arXiv: 1701.02151

Tightest bounds on PBH abundance with HSC observation of M31

Hiroko Niikura (UTokyo / KIPMU)

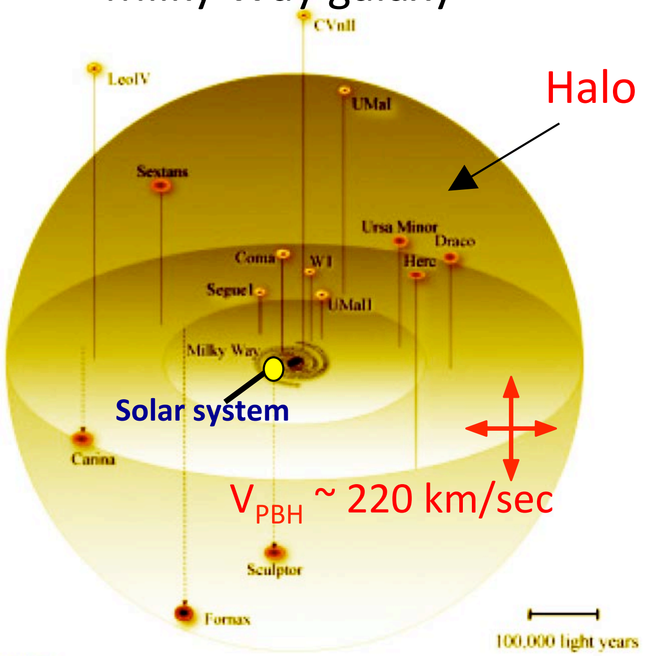
Collaborators: Masahiro Takada, Naoki Yasuda (Kavli IPMU), Robert Lupton (Princeton), Takahiro Sumi (Osaka), Surhud More, Anupreeta More, Masamune Oguri (UTokyo), Masashi Chiba (Tohoku)

@ Auckland U., 2018

Target: dark matter in the galactic halo

- Searching for dark matter in the local universe
  - Massive Compact Object (MACHO), Weakly Interacting Massive Particle (WIMP), Primordial Black Hole (PBH)
- Primordial black hole (PBH)
  - Proposed to be generated in the early universe, and can survive as dark matter today if not evaporated (Hawking 1974)
  - Previous research still leaves some room for PBH to be a part of dark matter
  - This study, the M31 microlensing search, targets PBHs with $10^{-10} M_{sun}$

Milky Way galaxy

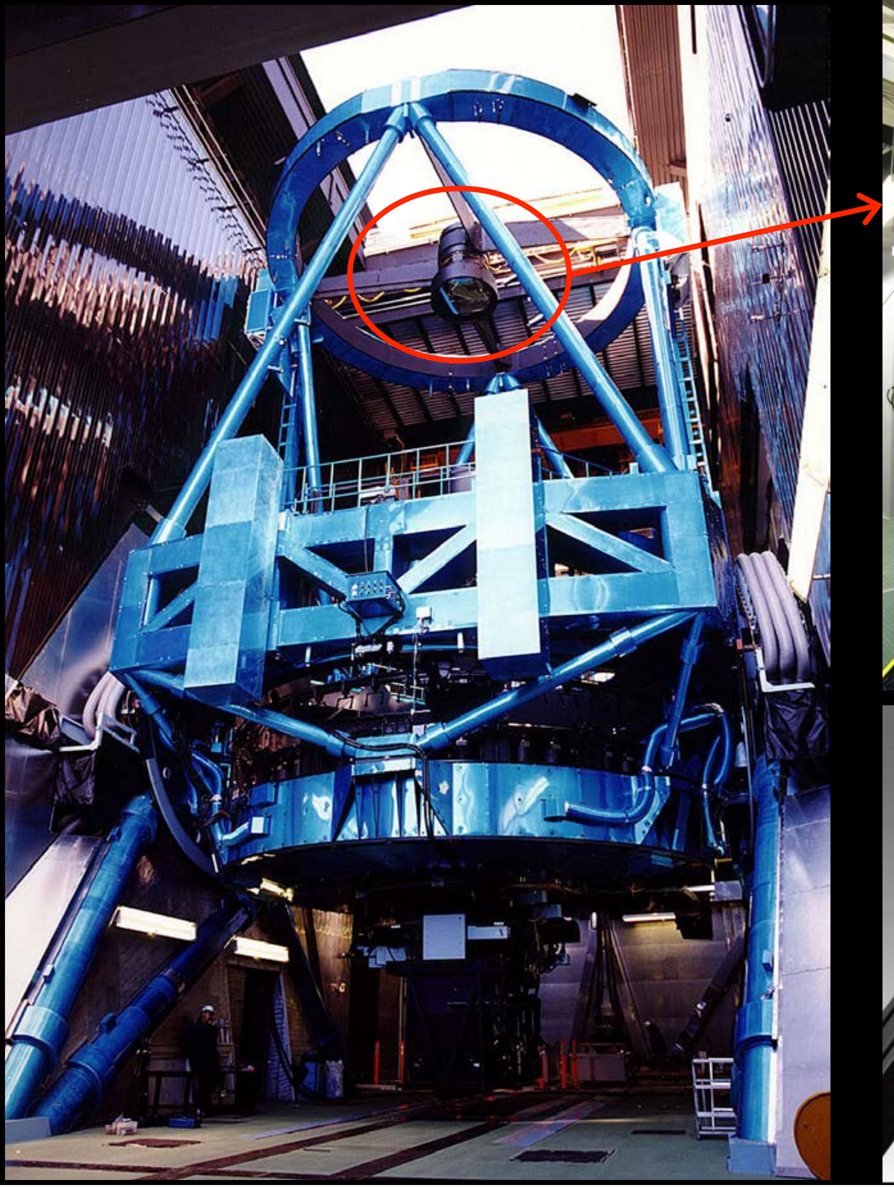


Credit: J. Bullock/M. Geha/UCI.

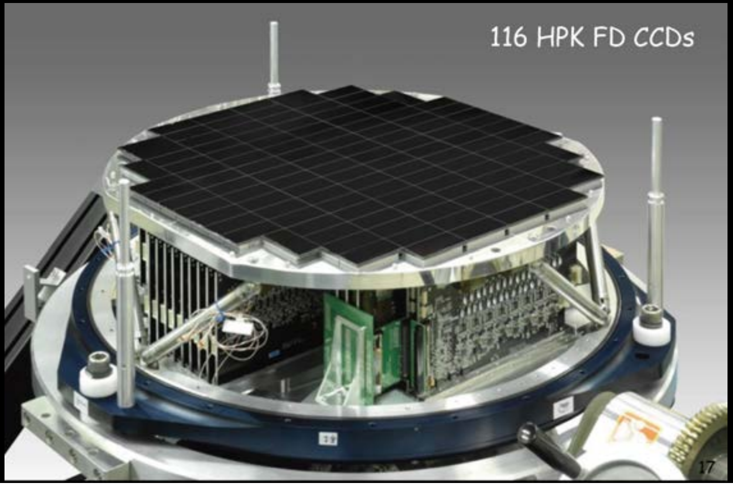
→ Search of magnification event due to microlensing effect

