Astrophysical Constraints on Long-Range Interactions of Dark Matter

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Based on hep-ph/2311.07648 and hep-ph/2312.xxxxx
with Peter Graham and Harikrishnan Ramani

Outline

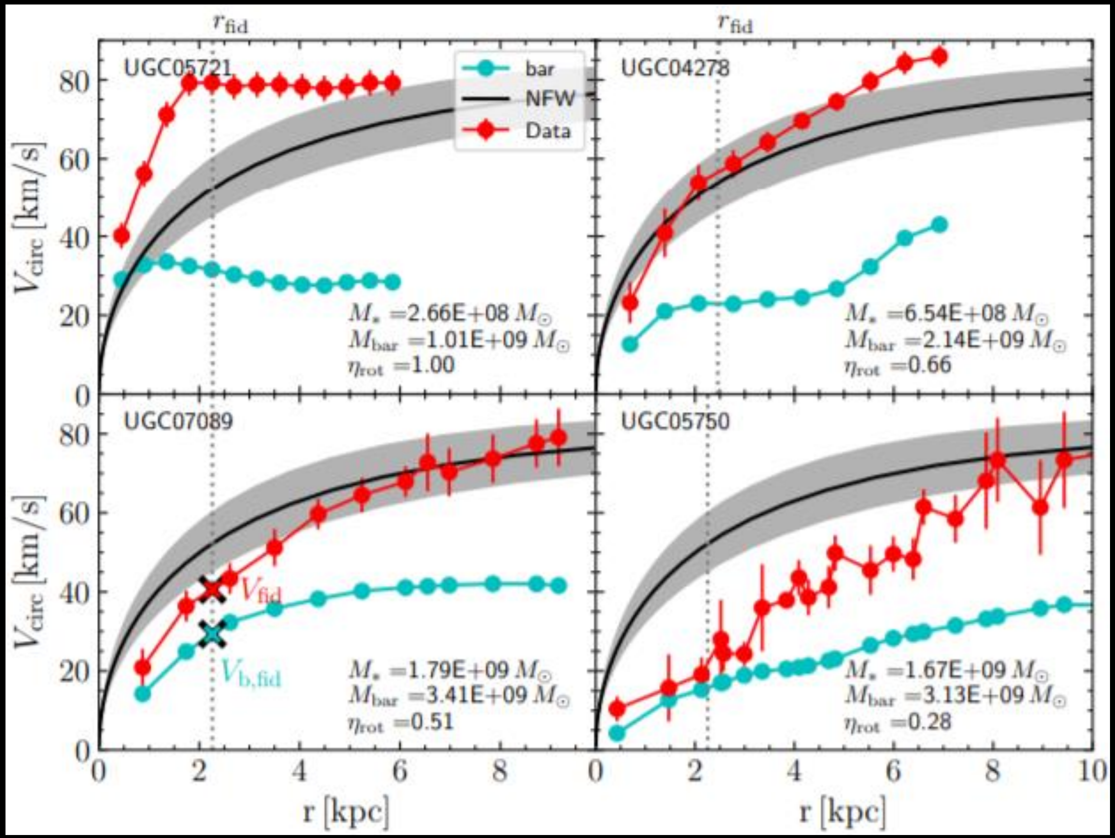
- Dark matter self-interactions
  - Short- and long-range constraints
  - Constraints on intermediate-range forces

- Dark matter-Standard Model interactions
  - Constraints from combining SM-only and DM-only constraints
  - Dynamical friction in ultrafaint dwarf galaxies

Dark Matter Self-Interactions

Dark matter self-interactions are motivated by several astrophysical tensions

- Various galaxy properties don’t quite match simulations of ΛCDM:
  - Core-cusp
  - Missing satellites
  - Void emptiness
  - The diversity problem
- Recent simulations have eased some of these but still unclear if they can all be resolved in ΛCDM



astro-ph.GA/1911.09116

A standard form for DM self-interactions is a Yukawa potential

Strength Relative to Gravity (for **D**ark Matter)

Dark Matter particle mass

Force Range

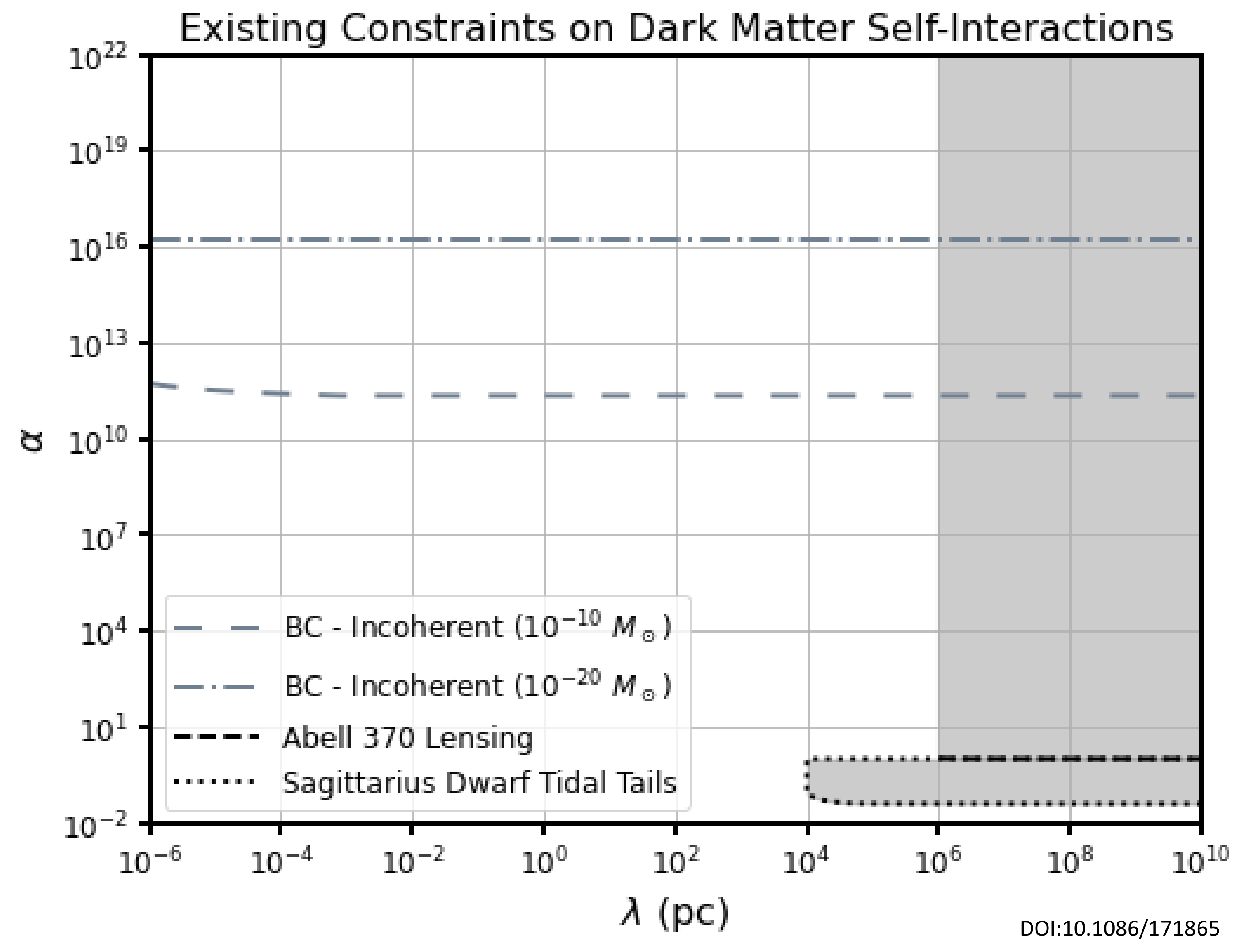
$$V \sim \pm \alpha_{DD} G \frac{m_{DM}^2}{r} e^{-r/\lambda}$$

