HINTS ON THE NATURE OF DM FROM GRAVITATIONAL LENSING

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OUTLINE

- The dark matter particle-halo connection

- Current millilensing methods
  - Flux ratios
  - Gravitational imaging

- ELT improvements:
  - Improved flux sensitivity
  - Improved astrometric precision
  - Line of sight detection
  - Deflector mass modelling

- Early forecasting

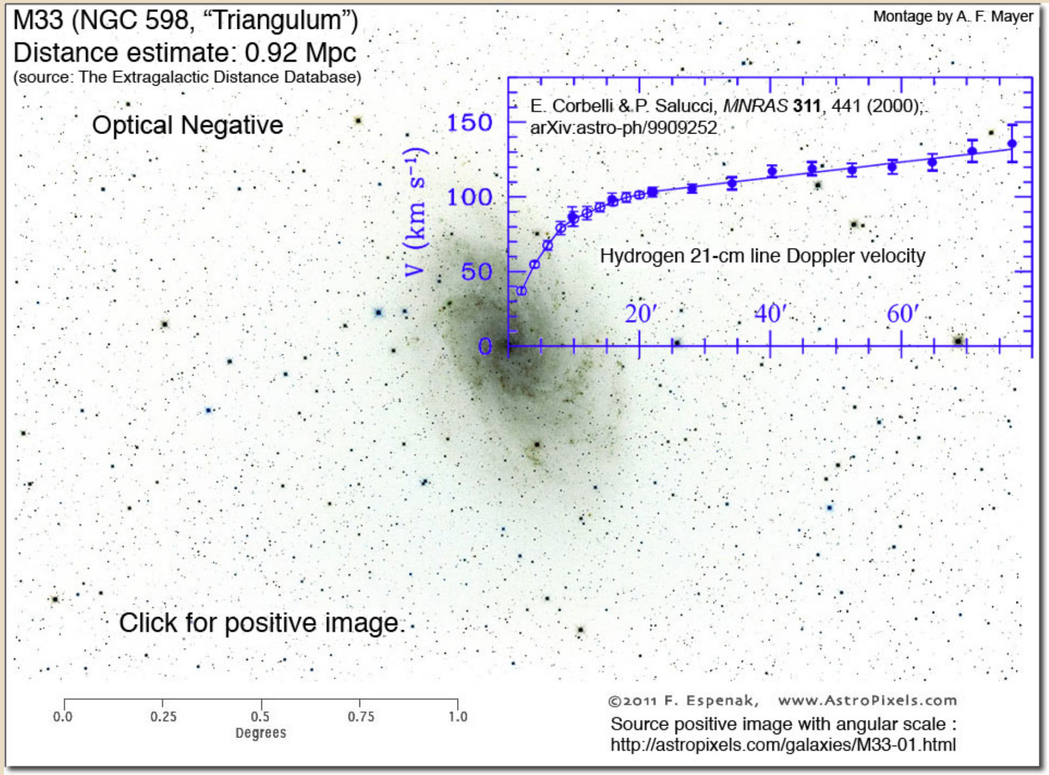
WHAT IS DARK MATTER?????

Is it a particle?

What is the particle mass?

On what scales does it form self-gravitating structures?

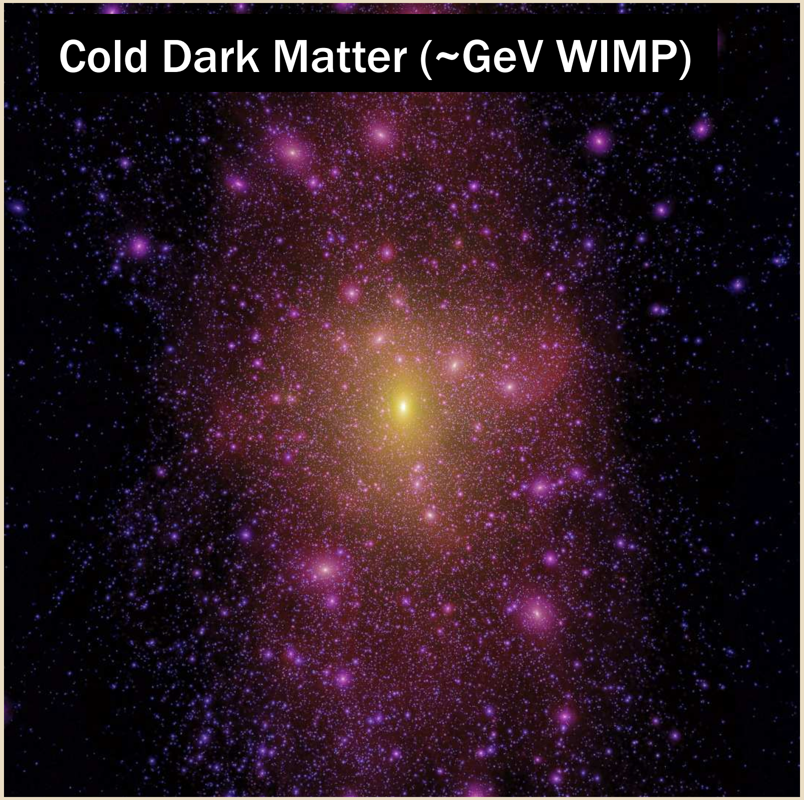
How does it interact with other matter/itself?

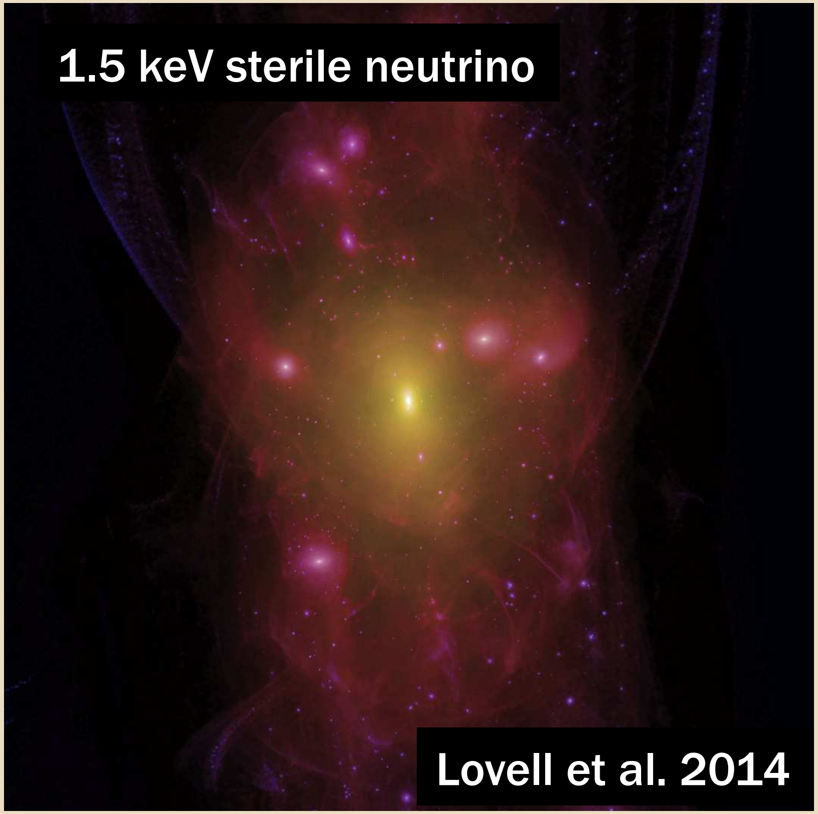


To date the only evidence we have for the existence of dark matter is from astronomical observations!

THE MICROSCOPIC PROPERTIES OF DARK MATTER AFFECT THE NUMBER AND SHAPE OF DM HALOS

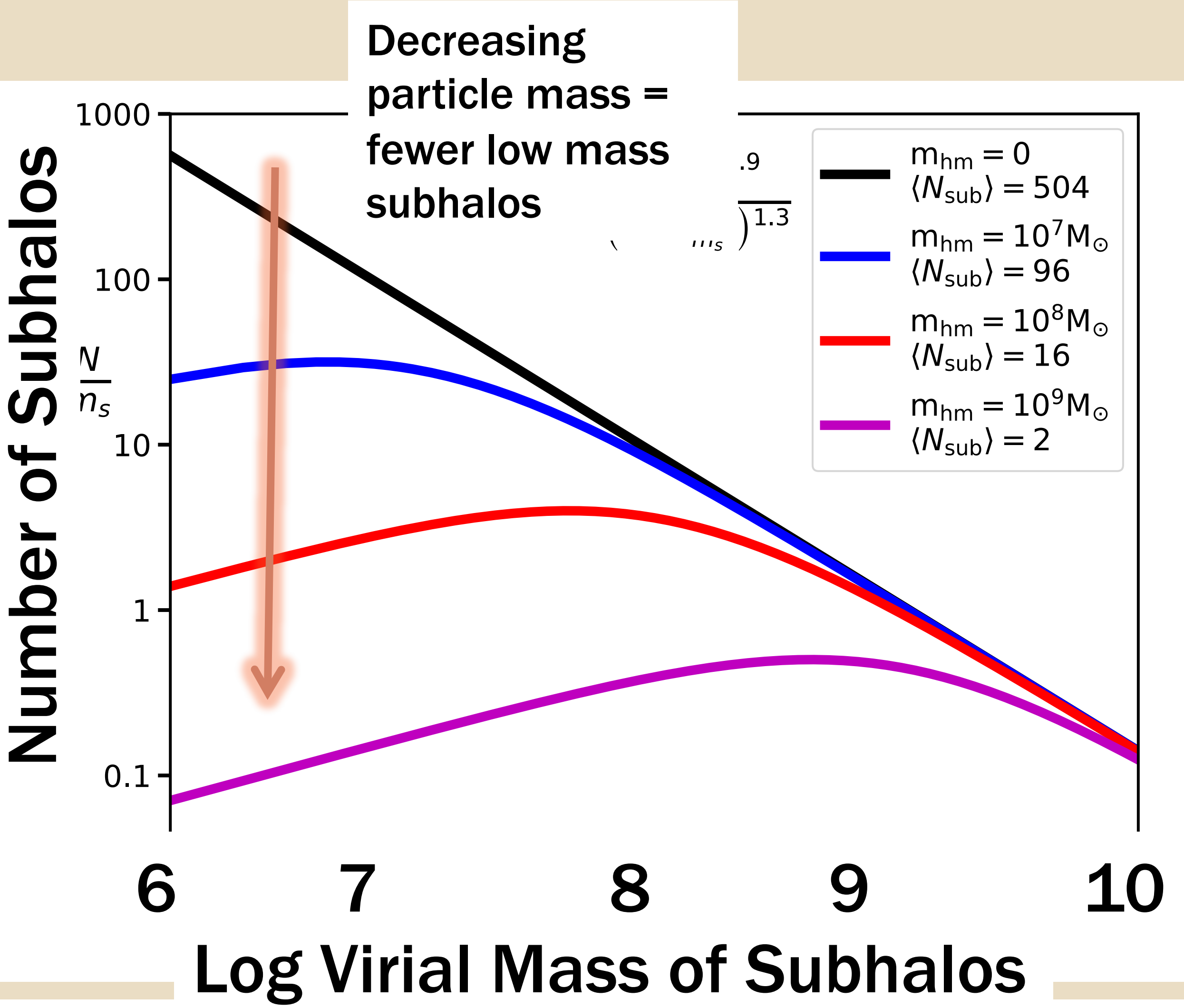
E.g. Warm Dark Matter has a large free streaming length at early times which erases structure on small scales.





