Constraining primordial black holes with microlensing

Masahiro Takada (Kavli IPMU)

Based on Niikura, MT, Yasuda, et al. Nature Astron. 2019

Niikura, MT, et al. PRD 2019

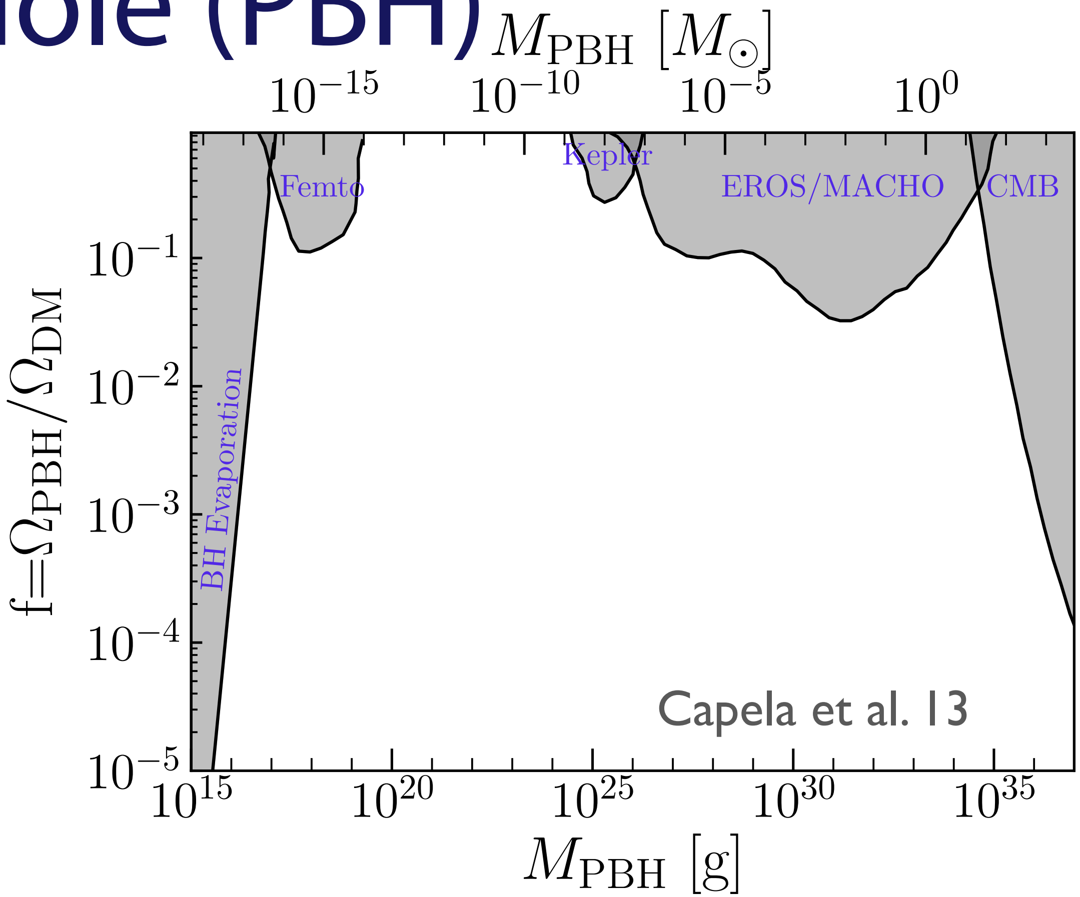
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

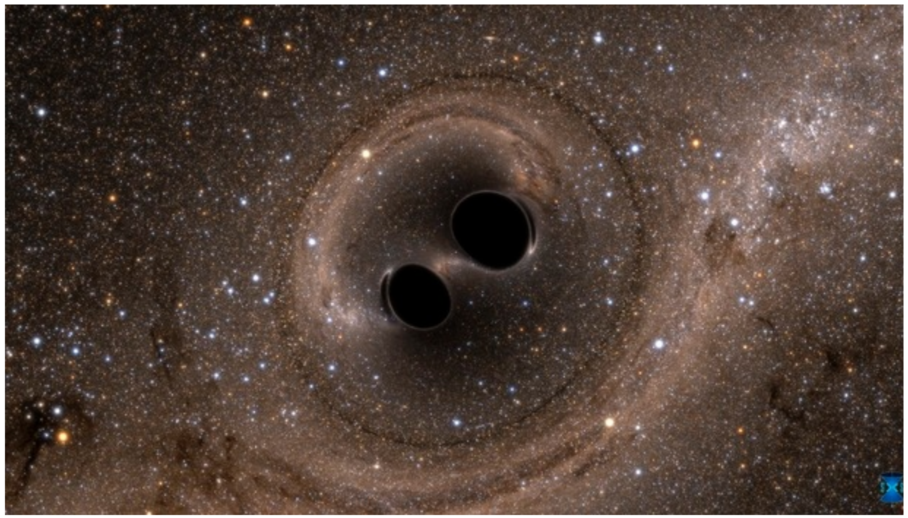
東京大学 THE UNIVERSITY OF TOKYO

wpi

Primordial Black Hole (PBH)

- Can be formed in the early universe (Hawking1971); not from any astrophysical processes)
- One of viable candidates of CDM
- Progenitor of LIGO GW binary BHs? (Sasaki, Suyama, Tanaka & Yokoyama, PRL 2016; Bird et al. 16)





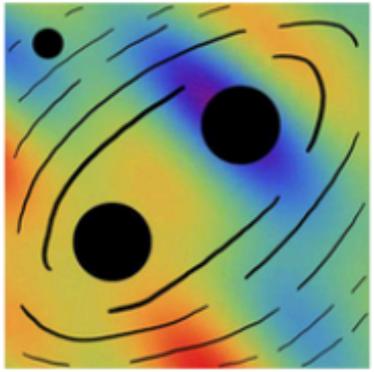
$$M_{\rm PBH} \sim 10^{24}{\rm g} \sim M_H \ @\ T \sim 10\ {\rm TeV}$$

Editors' Suggestion

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

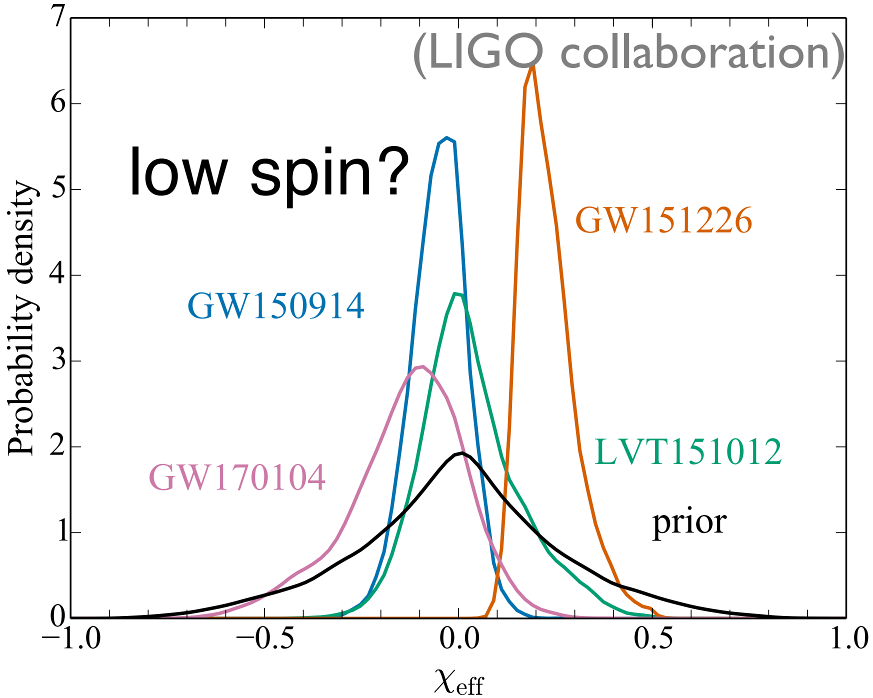
Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama

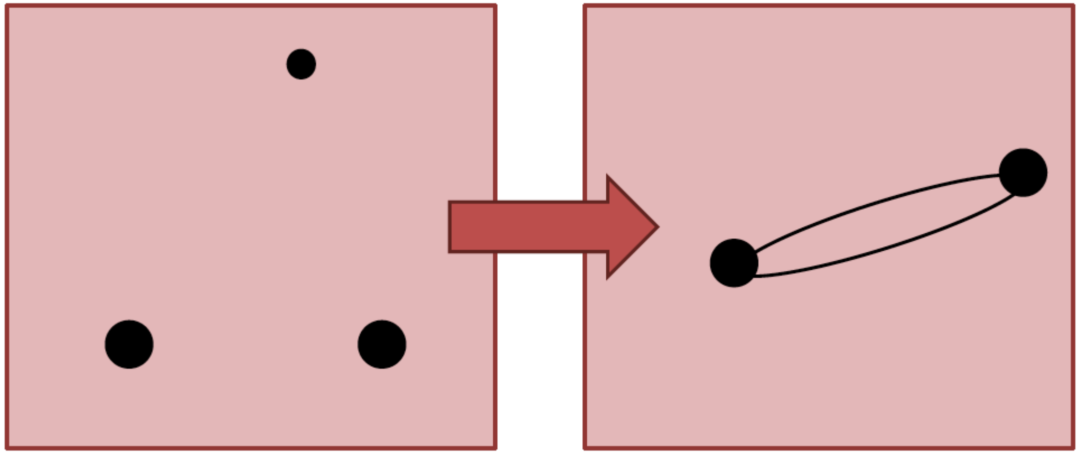
Phys. Rev. Lett. **117**, 061101 (2016) – Published 2 August 2016



A theoretical analysis examines the possibility that the gravitational wave signal (GW150914) detected by LIGO was due to the coalescence of primordial black holes created by the extremely dense matter present in the early Universe.

Show Abstract +

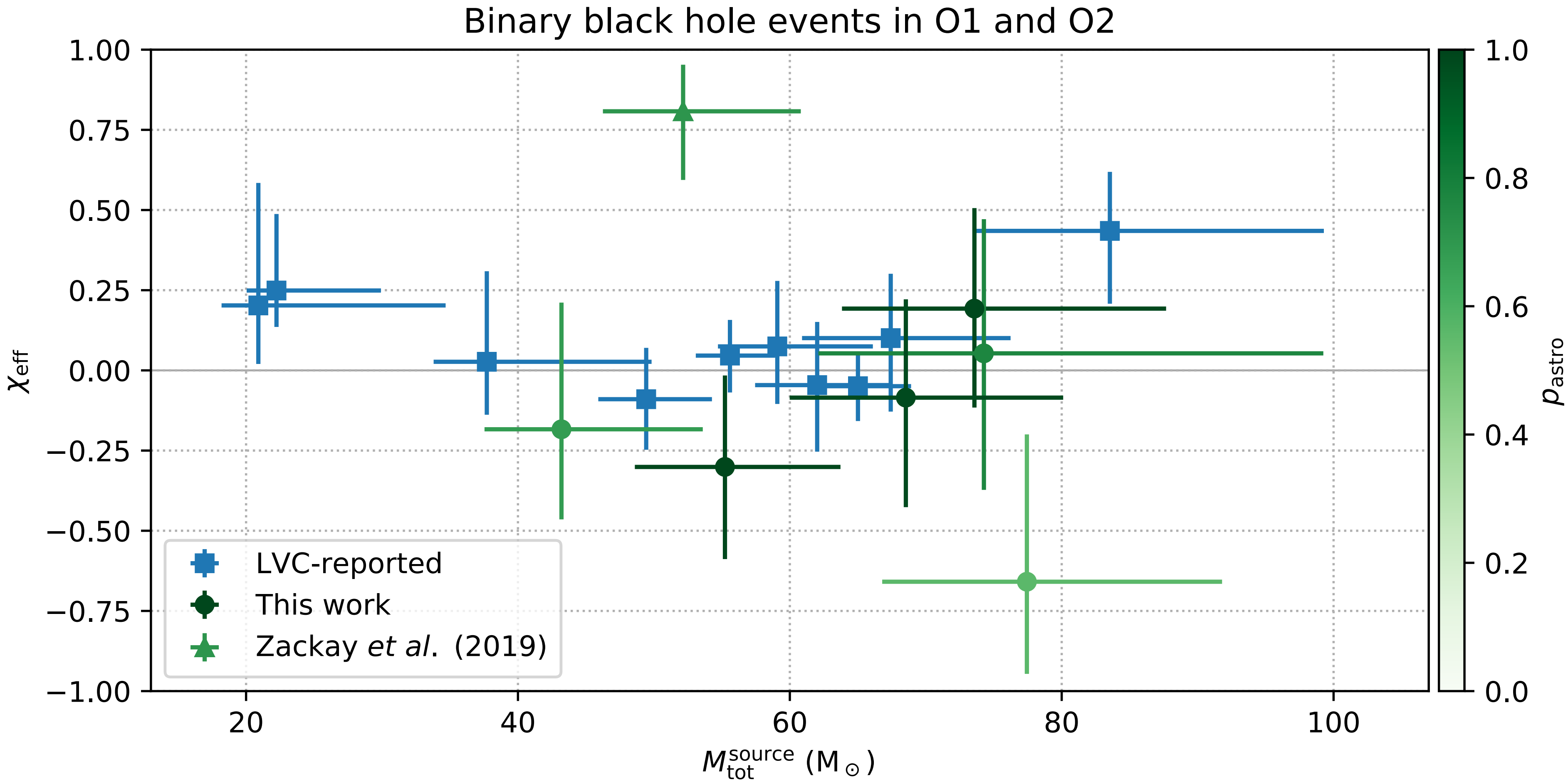




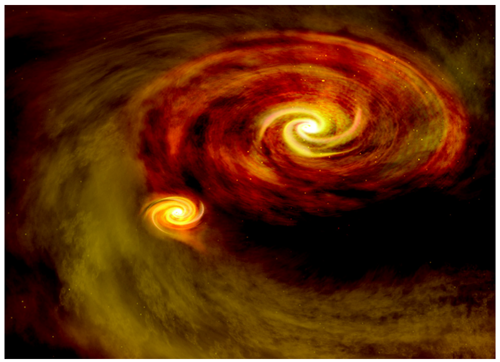
$$f_{\rm PBH/DM} \sim 10^{-2} - 10^{-3}$$

needed to explain the LIGO event rate

Venumadhav, Zackay, … 19



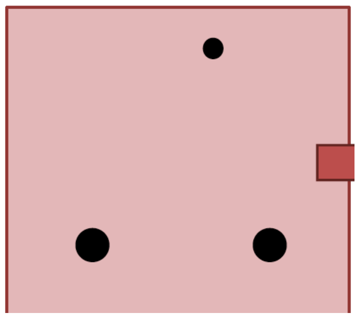
binary star sys. origin $\chi_{\rm eff} \sim +1$

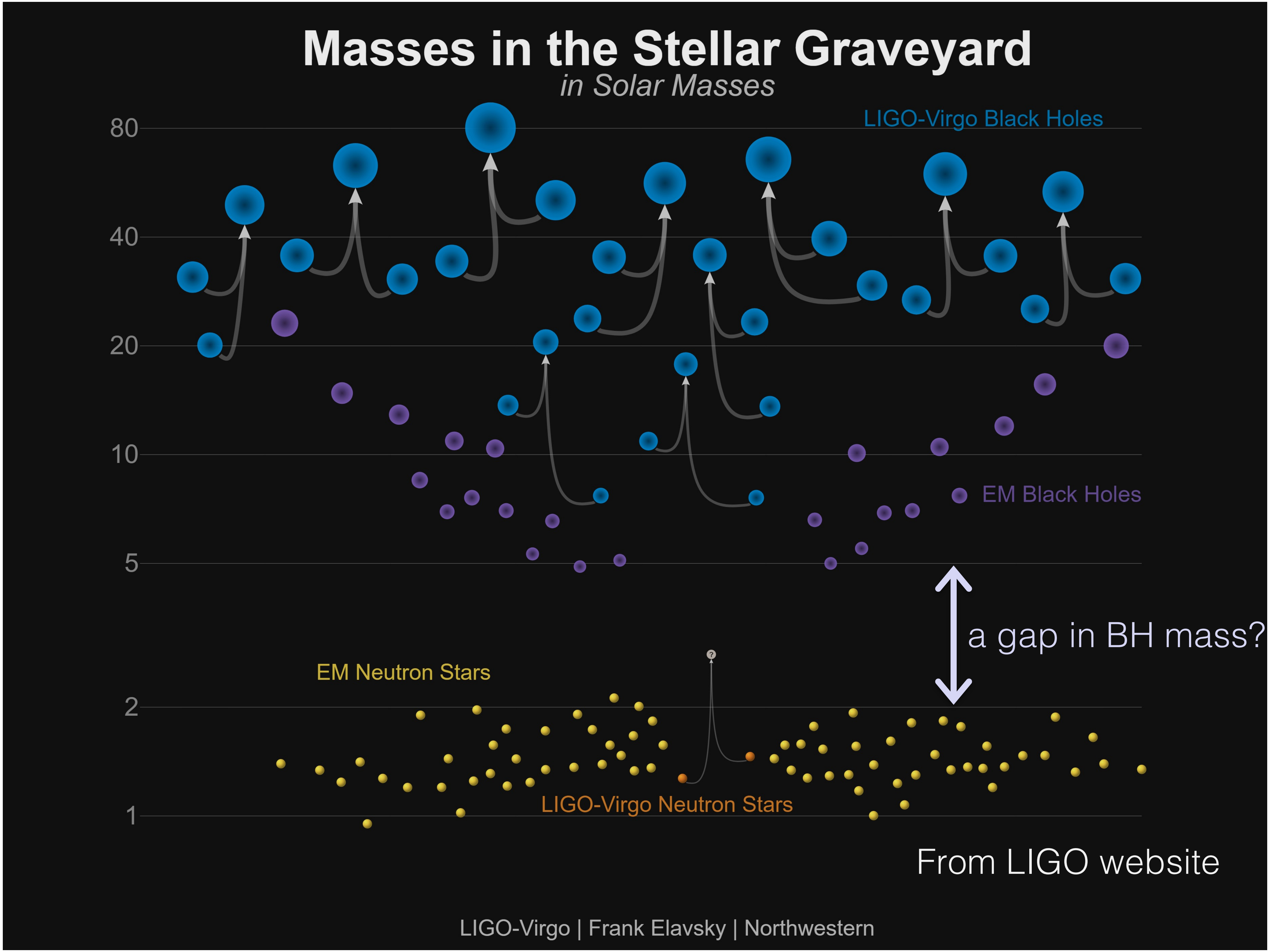


PBH

star cluster (merger)

