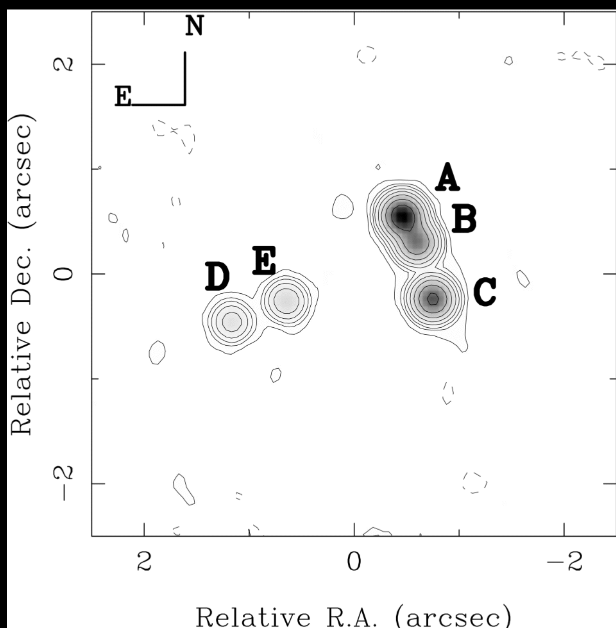
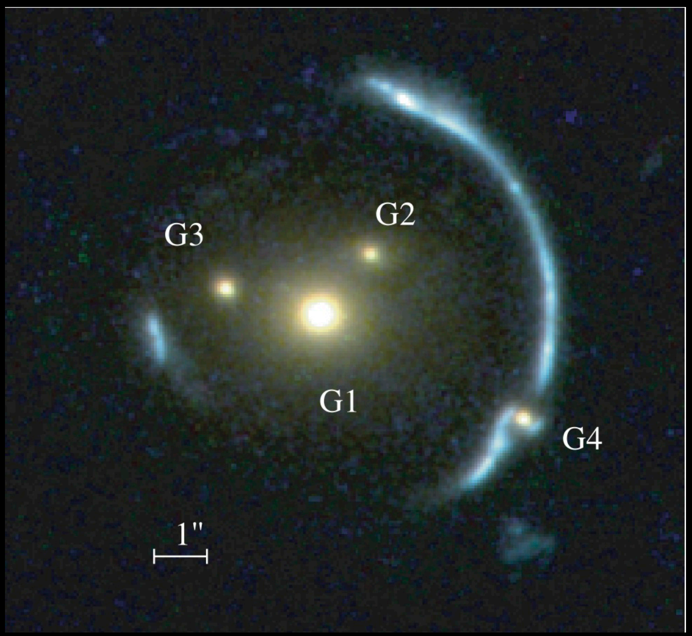
New constraints on dark matter from gravitational lensing





Chris Fassnacht (UC Davis)
Jen-Wei Hsueh (UCD / Kapteyn) and team SHARP

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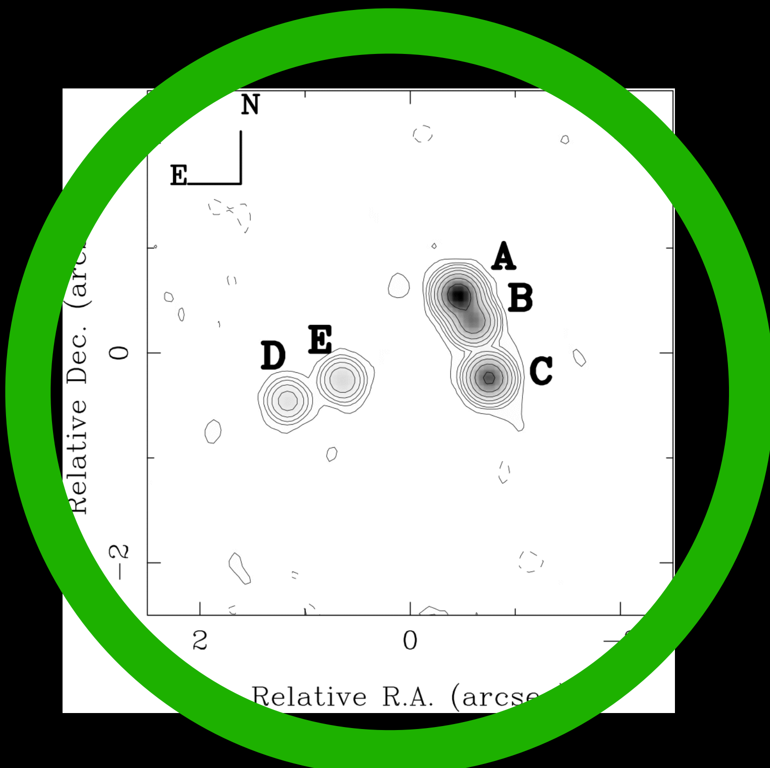

