Measuring the properties of dark matter with galaxy-scale strong gravitational lenses

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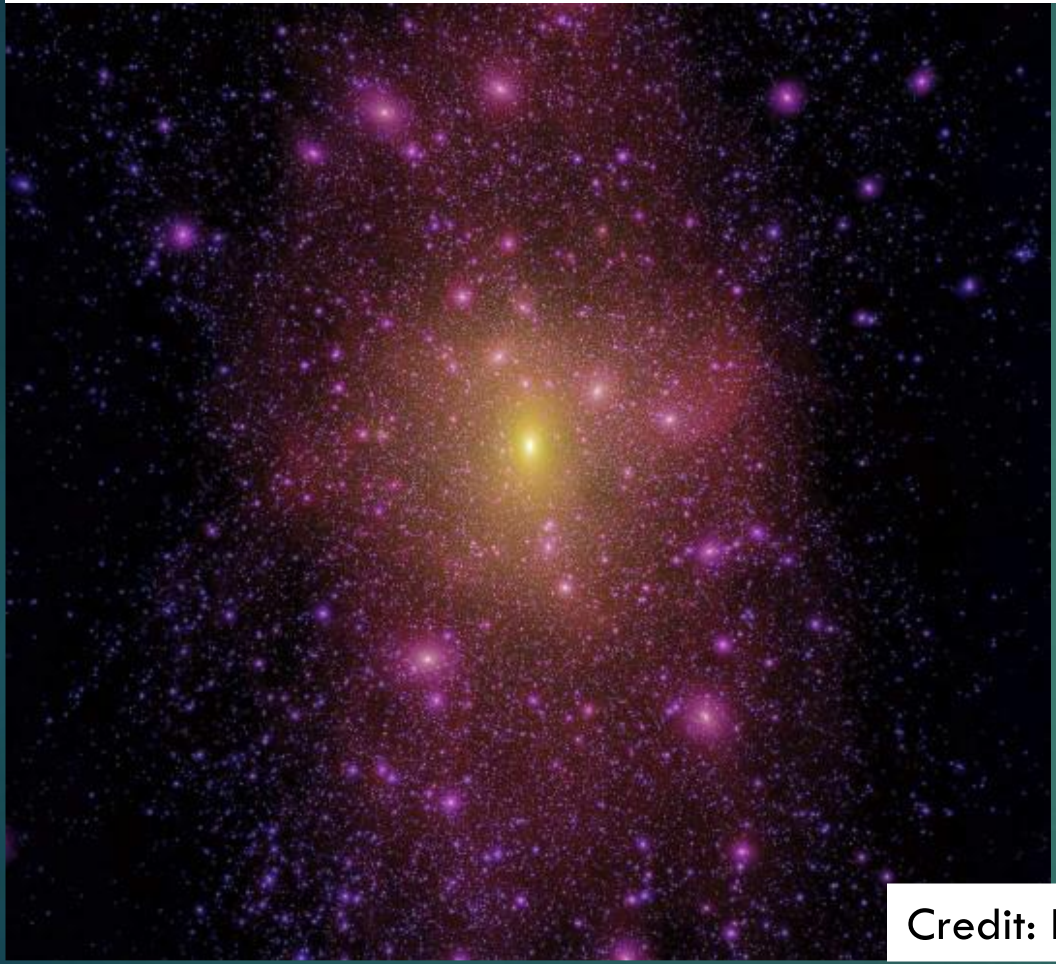
Overview

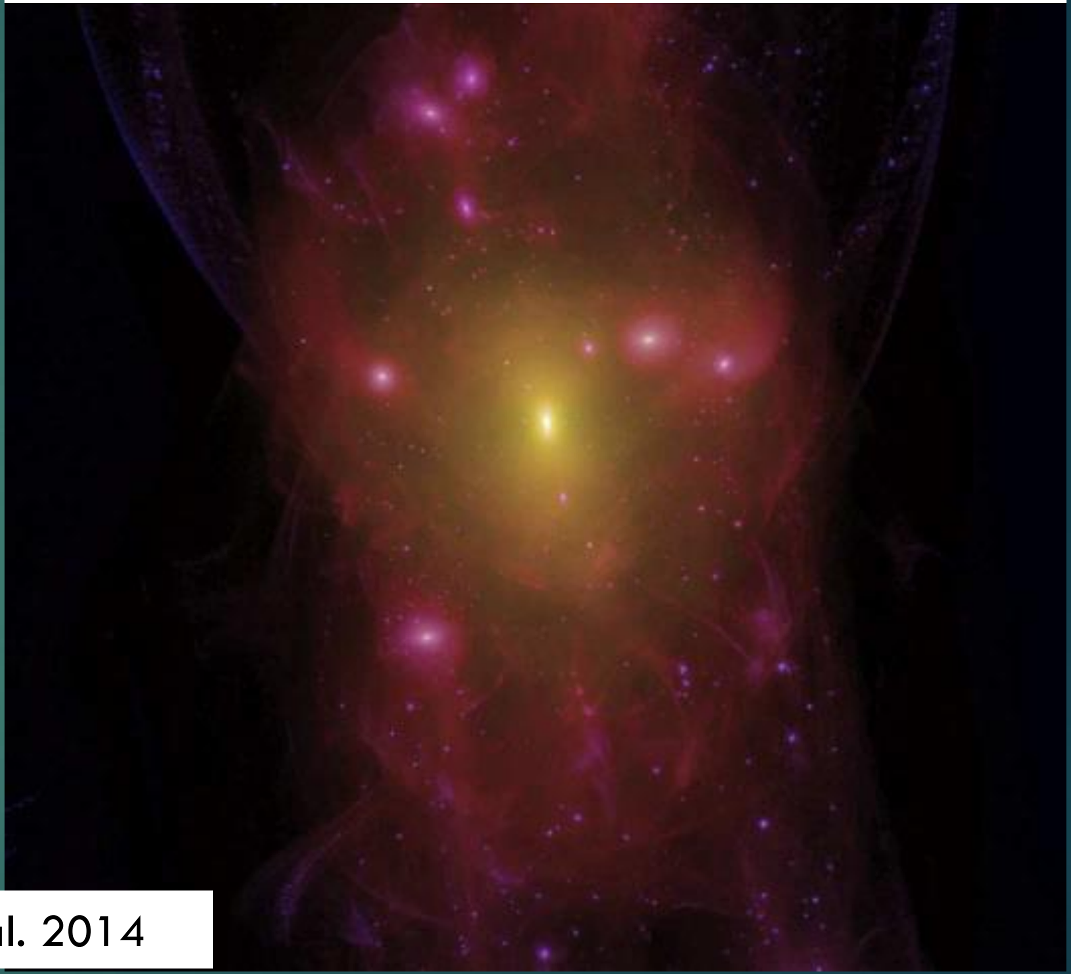
- Gravitational lensing-dark matter connection
- Overview of techniques
- Recent Results
- Future Prospects

Different dark matter models <-> different dark matter halos

Cold Dark Matter e.g. WIMP



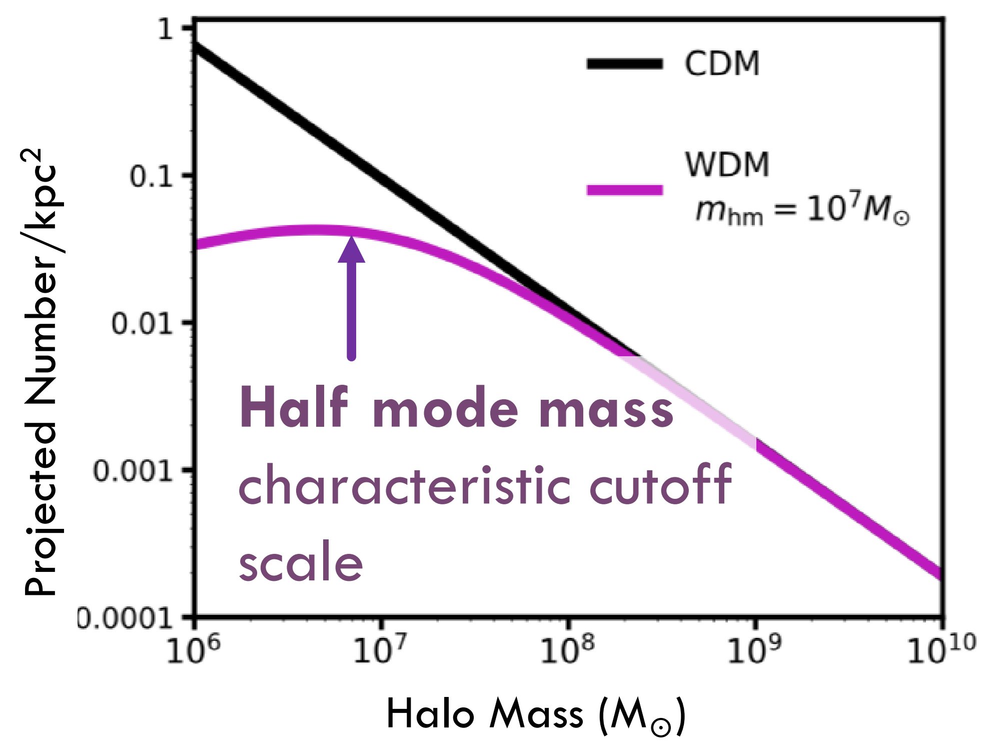
Warm Dark Matter – e.g. Sterile Neutrino



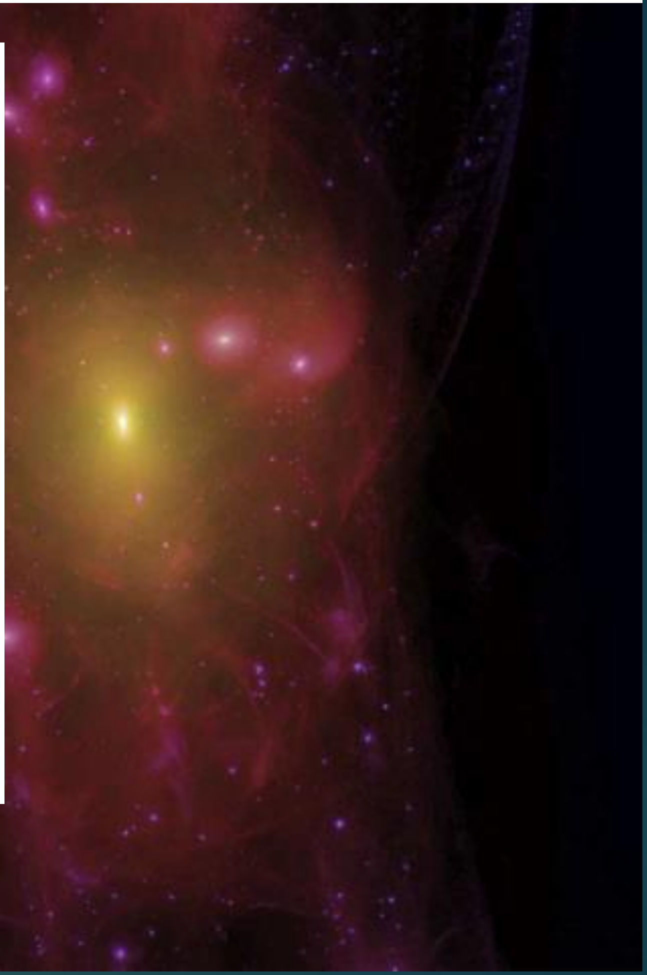
Credit: Lovell et al. 2014

Different halo **Mass Functions**

Cold Dark Matter e.g. WIMP

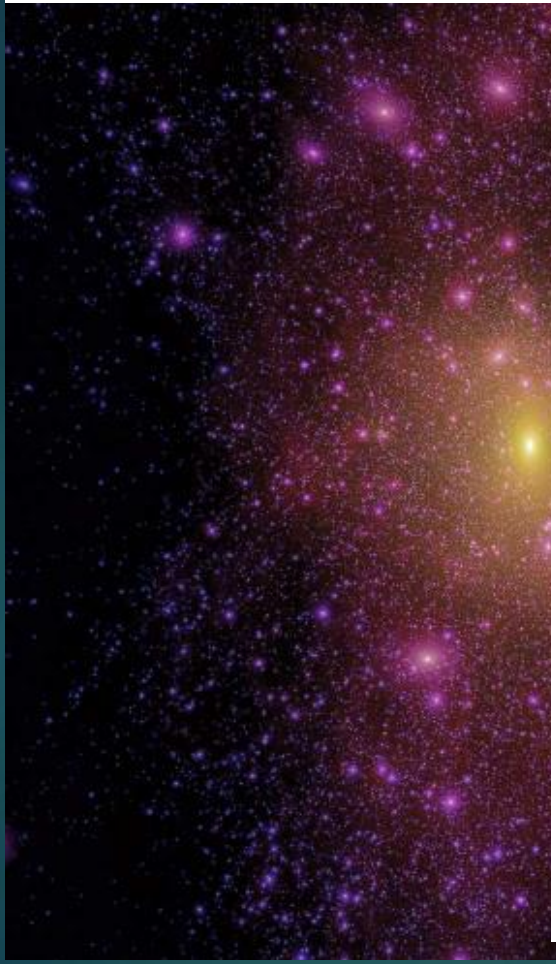


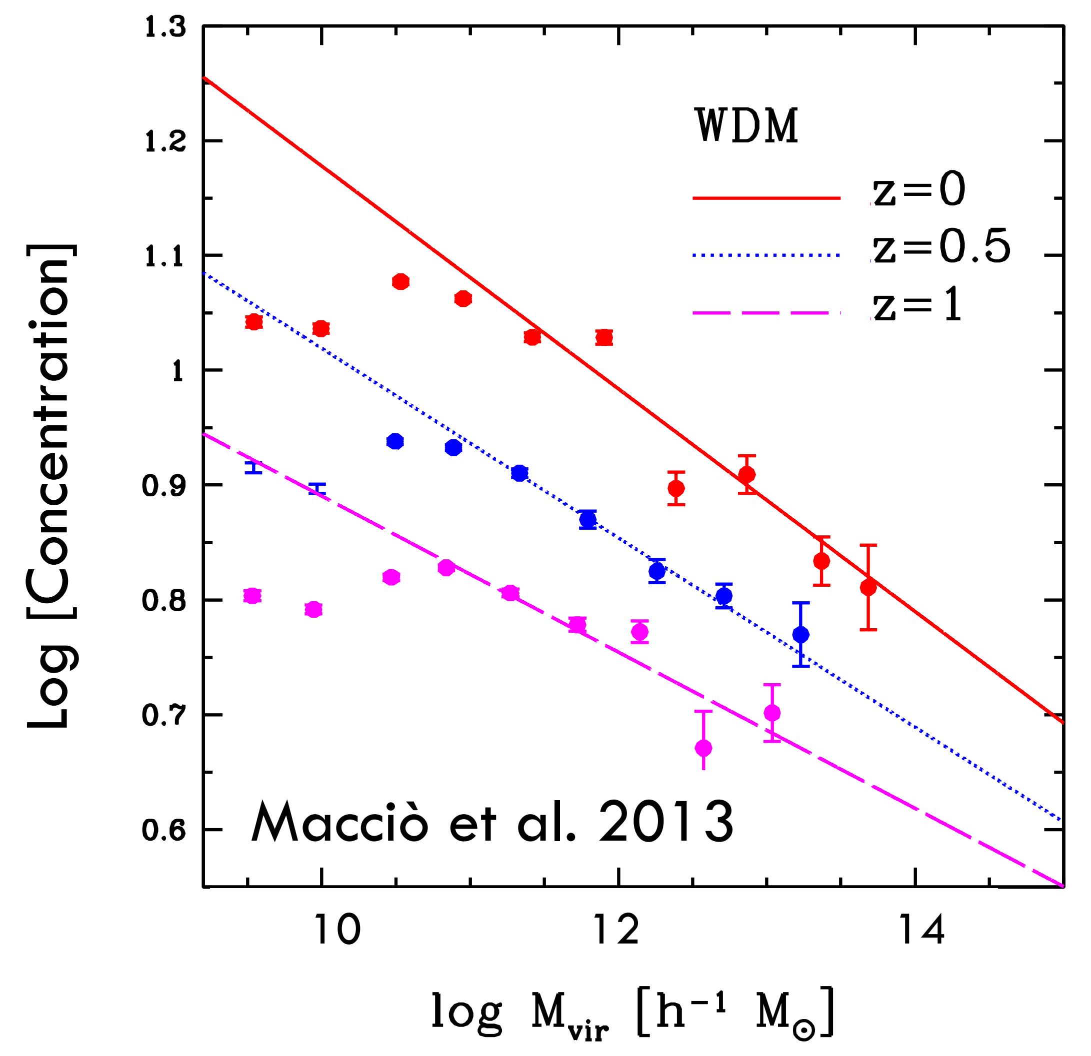
Warm Dark Matter – e.g. Sterile Neutrino



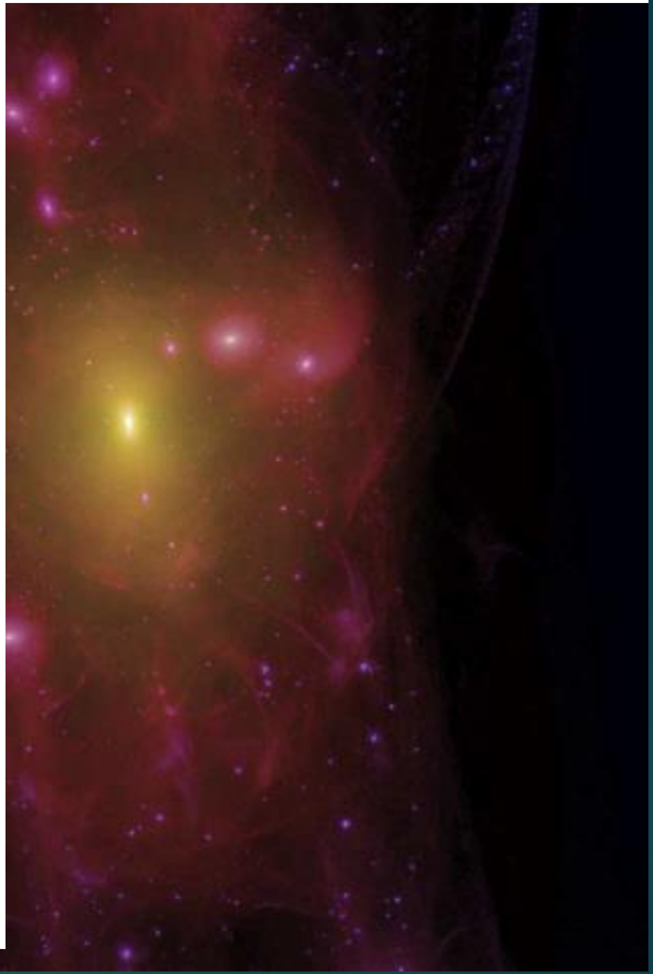
Different halo **Density Profiles**

Cold Dark Matter e.g. W



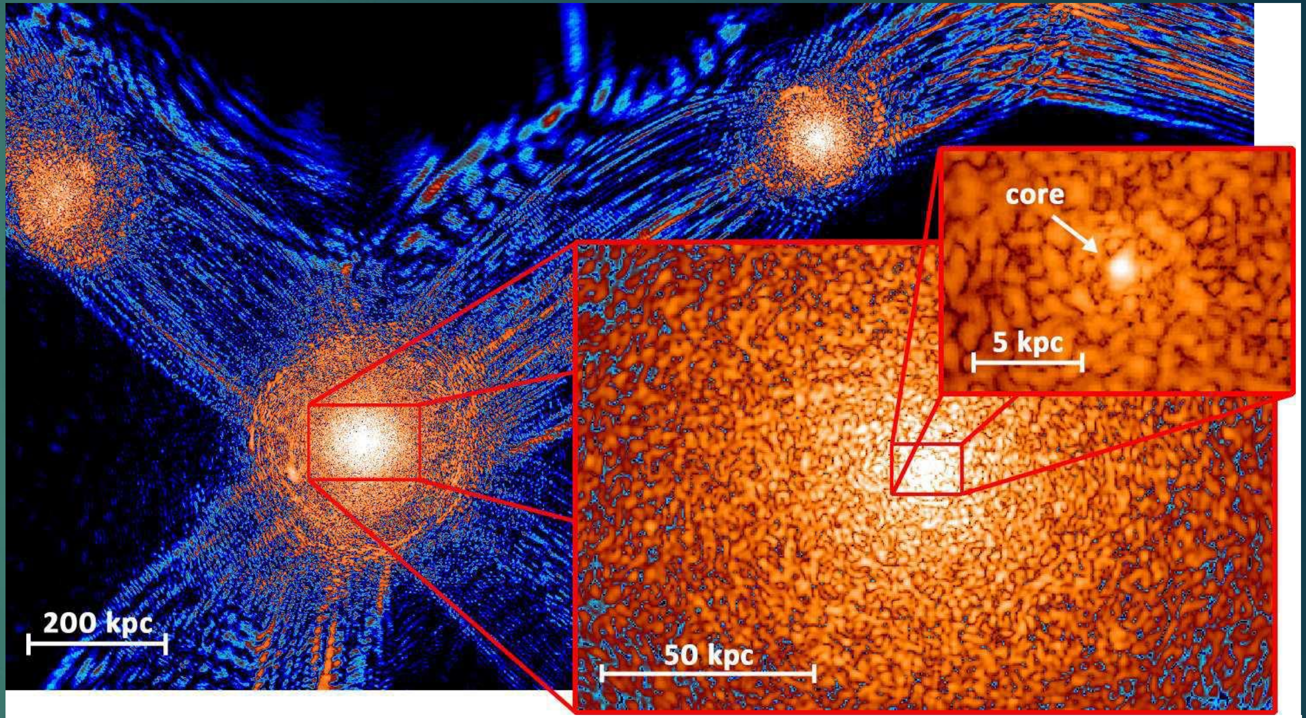


- e.g. Sterile Neutrino



A huge space of dark matter models to explore

- Weakly Interacting Massive Particles (WIMPs)
- Sterile Neutrinos
- Axions
- **Primordial black holes** – (Massive Compact Halo Objects) explain LIGO detections, seeds for supermassive black holes.
- Self-interacting dark matter
- ….



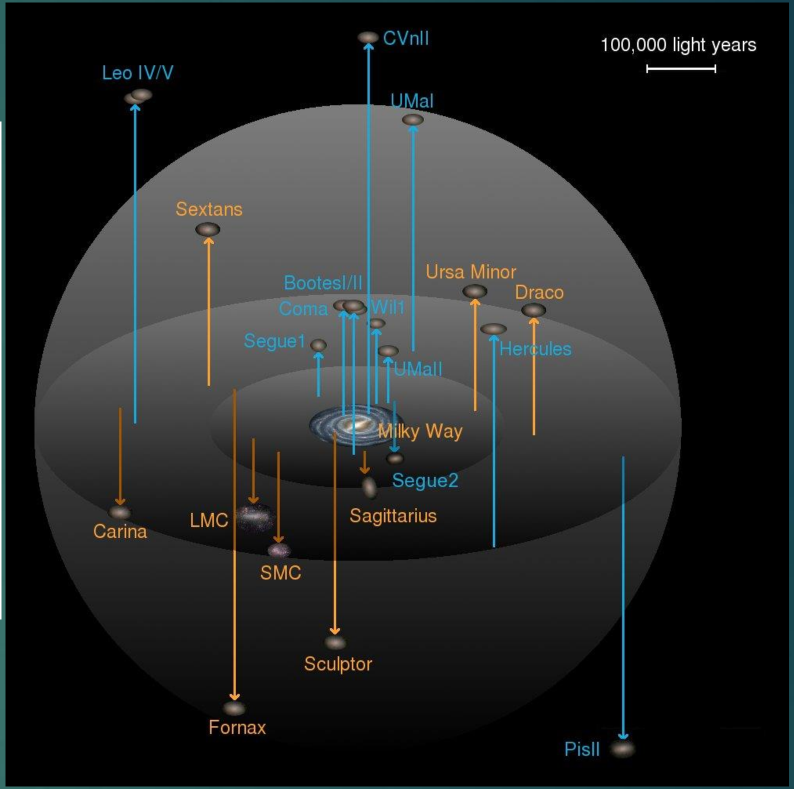
Schive et al. 2014

Dark matter structure measurements traditionally rely on galaxies as tracers

Cold Dark Matter Prediction

Credit: Lovell et al. 2014

Observed Milky Way Structure

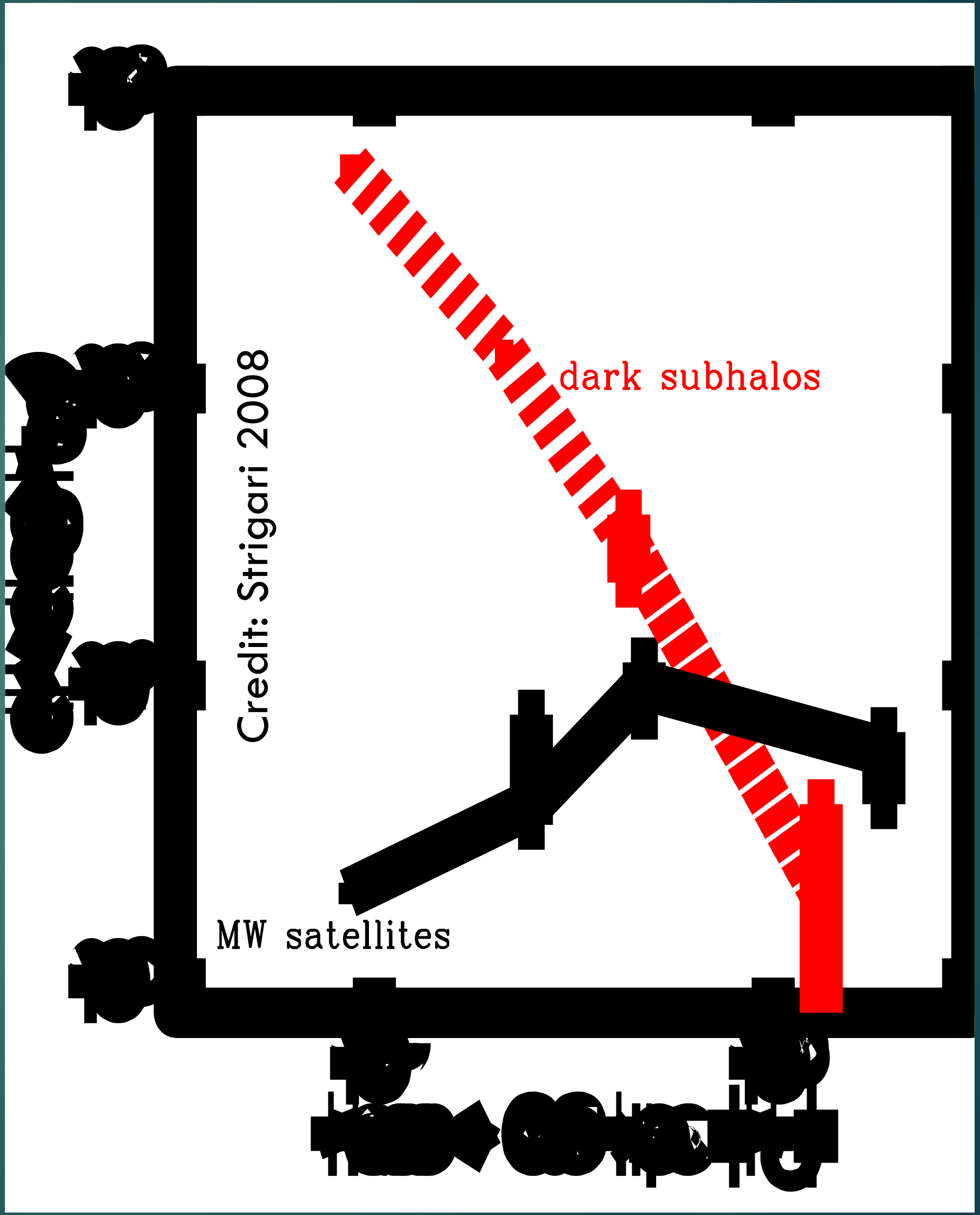


Credit: J.T.A de Jong

Galaxies are collections of stars, which we believe to be embedded in a dark matter halos, so there are two solutions:

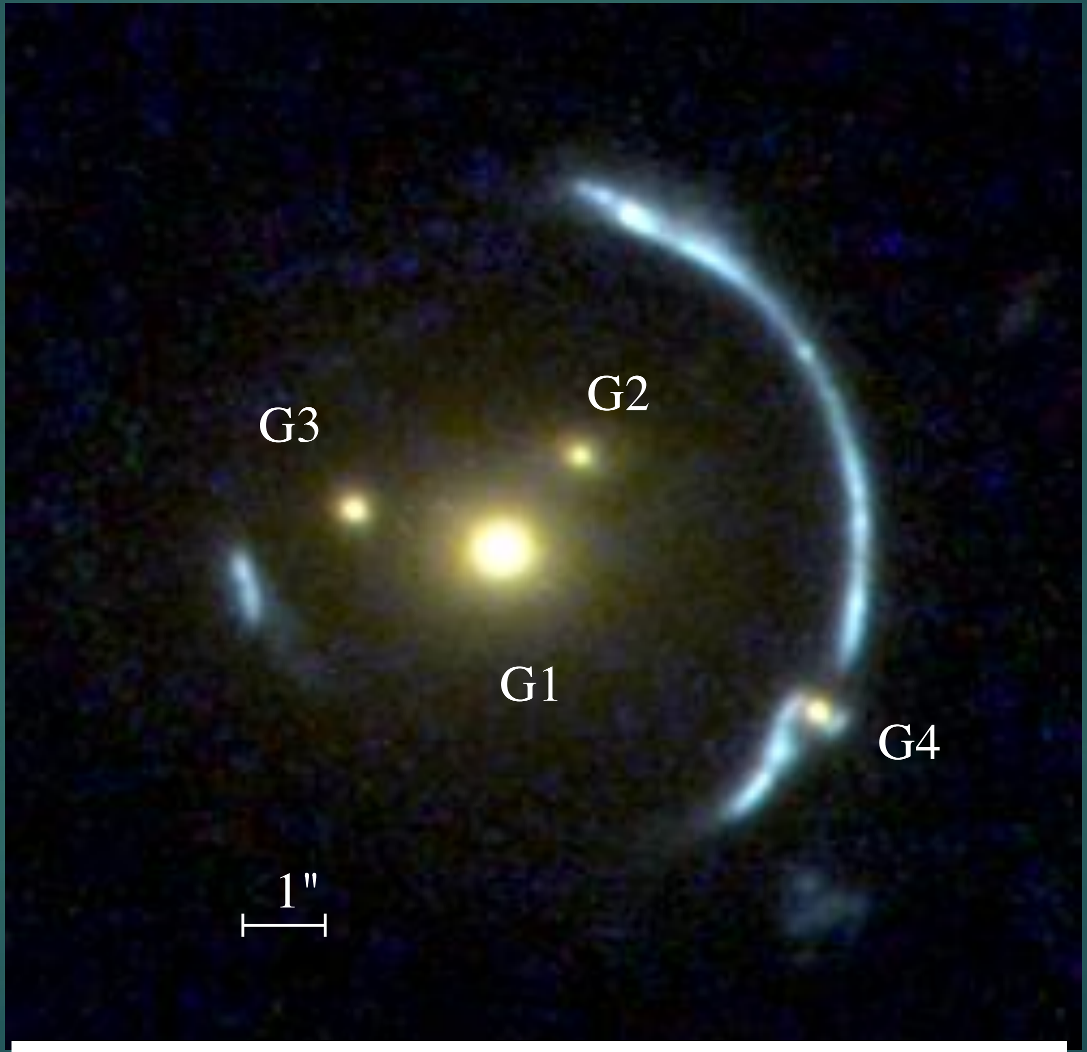
1) There are a large number of halos below some mass scale which do not contain enough gas or stars for us to see (almost certainly true)
2) Dark matter doesn’t form structure on small scales

Goal: Detecting halos in the dark regime



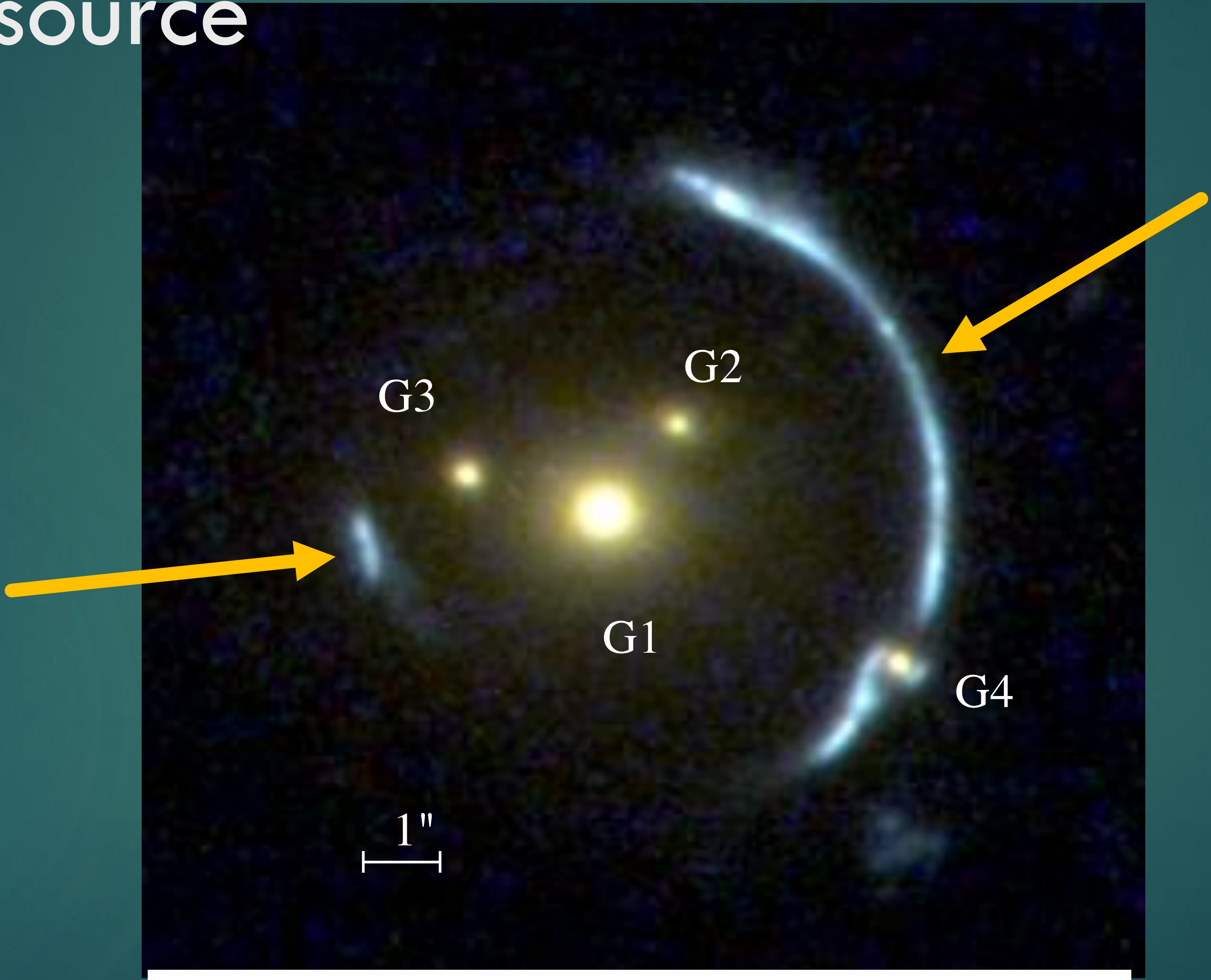
Credit: Strigari 2008

Gravitational lensing-dark matter connection



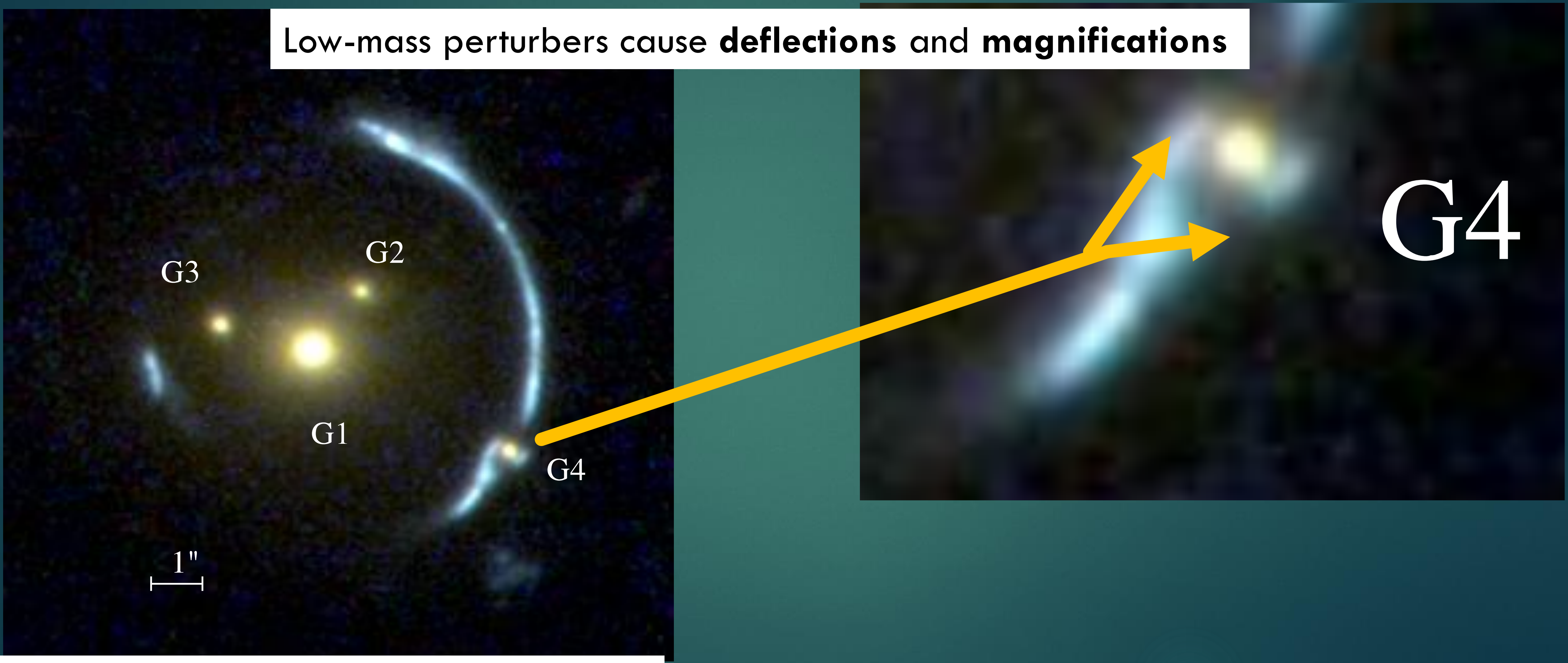
Vegetti et al. 2010

Strong lenses have multiple images of the same background source



Vegetti et al. 2010

Gravitational lensing is sensitive to perturbations by dark matter halos



Low-mass perturbers cause **deflections** and **magnifications**

Vegetti et al. 2010

Gravitational lensing is sensitive to perturbations by dark matter halos

Low-mass perturbers cause **deflections** and **magnifications**

Deflection ∝ first derivative

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

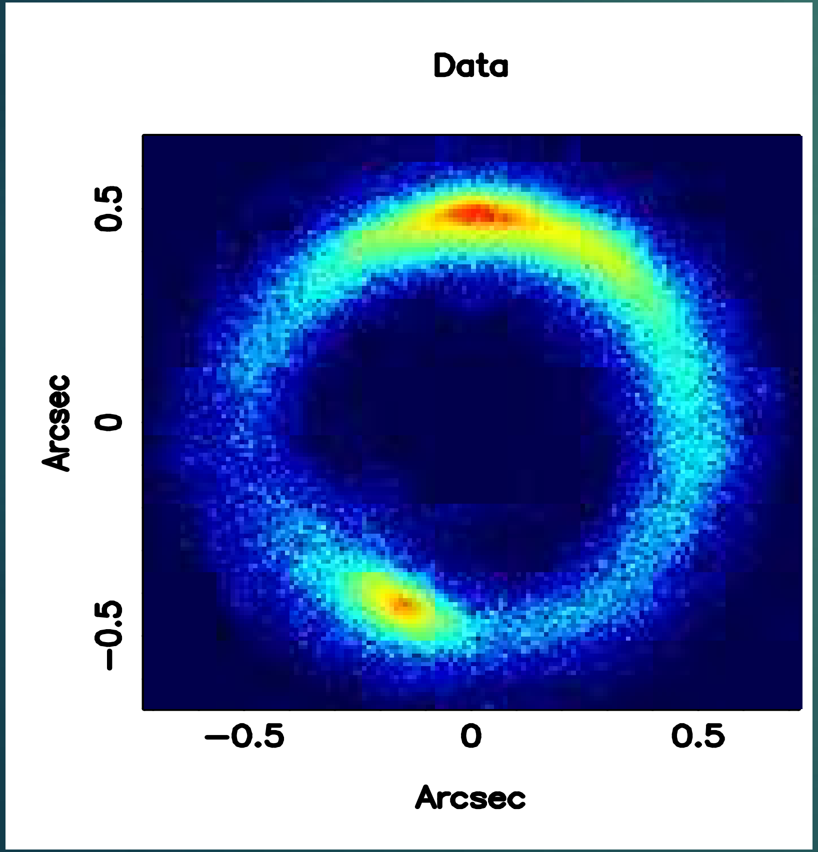
Magnification ∝ second derivative

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

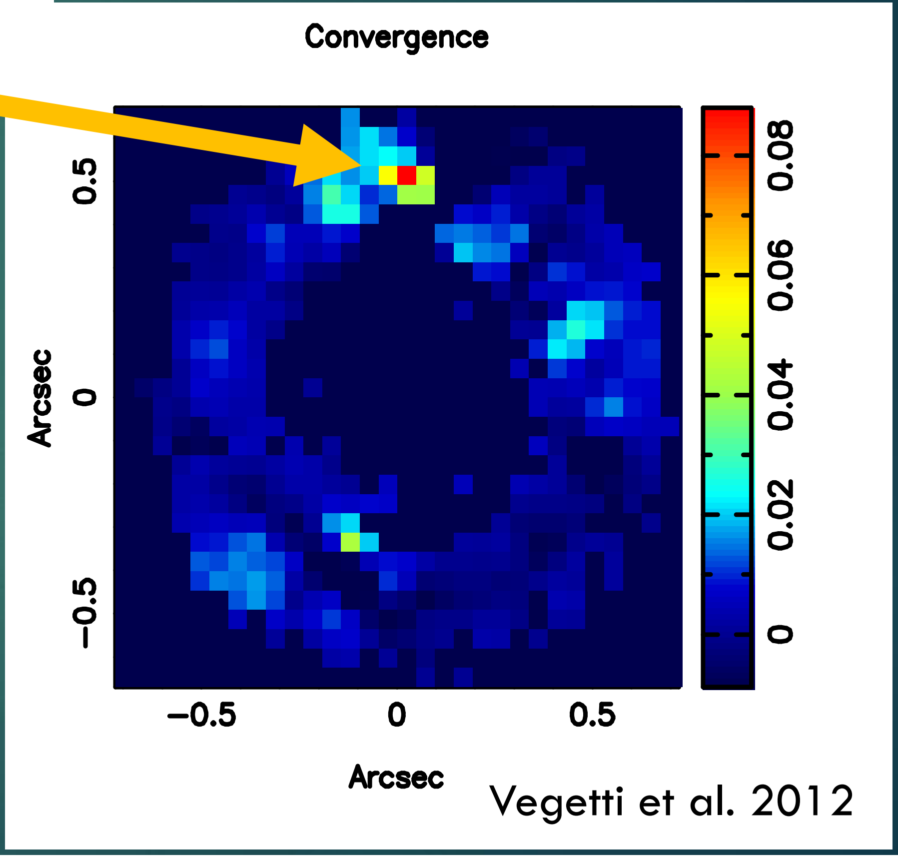
Gravitational Potential

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

We detect perturbations as deviations from the single deflector model.



$\sim 10^9$ ($M_\odot$) halo detected, not visible in imaging

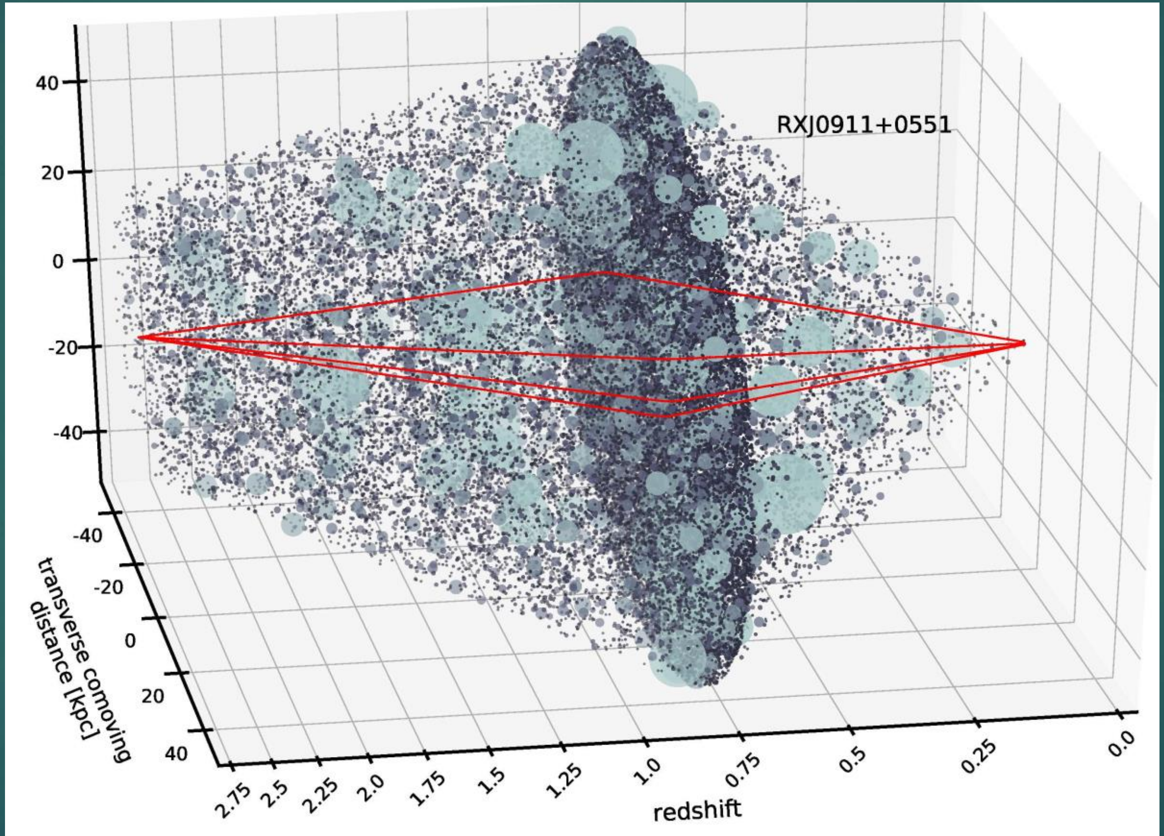


Vegetti et al. 2012

See also Minor et al. 2022 for an analysis of concentration

Strength of using lensing to measure dark matter

- No dependence on halos containing baryons (could be completely dark)
- Measure low-mass halo properties at a range of cosmological distances and environments



Simulation from `pyhalo` Gilman et al. 2022

Types of **Background Sources**

- **Resolved (Galaxies)**

  current sensitivities to ~10^8 $M_\odot$ halos, main signal from deflections. (a.k.a. gravitational imaging)

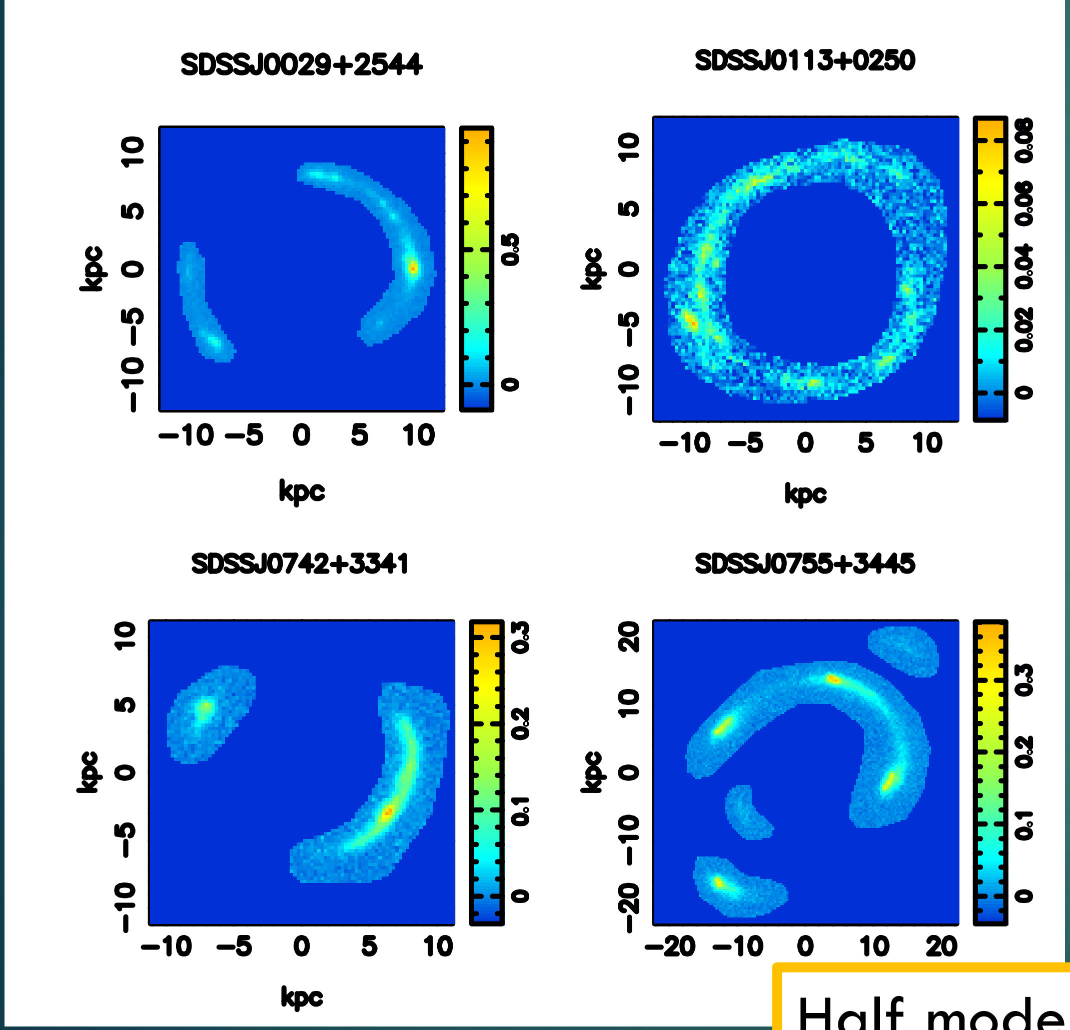
Fundamentally the same process, different sensitivity regimes