credit: Masahiro Takada

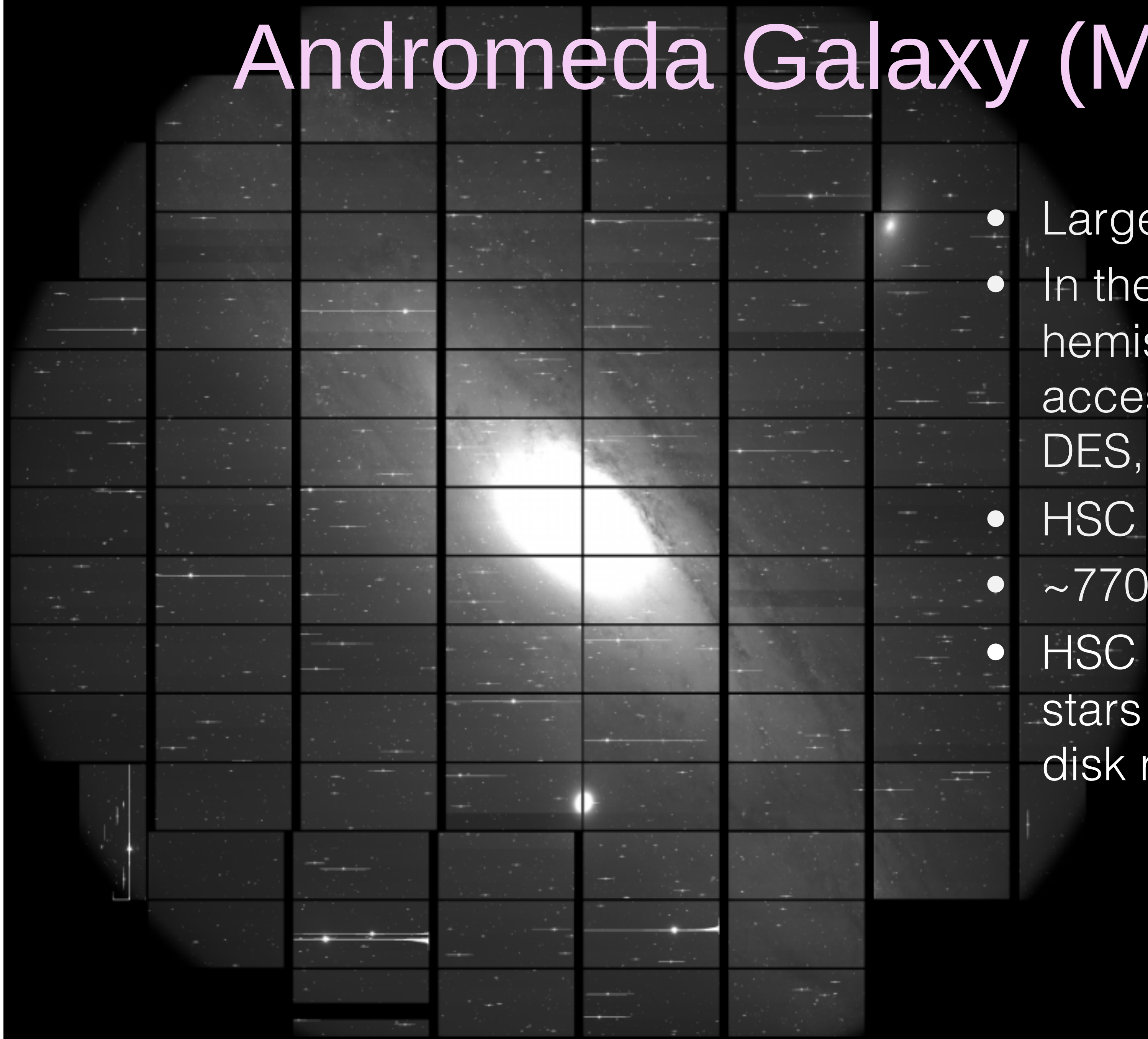
Hyper Suprime-Cam



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



Andromeda Galaxy (M31)

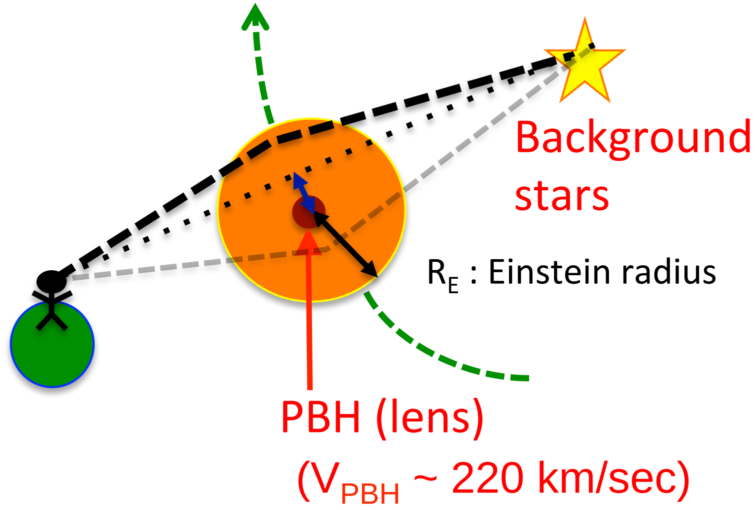


- Large spiral galaxy
- In the northern hemisphere (not accessible from VLT, DES, LSST)
- HSC FoV ~ entire M31
- ~770kpc (μ~24.4)
- HSC can monitor all stars in the bulge and disk regions of M31

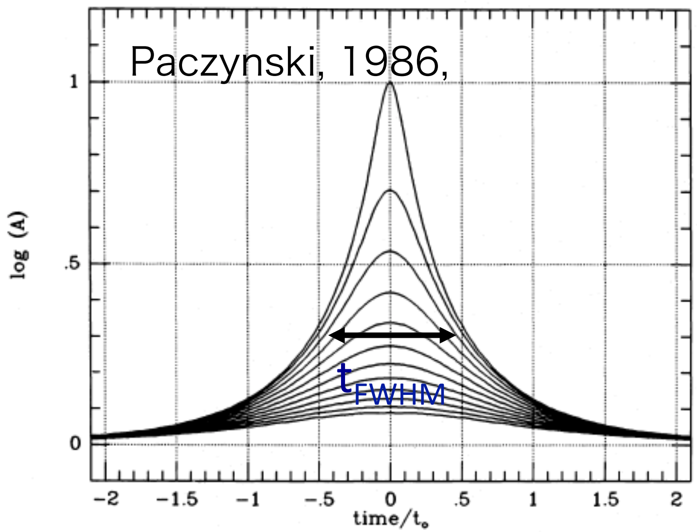
HSC Image of M31 (HSC FoV=1.8 sq. degrees)

PBH microlensing effect on M31 stars

- Only proved by magnification (separation angle of two images is ~μ arcsec and cannot be separated)
- Time variance of magnification (light curve) depends on lens mass and impact parameter β .
- Time scale: a few months for MACHO ($1M_{sun}$), a few hours for PBH ($10^{-7}M_{sun}$)



$$t_0 = \frac{R_E}{v} \simeq 1.6\text{hours}\left(\frac{M}{10^{-7}M_\odot}\right)^{\frac{1}{2}}\left(\frac{xDs}{100\text{kpc}}\right)^{\frac{1}{2}}\left(\frac{220\text{km/sec}}{v}\right)$$

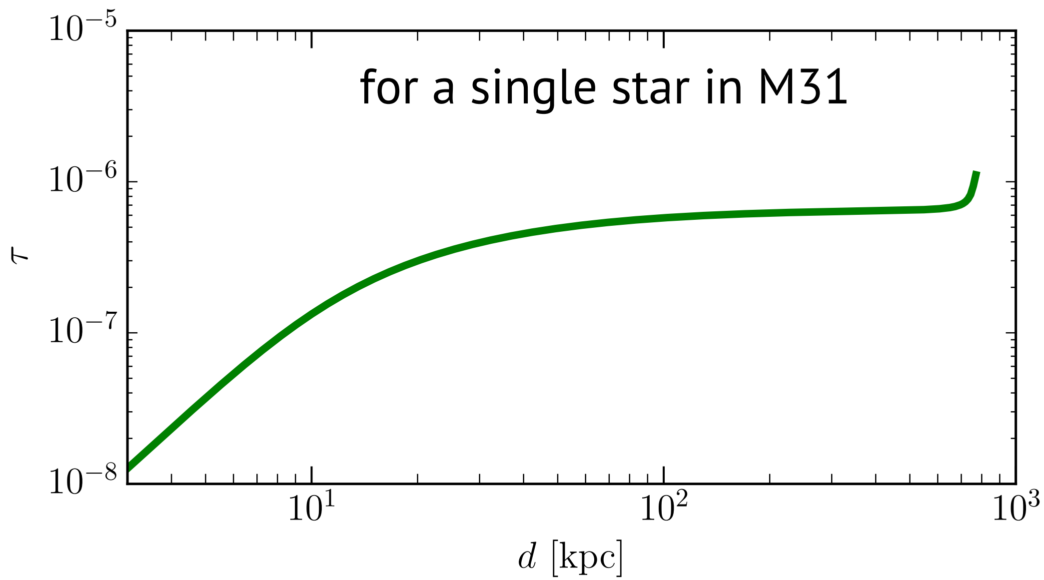


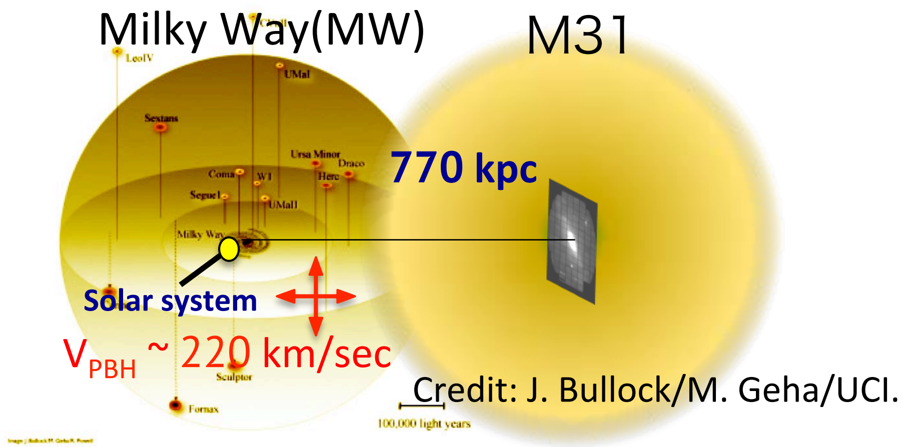
★ *Since M31 contains many stars (>tens of million stars), we can expect high event rates for PBH microlensing*

