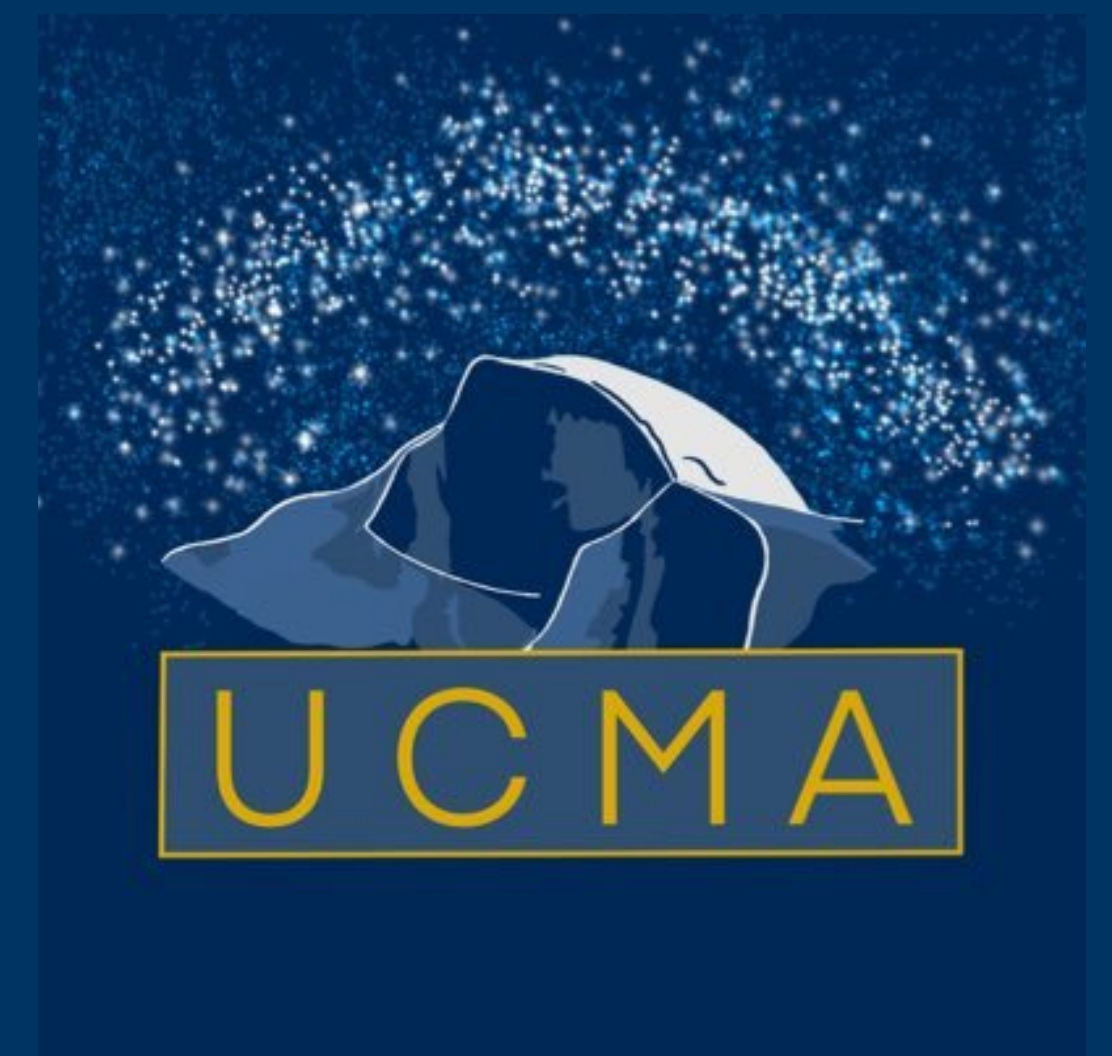


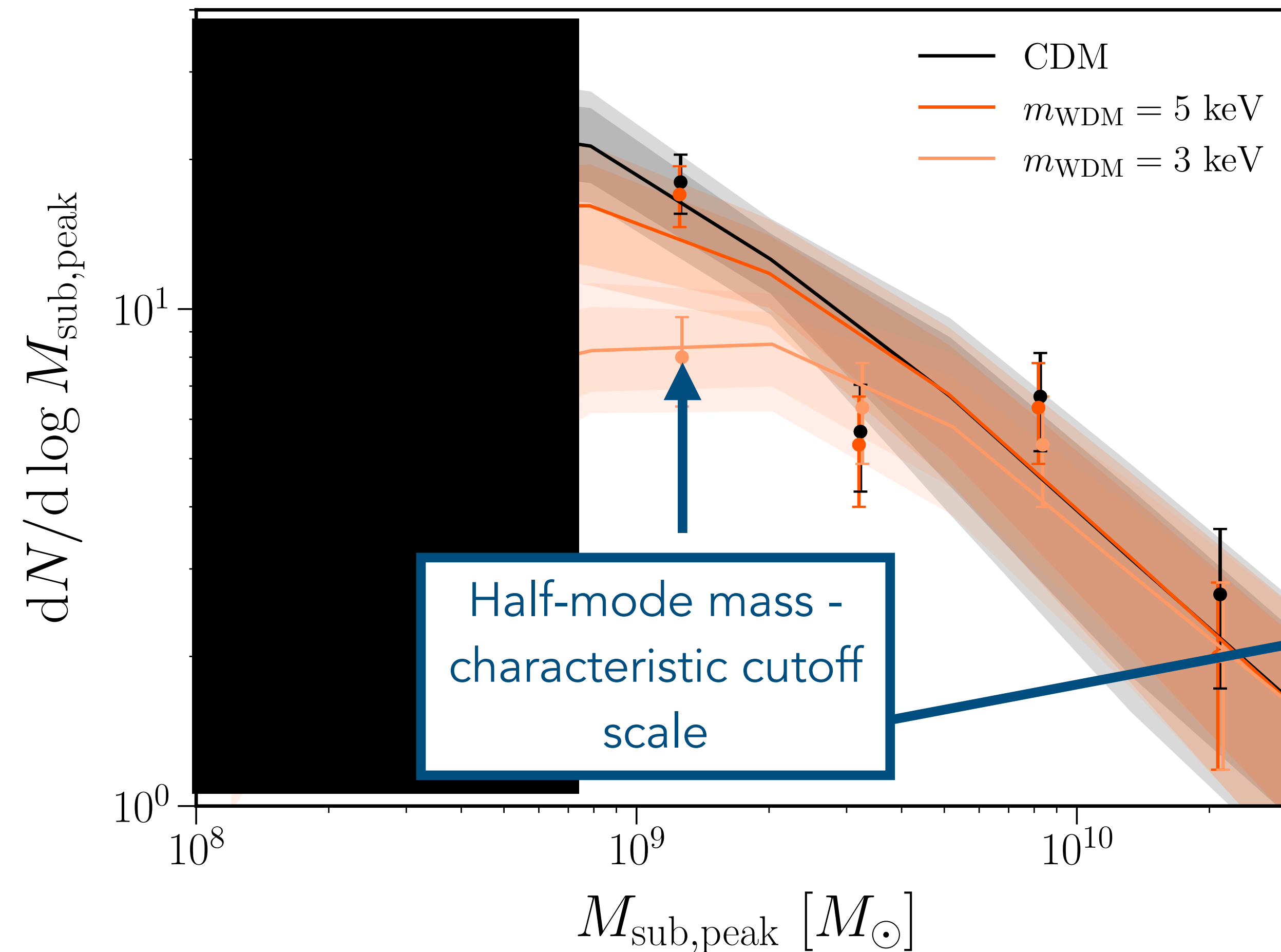
Measuring the properties of dark matter with strong gravitational lensing

CCAPP 20th Anniversary Conference

Anna Nierenberg, UC Merced



The halo mass function depends on dark matter model

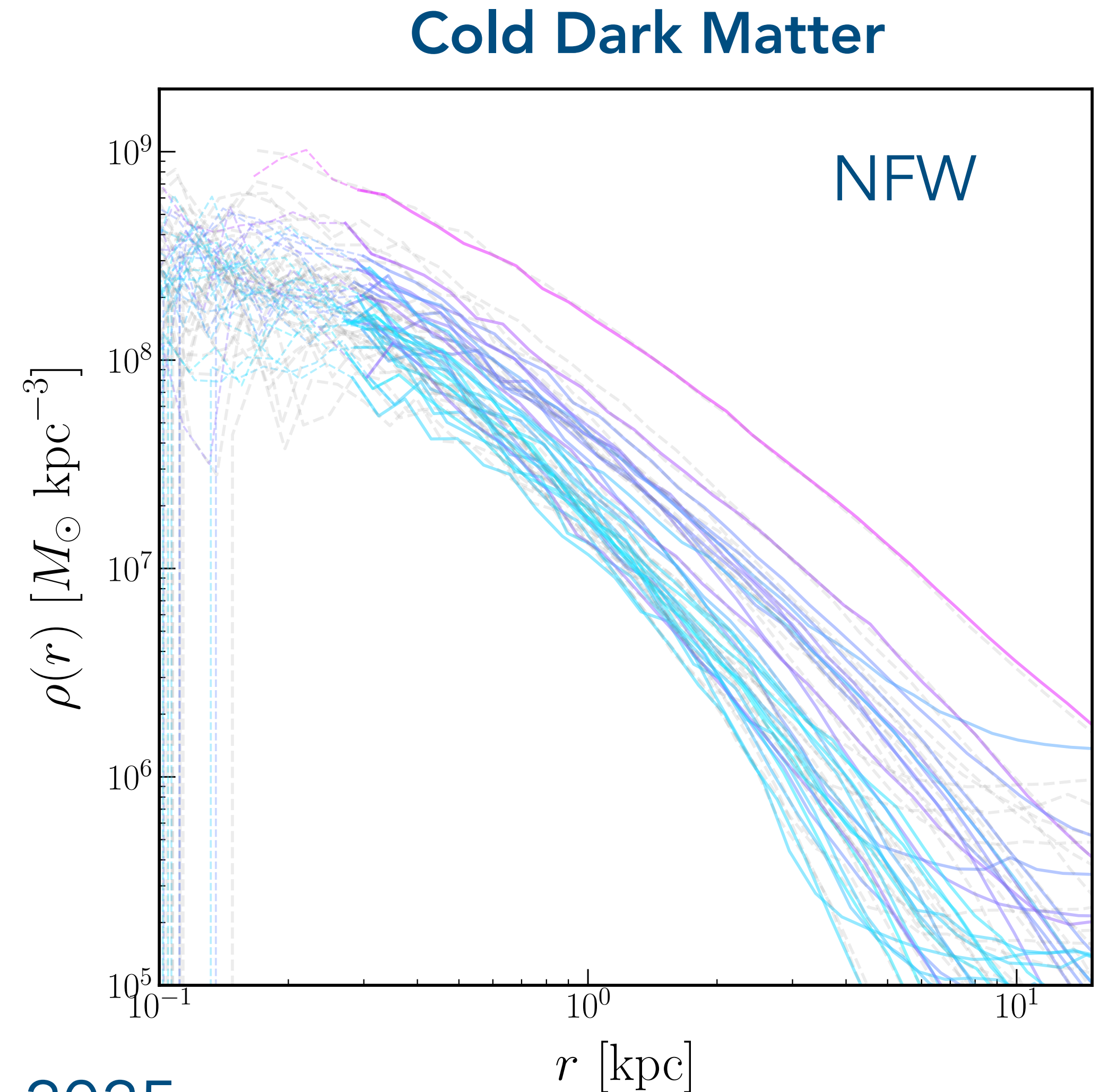
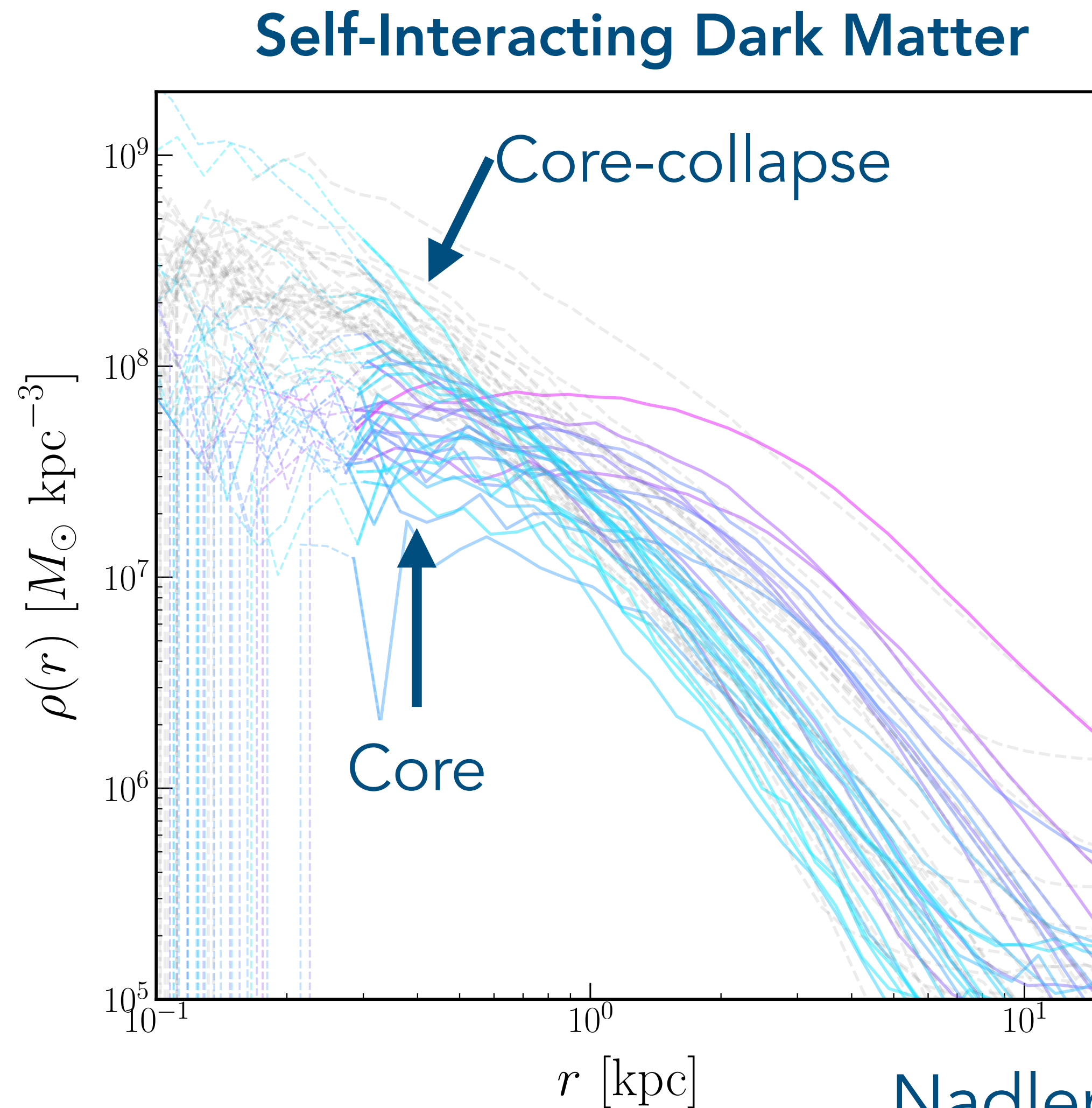


$$\frac{d^2 N_{\text{WDM}}}{dM dV} = \frac{d^2 N_{\text{CDM}}}{dM dV} f_{\text{WDM}}(M, M_{\text{hm}})$$

$$f_{\text{WDM}}(M, M_{\text{hm}}) = \left(1 + \left(\alpha \frac{M_{\text{hm}}}{M} \right)^{\beta} \right)^{\gamma}$$

Nadler et al. 2024

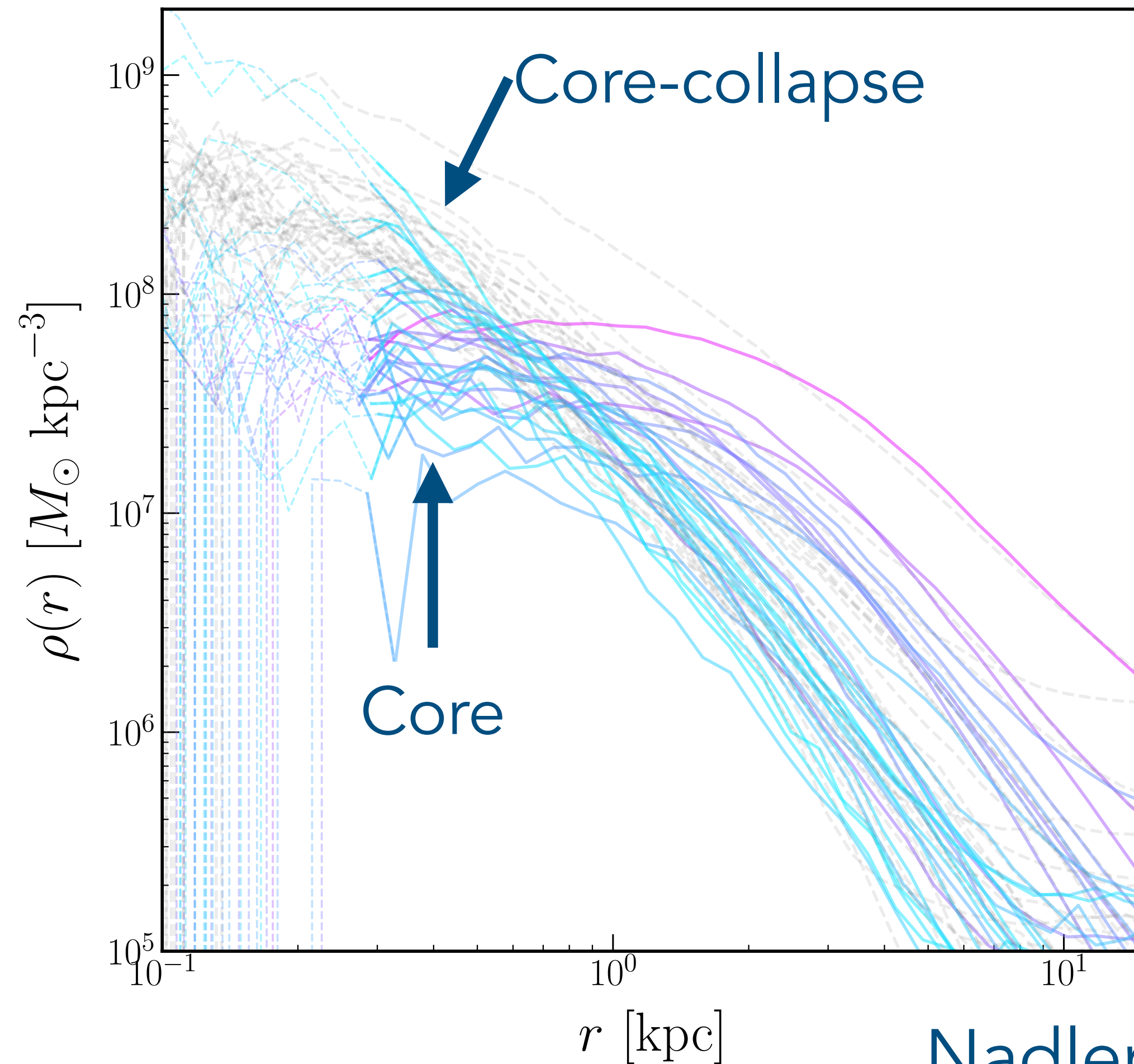
Halo density profiles depend on dark matter model



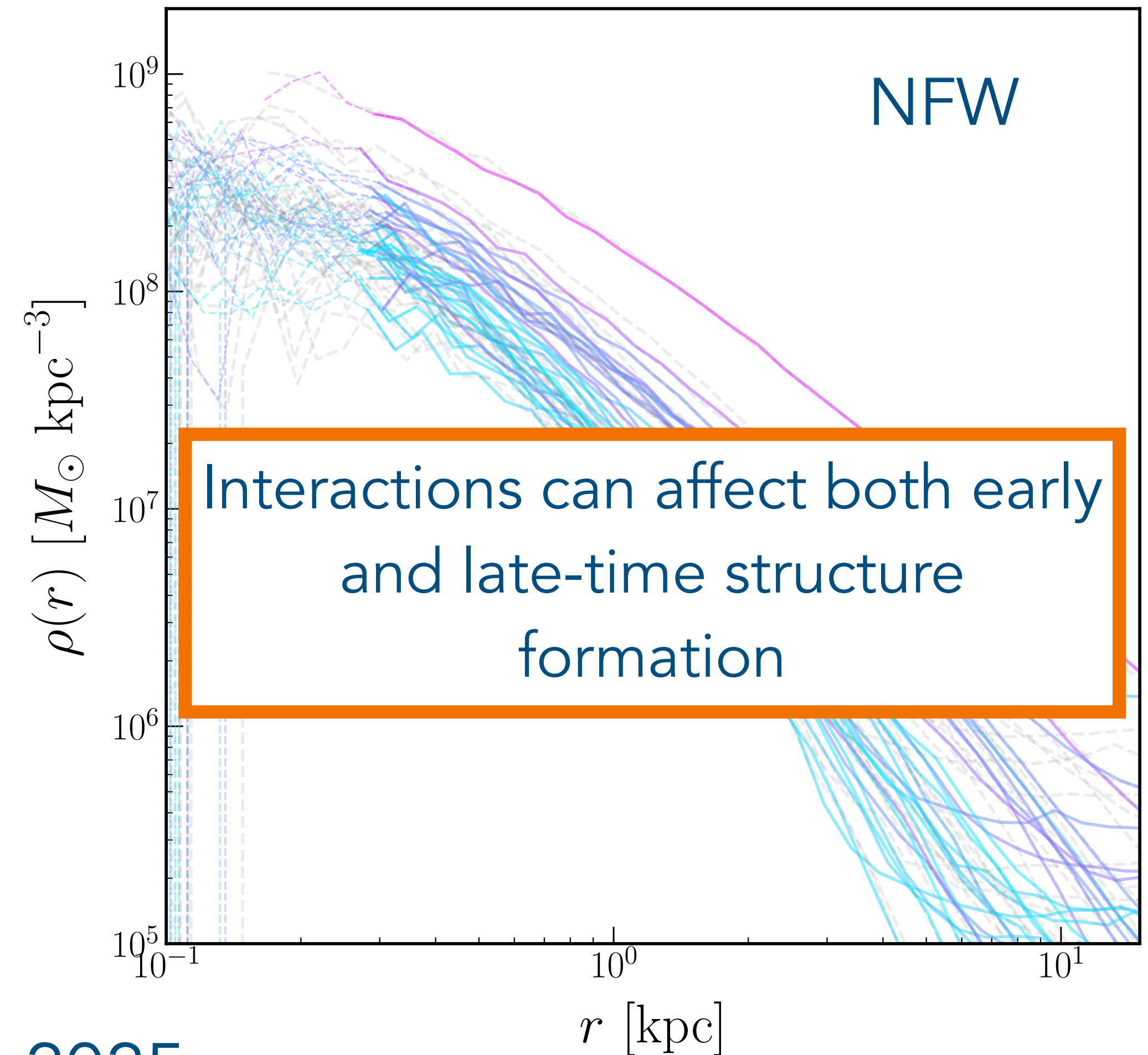
Nadler et al. 2025

Halo density profiles depend on dark matter model

Self-Interacting Dark Matter



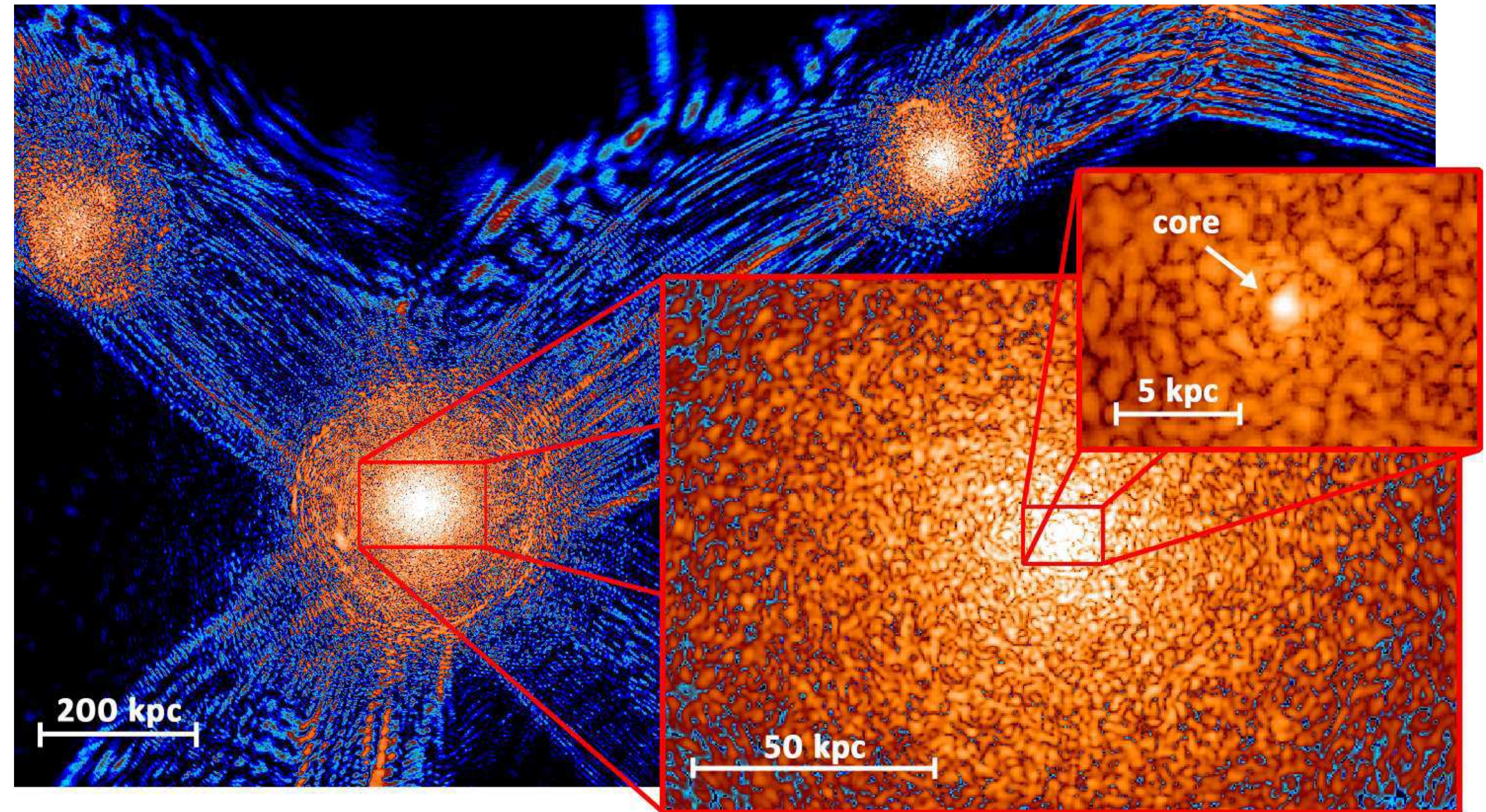
Cold Dark Matter



Nadler et al. 2025

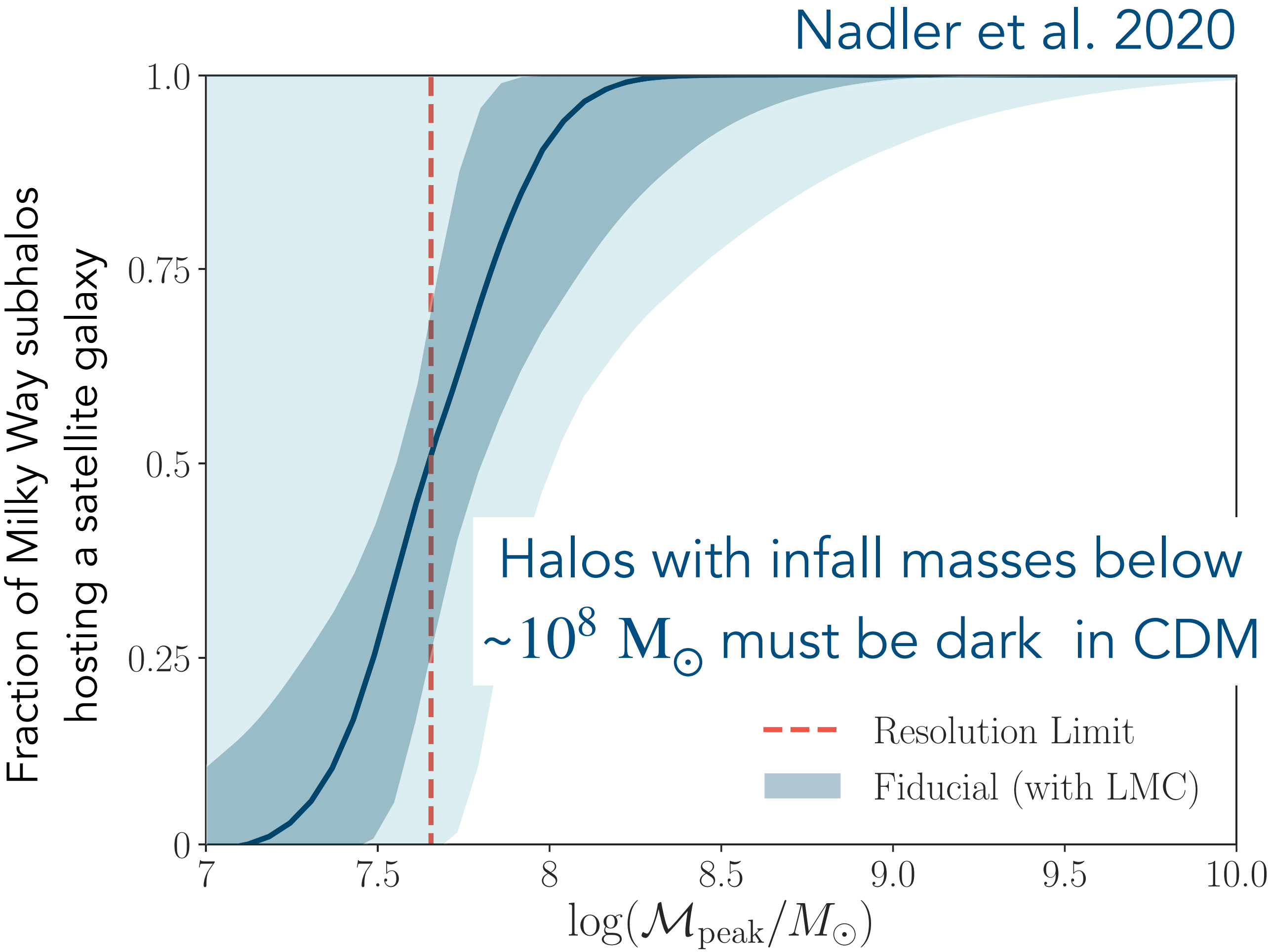
By measuring the properties of dark matter halos we can test different dark matter models

