arXiv:1701.02151 Niikura et al.

Hiroko Niikura (U.Tokyo/IPMU)

Microlensing constraints on PBHs with Subaru/HSC observation of M31

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)

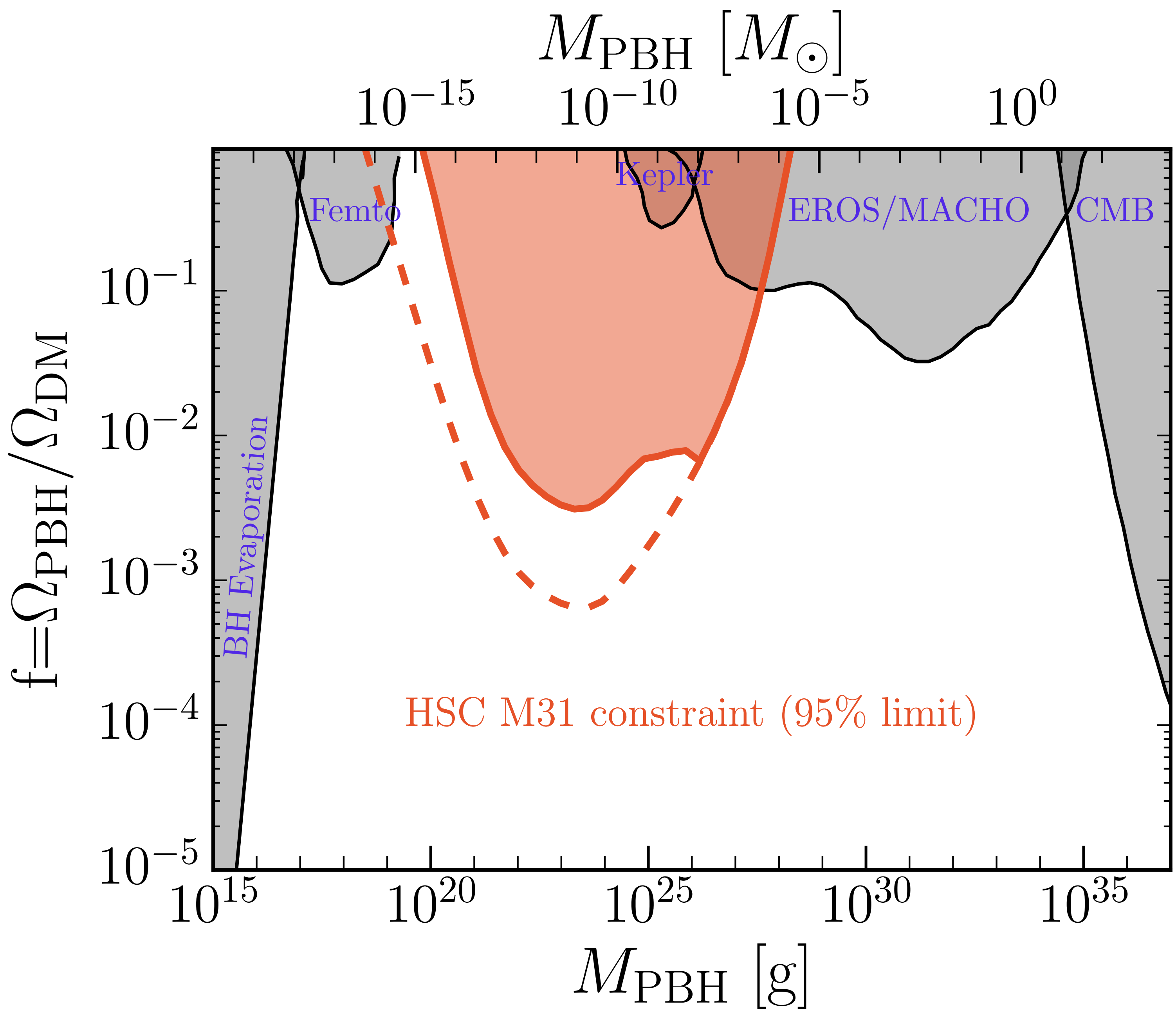
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

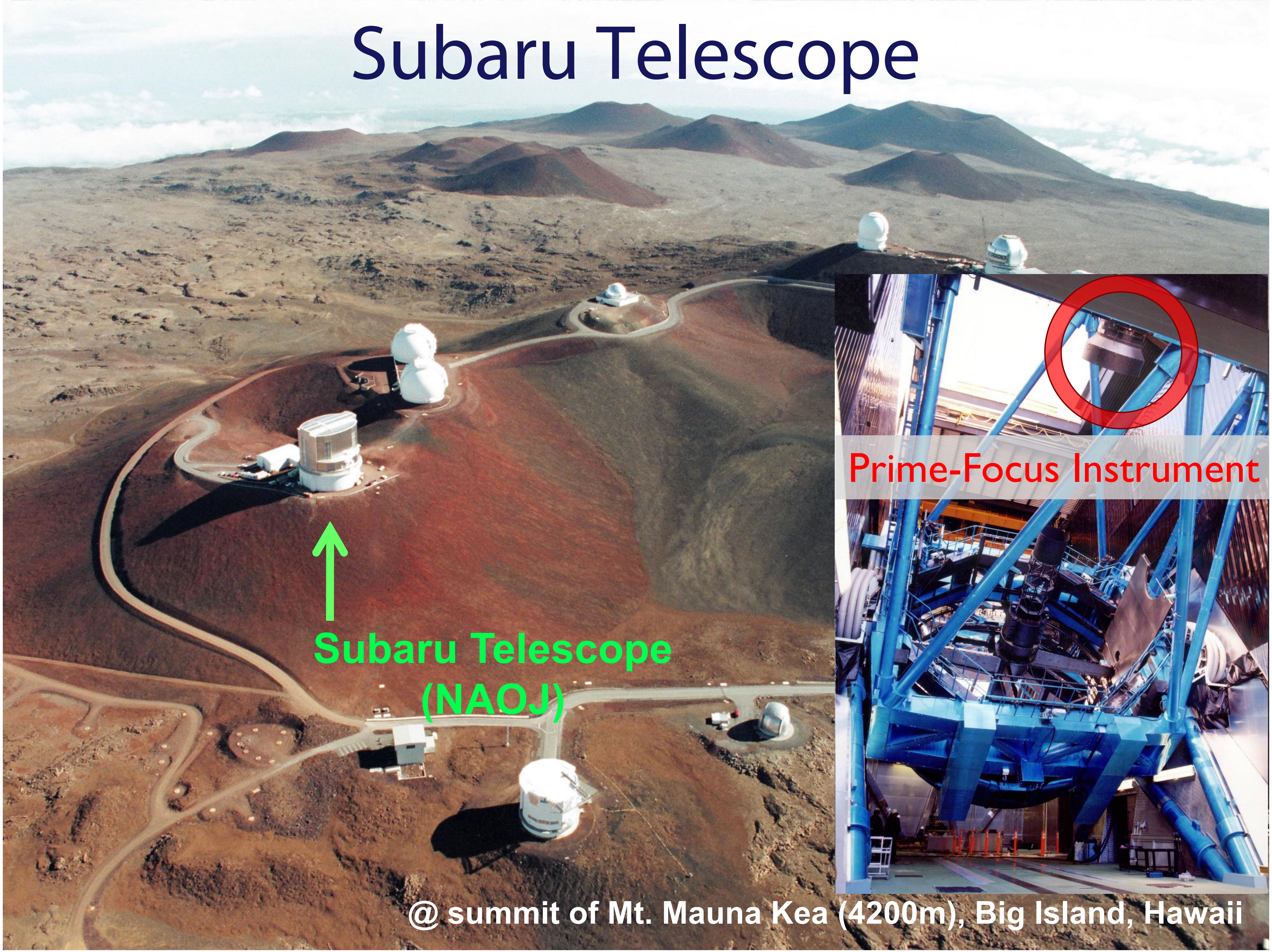
wpi

@ IPMU, Nov 2017

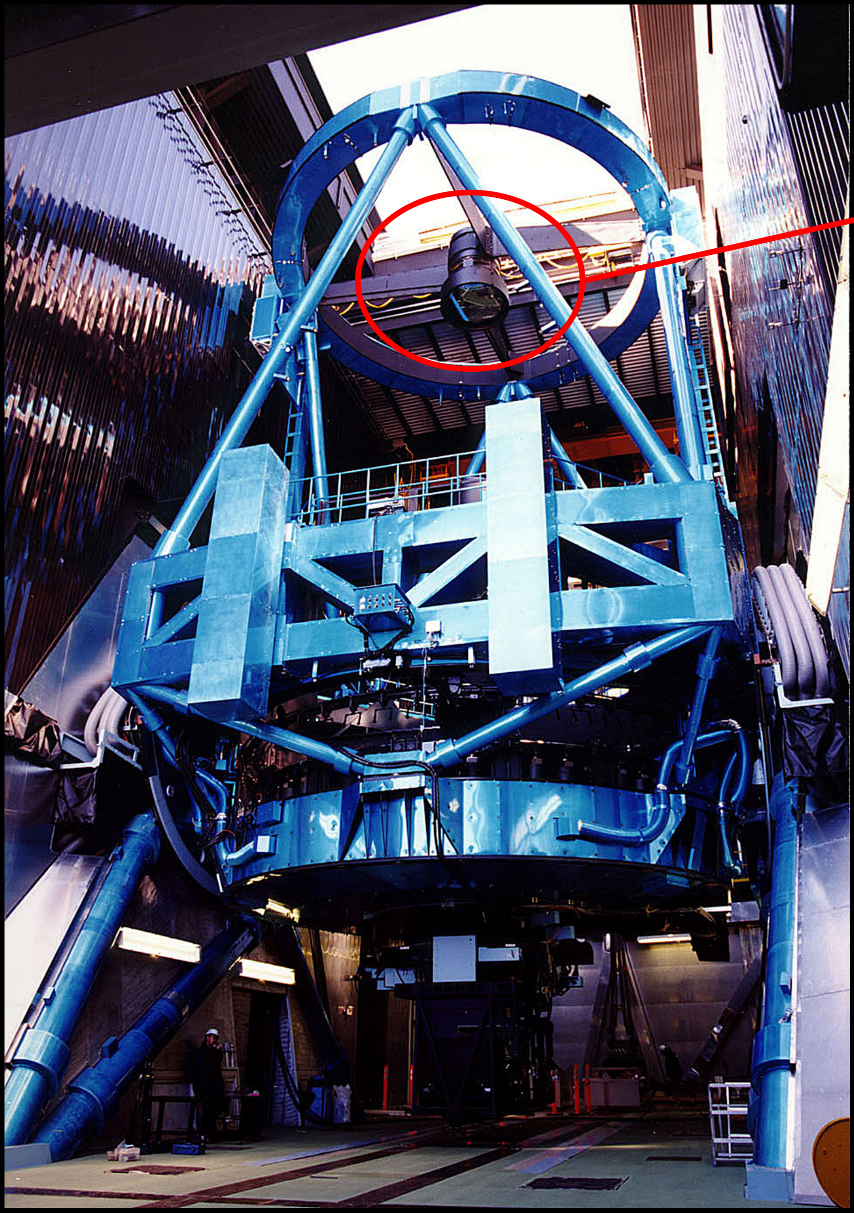
Niikura+17: updates needed … good or bad news?