→ M31 observation expects high event rate

PBH microlensing event rate

- Cumulative optical depth of microlensing for a sigle star in M31





NFW model for each of the MW and M31 halos (Klypin 2002)

$$\tau = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \int_0^{d_L} {\rm d}d \, \frac{\rho_{\rm DM}(d)}{M_{\rm PBH}} \pi R_E^2$$

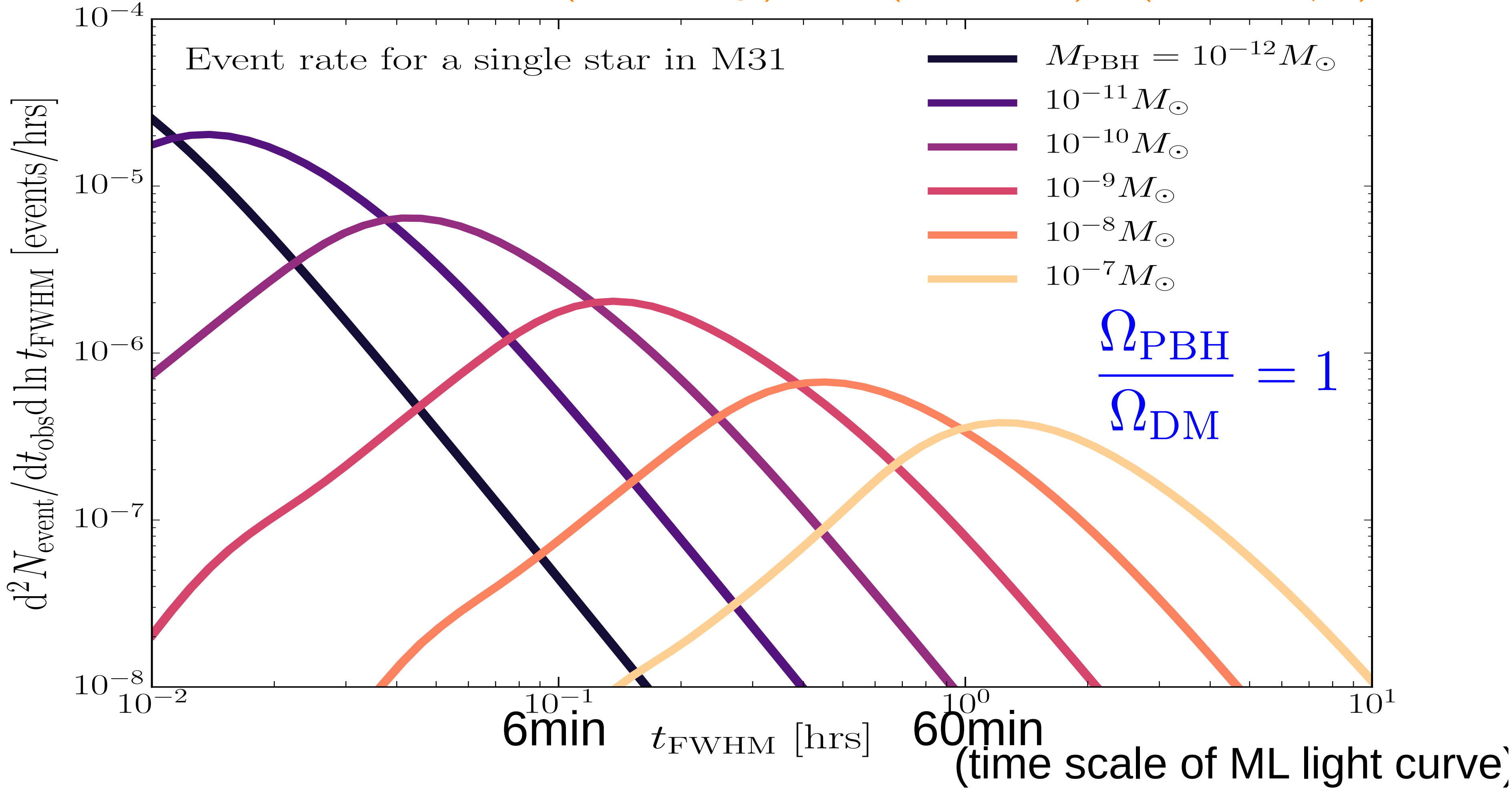
Assumed $\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = 1$

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

M31 has ~10^{11} stars, highly expected event

PBH microlensing event rate

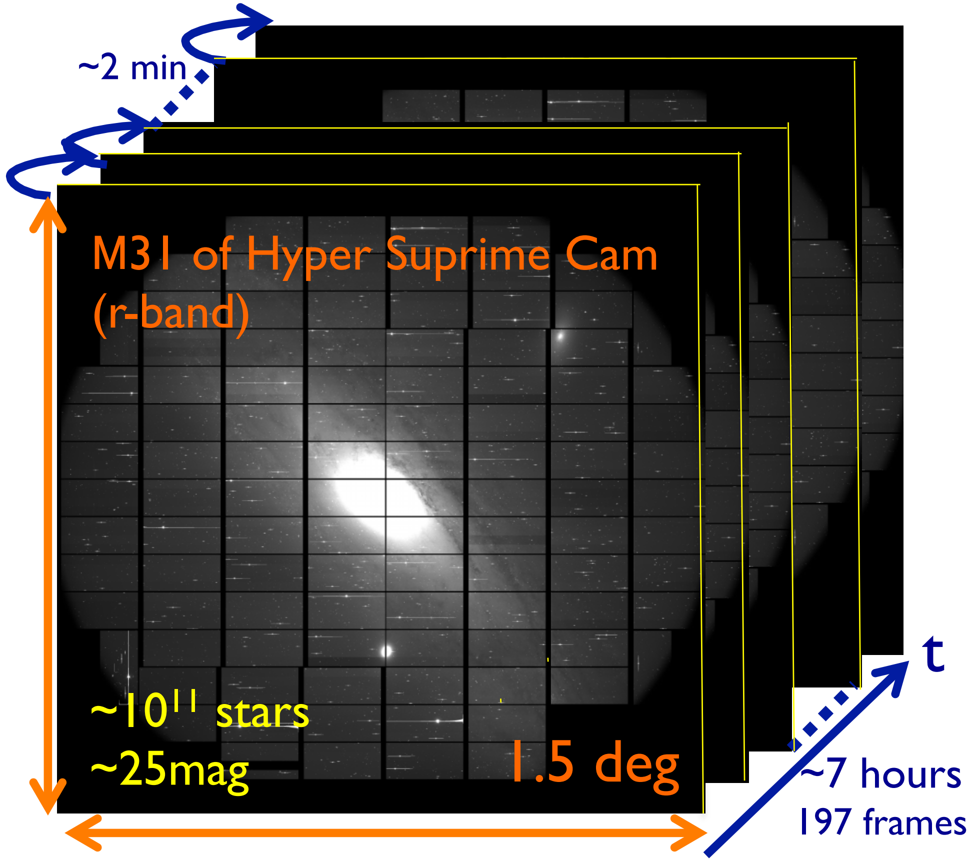
$$t_E \sim \frac{d_L \theta_E}{v_{\rm PBH}} \sim 34\ \text{min} \left(\frac{M_{\rm PBH}}{10^{-8} M_\odot}\right)^{1/2} \left(\frac{d_L}{100\ \text{kpc}}\right) \left(\frac{v_{\rm PBH}}{200\ \text{km/s}}\right)^{-1}$$



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

Observation: wide field survey of PBH microlensing search using HSC

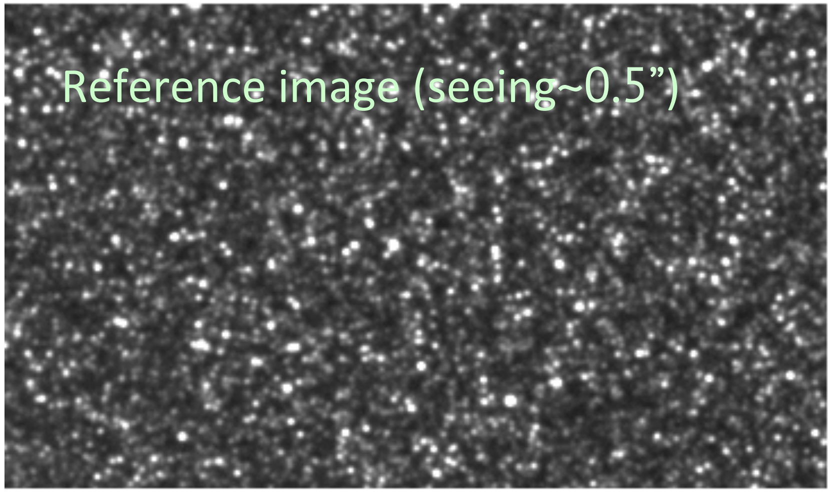
- Search for gravitational lensing effect by PBH, a candidate of dark matter (or put constraint on the abundance of PBH.)
- The wide and deep imaging with Hyper Suprime-Cam; HSC
  - ★ Can cover the entire disk and bulge regions of M31 with its one pointing
  - ★ 90sec exposure can reach to ~26mag depth for a star
- Observation for 7-hours, taking images every 2 minutes at M31-disk region (r-band)