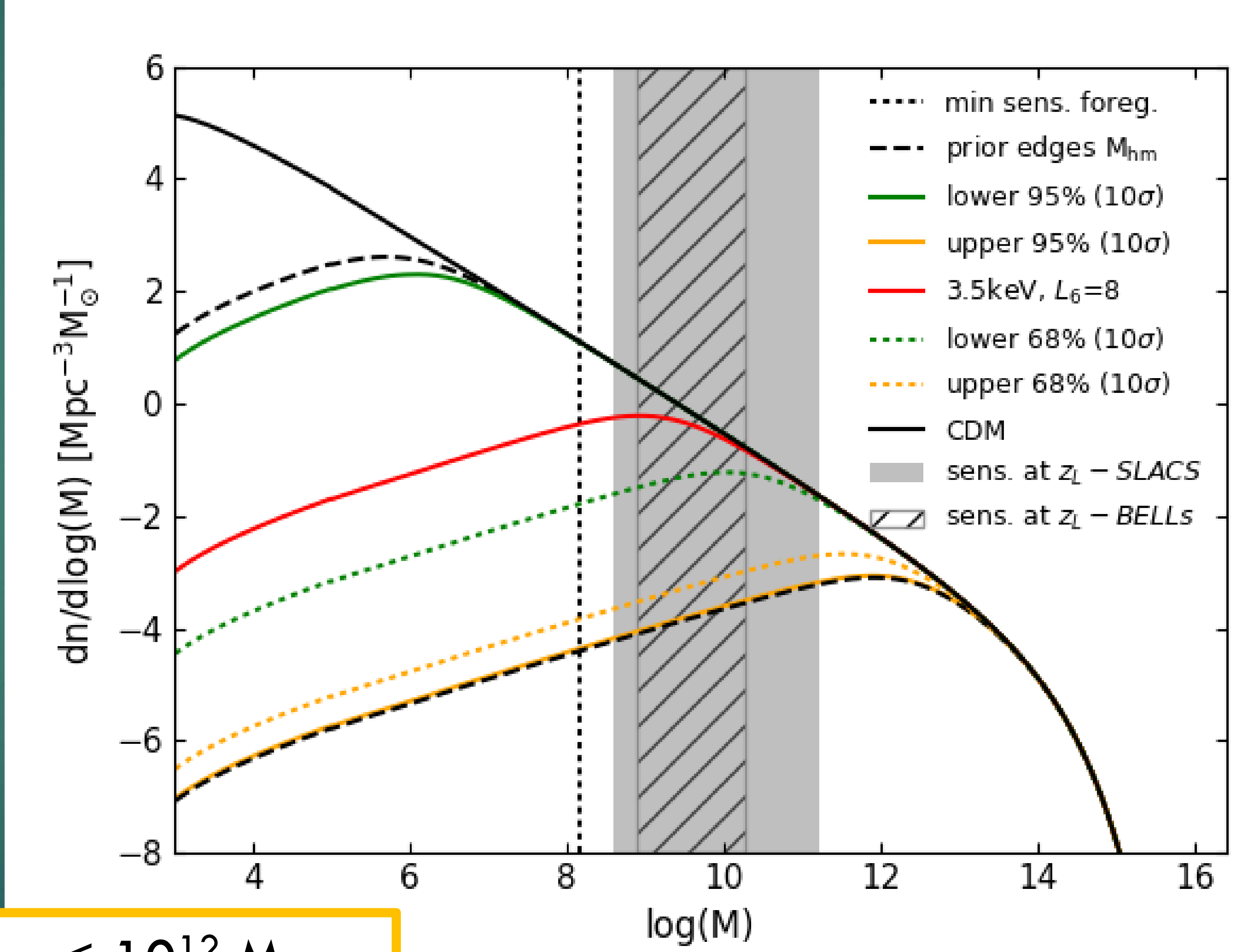
- Unresolved (narrow-line emission, some radio)

  current sensitivities to ~$10^{6.5}$ $M_\odot$ halos main signal from magnification (a.k.a. flux ratio anomalies)

Results from resolved source lensing – individual subhalo detection

Results from resolved galaxy sources – individual detection 34 lenses

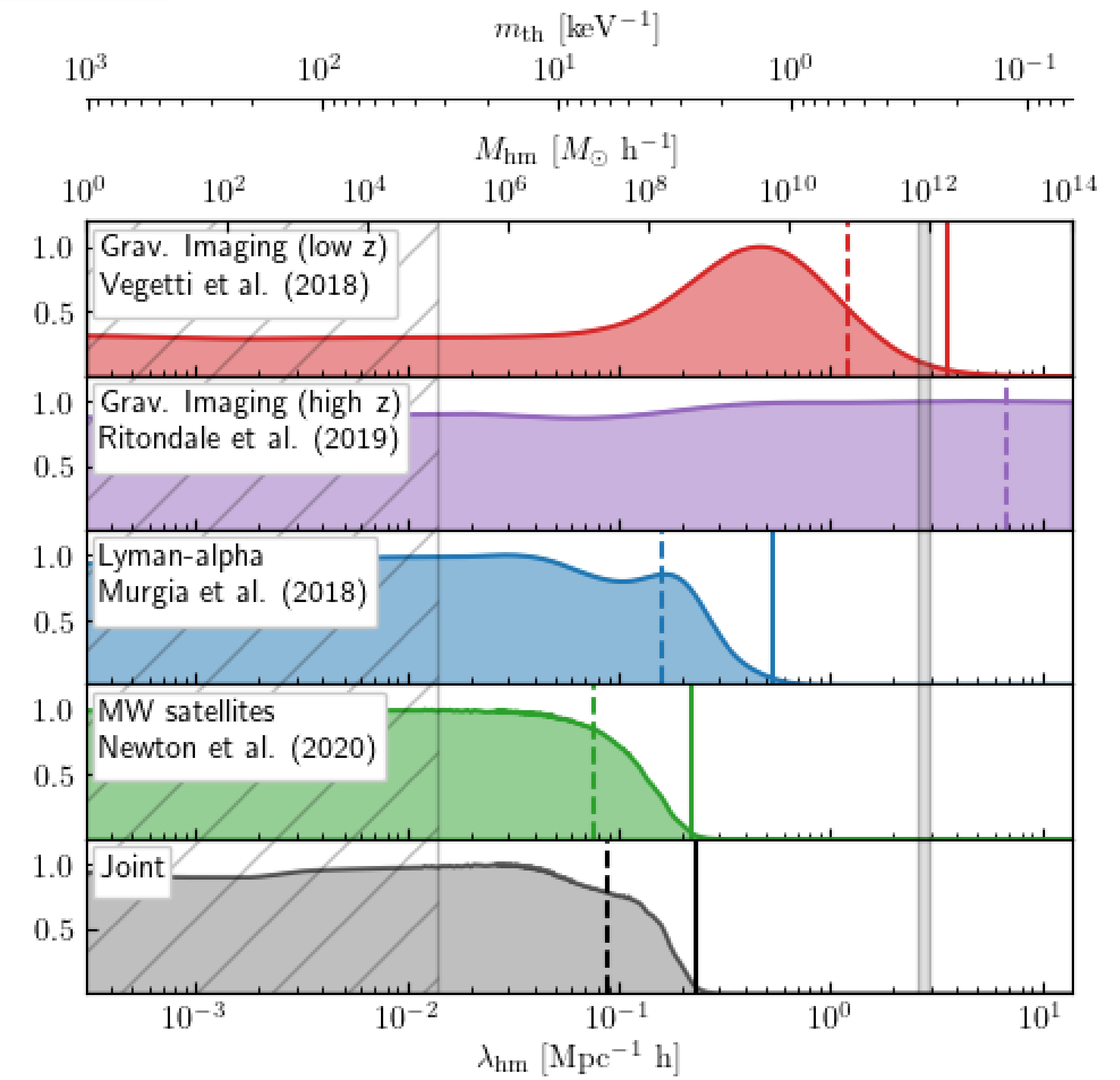


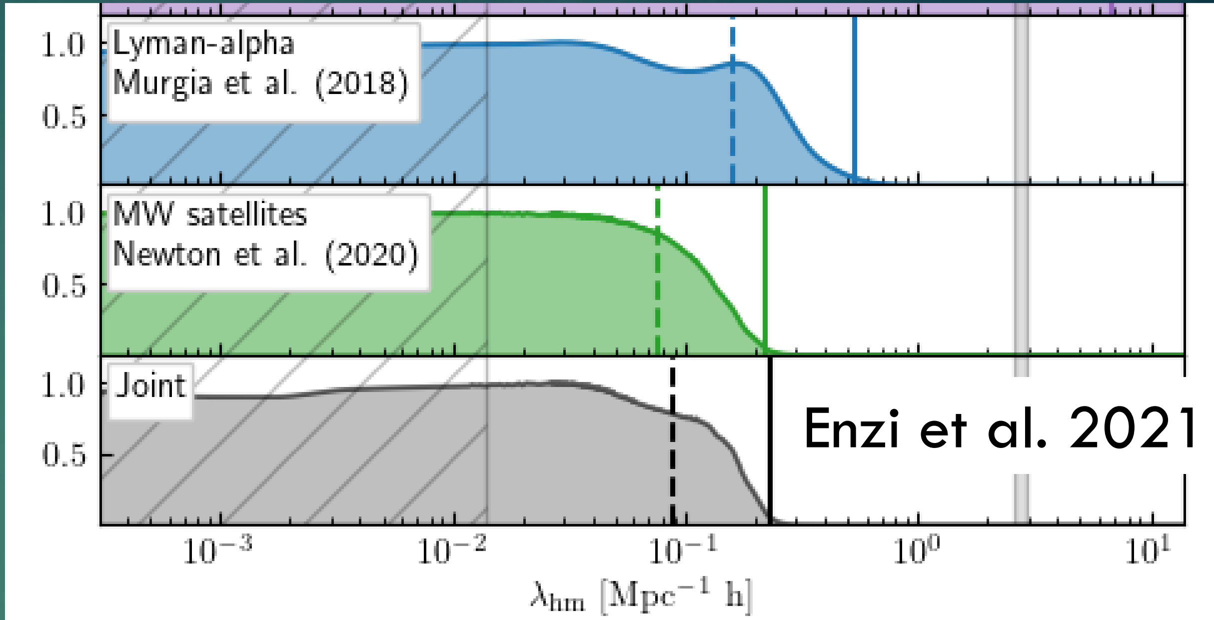


Half mode mass < 10^{12} $M_\odot$ (2σ)

Ritondale et al. 2017

Results from combining with other probes





Enzi et al. 2021

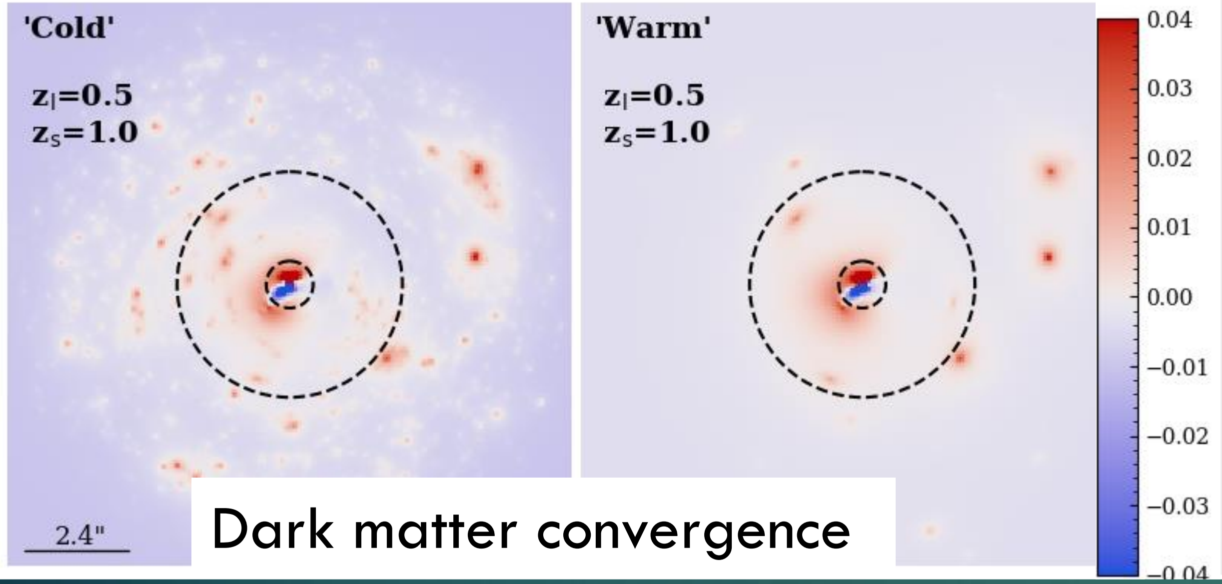
Combining results with Ly-alpha and MW satellites yields stronger constraints

Half mode mass < 3×10^7 $M_\odot$ (2σ)

Resolved source-multiple detections (power spectrum)

He et al. 2022

With higher resolution we expect multiple detections per lens



Dark matter convergence

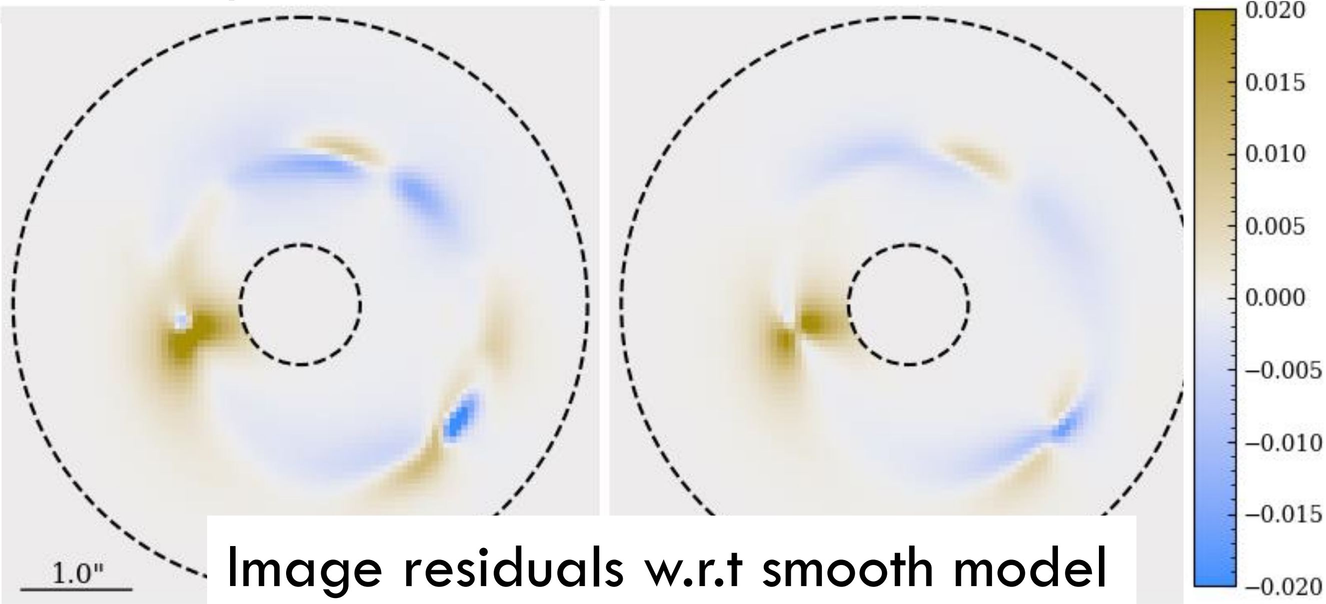
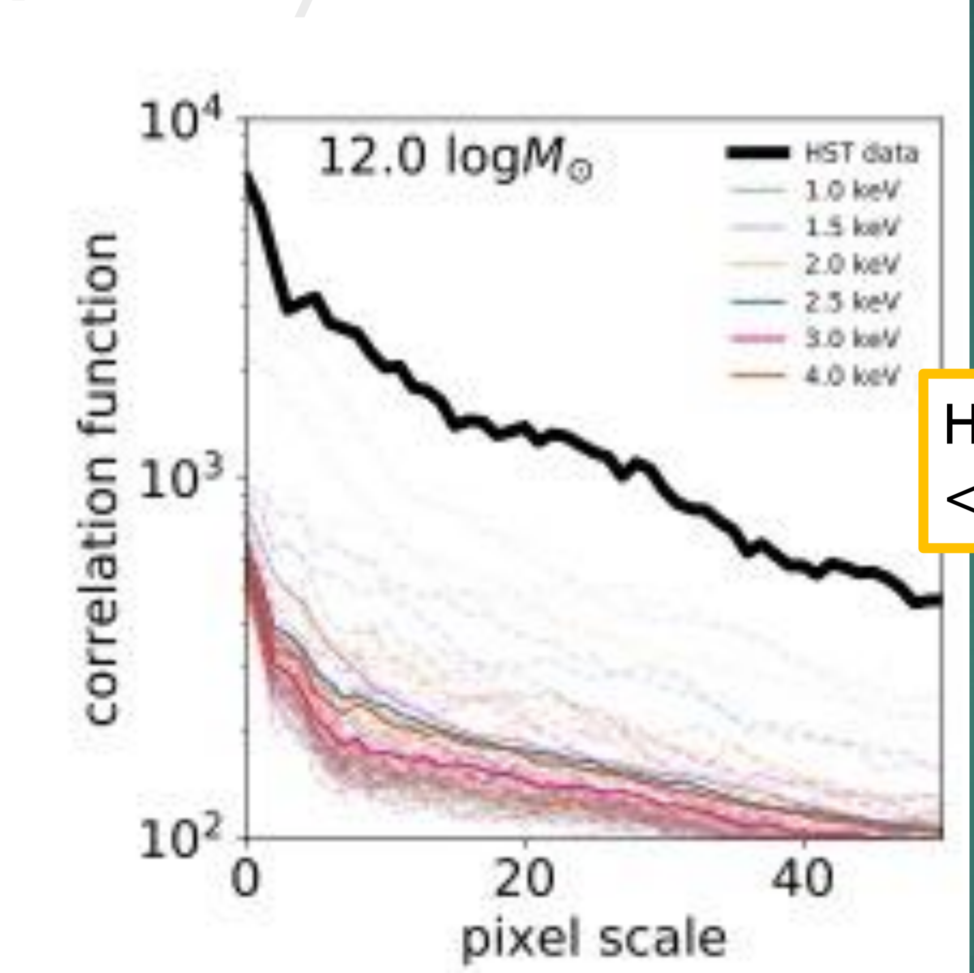


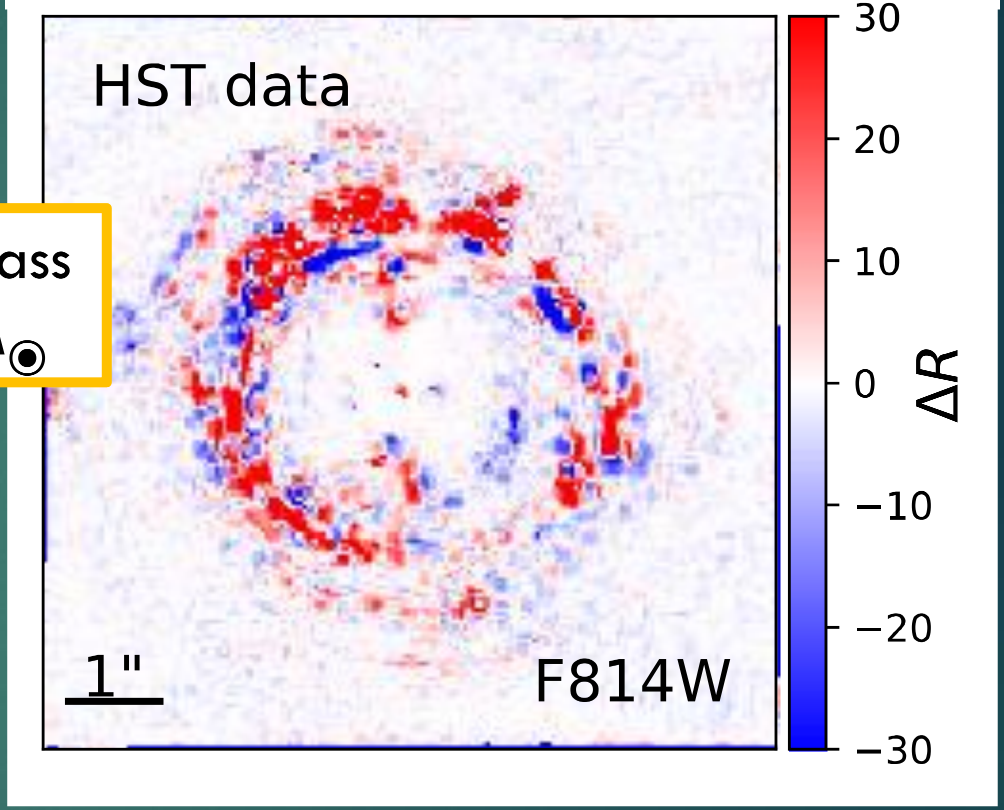
Image residuals w.r.t smooth model

Quantify via a residual power spectrum



Half mode mass $< 10^9$ (2σ) $M_\odot$

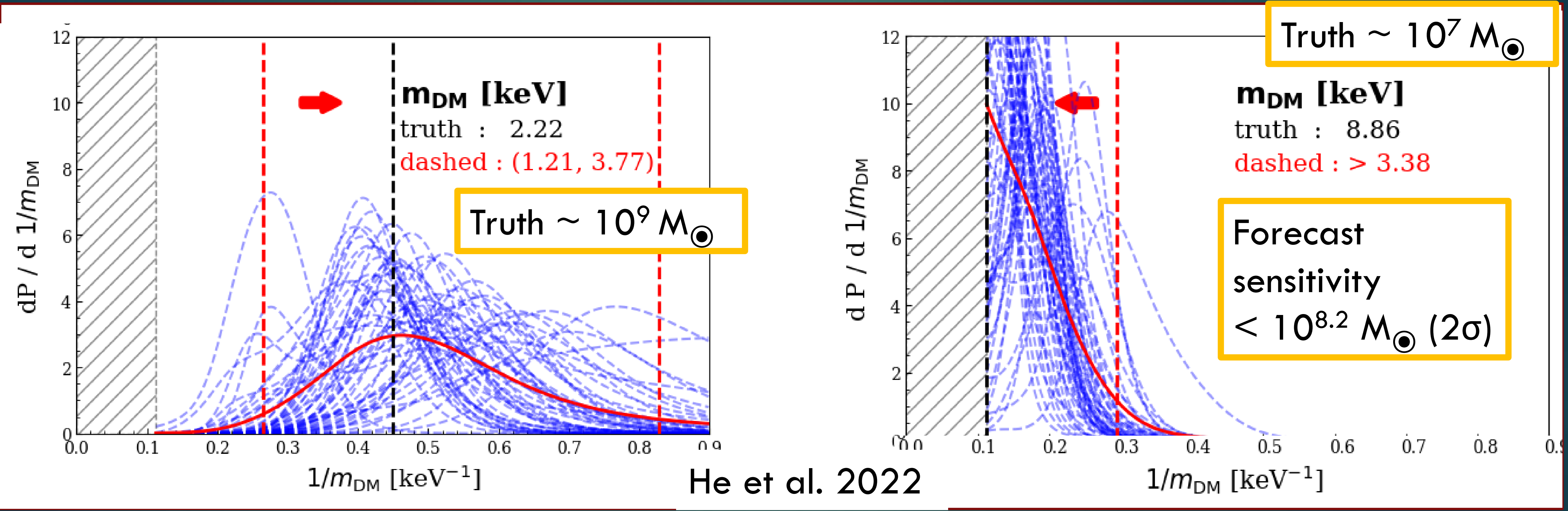
Birrer et al. 2017



Caveat: does not include line of sight structure

See also forecasting work by Hezaveh et al. (2014), Cyr-Racine et al. (2019)

Forecast power spectrum forecast with line-of-sight structure- 50 lenses HST single orbit



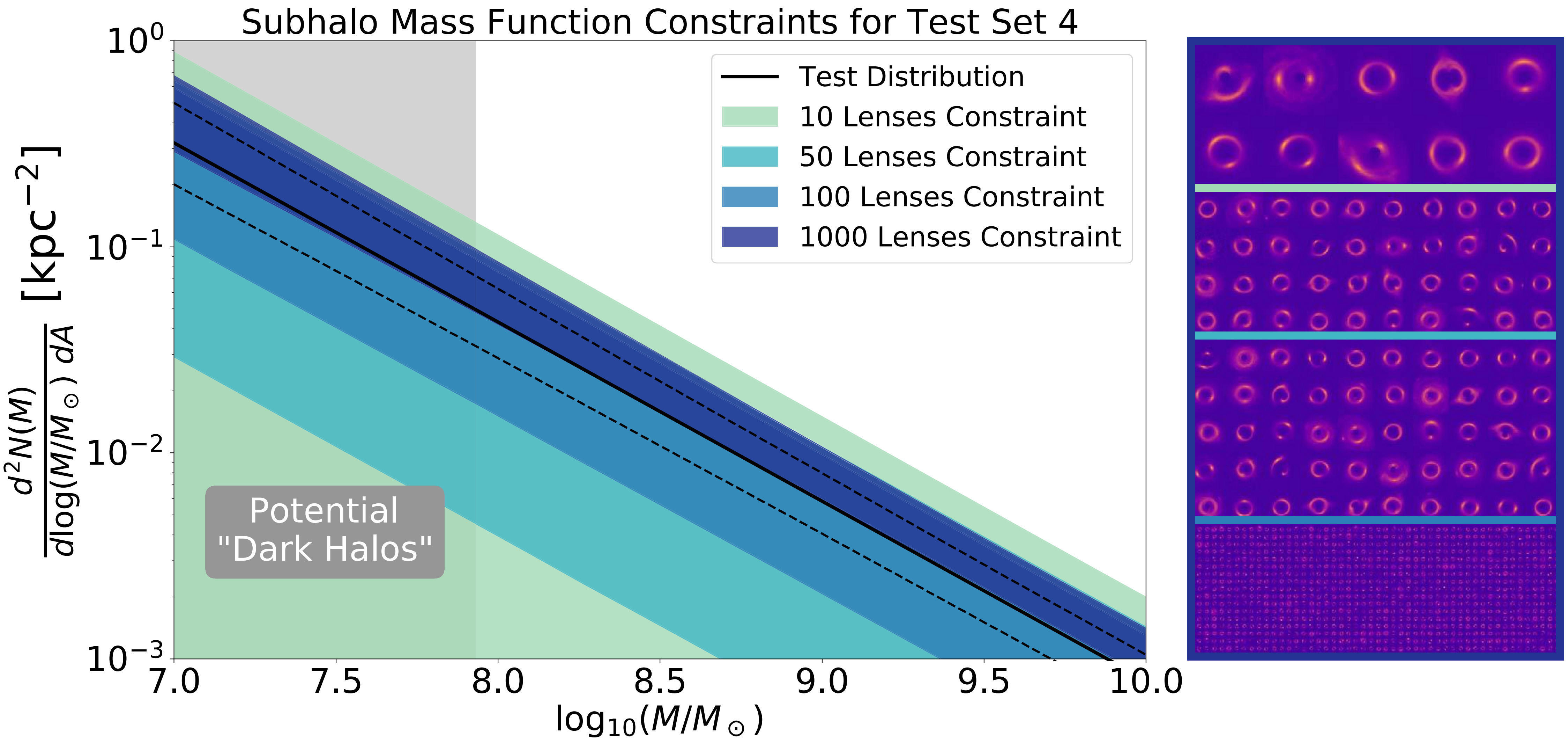
Truth ~ $10^9\ M_\odot$

Truth ~ $10^7\ M_\odot$

Forecast sensitivity $< 10^{8.2}\ M_\odot$ (2σ)

