

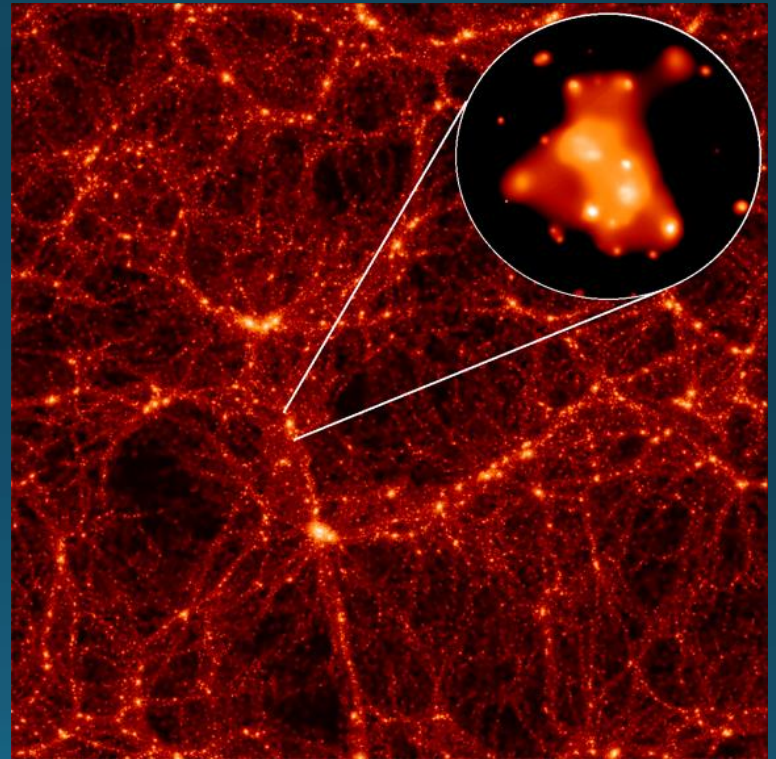
Physics of Galaxies 2019

Lecture 7: Groups, clusters and lensing



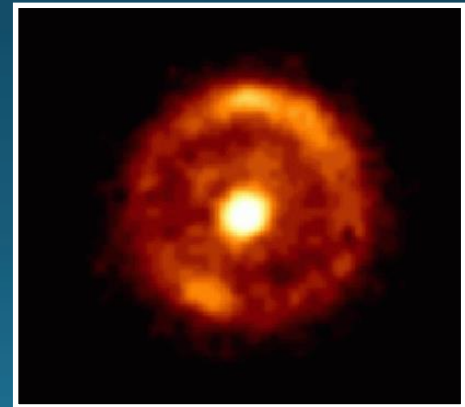
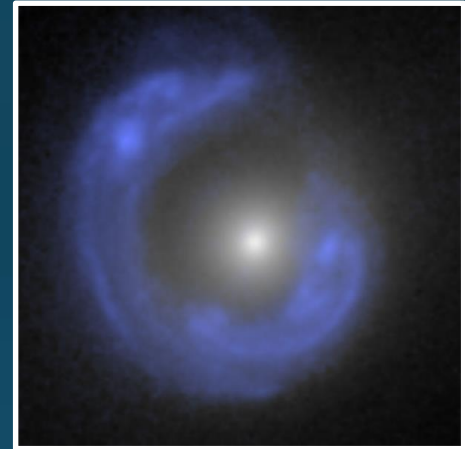
Outline: Galaxy groups & clusters

- Basic characteristics
- Gas and galaxy content
- Clusters in our vicinity
- The Sunyaev-Zeldovich effect



Outline: Gravitational lensing

- Basic principles
- Different types of lensing:
Strong, weak and micro
- Multiply-imaged quasars
- Cluster lensing



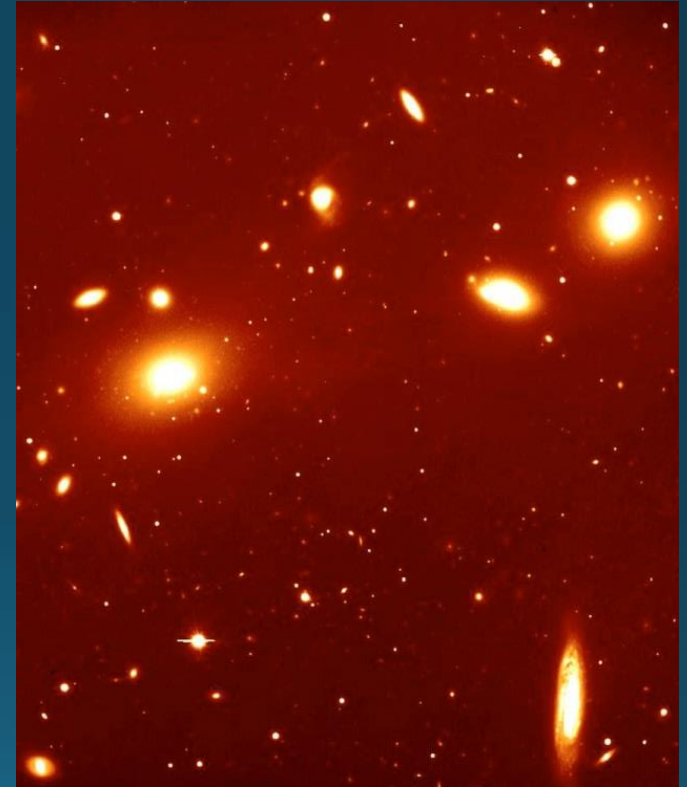
Galaxy groups and clusters I

- Around 50% of all galaxies at low redshift are located in groups and clusters – the rest are in “the field”
- Characteristic group/cluster sizes: 1—10 Mpc
- Clusters: More than 30—50 giant galaxies
- Groups: Less than 30—50 giant galaxies




Galaxy groups and clusters II

- Clusters:
 - $\sigma_r \sim 500\text{—}1200$ km/s
 - Masses $10^{14}\text{—}10^{15} M_\odot$
- Groups:
 - $\sigma_r \sim 100\text{—}500$ km/s
 - Masses 10^{13} solar masses
- Typical $M/L \approx 100\text{—}500$
 - A few times higher than in individual galaxies
 - Most dark matter is located between the galaxies



Cluster classification

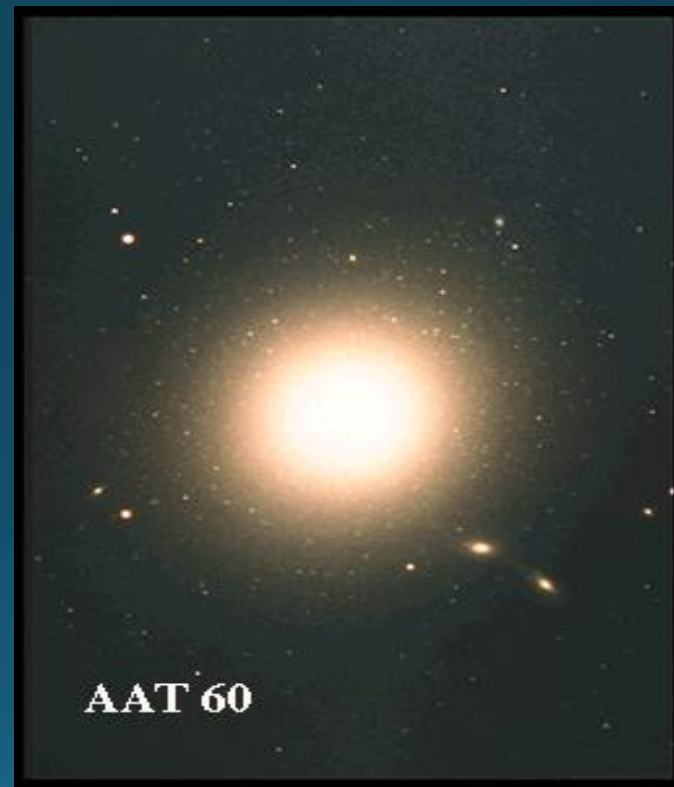
- Abell richness class:
 - Class 0: 30-49 galaxies
 - Class 1: 50-79
 - Class 2: 80-129
 - Class 3: 130-199
 - Class 4: 200-299
 - Class 5: ≥ 300
- 
- Increasing
rareness
- Many other schemes in use:
 - Zwicky (Based on compactness)
 - Rood and Sastry (Based on dominant galaxy)
 - Bautz-Morgan (Based on projected distribution of 10 brightest members)

Intermission: What is this?



Brightest Cluster Galaxies

- Limited luminosity range:
 $M_V \approx -22.8 \pm 0.28 \rightarrow$ Possibly
useful as standard candles
- Some, but not all, are cD galaxies



Galaxy content

- Fraction of E/So galaxies depends on local galaxy density
- Groups and outskirts of clusters: Many S / SB
- Cluster cores: Many E / So
- Mass segregation (in analogy with stars in star clusters):
 - Massive galaxies close to centre
 - Light-weight galaxies further out

The Butcher-Oemler effect

- More blue galaxies in high- z clusters than in low- z ones
- Blue galaxies: Irr / S / SB
- Red galaxies: E / So
- Possible interpretation: Mergers
 - Irr / S / SB \rightarrow E / So over time