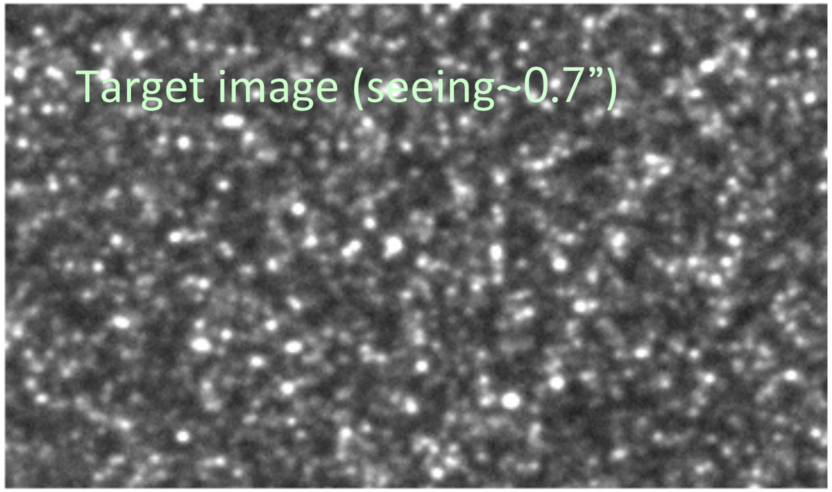


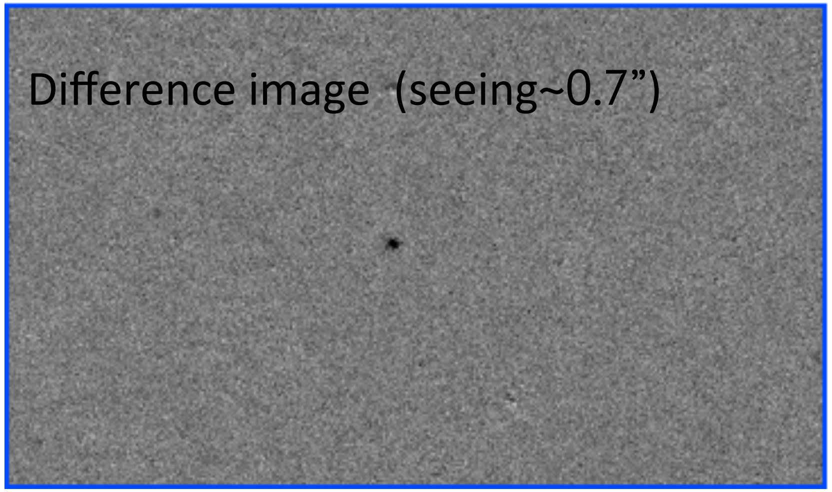
8

Detection of transients: difference imaging

Pixel lensing regime: multiple stars in each CCD pixel

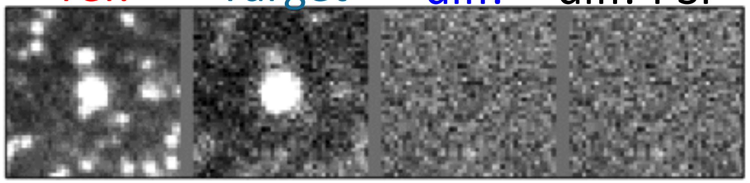






○

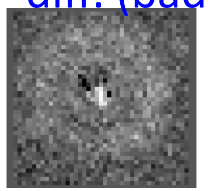
ref. Target diff. diff.-PSF



×

-tiny objects (< pixel size)
-distorted object
-object with flux distribution unsimilar to stars

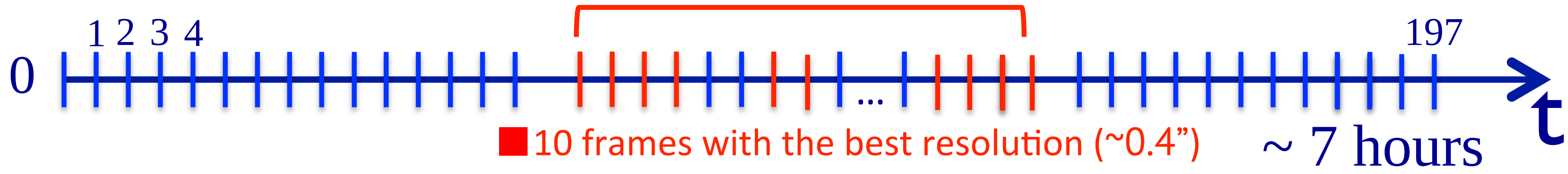
diff. (bad)



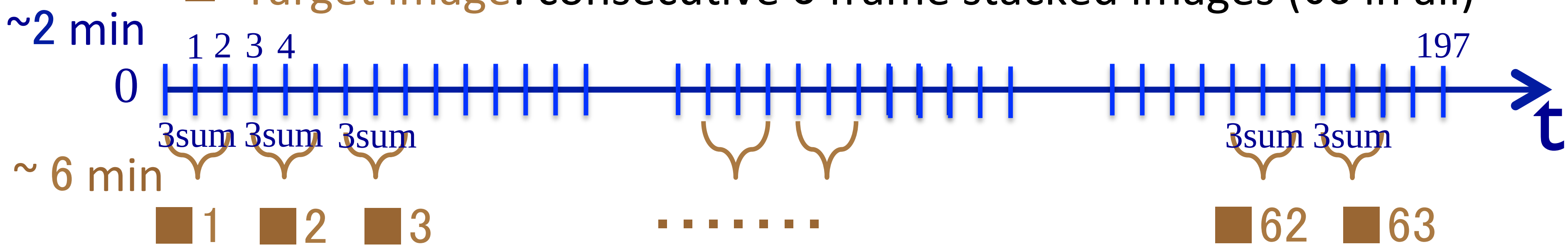
Difference imaging method (time scale>6 min.)

- Observation: 188 images (+three focusing)

■ Reference image: stacked image of the best-seeing 10 frames



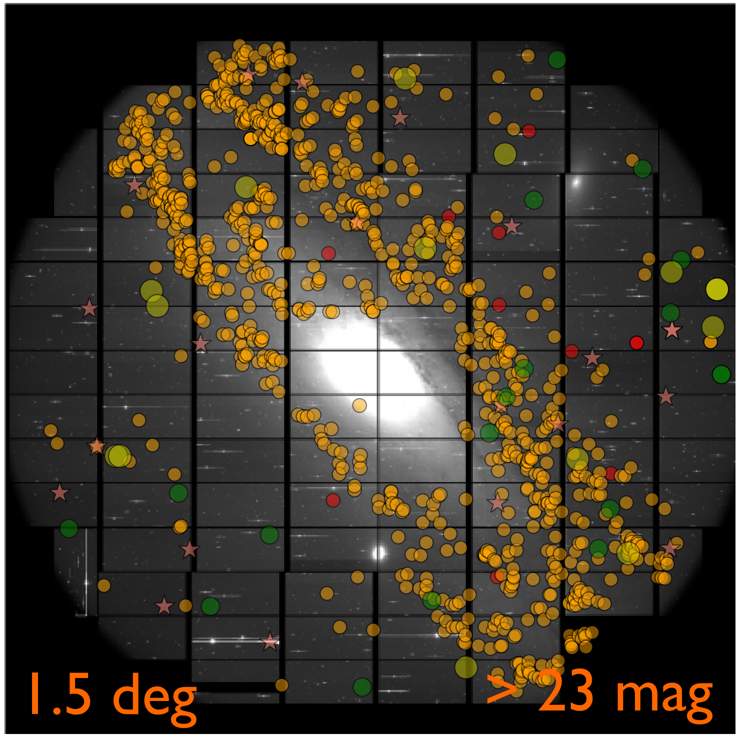
■ Target image: consecutive 3 frame stacked images (63 in all)