- *WIMPS
- *Sterile Neutrinos
- *Axions
- *Primordial Black Holes
- *Self-Interacting Dark Matter



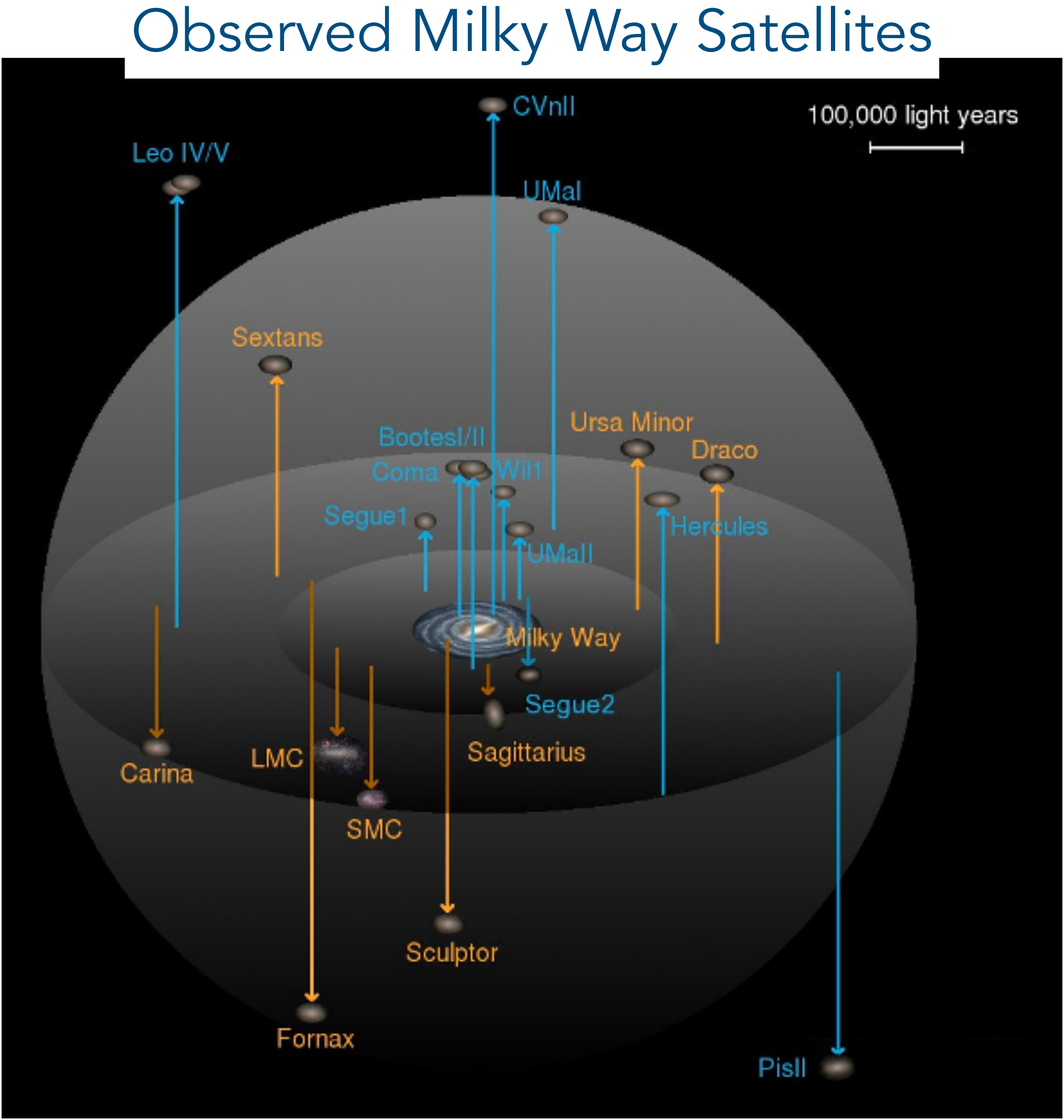
Schive et al. 2014

Traditional measurements of dark matter halos rely on galaxies as tracers



See also Kim, Peter and Hargis 2018

Credit: J.T.A. de Jong



The power of strong gravitational lensing



Credit NASA/ESA HST GO-15177, 13732 PI Nierenberg

The power of strong gravitational lensing

* Enables the measurement of density profiles and mass distribution of completely dark halos



Credit NASA/ESA HST GO-15177, 13732 PI Nierenberg

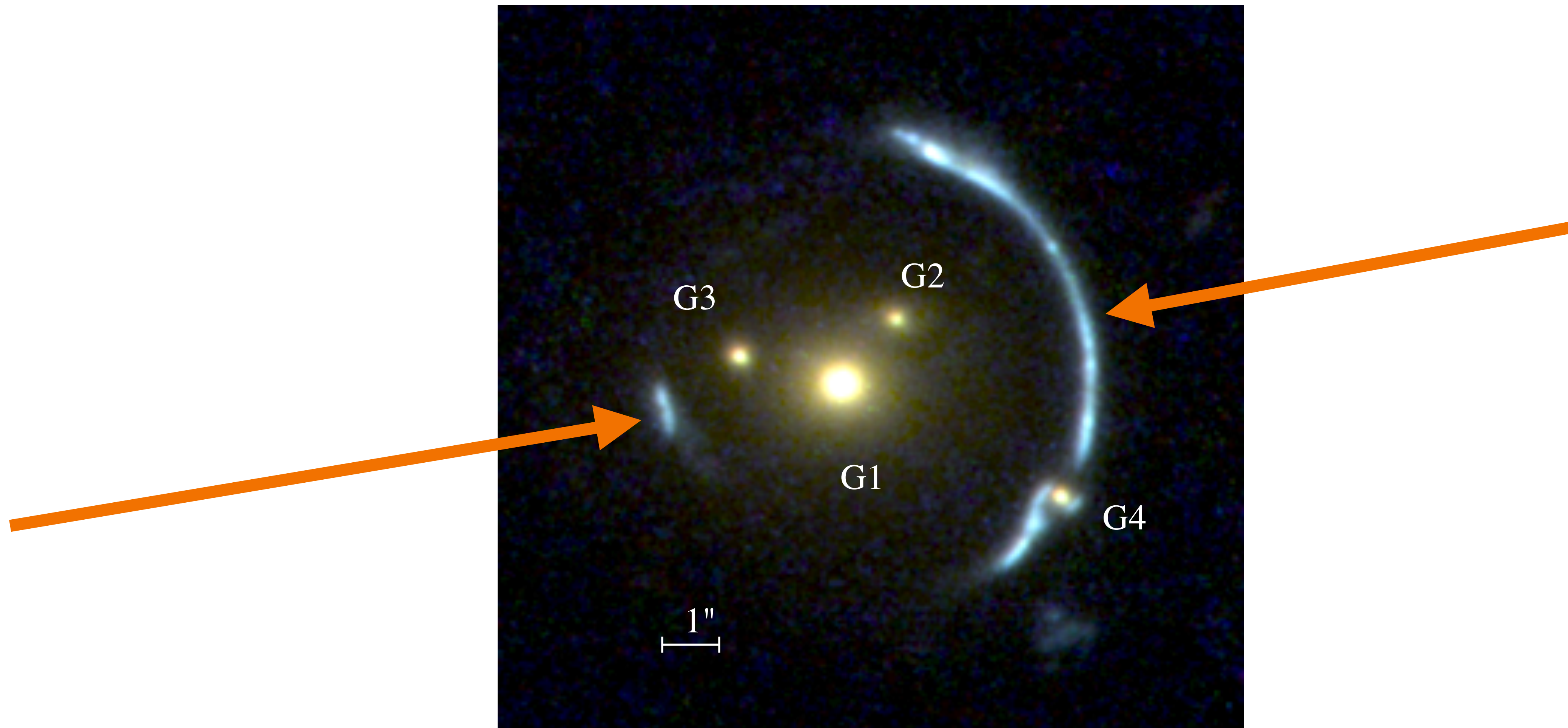
The power of strong gravitational lensing

- * Enables the measurement of density profiles and mass distribution of completely dark halos
- * Works over cosmological distances



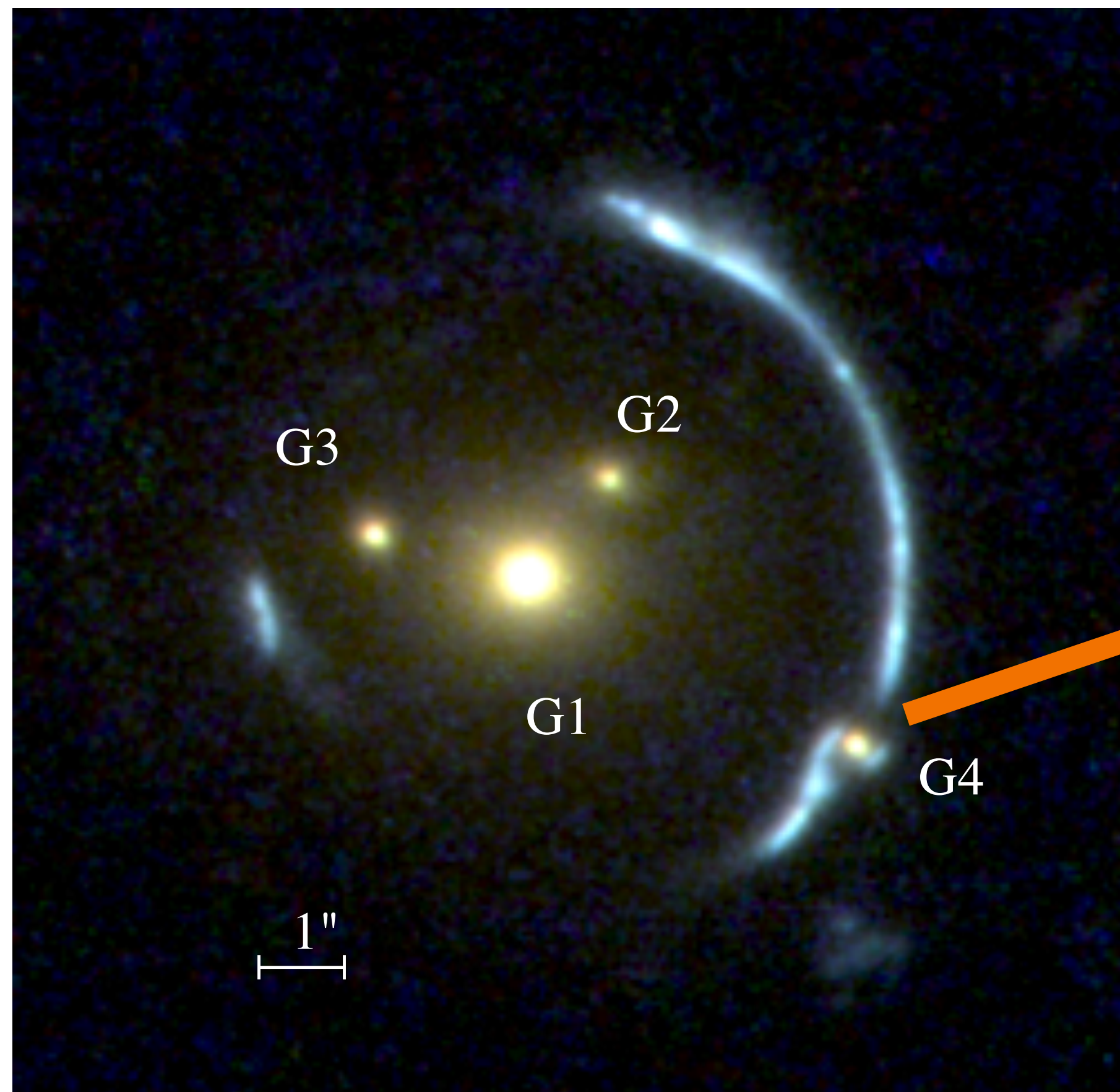
Credit NASA/ESA HST GO-15177, 13732 PI Nierenberg

Strong lenses have multiple images of one background source



Vegetti et al. 2010

Lensed images can be affected by dark matter halos



Vegetti et al. 2010



Low mass perturbers cause **deflections** and **magnifications** to lensed images

Effect of low-mass halos

Gravitational Potential

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

Deflection $\propto$ first
derivative

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

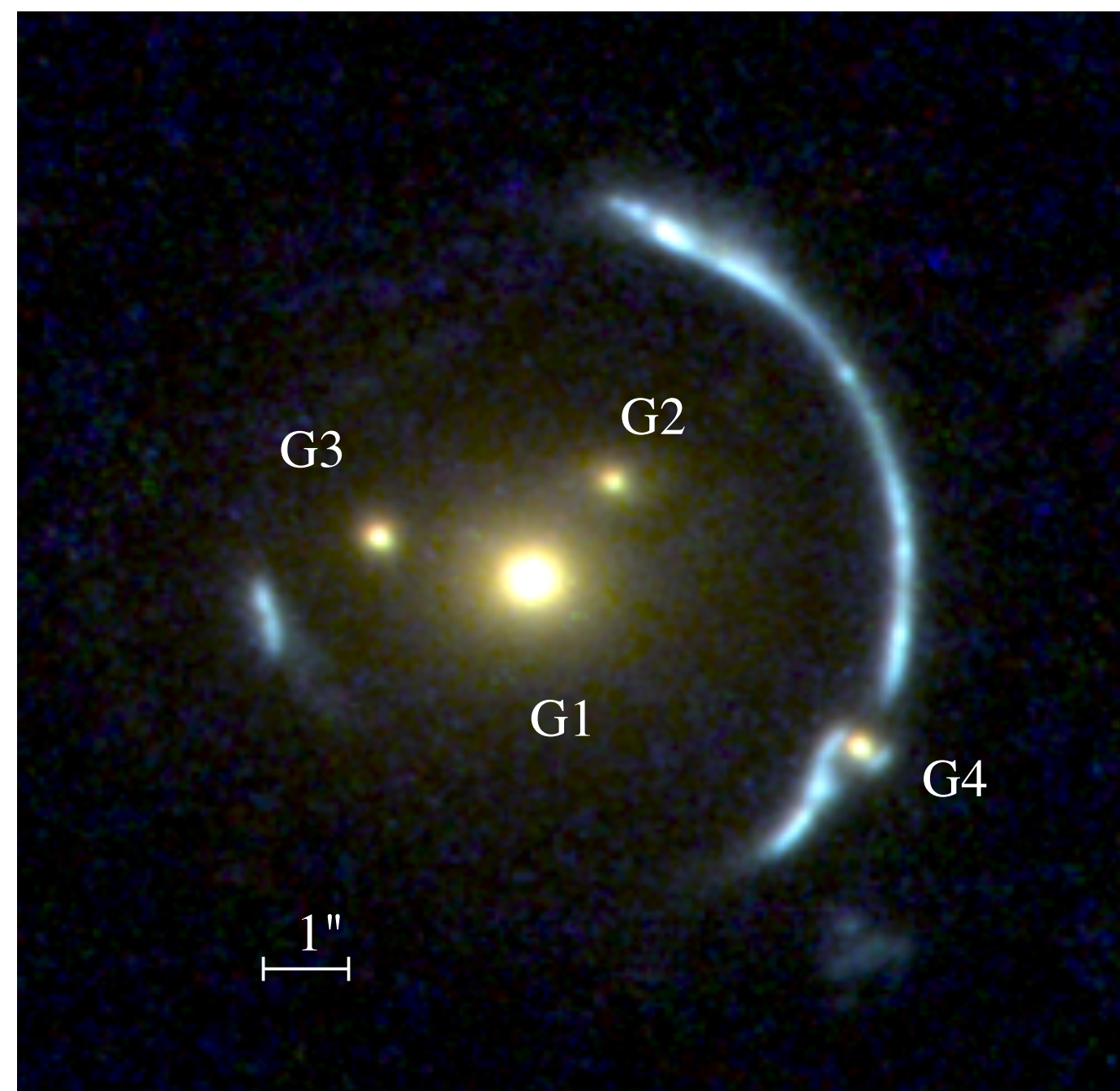


Magnification $\propto$
second derivative

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

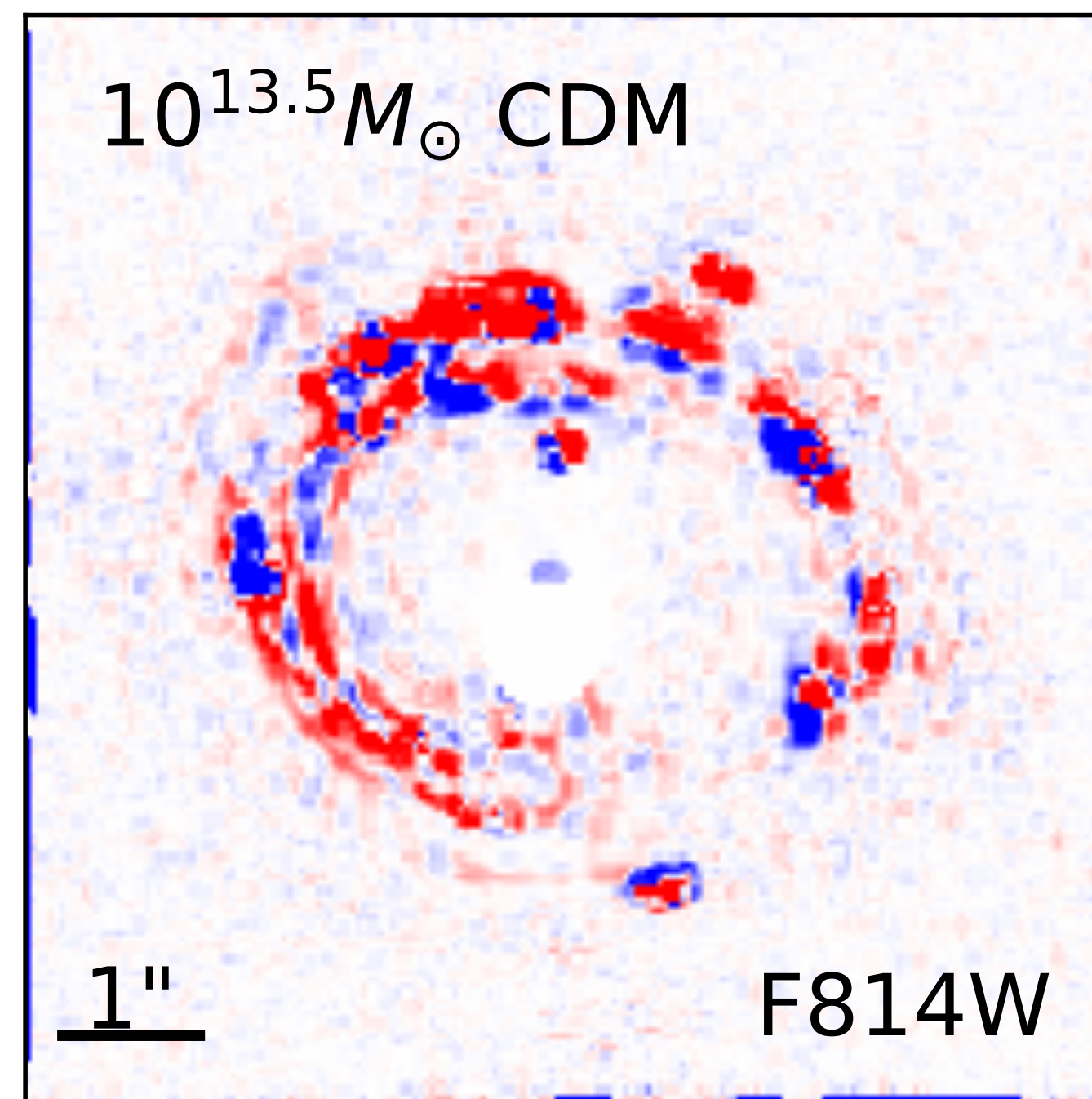
Strong gravitational lensing studies of dark matter measure **deflections** and **magnifications** of images relative to the main lens gravitational potential

Resolved source,
single detection



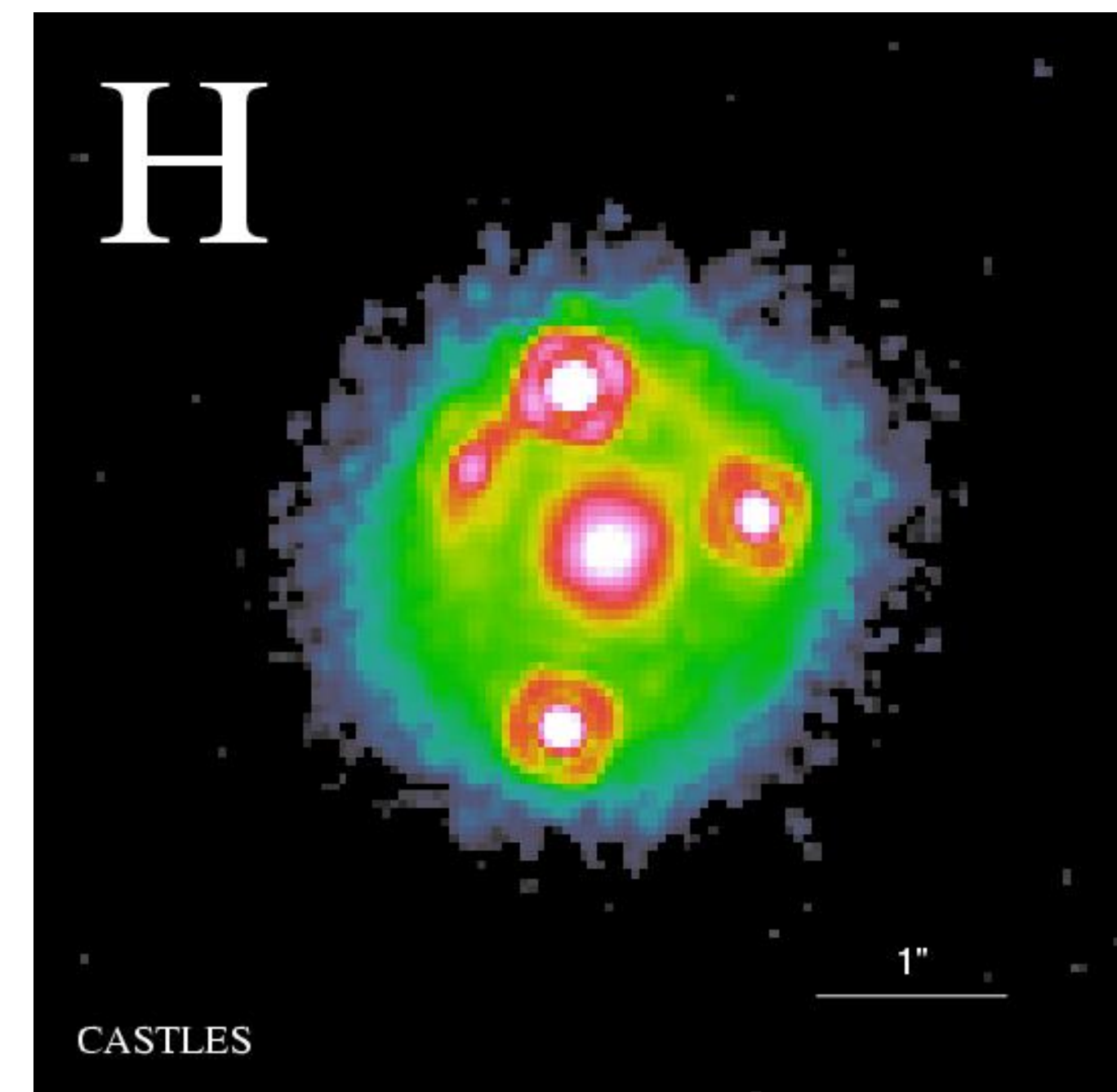
Vegetti et al. 2010

Resolved source,
multi-detection

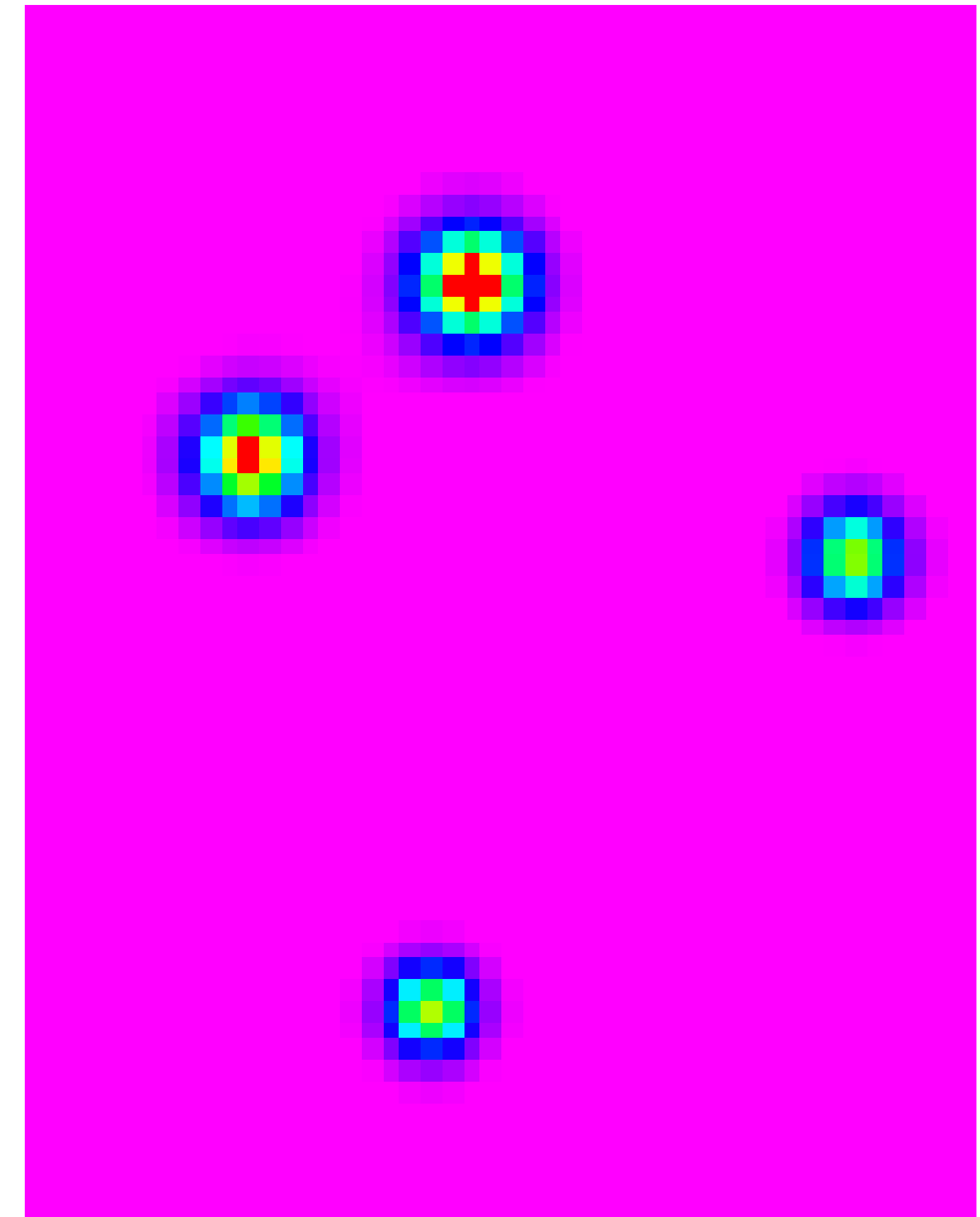
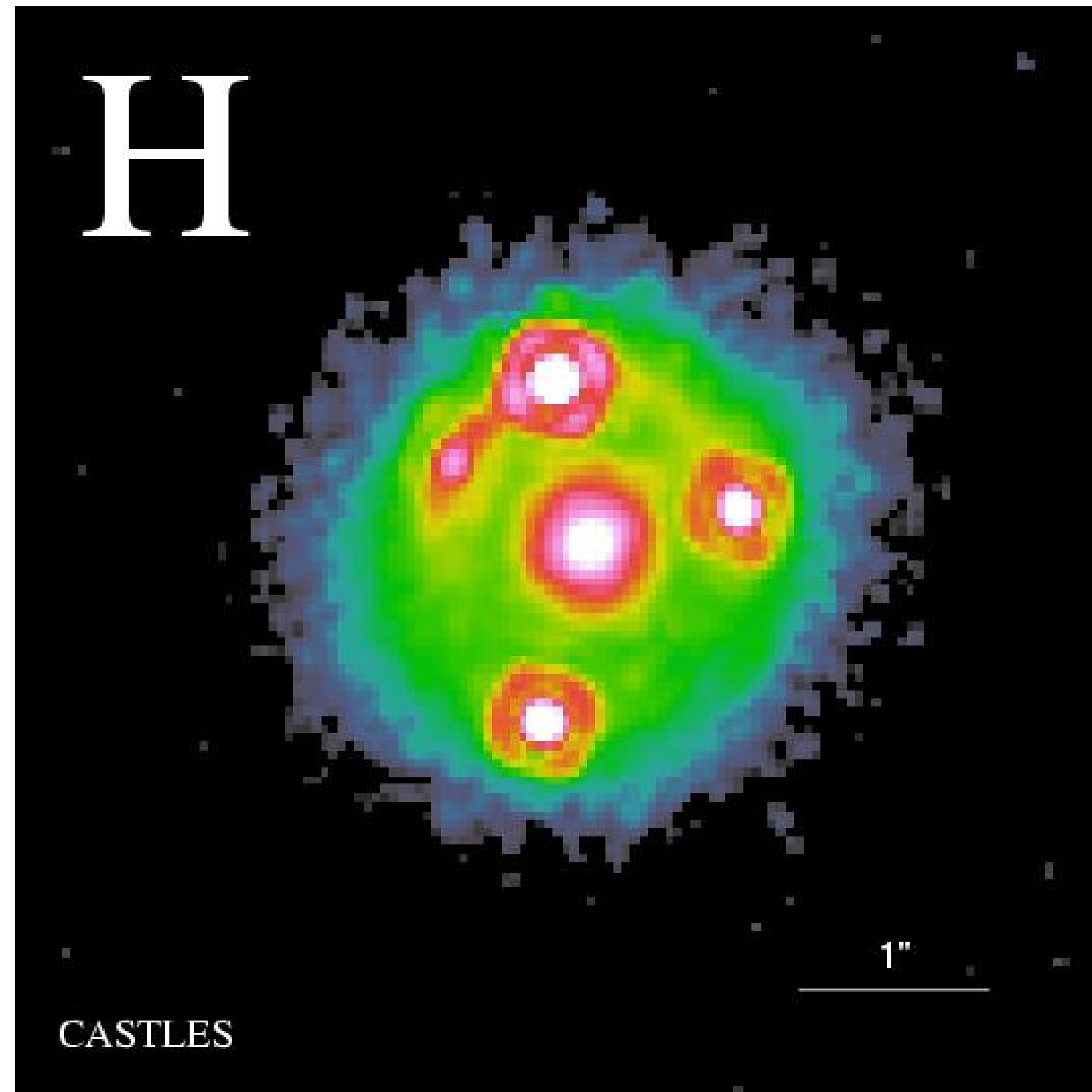


