New applications of gravitational lensing to probe dark matter substructure

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Astro Seminar @ Kavli IPMU
June 2018

The physical nature of the dark matter?

The physical nature of the dark matter?

Topics

- Caustic crossing stars in lensing clusters

  with Tejaswi Venumadhav (IAS), Jordi Miralda-Escudé (Barcelona)

- Probing dark matter substructure with highly magnified stars

  with Tejaswi Venumadhav (IAS), Jordi Miralda-Escudé (Barcelona), Alexander Kaurov (IAS)

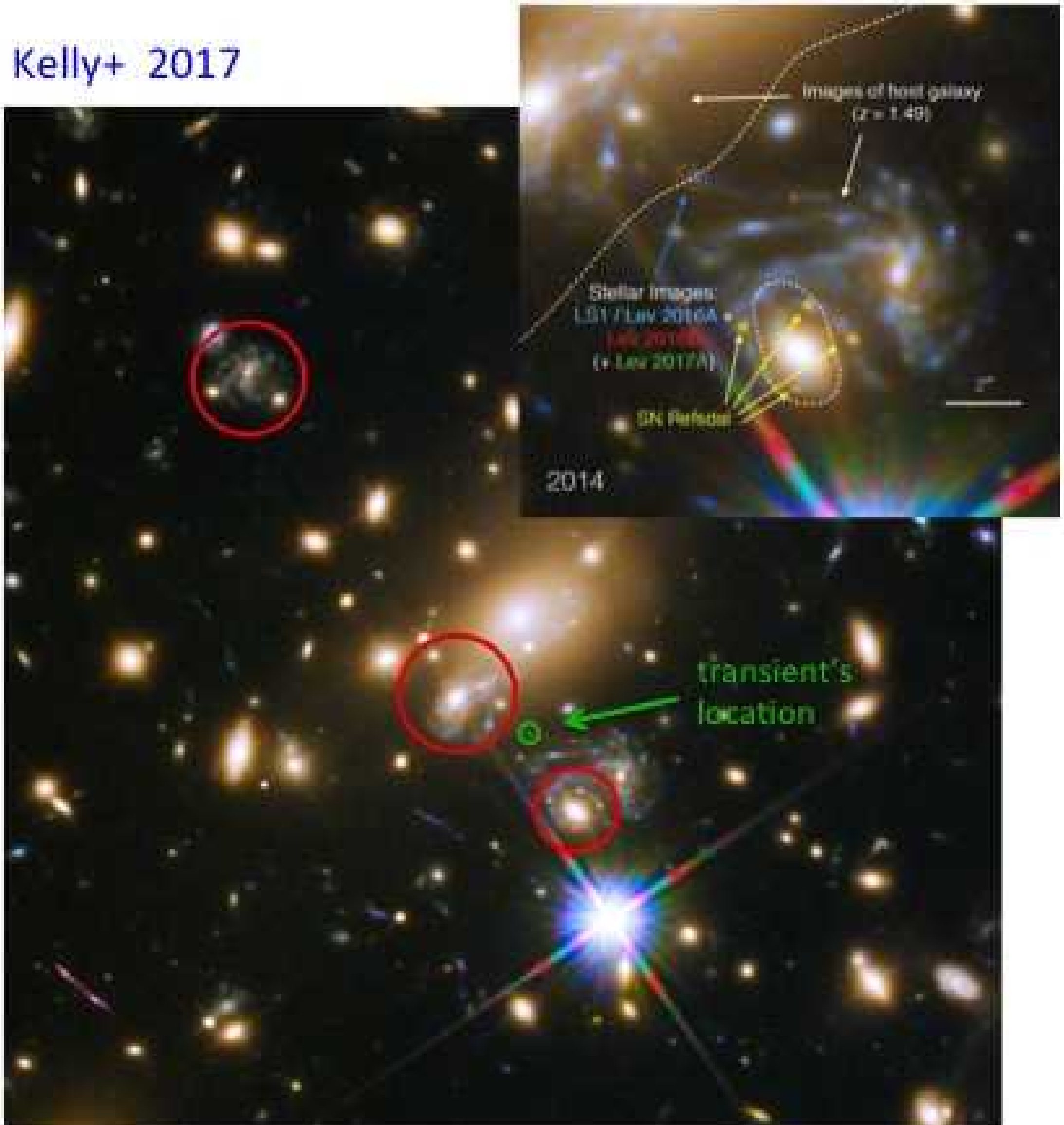
- Diffractive lensing of gravitational waves by substructure

  With Shun-Sheng Li (NAOC), Barak Zackay (IAS), Shude Mao (Tsinghua), You-jun Lu (NAOC)

Part I: Caustic crossing stars in strong lensing clusters

An Intriguing Transient in MACS J1149

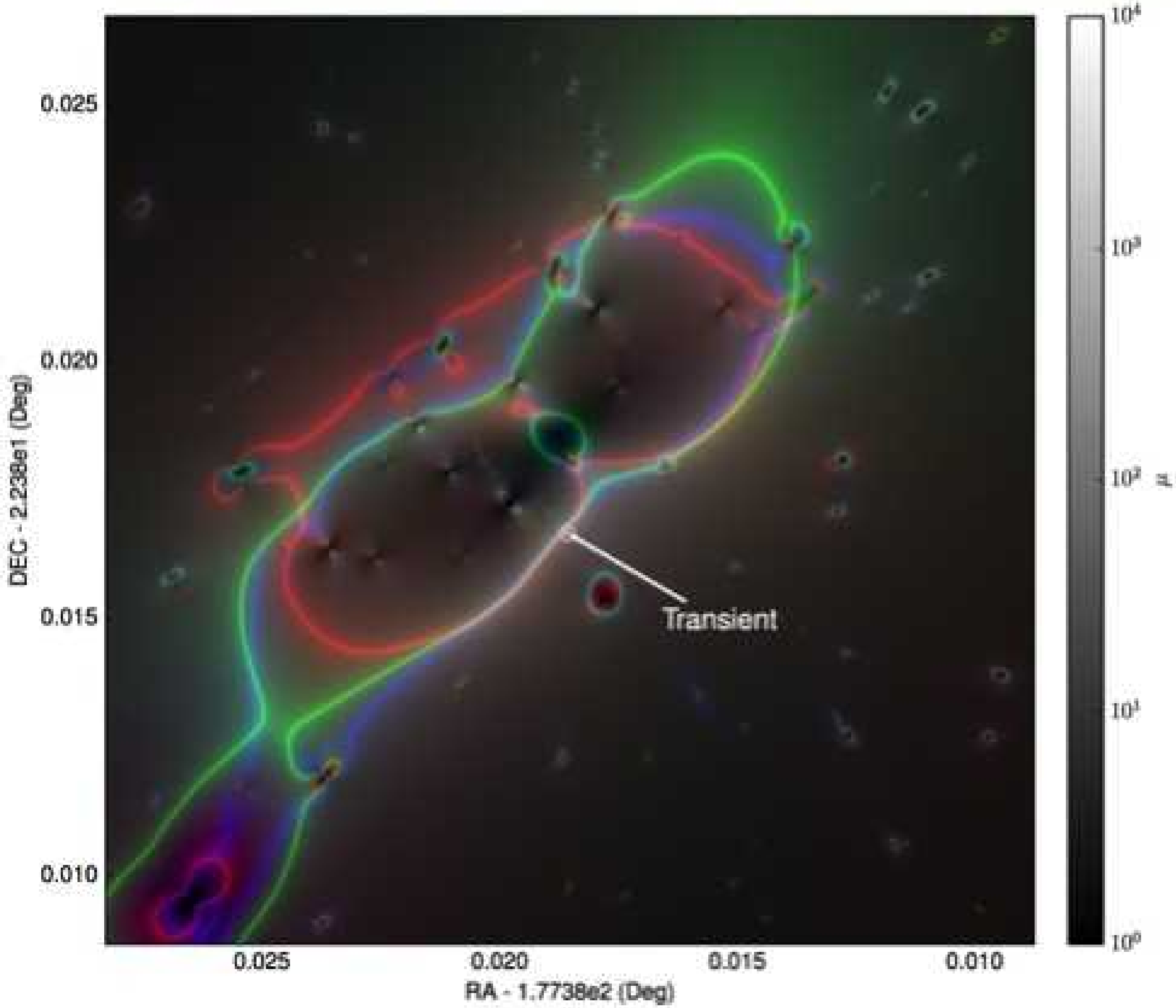
Kelly+ 2017



- Strong lensing cluster at z~0.54
- Host galaxy of SN Refdal at z ~ 1.5
- Point-like slowly brightened to peak mag. < 26
- Color resembles a B-type star; Balmer break detected;

Gravitational lensing phenomenon?

magnification map predicted by mass reconstruction for source at z = 1.5

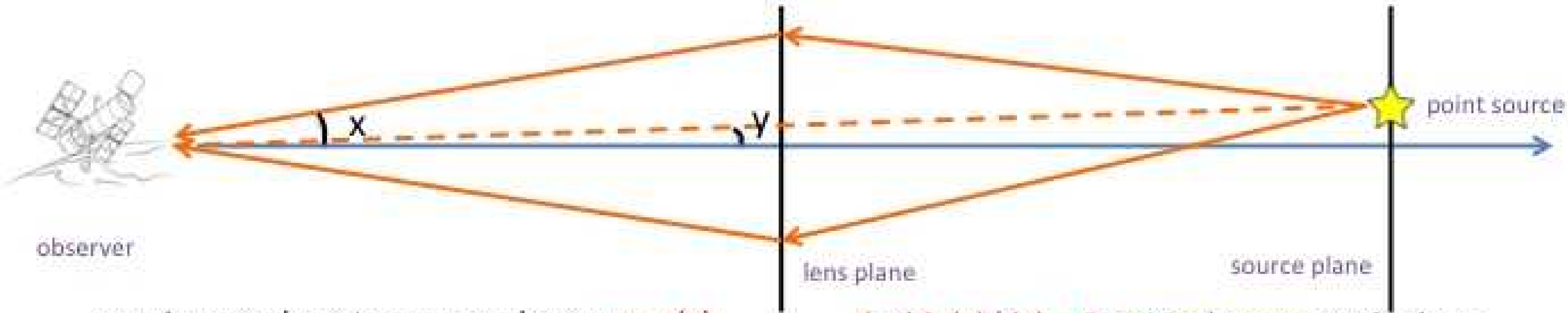


Frontier Field Lens Models

Zitrin-ltm
Sharon
GLAFIC

Coincidence with critical curve by foreground cluster lens!

Caustic & Critical Curve



map image plane to source plane: $y = y(x)$
magnification: $\mu(x)=1/\det(dy(x)/dx)$

$\det(dy(x)/dx) = 0$: critical curve on the lens plane, and caustic on the source plane

A pair of images

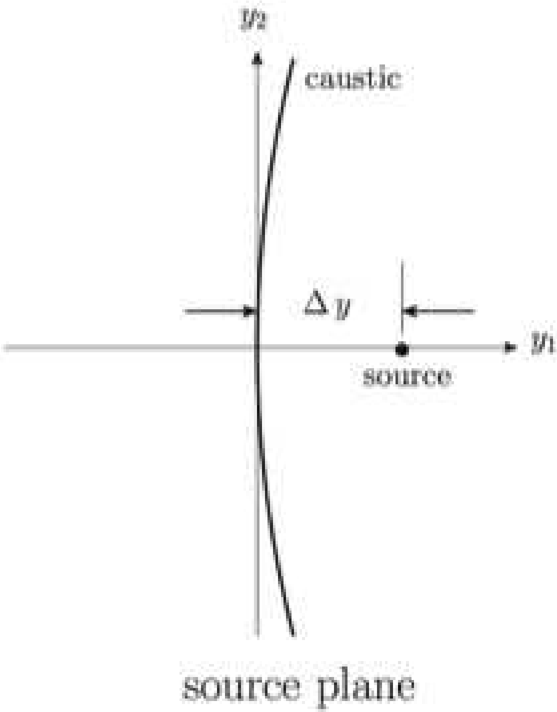
$\delta\theta \sim 10 - 100\,\mathrm{mas}$

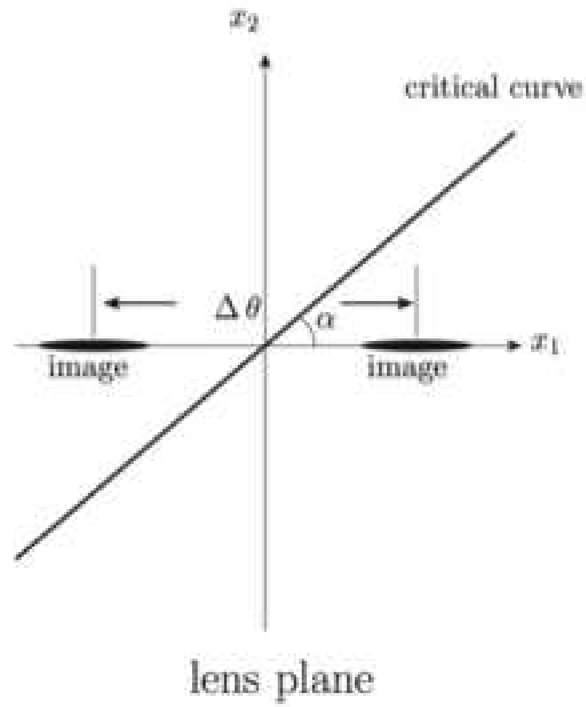
Extreme magnification factor

$\mu \sim \frac{\theta_C}{\theta} \sim \mathrm{few} \times 10^{2-3}$

Invidivual star visible

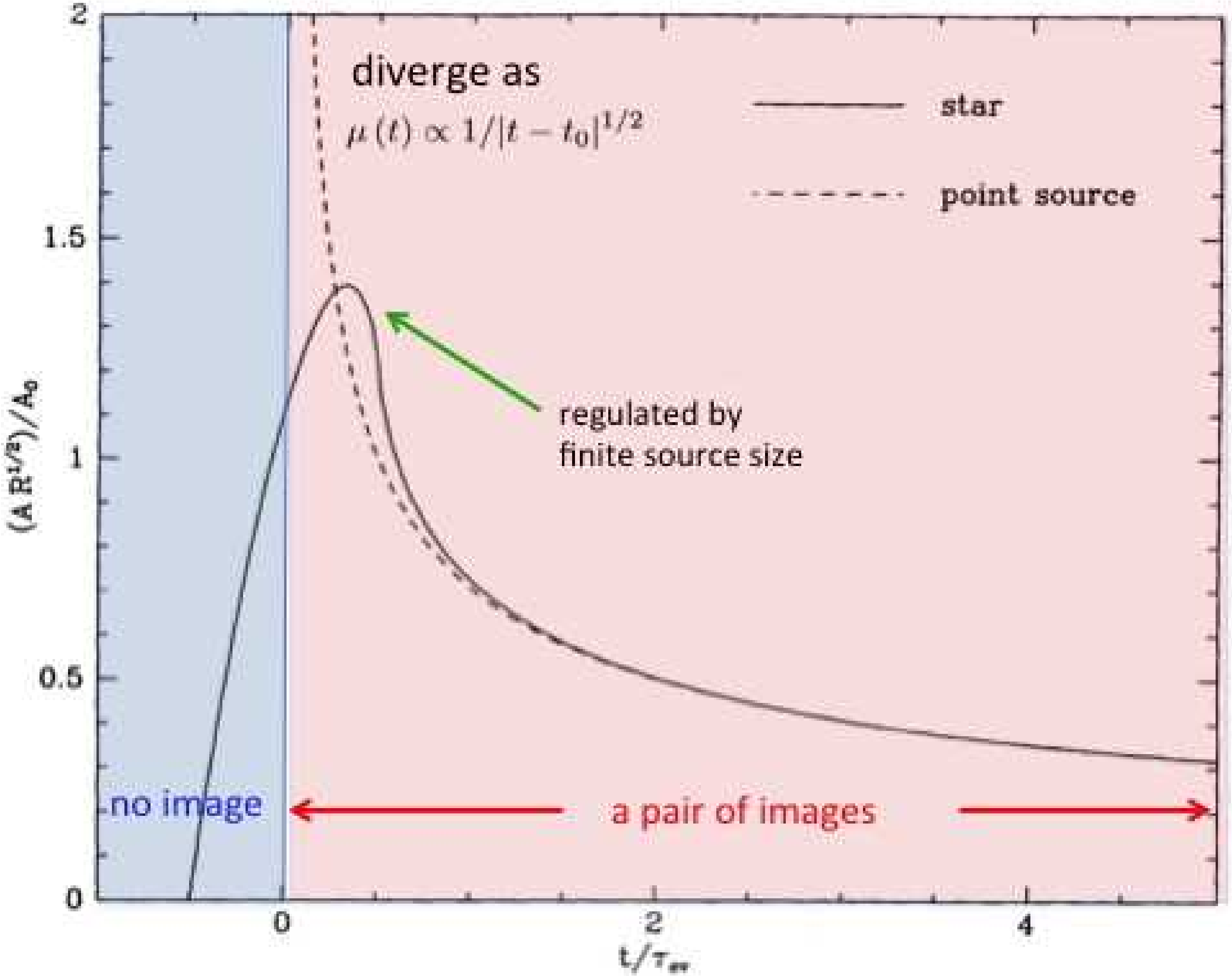
$L \simeq 10^{4-6}\, L_\odot$





(Unresolved) light curve

Miralda-Escudé 1991



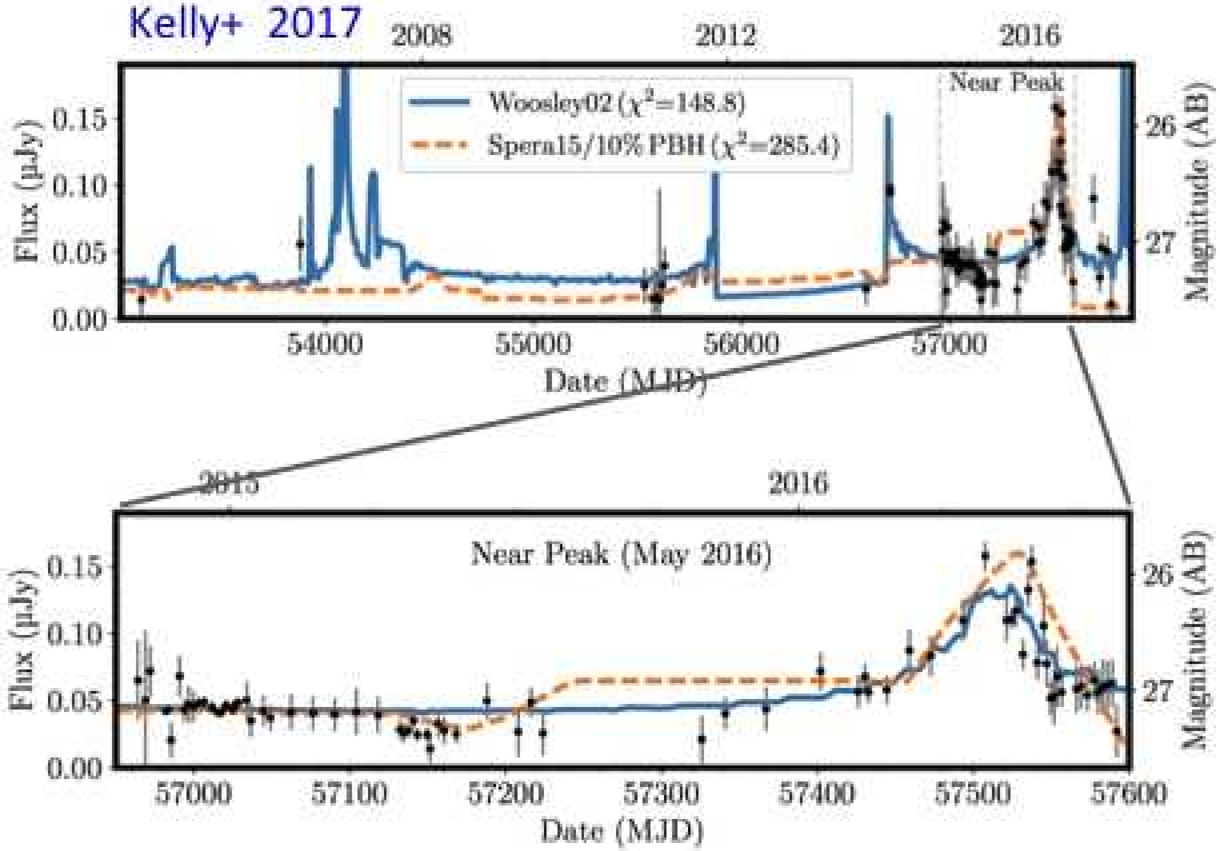
infinite magnification factor regulated for two reasons:

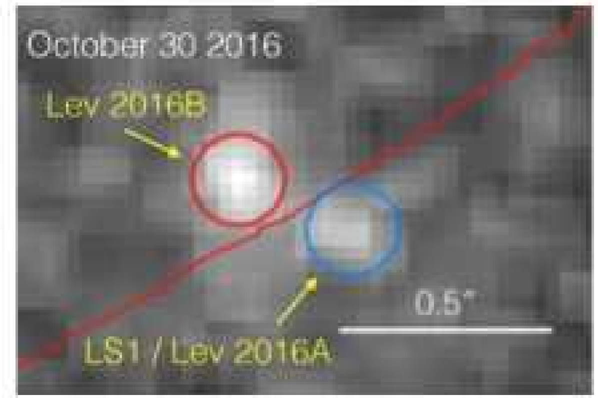
(1) Finite source size < 10^7 for one solar radius

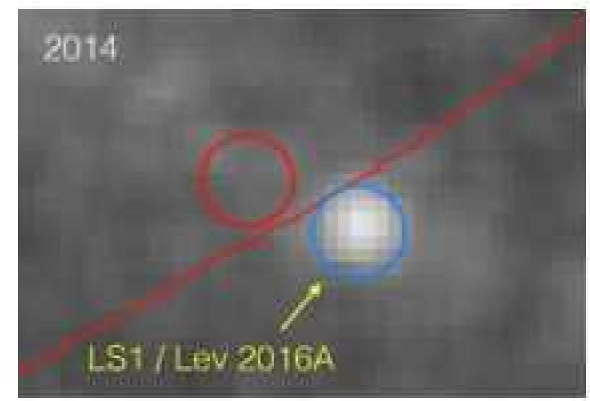
(2) Diffraction < 10^9 at ~ 10^{15} Hz

Observed light curve

Kelly+ 2017







What was observed looked very different:

- Multiple brightening peaks observed; object persistently visible.
- An pair of images resolved; far from merging together

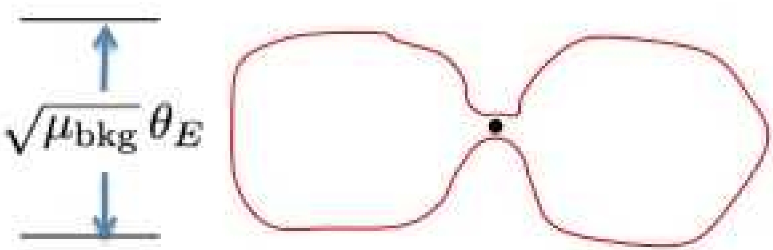
Importance of micro-lensing

An isolated star: tiny Einstein angular scale, very improbable to cause micro-lensing

⊙ $$\theta_E = \left[4GM\frac{D_{LS}}{D_L D_S}\right]^{1/2} \sim 10^{-6}\mathrm{arcsec}$$

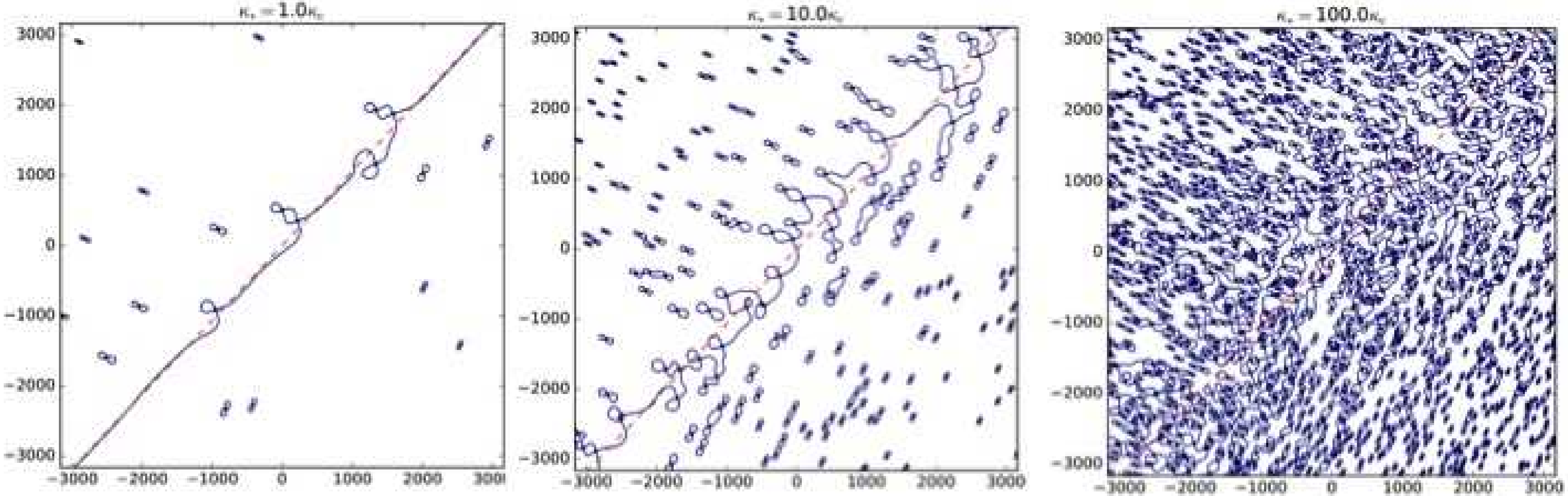
By contrast, cluster lensing has typical angular scale ~ arcmin

Under the influence of a massive cluster:
Bkg. Magnification and shear ~ $10^3 - 10^6$ near macro-critical curve!



Effect of many microlenses

Diego+ 17
Venumadhav Dai & Mirada-Escudé 17
Oguri+ 17



occasionally perturbed | entirely disrupted | corrugated network

Critical surface density:

$$\kappa_c \sim (\theta_E/\theta_C)^{2/3} \sim 10^{-5}\left(\frac{\theta_E}{10^{-6} arcsec}\right)^{2/3}\left(\frac{arcmin}{\theta_C}\right)^{2/3} \ll 1$$

Surface density:

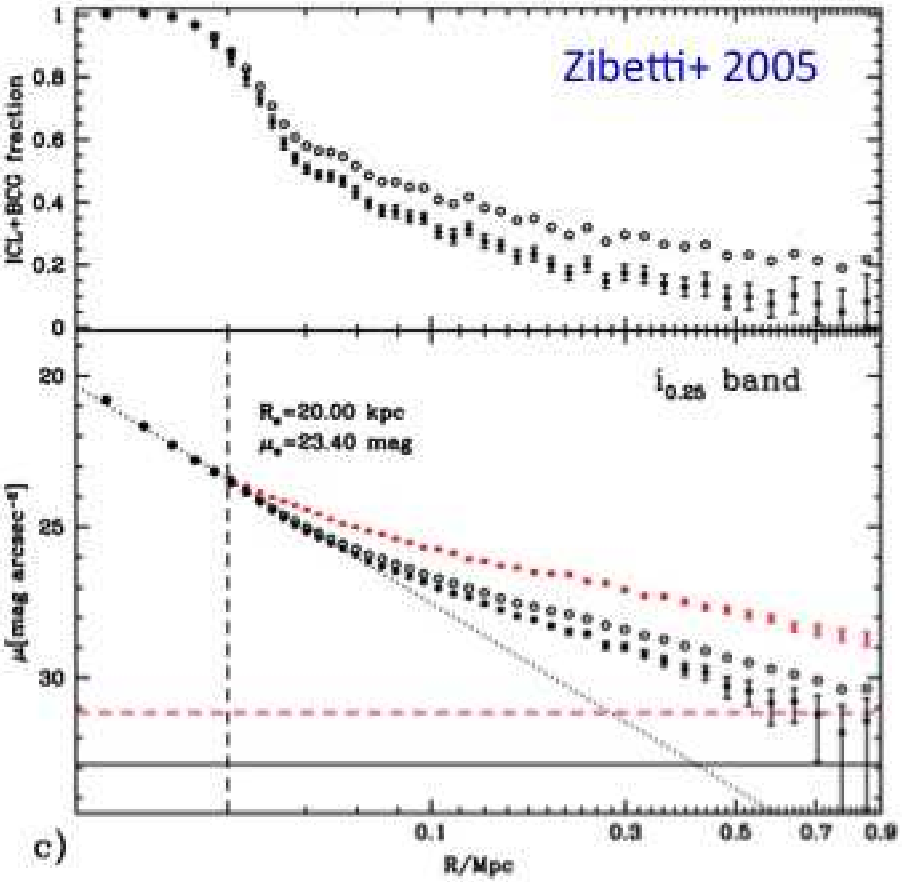
$$\kappa_\star = \frac{\Sigma_F}{\Sigma_{\rm crit}} = 4\pi\, G\, \Sigma_F\, \frac{D_{LS}}{D_L\, D_S} = 0.01\left(\frac{\Sigma_F}{10^9\, M_\odot/{\rm arcsec}^2}\right)$$

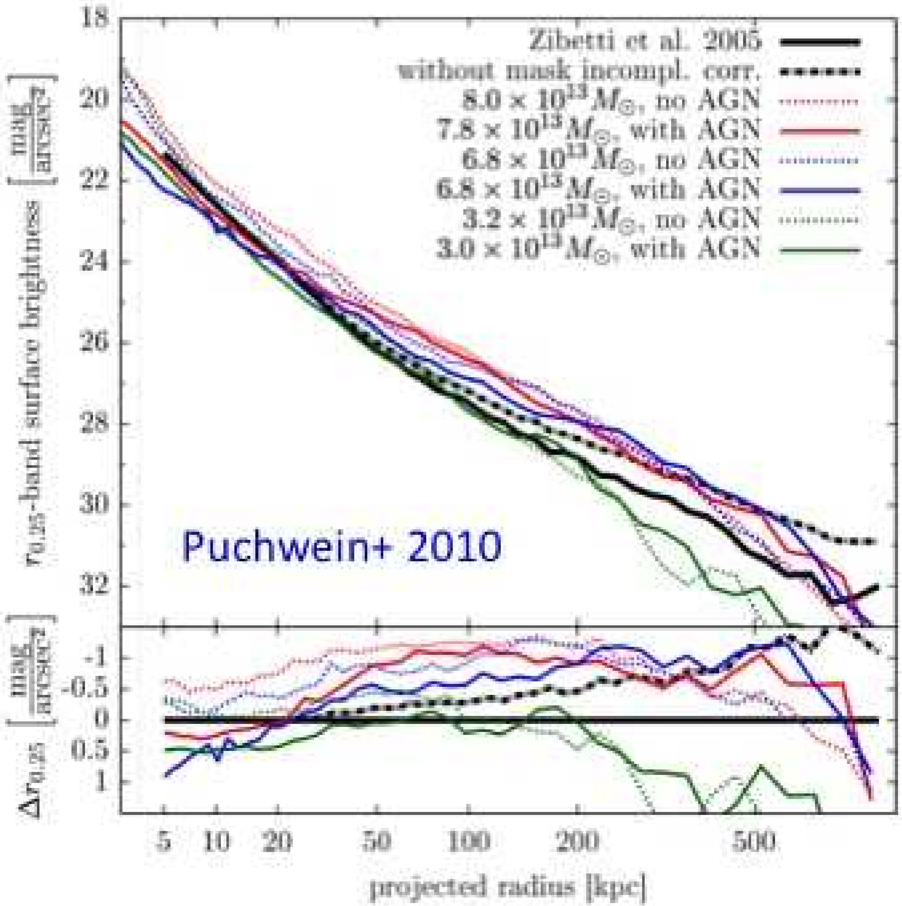
Intracluster stars as microlenses

Line of sight ~ 60kpc away from the BCG center

Traverses a halo of intracluster stars !

Formation: merger assembly and tidal disruption





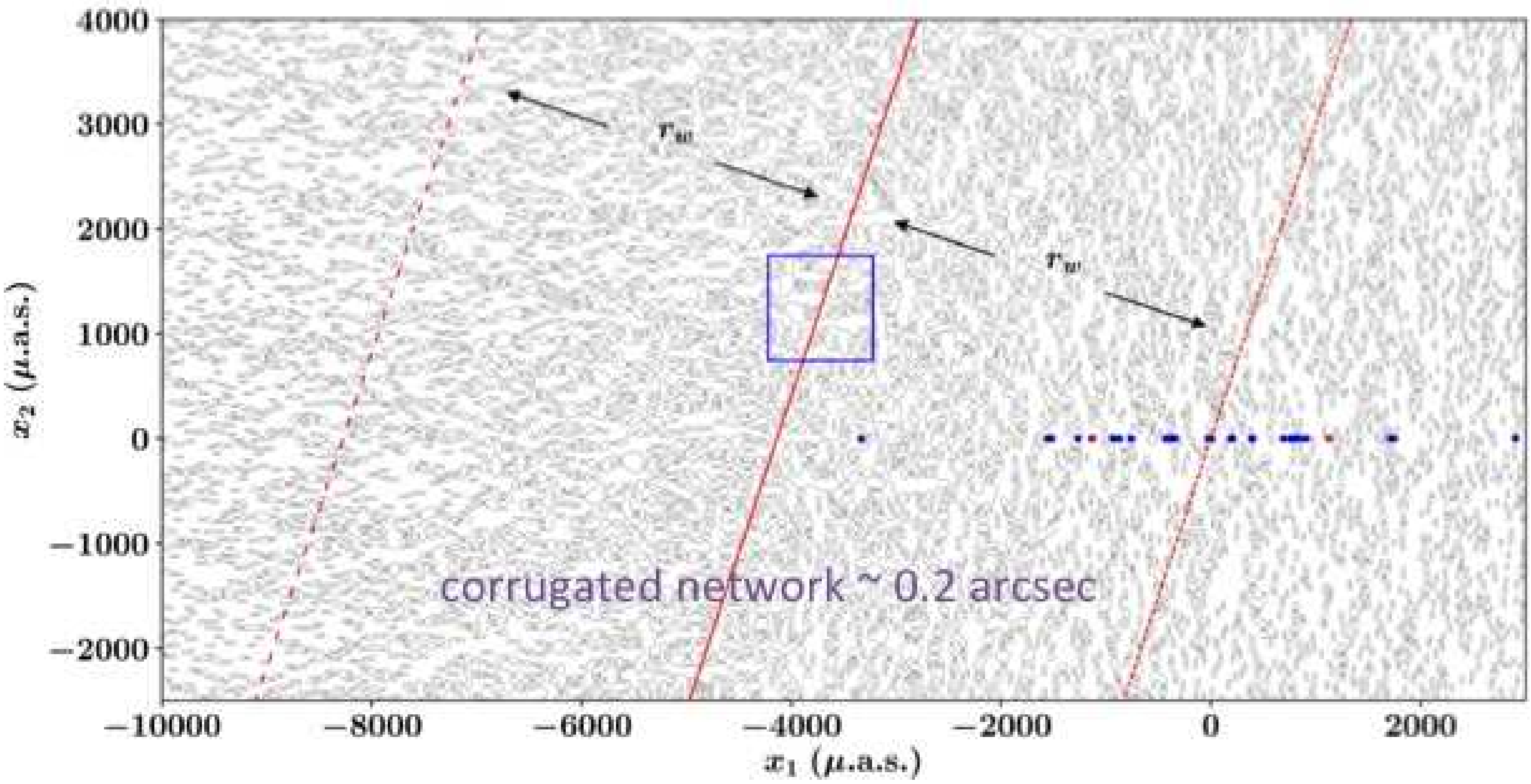
Corrugated network of micro critical curves

Venumadhav, Dai & Miralda-Escudé 17
Oguri+ 17

"Dumbbells" join and form a corrugated network of micro-critical curves even for small surface density of intracluster stars

