

Quasar milli-lensing and cold DM (TNG50) sub-haloes

Numerical density profiles of sub-haloes -> milli-lensing of lensed quasar images

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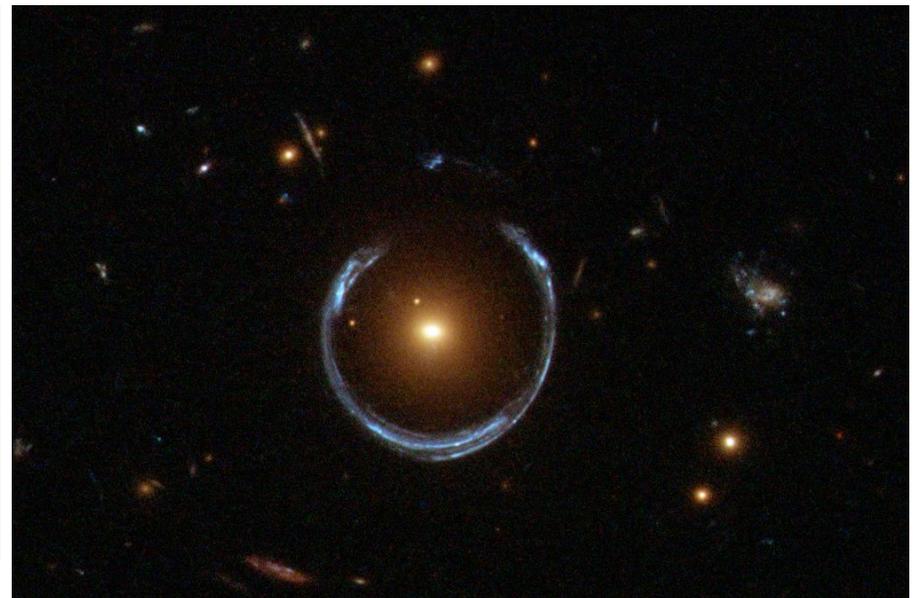