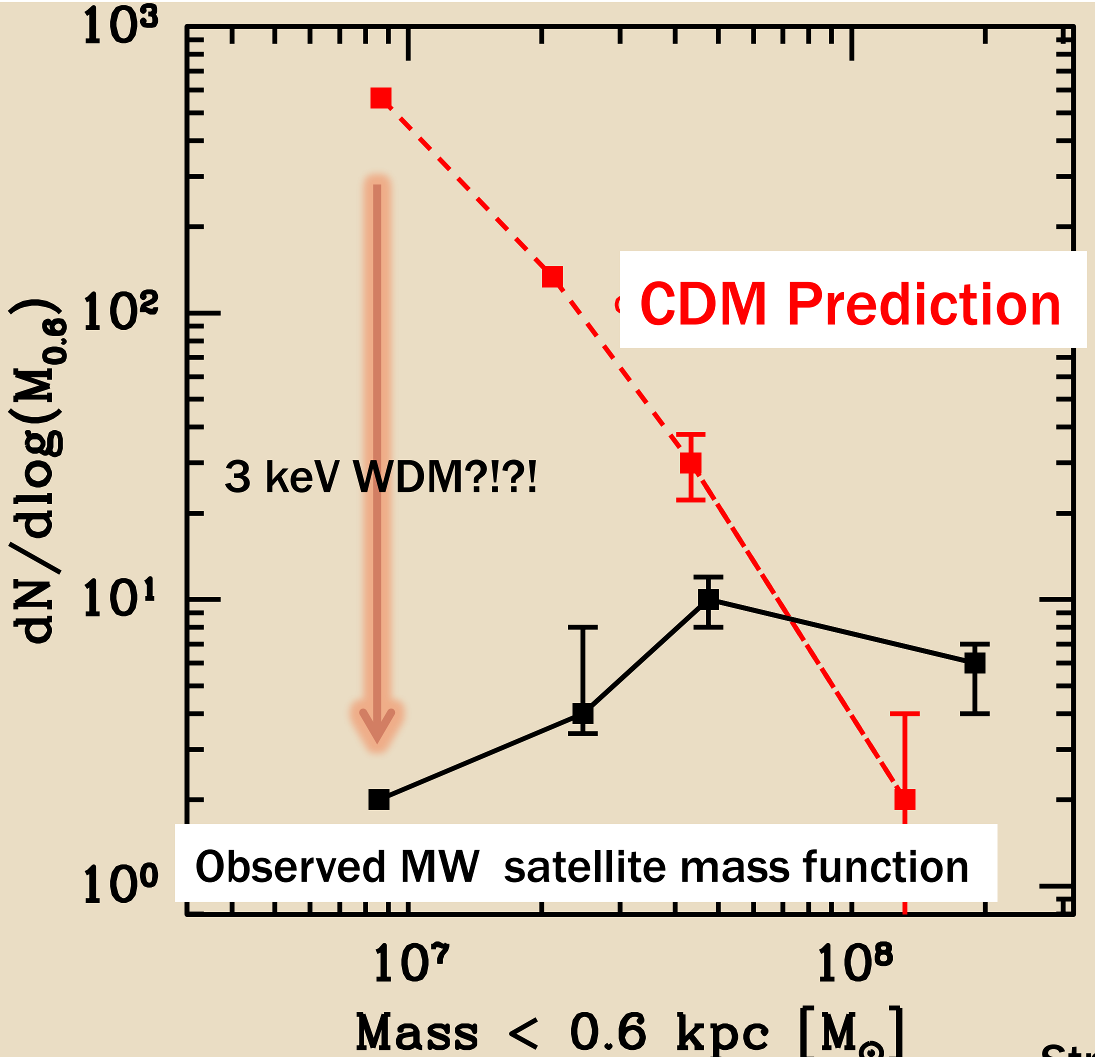
Simulated Milky Way mass dark matter halos

DARK MATTER PARTICLE -STRUCTURE CONNECTION



The lower in mass you can measure the subhalo mass function, the more stringent your constraints on dark matter free streaming length.

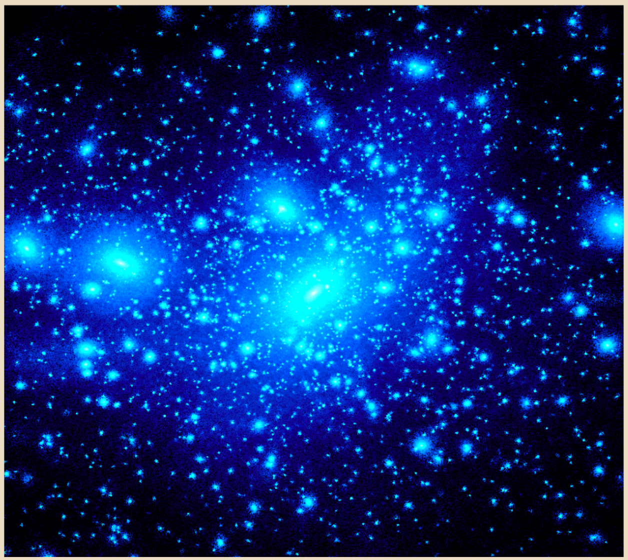
MILKY WAY SUBHALO MASS FUNCTION



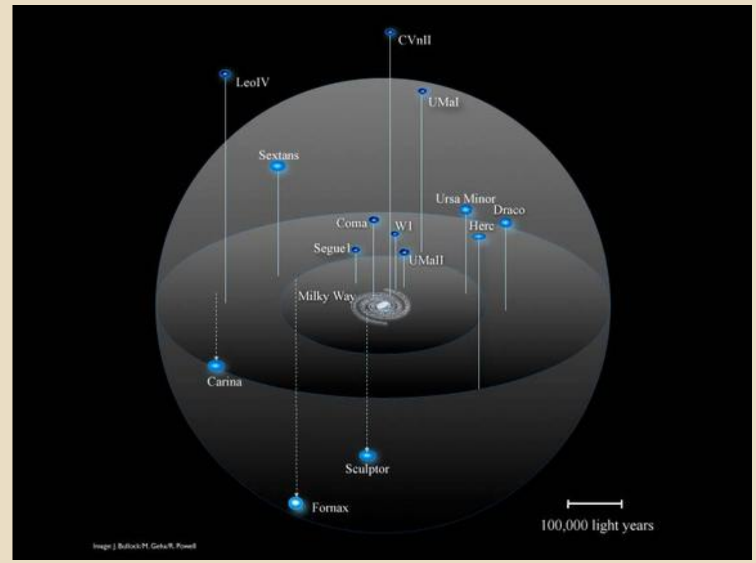
Strigari et al. 2008.

HOW MANY DARK MATTER SUBHALOS ARE THERE?

Kravtsov 2010



Bullock, Geha & Powell

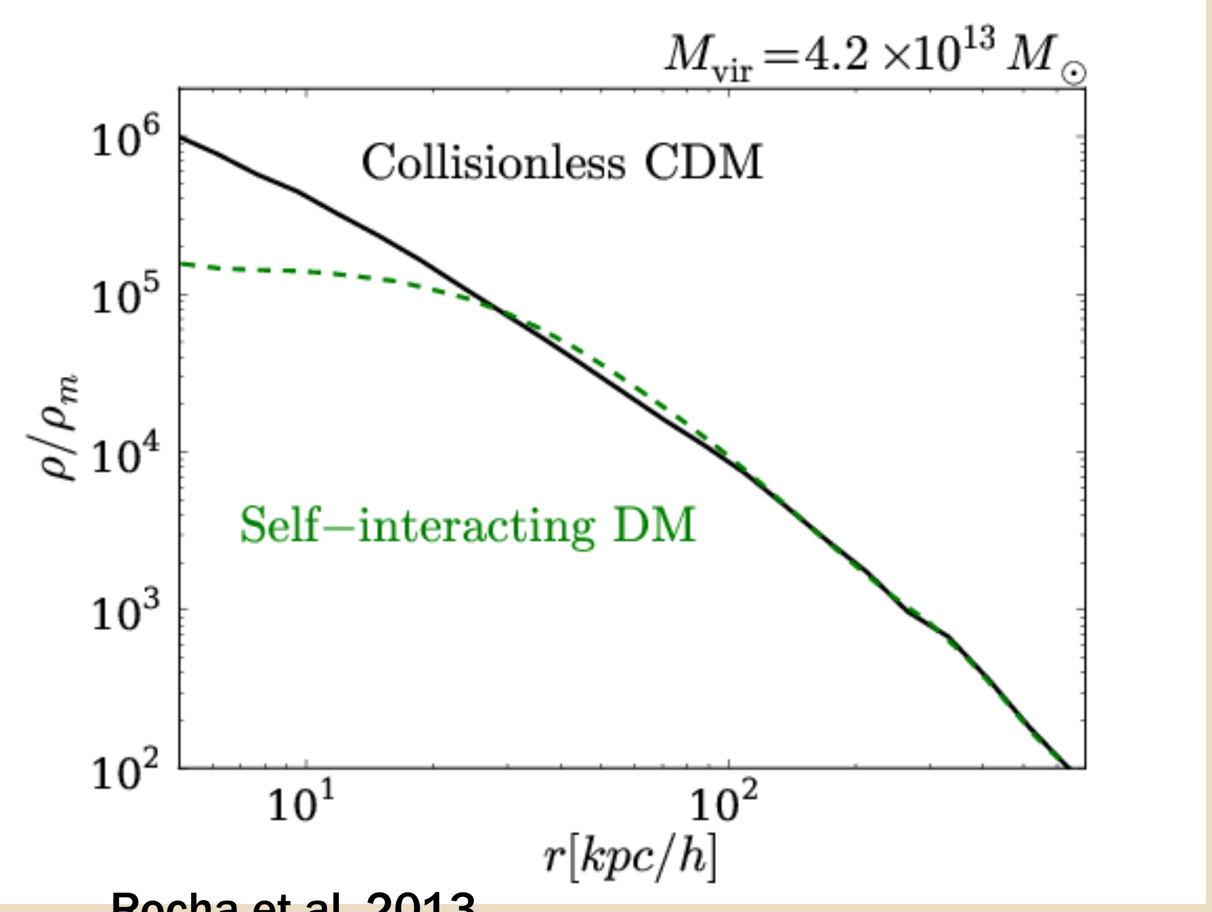


Satellite galaxies are collections of stars, which we believe to be embedded in a dark matter halos, so there are two solutions:

1) There are a large number of dark subhalos which do not contain enough gas or stars for us to see
2) CDM is incorrect

