Physics of Galaxies 2020
Lecture 7: Groups, clusters and lensing

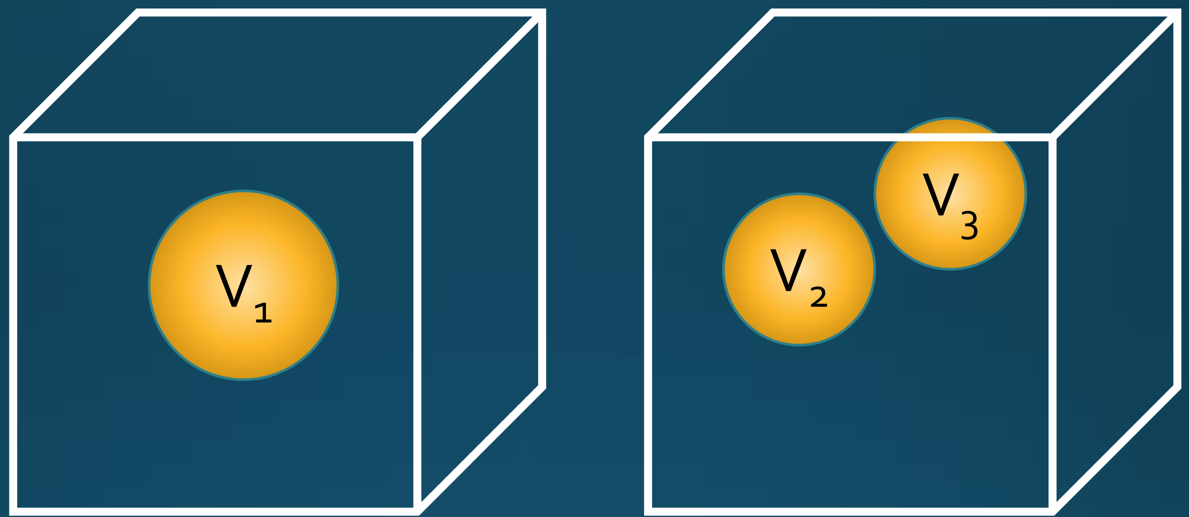
Questions from last time: Cloud sizes in the broad-line region

1. Emission line ratios → Density and temperature of gas → Intrinsic line luminosity per volume
2. Observed line flux + Distance from observer to AGN (based on redshift) → Observed line luminosity
3. Observed line luminosity / Intrinsic line luminosity per volume = total volume in line-emitting gas
4. Estimate total BLR size using reverberation mapping
5. Total volume in line-emitting gas much smaller than total BLR volume → Volume filling factor
6. Compare ionzing continuum luminosity with line luminosity → Estimate of fraction (solid angle captured by clouds)
7. Filling factor & solid angle covering fraction → Size of individual clouds

How does that last step work?

Spherical clouds assumed…

BLR region volume element



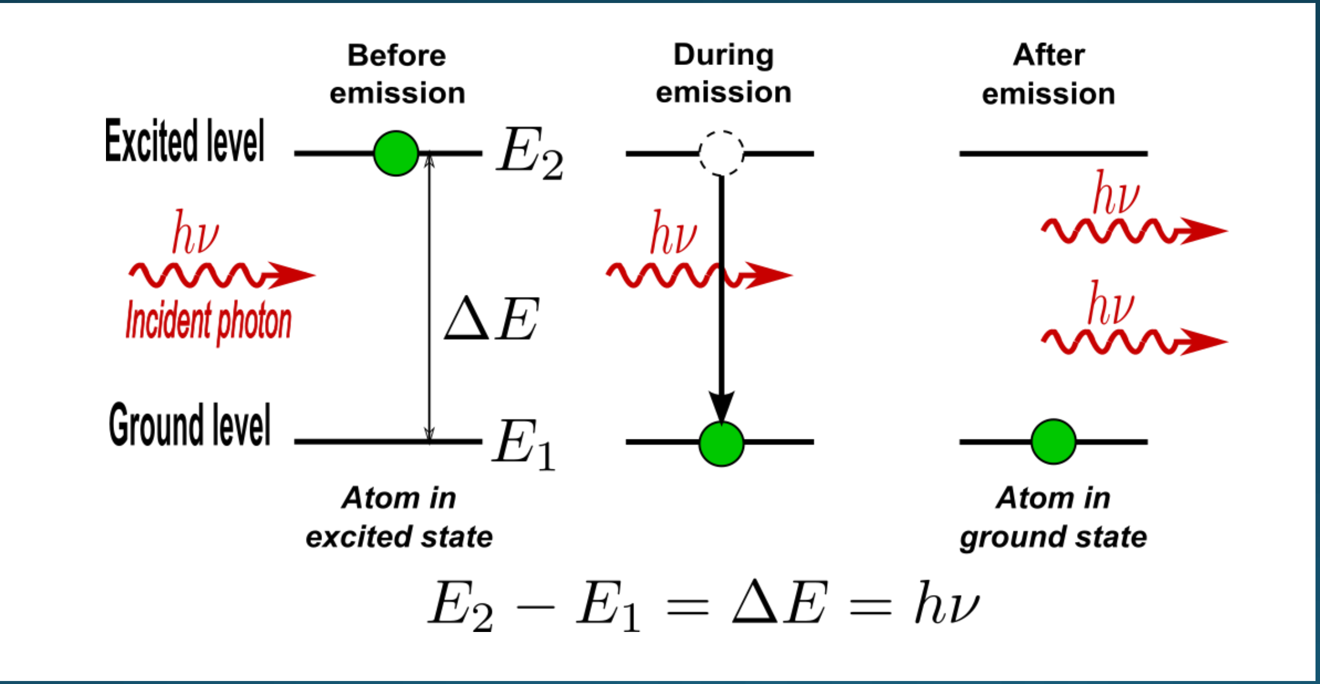
Total line-emitting volume (same in both cases):
$V_1 = V_2 + V_3$

Same volume element, as seen from accretion disk

2D projection (used by solid angle constraint)
$A_1 \neq A_2 + A_3$

Questions from last time: Water masers in AGN

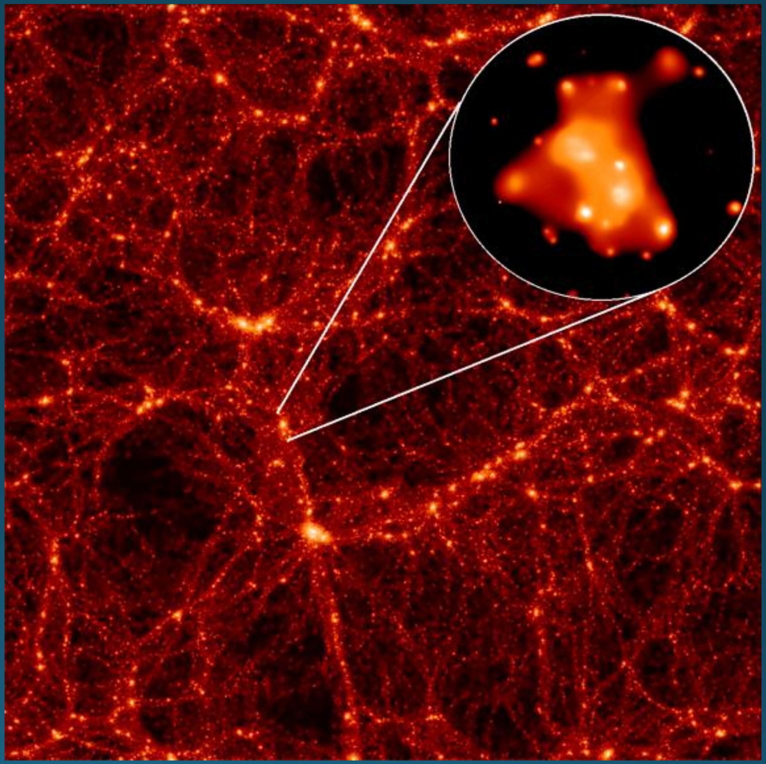
The principle behind a maser



This becomes an efficient emission process only if there is some pumping mechanism that creates an overabundance of molecules (population inversion) in the excited state above. In the case of a water molecule maser, the pumping comes from shock waves that permeate the gas. For hydroxyl masers in AGN, far-IR photons are believed to cause the pumping.

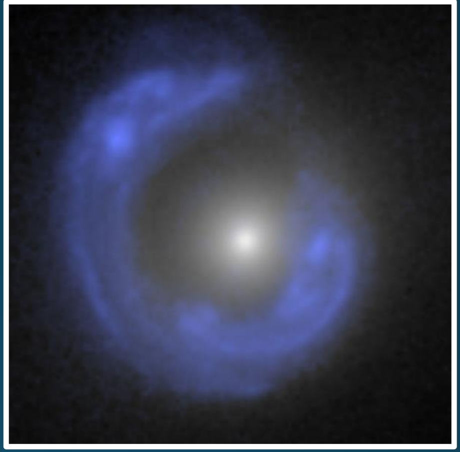
Outline: Galaxy groups & clusters

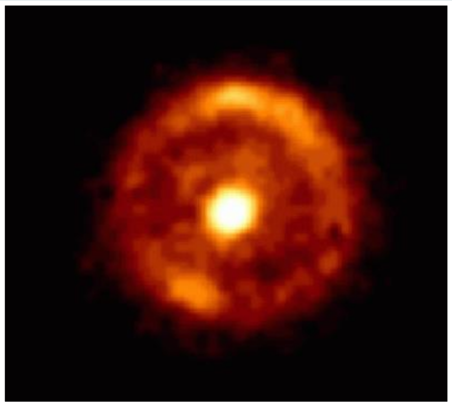
- Basic characteristics
- Gas and galaxy content
- Clusters in our vicinity
- The Sunyaev-Zeldovich effect



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:
  - σ_r~500—1200 km/s
  - Masses ~10^{14}—10^{15} $M_\odot$
- Groups:
  - σ_r~100—500 km/s
  - Masses ~10^{13} solar masses
- Typical M/L ≈ 100—500
  - A few times 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: $\geq$ 300

↓ Increasing rareness

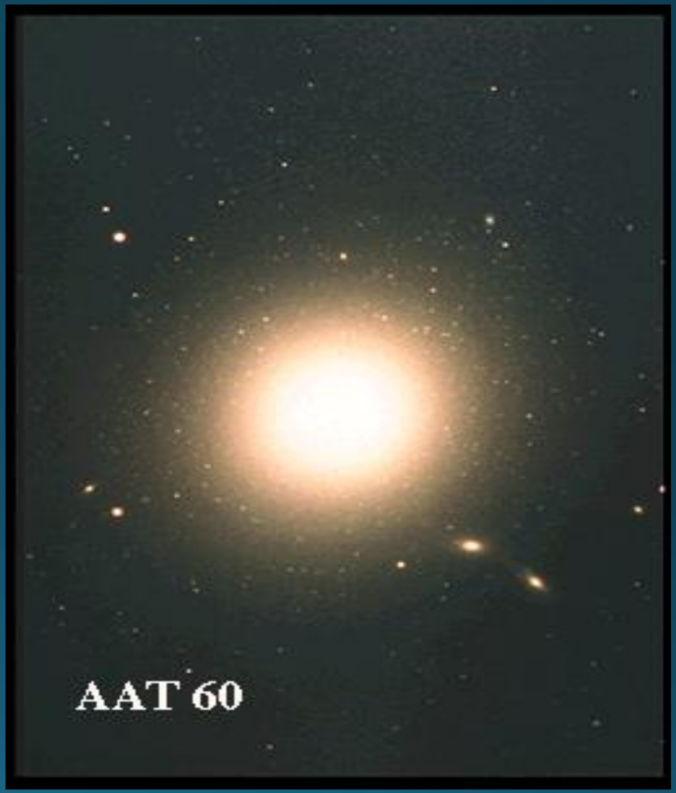
- Many other schemes in use:
  - Zwicky (Based on compactness)
  - Rood and Sastry (Based on dominant galaxy)
  - Bautz-Morgan (Based on projected distribution of 10 brightest members)