+

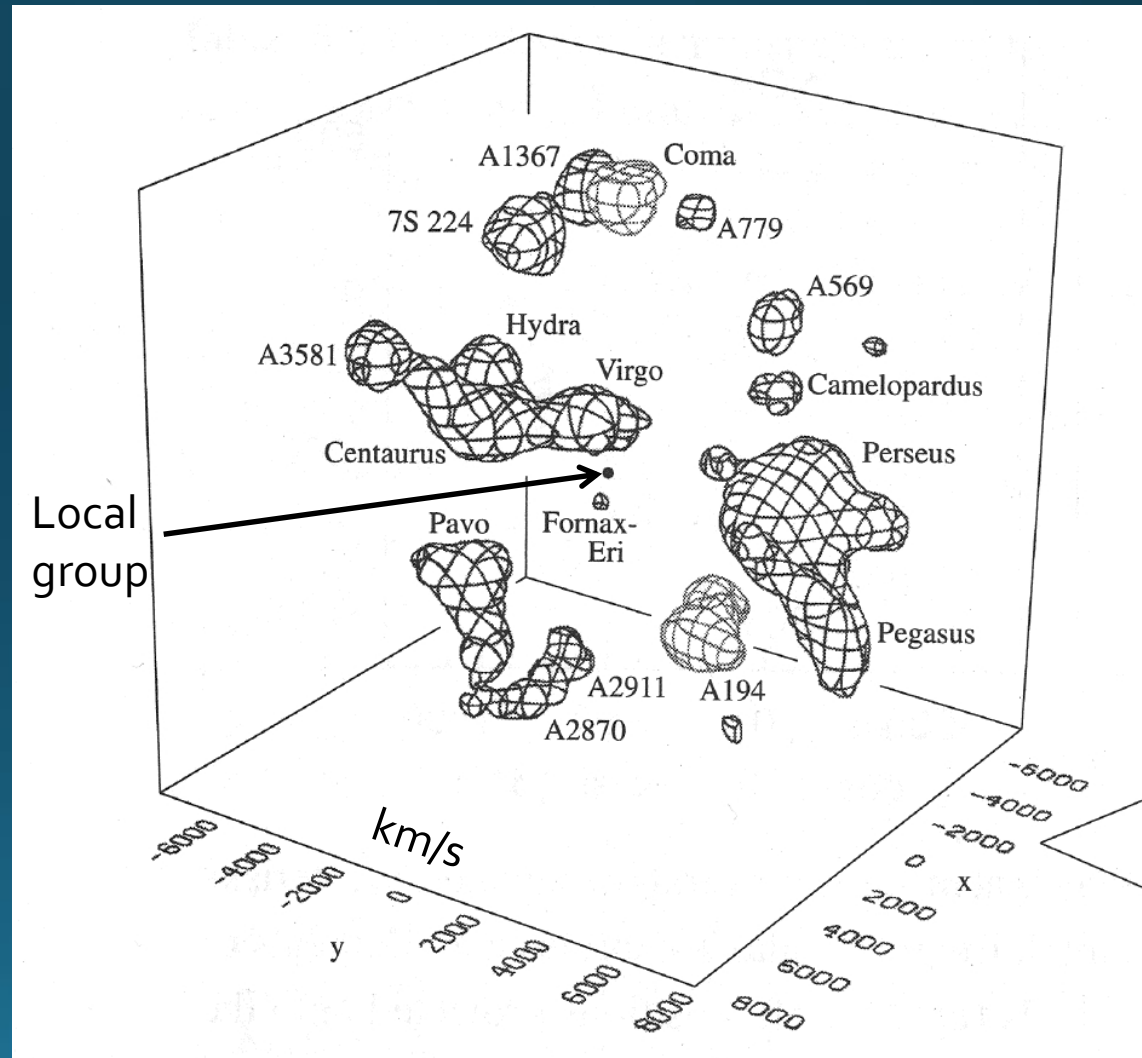


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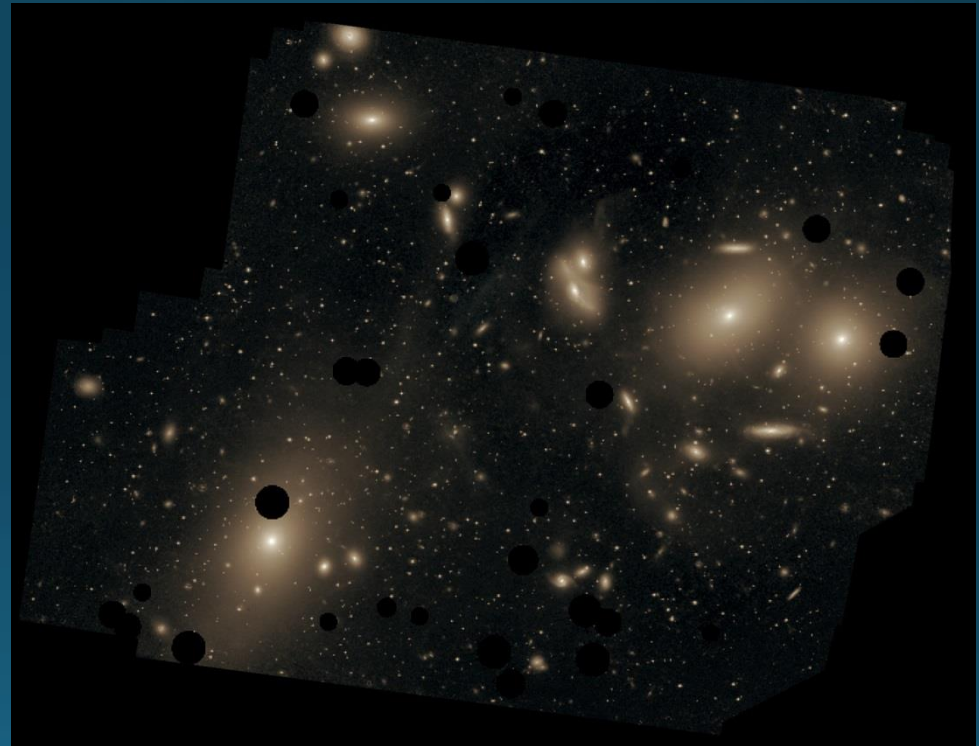
Galaxy groups & clusters in our backyard

- **Groups:**
Sculptor, Fornax, Centaurus A...
- **Clusters:**
Virgo, Coma, Hydra, Centaurus, Perseus...
- **Superclusters:**
Virgo supercluster, Hydra-Centaurus supercluster...
(but the definitions of superclusters are messy)



Galaxy groups & clusters in our backyard II

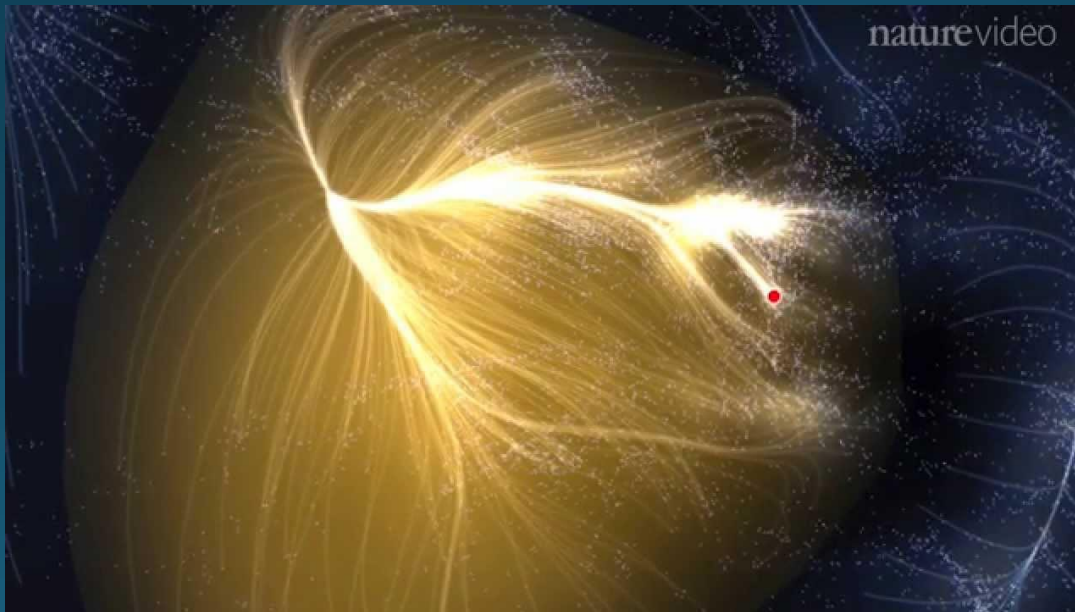
- Virgo cluster
 - Nearest large galaxy cluster with more than 2000 galaxies brighter than $M_B \approx -14$
 - Extent ~ 3 Mpc
 - Velocity dispersion $\sigma_R \approx 600$ km/s
 - Mass $\sim 1 \times 10^{15} M_\odot$
 - Distance 15—20 Mpc



Virgo cluster & M87 (lower left)
with foreground objects masked

The Laniakea Supercluster

- We belong to the **Local Group**, which belongs to the **Virgo Supercluster**, which belong to the (even bigger) **Laniakea Supercluster**
- **Laniakea**: “immeasurable heaven” in Hawaiian
- 100 000 galaxies and 300-500 groups and clusters over 160 Mpc
– total mass $\sim 10^{17} M_{\odot}$



<https://www.youtube.com/watch?v=rENyyRwxpHo>

Compact groups

- Typically 4—7 galaxies inside few ~ 100 kpc
- Very often spirals
- Short predicted lifetimes (due to expected merging)
- $\approx 1/3$ discordant redshifts
- Can injection of high-velocity members into these groups prevent mergers?

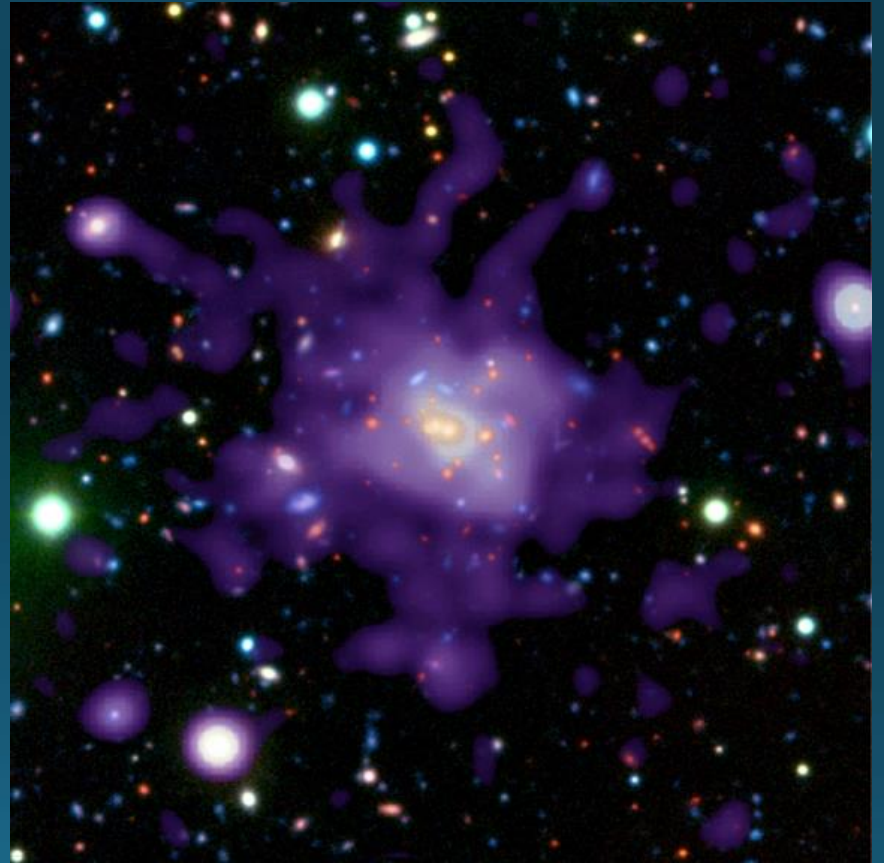


Intermission: Group or cluster?



Gas in groups and clusters

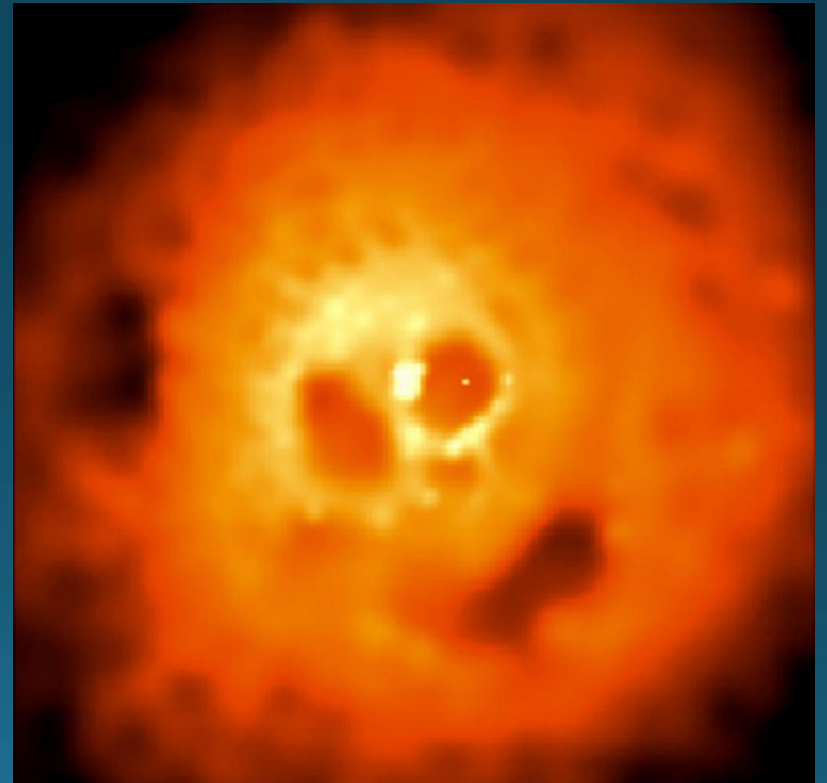
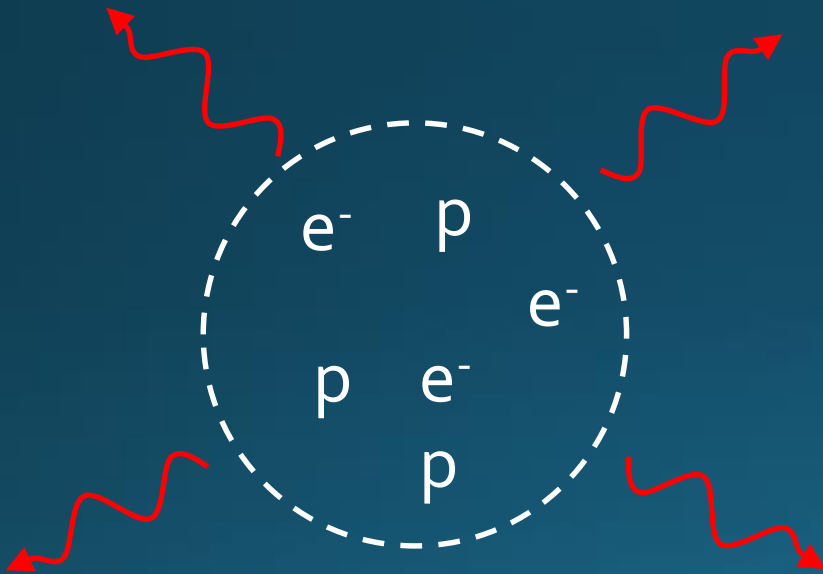
Most baryonic material
in groups and clusters
is not stars, but hot gas



X-ray gas, $T=10^7\text{--}10^8$ K

Why does the gas glow?

Free-free radiation or Brehmsstrahlung
(radiation from electrons accelerated by
charged particles)



Why is the gas so hot?

