



Astrometric Weak Lensing Constraints on Dark Matter Substructure

With Gaia EDR3

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

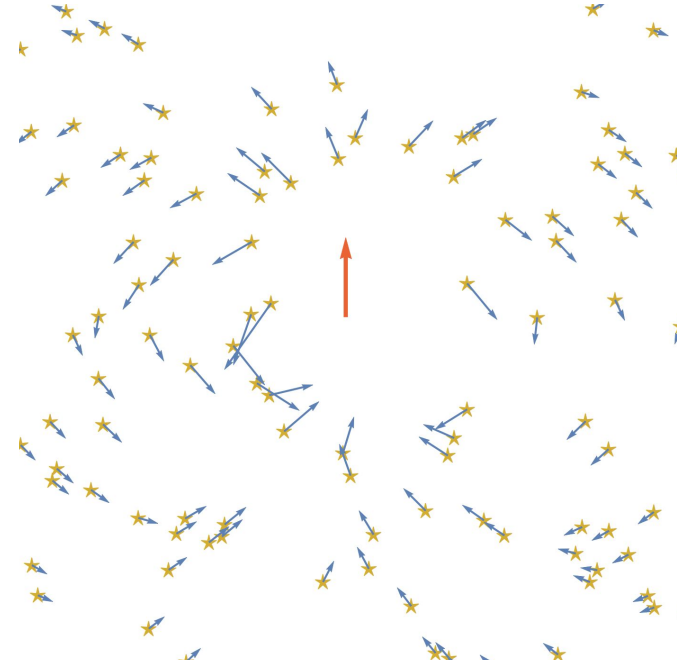
Based on: *Mondino et al. (prep)*, [1804.01991](#), [2002.01938](#)

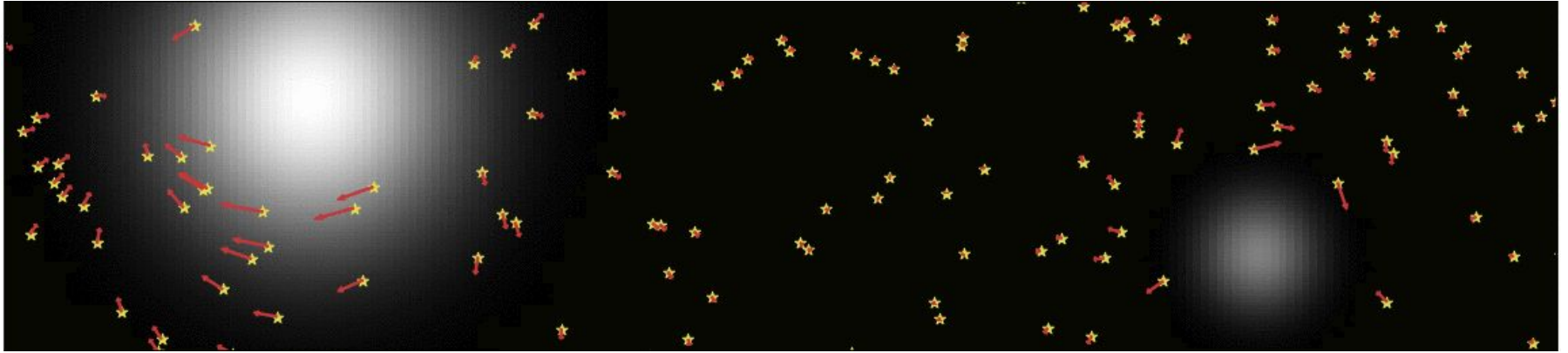




Gravitational Searches for Dark Matter

- Dark Matter is known to interact gravitationally
- This allows us to test broad classes of DM models
 - Can look for deviations from Λ CDM 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

