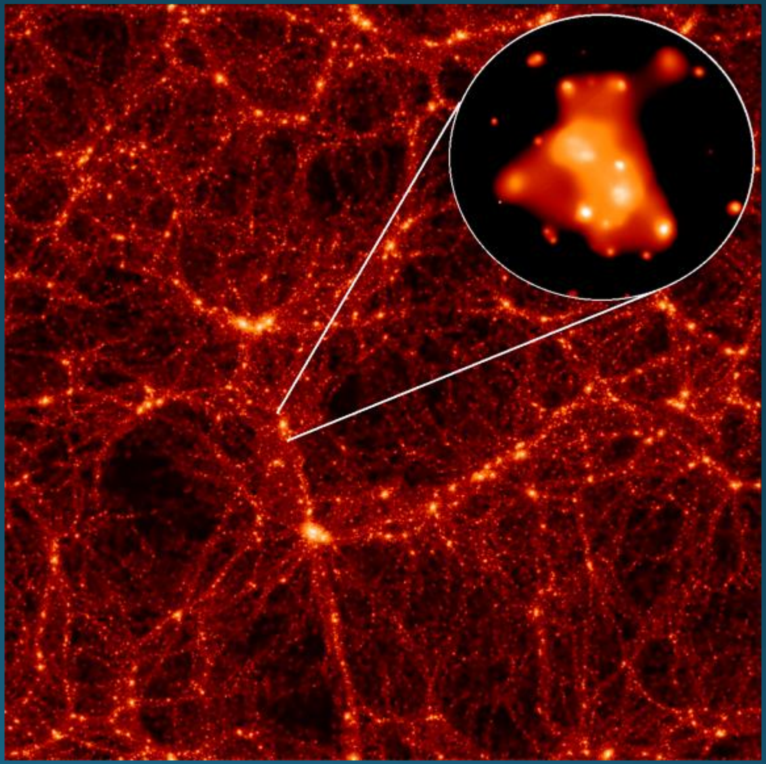
Physics of Galaxies 2018
Lecture 7: Groups, clusters and lensing

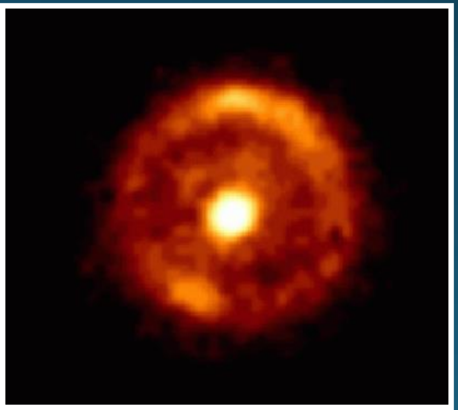
Outline: Galaxy groups & clusters

- 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:
  - 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
  - 10 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

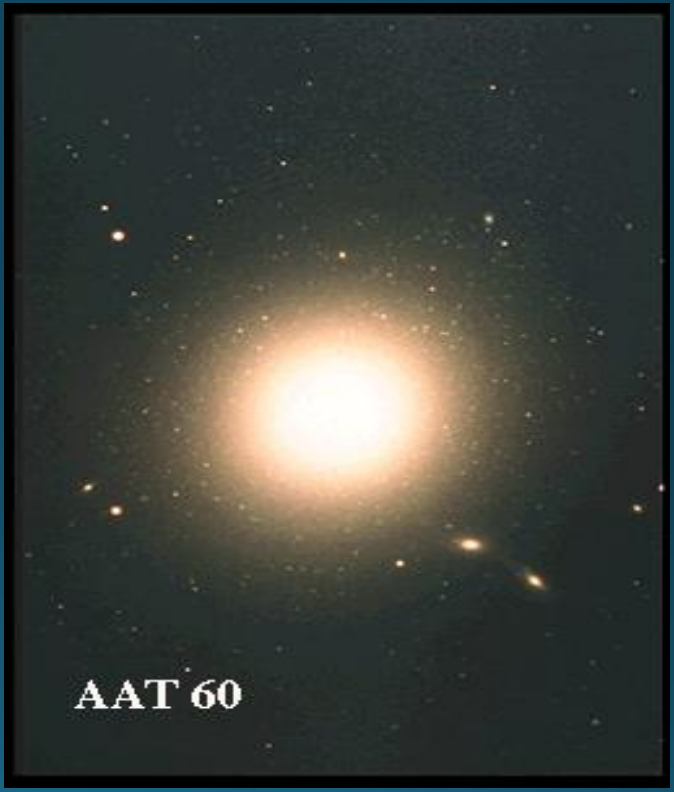
Increasing rareness

- 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 are you looking at?

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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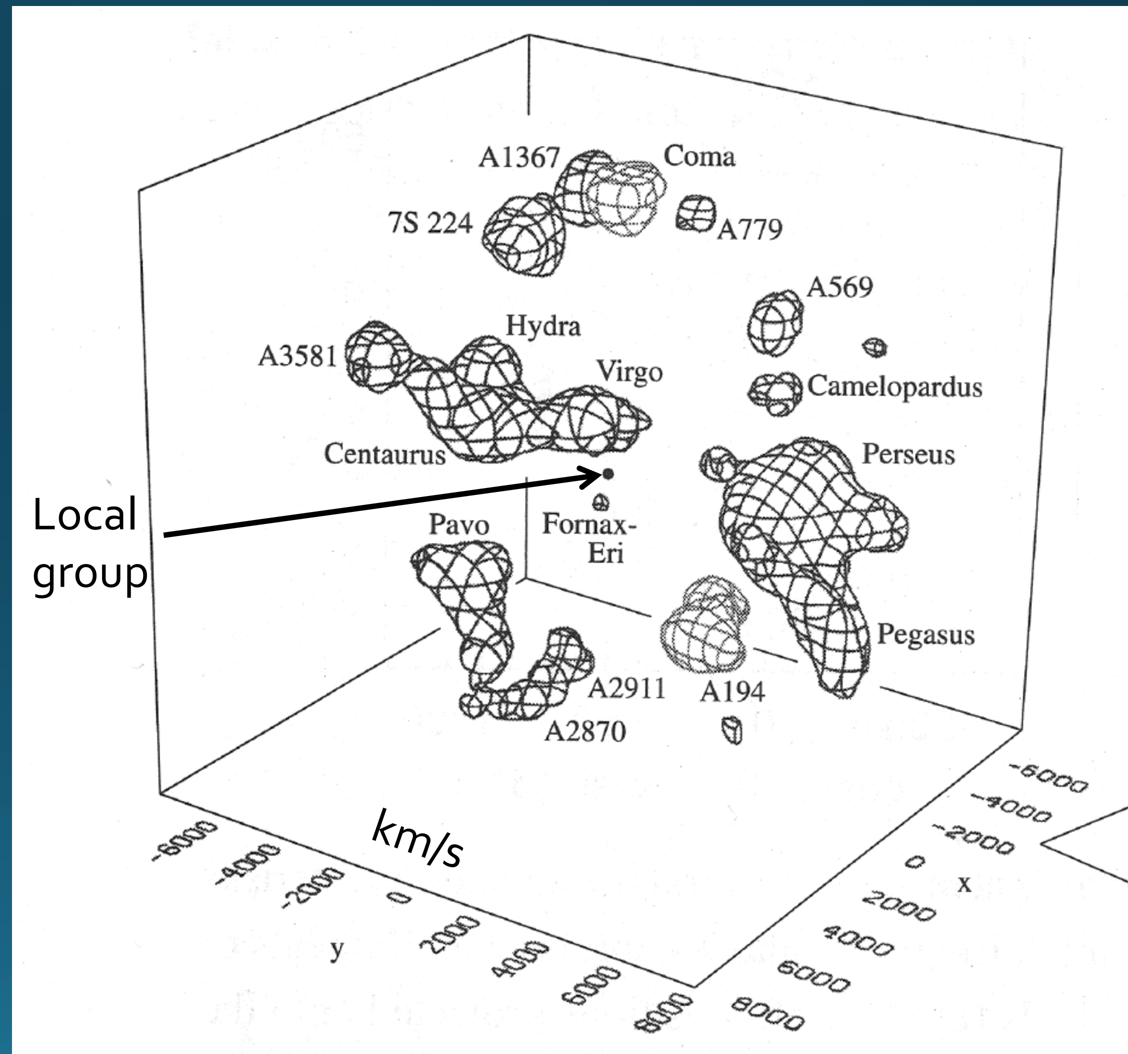
Galaxy groups & clusters in our backyard

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

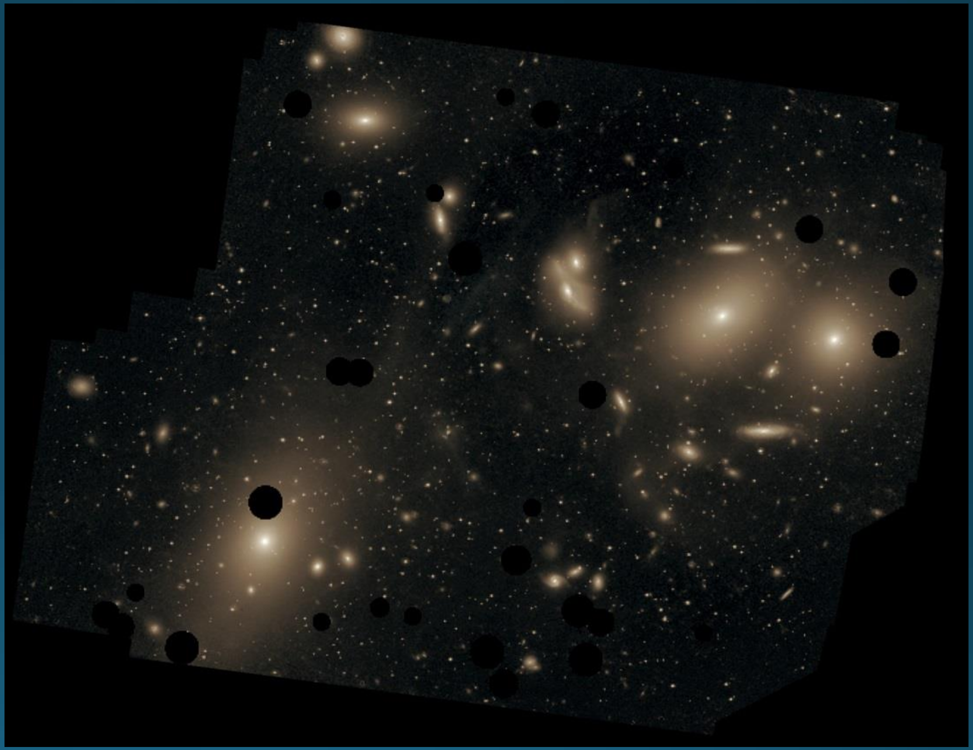
  Virgo supercluster, Hydra-Centaurus supercluster…

  (but the definitions of superclusters are messy)



Galaxy groups & clusters in our backyard II

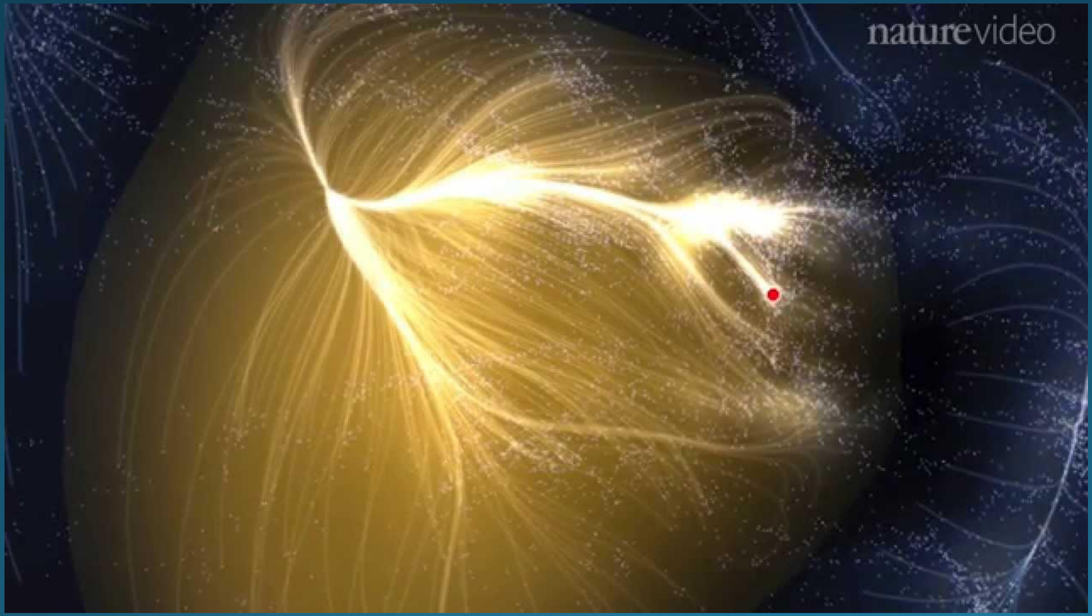
- Virgo cluster
  - Nearest large galaxy cluster with more than 2000 galaxies brighter than $M_B \approx -14$
  - Extent ~ 3 Mpc
  - Velocity dispersion $\sigma_R \approx$ 600 km/s
  - Mass ~$1 \times 10^{15}\ M_\odot$
  - Distance 15—20 Mpc



