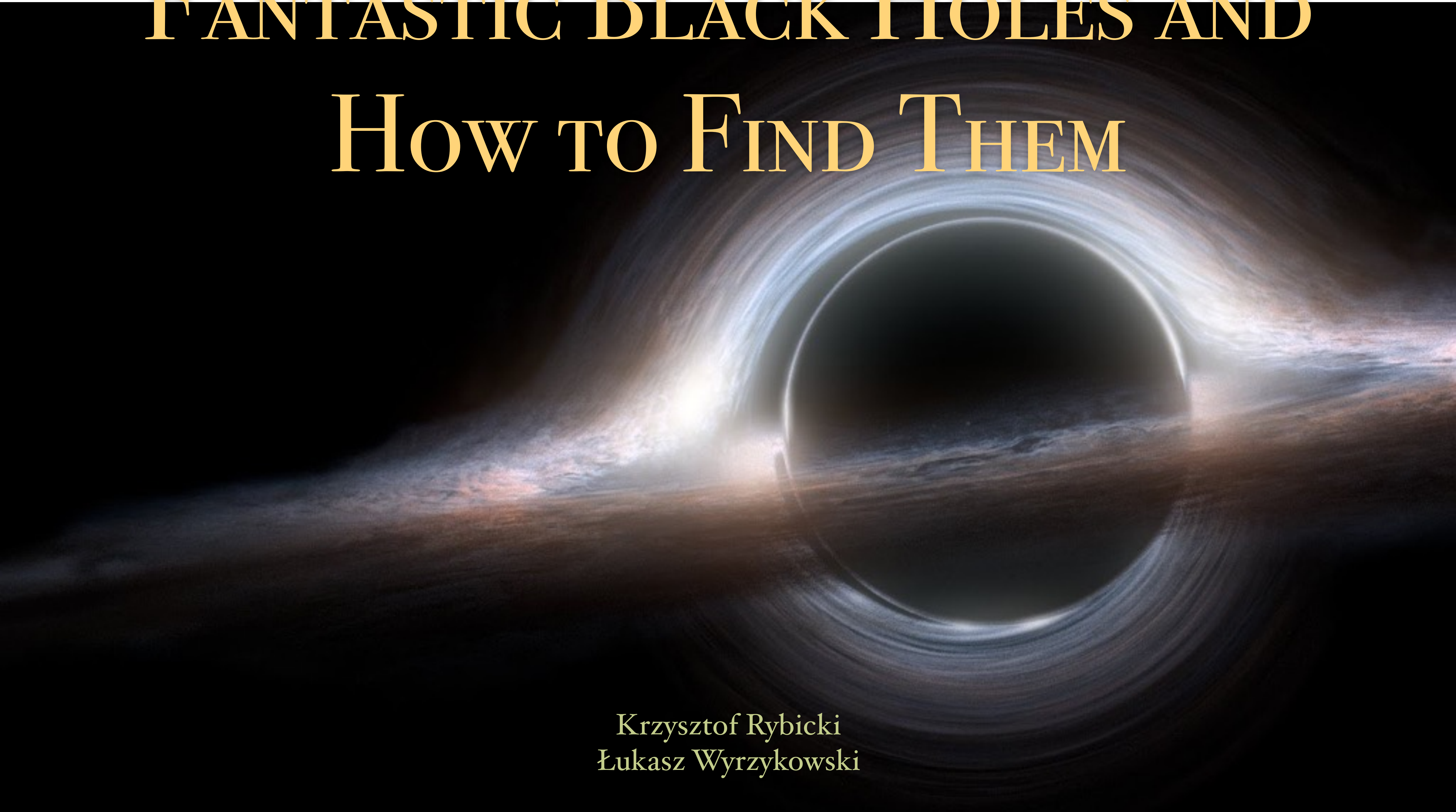
Fantastic Black Holes and How to Find Them



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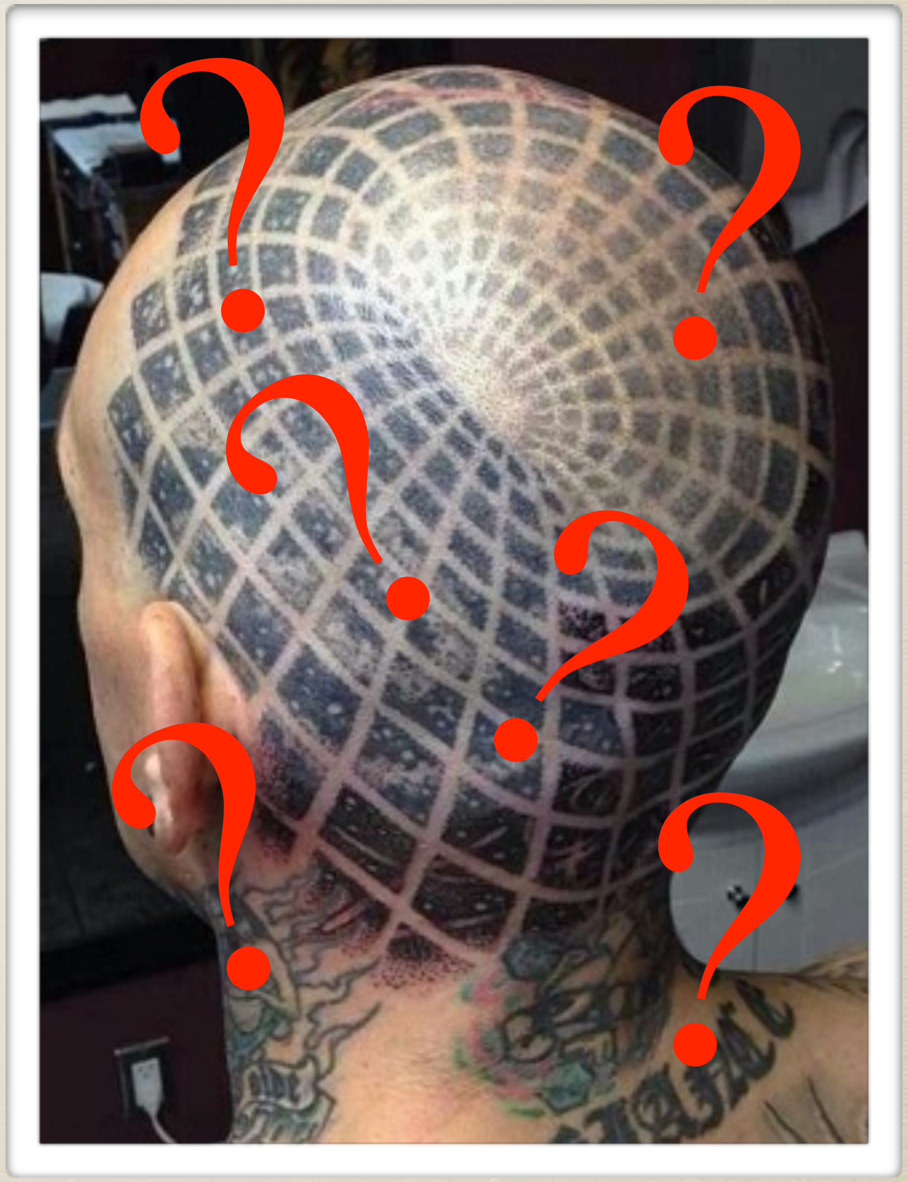
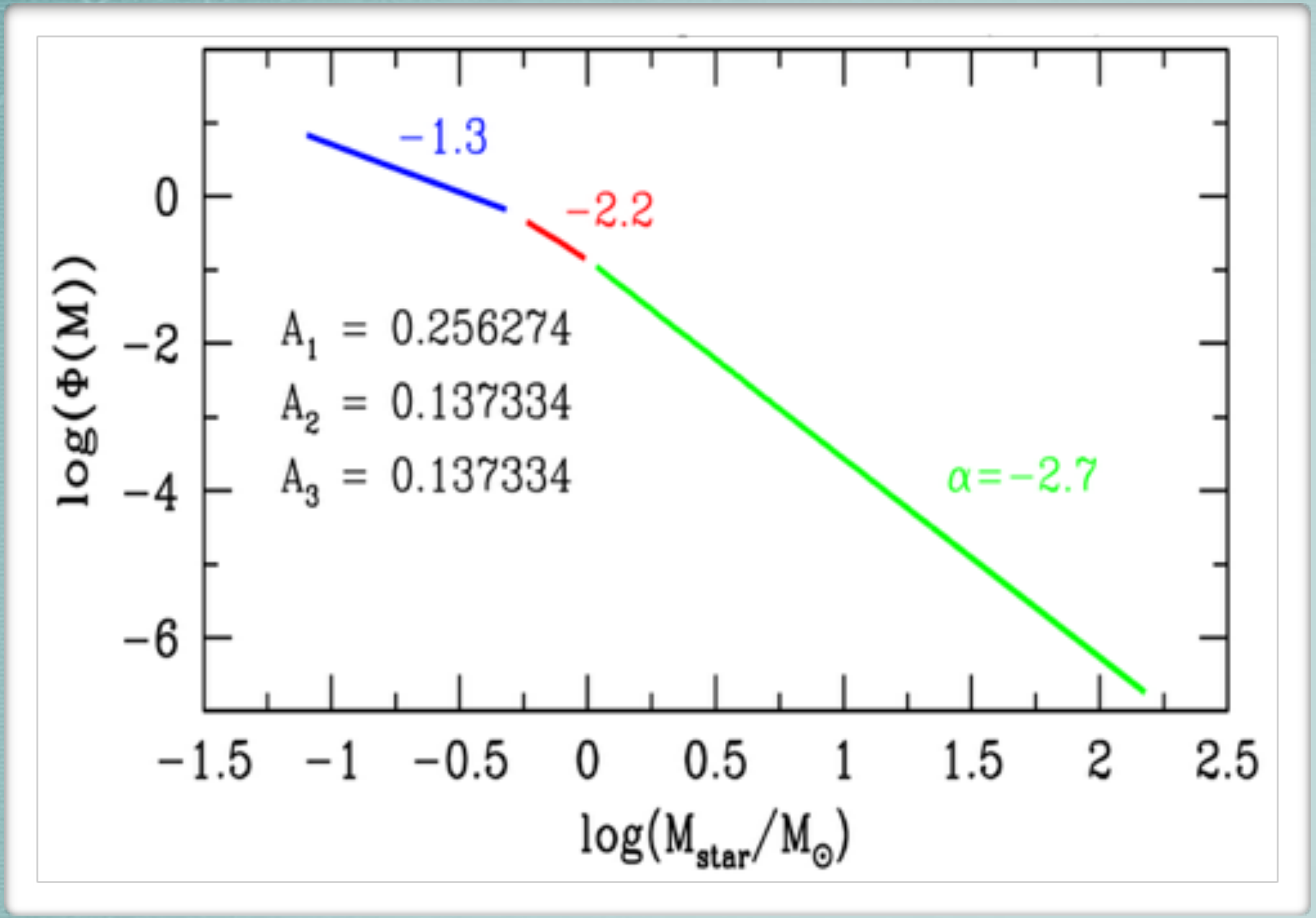
7th Gaia Science Alerts Workshop, Utrecht 8 December 2016.

Few questions…

* How many BHs are there in our Galaxy?
* How are they formed?
* Single or in binaries?
* ...Or in multiple systems?
* What is the mass function (Gap?)
* What is their spatial distribution, dynamics (natal kicks?)
* How do we find them?



How many Black holes are there?