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 → E / So over time

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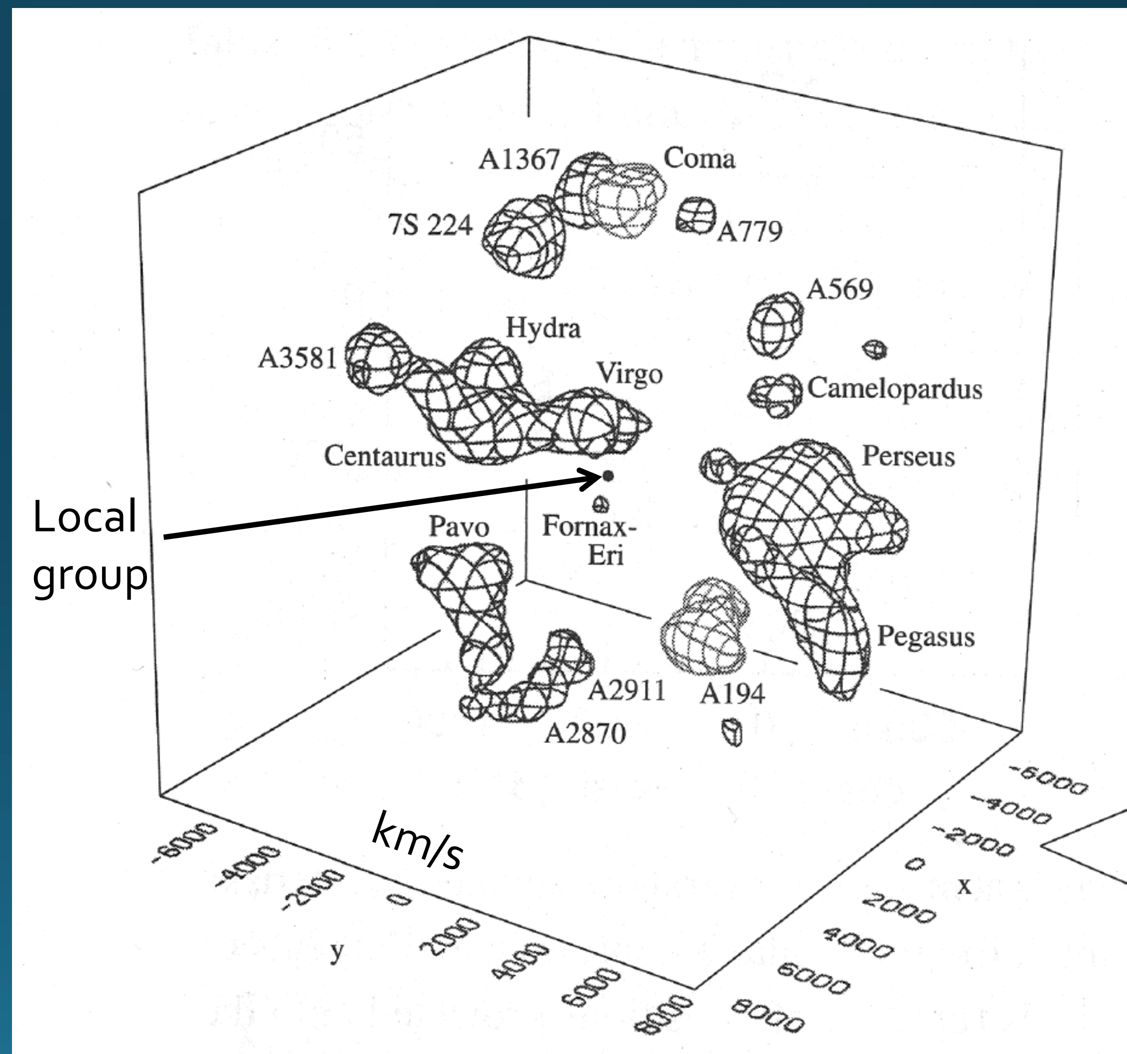
Galaxy groups & clusters in our backyard

- **Groups:** Sculptur, Fornax, Centaurus A…
- **Clusters:** Virgo, Coma, Hydra, Centaurus, Perseus…
- Superclusters:

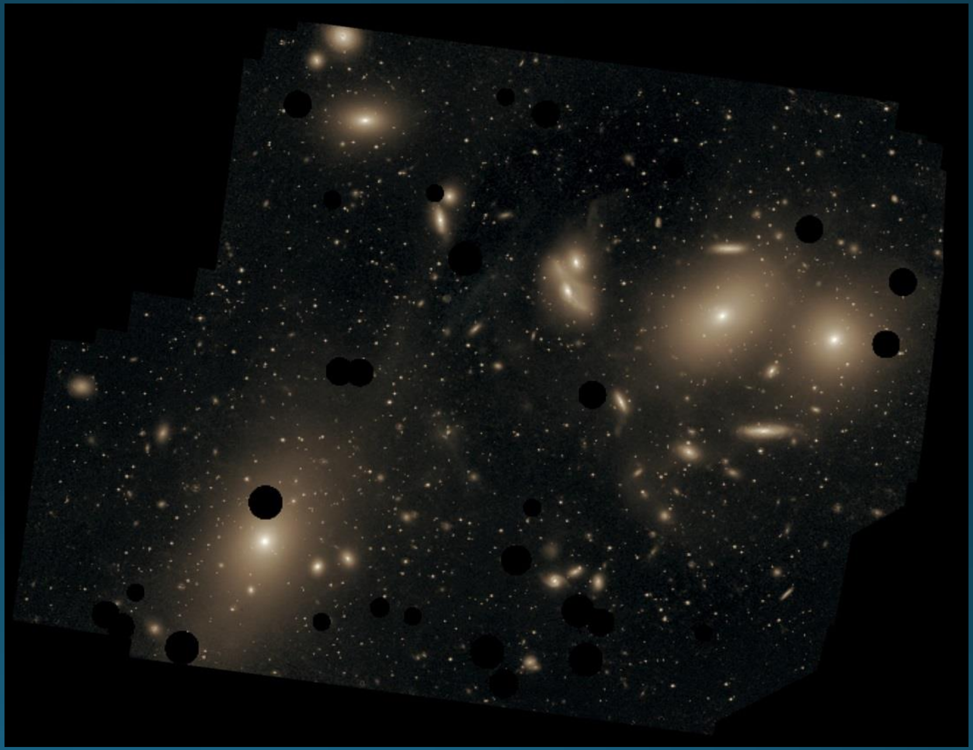
  Virgo supercluster, Hydra-Centaurus supercluster…

  (but the definitions of superclusters are messy)



Galaxy groups & clusters in our backyard II

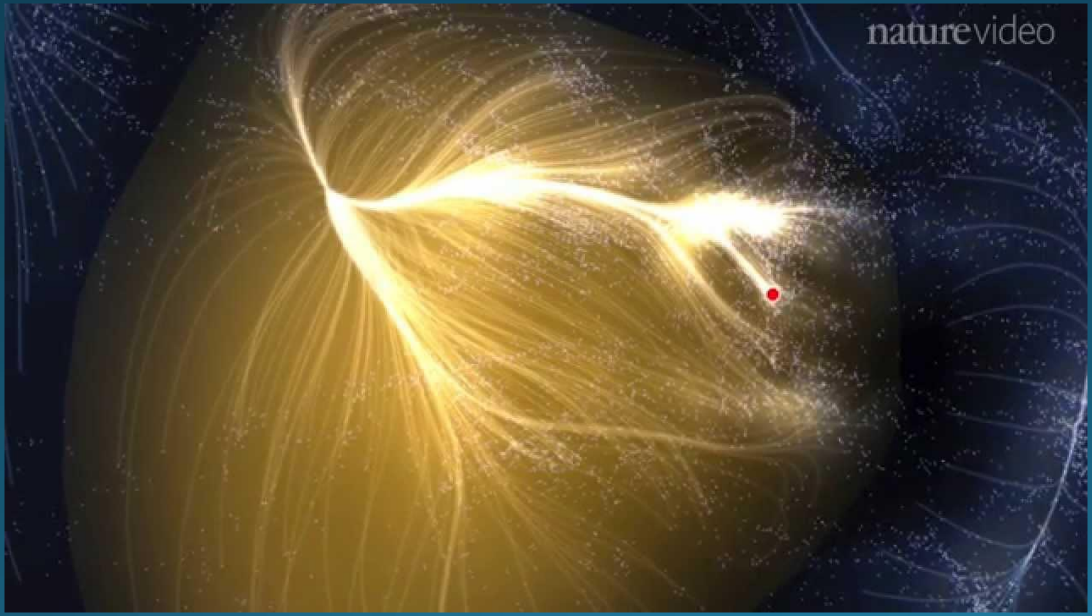
- Virgo cluster
  - Nearest large galaxy cluster with more than 2000 galaxies brighter than $M_B \approx -14$
  - Extent ~ 3 Mpc
  - Velocity dispersion $\sigma_R \approx$ 600 km/s
  - Mass ~$1\times10^{15}\ M_\odot$
  - Distance 15—20 Mpc



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 ~10^{17} $M_\odot$



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

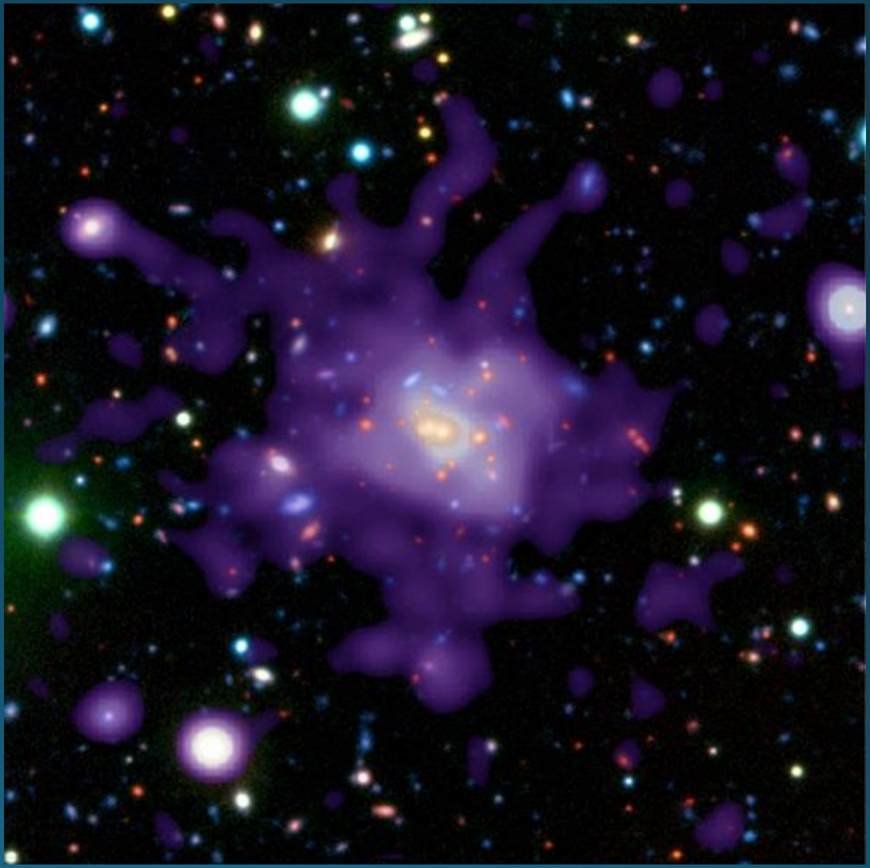
Compact groups

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

Intermission: Group or cluster?

Gas in groups and clusters

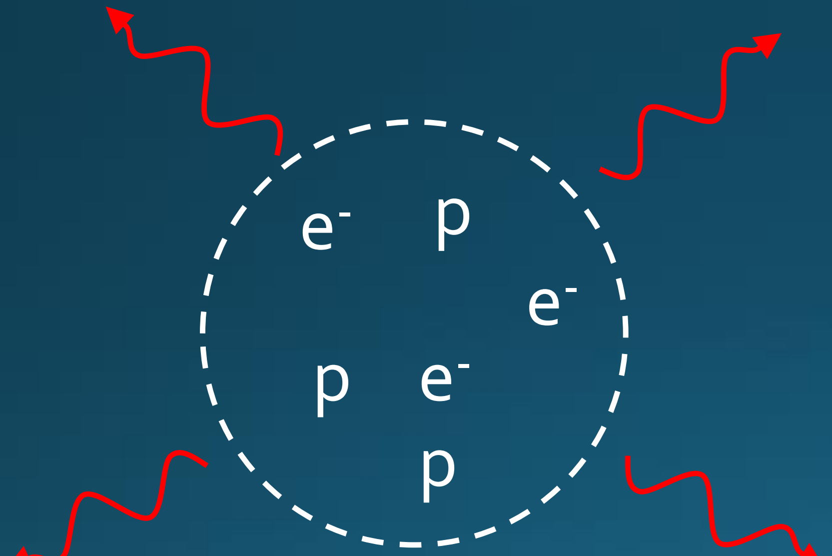
Most baryonic material in groups and clusters is not stars, but hot gas

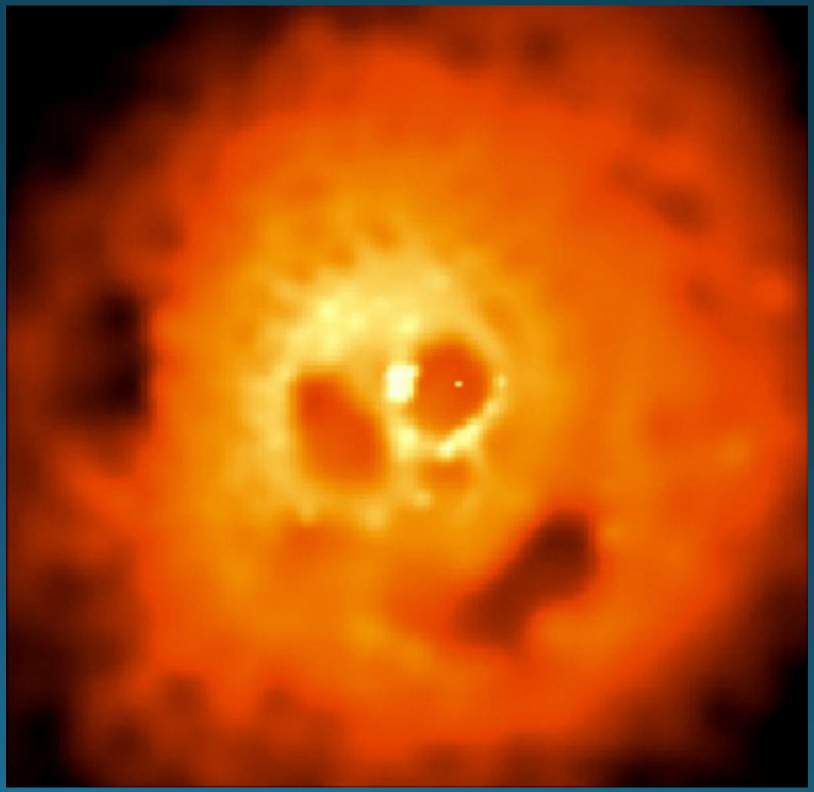


X-ray gas, $T=10^7$—10^8 K

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 → High galaxy velocities
  - $kT \sim mv^2$ → 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:

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

Gravitational radius (R_{grav})

- Hence, high cluster mass → high v → high T → 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~10% Solar

Gas in the Coma cluster

Mass estimates

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

Depends on the radiation process

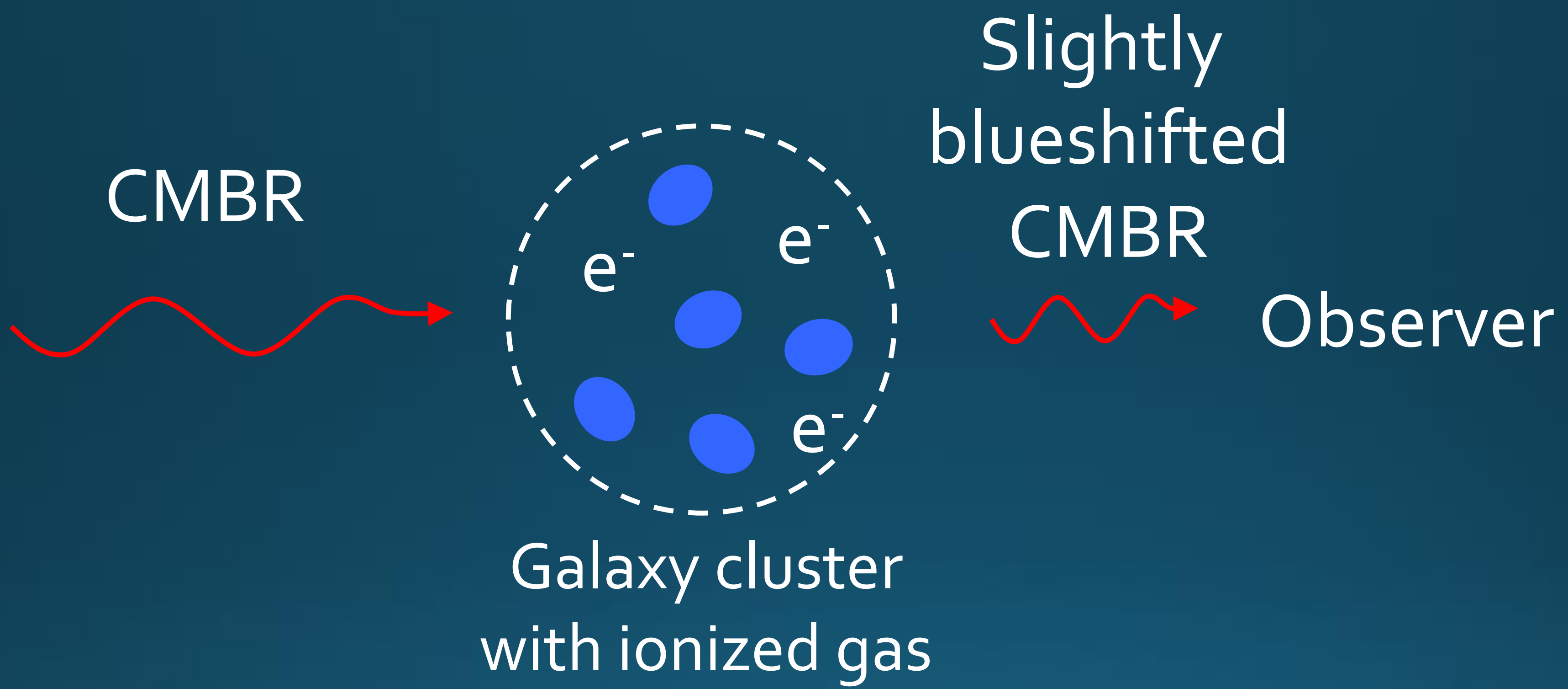
$$L = n_{\mathrm{e}} n_{\mathrm{H}} \Lambda(T)$$

Number densities

- Mass:

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

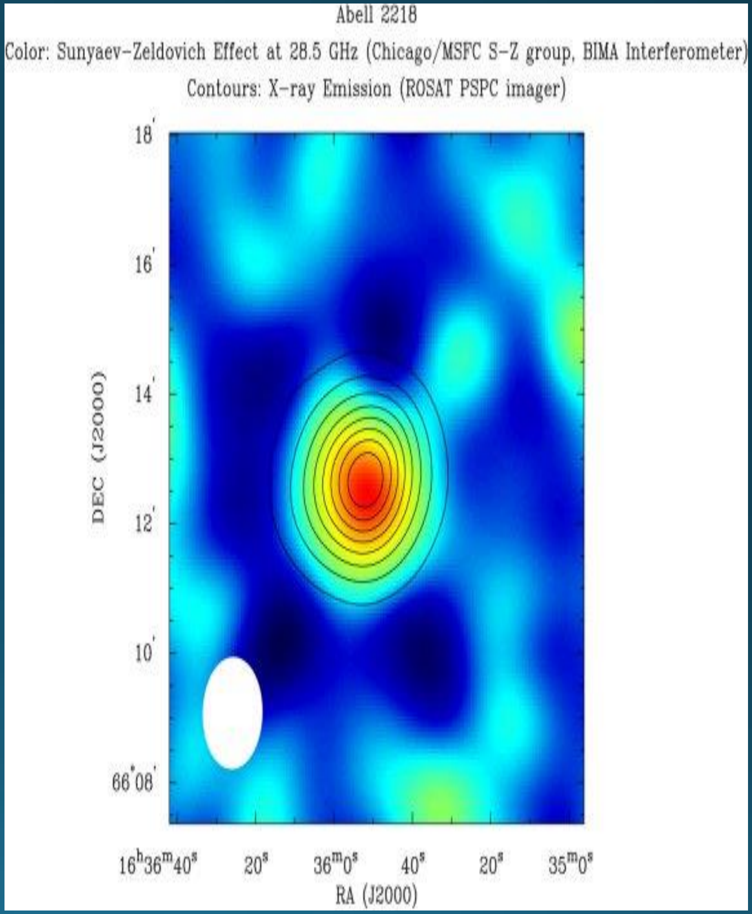
The Sunyaev-Zeldovich effect I



- 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

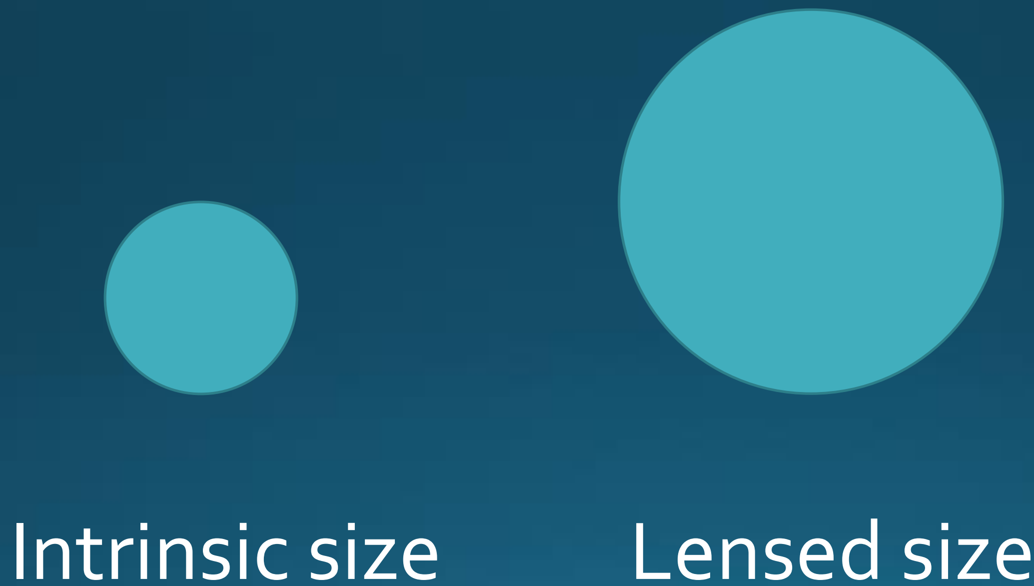
Surface brightness conserved
(as long as the whole source experiences the same magnification)

Intrinsic source size

Apparent source size
(boosted due to lensing)

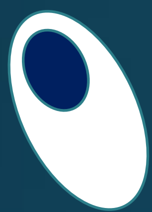
Increased size + conserved surface brighness → increased apparent flux

Intermission: What magnification?



Lensing – quick overview III

Distorted morphology



Intrinsic source morphology/orientation/parity

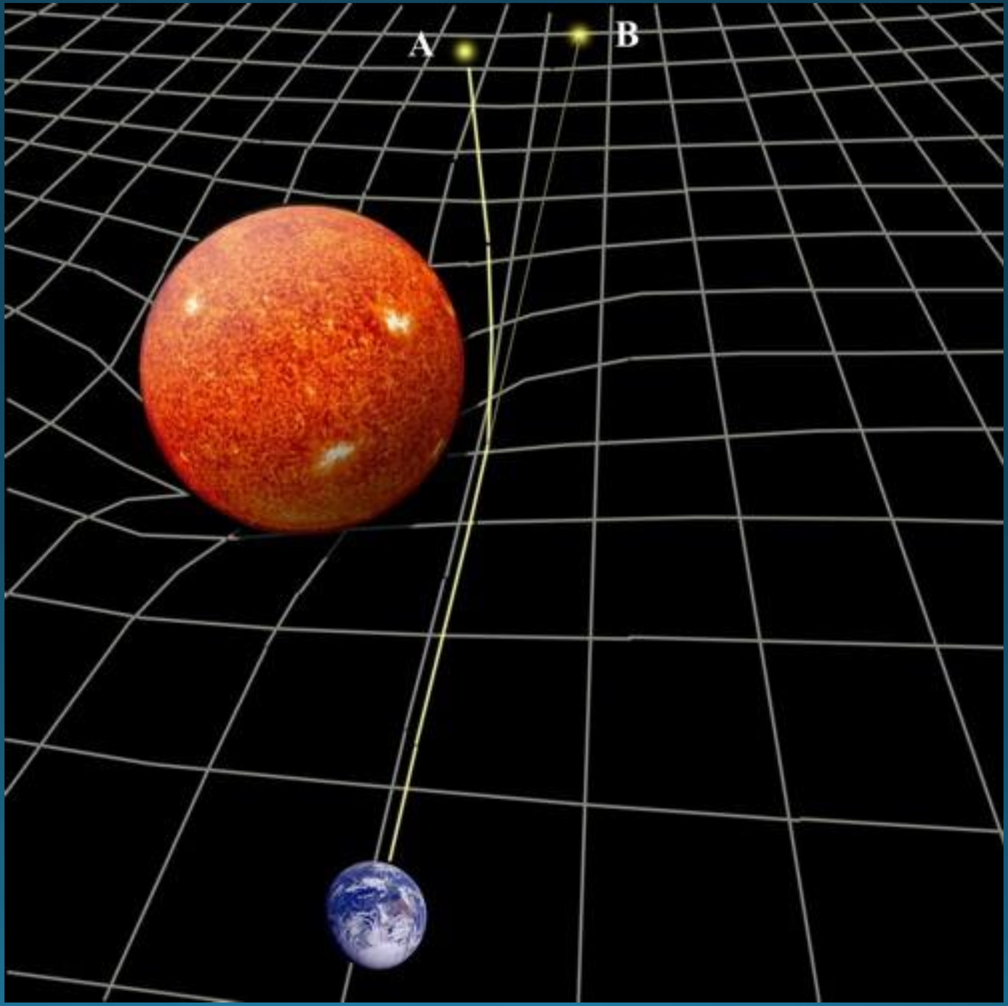
Apparent source morphology/orientation/parity

Stretched, curved and mirror-flipped!

