Galaxy cluster masses from magnification

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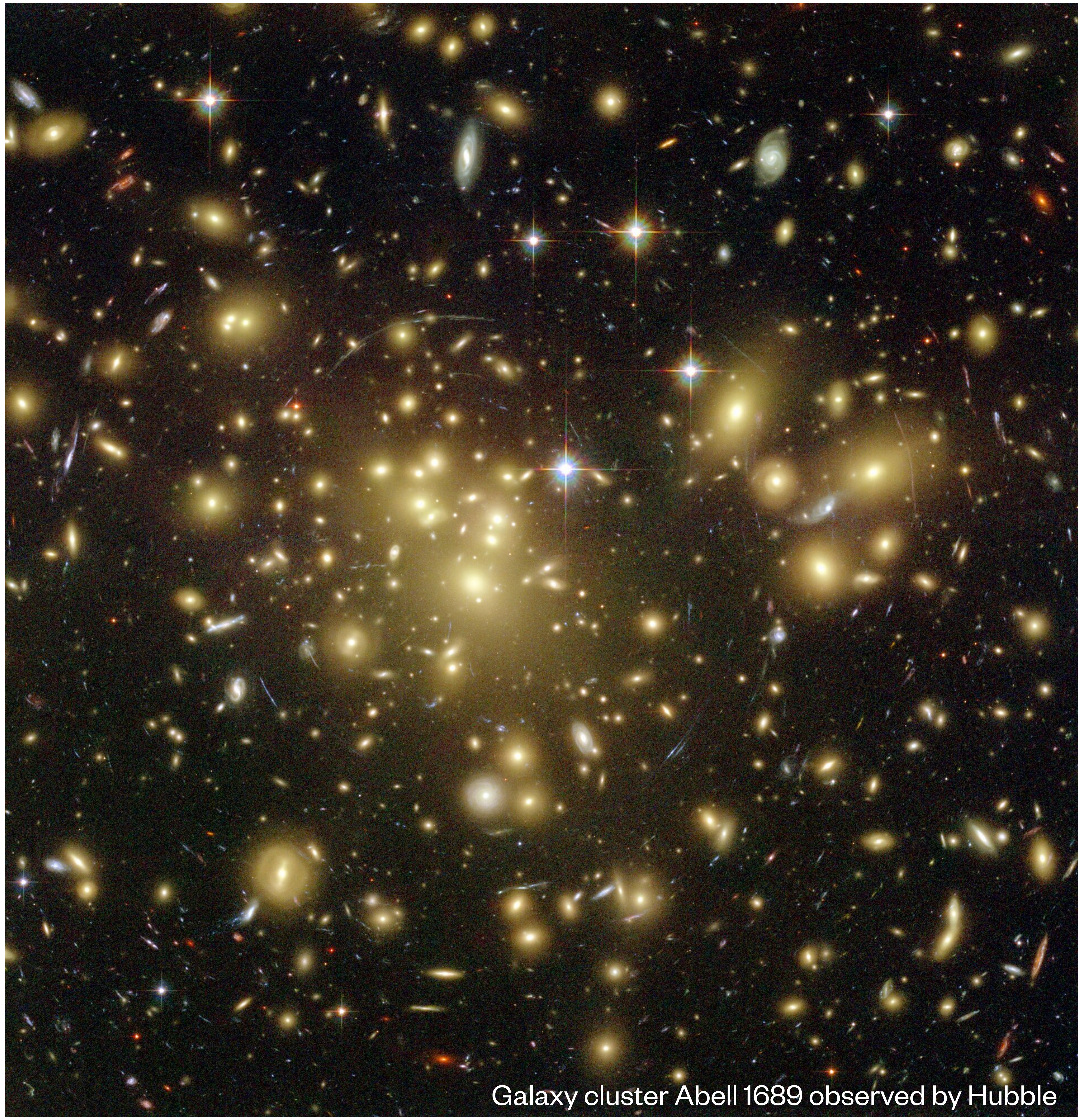
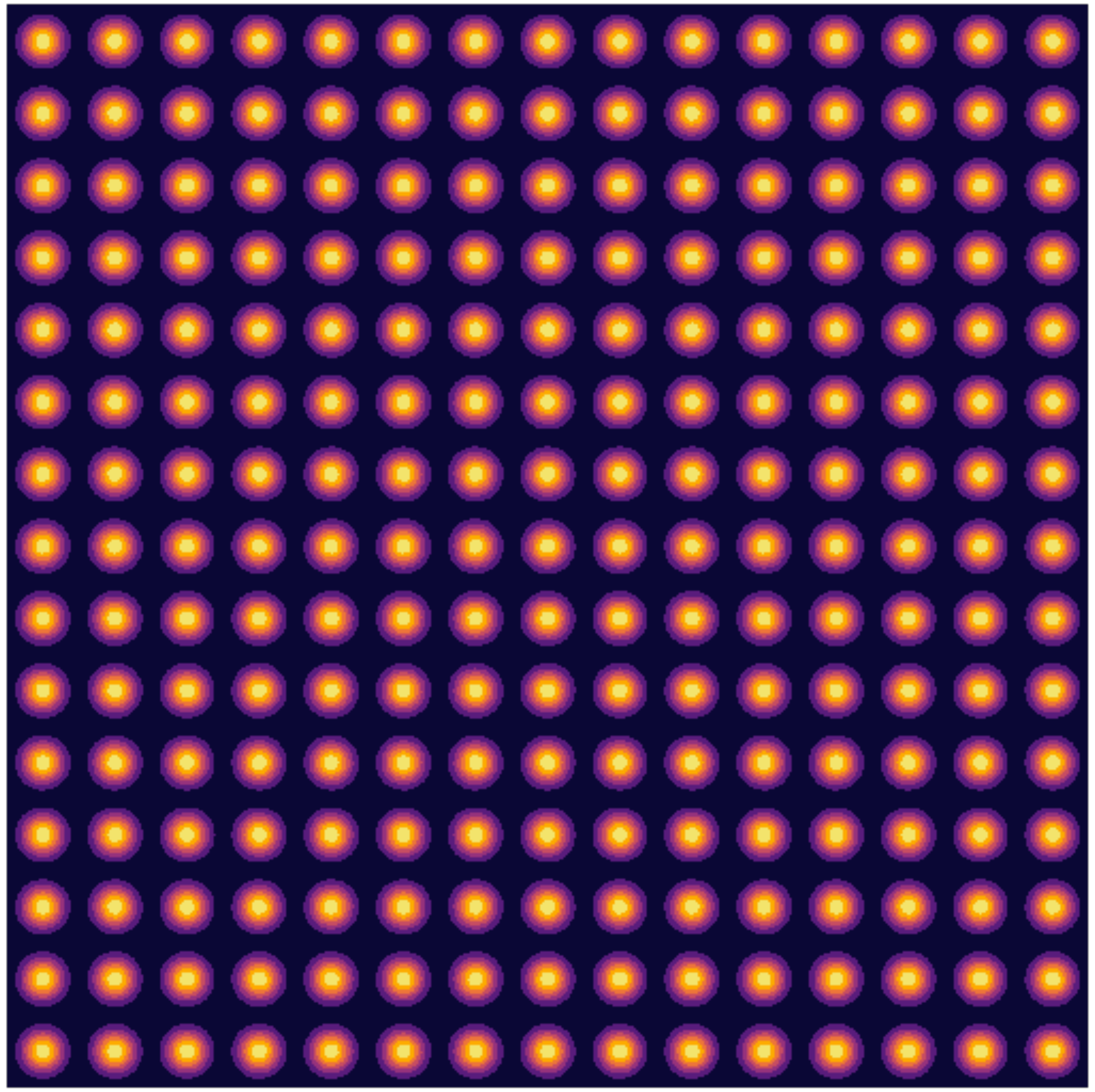
Galaxy clusters

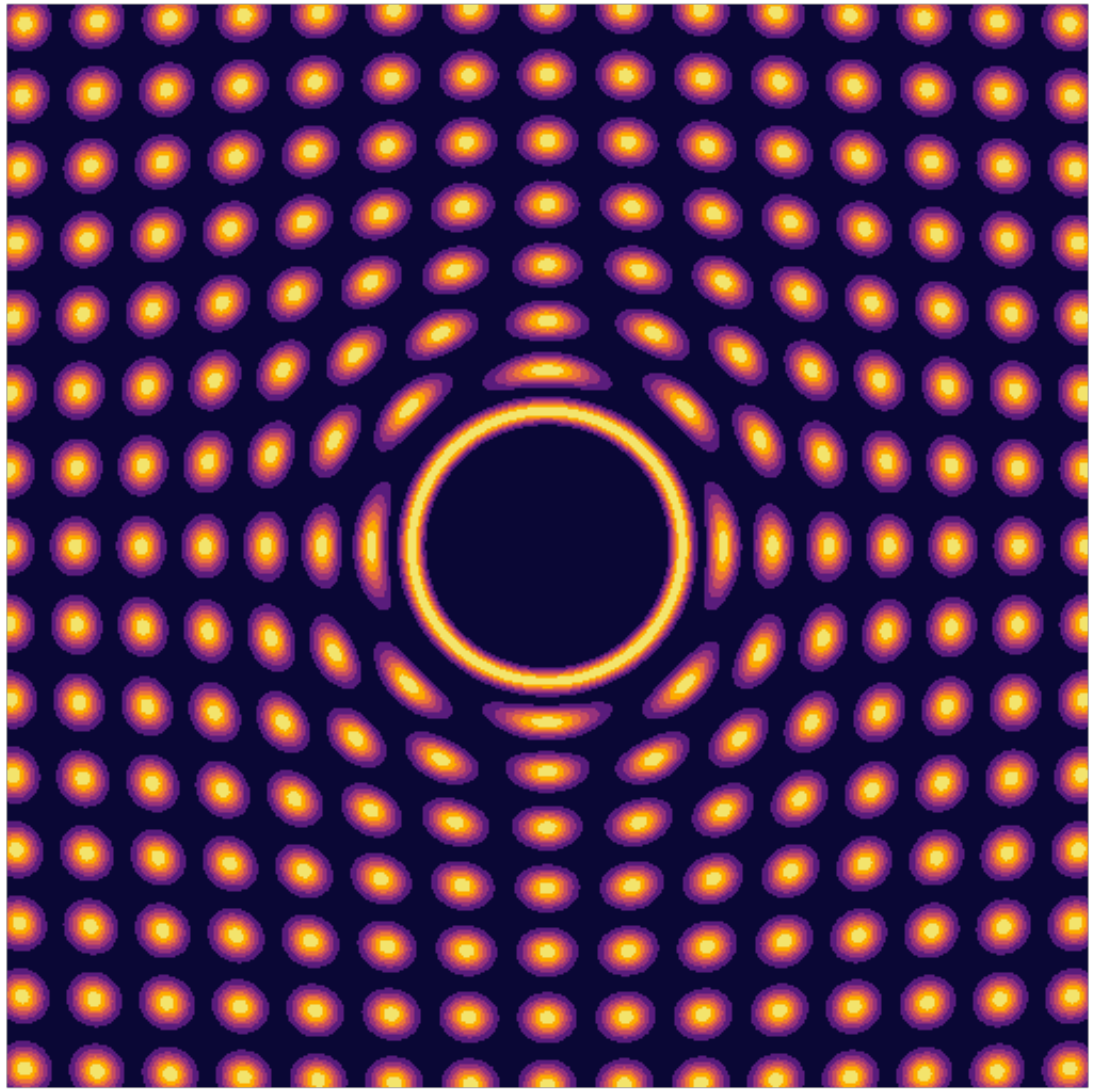
- Largest bound objects in the universe $> 10^{14}\,\mathrm{M}_\odot$
- Composition
  - 85% dark matter
  - 12% hot gas
  - 3 % stellar mass
- They provide strong constraints on the matter content, geometry, the nature of gravity and the formation of structure in the universe and **gravitational lensing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



