Statistics of flux ratios in strong lenses: probing of dark matter on small scales

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With: Simon Birrer, Tommaso Treu, Anna Nierenberg, Chuck Keeton, Andrew Benson

image: ESA/Hubble, NASA, Suyu et al.

CDM:

- structure on all scales; plethora of halos < 10^8 solar masses

WDM:

- no structure below a ‘free streaming’ scale

Self-interacting DM:

- cored density profiles

How do flux ratios help us tell the difference?

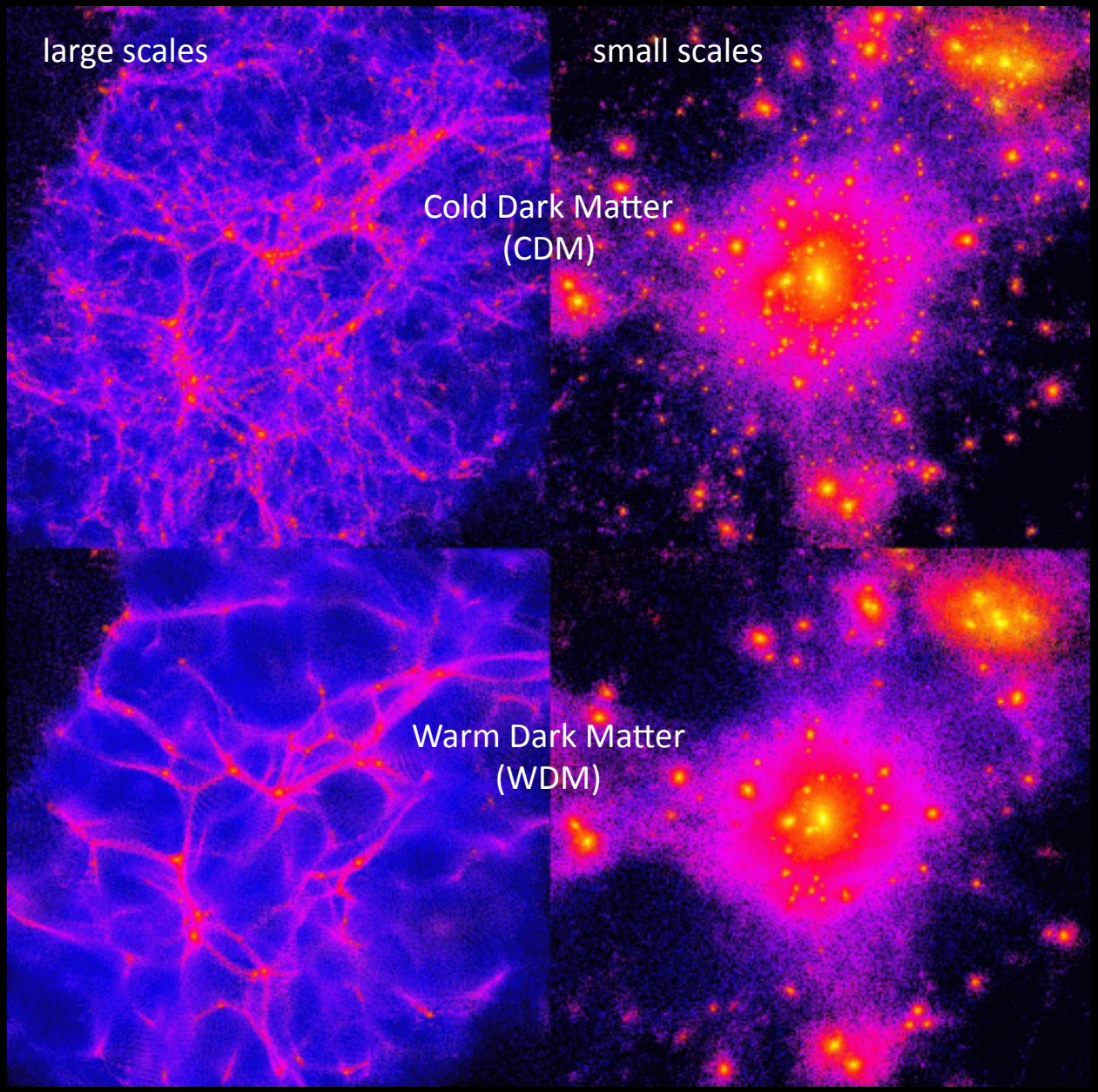
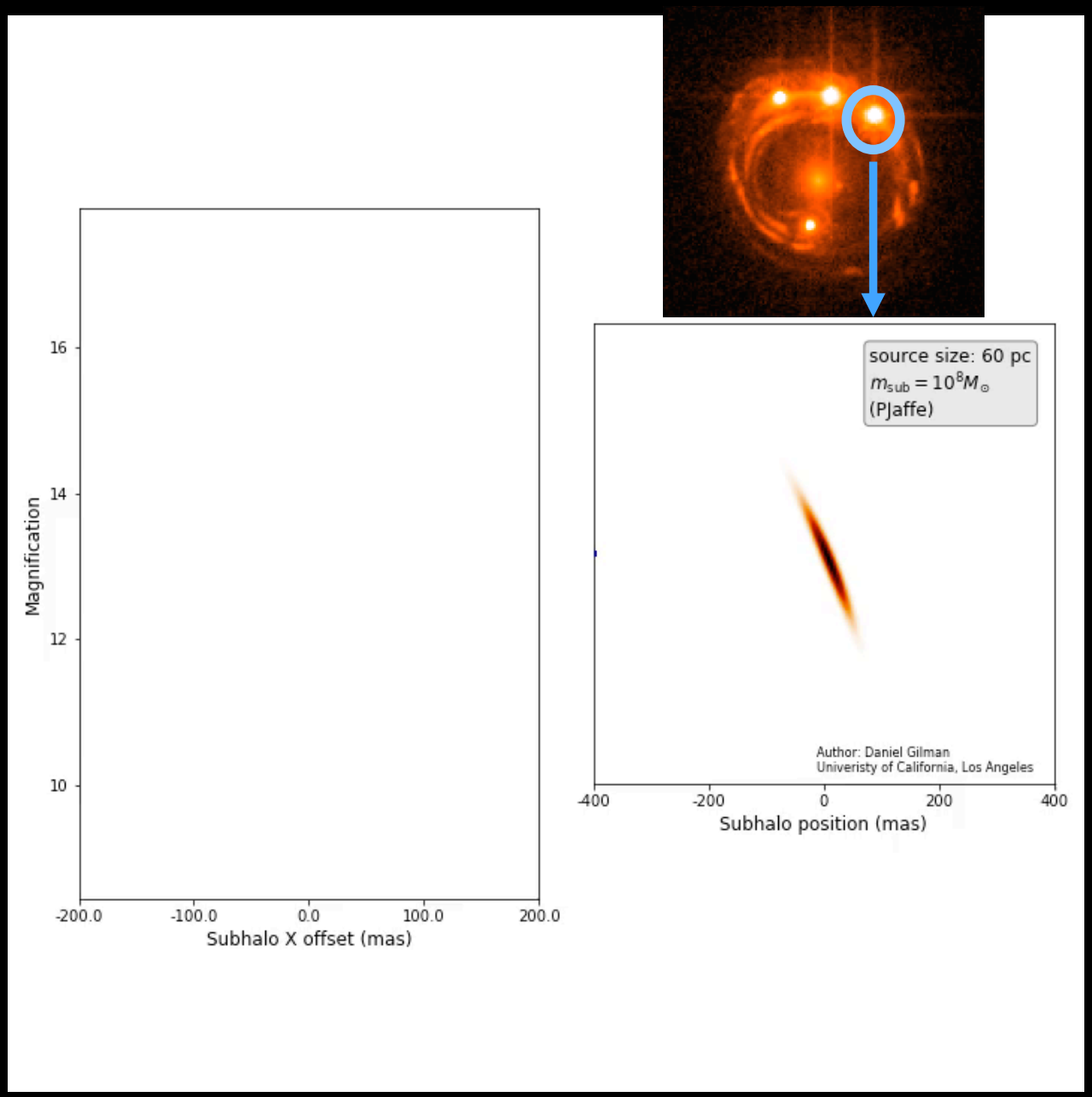


image credit: ITC @ University of Zurich

Image magnifications probe structure on small scales

Massive, dense objects the the most efficient lenses.

