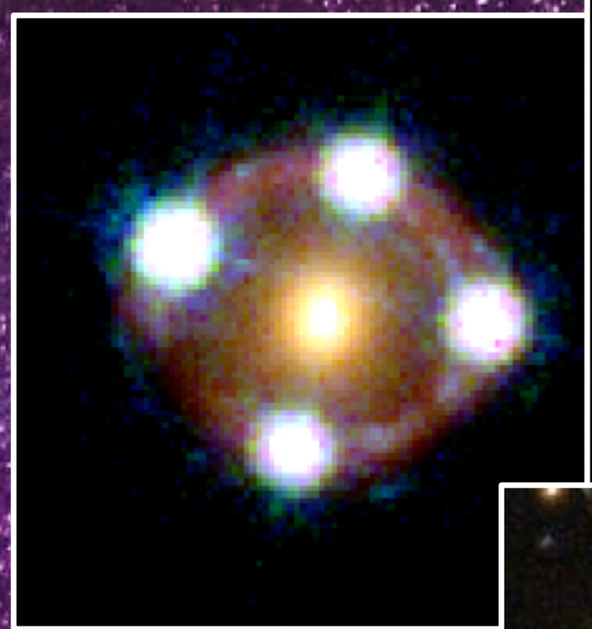
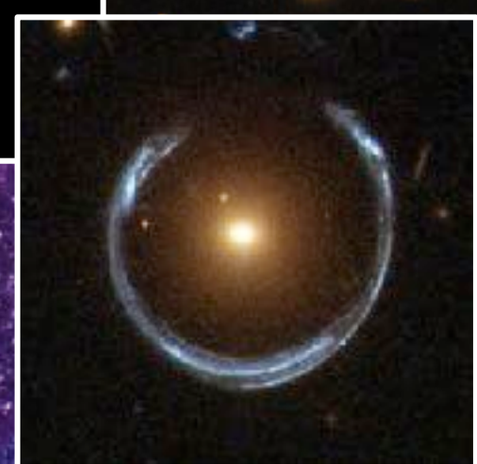
Strong lensing probes of dark matter





See also talks on Tue afternoon by:

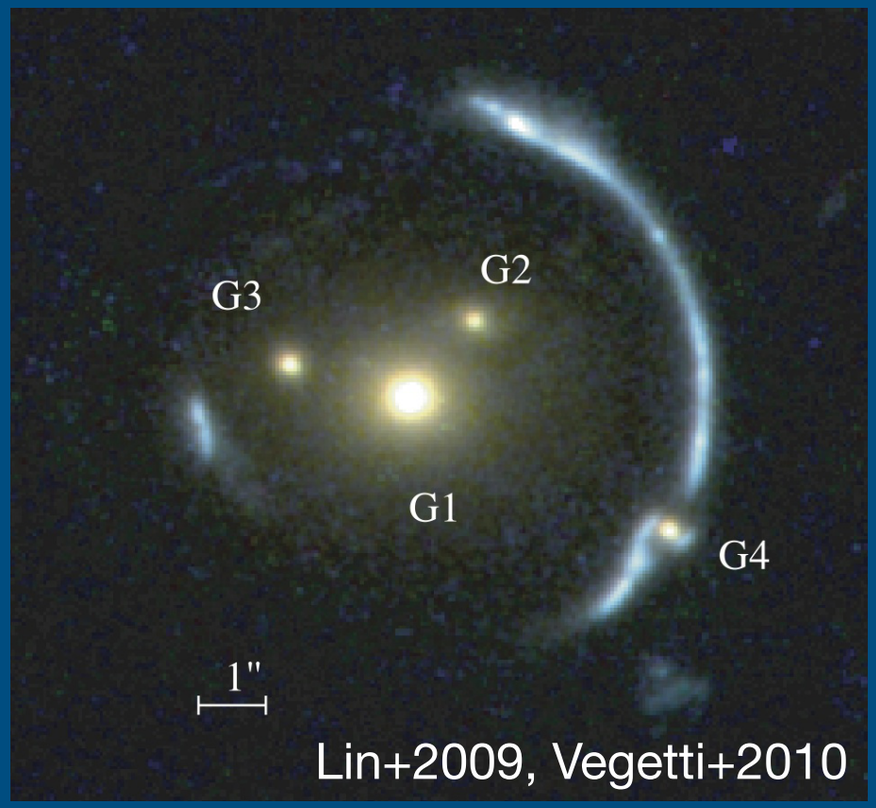
- Chris Fassnacht
- Daniel Gilman
- Cora Dvorkin
- Lukasz Wyrzykowski
- Siddharth Mishra-Sharma

Simon Birrer
University of California, Los Angeles

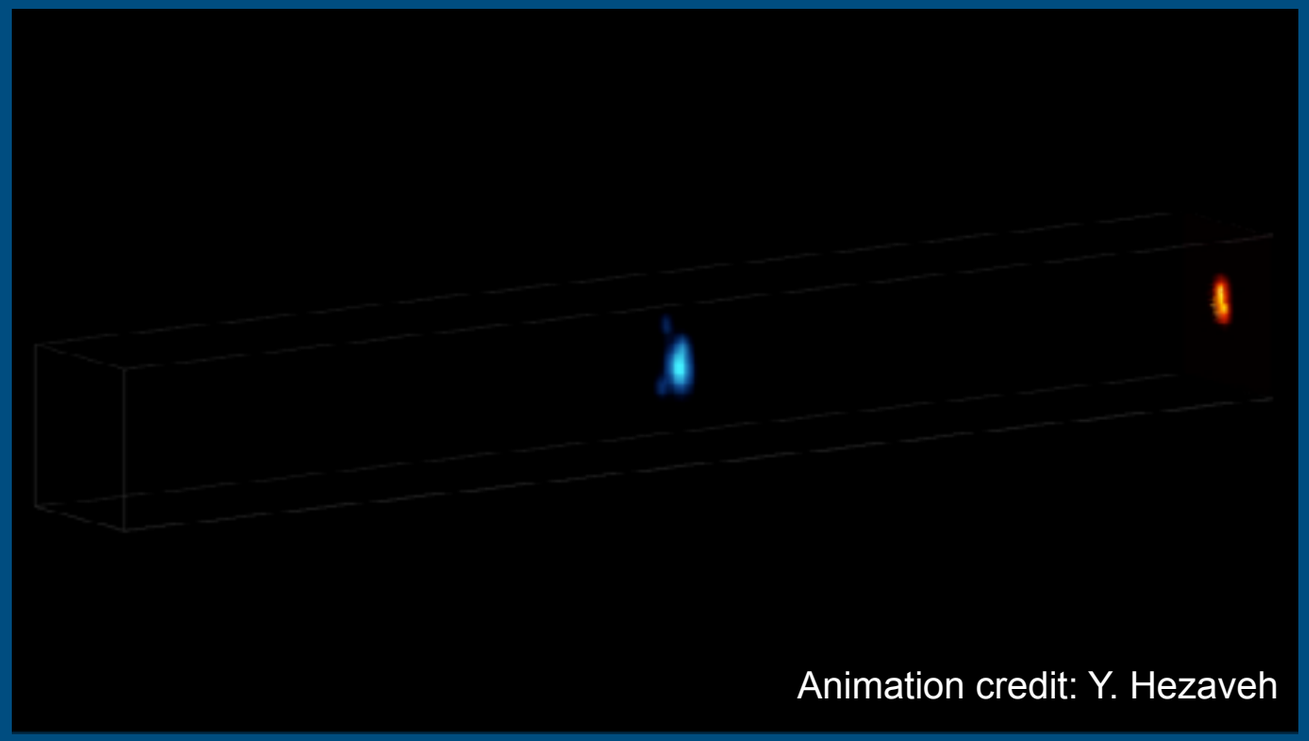
LSST Dark Matter Workshop, Chicago, Aug 5th 2019

Strong Gravitational Lensing

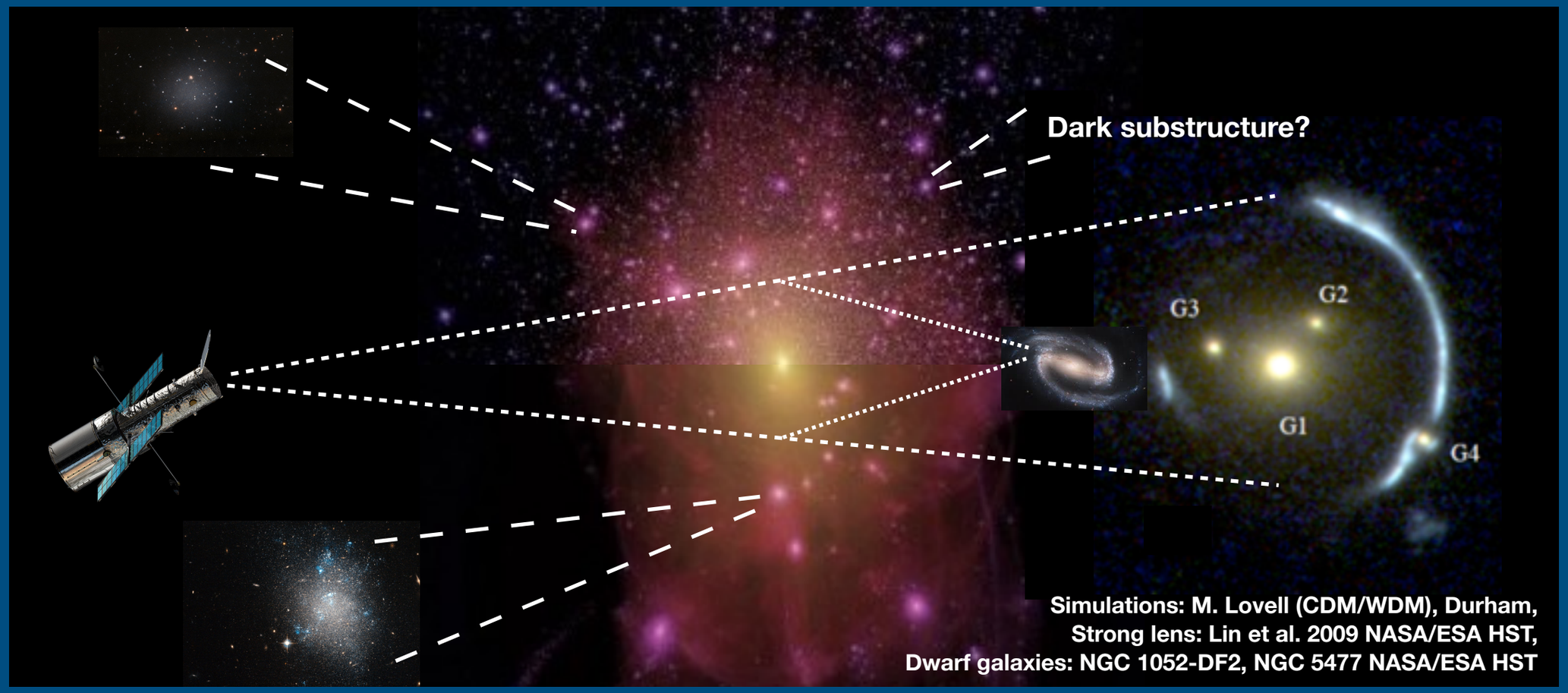
- Effect predicted by General Relativity
- Space-time curvature induced by matter creates an optical effect
- This effect is mostly “weak”, leading to small distortions
- Rare alignments lead to multiple images of the same source - strong lensing