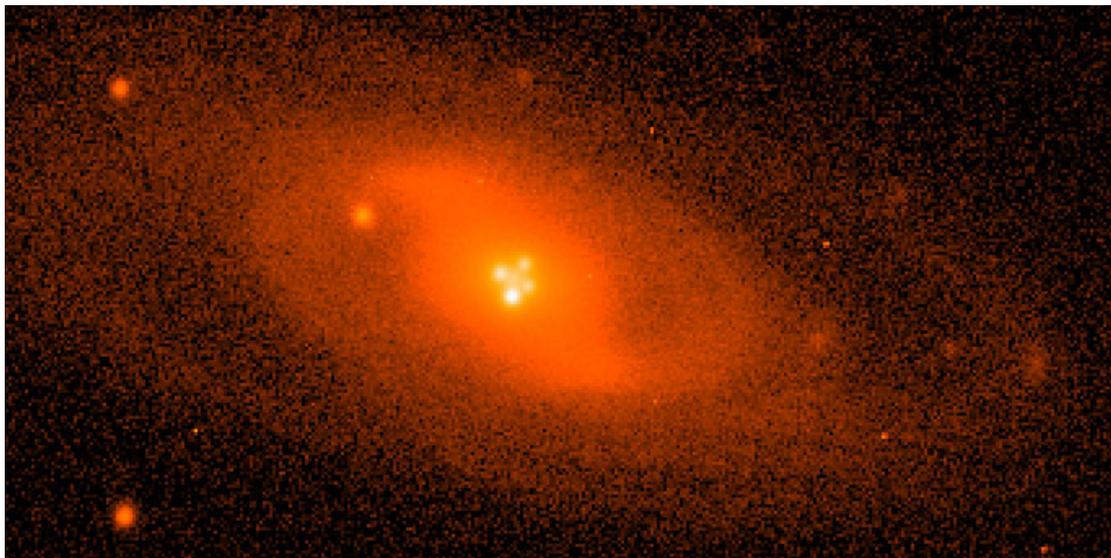
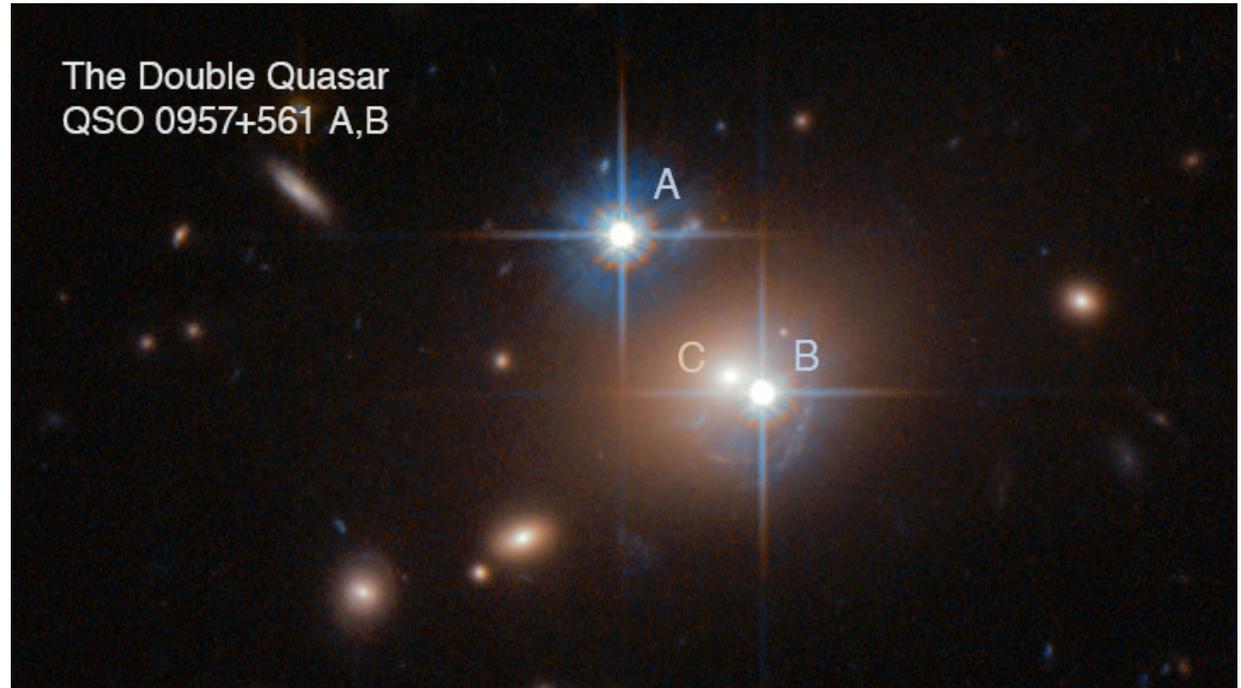
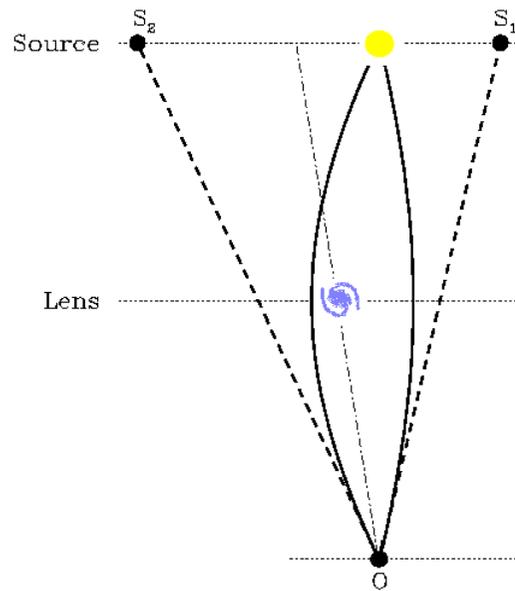
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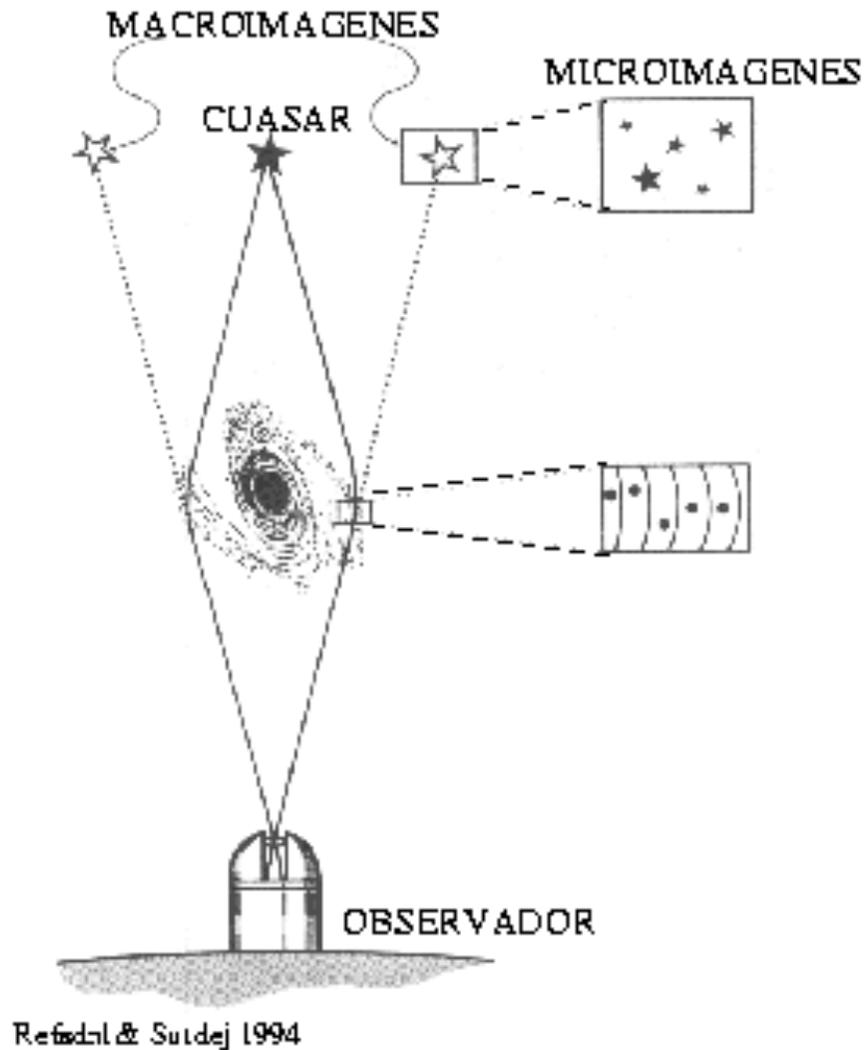
Outline – milli-lensing and TNG50 sub-haloes

