DARK MATTER AND HUNT FOR BLACK HOLES

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(pron: Woo-cash Vi-zhi-kov-ski)

Warsaw University Astronomical Observatory, Poland

Sagan Workshop, Pasadena, 8 Aug 2017

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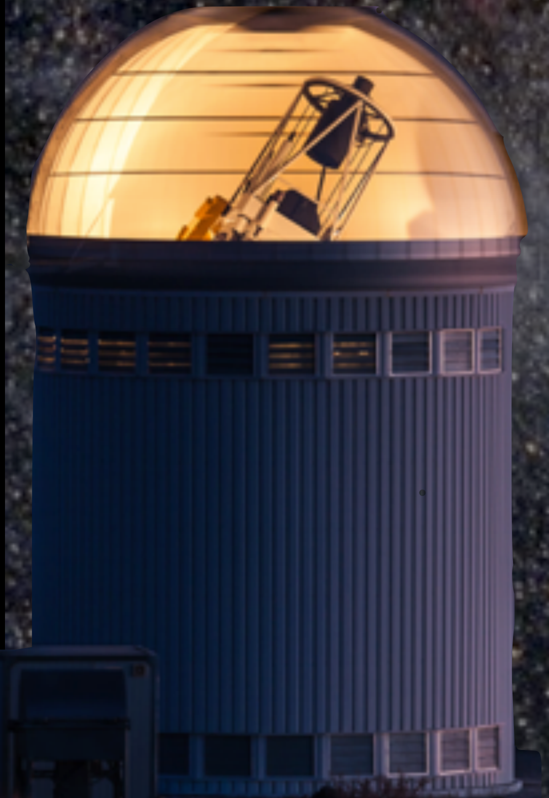

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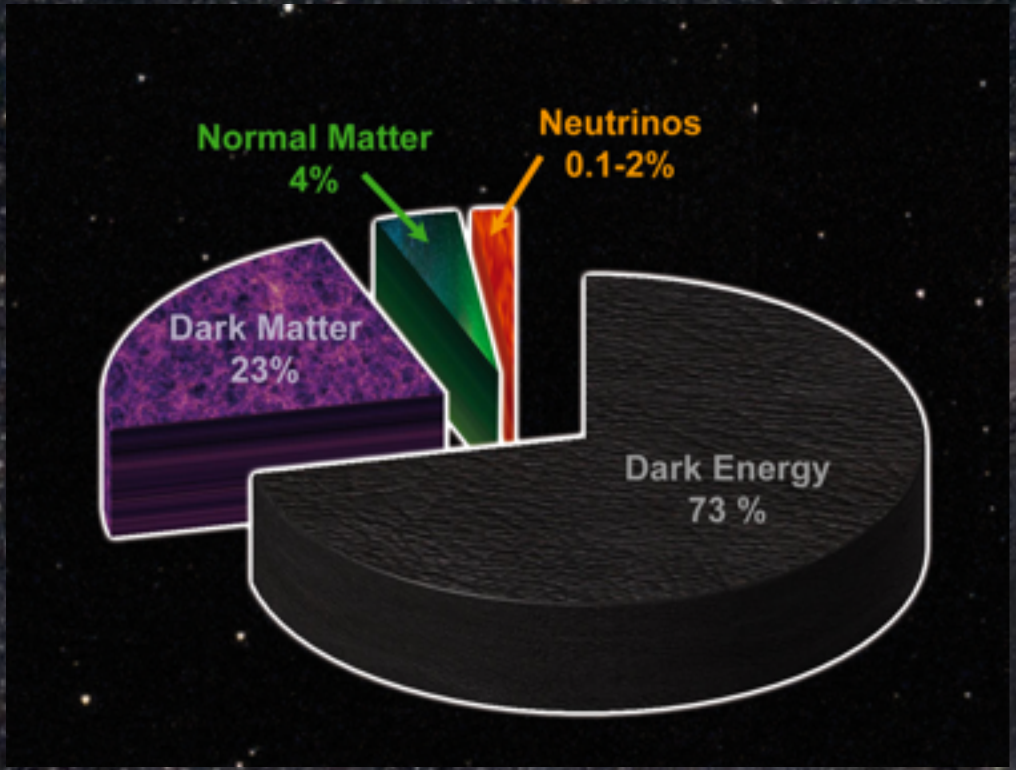
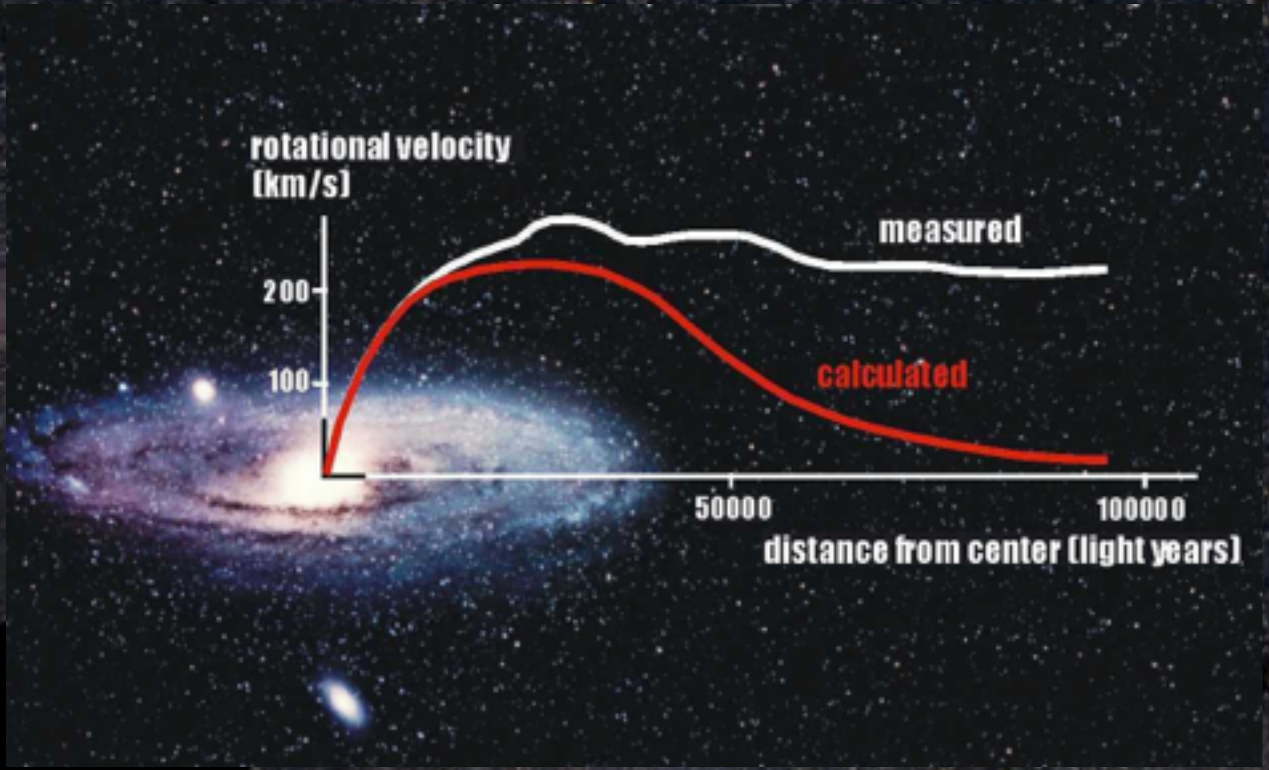
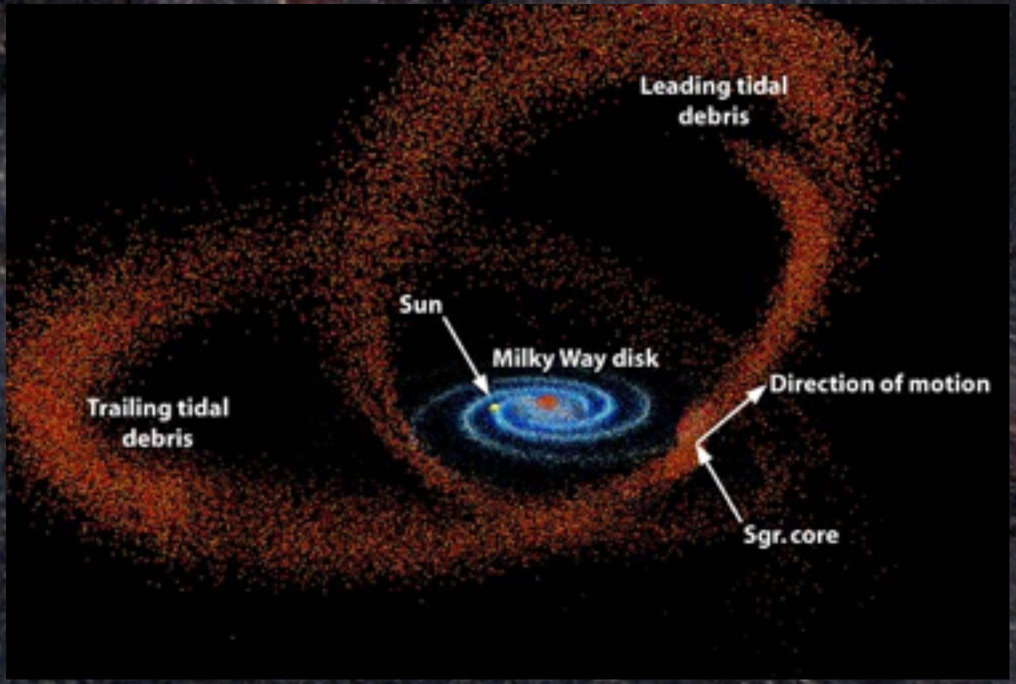
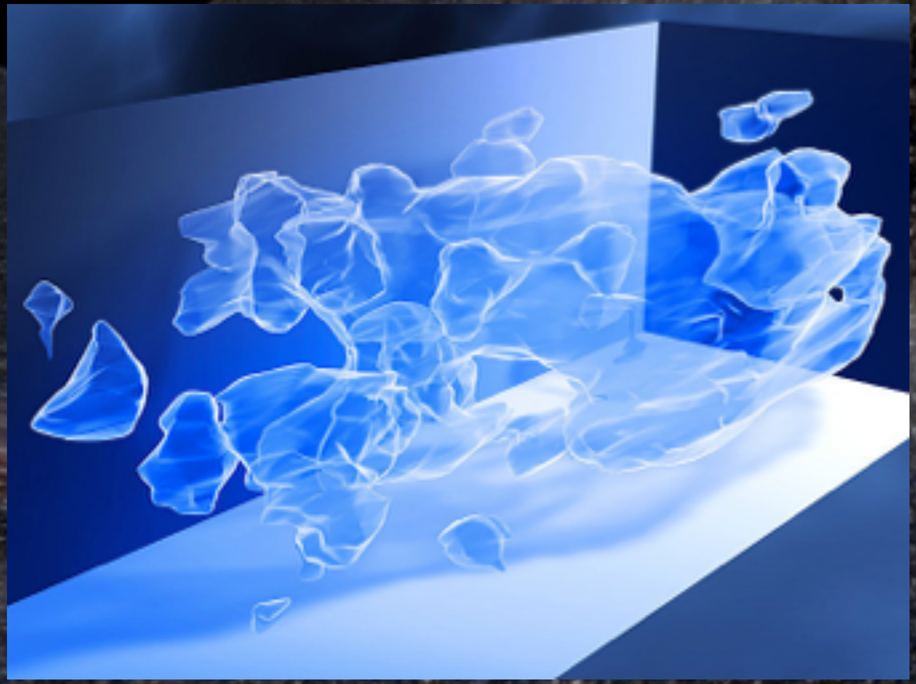
DARK MATTER DOES EXIST!









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HOW TO FIND DARK MATTER?

Paczyński's 1986 proposal to use Gravitational Lensing to find MACHOs*

THE ASTROPHYSICAL JOURNAL, **304**: 1–5, 1986 May 1

GRAVITATIONAL MICROLENSING BY THE GALACTIC HALO

BOHDAN PACZYŃSKI[1]
Princeton University Observatory
Received 1985 August 1; accepted 1985 October 23

ABSTRACT

The massive halo of our Galaxy has an optical depth to gravitational microlensing $\tau \approx 10^{-6}$. If the halo is made of objects more massive than $\sim 10^{-8}\ M_\odot$, then any star in a nearby galaxy has a probability of 10^{-6} to be strongly microlensed at any time. The lensing events last ~ 2 hr if a typical "dark halo" object has a mass of $10^{-6}\ M_\odot$, and they last ~ 2 yr for objects of $100\ M_\odot$. Monitoring the brightness of a few million stars in the Magellanic Clouds over a time scale between 2 hr and 2 yr may lead to a discovery of "dark halo" objects in the mass range 10^{-6}–$10^{2}\ M_\odot$ or it may put strong upper limits on the number of such objects.
Subject headings: galaxies: Magellanic Clouds — gravitation — stars: variables

*Massive Astrophysical Compact Halo Objects

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POLISH CONTRIBUTION TO MICROLENSING

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POLISH CONTRIBUTION TO MICROLENSING

Celebrating **25** years of the OGLE project

24-28 July 2017 Warsaw, Poland

ogle25.astrouw.edu.pl

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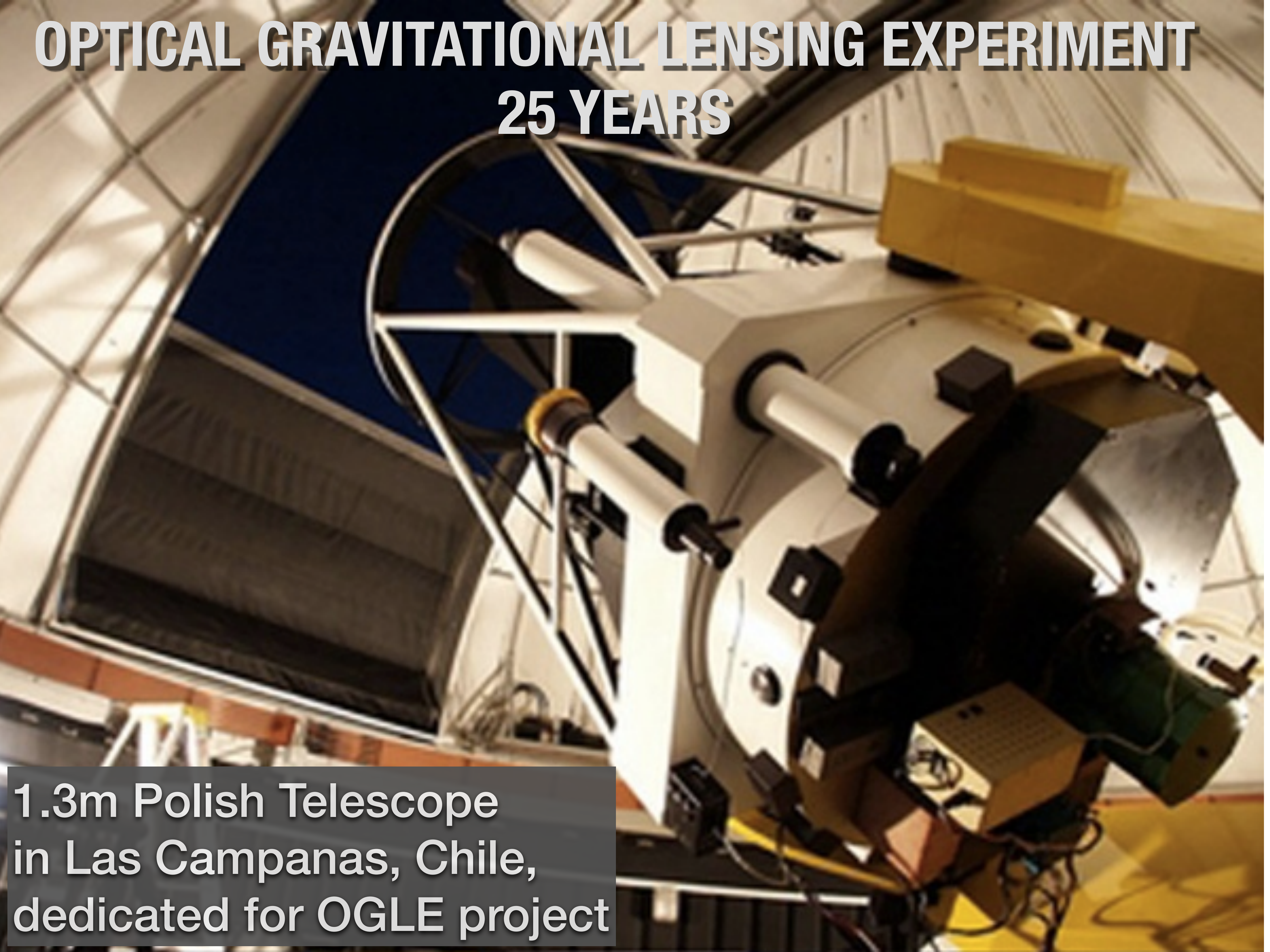
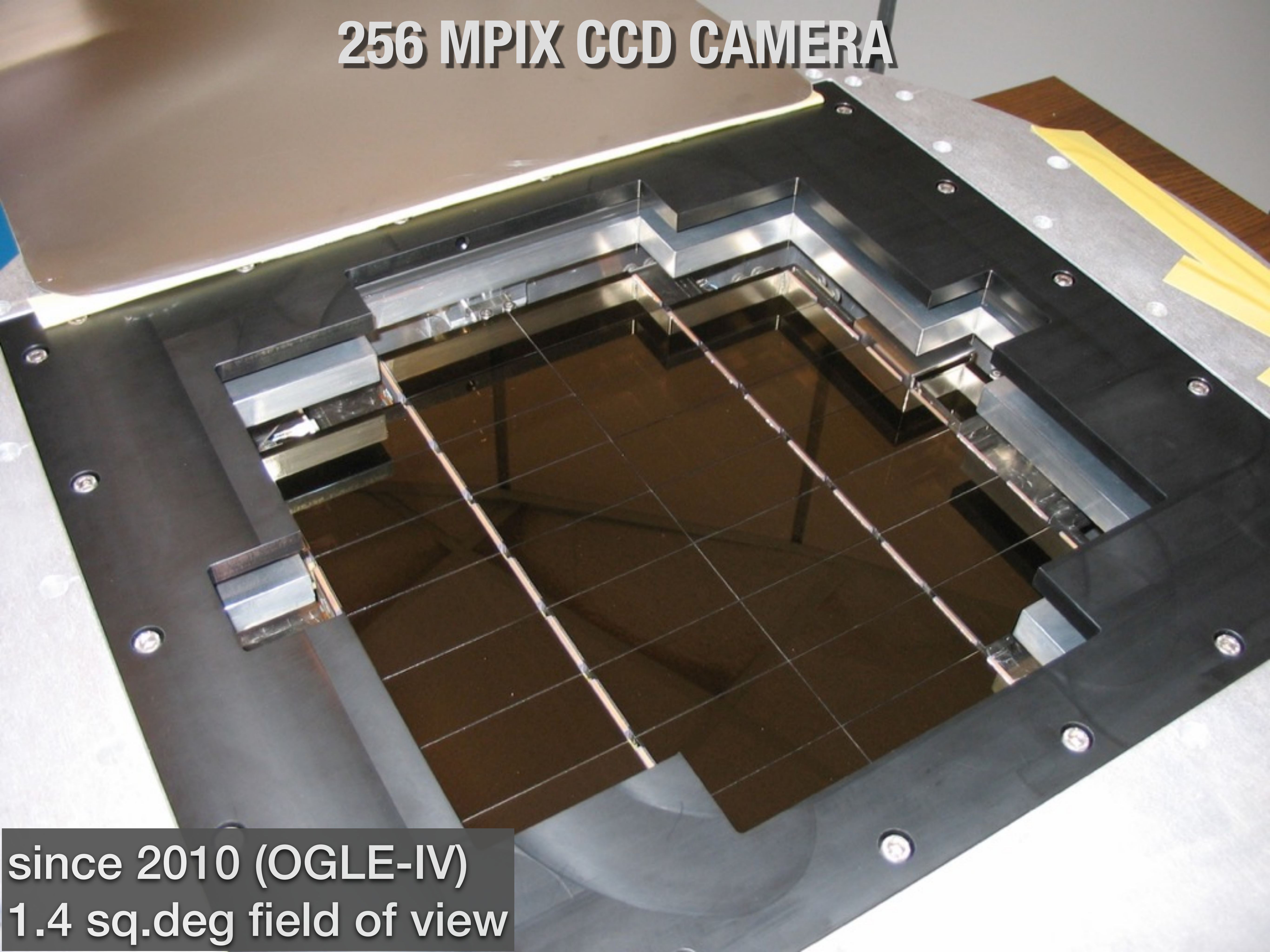
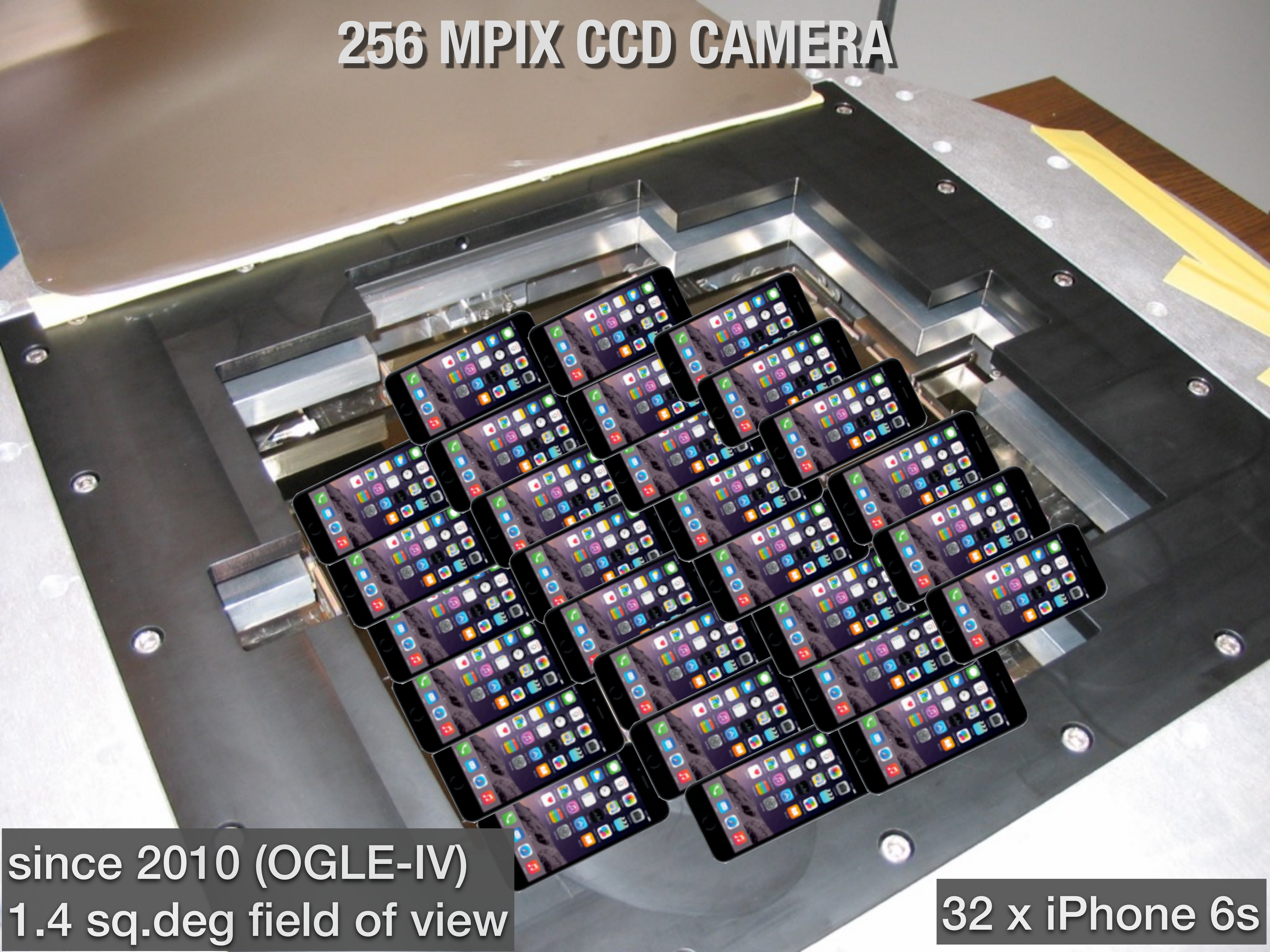
OGLE IN LAS CAMPANAS OBSERVATORY CHILE