$\chi_{\rm eff} \sim 0$




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

PBH formation

- PBH can be formed by the gravitational collapse of the Hubble patch in the radiation dominated era, if a large orverdensity of δ~O(0.1) is injected in the patch (Hawking 71)

$$\left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \frac{8\pi G}{3}\bar{\rho}_r(1+\delta_r) - \frac{k}{R^2}$$

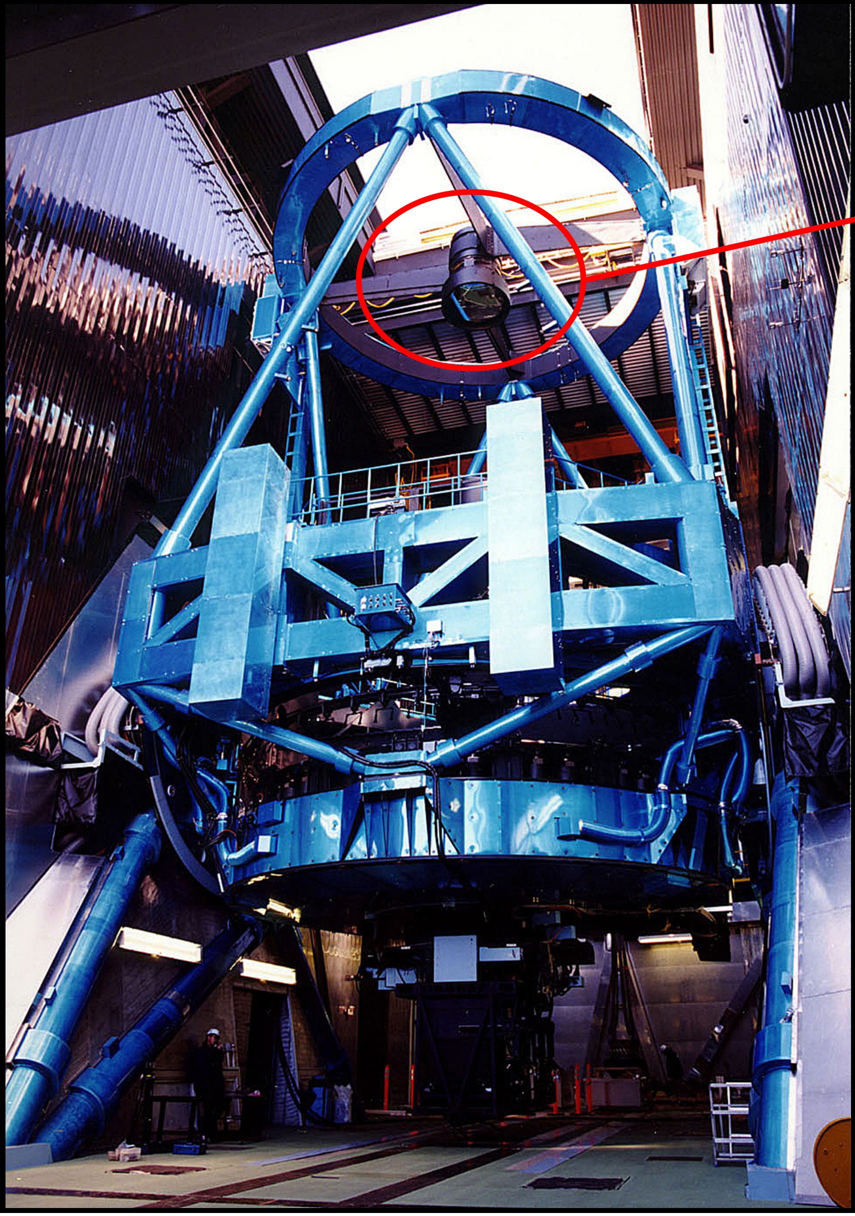
- PBHs can contribute DM, by a fraction given as

$$\frac{\Omega_{\rm PBH}(M_{\rm PBH})}{\Omega_{\rm DM}} \sim \left(\frac{\beta(M_{\rm PBH})}{6\times 10^{-14}}\right)\left(\frac{100}{g}\right)^{1/4}\left(\frac{0.12}{\Omega_{\rm DM}h^2}\right)\left(\frac{M_{\rm PBH}}{10^{-10}M_\odot}\right)^{-1/2}$$

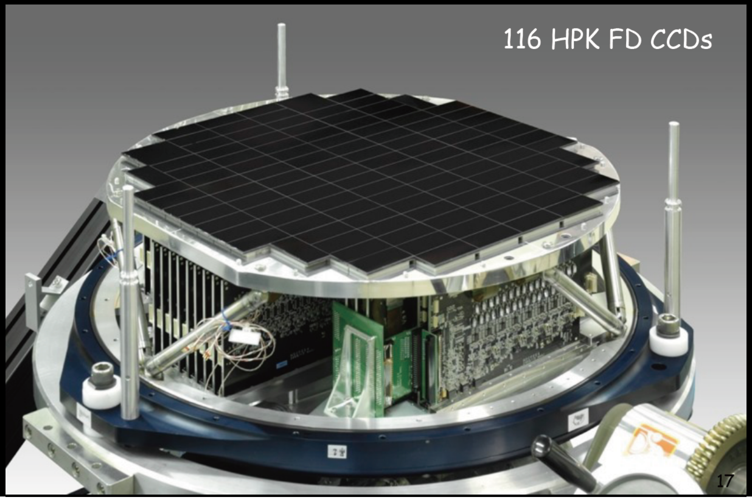
$$\beta(M_{\rm PBH}(k)) = \int_{O(1)}^{\infty} {\rm d}\delta\, \frac{1}{\sqrt{2\pi}\sigma(k)} e^{-\frac{\delta^2}{2\sigma(k)^2}}$$

Subaru Telescope

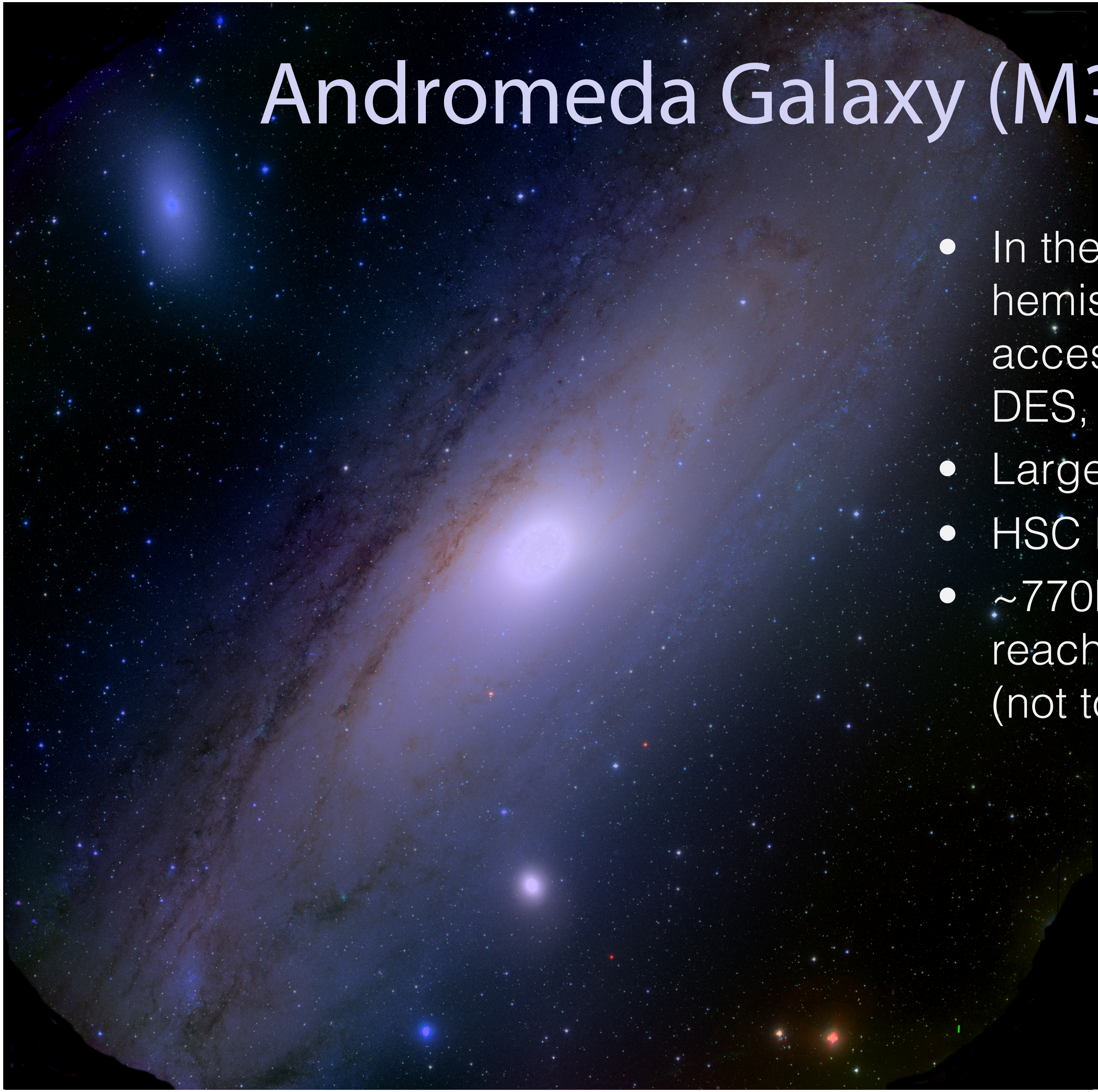
Hyper Suprime-Cam



- largest camera
- 3m high
- weigh 3 ton
- 104 CCDs (~0.9B pixels)



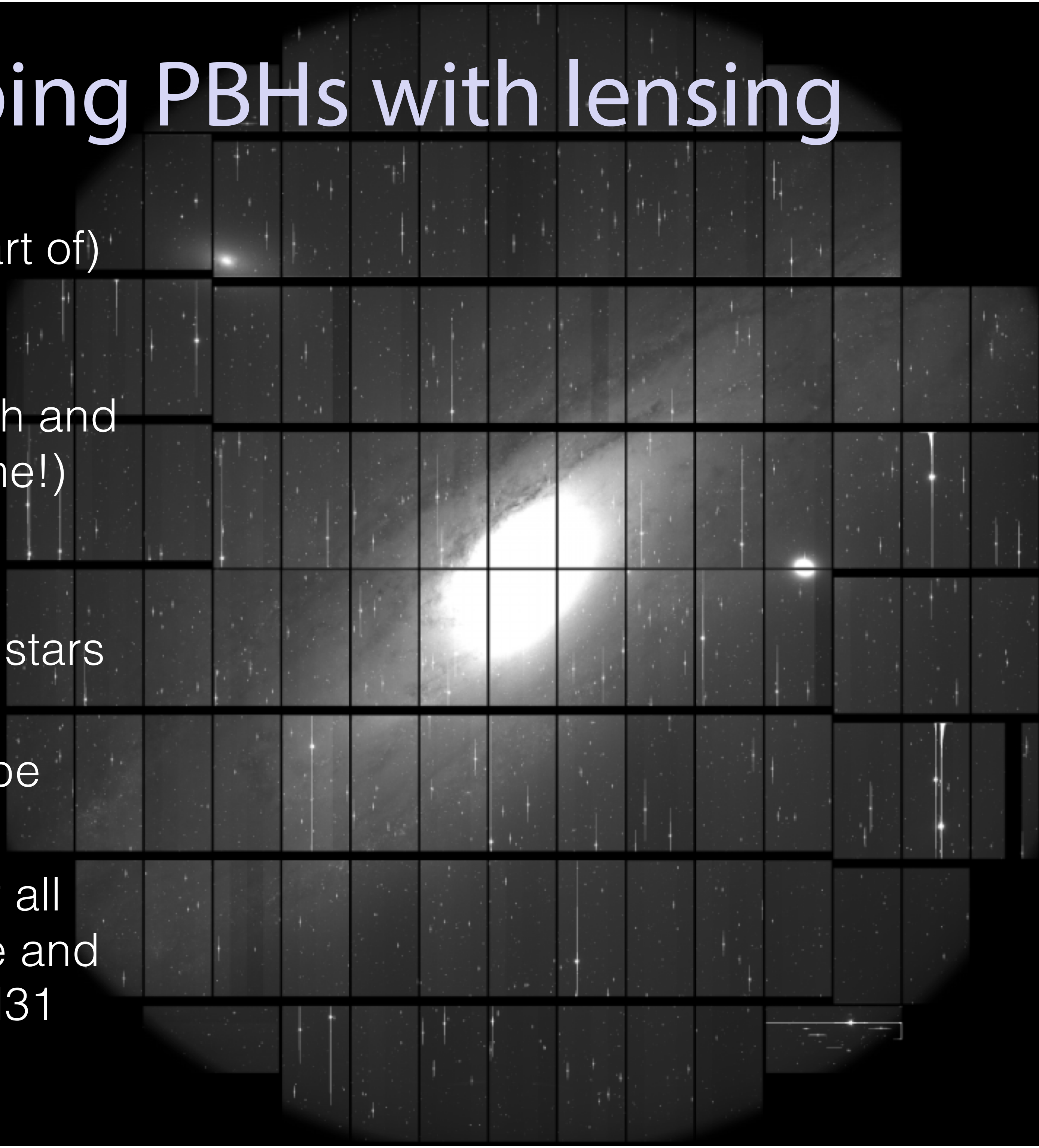
Andromeda Galaxy (M31)



- 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)!

probing PBHs with lensing

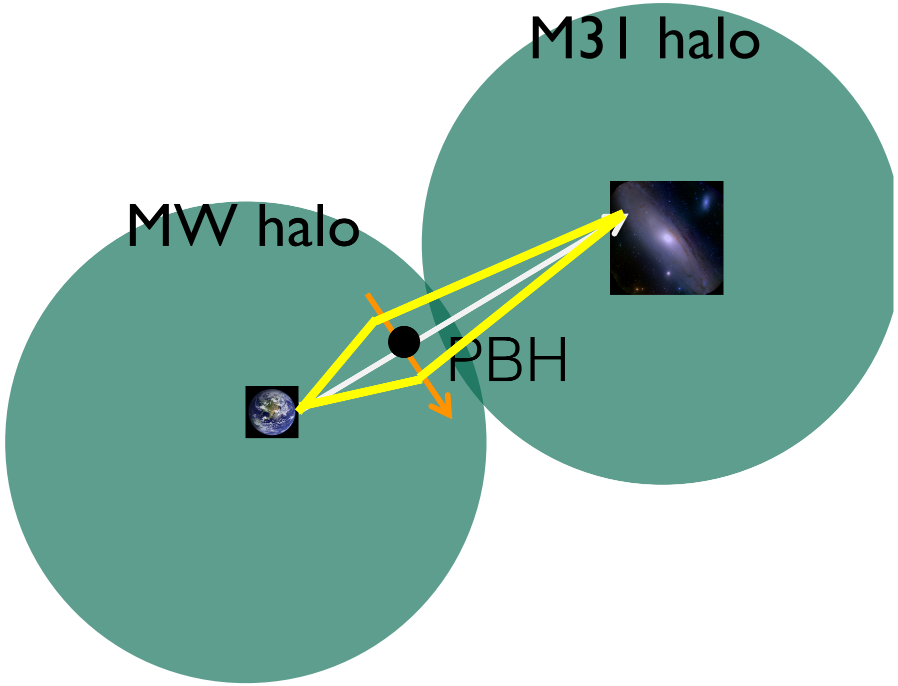
- If PBHs are (a part of) dark matter, they should exist in between the Earth and M31 (huge volume!)
- PBHs cause microlensing magnification on stars in M31
- Lensing can probe invisible
- HSC can monitor all stars in the bulge and disk regions of M31



