

arXiv:1701.02151 Niikura et al.



Hiroko Niikura (U.Tokyo/IPMU)

# Tightest bounds on PBH abundance with HSC observation of M31 *- end of PBH scenario? -*

Masahiro Takada (Kavli IPMU)

Collaborators: M. Chiba (Tohoku), M. Ishigaki, K. Hayashi, S. More,  
**Hiroko Niikura**, N. Yasuda (Kavli IPMU), T. Sumi (Osaka), R.  
Lupton (Princeton), S. Miyazaki, M. Tanaka, F. Yoshida (NAOJ)



東京大学  
THE UNIVERSITY OF TOKYO



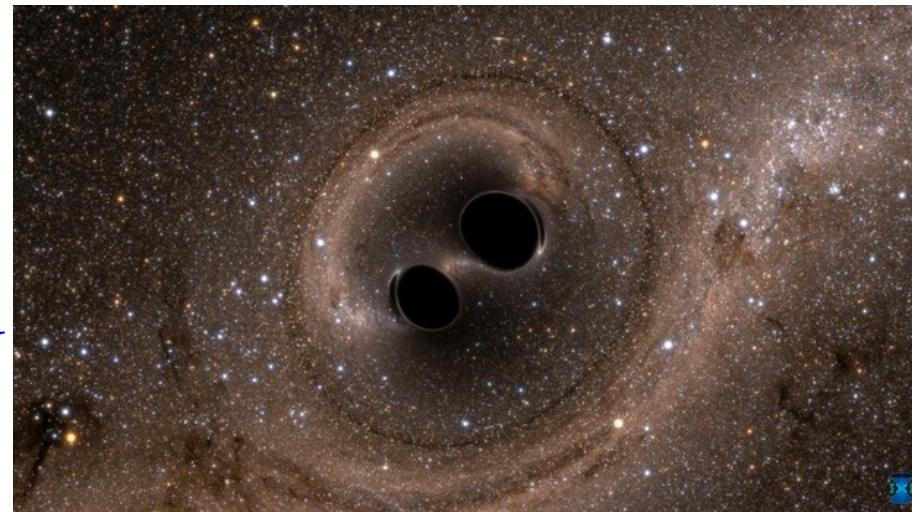
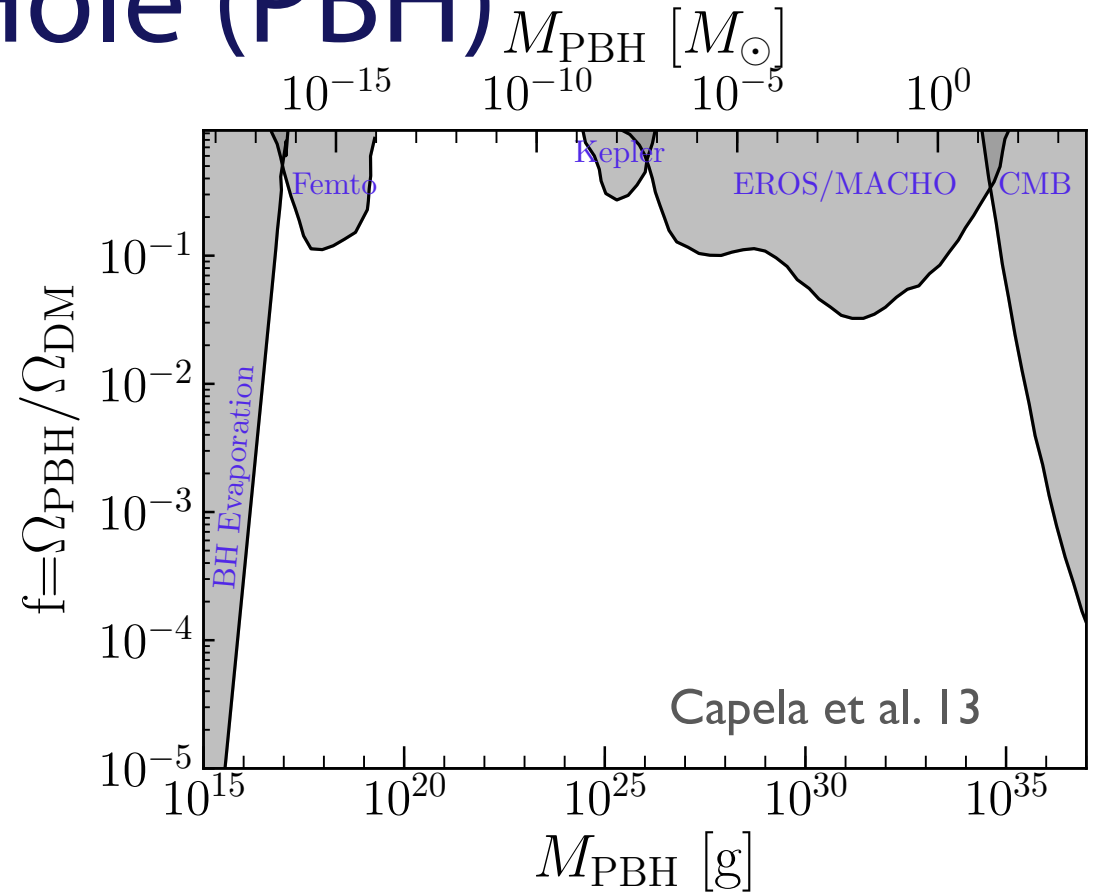
@ Kyoto U., Sep 2017

# Candidates of dark matter

- Weakly Interacting Massive Particles (WIMP), but has yet to be found by LHC, Fermi, other direct experiments, ...
- Neutrinos  $\Rightarrow$  *No!*
- MAAssive Compact Halo Objects (MACHO)  $\Rightarrow$  *No!*
- Primordial Black Hole (PBH)  $\Rightarrow$  this talk

# Primordial Black Hole (PBH)

- Dark matter needed
- Can be formed in the early universe (Zel'dovich & Novikov 67; Hawking 1971); 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)

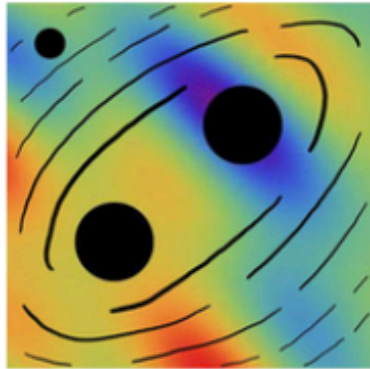


$$M_{\text{PBH}} \sim 10^{24} \text{g} \sim M_H @ T \sim 10 \text{ TeV}$$

# Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

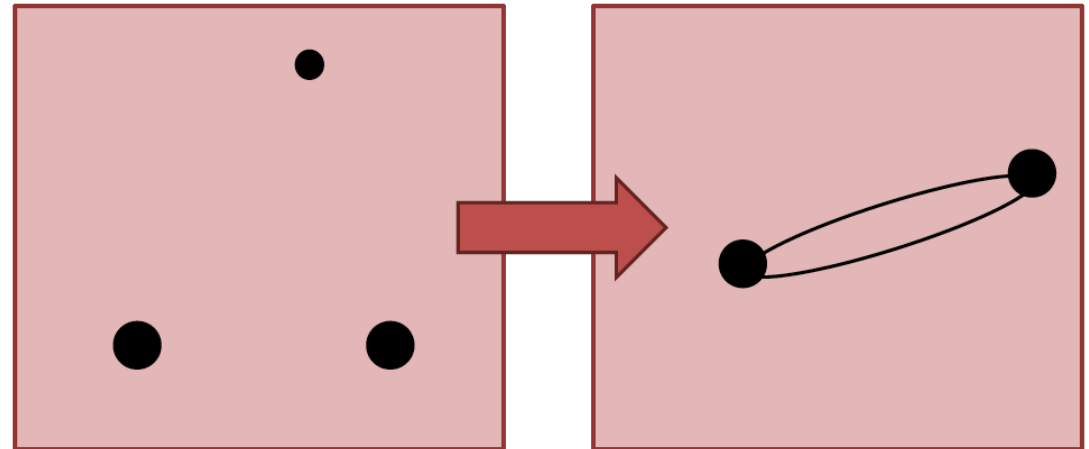
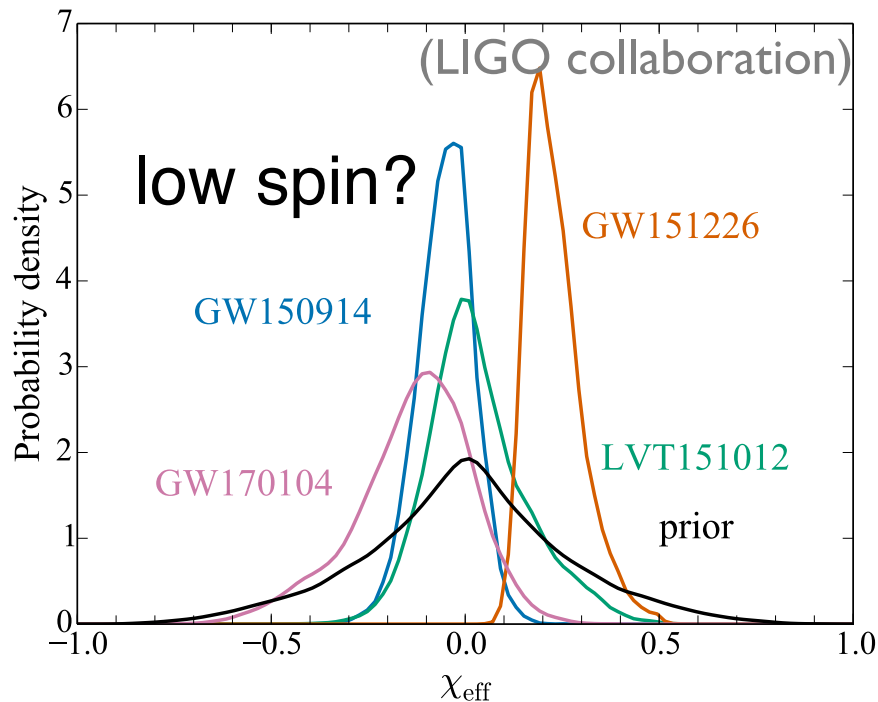
Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama

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 +](#)



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

needed to explain the LIGO event rate

# PBH formation

- PBH can be formed by the gravitational collapse of the Hubble patch in the radiation dominated era, if a large overdensity of  $\delta \sim O(0.1)$  is injected in the patch (Zel'dovich & Novikov 67; 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