OPTICAL GRAVITATIONAL LENSING EXPERIMENT
25 YEARS
1.3m Polish Telescope
in Las Campanas, Chile,
dedicated for OGLE project

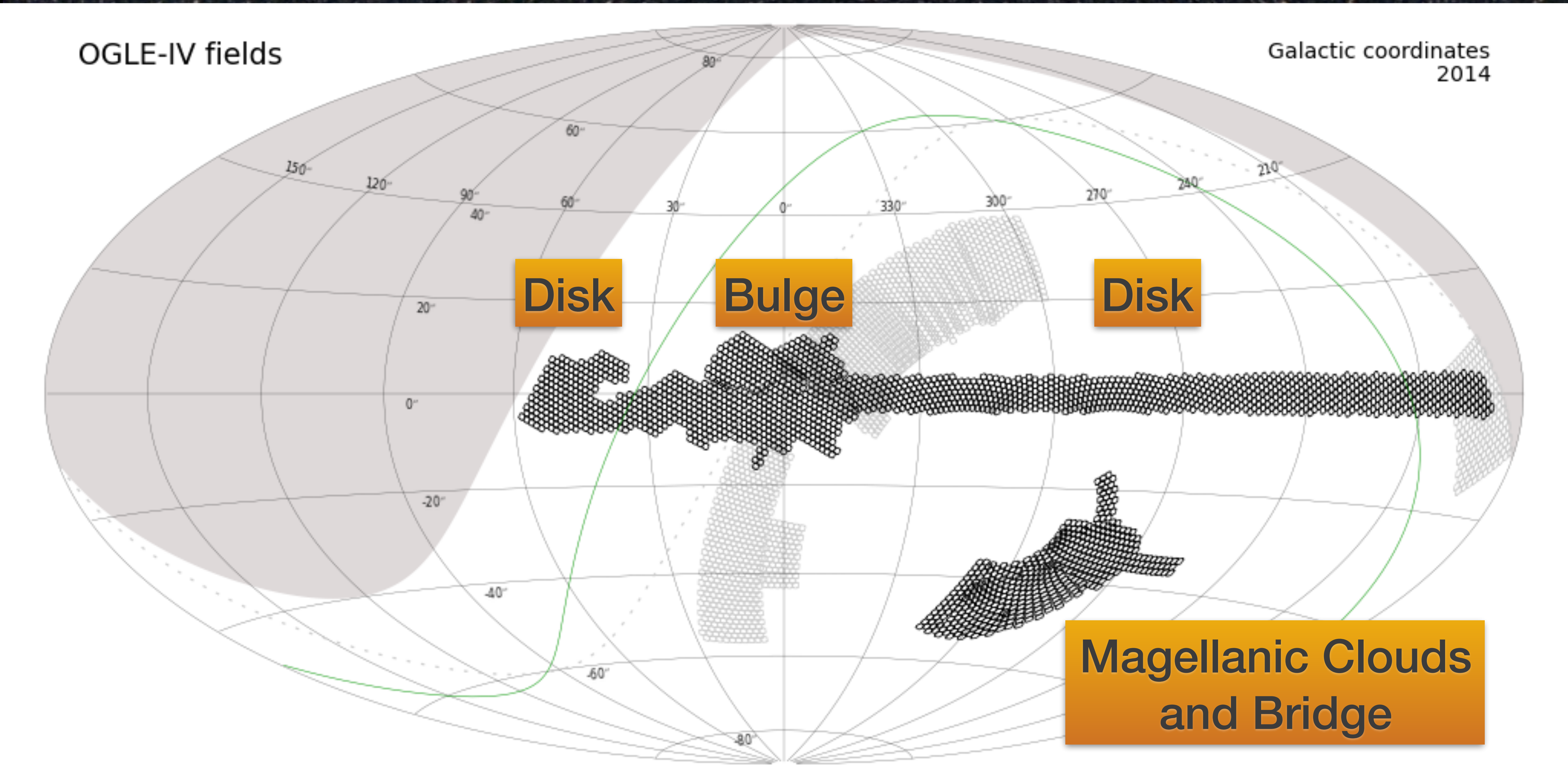
256 MPIX CCD CAMERA



since 2010 (OGLE-IV)
1.4 sq.deg field of view


256 MPIX CCD CAMERA
since 2010 (OGLE-IV)
1.4 sq.deg field of view
32 x iPhone 6s

OGLE-IV SKY since 2010



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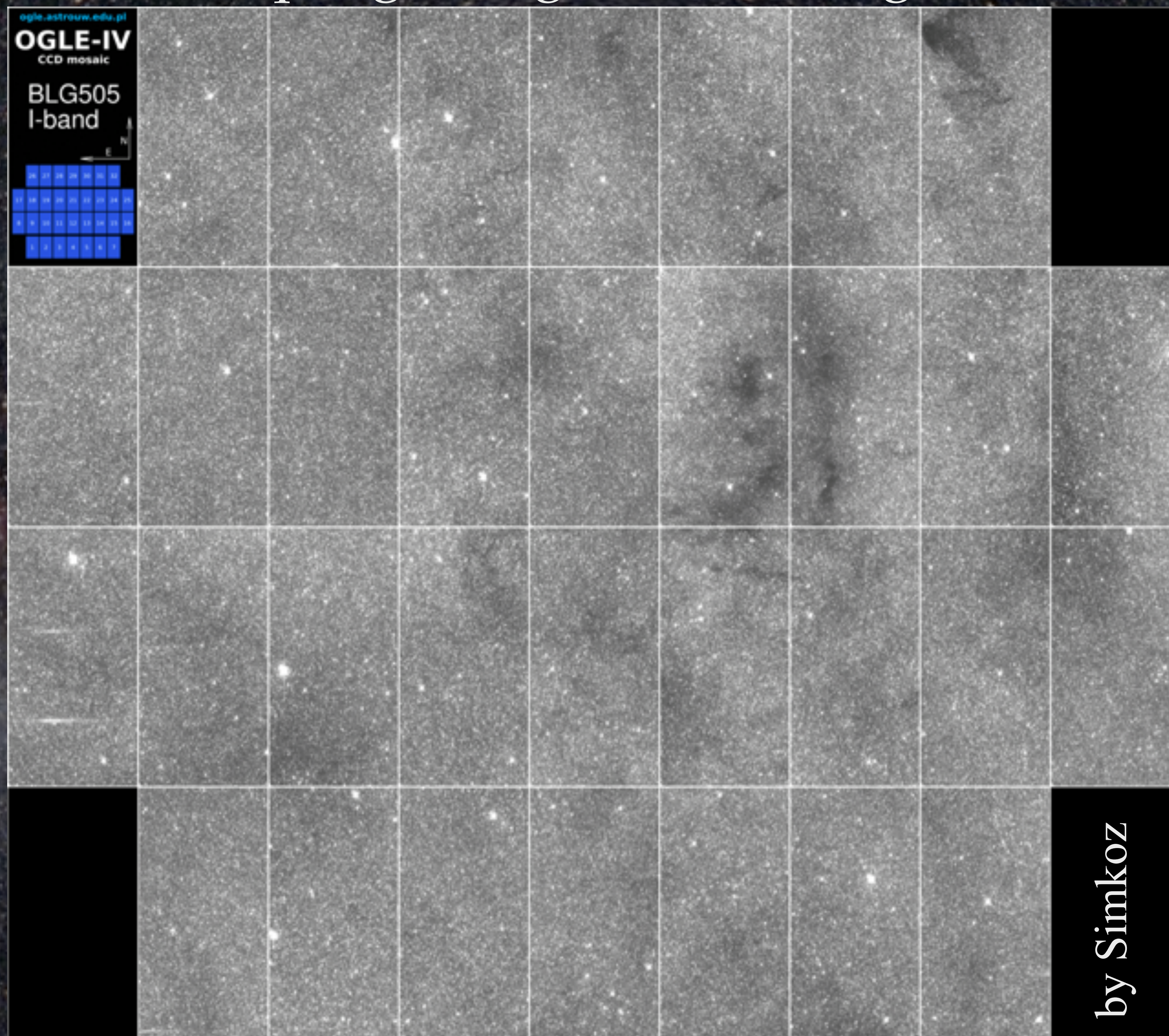
5 MILLION STARS EVERY 3 MINUTES

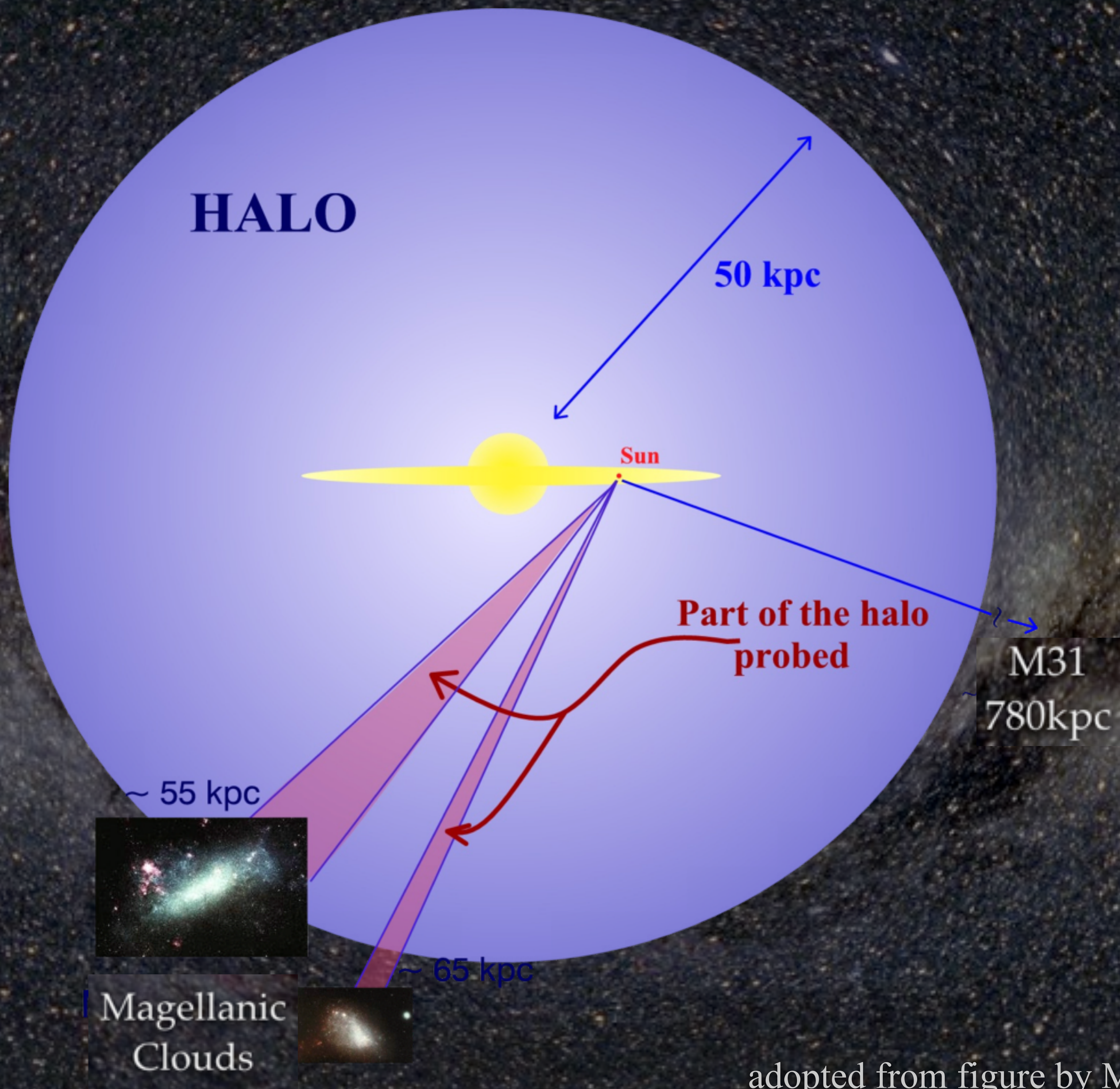
OGLE bulge field

FoV 1.4 sq.deg., mag limit 21 mag in I-band



HOW TO FIND DARK MATTER?

Massive Astrophysical Compact Halo Objects



adopted from figure by M.Moniez

HOW TO FIND DARK MATTER?

Microlensing optical depth

$$\tau = \frac{1}{N_{obs}\Delta T_{obs}} \frac{\pi}{2} \sum_{events} \frac{t_{\rm E}}{\epsilon(t_{\rm E})}$$

- sum over all detected events
- time-scale
- efficiency of detection of time-scale t_E
- number of monitored stars
- total time of observation

If the 100% of DM halo in form of MACHOs:

$\tau_{LMC} = 4.7 \times 10^{-6}$

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IS ALL LENSING FROM MACHOS?

WARNING!

letters to nature

Nature **370**, 275 - 276 (28 July 1994); doi:10.1038/370275a0

Stars within the Large Magellanic Cloud as potential lenses for observed microlensing events

KAILASH C. SAHU

Instituto de Astrofisica de Canarias, 38200 La Laguna, Tenerife, Spain

MASSIVE compact objects in the Galactic halo, known as MACHOs, have been postulated as the origin of a substantial fraction of the 'dark matter' known to exist in the haloes of galaxies[1,2]. Paczyński[3] has suggested that it might be possible to detect these low-luminosity objects by their potential to act as gravitational lenses, causing a characteristic brightening when they cross the path of light from a star in a nearby galaxy. Very recently, two groups reported possible detections of microlensing of stars in the Large Magellanic Cloud (LMC)[4,5], which was interpreted as a possible fingerprint of MACHOs. Here I show that microlensing by stars within the LMC itself can account for the observed events. In the future it should be possible to distinguish between the two possible sources of microlensing events, however, because events caused by stars in the LMC should be clustered toward the central region of that galaxy whereas those caused by MACHOs should be uniformly distributed over the whole LMC.

Contribution from self-lensing in the LMC:

$$\tau_{LMC\text{-}SL} = 0.4\times10^{-6}$$

LMC MICROLENSING SURVEYS

in search for DM in form of MACHOs

project	MACHO	EROS I + II
duration in years	5.7 from 1992	6.7 from 1996
sky coverage in sq deg	13.4	93
stars sample in millions	10	7 (bright)
no.of candidates	**10 to 17**	**none**
optical depth (10^{-7})	**1.0 ± 0.3**	**< 0.36**
MACHO halo fraction at M=0.4 $M_\odot$	**20%**	**<8%**
reference	Bennett (2005)	Tisserand et al. (2007)

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Significant discrepancy in results!

