PBH search with microlensing

Masahiro Takada

(Kavli IPMU)

Based on collaborations with Hiroko Niikura, Sunao Sugiyama (IPMU), Naoki Yasuda (IPMU), T. Sumi (Osaka), S. More (IUCAA/IPMU), Robert Lupton (Princeton), Toshiki Kurita (IPMU), Misao Sasaki (IPMU), Volodymyr Takhistov (IPMU), Alex Kusenko (UCL/IPMU)

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

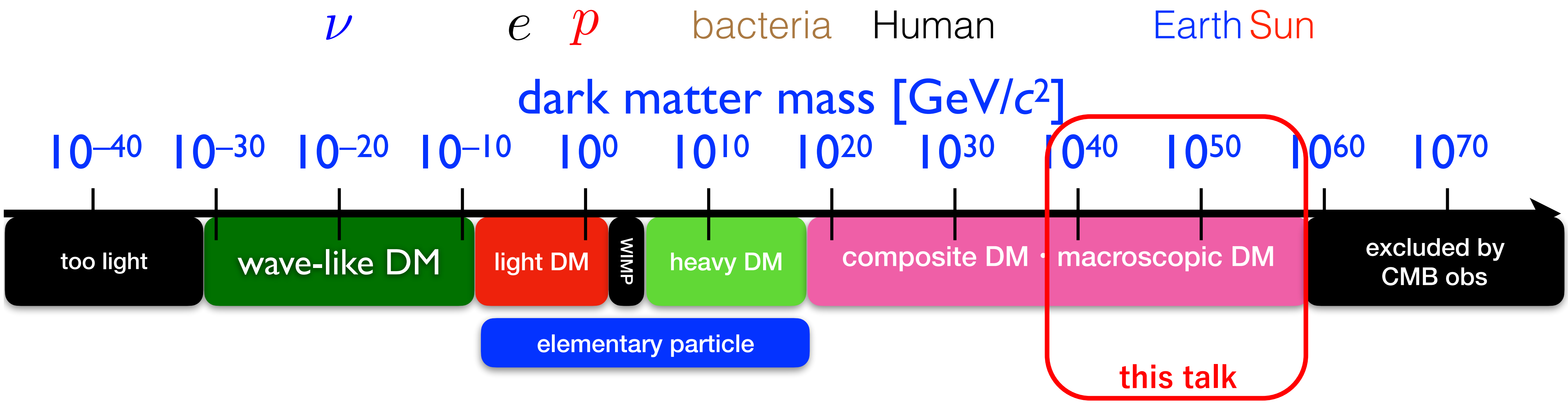
wpi

@AstroDark-2021, Dec 2021

Primordial black hole (PBH) = A viable DM candidate

Zel'dovich & Novikov 67; Hawking 74

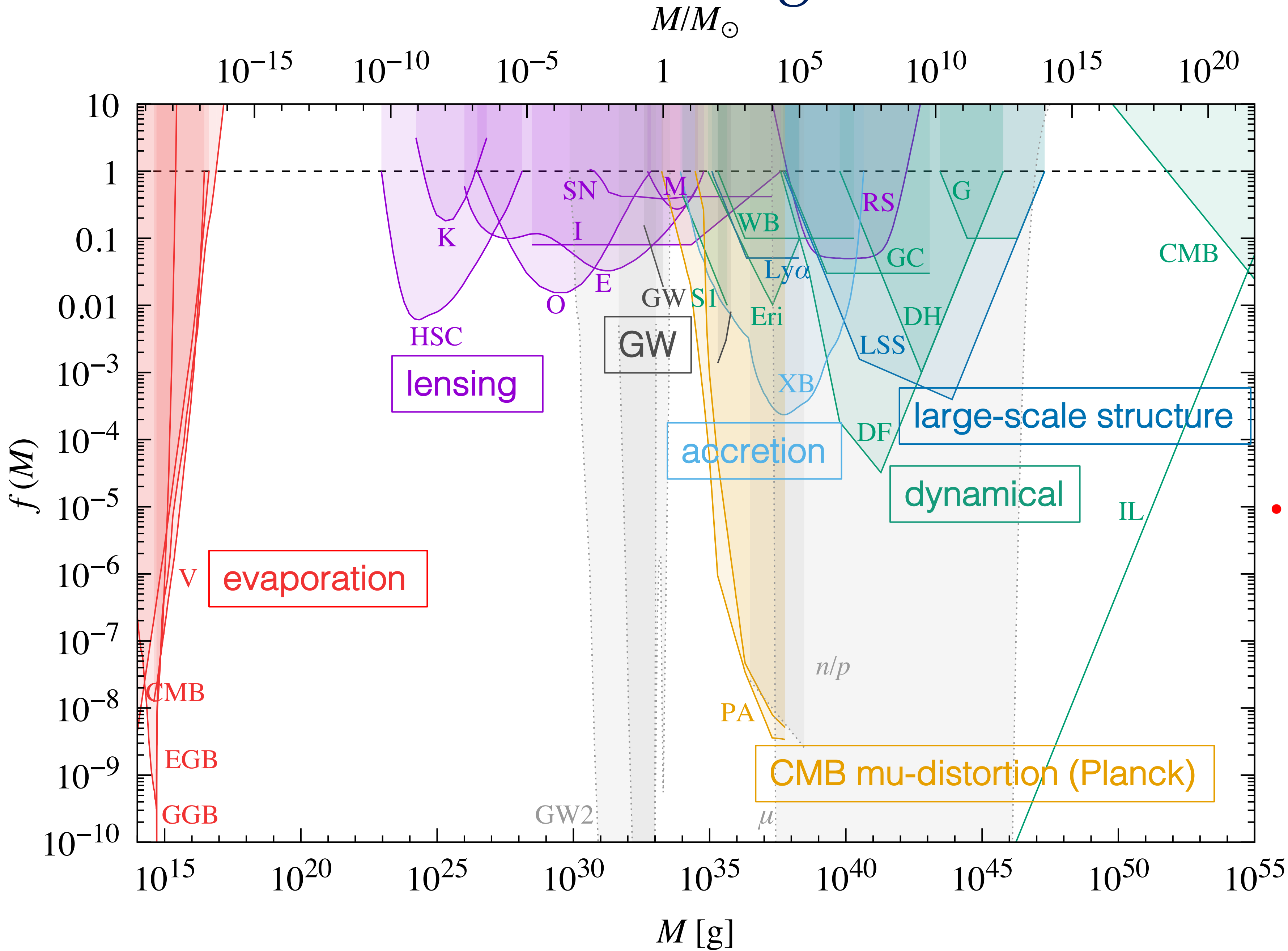
figure: Hitoshi Murayama



macroscopic DM candidate
= PBH, axion stars, …

Astronomical data is a way to explore
this macroscopic DM candidate

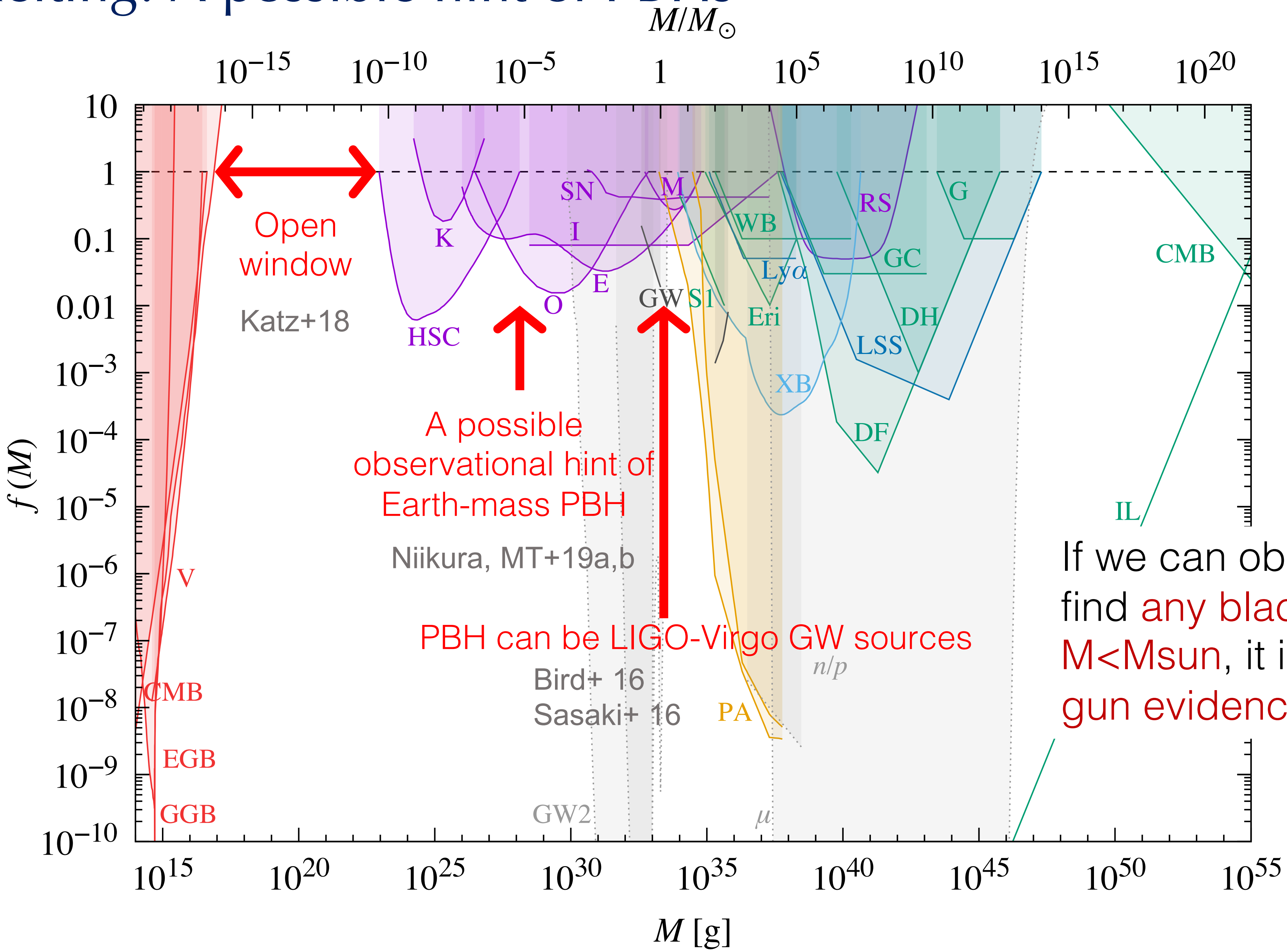
Current status: excluded regions of PBHs



Carr, Kohri, Sendouda & Yokoyama 20

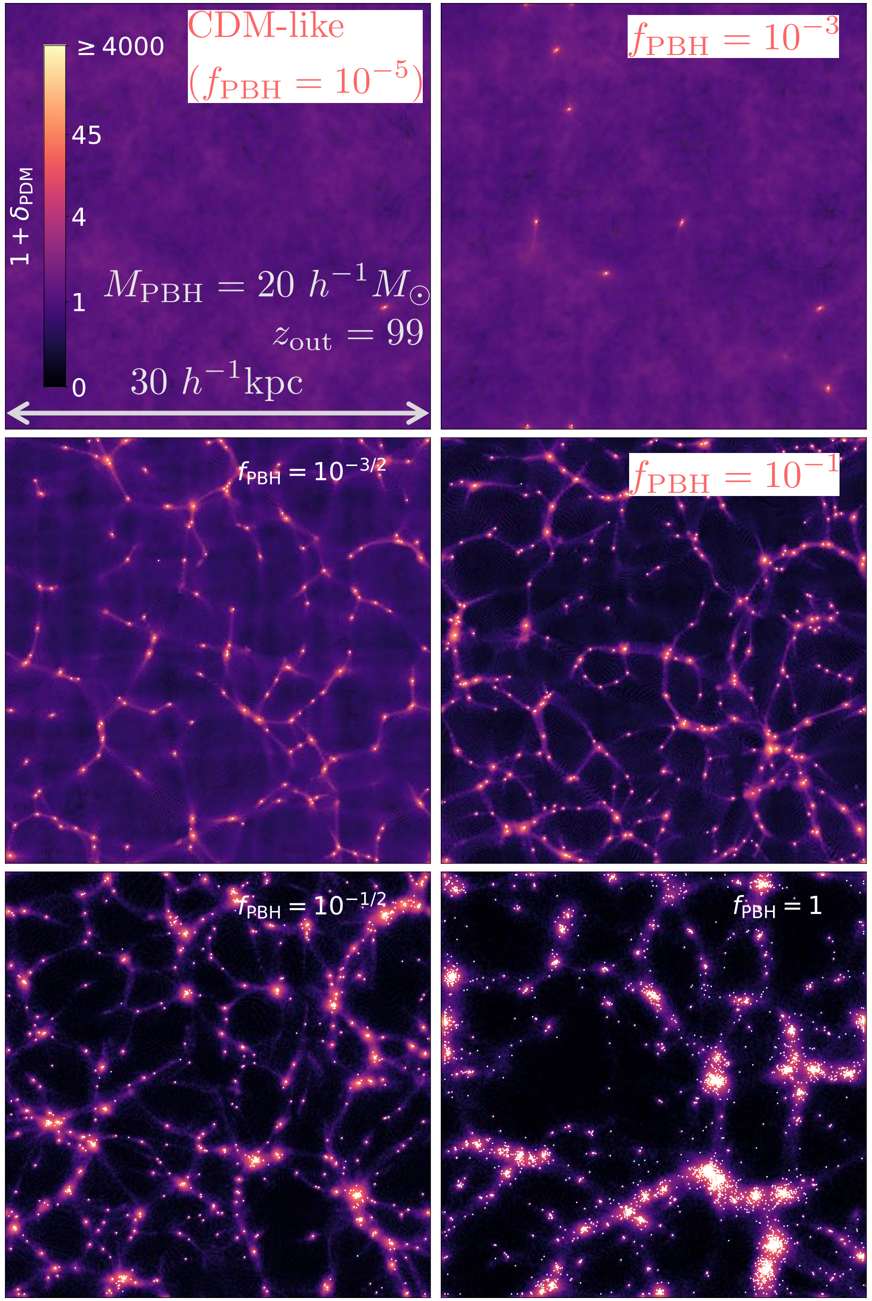
- Assume that all experiments are null results (shaded regions are excluded regions of PBH assuming a monochromatic mass function in x-axis)