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

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

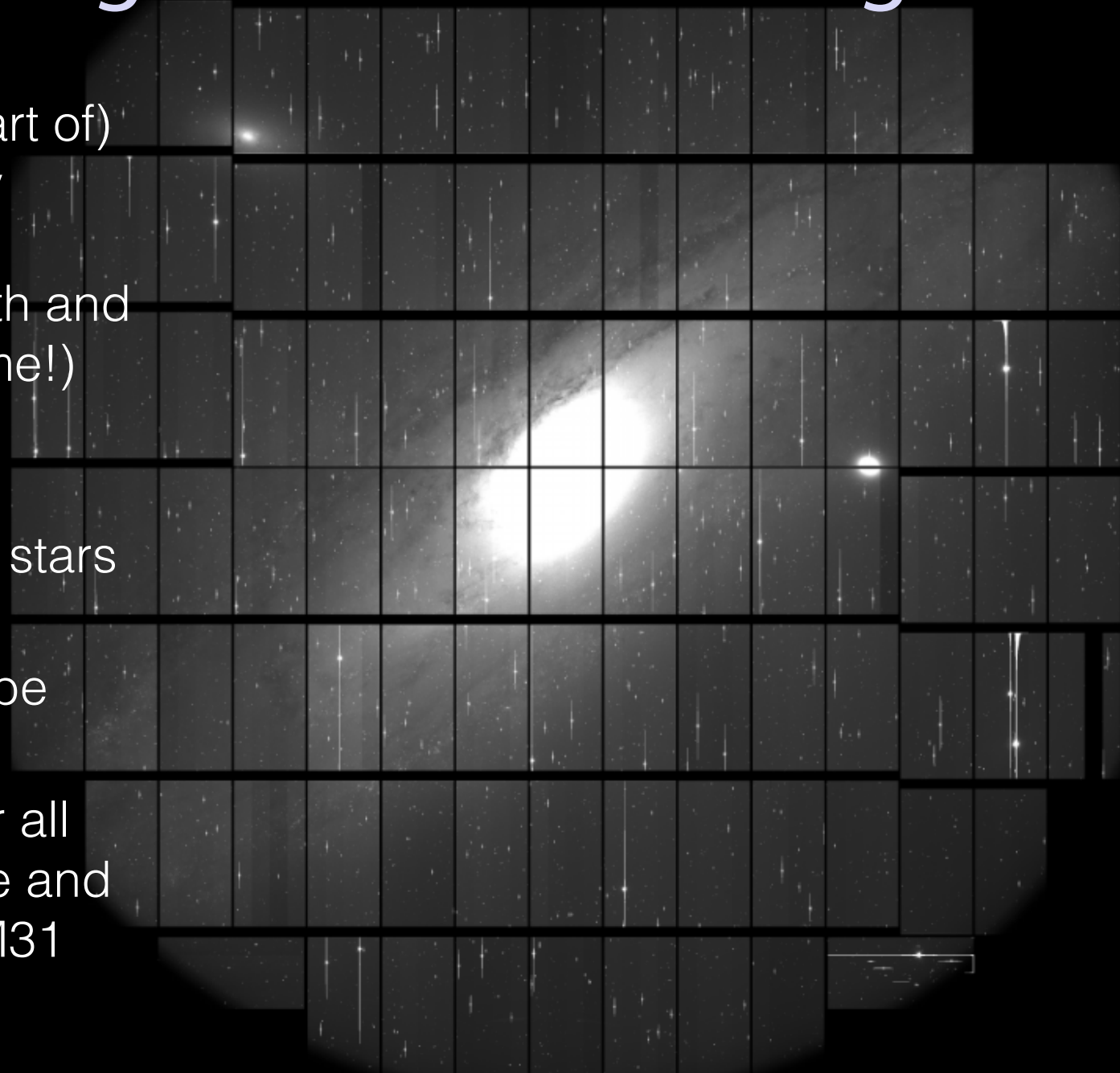
# Andromeda Galaxy (M31)



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

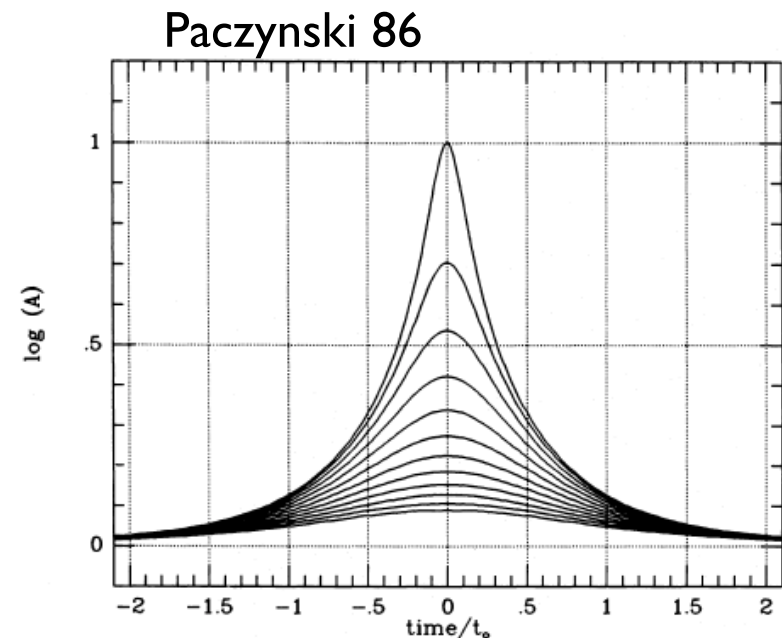
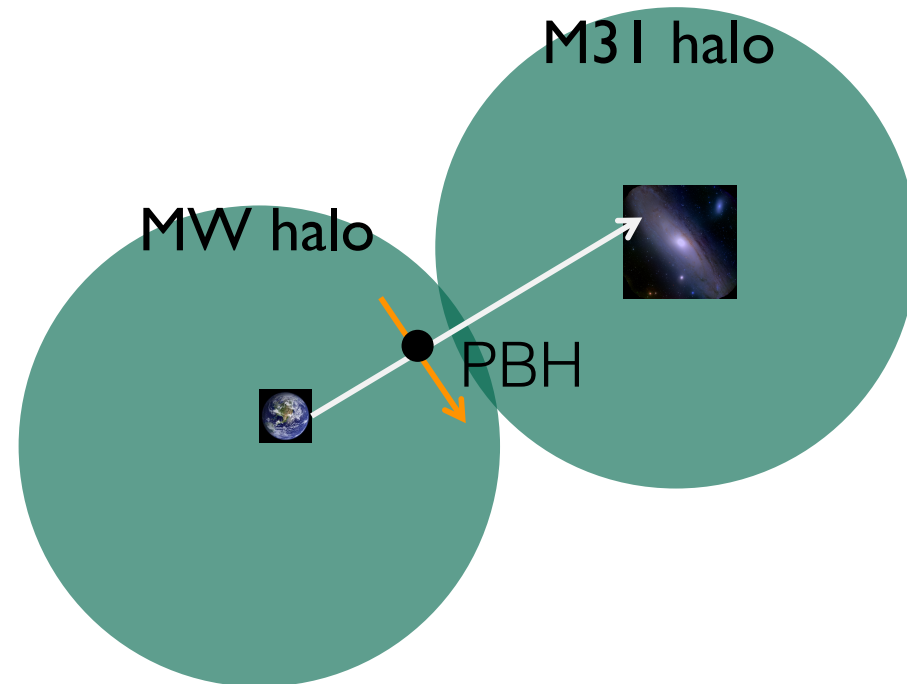
# probing PBHs with lensing

- 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 ( $\sim 10^{-8}$  arcsec)  $\Rightarrow$  only light curve is a signal
- So huge volume
- MW/M31 halo  $\sim 10^{12} M_{\text{sun}}$  (we assumed NFW models)
- PBH has a peculiar velocity of  $\sim 200 \text{ km/s}$



