TOWARD THE TIGHTEST CONSTRAINT ON THE FREE STREAMING LENGTH

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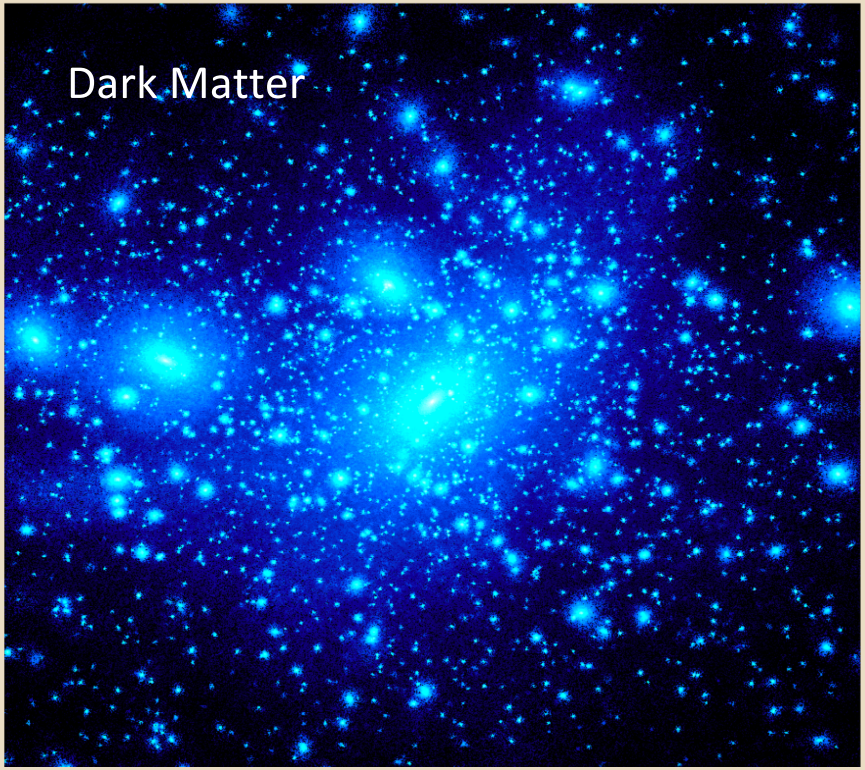
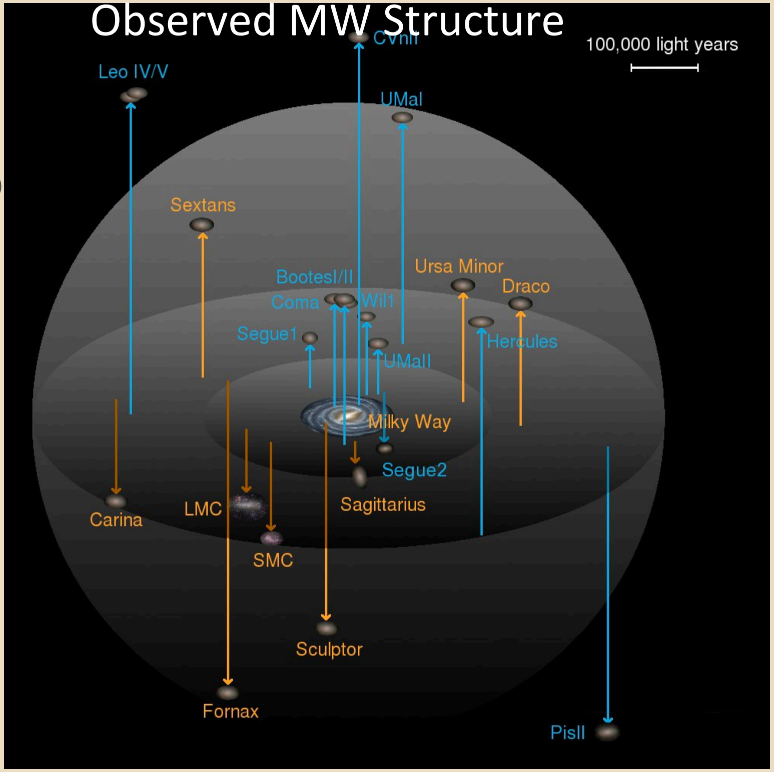
GALAXIES ARE UNCERTAIN TRACERS OF DARK MATTER AT LOW MASSES

Kravtsov 2010



J.T.A de Jong



We have heard/will hear many talks about the complexities of galaxy formation at low mass scales. Given this, **can we measure the halo mass function at low masses? Can we measure it below the mass scale of galaxy formation?**

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

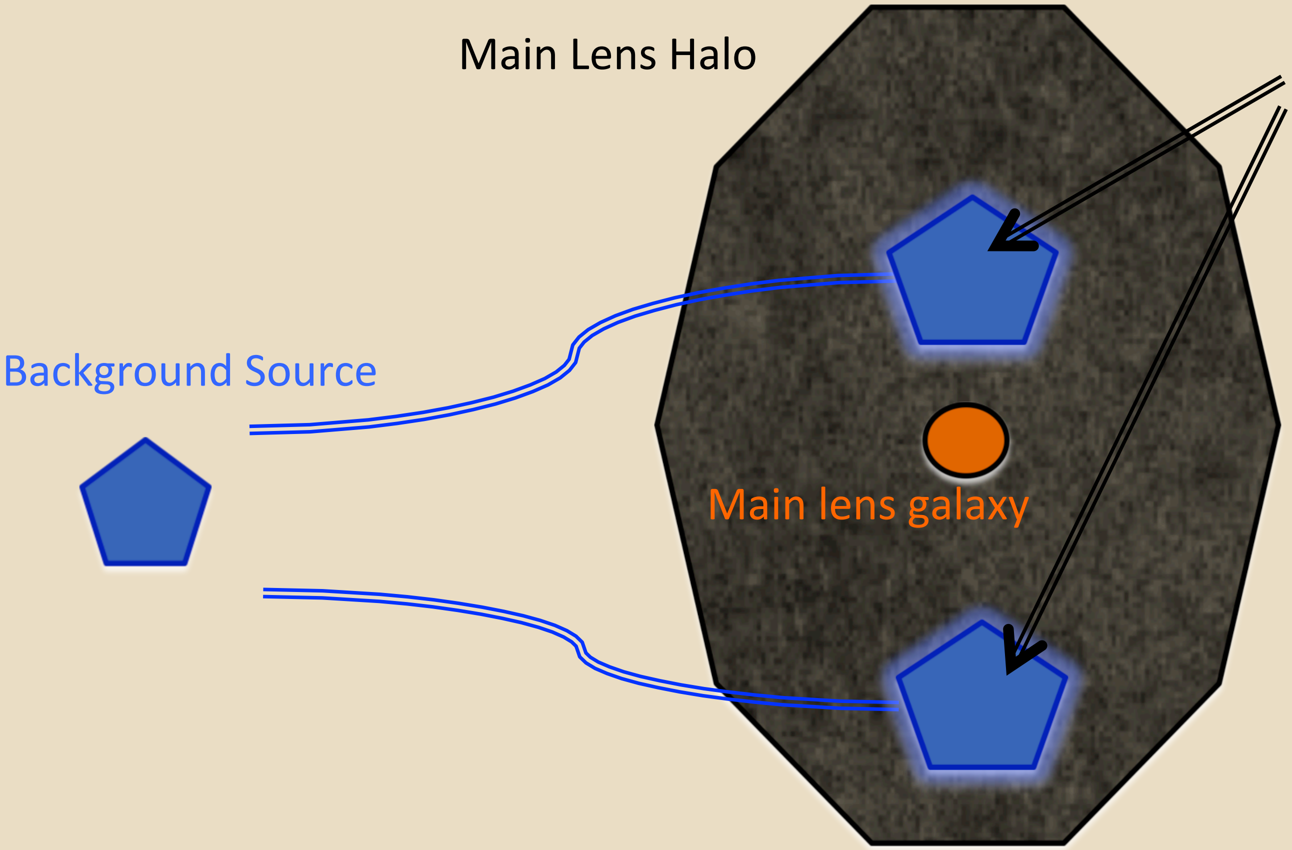
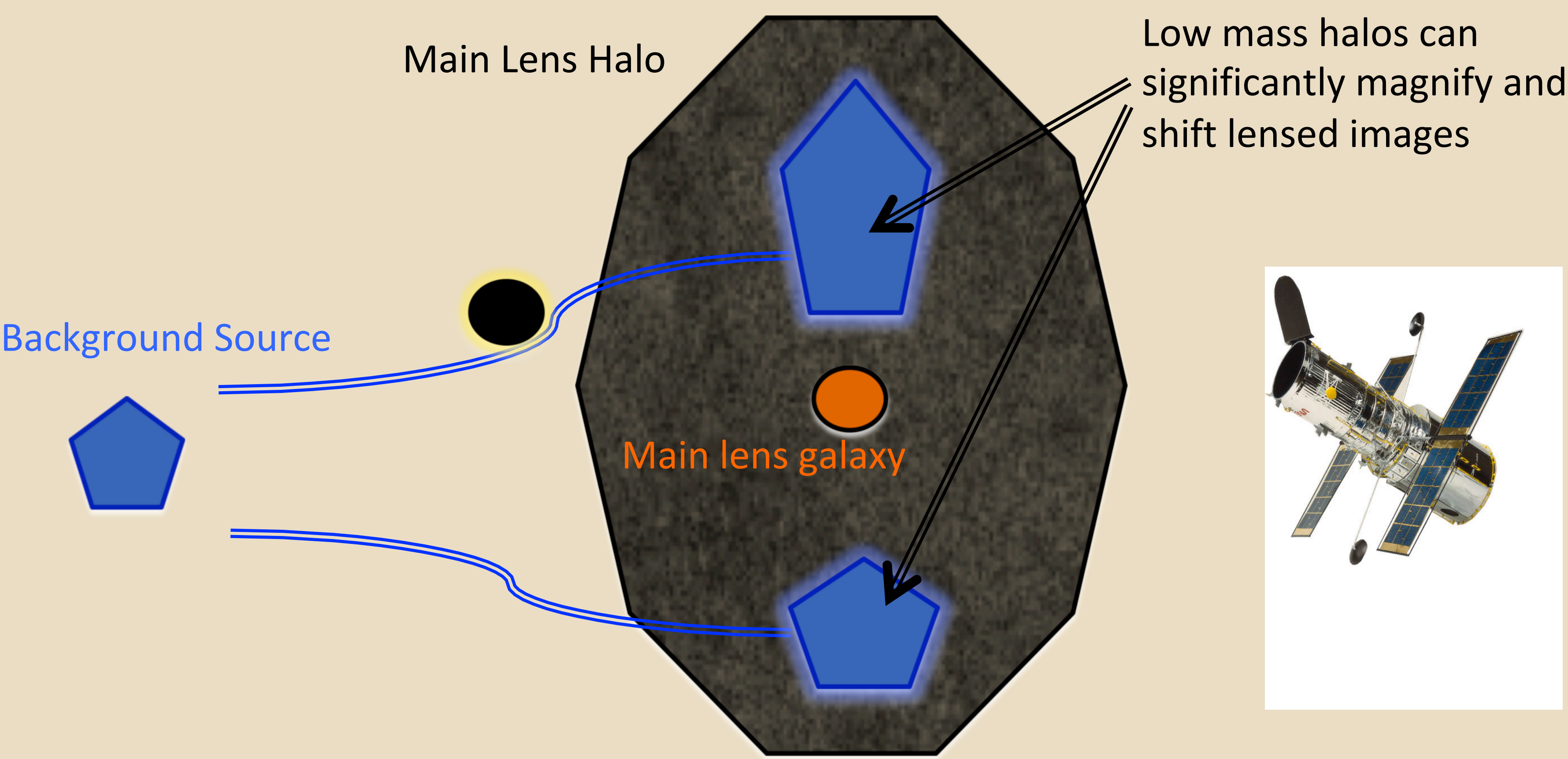
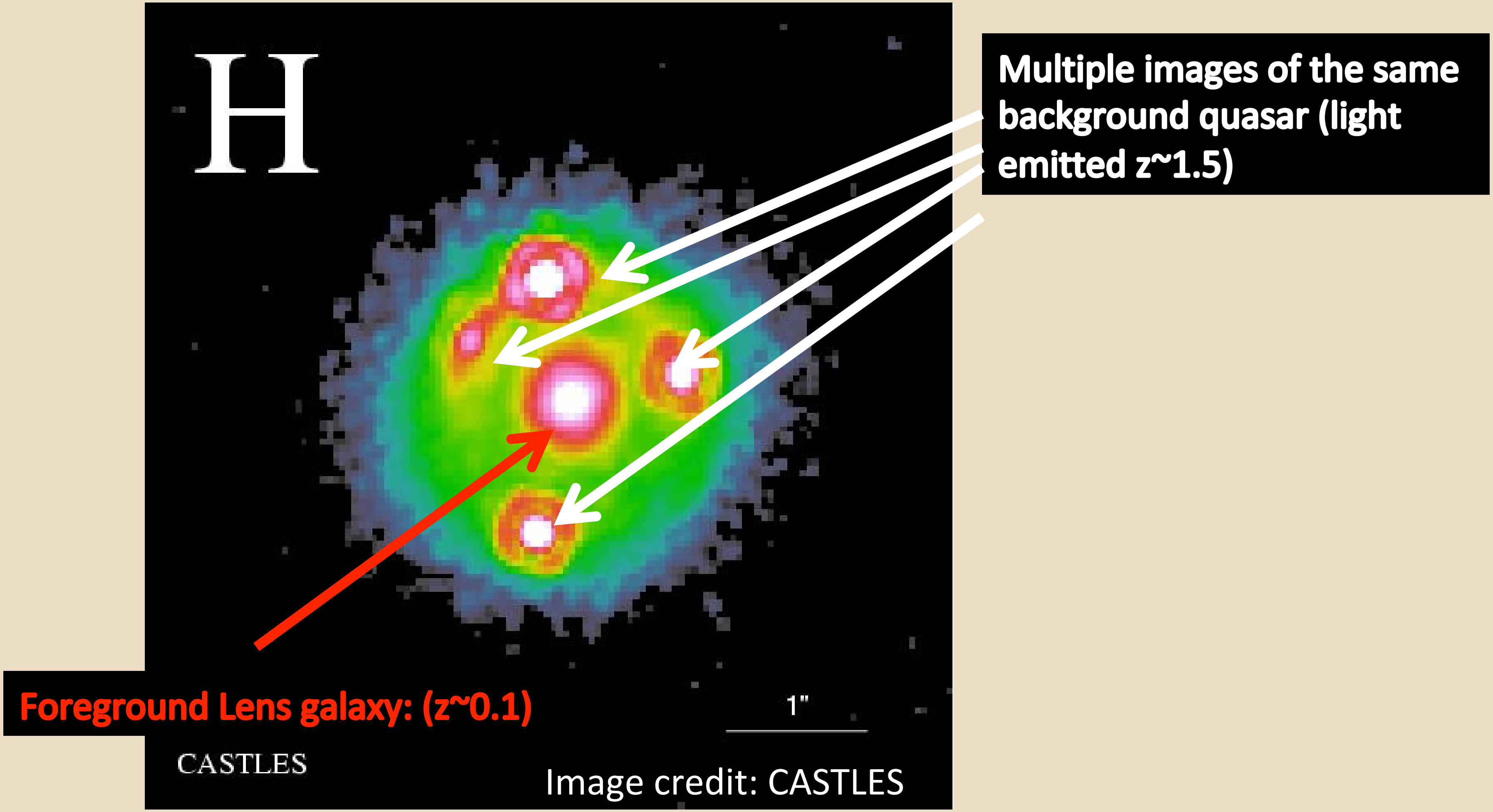


Image positions and brightnesses depend on the mass distribution of the deflector

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

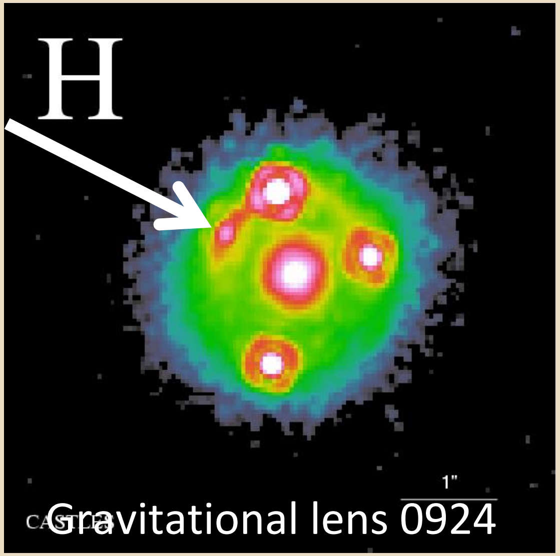


STRONG GRAVITATIONAL LENSING IN REAL LIFE

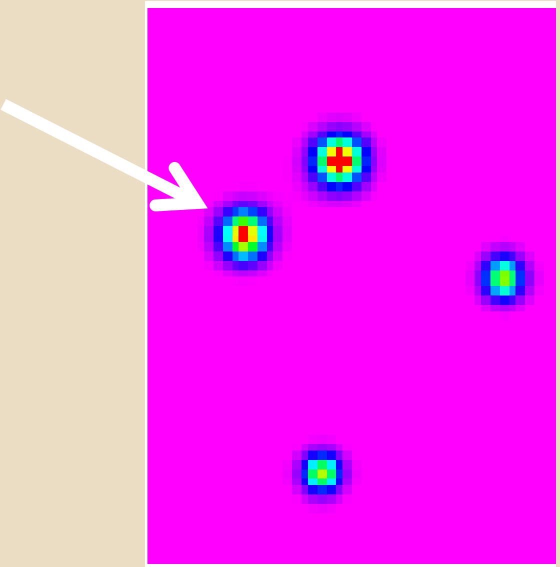


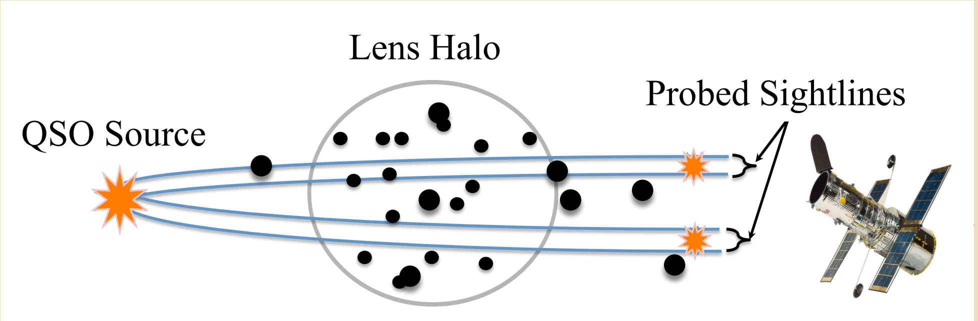
STRONG GRAVITATIONAL LENSING IN REAL LIFE

Observed quad lens



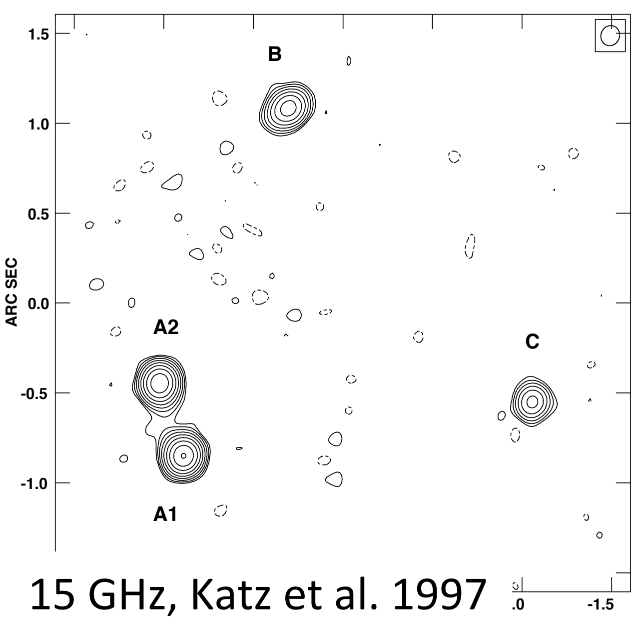
Smooth halo model prediction





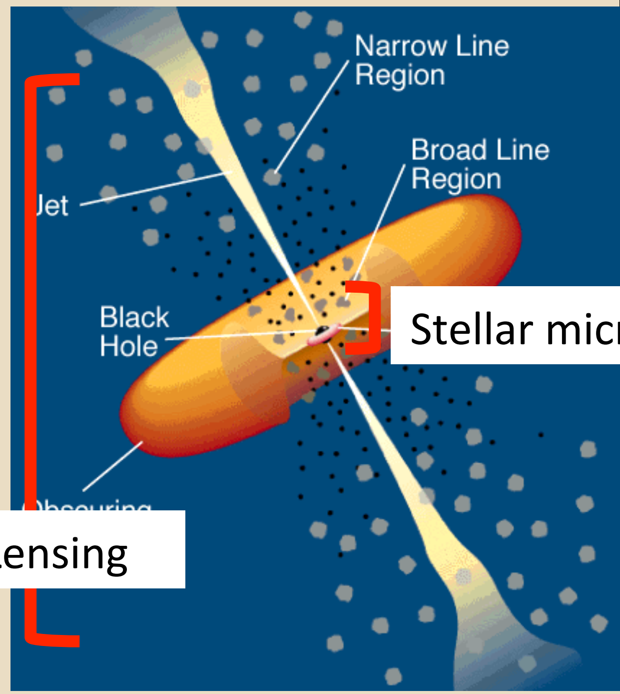
CAUTION!!!