More exciting! A possible hint of PBHs

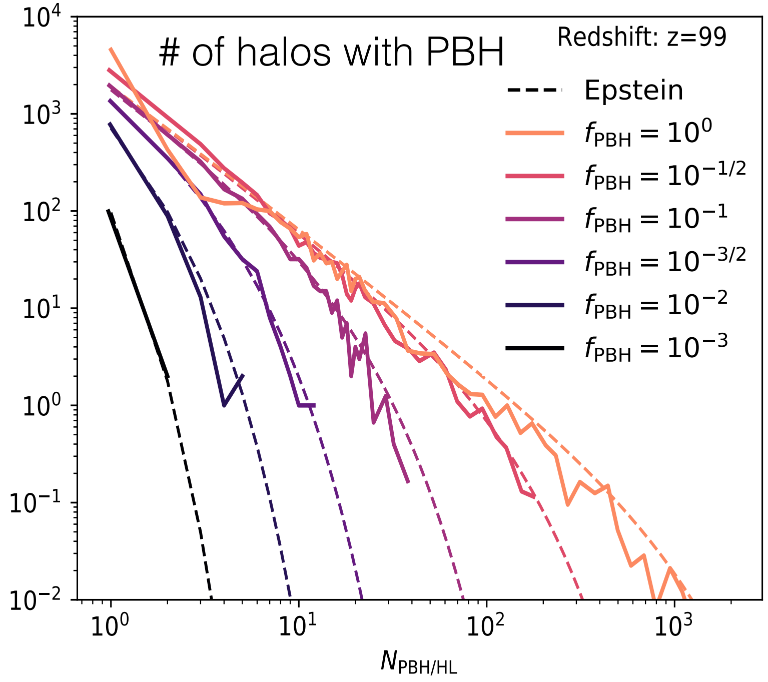


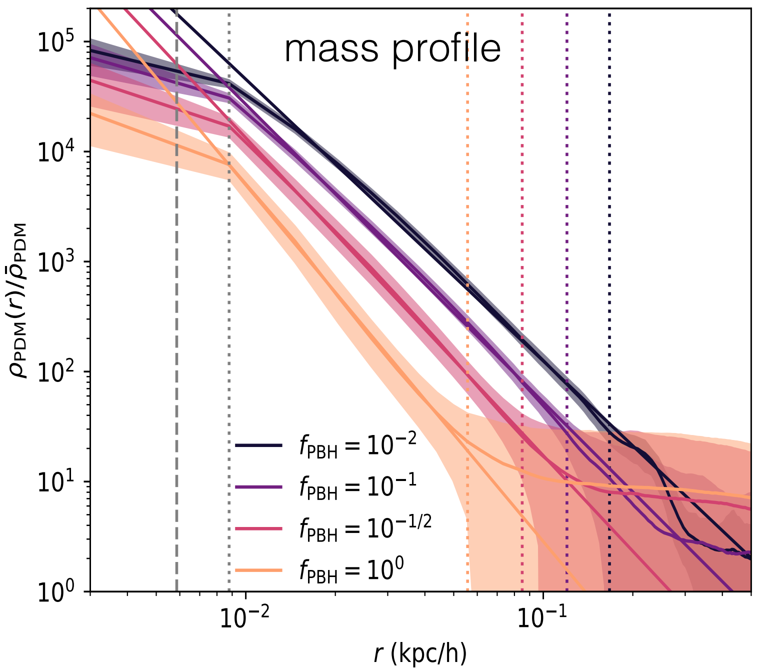
If we can observationally find any black hole with M<Msun, it is a smoking-gun evidence of PBH

Open-minded! PBH+CDM scenario



- Inman & Ali-Haimoud (19) studied structure formation for PBH+CDM model using N-body simulations
- PBH accelerates growth of structure formation
- DM halos containing PBH at the center display a cuspy profile (also see Gosenca, Adamek, Byrnes+17)
- PBH+CDM scenario gives tighter limit on WIMP annihilation signal for dwarfs (or G.C.) (also might be relevant for cuspy profile of Draco in Mariangela's talk for SIDM).





Microlensing: robust, powerful method to search for invisible PBH

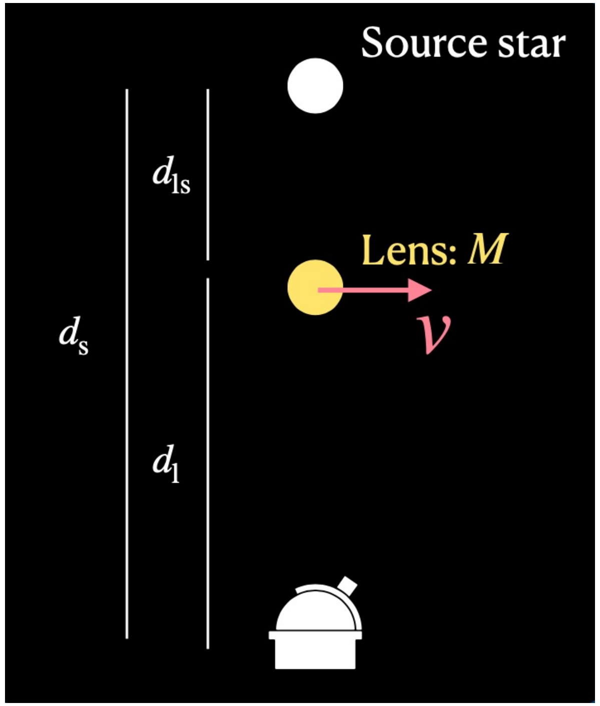
Paczynski 86; Griest 91

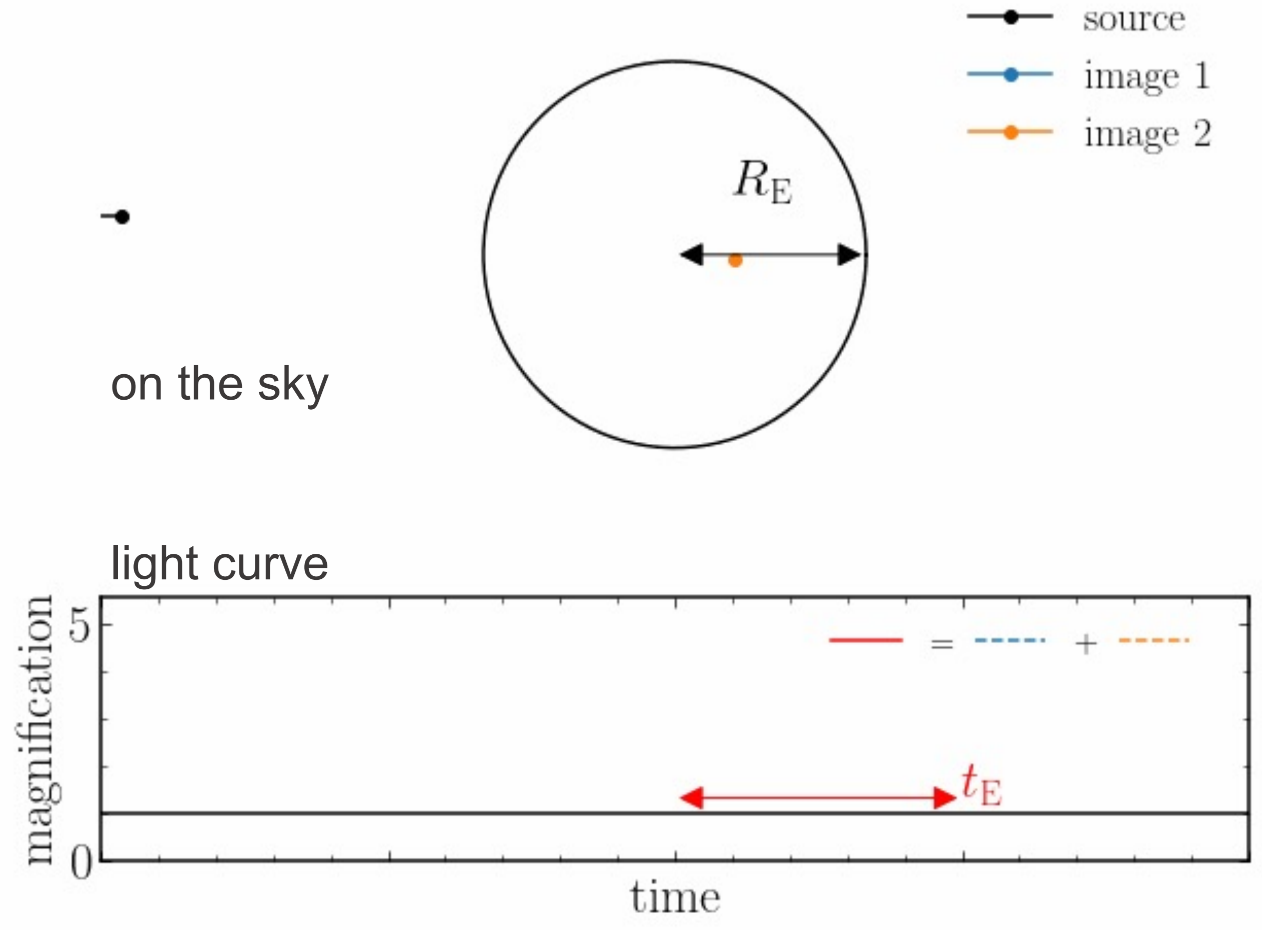
- Microlensing occurs when observer-lens-source are almost aligned
- Einstein radius

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

- Light curve timescale

$$t_E \sim \frac{2R_E}{v_{\rm rel}}$$



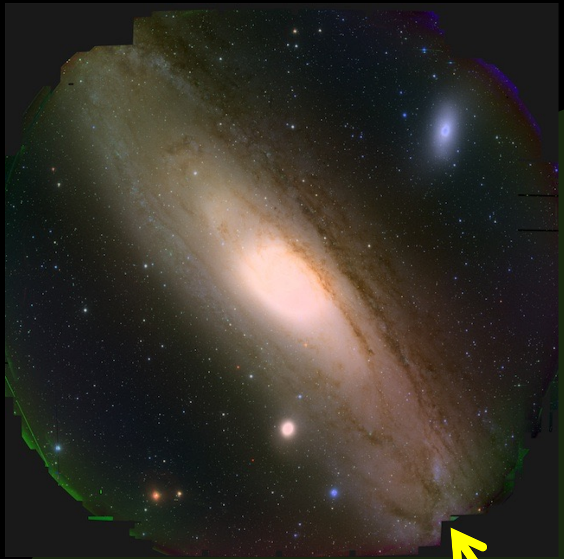


credit: Sunao Sugiyama

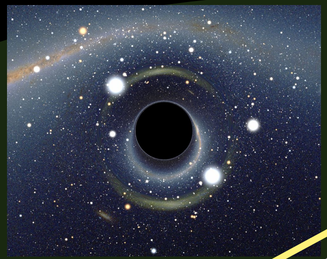
Microlensing experiment

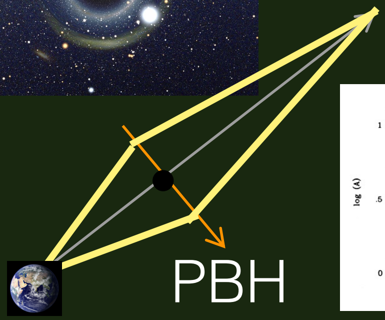
- What we need are …
  - Need a wide field-of-view camera (plus large-aperture telescope if possible)
  - Need a monitoring observation of the same stars in a target region (LMC, Galactic bulge and Andromeda galaxy (M31))
- Previous and ongoing microlensing experiments
  - MACHO (1992-99: 1.27m, Alcock+00, 01: LMC), OGLE (1992-: 1.3m, LMC/G.C.), EROS-I/II (90-03: 1.5m, LMC, G.C.), EROS2 ...
  - For M31, several attempts were made, but face difficulty (pixel lensing) (e.g., Novati 10 for a review)
  - Griest+ (2014) used the public Kepler data to search for PBH microlensing
  - Subaru HSC microlensing observations for M31 (PI: Takada: 2014 -)
- Upcoming experiments (more focused on exoplanet search, but the same data can be used for PBH search)
  - VRO LSST (G.C.), PRIME (PI: T. Sumi, Osaka U.: G.C.), Roman Space Telescope (G.C.), ….

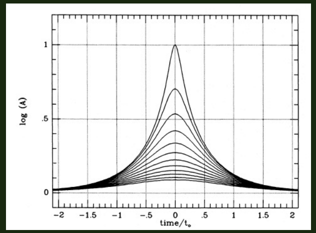
Search of PBH with microlensing

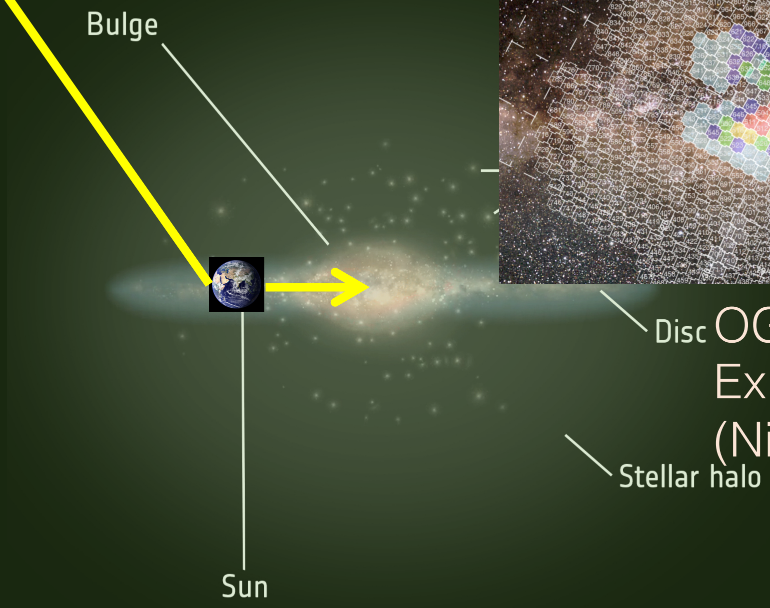


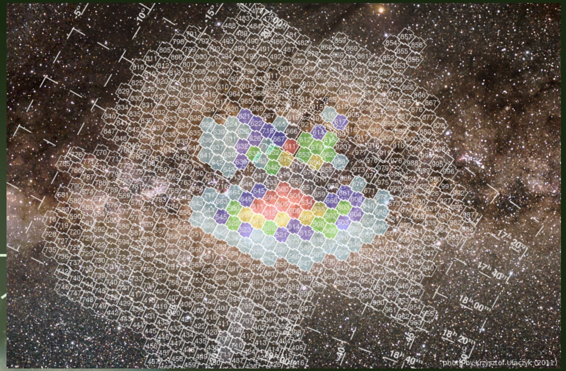
HSC M31 PBH
microlensing search
(Niikura, MT+Nature Astron. 19)









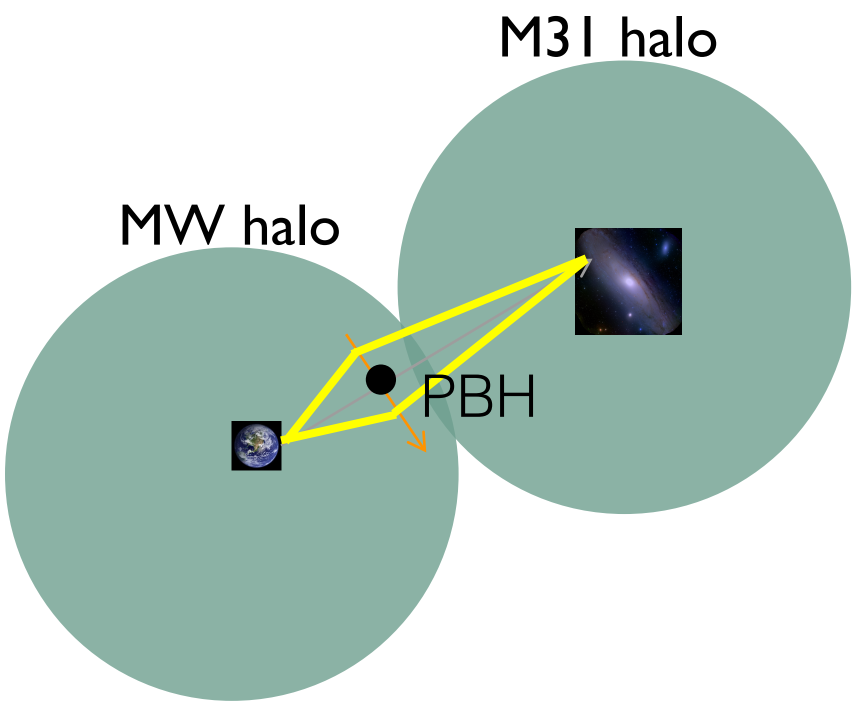


OGLE (Optical Gravitational Lensing
Experiment) for PBH search
(Niikura, MT+, PRD 19)