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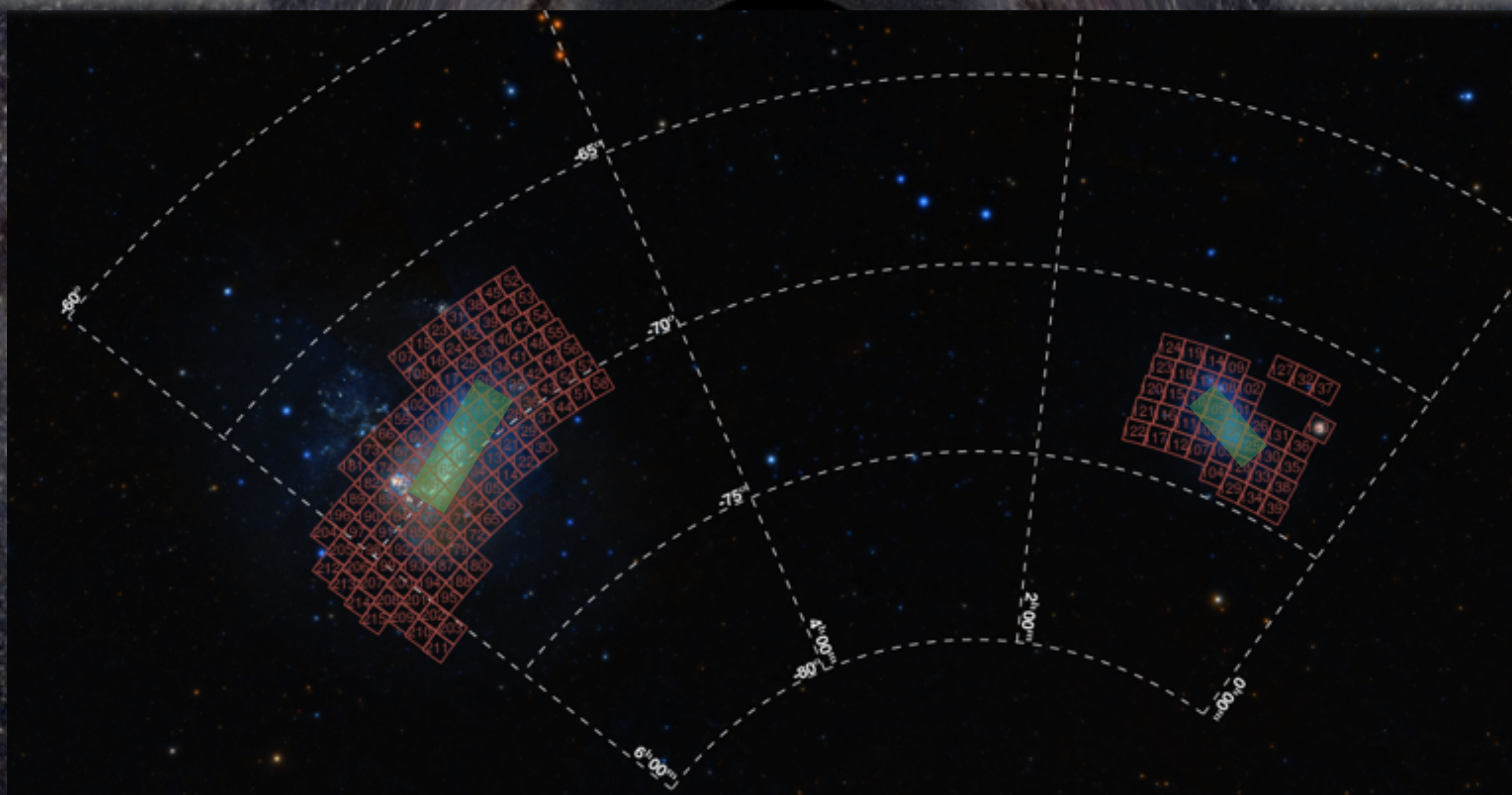
OGLE-II AND OGLE-III

1997-2000 and 2001-2009

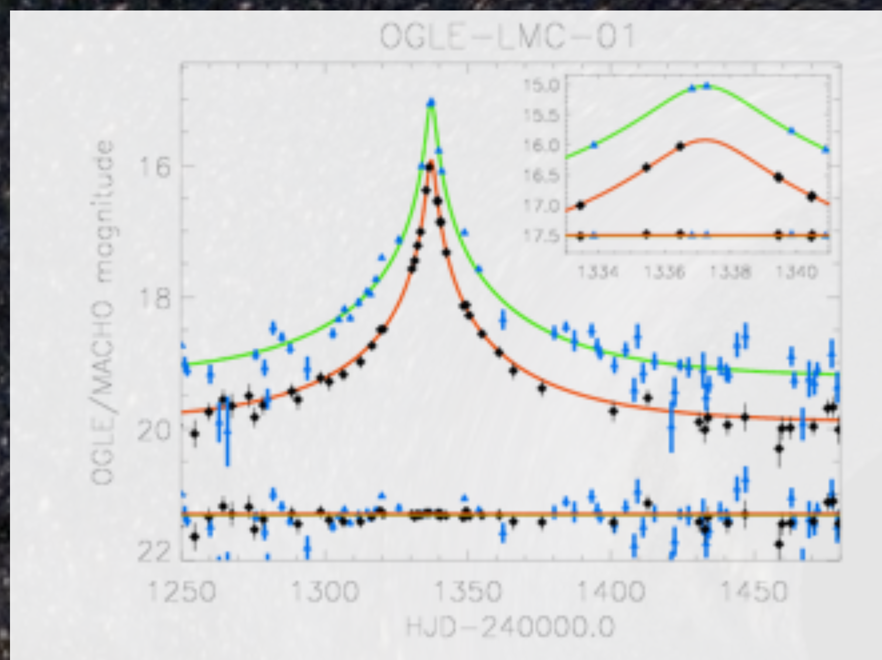


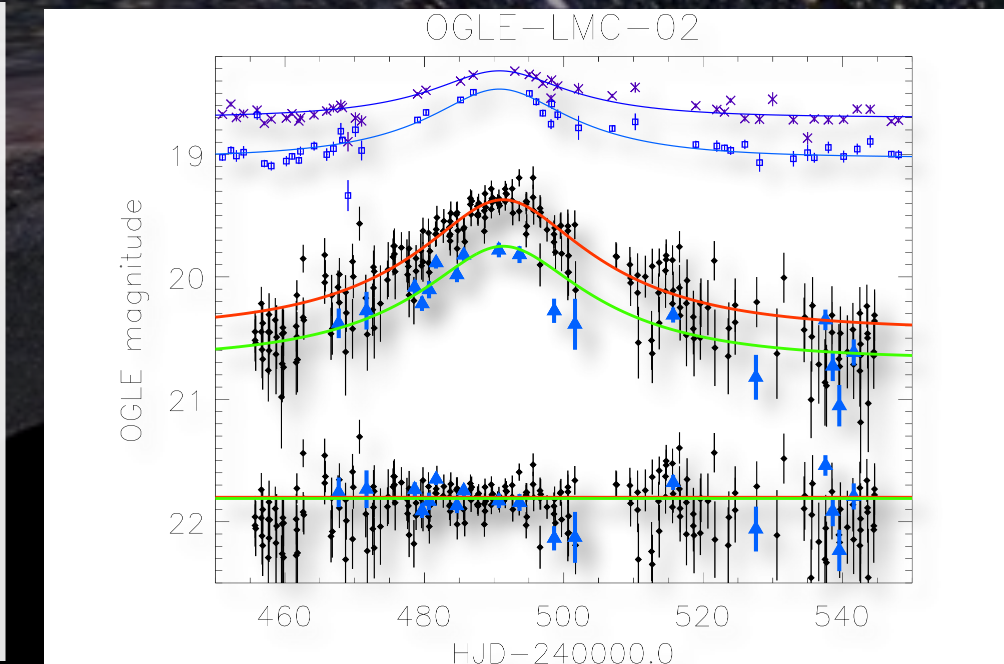
credit J.S.

OGLE LMC EVENTS

OGLE-II LMC: **2 events** among **5.5 million** objects over **4 years**

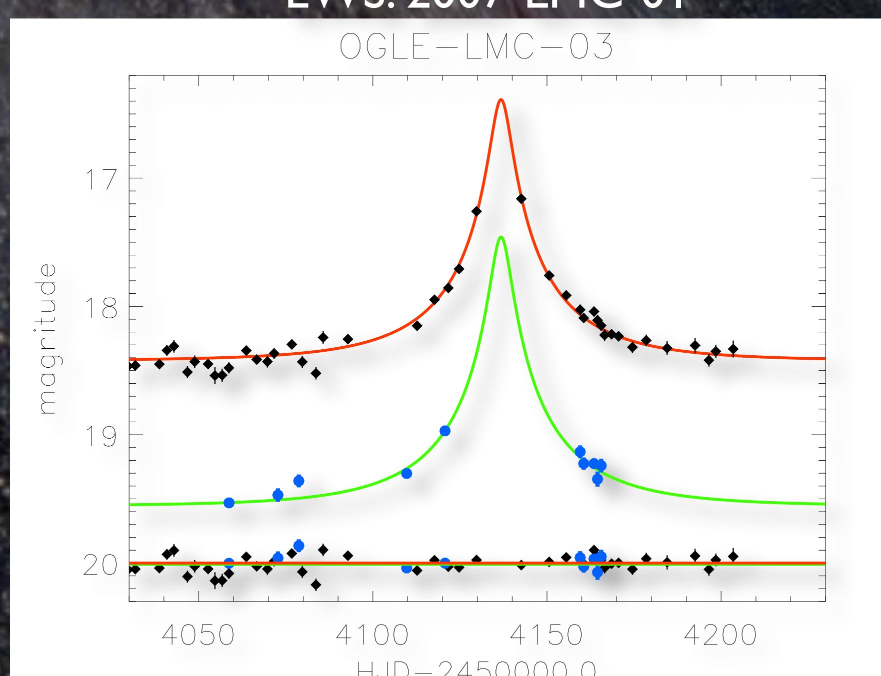
EWS: 1999-LMC-01

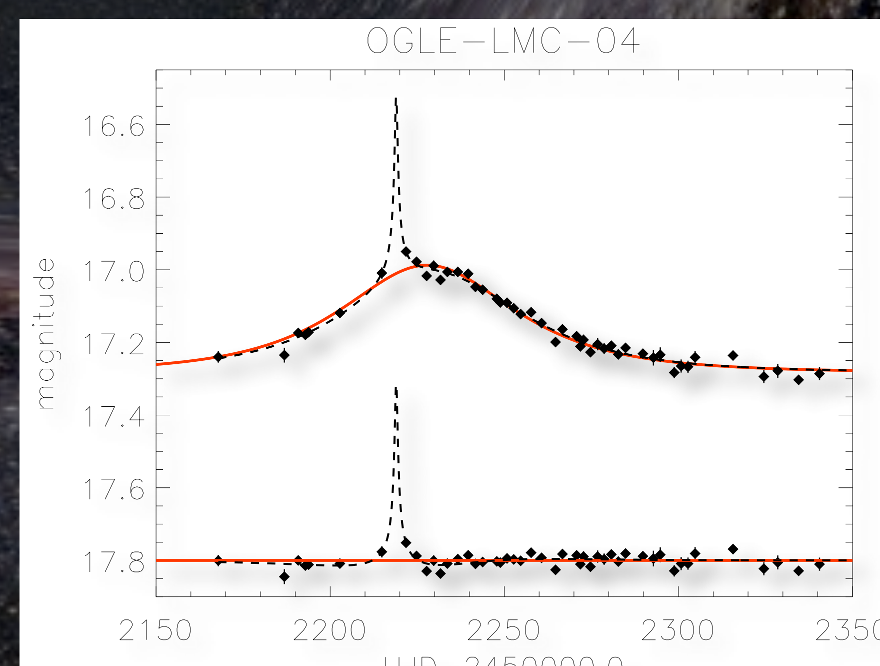




OGLE-III LMC: **2 events** among **35 million** objects over **8 years**

EWS: 2007-LMC-01





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LMC MICROLENSING SURVEYS

in search for DM in form of MACHOs

project	MACHO	EROS I + II	OGLE-II	OGLE-III
duration in years	5.7 from 1992	6.7 from 1996	4 from 1997	8 from 2001
sky coverage in sq deg	13.4	93	4.7	40
stars sample in millions	10	7 (bright)	5.5	35
no.of candidates	**10 to 17**	**none**	**2**	**2**
optical depth (10^{-7})	**1.0 ± 0.3**	**< 0.36**	**0.43±0.33**	**0.16±0.12**
MACHO halo fraction at M=0.4 M⊙	**20%**	**<8%**	**<19%**	**<7%**
reference	Bennett (2005)	Tisserand et al. (2007)	Wyrzykowski et al. (2009)	Wyrzykowski et al. (2011)

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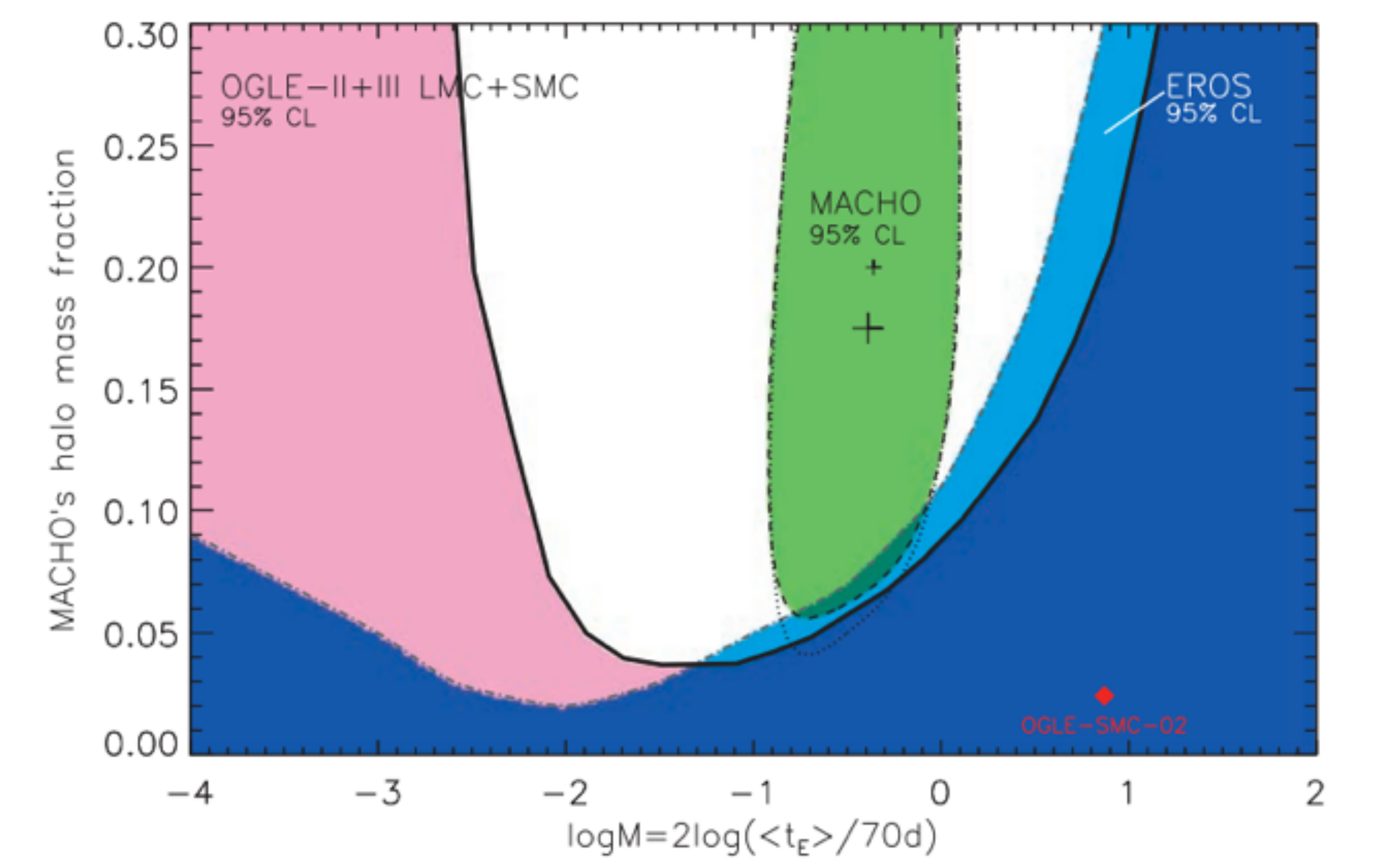
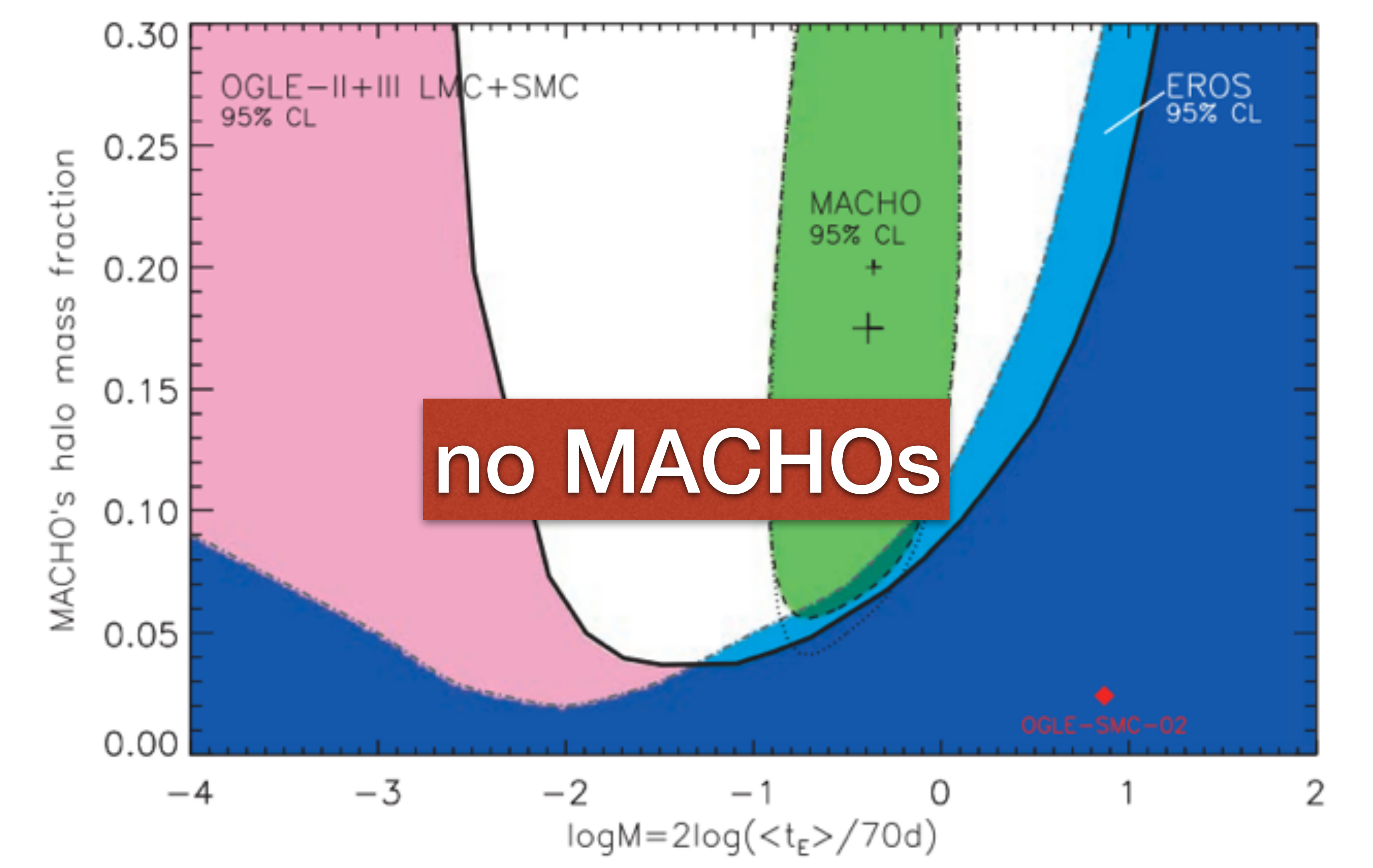
MICROLENSING CONSTRAINS ON HALO DARK MATTER



Low mass compact objects excluded from MW halo up to ~10 MSun.

