Future measurements of the nature of dark matter with strong lensing

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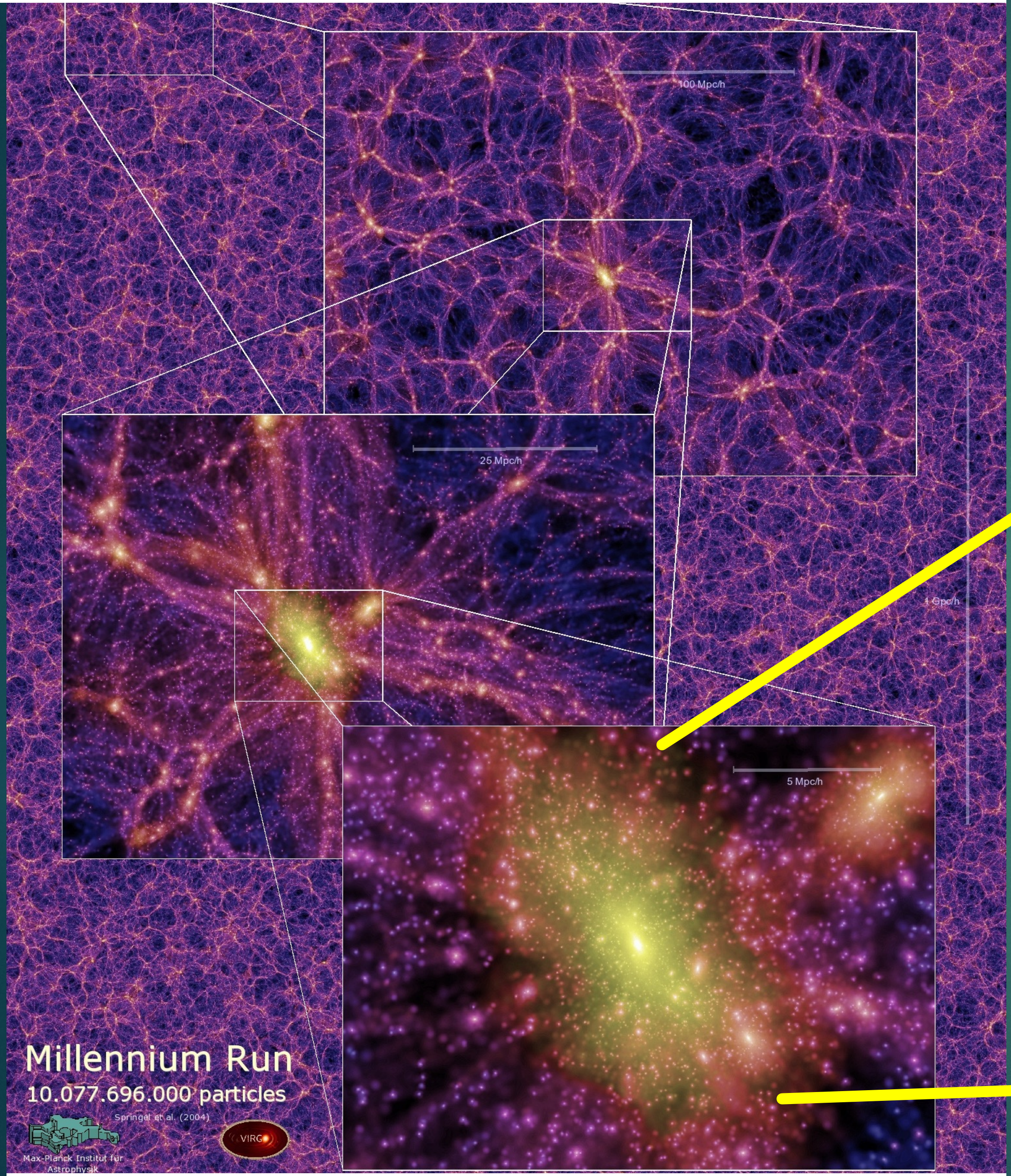
Overview

- Background: Using strong lensing to test models of dark matter
- The future: How high precision astrometry can help us

If we could see dark matter…



Millenium Simulation, Springel et al. 2005

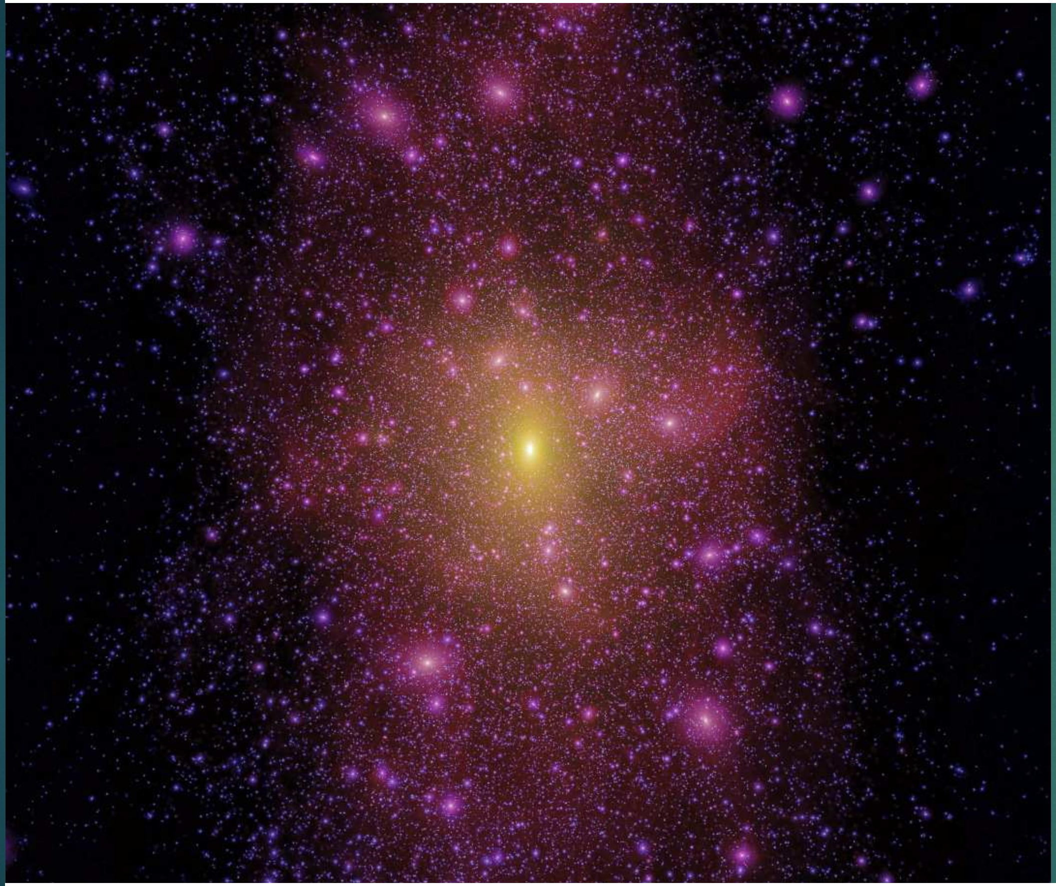
Dark matter 'halo' – self-gravitating dark matter structure

Dark matter 'halo' ~100x more extended than galaxy stars

Galaxy Image Credit; ESO/NASA

Different dark matter models produce different dark matter halos

Cold Dark Matter e.g. WIMP



Warm Dark Matter – e.g. Sterile Neutrino

Credit: Lovell et al. 2014

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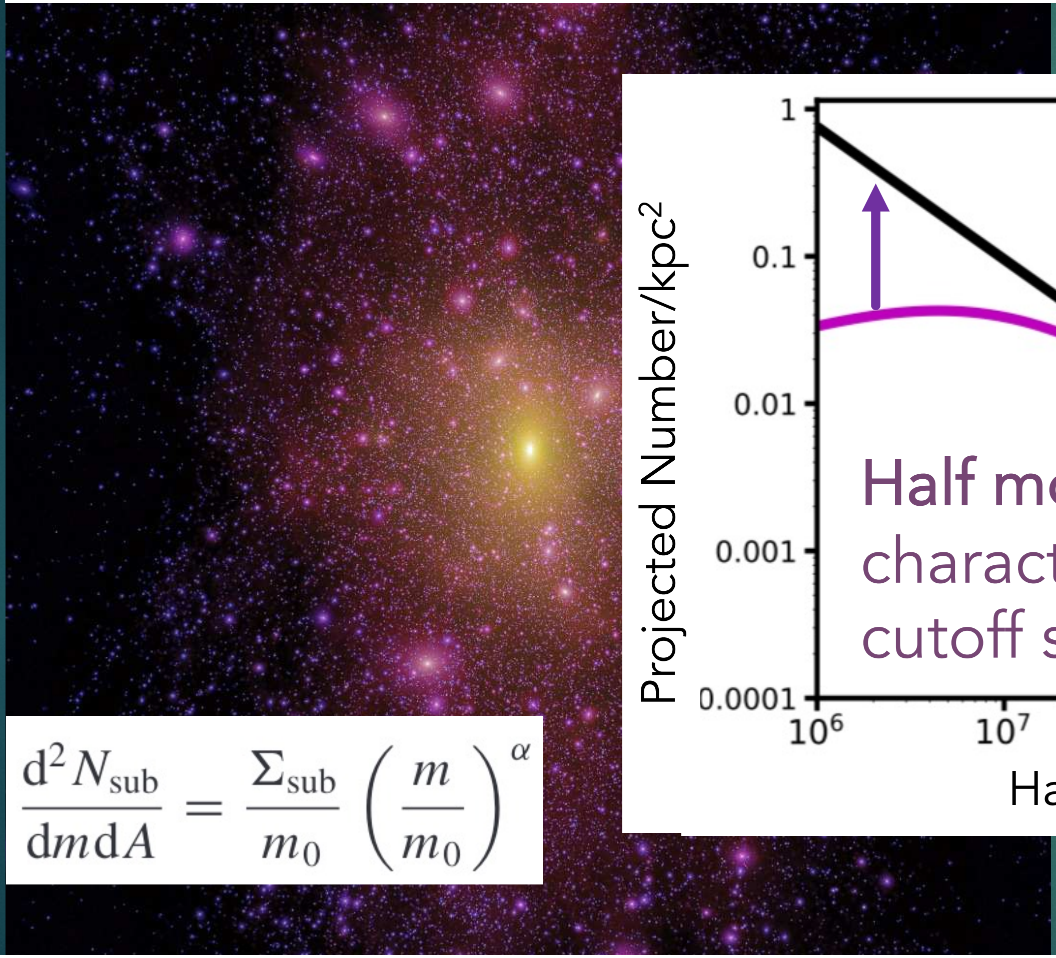
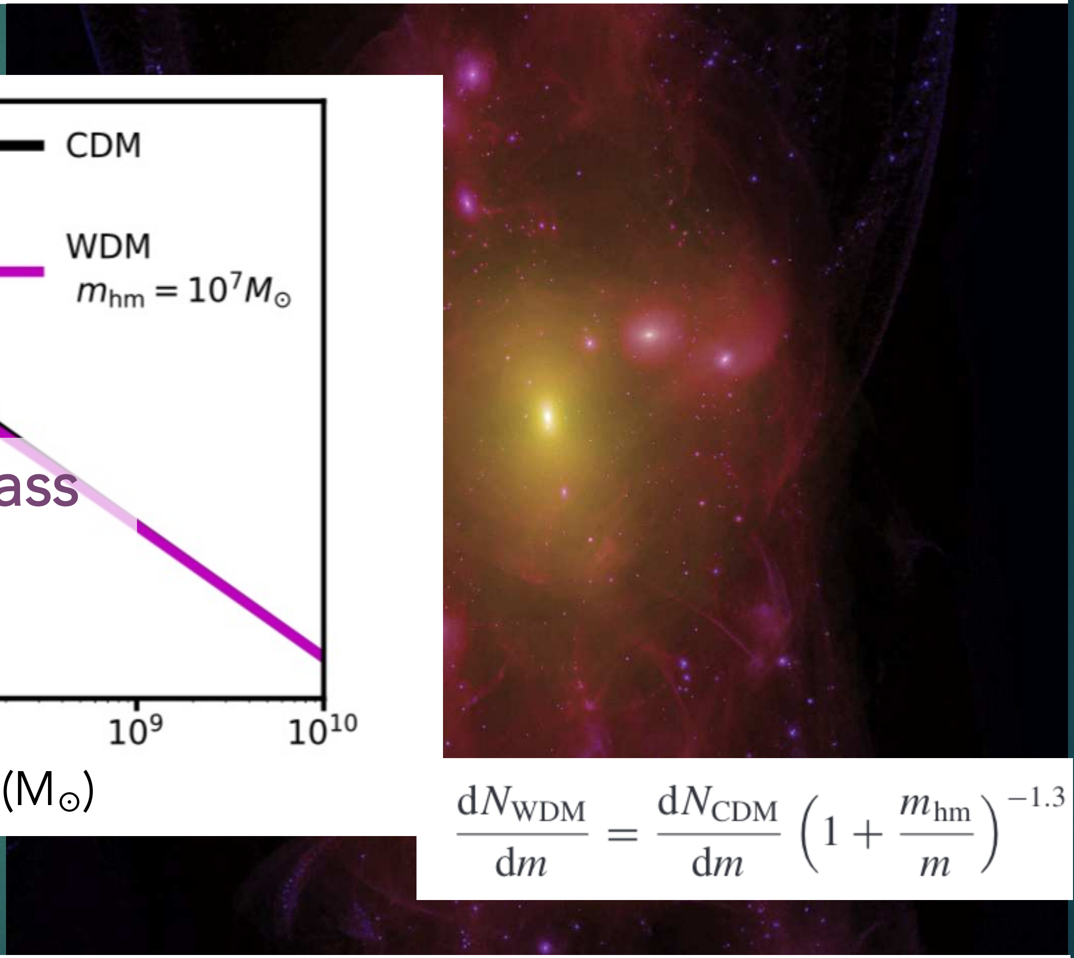
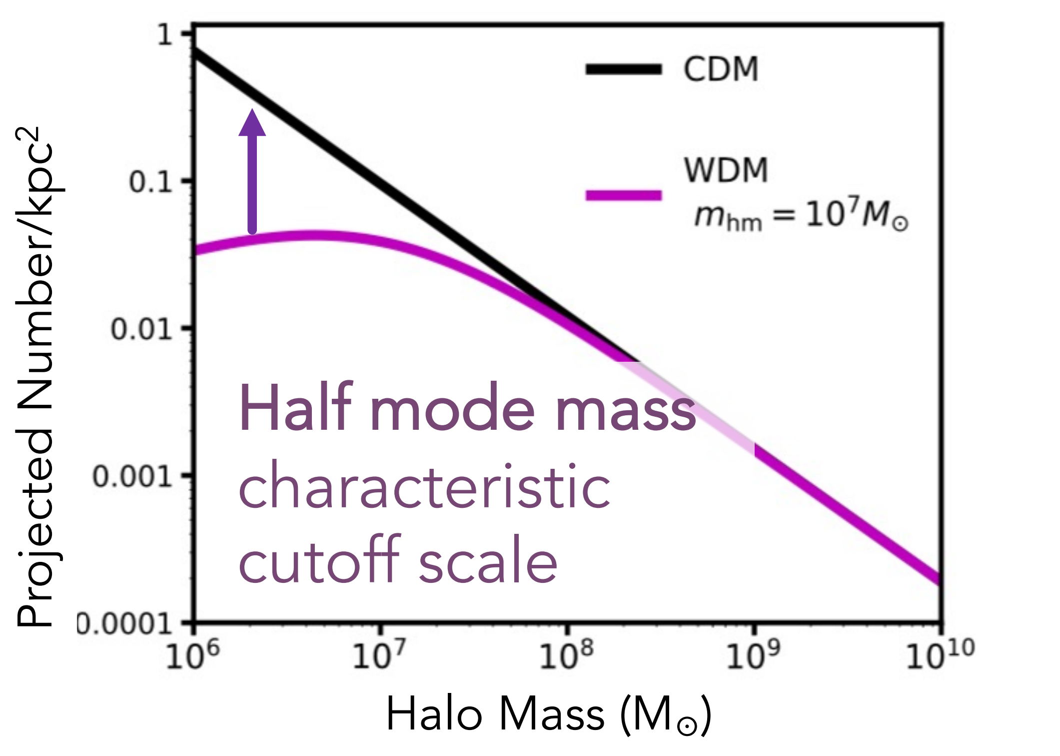