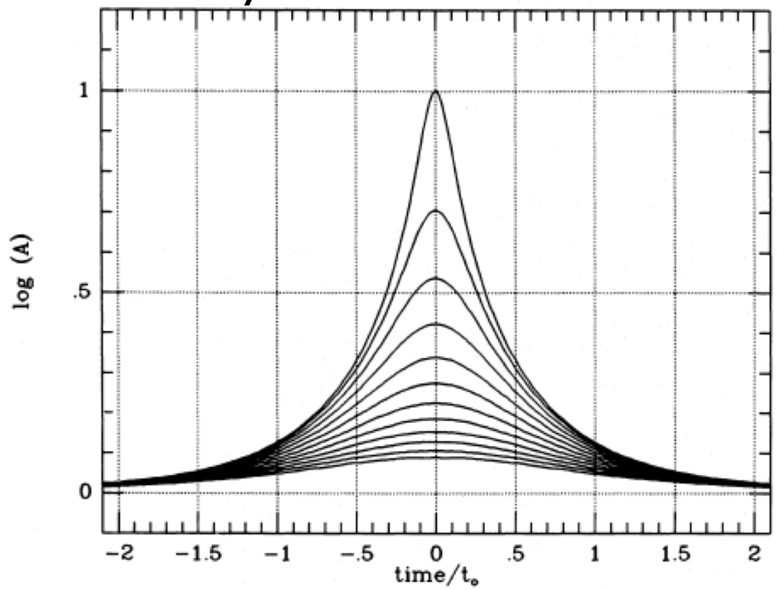
PBH microlensing on M31 star

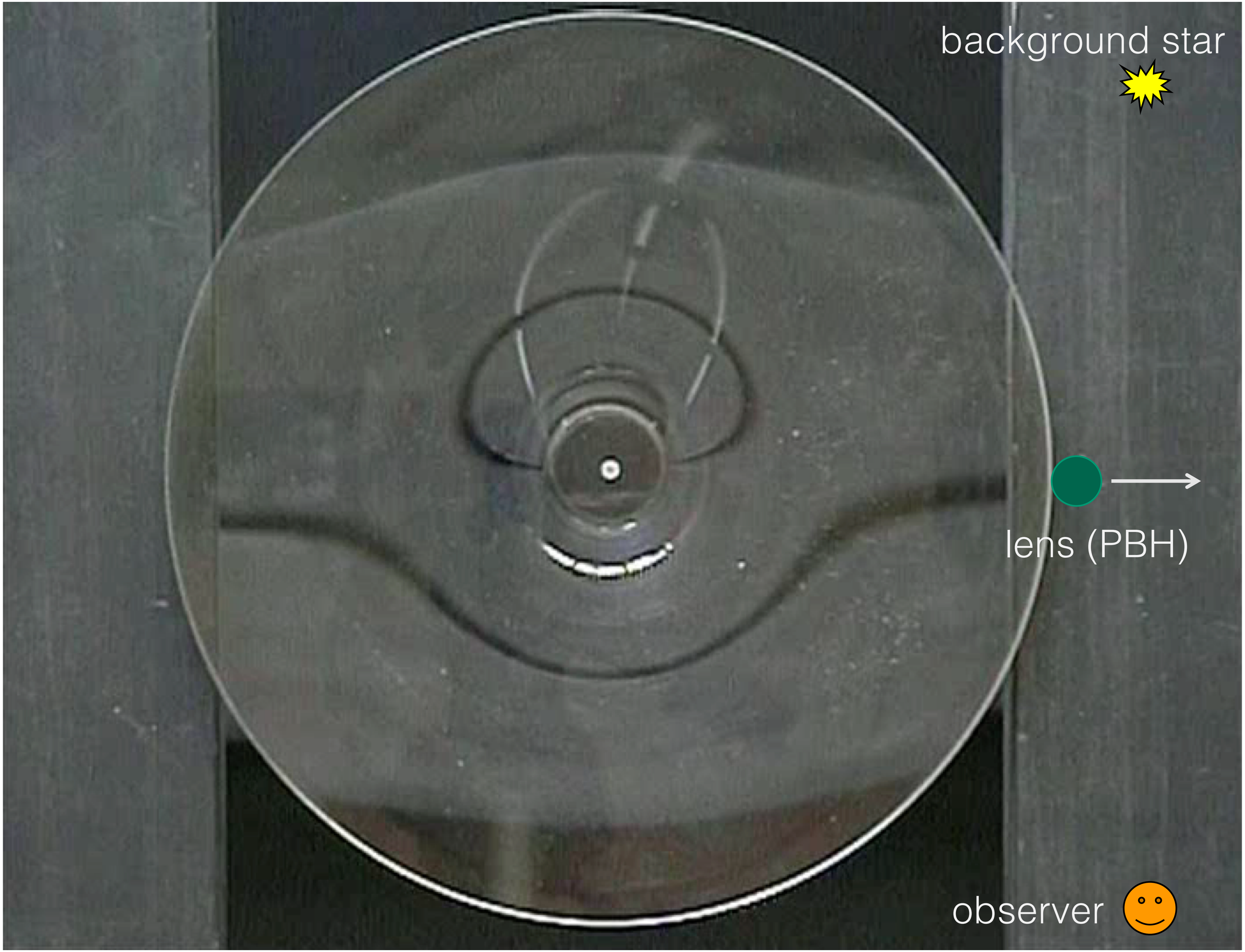
- Lensed image can't be resolved with optical resolution (~10^{-8} arcsec) ⇒ only light curve is a signal
- Huge volume
- MW/M31 halo ~ 10^{12}Msun (we assumed NFW models)
- PBH has a peculiar velocity of ~200km/s
- Need to monitor brightness of the same star as a function of "time" (time domain astronomy)

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

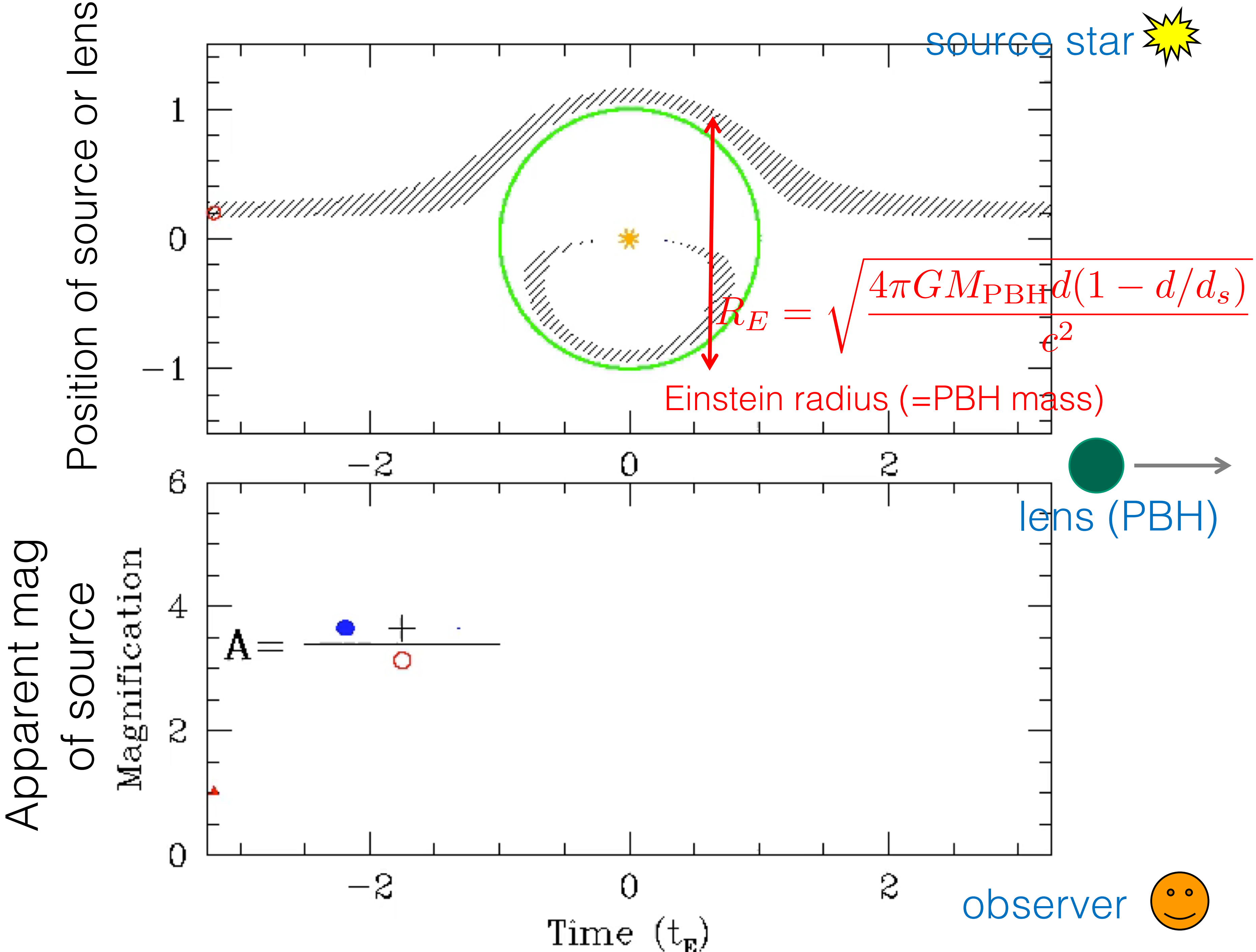


Paczynski 86





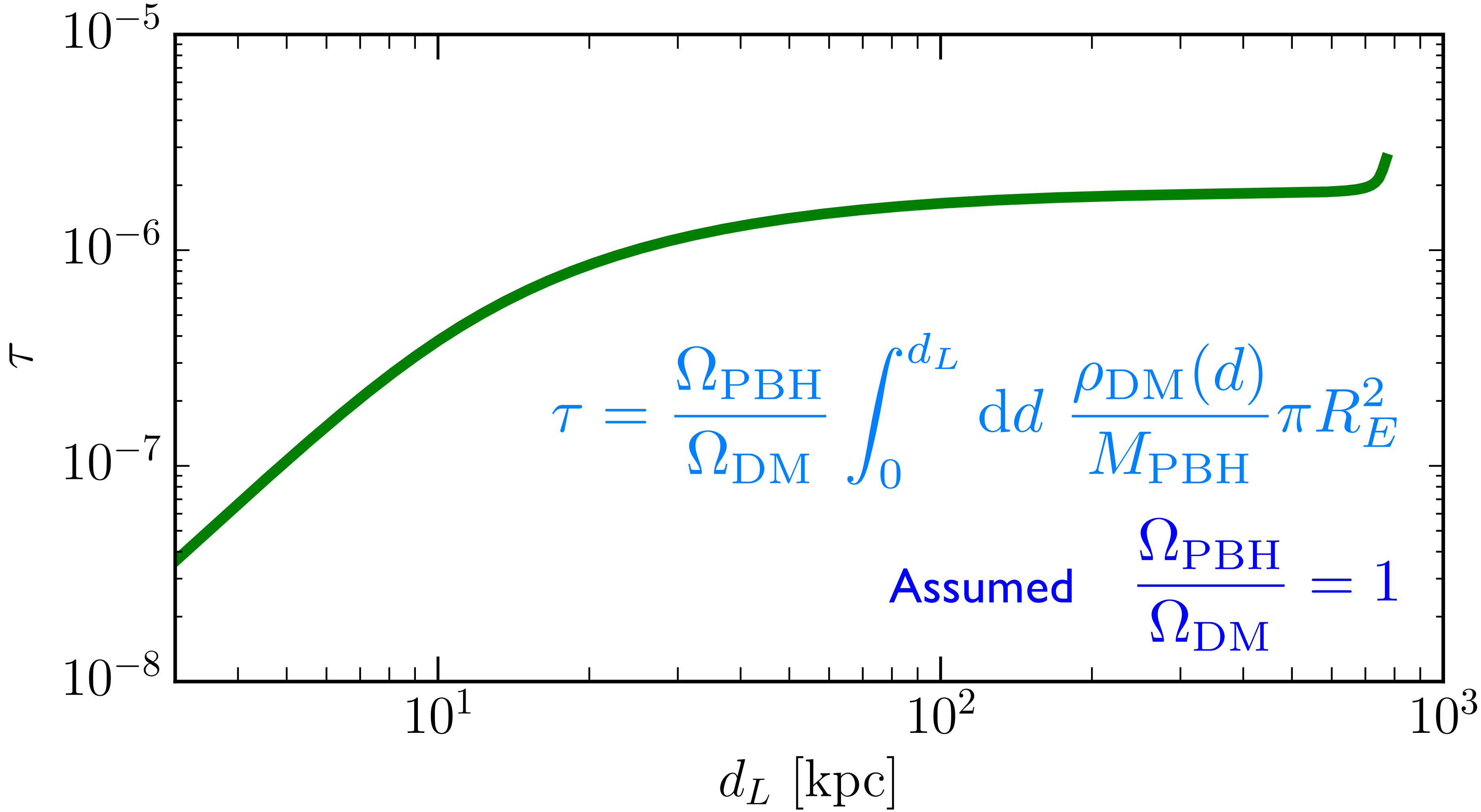
background star
lens (PBH)
observer



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

Event rate of PBH ML

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

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

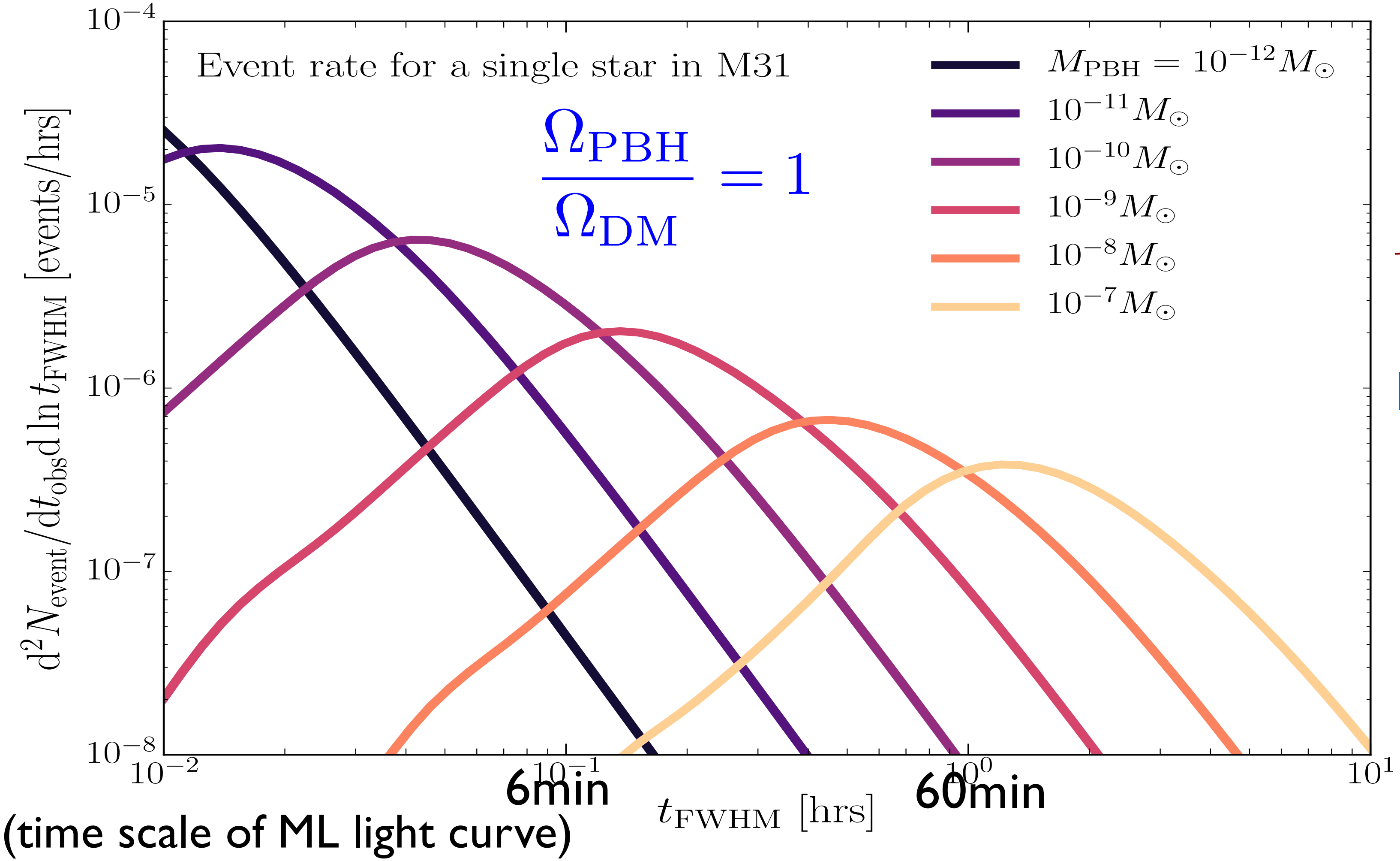
total observation time (duration of monitoring observation)

