Potential of Gaia to constrain Primordial Black Holes using astrometric microlensing

[arXiv 2208.14460]

COST MW-Gaia WG1/WG4 Workshop

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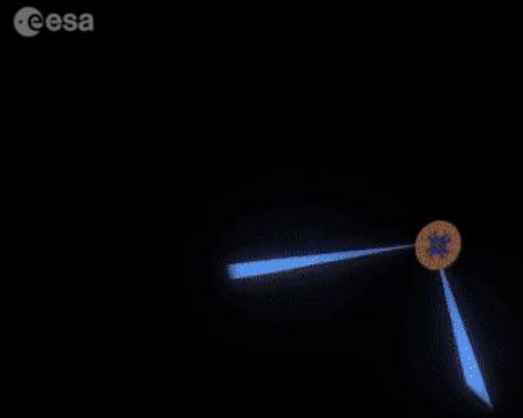
Sep 28, 2022

Goal



Credit: B. Holl (University of Geneva, Switzerland), A. Moitinho & M. Barros (University of Lisbon)

Goal

1. Gaia Telescope: More than a ***billion trajectories*** of galactic and extra-galactic sources.

2. Primordial Black Holes: Primordial Black Holes one of the candidate of ***Dark Matter.***

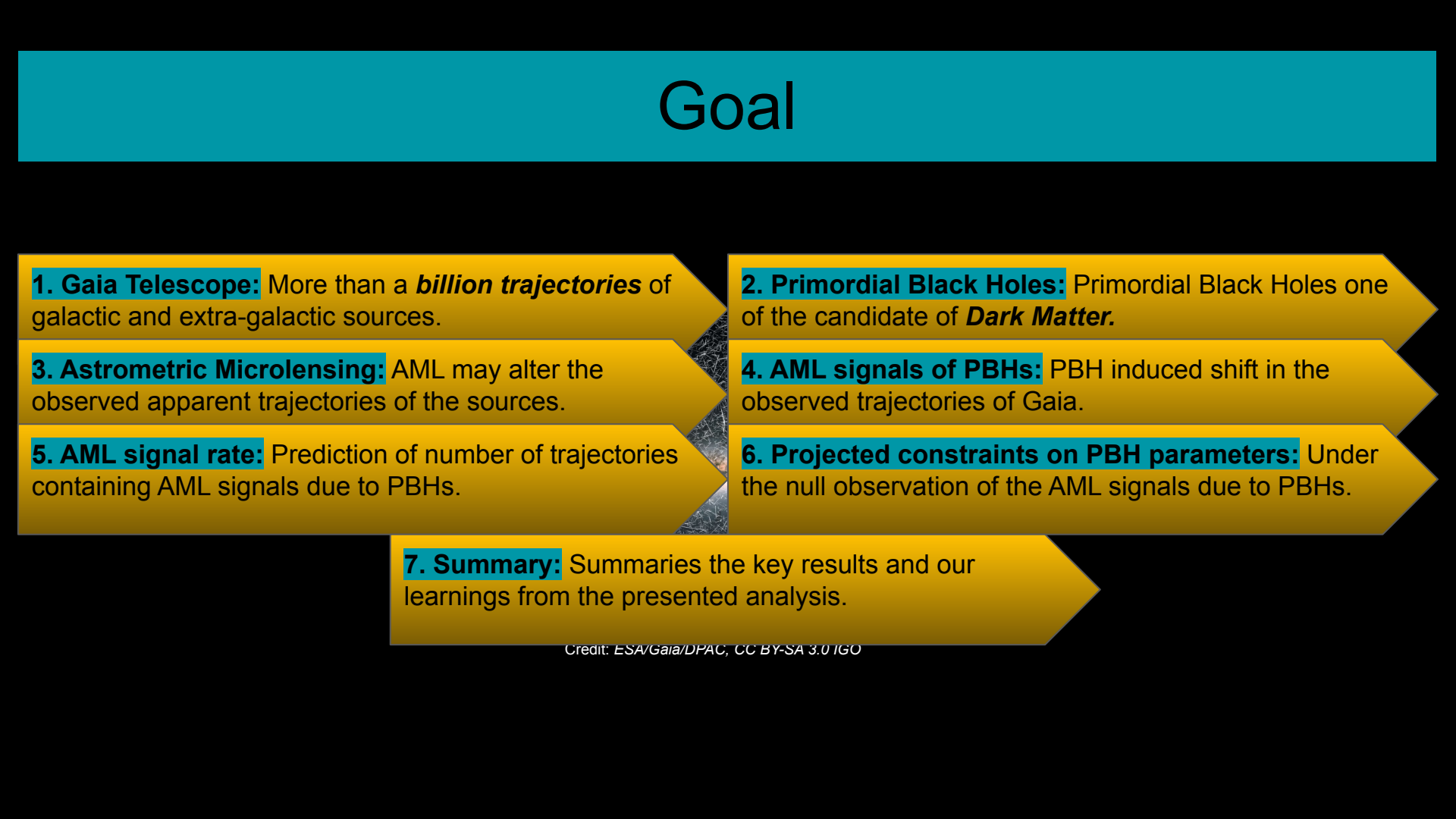
3. Astrometric Microlensing: AML may alter the observed apparent trajectories of the sources.