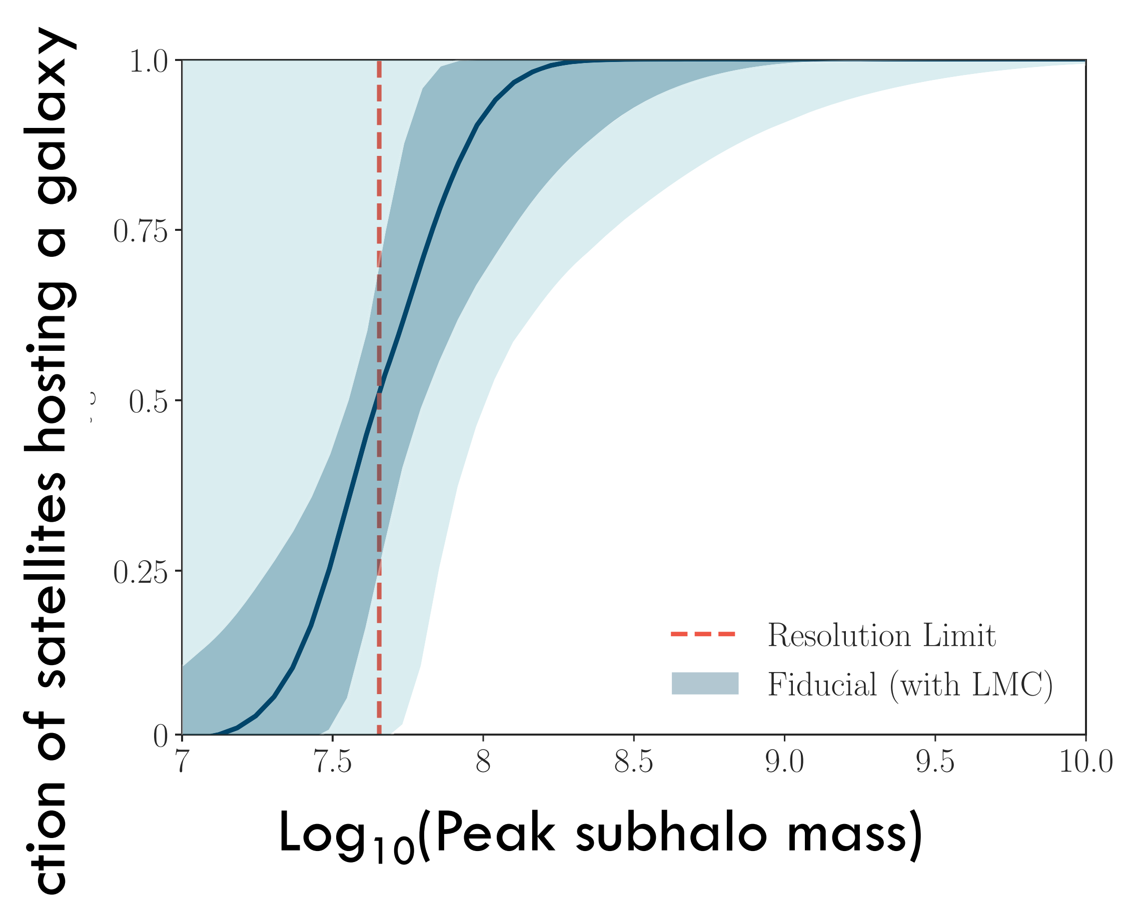
$$\frac{\mathrm{d}^2 N_{\rm sub}}{\mathrm{d}m\,\mathrm{d}A} = \frac{\Sigma_{\rm sub}}{m_0}\left(\frac{m}{m_0}\right)^{\alpha}$$

$$\frac{\mathrm{d}N_{\rm WDM}}{\mathrm{d}m} = \frac{\mathrm{d}N_{\rm CDM}}{\mathrm{d}m}\left(1+\frac{m_{\rm hm}}{m}\right)^{-1.3}$$

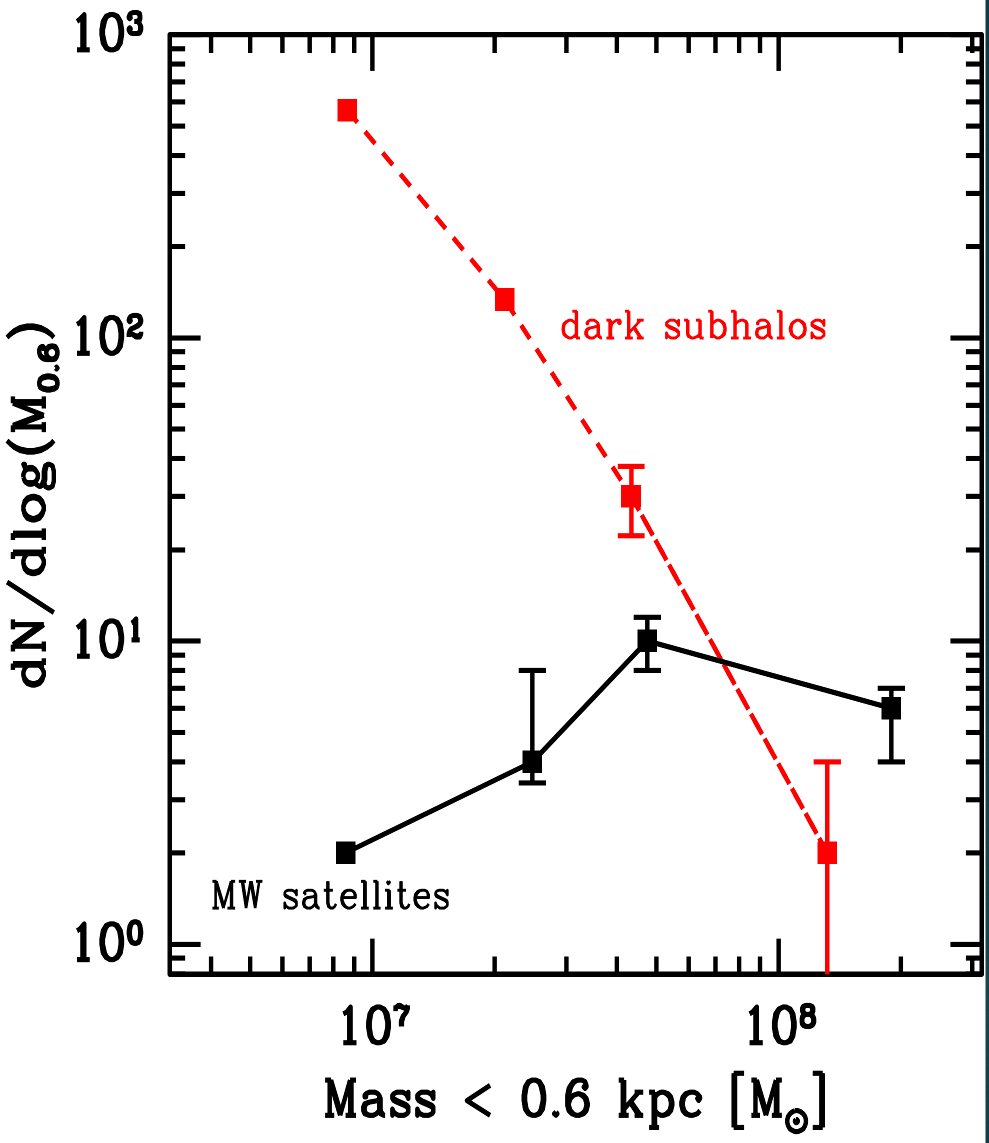
CDM mass fn

WDM mass fn

Goal: Detecting halos in the dark regime

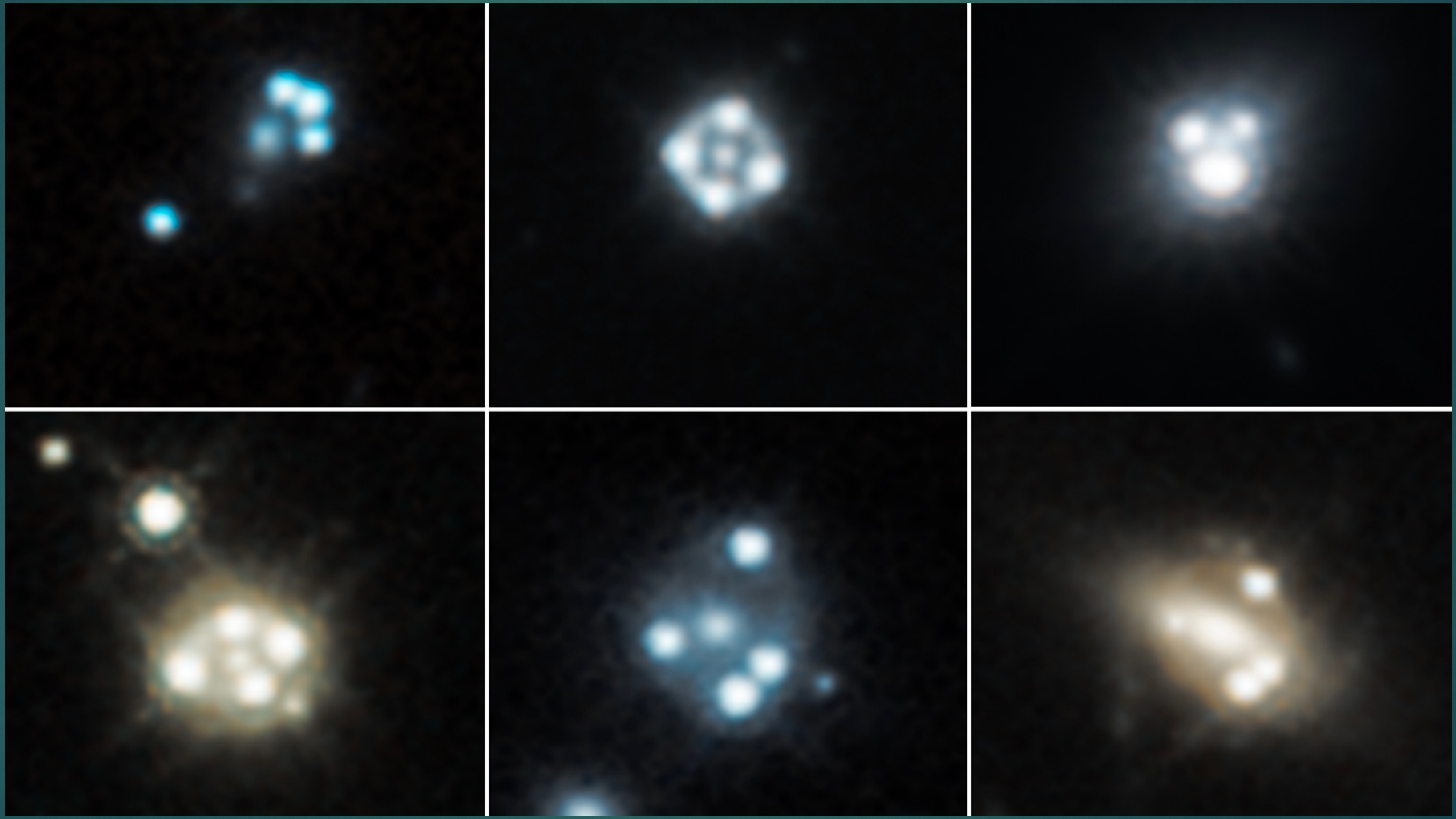


Nadler et al 2020



Credit: Strigari 2008

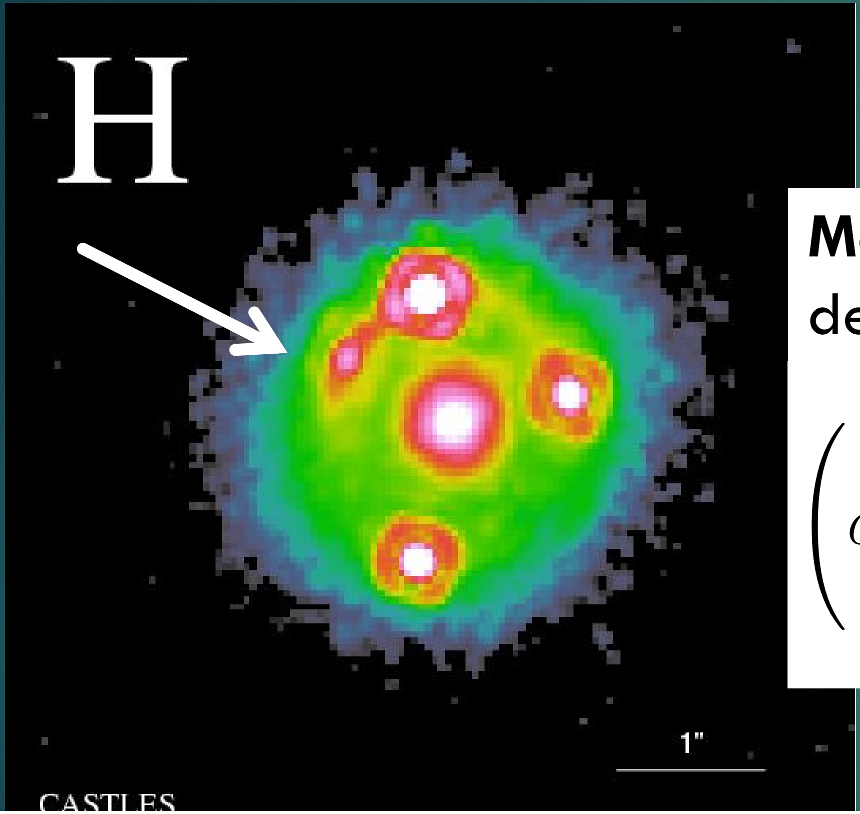
Dark matter measurements with strong gravitational lensing