Galaxy cluster Abell 1689 observed by Hubble



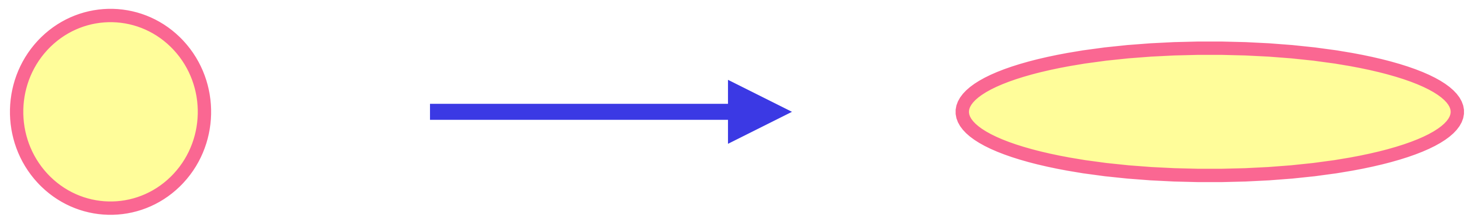
Field of **unlensed** galaxies



Field of **lensed** galaxies

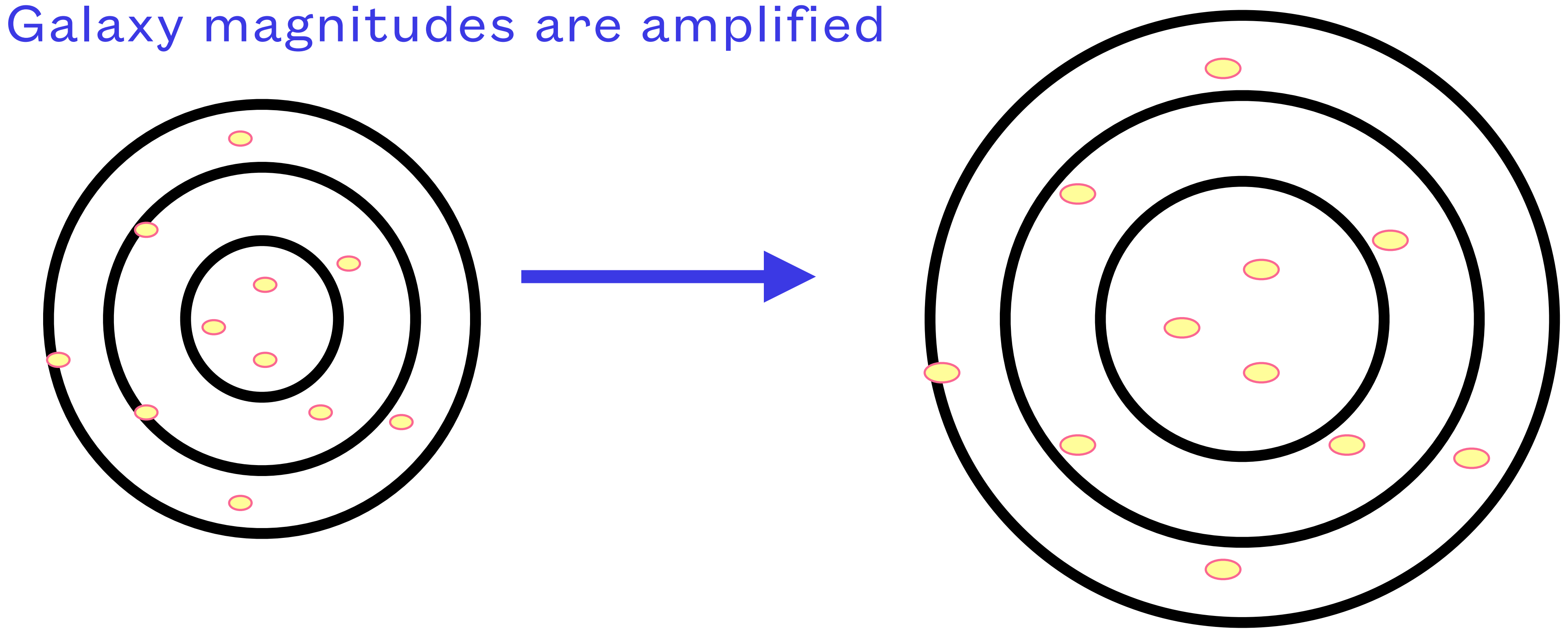
Cluster Lensing

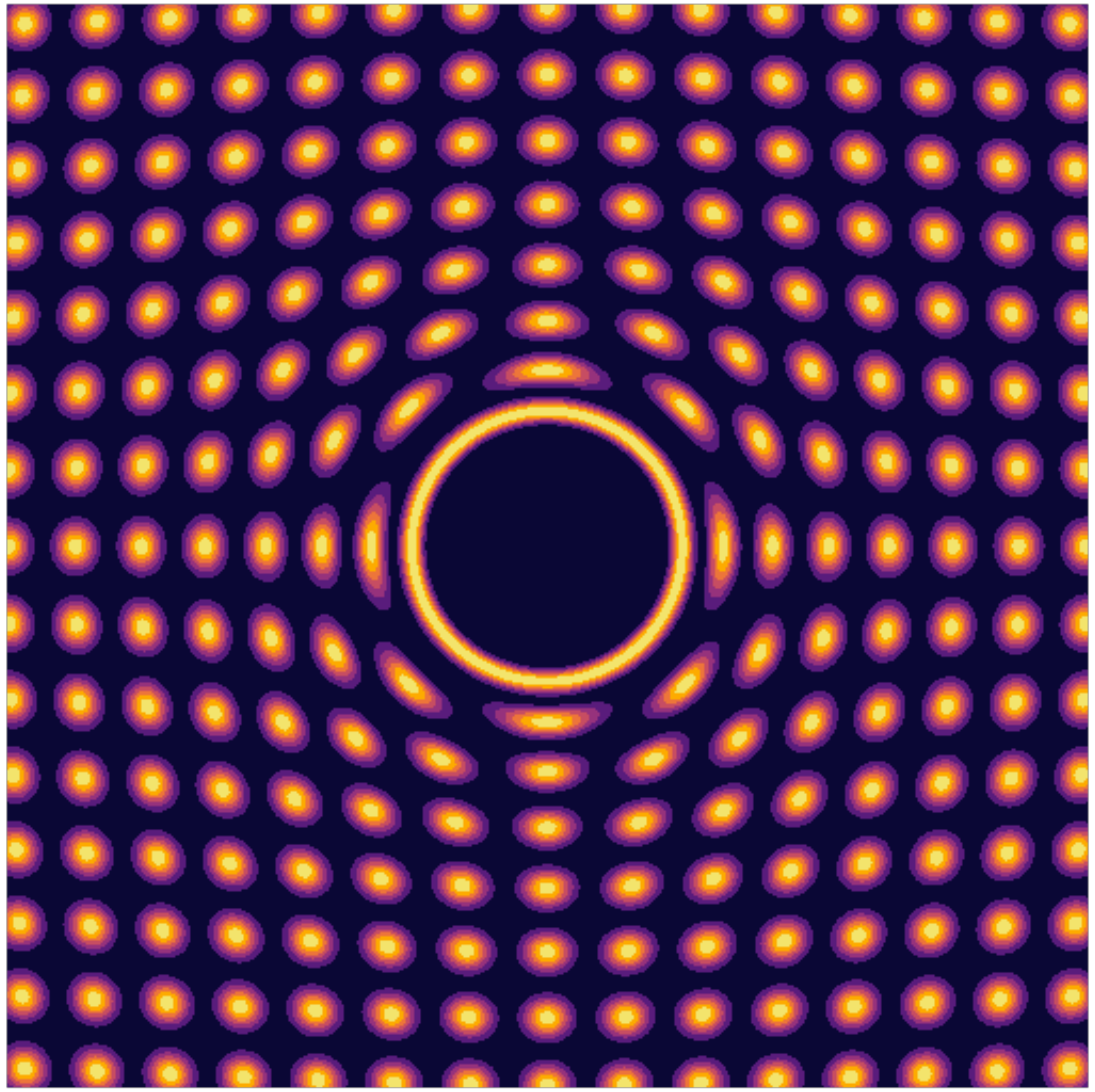
- Shears galaxy images



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

} Magnification





Cluster Lensing

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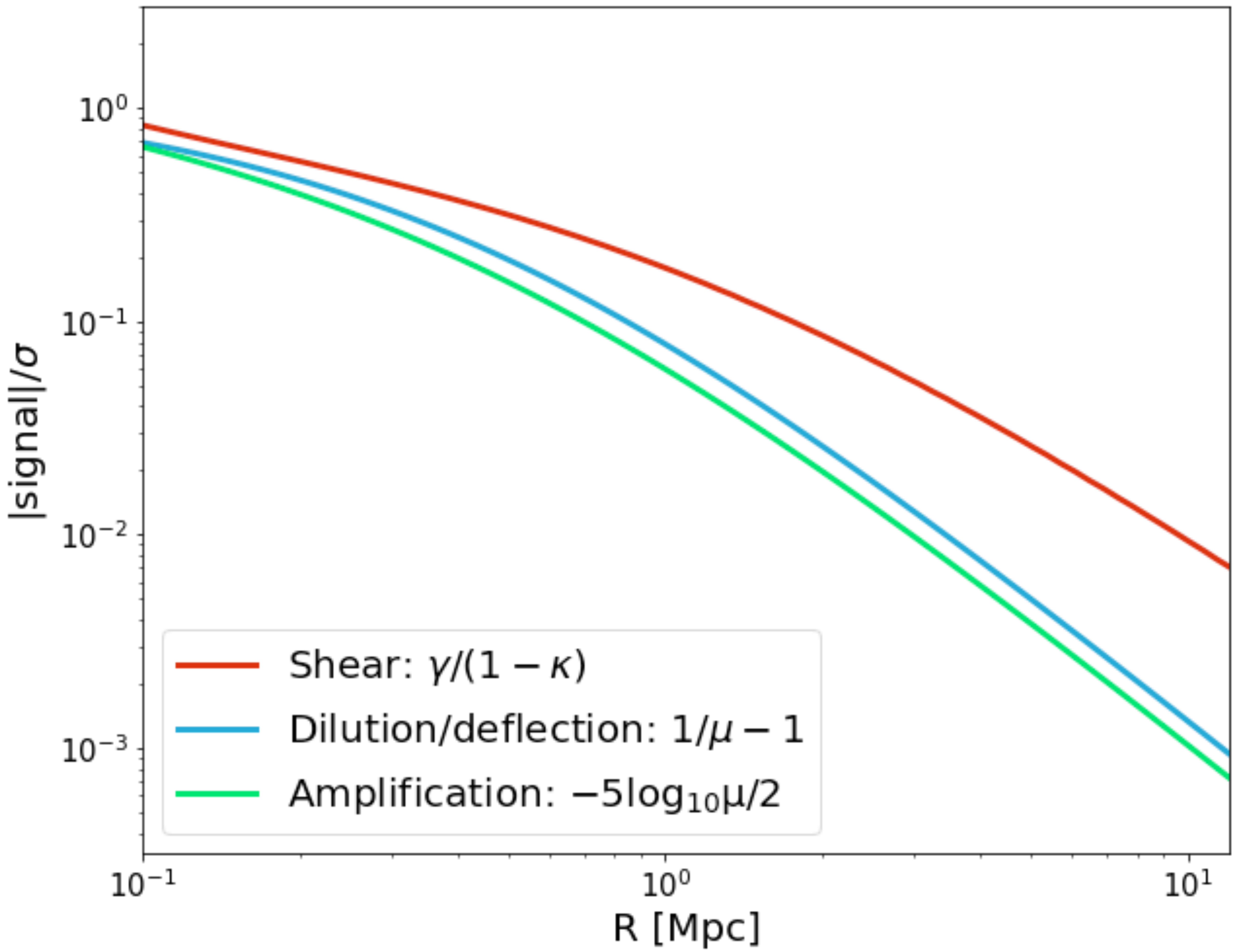
- Shear of galaxy shapes $\epsilon \approx \epsilon_o + \gamma/(1-\kappa)$
  - $\sigma_\gamma \approx 0.3/\sqrt{n}$
- **Amplification** $\Delta m \approx -5\log_{10}(\mu)/2$. with $\mu \approx 1/[(1-\kappa)^2 - \gamma^2]$
  - $\sigma_{\Delta m} \approx 1.5/\sqrt{n}$
- **Dilution**, the change in the number of galaxies $\Delta n = \frac{1}{\mu} - 1$
  - $\sigma_d \approx 1/\sqrt{n}$ poisson shot noise
- 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**