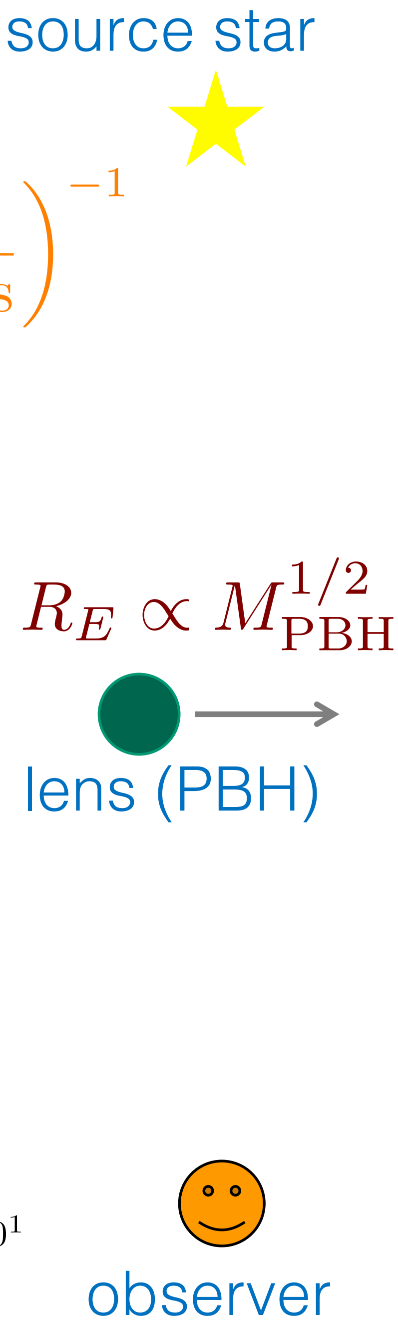
ML optical depth – depends on the nature of compact DM (e.g. PBH), and the mass fraction of compact DM to total

efficiency – depends on cadence and quality of data

PBH microlensing event rate

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

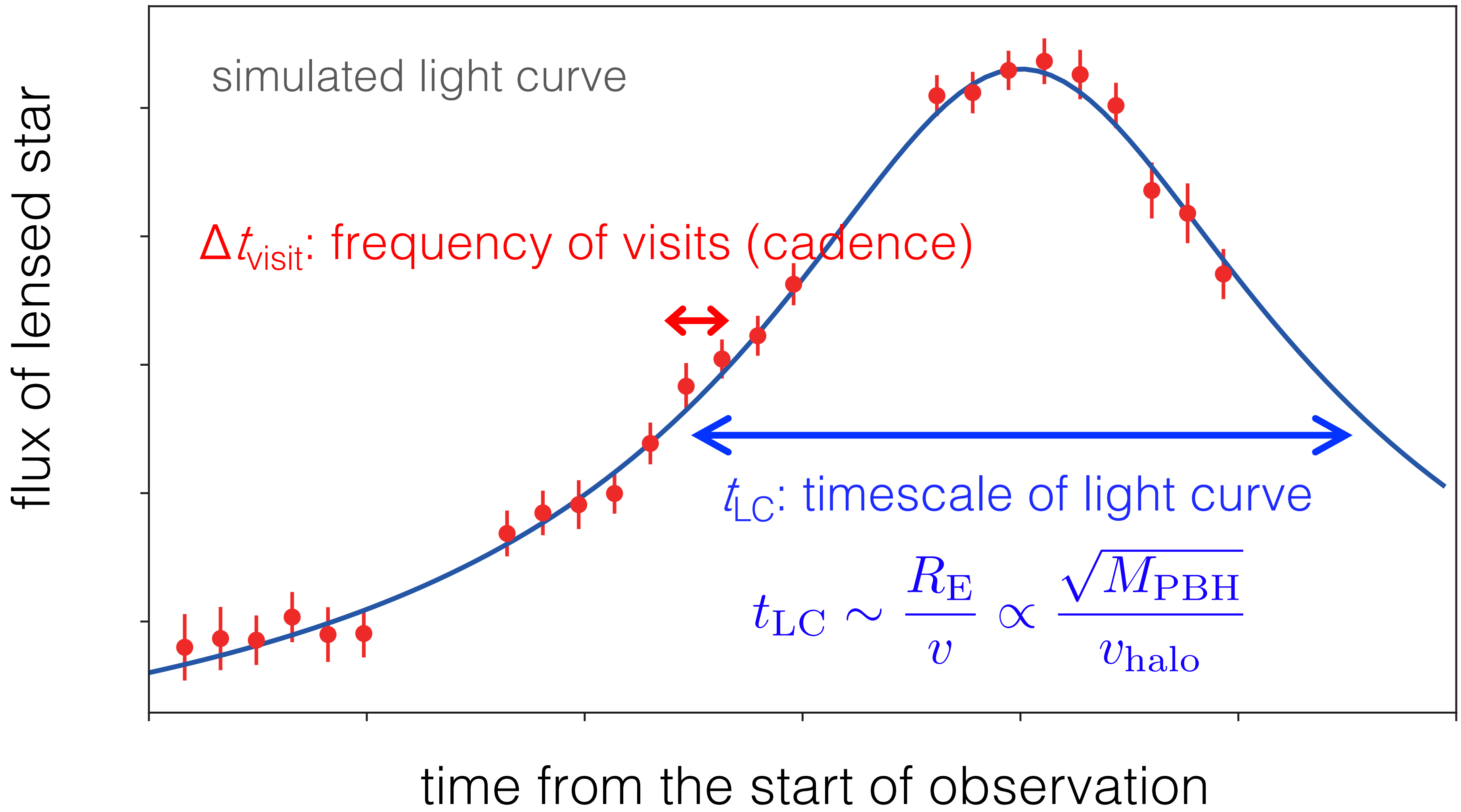


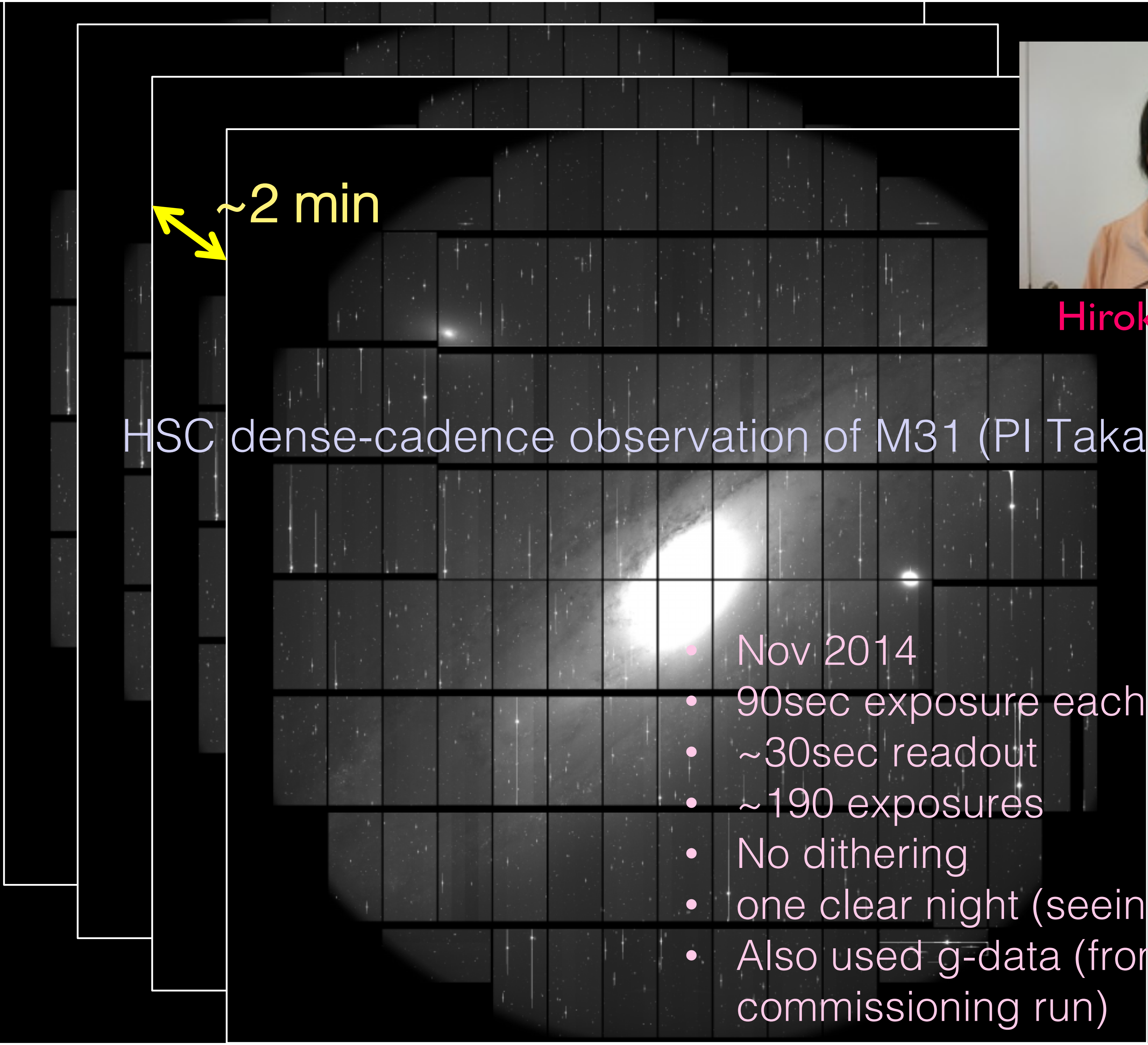


Event rate per **unit obs. time** and per **a single star** in M31 for **a given timescale of light curve (we monitored ~10^8 stars)**

Rule of the game: LC timescale vs. Cadence

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





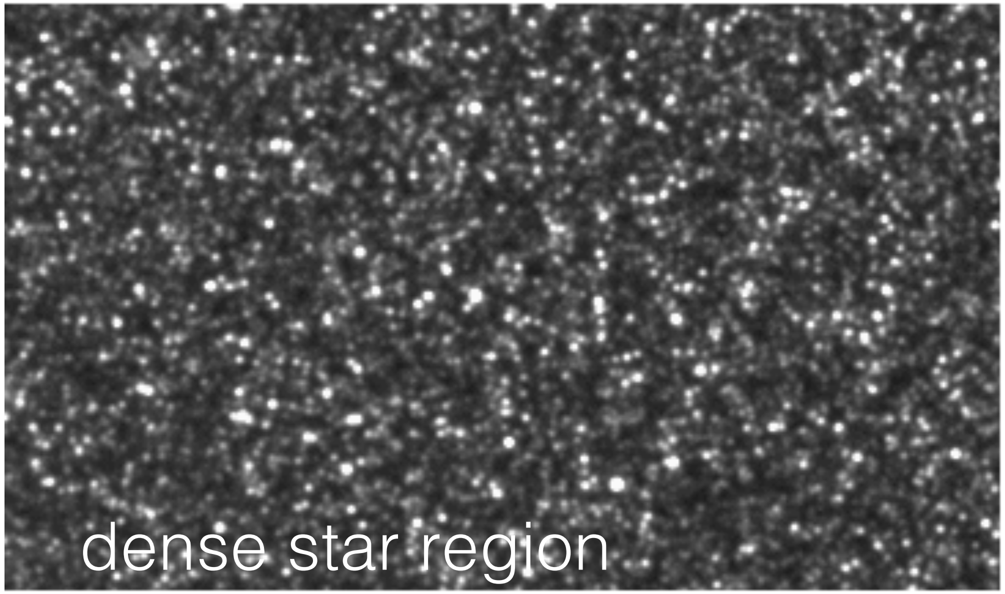
Hiroko Niikura

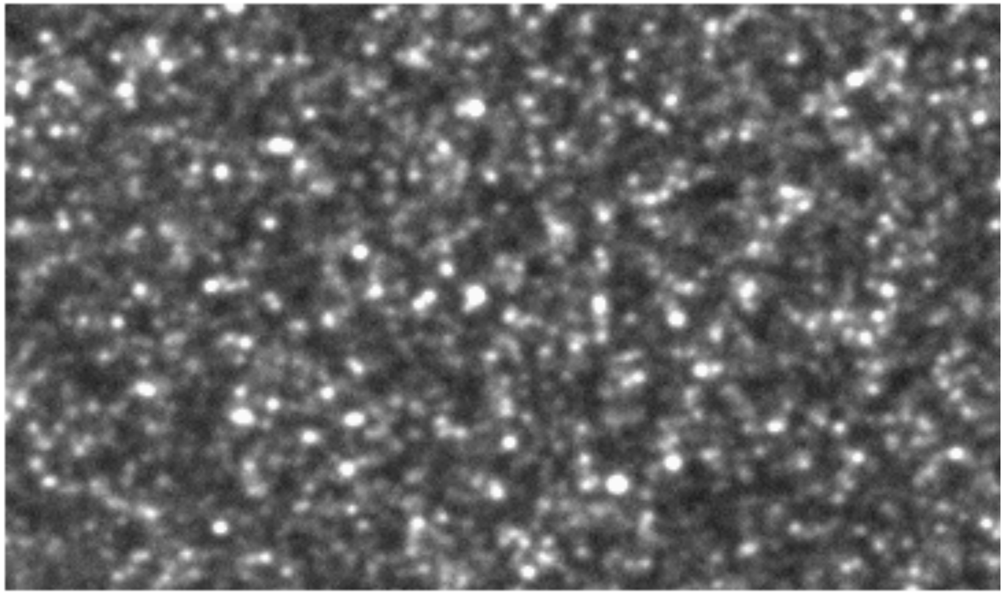
HSC dense-cadence observation of M31 (PI Takada, S14B)

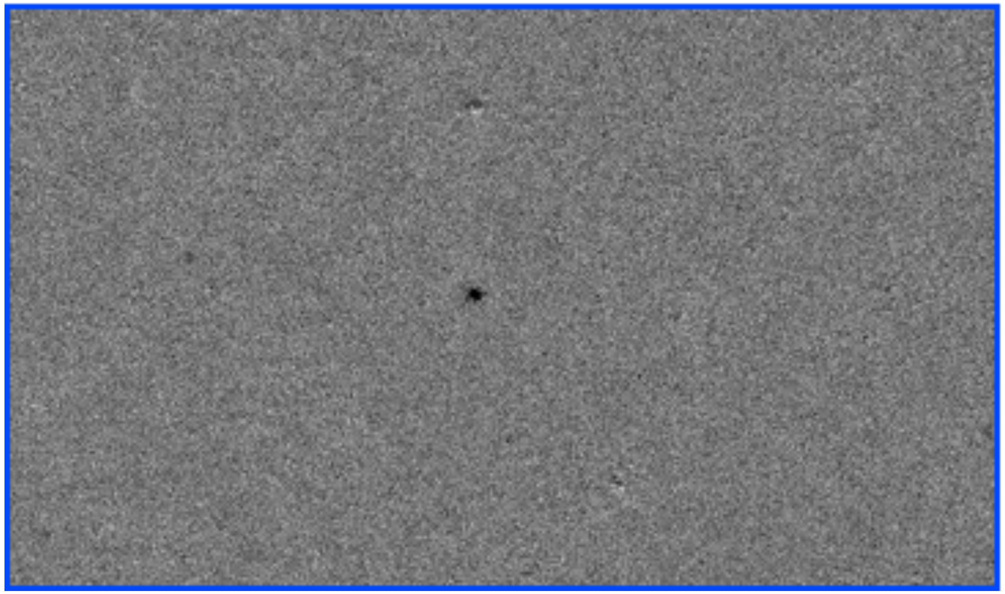
- Nov 2014
- 90sec exposure each (r-band)
- ~30sec readout
- ~190 exposures
- No dithering
- one clear night (seeing~0.5-0.6'')
- Also used g-data (from commissioning run)