4. AML signals of PBHs: PBH induced shift in the observed trajectories of Gaia.

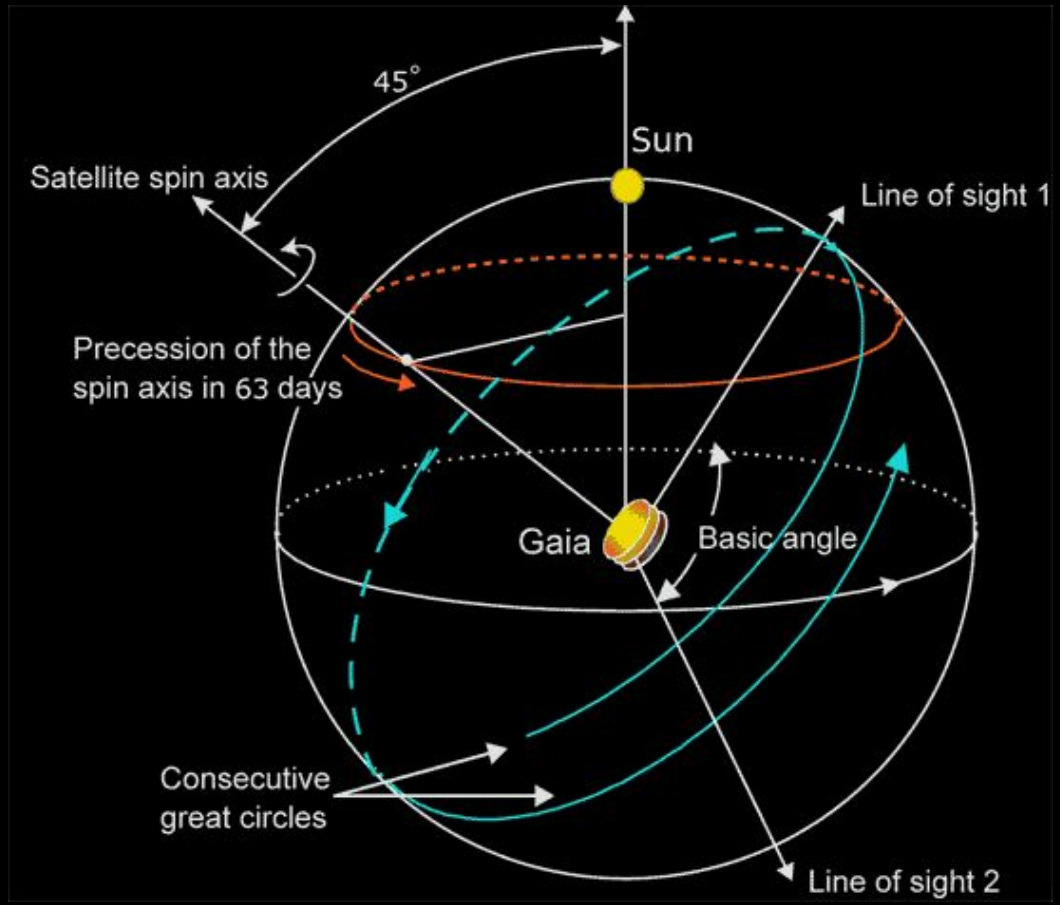
5. AML signal rate: Prediction of number of trajectories containing AML signals due to PBHs.

6. Projected constraints on PBH parameters: Under the null observation of the AML signals due to PBHs.

7. Summary: Summaries the key results and our learnings from the presented analysis.



A space based telescope surveying all sky to observe the trajectories of more than a billion sources



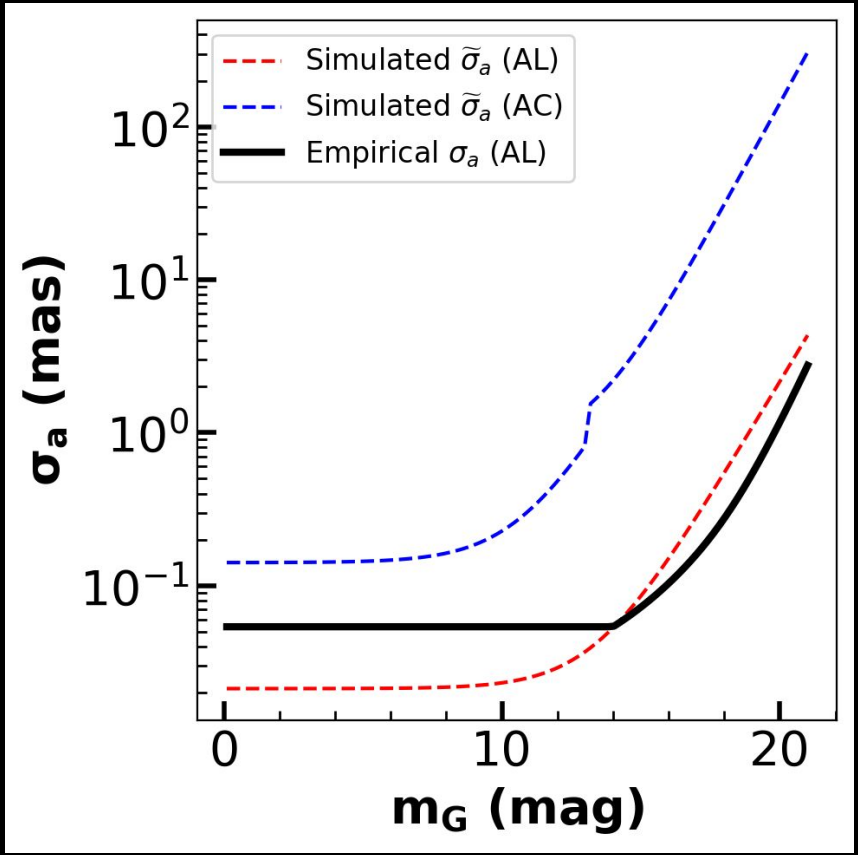
PC: Gaia Collaborations

Each telescopic arm observes each patch in the sky once in ~1 month

It would provide 35 individual angular positions of more than a billion sources

With an accuracy as small as 0.076 mas for stars brighter than 14 mag.

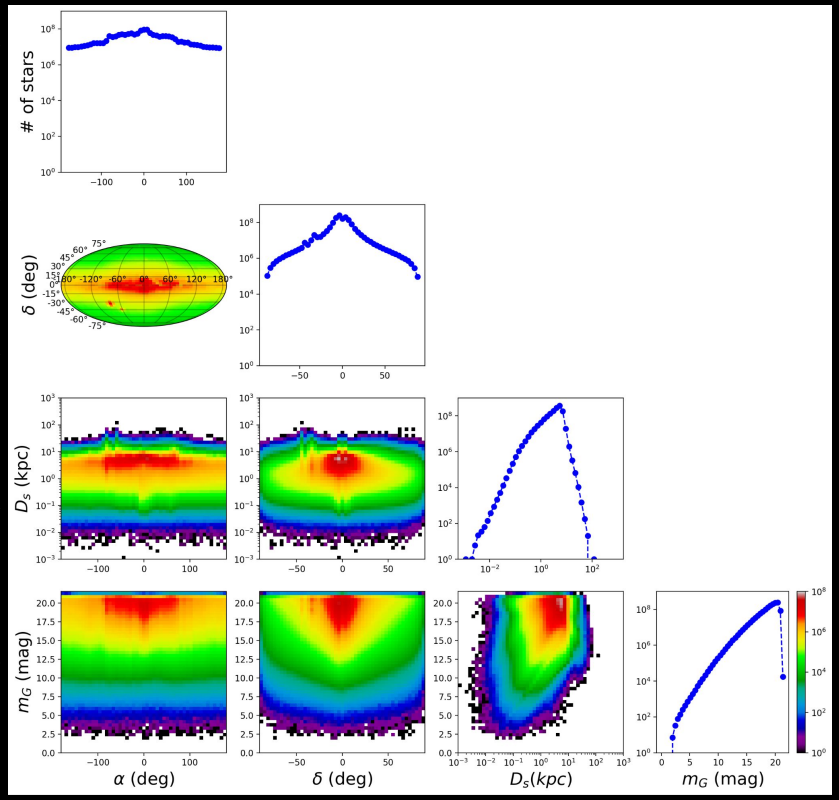
Modelling of uncertainty per epoch in the angular position