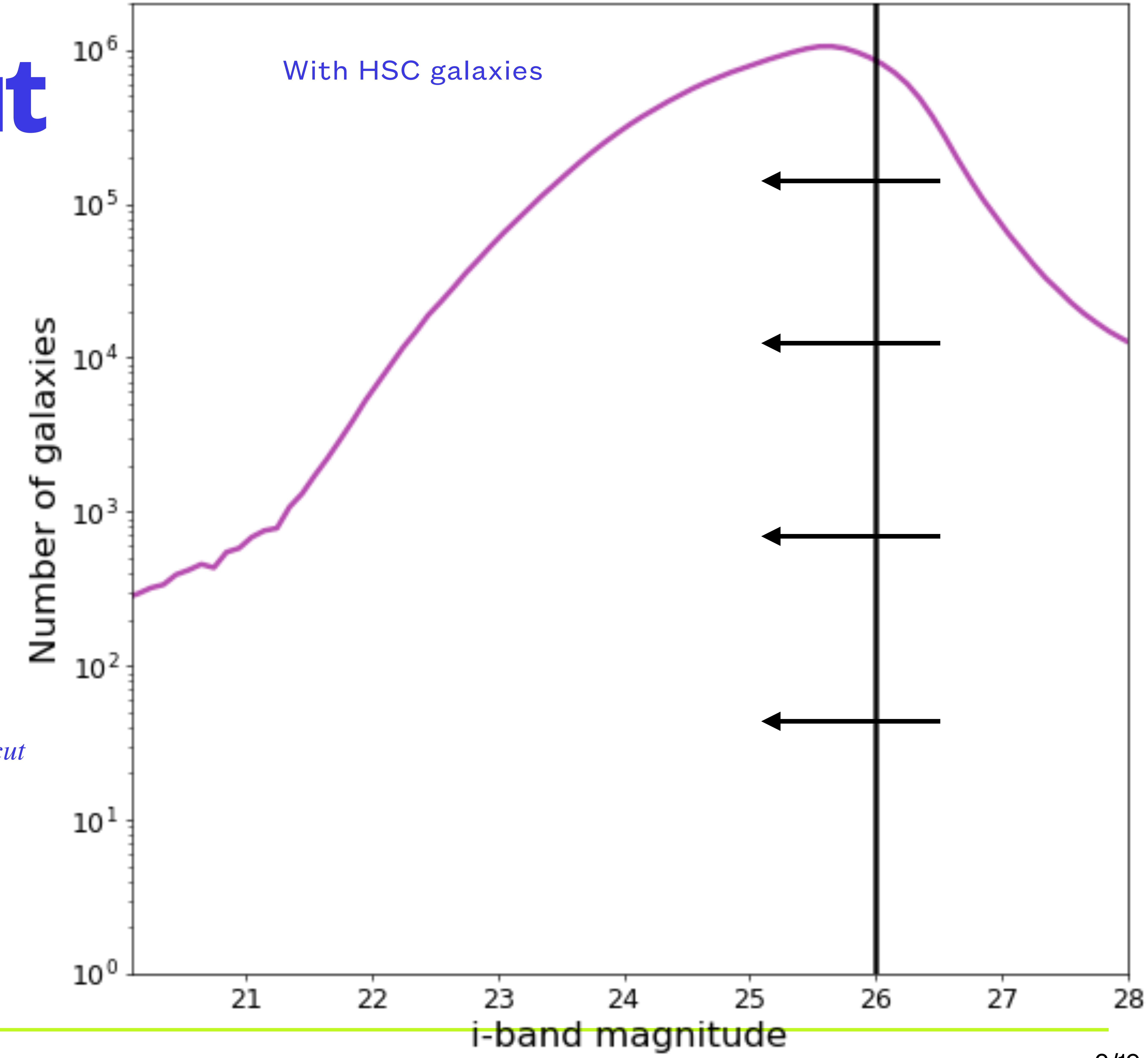
Single magnitude cut

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

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

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

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

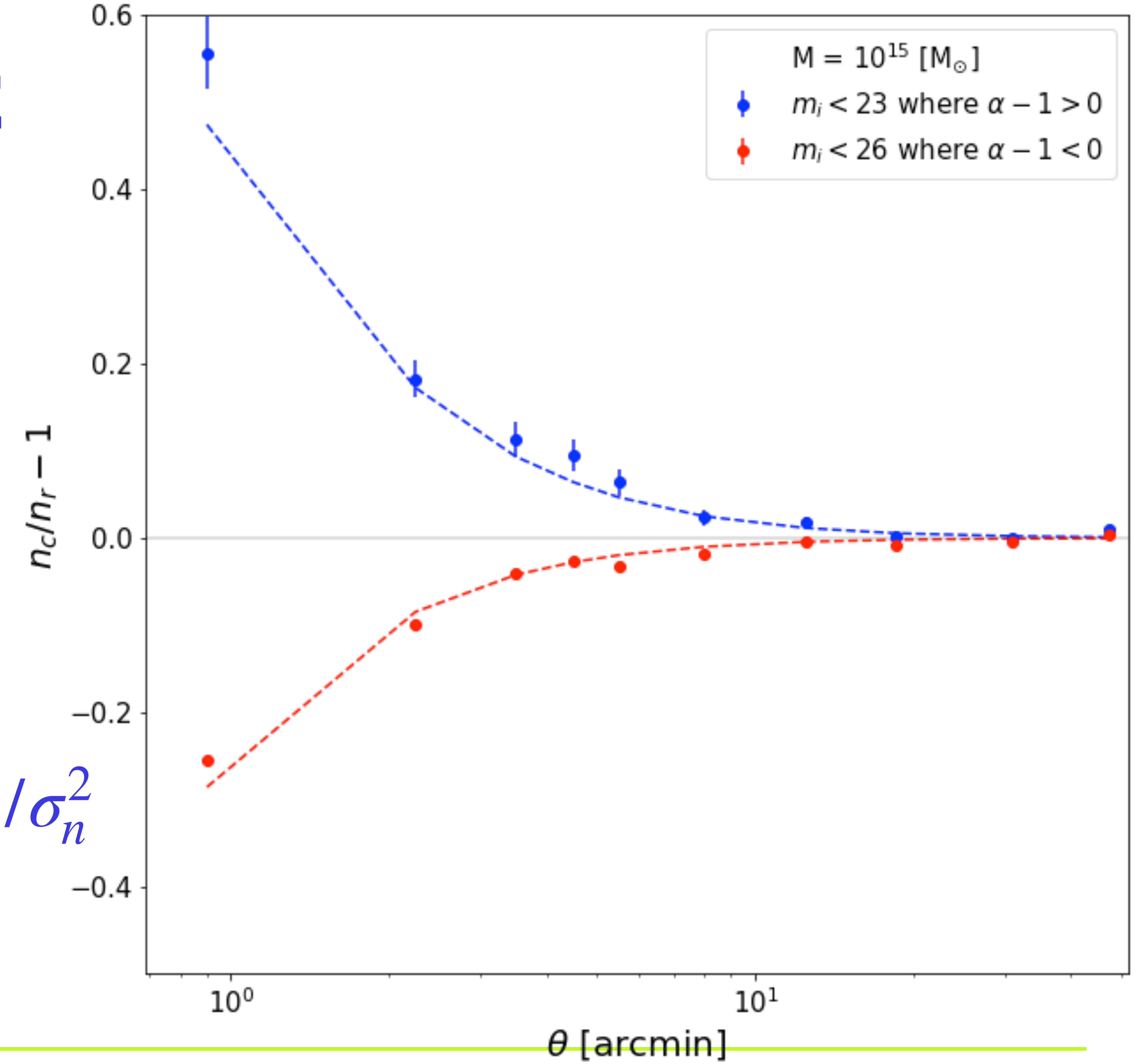


Single magnitude cut

- 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**

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

$$ln\mathscr{L} = -\frac{1}{2}\sum_i \left(n_{obs}(\theta_i) - n(\theta | M_{lens})\right)^2 / \sigma_n^2$$



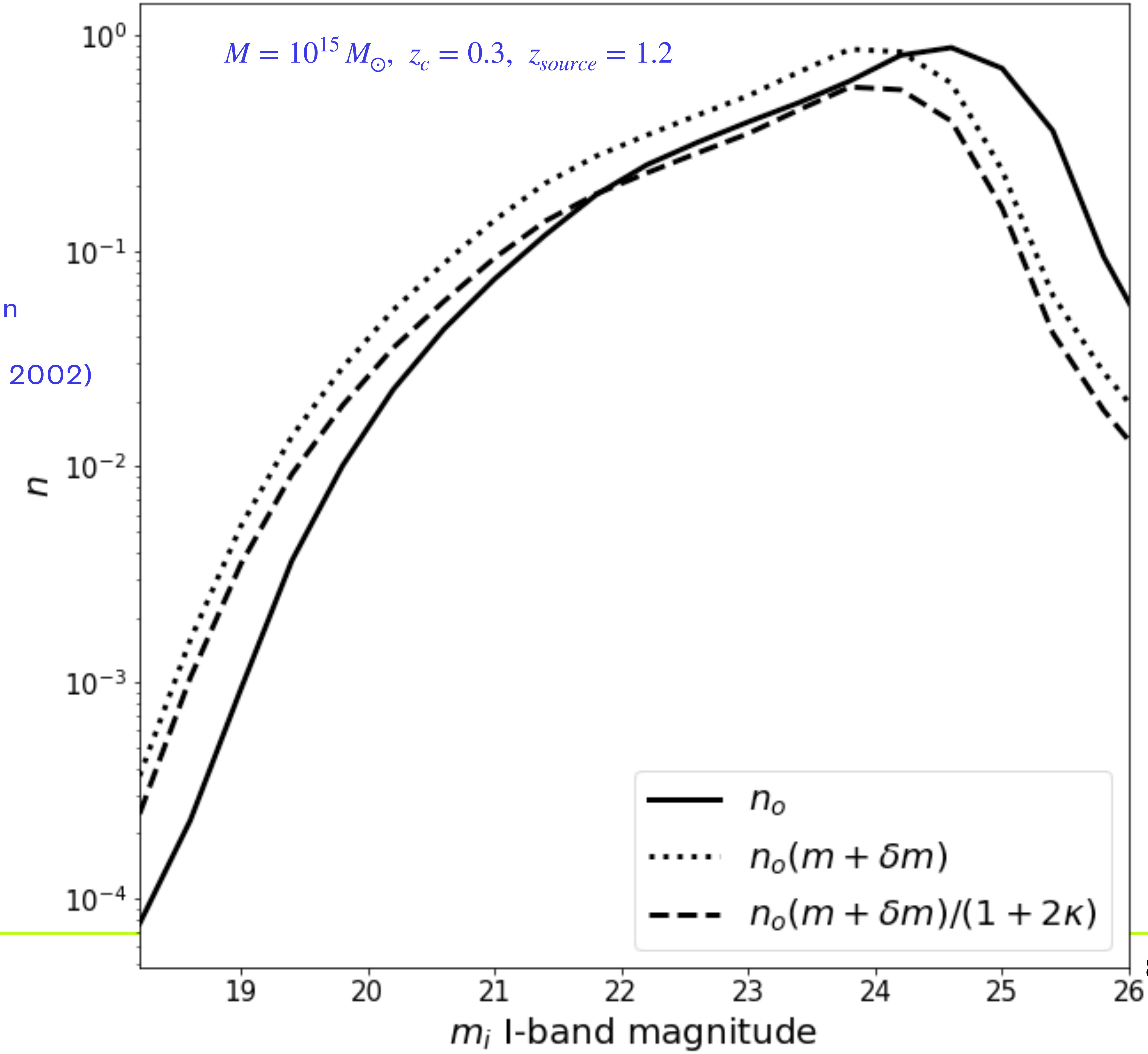
New approach - full magnitude distribution

- Resolution: use the full galaxy magnitude distribution
- Two effects
  - Change in magnitude δm -> shifts distribution
  - Change in **solid angle on the sky** A -> changes normalisation
- There are closely related approaches (Ménard and Bartelmann 2002) although we should be able to deal with larger δm

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

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

$$n_{obs}(\vec{\theta}) \rightarrow n_{obs}(\vec{\theta}, \vec{m}, \vec{z})$$



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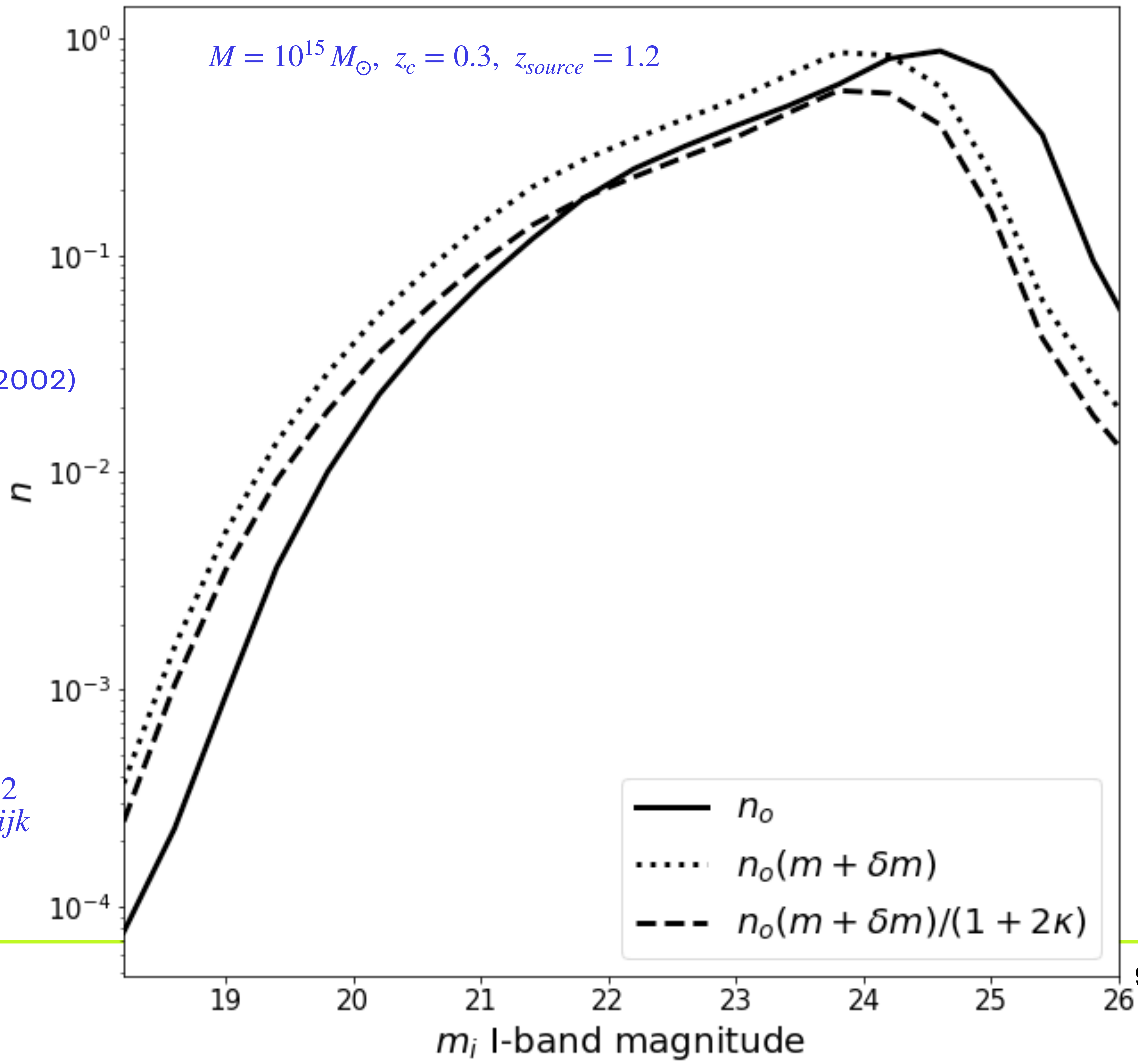
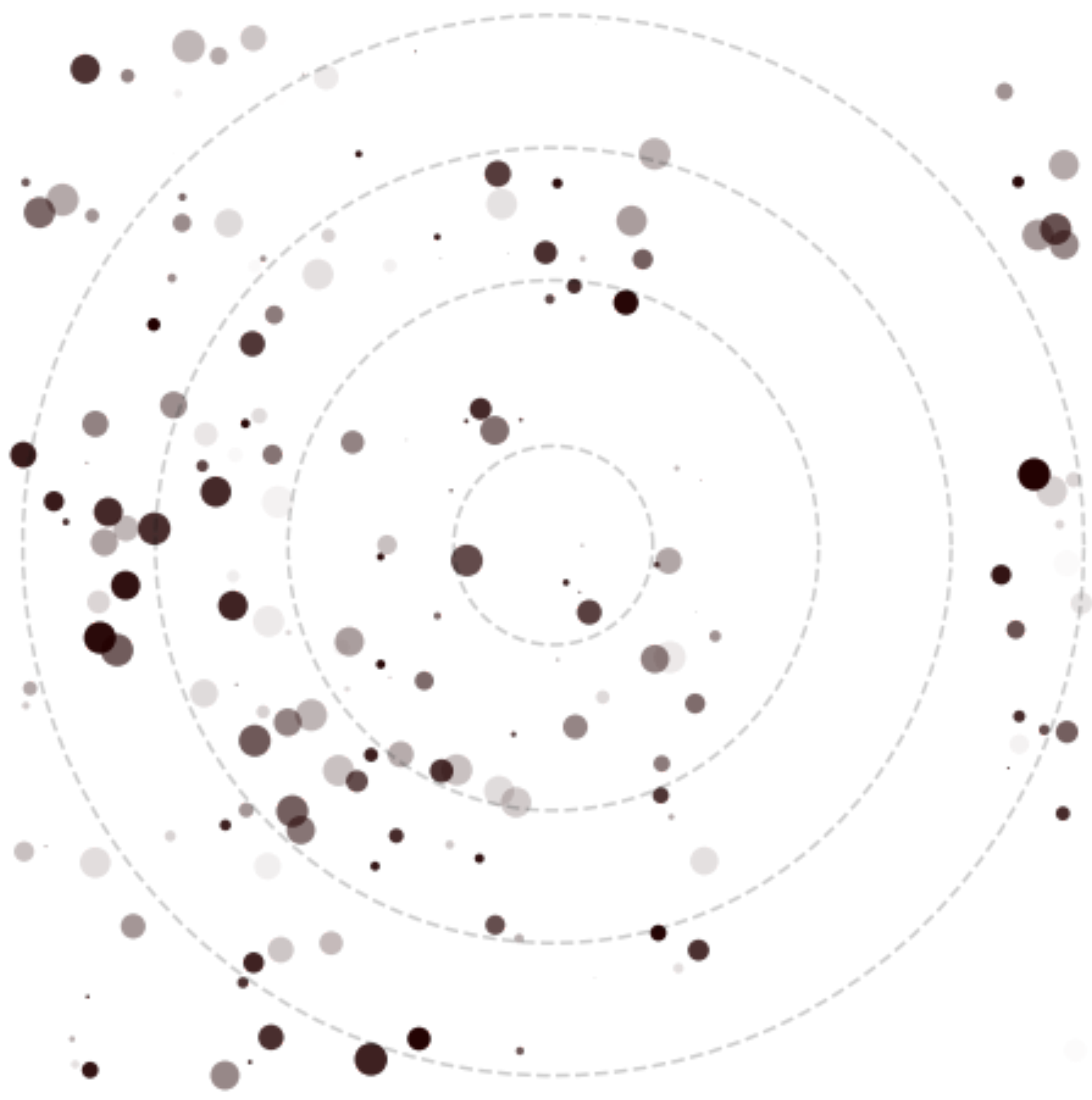
$$ln\mathscr{L} = -\frac{1}{2}\sum_{ijk} \left(n_{obs}(\theta_i, m_j, z_k) - n(\theta, m, z\,|\,M_{lens})\right)^2/\sigma_{ijk}^2$$