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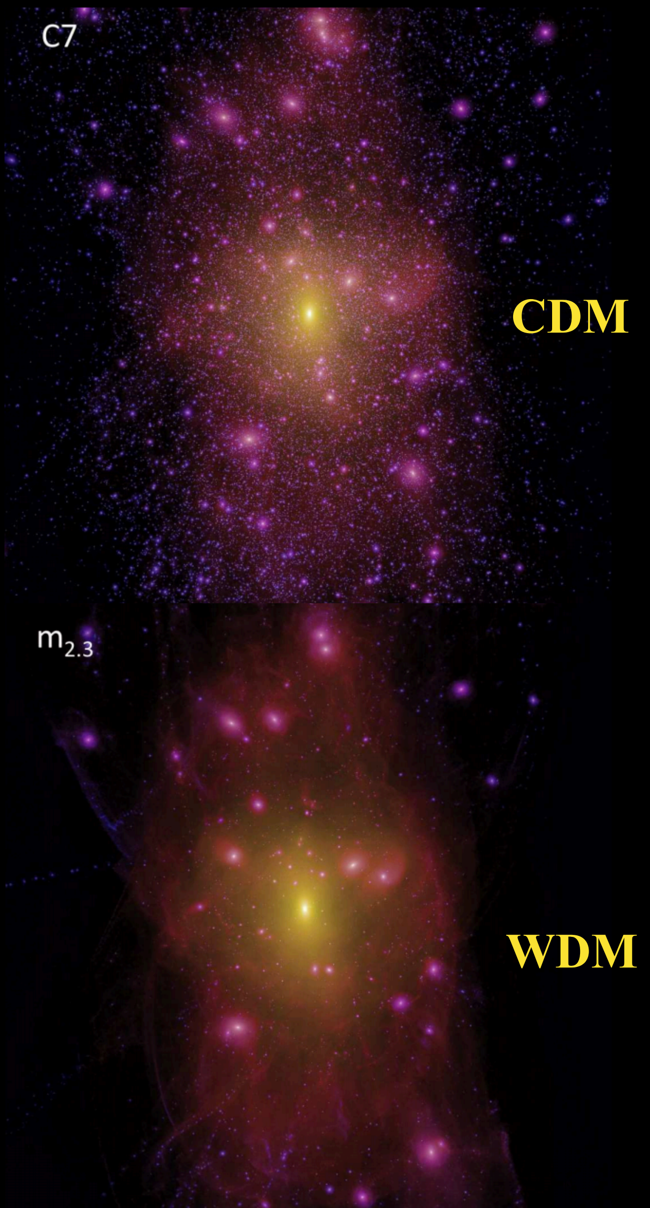
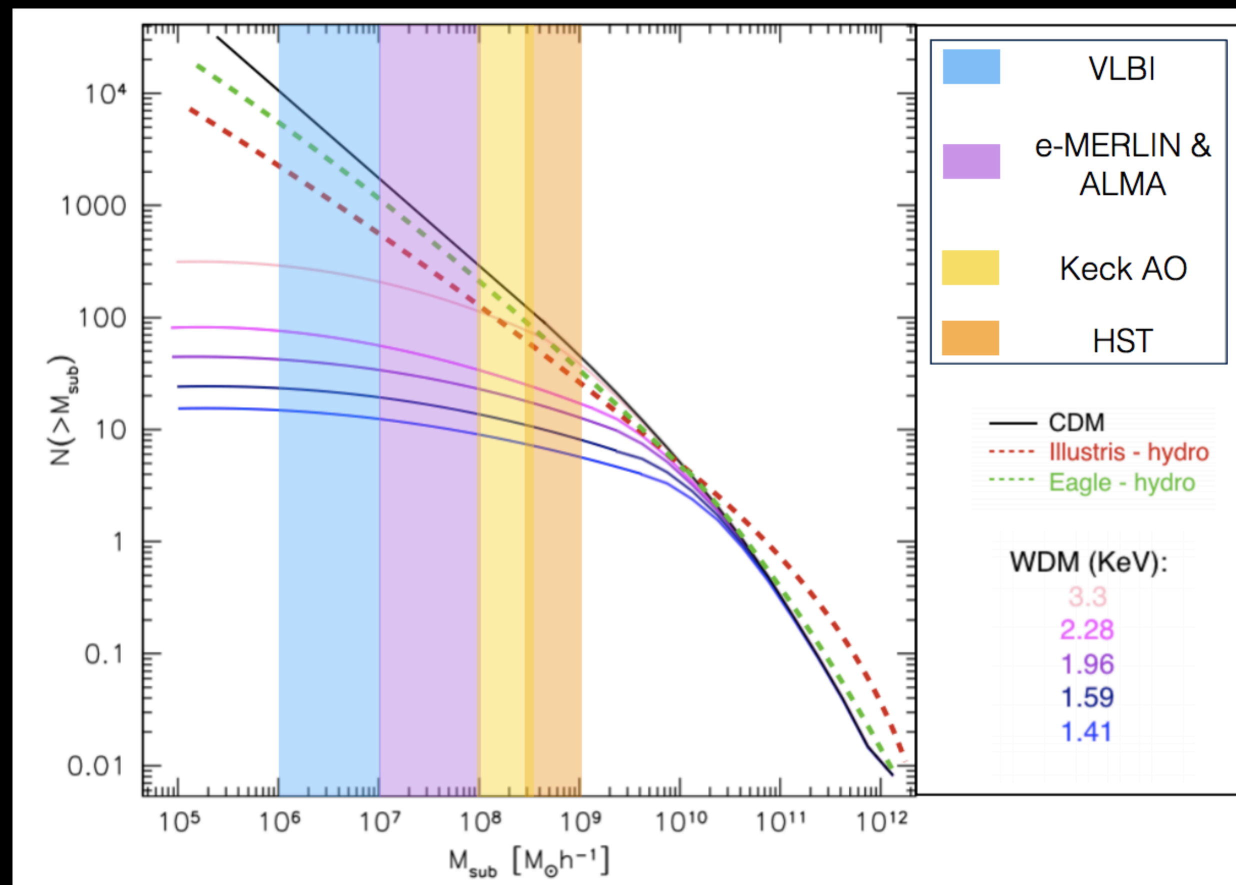
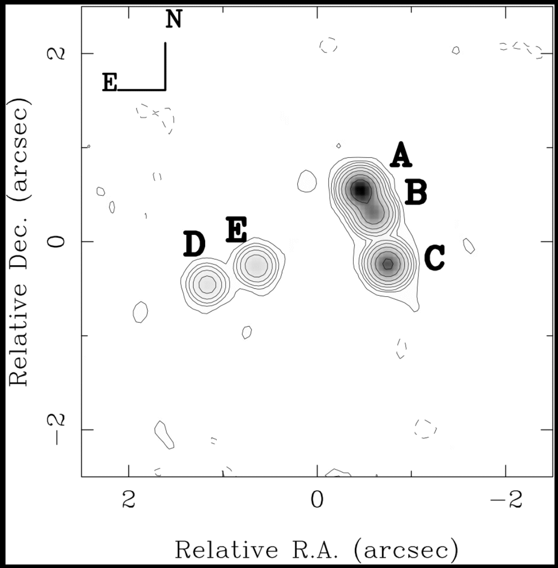
The motivation: quantifying statistics of low-mass halos