- Galaxy motions

Consider a “gas of galaxies”:

- High cluster mass \rightarrow High galaxy velocities
 - $kT \sim mv^2 \rightarrow$ High galaxy velocities imply high T
- Winds from supernova explosions inject additional kinetic energy into the gas

Why do the galaxies move so fast?

- Balance between kinetic and potential energy

The virial theorem:

$$M \sim \frac{\langle v^2 \rangle R_{\text{grav}}}{G}$$

Gravitational
radius

- Hence, high cluster mass \rightarrow high $v \rightarrow$ high T
 \rightarrow High X-ray luminosity

Where does the gas come from?

- Mixture of:
 - Gas never captured by galaxies (primordial chemical abundances)
 - Gas (metal-enriched) ejected from galaxies by stellar winds and supernova explosions
- Gas metallicity:
 $Z \sim 10\%$ Solar



Gas in the Coma cluster

Mass estimates

- X-ray spectrum $\rightarrow T(r)$
- X-ray luminosity $\rightarrow \rho(r)$

Depends on the radiation process

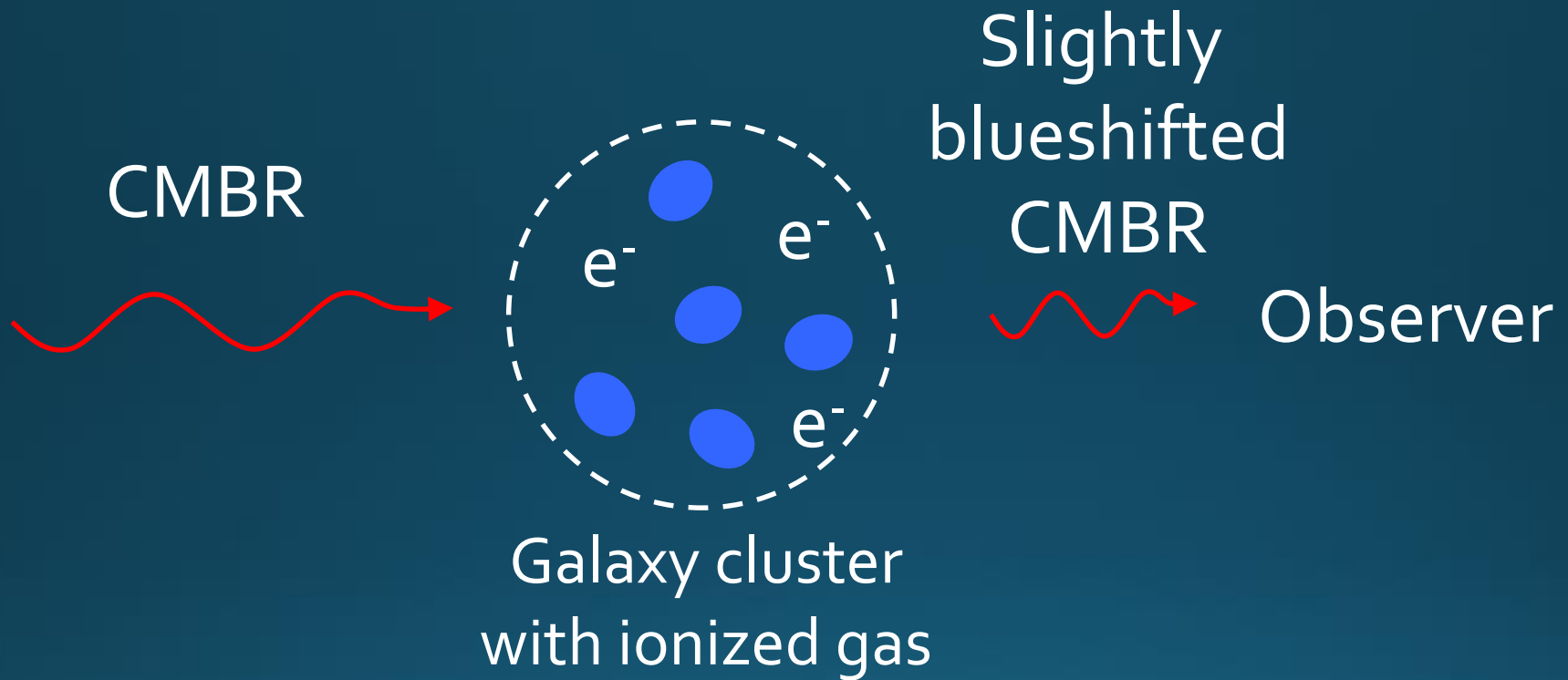
$$L = n_e n_H \Lambda(T)$$

- Mass:

Number densities

$$M(< r) = \frac{k_B}{\mu m_p} \frac{r^2}{G \rho(r)} \frac{d}{dr} (-\rho T)$$

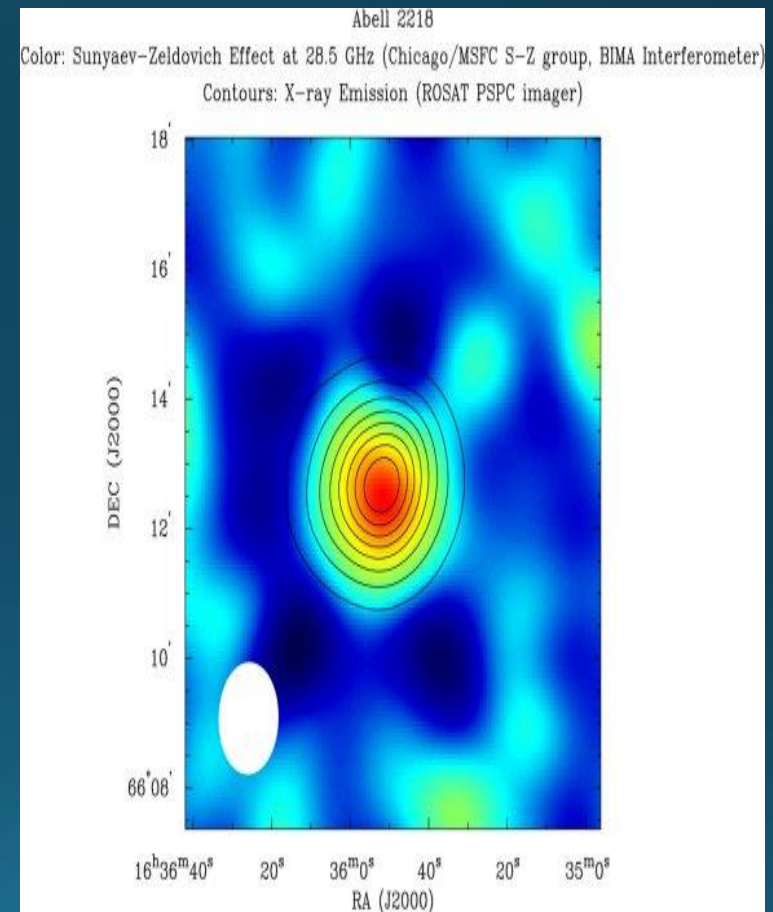
The Sunyaev-Zeldovich effect I



- Inverse Compton scattering of CMBR by free electrons in the intracluster medium increases the energy of CMBR photons

The Sunyaev-Zeldovich effect II

- Measure S-Z \rightarrow thickness of cluster
- Assume thickness=diameter \rightarrow Linear size of cluster in sky
- Measure angular size of cluster in sky
- Combine angular and linear size \rightarrow Distance



The S-Z effect is an important tool for cosmology!

Gravitational lensing

- Lensing – basic stuff:
What? Why? Where?
- What do you need it for?
Want to probe the *source*, the *lens*, or the *Universe*?



Lensing – quick overview I

Overdensities of matter along line of sight →

- Magnification
- Distorted morphology
- Shift in apparent position
- Multiple images
- Delays in time signals



Lensing – quick overview II

Magnification



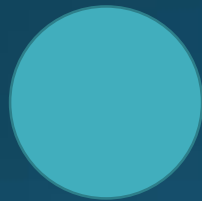
Surface brightness
conserved
(as long as the whole
source experiences the
same magnification)

Intrinsic source size

Apparent source size
(boosted due to lensing)

Increased size + conserved surface brightness →
increased apparent flux

Intermission: What magnification?



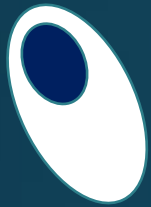
Intrinsic size



Lensed size

Lensing – quick overview III

Distorted morphology



Intrinsic source morphology/orientation/parity



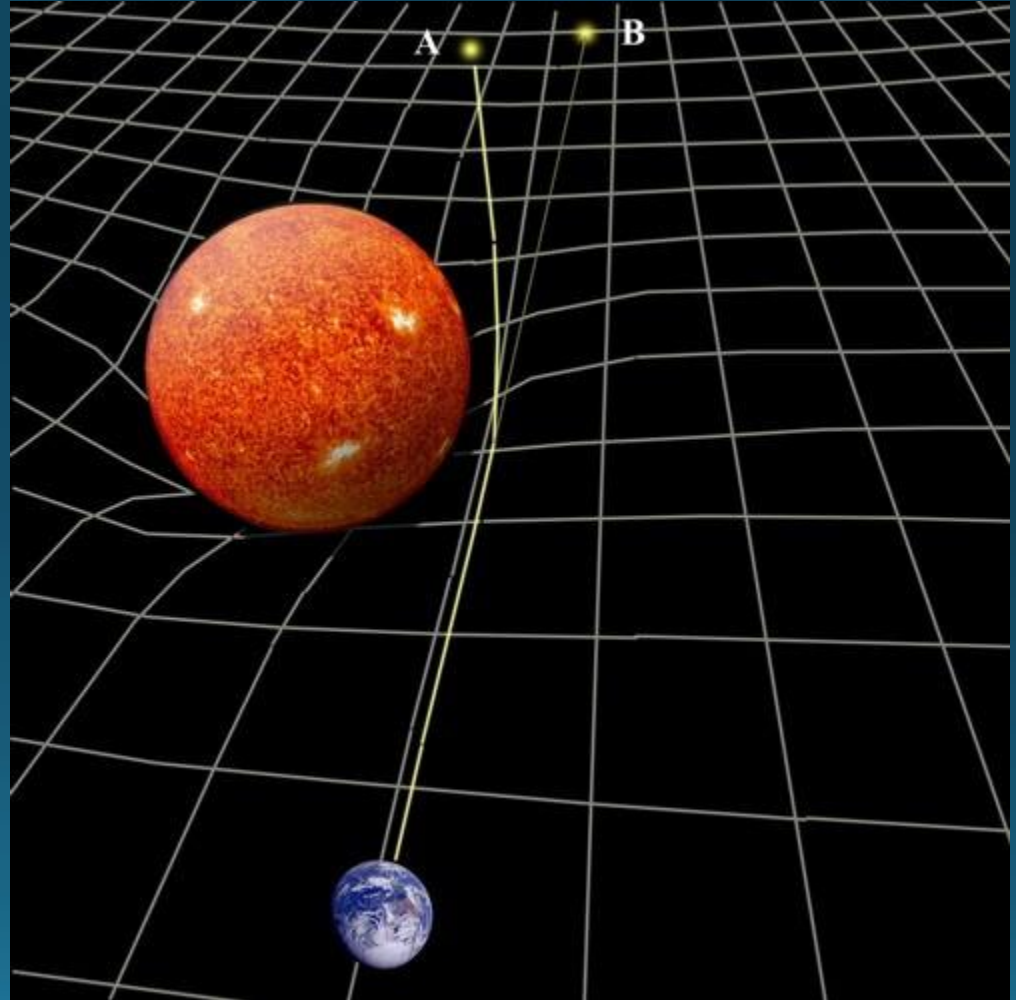
Apparent source morphology/orientation/parity

Stretched, curved and mirror-flipped!