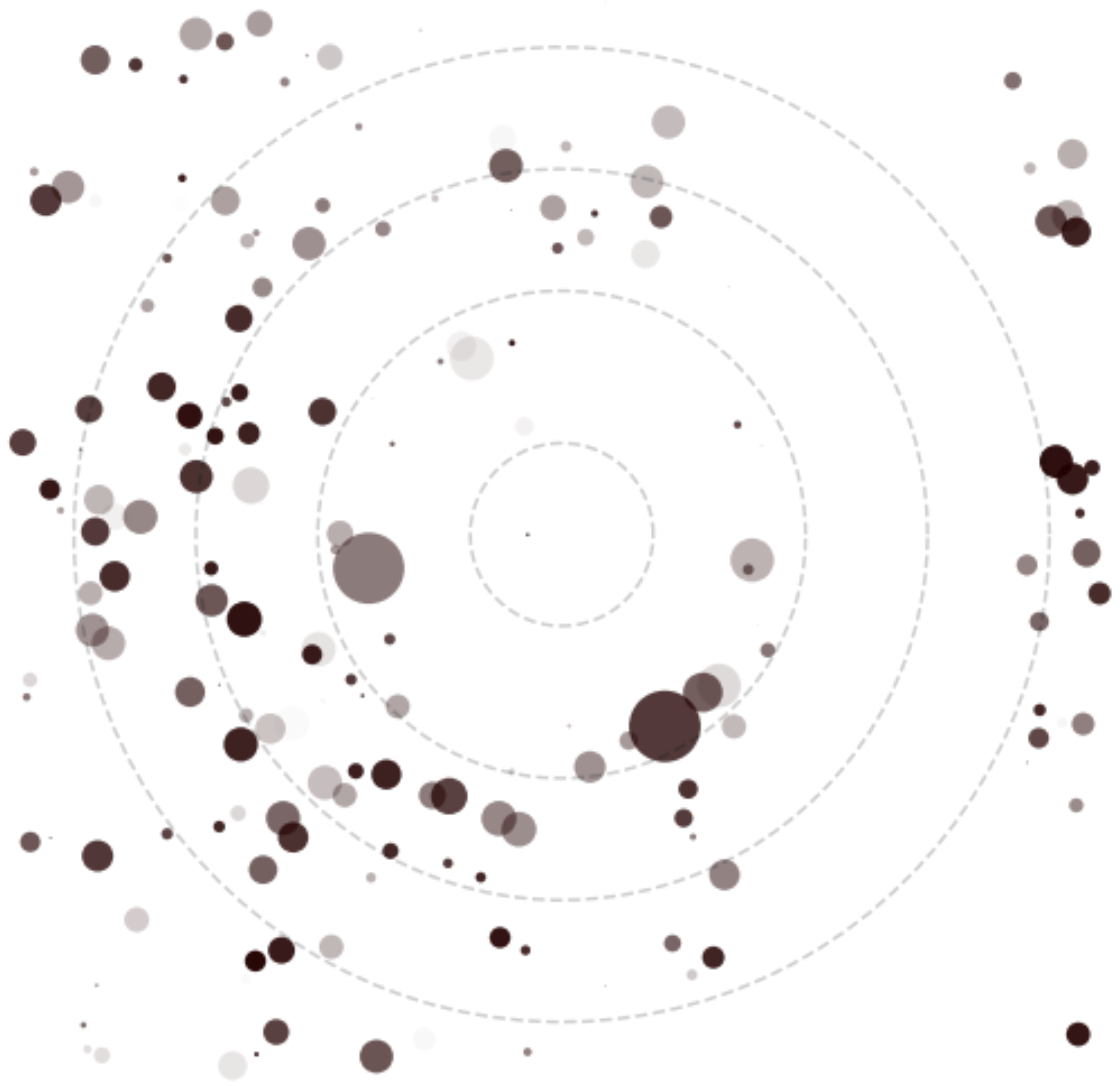


Mock creation

- We generate random positions within the HSC survey and inject a fake cluster signal
  - Move the galaxies to the lensed galaxy positions
  - $\theta_{\text{obs}} = \theta_o + \alpha(M_{\text{lens}})$
  - Lensed galaxy magnitudes
  - $\Delta m \approx -5\log_{10}(\mu(\mathrm{M}_{\text{lens}}))/2.$
- Non-trivial test of our model



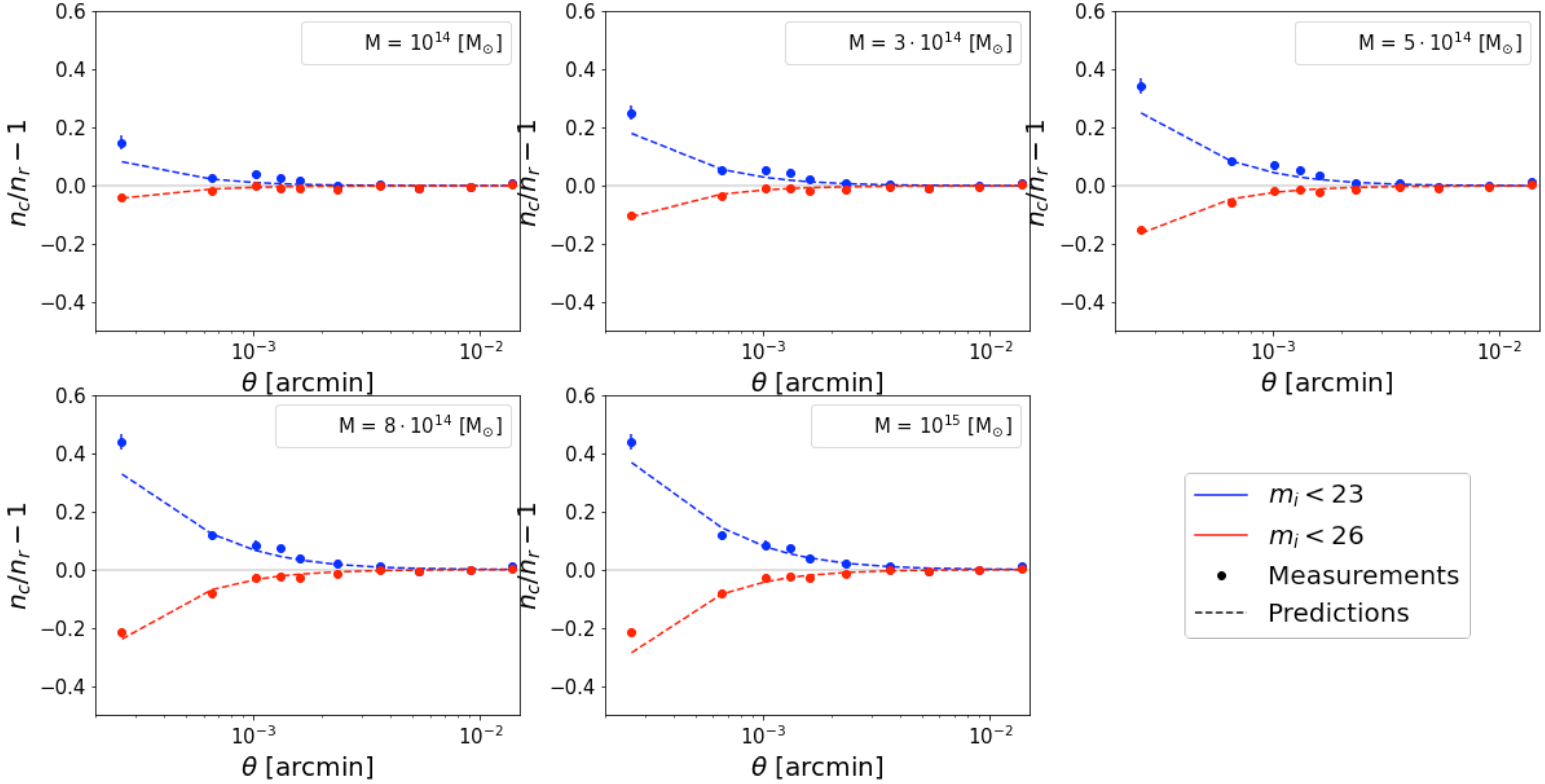
Field of **unlensed** galaxies



Field of **lensed** galaxies

Mock results

- We stack the mock signals around 250 positions
- Measured number count depletion/ increase in excellent agreement with our model



Mass estimation with mocks

- Significant improvements ~factor of 2, on the estimated errors with the full magnitude distribution ($\sigma_{ln\,M}$)

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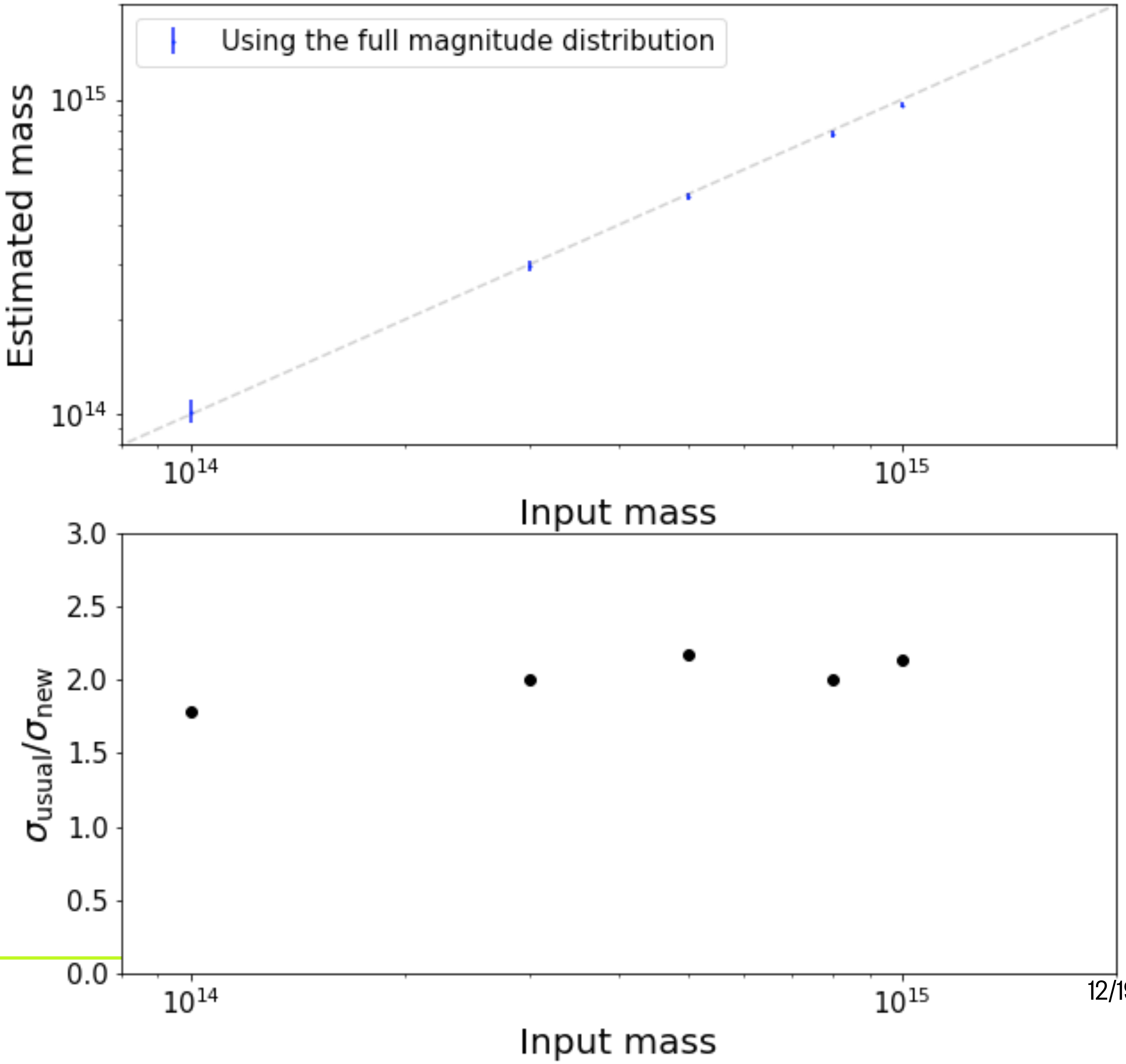
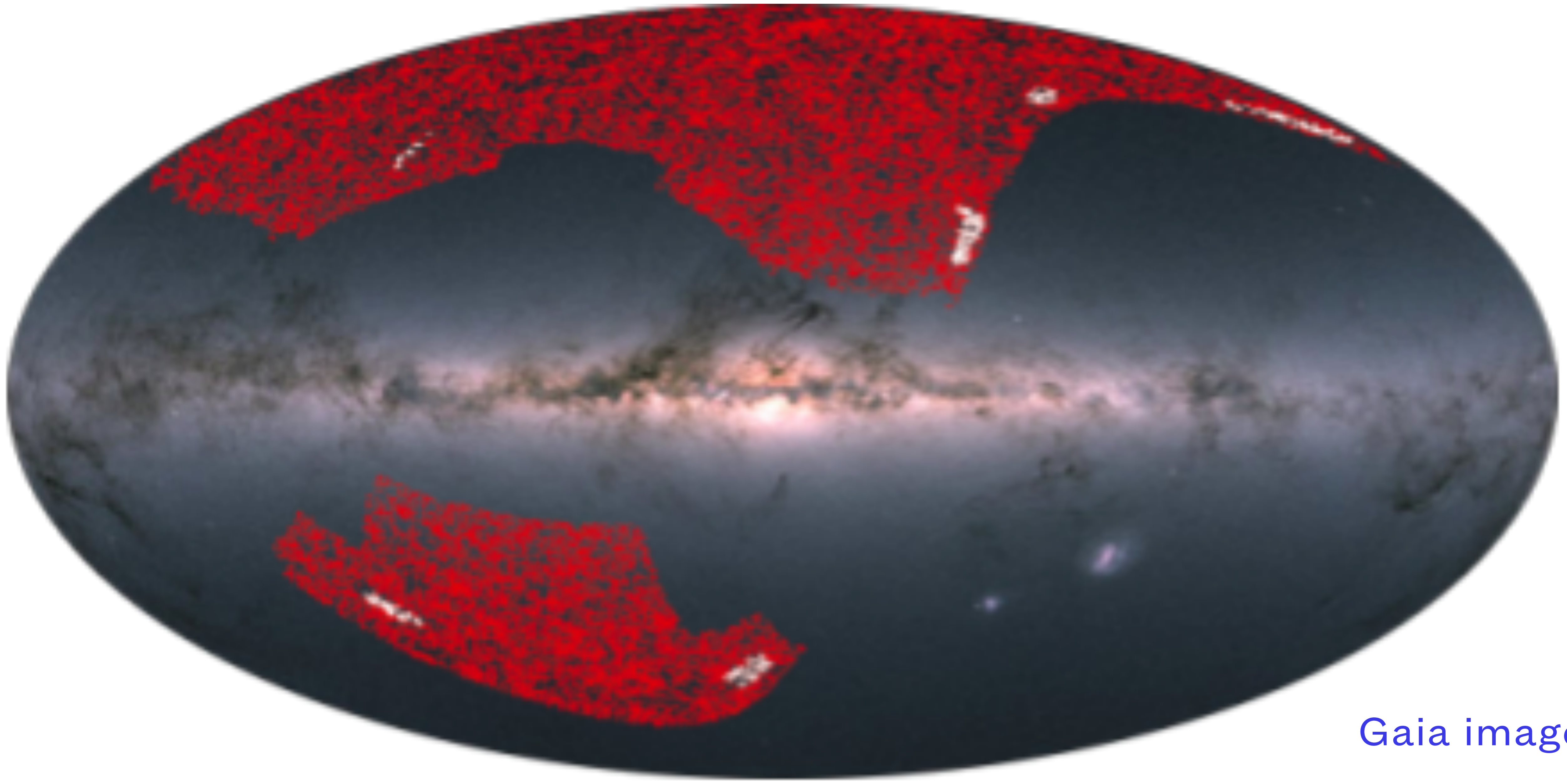


