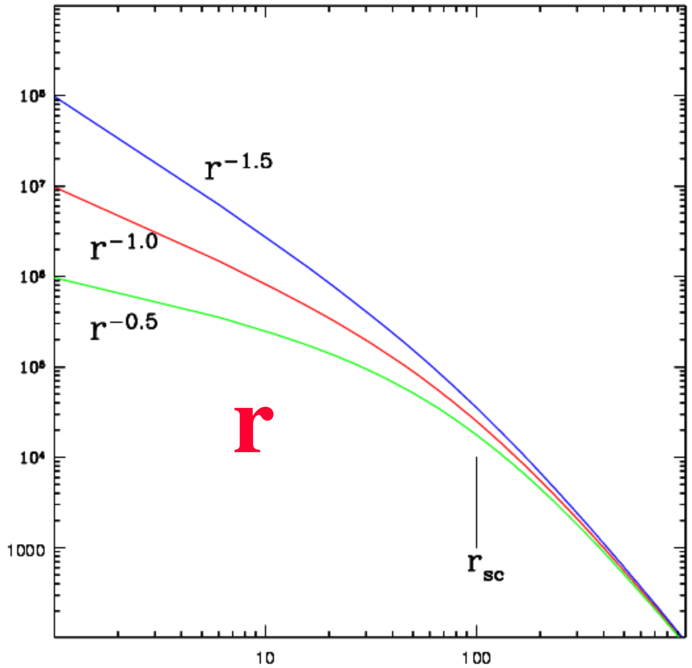
$$\rho_{\rm lum}(r) = \frac{M_* \, r_*}{2\pi \, r \, (r + r_*)^3} \qquad \rho_{\rm DM}(r) = \frac{\rho_{\rm DM,0} \, r_{\rm b}^3}{r^\gamma \, (r_{\rm b}^2 + r^2)^{(3-\gamma)/2}}$$

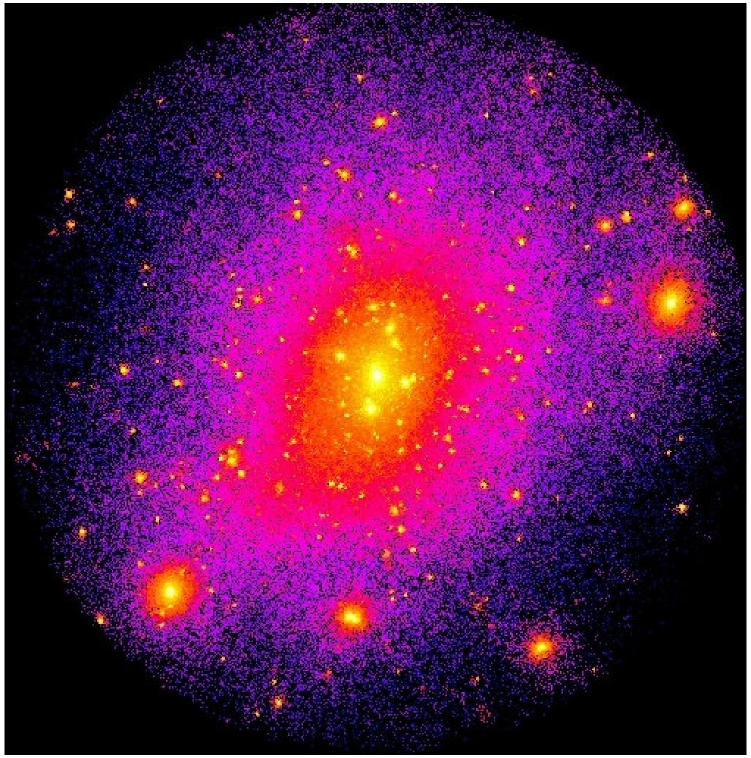


Find total mass profile is isothermal with mass tracing light in shape and remarkably little evolution in density profile with redshift - indicates collisional coupling of gas and DM in ellipticals

Separating DM from Baryons: Universal Profile?

$\rho(r)$

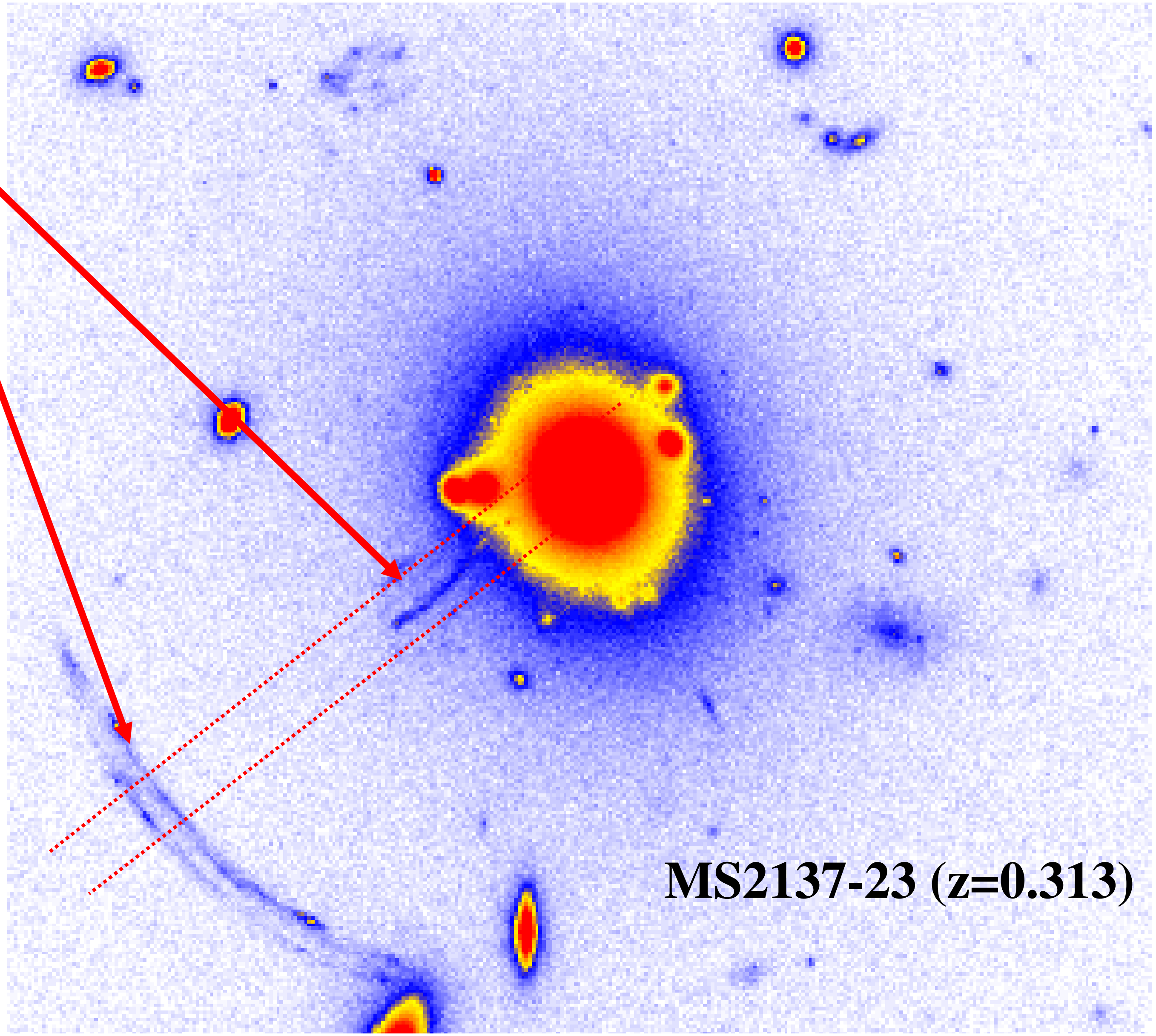




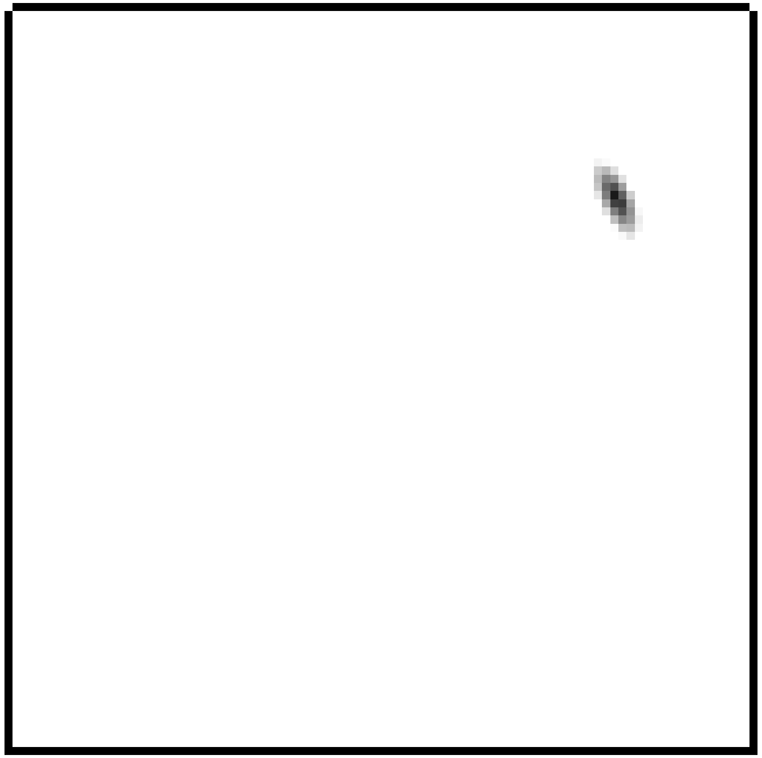
- **Numerical simulations suggest cold (non-interacting) dark matter concentrates with a *inner* density profile $\rho_D \propto r^{-\beta}$ whose form is "universal": 1.0 <β <1.5**
- **Can gravitational lensing be used to separate dark matter from baryons and see how it is distributed on small scales ?**