Lensing – quick overview IV

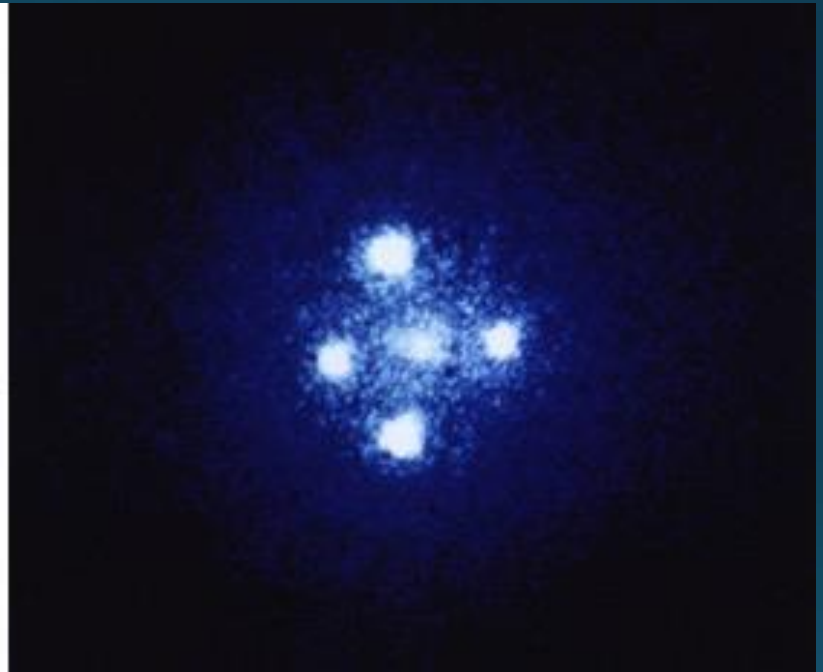
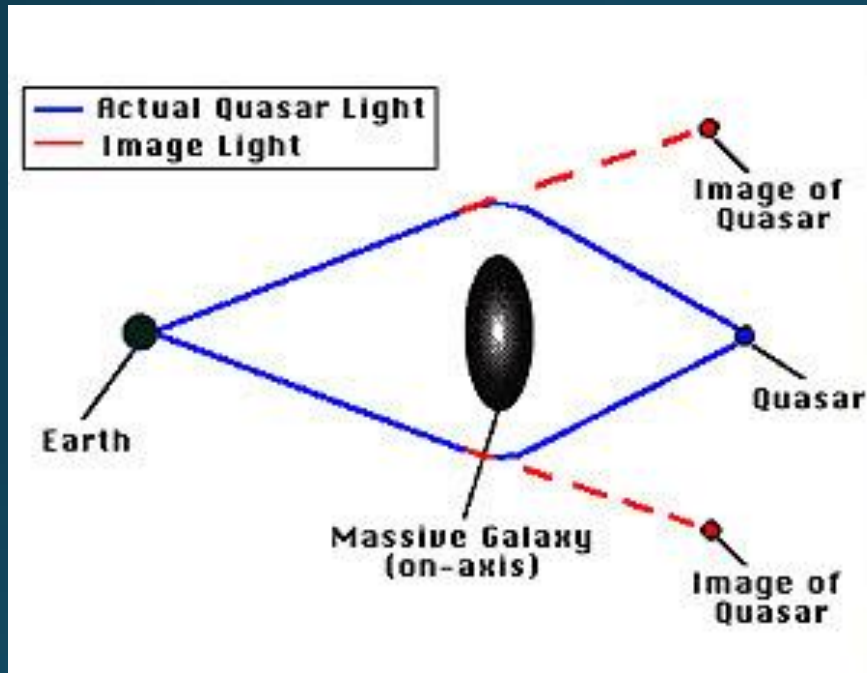
Shift in apparent positions

The mass of the Sun shifts the apparent positions of stars close to the limb



Lensing – quick overview V

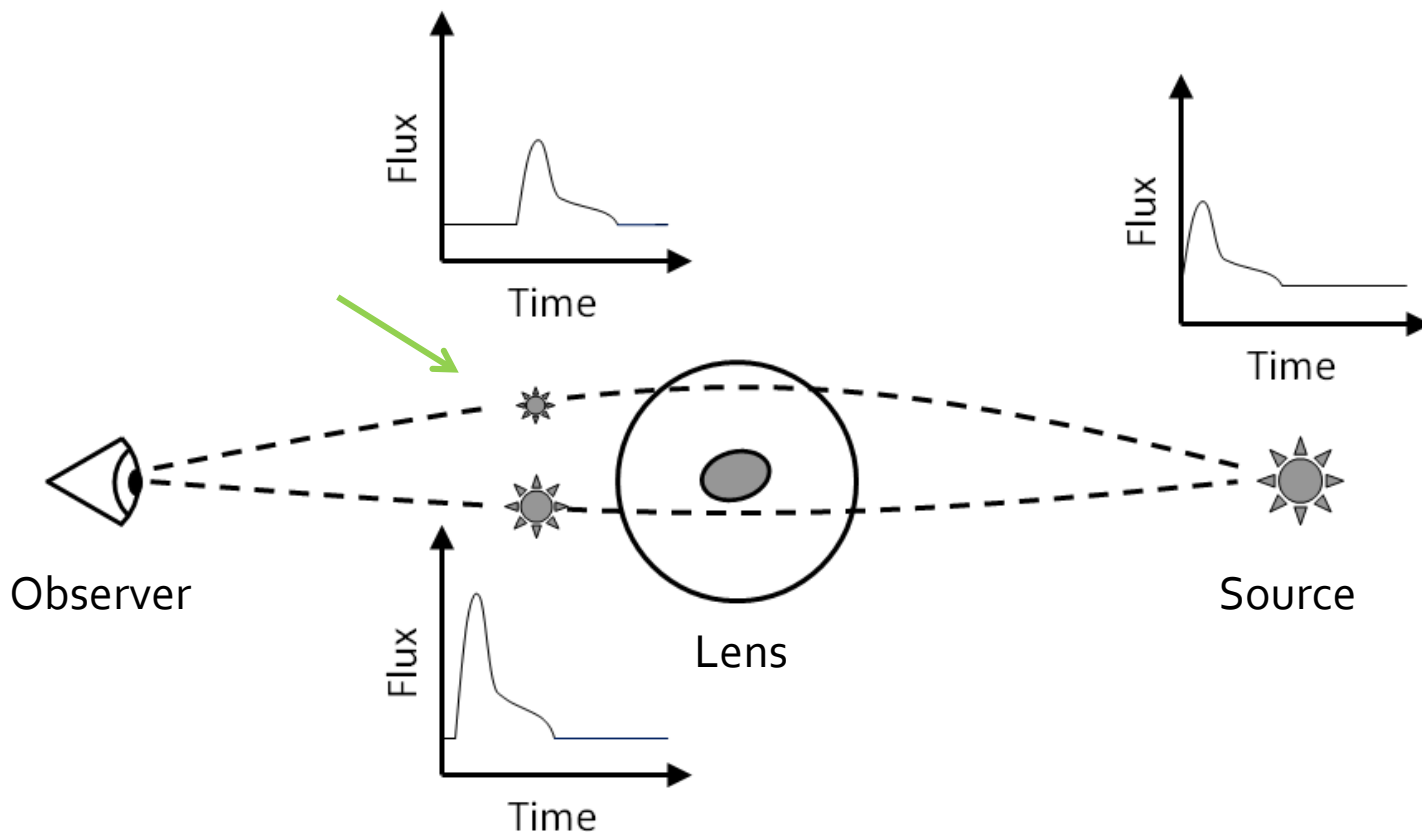
Multiple images



Lensing – quick overview VI

Delays in time signals

Longer path length & Shapiro time delay
(clocks running slow in strong gravitational fields) → outburst delayed



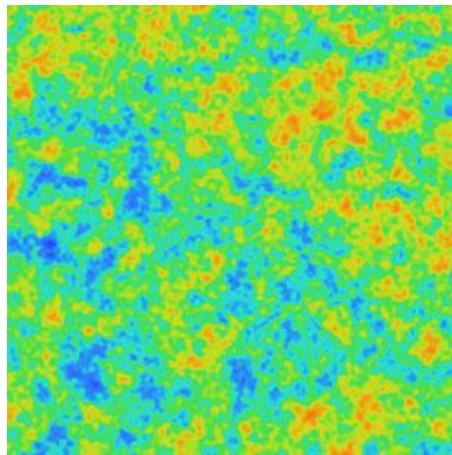
Lensing – A tool...

- Magnification → Can detect sources too faint to be seen otherwise
- Multiple images, distortions time delays → Probes of structure and dust reddening along line(s) of sight
- Testing gravity & cosmology

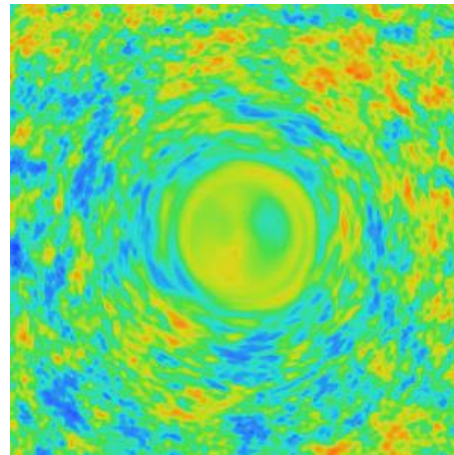
... and a nuisance

A couple of examples:

- The flux you measure doesn't directly reflect the intrinsic luminosity
 - Can standard candles (e.g. type Ia supernovae) always be trusted?
- Cosmic Microwave Background Radiation (CMBR) maps distorted



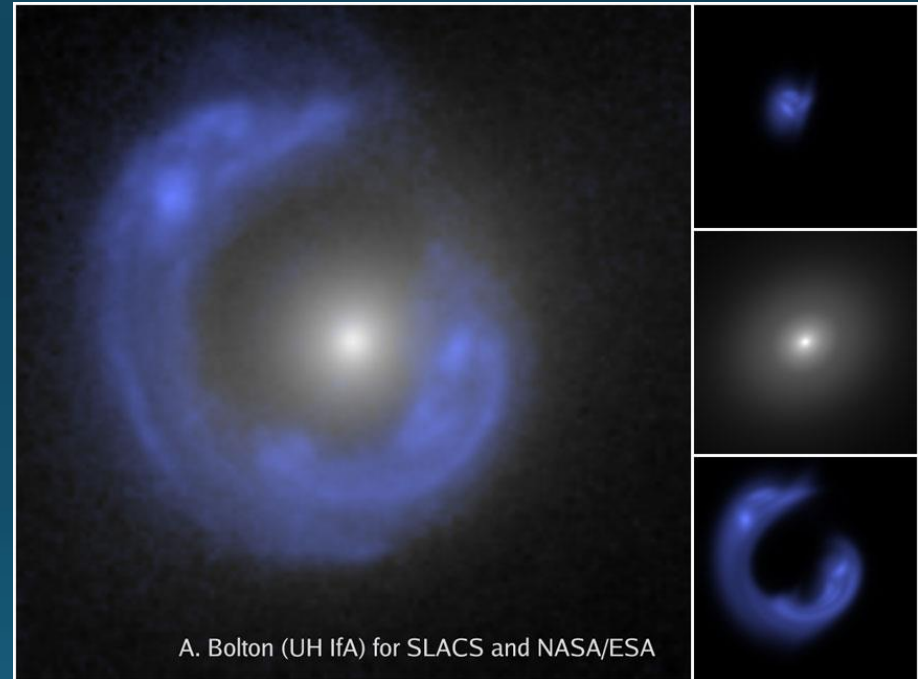
Intrinsic CMBR



Lensed CMBR

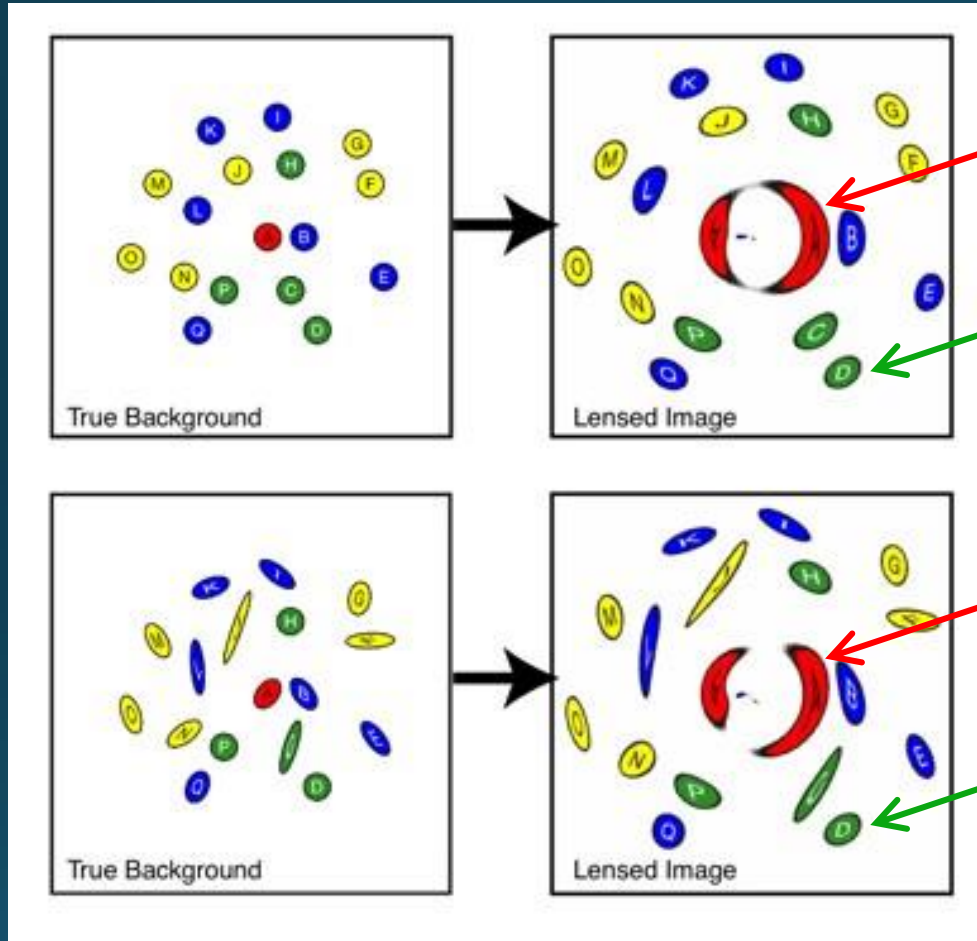
Different types of lensing I:

Strong lensing



Strong lensing: Multiple images, large distortions, high magnifications
Very rare!