Lensed Radio Jet



15 GHz, Katz et al. 1997

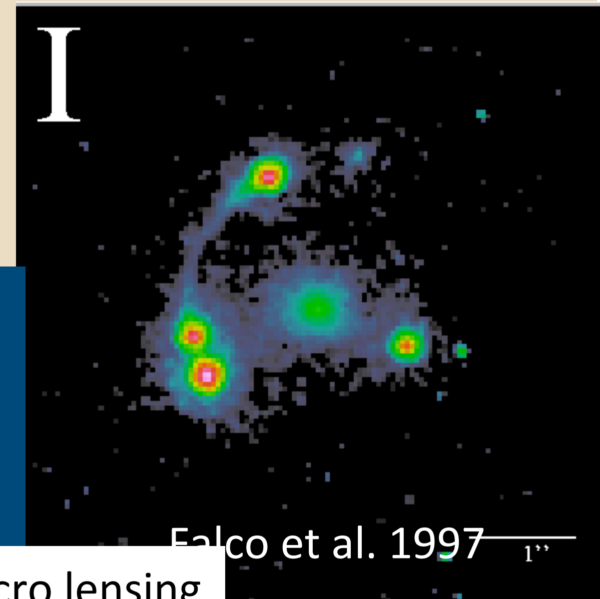
Gravitational lens MG 0414



Stellar micro lensing

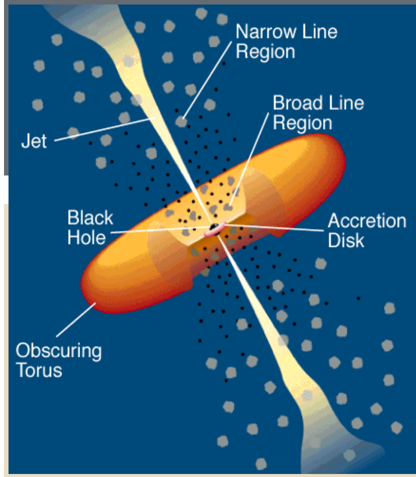
Subhalo Lensing

Lensed Accretion Disk

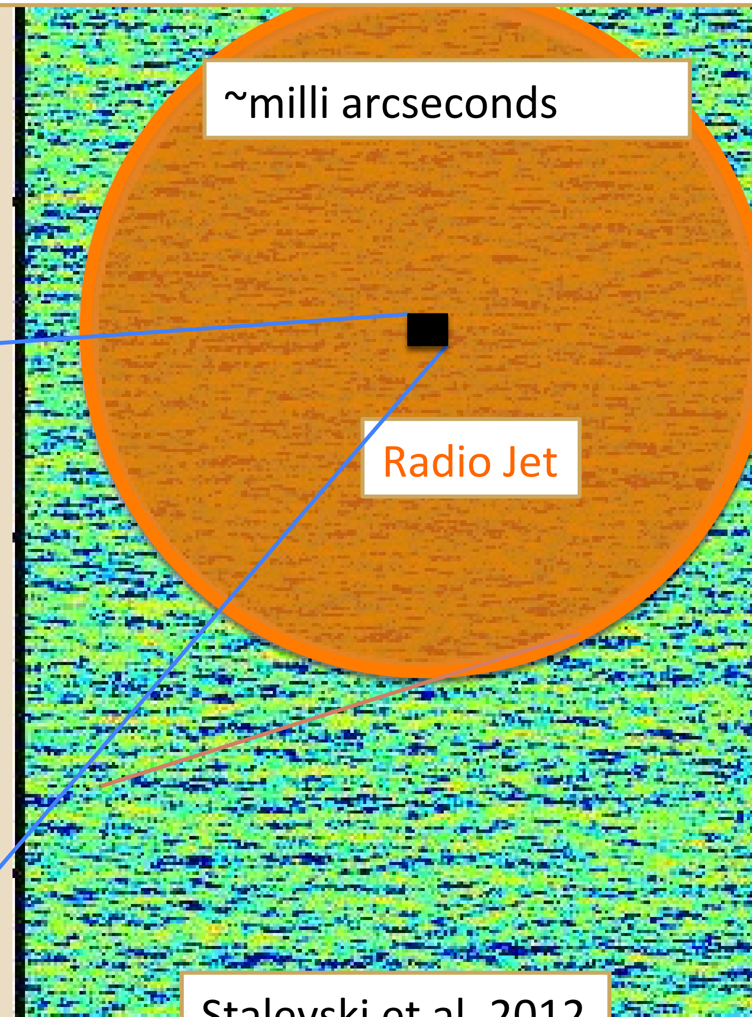


Falco et al. 1997

MICROLENSING



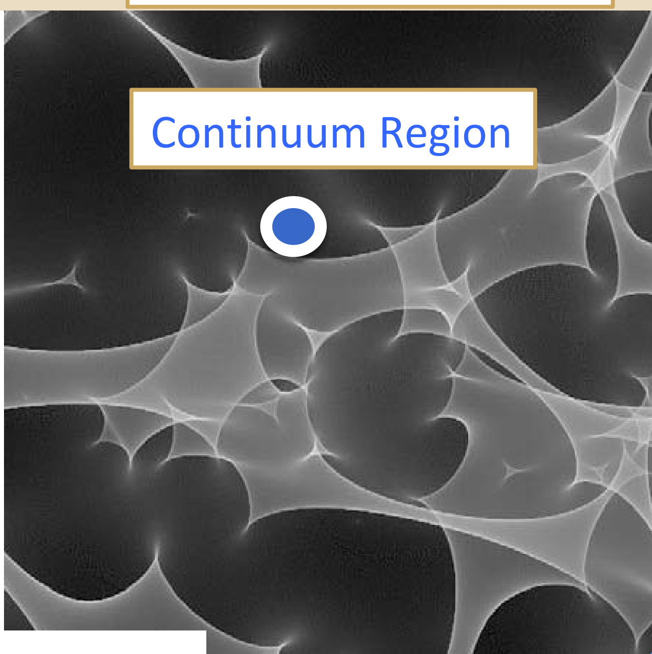
Magnification due to stars in the lens galaxy



~milli arcseconds

Radio Jet

Micro arcseconds



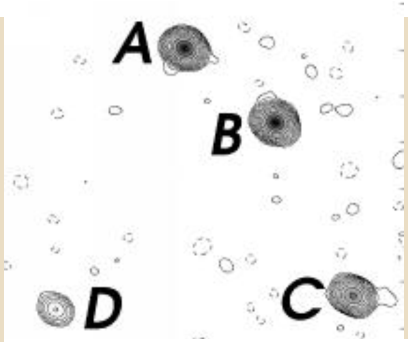
Continuum Region

Gardsten et al. 2009

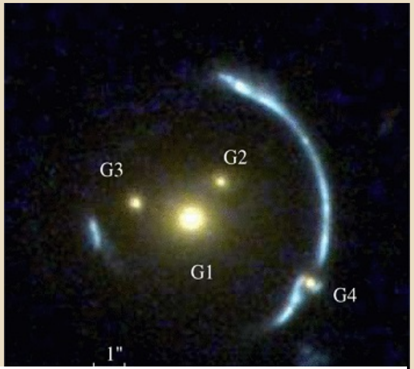
Stalevski et al. 2012

GRAVITATIONAL LENSING AS A PROBE OF DM REQUIRES A ~MAS SOURCE

- Traditionally limited to 7 **radio loud lensed quasars** (Dalal and Kochanek 2002)- new sample of 7 radio-loud lenses recently by Hsueh et al. 2019 mass WDM >3.8 keV sterile neutrino. **Very rare**
- **Galaxy-scale lenses -**Ritondale et al. 2019, Despali et al. 2018, Spignola et al. 2019, Vegetti et al. 2012, 2014) ~10^9 M_200 is the current lowest mass detection with current telescope resolution. Arcs give good constraint on macromodels.
- **This work: More compact source lenses with narrow-line lensing**



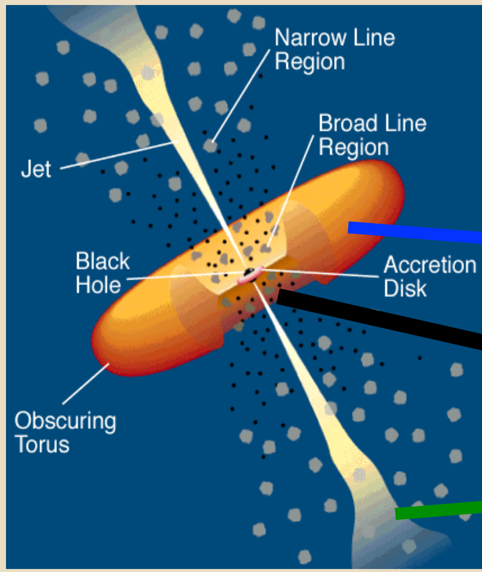
Patnaik et al. 1992

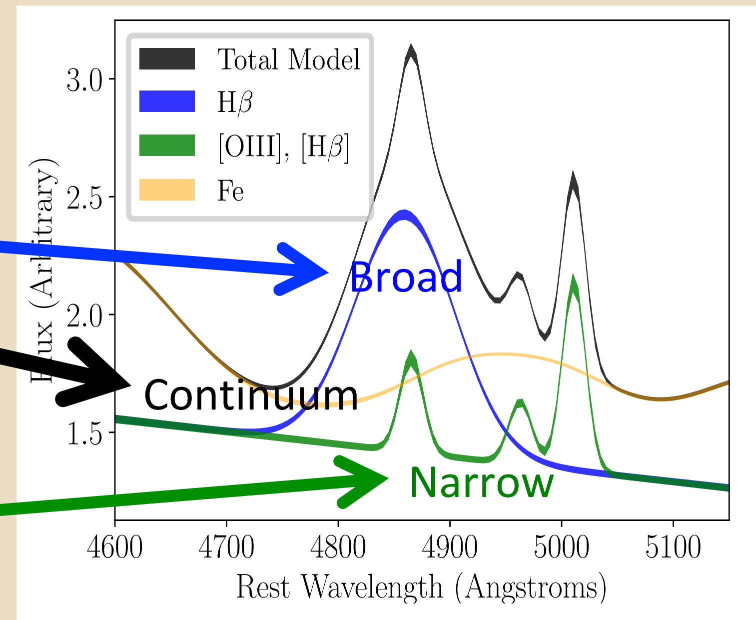


Vegetti et al. 2010a

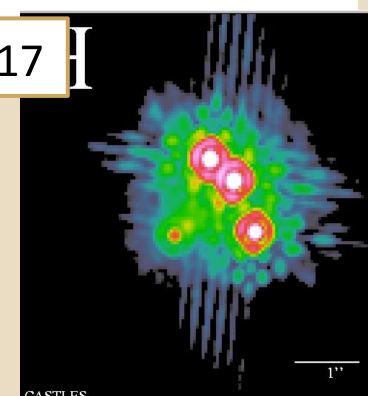
QSO NARROW LINE EMISSION

- Most qsos show significant narrow line emission - **can double the number of systems used to detect substructure**





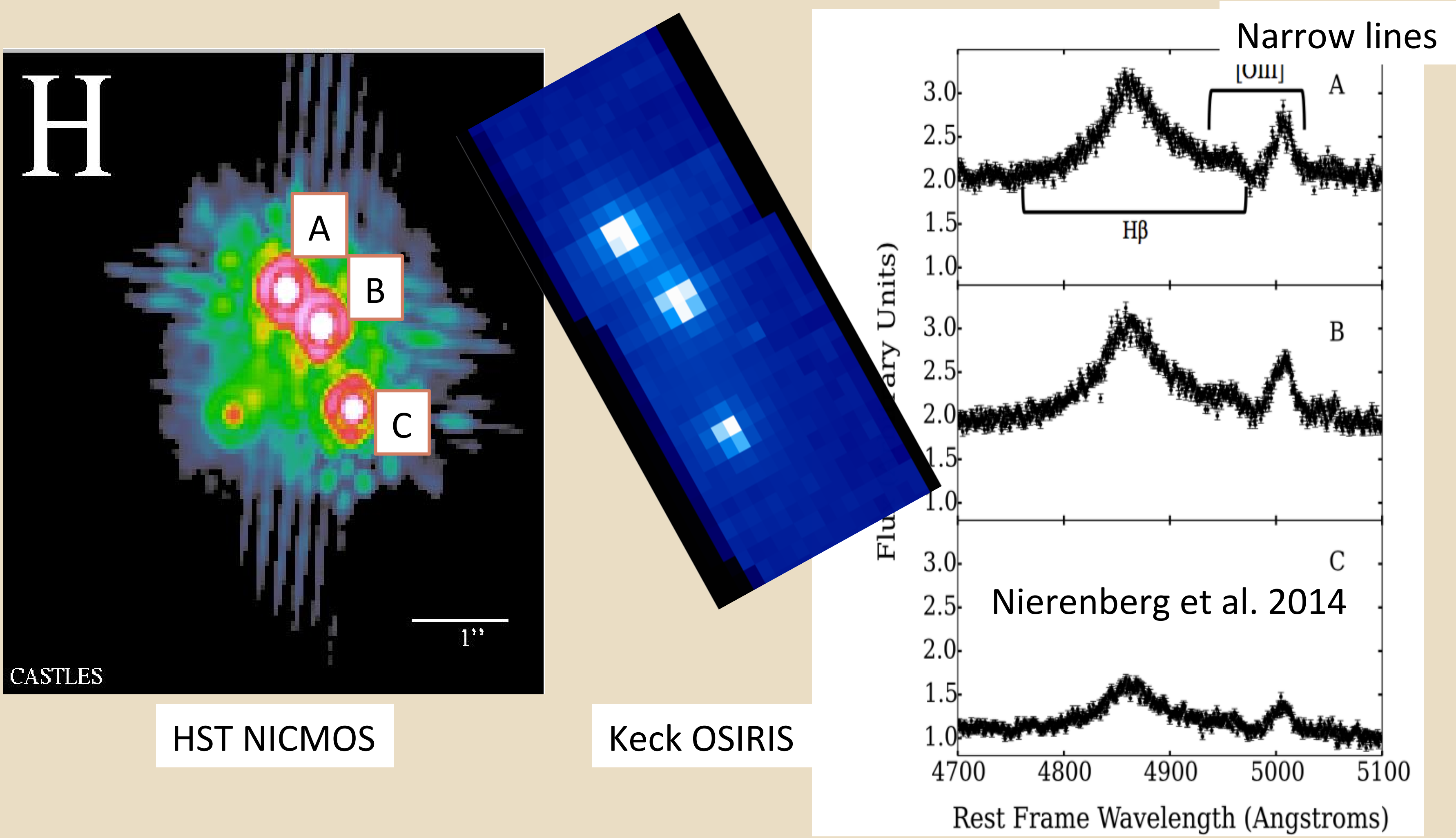
Nierenberg et al. 2017



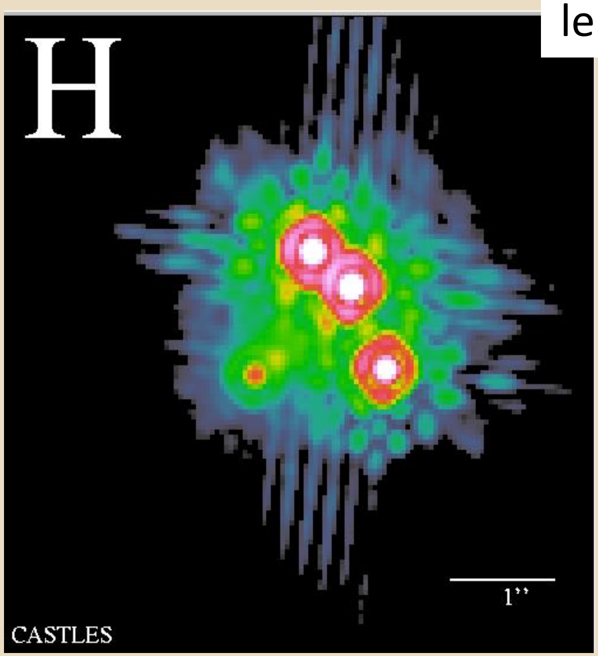
- Narrow-line is not variable and not microlensed

Need high res, spatially resolved spectroscopy

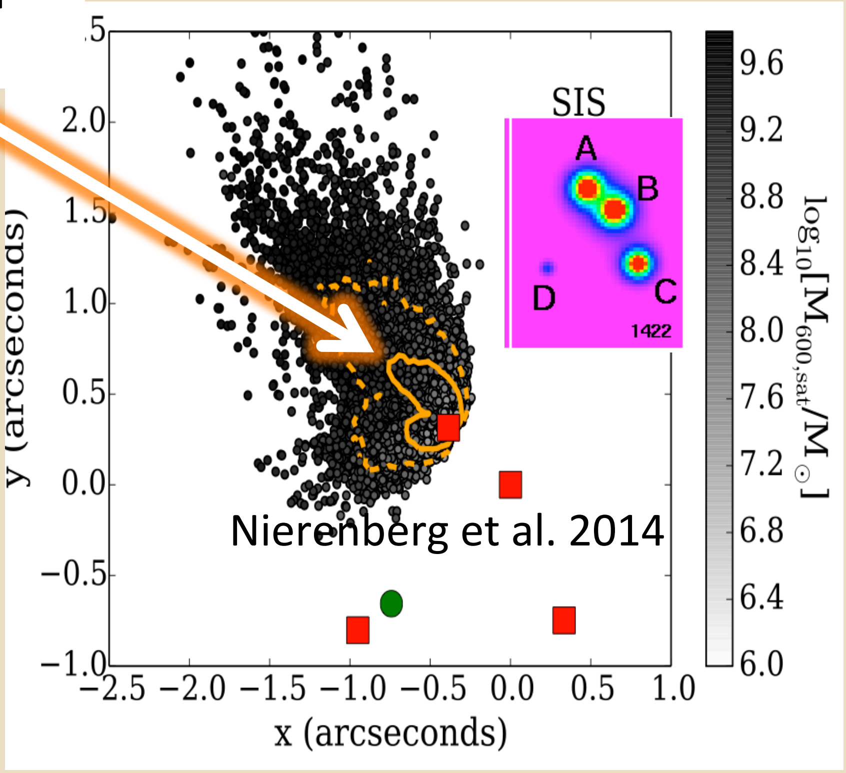
EXAMPLE 1: NL LENSING IN B1422+231, OSIRIS WITH KECK AO