Kroupa&Weidner 2003

Initial Mass Function

$$\xi(M) = A_i M^{\alpha}$$

$$\alpha = -1.3 \ for \ M \in [0.08, 0.5] M_{\odot}$$

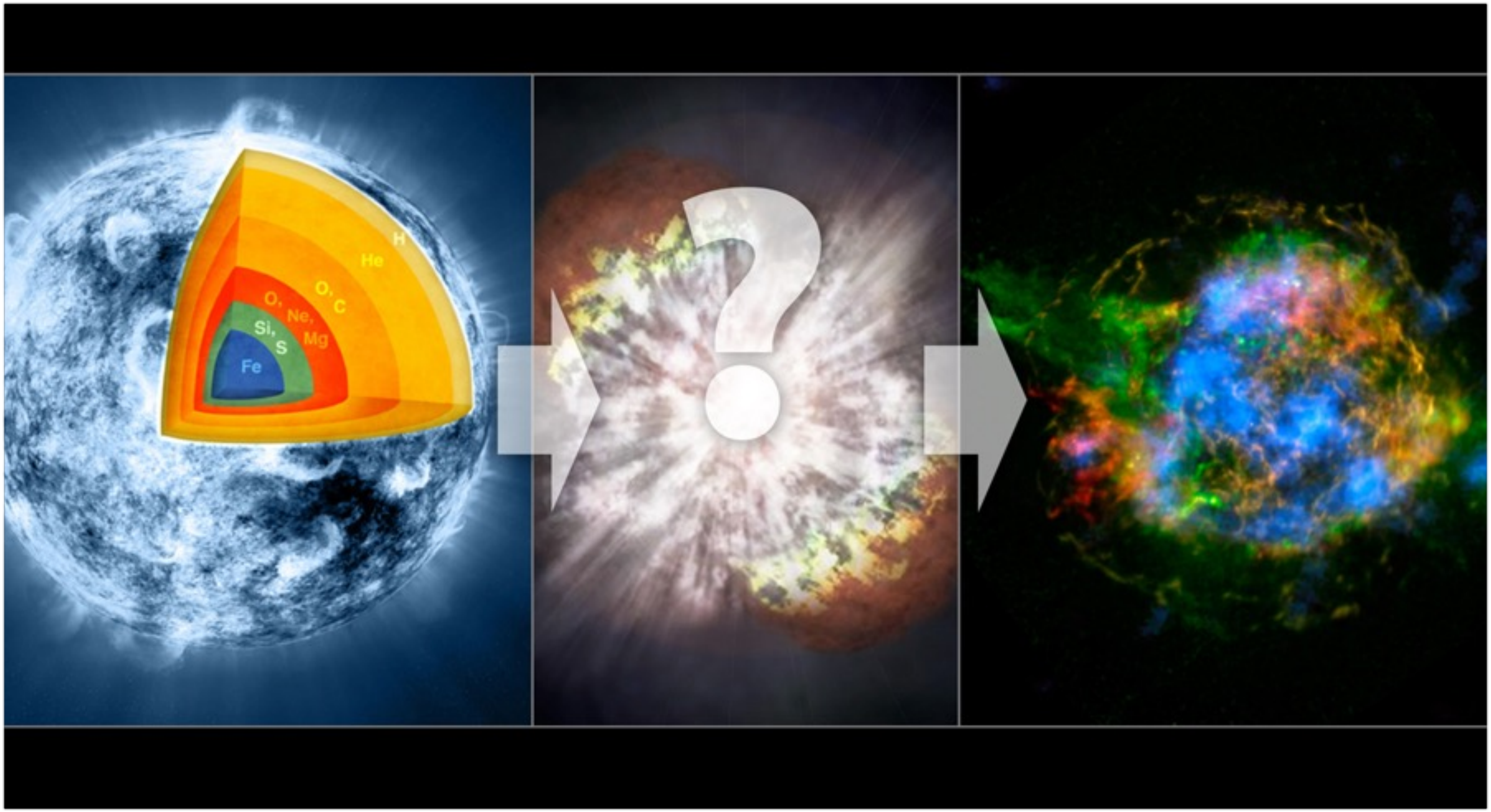
$$\alpha = -2.2 \ for \ M \in [0.5, 1] M_{\odot}$$

$$\alpha = -2.7 \ for \ M \in [1, 150] M_{\odot}$$

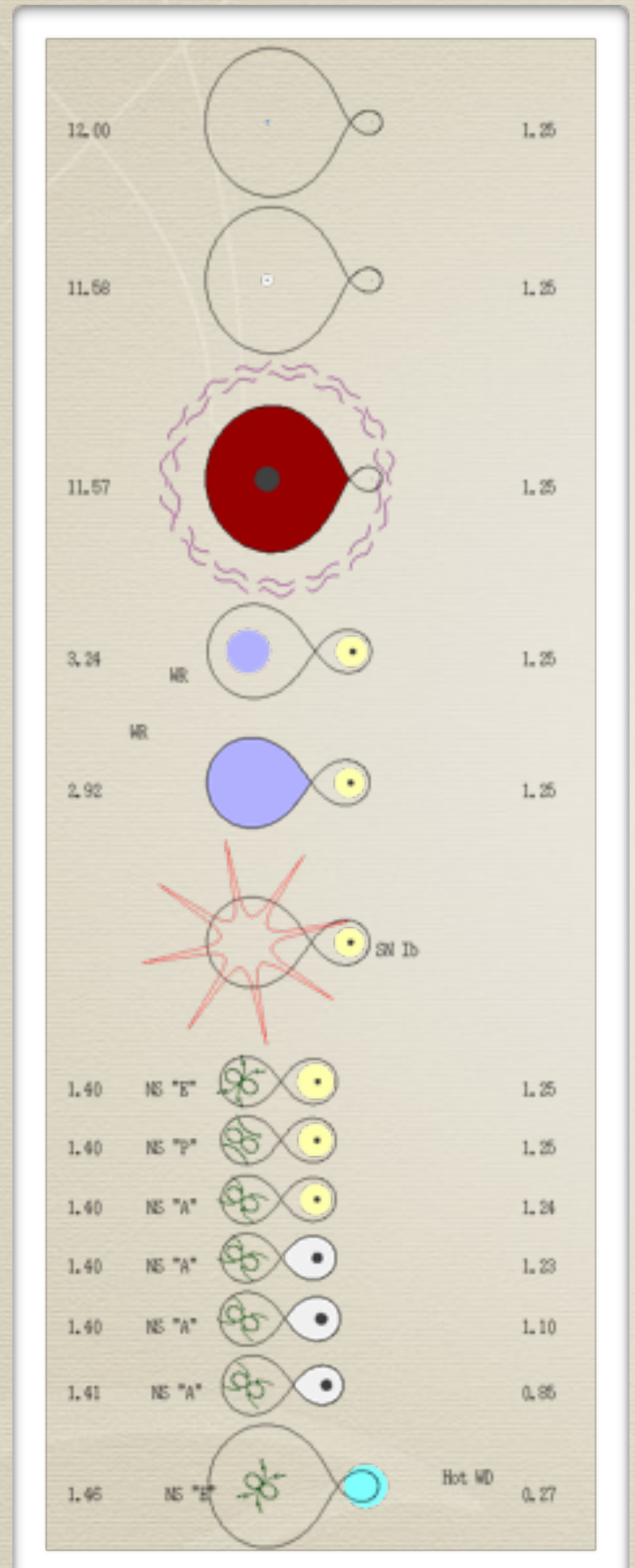
- Observational biases for the most massive stars,
- Binary evolution changes the shape of IMF and shifts BHs formation towards lower masses
- IMF itself not fully constrained

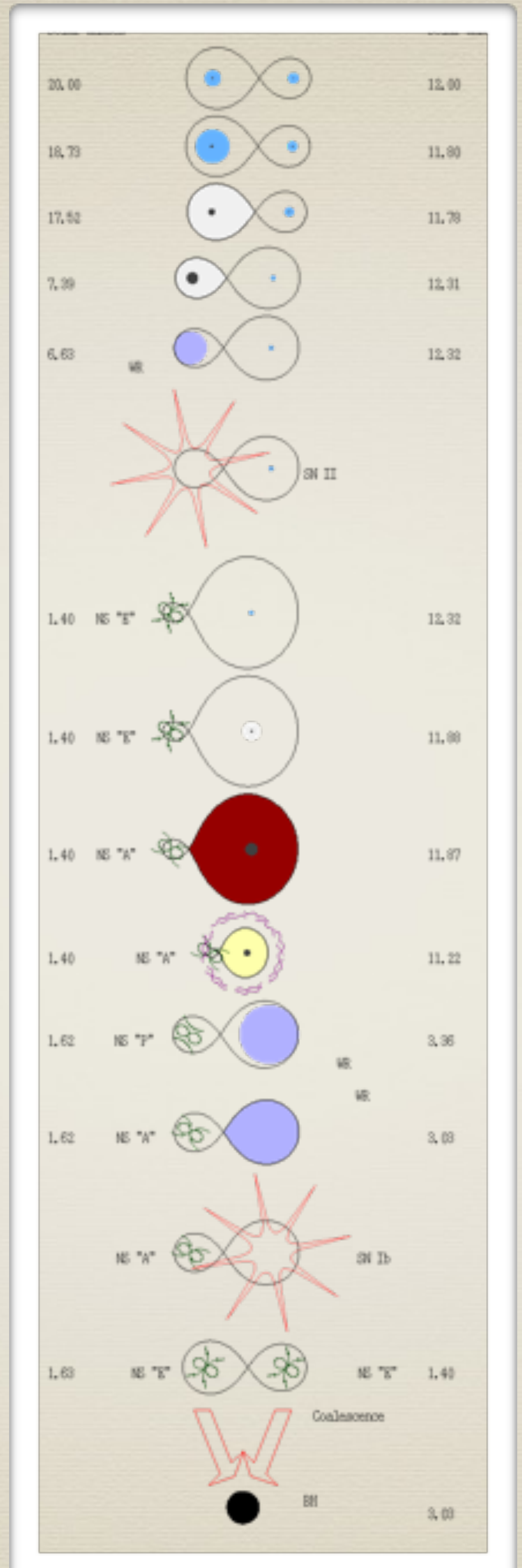
~400 milions!

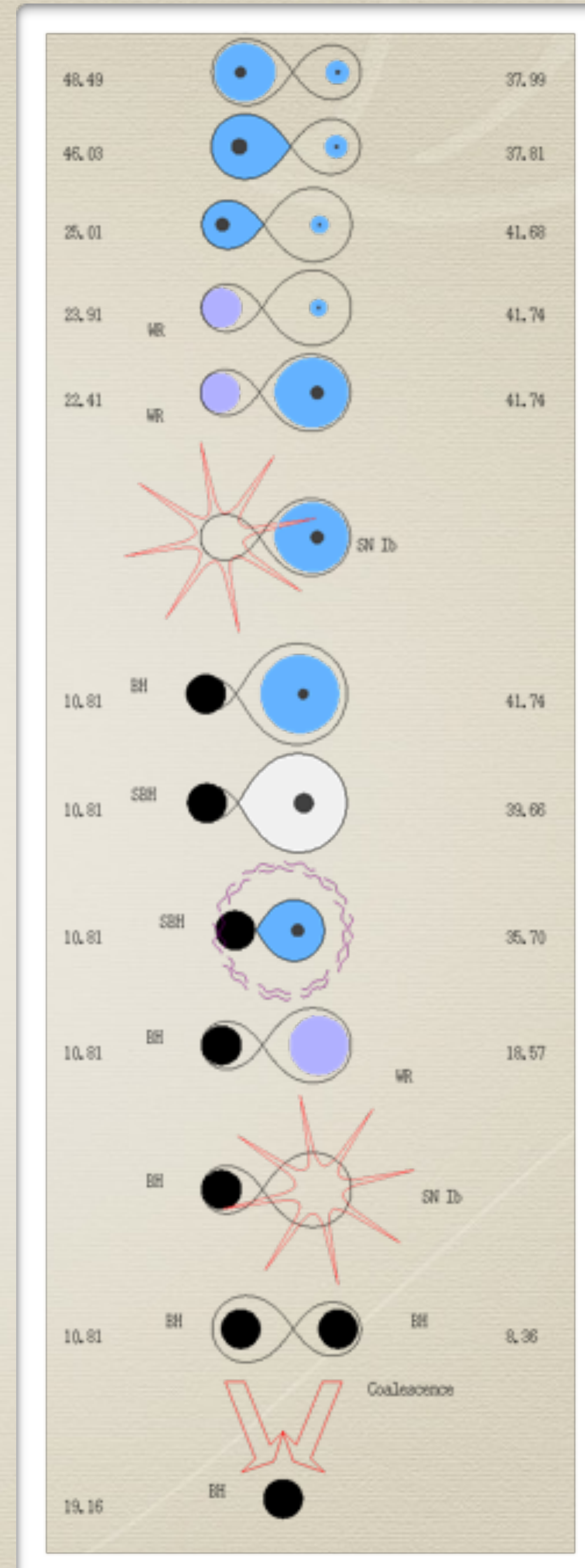
Core collapse SN



Binary scenario







Generated using "Scenario Machine", credits: http://xray.sai.msu.su/sciwork/credits.html

