# TESTING CDM WITH STRONG GRAVITATIONAL LENSING OF AGN

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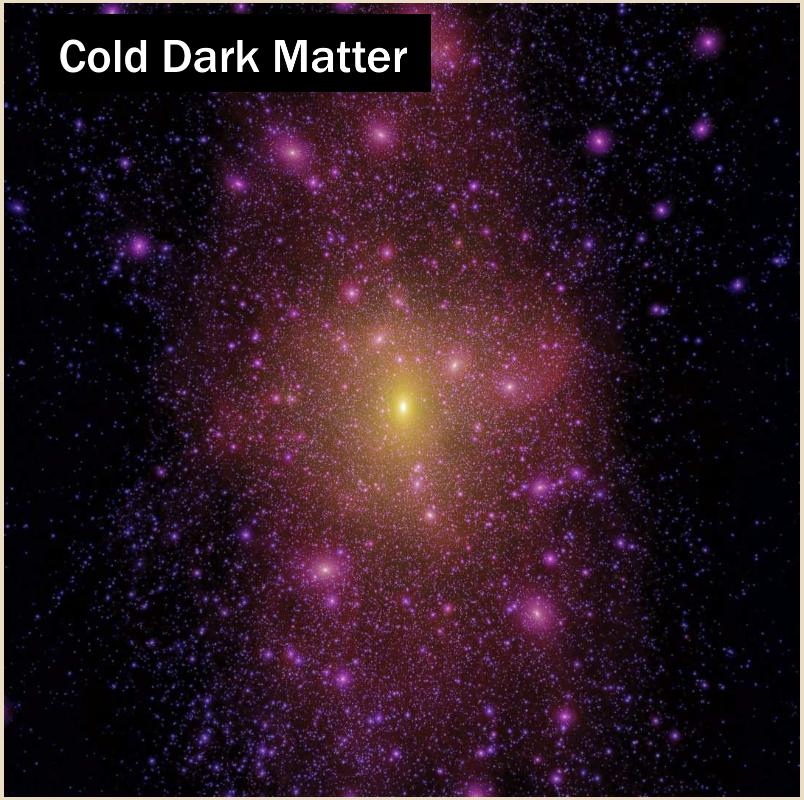
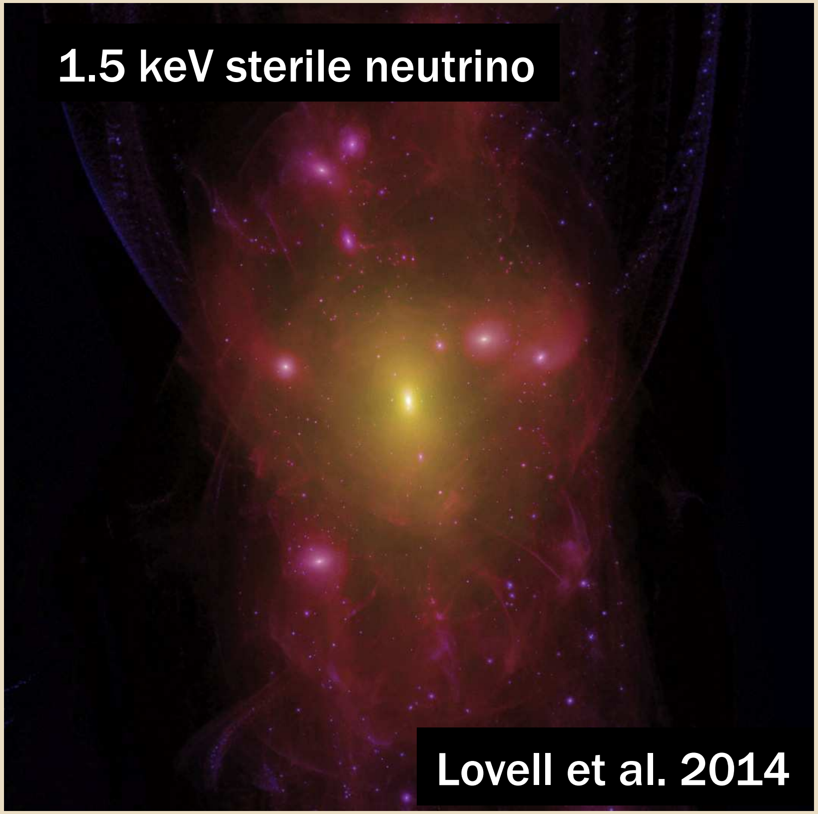
# OUTLINE

- Dark matter and the matter power spectrum
- Measuring the small scale matter power spectrum with strong gravitational lensing
- Many new lenses with AGN narrow-line lensing
- Future prospects

# THE MICROSCOPIC PROPERTIES OF DARK MATTER AFFECT THE POWER SPECTRUM

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

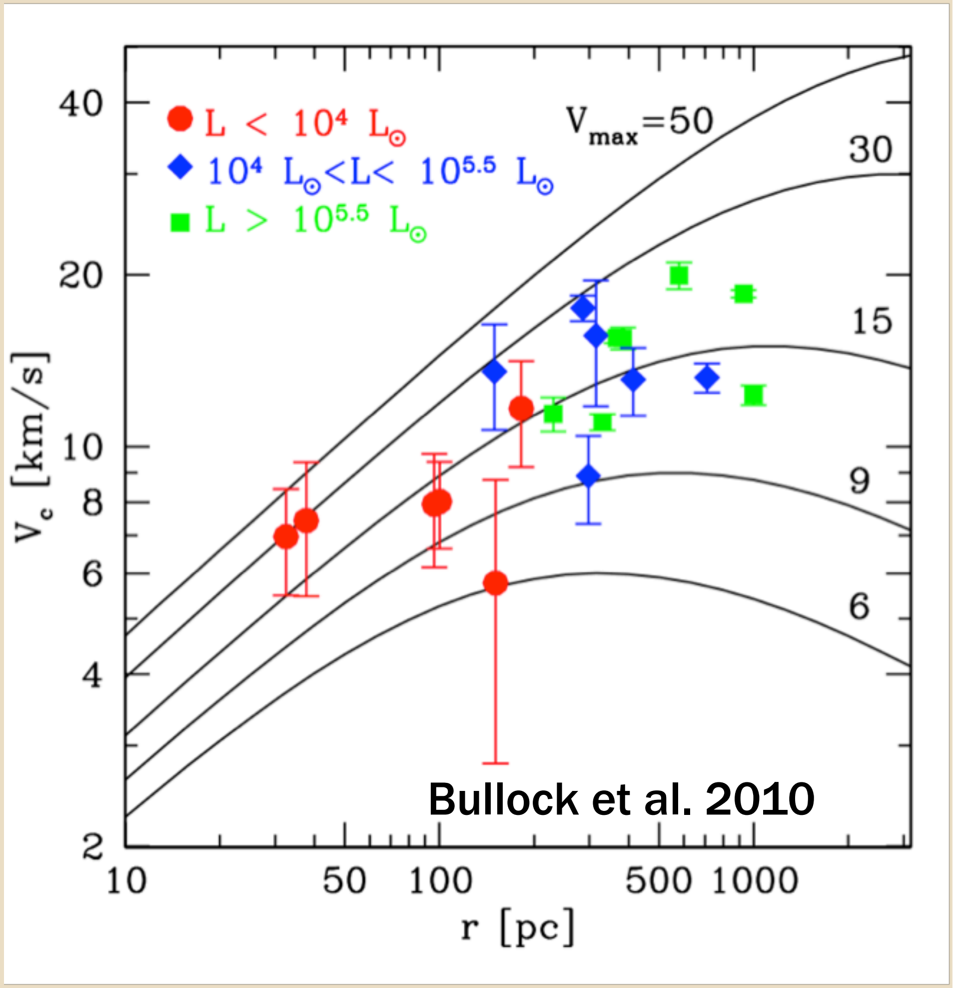



Simulated Milky Way mass dark matter halos

# MEASURING THE SMALL SCALE POWER SPECTRUM IS DIFFICULT WITH STAR TRACERS

- Kinematic measurements rely on bright stars, of which there are very few in small halos
- Stars occupy <100 pc of their DM halo which is believed to extend out ~kpc even for small halos
- Some fraction of halos may contain no stars at all.



