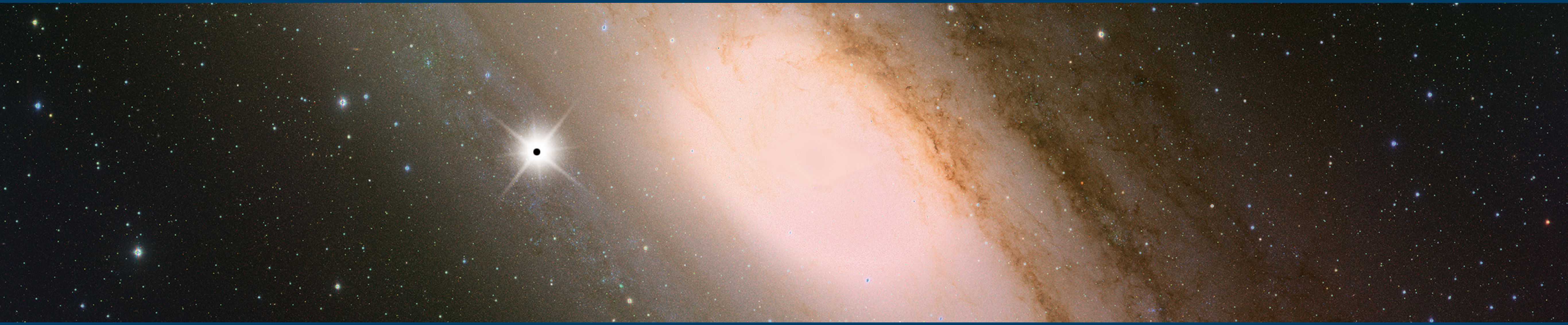
Exploring primordial black hole with microlensing observation of Andromeda galaxy



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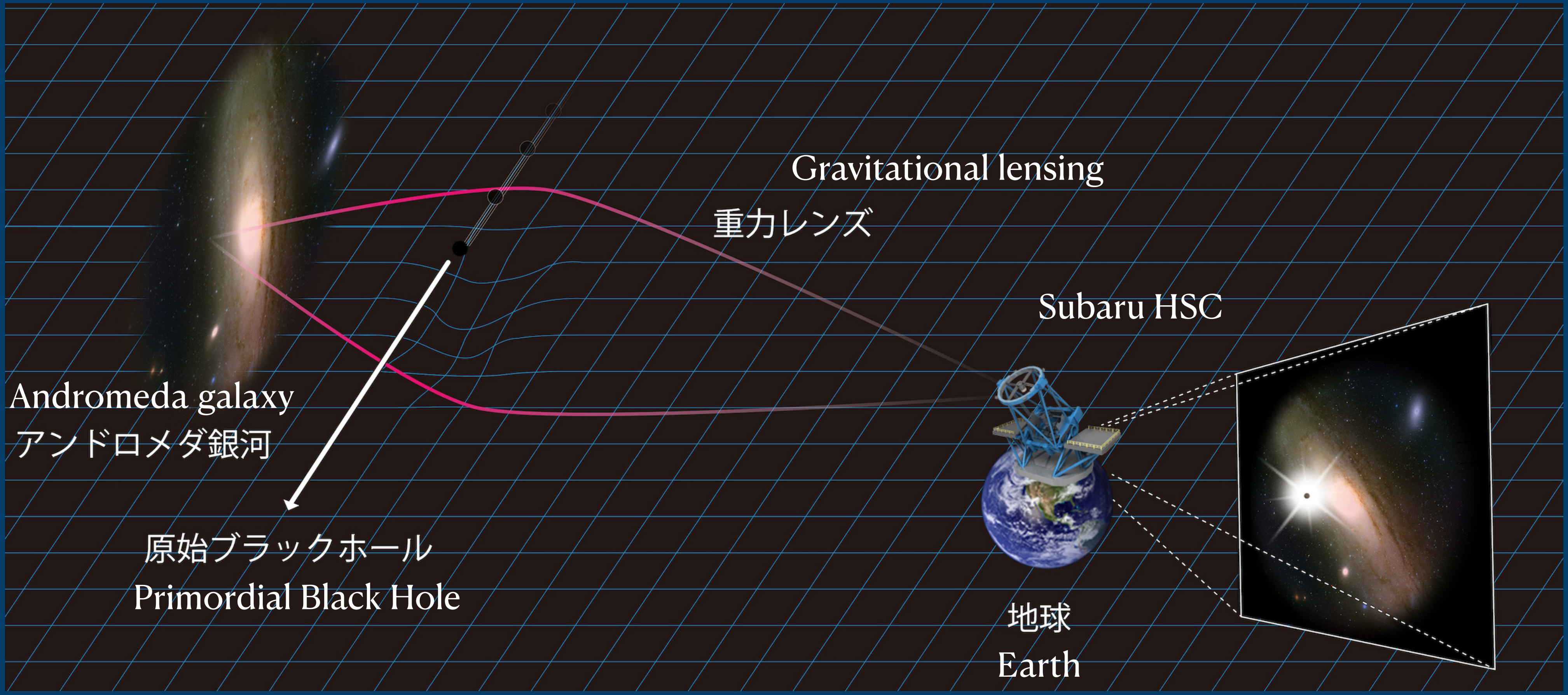
Microlensing(ML)

