Probing Dark Matter with strong gravitational lensing

Simon Birrer, UCLA

Collaborators:
Tommaso Treu, Daniel Gilman, Anowar Shajib
Adam Amara, Alexandre Refregier
Anna Nierenberg, Chuck Keeton, Andrew Benson

UCLA, Apr 3rd 2018

Strong gravitational lensing

Source
unknown

Lens
unknown

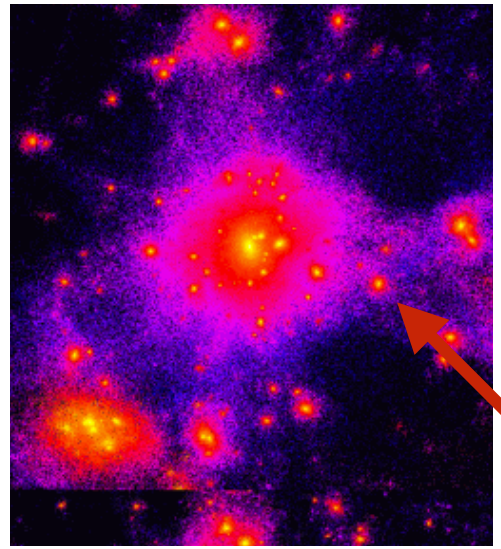
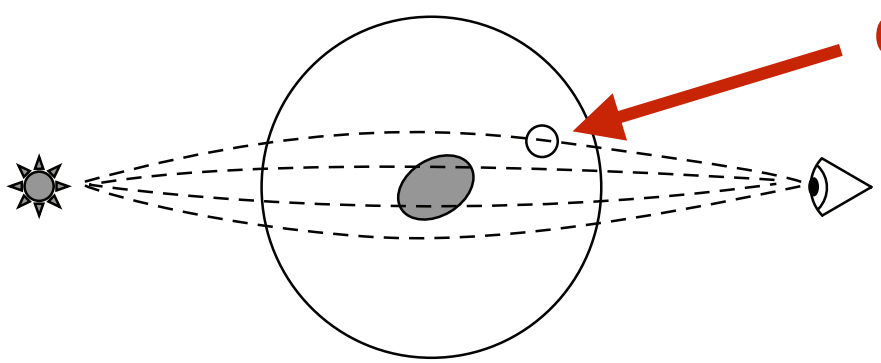


Image
data

can be dark!



Metcalf & Madau 2001
Dalal & Kochanek 2002
Moustakas & Metcalf (2003)
Koopmans 2005

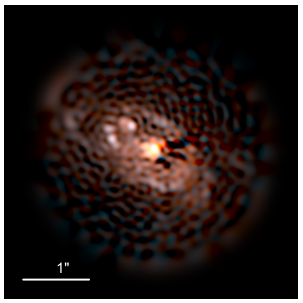
Vegetti+ 2010, 2012
Hezaveh+ 2016
Nierenberg+ 2014, 2017
Birrer+ 2017

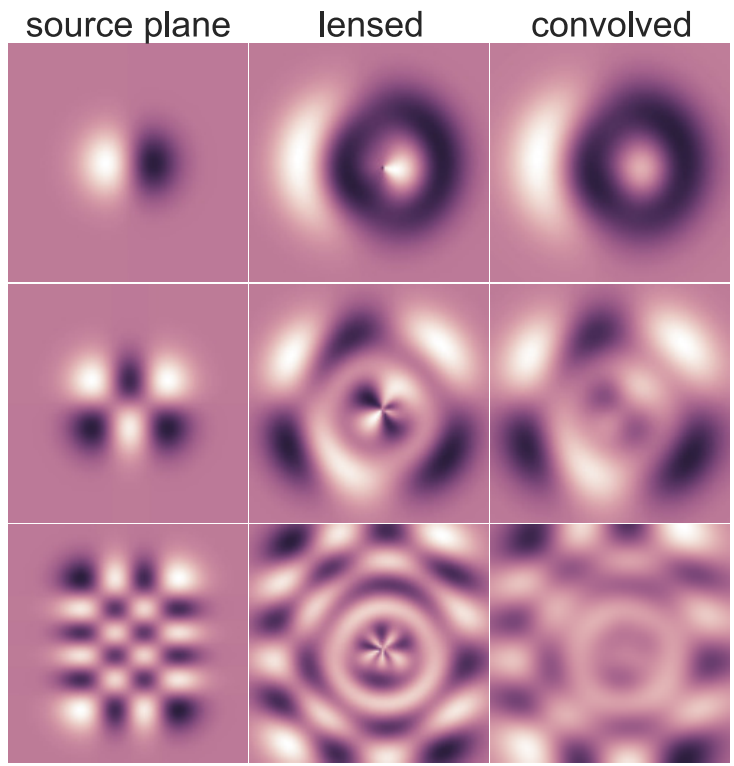
gravitational imaging with basis sets

Requirement: **Simultaneous** reconstruction of source and lens

computational cost of linear inversion and number of non-linear parameters as limitations

10^5 - 10^6 proposals required



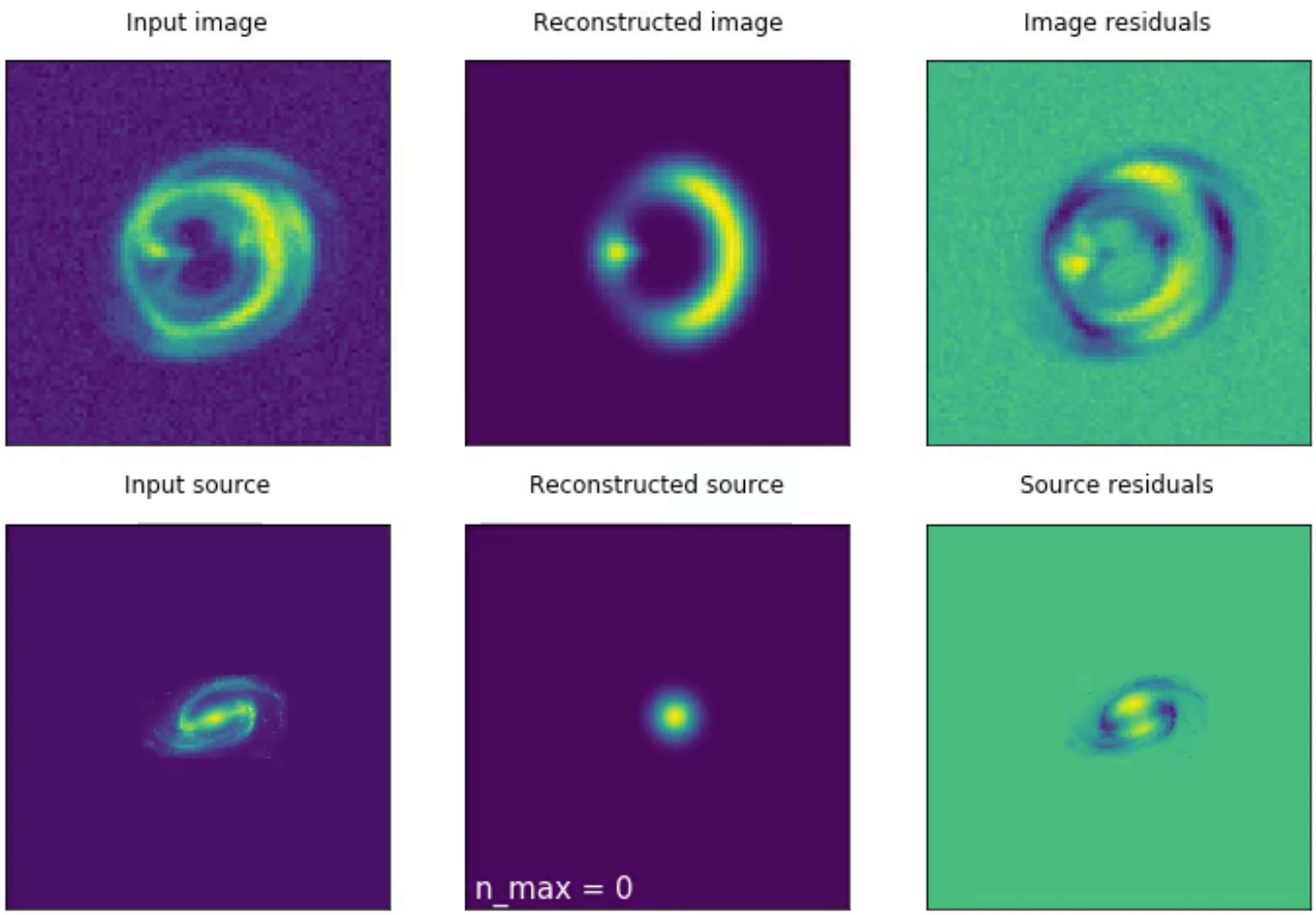


High resolution reconstruction of source with Shapelet **basis set**

Lensing: Birrer+ 2015, 2016, 2017
Shapelets: Refregier 2003
Software: Birrer&Amara 2018

gravitational imaging: example with perfect lens model

FWHM 0.1”