Dark Remnants - Neutron Stars

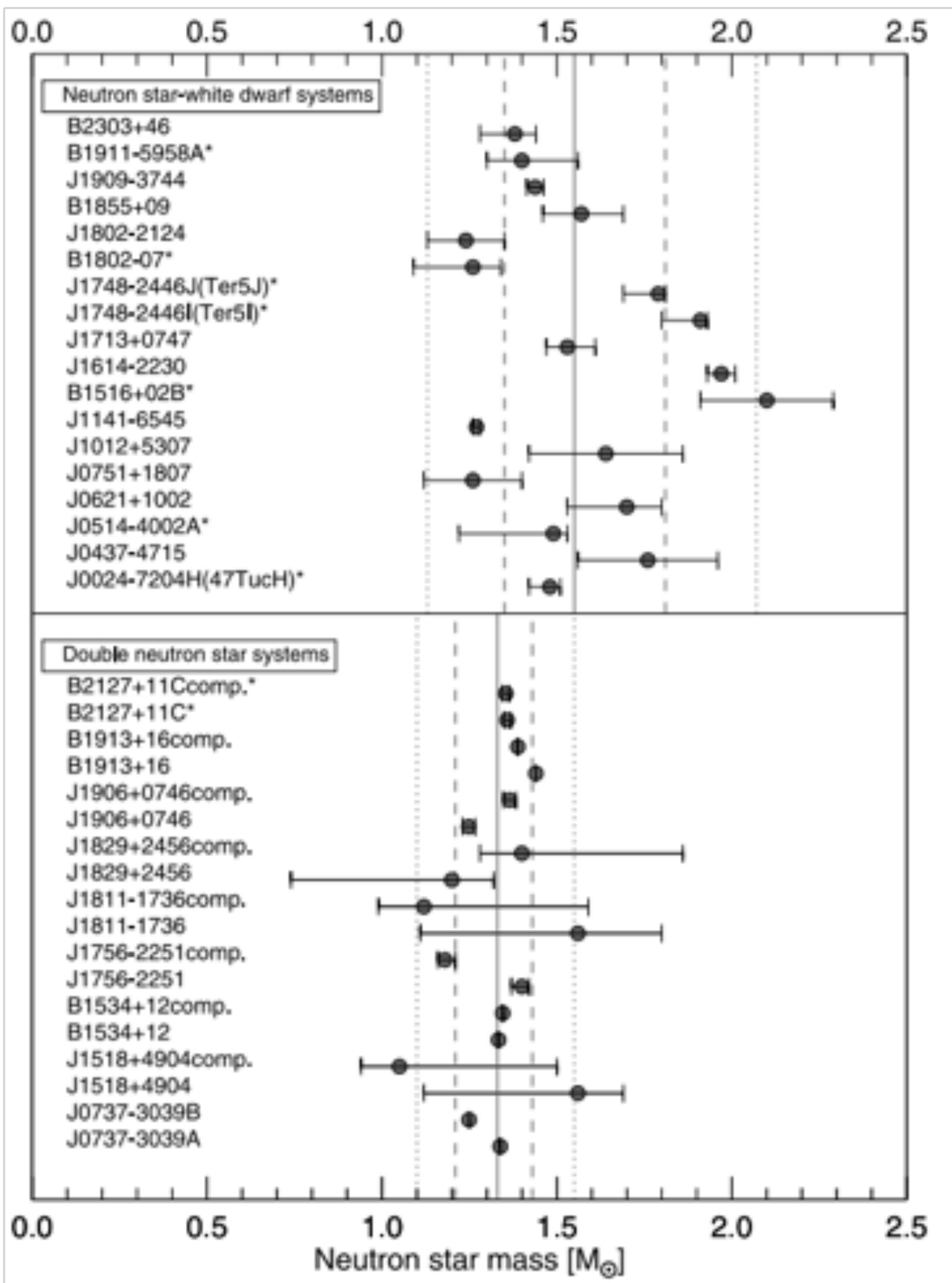


Figure 1. Measured masses of radio pulsars. All error bars indicate the central 68% confidence limits. Vertical solid lines are the peak values of the underlying mass distribution for DNS ($m = 1.33\,M_\odot$) and NS–WD ($m = 1.55\,M_\odot$) systems. The dashed and dotted vertical lines are the central 68% and 95% predictive probability intervals of the inferred mass distribution in Figure 2. Systems marked with asterisks are found in globular clusters.

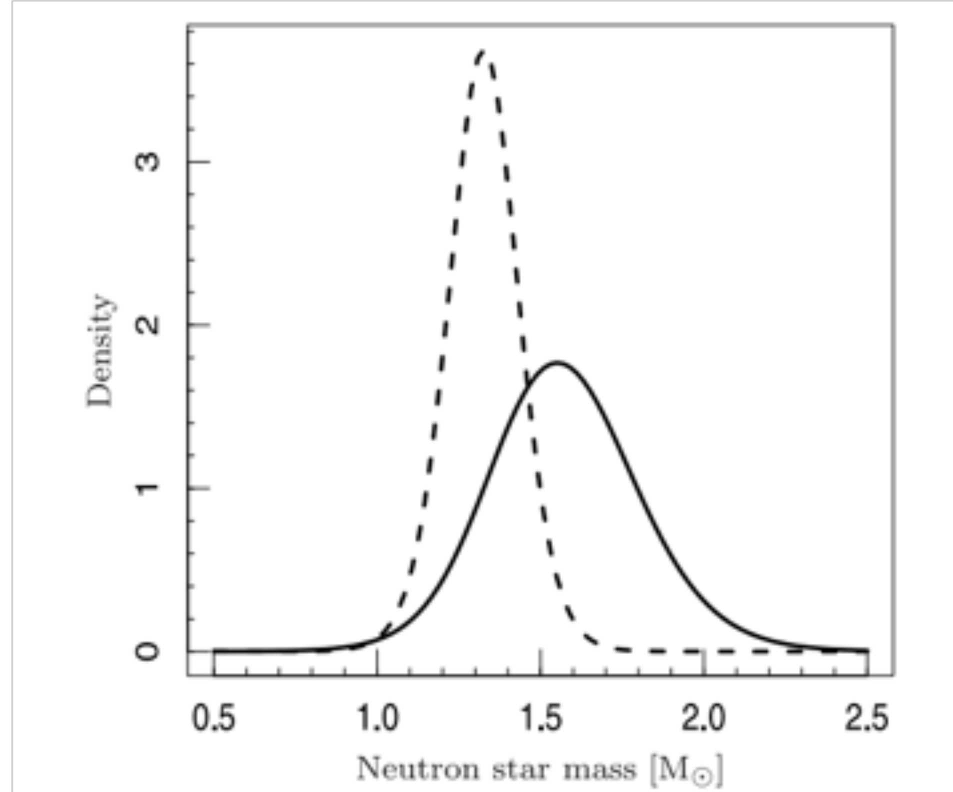


Figure 2. Posterior predictive density estimates for the NS mass distribution. DNS systems (dashed line) and NS–WD systems (solid line) mass densities have respective peaks at 1.33 $M_\odot$ and 1.55 $M_\odot$. The 68% and 95% posterior predictive intervals are given by (1.21 $M_\odot$, 1.43 $M_\odot$) and (1.10 $M_\odot$, 1.55 $M_\odot$) for the DNS systems, and by (1.35 $M_\odot$, 1.81 $M_\odot$) and (1.13 $M_\odot$, 2.07 $M_\odot$) for the NS–WD systems.

Kiziltan et al. 2013

- NSs slightly less challenging than BHs
- very accurate mass measurements possible
- only binaries in the sample

Dark remnants - Black Holes

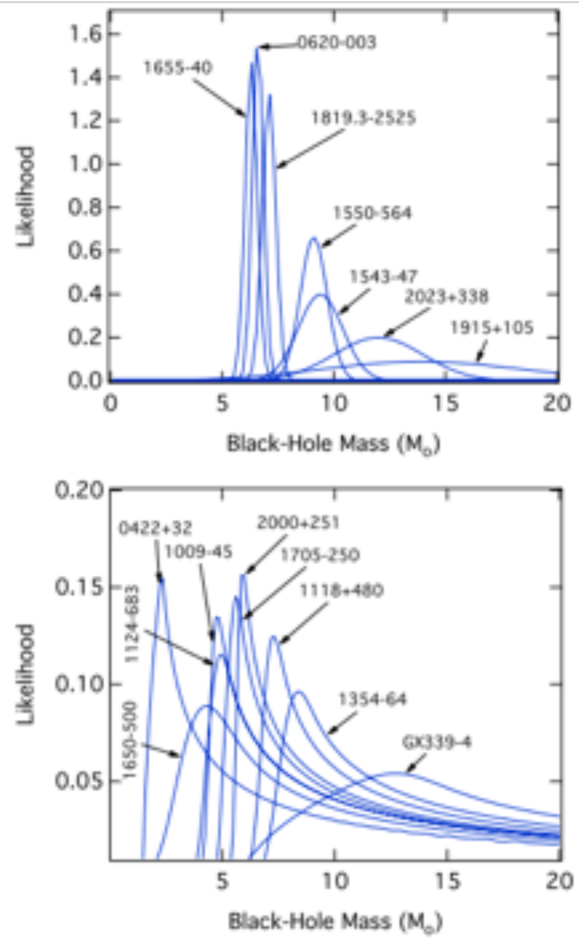


Figure 1. Likelihoods $P_i(\text{data}|M)$ for the 16 sources in low-mass X-ray binaries that have been securely identified as black holes. The top panel includes sources in categories (1) and (3), while the bottom panel shows those in category (2). The categories are based on the amount of information available on the mass ratios and inclinations of the black hole binaries and are discussed in more detail in the text.

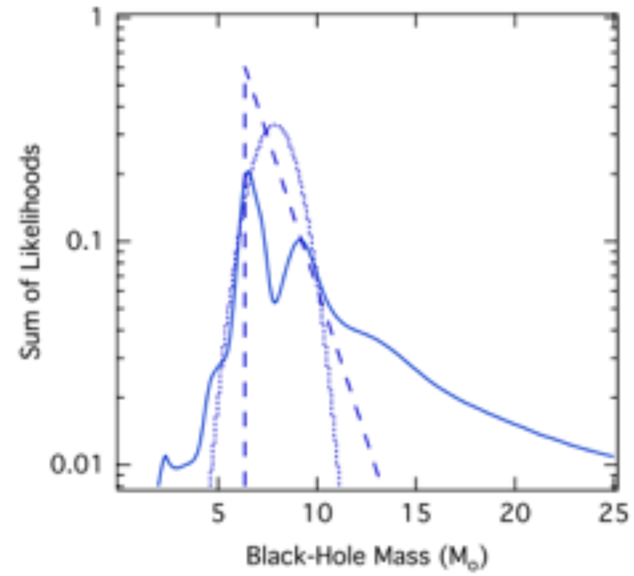


Figure 2. Solid line shows the sum of likelihoods for the mass measurements of the 16 black holes in low-mass X-ray binaries. Note that because of the high-mass wings of the individual likelihoods, the shape of their sum is artificial at the high-mass end. The dashed and dotted lines show the exponential and Gaussian distributions, respectively, with parameters that best fit the data (see Section 4).