Lin+2009, Vegetti+2010

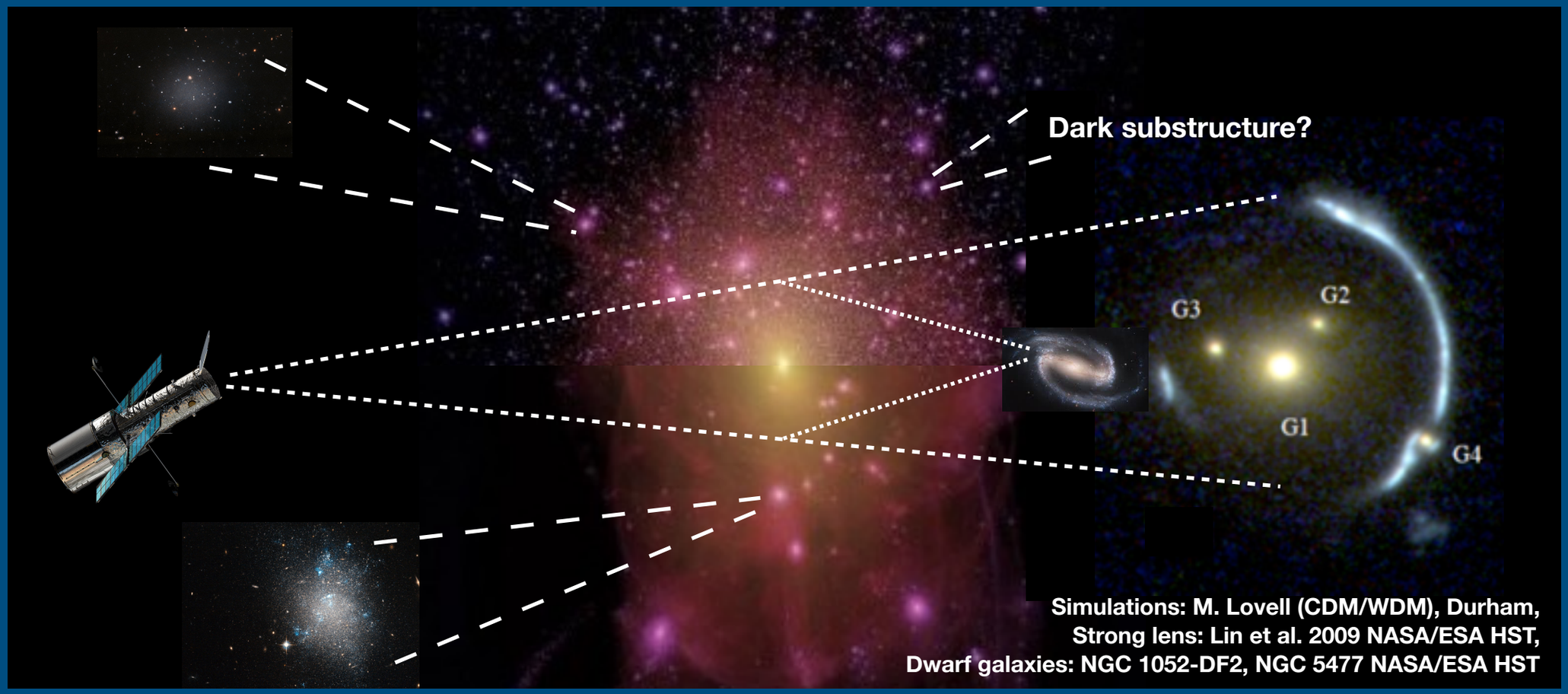

Animation credit: Y. Hezaveh

Strong Gravitational Lensing



Can gravitational lensing discriminate between different dark matter models?

Strong Gravitational Lensing

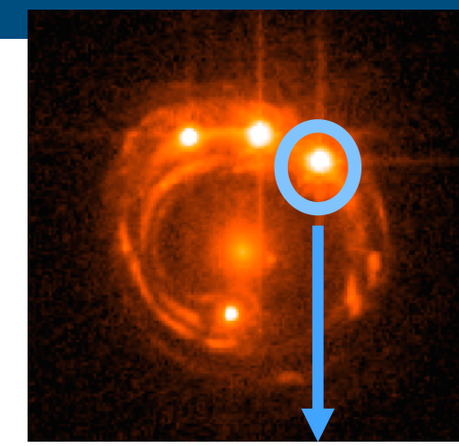


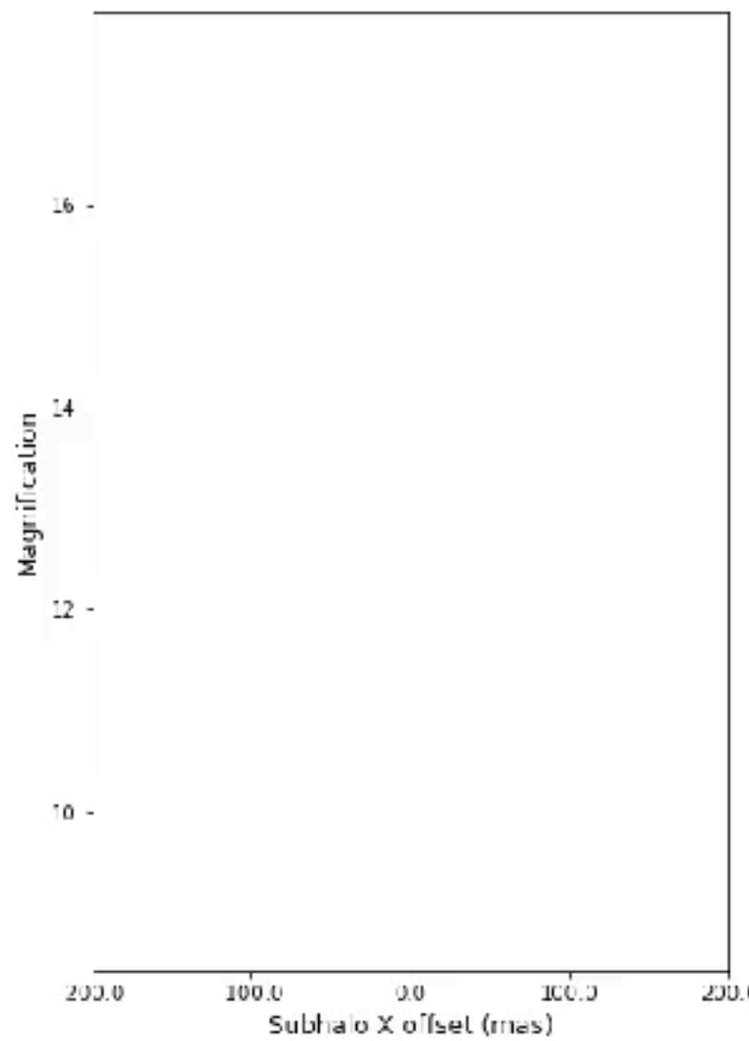
Model	Probe	Parameter	Value
Warm Dark Matter	Halo Mass	Particle Mass	$m \sim 18\,\mathrm{keV}$
Self-Interacting Dark Matter	Halo Profile	Cross Section	$\sigma_{\mathrm{SIDM}}/m_\chi \sim 0.1\text{–}10\,\mathrm{cm}^2/\,\mathrm{g}$
Baryon-Scattering Dark Matter	Halo Mass	Cross Section	$\sigma \sim 10^{-30}\,\mathrm{cm}^2$
Axion-Like Particles	Energy Loss	Coupling Strength	$g_{\phi e} \sim 10^{-13}$
Fuzzy Dark Matter	Halo Mass	Particle Mass	$m \sim 10^{-20}\,\mathrm{eV}$
Primordial Black Holes	Compact Objects	Object Mass	$M > 10^{-4} M_\odot$
Weakly Interacting Massive Particles	Indirect Detection	Cross Section	$\langle \sigma v \rangle \sim 10^{-27}\,\mathrm{cm}^3/\,\mathrm{s}$
Light Relics	Large-Scale Structure	Relativistic Species	$N_{\mathrm{eff}} \sim 0.1$

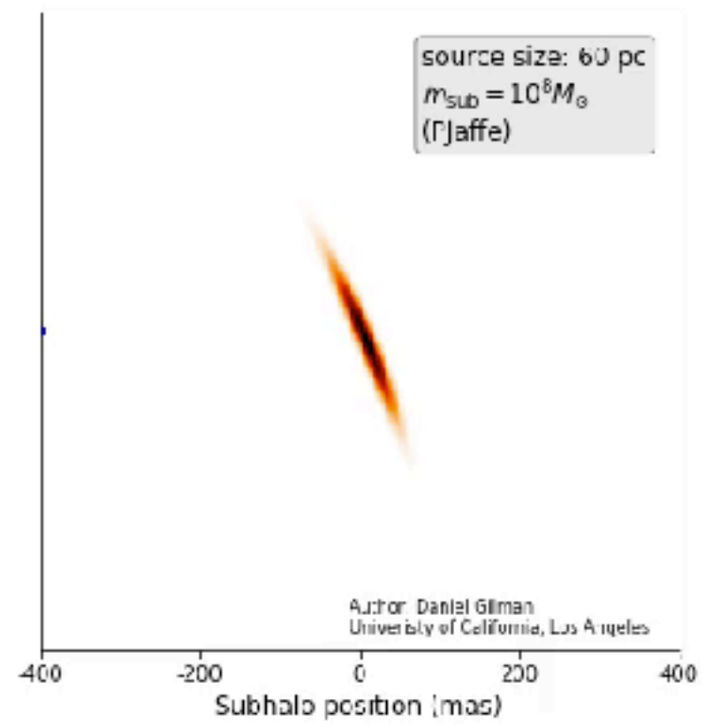
Resolved vs unresolved lensing

Observable degeneracies:

- clump mass
- clump profile
- clump position
- source size
- source shape
- mass sheet
- absolute scales
- …