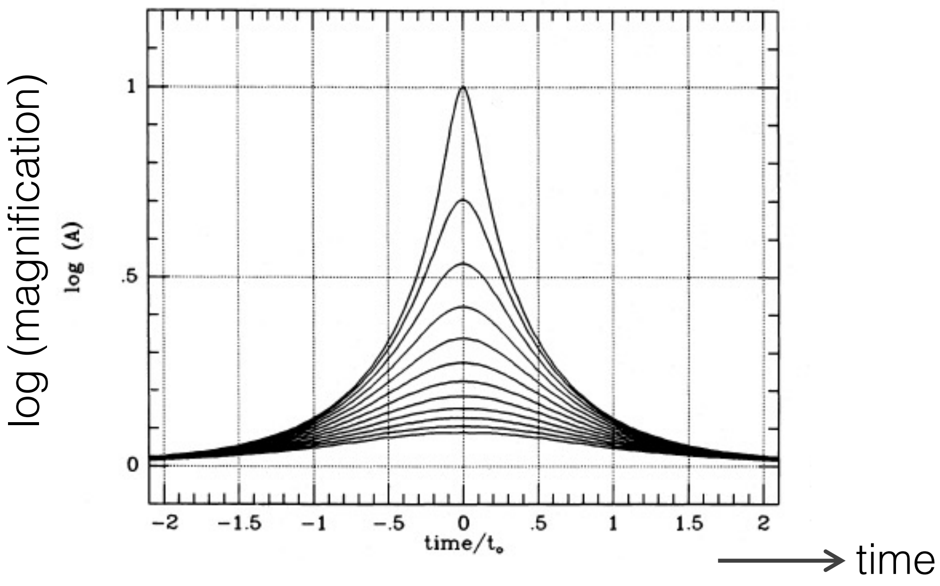
PBH microlensing of M31 star

- For a case to monitor many stars in Andromeda galaxy (M31) (stars in M31 are sources for ML)
- Lensed image can't be resolved with optical resolution (~10^{-8} arcsec) ⇒ only light curve is a signal
- MW/M31 halos known to be ~ 10^{12}Msun within a factor of 2 (e.g. NFW models)
- PBH has a peculiar velocity of ~200km/s
- ~1000 expected events for one night if PBH is DM in the MW and M31 halo regions and if we can monitor 10^8 stars
- Need to monitor brightness of the same star as a function of "time" (time domain astronomy)

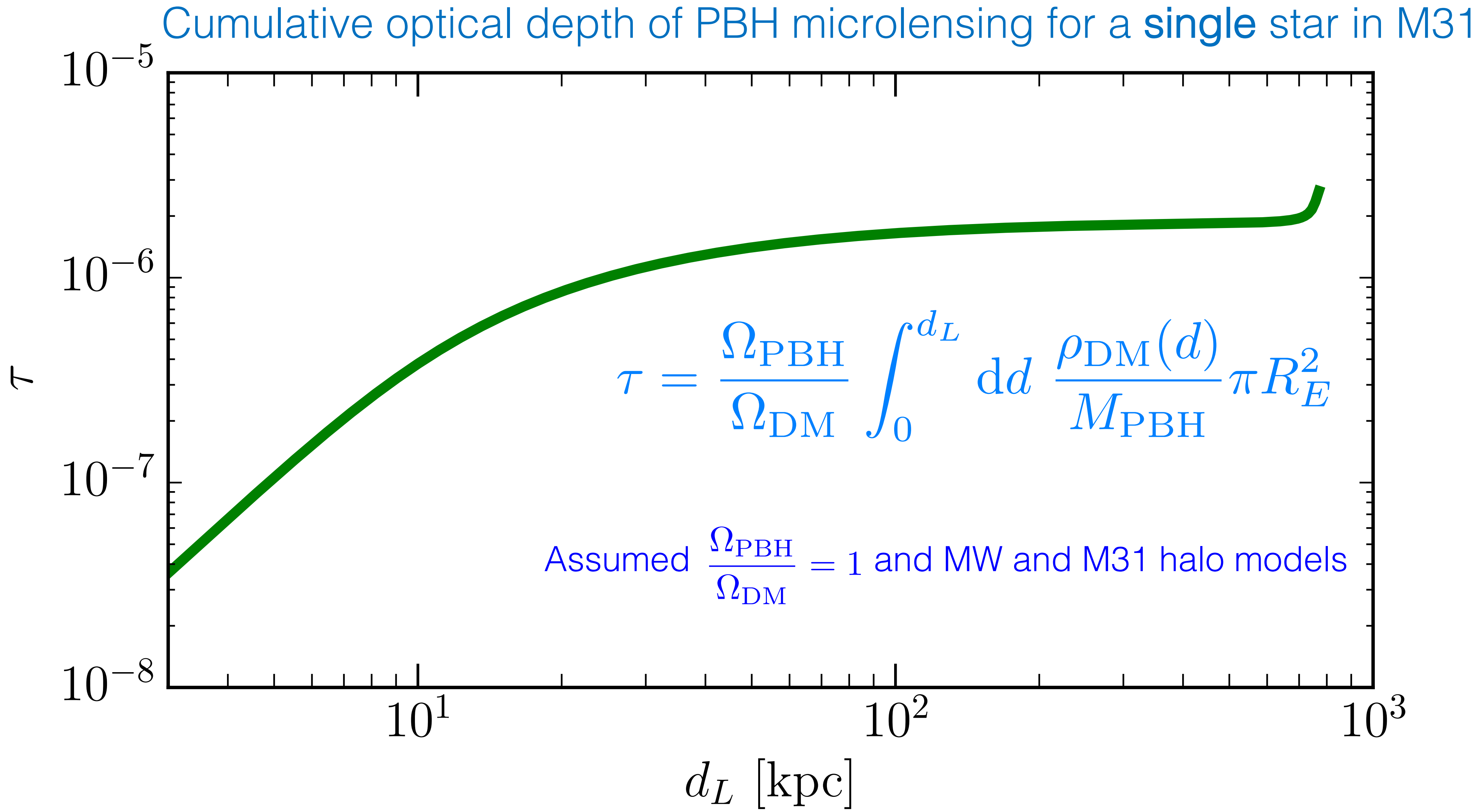
$$R_E = \sqrt{\frac{4\pi G M_{\rm PBH} d(1-d/d_s)}{c^2}}$$



Paczynski 86



PBH microlensing optical depth for a M31 star



If we observe **~10^6 stars** at any given moment, **one star at least** should be micro-lensed if PBHs are DM
(a microlensing optical depth for a star in LMC or Galactic bulge is also similar, ~10^{-6})

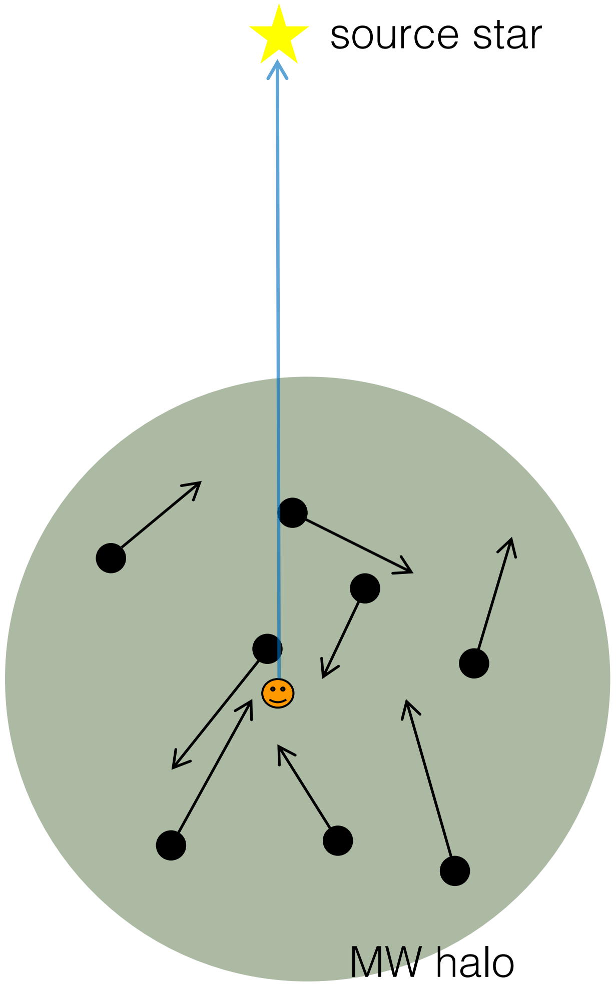
Event rate of microlensing with light curve of a given timescale

Griest 91

- Differential event rate [events/sec/sec]
  - Need to model velocity distribution of PBHs, e.g. the model that reproduces the random virial motions

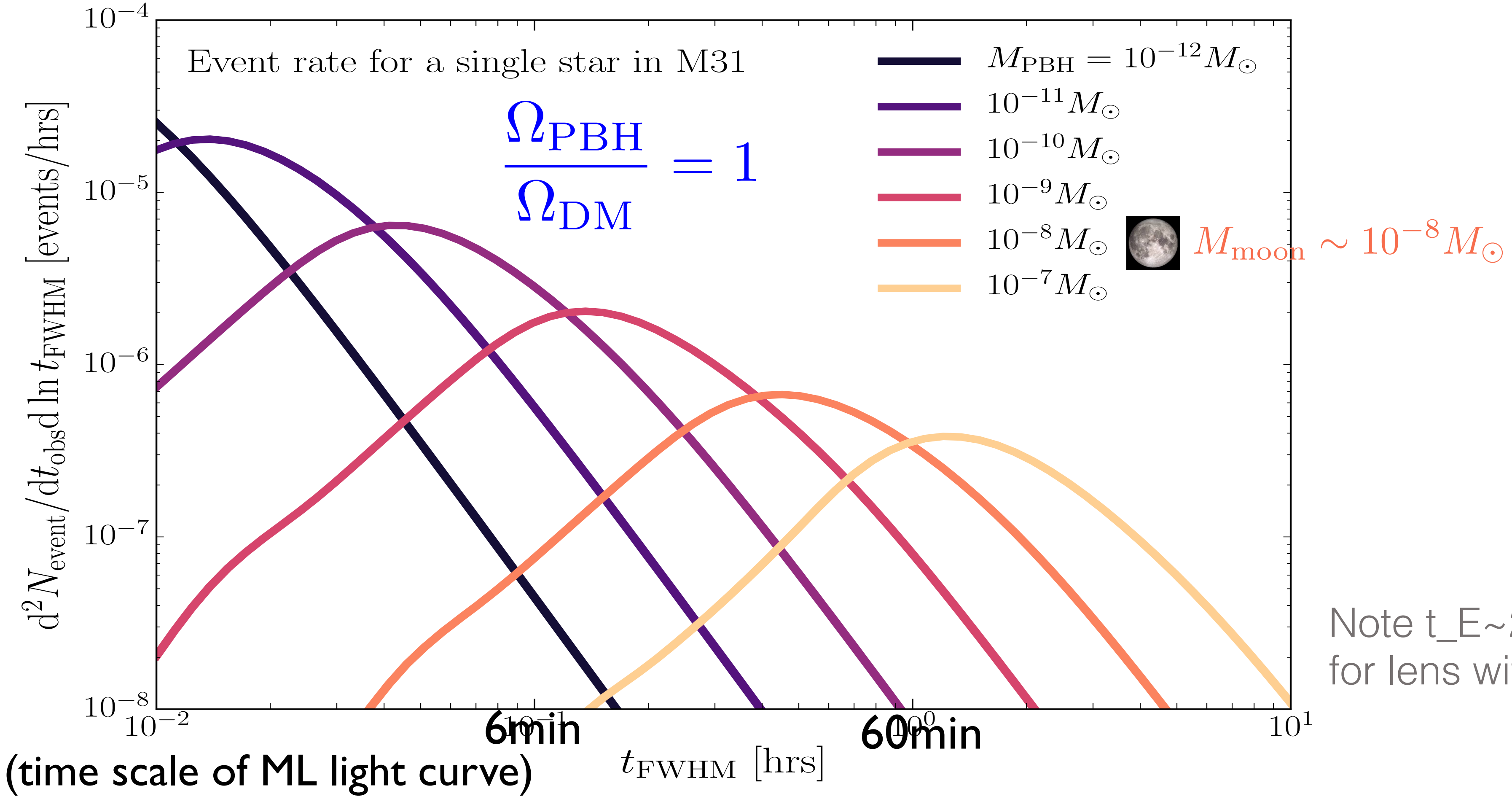
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}t_E} = \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}}\int_0^{d_\mathrm{s}} \mathrm{d}d_\mathrm{l}\,\frac{\rho_{\mathrm{DM}}(d_\mathrm{l})}{M_{\mathrm{PBH}}} 2\pi R_E(d_\mathrm{s}, d_\mathrm{l}) \times \int_0^{\infty}\mathrm{d}v_\perp \int_{-\pi/2}^{\pi/2}\mathrm{d}\theta\; v_\perp^2 \cos\theta\, f_{\mathrm{DM}}(v_\perp,\theta)\,\delta_D\left(t_E - \frac{2R_E\cos\theta}{v_\perp}\right)$$

$$= \pi\frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}}\int_0^{d_\mathrm{s}} \mathrm{d}d_\mathrm{l}\,\frac{\rho_{\mathrm{DM}}(d_\mathrm{l})}{M_{\mathrm{PBH}}}\int_{-\pi/2}^{\pi/2}\mathrm{d}\theta\; v_\perp^4 f_{\mathrm{DM}}(v_\perp,\theta)\Big|_{v_\perp = 2R_E\cos\theta/t_E}$$

