Galaxy cluster masses from magnification

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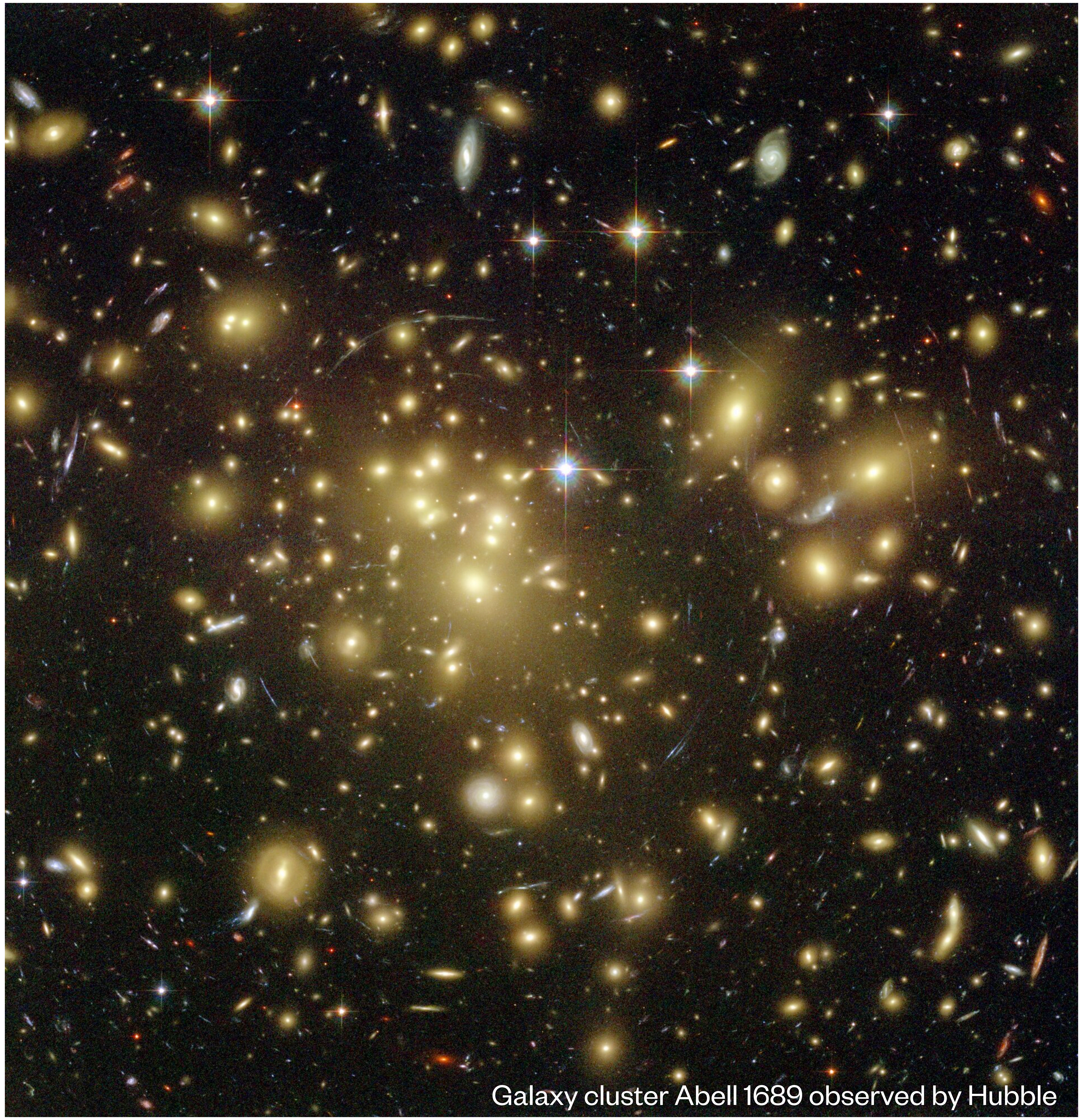
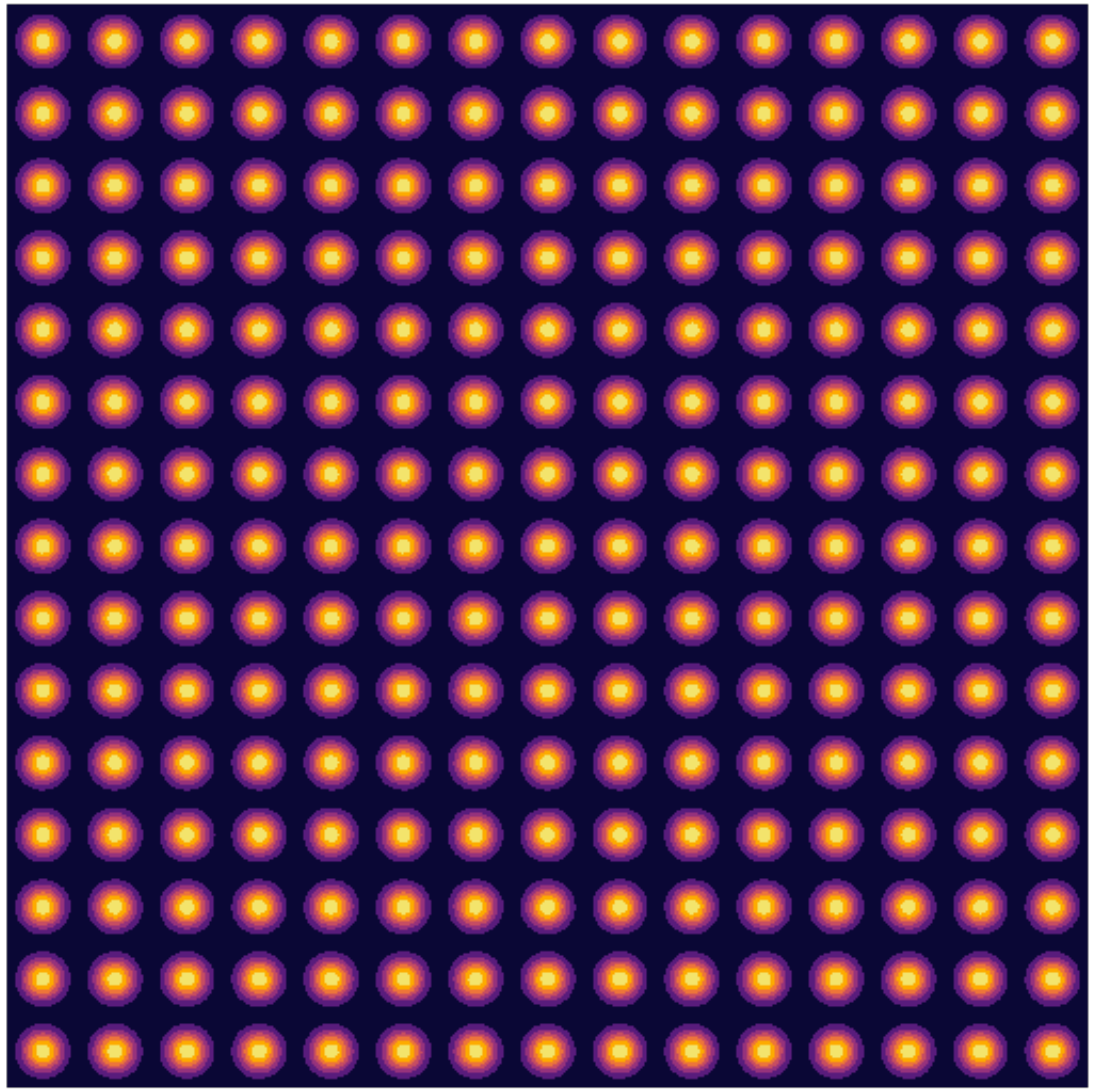
Galaxy clusters

