Constraining PBHs with microlensing

Masahiro Takada (Kavli IPMU)

Collaborators: Hiroko Niikura (IPMU), Naoki Yasuda (IPMU), T. Sumi (Osaka), S. More (IUCAA/IPMU)、Robert Lupton (Princeton), Sunao Sugiyama (IPMU), Toshiki Kurita (IPMU), et al.

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

wpi

@Kavli IPMU, Dec 2019

PBH special session at annual meeting of the Physics Society of Japan (over 200 participants)

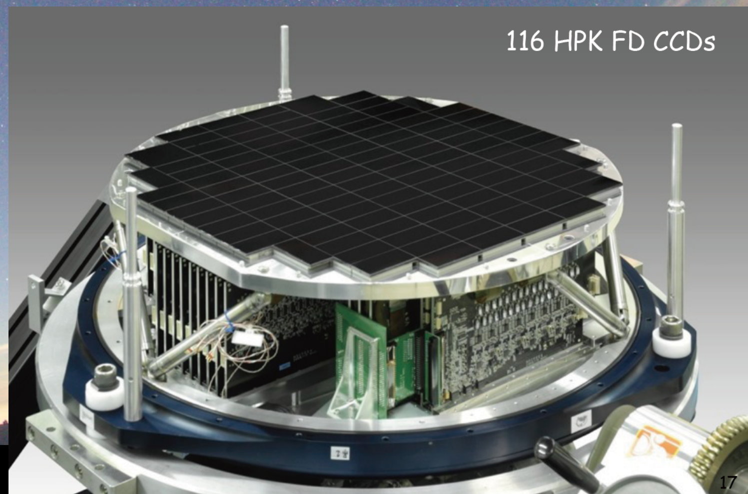
Contents of my talk

- Microlensing constraints on PBH with Subaru
- Microlensing constraints on PBH with OGLE
- Future prospects for PBHs/LIGO BHs

8.2m Subaru/Hyper Suprime-Cam

- Large aperture (8.2m)
- Wide FoV = 9×full moon
- ~1G pixels (104 CCDs)

Kavli IPMU+NAOJ+Princeton+ASIAA

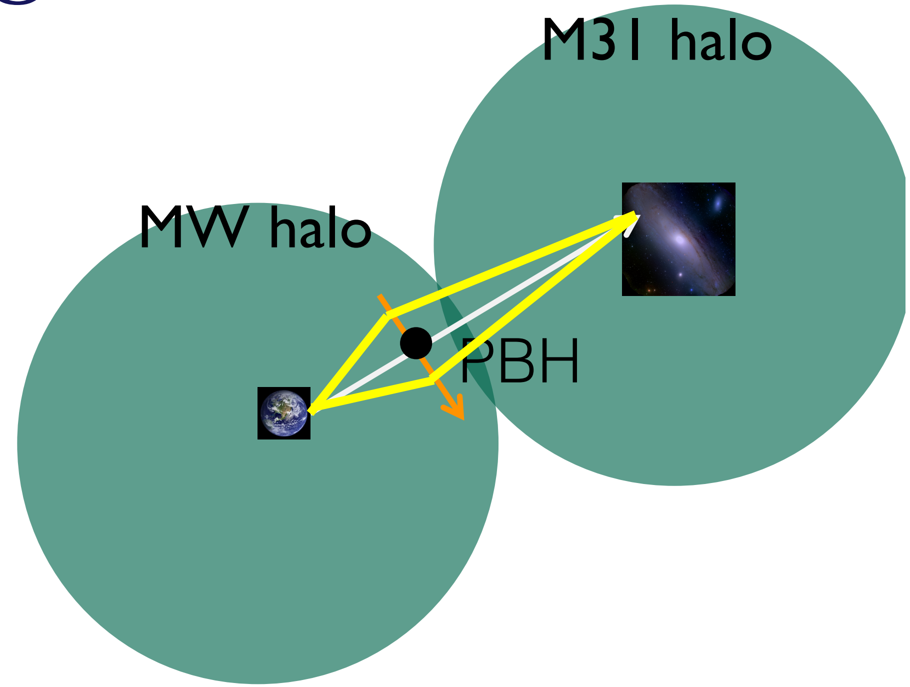


Microlensing search of stars in Andromeda Galaxy (M31)

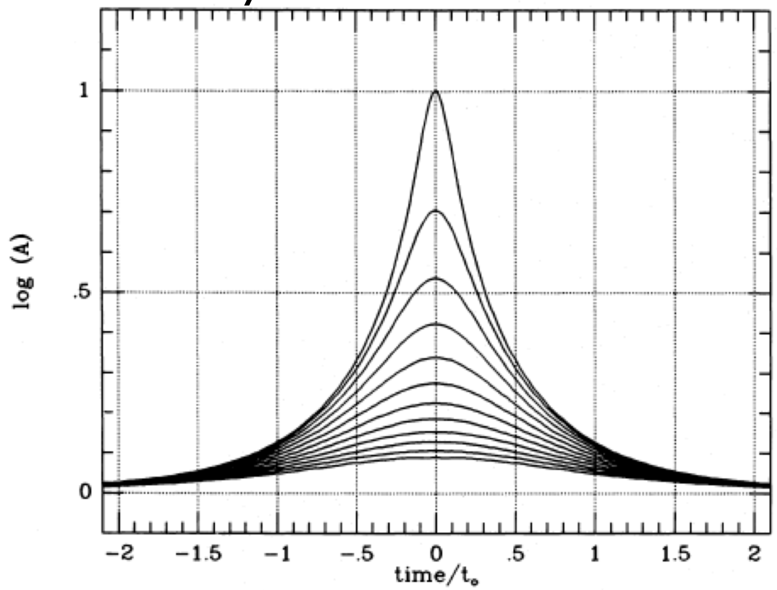
- In the northern hemisphere (not accessible from VST, DES, LSST)
- Large spiral galaxy
- HSC FoV ~ entire M31
- ~770kpc (μ~24.4), reachable distance (not too far)!

PBH microlensing of M31 star

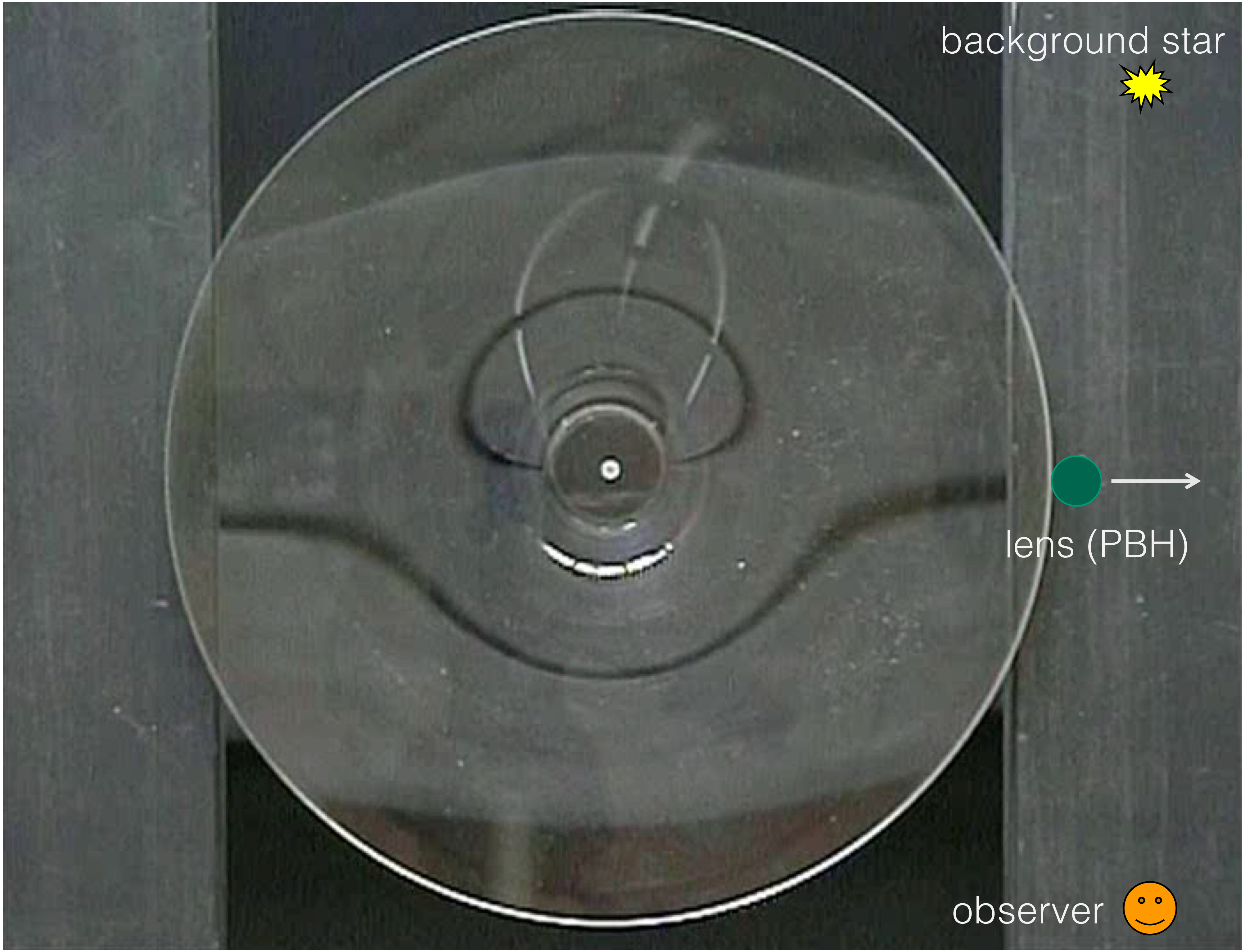
- <a few Msun BH ⇒ PBH
- Lensed image can't be resolved with optical resolution ($\sim 10^{-8}$ arcsec) ⇒ only light curve is a signal
- MW/M31 halo ~ 10^{12}Msun (we assumed NFW models)
- PBH has a peculiar velocity of ~200km/s
- ~1000 expected events if PBH is DM
- Need to monitor brightness of the same star as a function of "time" (time domain astronomy)

