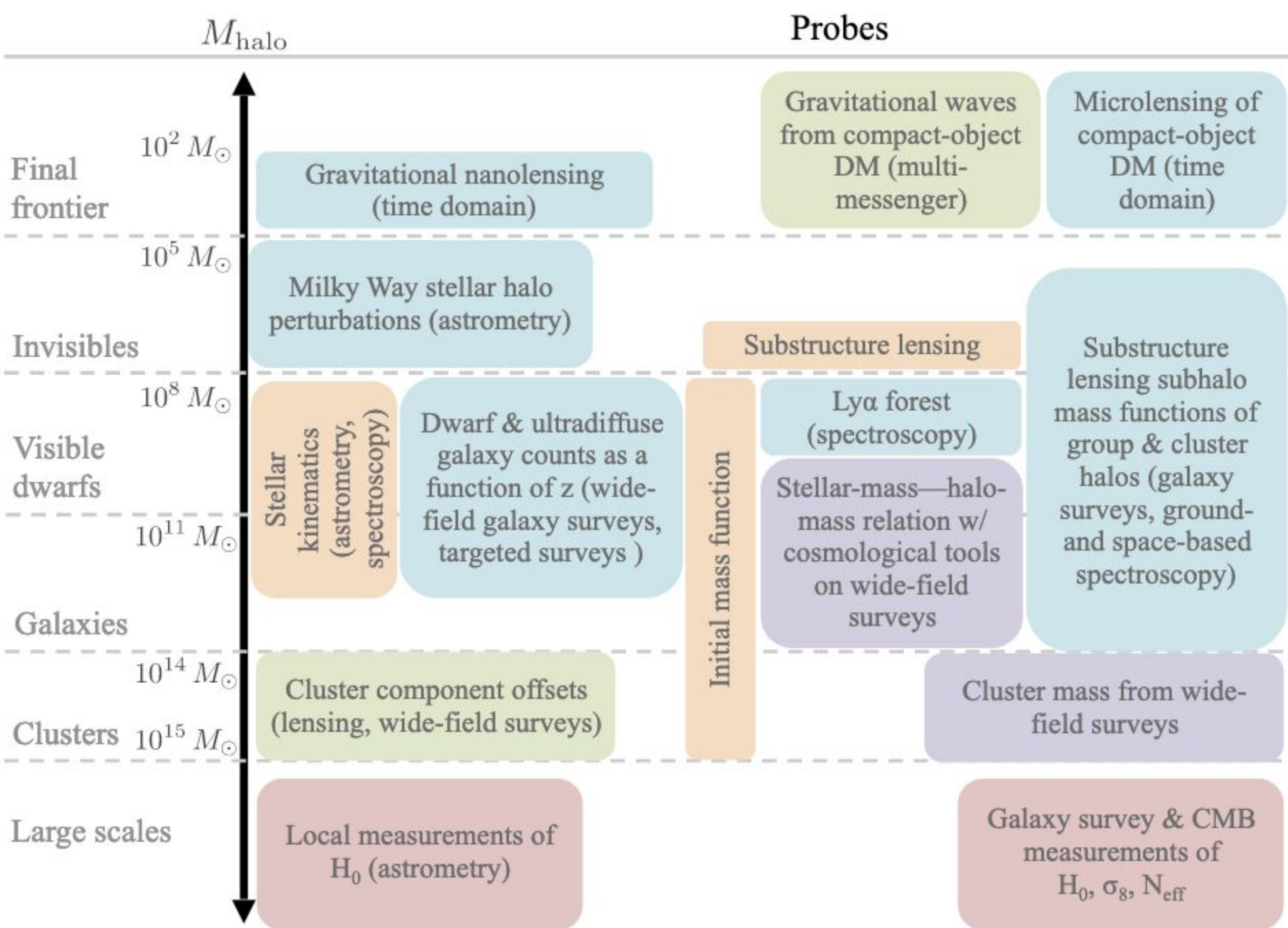
Current state and prospects of strong gravitational lensing in probing dark matter at and below the galaxy formation threshold

Simon Birrer

Pollica, June 26th 2023

Astrophysical small scale structure probes

exploring 20 orders in mass of discovery space



Credit: K. Bechtol

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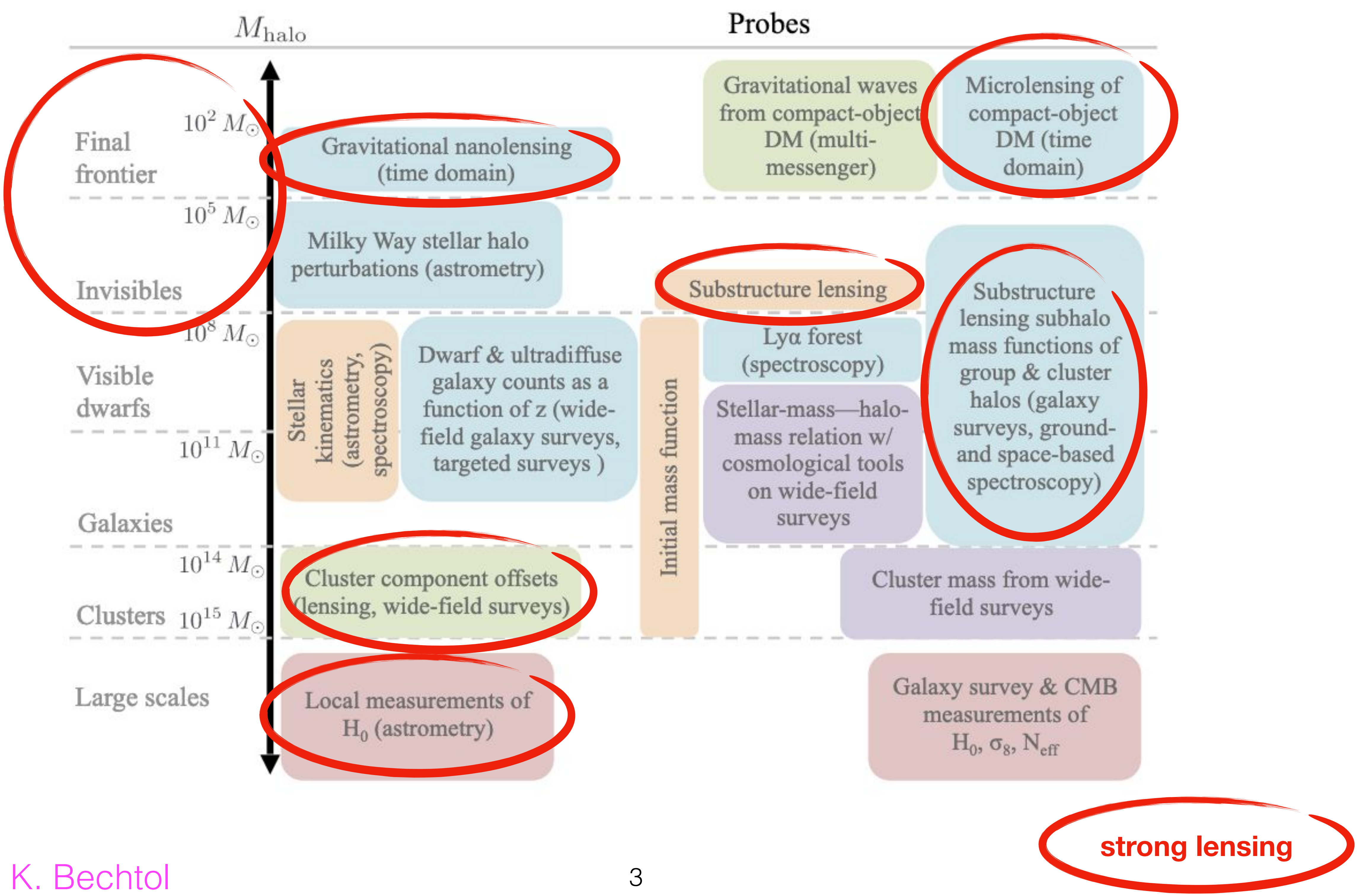
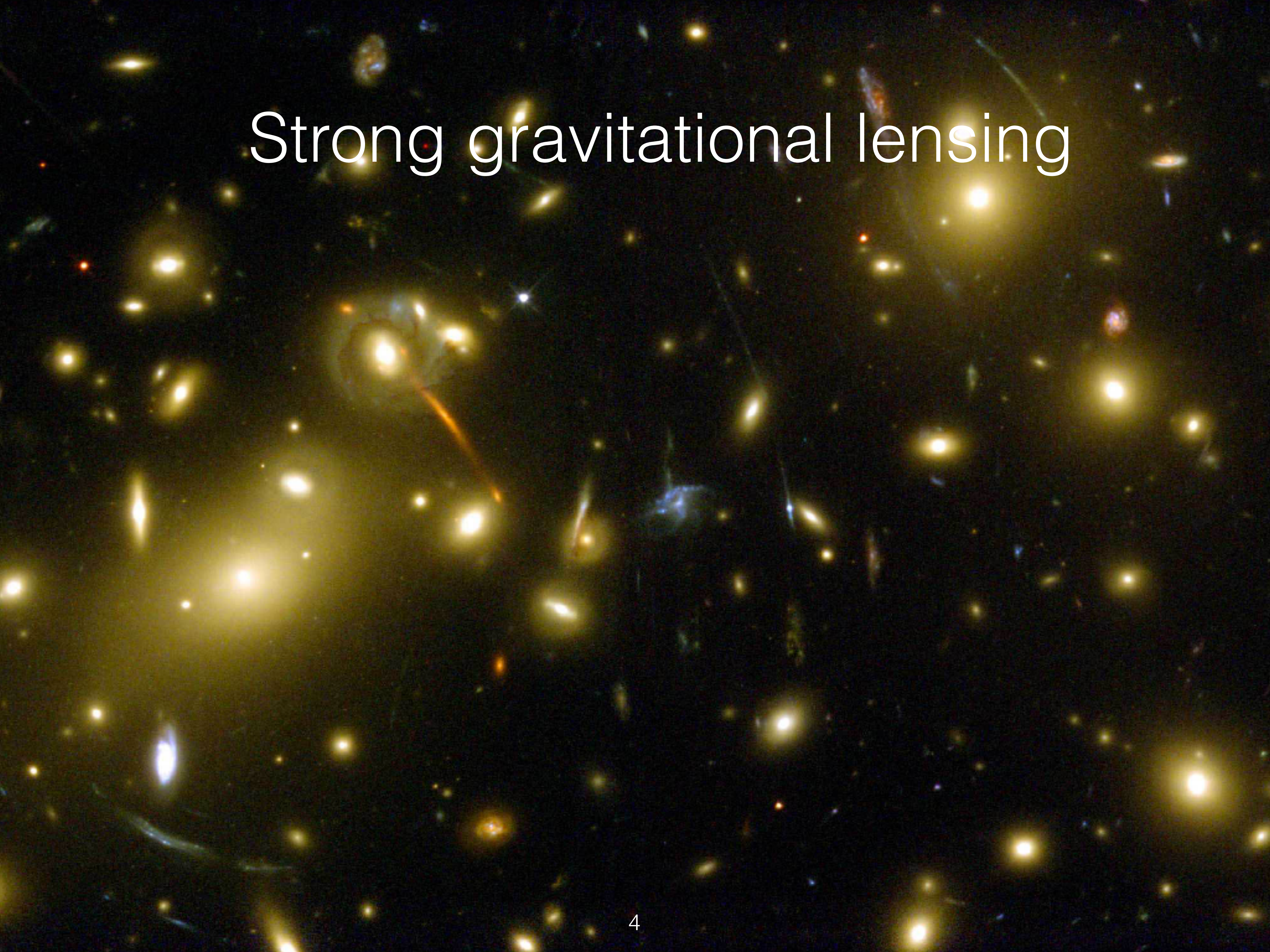