THE MICROSCOPIC PROPERTIES OF DARK MATTER AFFECT THE SHAPE OF DM HALOS

Self interacting dark matter produces halos with central cores



Rocha et al. 2013

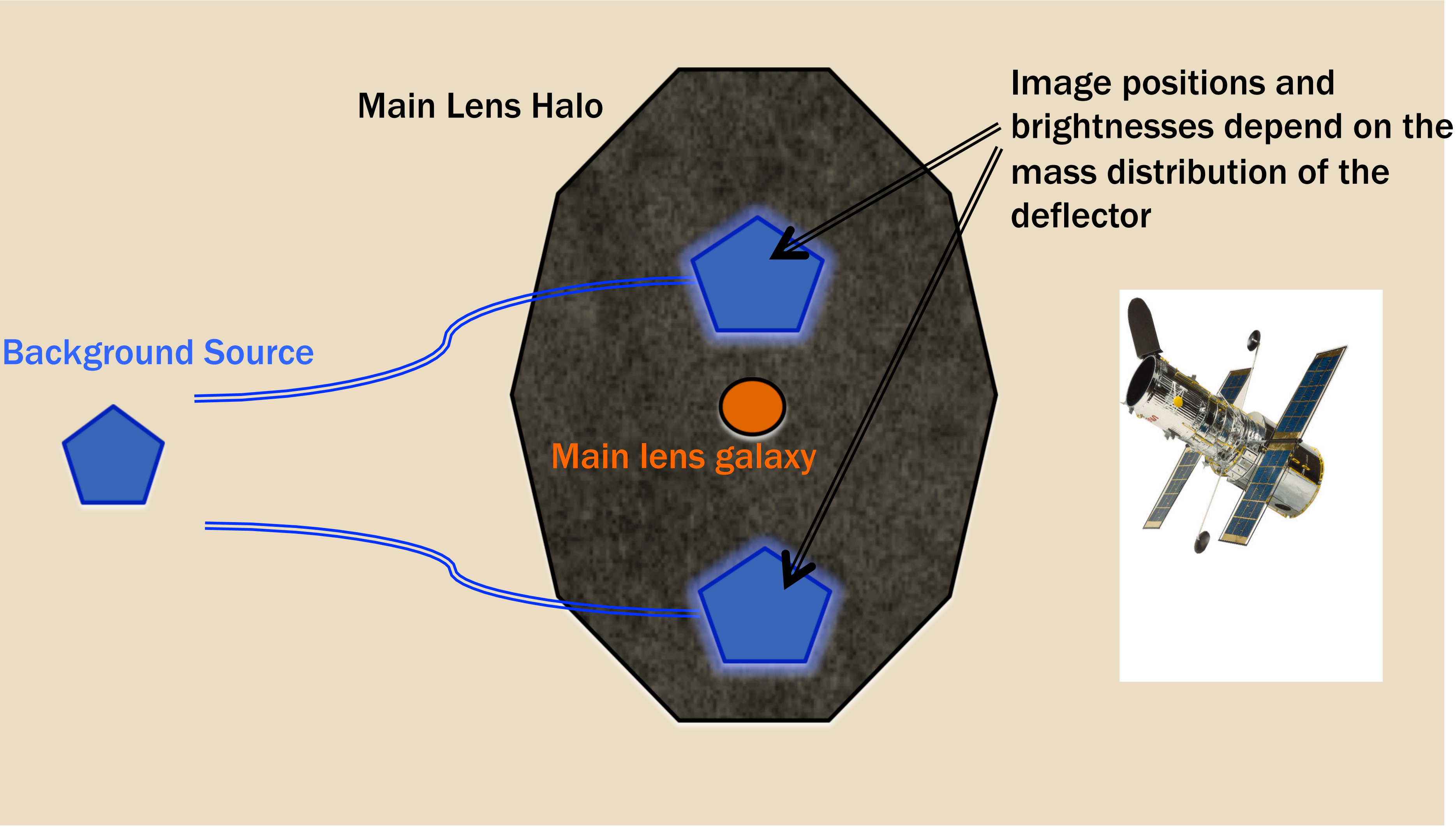
GRAVITATIONAL LENSING

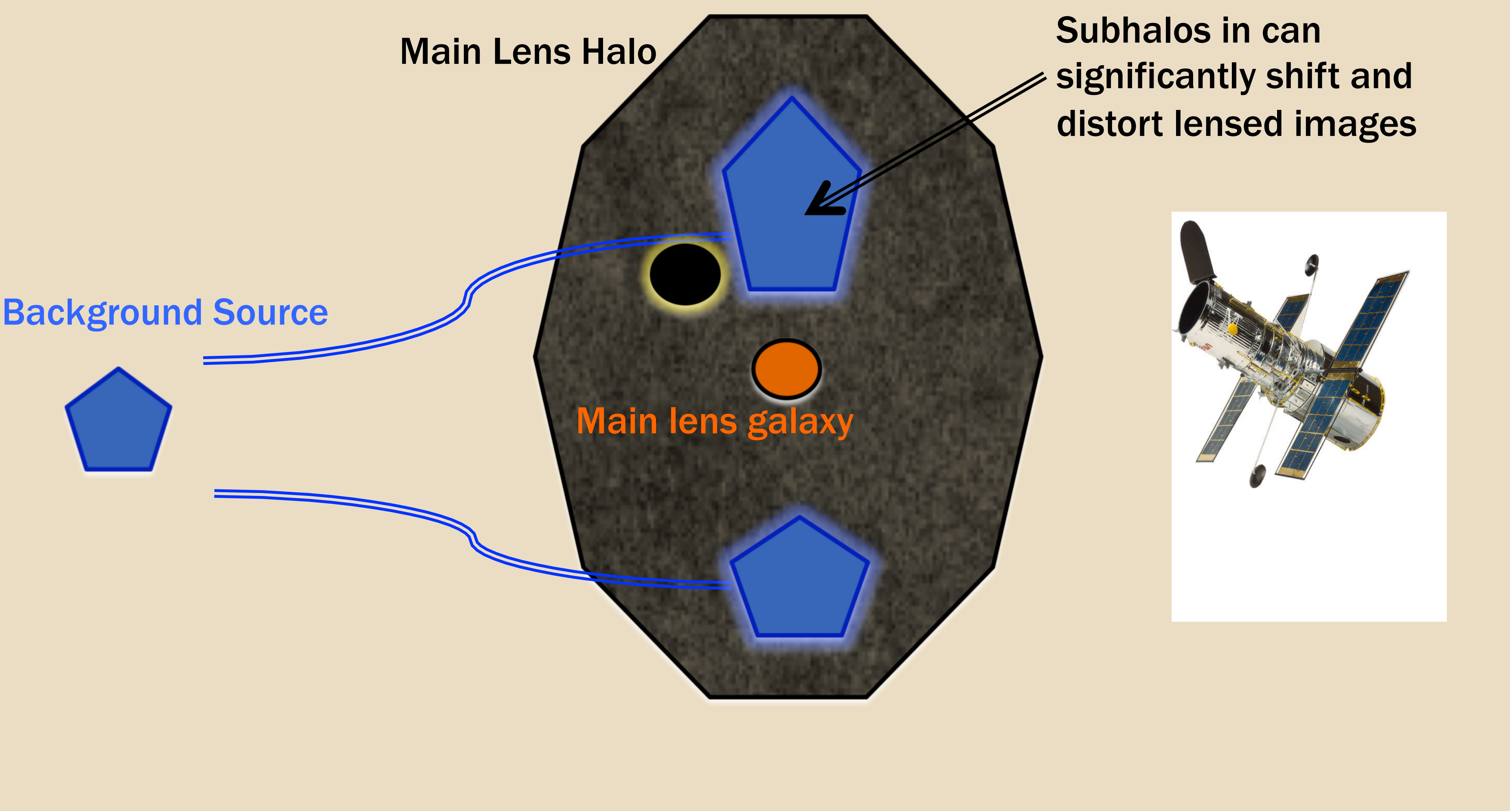
- Weak and strong lensing can probe the *density profiles* of dark matter halos.
- Strong lensing by in our galaxy can probe the fraction of dark matter in massive compact objects

- Strong lensing outside of our galaxy can probe the low mass end of the halo mass function (This talk)

STRONG GRAVITATIONAL LENSING TO PROBE THE HALO MASS FUNCTION

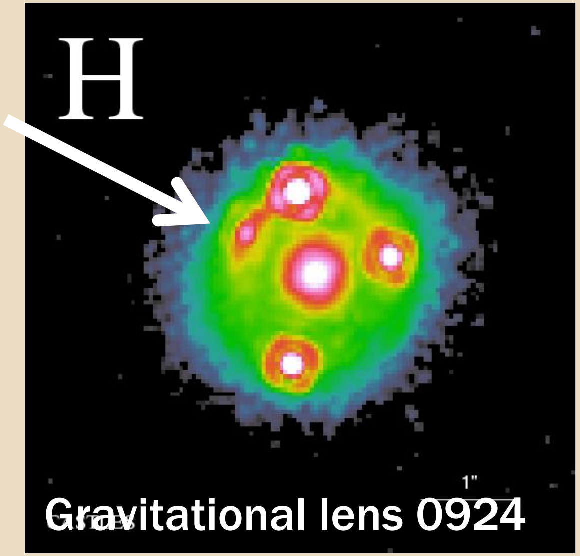
STRONG GRAVITATIONAL LENSING; THE NEXT BEST THING TO DARK MATTER GOGGLES



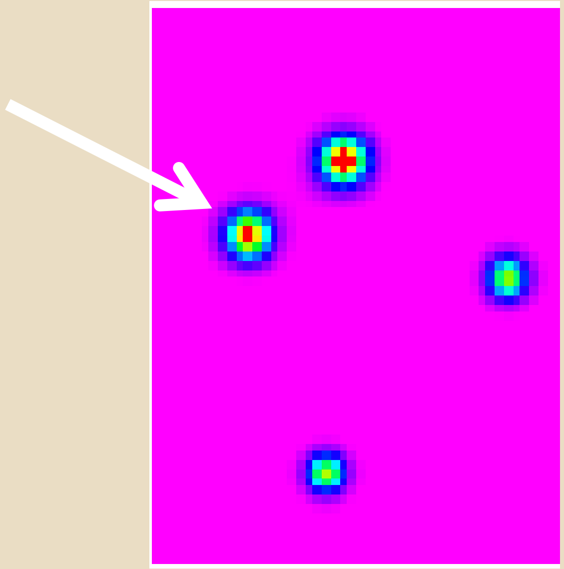

Main Lens Halo
Subhalos in can
significantly shift and
distort lensed images
Background Source
Main lens galaxy

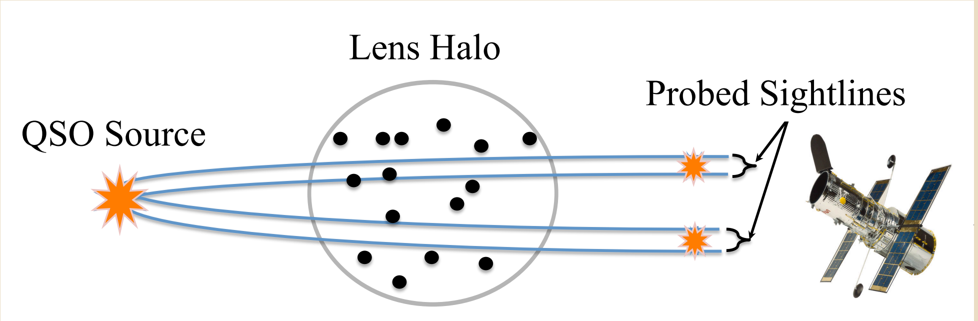
STRONG GRAVITATIONAL LENSING IN REAL LIFE