Different types of lensing II: Weak lensing



Strong lensing

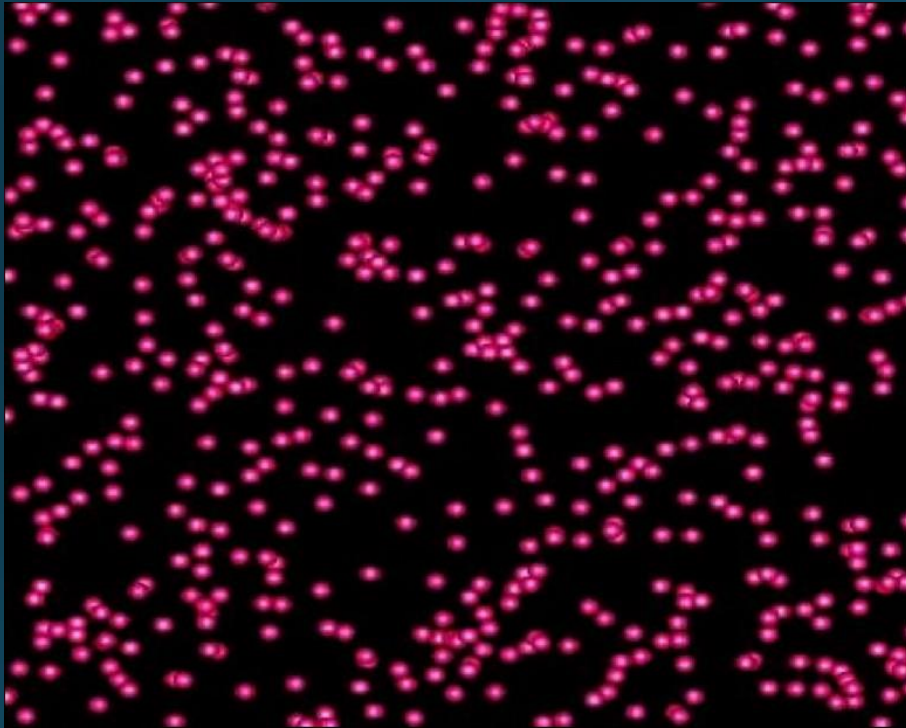
Weak lensing

Strong lensing

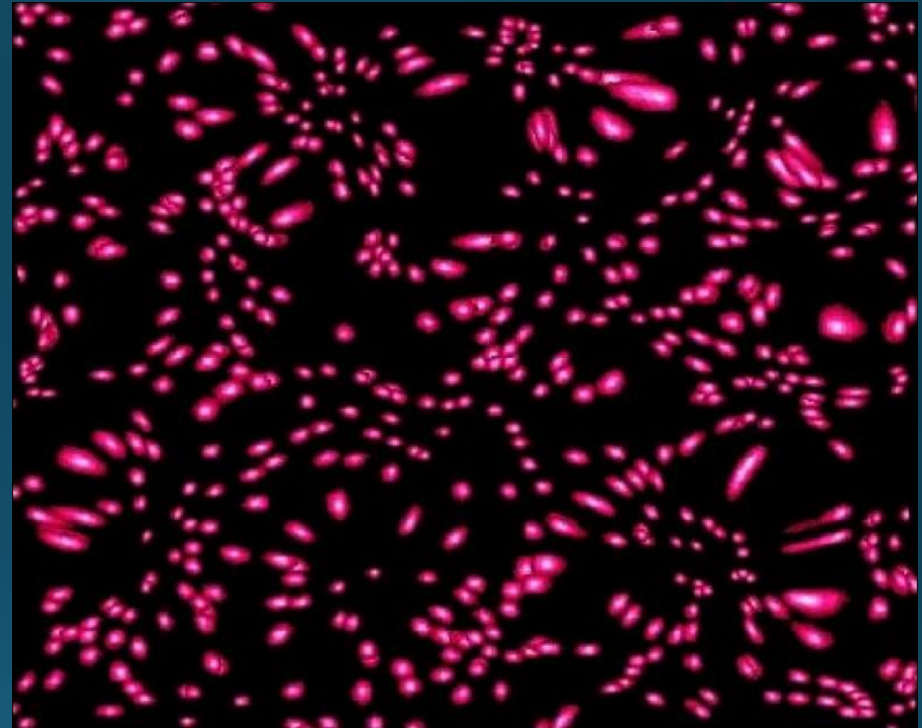
Weak lensing

Weak lensing: Mild distortions, small magnifications
Very common!

Different types of lensing II: Weak lensing



Unlensed



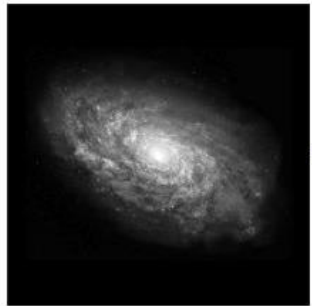
Lensed

Cosmic shear

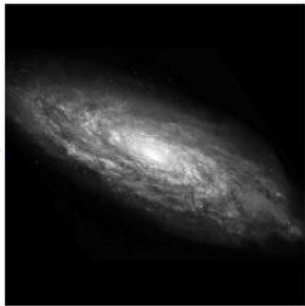
Technological challenges for weak lensing

Weak lensing distorts the ellipticities of sources at the $\sim 1\%$ level - very difficult to measure!

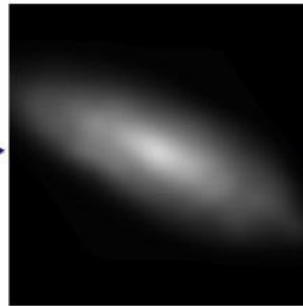
Galaxies: Intrinsic galaxy shapes to measured image:



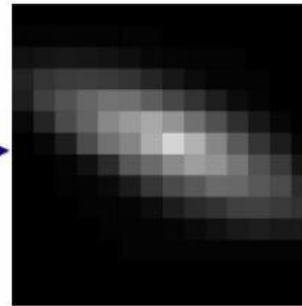
Intrinsic galaxy
(shape unknown)



Gravitational lensing
causes a **shear (g)**



Atmosphere and telescope
cause a convolution



Detectors measure
a pixelated image

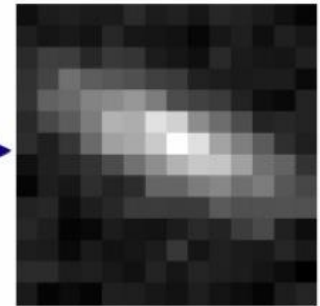
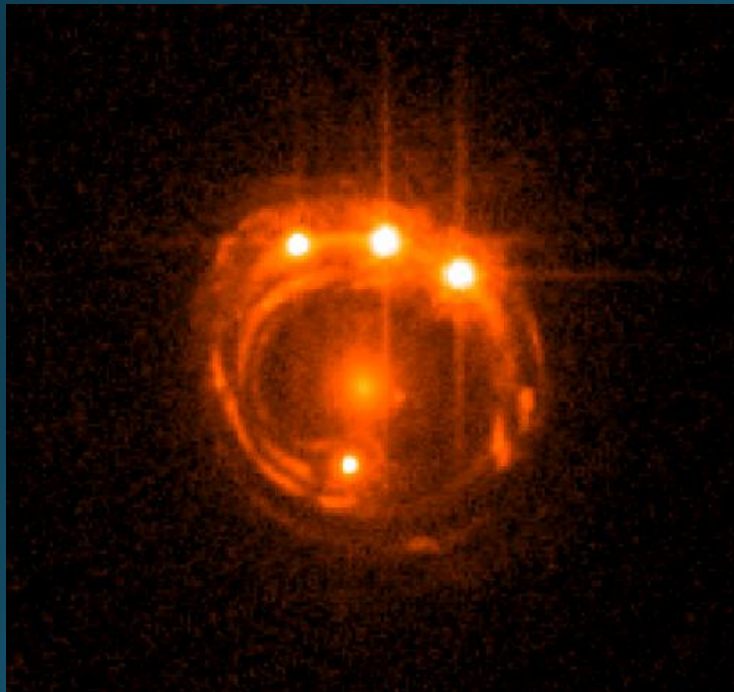
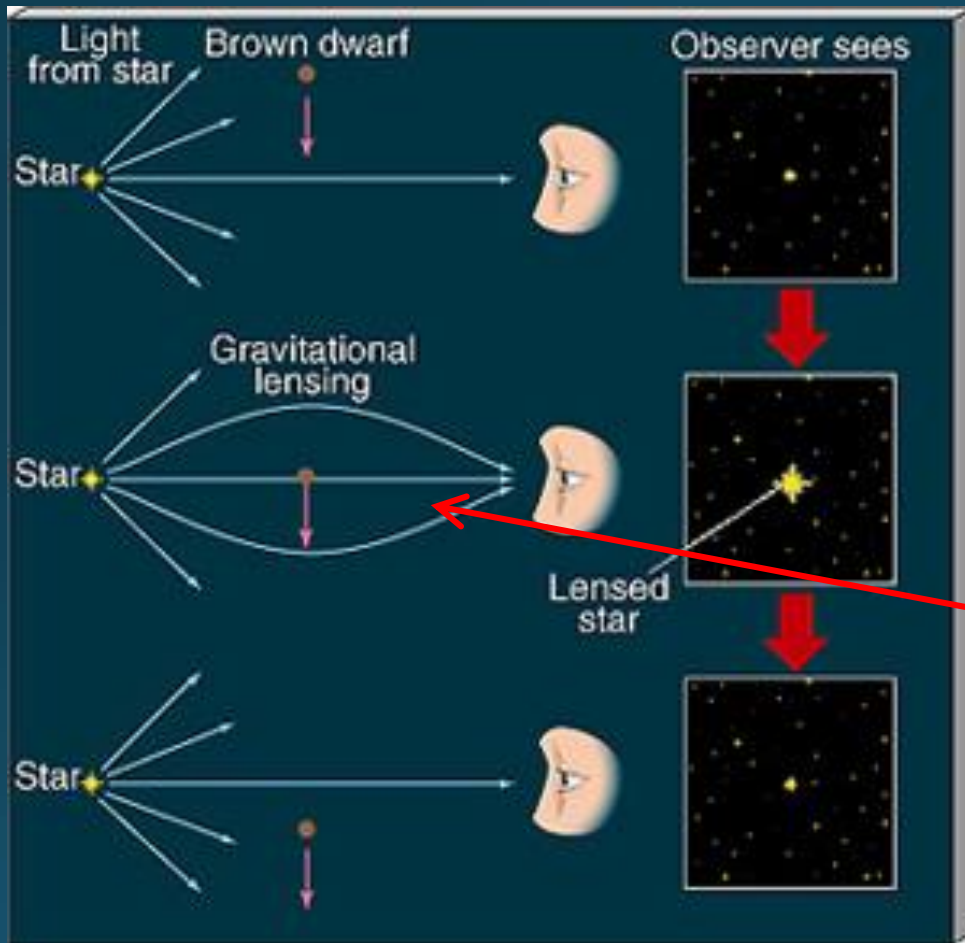


Image also
contains noise

Intermission: Strong or weak lensing?