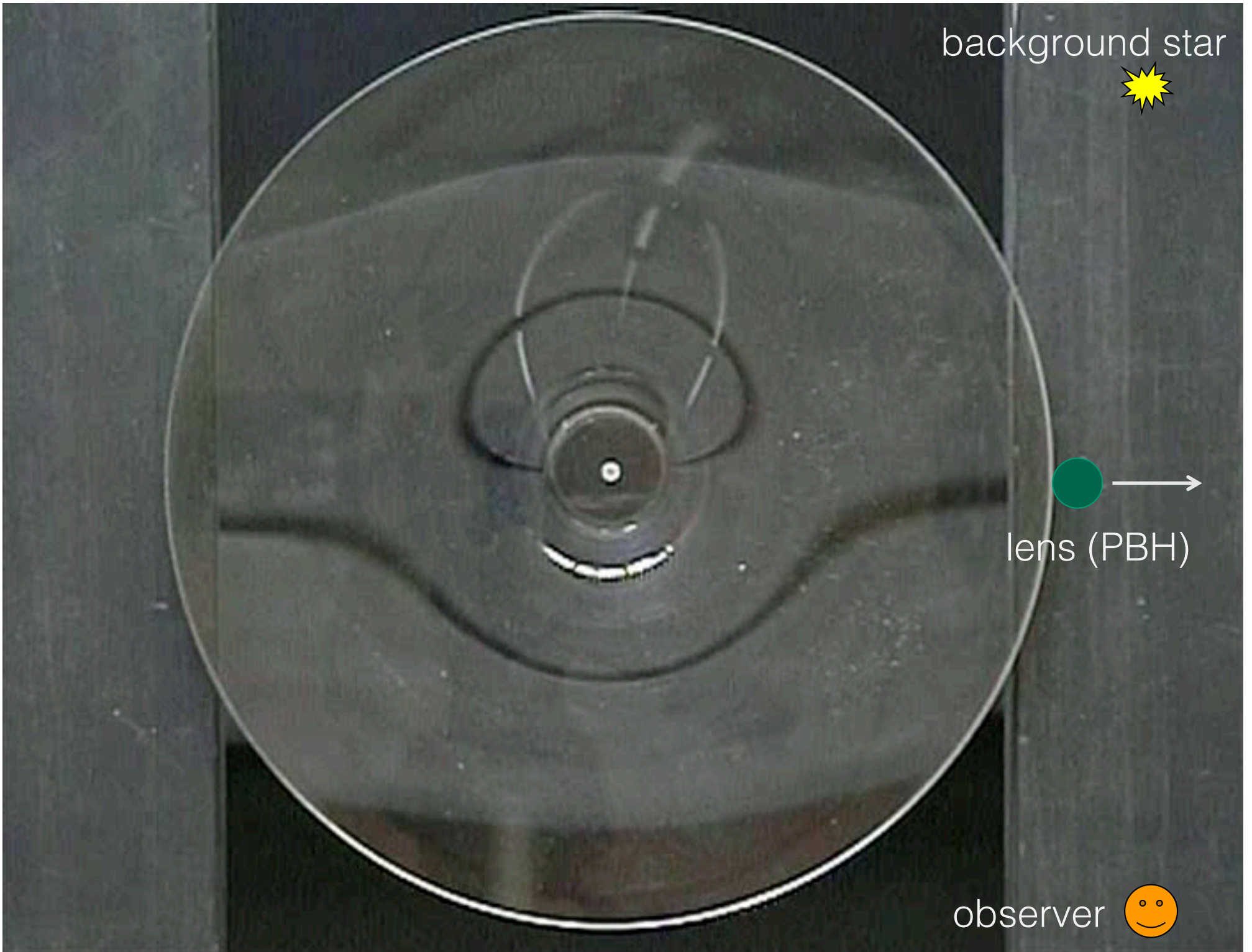


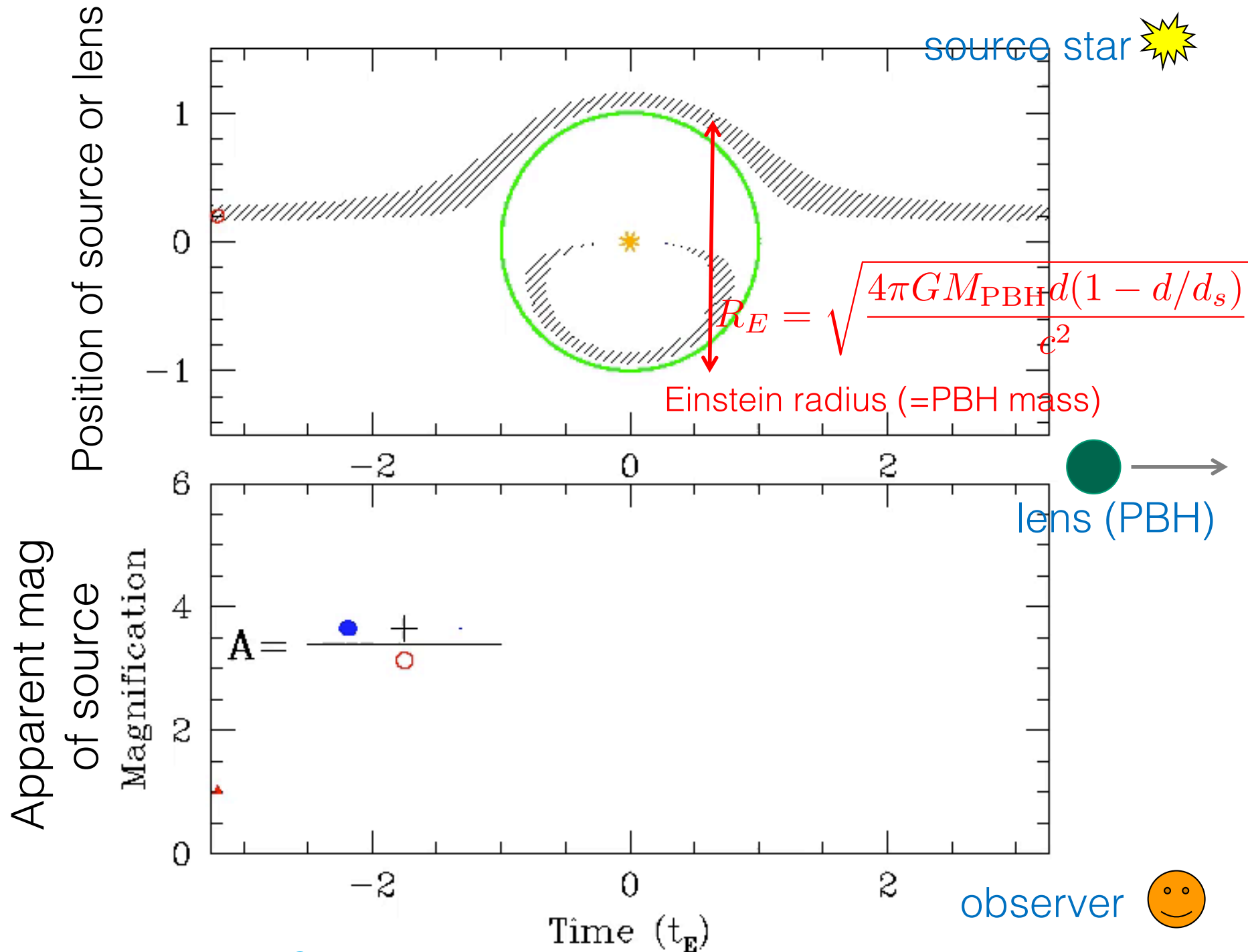
background star



lens (PBH)

observer

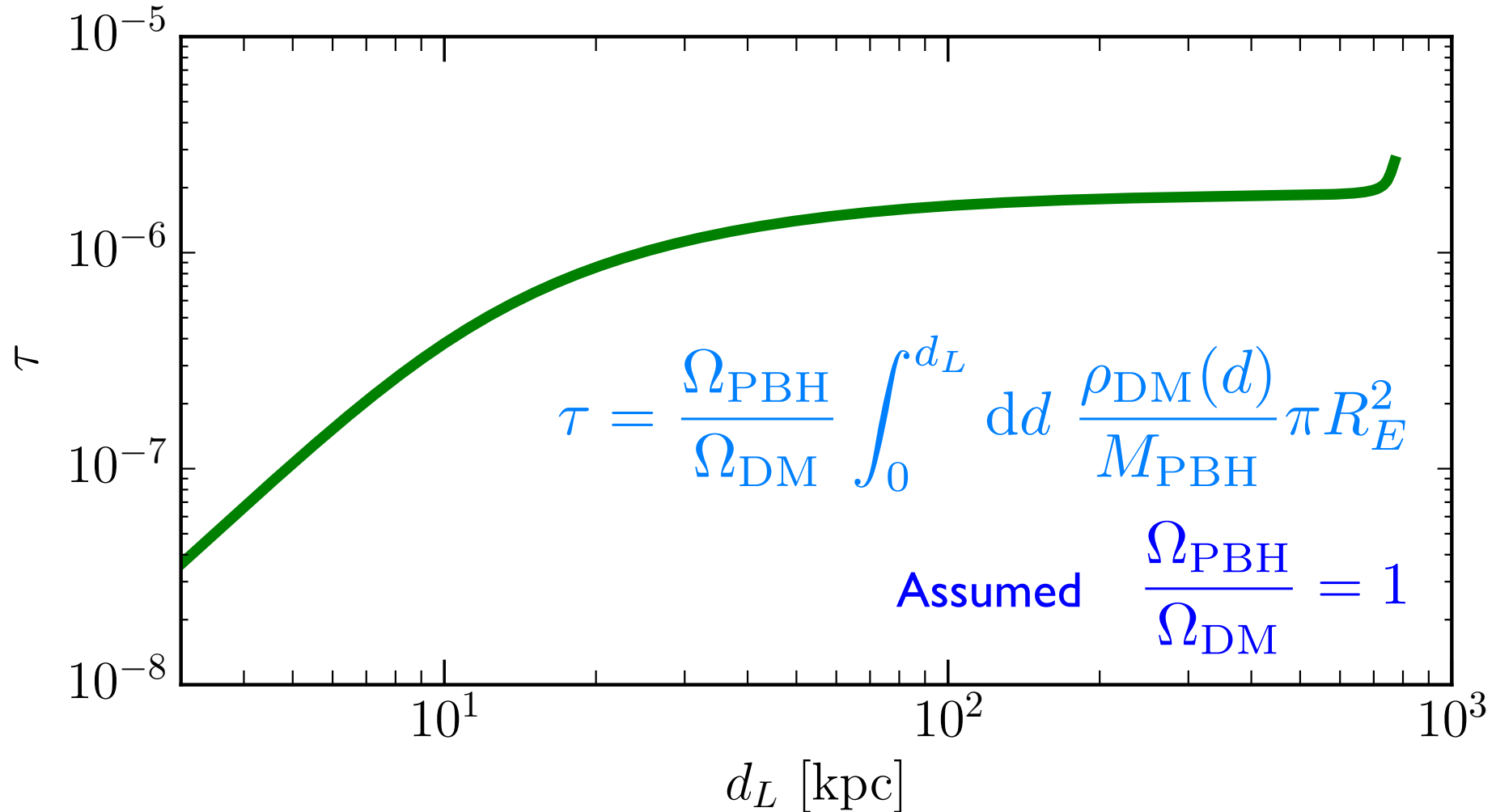




PBS lensing  $\Rightarrow$  multiple image can't be resolved  $\Rightarrow$  microlensing

# PBH microlensing on M31 star

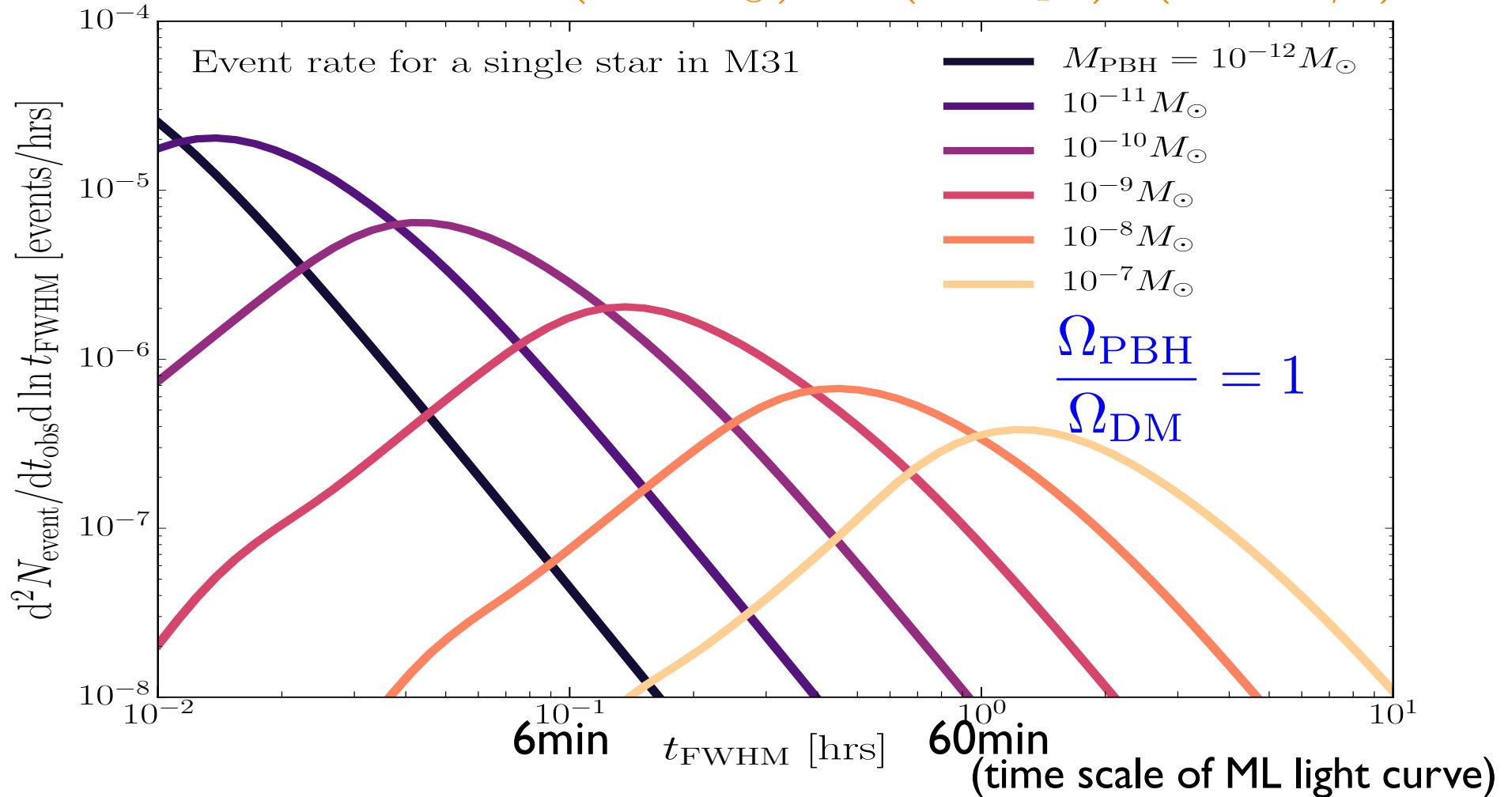
Cumulative optical depth of PBH microlensing for a **single** star in M31



If we observe  **$\sim 10^6$  stars** at one time, **one star at least** should be micro-lensed if PBHs are DM

# PBH microlensing event rate

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



Event rate per **unit obs. time** and per **a single star** in M31  
for **a given timescale of light curve**



Hiroko Niikura

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

*Got this idea from conversation with Hitoshi  
and Masahiro Kawasaki*

90sec exposure each (r-band)