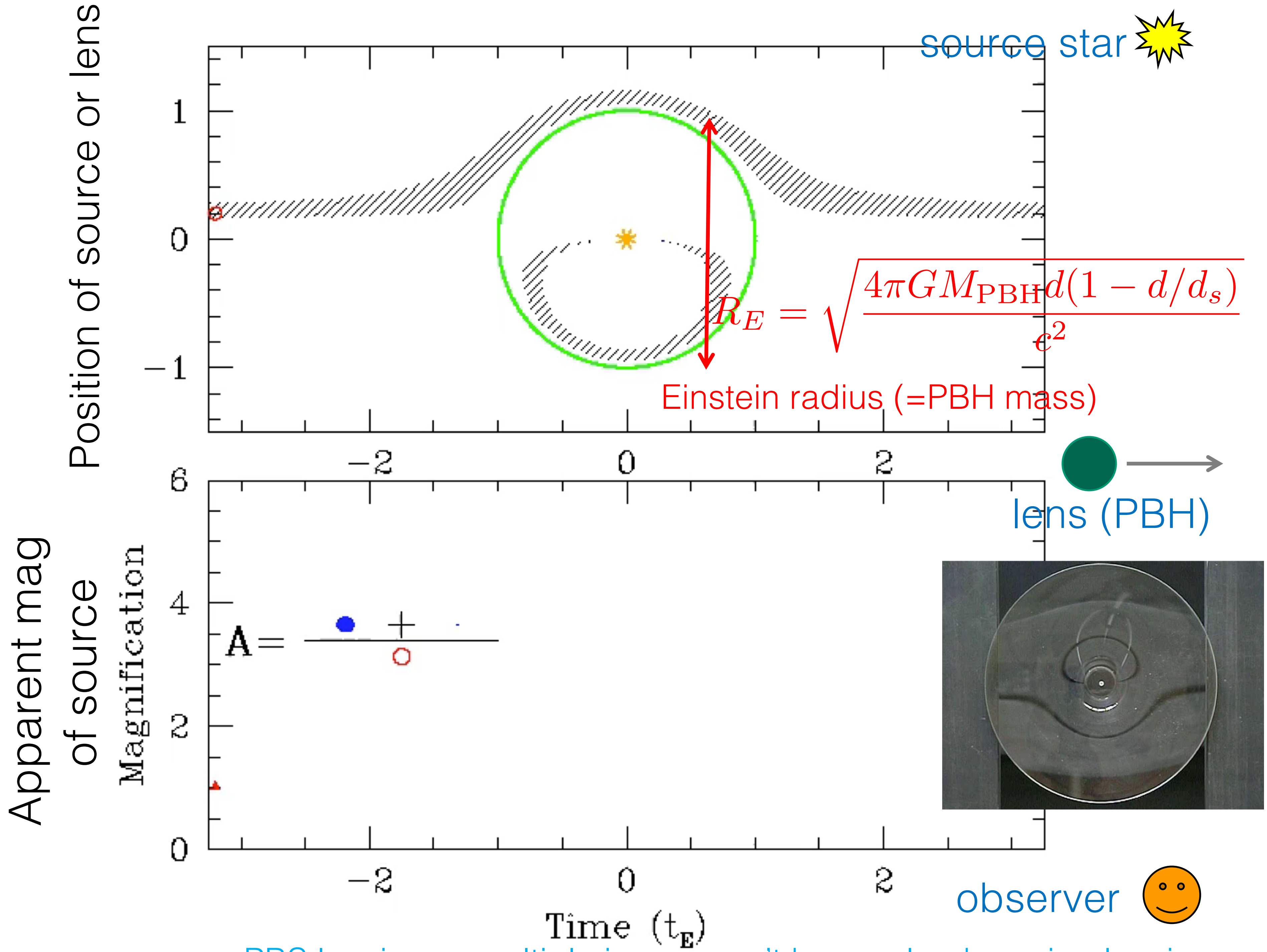


Paczynski 86



$$R_E = \sqrt{\frac{4\pi G M_{\rm PBH} d(1-d/d_s)}{c^2}}$$

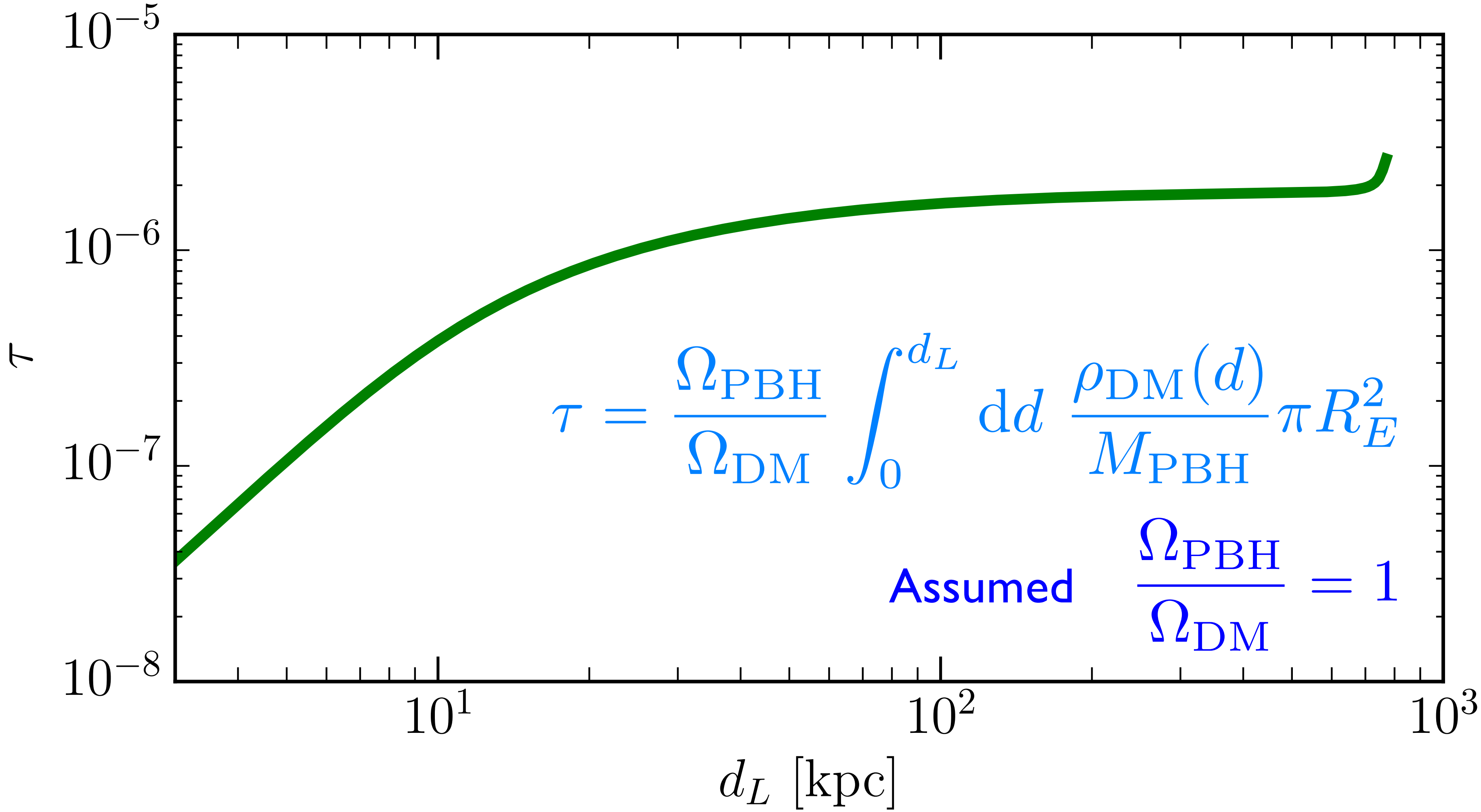

background star
lens (PBH)
observer



PBS lensing ⇒ multiple image can't be resolved ⇒ microlensing

PBH microlensing on M31 star

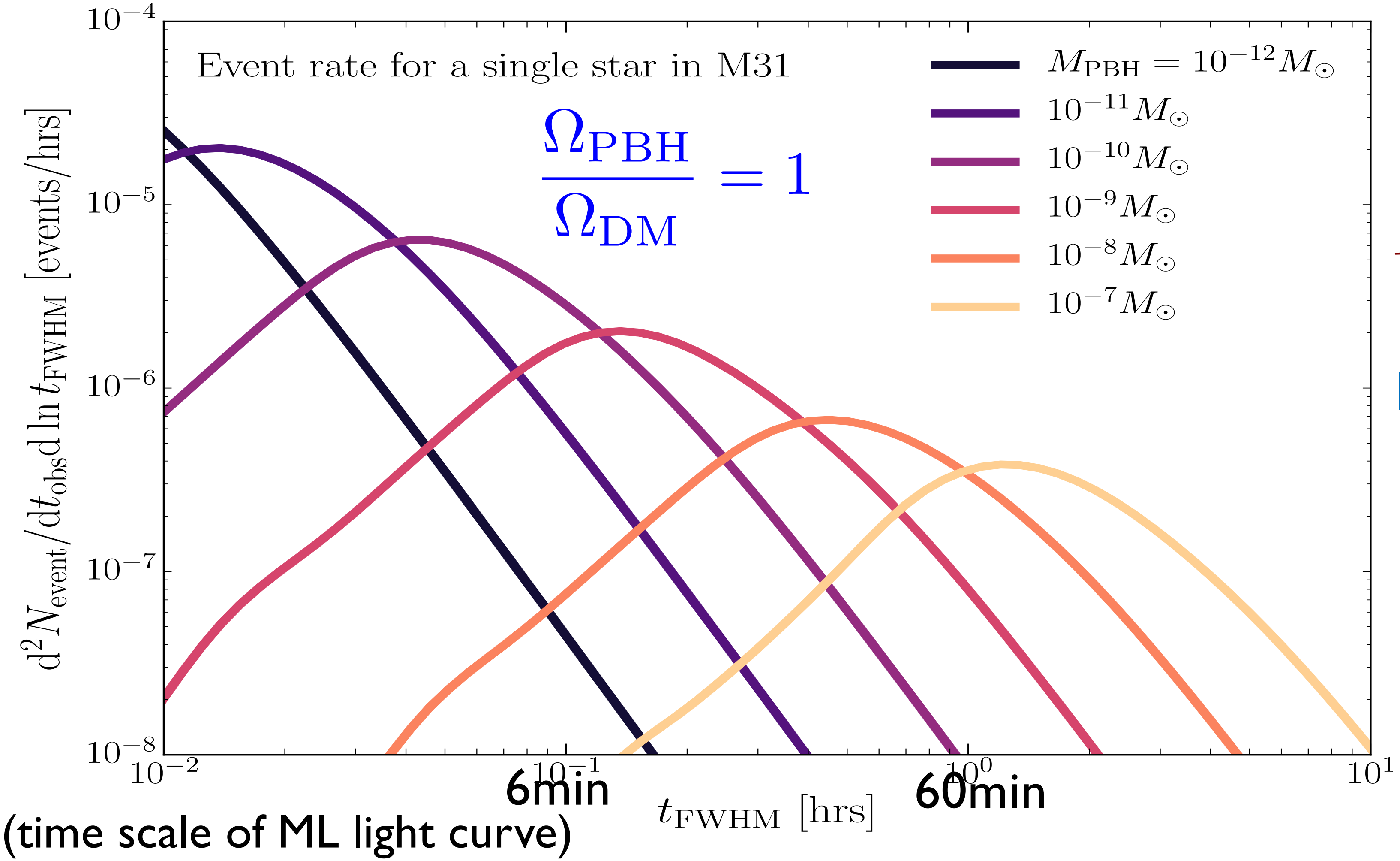
Cumulative optical depth of PBH microlensing for a **single** star in M31

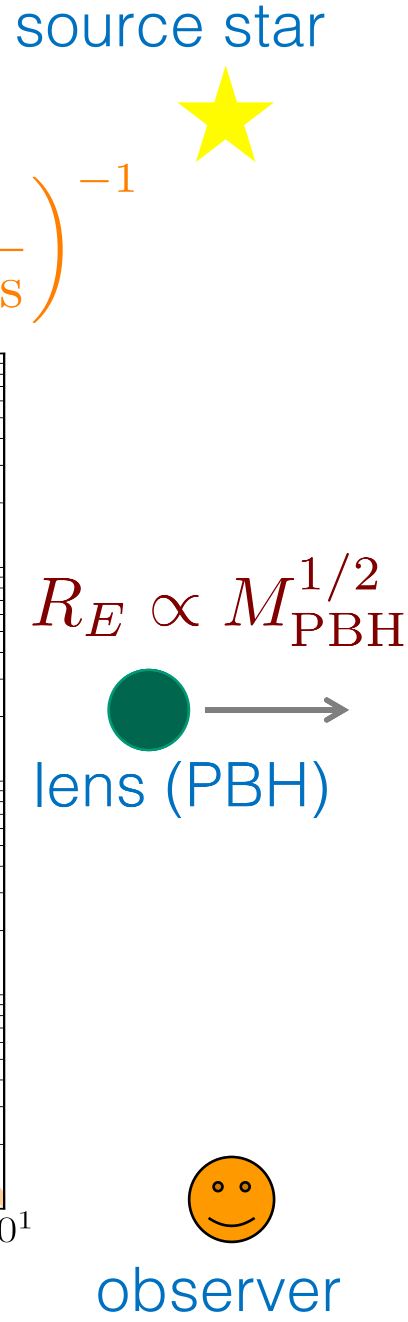


If we observe **~10^6 stars** at one time, **one star at leas** should be micro-lensed if PBHs are DM

PBH microlensing event rate

$$t_E \sim \frac{d_L \theta_E}{v_{\rm PBH}} \sim 34\ {\rm min} \left(\frac{M_{\rm PBH}}{10^{-8} M_\odot}\right)^{1/2} \left(\frac{d_L}{100\ {\rm kpc}}\right) \left(\frac{v_{\rm PBH}}{200\ {\rm km/s}}\right)^{-1}$$

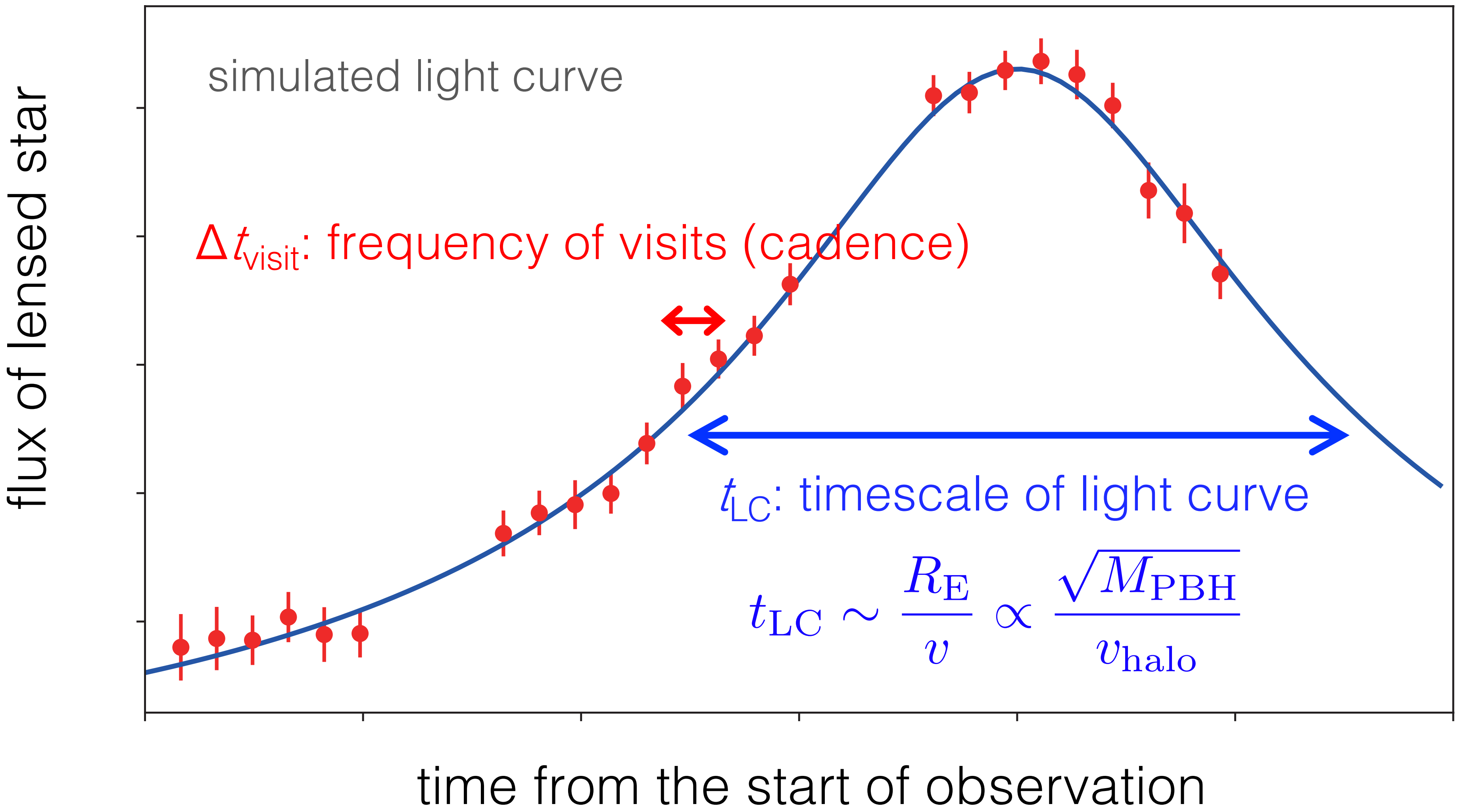


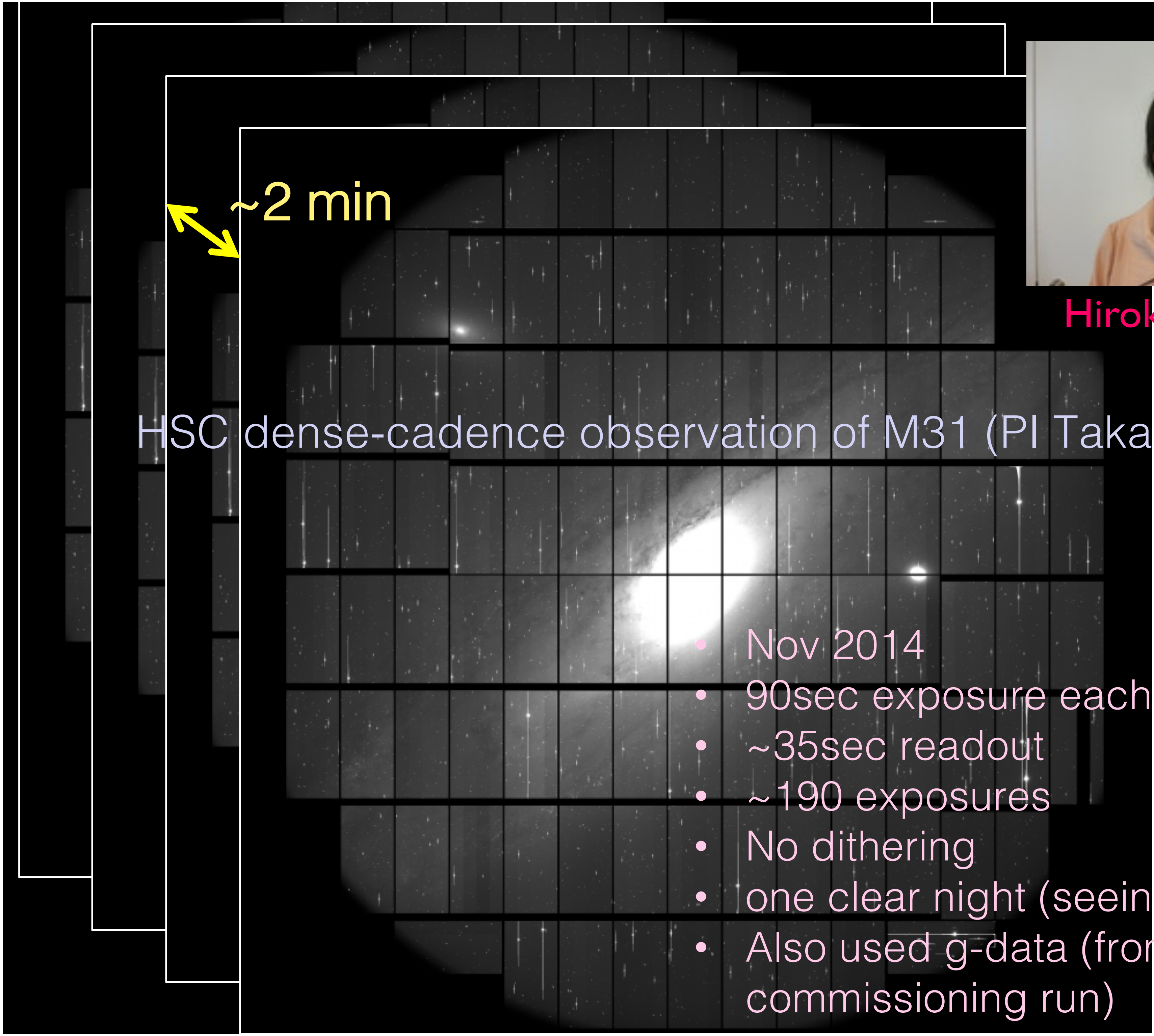


Event rate per **unit obs. time** and per **a single star** in M31 for **a given timescale of light curve (we monitored ~10^8 stars)**