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 ~10^{17} $M_\odot$



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

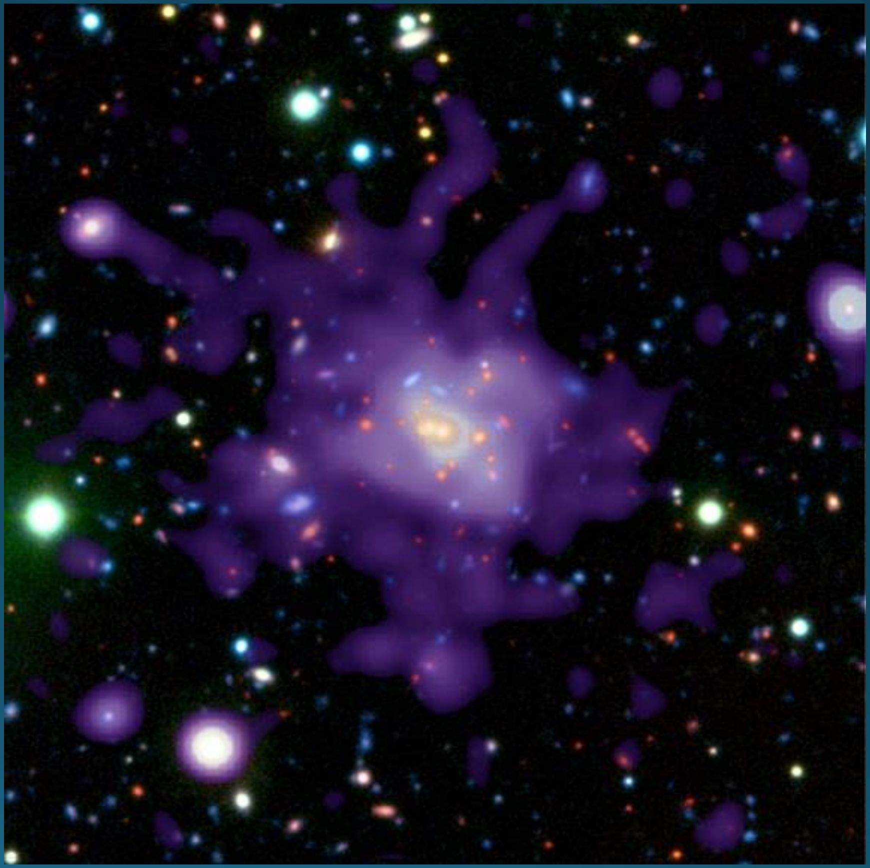
Compact groups

- 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

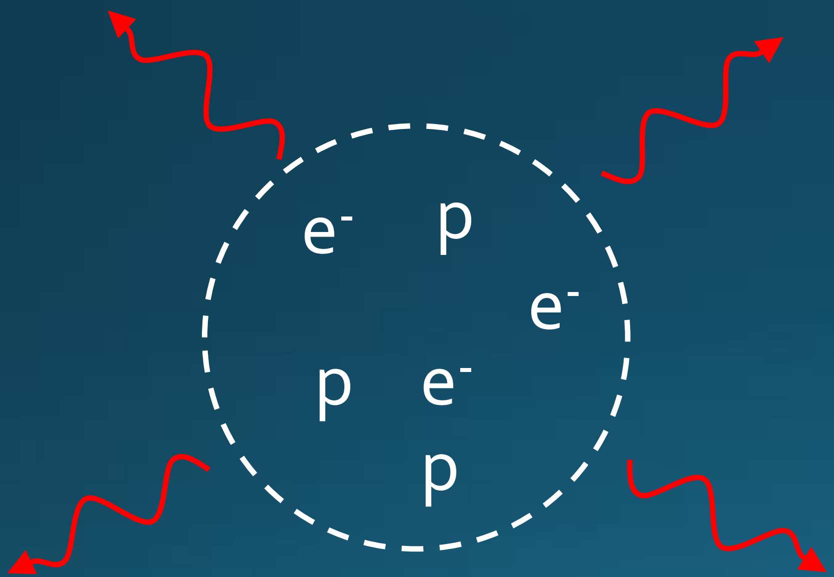
Most baryonic material in groups and clusters is not stars, but hot gas

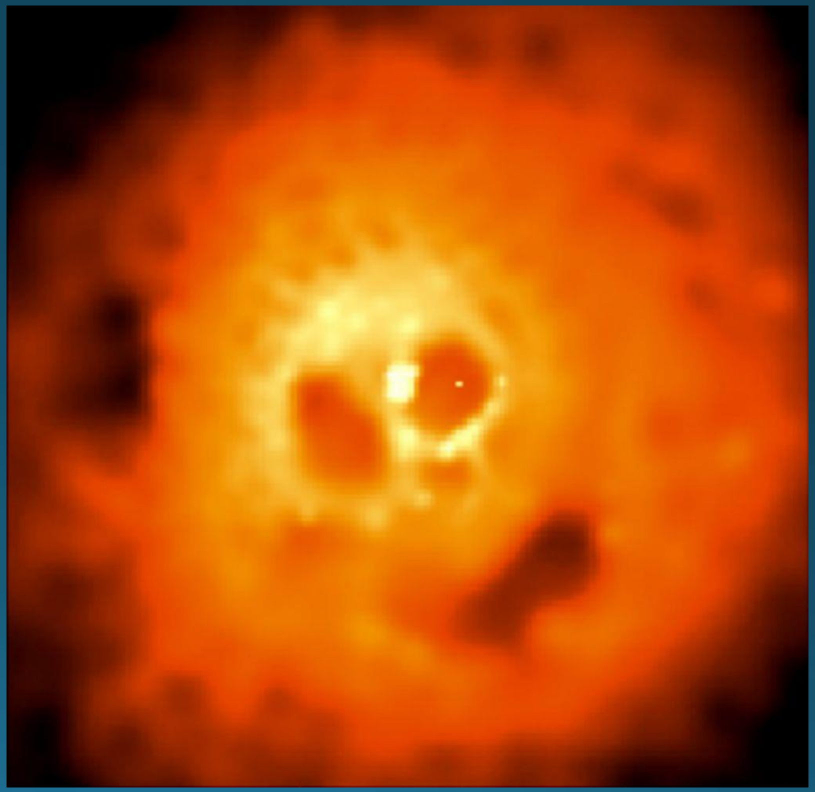


X-ray gas, $T=10^7$—10^8 K

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

- 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~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

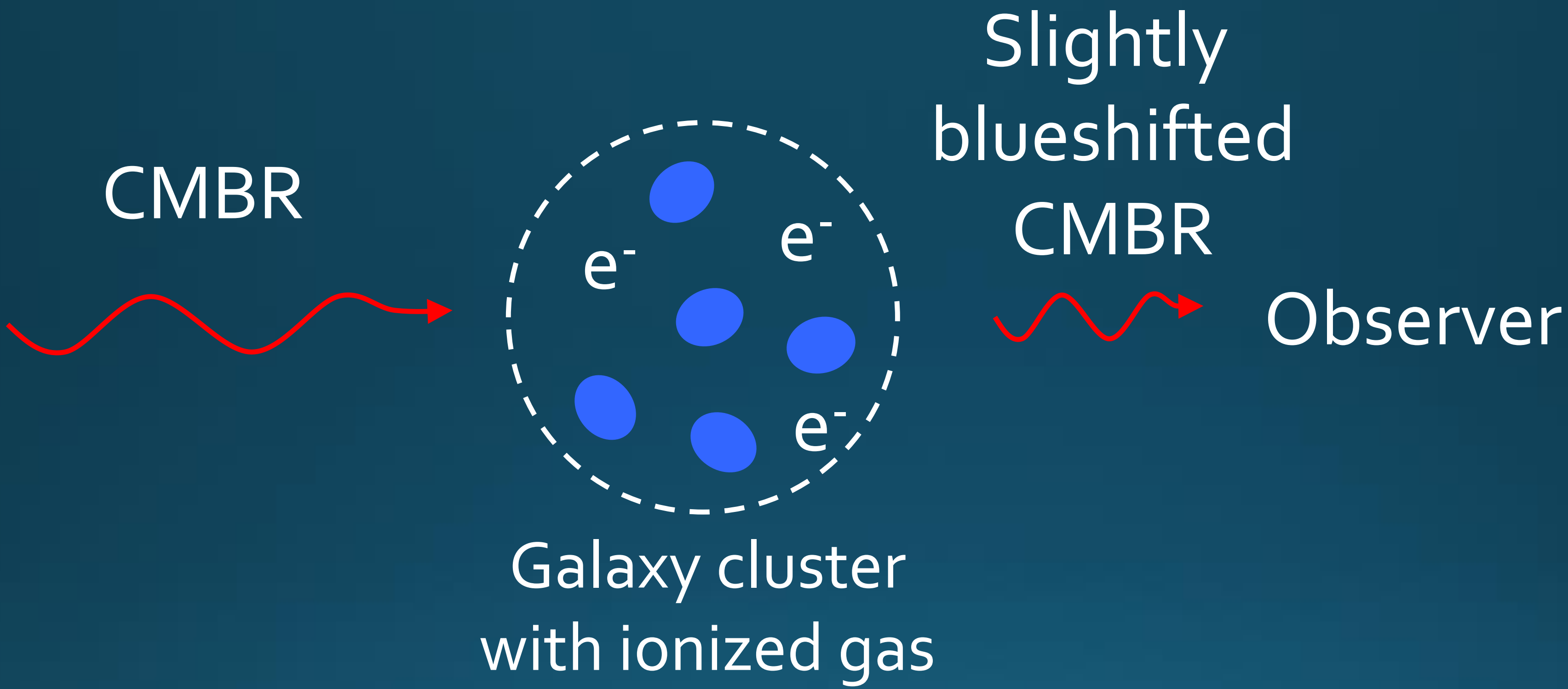
$$L = n_{\mathrm{e}} n_{\mathrm{H}} \Lambda(T)$$

Number densities

- Mass:

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

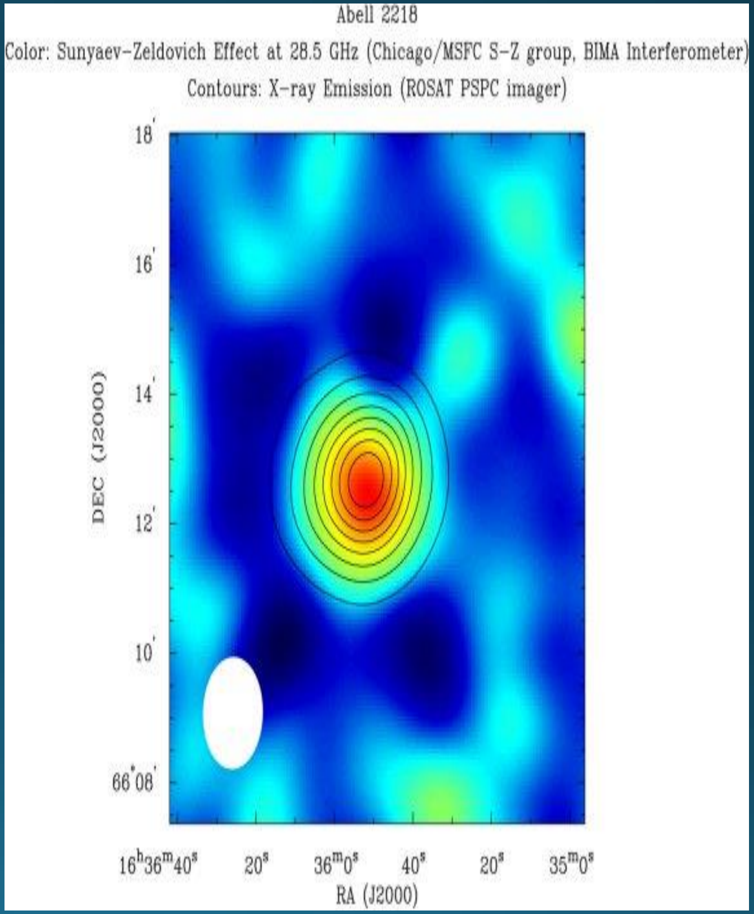
The Sunyaev-Zeldovich effect I



- Compton scattering of CMBR by free electrons in the intercluster 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)

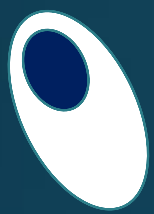
Increased size + conserved surface brighness $\rightarrow$ increased apparent flux

Intermission: What magnification?