Credit: STSCI, GO-15177, 13732 PI Nierenberg

Signal of a perturbation in an unresolved source

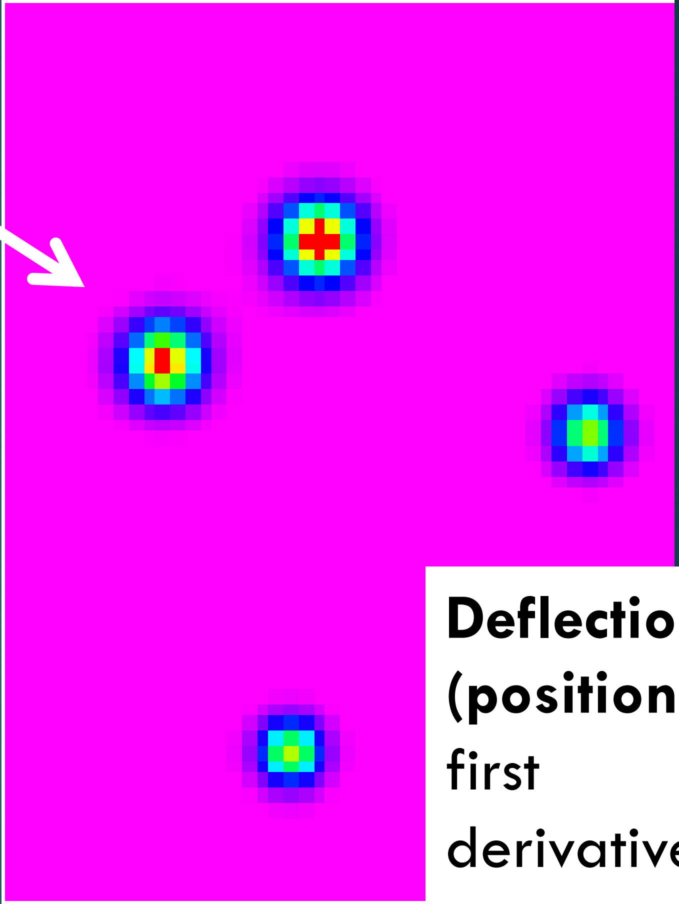
Observed lens



Magnification ∝ second derivative

$$\left(\delta_{ij} - \frac{\partial^2 \psi(\vec{\theta})}{\partial\theta_i \partial\theta_j}\right) = \mathcal{M}^{-1} \, .$$

Best 1 halo model fit



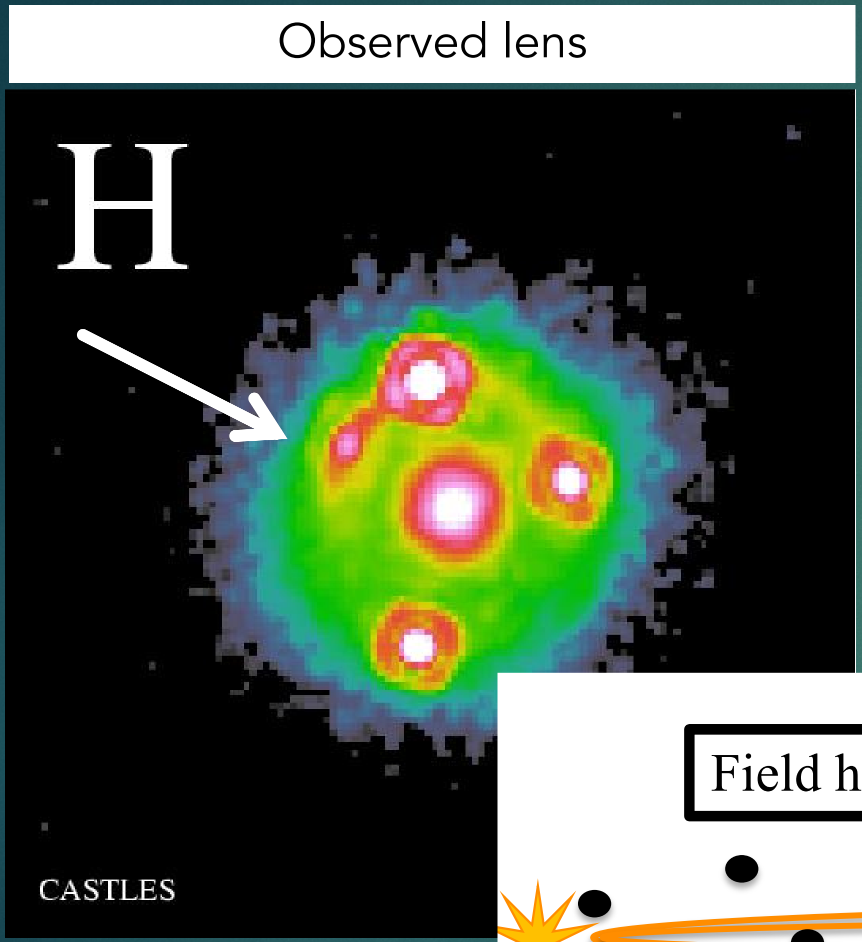
Deflection (positions) ∝ first derivative

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi$$

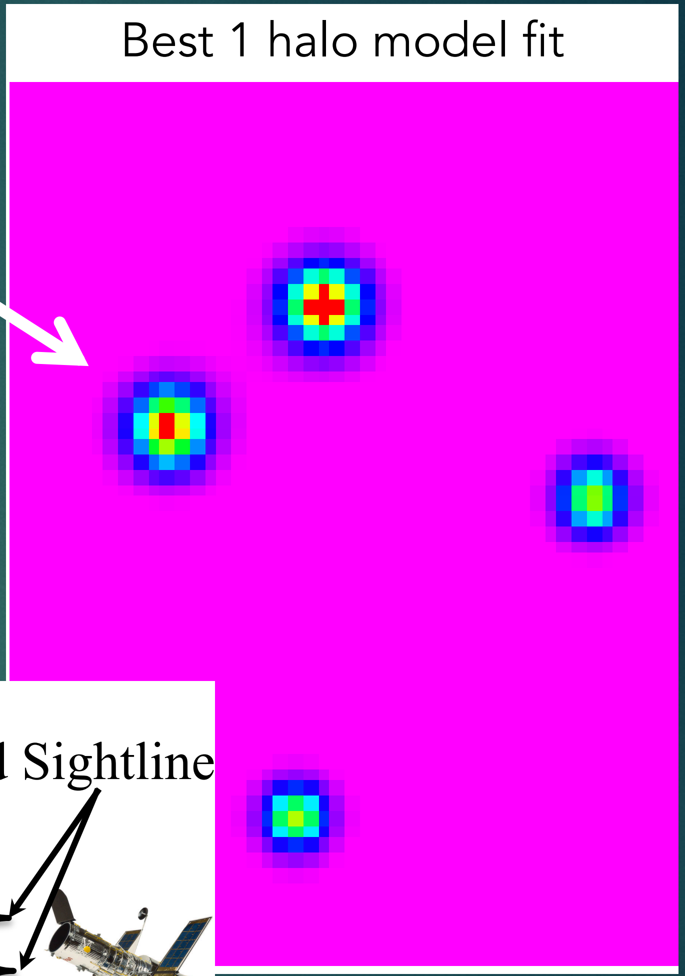
Gravitational Potential

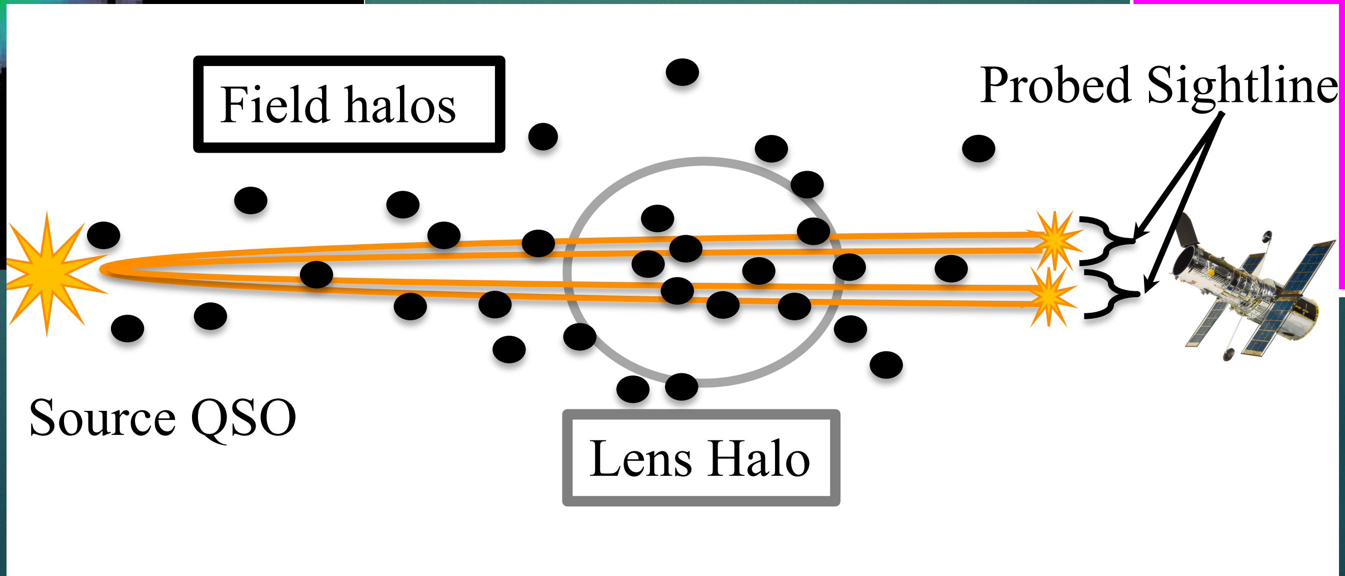
$$\psi(\vec{\theta}) = \frac{D_{\rm ds}}{D_{\rm d} D_{\rm s}} \frac{2}{c^2} \int \Phi(D_{\rm d}\vec{\theta}, z)\, dz \, .$$

Signal of a perturbation in an unresolved source



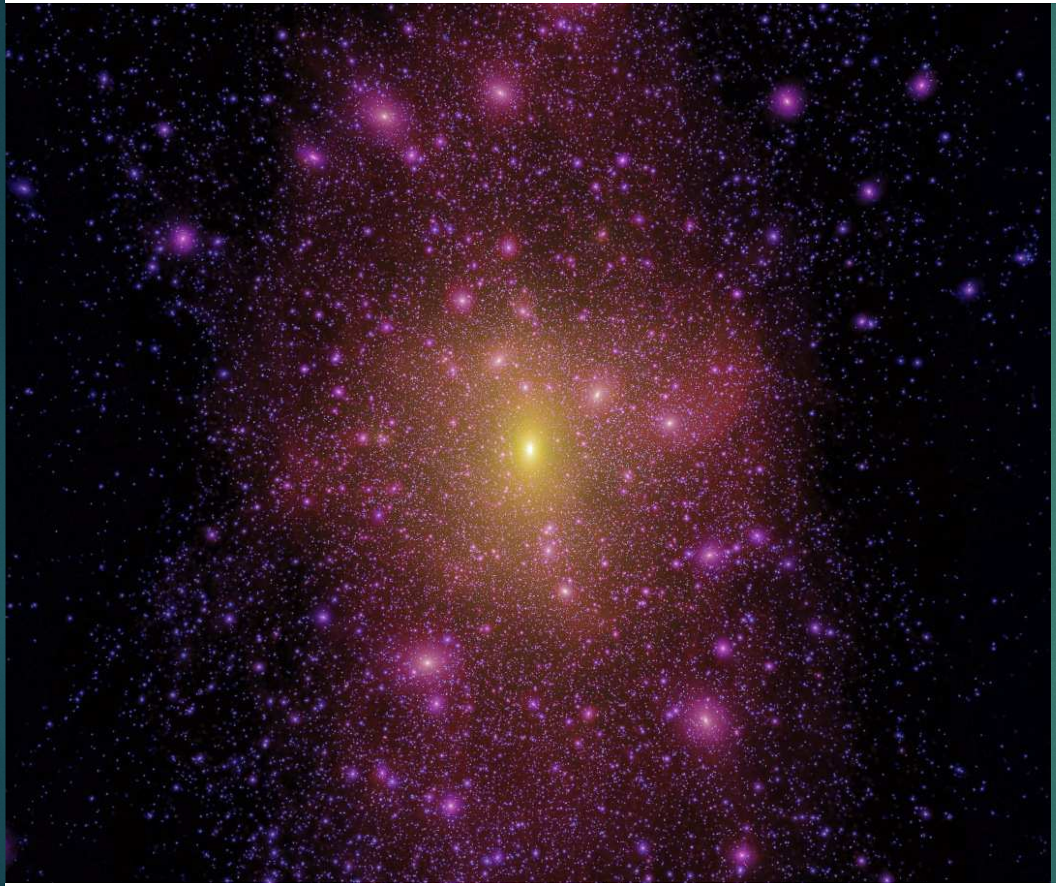
Perturbation needs to be localized and small scale – positions unperturbed





With enough lenses we can statistically distinguish these scenarios

Cold Dark Matter e.g. WIMP

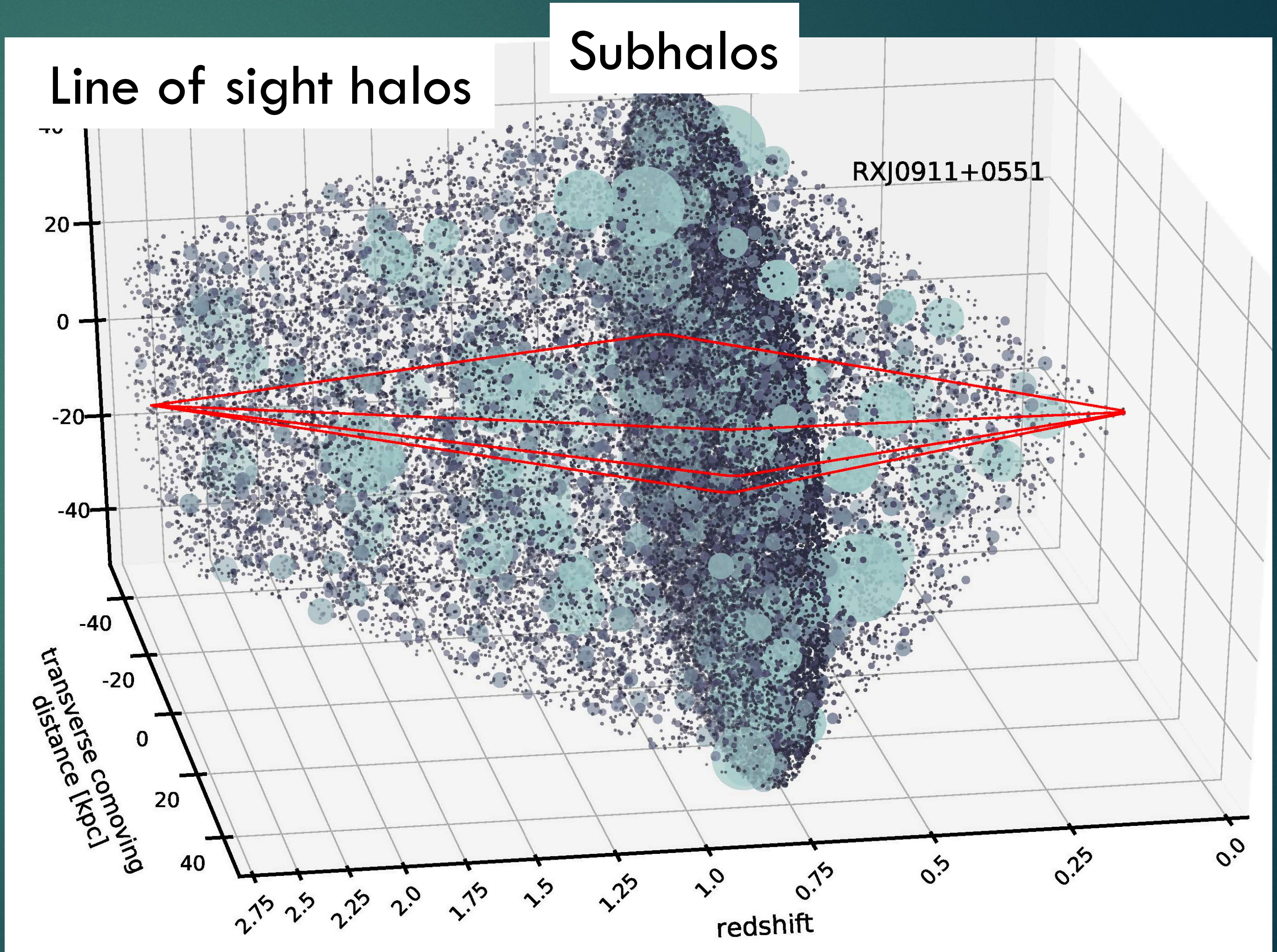


Warm Dark Matter – e.g. Sterile Neutrino

Credit: Lovell et al. 2014

Comparison of flux ratios with predictions from full cosmological dark matter predictions