Observed quad lens

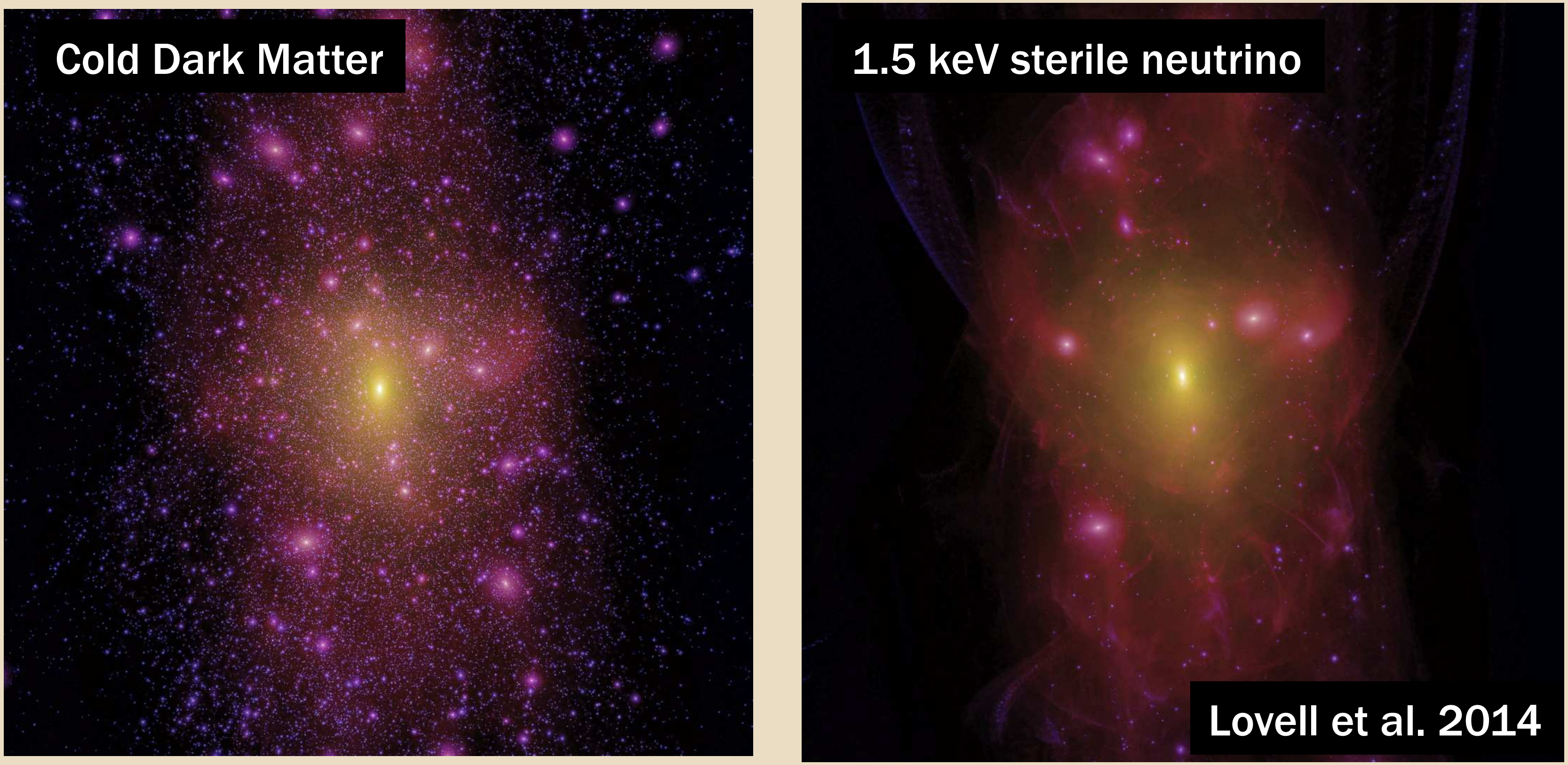


Smooth halo model prediction





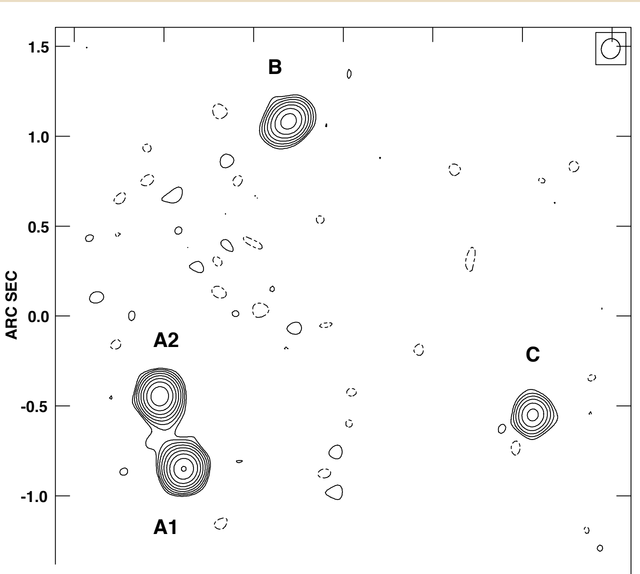
WITH ENOUGH LENSES IT IS POSSIBLE TO DISTINGUISH BETWEEN THESE SCENARIOS



Simulated Milky Way- mass dark matter halos

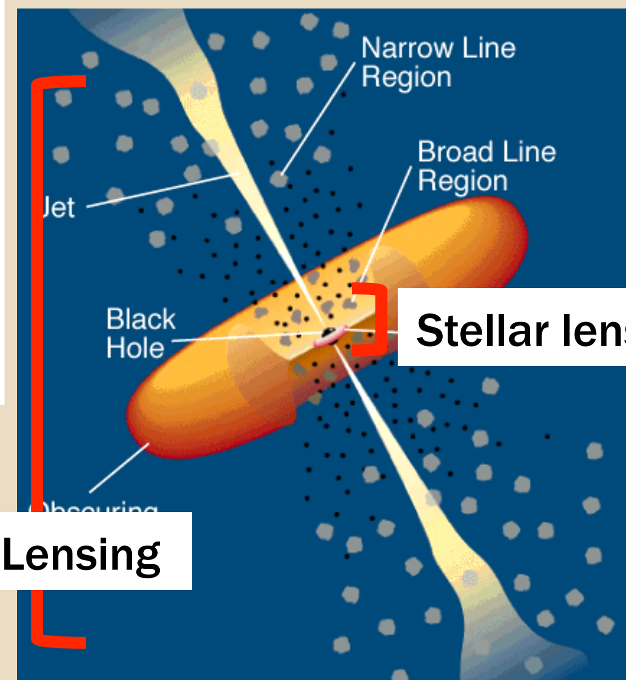
THE LENS MASS SENSITIVITY DEPENDS ON THE SIZE OF THE *SOURCE*

Lensed Radio Jet



15 GHz, Katz et al. 1997

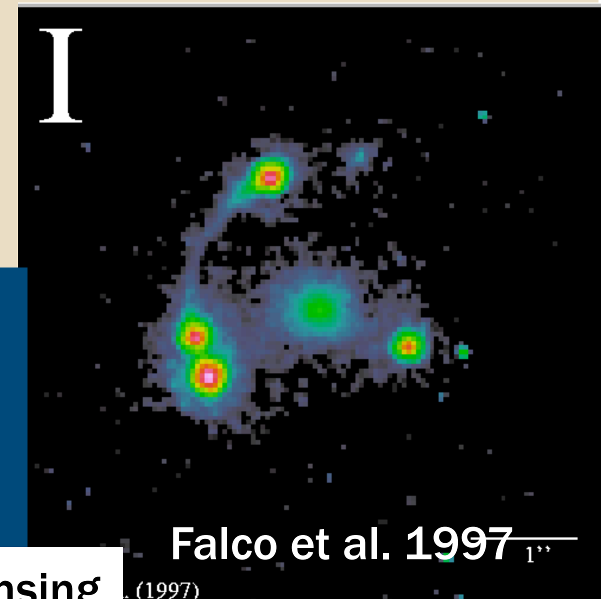
Gravitational lens MG 0414



Stellar lensing

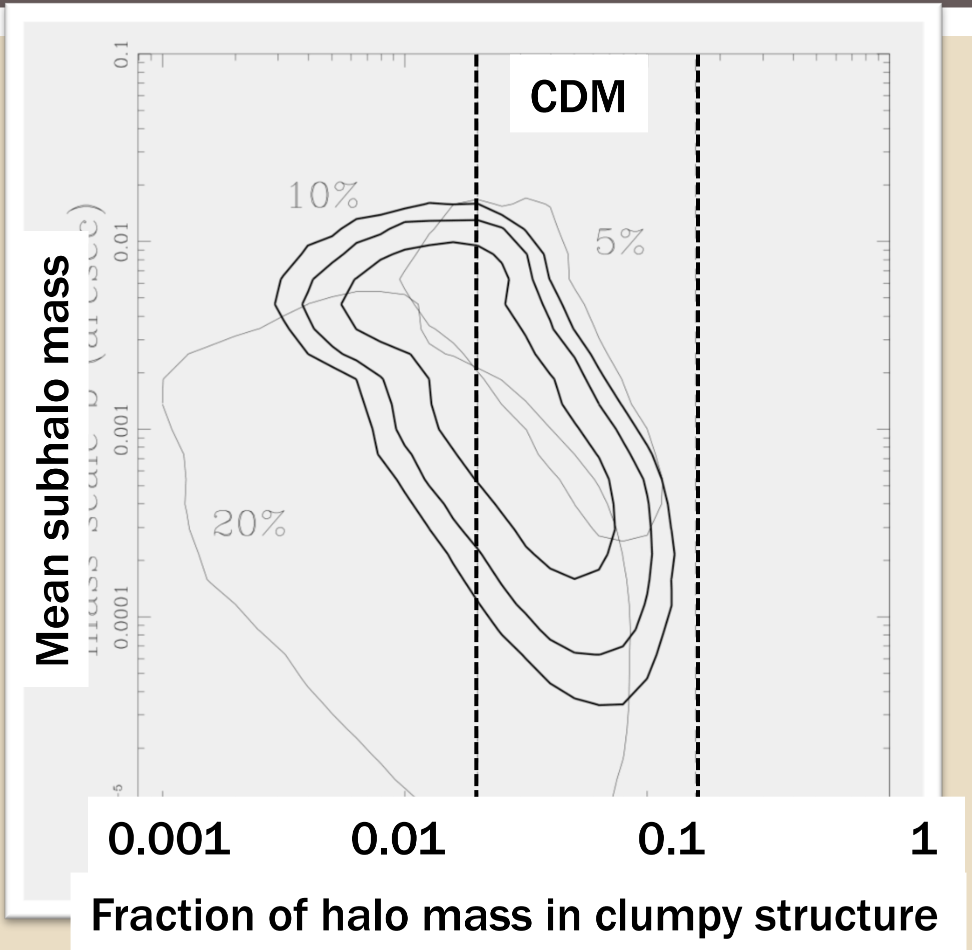
Subhalo Lensing

Lensed Accretion Disk



Falco et al. 1997

THERE ARE ONLY 9 RADIO LOUD QUAD LENSES KNOWN

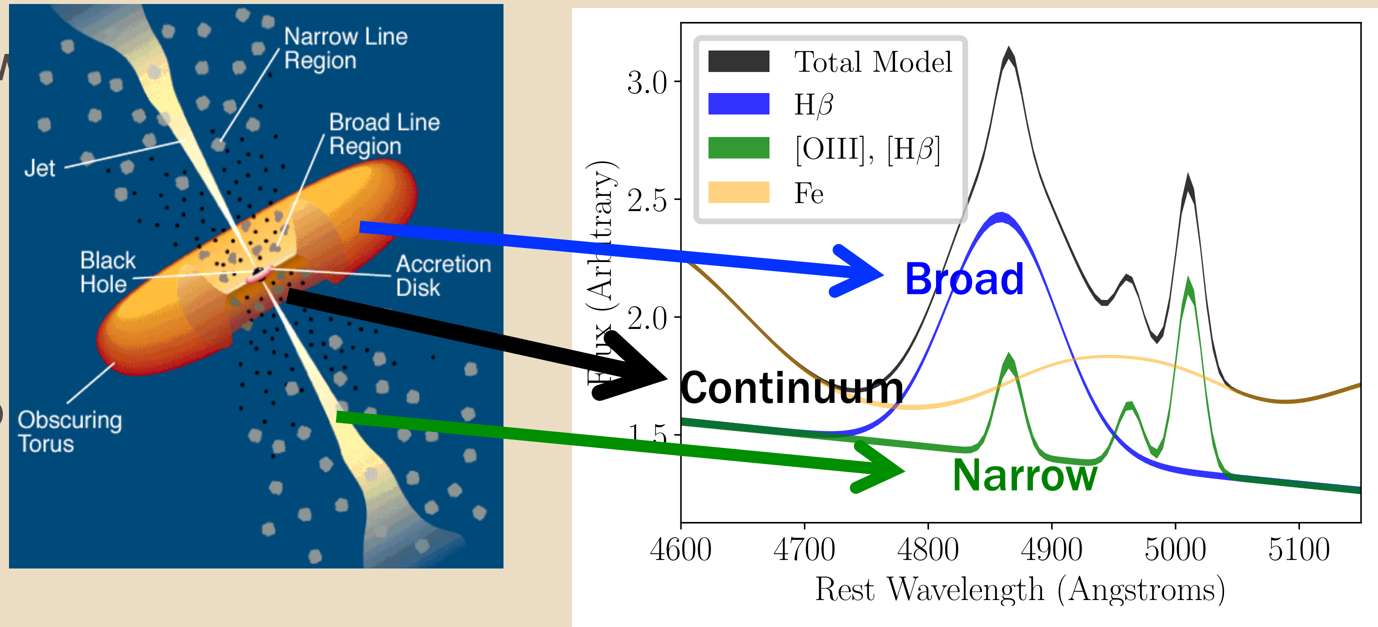


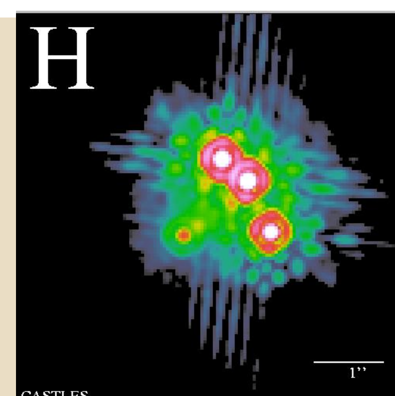
Dalal and Kochanek 2002, 7 radio-loud lens systems