Intrinsic size Lensed size

Lensing – quick overview III

Distorted morphology



Intrinsic source morphology/orientation/parity

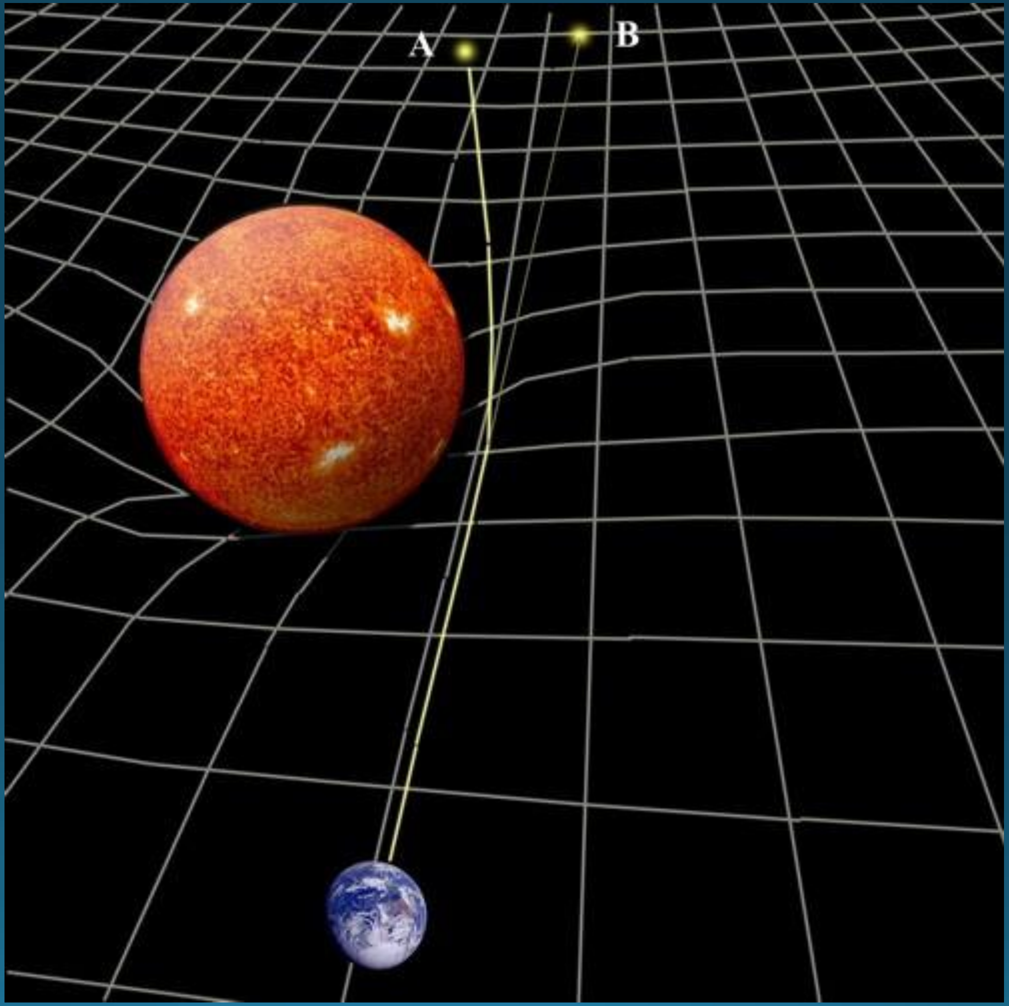
Apparent source morphology/orientation/parity

Stretched, curved and mirror-flipped!

Lensing – quick overview IV

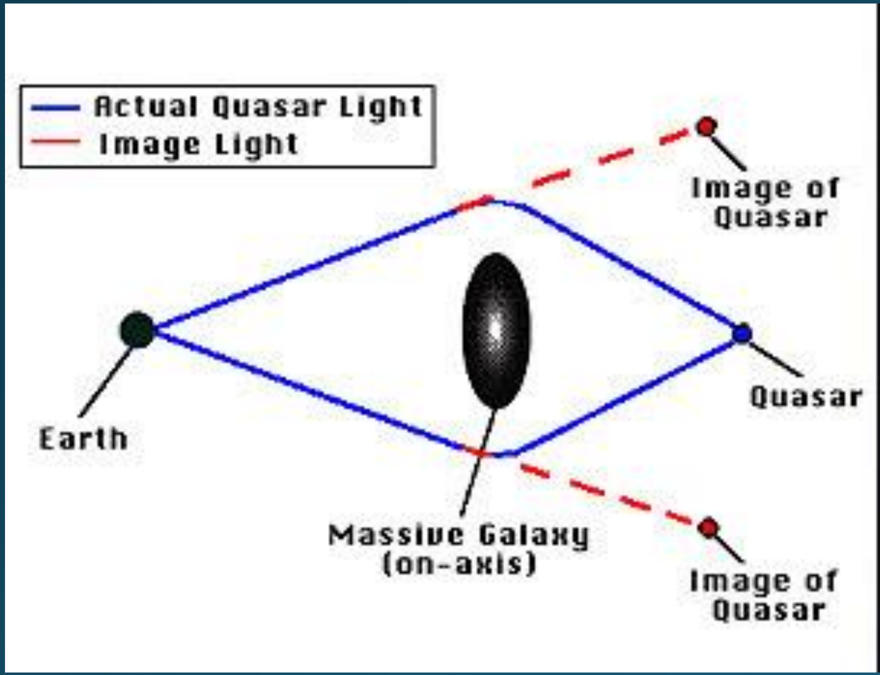
Shift in apparent positions

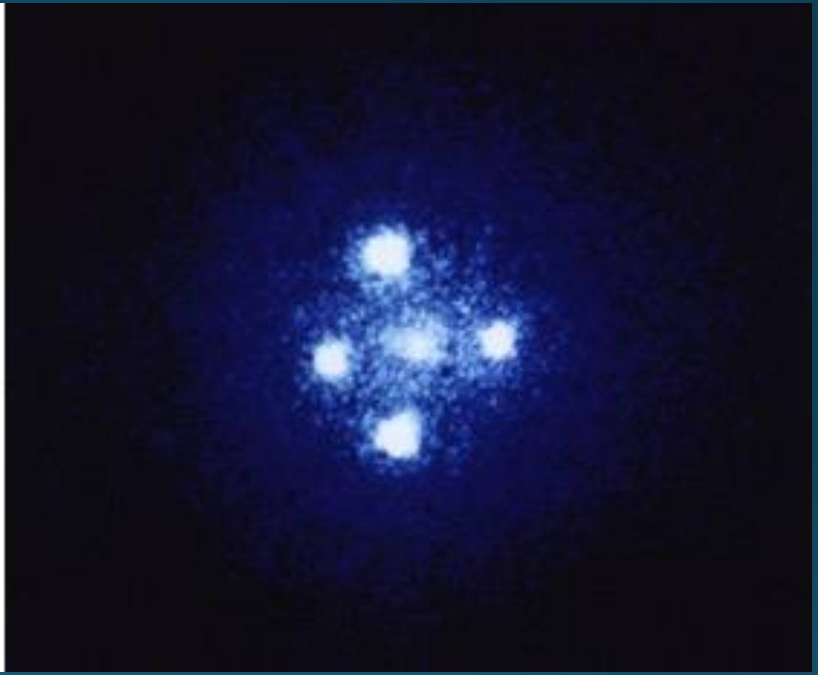
The mass of the Sun shifts the apparent positions of stars close to the limb