Species-dependent factors

Can be attractive, repulsive, or have mixed charges

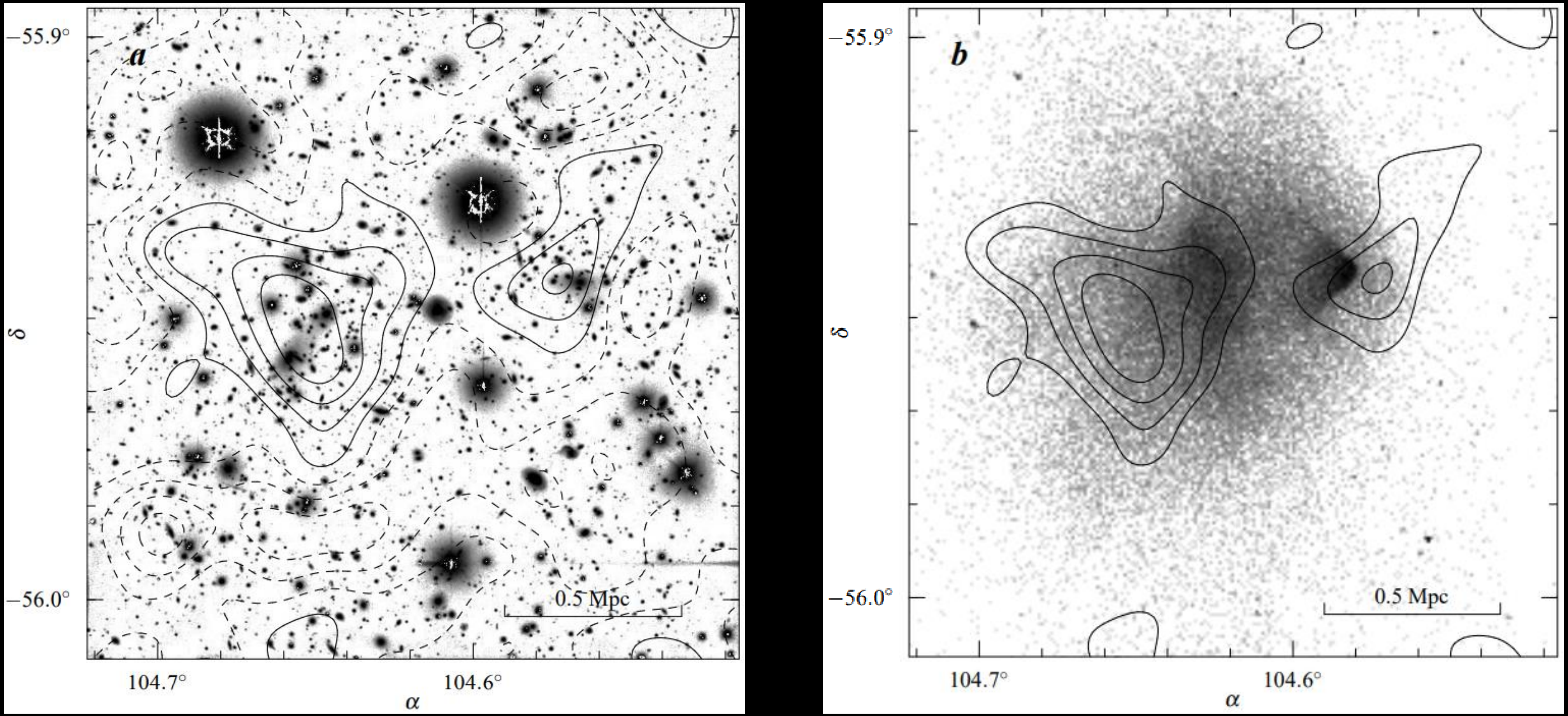
Long-range effects will only matter with a net charge

Existing constraints on long-range dark matter self-interactions



DOI:10.1086/171865

The Bullet Cluster



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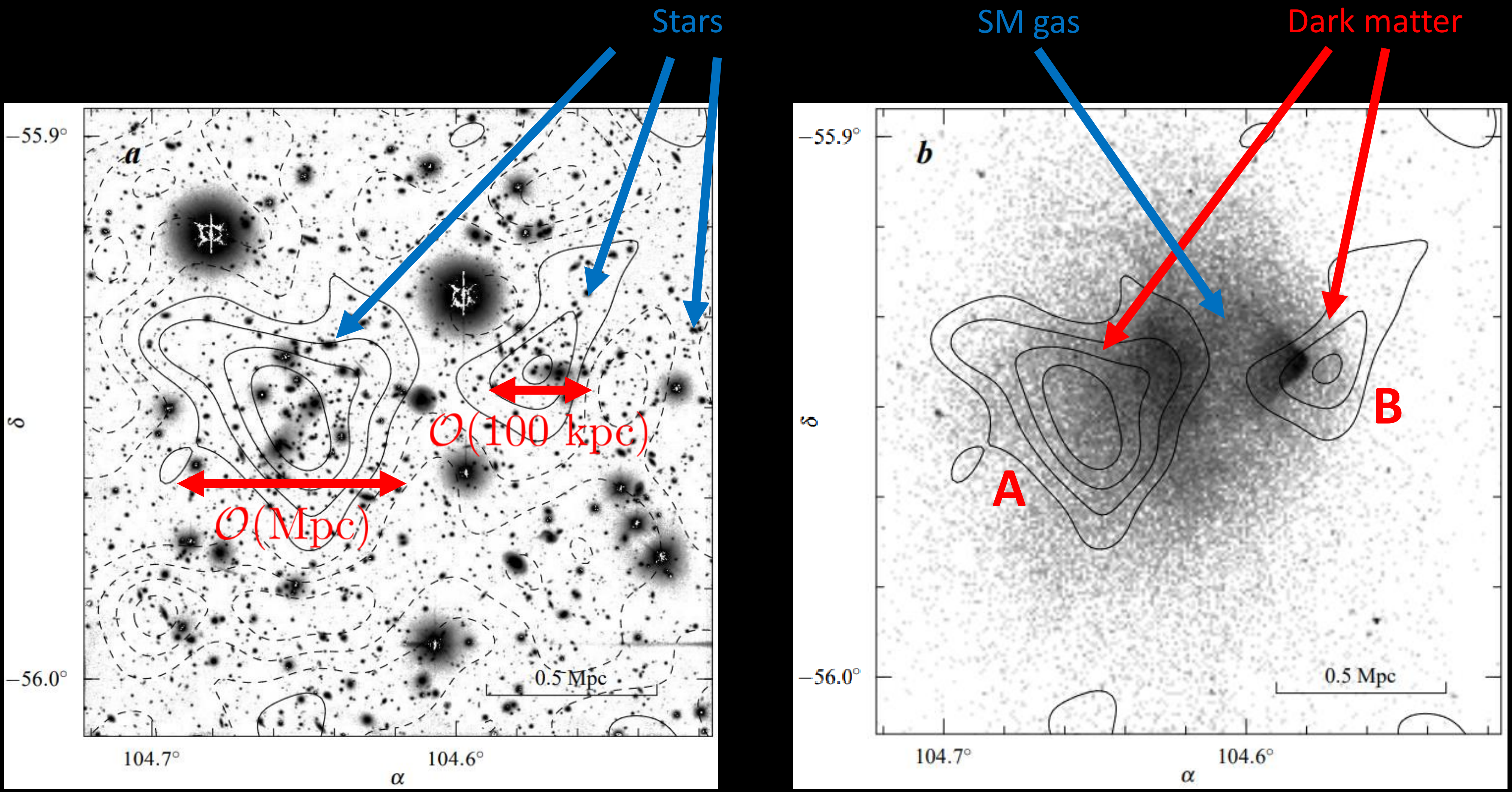
The Bullet Cluster