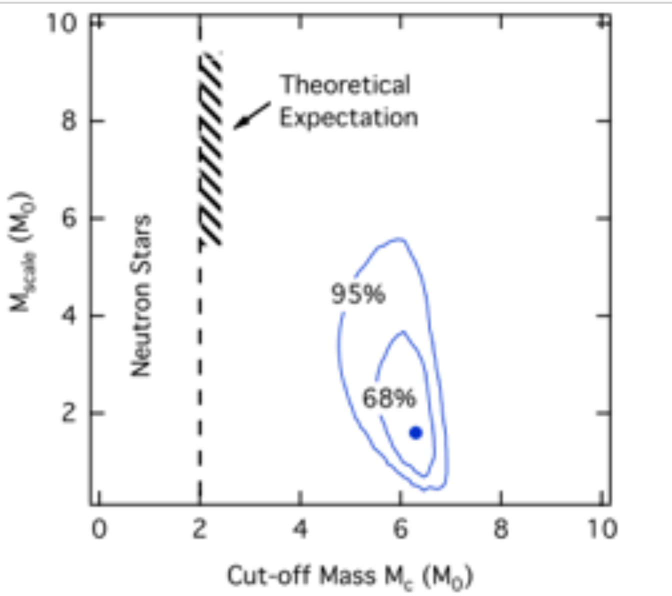


Figure 3. Parameters of an exponential black hole mass distribution with a low-mass cutoff. The cutoff mass is well above theoretical expectations, indicating a sizable gap between neutron-star and black hole masses. Furthermore, the mass scale in the exponential is significantly smaller than theoretical expectations.

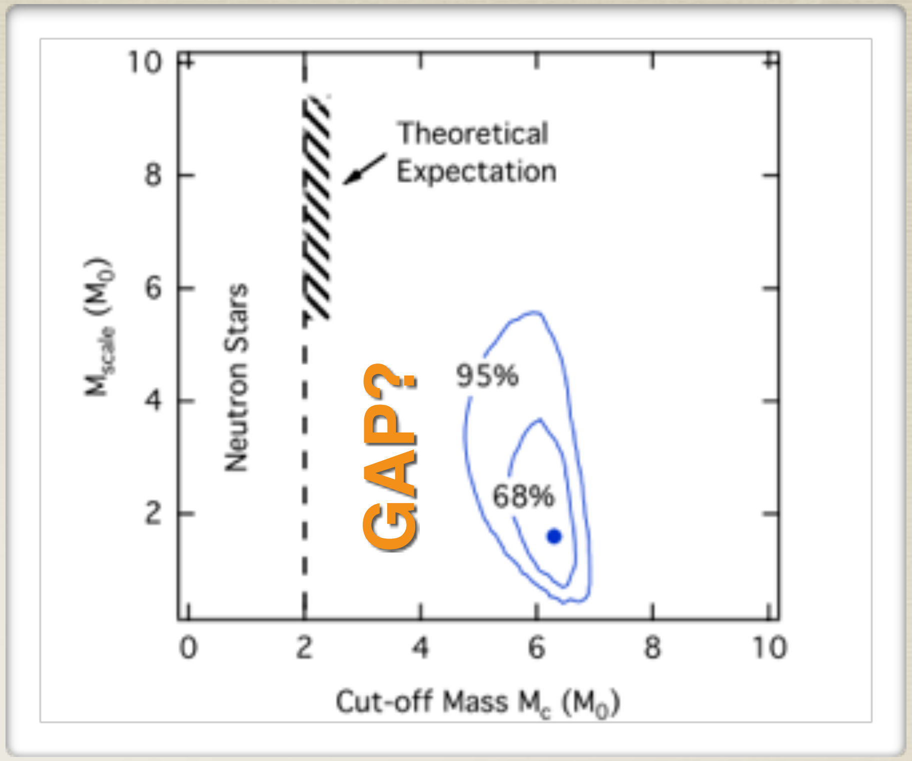
- ~20 X-ray binaries with mass estimations
- BHs mass distribution
- Gap in 2-5 solar masses range?

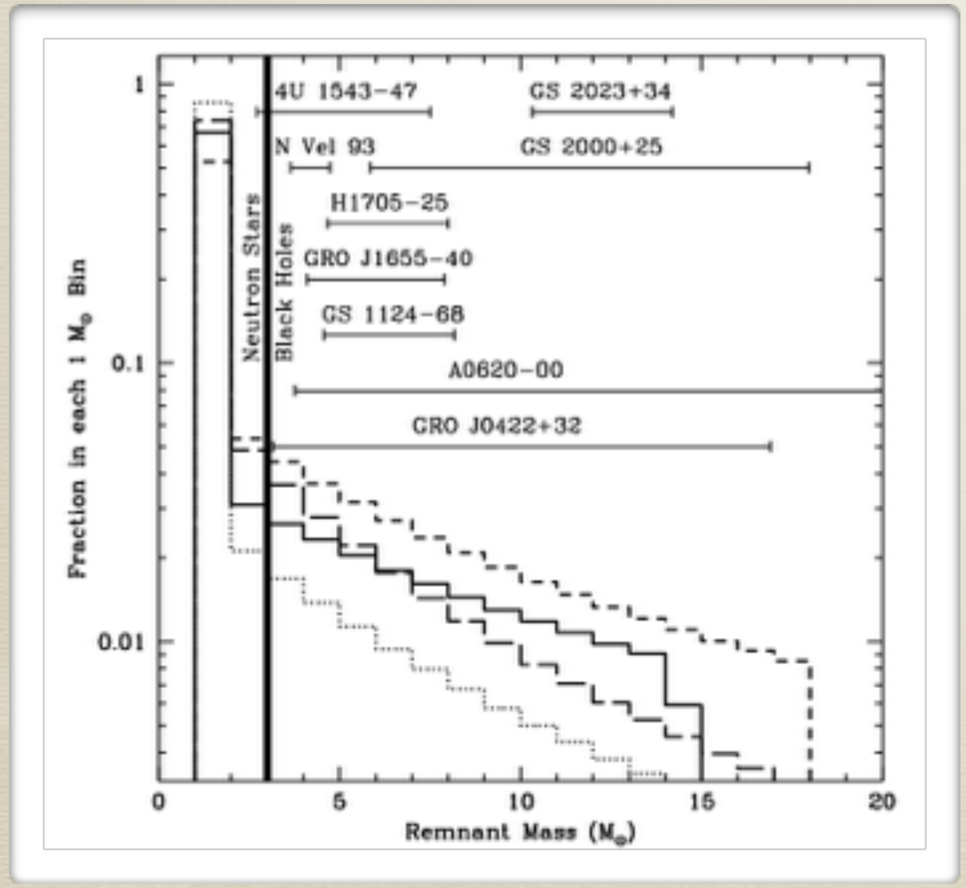
Özel et al, 2010

GAP?