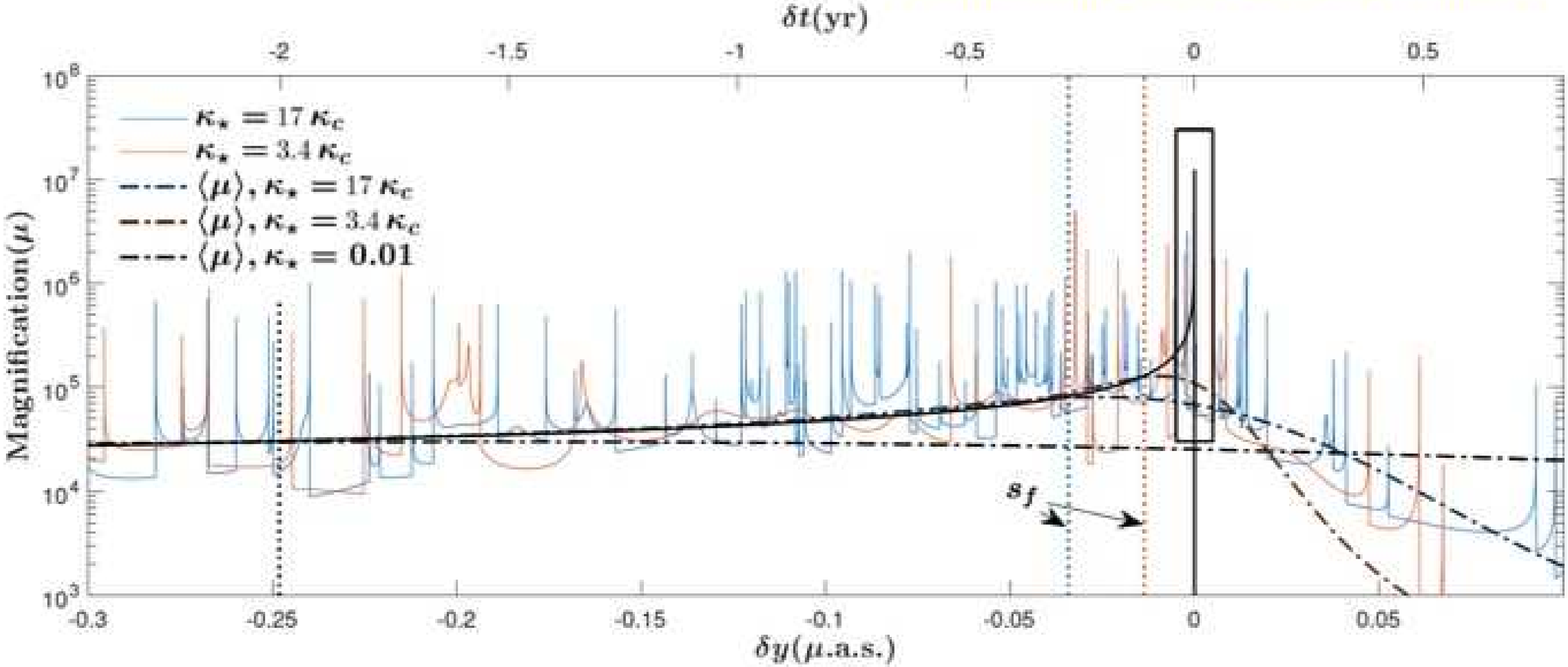
$$\kappa_{\rm crit} \sim (\theta_\star/\theta_C)^{2/3} \sim \text{few} \times 10^{-5}$$

$$\kappa_\star \sim 10^{-3} - 10^{-2} \gg \kappa_{\rm crit}$$



Microlensing Light Curves

Venumadhav, Dai & Miralda-Escudé 17



- Maximum peak magnification reduced: $\mu_{\rm peak} \sim 10^4\,(R/10\,R_\odot)^{-1/2}$
- Spend tens of thousands of years crossing the network!!
- Frequent micro-caustic crossings: 1-100 per year ---- **better chance to see individual stars!**
- Culmination of each crossing lasts for $\sim 5\,{\rm hr}\,(R/10\,R_\odot)$

Re-appearance due to microlensing?

Detection of a Microlensing Event of a Magnified Star at Redshift z = 1.5

ATel #11708; *Patrick Kelly (UMN), Jose Maria Diego (IFCA), Liliya Williams (UMN), Pablo Perez-Gonzalez (UCM), Alexei V. Filippenko (UC Berkeley), Masamune Oguri (Tokyo), Alberto Molino Benito (IAG), Jens Hjorth (DARK)*
on 12 Jun 2018; 03:36 UT
Credential Certification: Patrick Kelly (pkelly@astro.berkeley.edu)

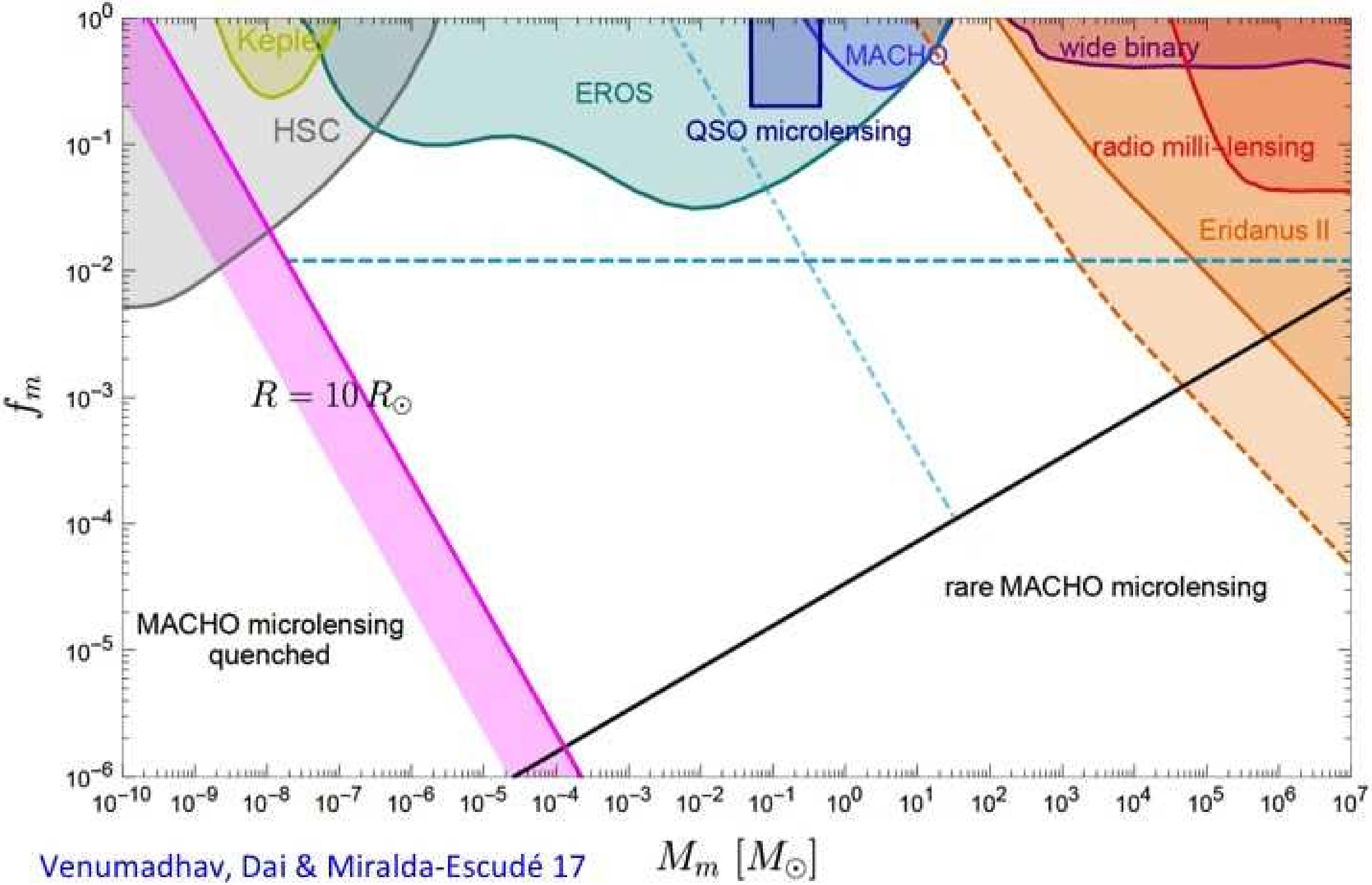
Subjects: Optical, Request for Observations, Microlensing Event, Star, Transient, Gravitational Lensing

Referred to by ATel #: 11724

Tweet Recommend 0

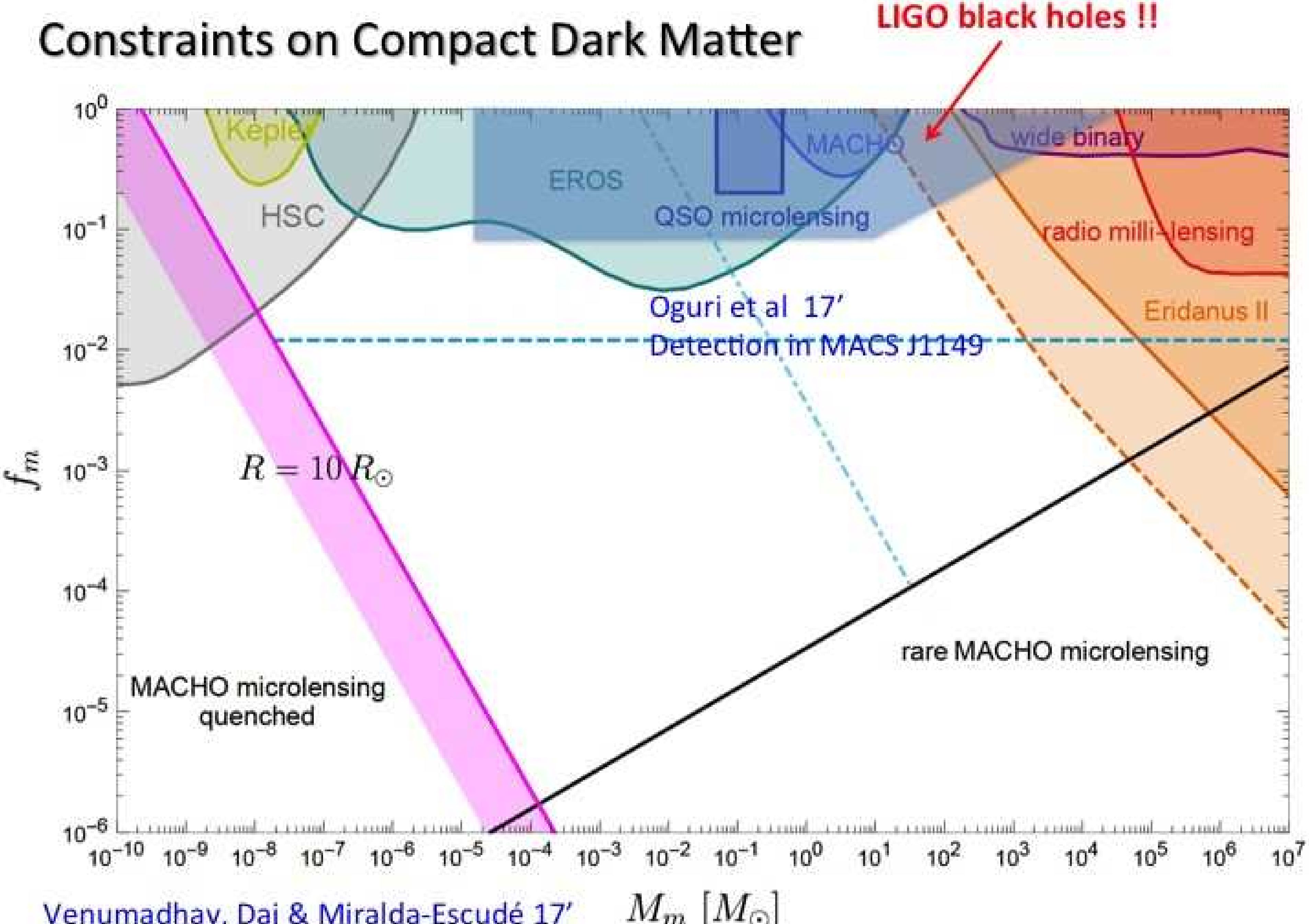
On June 5, 2018 UT, we acquired simultaneous g and r broadband imaging of the MACS J1149 galaxy cluster (redshift z = 0.54) field with the Large Binocular Telescope (LBT). We report the detection of a bright unresolved source with a position consistent with the image (or likely counterimage) of Lensed Star 1 (LS1), a highly magnified blue supergiant star at z = 1.49 (Kelly et al. 2018). We measure preliminary magnitudes of g = 26.9 +/- 0.2 mag AB and r = 26.4 +/- 0.3 mag AB, which imply a color statistically consistent with that of LS1. The measured optical flux densities are comparable to those observed during LS1's May 2016 microlensing peak, when the star's magnification likely reached several thousand. A Gemini Director's Discretionary Time program (GN-2018A-DD-107) for imaging follow up has been approved, and all observations of the microlensing event are encouraged.

Constraints on Compact Dark Matter



Venumadhav, Dai & Miralda-Escudé 17

Constraints on Compact Dark Matter



Venumadhav, Dai & Miralda-Escudé 17'

Part II: Using highly magnified stars to probe dark matter subhalos

"Halos inside halos"

Why to look near critical curves?

Subhalos are puffy. Usually inefficient gravitational deflectors:

deflection angle $$\alpha \lesssim \frac{G\,M_{\rm sub}}{b} \sim 1\,{\rm mas}\left(\frac{M_{\rm sub}}{10^7\,M_\odot}\right)\left(\frac{b}{100\,{\rm pc}}\right)^{-1}$$

Argument due to Katz 1986

$$\boldsymbol{x} - \boldsymbol{y} = \boldsymbol{\alpha}_{\rm cl}(\boldsymbol{x})$$

$$\boldsymbol{x}' - \boldsymbol{y} = \boldsymbol{\alpha}_{\rm cl}(\boldsymbol{x}') + \boldsymbol{\alpha}_{\rm sub}(\boldsymbol{x}') \qquad \boldsymbol{x}' = \boldsymbol{x} + \Delta\boldsymbol{x}$$

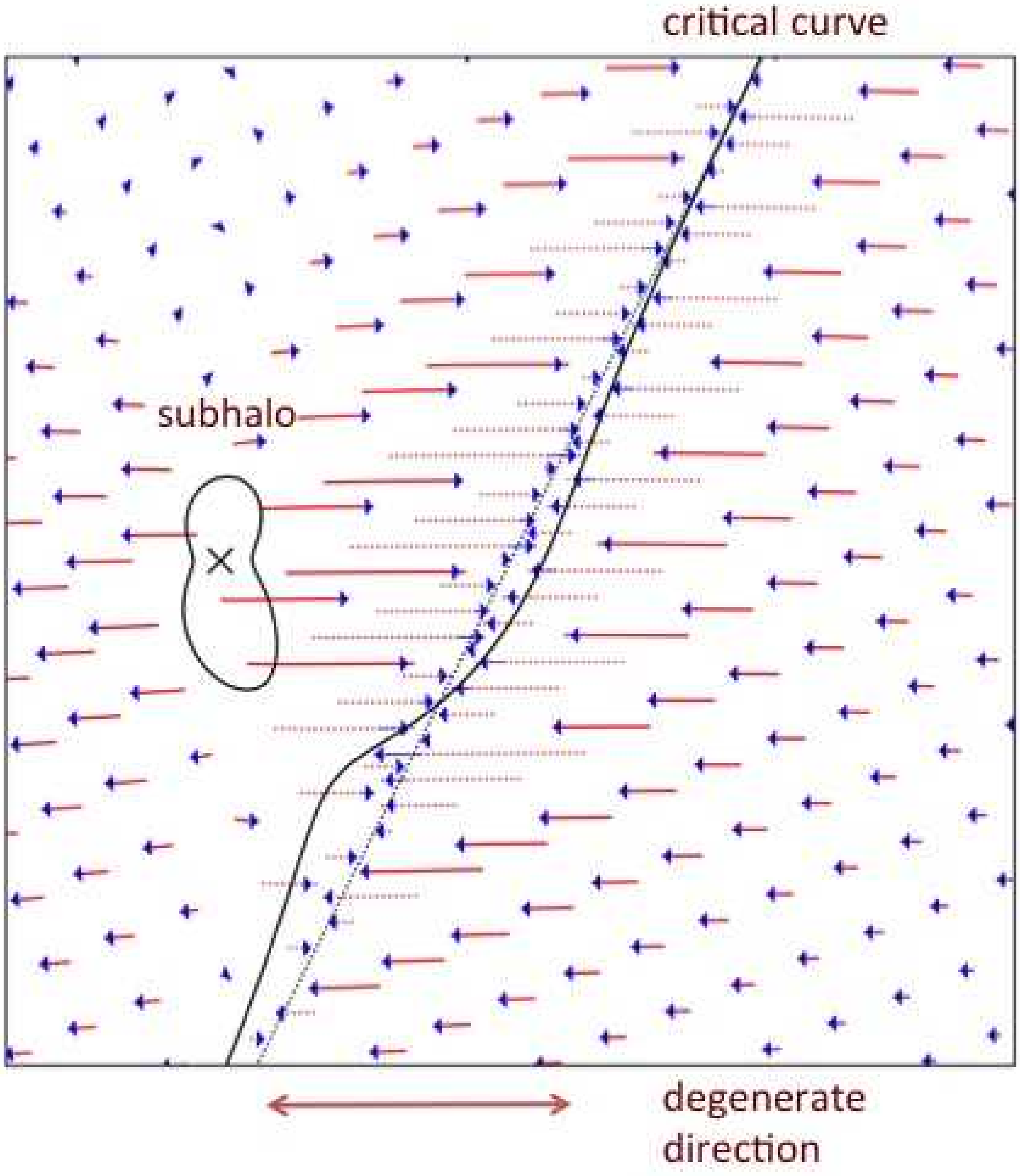
$$\Delta\boldsymbol{x} = \Delta\boldsymbol{x}\cdot\boldsymbol{\nabla}\boldsymbol{\alpha}_{\rm cl} + \boldsymbol{\alpha}_{\rm sub}(\boldsymbol{x}')$$