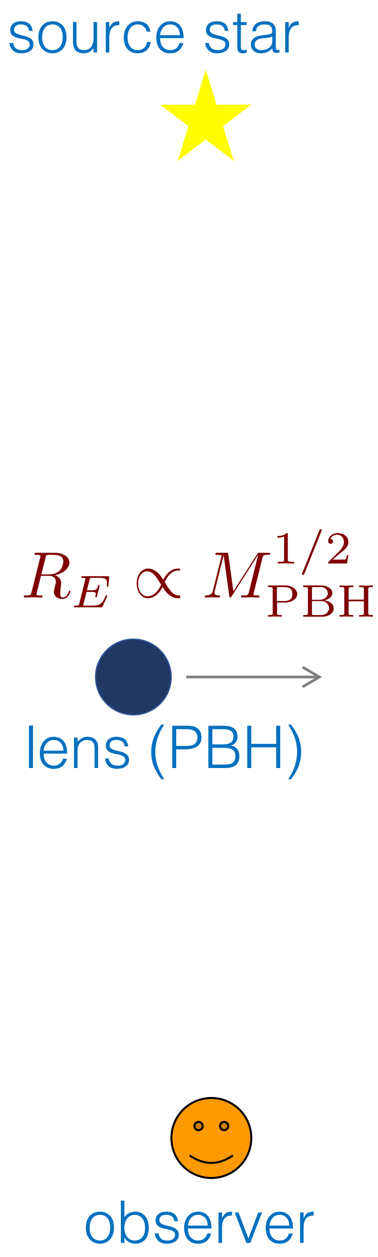


PBH microlensing event rate

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



Note t_E~200 days
for lens with M_sun

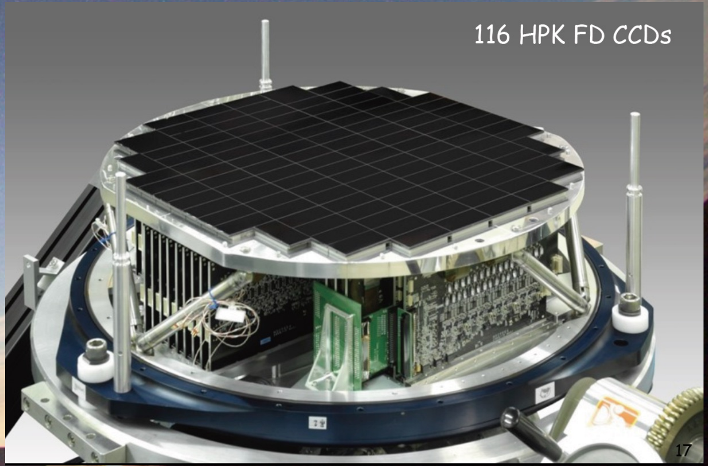


Event rate per **unit obs. time** and per **a single star** in M31 for **a given timescale of light curve: 10^{-6} = one event per one source million stars (we monitored ~10^8 stars)**

Subaru Hyper Suprime-Cam (HSC)

- Large aperture (8.2m)
- Wide FoV = 9×full moon
- ~1G pixels (104 CCDs)
- Most powerful instrument for microlensing (before VRO LSST)

Kavli IPMU+NAOJ+Princeton+ASIAA

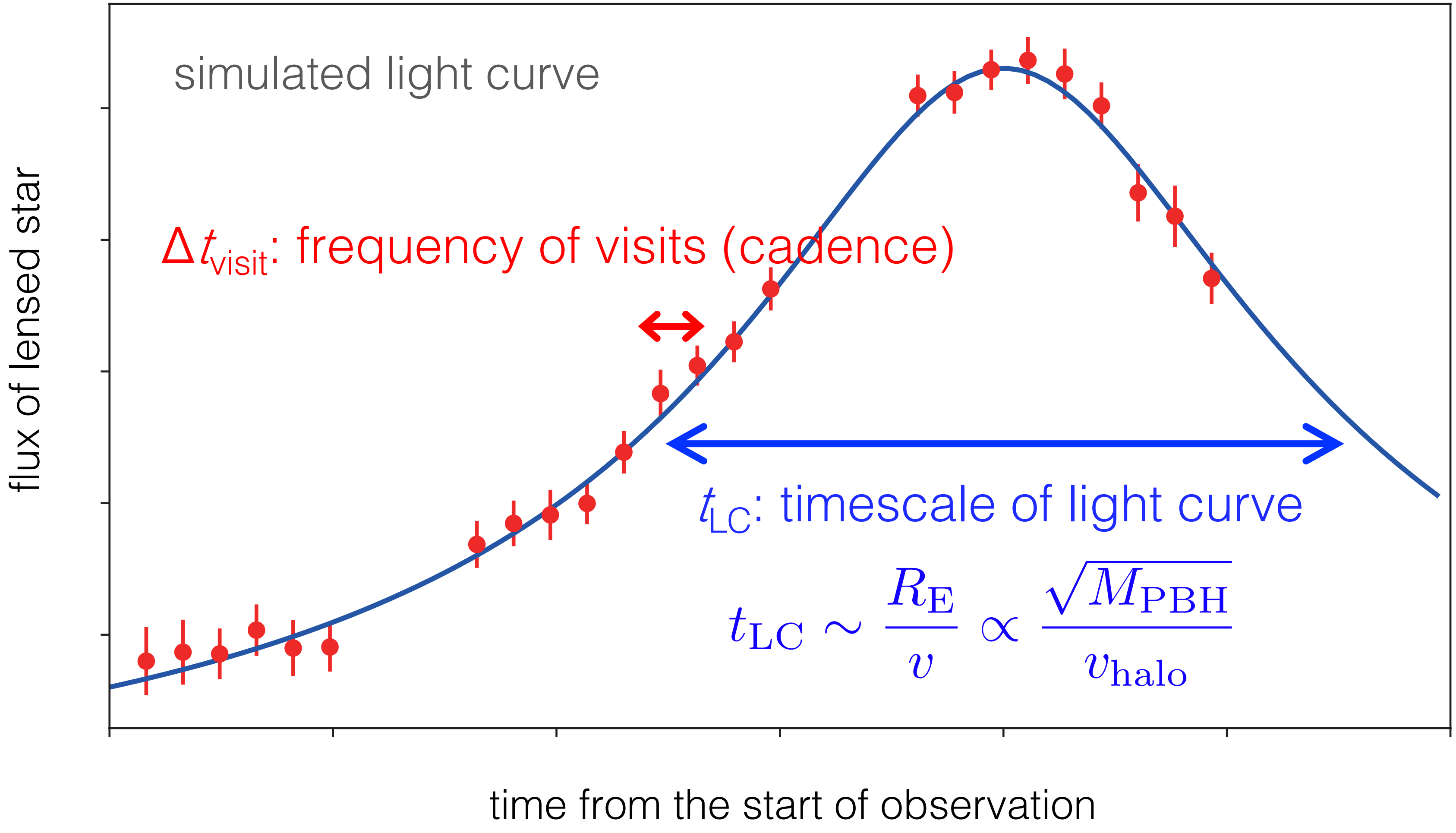


Microlensing search of stars in Andromeda Galaxy (M31)

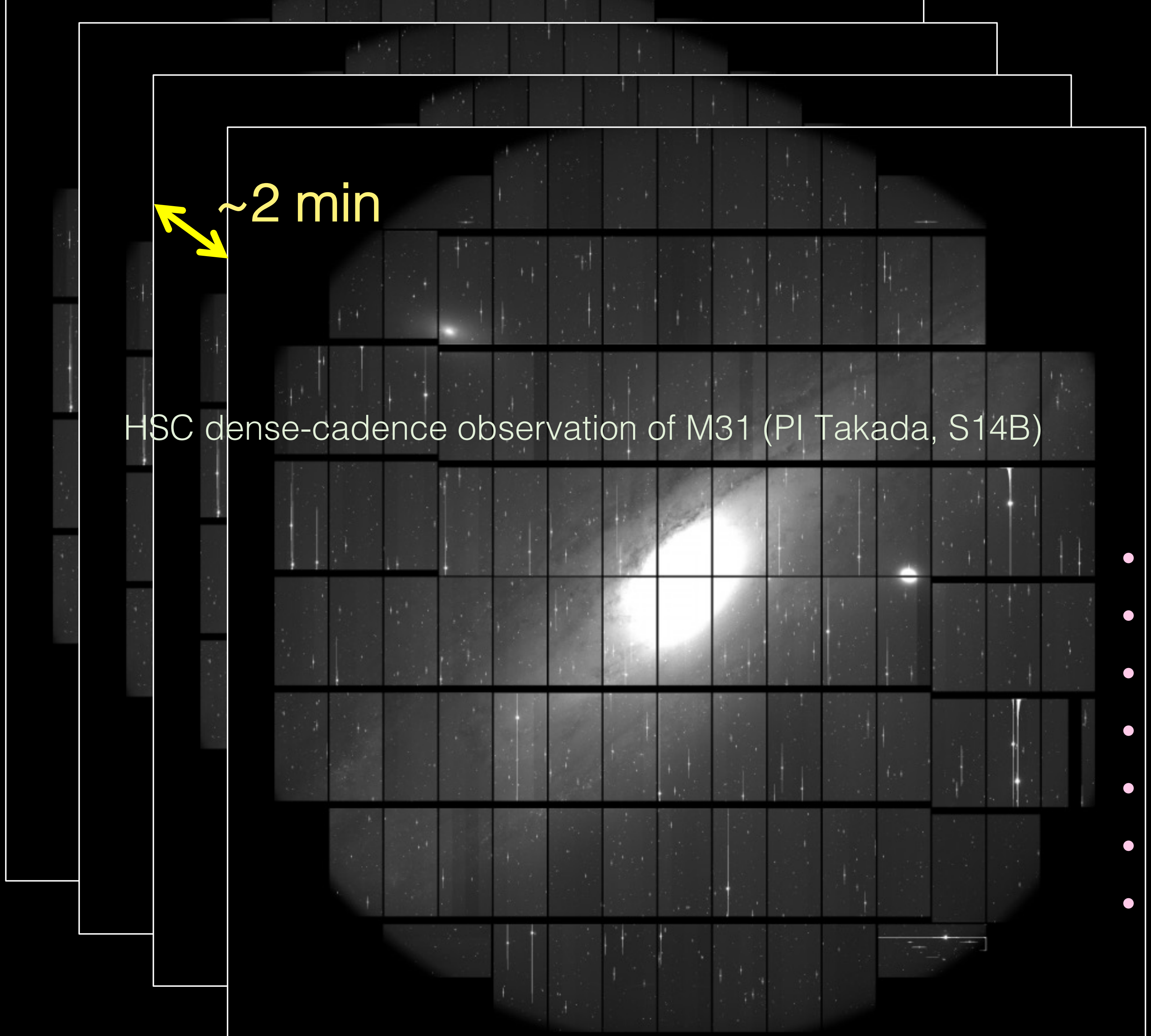
- In the northern hemisphere (not accessible from VST, DES, LSST)
- Large spiral galaxy
- HSC FoV ~ entire M31 (neither too closer nor too far!)
- ~770kpc (μ~24.4), reachable distance (not too far)!

Rule of the game: light curve timescale vs. cadence

Design the ML observation satisfying the condition $\Delta t_{\rm visit} \sim \frac{t_{\rm LC}}{O(10)}$



- ✓ As many stars to monitor as possible (M31, GC bulge, LMC)
- ✓ “right” cadence for a target light-curve timescale (short time-scale cadence for light-mass PBH, and vice versa)
- ✓ Shortest timescale is limited by CCD readout (Subaru HSC CCD has 30sec readout time, while VRO LSST CCD has 2 sec)
- ✓ Longest timescale = a duration of observation

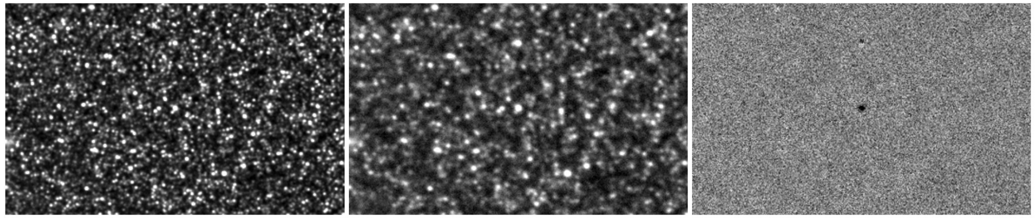


Hiroko Niikura (PhD 2016)

- Nov 2014
- 90sec exposure each (r-band)
- ~35sec readout
- ~190 exposures
- No dithering
- one clear night (seeing~0.5-0.6'')
- Also used g-band data (from commissioning run)

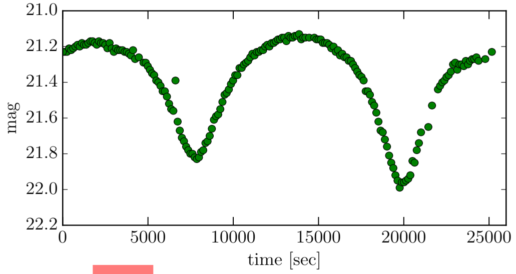
Procedures: search for ML events

difference image (coadds of 3 exposures)



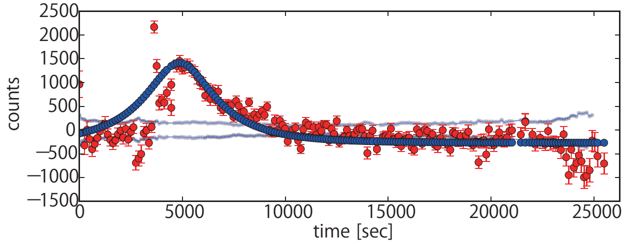
identify candidates in each diff. image
⇒15,571

measure light curve (188 data points)



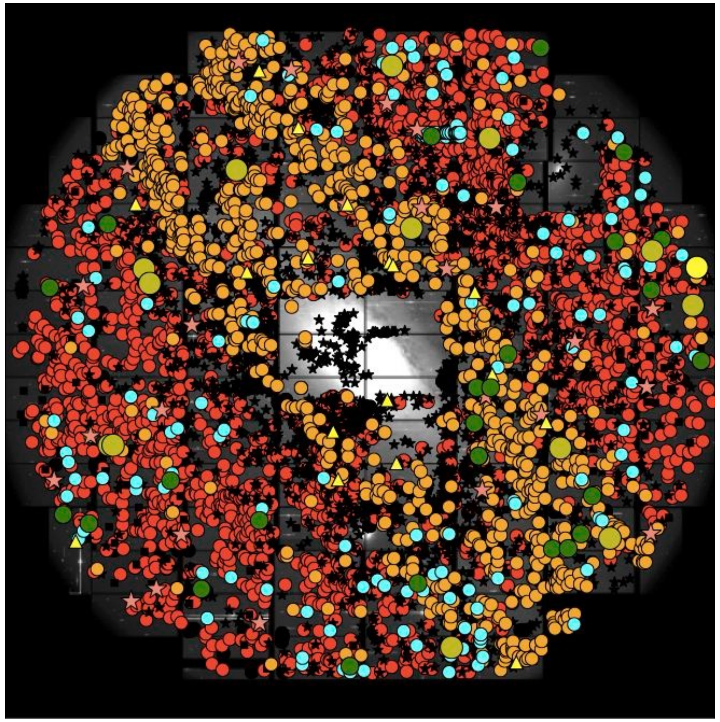
candidates with bump-like light curve
⇒ 11,703