~35sec readout

~190 exposures

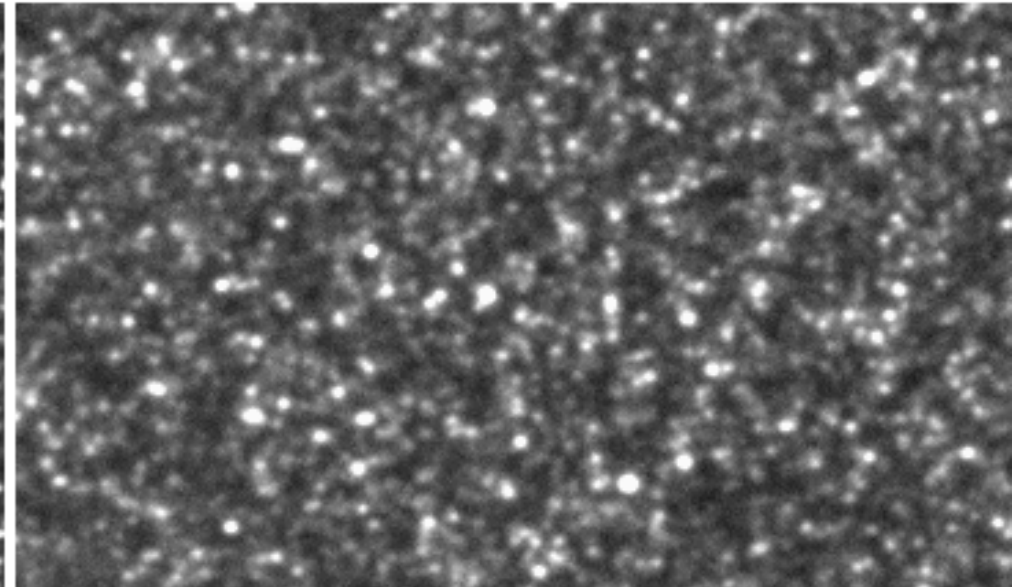
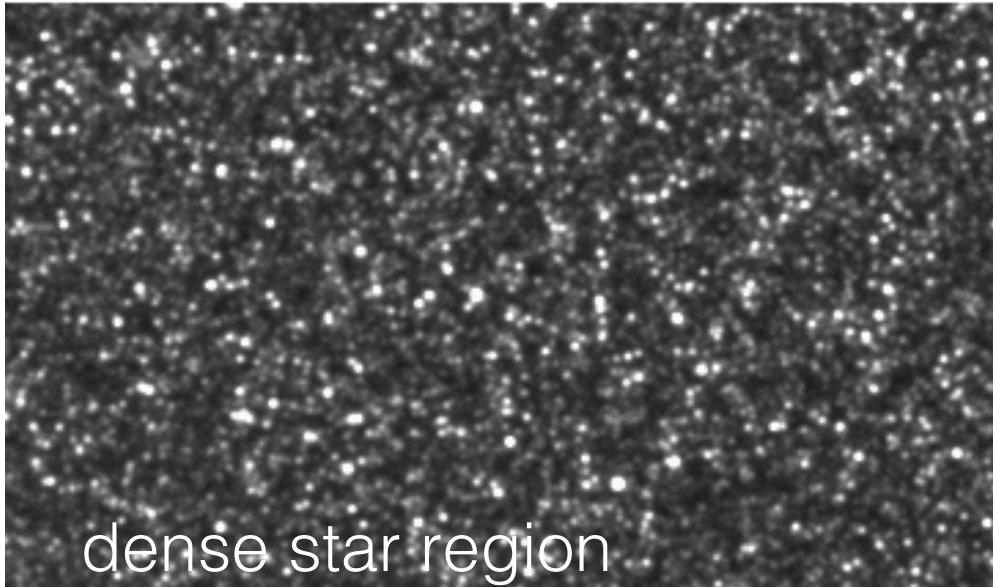
No dithering

one clear night (seeing ~0.5-0.6")

Also used g-data (from commissing)

# Challenges: Pixel lensing

**Fluxes from multiple stars** are overlapped at each position



Upper left: **reference** image (0.5'')

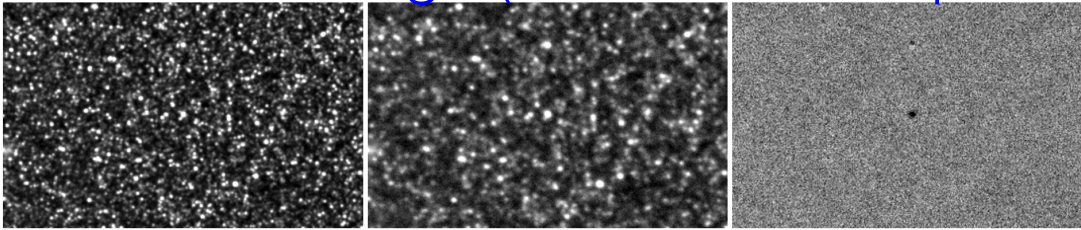
Upper right: **target** image (0.8'')

Lower: difference image

*Accurate PSF and astrometry  
measurements needed.  
HSC pipeline works!*

# Procedures: search for ML events

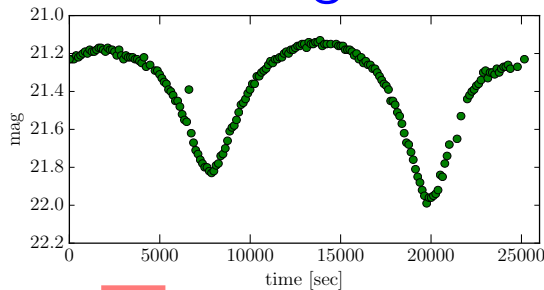
difference image (coadds of 3 exposures)



identify candidates in each diff. image

⇒ **15,571**

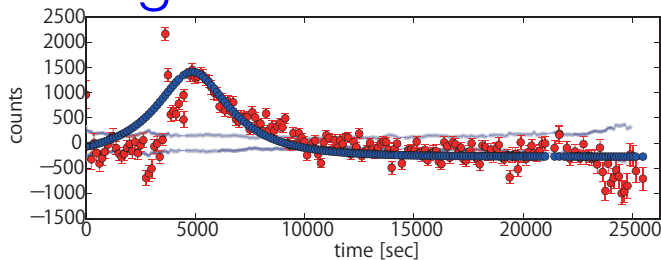
measure light curve (188 data points)



candidates with bump-like light curve

⇒ **11,703**

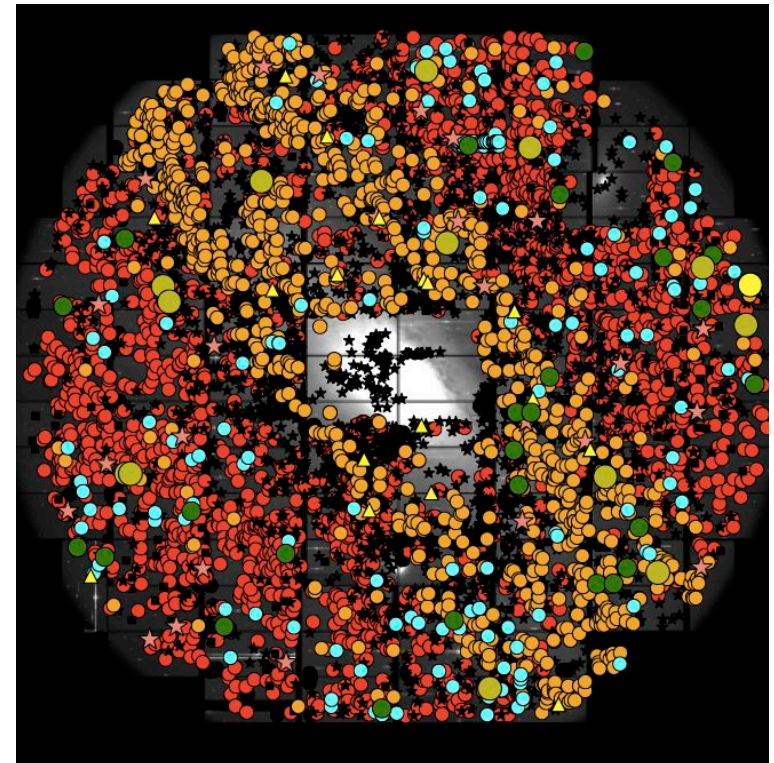
fitting of LC to the microlensing model

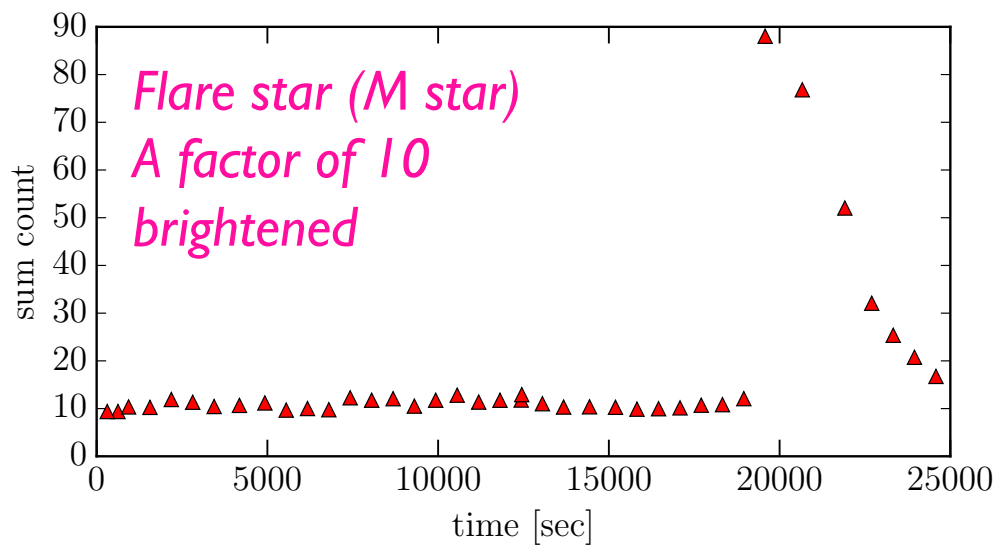
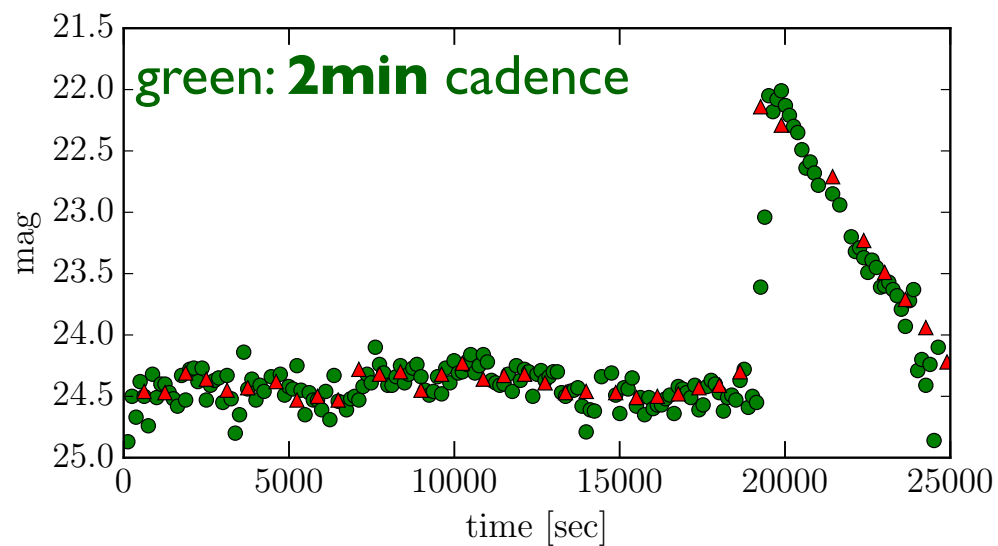
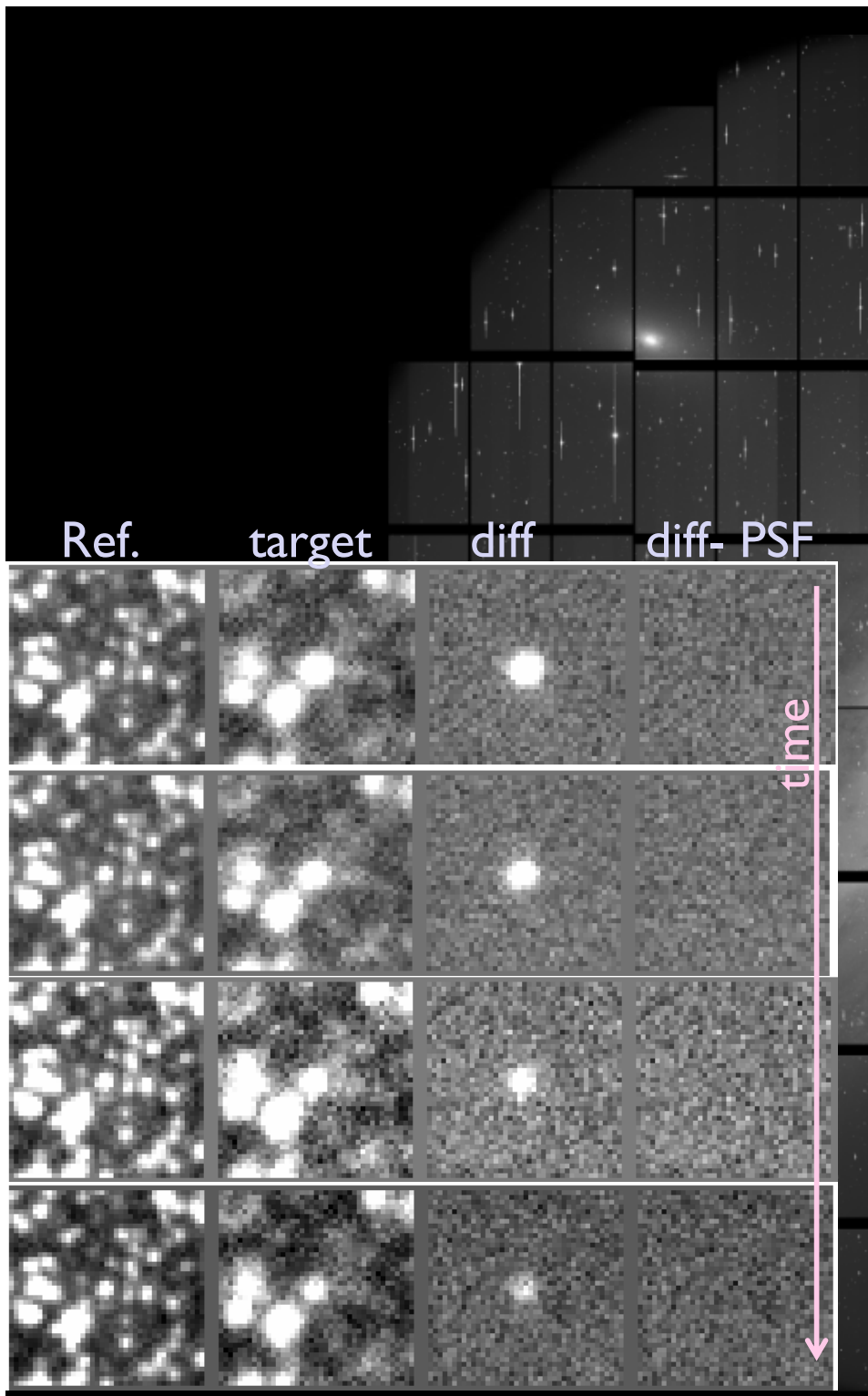