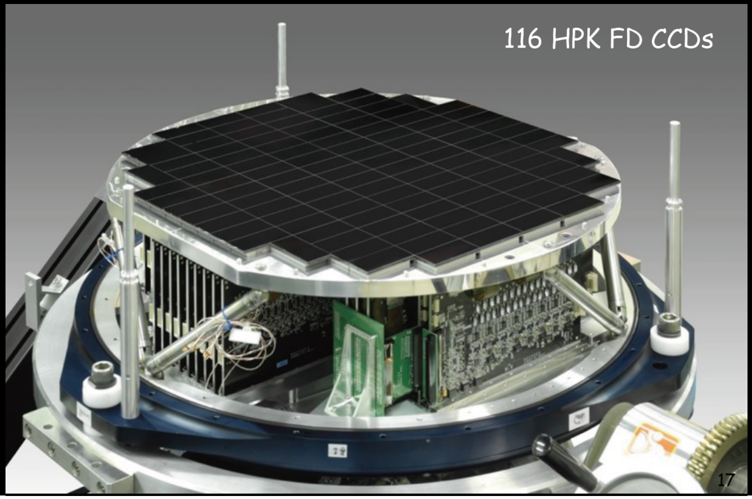
Subaru Telescope



Hyper Suprime-Cam



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




HSC

wi

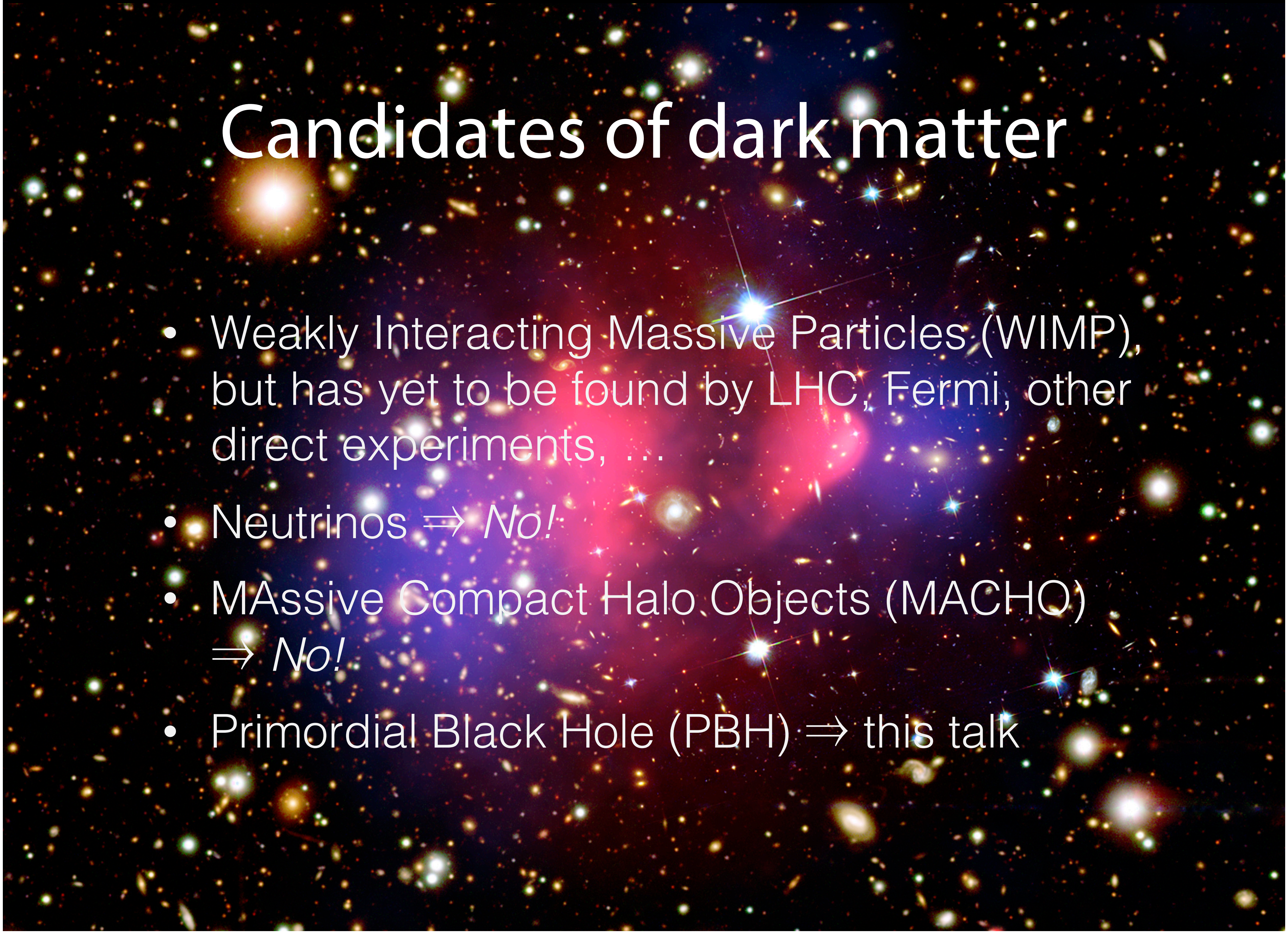
Hyper Suprime-Cam FoV

- **Fas**
- a cos

すばる望遠鏡に搭載された
Hyper Suprime-Cam

2012年8月16日撮影 (180倍速)

Installing Hyper Suprime-Cam on the Subaru Telescope

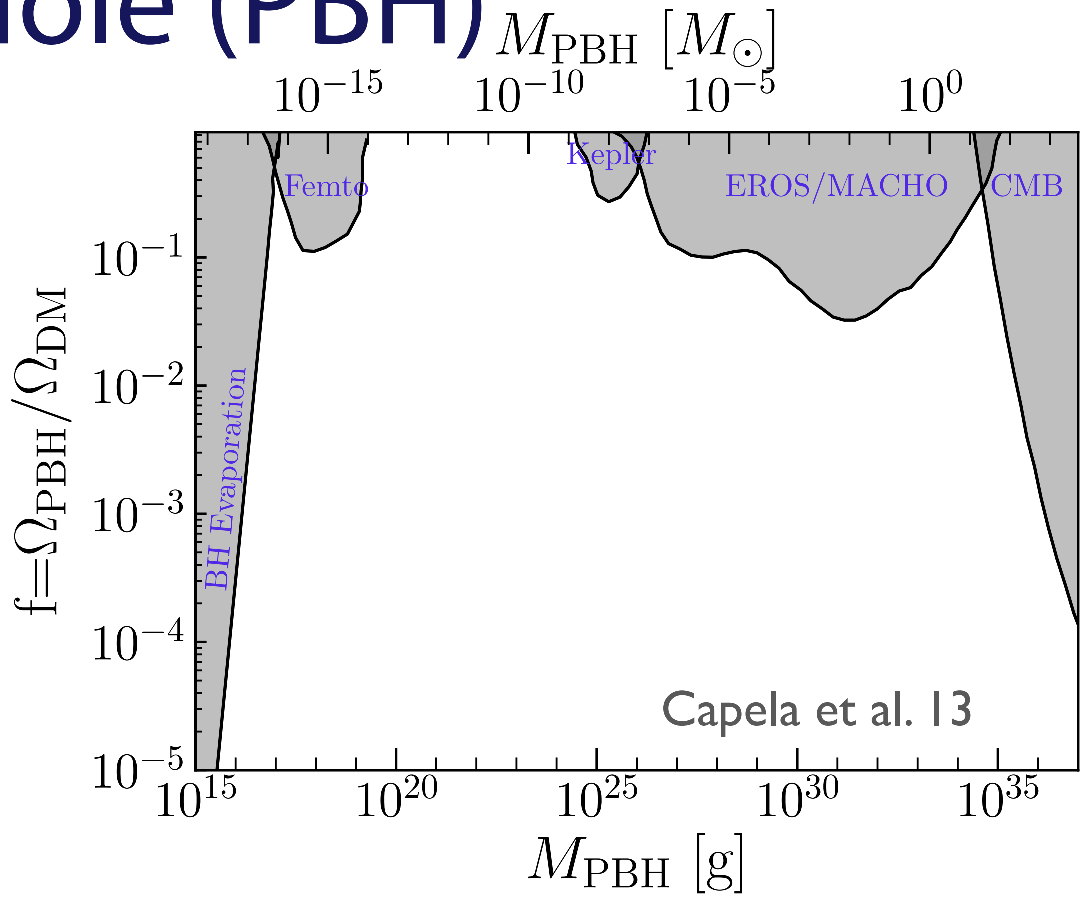


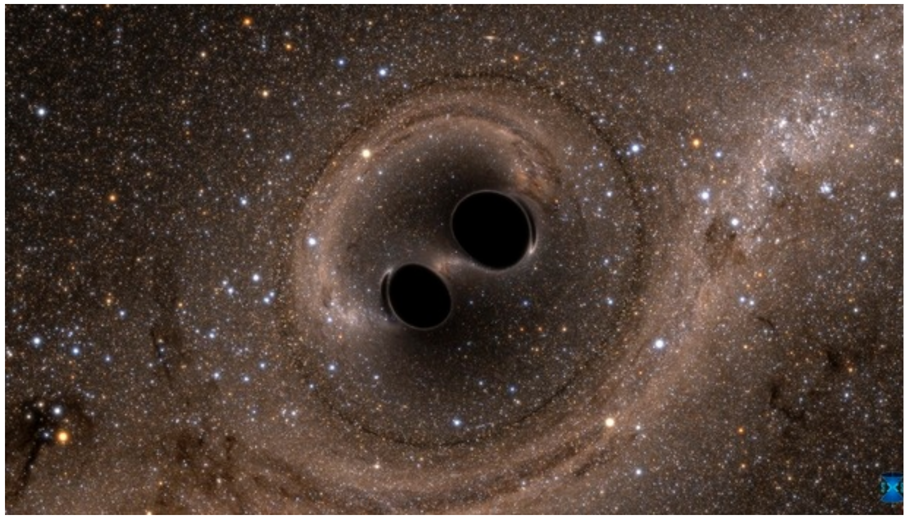
Candidates of dark matter

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

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 te al. 16)





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

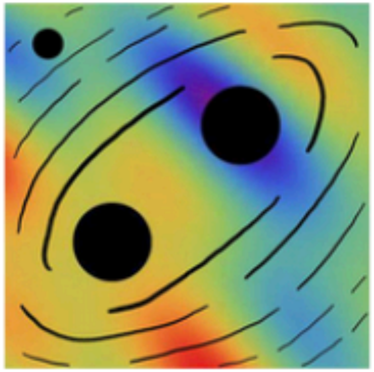
Sasaki, Suyama, Tanaka & Yokoyama 16
Also see Bird et al. 16

Editors' Suggestion

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

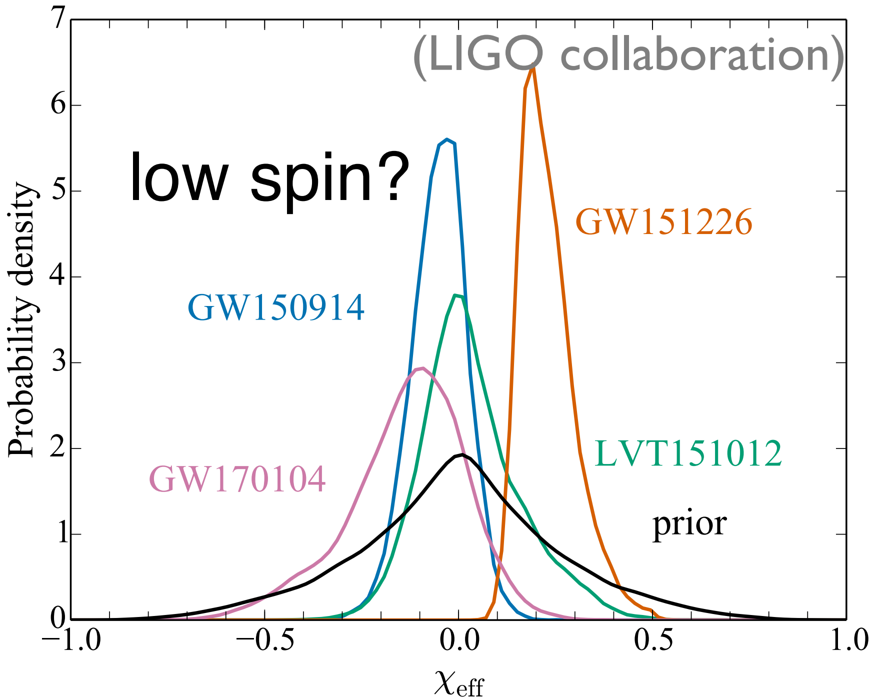
Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama

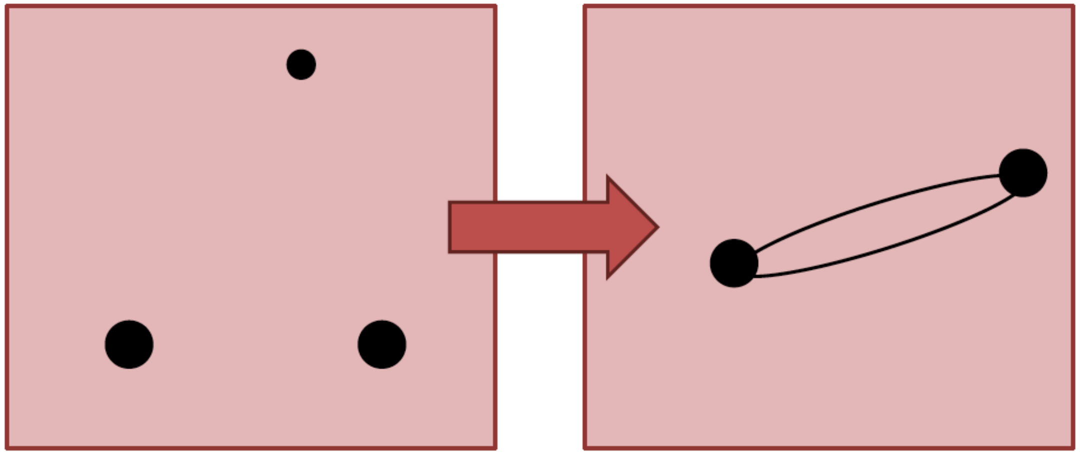
Phys. Rev. Lett. **117**, 061101 (2016) – Published 2 August 2016



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.