$$\Delta\boldsymbol{x} = \boxed{(\boldsymbol{I} - \boldsymbol{\nabla}\boldsymbol{\alpha}_{\rm cl})}^{-1}\cdot\boldsymbol{\alpha}_{\rm sub}(\boldsymbol{x}')$$

lensing Jacobian matrix

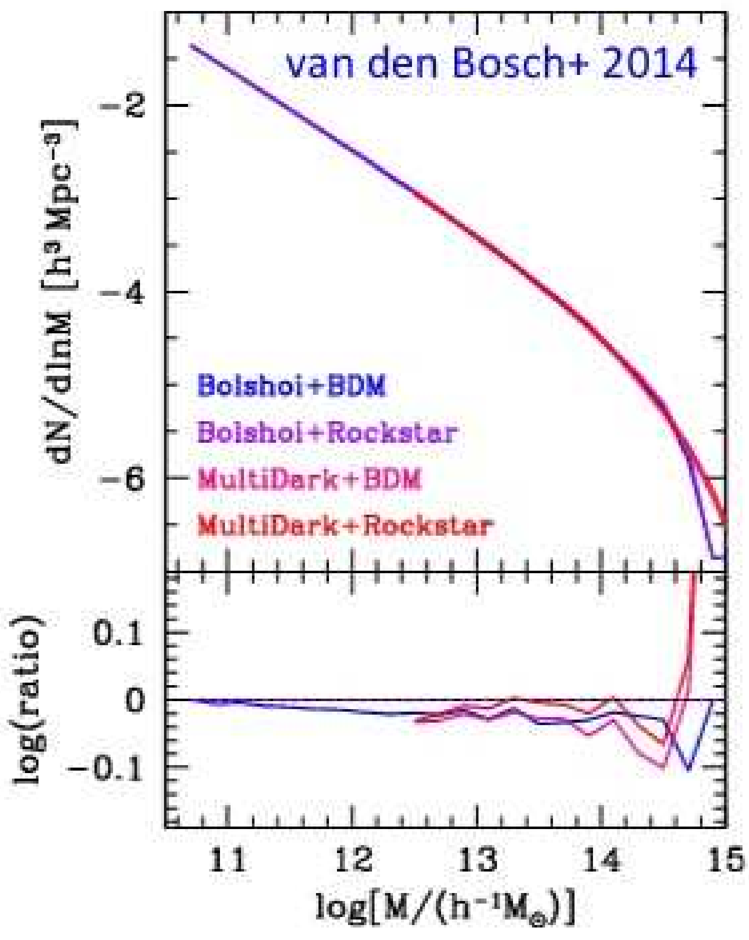
- Deflection angle "amplified" by a factor of the fold magnification ~ 10^2 – 10^3
- Amplified deflection always along the degenerate direction.

Astrometric perturbation near critical curves

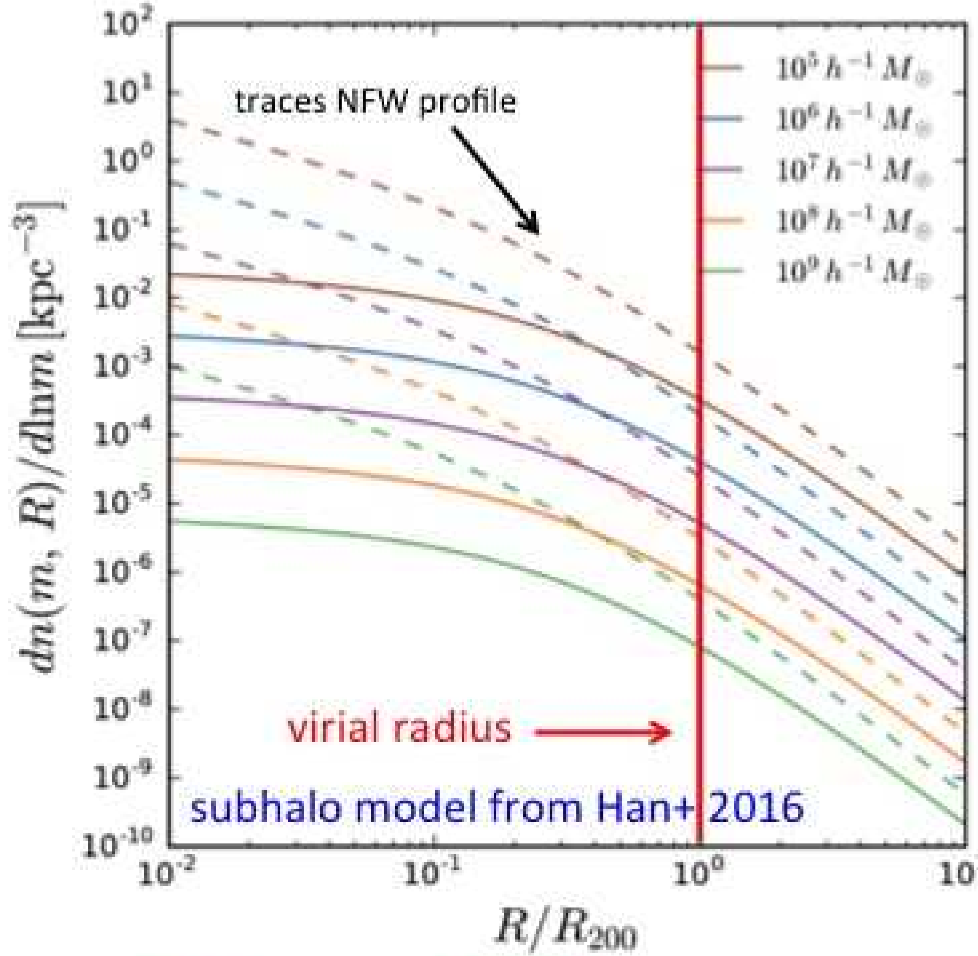


Substructure in CDM halos

- Power-law mass function $dN/d\log m \propto m^{-0.9}$ Mo+ 2010
- ~1-10% mass in subhalos across a wide mass range



cluster size halo

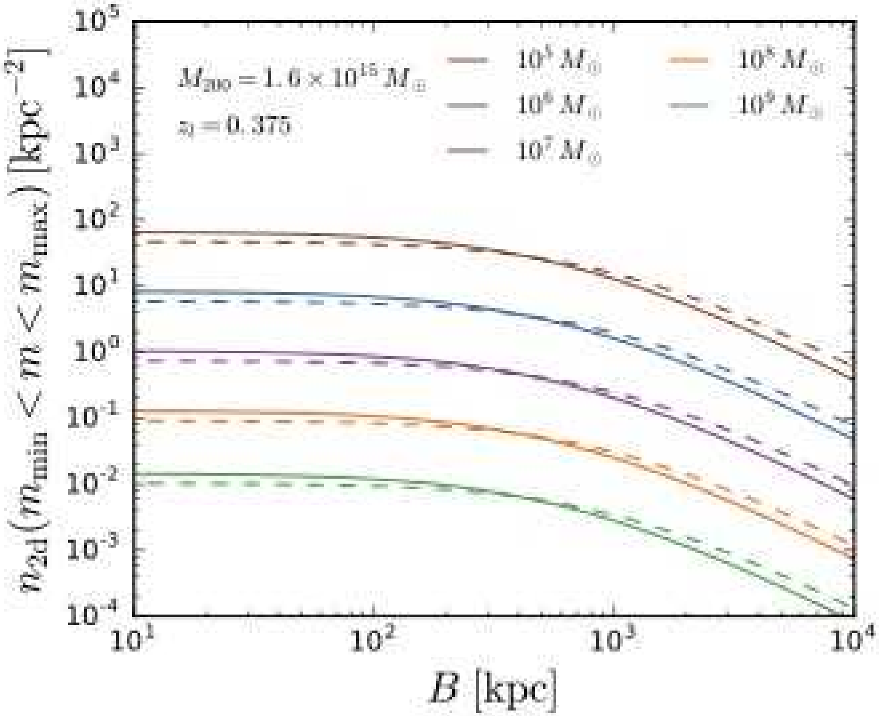


Infall mass vs bound mass

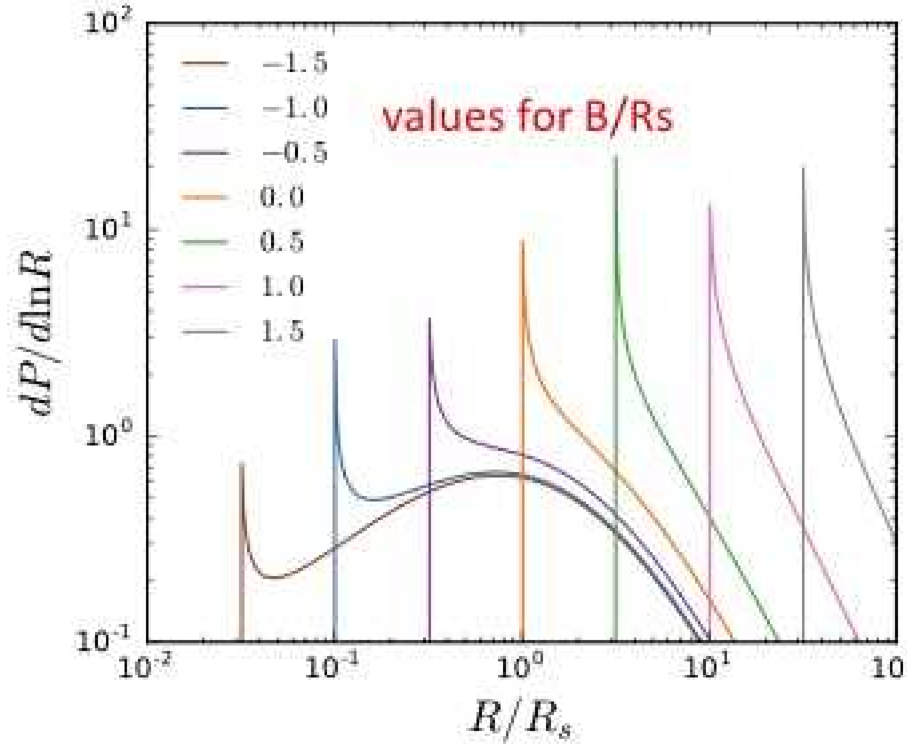
“unbiased accretion”