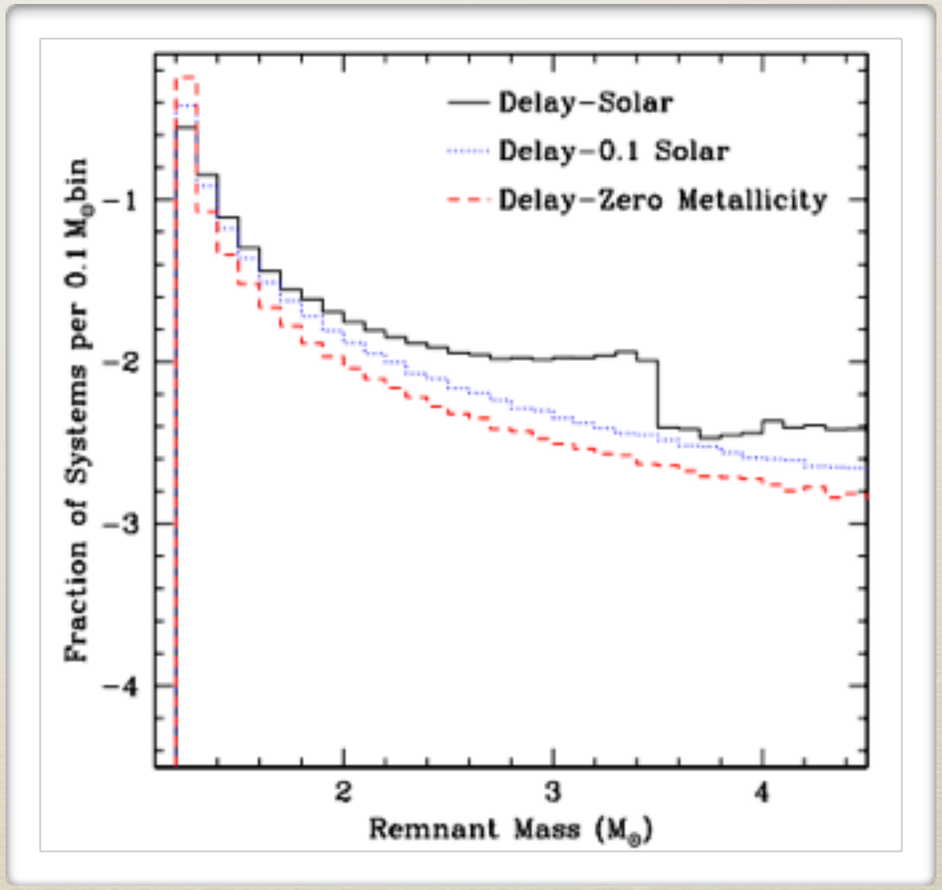
observations of 20 X-ray binaries

theoretical distributions



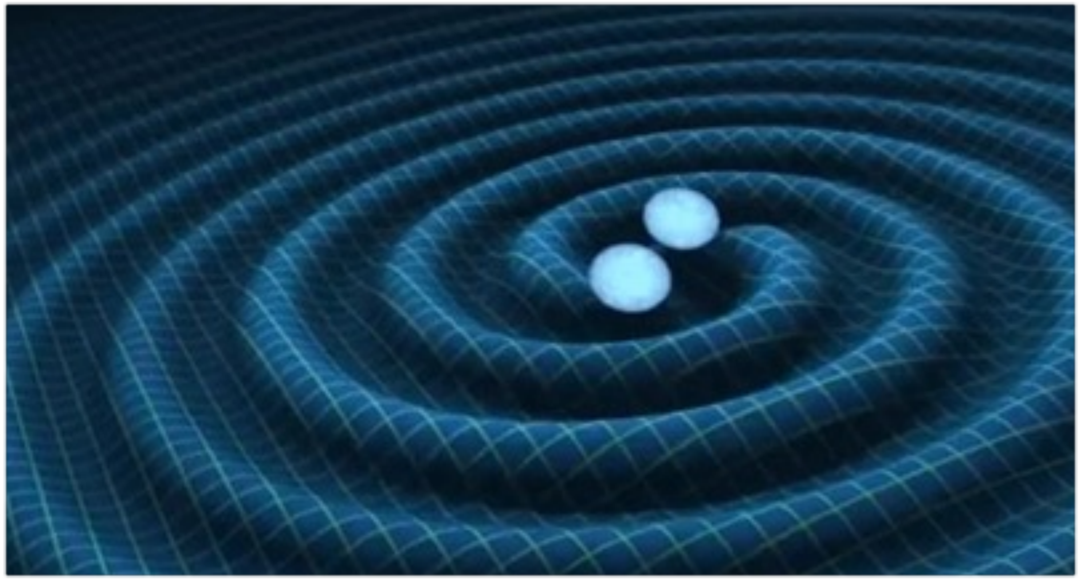


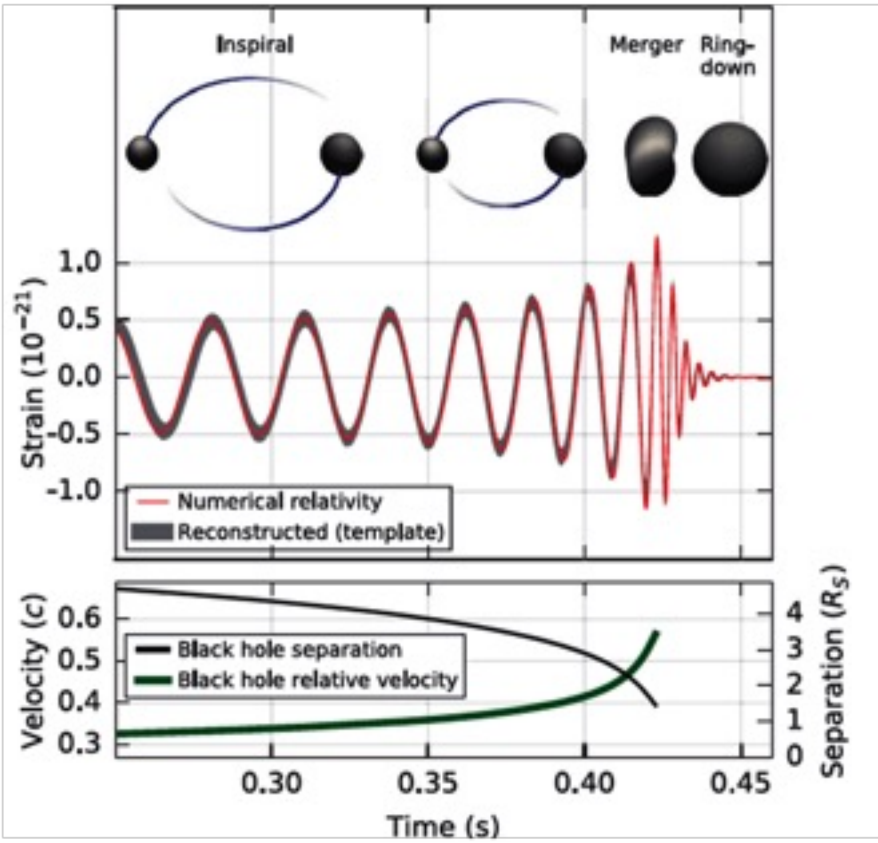
Fryer &Kalogera 2001

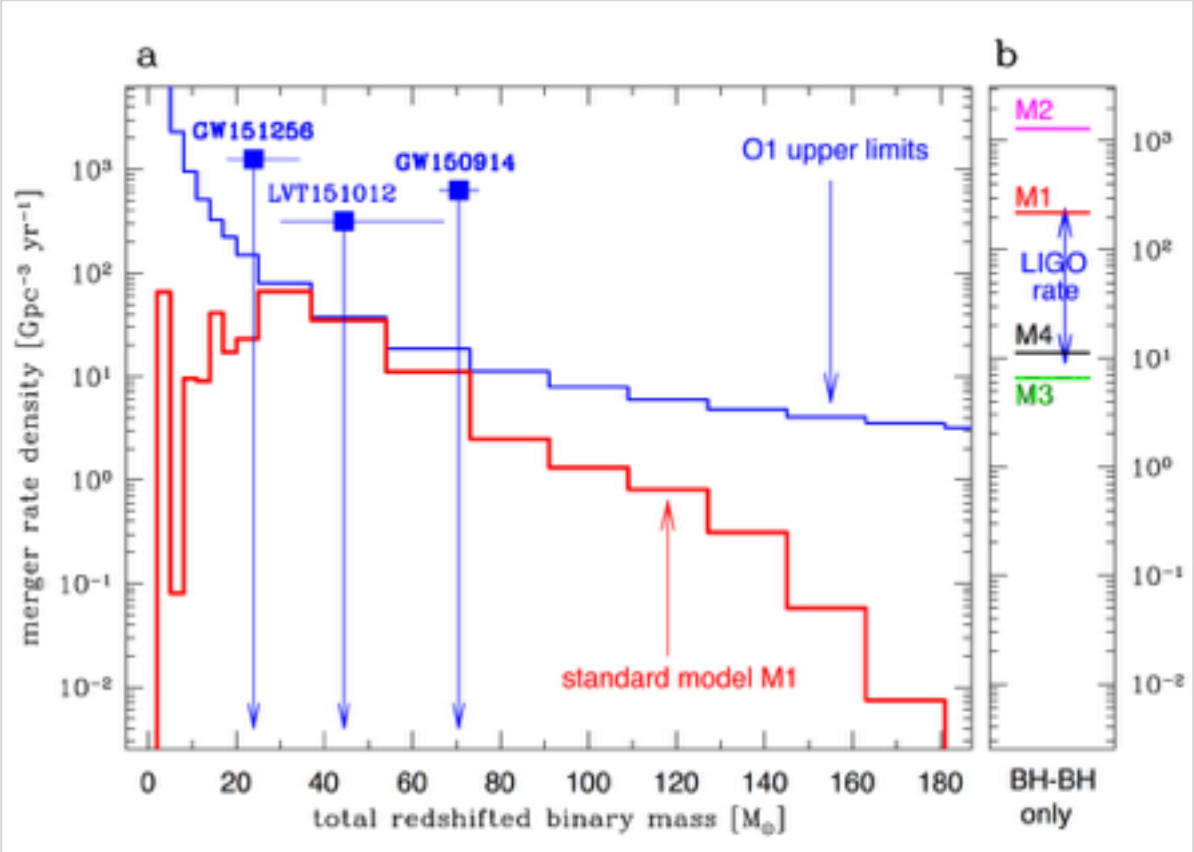


Fryer et al. 2012

Gravitational Waves



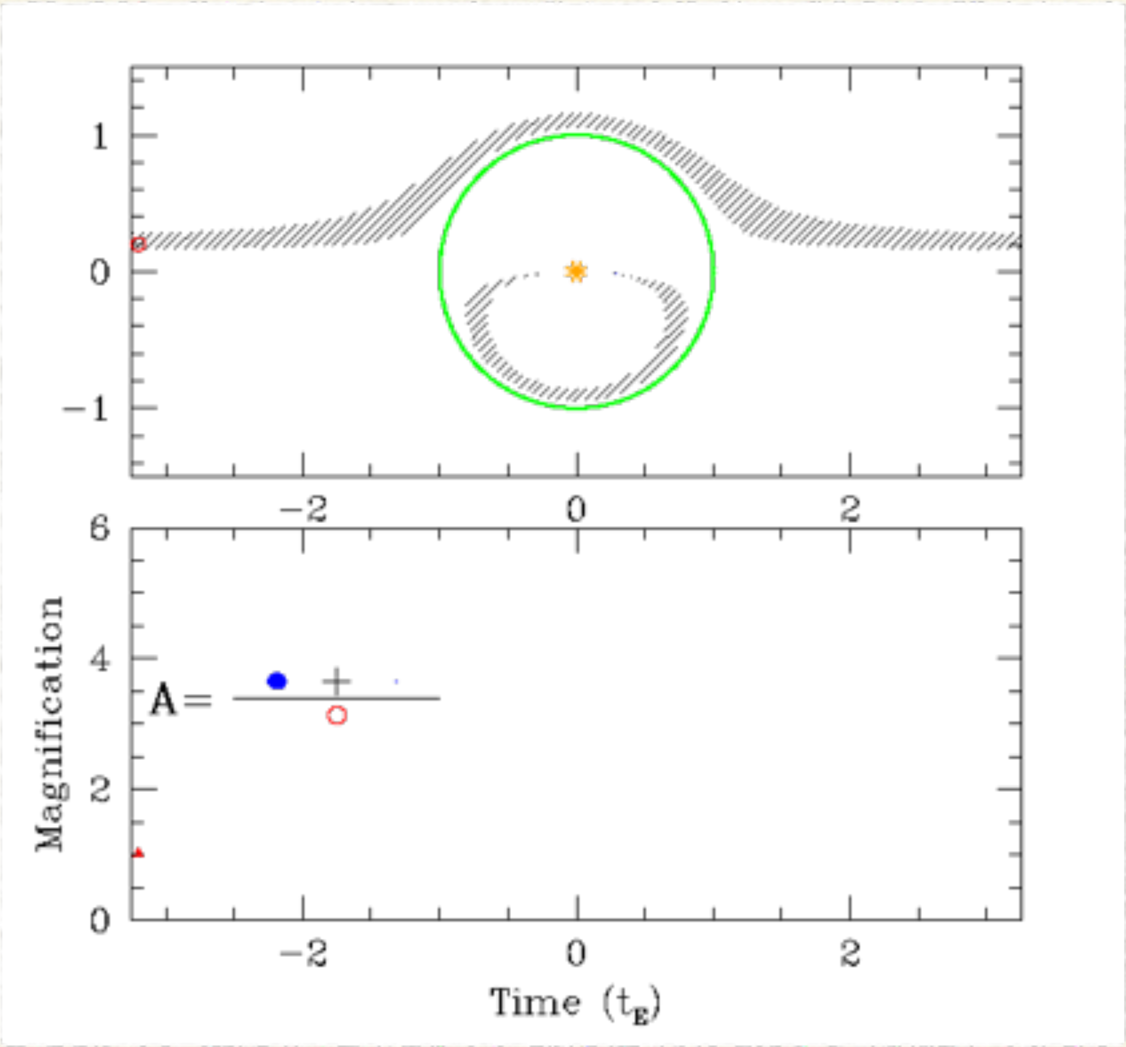


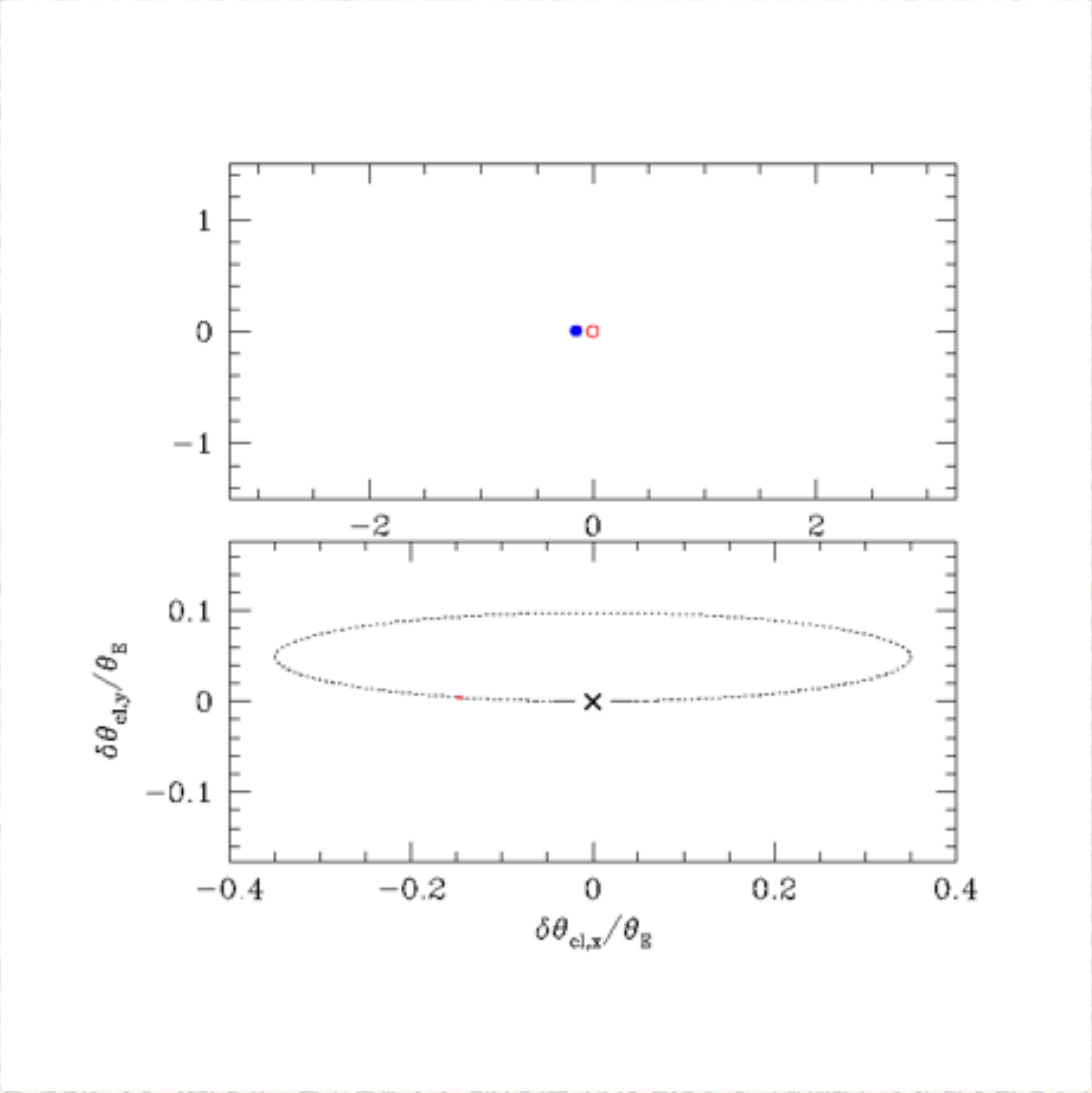


* Very promising
* Up to few hundreds per yr with Advanced LIGO
* Only binary systems
* Extragalactic sources
* Mostly very massive BHs

