Astrometric Weak Lensing Constraints on Dark Matter Substructure

With Gaia EDR3

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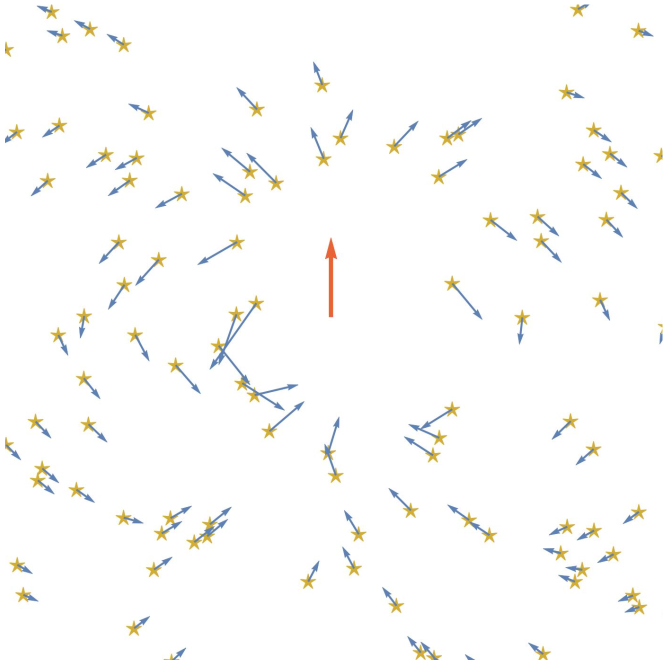
APS April Meeting 2022

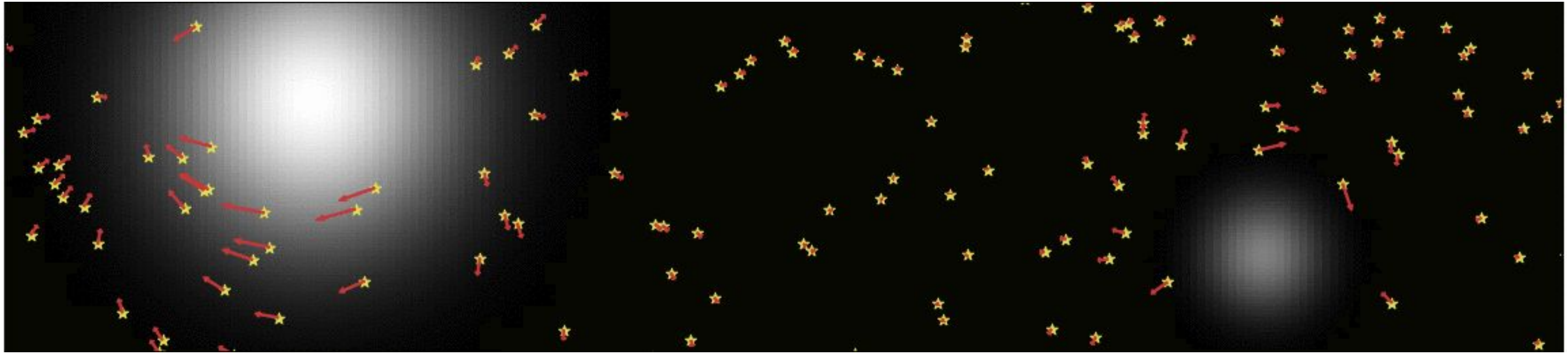
In collaboration with: Cristina Mondino, Anna-Maria Taki, Ken Van Tilburg, and Neal Weiner

Based on: *Mondino et al. (prep)*, *1804.01991*, *2002.01938*

Gravitational Searches for Dark Matter

- Dark Matter is known to interact gravitationally
- This allows us to test broad classes of DM models
  - Can look for deviations from ΛCDM at small scales
  - Differences in formation history, initial conditions, dissipation
  - Complements direct detection searches
- Our method: Astrometric weak lensing
  - Look for **correlated**, **lens-induced** motions of background stars to determine properties of DM substructure