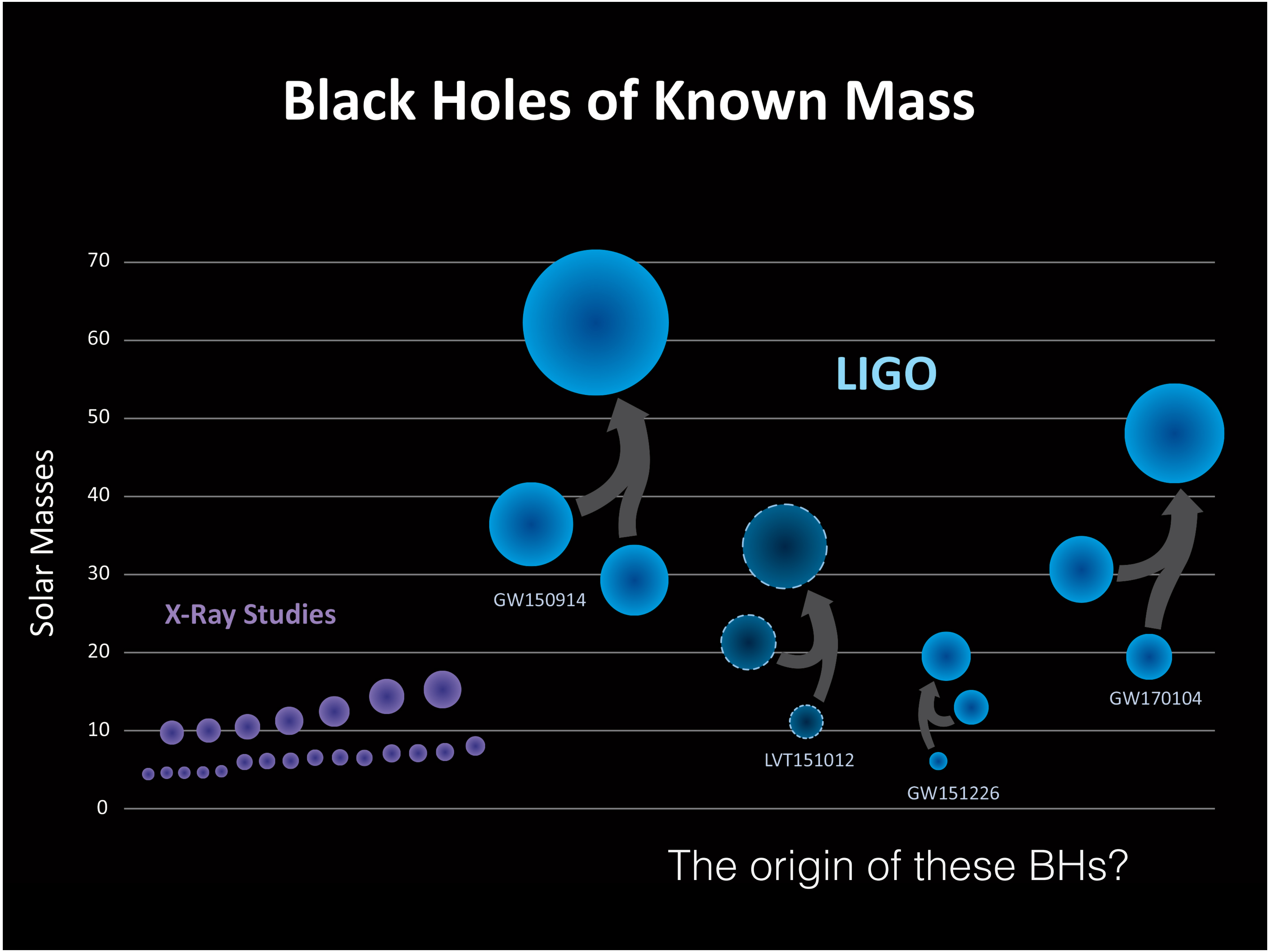
Show Abstract +





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

needed to explain the LIGO event rate



Black Holes of Known Mass
70
60
50
40
30
20
10
0
Solar Masses
LIGO
X-Ray Studies
GW150914
LVT151012
GW151226
GW170104
The origin of these BHs?

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The Nobel Prize in Physics 2017
Rainer Weiss, Barry C. Barish, Kip S. Thorne

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The Nobel Prize in Physics 2017

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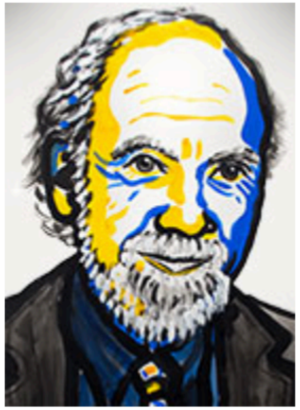
Rainer Weiss
Prize share: 1/2



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Barry C. Barish
Prize share: 1/4

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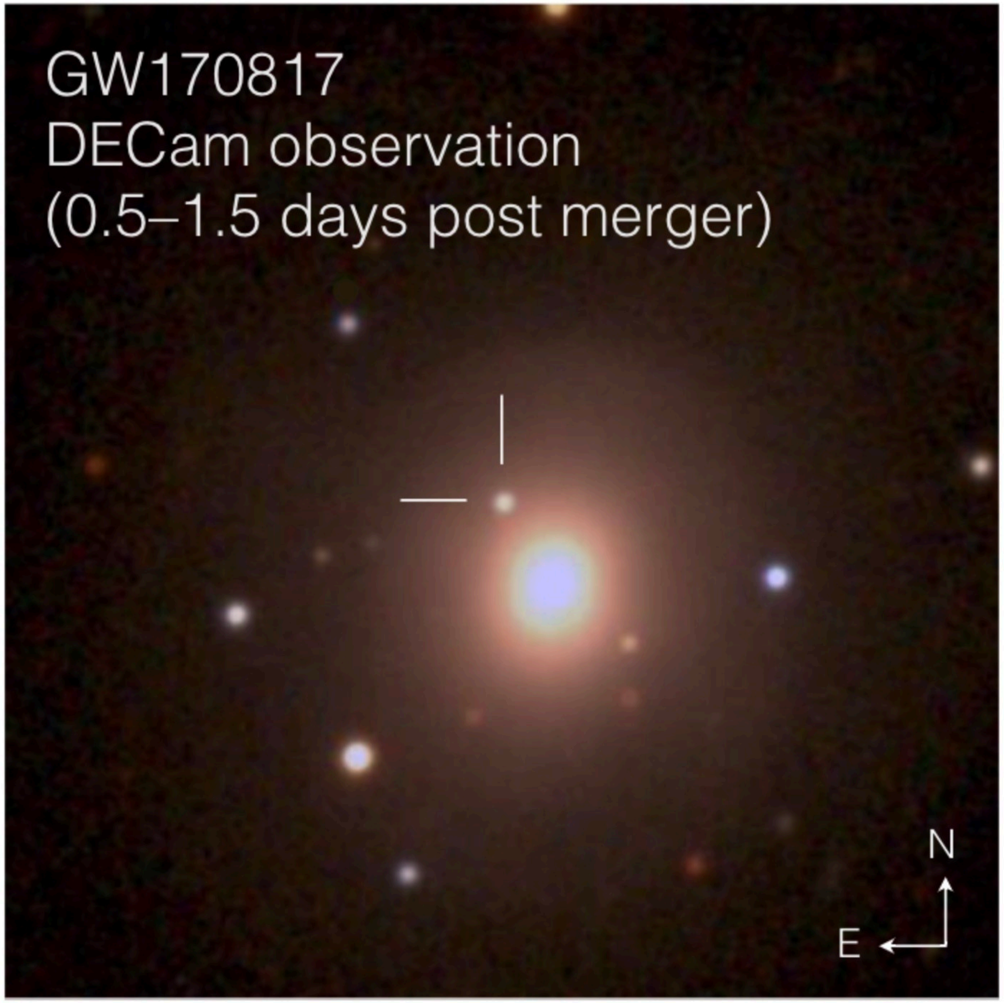
Kip S. Thorne
Prize share: 1/4

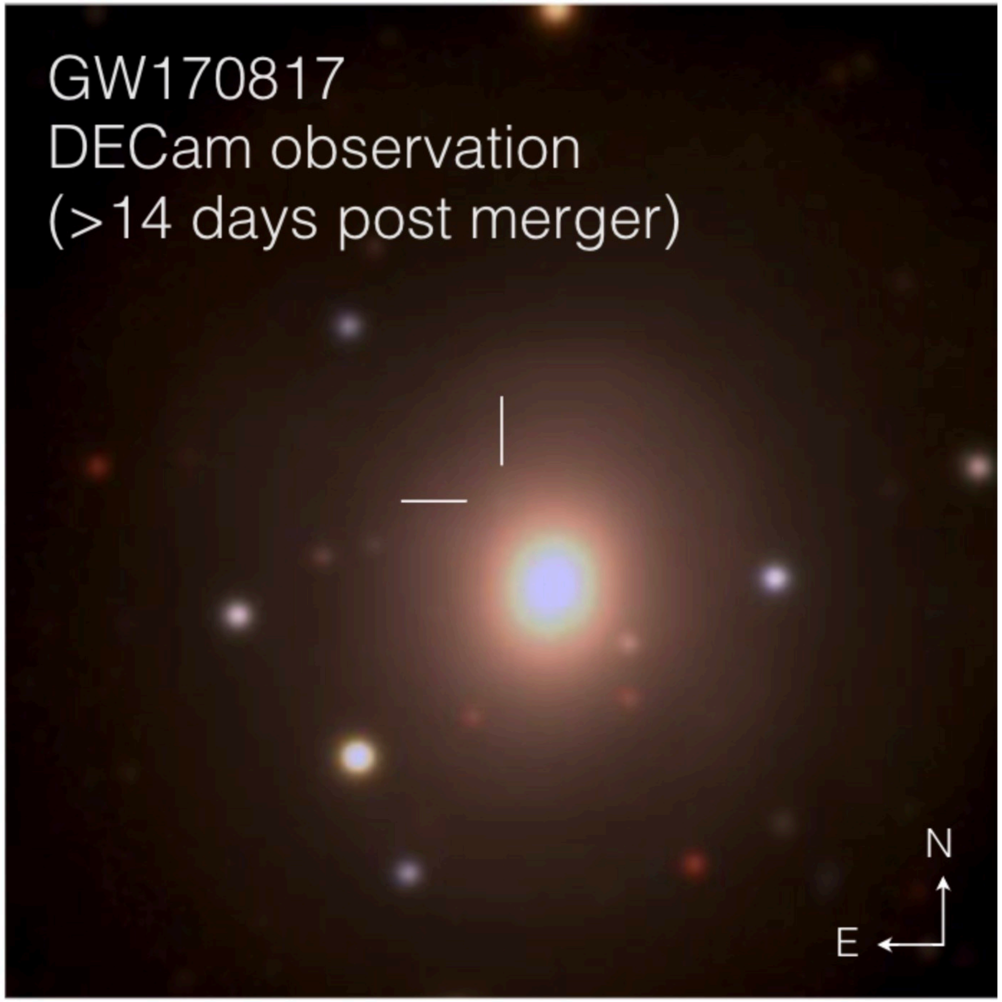
The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

We did it!

Kick is common?

See talk by Masaomi Tanaka this Thus





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 (Zel'dovich & Novikov 67; Hawking 71)

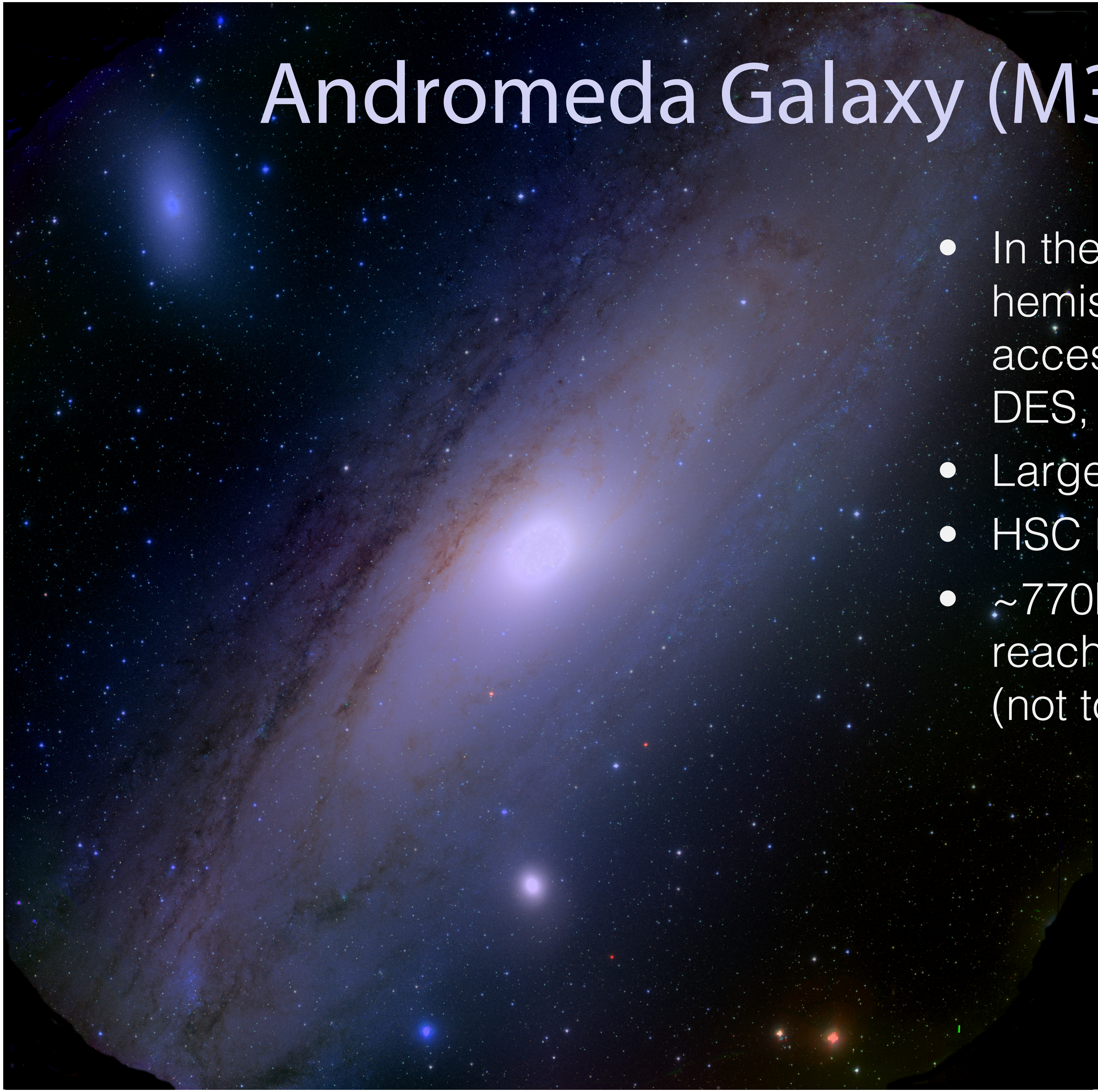
$$\left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \frac{8\pi G}{3}\bar{\rho}_r(1+\delta_r) - \frac{k}{R^2}$$