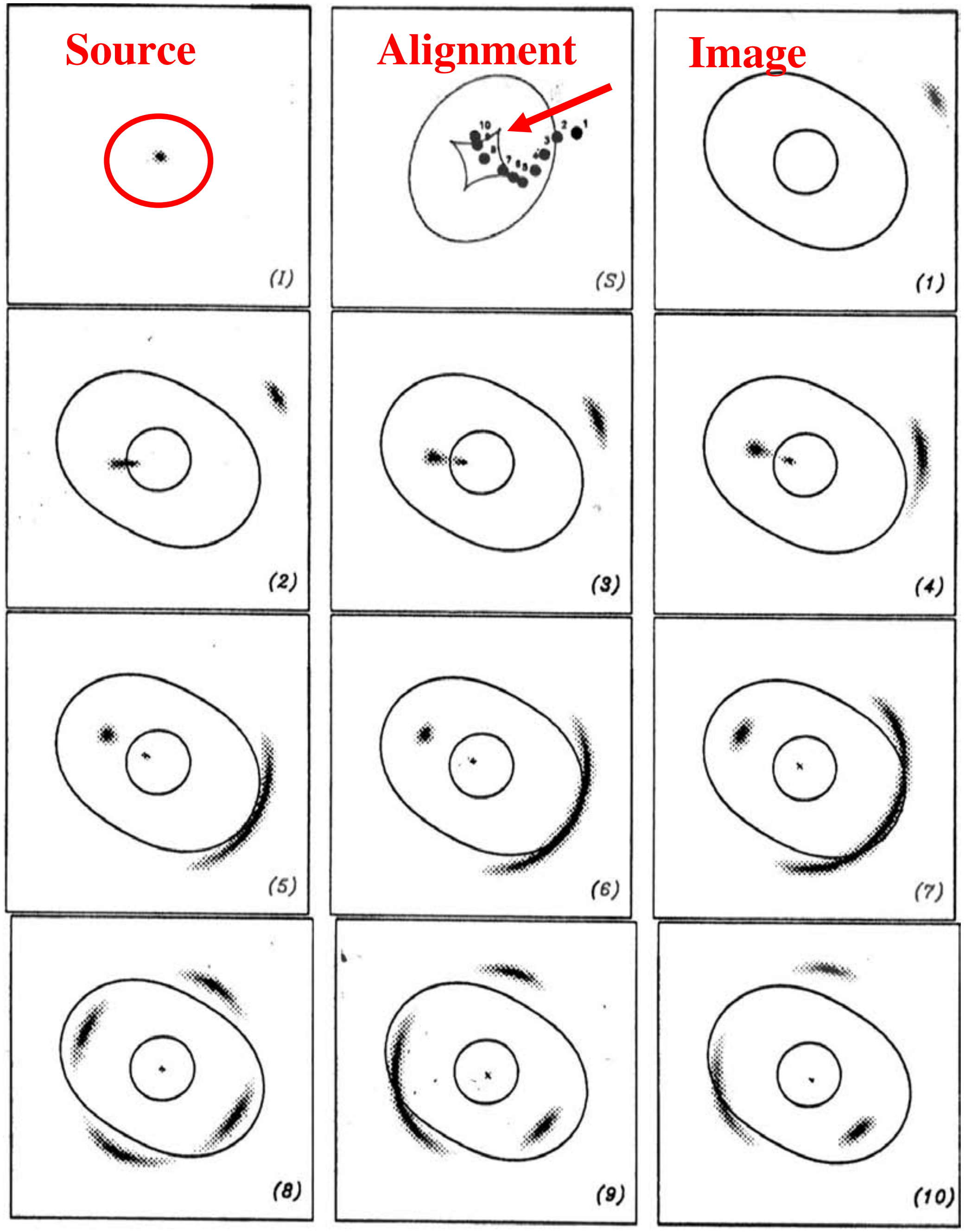
Mass profiles in cluster cores

Presence of *radial and tangential* arcs of known z strongly constrains mass on 20-50 kpc scales