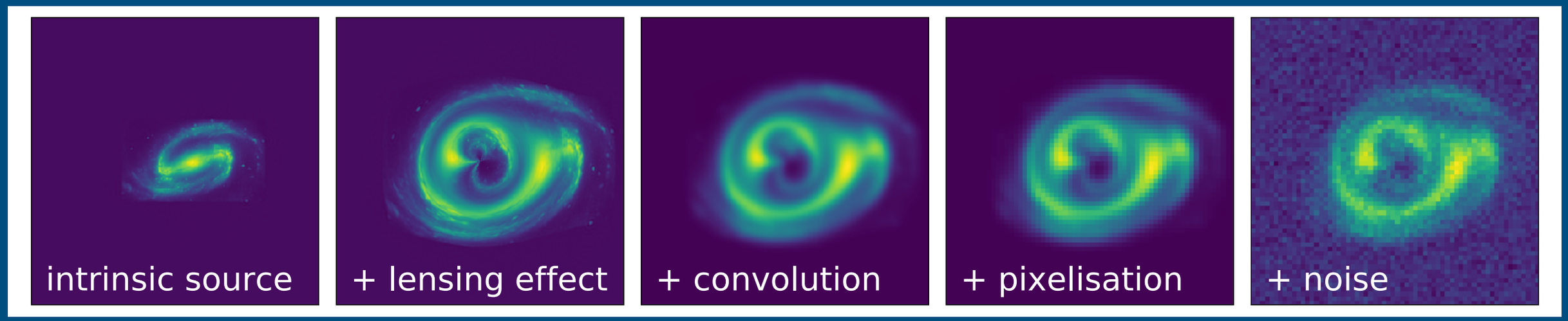






Credit: D. Gilman (UCLA)

Strong lensing:
a forward modeling example



Strong lensing:
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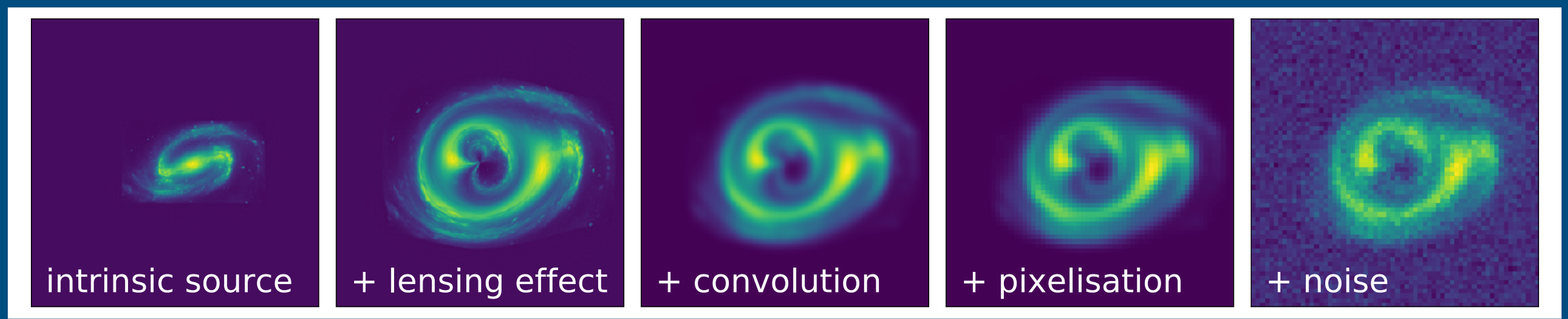


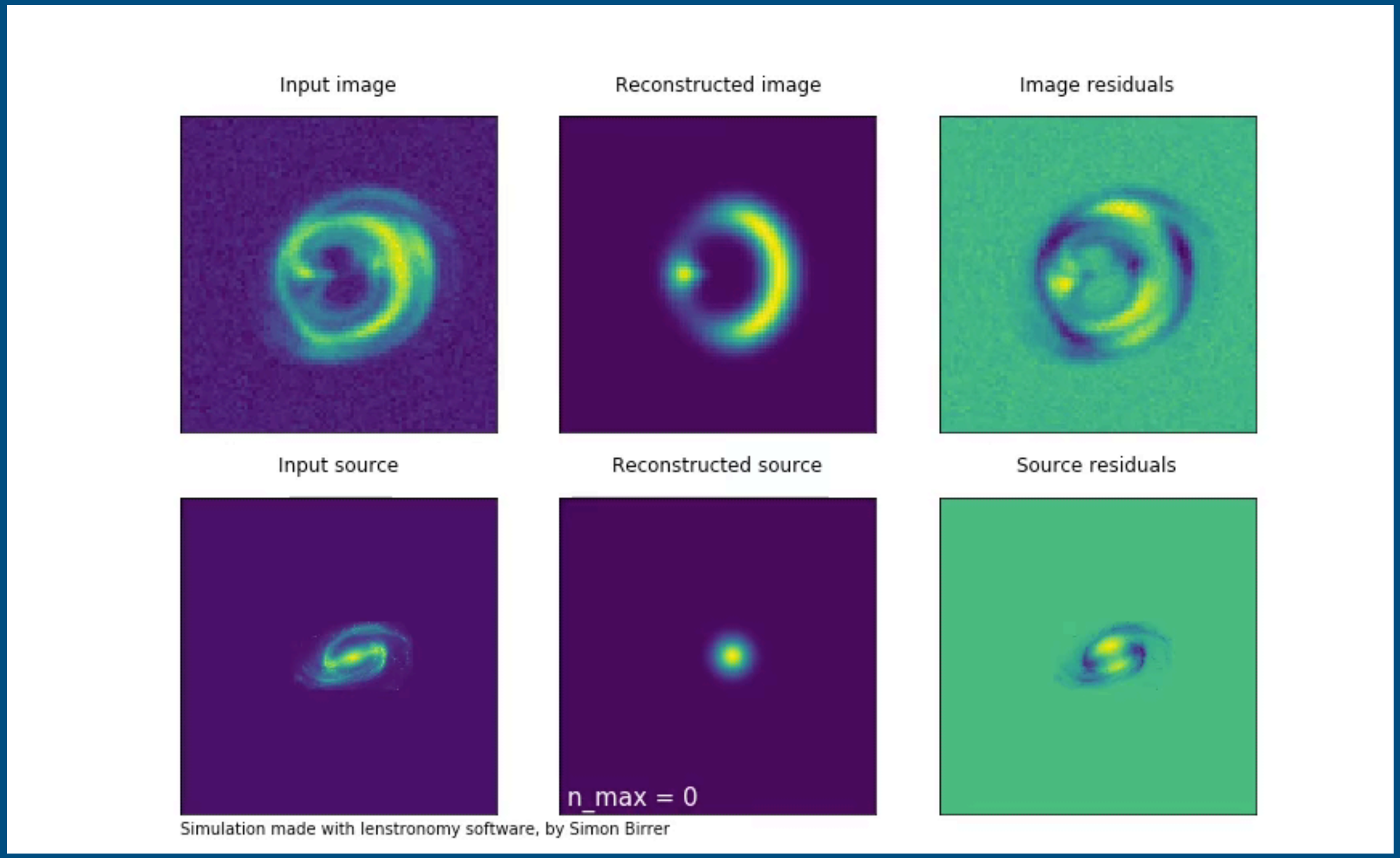
a lot of nuisance!

that's what we care!

that's what we need to know!

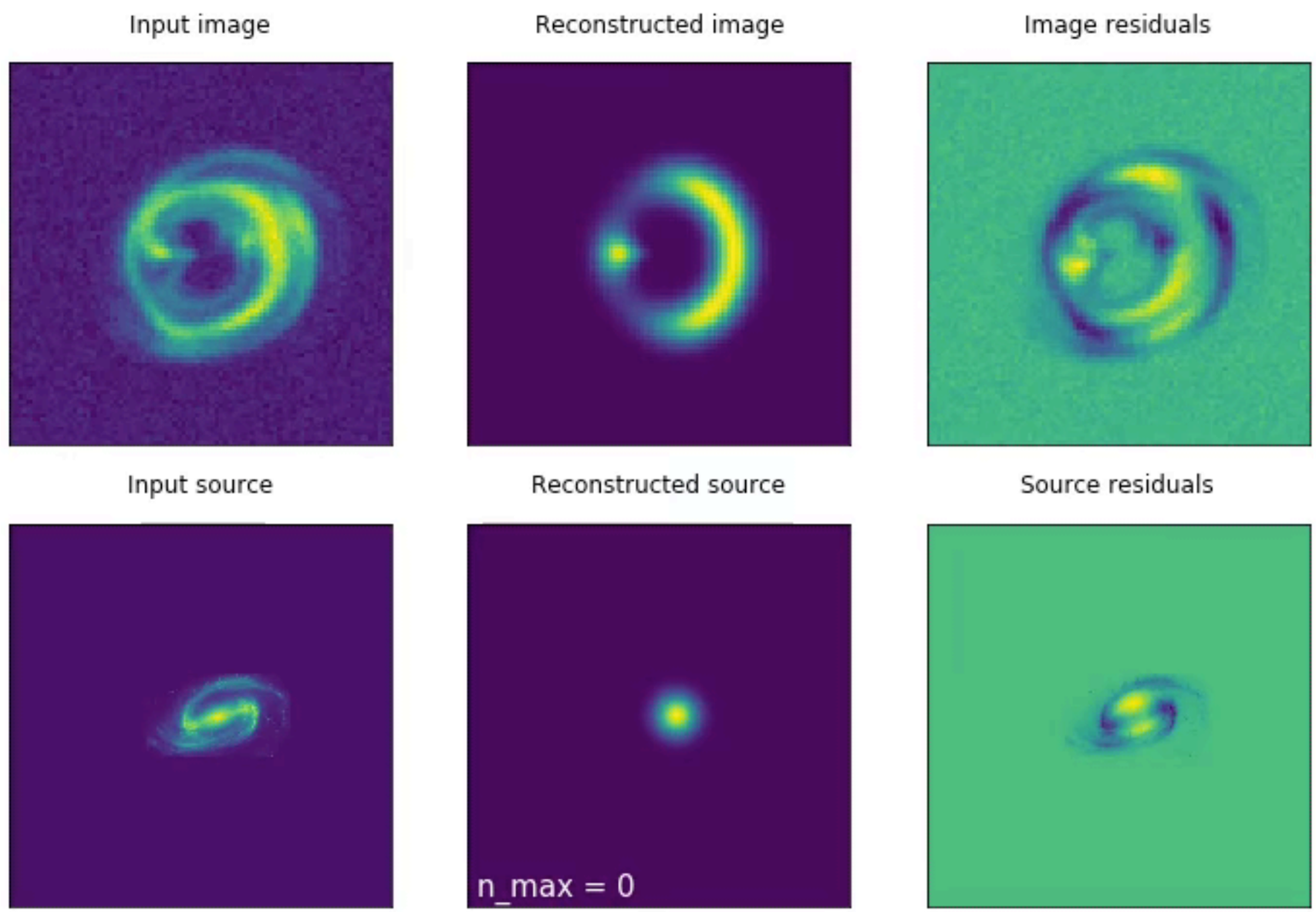
?