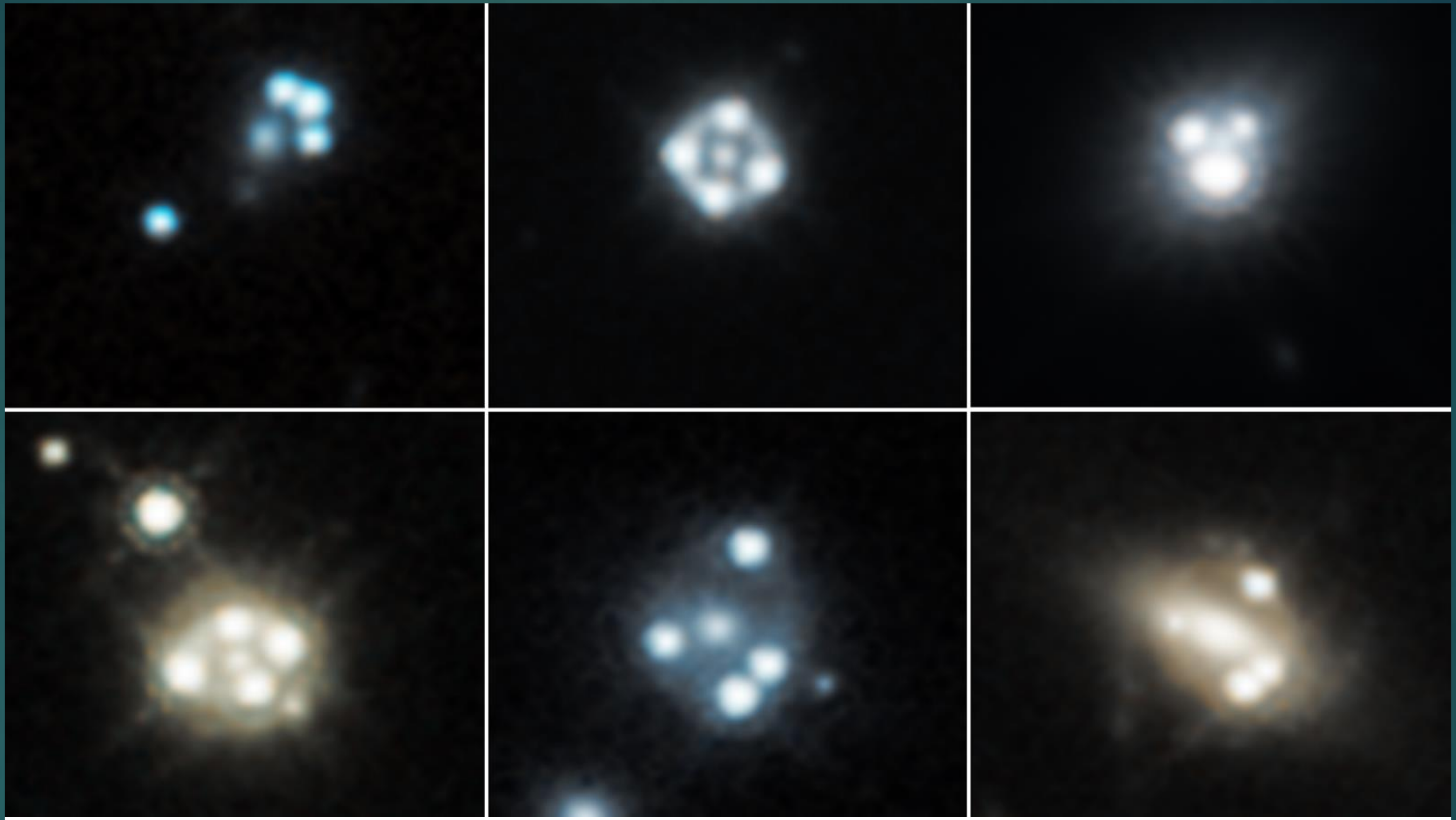
He et al. 2022

Forecast for varying lens samples, using ML



Wagner-Carena 2023 (assume CDM, measure subhalo mass function normalization).

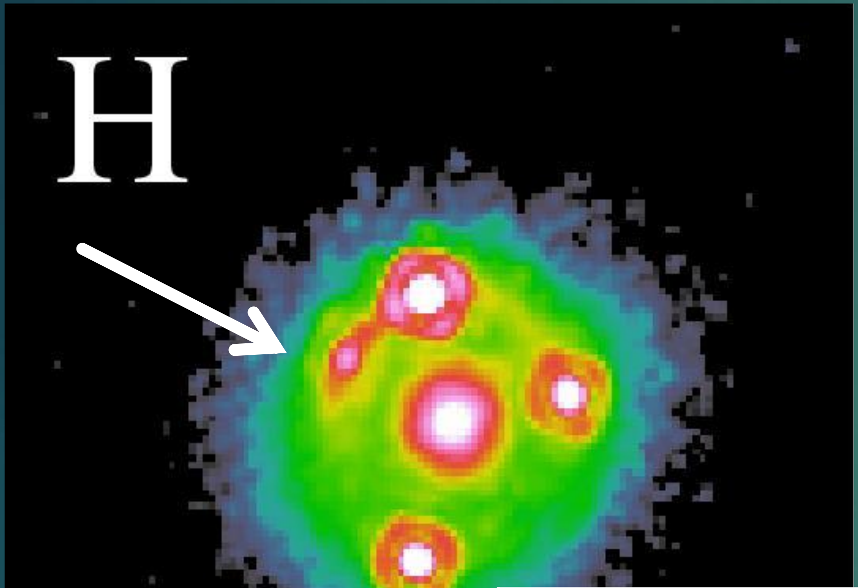
Unresolved sources



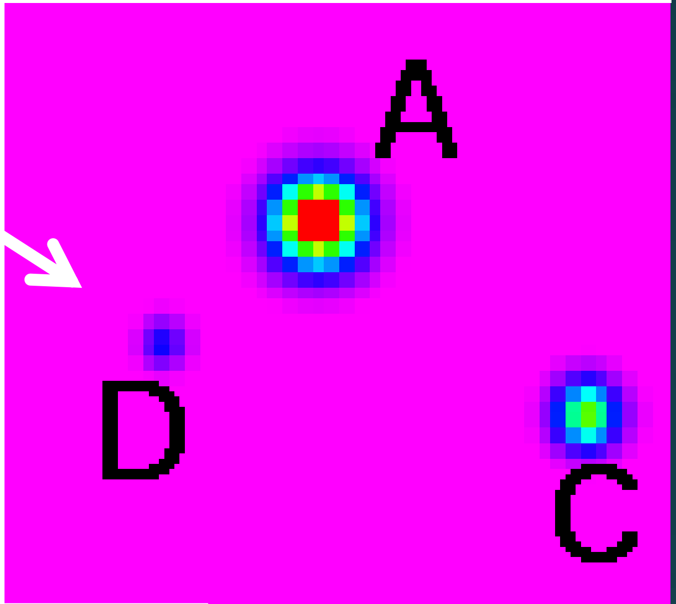
Credit: STSCI, GO-15177, 13732 PI Nierenberg

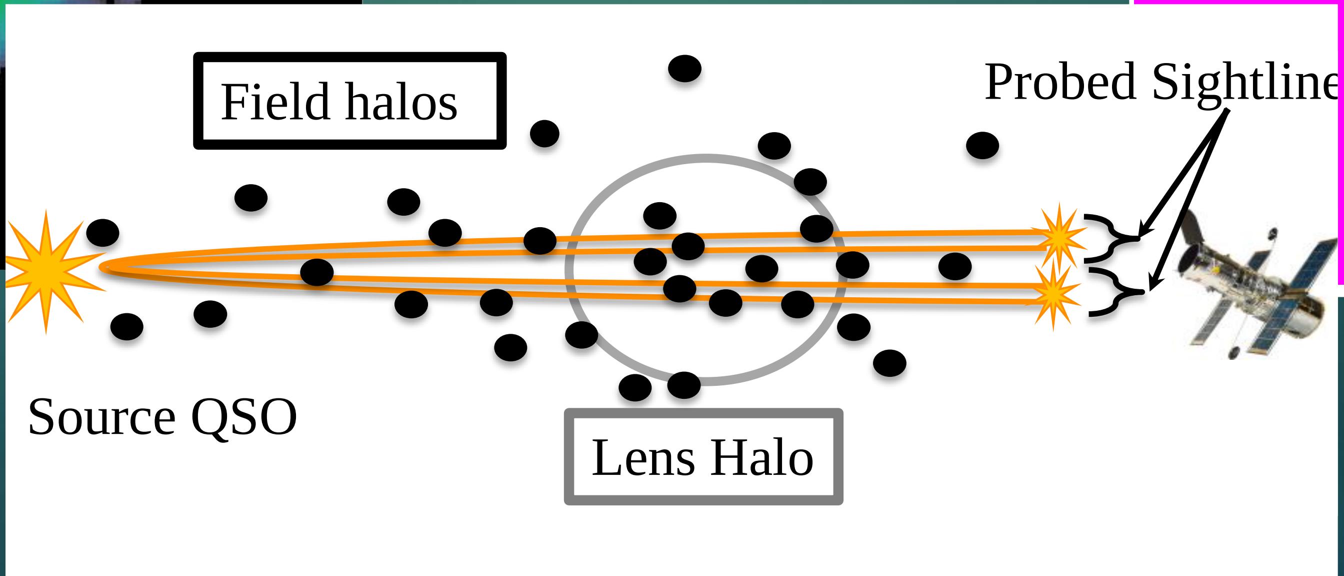
Signal of a perturbation in an unresolved source

Observed lens

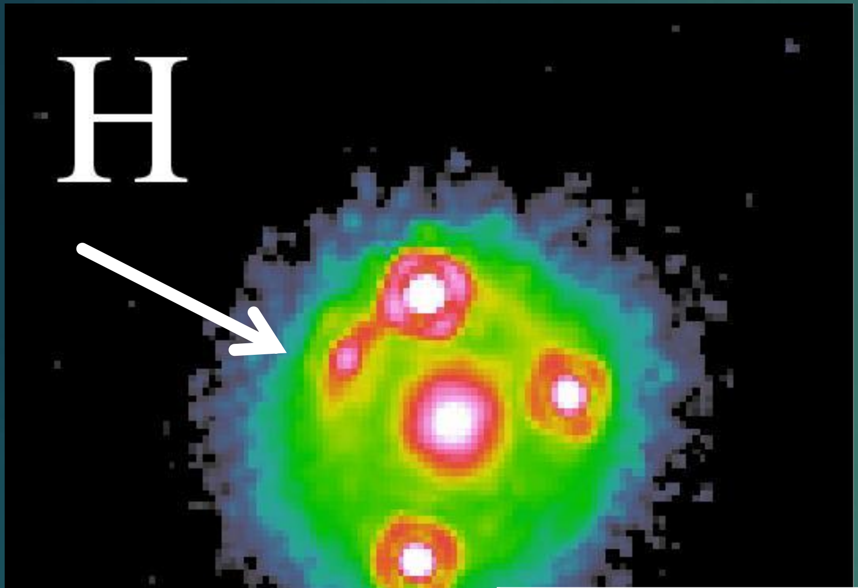


Best 1 halo model fit



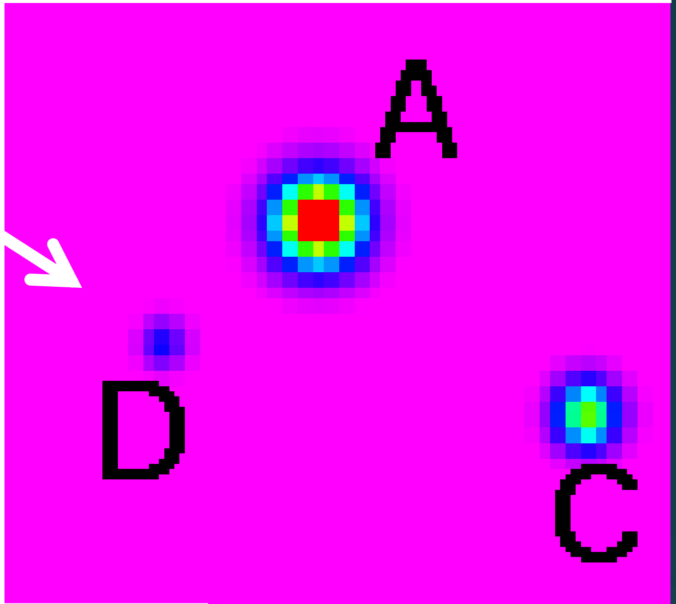


Signal of a perturbation in an unresolved source

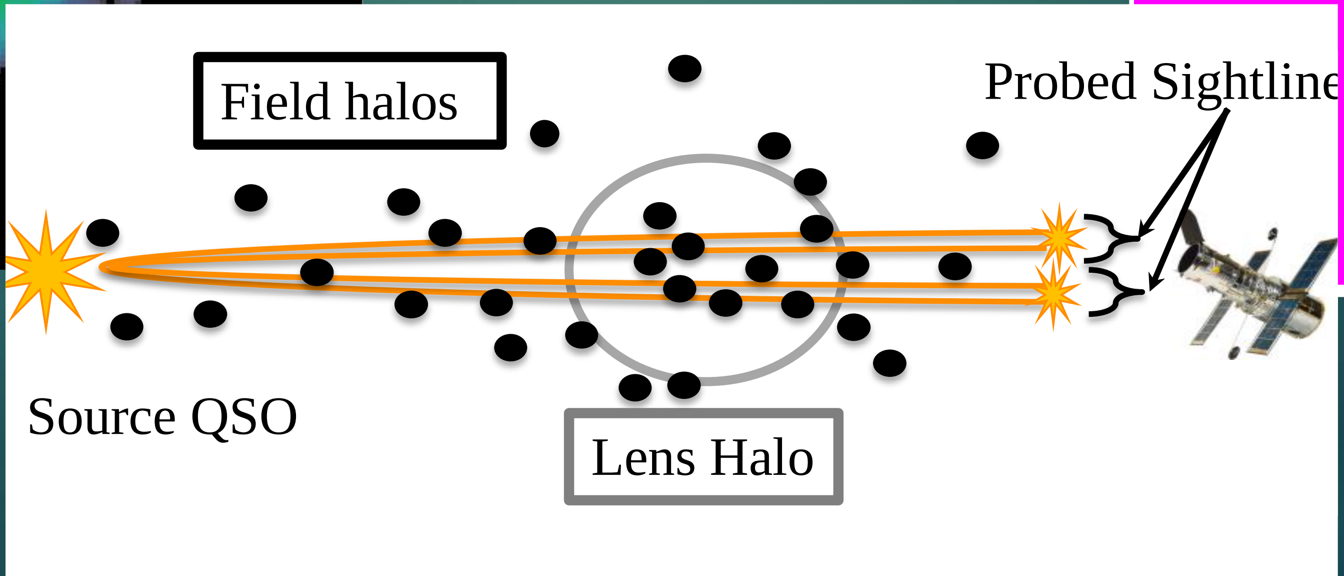


Observed lens

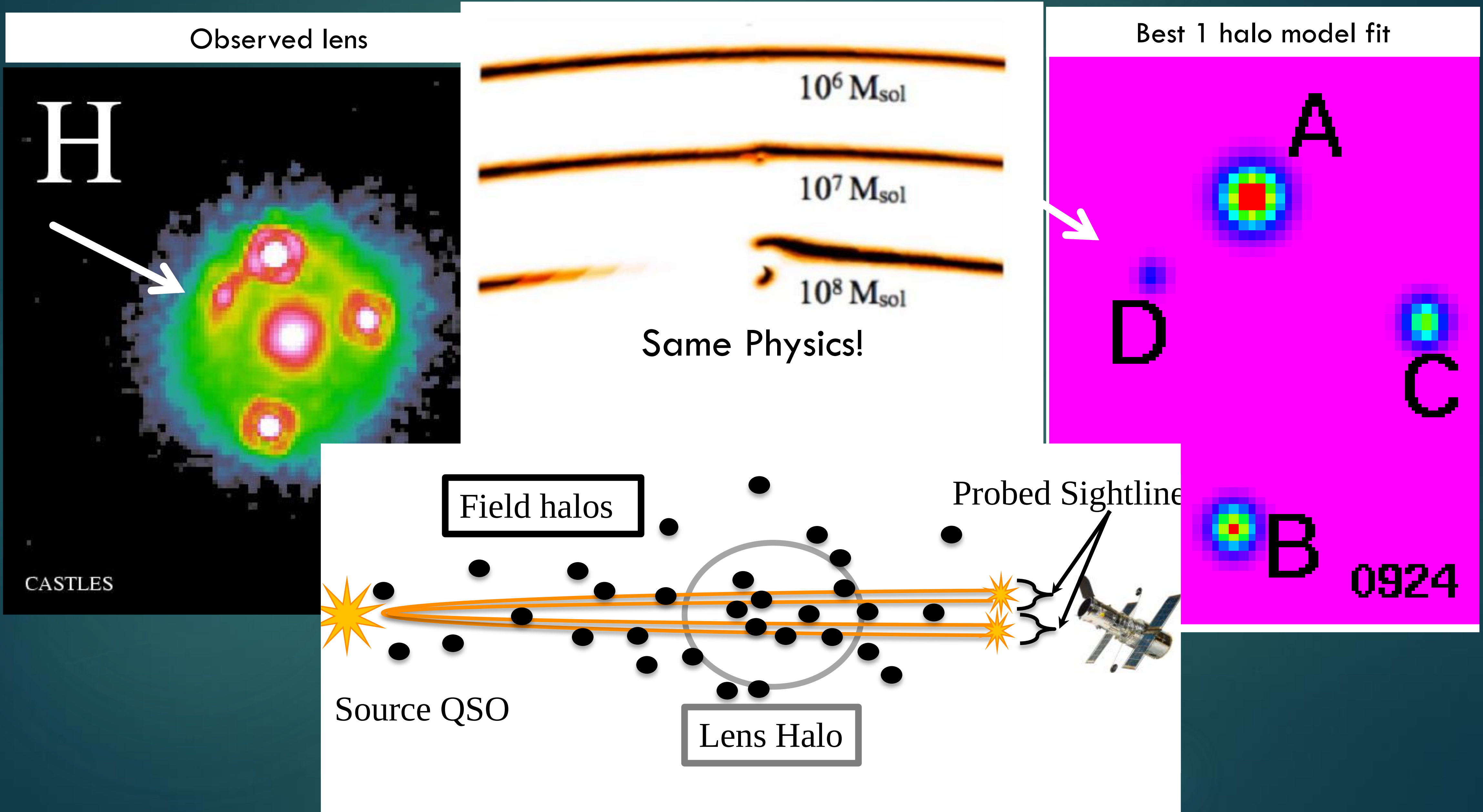
Perturbation needs to be localized and small scale – **positions unperturbed**



Best 1 halo model fit



Signal of a perturbation in an unresolved source



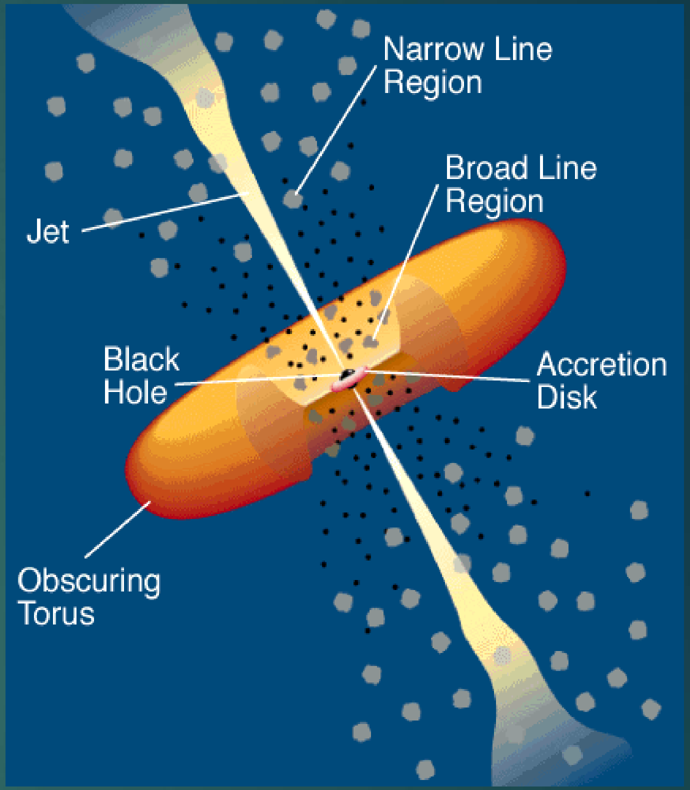
Observed lens

Same Physics!

Best 1 halo model fit

Unresolved source types

- Quasar **radio emission** (traditional, e.g. Dalal and Kochanek 2002), very rare
- Quasar **narrow-line emission** detected in virtually all quasars
- Quasar cold torus



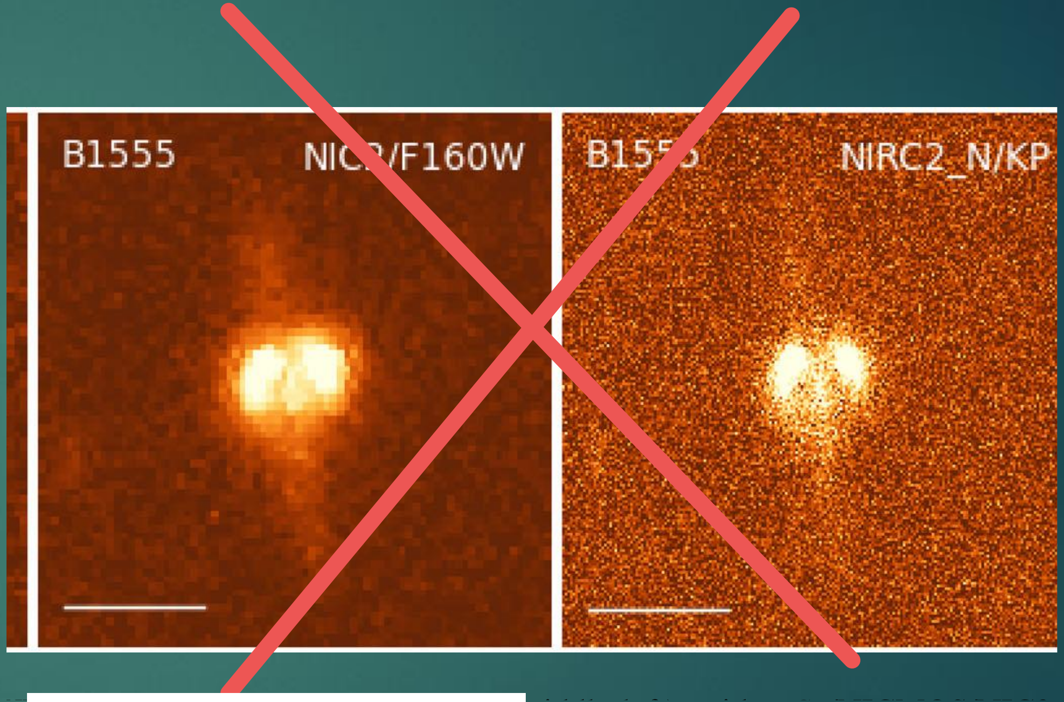
Caveat: Cannot use quasar accretion disk, is affected by lensing by stars.