Belczyński et al. 2016

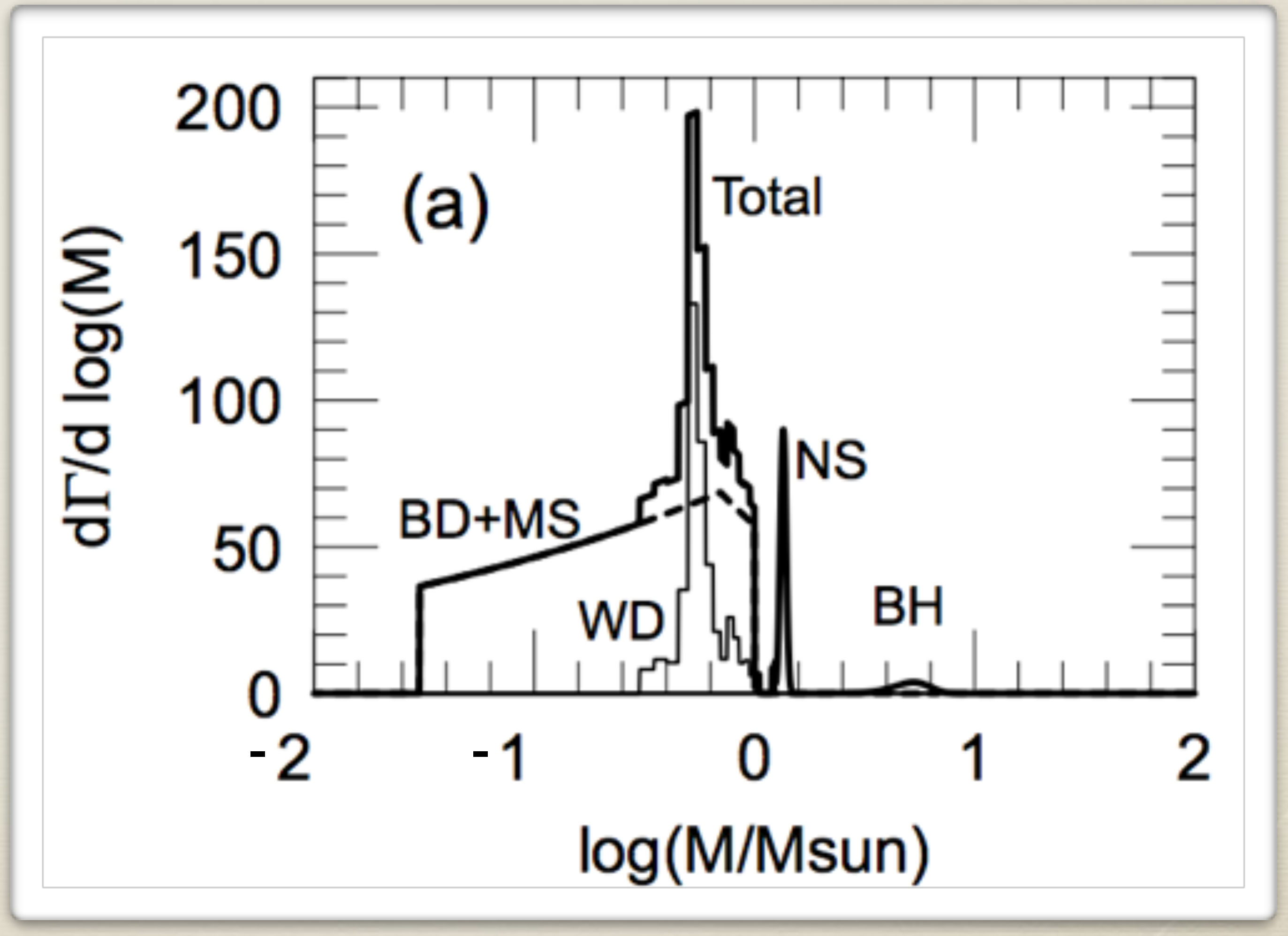
Microlensing





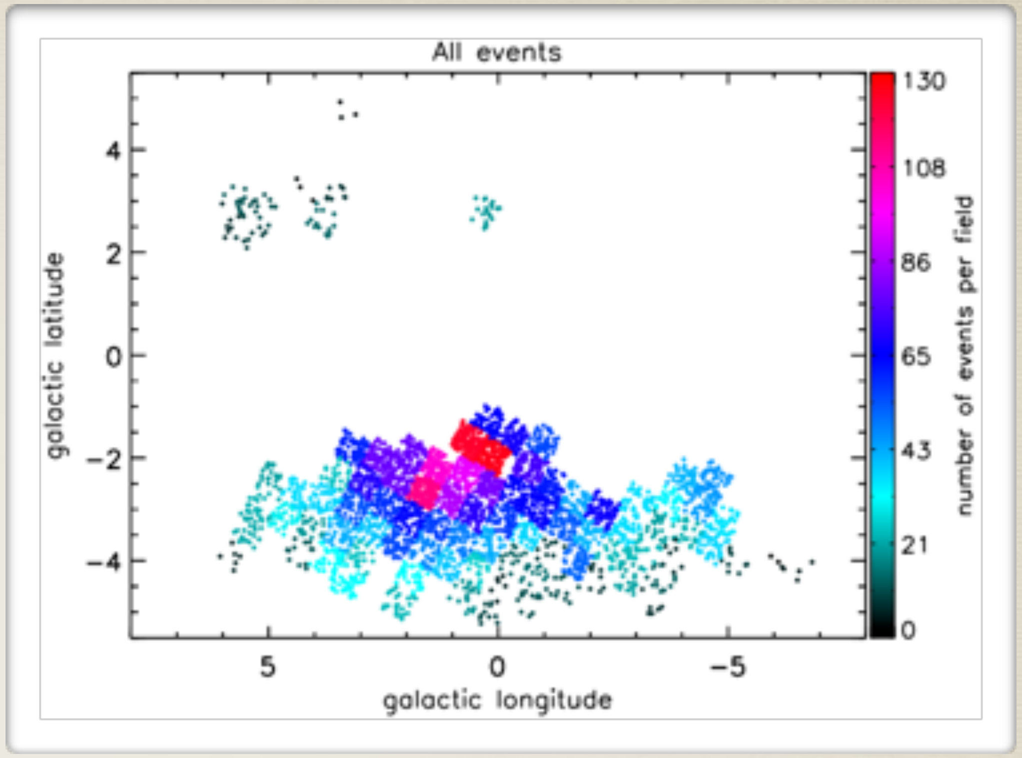
Credit: Scott Gaudi

- About 20% of microlensing events should be due to stellar remnants (Gould, 2000)
- WD – 17%
- NS – 3%
- BH – 0.8%

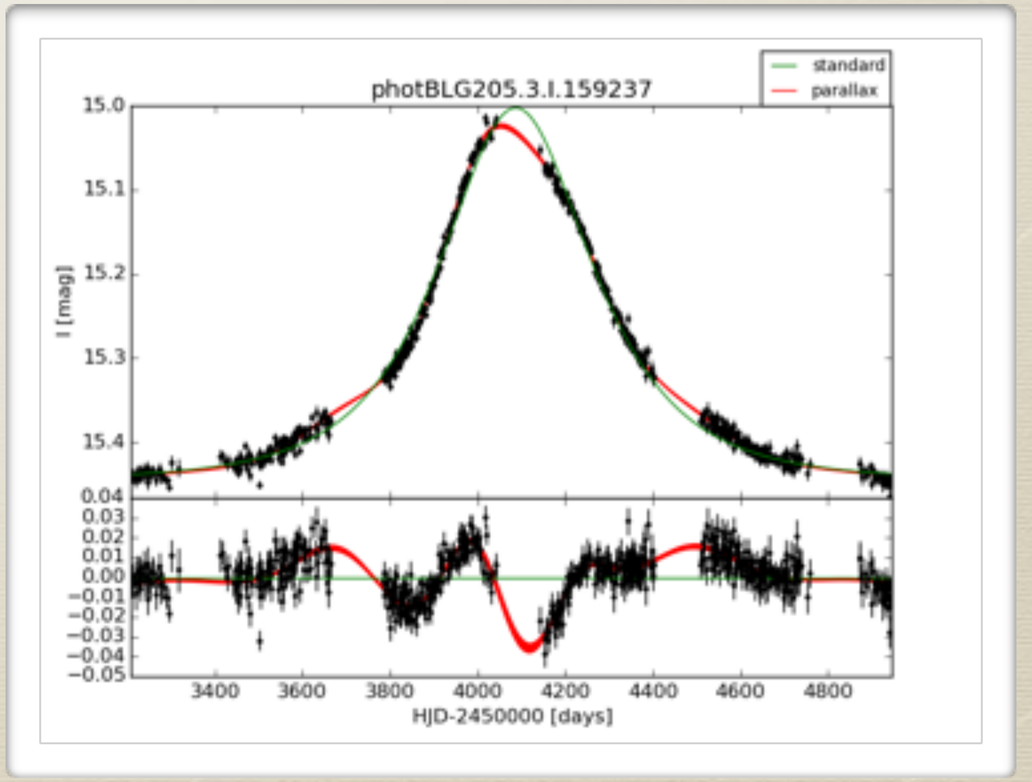


Search for lensing remnants

- OGLE-III: 2001-2009
- 150 millions of stars in the Bulge
- 3500 standard events for Bulge structural studies
- 59 high quality parallax events
- 19 events with P>50% having a remnant (dark) lens
- 15 events with P>75% having a remnant (dark) lens
- 3 BH lens candidates (P>95% remnant) + NSs