fitting of LC to the microlensing model

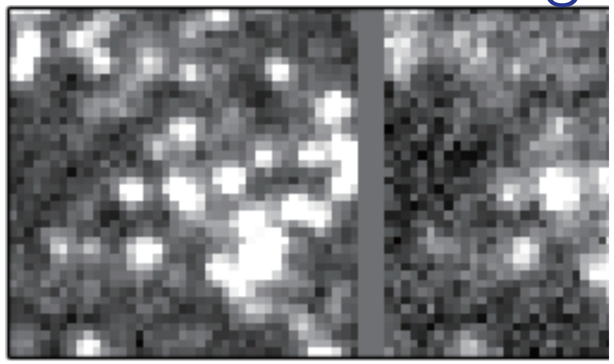


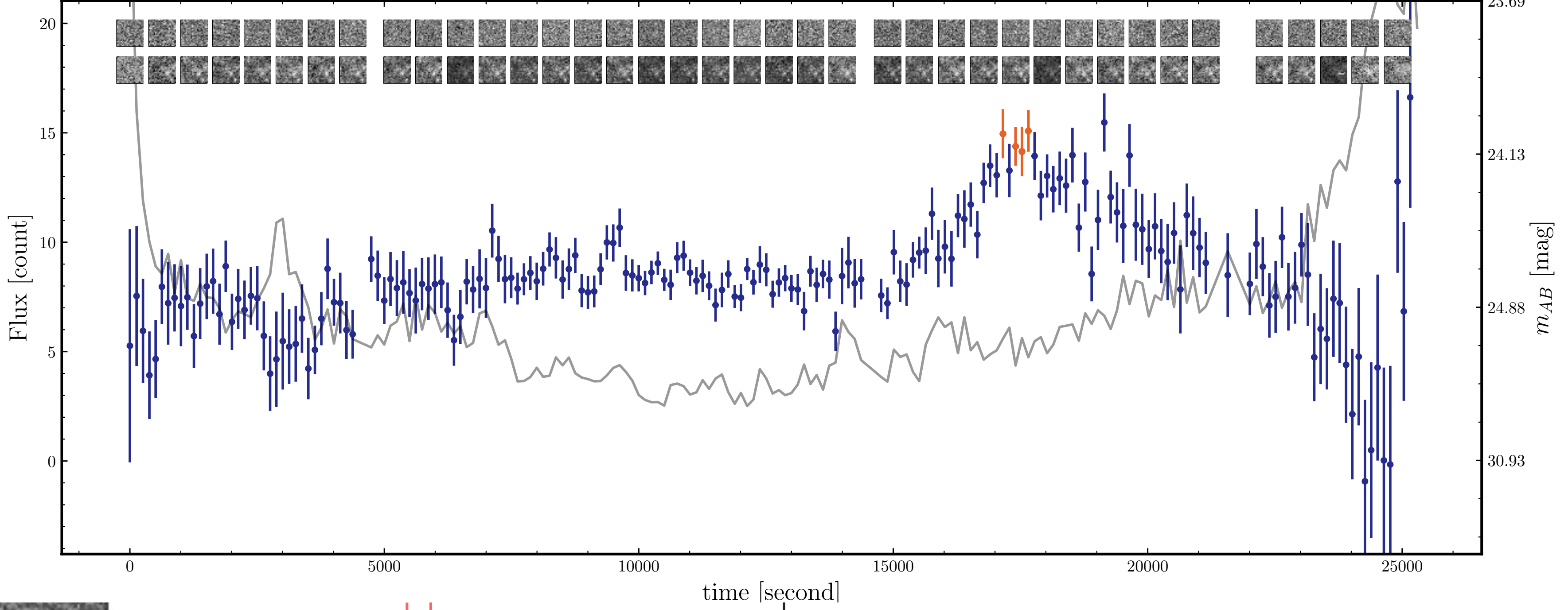
selection criteria
⇒ 66

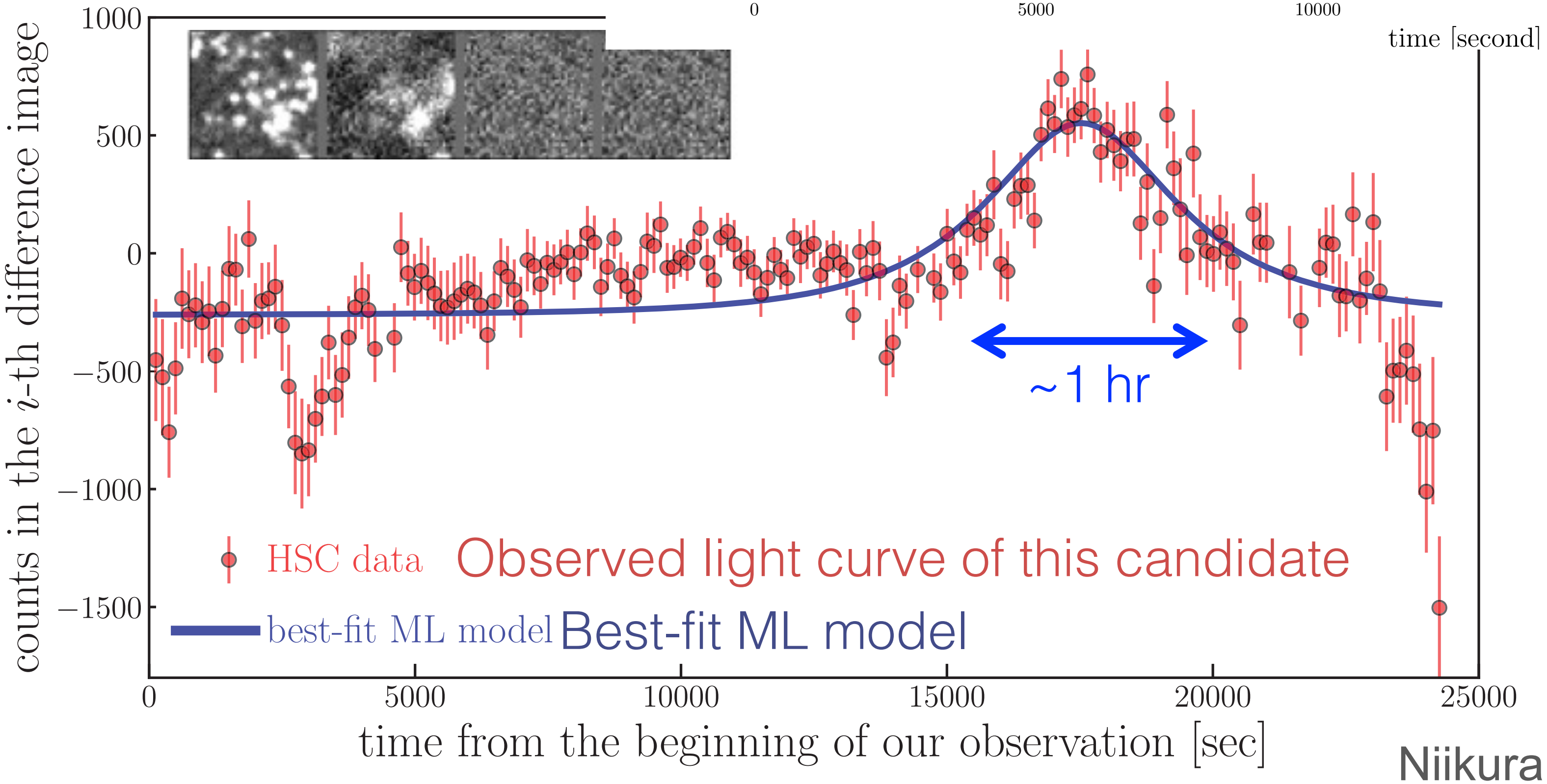
visual inspection of individual candidates…



One possible microlensir compared to expected ~







confirmed with the latest HSC pipeline (based on the LSST stack)

Sunao Sugiyama
(Kavli IPMU)

Niikura, MT+ 19, Nature Astronomy

Expectation number of ML events of a given timescale t_E

$$N_{\mathrm{ML,exp}} \simeq N_{\mathrm{s}} \times t_{\mathrm{obs}} \times \frac{d\tau}{dt_E} \times \epsilon(t_E)$$

N_{s}: # of source stars – depends on target gals (M31, LMC, Galactic bulge), tel. aperture, seeing, …

t_{obs}: total observation time (duration of monitoring observation)

$\frac{d\tau}{dt_E}$: ML optical depth – depends on the number of compact objects (MS, WD, NS, BH) … PBHs (assume, for M31, that all lenses for are PBHs)

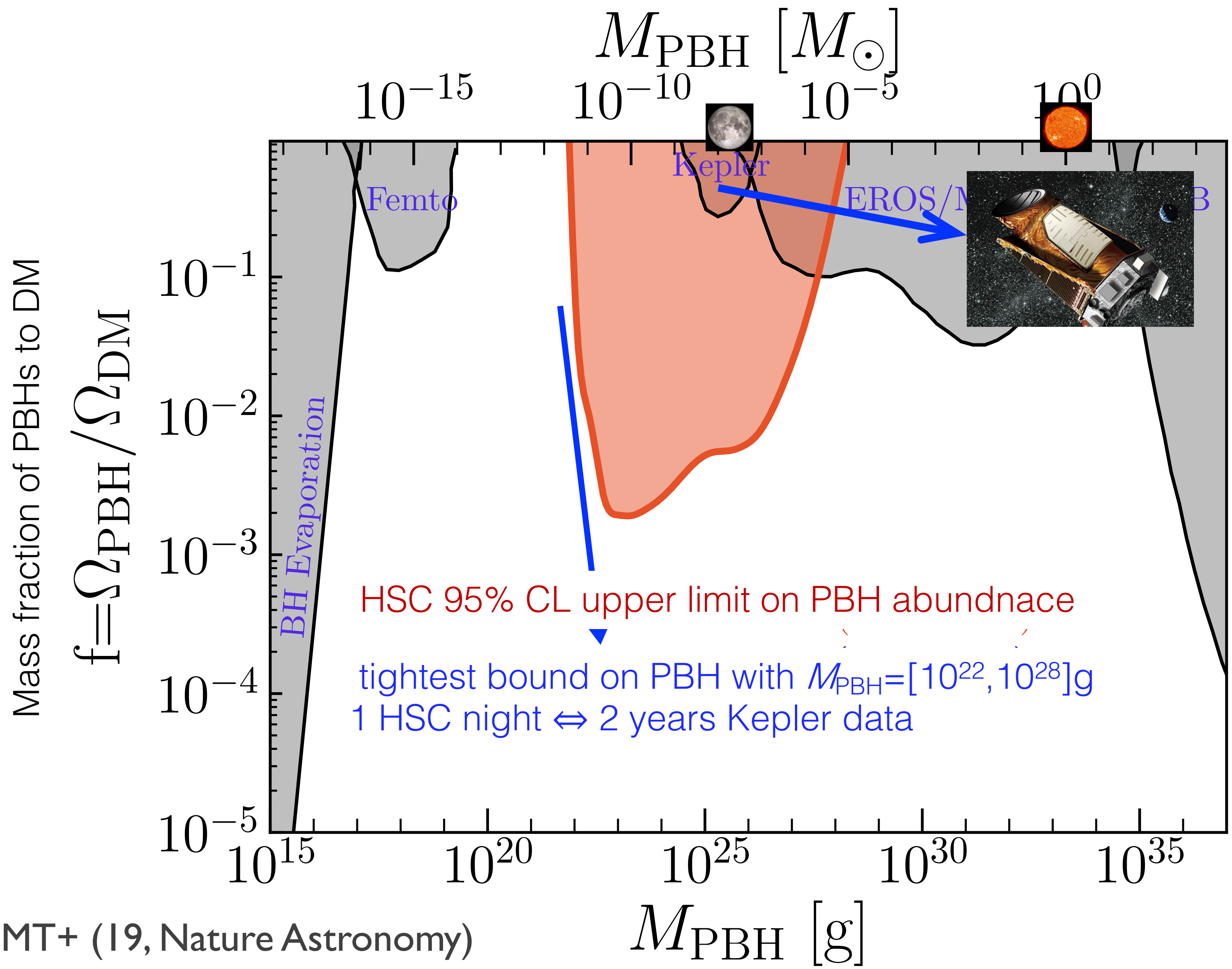
$\epsilon(t_E)$: efficiency – depends on cadence and quality of data

$$R_{\mathrm{E}} = \sqrt{\frac{4\pi G M_{\mathrm{PBH}} d_{\mathrm{PBH}} (1 - d_{\mathrm{PBH}}/d_{\mathrm{s}})}{c^2}}$$

$$t_{\mathrm{E}} \simeq \frac{R_{\mathrm{E}}}{v}$$

$$\frac{d\tau}{dt_{\mathrm{E}}} \propto \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}}$$

Subaru/HSC constraint on PBH abundance

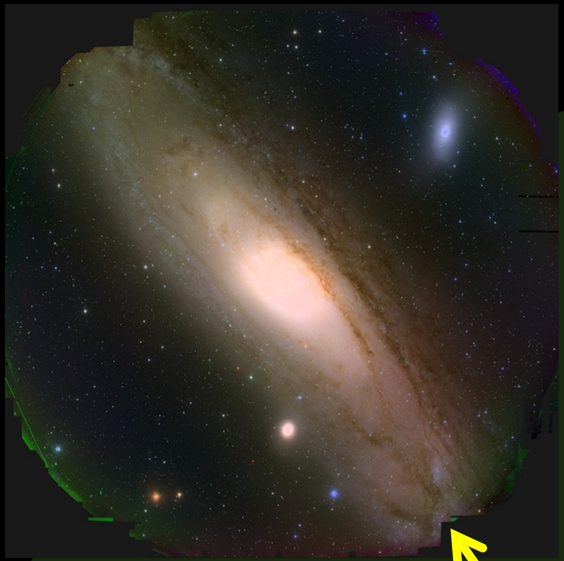


Sunao Sugiyama
(Kavli IPMU)

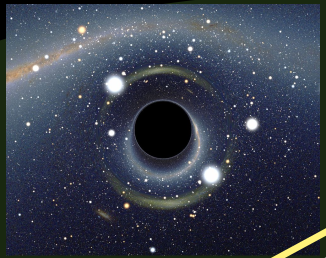
Sunao is now working on 2014, 16, 20 datasets with the latest HSC pipeline

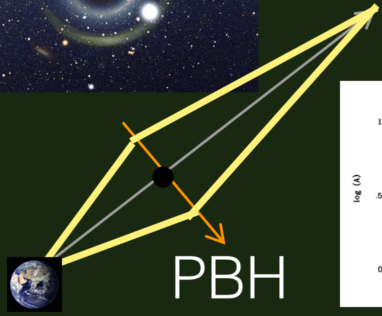
Niikura, MT+ (19, Nature Astronomy)