NEW METHODS: INCREASING THE NUMBER OF LENSES

NARROW-LINE LENSING

- All quasars show significant narrow line emission - can double the number of systems used to detect substructure





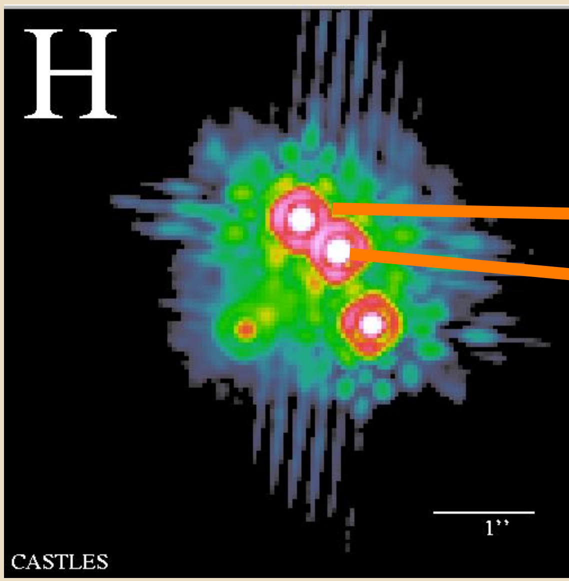
- Narrow-line is not variable and not microlensed

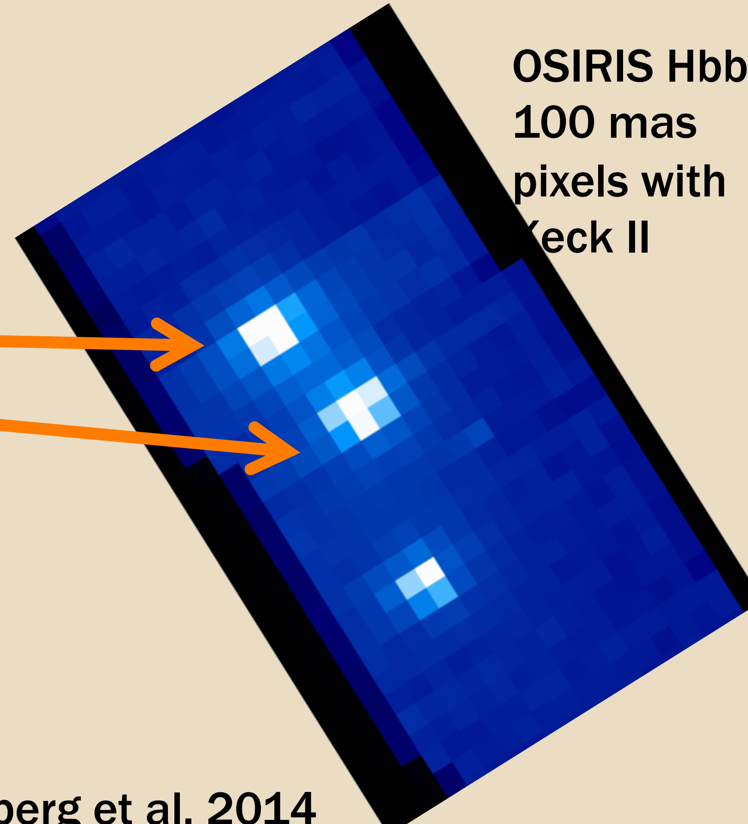
Need high res, spatially resolved spectroscopy

EXAMPLE: NARROW-LINE LENSING WITH KECK-OSIRIS

- Adaptive optics gives ~mas spatial resolution
- Integral field spectrograph gives spectra at each spatial pixel

HST NICMOS

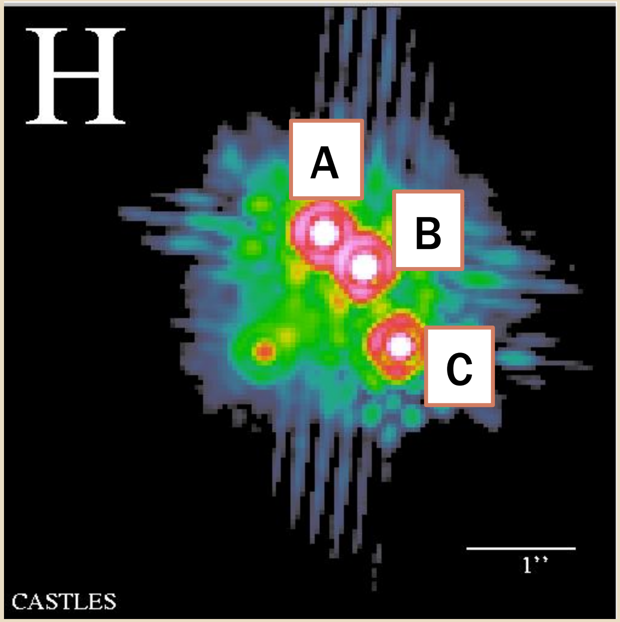


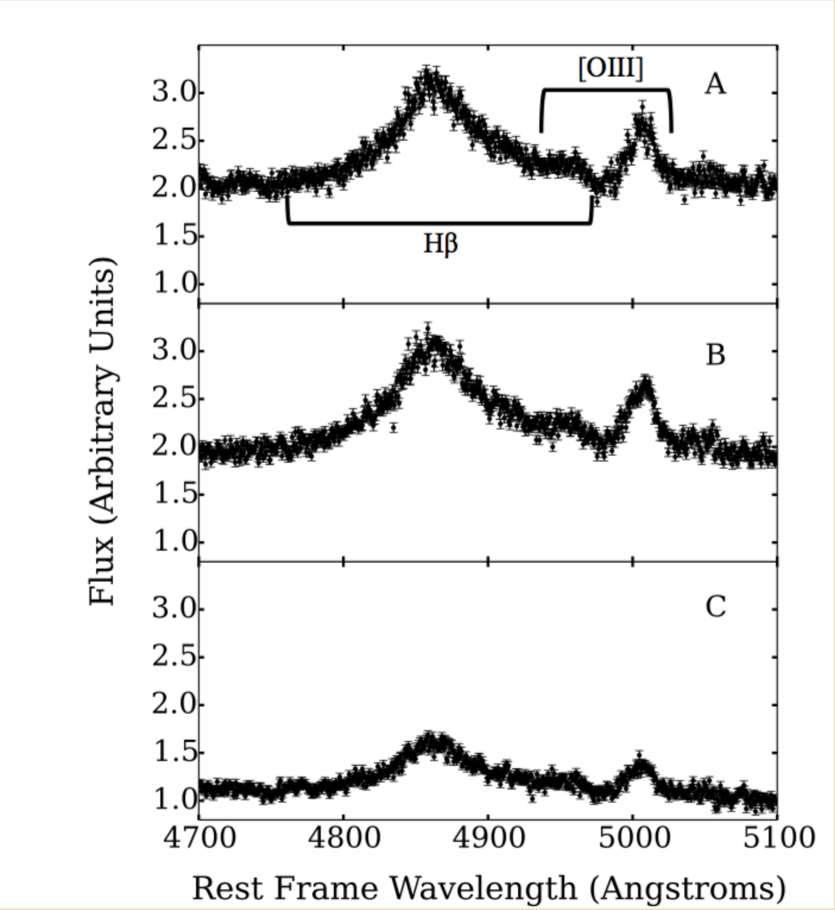


OSIRIS Hbb, 100 mas pixels with Keck II

Nierenberg et al. 2014

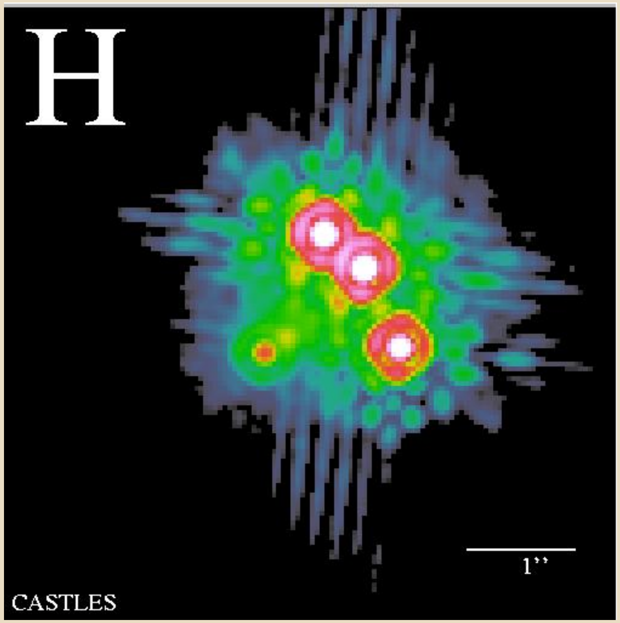
NL LENSING IN B1422+231, OSIRIS WITH KECK AO