- The mass function of halos bound to the main lens
- Effects of tidal stripping and disruption
- The spatial distribution of halos bound to the main lens
- The mass function of halos outside of the main lens
- The mass-concentration relation
- Unknown finite source size

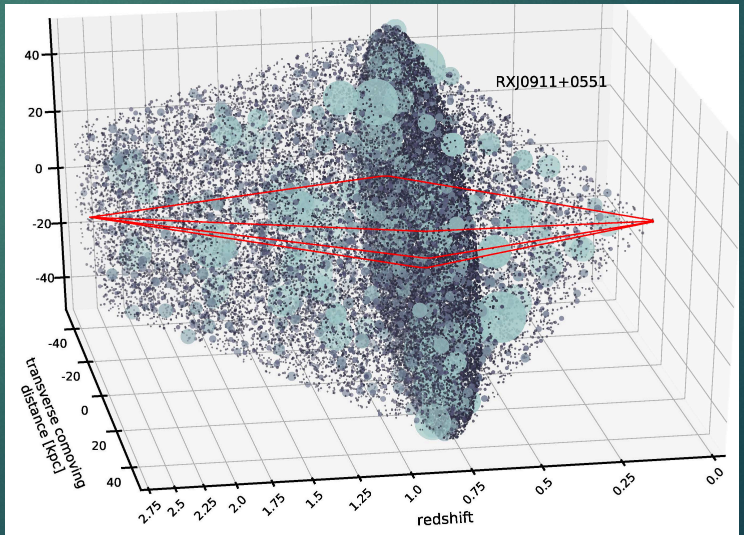


Gilman et al 2019, 2020

All software is open source and publicly available on github

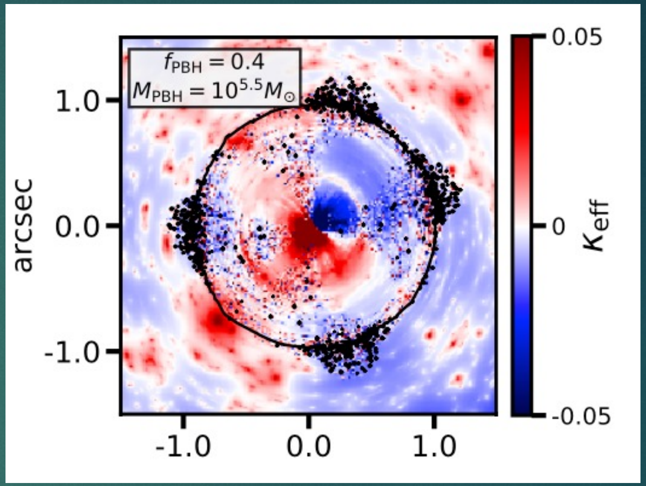
- **Lenstronomy**: All data analysis and gravitational lensing calculations. (Birrer and Amara 2018, Birrer et al. 2021)

- **PyHalo**: Generates populations of dark matter halos and profiles along the line of sight and in the main lens. (Gilman et al. 2022)

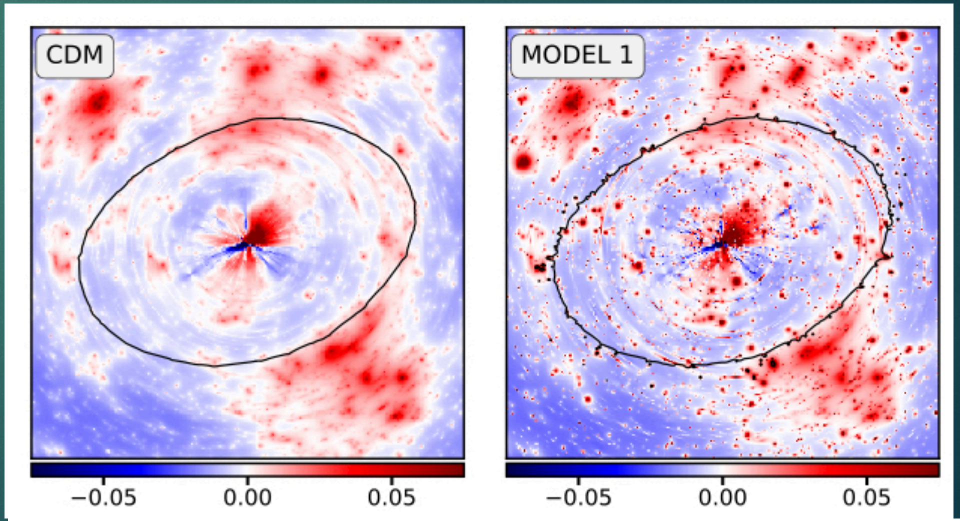


Many dark matter models tested

- SIDM with resonance (Gilman et al. 2022)
- Fuzzy dark matter (Laroche et al. 2023)
- Primordial power spectrum (Gilman et al. 2022)
- Primordial black hole dark matter (Dike et al. 2022)
- Four different sterile neutrino models (Zelko et al. 2022)



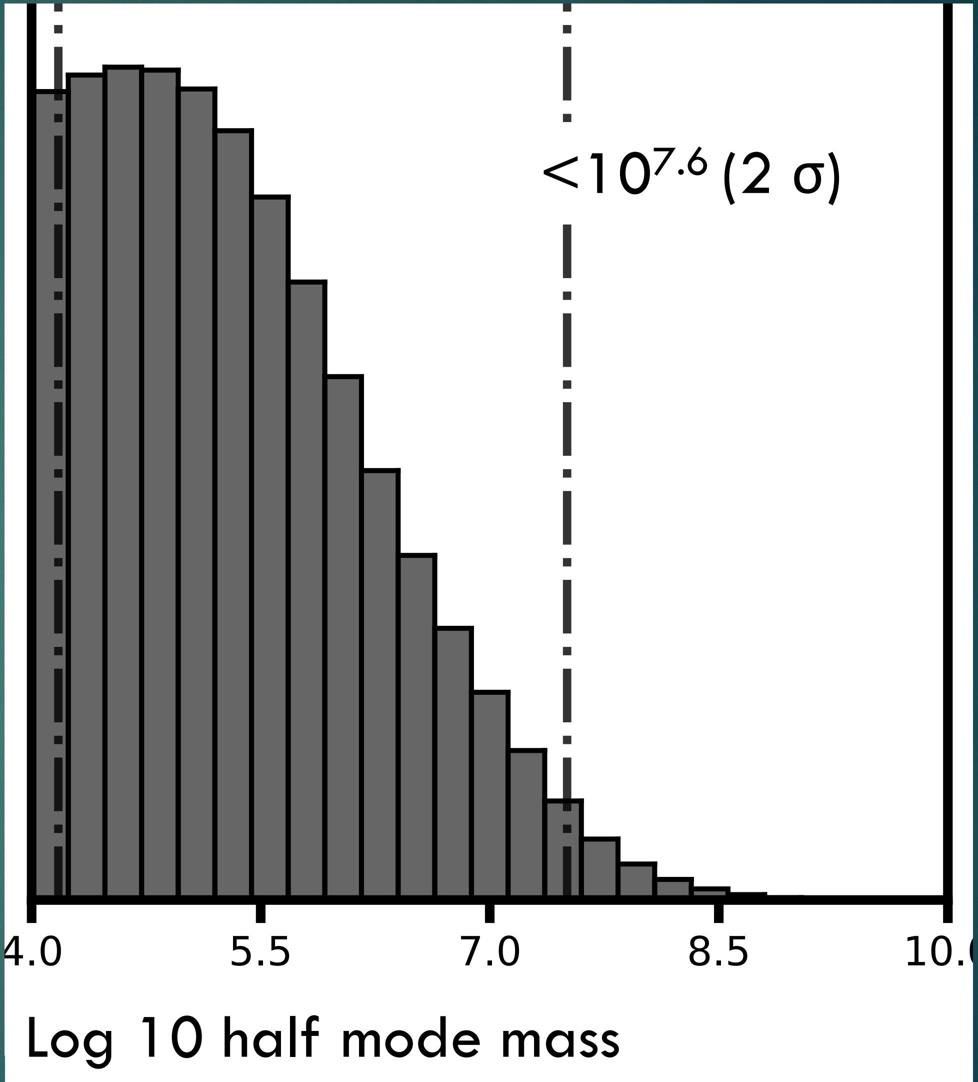
Dike et al. 2022



Gilman et al. 2022

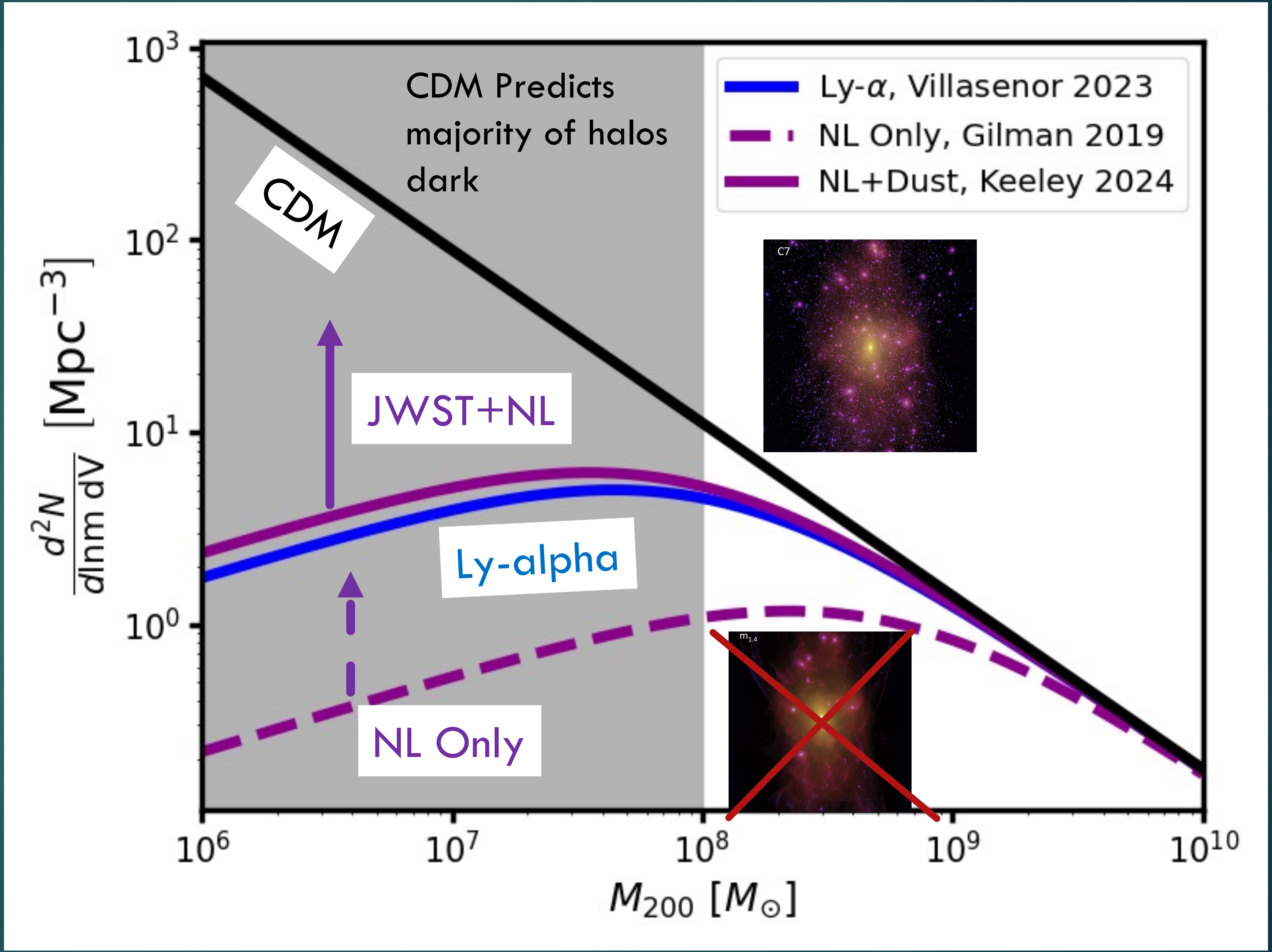
Results from 14 lenses JWST+HST+Keck

Keeley, Nierenberg, et al. 2024



JWST: 9 of 31 Lenses GO-2046 (PI Nierenberg)
HST: GO 15177, 13732 (PI Nierenberg)