Challenges: Pixel lensing

Fluxes from multiple stars are overlapped at each position





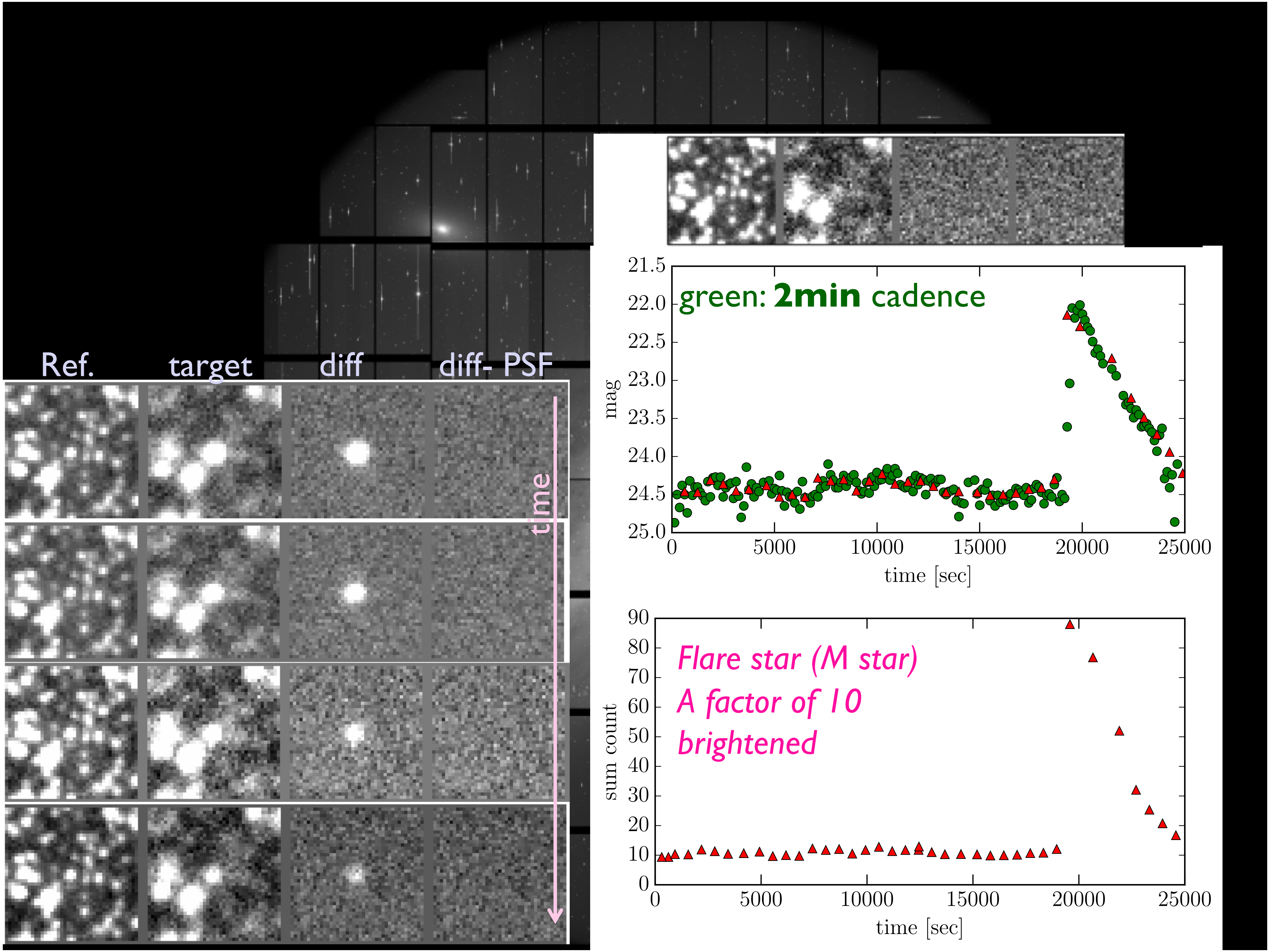


Upper left: reference image (0.5'')

Upper right: target image (0.8'')

Lower: difference image

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



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]

To constrain the PBH abundance

- Expectation number of PBH microlensing events

$$N_{\rm exp} = \Delta t_{\rm obs} \int {\rm d}m_r \, \frac{{\rm d}N_{\rm s}}{{\rm d}m_r} \int {\rm d}t_{\rm FWHM} \, \frac{{\rm d}\Gamma}{{\rm d}t_{\rm FWHM}} \, \epsilon(t_{\rm FWHM}, m_r)$$

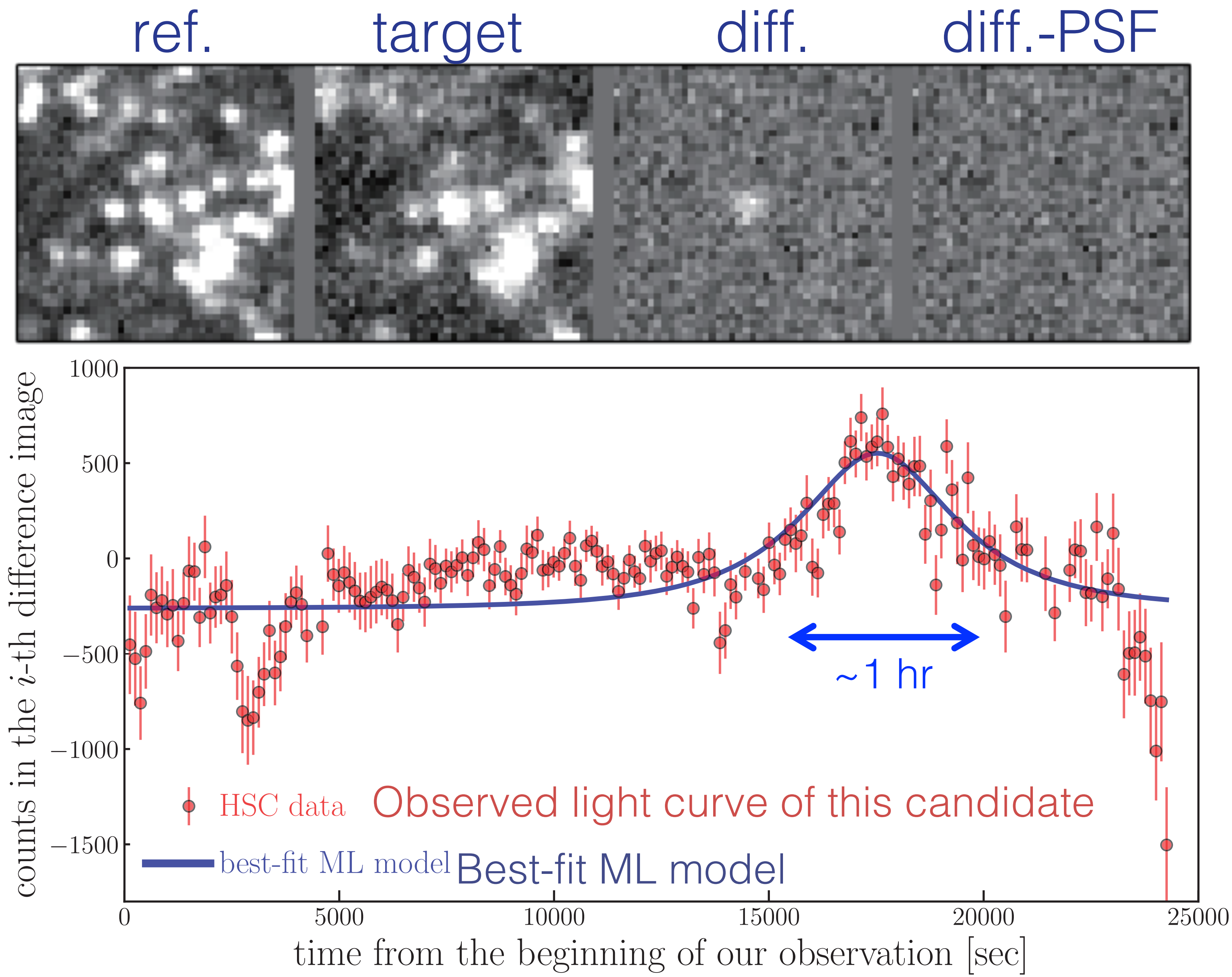
duration of observation time (about 7 hours)

number of source stars in the magnitude range [m, m+dm] (see later)

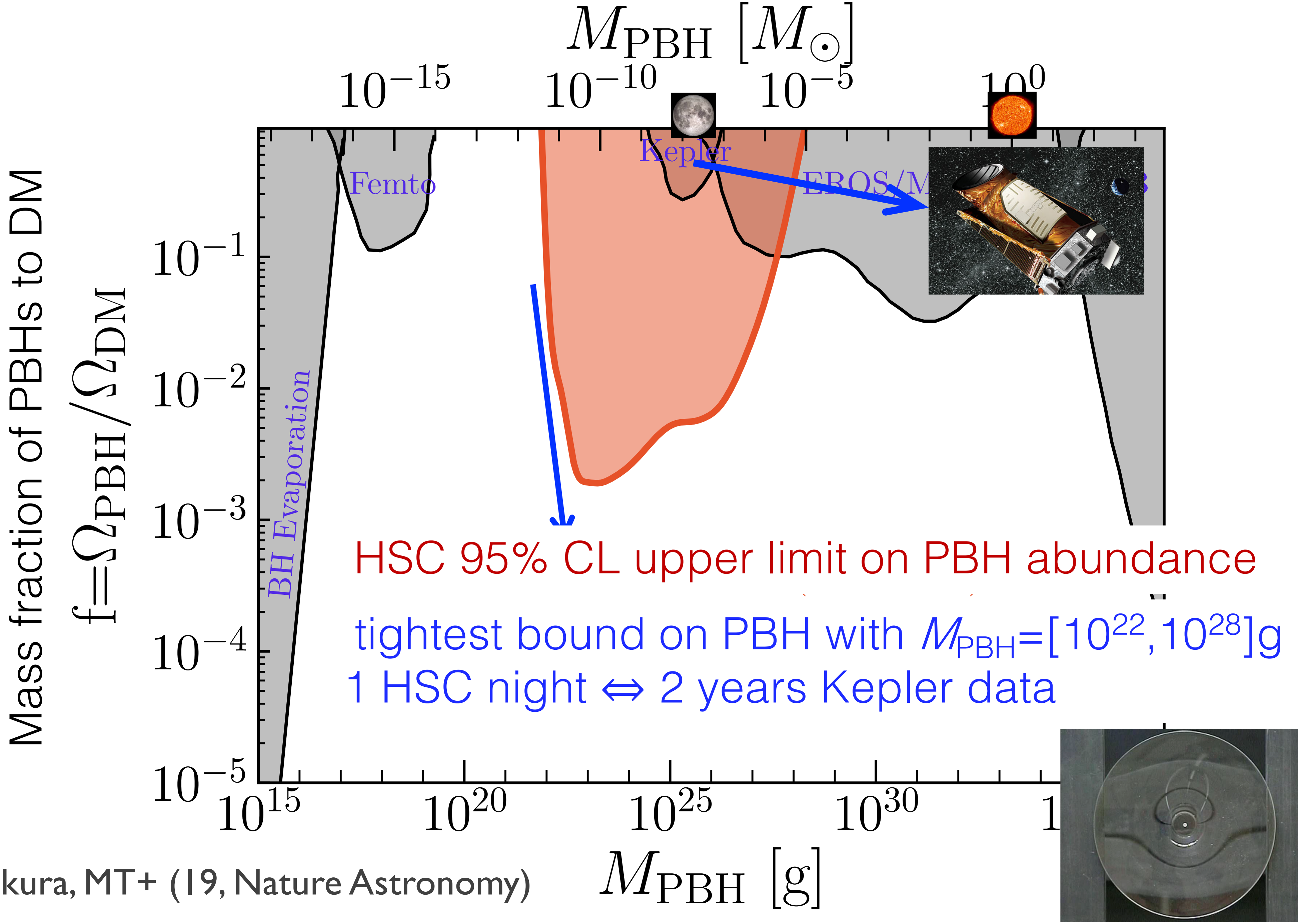
Event rate of PBH microlensing (computed assuming NFW profiles of the MW and M31 halos)

Detection efficiency for microlensing event of timescale t_FWHM for a star of magnitude, m_r (see later)

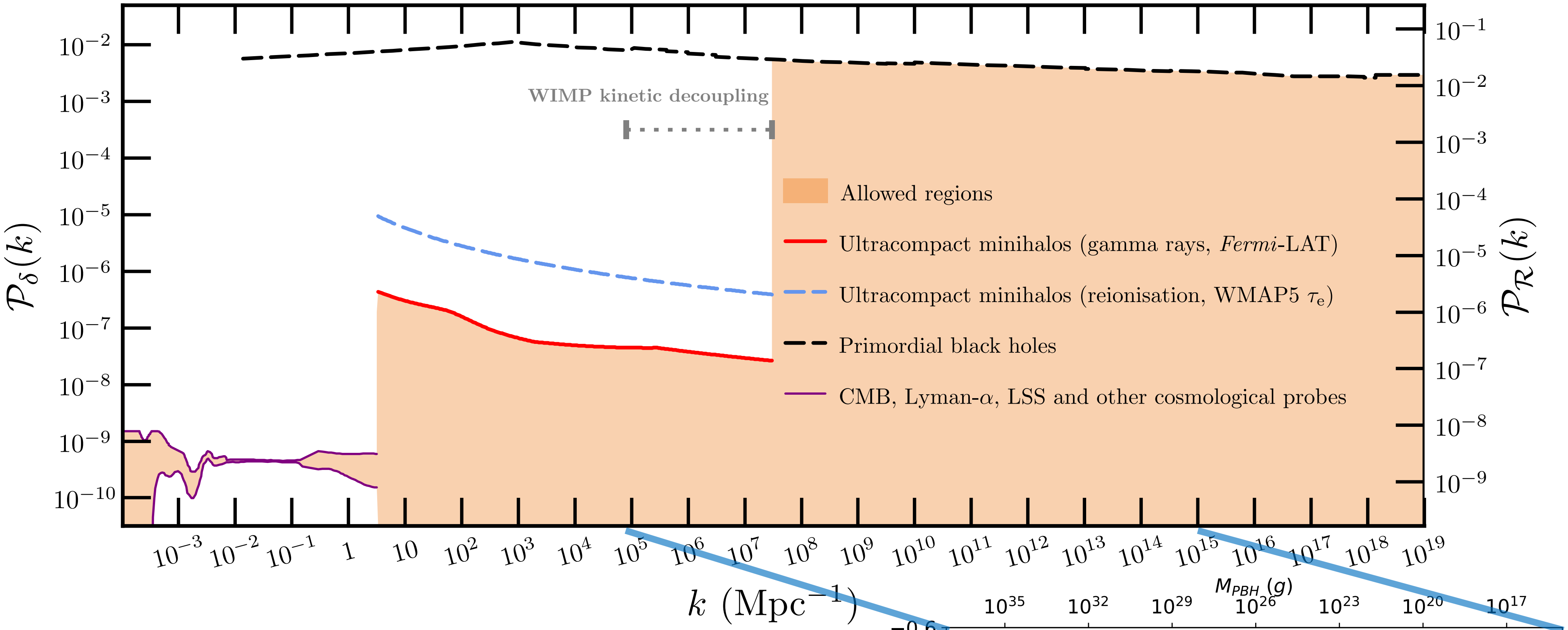
One microlensing candidate among **~15,000** variable stars …?