VERY SENSITIVE TO LOW MASS STRUCTURE

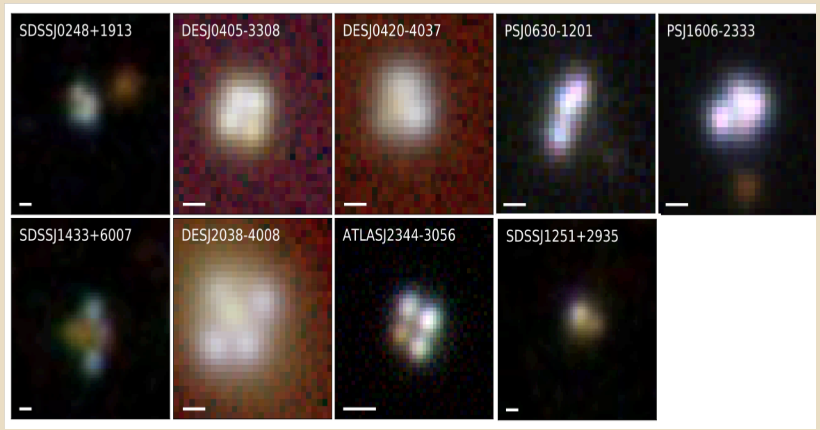


Msub~10^7 Msun
(if single perturber in lens plane)



Compact 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)

15 NEW NL LENSES WITH THE WFC3 GRISM!



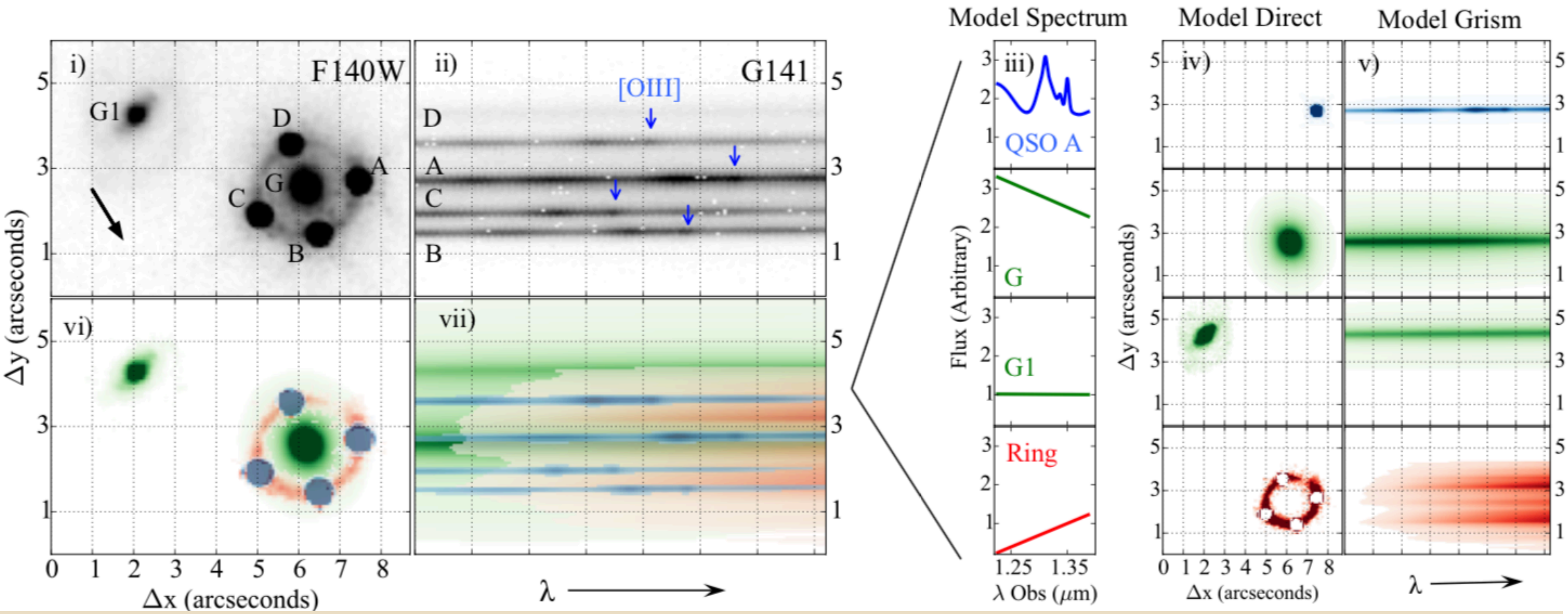
HST GO-13732 and GO-15177 (PI Nierenberg) **15 NL** quad lenses from SDSS, DES and PAN-STARRS

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

SPECTRAL FITTING FOR 9 NEW LENSES

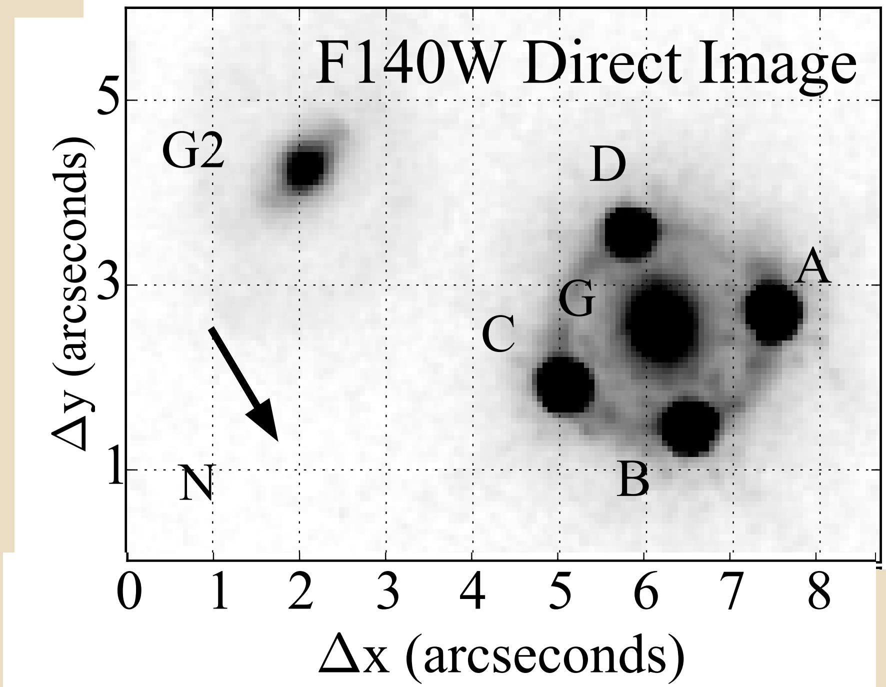
Nierenberg et al 2017, Nierenberg et al. 2019 in prep…

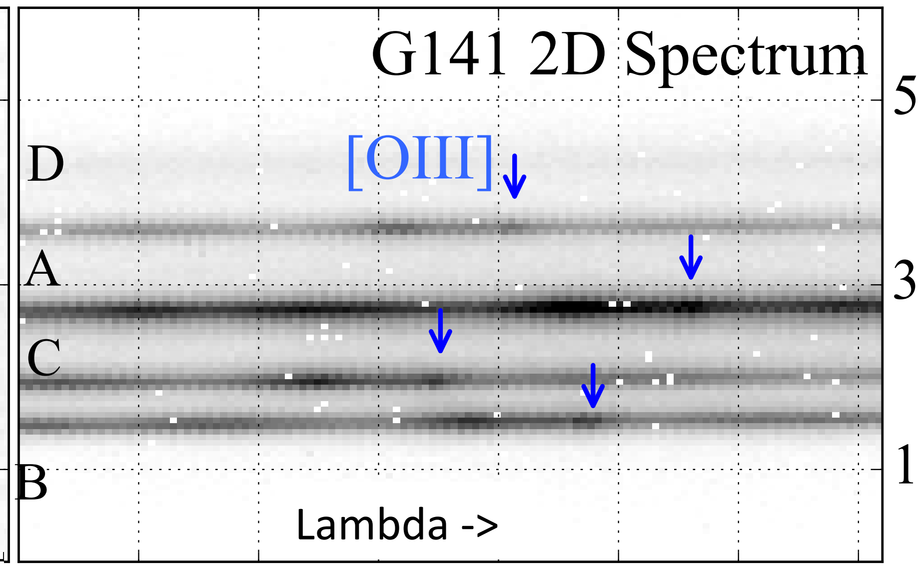
MEASURING SPECTRA WITH THE GRISM



Nierenberg et al. 2017

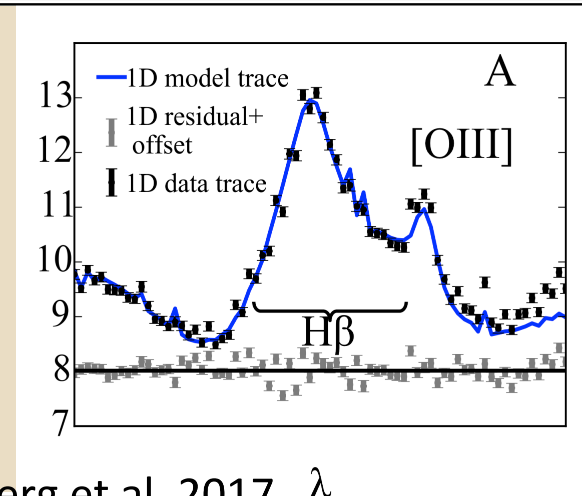
GRAVITATIONAL LENS HE0435-1223





HST-GO 13732 PI: Nierenberg

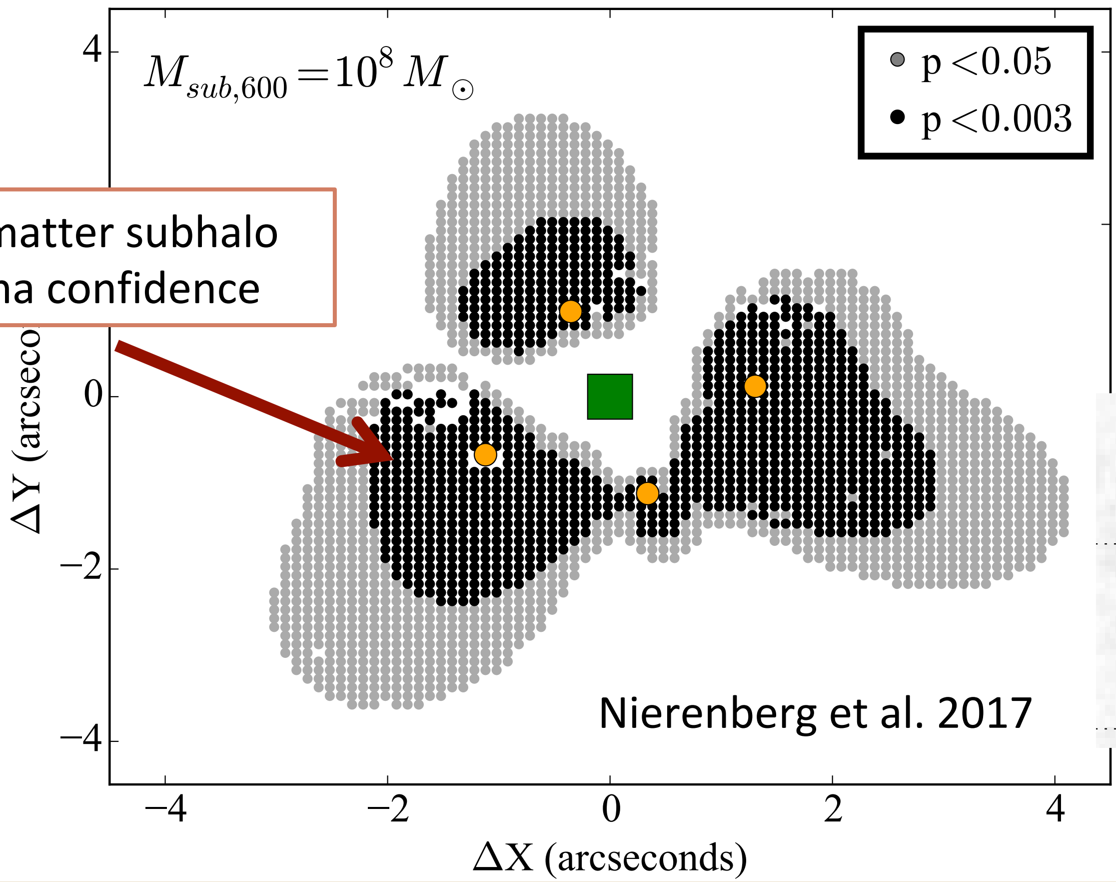
1D, PSF-weighted grism trace,
Nierenberg et al. 2017



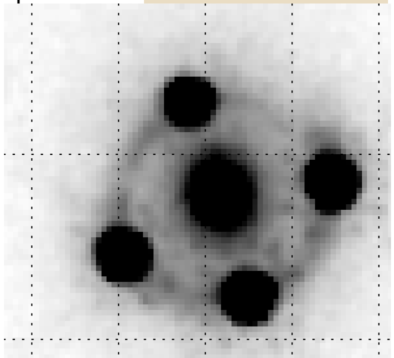
Nierenberg et al. 2017

LIMITS ON THE PRESENCE OF AN NFW DARK MATTER SUBHALO

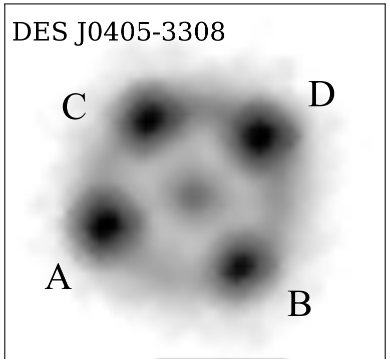
Flux Ratio Precision~ 7%



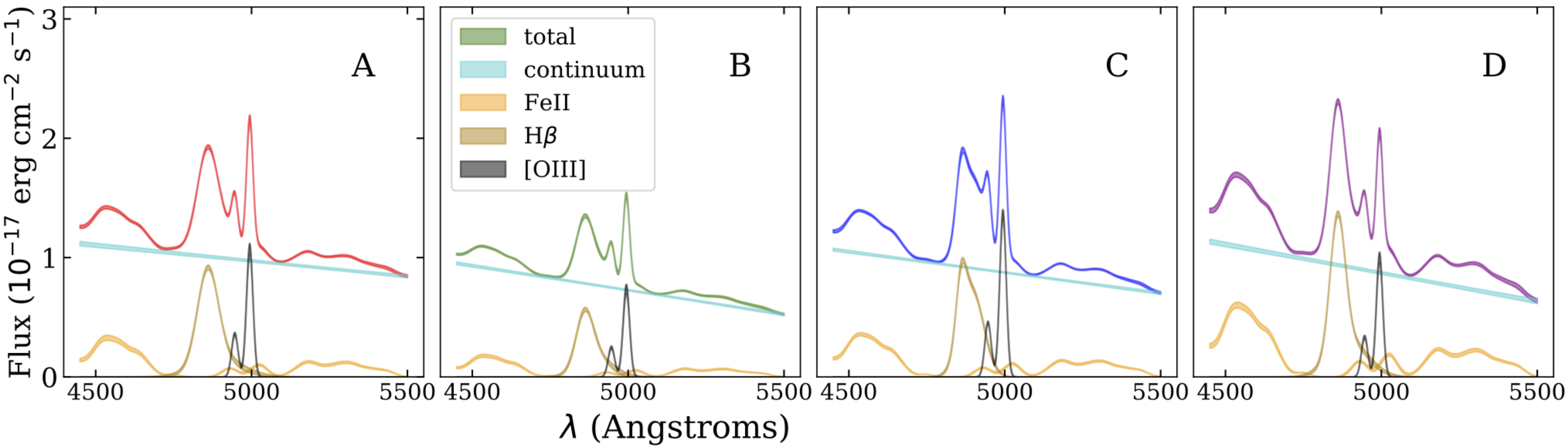
10^9 M200 dark matter subhalo excluded at 3 sigma confidence

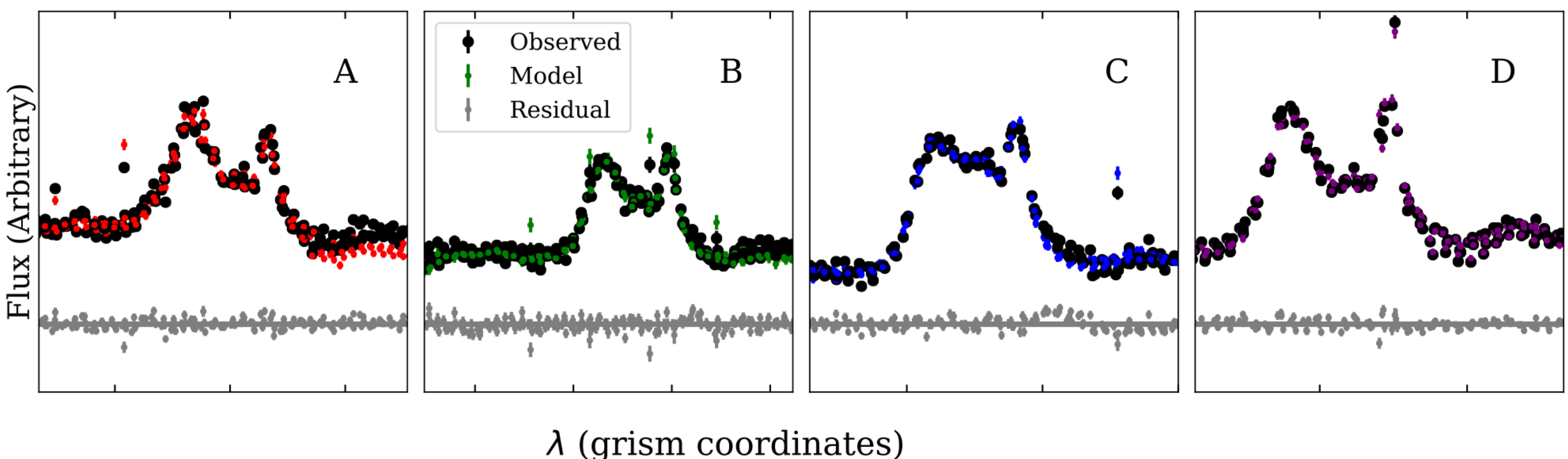


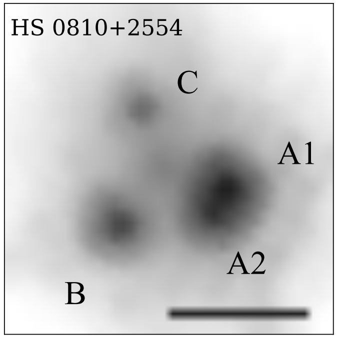
~1” radius excluded around each image (~5.5 kpc)