Probability of intersecting subhalos

Massive galaxy cluster has size ~ 1 Mpc;
Huge column density of dark matter

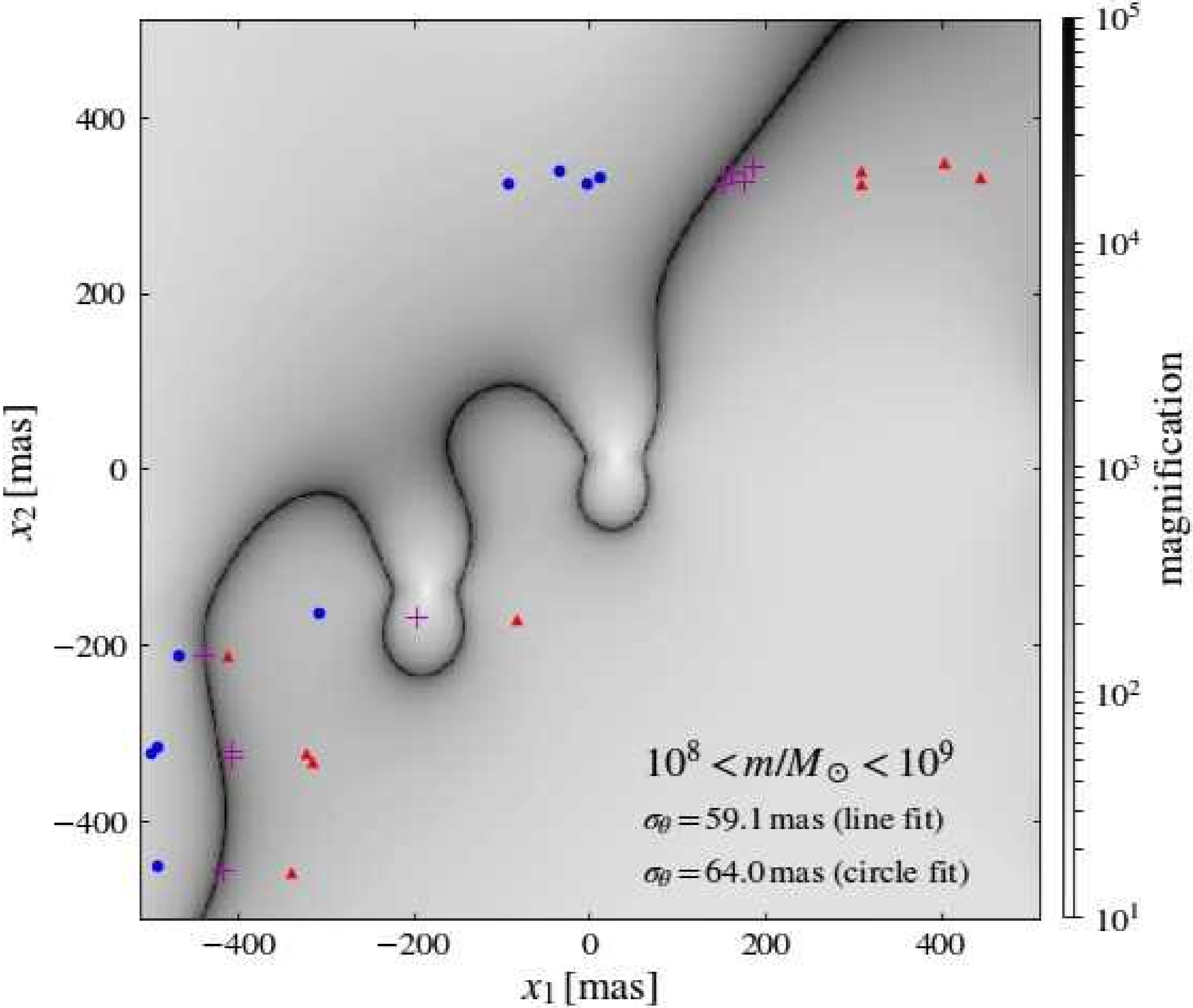


~ 1 halo of 10^6 --- 10^7 Msun in each 0.2" x 0.2" patch



Most likely to be at halocentric distance R_s ~ 300 kpc

Effect of Subhalos on Image Locations



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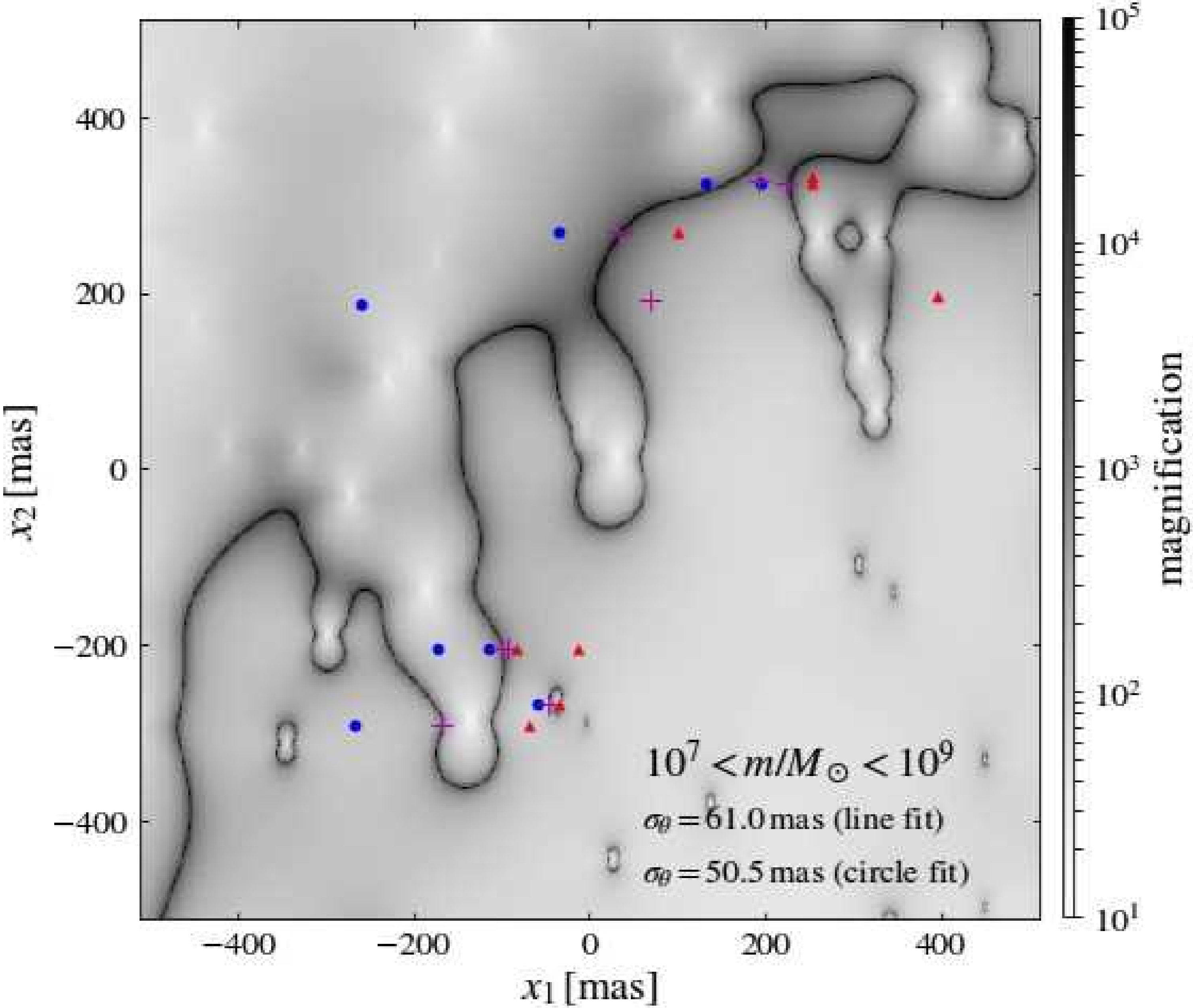
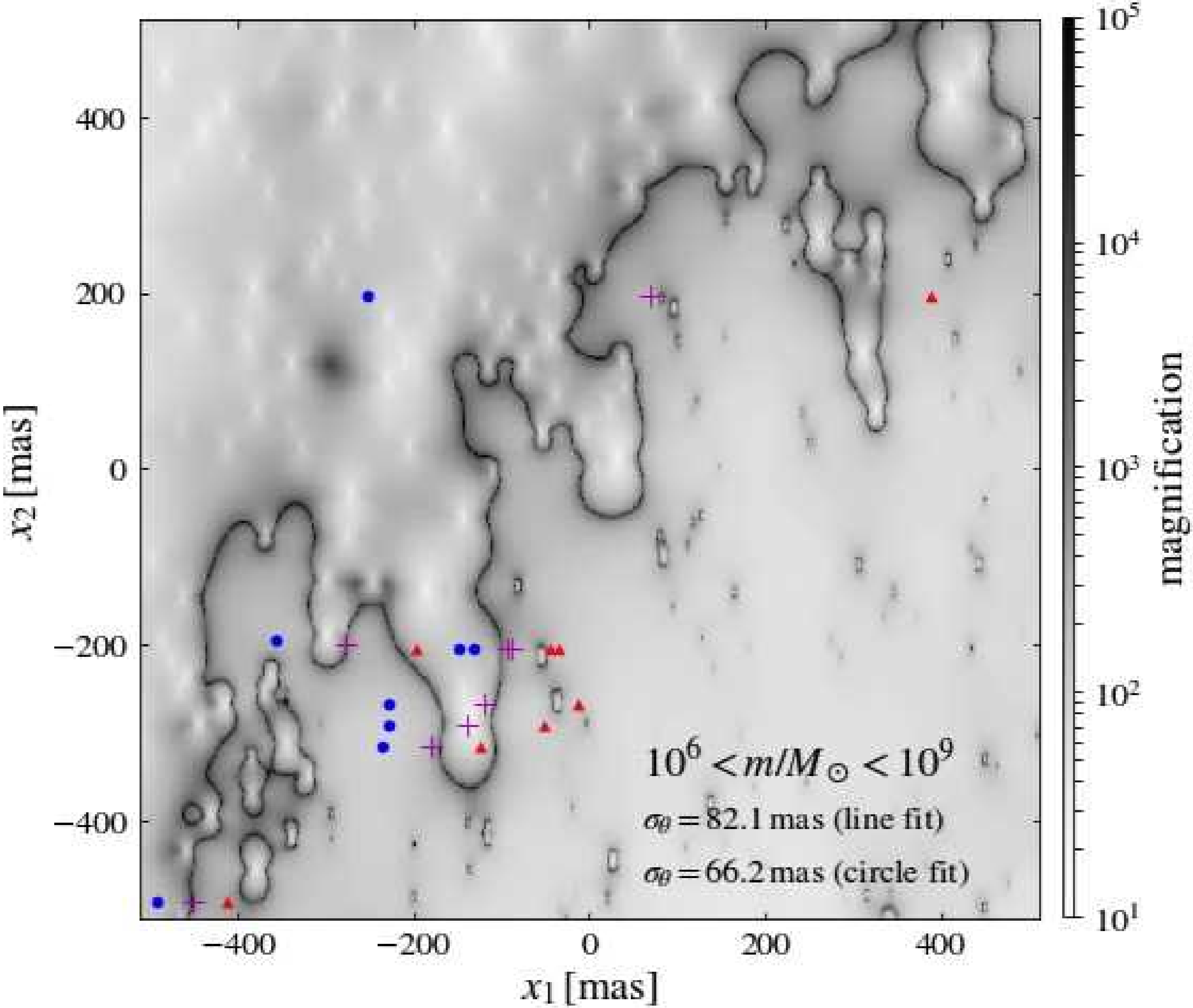
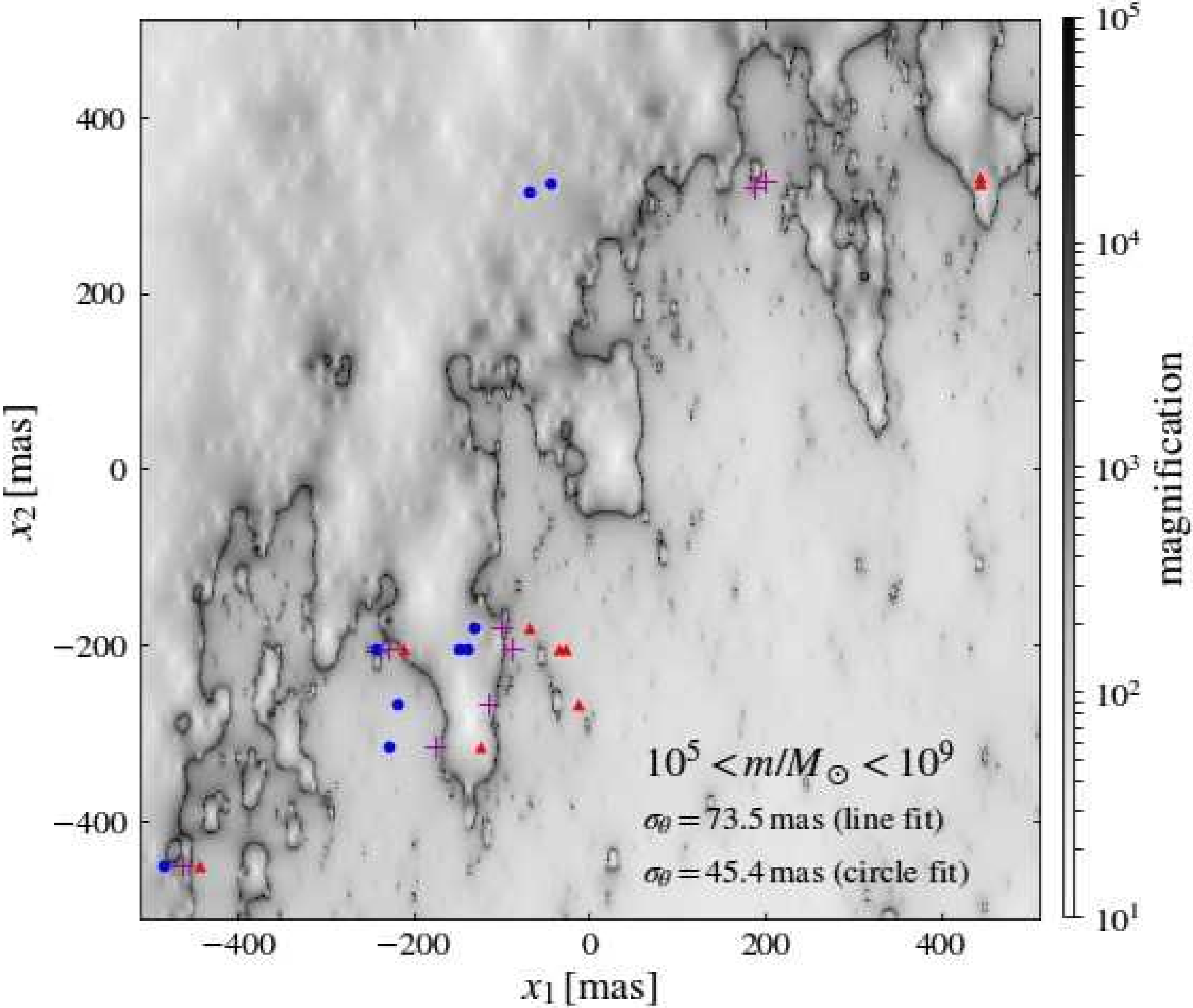


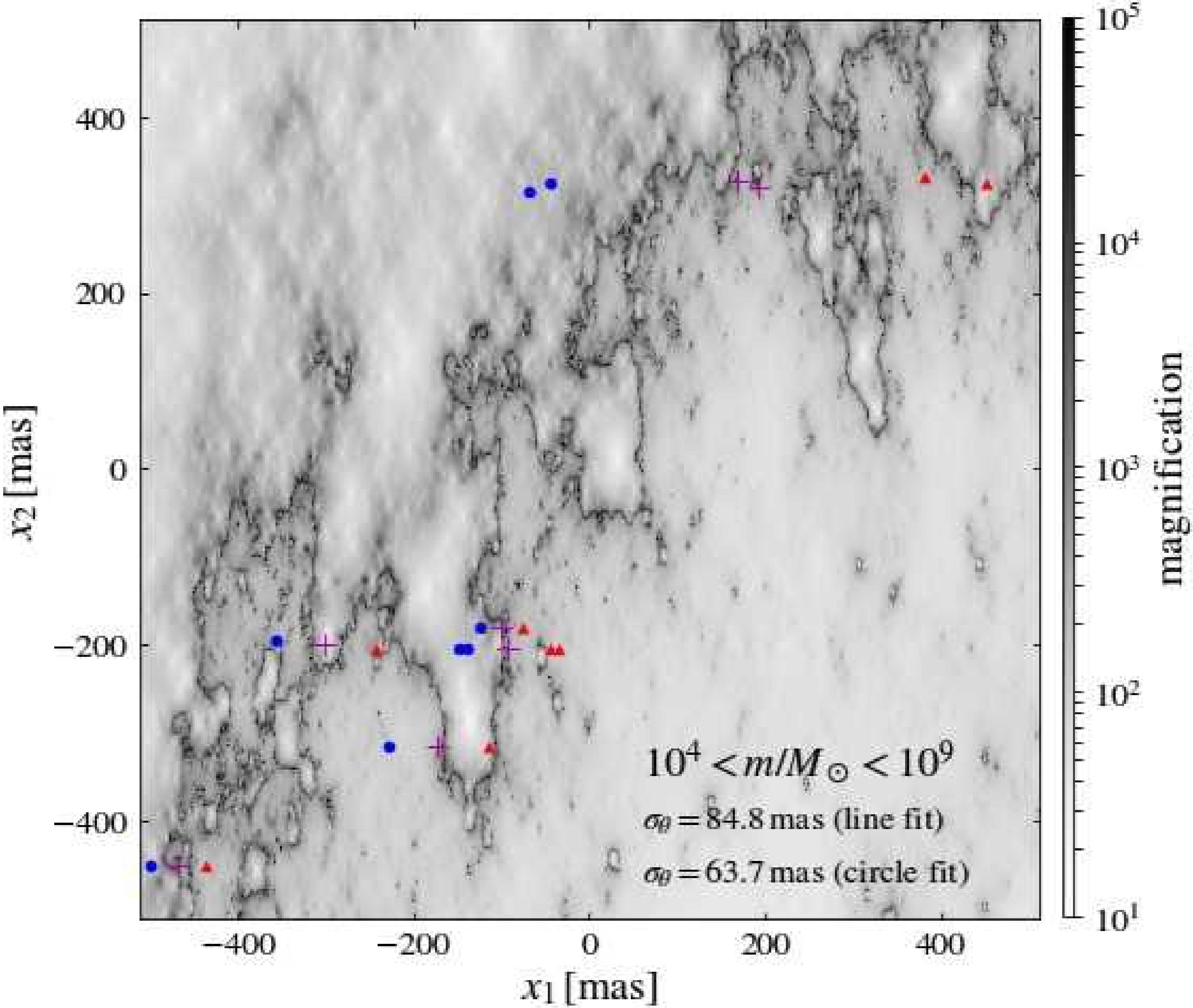
Effect of Subhalos on Image Locations



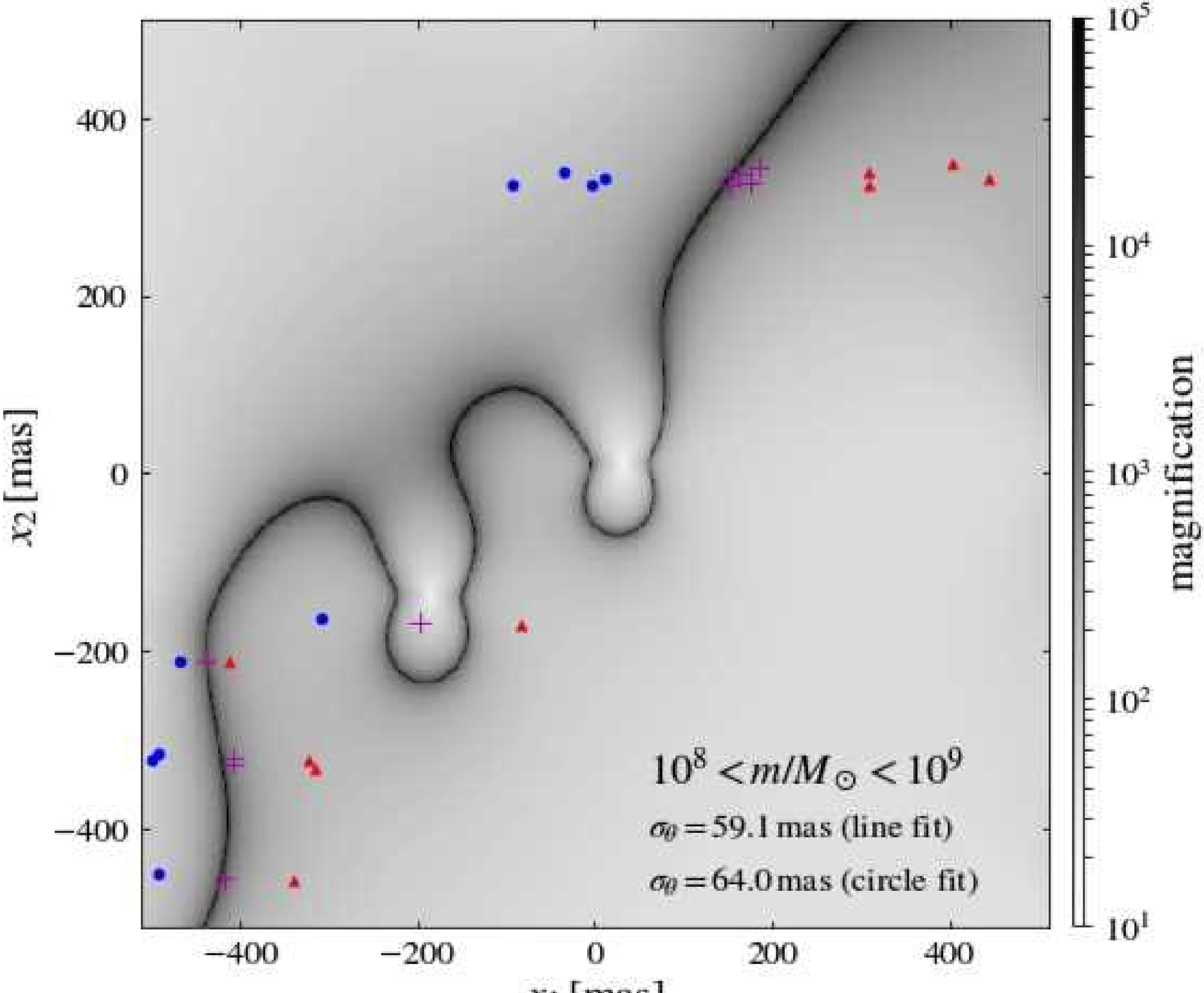
Effect of Subhalos on Image Locations



Effect of Subhalos on Image Locations

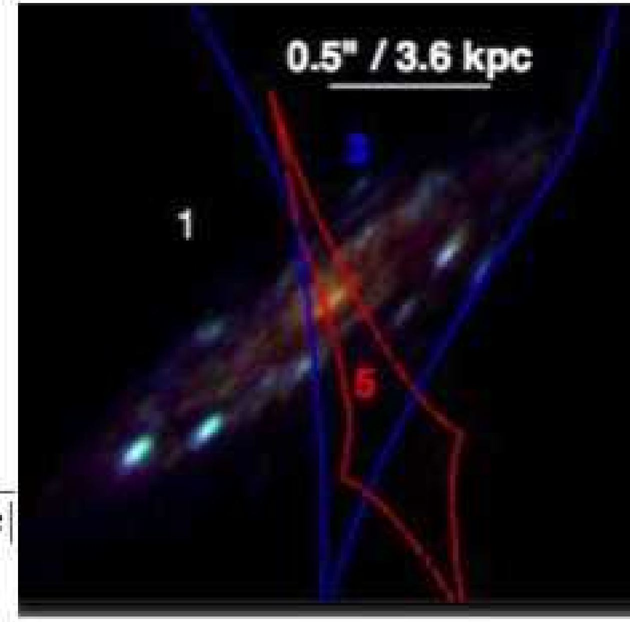


Effect of Subhalos on Image Locations

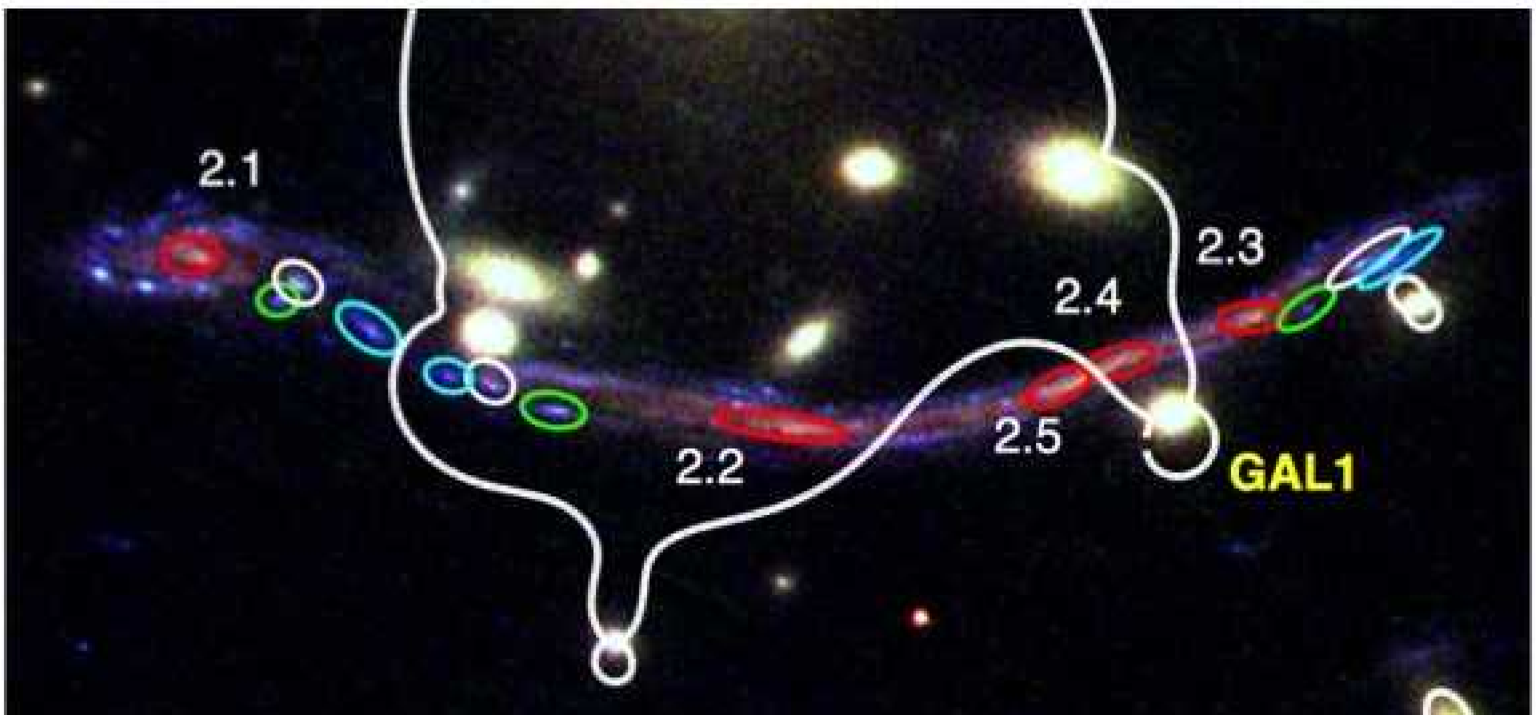


What systems are the most promising?