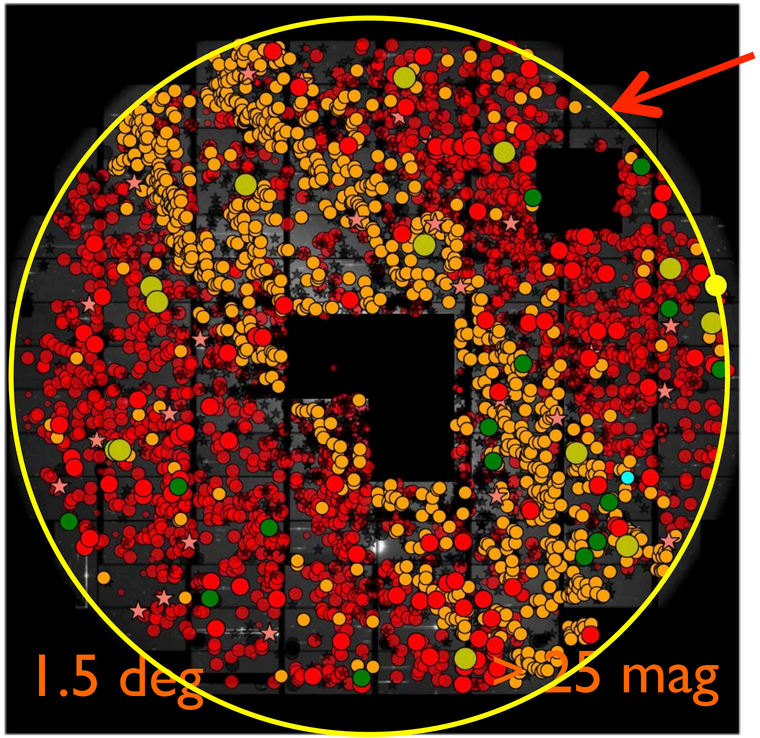


detect transients on every 63 difference images created from a Reference and Target images.

- Transient candidates are those detected more than twice among 63 difference images (time scale > 6 min.)
- Photometry on one-visit image (194 warp images) for light curves

Result: Distribution of transient candidates

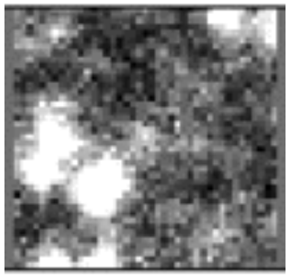


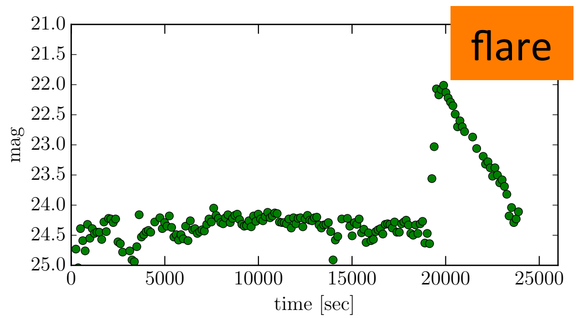


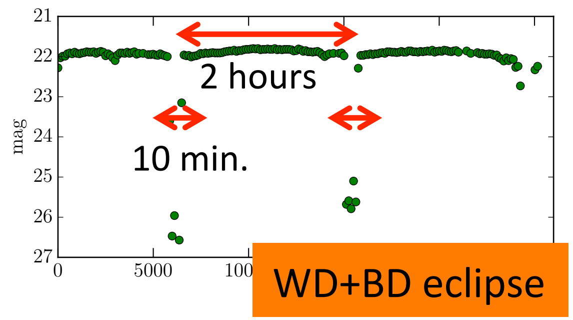
HSC-M31
focal plane

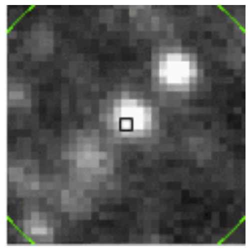
More than 10,000 transient candidates in one field-of-view of HSC.
(6 min.-)

- fake (incl. RR-Lyrae)
- Cepheid variable
- asteroid
- stellar flare
- eclipsing binary
- contact binary



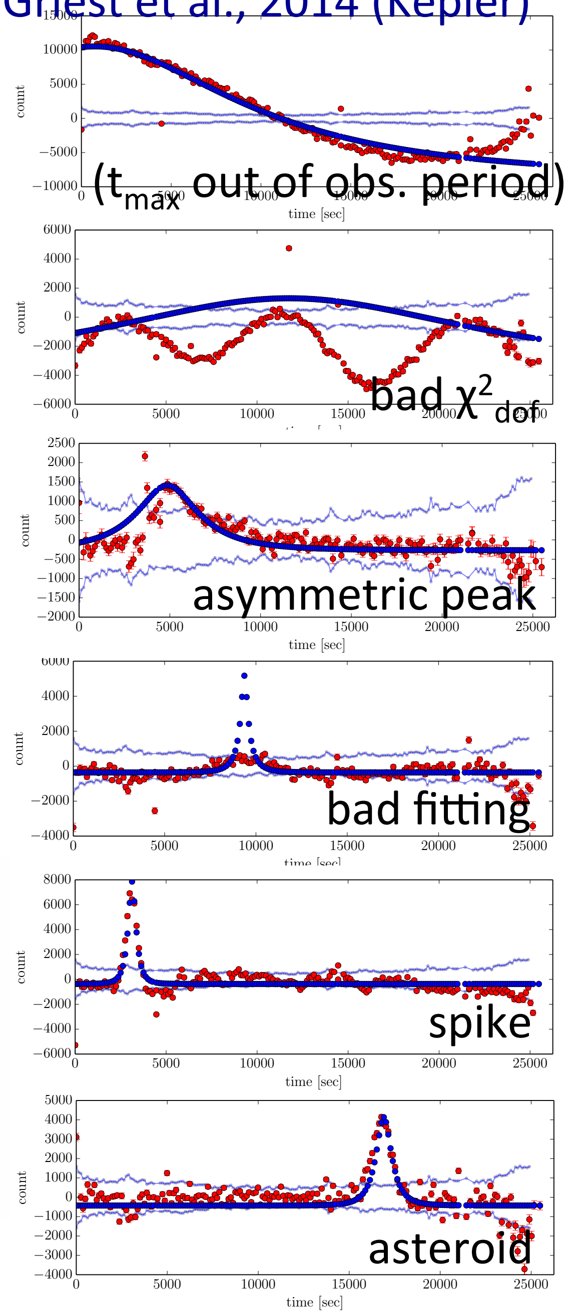






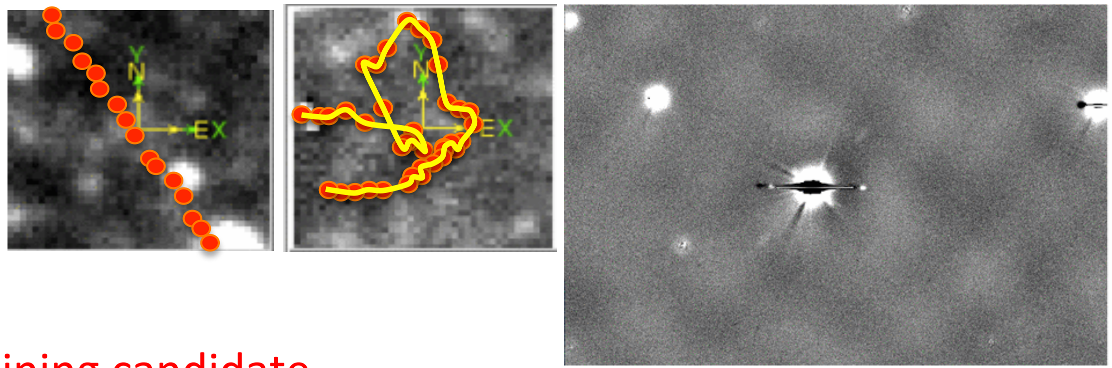
Analysis: Selection of microlensing candidates (6 min.-4 hours)

Follow selection method by Griest et al., 2014 (Kepler)



Total number of events : 15,571

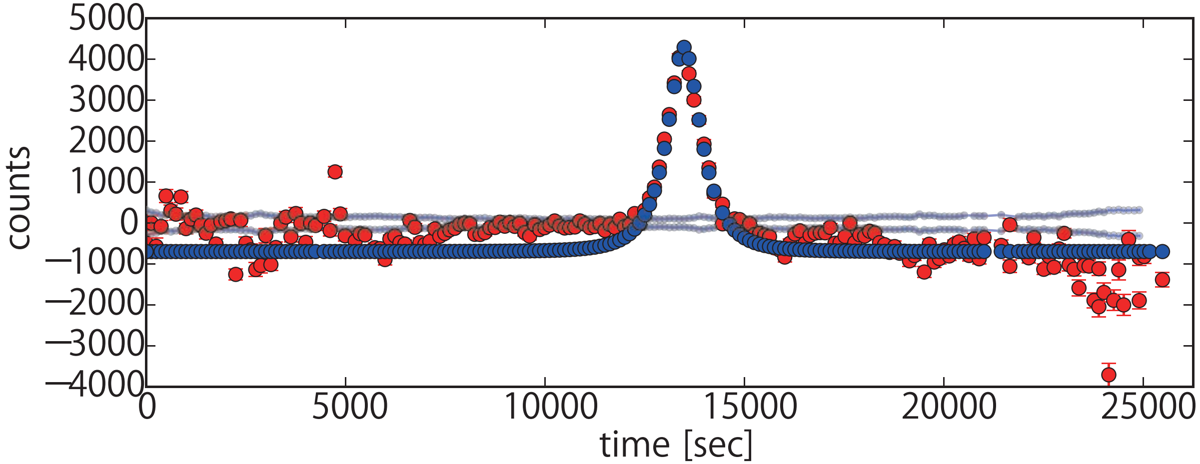
# of candidates		
	Noise threshold (S/N > 5 for 3 consecutive visits)	
11,703	Apart from CCD edge	fake events, binary stars
	Fitting of ML lightcurve model (for lightcurves in difference images)	
227	Symmetric shape of peak around the peak in the light curve	flare stars, fake events
146	significant peaks	noisy events
66	Visual inspection	spikes, asteroid or some defects
1		