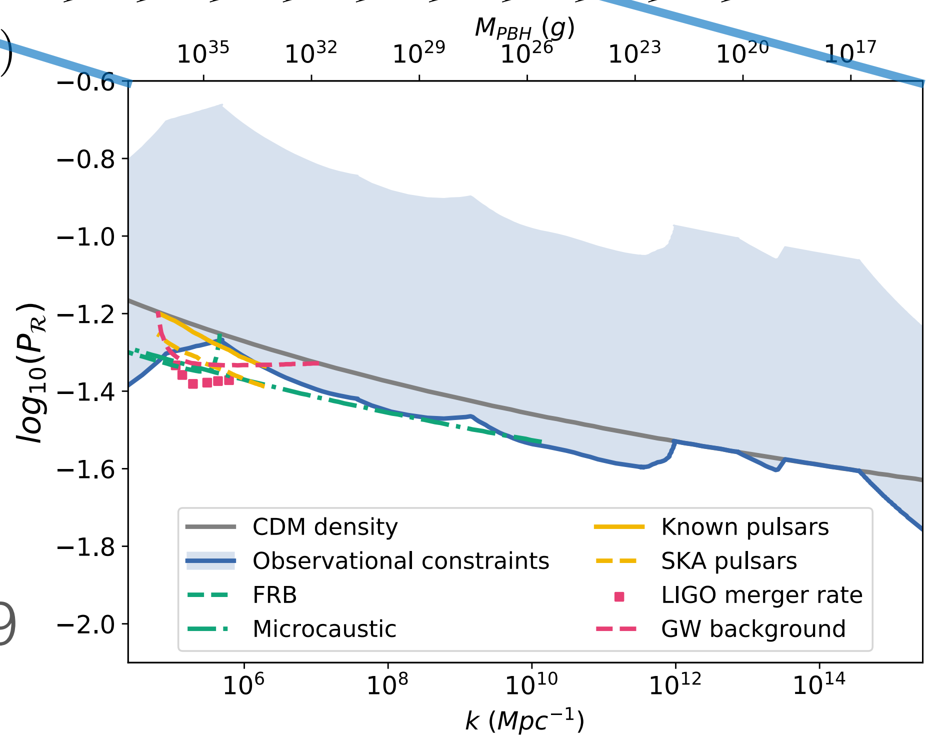
Subaru/HSC constraint on PBH abundance



Niikura, MT+ (19, Nature Astronomy)



Bringmann et al. 11

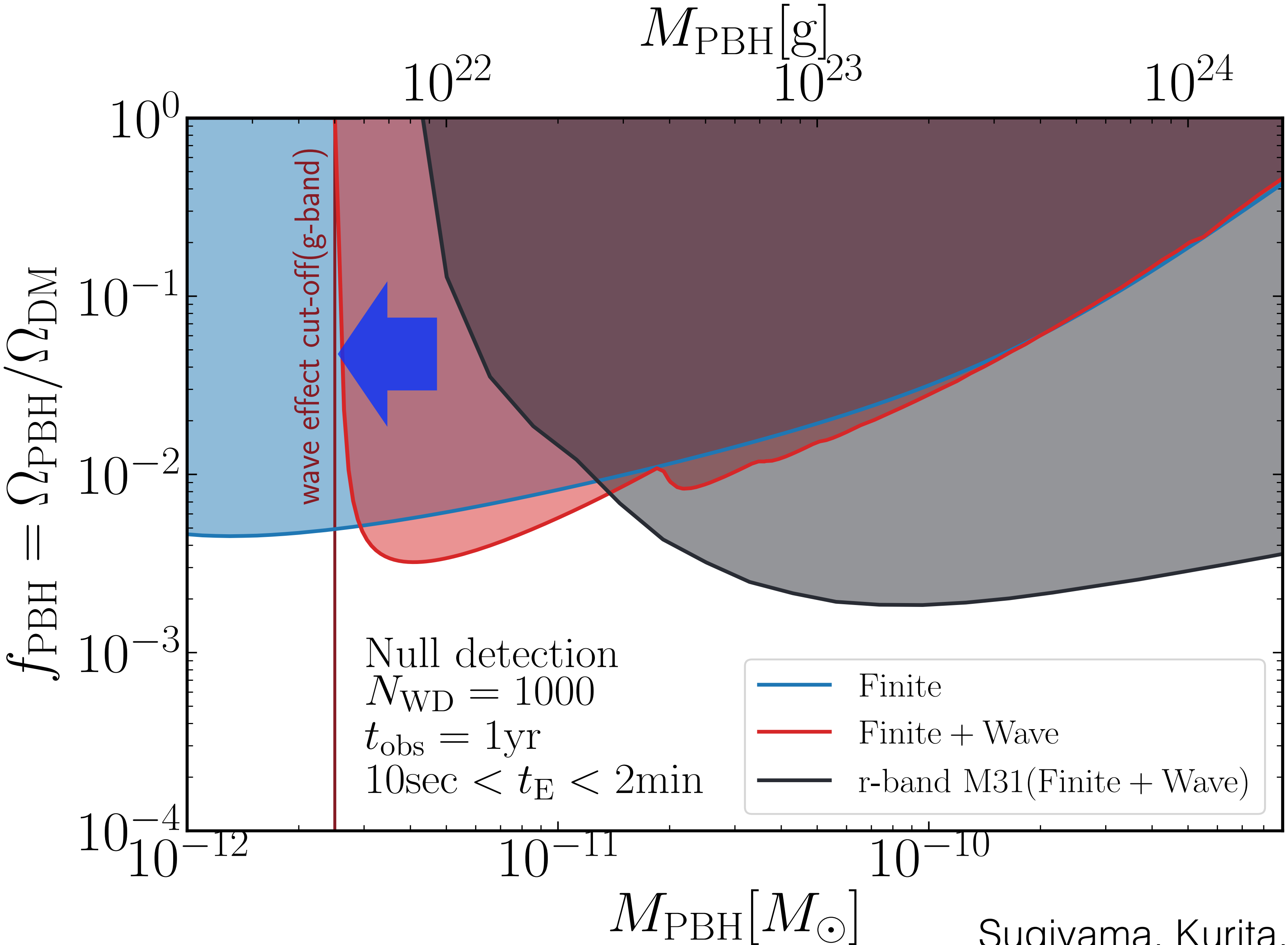


Recent update by Sato-Polite et al. 19

Any further improvement in optical microlensing?

Sunao Sugiyama

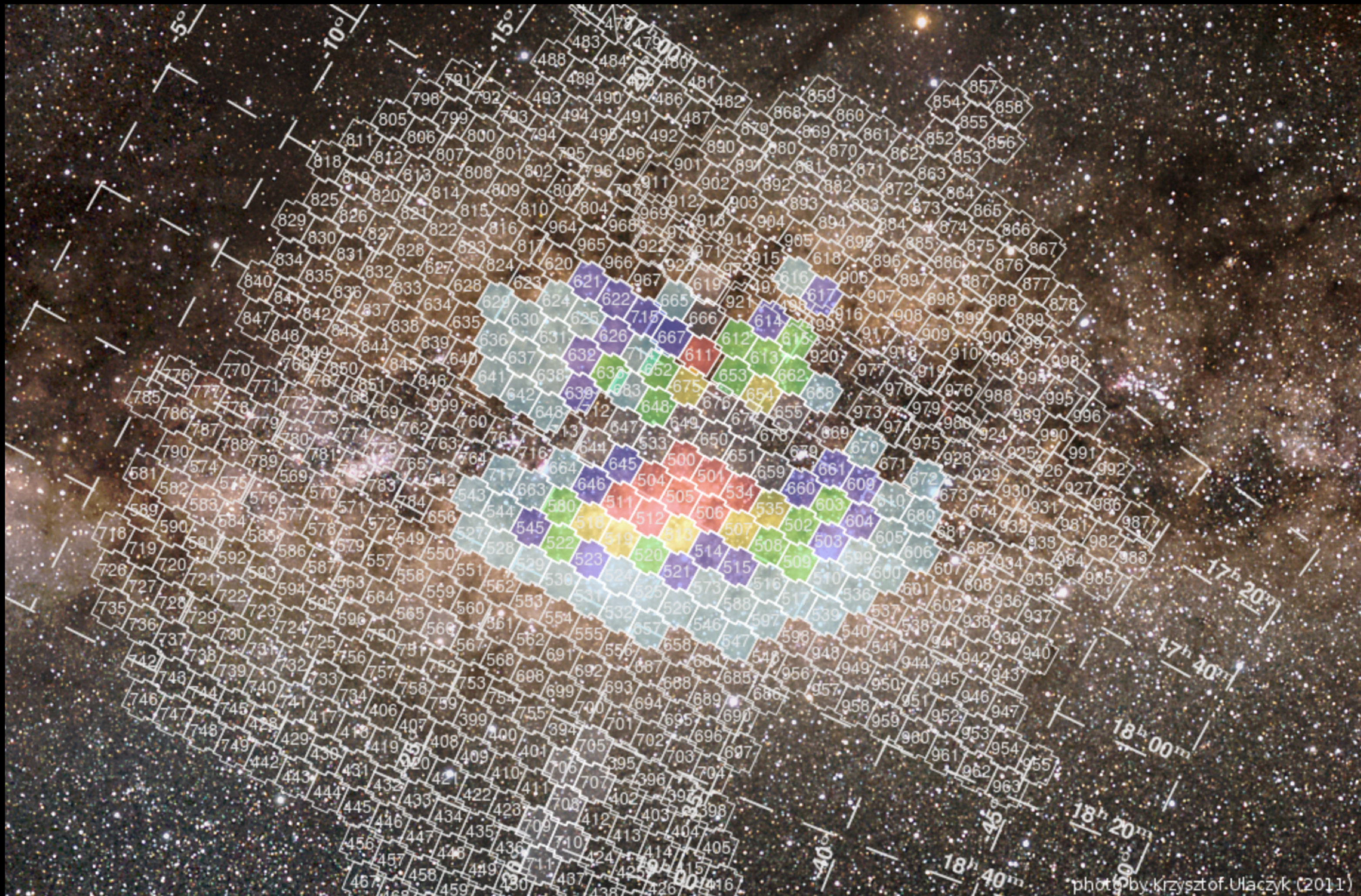
Toshiki Kurita



Sugiyama, Kurita, MT 19

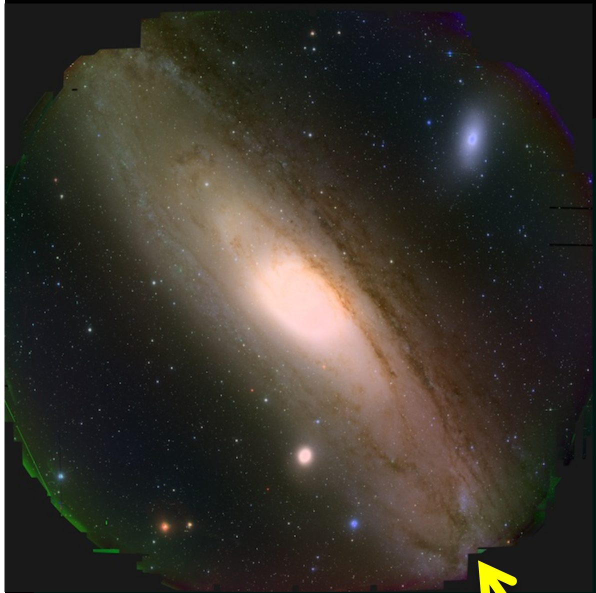
Optical Gravitational Lensing Experiment (OGLE)

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

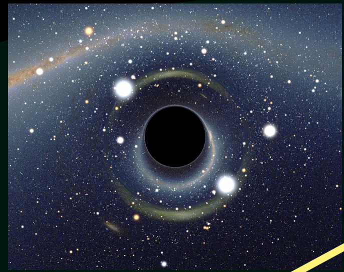


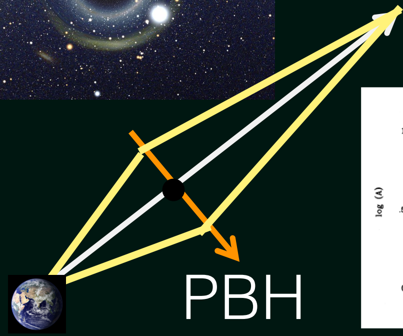
Constraining PBH with microlensing

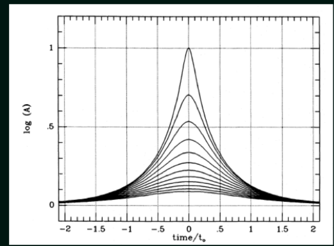
Hiroko Niikura
(U. Tokyo/IPMU
just graduated!)

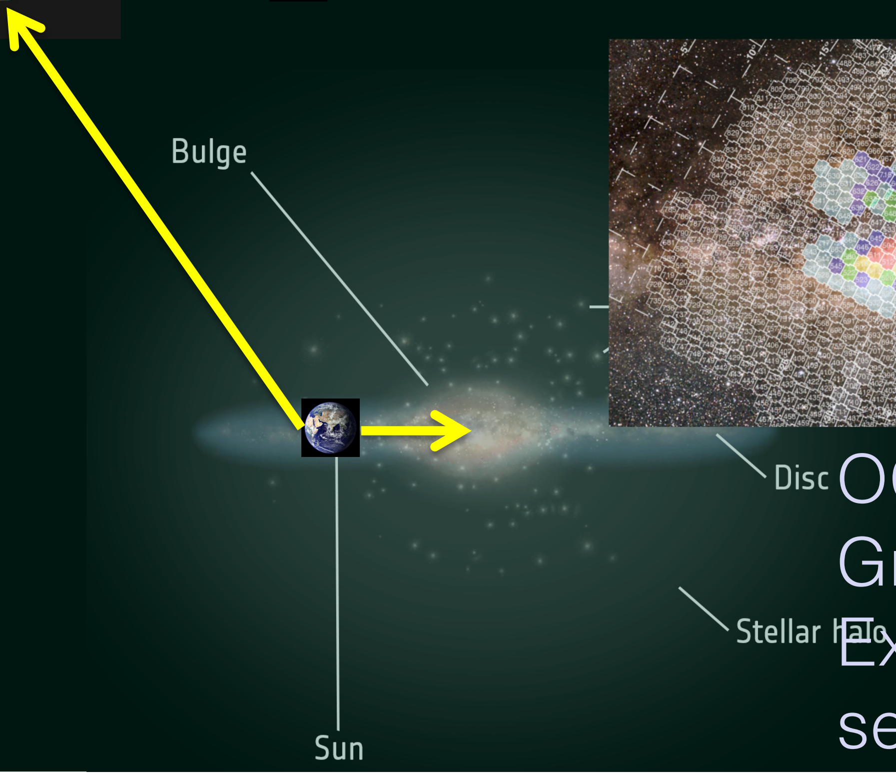


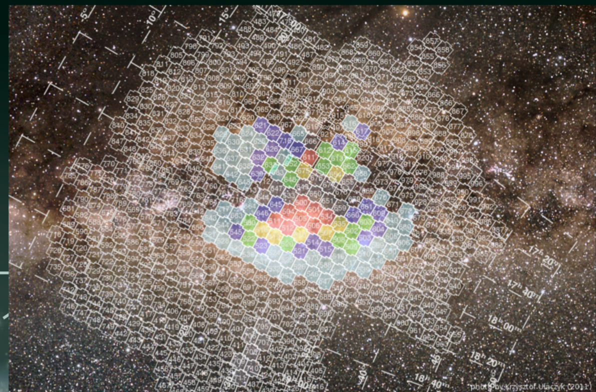
HSC M31
PBH
microlensing
search











OGLE (Optical
Gravitational Lensing
Experiment) for PBH
search

25yrs for ML search

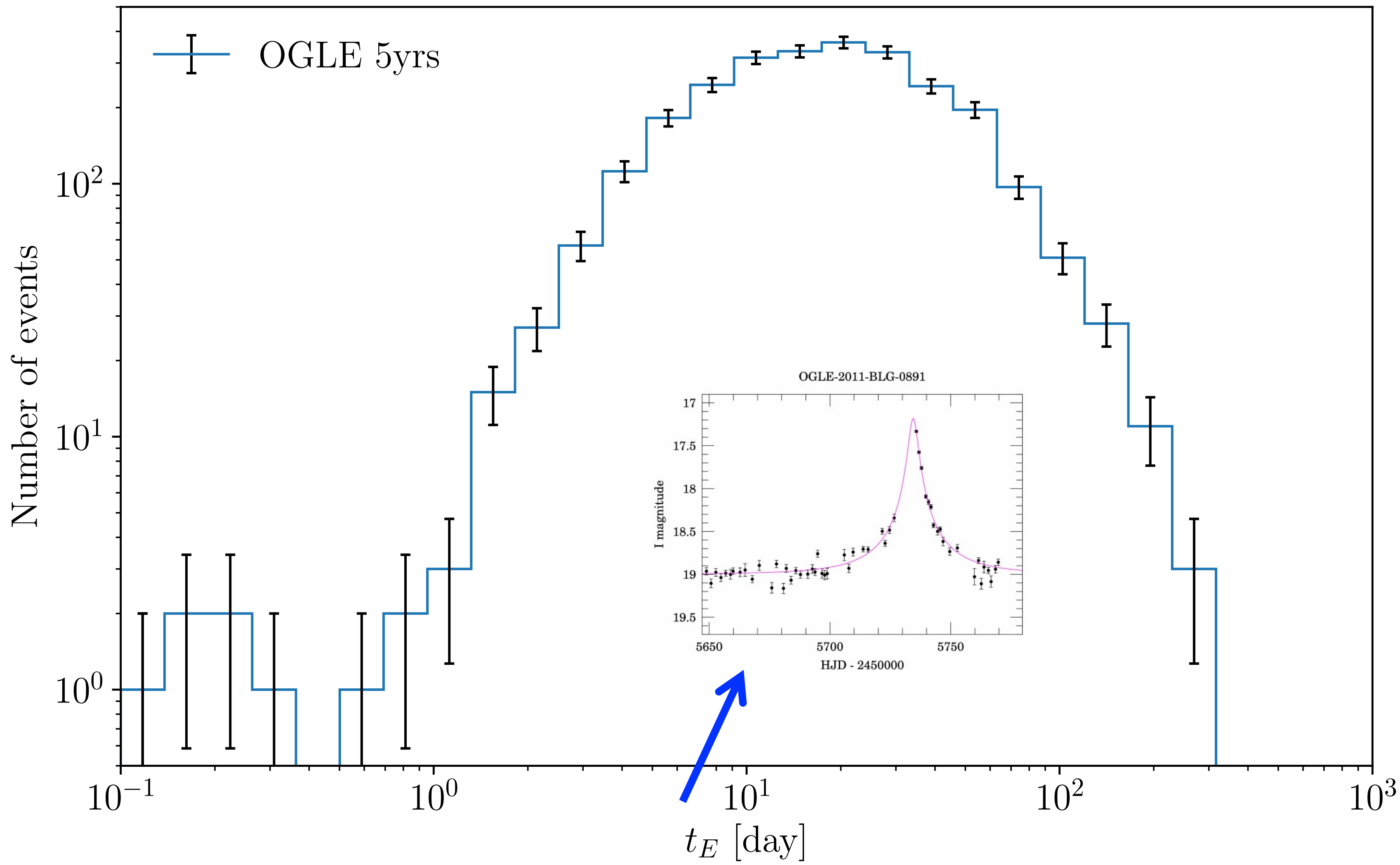
20yrs for multi-purpose use

1.3m Warsaw tel. (Chile)