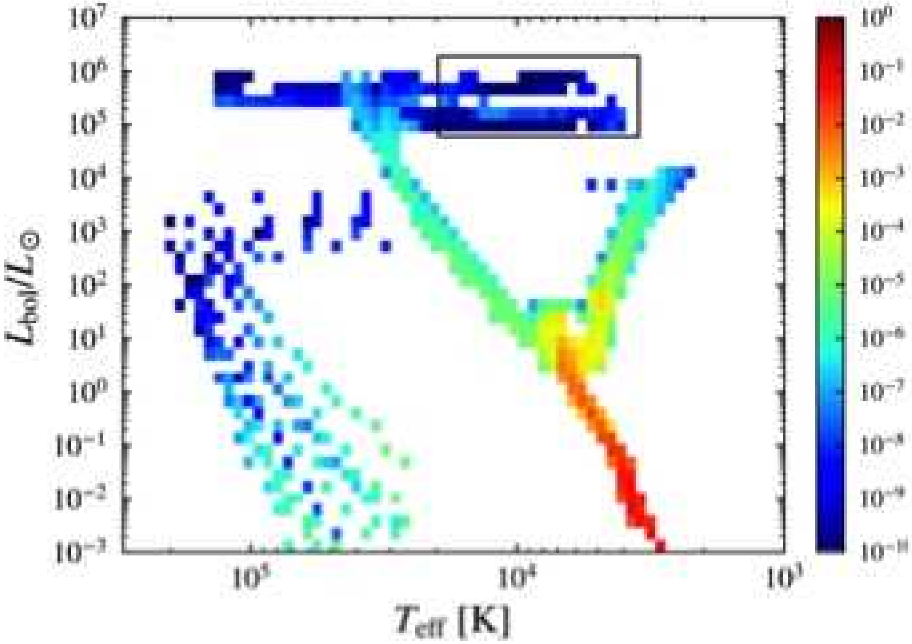
- Source galaxy at low redshift
- Active star formation
- Wide giant arc favorable
- Near critical convergence
- Shear has small derivative $\mu = \frac{1}{|2\,(1-\kappa_0)\,\boldsymbol{d}\cdot\boldsymbol{x}|}$



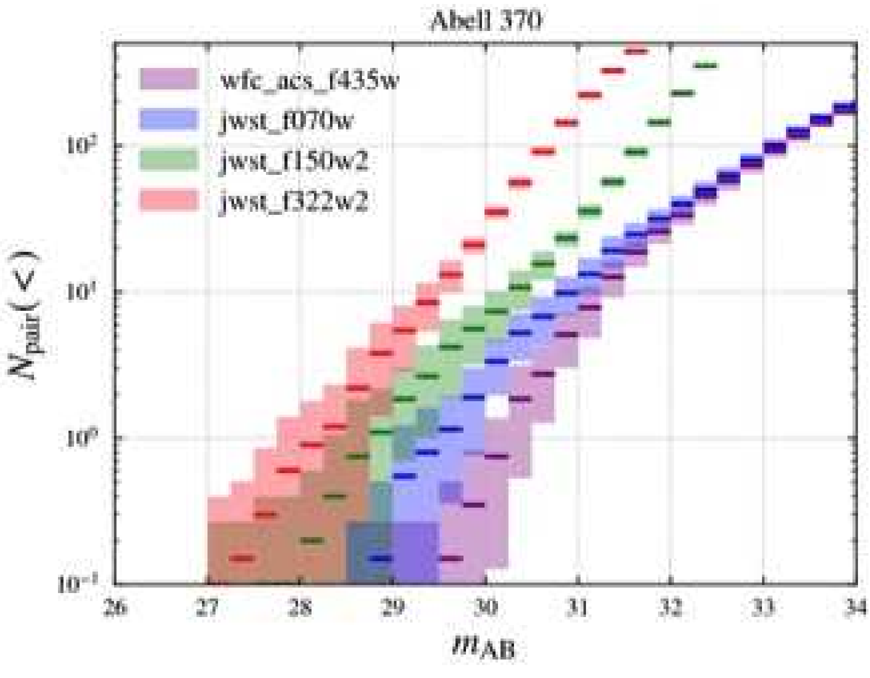
The "Dragon" of Abell 370 Richard+ 2009



Estimation of the abundance of bright source stars



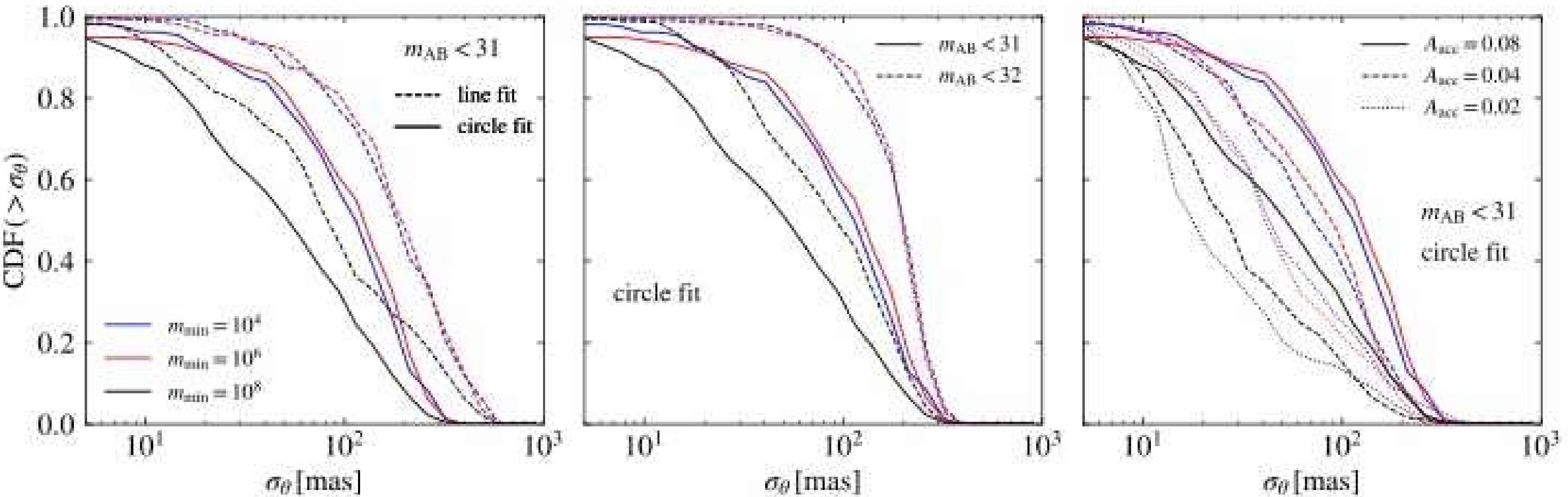
Red super-giants may be very promising (more than blue super-giants, or hot main-sequence stars)



Crude prediction for JWST
Try go down to mag ~ 29-30 in the near-IR (but on top of a bright arc).

Astrometric precision required to probe subhalos

Statistical forecast for the giant arc in Abell 370



- Sensitive to 10^6 – 10^8 Msun subhalos, 7-8 orders of magnitude down the cluster's mass scale; those expected to be non-luminous
- With clear detection of 5-10 pairs, require mean astrometric precision 20-100 mas

Comments

- For individual stars, microlensing inevitably induces flux variability. However, image shift due to microlensing negligibly small < 1 mas. Astrometric signal should be robust.

- How do we know which images belong to the same star? Make use of universal property of lensing near a fold. Color and variability information would be supplementary.

- Any under-resolved, compact feature in the surface brightness pattern equally useful for the astrometric test. Examples: star clusters, star-forming complexes, HII regions, dust lanes.

- Even without compact feature detected, a sharper image of the critical curve's neighborhood is highly desired. Surface brightness reconstruction techniques applicable.

Promise of future ELTs

- ❑ Caustic crossing sources are faint, even with huge lensing amplifications. Faster photon collecting rate is good.

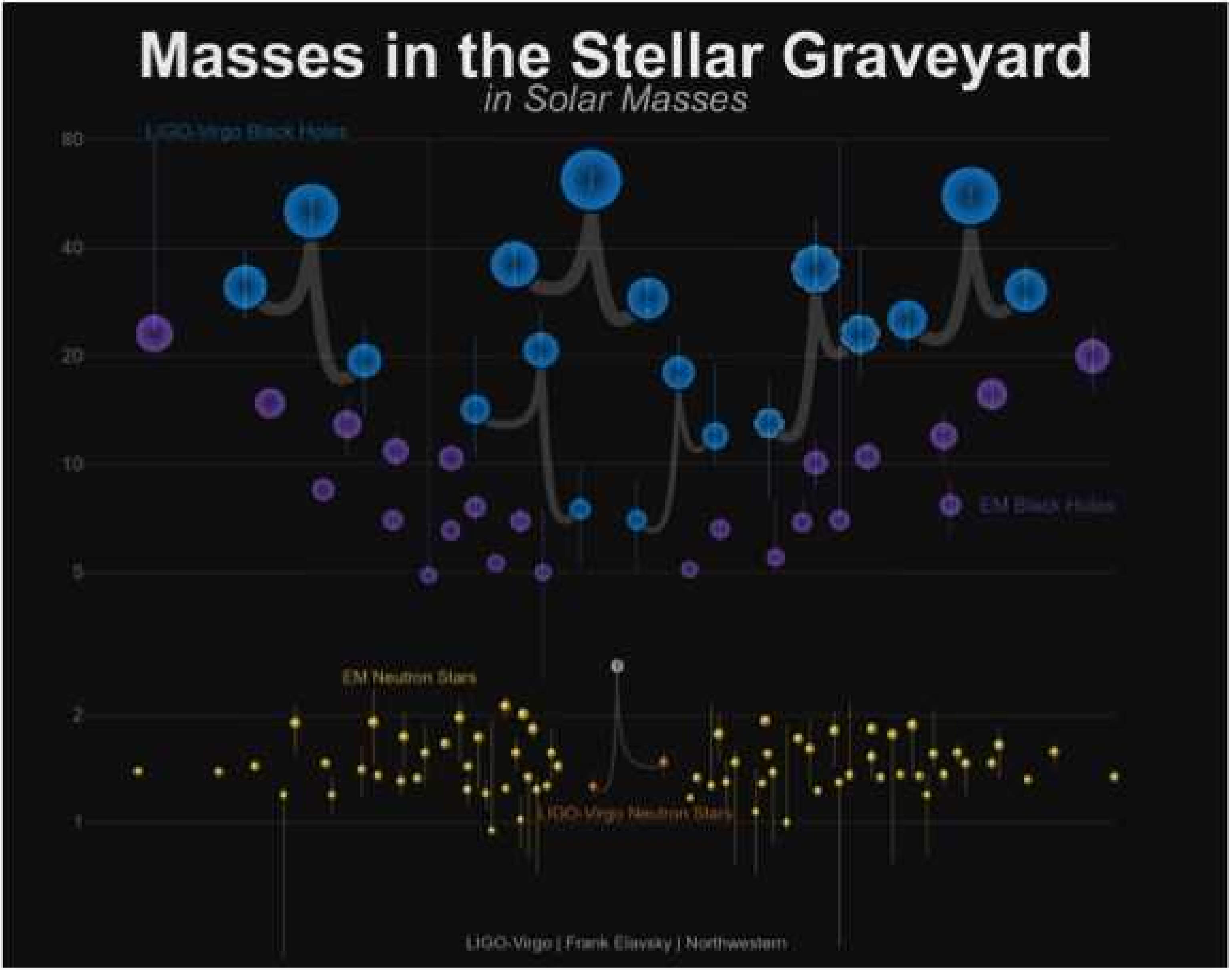
- ❑ Smaller diffraction-limited PSF extremely beneficial for detecting point sources.

- ❑ Higher angular resolution crucial for detecting astrometric distortions from subhalos.

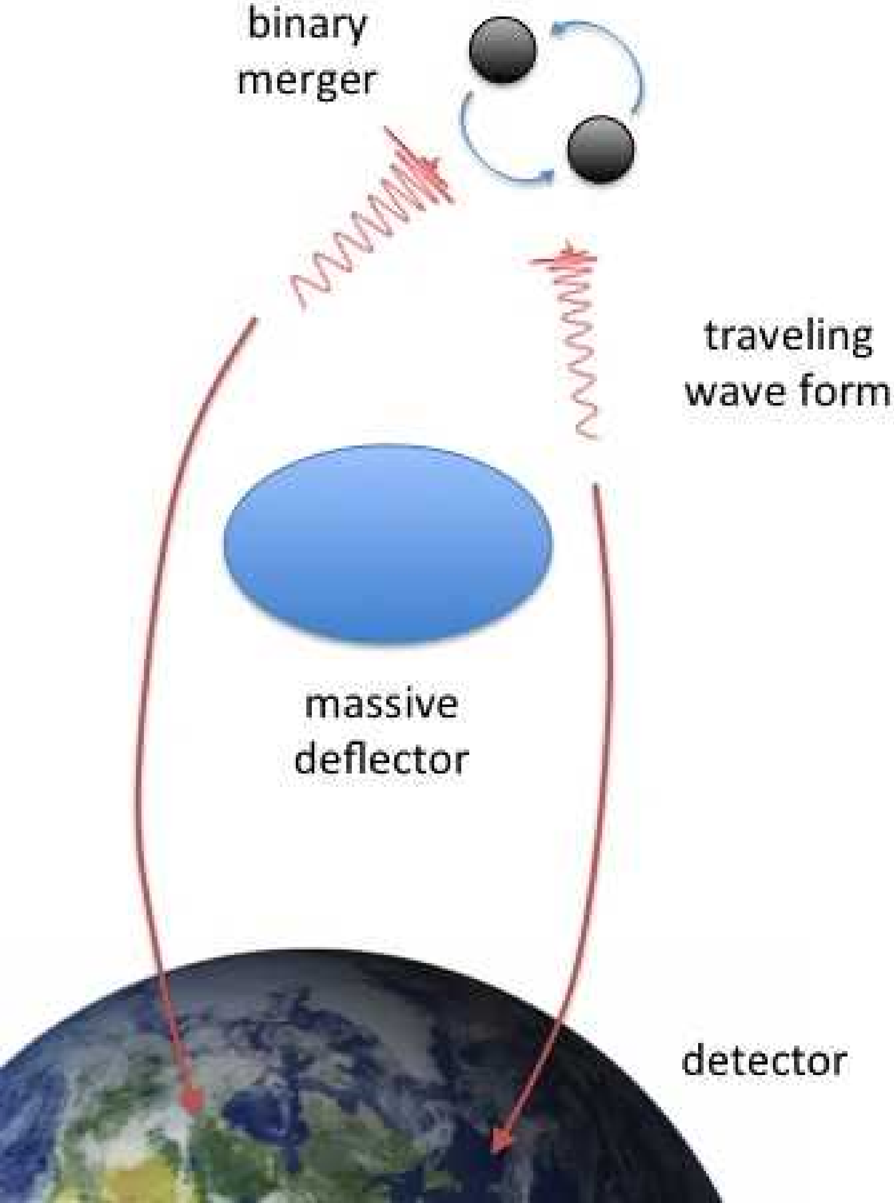
- ❑ Red/white super-giants very bright in J,H,K bands. These are very important and powerful bands for ELTs aided with AO.