Wyrzykowski+ 2009,2010,2011a,2011b

MICROLENSING CONSTRAINS ON HALO DARK MATTER

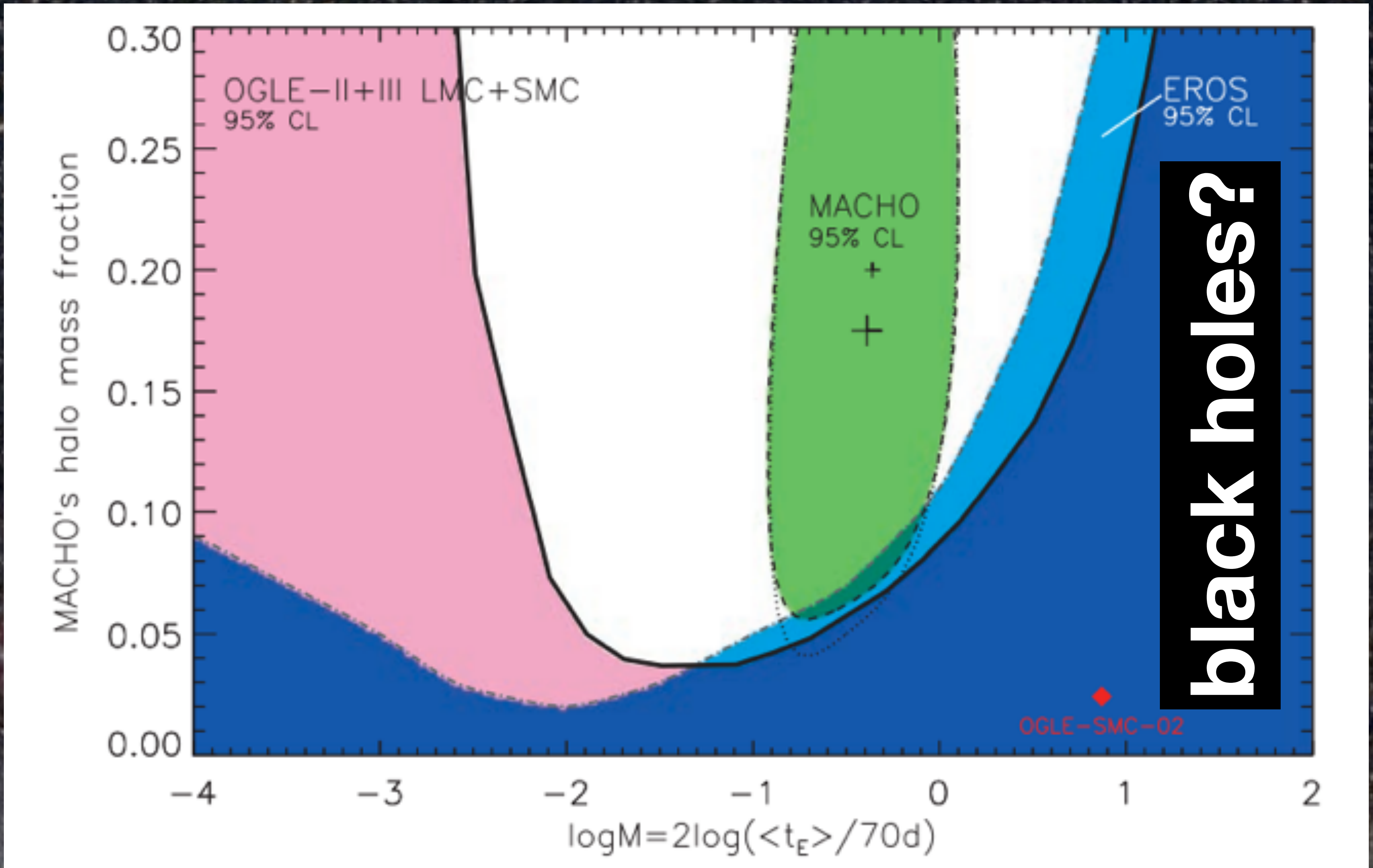


no MACHOs

Low mass compact objects excluded from MW halo up to ~10 MSun.

Wyrzykowski+ 2009,2010,2011a,2011b

MICROLENSING CONSTRAINS ON HALO DARK MATTER



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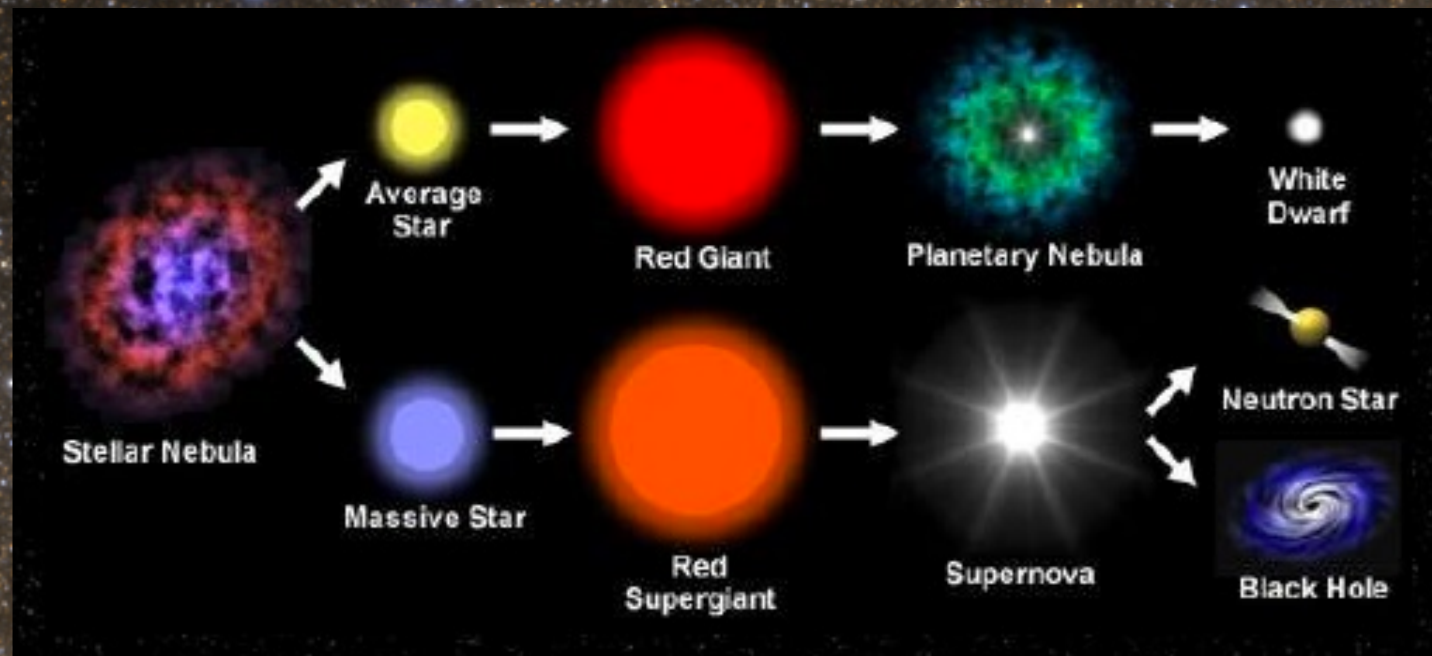
BLACK HOLES DO EXIST!



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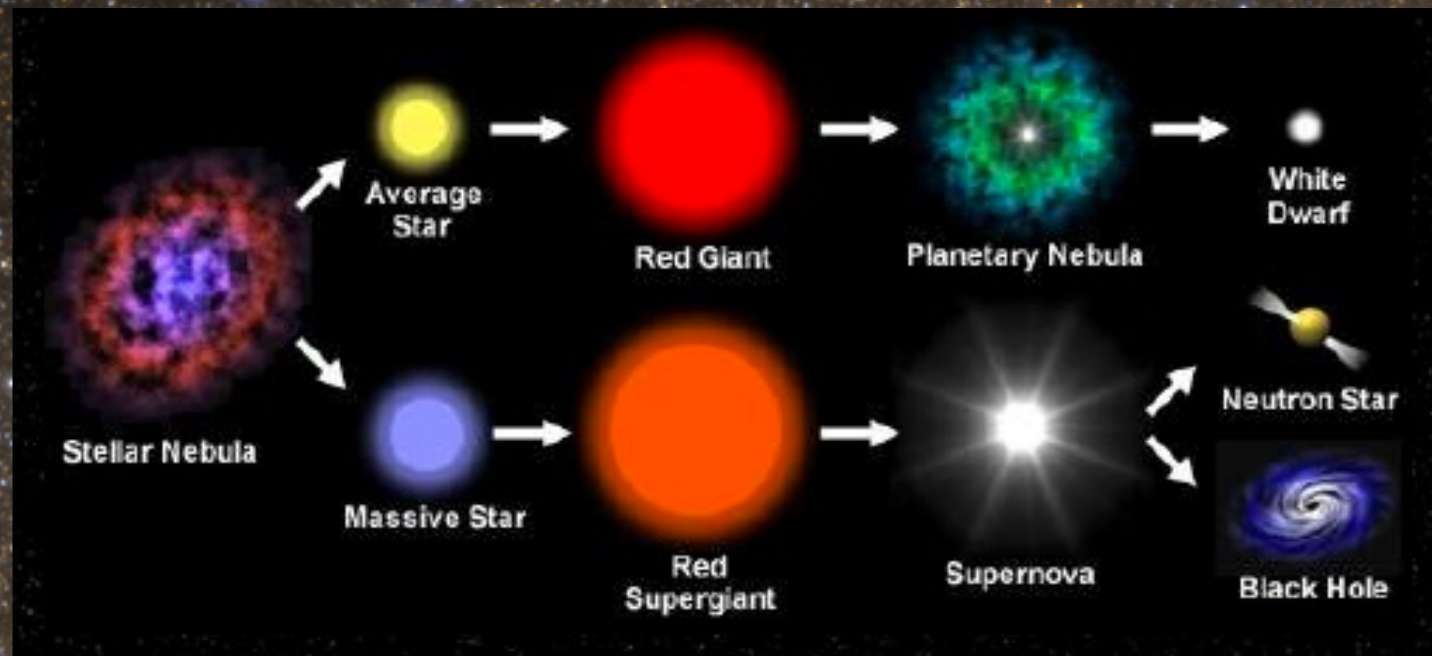
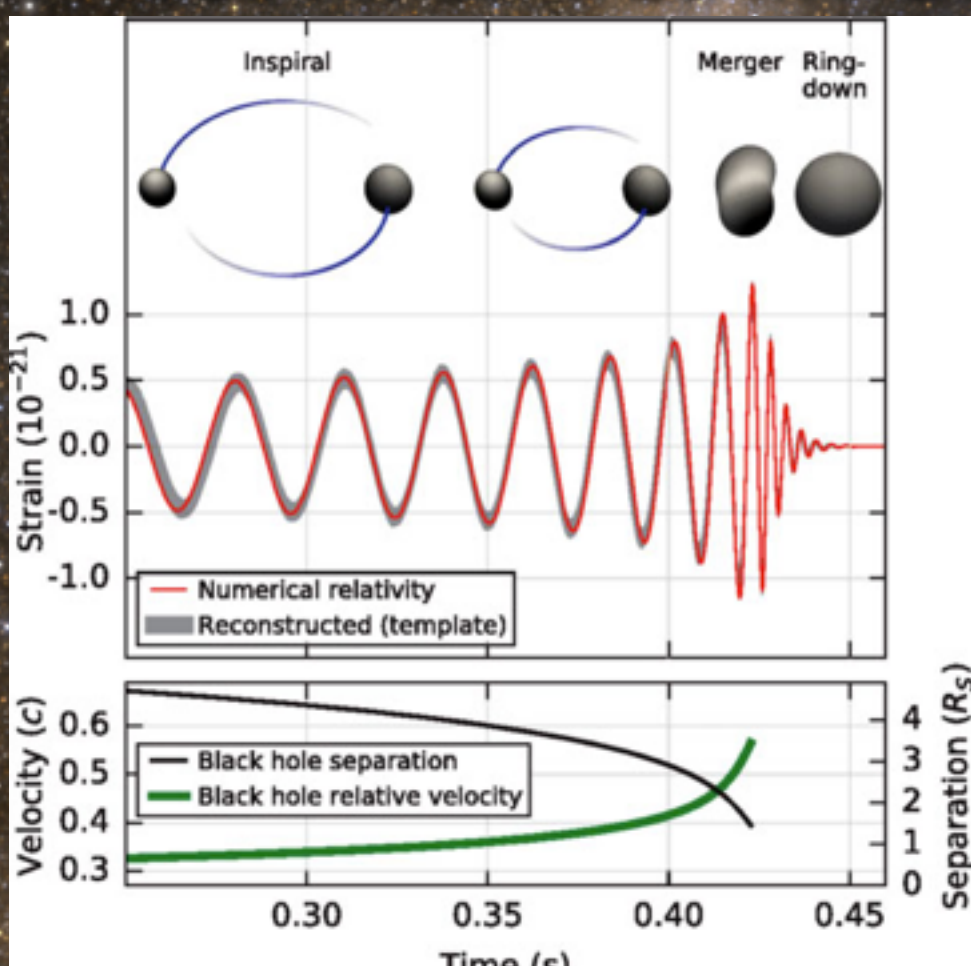
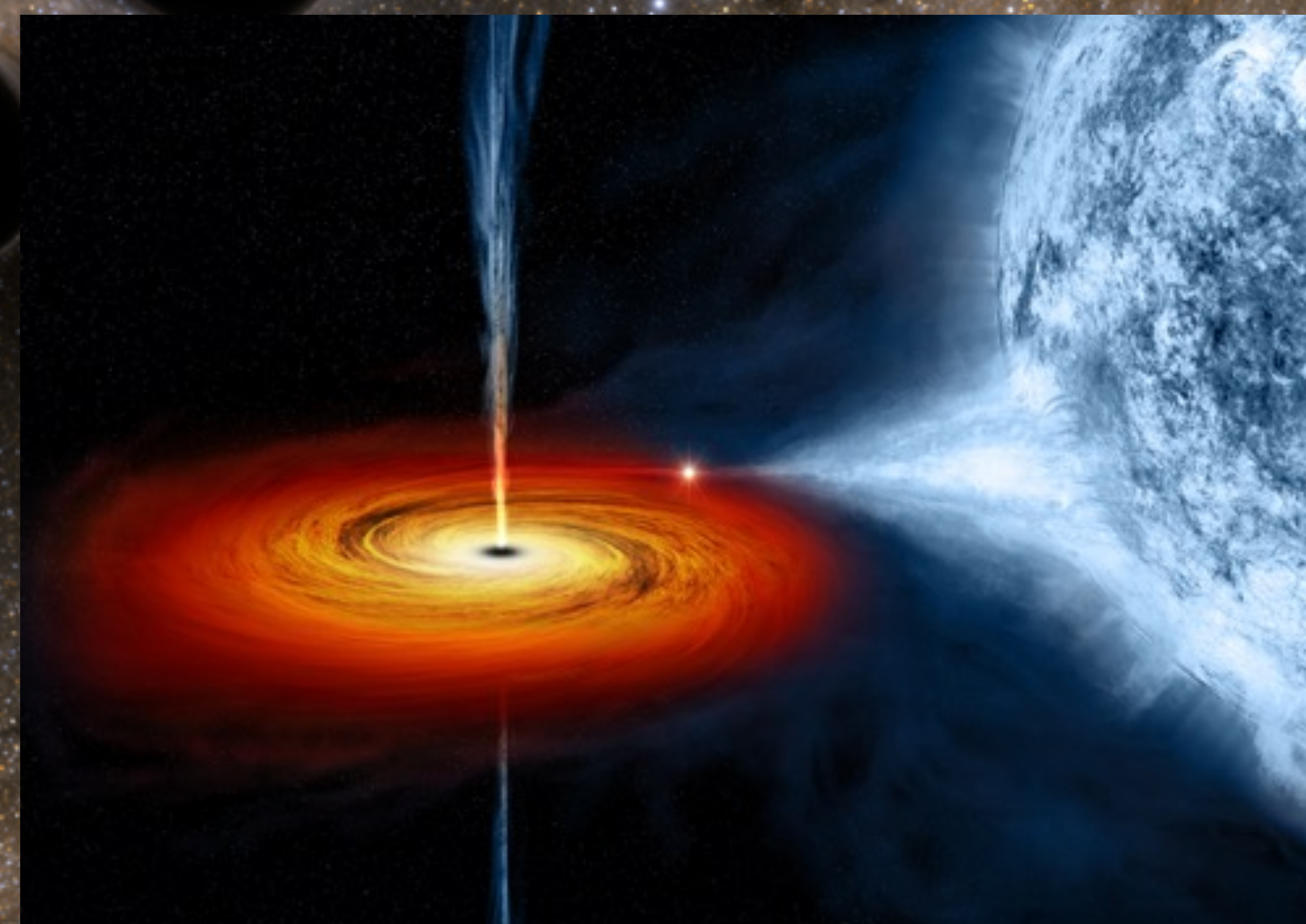