- PBHs can contribute DM, by a fraction given as

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

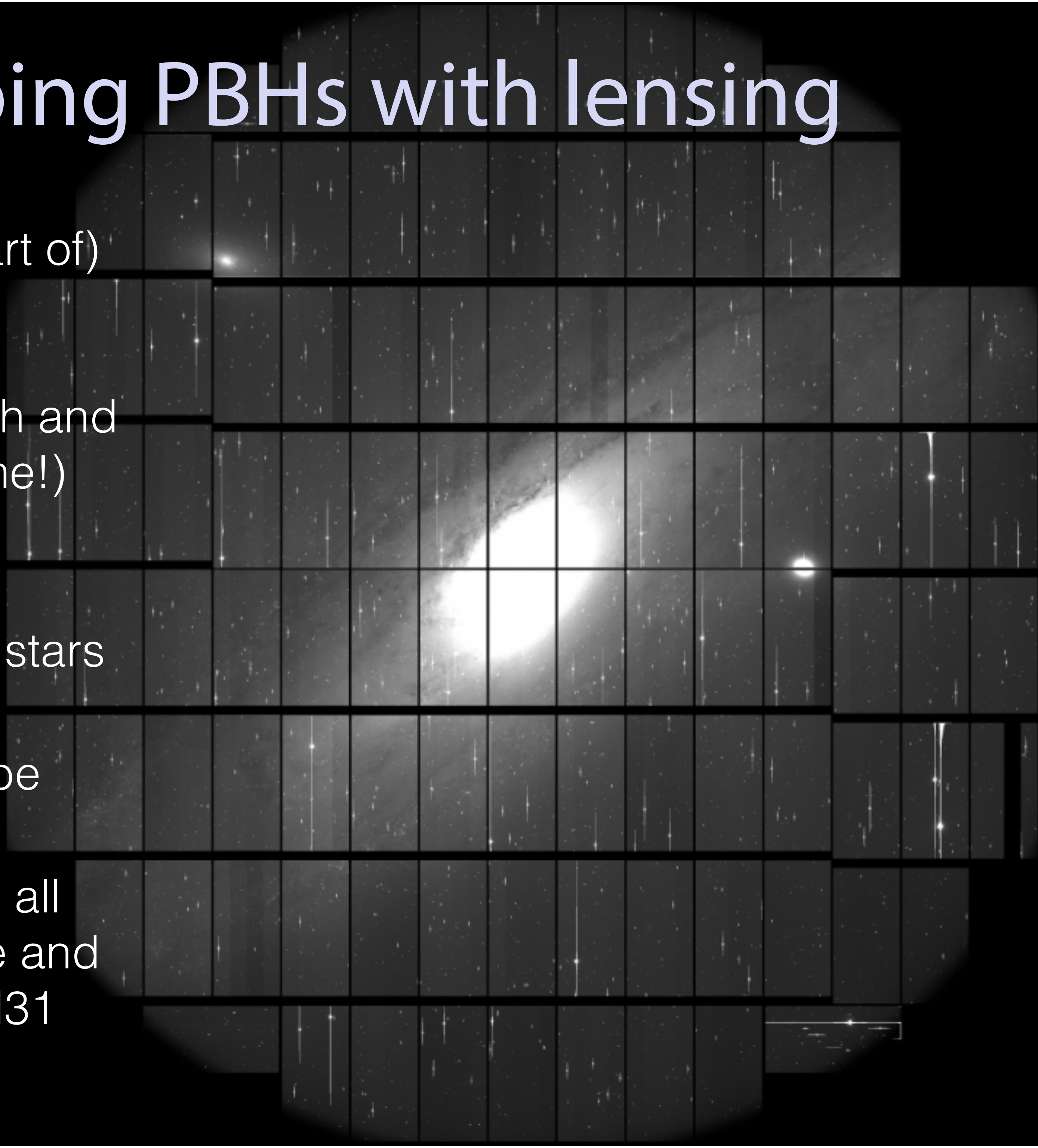
$$\beta(M_{\rm PBH}(k)) = \int_{O(1)}^{\infty} {\rm d}\delta \, \frac{1}{\sqrt{2\pi}\sigma(k)} e^{-\frac{\delta^2}{2\sigma(k)^2}}$$

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

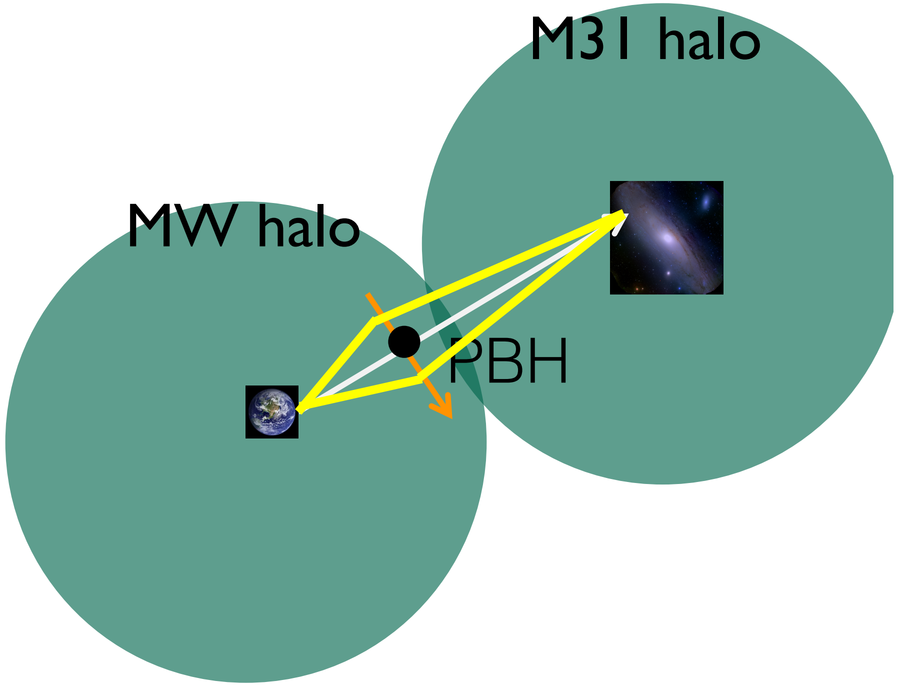


- If PBHs are (a part of) dark matter, they should exist in between the Earth and M31 (huge volume!)
- PBHs cause microlensing magnification on stars in M31
- Lensing can probe invisible
- HSC can monitor all stars in the bulge and disk regions of M31

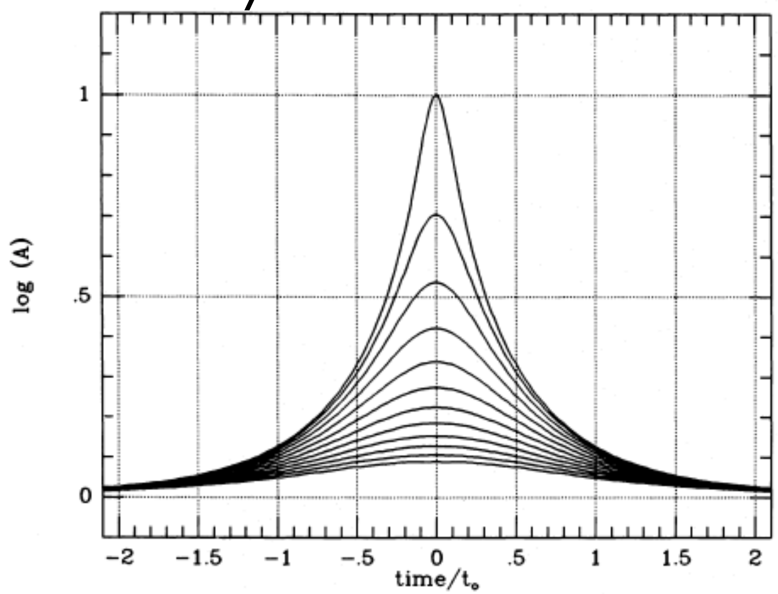
PBH microlensing on M31 star

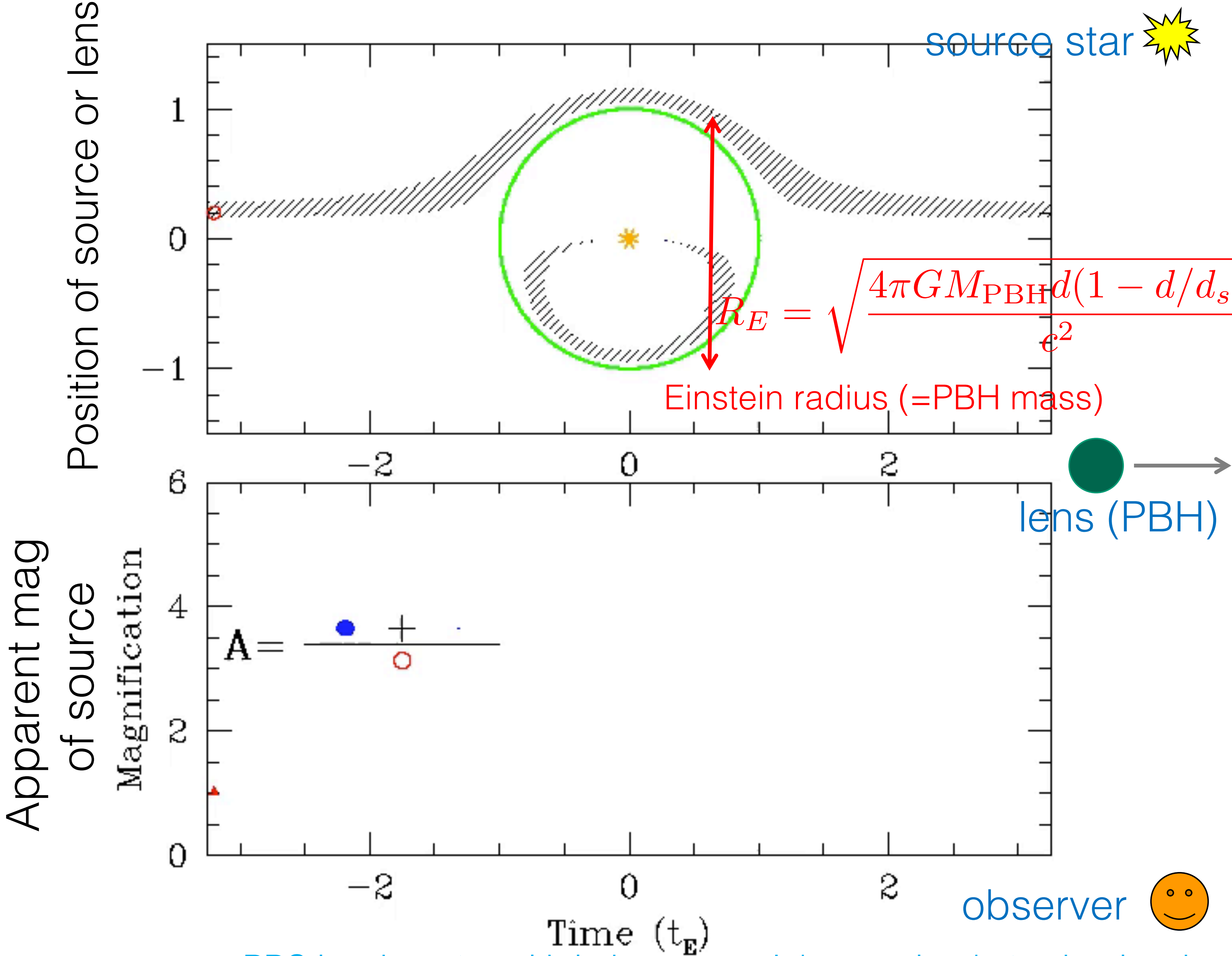
- Lensed image can't be resolved with optical resolution (~10^{-8} arcsec) ⇒ only light curve is a signal
- Huge volume
- MW/M31 halo **~ 10^{12}Msun** (we assumed NFW models)
- PBH has a peculiar velocity of **~200km/s**
- Need to **monitor** brightness of the same star as a function of **"time"** (time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