Credit: K. Bechtol

Strong gravitational lensing



Strong gravitational lensing

Strong lensing:
multiple images of a background source

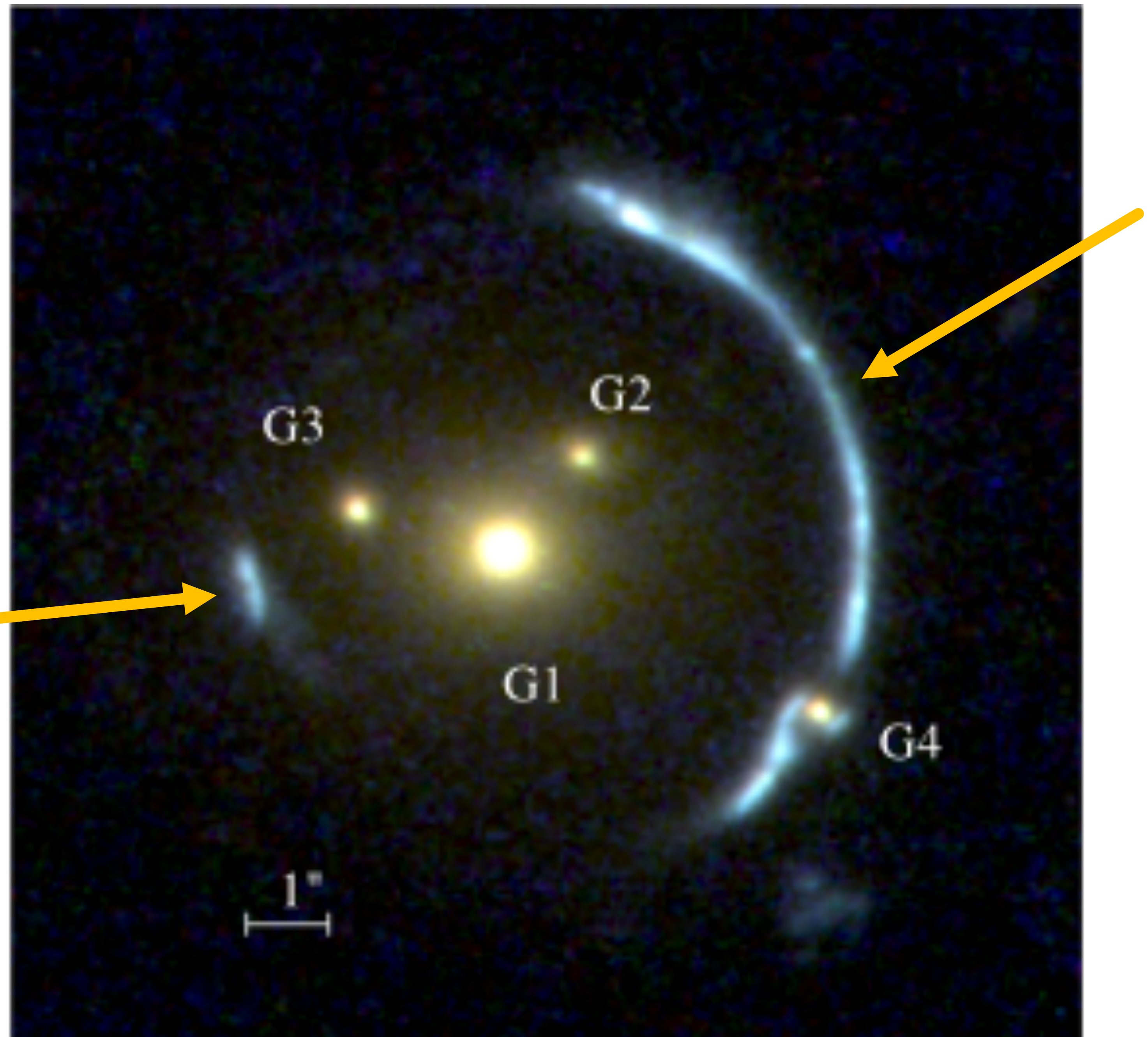


Figure by Vegetti+2010

Strong lensing:
sensitivity to small scale dark matter haloes

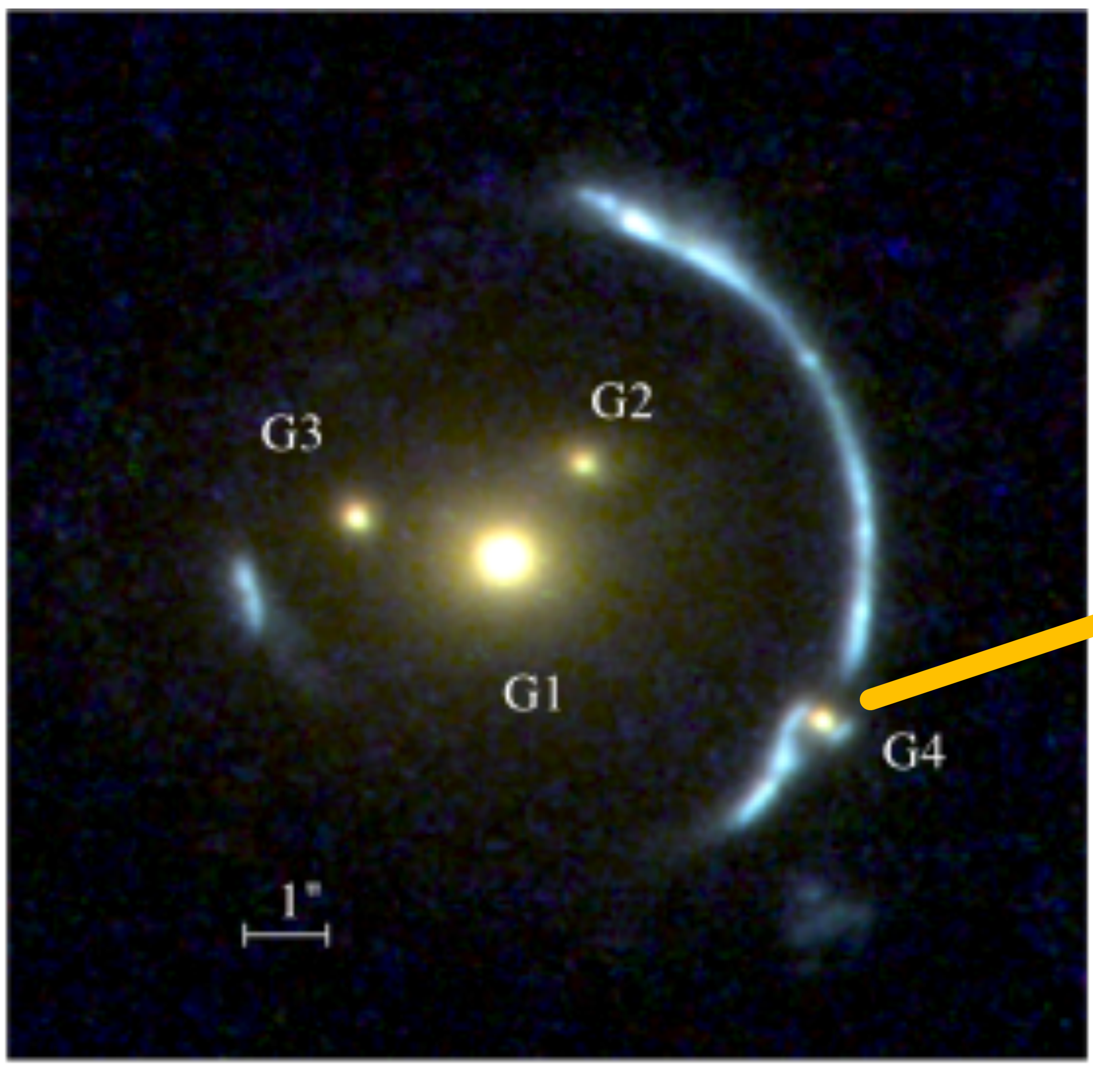


Figure by Vegetti+2010

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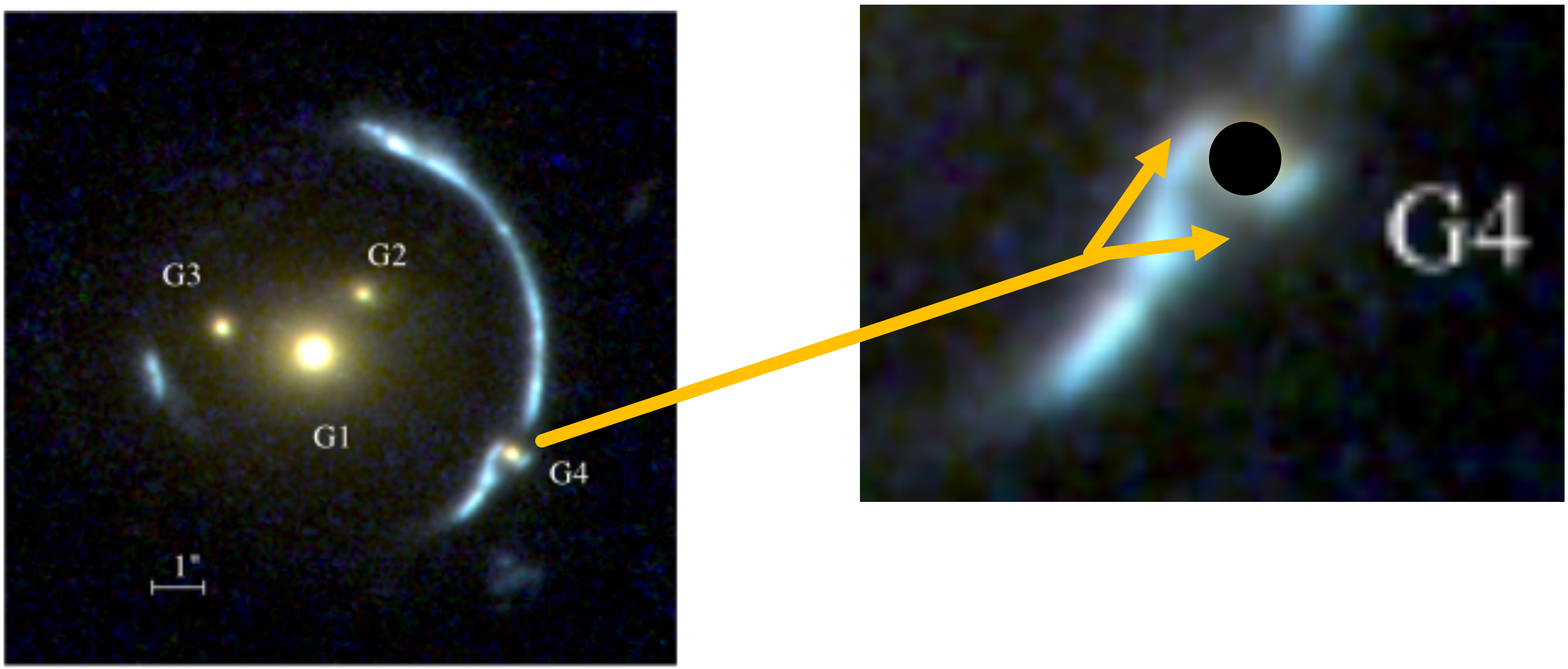
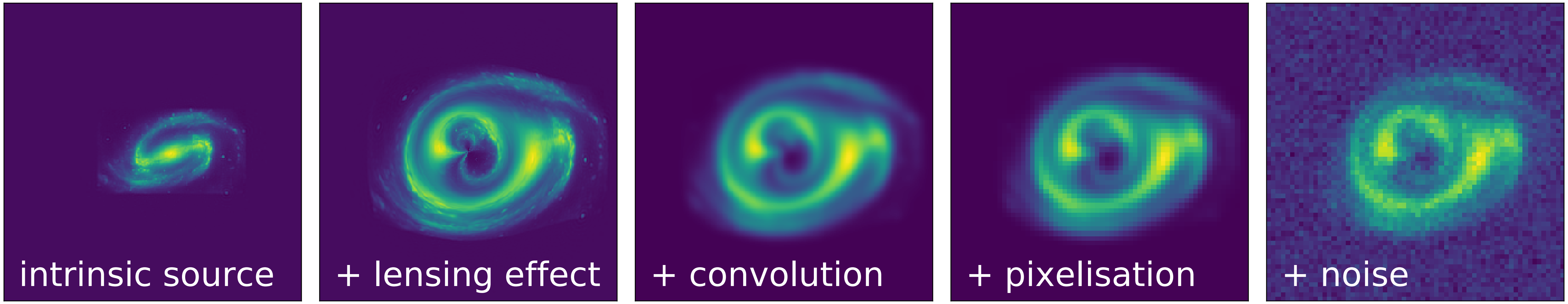


Figure by Vegetti+2010

Strong lensing:
a forward modeling example



Strong lensing:
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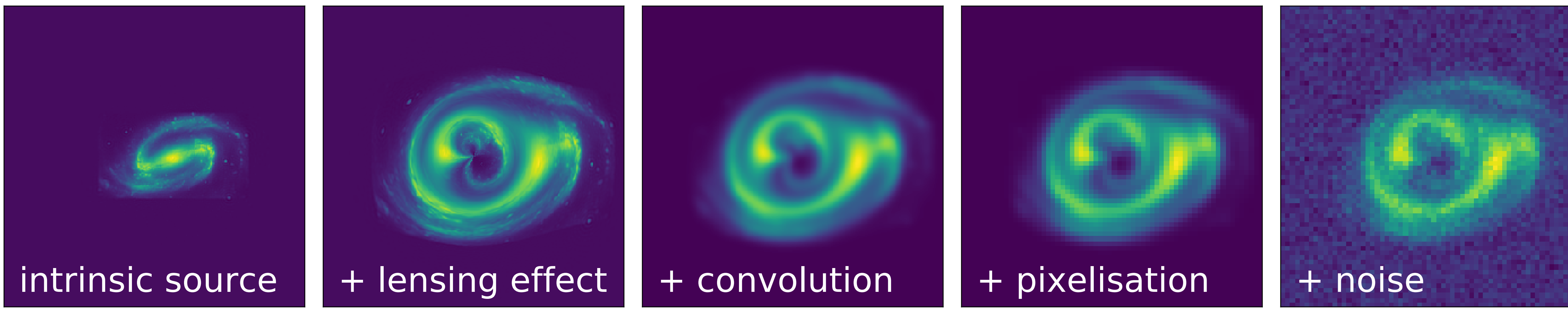


a lot of nuisance!

that's what we care!

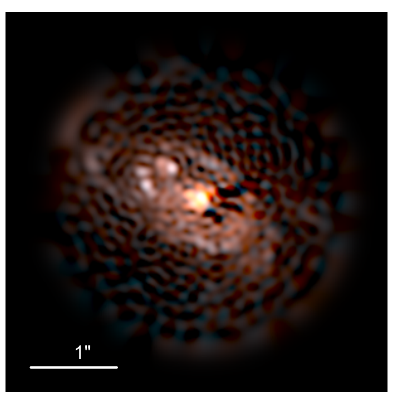
that's what we need to know!

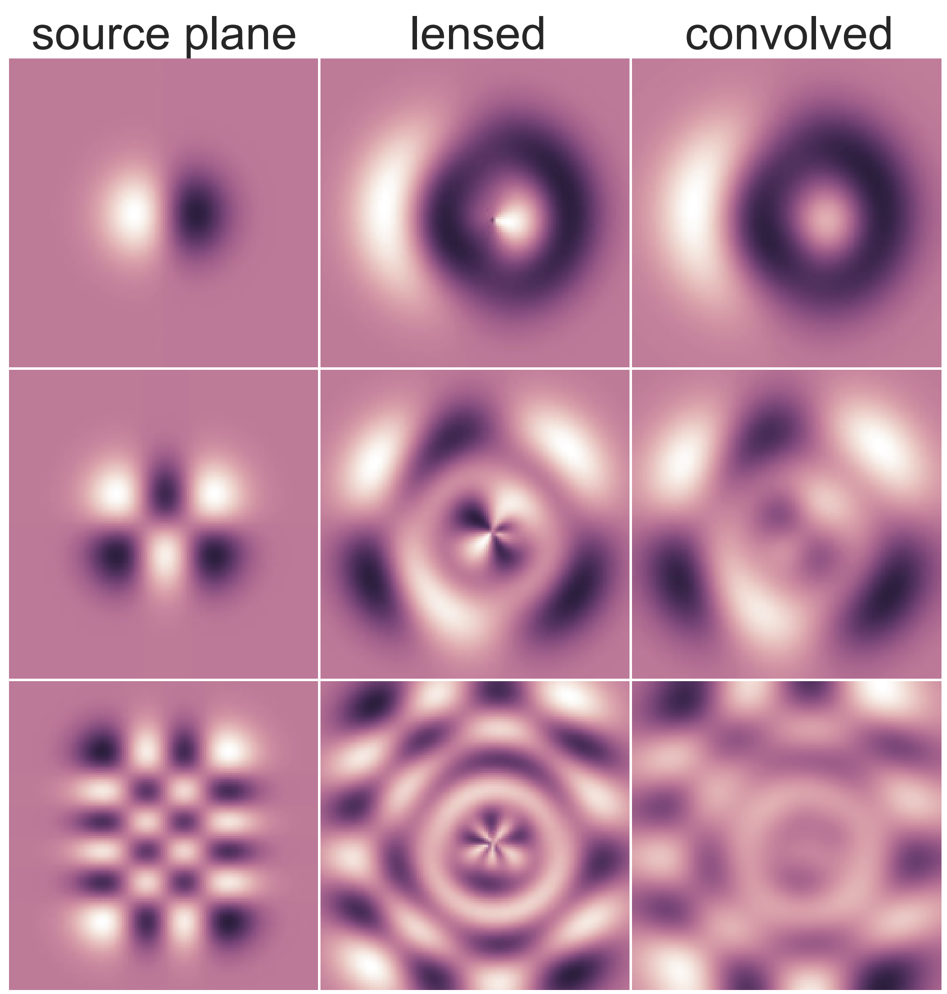
?

De-lensing de-convolution with linear basis functions

Formulation as a
linear problem

Reconstructed source



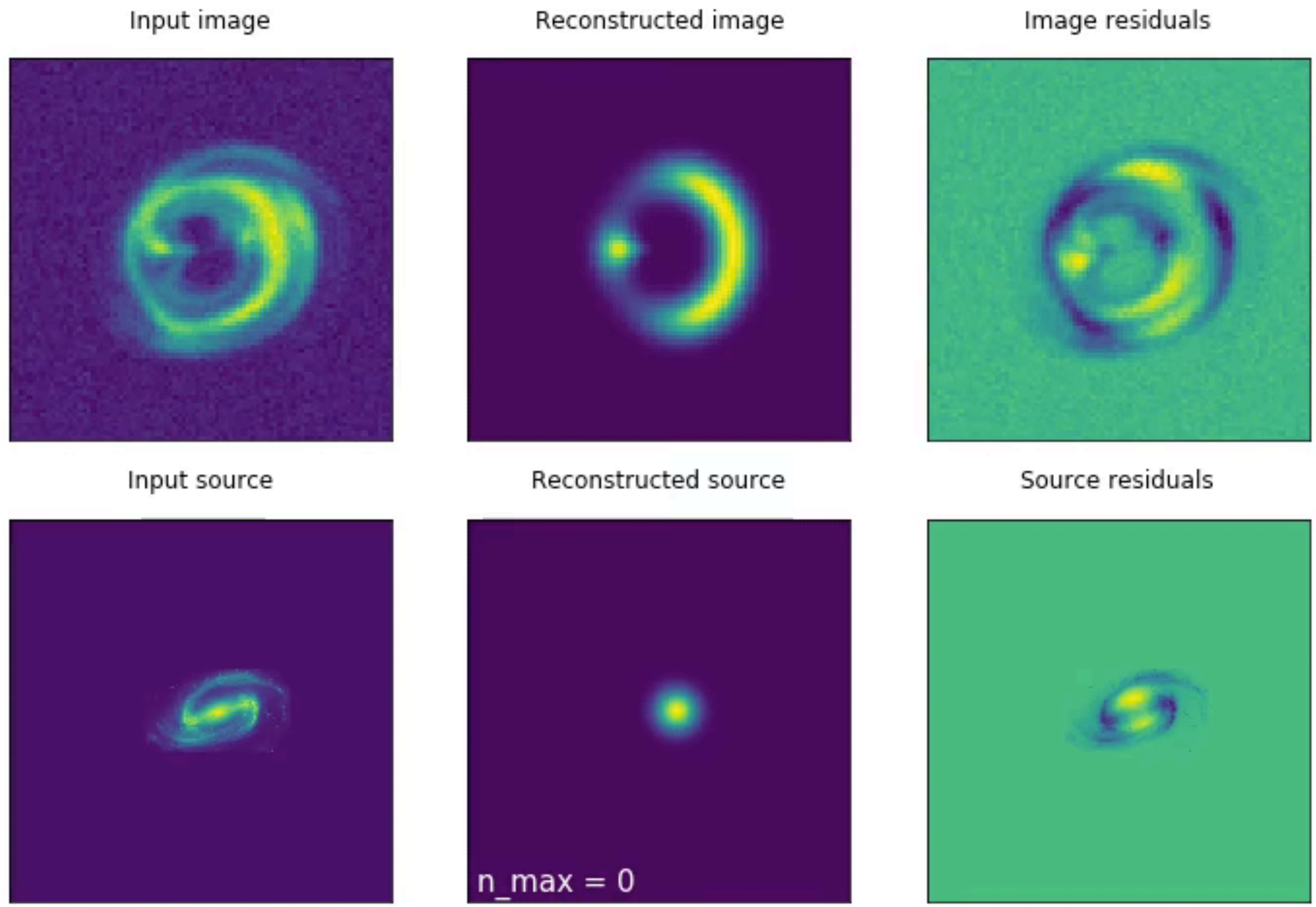


Data

See also: Waren&Dye 2003, Suyu+2006, Vegetti+2006
for (adaptive) pixelized source reconstruction techniques

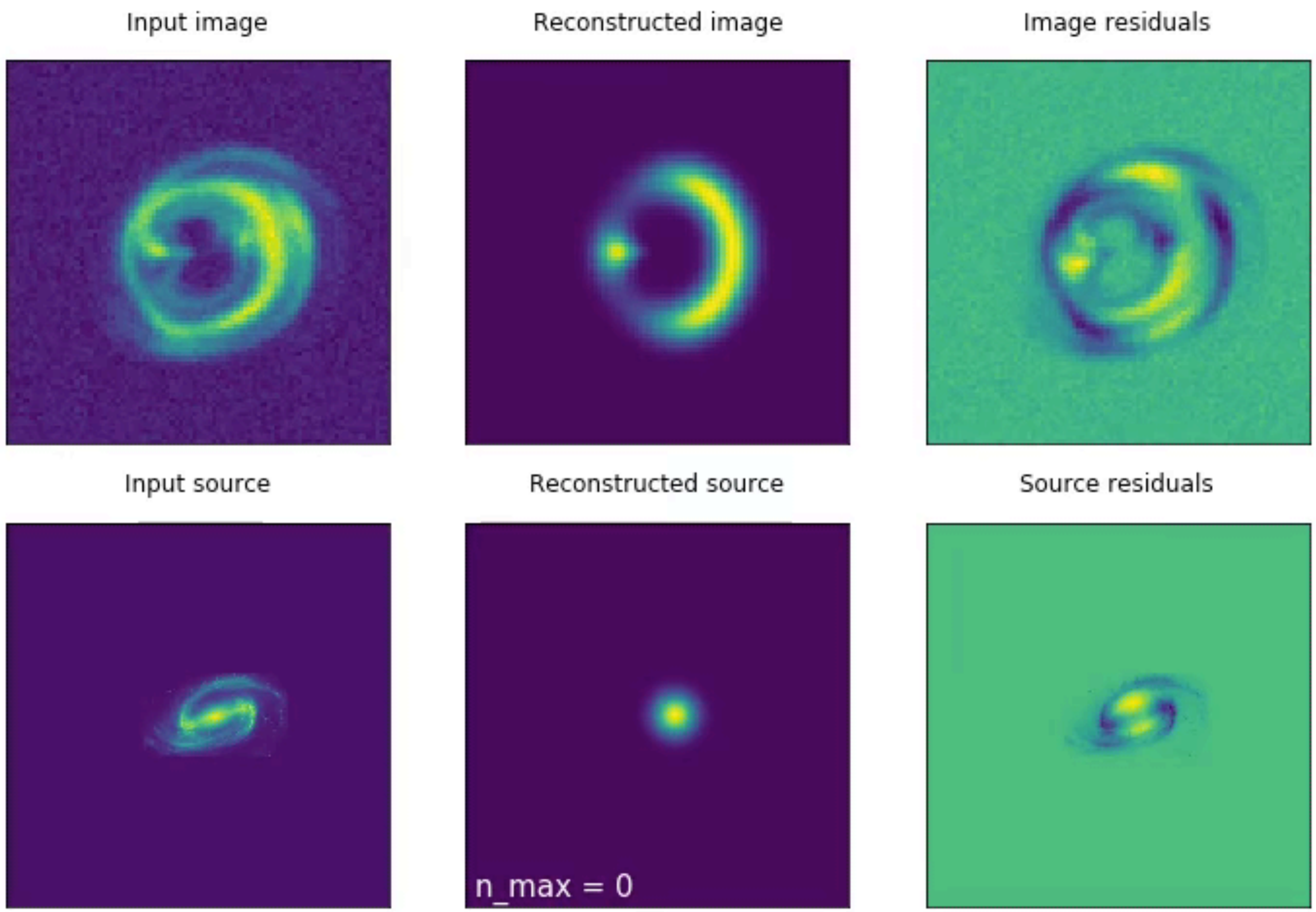
Lensing: SB+2015, 2016, …
Shapelets: Refregier 2003
Software: SB&Amara 2018, SB+2021