Comparison with other studies



Results from full sample of 31 JWST lenses coming soon…

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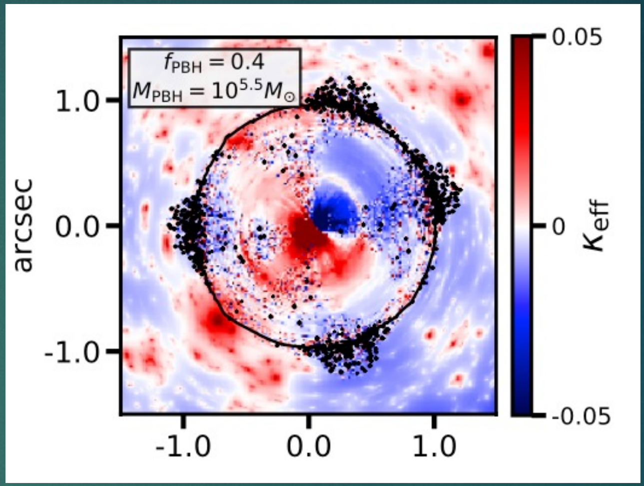
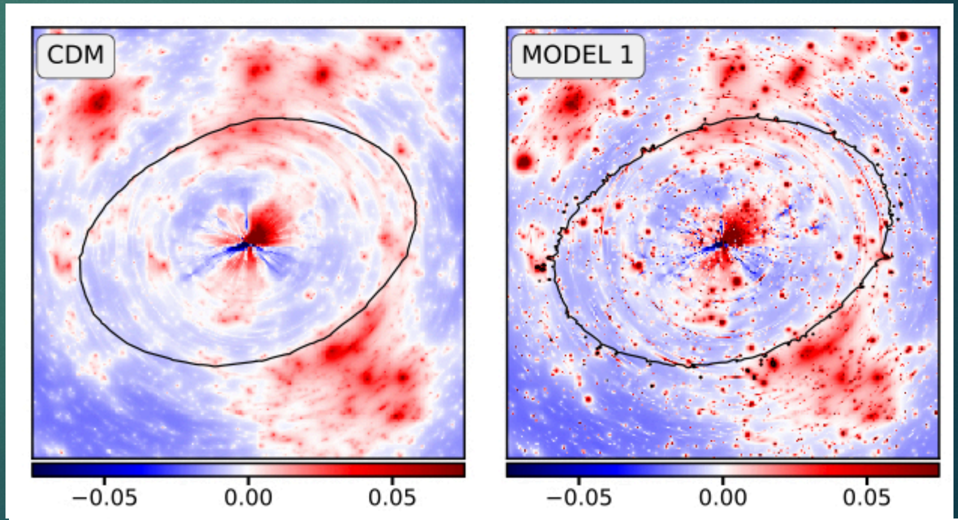


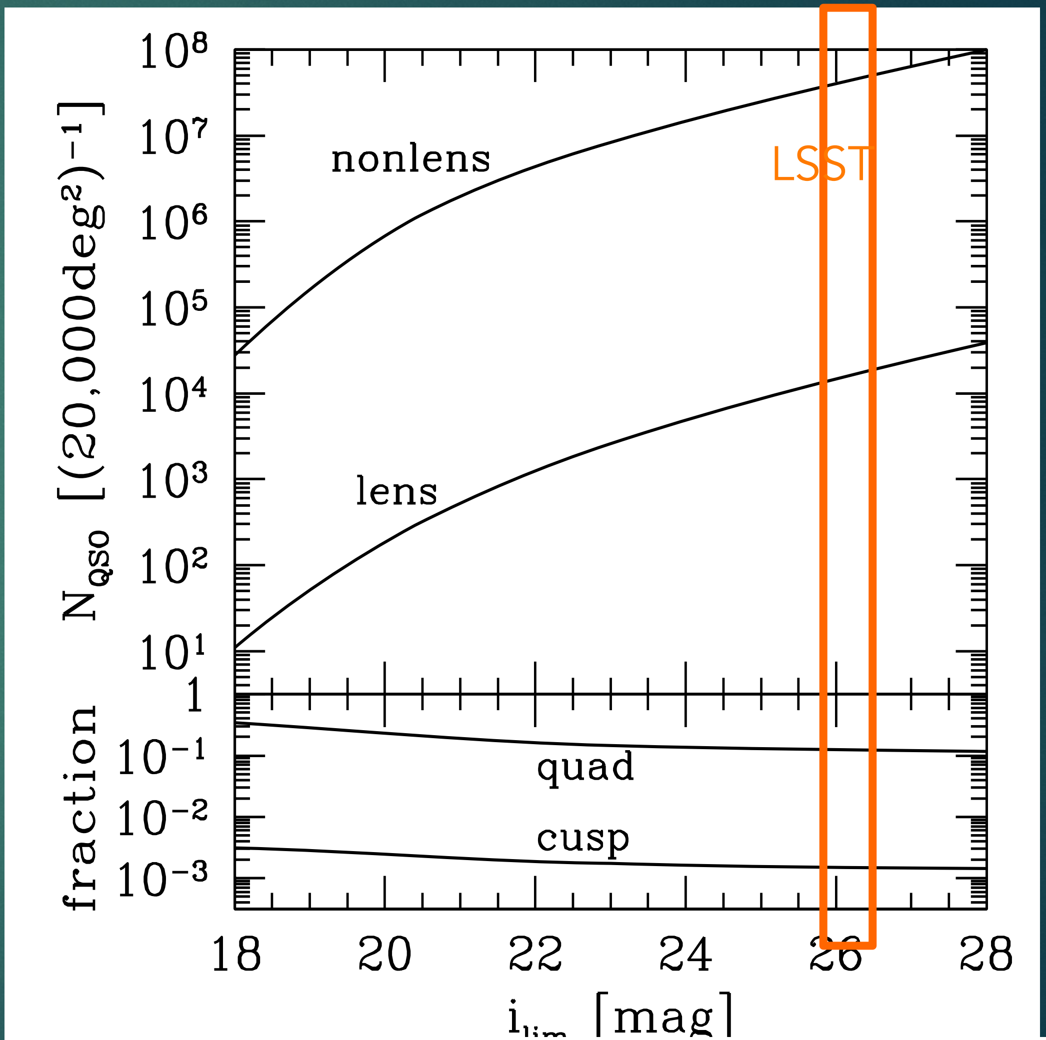
Dike et al. 2022



Gilman et al. 2022

Thousands of quadruply imaged quasars will be detectable in LSST Euclid and Roman

- ~200 easily accessible in the next 5 years with current facilities on Keck
- Next generation instruments/observatories will let us measure dark matter in thousands.

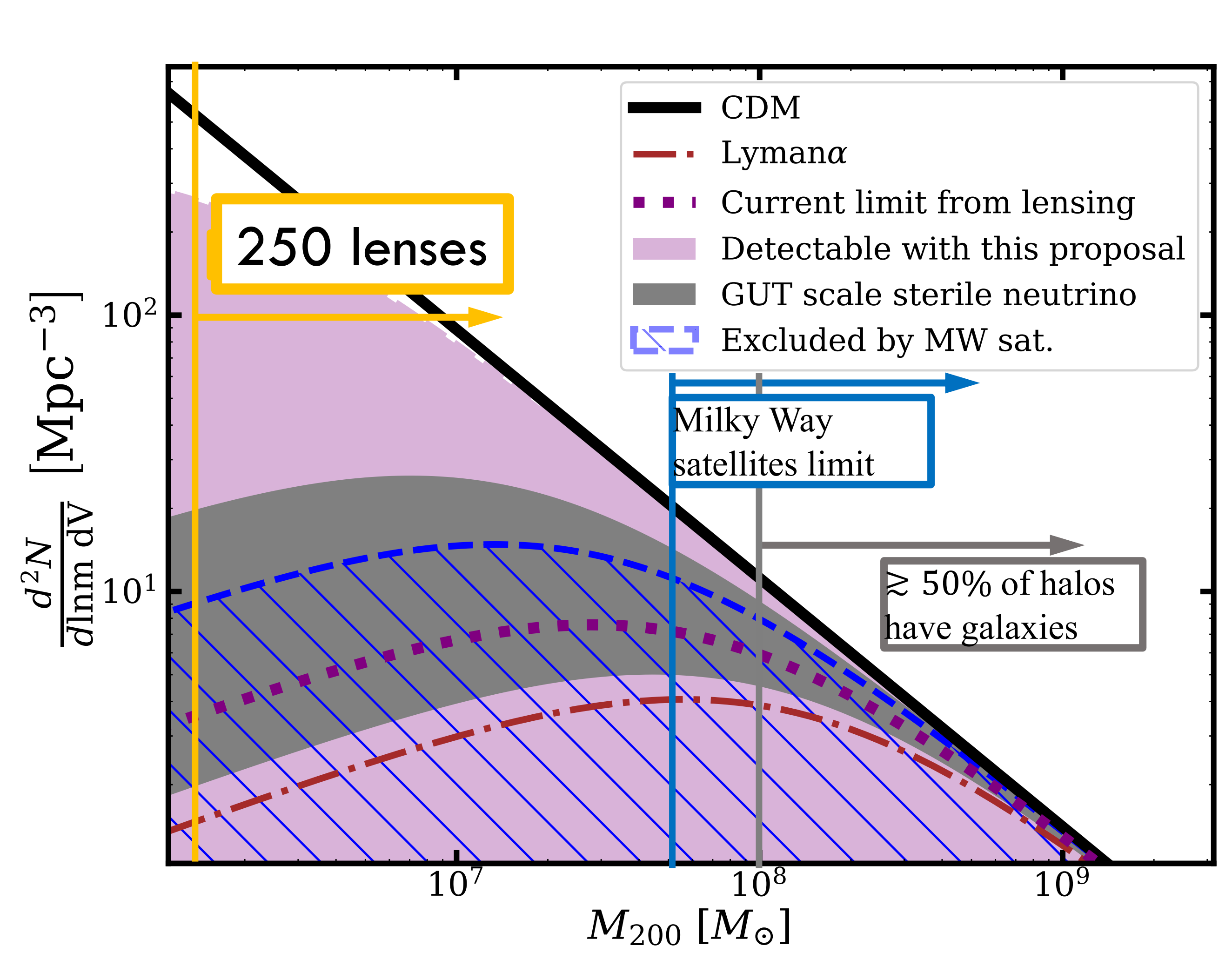


Oguri and Marshall 2010

The near future: hundreds of lenses with Keck OSIRIS

Time scale ~5 years for lenses discovered in Euclid+LSST.

Follow up ~6 nights per semester can do 250 lenses from Keck over the next 5 years

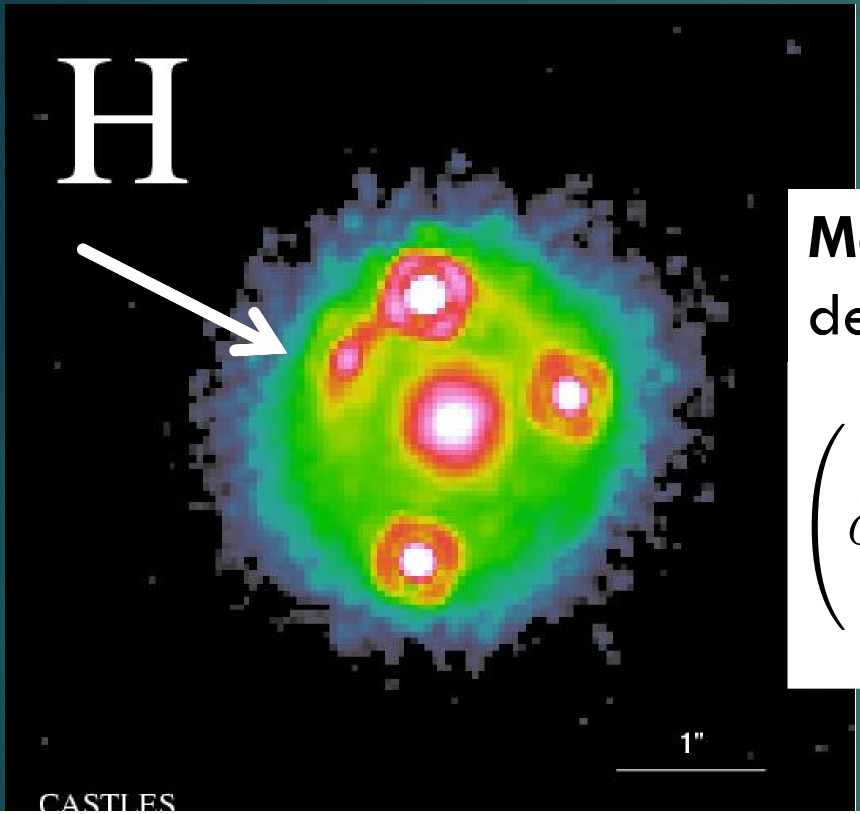


How can micro-arcsecond astrometry help us?

- Better constraints on deflector macromodel.
- High precision microlensing tracking.

Macromodel-mass distribution of main lens halo and galaxy

Observed lens



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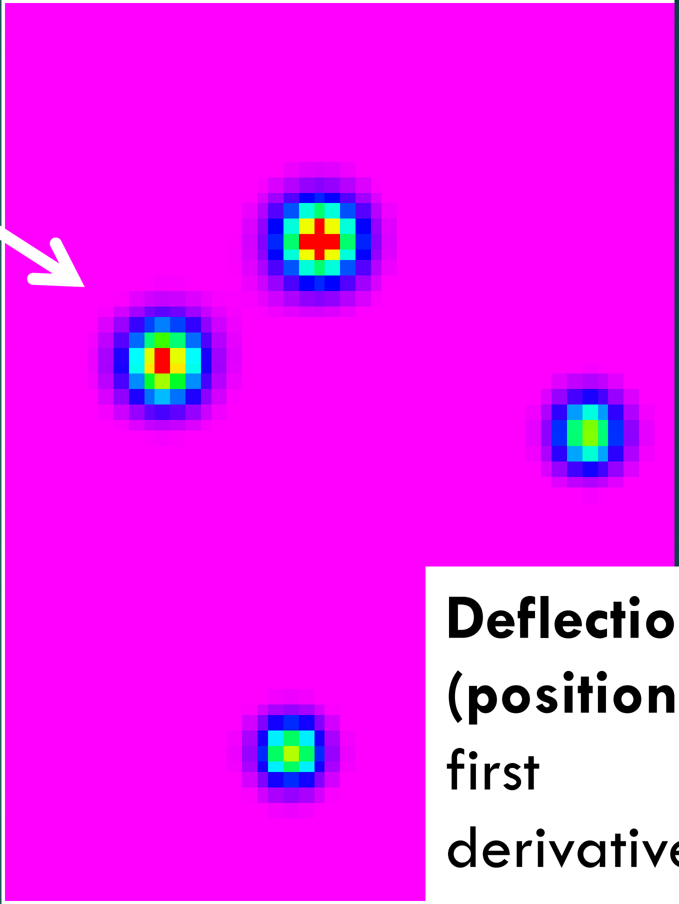