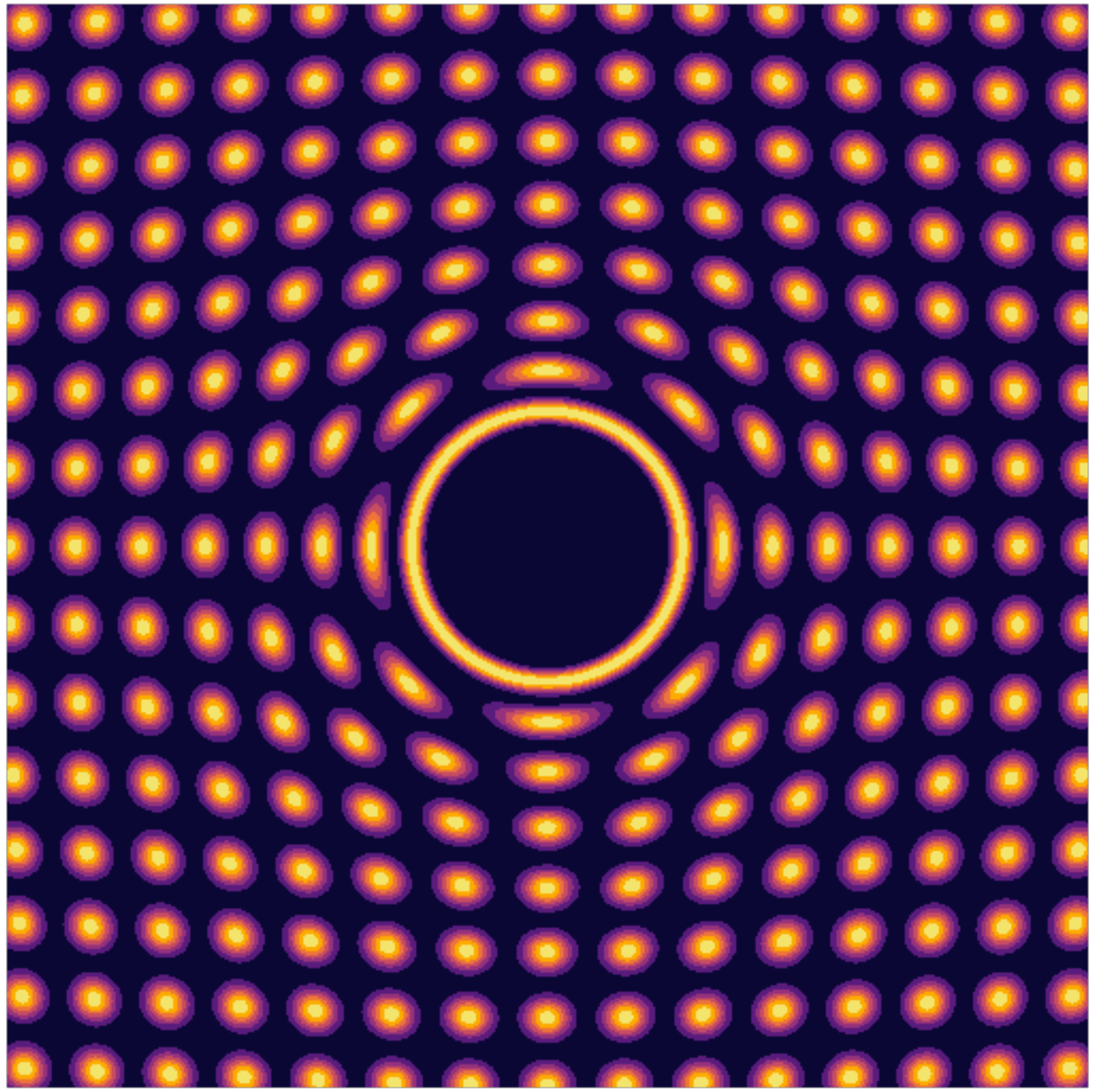
- Largest bound objects in the universe
  $> 10^{14}\,M_\odot$
- Composition
  - 85% dark matter
  - 12% hot gas
  - 3 % stellar mass
- They provide strong constraints on the matter content, geometry, the nature of gravity and the formation of structure in the universe and **gravitational lensing gives information on all of this!**