Lensing – quick overview V

Multiple images

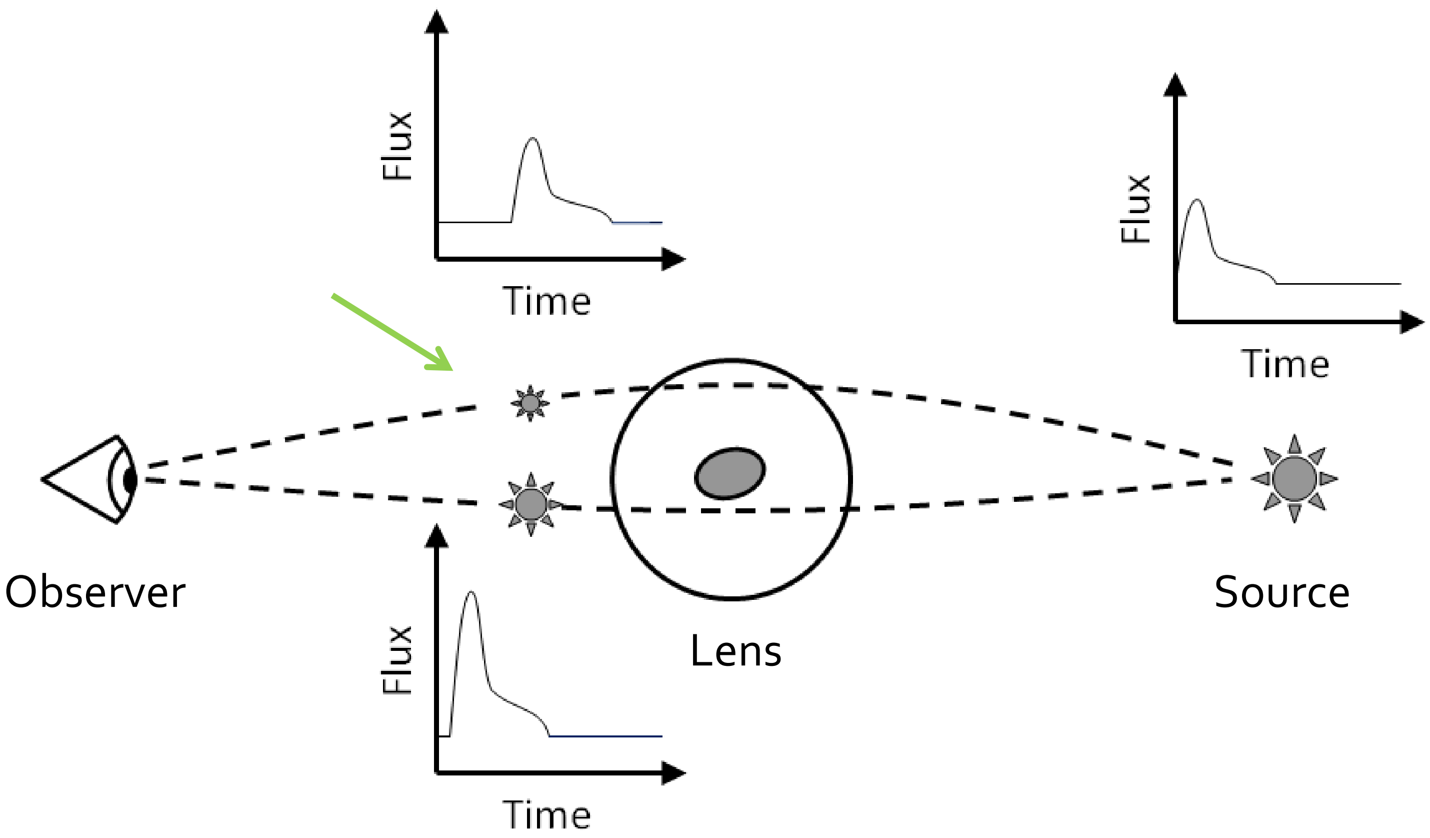




Lensing – quick overview VI

Delays in time signals

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



Lensing – A tool…

- Magnification $\rightarrow$ Can detect sources too faint to be seen otherwise

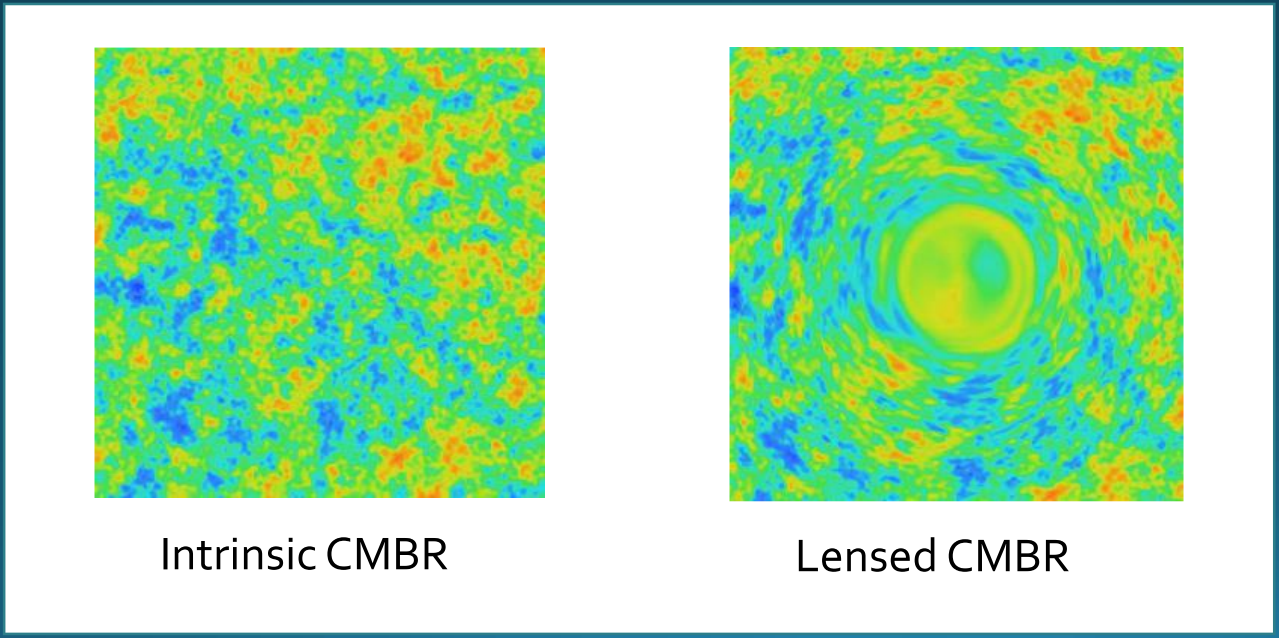
- Multiple images, distortions time delays $\rightarrow$ Probes of structure and dust reddening along line(s) of sight

- Testing gravity & cosmology

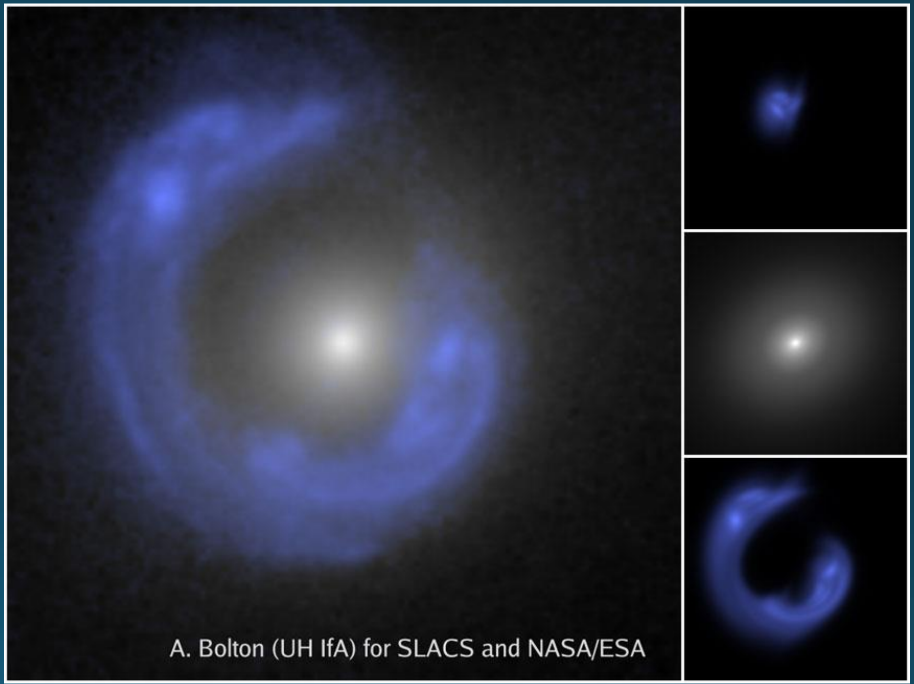
… and a nuisance

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



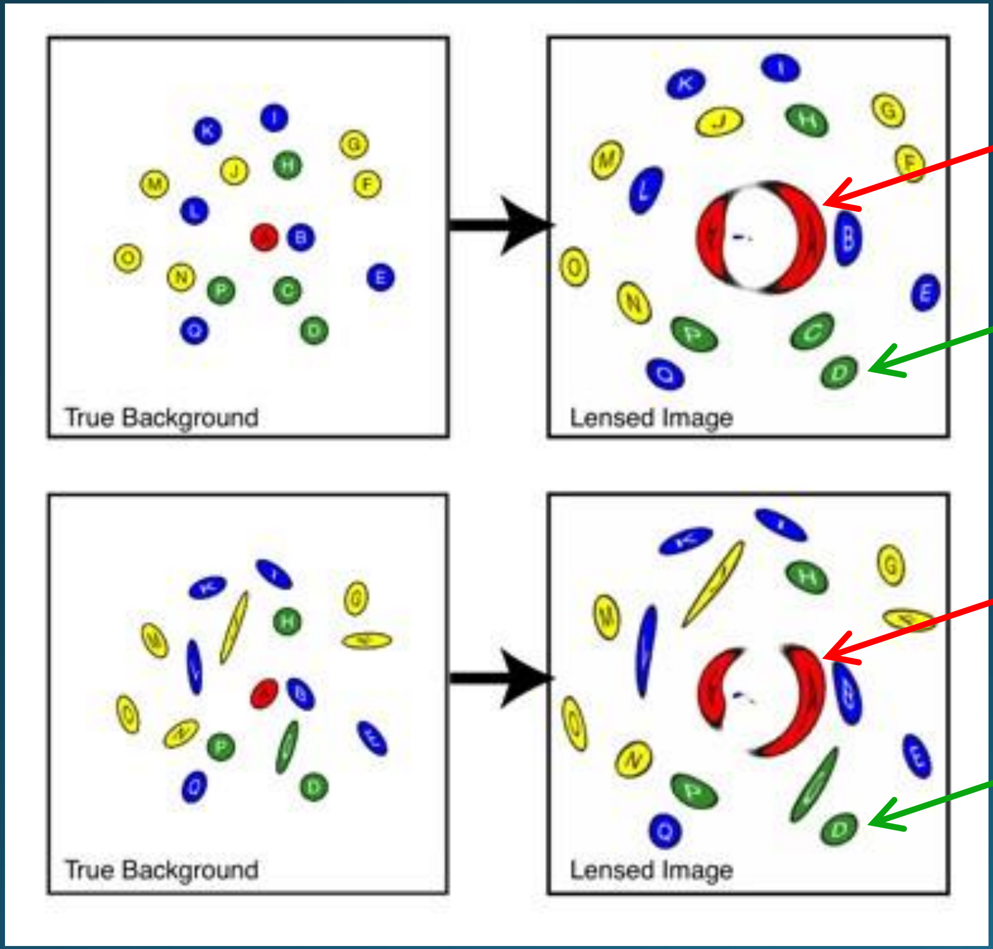
Different types of lensing I: Strong lensing



Strong lensing: Multiple images, large distortions, high magnifications

Very rare!

Different types of lensing II: Weak lensing



Strong lensing

Weak lensing

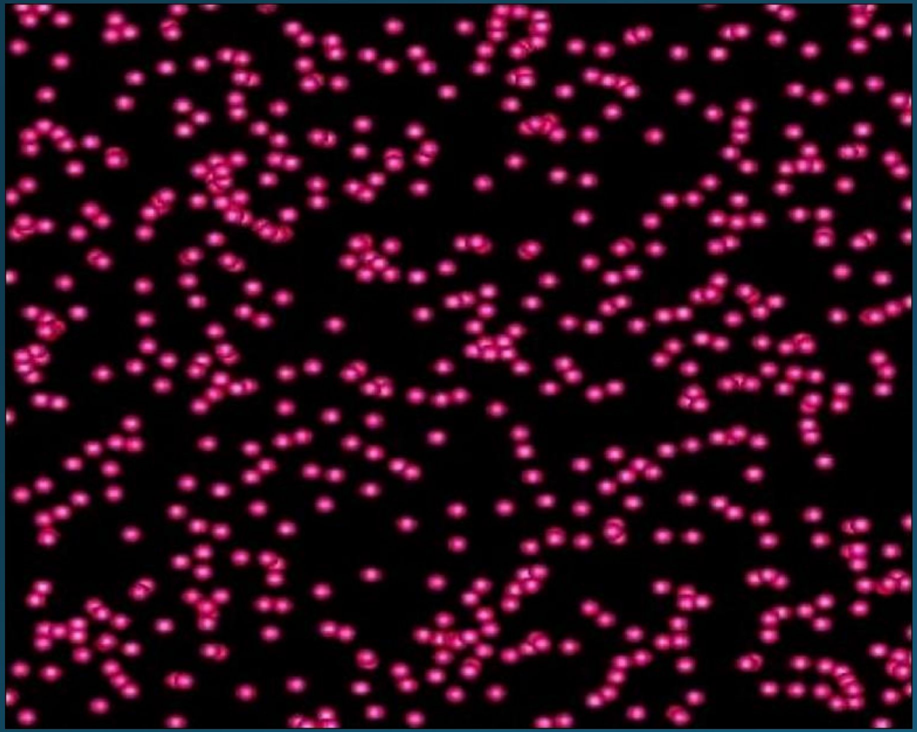
Strong lensing

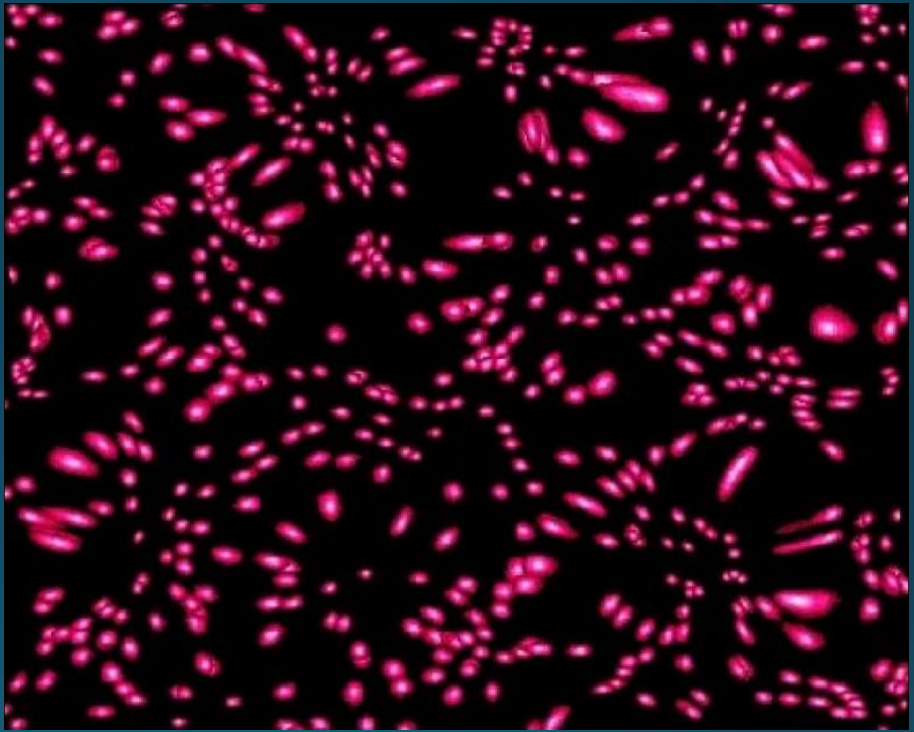
Weak lensing

Weak lensing: Mild distortions, small magnifications

Very common!