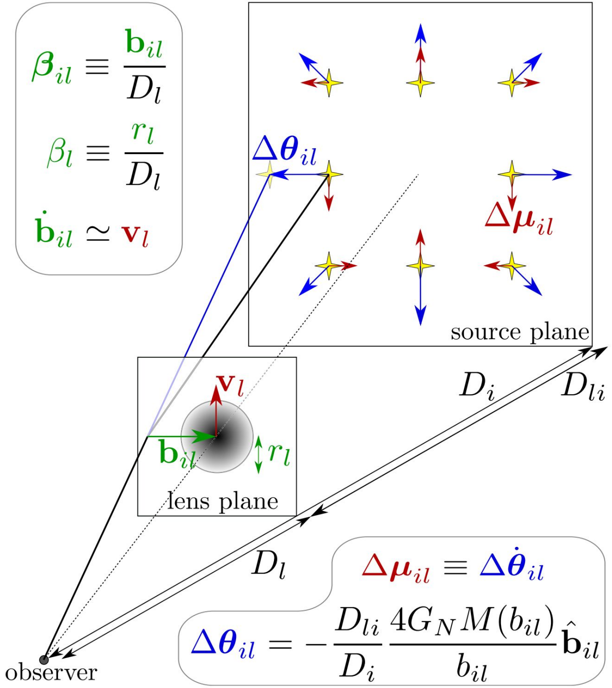


Animation Credit: Siddharth Mishra-Sharma

In this talk…

- Discuss how **Astrometric Weak Lensing** techniques can place constraints on Dark Matter substructure in the Milky Way
- Provide updated constraints on DM substructure using **proper motion** data from Gaia EDR3
- Introduce a **new technique** to discover low-mass dark objects using stellar **accelerations**
    - Provide sensitivity projections for measuring acceleration observables

What is Astrometric Weak Lensing?



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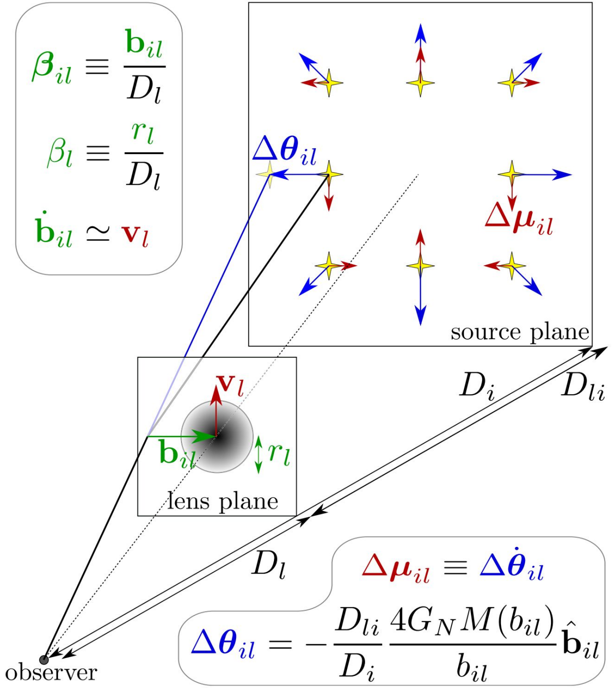

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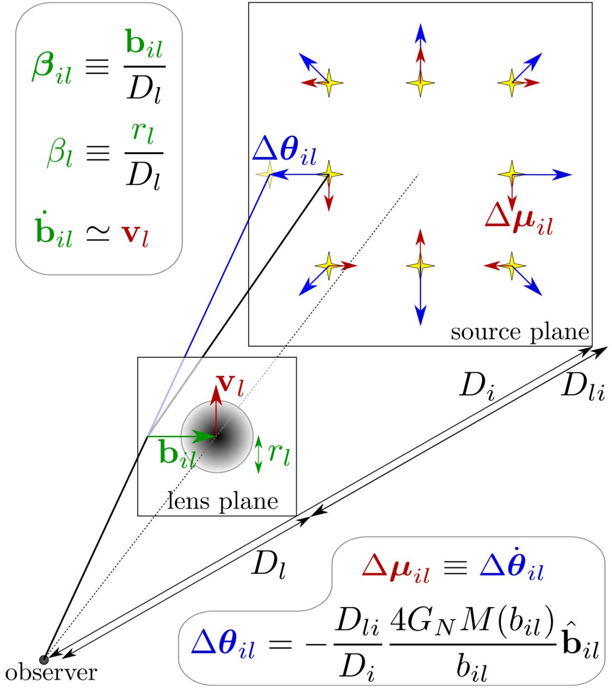