Restrict to non-disk deflectors

Choose only lenses with elliptical deflectors

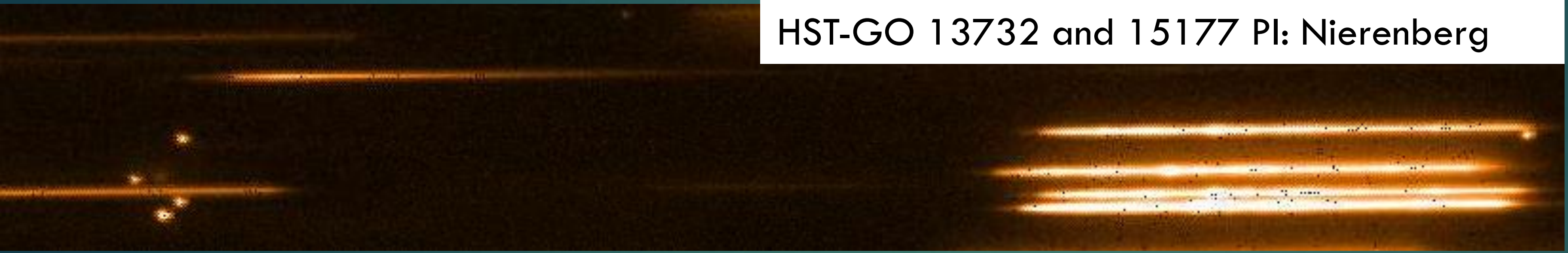
Marginalize over a broad range of macromodel parameters

Quantify effects of asymmetry in deep images of elliptical galaxies (Gilman et al. 2016, Hsueh et al. 2016)

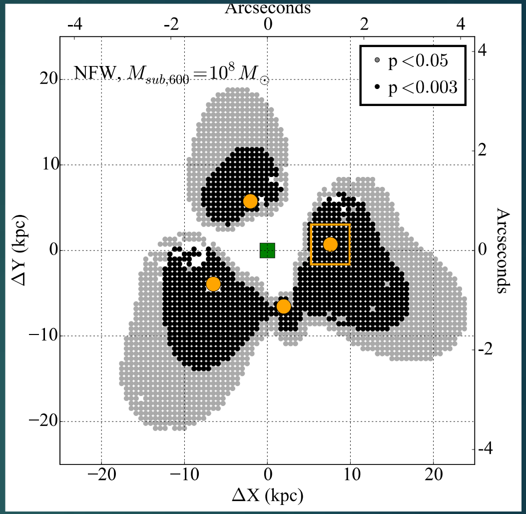


Hsueh et al. 2017

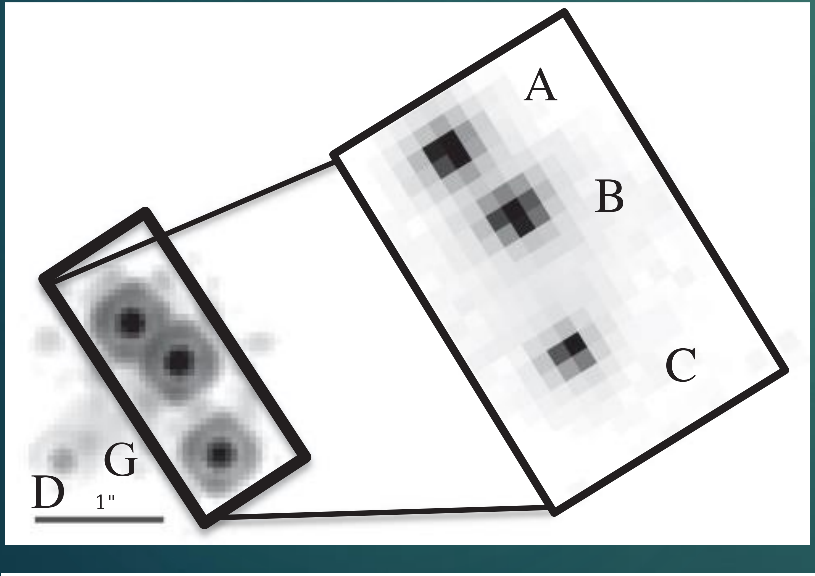
Narrow-line flux ratios measured with HST grism and Keck-OSIRIS

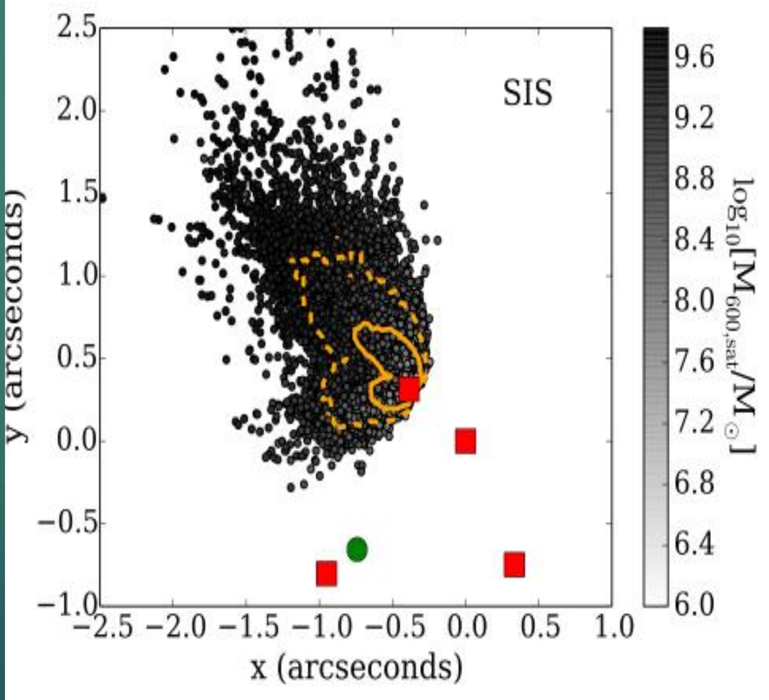


HST-GO 13732 and 15177 PI: Nierenberg



Flux Ratios: Nierenberg et al. 2017, 2020



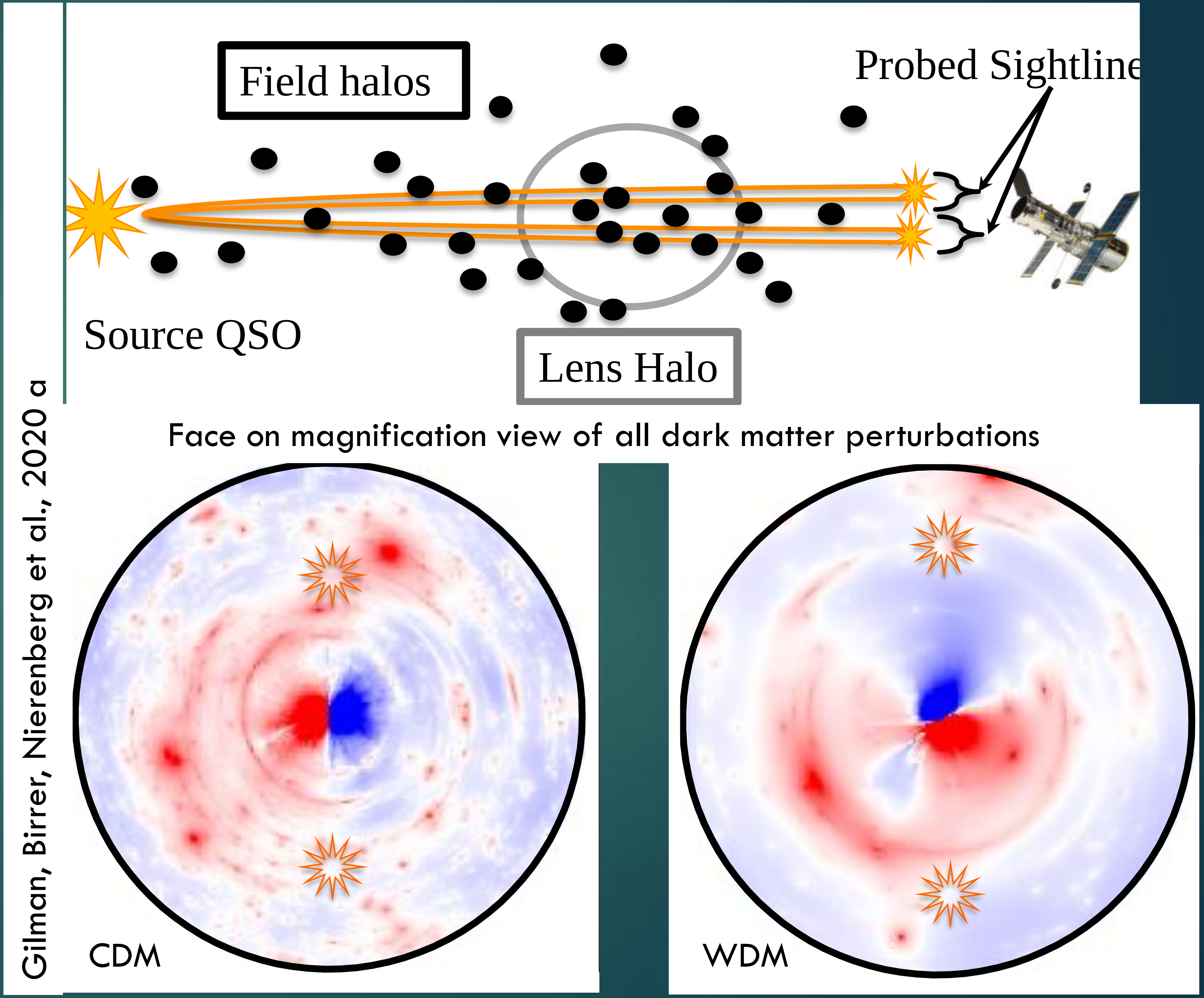


Keck OSIRIS, Nierenberg et al. 2014

Results from a sample of 8 lenses

The model

- The mass function of halos bound to the main lens
- The spatial distribution of halos bound to the main lens
- The mass function of halos outside of the main lens
- The mass concentration relation of the subhalos
- Unknown finite source size’

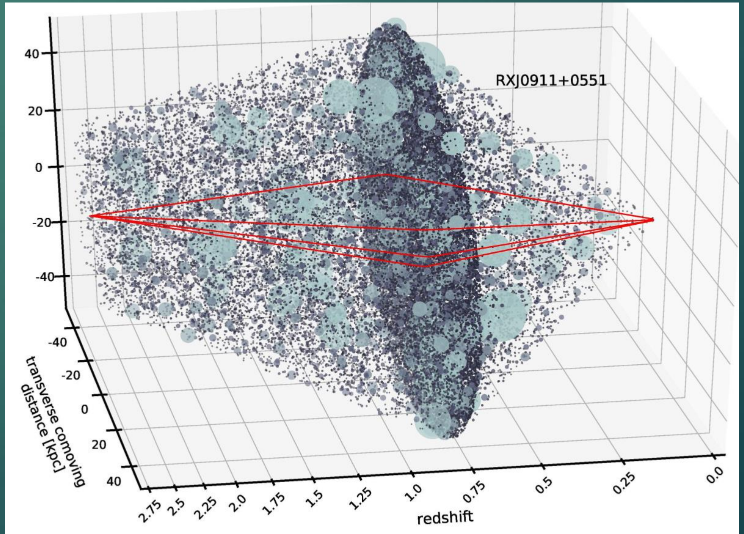


Gilman, Birrer, Nierenberg et al., 2020 a

All software is open source and publicly available on github

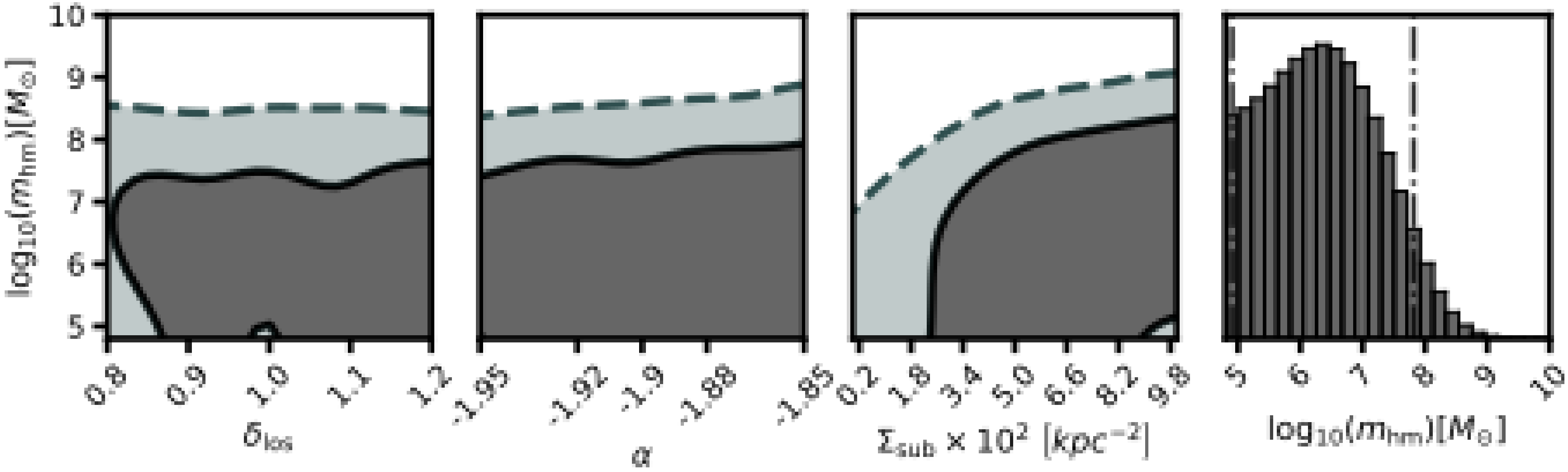
- **Lenstronomy**: All data analysis and gravitational lensing calculations. (Birrer and Amara 2018, Birrer et al. 2021)

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



NL Flux Ratios Results from 8 lenses

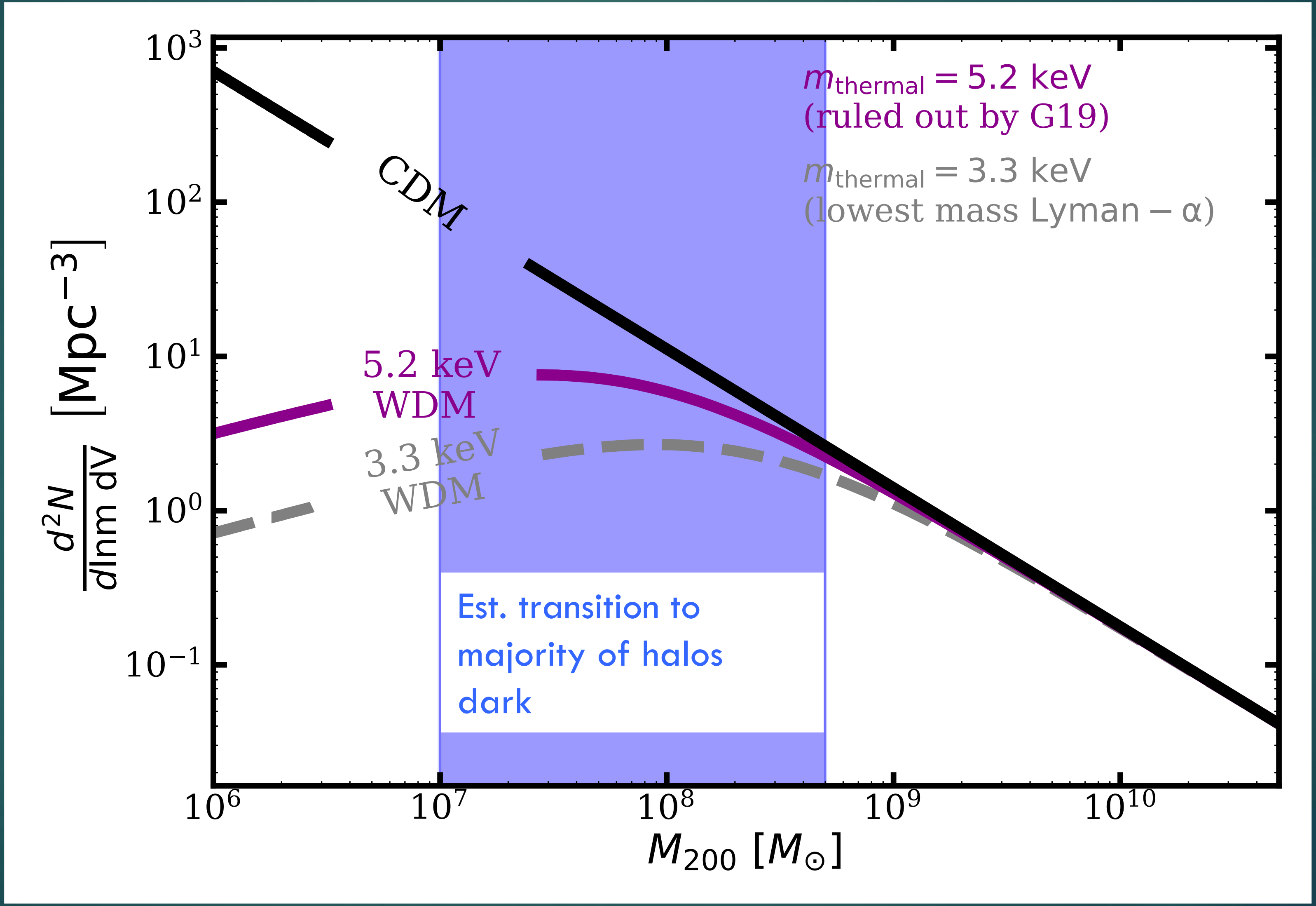
2σ $m_{\text{half mode}} < 10^{7.8}$, $M_{DM} > 5.2$ keV (thermal relic)



Gilman, et al. 2020a

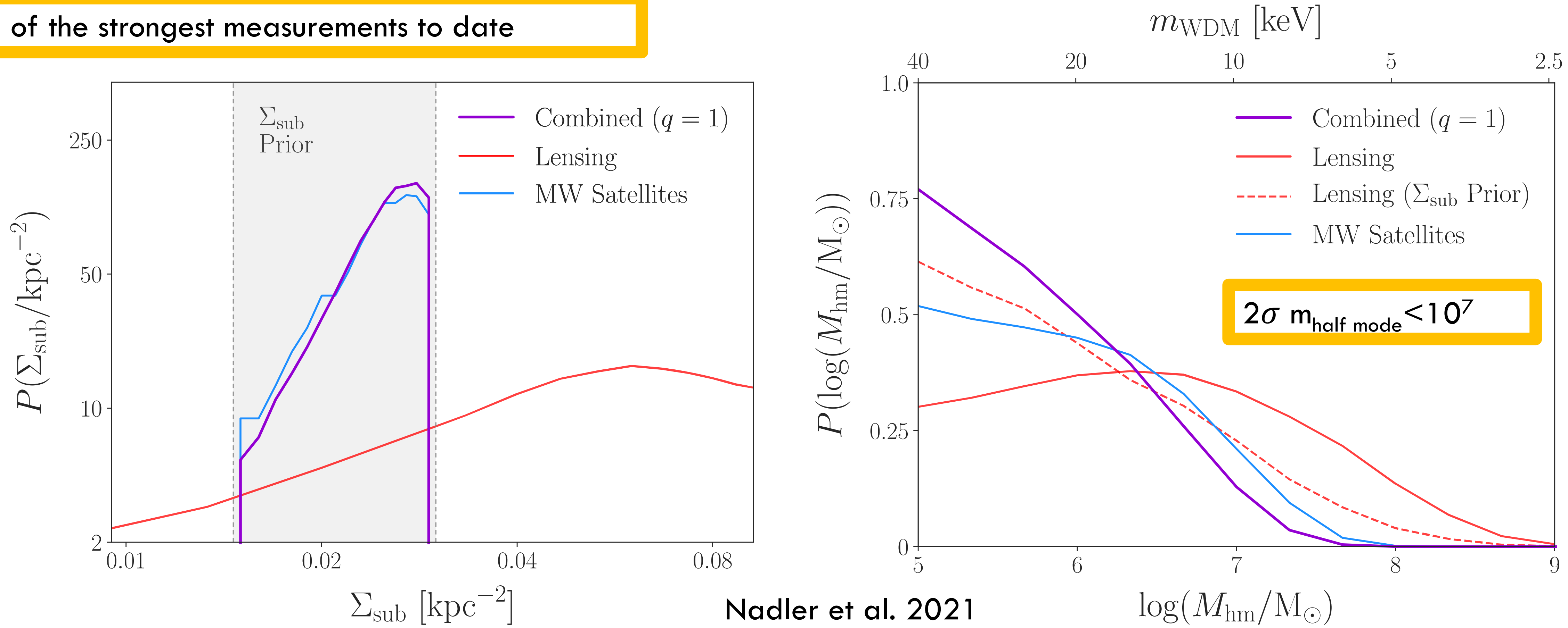
C.f. consistent results also from Hsueh et al. 2020 with radio loud quads

Measuring the halo mass function where majority of halos are dark



Combining results with MW satellites

One of the strongest measurements to date

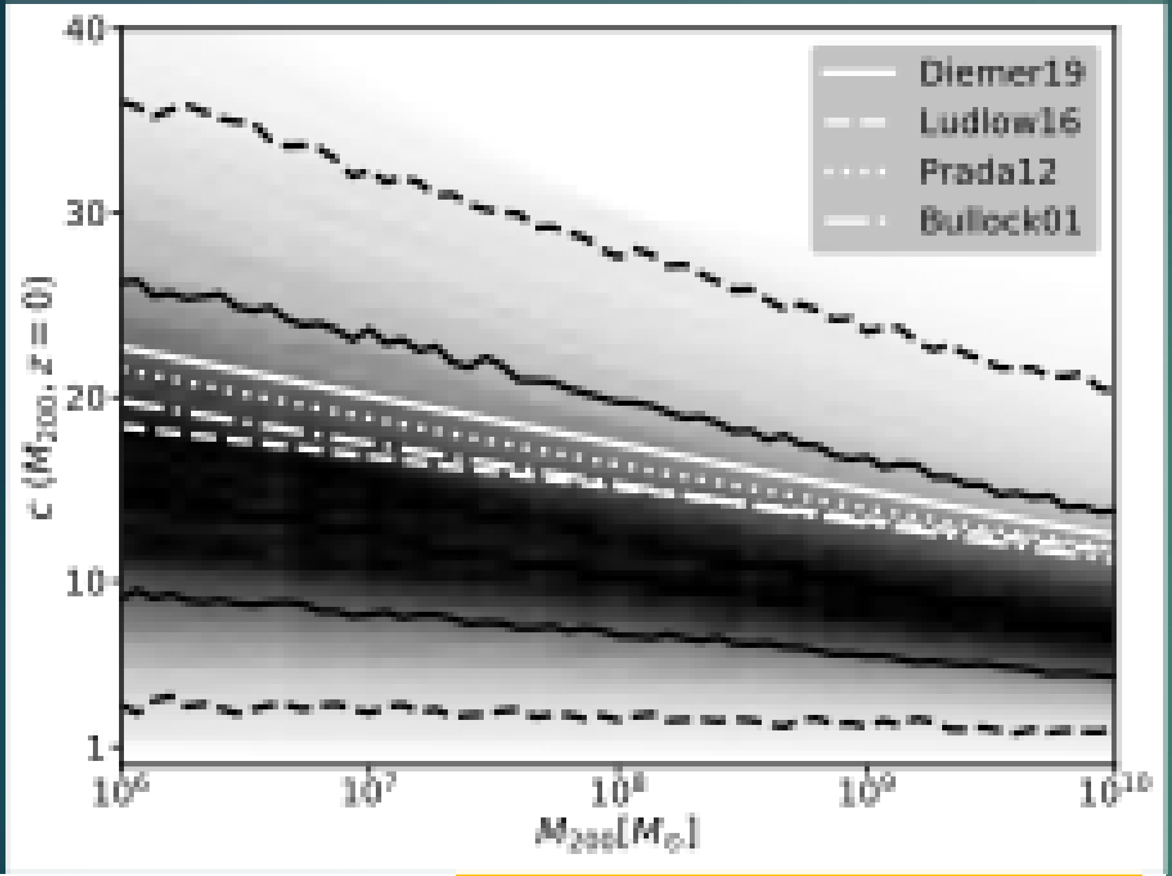


2σ $m_{\text{half mode}} < 10^7$

Nadler et al. 2021

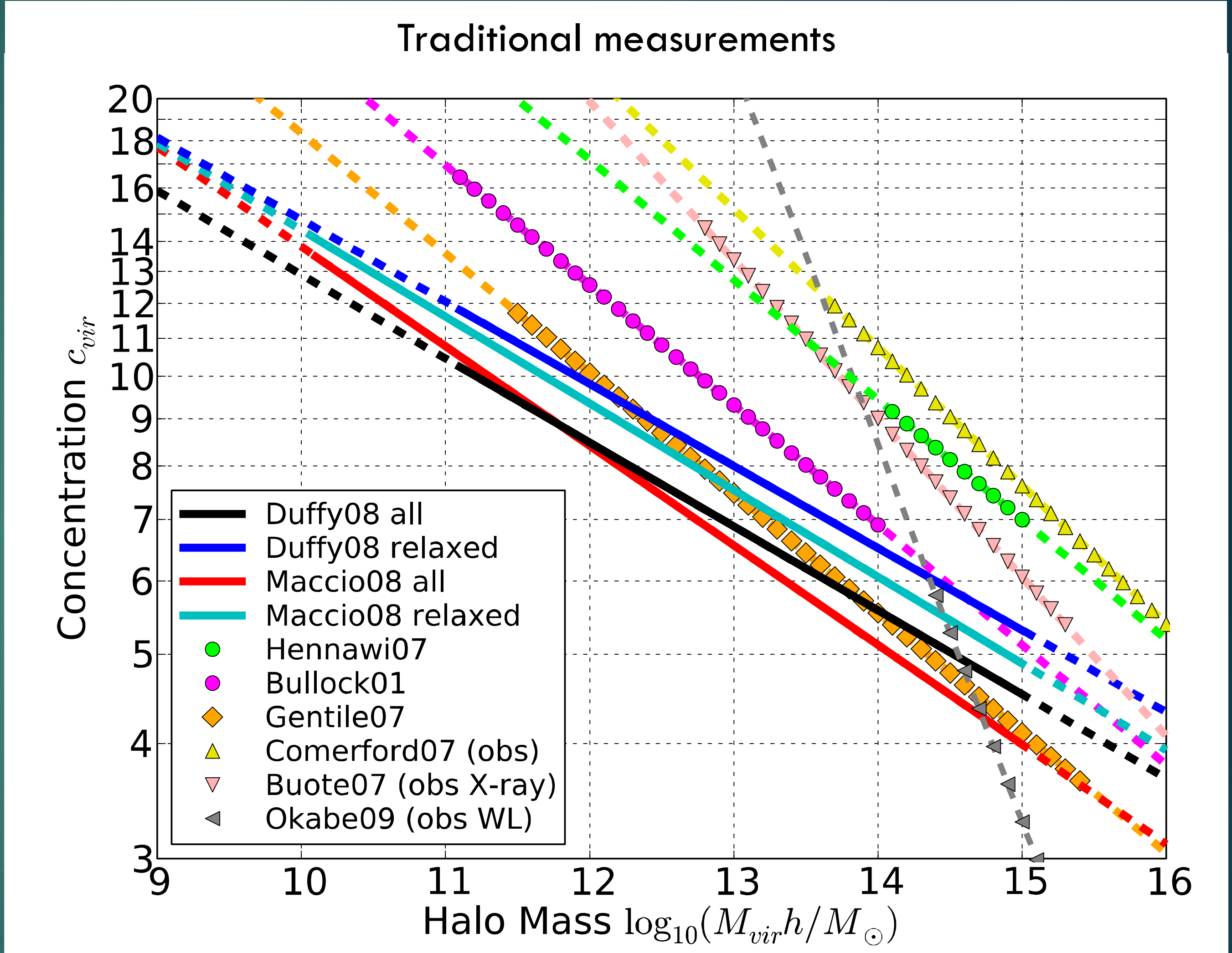
Many more aspects of dark matter are now being explored