- Microlensing(ML) is a phenomenon of gravitational lens effect



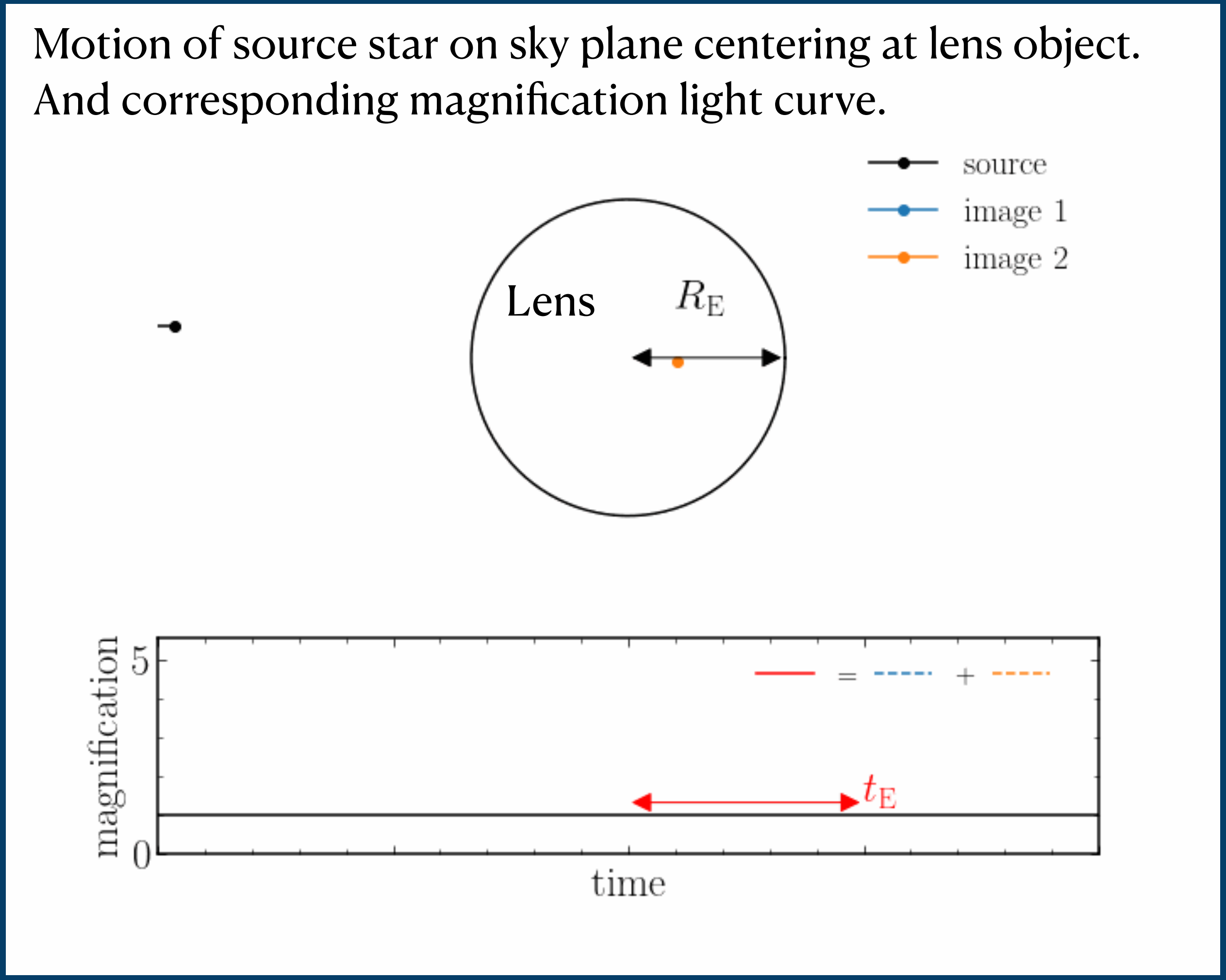
Credit: IPMU

- Microlensing can be used to search faint/**invisible** object.
- Massive compact halo objects (MACHO), e.g. **PBH**.
- **Subaru HSC** enables to obtain clear image, and simultaneous observations more than 10^9 **stars** (FoV matches size of Andromeda (M31) in the sky).

Time scale of ML and eventrate

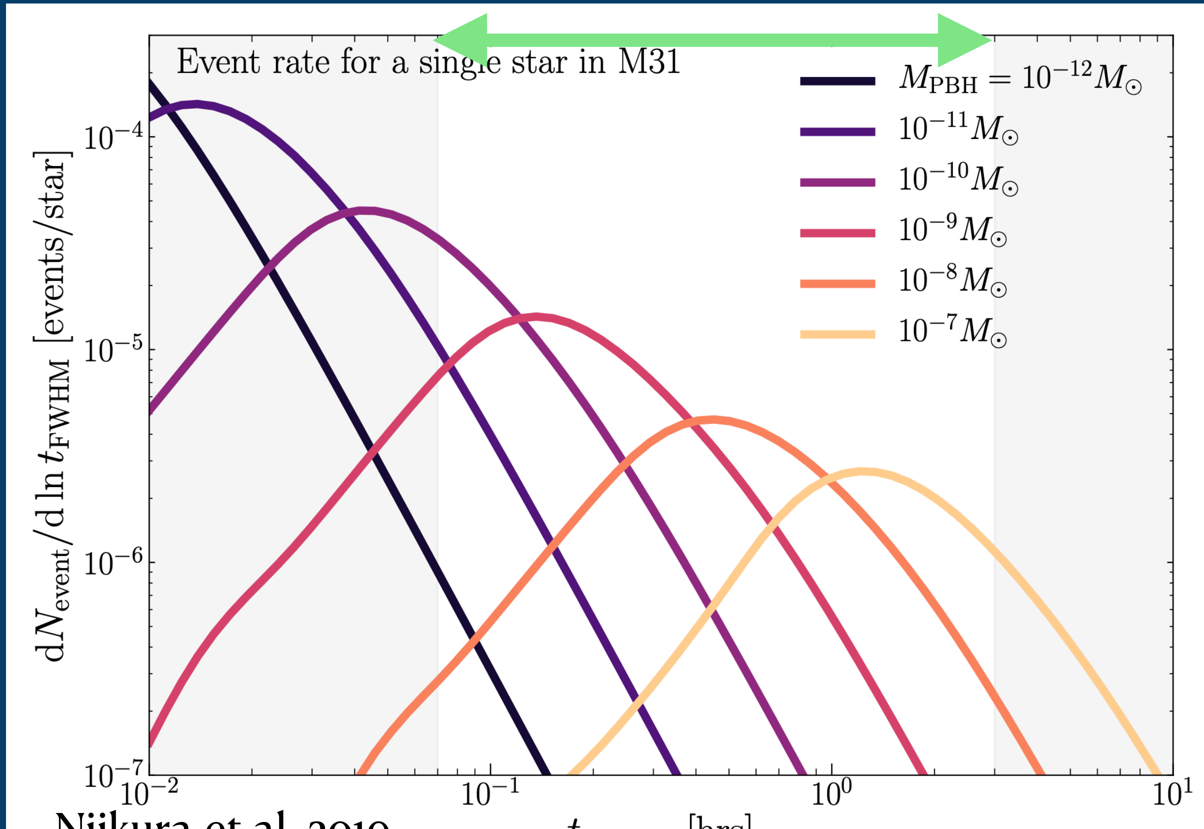
- Einstein radius/time

$$t_E = R_E/v \sim 1\text{hour}\left(\frac{M_{PBH}}{10^{-7}M_\odot}\right)^{1/2}\left(\frac{d_s}{770\text{kpc}}\right)^{1/2}\left(\frac{v}{100\text{km/sec}}\right)^{-1}\left(\frac{d_l/d_s[1-d_l/d_s]}{10/770[1-10/770]}\right)^{1/2}$$



You can get gif here.