Galaxy cluster Abell 1689 observed by Hubble



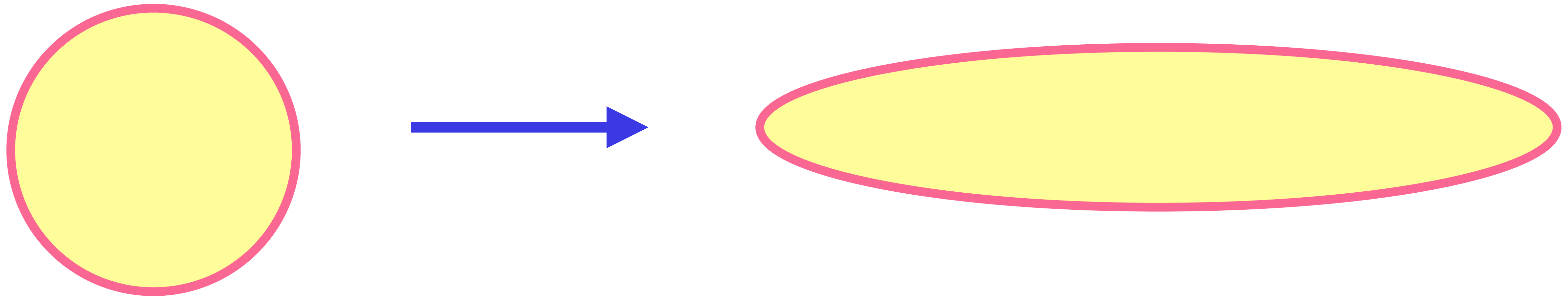
Field of **unlensed** galaxies



Field of **lensed** galaxies

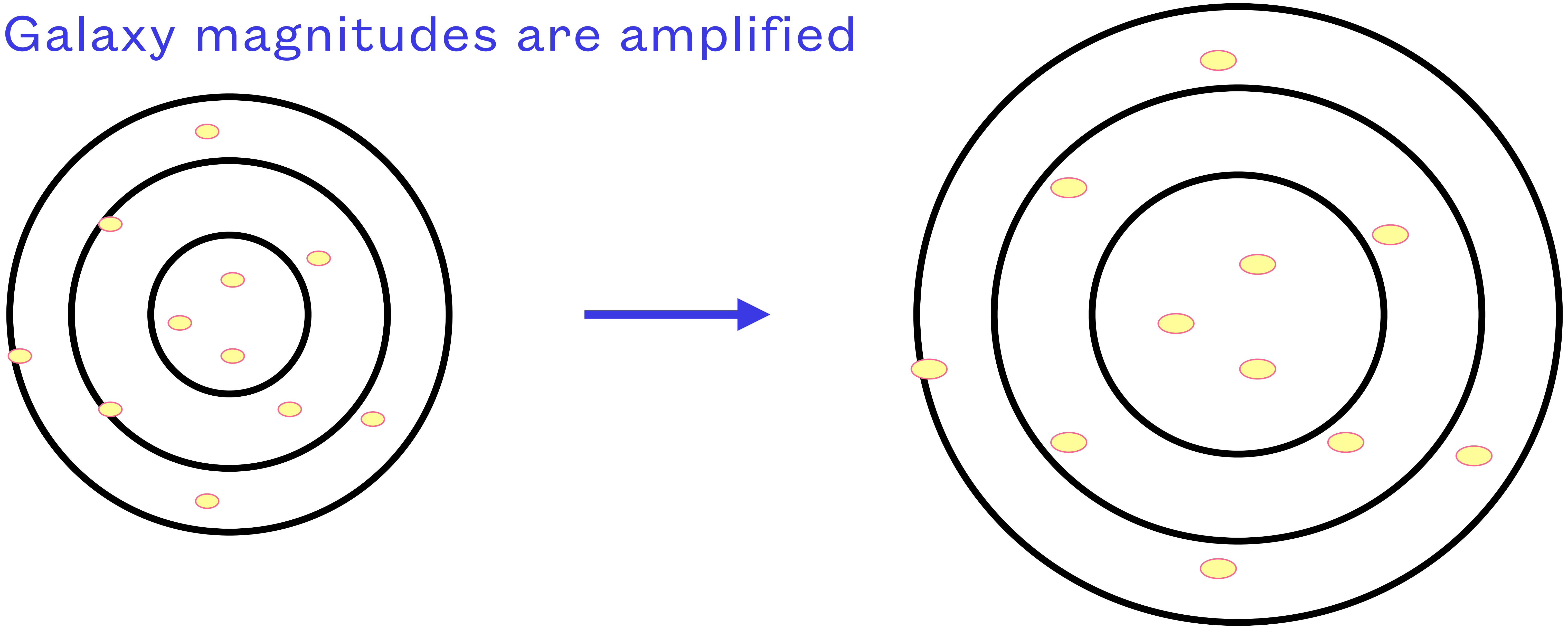
Cluster Lensing

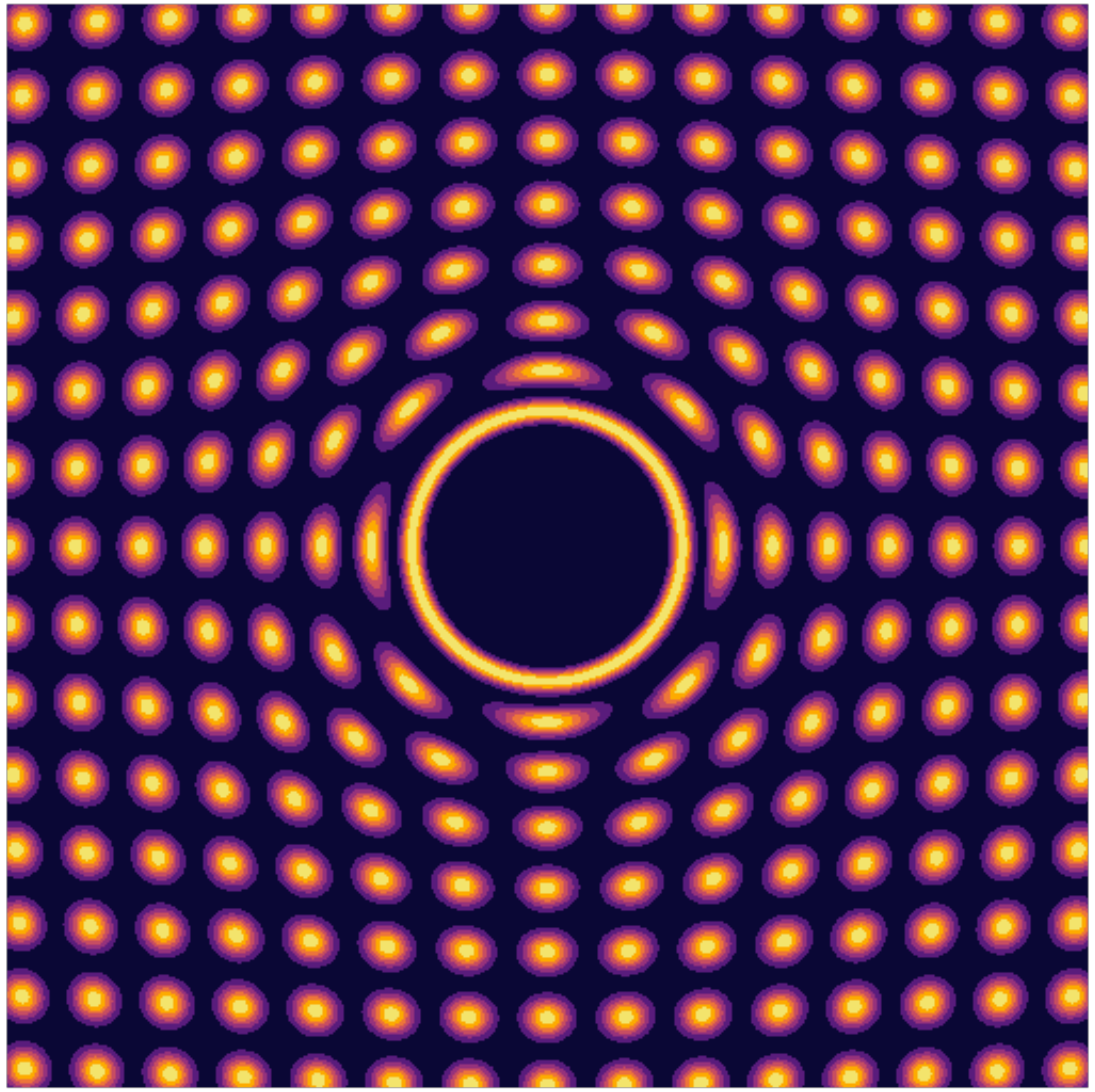
- Shears galaxy images



- Solid angles on the sky are amplified/ galaxies are deflected from the lens centre

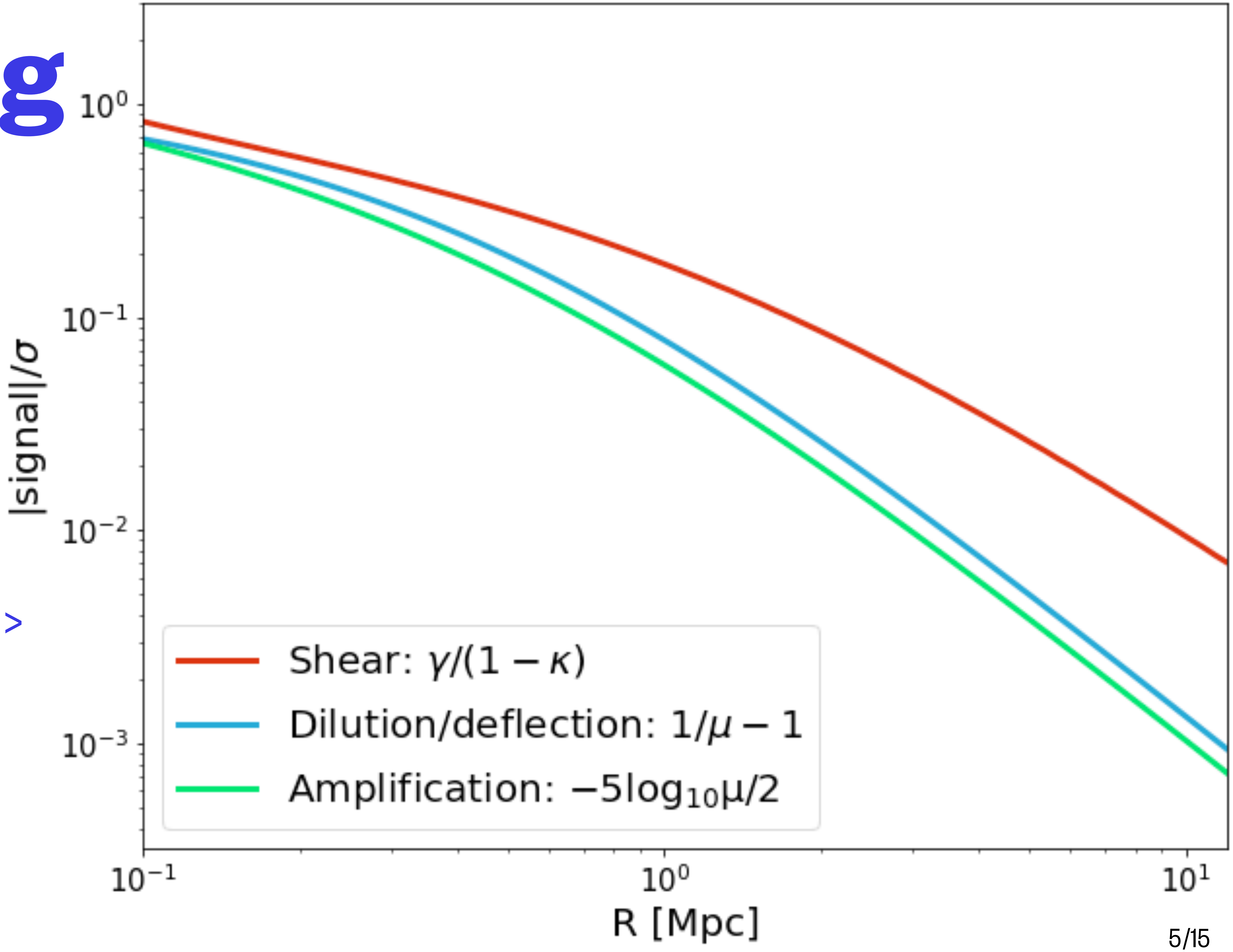
- Galaxy magnitudes are amplified





Cluster Lensing

- We will use the **amplification** and **dilution**!
  - Completely **different systematics** from shear, magnitudes opposed to shape measurements
  - We can go deeper in magnitude => **more galaxies**