DES J0405-3308
C
D
A
B

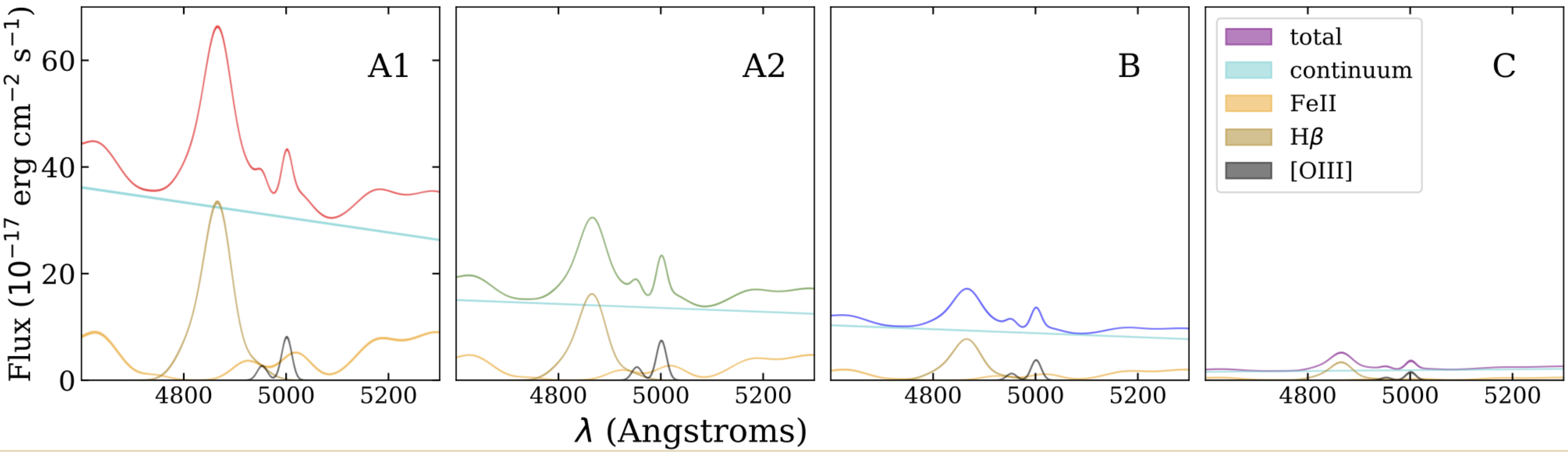
0405

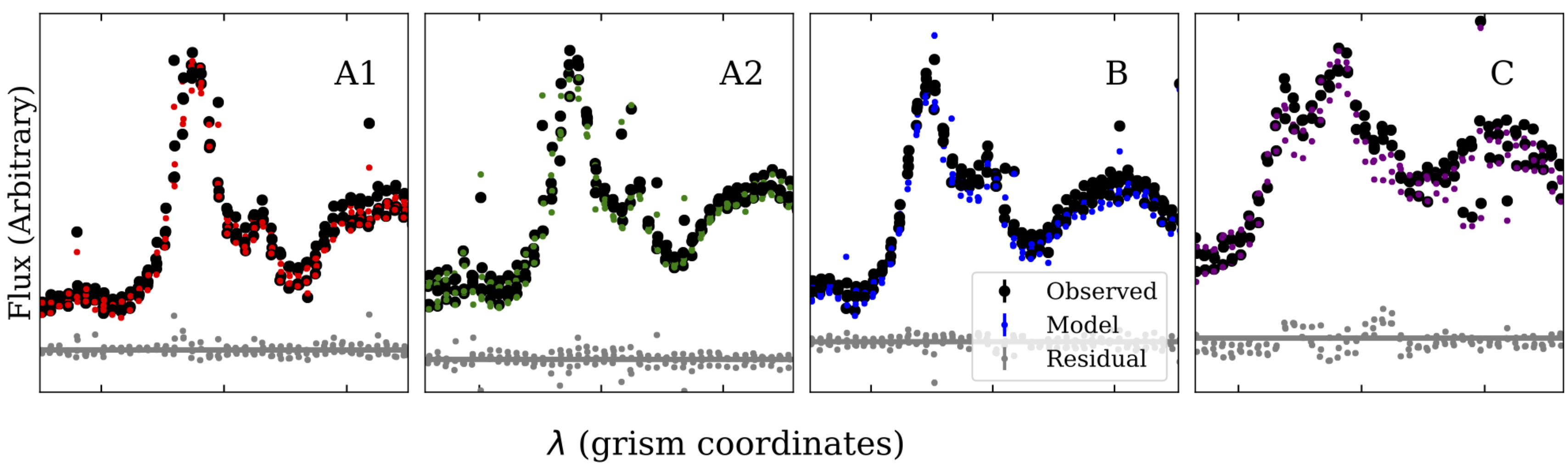

Flux (10^{-17} erg cm^{-2} s^{-1})
A
B
C
D
total
continuum
FeII
Hβ
[OIII]
λ (Angstroms)

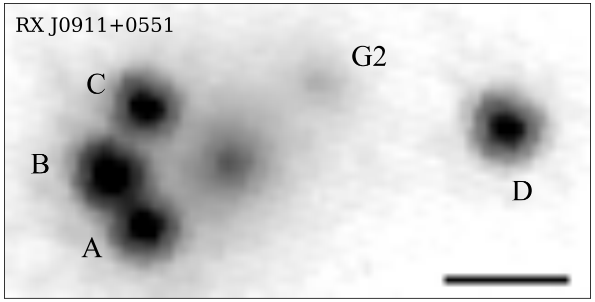

Flux (Arbitrary)
A
B
C
D
Observed
Model
Residual
λ (grisim coordinates)


HS 0810+2554
C
A1
A2
B

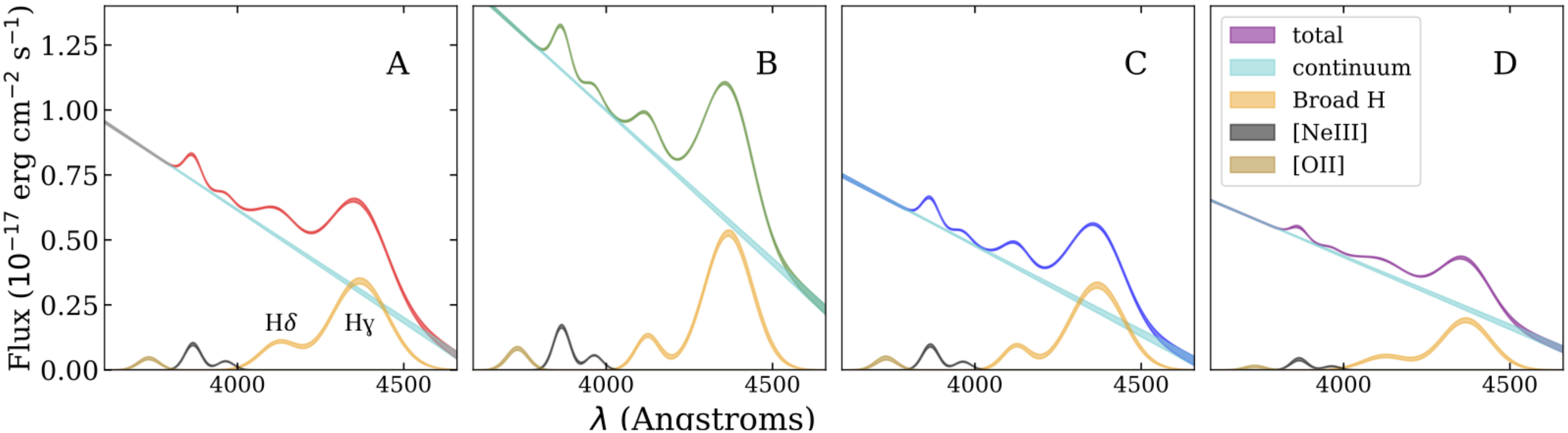
0810

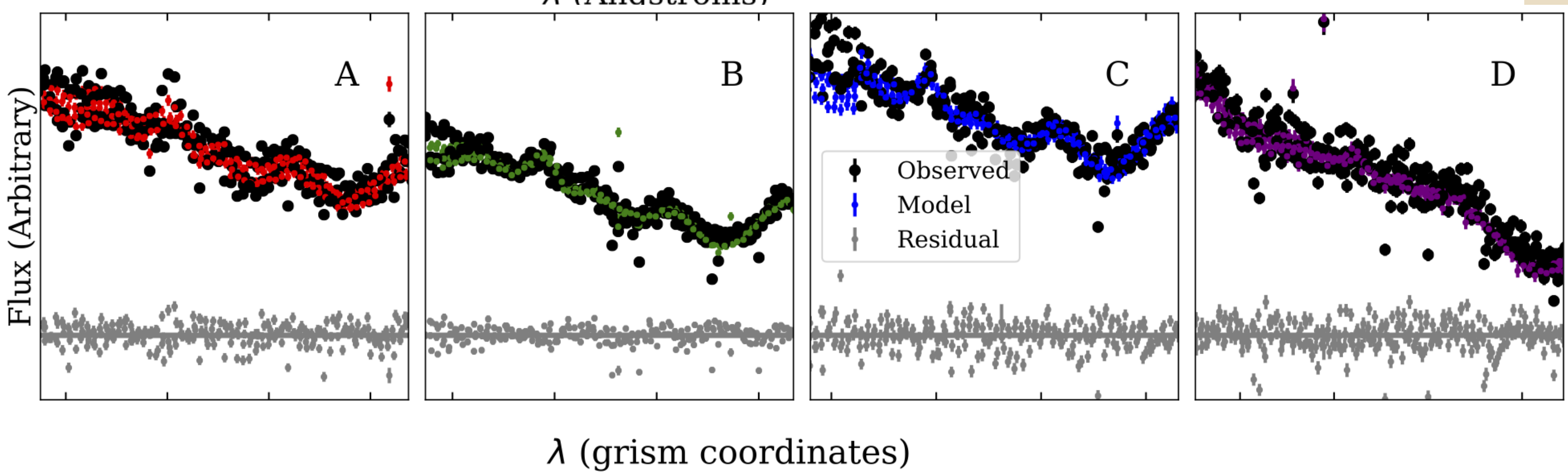

Flux (10^{-17} erg cm^{-2} s^{-1})
0
20
40
60
4800
5000
5200
A1
A2
B
C
total
continuum
FeII
Hβ
[OIII]
λ (Angstroms)

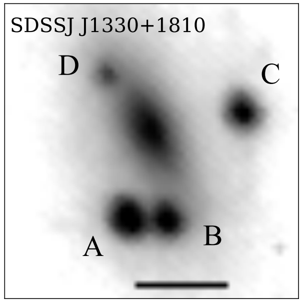

Flux (Arbitrary)
A1
A2
B
C
Observed
Model
Residual
λ (grism coordinates)


RX J0911+0551
G2
C
B
D
A

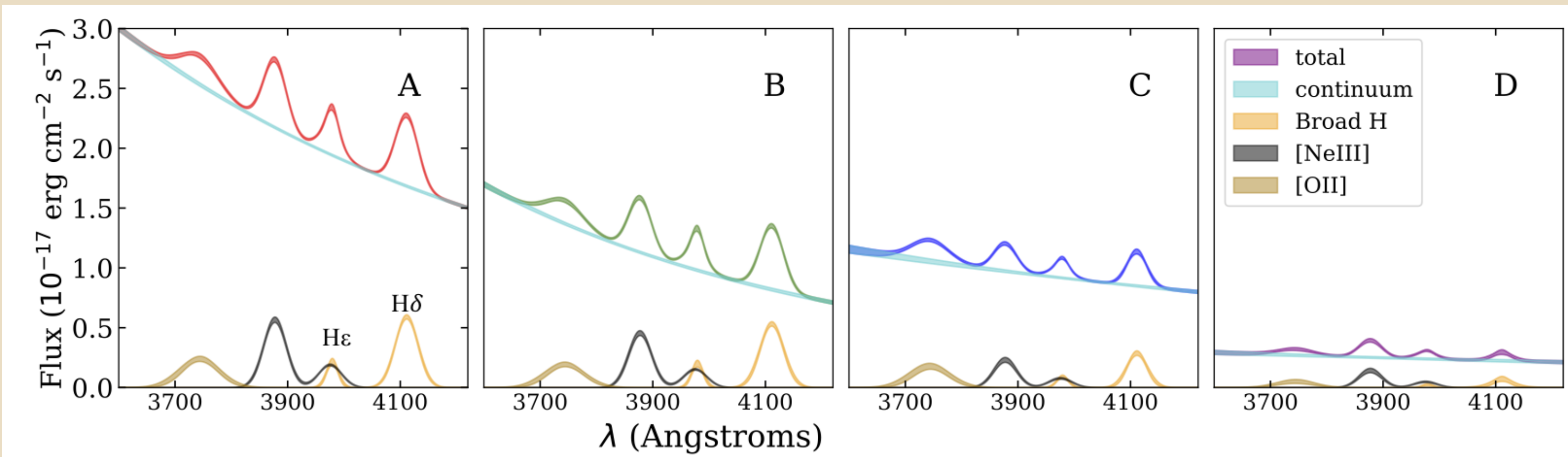
0911

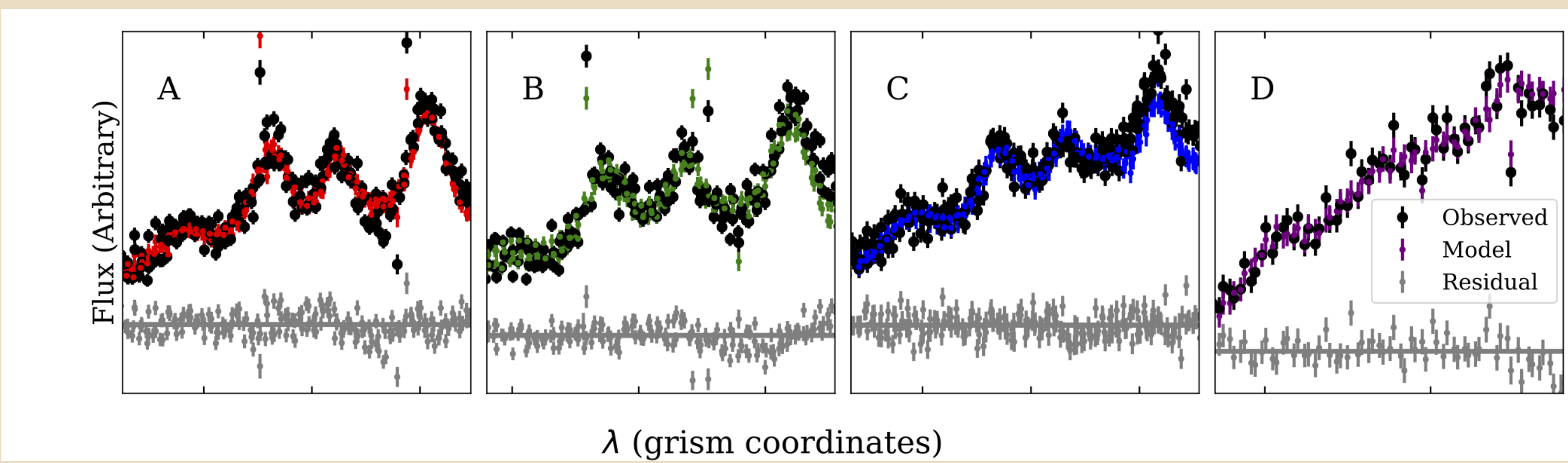

Flux (10^{-17} erg cm^{-2} s^{-1})
A
B
C
D
total
continuum
Broad H
[NeIII]
[OII]
Hδ
Hγ
0.00
0.25
0.50
0.75
1.00
1.25
4000
4500
λ (Angstroms)

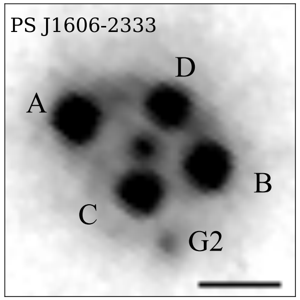

Flux (Arbitrary)
A
B
C
D
Observed
Model
Residual
λ (grism coordinates)


SDSSJ J1330+1810
D
C
A
B

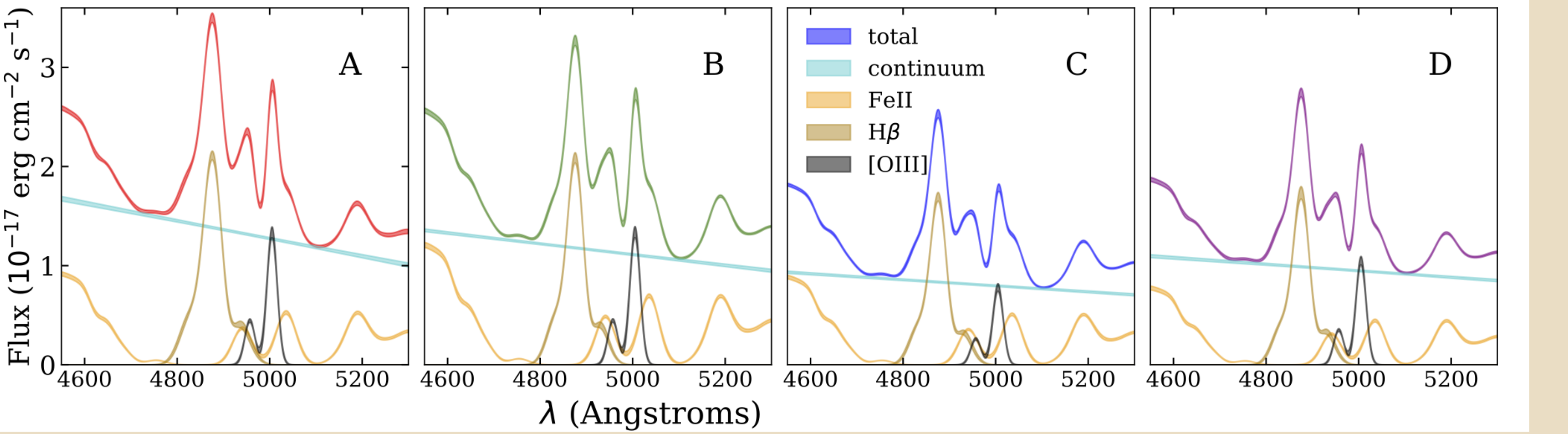
1330

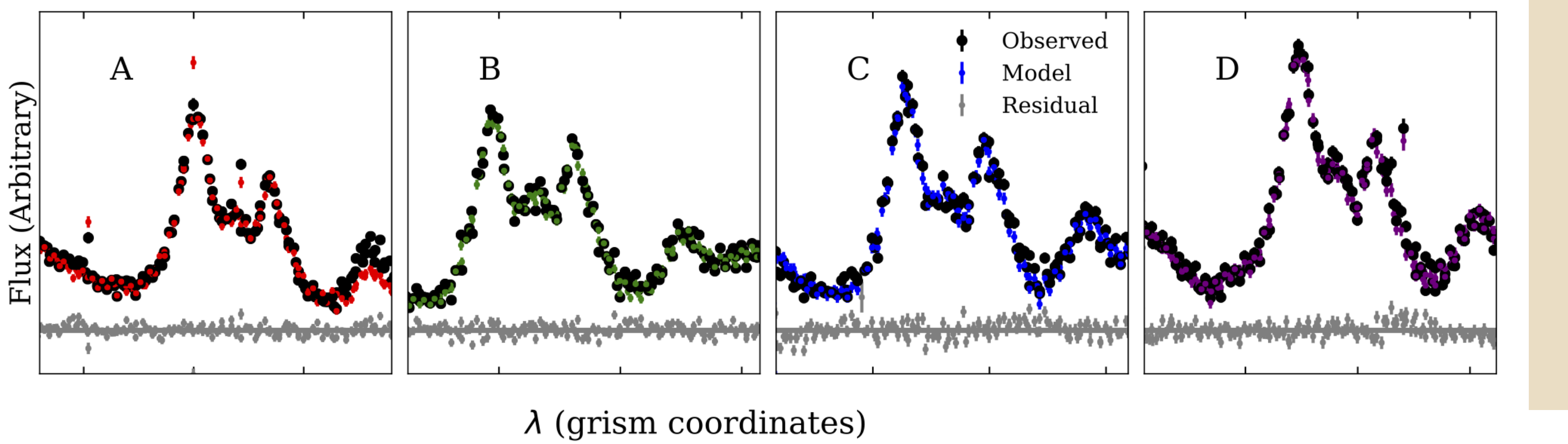

Flux (10^{-17} erg cm^{-2} s^{-1})
0.0
0.5
1.0
1.5
2.0
2.5
3.0
A
B
C
D
Hε
Hδ
total
continuum
Broad H
[NeIII]
[OII]
3700
3900
4100
λ (Angstroms)