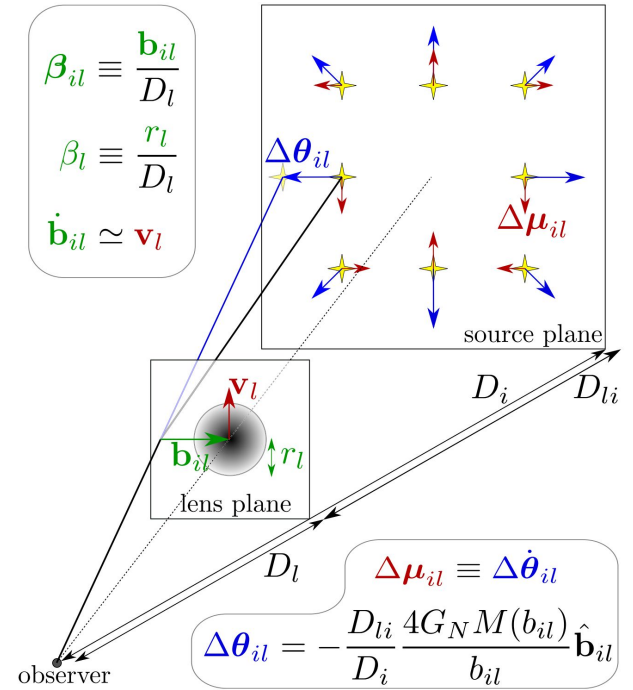


In this talk...