Lensing – quick overview IV

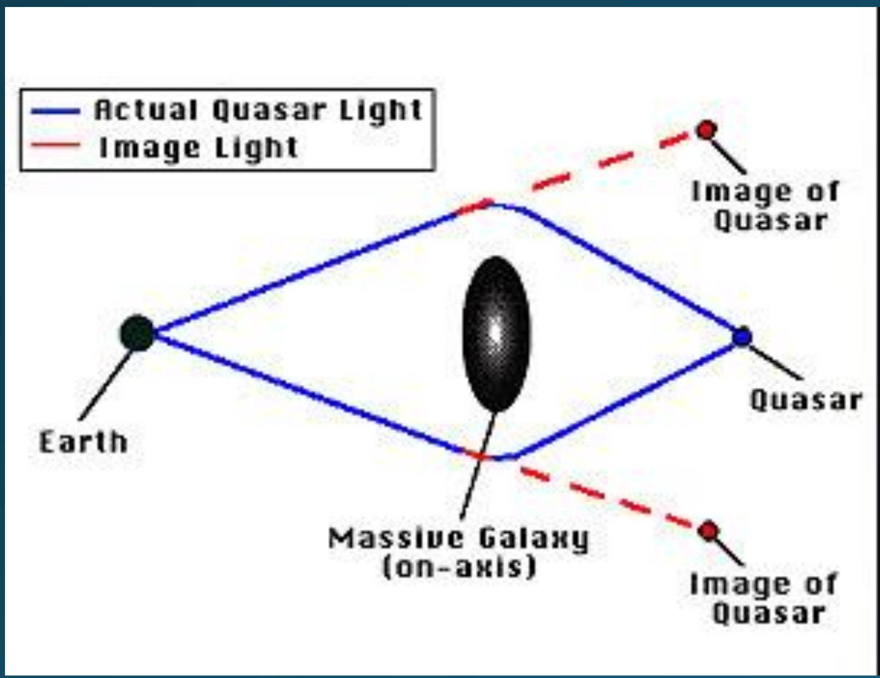
Shift in apparent positions

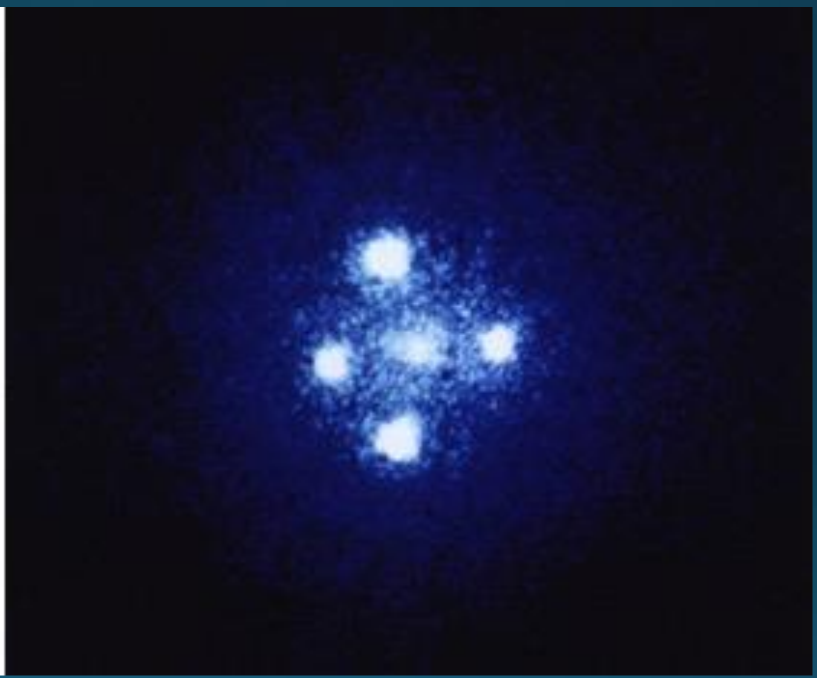
The mass of the Sun shifts the apparent positions of stars close to the limb