Lens modeling:
example with perfect lens model



software available: `$pip install lenstronomy`
`https://github.com/sibirrer/lenstronomy`

Lens modeling:
example with missing (sub)-structure



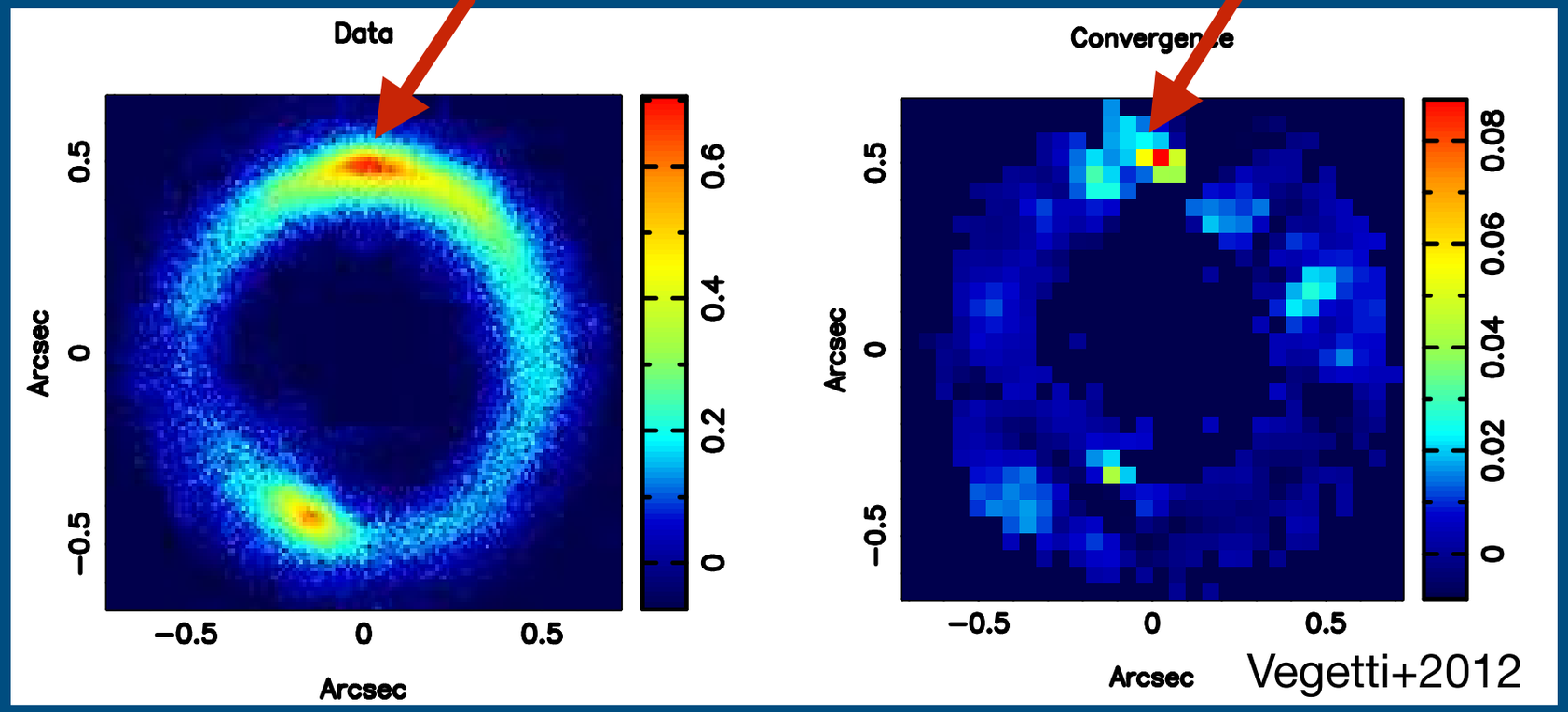
Simulation made with lenstronomy software, by Simon Birrer

software available: `$pip install lenstronomy`
`https://github.com/sibirrer/lenstronomy`

Method 1: resolved imaging

resolved strong lensing from galaxy surface brightness

direct detection through lens modeling



sensitive to **individual** clumps near the Einstein ring

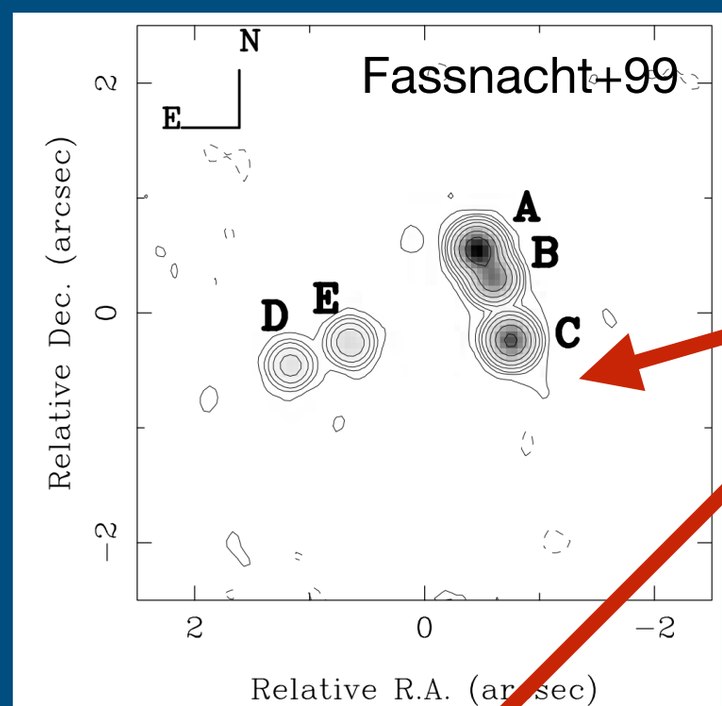
sensitivity depends on **spatial resolution** and **source** structure

quantifying a detection challenging and **high S/N** required

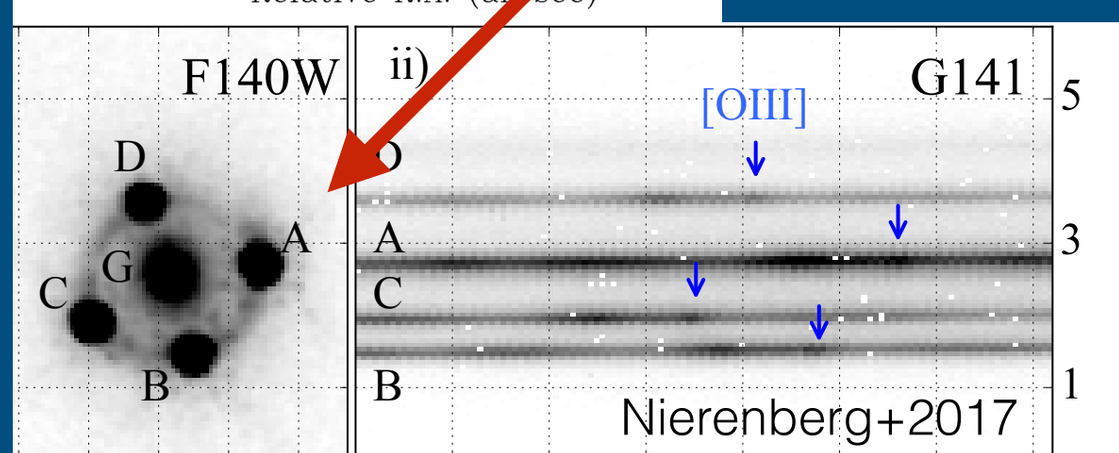
Koopmans 2005, Vegetti+2010, 2012, 2018
Birrer+2017, Hezaveh+ 2016, Ritondale+2018