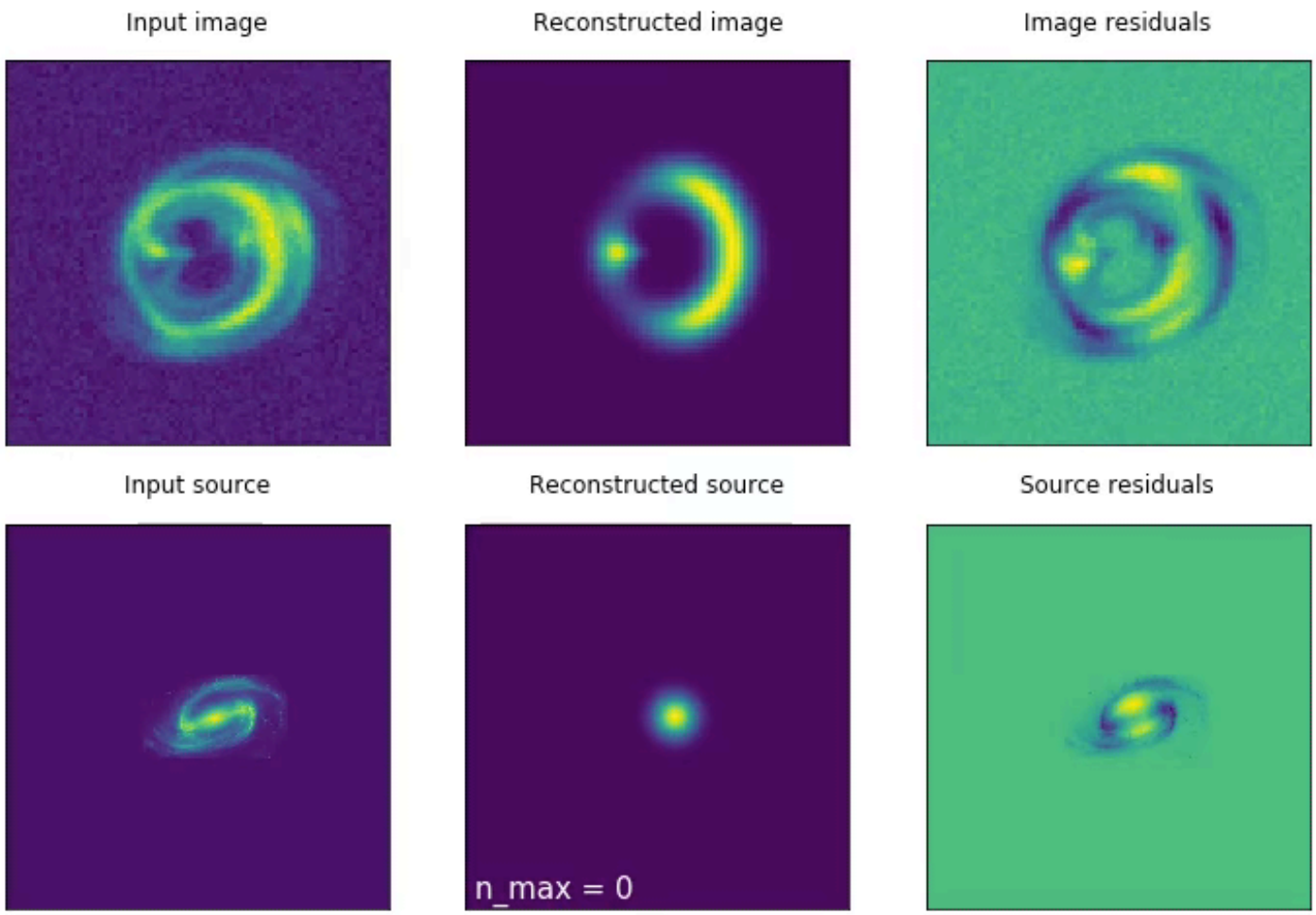
Simulation made with lenstronomy software, by Simon Birrer

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

Lensing: Birrer+ 2015, 2016, 2017
Shapelets: Refregier 2003
Software: Birrer&Amara 2018

gravitational imaging: example with missing substructure

FWHM 0.1”



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Software: Birrer&Amara 2018

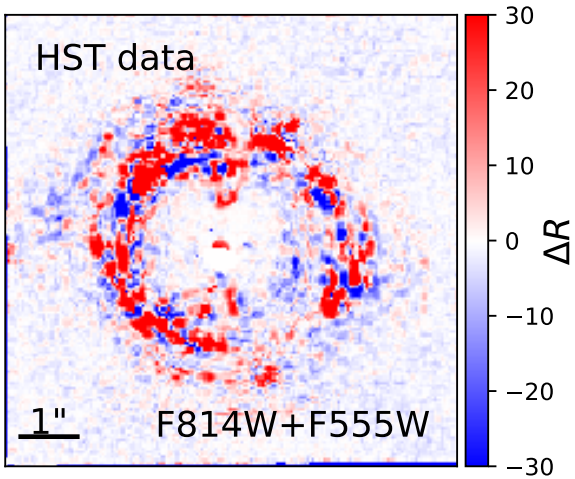
statistical analysis of gravitational imaging

Extract **statistical features** attributed to substructure

Can probe substructure at the **sensitivity limit**

smooth preferred

clump preferred

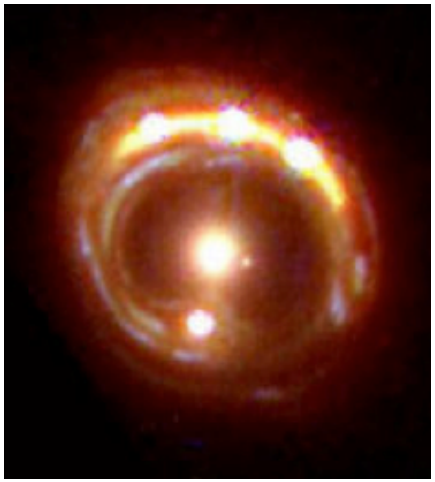


Interpretation of features relies on **simulations**

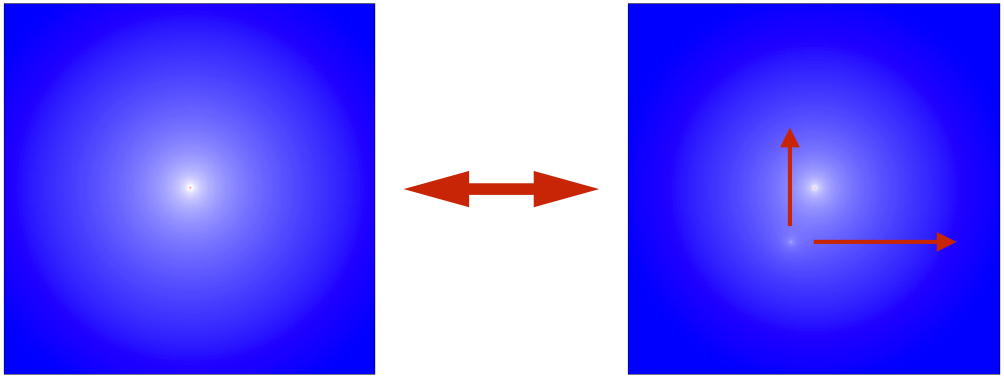
does **not rely** on assumption on **number** and **shape** of sub-clumps

Birrer+ 2017

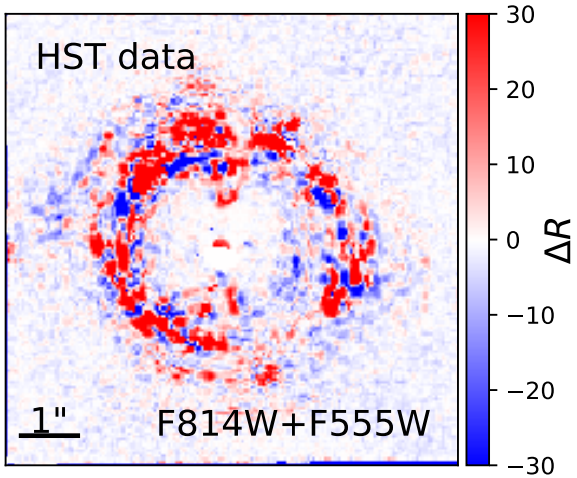
statistical analysis of gravitational imaging