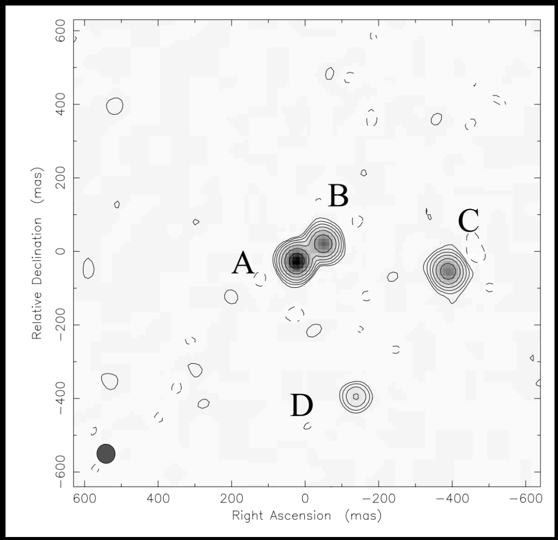
The technique: Flux-ratio anomalies

- Look for deviations in lensed image fluxes from ratios predicted by a smooth mass model of the lensing galaxy
- These are caused by low-mass line-of-sight halos or substructure in the main lensing galaxy
  - LOS halos should dominate the signal for higher-z lenses, and provide a cleaner signal (no tidal stripping)
- Need to observe at a wavelength at which the angular size of the emitting region (quasar accretion disk / jets) is larger than a few microseconds
  - Otherwise stars in the lensing galaxy will affect the lensed image fluxes
  - Traditionally this pushes you to radio or mid-IR observations (although see Daniel's talk for a very promising alternative)



Fassnacht et al. 1999

Image B should be significantly brighter than images A and C

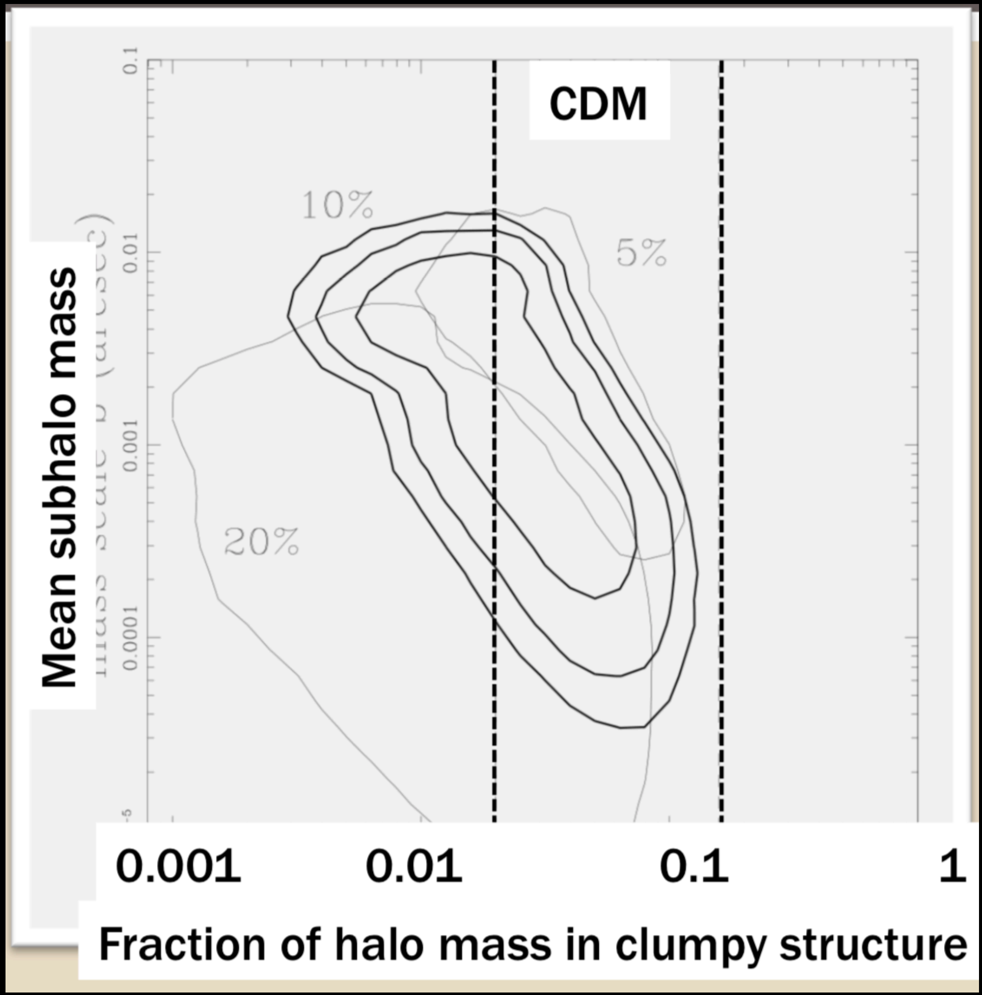


Marlow et al. 1999

Images A and B should have roughly the same flux

Previous status of flux-ratio anomaly analysis

- Only ~9 radio-loud or mid-IR lens systems
  - Only ~10% of quasars are radio-loud
  - Ground-based mid-IR observations are very challenging
- Dalal and Kochanek (2002) analyzed 7 systems and found rough agreement with CDM predictions for substructure
  - This sample has not changed much in 15 years



Dalal & Kochanek 2002

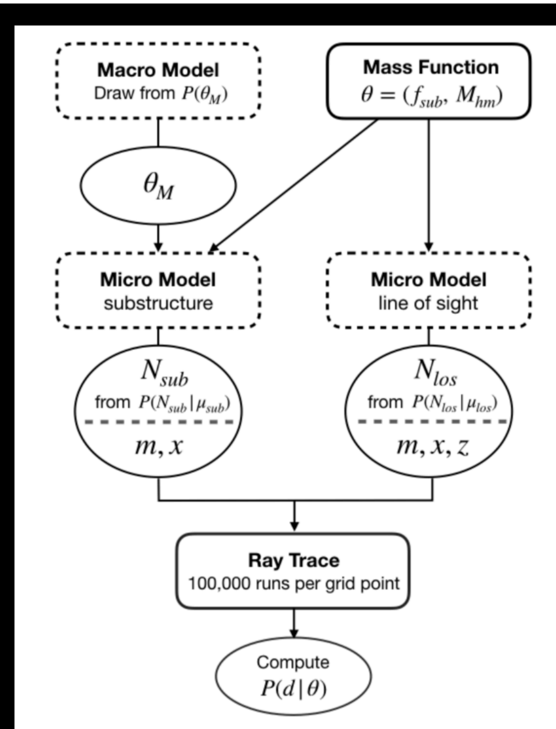
A new analysis of flux ratios in radio/MIR strong lenses

SHARP – VII. New constraints on warm dark matter free-streaming properties and substructure abundance from flux-ratio anomalous lensed quasars