De-lensing de-convolution: example with perfect lens model



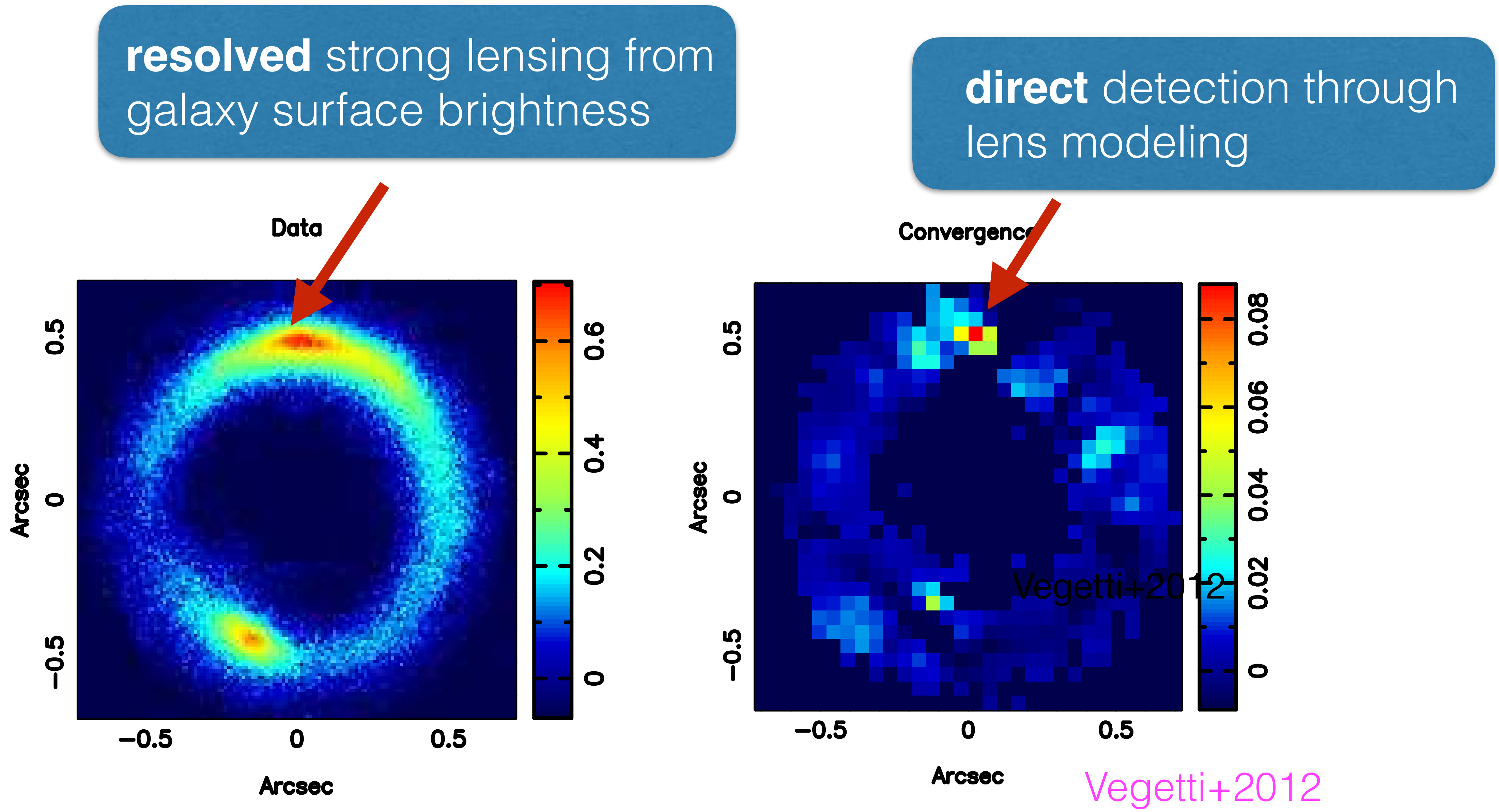
Simulation made with lenstronomy software, by Simon Birrer

De-lensing de convolution: example with missing (sub)-structure



Simulation made with lenstronomy software, by Simon Birrer

Resolved data can localize lensing substructure through forward modeling



Vegetti+2012

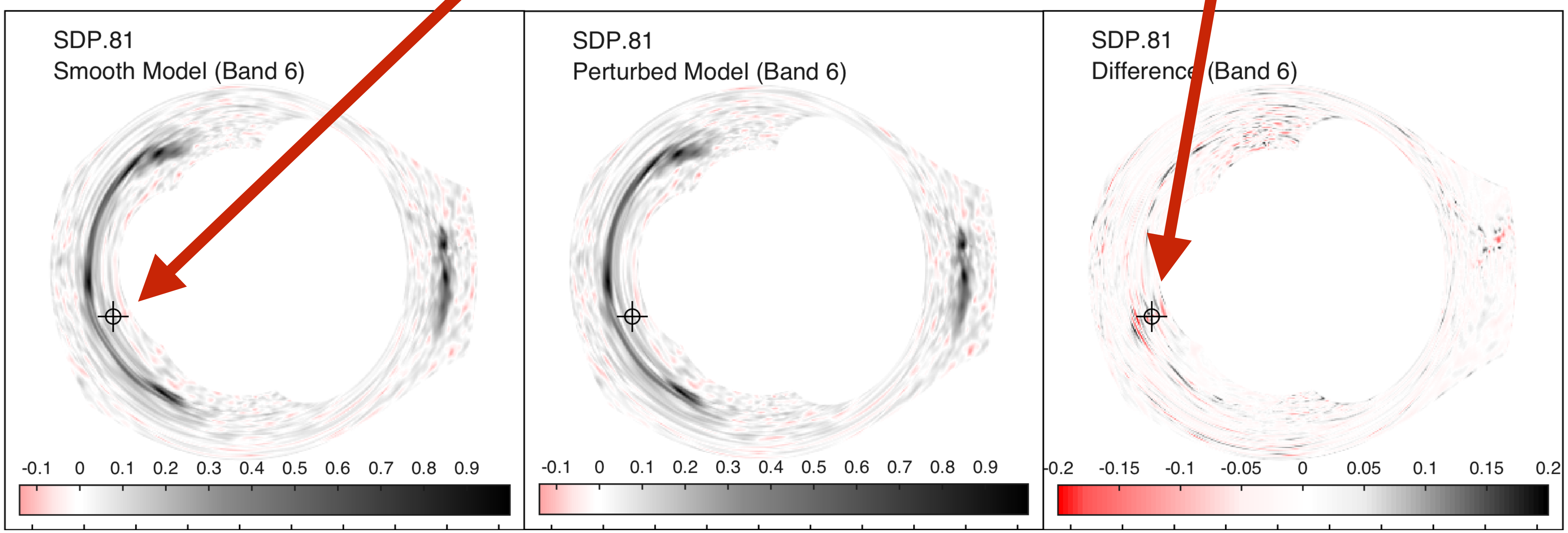
Keck adaptive optics imaging

Koopmans 2005, Vegetti+2010, 2012, 2018
SB+2017, Hezaveh+ 2016, Ritondale+2018

Resolved data can localize lensing substructure through forward modeling

resolved strong lensing from galaxy surface brightness

direct detection through lens modeling

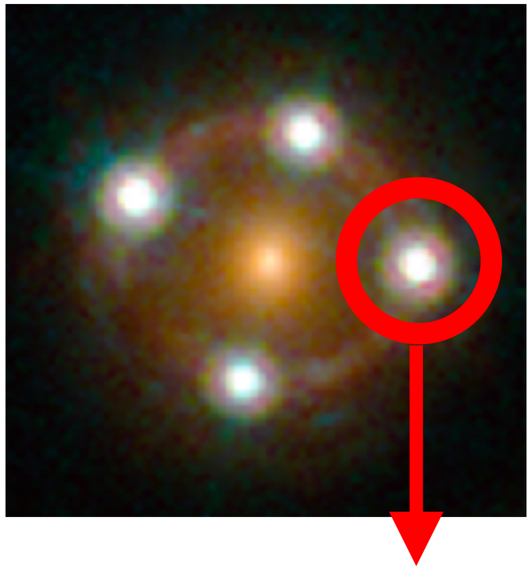


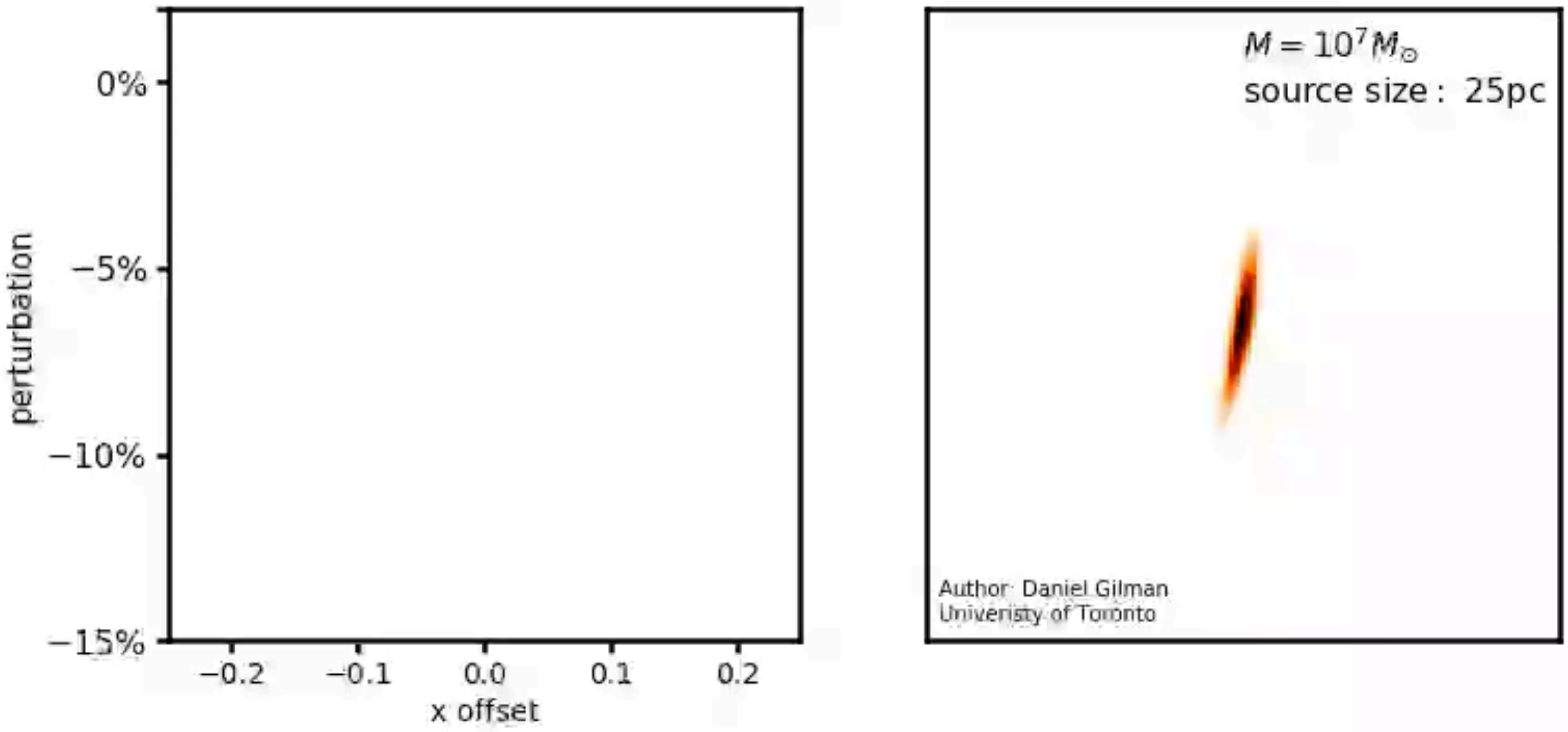
Hezaveh+ 2016

ALMA interferometry

Koopmans 2005, Vegetti+2010, 2012, 2018
SB+2017, Hezaveh+ 2016, Ritondale+2018

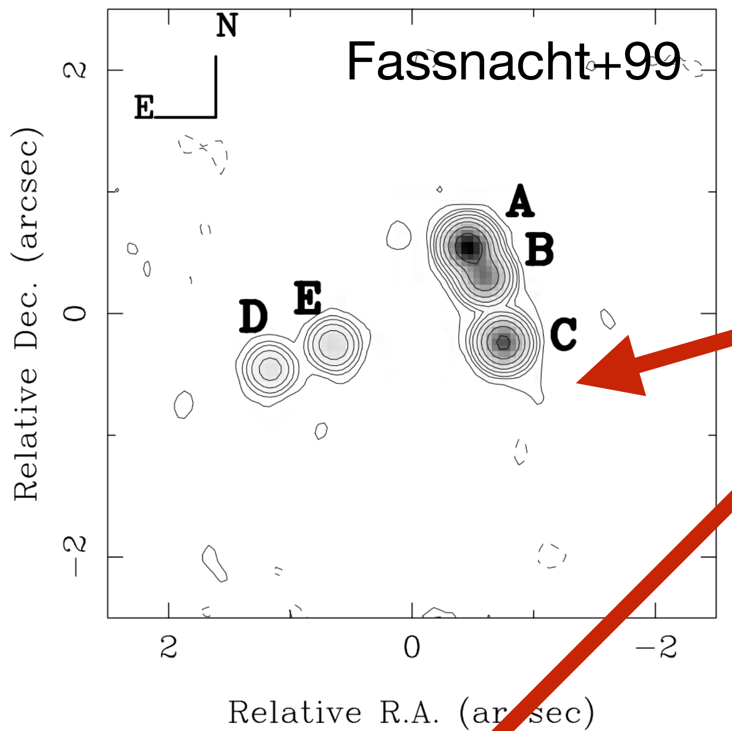
Flux-ratios are sensitive to completely dark structure



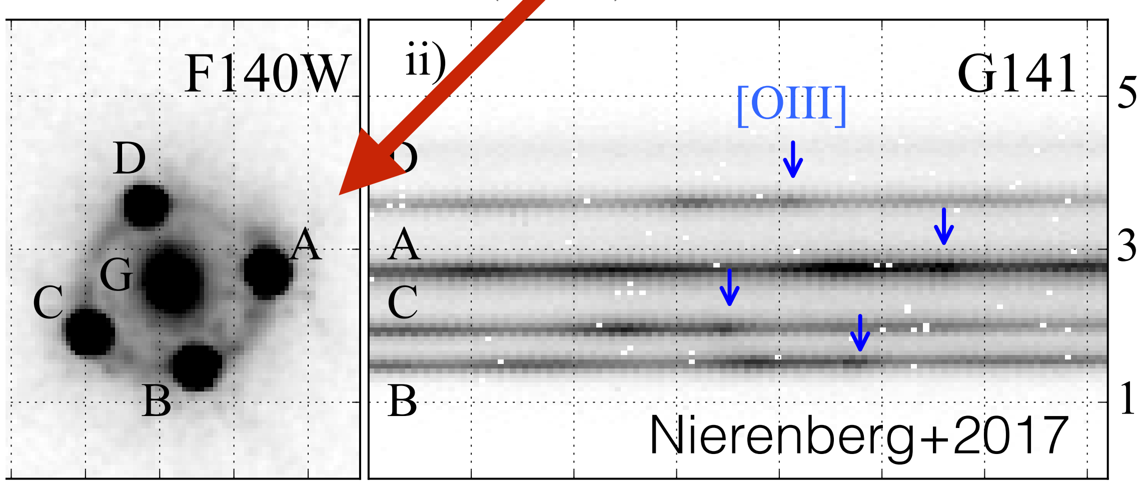


Mao & Schneider 1998, Dalal & Kochanek 2002, Moustakas & Metcalf 2003, Nierenberg+2014, 2017 Hsueh+2016, 2017, 2020, Gilman+2018, 2019, 2020a,b