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



Paczynski 86

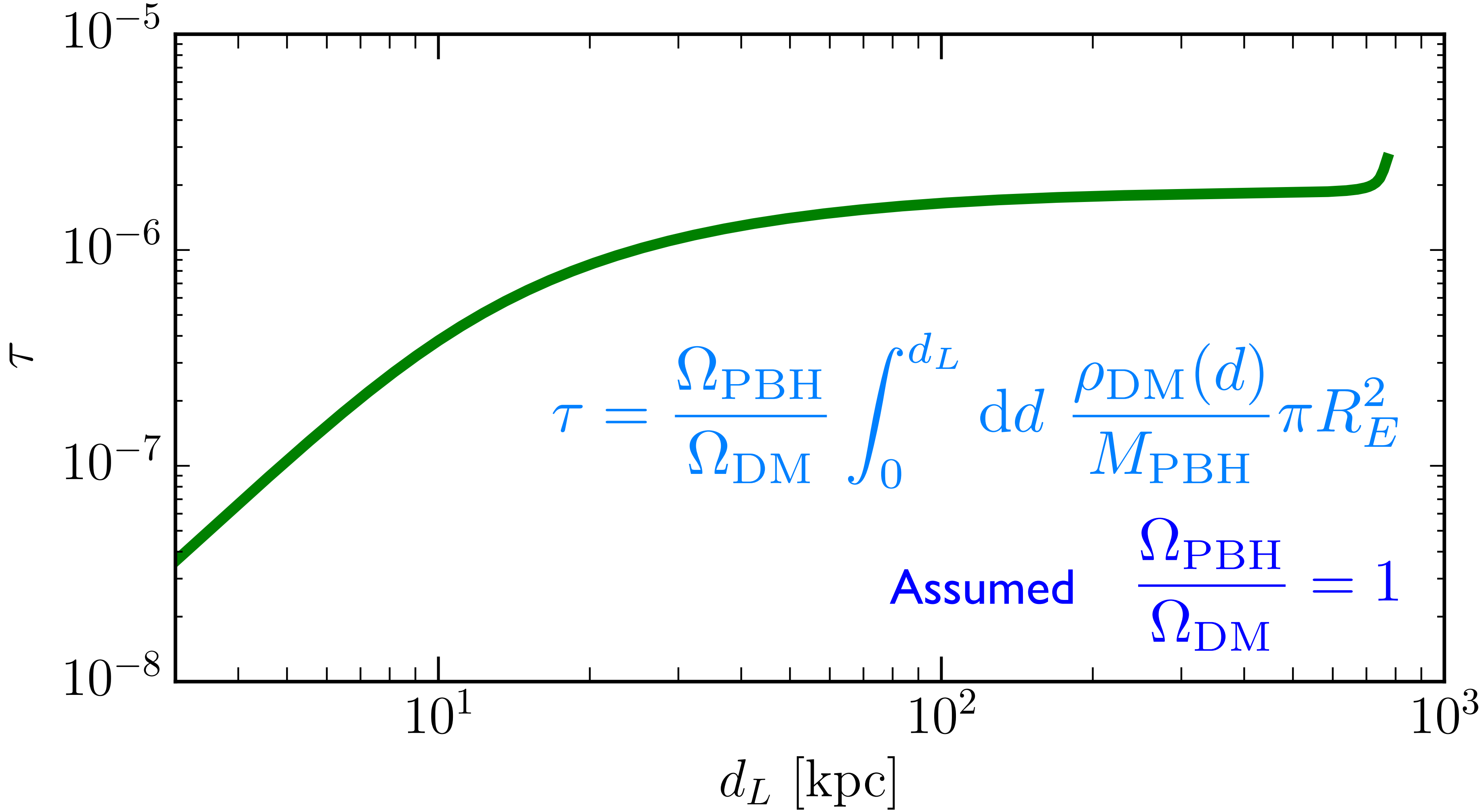




PBS lensing ⇒ multiple image can't be resolved ⇒ microlensing

PBH microlensing on M31 star

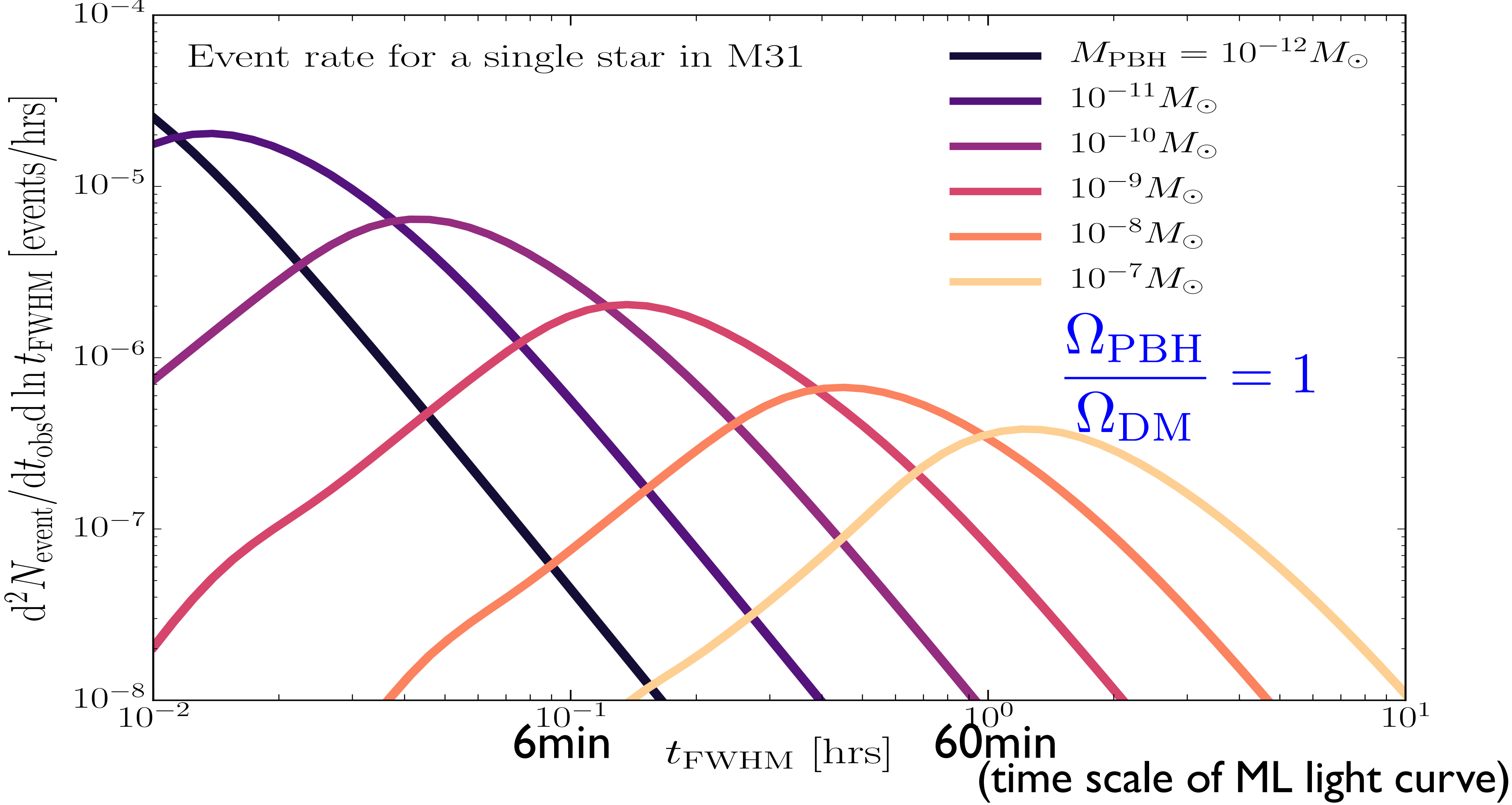
Cumulative optical depth of PBH microlensing for a **single** star in M31



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

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**

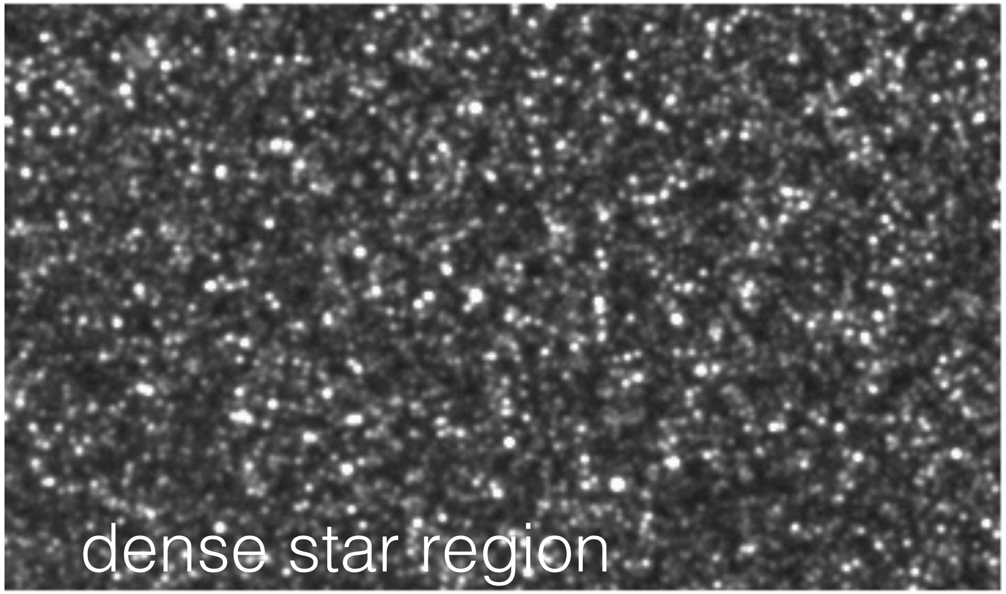
Hiroko Niikura

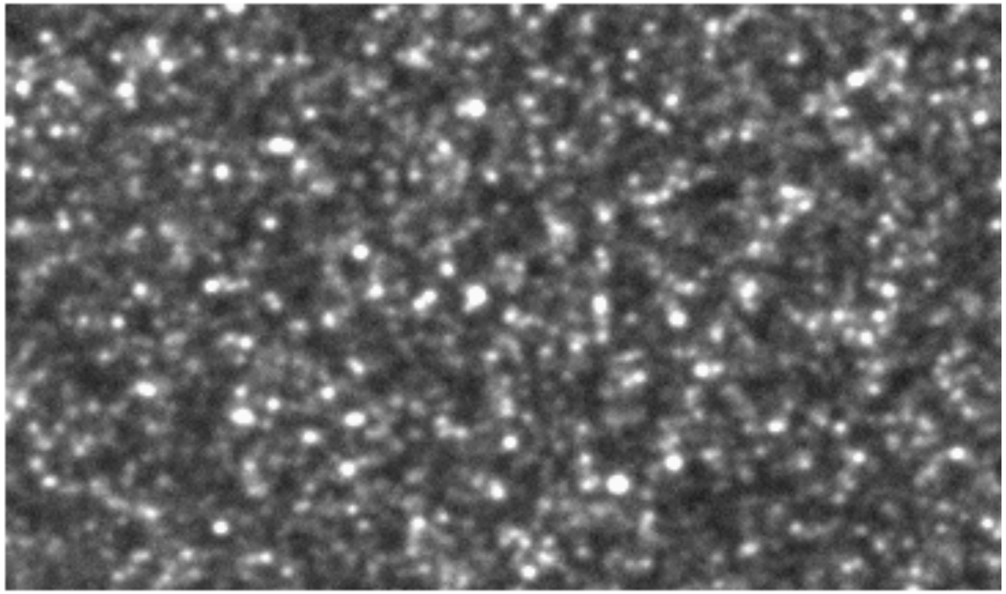
HSC dense-cadence observation of M31 (PI Takada, S14B)

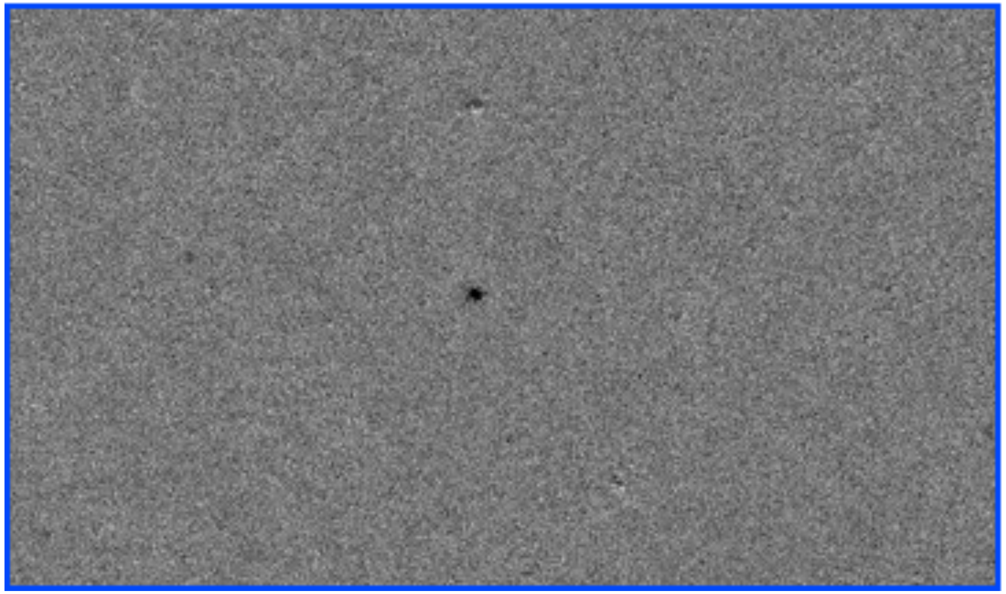
- *Got this idea from conversation with Hitoshi and Masahiro Kawasaki*
- 90sec exposure each (r-band)
- ~35sec readout
- ~190 exposures
- No dithering
- one clear night (seeing~0.5-0.6'')
- Also used g-data (from commissining)

Challenges: Pixel lensing

Fluxes from multiple stars are overlapped at each position







Upper left: reference image (0.5'')