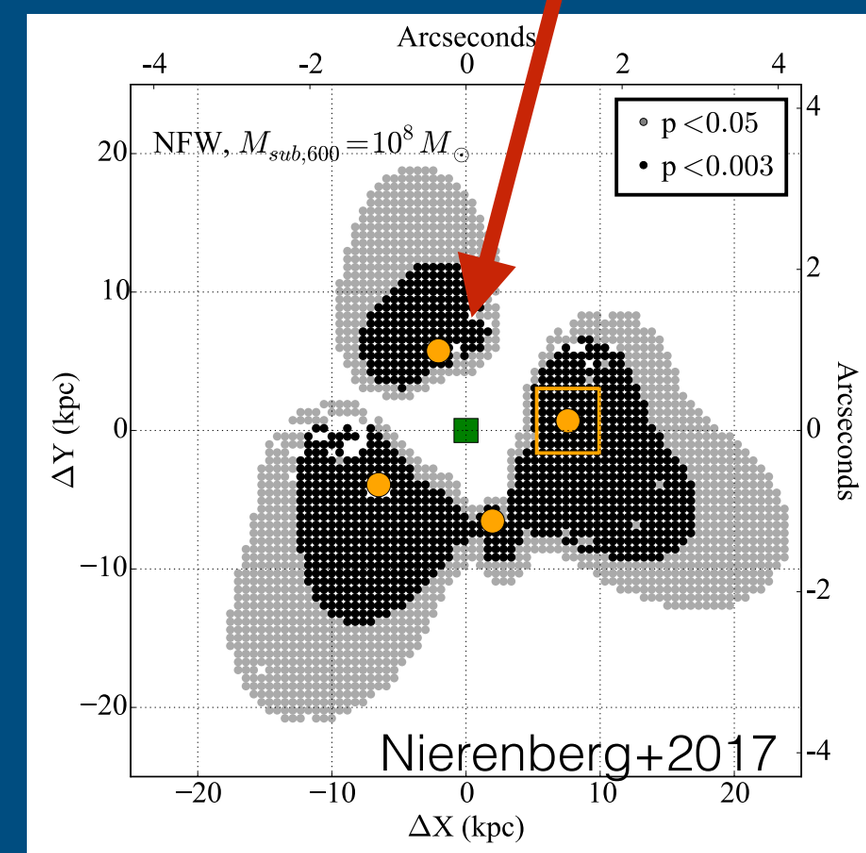
Method 2: unresolved flux ratios

exclusion regions for a certain type of sub-clump



unresolved strong lensing from quasar narrow line emission region



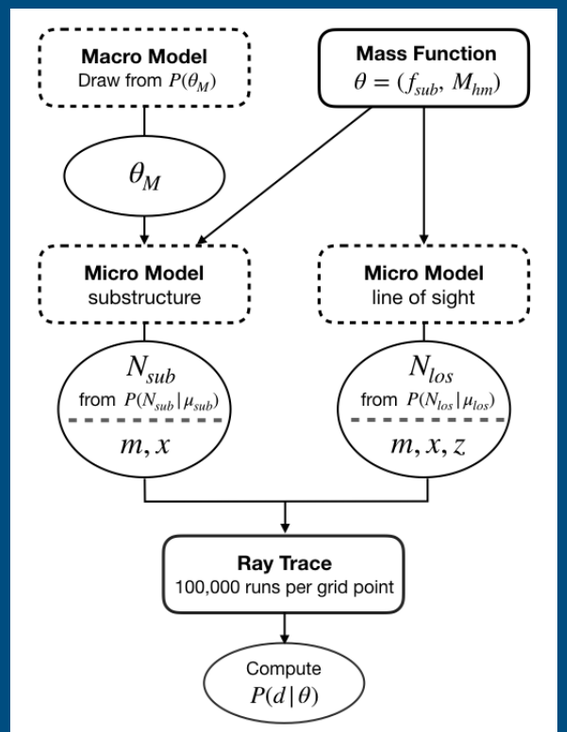


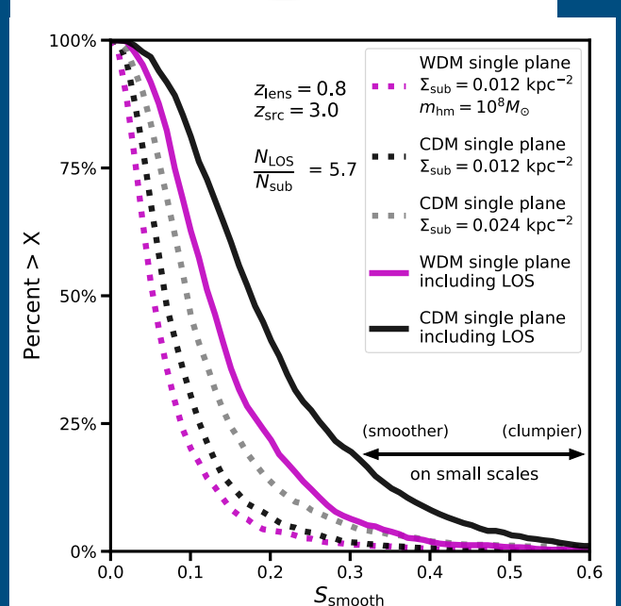
Mao & Schneider 1998,Dalal & Kochanek 2002
Moustakas & Metcalf 2003 ,Nierenberg+2014, 2017
Hsueh+2016, 2017, 2019, Gilman, SB+2018, 2019

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

Statistical methods

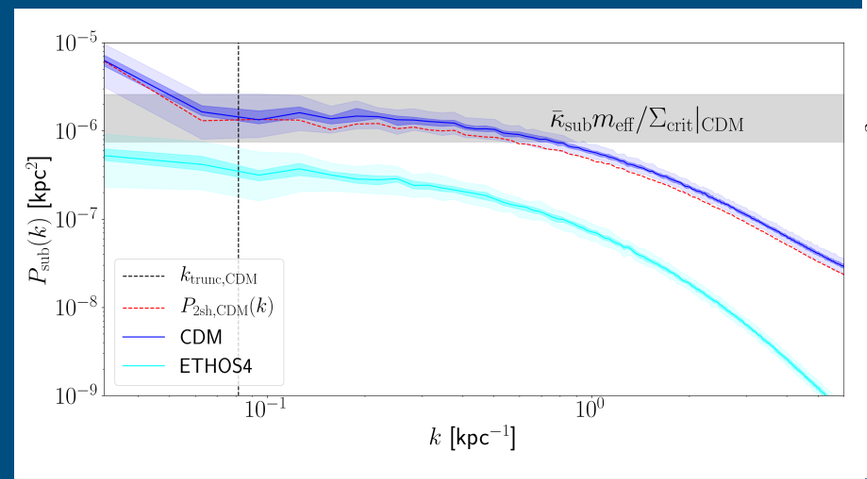
Flux ratio distributions



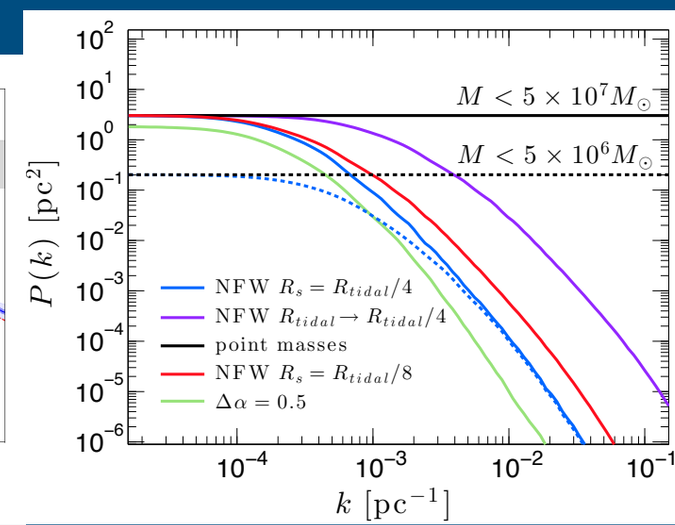


Hsueh+19, Gilman, Birrer+19

Convergence Power-spectrum



Diaz-Rivero+18



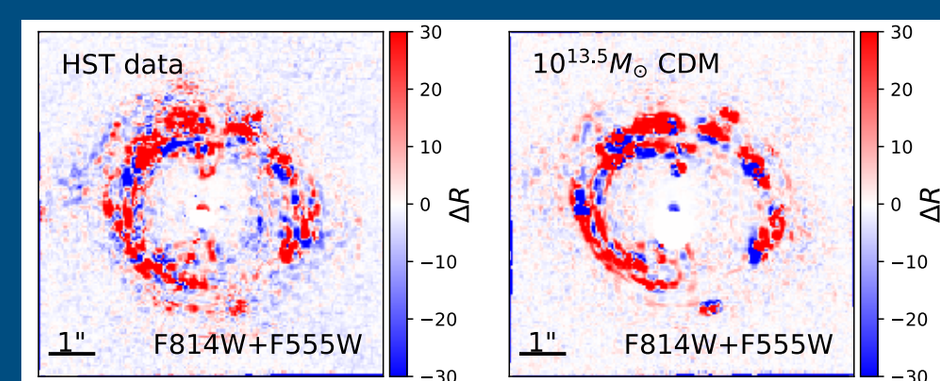
Hezaveh+14

See also: Cry-Racine+2018, Bayer+2018

Informative?
Robust?
Feasible?

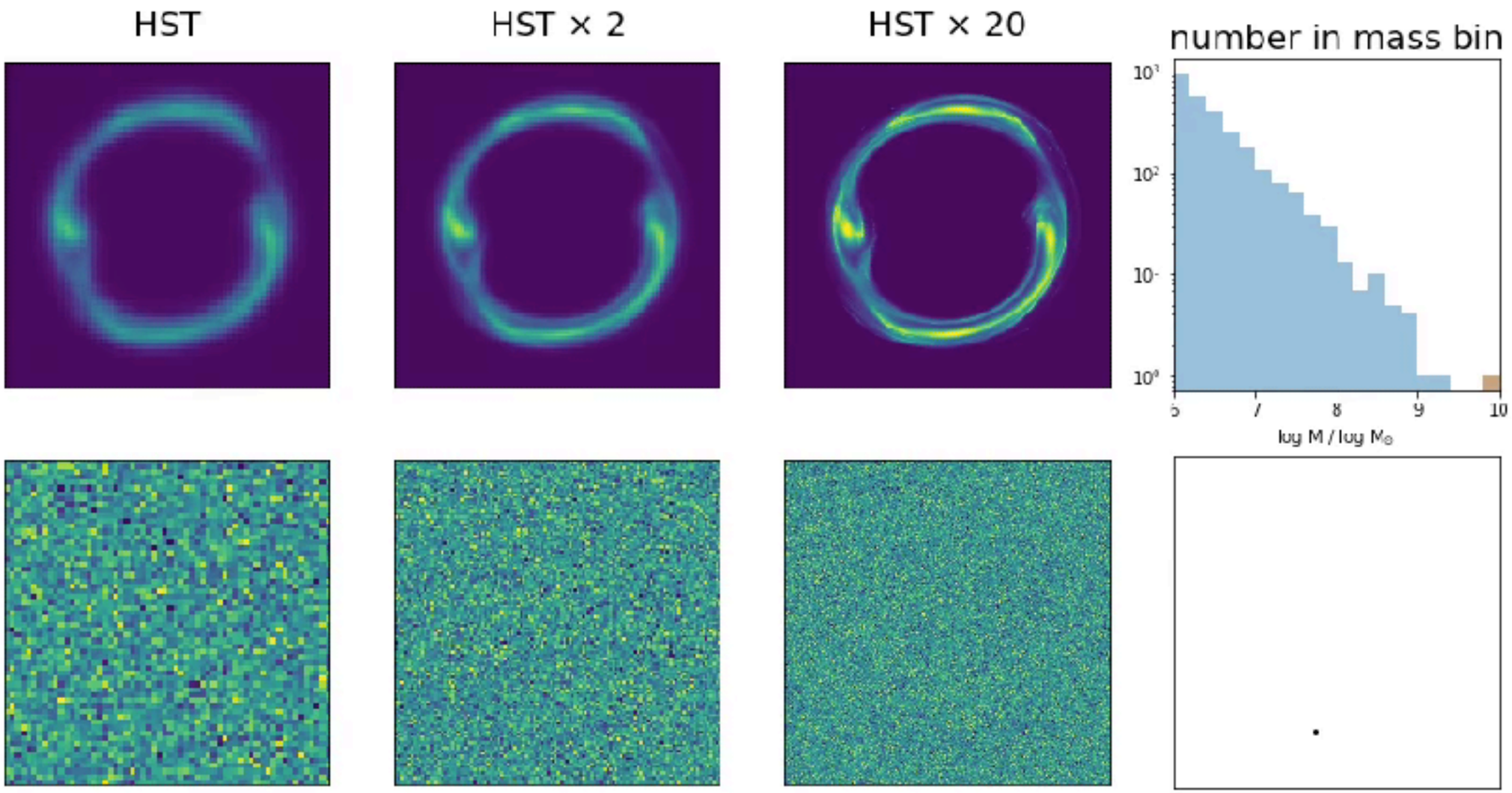
Active work!

