

# Updates in B03 group & HSC constraints on PBHs

Masahiro Takada (Kavli IPMU)

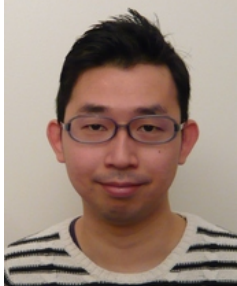
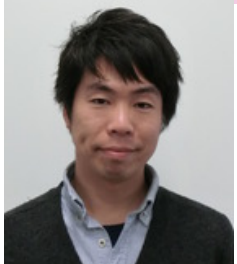
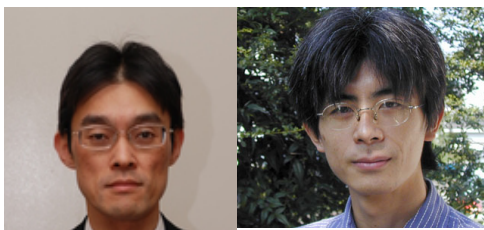


東京大学  
THE UNIVERSITY OF TOKYO

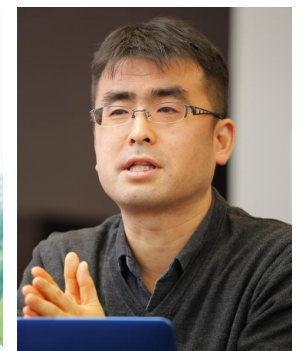


Cosmic Acceleration @ KEK, March 2017

# Our team



- Masahiro Takada: oversee
- Naoyuki Tamura: PFS Project Manager
- Ryuichi Takahashi: simulations
- Naoki Yasuda: pipeline
- Ikuru Iwata: Subaru
- Yousuke Minowa: Subaru
- Surhud More: theory
- Kiyoto Yabe: PFS
- Tomomi Sunayama (Yale → IPMU, Sep 2016)
- Kohei Hayashi (IPMU → KIAA, Beijing Oct 2016)
- Teppei Okumura (IPMU → ASIAA, Jan 2017)
- Yuki Moritani: PFS
- Chiaki Hikage
- Collaborators: Takahiro Nishimichi, Masato Shirasaki, ...
- Students: H. Niikura, K. Akitsu, R. Murata, Y. Kobayashi, T. Nozawa, further 2+2





# Activities (FY2016)

- PFS project (see Tamura-san's talk)
- HSC collaboration meeting @IPMU, Aug 23-26
- PFS Science WG meeting @Princeton, Sep 5-9
- Observational Cosmology WS @Hiroshima U., Dec 24-26
- PFS collaboration meeting @JHU, Dec 12-16
- HSC WLWG group meeting @Princeton, Feb 6-8 2017
- various visitors
- regular small-group meeting

# Publications

- HSC DR1 paper, arXiv:1702.08449! (see B02 talks)
- [Niikura](#), Takada, Yasuda et al, arXiv:1701.02151: *HSC microlensing constraints on PBHs*
- Oguri et al. arXiv:1701.00818: *HSC cluster catalog*
- [Akitsu](#), Takada & Li, arXiv:1611.04723: *LSS & large-scale tide*
- Okumura, Takada, More, Masaki, arXiv:1611.04165: *RSD*
- Okumura, Hikage, ..., PASJ: FMOS RSF measurement
- [Honma](#), Chiba, et al., ApJ: *A new dwarf satellite with HSC*
- Tamura et al., SPIE: *PFS*
- Shirasaki, Takada, et al., arXiv:1607.08679: *SDSS mocks*
- More et al., ApJ: *a detection of halo boundary*
- Clampitt, Jain, & Takada, MNRAS: *a detection of filament lensing*

# Research plans for FY2017

- Make progress in PFS project, instrumentation and survey design (B02+D01)
  - PFS collaboration meeting at Kavli IPMU, Nov 27-Dec 1
- Prepare “Dark Emulator” (an emulator for cosmological quantities for halos, from a large number of sets of N-body simulations) → Takahashi san’s talk
- Carry out cosmological analysis with HSC (B02) and SDSS BOSS data, in preparation for HSC+PFS
- Explore the nature of DM in the MW halo (led by Hiroko Niikura)
- Cosmology with SDSS clusters (Ryoma Murata)
- Explore large-scale tides from SDSS (Kaz Akitsu)

Research highlight (inflation, DM, HSC, ...)

arXiv:1701.02151



Hiroko Niikura (U.Tokyo/IPMU)

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

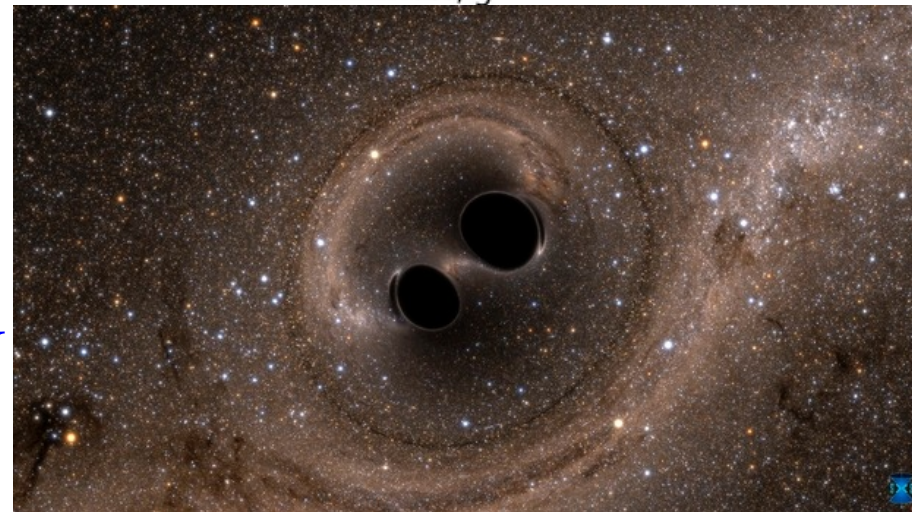
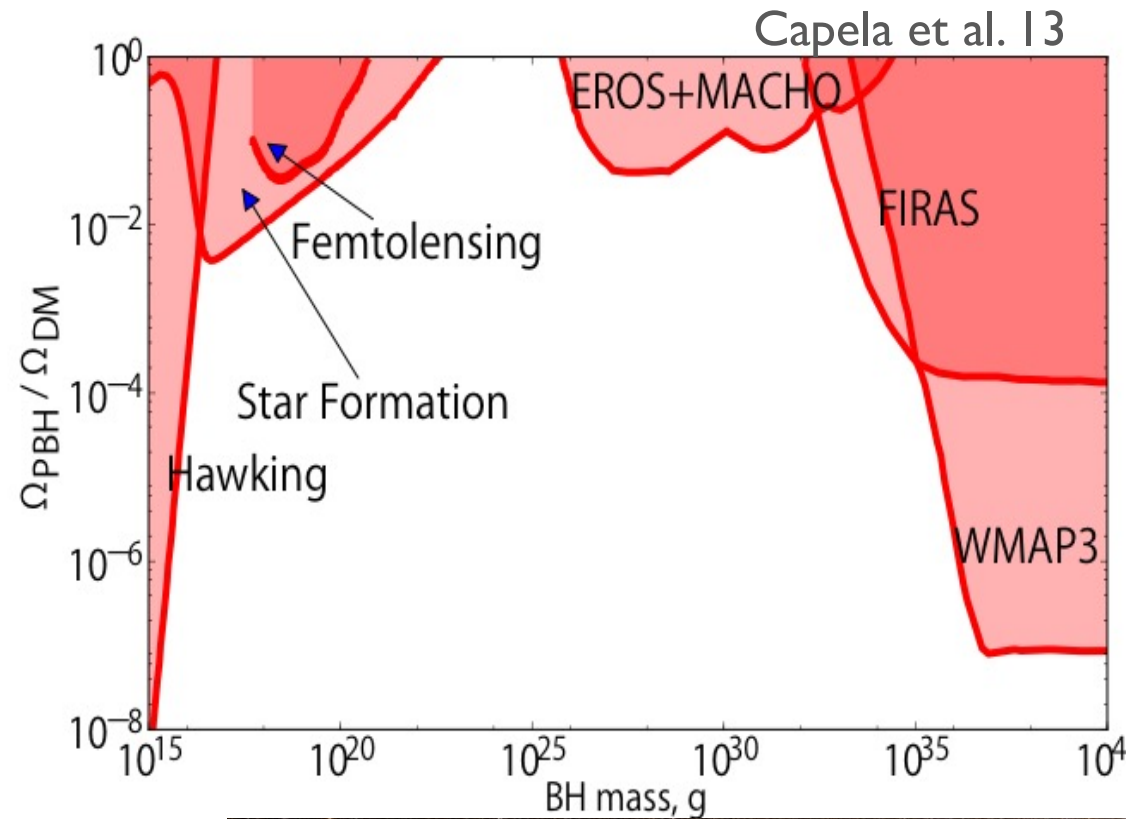
Masahiro Takada (Kavli IPMU)

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)



# Primordial Black Hole (PBH)

- Dark matter needed
- Can be formed in the early universe (Zel'dovich & Novikov67; 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)



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

# 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

Inomata et al. 2017: PBHs from one patch among  $10^{14}$  Hubble patches are enough to reproduce “all” DM