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

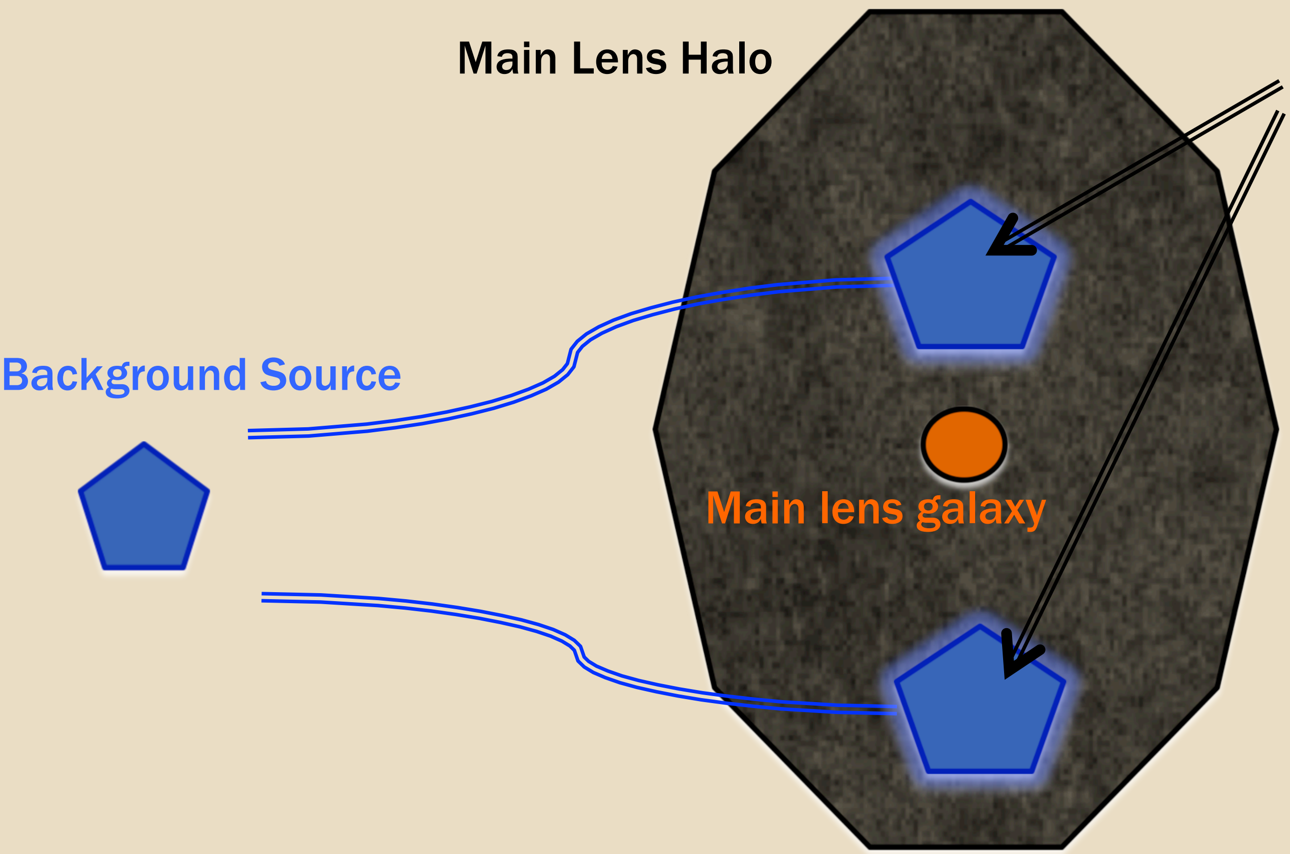
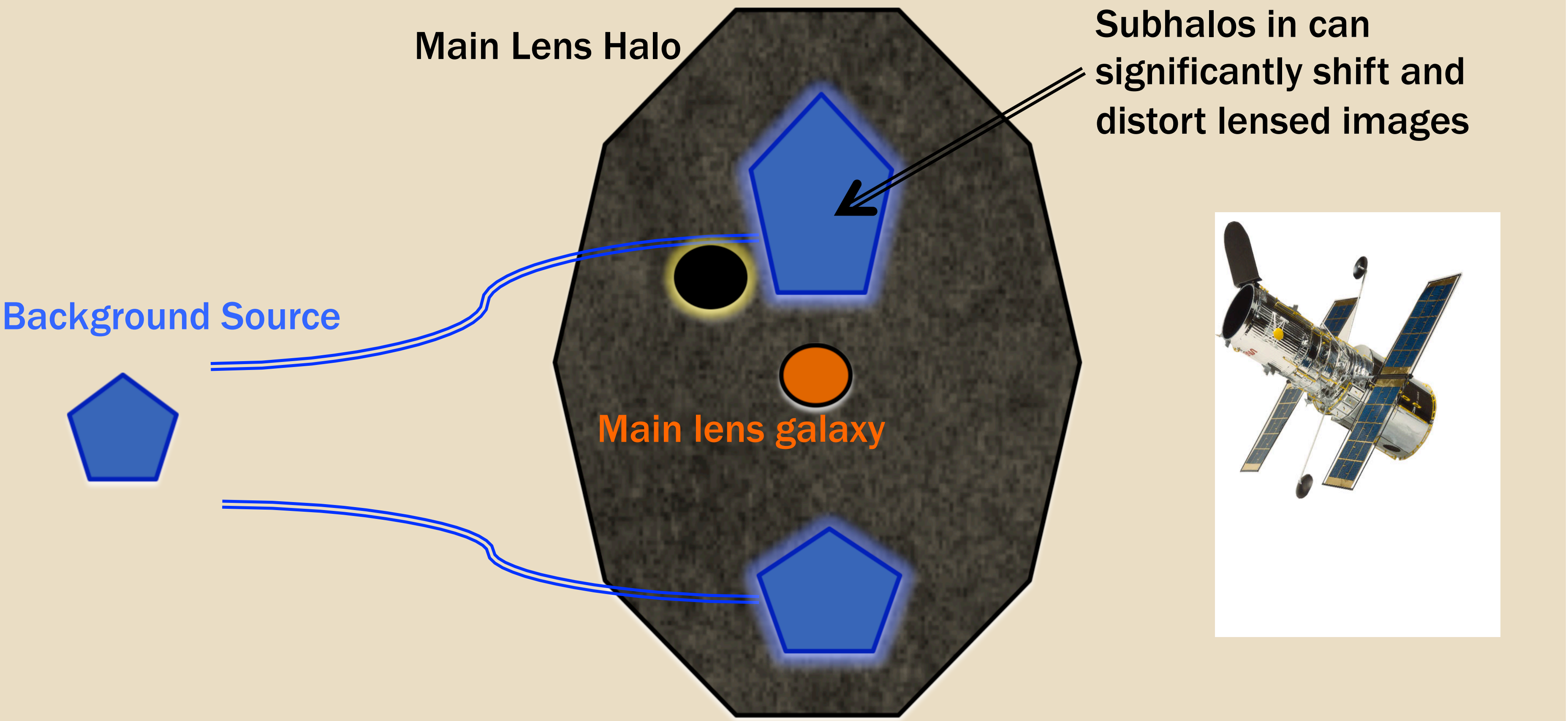


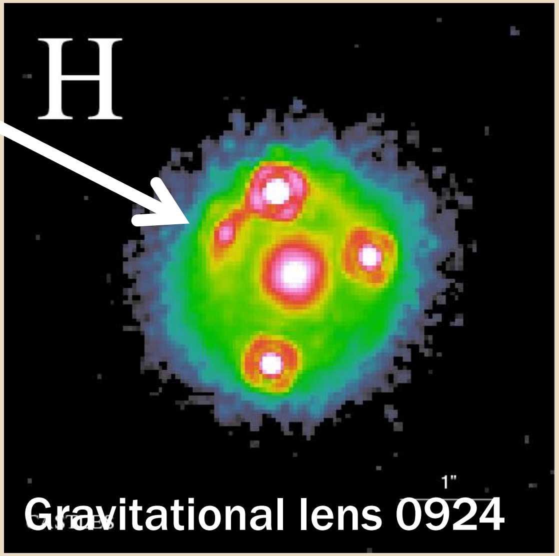

Image positions and brightnesses depend on the mass distribution of the deflector



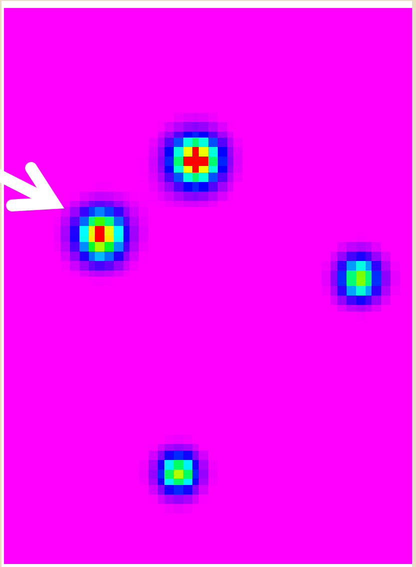
Main Lens Halo
Subhalos in can significantly shift and distort lensed images
Background Source
Main lens galaxy

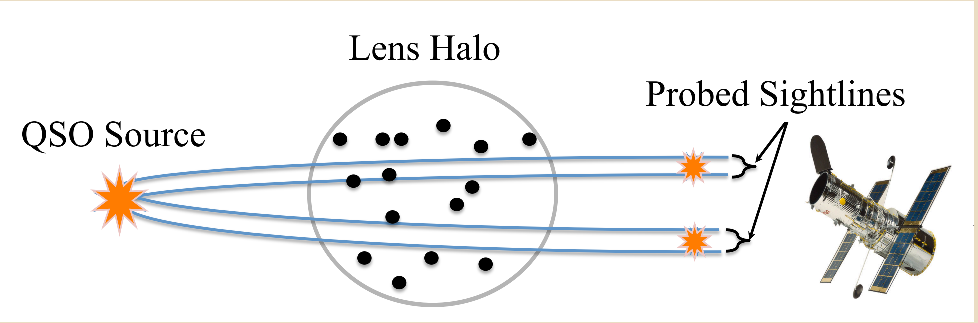
# STRONG GRAVITATIONAL LENSING IN REAL LIFE