Birrer et al. 2017

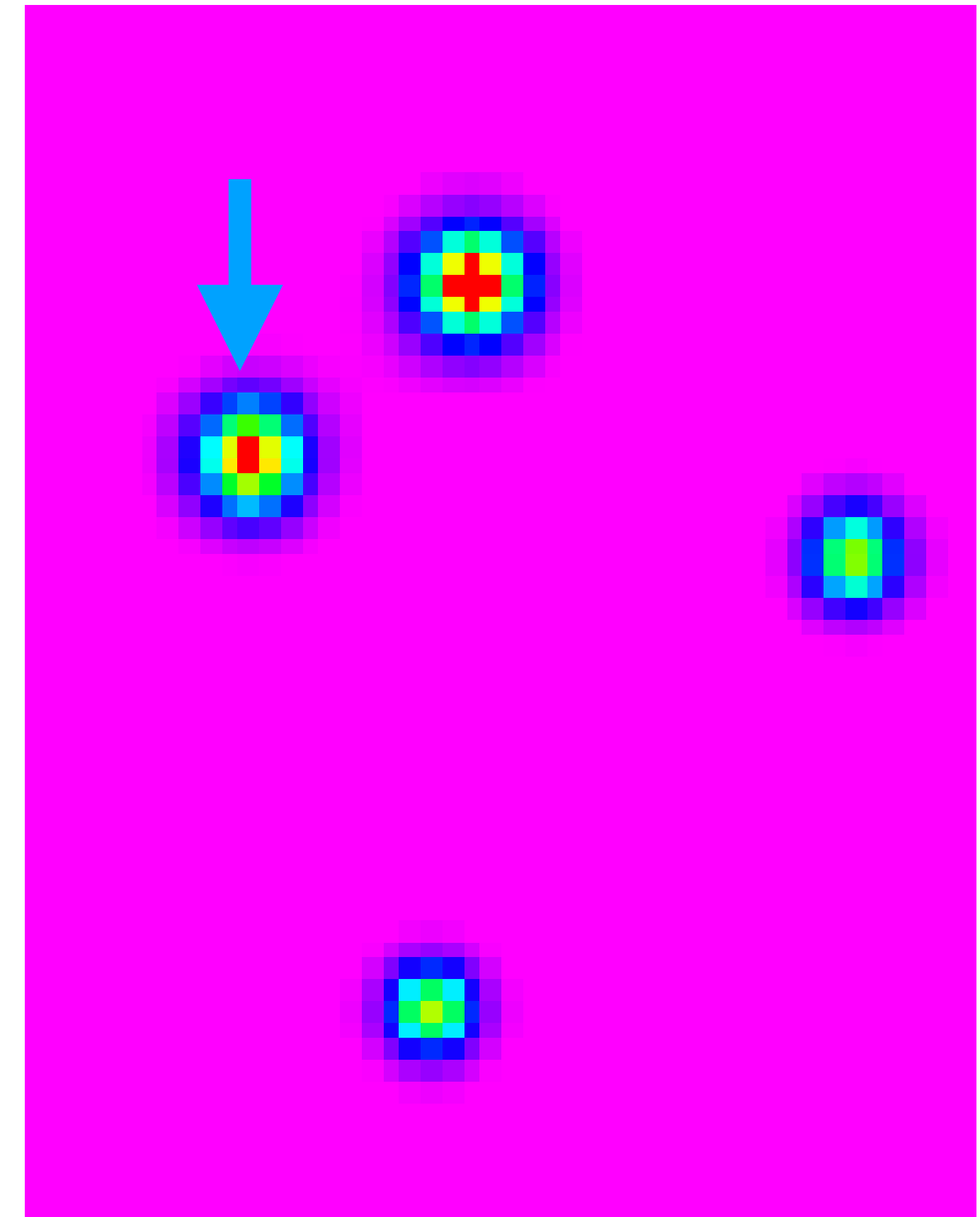
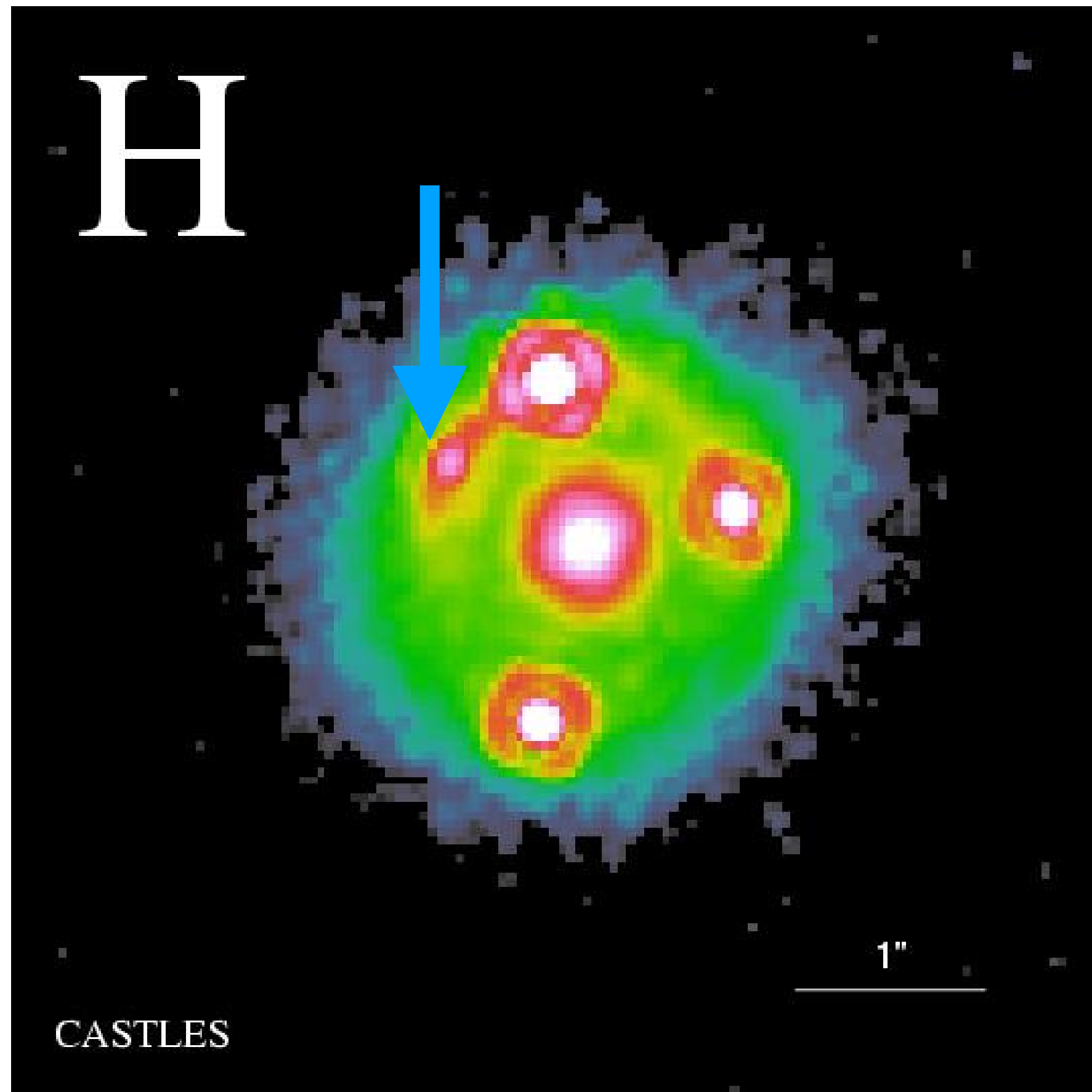
Unresolved source,
multi-detection



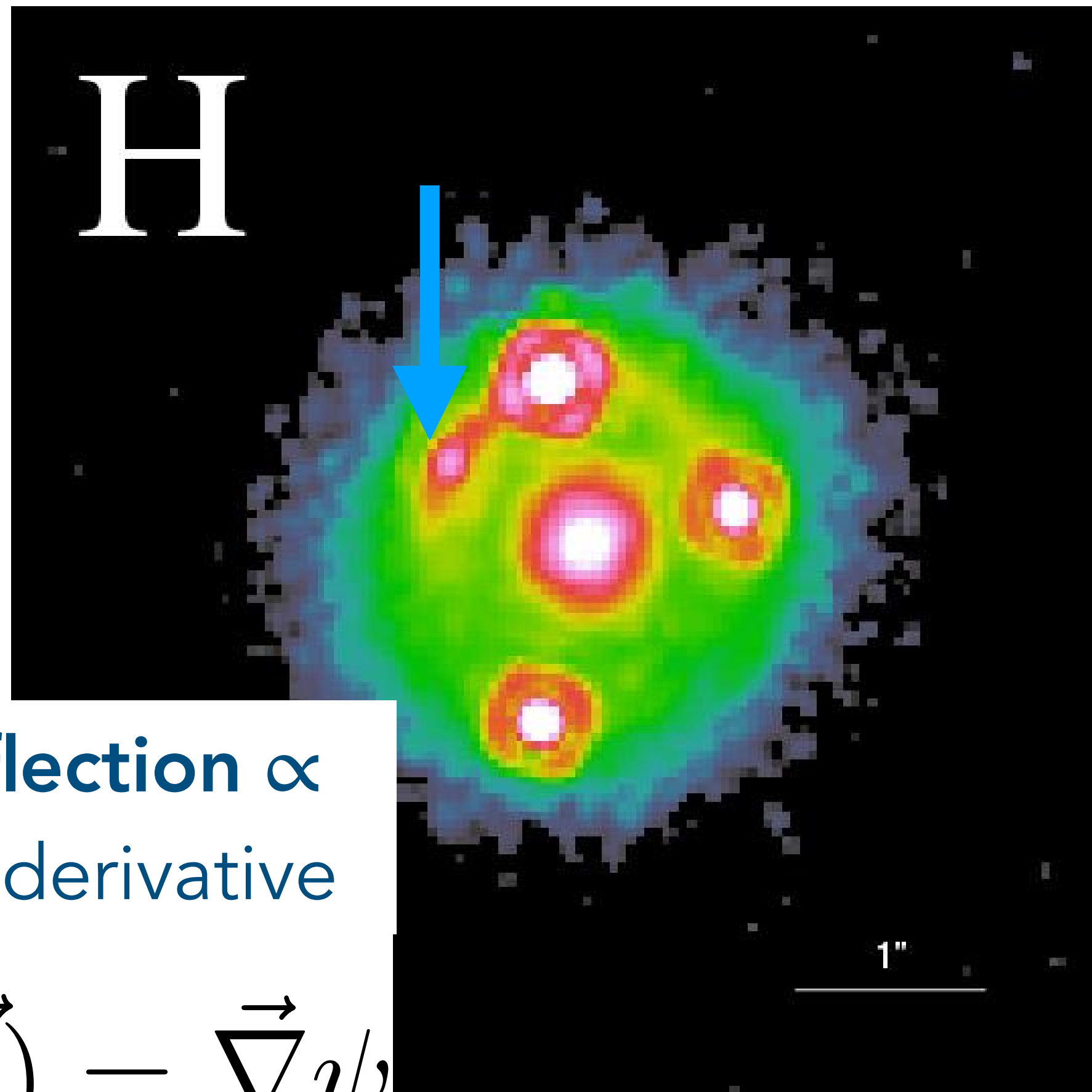
Example of the signal



Example of the signal

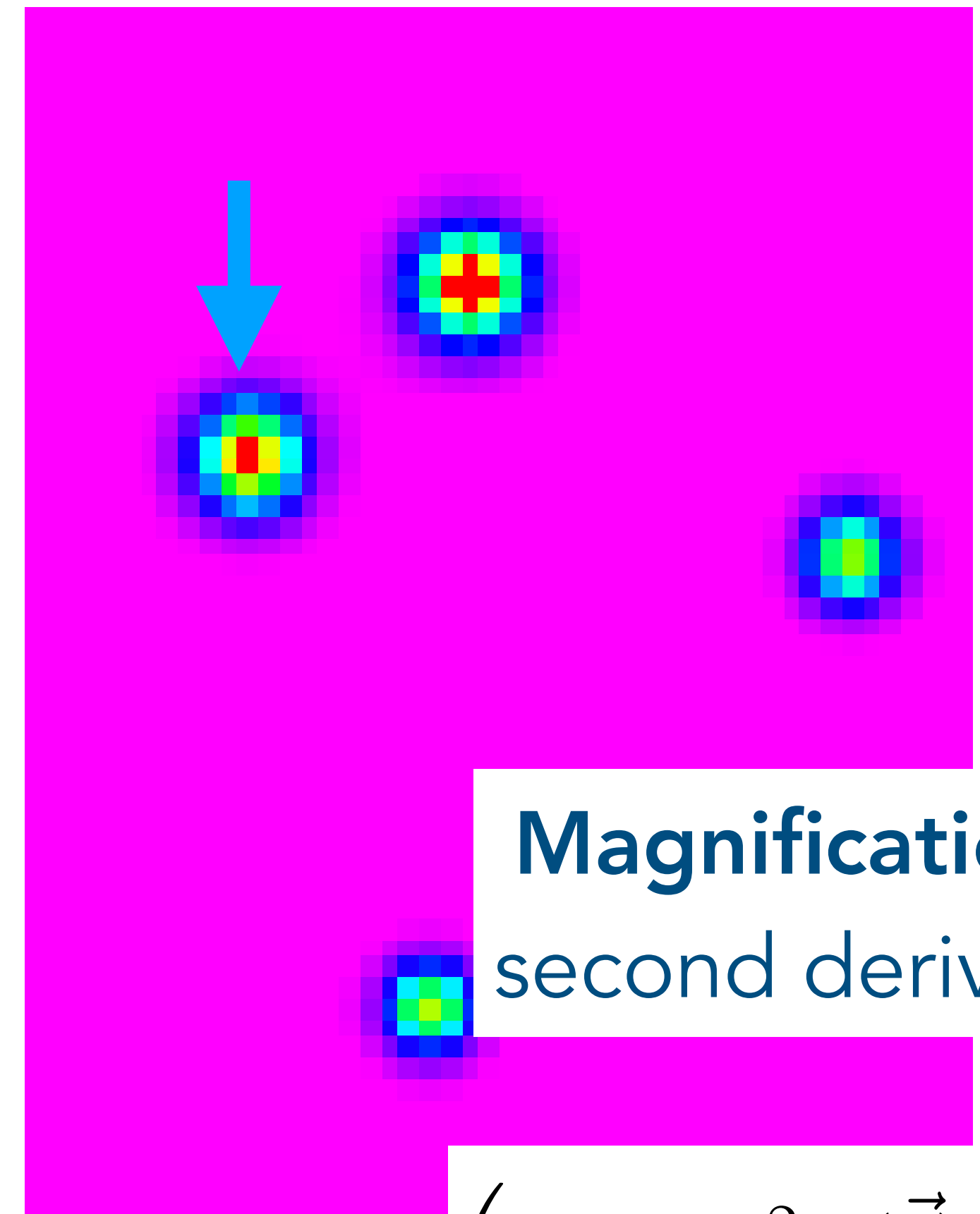


Example of the signal



Deflection $\propto$
first derivative

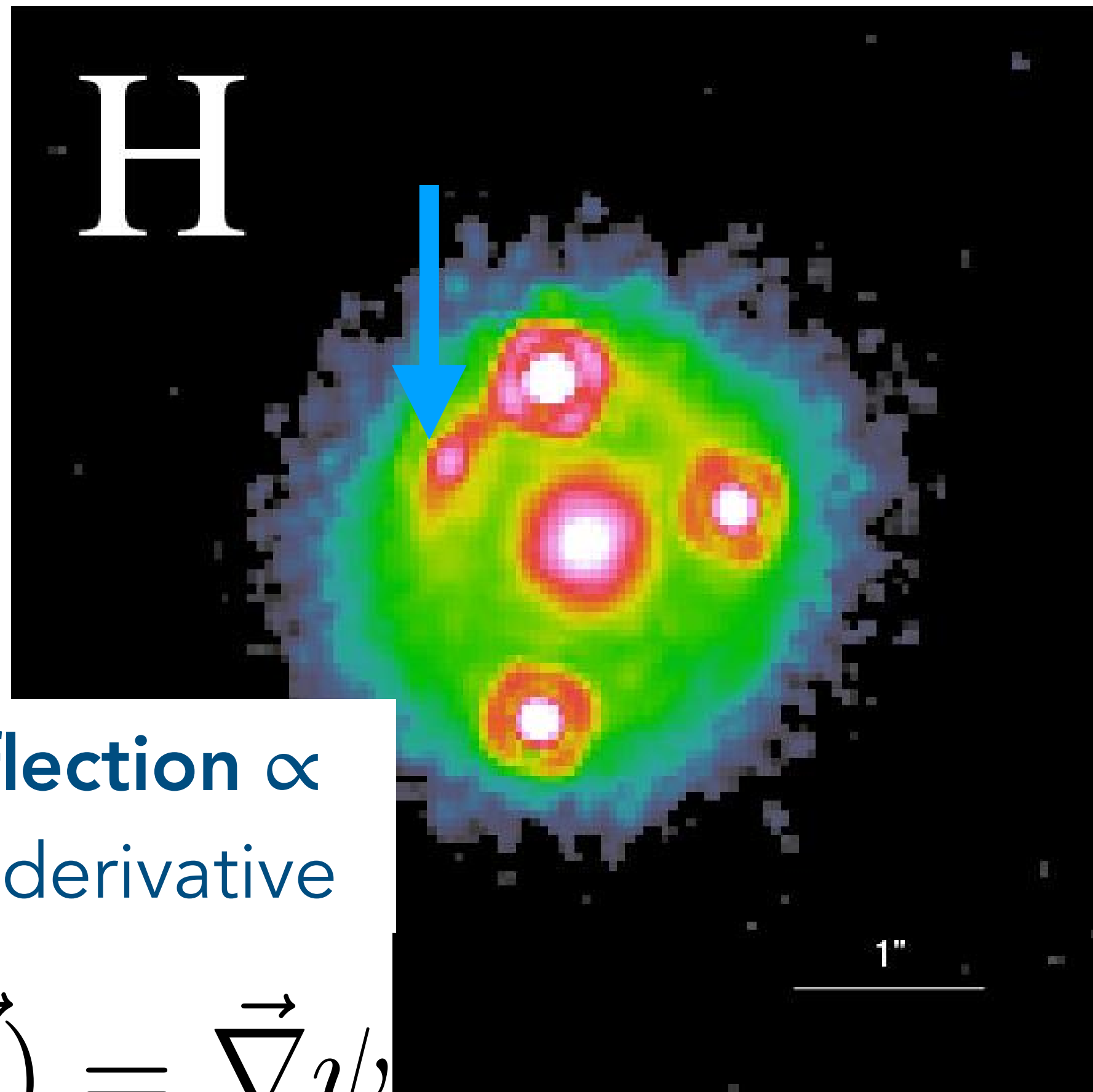
$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla} \psi$$



Magnification $\propto$
second derivative

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

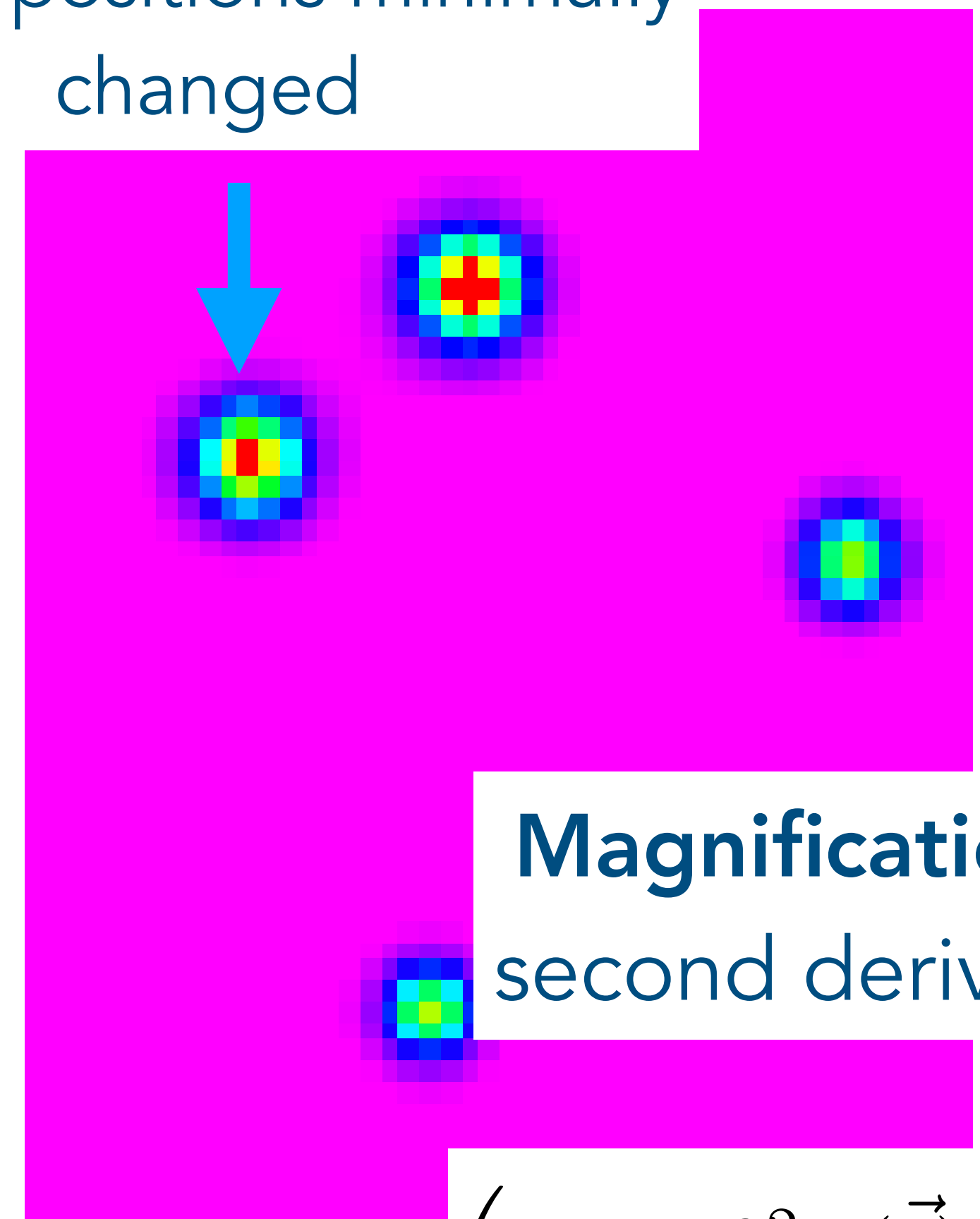
Example of the signal



Deflection $\propto$
first derivative

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

Localized perturbations
change the image
magnifications while
leaving positions minimally
changed