Different types of lensing II: Weak lensing





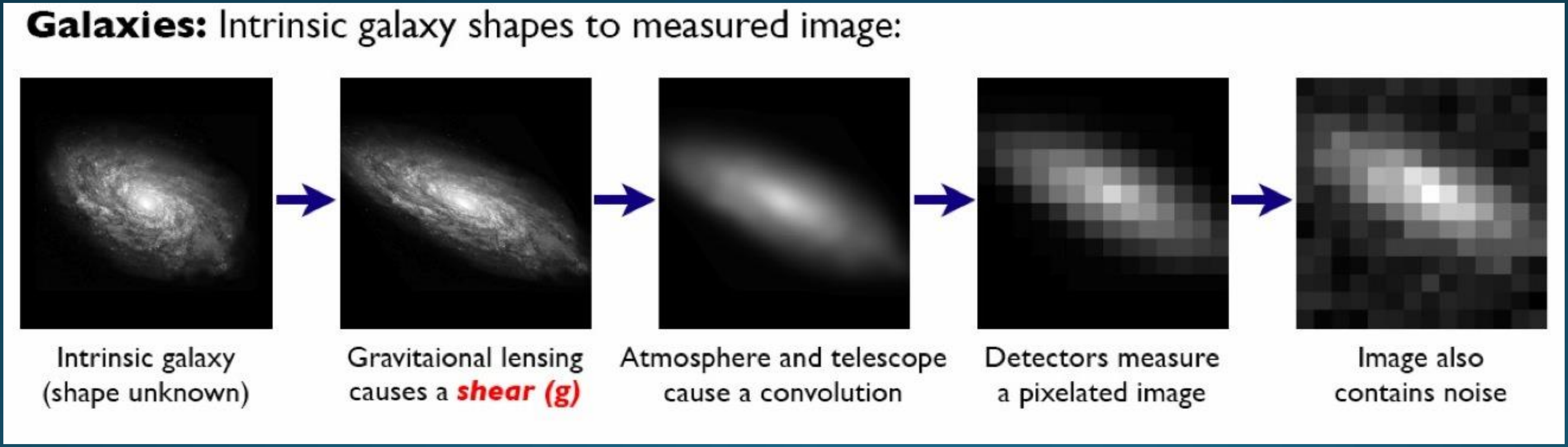
Unlensed

Lensed

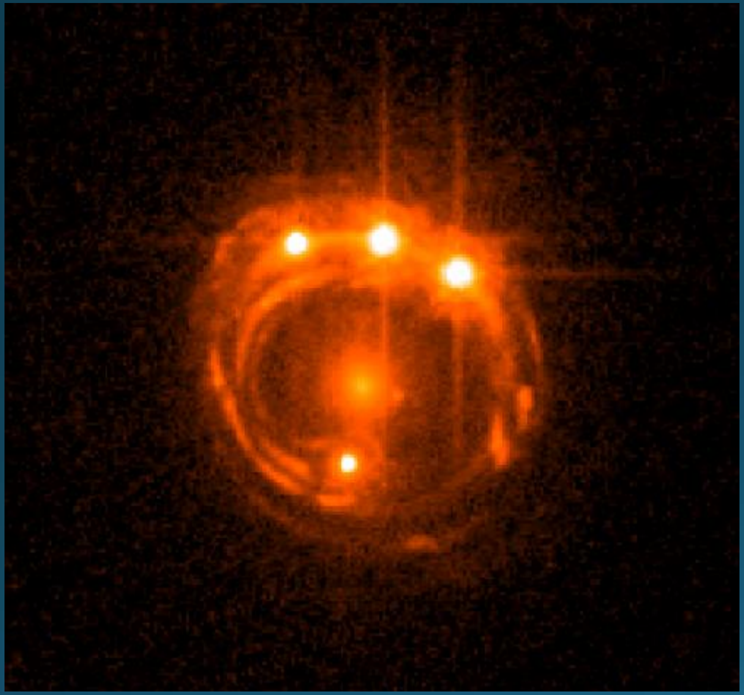
Cosmic shear

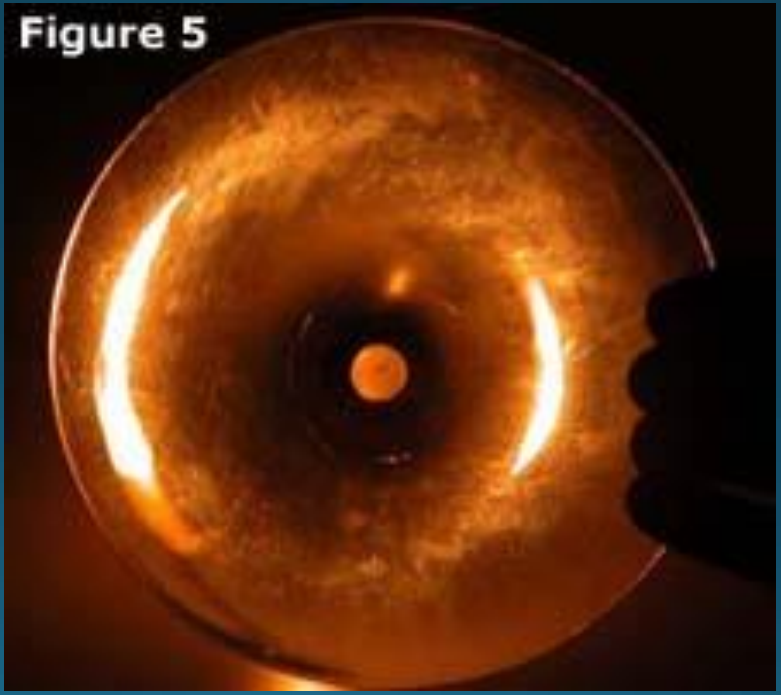
Technological challenges for weak lensing

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

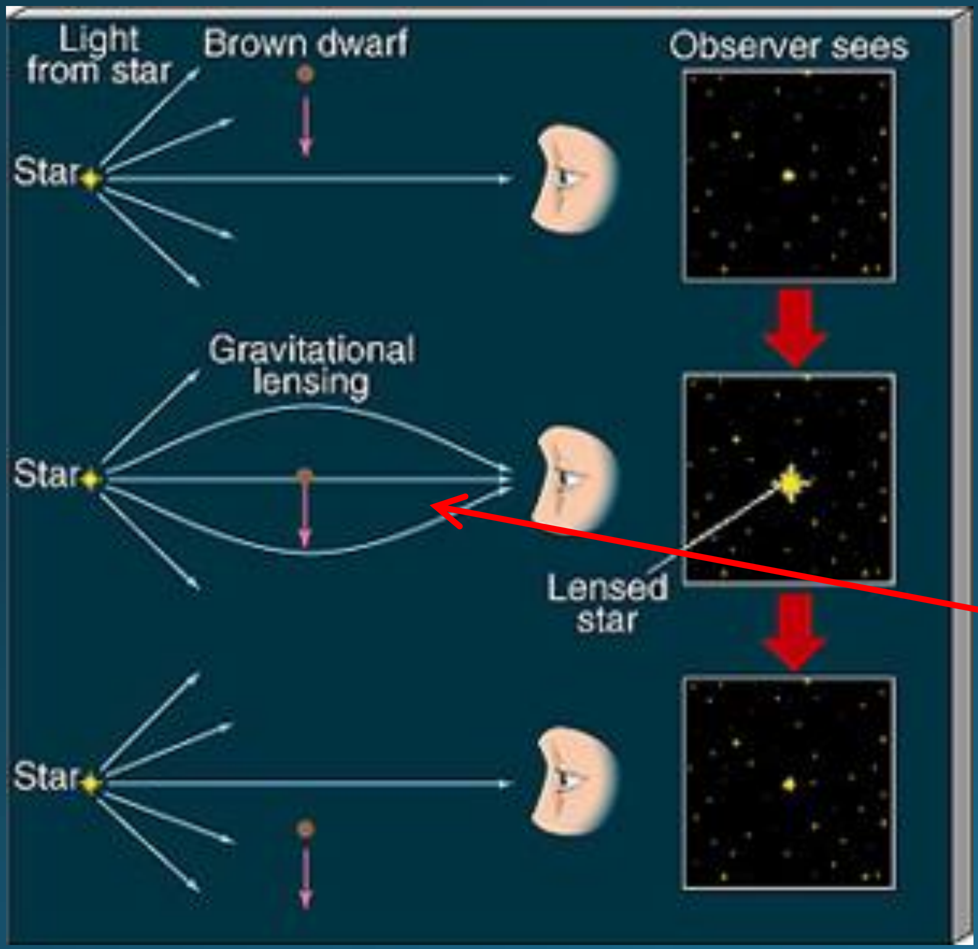


Intermission:
Strong or weak lensing?





Different types of lensing III: Microlensing



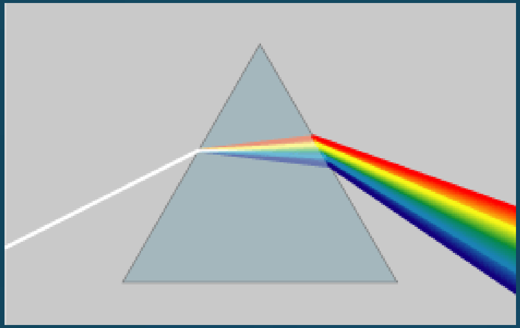
Microlensing is a special, time-dependent case of strong lensing. There's also nanolensing, attolensing, femtolensing…

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



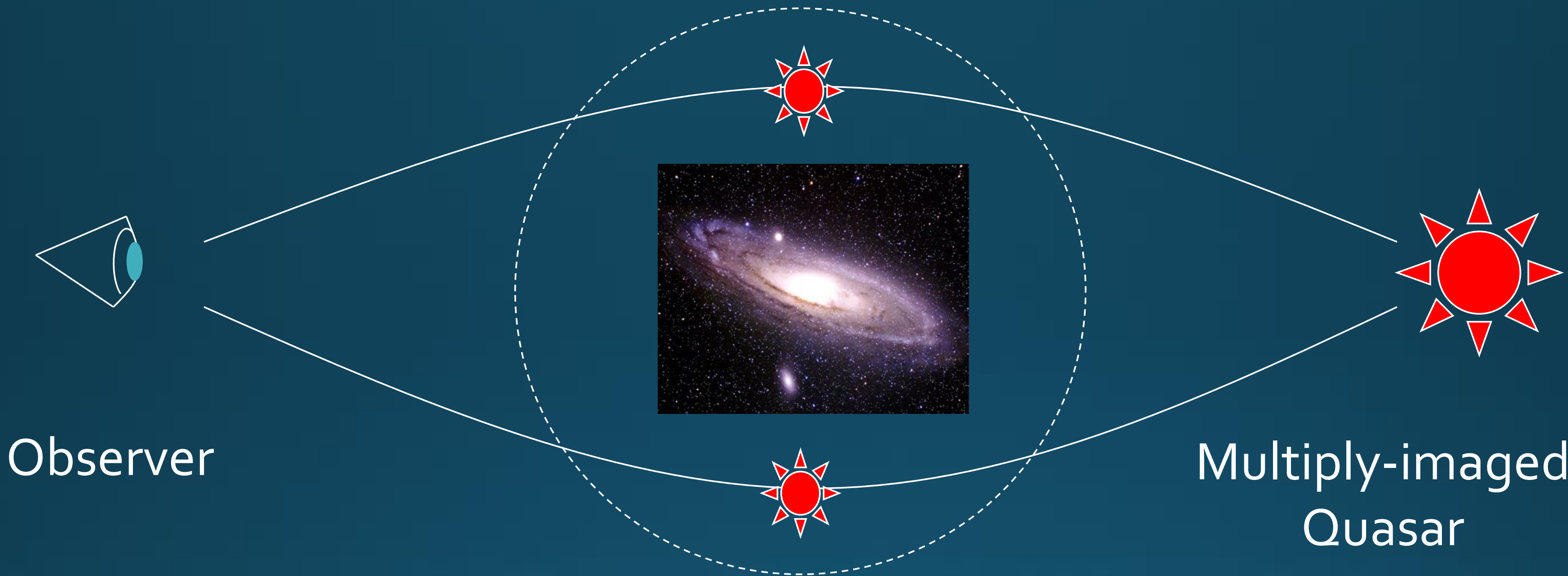
- Graviational lenses are achromatic
  - But note: GL may still alter the colour profiles of extended sources experiencing non-uniform magnification