selection criteria

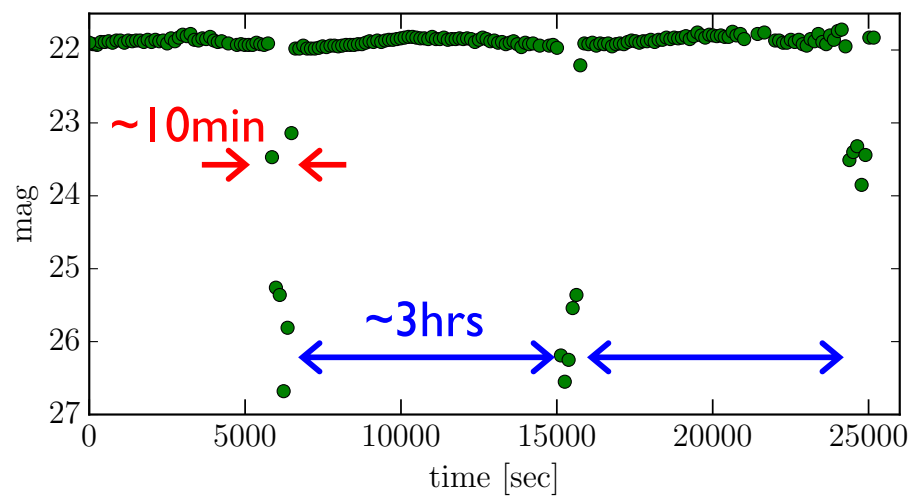
⇒ **66**

visual inspection of individual candidates...



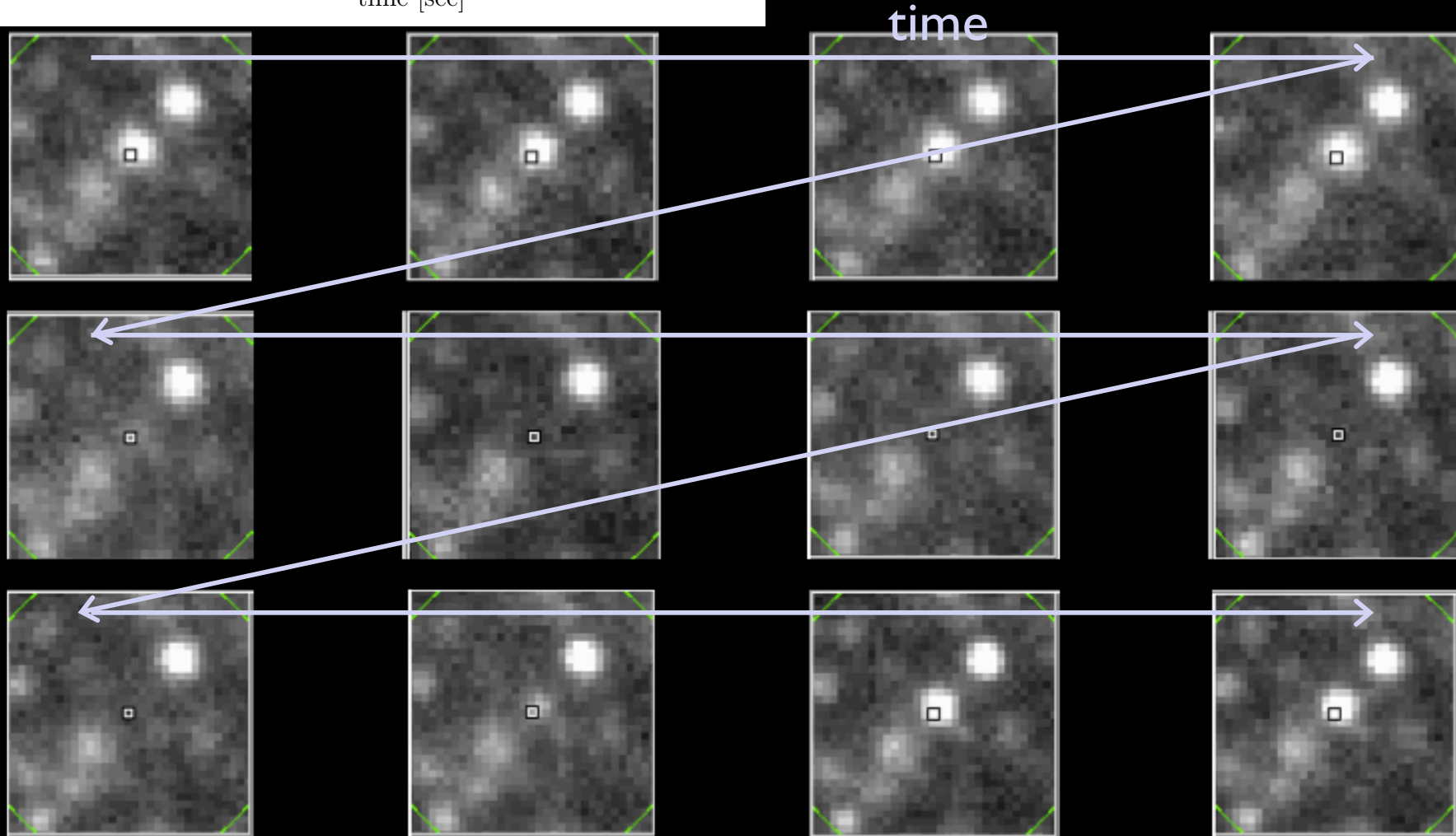






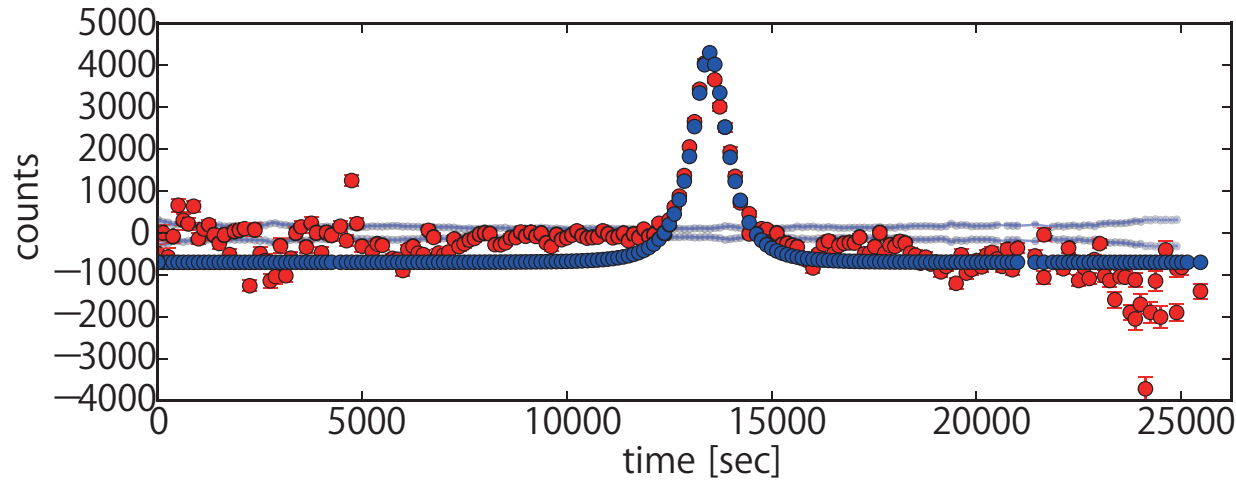
An entire star disappears for  
 ~10min, with a 3hrs interval