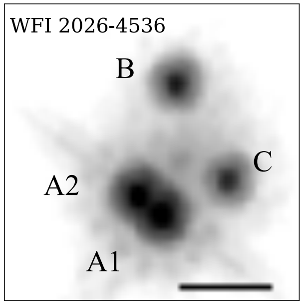

Flux (Arbitrary)
A
B
C
D
Observed
Model
Residual
λ (grism coordinates)


PS J1606-2333
D
A
B
C
G2

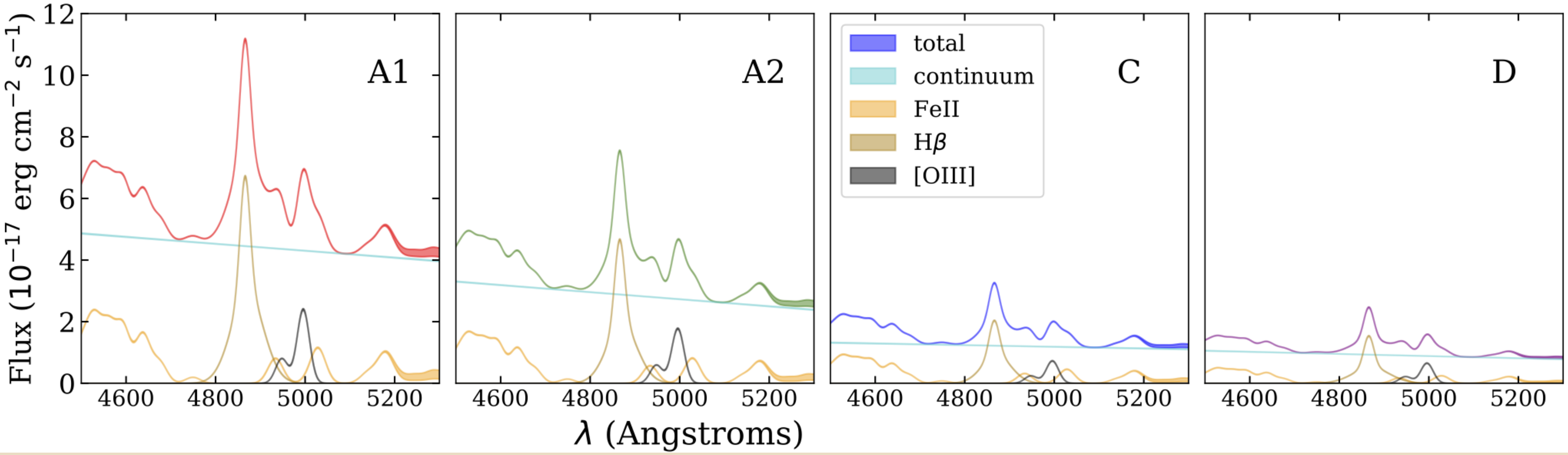
1606

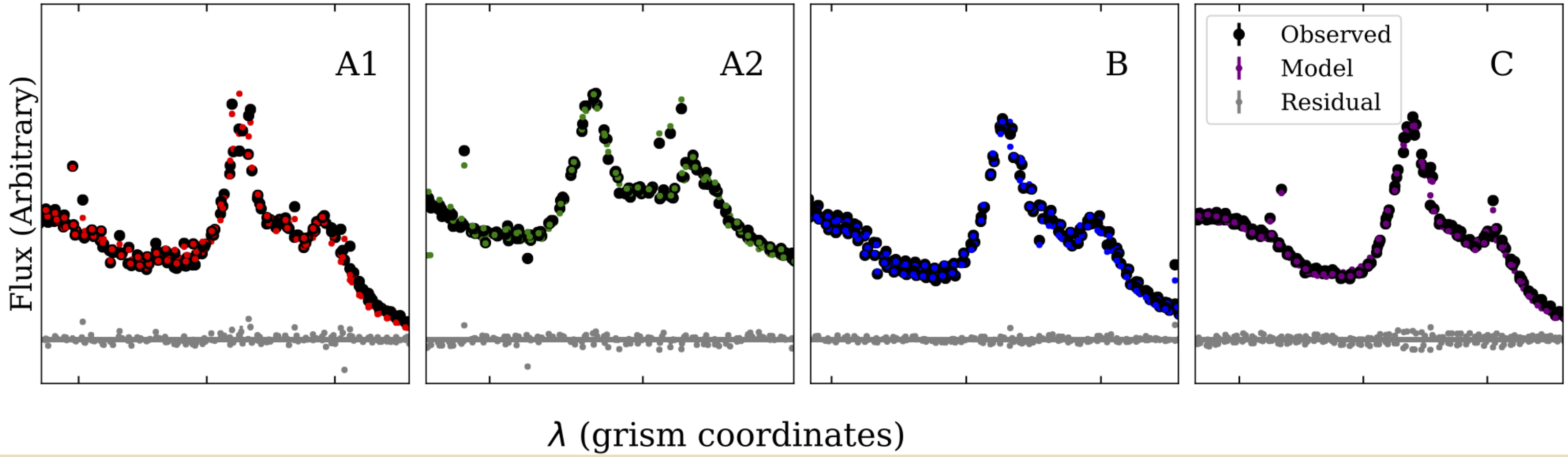

Flux (10^{-17} erg cm^{-2} s^{-1})
A
B
C
D
total
continuum
FeII
Hβ
[OIII]
0
1
2
3
4600
4800
5000
5200
λ (Angstroms)

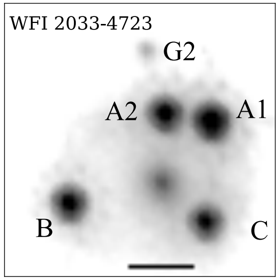

Flux (Arbitrary)
A
B
C
D
Observed
Model
Residual
λ (grism coordinates)


WFI 2026-4536
B
C
A2
A1

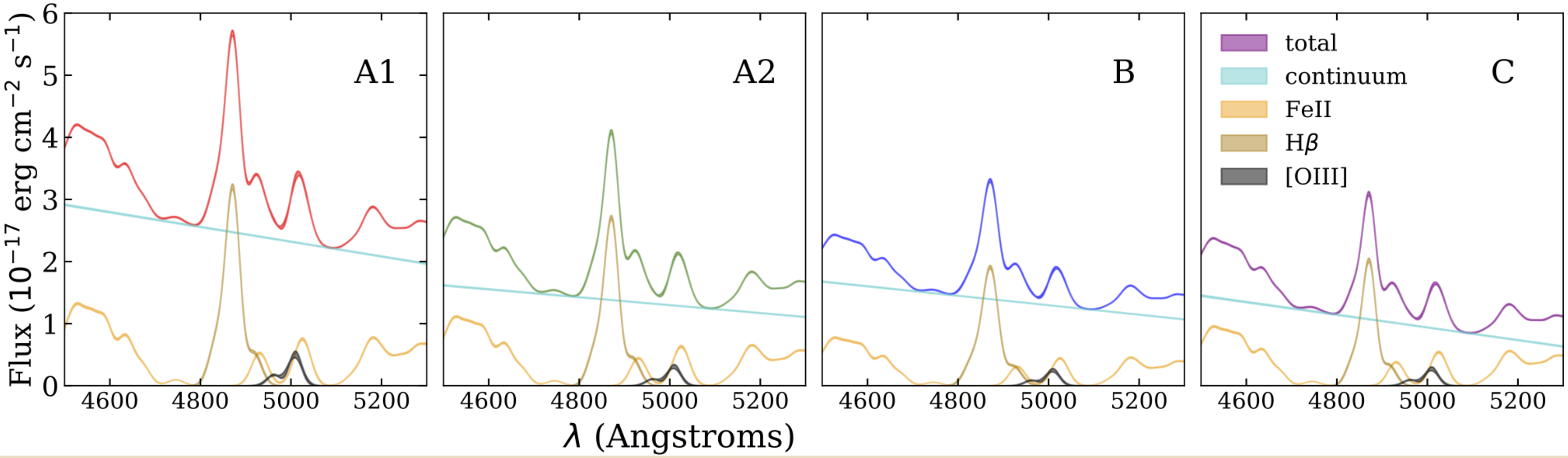
2026

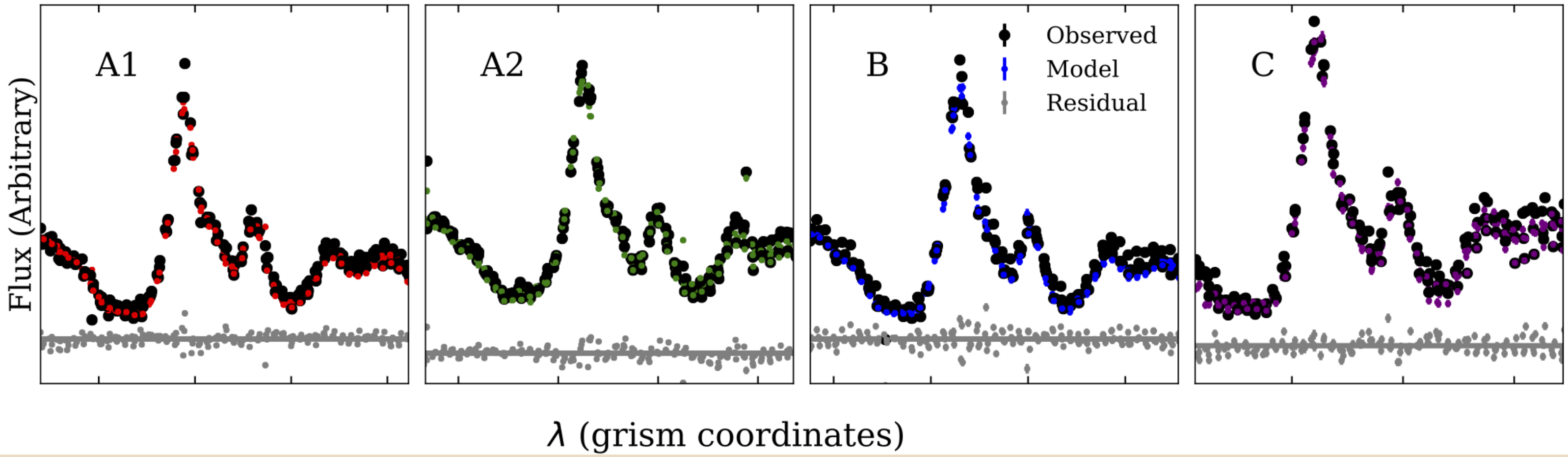

Flux (10^{-17} erg cm^{-2} s^{-1})
A1
A2
C
D
total
continuum
FeII
Hβ
[OIII]
λ (Angstroms)

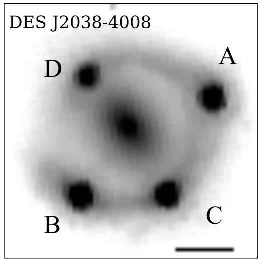

Flux (Arbitrary)
A1
A2
B
C
Observed
Model
Residual
λ (grism coordinates)


WFI 2033-4723
G2
A2
A1
B
C

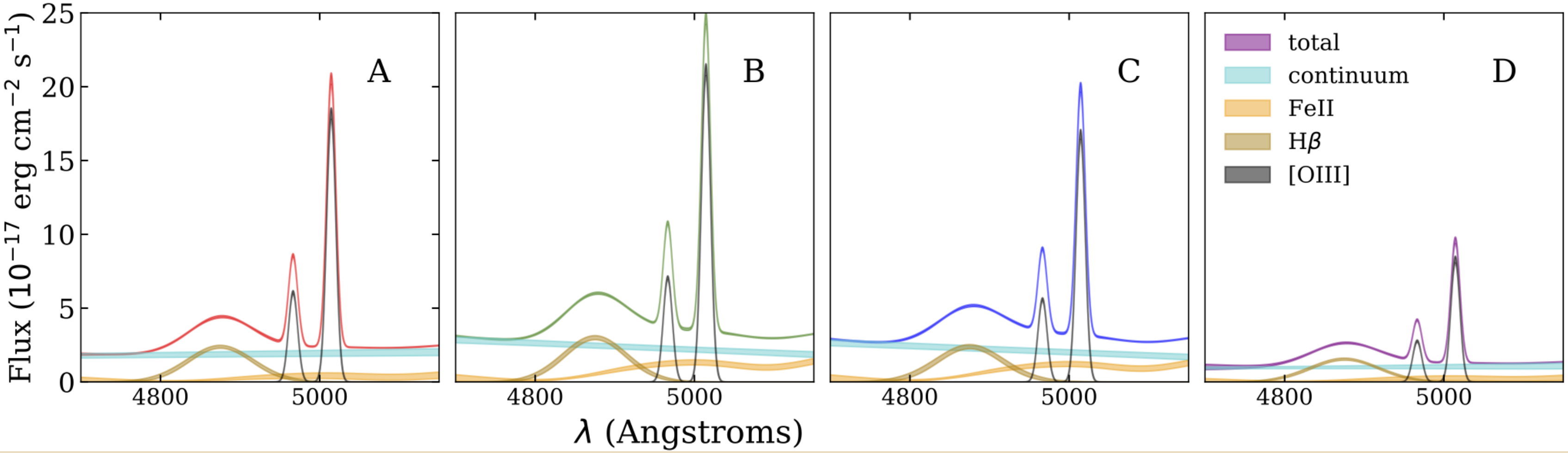
2033

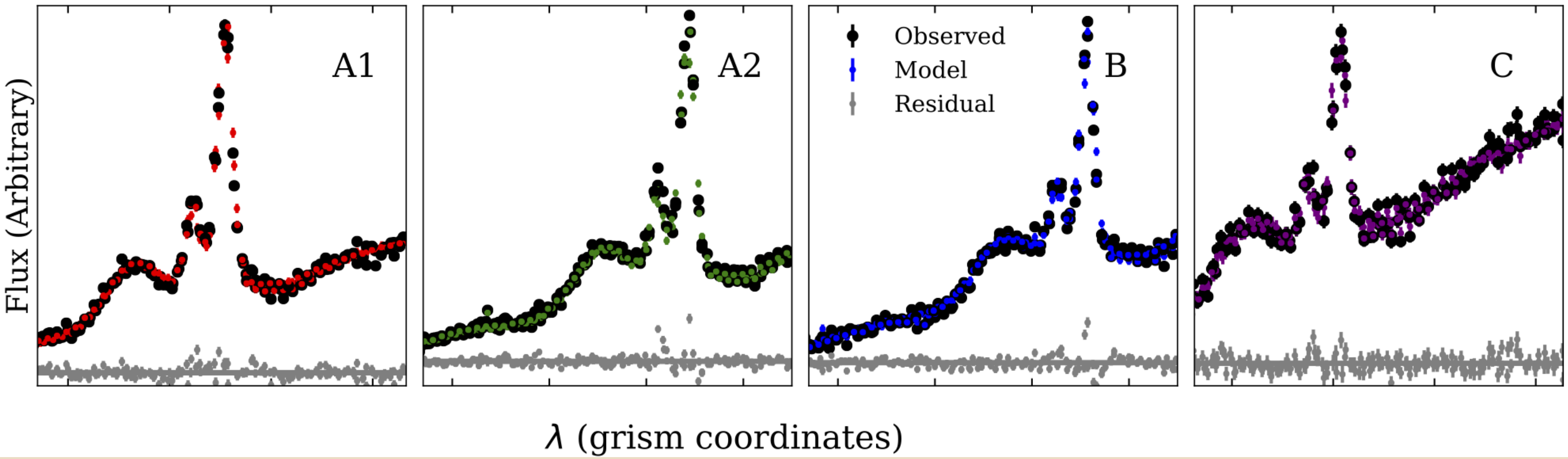

Flux (10^{-17} erg cm^{-2} s^{-1})
A1
A2
B
C
total
continuum
FeII
Hβ
[OIII]
4600
4800
5000
5200
λ (Angstroms)


Flux (Arbitrary)
A1
A2
B
C
Observed
Model
Residual
λ (grism coordinates)


DES J2038-4008
A
B
C
D

2038


Flux (10^{-17} erg cm^{-2} s^{-1})
A
B
C
D
total
continuum
FeII
Hβ
[OIII]
4800
5000
λ (Angstroms)

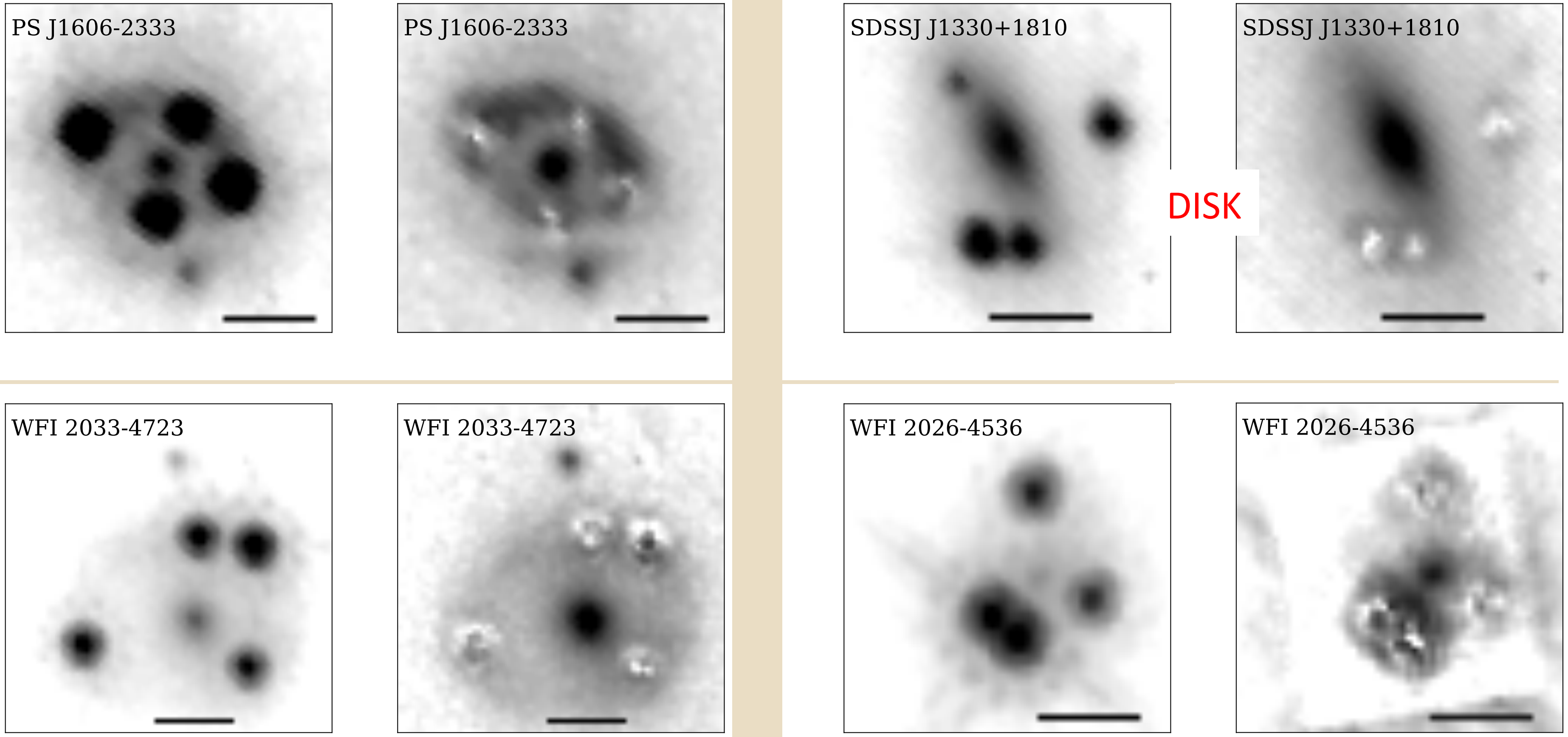

Flux (Arbitrary)
A1
A2
B
C
Observed
Model
Residual
λ (grism coordinates)

These 8 new measurements DOUBLE the number of ‘compact source systems which can be used for measuring the halo mass function

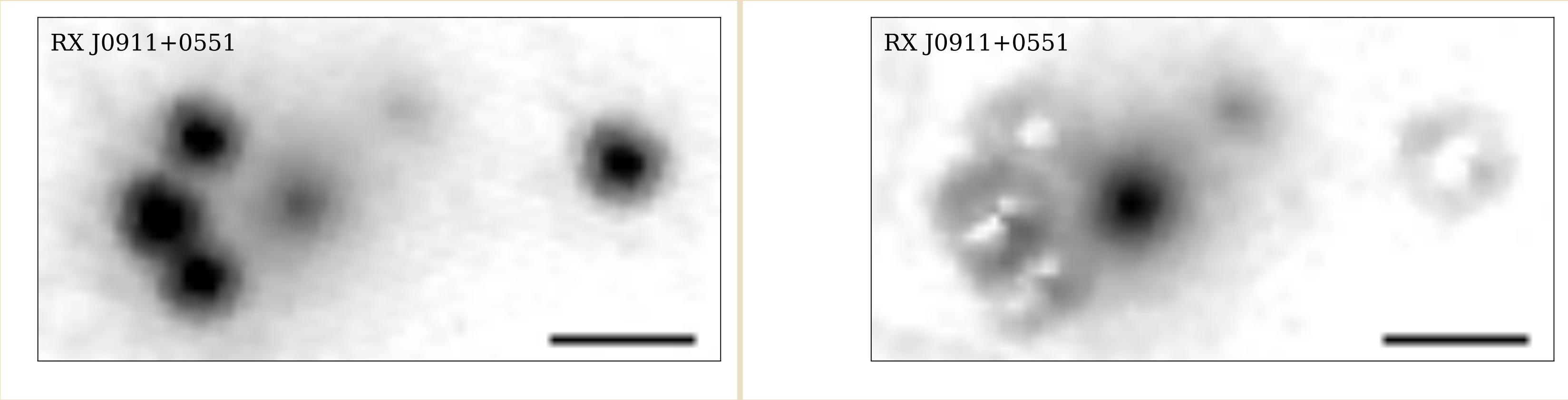
Data for 6 additional systems from grism published in subsequent paper after measurements are complete in the fall.