Rule of the game: LC timescale vs. Cadence

Design the ML observation satisfying the condition $\Delta t_{\rm visit} \sim \dfrac{t_{\rm LC}}{O(10)}$





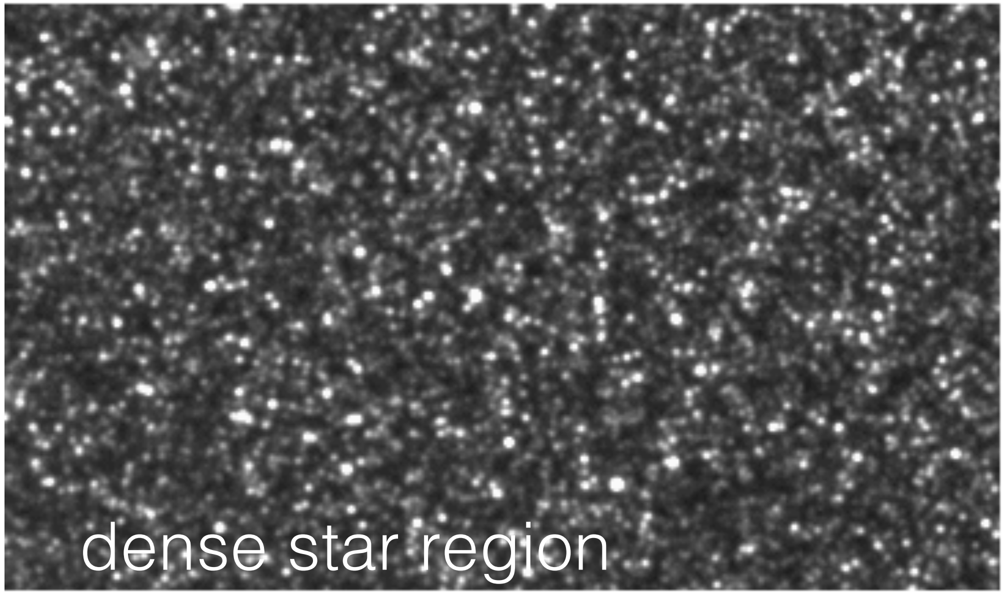
Hiroko Niikura

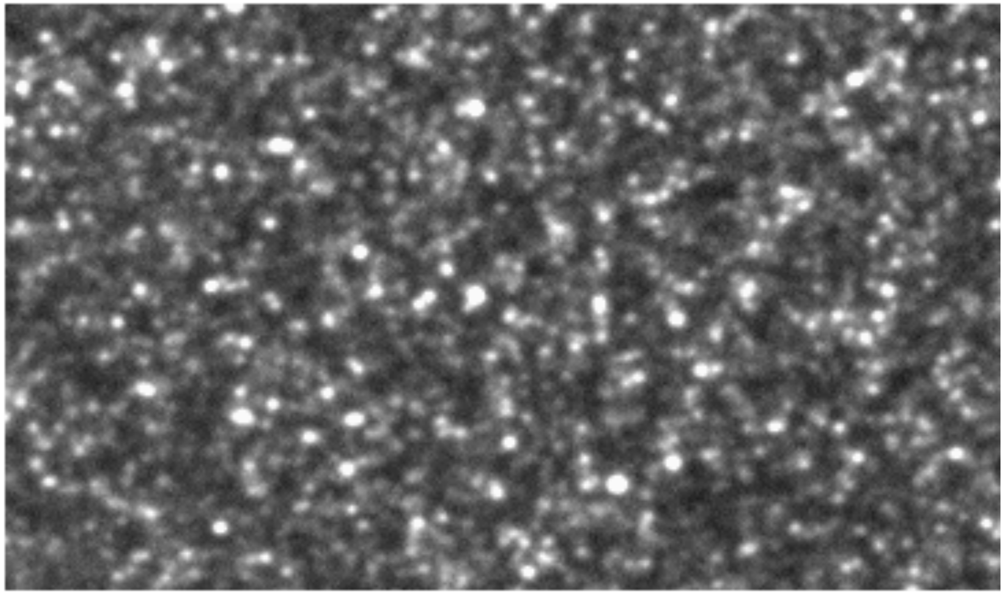
HSC dense-cadence observation of M31 (PI Takada, S14B)

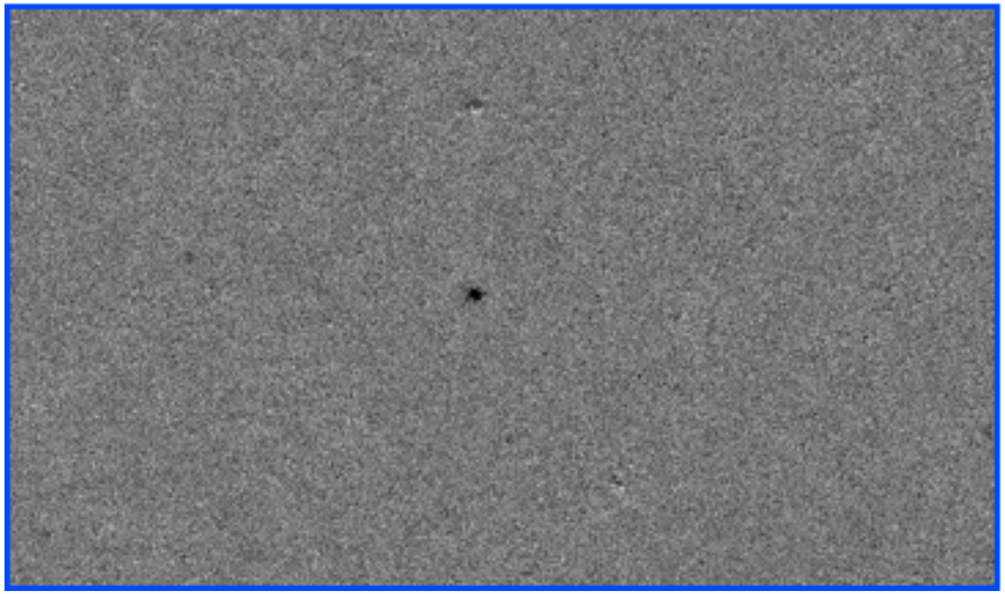
- Nov 2014
- 90sec exposure each (r-band)
- ~35sec readout
- ~190 exposures
- No dithering
- one clear night (seeing~0.5-0.6'')
- Also used g-data (from commissioning run)

Challenges: Pixel lensing

Fluxes from multiple stars are overlapped at each position







Upper left: reference image (0.5'')

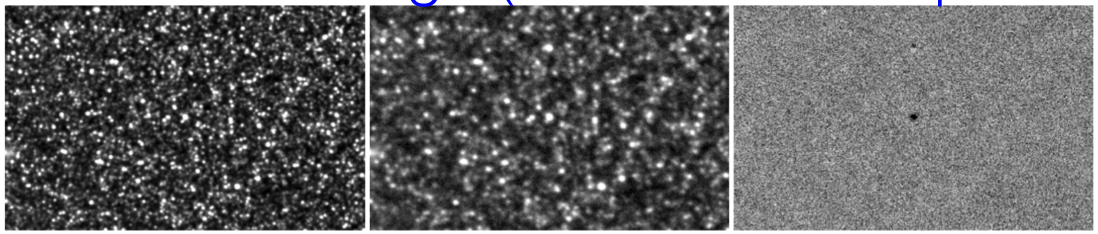
Upper right: target image (0.8'')

Lower: difference image

Accurate PSF and astrometry measurements needed.
HSC pipeline (hscPipe) works!

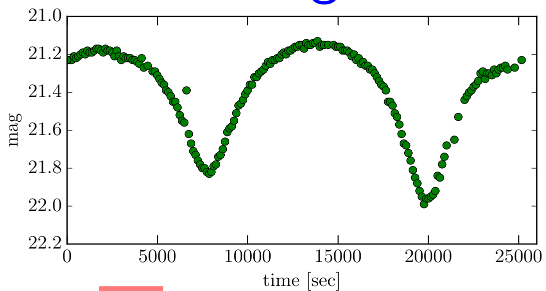
Procedures: search for ML events

difference image (coadds of 3 exposures)



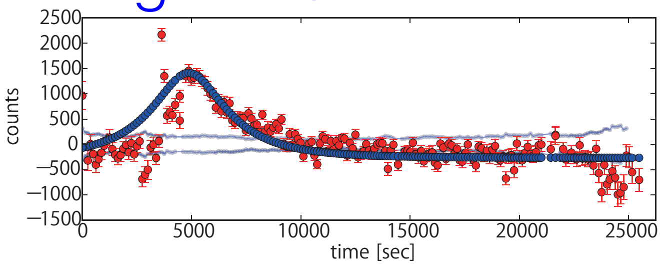
identify candidates in each diff. image
⇒15,571

measure light curve (188 data points)



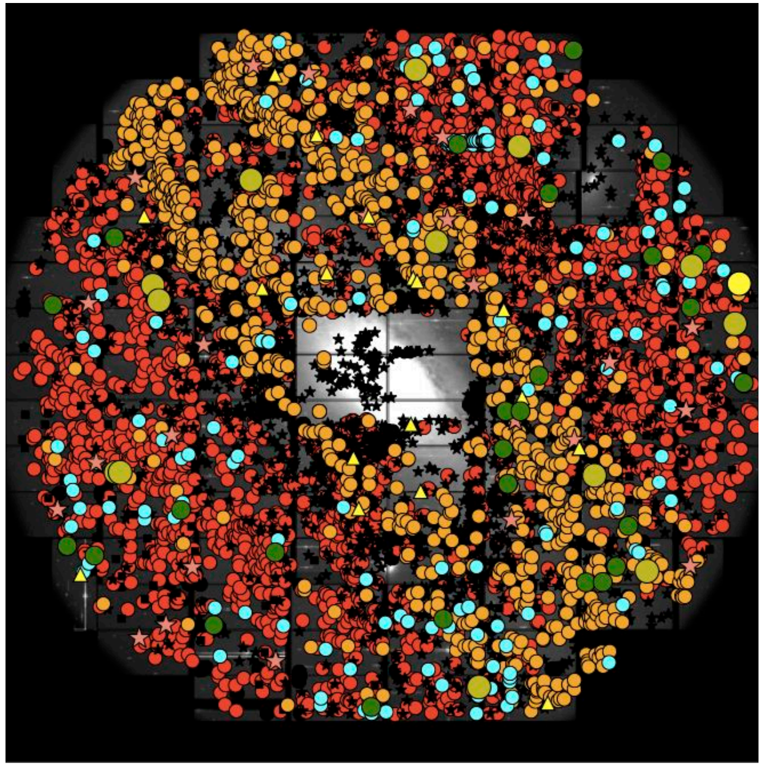
candidates with bump-like light curve
⇒ 11,703