redMaPPer clusters

- 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

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



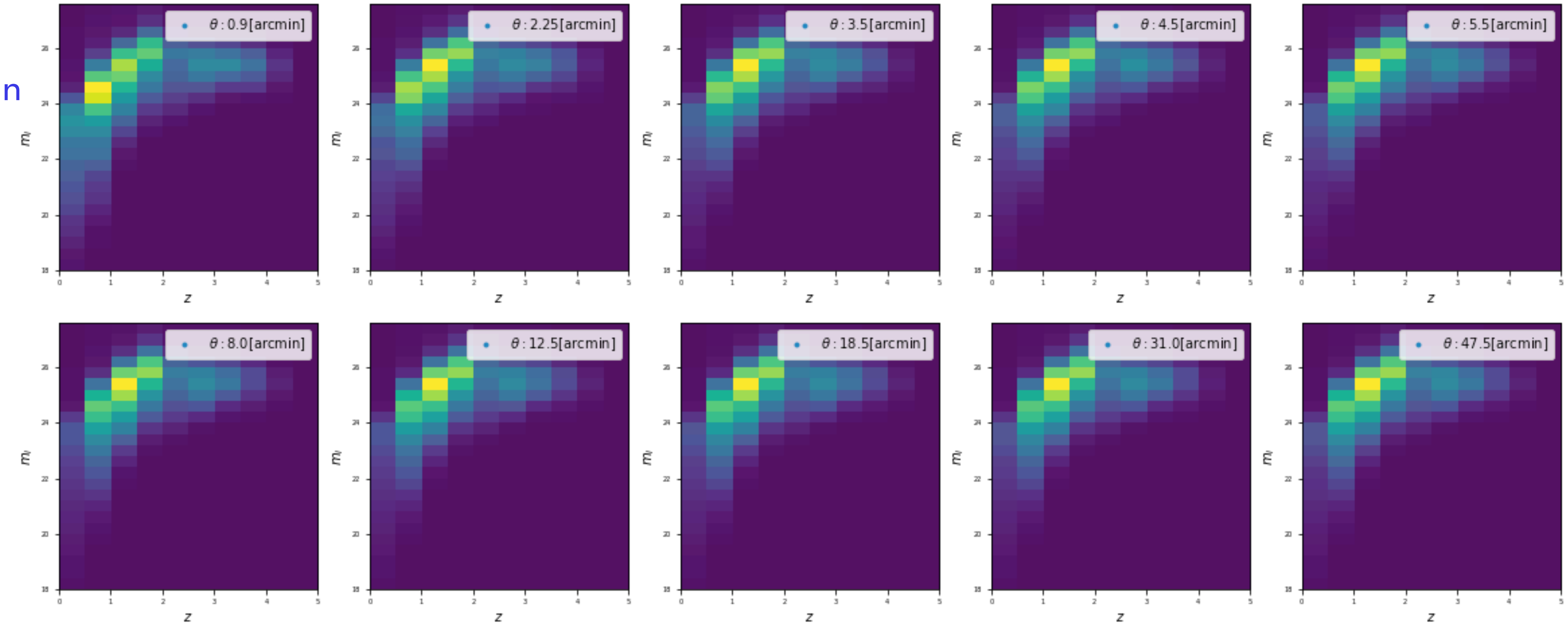
Gaia image

redMaPPer clusters

- Clusters found with redMaPPer in SDSS data
- 200 clusters with redshift > 0.3 and richness > 40
- Using the full likelihood we can constrain the mass using
  - 6 angular bins: $\theta \in [0.9, 10]$ [arcmin]
  - 4 bins in redshift: $z \in [1, 3]$
  - 14 bins in i-band magnitude: $m_i \in [20, 25.5]$

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

Magnitude bins



Redshift bins

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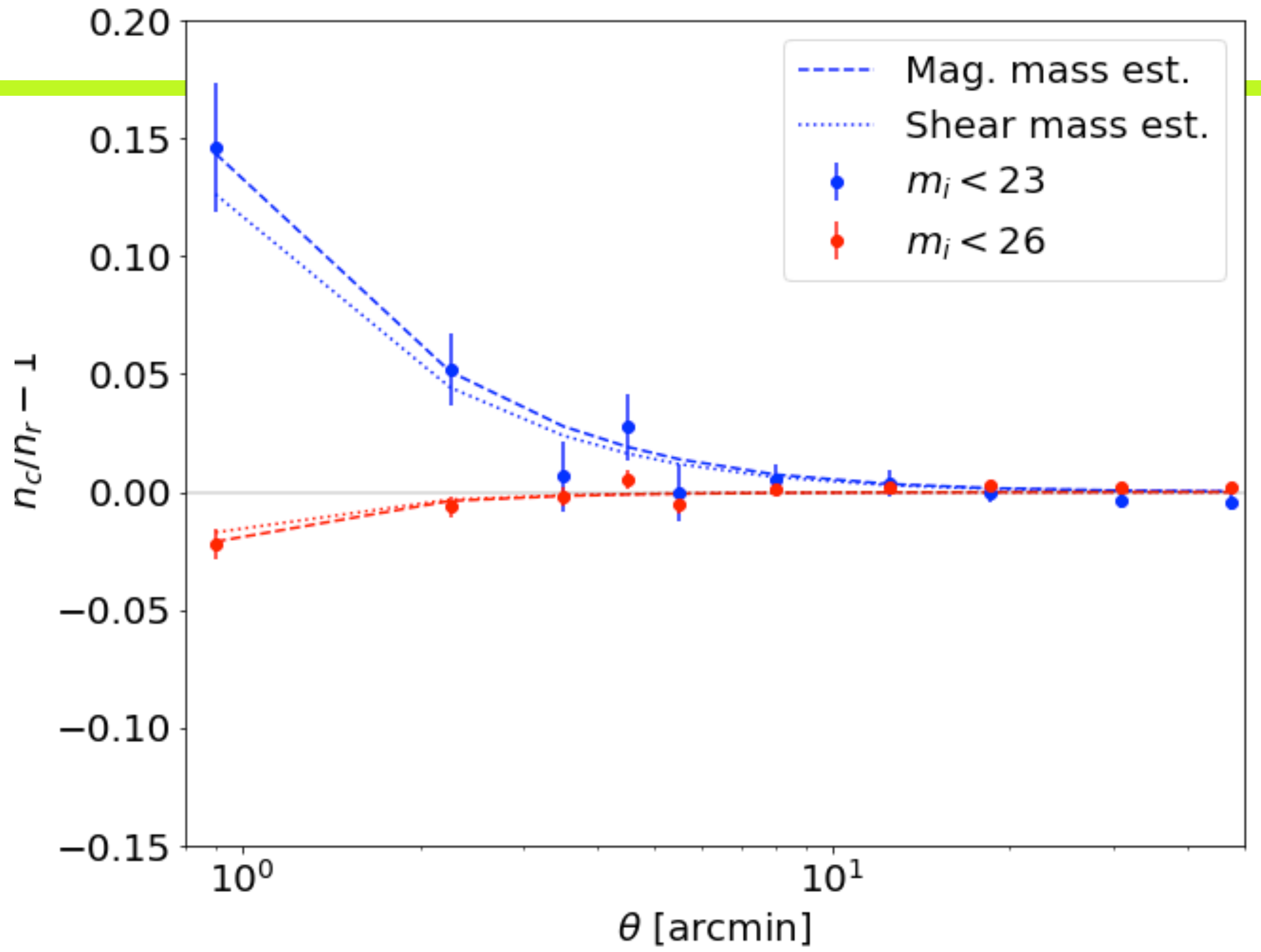
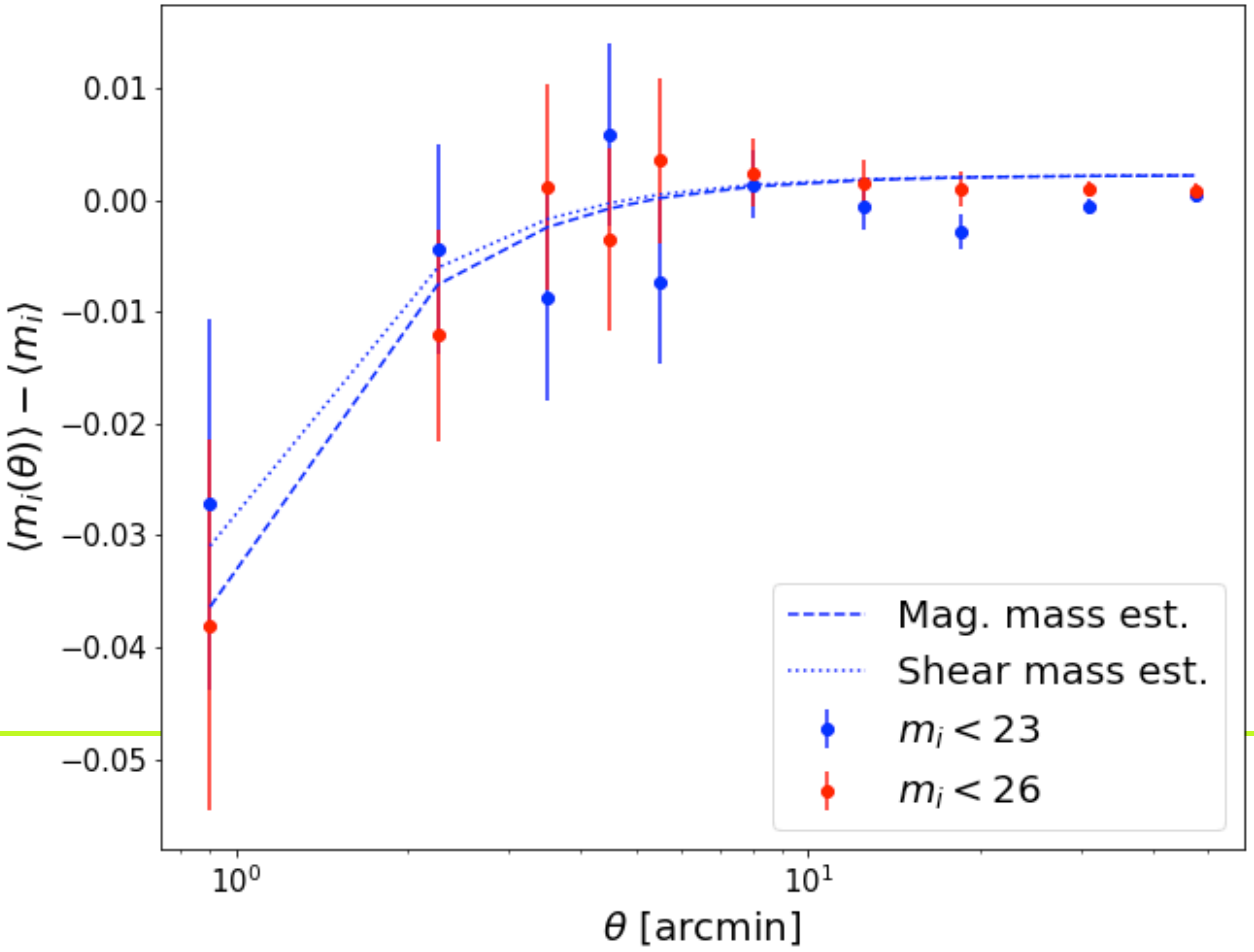
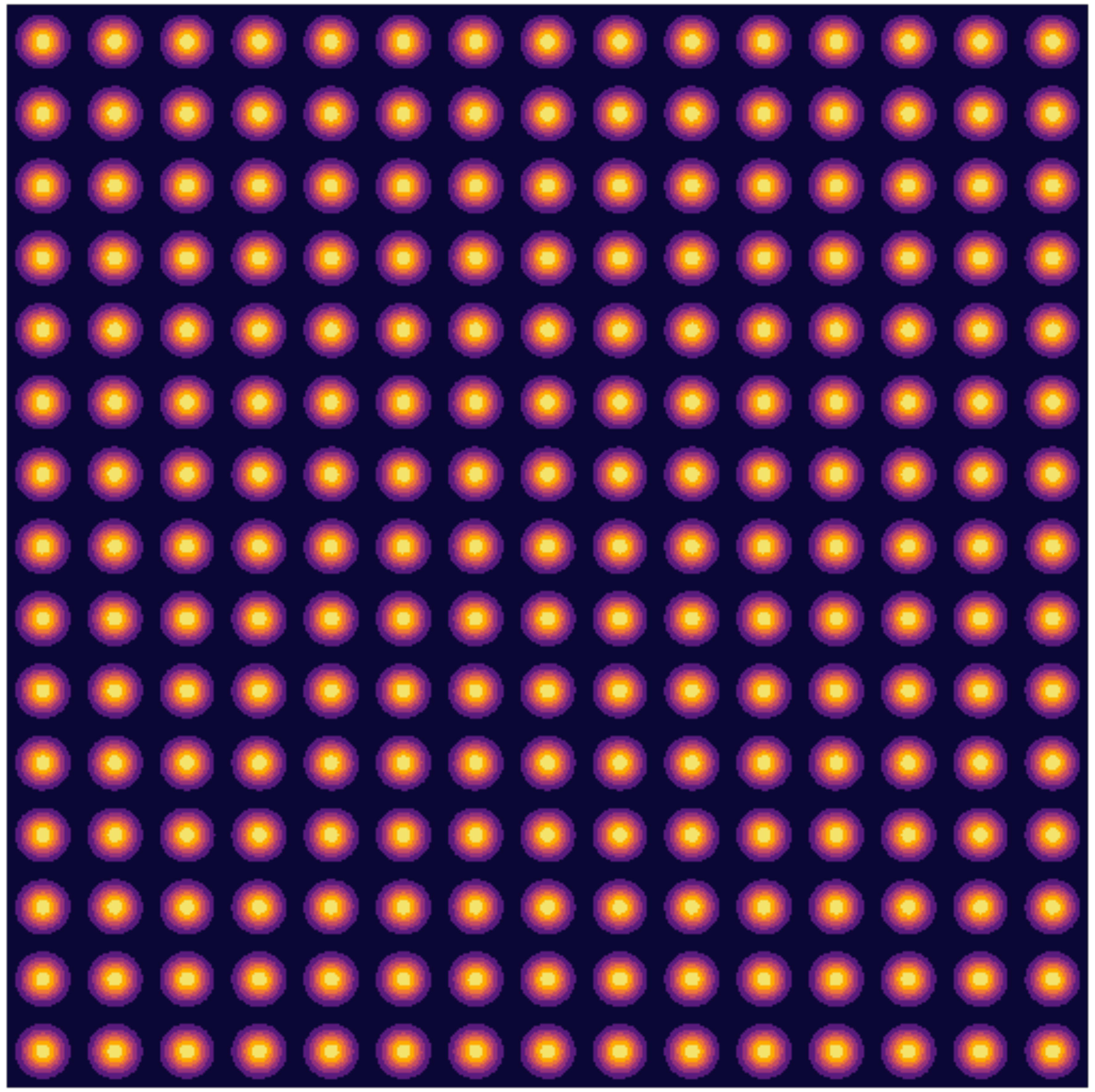
$$\log_{10} \mathrm{M}_{\mathrm{stack}} = 14.37 \pm 0.04$$