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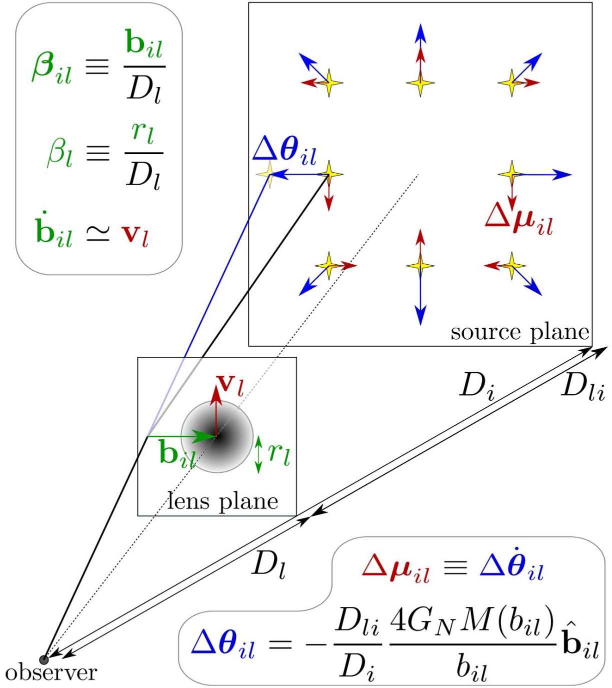
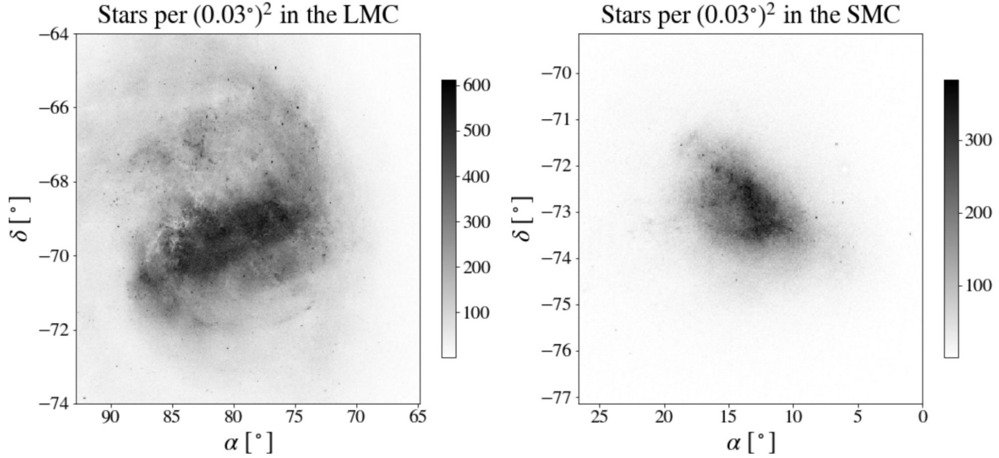
- **Time Domain**: changes in deflection angles allow us to infer additional information about foreground dark objects



Gaia EDR3

- EDR3 Provides **high quality** astrometric data for stellar sources
  - 1.8 billion stars in total
  - Proper motion measurements for 1.5 billion stars
  - $\mathcal{O}(100\ \mu\mathrm{as})$ precision
  - Planned to endure for 10 years