Different types of lensing III: Microlensing



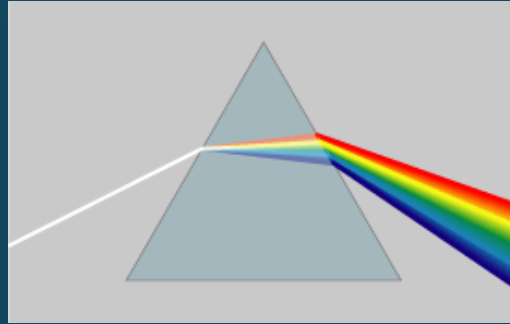
Microlensing is a special, time-dependent case of strong lensing. There's also nanolensing, attolensing, femtolensing...

The angle between images is at the microarcsecond level if the lens has the mass of a star or planet

Unresolvable with current telescopes → Observer sees just one image!

Gravitational lensing is achromatic

- Glass lenses are chromatic



- Gravitational lenses are achromatic
 - But note: GL may still alter the colour profiles of extended sources experiencing non-uniform magnification



Unlensed source

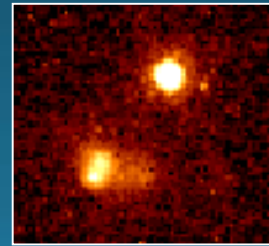
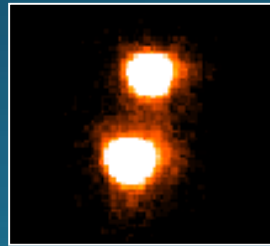


Lens magnifies
red area



Total colour
becomes redder

Strong lensing: Multiply-imaged quasars I



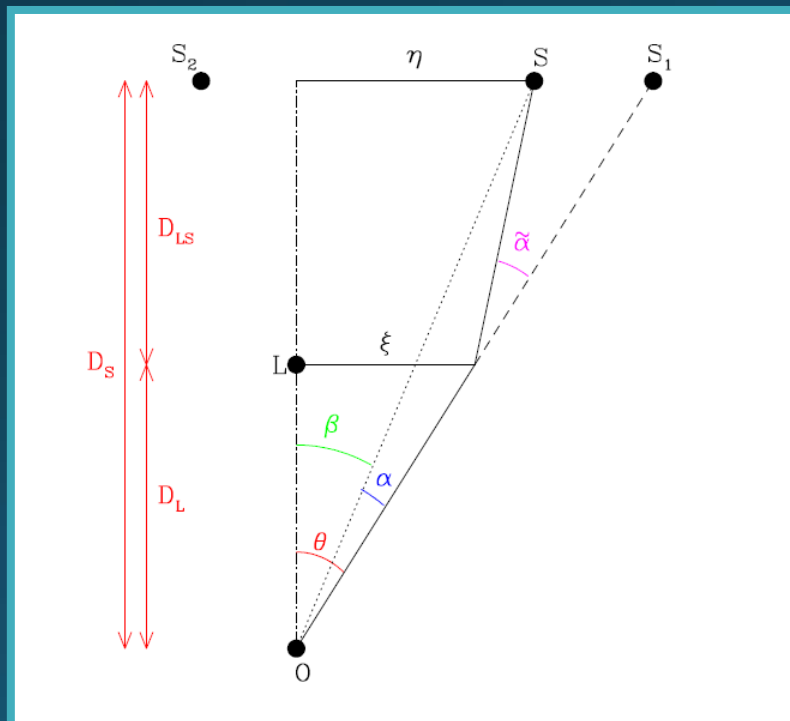
Multiply-imaged quasars II: Measuring the Hubble parameter

$$\tau(\vec{\theta}, \vec{\beta}) = \tau_{\text{geom}} + \tau_{\text{grav}} = \frac{1+z_L}{c} \frac{D_L D_S}{D_{LS}} \left(\frac{1}{2} (\vec{\theta} - \vec{\beta})^2 - \psi(\theta) \right).$$

Time delay

Measured

Depends on lens model



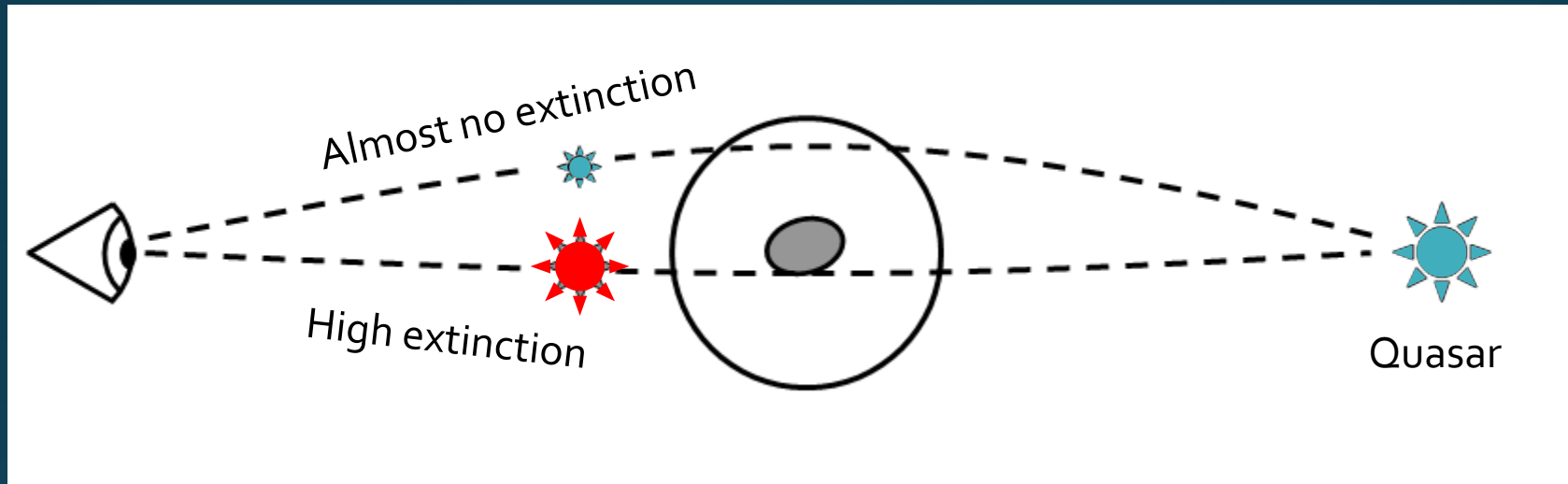
Angular size distances -
Depend on cosmology (mostly H_0)

$$\psi(\theta) = \frac{D_{LS}}{D_L D_S} \frac{2}{c^2} \int \Phi(r) dz$$

Projected
gravitational
potential

3D gravitational potential
(depends on density
profile of lens)

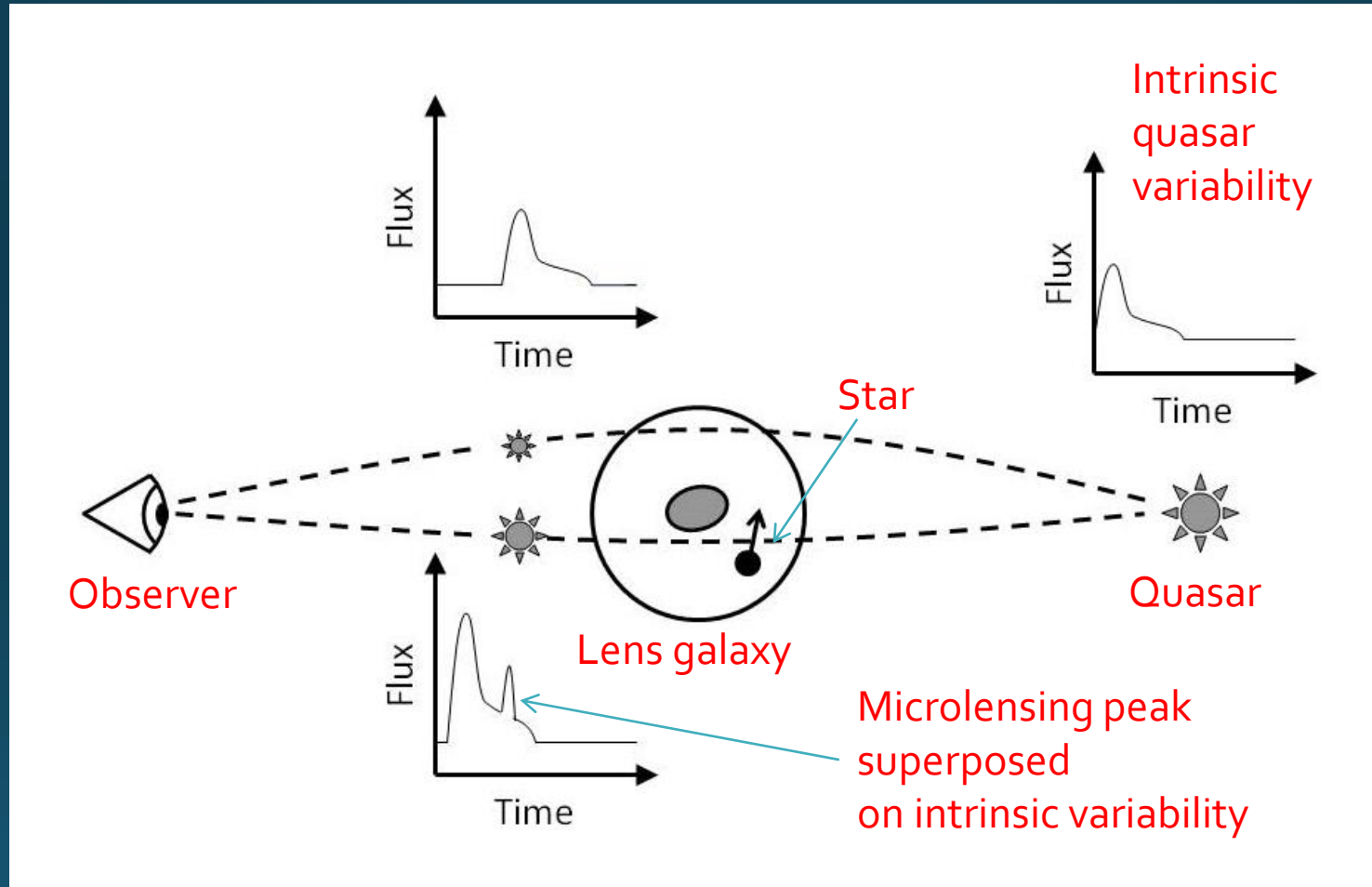
Multiply-imaged quasars III: Dust extinction