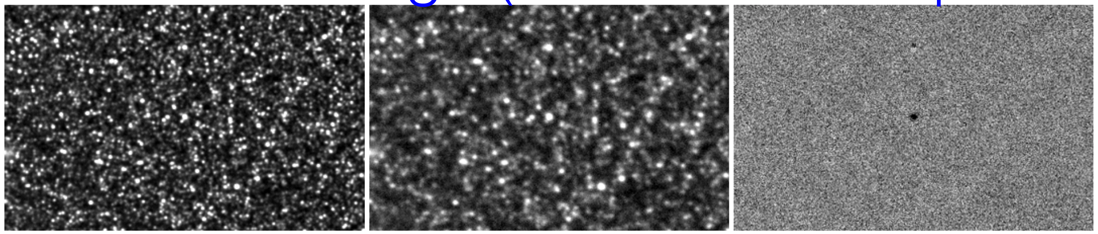
Upper right: target image (0.8'')

Lower: difference image

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

Procedures: search for ML events

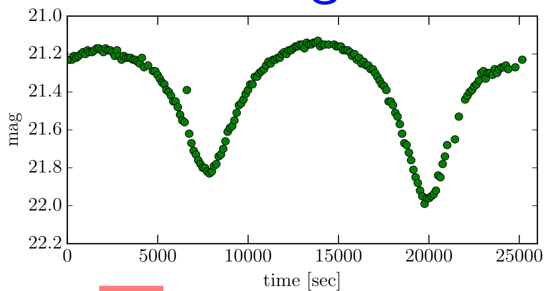
difference image (coadds of 3 exposures)



identify candidates in each diff. image

⇒15,571

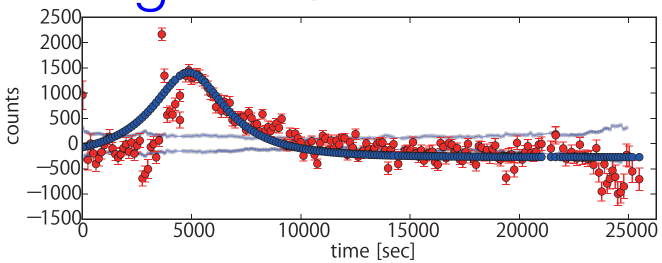
measure light curve (188 data points)



candidates with bump-like light curve

⇒ 11,703

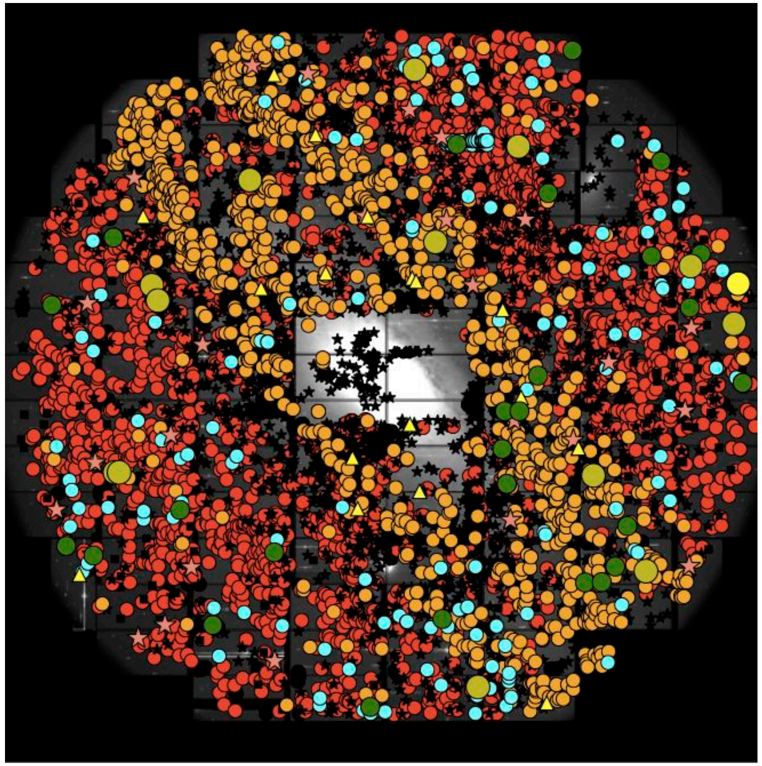
fitting of LC to the microlensing model

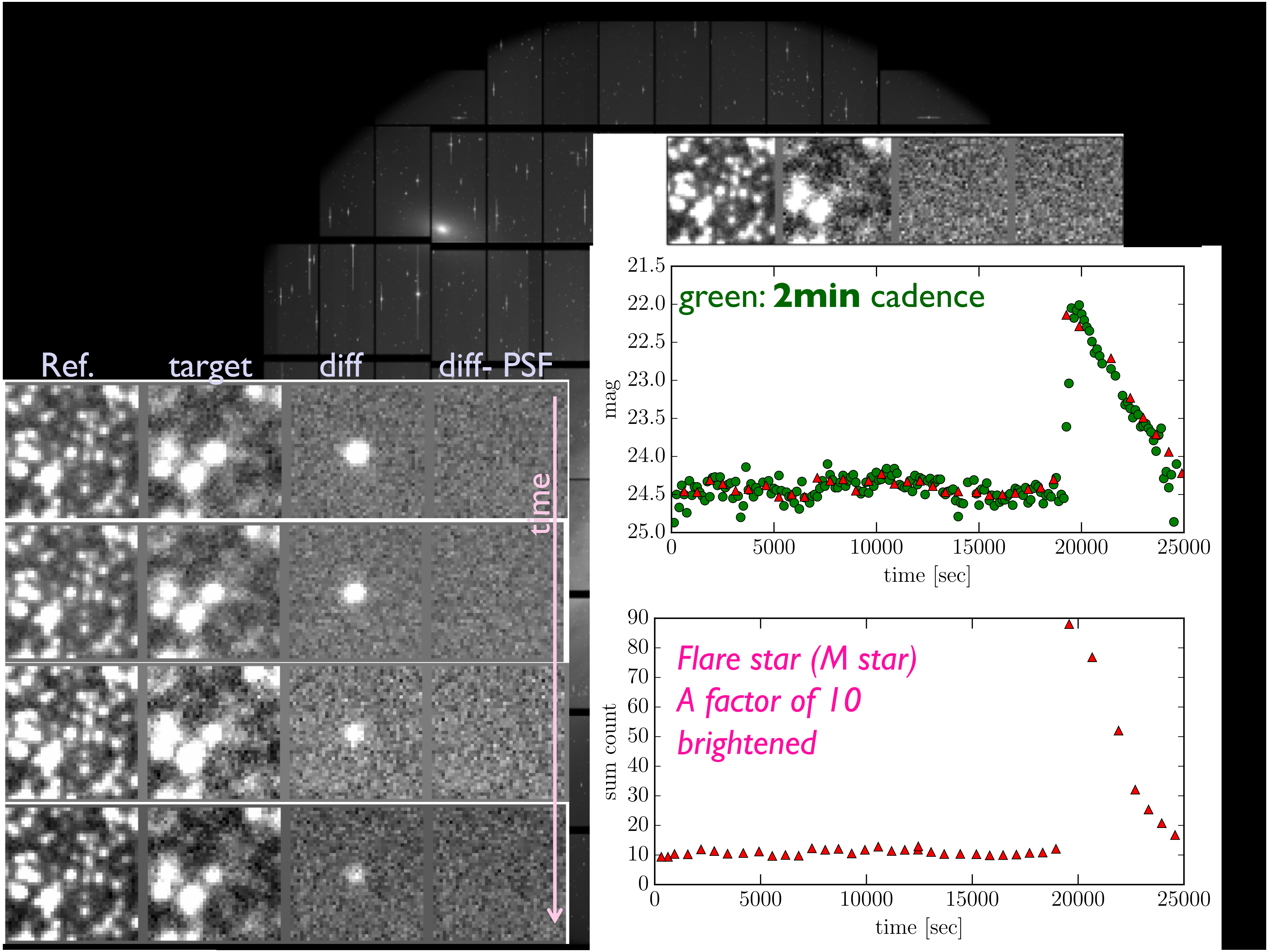


selection criteria

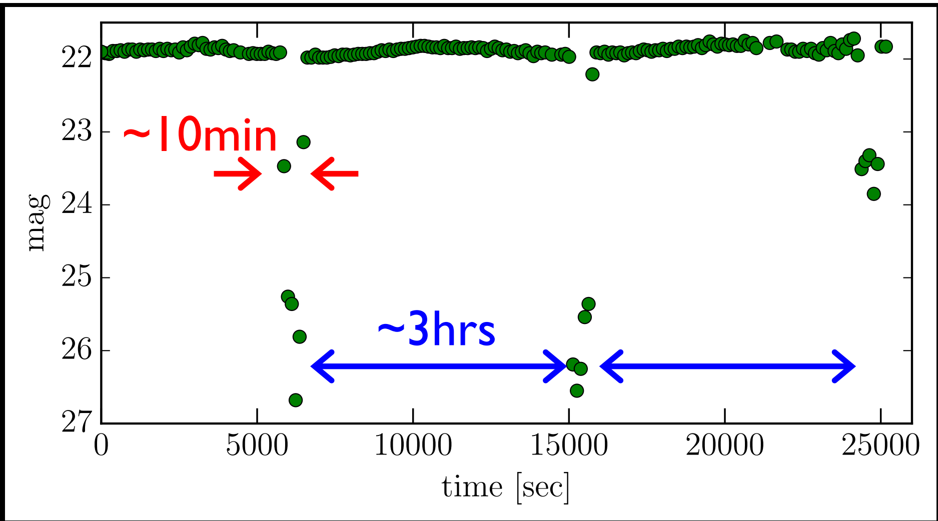
⇒ 66

visual inspection of individual candidates…



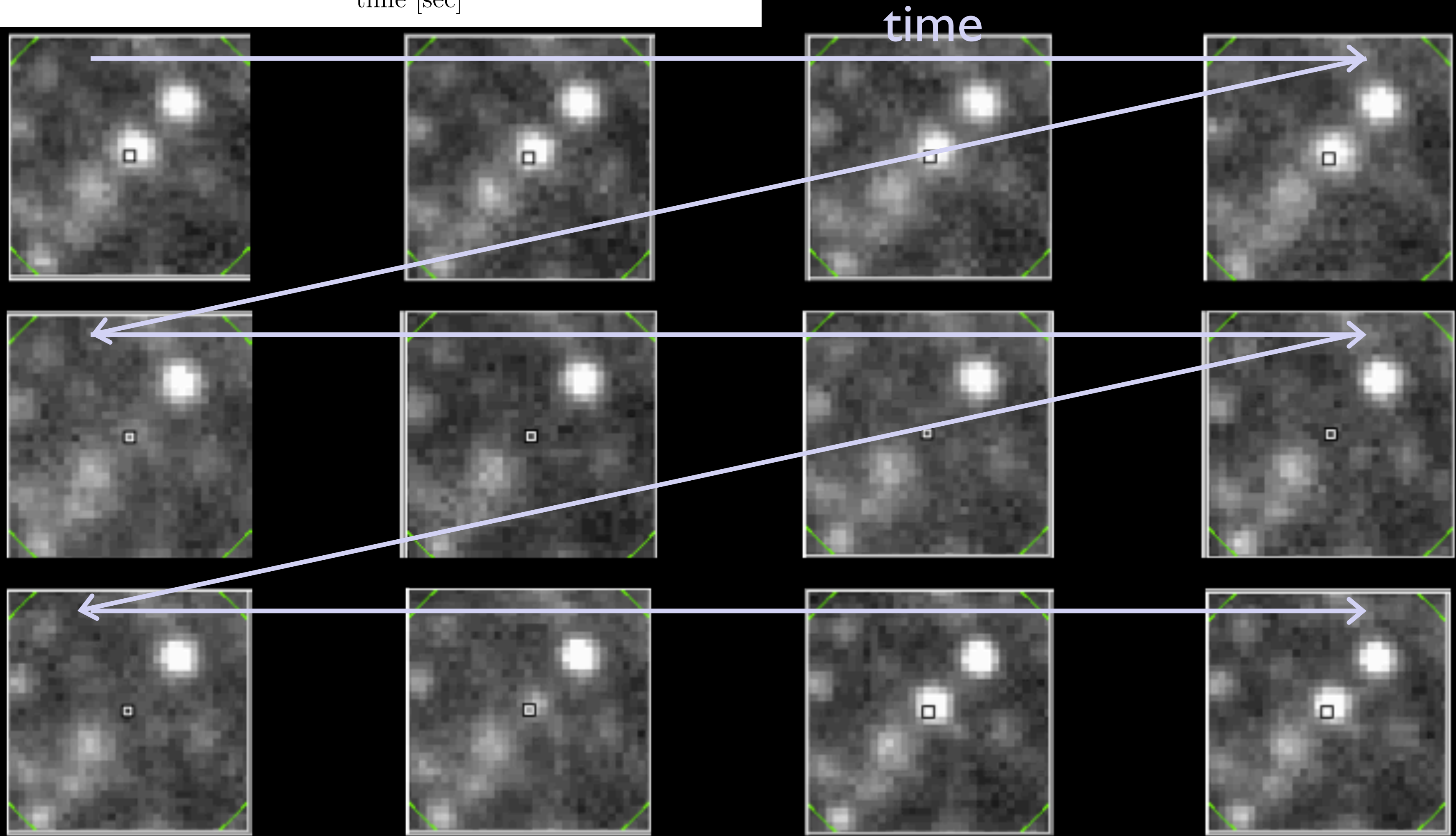


Ref.
target
diff
diff- PSF
time
green: **2min** cadence
mag
time [sec]
sum count
time [sec]
Flare star (M star)
A factor of 10
brightened