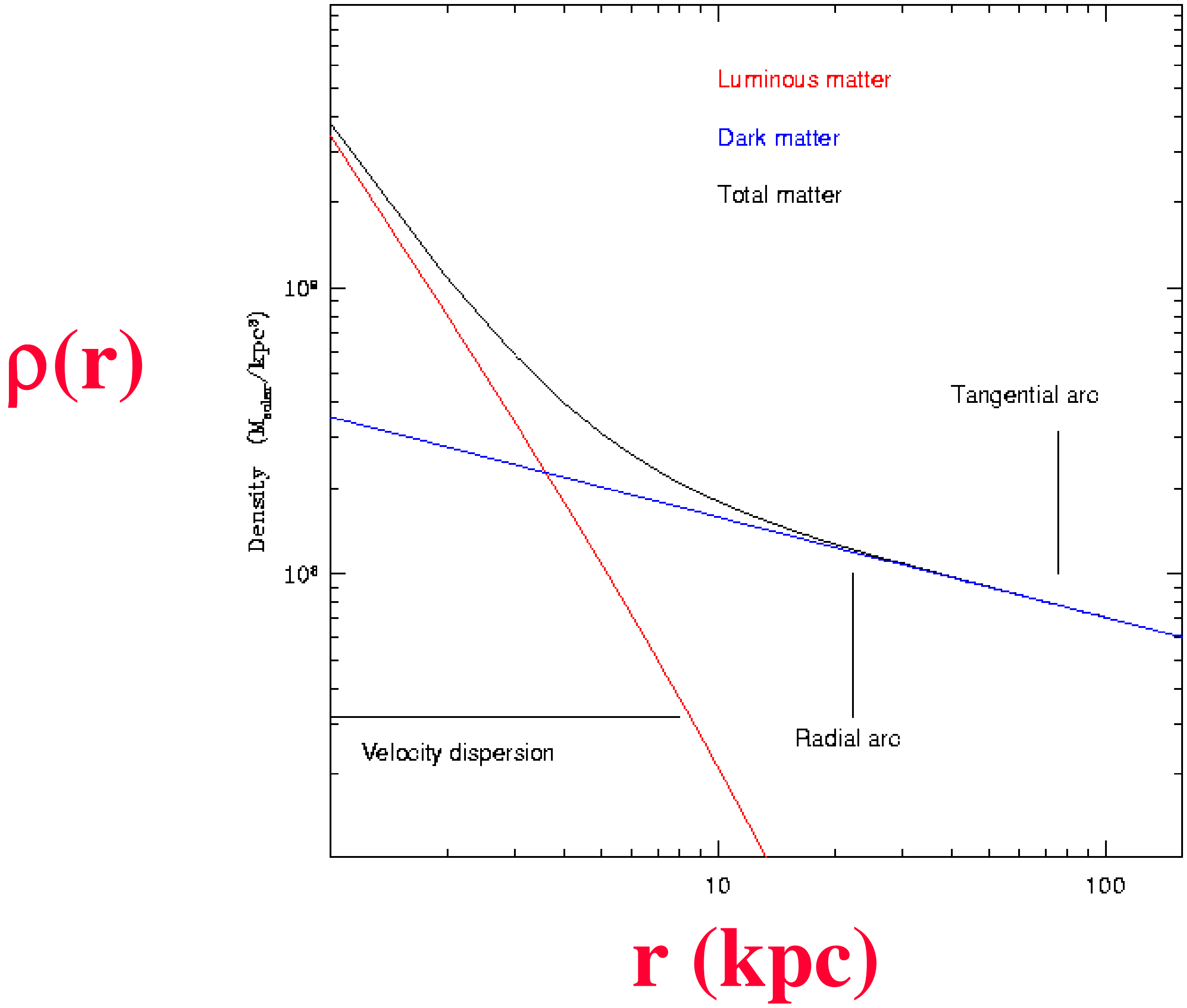
Arcs & Multiple Images - Reminder





Origin of tangential and radial arcs

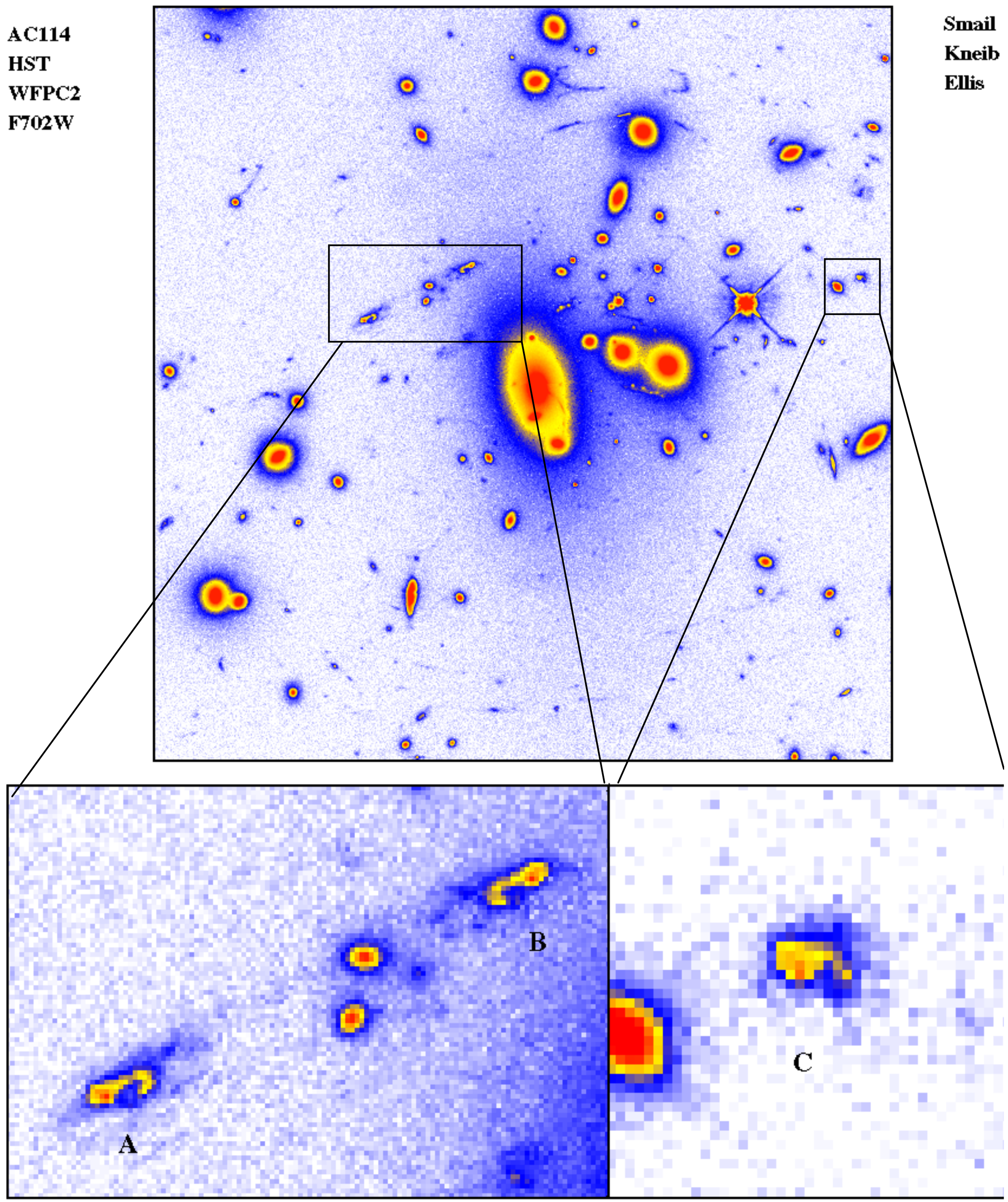
Best-fitting density profile for MS2137-23



Multiple Images

The exquisite resolution of Hubble locates same source seen in 3 different locations!

This is particularly informative if the distances to the lens and the source can be determined as it tells us how lensing matter is distributed in the cluster.

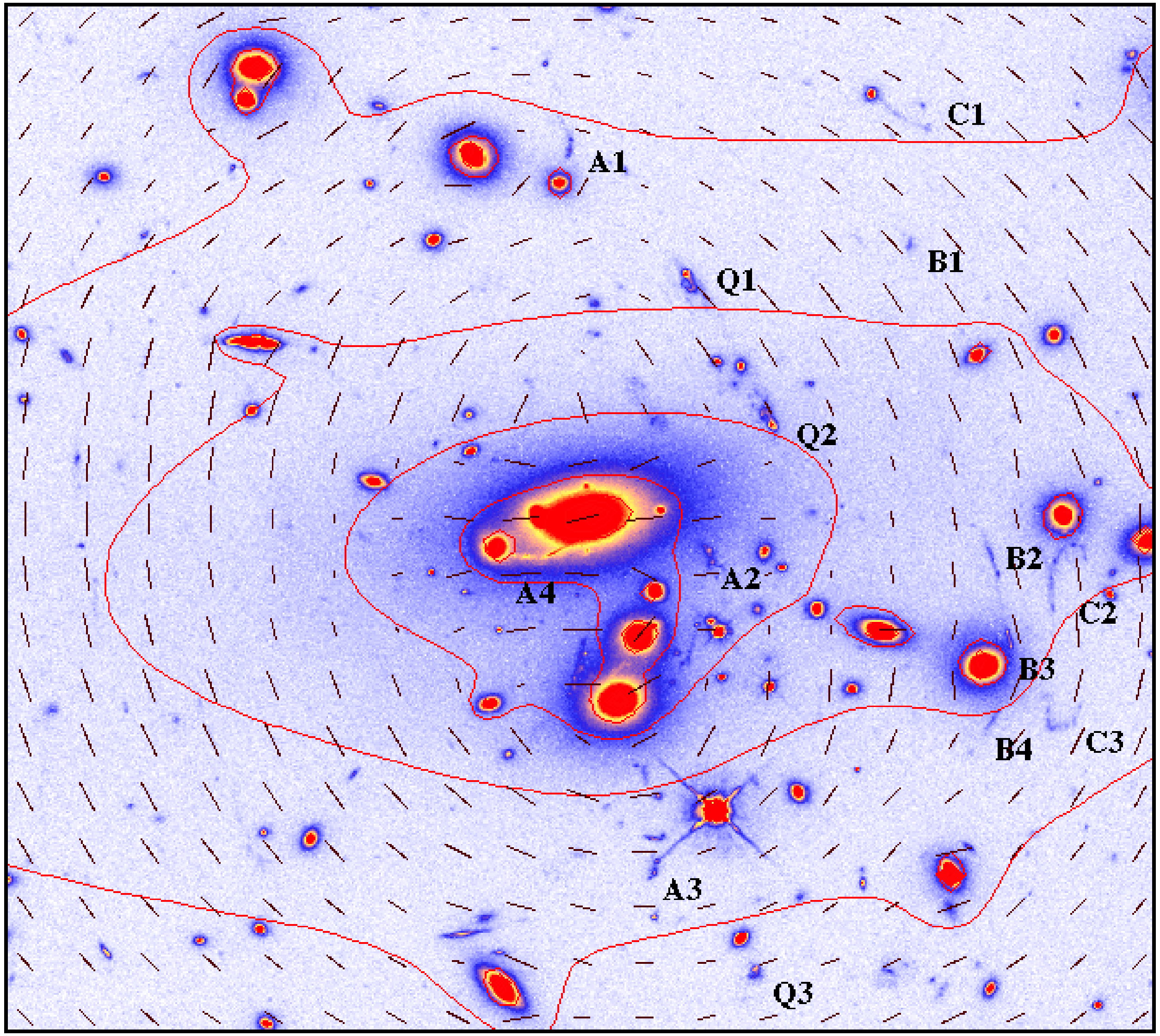


Analysis of Multiple Images

We find the dark matter is:

• dominant (50-100 times more than the mass associated with the visible cluster galaxies)