Extract local deflection anomalies
by a substructure **scanning process**



Birrer+ 2017



smooth preferred

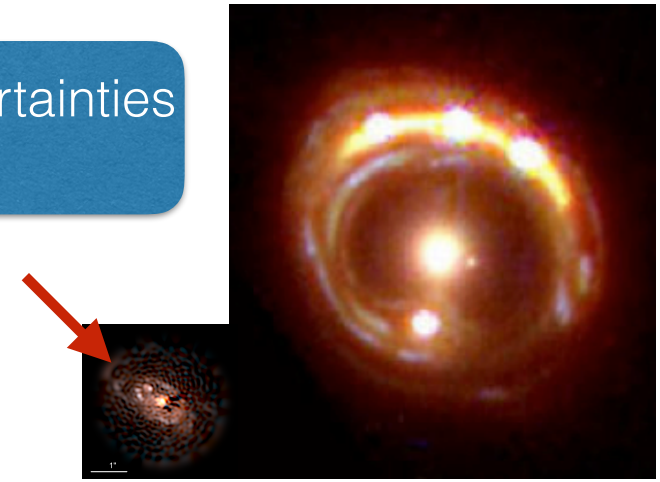
clump preferred

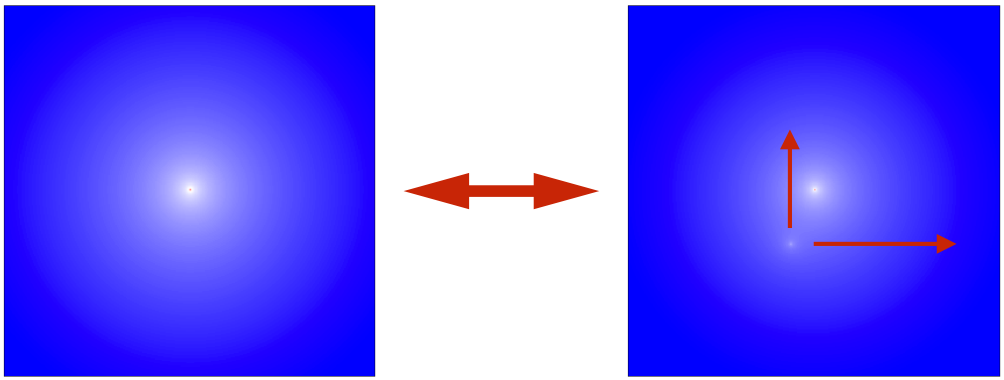
Birrer+ 2017

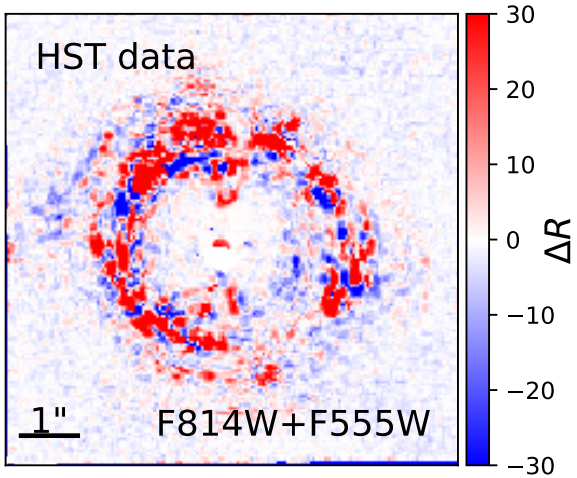
statistical analysis of gravitational imaging

control for limitations and uncertainties in the **source reconstruction**

Extract local deflection anomalies by a substructure **scanning process**







smooth preferred

clump preferred

Birrer+ 2017

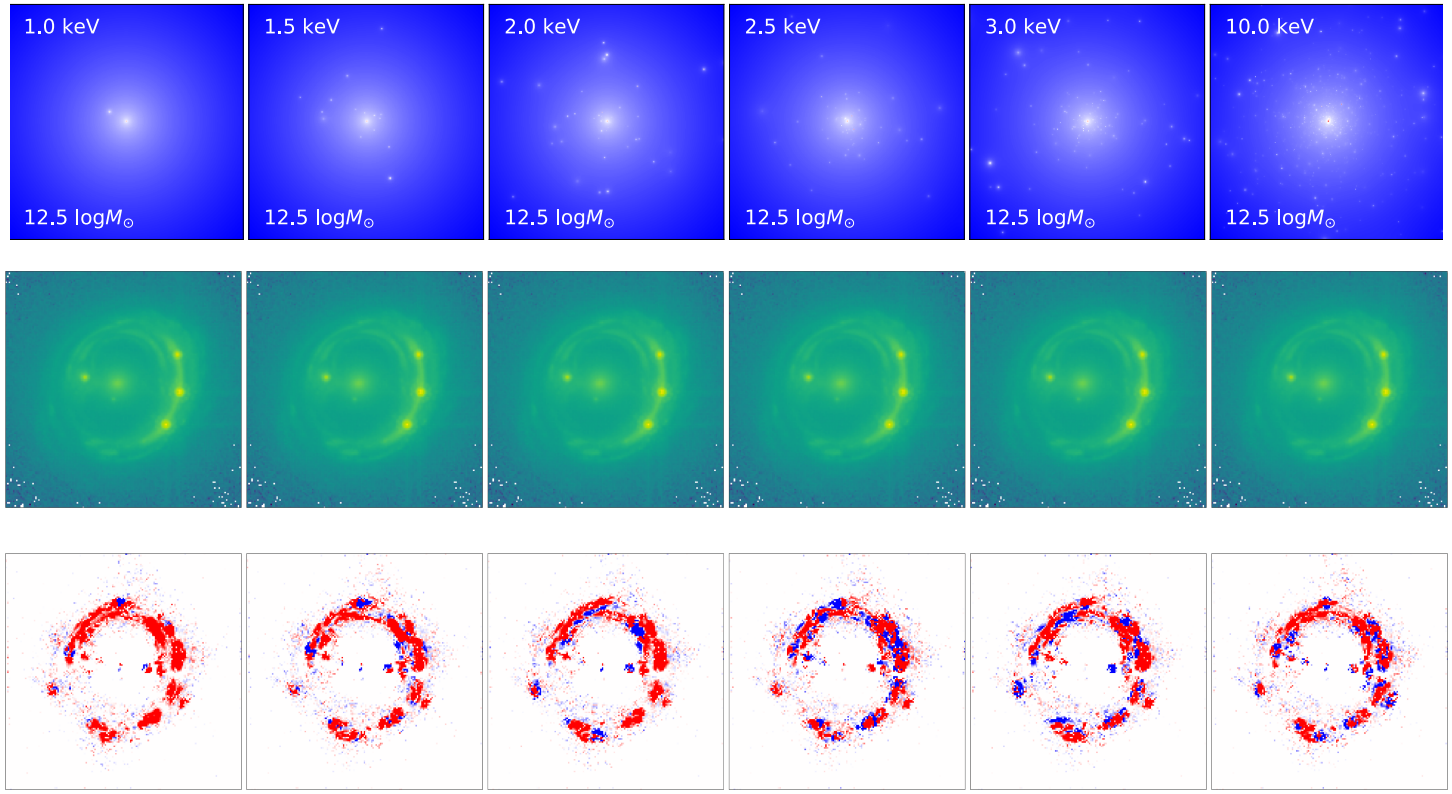
Birrer+ 2017

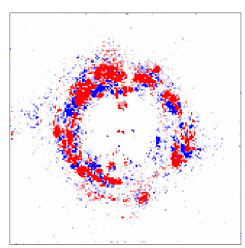
Dark Matter thermal relic mass constraints from lensing substructure

Turn a physical model stochastically into **simulated data**

look for the **same features** in your simulated data

Accept/reject simulations based on **summary statistics**



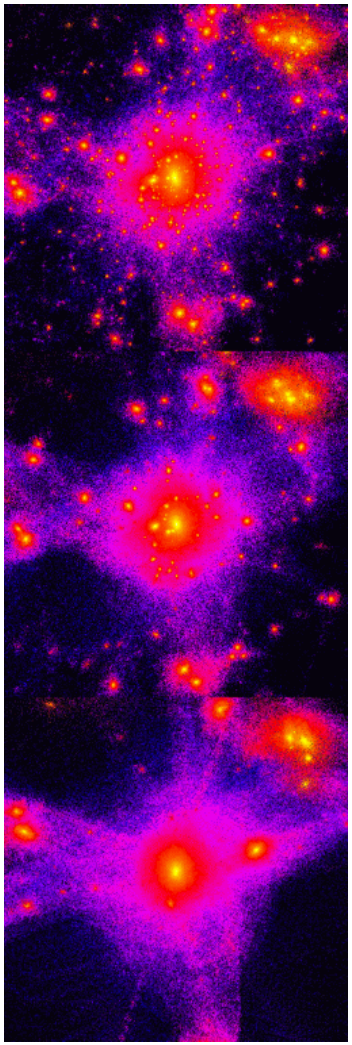


Approximate Bayesian Computing (ABC)