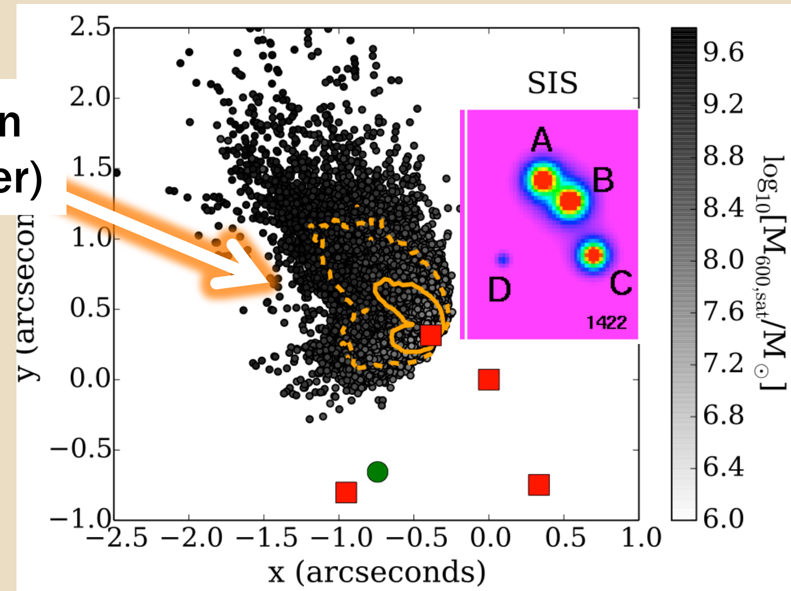


Nierenberg et al. 2014

NARROW-LINE LENSING SENSITIVITY TO ‘INVISIBLE’ DM HALO



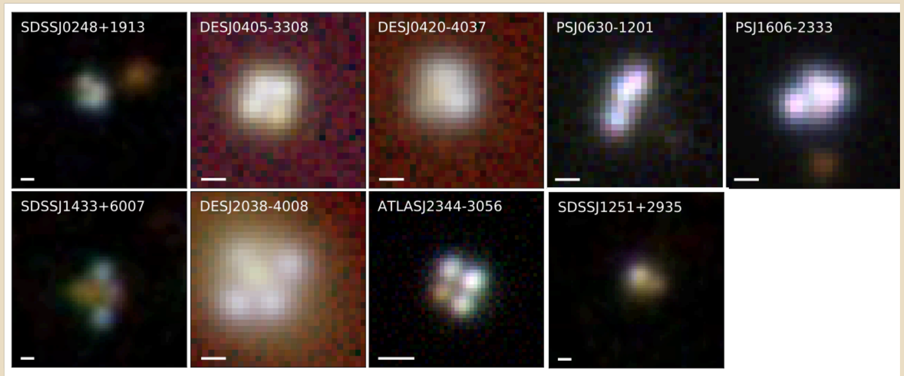
Msub~10^7 Msun
(if single perturber)



Nierenberg et al. 2014

Lens sources include radio jets (e.g. Dalal and Kochanek 2002), radio quiet core emission (Jackson et al. 2015) and quasar narrow-line emission (Nierenberg et al. 2014, 2017)

MORE NL LENSING WITH HST GRISM



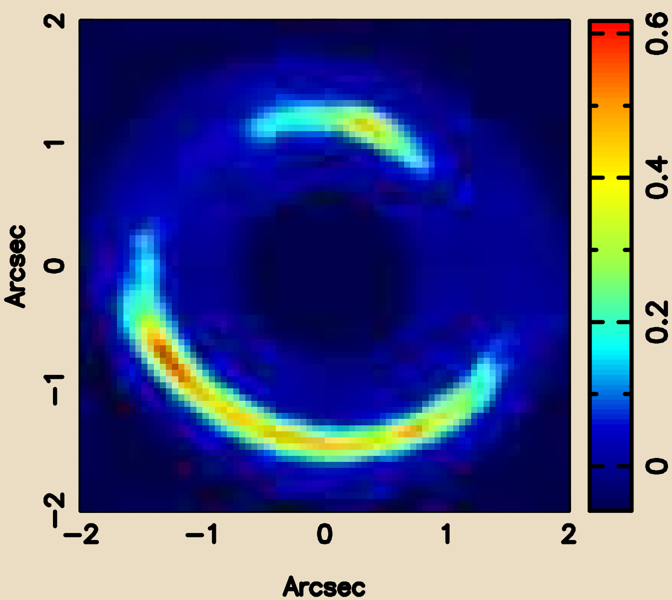
HST GO-13732 and GO-15177 (PI Nierenberg) 15 NL quad lenses from SDSS, DES and PAN-STARRS

+ 3 more with Keck-OSIRIS –e.g. Nierenberg et al 2014

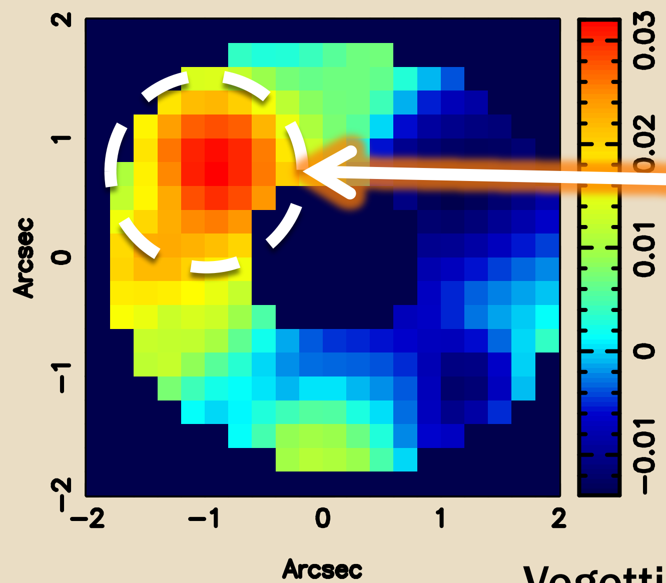
ALTERNATE METHOD: GRAVITATIONAL IMAGING

HST

Lensed Image



Inferred 2D Mass distribution



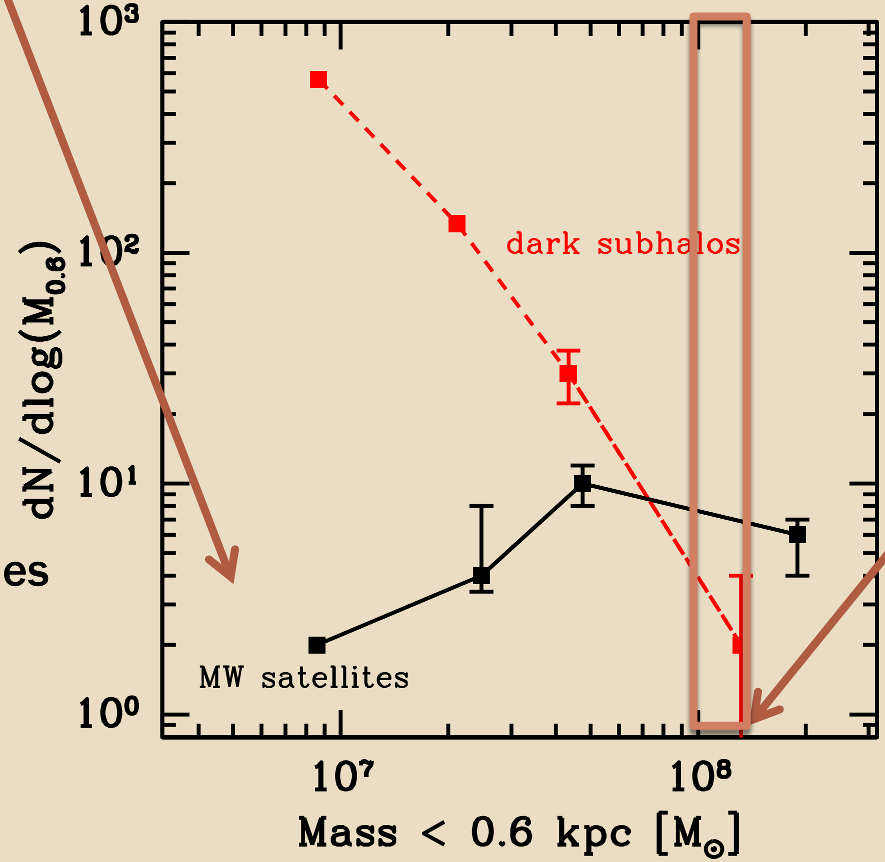
Msub~ 10^9 Msun within M600

Vegetti et al. 2010

Sources include optical and sub-millimeter galaxies (Vegetti et al. 2010, 2014, Hezaveh et al. 2016

COMPARING GRAVITATIONAL IMAGING AND NARROW-LINE LENSING

NL lensing is **currently** sensitive to these masses!



Lowest mass gravitational imaging detection

Gravitational imaging and NL lensing probe complementary regimes of the subhalo mass function.

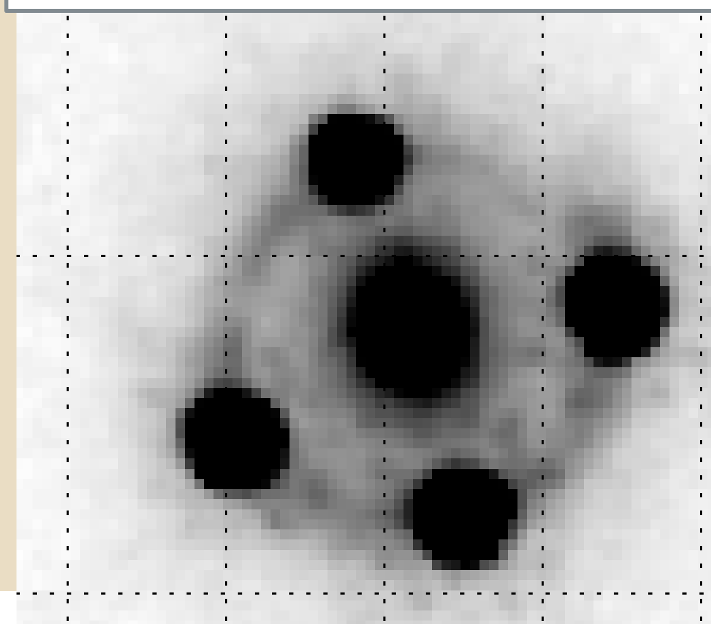
Strigari et al. 2008.