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The Bullet Cluster: hard scattering

- Dark matter halos passing through one another sets limits on self-interactions

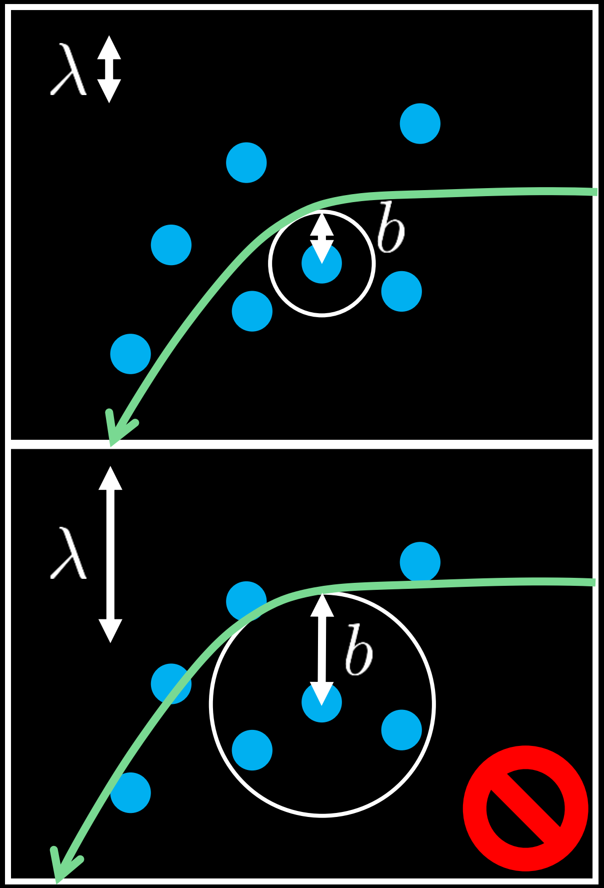
- For hard sphere scattering:

$$\frac{\sigma}{m} \lesssim 1 \ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

- Can roughly generalize with momentum-transfer cross-section:

$$\frac{\sigma_T}{m} \lesssim 1 \ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

The Bullet Cluster: hard scattering



- Usual BC limit uses 1-on-1 particle scattering
- This isn't right when scattered particles see multiple others:

$$\lambda \gtrsim b \gtrsim n^{-1/3}$$

- Can still set a constraint on long-range forces by restricting to hard scattering events, but this is throwing out most of the effect

The Bullet Cluster: soft scattering

- Could instead consider soft scattering events, but less clear what the effect is
  - Nearby incident particles should stay nearby after the collision, so you aren’t breaking the clusters in the same way

- Better way to think about this regime is as dynamical friction

Dynamical friction slows particles interacting with a surrounding fluid

Acceleration of the moving object (the “B” cluster)

$$v_B \sim v_{\mathrm{esc},A} > \sigma_A$$

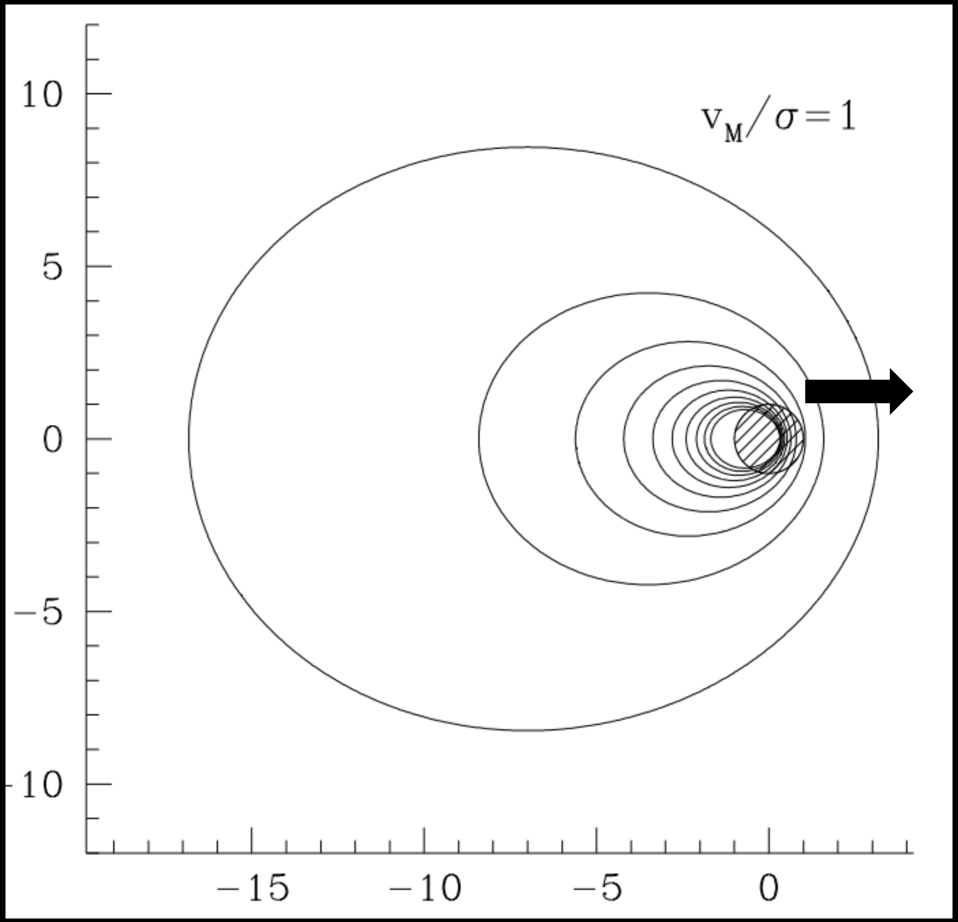
Effects of e.g. force range

$$\frac{\mathrm{d}\mathbf{v}_B}{\mathrm{d}t} = -\frac{16\pi^2}{3}\alpha^2 G^2 M_B \rho_A \frac{\mathbf{v}_B}{v_B^3}\ln(\ldots)$$

Mass of the object

Velocity of moving object

Mass density of the fluid (the “A” cluster)



Binney and Tremaine. *Galactic Dynamics* (2nd Ed.), 2008. https://doi.org/10.1515/9781400828722

The Bullet Cluster: dynamical friction

- Dynamical friction will thus slow the small “B” cluster as it falls through the halo of the “A” cluster

