The Most Powerful Lenses in the Universe: Quasar Micro-lensing

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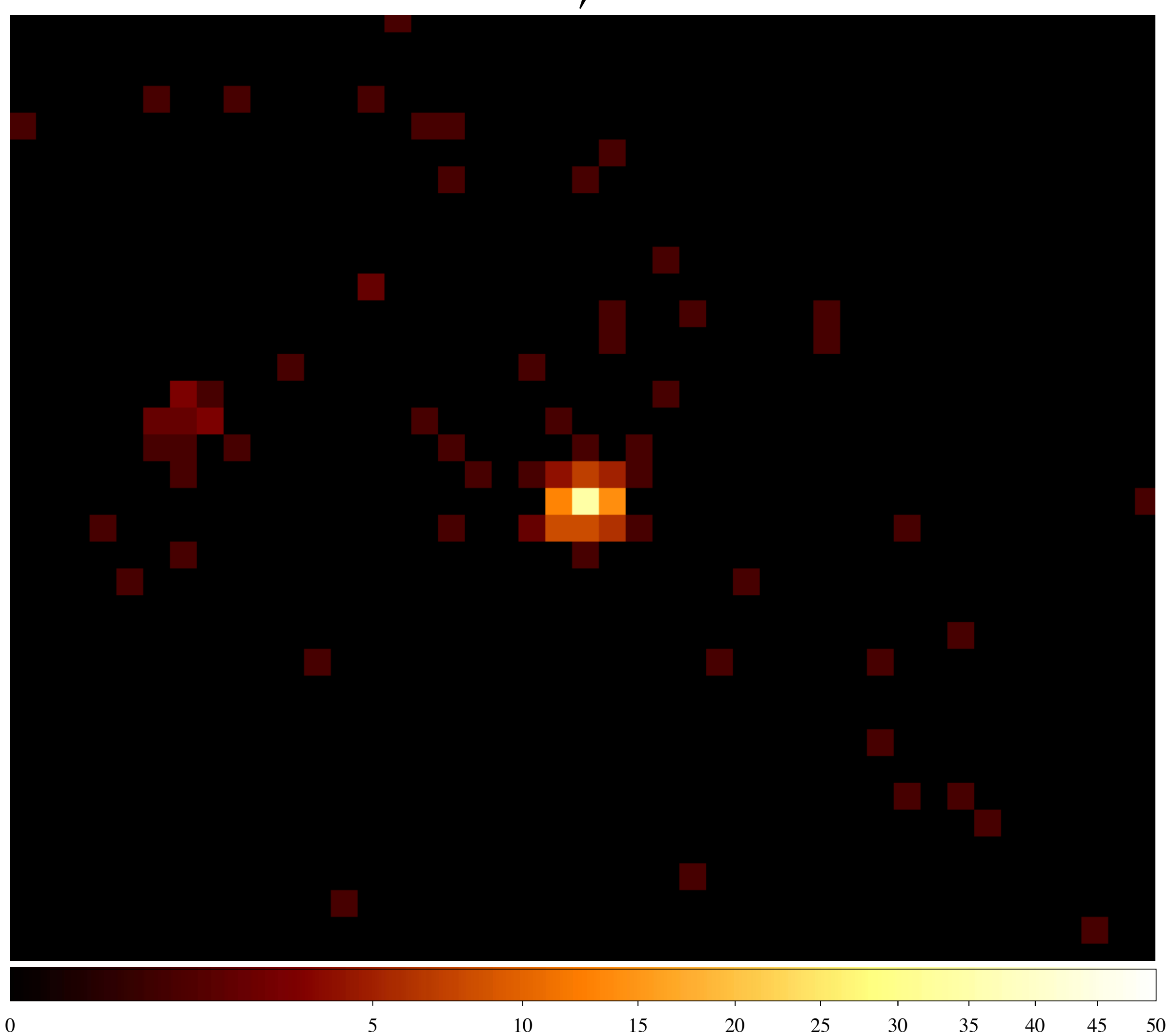
This Saturday will be my 20th anniversary of analyzing *Chandra* data.

SN 1999em, ObsID 763




```
Subject: Chandra data
Date: December 7, 1999 at 7:56:02 PM EST
To: dave@MIT.EDU, derekfox@space.mit.edu, jmm@space.mit.edu

From tpg@head-cfa.harvard.edu  Tue Dec  7 17:58:28 1999
Message-Id: <199912072257.RAA11778@head-cfa.harvard.edu>
X-Mailer: exmh version 2.0.2 2/24/98
To: LEWIN (Walter Lewin)
cc: pepi@head-cfa.harvard.edu (Pepi Fabbiano), ievans@head-cfa.harvard.edu,
       arcops@head-cfa.harvard.edu (Arcops Account),
       jnichols@head-cfa.harvard.edu (Joy S. Nichols),
       rjb@head-cfa.harvard.edu (Roger J. Brissenden)
Subject: Your Chandra Observation 500059
Mime-Version: 1.0
Content-Type: text/plain; charset=us-ascii
Date: Tue, 07 Dec 1999 17:57:27 -0500
From: "Tomas P. Girnius" <tpg@head-cfa.harvard.edu>
Status: RO


Dear Dr. Lewin,

This message is to let you know that your observation

       SeqNum 500059, ObsId 763

is available for downloading by you through anonymous ftp:

ftp asc.harvard.edu
anonymous
<your name and address as password>
bin
cd /pub/arcftp/.go/763/763_3399/tar_1805
dir
-rw-r--r--   1 arcops       2465 Dec  7 17:47 500059.contents
-rw-r--r--   1 arcops   144389120 Dec  7 17:47 500059.tar
-rw-r--r--   1 arcops       2216 Dec  7 17:42 README
-rw-r--r--   1 arcops       1090 Dec  7 17:47 caveat.txt
-rw-r--r--   1 arcops       4096 Dec  7 17:42 vv.763
mget *
bye

Untarring the data will create a directory
       500059
in the current directory, containing a small directory tree with the data.

The .contents file contains a listing of the .tar file.
The .vv file contains the V&V report
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Fundamental astronomy has a fundamental problem.

Nobody ever measures the stellar mass. That is not a measurable thing; it's an inferred quantity. You measure light, OK? You can measure light in many bands, but you infer stellar mass. Everybody seems to agree on certain assumptions that are completely unproven.

— Carlos Frenk, 2017 May 15

THE ASTROPHYSICAL JOURNAL, 845:157 (18pp), 2017 August 20 https://doi.org/10.3847/1538-4357/aa816d

CrossMark

The Initial Mass Function in the Nearest Strong Lenses from SNELLS: Assessing the Consistency of Lensing, Dynamical, and Spectroscopic Constraints

Andrew B. Newman[1], Russell J. Smith[2], Charlie Conroy[3], Alexa Villaume[4], and Pieter van Dokkum[5]

Main sources of uncertainty

lensing: contribution of dark matter

stellar dynamics: contribution of dark matter

stellar pop. synthesis: low-mass cutoff of IMF

THE ASTROPHYSICAL JOURNAL, 837:166 (8pp), 2017 March 10 https://doi.org/10.3847/1538-4357/aa6190

CrossMark

The Stellar Initial Mass Function in Early-type Galaxies from Absorption Line Spectroscopy. IV. A Super-Salpeter IMF in the Center of NGC 1407 from Non-parametric Models

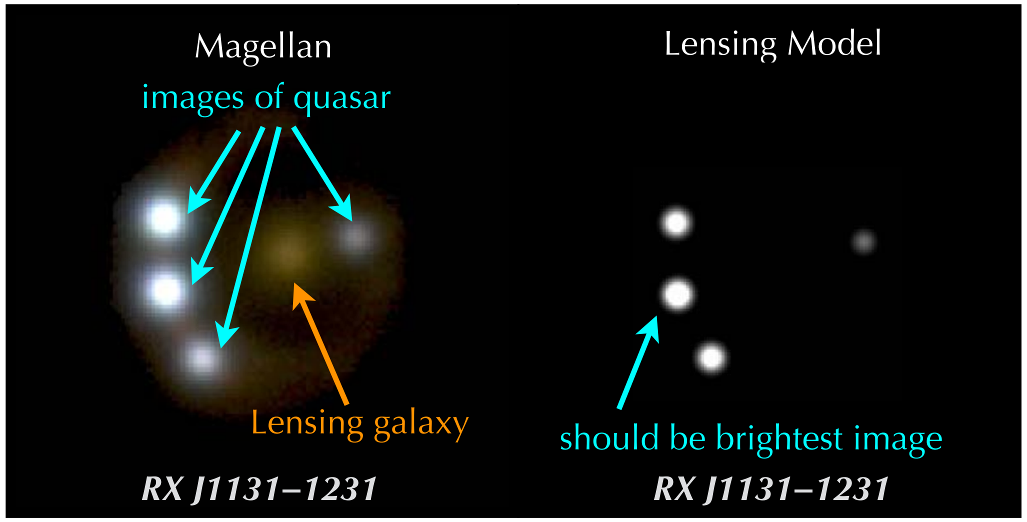
Charlie Conroy[1], Pieter G. van Dokkum[2], and Alexa Villaume[3]

"To illustrate the sensitivity of the total mass to the cutoff, for a single power law with α=2.7, the mass-to-light ratio is 70% higher if the cutoff is $0.05M_\odot$ compared to $0.08M_\odot$."

Chandra enabled the use of micro-lensing as powerful tool.

Flux ratio anomalies in lensed quasars were known in the optical for decades, but the explanation was unclear (*milli*lensing vs. *micro*lensing).