- **Introduction:** quasar micro and milli-lensing - TNG50 sub-haloes
- **Methods:** analytical and numerical solutions of the lens equation - sub-images
- **Results:** detection limits - optical depth
- **Discussion:** sub-halo mass fraction
- **Summary**

Quasar lensing scenario



Quasar micro- and milli-lensing - phenomenology

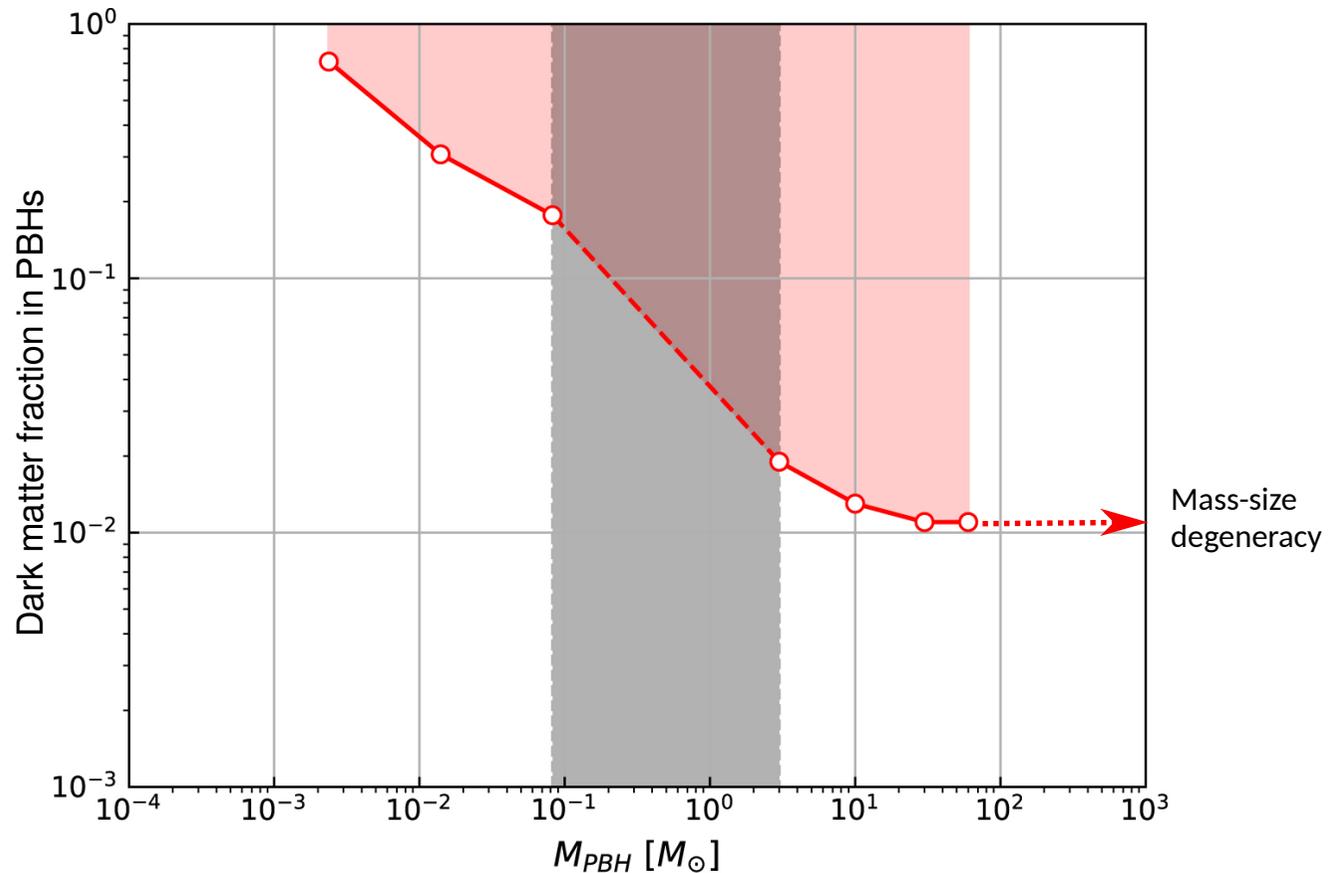


- Granulation in MACHOs of stellar mass -> microlensing
- Microlensing main effect -> split image in microimages that can not be resolved with a telescope
- (In a similar way) presence of DM subhaloes -> sub-images -> milli-lensing
- Milli-lensing -> may split image in sub-images that may be (or may be not) resolved with a telescope
- Observables -> flux ratio anomalies, astrometric anomalies and, even, **image splitting** (in the case of milli-lensing).