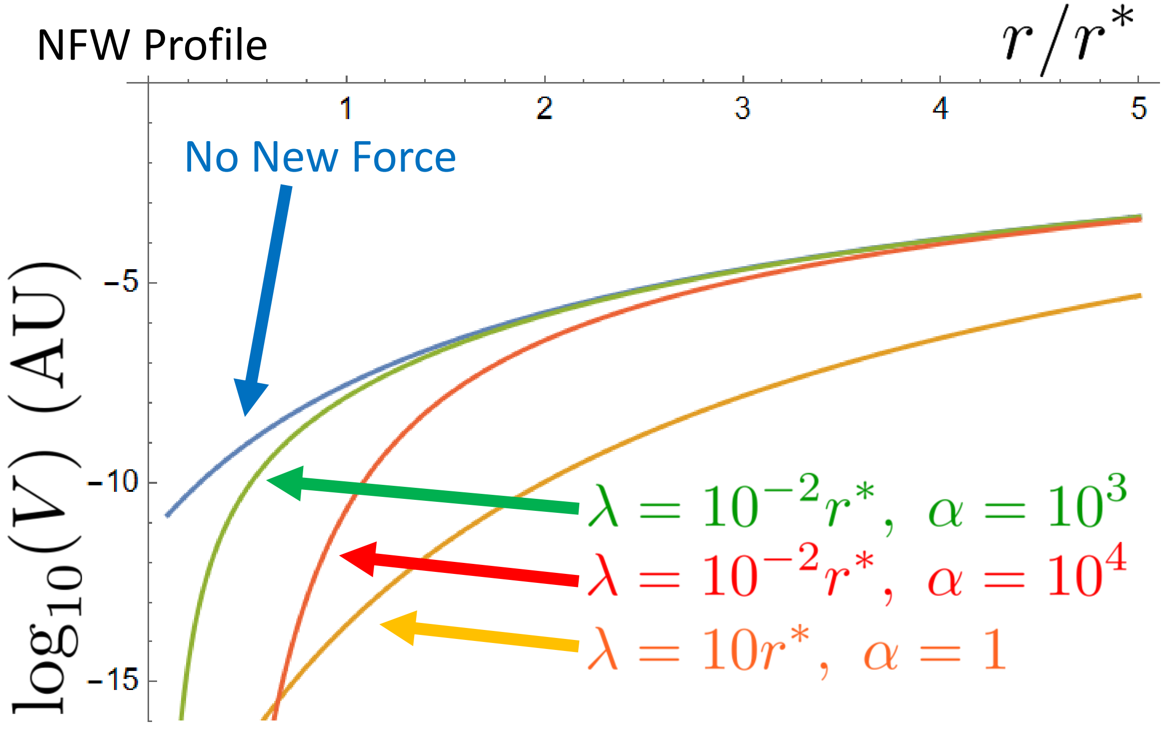
- Integrating gives (for all couplings we consider)

$$\frac{\Delta v_B}{v_B} \lesssim 0.04$$

- This isn’t observable… and it’s also not the main effect

The Bullet Cluster: modified infall

- New long-range DMSI change the B cluster's trajectory much more by directly affecting its potential
- Infinite-range forces with $\alpha = 1$ would change the potential, and thus the velocity, by $\mathcal{O}(1)$
- This has been pointed out before; we'll focus on the finite-range, stronger-than-gravity regime



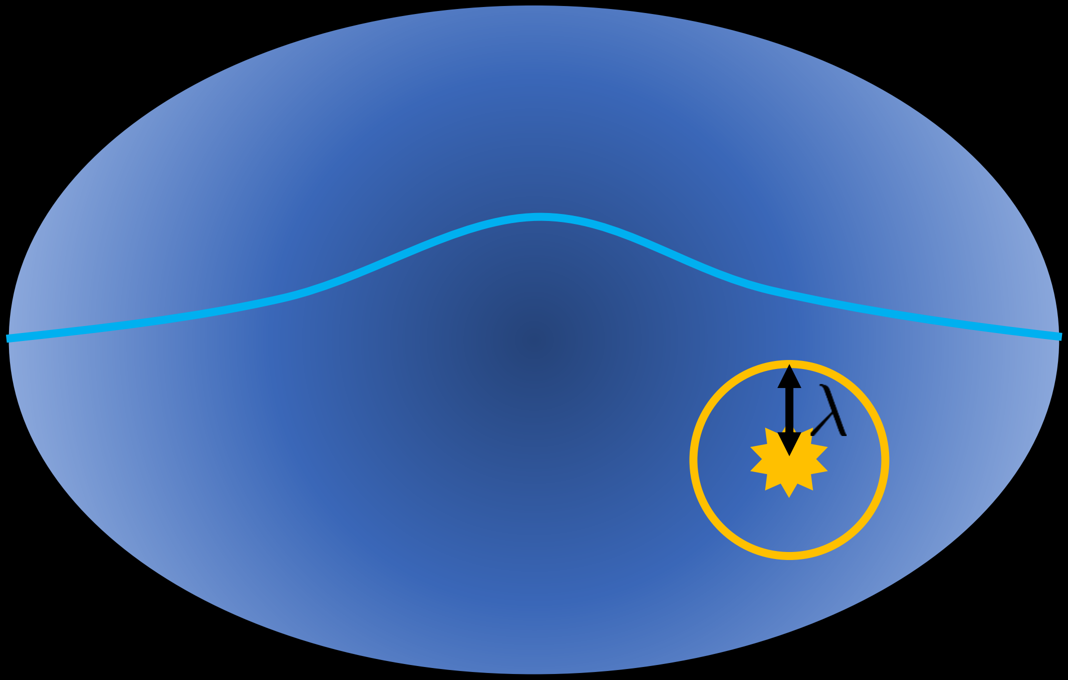
Finite-range forces in dark matter halos

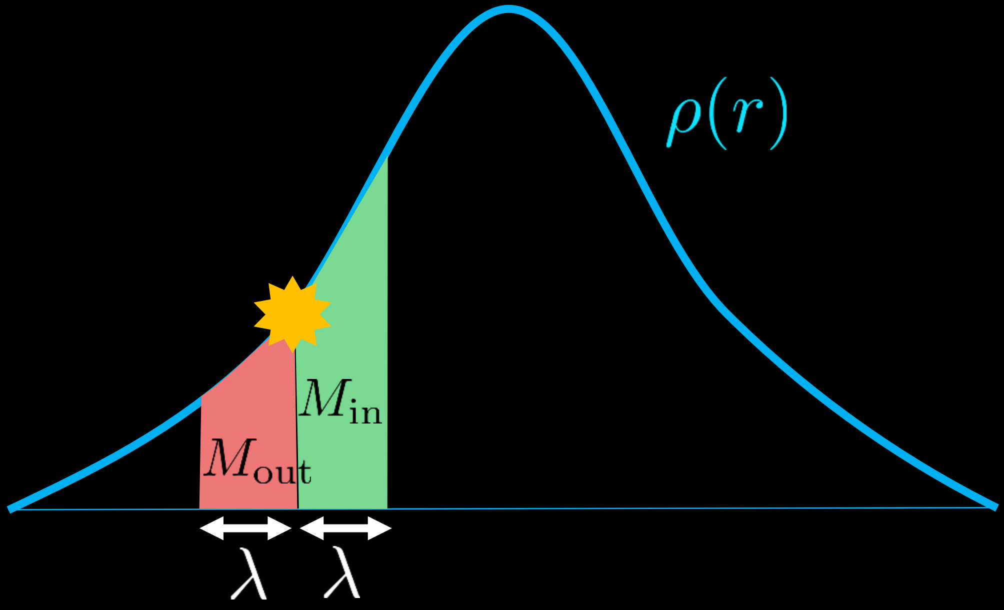
- If dark matter halos had a sharp cutoff, accelerations beyond that cutoff would fall off exponentially:

$$a(r > r_c) \sim e^{-(r-r_c)/\lambda}$$

- But realistic halos have density gradients, so there's no notion of being some distance from a boundary.
  - Suppression is only a power law in λ as a result