HSC 1 night sensitivity

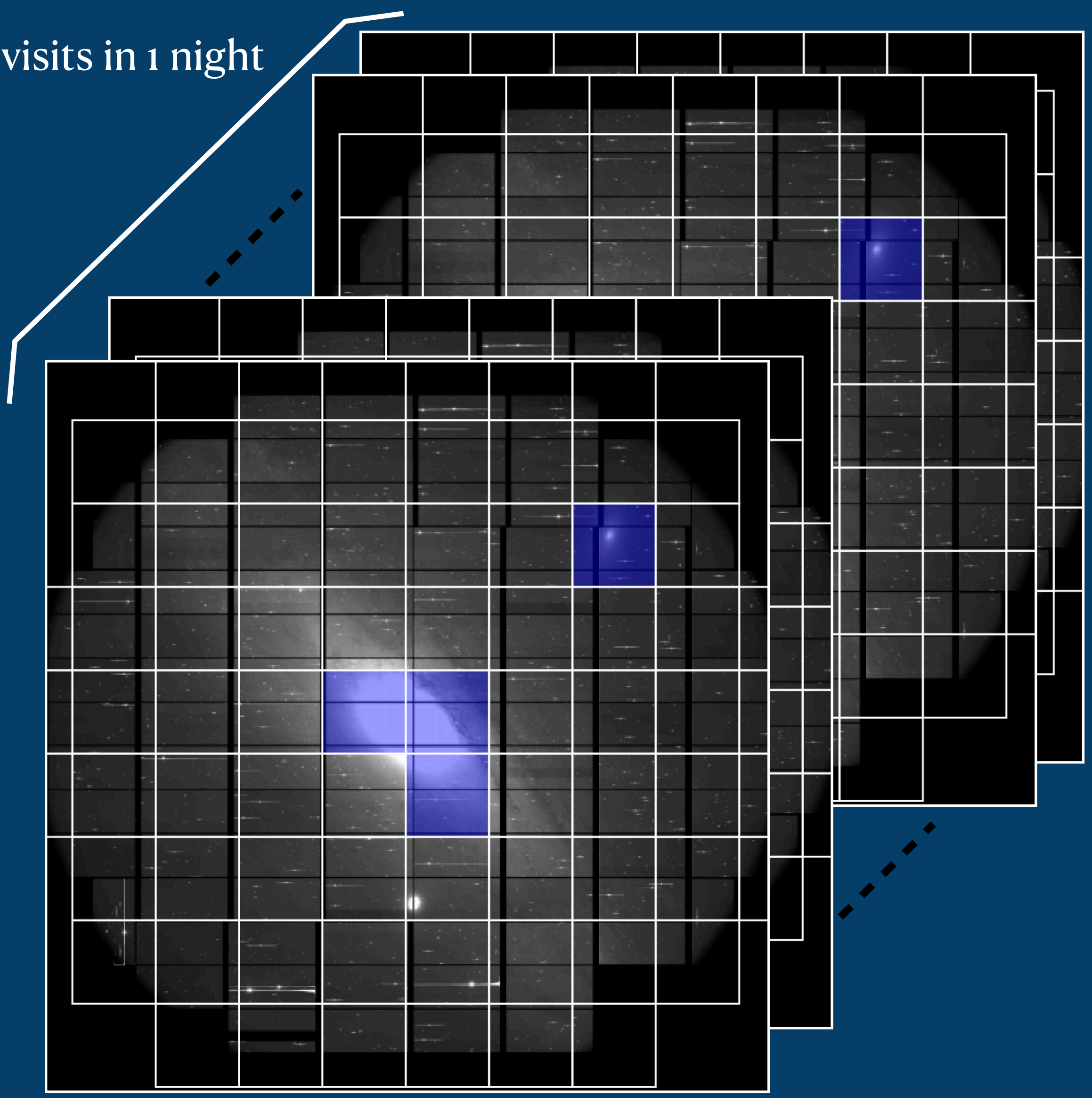


Niikura et al. 2019

ML detection with Image subtraction

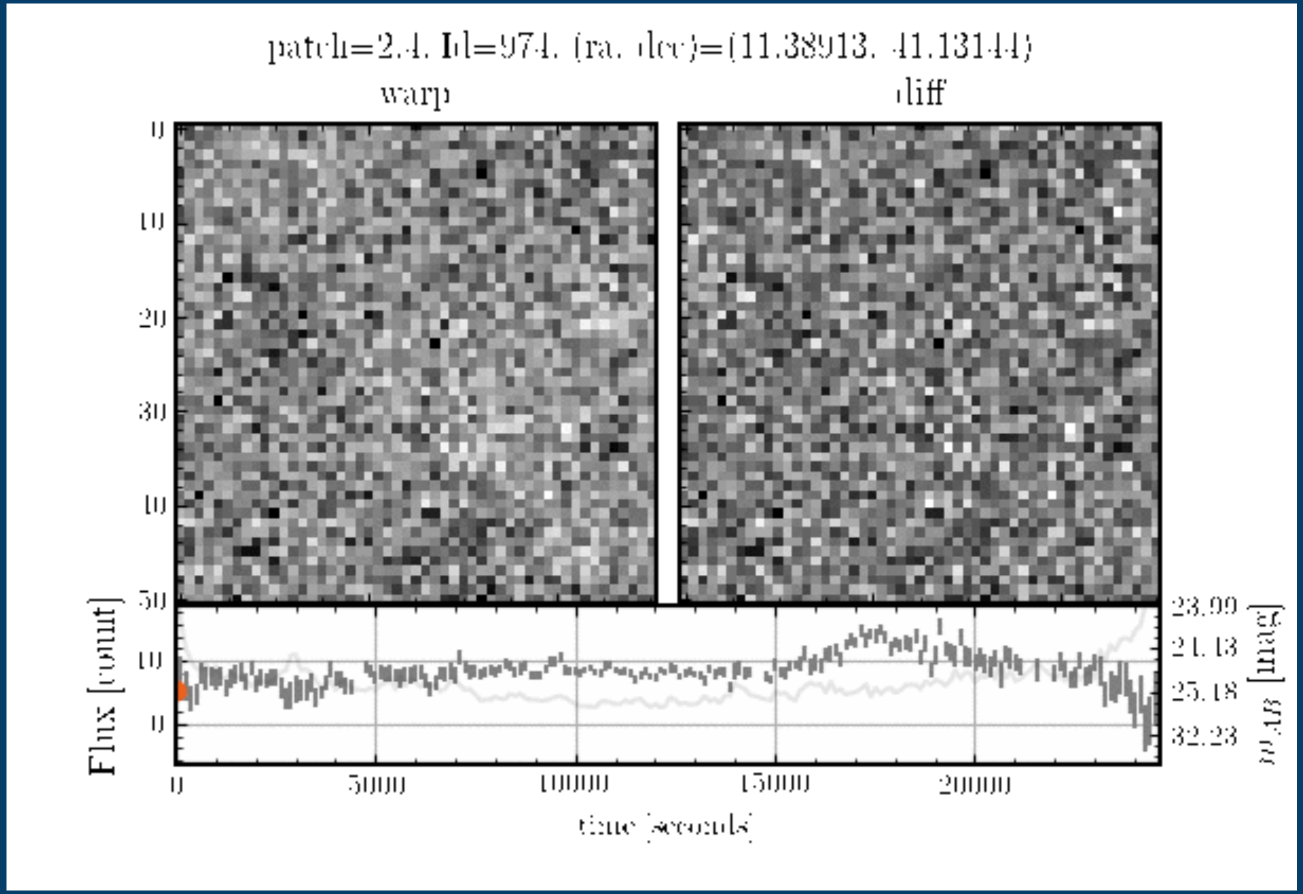
- Stars in M31 are blended in pixels: **pixel lensing** regime.
- We cannot monitor resolved individual stars.
  → We instead use **image subtraction** technique to detect microlensing events.