METHOD COMPARISON

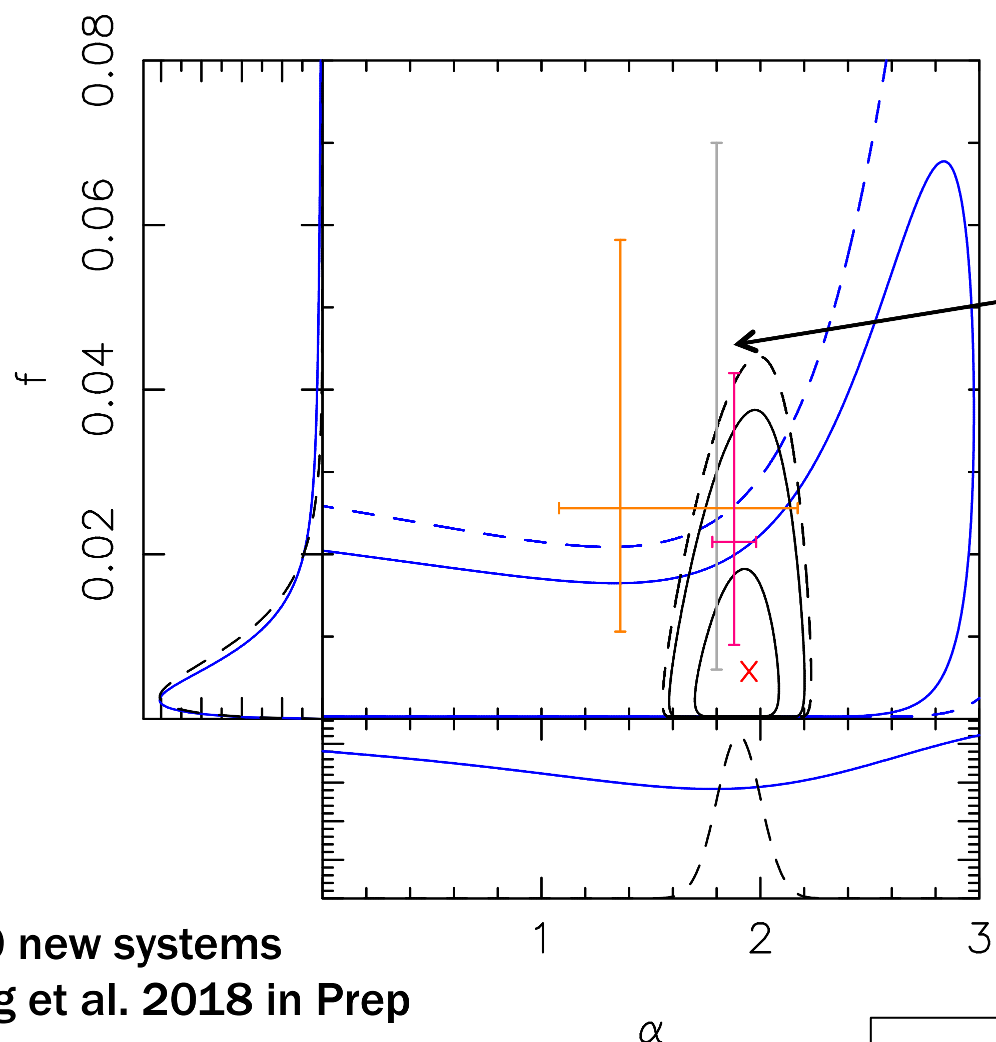
- NL Lensing sensitive to much lower masses, and computationally simpler.
- Gravitational imaging provides better constraint on the 'macromodel' and perturber location.

Goal: select systems where both methods can be used so we can combine the strengths of both

HE0435: Nierenberg et al. 2017



SO WHERE DO WE STAND?

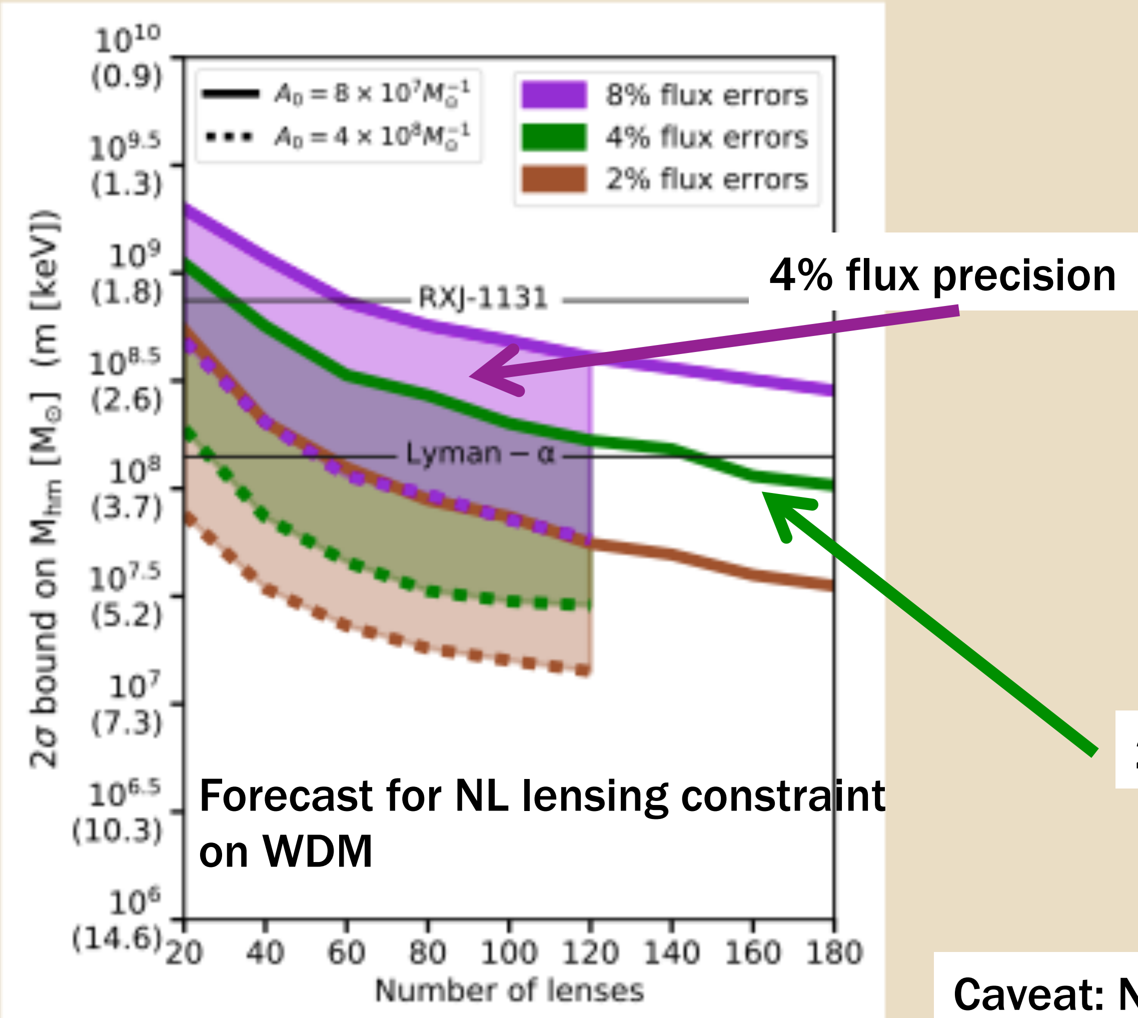


Dalal and Kochanek 2002

New constraints ~ 10 new systems soon from Nierenberg et al. 2018 in Prep (~20 total)

Vegetti et al. 2014

HOW MANY LENSES DO WE NEED?



With about ~40 NL lensing systems we can place tighter constraints on the DM free streaming length than Ly-alpha forest with completely different systematics

Caveat: No LOS structure yet

CAN WE GET TO ~100 LENSES?

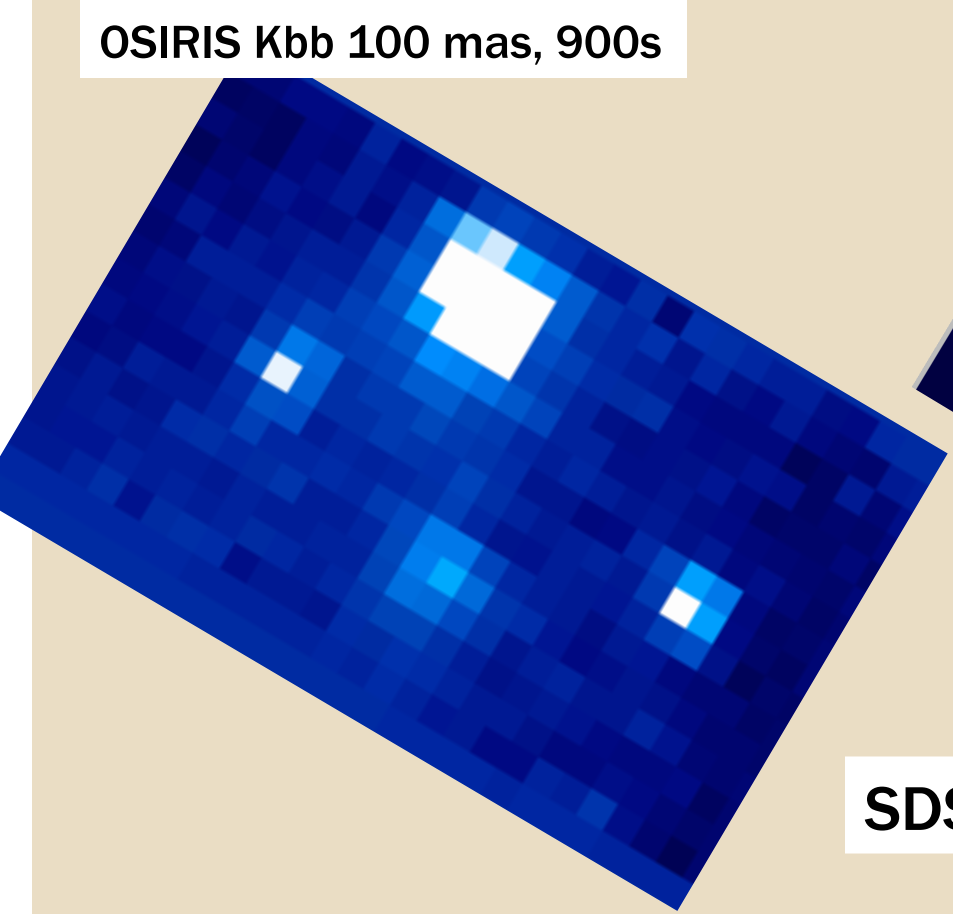
- Several tens more quad quasar lenses expected in DES and PANSTARRS within the next few years
- Hundreds of suitable systems to be detected by LSST and Euclid (Oguri and Marshall 2010)
- Next generation of telescopes enable rapid followup and higher astrometric and photometric precision, allowing us to push the measurement to lower masses.