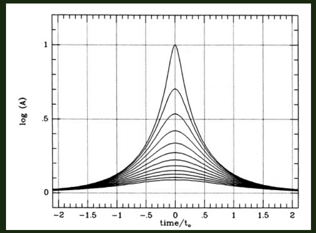
Search of PBH with microlensing

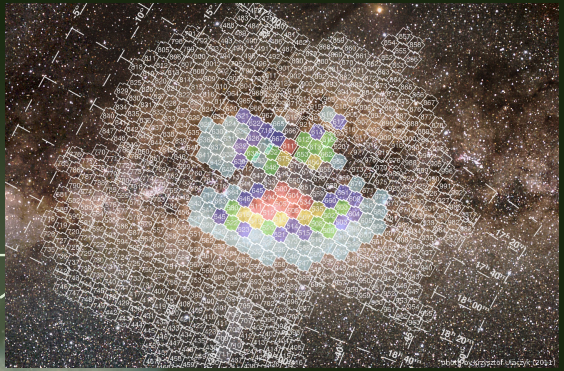


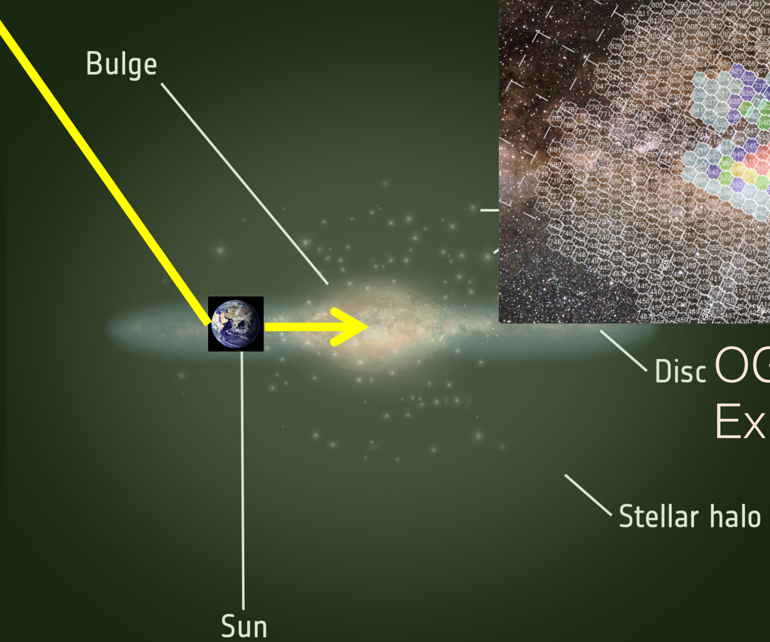
HSC M31 PBH
microlensing search







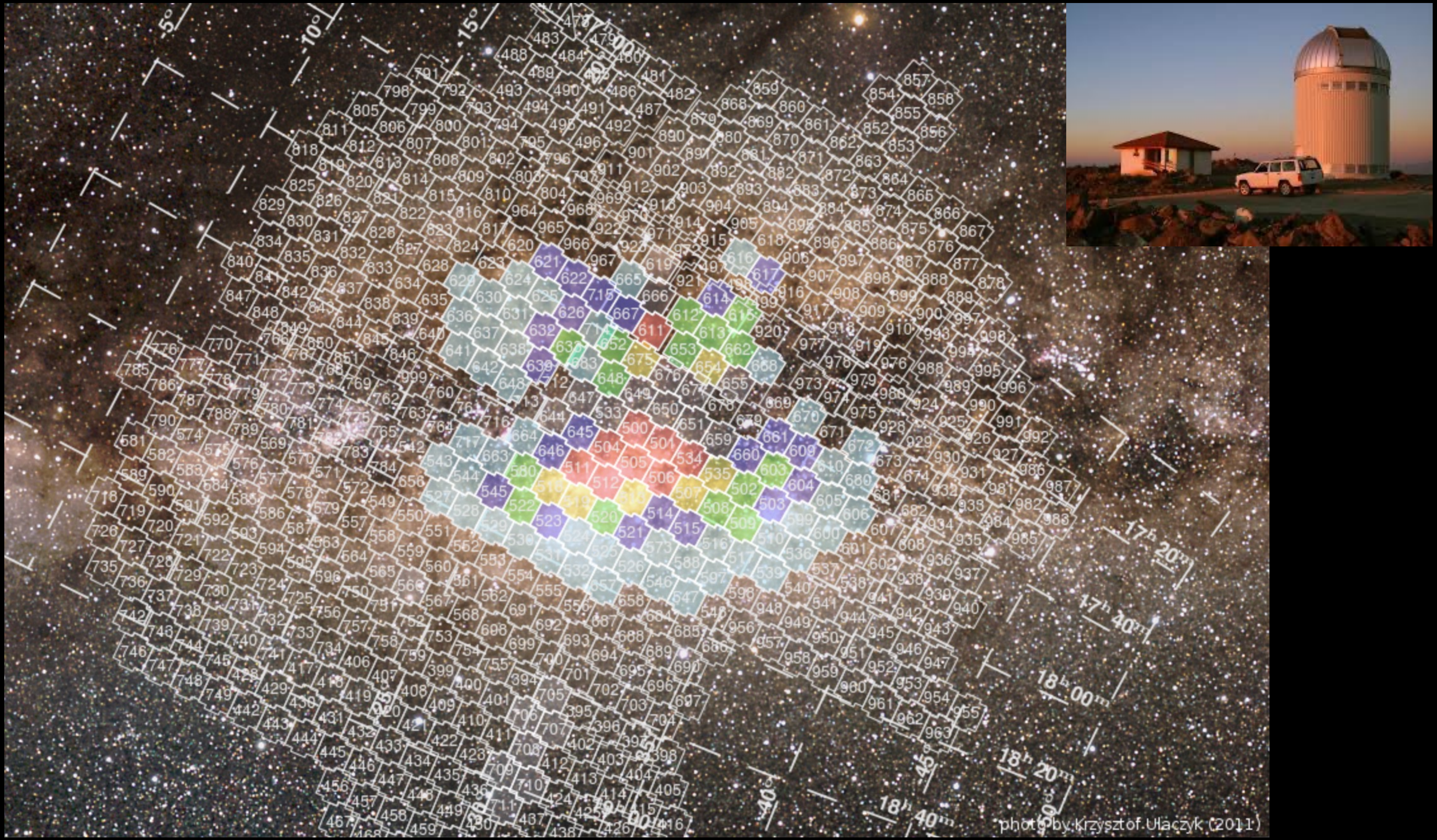




OGLE (Optical Gravitational Lensing
Experiment) for PBH search

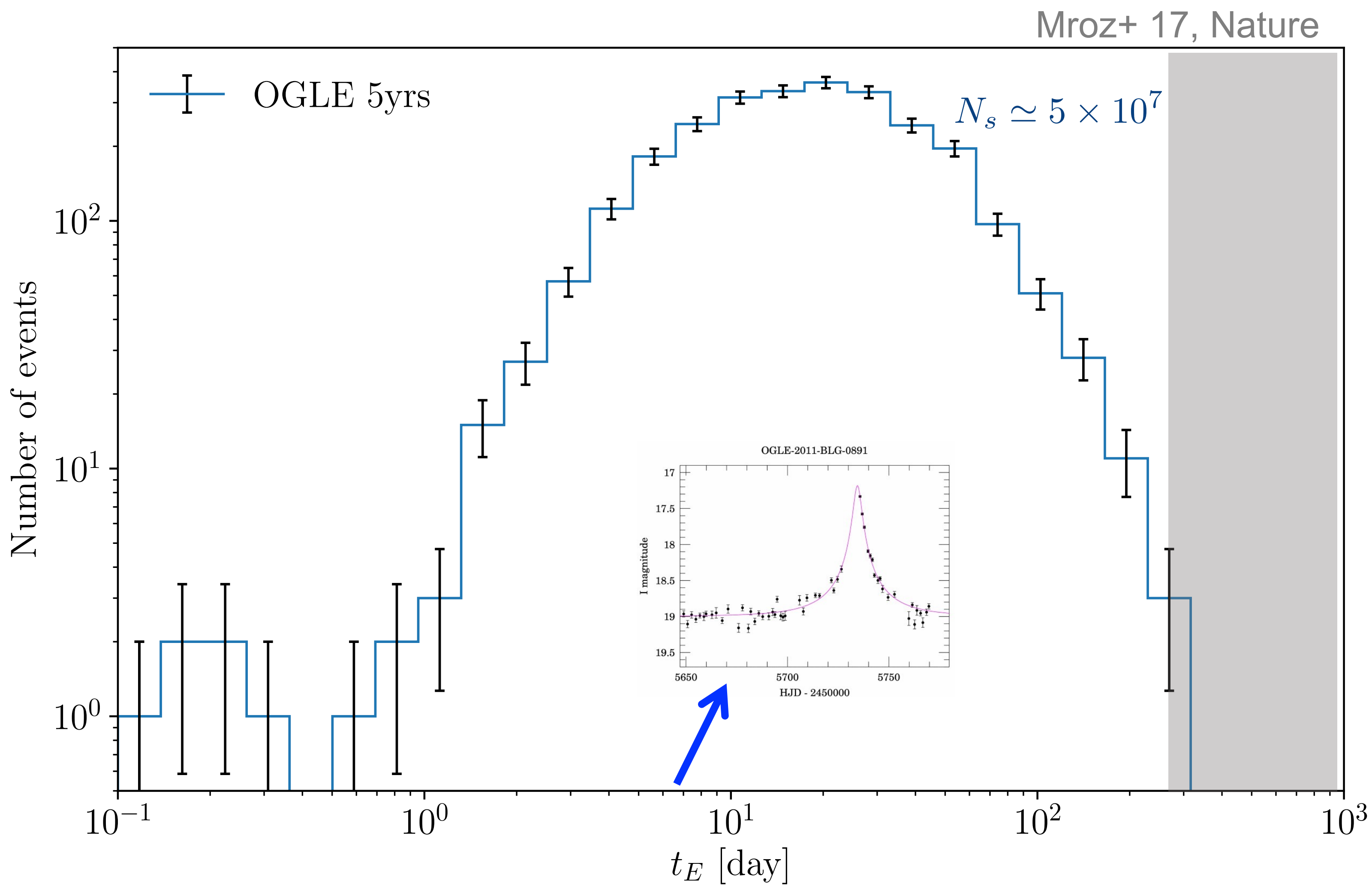
Optical Gravitational Lensing Experiment (OGLE)

- A long-term monitoring observation of Galactic bulge (**1992-**). PI Prof. Udalski (Warsaw)
- 1.3m Warsaw U. Telescope at Las Campanas, Chile



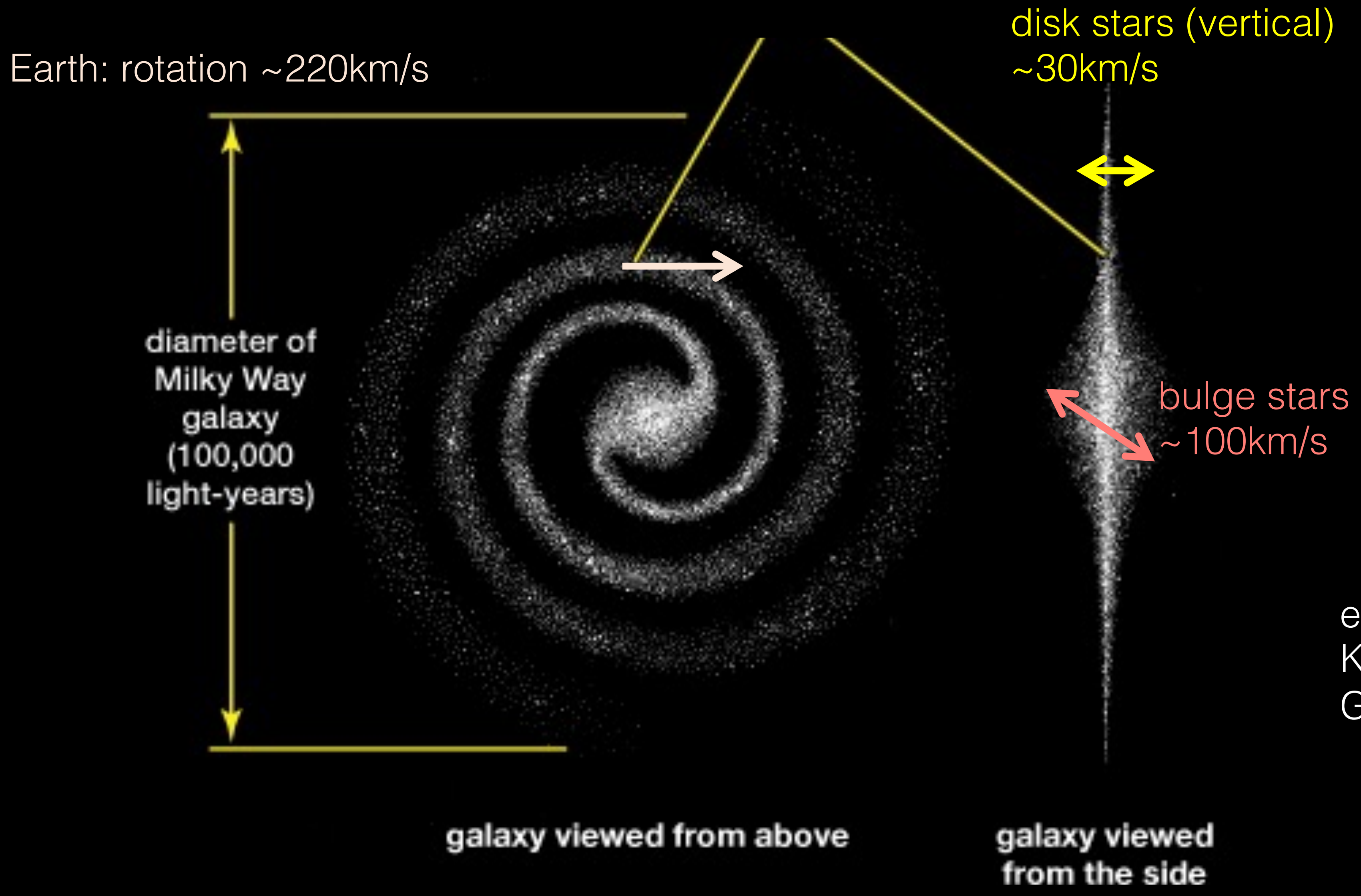
5-year OGLE ML data: Mroz et al. Nature 2017

- 2622 ML events: the ML timescale distribution is provided



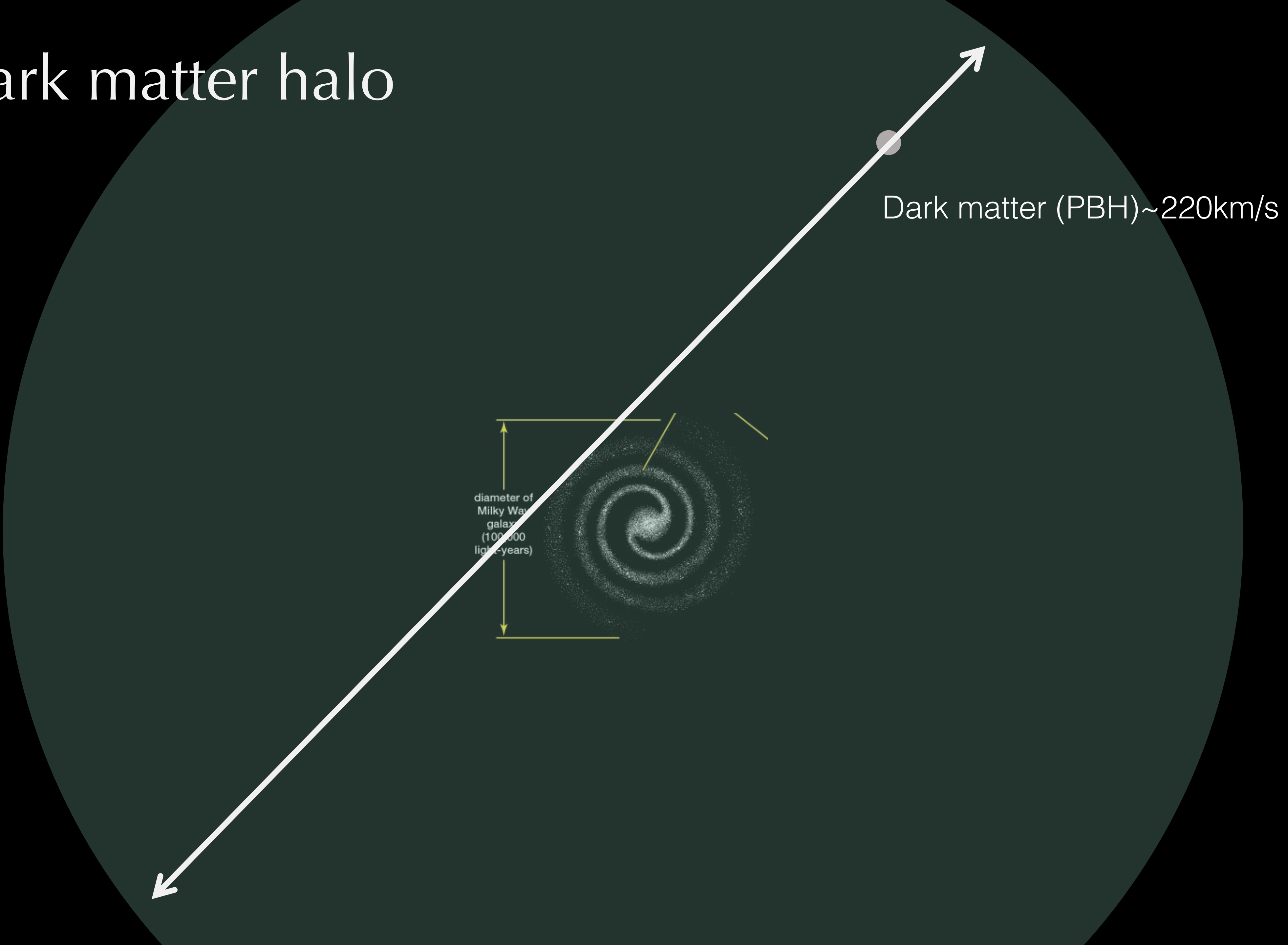
However, the individual microlensing light curves are not publicly available