- 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



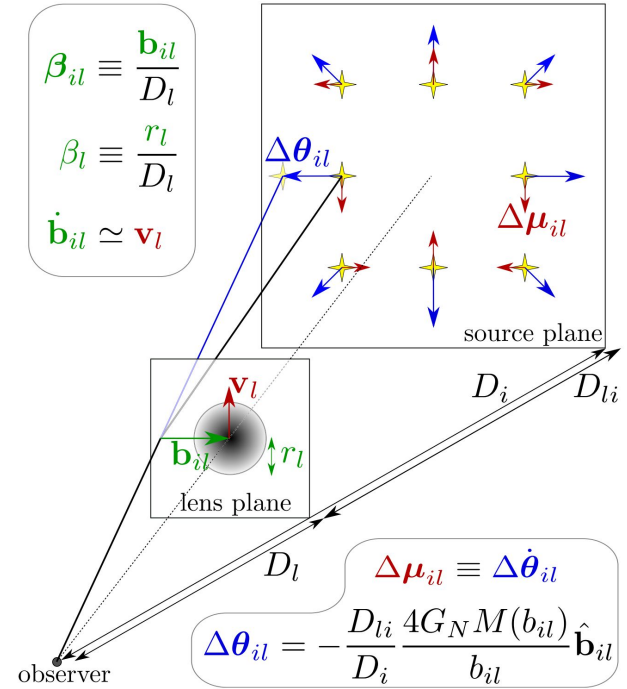
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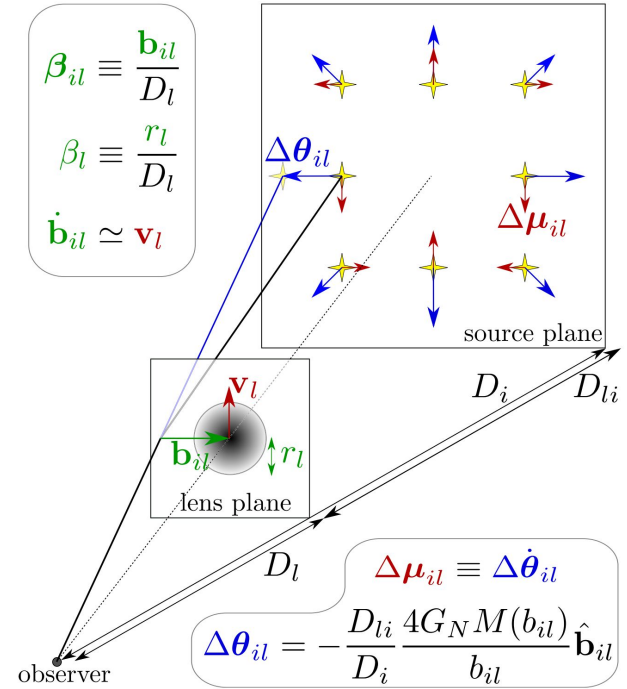
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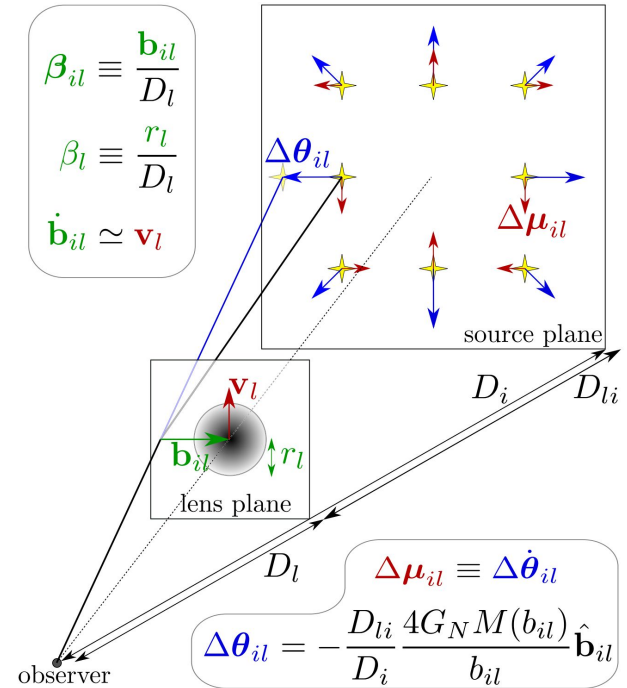
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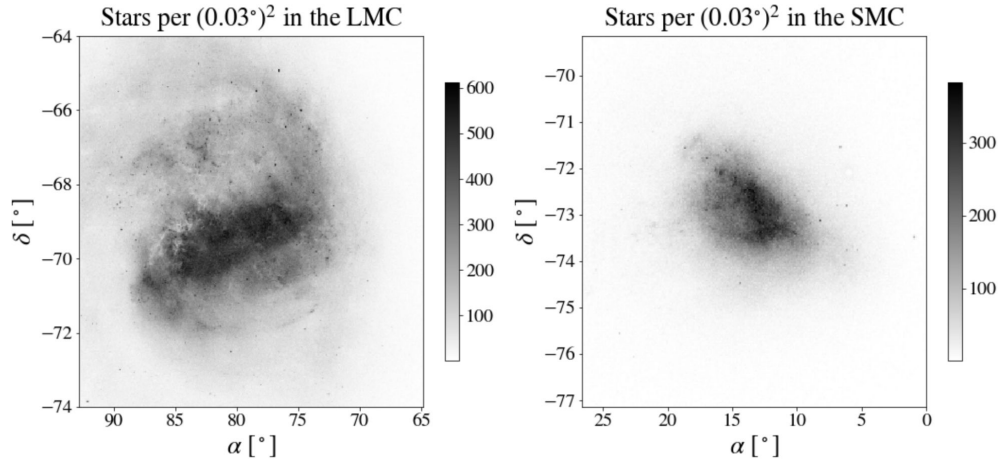
- **Astrometric**: looking at angular deflection of light centroid
- **Weak Lensing**: regime where gravitational aberrations are weak
- **Time Domain**: changes in deflection angles allow us to infer additional information about foreground dark objects





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
 - $\mathcal{O}(100 \mu\text{as})$ precision
 - Planned to endure for 10 years