Uncertainty in the angular position "only" depends upon how bright a source is i.e. apparent magnitude (m_G)

We took an empirical fit to the observed uncertainty according to 34 months of observation

Early Data Release 3: # of stars distributed over the characteristics of stars



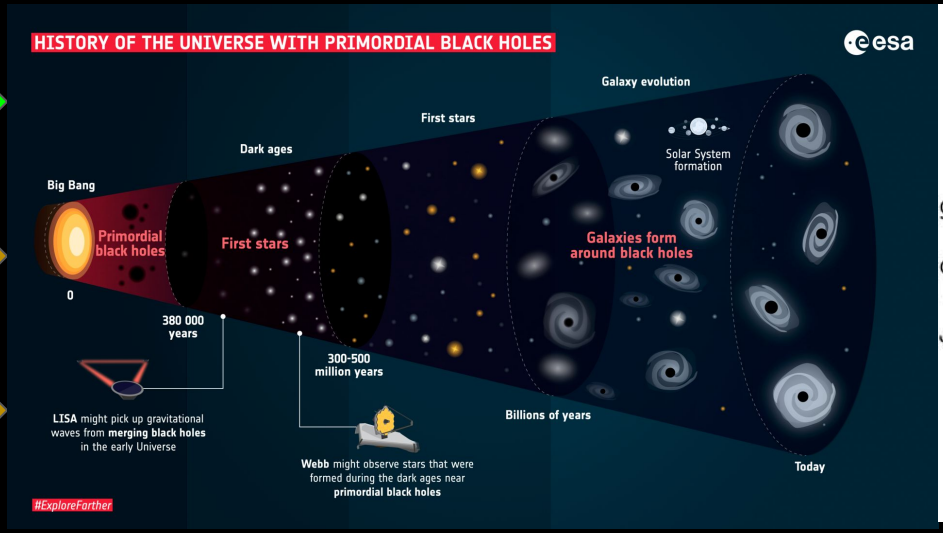
Total 1.43 billions sources out of 1.8 billion stars

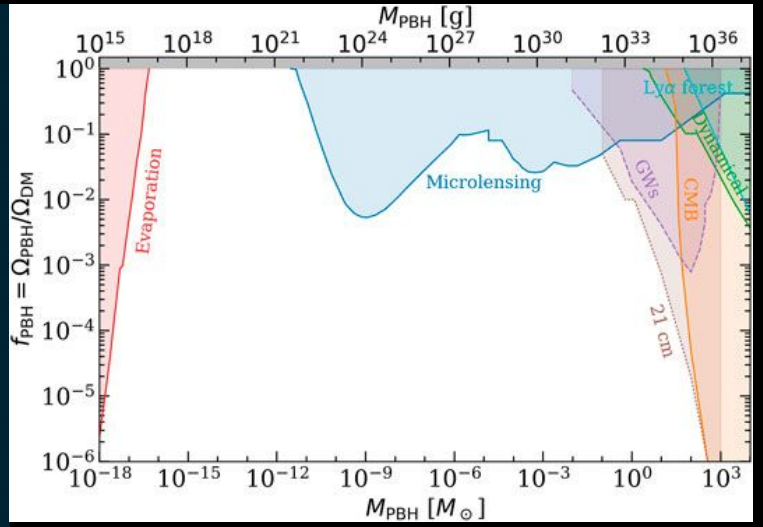
Having characteristics:

- Right Ascension
- Declination
- Distance (1/parallax)
- Apparent magnitude

Apparent distortion in the trajectory of these sources due to Primordial Black Holes

Collapse of excess density in the early universe: Dark Matter Candidate

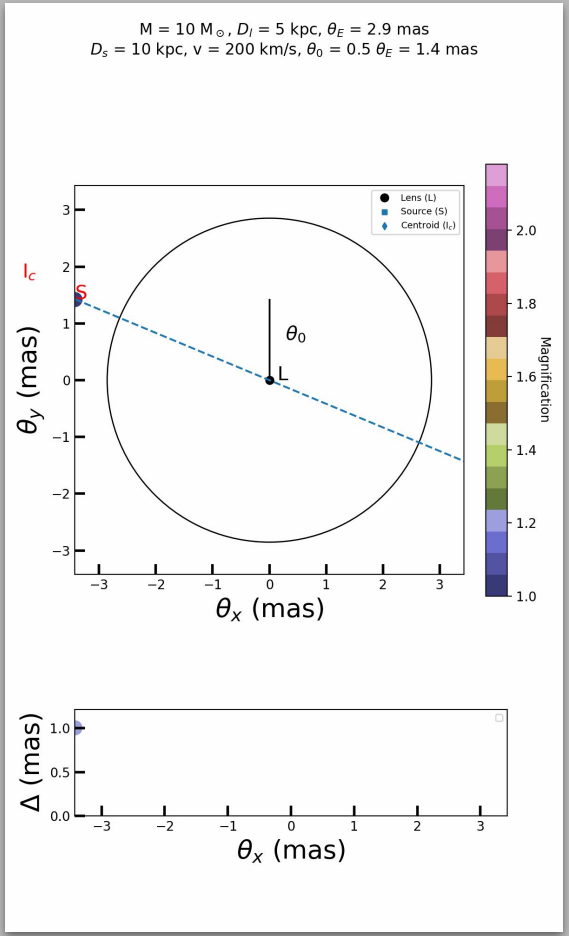




Ref: Pablo Villanuevo Domingo et. al.