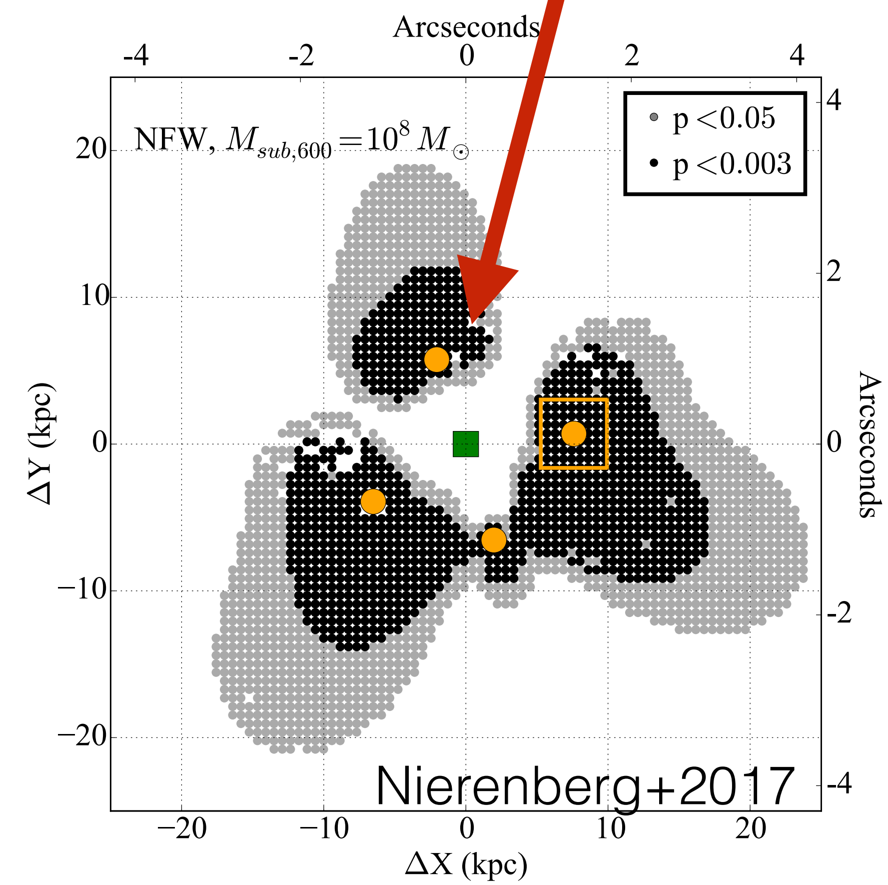
Flux-ratios are sensitive to completely dark structure



unresolved strong lensing from quasar narrow line emission region



exclusion regions for a certain type of sub-clump



Mao & Schneider 1998, Dalal & Kochanek 2002
Moustakas & Metcalf 2003 ,Nierenberg+2014, 2017
Hsueh+2016, 2017, Gilman, SB+2018, 2019, 2020a,b,
Hsueh+2020,….

small physical source size allows for sensitivity to very **low masses**

Inference of dark matter microphysics

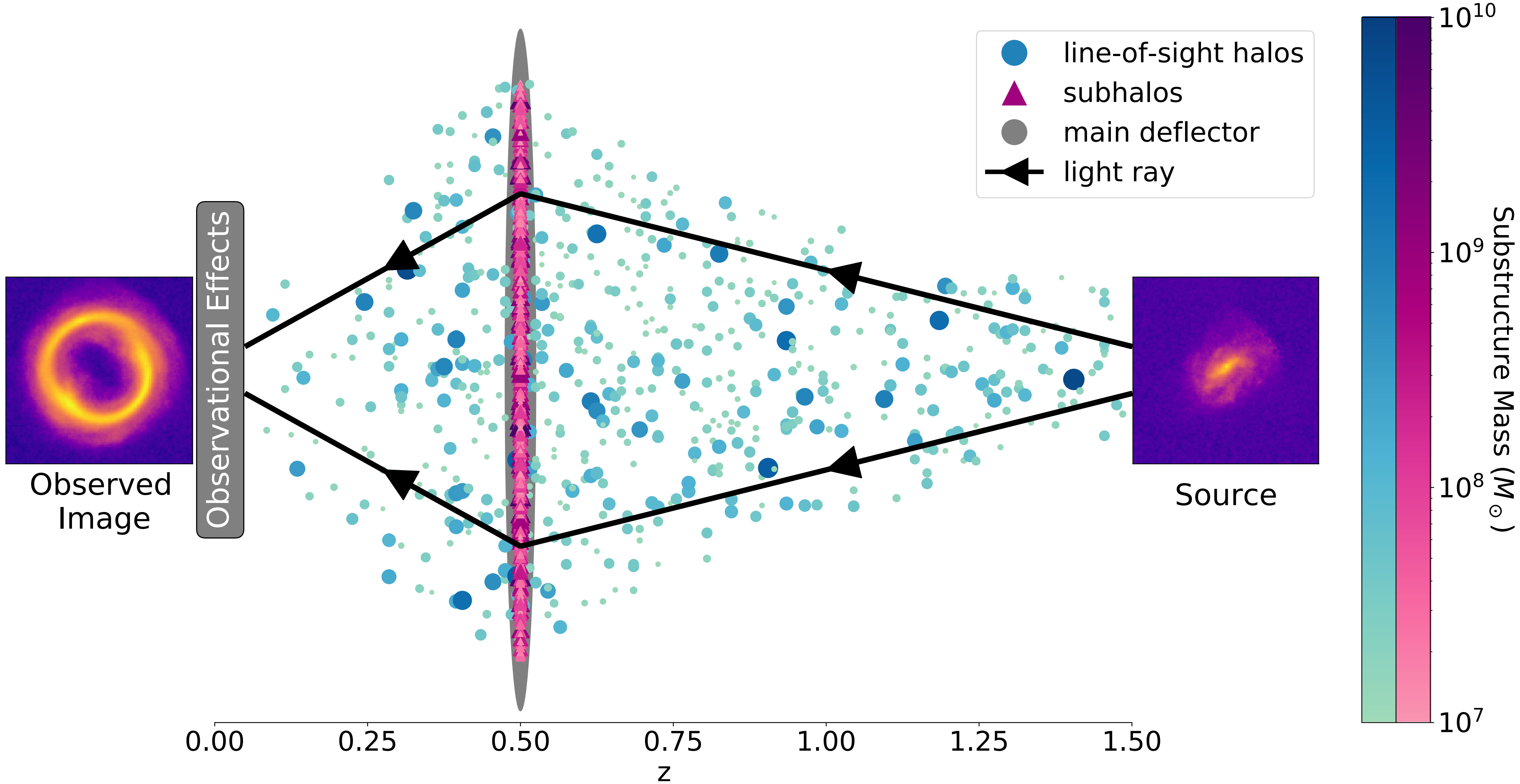


Figure from Wagner-Carena, Aalbers, SB+ 2021

Inference of dark matter microphysics

- complex substructure and line-of-sight halos
- complex source morphology
- complex data

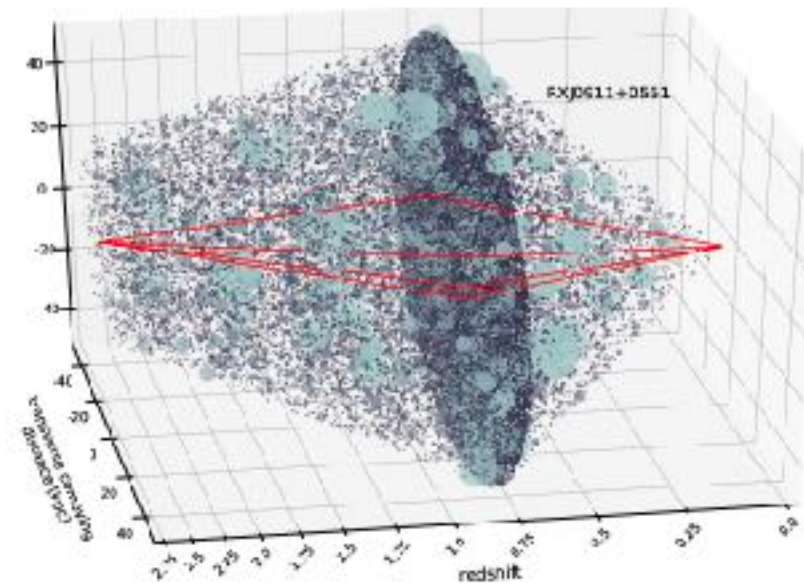
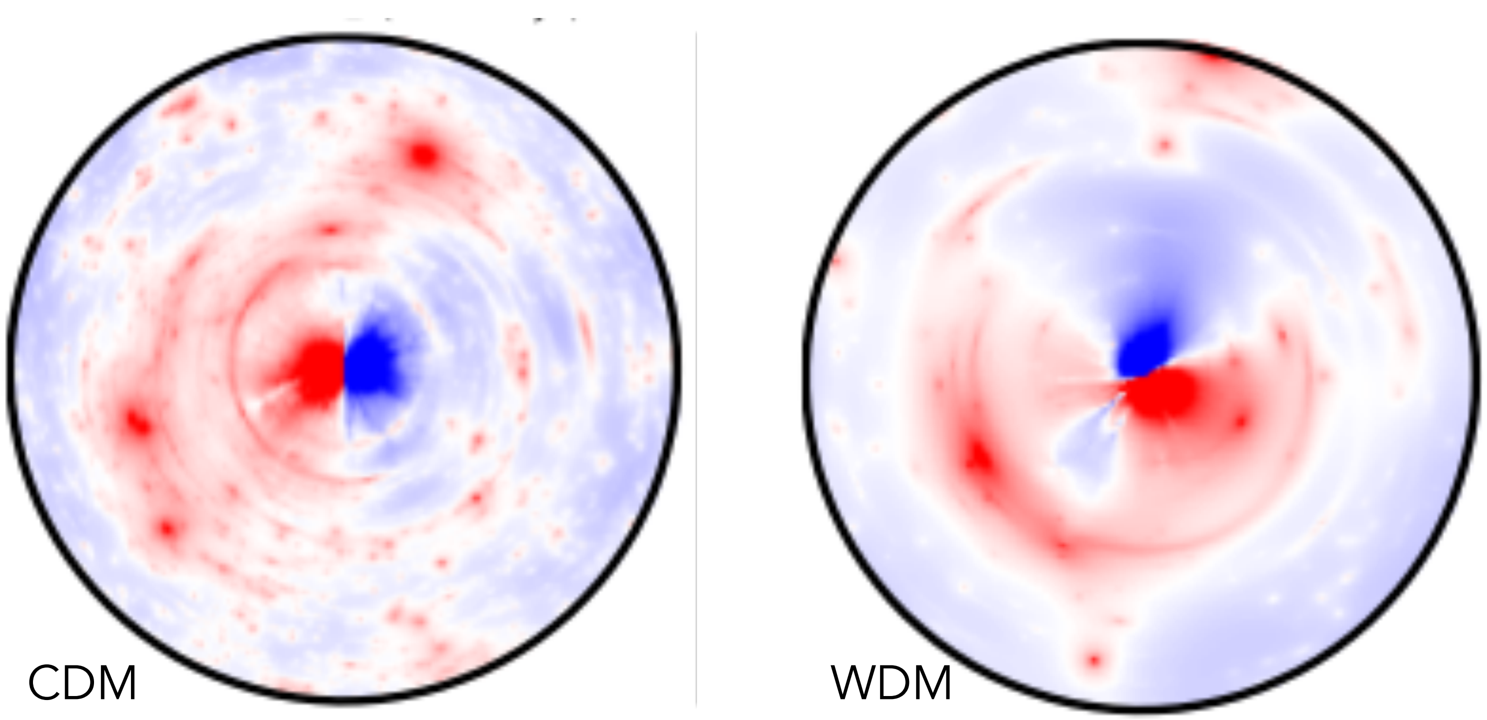


Figure: Gilman with PyHalo



End-to-end inference of dark matter microphysics

Individual detection

How do we know what we detect and what not?

How do we statistically interpret the signal?

Statistical detection

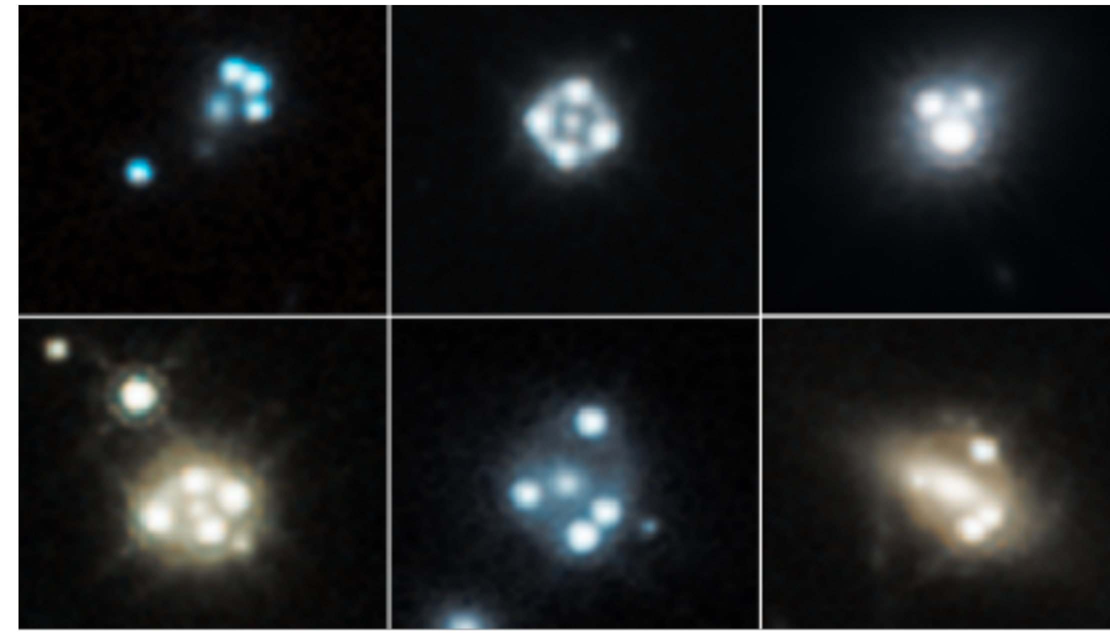
How do we know where the signal is coming from?

What is a good summary statistics that captures the **information** and is **robust** to systematics?

ABC, Machine learning, residual power spectrum, sensitivity map,…

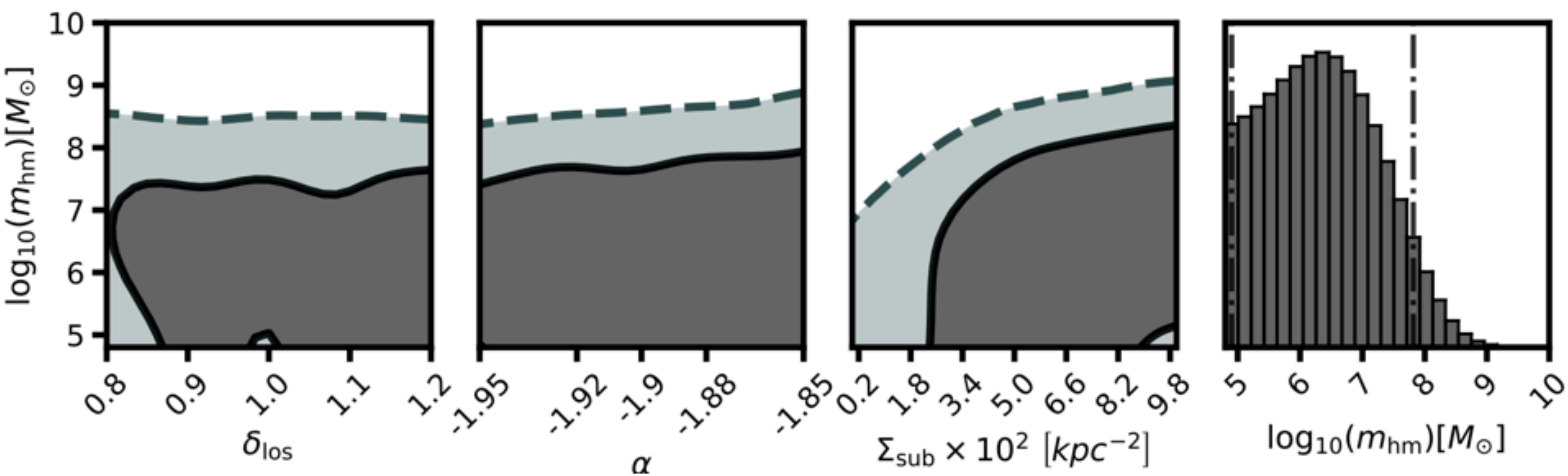
Results: Flux ratios

- statistical detection of substructure
- consistent with CDM
- competitive constraints on WDM



