Tightest bounds on PBH abundance with HSC observation of M31

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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 $10^{-10} M_{\text{sun}}$

Search of magnification event due to microlensing effect
Hyper Suprime-Cam

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

credit: Masahiro Takada
Andromeda Galaxy (M31)

- Large spiral galaxy
- In the northern hemisphere (not accessible from VLT, DES, LSST)
- HSC FoV ~ entire M31
- ~770kpc ($\mu \sim 24.4$)
- 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 \(\sim\)\(\mu\) arcsec and cannot be separated)
- Time variance of magnification (light curve) depends on lens mass and impact parameter \(\beta\).
- Time scale: a few months for MACHO (1\(M_\odot\)), a few hours for PBH (10\(^{-7}\)\(M_\odot\))

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

\(\star\) 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 single star in M31

\[ \tau = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \int_0^{d_L} dd \frac{\rho_{\text{DM}}(d)}{M_{\text{PBH}}} \pi R_E^2 \]

Assumed \[ \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} = 1 \]

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

M31 has \( \sim 10^{11} \) stars, highly expected event
PBH microlensing event rate

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

Event rate for a single star in M31

$$\frac{d^2 N_{\text{event}}/dt_{\text{obs}}}{d \ln t_{\text{FWHM}}}$$

(\text{events/hrs})

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

$$\frac{\Omega_{PBH}}{\Omega_{DM}} = 1$$
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)
Detection of transients: difference imaging

**Pixel lensing regime:** multiple stars in each CCD pixel

- Tiny objects (< pixel size)
- Distorted object
- Object with flux distribution unsimilar to stars

Reference image (seeing ~0.5")  
Target image (seeing ~0.7")  
Difference image (seeing ~0.7")

**Difference image:**
- Good objects (stars, 
- Bad objects (not well detected)

**Difference-PSF:**
- ref.  
- Target  
- diff.  
- 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

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

HSC-M31 focal plane

flare

WD+BD eclipse

1.5 deg > 23 mag

1.5 deg > 25 mag
**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:
  - 11,703
  - 227
  - 146
  - 66
  - 1

- Noise threshold: (S/N > 5 for 3 consecutive visits)
- Apart from CCD edge: fake events, binary stars
- Fitting of ML lightcurve model: flare stars, fake events
- Symmetric shape of peak around the peak in the light curve: noisy events
- Significant peaks: fake events
- Visual inspection: spikes, asteroid or some defects

- One remaining candidate
Visual inspection of 66 candidates to identify junks...

**asteroid**

**spike around a bright star**

66 \Rightarrow 65 junks
Total number of events: 15,571

One remaining candidate

blue: ±1σ noise on difference images
**Discussion:** Constraint on the PBH abundance

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

\[
N_{\text{exp}}(M) = E \int_0^\infty \frac{d\Gamma}{dt}(\hat{t}, M)\epsilon(\hat{t})d\hat{t}
\]

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

Event rate of microlensing (per background star)
Results: New bound on PBH abundance

$M_{\text{PBH}}$ [$M_\odot$]  
$10^{-15}$ $10^{-10}$ $10^{-5}$ $10^0$

$f = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}}$  
$10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$

A mass fraction of PBHs to DM

HSC (95%) using HST-inferred counts

tightest bound on PBH with $M_{\text{PBH}} = [10^{20}, 10^{28}]$g
1 HSC night $\leftrightarrow$ 2 years Kepler data

Niikura, MT, + 17
tightest bound on PBH with $M_{\text{PBH}} = [10^{20}, 10^{28}]$ g
1 HSC night $\Leftrightarrow$ 2 years Kepler data
$f = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}}$

$M_{\text{PBH}} [M_\odot]$

$10^{-15} \quad 10^{-10} \quad 10^{-5} \quad 10^0$

$10^{-1} \quad 10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \quad 10^0$

QCD axion minihalo (Fairbairn+17)

Inomata et al. PBHs as all DM

HSC+finite source size

HST+finite source size

BH Evaporation

Femto

Kepler

EROS/MACHO

CMB

+ 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,..