Summary statistics with ABC



Birrer+17

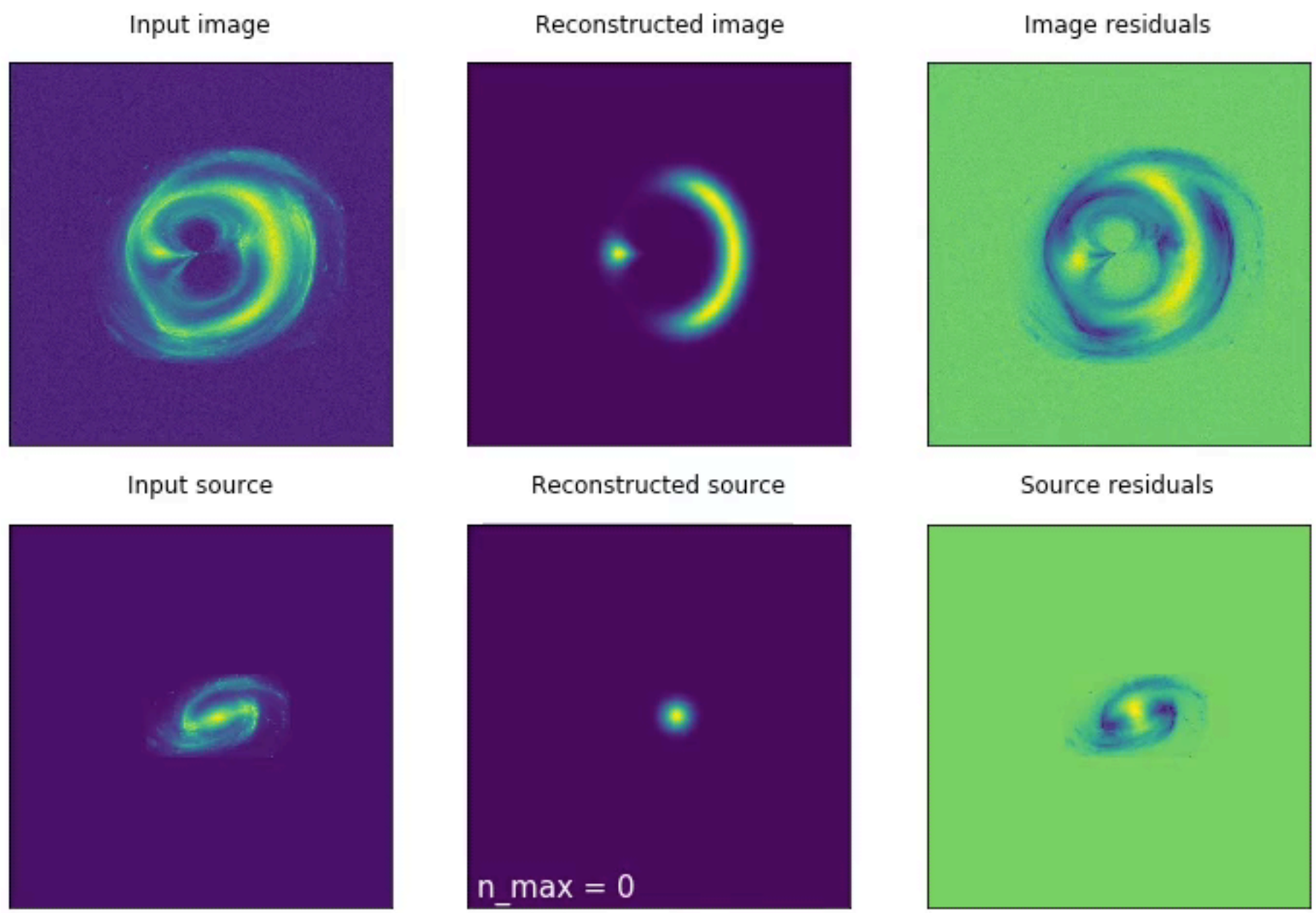
High resolution ELT / VLBI era



Resolution matters if:

- **S/N ratio is high at the resolution element**
- **surface brightness variability at the resolution scale**

ELT / VLBI era



Simulation made with lenstronomy software, by Simon Birrer

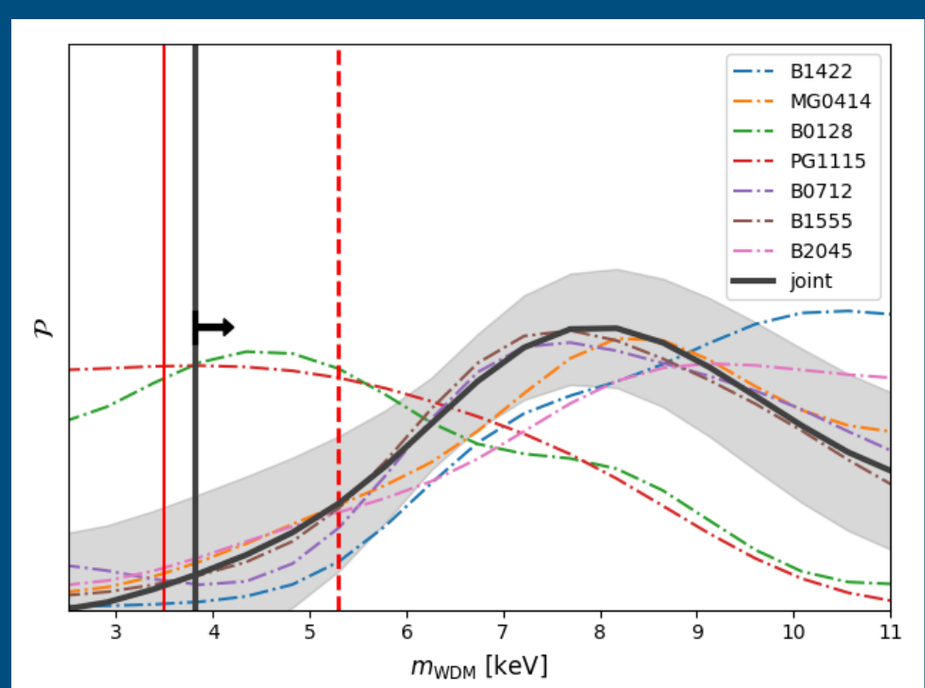
Current constraints

- **resolved imagine: detection of 10^(8-9) (ish) halos, statistics is limited**

- **quasar flux ratios: Huesh+2019, Gilman, SB+2019 (on arXiv soon)**

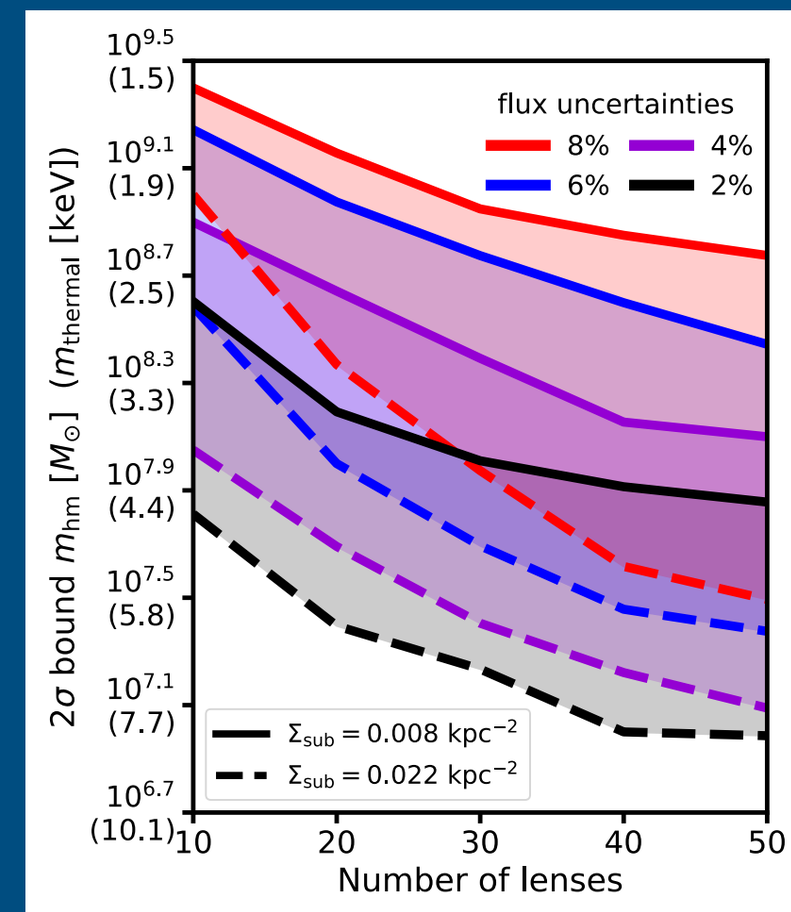
Spoiler alert: Tuesday talks by Chris Fassnacht and Daniel Gilman

- **two independent teams working on different data sets to perform a similar analysis**
- **Consistent among each other**
- **Precision of order Lyman-alpha forest**



Hsueh+19

forecast



Gilman, SB+19

Challenges

- Uncertainty in theory prediction of sub halo mass function (M, z)
- Selection (bias) of lenses
- Imaging: choosing a robust summary statistics