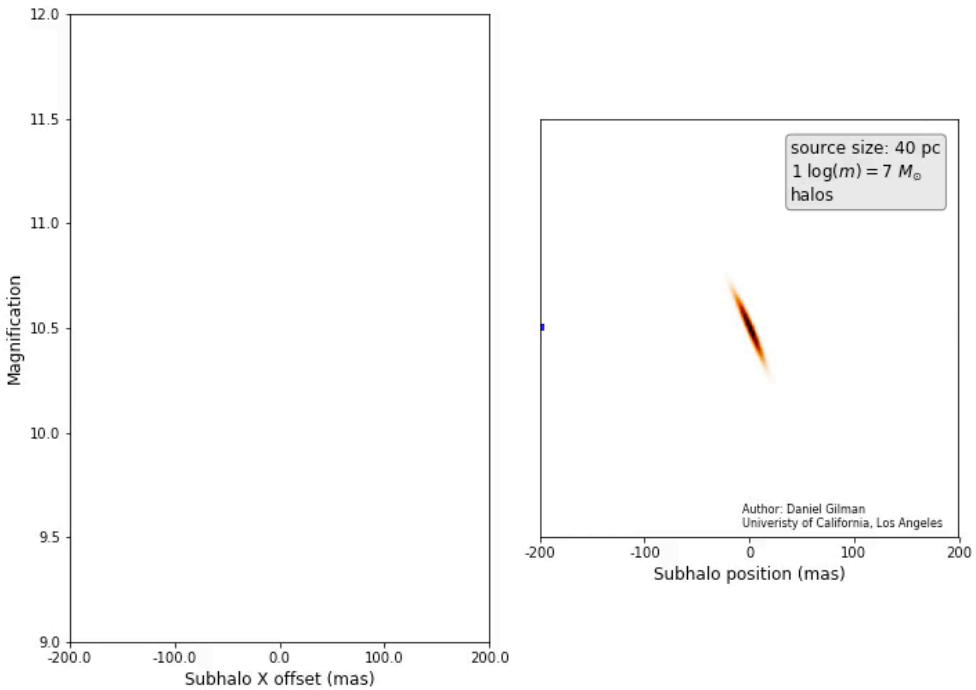
example: 10^8 solar mass isothermal perturber



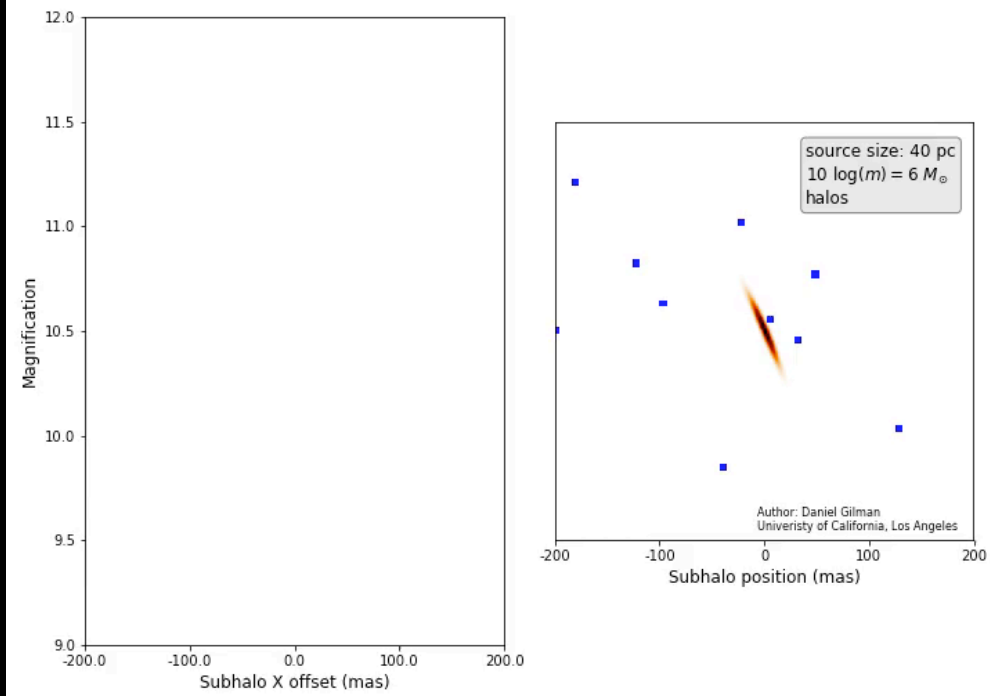
Subhalos are believed to be less dense (NFW)