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

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



# 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)!



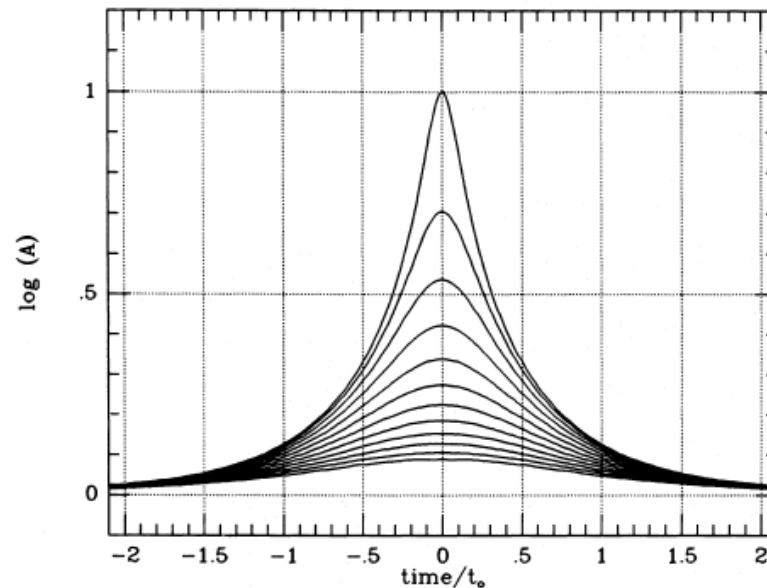
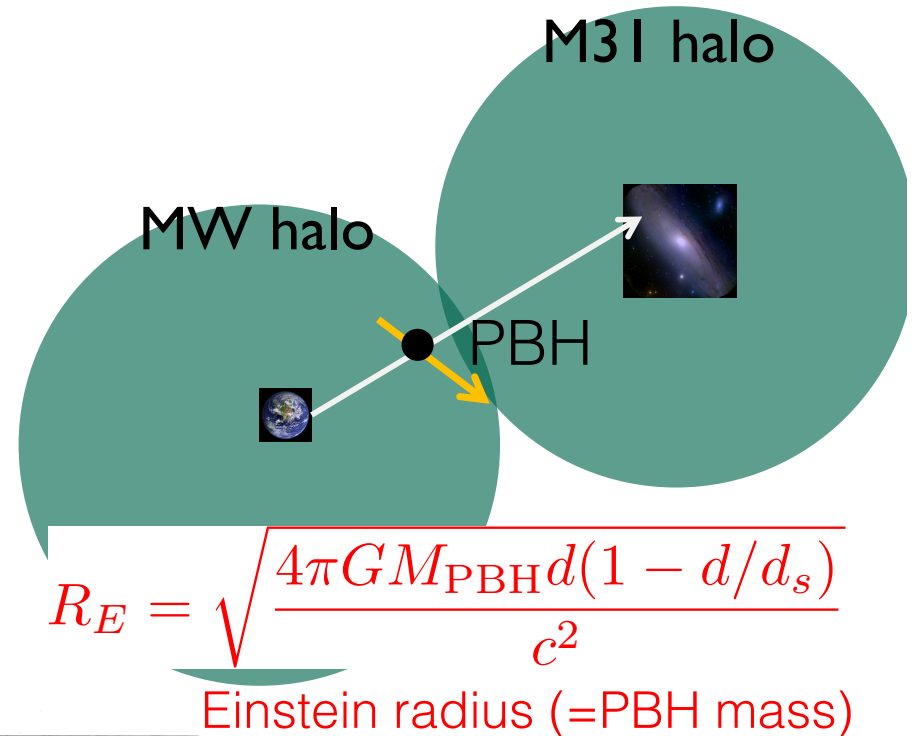
# probing PBHs with lensing

- 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

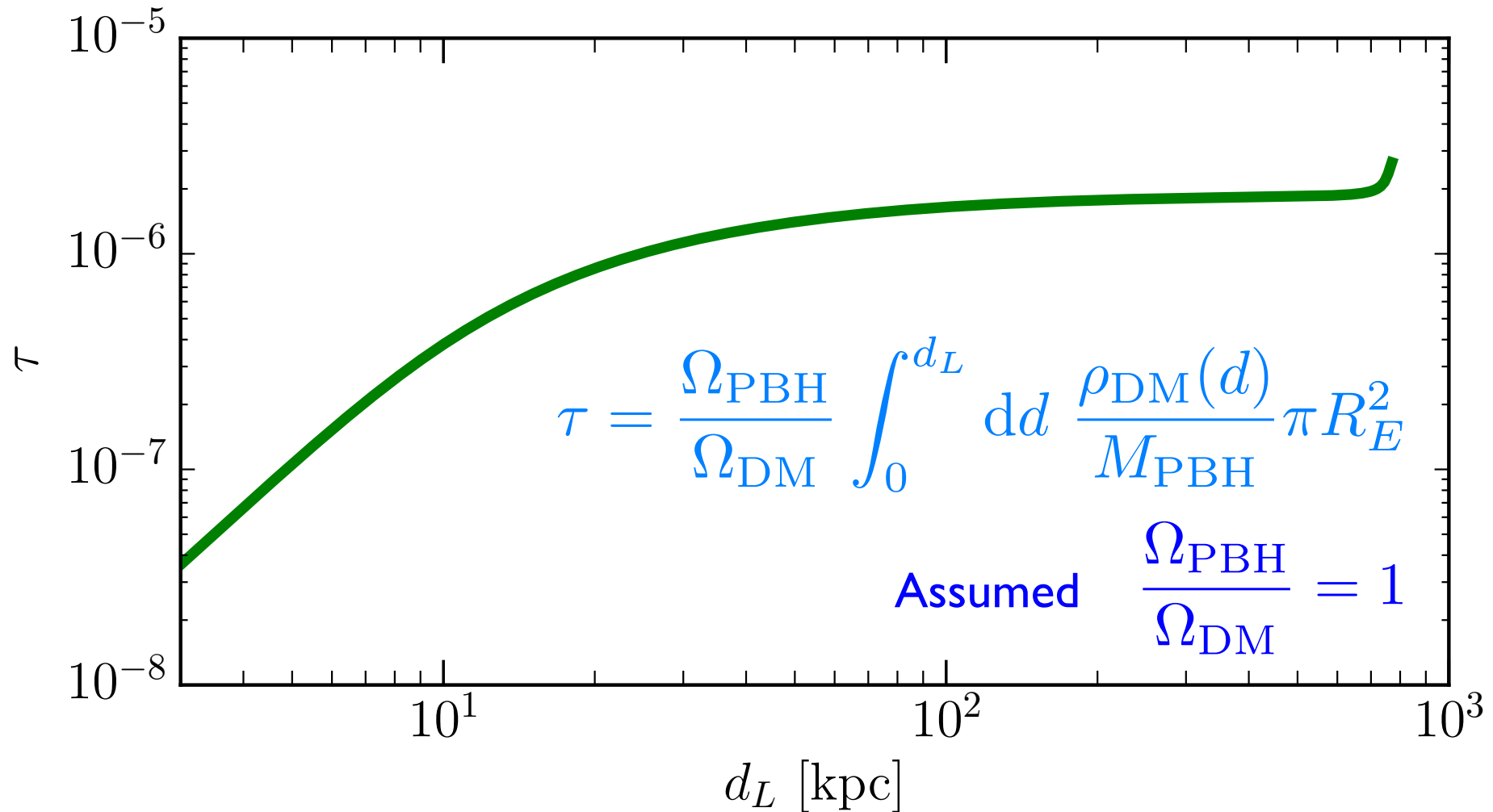
- Lensed image can't be resolved with optical resolution ( $\sim 10^{-8}$  arcsec)  $\Rightarrow$  only light curve is a signal
- So huge volume
- MW/M31 halo  $\sim 10^{12} M_{\text{sun}}$  (we assumed NFW models)
- PBH has a peculiar velocity of  $\sim 200 \text{ km/s}$