DM subhalos ✗ stars ✔



Blackburne, DP, & Rappaport 2006

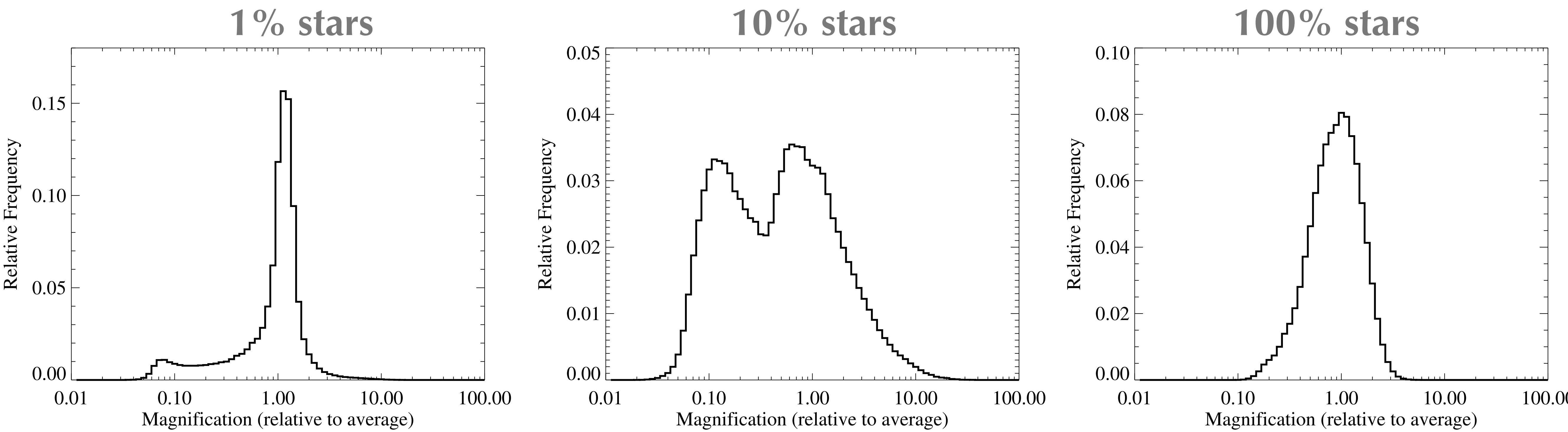
Chandra observations established that stronger X-ray anomalies are nearly universal, indicating microlensing is the cause of the anomalies. *DP et al. 2007*

This allowed microlensing to be used as a tool to study both the sources (quasars) and the lenses (elliptical galaxies) on scales of micro-arseconds.

Einstein radius of a star in typical lensing galaxy

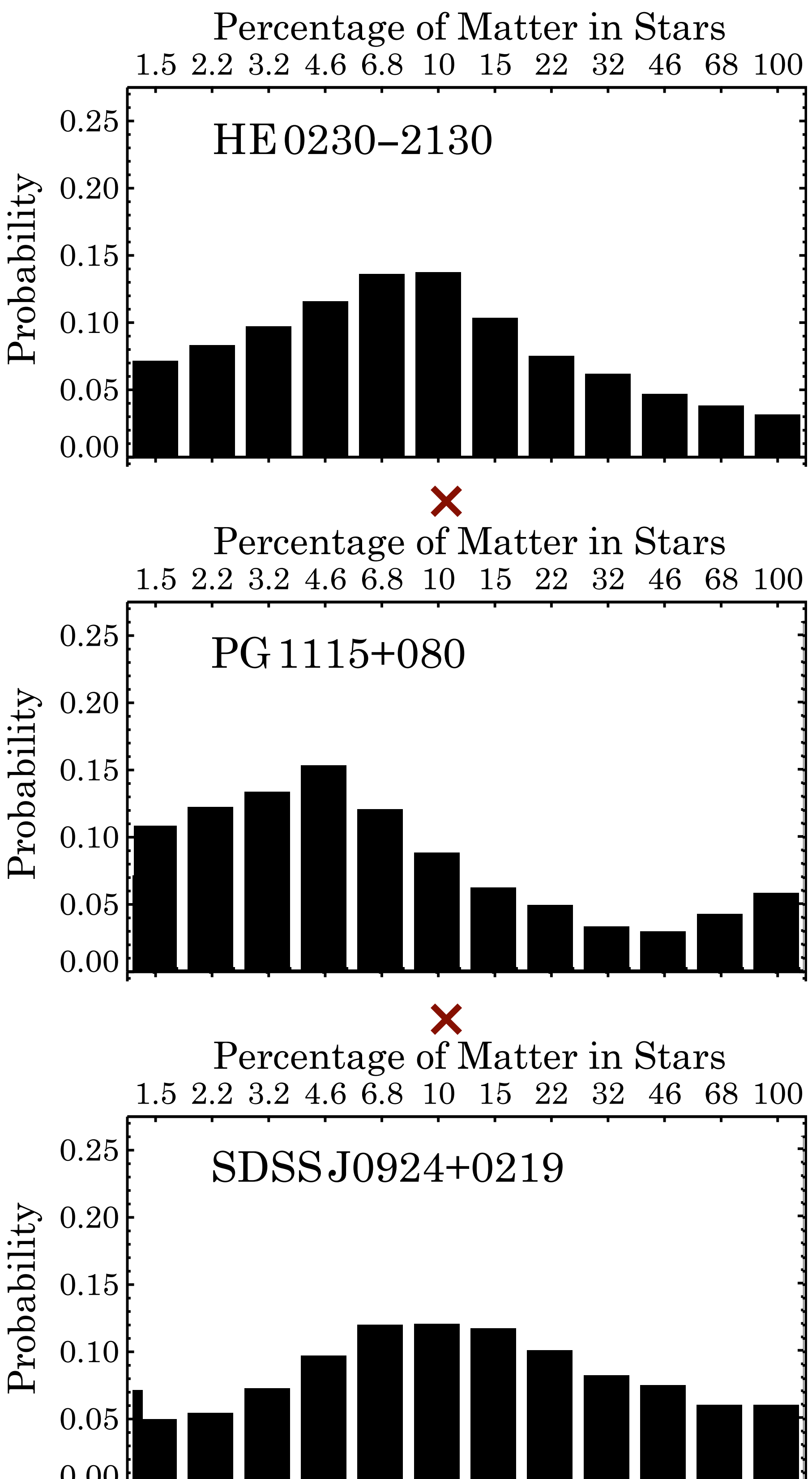
$$\theta_{\rm Ein} \approx 3 \left[\left(\frac{m}{M_\odot} \right) \left(\frac{\rm Gpc}{D_L} \right) \right]^{1/2} \mu{\rm as}$$

The probability of strong micro-lensing effects is a non-monotonic function of stellar density.



Lensing galaxy contents:

The ensemble average stellar fraction is ~7% at typical impact parameter of 7 kpc.



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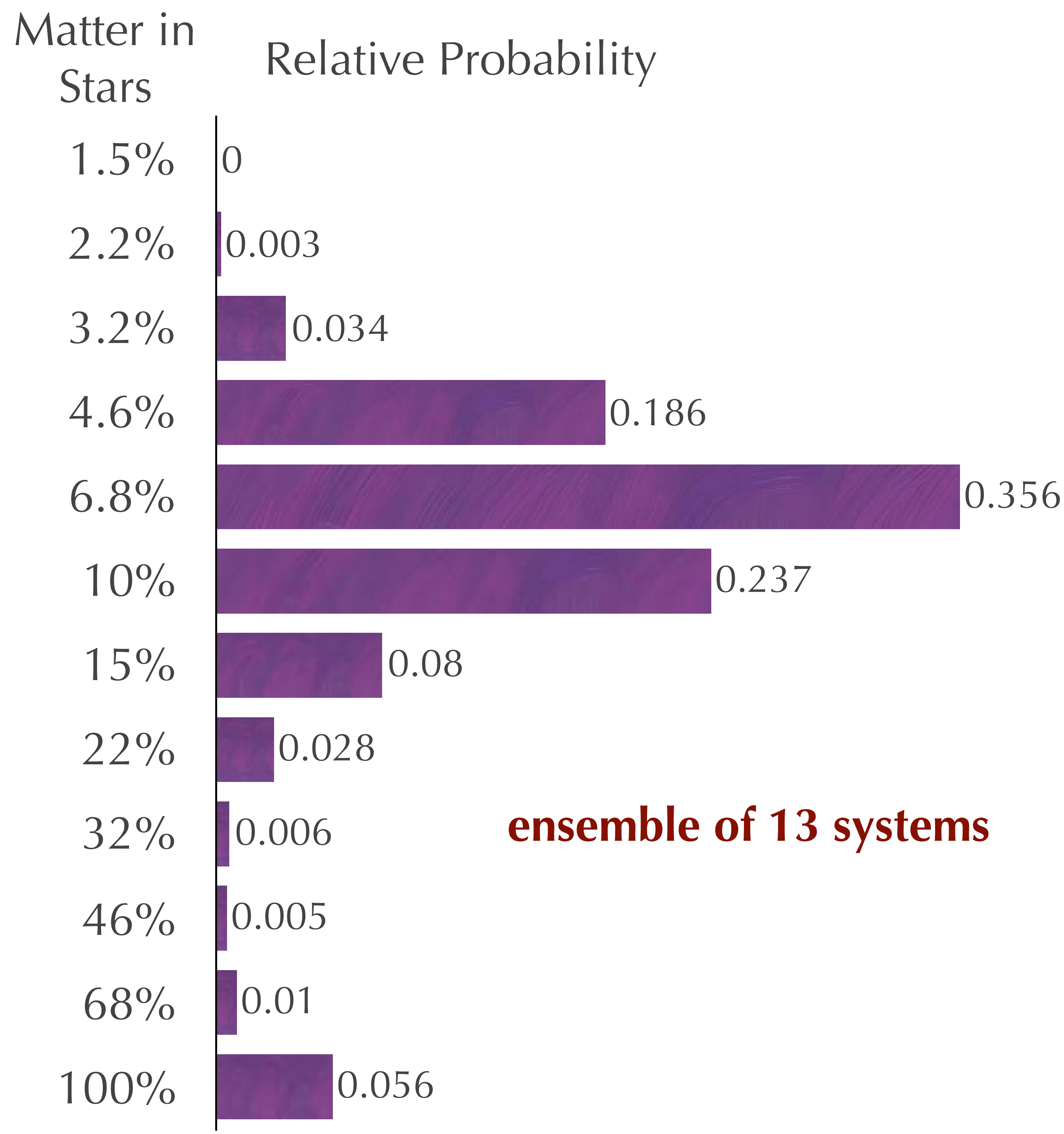
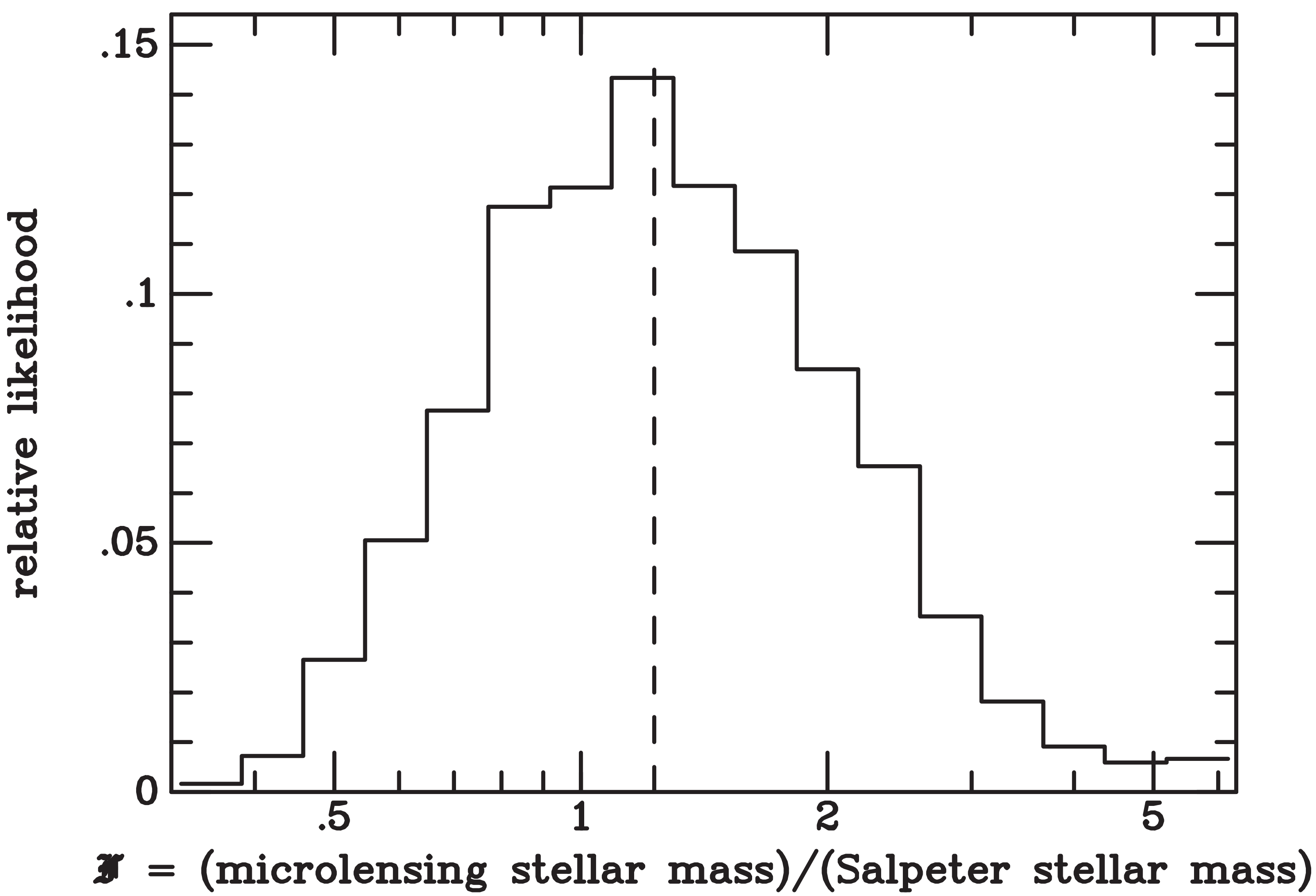


DP et al. 2012

Lensing galaxy contents:

Chandra data determine stellar M/L via the Fundamental Plane.

- Overall mass density of lensing galaxy is known from macro-lensing.
- *Chandra* gives level of micro-lensing → mass in individual stars, including stellar remnants, brown dwarfs, and red dwarfs too faint to produce photometric or spectroscopic signatures.
- We assess stellar M/L via a calibration factor $\mathscr{F}$ that multiplies the stellar mass fundamental plane.



$0.77 < \mathscr{F} < 2.10$

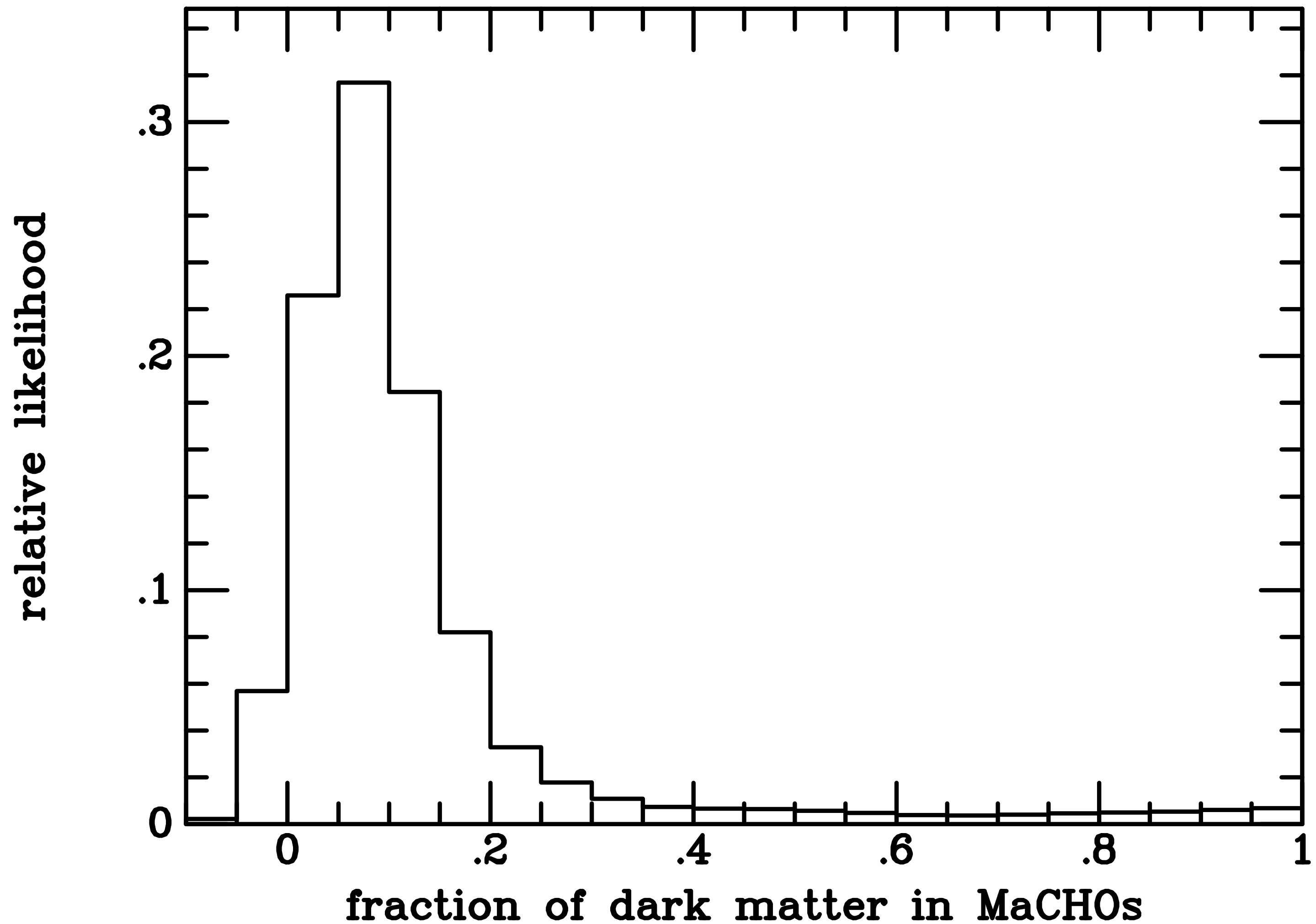
Uncertainty dominated by small sample size.

Schechter et al. 2014

Lensing galaxy contents:

Chandra data constrain fraction of dark halo in MaCHOs to $\lesssim$10%.

- Previous assumption: dark halo component is smooth → halo particles of at most planetary mass (depends on X-ray size of quasar)
- Instead, take stellar surface mass density to be known and let the factor $\mathscr{F}$ represent the fraction of the dark halo in Massive Compact Halo Objects (MaCHOs), which includes ~$20M_\odot$ black holes.