Credit: STSCI, GO-15177, 13732 PI Nierenberg

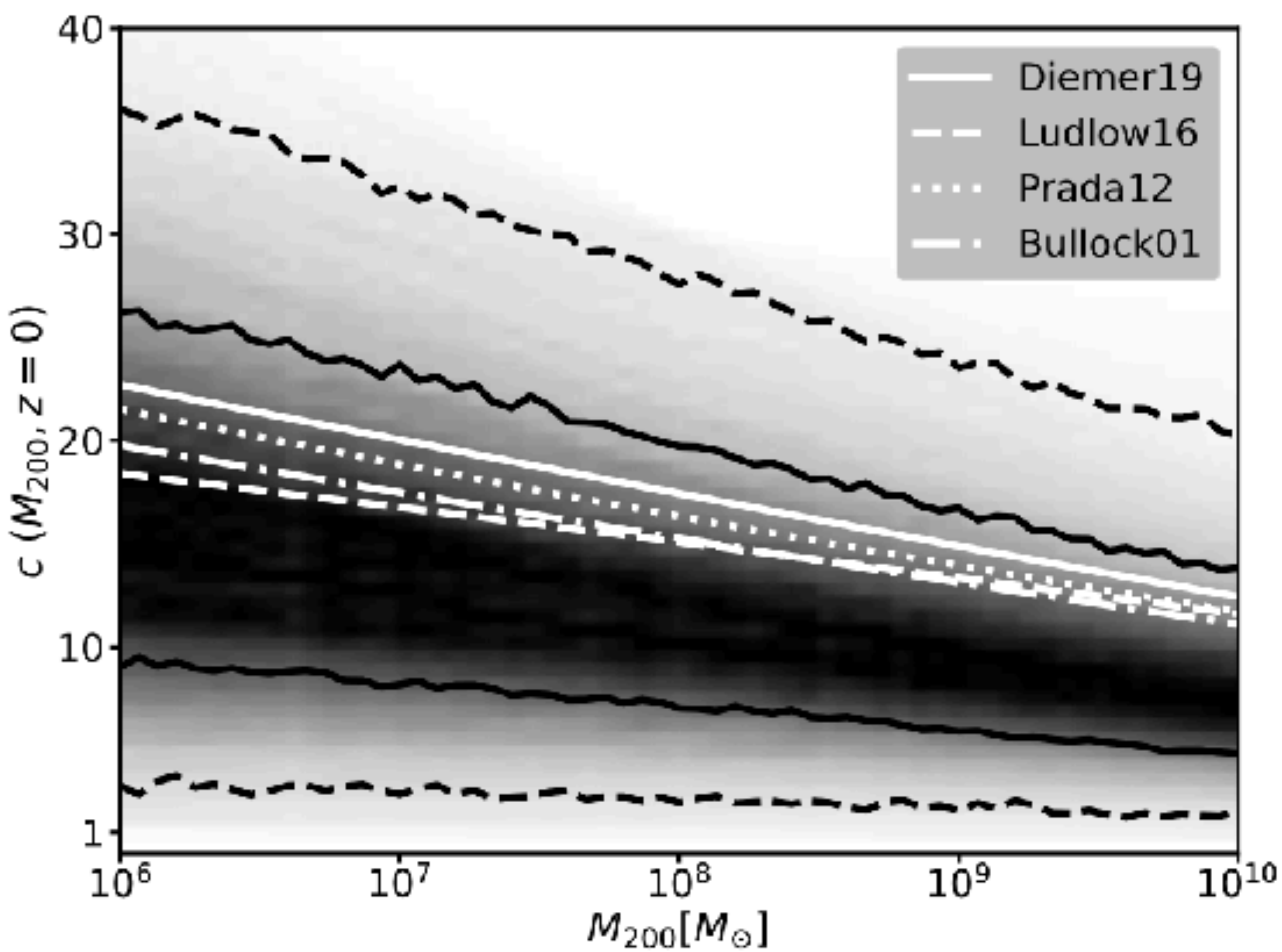
WDM constraints from 8 quad lenses



Gilman, SB, Nierenberg+2020, see also Hsueh+2020

Results: Flux ratios

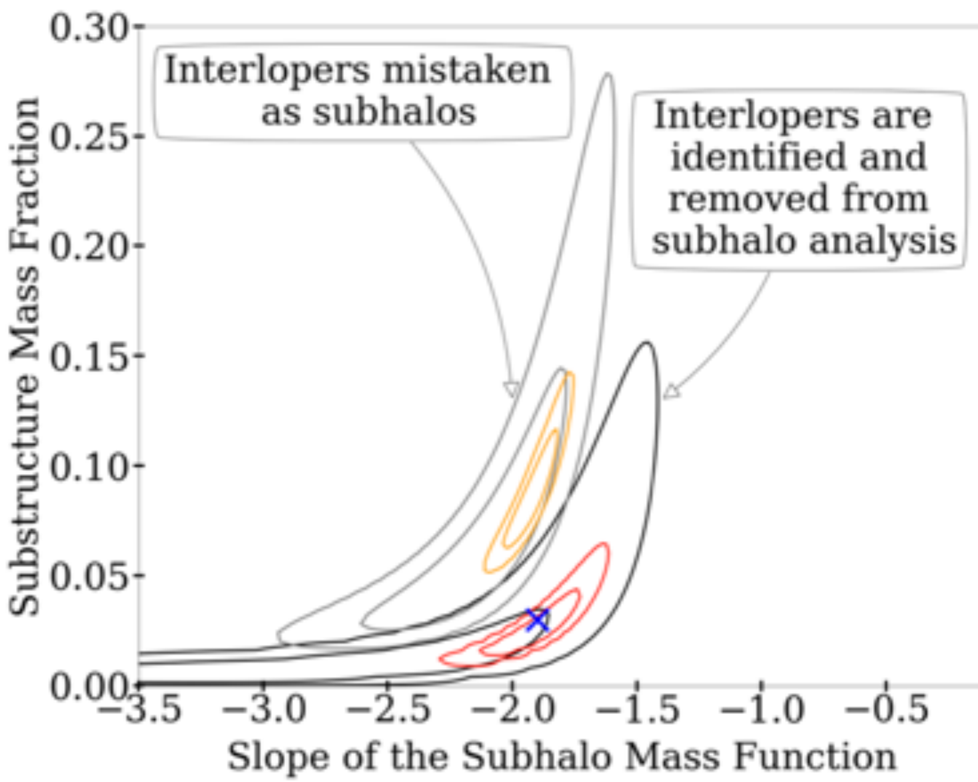
mass-concentration relation from 11 quad lenses



Gilman+2020b

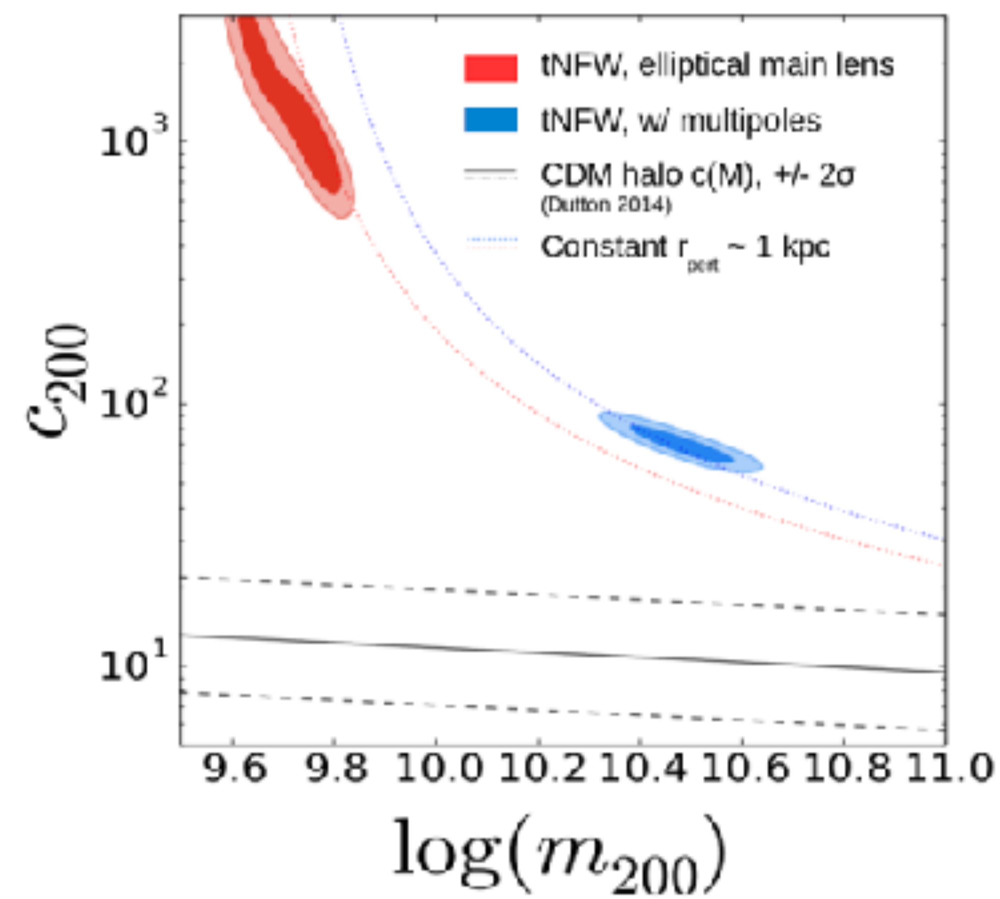
Results: imaging

Subhalo is a line-of-sight object



Sengul+2022

Subhalos have unusually high concentrations



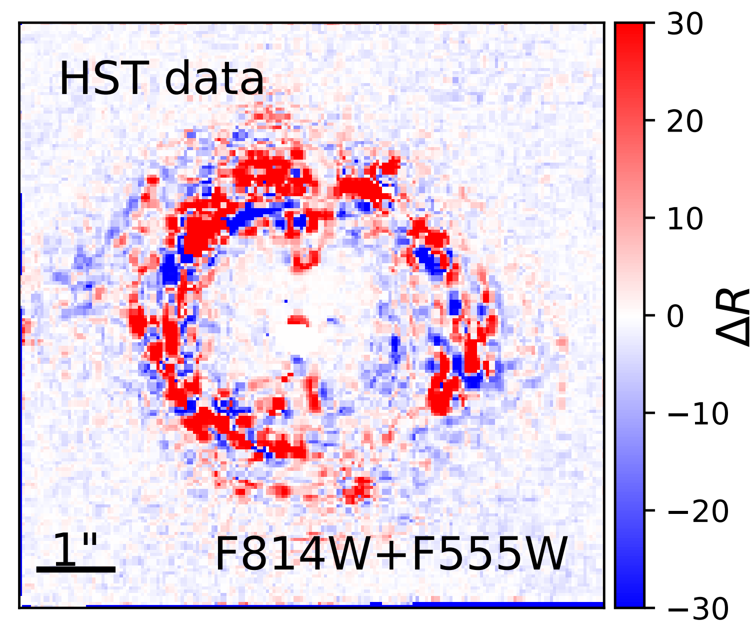
Minor et al. 2021

Results: imaging

Forward modeling and simulation based inferences with Approximate Bayesian Computing (ABC)

>2keV WDM ruled out (caveat: no line of sight structure modeled)