Lensing – quick overview V

Multiple images

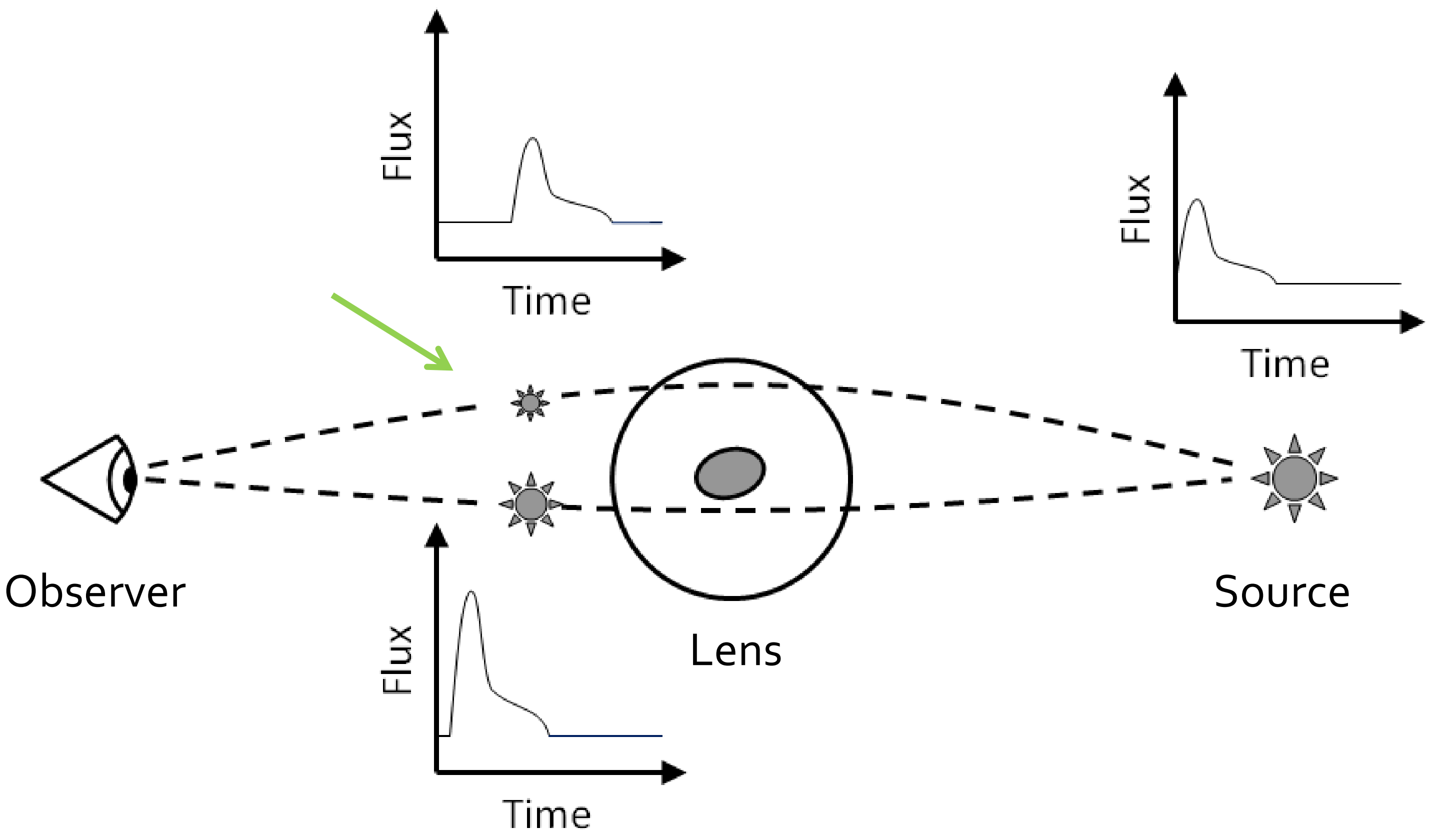




Lensing – quick overview VI

Delays in time signals

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



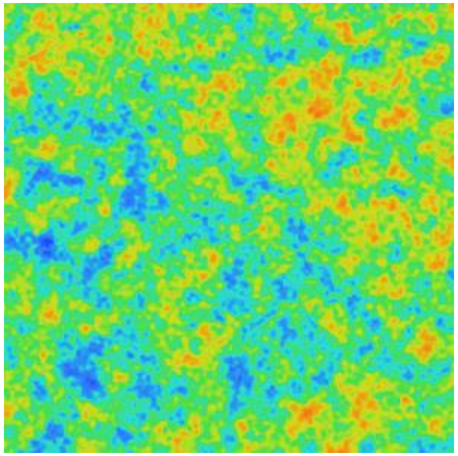
Lensing – A tool…

- 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

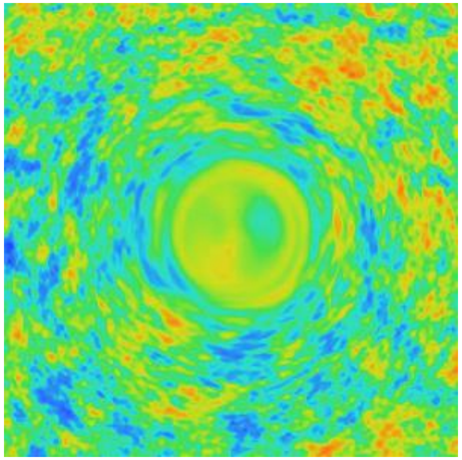
… and a nuisance

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

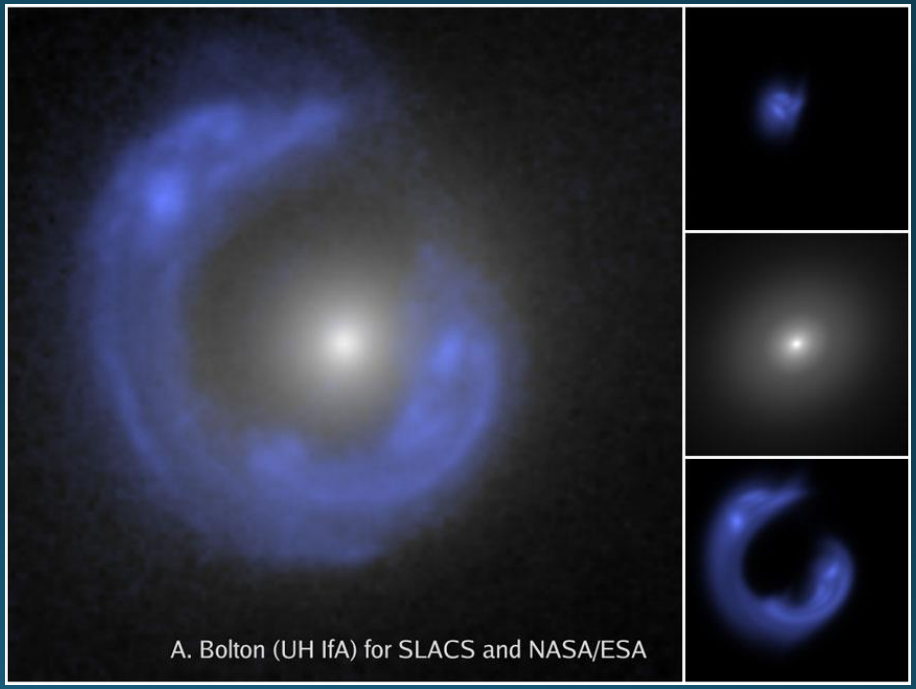


Intrinsic CMBR



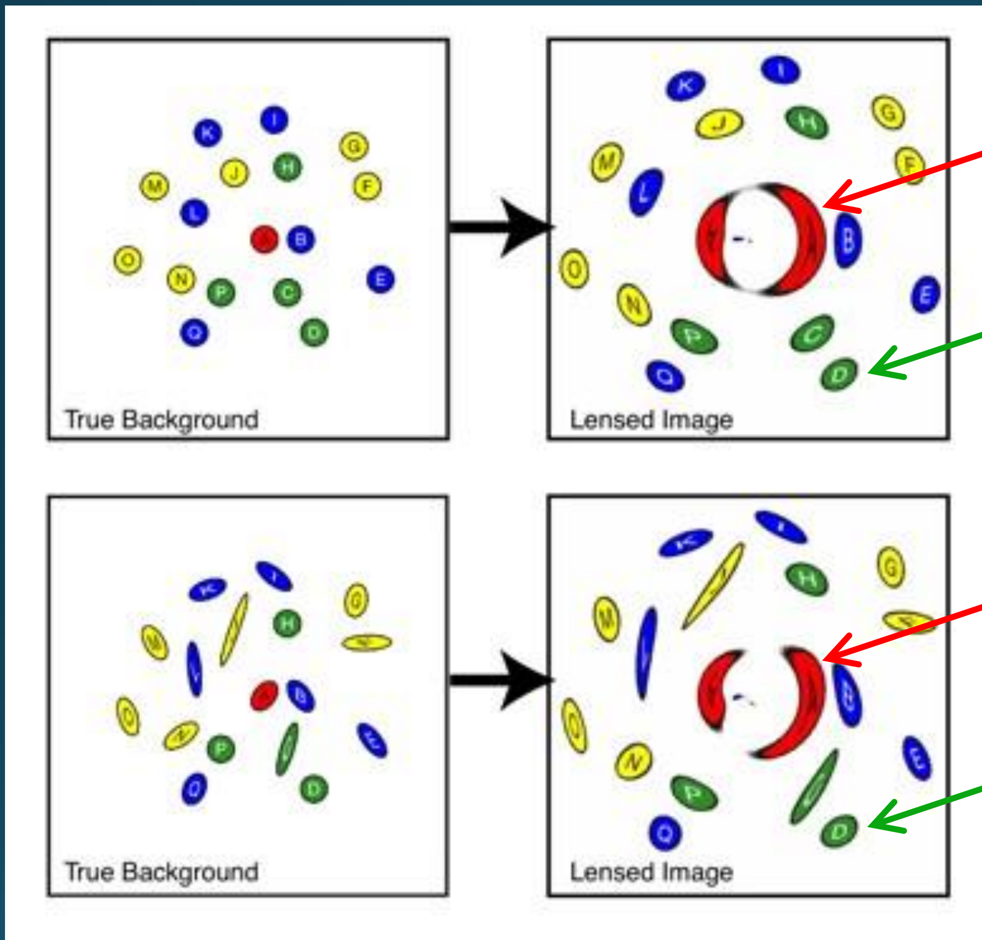
Lensed CMBR

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

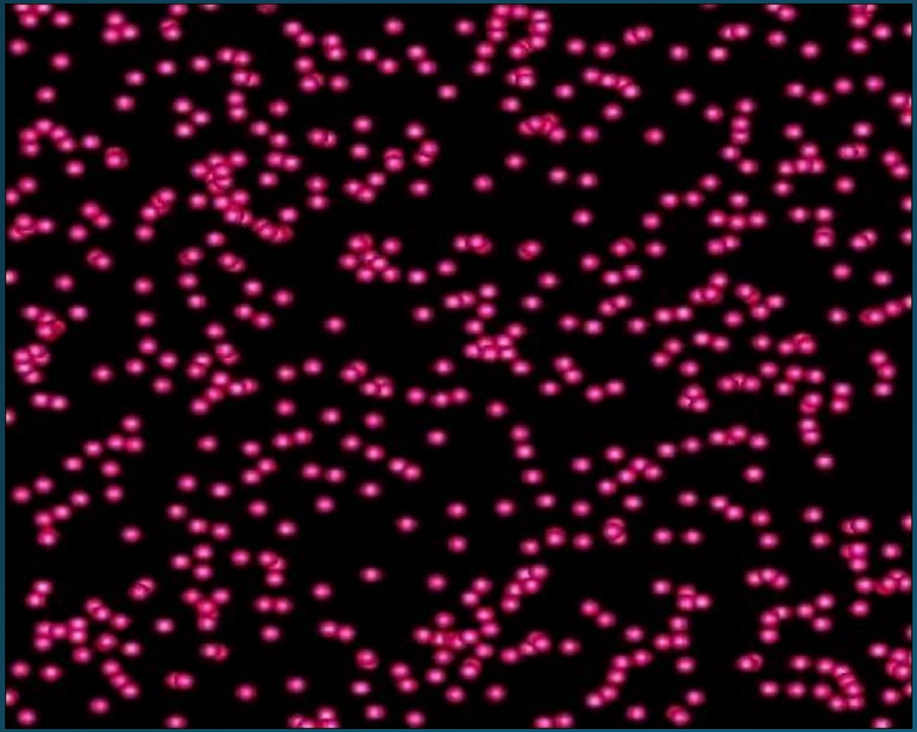
Strong lensing

Weak lensing

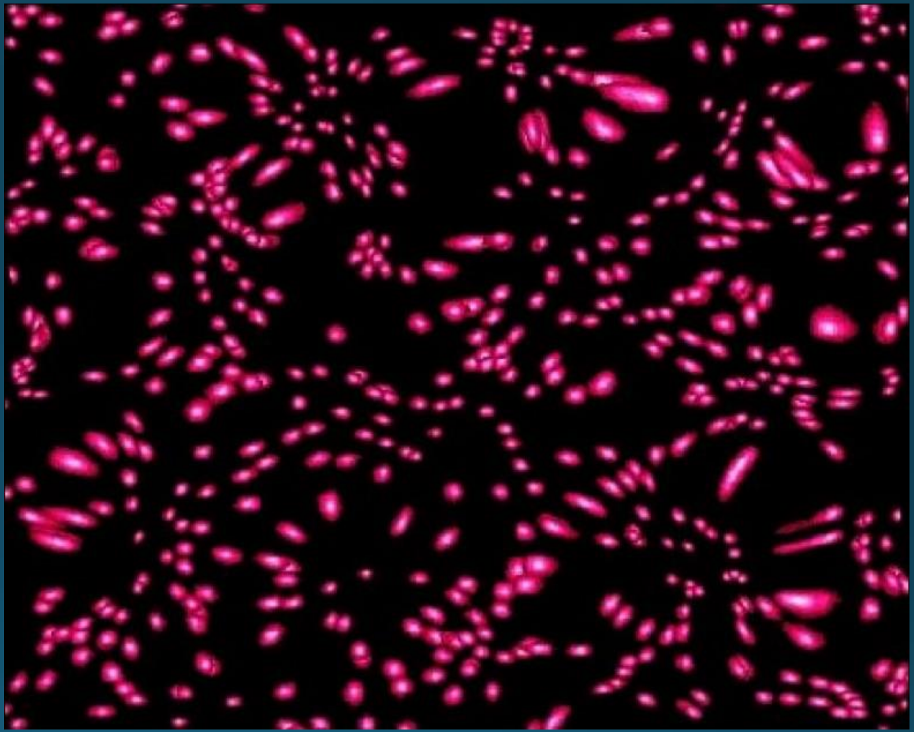
Weak lensing: Mild distortions, small magnifications

Very common!

Different types of lensing II: Weak lensing



Unlensed

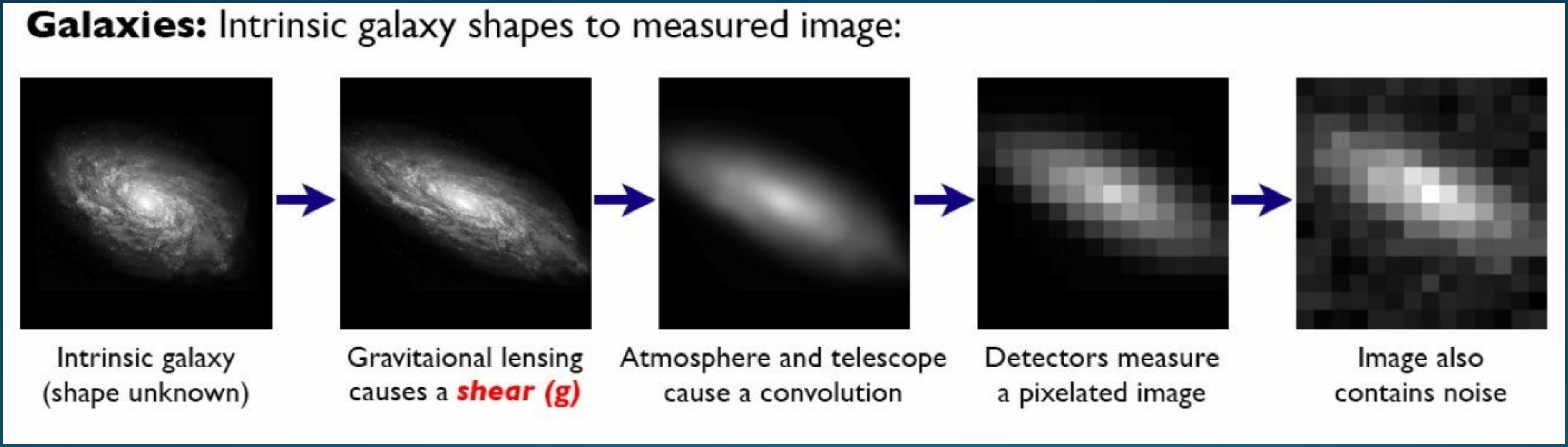


Lensed

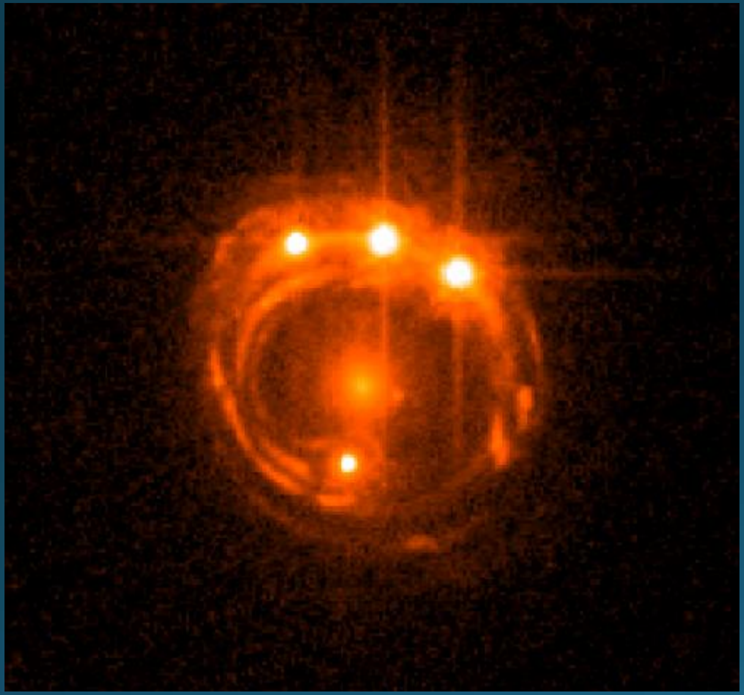
Cosmic shear

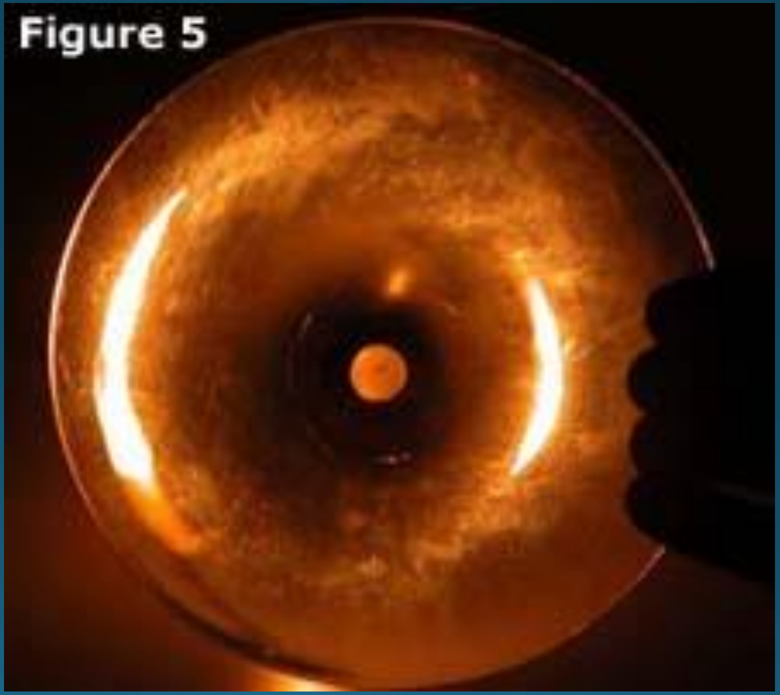
Technological challenges for weak lensing

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

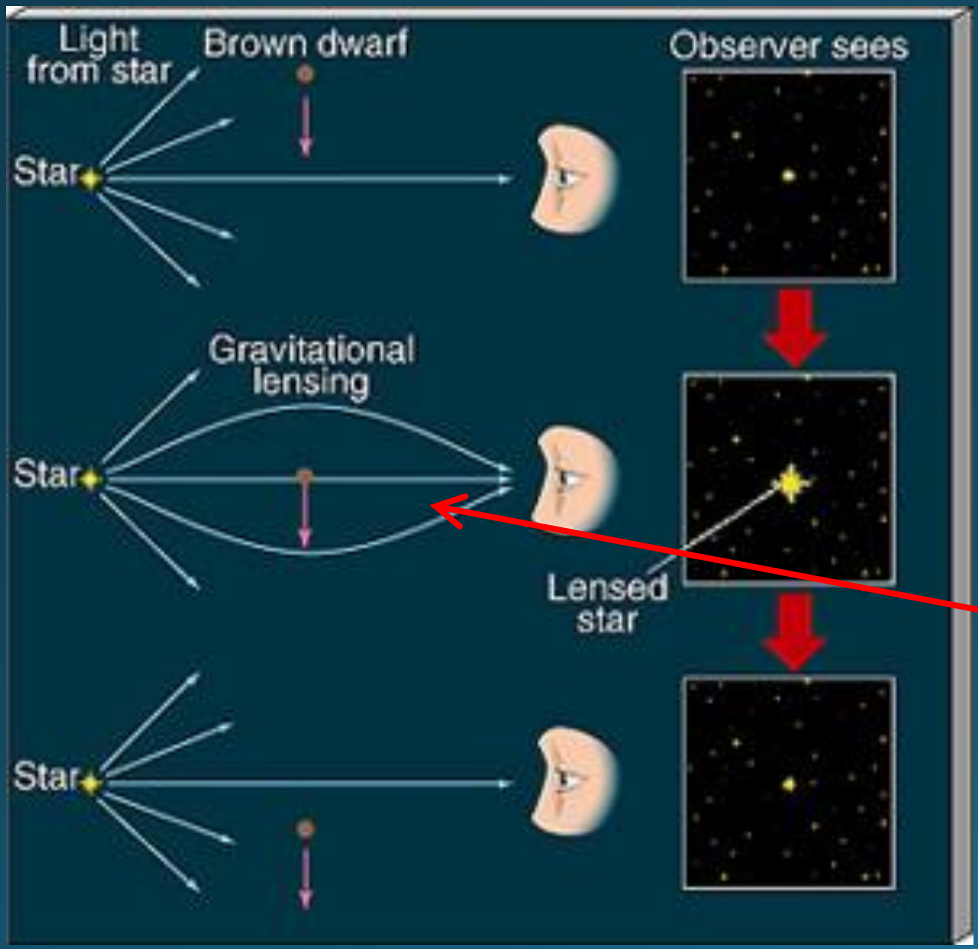


Intermission:
Strong or weak lensing?