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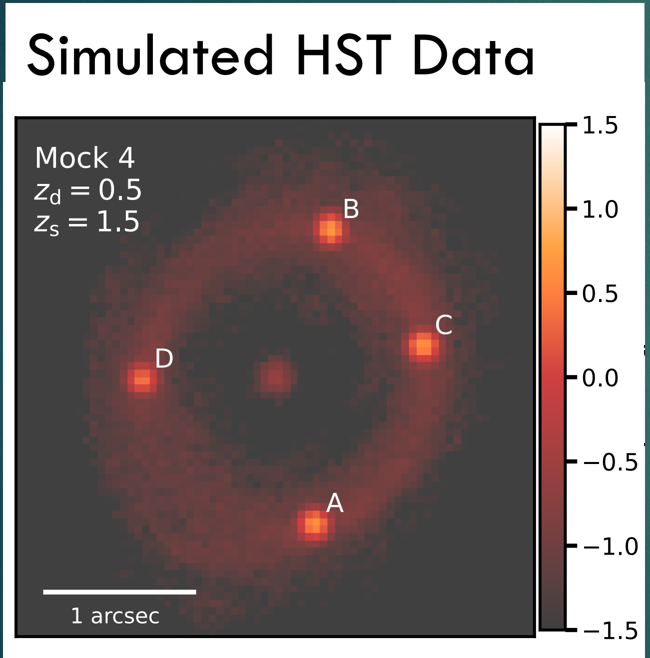
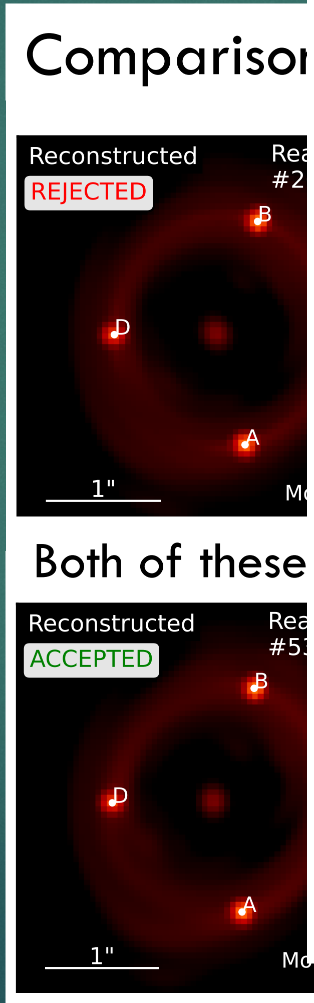
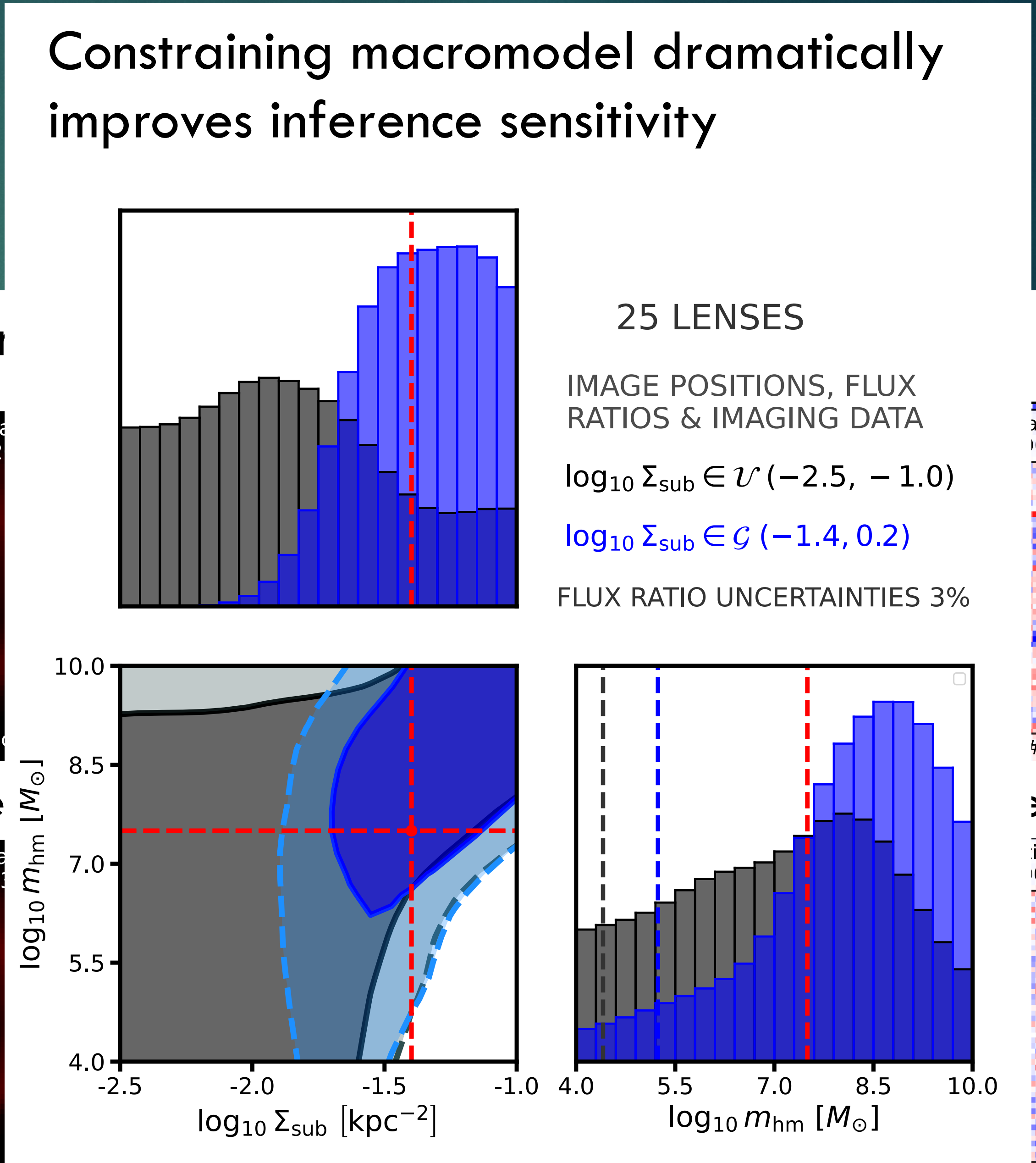
Deflector macromodel

Significant source of model uncertainty, can be well constrained with imaging of the quasar host galaxy.





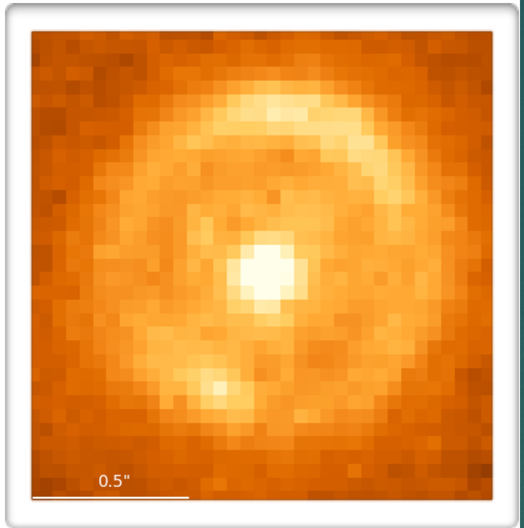


Gilman, Birrer, Nierenberg, Oh (2024)

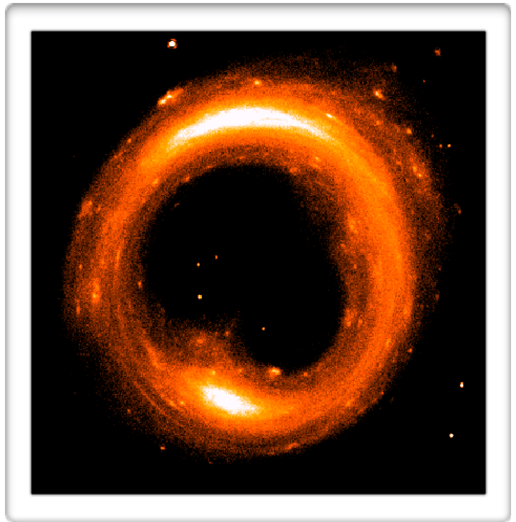
The future – Macromodel constraints with astrometry

- Higher resolution imaging (e.g. Habitable Worlds Observatory) yields better macromodel constraints

- Subhalos can introduce >10 mas perturbations to image positions (current precision is ~5-10 mas), however large degeneracy with macromodel, esp. if using only point source positions (Chen et al. 2007)