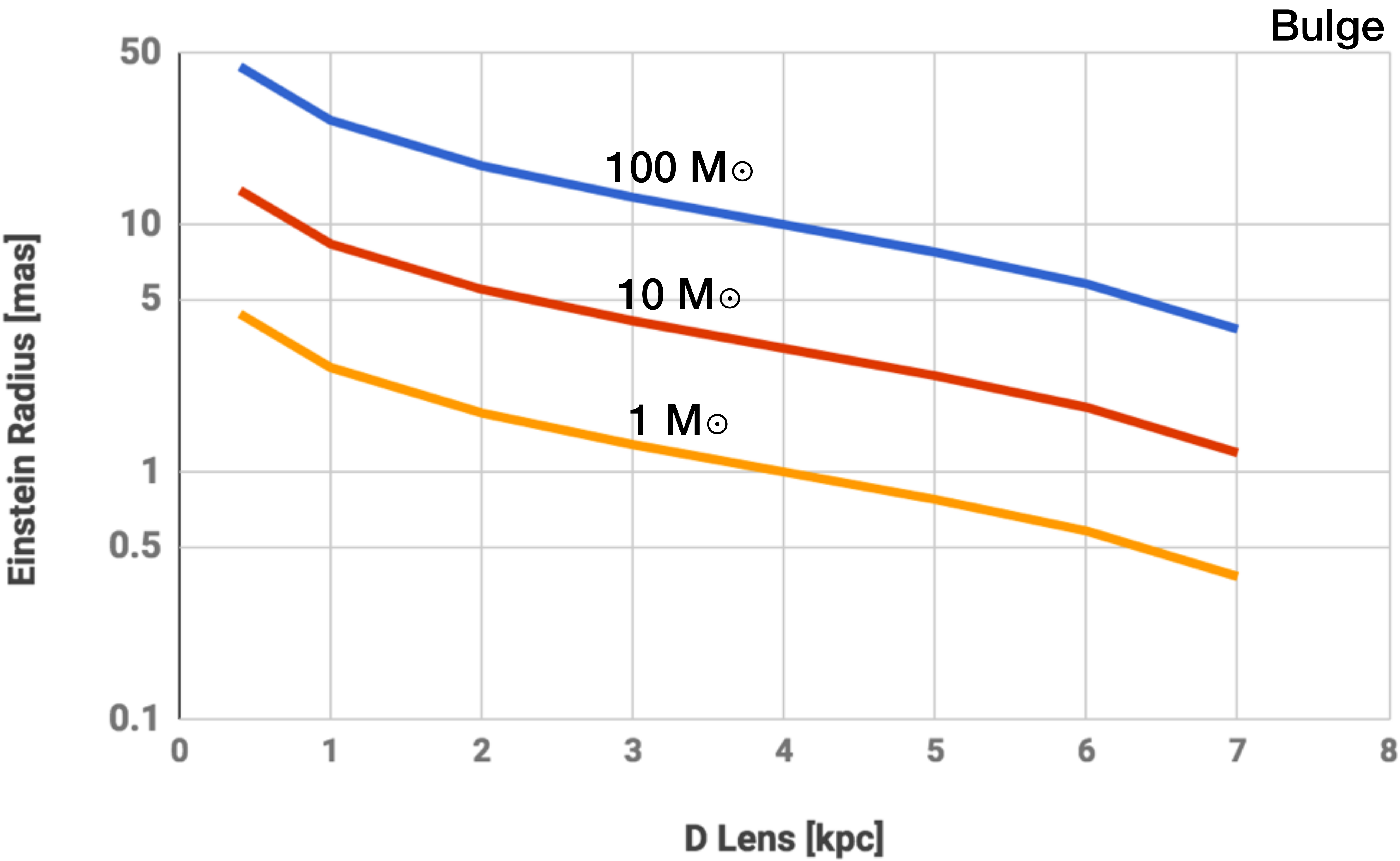
GW150914: 36 + 29 M⊙ BHs



BH+Star binary systems



BLACK HOLES AS LENSES



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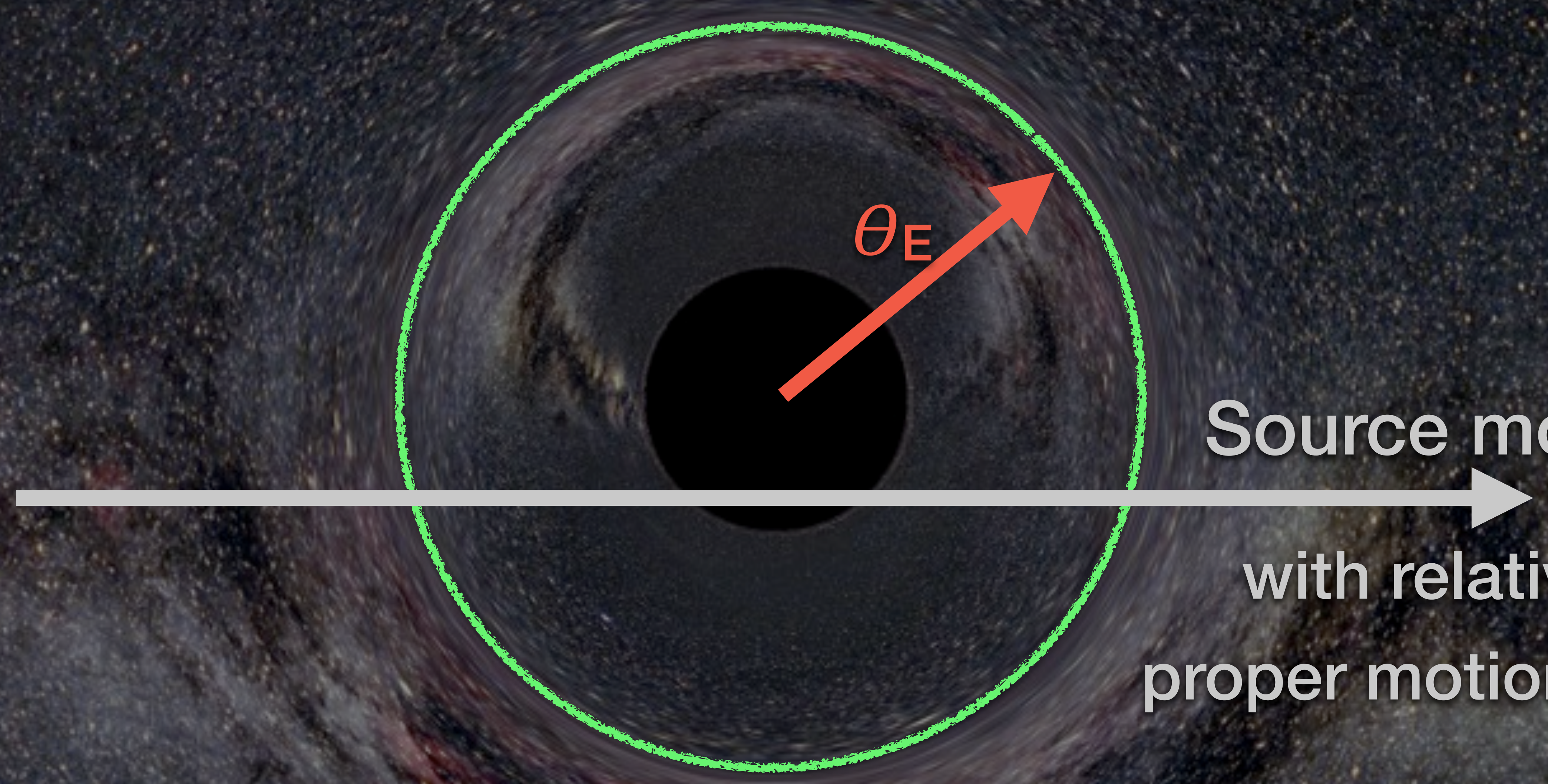

for example:

M_{BH} = 10 $M_\odot$ at D_L=1kpc

θ_E=10mas, μ_{rel} = 5mas/yr -> t_E = 2 yrs

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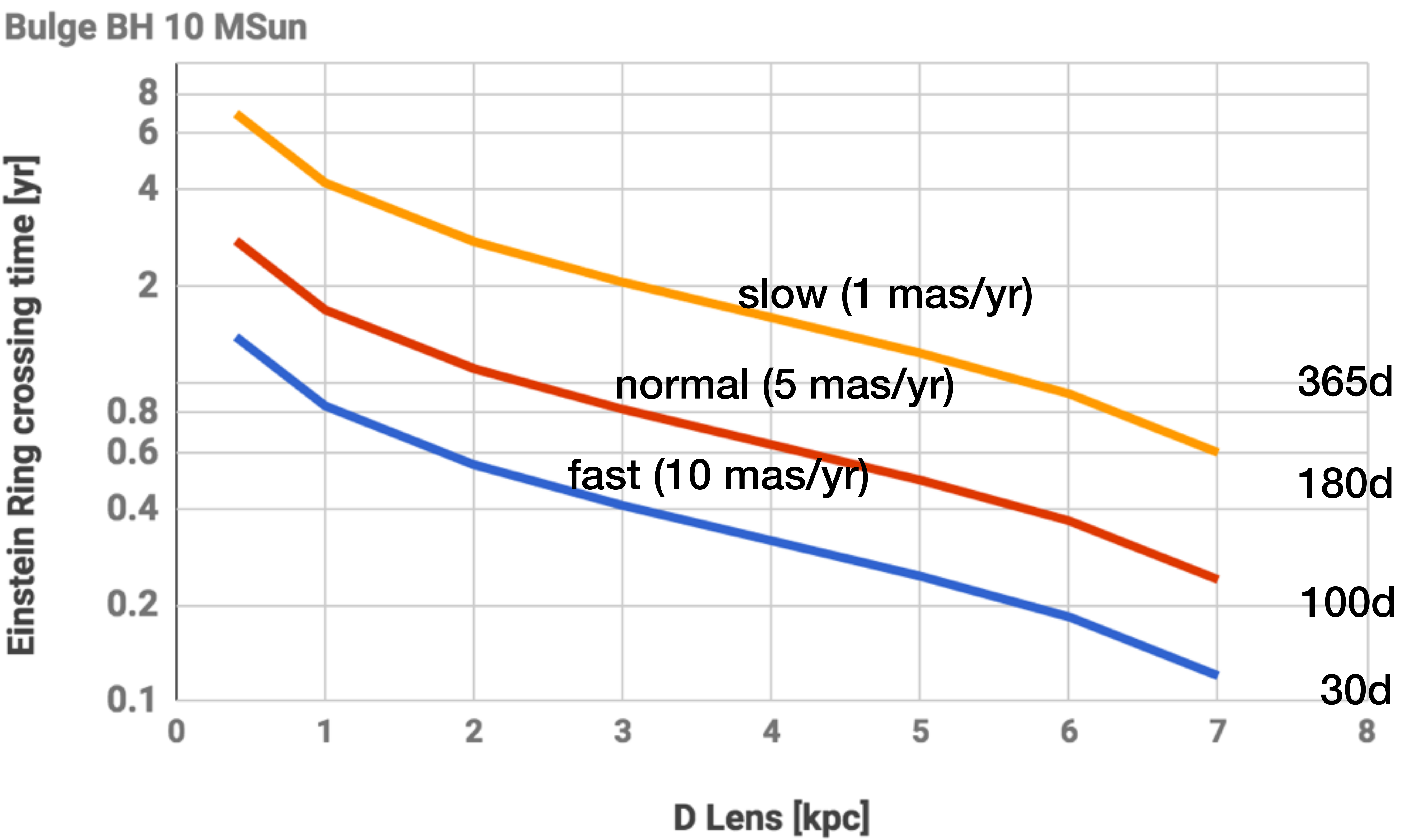
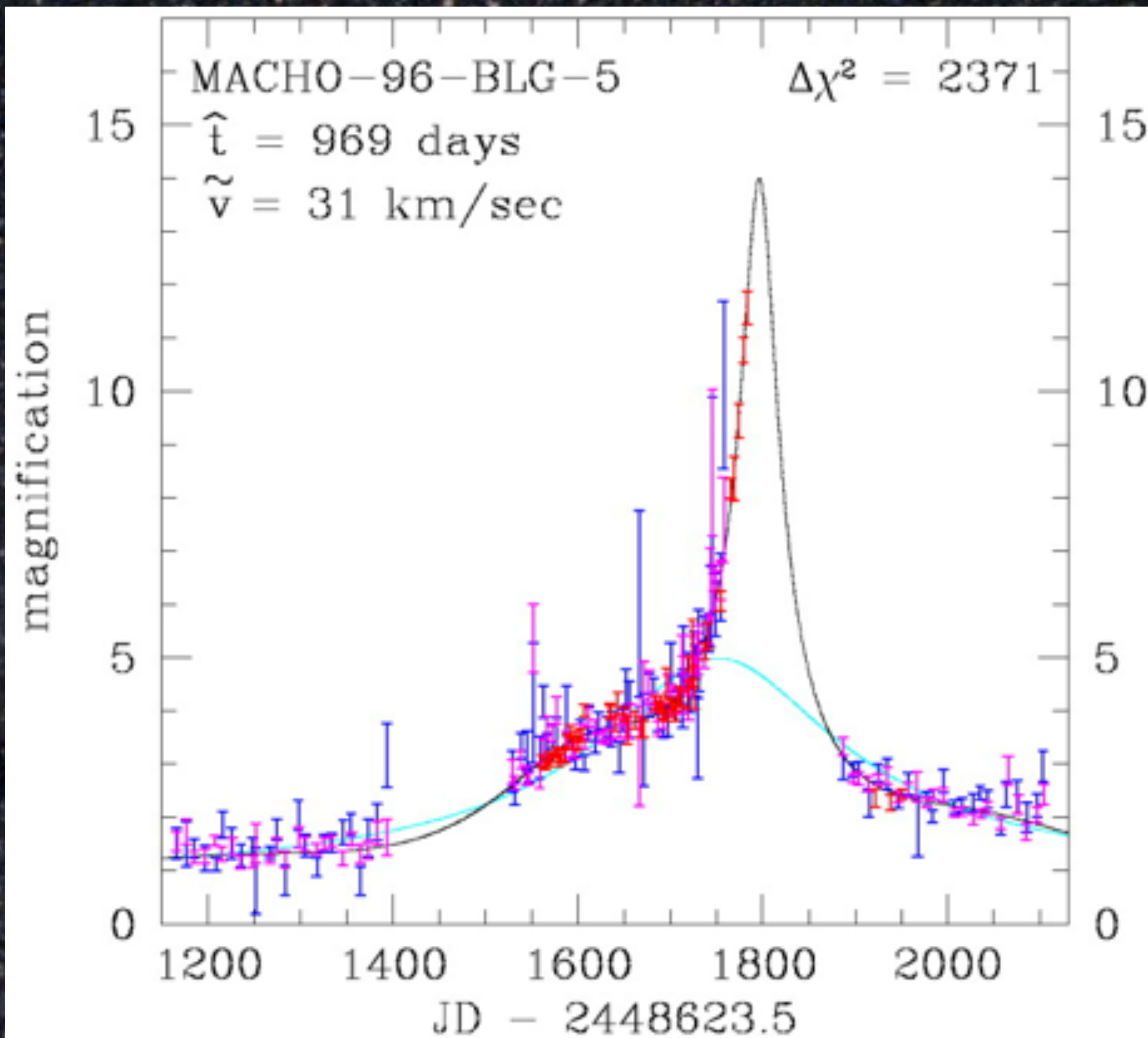
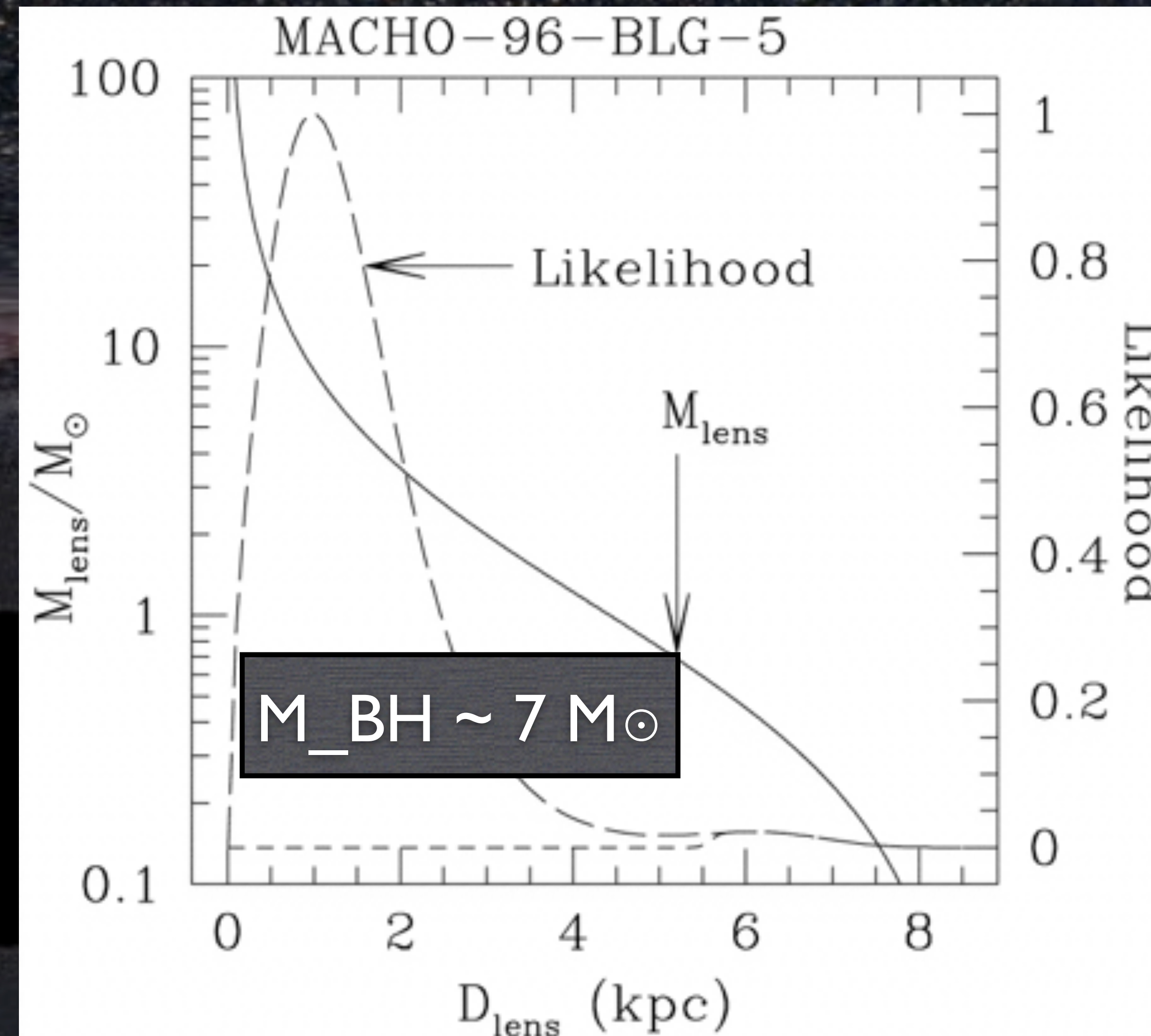
BLACK HOLES AS LENSES



BLACK HOLES FROM MICROLENSING



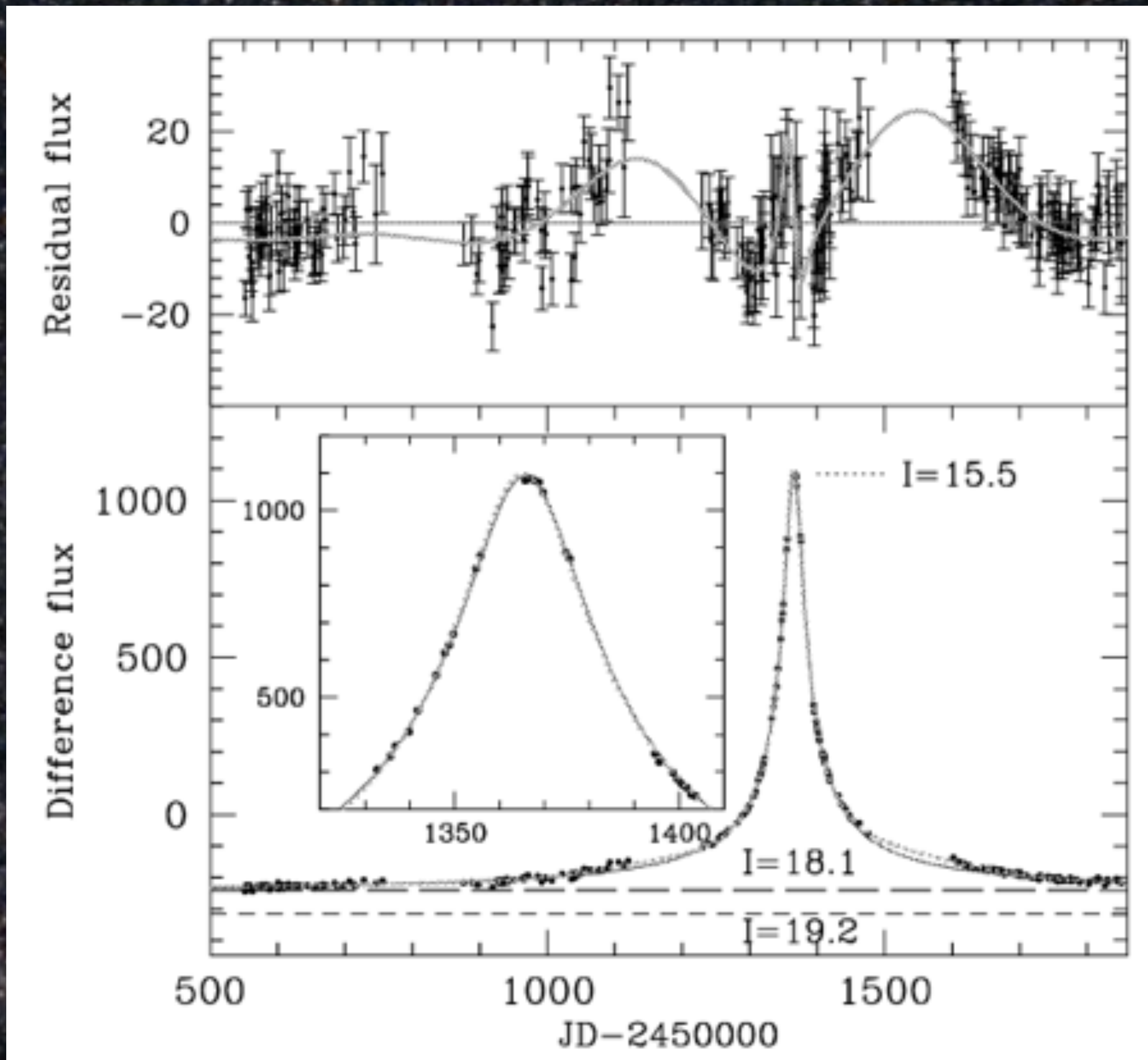


Bennett+2001

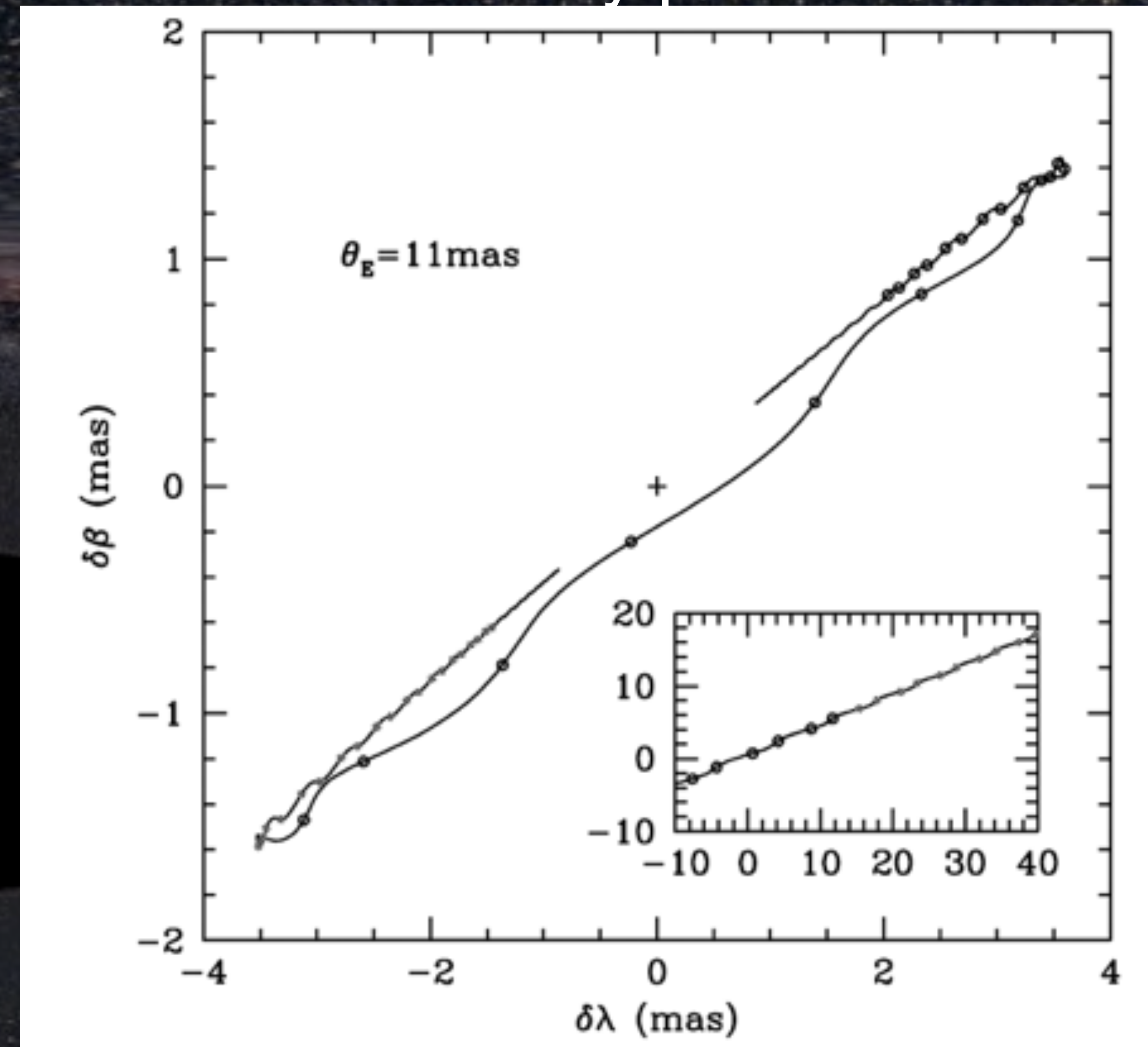
X-ray follow-up: no signal from ISM accretion
(Maeda et al. 2005; Nucita et al. 2006)