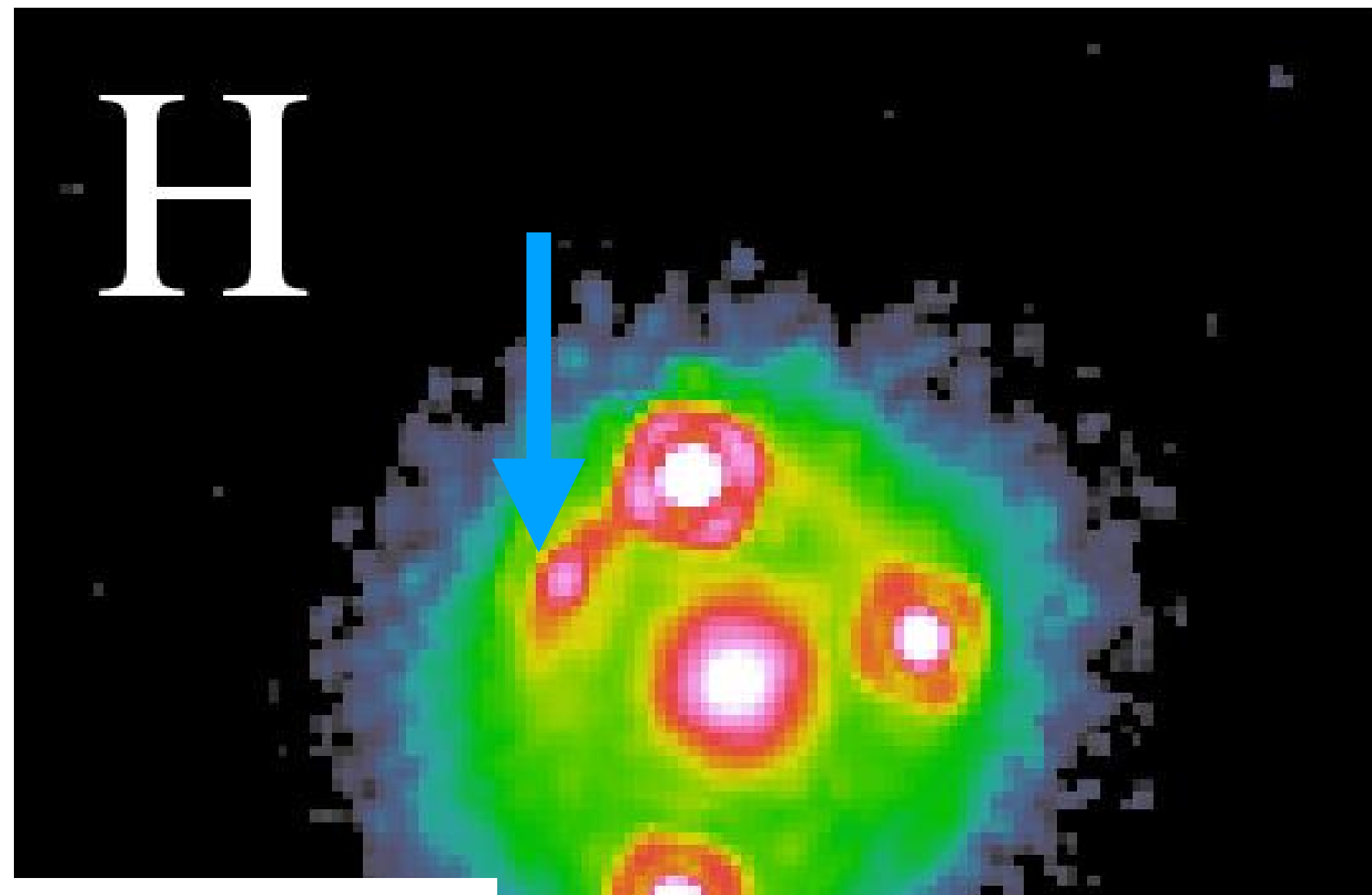


Magnification $\propto$
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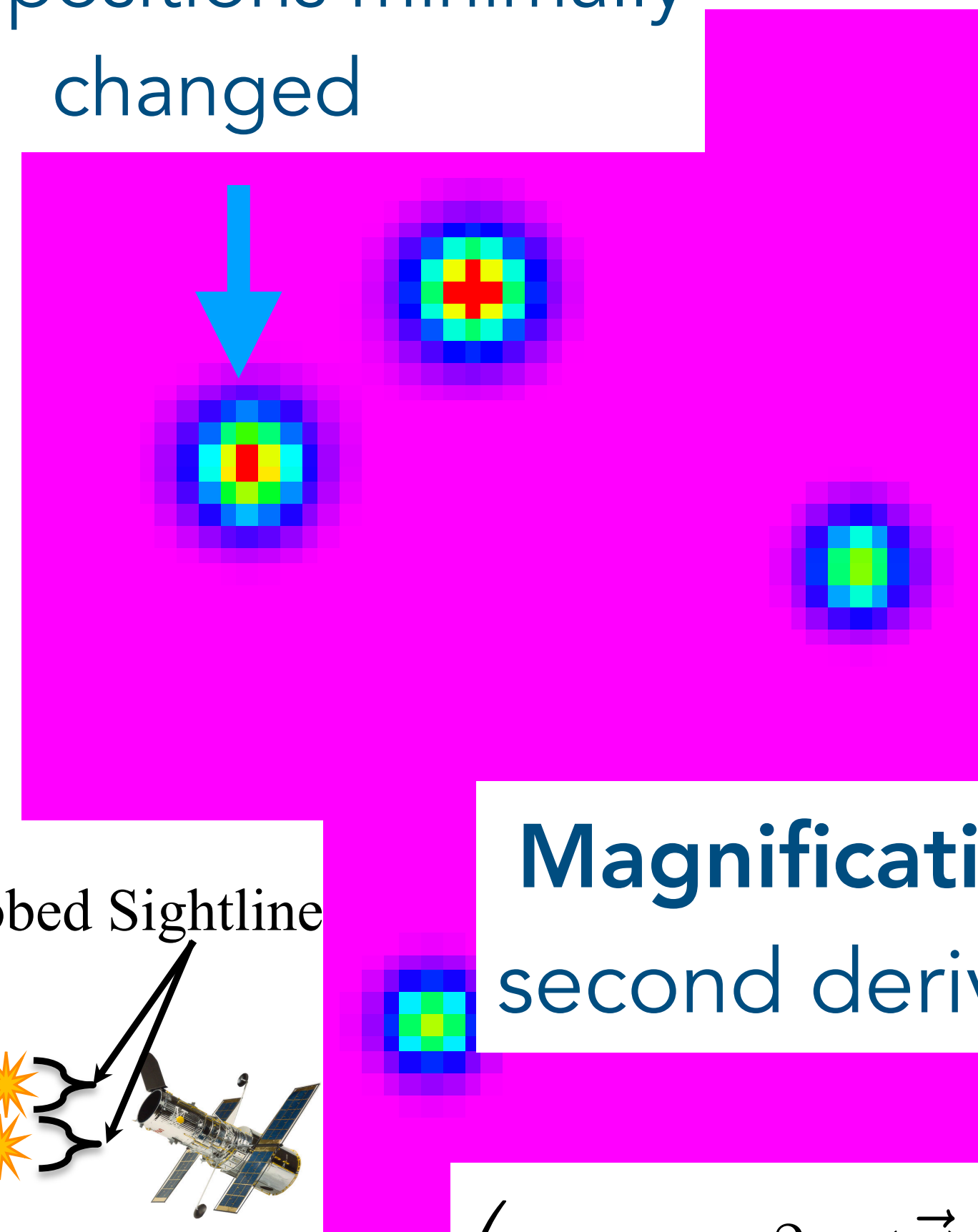
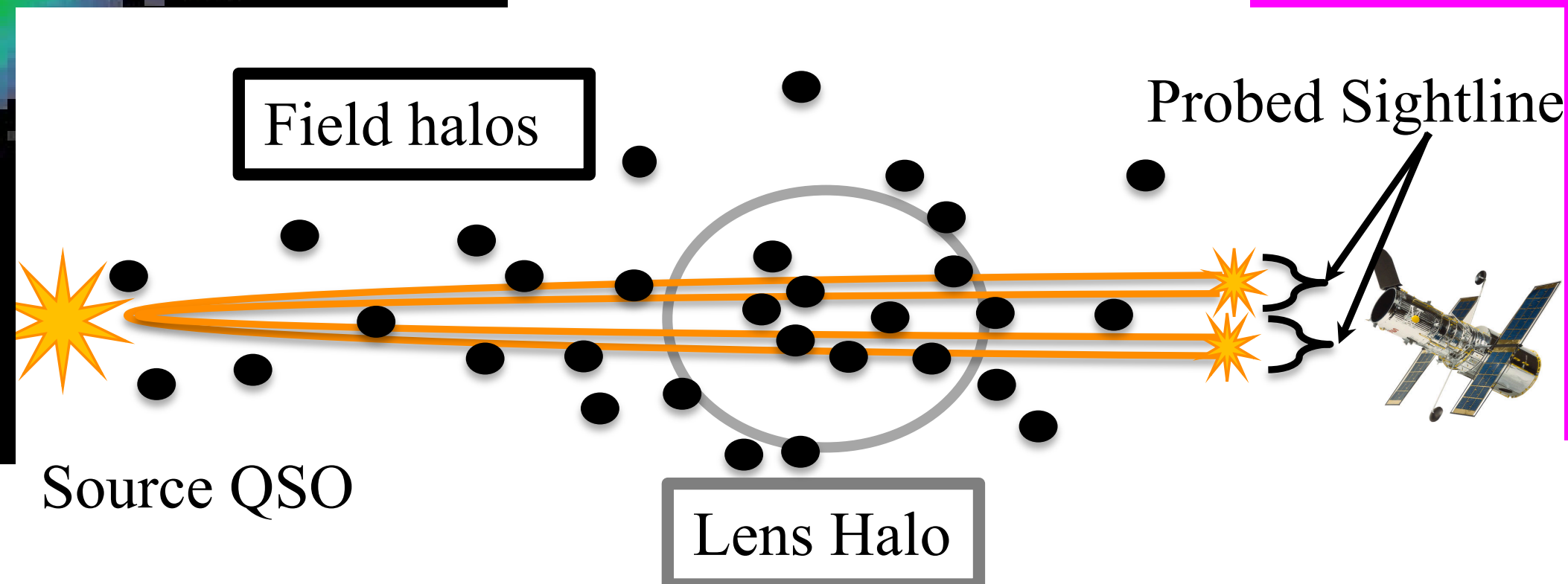
Example of the signal

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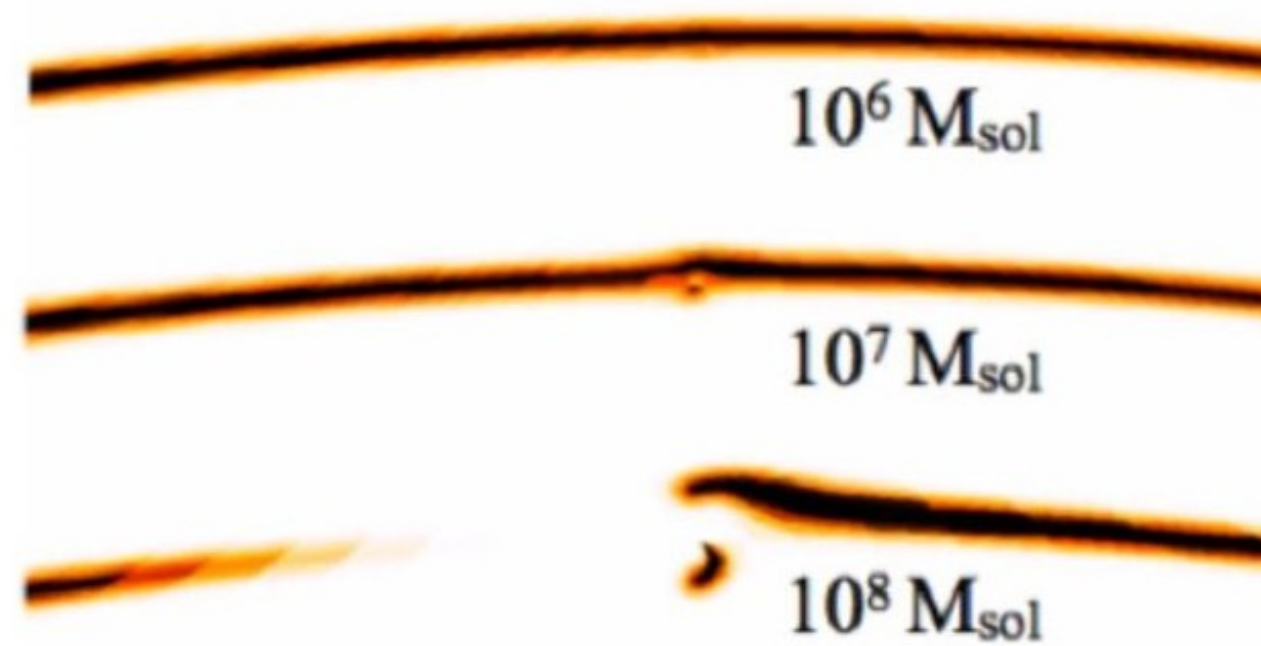
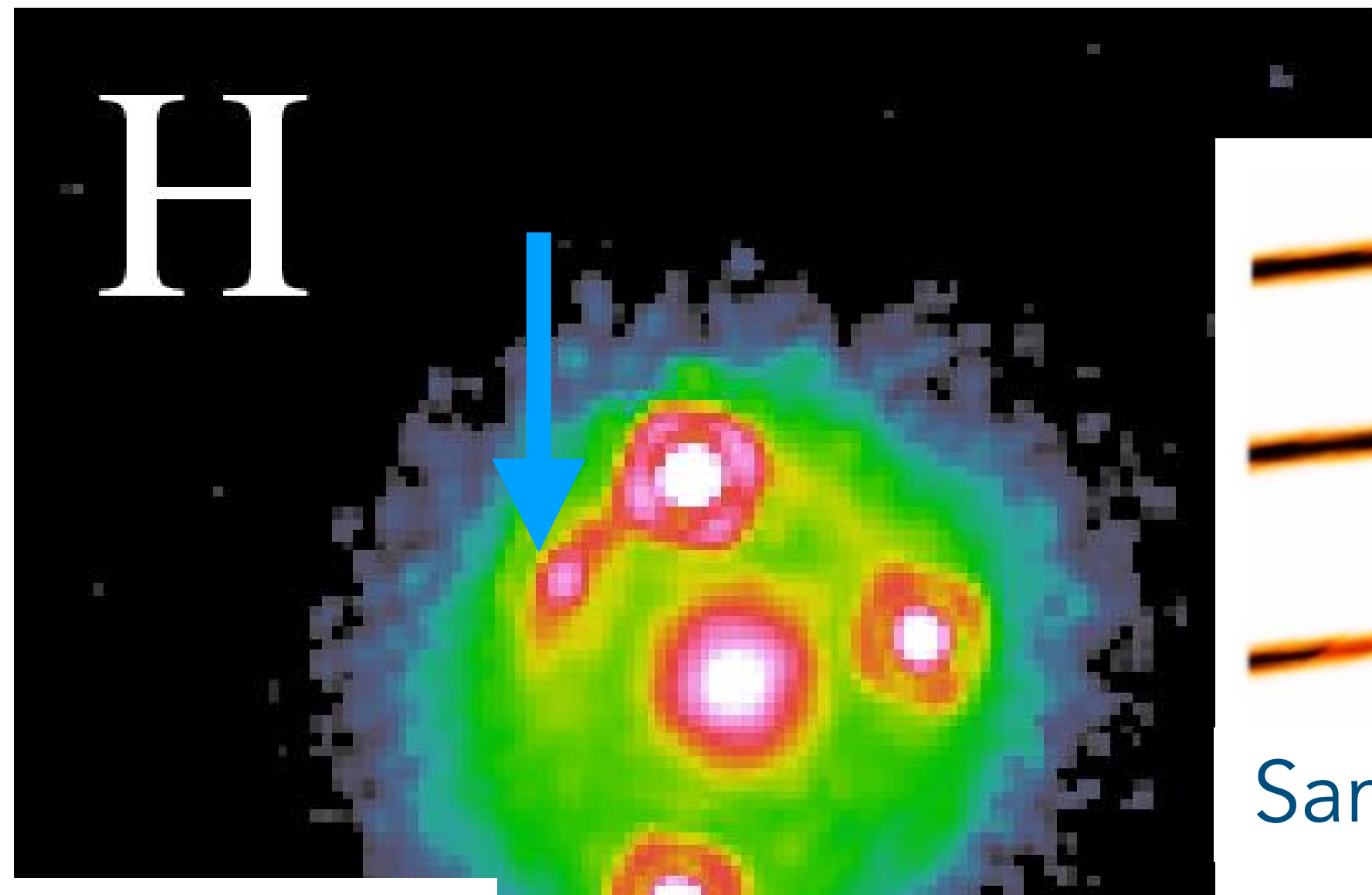


Magnification $\propto$
second derivative

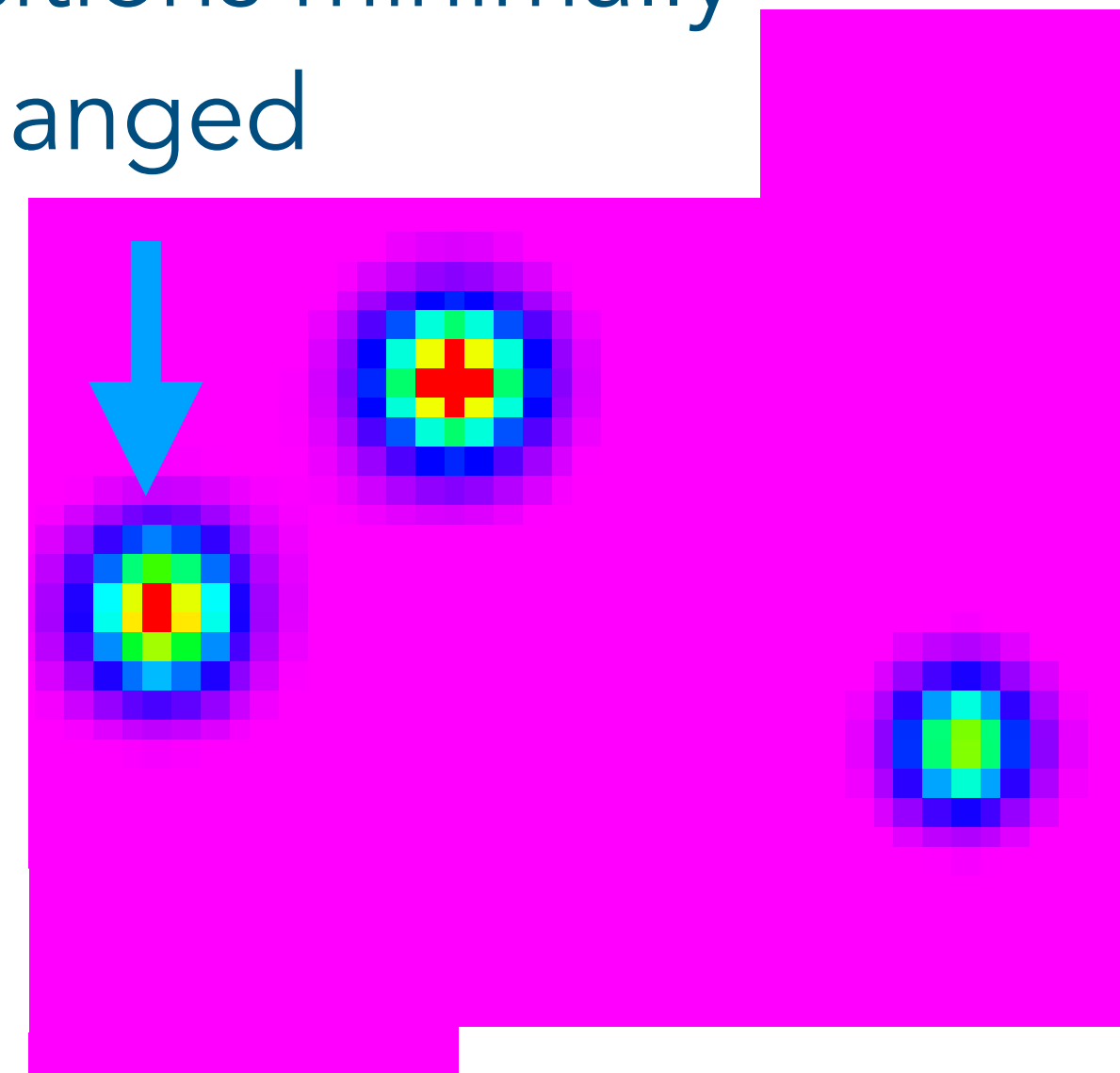
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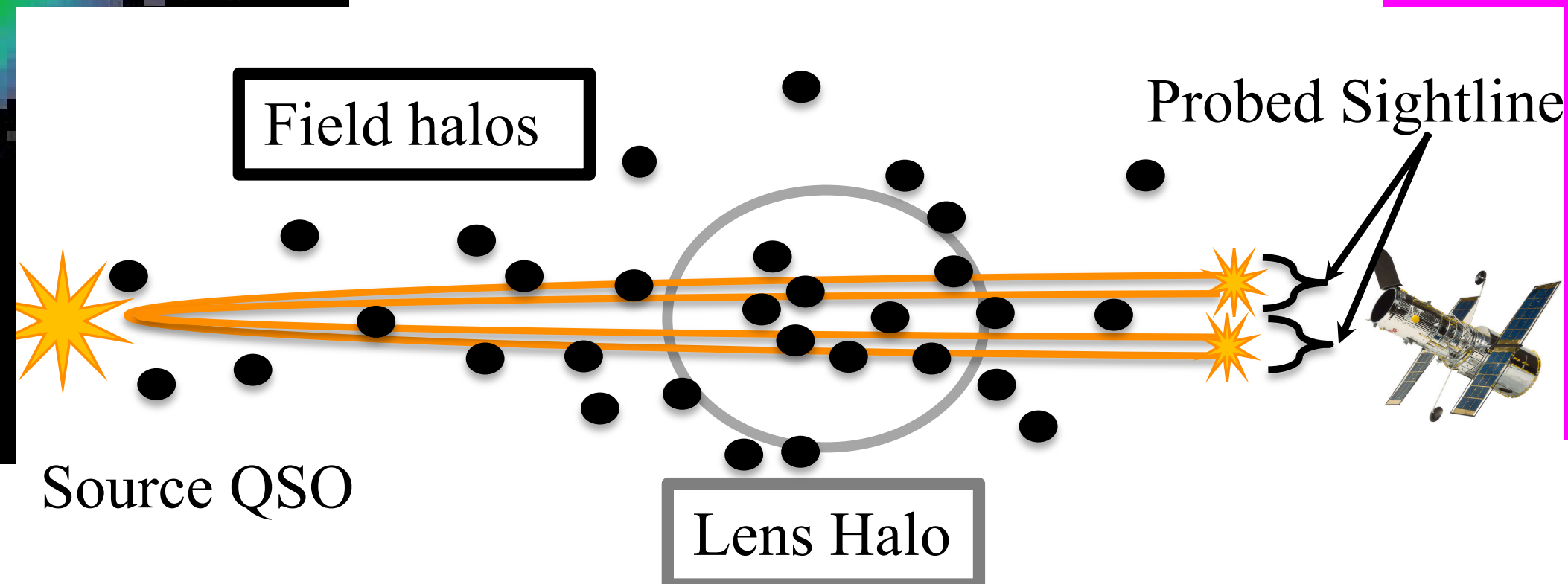


Same physics, just smaller



Deflection $\propto$
first derivative

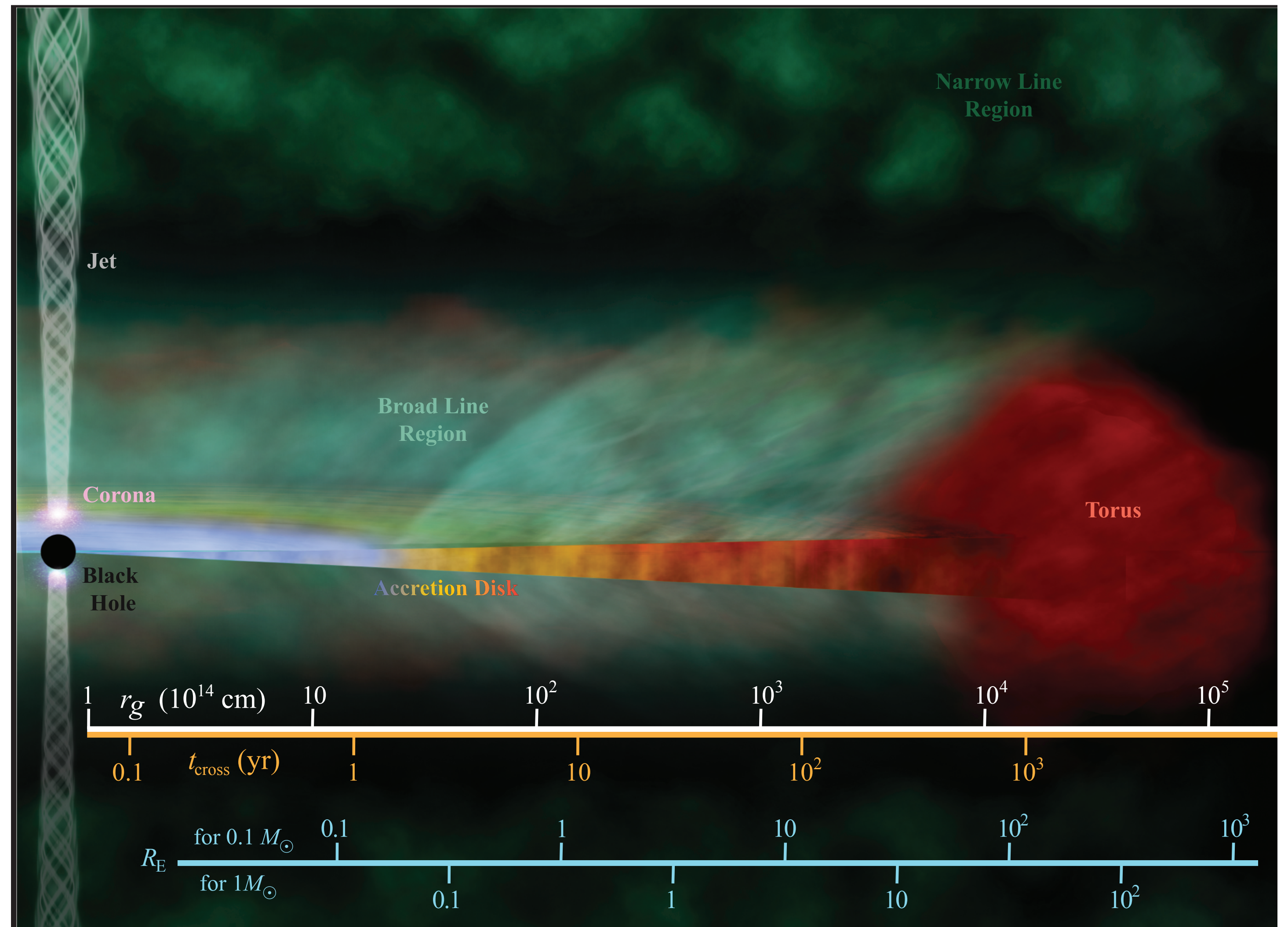
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Magnification $\propto$
second derivative

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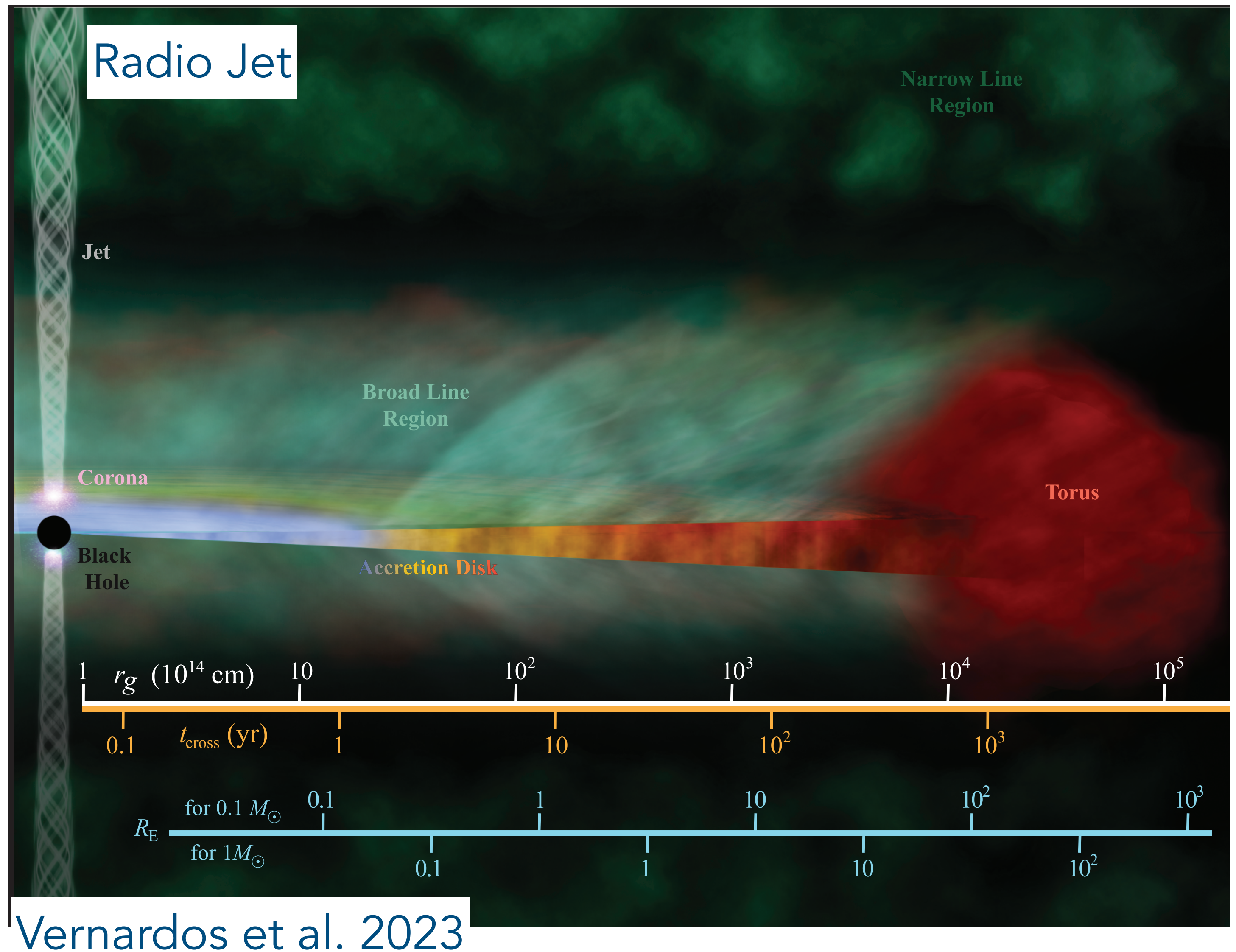
Have to use a $\sim$ mas source to average out lensing by stars