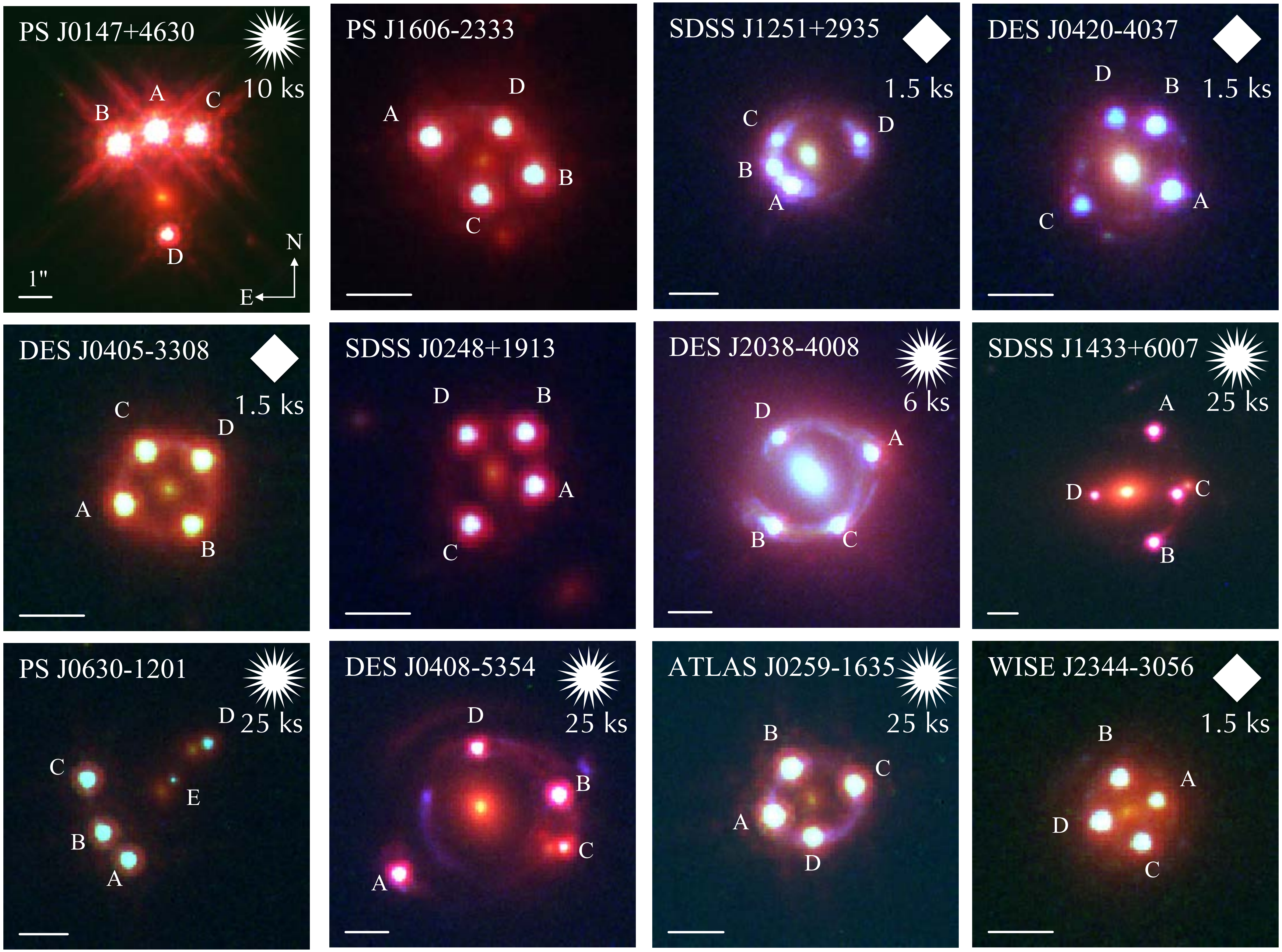


Schechter 2018

See also Mediavilla et al. (2009)

Further progress:

Chandra observations of newly discovered quads will improve the ensemble results.



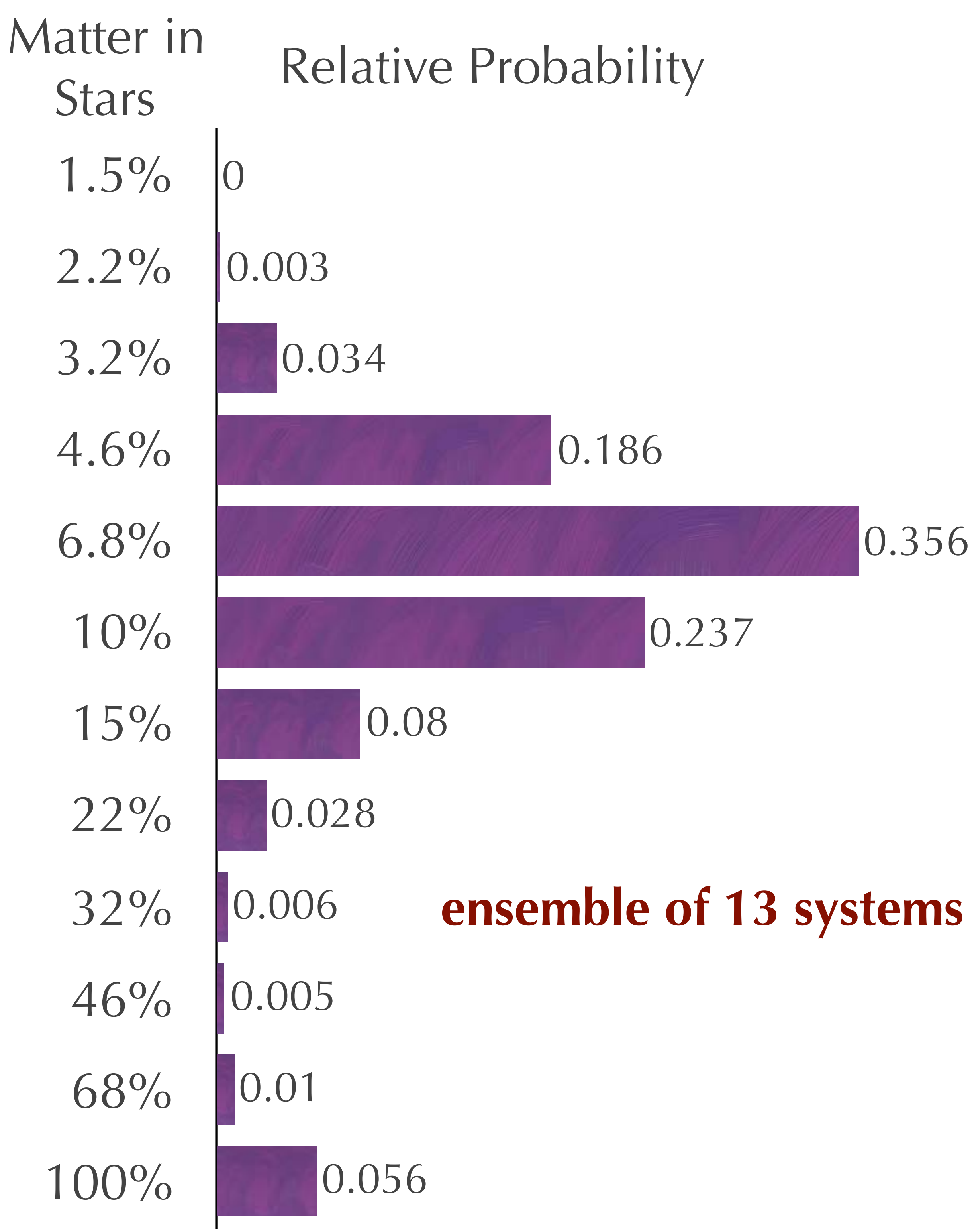
Shajib et al. 2018

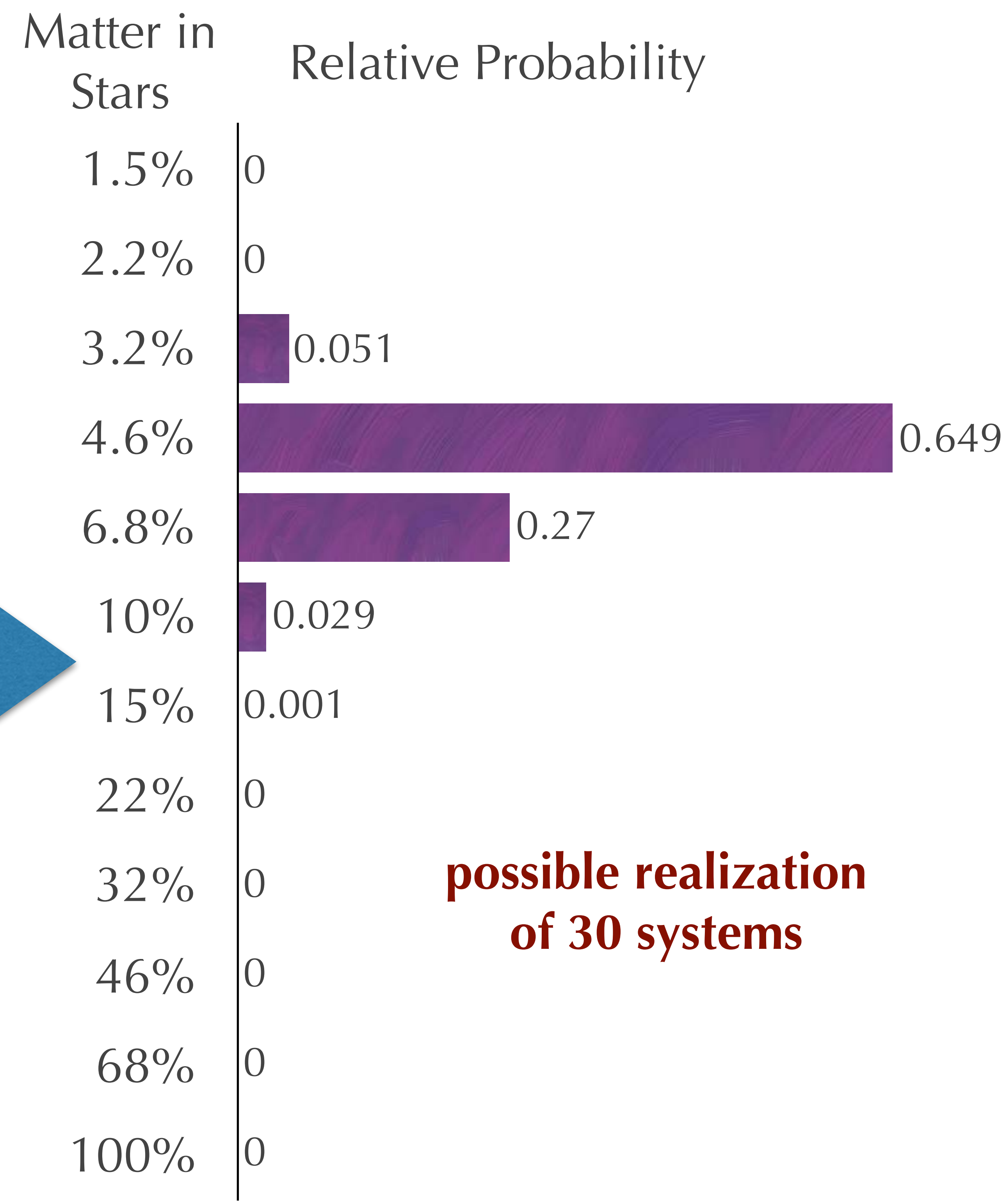
New surveys are finding many more quads.