Results for compact objects (stars, BHs, ...) - from flux-ratio anomalies

- Flux-ratio anomalies
- Astrometric anomalies
- Image-splitting

• Extended arcs
Despali et al. 2024, ArXiv



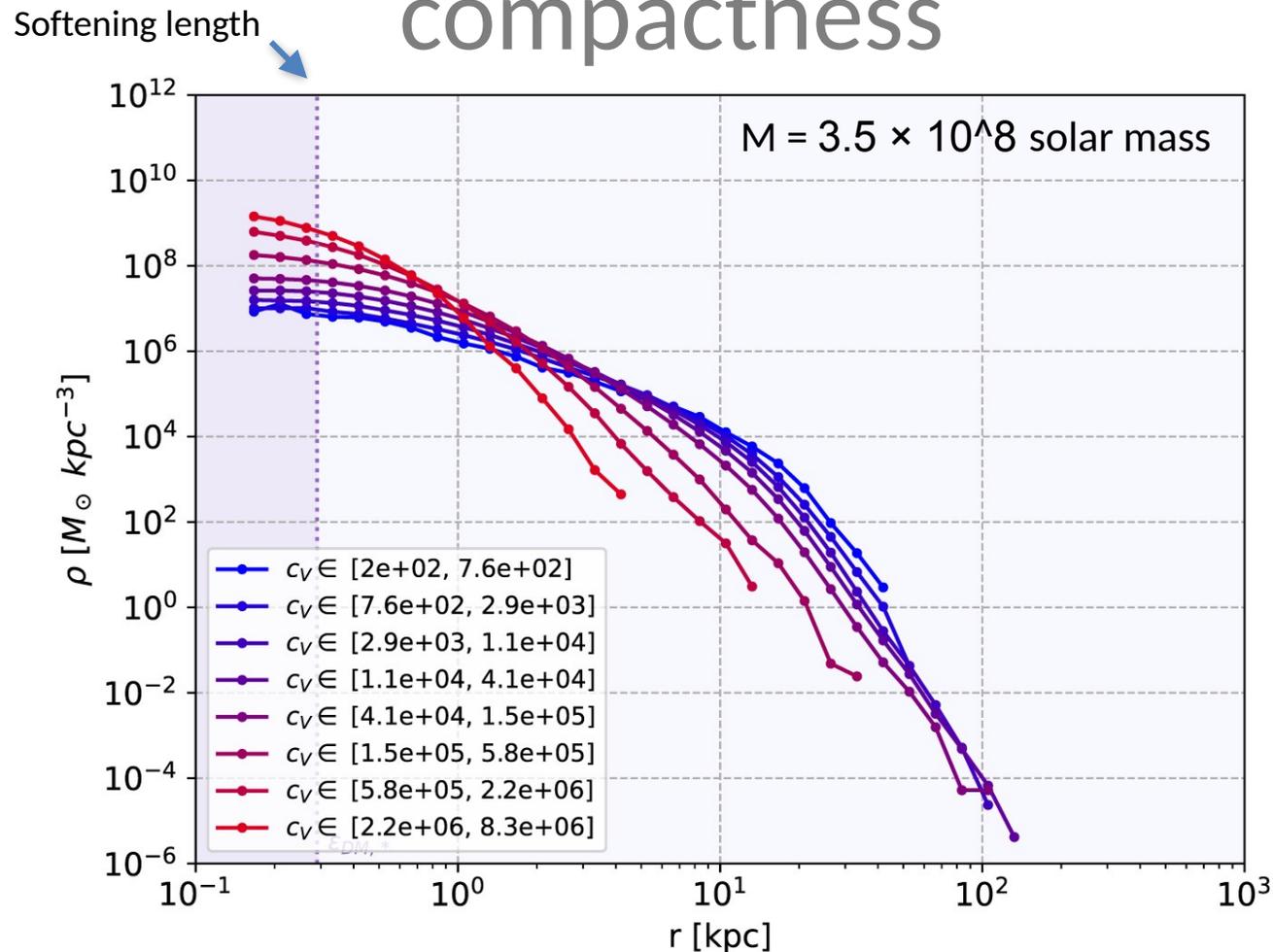
Mediavilla et al. 2009, ApJ

Mediavilla et al. 2017, ApJ

Estéban-Gutiérrez et al. 2023, ApJ

Mediavilla & Jiménez-Vicente, 2024, [arXiv:2405.14984](https://arxiv.org/abs/2405.14984)

Sub-haloes from TNG50 simulation - compactness



Heinze, Despali & Klessen 2024

Objective - probing DM sub-haloes with quasar image splitting

- Can quasar sub-images generated by TNG50 sub-haloes be detected with HST/JWST? - separation between sub-images
- What is the probability of detection? - optical depth

Lens equation - axi-symmetrical sub-halo - source aligned with the OA

$$\vec{y} = \begin{pmatrix} 1 - \kappa - \gamma & 0 \\ 0 & 1 - \kappa + \gamma \end{pmatrix} \vec{x} - \frac{\vec{x}}{x^2} m_{sh}(x),$$

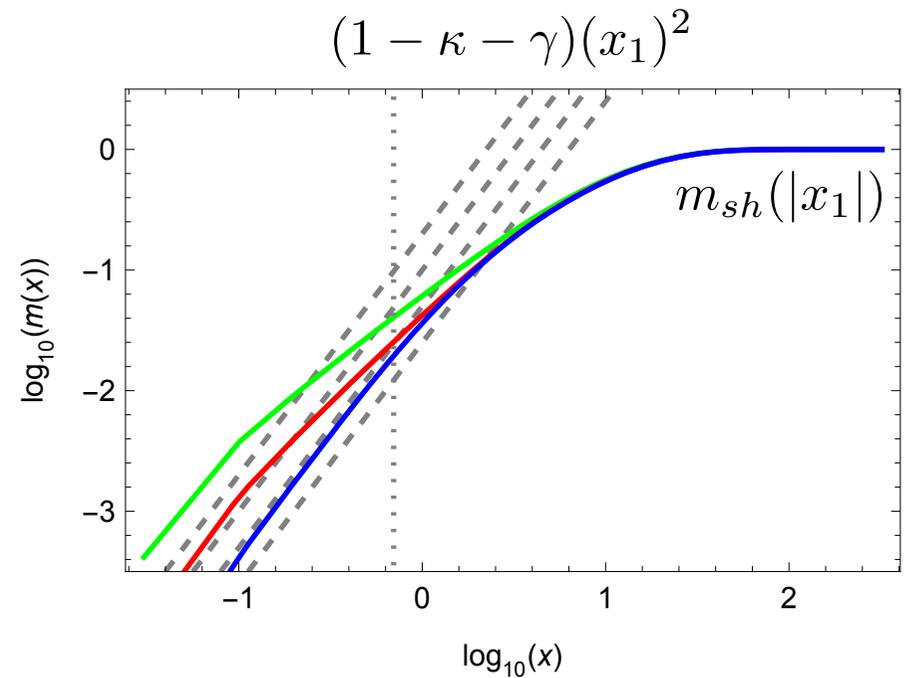
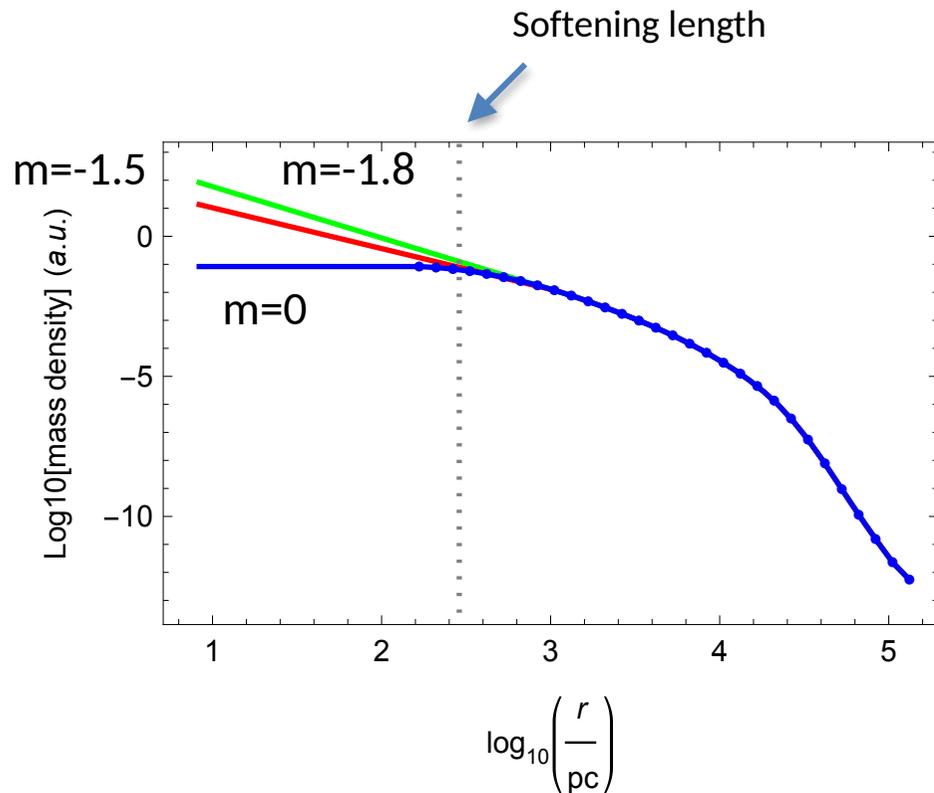
lens galaxy