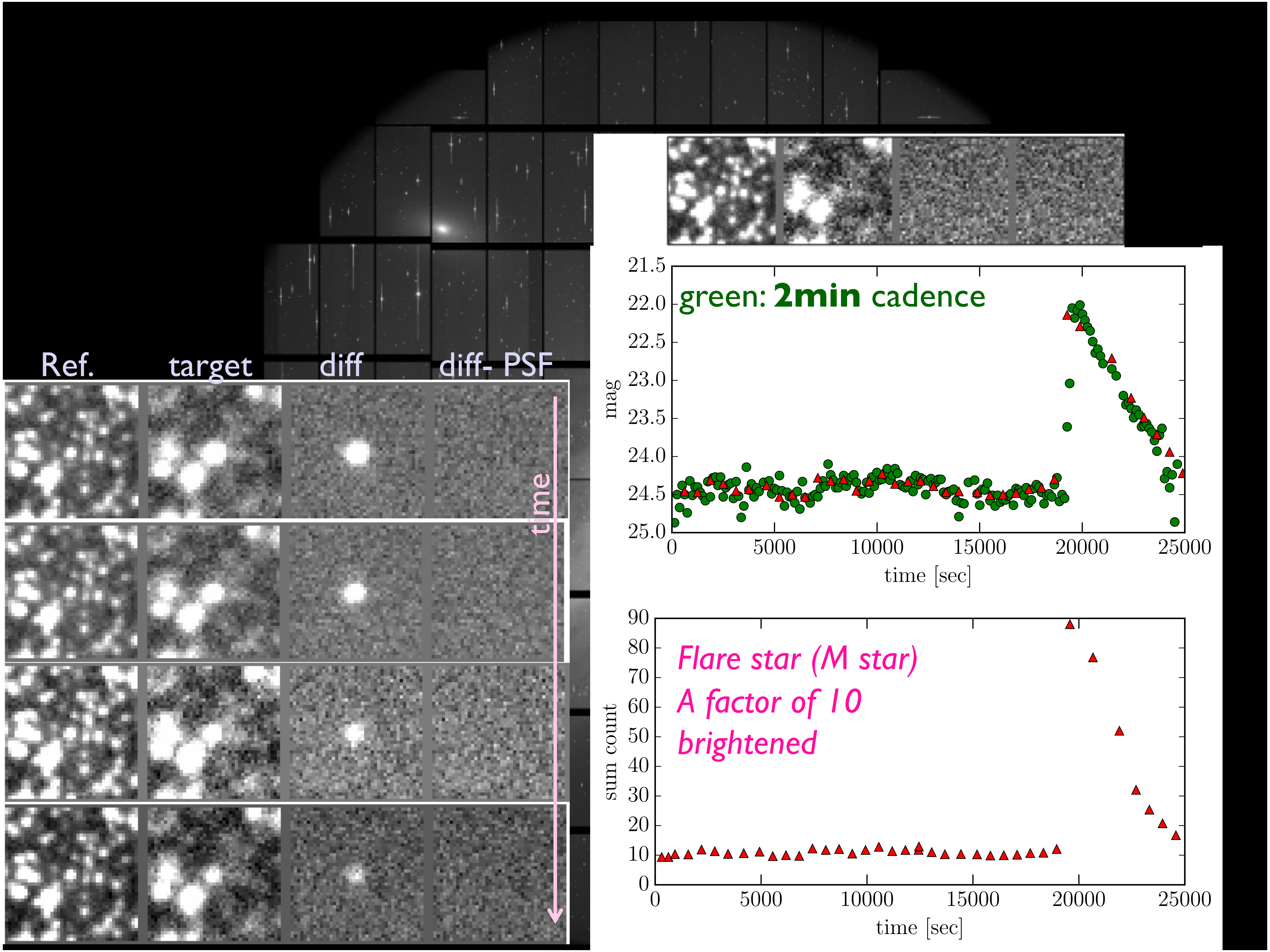
fitting of LC to the microlensing model



selection criteria
⇒ 66

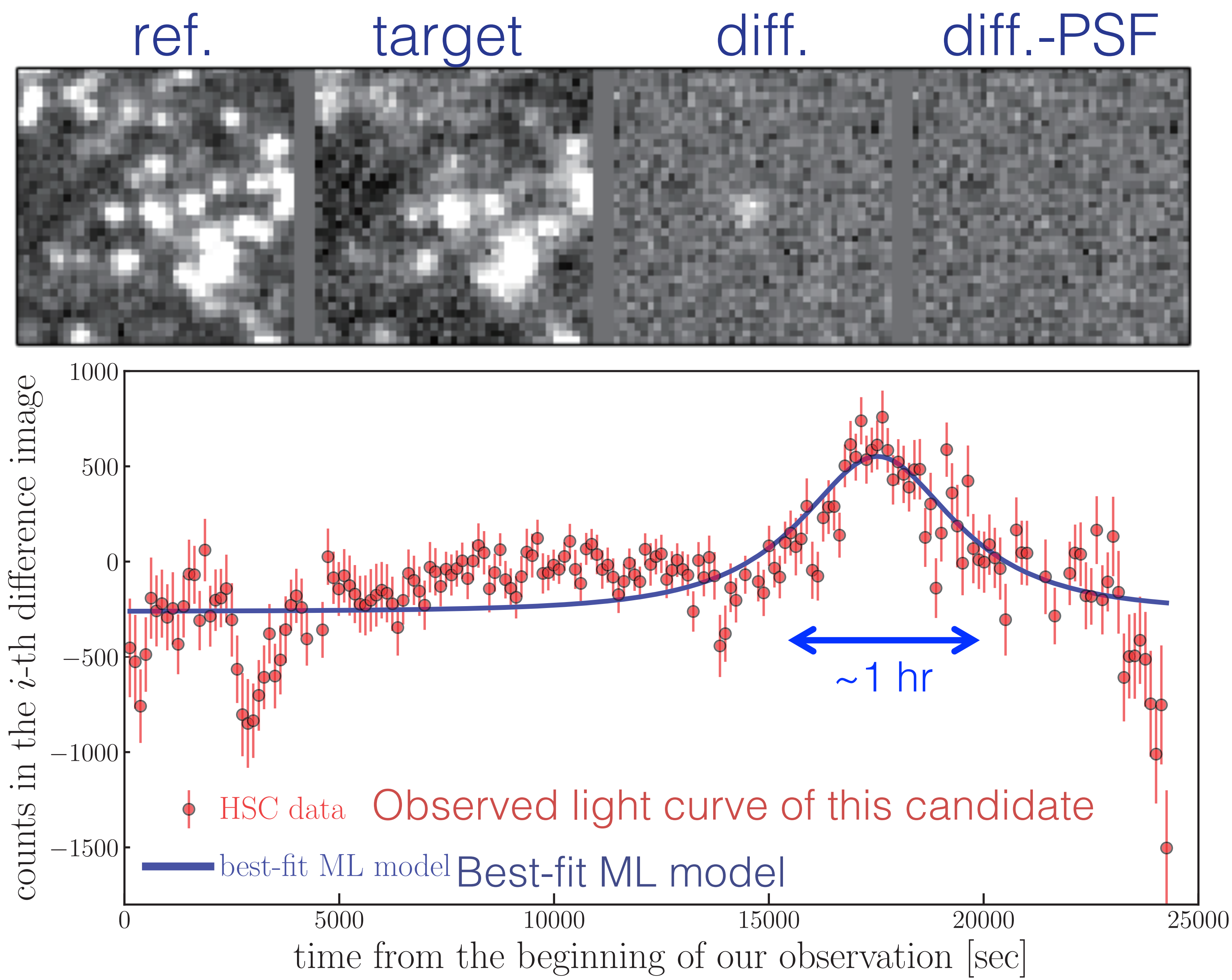
visual inspection of individual candidates…





Ref.
target
diff
diff- PSF
time
green: **2min** cadence
mag
time [sec]
Flare star (M star)
A factor of 10
brightened
sum count
time [sec]

One microlensing candidate among **~15,000** variable stars …?



Expected number of ML events

$$N_{\rm ML,exp} \simeq \underline{N_{\rm s}} \times \underline{t_{\rm obs}} \times \underline{\frac{{\rm d}\tau}{{\rm d}t_E}} \times \underline{\epsilon(t_E)}$$

# of source stars – depends on target gals (M31, LMC, Galactic bulge), tel. aperture, seeing, …

total observation time (duration of monitoring observation)

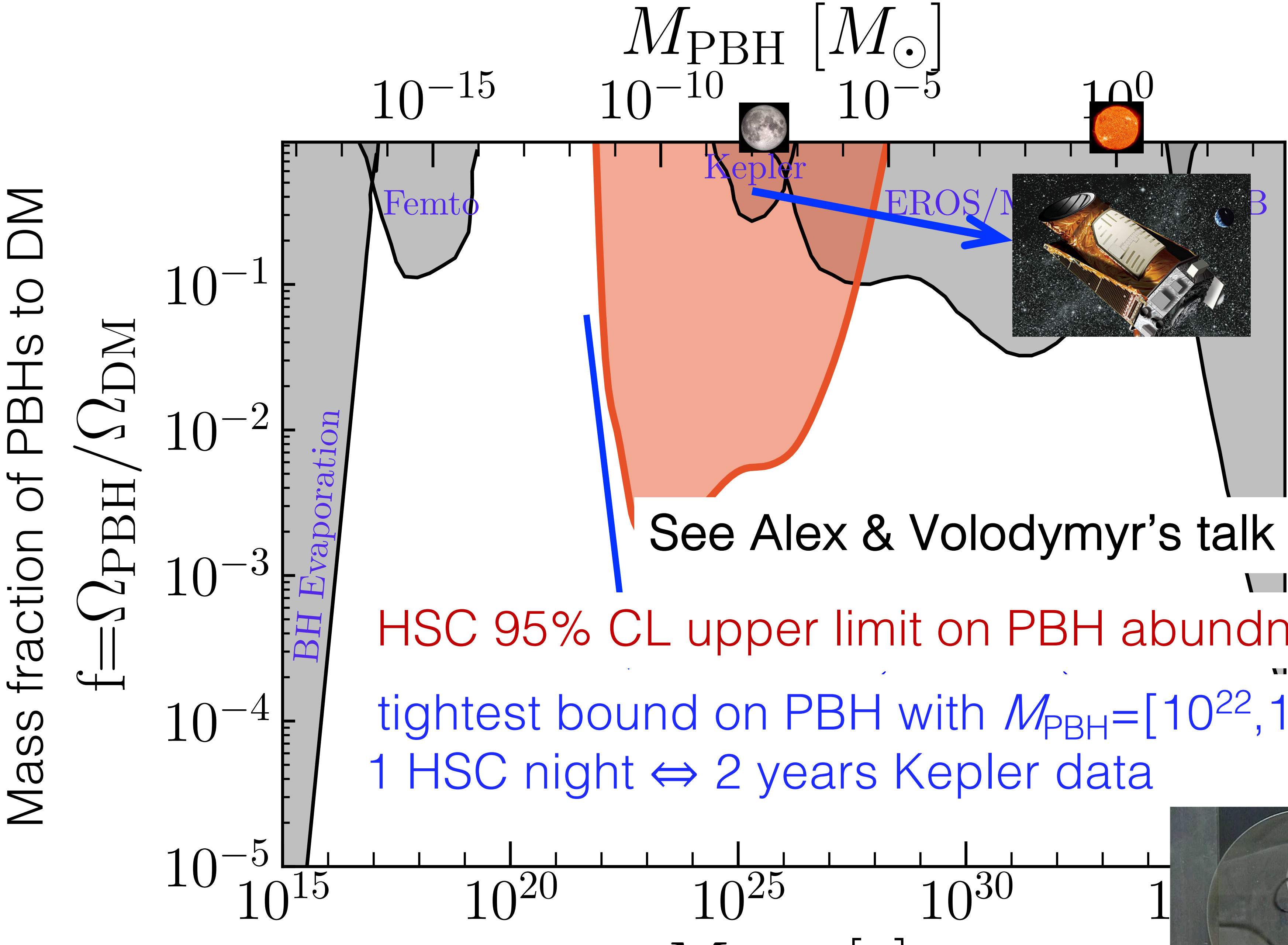
ML optical depth – depends on the number of compact objects (MS, WD, NS, BH) … PBHs

efficiency – depends on cadence and quality of data

$$R_{\rm E} = \sqrt{\frac{4\pi G M_{\rm PBH} d_{\rm PBH}(1 - d_{\rm PBH}/d_{\rm s})}{c^2}}$$

$$t_{\rm E} \simeq \frac{R_{\rm E}}{v}$$

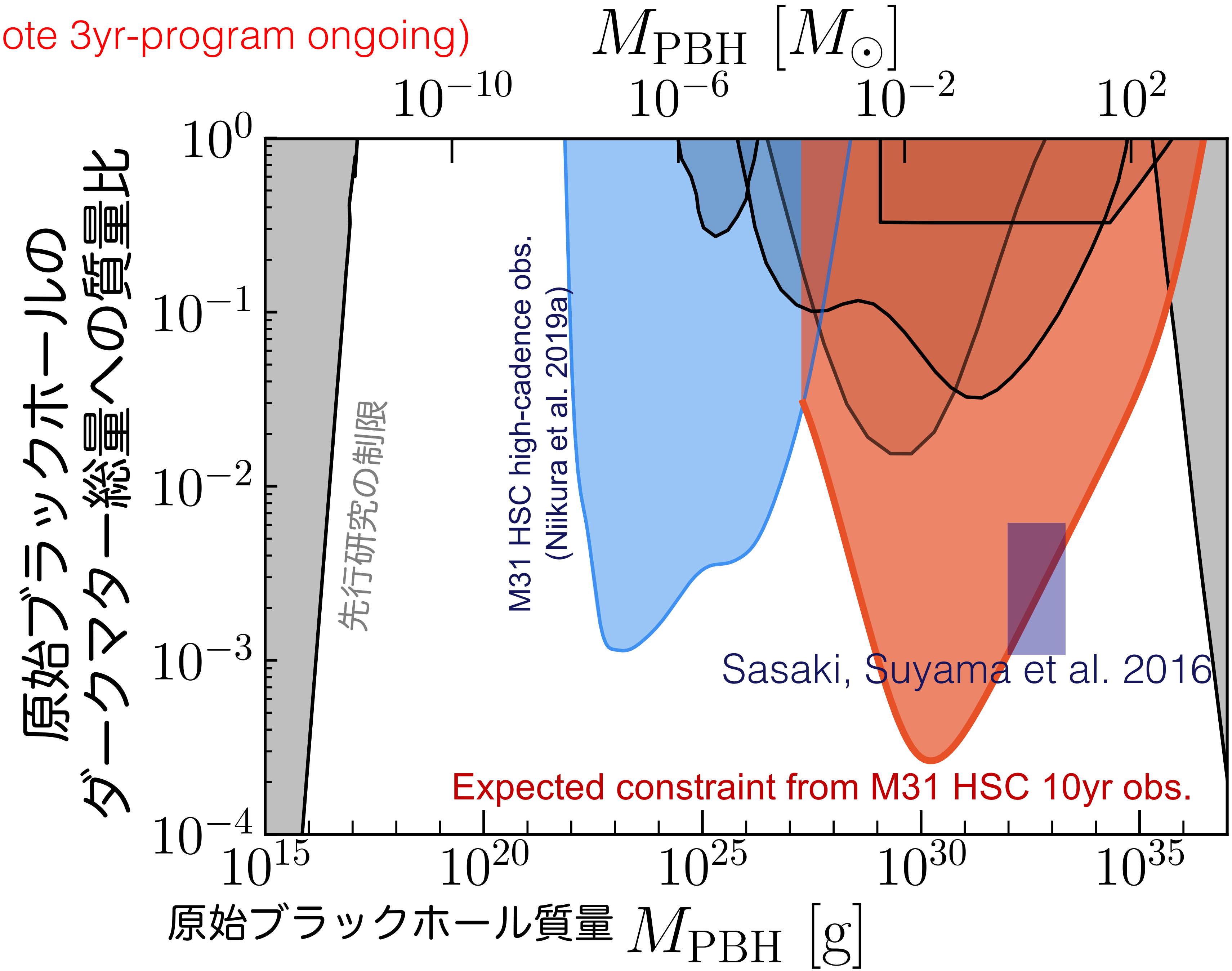
Subaru/HSC constraint on PBH abundance



Niikura, MT+ (19, Nature Astronomy)

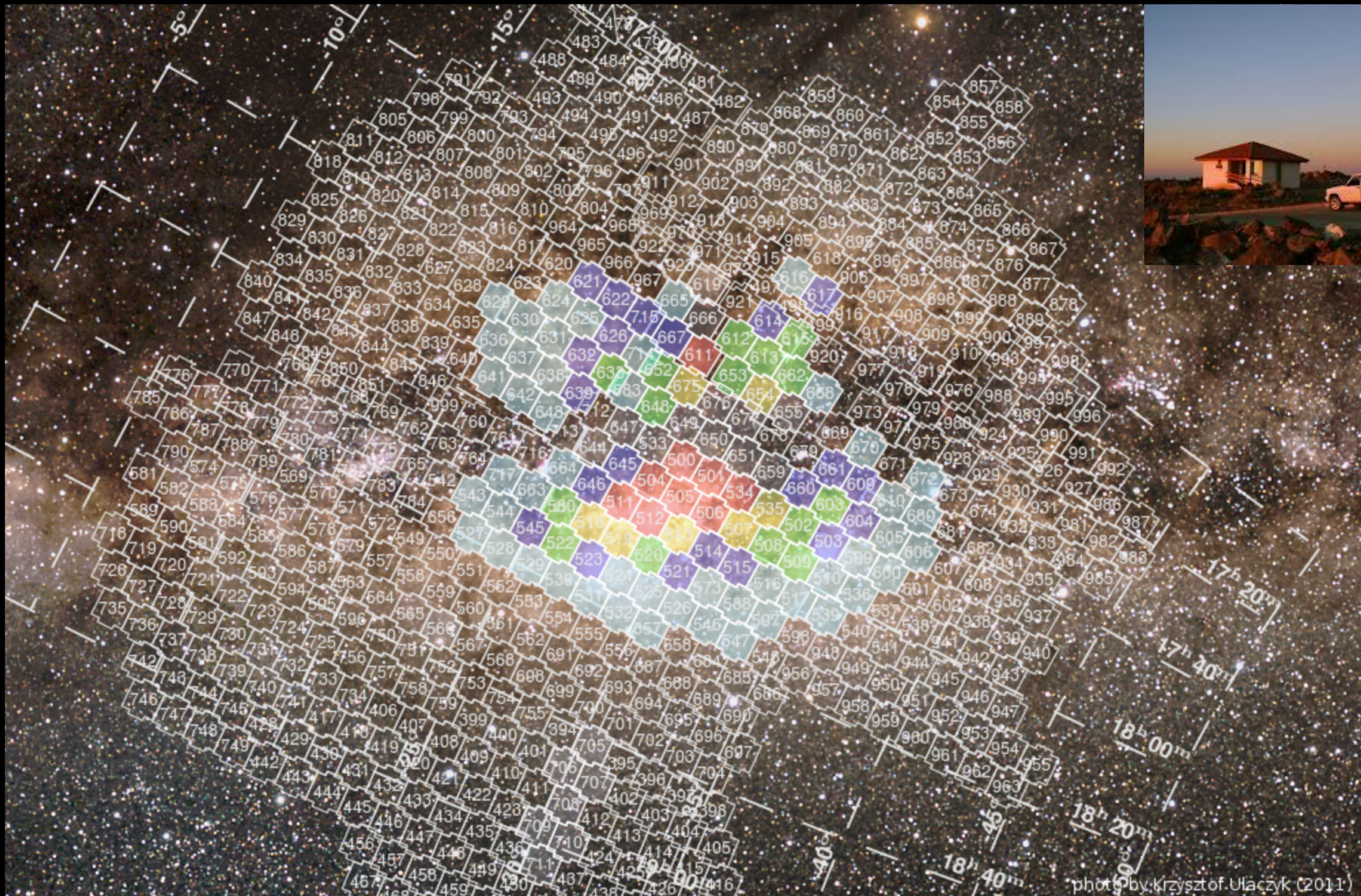
HSC 10yr ML search for M31

(Note 3yr-program ongoing)



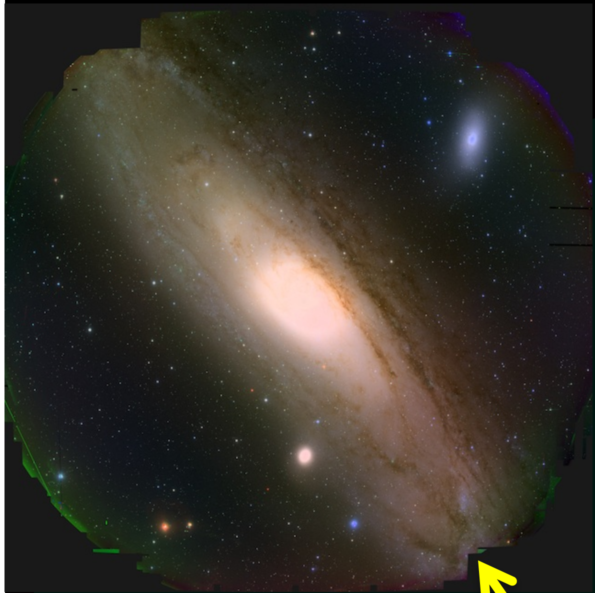
Optical Gravitational Lensing Experiment (OGLE)

- A long-term monitoring observation of Galactic bulge (**1992-**). PI Prof. Udalski (Warsaw): Note MOA (Nagoya, Osaka, ...)
- 1.3m Warsaw U. Telescope at Las Campanas, Chile

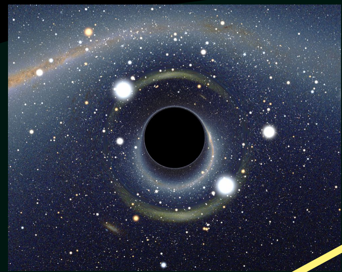


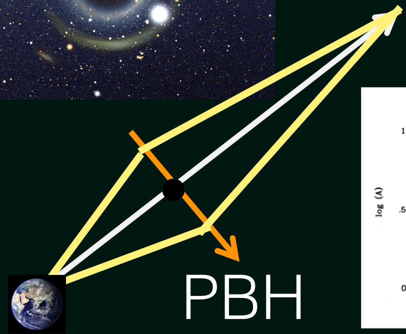
Constraining PBH with microlensing

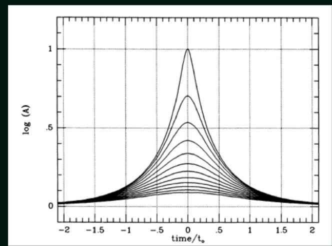
Hiroko Niikura
(U. Tokyo/IPMU
just graduated!)