Paczynski 86

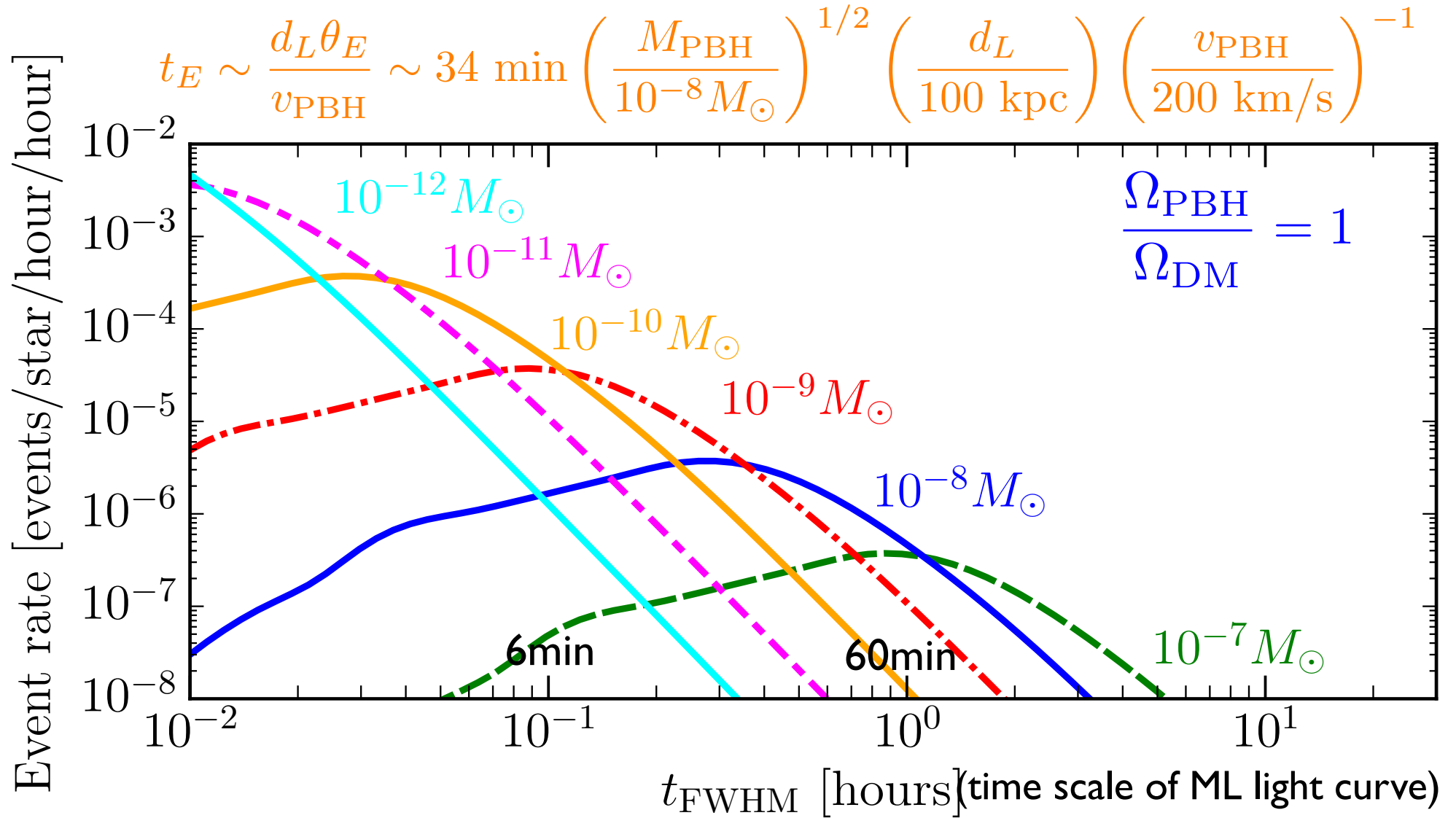
# PBH microlensing on M31 star

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



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





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

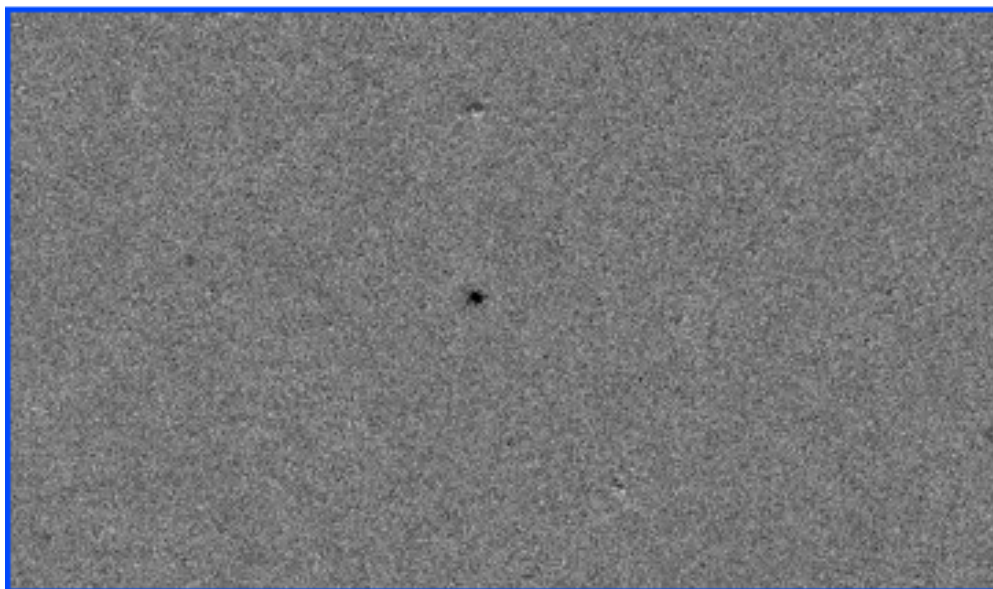
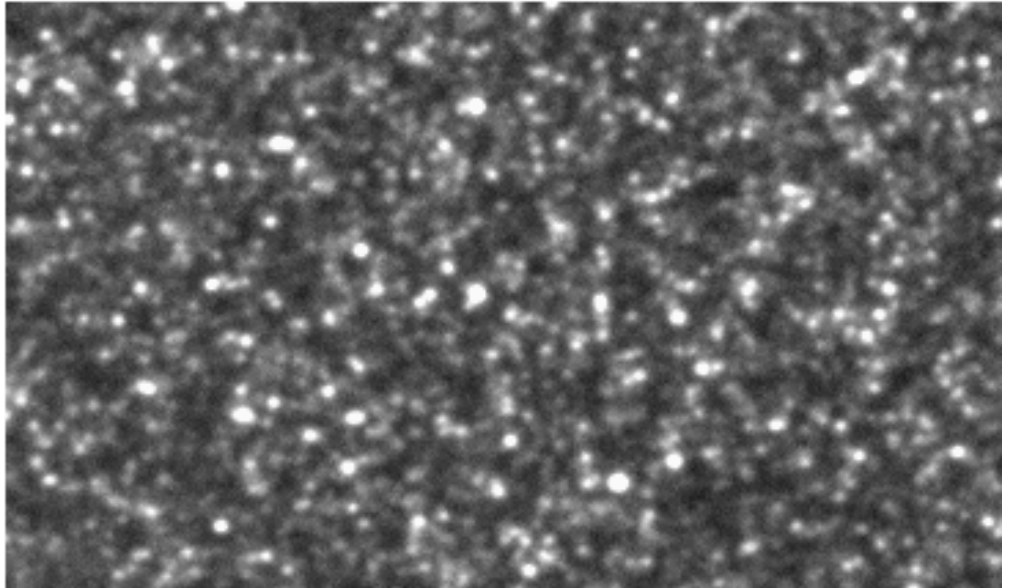
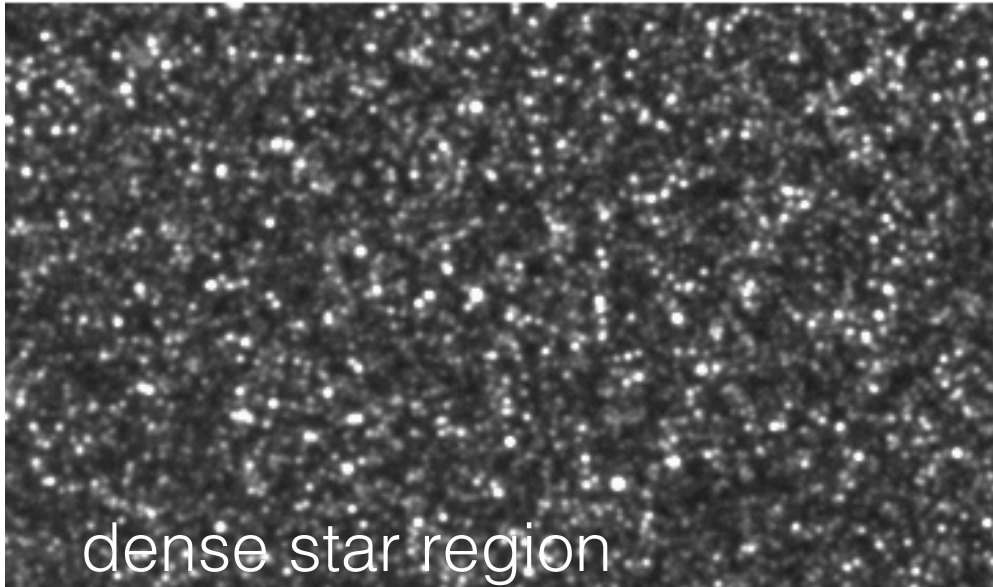
No dithering

one clear night (seeing ~0.5-0.6")

Also used g-data (from commissining)

# Challenges: Pixel lensing

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



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

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

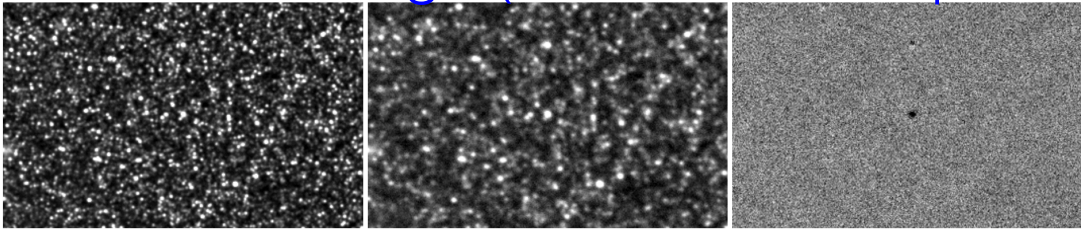
Lower: difference image

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



# Procedures: search for ML events

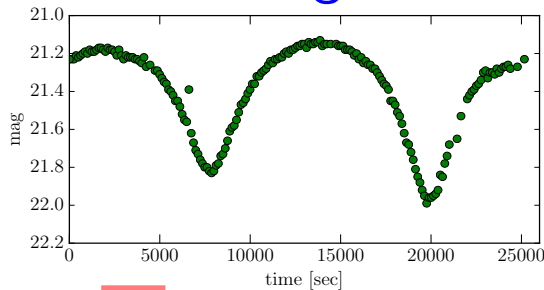
difference image (coadds of 3 exposures)



identify candidates in each diff. image

⇒ **15,571**

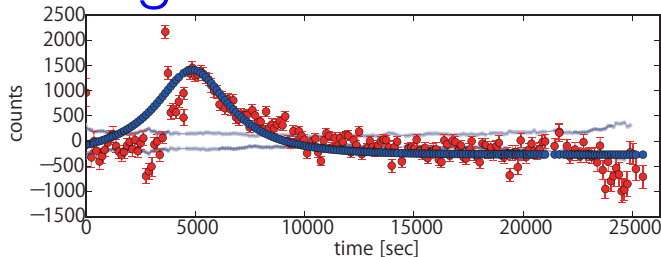
measure light curve (188 data points)