Flux ratios are non-linear: multiple (smaller) subhalos can boost the signal

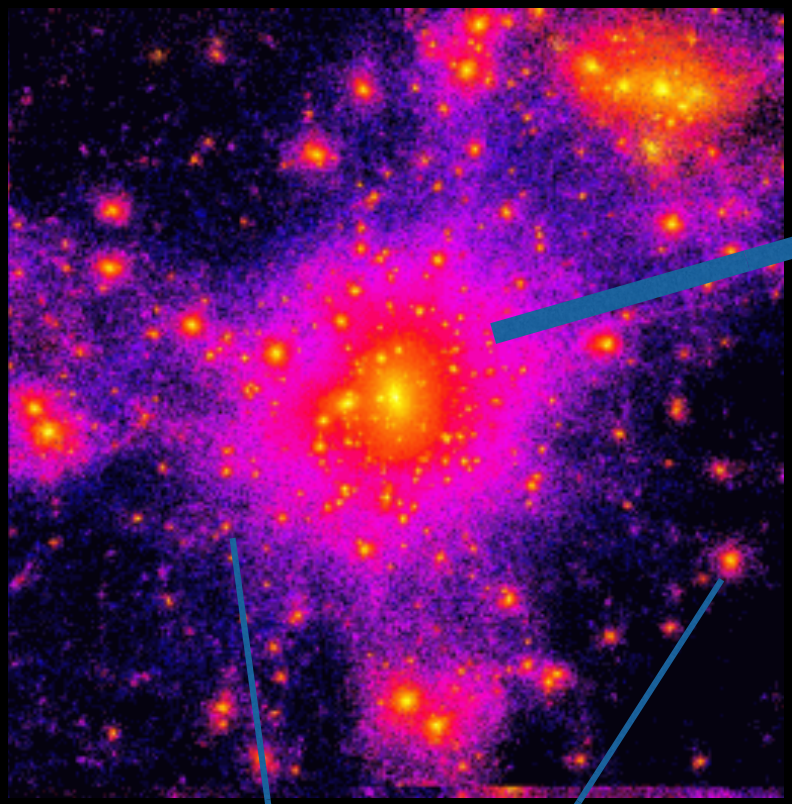
10^7 solar mass NFW halo



10 x 10^6 solar mass NFW halos



Modeling strong lenses

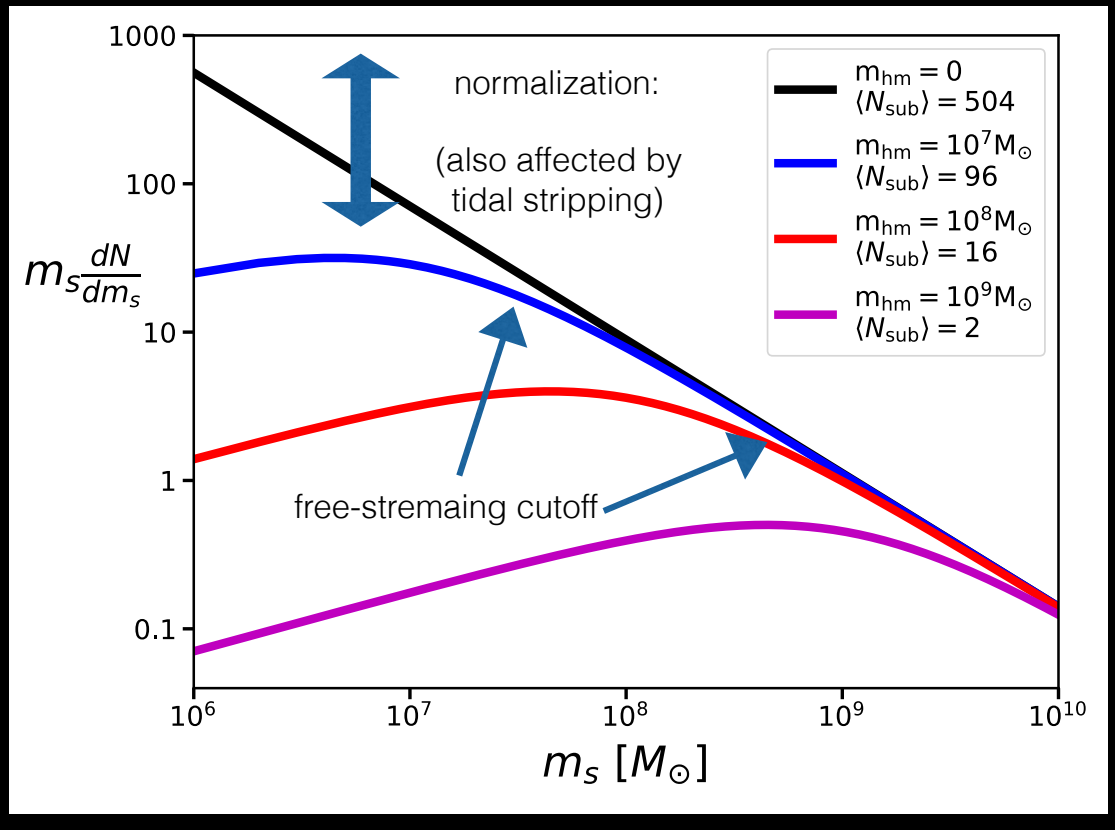


"macromodel":

- luminous galaxy + smooth dark matter field + external shear
- 99% of the deflecting mass; image positions, time delays

dark substructure:

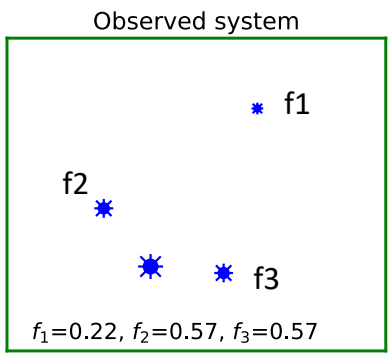
- strongly perturb the fluxes
- dark matter theories predict normalization, shape of mass function



Forward modeling procedure

1. observe positions, time delays, flux ratios

Forward modeling flux ratios step-by-step (1)

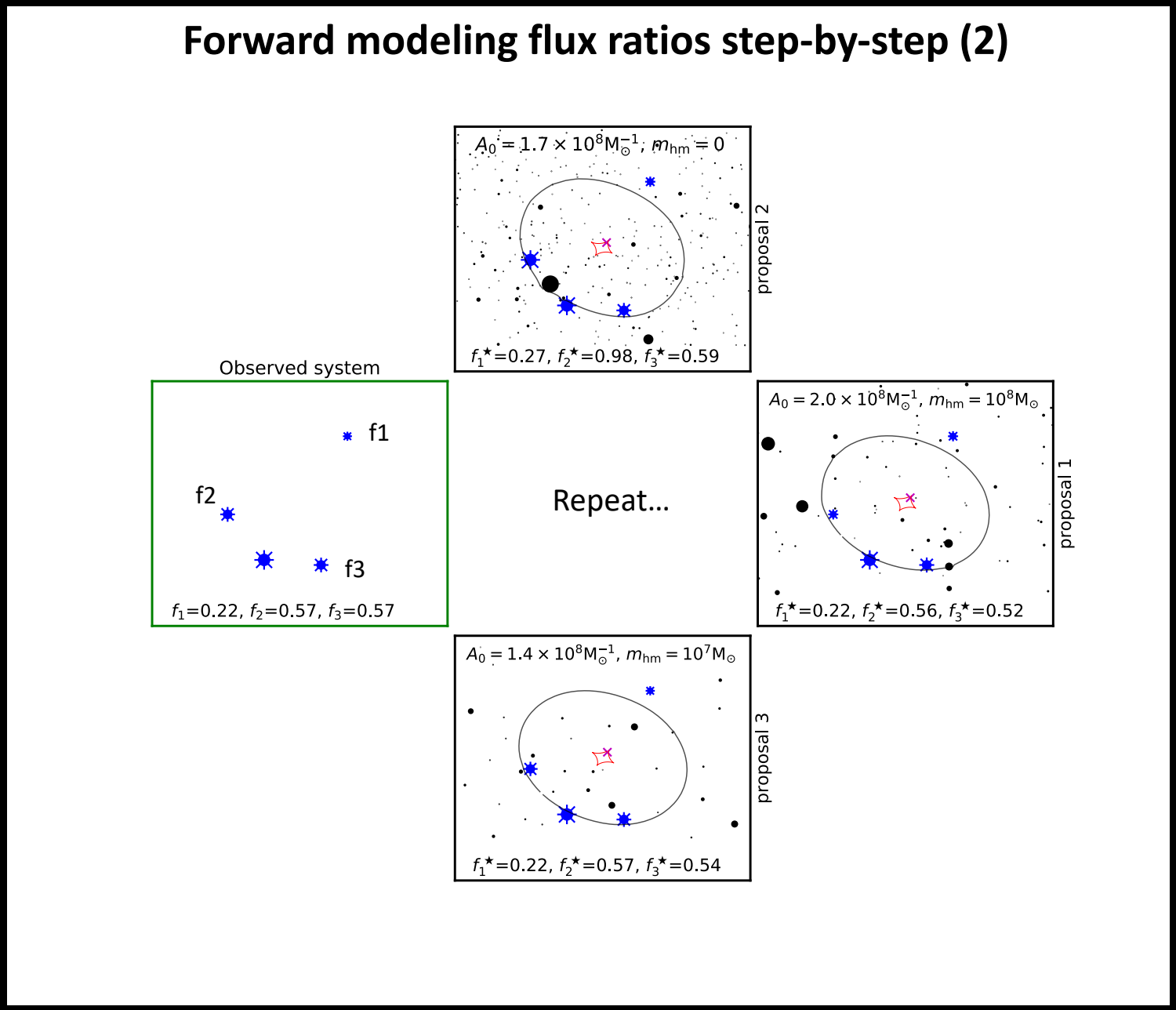


Forward modeling procedure

1. observe positions, time delays, flux ratios
2. Render substructure realization
   A. re-fit macromodel to positions
   B. compute model flux ratios