We are obtaining *Chandra* observations of all publicly announced new quads.

Further progress:

Chandra observations of newly discovered quads will improve the ensemble results.



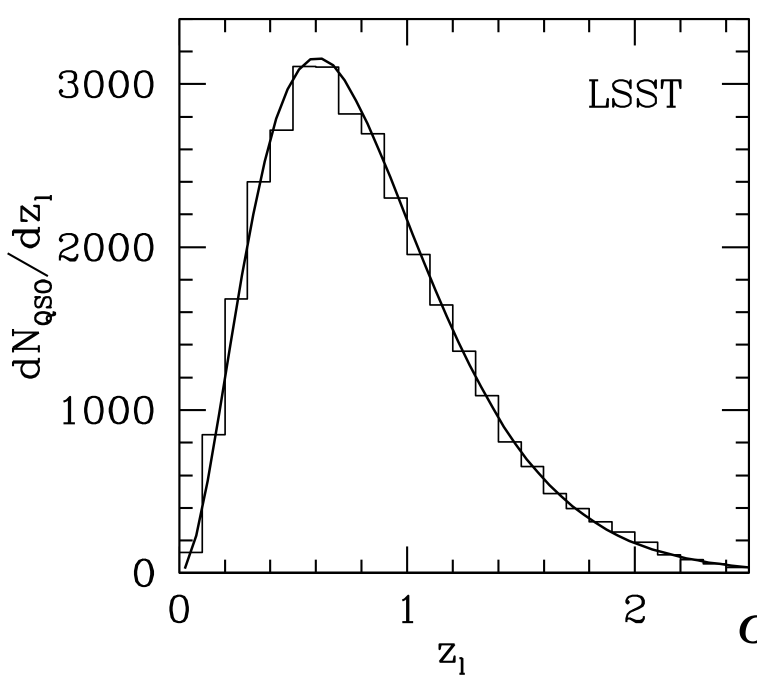


DP et al. 2012

Further progress:

Future X-ray observations will unlock the full potential of future LSST discoveries.

- LSST will discover thousands of quads, but there are fundamental degeneracies between the assumptions one makes about the optical emitting region(s) and what you can determine about the lensing galaxy contents.
- The full power of those discoveries will be unlocked with Lynx, which could study several hundred with a modest observing program.
- The snapshot ensemble analysis could be done as a function of redshift.



Oguri & Marshall 2010

artist's representation of Lynx

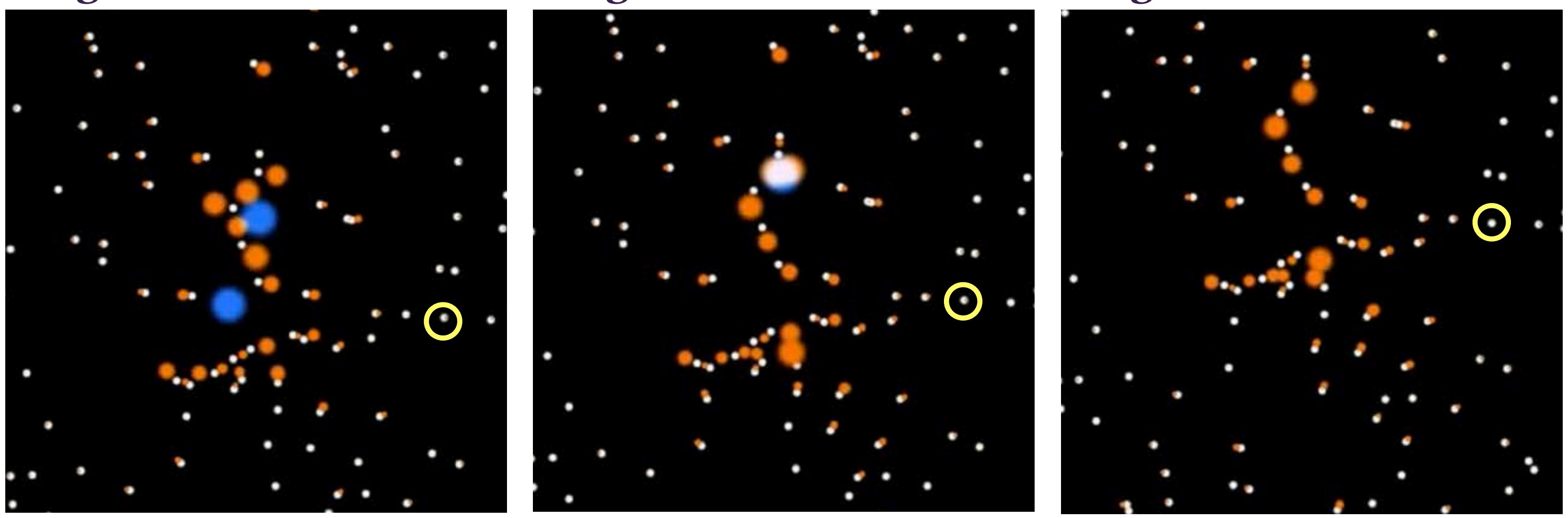
Main takeaways:

- Quasar micro-lensing is the only way to determine stellar *M/L* beyond the solar neighborhood.
- *Chandra* established that quasars are micro-lensed.
- Sub-arcsecond X-ray imaging is the best way to determine micro-lensing effects.
- I gave a micro-lensing talk without showing a single micro-lensing magnification map.
- I can't leave out my three year old.

Further progress:

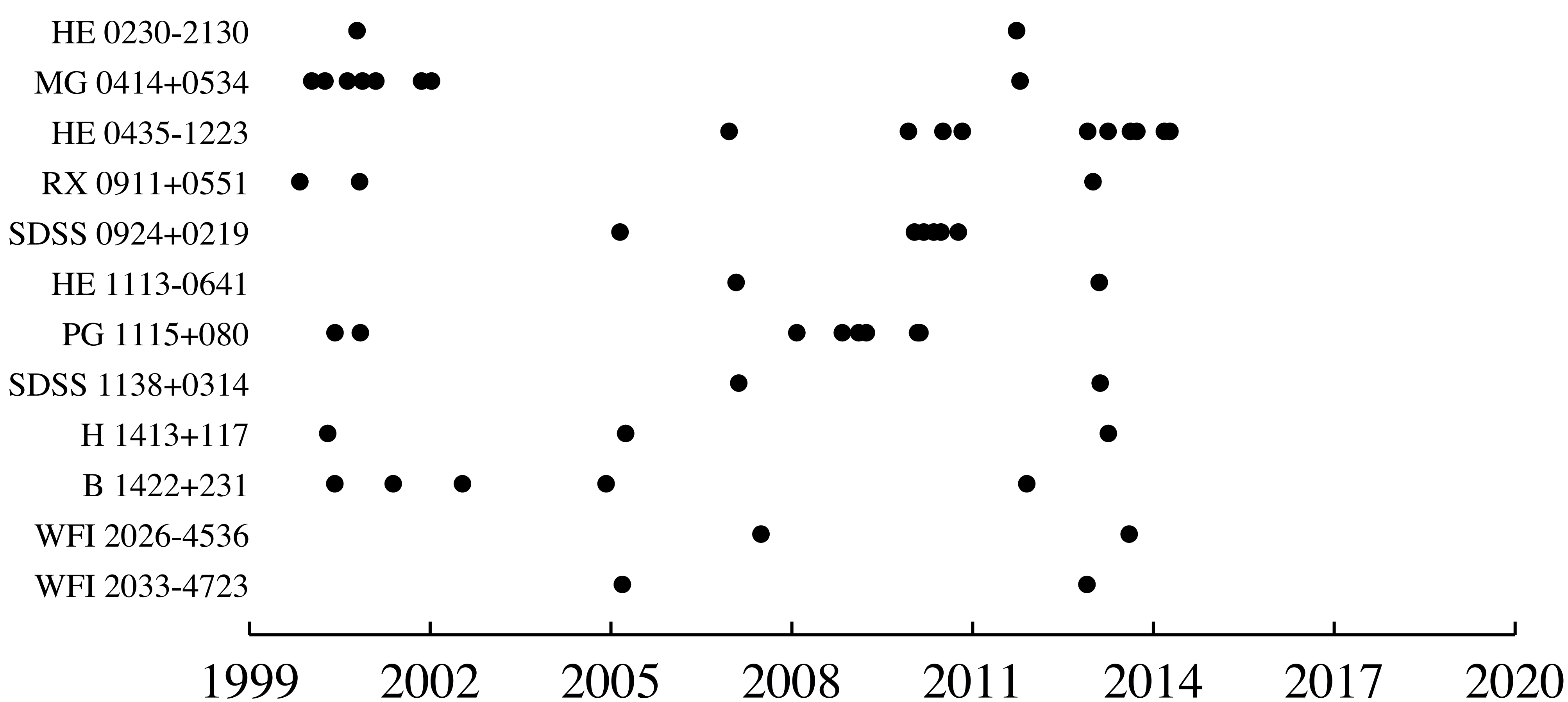
Long term *Chandra* (and then Lynx) follow-up of quads will determine stellar fraction and M/L for individual galaxies.