Finite-range forces in dark matter halos





Mass within λ outward/inward

$$a \sim \frac{\alpha G M_{\text{out}}}{\lambda^2} - \frac{\alpha G M_{\text{in}}}{\lambda^2} \sim -\frac{\alpha G}{\lambda^2}\left(\rho\lambda^3\right)\overbrace{\frac{\lambda}{r^*}}^{\text{Fractional density difference}} \sim -\alpha G\frac{\rho\lambda^2}{r^*}$$

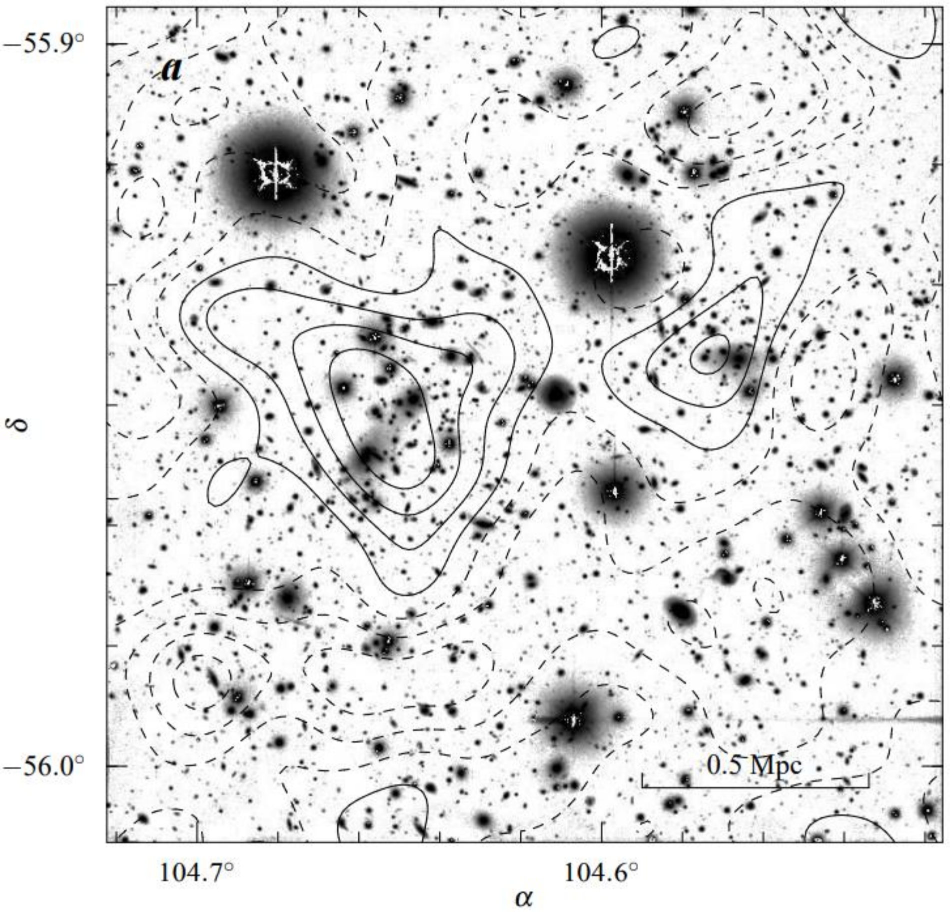
Length scale of the halo

Two scenarios for modified Bullet Cluster collisions:

- The dark matter and the Standard Model content of each cluster could separate or not as the clusters fall towards each other
  - Eventually gas collides and definitely separates, but this could potentially happen before the collision

- We’ll consider both cases

The Bullet Cluster collision if DM and SM separate



astro-ph/0309303

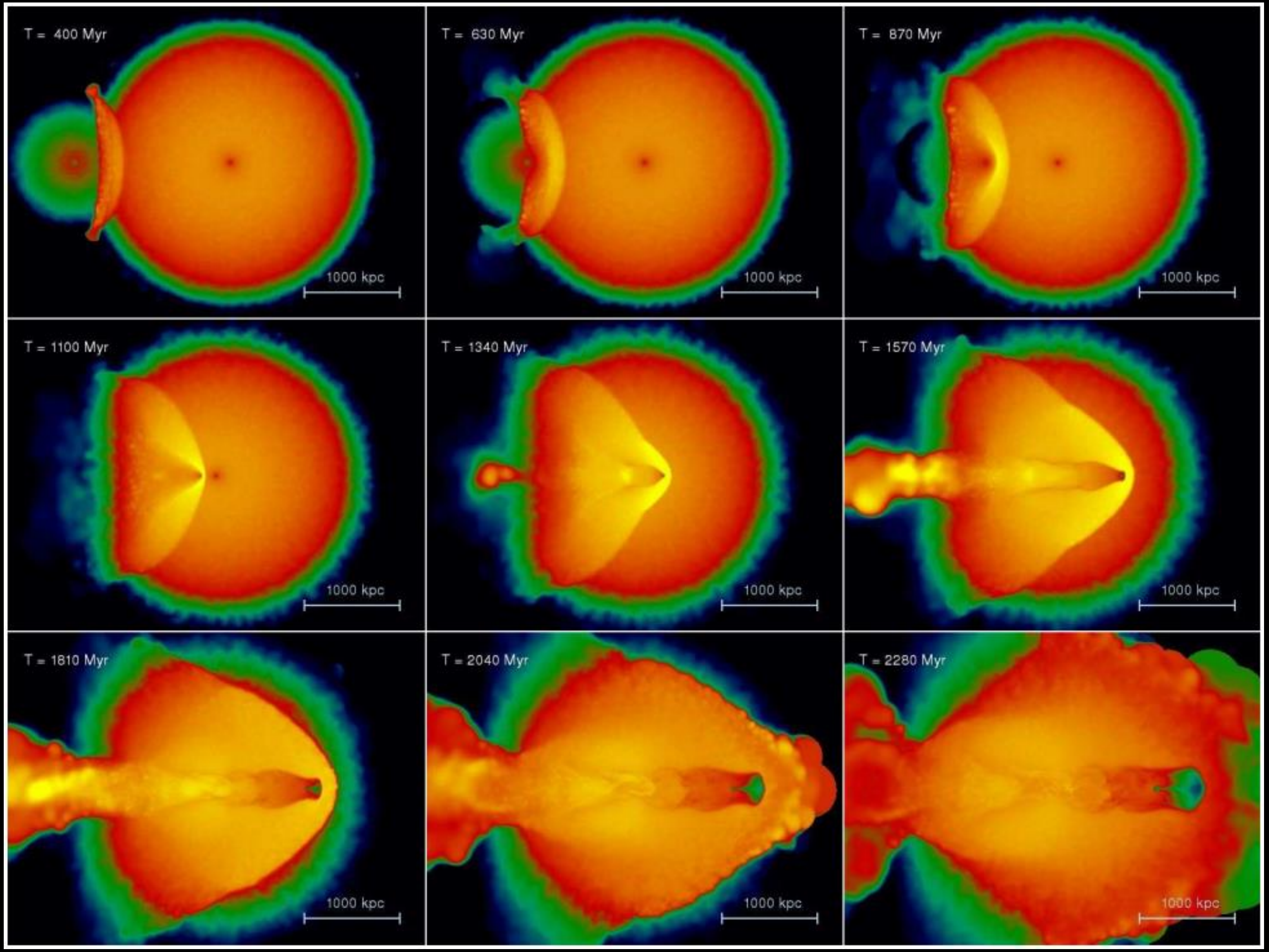
- DM positions measured via gravitational lensing
- Star positions seen optically
- Centroids match to within

$$25 \pm 29\ \text{kpc} \ll r_B^*$$

- This requires

$$\Delta V(r^*) \ll V(r^*) \quad \Rightarrow \quad \alpha \lesssim 1 + \left(\frac{r_A^*}{\lambda}\right)^2$$