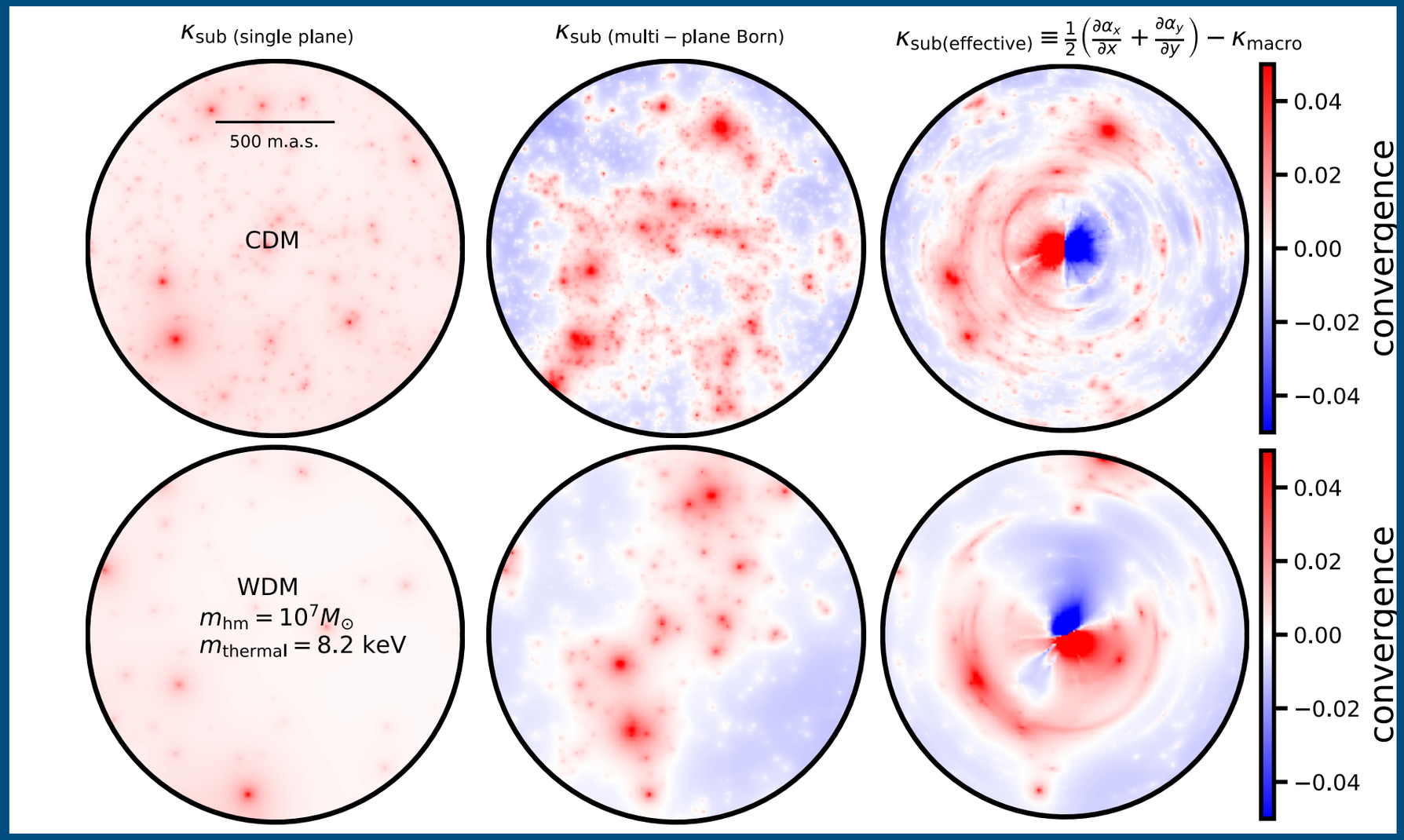
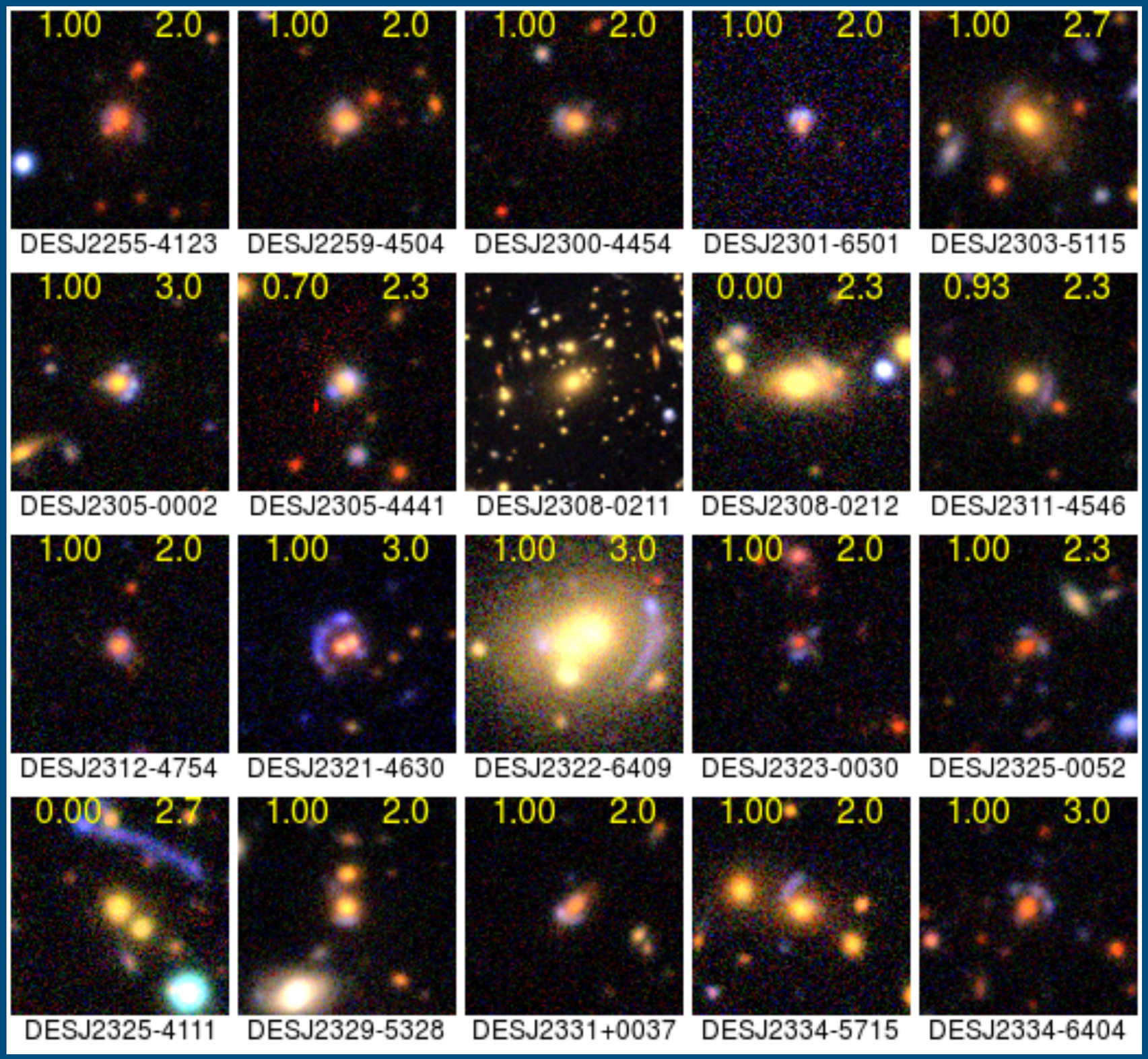