reconstructed source



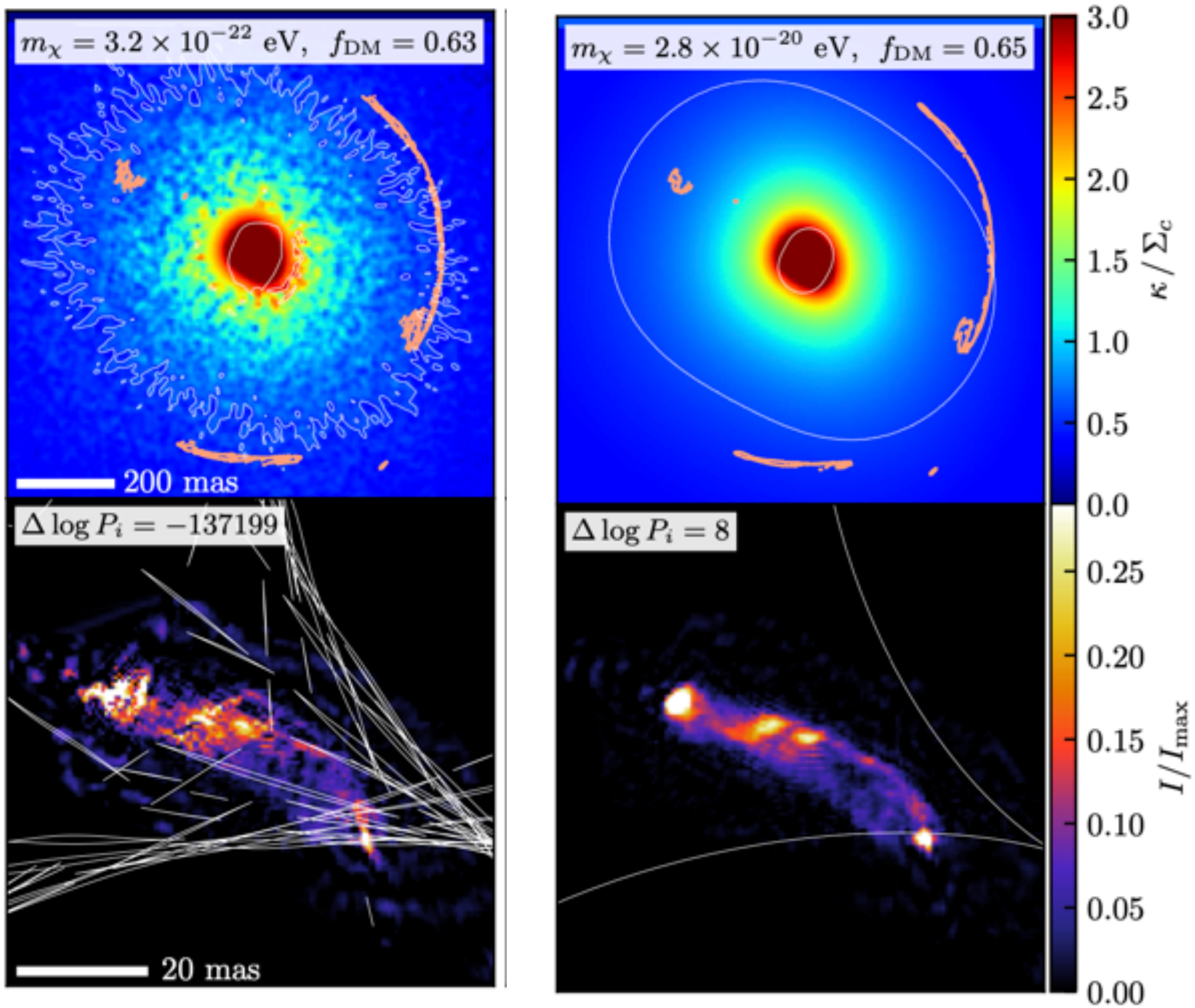
smooth preferred

clump preferred

Birrer+2017

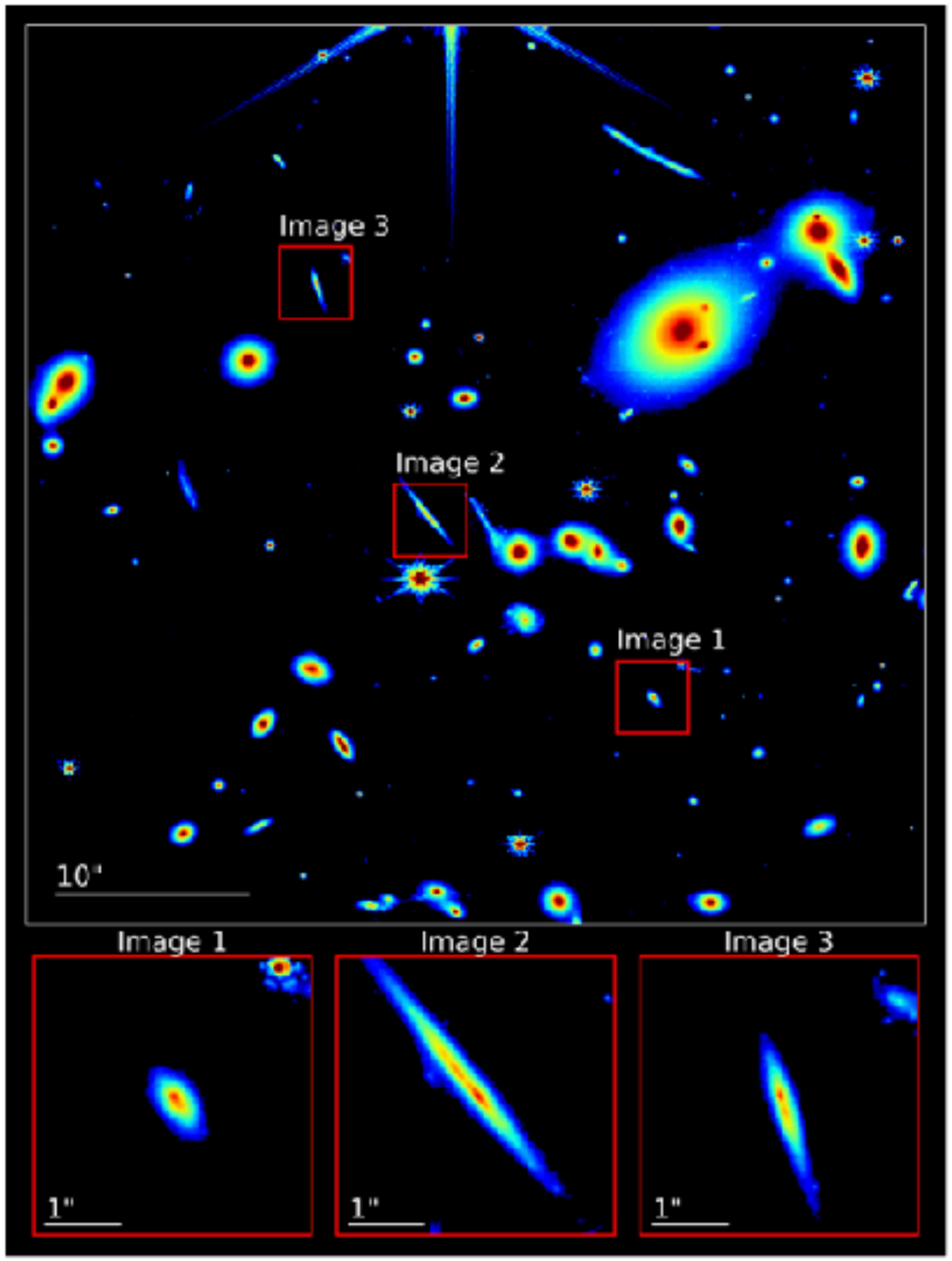
Results: imaging

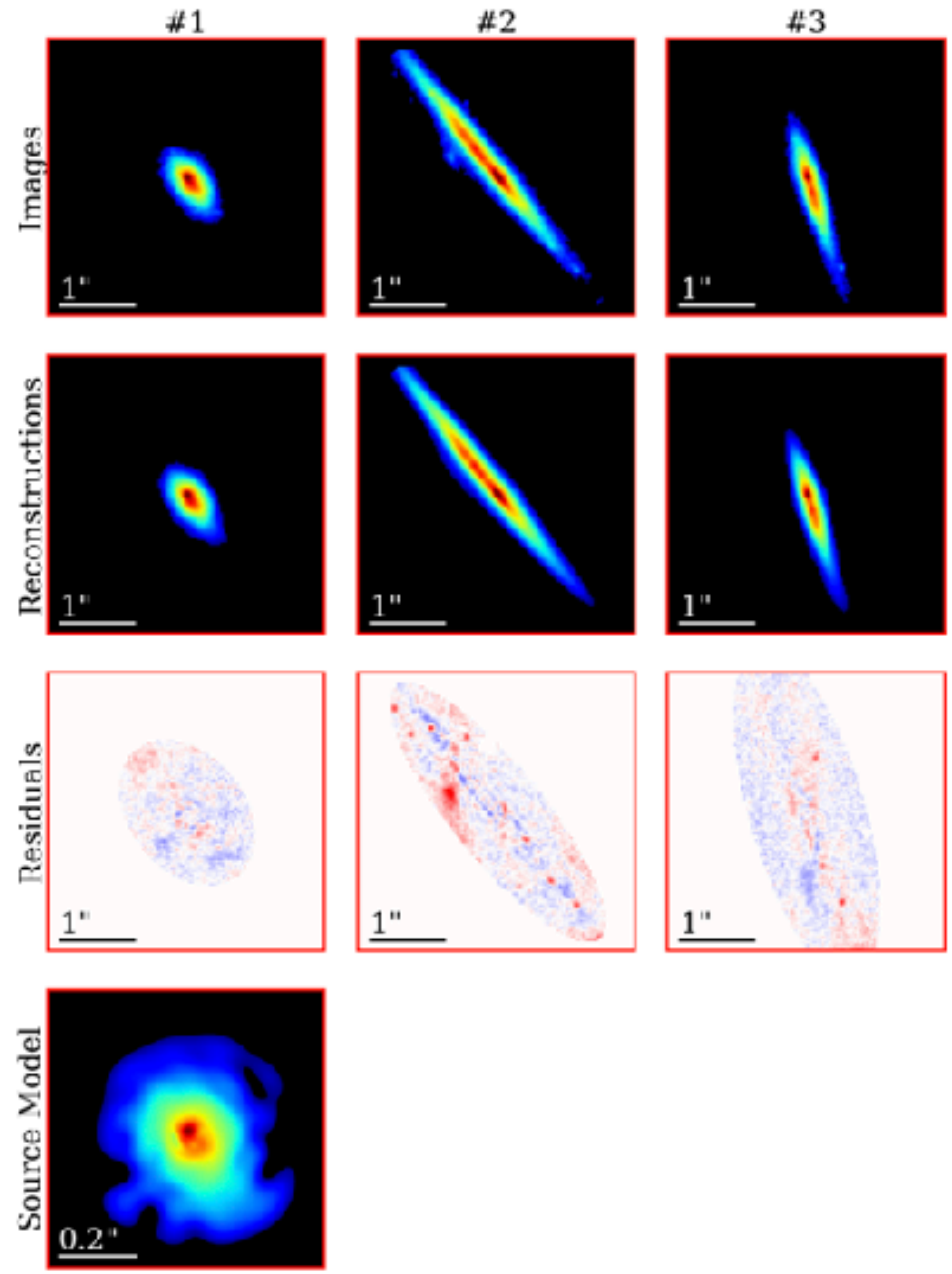
Fuzzy dark matter from a radio arc



Powell et al. 2023

substructure in clusters





See also Meneghetti+2022 for larger substructure

Sengul, SB+2023

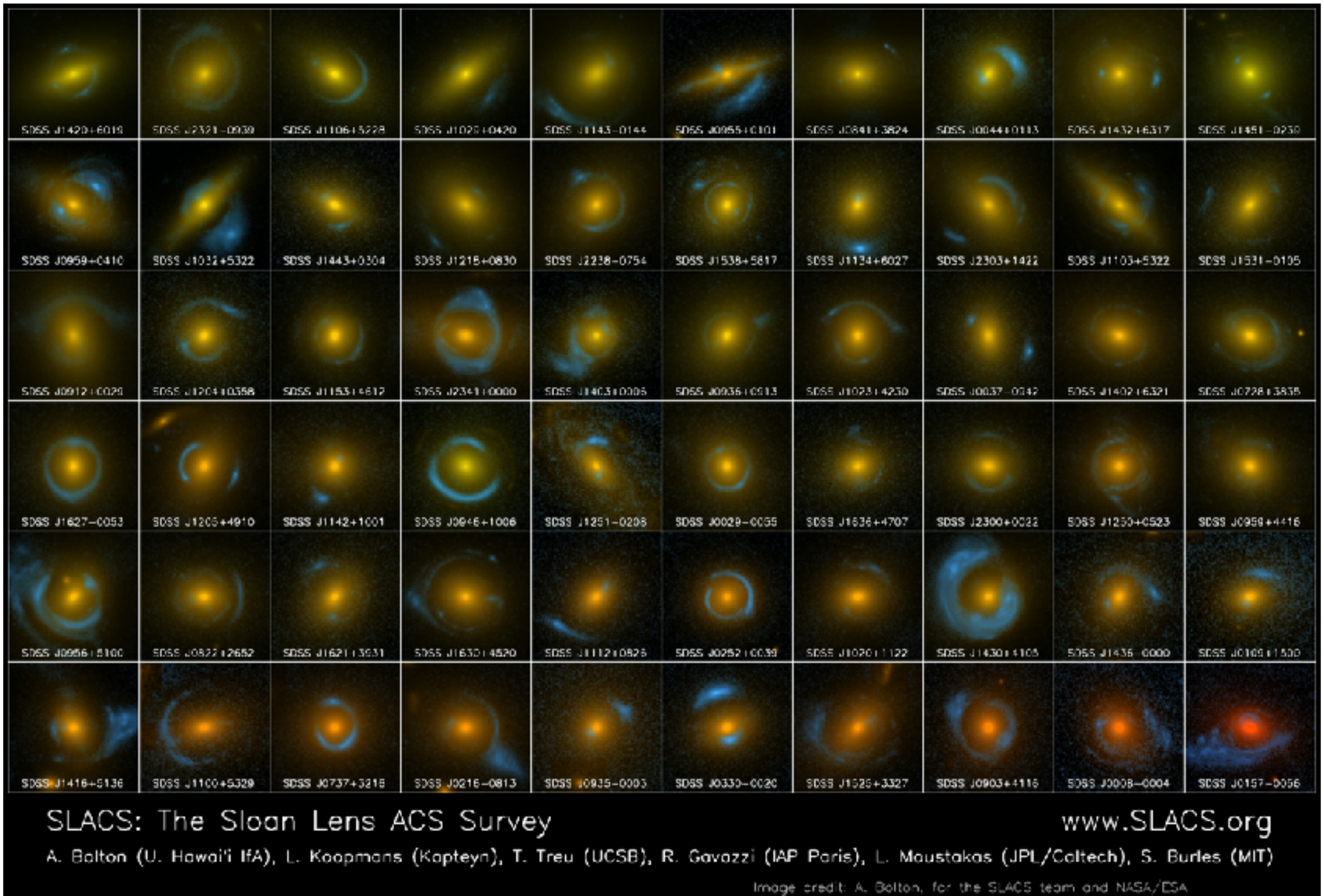
Galaxy-scale density profiles

- Understanding of (dark matter) density profiles required to accurately measure the Hubble constant with time-delay cosmography

- Extensive efforts in data acquisition and modeling underway

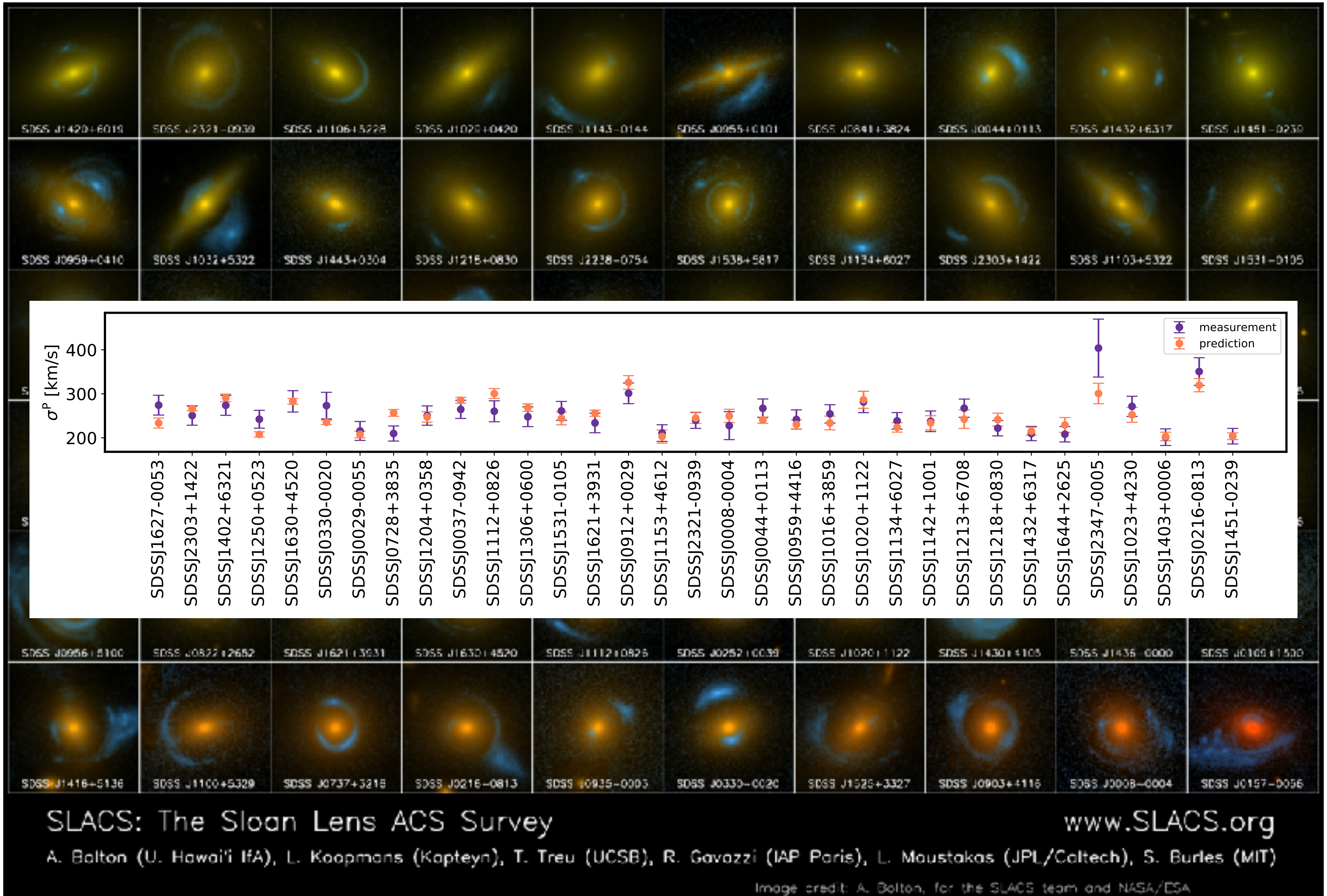
- Same data and results can be used to interpret dark matter microphysics on galactic scales

Constraining galaxy density profiles with lensing and kinematics



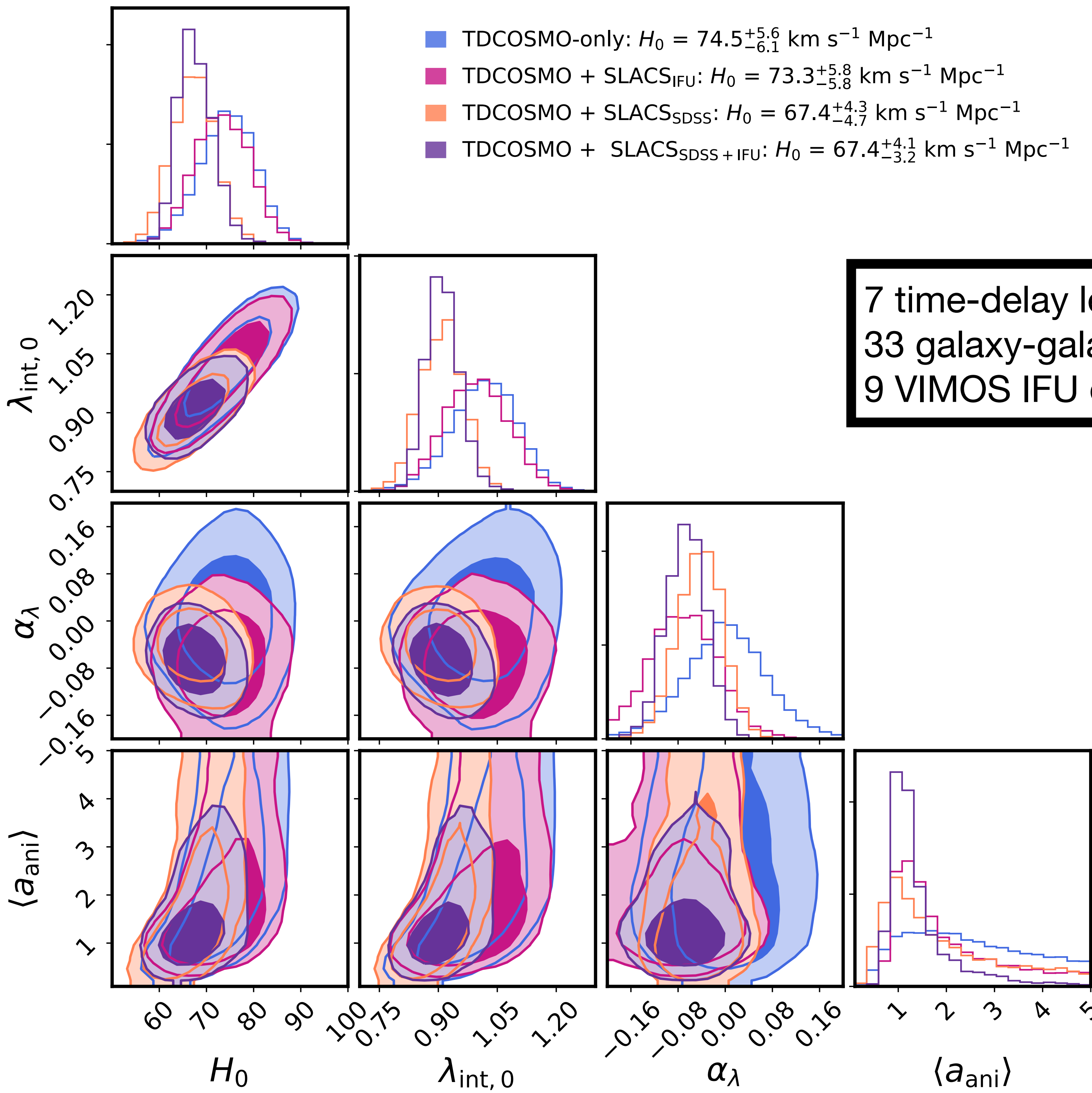
SB+2020 TDCOSMO IV, Shajib, SB+2020b

Constraining galaxy density profiles with lensing and kinematics



SB+2020 TDCOSMO IV, Shajib, **SB**+2020b

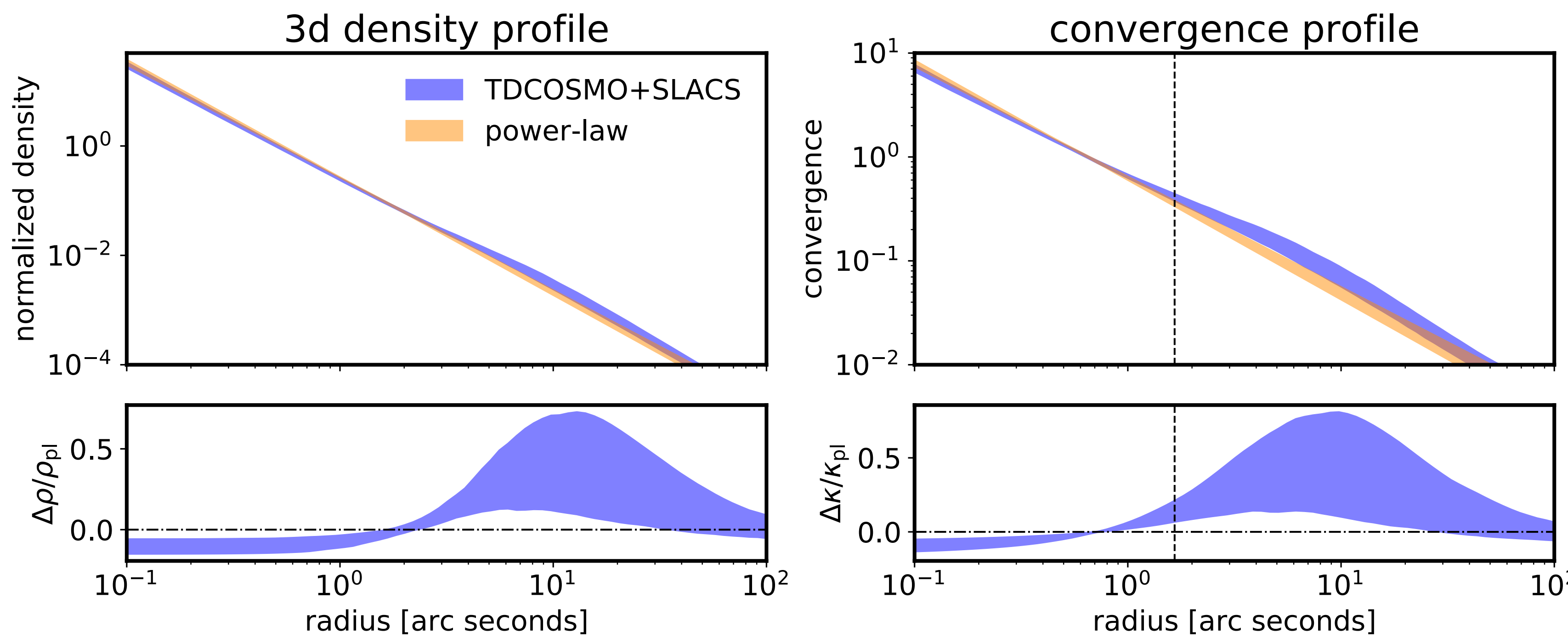
Joint hierarchical analysis of H0, galaxy density profiles and stellar anisotropy



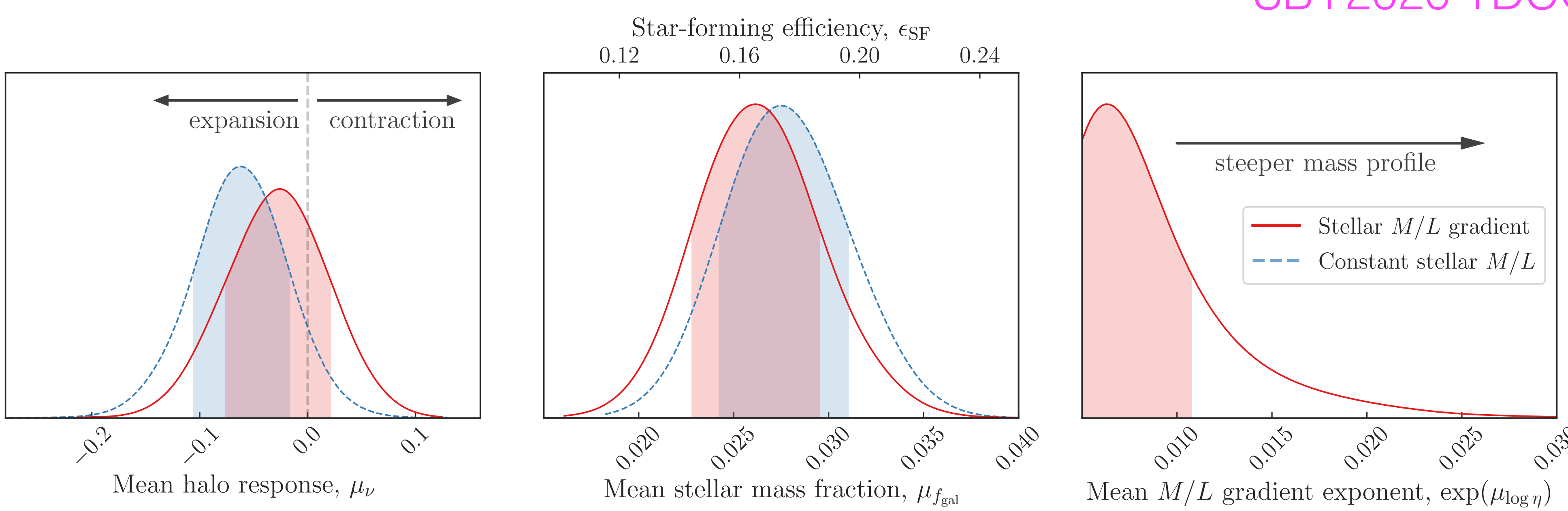
7 time-delay lenses from TDCOSMO
33 galaxy-galaxy lenses from SLACS
9 VIMOS IFU data sets

SB+2020 TDCOSMO IV

Constraining galaxy density profiles with lensing and kinematics



SB+2020 TDCOSMO IV



Shajib, Treu, SB+2020

This decade!