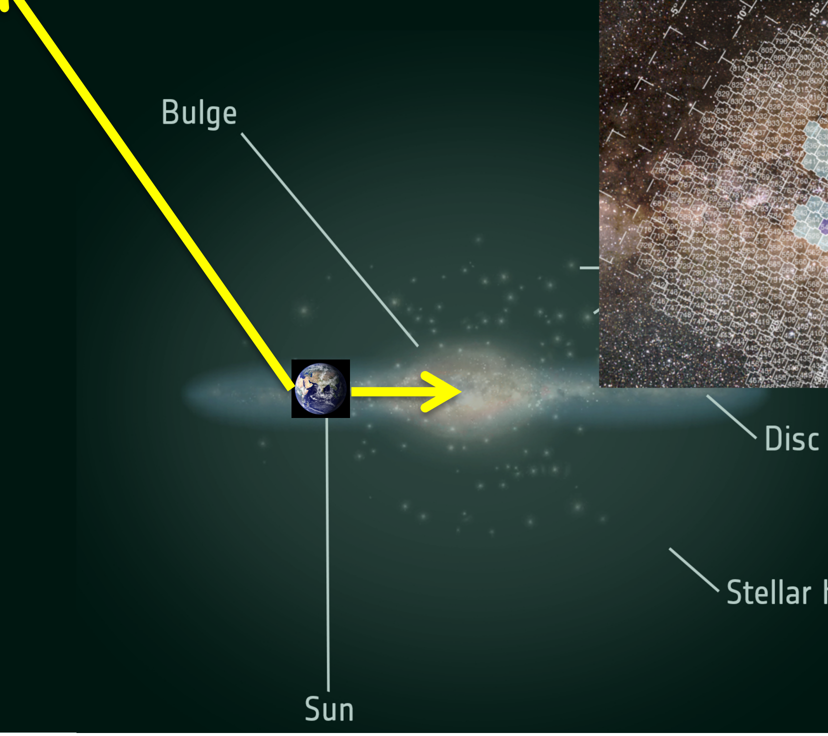


HSC M31
PBH
microlensing
search

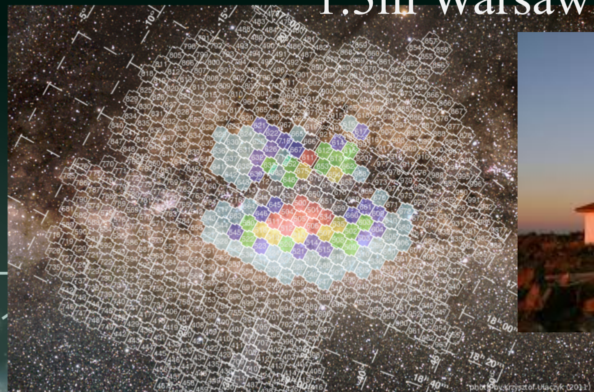








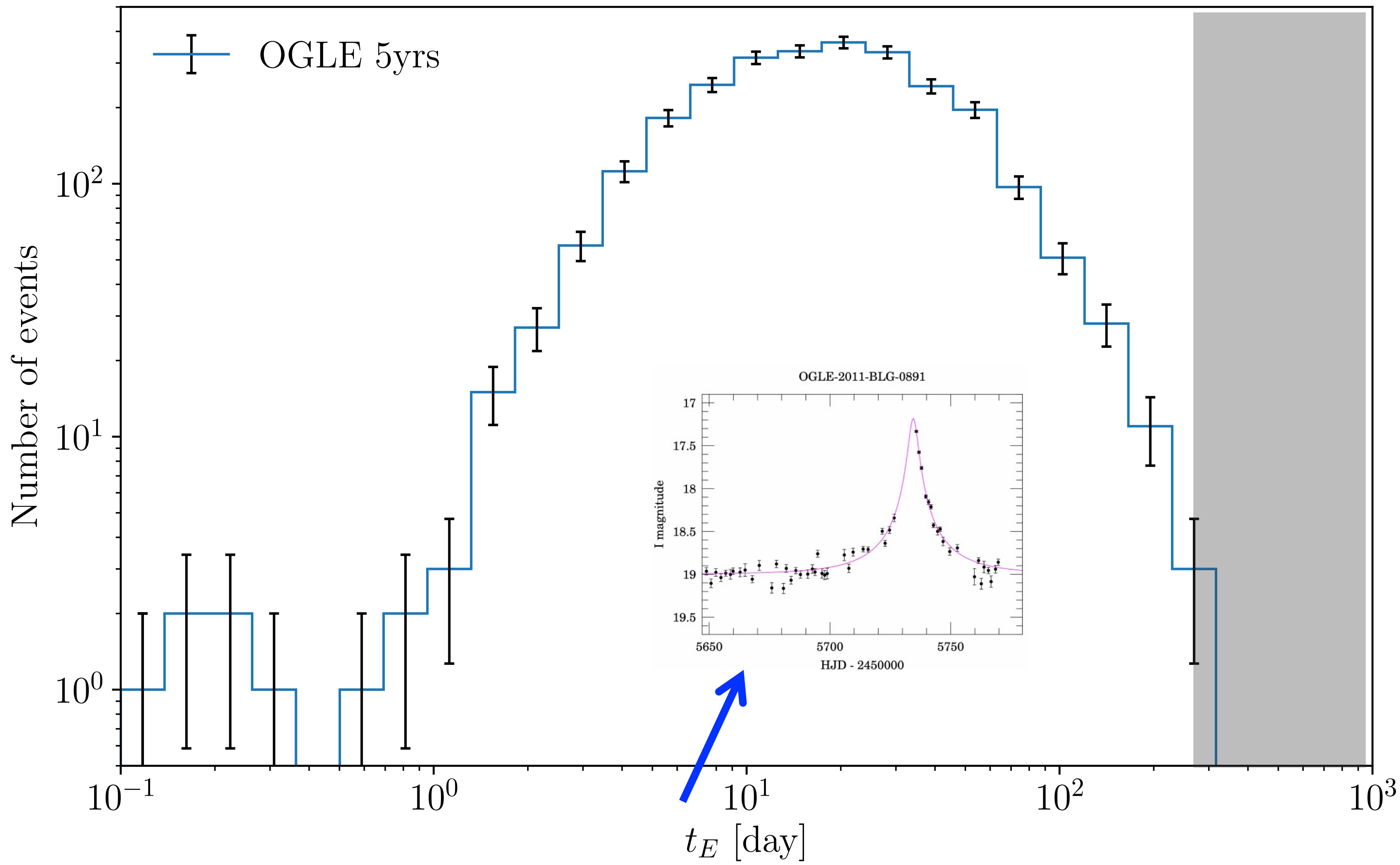
1.3m Warsaw telescope (1992-)



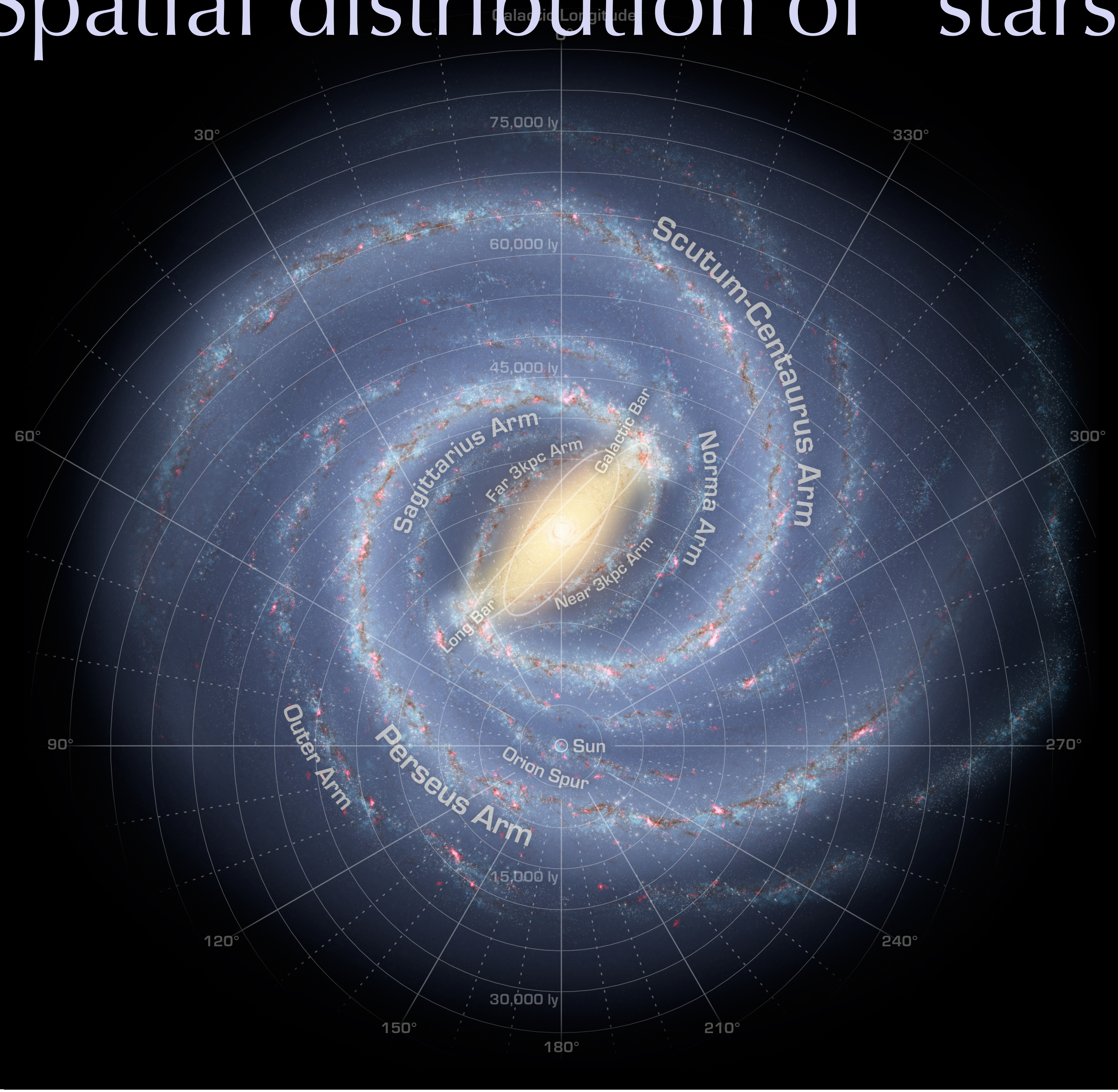
Use OGLE (Optical Gravitational Lensing Experiment) for PBH search

5-years OGLE data: Mroz et al. 2017

- 2622 ML events: the ML timescale distribution is provided (now >5000 events)



Spatial distribution of "stars"



Gould & Han 1995:
spatial structure of "stars"