Vernardos et al. 2023

Have to use a $\sim$ mas source to average out lensing by stars

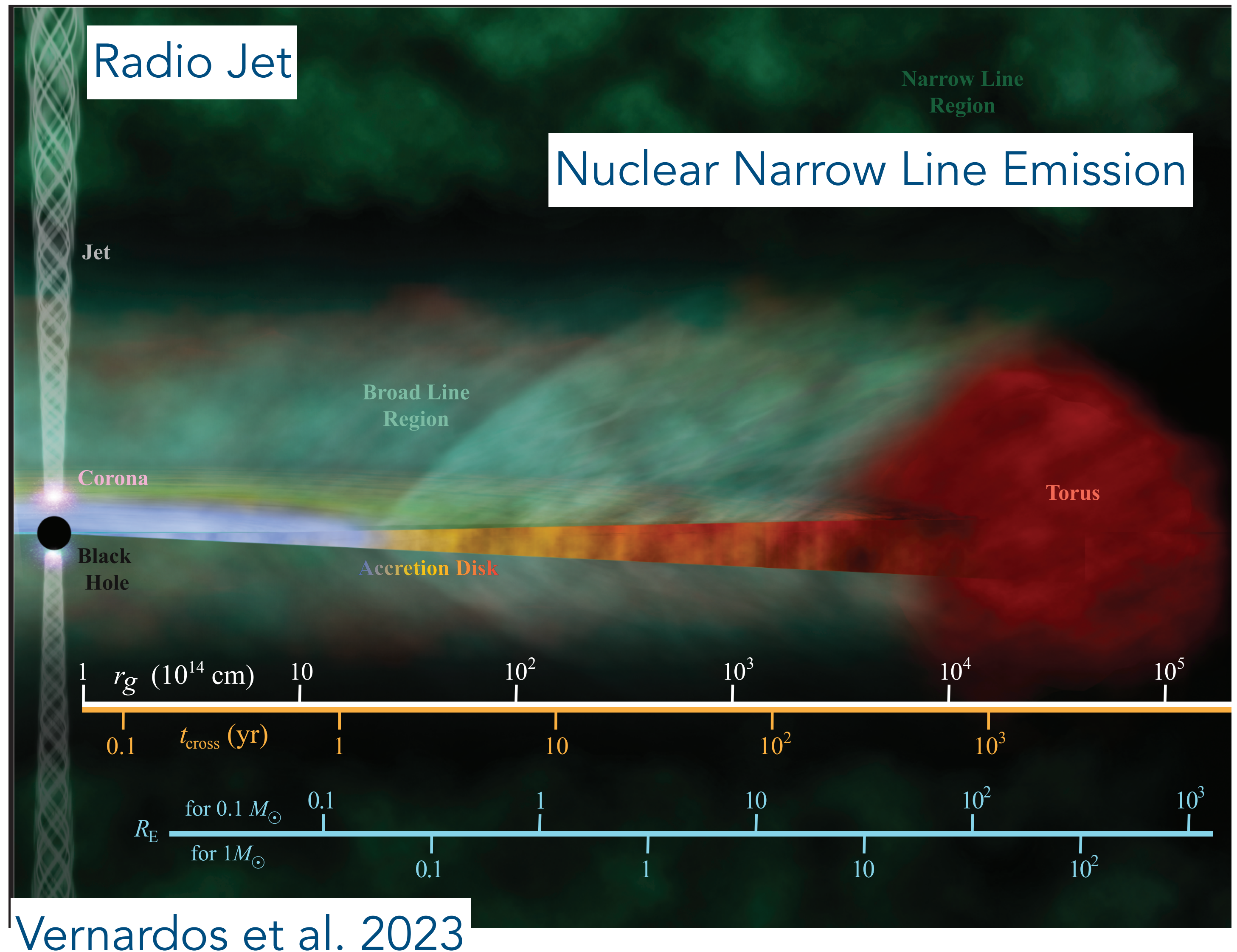
*Quasar Radio Jet (Mao and Schneider 1998, Dalal and Kochanek 2002)



Have to use a $\sim$ mas source to average out lensing by stars

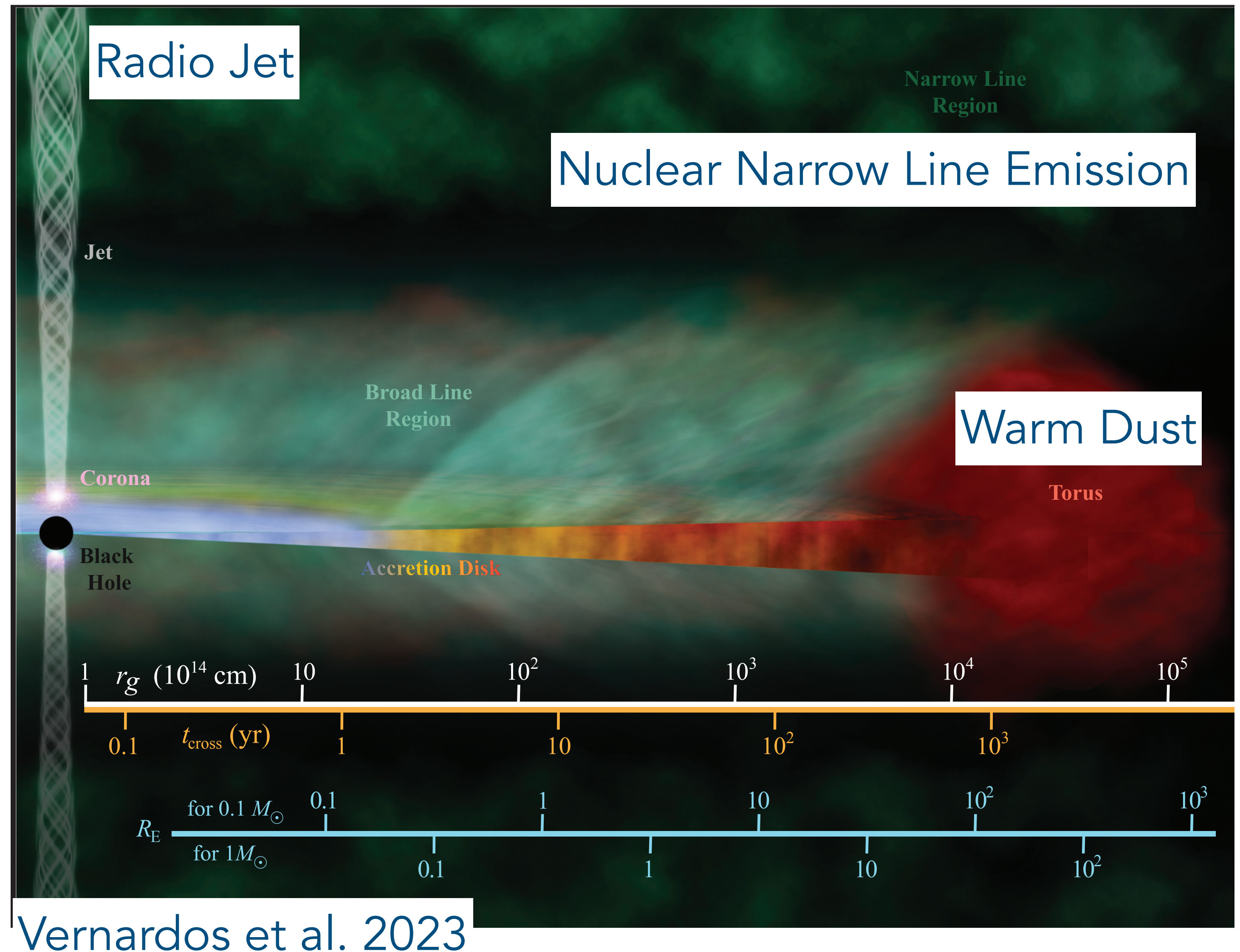
- *Quasar Radio Jet (Mao and Schneider 1998, Dalal and Kochanek 2002)

- *Quasar narrow-line emission (Moustakas and Metcalf 2003)



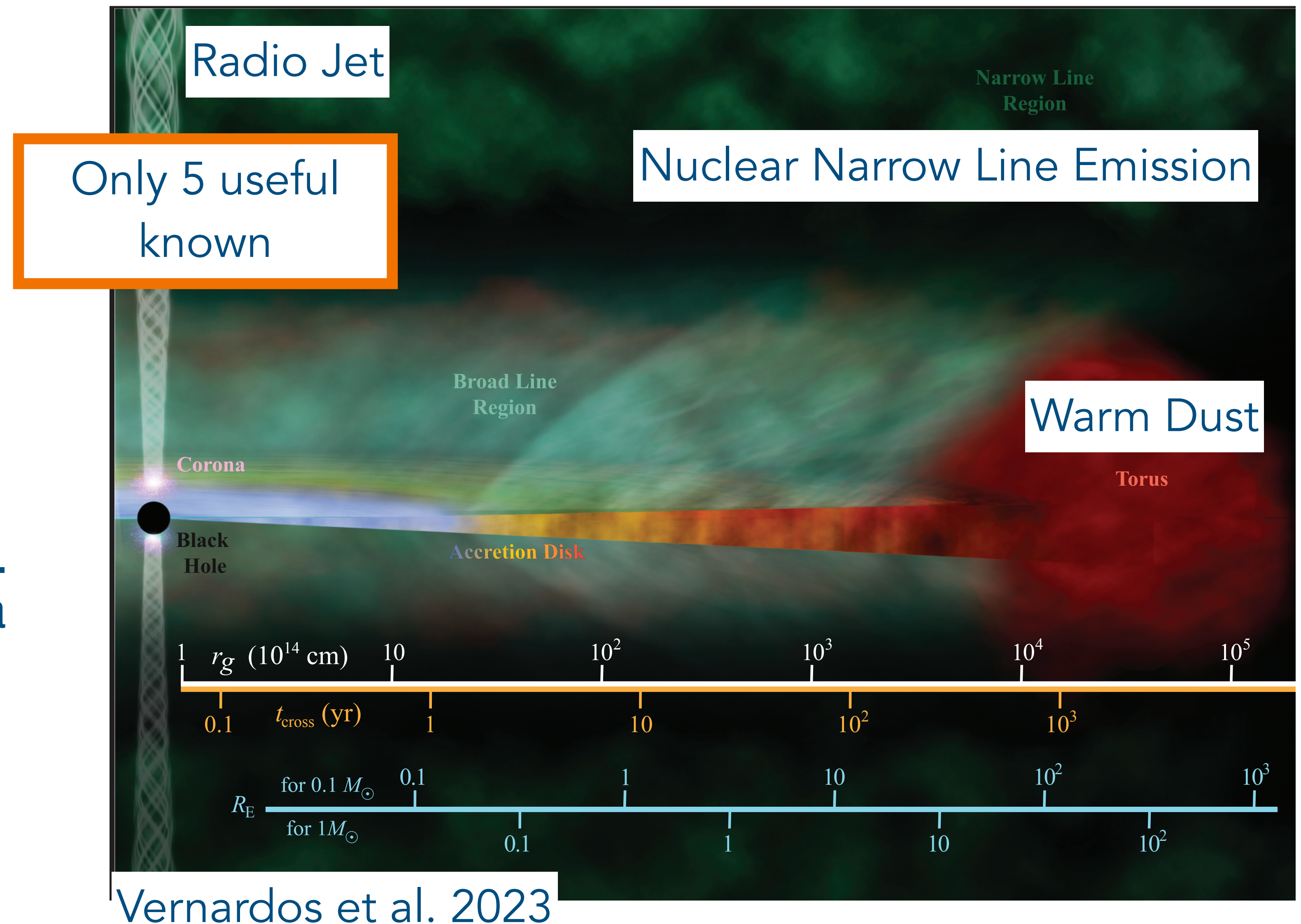
Have to use a $\sim$ mas source to average out lensing by stars

- * Quasar Radio Jet (Mao and Schneider 1998, Dalal and Kochanek 2002)
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- * Quasar warm dust (e.g. Algol et al. 2000, Chiba et al. 2005 Macleod et al. 2013 and more)



Have to use a $\sim$ mas source to average out lensing by stars

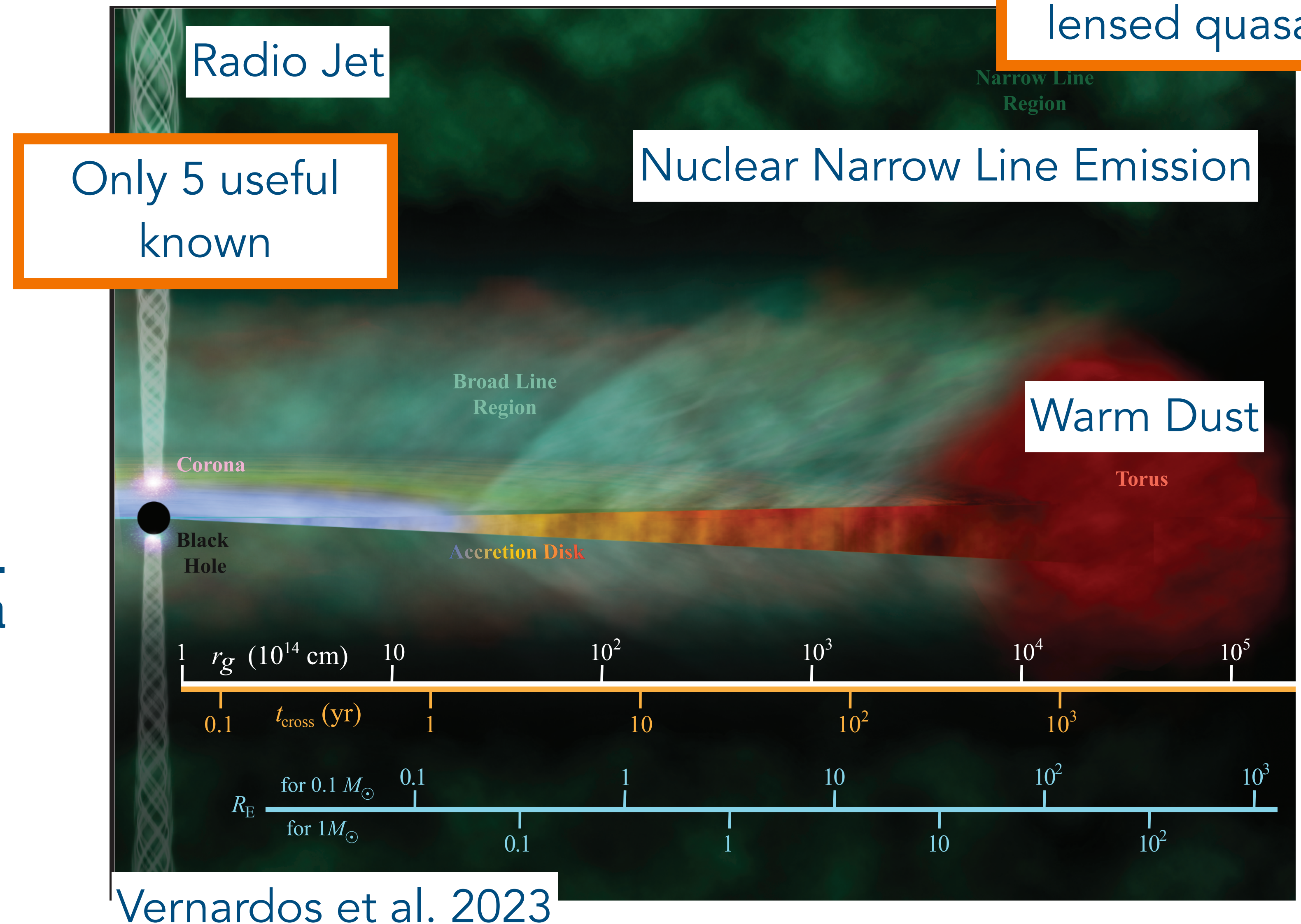
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In virtually every lensed quasar



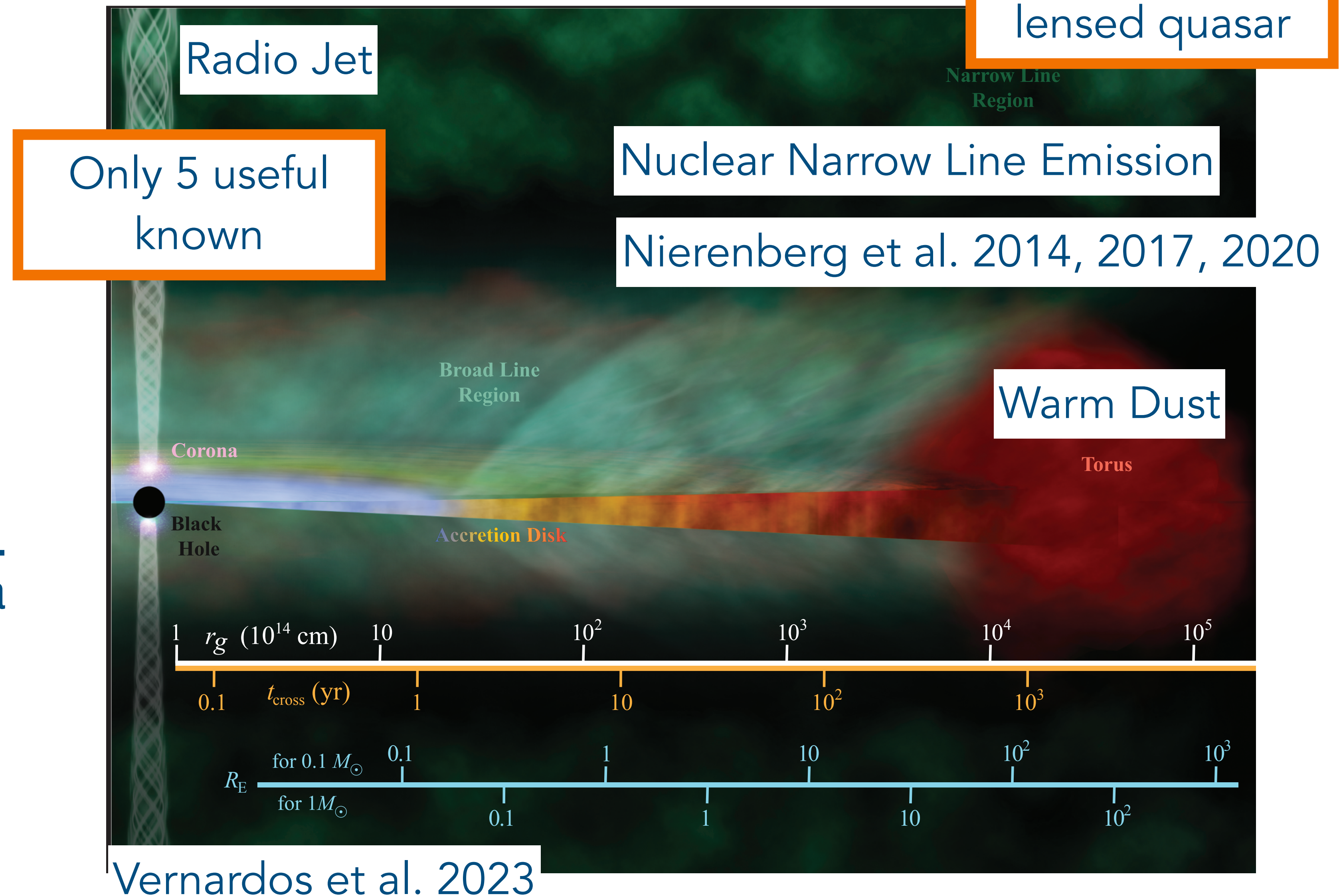
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In virtually every
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Have to use a $\sim$ mas source to average out lensing by stars

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*Quasar narrow-line emission (Moustakas and Metcalf 2003)

*Quasar warm dust (e.g. Algol et al. 2000, Chiba et al. 2005 Macleod et al. 2013 and more)

In virtually every lensed quasar

Radio Jet

Only 5 useful known

Nuclear Narrow Line Emission

Nierenberg et al. 2014, 2017, 2020

Narrow Line Region

Broad Line Region

Warm Dust

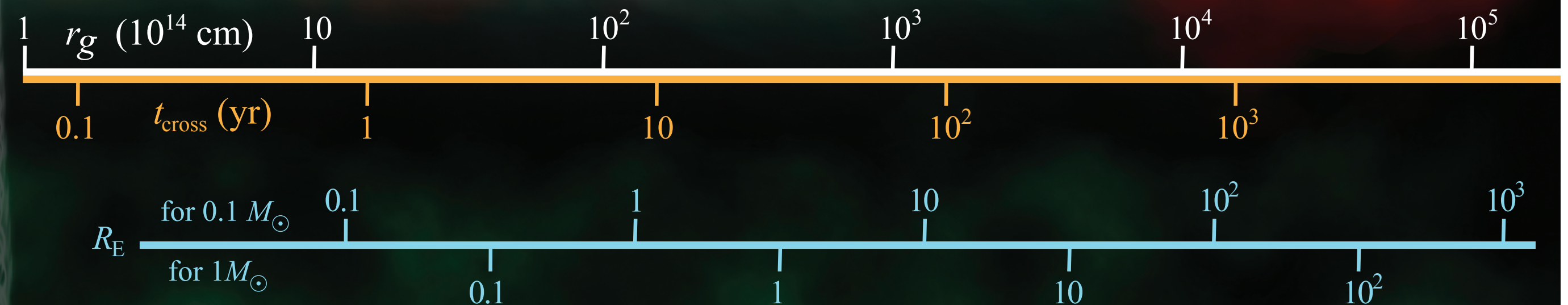
This talk

Corona

Black Hole

Torus

Accretion Disk

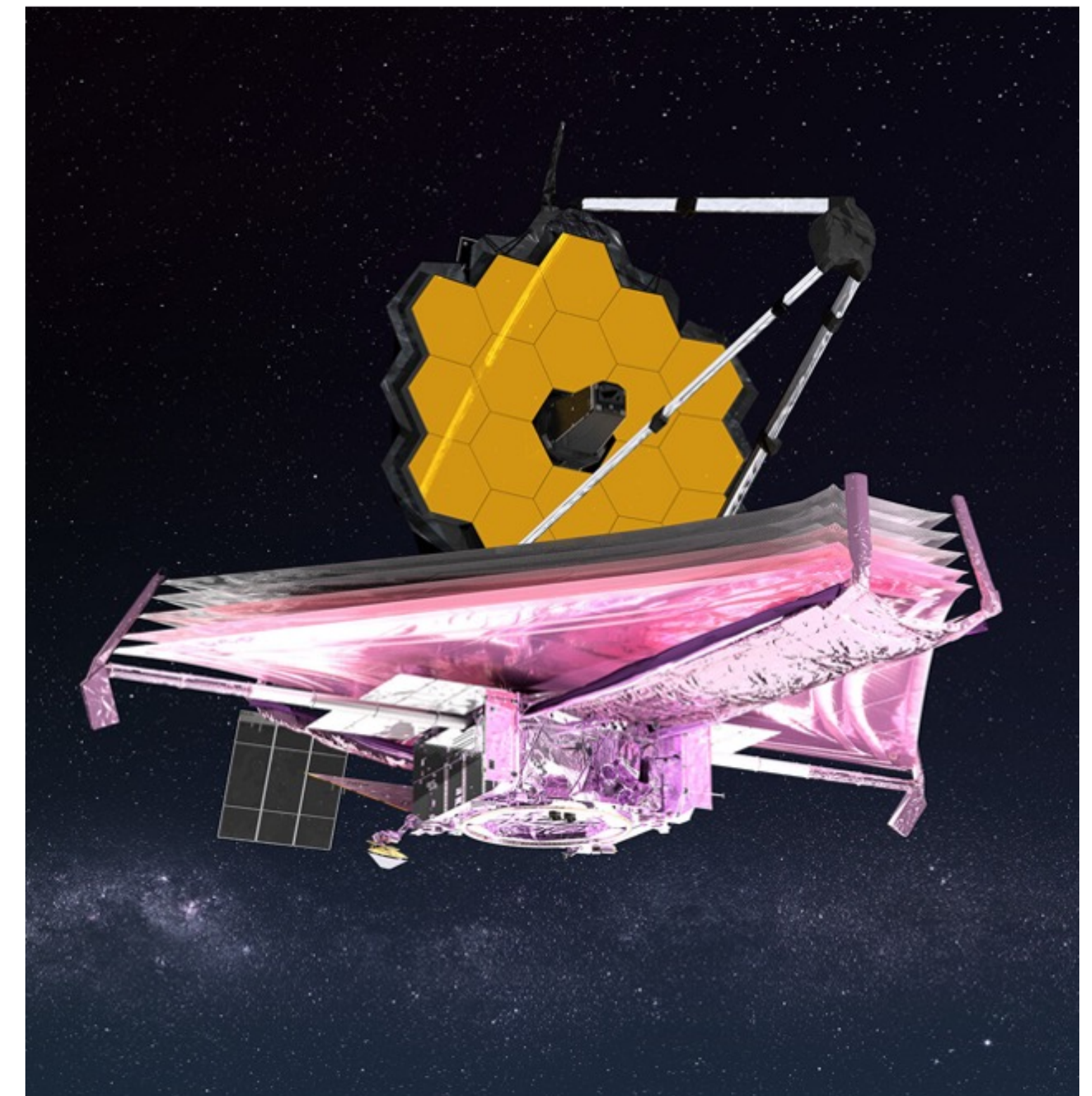


Vernardos et al. 2023

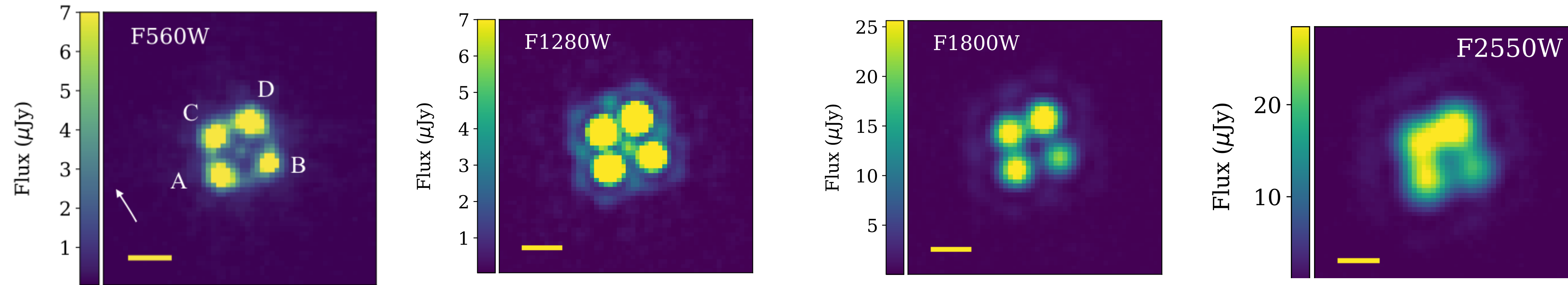
JWST Lensed Quasar Dark Matter Survey

GO 2046, PI Nierenberg

- * All known quadruply imaged quasars detected in WISE W4 with image separation greater than 0.1 arcsecond and no deflector disk
- * 43 hours, Medium Program
- * MIRI broad band imaging at 5.6, 12.8, 18 and 25.5 microns
- * 55s F560W, F1280W and F1800W, 570s in F2550 (fast observations!)

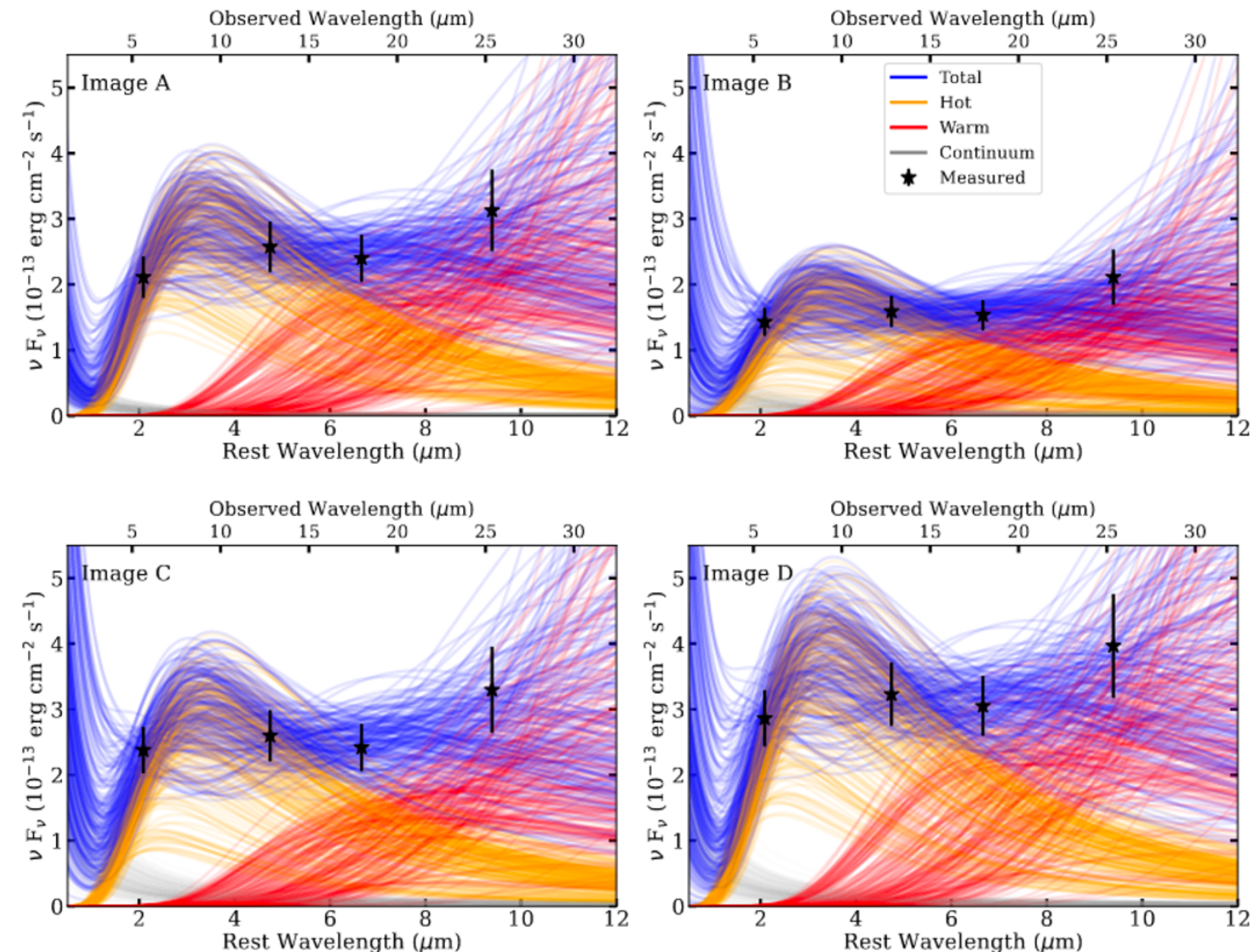


Multi-band imaging isolates light from the warm-dust region



* SED fitting with variable component temperatures and amplitudes

* Resulting fits provide estimates of microlensing contamination.