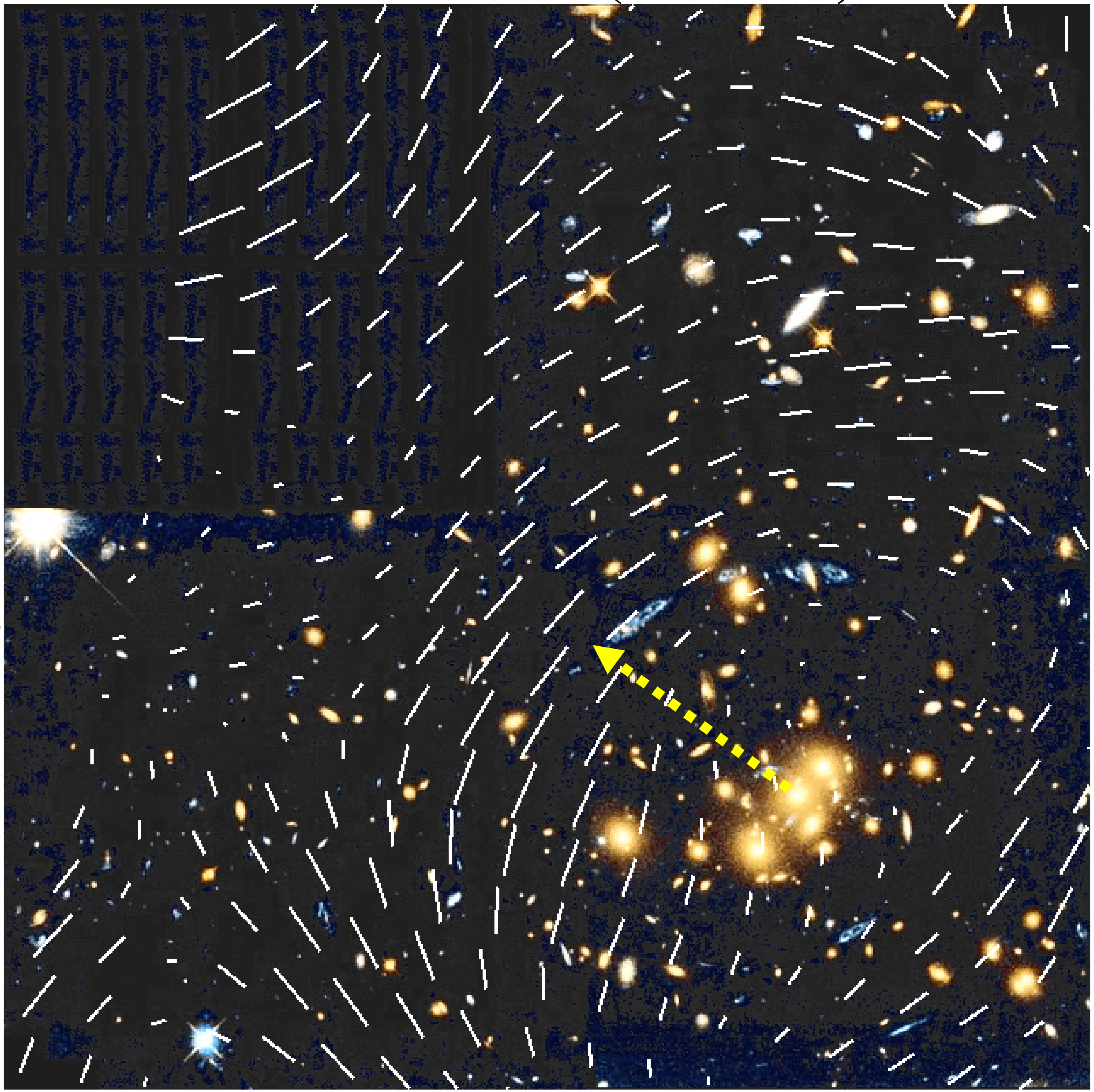
• smoothly distributed, broadly following that of the smoothed light



AC114 HST/WFPC2 Smail, Kneib, Ellis 96

Weak Statistical Distortions ("Shear")

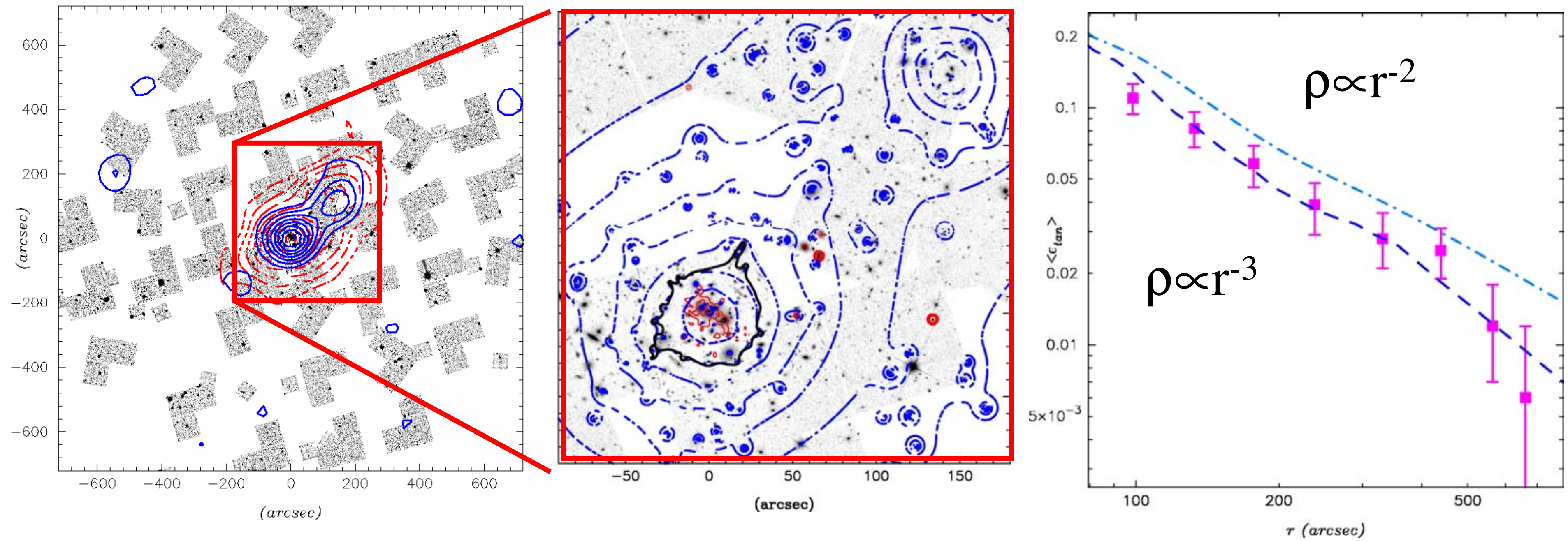
As we move away from the lens center, the arcs decrease in prominence. Because faint galaxies have their own intrinsic shapes, we must average over many faint galaxies to see the stretching effect clearly



Dark Matter Profile on Large Scales

Cl0024 (Kneib et al. 2003)

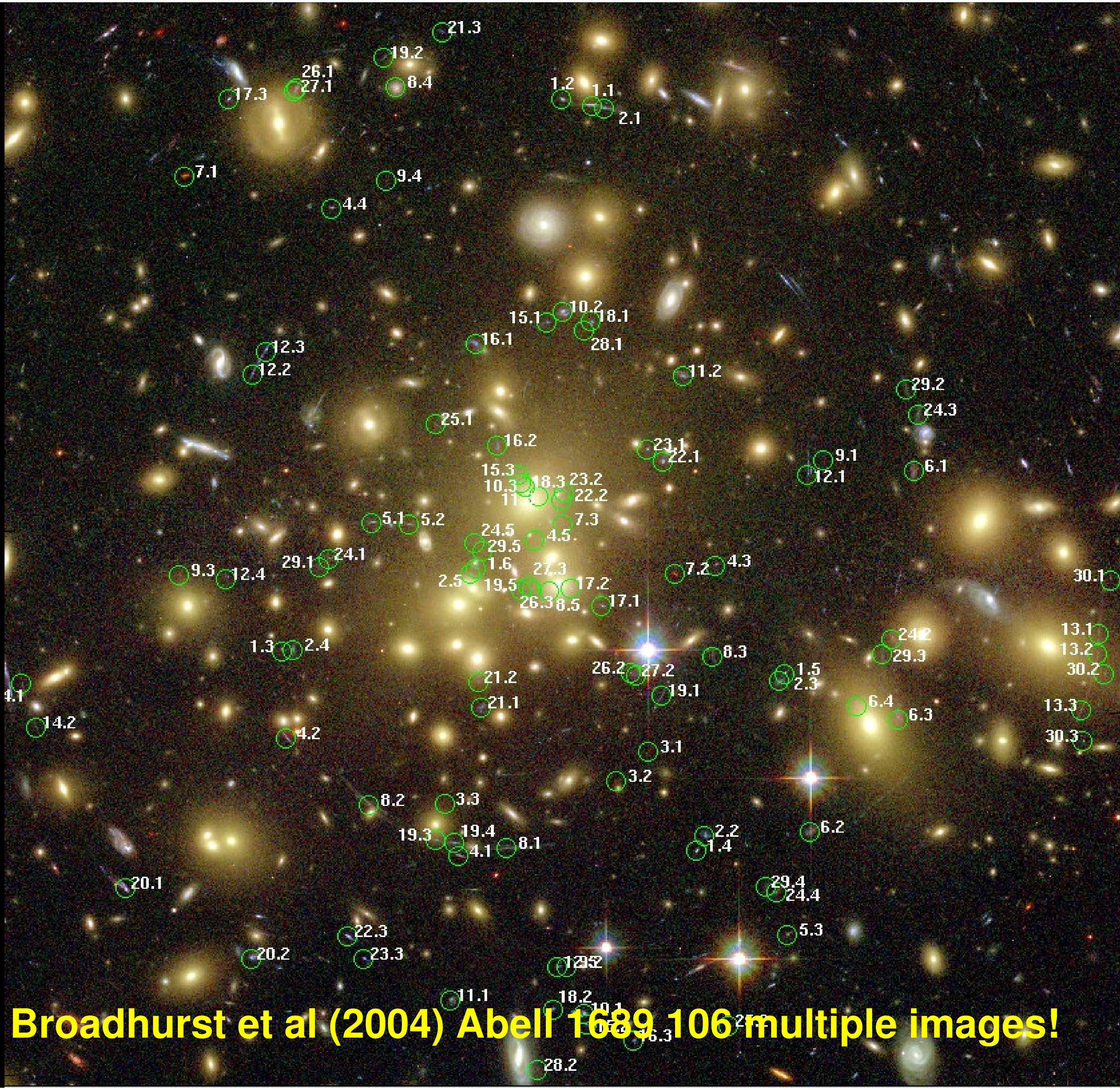
$M_{200}=6.1\pm1.1\times10^{14}\ h^{-1}_{65}\ M_\odot$