~180 visits in 1 night

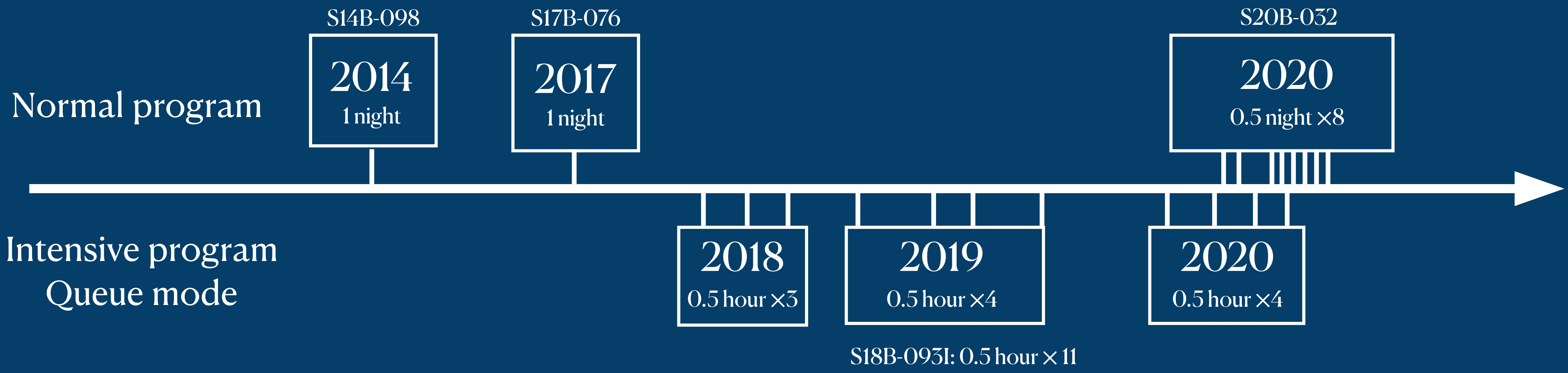


Each have 90sec exposure, and 30sec readout

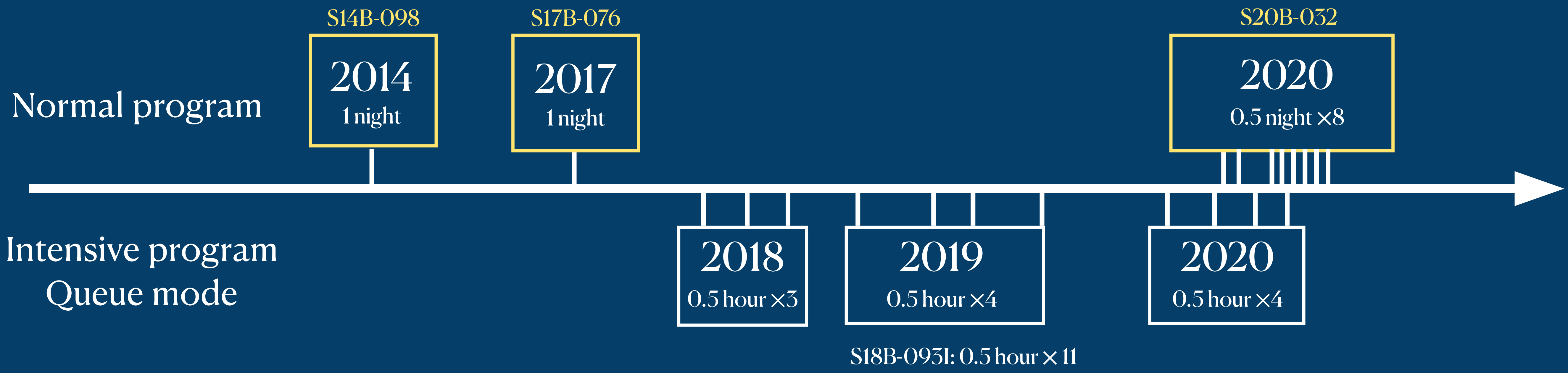
- We make a reference image by coadding 10 best seeing images.
- We subtract the reference image from image at each visit.



Observations



Observations



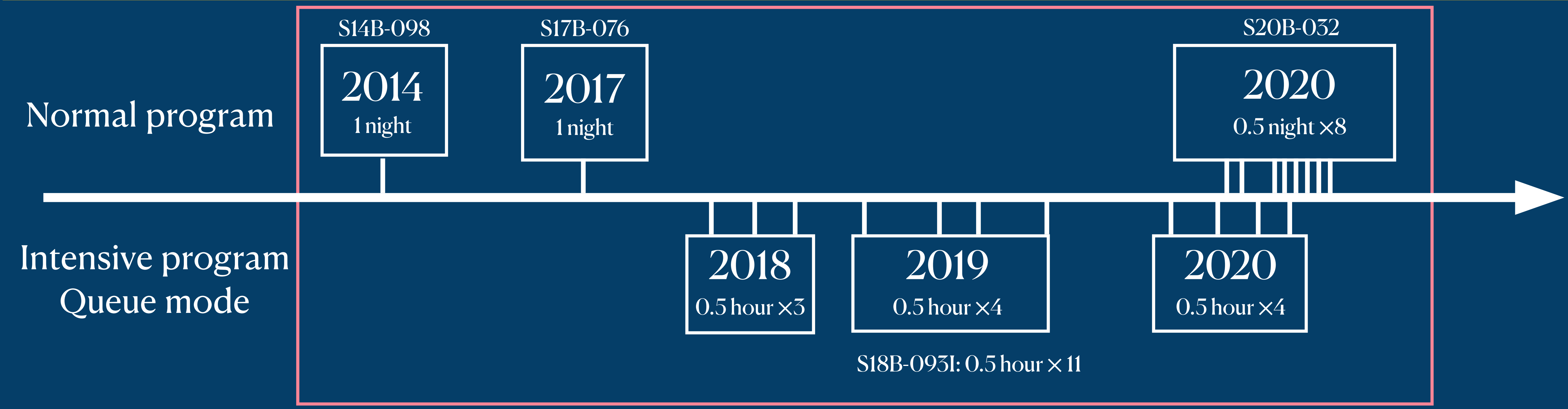
- Time scale of each obs. ~ 1night

  → Each observation can probe $M_{\rm PBH} \sim 10^{-7} M_{\odot}$ PBHs.