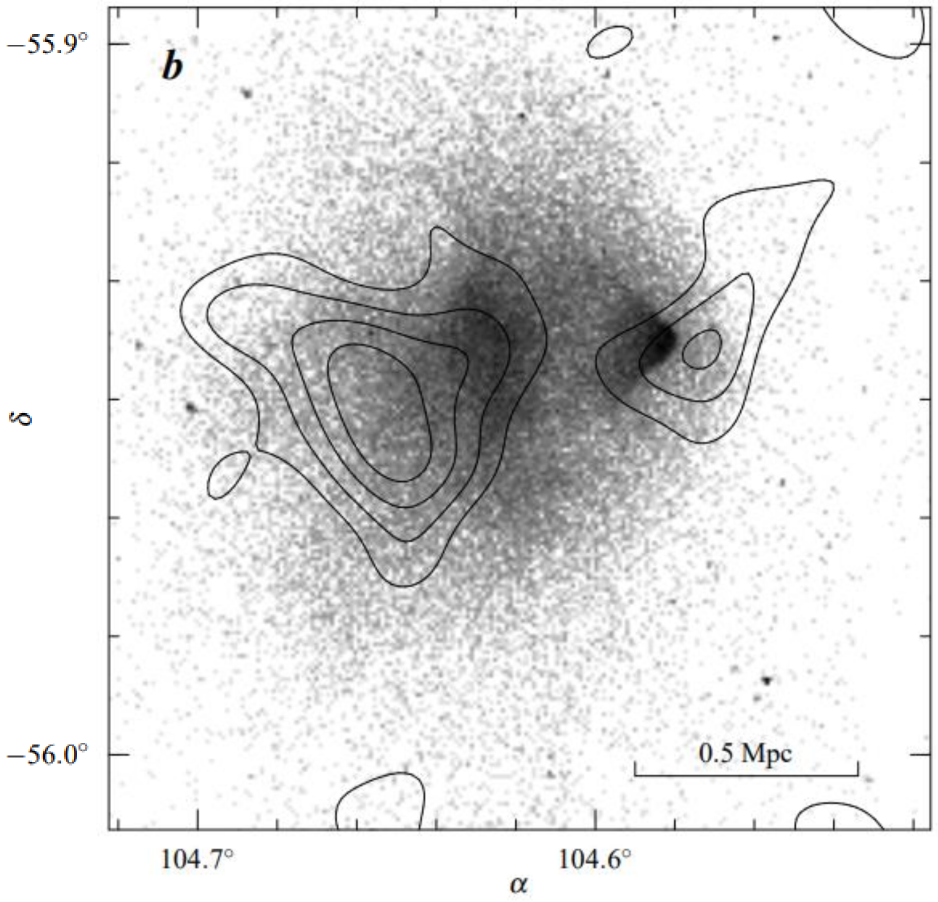
The Bullet Cluster collision if DM and SM do not separate



The Bullet Cluster gas collided supersonically, leading to complicated dynamics even without new forces

astro-ph/0703232

The Bullet Cluster collision if DM and SM do not separate



astro-ph/0309303

Speed at collision from measured mass:

$$1910 \pm 650 \text{ km/s}$$

Speed at collision from gas shock:

$$\sim 2860 \text{ km/s}$$

- This requires

$$\Delta V(r^*) \lesssim V(r^*) \quad \Rightarrow \quad \alpha \lesssim 1 + \left(\frac{r_A^*}{\lambda}\right)^2$$

astro-ph/0703232

Repulsive forces are constrained more strongly by dark matter halo binding

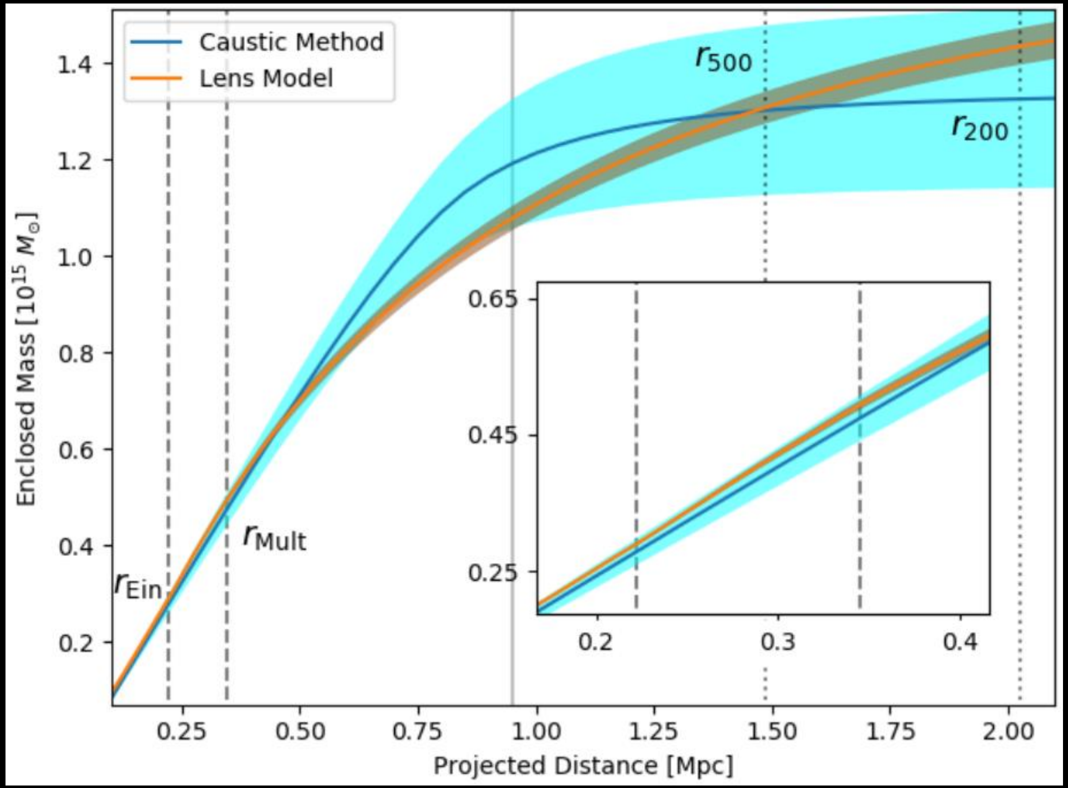
- Existence of DM halos of size $\mathcal{O}(1\ \mathrm{kpc})$ prohibits repulsive forces stronger than gravity with range $\gtrsim 1\ \mathrm{kpc}$