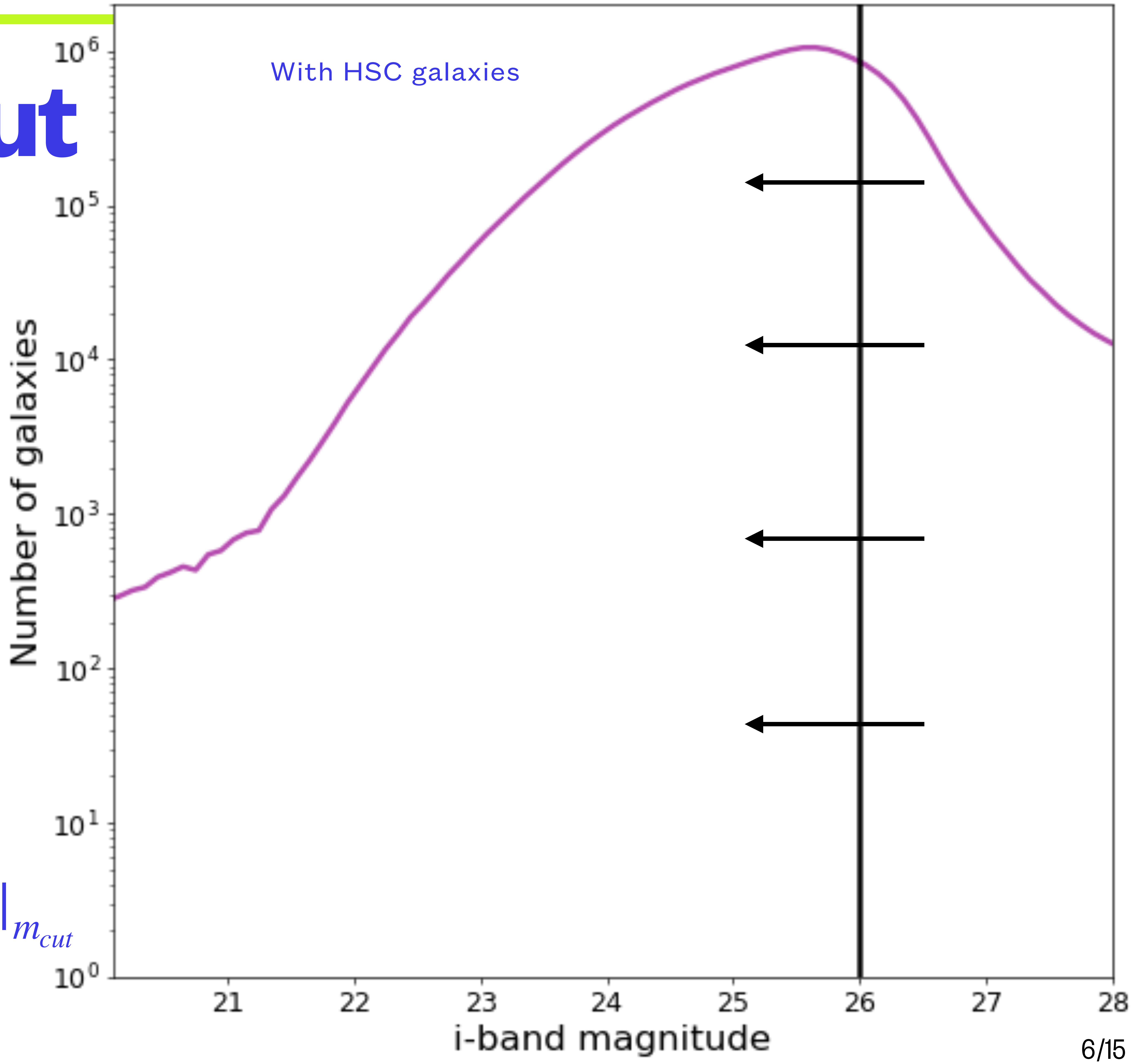
Single magnitude cut

- Count the number of galaxies
  - Galaxies are **magnified** which **introduces** faint galaxies into the sample
  - **Solid angles** on the sky are magnified which **reduces** galaxies per solid angle

$$n_{obs}(\overrightarrow{\theta}) \approx n_o \left[1 + 2\kappa(\overrightarrow{\theta})(\alpha - 1)\right]$$

- n_o is the intrinsic galaxy distribution
- n_{obs} is the observed distribution
- κ is the lensing convergence

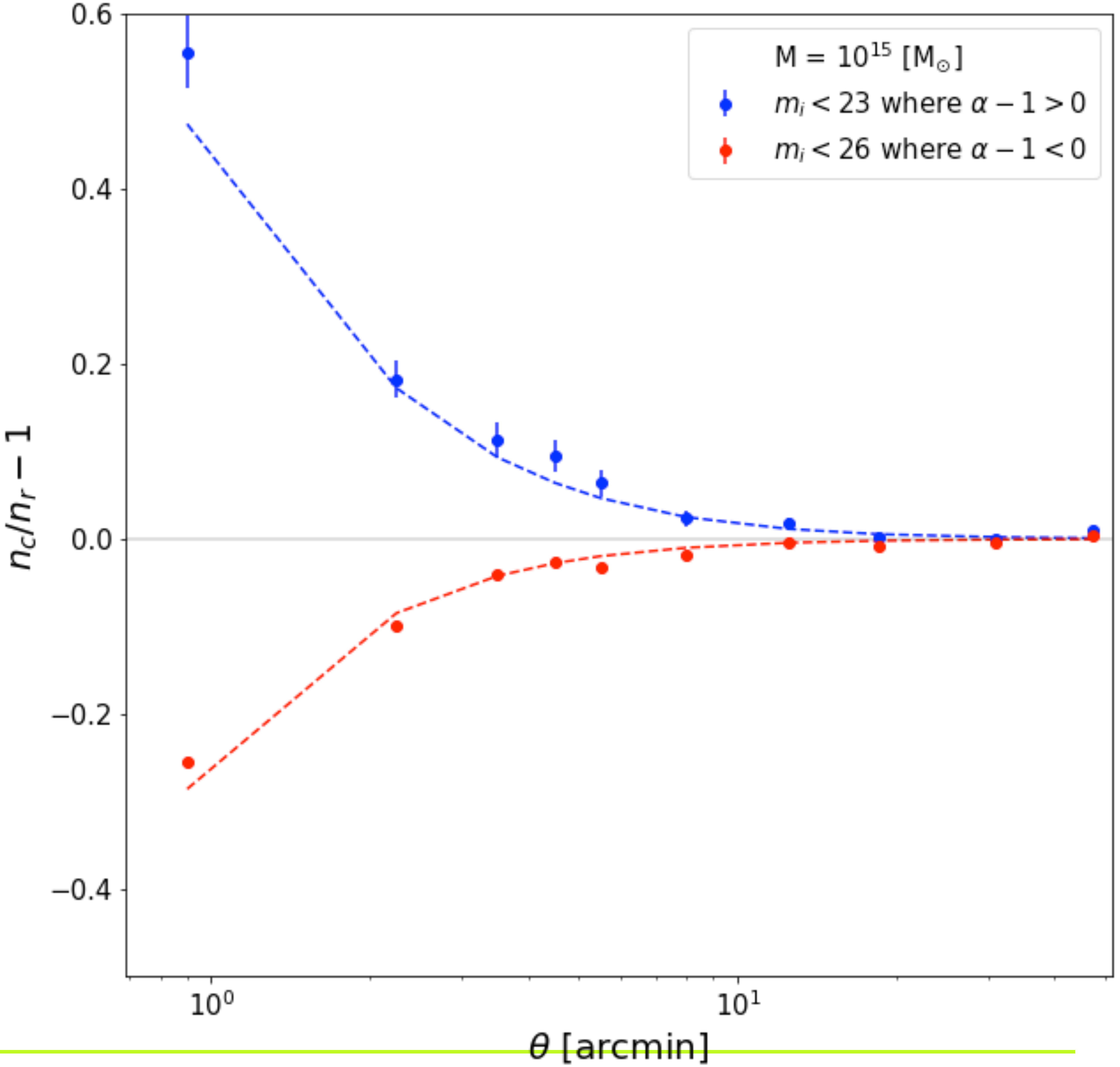
$$\alpha = 2.5 \frac{d\log_{10} n}{dm}\Big|_{m_{cut}}$$



Single magnitude cut

- Amplification or dilution can win out → the number of galaxies may increase or decrease depending on α
- The **competition** between the two effects will **reduce our signal**

$$n_{obs}(\overrightarrow{\theta}) \approx n_o \left[1 + 2\kappa(\overrightarrow{\theta})(\alpha - 1)\right]$$