J.-W. Hsueh,[1,2★] W. Enzi,[3] S. Vegetti,[3] M. W. Auger,[4] C. D. Fassnacht,[2] G. Despali,[3] L. V. E. Koopmans[1] and J. P. McKean[1,5]

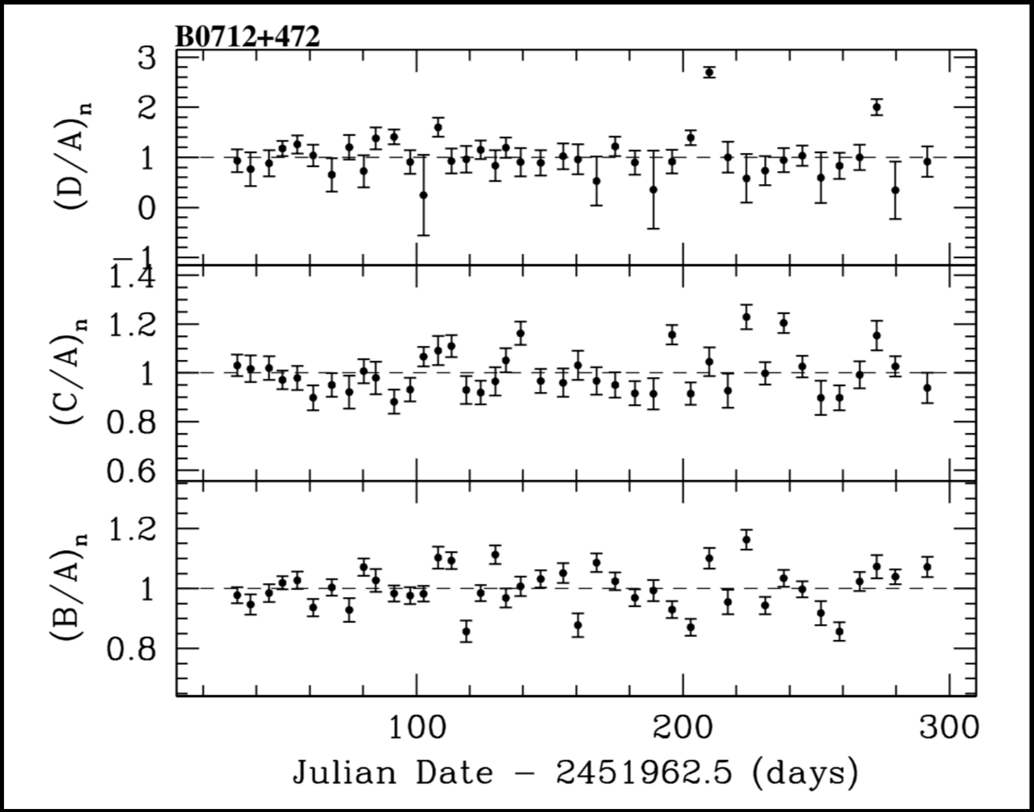
Lens	z_l	z_s
CLASS B0128+437	1.145	3.12
MG J0414+0534	0.96	2.64
CLASS B0712+472	0.41	1.34
PG 1115+080	0.3098	1.722
JVAS B1422+231	0.34	3.62
CLASS B1555+375	(1.0)	1.432
CLASS B2045+265	0.87	2.35

- Work led by Jen-Wei Hsueh (UCD -> Kapteyn)
  - arXiv:1905.04182
- Seven radio- or MIR-loud lens systems (slightly different from D&K sample)
- Several improvements over Dalal and Kochanek work
  - More precise flux-ratio measurements
  - Include baryonic structures in the lensing galaxy, e.g., stellar disks
  - Include line-of-sight halos
  - WDM analysis



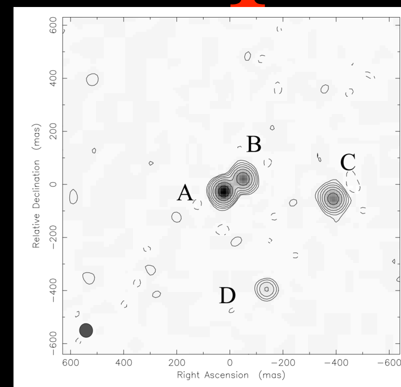
Improved flux ratios from monitoring programs

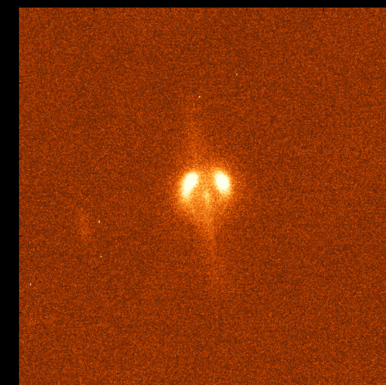
- Radio AGN are time variable and observing conditions can affect measured fluxes
- Koopmans et al. (2002) monitored a sample of radio four-images lenses
- NOTE: Flux ratios from single-epoch measurements can vary by up to 20%
- Monitoring allows much more precise flux ratios to be measured
- For systems with monitoring, we used <5% uncertainties on ratios. For the rest we used 20% uncertainties



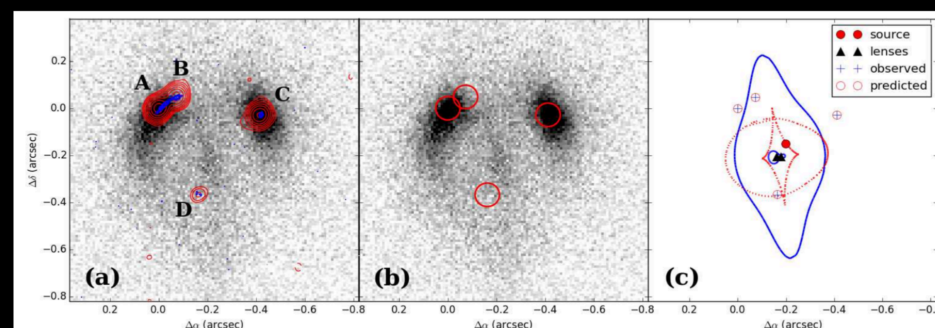
Including baryonic structures: Eliminating false positives

- Changes in flux are caused by a strong gradient in the potential
- For flux-ratio work, this is assumed to be due to clumpy mass distributions, i.e., substructure or line-of-sight halos
- However, baryonic structures in the lensing galaxy can also cause these strong gradients
- These could be edge-on disks
  - Hseuh et al. (2016, 2017)
- Also could be other non-smooth baryonic distributions
  - Gilman et al. (2017)
  - Hsueh et al. (2018)