- More generally, need $a_{\mathrm{new}}(\mathrm{kpc}) + a_{\mathrm{g}}(\mathrm{kpc}) < 0$

$$a_{\mathrm{new}} \sim \alpha G \frac{\rho \lambda^2}{\mathrm{kpc}} \quad \Rightarrow \quad \alpha \lesssim 1 + \left(\frac{\mathrm{kpc}}{\lambda}\right)^2$$

Various other systems might give constraints, but substructure complicates things

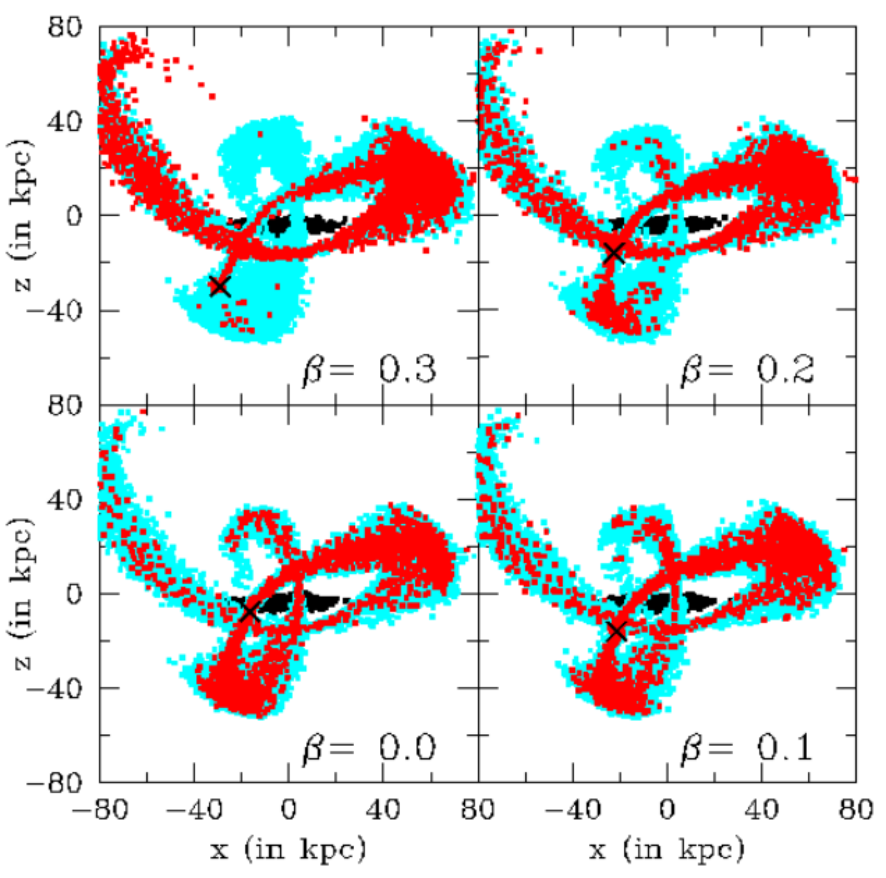
- Can measure mass of clusters using both
  - Gravitational lensing
  - Velocity dispersion of galaxies
- But, for short-range forces, most of mass near galaxy is bound to it; background is significantly disrupted
- Need to simulate



astro-ph.GA/2202.04663

Various other systems might give constraints, but substructure complicates things

- New forces could separate DM and stars in stellar streams; DM would then lead to asymmetry
  - But complicated by substructure, and unclear what happens for larger forces
- Other possibilities: tidal disruption of Milky Way satellites, subhalos disrupting stellar streams, …



astro-ph/0606566
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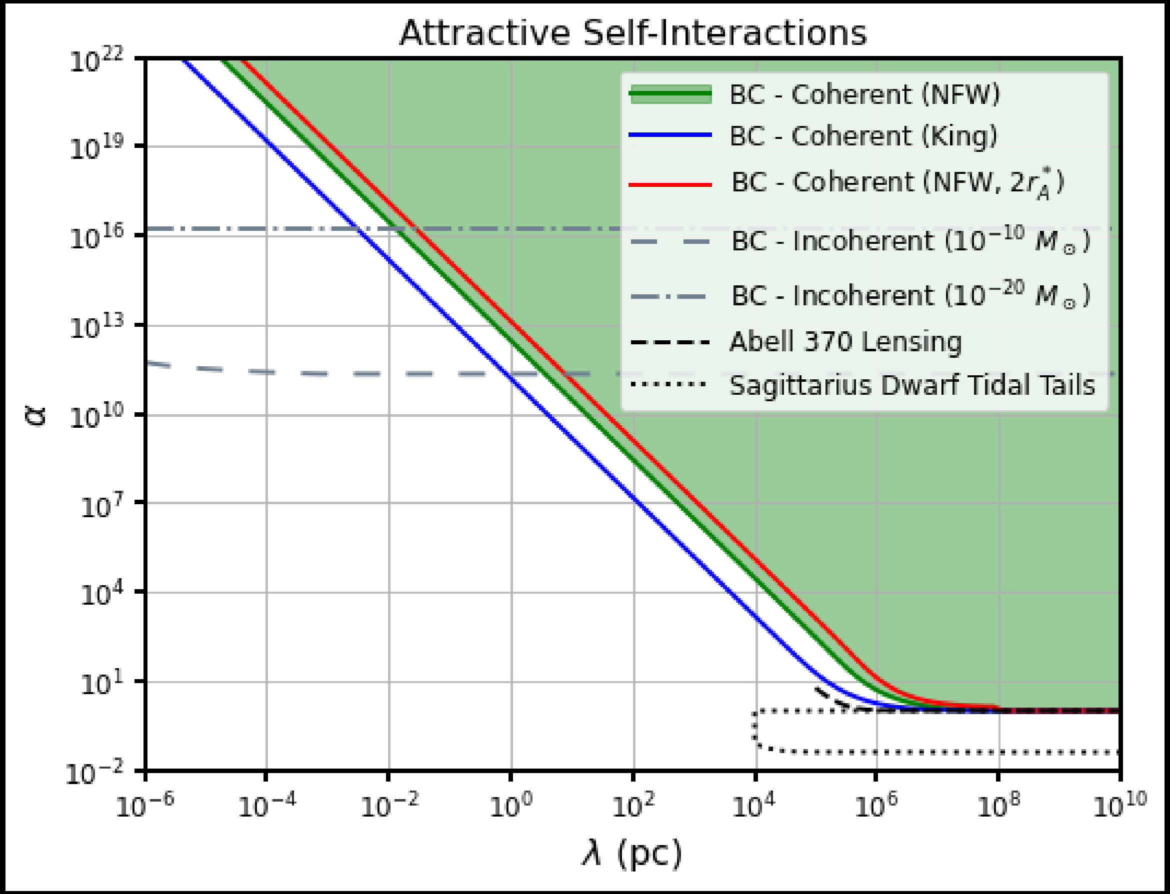
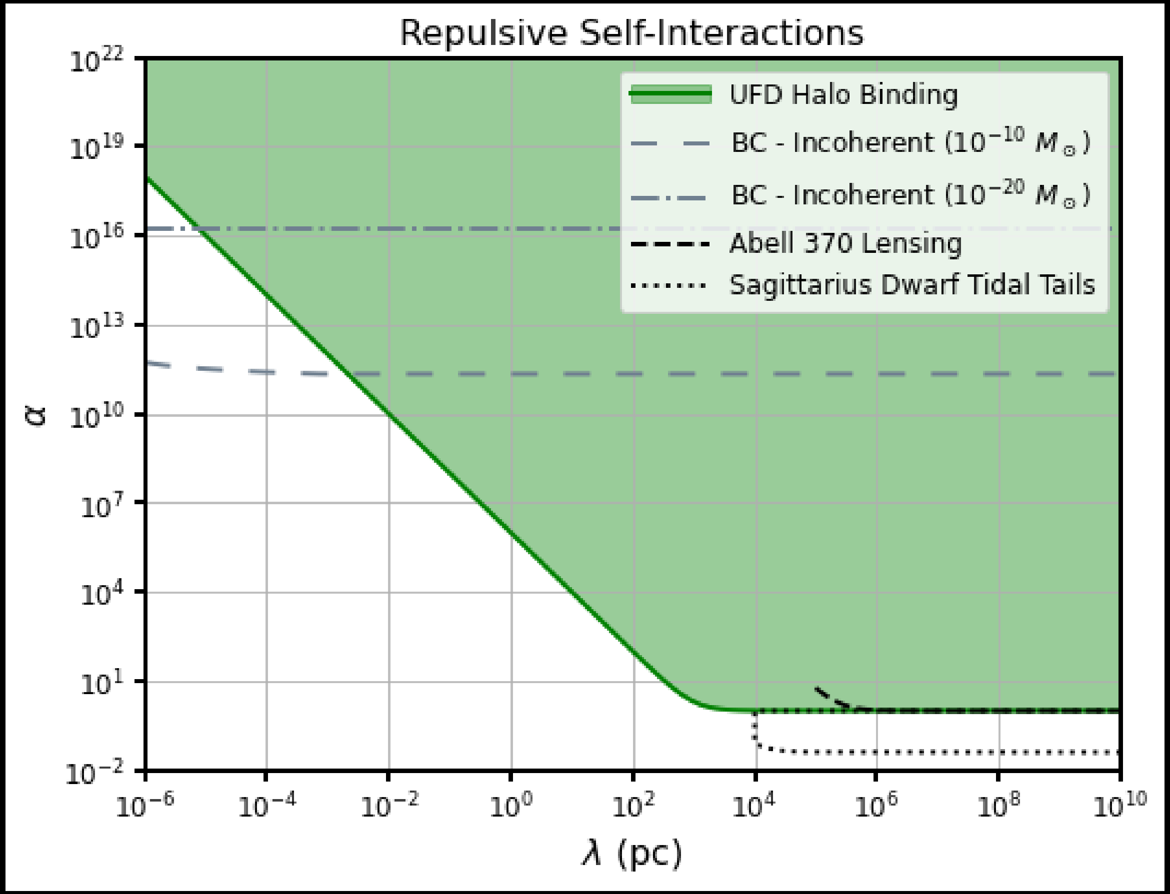
astro-ph.GA/0902.3452