Forward modeling flux ratios step-by-step (2)

Forward modeling procedure



1. observe positions, time delays, flux ratios
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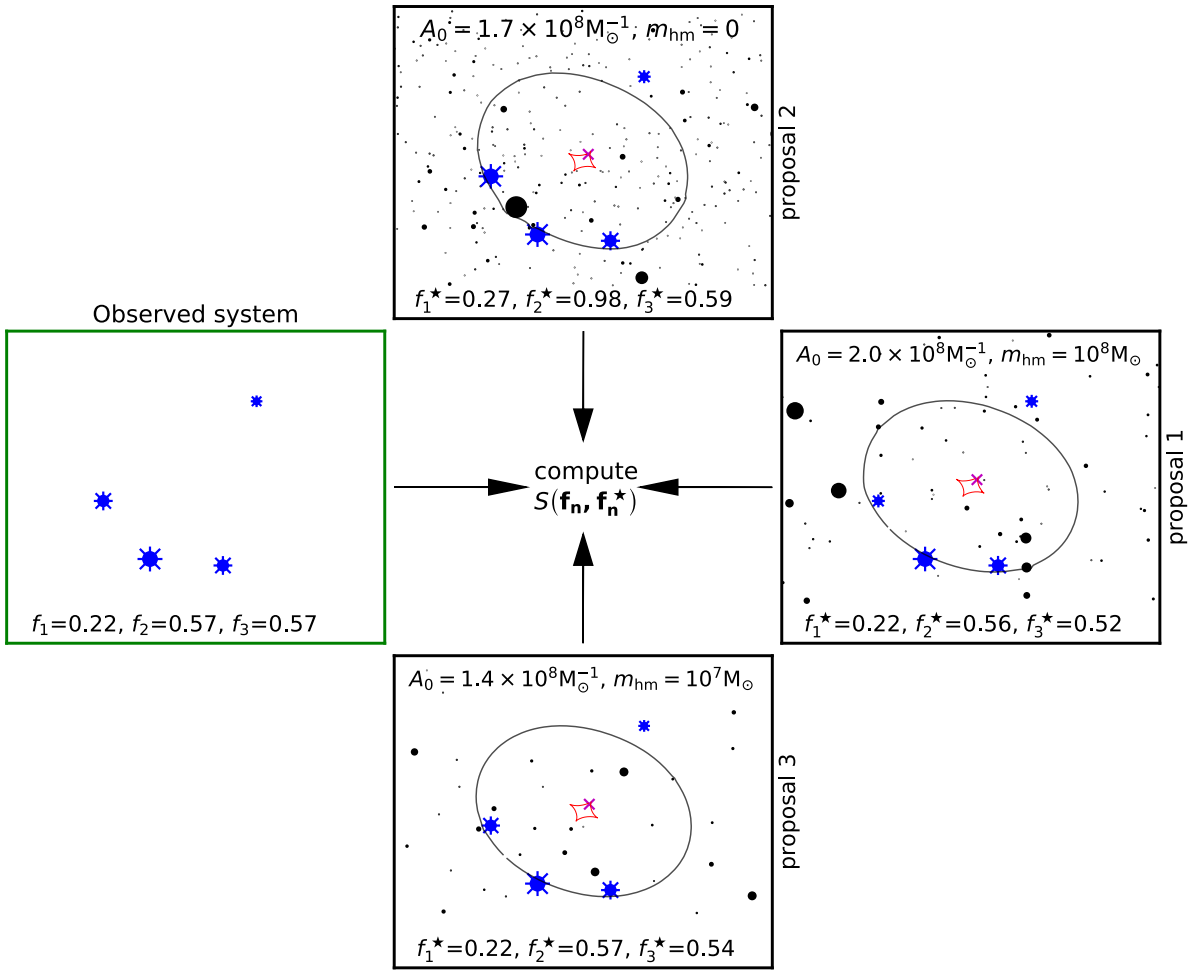
3. repeat 840,000 times per lens…

5.

Forward modeling procedure

Forward modeling flux ratios step-by-step (3)



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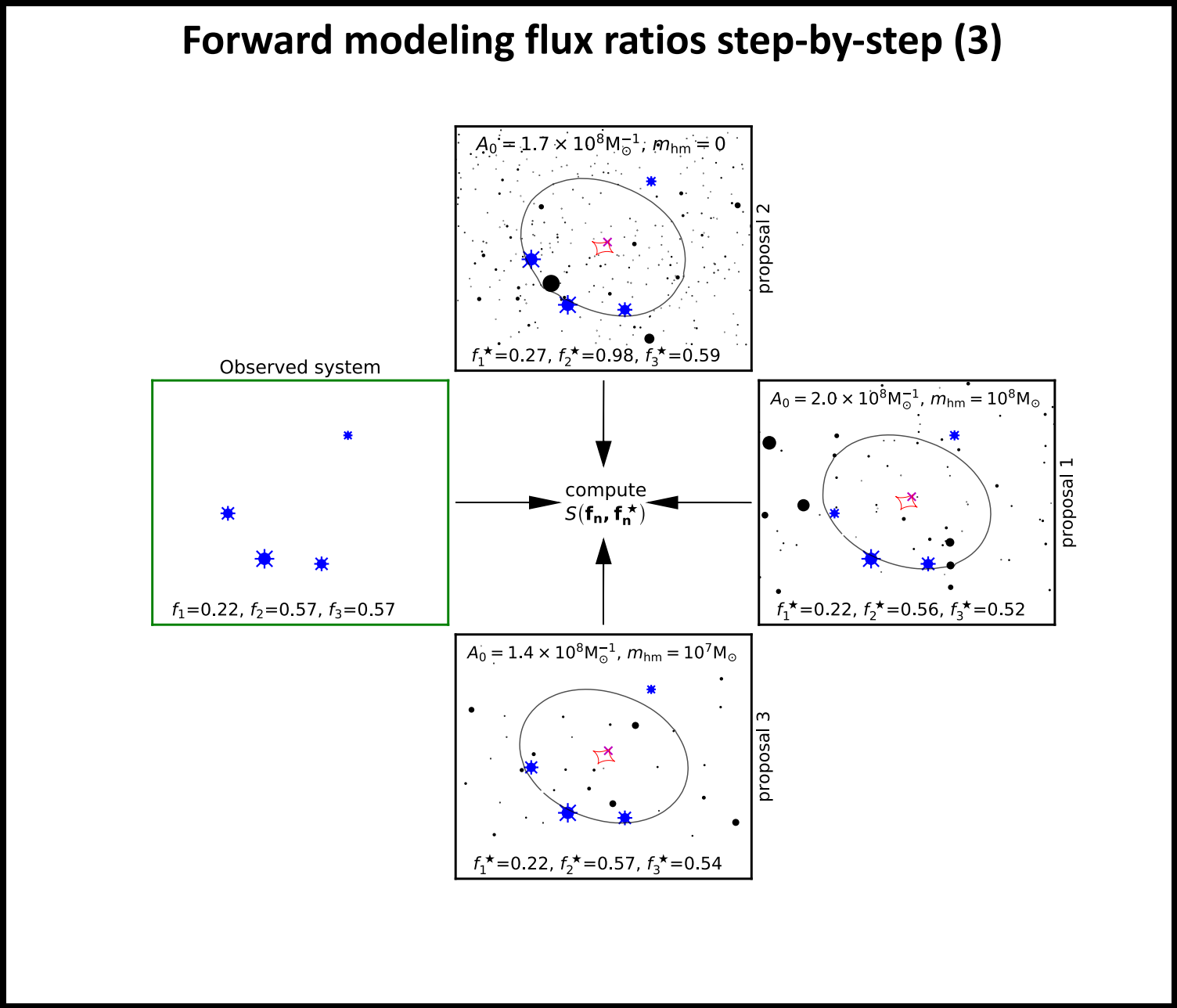
4. compute a summary statistic:

$$S(\mathbf{f_n}, \mathbf{f_n}^\star) = \sqrt{\sum_{i=1}^{3} \left(f_{n(i)} - f^\star_{n(i)}\right)^2}$$

observed flux ratio

model flux ratio

Forward modeling procedure



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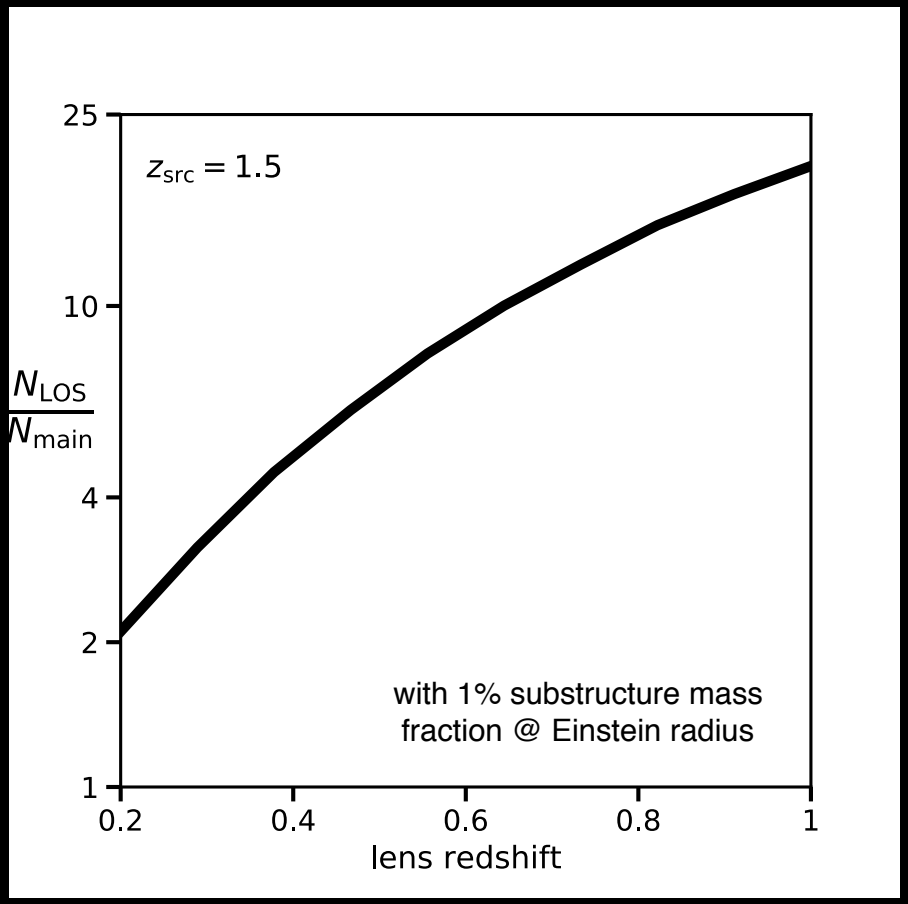
5. select based on summary statistic

Note: for now we are considering only lens plane halos

- the line of sight is important and boosts the signal!
(see e.g. Despali et al 2018)

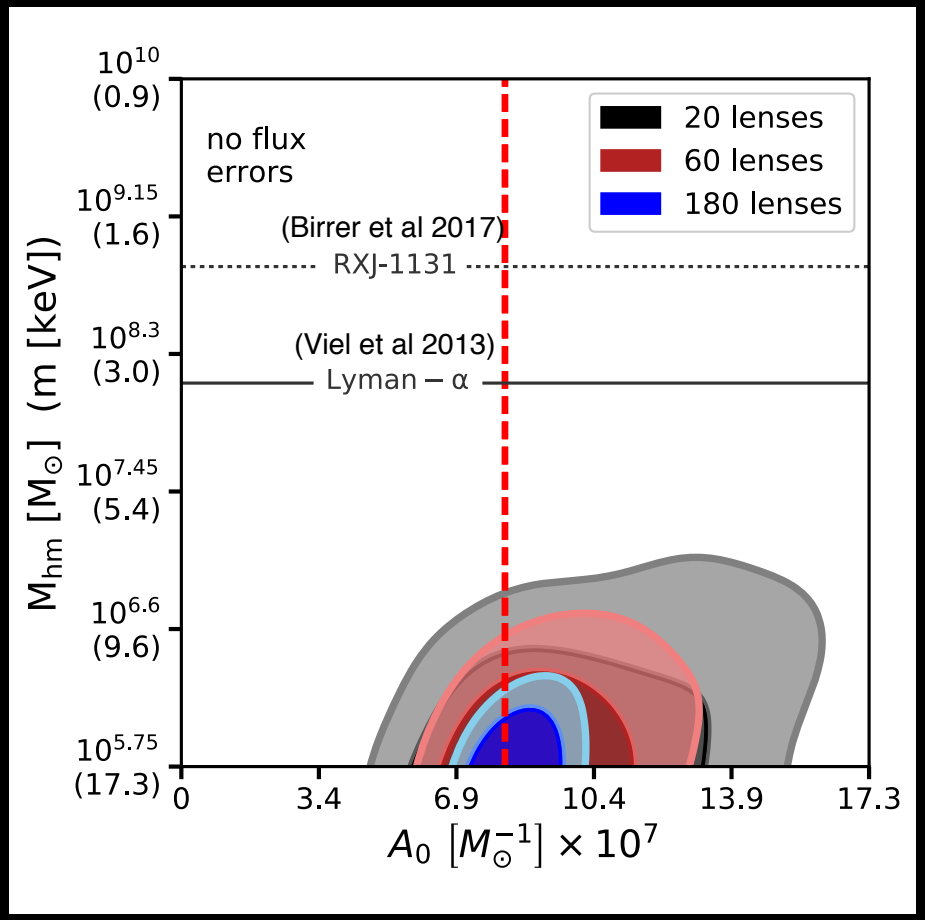
- By omitting the extra signal from the LOS our projected constraints are lower limits