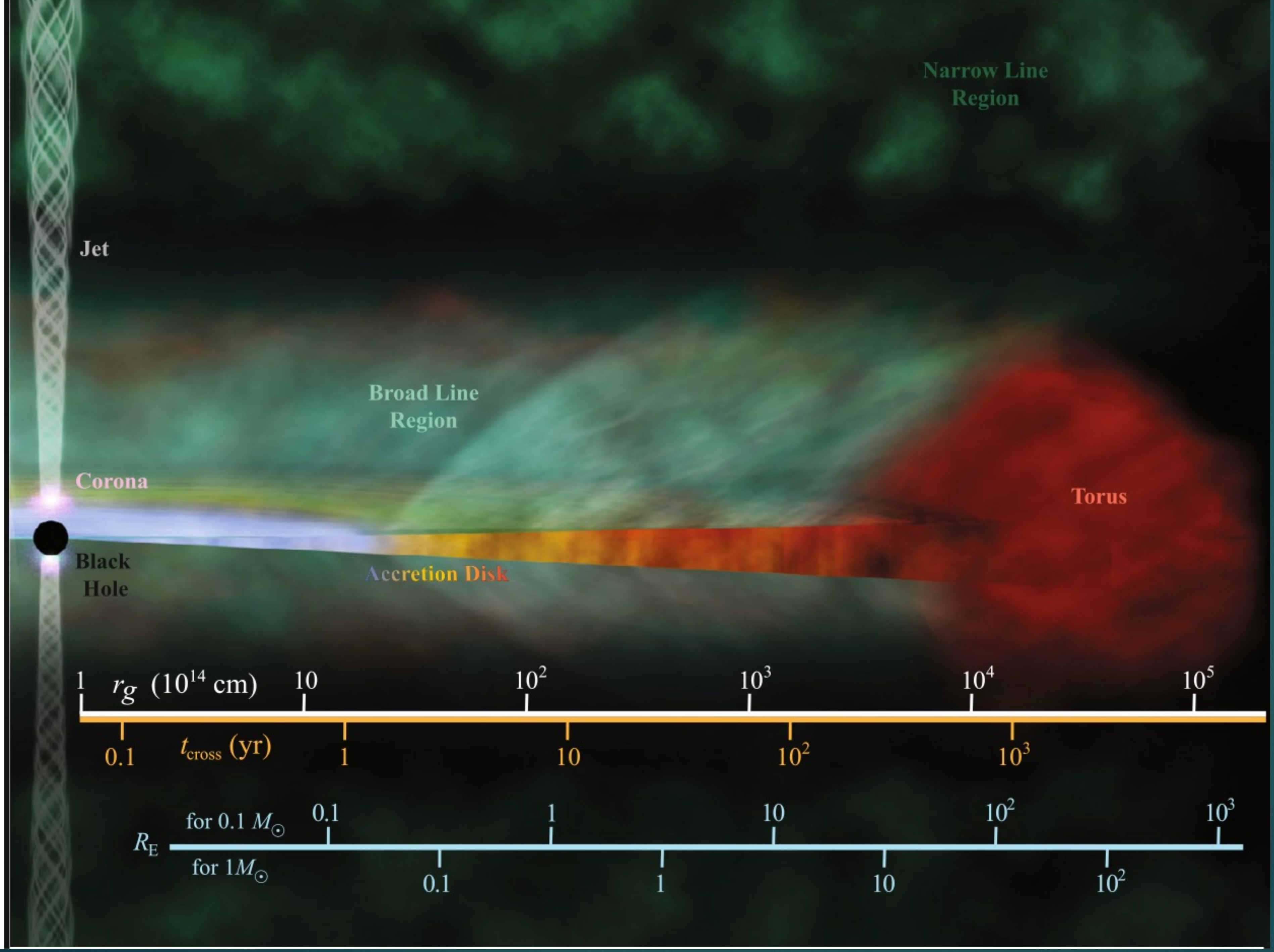
HST



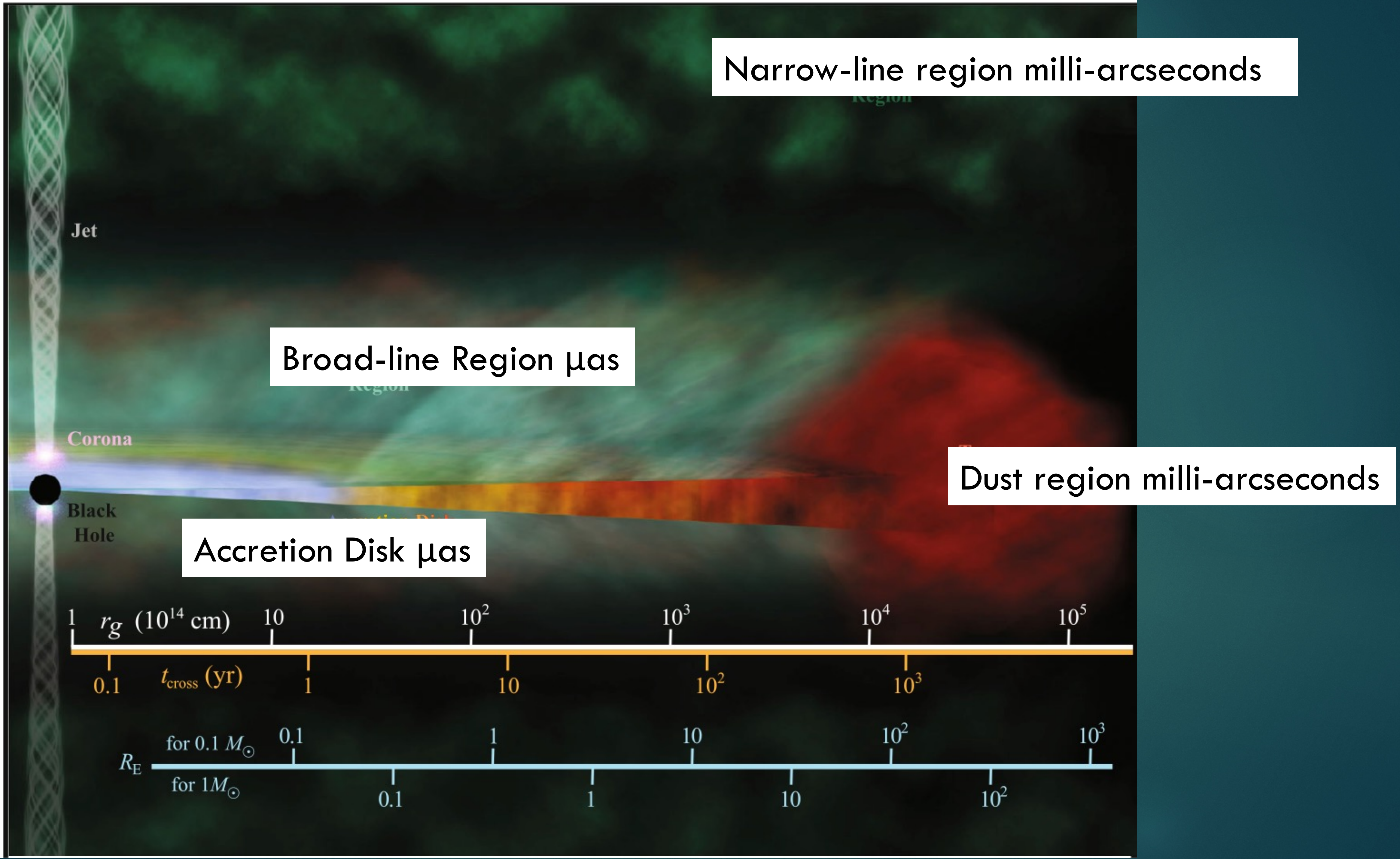
E-ELT

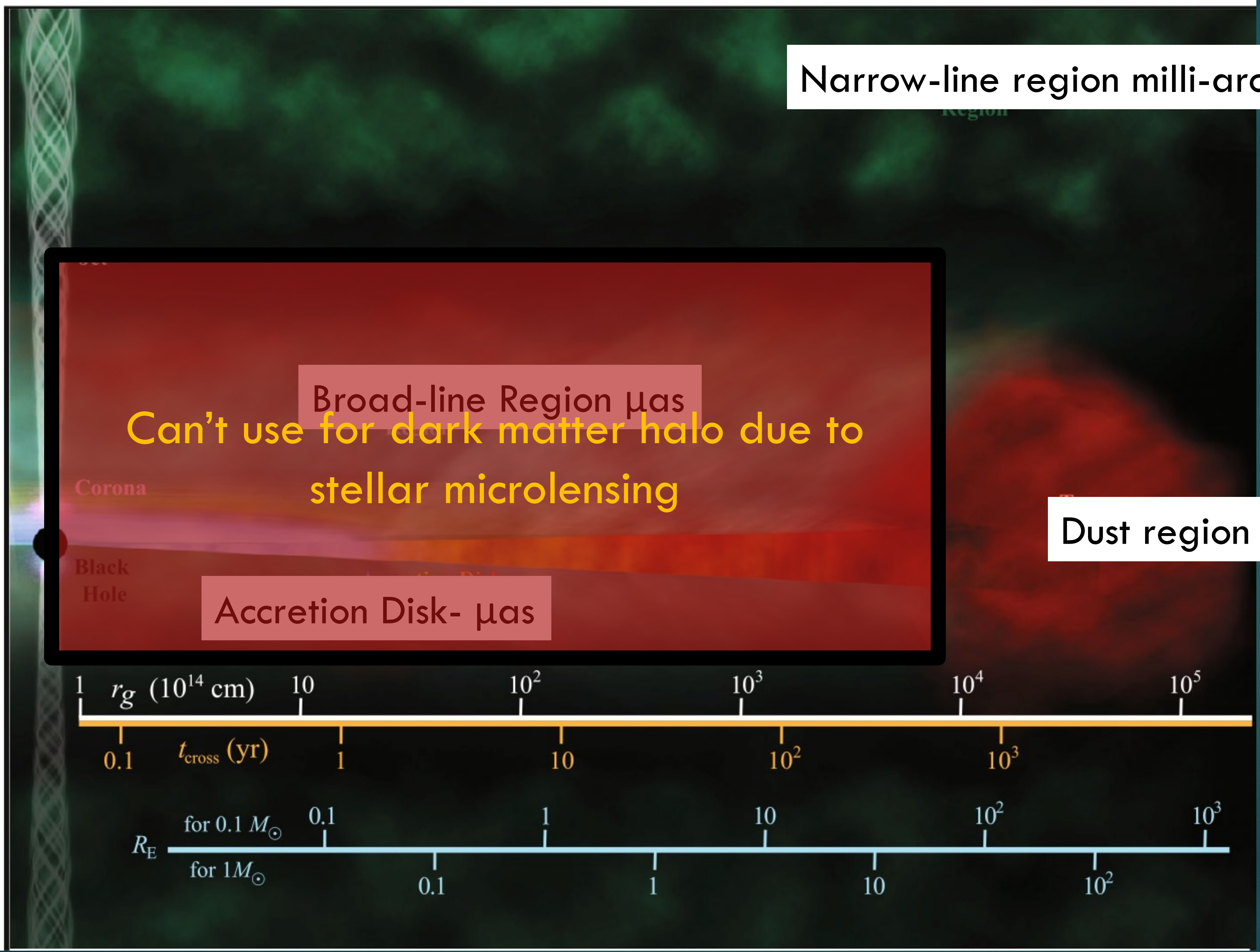
Simulation by Simona Vegetti

CAVEAT: need to be cautious about wavelength



The future II: Time variable astrometry to measure microlensing


Narrow-line region milli-arcseconds
Jet
Broad-line Region µas
Corona
Dust region milli-arcseconds
Black
Hole
Accretion Disk µas
1 r_g (10^{14} cm) 10 10^2 10^3 10^4 10^5
0.1 t_{cross} (yr) 1 10 10^2 10^3
R_E
for 0.1 $M_\odot$ 0.1 1 10 10^2 10^3
for 1$M_\odot$ 0.1 1 10 10^2



Narrow-line region milli-arcseconds

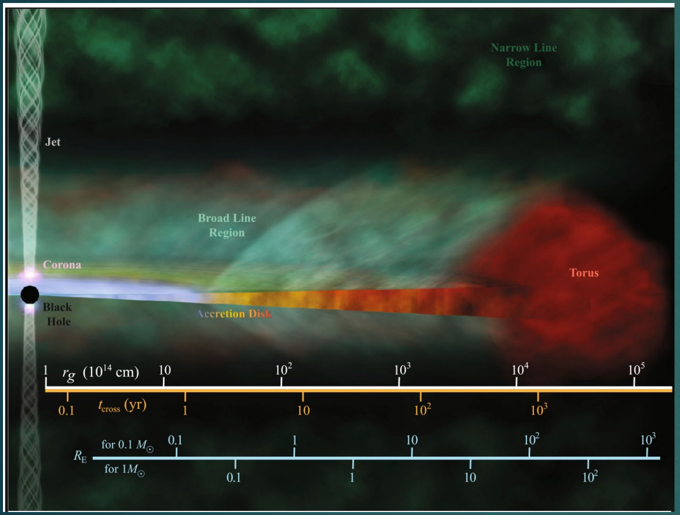
Broad-line Region μas

Can't use for dark matter halo due to stellar microlensing

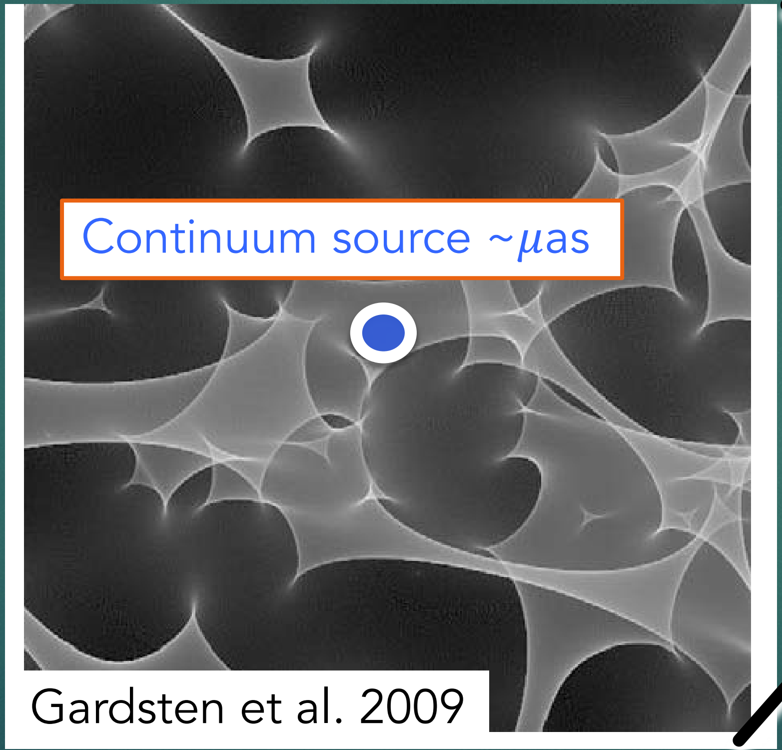
Dust region milli-arcseconds

Accretion Disk- μas

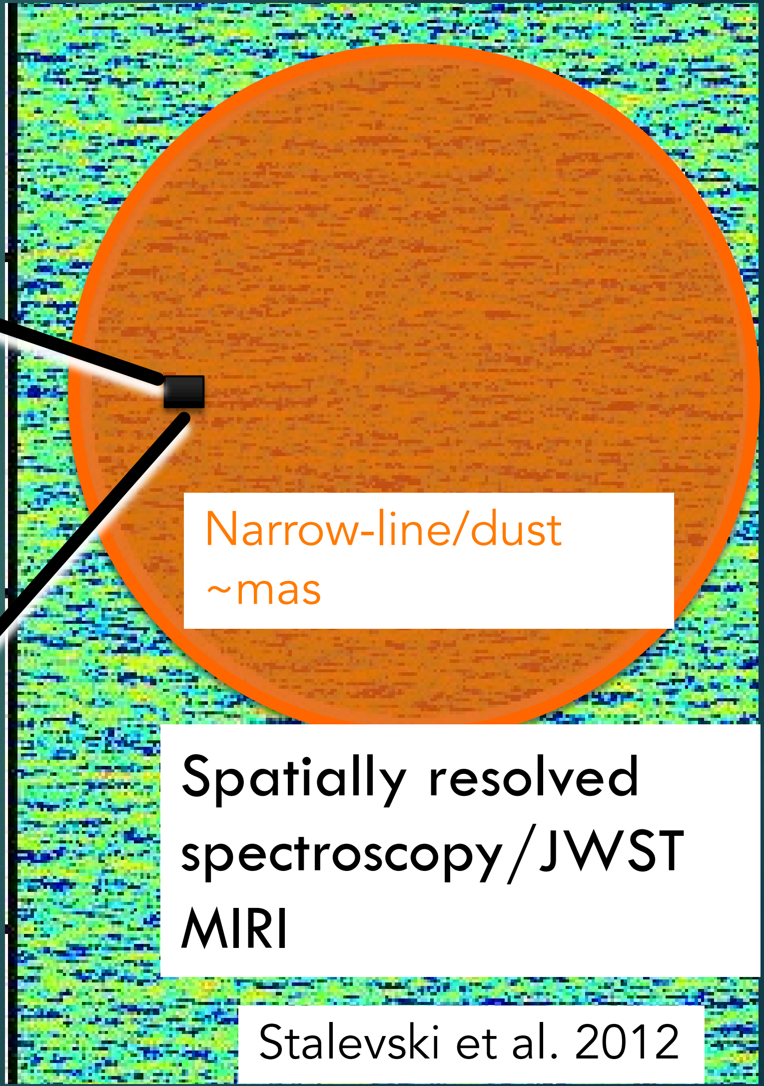
Microlensing – micro-arcsecond perturbations to a gravitational lens