candidates with bump-like light curve

⇒ **11,703**

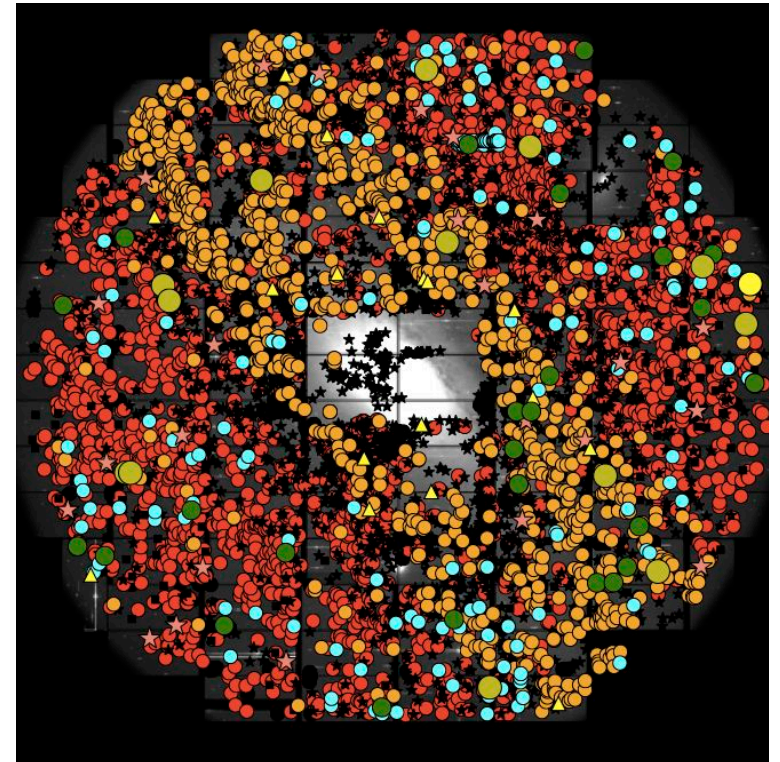
fitting of LC to the microlensing model

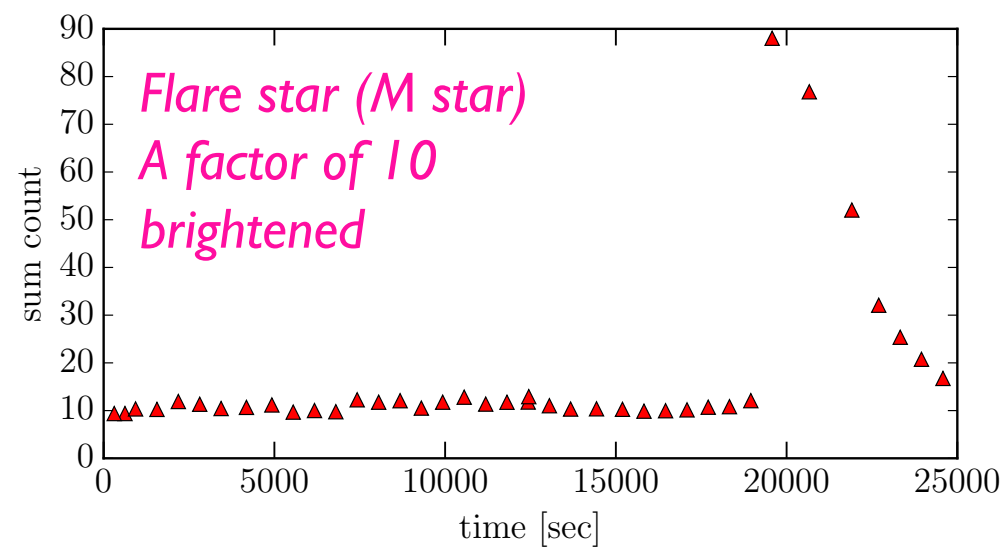
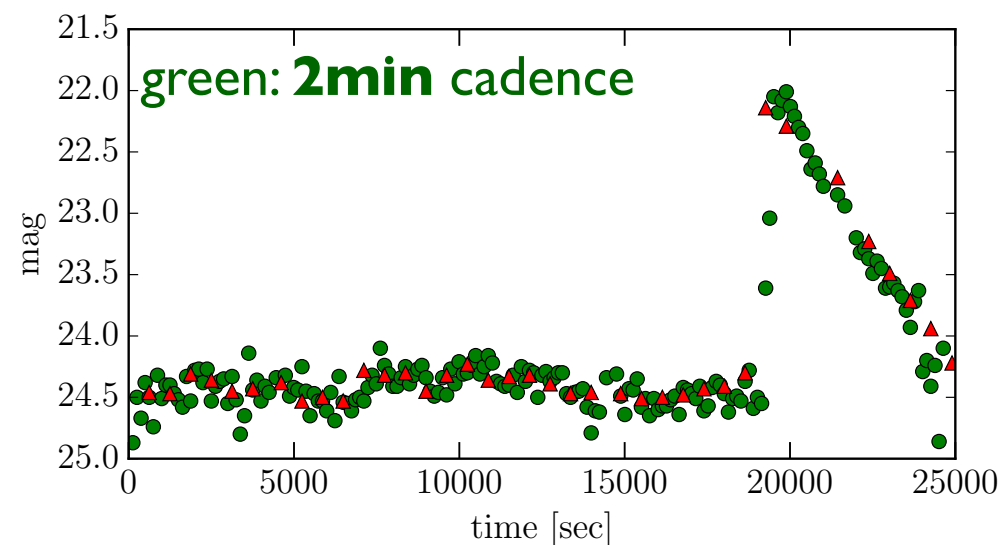
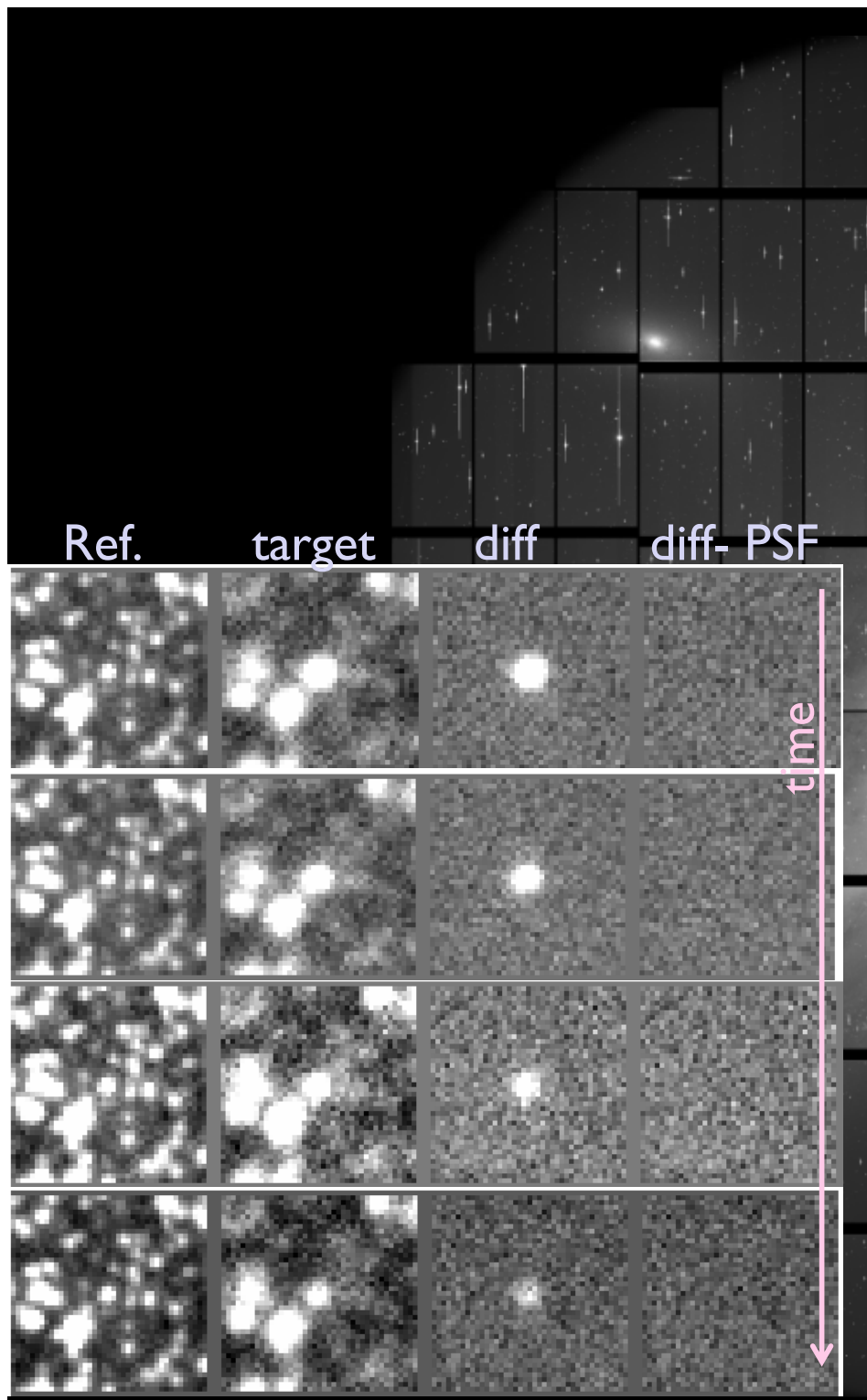


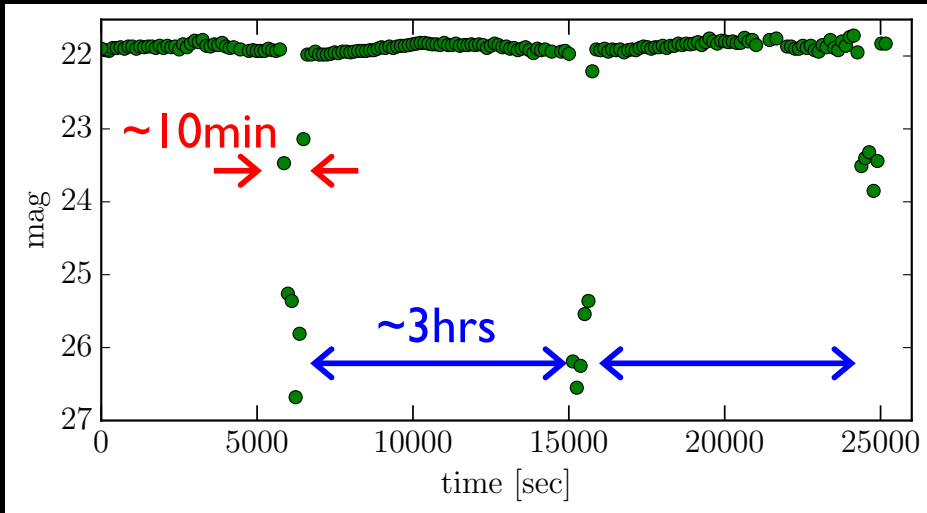
selection criteria

⇒ **66**

visual inspection of individual candidates...