BLACK HOLES FROM MICROLENSING

OGLE-1999-BUL-32



astrometry predictions



Mao+2002

$$M = \frac{c^2 \tilde{r}_E^2}{4G}\left(\frac{1}{D_l} - \frac{1}{D_s}\right) = 10.5\,\mathrm{M}_\odot \left(\frac{\tilde{r}_E}{29.1\,\mathrm{au}}\right)^2 \left(\frac{\pi_{rel}}{0.1\,\mathrm{mas}}\right),$$

still the largest timescale microlensing event (t_E=640d)

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BLACK HOLES FROM MICROLENSING

binary lens with remnant component

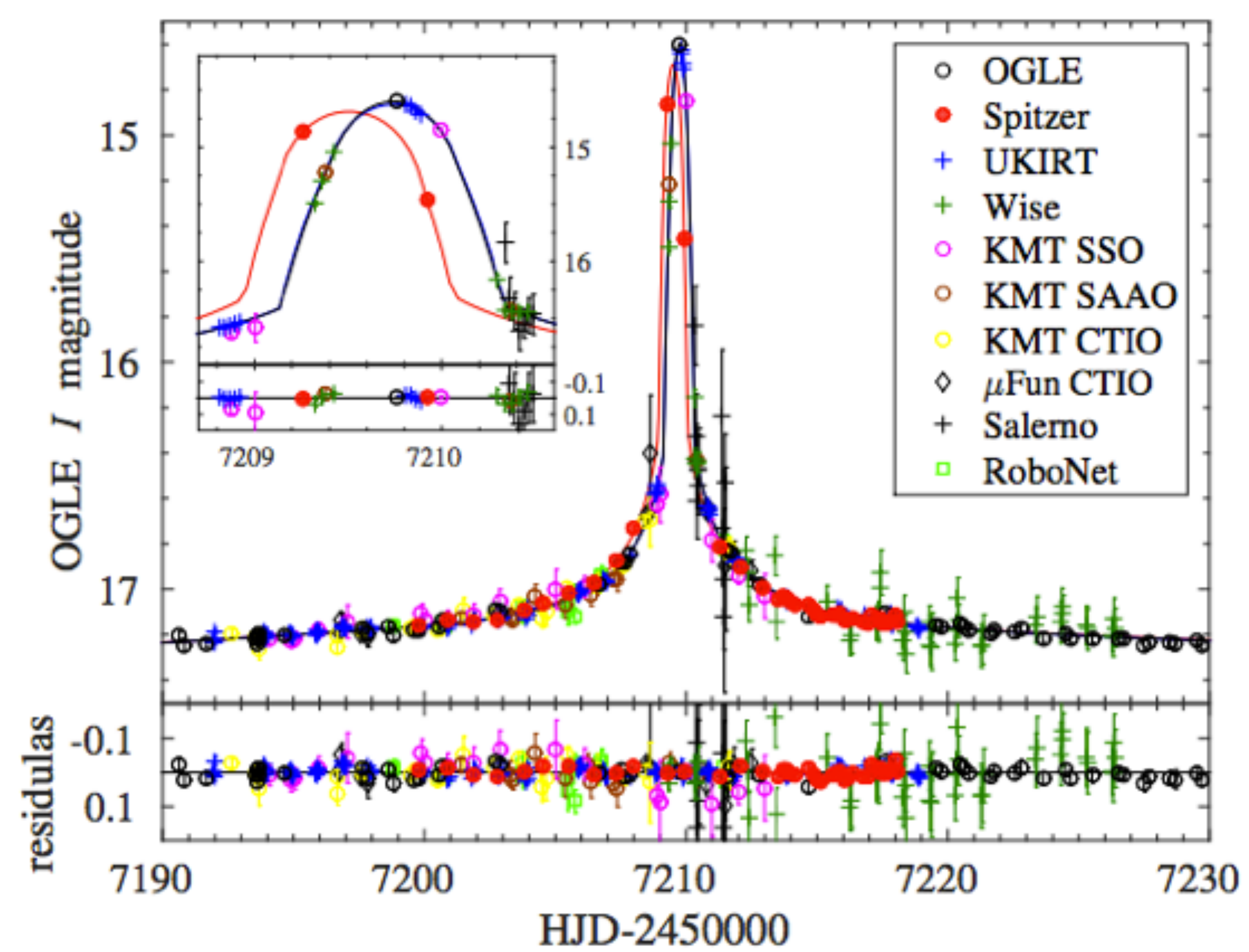

Fig. 1.— Light curve of OGLE-2015-BLG-1285 with data from *Spitzer* (red) and various

Parameter	Median	68% confidence intervals
M_1 [$M_\odot$]	2.0	[1.2,3.3]
M_2 [$M_\odot$]	0.8	[0.5,1.2]
$r_\perp$ [AU]	6.1	[5.7,6.5]
D_L [kpc]	7.5	[7.3,7.7]

Shvartzvald+2015

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BLACK HOLES MICROLENSING

- About 0.8% of microlensing events should be due to Black Holes! (Gould 2000)
- 2000 events found every year -> ~16 black holes every year!!
- so, where are they?

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- 2000 events found every year -> ~16 black holes every year!!
- so, where are they?

$$M = \frac{\theta_E}{\kappa \pi_E}$$

high amplification events/finite source (rare)

astrometry (VLT/AO, HST, Gaia)

Earth parallax

space-based parallax (e.g., Earth-Spitzer)

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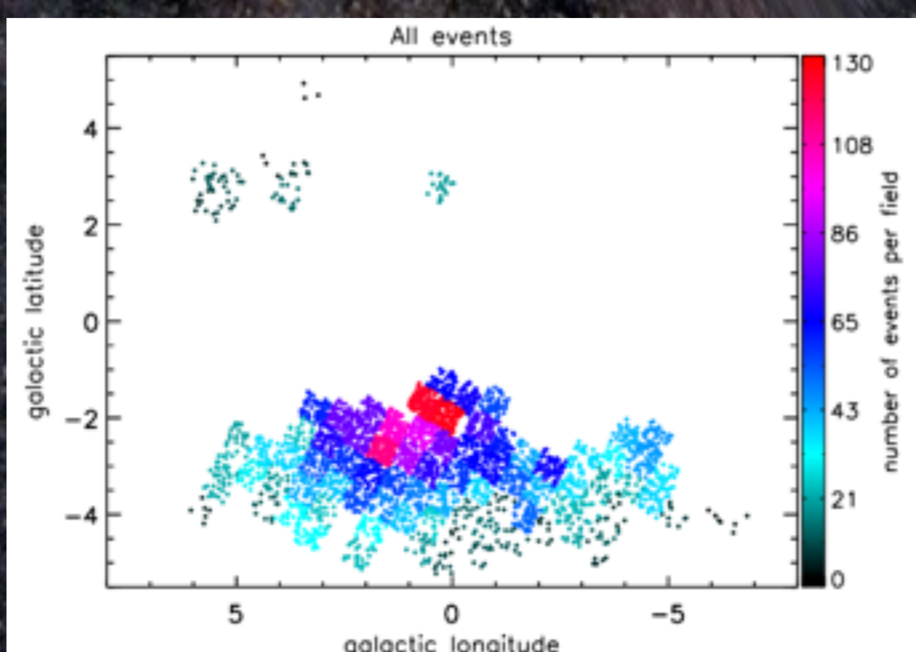
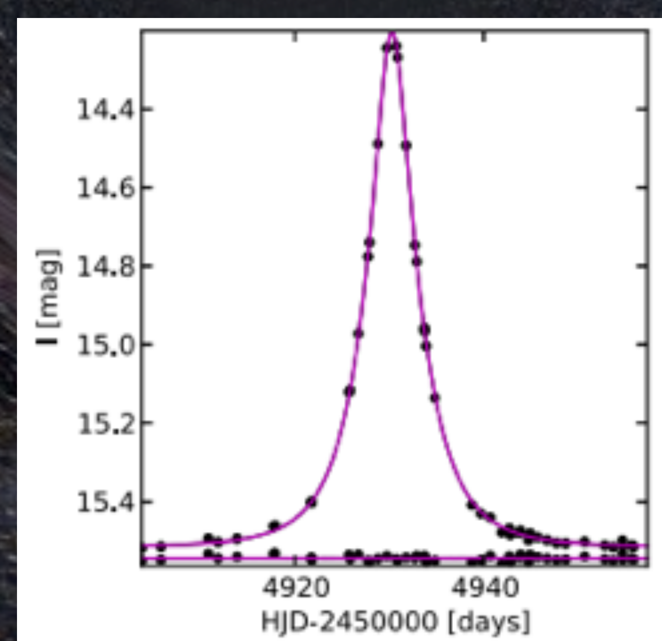
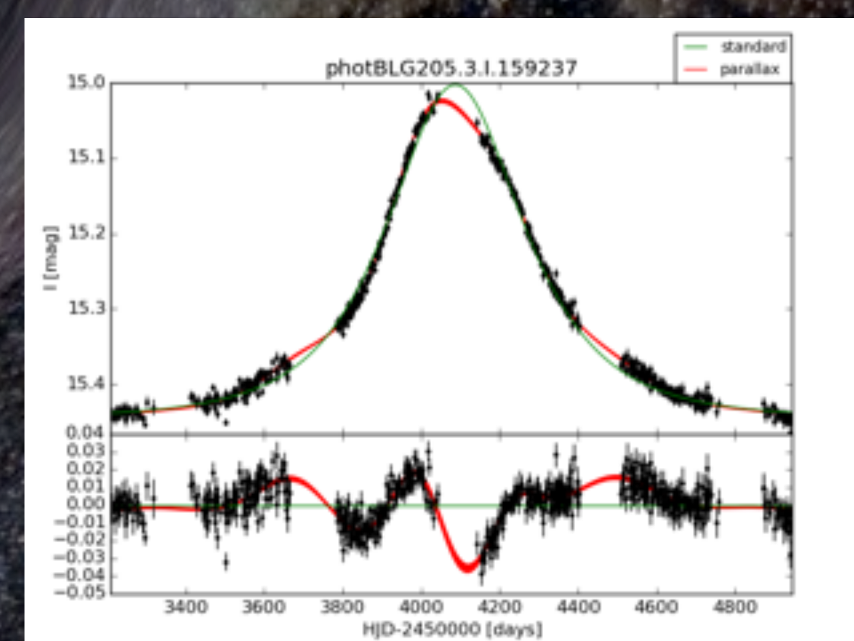
SEARCH FOR LENSING REMNANTS

- OGLE-III: 2001-2009
- 150 millions of stars in the Bulge
- 3500 standard events
- 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+2015





Wyrzykowski+ 2016

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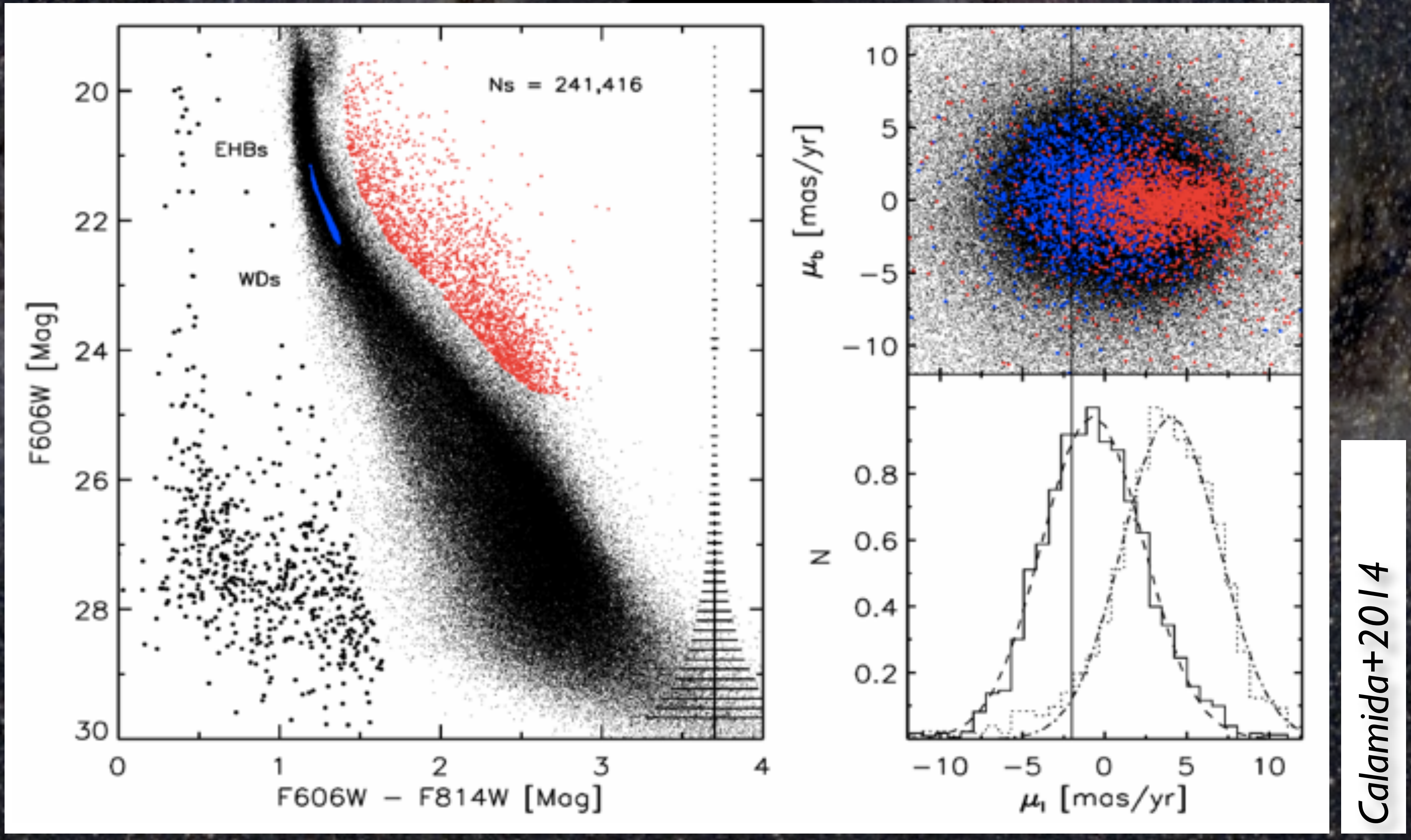
GUESSING THE MASS

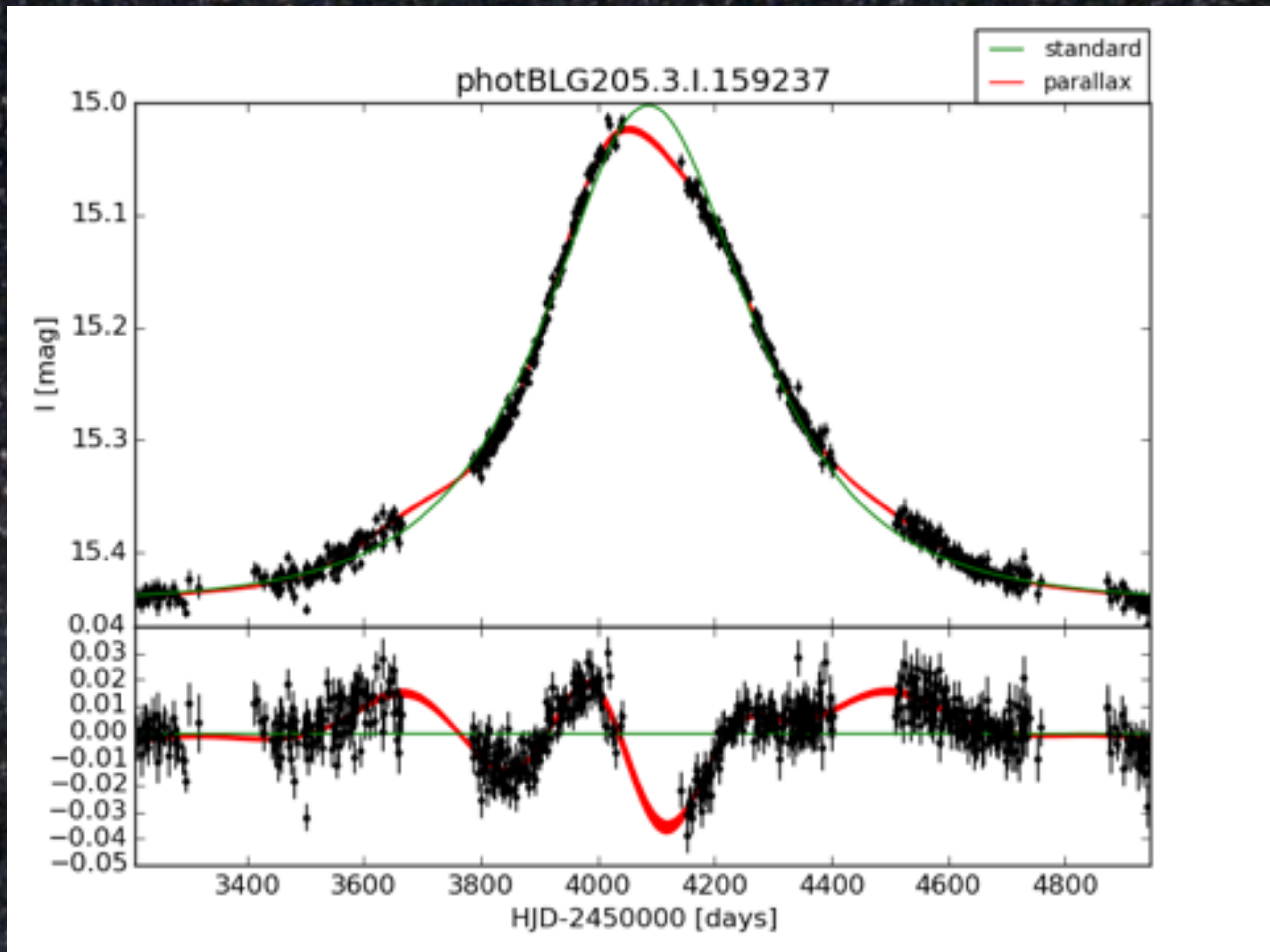
Assume:

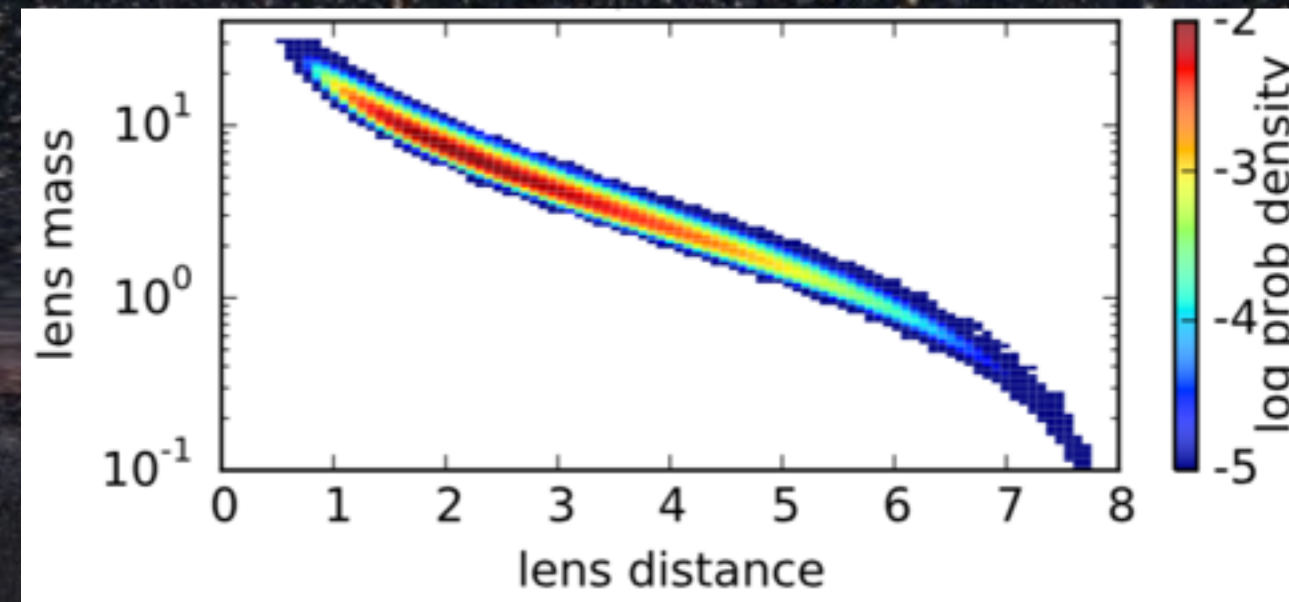
- source is in the Bulge (selected sources from RC region)
- lens is in the Disk
- stellar remnants in the Galactic Disk move as all the stars

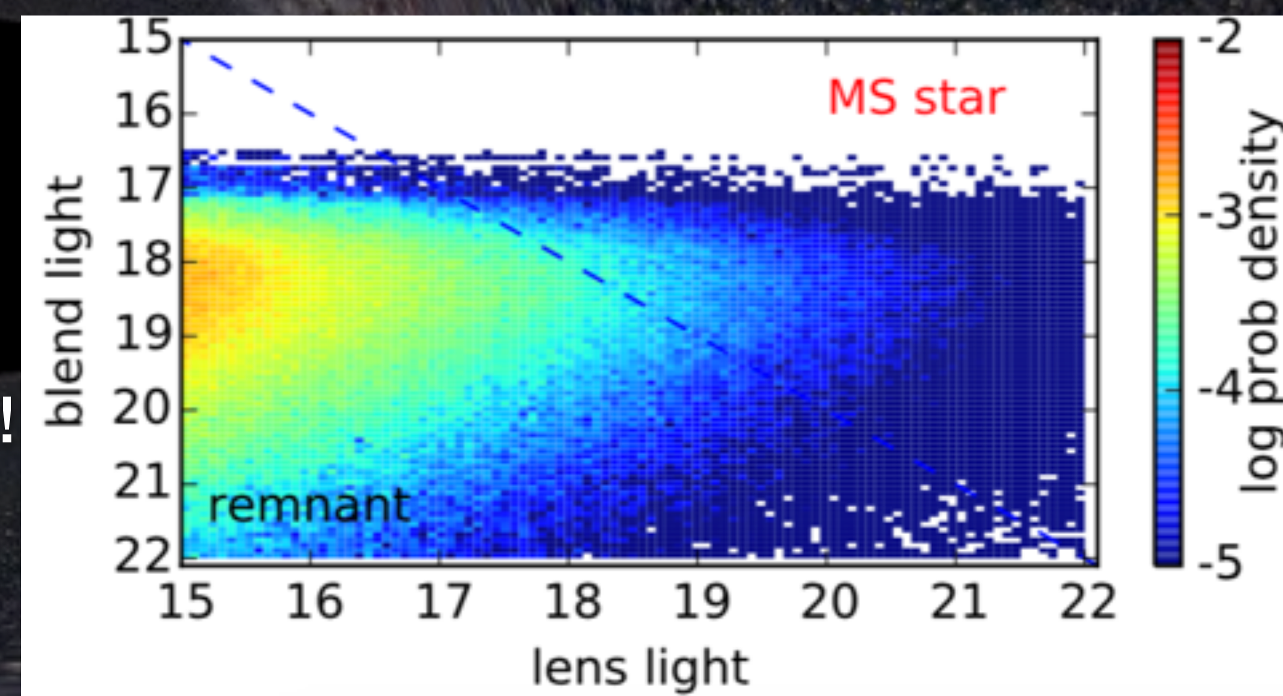
$$M = \frac{\theta_E}{\kappa \pi_E} = \frac{\mu_{rel} t_E}{\kappa \pi_E}$$



BH CANDIDATES







second longest lasting microlensing event ever!

~6 years of lensing!

OGLE3-ULENS-	t_E [d]	Mass [$M_\odot$]	Distance [kpc]
PAR-02 (Odra) solution +	296	$6.9^{+4.0}_{-3.0}$	$1.9^{+1.2}_{-0.6}$
solution -	256	$8.3^{+4.6}_{-3.2}$	$2.4^{+1.3}_{-0.7}$

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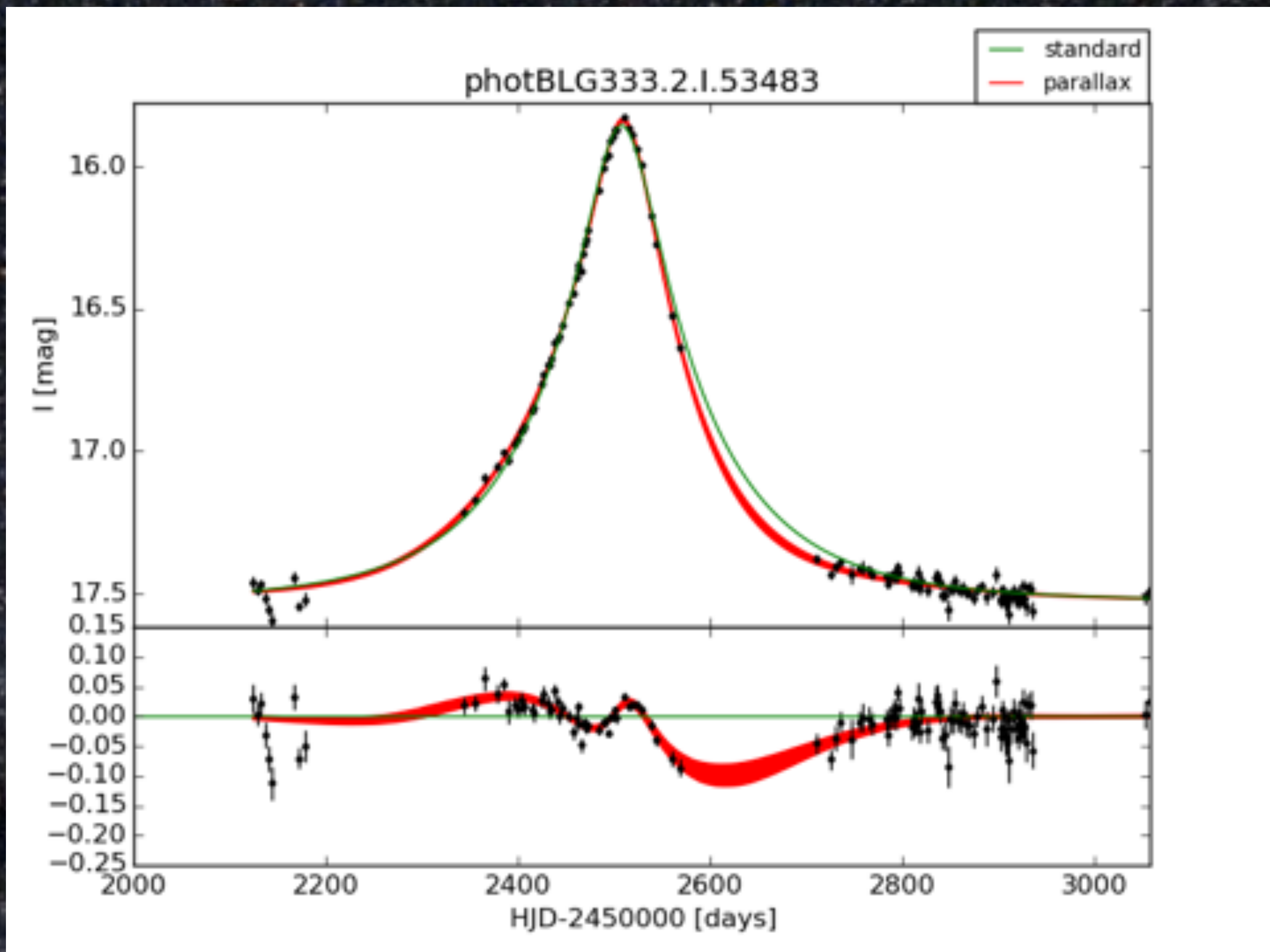

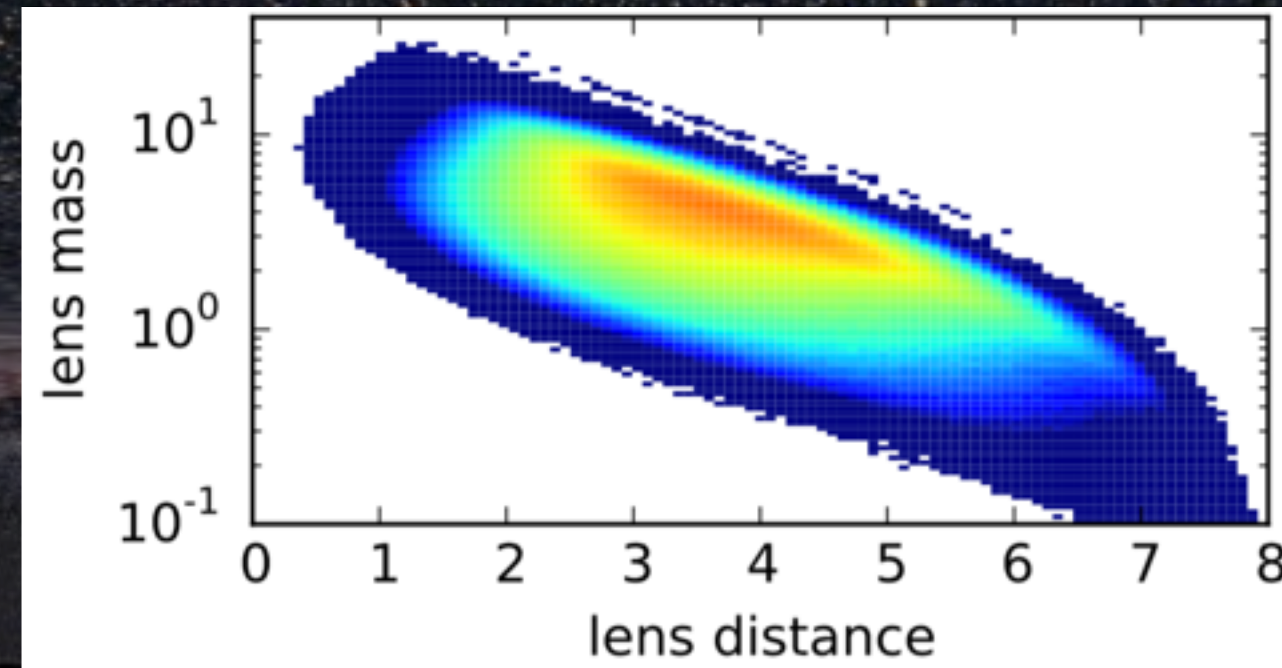

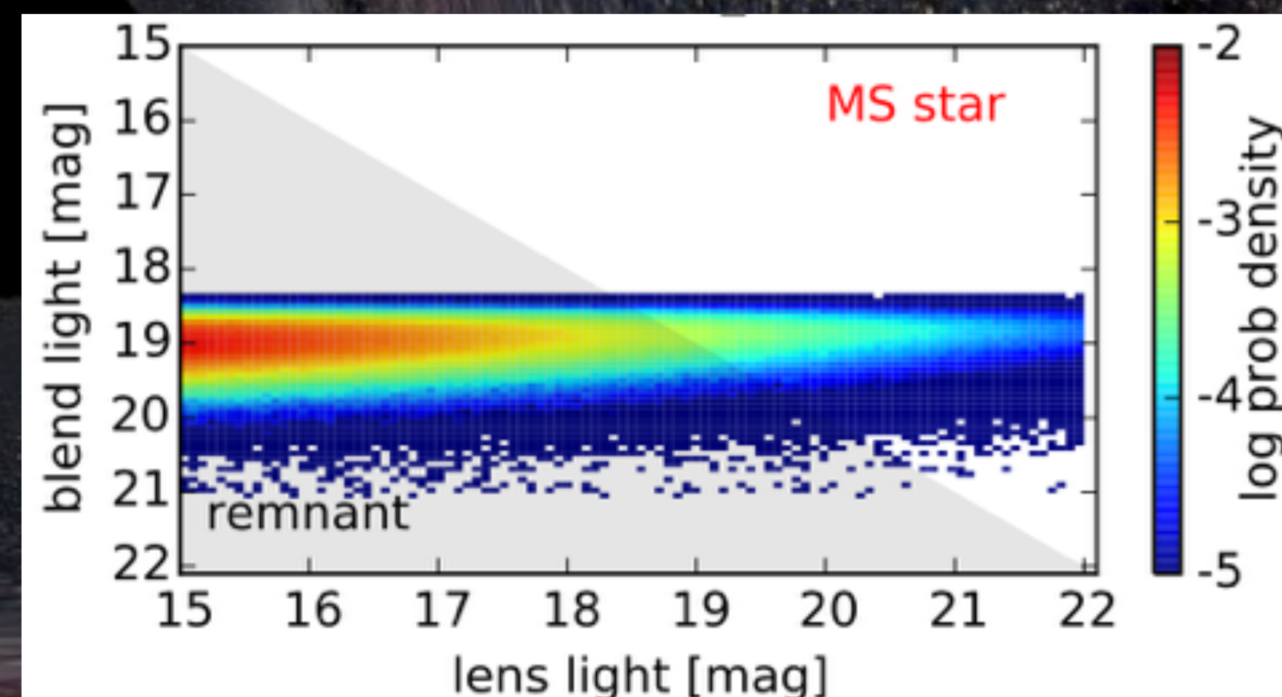

OGLE3-ULENS-	t_E [d]	Mass [$M_\odot$]	Distance [kpc]
PAR-13 (Obra) solution +	172	$5.3^{+2.7}_{-2.1}$	$2.9^{+1.4}_{-1.0}$
solution -	171	$4.9^{+2.8}_{1.9}$	$2.4^{+1.4}_{-0.9}$