See also Daniel Gilman's talk on ABC for flux-ratio statistics

Birrer+ 2017

Dark Matter thermal relic mass constraints from lensing substructure



Birrer+ 2017

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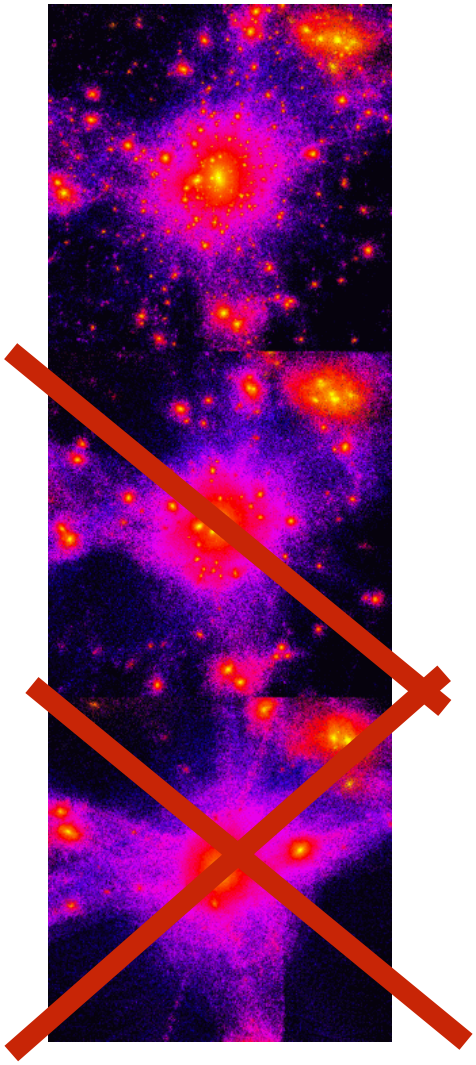