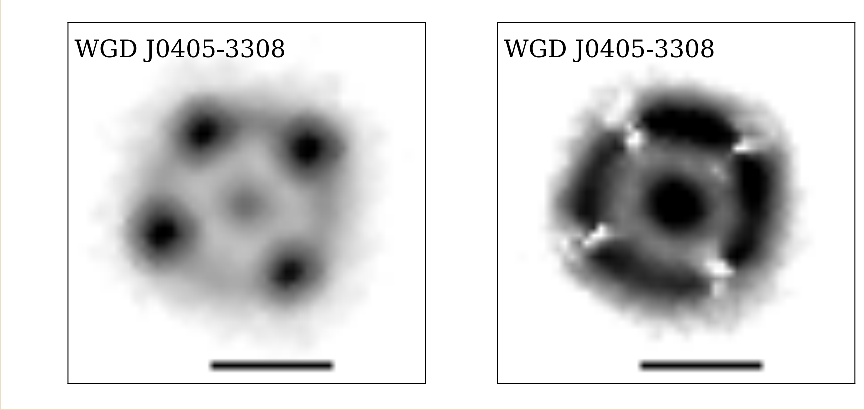
21 new lenses discovered in the last year are suitable for this method (15 from space, 6 from ground)

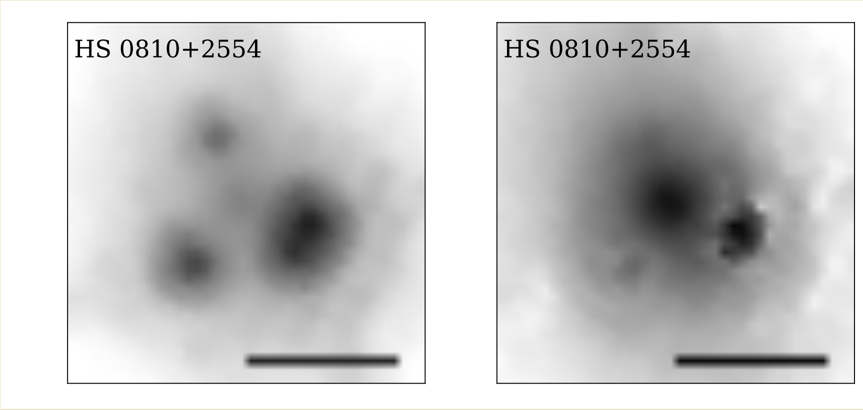
DEFLECTOR STELLAR MASS DISTRIBUTION



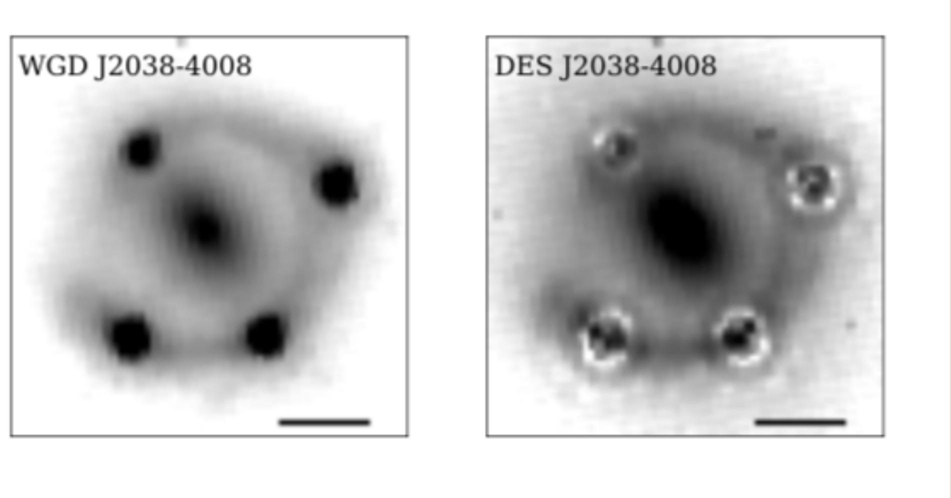
DEFLECTOR STELLAR MASS DISTRIBUTION







DEFLECTOR STELLAR MASS DISTRIBUTION



HOW WELL ARE THE NARROW FLUXES FIT BY SMOOTH MASS DISTRIBUTIONS?

- Variable deflector centroid (weak prior from light), ellipticity, angle, and power-law mass slope
- Variable external shear and orientation
- Nearby luminous objects included as SIS with weak prior on position from light
- Variable source size

EXCLUDE 1330 for now because this requires a more complex macromodel, and is therefore not ideal for substructure studies.

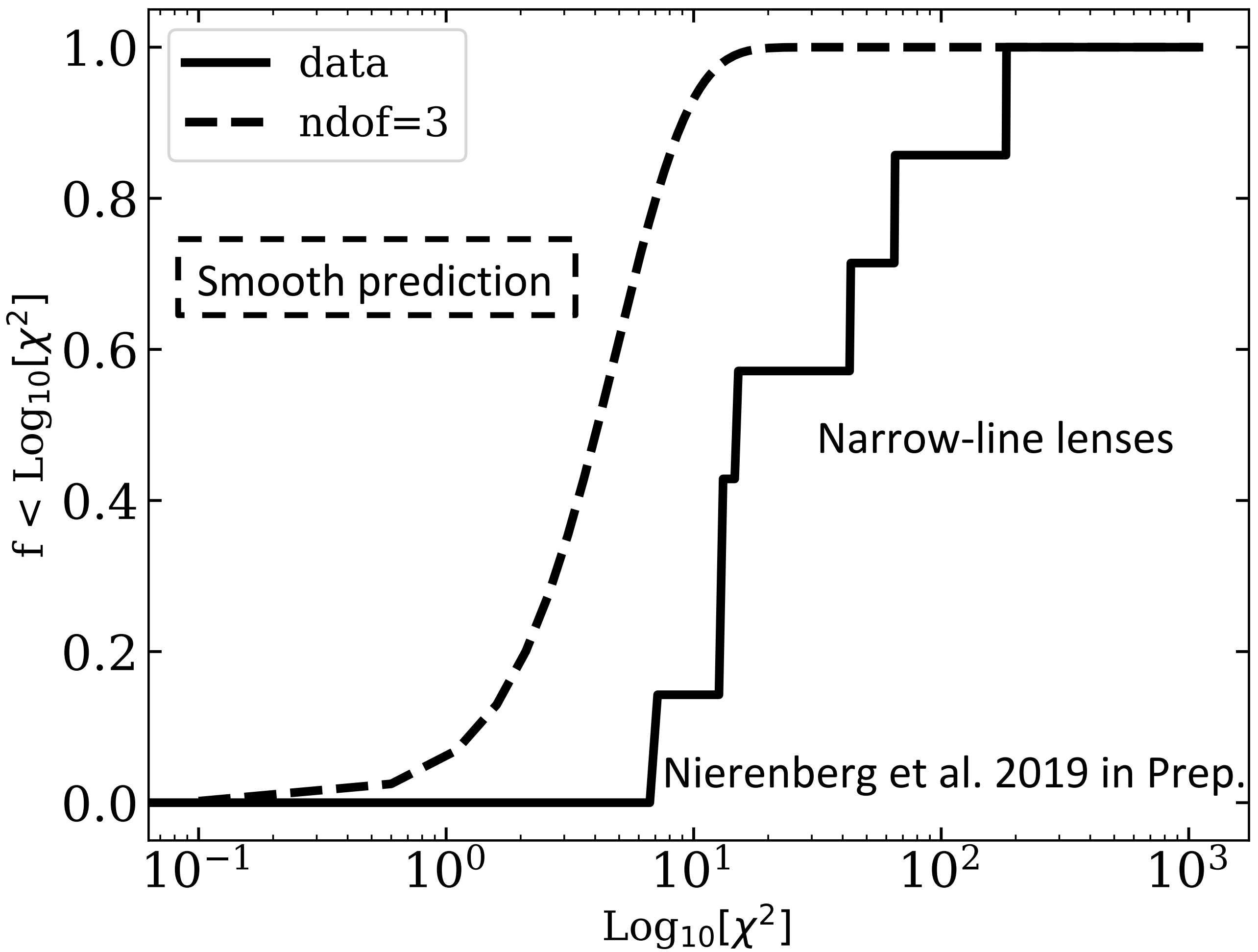
EXCLUDE 0810 because the narrow emission is resolved and blended.

CHI-SQUARED DISTRIBUTION OF FIT TO NARROW-LINE FLUXES

Just to give **an approximate idea** of how smooth the lenses are

They are not smooth!!

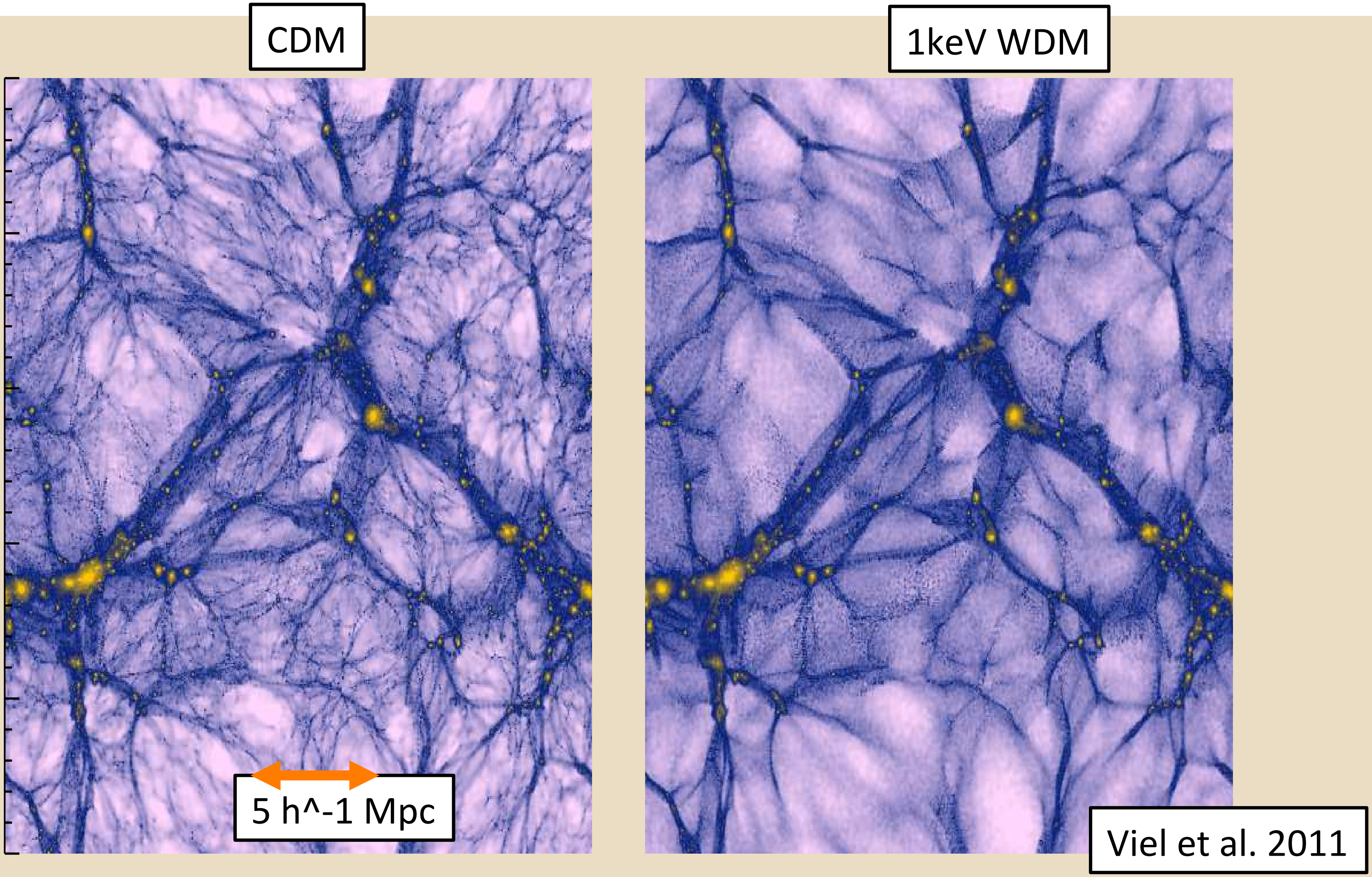
Caveat: likely~percent level contribution from imperfect modelling of deflector smooth mass distribution (Hsueh 2018, Gilman 2018)



GETTING QUANTITATIVE-PHYSICAL INTERPRETATION

Full forward modelling – Gilman et al. 2019

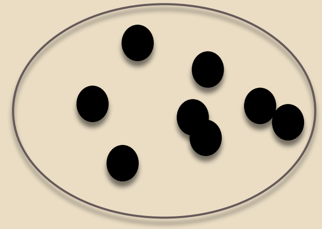
WHAT IS THE DARK MATTER POWER SPECTRUM ON SMALL SCALES?



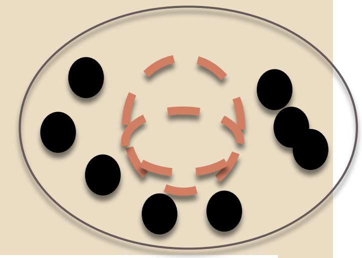
SOME OF THE THINGS THE SIGNAL DEPENDS ON

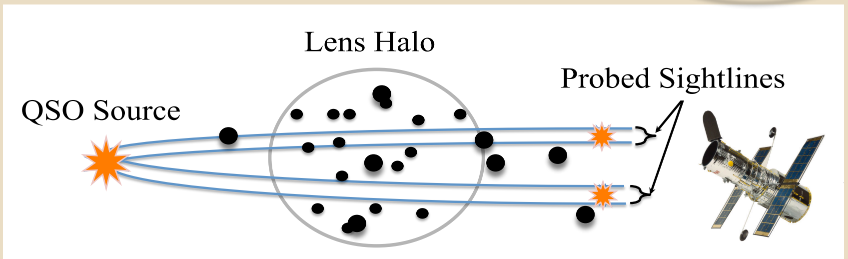
- **Flux measurement precision**
- **The number of halos within the lens virial radius**- explore extreme tidal destruction and no tidal destruction limits
- **The density of halos along the line of sight** (robustly determined from CDM simulations)
- **The warmness** of dark matter affects mass and concentration