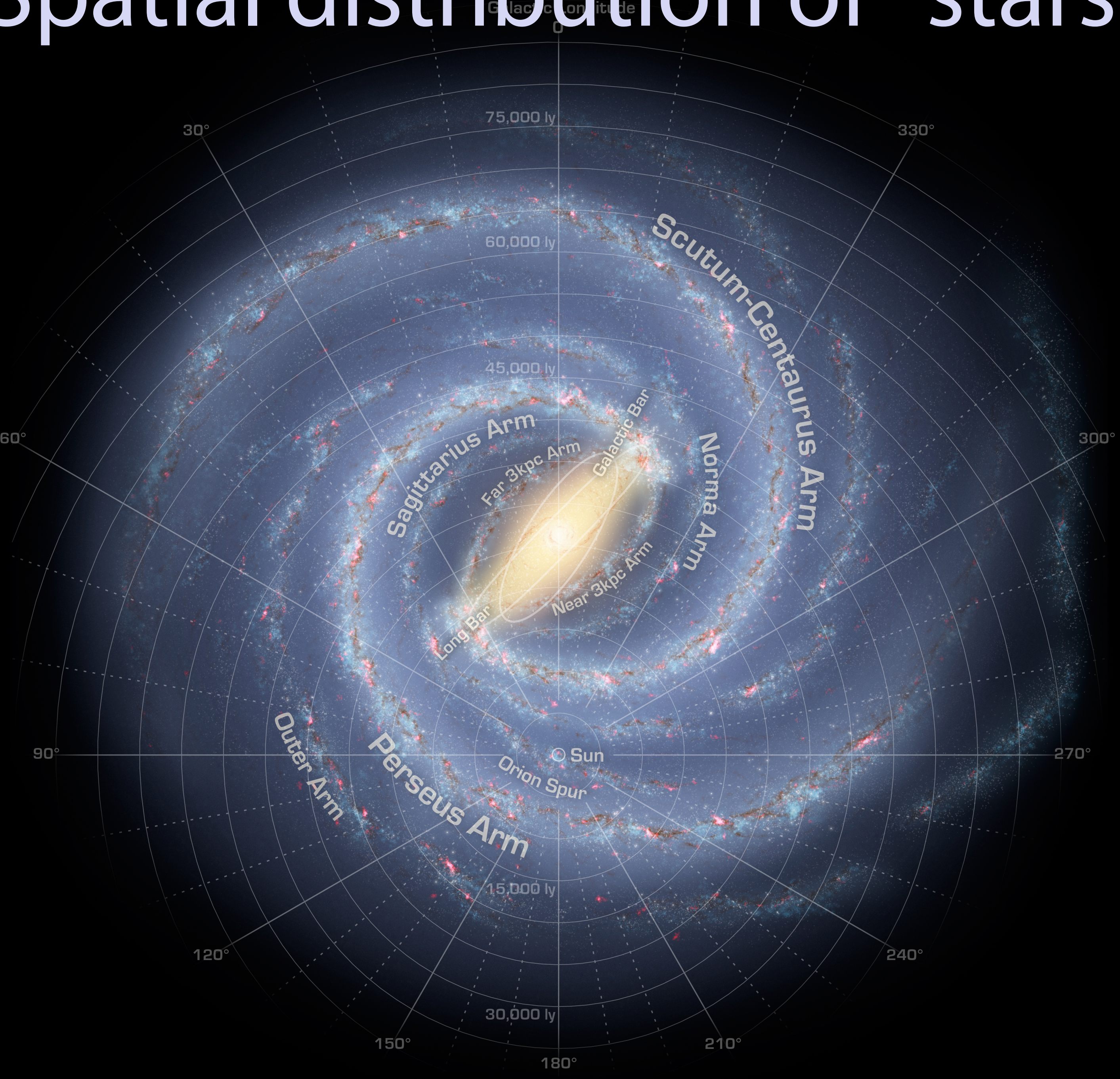
8.2m Subaru tel. (Hawaii)

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

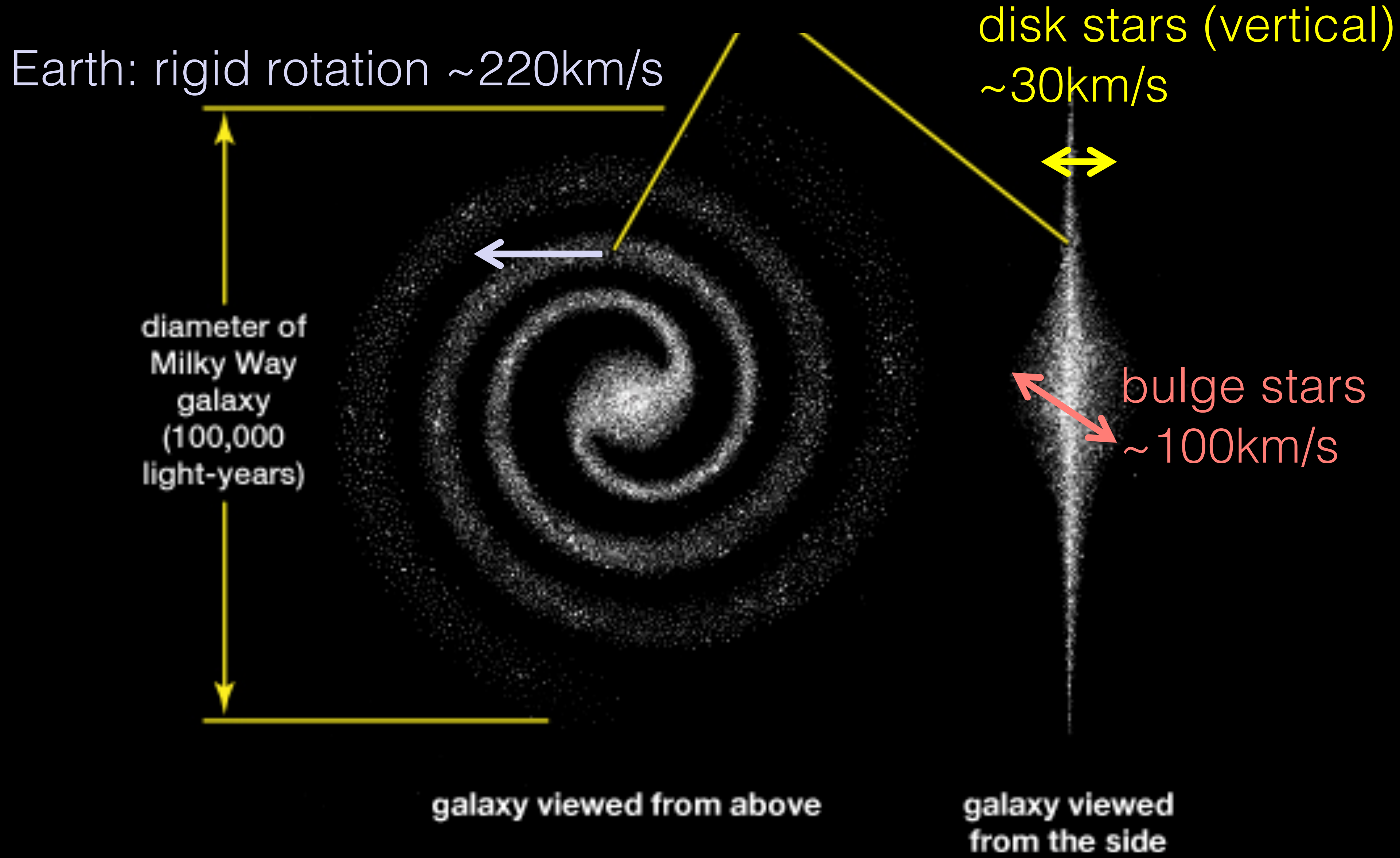
TABLE 2

BULGE AND DISK DENSITY MODELS

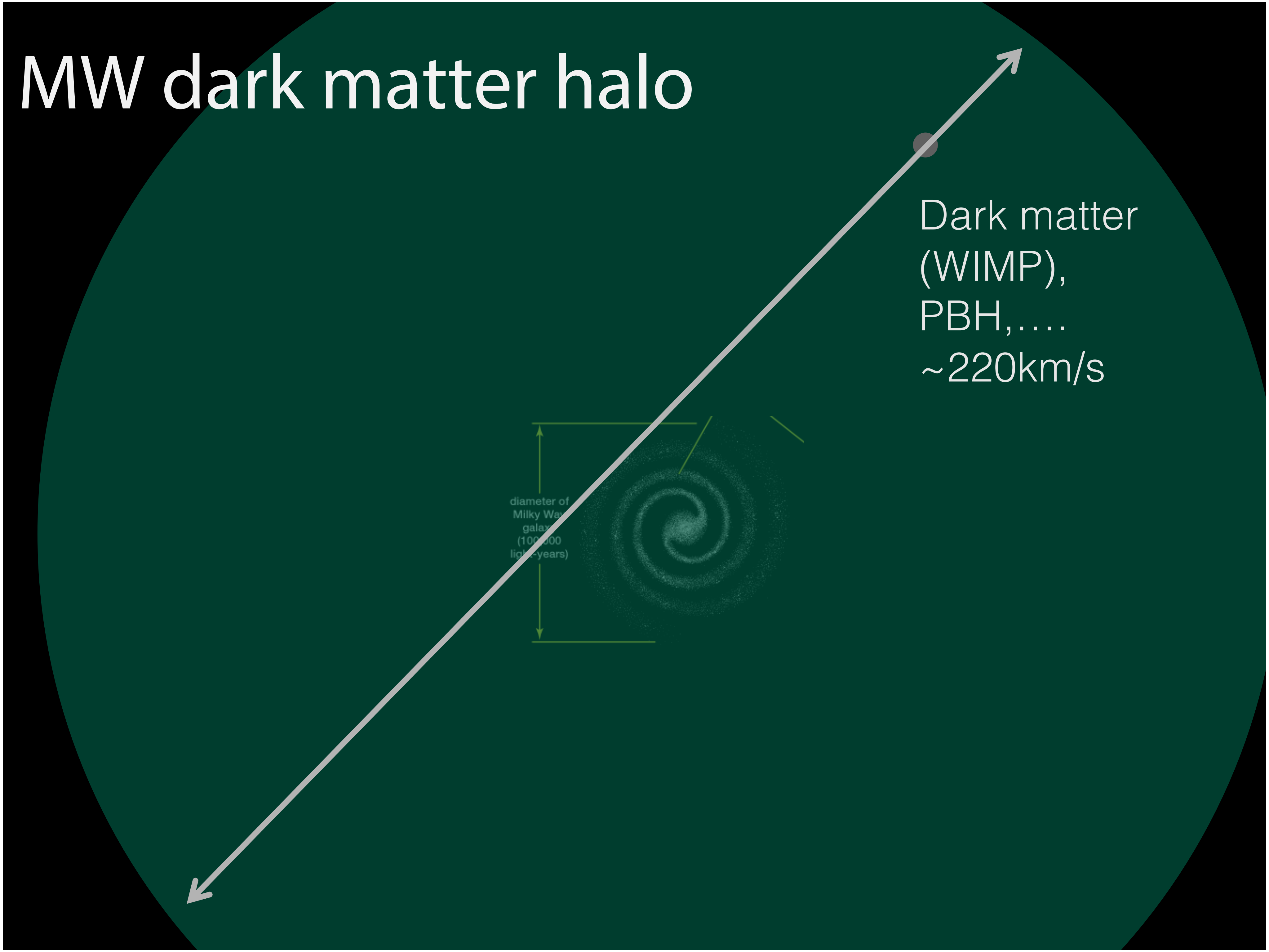
Location	Model	Distribution
Bulge......	isothermal	$\rho(r) = \sigma_{bulge}^2/2\pi G r^2 = 36.7(\sigma_{bulge}/r)^2\ M_\odot\ pc^{-3}$
	Kent	$\rho(s) = 1.04 \times 10^6 (s/0.482)^{-1.85}\ M_\odot\ pc^{-3}\quad (s < 938\ pc)$
		$\rho(s) = 3.53 K_0(s/667)\ M_\odot\ pc^{-3}\quad (s \geq 938\ pc)$
	bar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

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 $n(0, 0) = 0.097\ pc^{-3}$. We adopted $d_{max} \sim 4$ 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, $\nu_0 = 3.66 \times 10^7\ L_\odot\ kpc^{-3}$, 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.

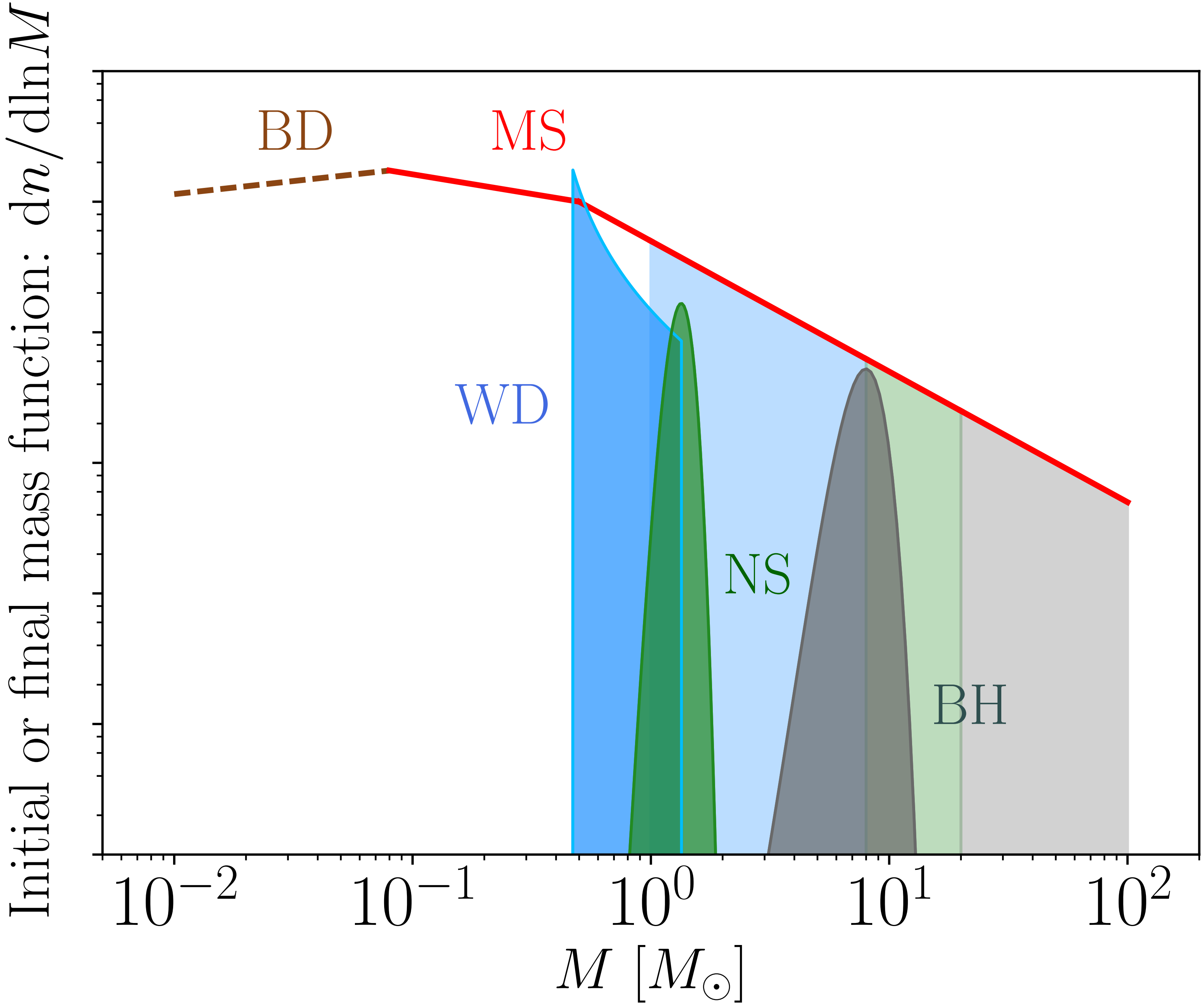
Velocity structure of “stars”