Figure: Gilman, SB+ 2019

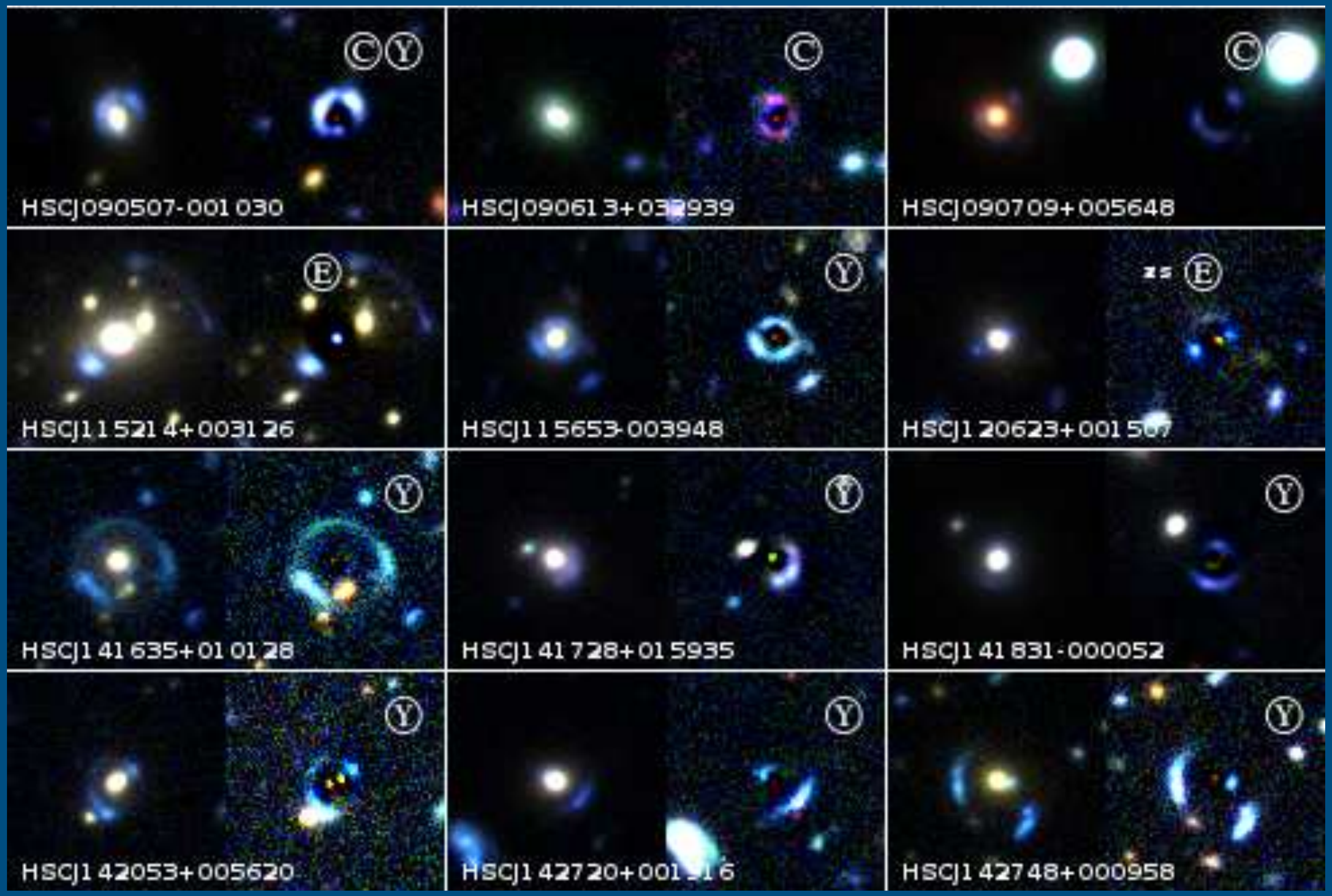
Prospects with LSST

Strong lensing arcs are discovered in DES…



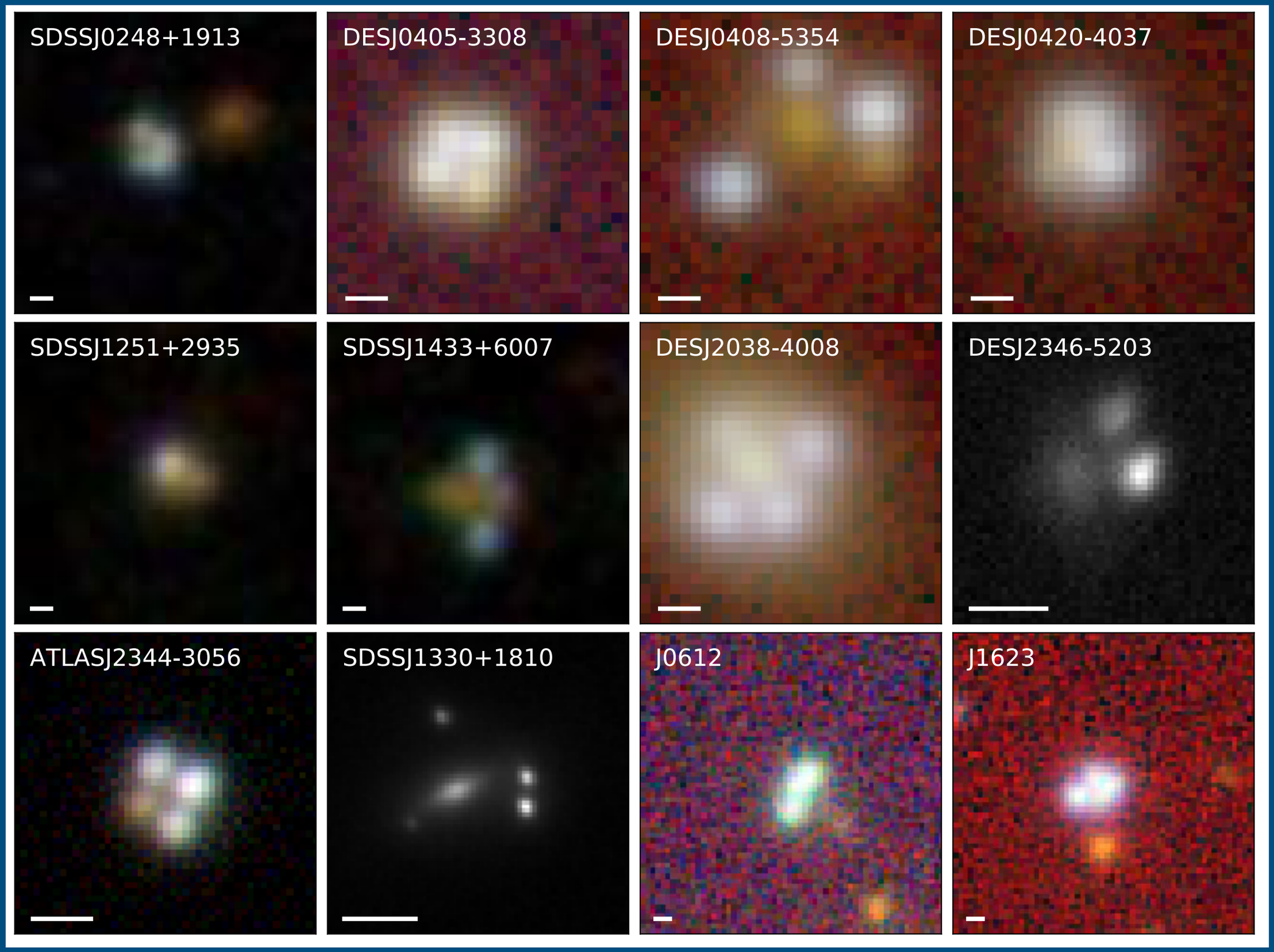
Jacobs+2019, DES collaboration

… and HSC…



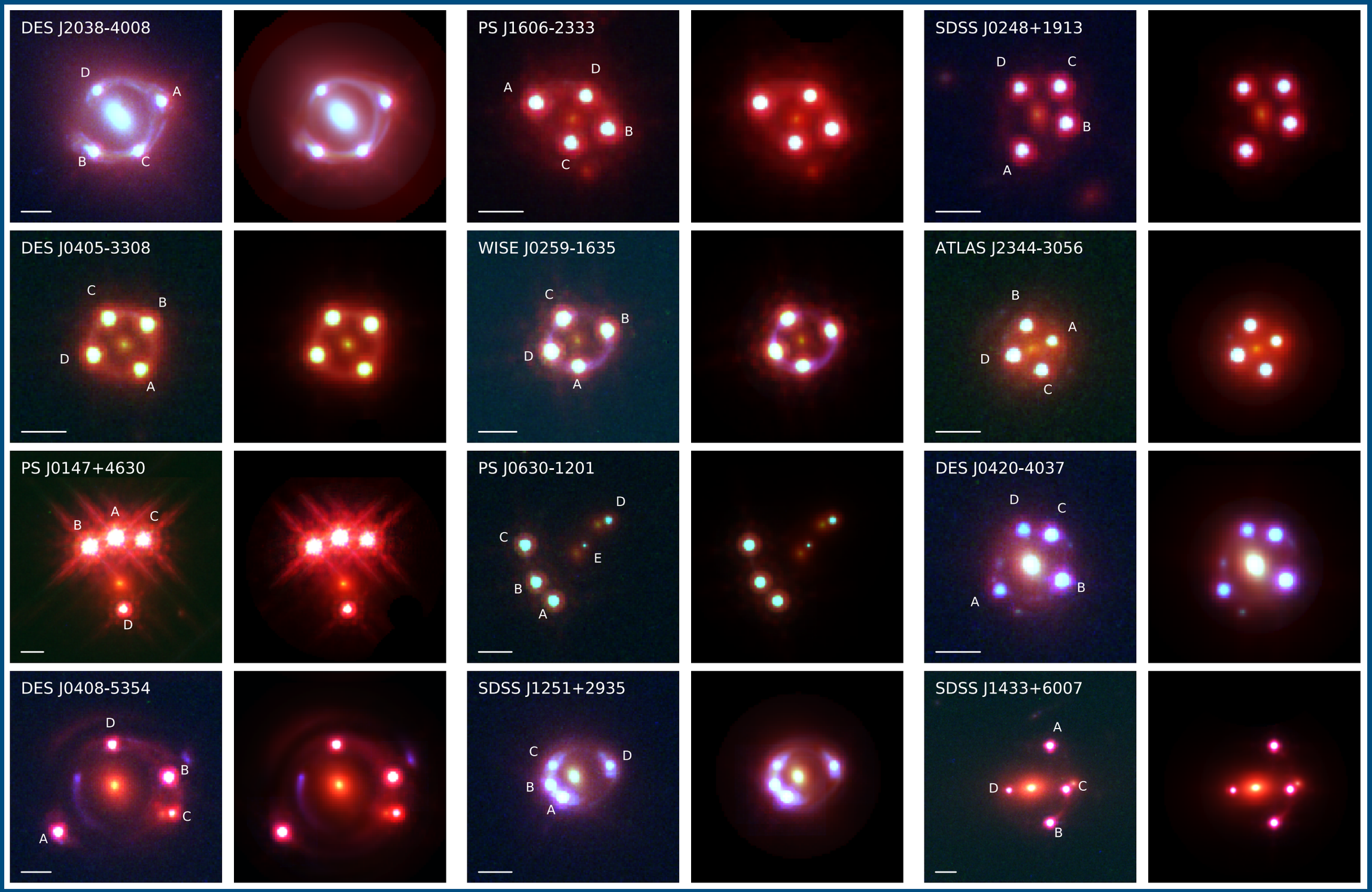
Sonnenfeld+2018, HSC collaboration

and quasar lenses too...



discovered: Ostrovski+, Lemon+, Agnello+, Schechter+, Oguri+ and the STRIDES/DES collaboration

…and followed up…



modeling: Shajib, Birrer+2018

…and more to come!

Follow up coordination in the LSST era

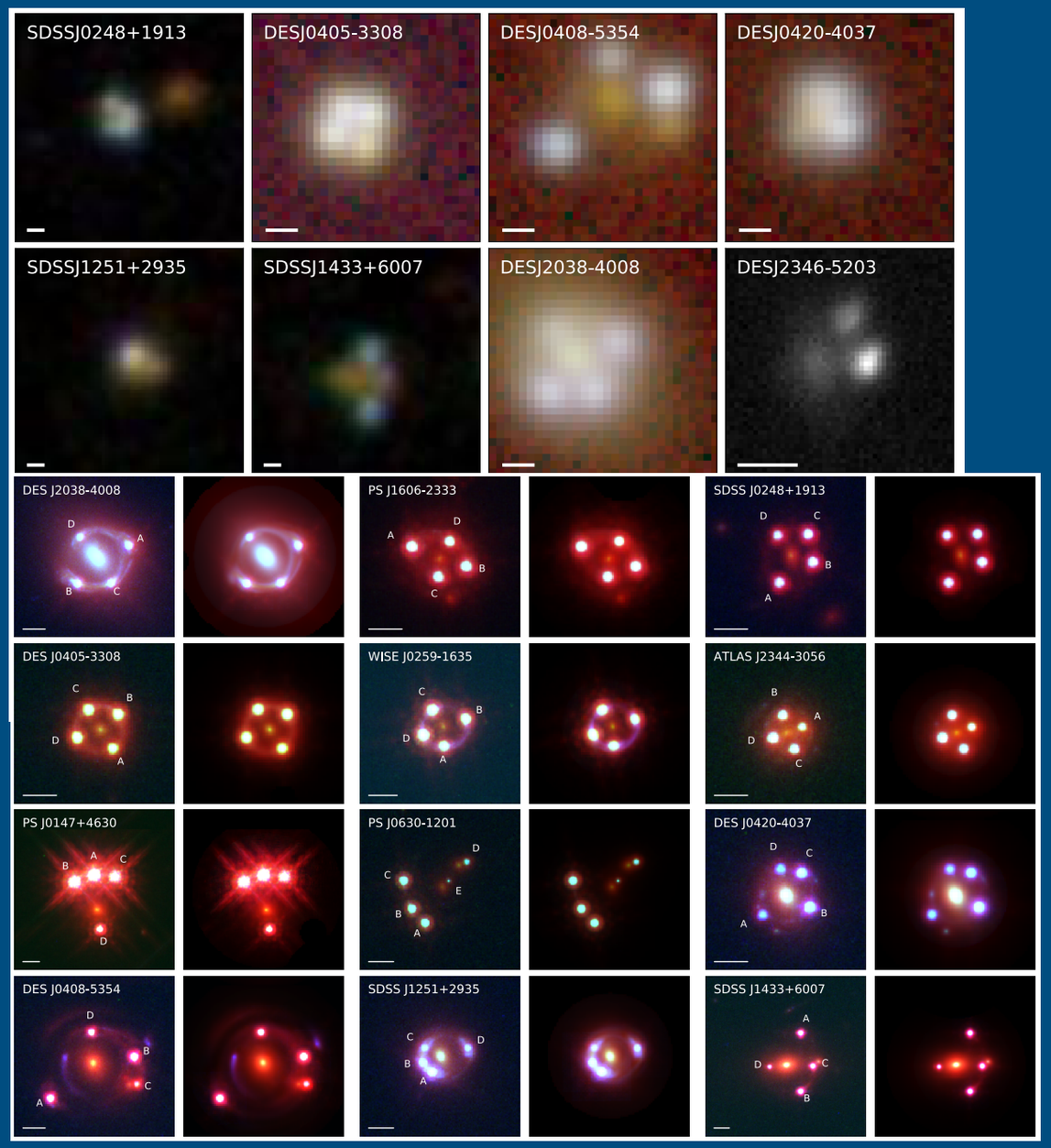
- **LSST will find 10’000s of arc lenses** Collett 2015
- **LSST will find 1000’s of quasar lenses** Oguri&Marshall 2010

Tasks:
- **find the lenses knowing their selection function**
- **pick the right lenses (for your science)**
- **follow them up with the right facilities**
- **chose the right analysis technique**

Finding, analyzing and doing the science in one unified framework

Summary

Gravitational lensing is an unique window to the dark universe



- **LSST will find 10’000s of arc lenses**
- **LSST will find 1000’s of quasar lenses**
- **follow-up and scalable analysis methods required**