Sparse-sampled Hubble pointings detect shear to 5 Mpc

Combining weak+strong lensing yields density profile $\rho \propto r^{-n}$ with $n > 2.4$

Consistent with universal NFW profile (c=22)



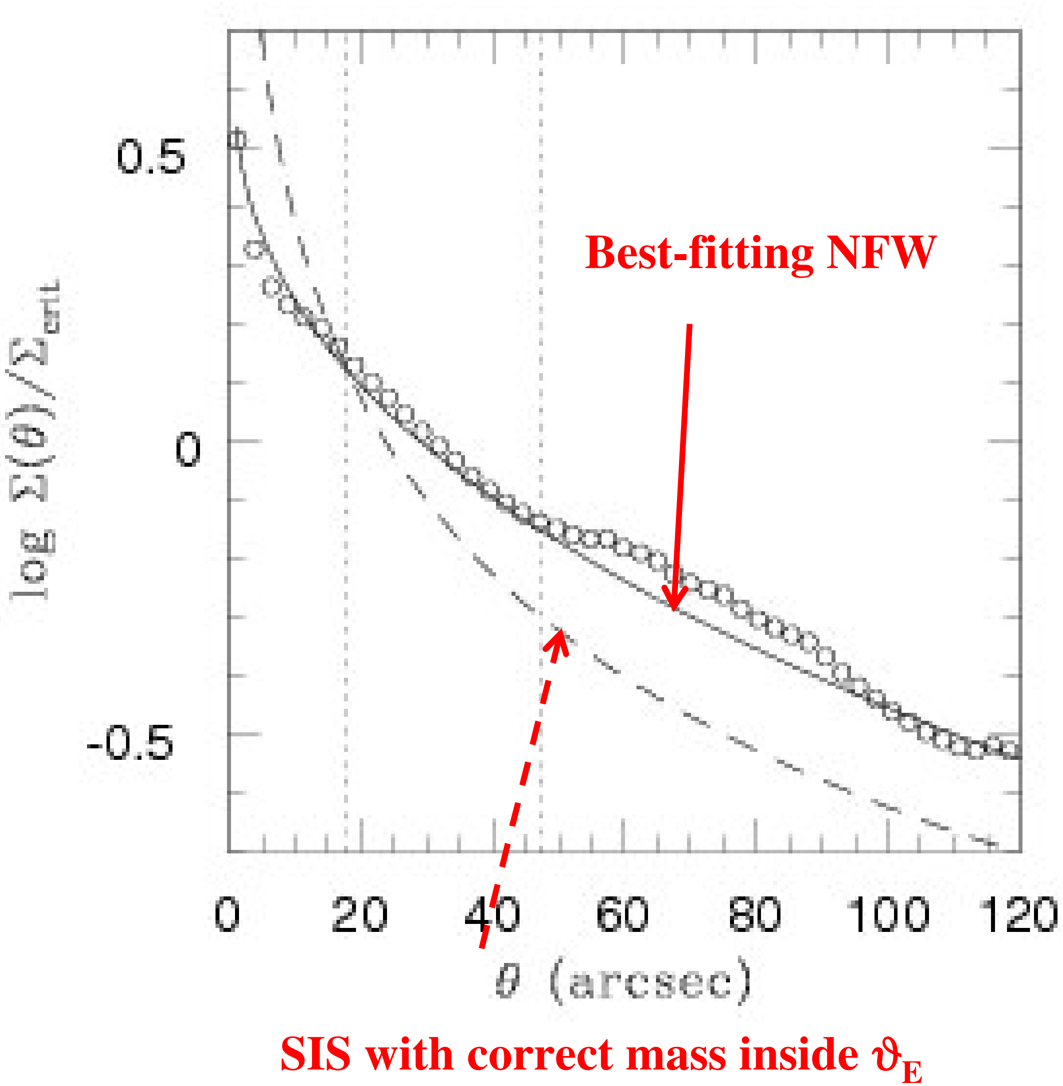
Broadhurst et al (2004) Abell 1689 106 multiple images!

Mass Distribution in Abell 1689

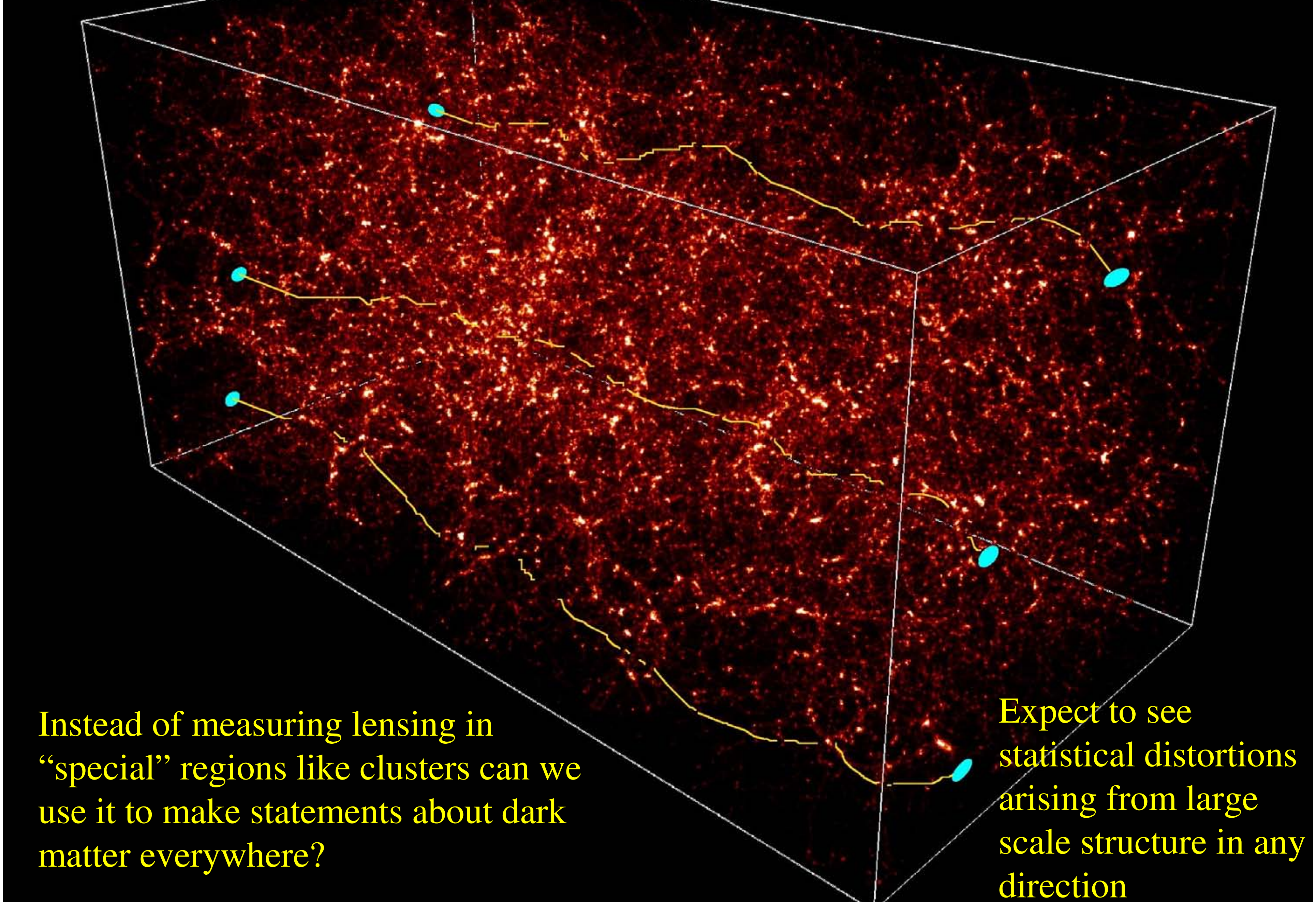
Broadhurst et al. 2005 Ap J 621, 53

- 4-band ACS imaging + ground based data
- 106 multiple images from 30 background sources
- Most distant arc: θ_E~50" probing M(<150 kpc)
- $\sum \propto \mathbf{r^{-0.55\pm0.1}}$

for the total surface mass matching universal NFW profile (c=8)