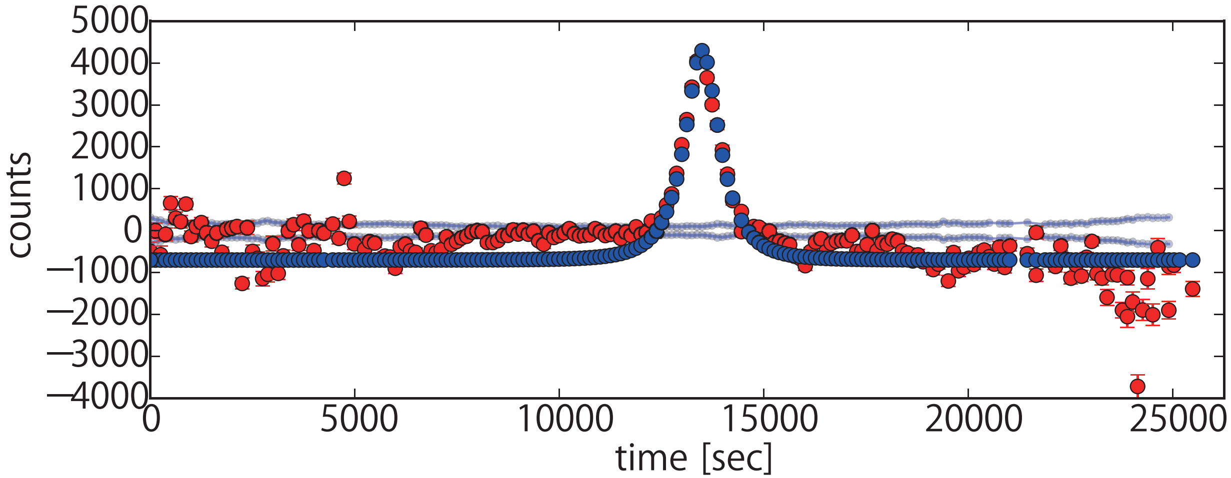
An entire star disappears for ~10min, with a 3hrs interval

WD – brown dwarf binary

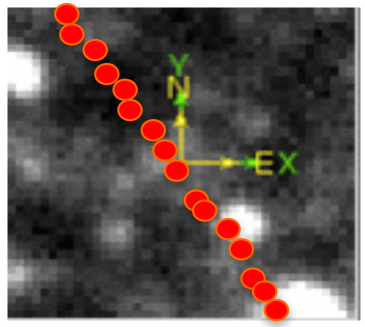


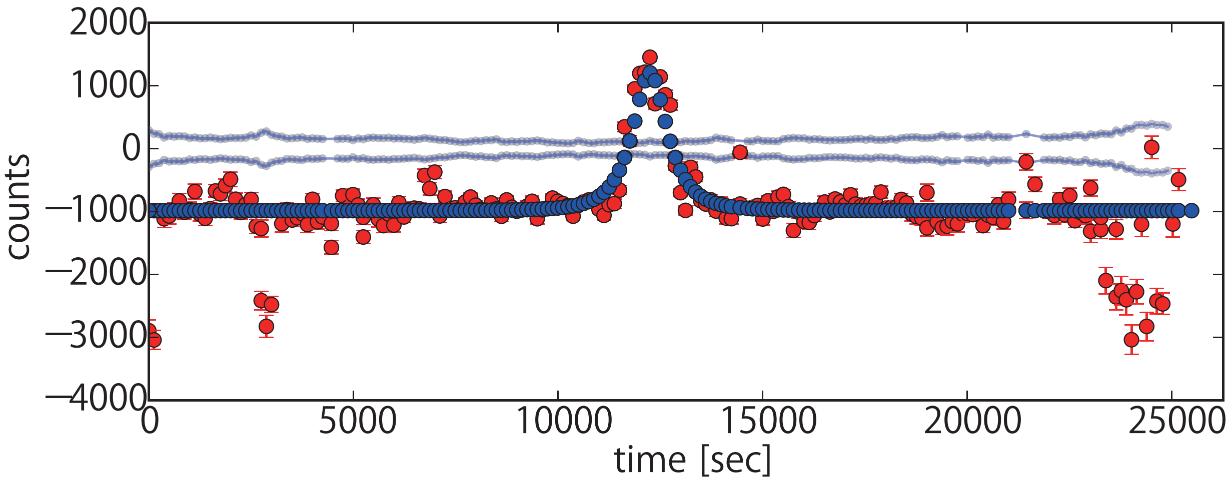
Visual inspection stage…

Visual inspection of 66 candidates to identify junks…

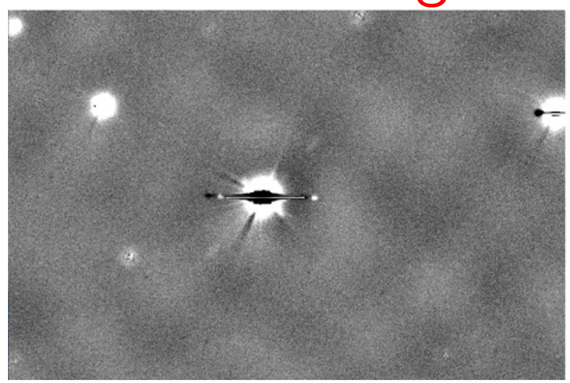


asteroid



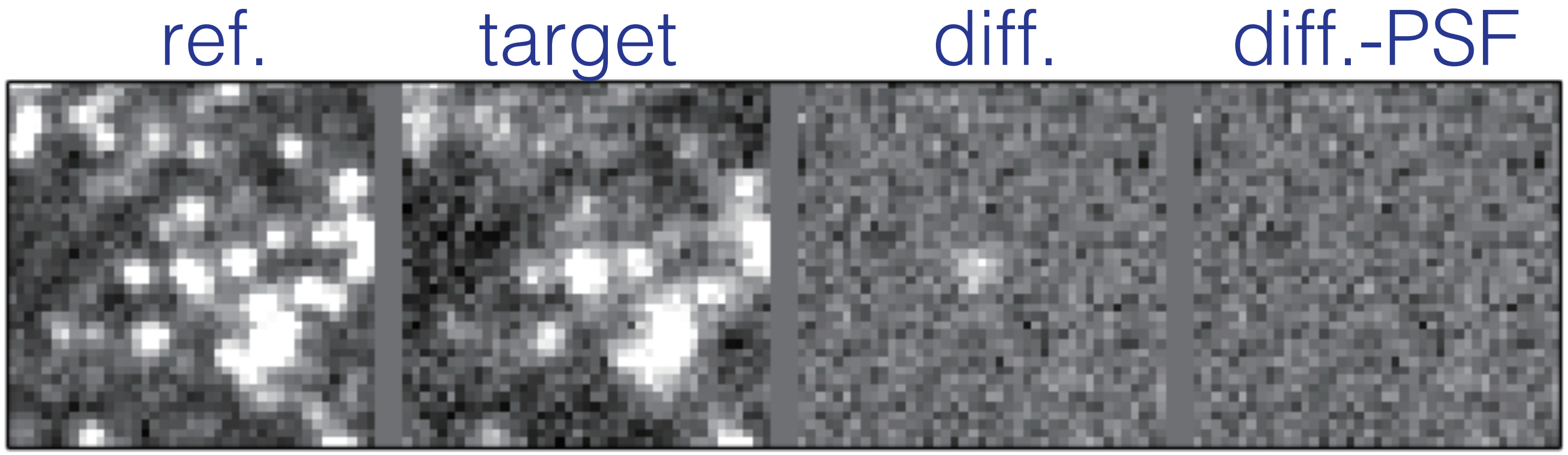


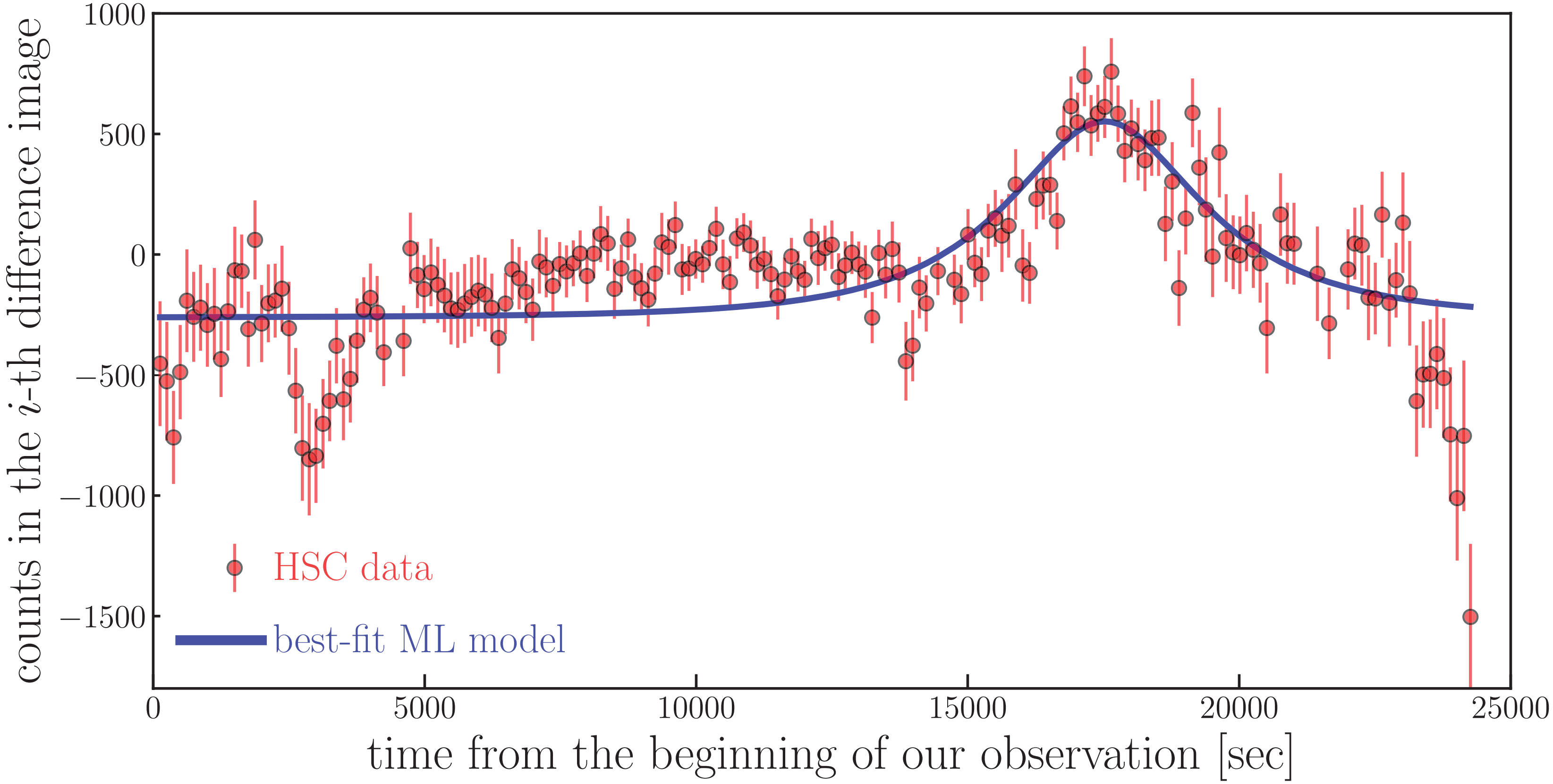
spike around a bright star



66 ⇒ 65 junks

One real candidate of microlensing …?