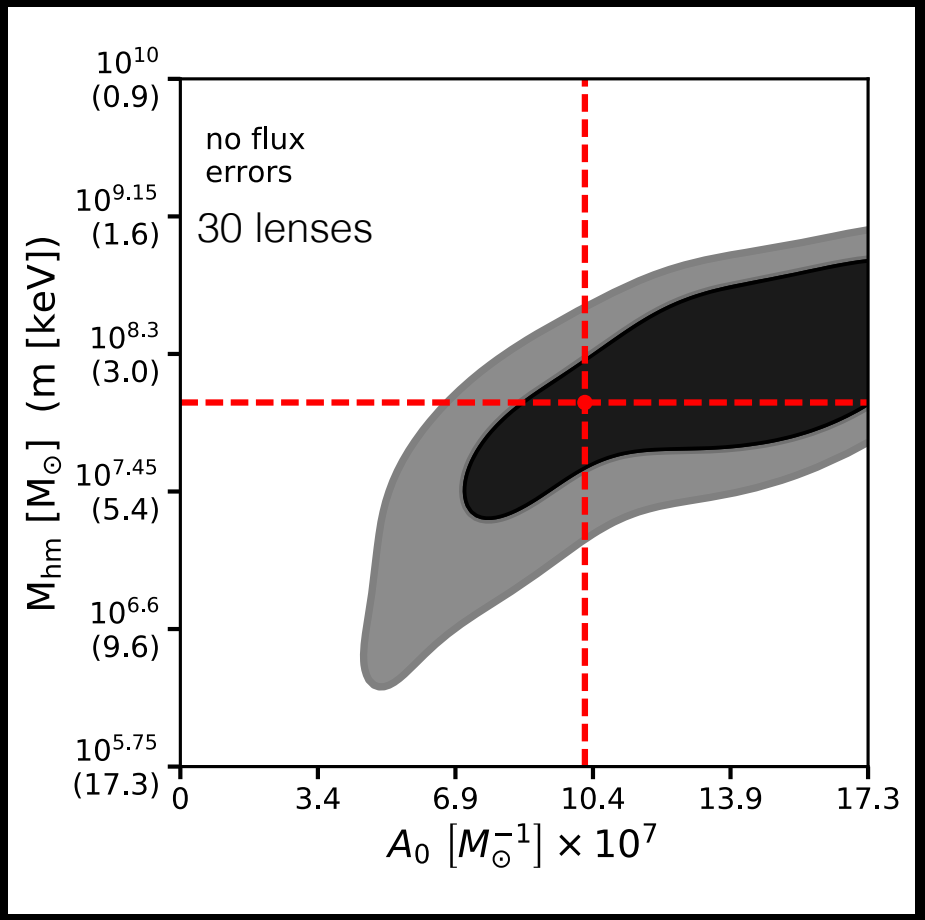
Does this method work, in principle?

Mock data: SIE+shear, plus substructure

CDM



WDM



But what about more realistic lens models?

Towards more realistic lenses

- We distinguish between dark matter mass functions through flux ratios computed w.r.t. a macromodel

  An accurate macromodel (and no microlensing) is therefore crucial!

- SIE+shear can yield incorrect fluxes at the percent level (Gilman et al 2017, Hsueh et al 2017)

Magnification residuals w.r.t. SIE

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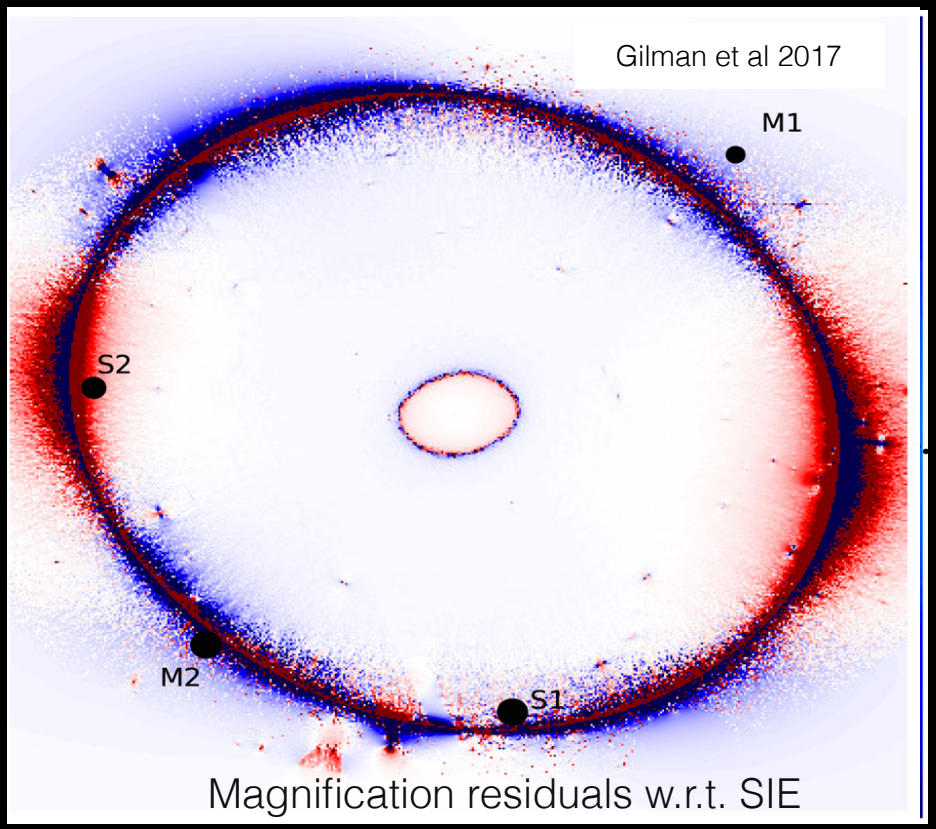
Example (right): Surface mass density of Virgo galaxy VCC1062 plus NFW halo (turned strong lens @ z = 0.5)

How can we handle these uncertainties?



Towards more realistic lenses; handling uncertainties

1. **Modeling**: Include additional features (e.g. the power law slope) in the forward model

   - can also explicitly model features like disks (e.g. Hsueh et al 2016, 2017)