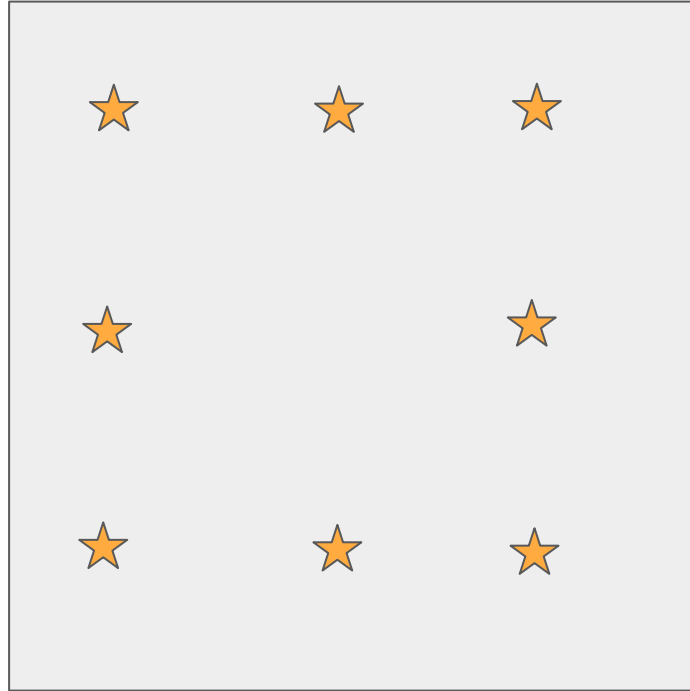
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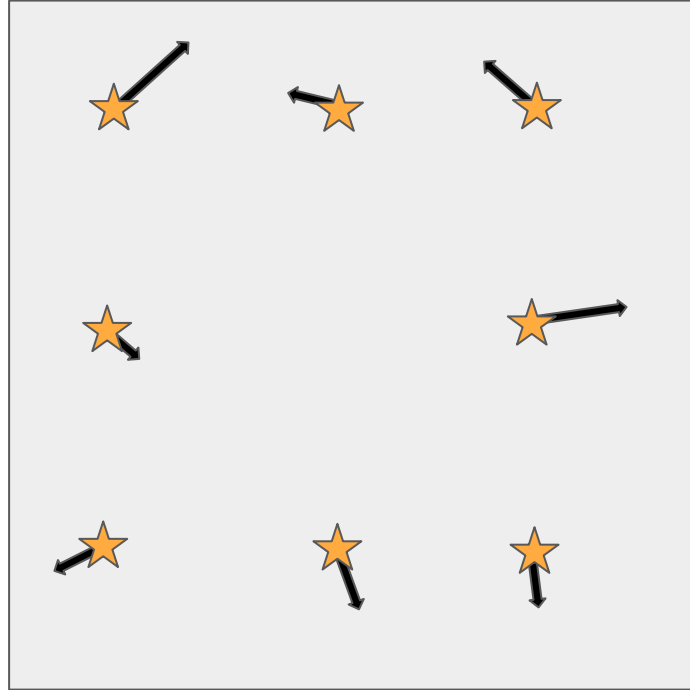




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Observed Proper Motions ($\vec{\mu}_i$)