Unlensed source

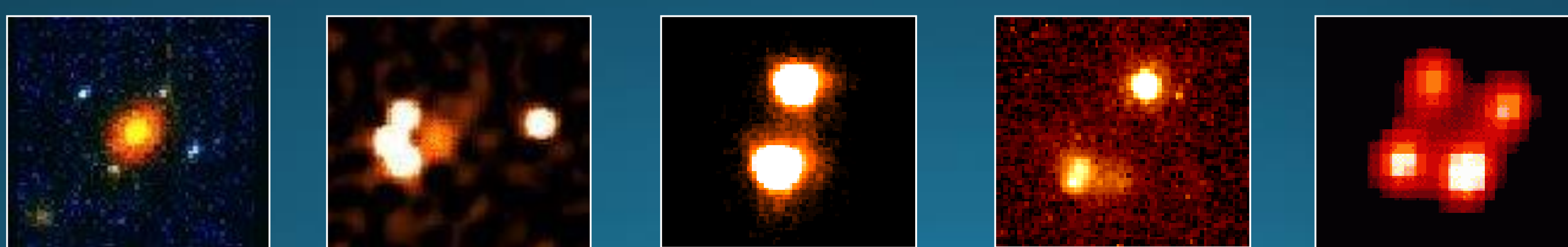
Lens magnifies red area

Total colour becomes redder

Strong lensing: Multiply-imaged quasars I



Lens galaxy (with dark halo)



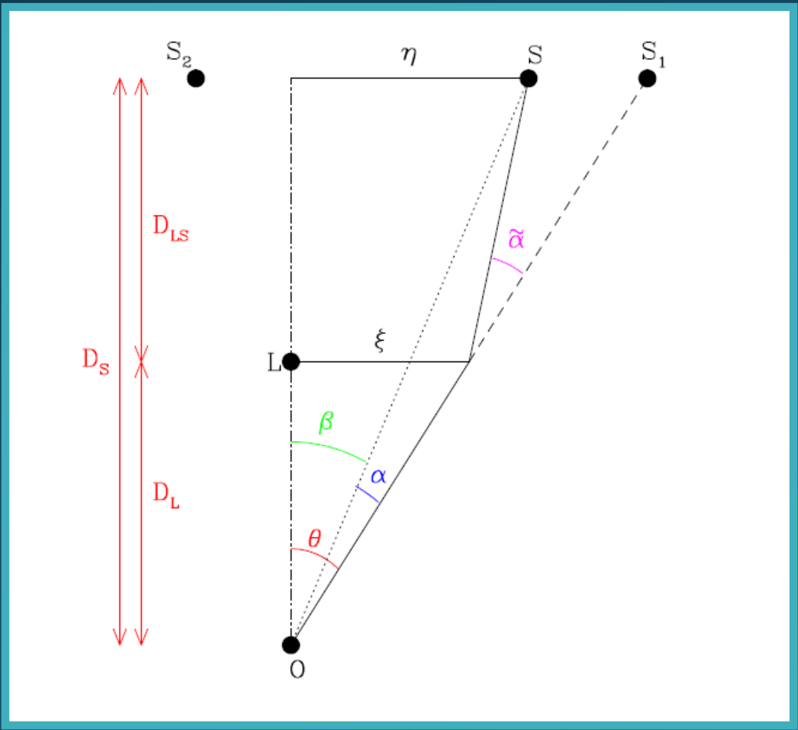
Multiply-imaged quasars II: Measuring the Hubble parameter

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

Time delay

Measured

Depends on lens model



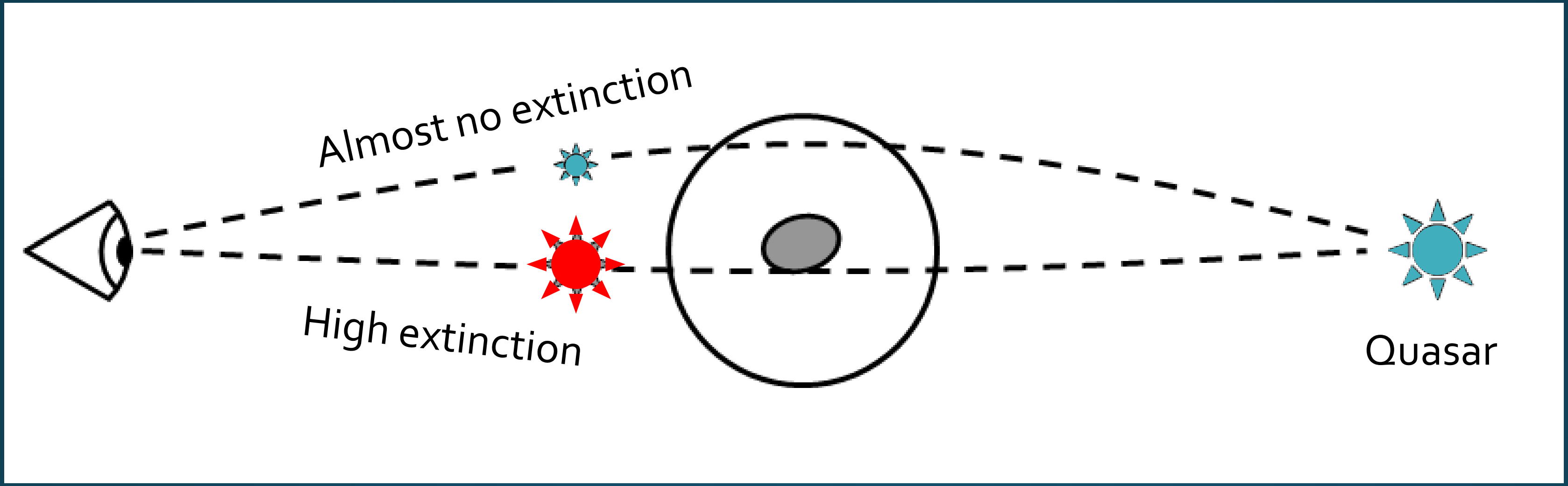
Angular size distances -
Depend on cosmology (mostly H_o)

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

Projected gravitational potential

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

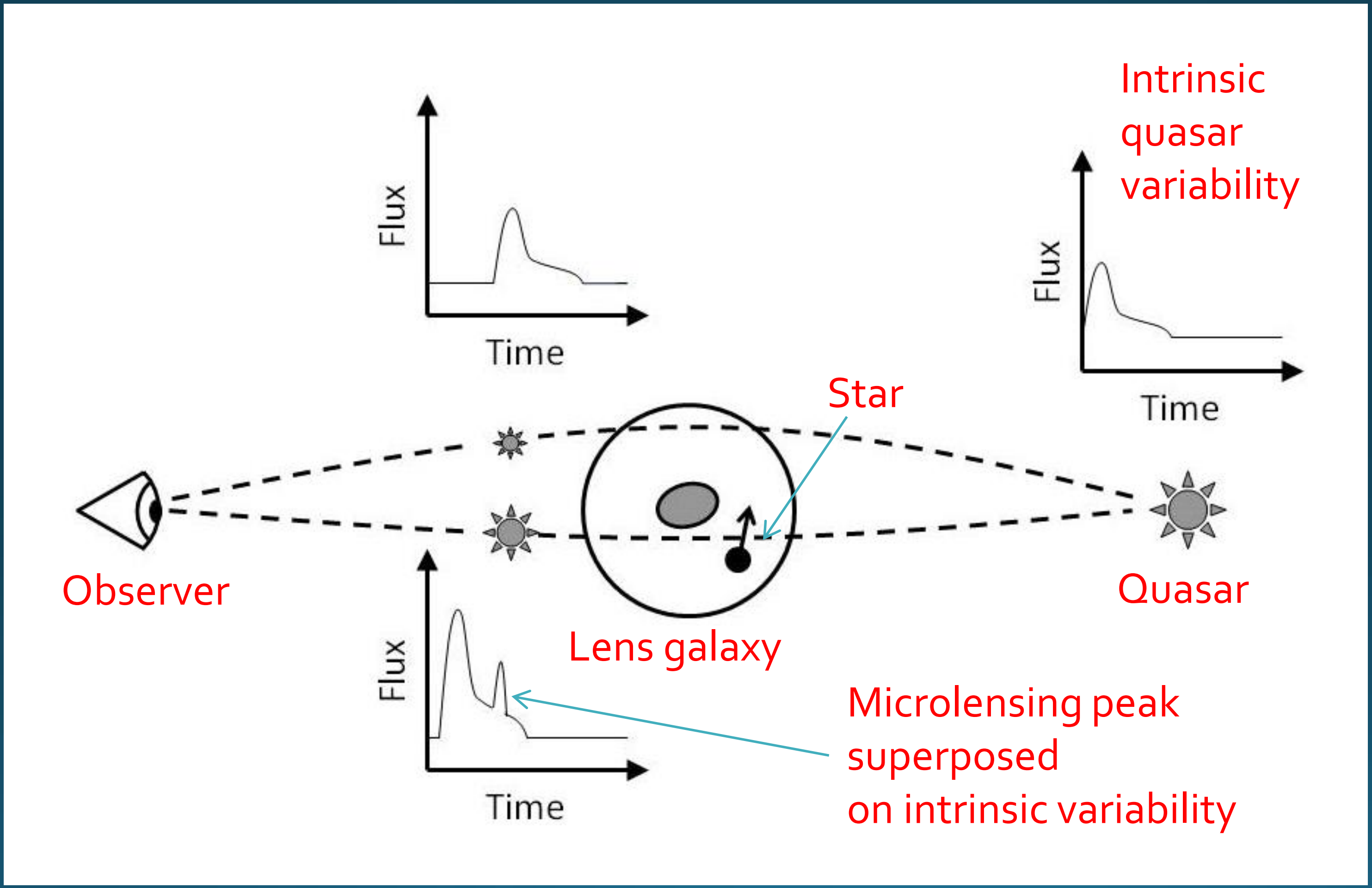
Multiply-imaged quasars III: Dust extinction