  (this mass window is hot in theory side in these days. See Sugiyama et al. 2020, Kusenko et al. 2020)

Recall: $t_E \sim 1\text{hour} \left(\frac{M_{\rm PBH}}{10^{-7} M_{\odot}} \right)^{1/2} \left(\frac{d_s}{770\text{kpc}} \right)^{1/2} \left(\frac{v}{100\text{km/sec}} \right)^{-1} \left(\frac{d_l/d_s[1 - d_l/d_s]}{10/770[1 - 10/770]} \right)^{1/2}$

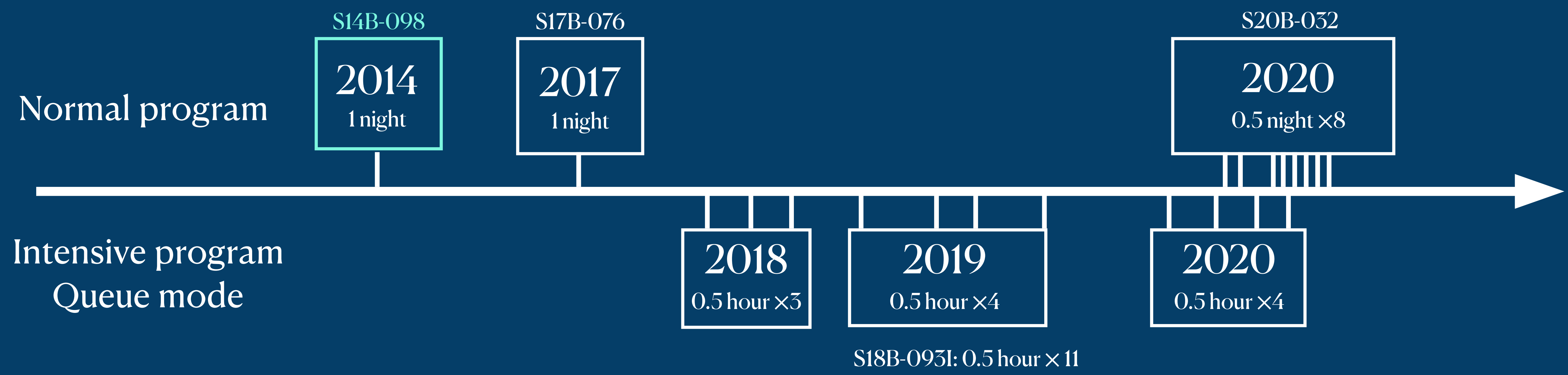
Observations



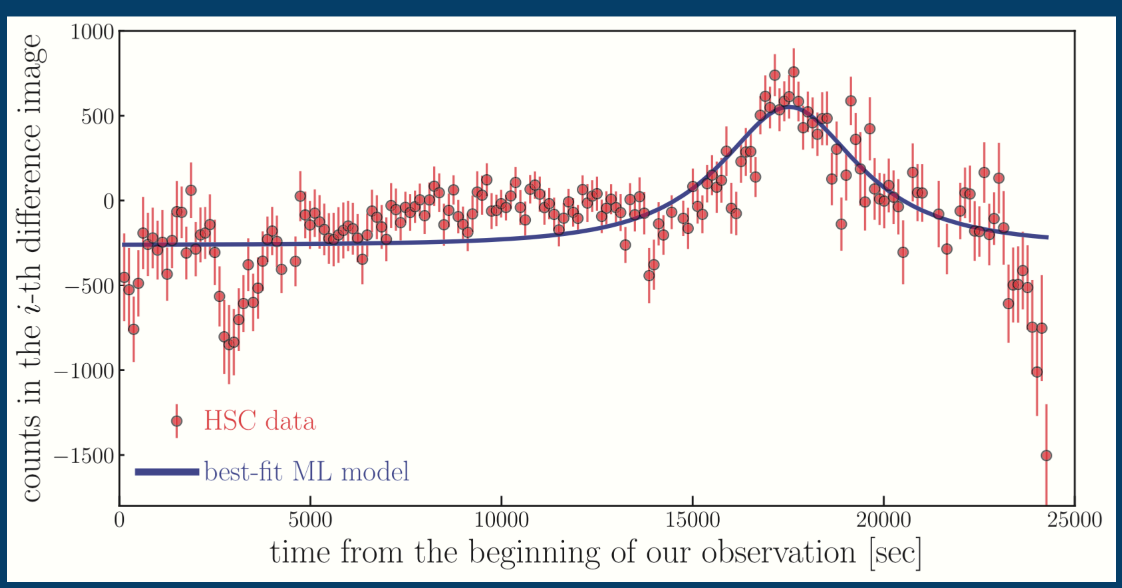
- Time scale of each obs. $\sim$ 1night
  → Each observation can probe $M_{\rm PBH} \sim 10^{-7} M_\odot$ PBHs.
  (this mass window is hot in theory side in these days. See Sugiyama et al. 2020, Kusenko et al. 2020)
- Time scale of whole observations ~ 6 years.
  → whole observations are designed to probe $M_{\rm PBH} \sim 10 M_\odot$ PBHs
  (useful to test the scenario that LIGO GW is due to $10M_\odot$ PBH. See Sasaki et al. 2016.)

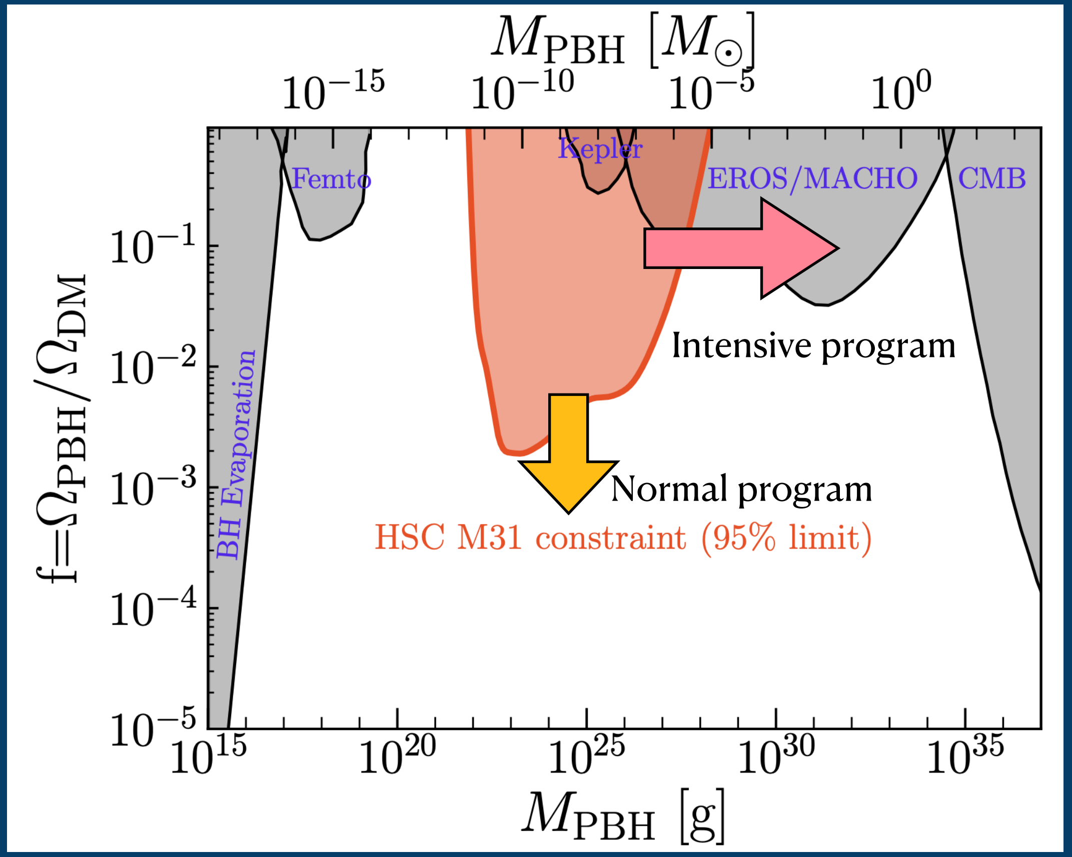
Recall: $t_{\rm E} \sim 1{\rm hour} \left(\frac{M_{\rm PBH}}{10^{-7}M_\odot}\right)^{1/2} \left(\frac{d_{\rm s}}{770{\rm kpc}}\right)^{1/2} \left(\frac{v}{100{\rm km/sec}}\right)^{-1} \left(\frac{d_{\rm l}/d_{\rm s}[1-d_{\rm l}/d_{\rm s}]}{10/770[1-10/770]}\right)^{1/2}$

Observations



- From 2014 data, Niikura et al.(2019) reported a single ML candidate event.
- This # of event is compared to theoretical prediction, $N_{\rm exp} = 10^3$
  → Upper limit, $f_{\rm PBH} < N_{\rm obs}/N_{\rm exp} \sim 10^{-3}$ @ $M_{\rm PBH} \sim 10^{-7} M_\odot$.