$x_2 = 0$

sub-halo enclosed mass fraction

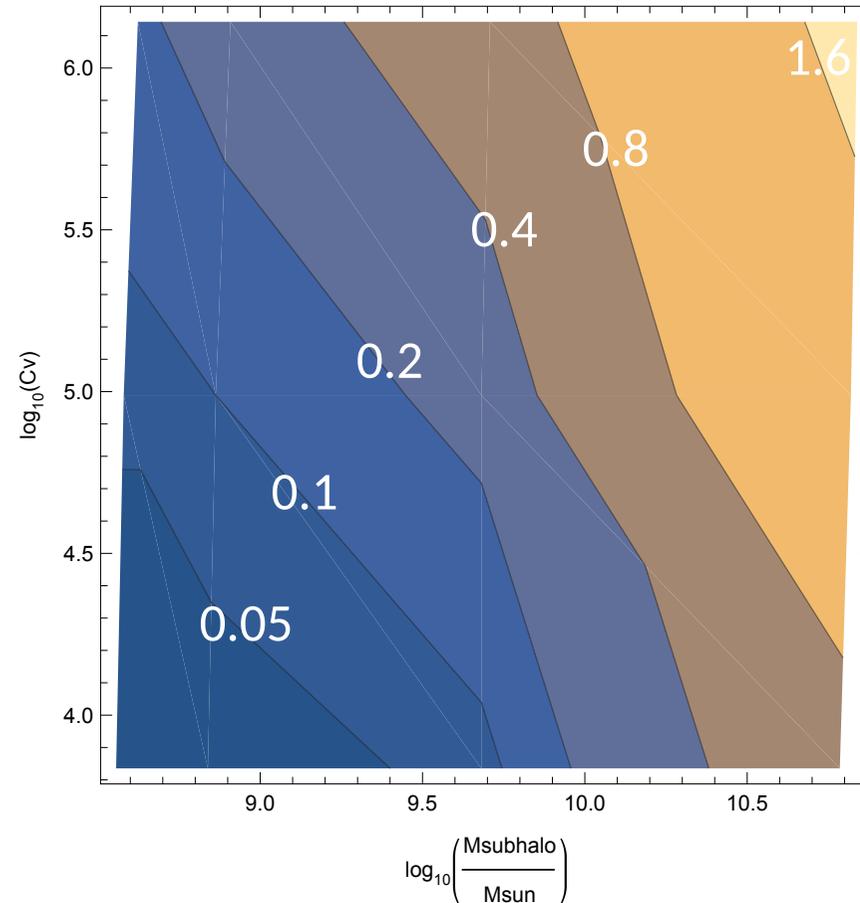
$$0 = (1 - \kappa - \gamma)(x_1)^2 - m_{sh}(|x_1|).$$

Separation between sub-images - graphical solutions



Sub-images separation ($2x$) depends on: M_{sh} , C_v , and m ; ($m \rightarrow -2$)

Sub-image separations - detection limits



macro-magnification = 10

TNG50 simulation -> if sub-haloes were frequently aligned with lensed quasar images, splitting should have been observed!