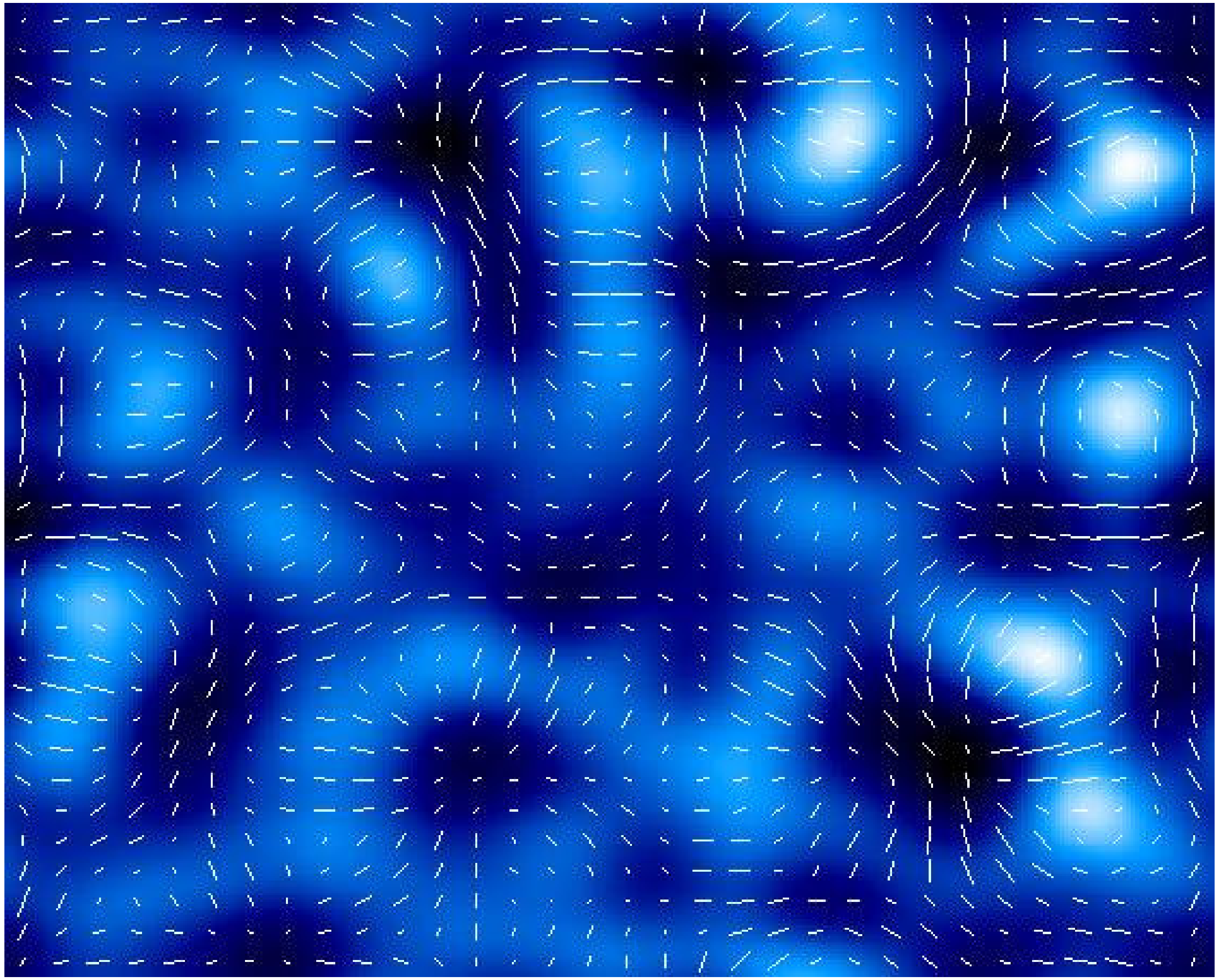
Deflection of Light Rays Crossing the Cosmos



Instead of measuring lensing in "special" regions like clusters can we use it to make statements about dark matter everywhere?

Expect to see statistical distortions arising from large scale structure in any direction

Cosmic Shear - Numerical Simulation

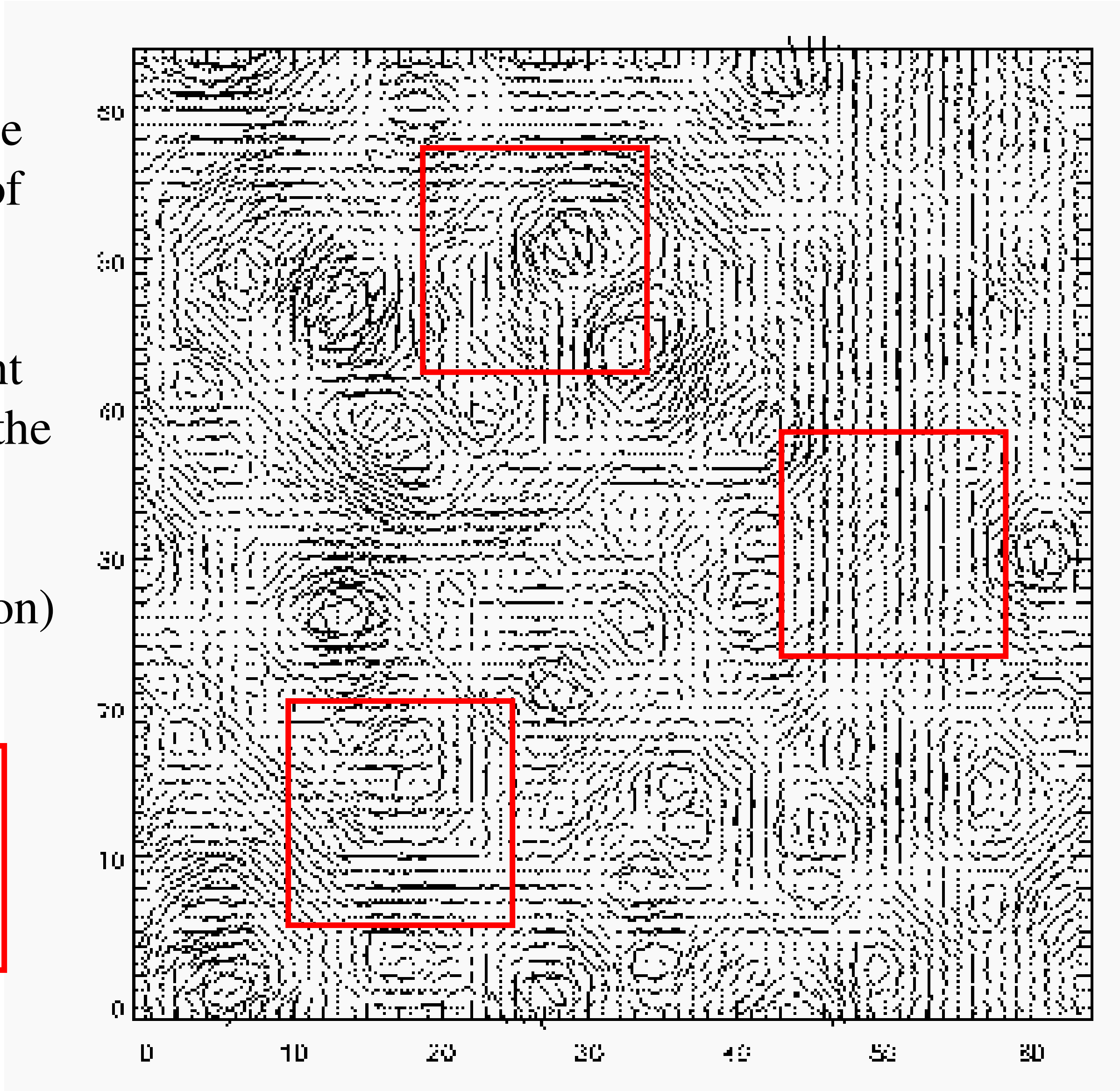


Techniques are available for converting the measured shear (vectors) into the foreground mass distribution (blue scale)

Statistical Detection of Cosmic Shear (2000)

Aim: average correlation of the shear of pairs of adjacent faint galaxies on the sky: a very weak effect (1% distortion)