"Astrometric Microlensing of Primordial Black Holes with Gaia"

Apparent brightening and shift in the angular position of a source



Photometric Microlensing (PML): Apparent brightening of a source due to bending of light

Astrometric Microlensing (AML): Apparent shift in the angular position of a source due to bending of light

Apparent shift depends upon the **angular separation** between the source and the lens

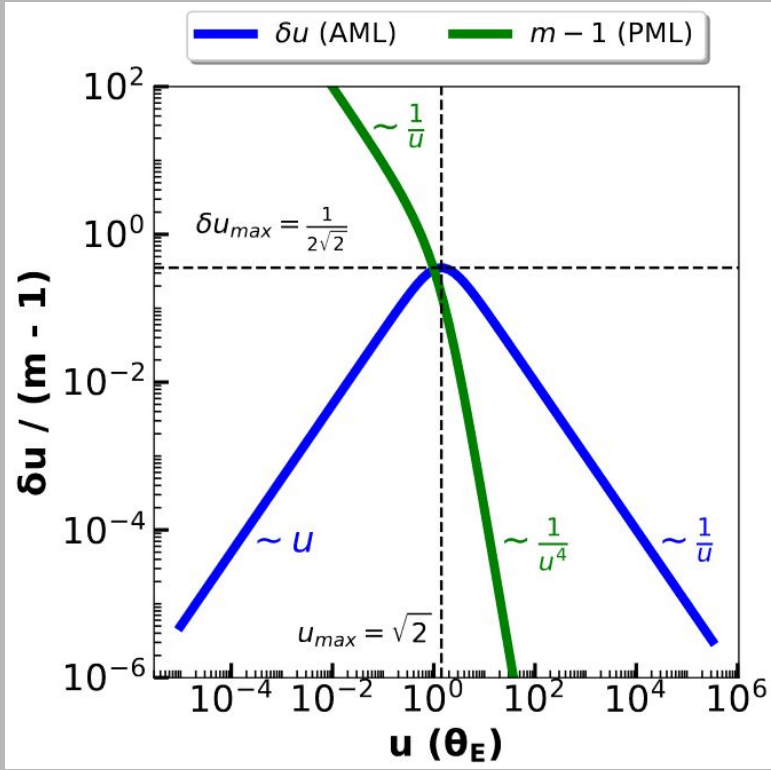
Apparent shift also depends upon **Einstein Angle**

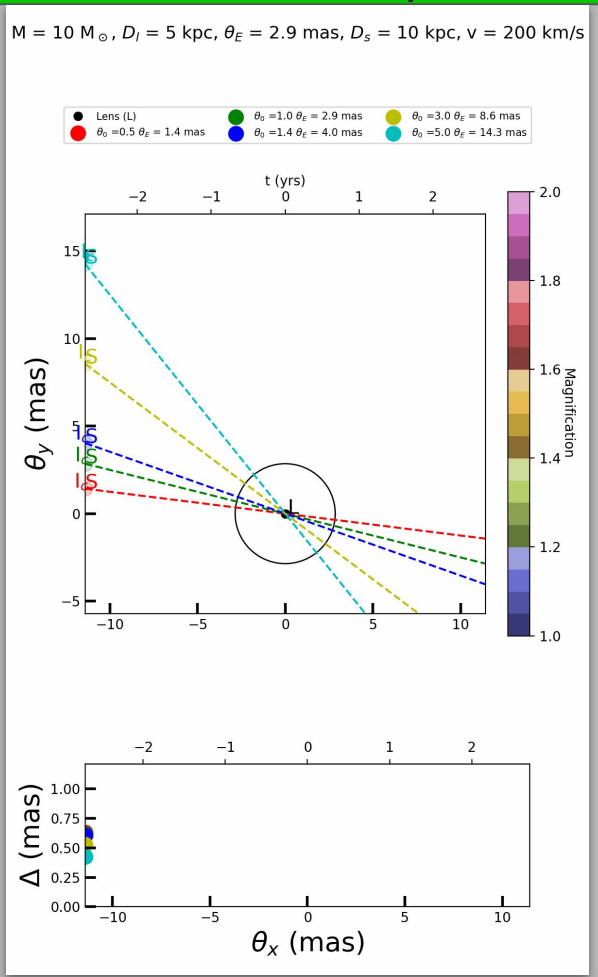
$$\theta_E \approx 2.854 \text{ mas} \sqrt{\frac{M}{10\ \mathrm{M}_\odot} \frac{10 \text{ kpc}}{D_s} \left(\frac{D_s}{D_l} - 1 \right)}$$

Microlensing

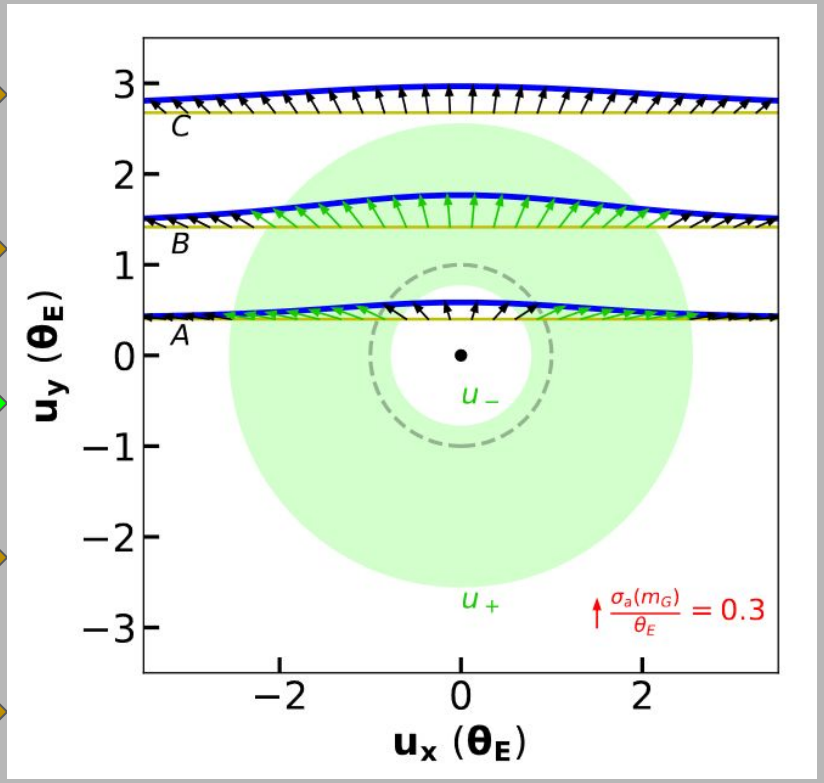
Comparison

Astrometric Microlensing has larger cross-section as compared to PML





Duration for which star remain in the sensitive area of detection



$$\langle t_e \rangle = \frac{\pi \theta_E (u_+^2 - u_-^2)}{2 u_+ \mu},$$

$$= \frac{\pi D_l \theta_E}{v} \frac{\frac{\theta_E}{\sigma_a(m_G)} \sqrt{\frac{\theta_E^2}{\sigma_a(m_G)^2} - 8}}{\frac{\theta_E}{\sigma_a(m_G)} + \sqrt{\frac{\theta_E^2}{\sigma_a(m_G)^2} - 8}},$$

$$\langle t_e \rangle (M,\ D_l,\ v\ ;\ D_s,\ m_G)$$

Identifying different kinds of AML signals depending upon the event duration

Short Duration Lensing Event

$$\langle t_e \rangle < t_s = 52.2 \text{ days}$$

No observable lensing signal for SDLE

Intermediate Duration Lensing Event

$$t_s < \langle t_e \rangle < t_{\rm obs} = 5 \text{ years}$$

IDLE observable: $\langle (\delta\theta)_{\rm max} \rangle = \langle \Delta_{\rm max} \rangle$