To constrain the PBH abundance

- Expectation number of PBH microlensing events

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

duration of observation time (about 7 hours)

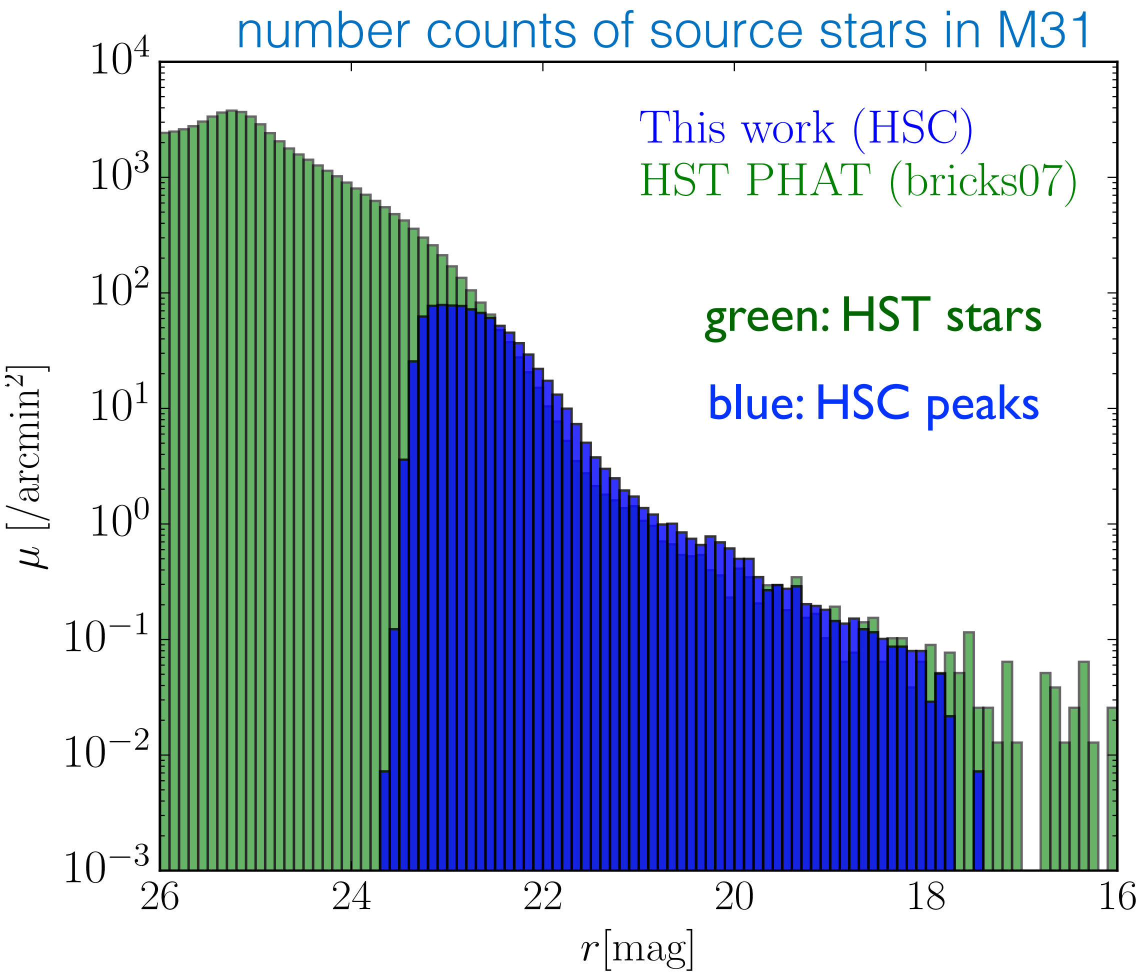
number of source stars in the magnitude range [m, m+dm] (see later)

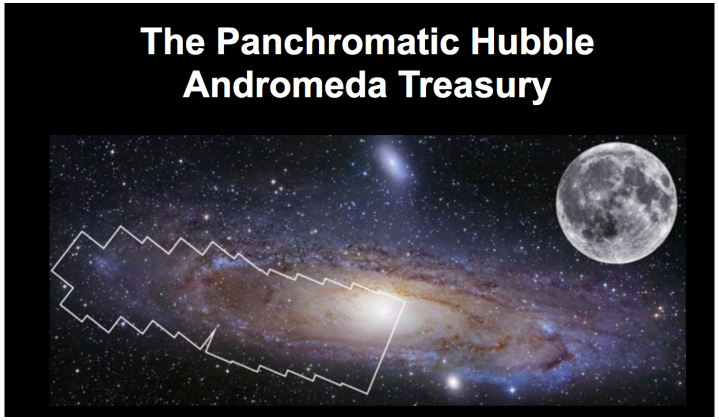
Event rate of PBH microlensing (computed assuming NFW profiles of the MW and M31 halos)

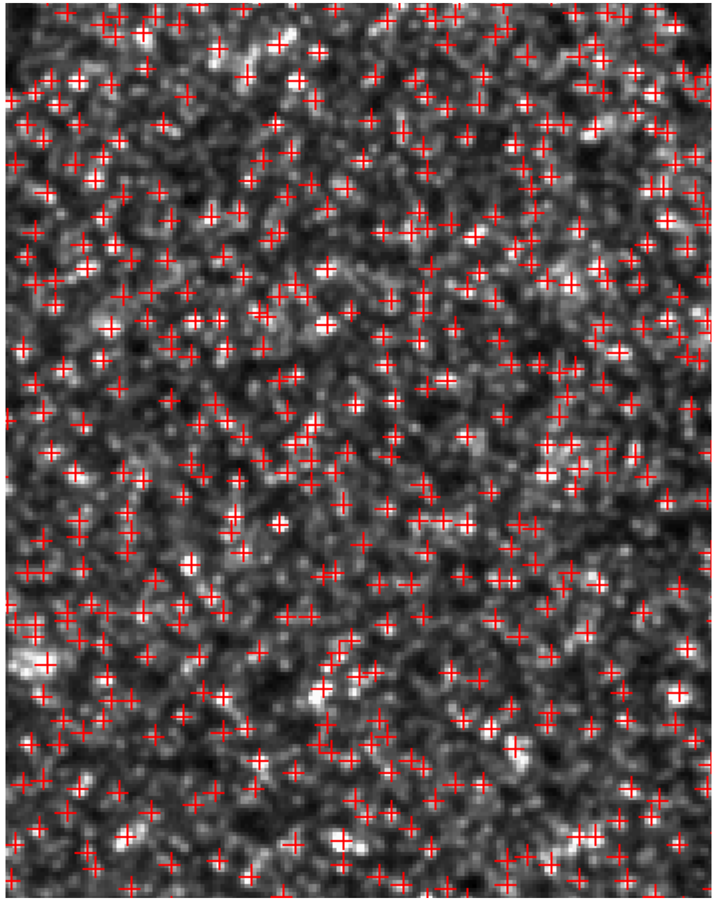
Detection efficiency for microlensing event of timescale t_FWHM for a star of magnitude, m_r (see later)

Number of source stars

HSC can't resolve individual stars due to blending





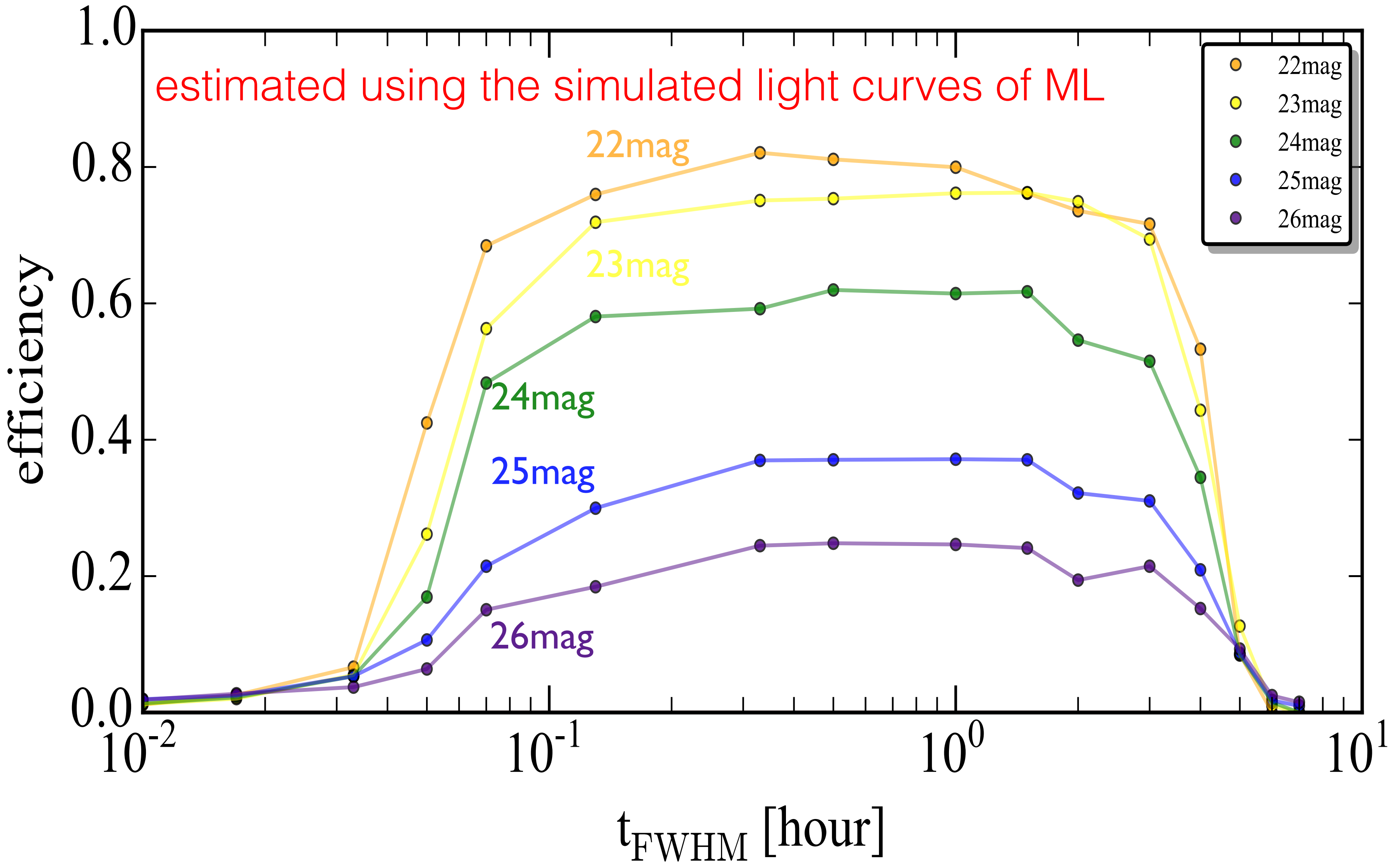


6.4×10^6 HSC peaks (conservative)

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

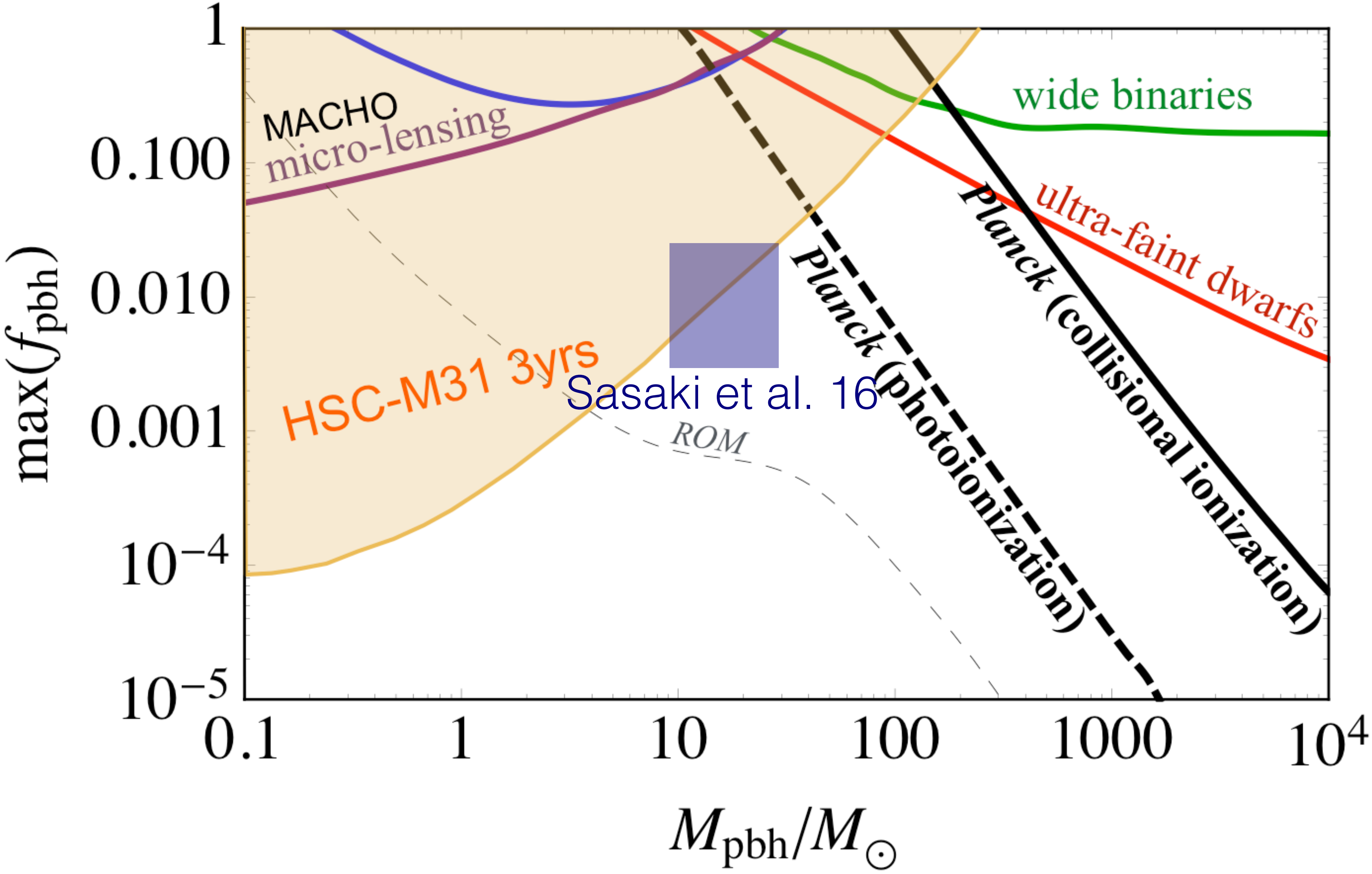
Detection efficiency

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



Prospect for further HSC observation

only one or a few Subaru nights in total, sparsely sampled over 3yrs



Summary

- Used “HSC one-night data” to derive the ***tightest*** upper bound on the abundance of PBHs, in the new window of mass scales $[10^{-13}, 10^{-6}]$Msun
  - 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, …. cosmic string?)
- We should make a **long-term monitor of M31** (microlensing, SNe, direct collapse, …)