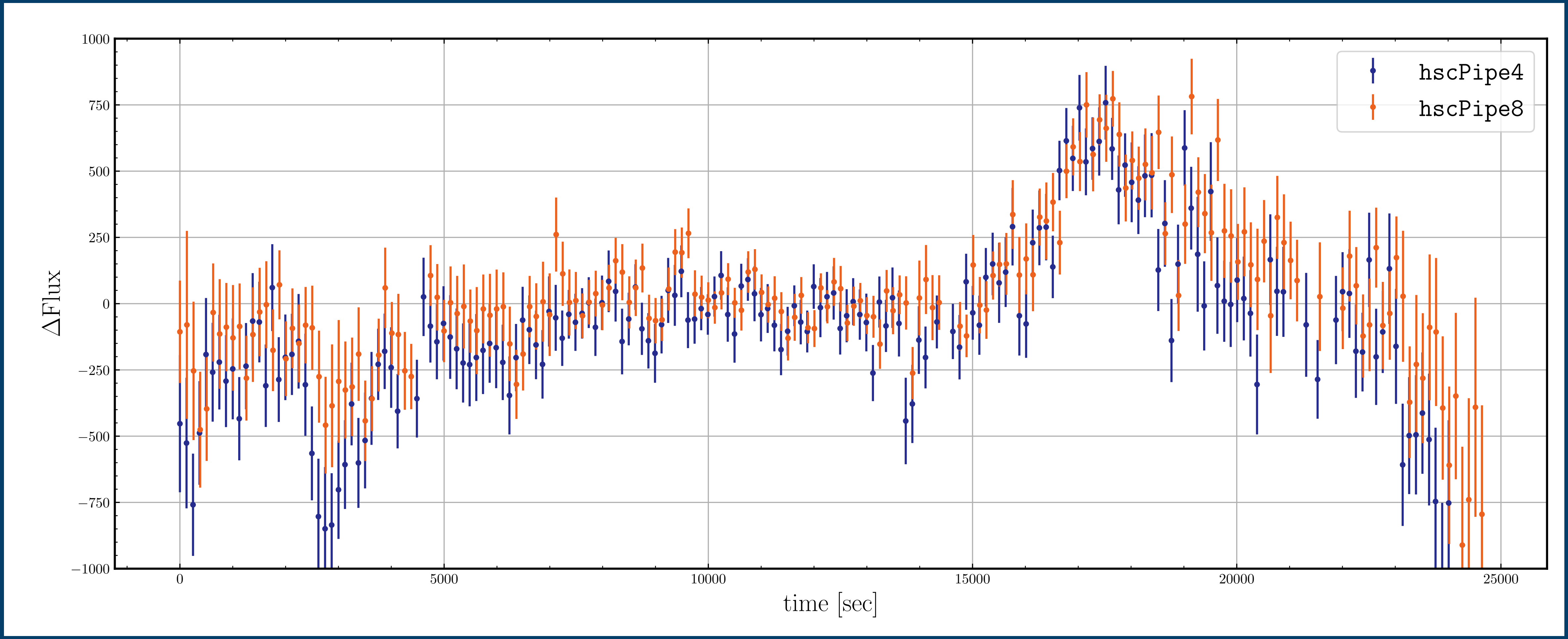




Niikura et al. (2019)

Update 1: `hscPipe8`

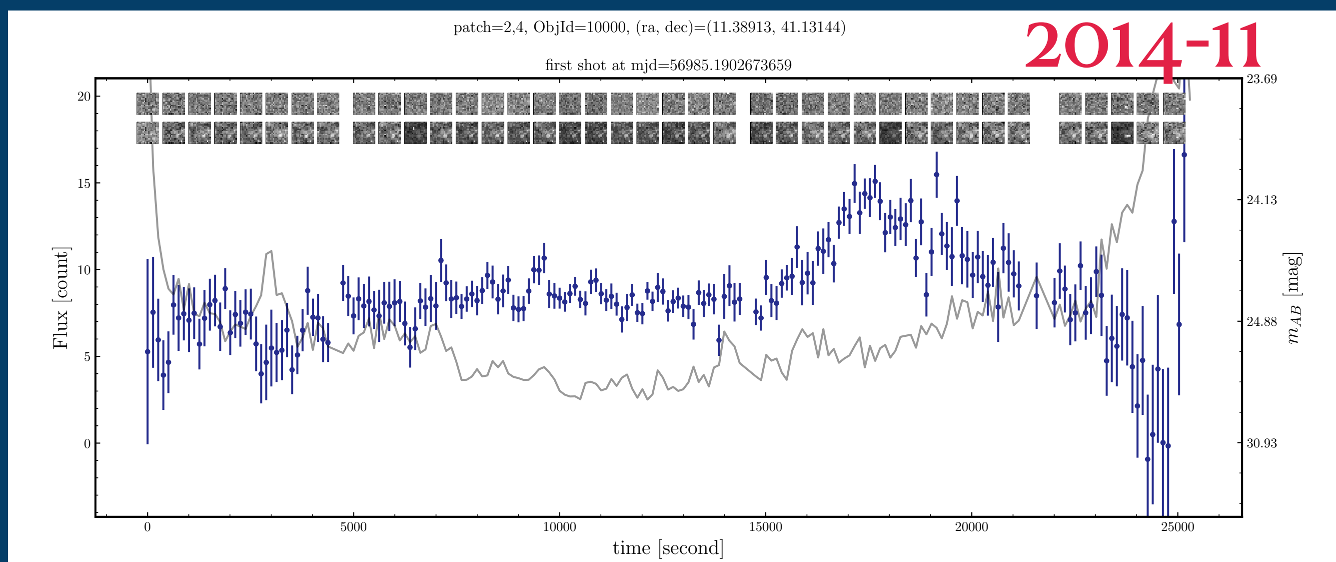
- We decided to use up-to-date pipeline, `hscPipe8`. (Previous study uses `hscPipe4`).
- **Image subtraction module** is also updated for `hscPipe8` (**Yasuda-san and Ohgami-san**).
- Validation: We reanalyzed 2014 data, and succeeded to reproduce the **reported ML candidate** with `hscPipe8`.
- Now ready to apply analysis to new data set.



Update 2: The 2014 candidate is really ML?