CDM spatial distribution

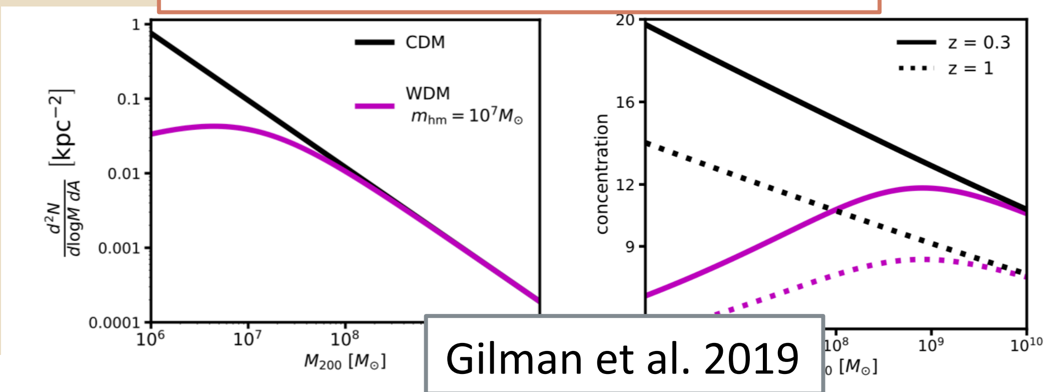


All SH within the scale radius destroyed



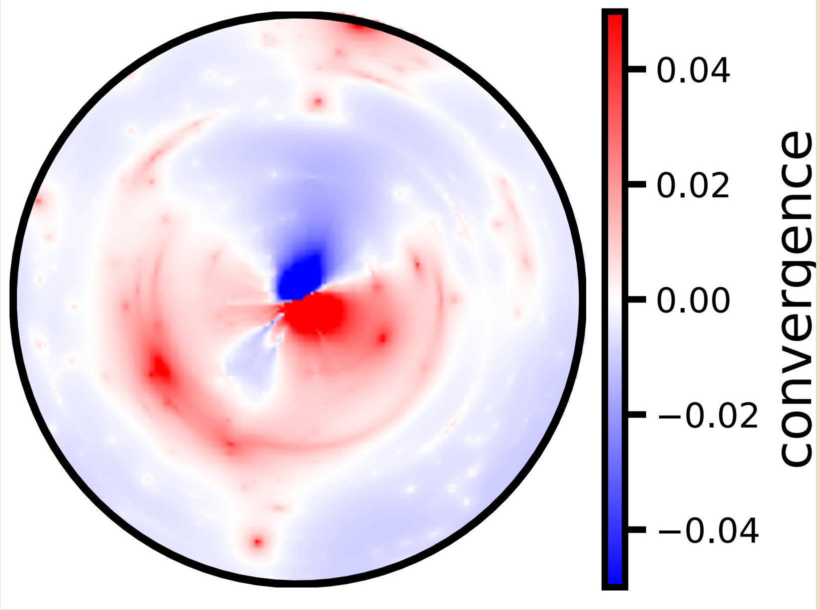


Values from Galacticus –A. Benson

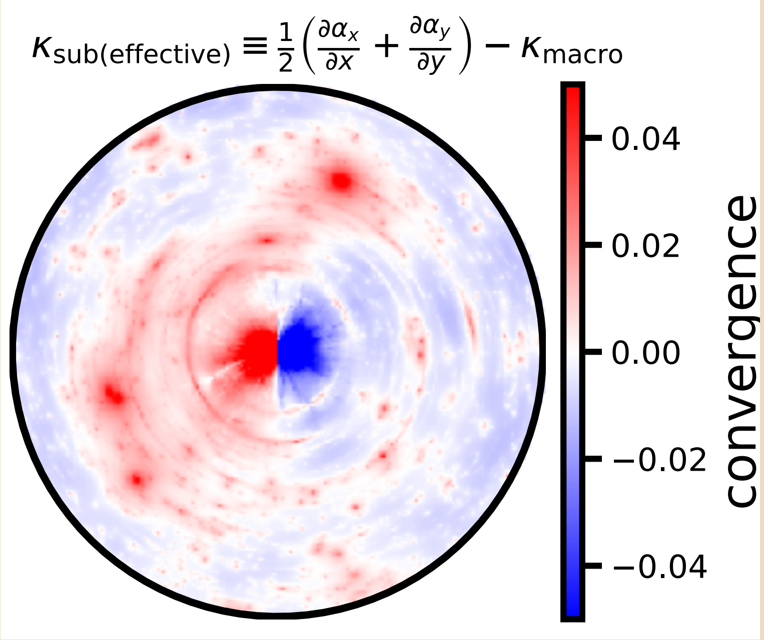


Gilman et al. 2019

NON-LINEAR EFFECT OF LOS STRUCTURE

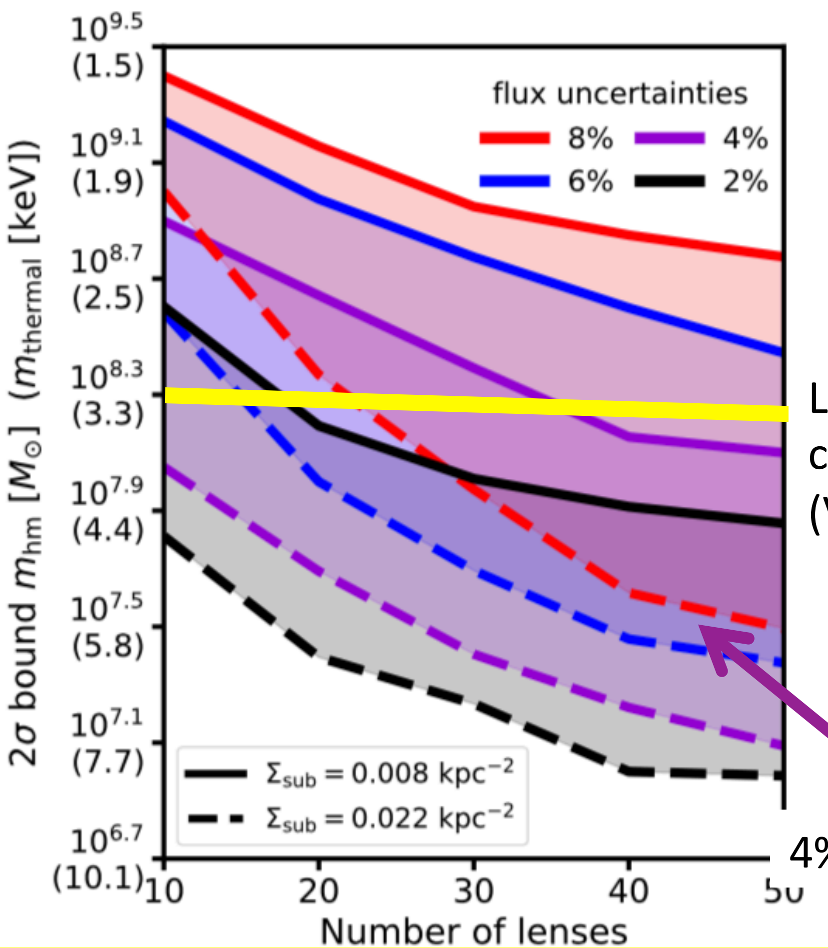


3.3 KeV WDM



CDM

FULL FORWARD MODELING **INCLUDING LINE OF SIGHT STRUCTURE**

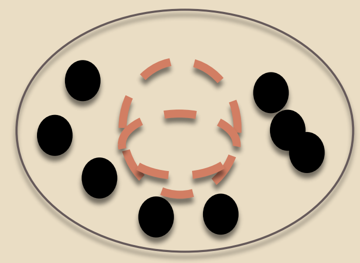


Ly-alpha constraint (Viel 2013)

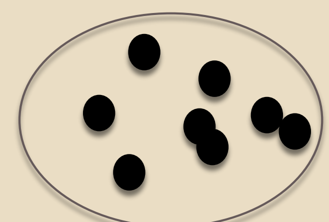
4% flux precision

Forecast from **Gilman et al. 2019**

Straight line = low normalization

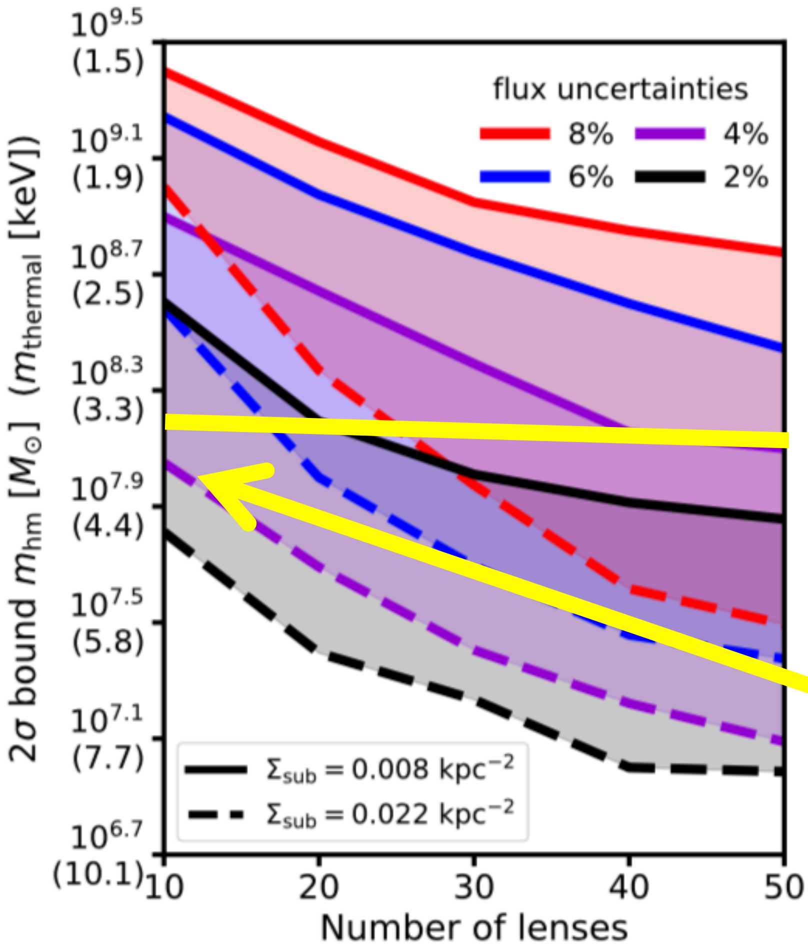


Dotted line= high normalization



Forecast for NL lensing constraint on WDM assuming CDM is correct

SNEAK PREVIEW



Ly-alpha constraint (Irsic 2018)

See Gilman et al. 2019b on ArXiv in next 2 weeks

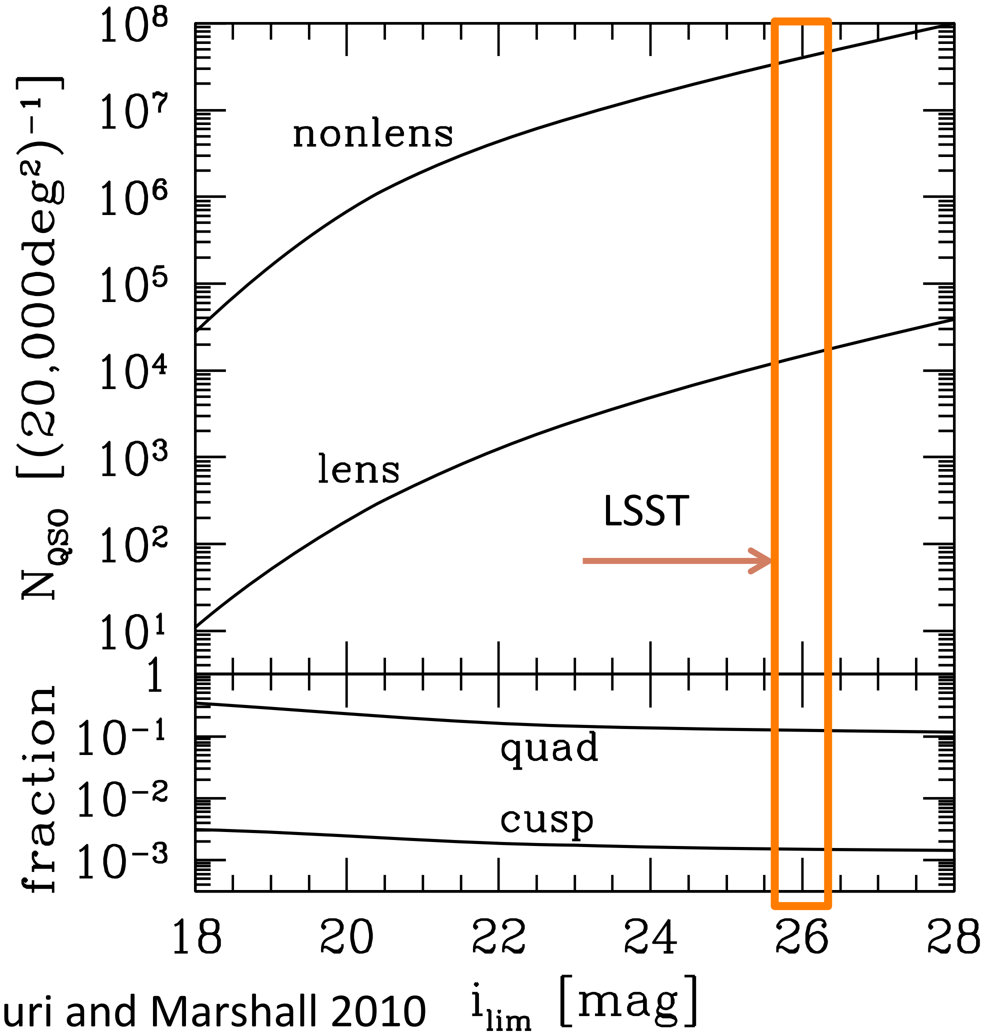
8 NL lenses (exclude 1330 and 0810) + 3 Radio Lenses

Our constraint is in this regime!
The projected density of subhalos is high!

LOOKING TO THE FURTHER FUTURE

- Simulate the effect of SIDM on FR anomalies
- Large numbers (DES, LSST, EUCLID, PAN-STARRS, SUBARU) – enable the selection of the best lenses (elliptical, good redshift range, strong NL source flux).
- Improved flux precision with next generation of ELTS
- State of the art comparison with new simulations- NASA ATP 17-ATP17-0120 (PI Peter)

FLUX SENSITIVITY: THERE ARE MORE FAINT THINGS THAN BRIGHT THINGS

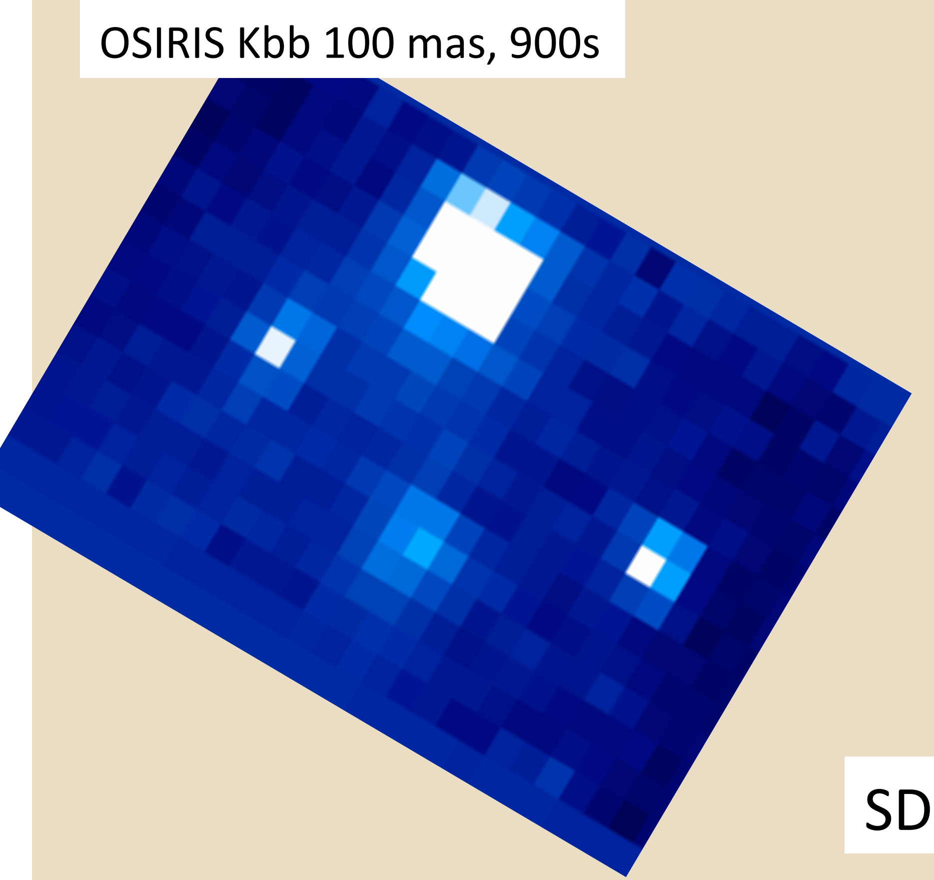


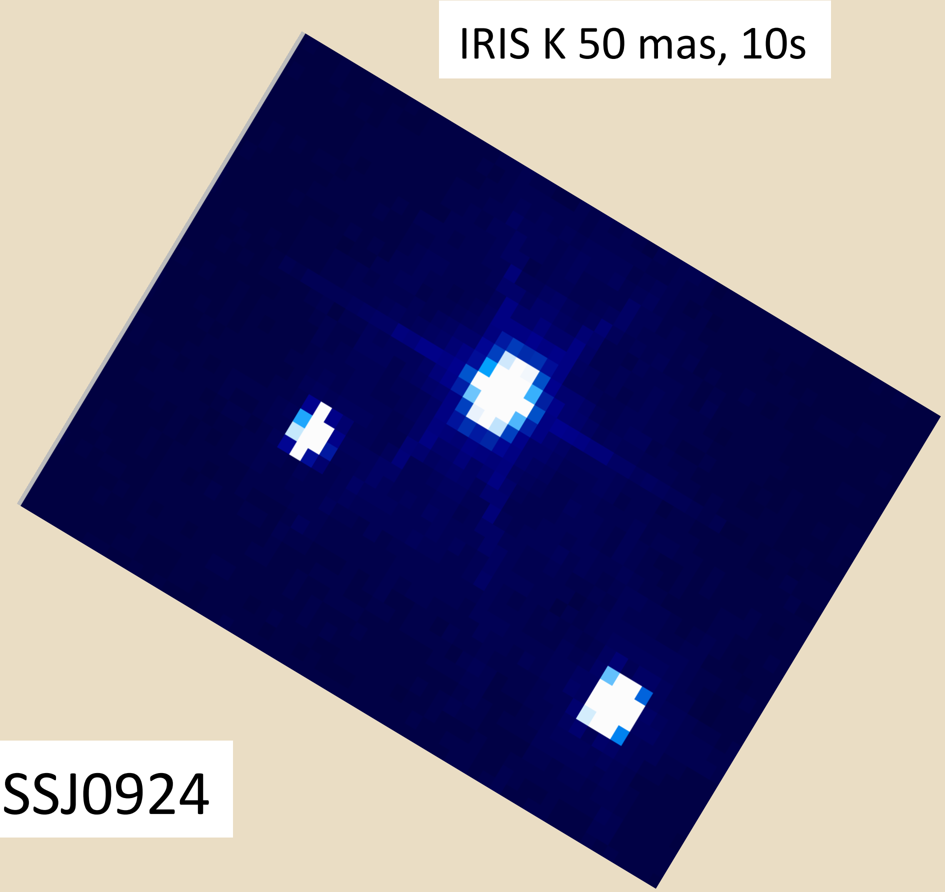
Oguri and Marshall 2010

LSST will find **hundreds** of optically bright quad quasar lenses which can be used for this method.

We need to be able to efficiently incorporate faint lenses.