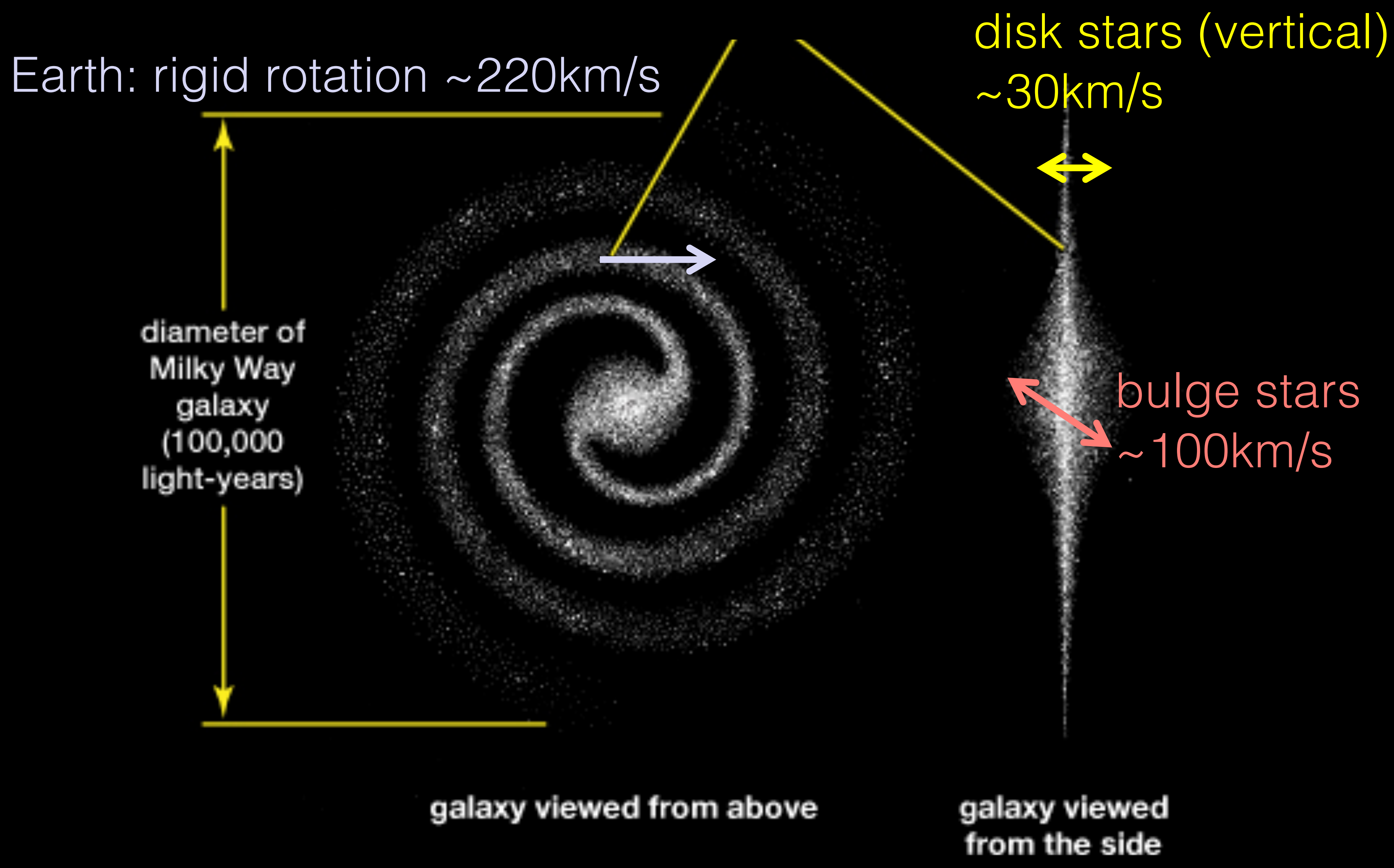
TABLE 2

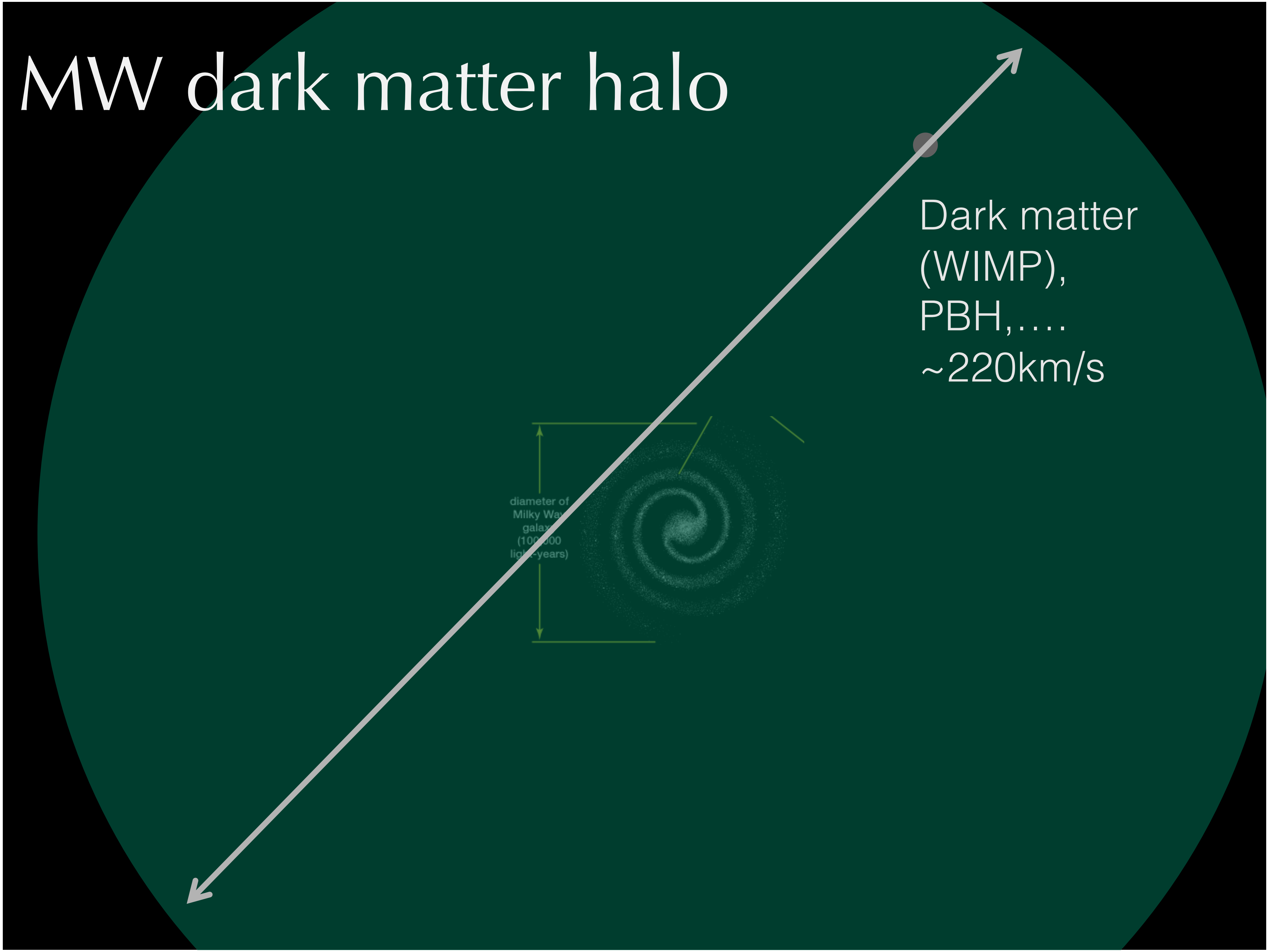
BULGE AND DISK DENSITY MODELS

Location	Model	Distribution
Bulge......	isothermal	$\rho(r) = \sigma^2_{\rm bulge}/2\pi G r^2 = 36.7(\sigma_{\rm bulge}/r)^2\ M_\odot\ {\rm pc}^{-3}$
	Kent	$\rho(s) = 1.04 \times 10^6 (s/0.482)^{-1.85}\ M_\odot\ {\rm pc}^{-3}\quad (s < 938\ {\rm pc})$
		$\rho(s) = 3.53 K_0(s/667)\ M_\odot\ {\rm pc}^{-3}\quad (s \geq 938\ {\rm pc})$
	bar	$\nu(r_s) = \nu_0 \exp(-0.5 r_s^2) \times 10^9\ L_\odot\ {\rm pc}^{-3}$
Disk.......	$\boxed{\text{Bahcall}}$	$n(R, z) = n(0, 0) \exp\{-[(R - 8000)/3500 + z/325]\}$
	Kent	$\nu(R, z) = 3.0 \exp[-(R/3001 + z/h_1)]\ L_\odot\ {\rm pc}^{-3}\quad (R < 5\ {\rm kpc})$
		$\nu(R, z) = 3.0(h_1/h_2) \exp[-(R/3001 + z/h_2)]\ L_\odot\ {\rm pc}^{-3}\quad (R \geq 5\ {\rm kpc})$
	KP	$\rho = 0.1\ M_\odot\ {\rm pc}^{-3}\quad (d < d_{\rm max})$
		$\rho = 0\ M_\odot\ {\rm pc}^{-3}\quad (d \geq d_{\rm max})$

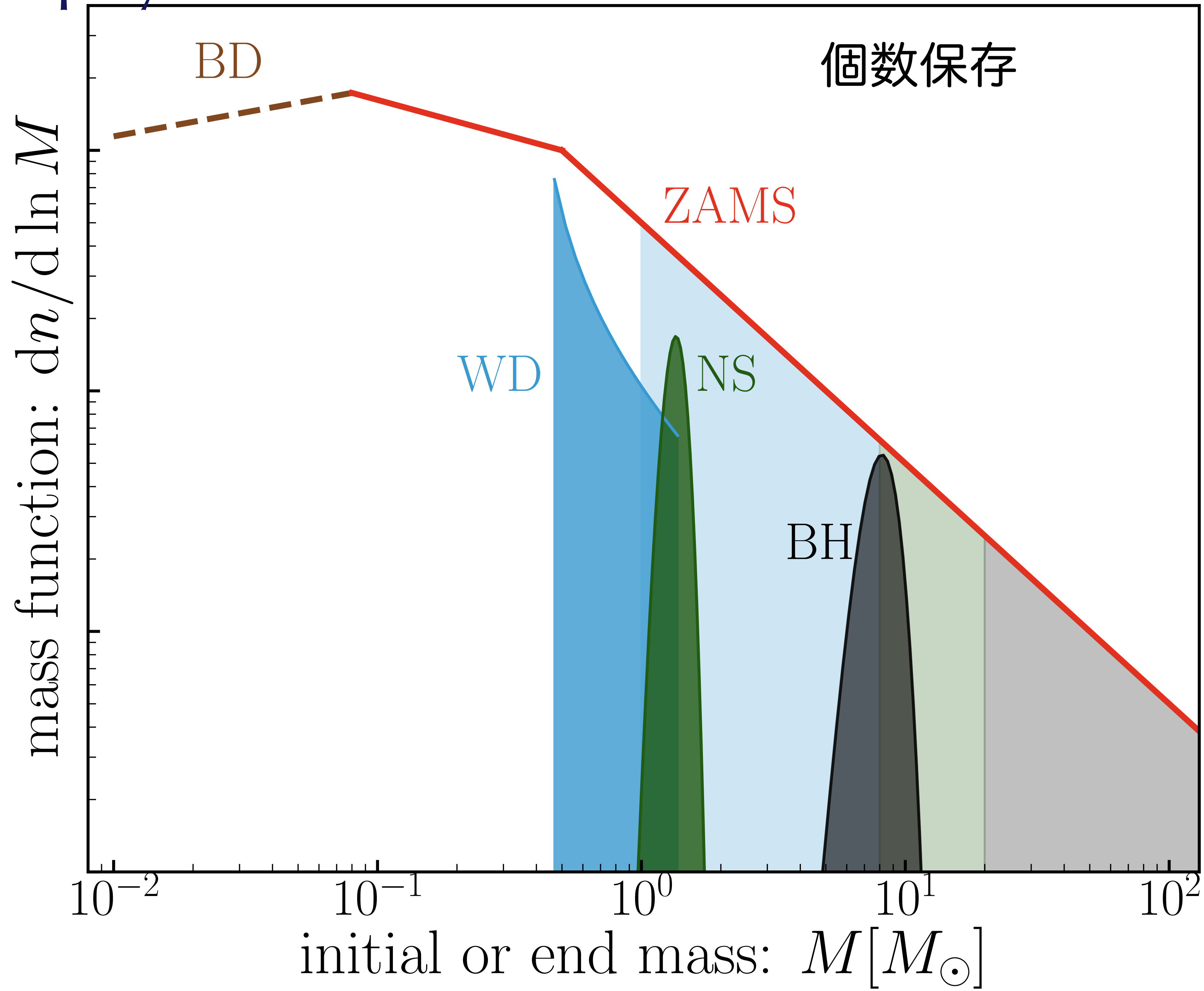
The density distribution models adopted for stellar populations. The values $r = (x^2 + y^2 + z^2)^{1/2}$, $R = (x^2 + y^2)^{1/2}$, $s^4 = R^4 + (z/0.61)^4$ are measured in pc. K_0 is a modified Bessel function and $n(0, 0) = 0.097\ {\rm pc}^{-3}$. We adopted $d_{\rm max} \sim 4$ kpc for the KP model. The Bahcall and Kent disk models and the barred bulge model are expressed in number density, $n(R, z)$, and luminosity functions, $\nu(R, z)$ and $\nu(r_s)$, respectively. For the Kent disk model two different scale heights are adopted for the inner (h_1 for $R < 5$ kpc) and outer (h_2 for $R \geq 5$ kpc) parts of the disk. The respective scale heights are $h_1 = 165$ pc and $h_2 = (0.027R + 28.3)$ pc. For the barred (anisotropic) bulge model, $\nu_0 = 3.66 \times 10^7\ L_\odot\ {\rm kpc}^{-3}$, and $r_s = \{[(x'/x_0)^2 + (y'/y_0)^2]^2 + (z'/z_0)^4\}^{1/4}$. Here the coordinates (x', y', z') have their center at the Galactic center, the longest axis is the x' axis, and the shortest axis is the z' axis. The values of the scale lengths are $x_0 = 1.58$ kpc, $y_0 = 0.62$ kpc, and $z_0 = 0.43$ kpc, respectively.

Velocity structure of “stars”

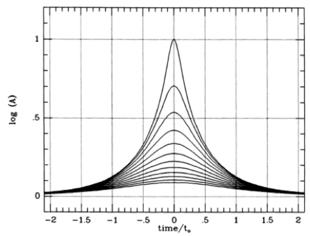



MW dark matter halo
Dark matter
(WIMP),
PBH,....
~220km/s
diameter of

Astrophysical lenses: stars and stellar remnants



Microlensing of Galactic bulge



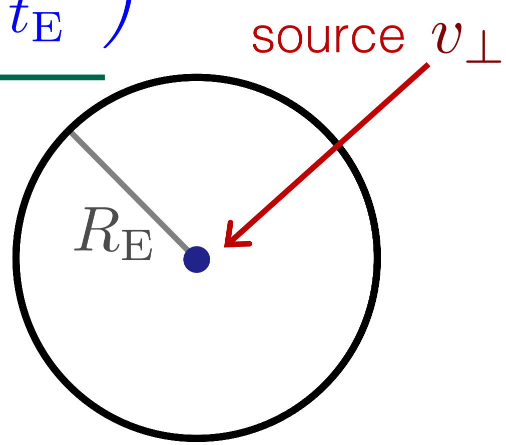
- Microlensing light curve timescale

$$t_{\rm E} = \frac{R_{\rm E}}{v_{\rm t}} \simeq 44 \text{ days} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{d_{\rm l} d_{\rm ls}/d_{\rm s}}{4 \text{ kpc}}\right)^{1/2} \left(\frac{v_{\rm t}}{220 \text{ km/s}}\right)^{-1}$$

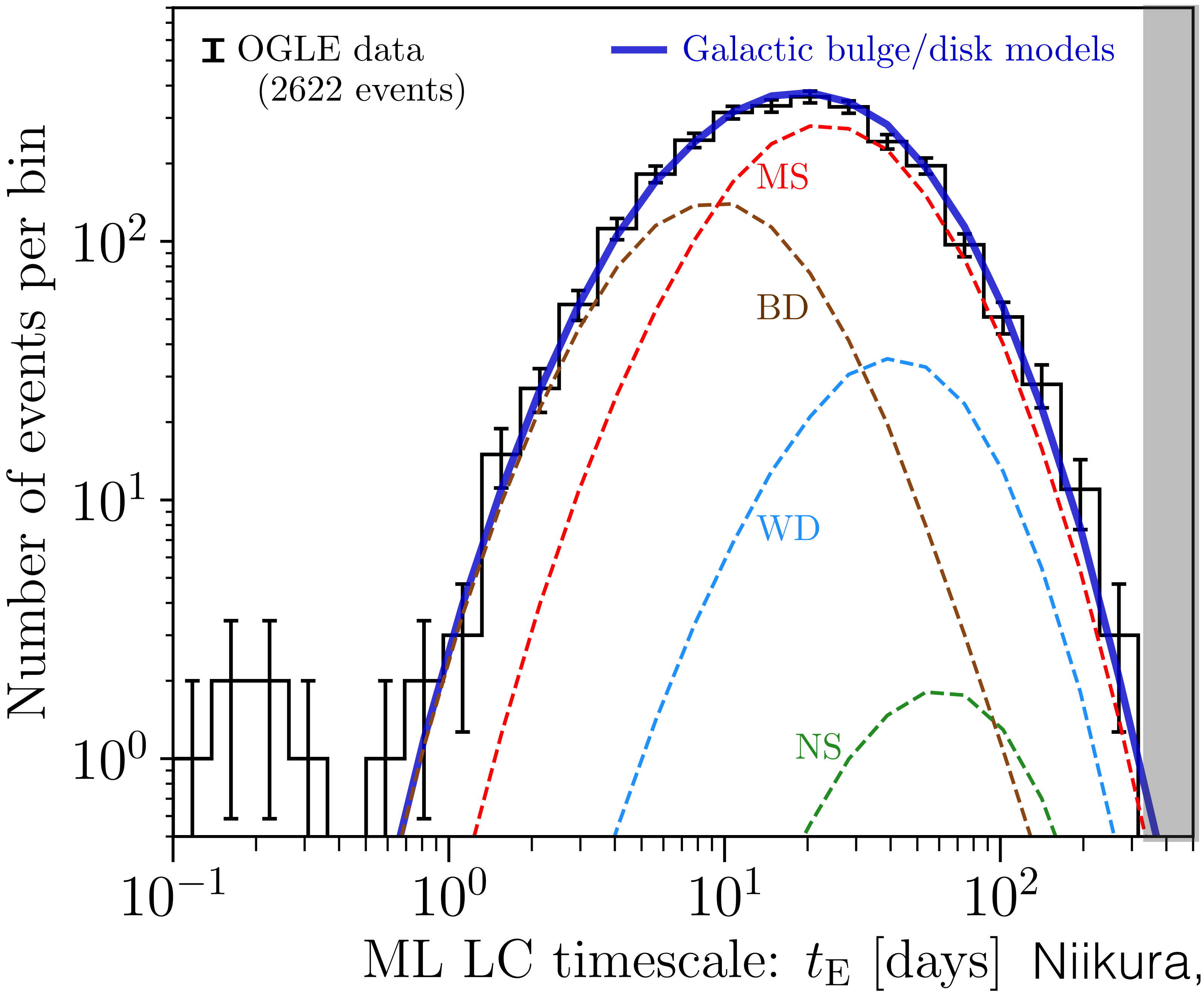
$$\mathbf{v}_t = \mathbf{v}_{\rm l} - \left(\frac{d_{\rm l}}{d_{\rm s}}\mathbf{v}_{\rm s} + \frac{d_{\rm l}}{d_{\rm s}}\mathbf{v}_{\rm o}\right)$$