**Observed quad lens**

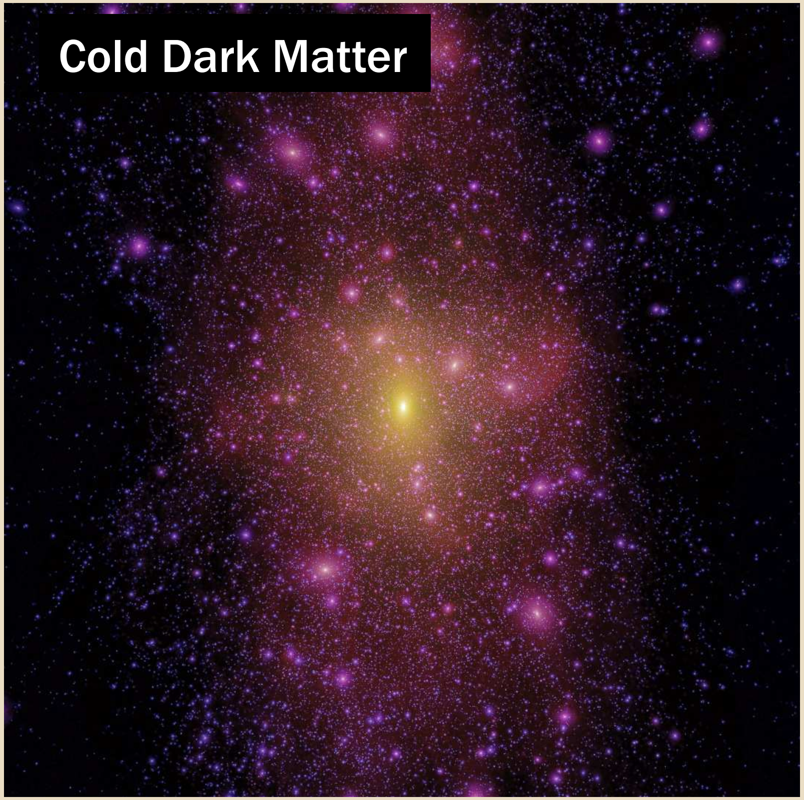


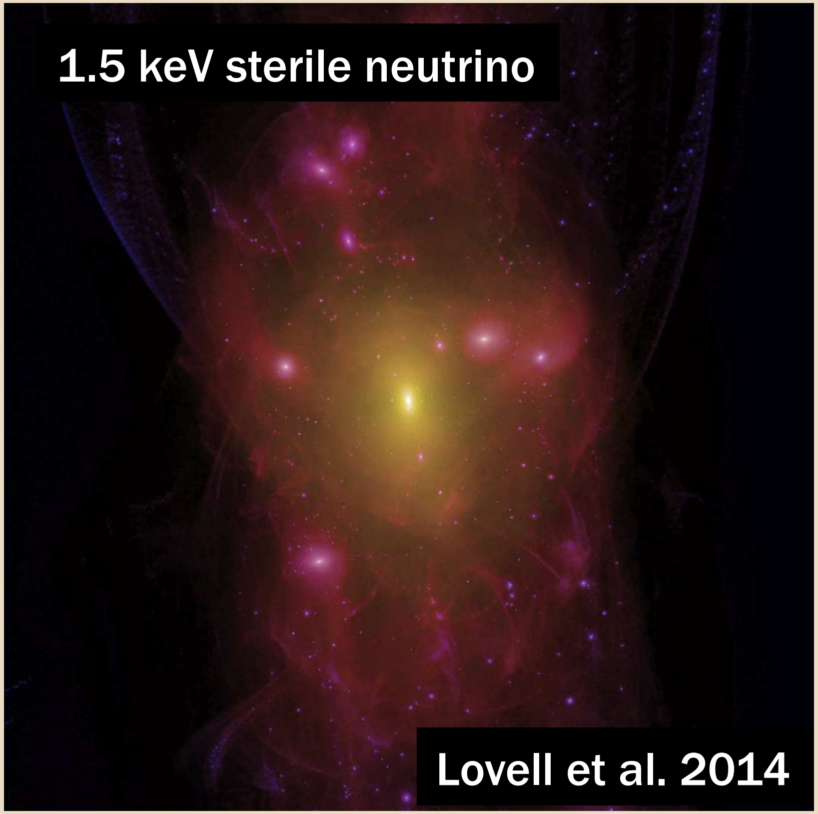

**Smooth halo model prediction**





# WITH ENOUGH LENSES IT IS POSSIBLE TO DISTINGUISH BETWEEN THESE SCENARIOS

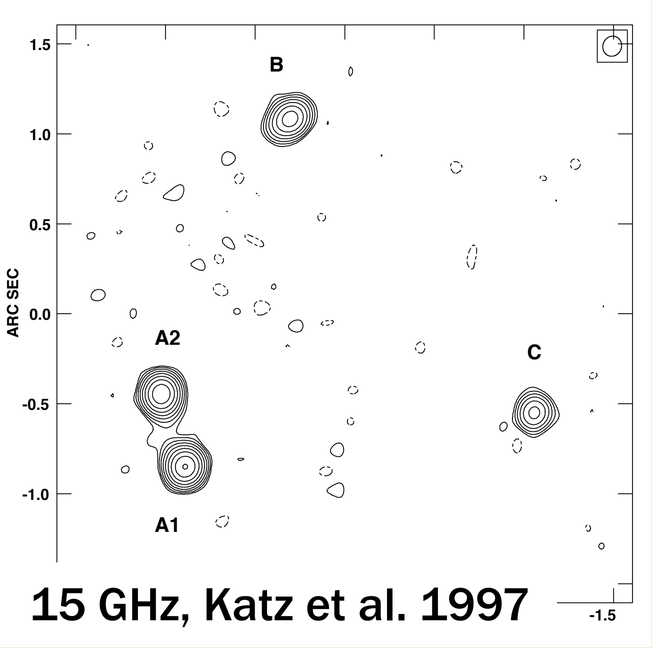



Simulated Milky Way- mass dark matter halos

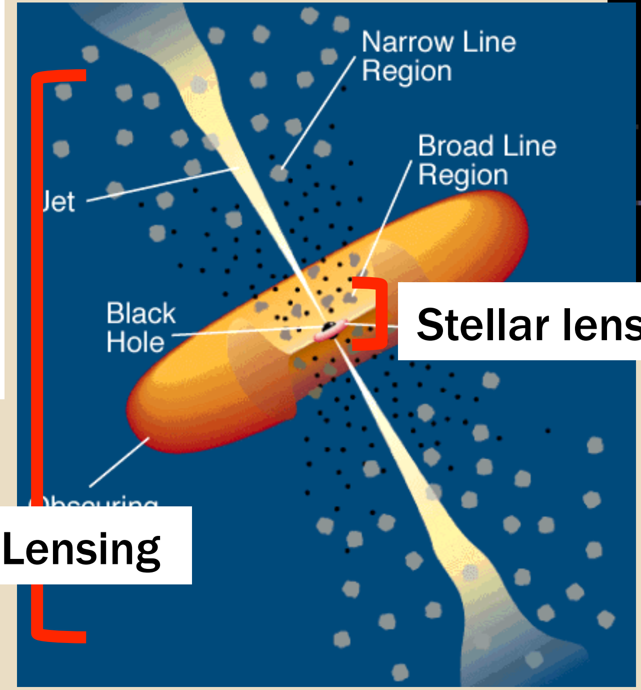
# THE LENS MASS SENSITIVITY DEPENDS ON THE SIZE OF THE *SOURCE*

**Lensed Radio Jet**

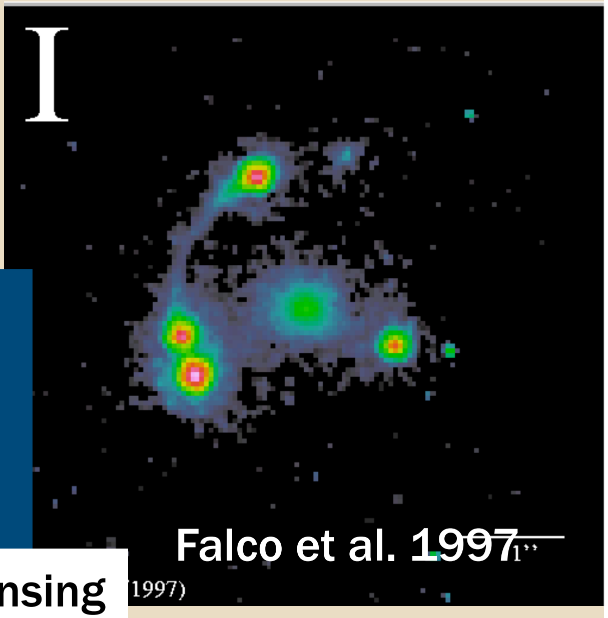



15 GHz, Katz et al. 1997

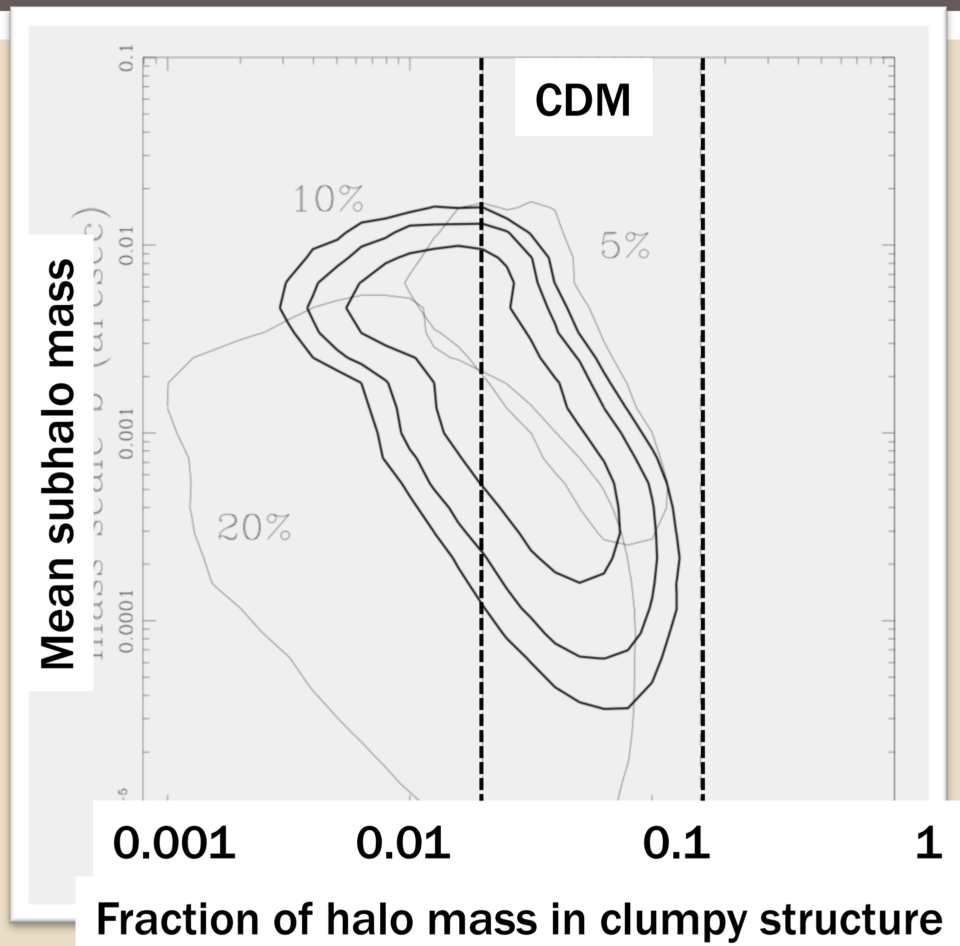
Gravitational lens MG 0414




**Lensed Accretion Disk**



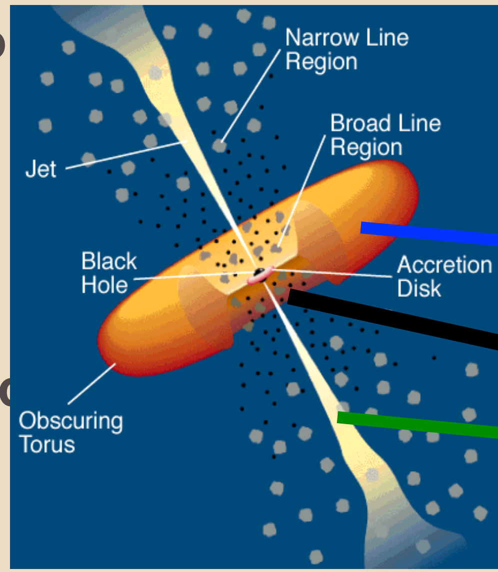
# THERE ARE ONLY 9 RADIO LOUD QUAD LENSES KNOWN

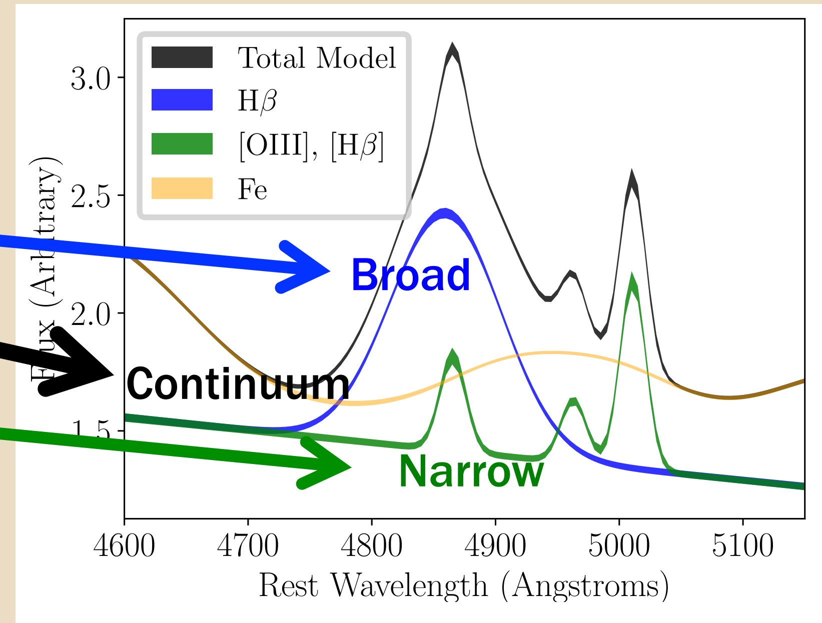



Dalal and Kochanek 2002, 7 radio-loud lens systems

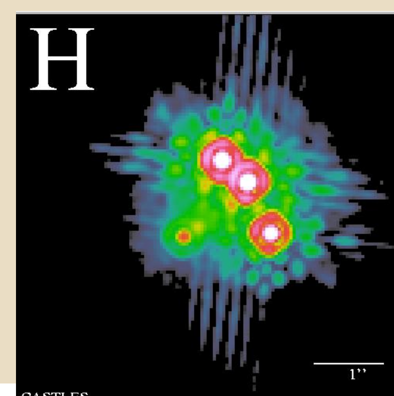
# INCREASE THE SAMPLE OF LENSES USING AGN NARROW LINE EMISSION

- All quasars sho significant narrow line emission - **can double the number of systems used t detect substructure**