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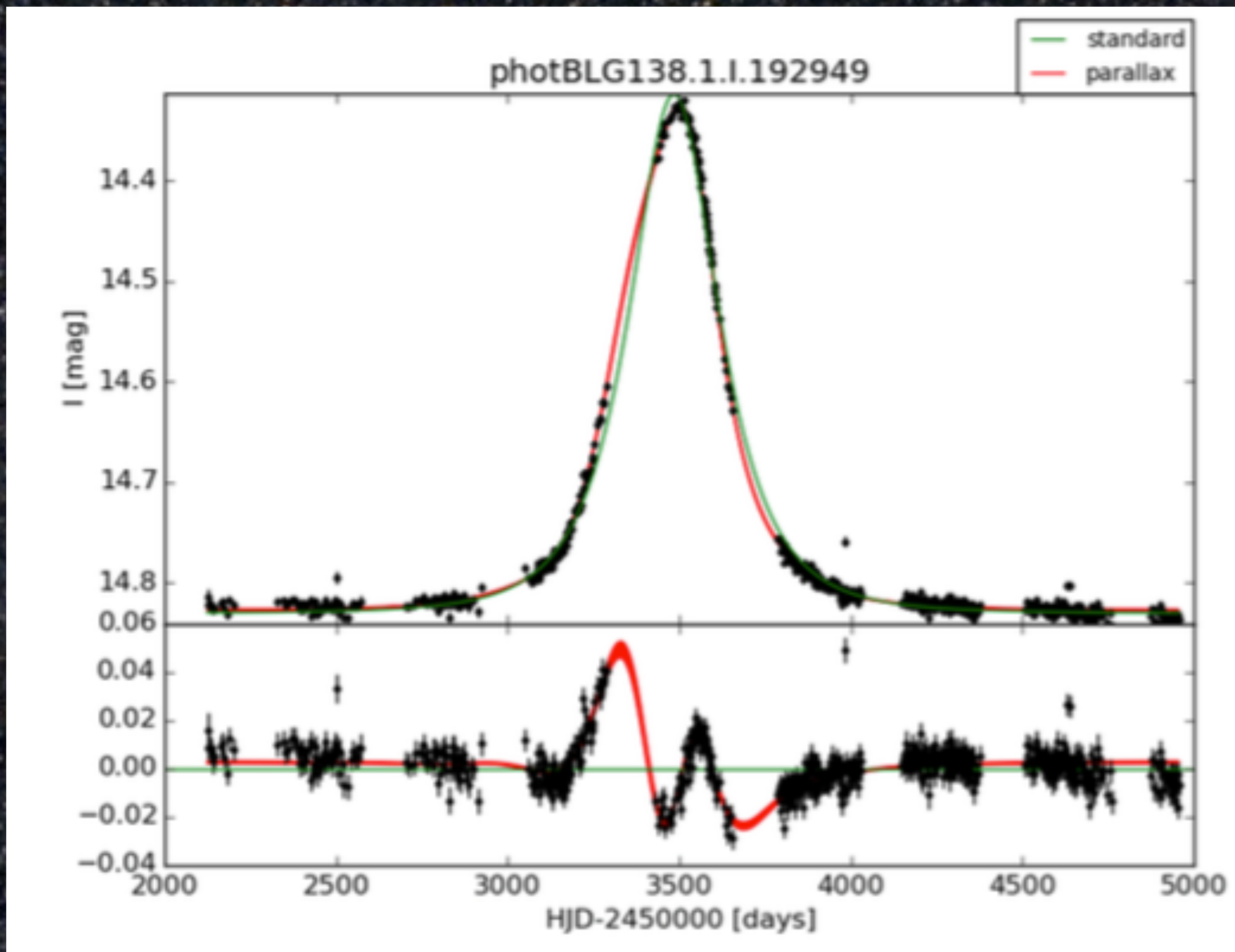
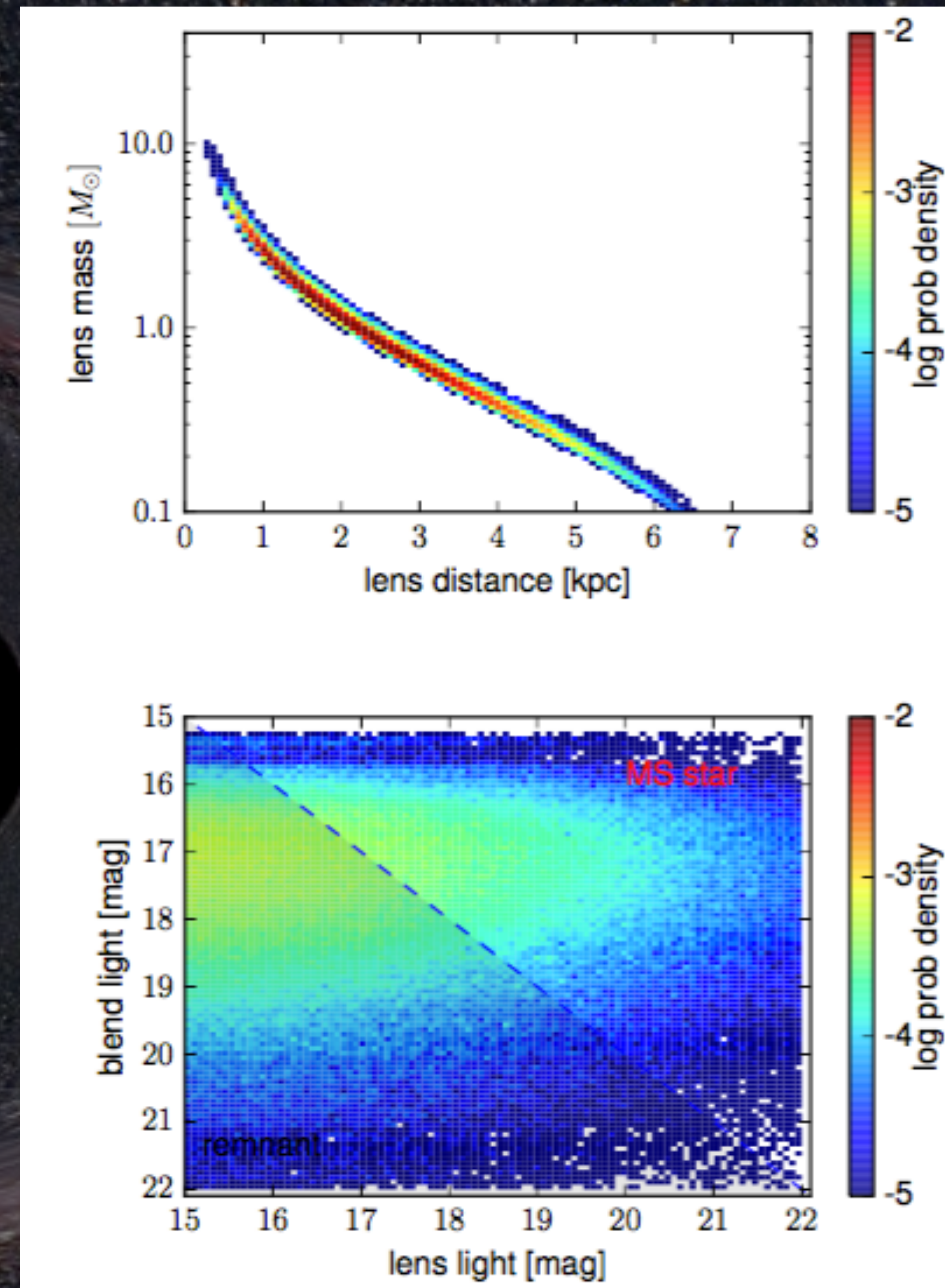
BH CANDIDATES





OGLE3-ULENS-	t_E [d]	Mass [$M_\odot$]	Distance [kpc]
PAR-05 (Narew) solution +	174	$3.3^{+1.9}_{-1.3}$	$2.6^{+1.3}_{-0.8}$
solution -	176	$4.0^{+2.1}_{-1.7}$	$2.0^{+1.1}_{-0.6}$

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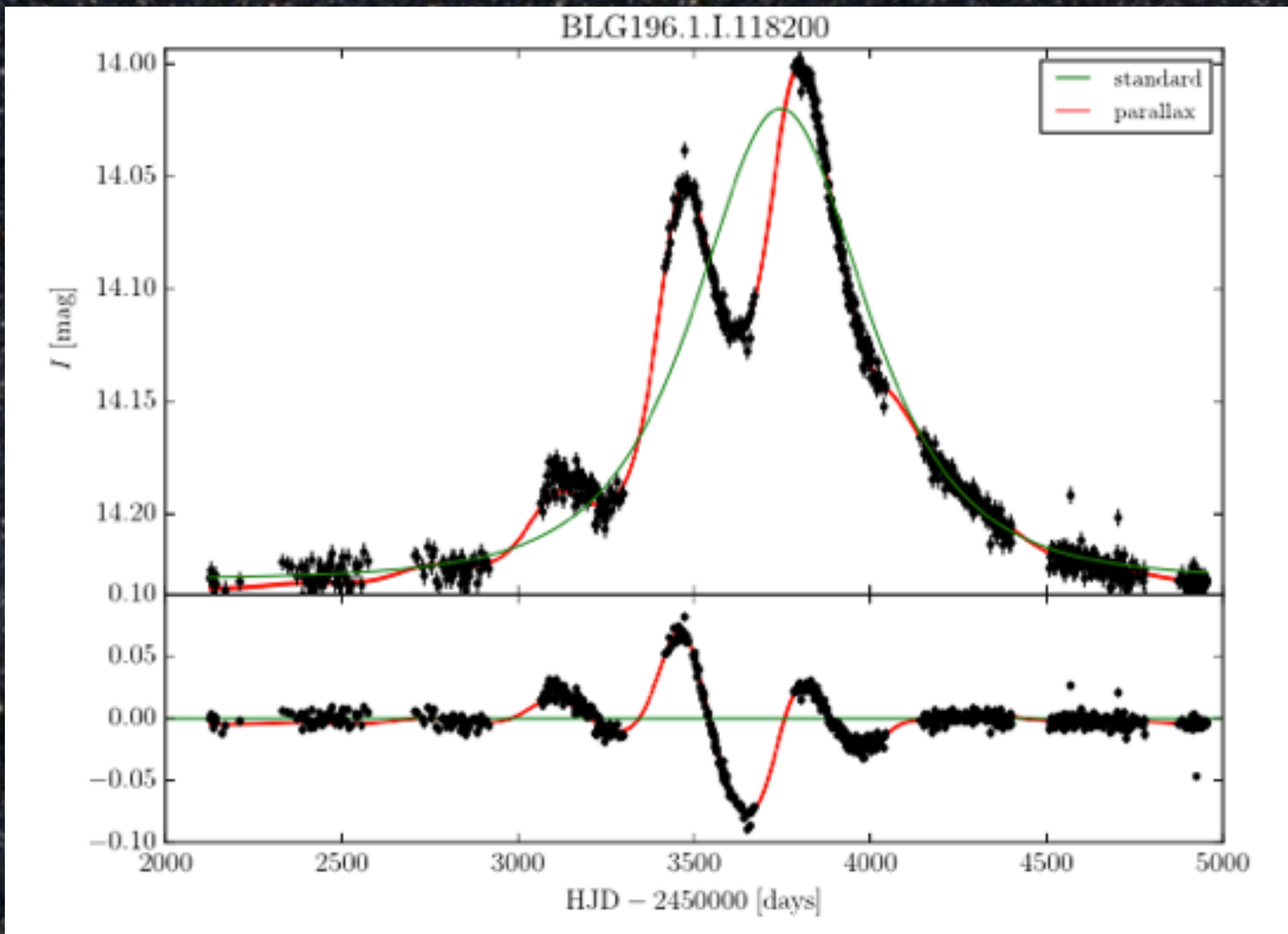
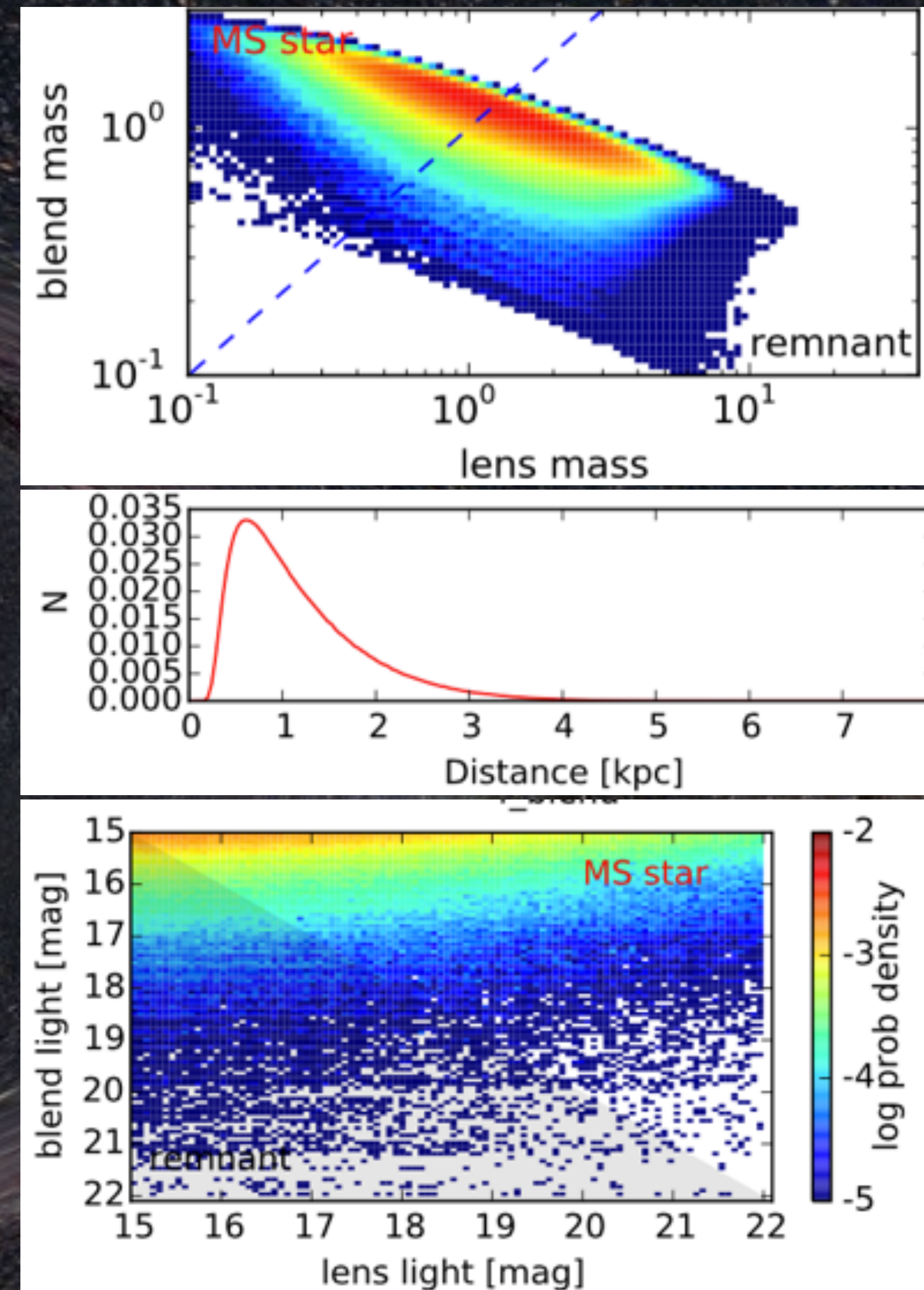
NEARBY WHITE DWARF OR NEUTRON STAR?





five-peak parallax event
length: ~8 years
the longest microlensing event ever!

OGLE3-ULENS-	t_E [d]	Mass [$M_\odot$]	Distance [kpc]
PAR-01 (Vistula)	325	$1.5^{+1.5}_{-0.9}$	$0.6^{+0.5}_{-0.2}$

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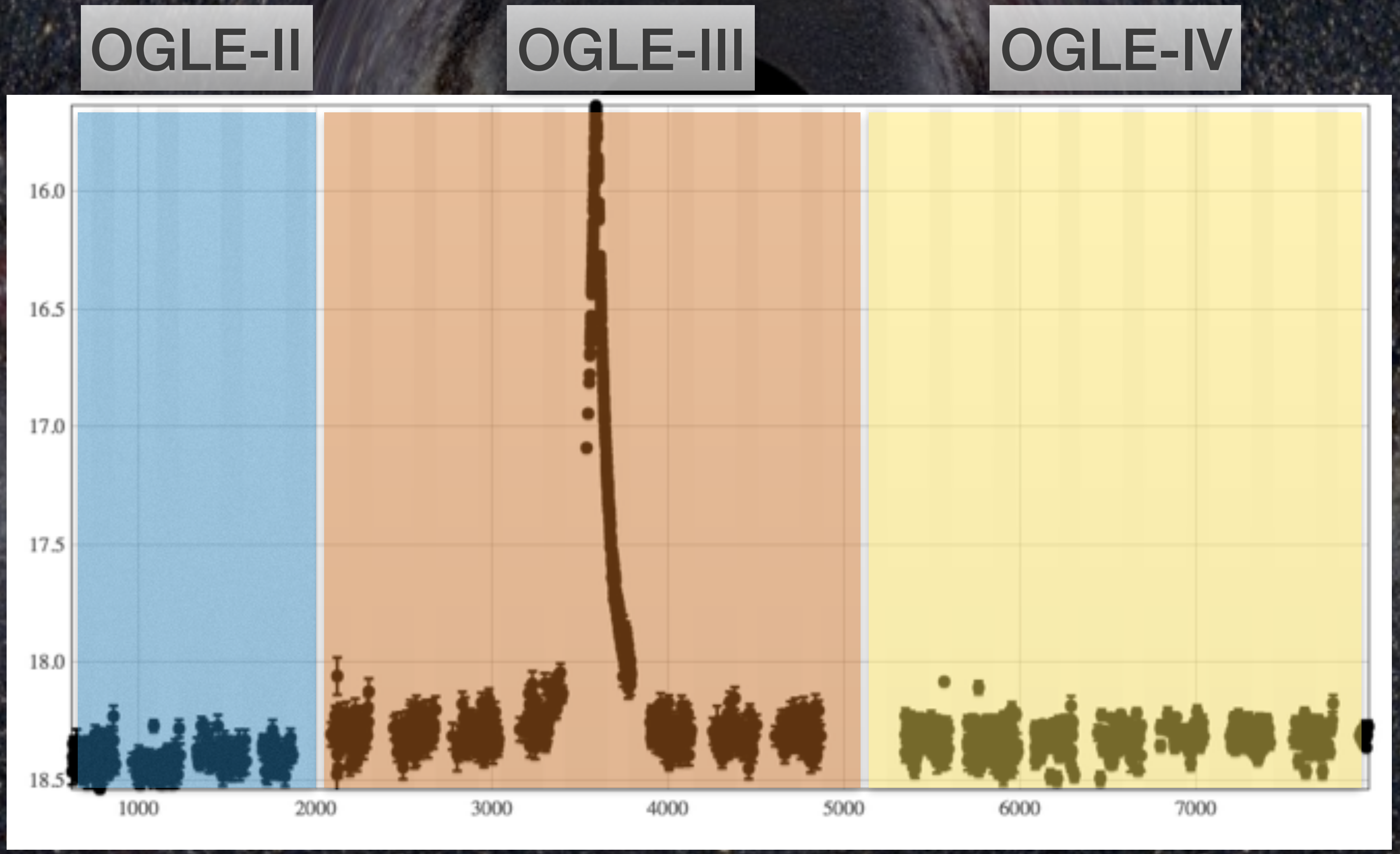
FUTURE WORK

OGLEII + OGLEIII + OGLEIV = 20 years-long light curves

search for events with M_{BH} ~100 MSun (GW-like)

t_E > 4 years



1997 OGLE-2005-SMC-001 2017

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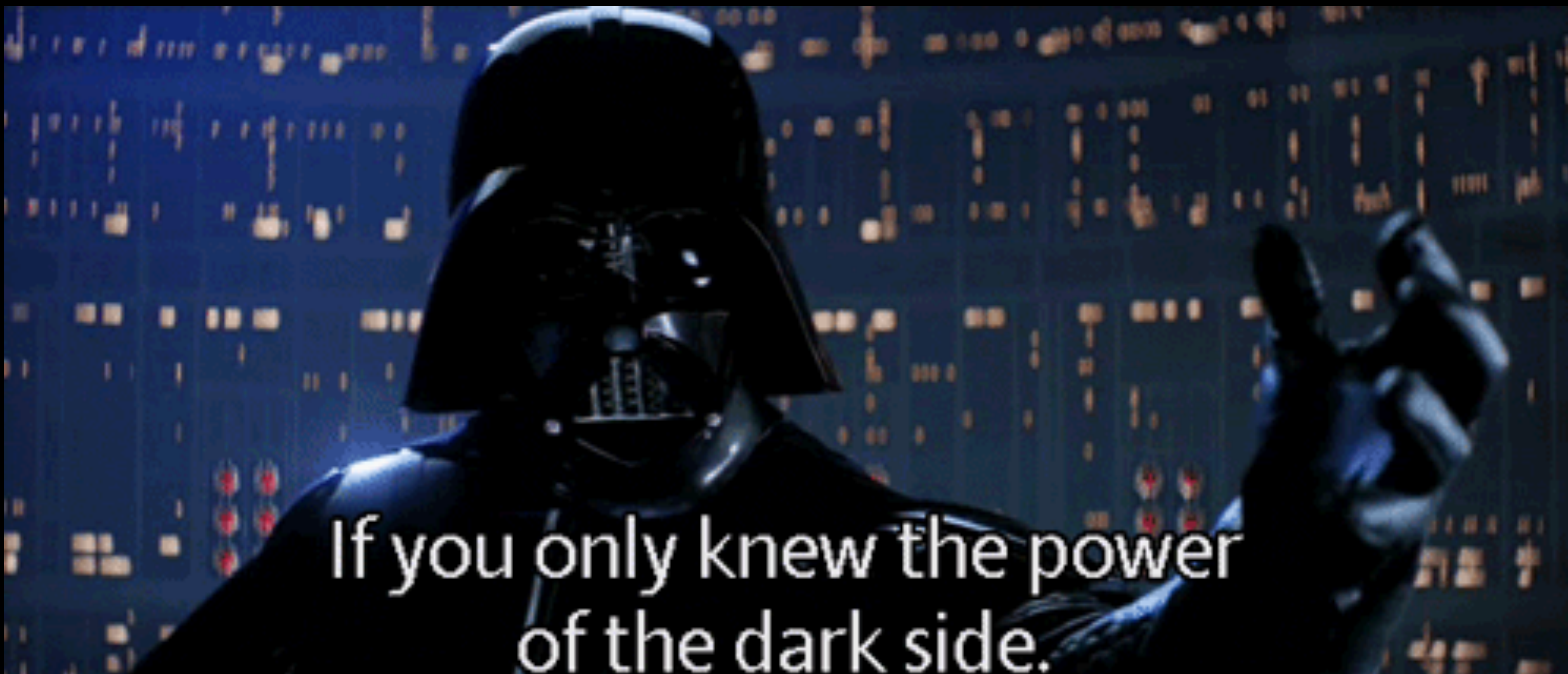
BLACK HOLES IN WFIRST

+ infrared - low extinction
+ Bulge densest area
+ many sources - higher lensing probability
+ astrometric microlensing = Einstein radius

- short monitoring time-baseline (2yrs)
- 6x72d seasons

SUMMARY

- no room for Dark Matter in form of MACHOs below 10 MSun
- M>10 MSun still possible -> Black Holes
- couple of candidates for lensing BHs so far
- parallax and Einstein Radius needed to confirm BH *(Gaia will help - see my Thursday talk)*
- microlensing can constrain GW BHs in the MW
- WFIRST would be great for BHs, but observing window too short


If you only knew the power
of the dark side.