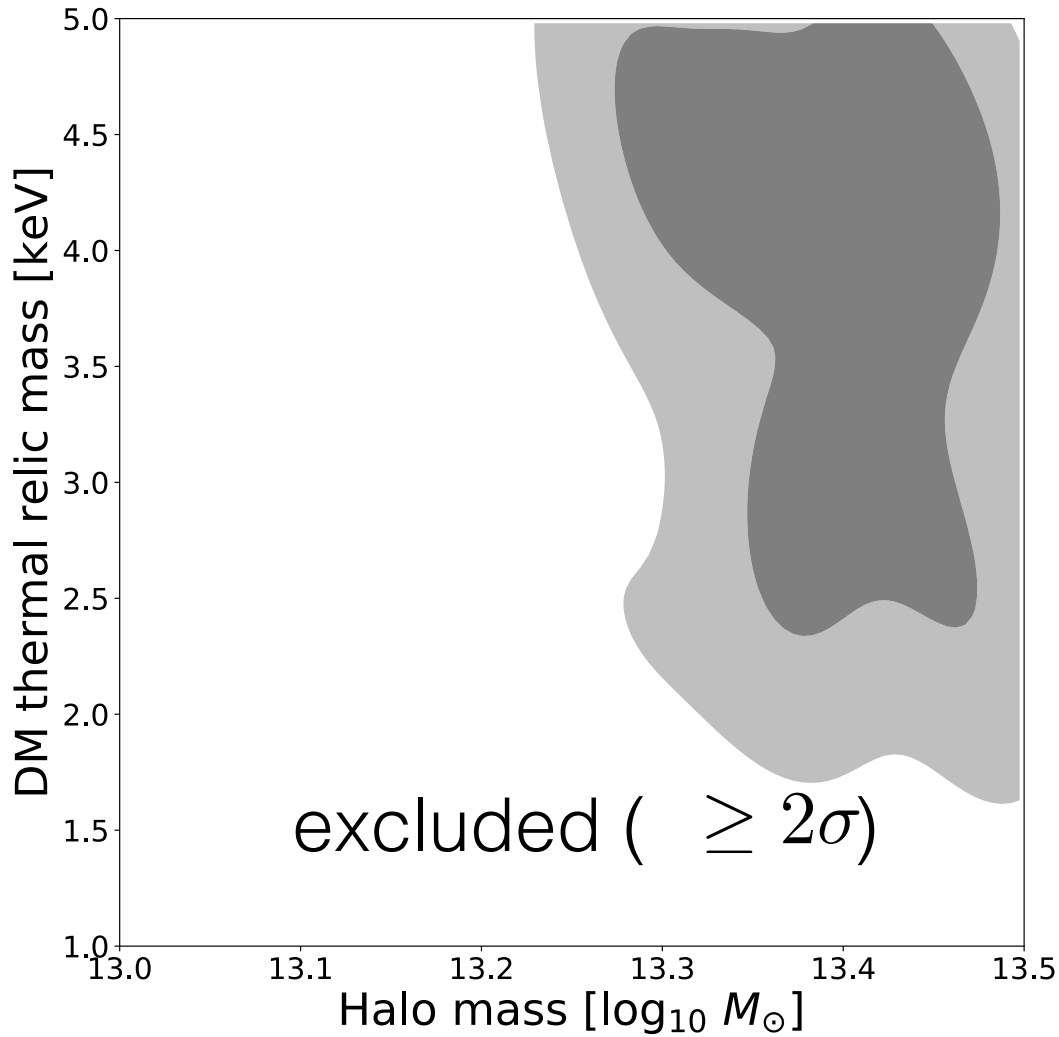

Birrer+ 2017

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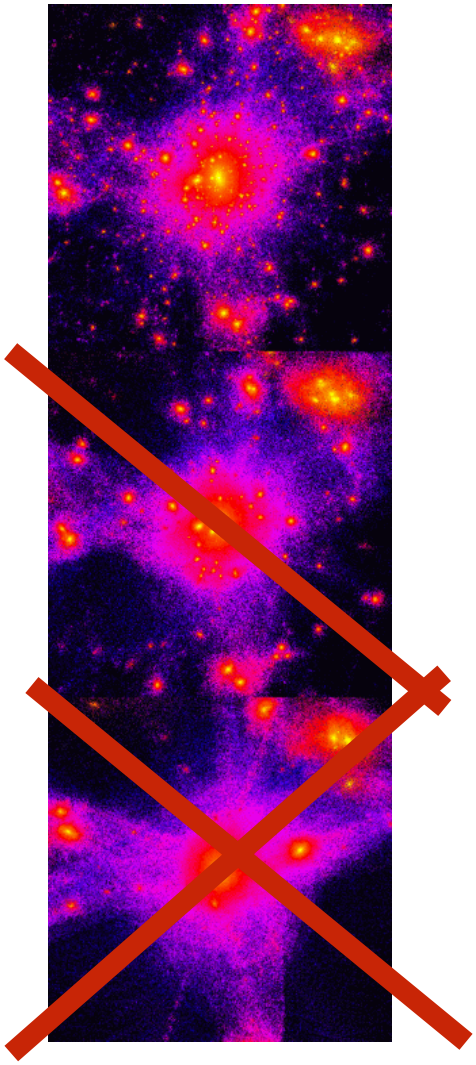
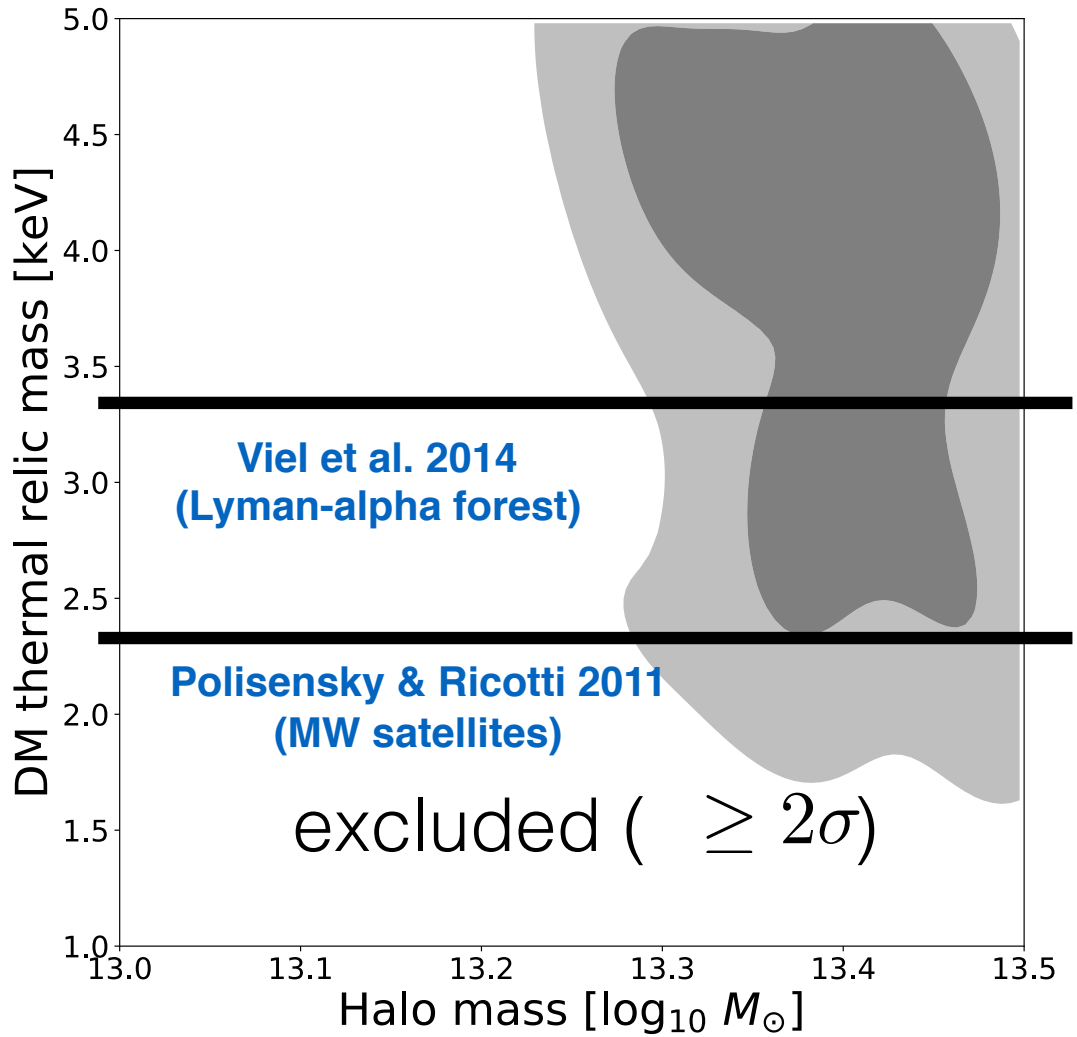
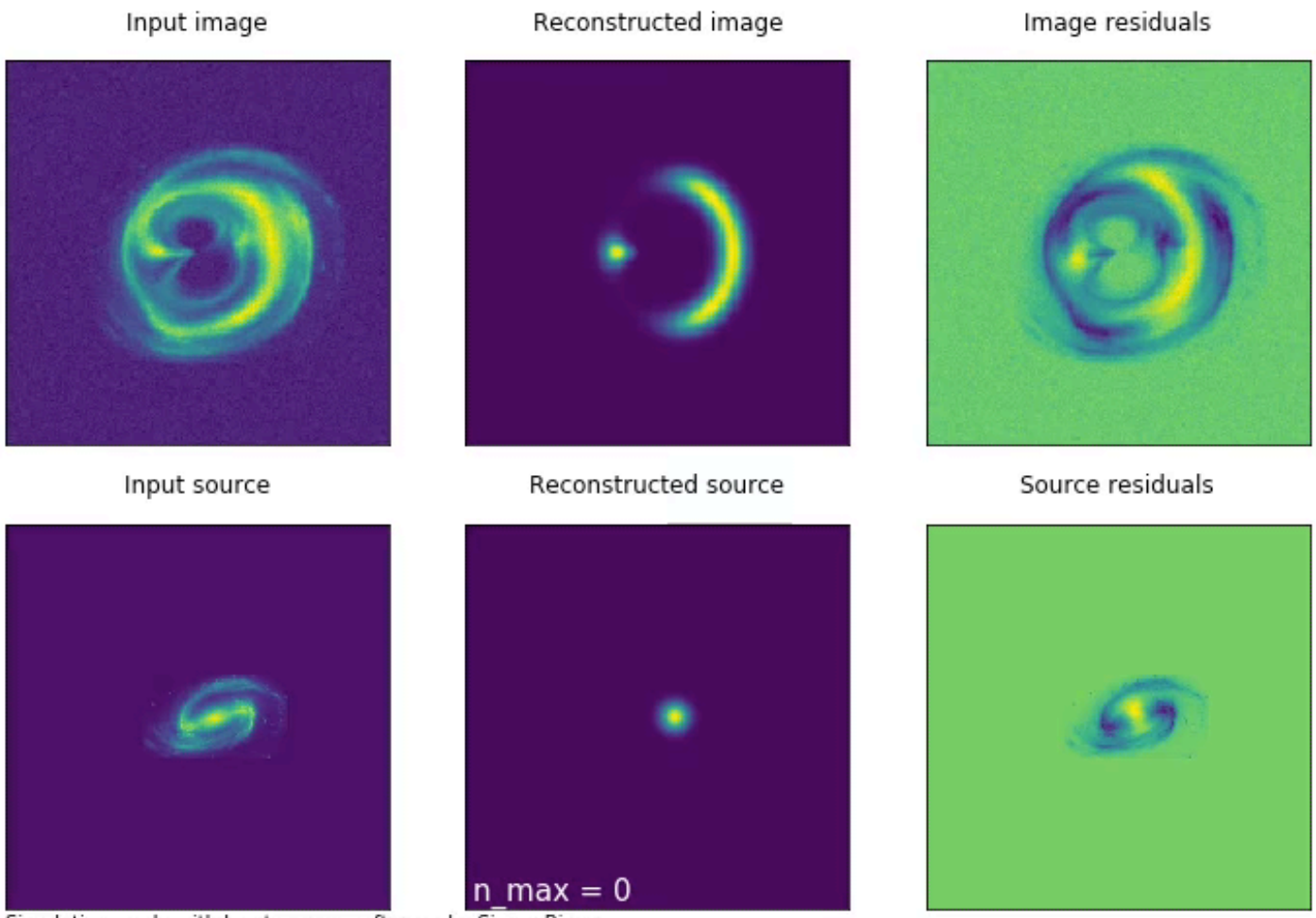




Birrer+ 2017

gravitational imaging in the ELT era



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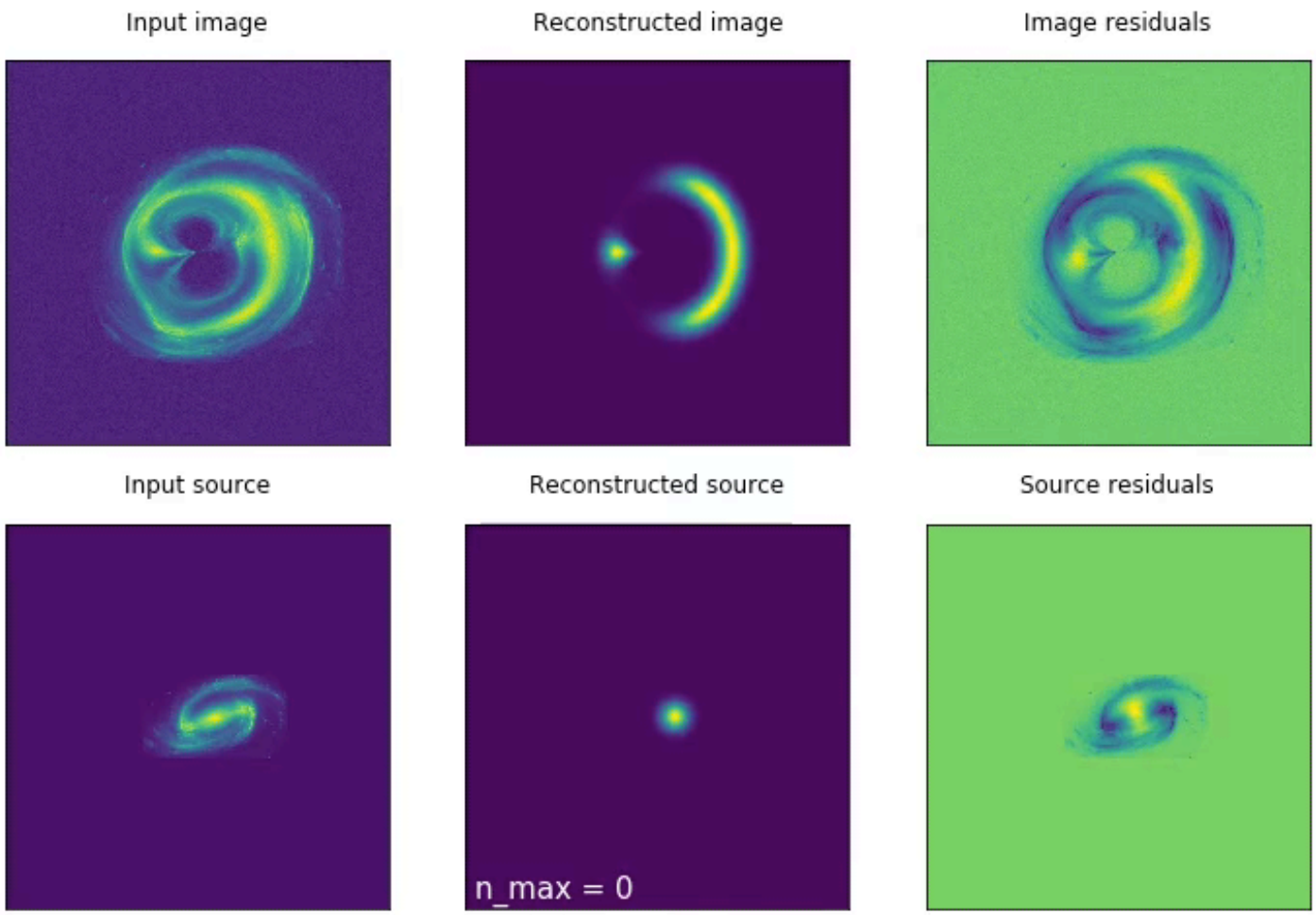
FWHM 0.05”

gravitational imaging in the ELT era



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FWHM 0.02”