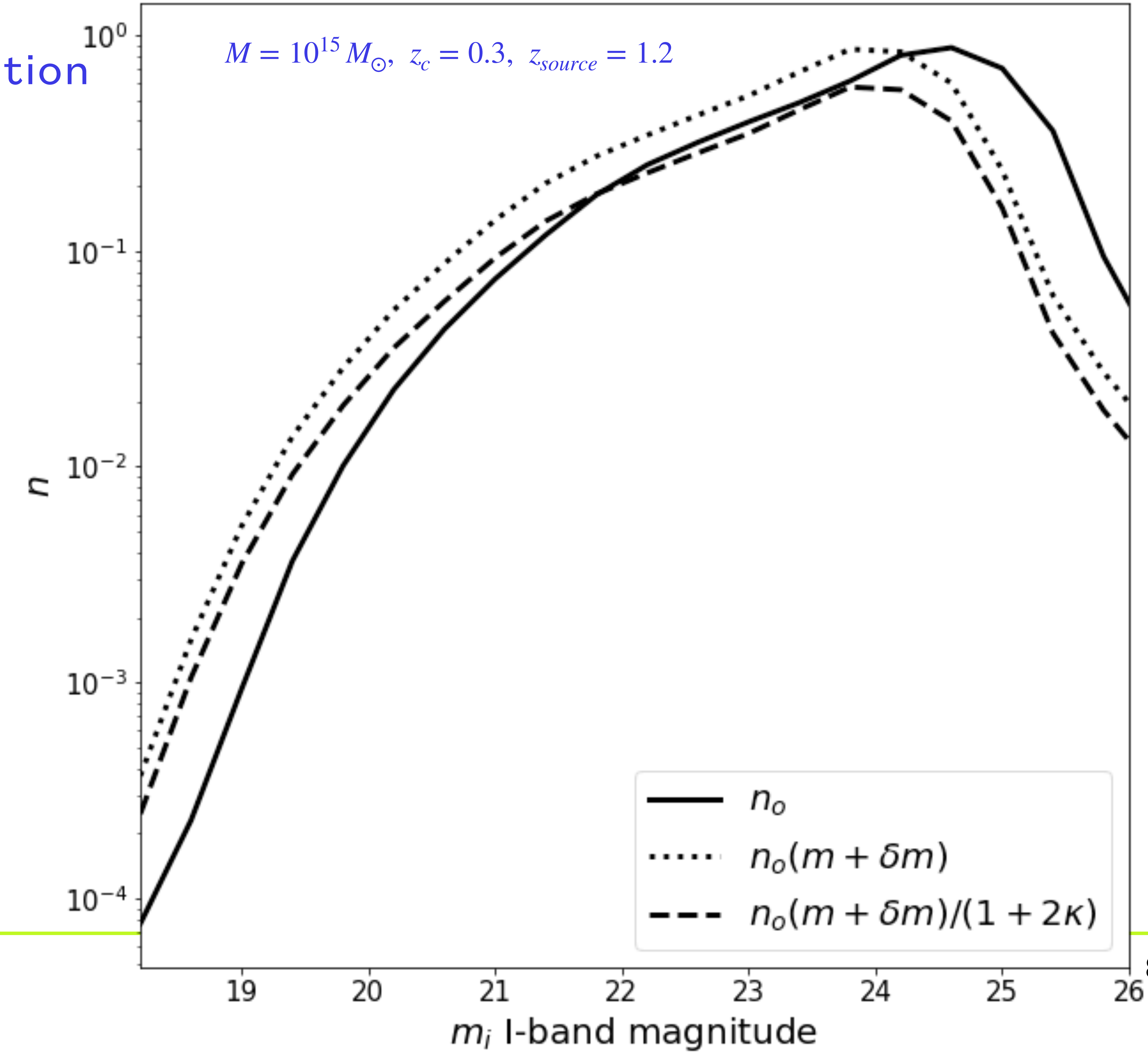


New approach - full magnitude distribution

- Resolution: full galaxy magnitude distribution
  - Change in magnitude δm -> shifts distribution
  - Change in **solid angle on the sky** A -> changes normalisation
- Factor of 2 reduction on $\ln \mathrm{M}$ errors compared to a single magnitude cut!
-(see also Ménard and Bartelmann 2002)

$$n_{obs} = n_o(m + \delta m)/\mu$$

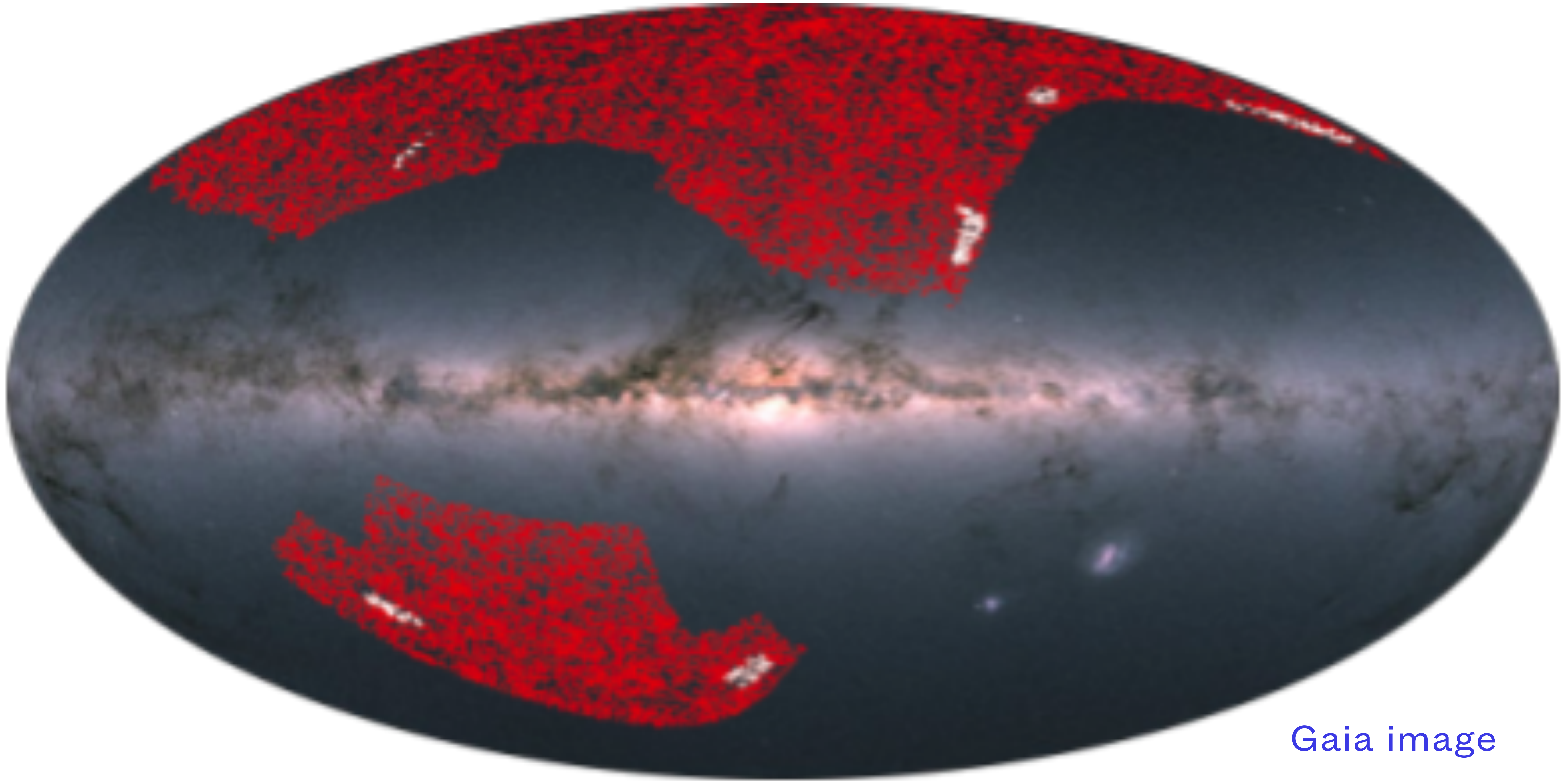
$$\mu \approx 1/[(1-\kappa)^2 - \gamma^2]$$



redMaPPer clusters

- Clusters found with redMaPPer in SDSS data
- 200 clusters with redshift > 0.3 and richness > 40
- We use Hyper Suprime Cam (HSC) wide field galaxies for our weak lensing data
- Using the full likelihood we can constrain the mass

$$ln\mathscr{L} = -\frac{1}{2}\sum_{ijk}\left(n_{obs}(\theta_i, m_j, z_k) - n(\theta, m, z\,|\,M_{lens})\right)^2/\sigma_{ijk}^2$$