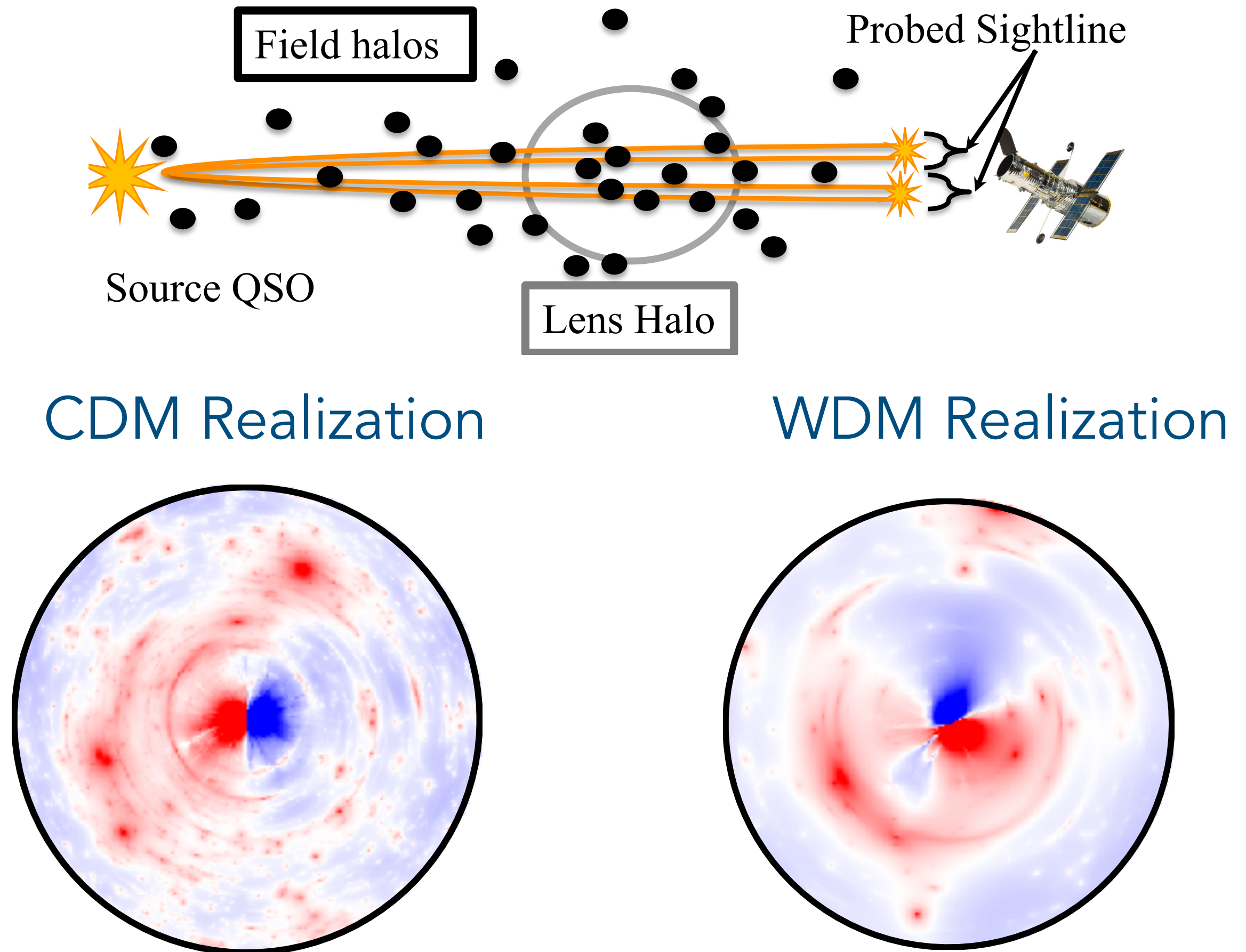
Nierenberg et al. 2023

Forward modelling pipeline

We generate millions of realizations of dark matter halos and subhalos, marginalizing over:

- * Dark matter properties (e.g. half-mode mass)
- * Tidal stripping of subhalos
- * Mass distribution of main deflector (including deviations from ellipticity)
- * Source size

Multi-plane lensing convergence maps



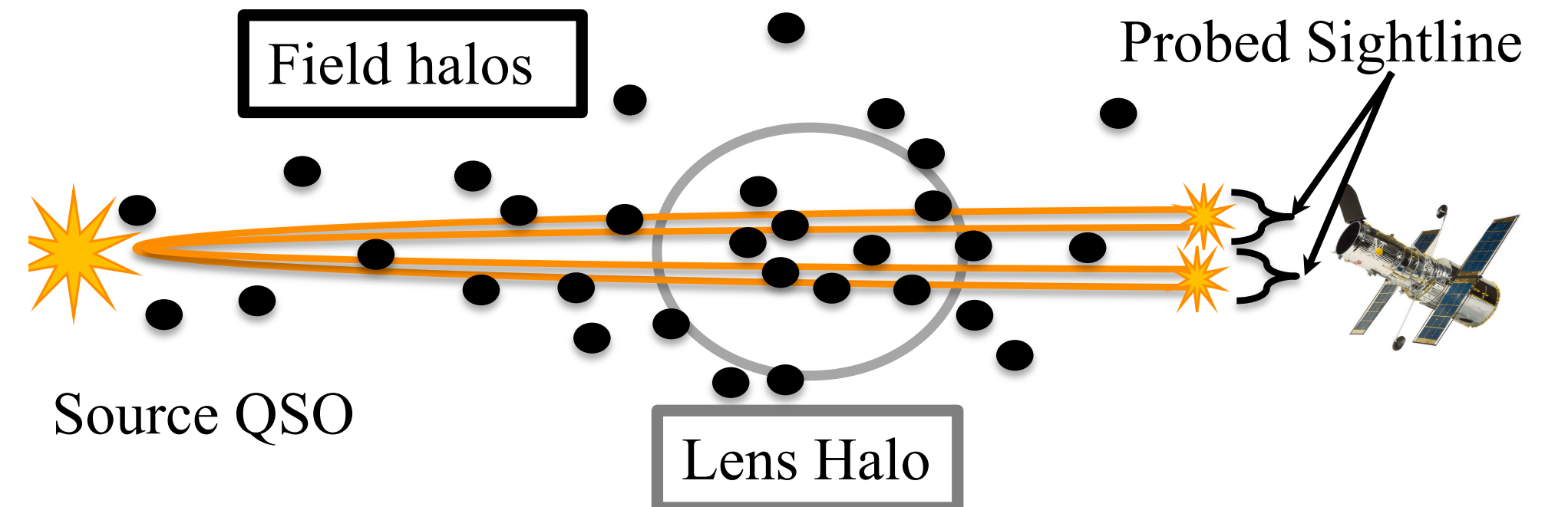
Gilman, Birrer, Nierenberg et al. 2020a

Forward modelling pipeline

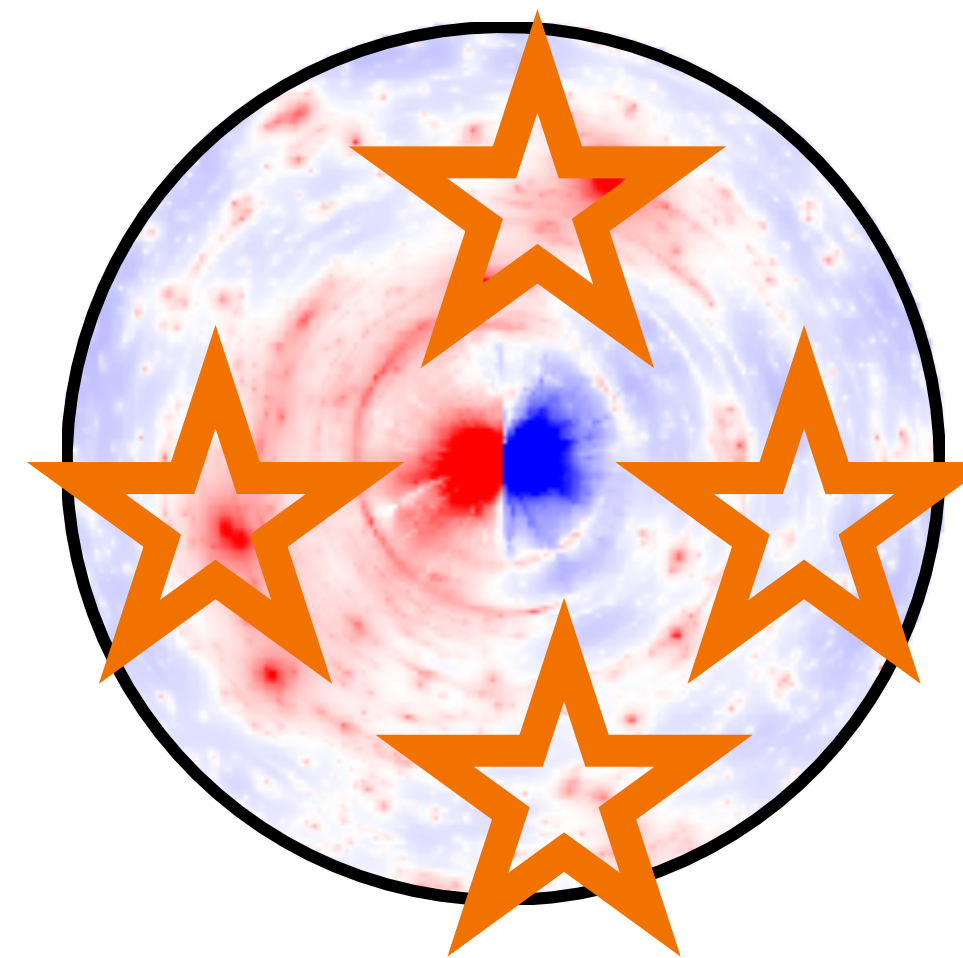
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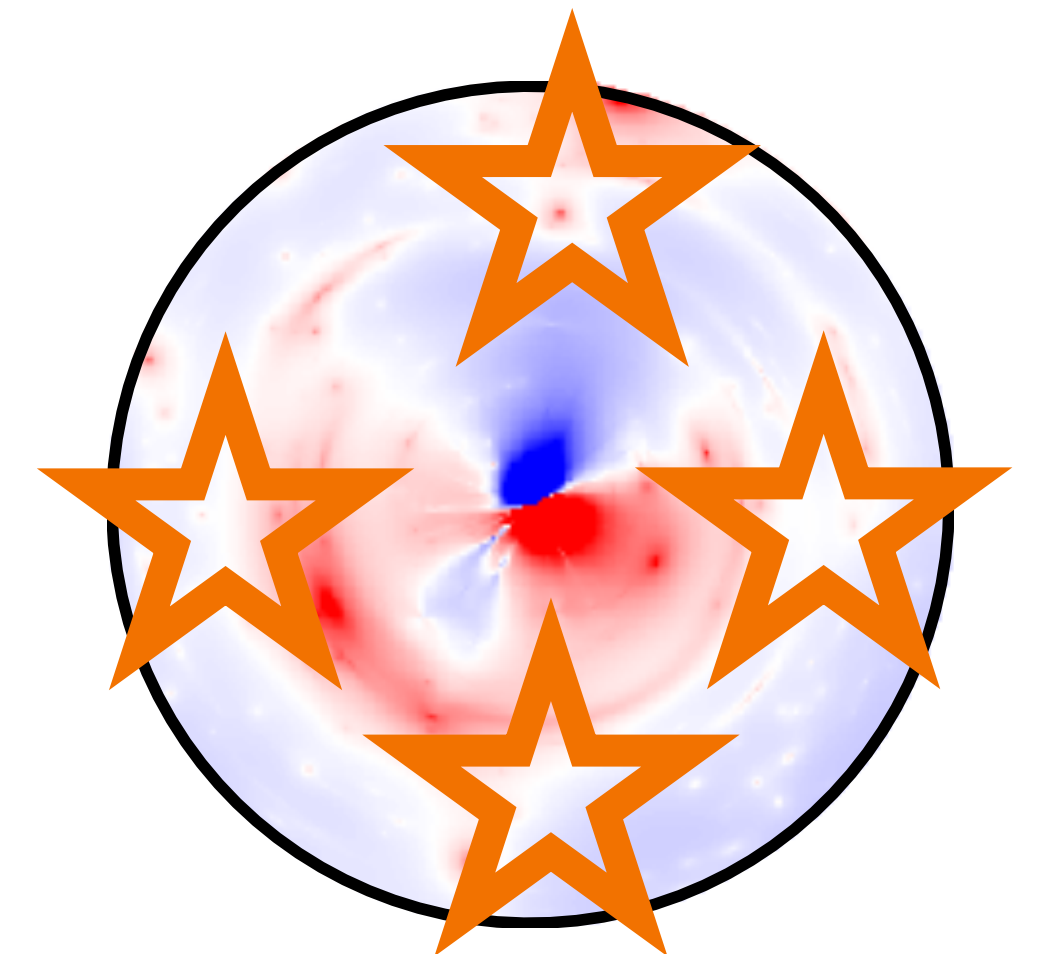
Multi-plane lensing convergence maps



CDM Realization



WDM Realization



Gilman, Birrer, Nierenberg et al. 2020a

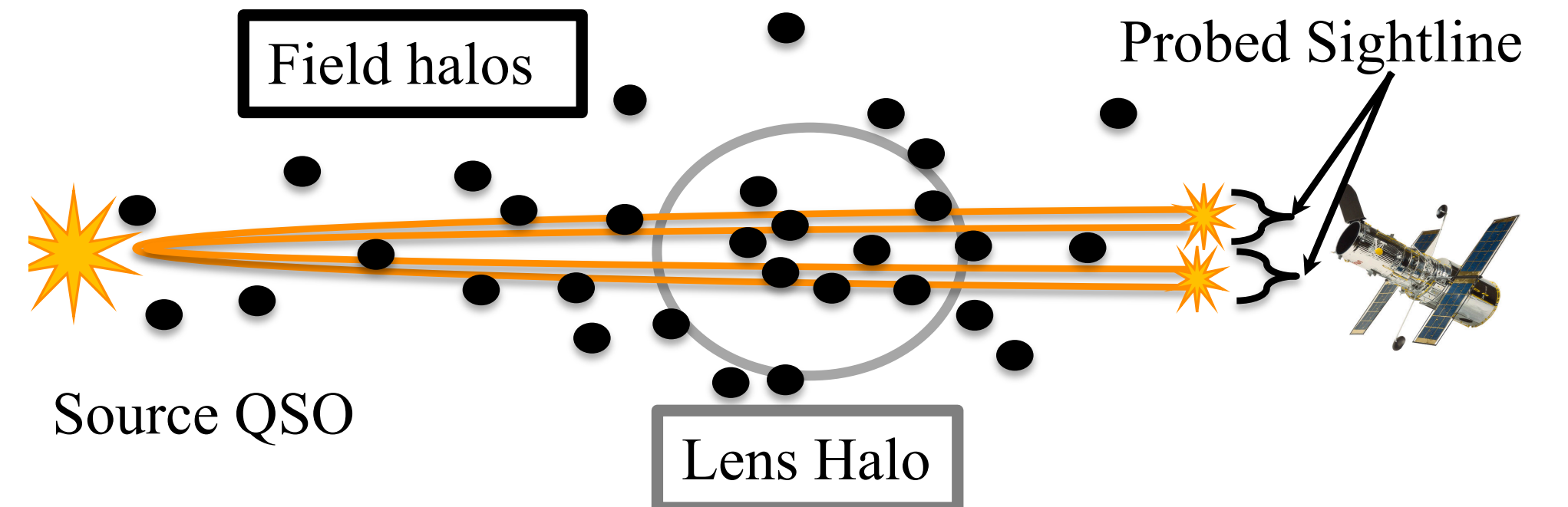
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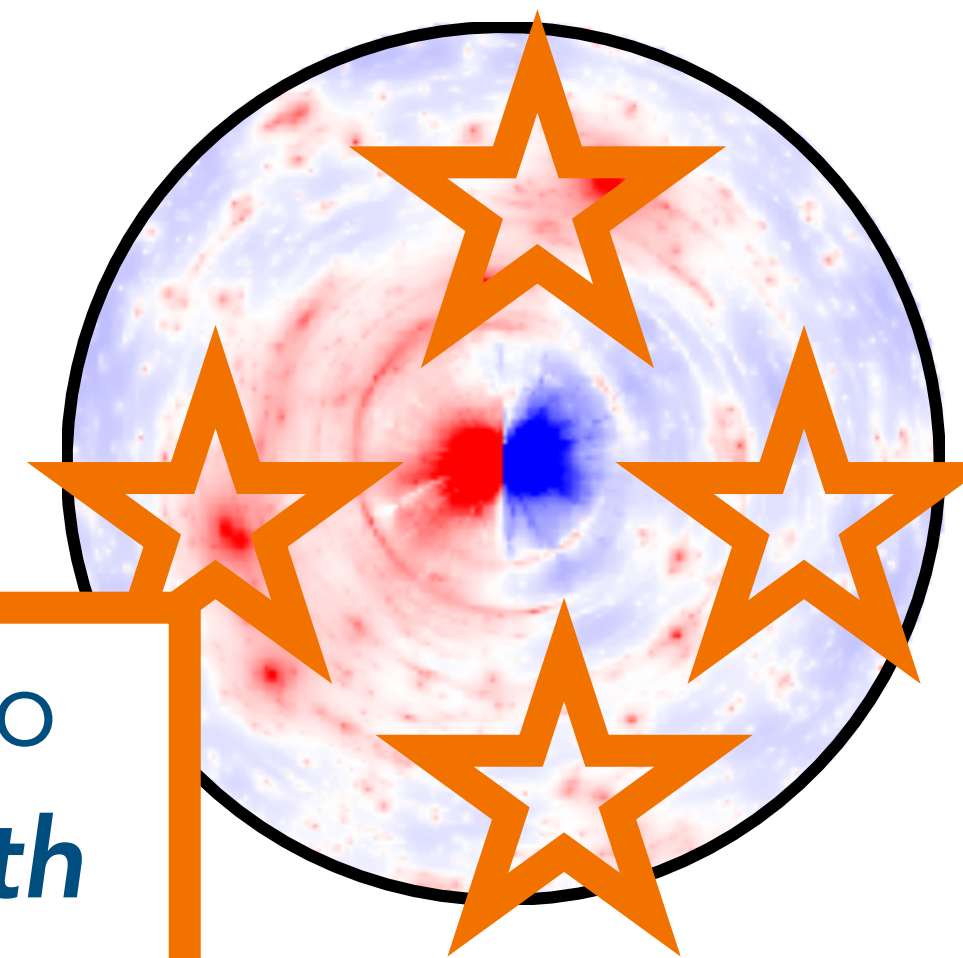
- * Dark matter properties (e.g. half-mode mass)
- * Tidal stripping of subhalos
- * Mass distribution of main deflector (including deviations from ellipticity)
- * Source size

Pipeline and data can be used to test *any dark matter model with analytic description for non-linear density field*

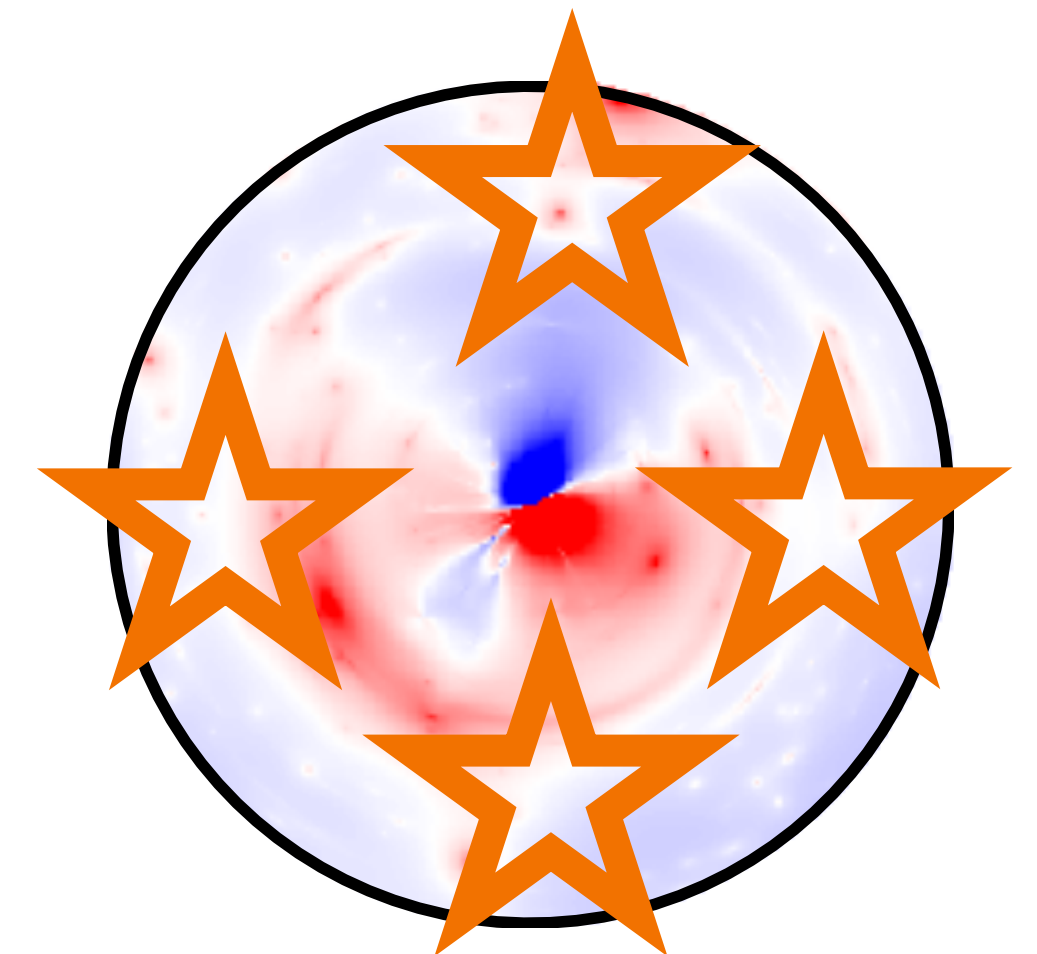
Multi-plane lensing convergence maps



CDM Realization



WDM Realization

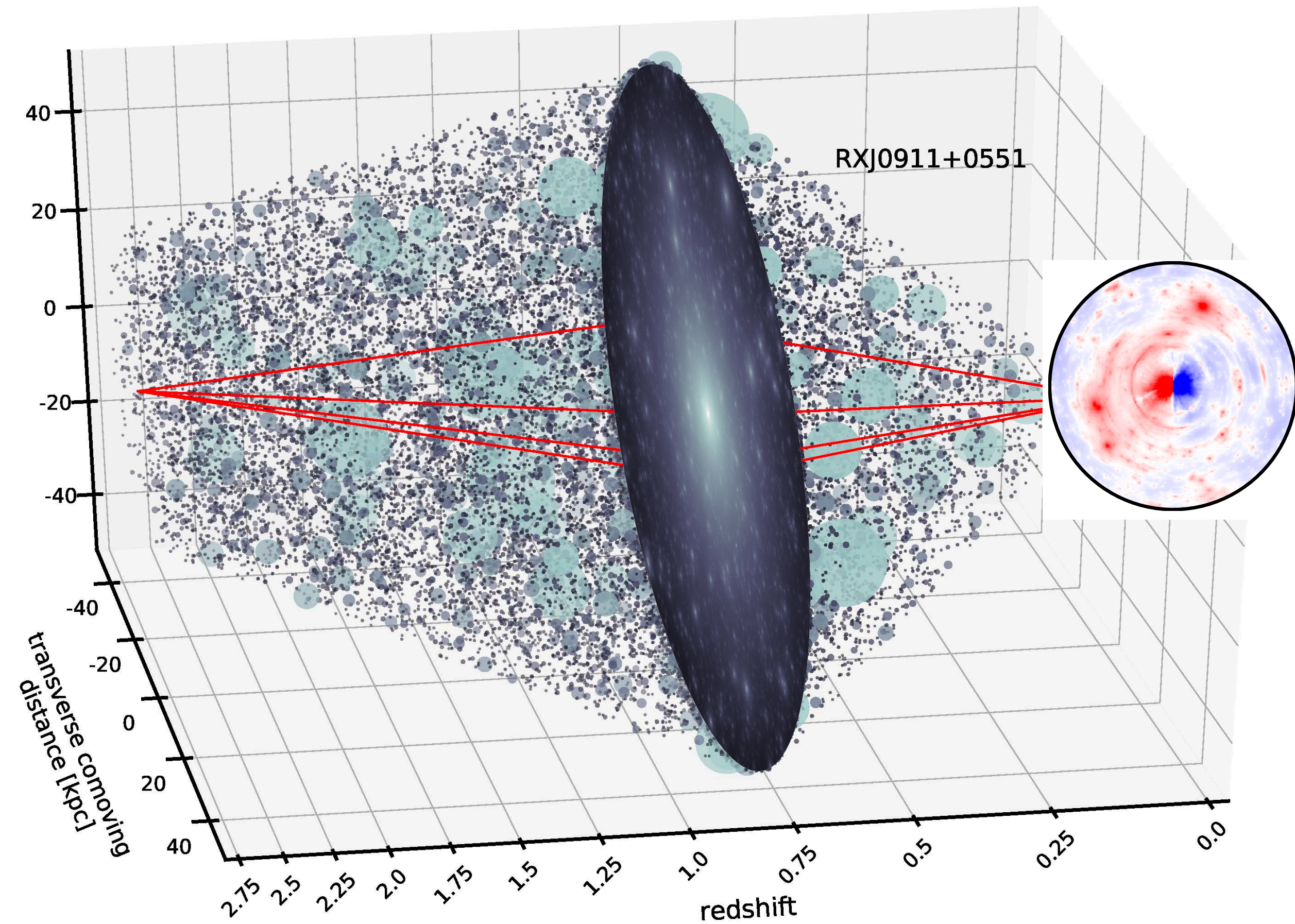


Gilman, Birrer, Nierenberg et al. 2020a

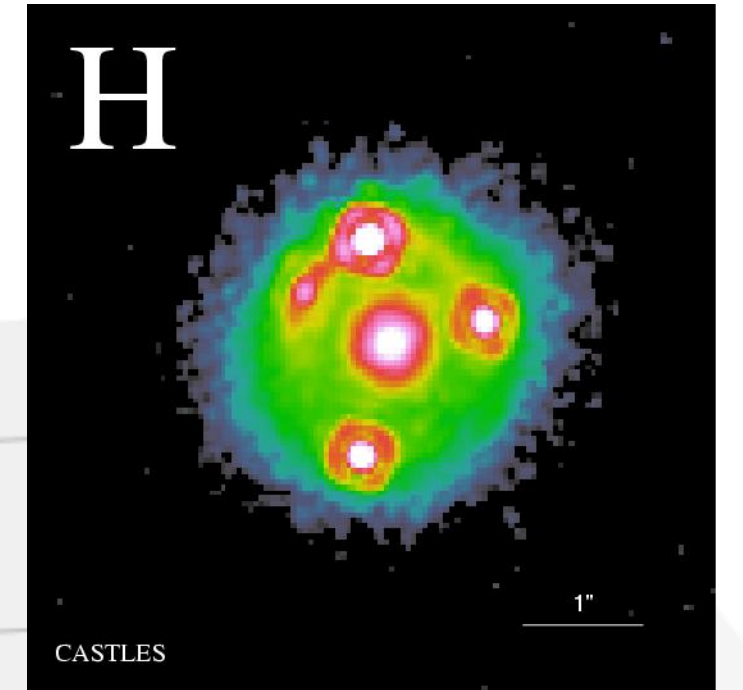
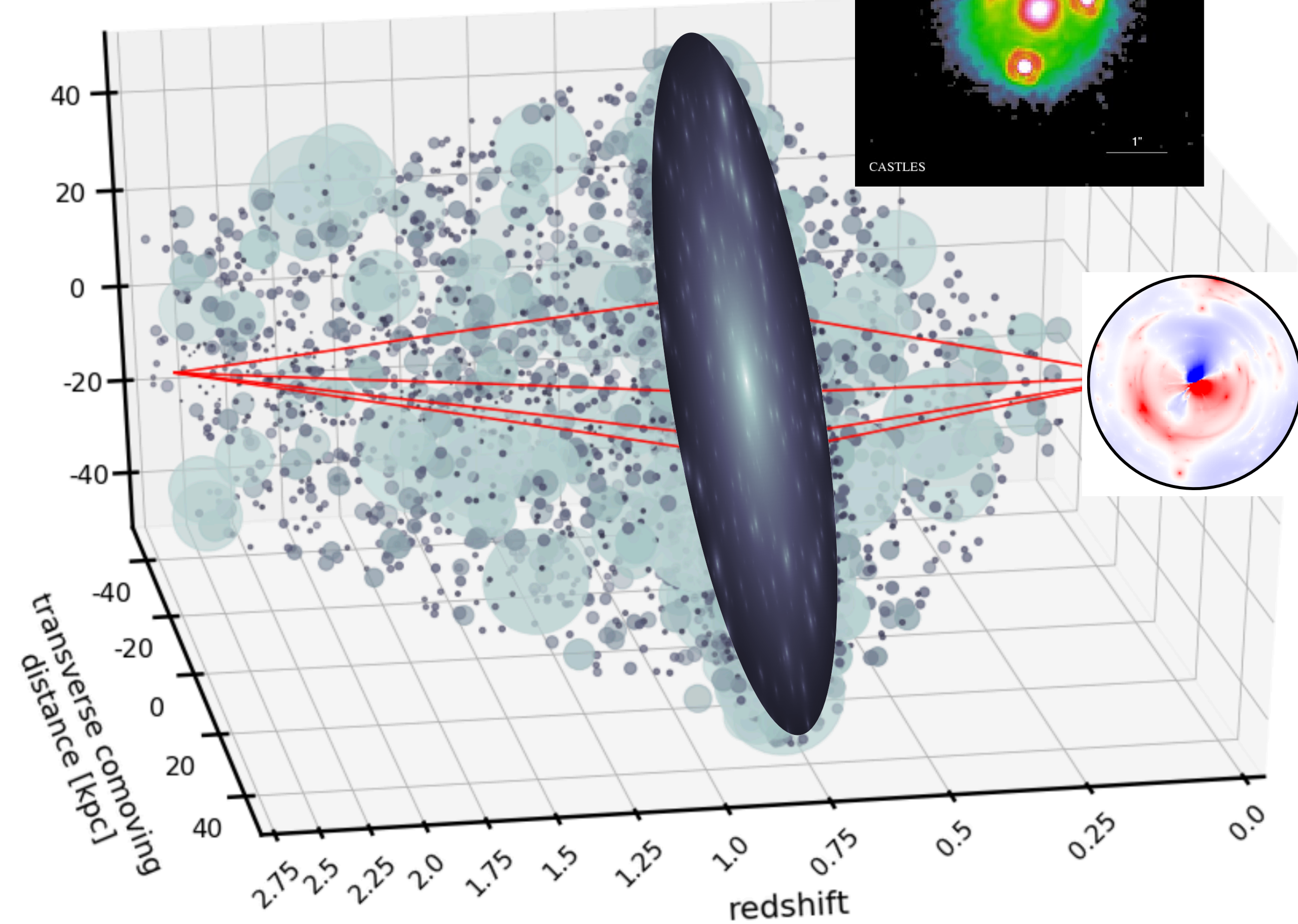
Simulation Pipeline Example