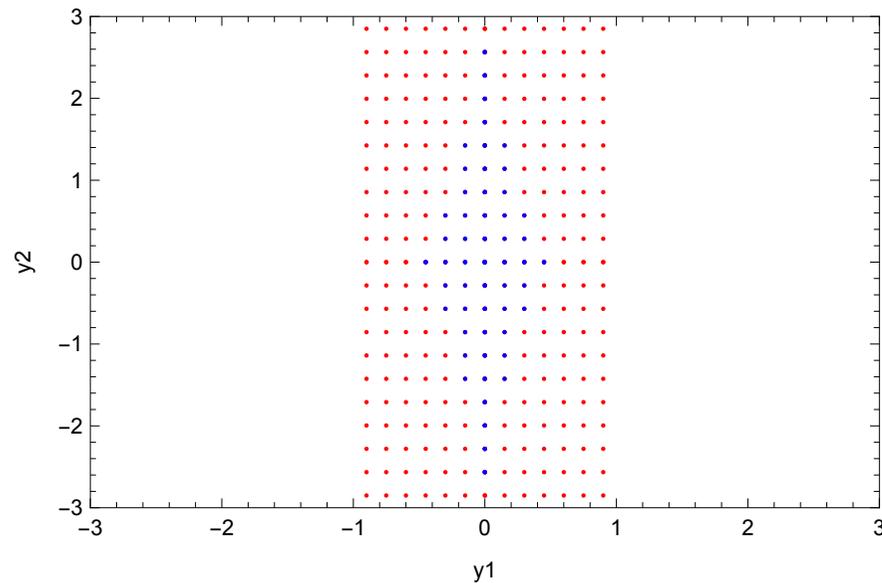
Results from observations

- More than 220 lensed quasars (doubles and quads)
- More than 700 images observed
- A significant part of them with enough spatial resolution (>300)
- To our knowledge, no clean image splitting has been reported

Then, the relatively compact and steep ($m=-2$) TNG50 density profiles may generate splitting but it is not observed \rightarrow constrain optical depth \rightarrow upper limit to the mass fraction in sub-haloes

Optical depth - IRS - numerical solutions

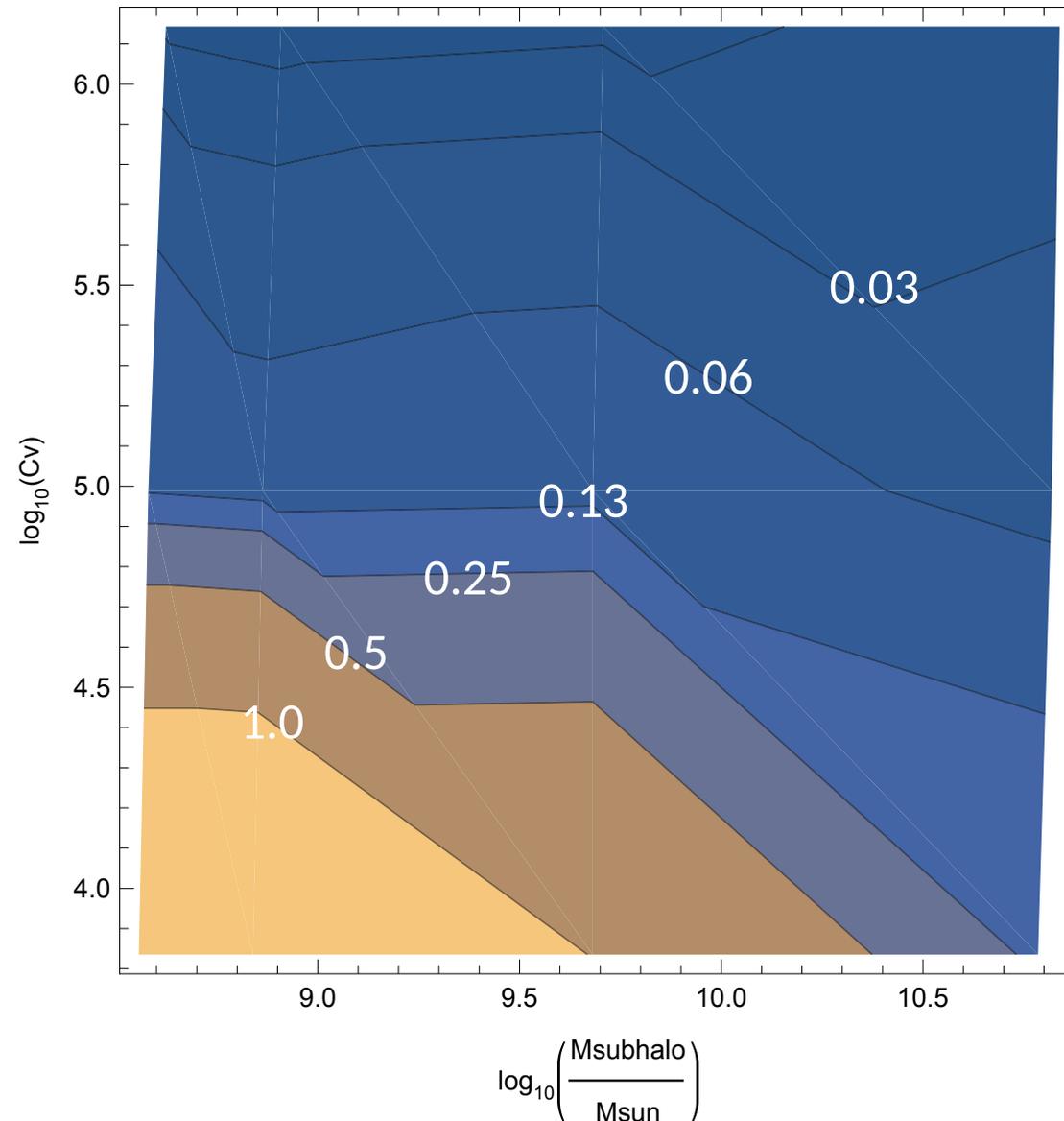
Determine the area of the region of the source plane where a quasar is going to be split in sub-images that can be resolved (with separations > 0.1 arcsec and with similar flux, $F_2/F_1 > 0.8$)