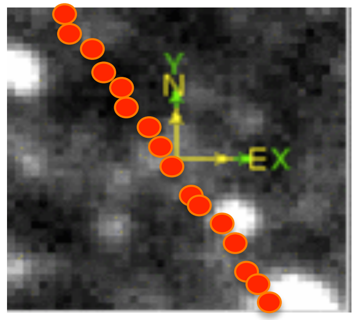
One remaining candidate

Visual inspection…

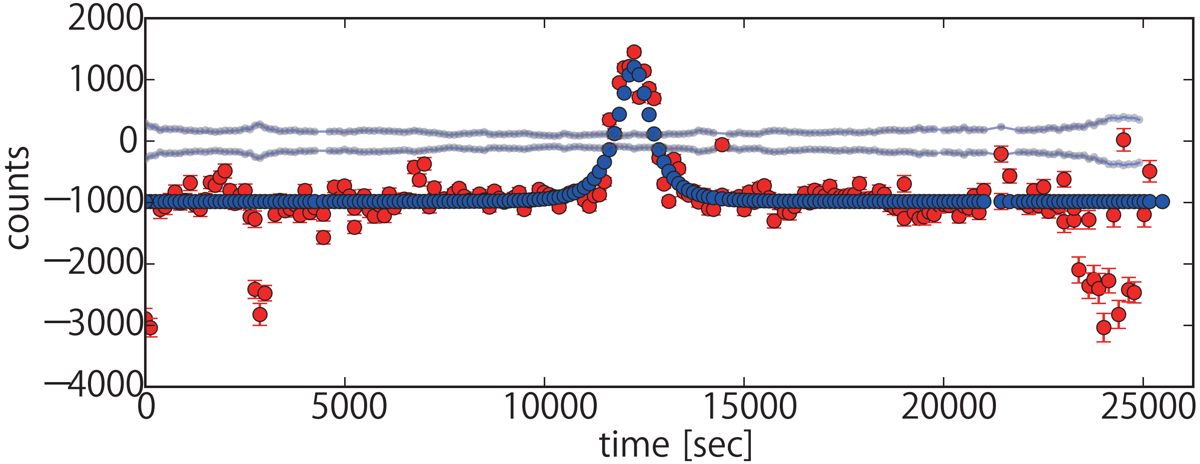
Visual inspection of 66 candidates to identify junks…

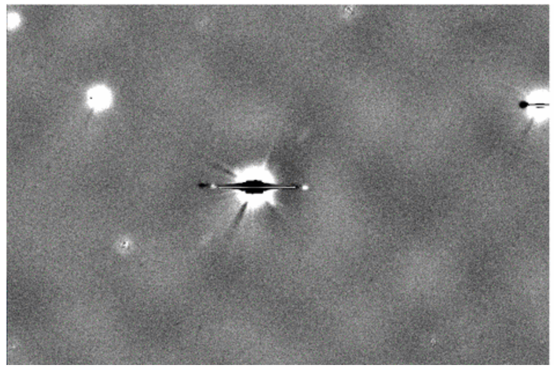


asteroid



spike around a bright star

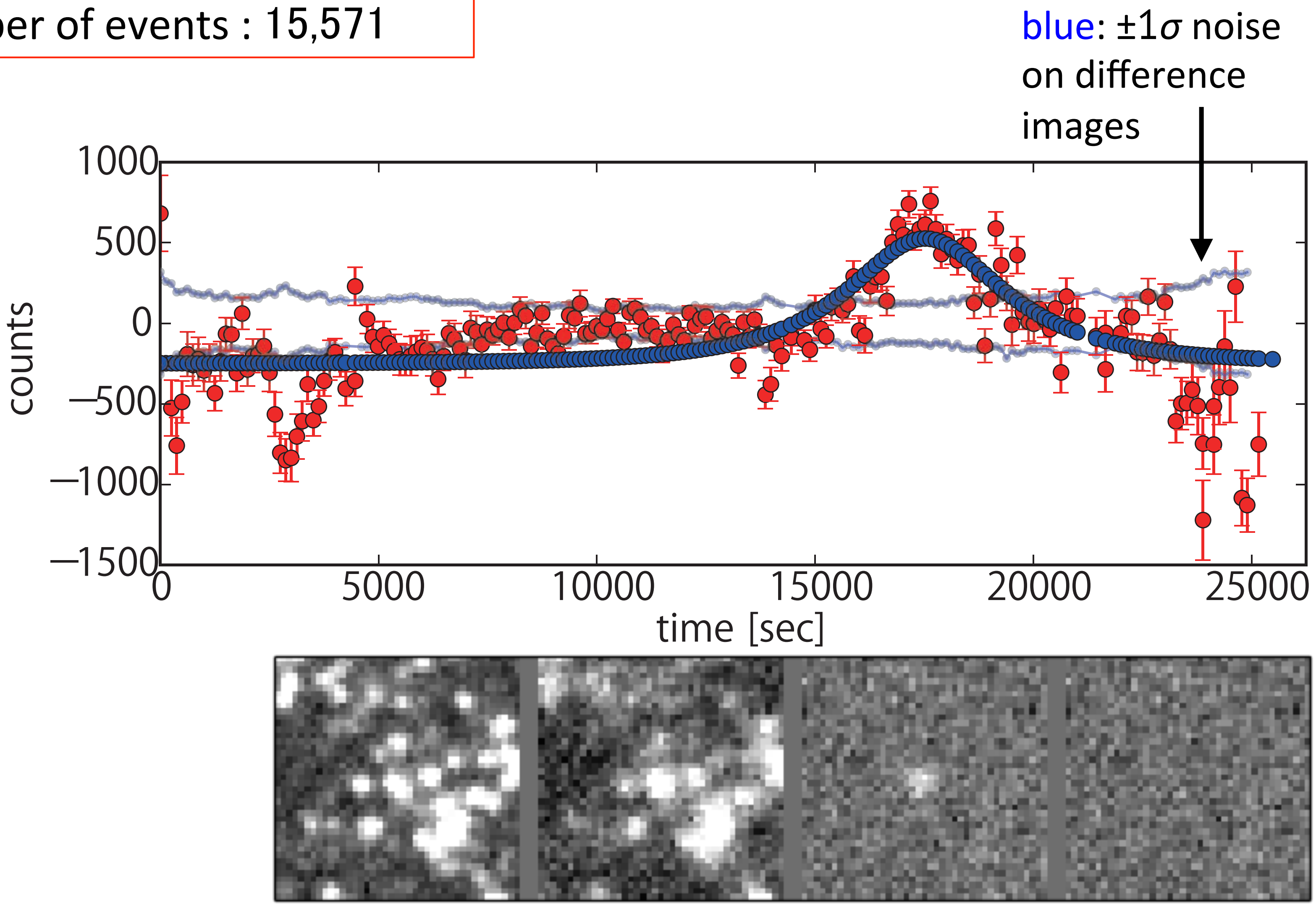




66 ⇒ 65 junks

One remaining candidate..