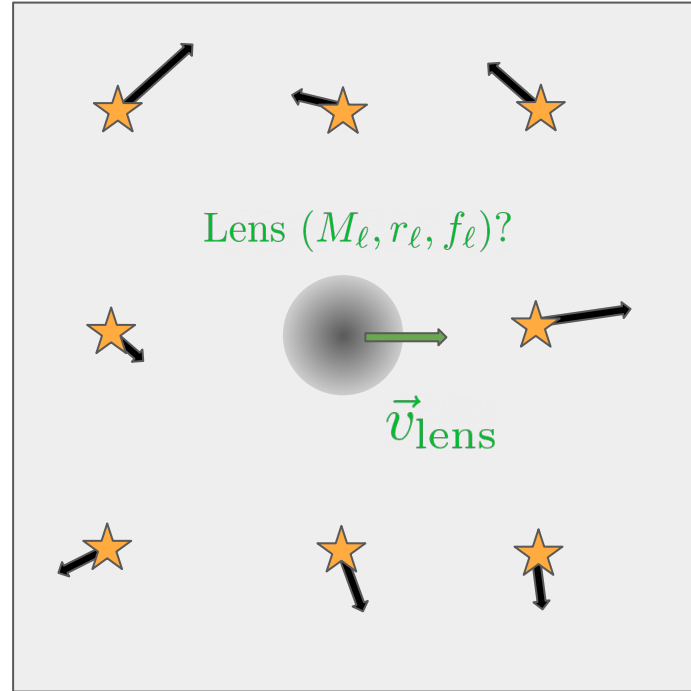




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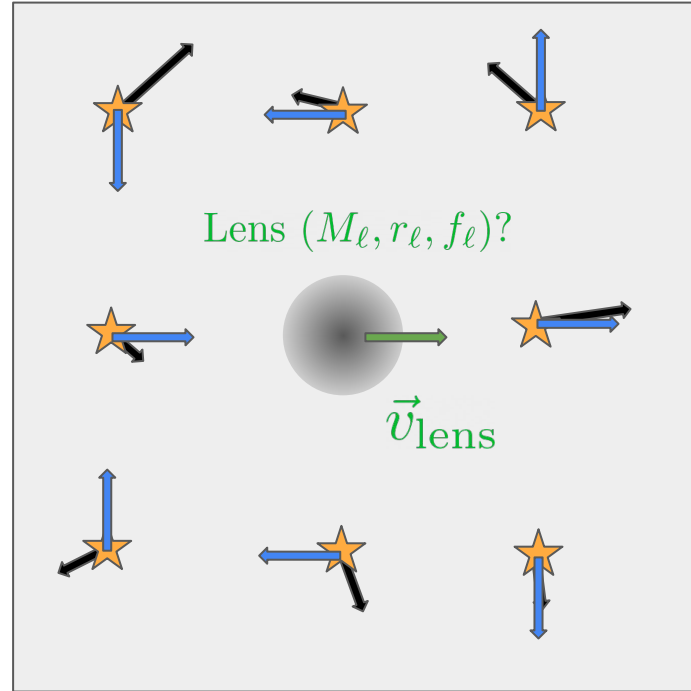


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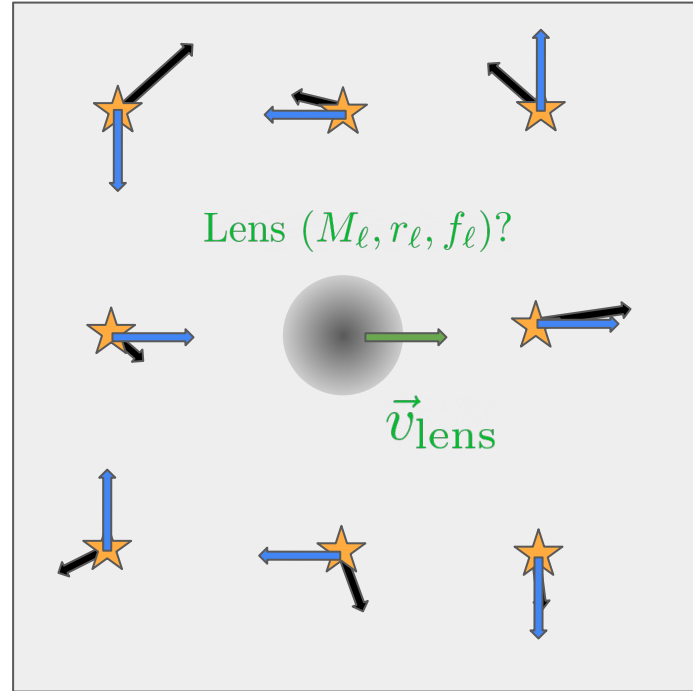
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$$\mathcal{T}_\mu \equiv \sum_i \frac{\vec{\mu}_i \cdot \vec{\tilde{\mu}}_i}{\sigma_{\mu,i}^2}$$