Spatial and velocity structures of stars, WDs and NSs

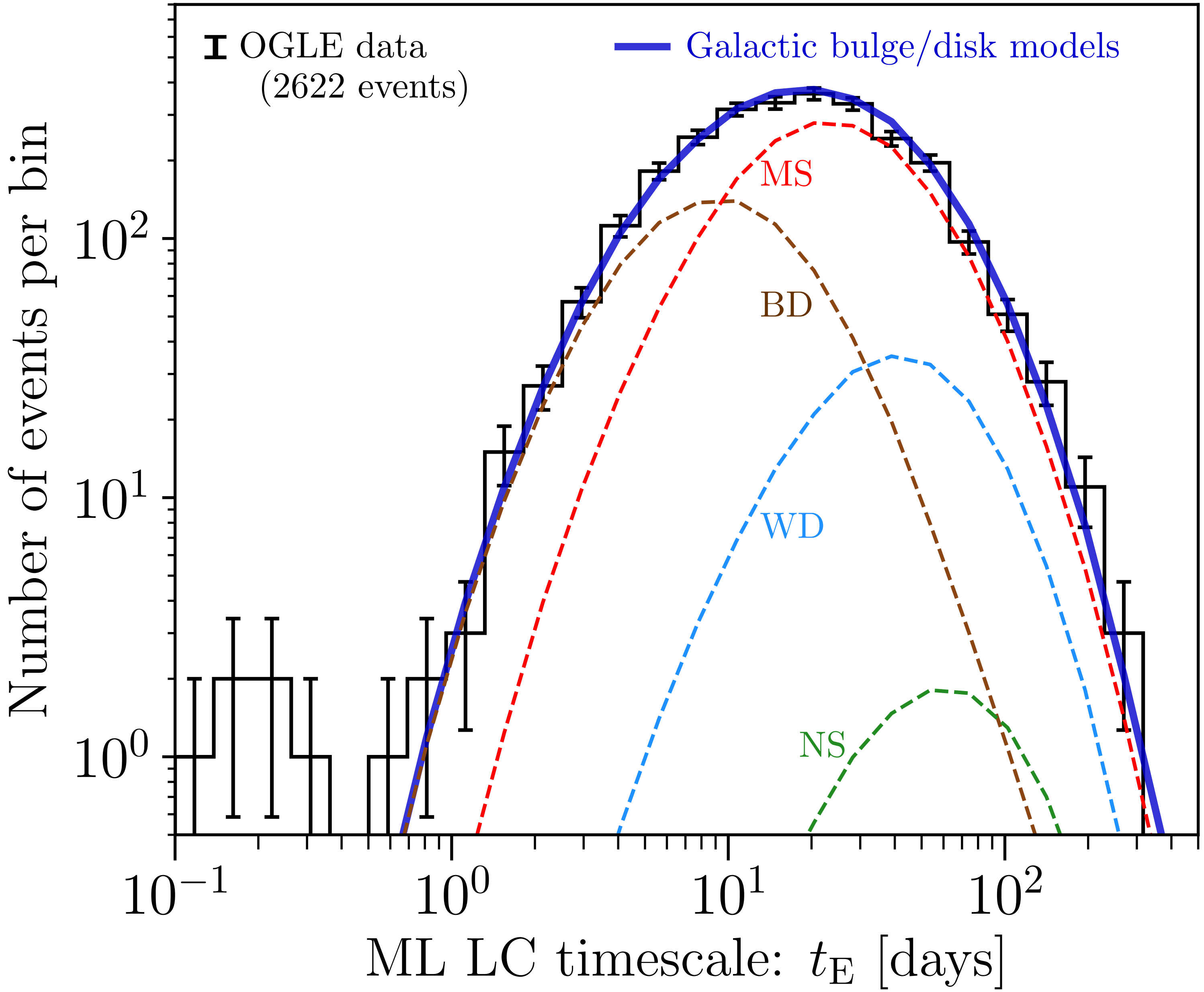


e.g., Bahcall 86; Kent 92; Han & Gould 95, 96

MW dark matter halo



(old-days) Astronomers very smart!

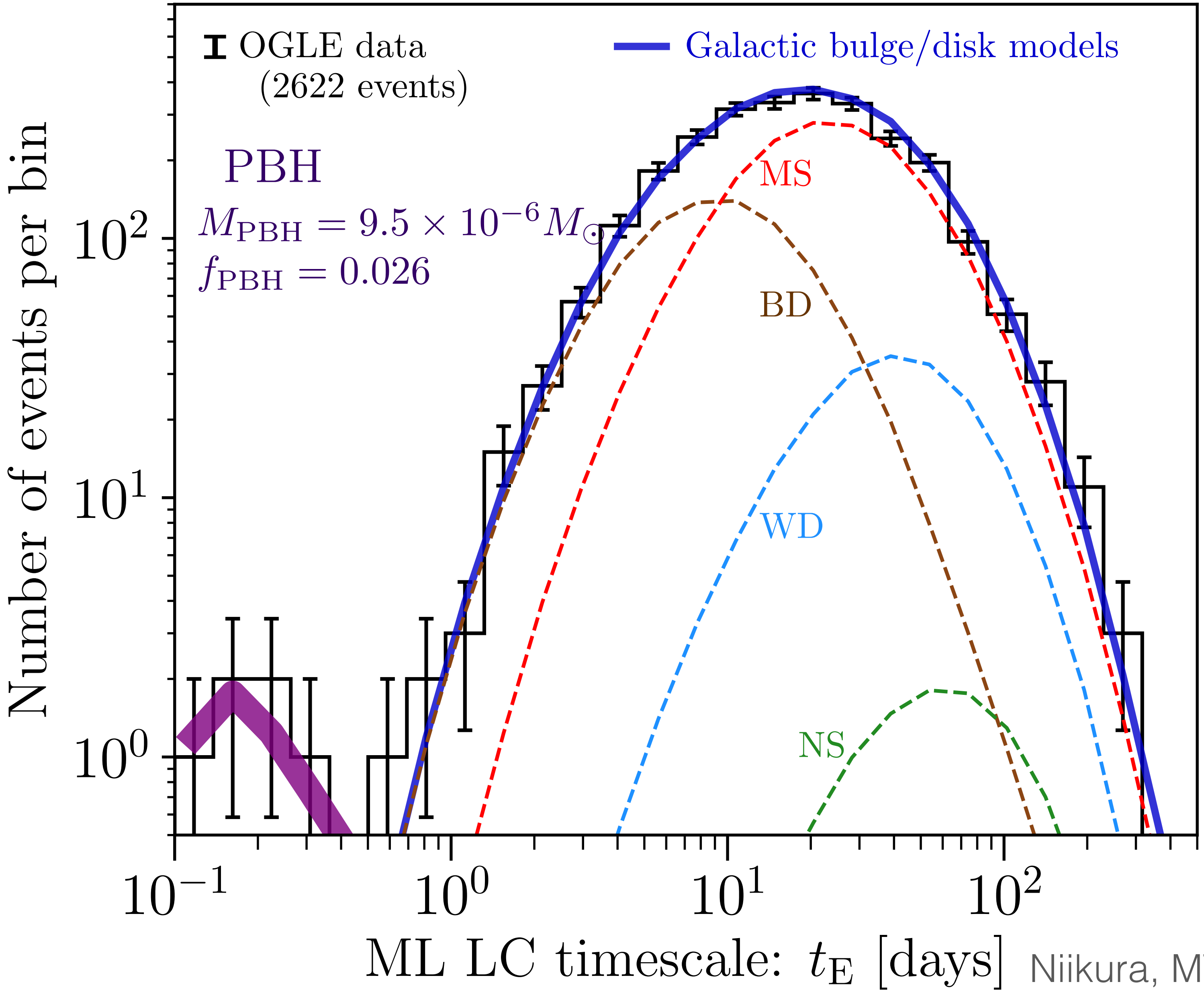


$$t_E = \frac{R_E}{v_{rel}} \propto \frac{\sqrt{M_{lens}}}{v_{rel}}$$

+ spatial and velocity structures in the Galactic bulge and disk regions

Niikura, MT+PRD 19

Earth-mass scale PBH?

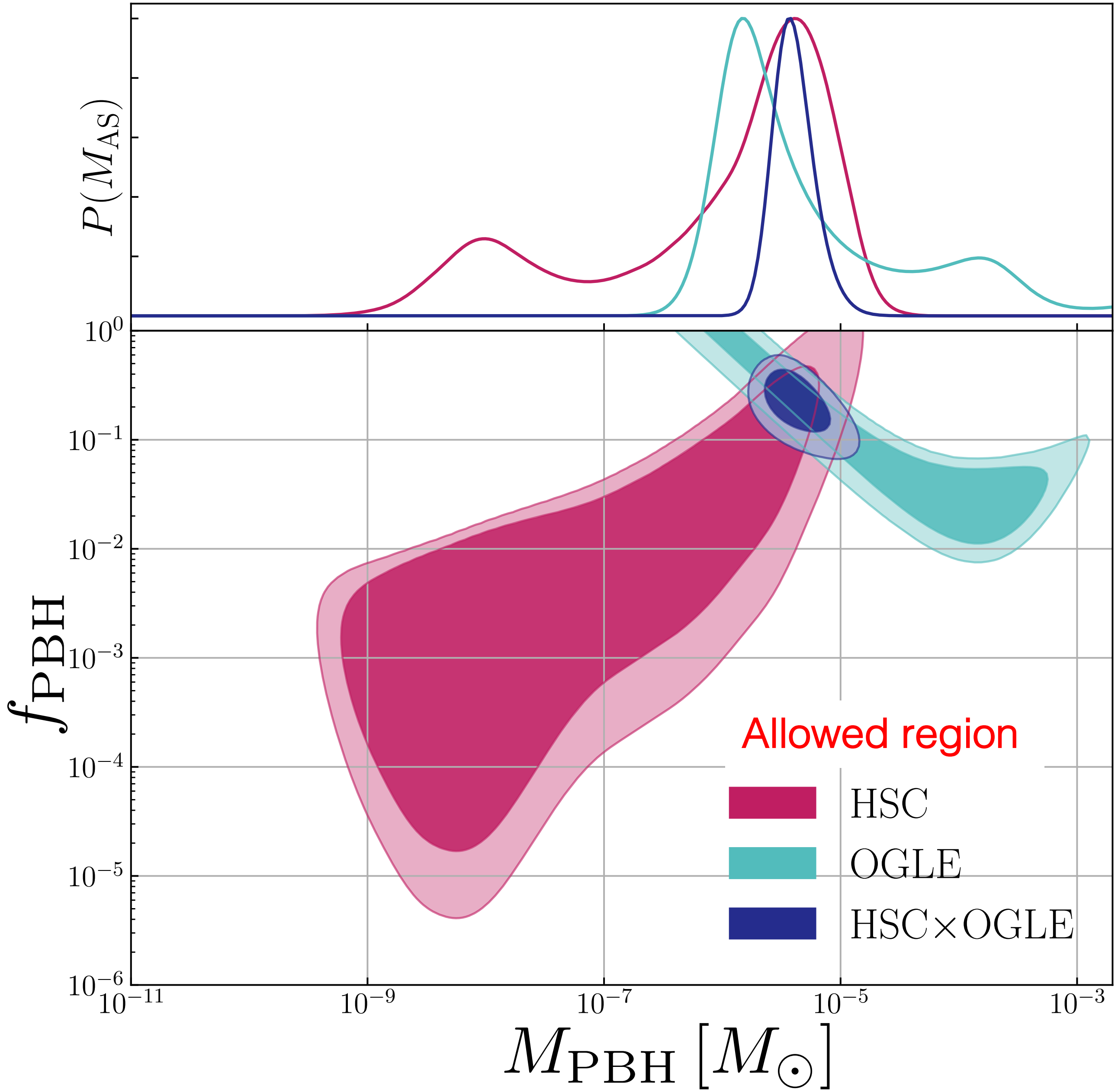


Niikura, MT+ 19

$$t_E = \frac{R_{\rm E}}{v_{\rm rel}} \propto \frac{\sqrt{M_{\rm lens}}}{v_{\rm rel}}$$

+ spatial and velocity structures in the Galactic bulge and disk regions

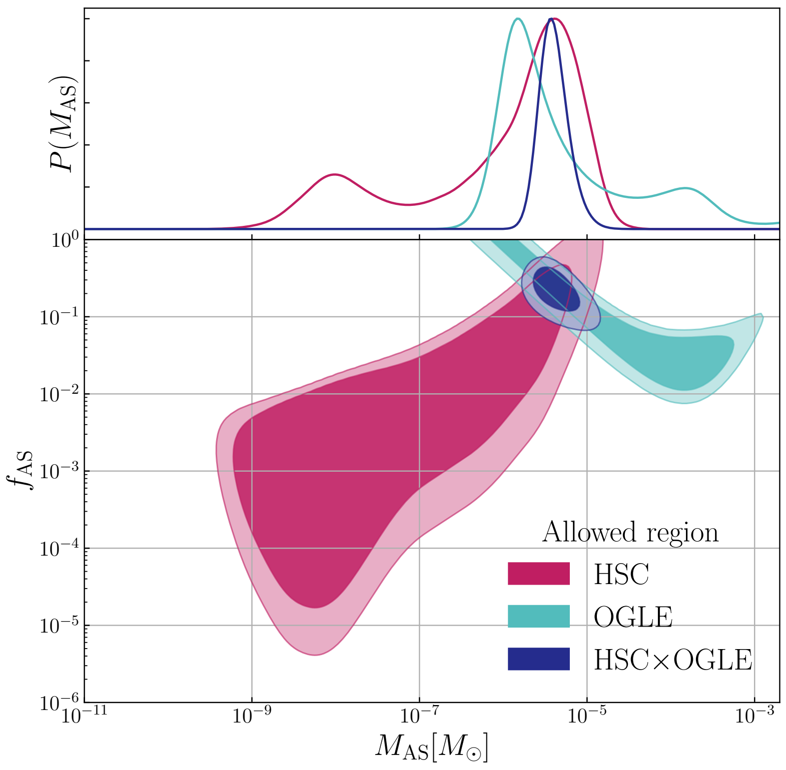
Assume both HSC and OGLE events are due to PBH … the two datasets are consistent (Sugiyama+21)