Gaia image

redMaPPer clusters

-Using the full likelihood we can constrain the mass using

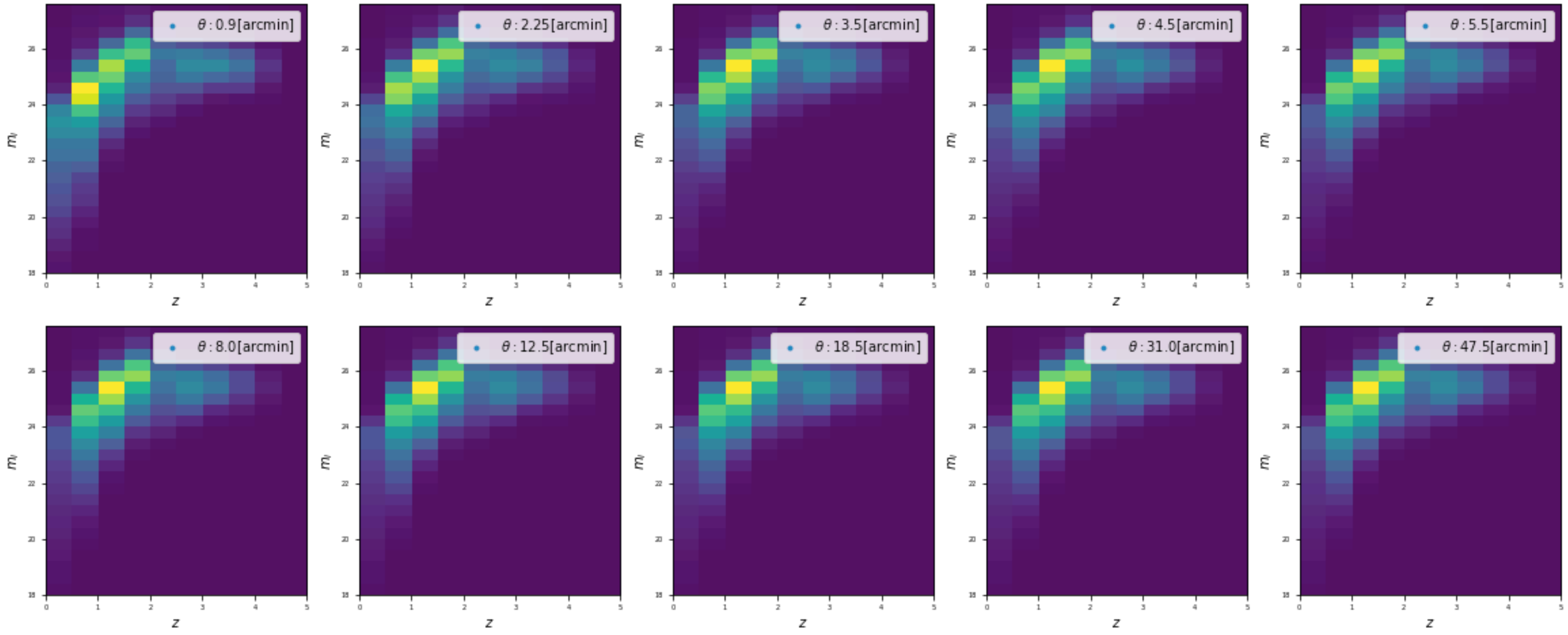
$$ln\mathscr{L} = -\frac{1}{2}\sum_{ijk}\left(n_{obs}(\theta_i, m_j, z_k) - n(\theta, m, z\,|\,M_{lens})\right)^2/\sigma^2_{ijk}$$

-6 angular bins: $\theta \in [0.9, 10]$ [arcmin]

-4 bins in redshift: $z \in [1, 3]$

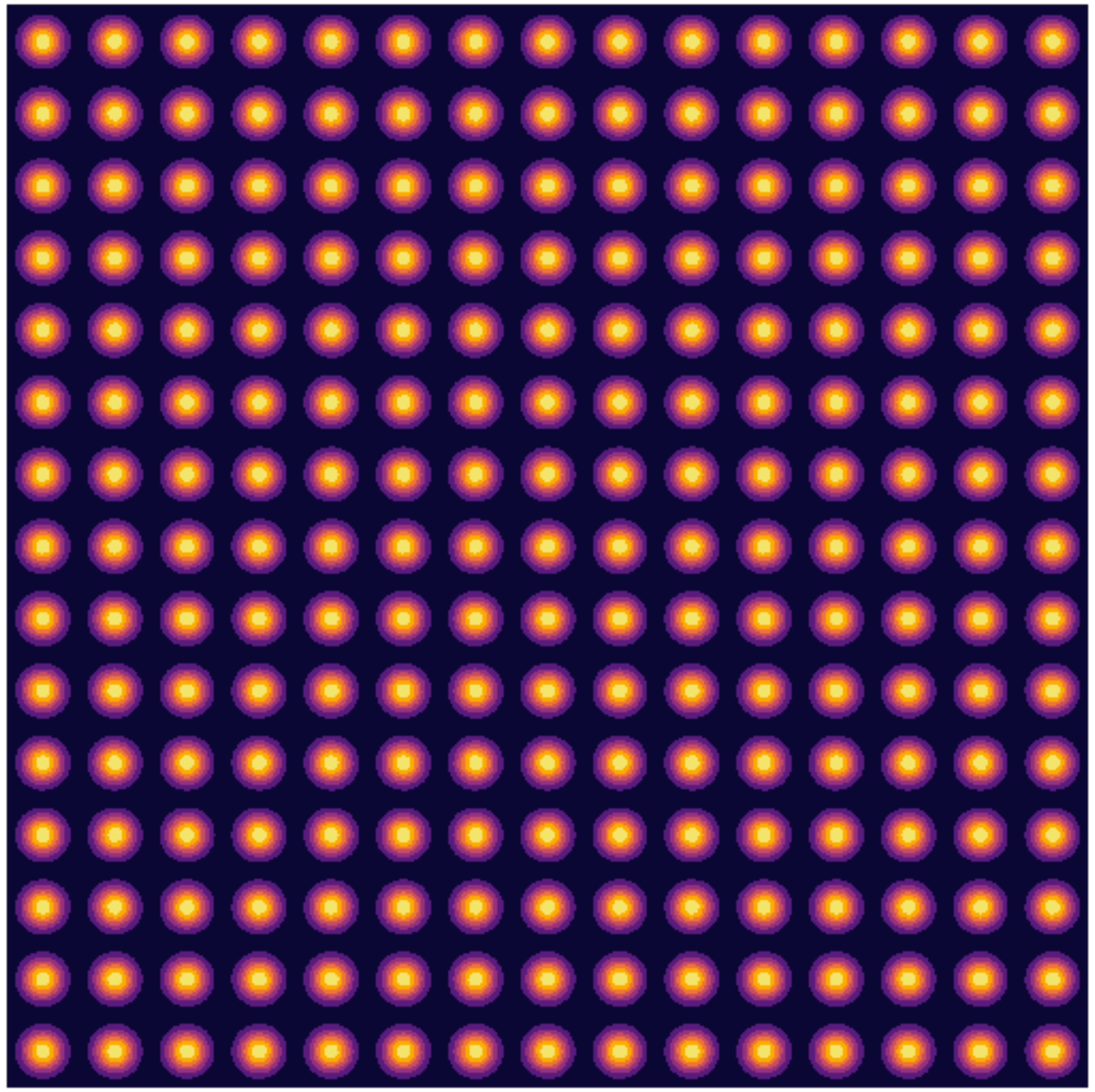
-14 bins in i-band magnitude: $m_i \in [20, 25.5]$