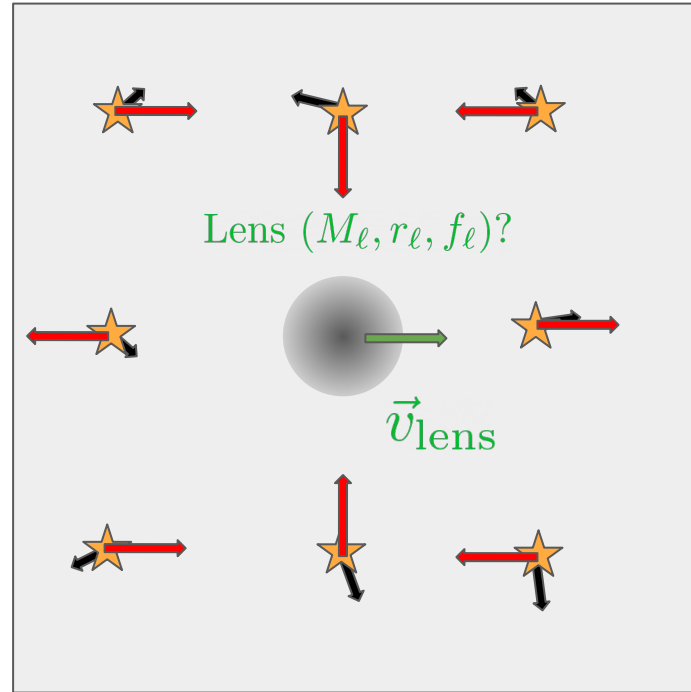


We can do the same with accelerations!

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

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

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



Constraining the Presence of Dark Matter





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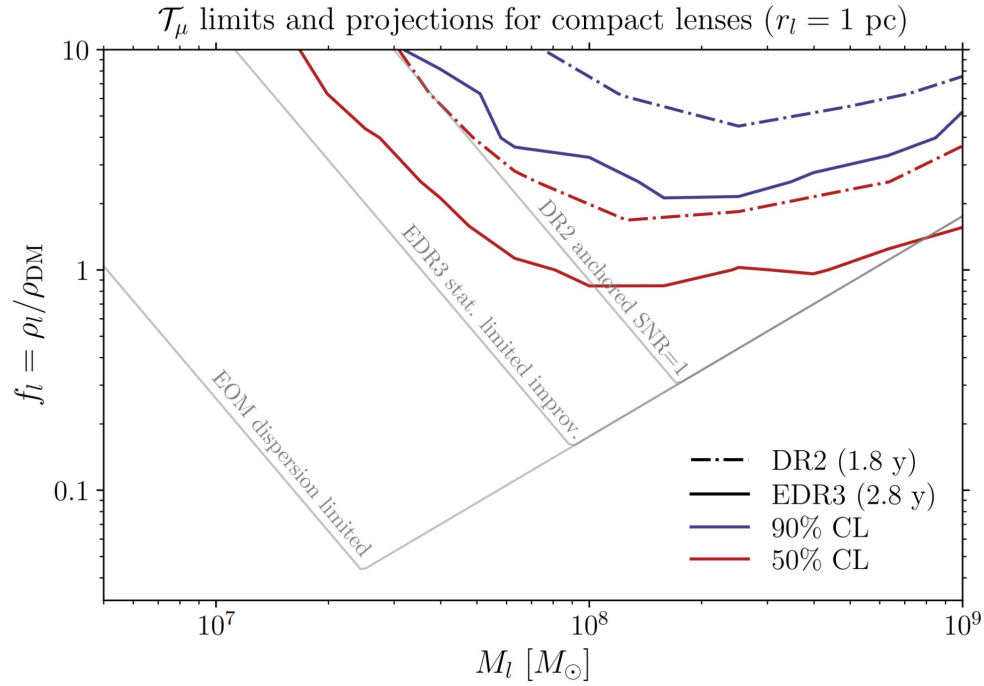
1. Fake data samples are created, injecting both signal and noise.
2. The optimal test statistic \mathcal{R} is computed for both **data** and **simulations**.
3. If in 90% of the simulations,

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

the parameter space is excluded at 90% CL.