Blue dots: quasar locations giving rise to sub-images that can be detected

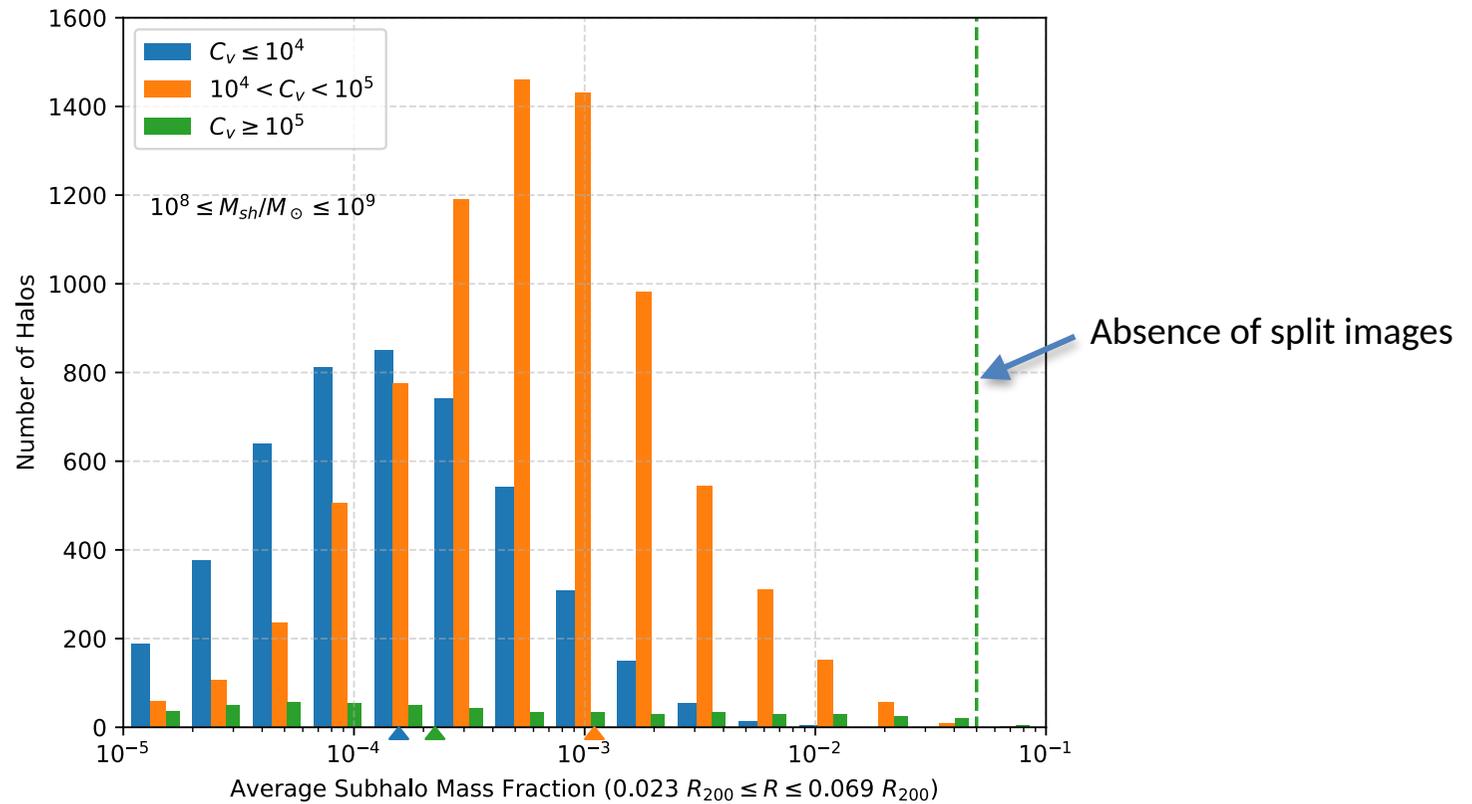
Weird 4-cusps figure: caustic of the numerical density profile

Optical depth - upper limit of the mass fraction on subhaloes



TNG50 subhalo mass fraction

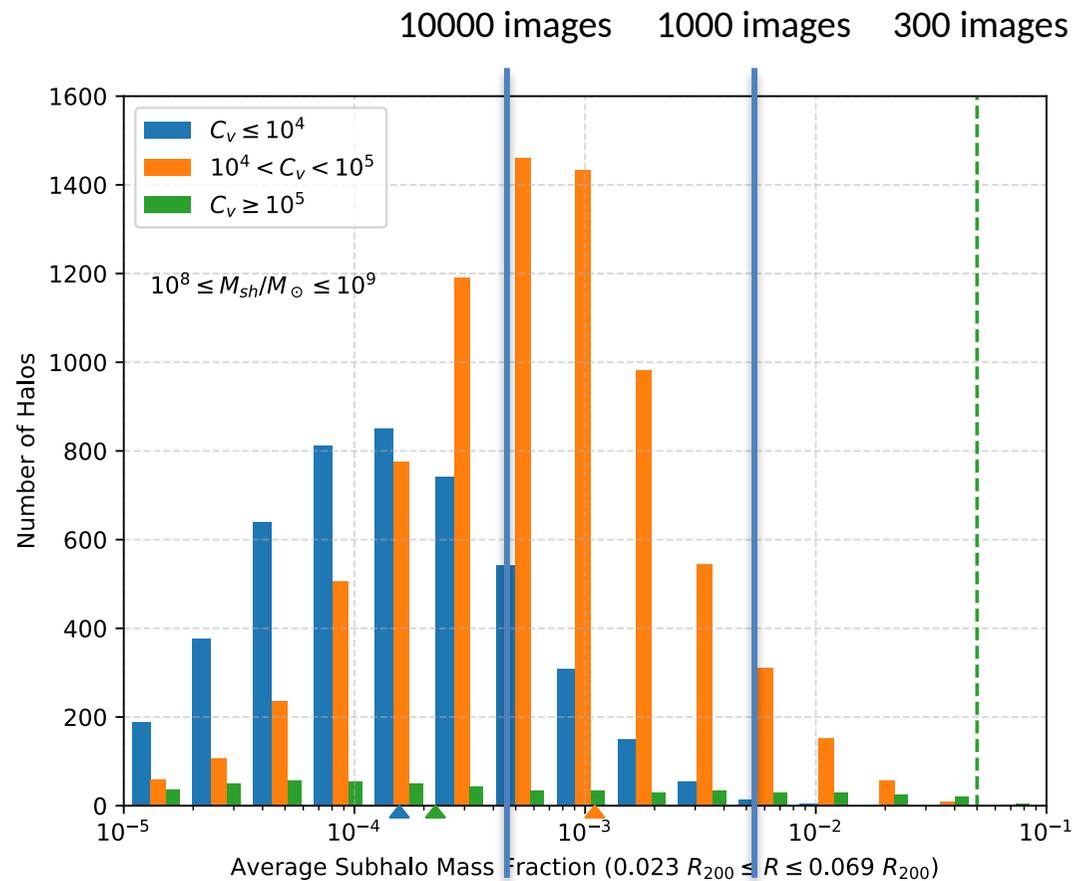
For 10000 haloes we compute the projected sub-halo mass fraction along the LOS typical of lensed quasar images (enclosed by cylindrical shells with $2 \text{ kpc} < r < 20 \text{ kpc}$)