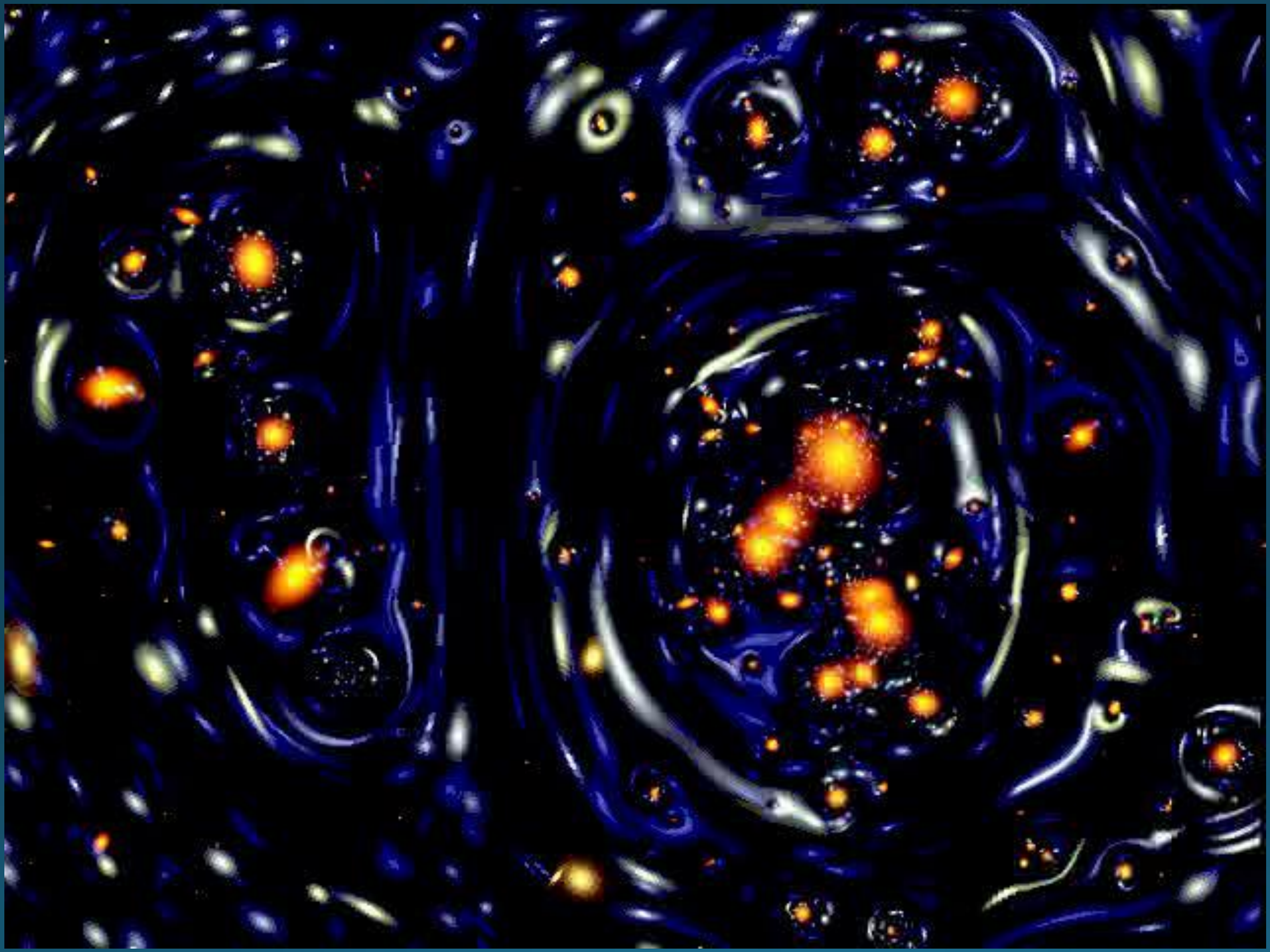
Lens galaxy with dark halo

Colour differences between images →
Extinction law measurement at high z

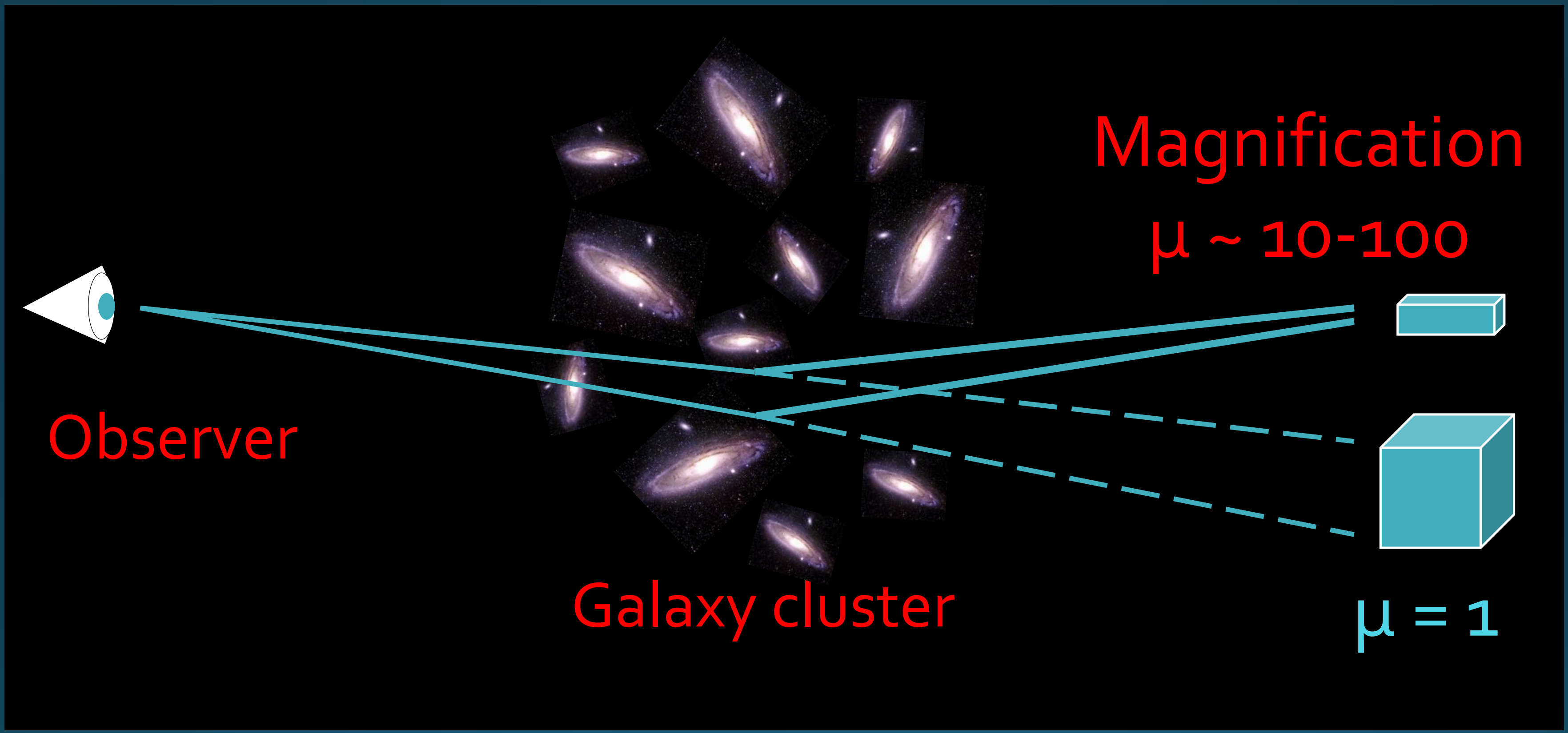
Microlensing in multiply-imaged quasars as as a probe of stars in the lens galaxy



Strong lensing in clusters I



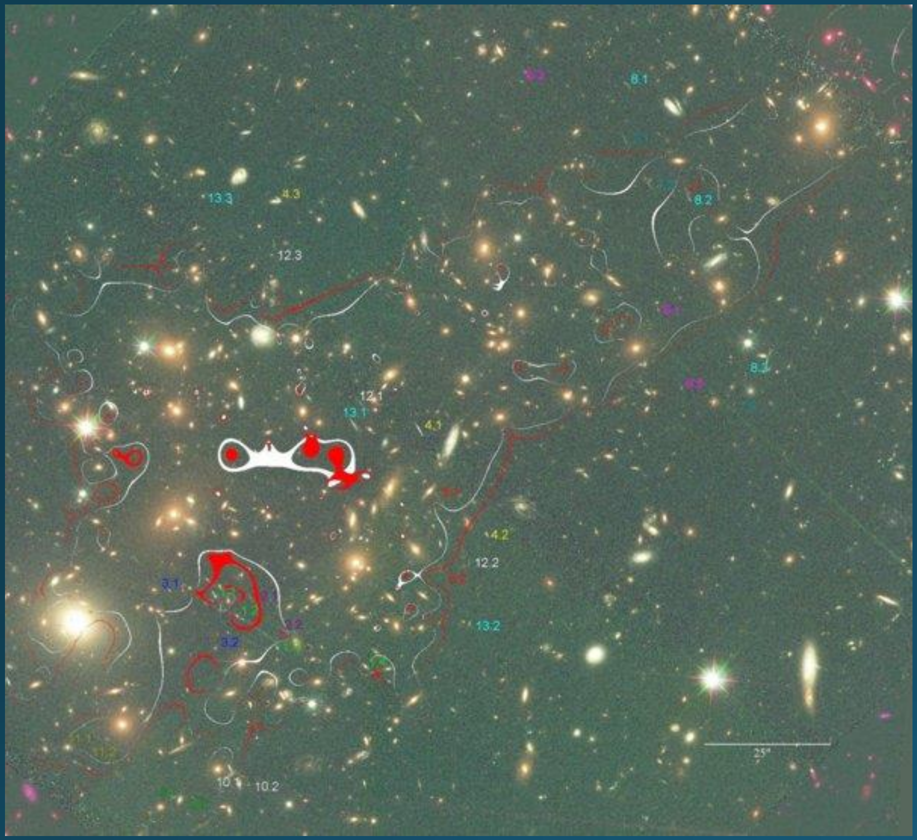
Lensing as gravitational telescopes



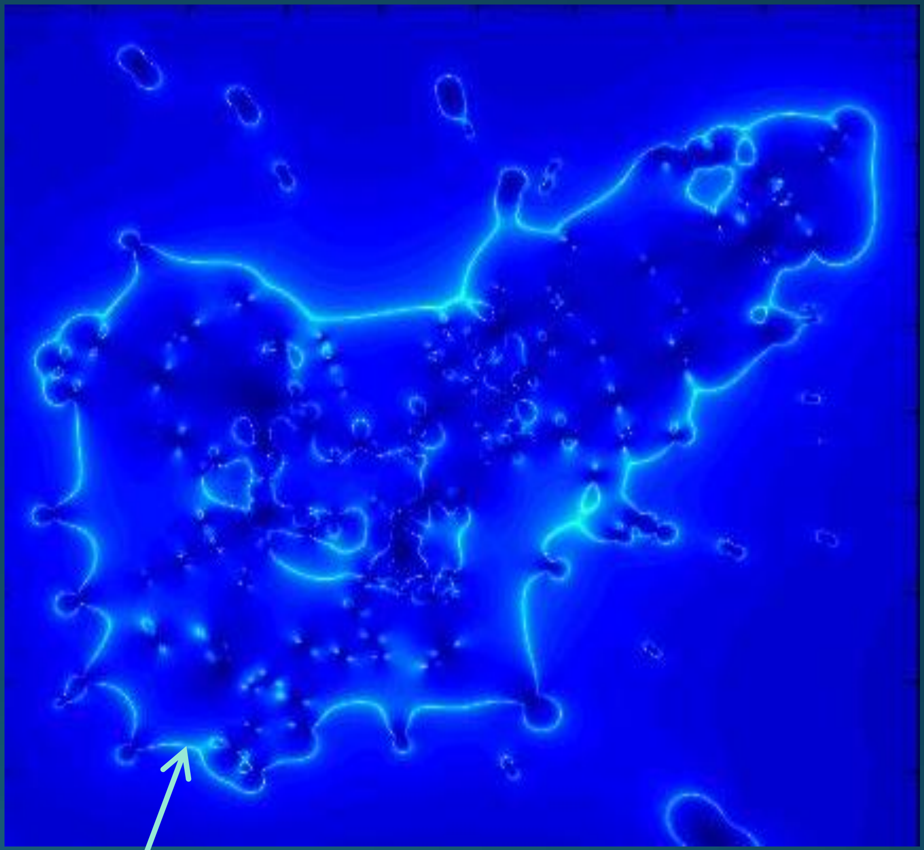
Lensing makes background objects brighter/bigger by a factor μ, but also zooms in on a volume that is smaller by the same amount