Quesion

Is this 2014 candidate really due to microlensing?

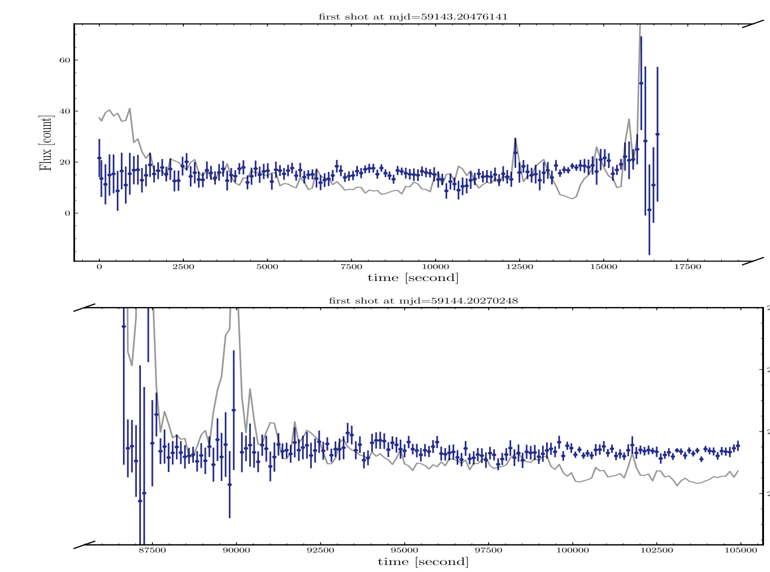


- If the candidate is variable star, similar variability should be found in the new data set.

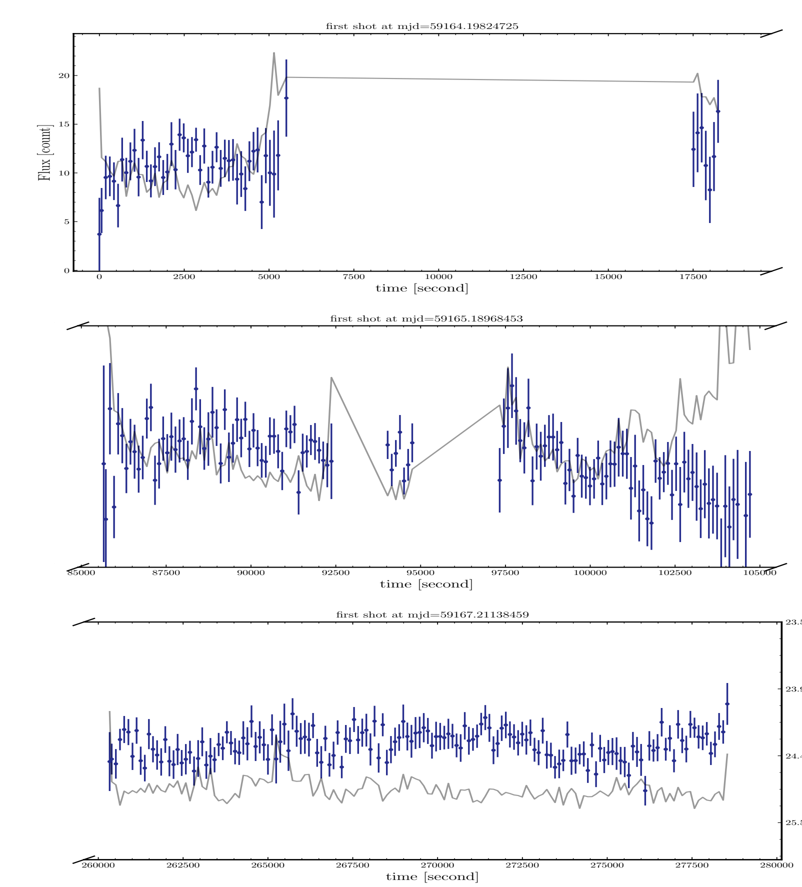
- We made **light curves at the same position** as 2014 ML candidate using new data set.

- We confirmed that there is **no variability** in 2020 light curves.
  → The 2014 candidate is likely to be ML.

2020-10



2020-11

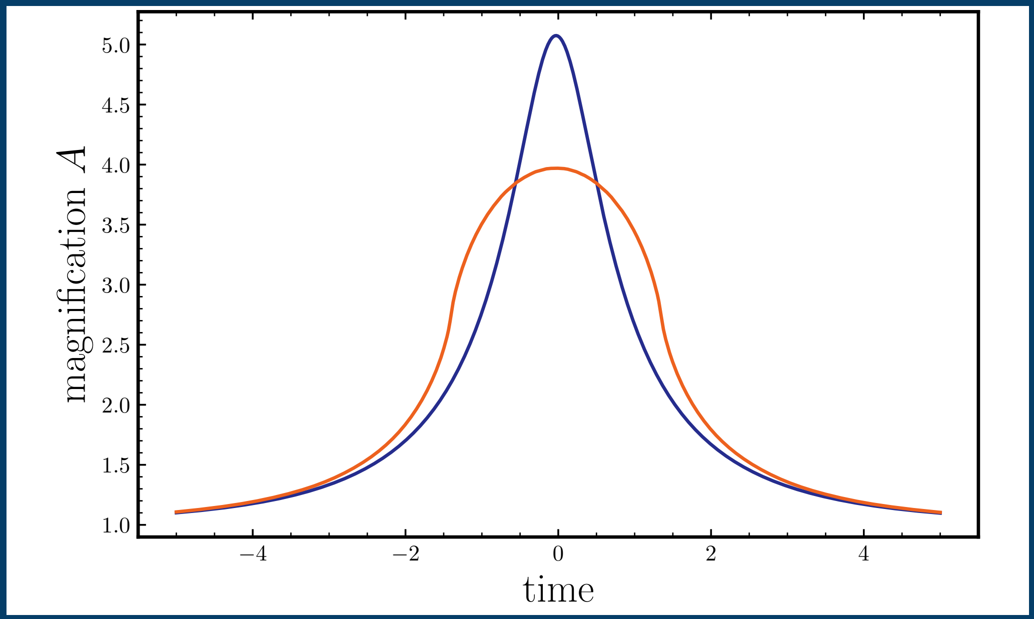


Update 3: Fast evaluation of finite source size effect on ML

Finite source size effect

$$A_{\rm finite}(u) = \frac{1}{\int d^2\vec{x} S(\vec{x})} \int d^2\vec{x} A_{\rm point}(\vec{x}) S(\vec{x} + u)$$

- Fitting with ML template with finite source size effect is **standard** in these day's ML analysis (e.g. OGLE.)
- **2-d integral** is computationally expensive.
- Fitting to 10^{5-6} **of light curves** taking account finite source size effect is much more expensive.