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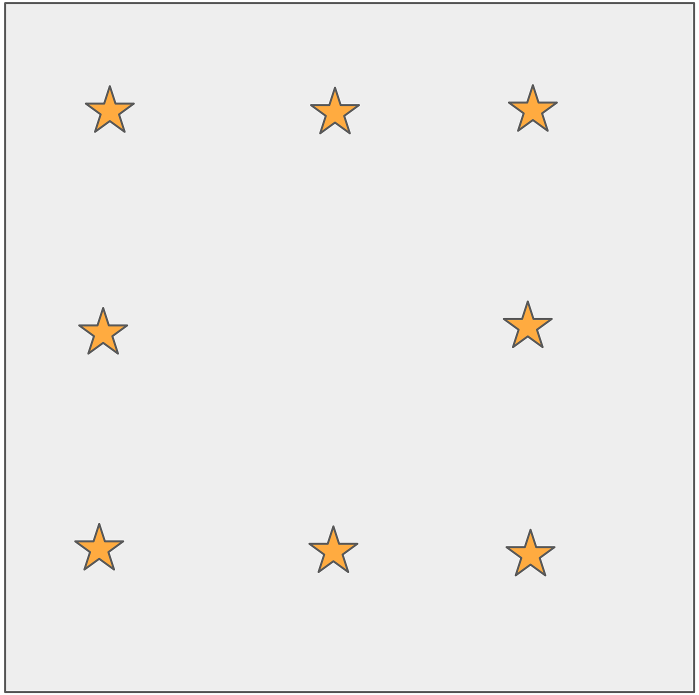

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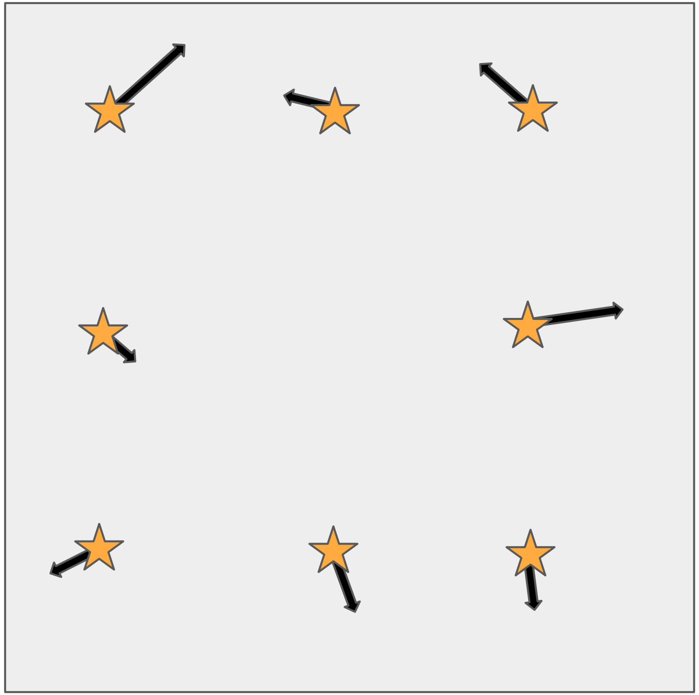

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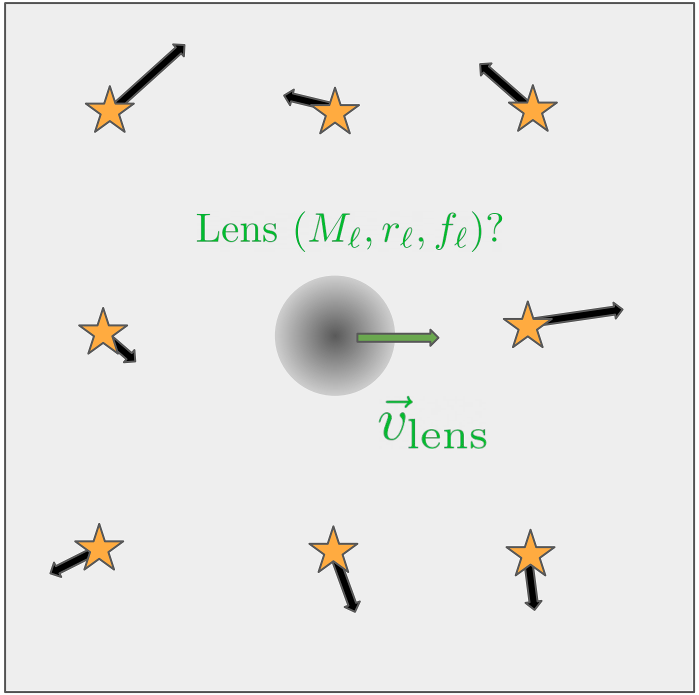