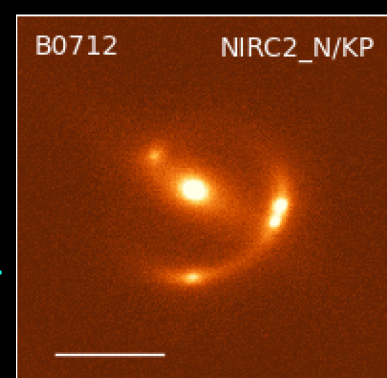


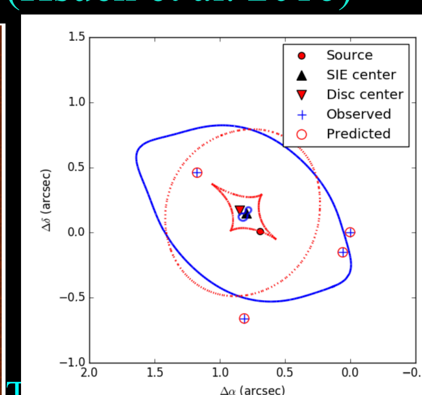
Marlow et al. 1999



Edge-on stellar disk in B1555+375 (Hsueh et al. 2016)

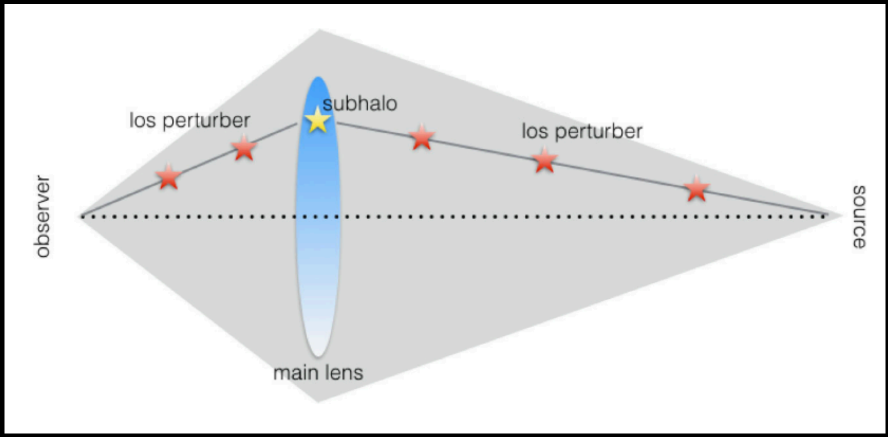
Edge-on stellar disk in B0712+472 (Hsueh et al. 2017)

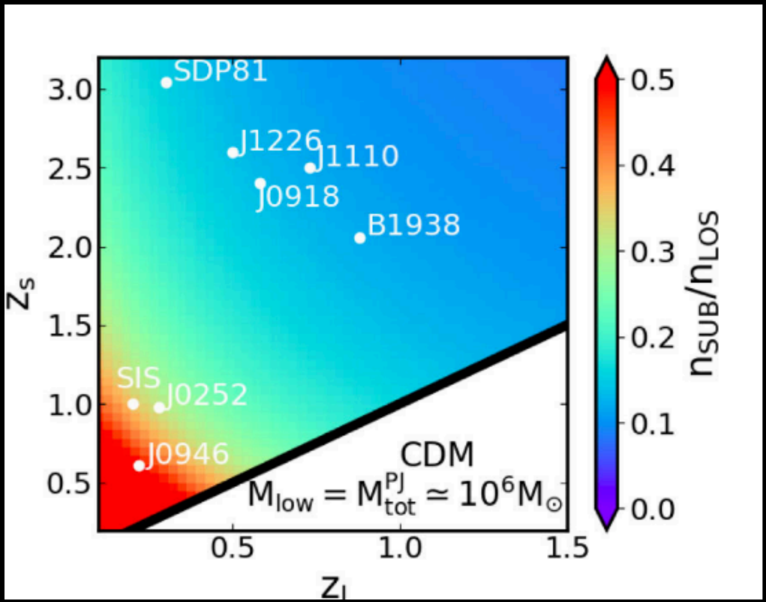




Including the line of sight

- We used to ignore line-of-sight halos and just focus on substructure in the halo of the main lensing galaxy
- However, LOS halos are a significant to dominant contributor to the lensing signal, depending on the redshifts
  - Despali et al. (2018) - gravitational imaging
  - Metcalf(2005), Gilman et al. (2019) - flux ratio anomalies
- This is a feature, not a bug
  - LOS halos are a much cleaner probe of the nature of dark matter - no tidal stripping