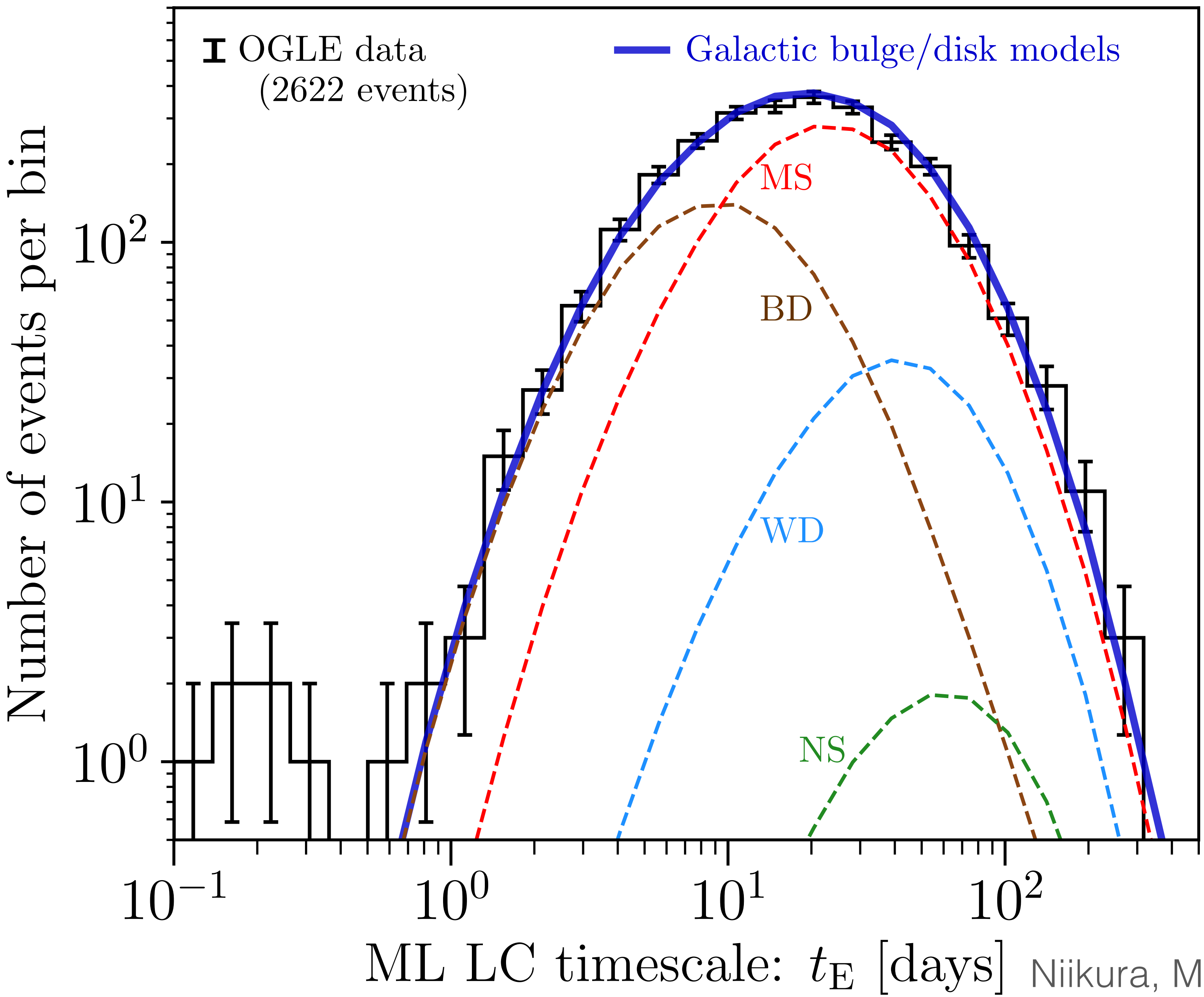
MW dark matter halo



Astrophysical lenses: stars and stellar remnants



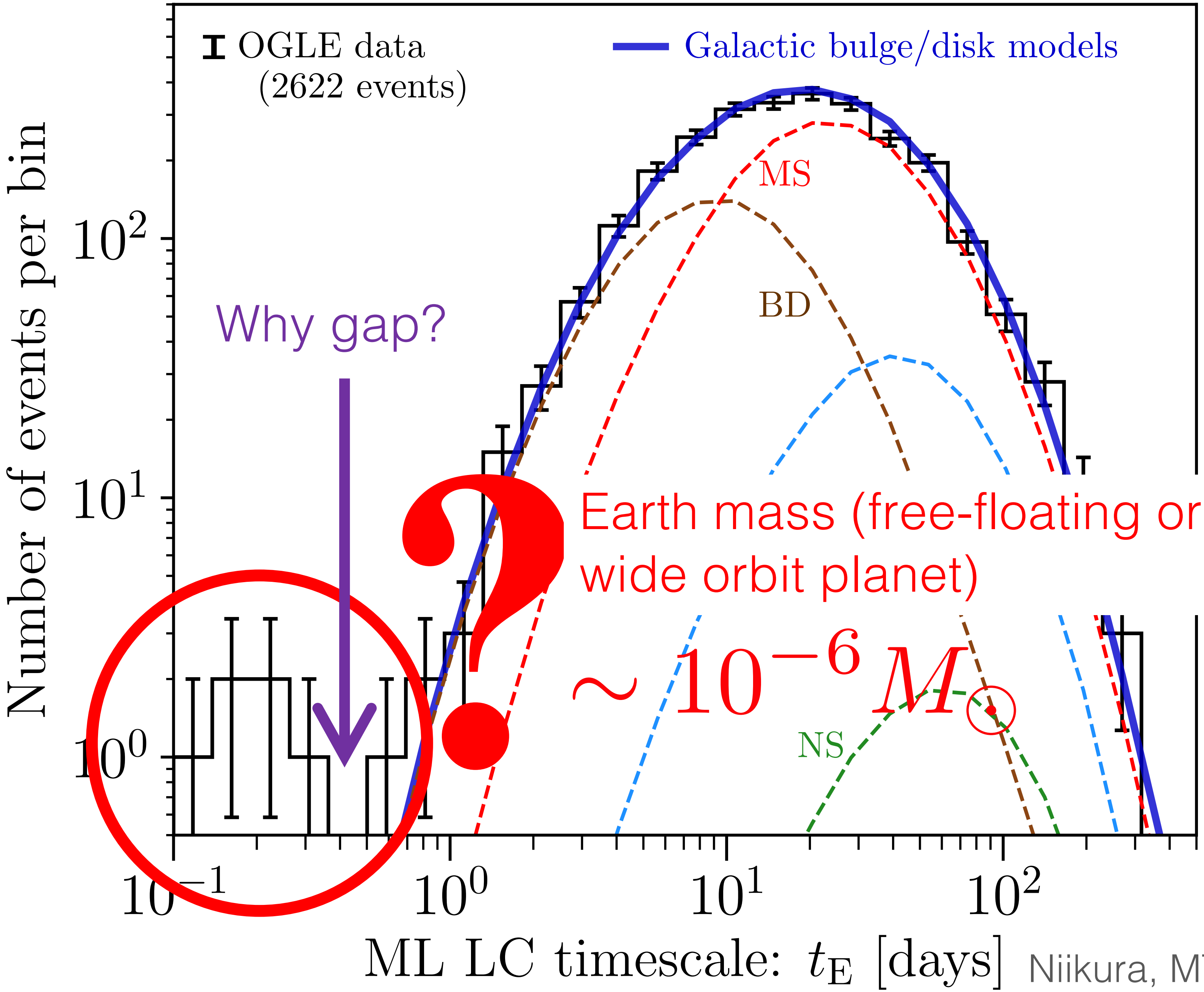
(old-days) Astronomers smart!



Bahcall,
Gould,
Kent, …

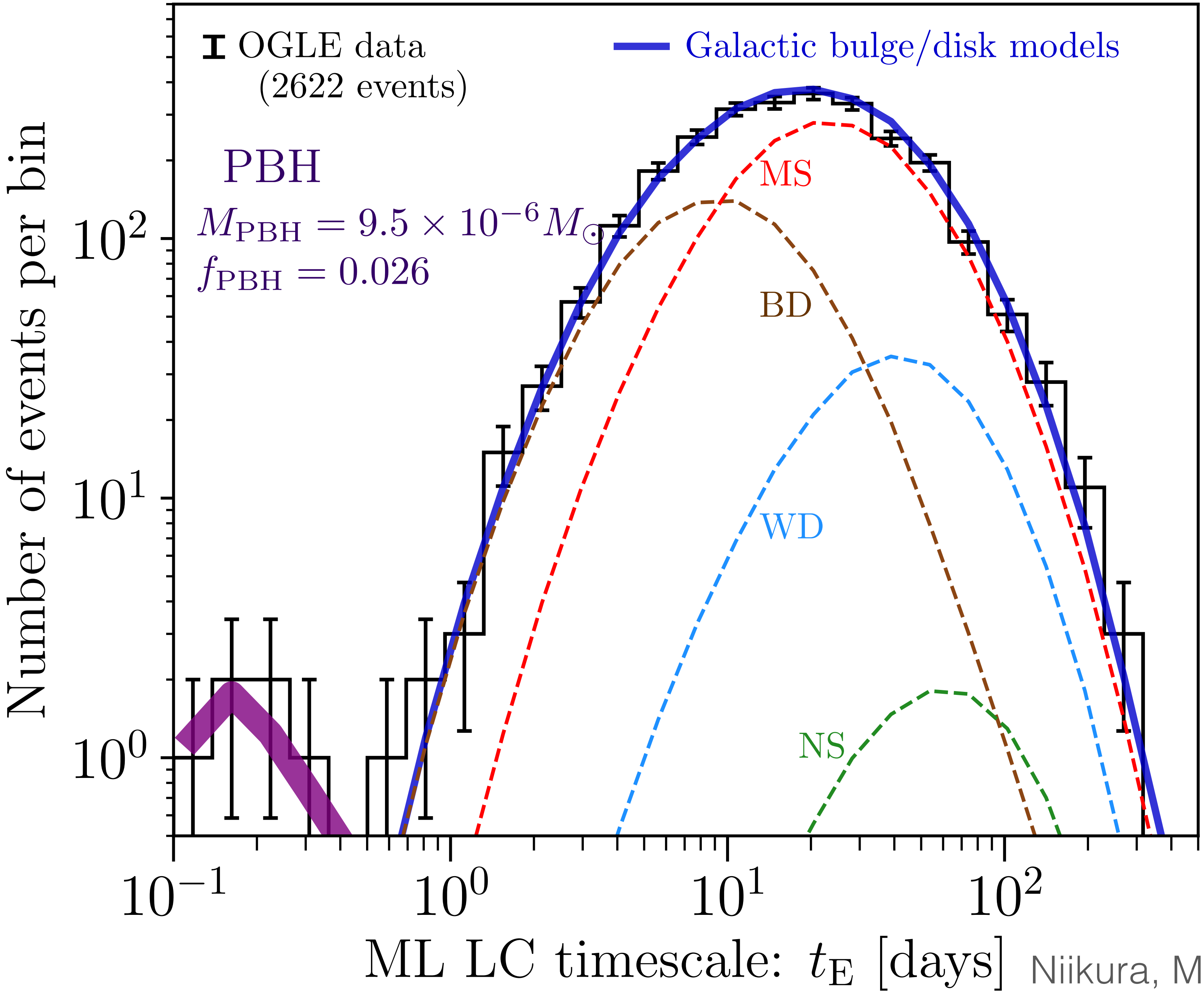
Niikura, MT+ 19

PBH lenses needed?



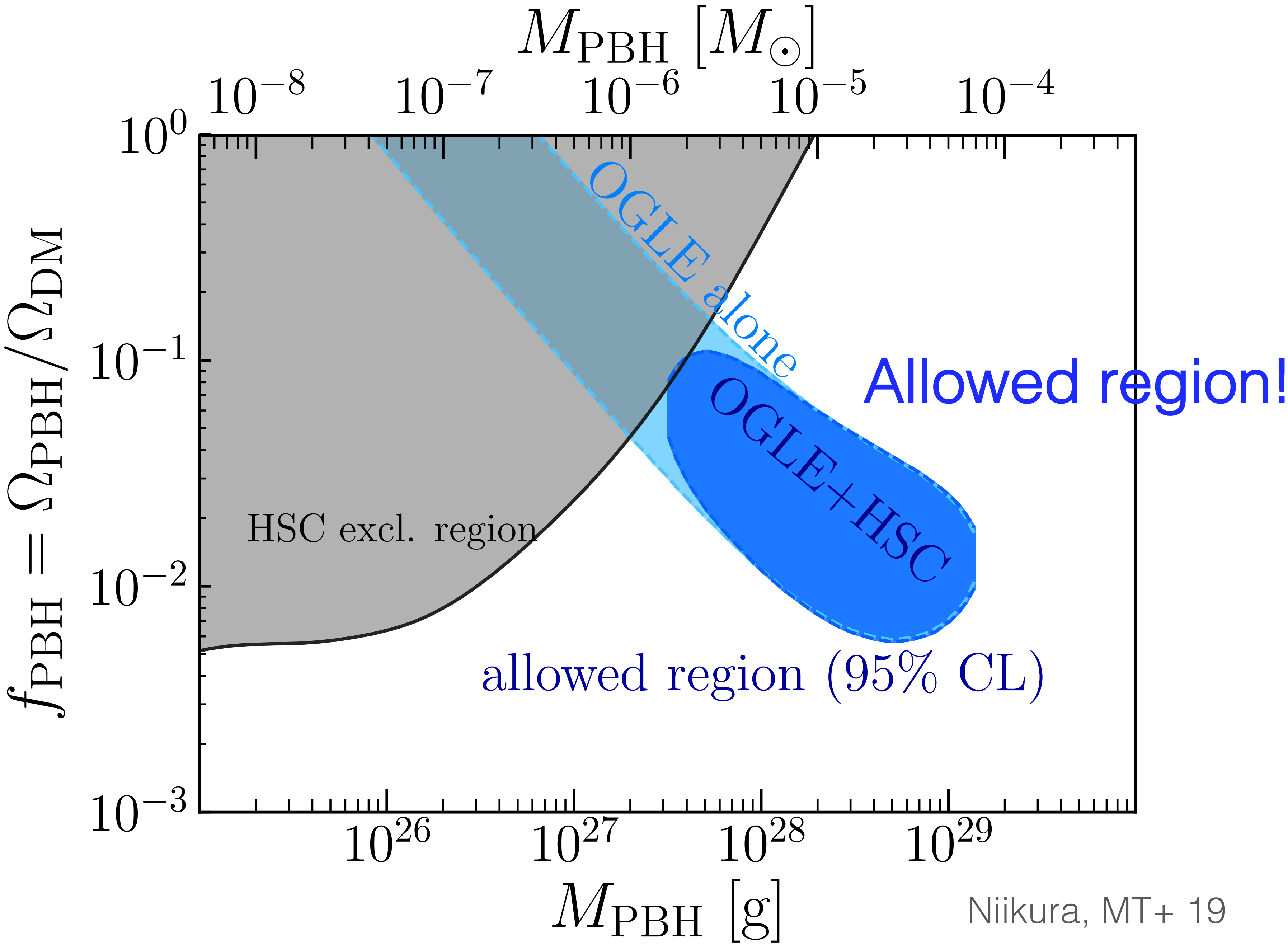
Niikura, MT+ 19

Earth-mass scale PBH?



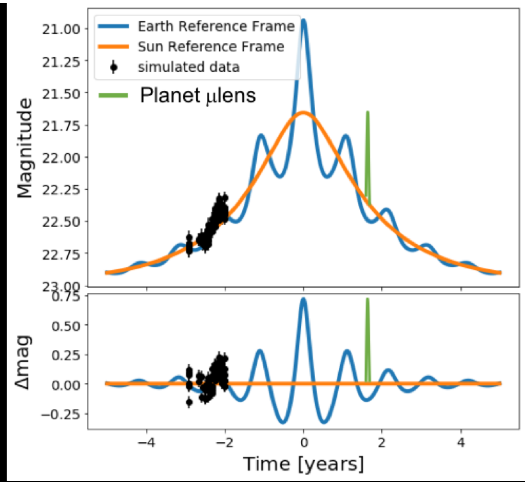
Niikura, MT+ 19

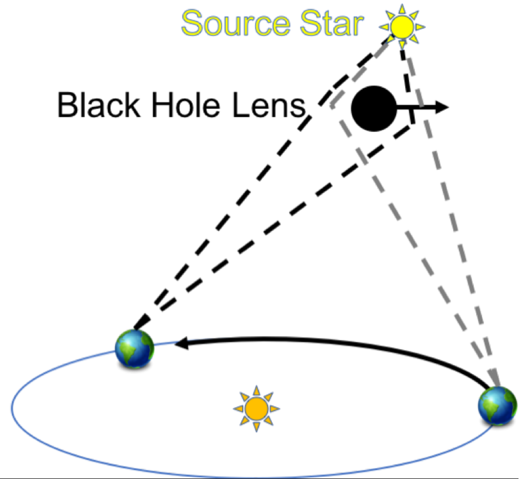
Earth-mass scale PBH?



Niikura, MT+ 19

Future prospects





Subaru

photometric + astrometric ML

$$t_E \sim \frac{R_E}{v} \sim \frac{\sqrt{M}}{v}$$

NASA WFIRST (2025-)

LSST (2022-)

TMT (2028-)

summary

- Microlensing is a powerful probe of compact DM candidate such as PBH
- Subaru & OGLE ML data place stringent constraints on the abundance of PBHs
  - However, PBH DM scenario in the mass range $[10^{-16},10^{-11}]M_s$ is not ruled out
  - Although subdominant (not total DM), some implications for Earth-mass and LIGO-mass PBHs → worth to explore these PBHs (e.g. Subaru M31)
- More exciting opportunities with future telescopes
  - PBHs
  - Constrain low-mass stars (constrain the initial mass function)
  - Exoplanets
  - Astrophysical black holes!