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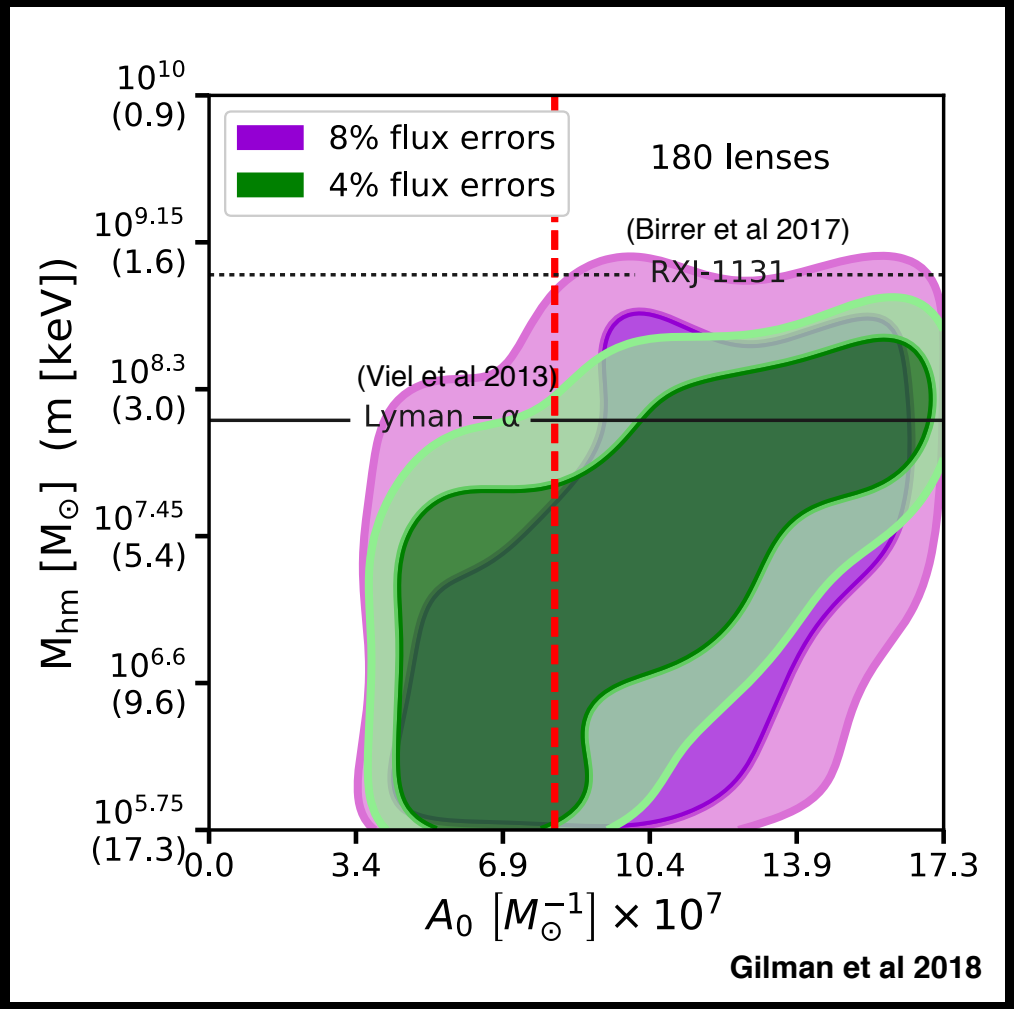
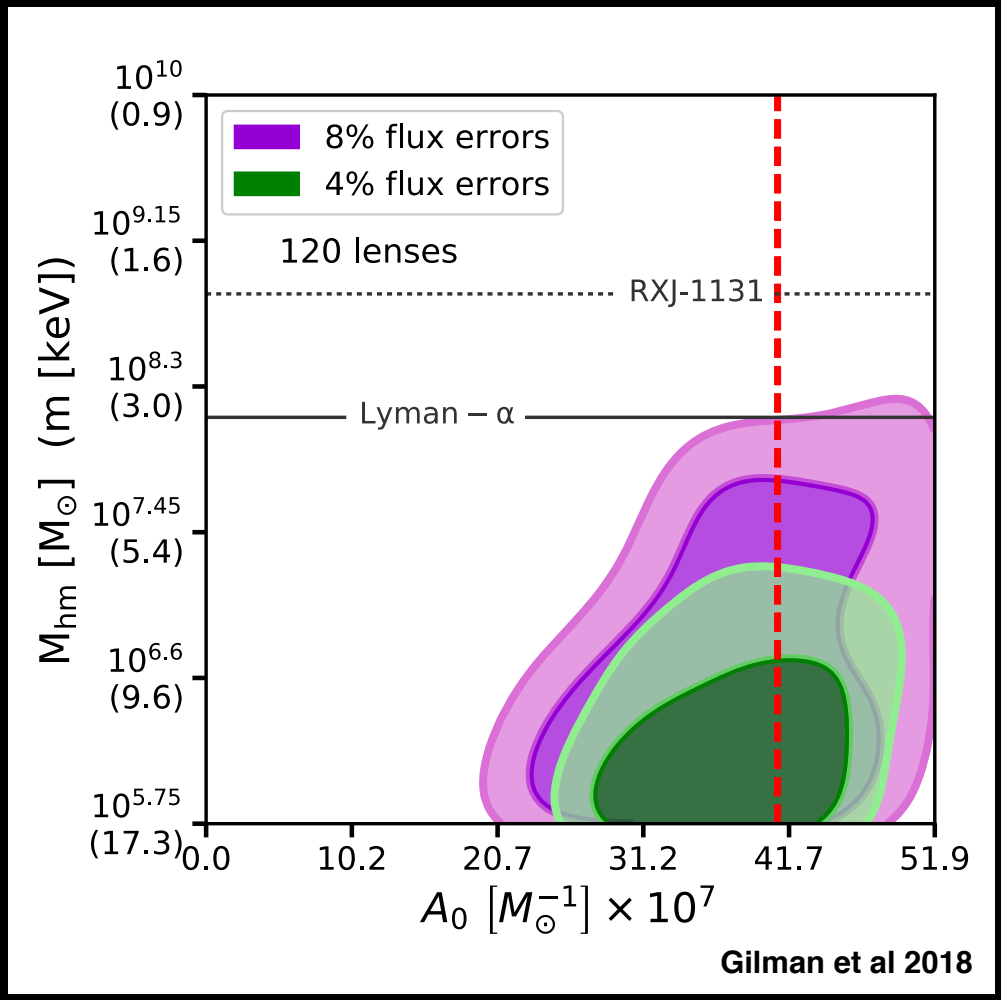
How does the precision of the inference change after introducing uncertainties in flux ratios?