Different types of lensing III: Microlensing



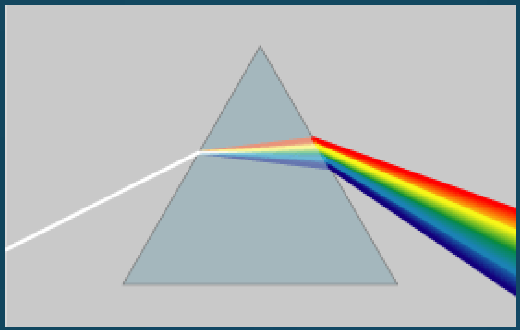
Microlensing is a special, time-dependent case of strong lensing. There's also nanolensing, attolensing, femtolensing…

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



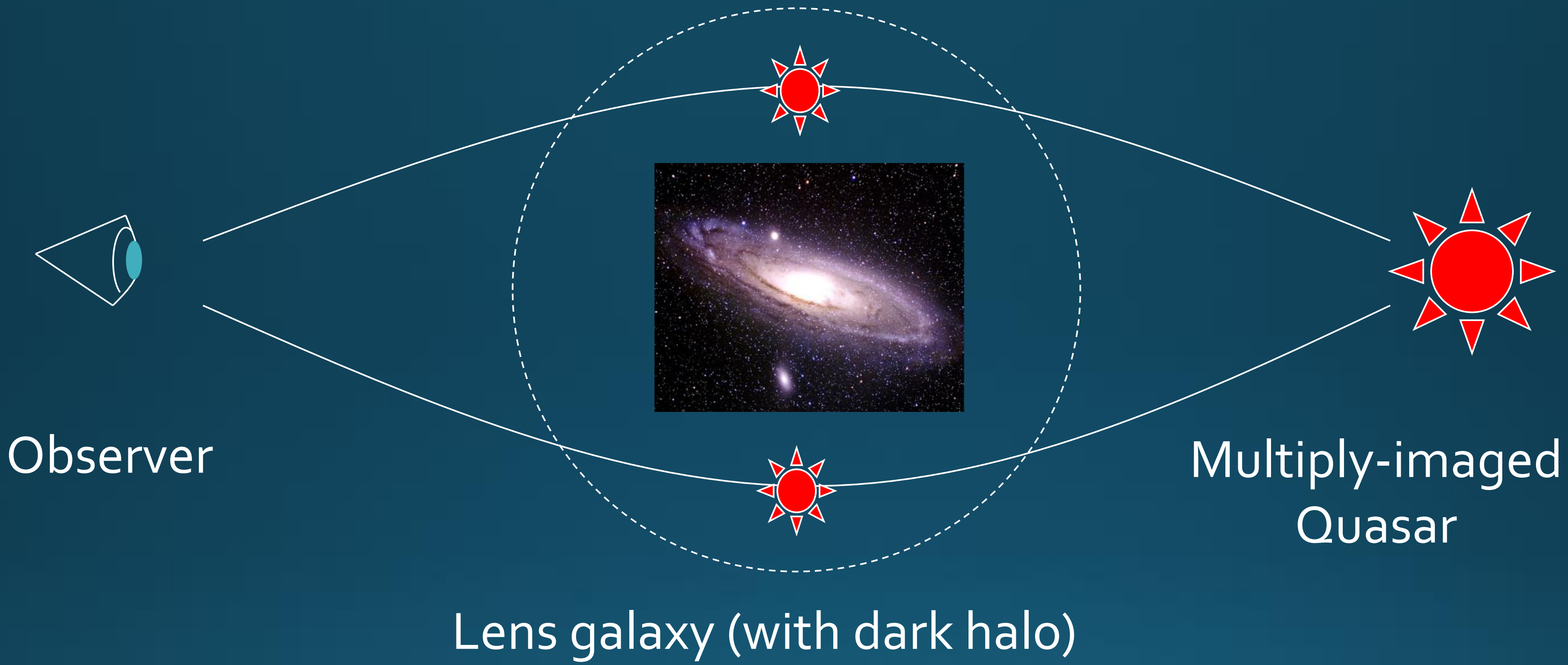
- Graviational lenses are achromatic
  - But note: GL may still alter the colour profiles of extended sources experiencing non-uniform magnification

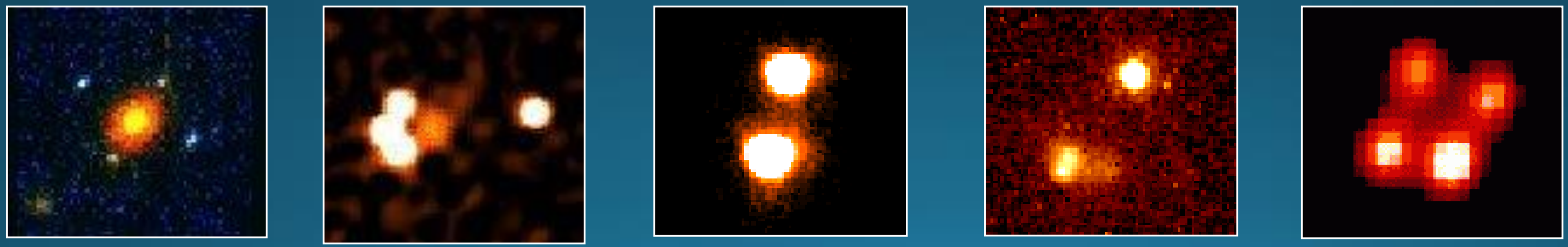
Unlensed source

Lens magnifies red area

Total colour becomes redder

Strong lensing: Multiply-imaged quasars I





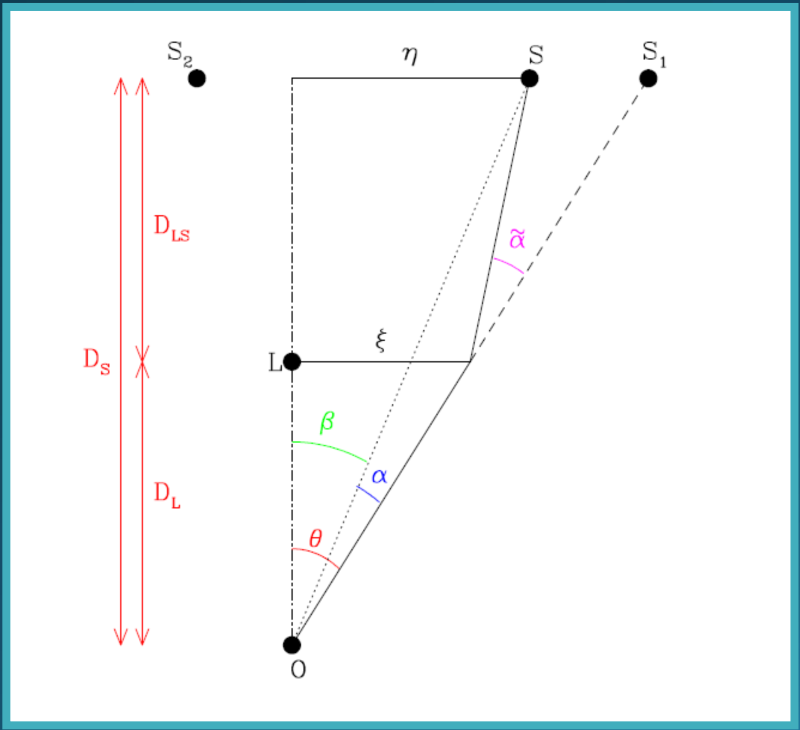
Multiply-imaged quasars II: Measuring the Hubble parameter

$$\tau(\vec{\theta},\vec{\beta}) = \tau_{\rm geom} + \tau_{\rm grav} = \frac{1+z_{\rm L}}{c}\frac{D_{\rm L}D_{\rm S}}{D_{\rm LS}}\left(\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \psi(\theta)\right).$$

Time delay

Measured

Depends on lens model



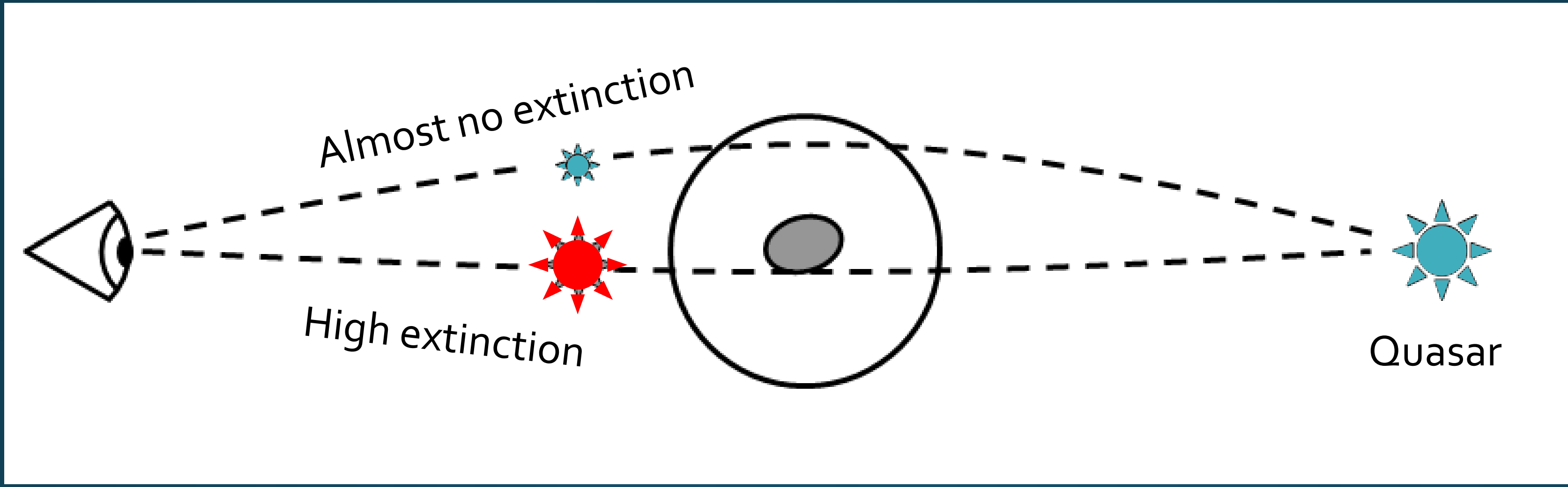
Angular size distances - Depend on cosmology (mostly H_0)

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

Projected gravitational potential

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

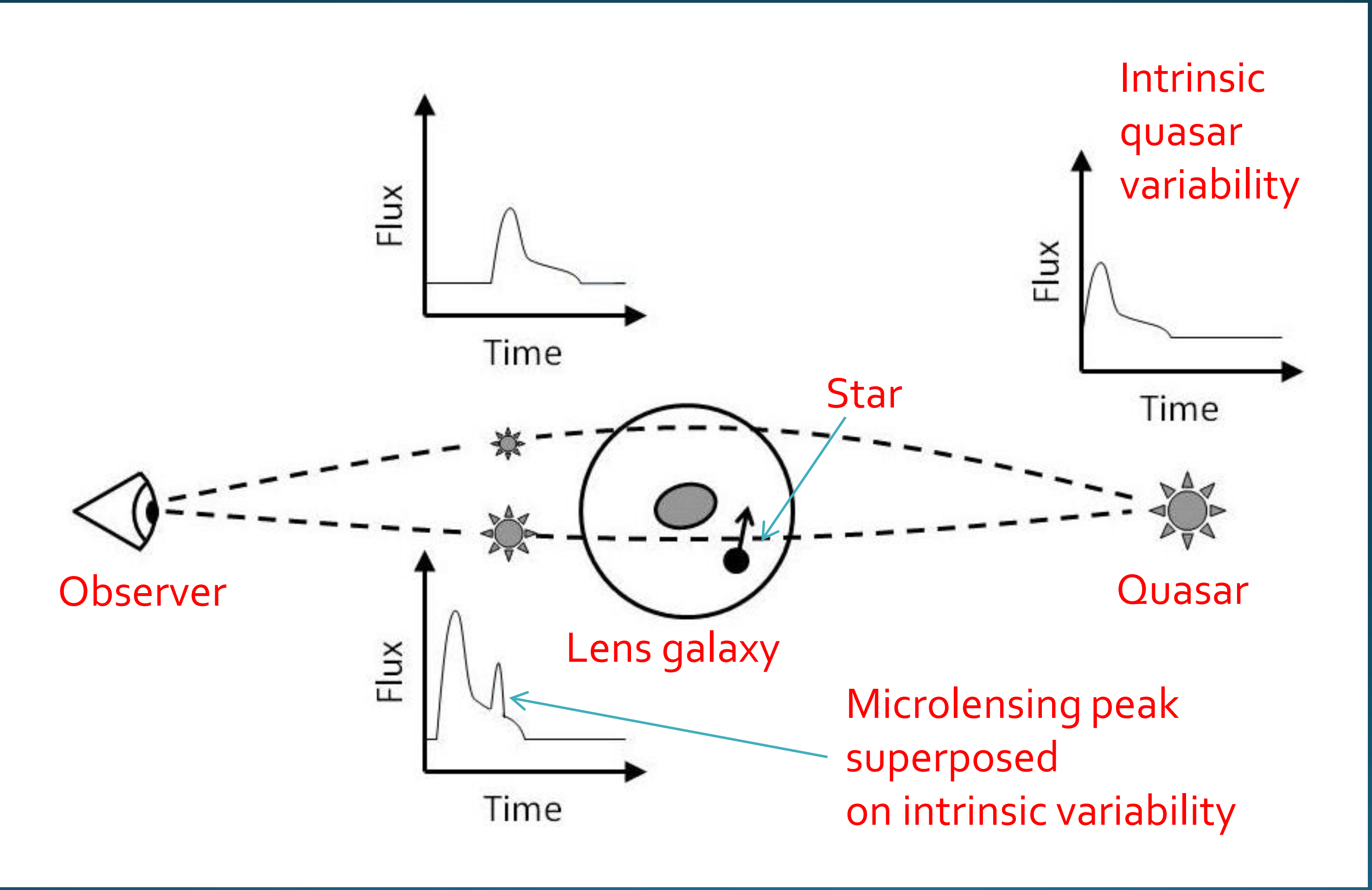
Multiply-imaged quasars III: Dust extinction