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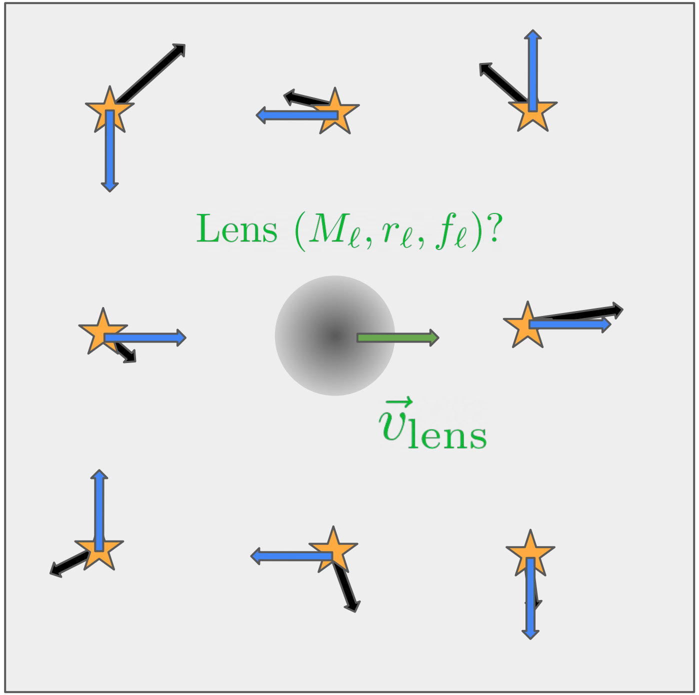

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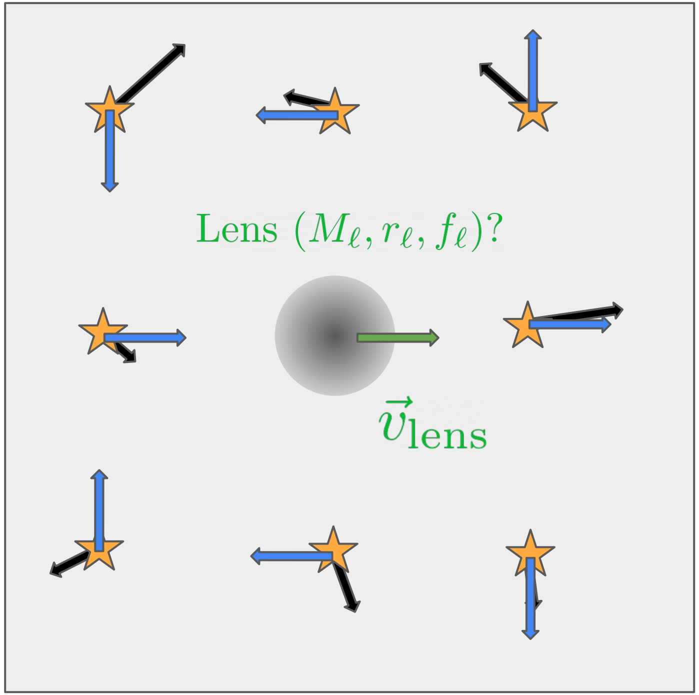
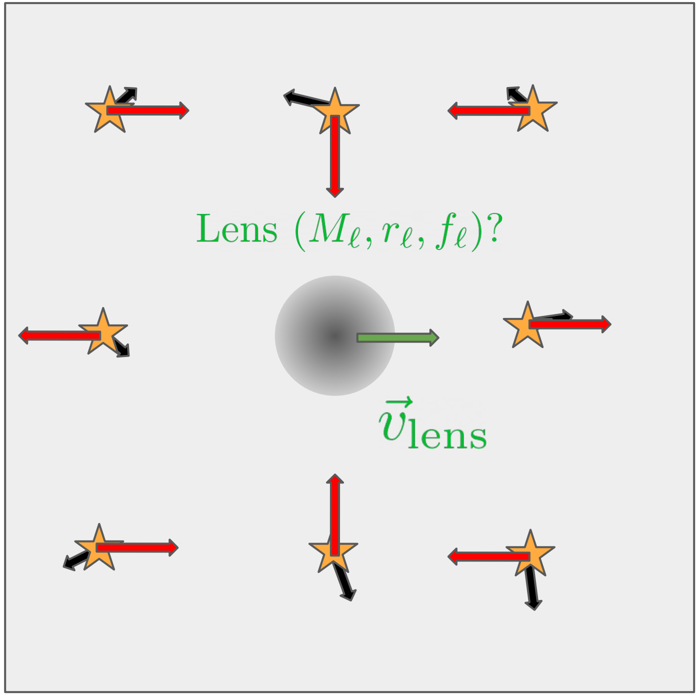