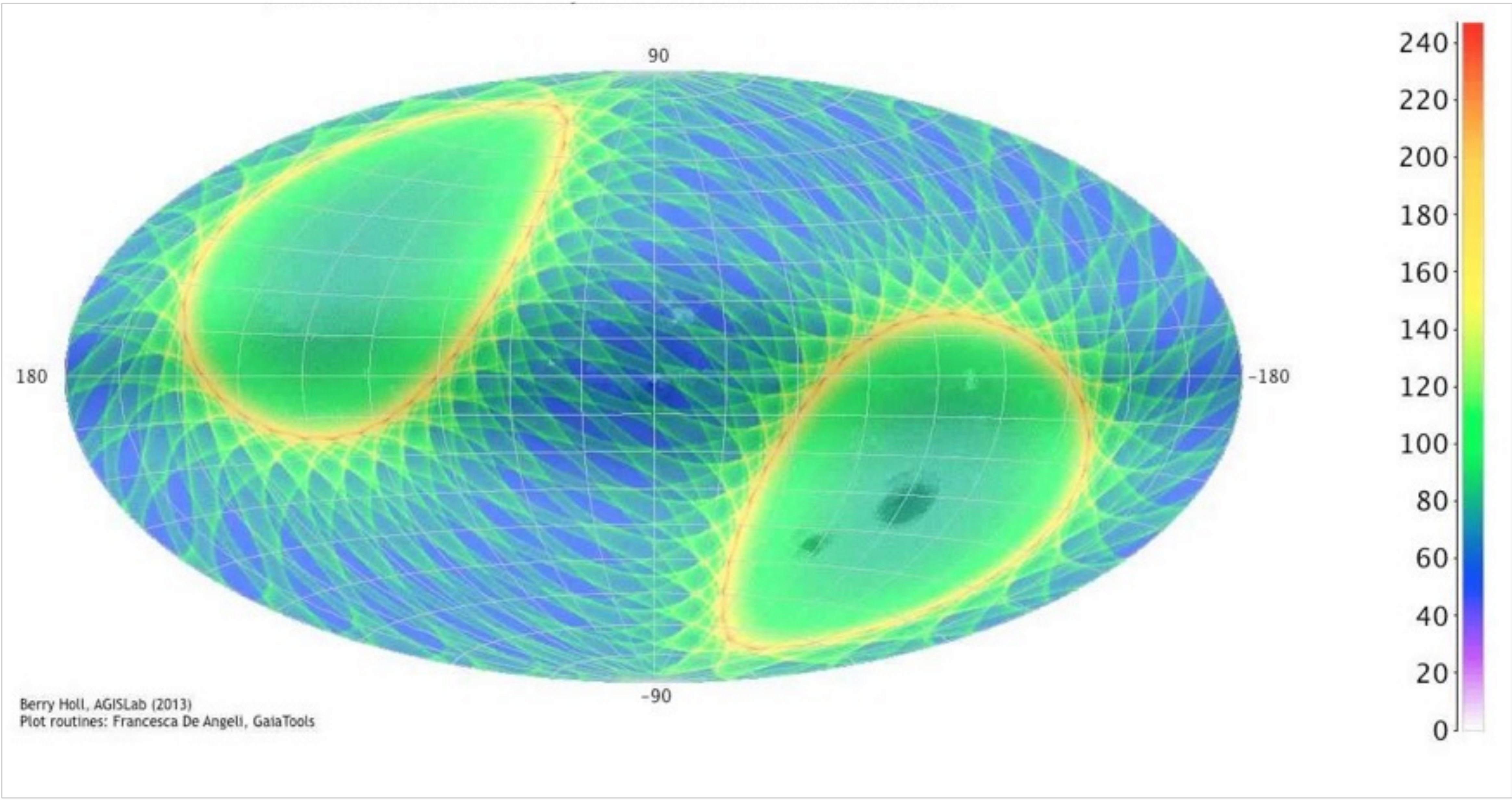


Wyrzykowski et al. 2015

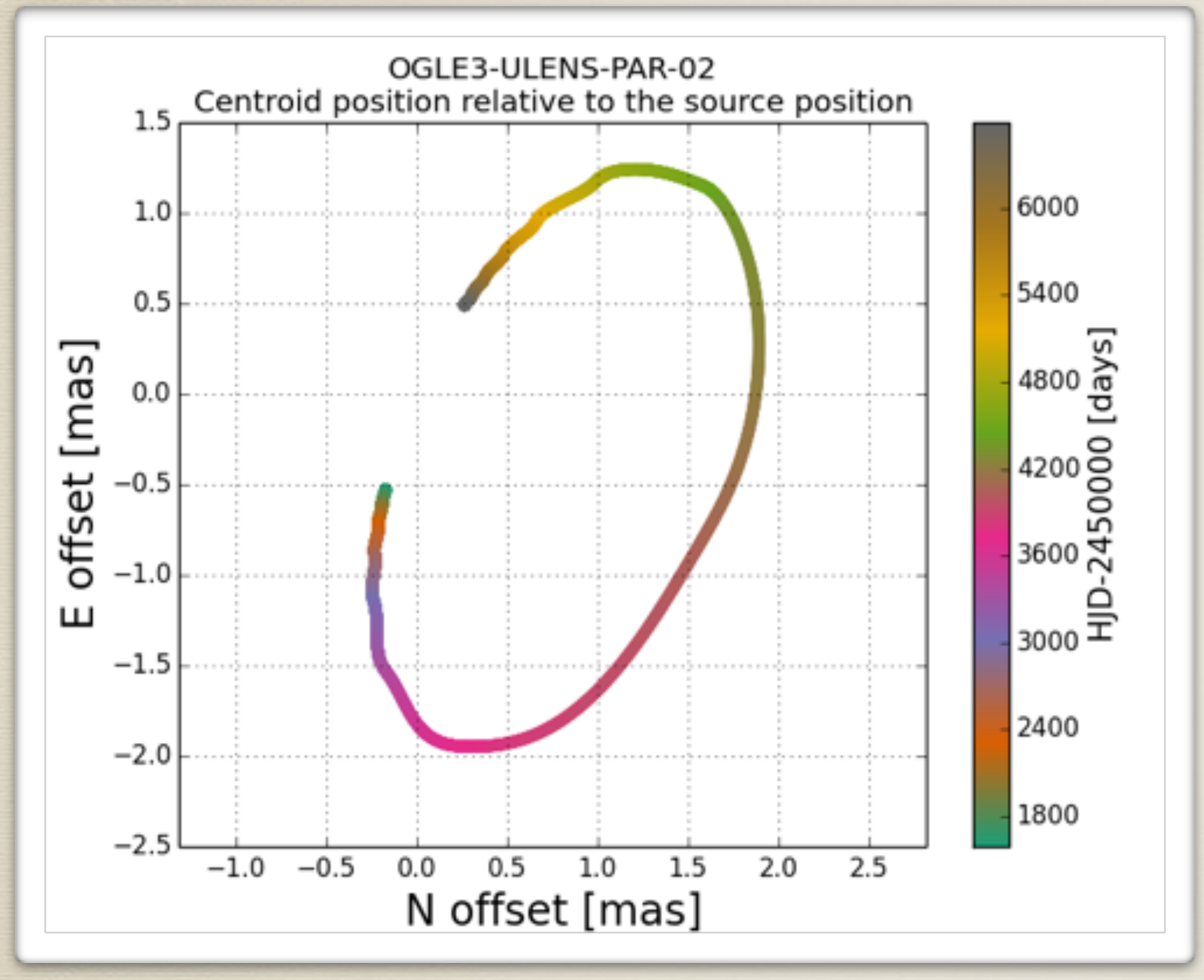


Wyrzykowski et al. 2016

Gaia and microlensing

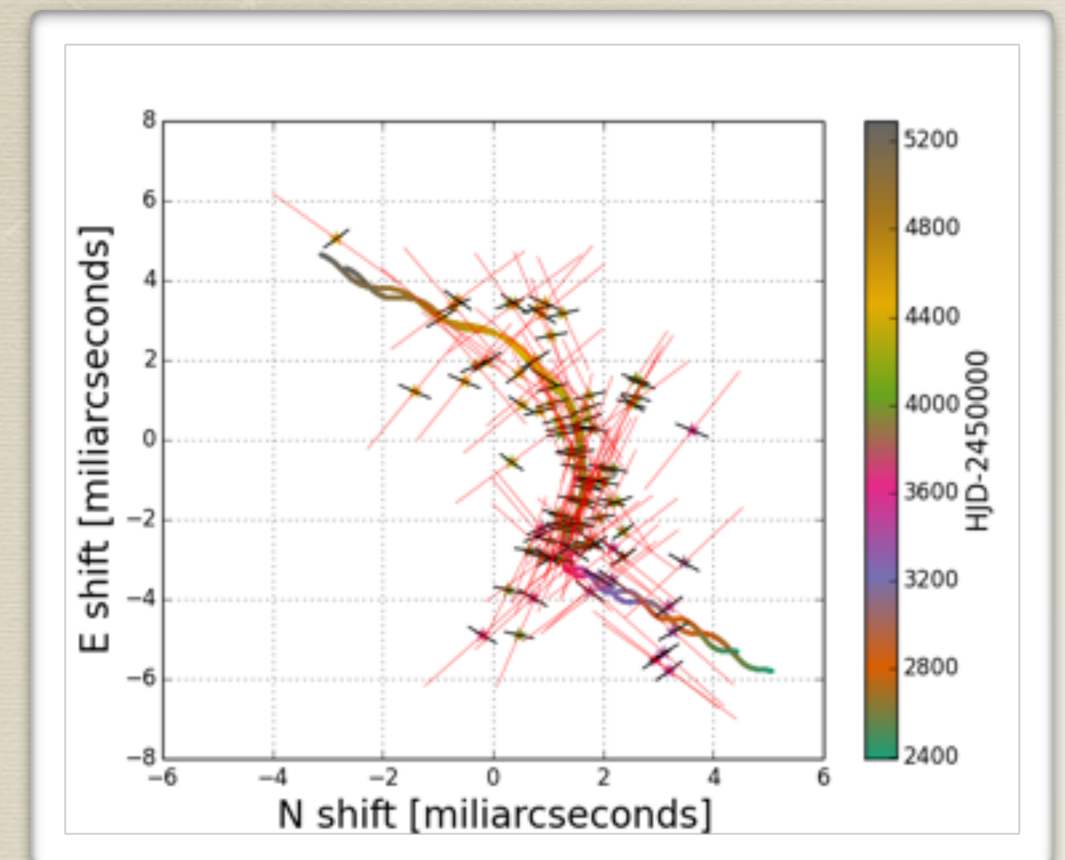


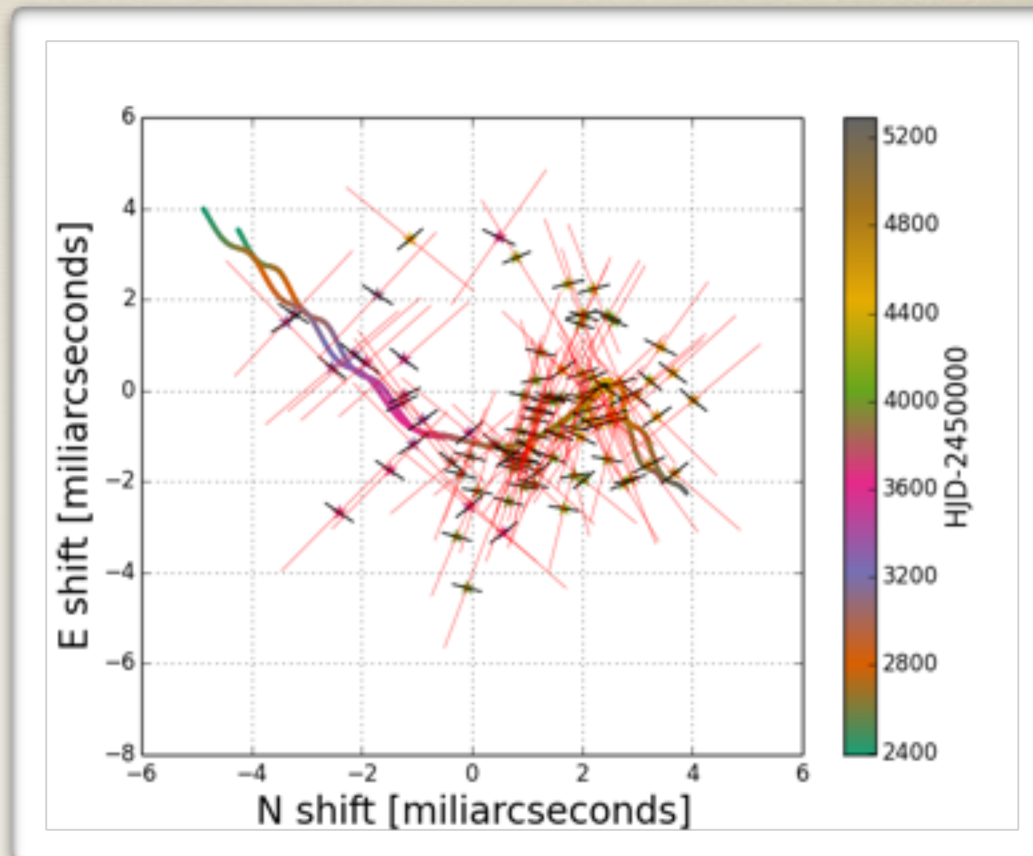
Astrometric microlensing



$$M = \frac{\theta_E}{\kappa \pi_E} = \frac{t_E \mu_{rel}}{\kappa \pi_E}$$

Astrometric microlensing in Gaia





$M \approx 8 M_\odot$

$t_E \approx 250\ days$

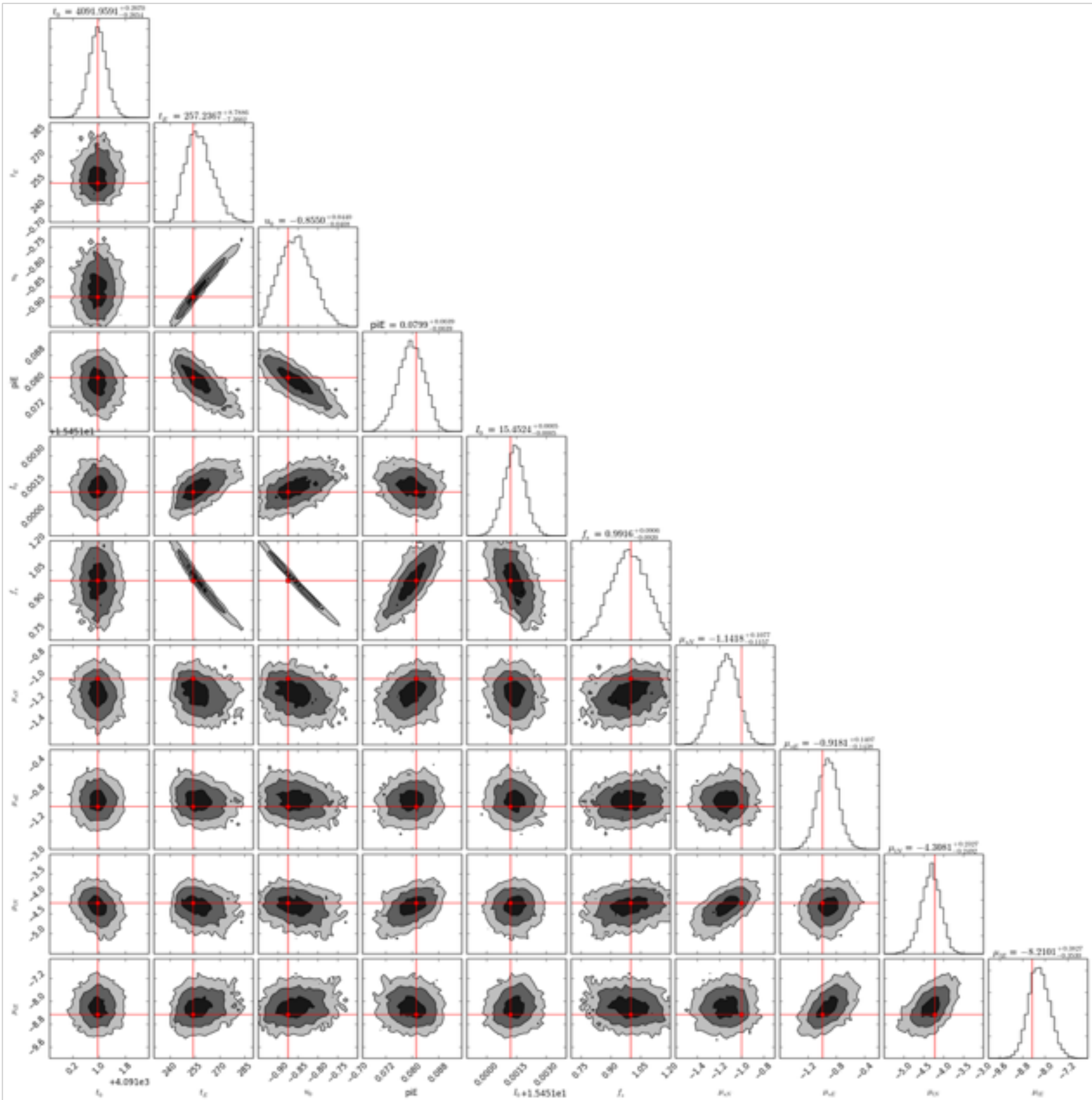
$D_s \approx 8\ kpc$

$\mu_{rel} \approx 4\ mas/yr$

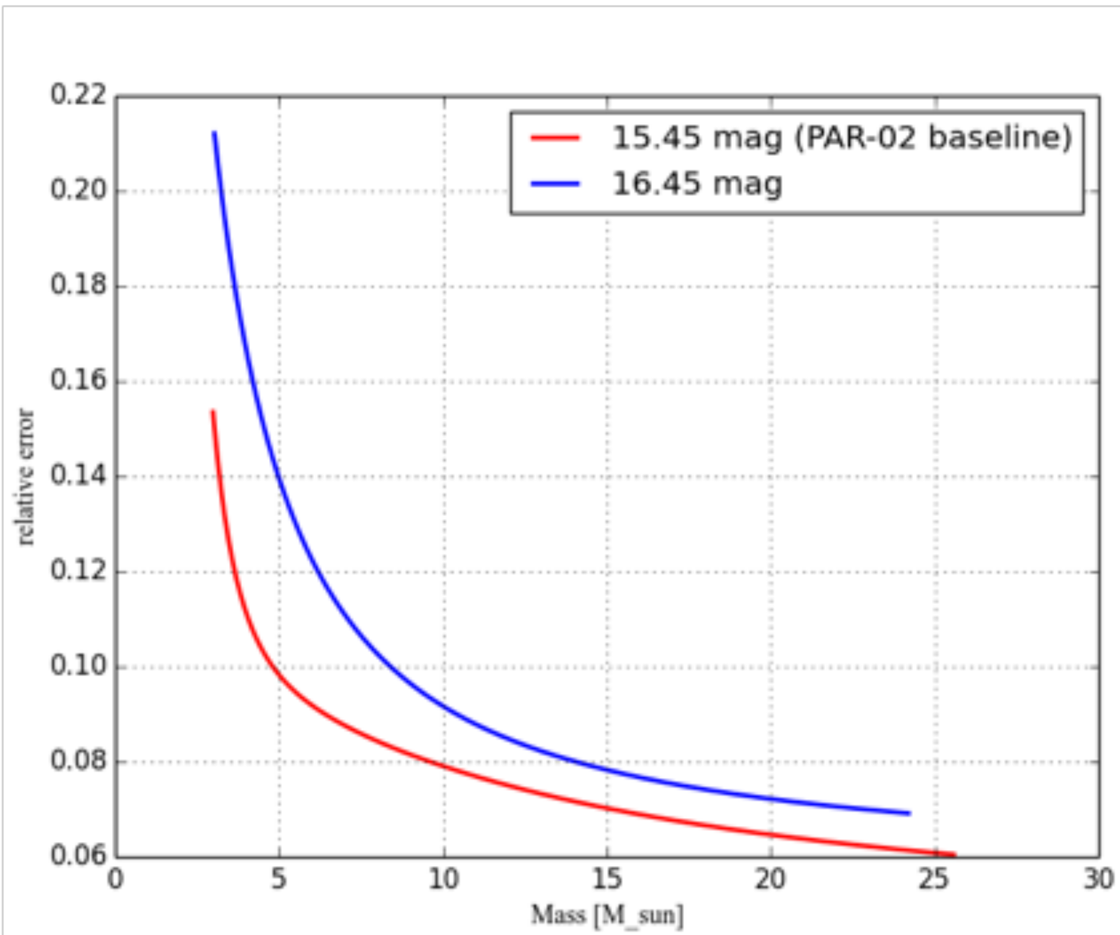
Table 1: AL CCD-level location-estimation errors in AF1 in units of μas as function of Johnson V magnitude (Jos de Bruijne 2009, JDB-053).

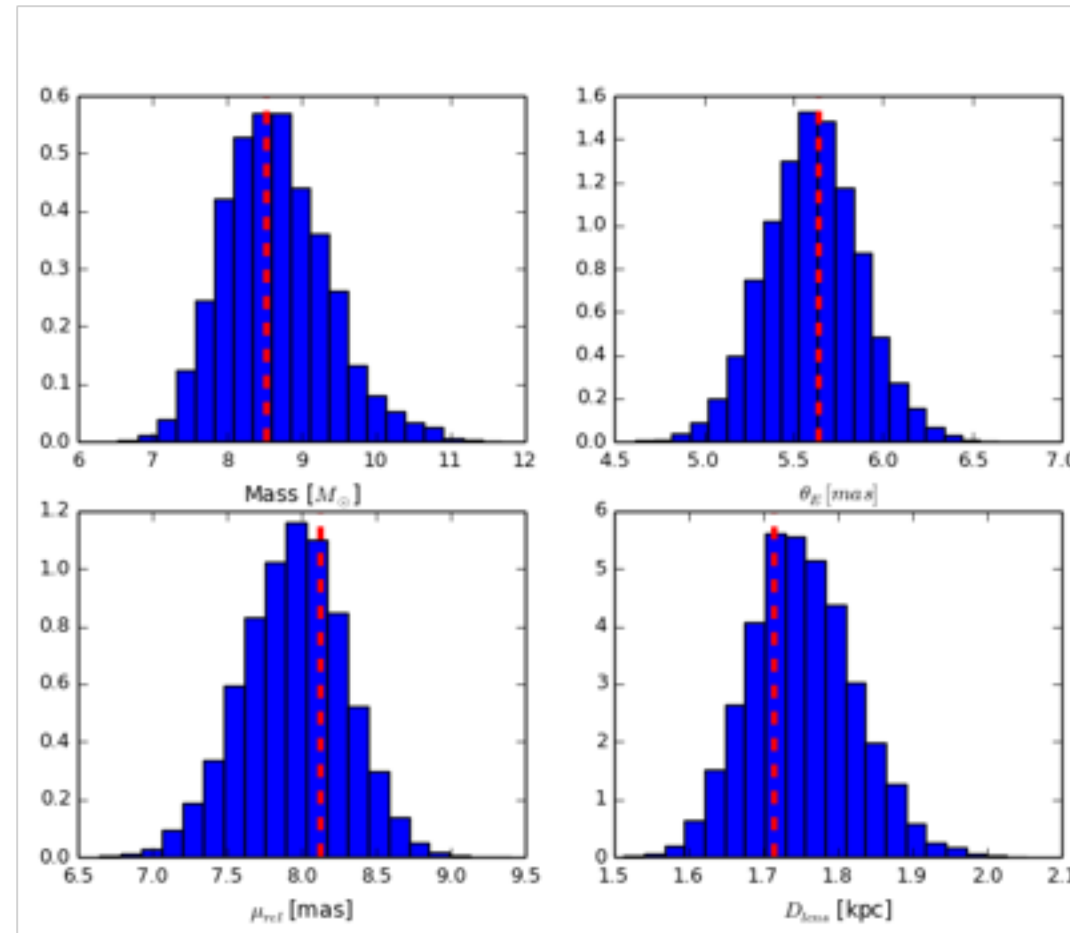
V-I \ V	12	13	14	15	16	17	18	19	20	21
0.97	94	86	143	232	383	660	1207	2386	5206	13065
1.22	93	92	135	219	362	620	1124	2212	4759	11771
1.77	55	83	118	190	311	527	940	1806	3783	8957
2.17	58	86	106	172	281	471	828	1563	3217	7353
2.53	52	83	94	151	246	409	713	1324	2667	5889
2.77	62	87	93	138	224	370	639	1171	2322	5037
2.97	56	59	90	128	207	341	584	1055	2066	4417
3.2	50	55	82	117	188	309	524	938	1804	3790

Photometry and astrometry



Lens masses


15.45 mag (PAR-02 baseline)
16.45 mag
relative error
Mass [M_sun]


Mass [$M_\odot$]
θ_E [mas]
μ_{rel} [mas]
D_{lens} [kpc]

Summary

* Microlensing is the only tool to observe (indirectly) and measure the mass of single stellar BHs

* Gaia astrometry combined with ground-based photometry of microlensing events can provide lens mass measurements with accuracy up to 5%

* The astrometric alerts would provide knowledge about the microlensing **prior** to the photometric signal and thus allow a necessary follow up