Long Duration Lensing Event

$$t_{\rm obs} < \langle t_e \rangle$$

LDLE observable: $\langle \Delta_{\rm LDLE} \rangle = \langle \Delta_{\rm out} - \Delta_{\rm in} \rangle$

IDLE or LDLE observable is above the uncertainty in the angular postion

For IDLEs:

$$\langle \delta\theta \rangle (\beta;\, M,\, D_l,\, v;\, D_s,\, m_G) \;>\; \sigma(m_G)$$

For LDLEs:

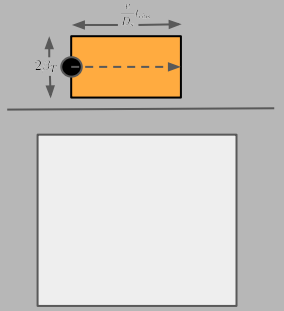
$$\langle \Delta_{\mathrm{LDLE}} \rangle (\beta;\, M,\, D_l,\, v;\, D_s,\, m_G;\, T_{\mathrm{obs}}) \;>\; \sigma(m_{\mathrm{G}})$$

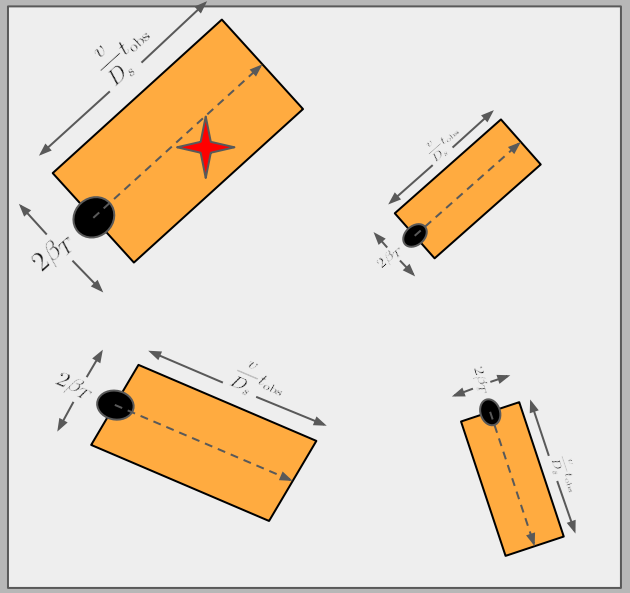
Probability of each source in Gaia eDR3 catalog have AML signal due to PBH

Fixing a PBH dark matter hypothesis $\left(f = \frac{\rho_{\rm PBH}}{\rho_{\rm DM}}, M\right)$

For each star with properties $(D_s,\ \alpha,\ \delta,\ m_G)$

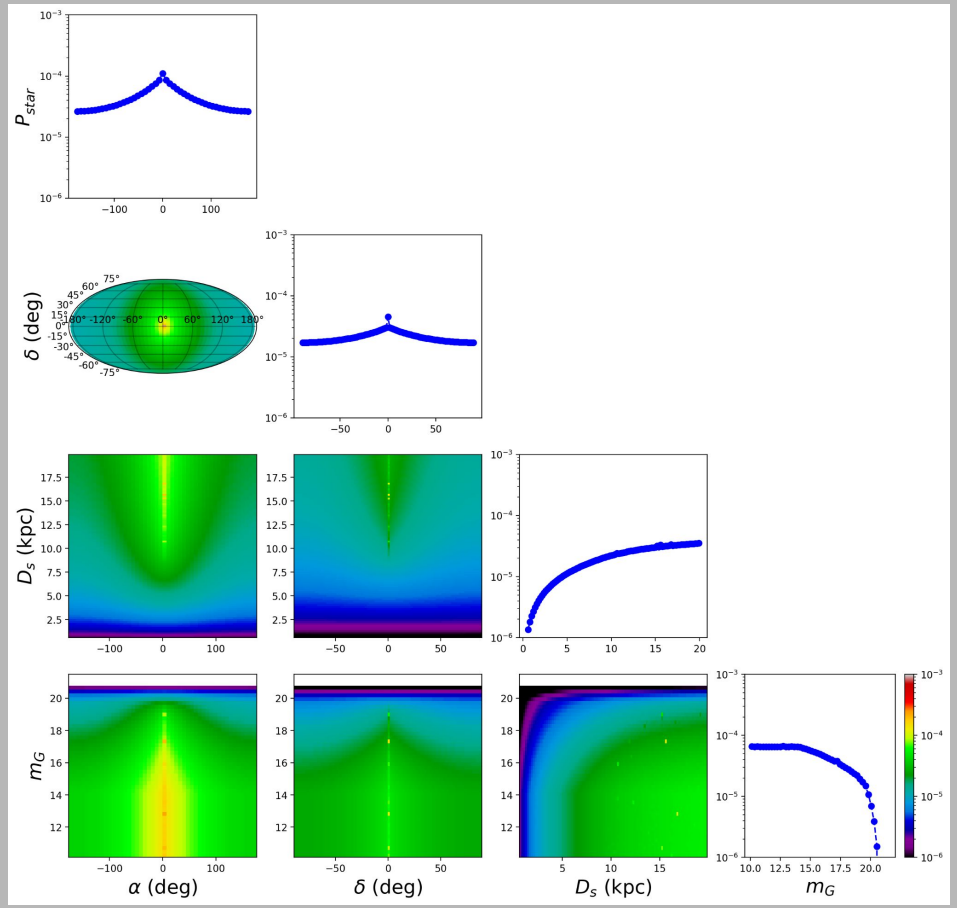
$$P = \sum_{D_l=0}^{D_s}$$





DIstribution of the probability of AML signals given the characteristics of sources