We can do the same with accelerations!

Observed Accelerations ($\vec{\alpha}_i$)

Expected Accelerations ($\vec{\tilde{\alpha}}_i$)

$$\mathcal{T}_\alpha \equiv \sum_i \frac{\vec{\alpha}_i \cdot \vec{\tilde{\alpha}}_i}{\sigma^2_{\alpha,i}}$$



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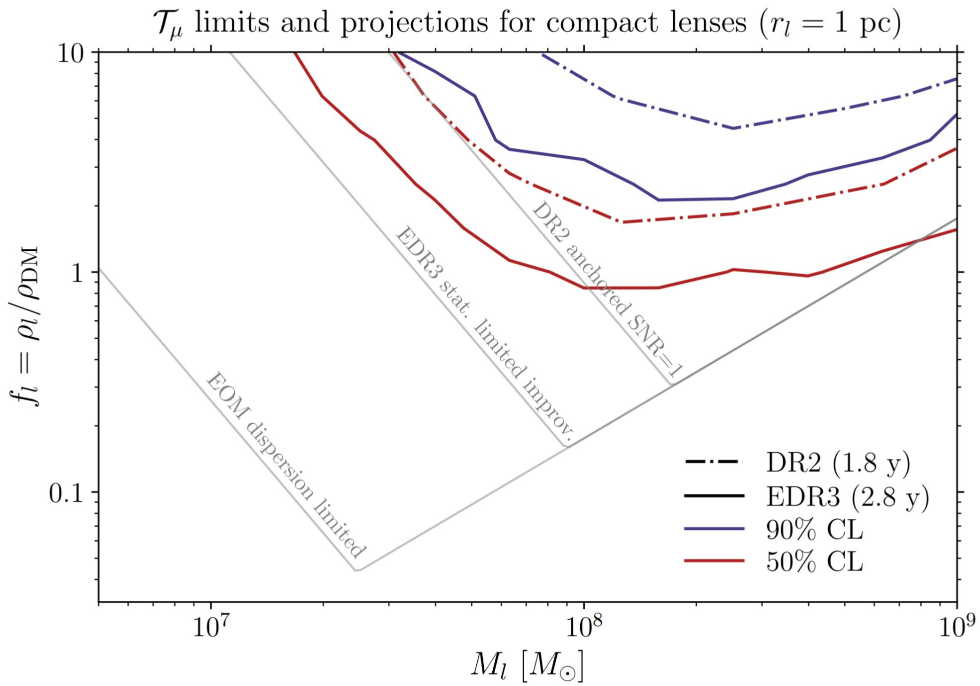
2. The optimal test statistic $\mathcal{R}$ is computed for both ***data*** and ***simulations***.
3. If in 90% of the simulations,

$$\max(\mathcal{R}_{\text{simulations}}) > \max(\mathcal{R}_{\text{data}})$$

the parameter space is excluded at 90% CL.