Euclid
(Discovery and imaging)

10’000+ strong lenses
200+ quasar lenses
Time-domain information

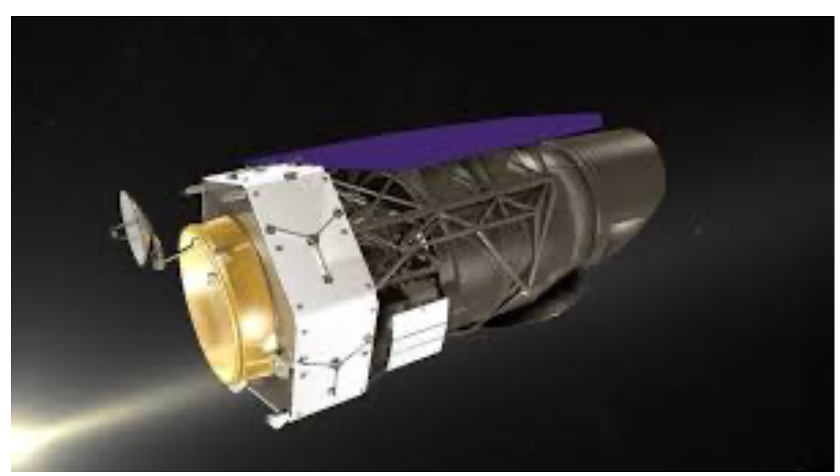
E-ELT, TMT, GMT
(high resolution imaging)

Square Kilometer Array, (ng)VLA
(high resolution interferometry)

KAGRA/LIGO/VIRGO
(gravitational waves)

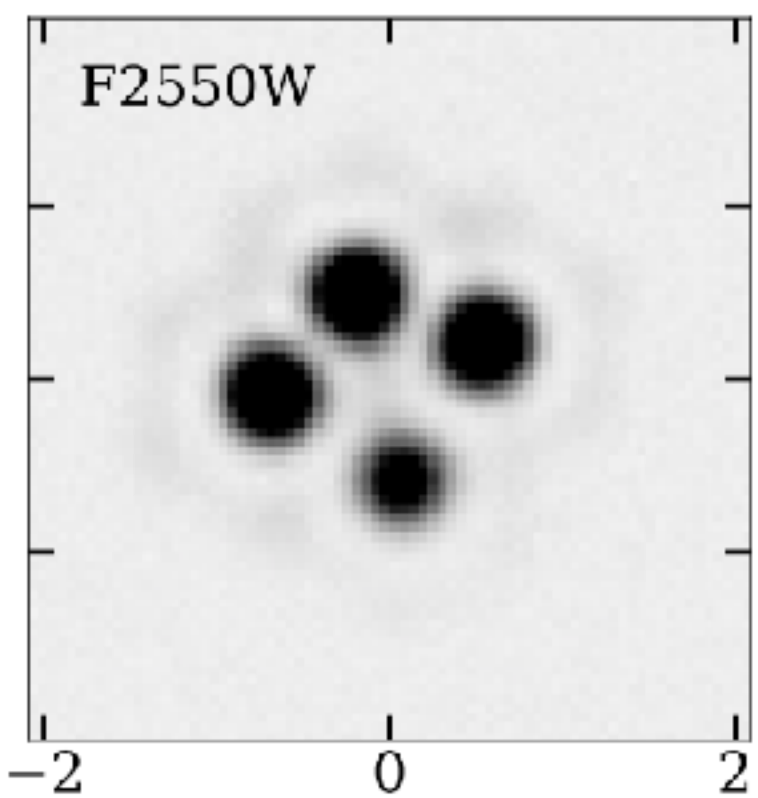
Vera Rubin Observatory
(discovery and time-domain)

Nancy Grace Roman telescope
(discovery and imaging)



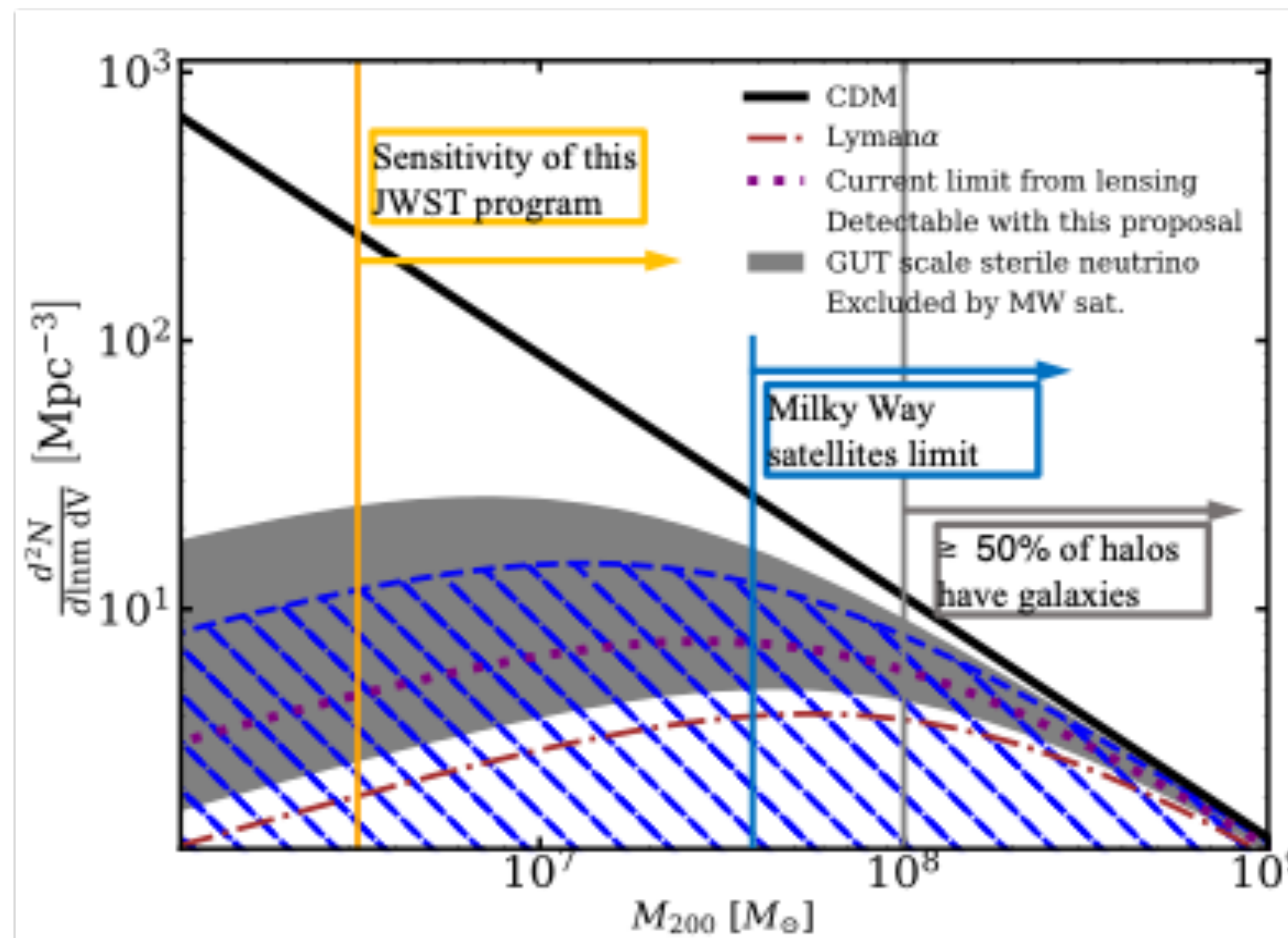
James Webb Space Telescope
(high resolution spectroscopy)

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



Simulated JWST MIRI image

JWST-GO-02046, PI Nierenberg



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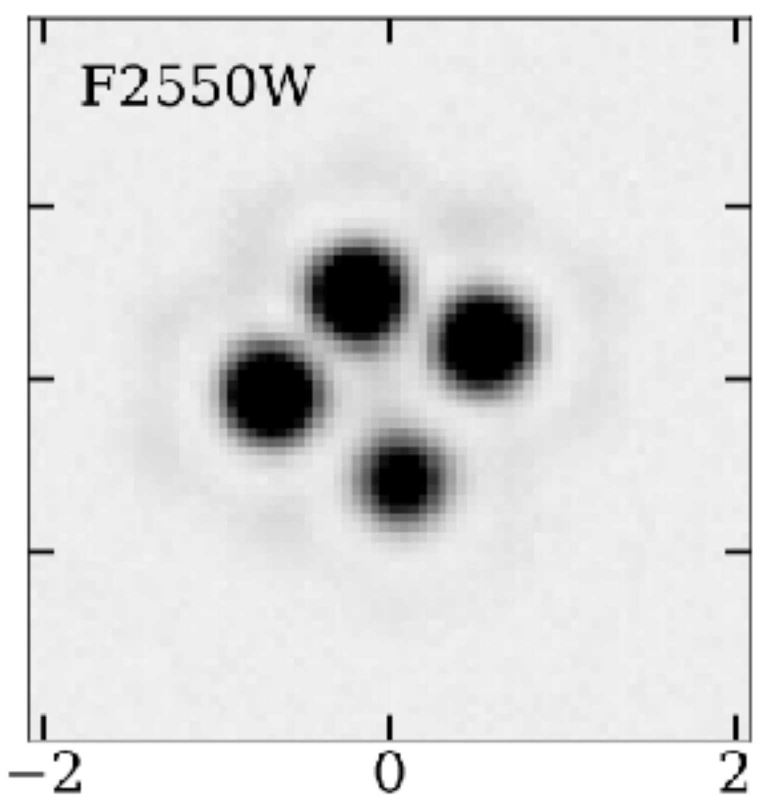
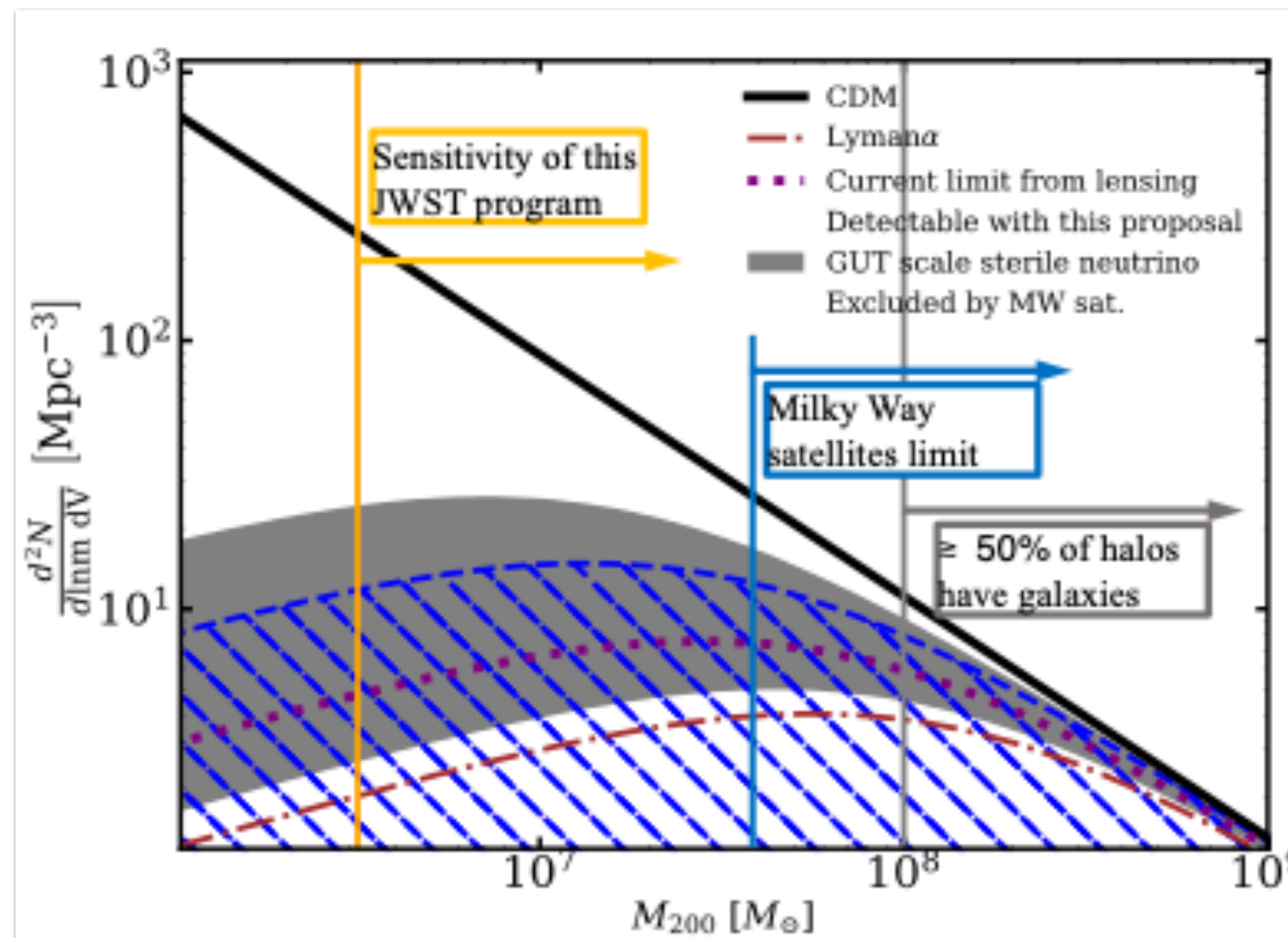