Part III: Diffractive lensing of gravitational waves from binary mergers

Stellar remnants uncovered by gravitational observatories



Gravitational lensing of gravitational waves



- Geometrical limit

$$\lambda_{GW} \ll R_{de}$$

- Observable is strain **amplitude**

$$h' = \sqrt{\mu}\, h$$

- Frequency as received not changed
- Multiple bursts: without spatial localization, delayed events in time domain

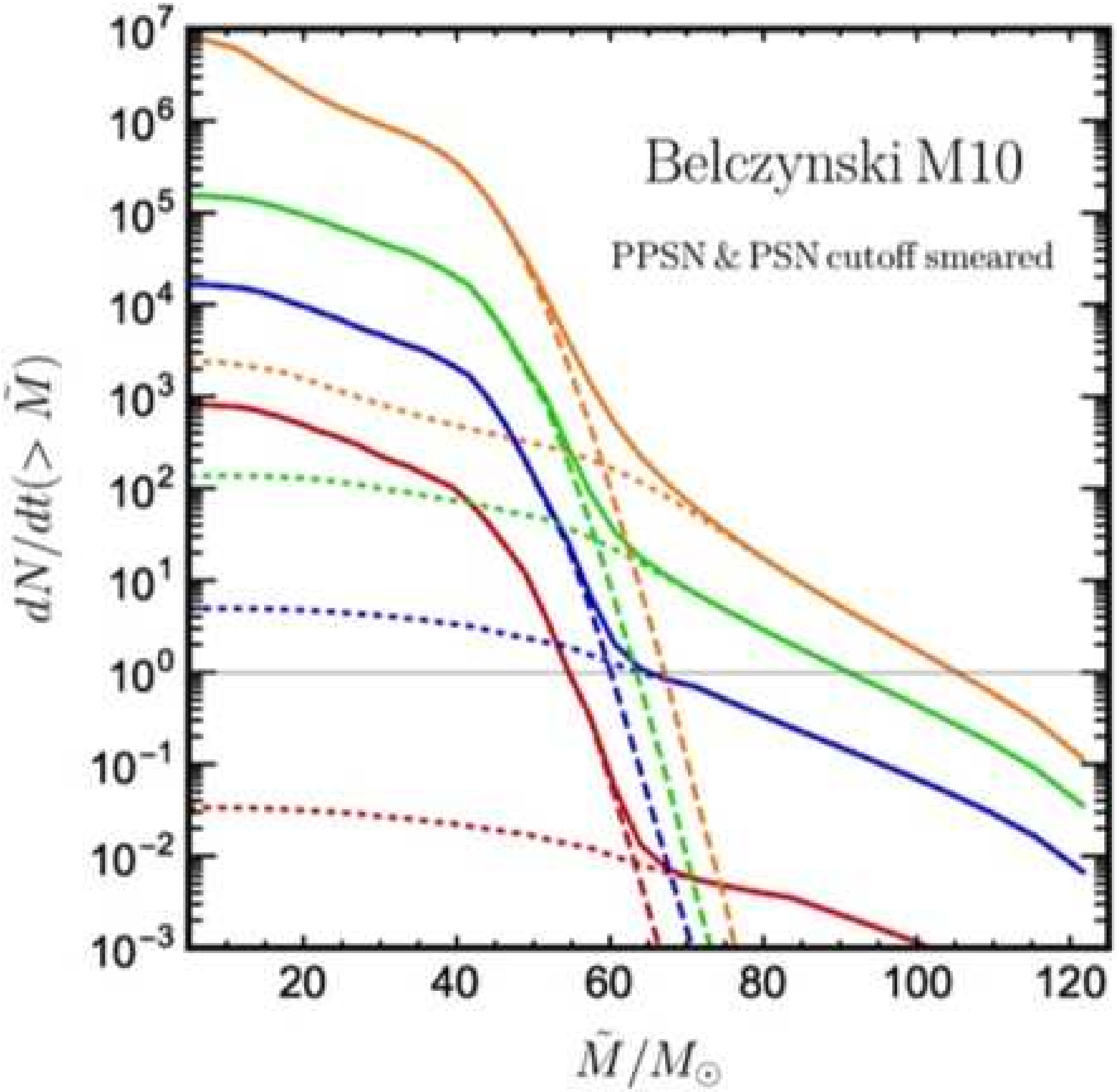
Biased black hole mass for strongly magnified events

Dai, Venumadhav & Sigurdson 17'
Broadhurst, Diego & Smoot 18'

Apparent mass scale **M'**
Apparent source redshift **z'**

$$M\,(1+z) = M'\,(1+z')$$

$$\frac{\sqrt{\mu}}{d_L\,(z)} = \frac{1}{d_L\,(z')}$$



Wave diffraction regime of lensing

Takahashi & Nakamura 2003
Takahashi PhD thesis

$$w = 2\pi f\,(1+z_L)\,G\,M_L/c^2 \sim \mathcal{O}(1)$$

In the band of ground-based detectors **f~10-1000 Hz**, sensitive to (interestingly) small lens masses **M ~ 100-1000 Msun**

Geometric lensing

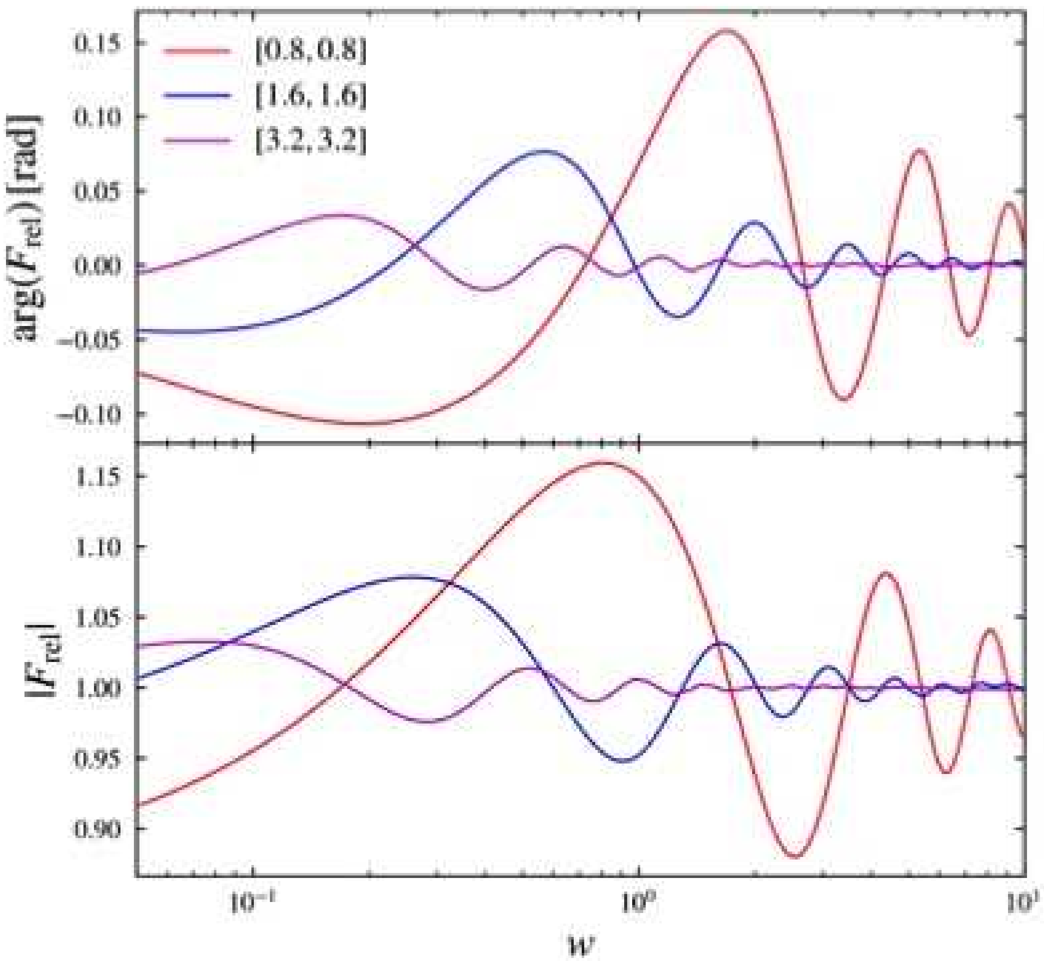
$$h_{\rm geo}(f) = \sqrt{\mu}\,e^{i\,2\pi\,f\,\tau}\,h_0(f)$$

Wave-diffractive lensing

$$h(f) = F(f)\,h_0(f)$$

Define a ratio:

$$F_{\rm rel}(f) = e^{-i\,2\pi\,f\,\tau}\,F(f)/\sqrt{\mu}$$



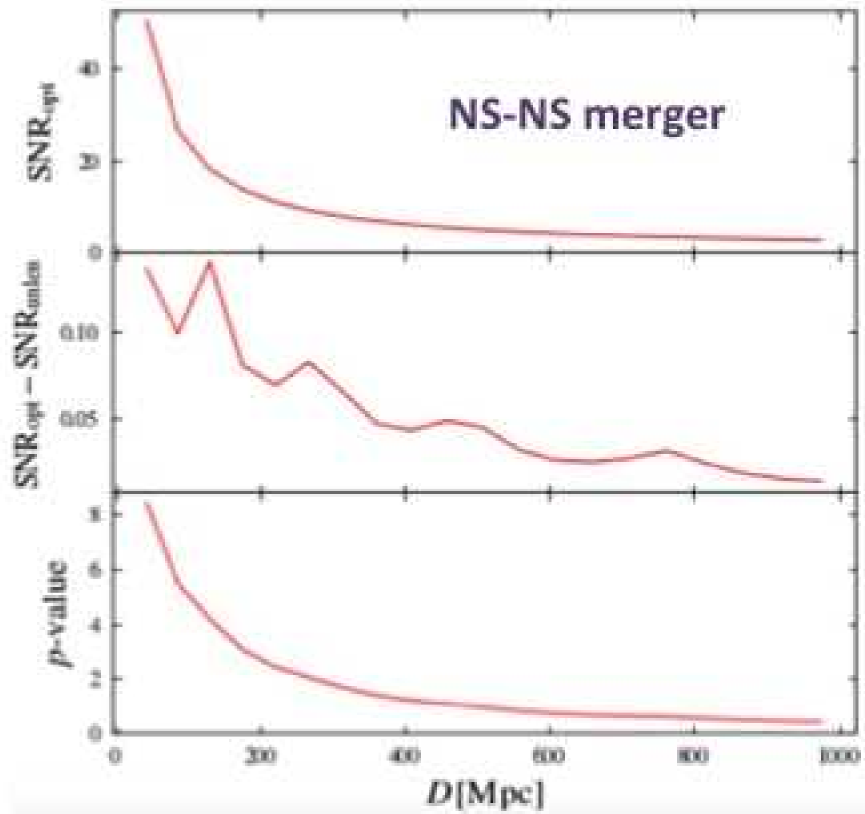
Detection of diffraction signal can be challenging

- There may not be multiple images (lens may be puffy)
- Small modulus and phase perturbations ~ 10-20%

In fact, using **unlensed** templates can yield sufficiently good matches

Ideal (through matched filtering) detection significance for diffraction signature

$$\ln p = -\left(\mathrm{SNR}_{\mathrm{opt}}^2 - \mathrm{SNR}_{\mathrm{unlen}}^2\right)/2$$
$$= -\frac{1}{2}\left(\langle h_L|h_L\rangle - \frac{\langle h_L|h_{\mathrm{BF}}\rangle^2}{\langle h_{\mathrm{BF}}|h_{\mathrm{BF}}\rangle}\right)$$

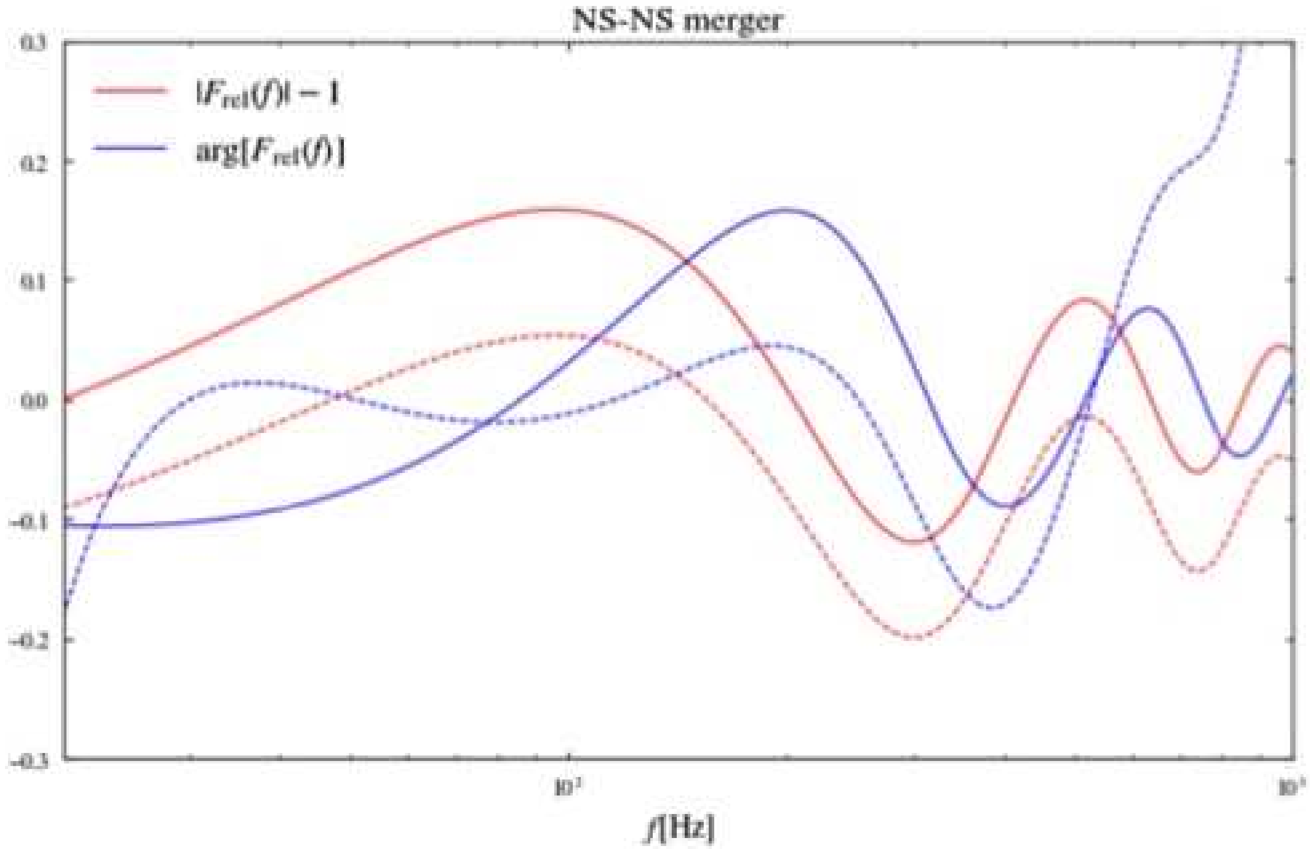


Difficulty with matched filtering: **lensed** template banks not known a priori

Phase/amplitude distortions (partially) degenerate with binary parameters

- **Intrinsic parameters:** chirp mass, mass ratio, spins, tidal deformability
- **Extrinsic parameters:** arrival time

Before/after fitting for the best unlensed model



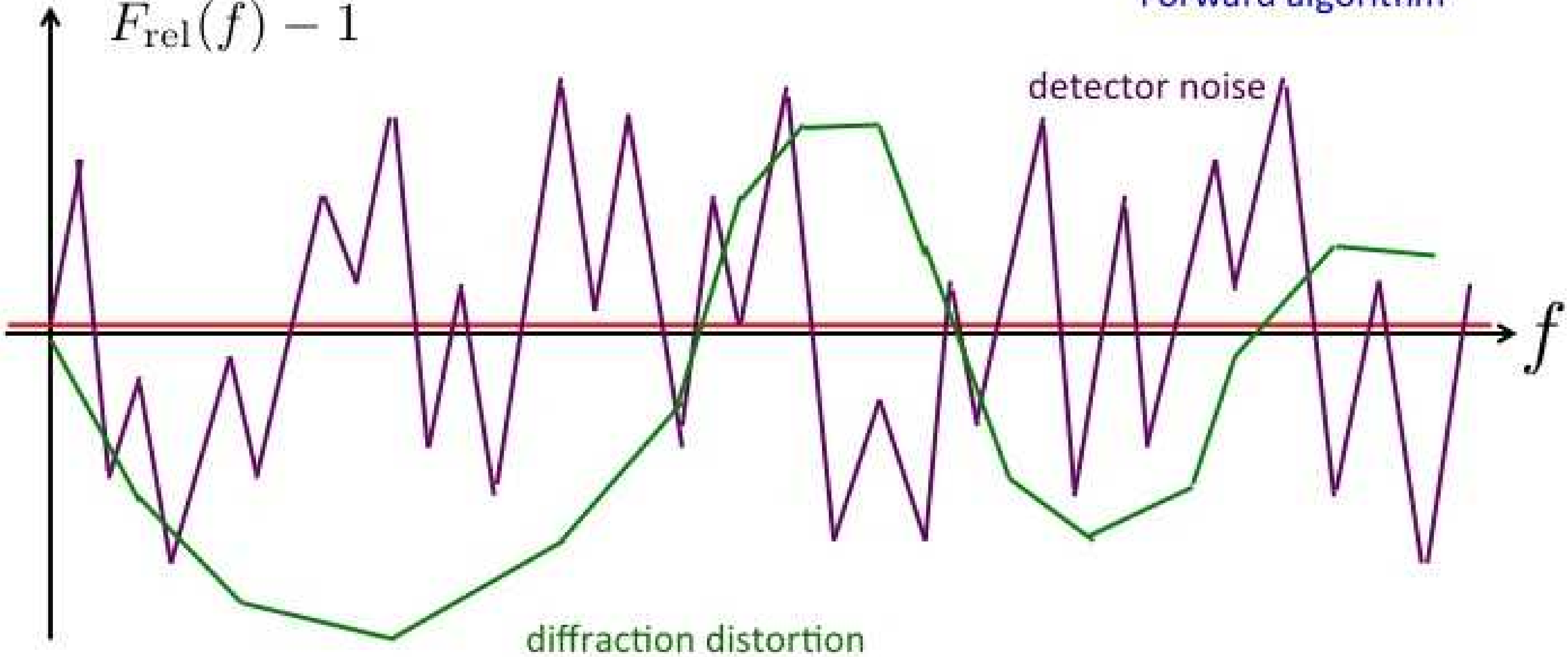
Agnostic search for diffraction signature