Magnification due to stars in the lens galaxy

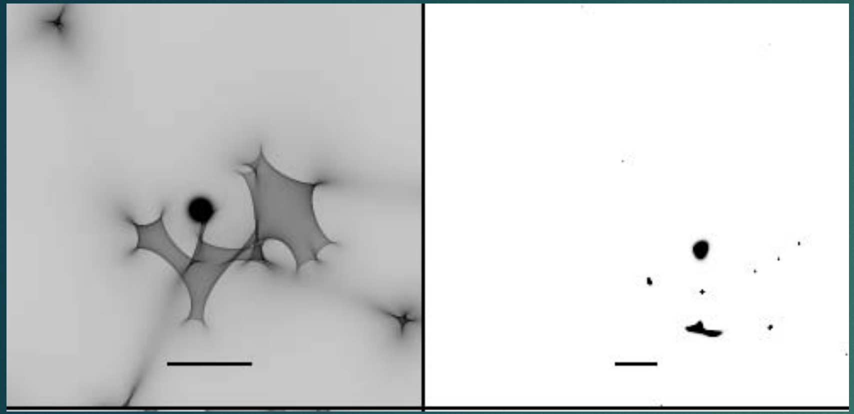


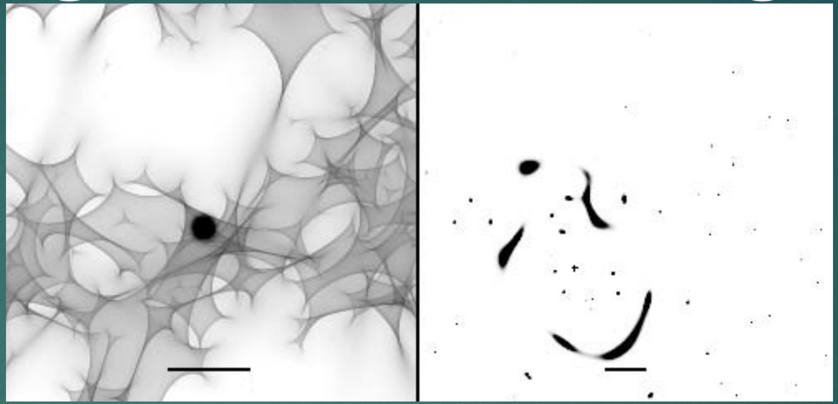
Gardsten et al. 2009

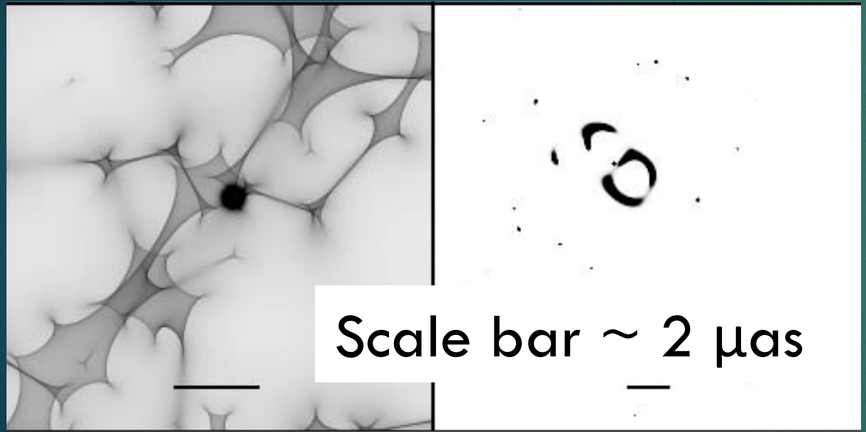


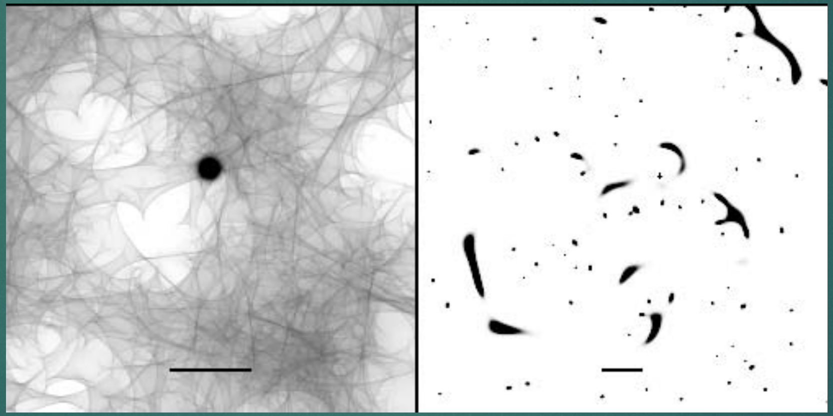
Stalevski et al. 2012

Quasar microlensing-with ultra-high resolution



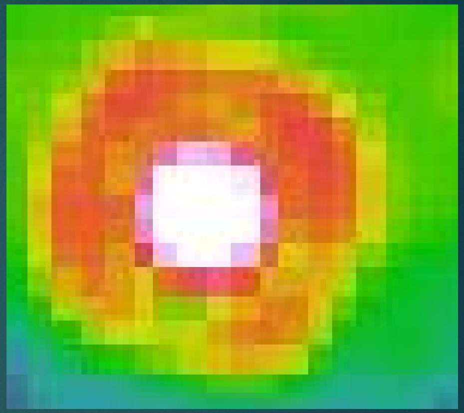






Scale bar ~ 2 μas

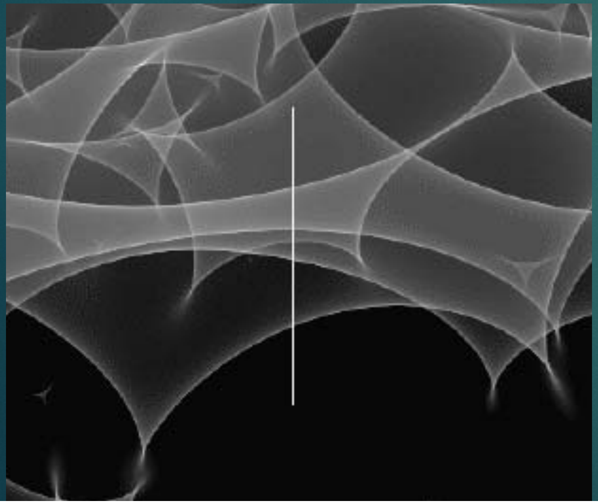
Treyer and Wambsganss 2003



What we see with 100 milli-arcsecond FWHM PSF

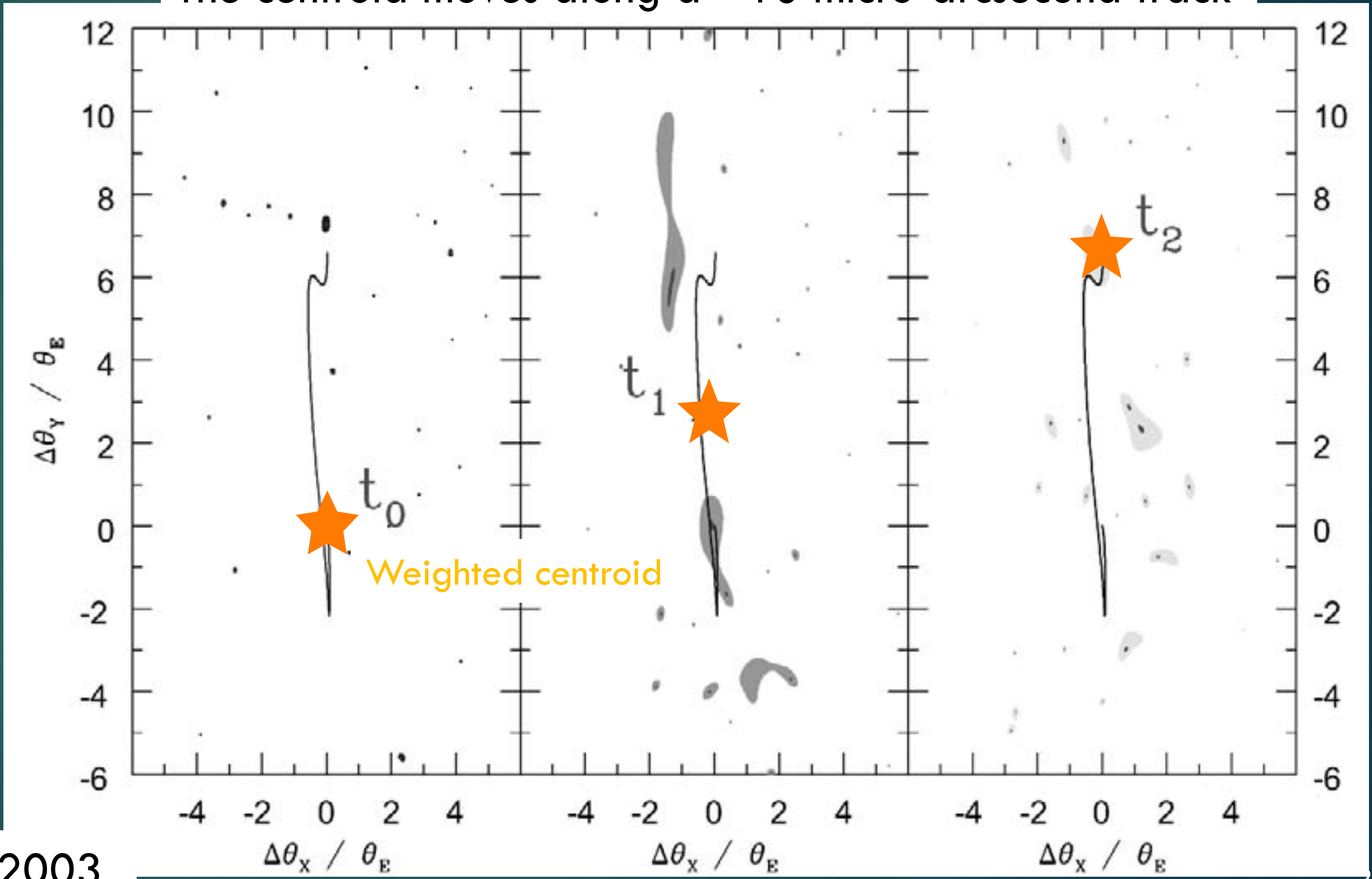
Microlensing is time variable

Given typical lens and quasar relative velocities, the source centroid will travel ~2 micro arcseconds in ~10 years



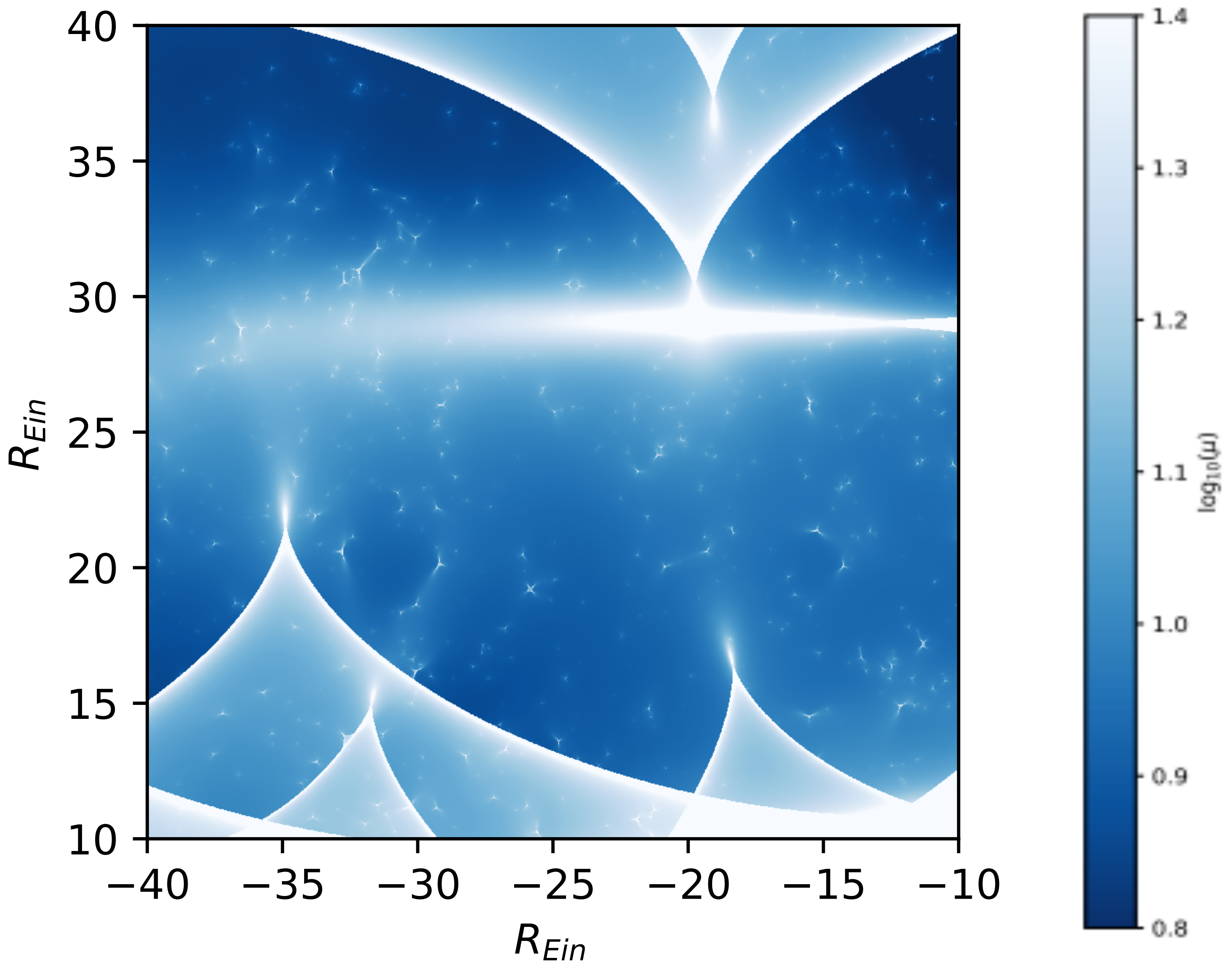
Treyer and Wambsganss 2003

The centroid moves along a ~10 micro-arcsecond track



Tracking quasar image positions over time could potentially yield an extremely high precision measurement of the microlens population, enabling novel constraints on primordial black hole dark matter.

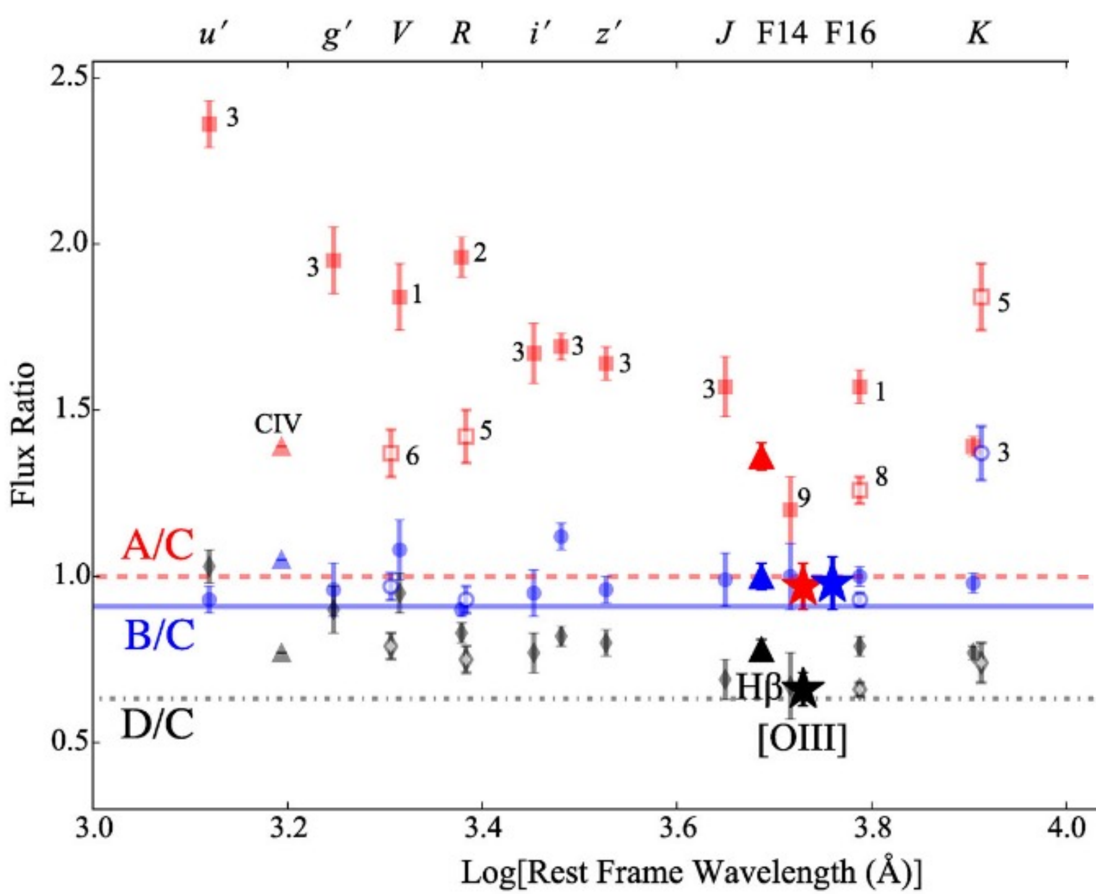
Clustered PBH dark matter



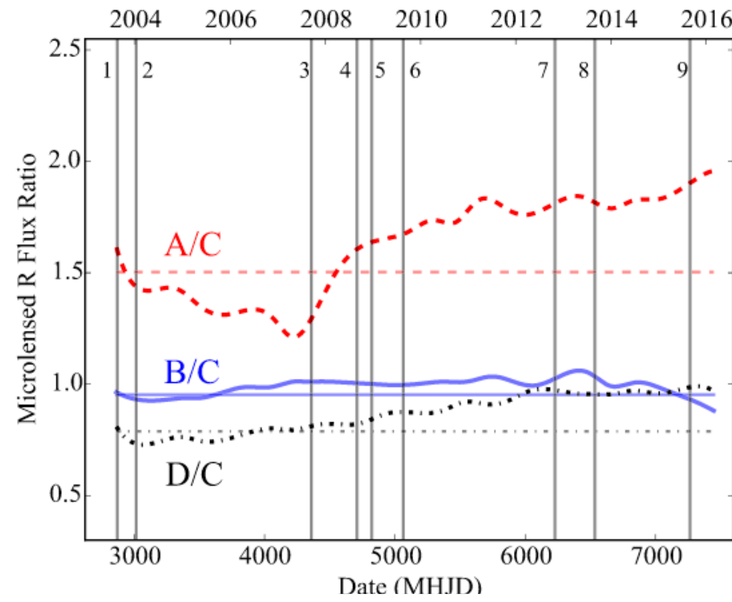
Jimenez-Vicente and Mediavilla 2022

Using time position variation to distinguish between microlensing and intrinsic variability

- Spatial variations will depend on intrinsic source size as well as the population of microlenses
- Microlensing can be used as a sensitive probe of primordial black hole populations
- Would need to measure centroid in a narrow wavelength range



Nierenberg et al. 2017



Estimate of microlensing from time delay measurements alone

Conclusions: High precision astrometry can significantly improve measurements of dark matter with gravitationally lensed quasars

- Improved constriants of the large-scale mass distribution of the deflector
- New constraints of quasar structure
- Time variable centroid mapping could yield new constraints on primordial black hole dark matter