Limits from Proper Motions

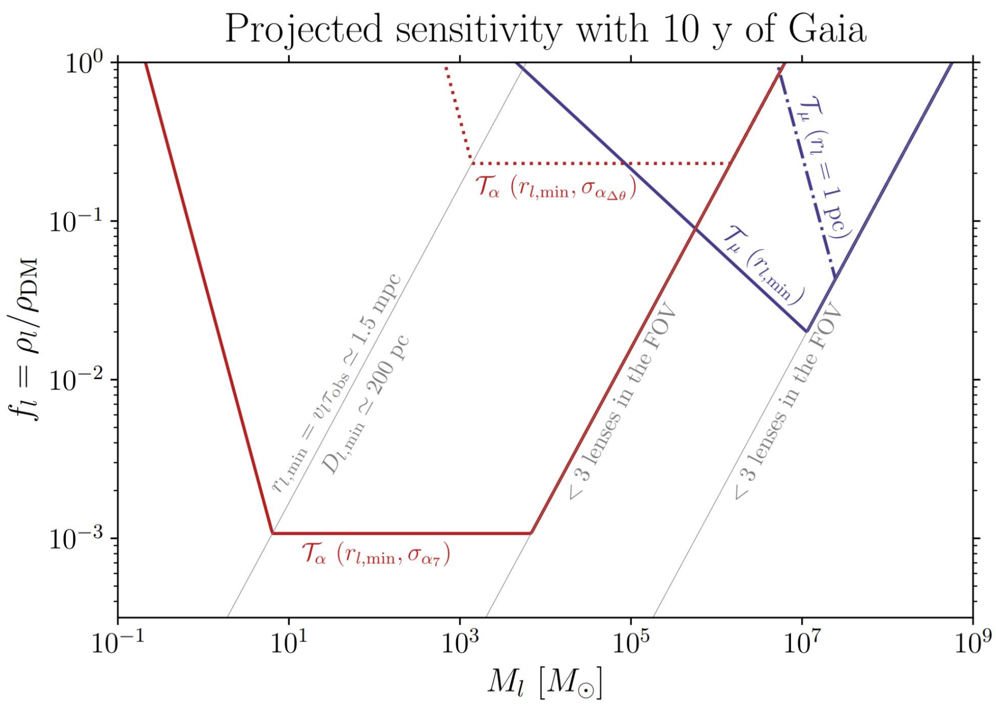


Acceleration Sensitivity Projections

- Gaia does **not** provide acceleration data
- **Accelerations** have low intrinsic noise

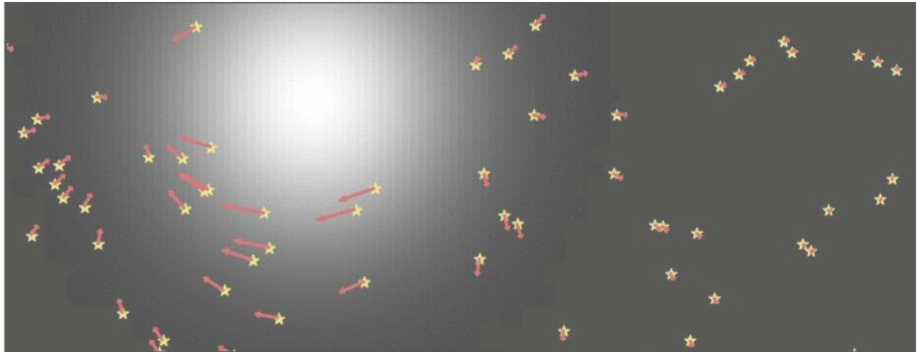
$$\mathrm{SNR}_{\mu} \sim \frac{4 G_N M_l v_l}{b_l D_l} \frac{\sqrt{\Sigma_s}}{\sigma_{\mu,\mathrm{eff}}}$$

$$\mathrm{SNR}_{\alpha} \sim \frac{8 G_N M_l v_l^2}{b_l^2 D_l} \frac{\sqrt{\Sigma_s}}{\sigma_{\alpha,\mathrm{eff}}}$$



Conclusions

- Gravitational searches for DM are **important**!
- Using the **proper motion** template, we can place ***actual limits*** on dark matter substructure today!
- **Acceleration** is a promising observable for detecting compact, low-mass objects
    - Not only DM substructure, but e.g. astrophysical black holes
- Expect rapid improvement of these limits ($\sim t^{9/2}$) as new data arrive



References

[1] (Van Tilburg et al., 2018) https://arxiv.org/abs/1804.01991

[2] (Mondino et al., 2020) https://arxiv.org/abs/2002.01938