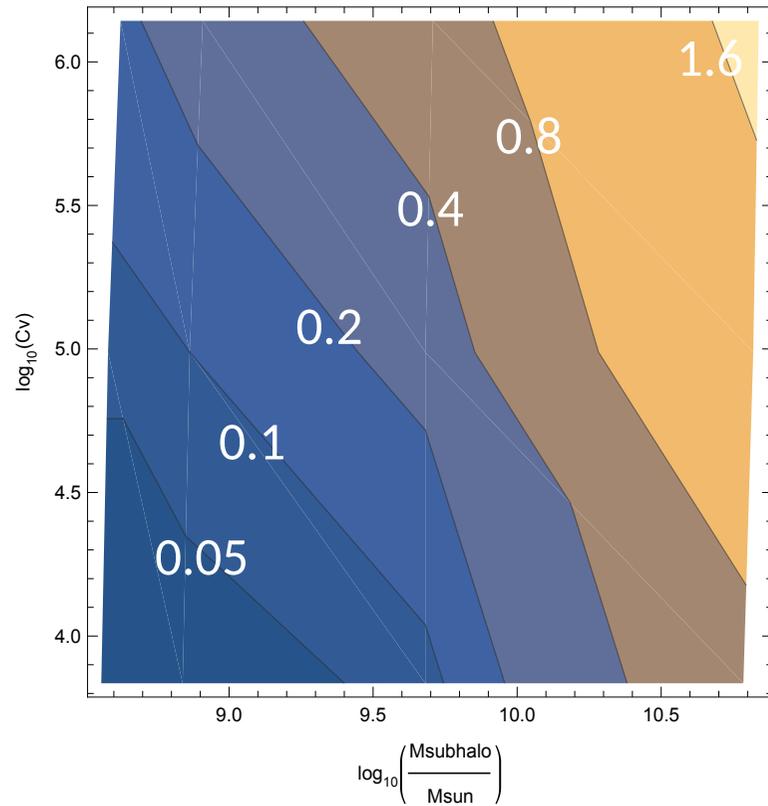
Summary -

some results from lensed quasars

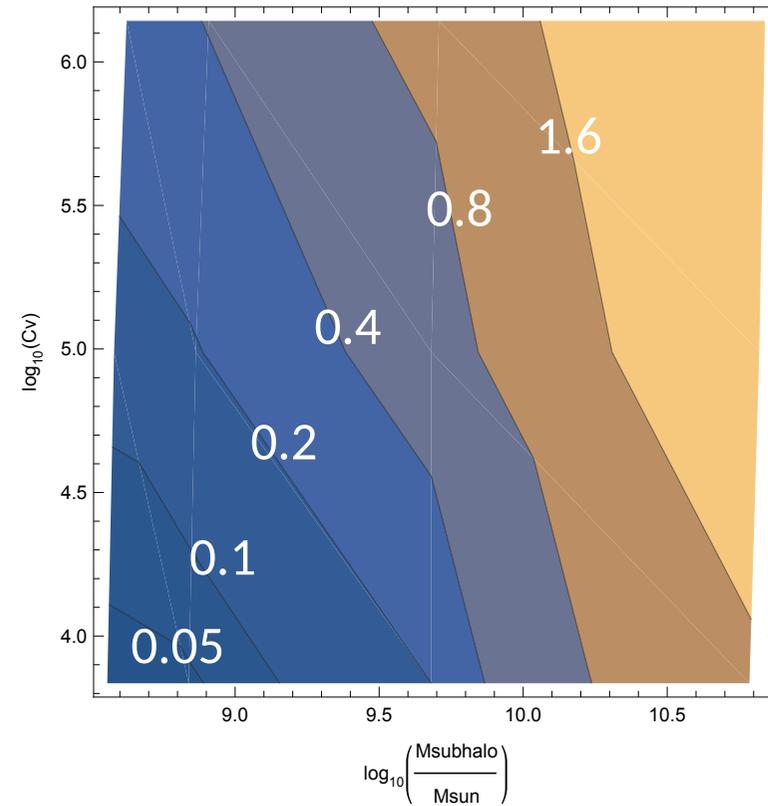
- Compact objects: mass fraction for masses larger than solar < 1%
- Sub-images separation depends on sub-halo mass, concentration and innermost slope
- Sub-images generated by TNG50 sub-haloes can potentially be detected with HST and JWST
- Absence of sub-images detection is consistent with TNG50 optical depth estimates
- Large survey results may challenge TNG50 statistics
- To explore I: flux-ratio anomalies, astrometric anomalies, gravitational arcs anomalies
- To explore II: other DM simulations, other DM candidates



Sub-image separations - detection limits



magnification = 10



magnification = 20