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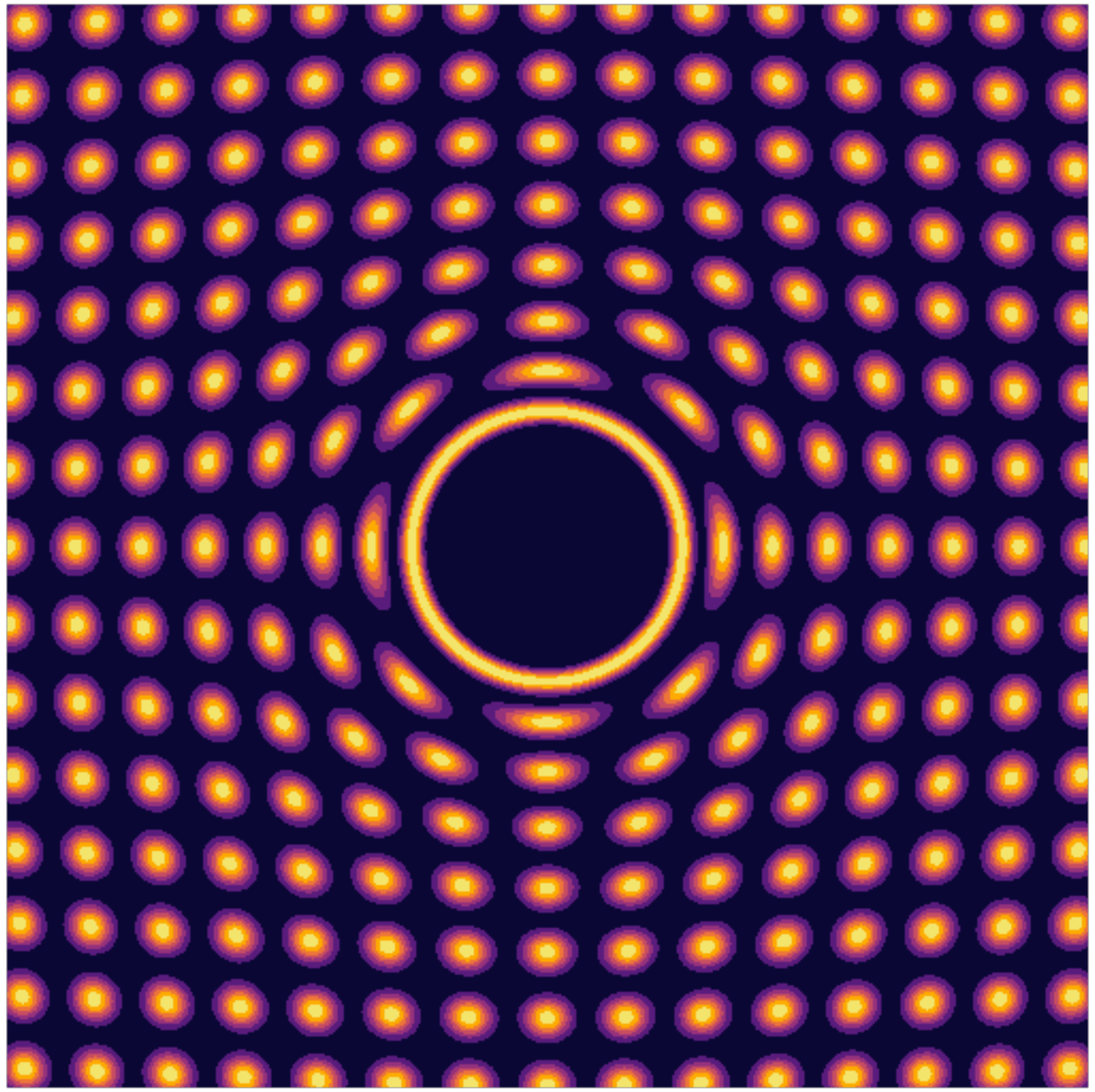
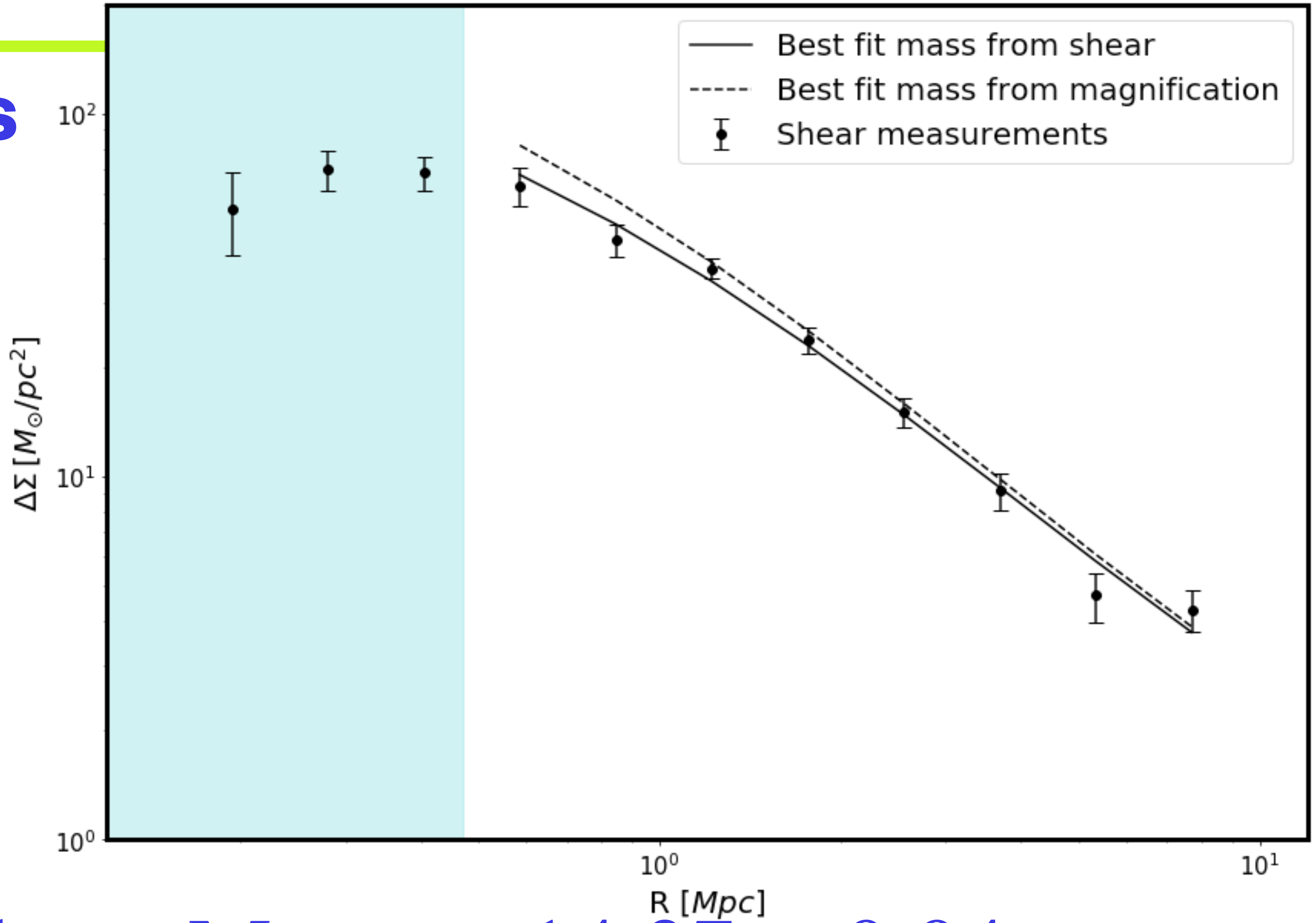


Field of **lensed** galaxies

Comparison to shear analysis

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

- We take the same stack of clusters and perform a stacked shear analysis using HSC data
- 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



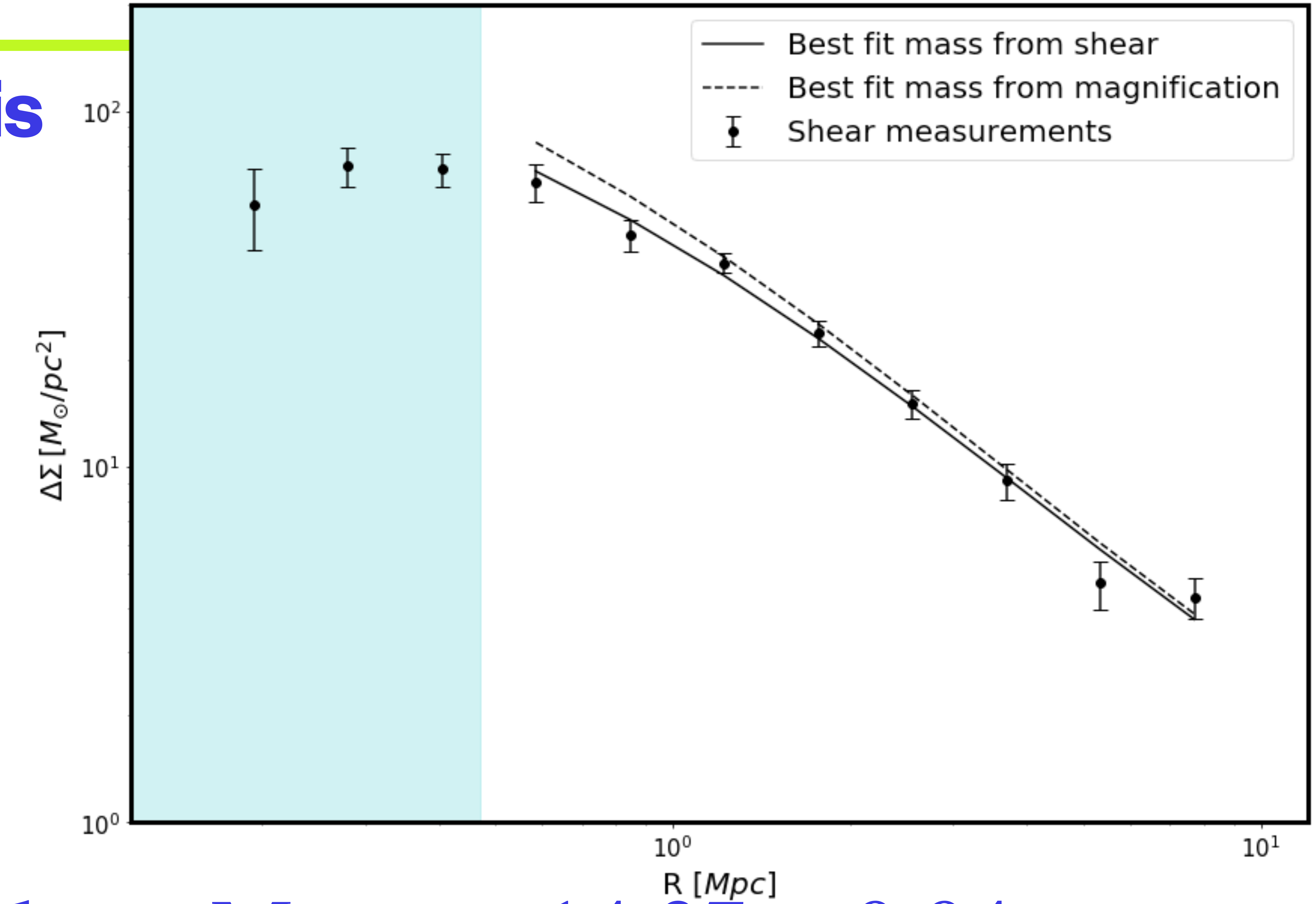
$$\mathrm{Magnification\ mass}: \log_{10} \mathrm{M_{stack}} = 14.37 \pm 0.04$$