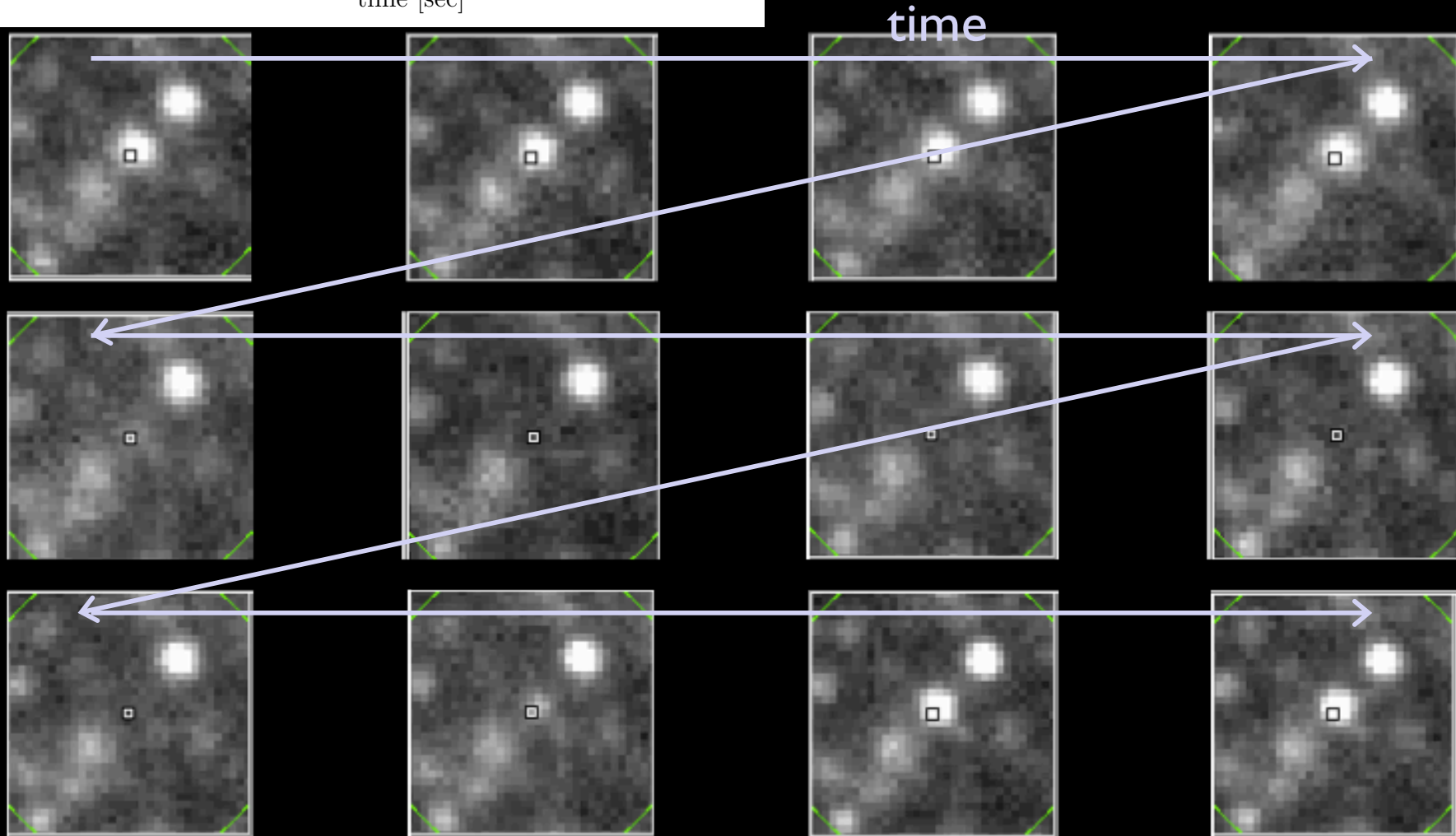






An entire star disappears for  
~10min, with a 3hrs interval

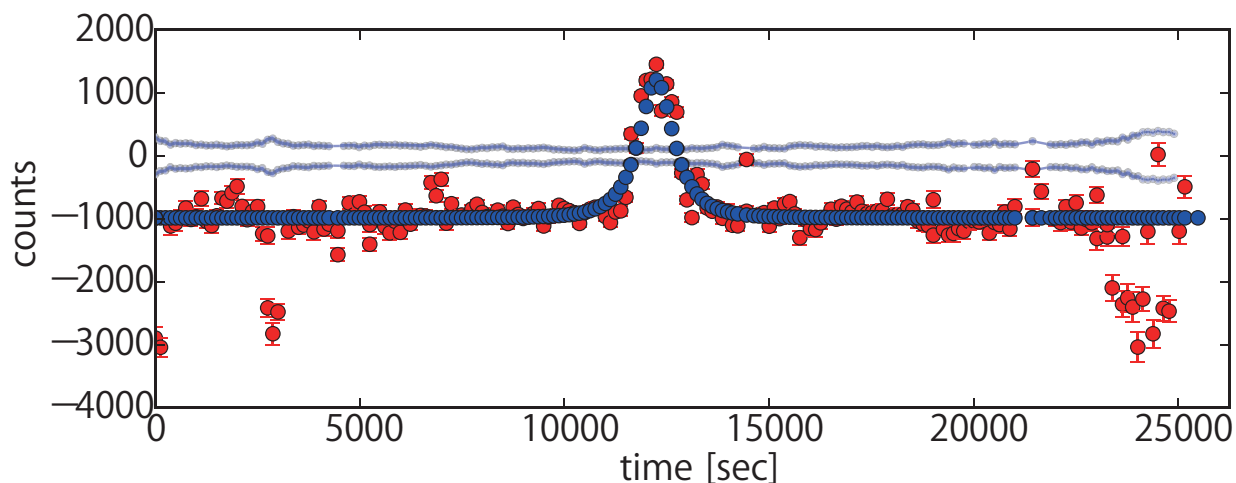
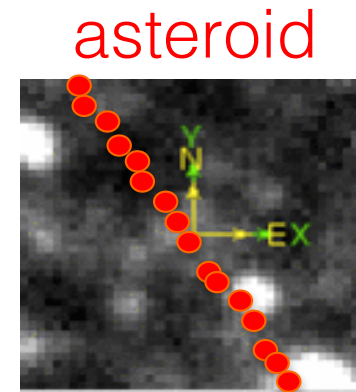
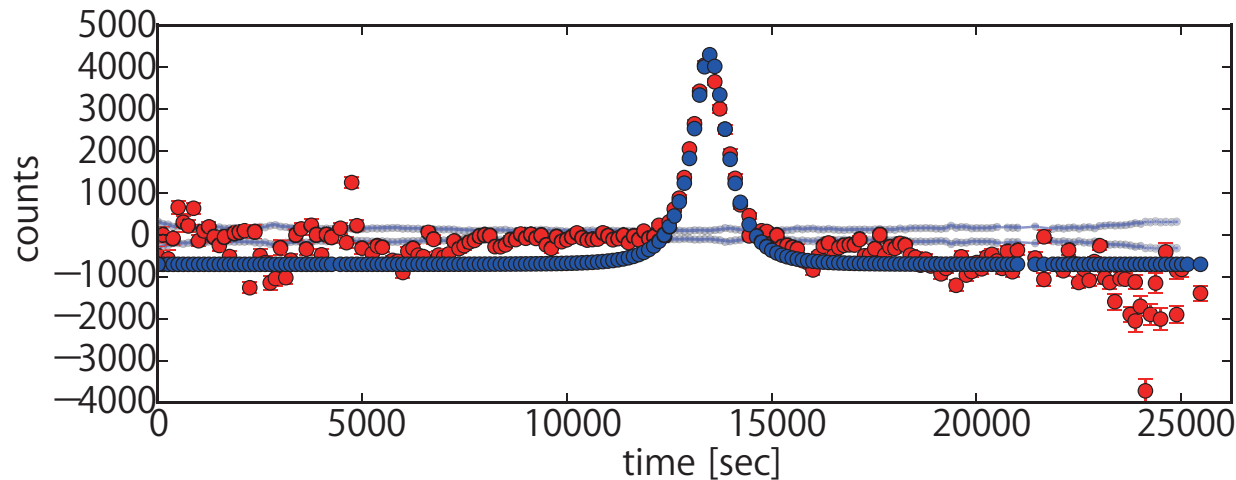
*WD – brown dwarf binary*



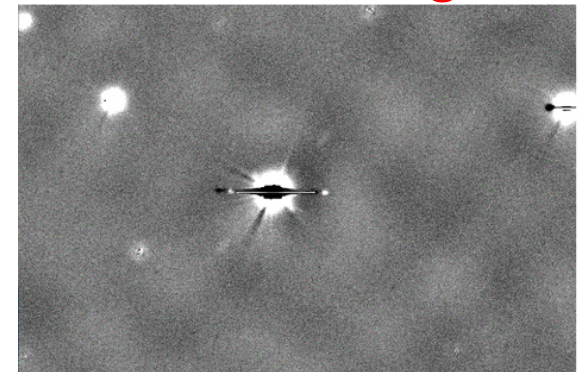


# Visual inspection stage...

Visual inspection of 66 candidates to identify junks...

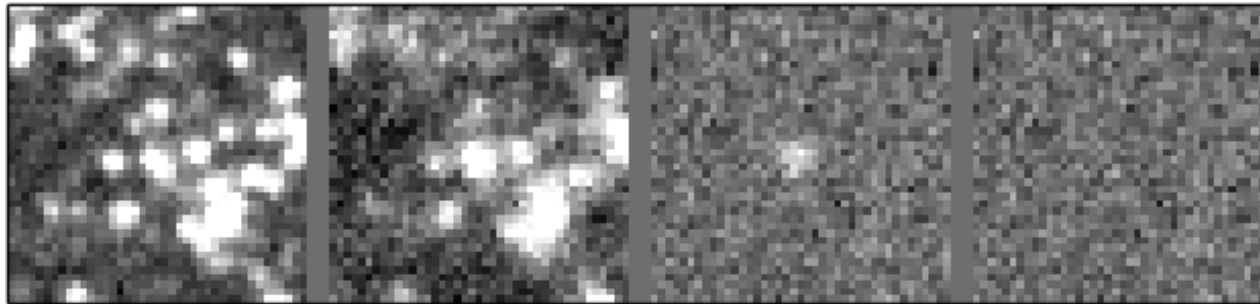
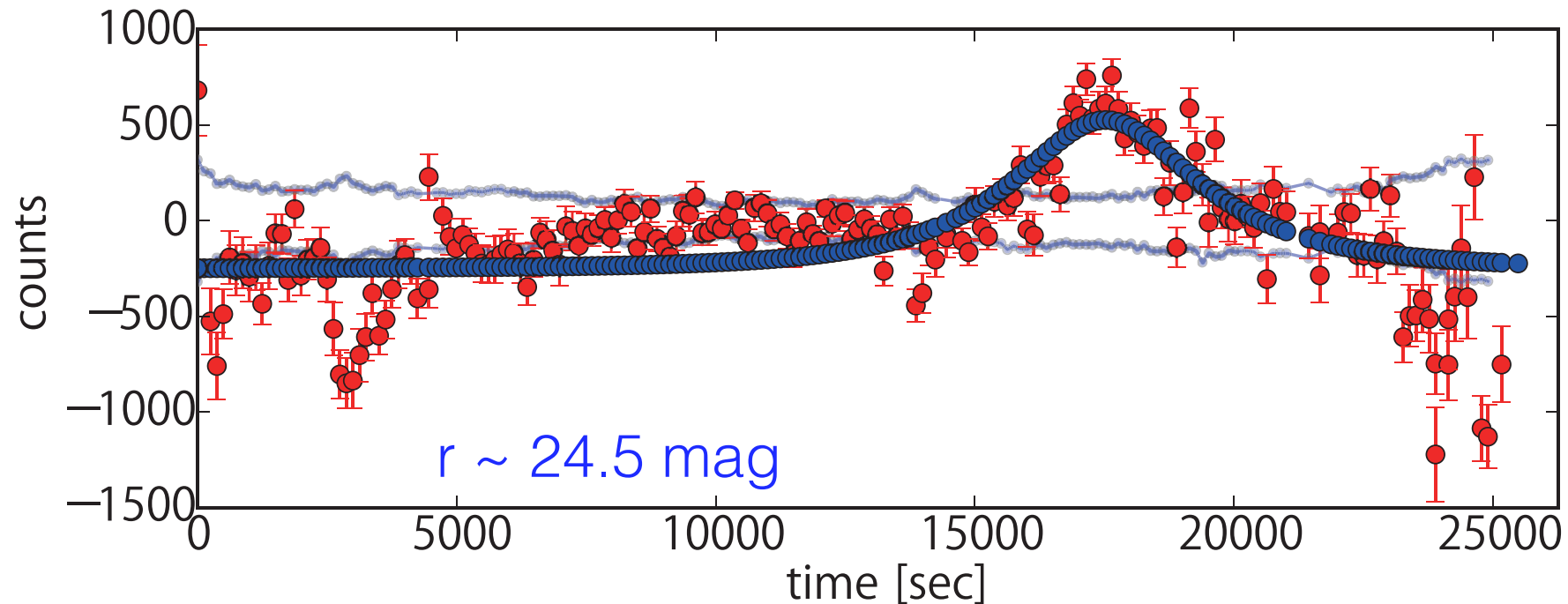