Dai+ in preparation

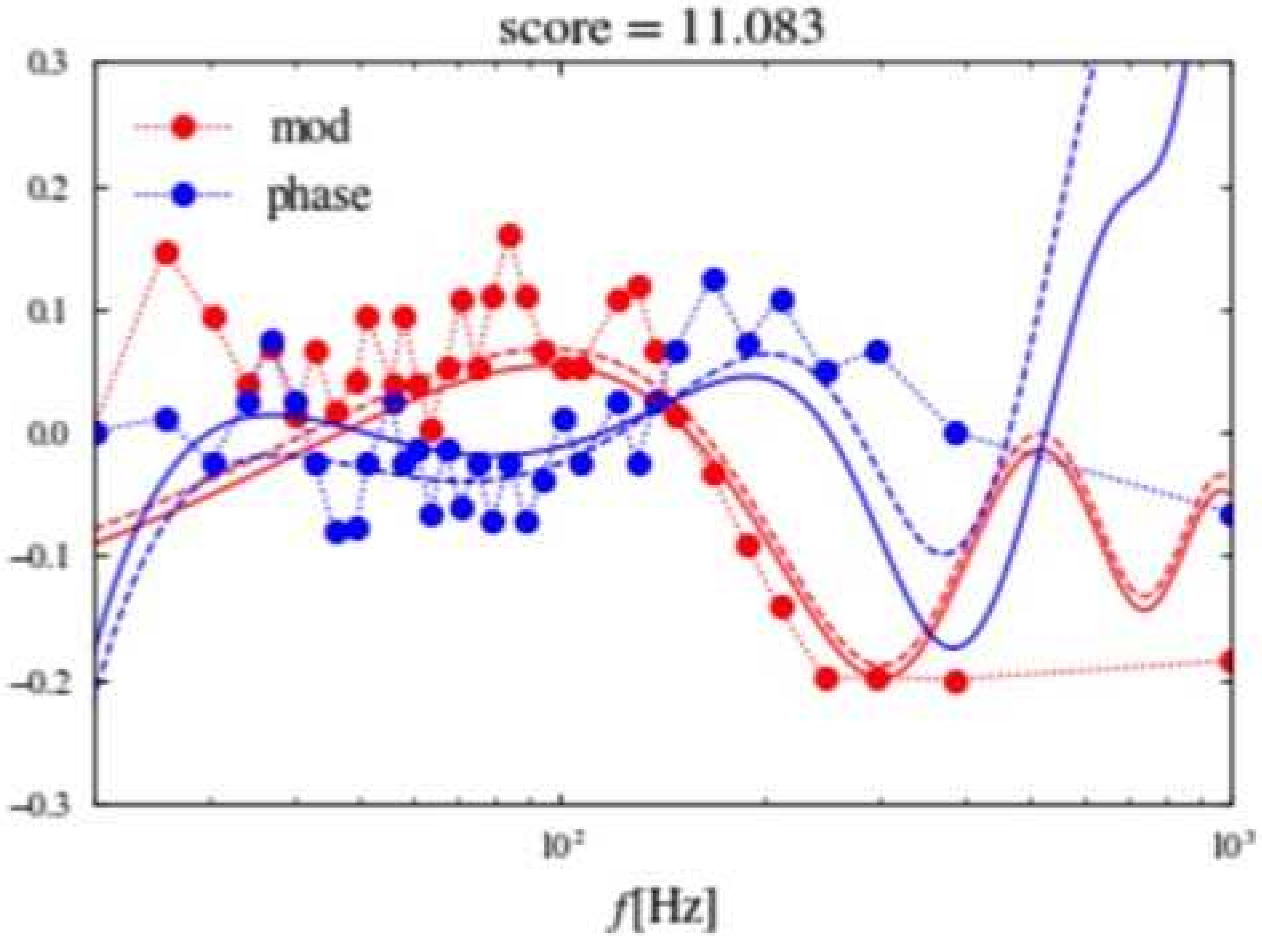
Marginalize over all distortions around the best-fit assuming a Markovian process

$$\mathcal{S} \equiv \int \mathcal{D}g(f)\, P\left(g(f)\right) \prod_{a=1}^{N_d} \frac{P(s_a|h_{L,a})}{P(s_a|h_{\mathrm{BF},a})}$$

Marginalization efficiently computable using Forward algorithm

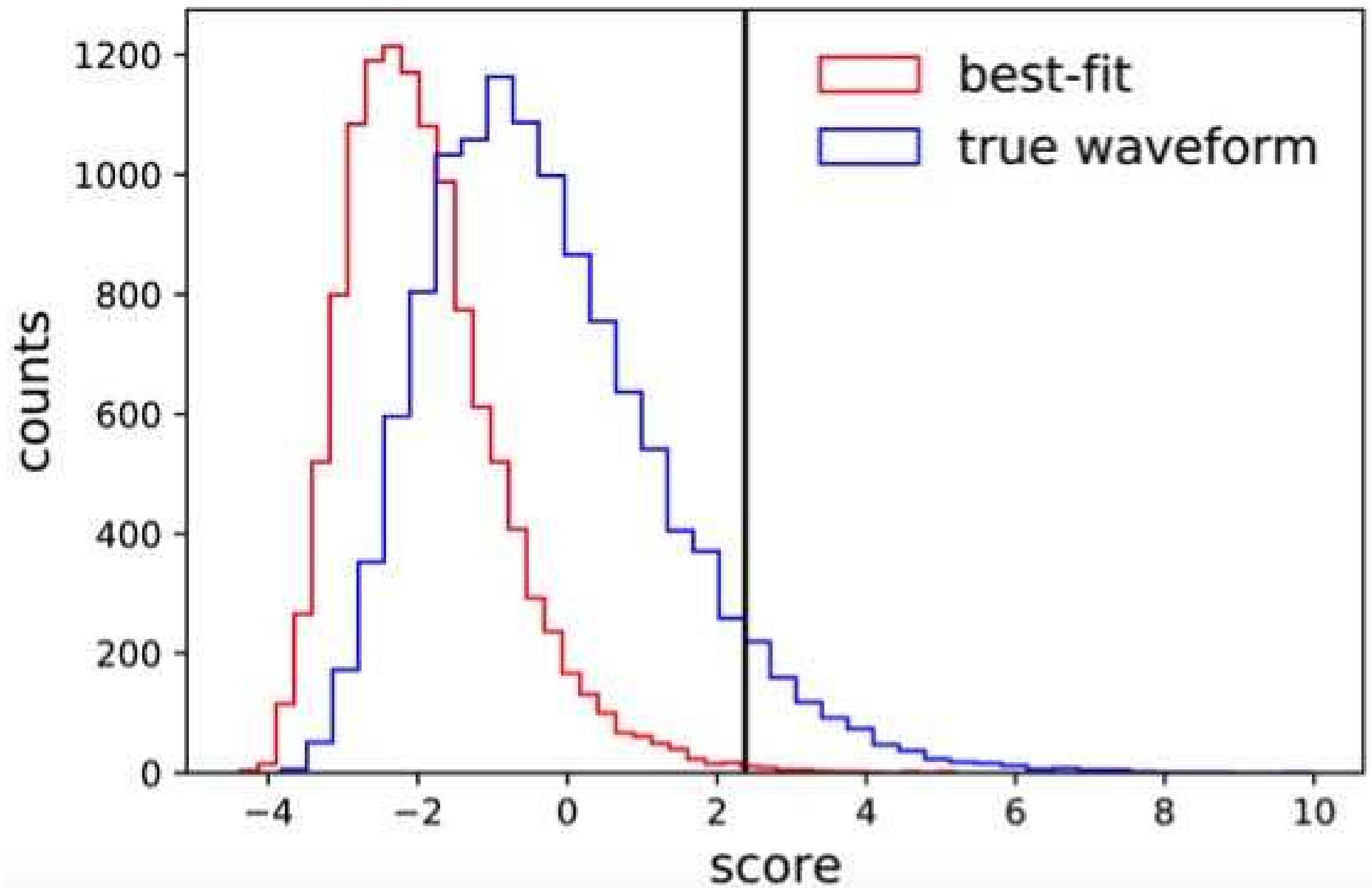


Testing the Forward-Viterbi algorithm



- Suitably choose frequency bins and steps.
- Apply proper priors to impose frequency “smoothness”

Determine statistical significance from mocks



It's important that one perturbs the best-fit unlensed model

Prospects

- Interesting mass range 100 – 1000 Msun for DM halos.

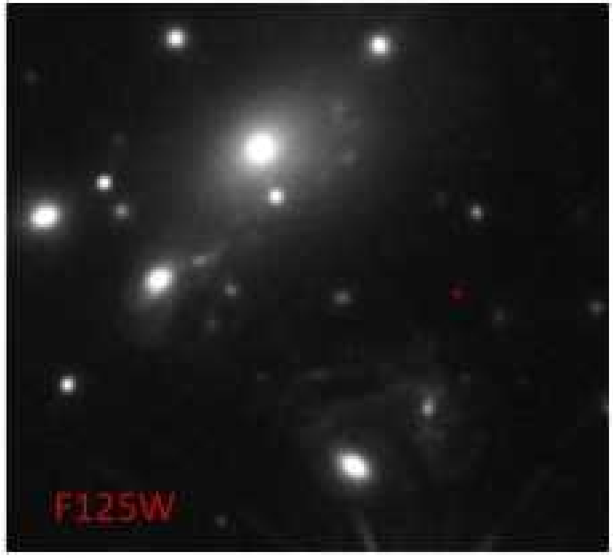
- Applicable to both NS-NS mergers and BH-BH mergers.

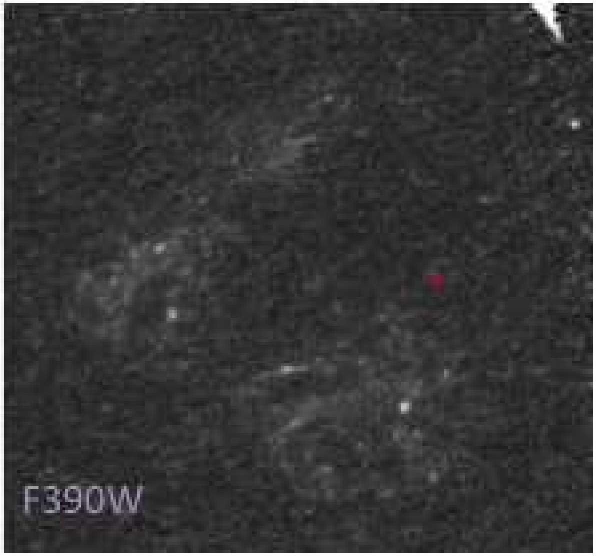
- Computationally very cheap; readily applicable to every GW detection.

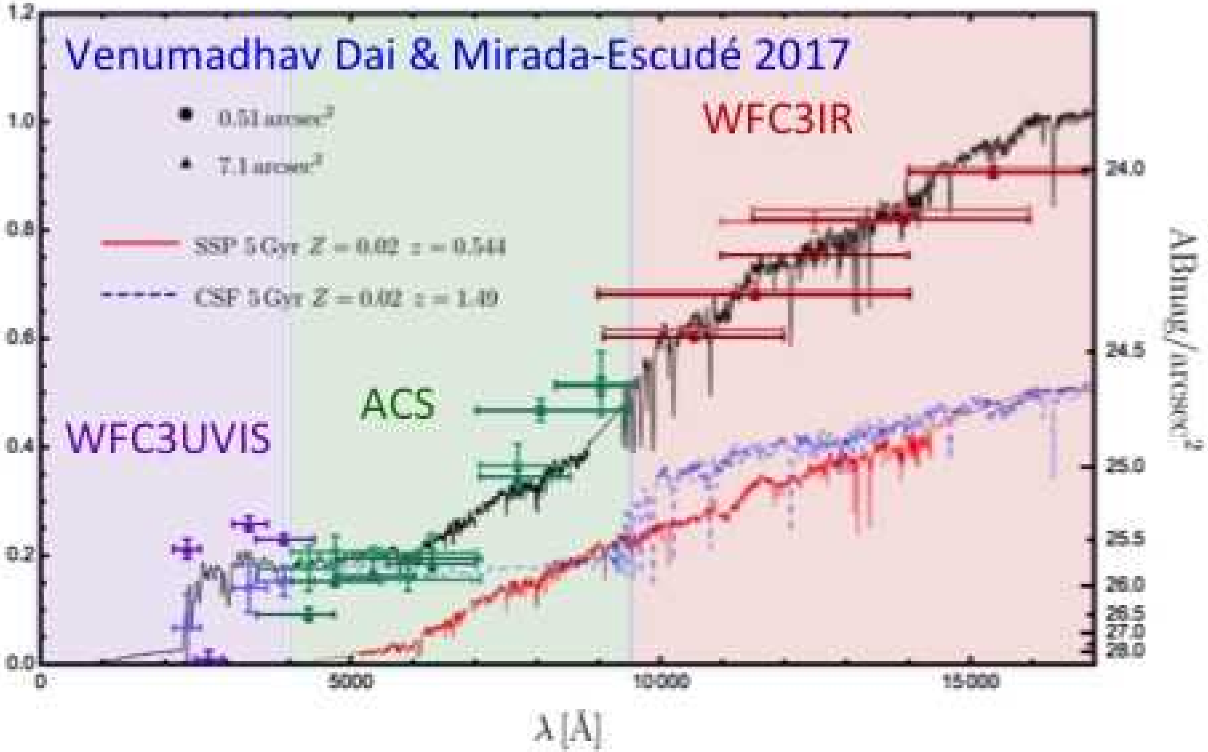
- Limitation is the required high SNR for performing this test. (Lensing optical depth grows sharply with distance). For the two advanced LIGO detectors at design sensitivity, NS-NS out to ~ 100 Mpc, and BH-BH out to ~ 700 Mpc. Virgo/KAGRA/ LIGOIndia joining the network is going to be very valuable. Also ET in the more distant future.

Thank you!

Infer microlens abundance from surface brightness







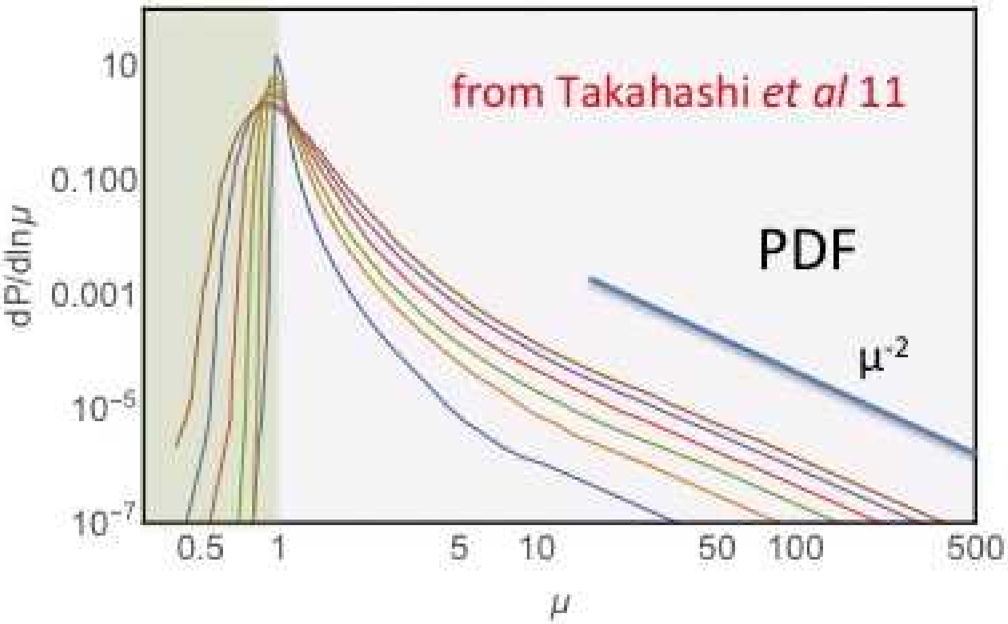
Foreground intracluster stars

+

Background star-forming galaxy

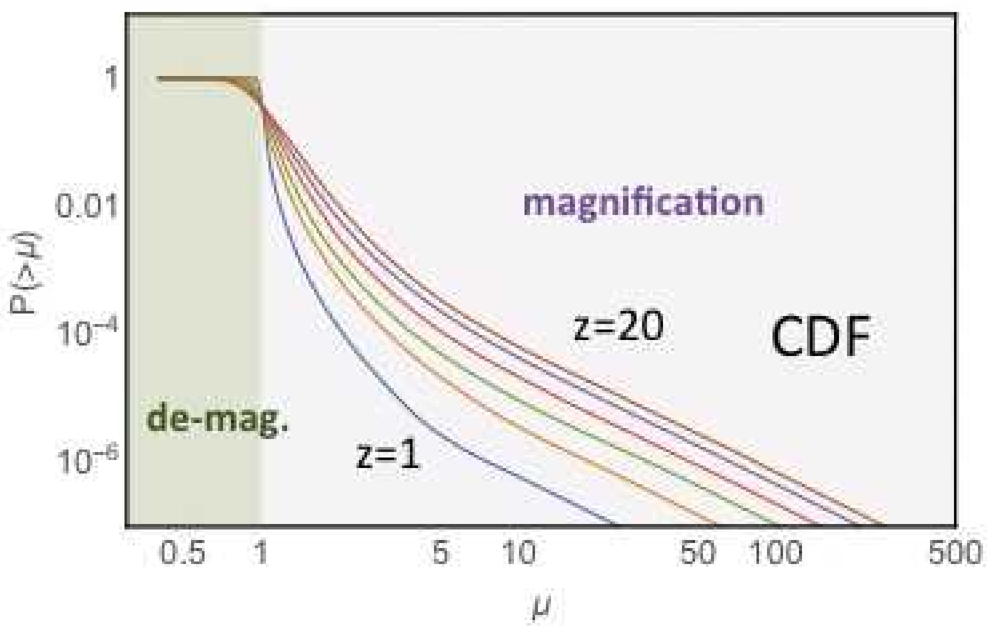
$$\Sigma_\star \sim 10^9 M_\odot/\mathrm{arcsec}^2$$

Lensing probability in ΛCDM



normalization

$$\int d\ln\mu \, \frac{dP(\mu,z)}{d\ln\mu} = 1$$



conservation of solid angle

$$<\mu> = \int d\ln\mu \, \frac{dP(\mu,z)}{d\ln\mu}\,\mu = 1$$

- Lensing by large-scale structure, DM haloes, galaxies
- Possible underestimation for point sources: lensing by compact stellar-mass objects?