- Expected event # at a given LC timescale (t_E)

$$\begin{aligned} N_{\rm exp}(t_{\rm E})\Delta t_{\rm E} &\sim N_{\rm s} t_{\rm obs} \Delta t_{\rm E} \int_0^{d_{\rm s}} {\rm d}d_{\rm l}\, n_{\rm l}(d_{\rm l}) R_{\rm E} \int {\rm d}v_\perp\ v_\perp^2 f(v_\perp)\delta_D\left(t_{\rm E} - \frac{2R_{\rm E}}{v_\perp}\right) \\ &\sim N_{\rm s} t_{\rm obs} \Delta t_{\rm E} \int_0^{d_{\rm s}} {\rm d}d_{\rm l}\, \underbrace{n_{\rm l}(d_{\rm l})}_{\text{lens dist.}} \frac{R_{\rm E}^4}{t_{\rm E}^4} \underbrace{f\left(v_\perp = \frac{2R_{\rm E}}{t_{\rm E}}\right)}_{\text{velocity distribution}} \\ &\propto M^2 \end{aligned}$$

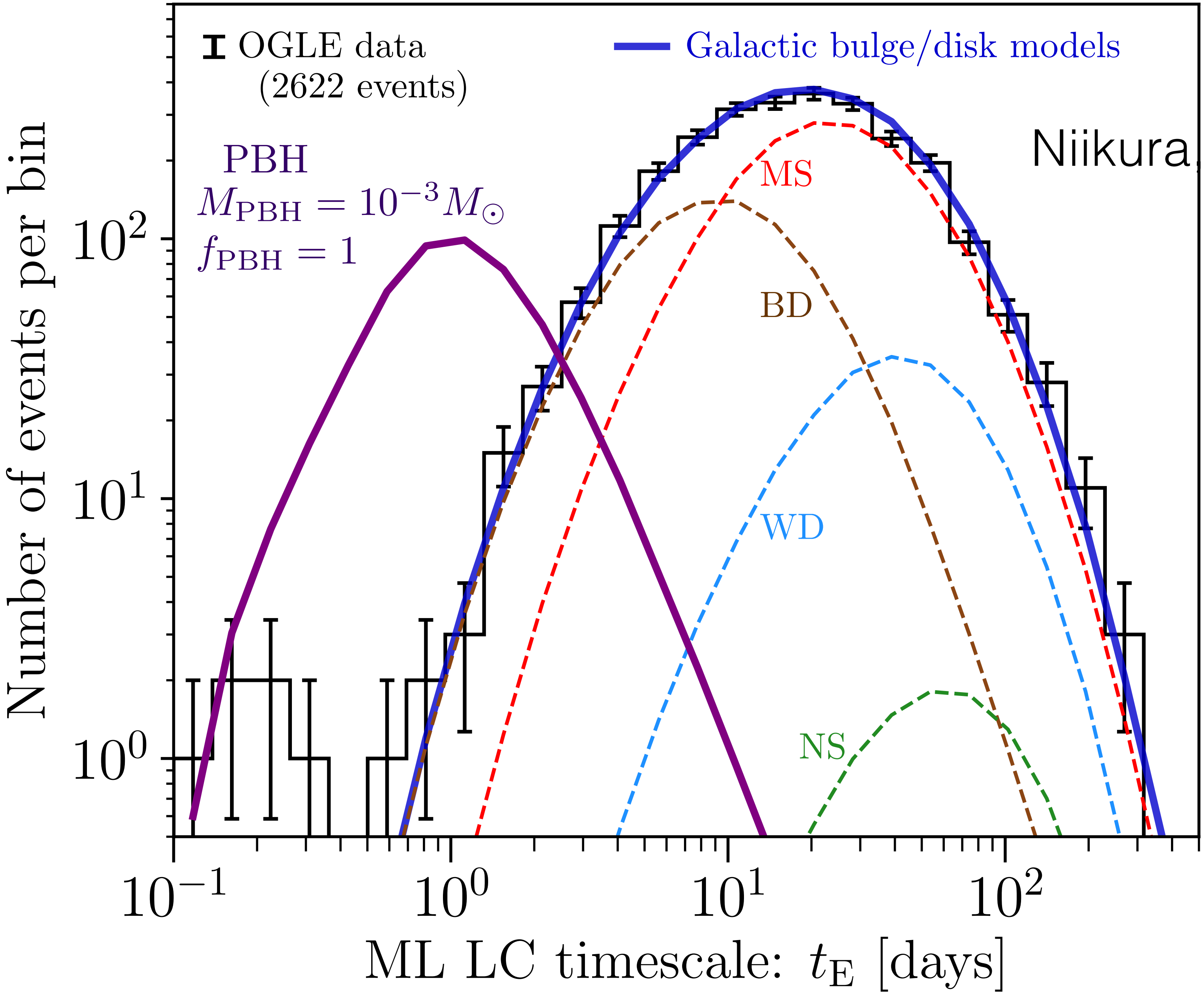


(old-days) Astronomers very smart!



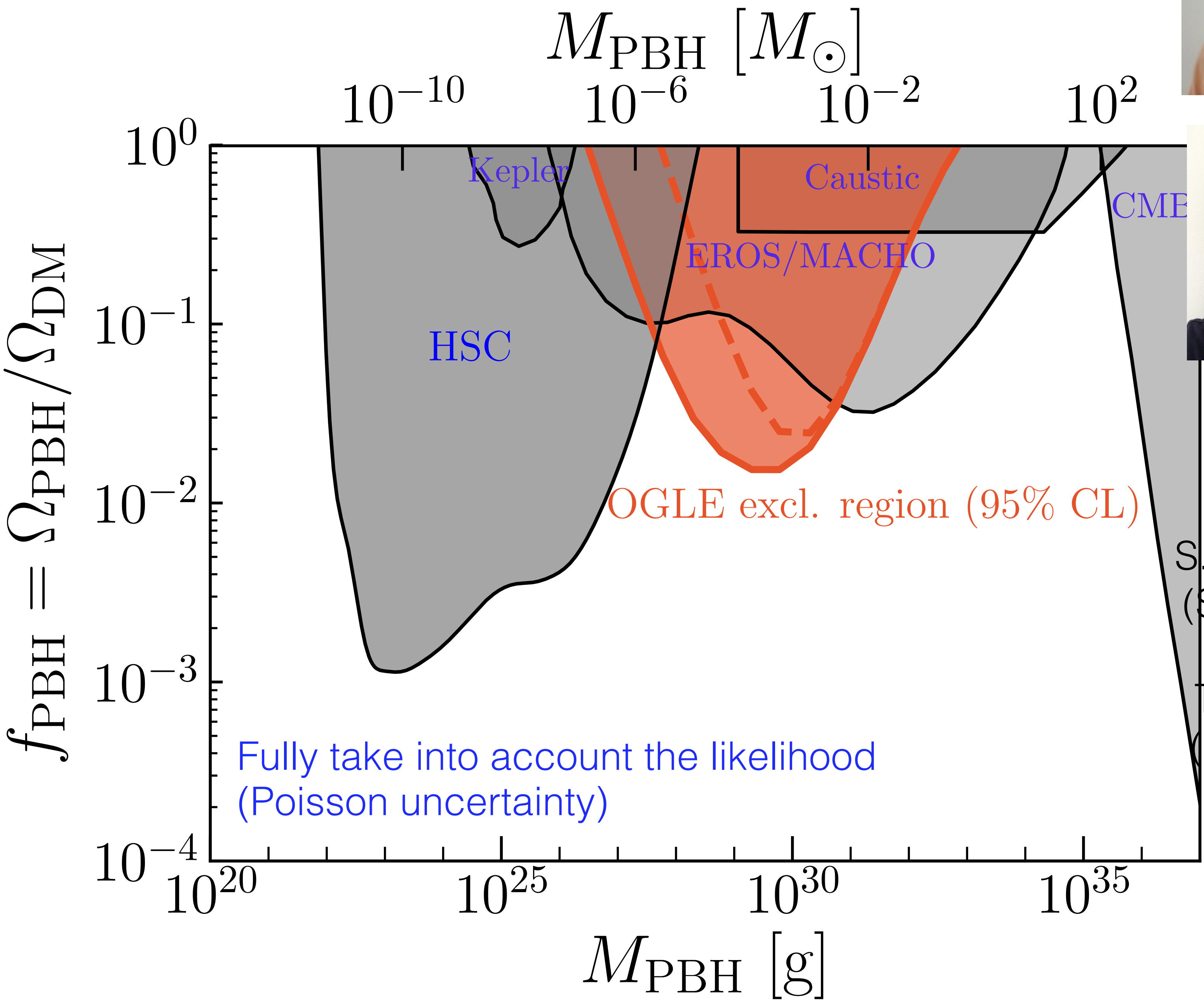
Niikura, MT+19

PBH lenses needed?



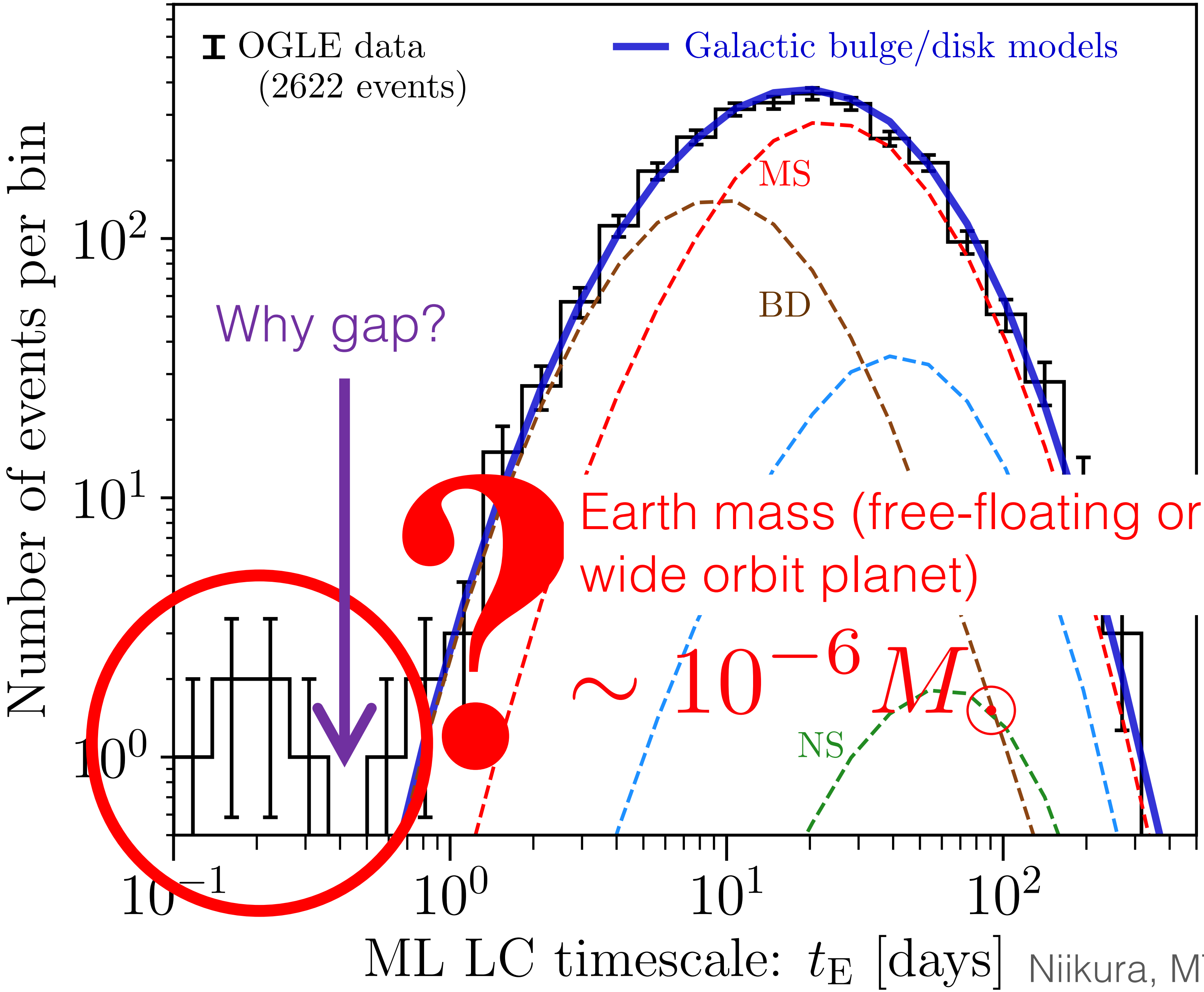
Niikura, MT+19

Null test: PBH upper bounds



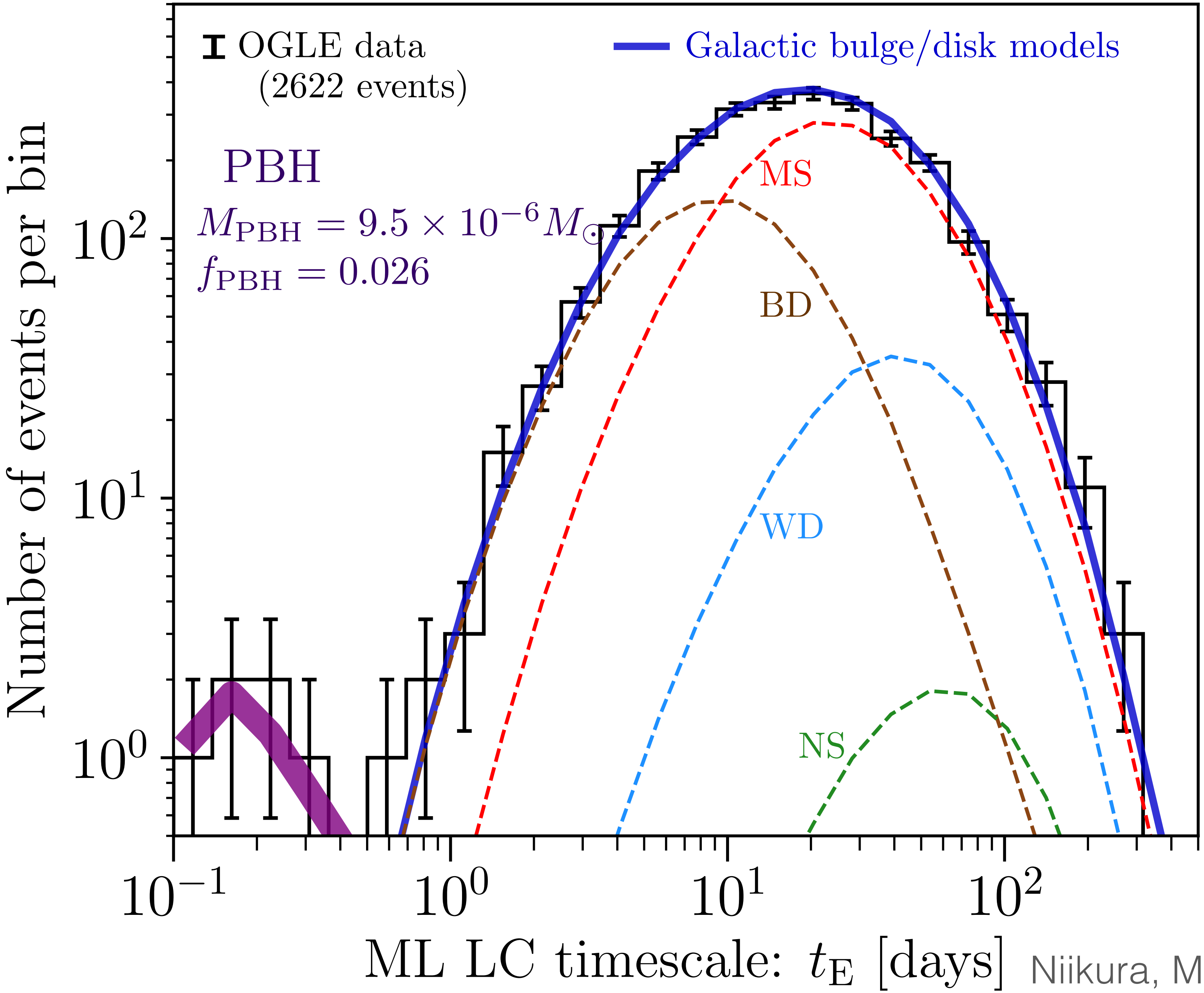
\+
S. Masaki
(Suzuka)
\+
T. Sumi
(Osaka)

PBH lenses needed?