- Narrow-line is not variable and not microlensed

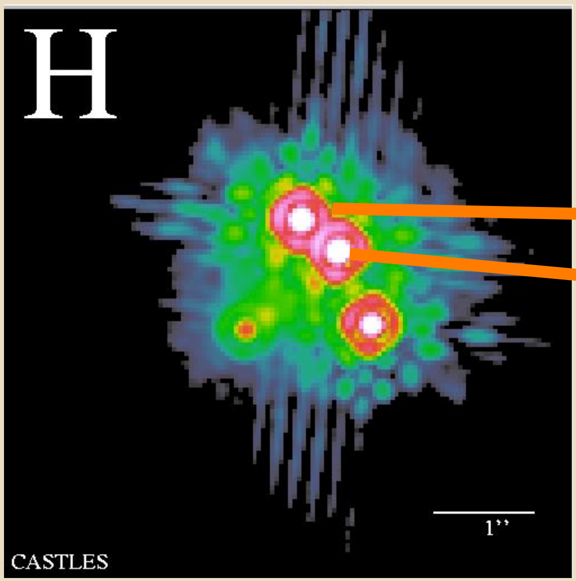


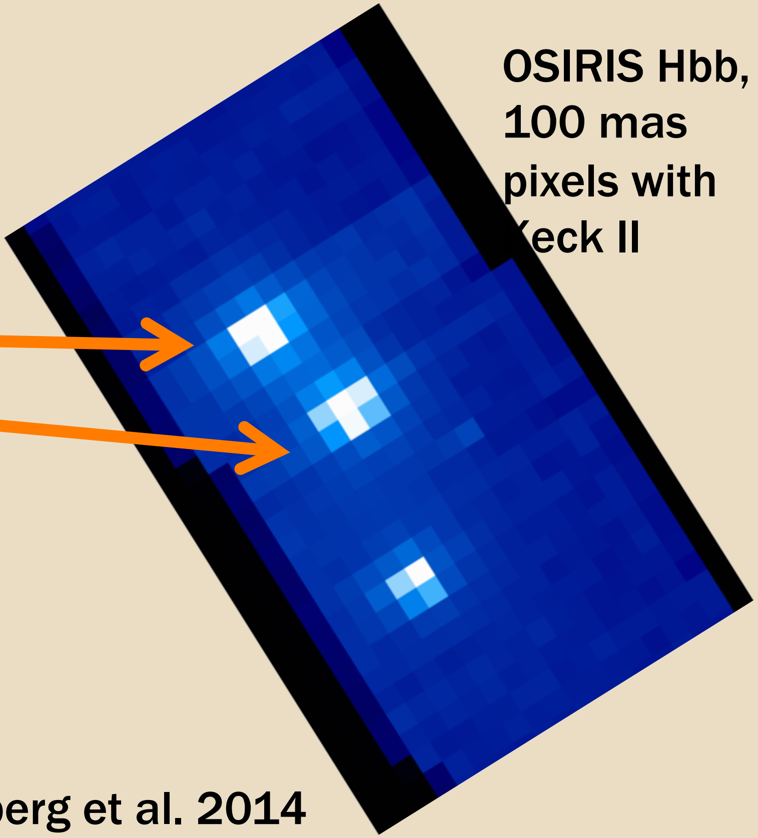

Need high res, spatially resolved spectroscopy

# METHOD 1: KECK OSIRIS

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

HST NICMOS

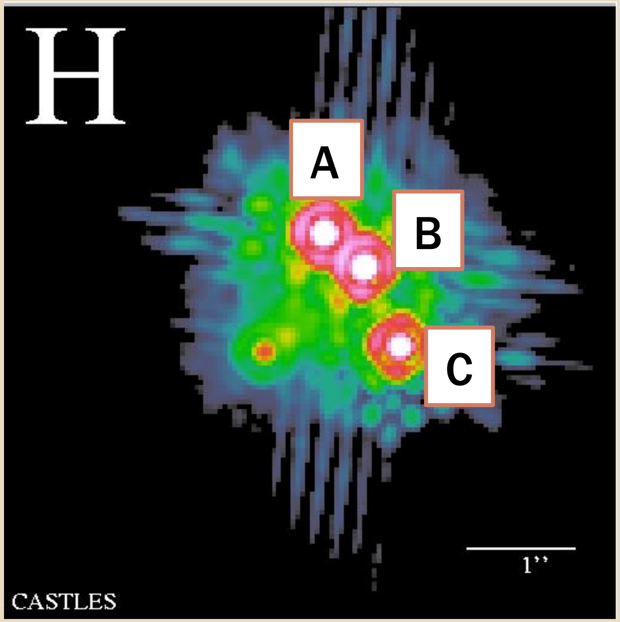


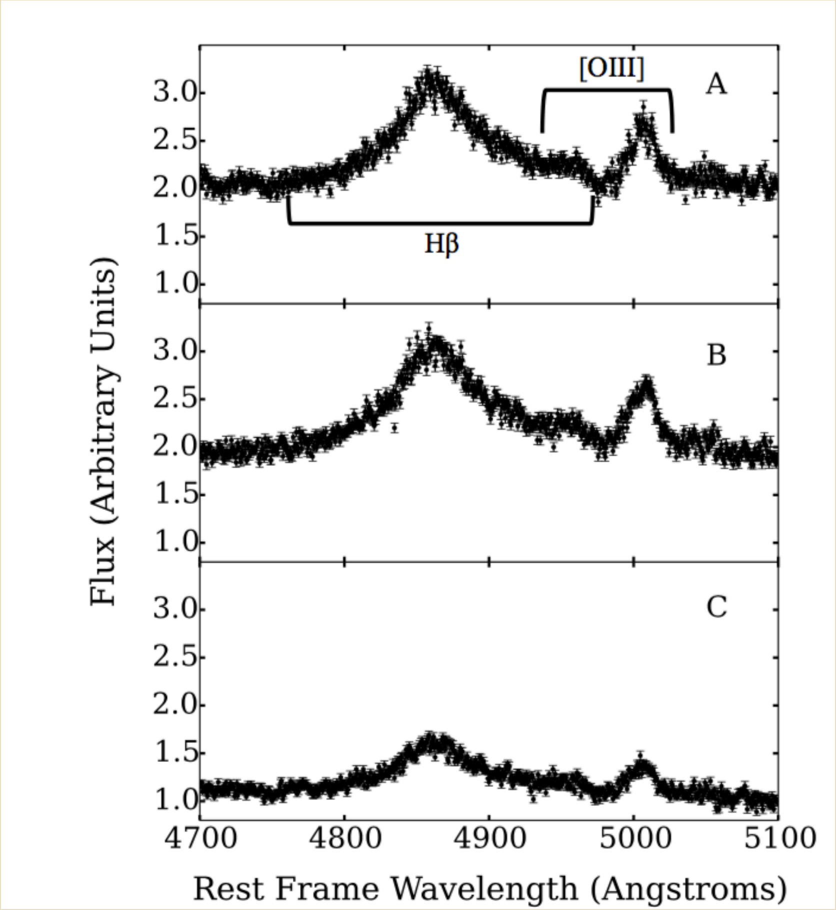



OSIRIS Hbb, 100 mas pixels with Keck II

Nierenberg et al. 2014

# EXAMPLE 1: NL LENSING IN B1422+231, OSIRIS WITH KECK AO

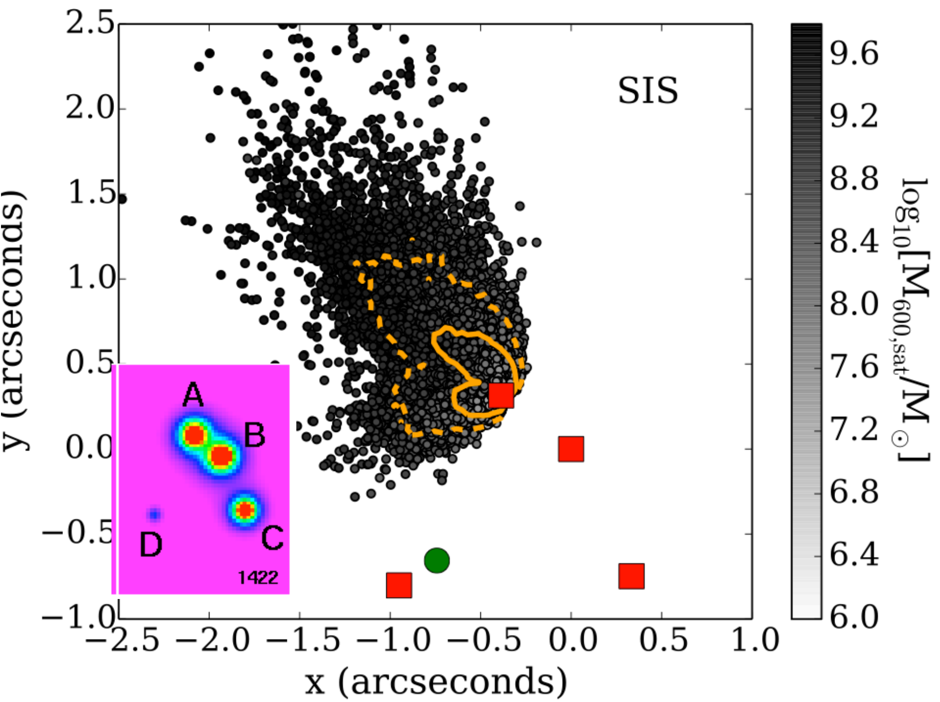