The challenges

- line-of-sight contributions: *field halos in projection, non-linear lensing effects* **e.g. Despali+ 2017, …, Gilman, Birrer + in prep**

- luminous (sub) structure: *globular clusters, stellar discs, ..* **e.g Gilman+ 2017, Huesh+ 2016, …**

- precise predictions of (sub) halo properties: *dynamical friction, tidal stripping, resolution limit, computational cost, baryonic physics, …* **e.g. talk of James Bullock, …**

Data requirements

- imagine resolution optical/NIR imaging capabilities: *e.g. extreme AO on 30 meter class ground based telescope*

- **stability**: *we need to understand (and model) the data on the pixel level (incl. PSF and noise properties*

Summary

- Statistical constraints excludes a thermal relic mass < 2 keV to 2 sigma confidence level, based on one single lens of HST data
- Modelling and inference methods are in place. Software is publicly available
- Sample of high quality HST data is vastly increasing
- Enables joint constraints with flux ratio statistics
- ELT's with good and stable AO performance opens exciting discovery space


Thank you!
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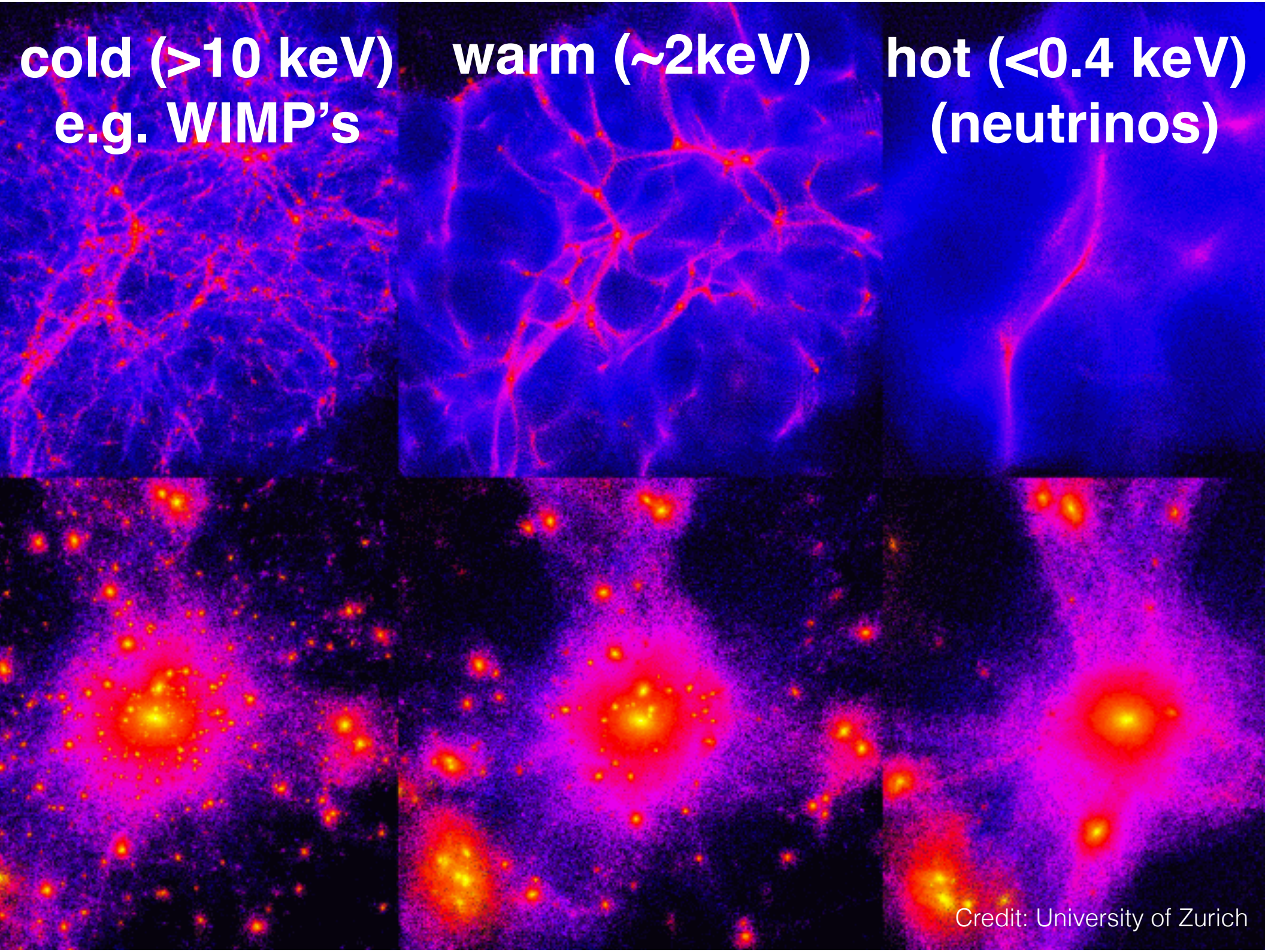
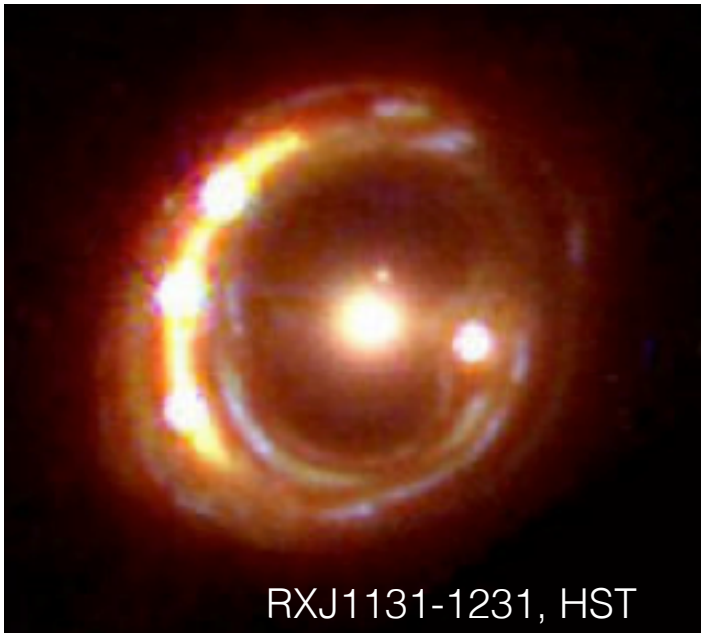

cold (>10 keV)
e.g. WIMP's
warm (~2keV)
hot (<0.4 keV)
(neutrinos)
Credit: University of Zurich

Strong gravitational lensing

Observables:
image positions + time delays



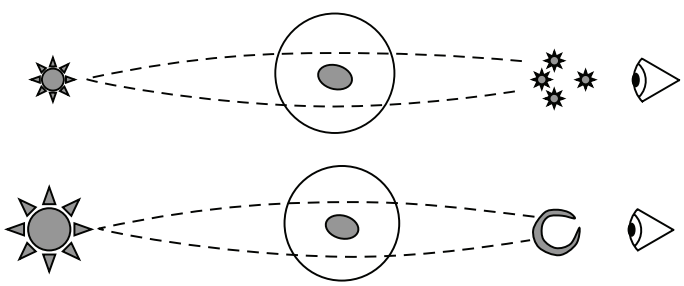
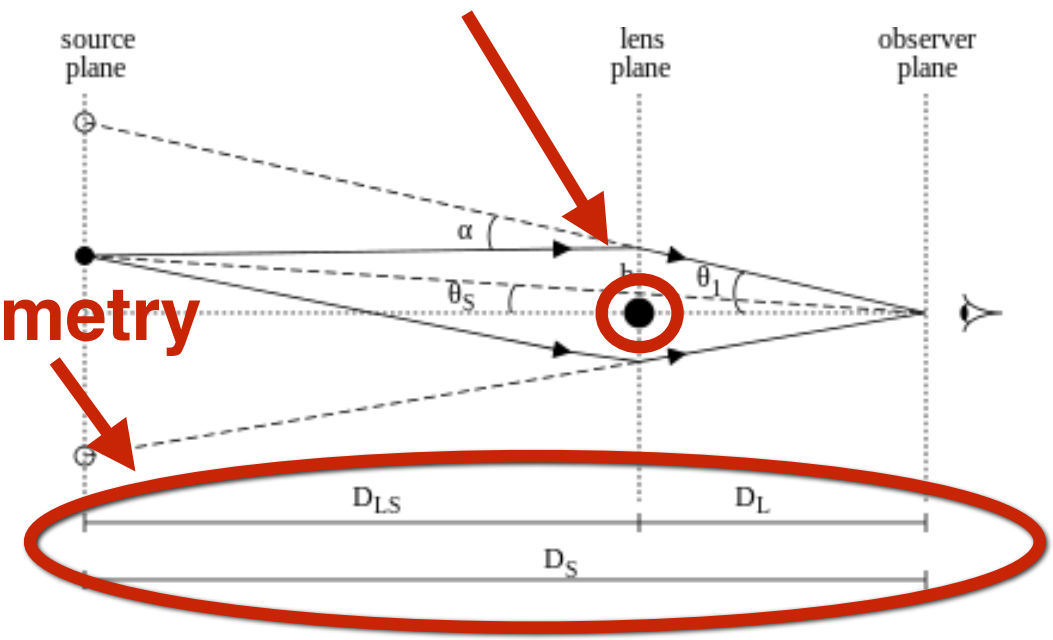