IMAGING MUCH MORE RAPID WITH TMT





SDSSJ0924

IRIS Simulation courtesy of Nils-erik Rundquist (UCSD)

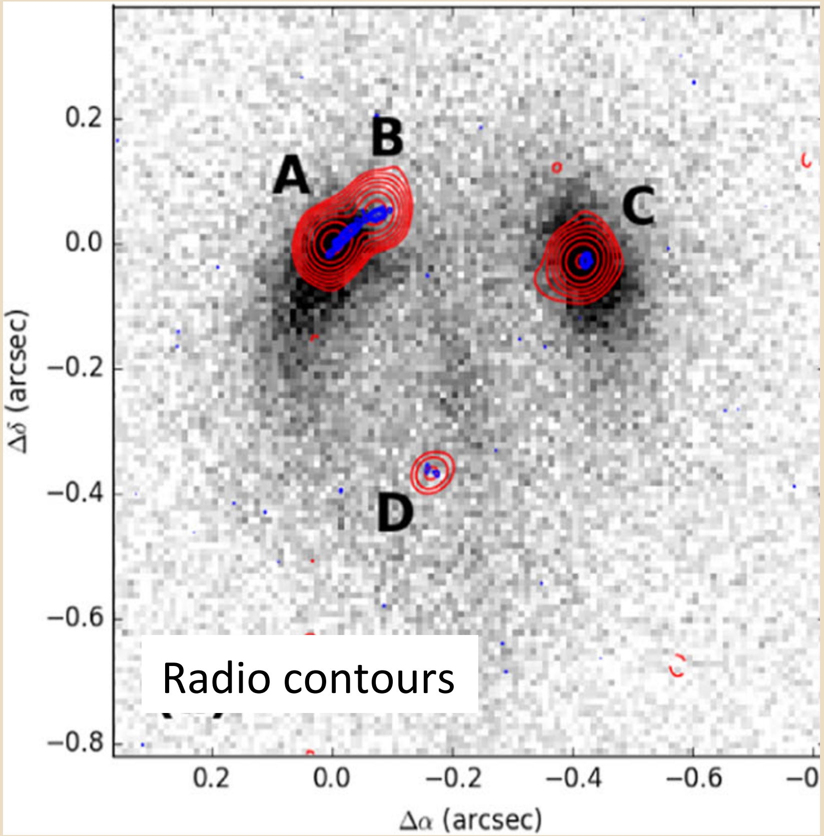
CONCLUSIONS

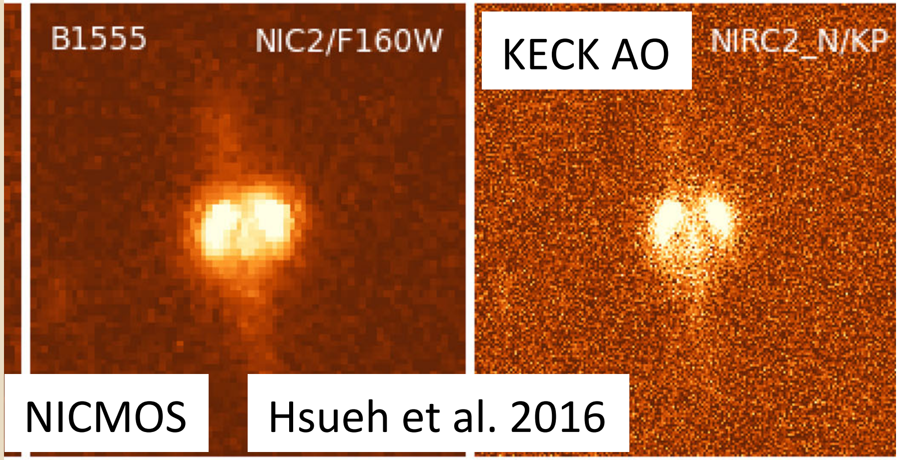
- Strong gravitational lensing is a powerful tool for constraining the properties of dark matter on small scales

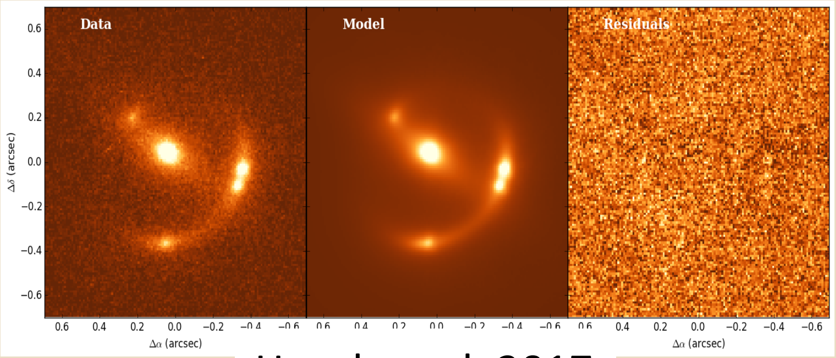
- Thanks to the increase in the lens sample from narrow-line lensing we can already get a stringent new constraint on the properties of dark matter

- Narrow-line lensing is ideal for future constraints of the halo mass function, as virtually every lensed quasar has significant narrow-line emission. We can expect to have many hundreds of high quality lenses from LSST/EUCLID which can be rapidly followed up with next generation of telescopes.

BETTER DETECTION AND MODELLING OF NON- SIE BARYONIC FEATURES

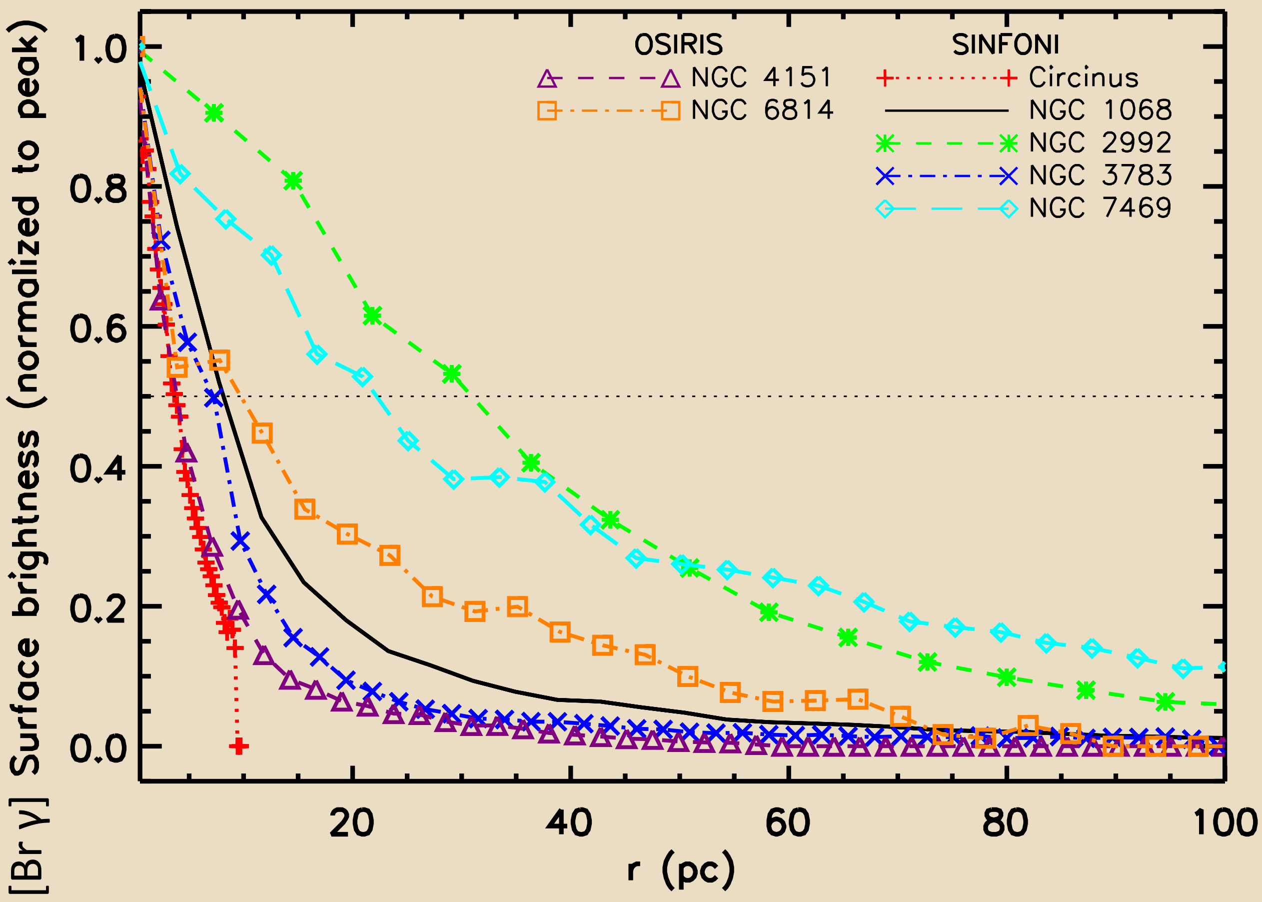






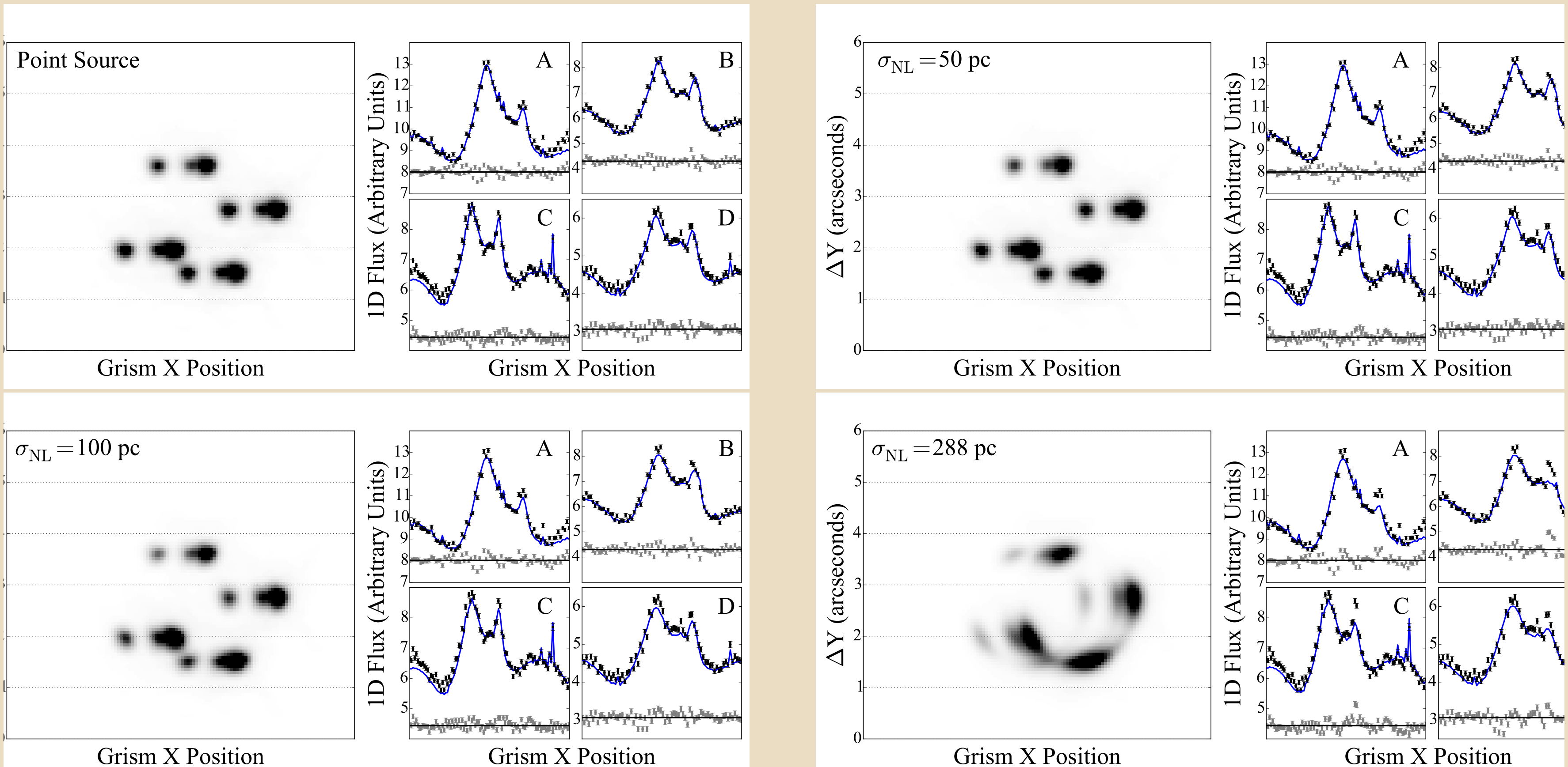
Hsueh et al. 2017

NARROW LINE LIGHT PROFILE



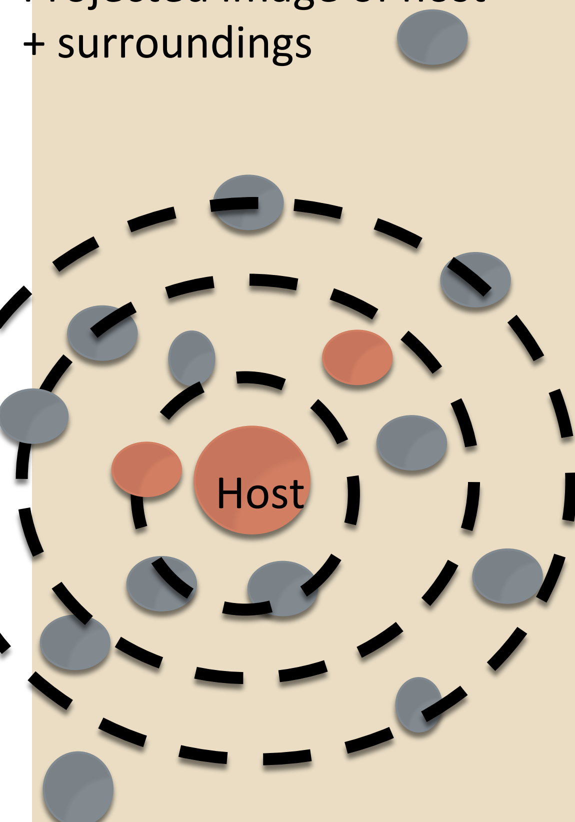
Müller-Sanchez et al. 2011

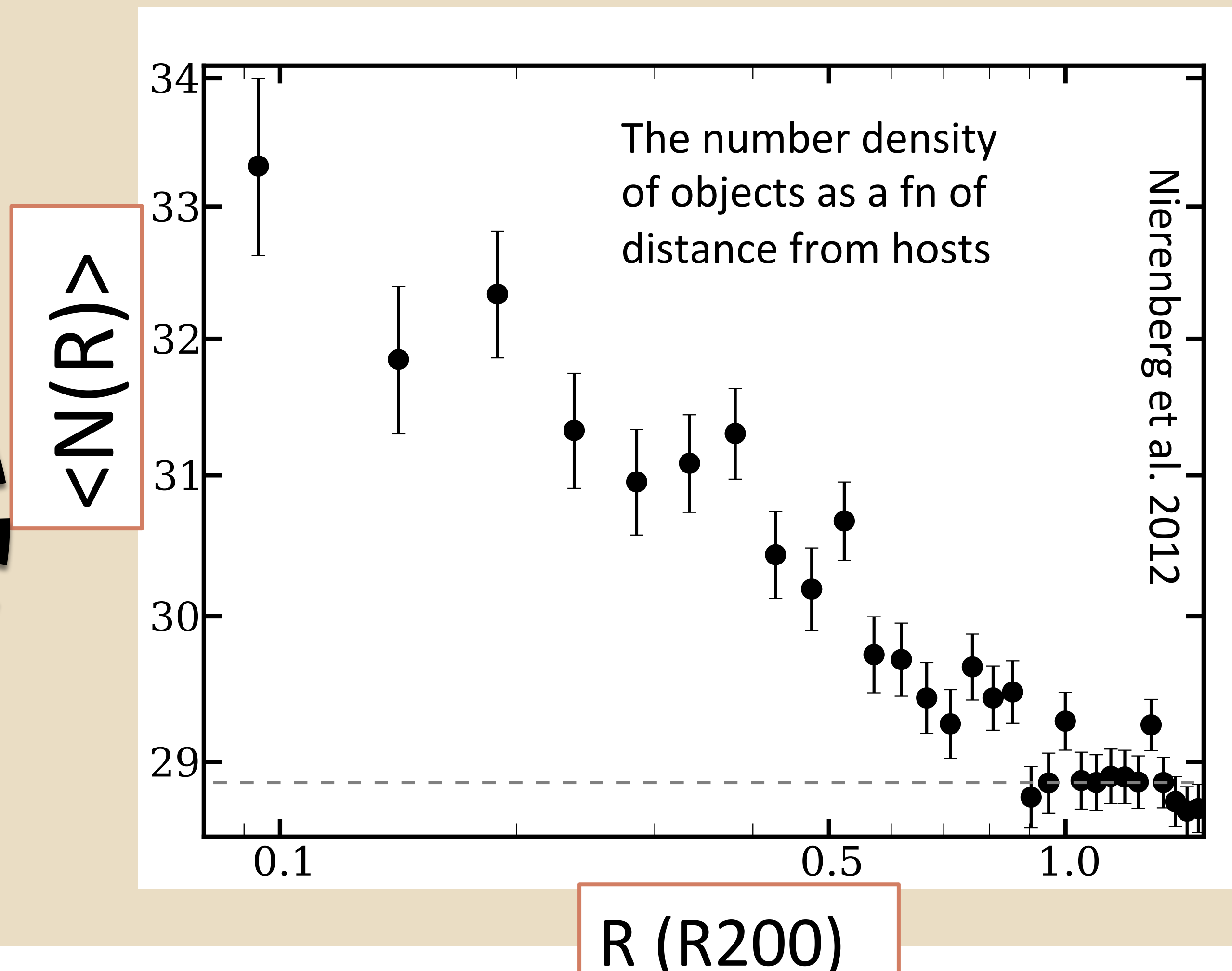
FINITE SOURCE EFFECTS FOR HE0435



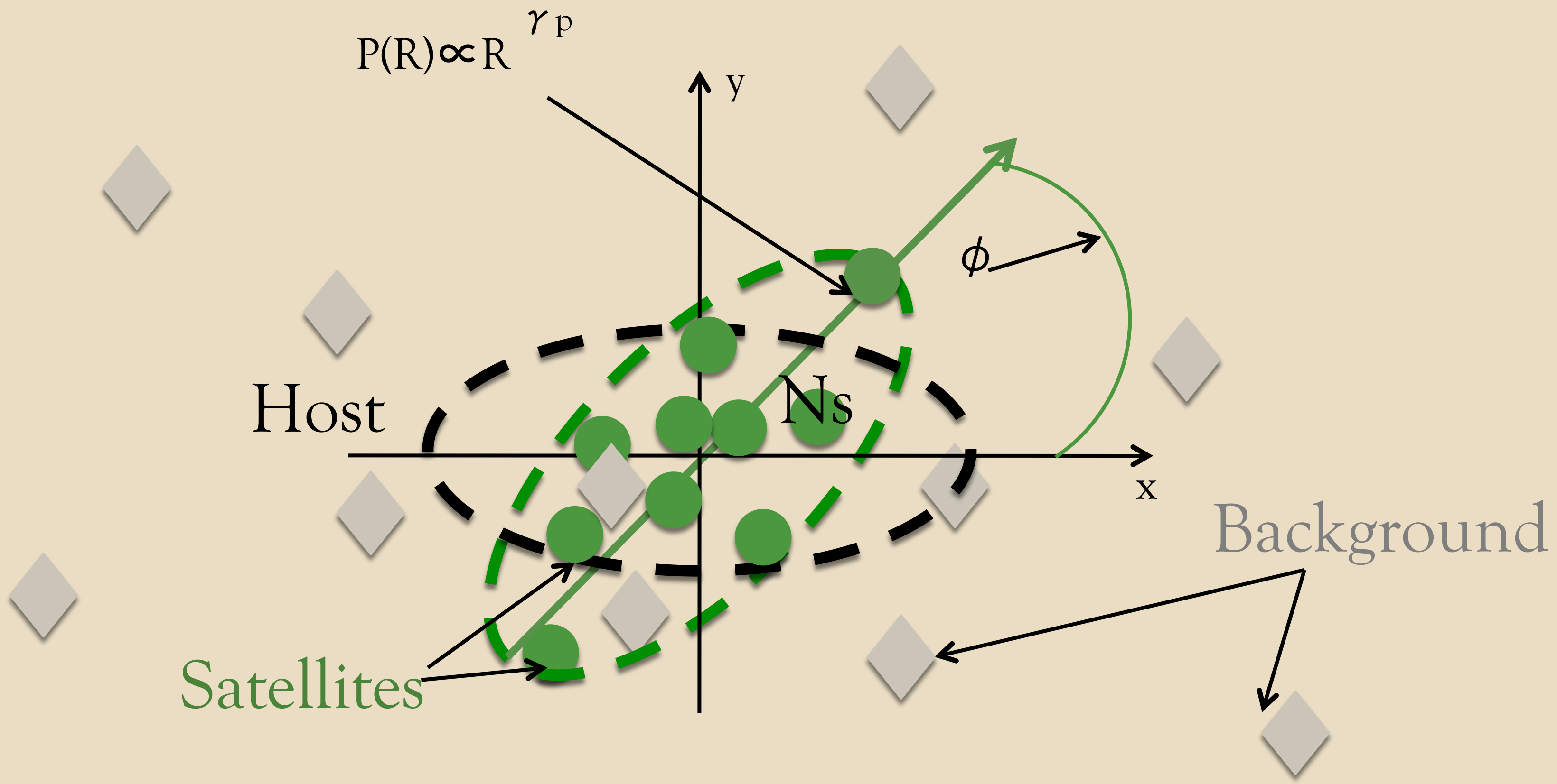
HOW TO IDENTIFY SATELLITES WITHOUT REDSHIFT INFO

Projected image of host + surroundings





A MODEL FOR THE OBSERVED NUMBER DENSITY



The number and positions of objects around the hosts is determined by the number of satellites, the radial and angular distribution of satellites, the number of background/foreground objects…ect….