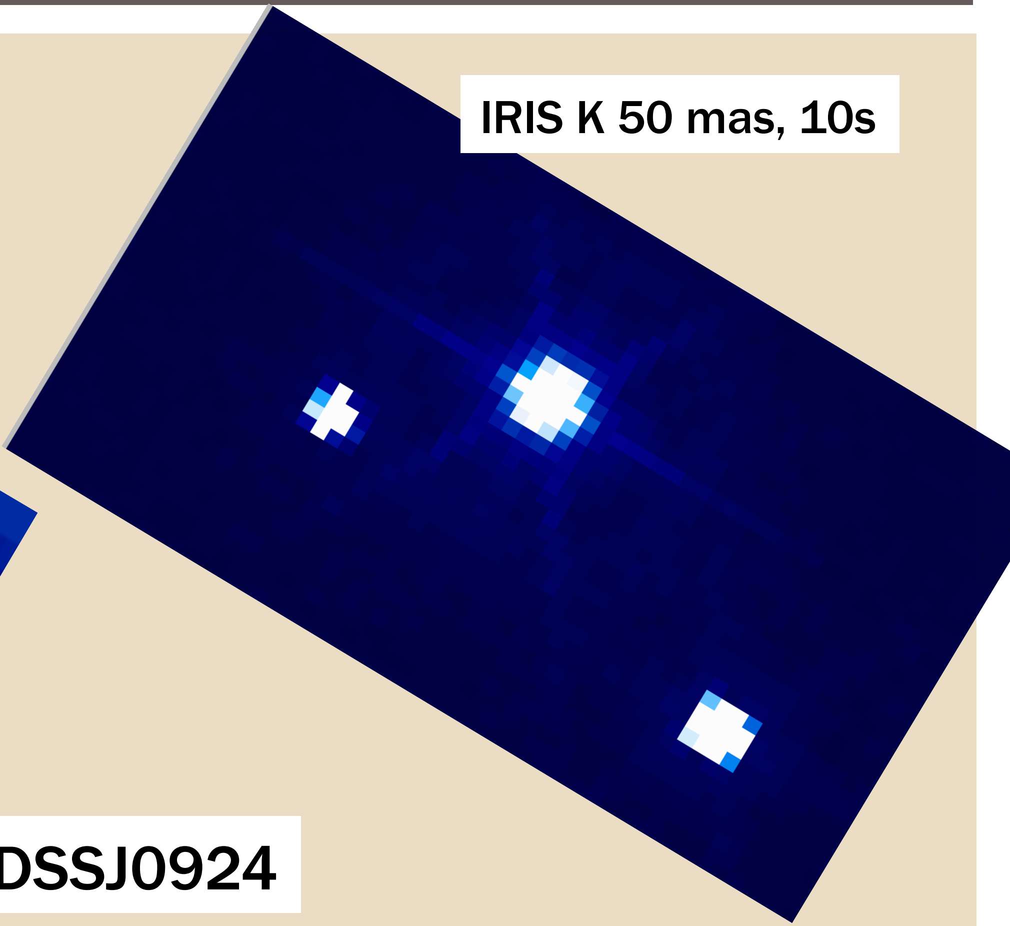
Yes!!

HOW NEXT GENERATION TELESCOPES WILL CHANGE THE GAME

- Improved flux sensitivity
  - More lenses can be studied
  - Better precision = better constraints on DM for all methods
- Improved astrometric precision
  - Lower mass sensitivities
  - Better deflector models (flux ratios esp.)
  - Direct measurement of LOS redshift in some cases
- Both
  - Important ancillary data such as deflector redshift.

IMAGING MUCH MORE RAPID WITH THIRTY METER TELESCOPE

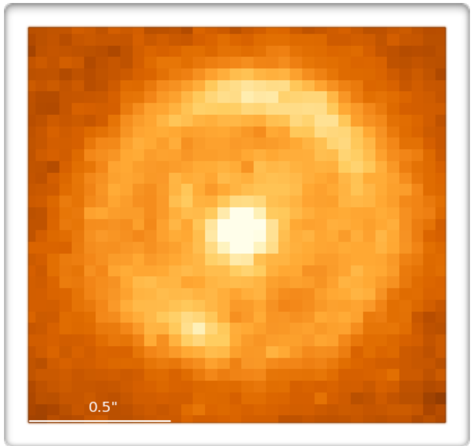


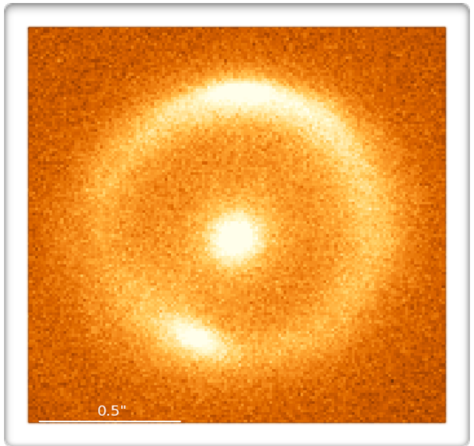


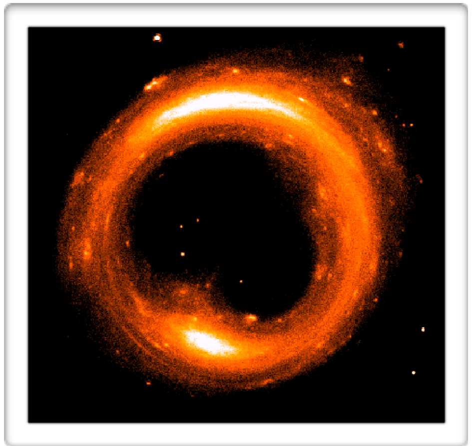
SDSSJ0924

IRIS Simulation courtesy of
Nils-erik Rundquist

GRAV. IMAGING WITH ELTS ~AN ORDER OF MAGNITUDE LOWER SUBHALO MASS SENSITIVITY





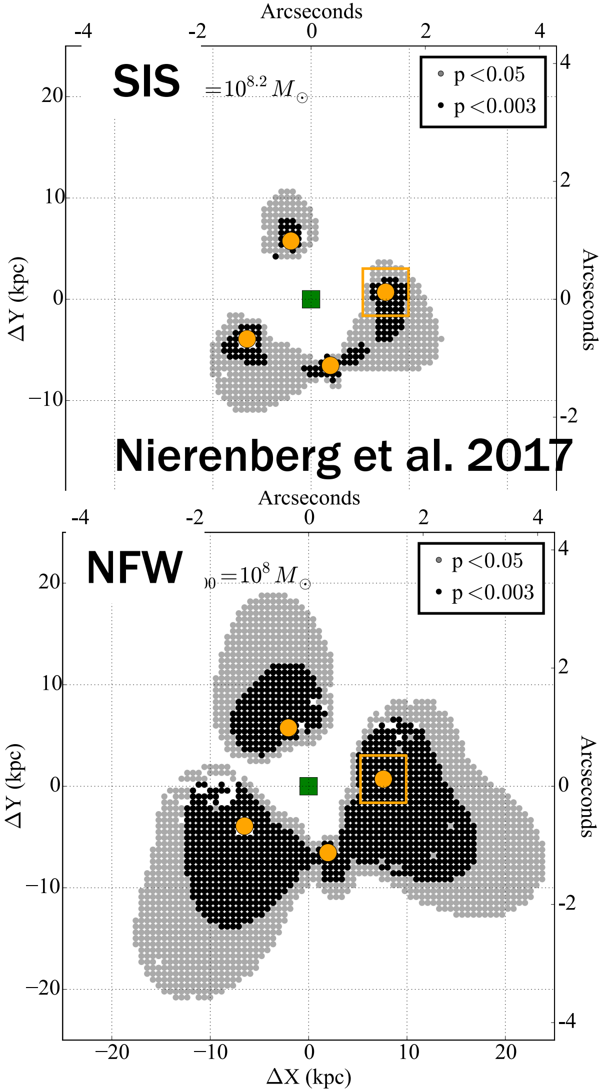


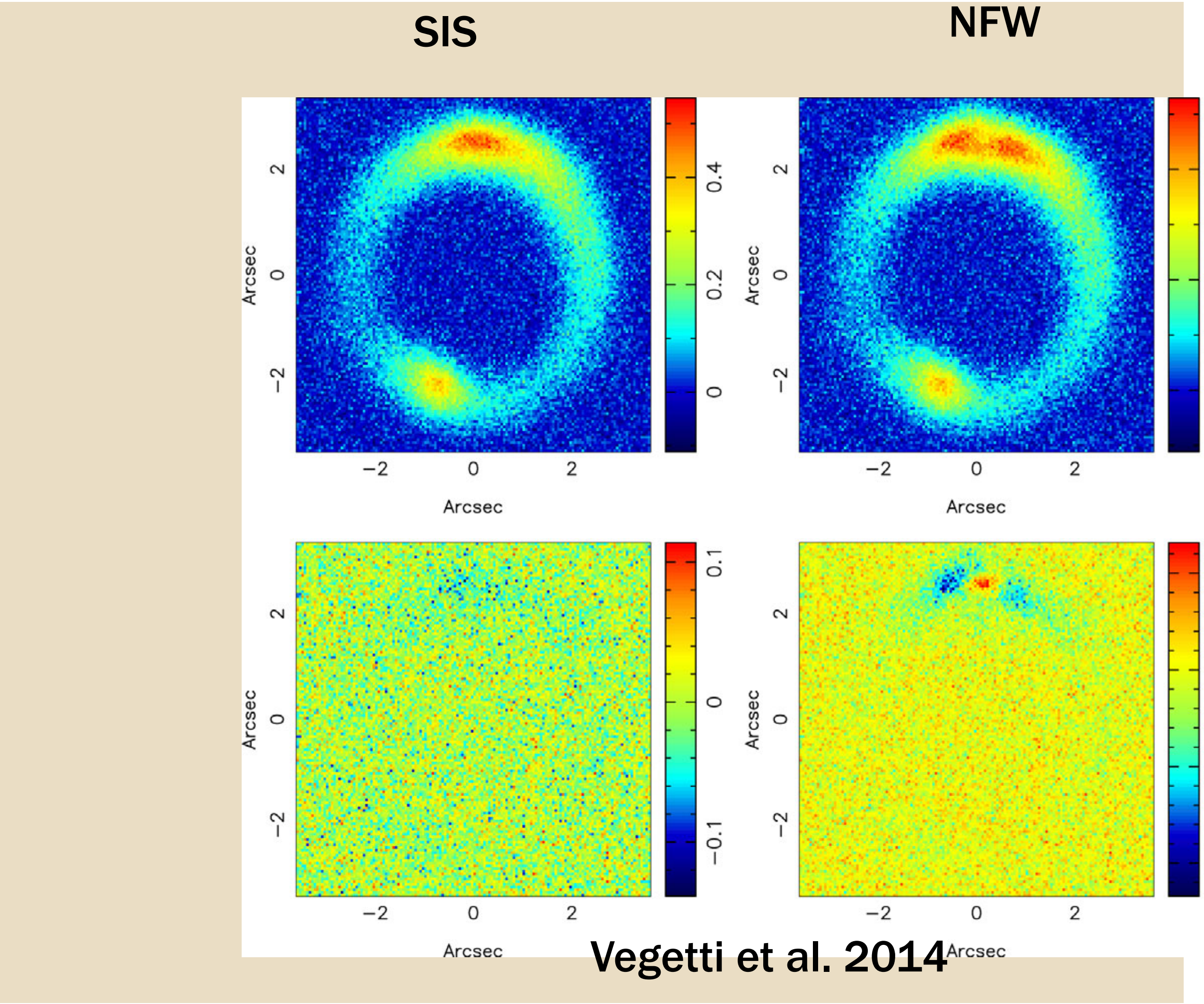
HST — Keck AO — E-ELT

10^9 M_{sun} — 10^8 M_{sun} — ?

Simulation courtesy of Simona Vegetti

SUBHALO DENSITY PROFILE AFFECTS LENS SENSITIVITY





CONCLUSIONS (THANKS FOR LISTENING!)

- Strong gravitational lensing is a powerful tool for constraining the properties of dark matter on small scales
- Improved astrometric precision directly improves mass sensitivity for gravitational imaging, and may also for flux ratios to a lesser extent
- Improved flux precision is important for flux ratios, and likely also for gravitational imaging
- New science with milli-lensing will be possible with ELTS