*WD – brown dwarf binary*

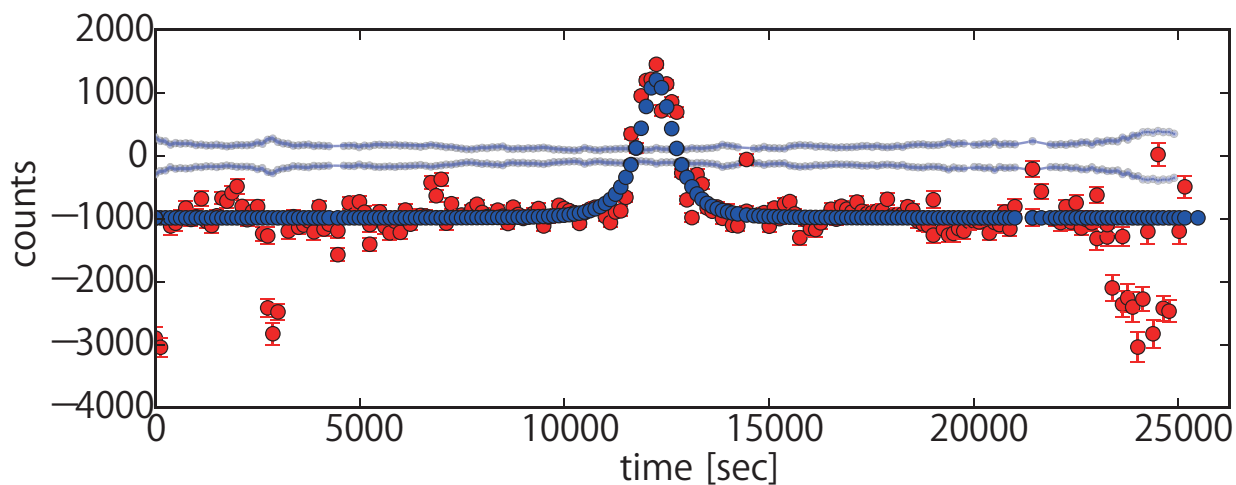
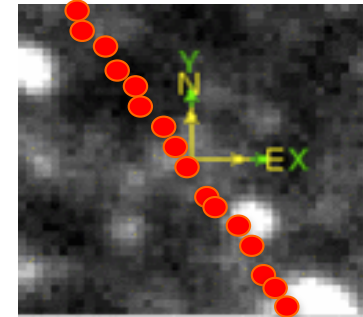


# Visual inspection stage...

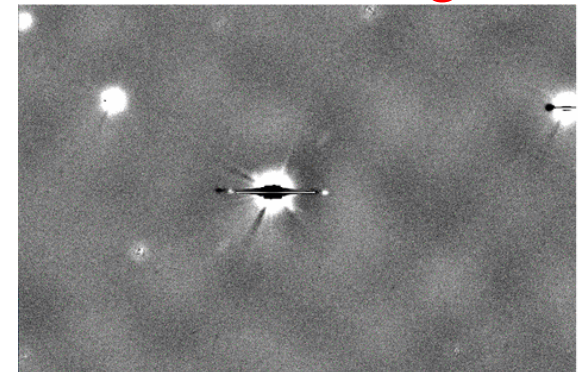
Visual inspection of 66 candidates to identify junks...



asteroid

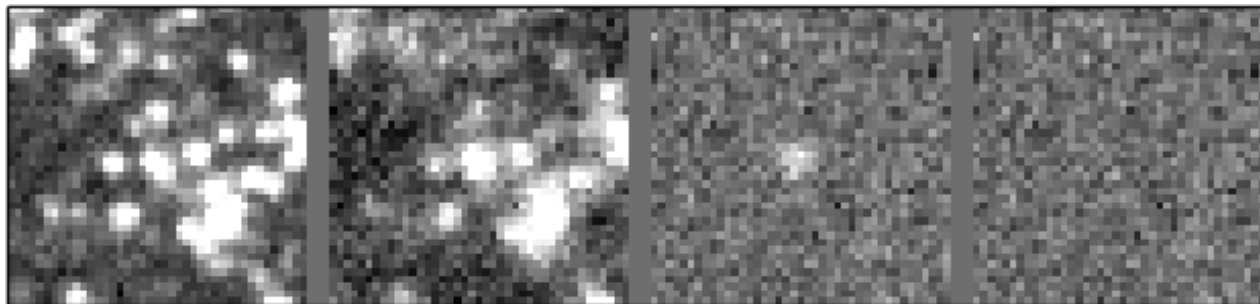
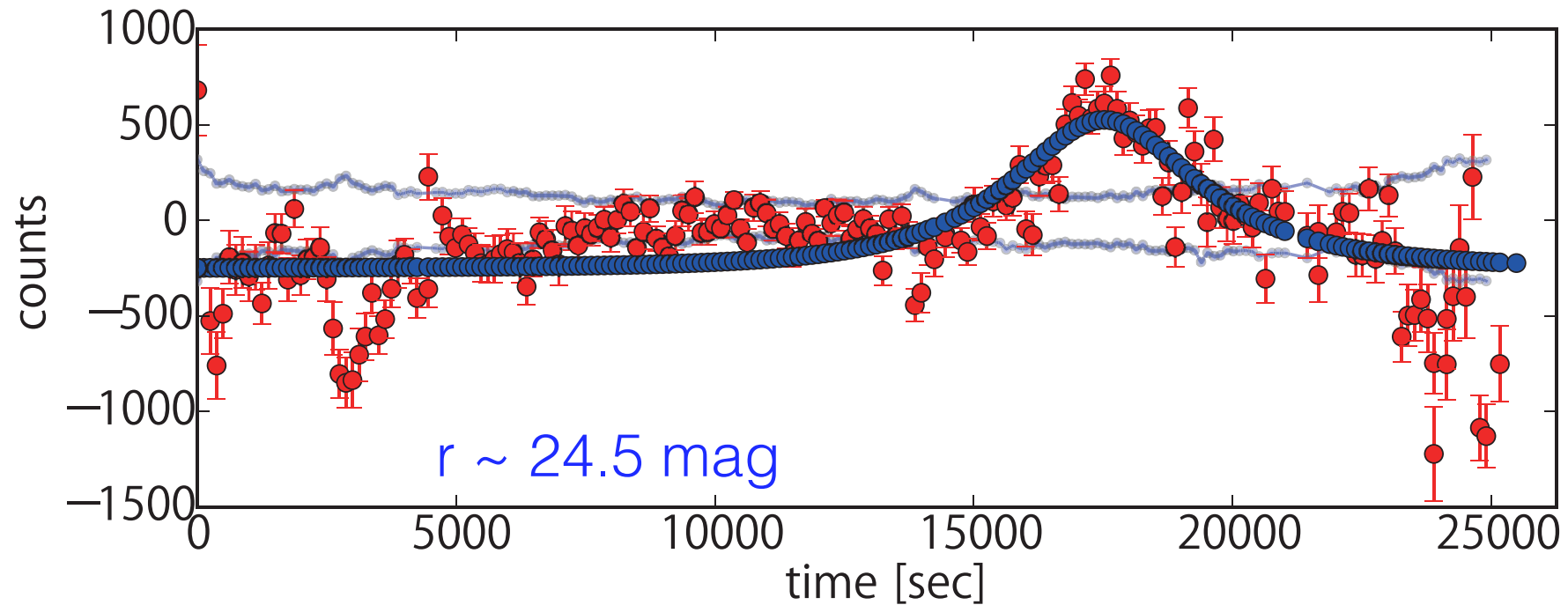


spike around a bright star



**66 ⇒ 65 junks**

# one remaining candidate ...



Here we assume that this is not real and we didn't find any PBH microlensing event

# To constrain the PBH abundance

- Expectation number of PBH microlensing events

$$N_{\text{exp}} = \underbrace{\Delta t_{\text{obs}}}_{\text{duration of observation time (about 7 hours)}} \int dm_r \underbrace{\frac{dN_s}{dm_r}}_{\text{number of source stars in the magnitude range [m, m+dm] (see later)}} \int dt_{\text{FWHM}} \underbrace{\frac{d\Gamma}{dt_{\text{FWHM}}}}_{\text{Event rate of PBH microlensing (computed assuming NFW profiles of the MW and M31 halos)}} \underbrace{\epsilon(t_{\text{FWHM}}, m_r)}_{\text{Detection efficiency for microlensing event of timescale } t_{\text{FWHM}} \text{ for a star of magnitude, } m_r \text{ (see later)}}$$

duration of observation time (about 7 hours)

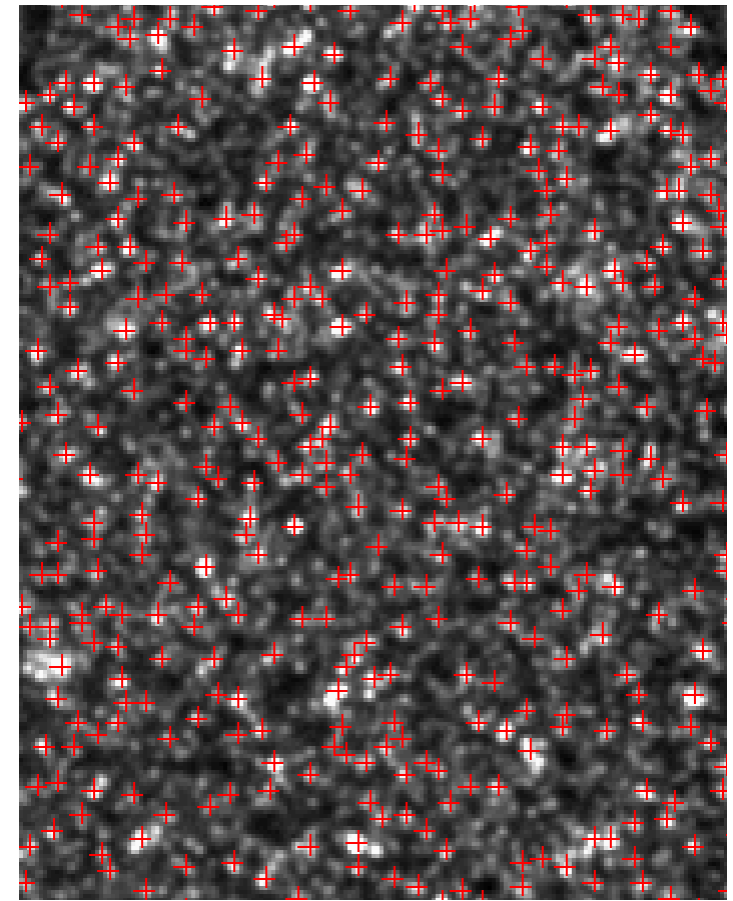
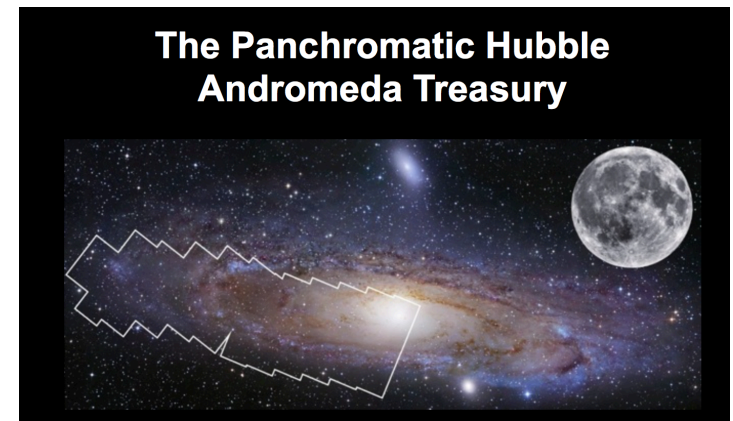
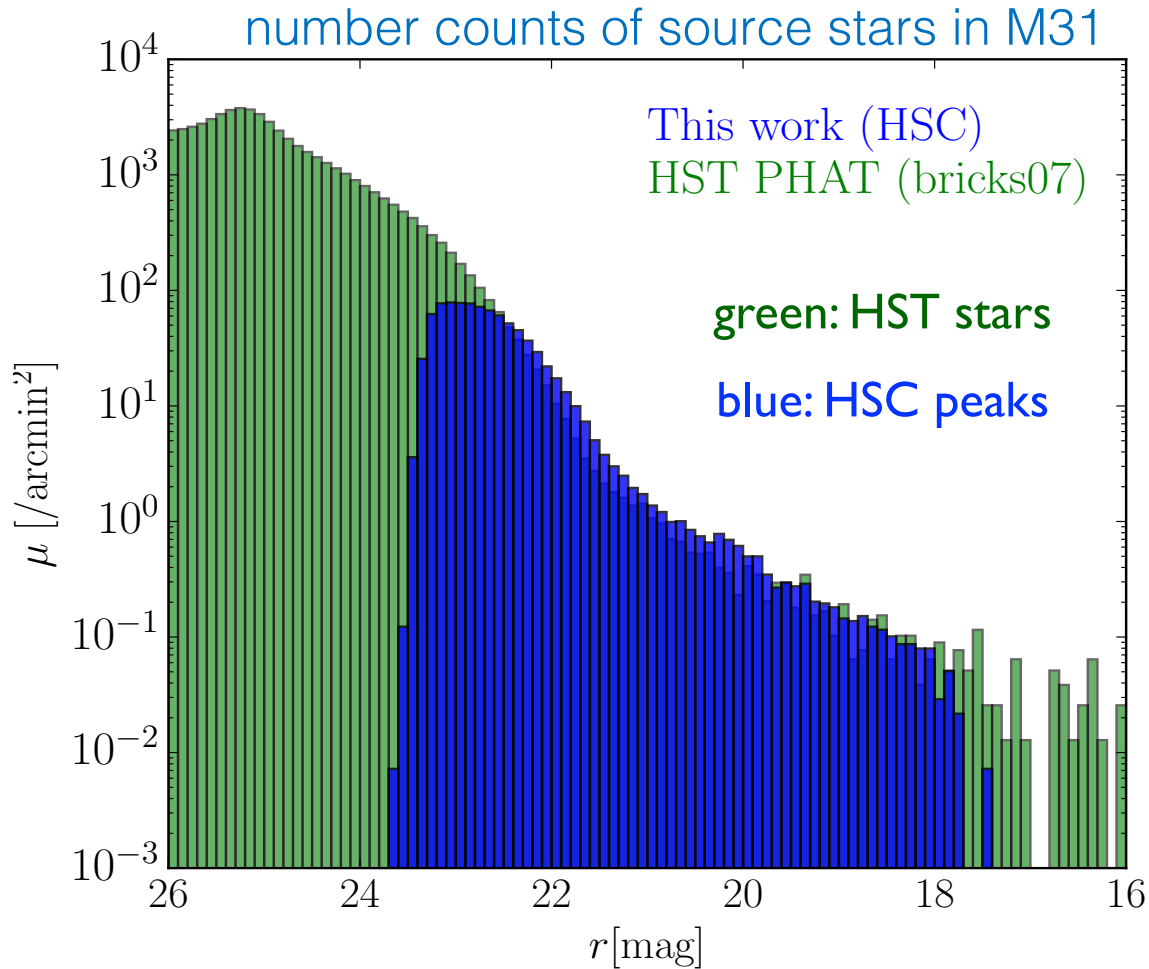
number of source stars in the magnitude range  $[m, m+dm]$  (see later)