Mass-concentration relation results with 11 lenses



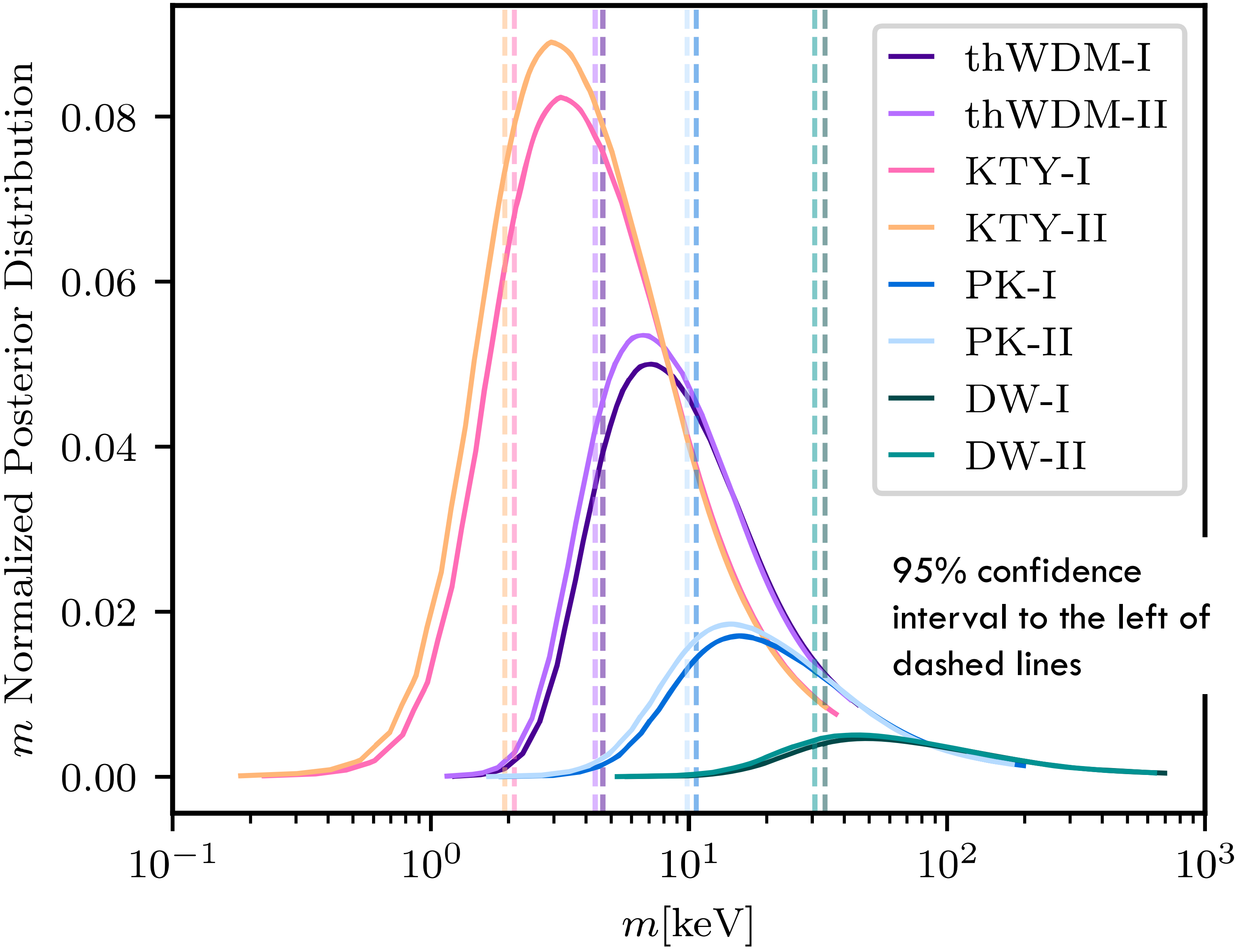
Gilman et al. 2020b

Assuming CDM



Coe 2010

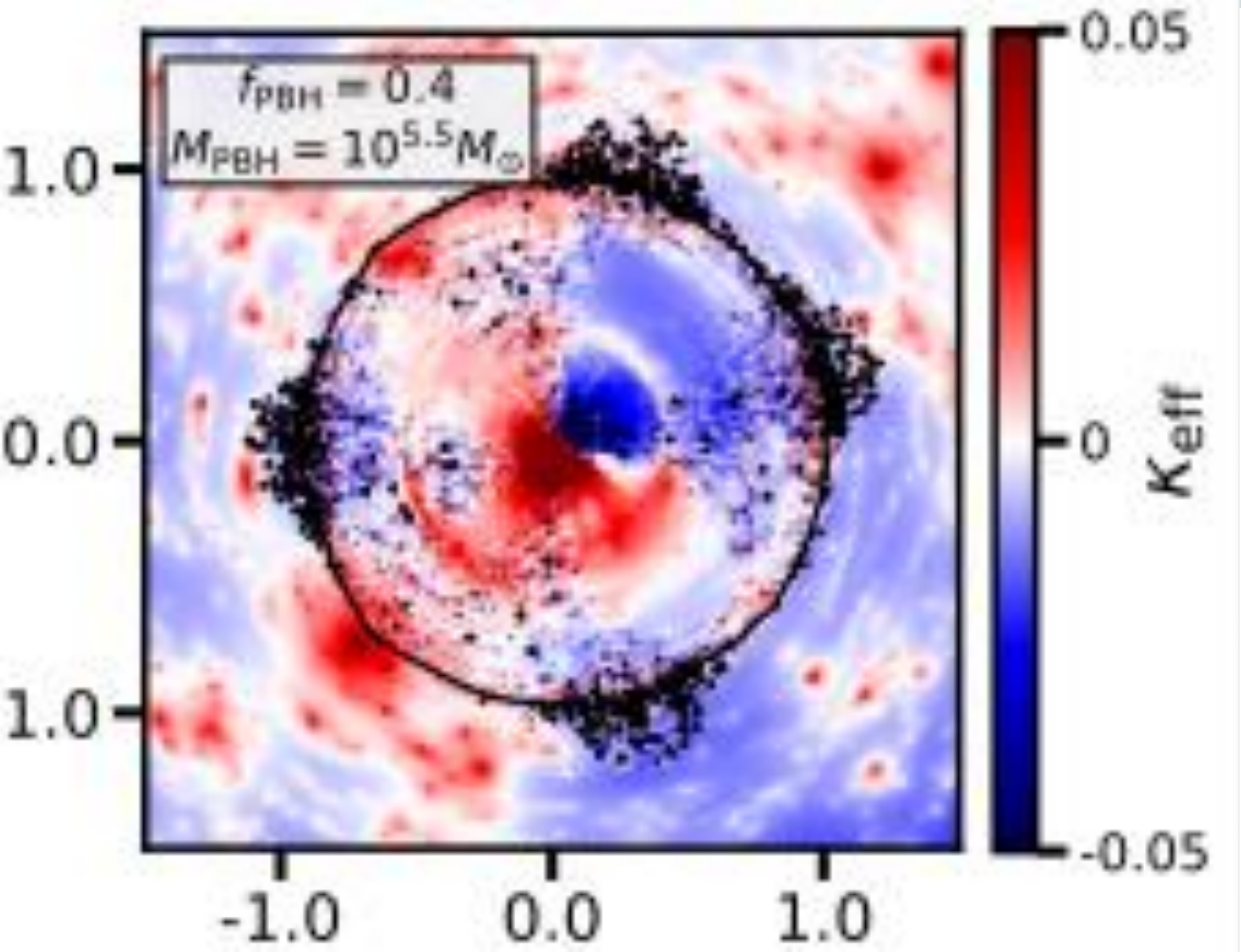
4 Different sterile neutrino models

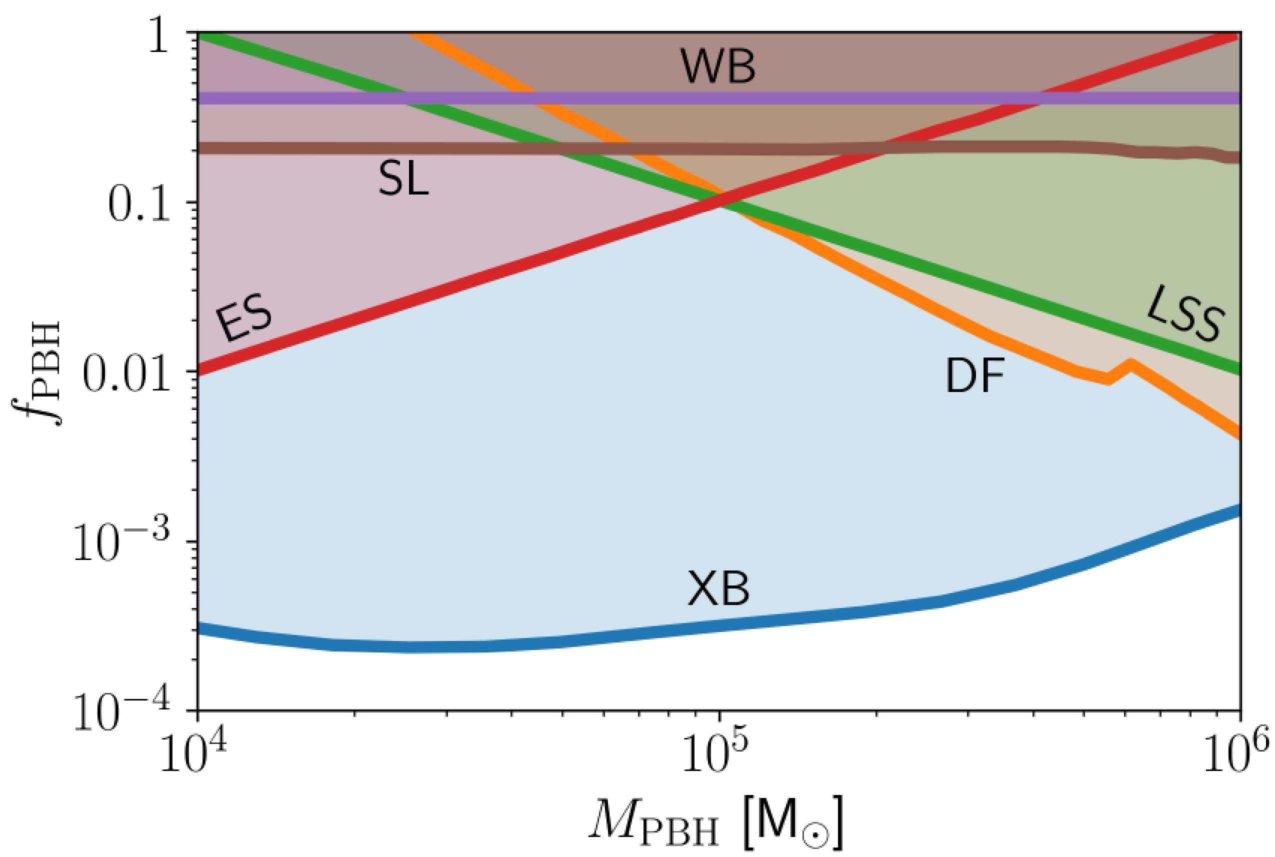


95% confidence interval to the left of dashed lines

Zelko et al. 2022 different WDM scenarios

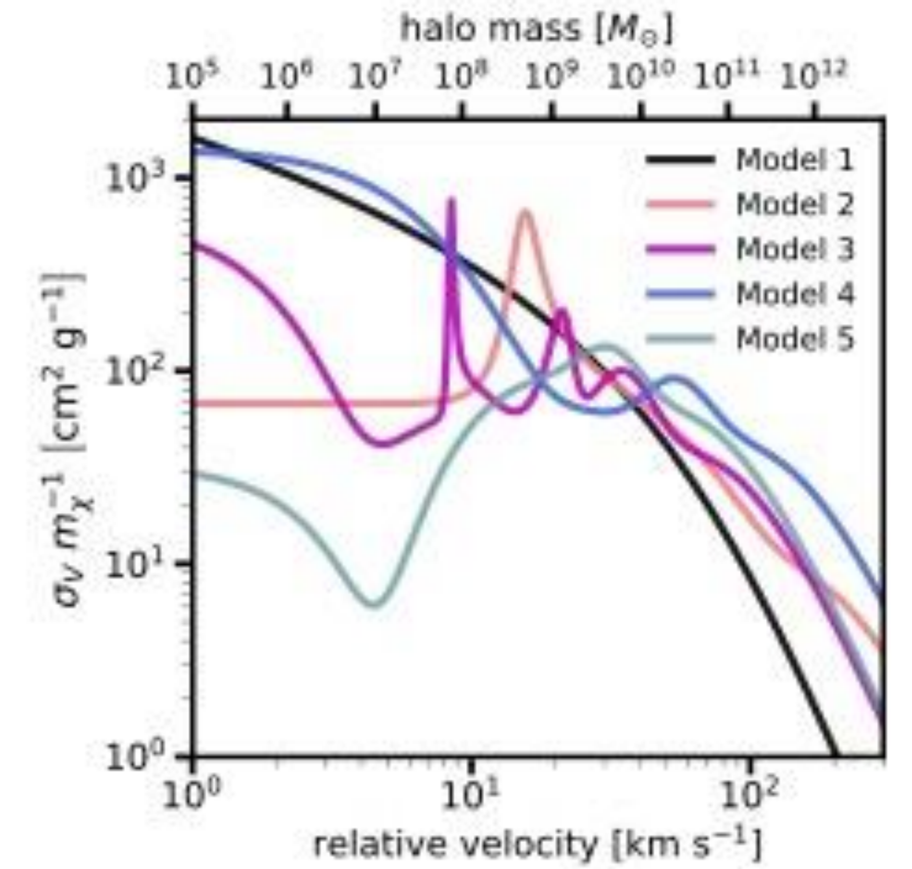
Primordial Black Holes

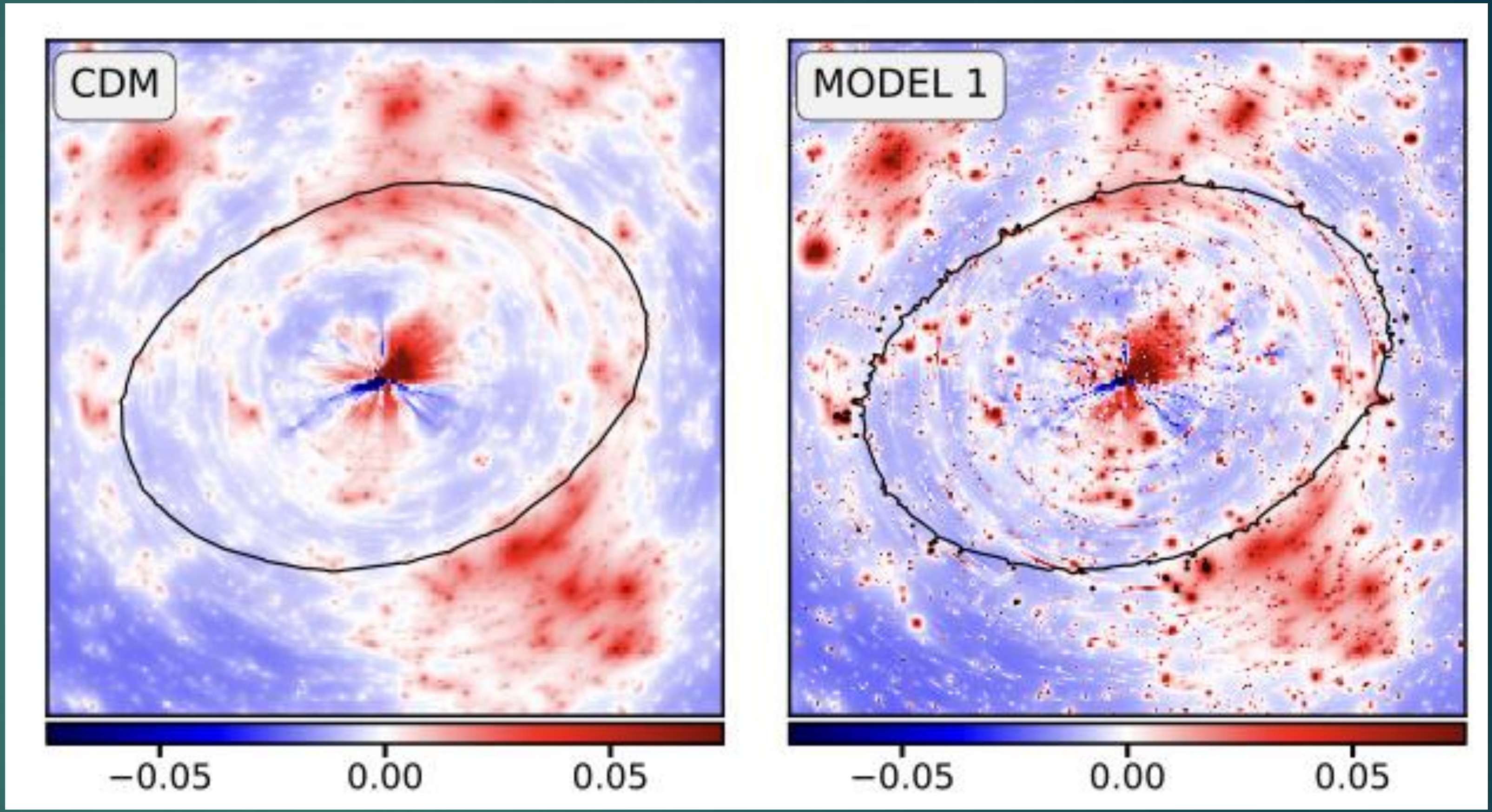




Dike et al. 2022

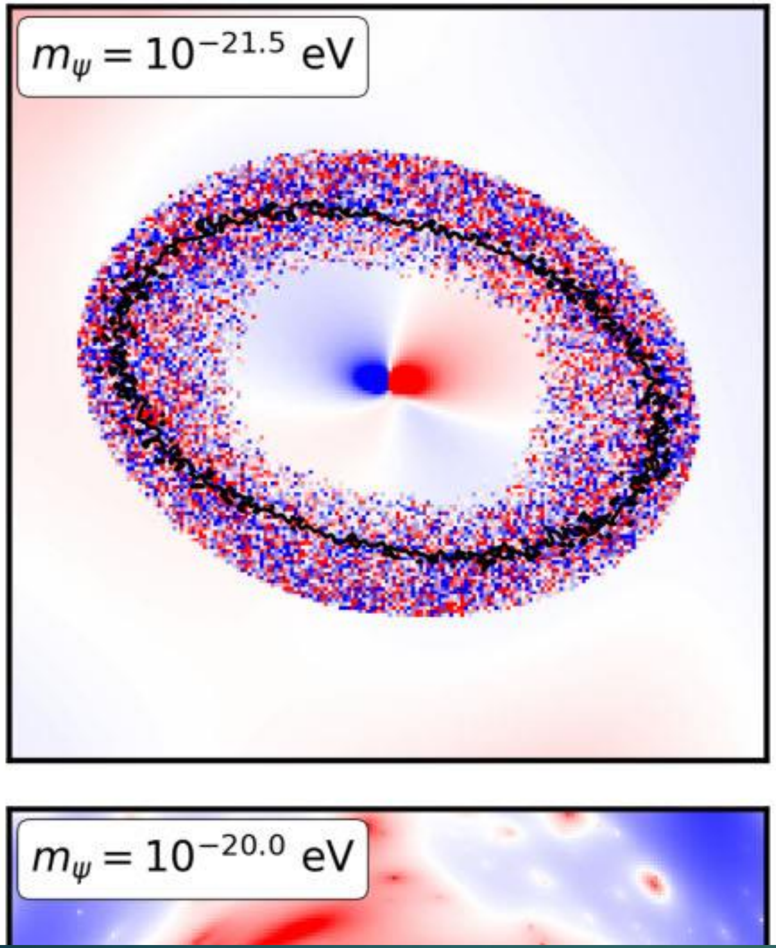
Self-interacting dark matter

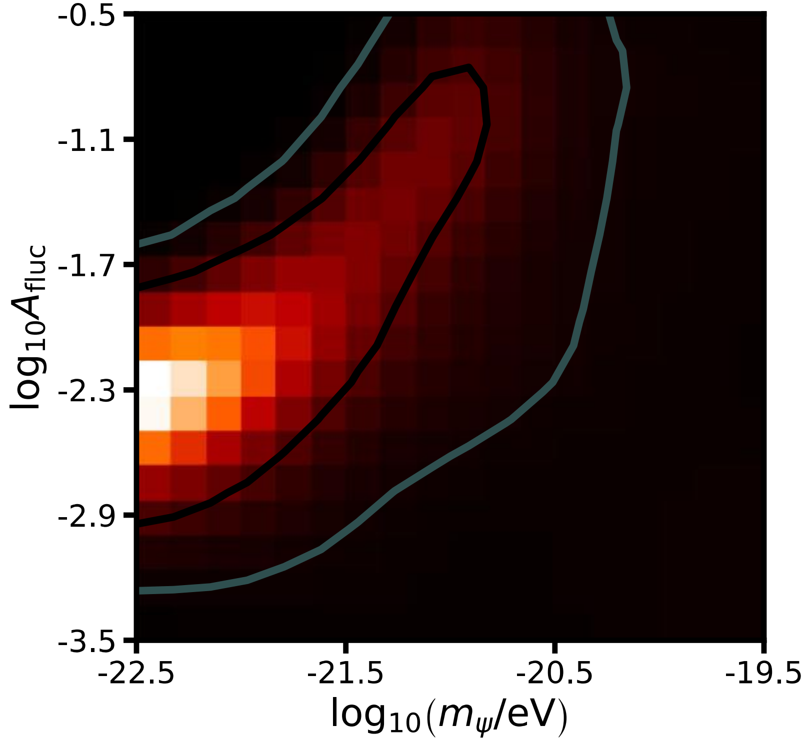




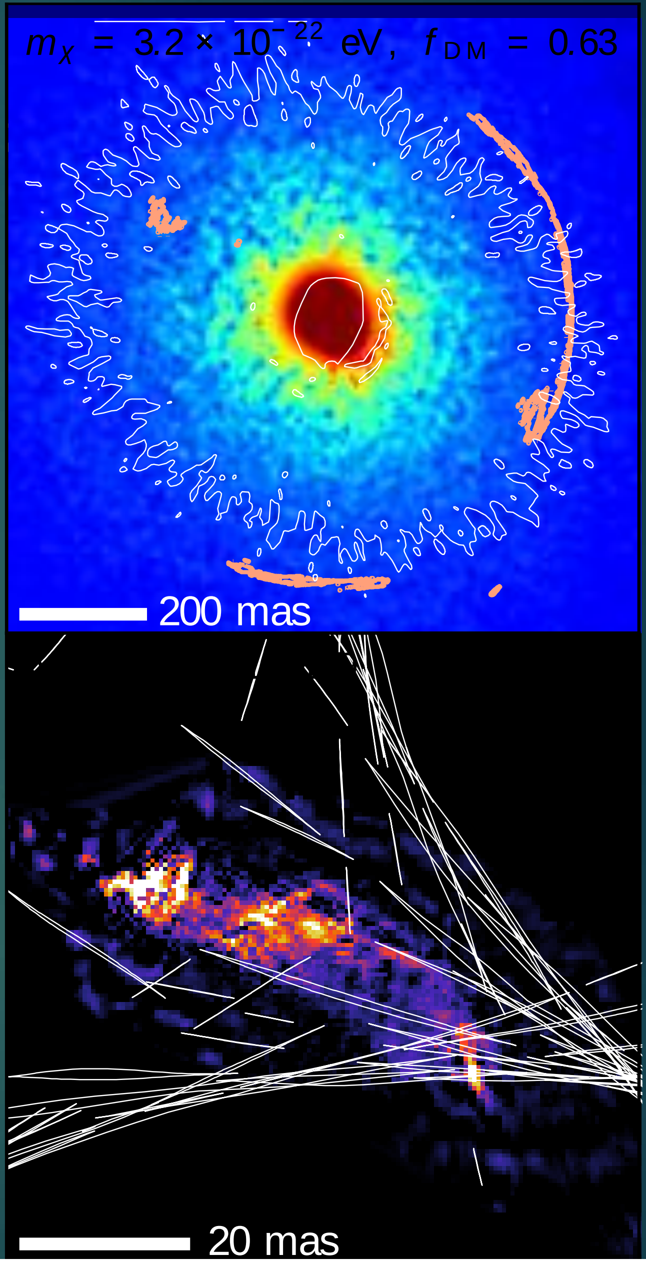
Tidal stripping leads to run-away collapse of dark matter subhalos 100 cm^2/g at velocities below 30 km/s strongly ruled out. (Gilman et al. 2022)