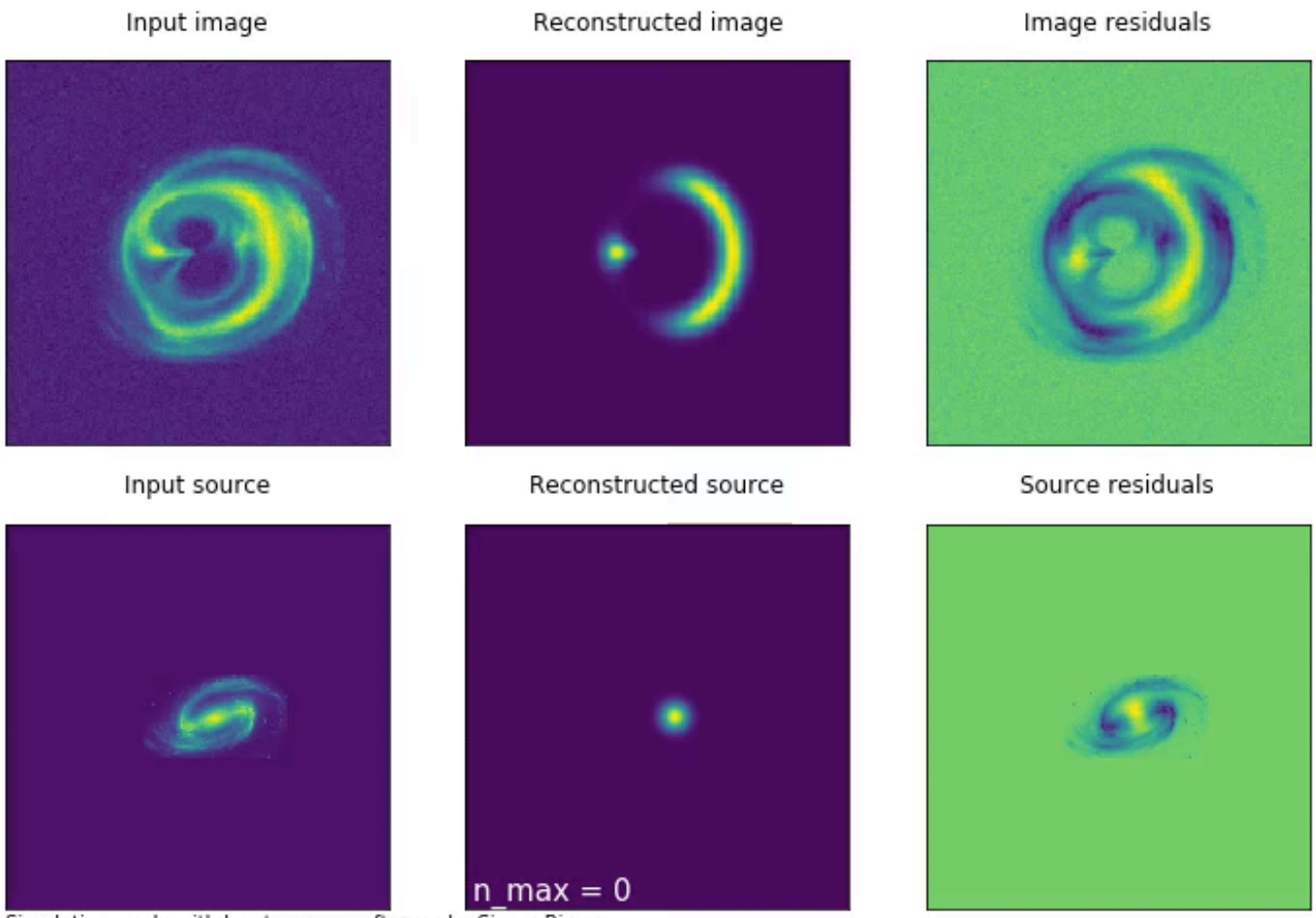
Illustration: Zachrisson & Riehe 2009

total mass

geometry



gravitational imaging in the ELT era



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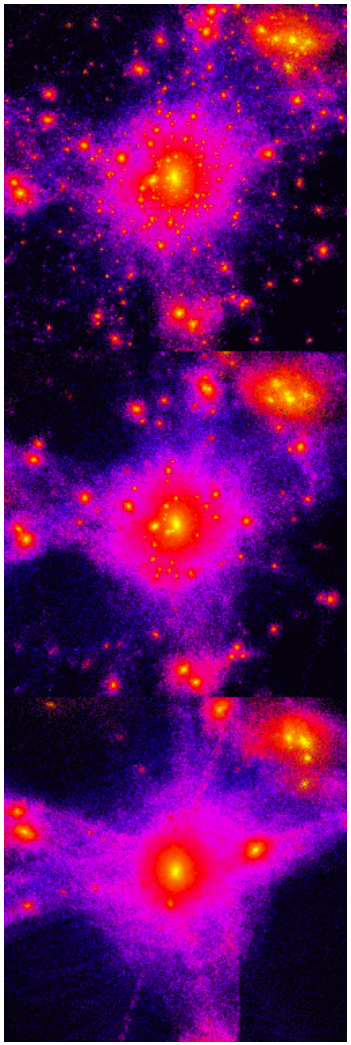
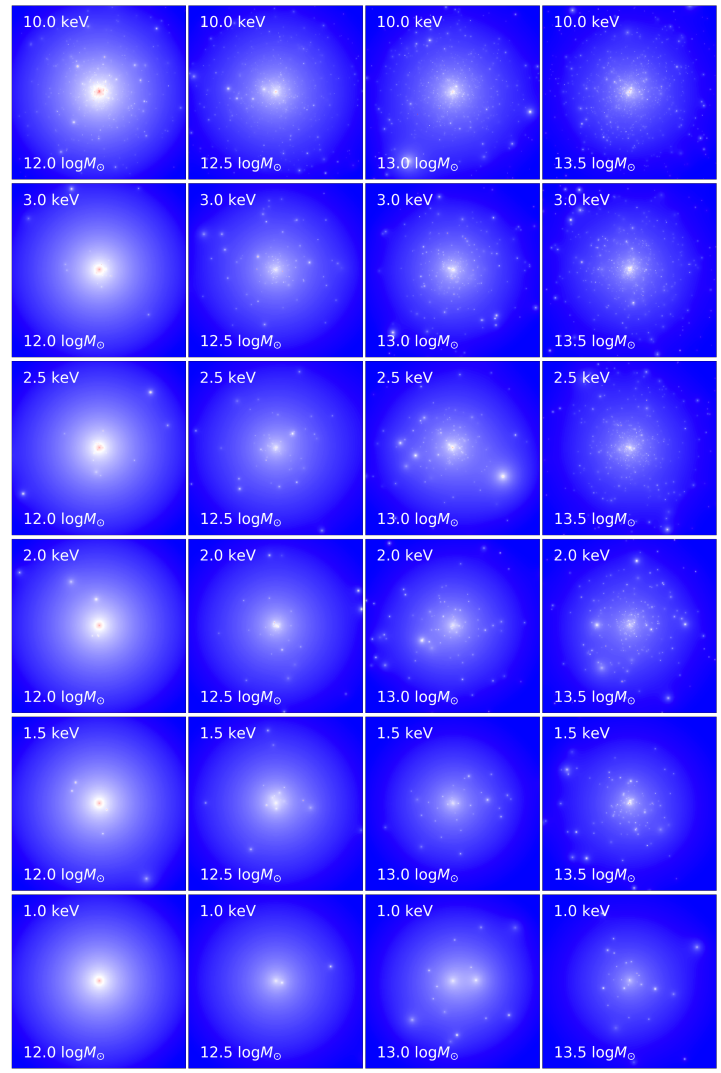


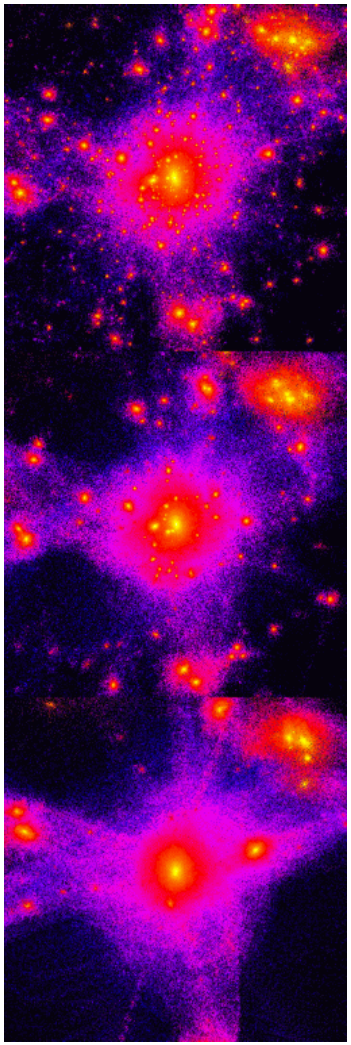
compare with **simulations** of different DM models