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

Detection efficiency for microlensing event of timescale  $t_{\text{FWHM}}$  for a star of magnitude,  $m_r$  (see later)

# Number of source stars

HSC can't resolve individual stars due to blending

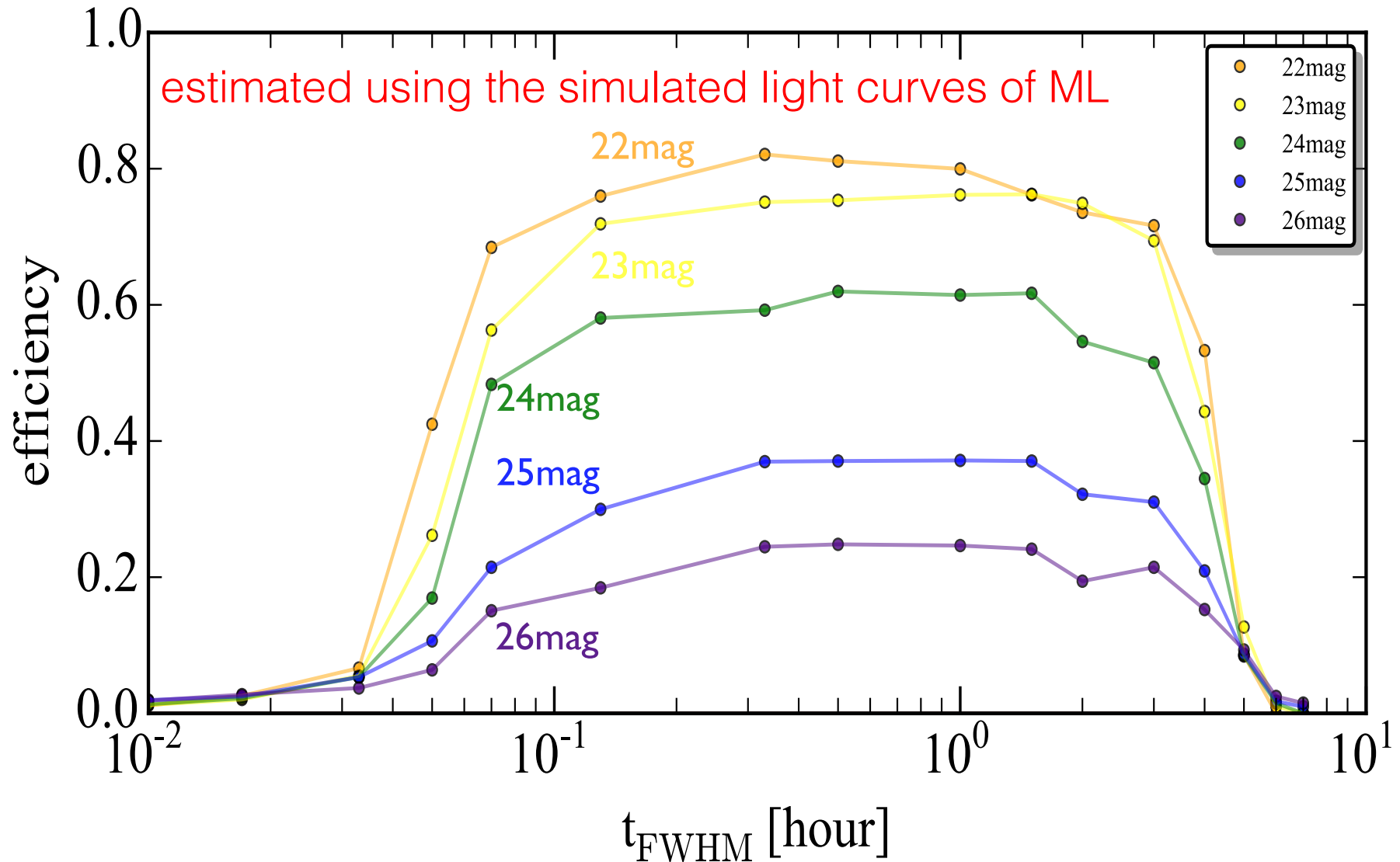


$6.4 \times 10^6$  HSC peaks (conservative)

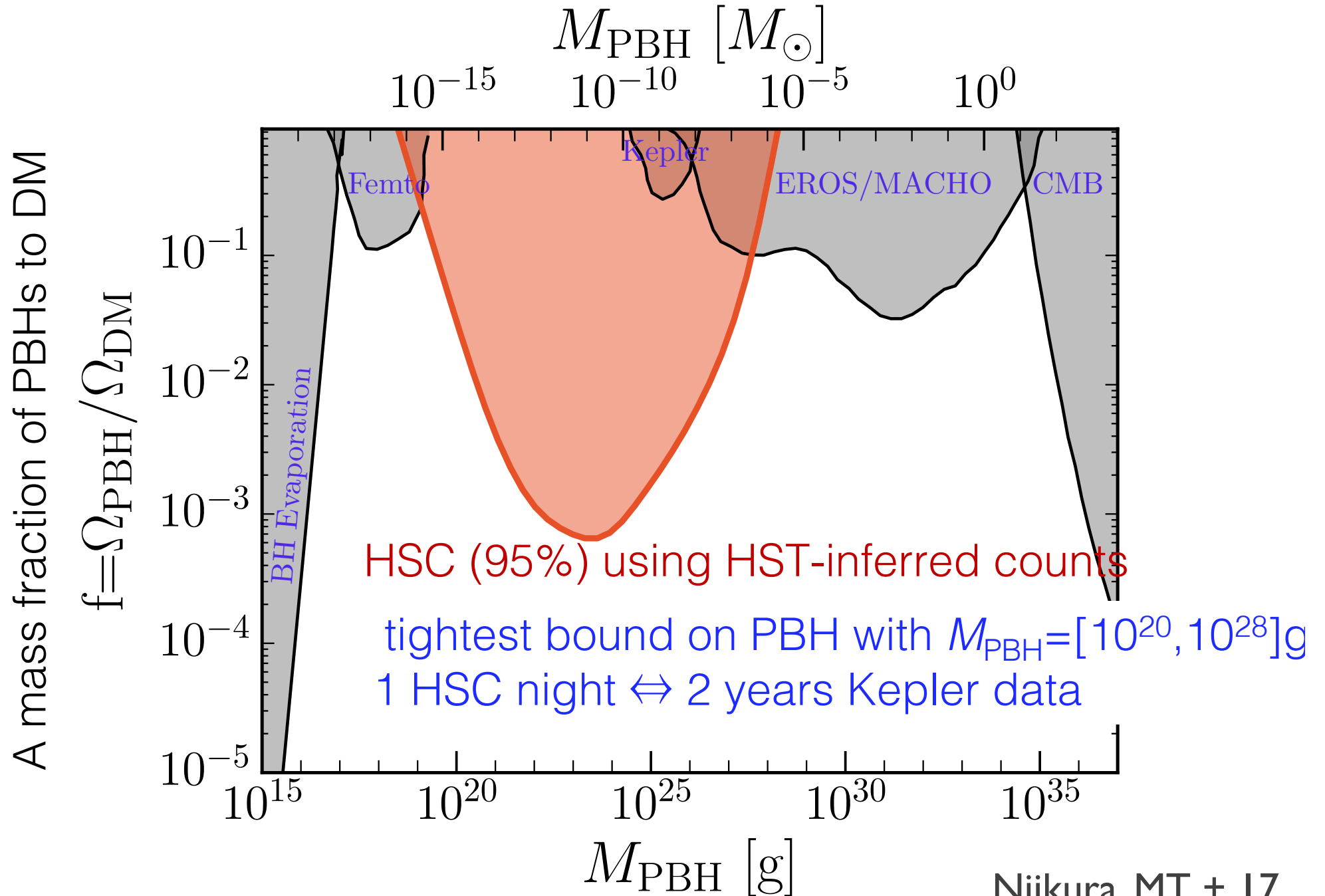
$8.7 \times 10^7$  stars if extrapolated from the HSC star counts for the M31 disk regions