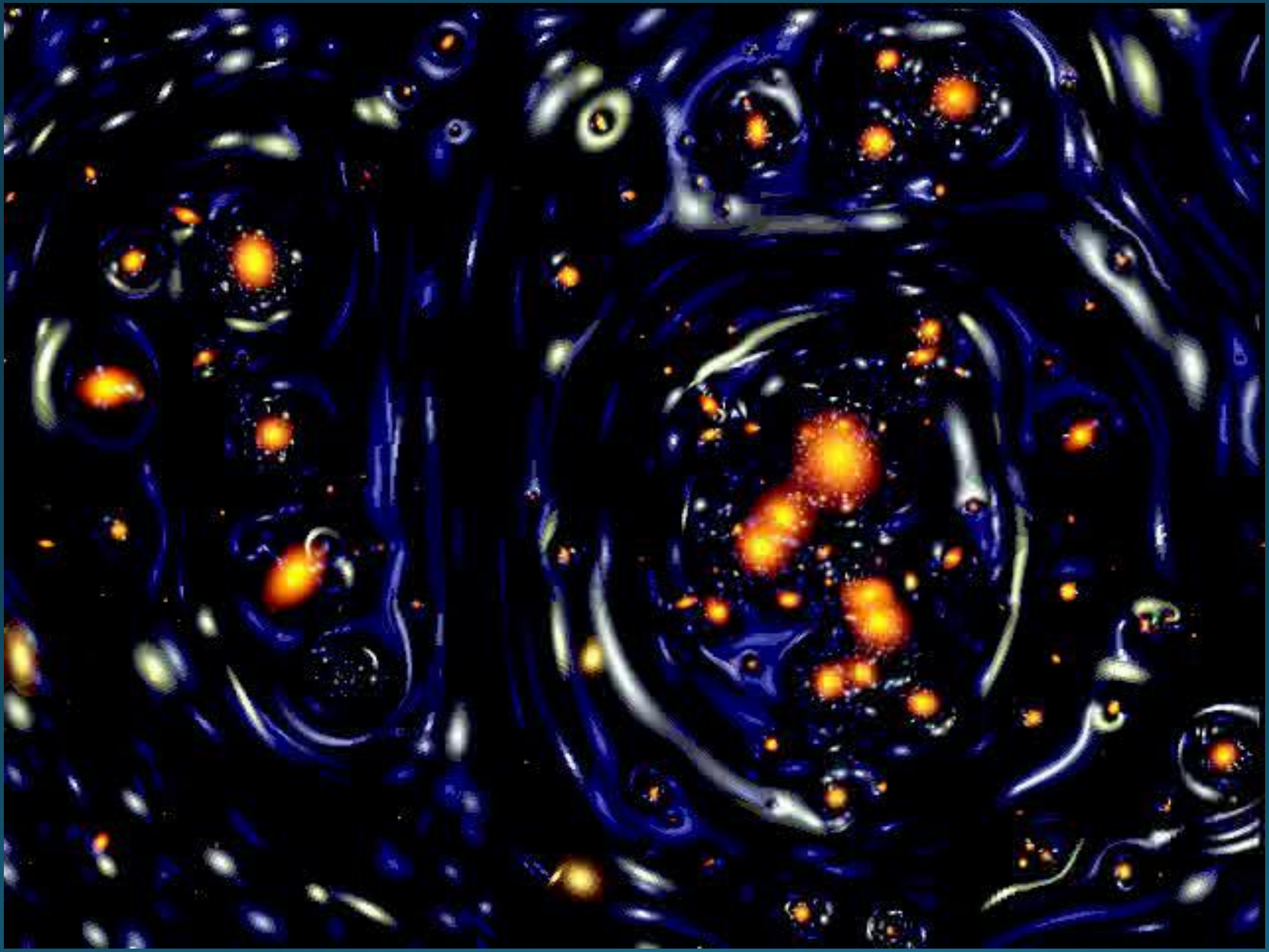
Lens galaxy with dark halo

Colour differences between images →
Extinction law measurement at high z

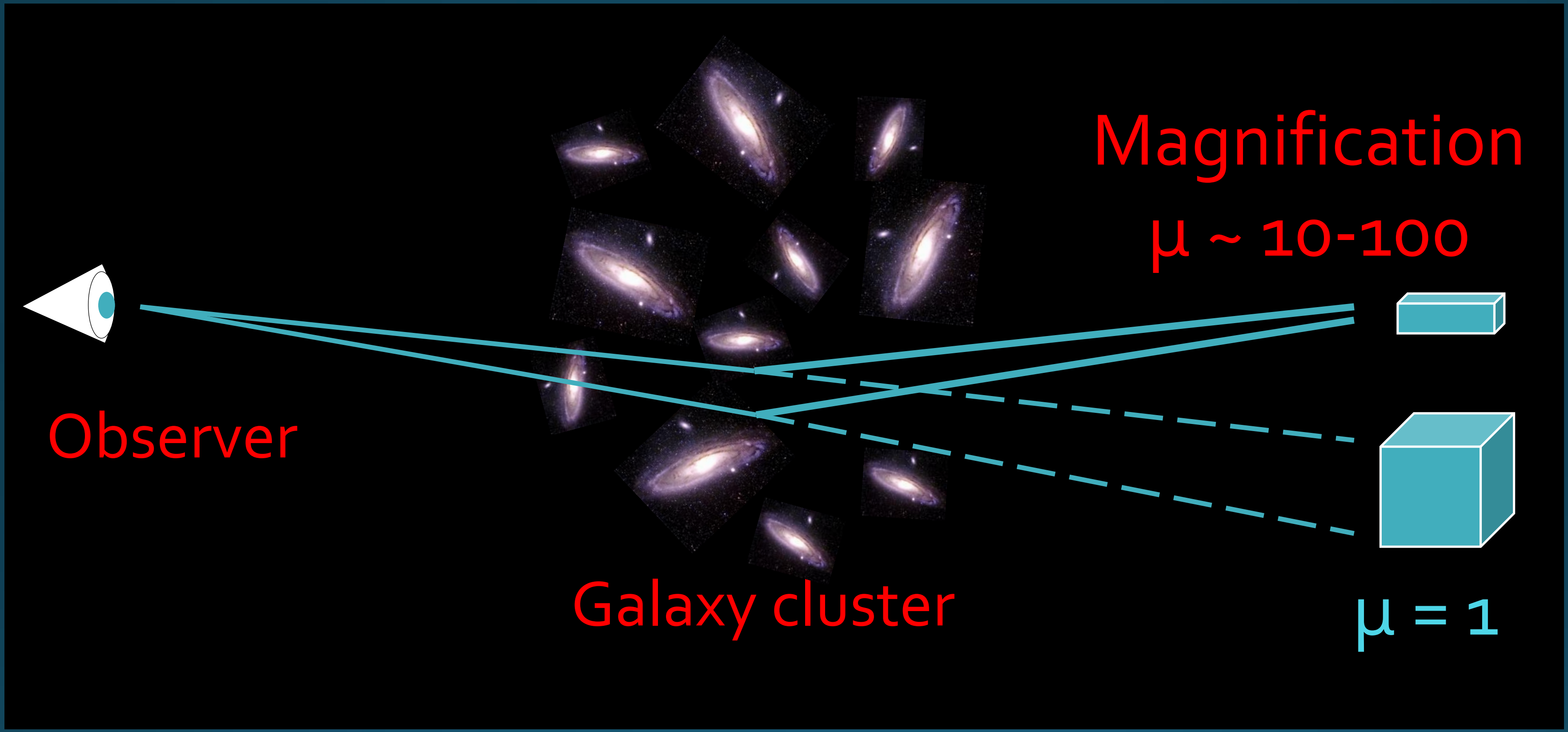
Microlensing in multiply-imaged quasars as as a probe of stars in the lens galaxy



Strong lensing in clusters I



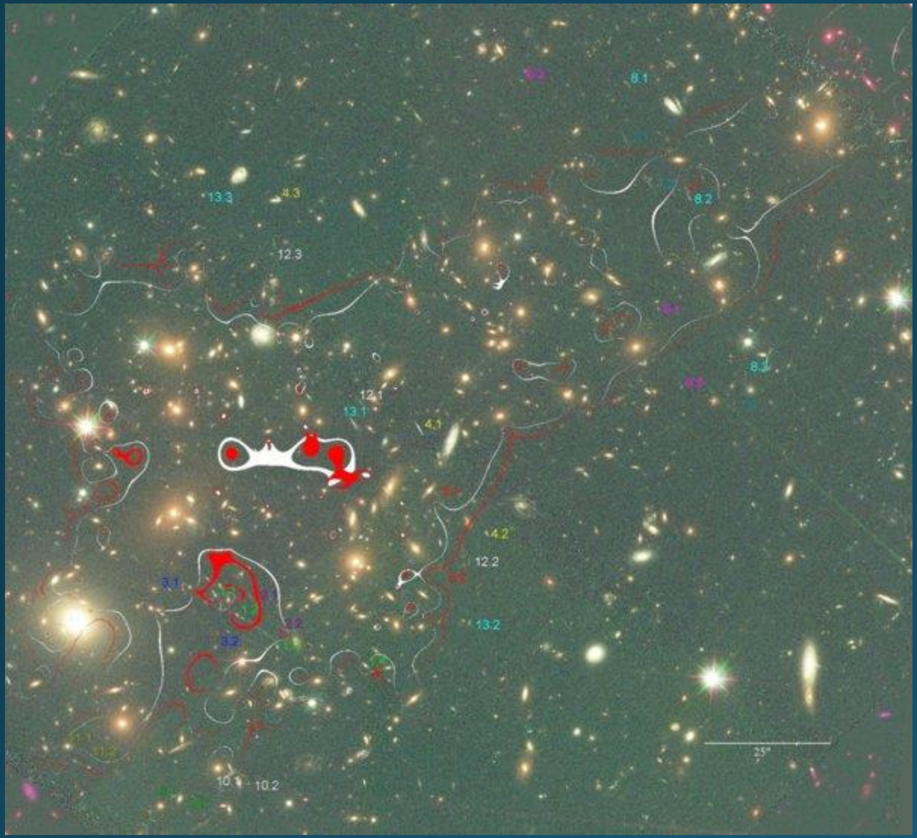
Lensing as gravitational telescopes



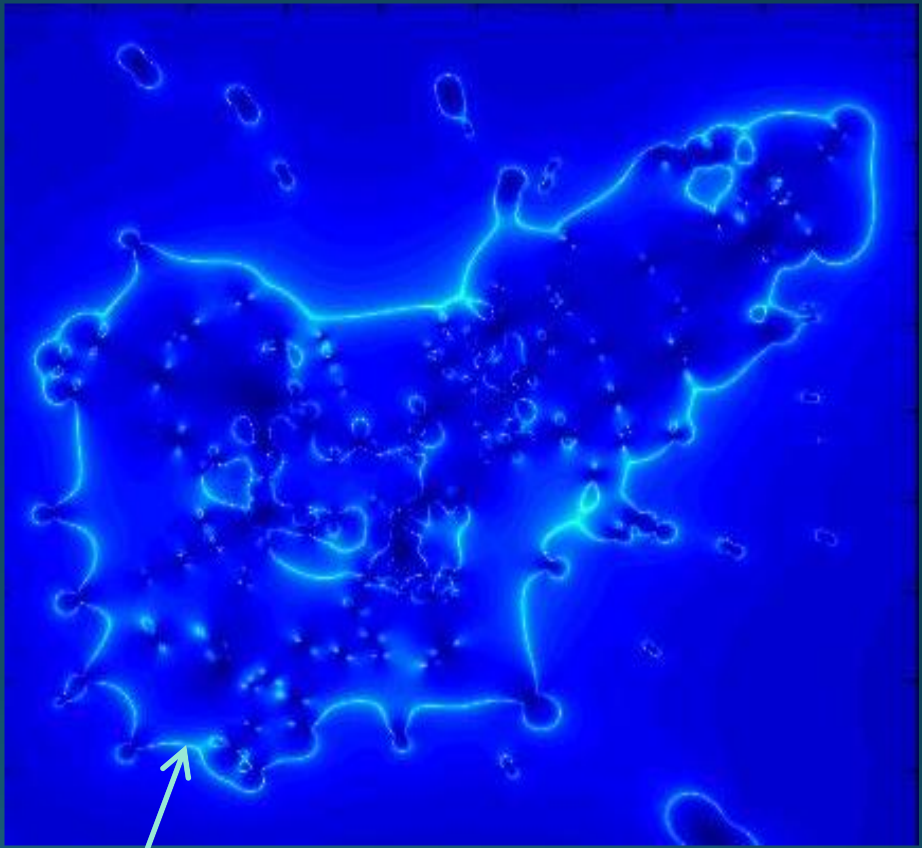
Lensing makes background objects brighter/bigger by a factor μ, but also zooms in on a volume that is smaller by the same amount