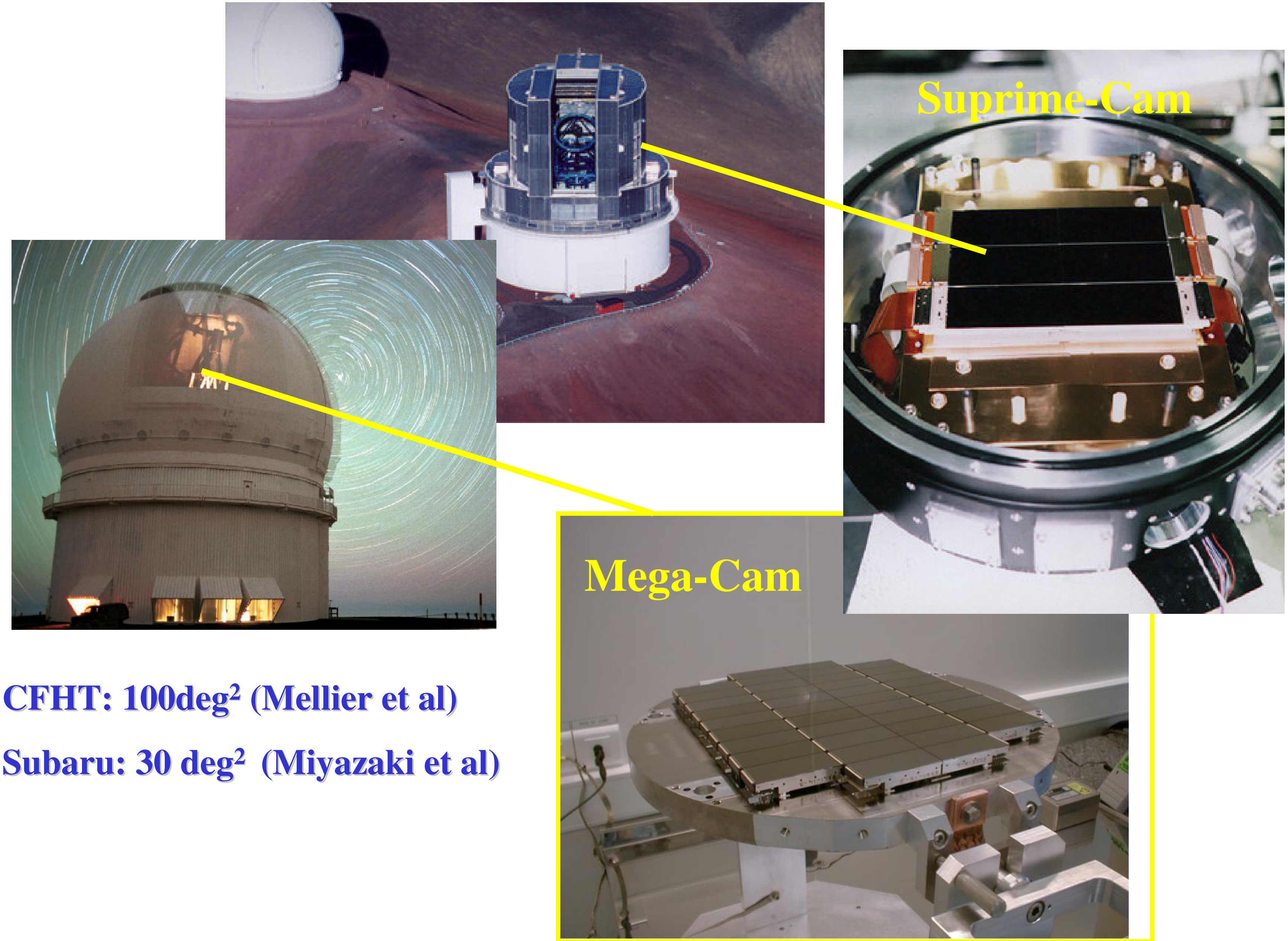
CCD camera



1 degree

The technology to make dark matter maps outside of clusters is hard but we can *statistically* compare the signals with theory

Panoramic Cameras on Canada-France & Subaru

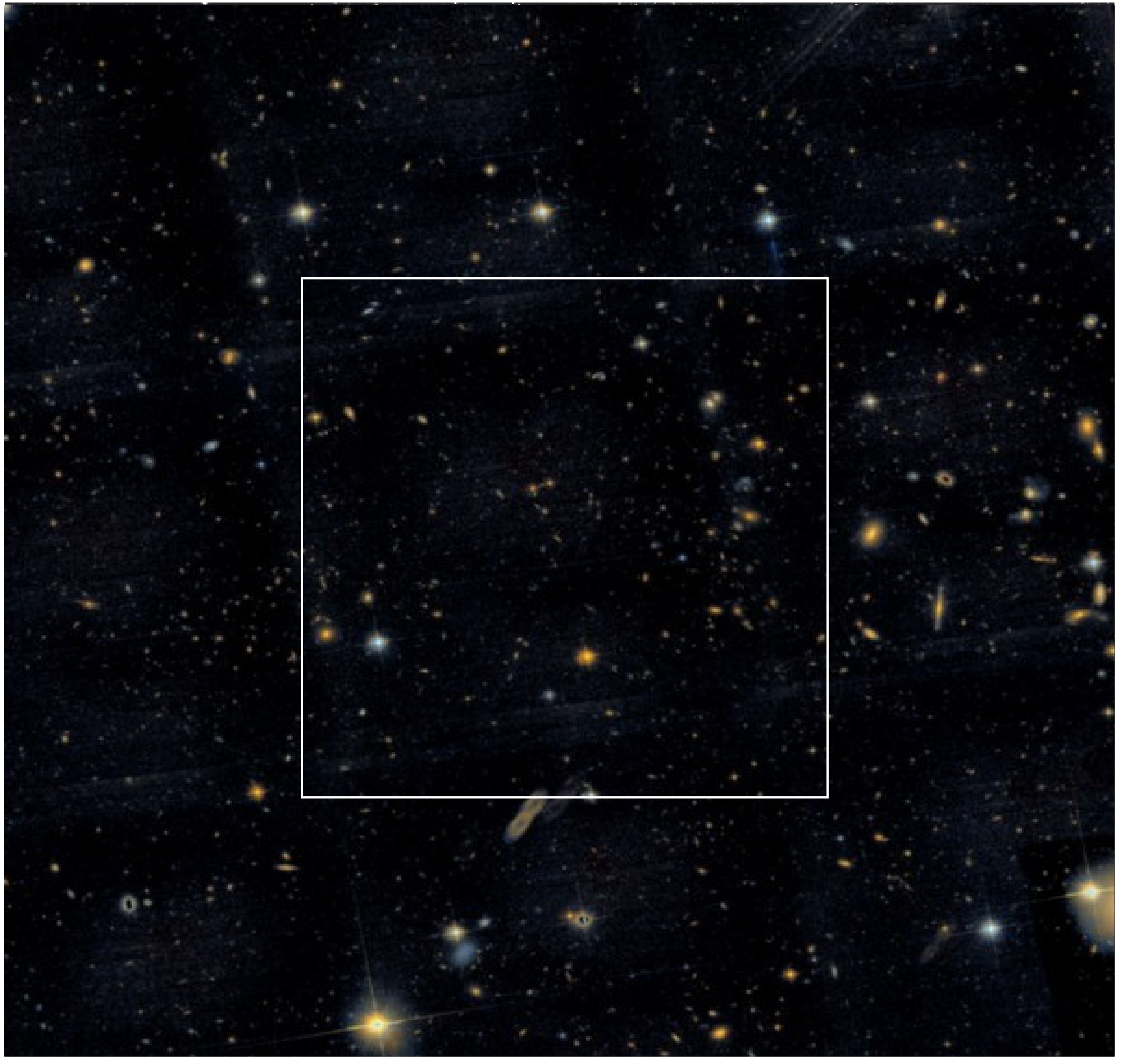


CFHT: 100deg^2 (Mellier et al)

Subaru: 30 deg^2 (Miyazaki et al)

Hubble "Cosmic Evolution Survey"

- 2 deg^2 Hubble data in 625 contiguous fields (largest ever Hubble program)
- > 2 million faint galaxies with measurable shapes
- Multicolor follow-up from Subaru to get distances
- Many other datasets in this special deep field, e.g. X-rays sensitive to hot hydrogen gas in clusters of galaxies