spike around a bright star



**66  $\Rightarrow$  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)

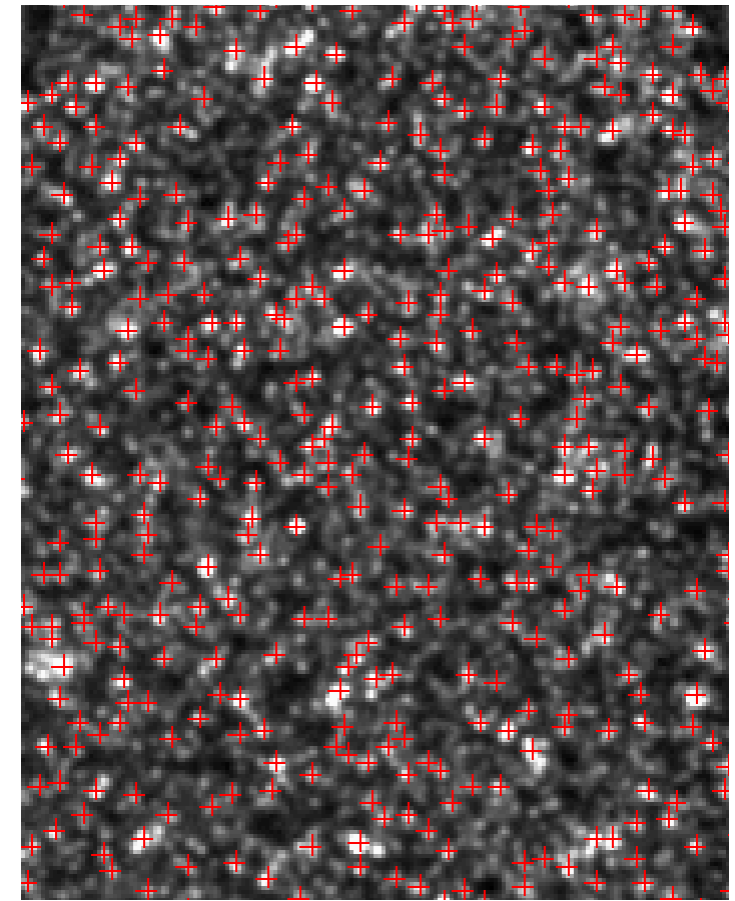
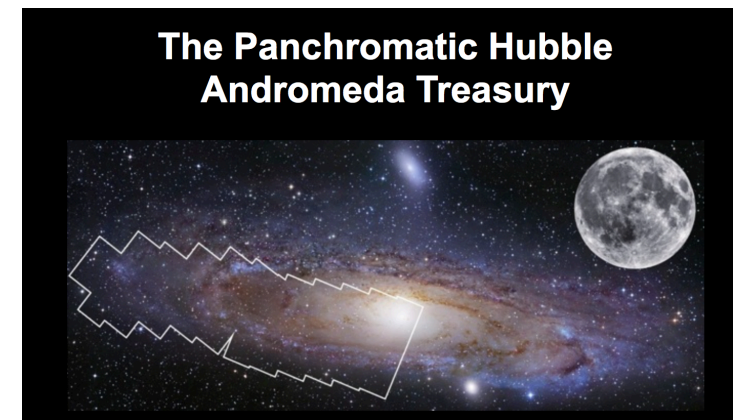
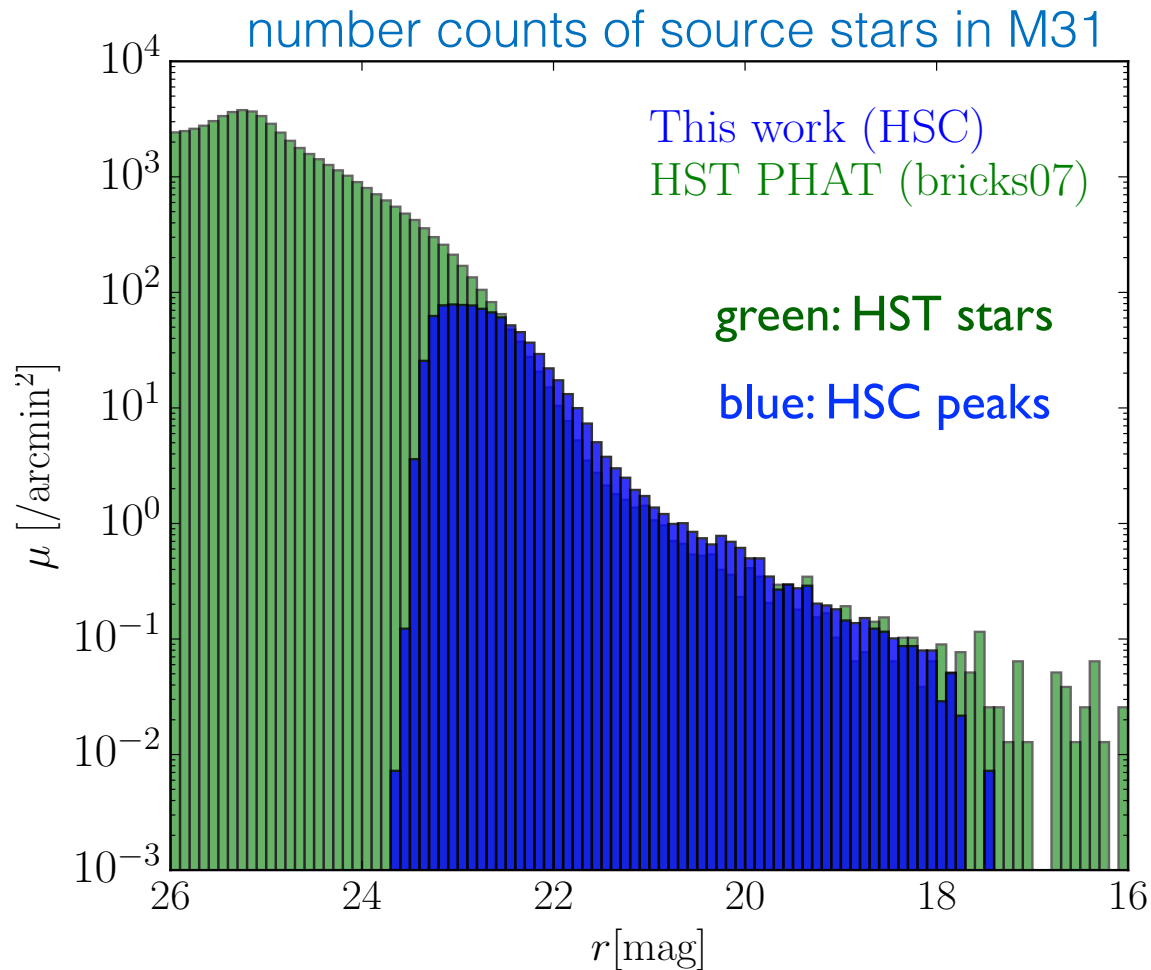
number of source  
stars in the  
magnitude range  
[m, m+dm] (see  
later)