Additional Microlensing Magnification: ×2 | Additional Microlensing Magnification: ×5 | Additional Microlensing Magnification: ×0.3



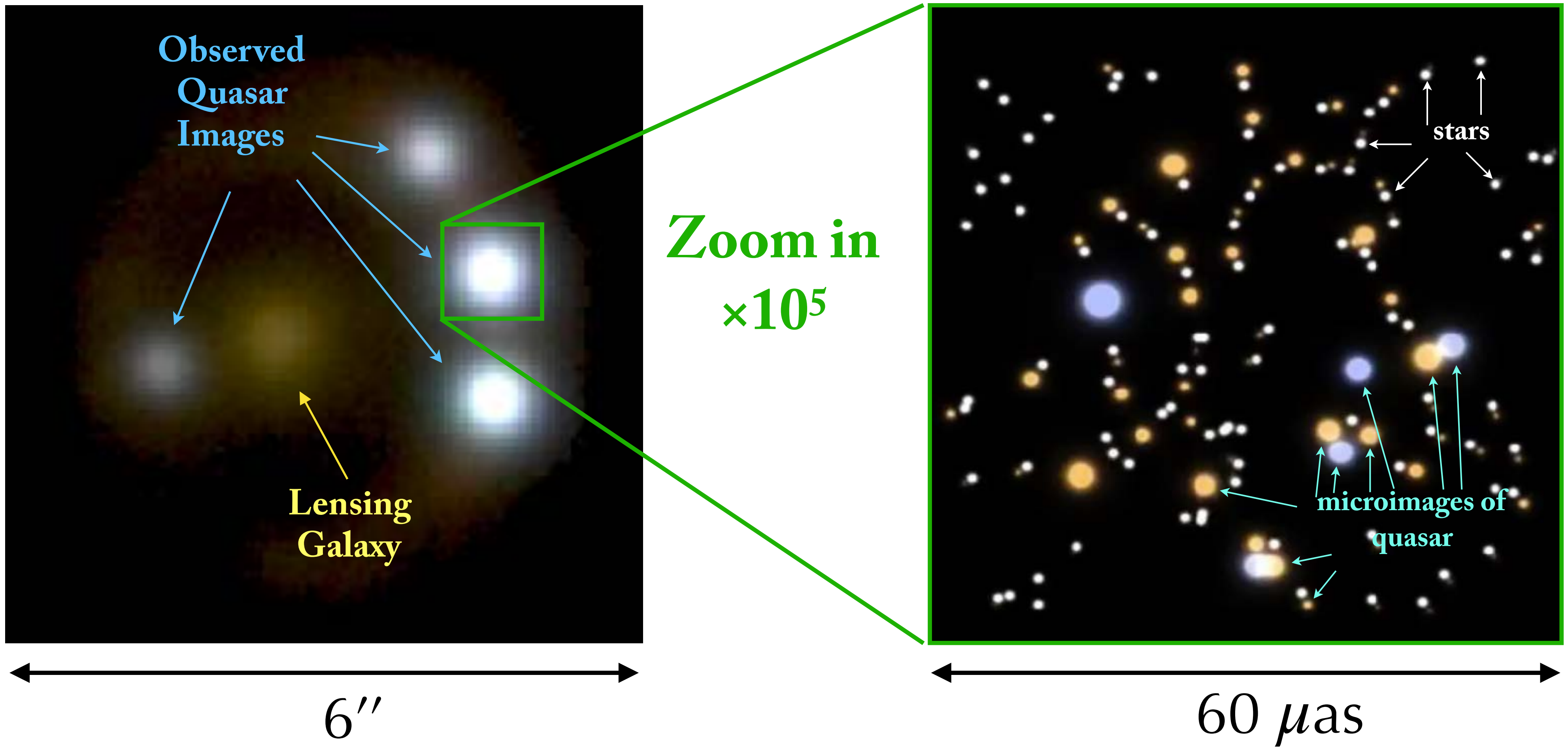
Observations spaced years to decades apart will provide independent samples of the lensing galaxy's stellar population.

Current state of observations:



Micro-lensing is not a single star phenomenon.

Each of the four “macro-images” comprises dozens of “micro-images.”



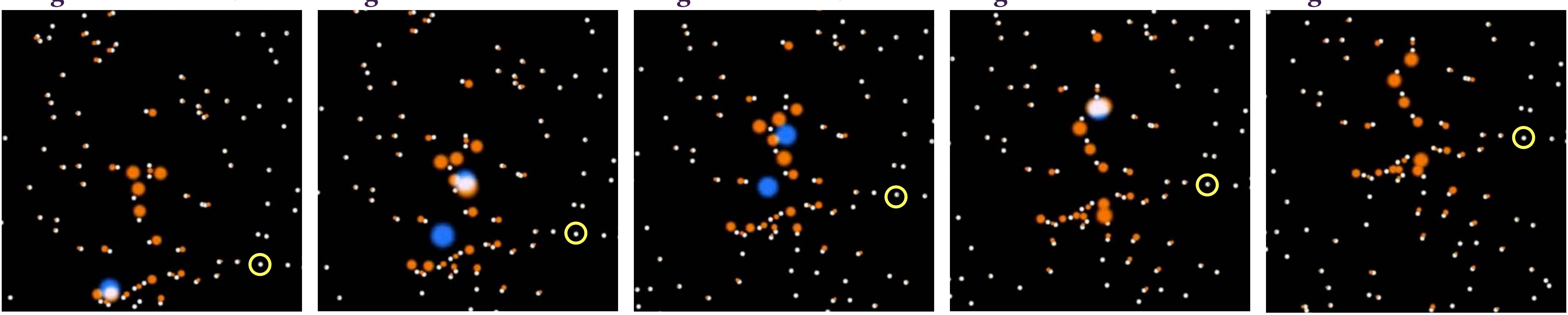
Additional Microlensing Magnification: ×1.2

Additional Microlensing Magnification: ×7

Additional Microlensing Magnification: ×2