$\sim 10^5 - 10^6$ simulations per lens for accurate statistics

CDM



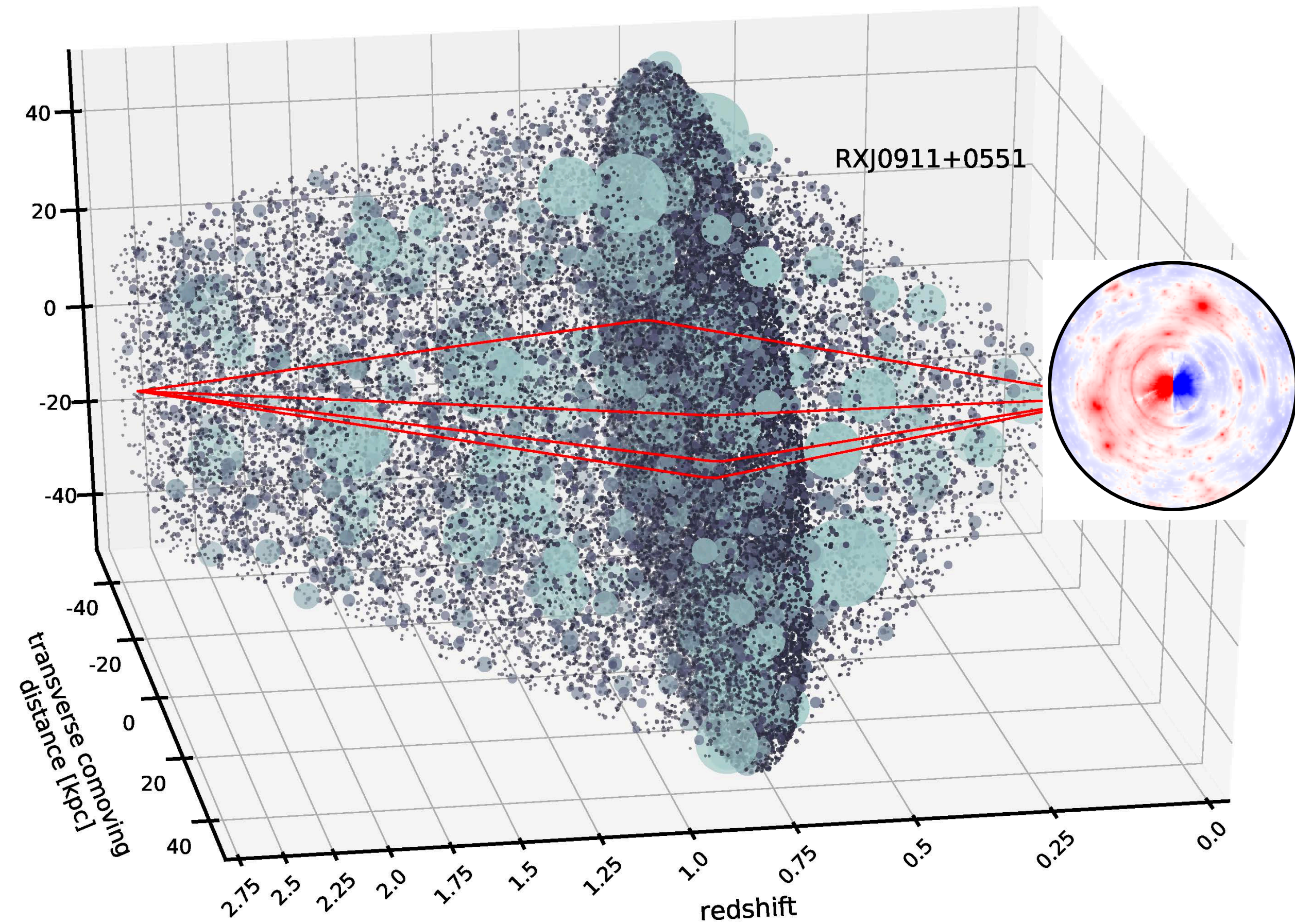
WDM



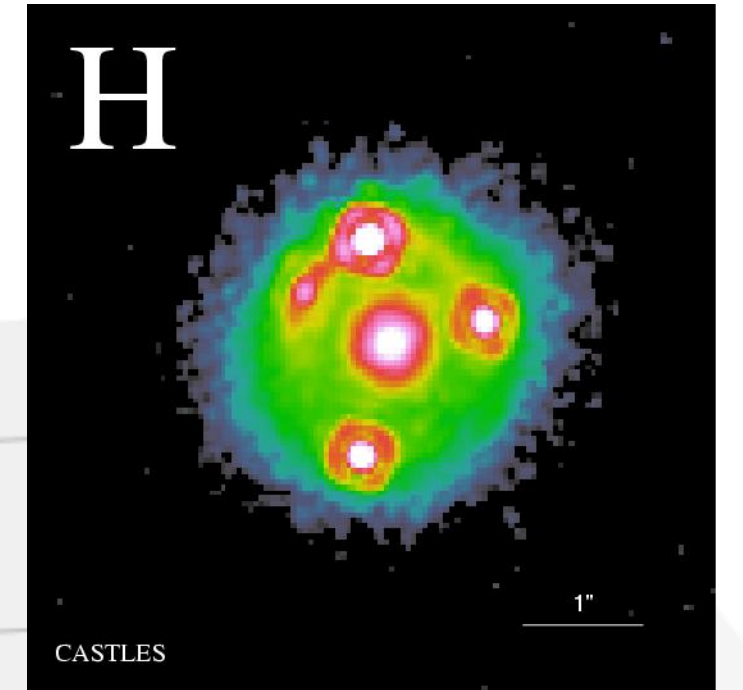
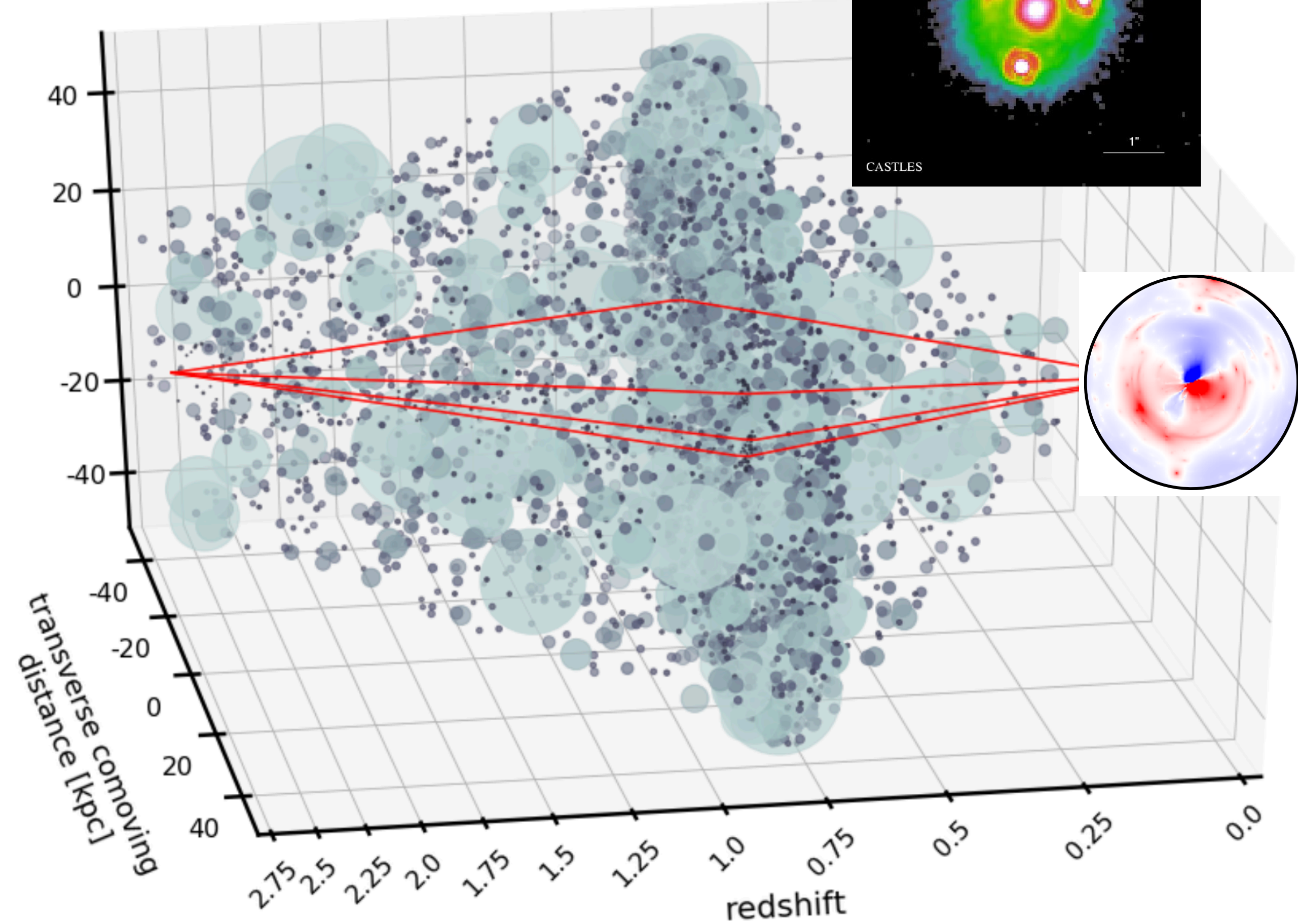
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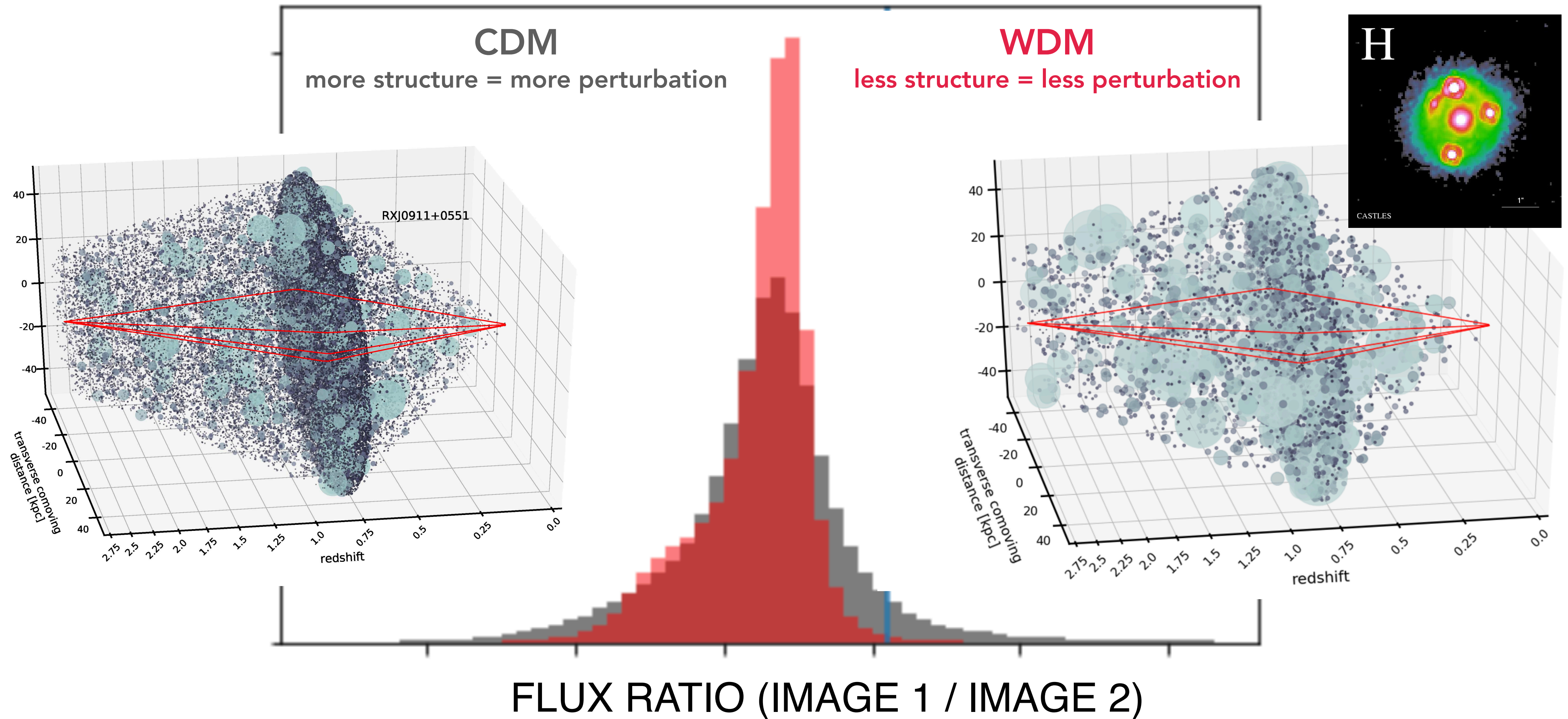
CDM



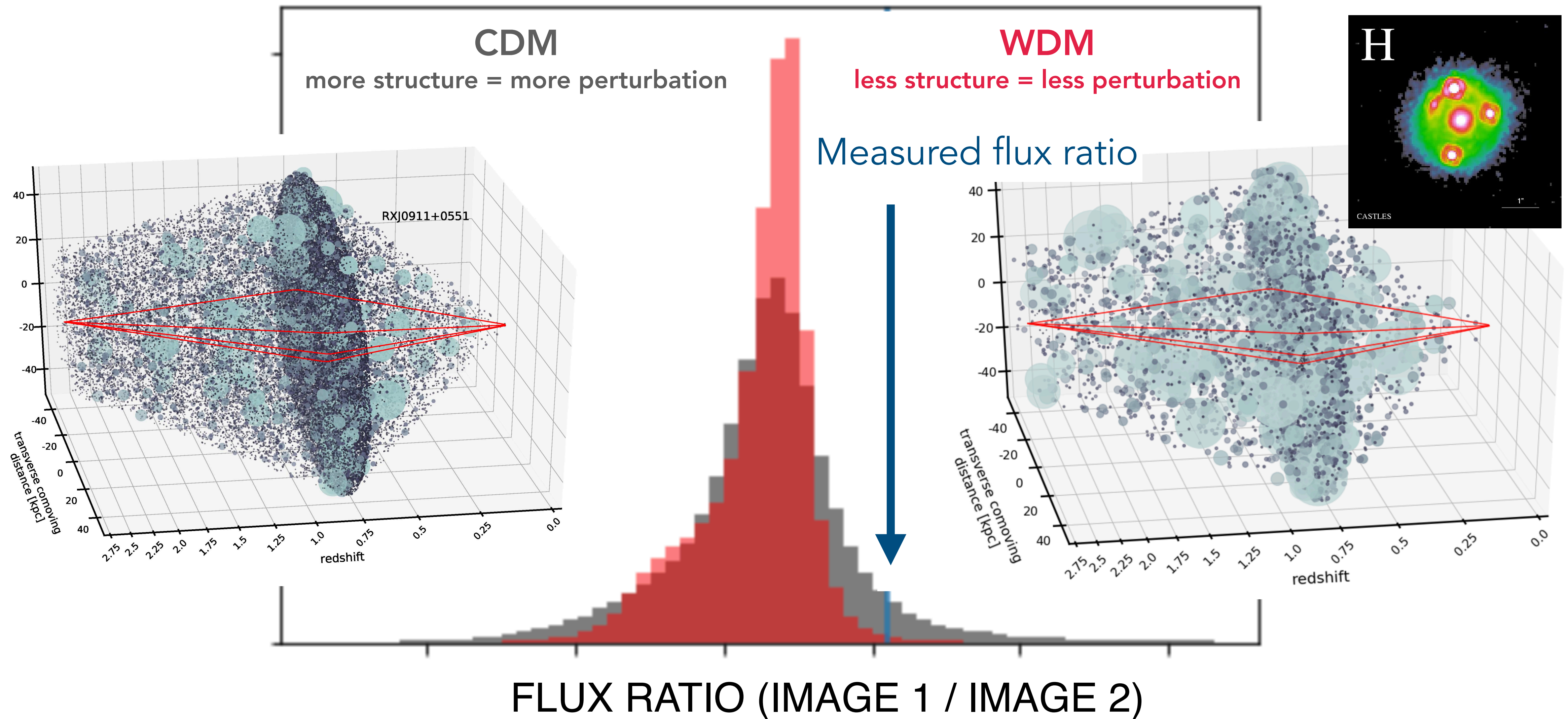
WDM



Compare measurement with simulation distribution

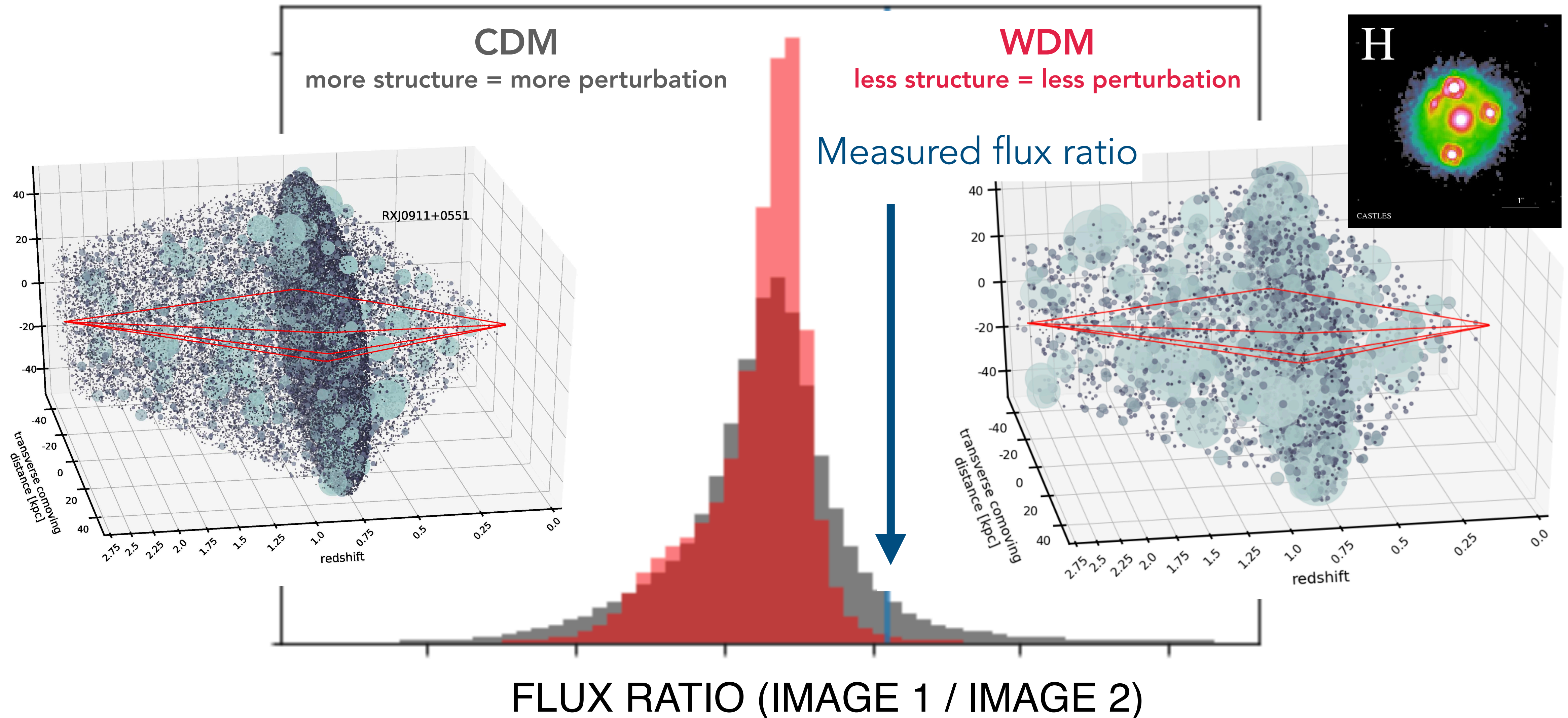


Compare measurement with simulation distribution



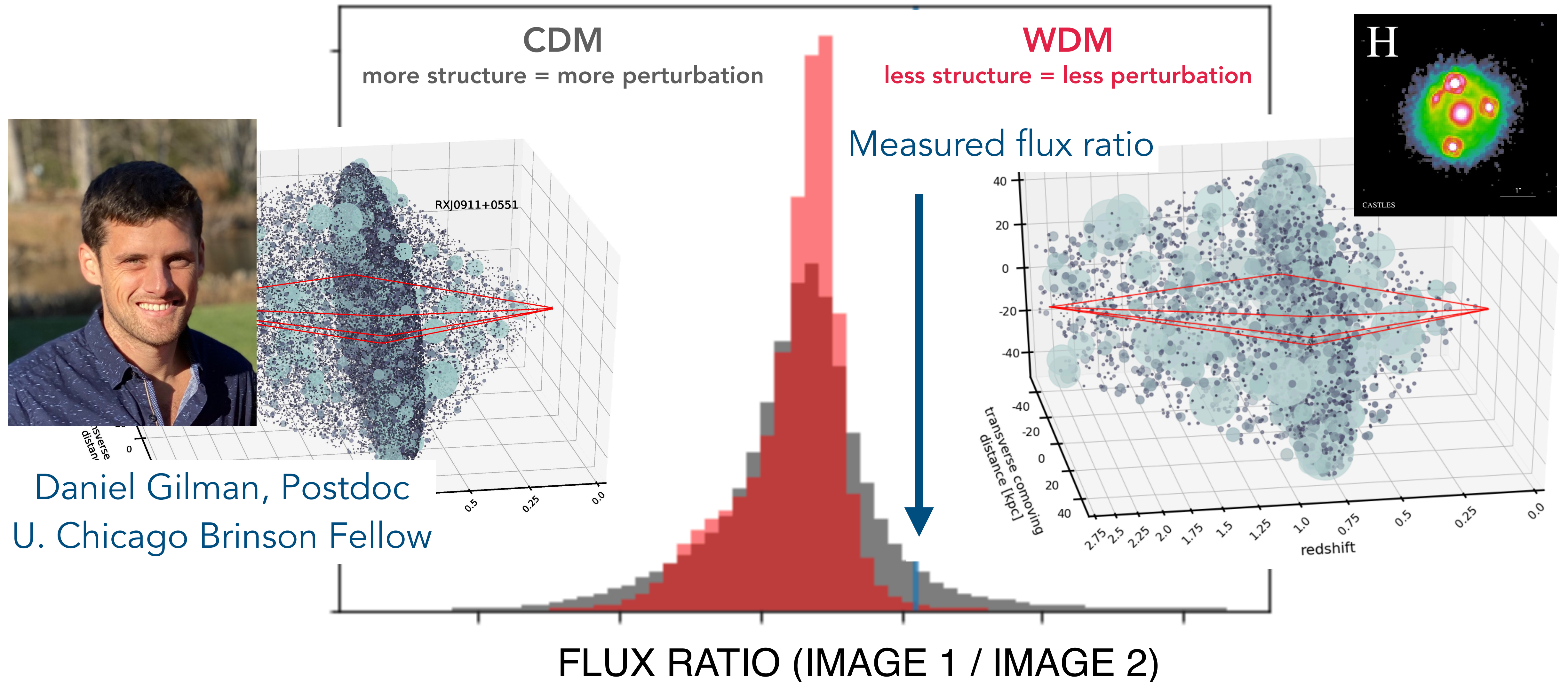
Compare measurement with simulation distribution

3 flux ratios per lens each with different responses to variations in macromodel/substructure



Compare measurement with simulation distribution

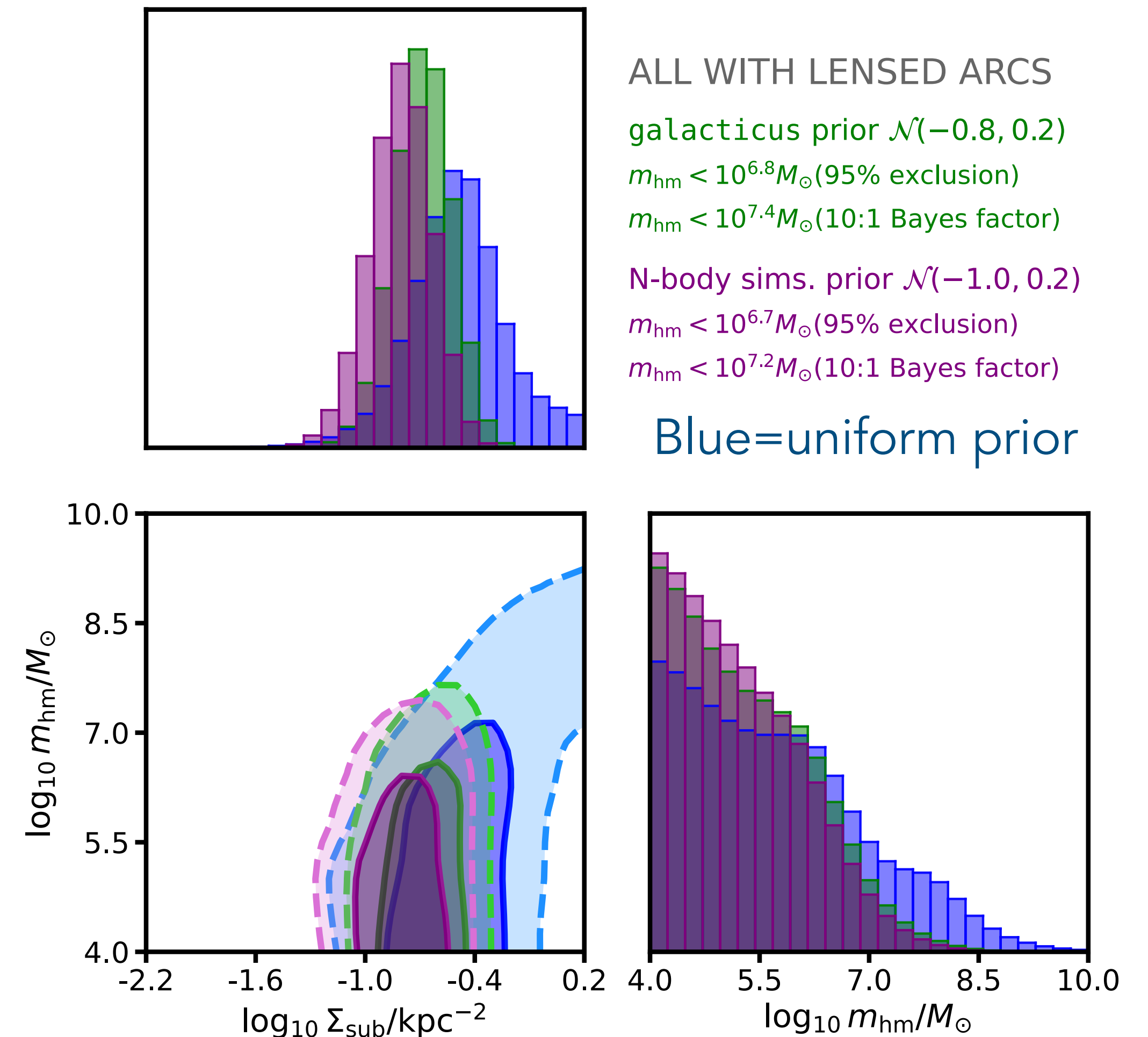
3 flux ratios per lens each with different responses to variations in macromodel/substructure



How warm can dark matter be?