Magnitude bins

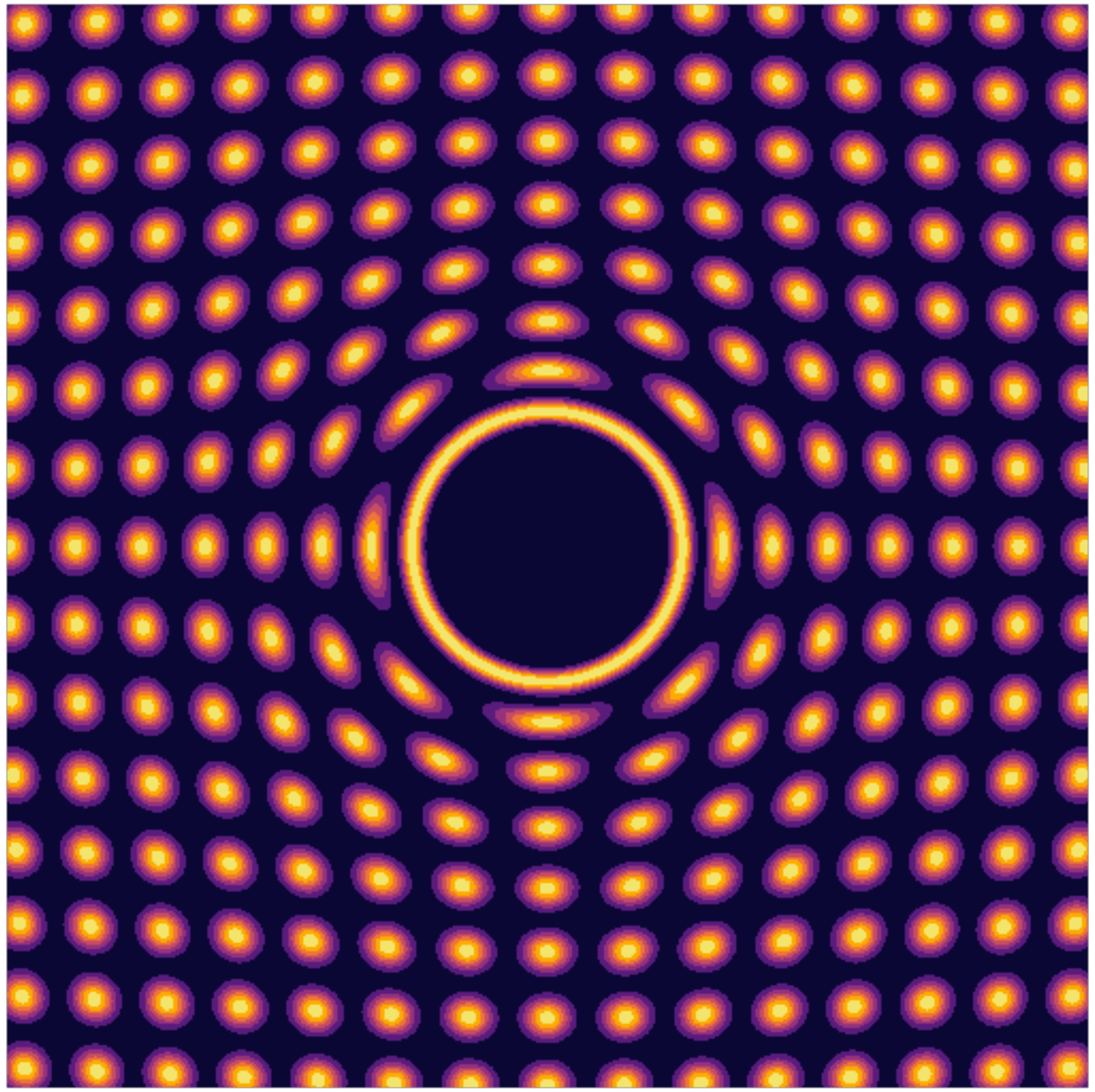


Redshift bins

$$\log_{10} \mathrm{M}_{\mathrm{stack}} = 14.37 \pm 0.04$$



Field of **unlensed** galaxies

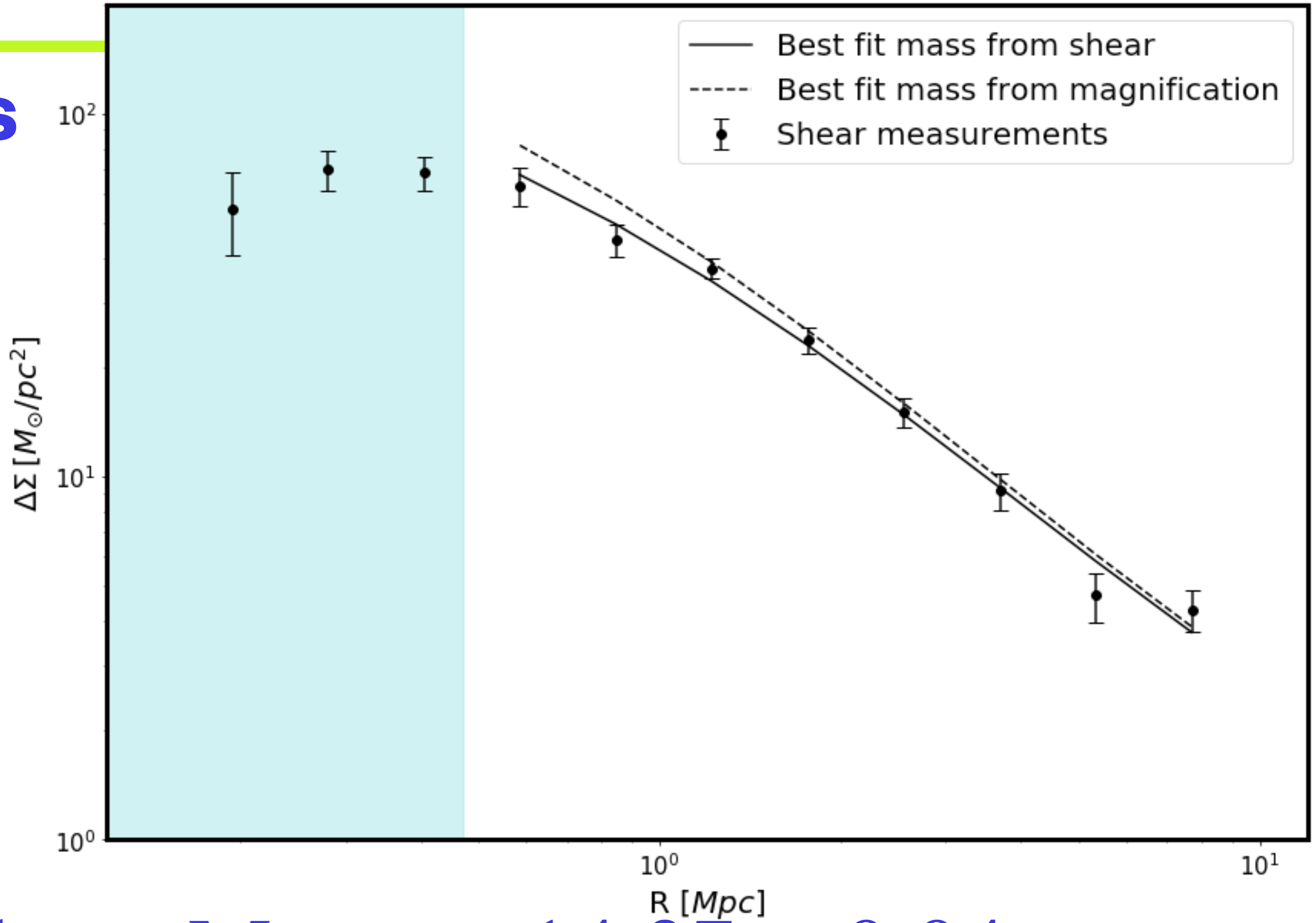


Field of **lensed** galaxies

Comparison to shear analysis

$$\epsilon_{+\text{obs}} \approx \epsilon_{+\text{int}} + \gamma$$

- We are now sensitive to the excess surface mass density (opposed to the surface mass density for magnification)
- Murray et al. 2022 *Measuring weak lensing masses on individual clusters*
- **Consistent** masses and **competitive** constraints