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

Comparison to shear analysis

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

- **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



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Conclusions

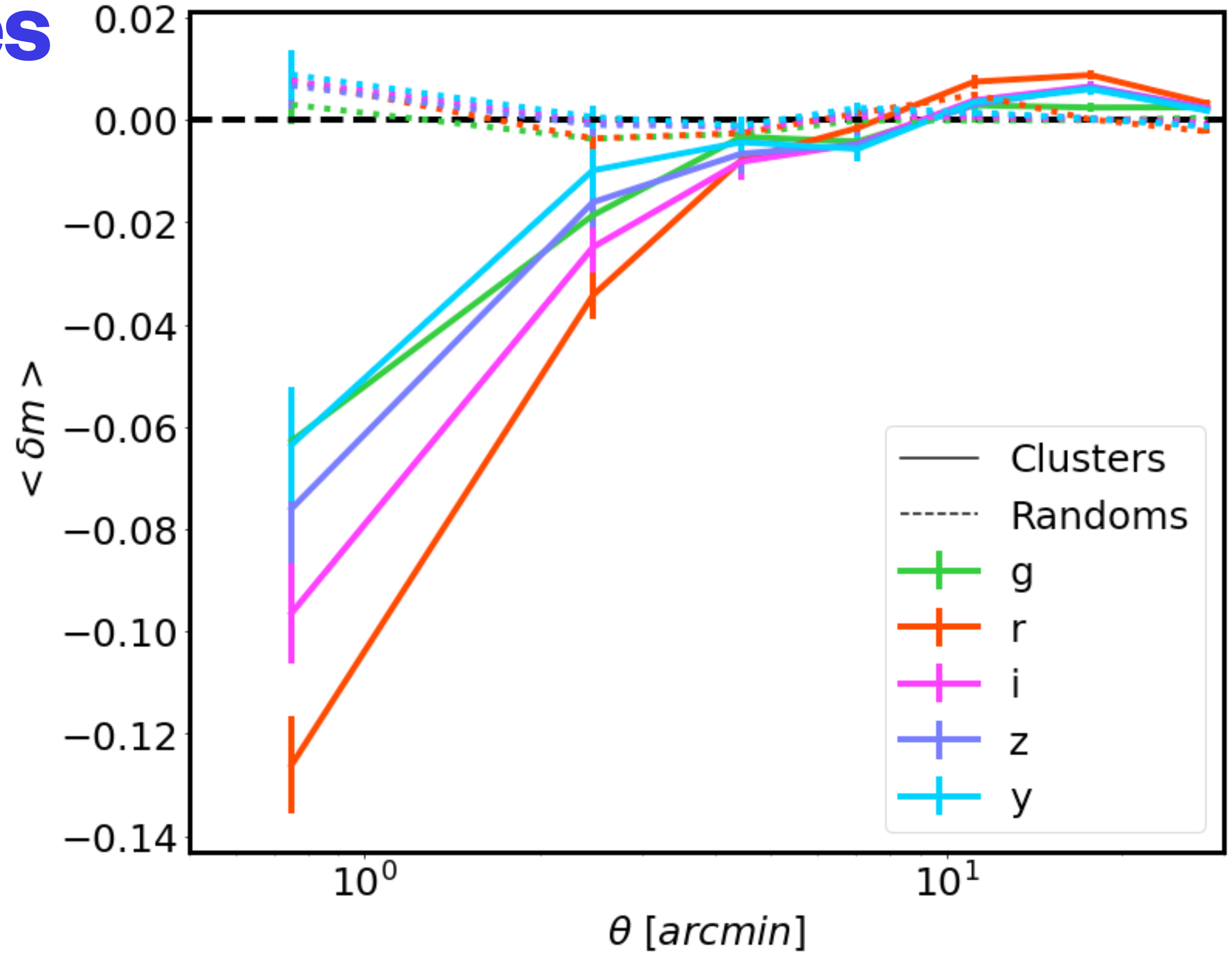
- We have introduced a new magnification method, using the full magnitude distribution for cluster mass estimation
- Validated with mocks
    - A factor of ~2 improvement stacked mass errors compared to a single magnitude cut
- Competitive constraints with shear!

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)

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

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



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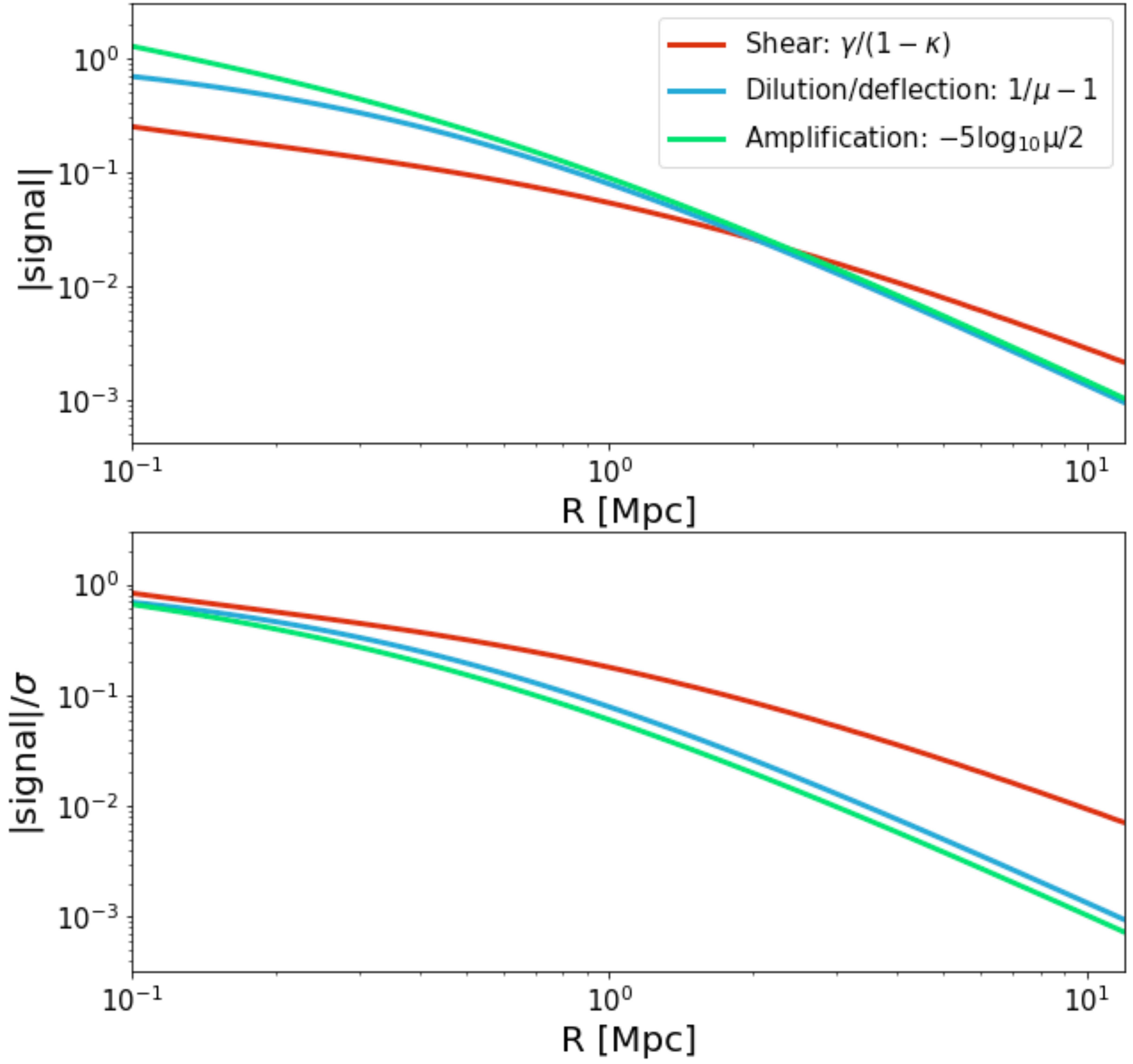

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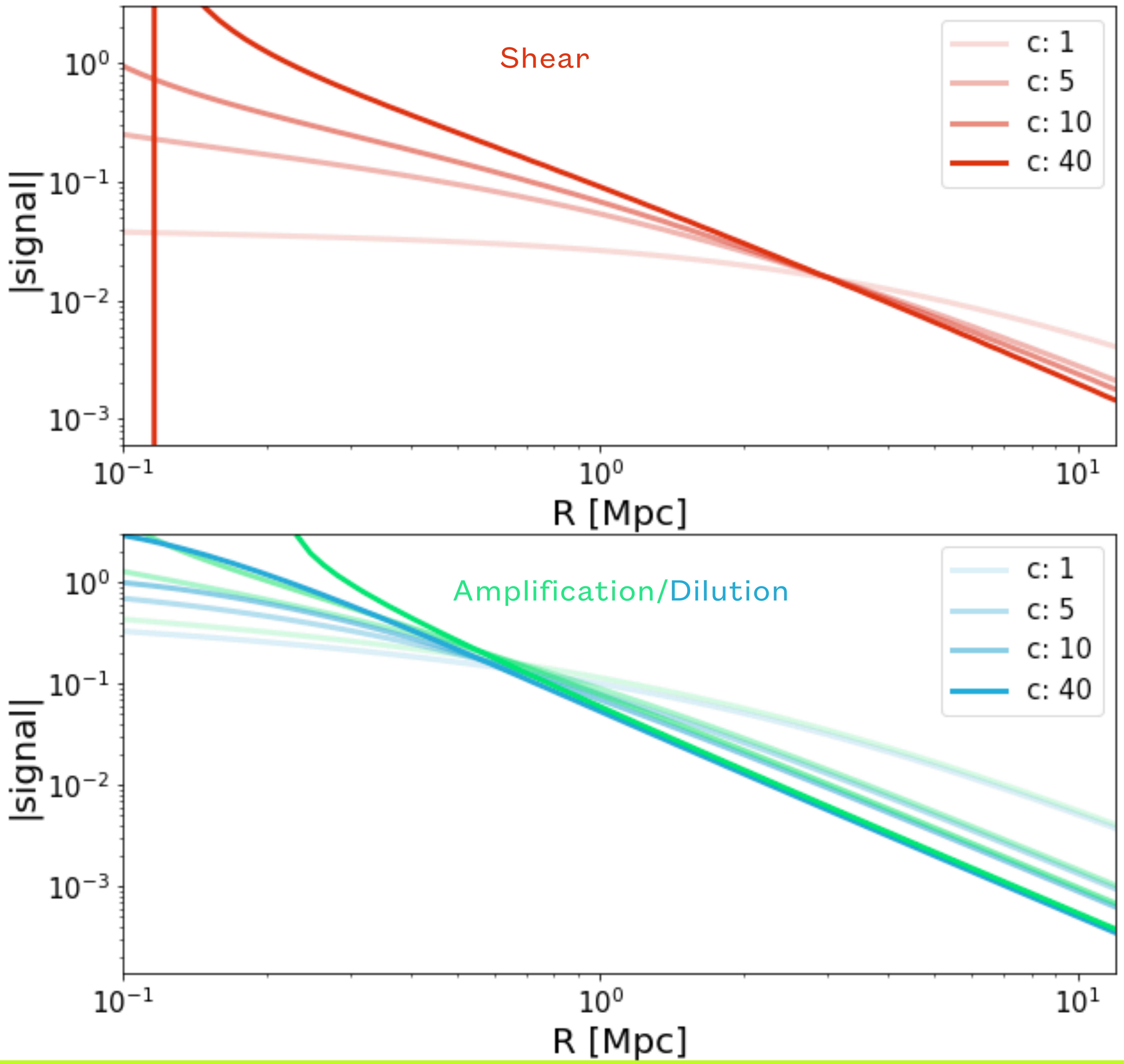