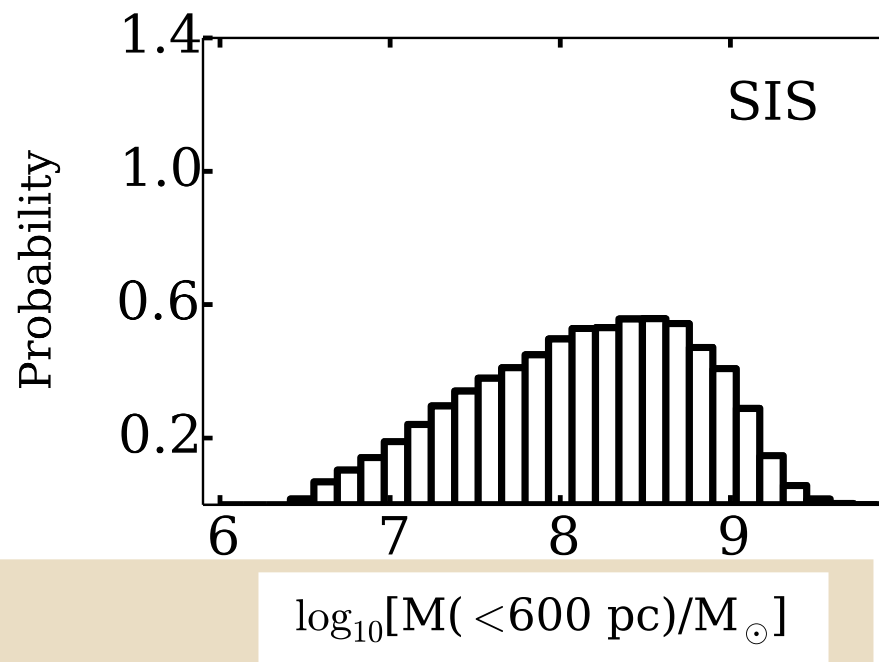




Nierenberg et al. 2014

# INFERRED PERTURBATION NEAR IMAGE A

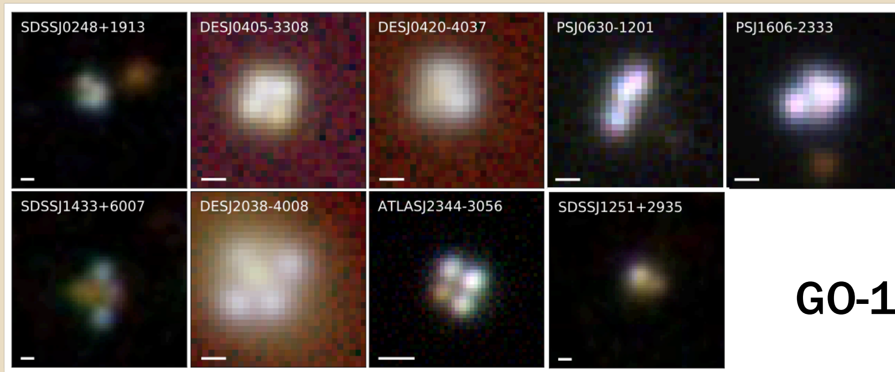
ρ(r)~r^(-2)




**Data for four more systems with OSIRIS**

# EVEN MORE LENSES WITH THE WFC3 GRISM

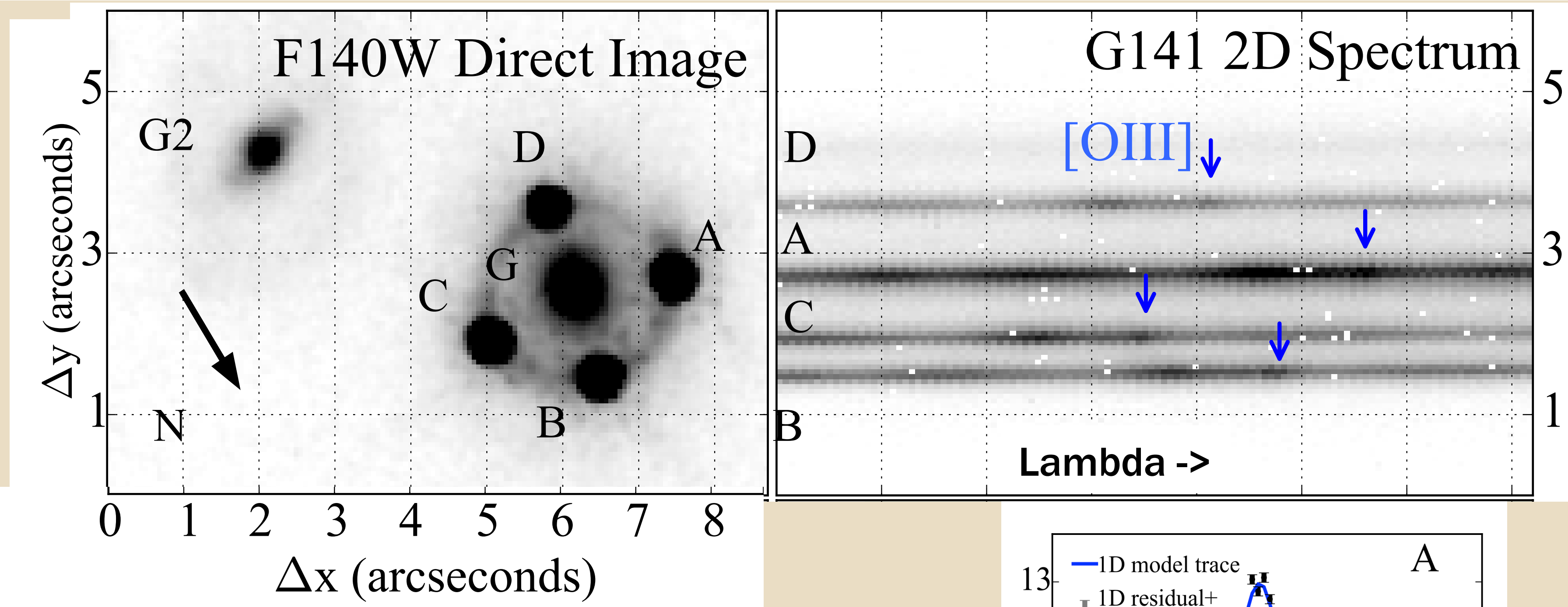



GO-15177

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

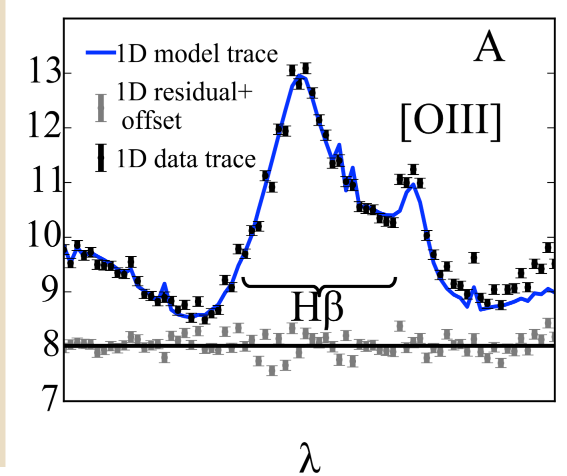
+ 3 more with Keck-OSIRIS –e.g. Nierenberg et al 2014