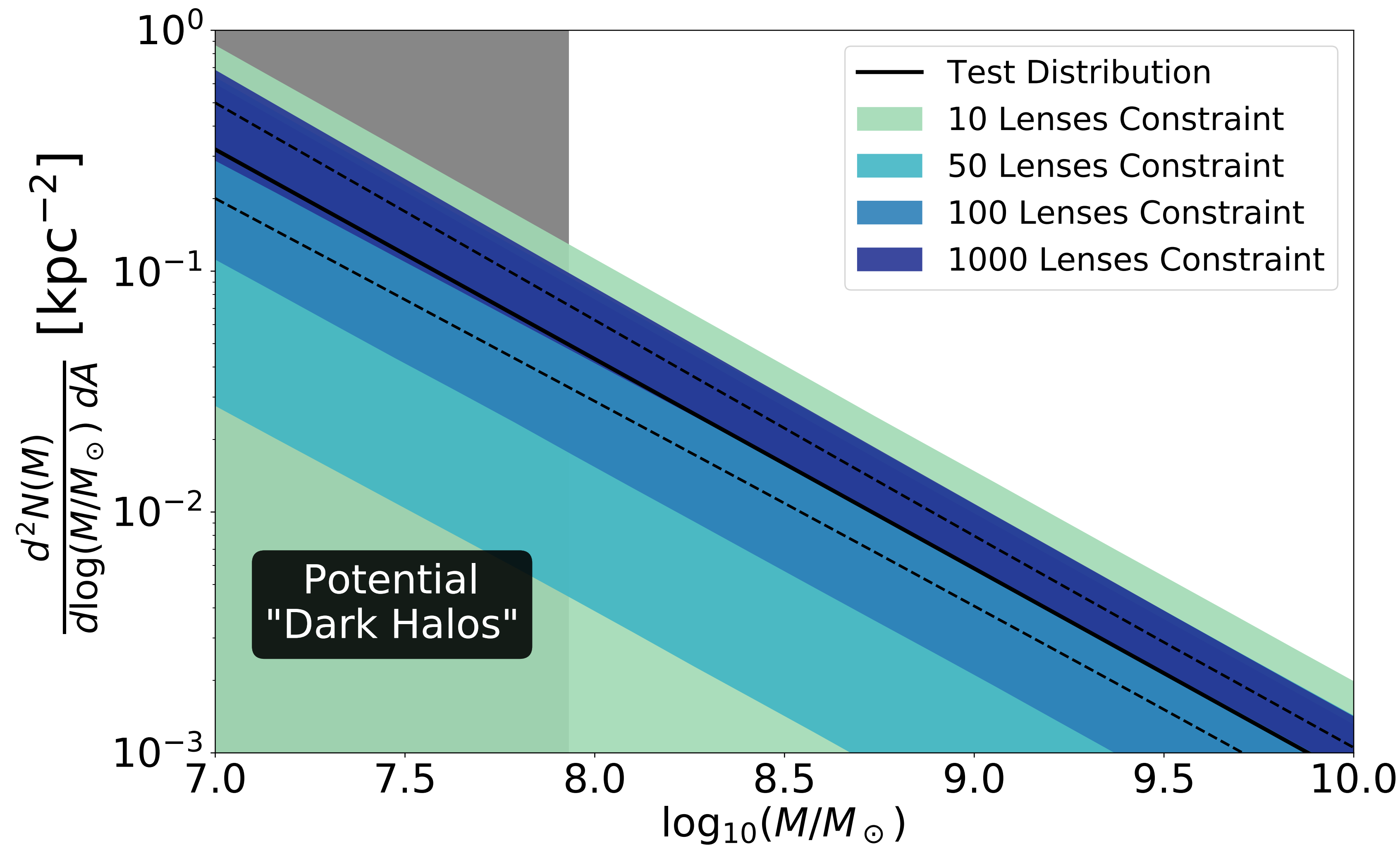
Simulated JWST MIRI image

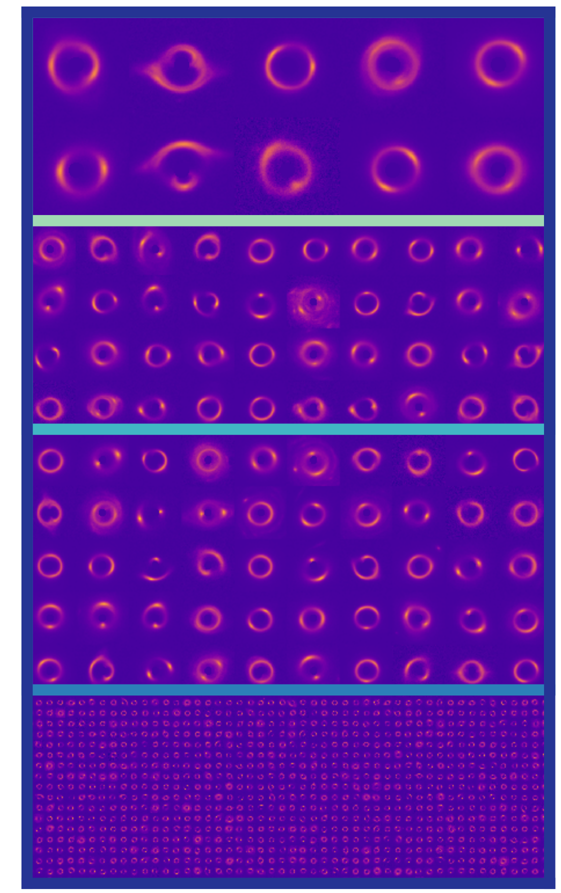
JWST-GO-02046, PI Nierenberg



We will be able to detect completely dark halos!

How to perform inference with a sample of 100-1000 lenses?

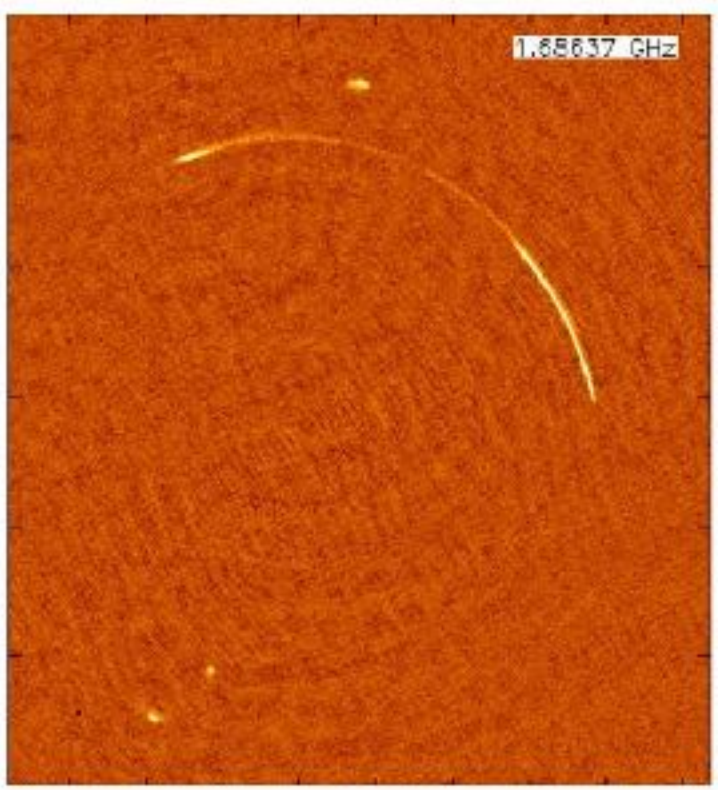




Are convolutional neural networks up to the task?

Figure from Wagner-Carena, Aalbers, SB+ 2022

Next-generation high-resolution capabilities (ELT, ngVLA, SKA)



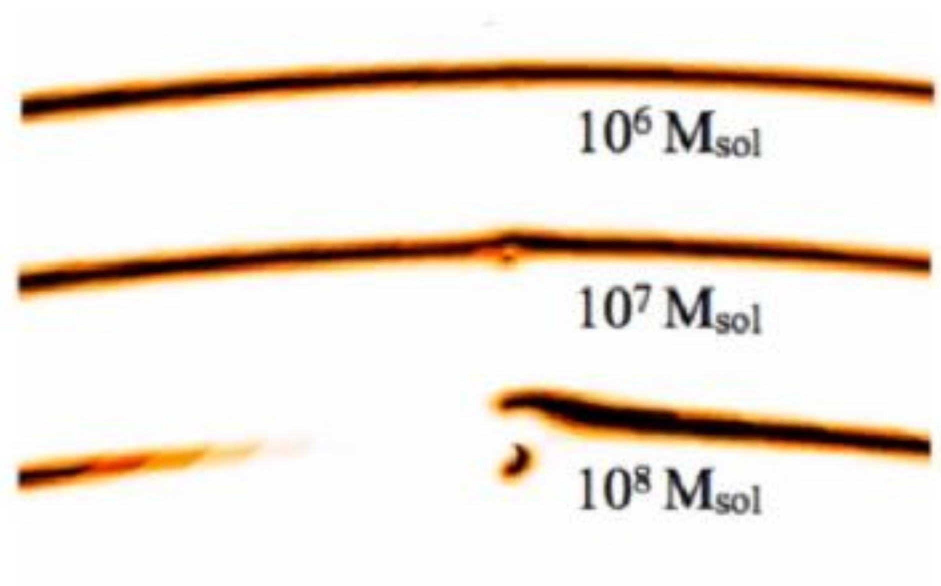
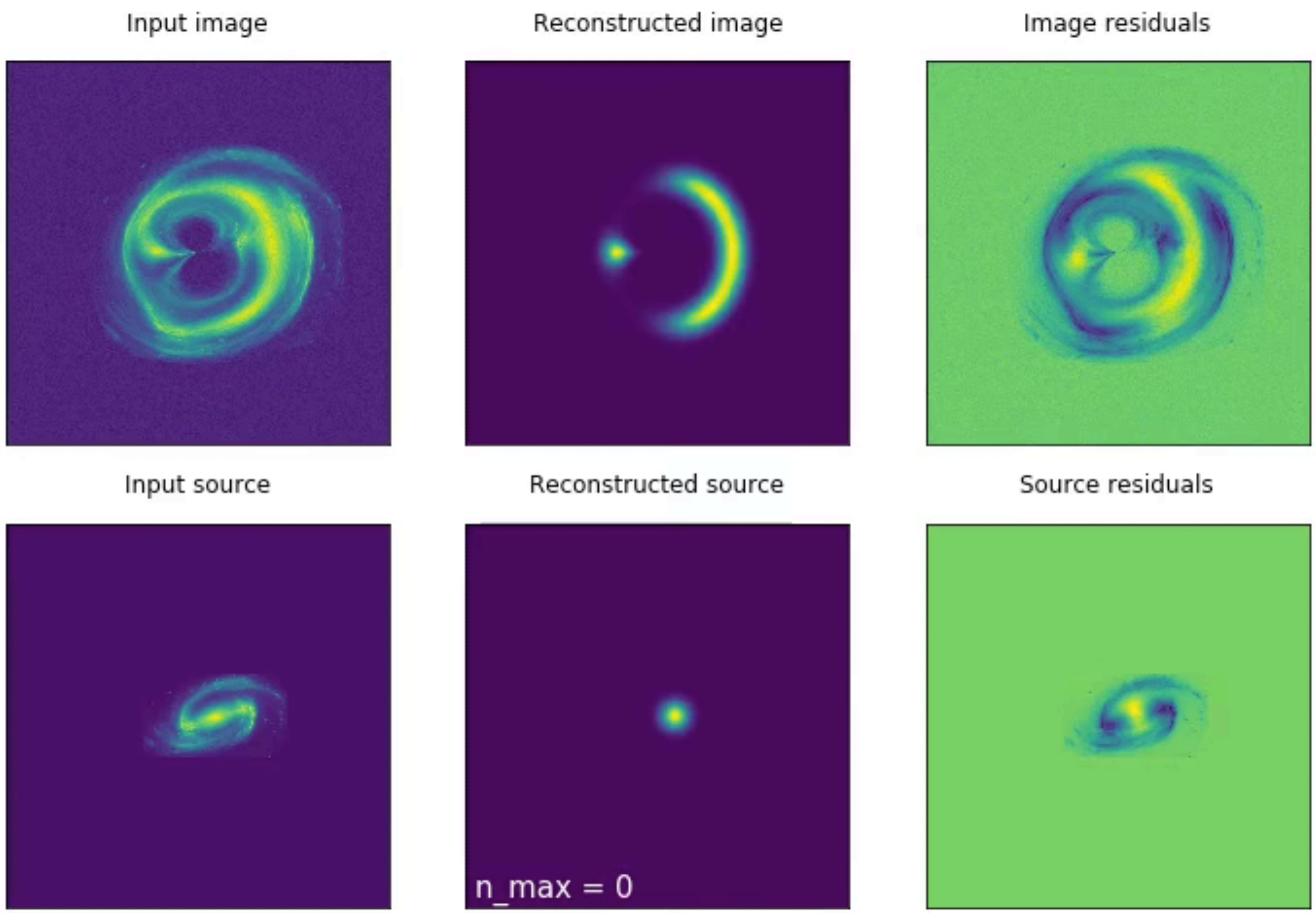


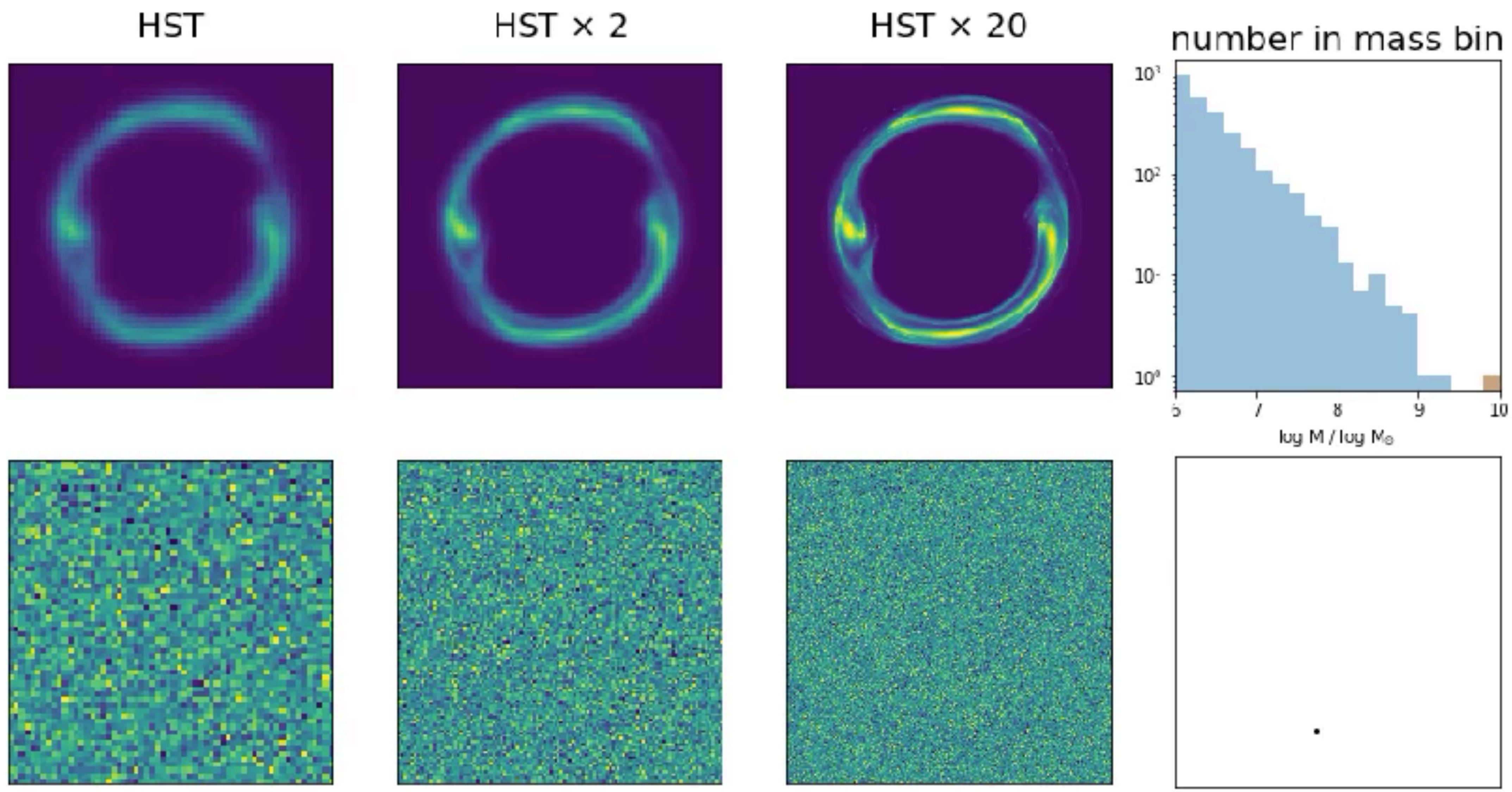
Figure: Vegetti

Next-generation high-resolution capabilities (ELT, ngVLA, SKA)



Simulation made with lenstronomy software, by Simon Birrer

Next-generation high-resolution capabilities (ELT, ngVLA, SKA)

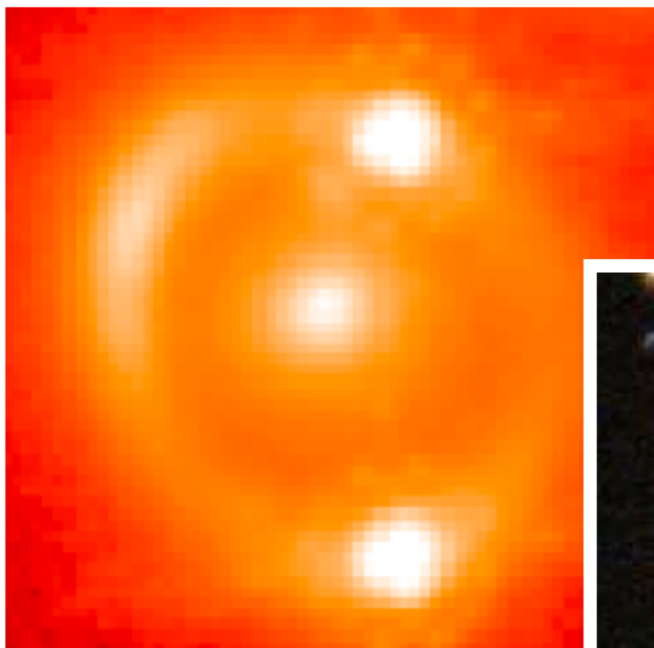


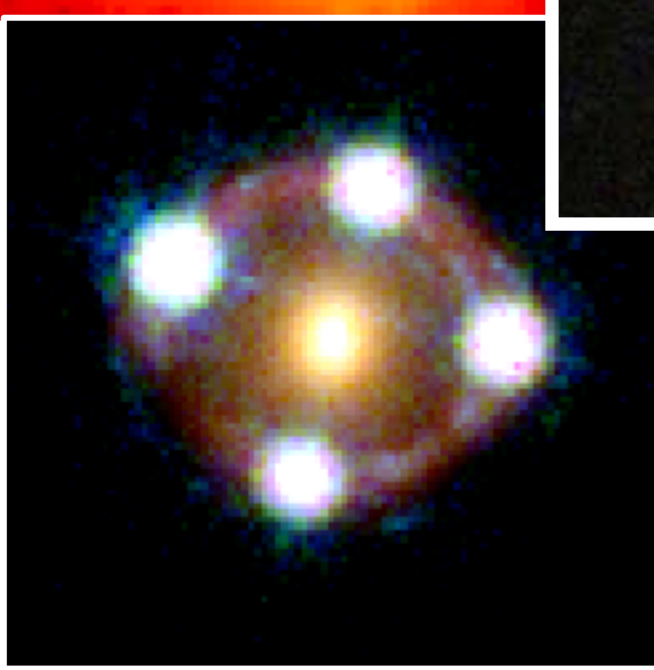
Think big with lensing!

- lensing is sensitive to the projected central density of sub haloes (how about combining it with satellite kinematics?)
- high (anomalous?) concentrations have been found. Do we have already a signal of something?
- redshift and mass evolution: A large sample of lenses can be sensitive to ‘smoking gun’ signals… so tell me what these signals are!

Summary

Gravitational lensing is…





- **unique** window to the dark universe
  - probes small (**dark**) matter structure
- **competitive** with other cosmological probes
- **advancing** with increased sample size and improved observational capabilities!
- **robust** with revised and well-tested and validated methodology