Total number of events : 15,571

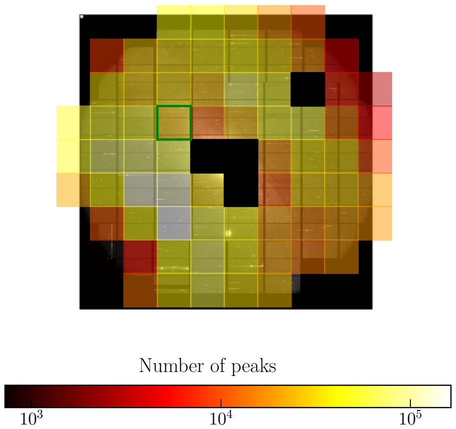


One remaining candidate

Discussion: Constraint on the PBH abundance

★ The expected number of events (from 7-hour observation)

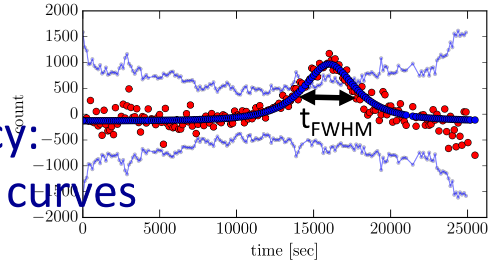
$$N_{\rm exp}(M) = E \int_0^\infty \frac{d\Gamma}{d\hat{t}}(\hat{t}, M)\epsilon(\hat{t})d\hat{t}$$

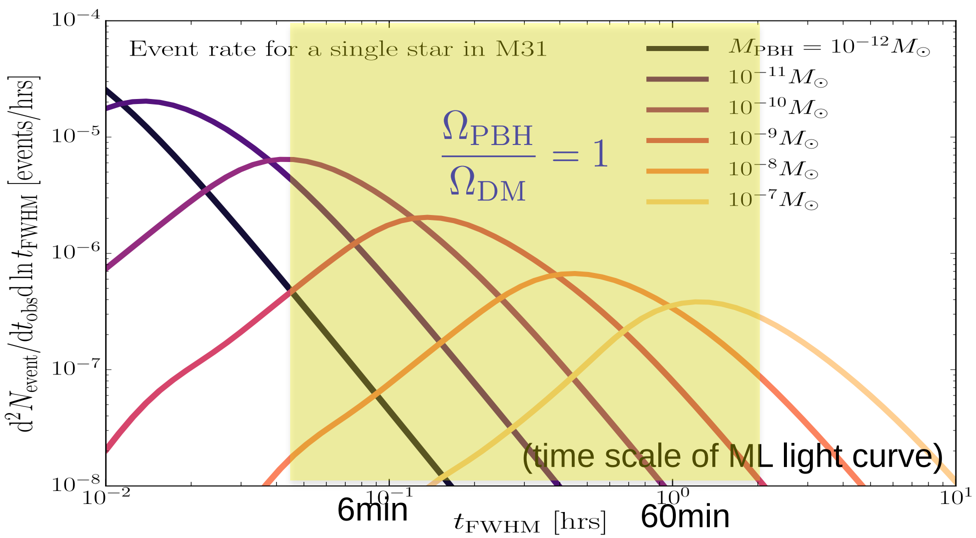


The number of stars at HSC-M31 region: evaluated as the number of peaks (10^5/patch)v

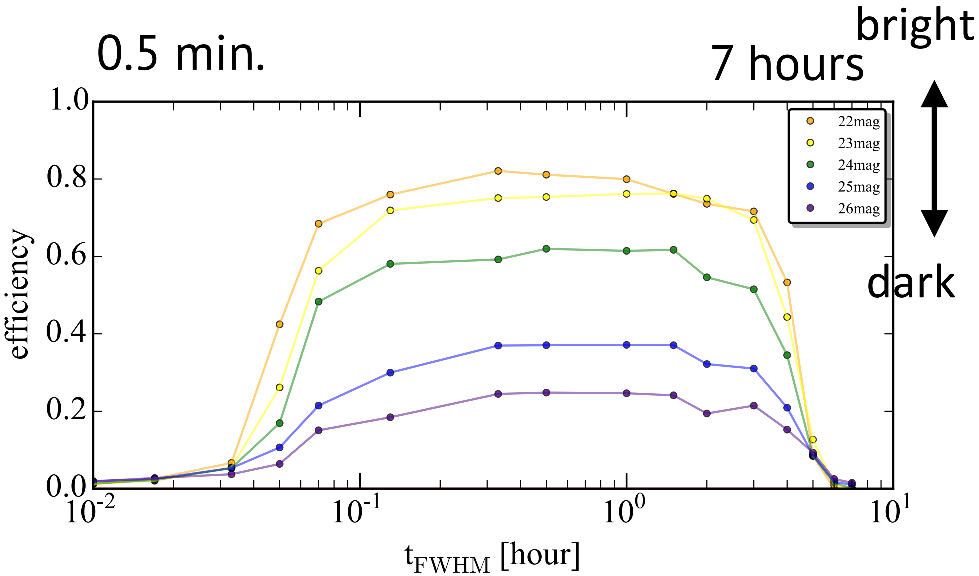
Event rate:
Higher event rate for PBHs with 10^{-7}-10^{-9}Msun

detection efficiency: simulation of light curves



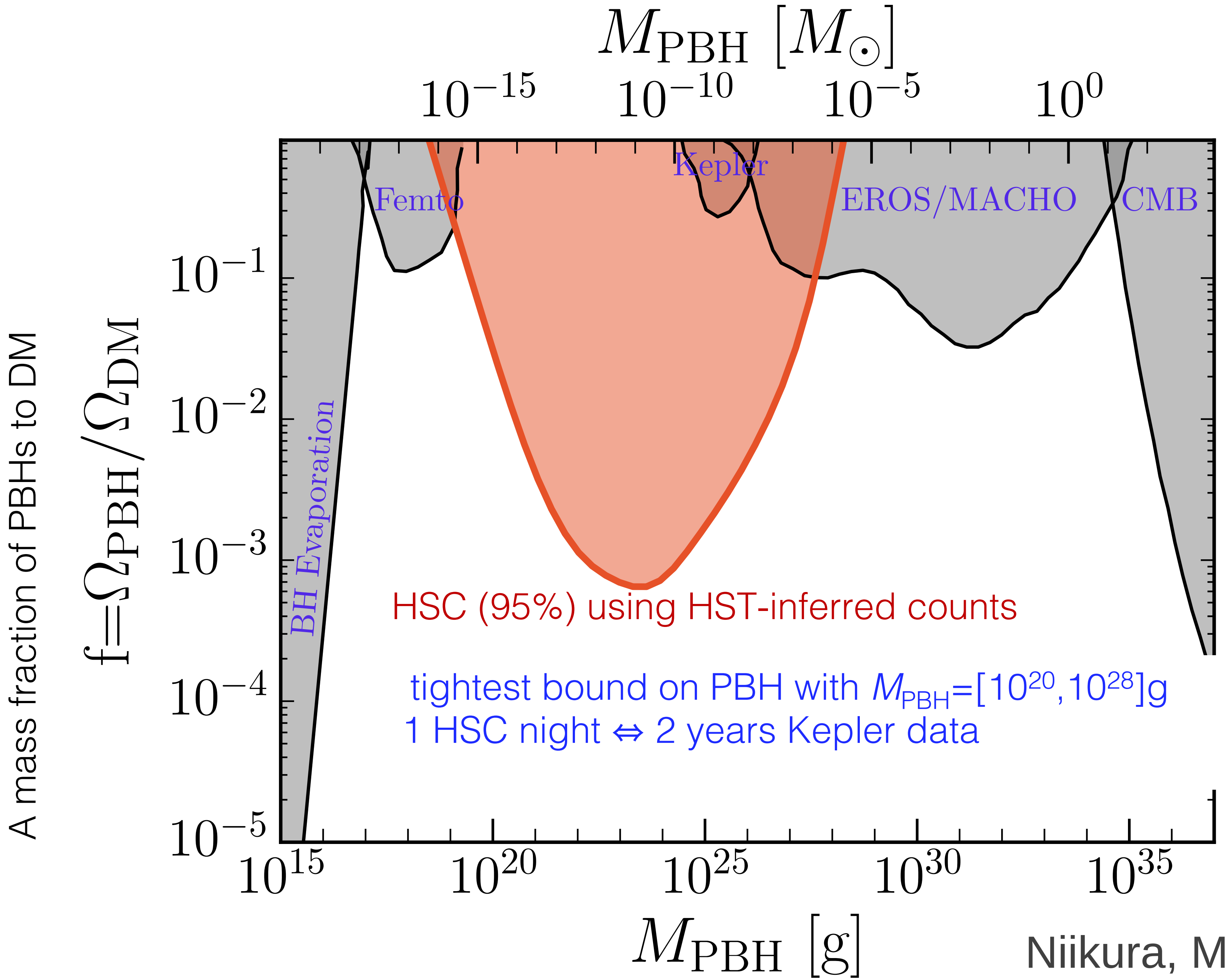


Event rate of microlensing (per background star)