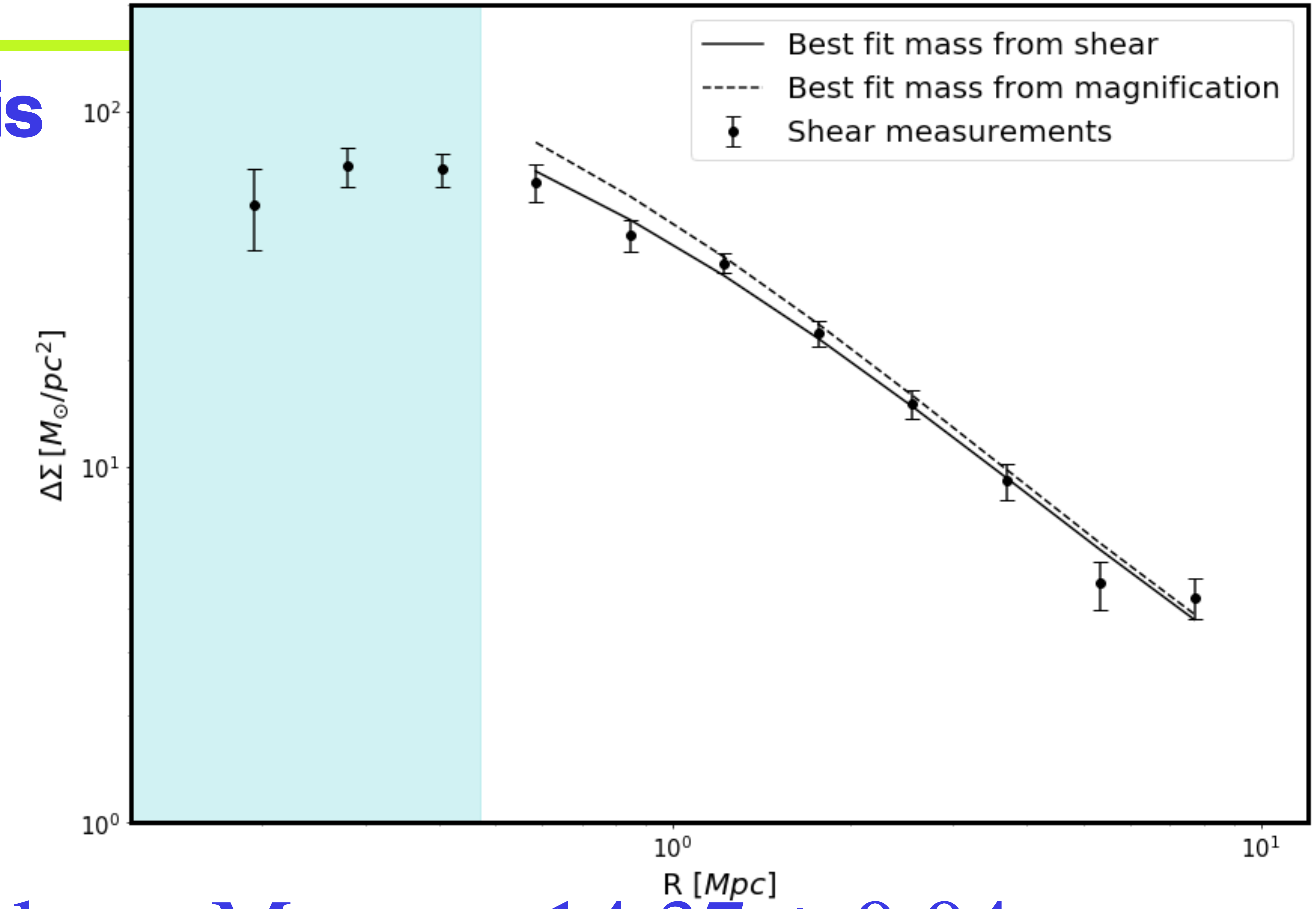


$$\text{Magnification mass}: \log_{10} M_{\text{stack}} = 14.37 \pm 0.04$$

$$\text{Shear mass}: \log_{10} M_{\text{stack}} = 14.31 \pm 0.03$$

Comparison to shear analysis

- **Consistent** masses and **competitive** constraints
  - ~ twice as many galaxies ($m_i < 25.5$ rather than $m_i < 24.5$ for shear)
  - Combination of amplification and dilution effects
  - Magnification is less sensitive to the cluster concentration



$$\text{Magnification mass}: \log_{10} \text{M}_{\text{stack}} = 14.37 \pm 0.04$$

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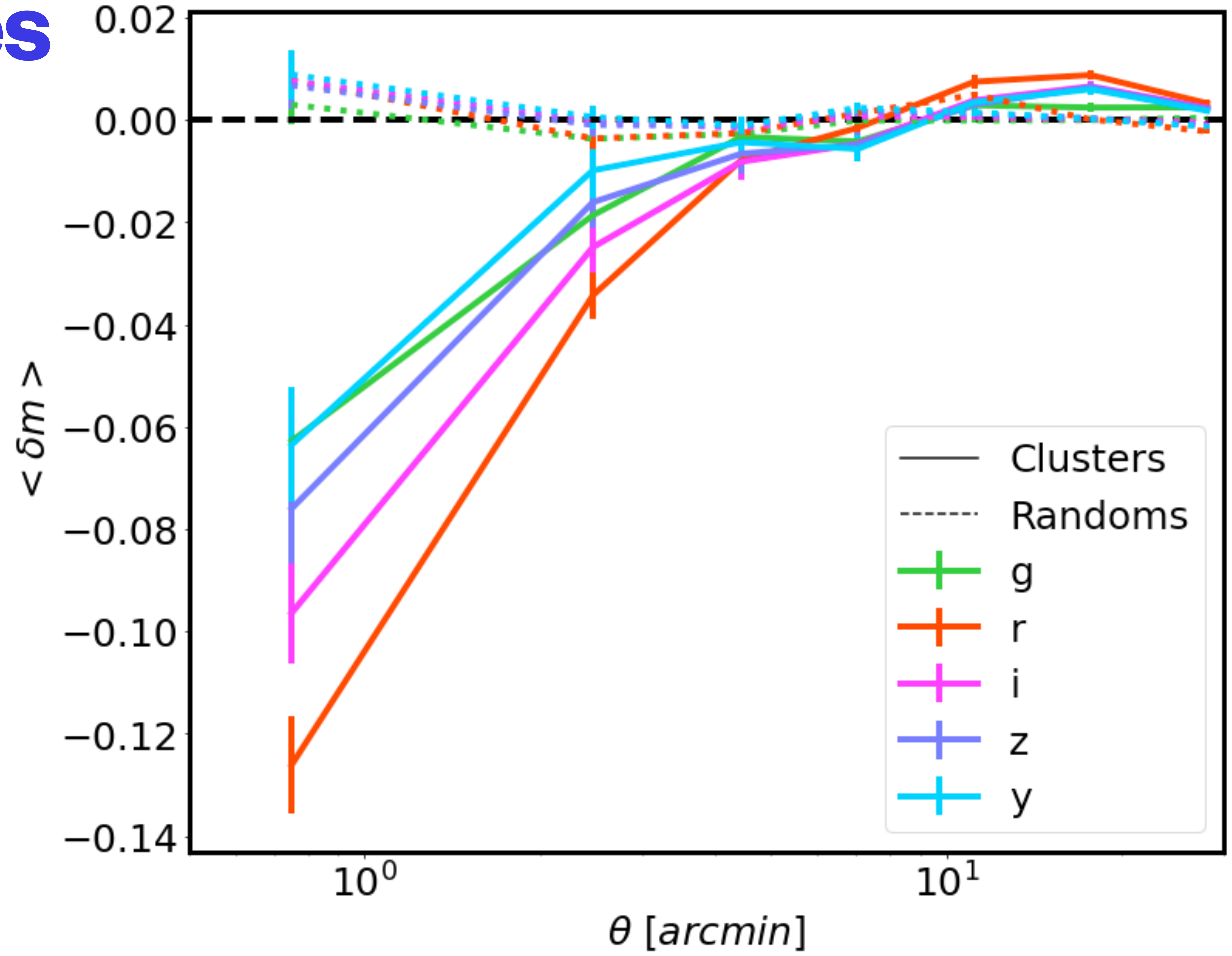
Stacked magnitude profiles

- Using a subsample of 90 clusters in the redshift interval $0.2 < z_{cluster} < 0.3$
- We measure the average magnitude for a stack of clusters in annuli from the cluster centre
- Clear chromatic signal
- **Attention,** lensing introduces colour changes, faint galaxies which are introduced to the sample have different colours to bright galaxies
- These profiles have been used to measure dust, not strictly true (Menard et al. 2009)

$$\langle \delta m \rangle = \langle m(\theta) \rangle - \left\langle m_{field} \right\rangle$$

$$m_{obs} \approx m_{int} - \frac{5}{2ln10}\left(2\kappa - \tau_\lambda\right)$$



Conclusions

- We have introduced a new magnification method, using the full magnitude distribution for cluster mass estimation
  - A factor of ~2 improvement stacked mass errors compared to a single magnitude cut
- In agreement with shear results
- Competitive constraints with shear!