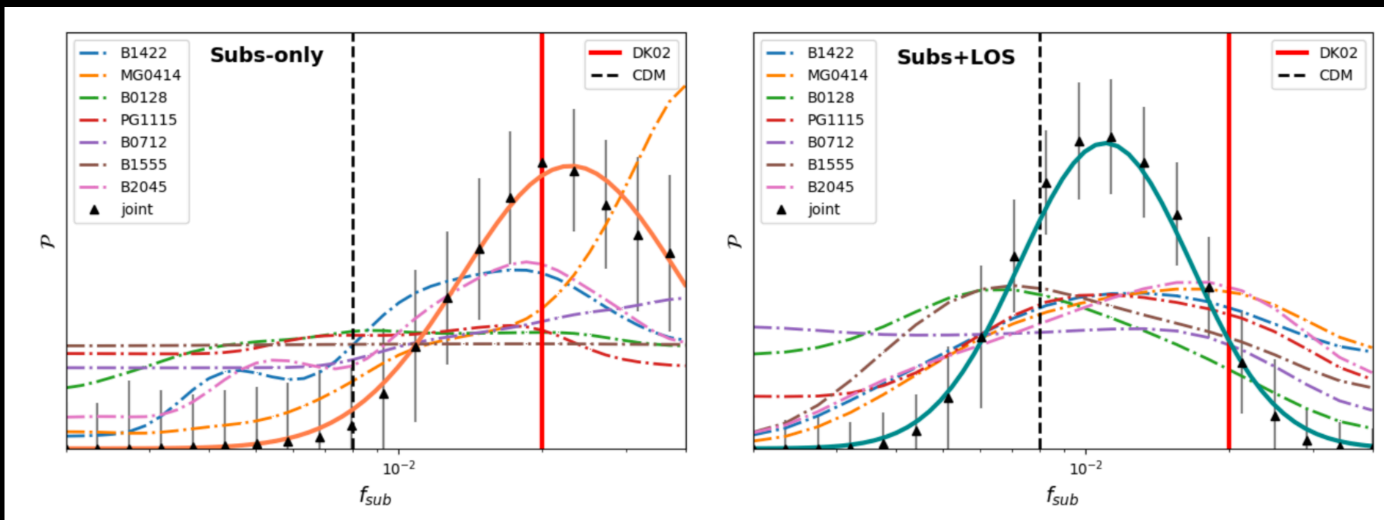


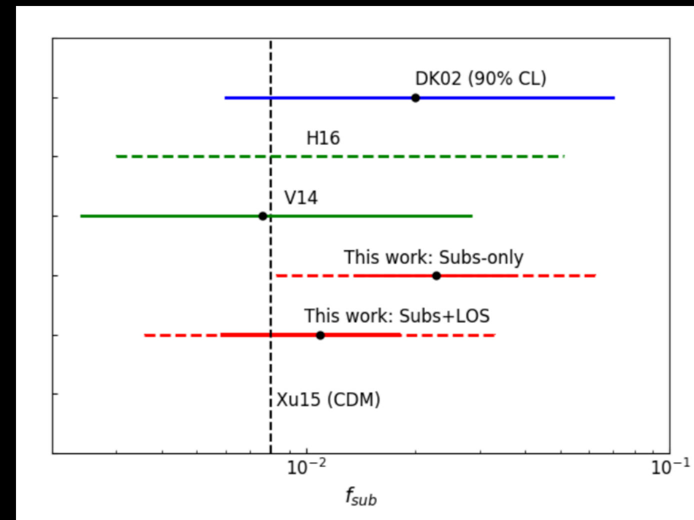


Despali et al. 2018

Color bar is ratio of number of substructure halos to LOS halos

CDM-only analysis: Both with and without LOS halos

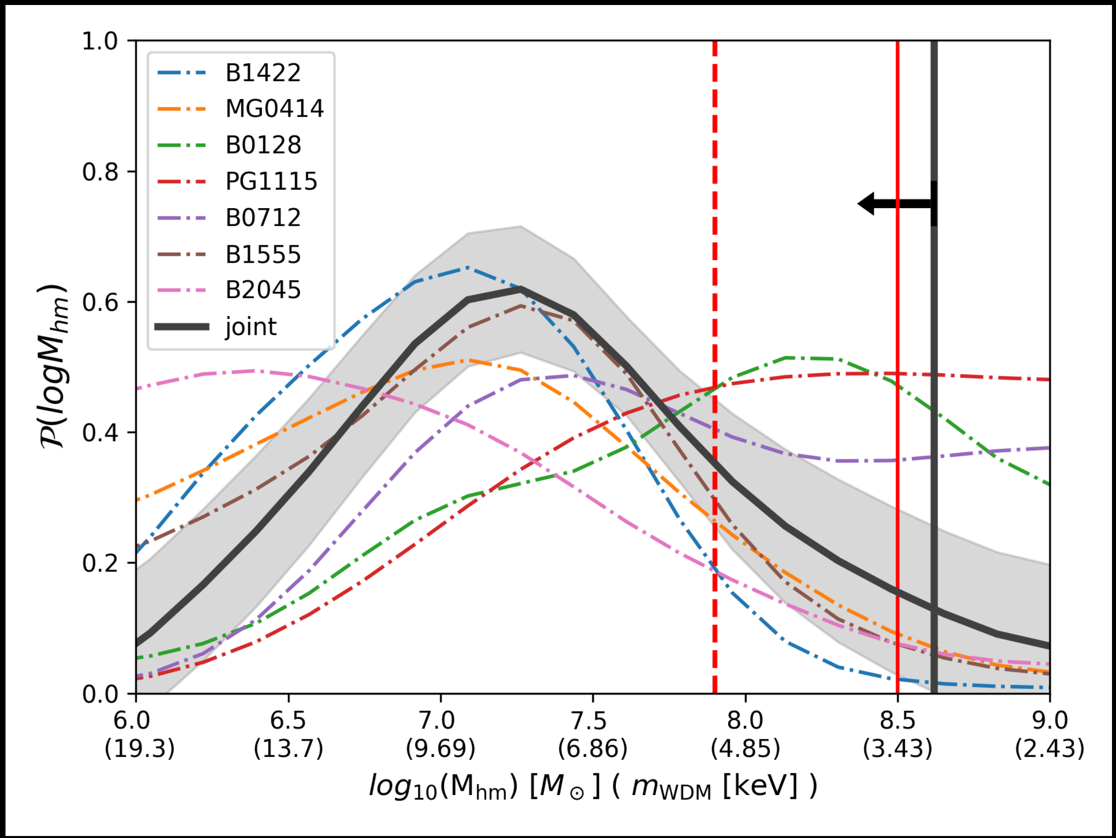




- First do the analysis <u>without</u> line-of-sight low-mass halos for direct comparison with Dalal and Kochanek (red vertical line in first two panels)
- Next repeat, but <u>include</u> the LOS halos, which are expected to dominate for essentially all of the lens redshifts being explored here
- Results:
  - Without LOS halos, our results are consistent with D&K, but with better precision (due to more precise flux ratio measurements)
  - Including LOS halos brings substructure inference in lines with predictions from simulations (dashed vertical line in figures)

WDM analysis

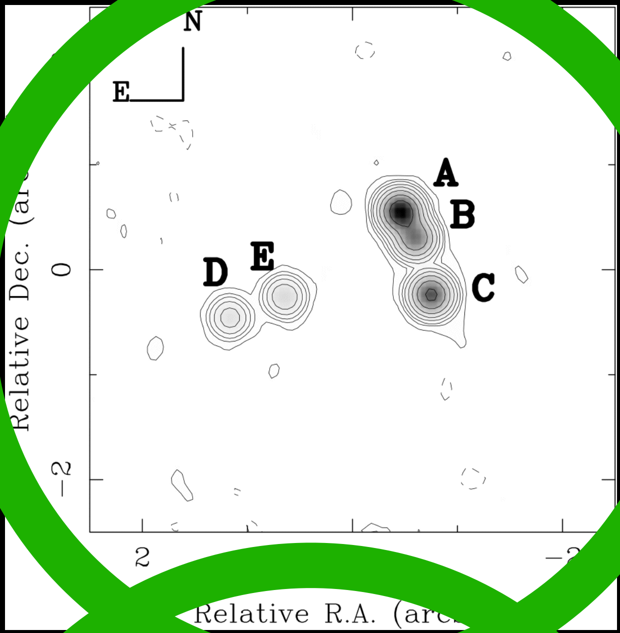
- Redo analysis with a WDM model
- Fit for half-mode mass (M_{hm})
- Convert to m_{WDM} in keV
  - Thanks to Ethan Nadler for catching an error in our conversion!!
- Results:
  - Gravitational lens flux ratios (vertical black lines) give comparable 95% limits to those from Ly-alpha forest analysis (red vertical lines)
  - NOTE: figure under re-construction since drop-off at low M_{hm} (high m_{WDM}) may be due to resolving the radio source
    - In that case, joint 95% constraint may shift to the left