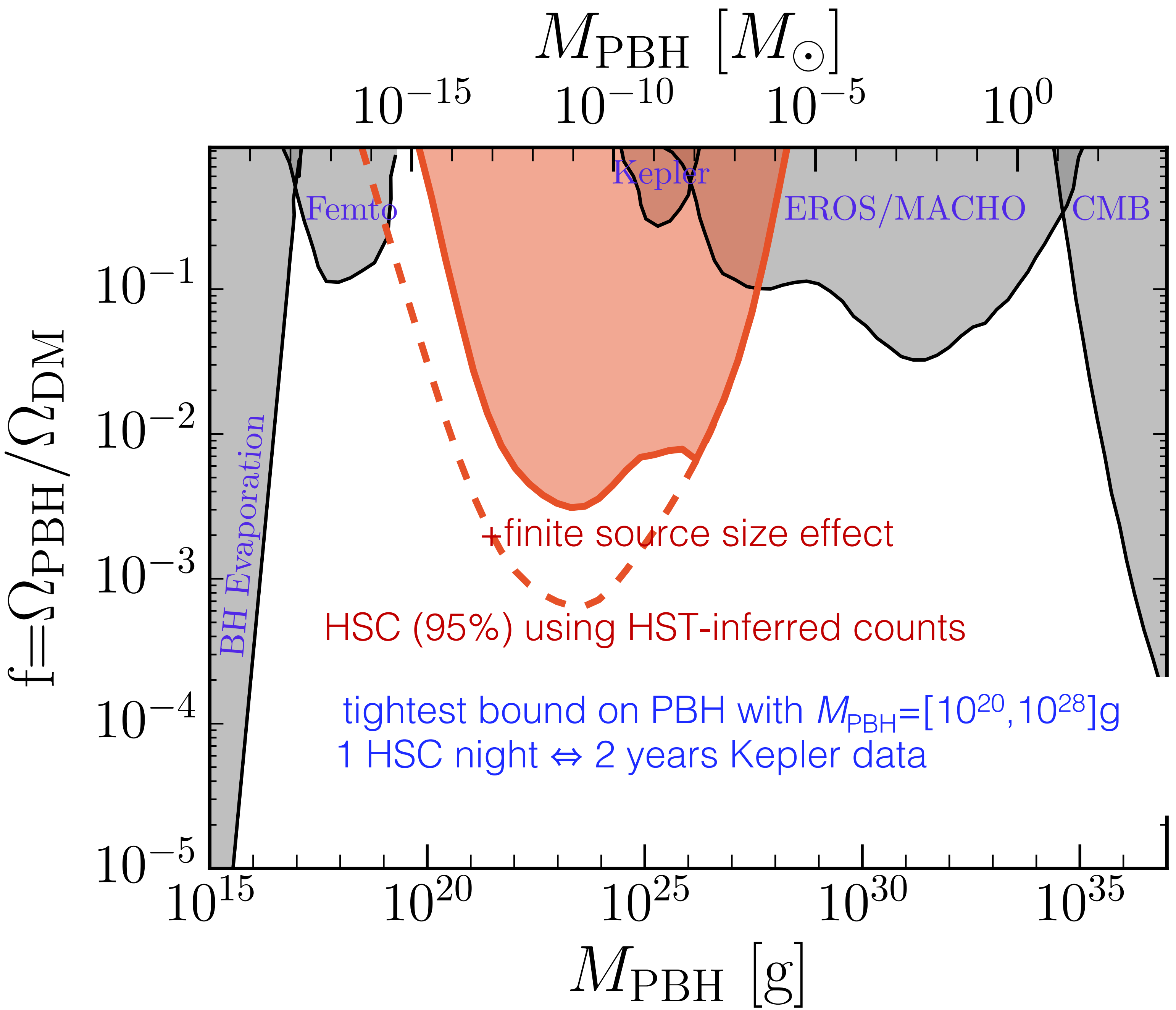


detection efficiency

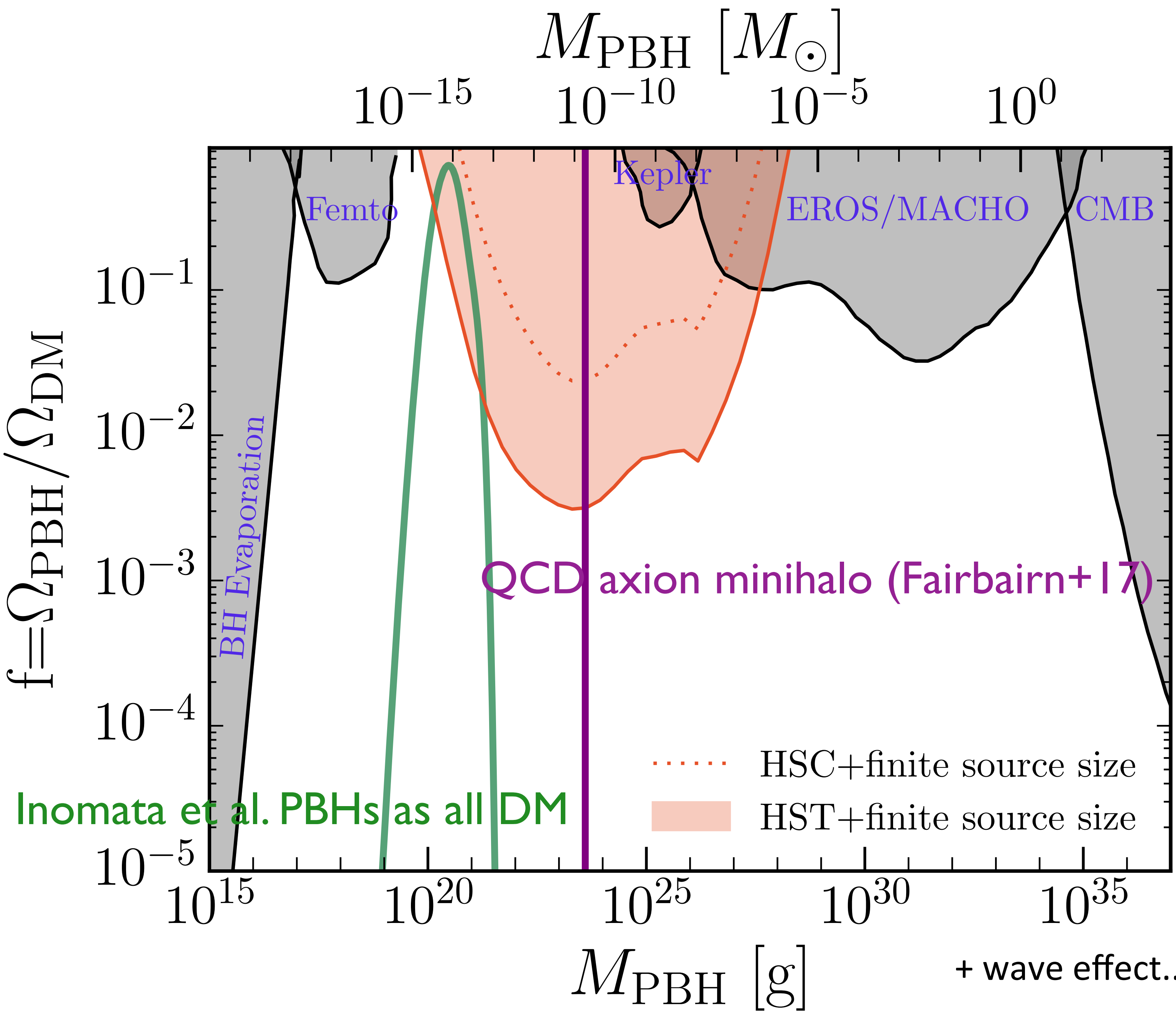
Results: New bound on PBH abundance



Niikura, MT, + 17



$M_{\rm PBH}$ $[M_\odot]$
10^{-15} 10^{-10} 10^{-5} 10^{0}
Kepler
Femto
EROS/MACHO
CMB
BH Evaporation
+finite source size effect
HSC (95%) using HST-inferred counts
tightest bound on PBH with $M_{\rm PBH}$=[10^{20},10^{28}]g
1 HSC night ⇔ 2 years Kepler data
10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5}
f=$\Omega_{\rm PBH}/\Omega_{\rm DM}$
10^{15} 10^{20} 10^{25} 10^{30} 10^{35}
$M_{\rm PBH}$ [g]


$M_{\rm PBH}$ $[M_\odot]$
10^{-15}
10^{-10}
10^{-5}
10^{0}
Femto
Kepler
EROS/MACHO
CMB
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
f=$\Omega_{\rm PBH}/\Omega_{\rm DM}$
BH Evaporation
QCD axion minihalo (Fairbairn+17)
HSC+finite source size
HST+finite source size
Inomata et al. PBHs as all DM
10^{15}
10^{20}
10^{25}
10^{30}
10^{35}
$M_{\rm PBH}$ [g]

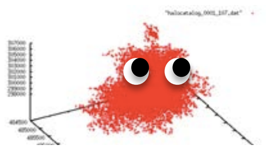
+ wave effect..?

Summary

- Used the image difference technique to identify variable star candidates; indeed found many secure variable stars (>3,000) such as stellar flares and contact/eclipse binaries
- One remaining candidate of PBH microlensing; need additional observation to reveal the nature of the candidate
- Use the microlensing search results to obtain the tightest upper bound on the abundance of PBHs
- When combined with other observational constraints, our results rule out almost all the window of PBH mass scales

Future works :

- Test the variability of the one remaining candidate (analysis ongoing..)
- Superstring microlensing, O(10) PBHs,..



Thank you very much for listening!