# PROOF OF METHOD: GRAVITATIONAL LENS HE0435-1223

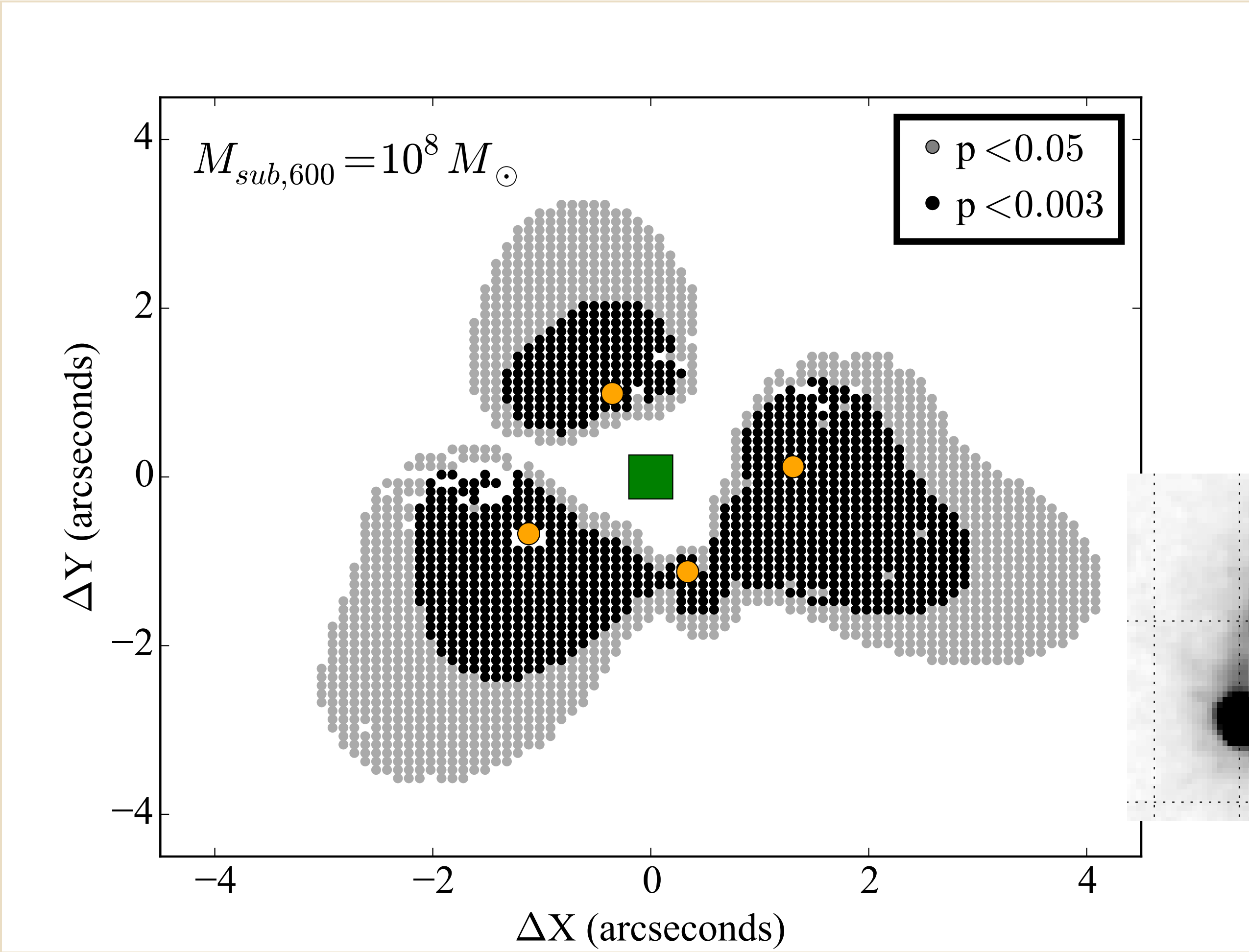


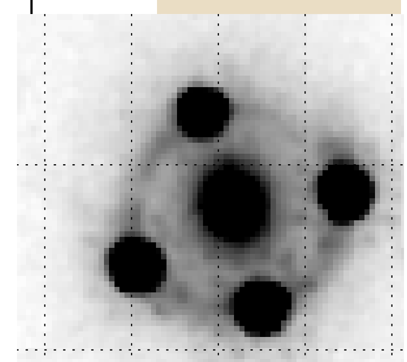

HST-GO 13732 PI: Nierenberg

1D, PSF-weighted grism trace,
Nierenberg et al. 2017



# LIMITS ON THE PRESENCE OF AN NFW PERTURBER



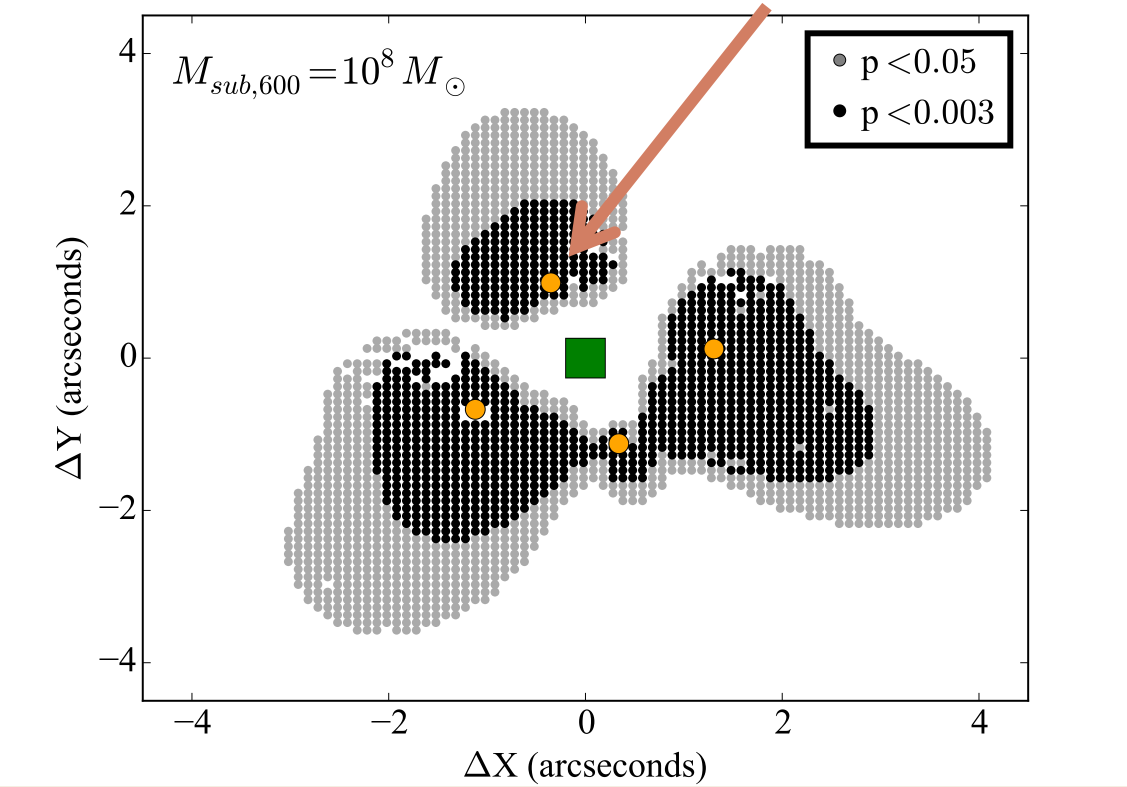



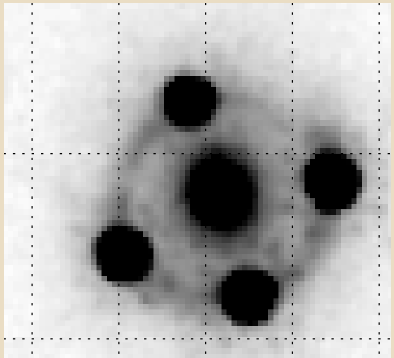
**~1” radius excluded around each image (~5.5 kpc)**

# APPROXIMATE CDM EXPECTATIONS

*Ignoring* the effects of tidal stripping, DM only sims (Han et al. 2016) give optimistic order of magnitude for the two scenarios:

**Expect ~1/( 0.1 with none in Rs) 10^8 M 600 satellites**



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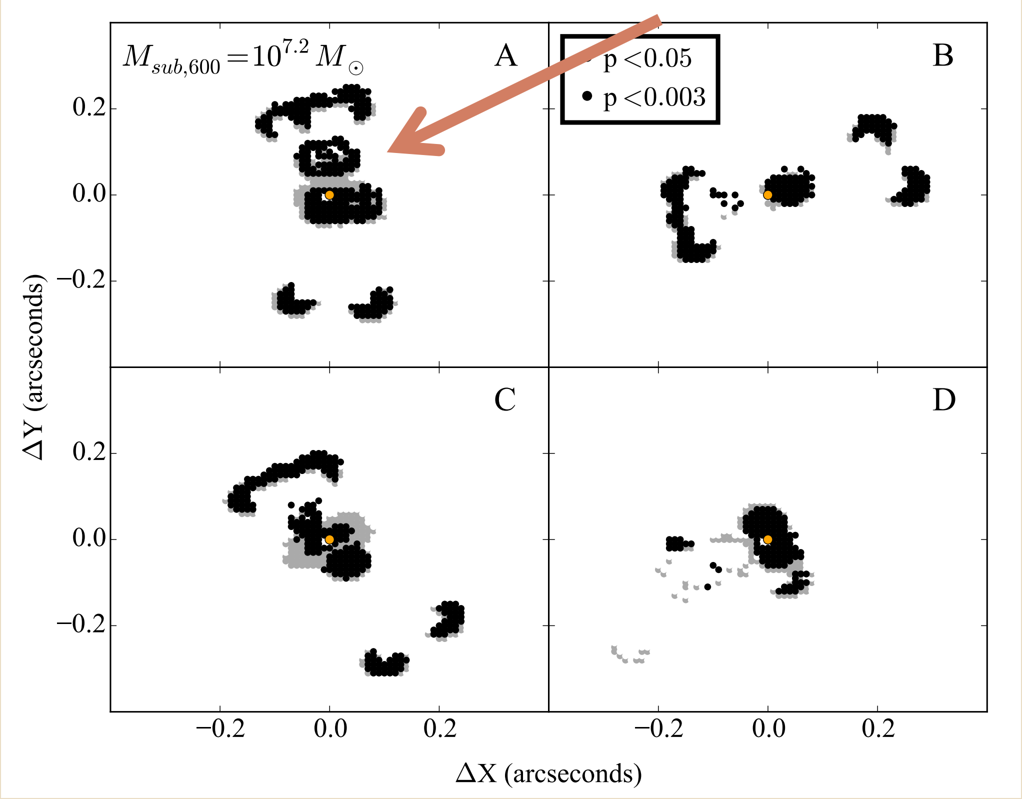
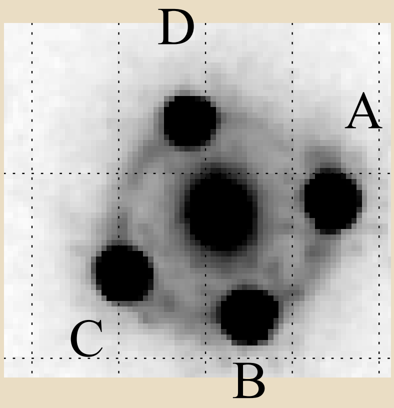
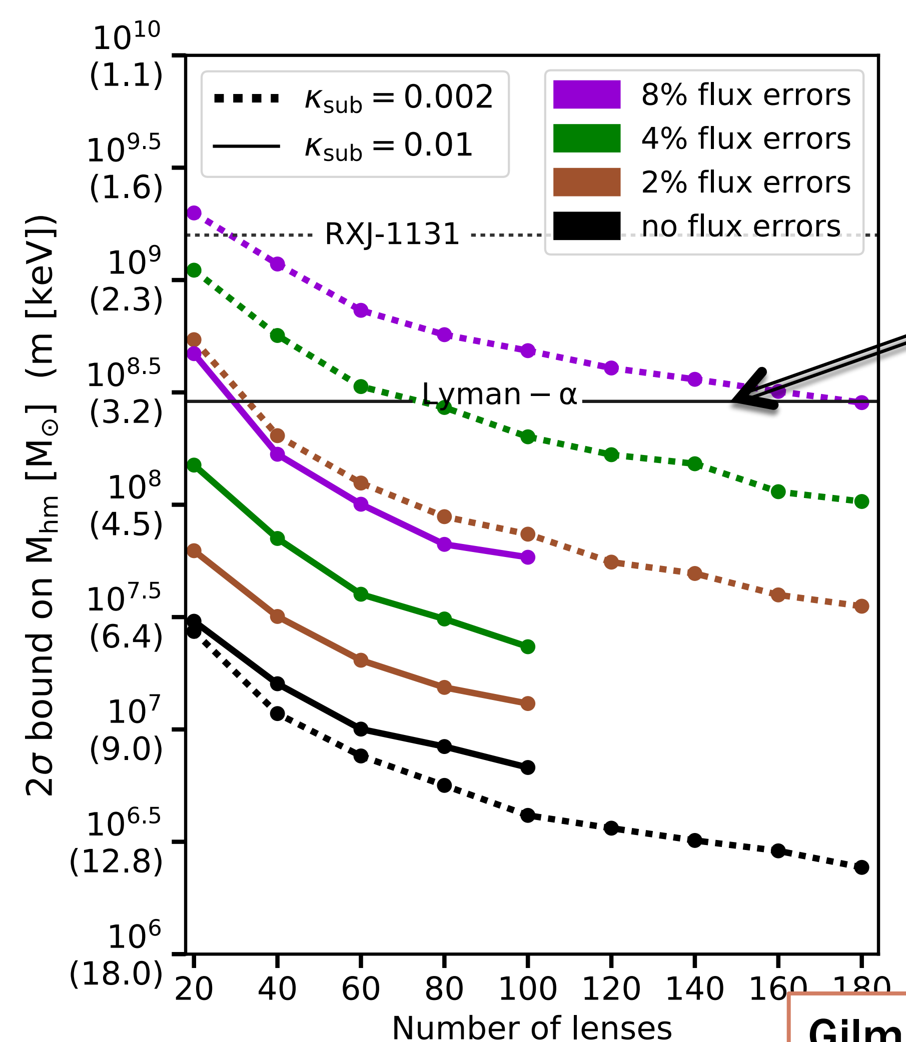


# HOW MANY LENSES DO WE NEED TO GET A NEW CONSTRAINT ON WARM DARK MATTER?

**Simulate realistic lenses with full populations of dark matter subhalos**

**Neglect added boost to signal from line of sight structure**




**Current limits on WDM cutoff from Ly-alpha forest**

**Gilman et al. 2018**

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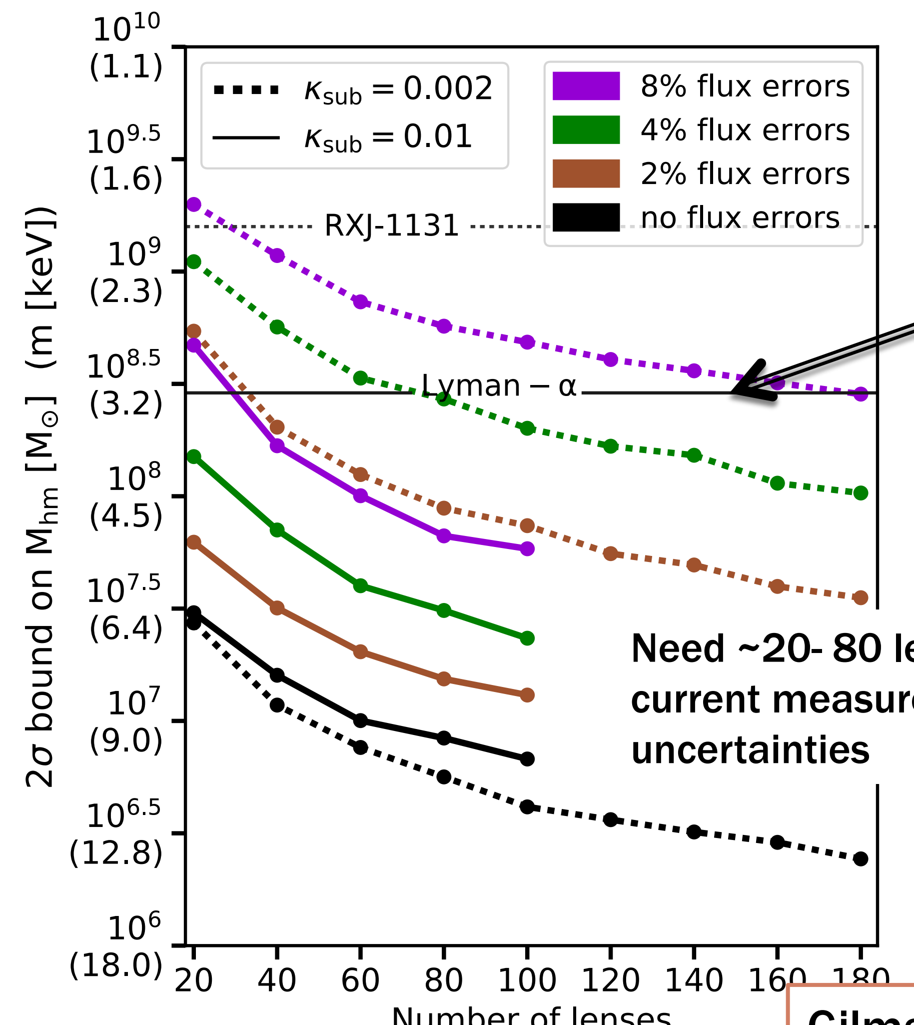