Sunao Sugiyama
(Kavli IPMU)

Sugiyama, MT & Kusenko 21

Or this is a signature of axion DM?



$$V(\phi) = \Lambda^4 [1 - \cos(\phi/f_a)] \simeq \frac{m_a^2}{2}\phi^2 - \frac{m_a^2}{24 f_a^2}\phi^4 + \cdots$$

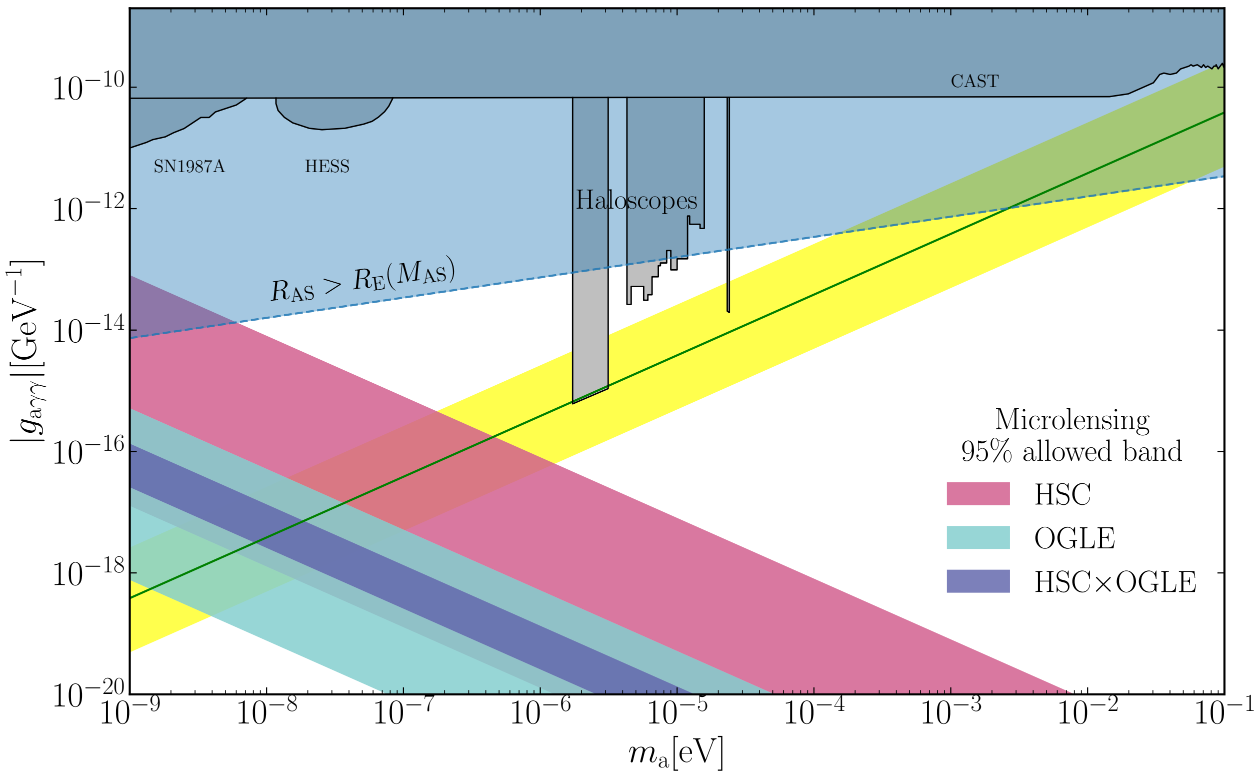
Schiappacasse & Hertzberg 18

self-interaction → leads to formation of axion "stars"

$$M_{\rm AS} = 1.2 \times 10^{-6} M_\odot \left(\frac{m_{\rm a}}{10^{-8}{\rm eV}}\right)^{-1} \left(\frac{f_{\rm a}}{10^{14}{\rm GeV}}\right)$$

$$R_{\rm AS} = 7.8 \times 10^2 {\rm km} \left(\frac{m_{\rm a}}{10^{-8}{\rm eV}}\right)^{-1} \left(\frac{f_{\rm a}}{10^{14}{\rm GeV}}\right)^{-1}$$

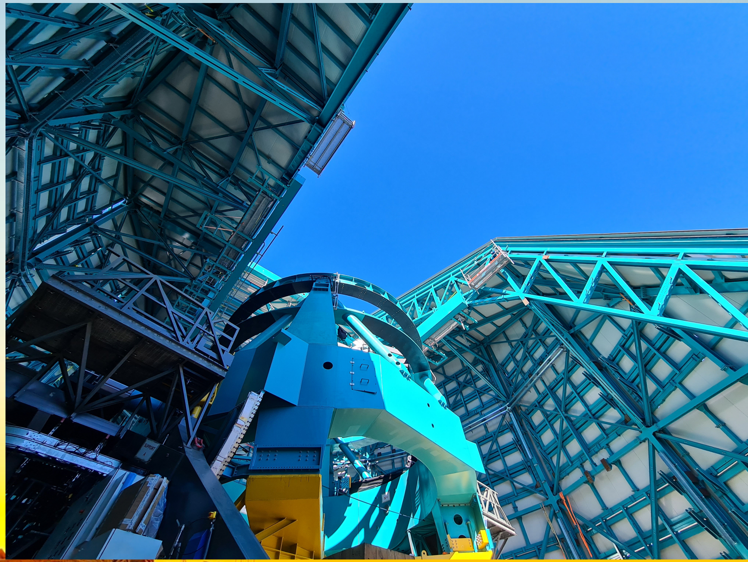
$M_{\rm AS} \sim M_{\rm Earth}, R_{\rm AS} \ll R_{\rm Earth}$



Microlensing can probe only "compact" axion stars (not diffuse axion)

Sugiyama, MT, Kusenko 21

Vera C. Rubin Observatory: Legacy Survey of Space and Time (LSST: 2024 - 2037)



- 6.4m aperture, FoV: 3.5 deg. ⇔ HSC: 1.5 deg.
- Submitted an in-kind contribution proposal in order for us (scientists in Japan) to join LSST (NAOJ: S. Miyazaki, Kavli IPMU: MT)
- Hopefully got ~40 PI's if the proposal is approved (including ~40 Subaru nights)
- LSST (Legacy Survey of Space and Time) will start in 2024, till ~2036
- Including a monitoring observation of Galactic bulge over ~10yrs

LSST bulge observation (TBD)

- read out: ~2sec (⇔HSC: 30sec), ugrizy (HSC: no u), ~10 yrs
- A nominal plan of "Wide-Fast-Deep (WFD)" field (~18000 sq. deg.): each visit: 15sec × 2, and then ~800 visits in total in ugrizy for each field over 10yrs
- Some "Deep Drilling Field" for ~50 sq. deg. in total
- Galactic plane, Galactic bulge, ….
- Detailed cadence plan of bulge observation hasn't yet been fully finalized
- NASA Roman Space Telescope (2026 launch expected)

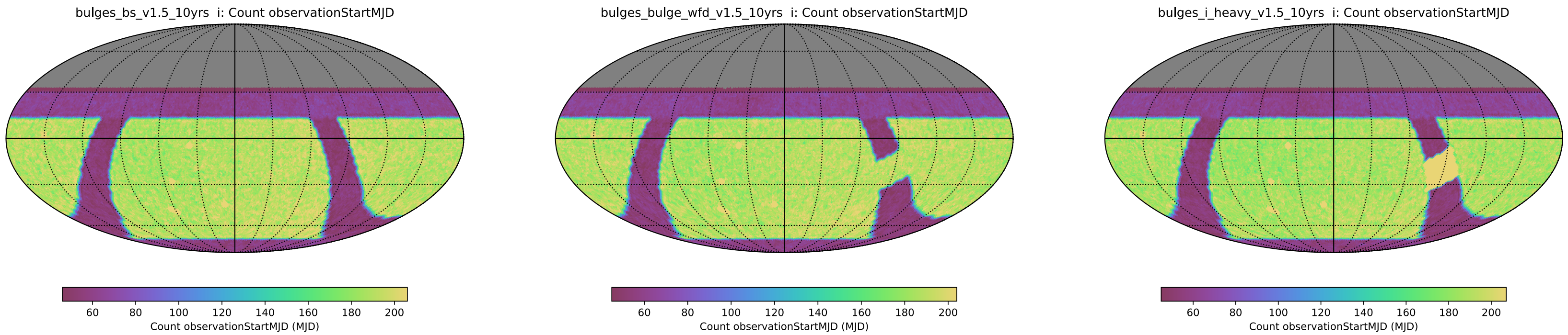


Figure 17. Series of simulations trying different bulge observing strategies; these vary from simple light coverage of the galactic bulge and plane to heavier coverage of the bulge (while maintaining light coverage of the rest of the galactic plane).

White paper of fundamental nature of DM with LSST

Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope

LSST Dark Matter Group

April 25, 2019

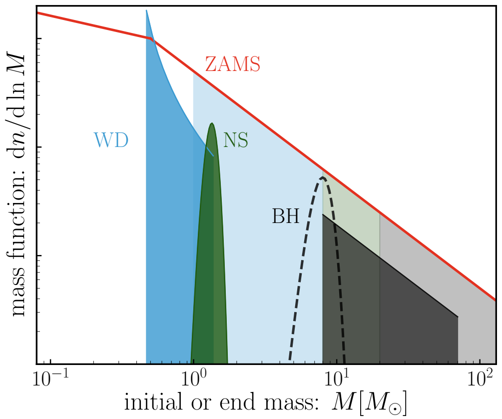
v1.1

Community efforts: A. Drlica-Wagner+ arXiv:1902.01055

- MW satellites and streams
- Strong lens systems
- Galaxy clusters

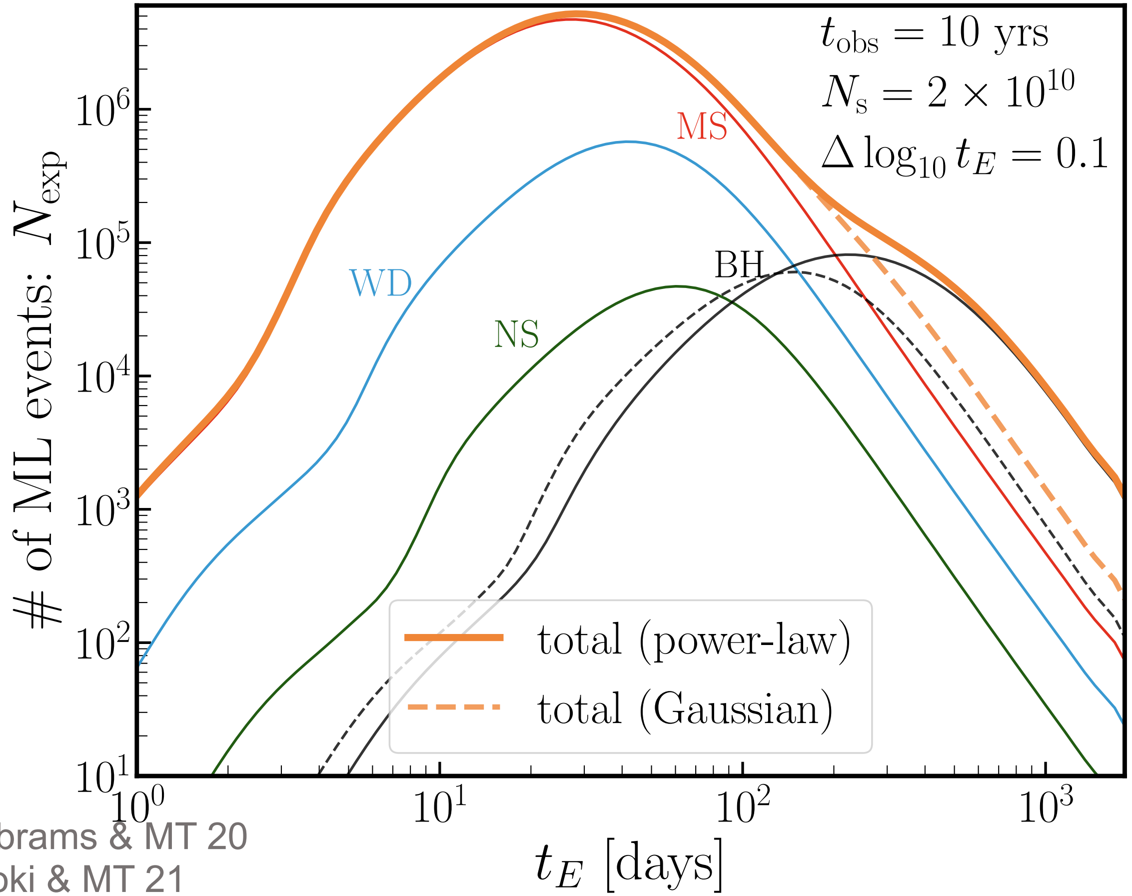
- WIMP
- Ultra-light DM
- PBH

Byproduct of microlensing PBH search



$$\frac{dN_{\rm event}}{dt_E} \propto \int_0^{d_s} dd_l\; n_l(d_l)\frac{R_E^4}{t_E^4} f(v_\perp)|_{v_\perp = 2R_E/t_E}$$

$$\propto M^2 \quad \text{for events with } v_\perp = \frac{2R_E}{t_E} \ll v_{\rm typical} \text{ or } t_E \gg \frac{2R_E}{v_{\rm typical}}$$



- The event rate of microlensing depends on the spatial and velocity structures of lenses
  - Bulge, ~100km/s; disk, ~30km/s; halos, ~200km/s
- If LIGO-Virgo BBHs are stellar-origined, long-timescale events are dominated by BH events of >10Msun
  - VRO LSST's bulge search will find >10^4 BH events
  - Can also study wide-orbit binary BHs: binary fraction, properties of binaries (separation, mass ratio, …)
- Microlensing events also enable to study properties of stars, WDs, BDs and planets

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summary

- Gravitational microlensing is very powerful to probe "compact, invisible objects" including PBH (and axion stars). Three windows that are worth further exploring
  - M_PBH~$[10^{-15},10^{-10}]$Msun: all DM can be explained by PBH
  - M_PBH~10^{-5}Msun (Earth mass): a possible candidate for Subaru M31 and OGLE microlensing events
  - M_PBH~10Msun: a counterpart of LIGO BBH GWs, might partly contribute DM (with mass fraction <0.1%)
- We used the 8.2m Subaru HSC data of M31 to search for shotr timescale (~1hr) microlensing events due to PBHs, and obtained the tightest upper bound on the abundance of PBHs
- 6 ultra short timescale events in the 5-year OGLE data (1.3m) indicate PBHs of Earth-mass scales
  - The HSC event and the 6 OGLE events, although completely independent, are consistent
- *Bright future*: Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) promises to make significant progresses in microlensing studies with 10-year monitoring observation of the Galactic bulge
  - Verify/falsify the Earth-mass PBH events