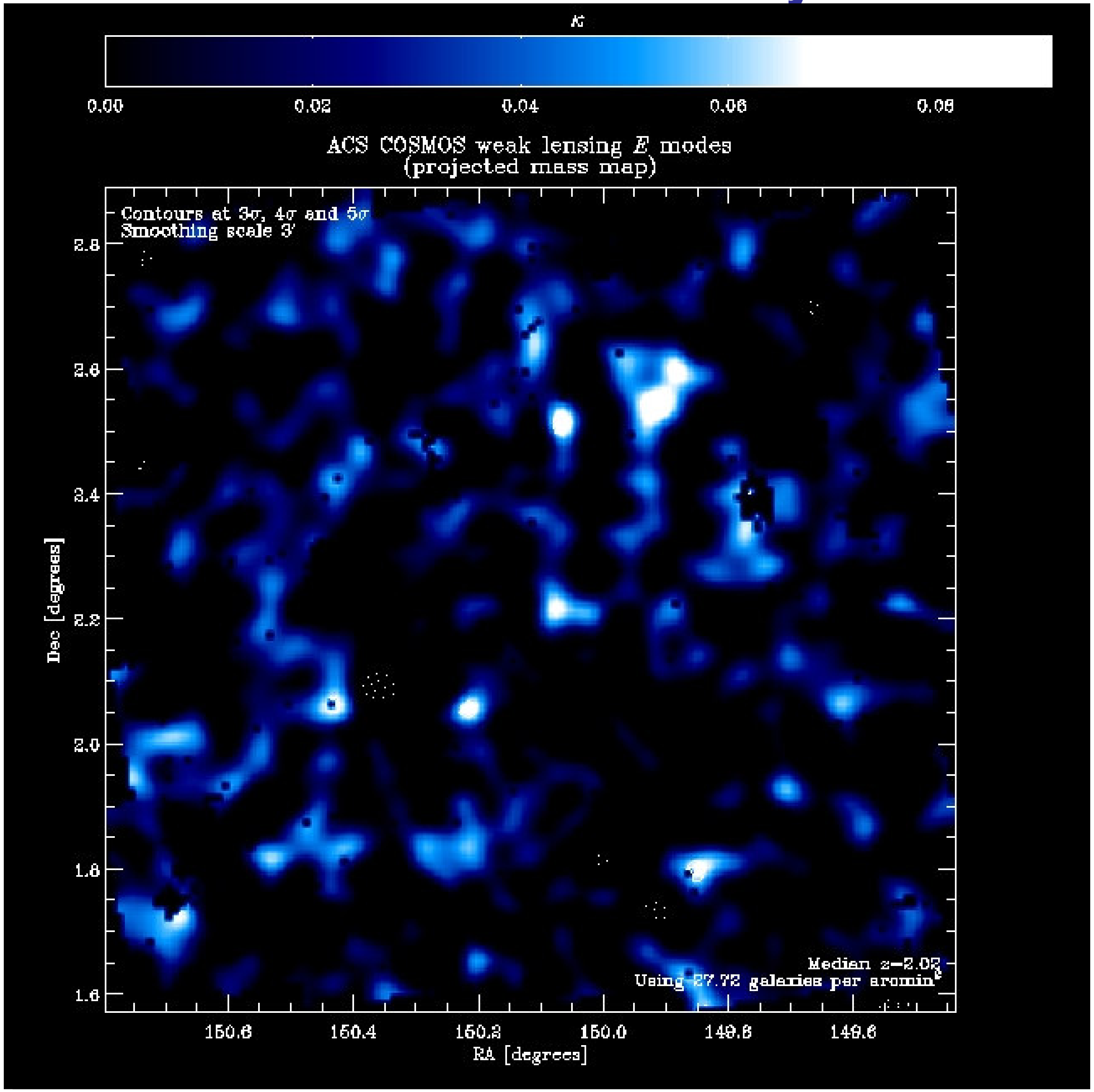


Hubble "Cosmic Evolution Survey"

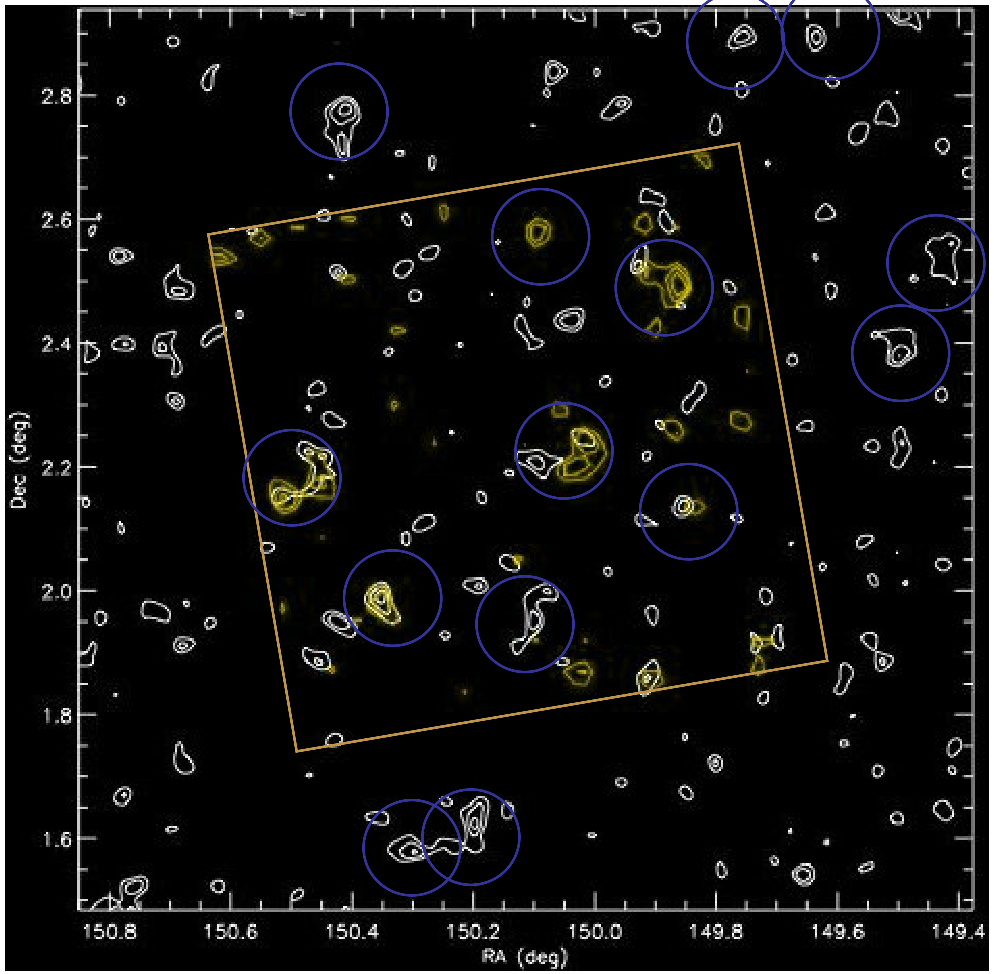
• 2 deg^2 Hubble data in 625 ACS contiguous fields (largest ever Hubble program)
• > 2 million faint galaxies with measurable shapes
• Multicolor follow-up from Subaru to get photo-z
• Demonstration of lensing tomography

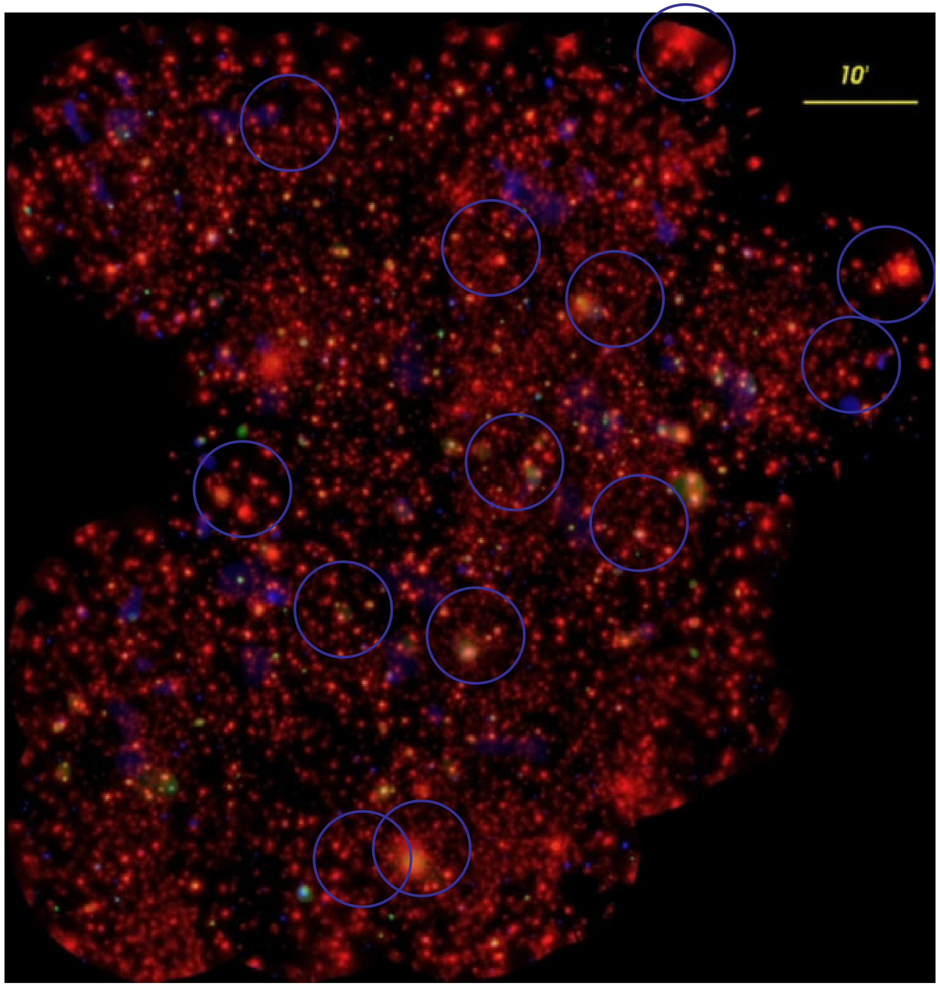
(z_B=0.7, 1, 2)

Massey, Rhodes et al



Lensing mass vs X-ray data in COSMOS





Subaru vs **Hubble**

X-ray map from XMM satellite

Summary of Lecture #1

• Great progress is being made in observational cosmology thanks to powerful ground and space-based facilities

• But we should not confuse the *precision measurement* of the key components (Ω_M, Ω_Λ, H_0…) with *physical understanding:* dark matter and dark energy constitute 95% of the energy density but neither is understood

• Gravitational lensing offers an unique probe of the distribution of dark matter for comparison with numerical models: observational techniques are well-advanced for studying both its large and small scale distribution