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



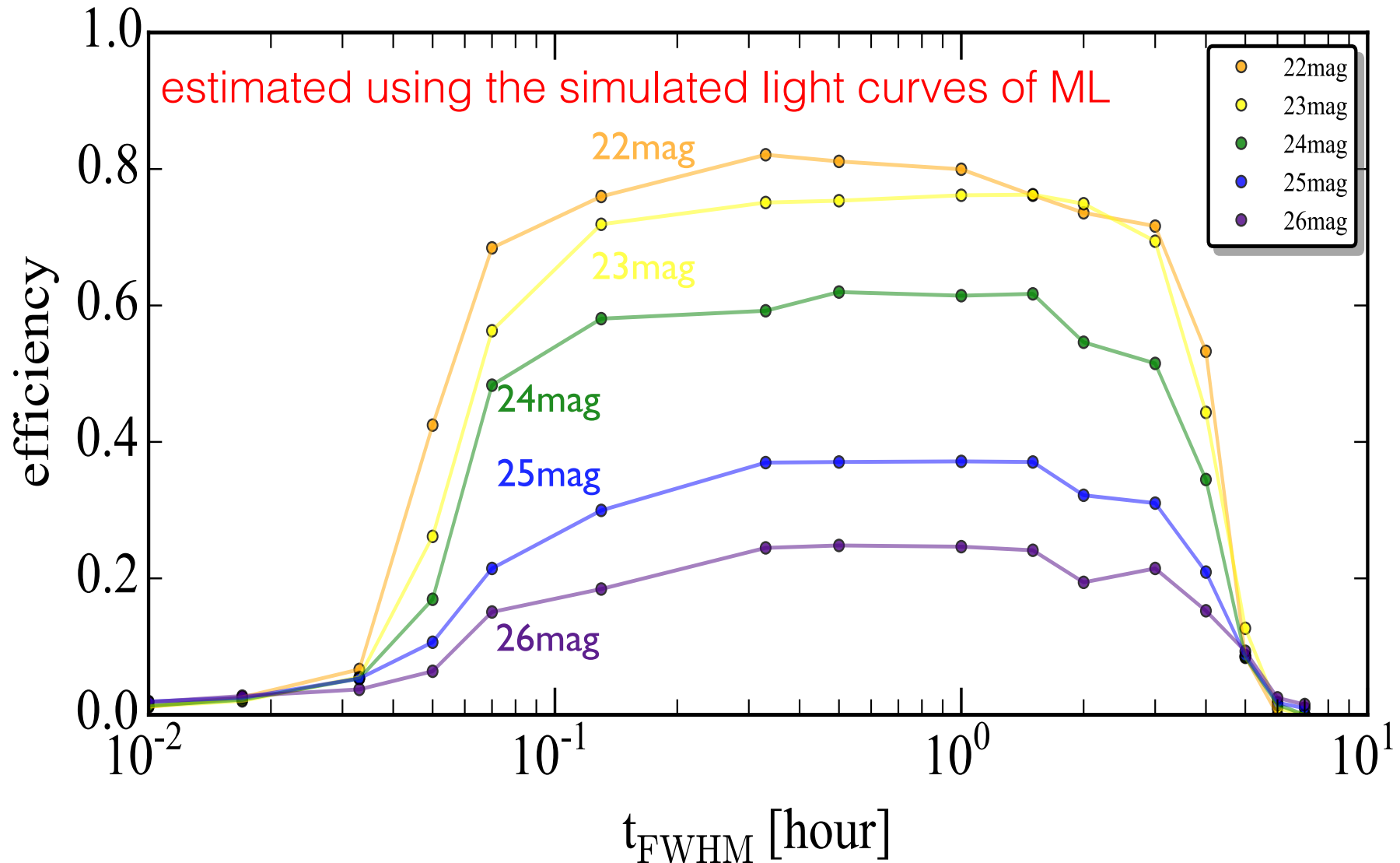
$6.4 \times 10^6$  HSC peaks (conservative)