$\rightarrow$ Very rare types of objects may be impossible to detect this way

Strong lensing in clusters II



Galaxy cluster



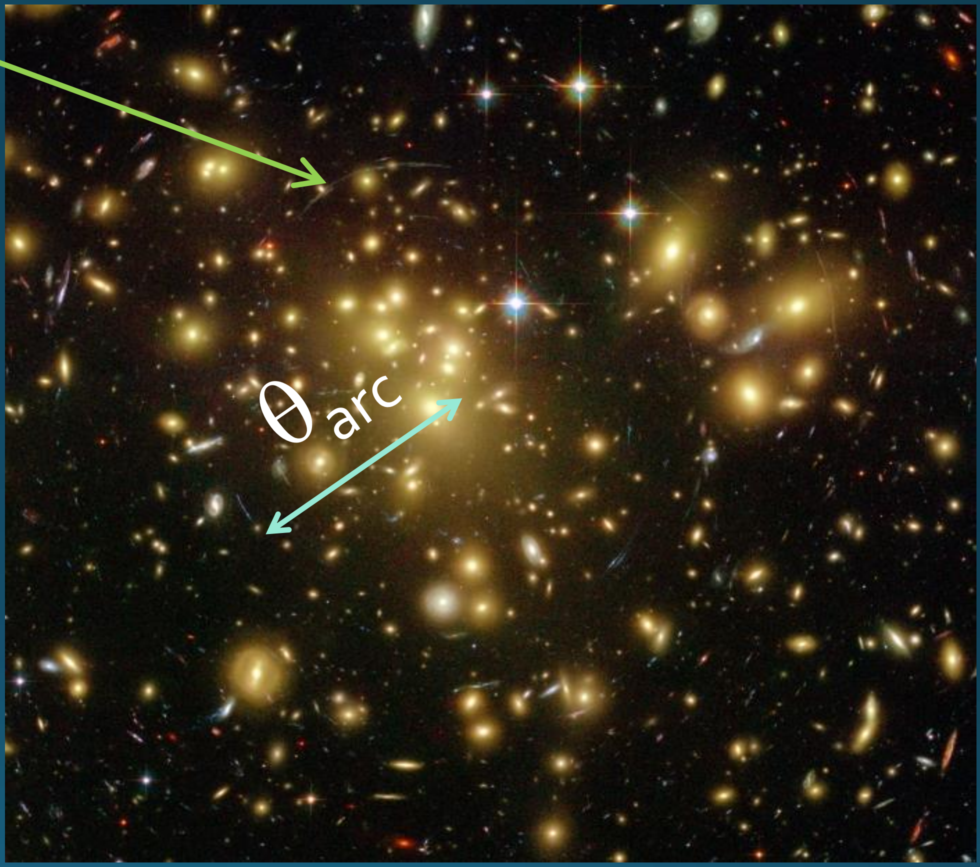
Magnification map

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

Strong lensing in clusters III

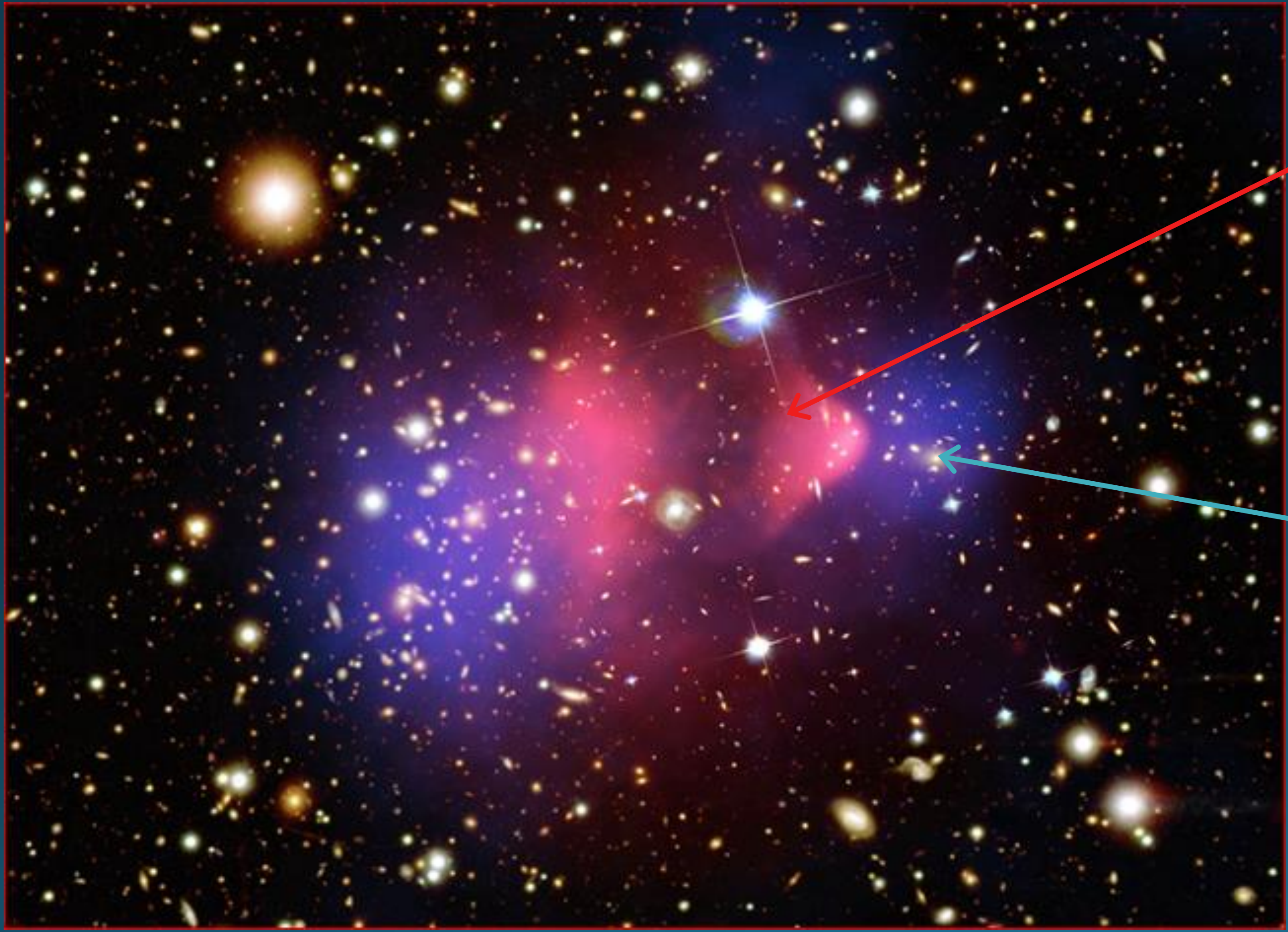
Giant arcs can be used to assesss:

- Enclosed mass
- Cluster shape
- Density profile (through arc curvature vs. θ_{arc})



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

Dark matter mapping – 2D

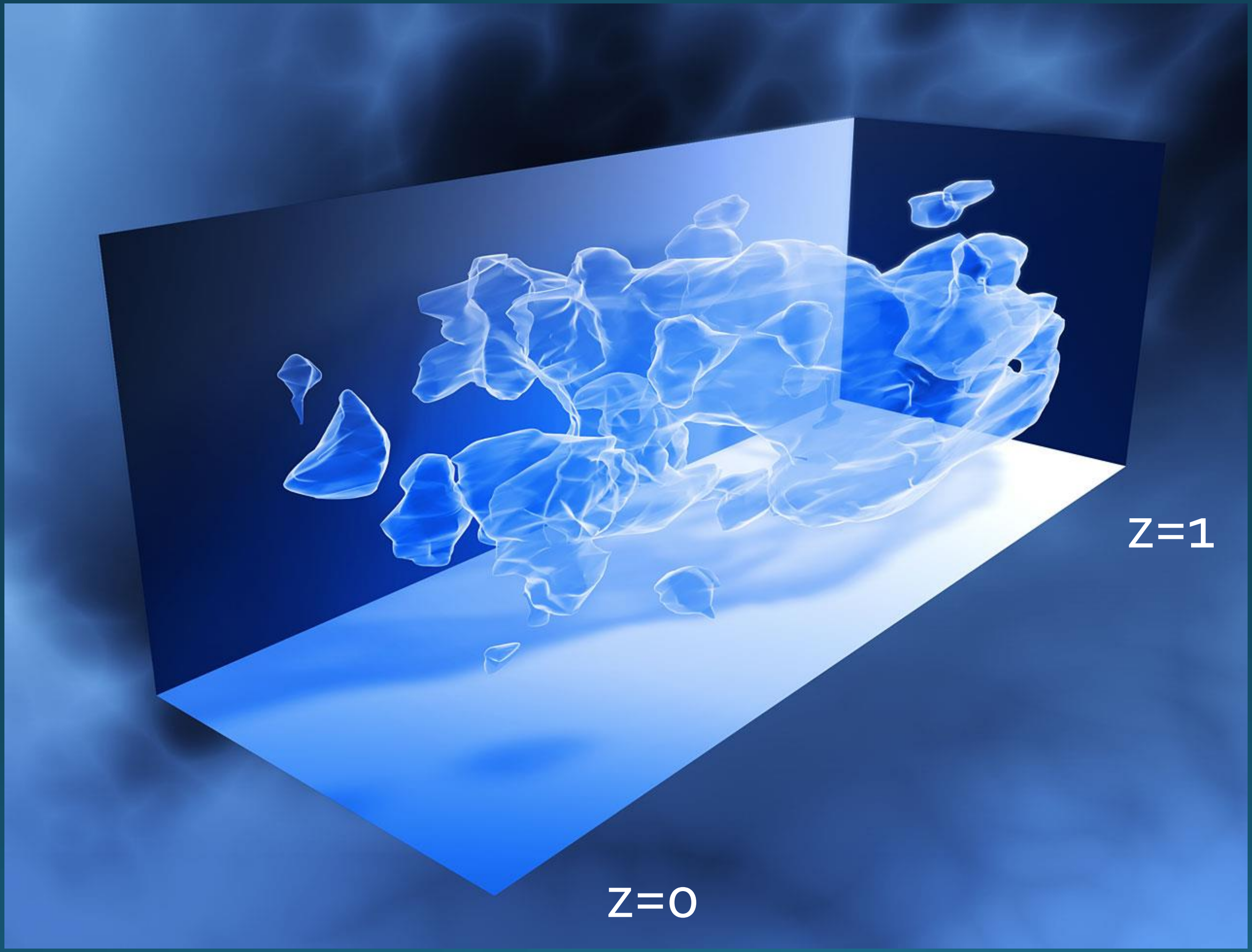


X-ray gas (believed to dominate baryon budget)

Overall matter distribution (dark matter) from weak lensing

The bullet cluster

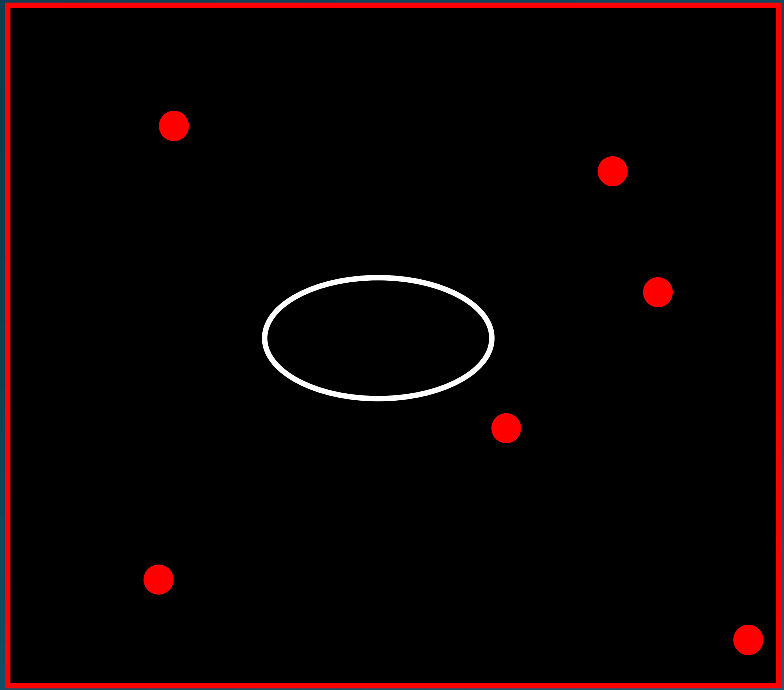
Dark matter mapping – 3D



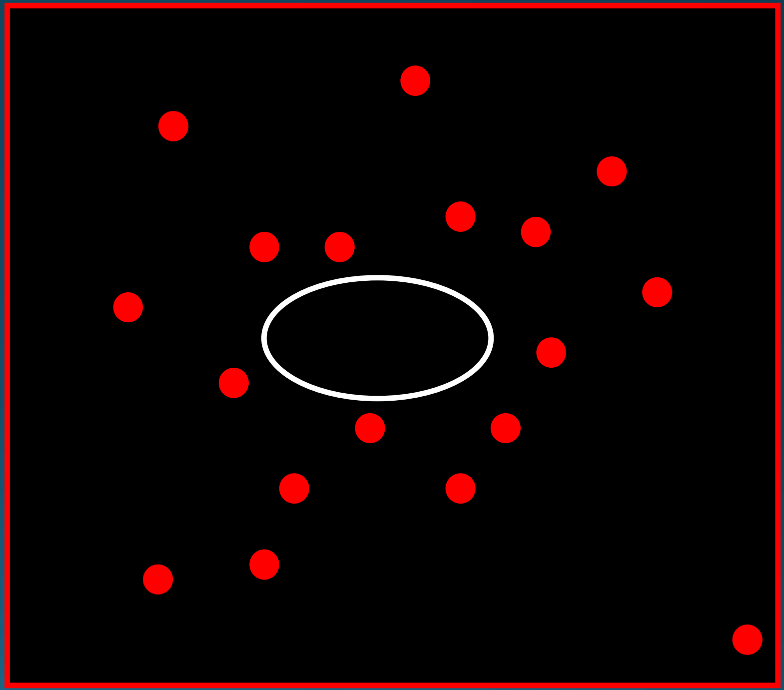
Dark matter tomography in the COSMOS survey based on weak lensing

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