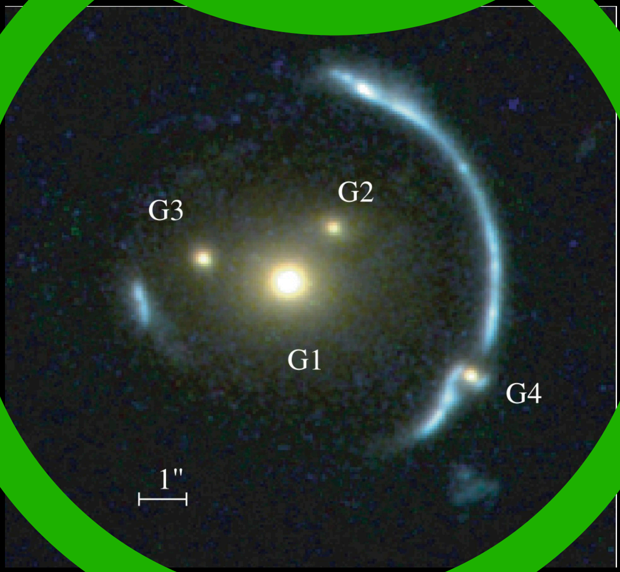


NOTE: Figure has been updated compared to version on arXiv

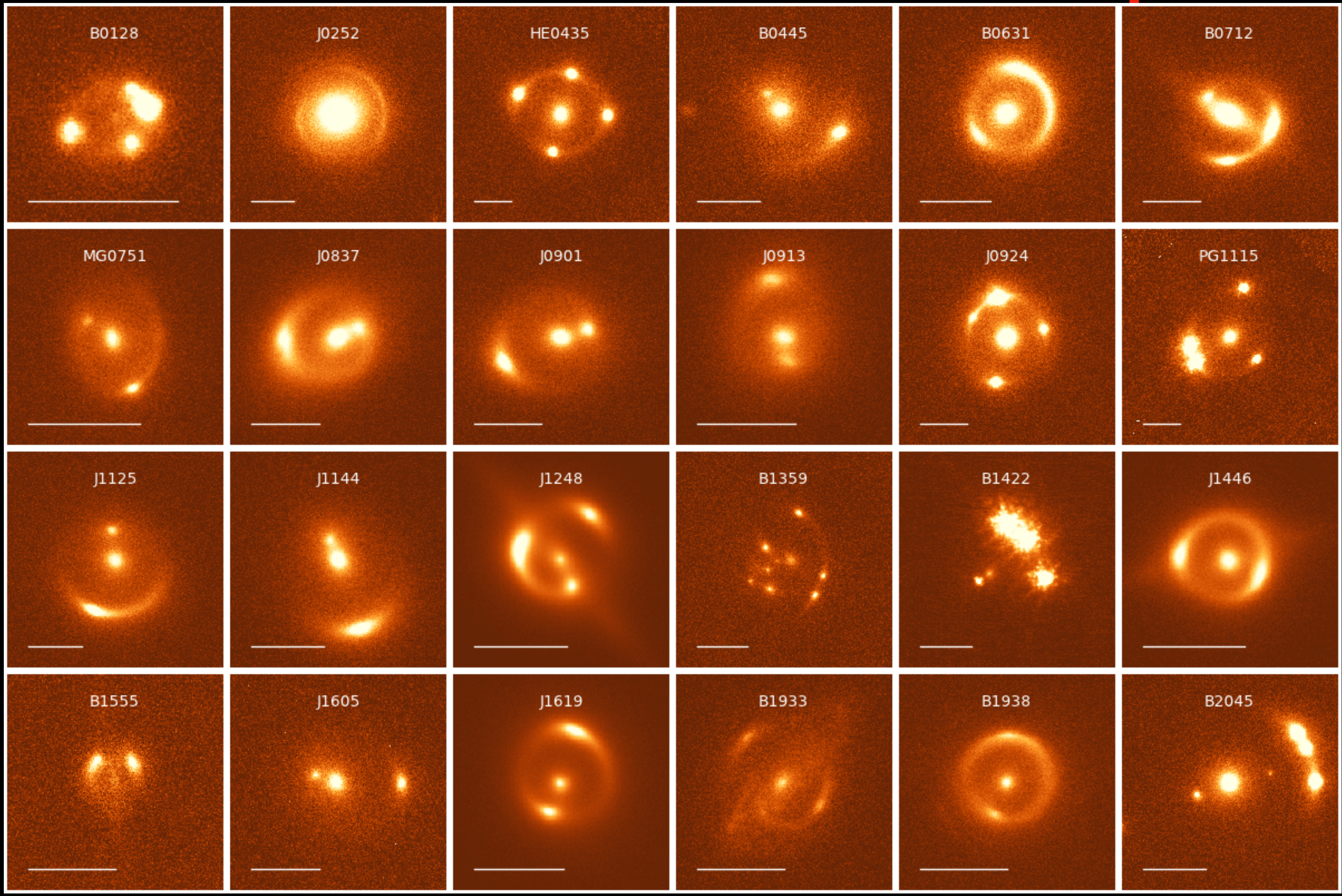
Moving forward

- Analyze VLBI imaging for the Hsueh et al. sample to quantify sizes of lensed sources
- Narrow-line samples: work of Anna Nierenberg and Daniel Gilman, etc.
- Gravitational imaging: work of Simona Vegetti and Elisa Ritondale, etc.
- ALMA has a lot of promise for both gravitational imaging (Hezaveh et al. 2016) and flux ratios (Stacey & McKean 2018)
- LSST will be a great lens discovery engine, for both lensed quasars (for flux-ratio analysis) and lensed galaxies (for gravitational imaging)
- Need high angular resolution imaging / spectroscopy follow-up for these new samples