→ Very rare types of objects may be impossible to detect this way

Strong lensing in clusters II



Galaxy cluster



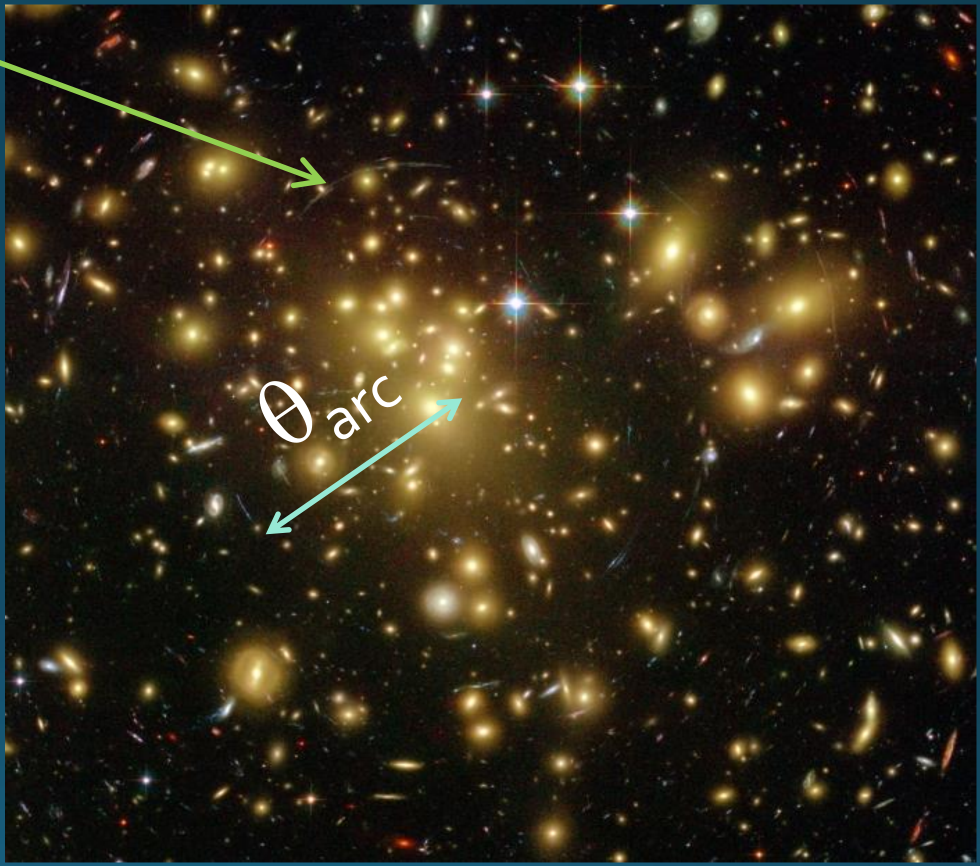
Magnification map

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

Strong lensing in clusters III

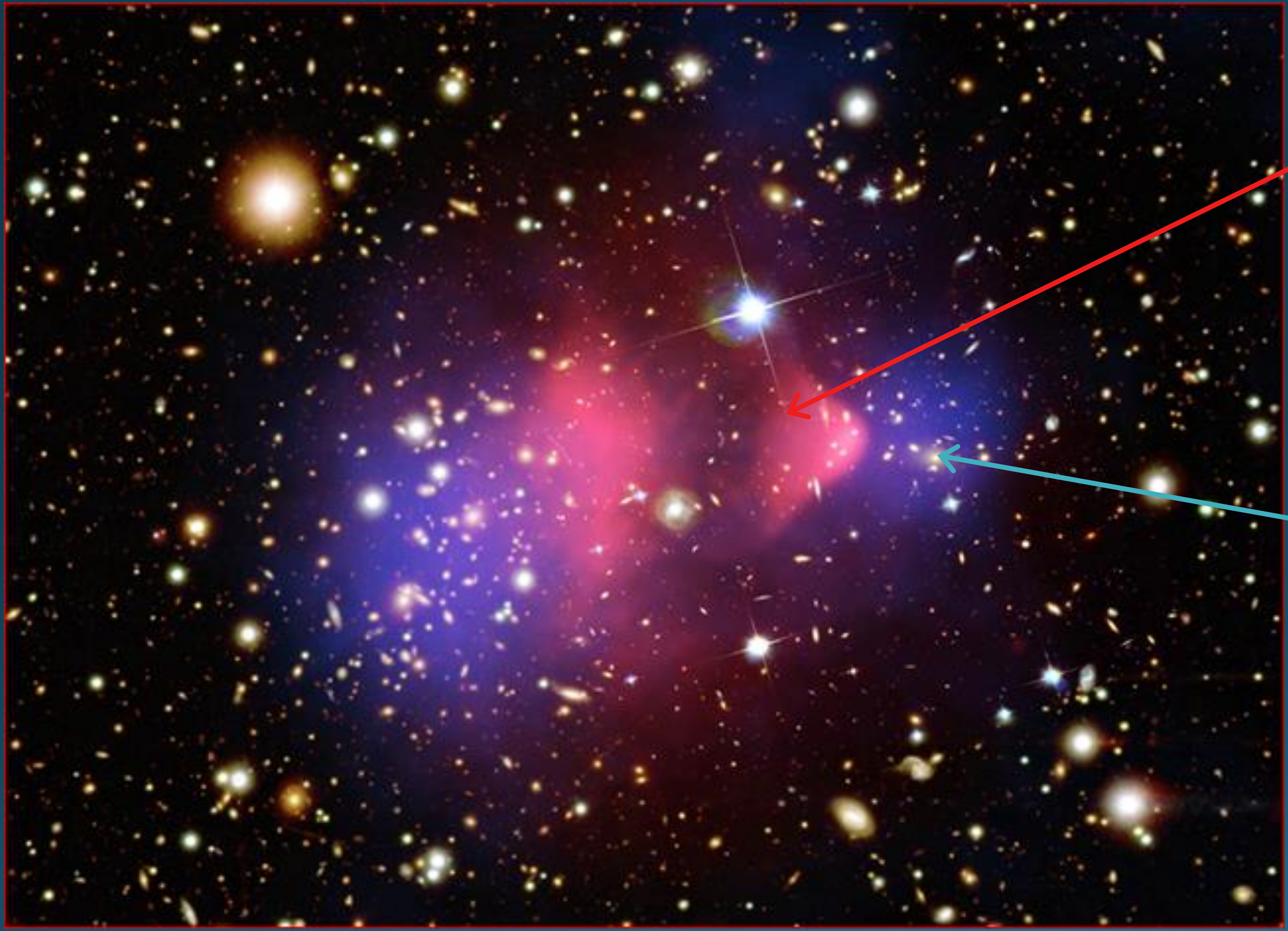
Giant arcs can be used to assessss:

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



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

Dark matter mapping – 2D

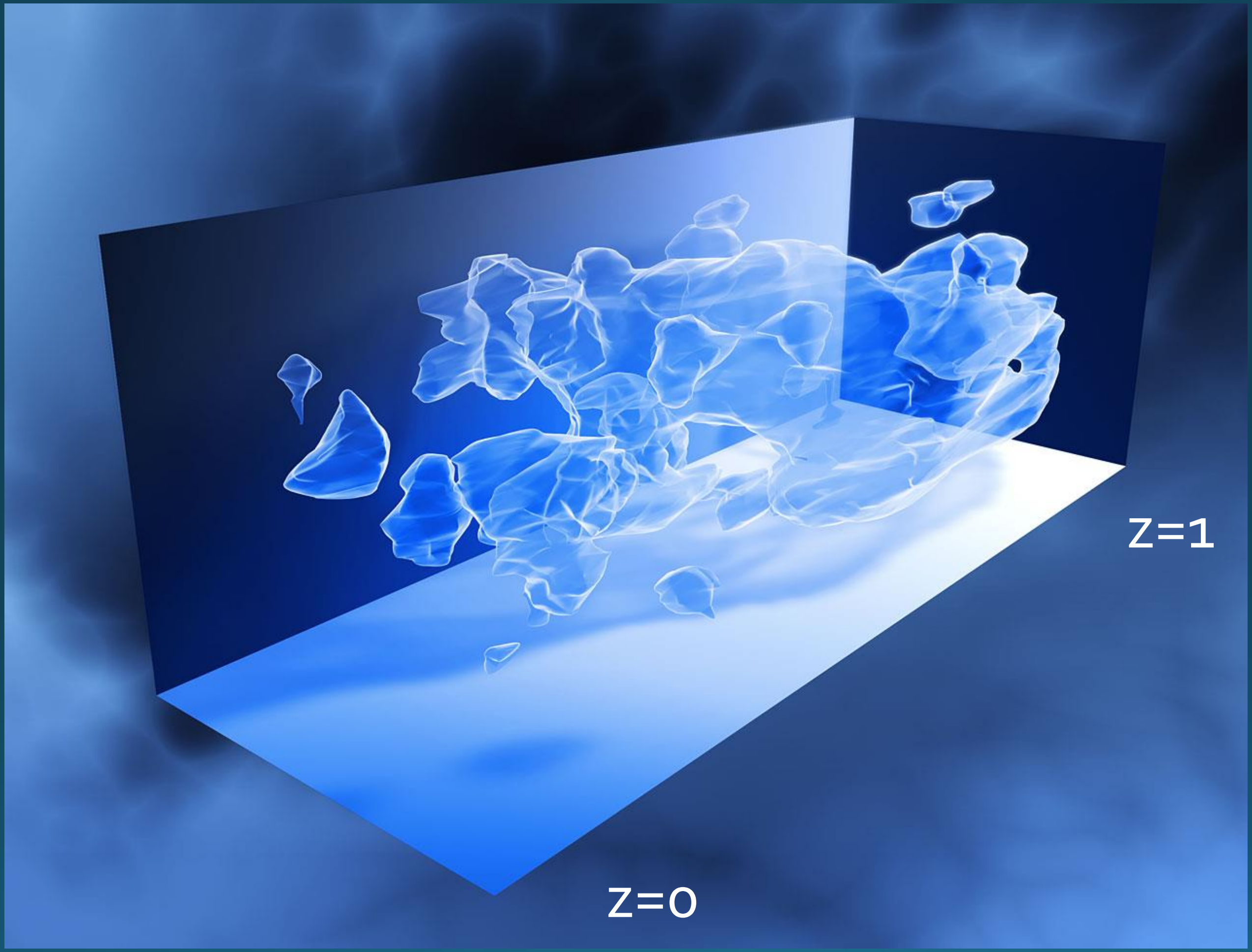


X-ray gas (believed to dominate baryon budget)

Overall matter distribution (dark matter) from weak lensing

The bullet cluster

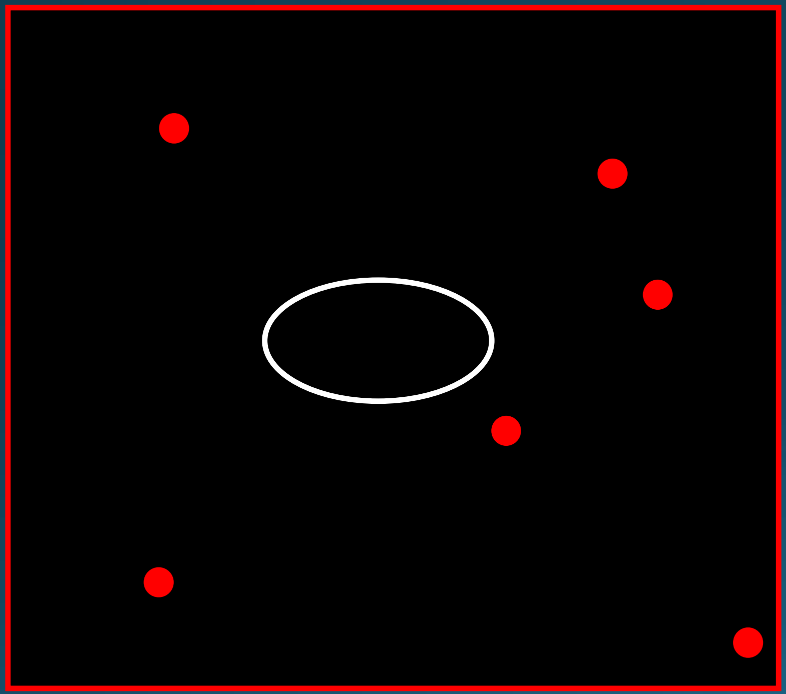
Dark matter mapping – 3D



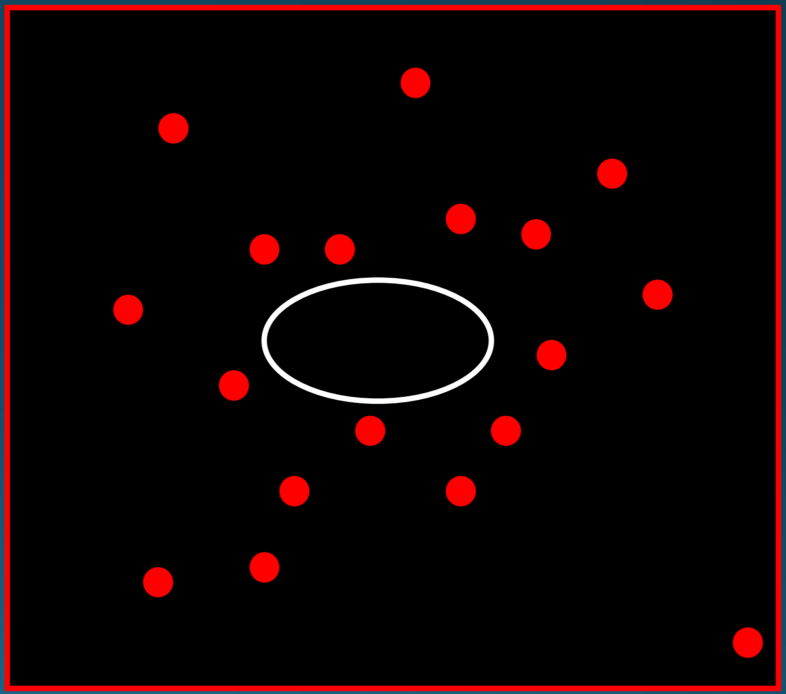
Dark matter tomography in the COSMOS survey based on weak lensing

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