“Fuzzy” Dark Matter



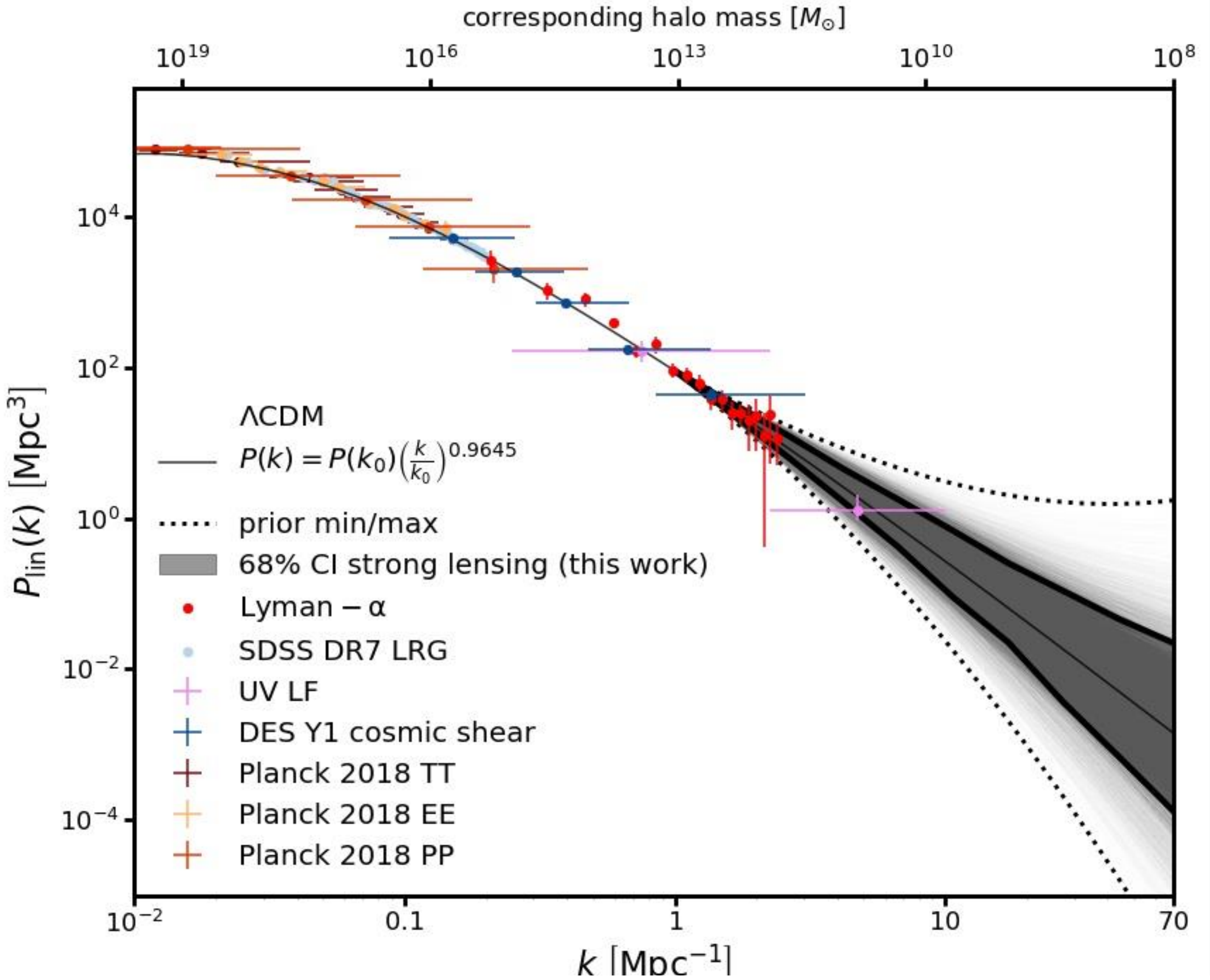


Laroche et al. 2022



Powell et al. 2023

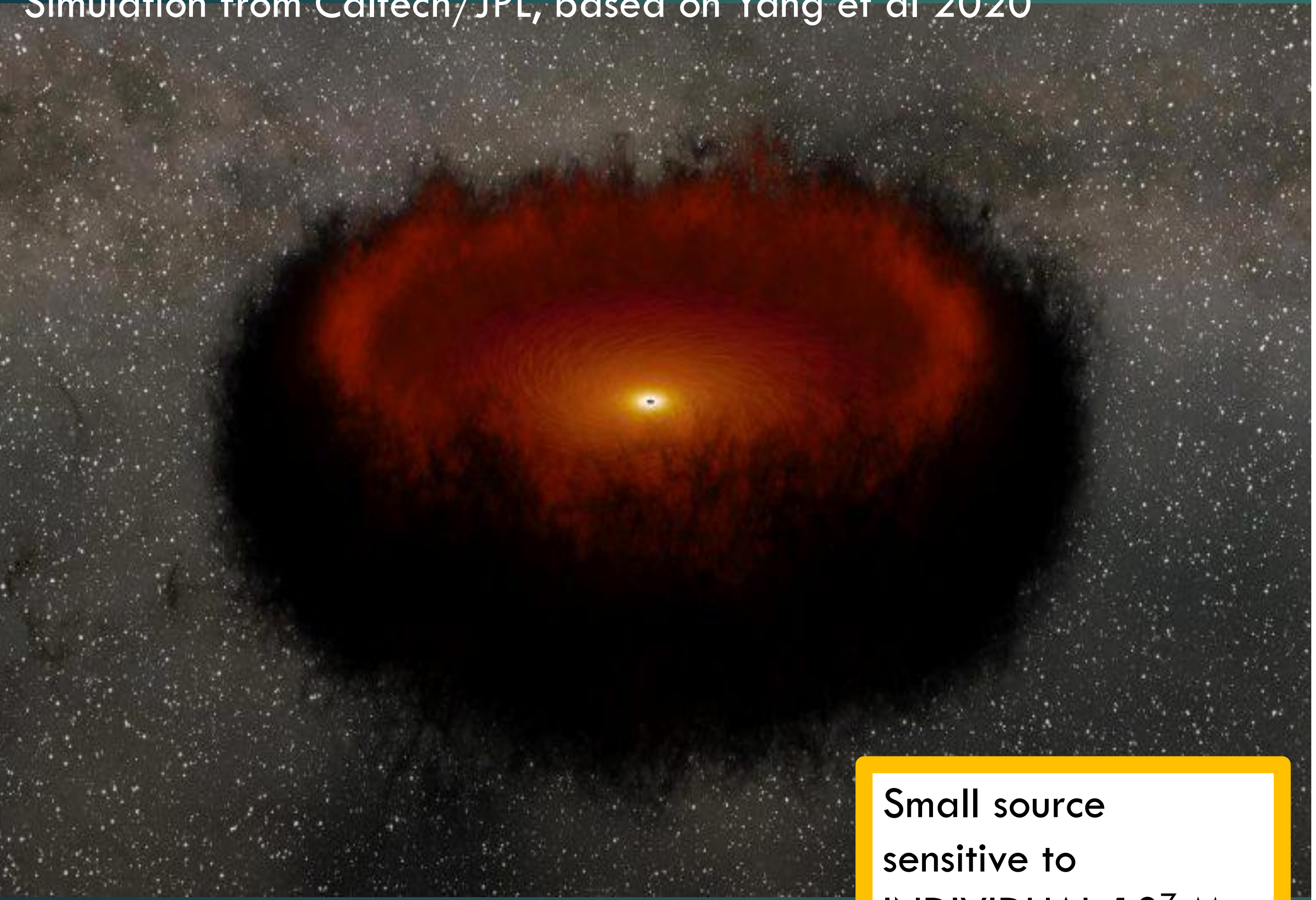
Tying the measurement back to the primordial power spectrum



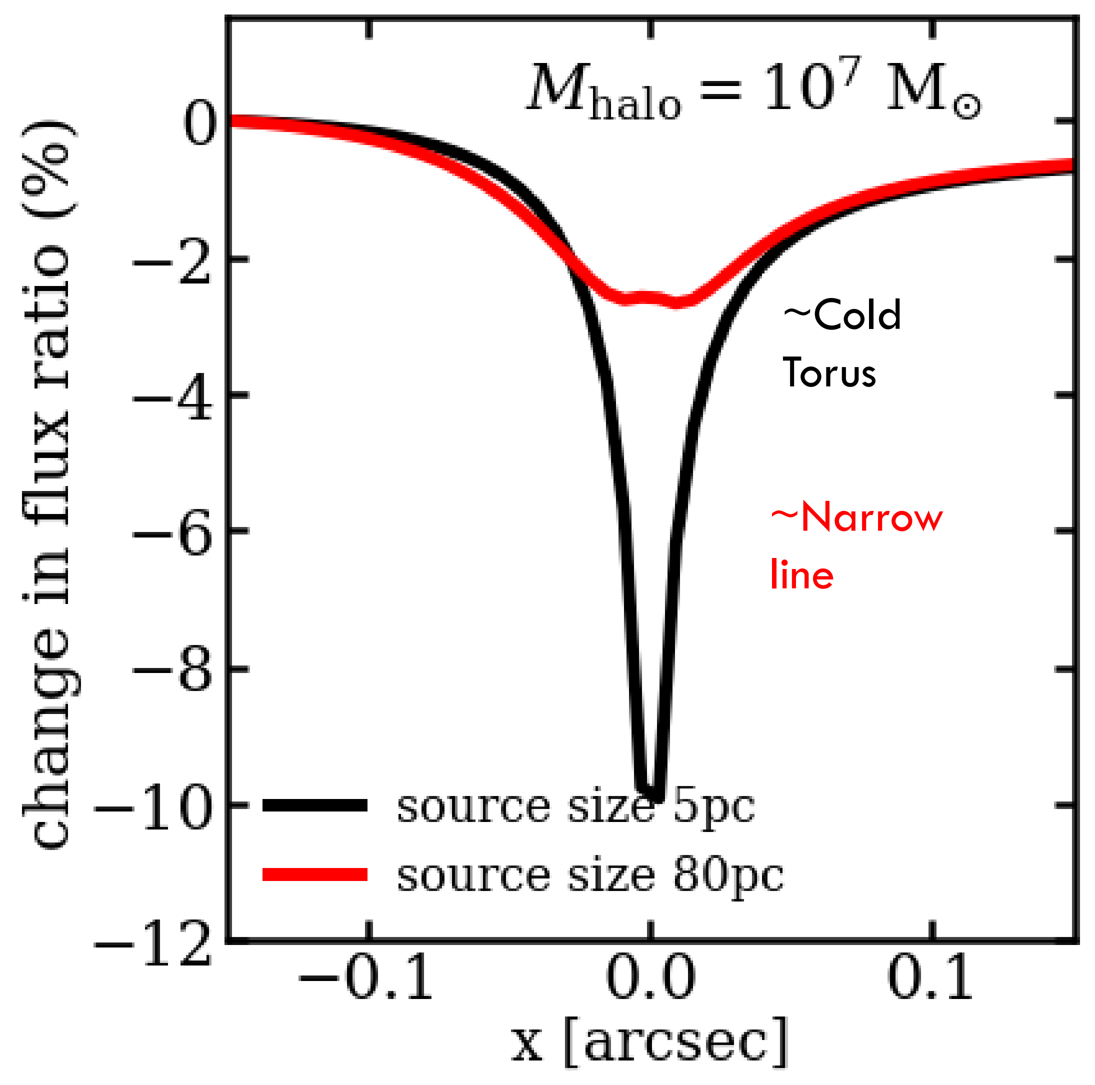
Gilman et al. 2022

Coming soon, the quasar cold torus flux with the James Webb Space Telescope

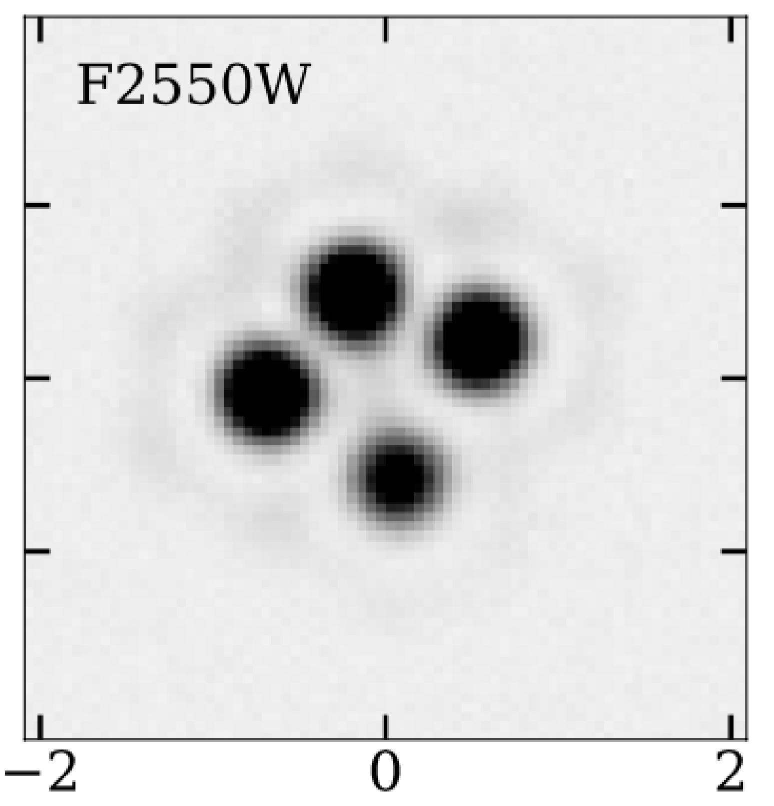
Simulation from Caltech/JPL, based on Yang et al 2020



Small source sensitive to INDIVIDUAL 10^7 $M_\odot$ perturbers

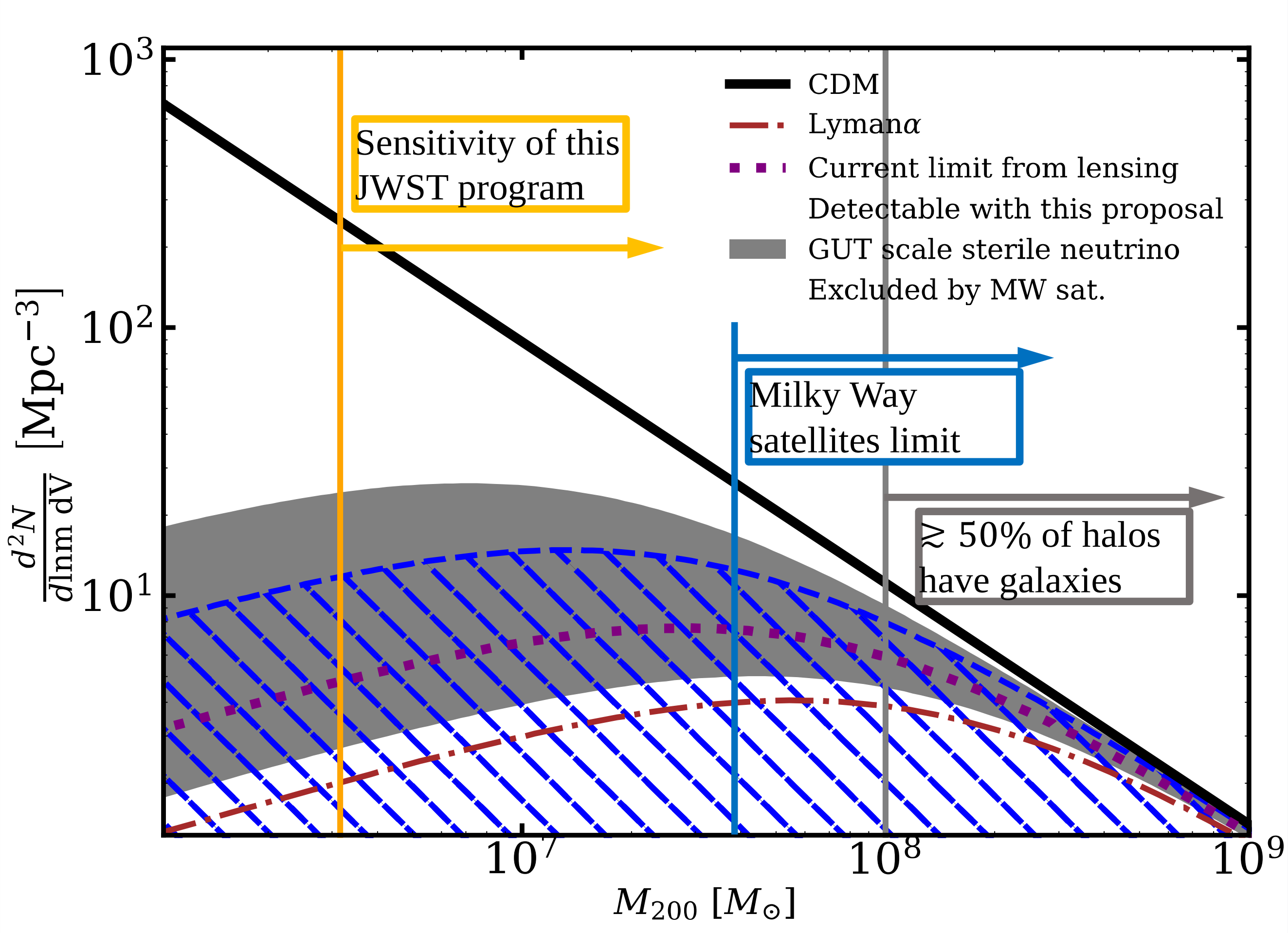


Forecast constraints with JWST- 38.4 hours to observe 31 lenses in Cycle 1

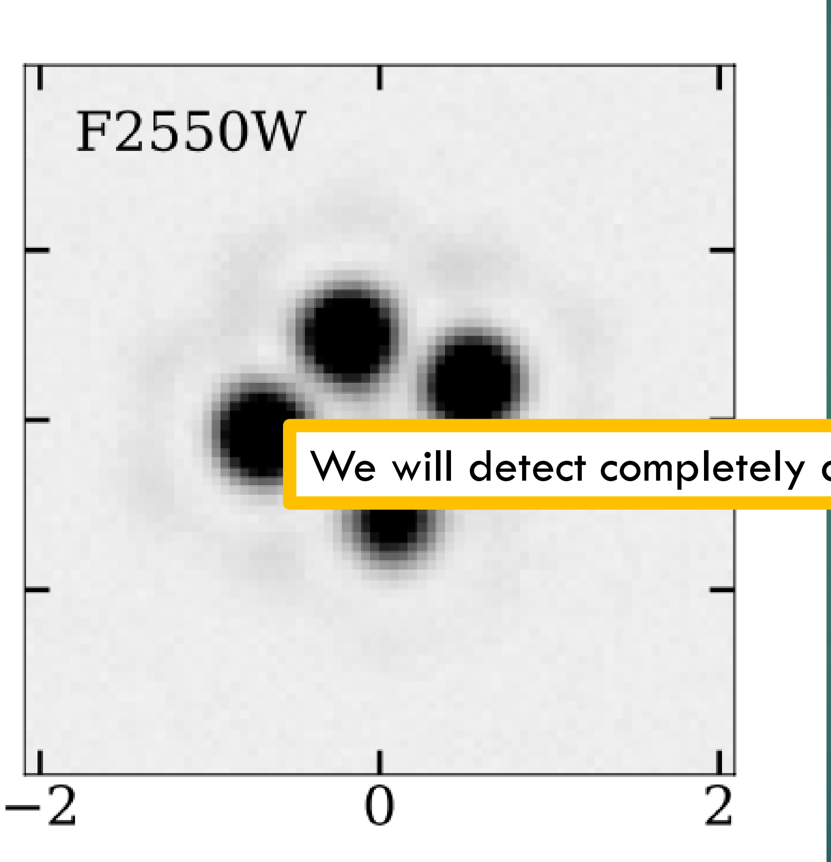


Simulated JWST MIRI image

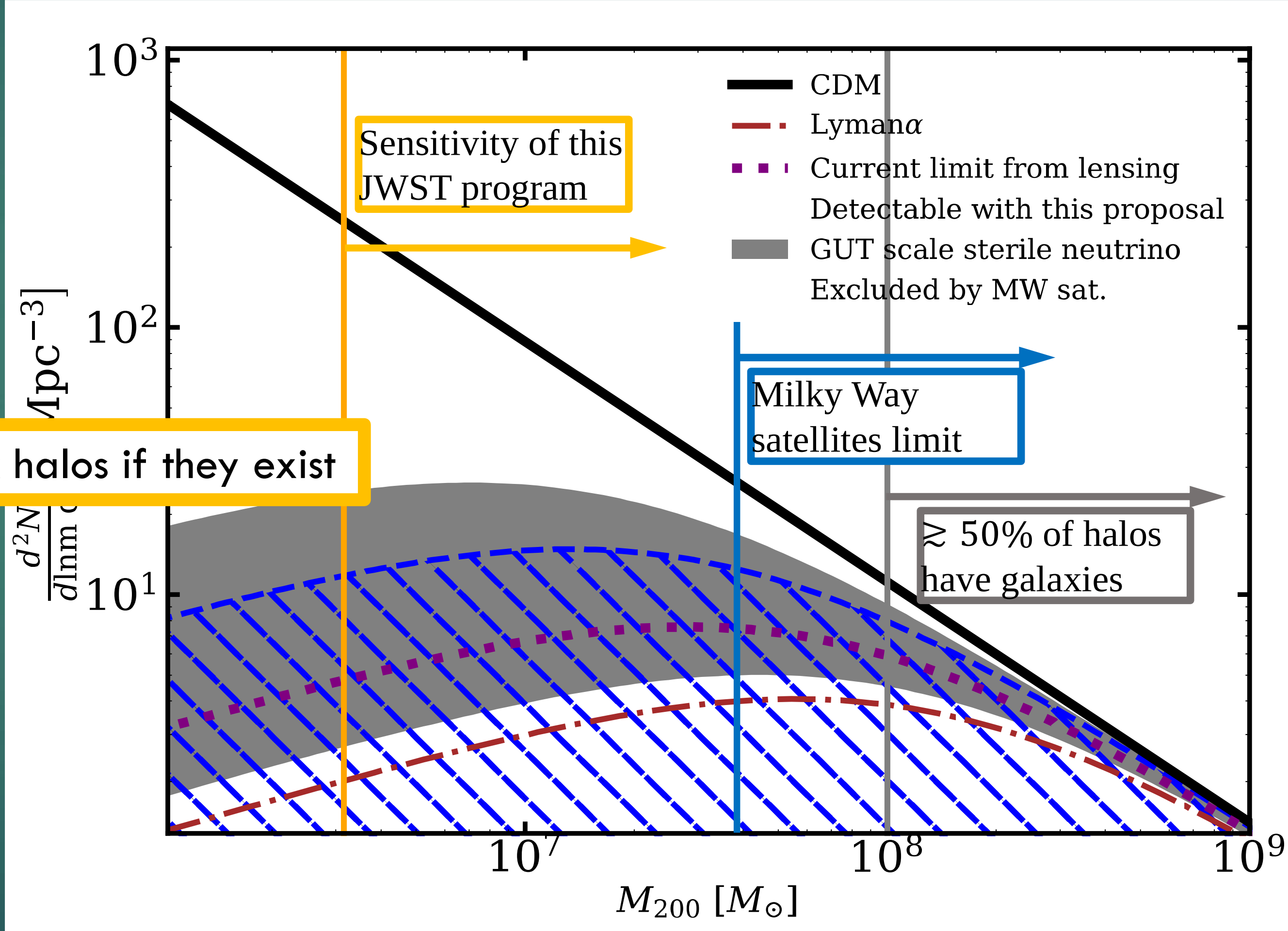
JWST-GO-02046, PI Nierenberg



Forecast constraints with JWST- 38.4 hours to observe 31 lenses in Cycle 1

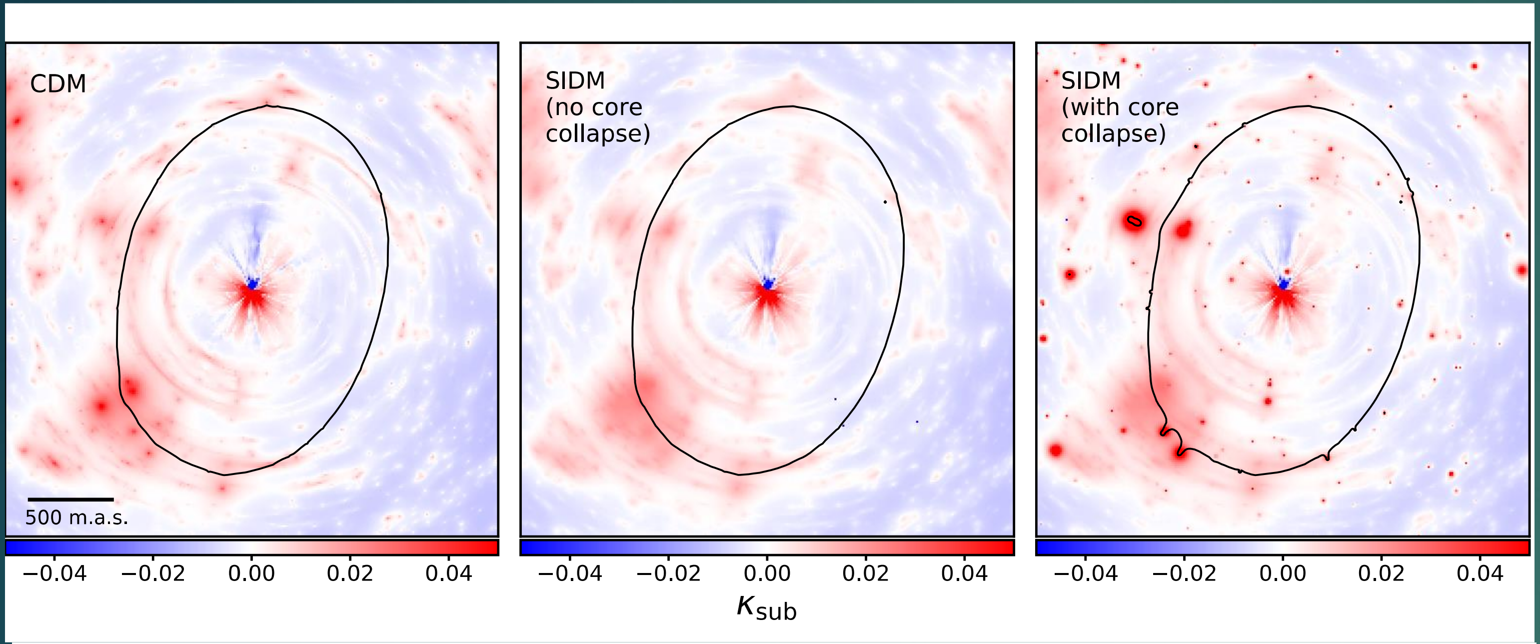


We will detect completely dark halos if they exist

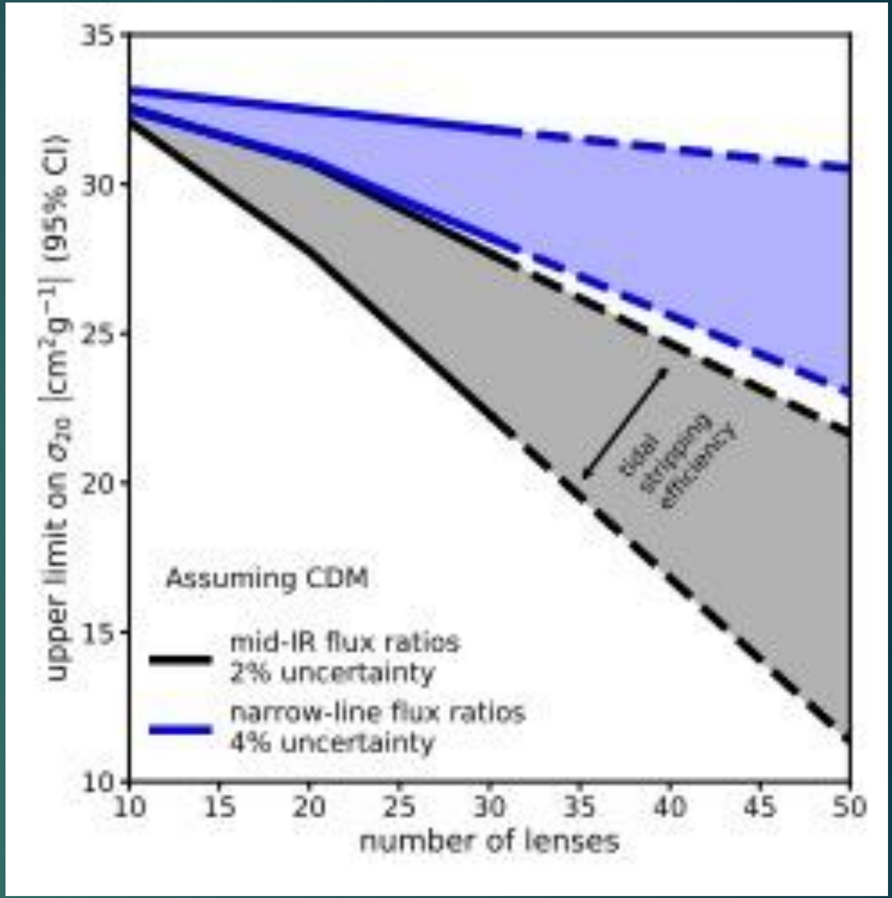


Simulated JWST MIRI image
JWST-GO-02046, PI Nierenberg

Some other forecasts with JWST:



SIDM: Gilman et al. 2021

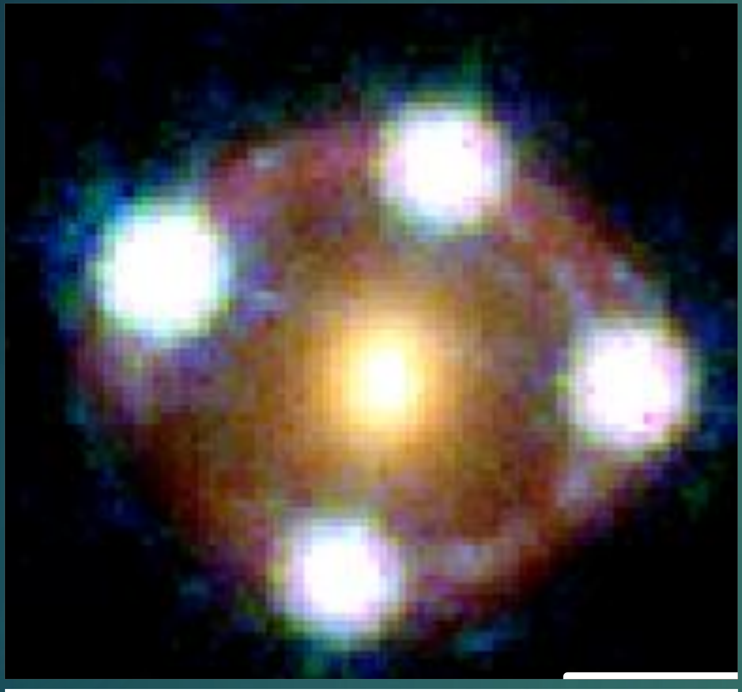


Also we will detect or rule out 50% mixed warm/dark matter (Keeley et al. 2022, see talk tomorrow!)