Additional Microlensing Magnification: ×5

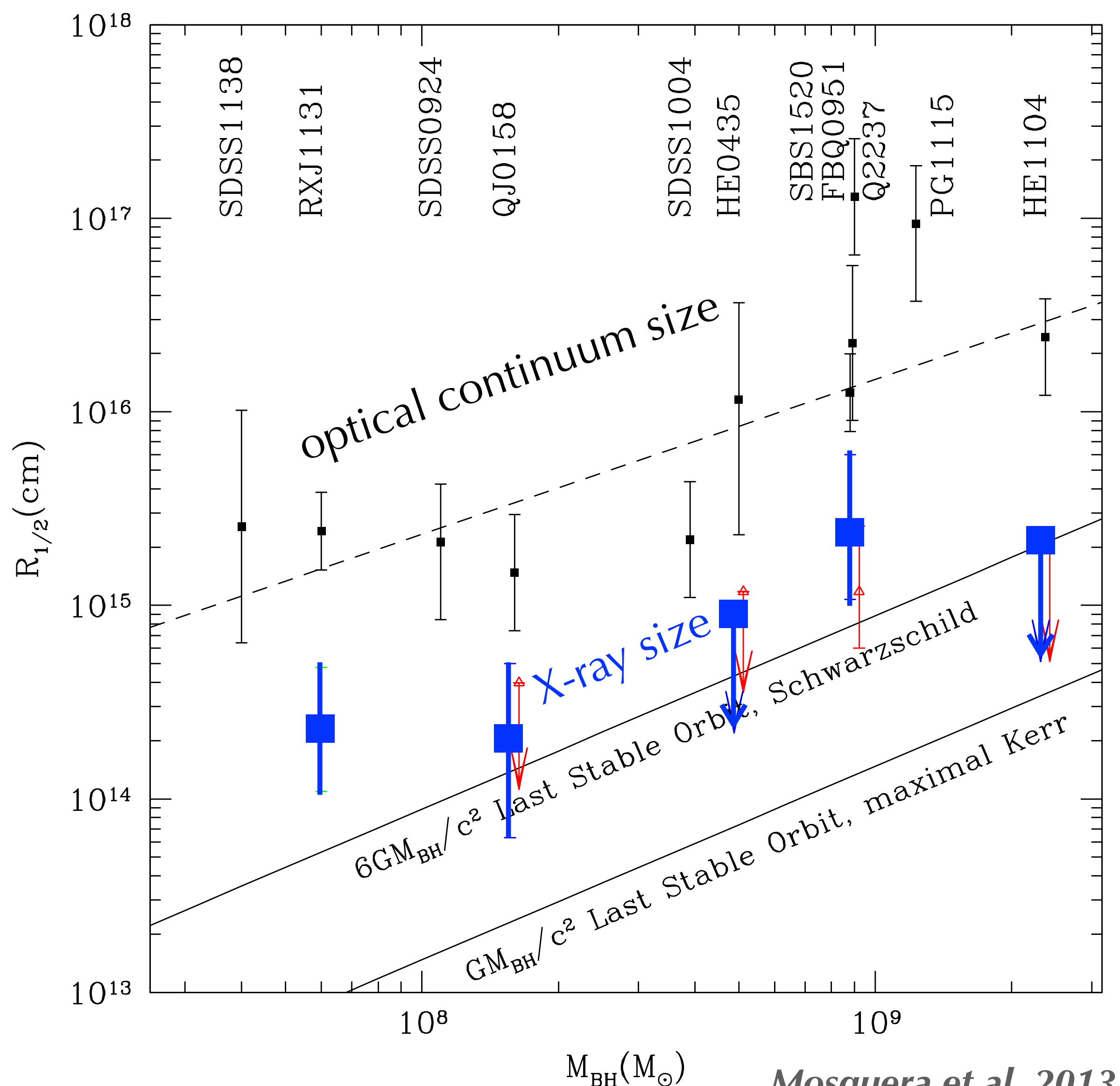
Additional Microlensing Magnification: ×0.3



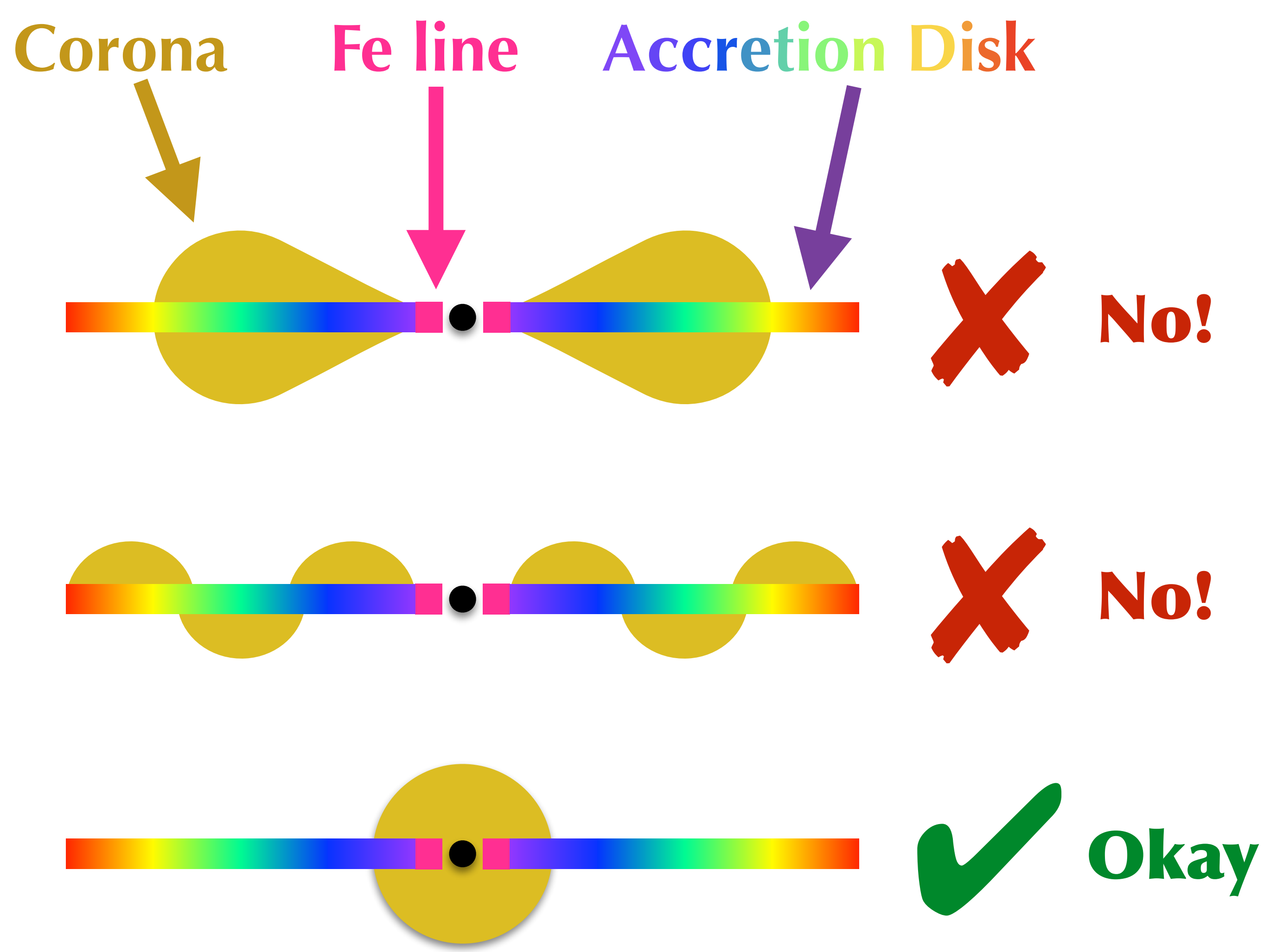
Quasar structure:

Micro-lensing has ruled out certain corona geometries and established that the corona must be compact.

THE ASTROPHYSICAL JOURNAL, 769:53 (8pp), 2013 May 20



Mosquera et al. 2013

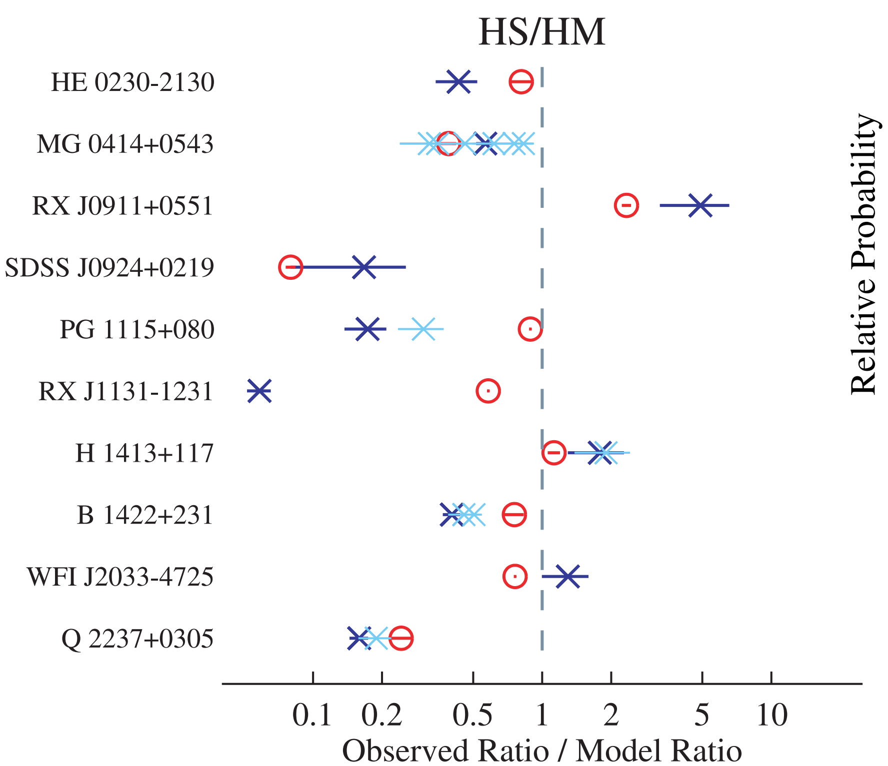


See also DP et al (2007), Chartas et al. (2009), Dai et al. (2010), Morgan et al. (2010, 2012), Blackburne et al. (2011a)

Quasar structure:

The optical disk is 3–30 times larger than standard thin-disk theory predicts.