Limits from Proper Motions

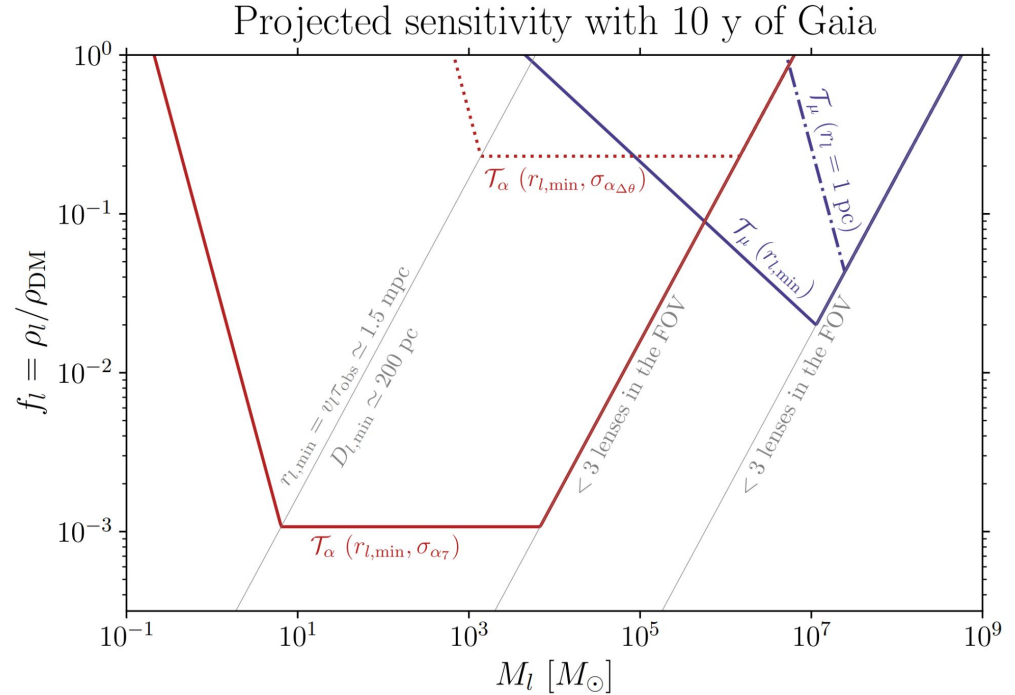




Acceleration Sensitivity Projections

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

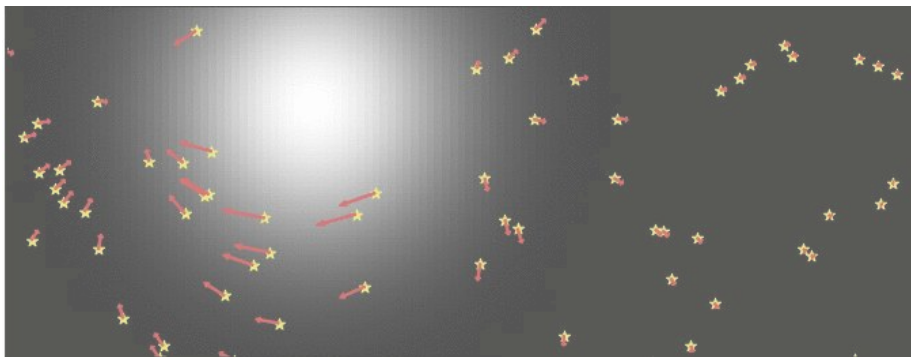
$$\text{SNR}_\mu \sim \frac{4G_N M_l v_l}{b_l D_l} \frac{\sqrt{\Sigma_s}}{\sigma_{\mu,\text{eff}}}$$
$$\text{SNR}_\alpha \sim \frac{8G_N M_l v_l^2}{b_l^2 D_l} \frac{\sqrt{\Sigma_s}}{\sigma_{\alpha,\text{eff}}}$$





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>