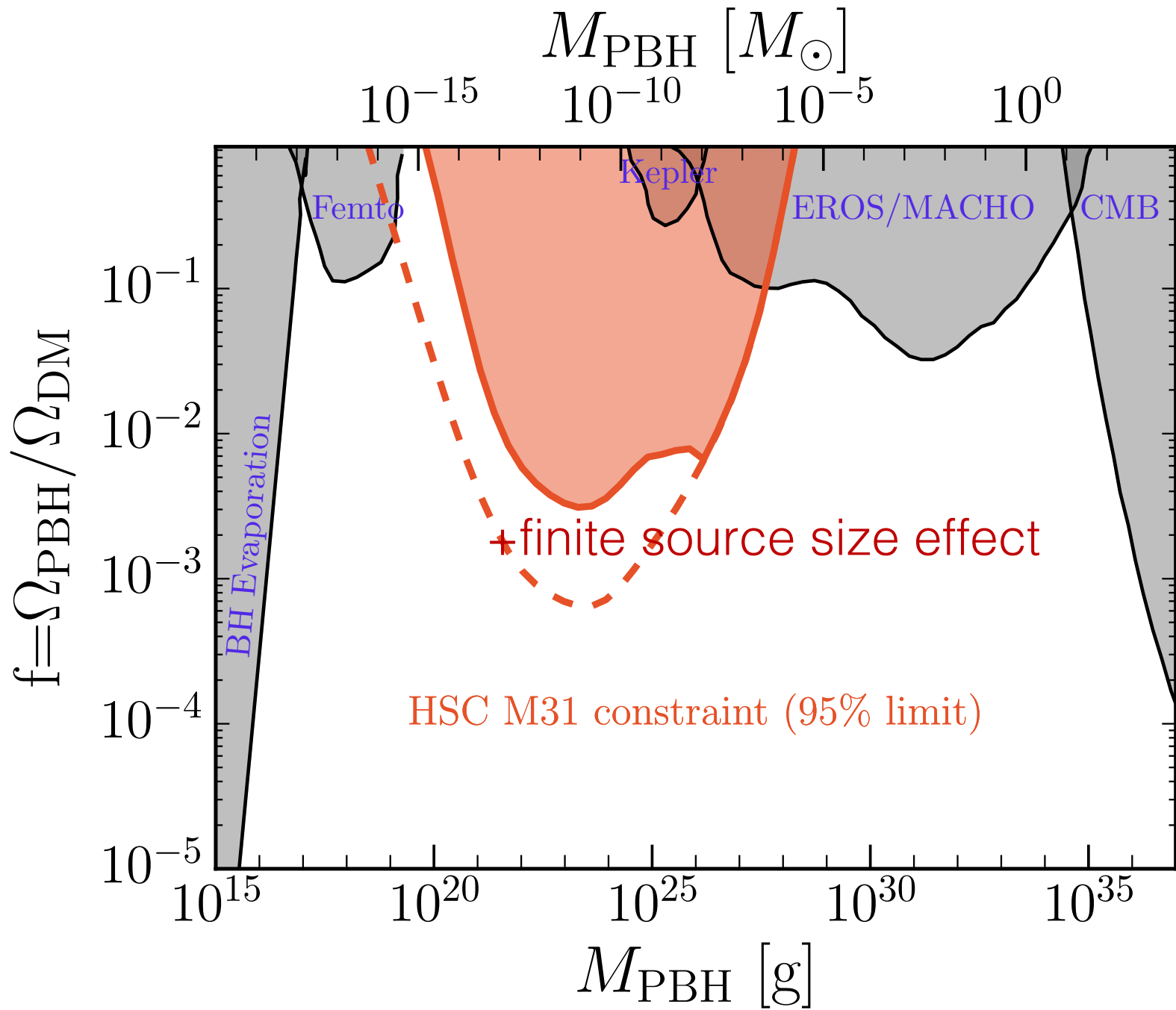
# Detection efficiency

$$N_{\text{exp}} = \Delta t_{\text{obs}} \int dm_r \frac{dN_s}{dm_r} \int dt_{\text{FWHM}} \frac{d\Gamma}{dt_{\text{FWHM}}} \epsilon(t_{\text{FWHM}}, m_r)$$

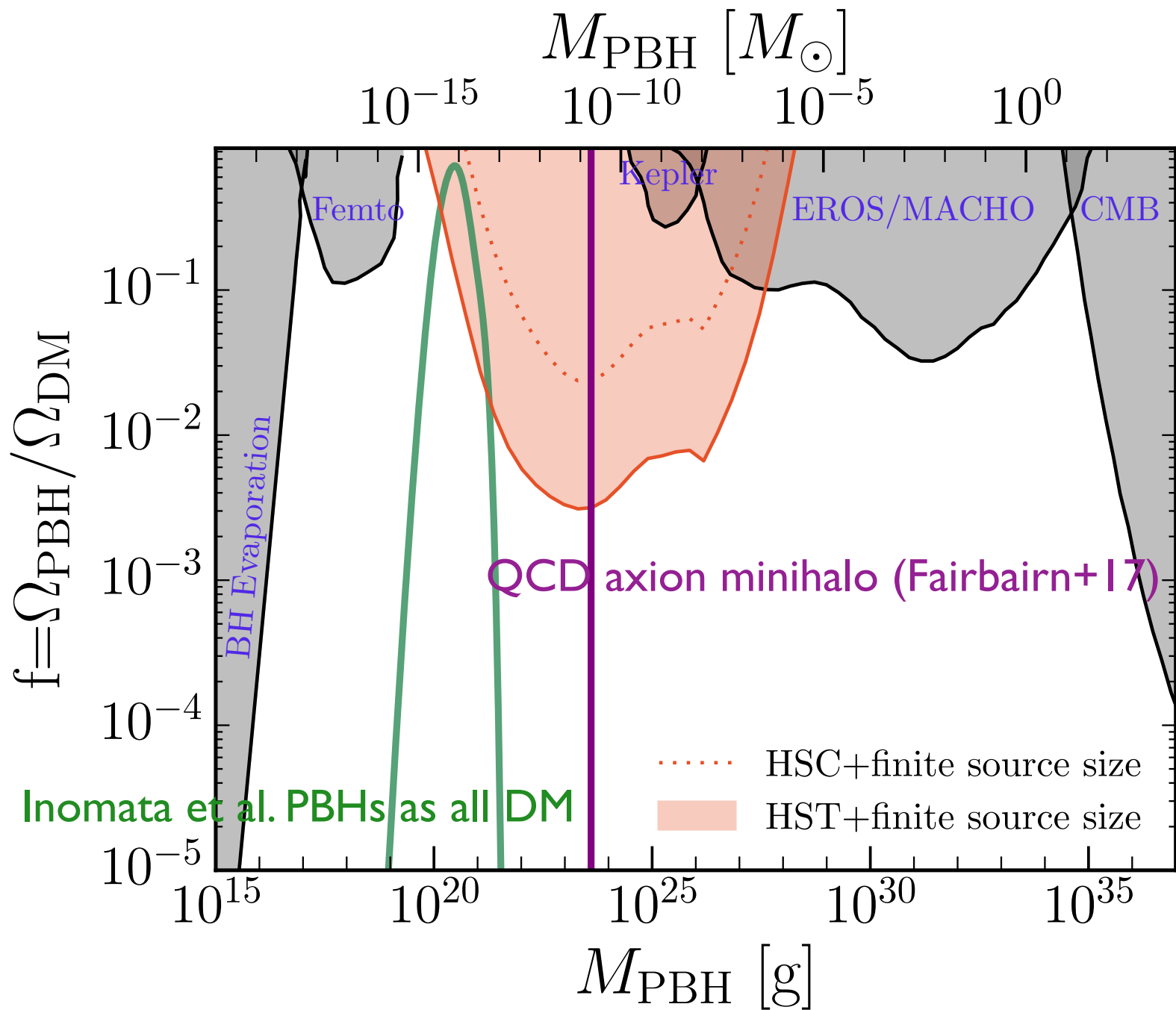


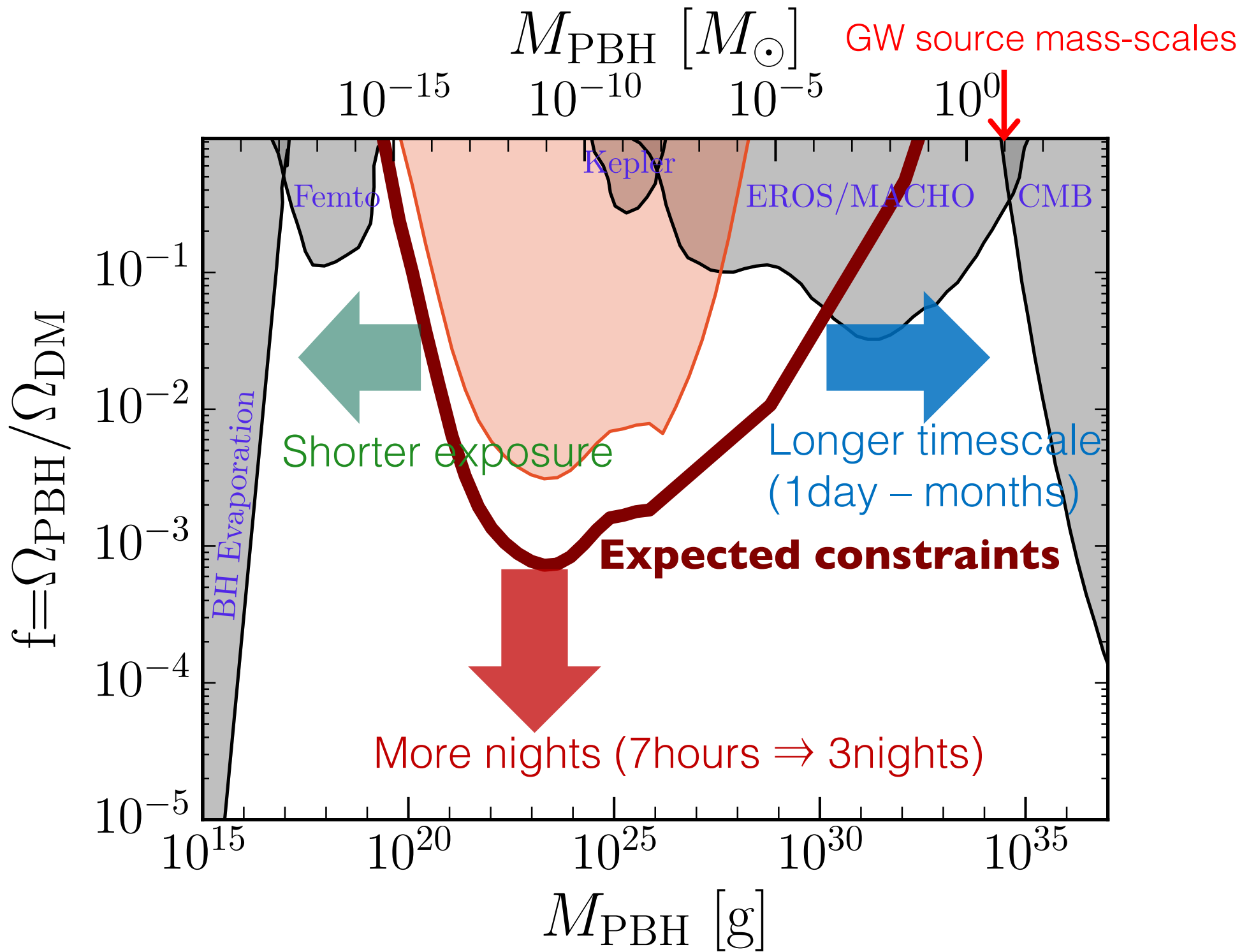
# Results: New bound on PBH abundance











# Summary

- Used “HSC one-night data” to derive the ***tightest*** upper bound on the abundance of PBHs, in the new window of mass scales  $[10^{-13}, 10^{-6}]M_{\text{sun}}$ 
  - One possible PBH microlensing candidate
  - Initiated from discussion with particle physicists (Hitoshi, Kawasaki san, Yanagida san, ...)
- **Unique capability** for **time domain** astronomy (Planet9, GW counterparts, moving objects, fast radio burst, ....)
- We should make a **long-term monitor of M31** (microlensing, SNe, direct collapse, ...)