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

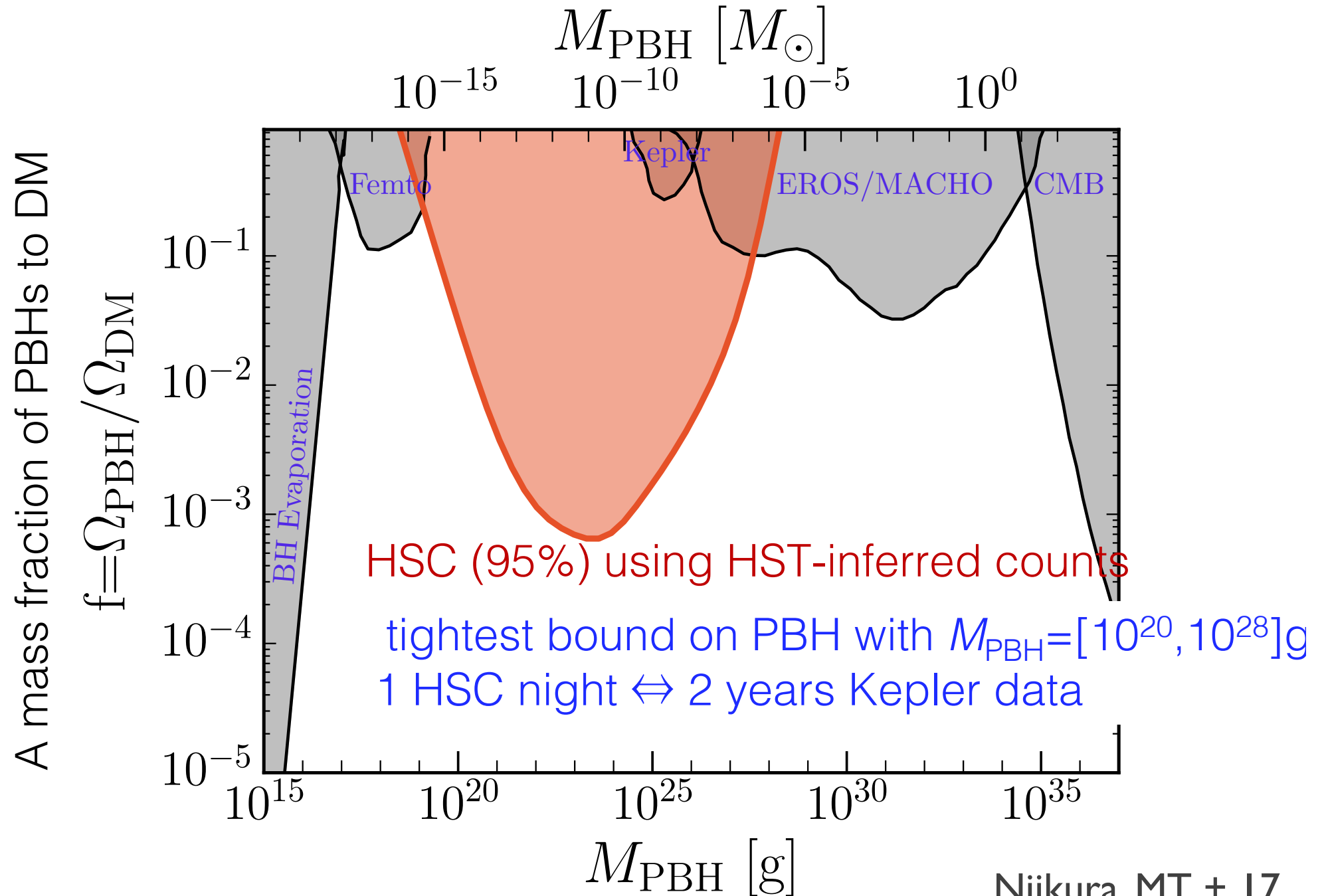


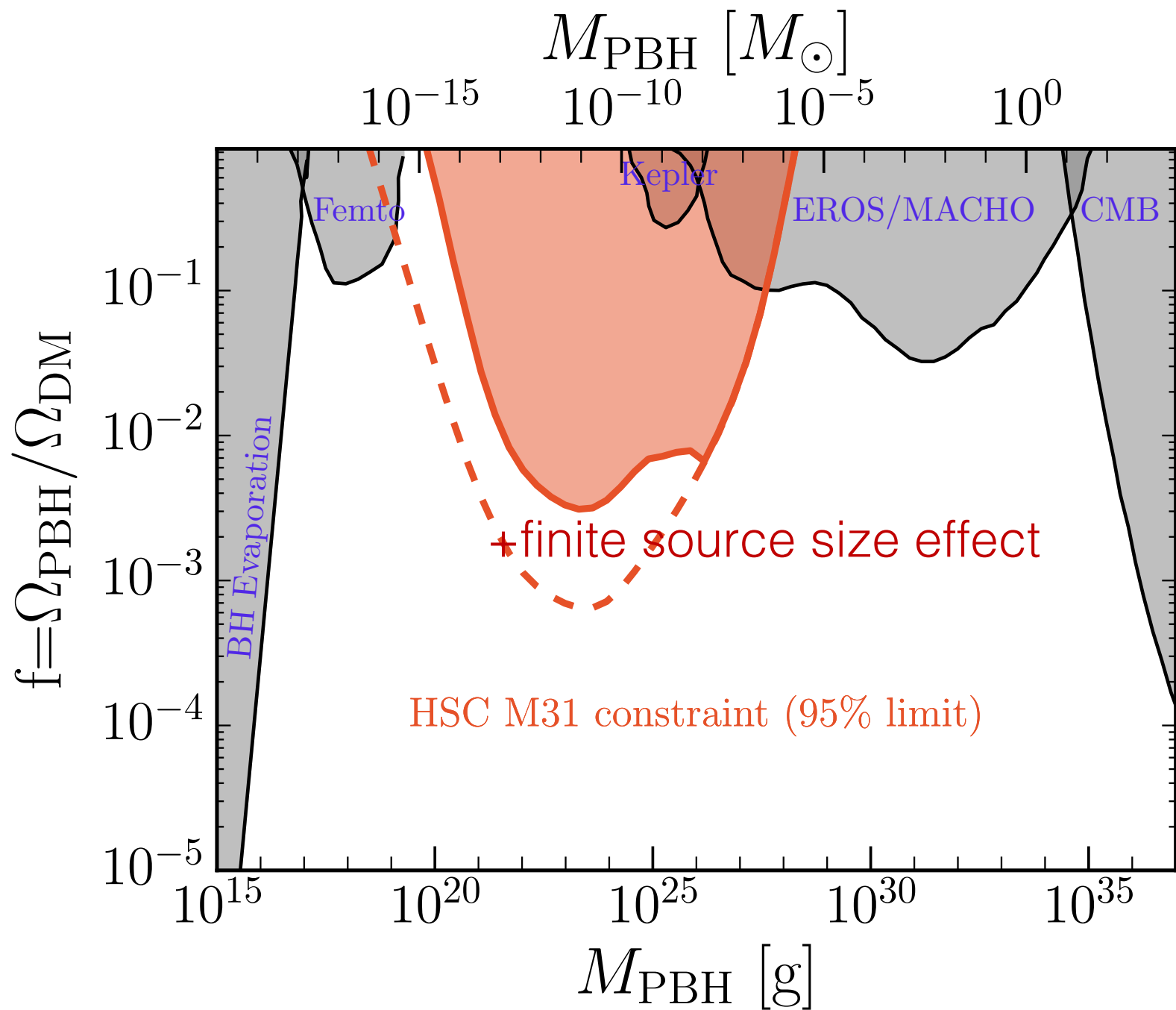
# Detection efficiency

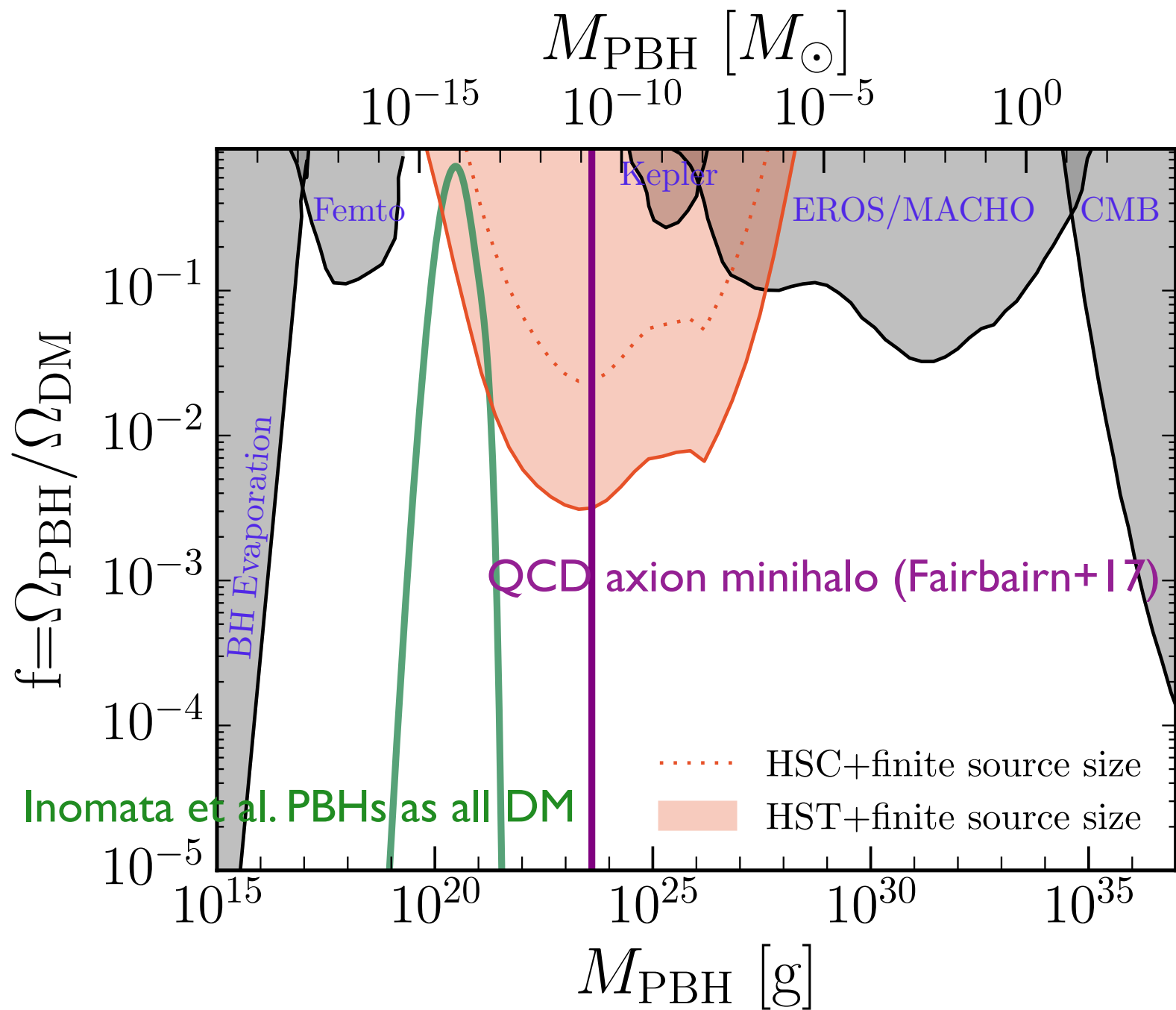
$$N_{\text{exp}} = \Delta t_{\text{obs}} \int dm_r \frac{dN_s}{dm_r} \int dt_{\text{FWHM}} \frac{d\Gamma}{dt_{\text{FWHM}}} \epsilon(t_{\text{FWHM}}, m_r)$$



# Results: New bound on PBH abundance







# HSC is so powerful for microlensing search & M31 is so unique

(Page 1)



Subaru Telescope  
National Astronomical Observatory of Japan

|             |            |
|-------------|------------|
| Semester    | S17B       |
| Proposal ID | S17B0076N  |
| Received    | 03/07/2017 |

## Application Form for Telescope Time (Normal+Intensive Programs)

### 1. Title of Proposal

Constraining primordial black holes with HSC observation of M31 – Part II

### 2. Principal Investigator

Name: Takada Masahiro

Institute: Univ. of Tokyo

Mailing Address: 5-1-5 Kashiwa-no-Ha, Kashiwa, 277-8568, Japan

E-mail Address: masahiro.takada@ipmu.jp Phone: +81-4-7199-7709

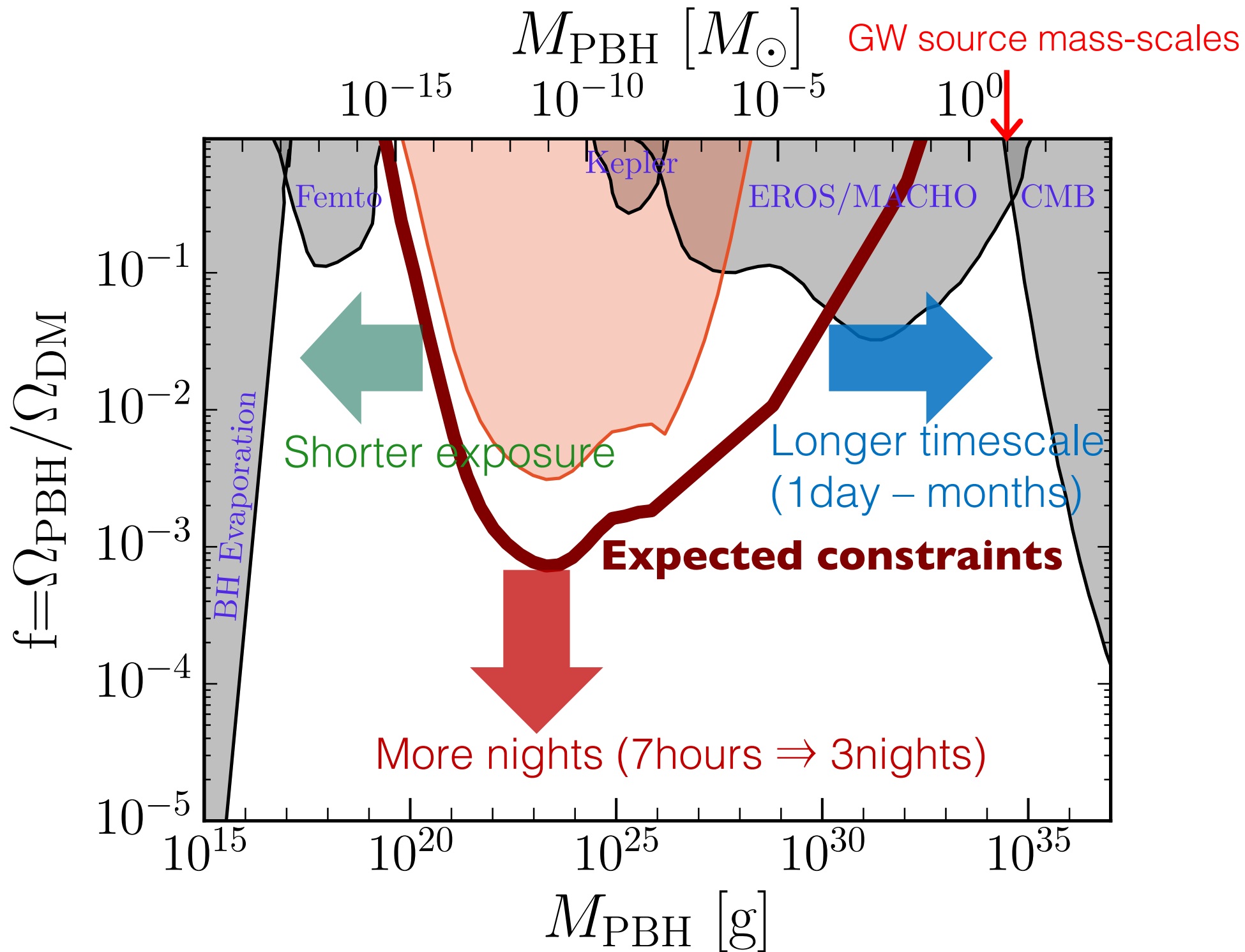
### 3. Scientific Category

- |                                               |                                                      |                                                                |                                                    |
|-----------------------------------------------|------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------|
| <input type="checkbox"/> Solar System         | <input type="checkbox"/> Normal Stars                | <input type="checkbox"/> Extrasolar Planets                    | <input type="checkbox"/> Star and Planet Formation |
| <input type="checkbox"/> Metal-Poor Stars     | <input type="checkbox"/> Compact Objects and SNe     | <input type="checkbox"/> Milky Way                             | <input type="checkbox"/> Local Group               |
| <input type="checkbox"/> ISM                  | <input type="checkbox"/> Nearby Galaxies             | <input type="checkbox"/> AGN and QSO Activity                  | <input type="checkbox"/> QSO Abs. Lines and IGM    |
| <input checked="" type="checkbox"/> Cosmology | <input type="checkbox"/> Gravitational Lenses        | <input type="checkbox"/> Proto-Clusters and Galaxy Environment |                                                    |
| <input type="checkbox"/> Clusters of Galaxies | <input type="checkbox"/> High-z Galaxies(LAEs, LBGs) | <input type="checkbox"/> High-z Galaxies(others)               | <input type="checkbox"/> Miscellaneous             |

### 4. Abstract (*approximately 200 words*)

We carried an unprecedented dense-cadence (2 min sampling)  $r$ -band observation of M31 with HSC to search for microlensing (ML) events of stars in M31 due to primordial black holes (PBHs) in the Milky Way (MW) halo, which are viable dark matter (DM) candidates (Niikura, Takada et al. 2017). We found one possible candidate of PBH ML that





# Summary

- The main project of B03 is PFS, and the project is underway (see Tamura san's talk)
- Preparation study of cosmology with spectroscopic survey (HSC+BOSS, HSC+PFS)
- Explore interdisciplinary field: a good example is primordial black hole (inflation, DM, GW, ...)
- 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, ...)