Inference with flux perturbations in mock data, forward model

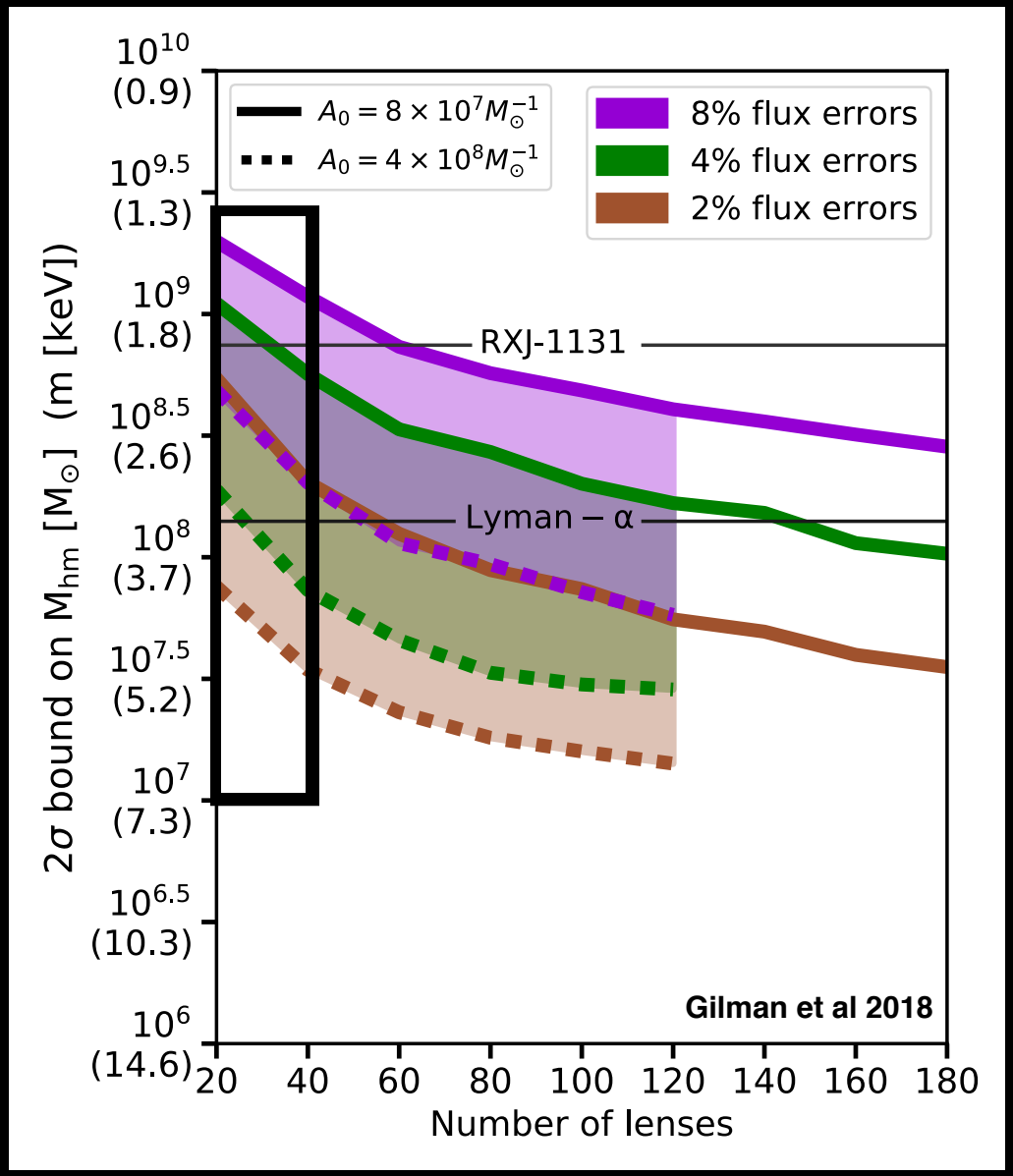




Normalization: 10^13 mass parent halo; **all** subhalos within scale radius destroyed by tidal effects

Normalization: 10^13.5 parent halo; **~50%** of subhalos within scale radius destroyed

The Future…


$A_0 = 8 \times 10^7 M_\odot^{-1}$
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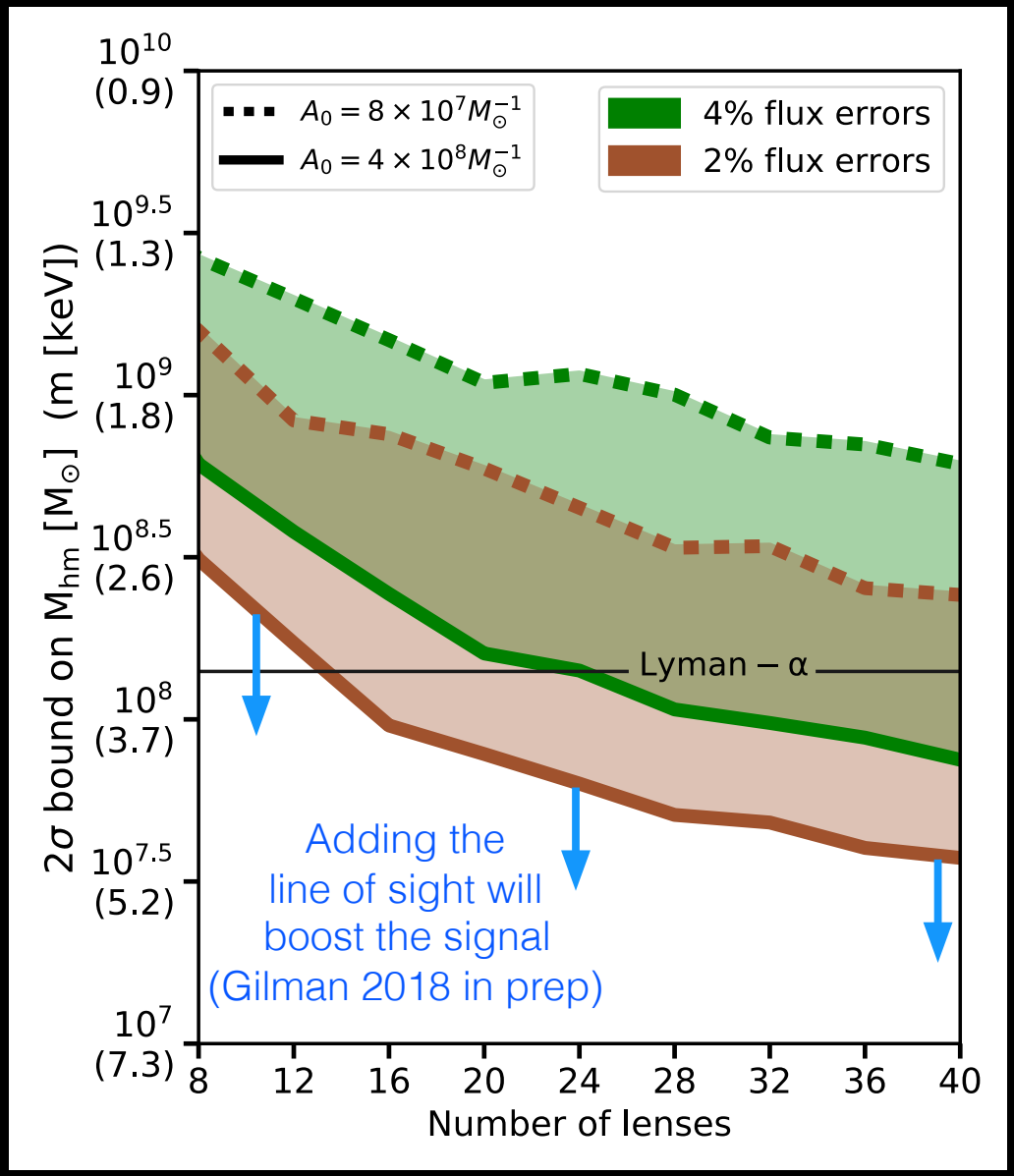
8% flux errors
4% flux errors
2% flux errors
RXJ-1131
Lyman − α
Gilman et al 2018
2σ bound on M_{hm} [$M_\odot$] (m [keV])
Number of lenses


$A_0 = 8 \times 10^7 M_\odot^{-1}$
$A_0 = 4 \times 10^8 M_\odot^{-1}$
4% flux errors
2% flux errors
Lyman − α
Adding the line of sight will boost the signal (Gilman 2018 in prep)
2σ bound on M_{hm} [$M_\odot$] (m [keV])
Number of lenses

Takeaways

With ELTs affording < 5 m.a.s. precision in image positions and <4-8% precision in image fluxes, we can measure:

1. The shape of the subhalo mass function
2. The normalization of the subhalo mass function

testing a fundamental prediction of particle dark matter theories.

Thanks!