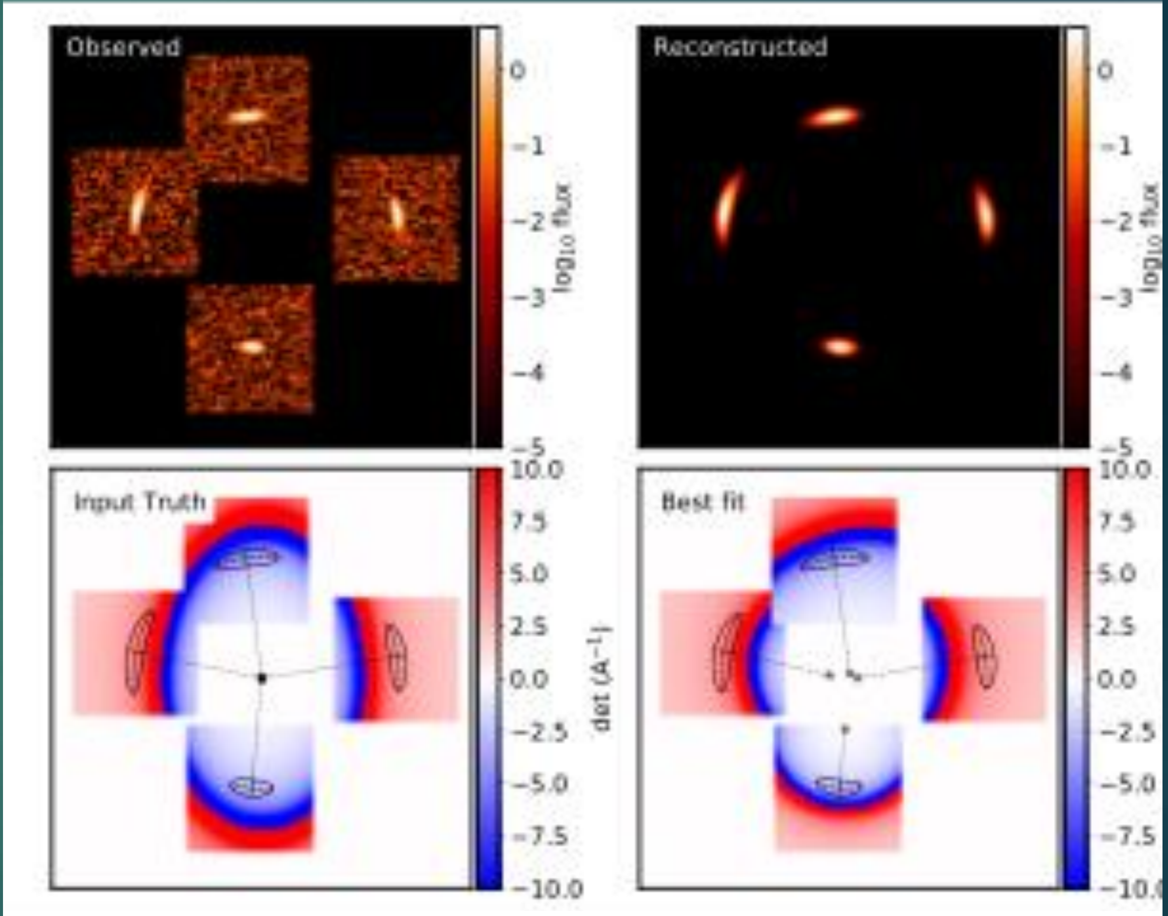
The future…

- Continuous improvement of lens models
- New data
- New lenses

Host galaxy modelling for stronger constraint on macromodel



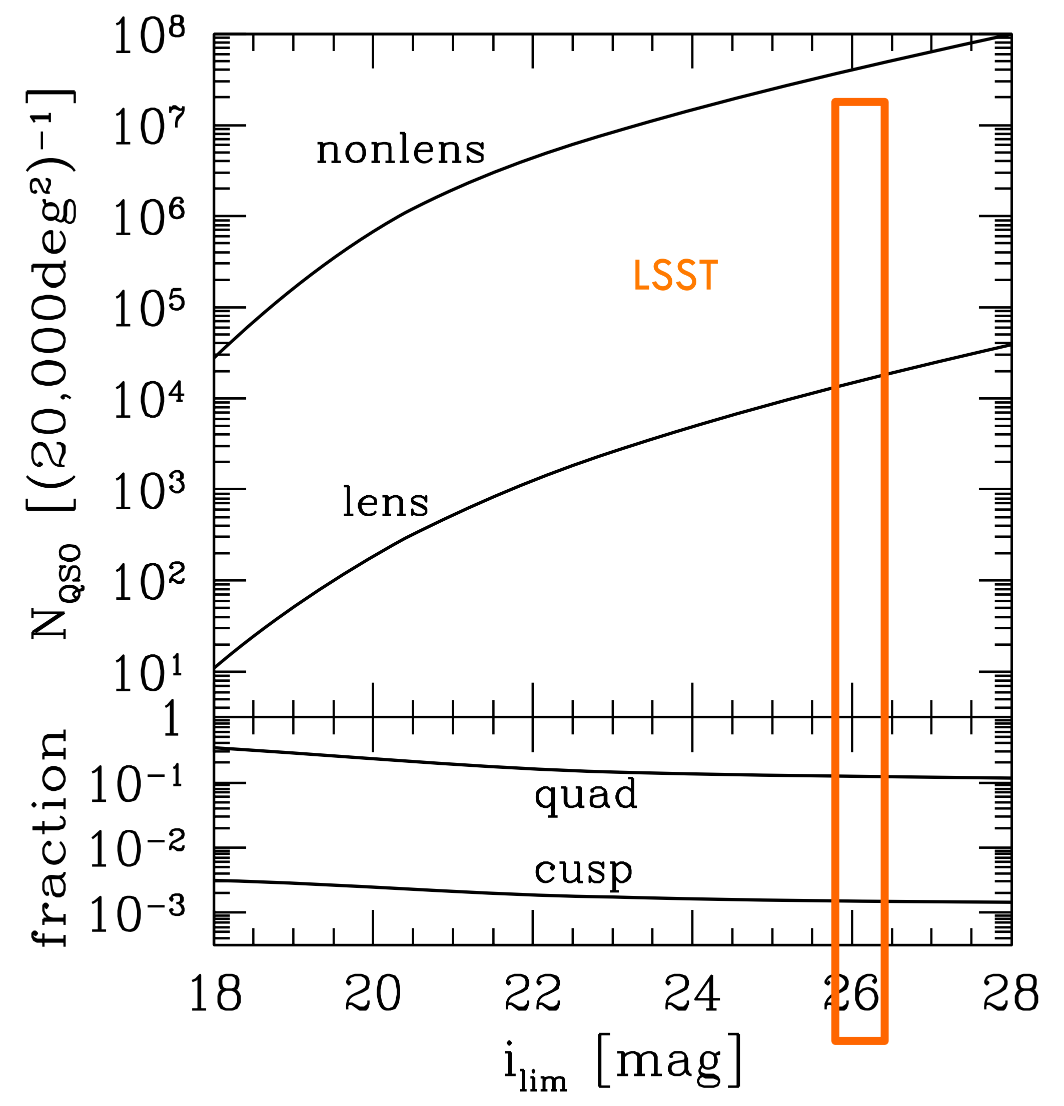
High sensitivity of narrow-line magnification with large-scale constraint from arcs



Birrer 2021

Future prospects for unresolved source lensing

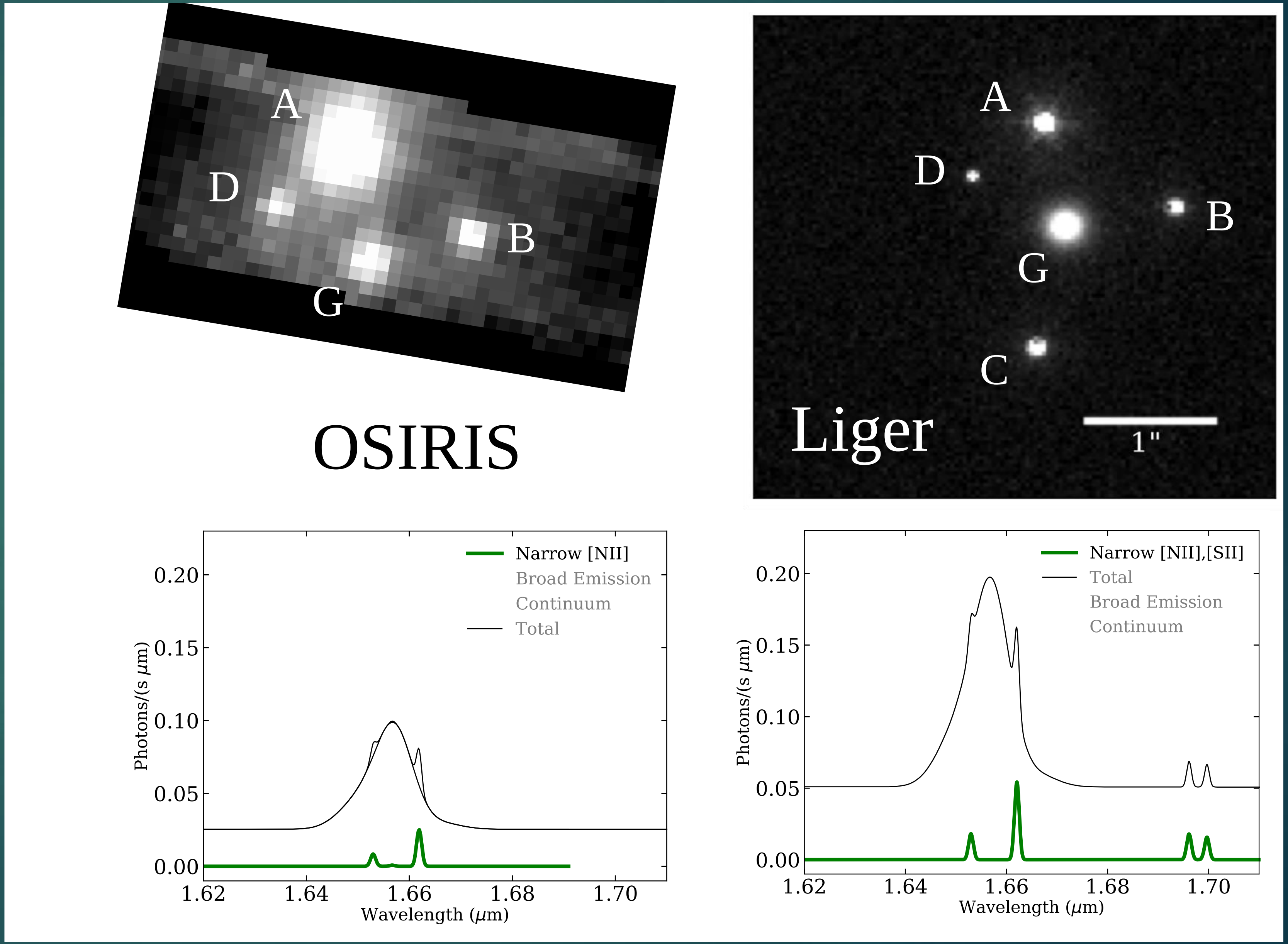
- **Hundreds of new lenses** will be discovered in upcoming surveys (LSST, Euclid, Roman~ mid 2020s)
- **Improved flux precision** with next generation instruments and observatories



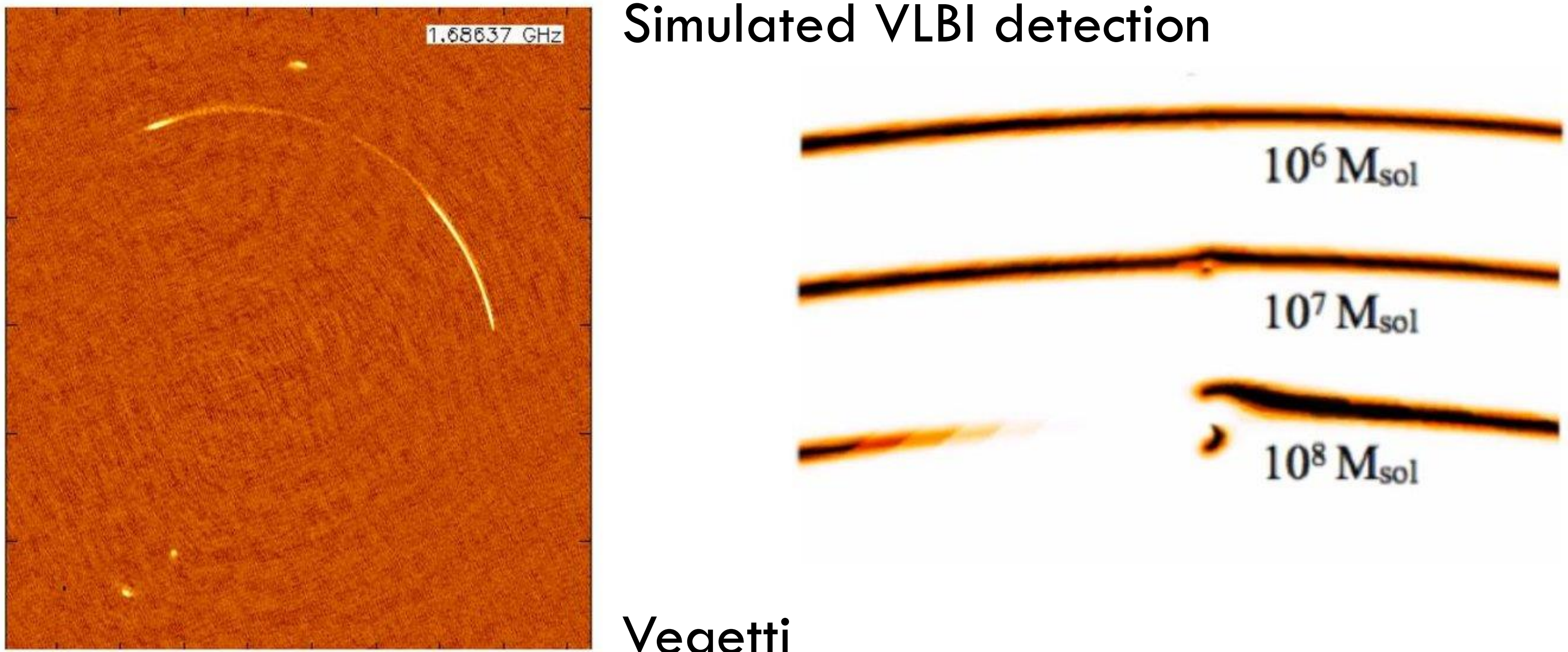
Oguri and Marshall 2010

Development of next generation detectors

- Liger is an upgrade to the current IFS on Keck
- NL lensing was one of three main science goals highlighted in recent MSIP funding proposal
- Status: Advanced to stage 3 NSF MSRI-2, now up to NSF site visit.



Future prospects for gravitational imaging- single detection- higher spatial resolution



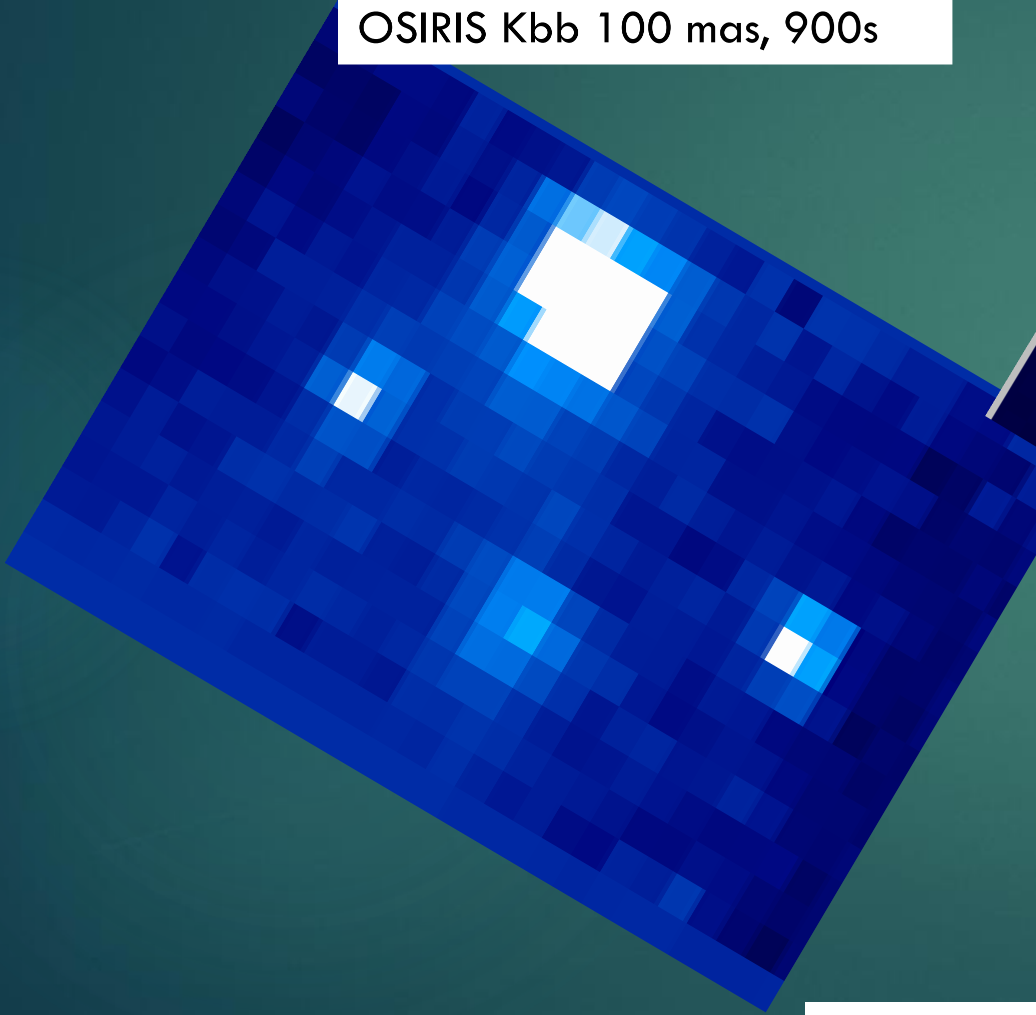
Simulated VLBI detection

Vegetti

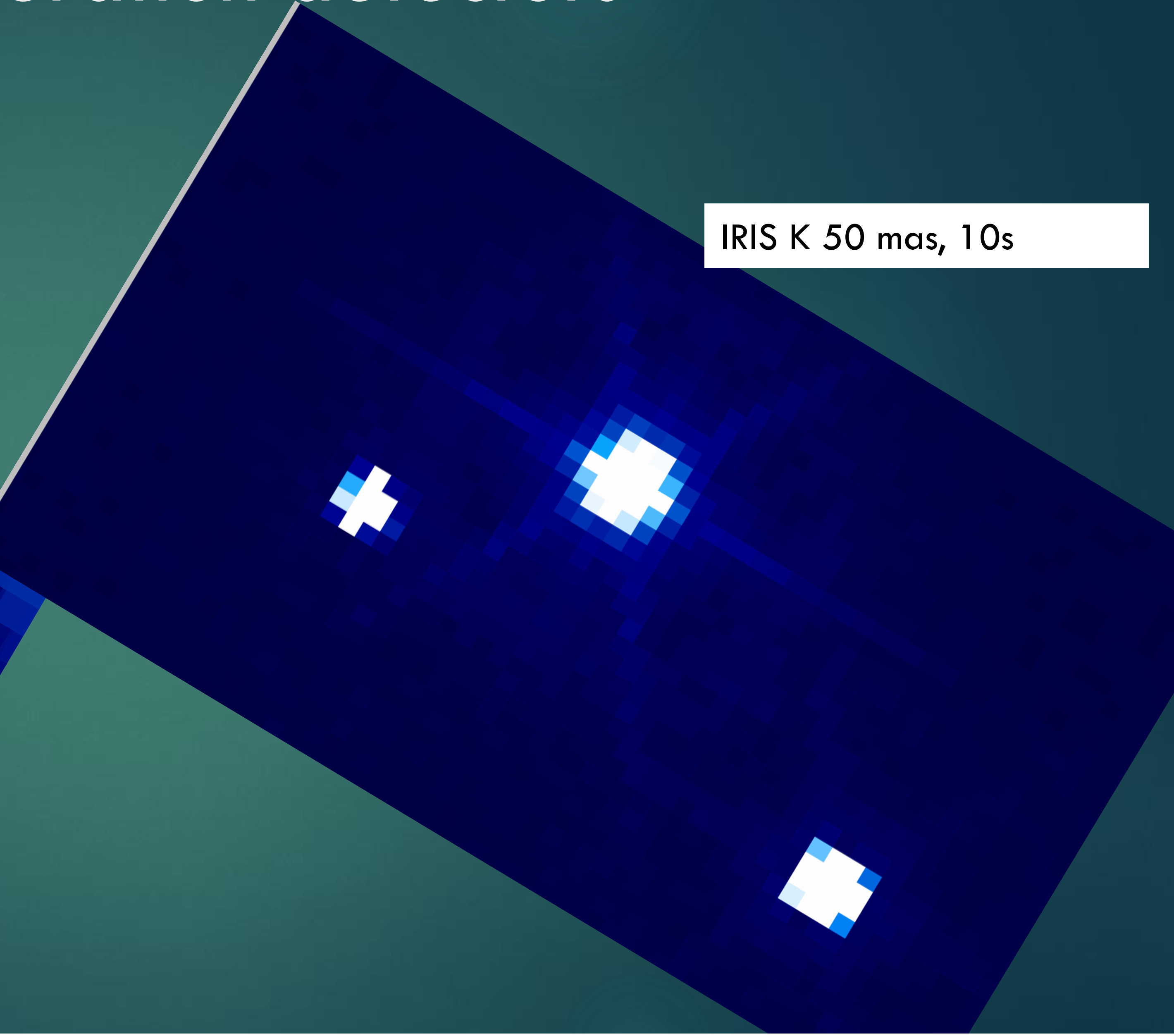
- VLBI imaging of radio jets
- Next generation AO
- EELTs

Development of next generation detectors

- IRIS is the OSIRIS analog in development for TMT



OSIRIS Kbb 100 mas, 900s



IRIS K 50 mas, 10s

IRIS Simulation courtesy of Nils-Erik Rundquist (UCSD)

Conclusions

- Galaxy-scale strong gravitational lensing provides a rich variety of tests of dark matter models
- Constraints on WDM models from galaxy-scale lenses are among the tightest we have
- Future surveys will enable us to push these methods into new regimes