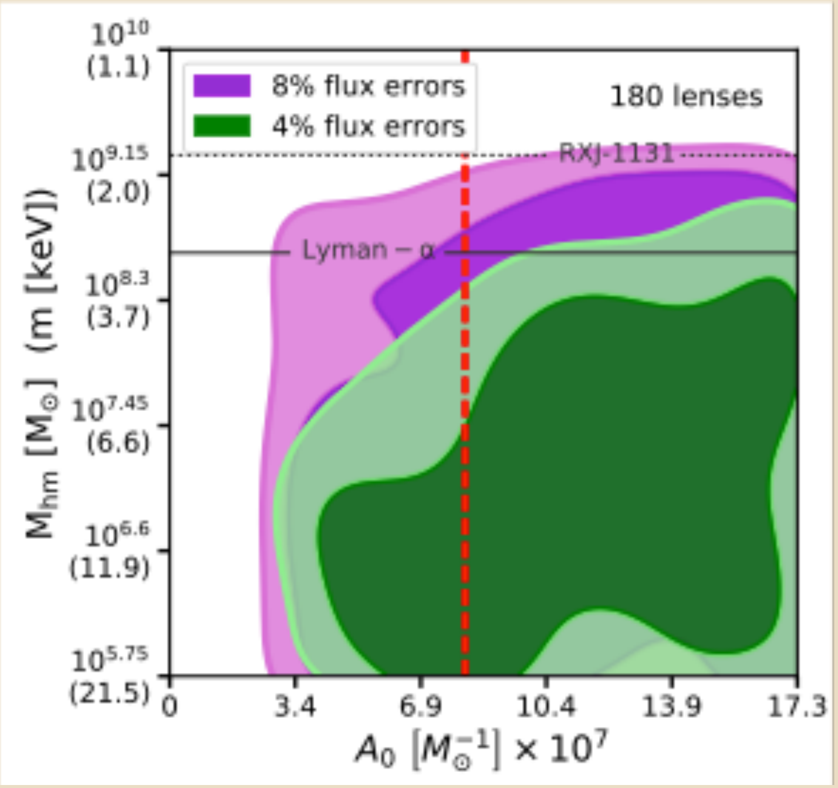

**Current limits on WDM cutoff from Ly-alpha forest**

**Need ~20- 80 lenses given current measurement uncertainties**

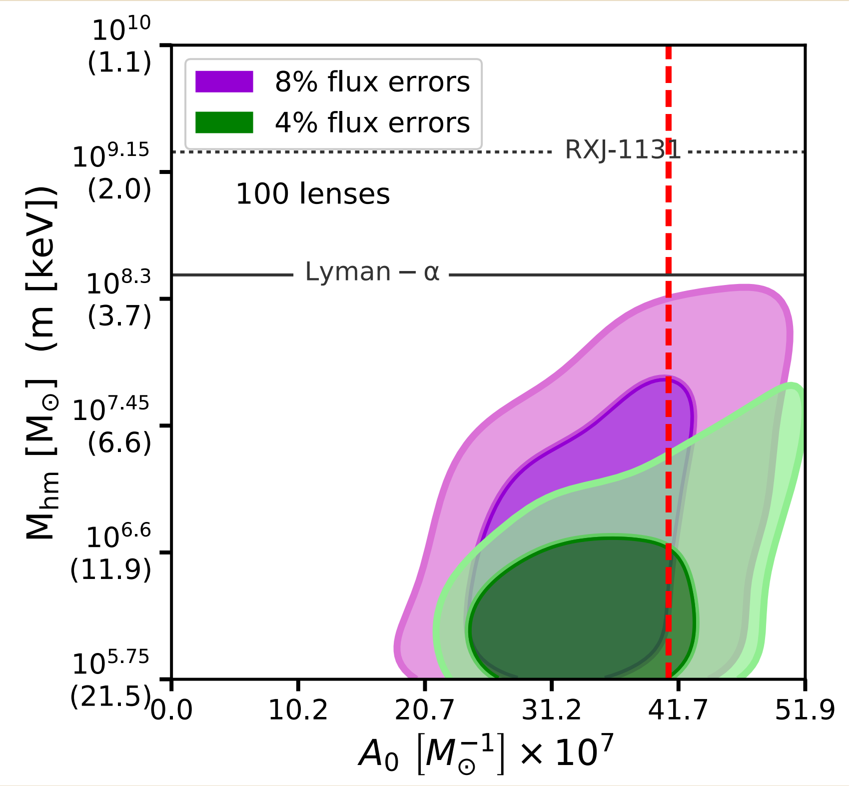
**Gilman et al. 2018**

# DISTINGUISHING BETWEEN A CUTOFF AND CHANGE IN NORMALIZATION

**No subhalos within host scale radius**




**Subhalos follow NFW radial profile of host halo**



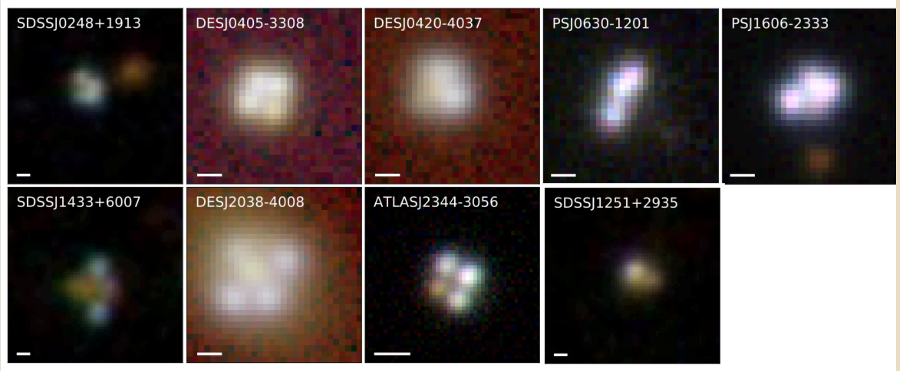

**Gilman et al. 2018**

**NB: No LOS substructure**

# CAN WE GET ~100 QUAD QUASAR LENSES?

**YES!!**

- ALREADY have 18 systems with spatially resolved narrow-line emission data
- Next <5 years: DES/PANSTARRS/GAIA teams are finding new systems (~10 since last HST proposal, more on the way, a total of ~100 expected)
- Next decade: HUNDREDS are forecast to be discovered in LSST (Oguri and Marshall 2008)

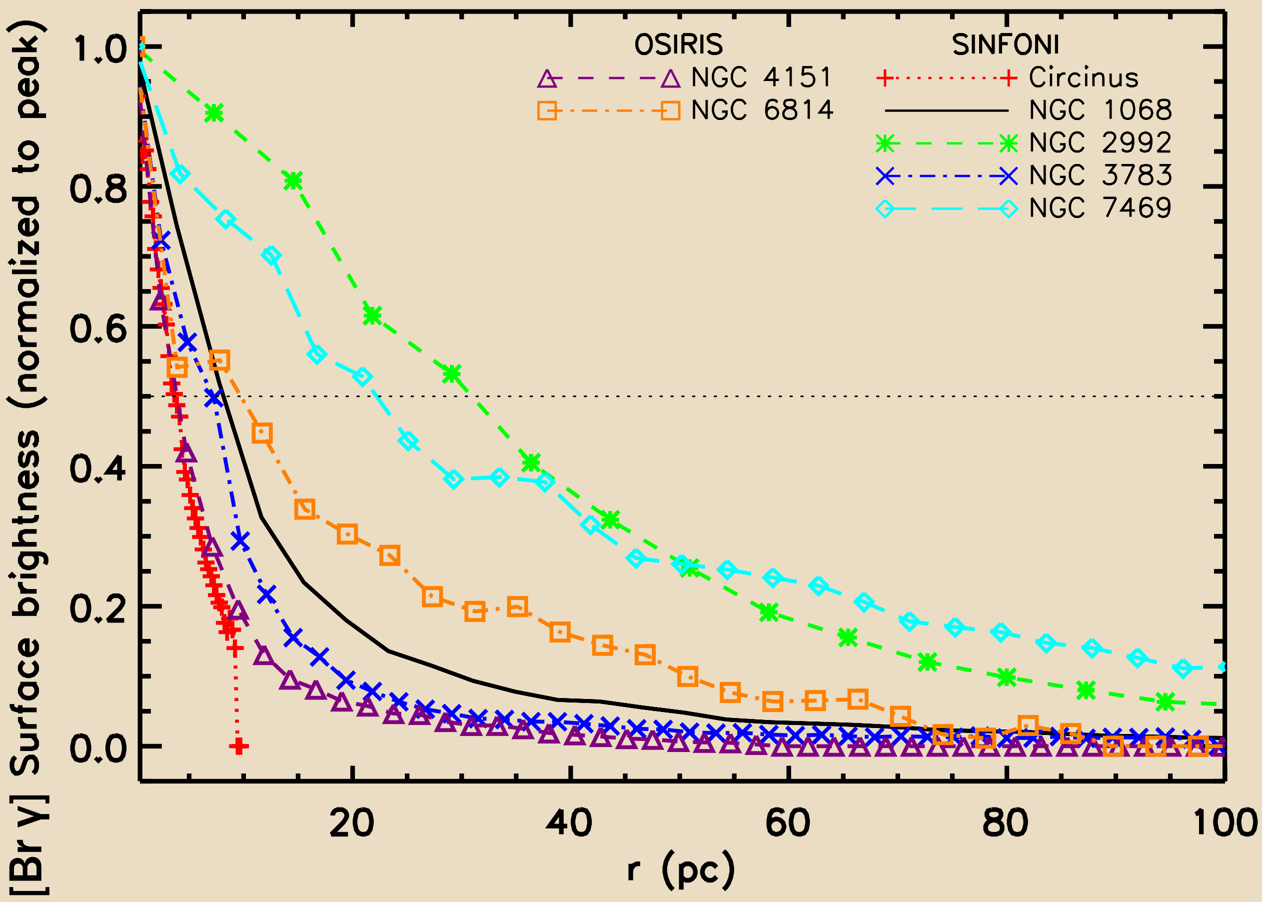



JWST will enable study of fainter systems and systems inaccessible to ground/HST WFC3

# CONCLUSIONS (THANKS FOR LISTENING!)

- Strong gravitational lensing is a powerful tool for constraining the properties of dark matter on small scales
- Narrow-line lensing is a promising new way to expand the sample of gravitational lenses with can be used to probe dark matter substructure
- The WFC3 grism provides sufficient spatial and spectral resolution to detect low mass subhalos, well below the regime where stars become unreliable tracers of dark matter.
- With the current sample of narrow-line lenses we expect to be able to place new constraints on WDM/CDM.
- Thousands of new lenses will be discovered in LSST and can be followed up with this method with JWST/next generation of telescopes.

# NARROW LINE LIGHT PROFILE




Müller-Sanchez et al. 2011

# FINITE SOURCE EFFECTS FOR HE0435