Ensemble average



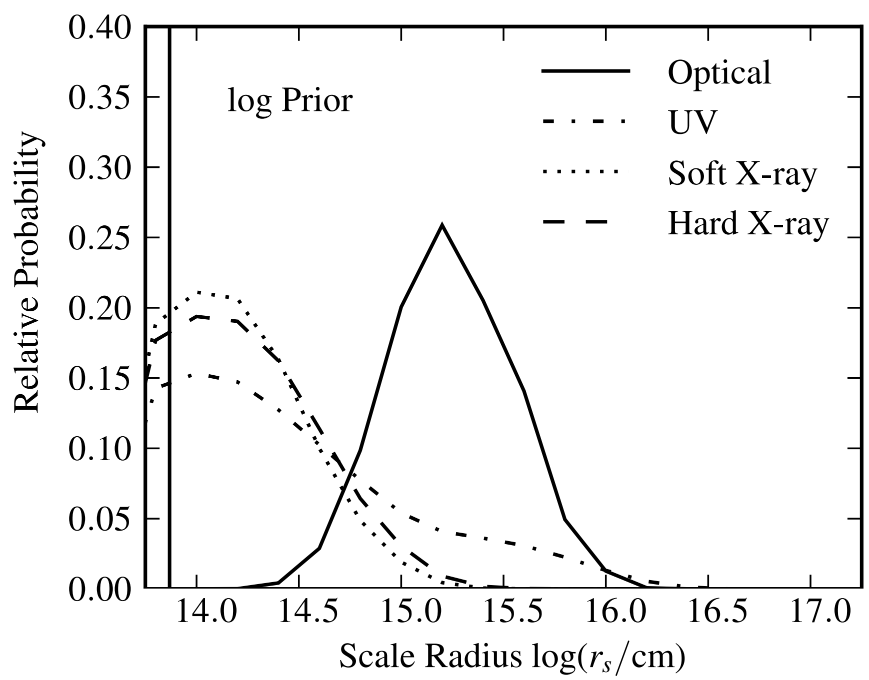
DP et al. 2007

Diminished micro-lensing in optical

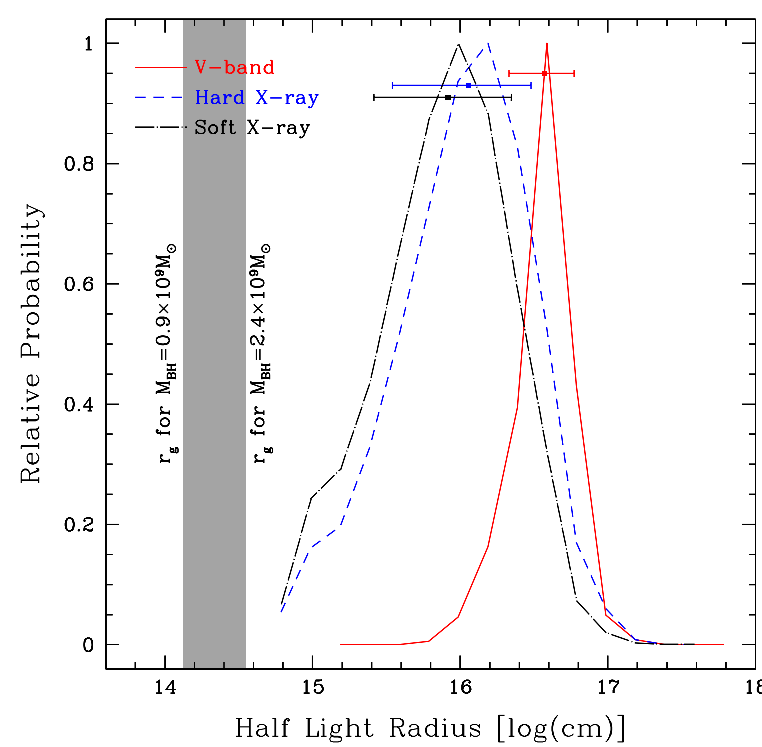
Estimate size of optical disk necessary to give that less variability

Individual systems

HE 0435−1223 *Blackburne et al. 2014*

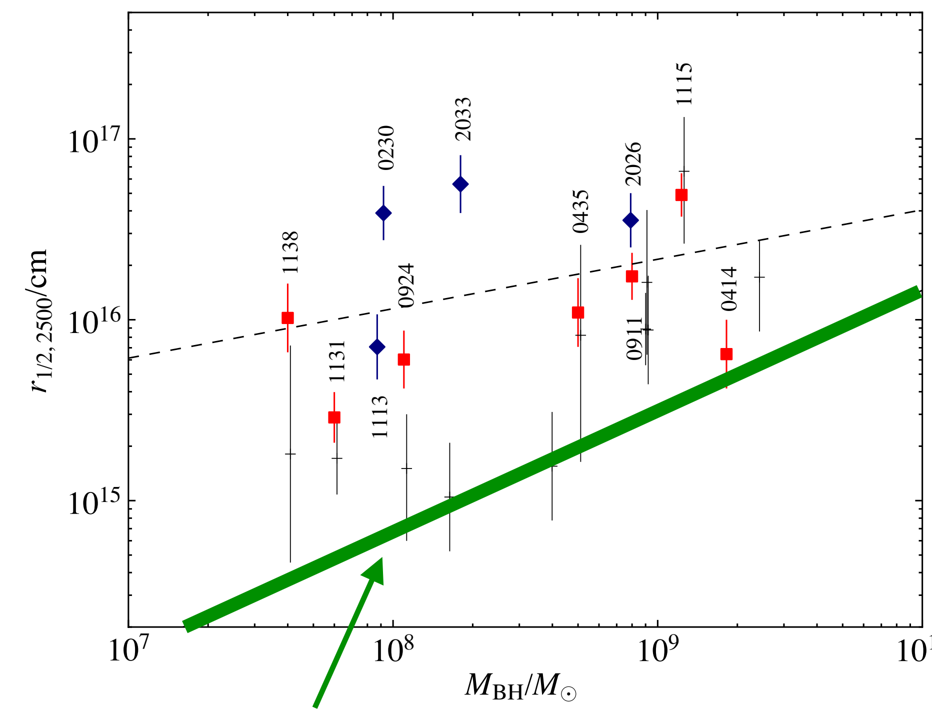


Q 2237+0305 *Mosquera et al. 2013*



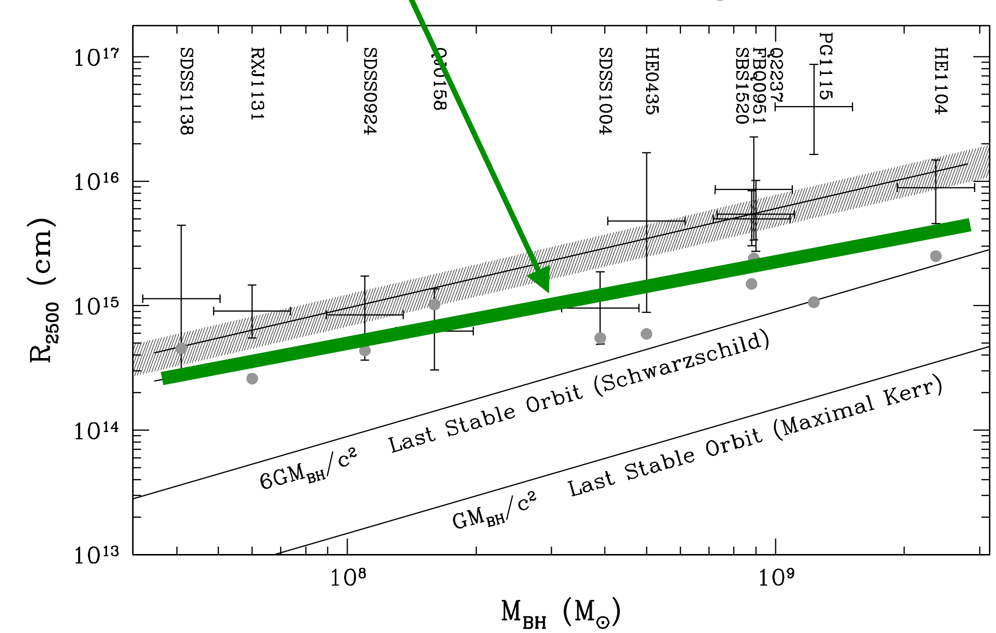
Population

Blackburne et al. 2011



Standard SS Disk

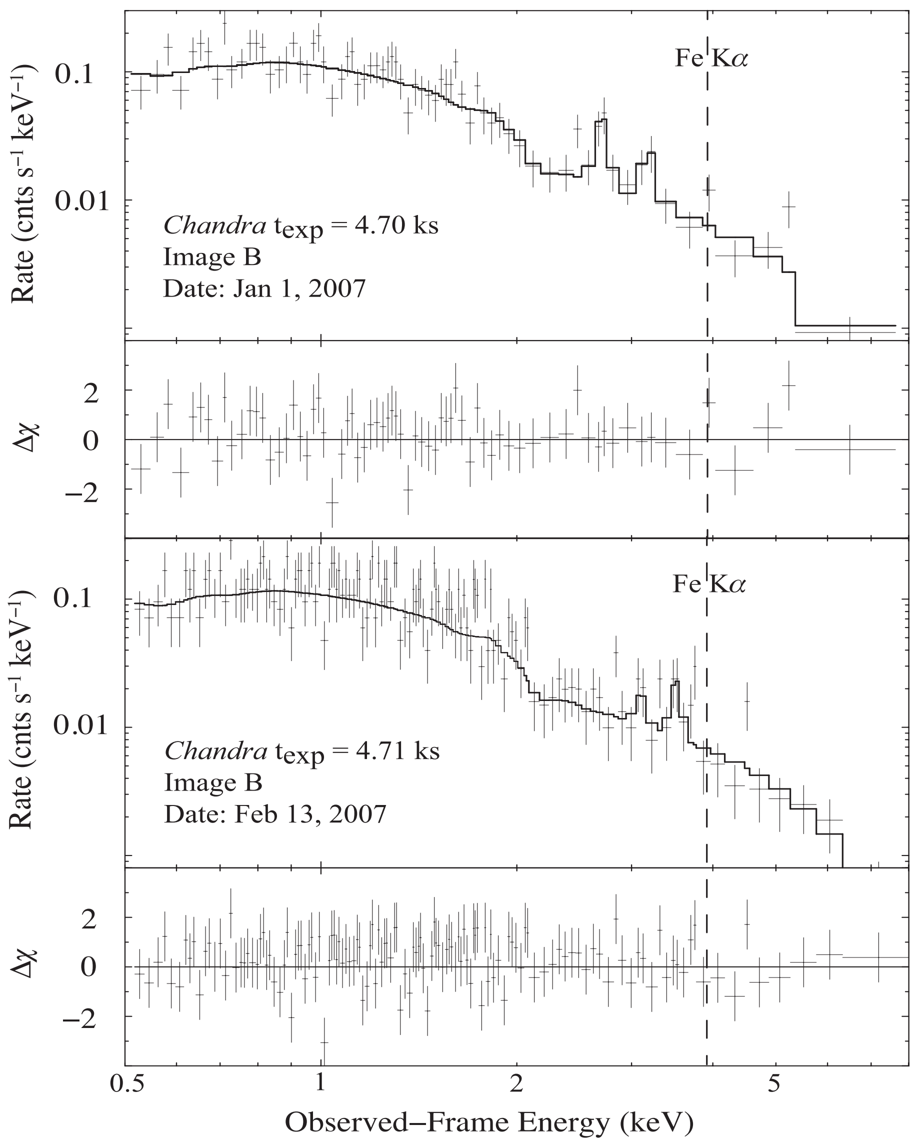
Morgan et al. 2010



Quasar structure:

Micro-lensing of Fe line strongly constrains inner disk.

Fe line micro-lensing has been observed in several systems (e.g., Chartas et al. 2002, Dai et al. 2003, Ota et al. 2006, Chartas et al. 2007, Chen et al. 2012, Chartas et al. 2012, Chartas et al. 2017)



Chartas et al. 2012

Utilizing such observations requires advanced modeling of both strong-field gravity and micro-lensing features.

- Heyrovský & Loeb (1997)
- Popovic et al. (2001, 2003a, 2003b, 2006)
- Jovanovic et al. (2009)
- Neronov & Vovk (2016)
- Krawczynski & Chartas (2017)
- Ledvina et al. (2018)

RX J1131−1231: $R_{ISCO} \lesssim 9\ R_g$