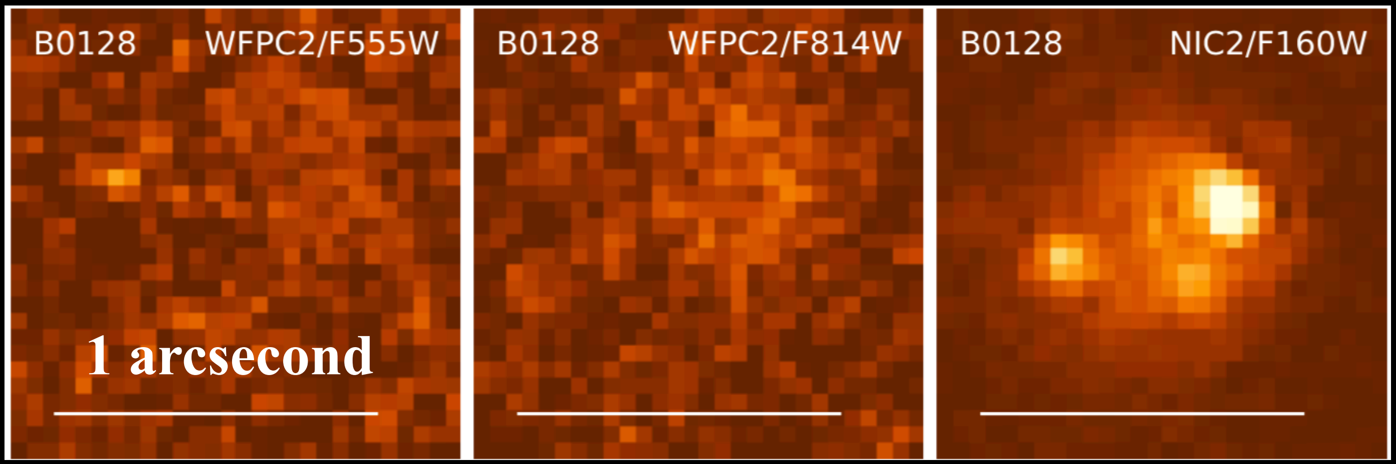


SHARP: Example of high-resolution follow-up



Part of the SHARP sample. Keck adaptive optics imaging (Fassnacht et al., in prep)
Gravitational imaging analysis in progress — Elisa Ritondale et al., in prep

The power of adaptive optics

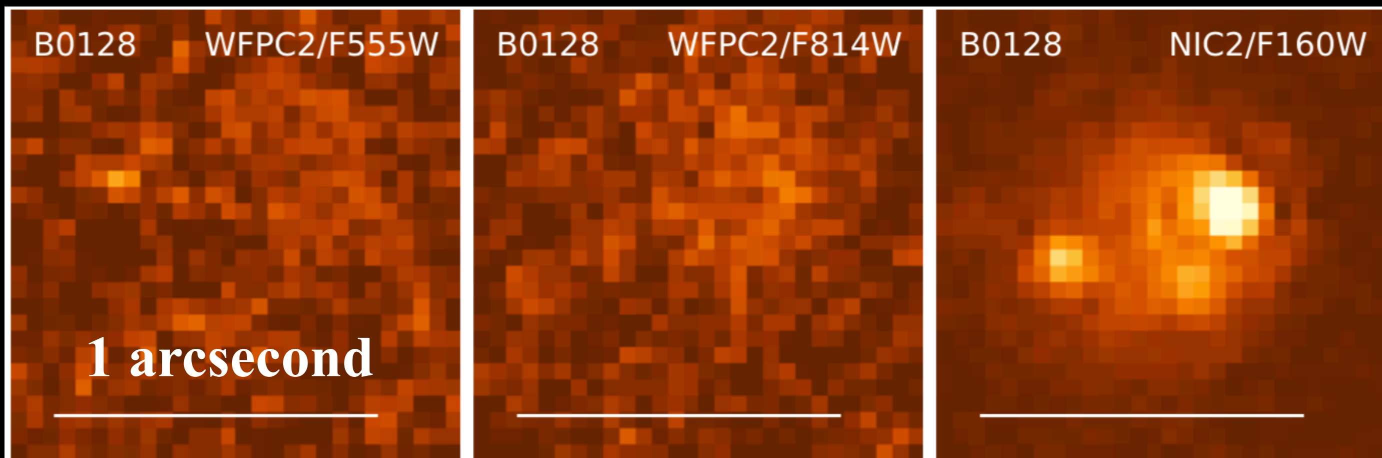


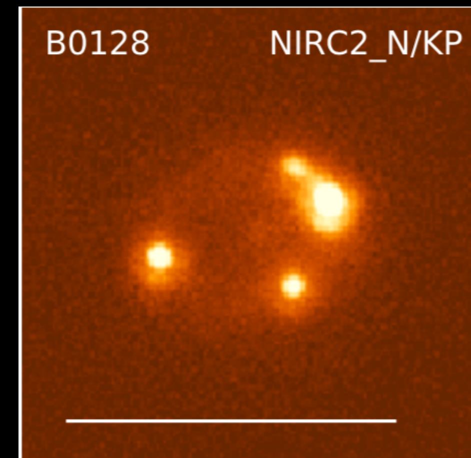
HST

Fassnacht et al, in prep

For red objects, Keck AO gives better angular resolution than HST

The power of adaptive optics





HST

Keck AO

Fassnacht et al, in prep

For red objects, Keck AO gives better angular resolution than HST

TL;DR

- A new analysis of flux ratios for lensed quasar systems in which it is possible to observe in the radio or mid-IR — 7 systems in total
- In a CDM model, the inference on the amount of substructure in the halos of the lensing galaxies is consistent with predictions from simulations IF you take into account the effect of LOS halos as well
- Limits on the properties of WDM are similar to those from Ly-alpha forest analyses, and are completely independent
- The current sample size is very small, and the strength of inferences will only improve as sample sizes grow
  - Narrow-line region work (Nierenberg, Gilman, etc.)
  - Gravitational imaging (Vegetti, Ritondale, etc.)
- LSST will provide a huge increase in the number of strong lens systems for which we can do these kind of analyses