Thermal relic mass > 10.2 (9.6) keV
N-body (galacticus prior)

Comparable to or stronger than
any other existing single method
measurement of WDM



Keeley, Nierenberg et al. 2026
Gilman, Nierenberg et al. 2026 a, b

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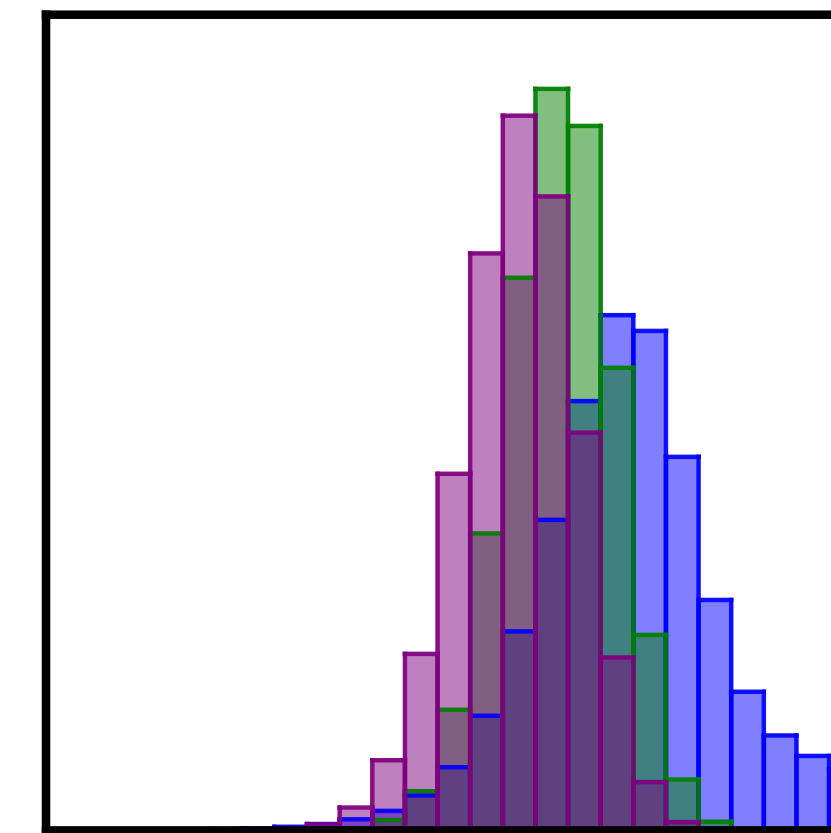
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MW satellites $m_{\text{th}} > 6.5$ keV
(Nadler 2021)

Ly-alpha forest $m_{\text{th}} > 3.1$ keV
(Villaseñor 2023)

Stellar streams

Stellar streams $m_{\text{th}} > 3.6$ keV
(Banik 2019)



ALL WITH LENSED ARCS

galacticus prior $\mathcal{N}(-0.8, 0.2)$

$m_{\text{hm}} < 10^{6.8} M_{\odot}$ (95% exclusion)

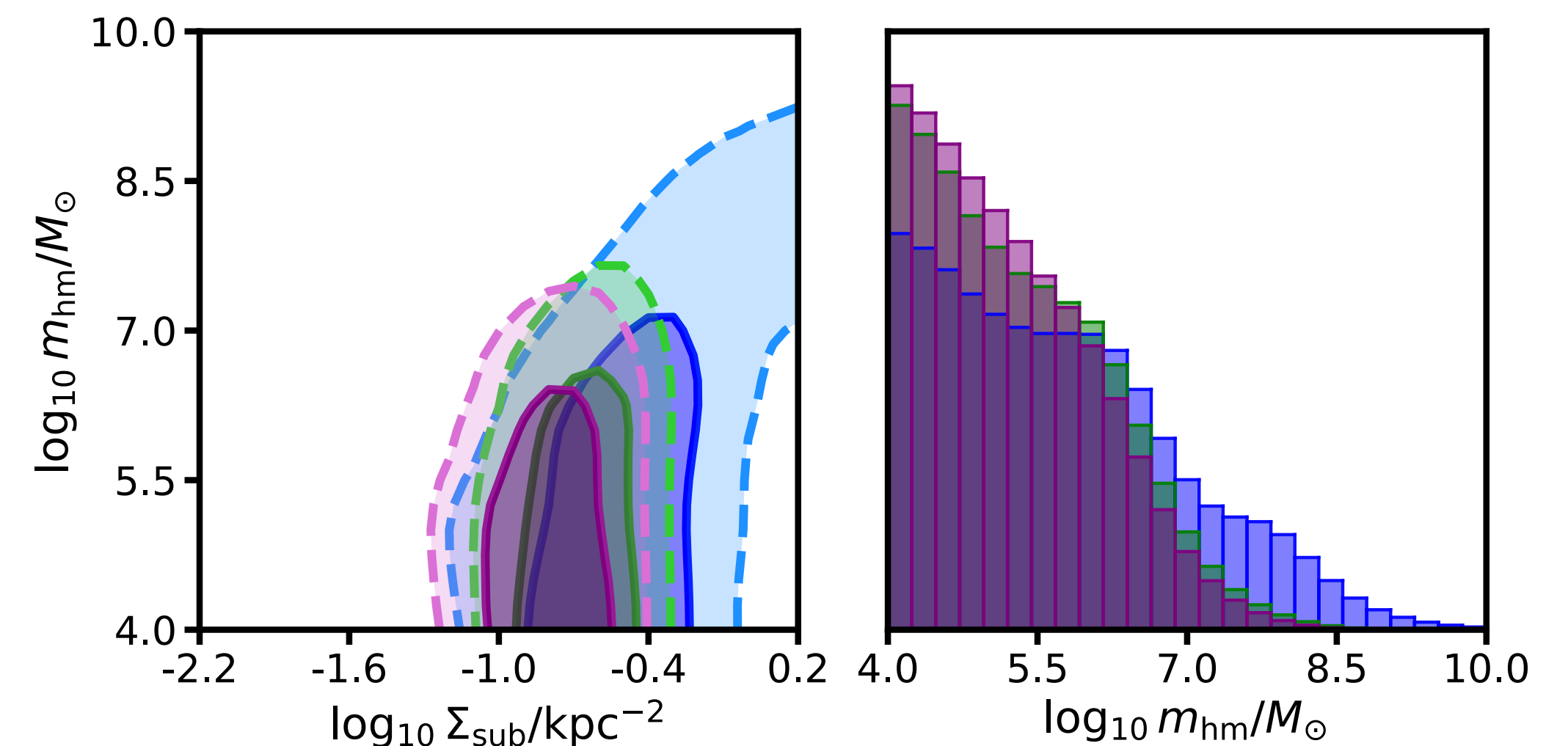
$m_{\text{hm}} < 10^{7.4} M_{\odot}$ (10:1 Bayes factor)

N-body sims. prior $\mathcal{N}(-1.0, 0.2)$

$m_{\text{hm}} < 10^{6.7} M_{\odot}$ (95% exclusion)

$m_{\text{hm}} < 10^{7.2} M_{\odot}$ (10:1 Bayes factor)

Blue=uniform prior

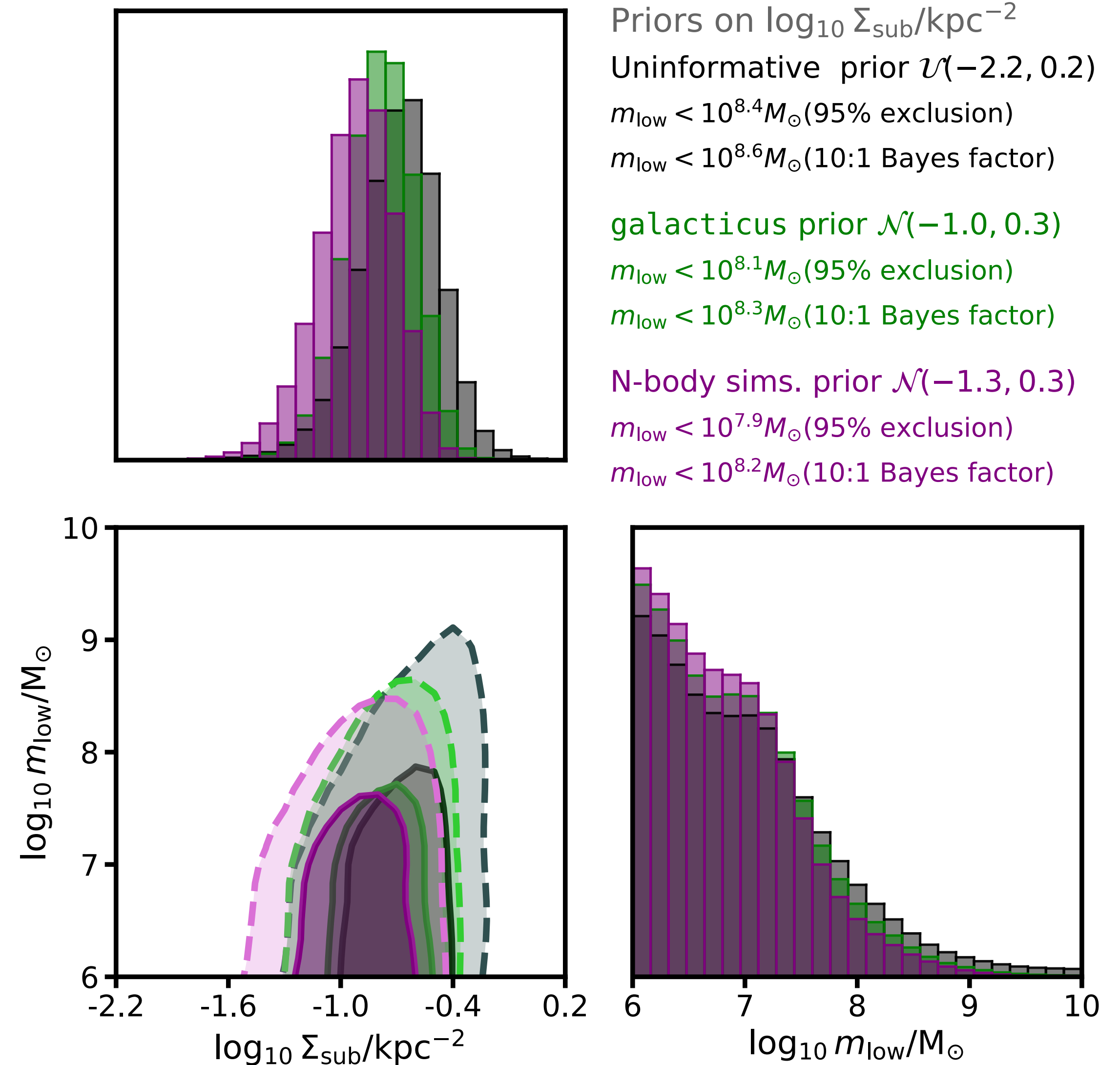


Keeley, Nierenberg et al. 2026

Gilman, Nierenberg et al. 2026 a, b

What are the lowest mass halos that must exist?

$m_{\text{low}} < 10^{8.1} \text{ (} 10^{7.9} \text{)} M_{\odot}$
N-body (galacticus) priors



Nierenberg et al. 2026

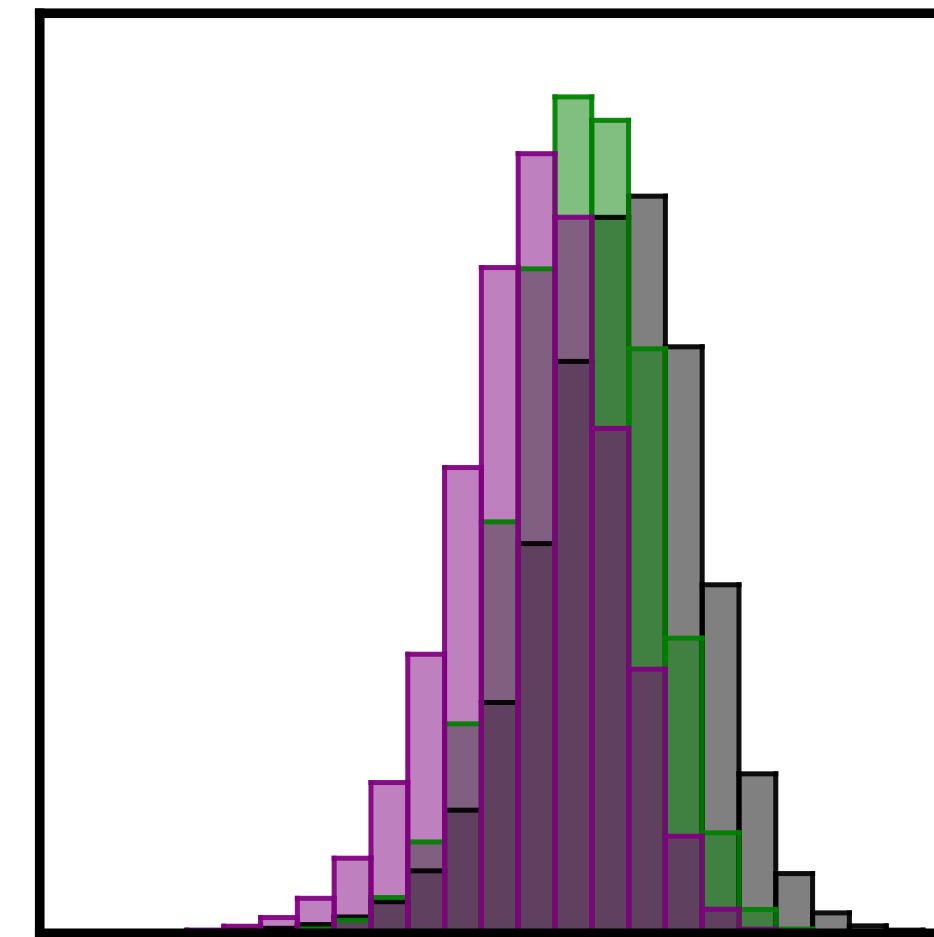
What are the lowest mass halos that must exist?

$$m_{\text{low}} < 10^{8.1} \text{ (} 10^{7.9} \text{)} M_{\odot}$$

N-body (galacticus) priors

Comparable to current constraints
from MW satellites

$$m_{\text{low}} < 10^{8.4} M_{\odot} \text{ (Nadler 2021)}$$



Priors on $\log_{10} \Sigma_{\text{sub}}/\text{kpc}^{-2}$

Uninformative prior $\mathcal{U}(-2.2, 0.2)$

$m_{\text{low}} < 10^{8.4} M_{\odot}$ (95% exclusion)

$m_{\text{low}} < 10^{8.6} M_{\odot}$ (10:1 Bayes factor)

galacticus prior $\mathcal{N}(-1.0, 0.3)$

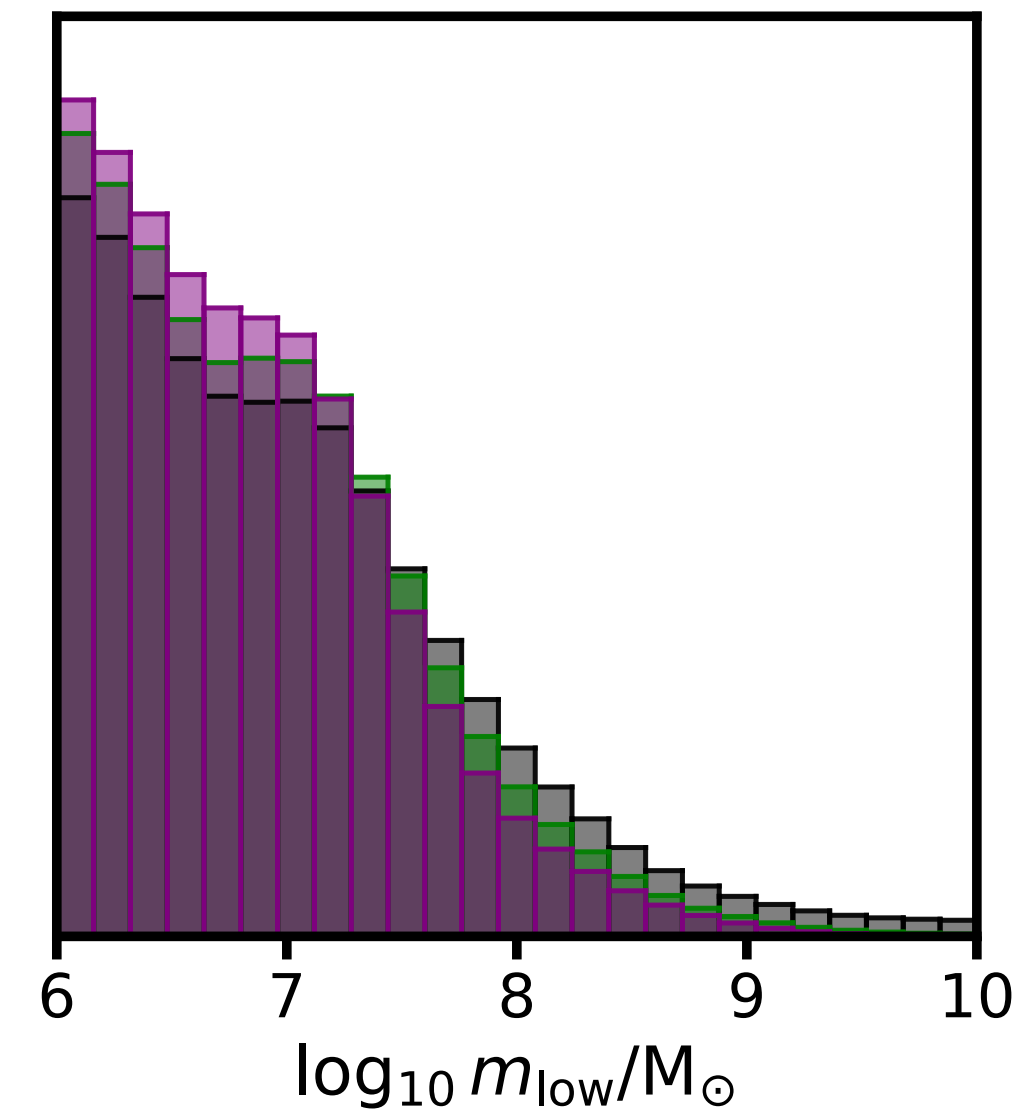
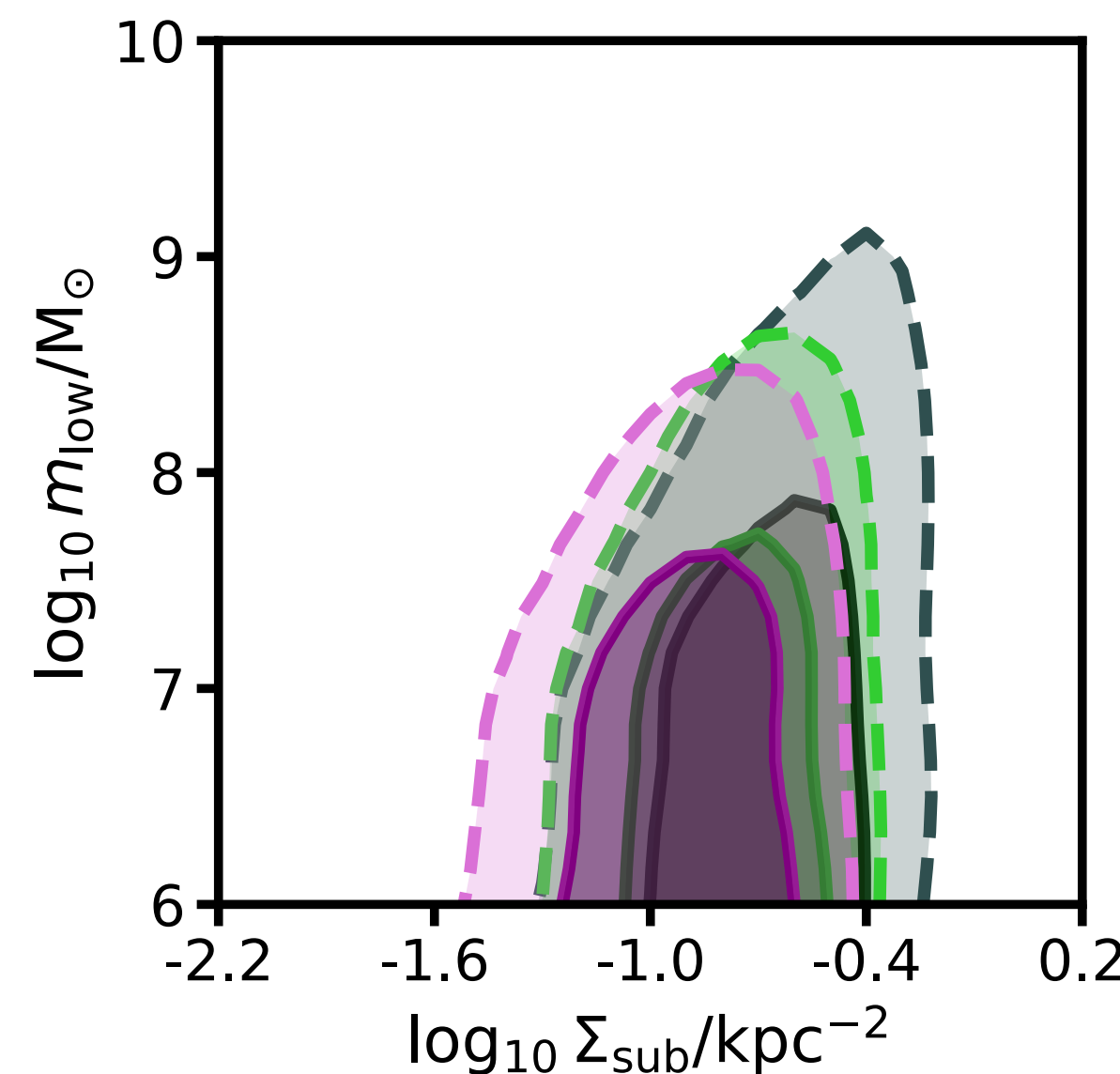
$m_{\text{low}} < 10^{8.1} M_{\odot}$ (95% exclusion)

$m_{\text{low}} < 10^{8.3} M_{\odot}$ (10:1 Bayes factor)

N-body sims. prior $\mathcal{N}(-1.3, 0.3)$

$m_{\text{low}} < 10^{7.9} M_{\odot}$ (95% exclusion)

$m_{\text{low}} < 10^{8.2} M_{\odot}$ (10:1 Bayes factor)

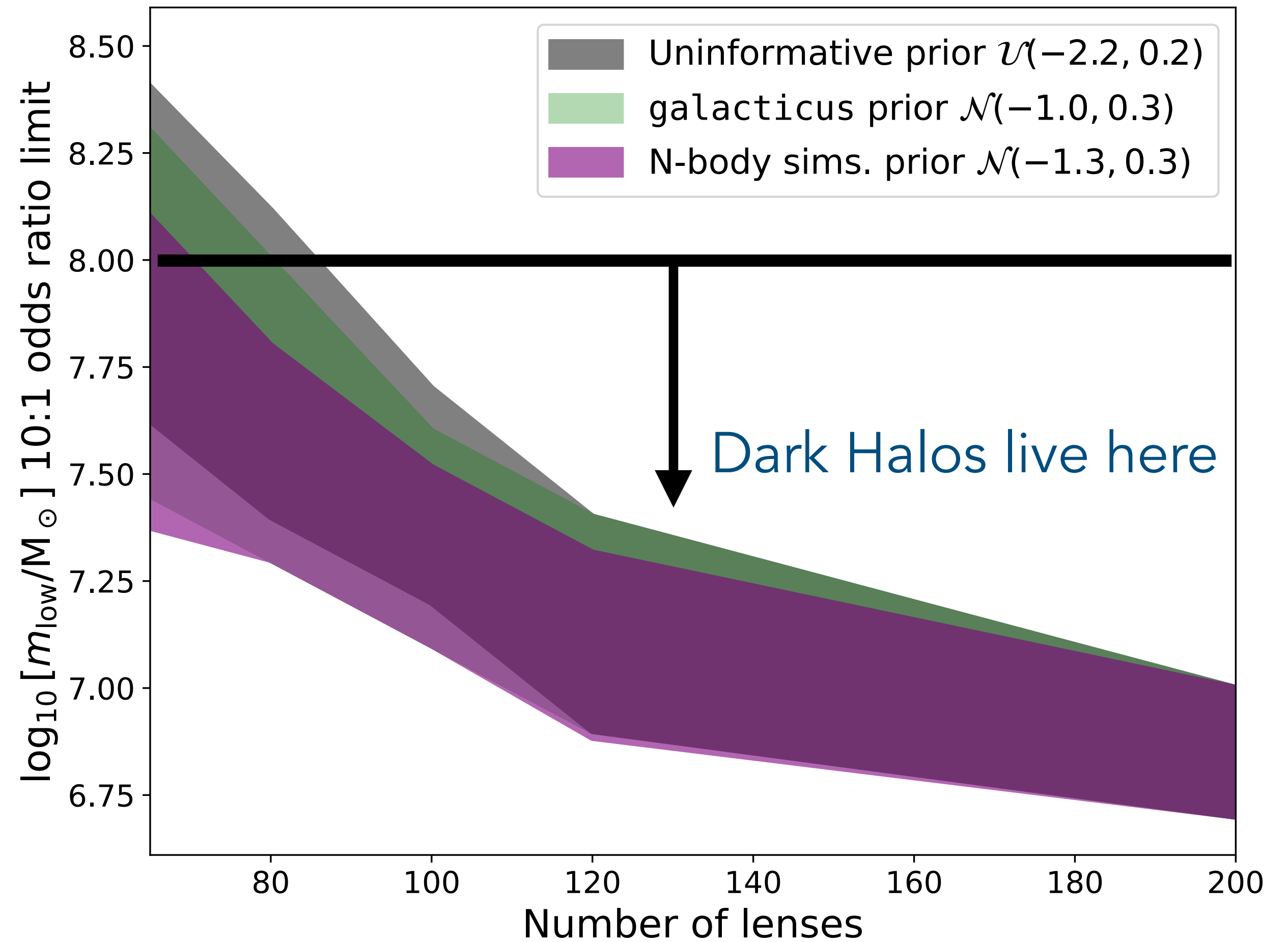


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The future

- * Stay tuned for constraints of other dark matter models
- * Hundreds of new lenses with Euclid/LSST
- * Measurements of flux ratios with Keck

Forecast measurement for 200 lenses



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How CCAPP helped me get here!

- * Strongly multidisciplinary environment with collaboration between many research groups
- * Faculty mentors in a range of disciplines
- * Constant guidance and support from all faculty
- * Learned the importance of faculty participation in department events (AstroCoffee)



Conclusions

- * Gravitational lensing enables us to measure the properties of dark matter, **consistently revealing low-mass structure signals in lenses.**
- * Our pipeline enables a **broad range of dark matter models** to be tested
- * Lensing has a **bright future** with many new lenses being discovered and new instruments/telescopes being built

This work supported by