$$P_{\rm star}(f = 1,\ M = 14\,M_\odot; D_s\,, \alpha,\ \delta,\ m_G)$$



1. Gaia Telescope:

2. Primordial Black Holes:

3. Astrometric Microlensing:

4. AML signals of PBHs:

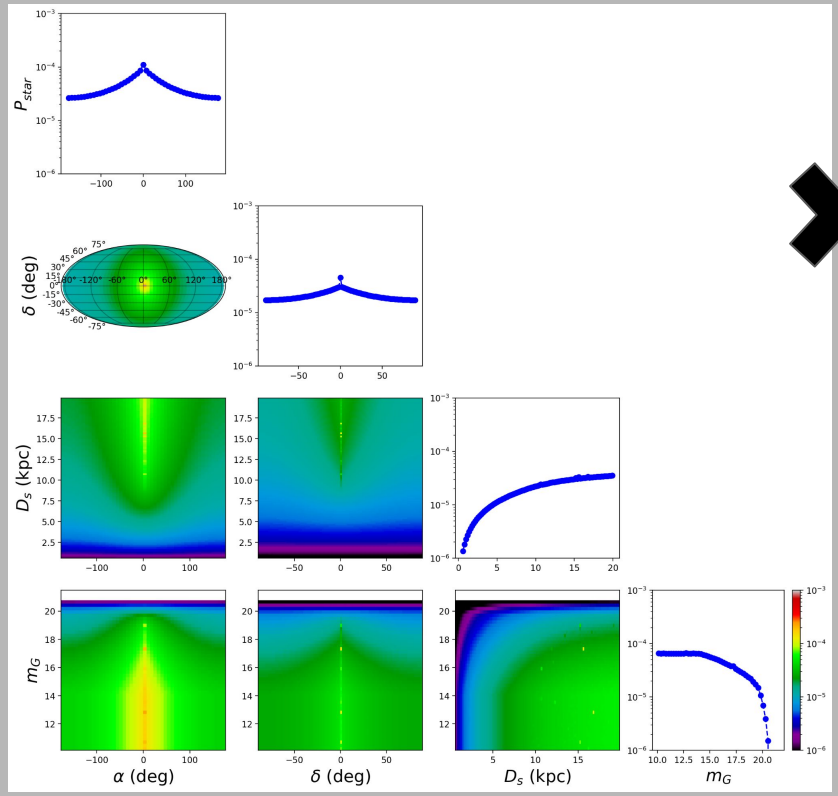
5. AML signal rate:

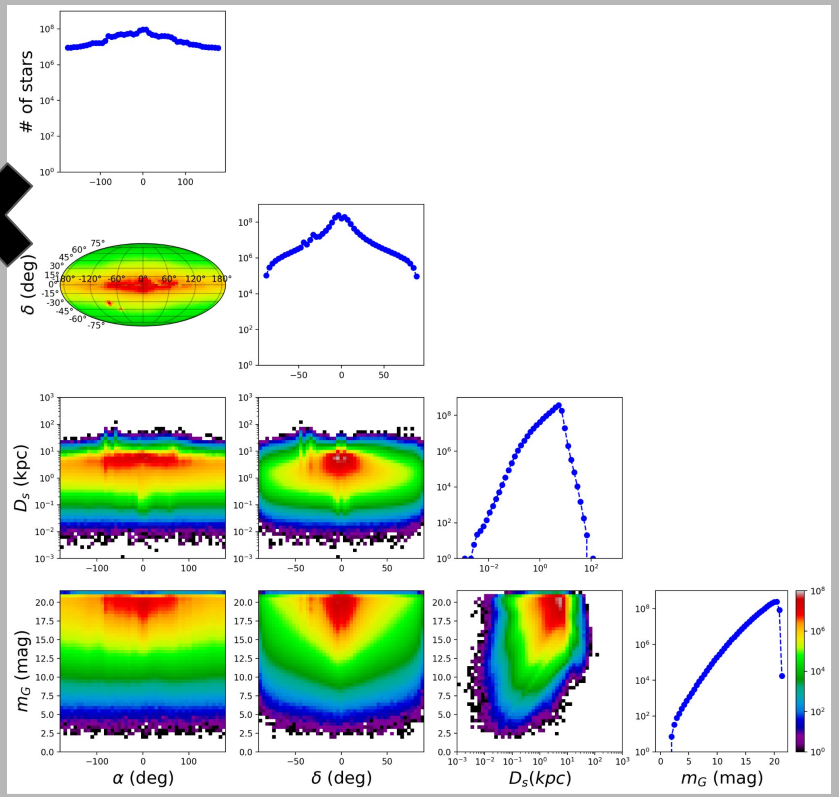
8. Projected constraints on PBH parameters:

9. Summary:

Probability Calculation | Distribution of the AML Signal | **Events potentially observed by Gaia**

Total number of sources in Gaia eDR3 catalog that will have AML signal due to PBH





$$P_{\rm star}(f=1,\, M=14\,M_\odot; D_s\,, \alpha,\, \delta,\, m_G)$$

$$N_{\rm star}^{\rm eDR3}(D_s,\, \alpha,\, \delta,\, m_G)$$

ArXiv: 2208.14460

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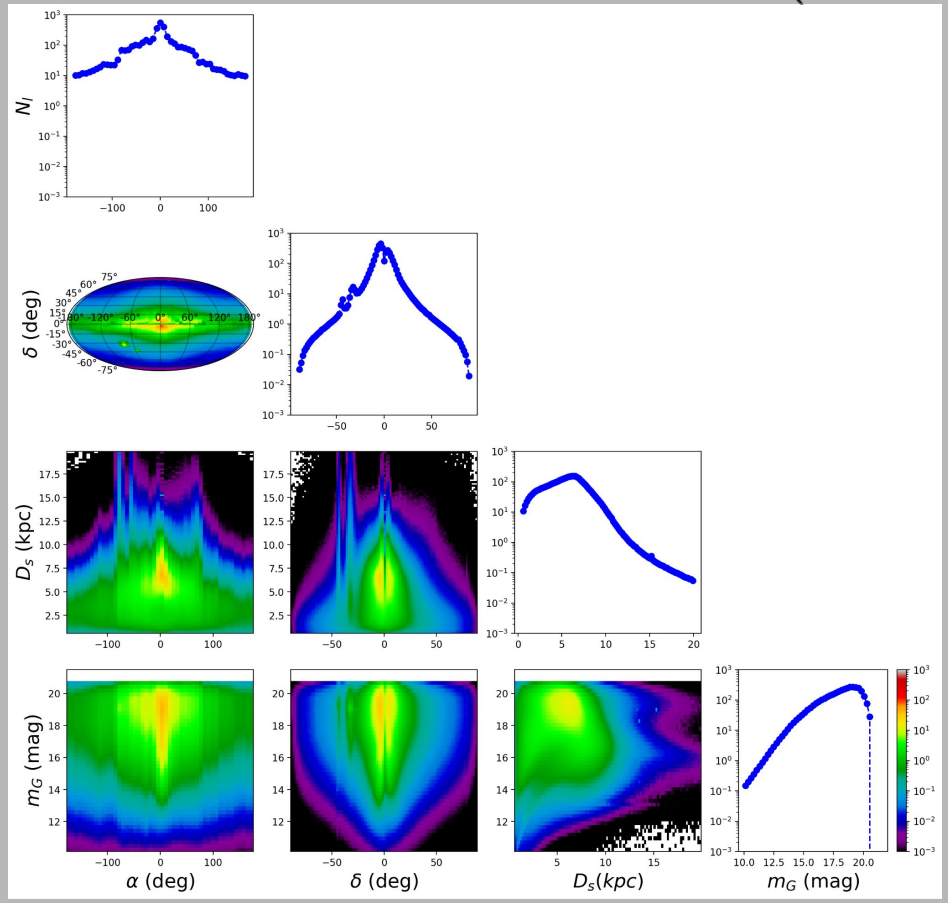
Probability Calculation | Distribution of the AML Signal | **Events potentially observed by Gaia**