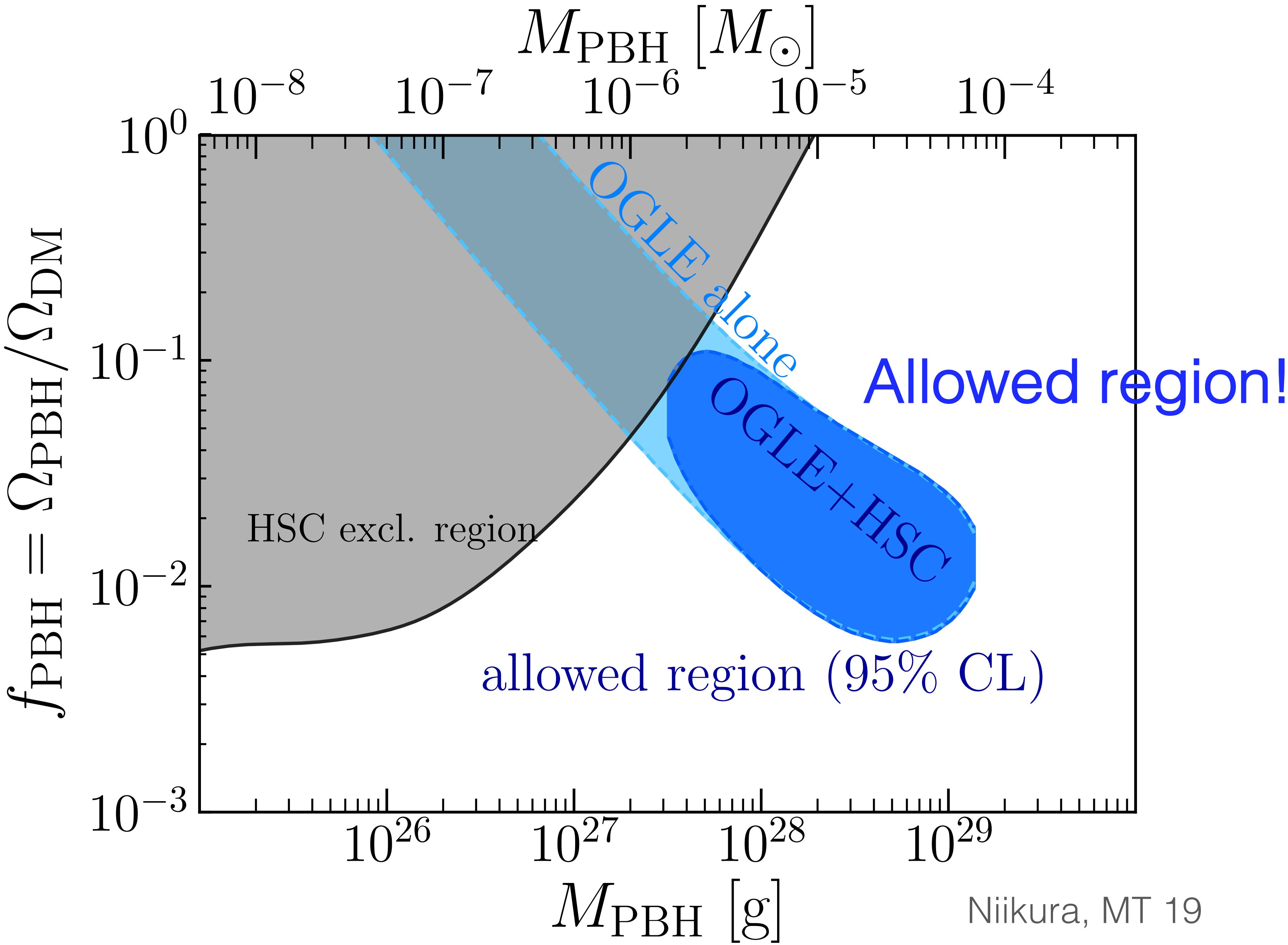
Niikura, MT 19

Earth-mass scale PBH?



Niikura, MT+ 19

Earth-mass scale PBH?



Niikura, MT 19

From today's arXiv

Compact Dark Matter Objects via N Dark Sectors

Gia Dvali,[1,2] Emmanouil Koutsangelas,[1,2,*] and Florian Kühnel[3]

[1] *Arnold Sommerfeld Center, Ludwig-Maximilians-Universität, Theresienstraße 37, 80333 München, Germany,*
[2] *Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*
[3] *The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova University Center, Roslagstullsbacken 21, SE-10691 Stockholm, Sweden*

(Dated: Monday 2nd December, 2019, 1:38am)

We propose a novel class of compact dark matter objects in theories where the dark matter consists of multiple sectors. We call these objects N-MACHOs. In such theories neither the existence of dark matter species nor their extremely weak coupling to the observable sector represent additional hypotheses but instead are imposed by the solution to the Hierarchy Problem and unitarity. The crucial point is that particles from the same sector have non-trivial interactions but interact only gravitationally otherwise. As a consequence, the pressure that counteracts the gravitational collapse is reduced while the gravitational force remains the same. This results in collapsed structures much lighter and smaller as compared to the ordinary single-sector case. We apply this phenomenon to a dark matter theory that consists of N dilute copies of the Standard Model. The solutions do not rely on an exotic stabilization mechanism, but rather use the same well-understood properties as known stellar structures. This framework also gives rise to new microscopic super
example with mass 10^8 g and size 10^{-13} cm. By confronting the resulting obje
constraints, we find that, due to a huge suppression factor entering the mass sp
evade the strongest constrained region of the parameter space. Finally, we disc
scenarios of N-MACHOs. We argue that, due to the efficient dissipation of e
high-density regions such as ultra-compact mini-halos could serve as formation

I. INTRODUCTION

To the present day the fundamental nature of the dark matter (DM) remains one of the major mysteries in cosmology and particle physics. At the same time, another major unanswered question in particle physics is what stabilizes the mass term of the Higgs boson against quantum corrections at a value more than 32 orders of magni-

In the present paper
which goes under the n
the Hierarchy Problem
low-energy effective th
species, the quantum-gr

M_*

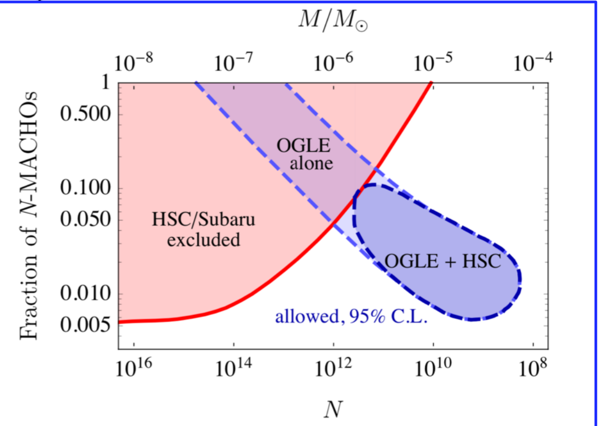
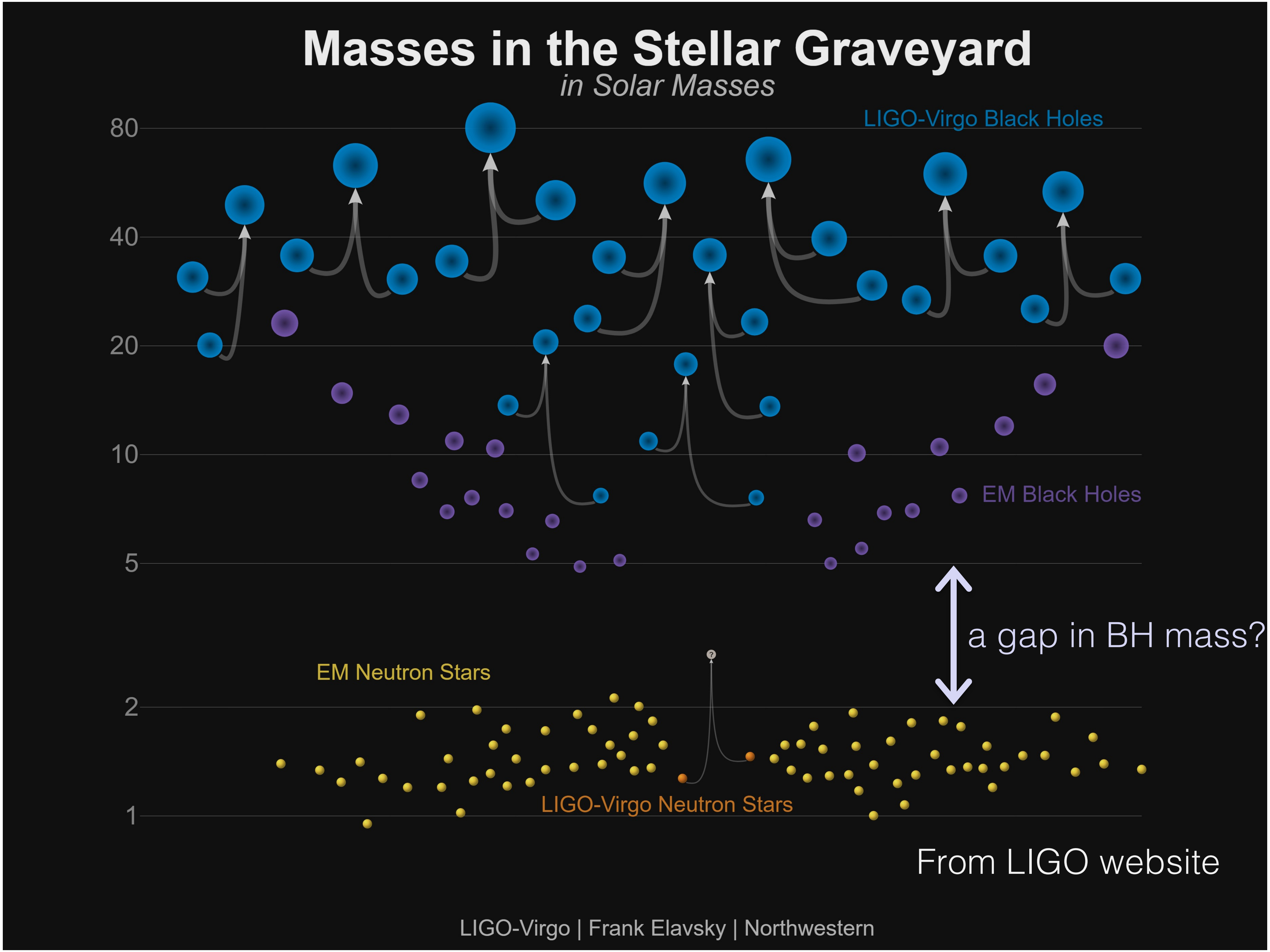


FIG. 2: The blue-shading represents the 95% C.L. allowed region of N-MACHO abundance using combined data from OGLE [42] and HSC/Subaru [41]. (Figure adapted from Ref. [43])


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
a gap in BH mass?
EM Neutron Stars
LIGO-Virgo Neutron Stars
From LIGO website
LIGO-Virgo | Frank Elavsky | Northwestern

~70Msun BH found! (last week Nature paper)

Article

A wide star–black-hole binary system from radial-velocity measurements

https://doi.org/10.1038/s41586-019-1766-2

Received: 1 March 2019

Accepted: 28 August 2019

Published online: 27 November 2019

Jifeng Liu[1,2,3]*, Haotong Zhang[1]*, Andrew W. Howard[4], Zhongrui Bai[1], Youjun Lu[1,2], Roberto Soria[2,5], Stephen Justham[1,2,6], Xiangdong Li[7,8], Zheng Zheng[9], Tinggui Wang[10], Krzysztof Belczynski[11], Jorge Casares[12,13], Wei Zhang[1], Hailong Yuan[1], Yiqiao Dong[1], Yajuan Lei[1], Howard Isaacson[14], Song Wang[1], Yu Bai[1], Yong Shao[7,8], Qing Gao[1], Yilun Wang[1,2], Zexi Niu[1,2], Kaiming Cui[1,2], Chuanjie Zheng[1,2], Xiaoyong Mu[2], Lan Zhang[1], Wei Wang[3,15], Alexander Heger[16], Zhaoxiang Qi[1,17], Shilong Liao[17], Mario Lattanzi[18], Wei-Min Gu[19], Junfeng Wang[19], Jianfeng Wu[19], Lijing Shao[20], Rongfeng Shen[21], Xiaofeng Wang[22], Joel Bregman[23], Rosanne Di Stefano[24], Qingzhong Liu[25], Zhanwen Han[26], Tianmeng Zhang[1], Huijuan Wang[1], Juanjuan Ren[1], Junbo Zhang[1], Jujia Zhang[26], Xiaoli Wang[26], Antonio Cabrera-Lavers[12,27], Romano Corradi[12,27], Rafael Rebolo[13,27], Yongheng Zhao[1,2], Gang Zhao[1,2], Yaoquan Chu[10] & Xiangqun Cui[28]

All stellar-mass black holes have hitherto been identified by X-rays emitted from gas that is accreting onto the black hole from a companion star. These systems are all binaries with a black-hole mass that is less than 30 times that of the Sun[1–4]. Theory predicts, however, that X-ray-emitting systems form a minority of the total population of star–black-hole binaries[5,6]. When the black hole is not accreting gas, it can be found through radial-velocity measurements of the motion of the companion star. Here we report radial-velocity measurements taken over two years of the Galactic B-type star, LB-1. We find that the motion of the B star and an accompanying Hα emission line require the presence of a dark companion with a mass of 68^{+11}_{-13} solar masses, which can only be a black hole. The long orbital period of 78.9 days shows that this is a wide binary system. Gravitational-wave experiments have detected black holes of similar mass, but the formation of such massive ones in a high-metallicity environment would be extremely challenging within current stellar evolution theories.

summary

- Gravitational microlensing is a very powerful probe of "compact, invisible objects" including PBH and astrophysical BH
- We used the 8.2m Subaru HSC data of M31 to search for ML due to PBHs, and obtained the tightest upper bound on the abundance of PBHs
- Also used the 5yrs OGLE data (1.3m) to constrain PBH
  - A hint of the Earth-mass PBHs?
- ML can be used to search for LIGO-counterpart BH of ~10Msun, if we can have ~10yr data of Galactic bulge/disk with HSC or LSST
  - The same data allows various science cases (IMF, exoplanets, …)