-power-spectra based
-merger tree tuned to simulations
-disruption description tuned to simulations
-radial distribution based on infall trajectories tuned to simulations



Birrer+ 2017

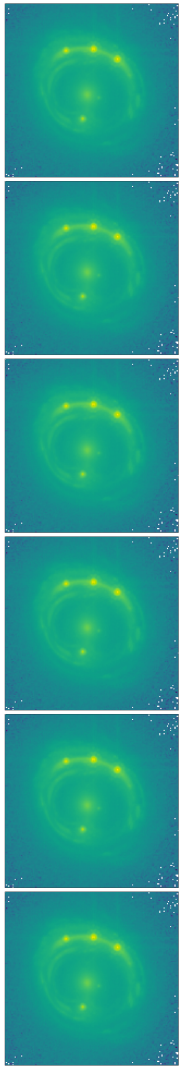
Dark Matter thermal relic mass constraints from lensing substructure



Birrer+ 2017

Turn simulations into images

- **same** macro-model
- **same** source surface brightness
- **same** noise and PSF as data
- **different** small scale lens model



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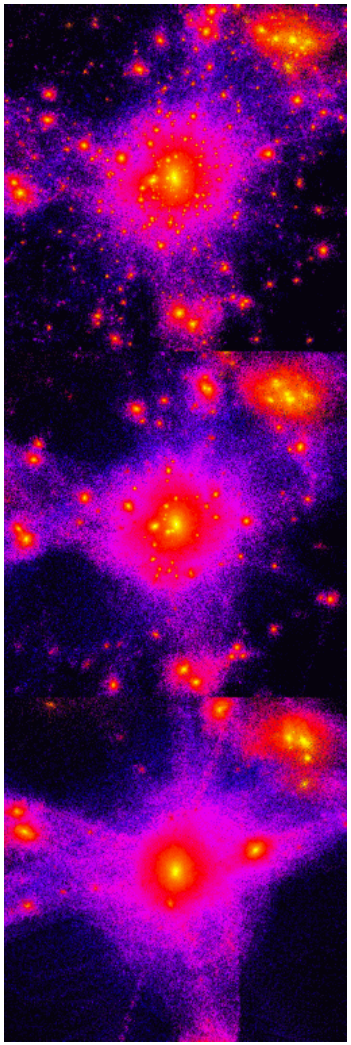
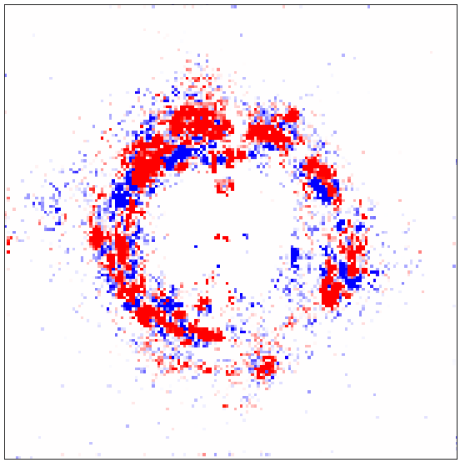


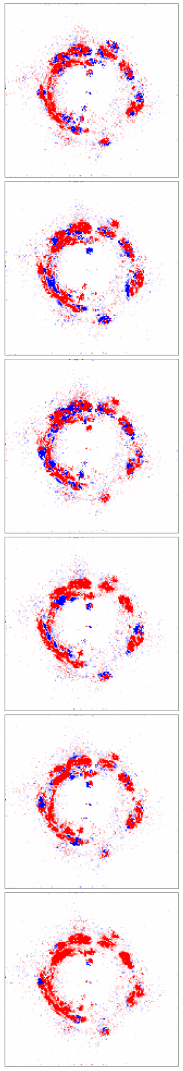
Birrer+ 2017

Perform a sub-clump scanning procedure



smooth preferred

clump preferred



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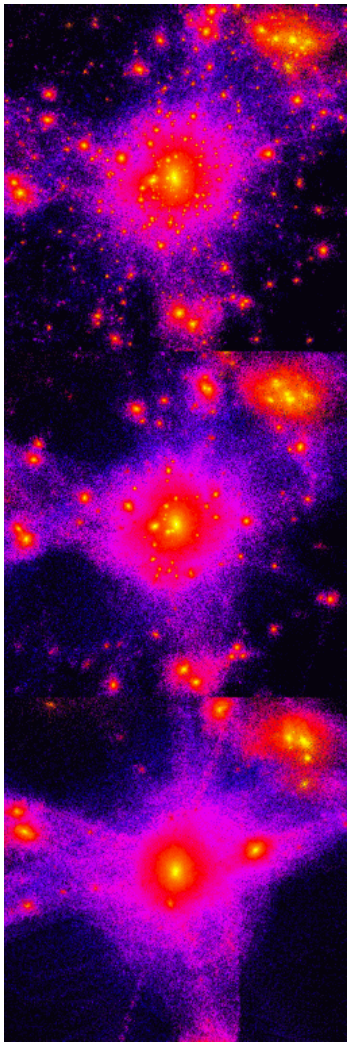
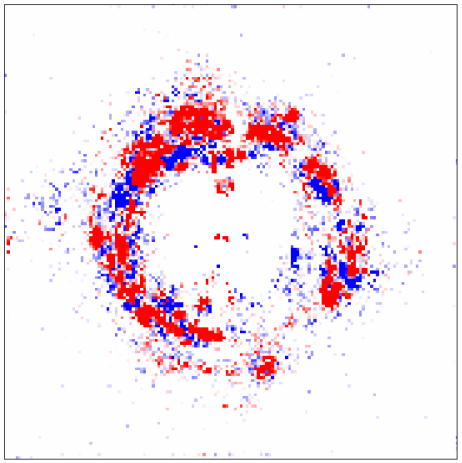


Birrer+ 2017

Accept/reject simulations based on summary statistics



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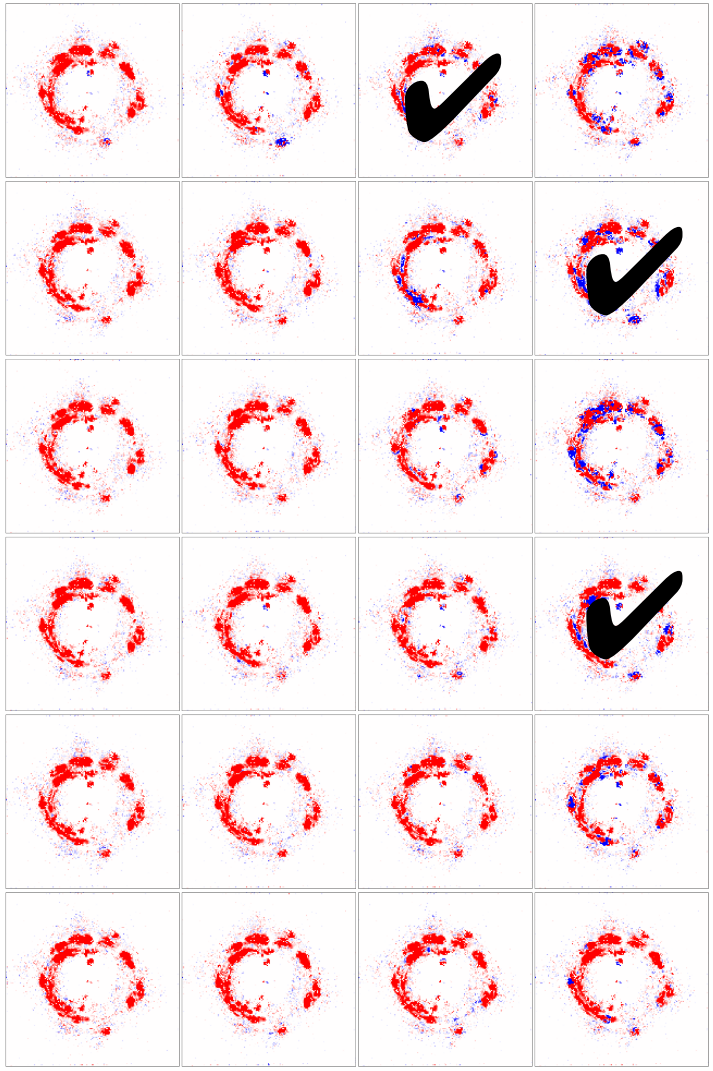

Approximate Bayesian Computing (ABC)