Total number of sources in Gaia eDR3 catalog that will have AML signal due to PBH

$$N_l(f = 1, M = 14\,M_\odot) = \Sigma_{\rm star}\left(P_{\rm star} \otimes N^{\rm eDR3}_{\rm star}\right)$$



ArXiv: 2208.14460

A new exclusion on PBH parameters potentially set by Gaia

1. Gaia Telescope:
A fraction f of Dark Matter is PBHs

2. Primordial Black Holes:
Monochromatic Mass function of PBHs with parameter M

3. Astrometric Microlensing:
Dark matter distribution is assumed to be NFW profile

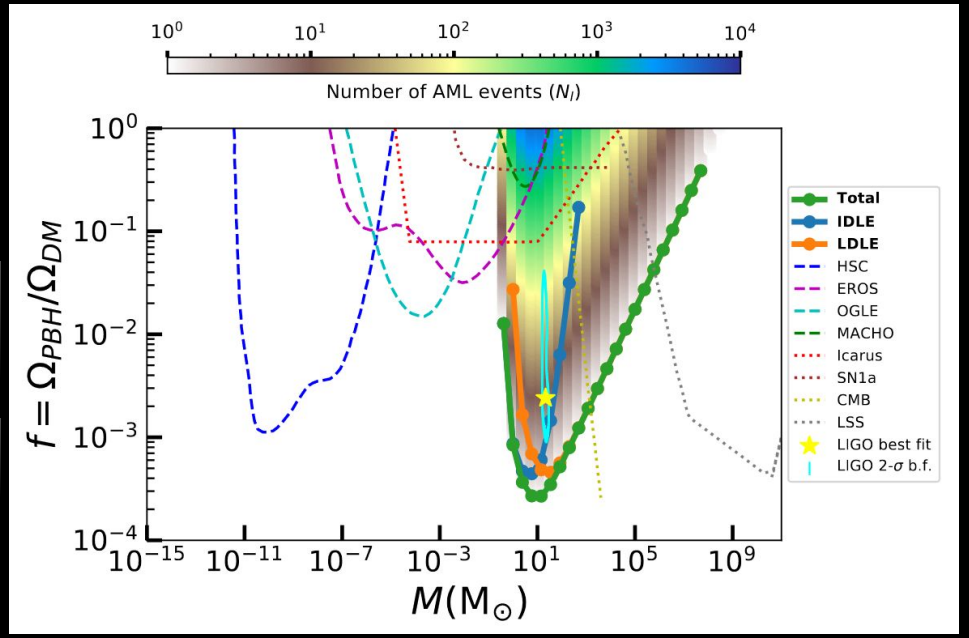
4. AML signals of PBHs:
All PBHs are moving with speed v=200 km/sec relative to the stars in Milky Way

5. AML signal rate:
Rectilinear motion of stars

8. Projected constraints on PBH parameters:
Uniform sampling of trajectories of Gaia

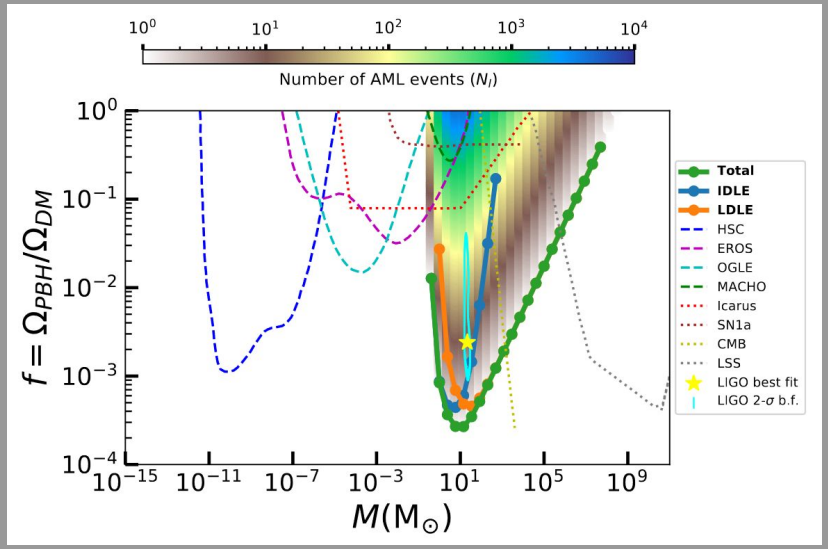
9. Summary:
Only Along scan direction error is used

Exclusion is solely based on Gaia astrometric measurements only



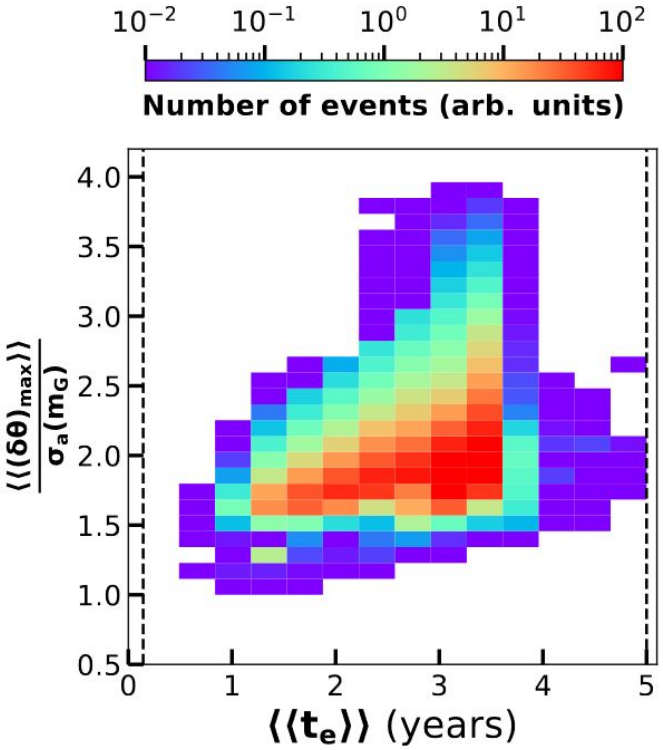
A new exclusion on PBH parameters potentially set by Gaia