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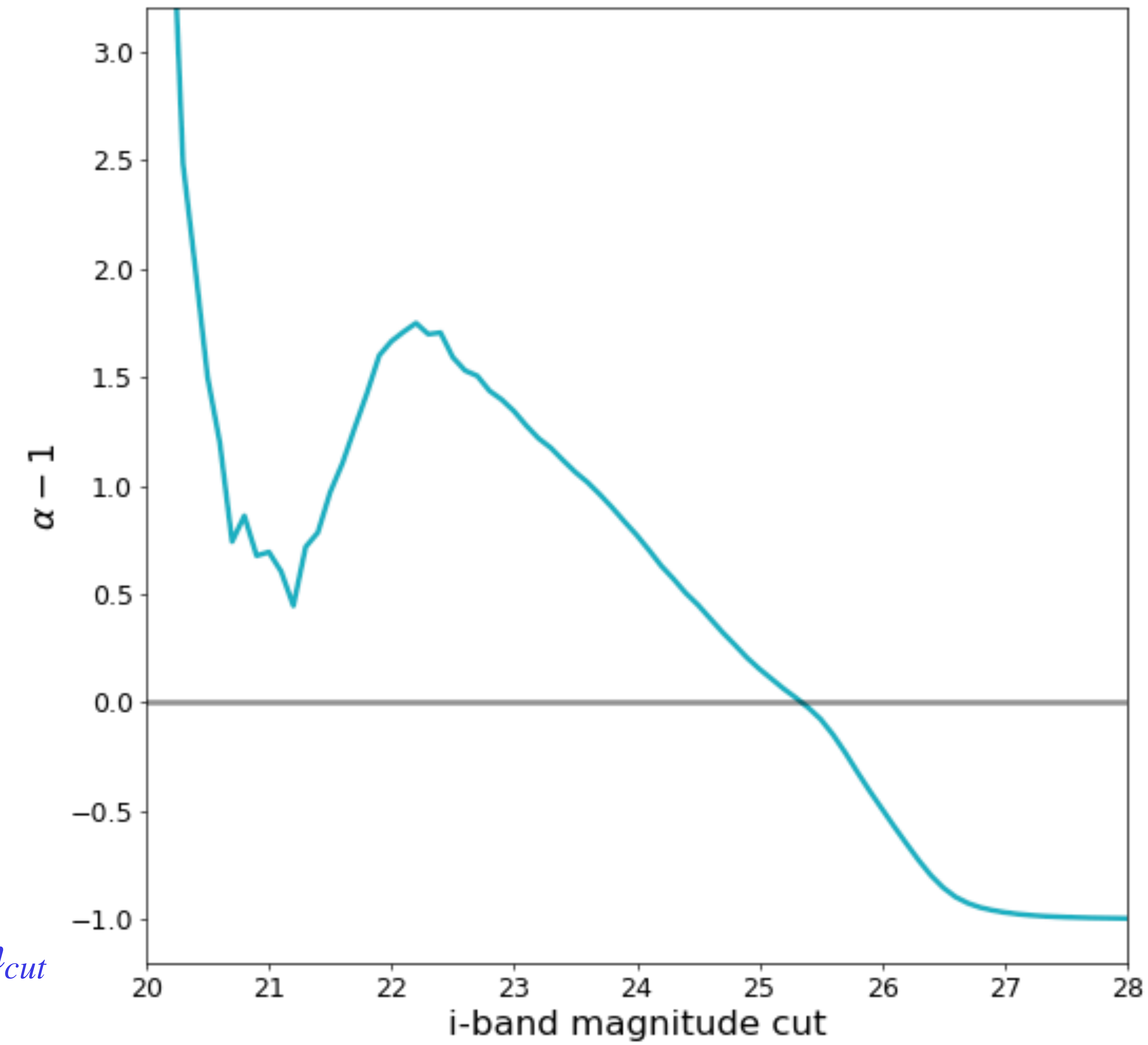
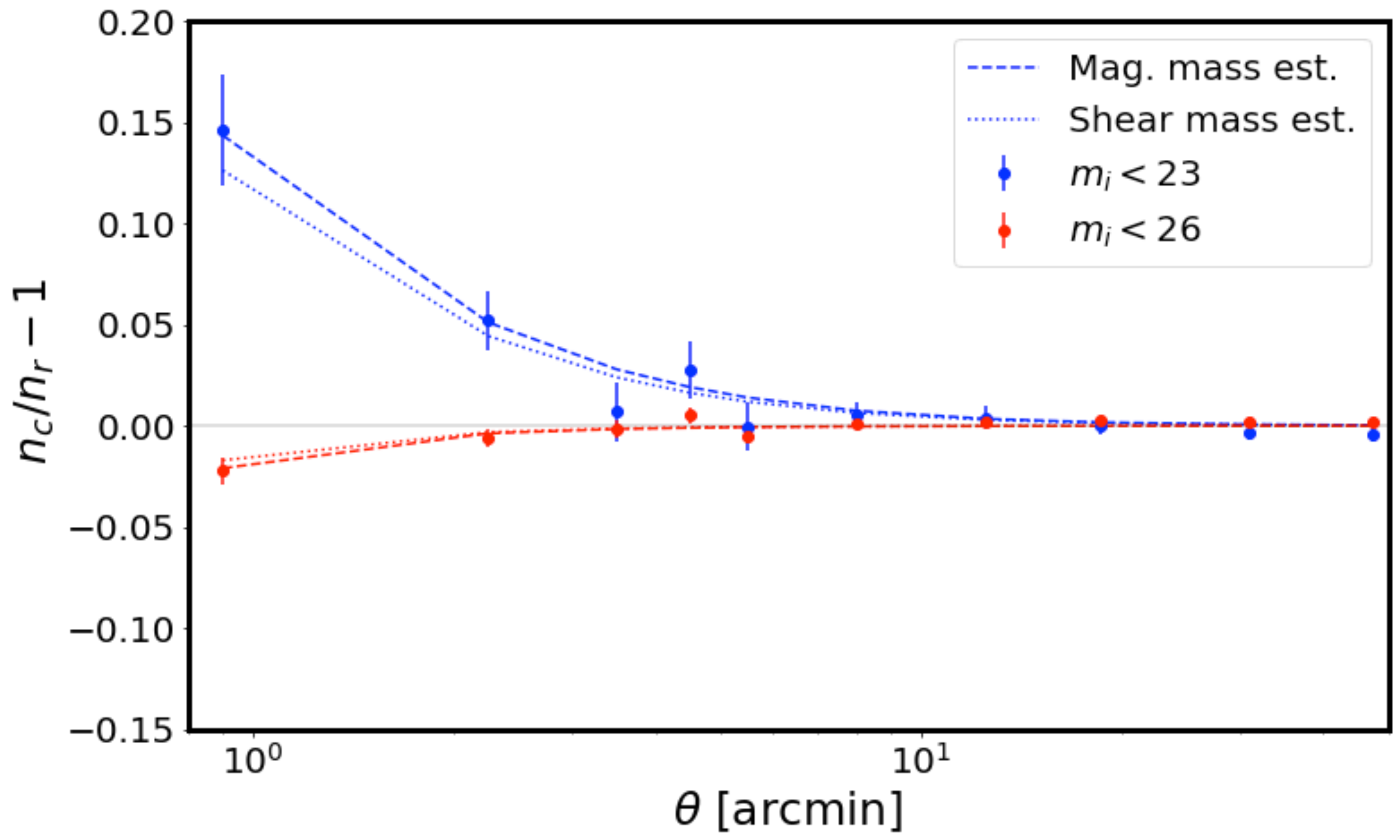
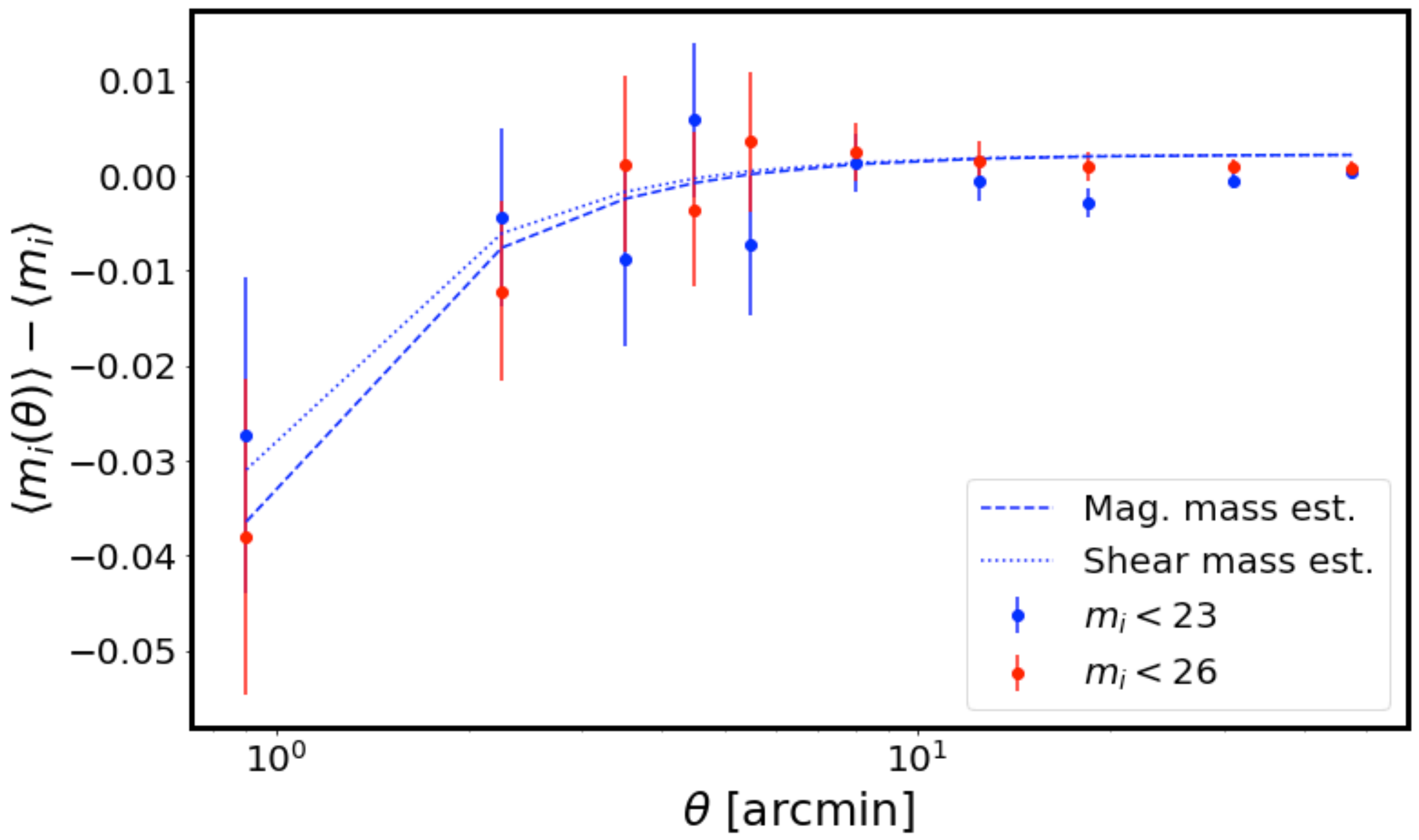



Mag. mass est.
Shear mass est.
$m_i < 23$
$m_i < 26$
$n_c/n_r - 1$
θ [arcmin]


Mag. mass est.
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$\langle m_i(\theta)\rangle - \langle m_i\rangle$
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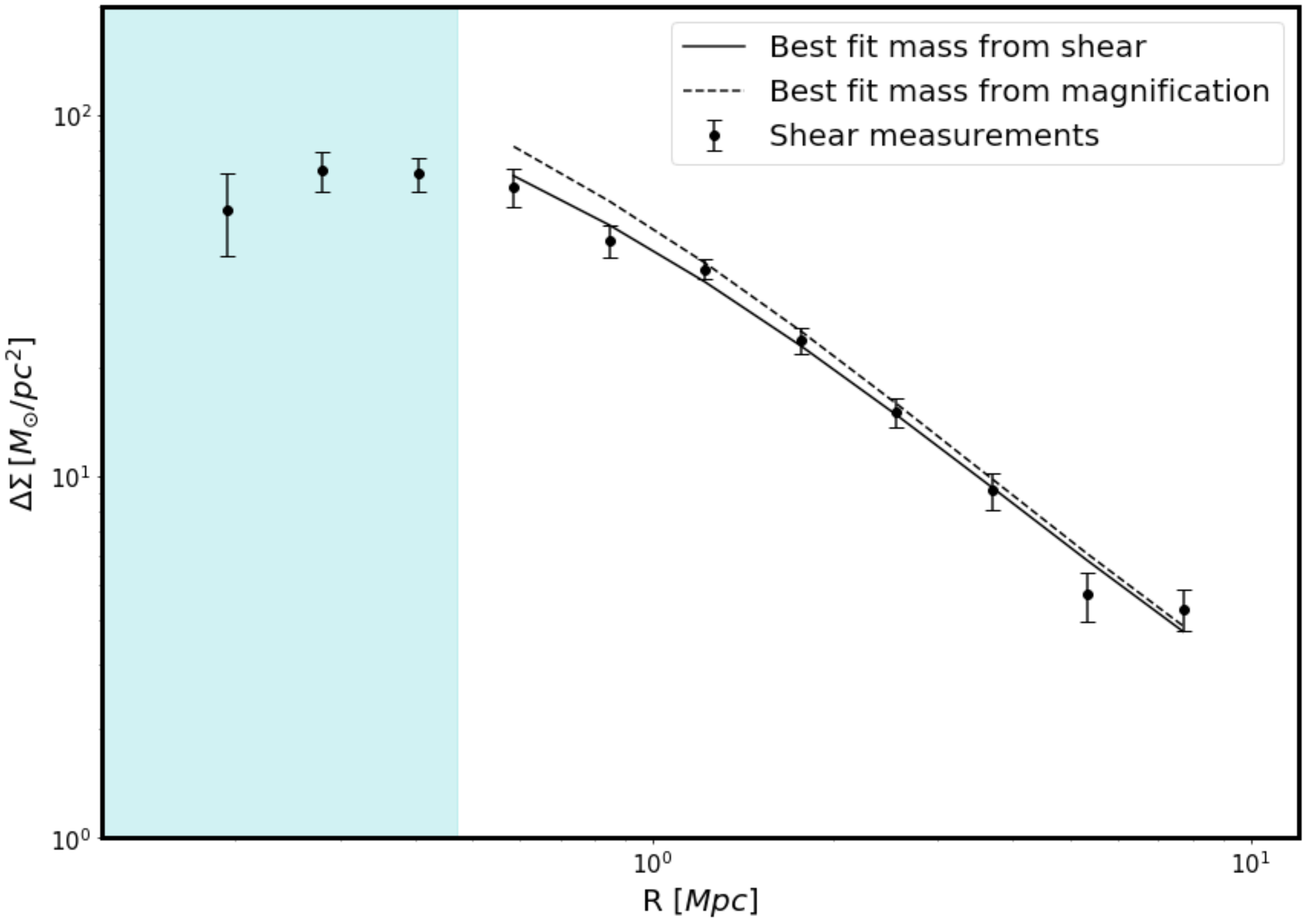
Best fit mass from shear
Best fit mass from magnification
Shear measurements
$\Delta\Sigma\,[M_\odot/pc^2]$
R $[Mpc]$