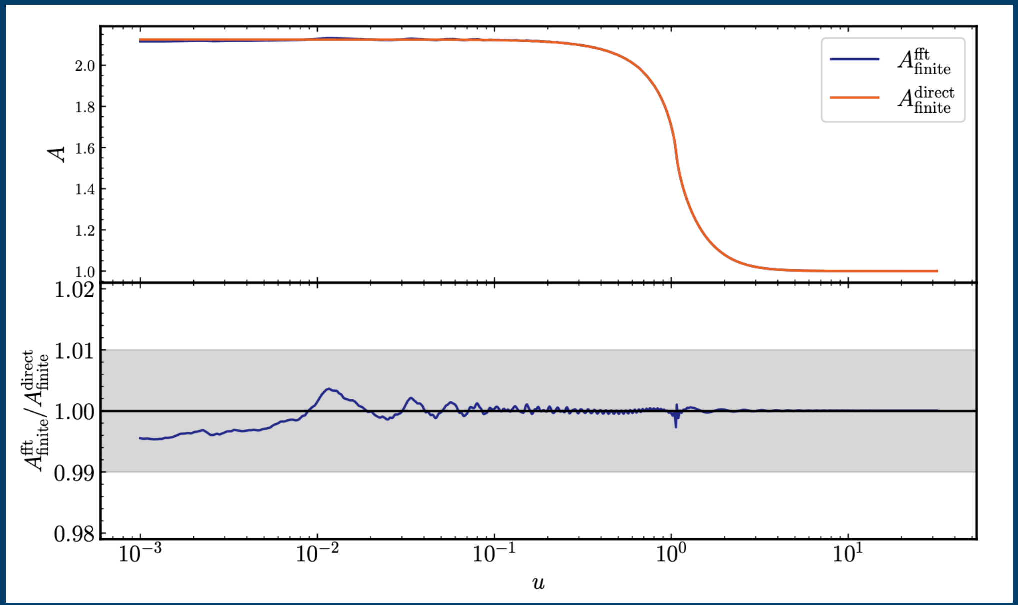


- We developed FFT based evaluation of finite source size effect, which is **very fast** (100 times faster than 2-d integral) and applicable to **any source profile** (disk, linear/parabolic limb darkening, or any profile you desire), keeping precision better than to **1%**.

$$A_{\rm finite}(u) = \frac{1}{2\pi} \int dk k \tilde{A}_{\rm point}(k) \tilde{S}(k) J_0(ku)$$

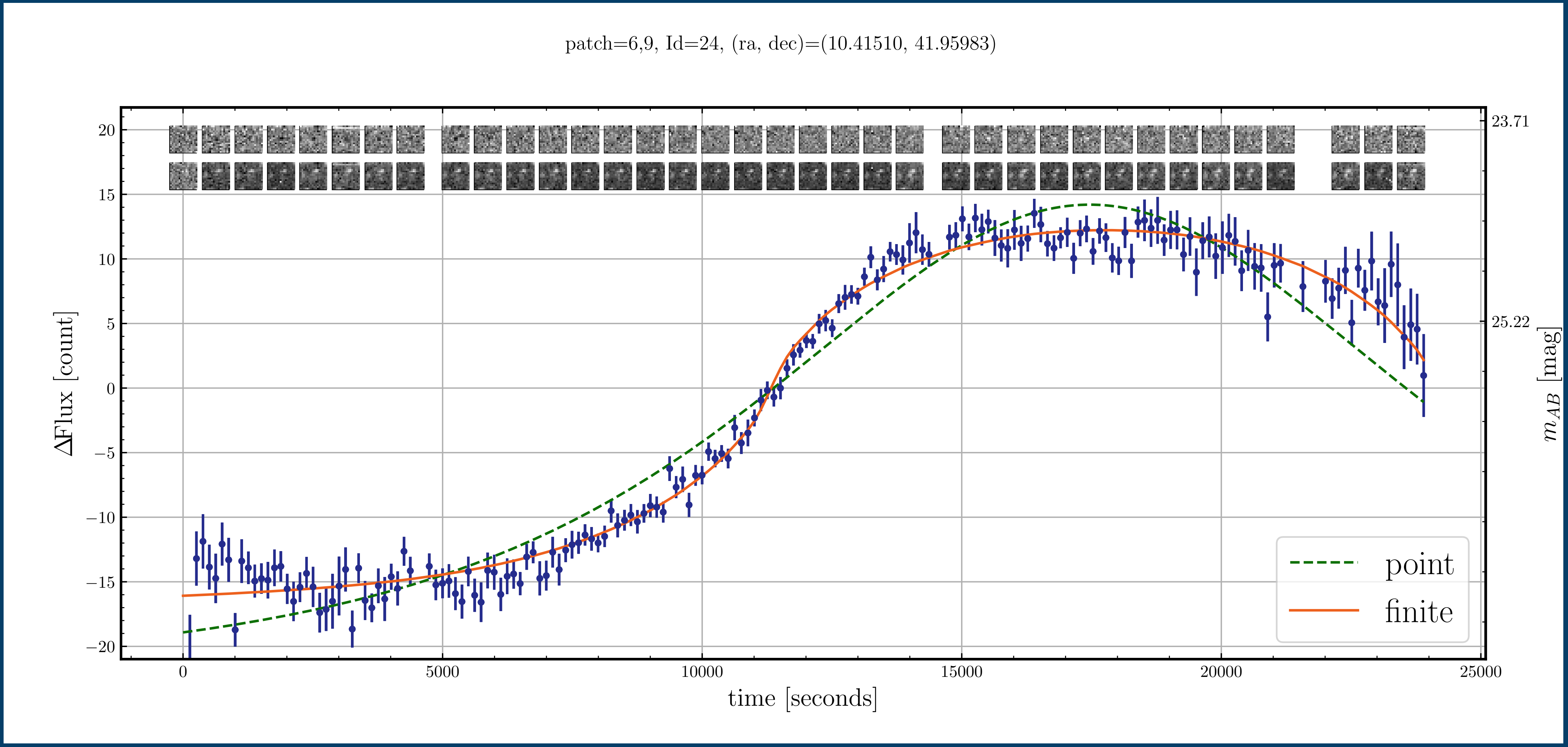
c.f. Exposure time average can be also evaluated by FFT.

Precision test: FFT based vs direct evaluation



Update 3: Fast evaluation of finite source size effect on ML

- With finite source template, we found new microlensing events.
- New events will be useful to obtain plausible parameter space of PBH, ($f_{\rm PBH}$, $M_{\rm PBH}$). (see Sugiyama et al. 2021, arXiv:2108.03063 for similar analysis.)



Summary

- Microlensing (ML) is useful to search the faint/invisible object, e.g. **Primordial Black Hole (PBH)**.
- We carried out Microlensing observations monitoring M31 (Andromeda) galaxy by Subaru HSC.
  - Normal program: **~ 1 night scale → probing** $M_{\mathrm{PBH}} \sim 10^{-7} M_{\odot}$.
  - Intensive program: **~ years scale → probing** $M_{\mathrm{PBH}} \sim 10 M_{\odot}$.
- Updates/Upgrade of analysis
  - We reproduced 2014 ML candidate event with `hscPipe8`.
  - No variability at the **2014 ML candidate** coordinate → the candidate is likely to be **really due to ML**.
  - Developed a new method to evaluate **finite source size** effect on ML fast with **FFT**, and find **new events**.
  - We are now analyzing **full data** taken by Subaru HSC.

Thank you!