- Predicted number of Astrometric Microlensing events expected to be observed by Gaia due to PBHs.
- Two different classes of detectable lensing events: IDLEs and LDLEs.
- Distribution of lensing events over the Gaia eDR3 catalog.
- Gaia is sensitive to PBHs with mass between 0.4 $M_\odot$ to $5 \times 10^7\ M_\odot$ with peak sensitivity to PBH masses of 10 $M_\odot$ with fraction f = 3×10^{-4}



Thank You

Comparison of the distribution of observables of stellar population



(a) IDLE observables

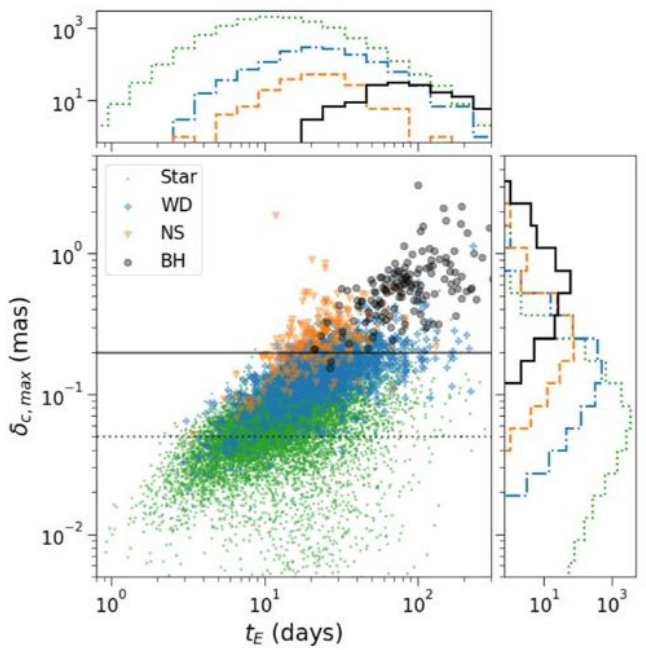
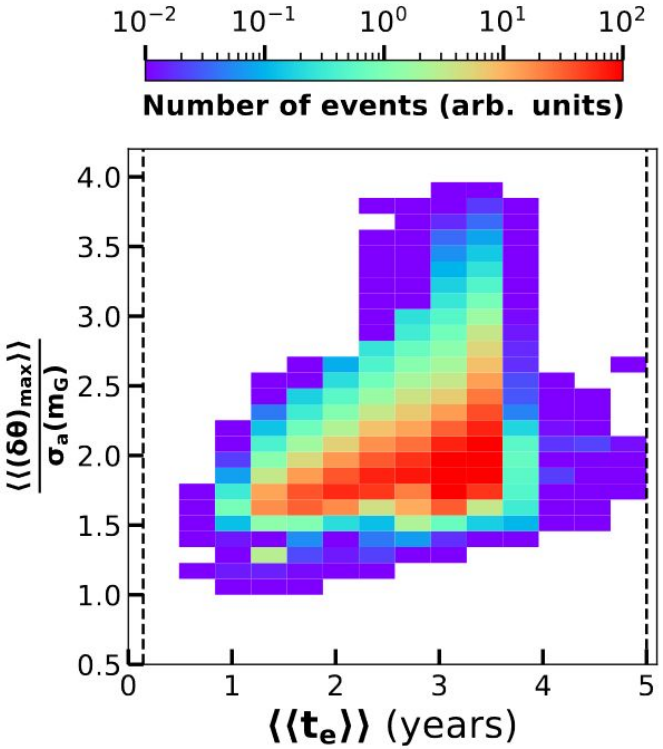
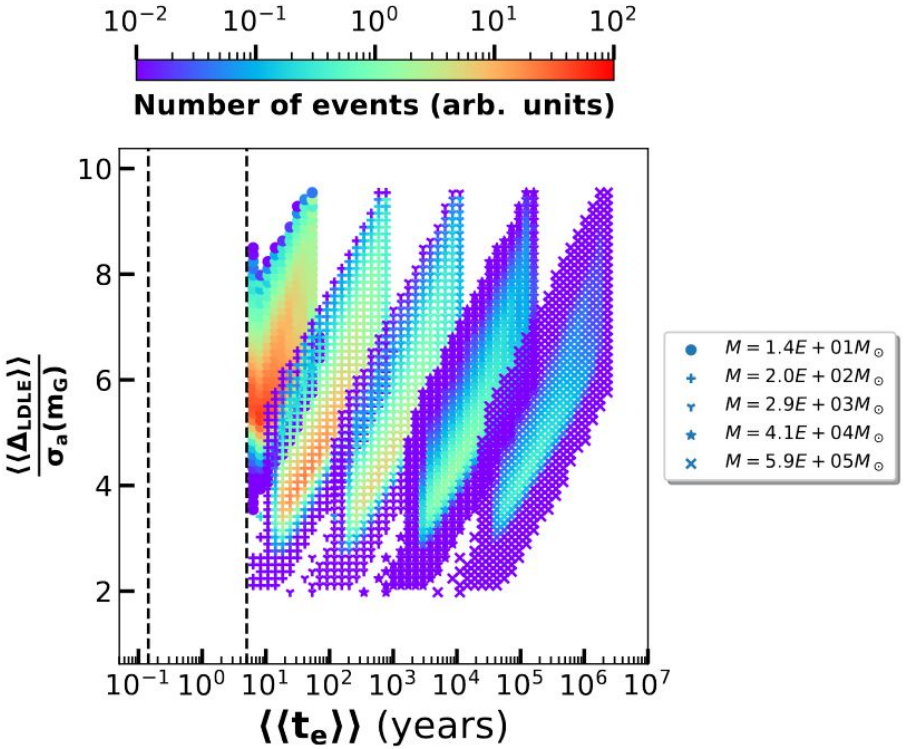


Figure 14. Maximum astrometric shift $\delta_{c,max}$ vs. the Einstein crossing time t_E. We assume blending between the lens and source when calculating $\delta_{c,max}$. The solid line denotes the achievable astrometric precision of ~0.2 mas using the Keck laser guide star adaptive optics system (Lu et al. 2016). The dotted line denotes anticipated astrometric precision achievable in the next decade (e.g., ~0.05 mas, using *WFIRST* or the Thirty Meter Telescope). The points correspond to microlensing events in the Mock EWS simulation.

IDLE and LDLE distribution of AML signals



(a) IDLE observables



(b) LDLE observables