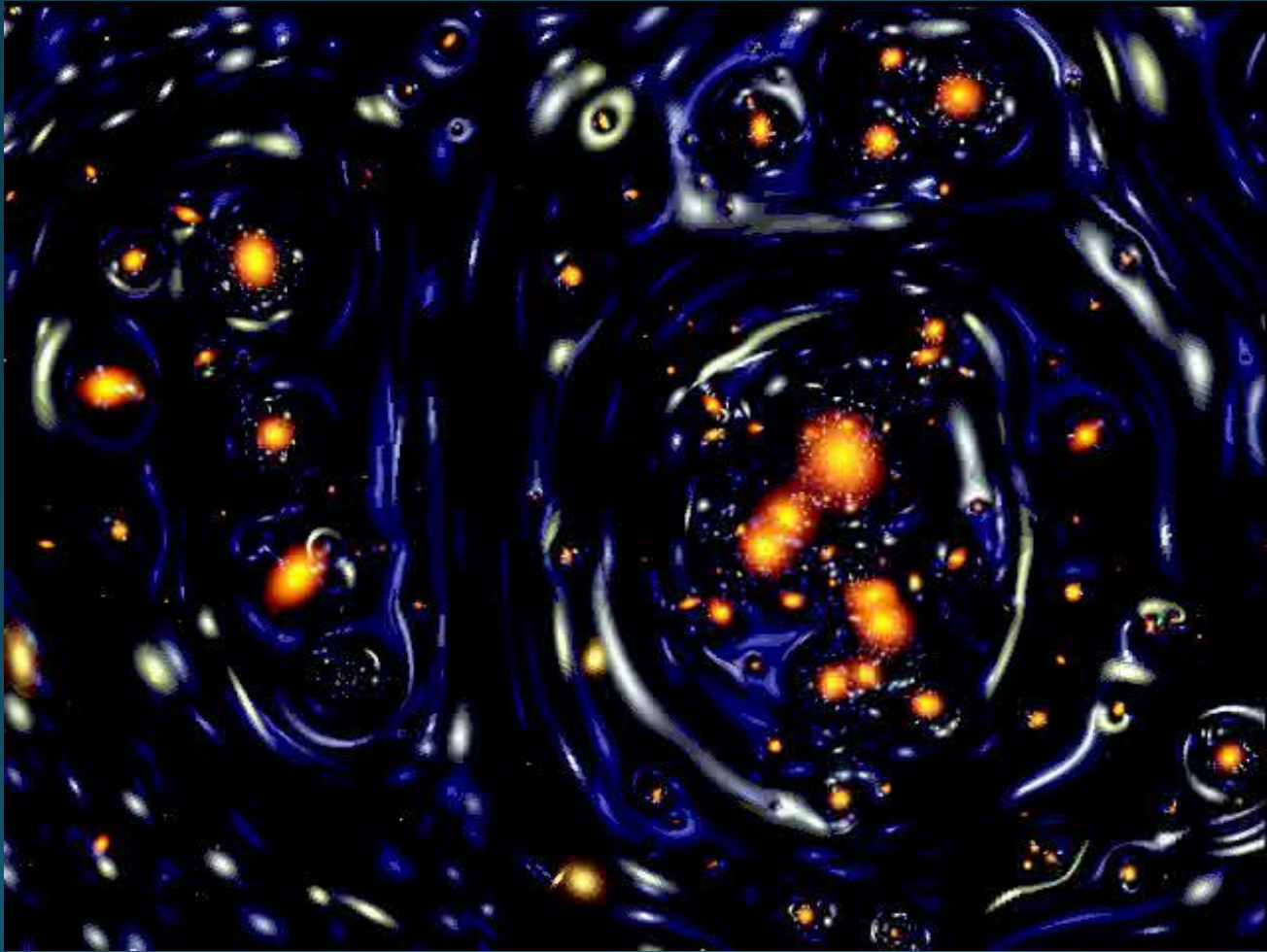
Lens galaxy with dark halo

Colour differences between images →
Extinction law measurement at high z

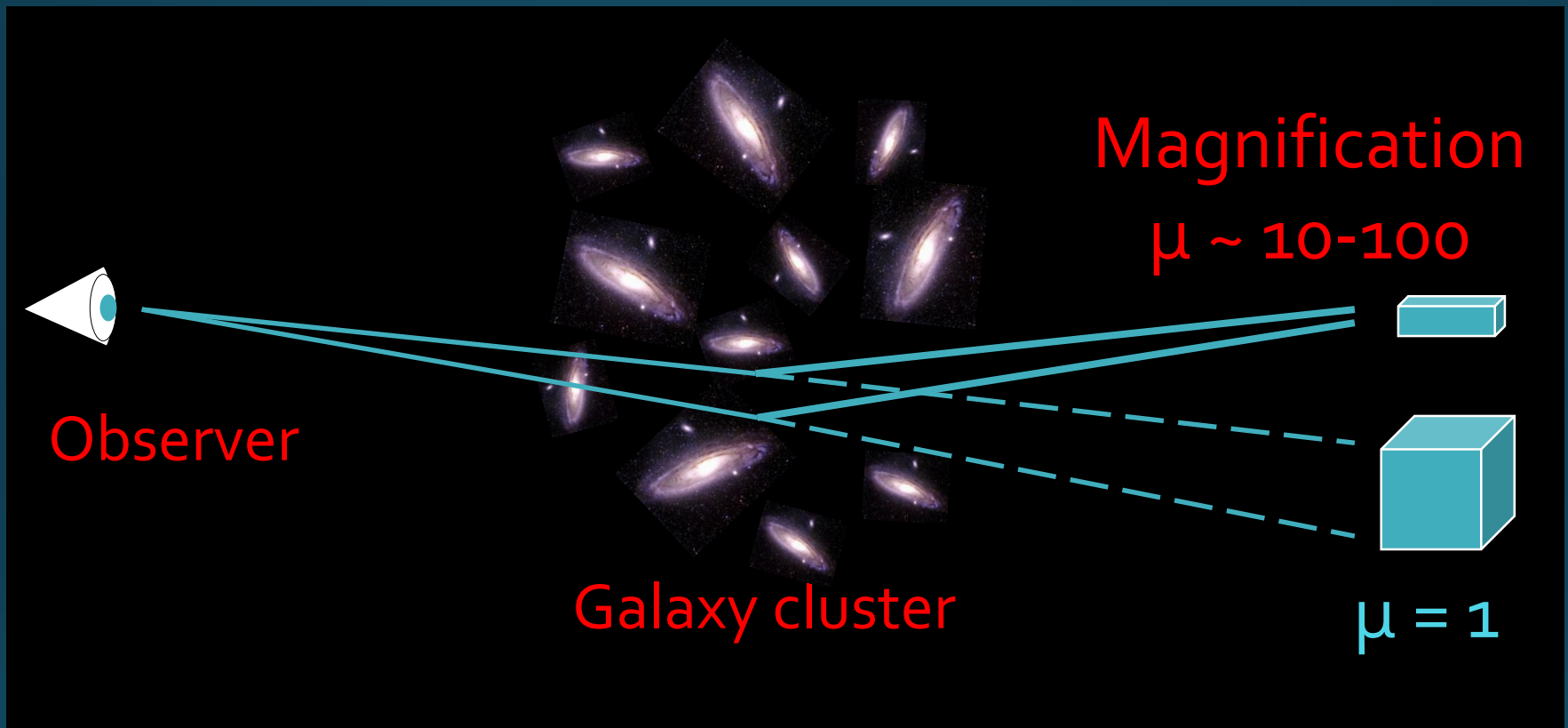
Microlensing in multiply-imaged quasars as a probe of stars in the lens galaxy



Strong lensing in clusters I

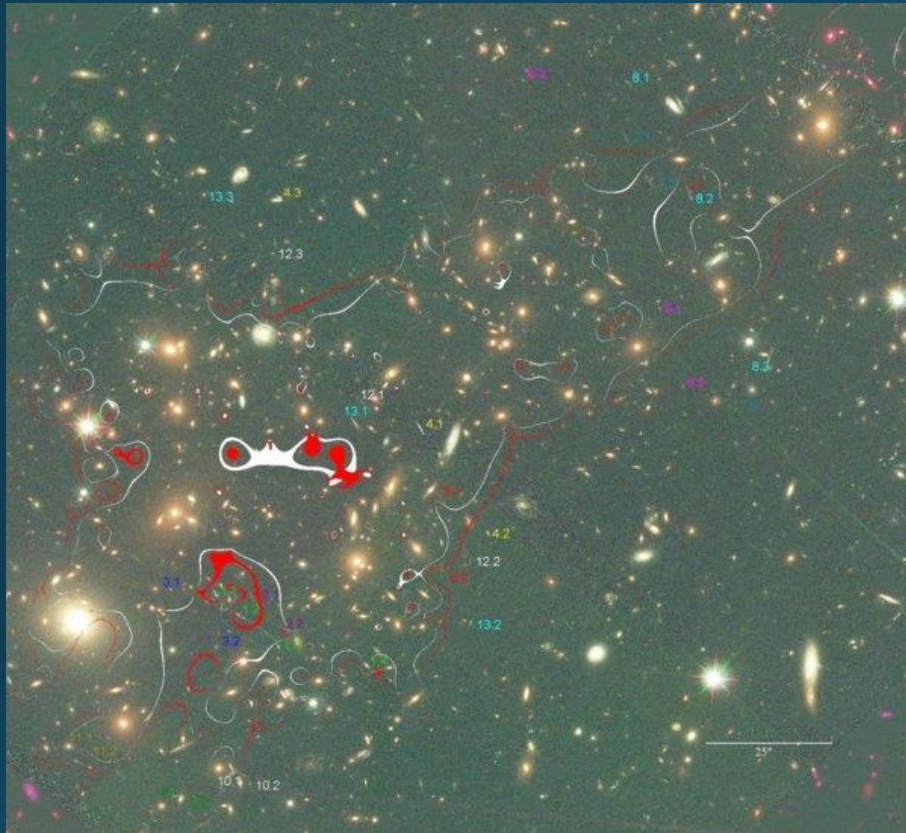


Lensing as gravitational telescopes

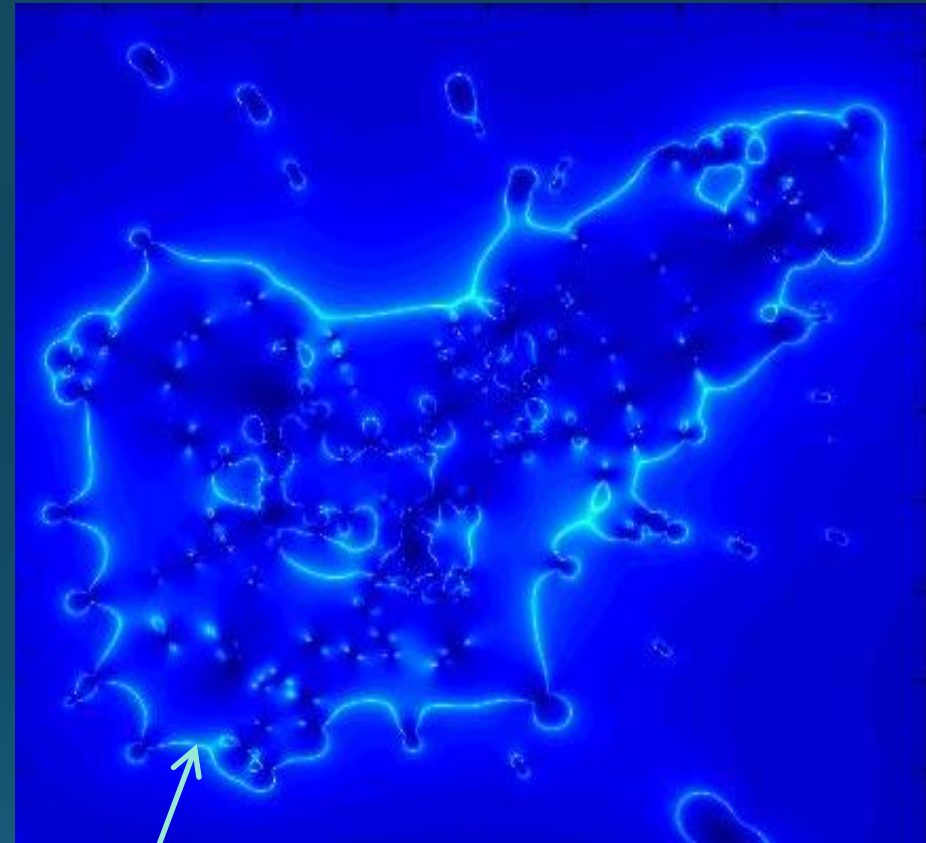


Lensing makes background objects brighter/bigger by a factor μ , but also zooms in on a volume that is smaller by the same amount
→ Very rare types of objects may be impossible to detect this way

Strong lensing in clusters II



Galaxy cluster



Magnification map

The magnification attains its highest value along a narrow strip – the critical line

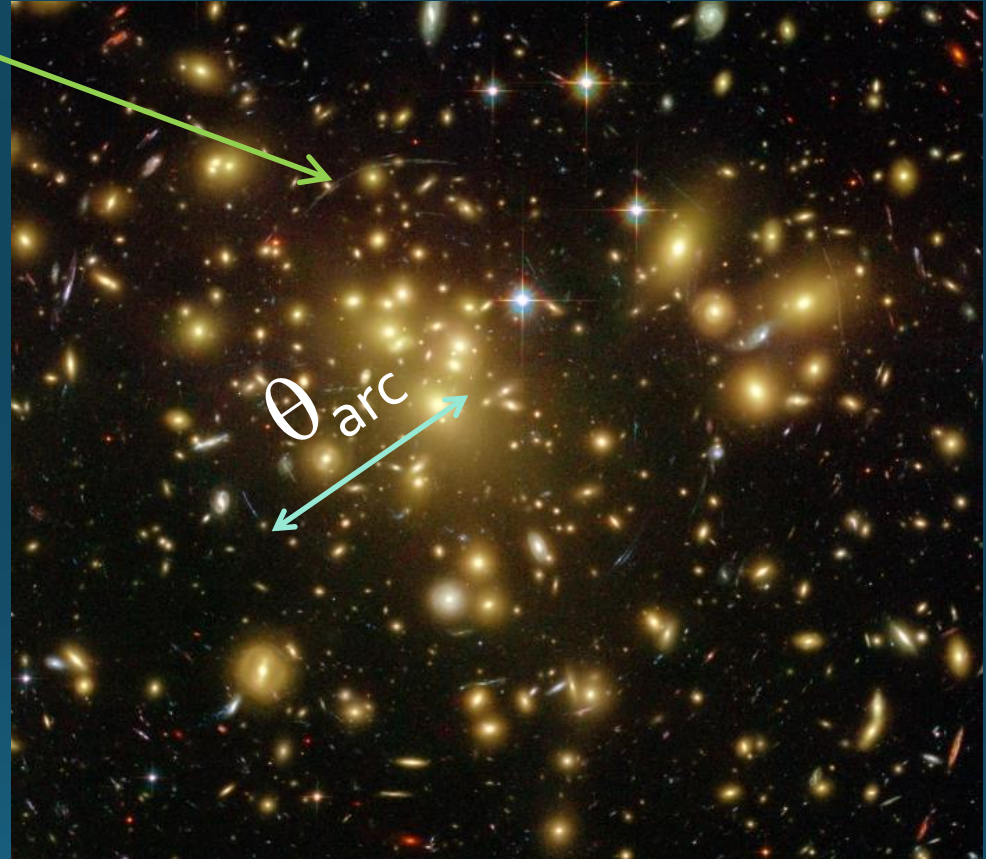
Strong lensing in clusters III

Giant arc

Giant arcs can be used to assess:

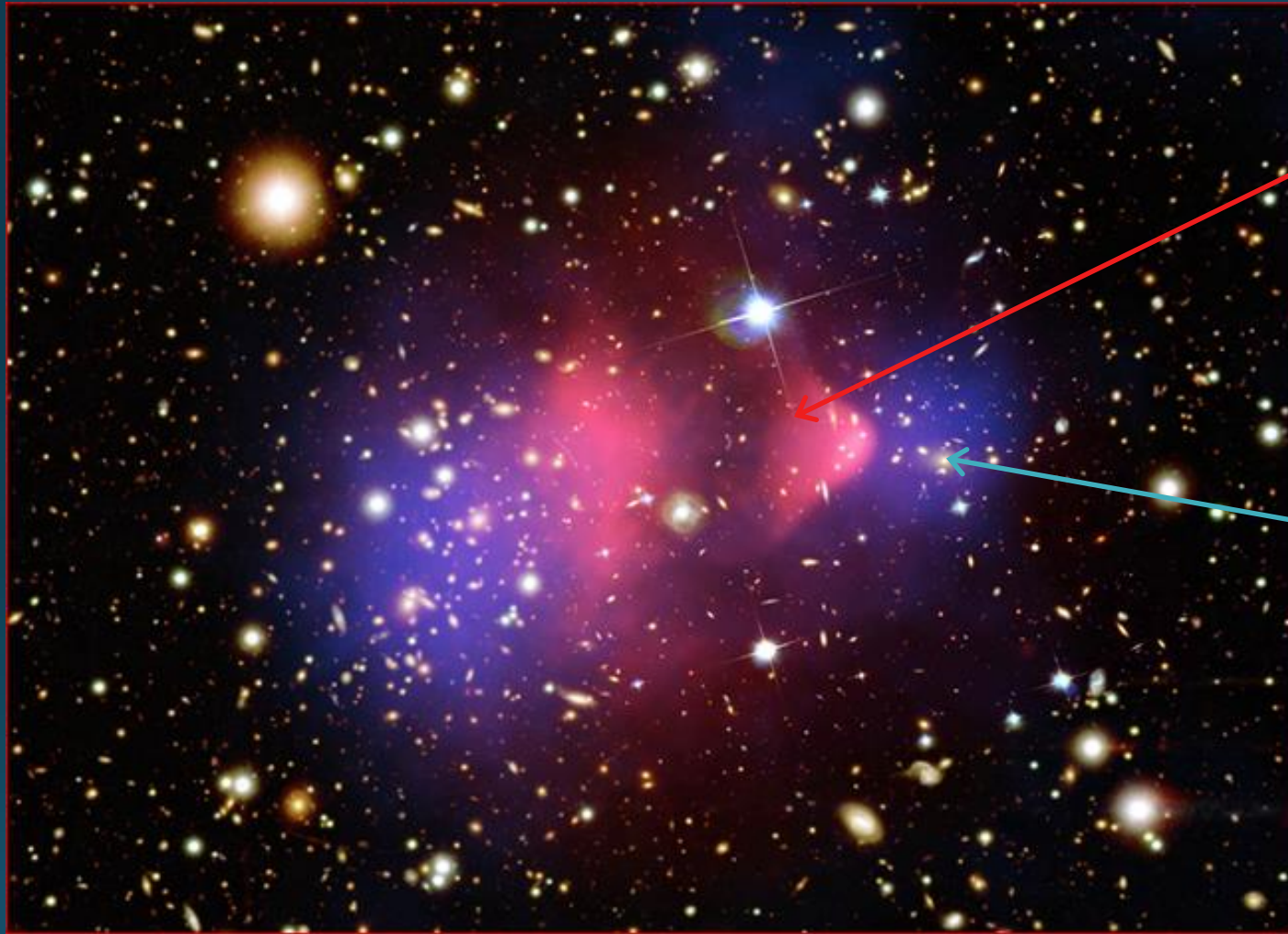
- Enclosed mass
- Cluster shape
- Density profile

(through arc curvature vs. θ_{arc})



$$M(< \theta_{\text{arc}}) = 1.1 \times 10^{14} M_{\text{solar}} \left(\frac{\theta_{\text{arc}}}{30''} \right)^2 \left(\frac{D_L}{1 \text{ Gpc}} \right)$$

Dark matter mapping – 2D

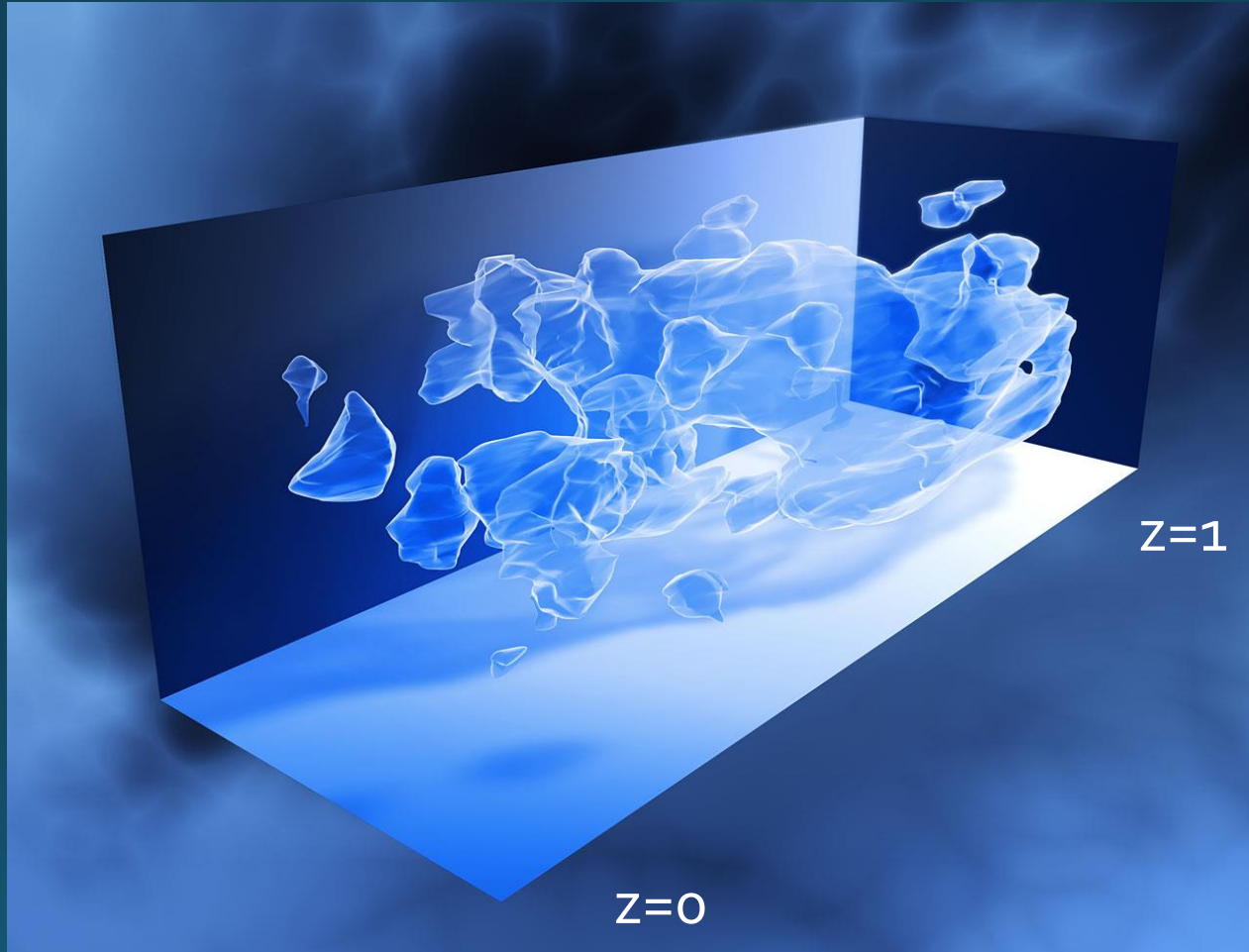


X-ray gas
(believed to
dominate
baryon
budget)

Overall
matter
distribution
(dark matter)
from weak
lensing

The bullet cluster

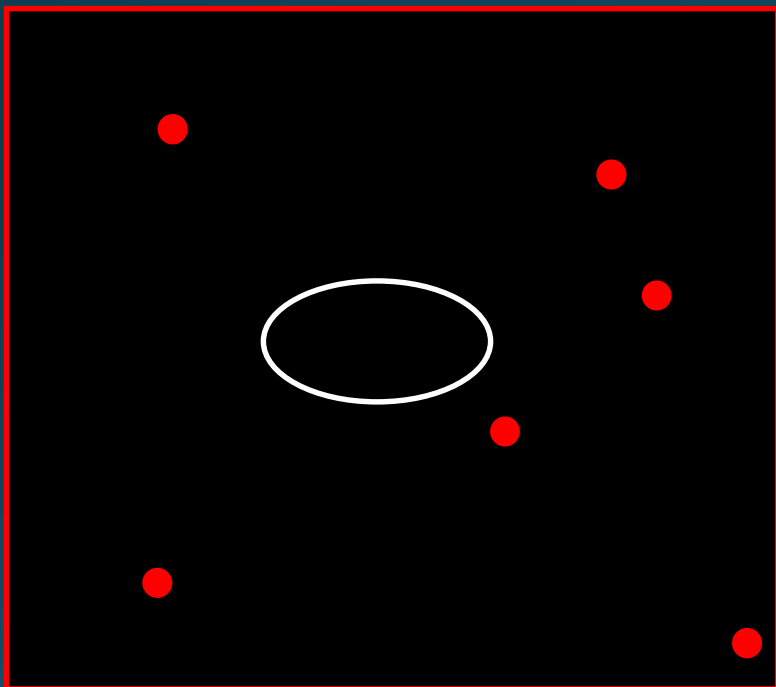
Dark matter mapping – 3D



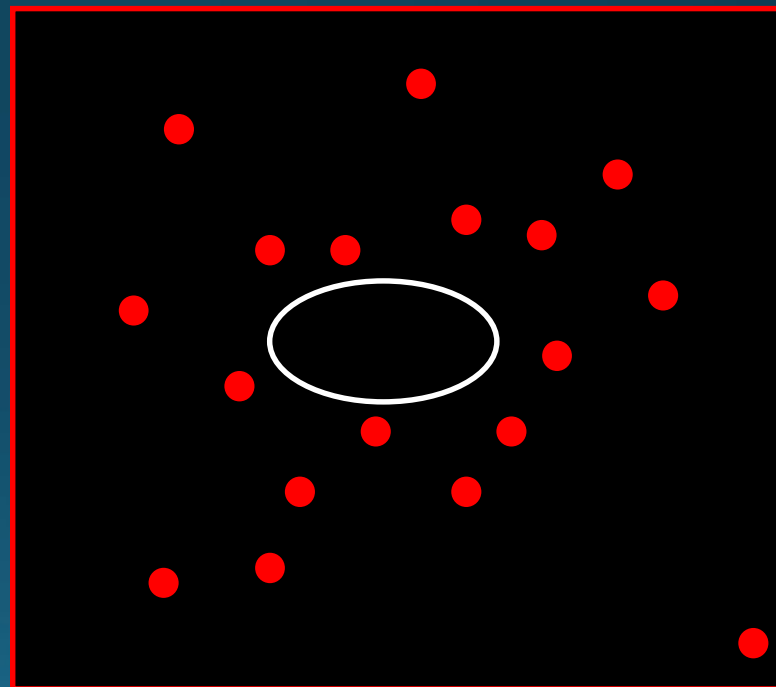
Dark matter tomography in the COSMOS survey
based on weak lensing

Magnification bias

A flux-limited survey: Containing objects with fluxes higher than a certain magnitude threshold



True flux-limited distribution
around massive foreground
object



Observed flux-limited distribution
around massive foreground object