Constraints on DMSI - summary





Dark Matter-Standard Model Interactions

Dark matter can interact with the Standard Model through weak, long-ranged forces

Strengths Relative to Gravity (for **S**tandard Model/**D**ark Matter)

Masses (for Standard Model/Dark Matter)

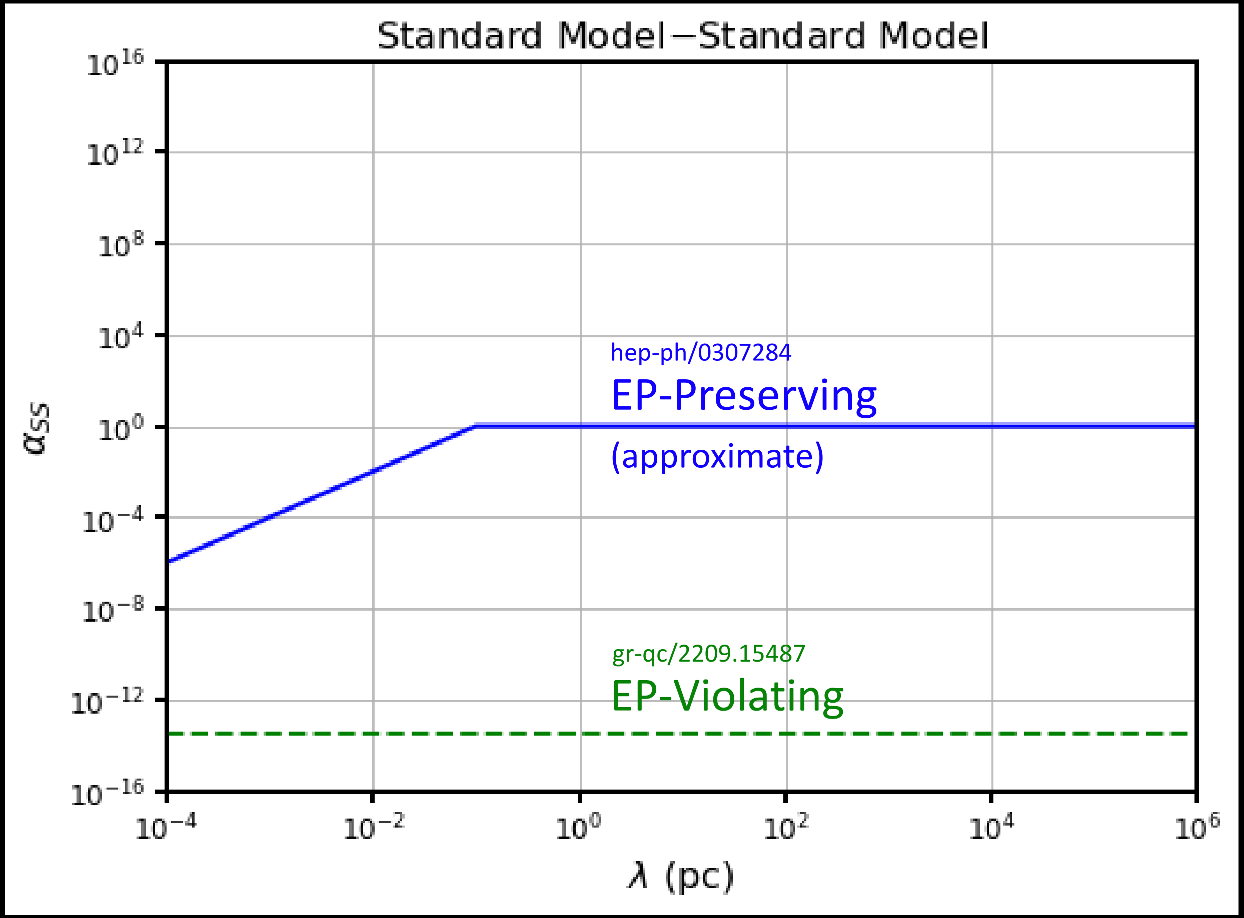
Force Range

$$V \sim \pm \underbrace{\sqrt{\alpha_{SS}\alpha_{DD}}G}_{\alpha_{SD}} \frac{m_{SM}m_{DM}}{r} e^{-r/\lambda}$$

Species-dependent factors

- SM matter can’t be net-neutral (for this work)
- DM could be net-neutral or not

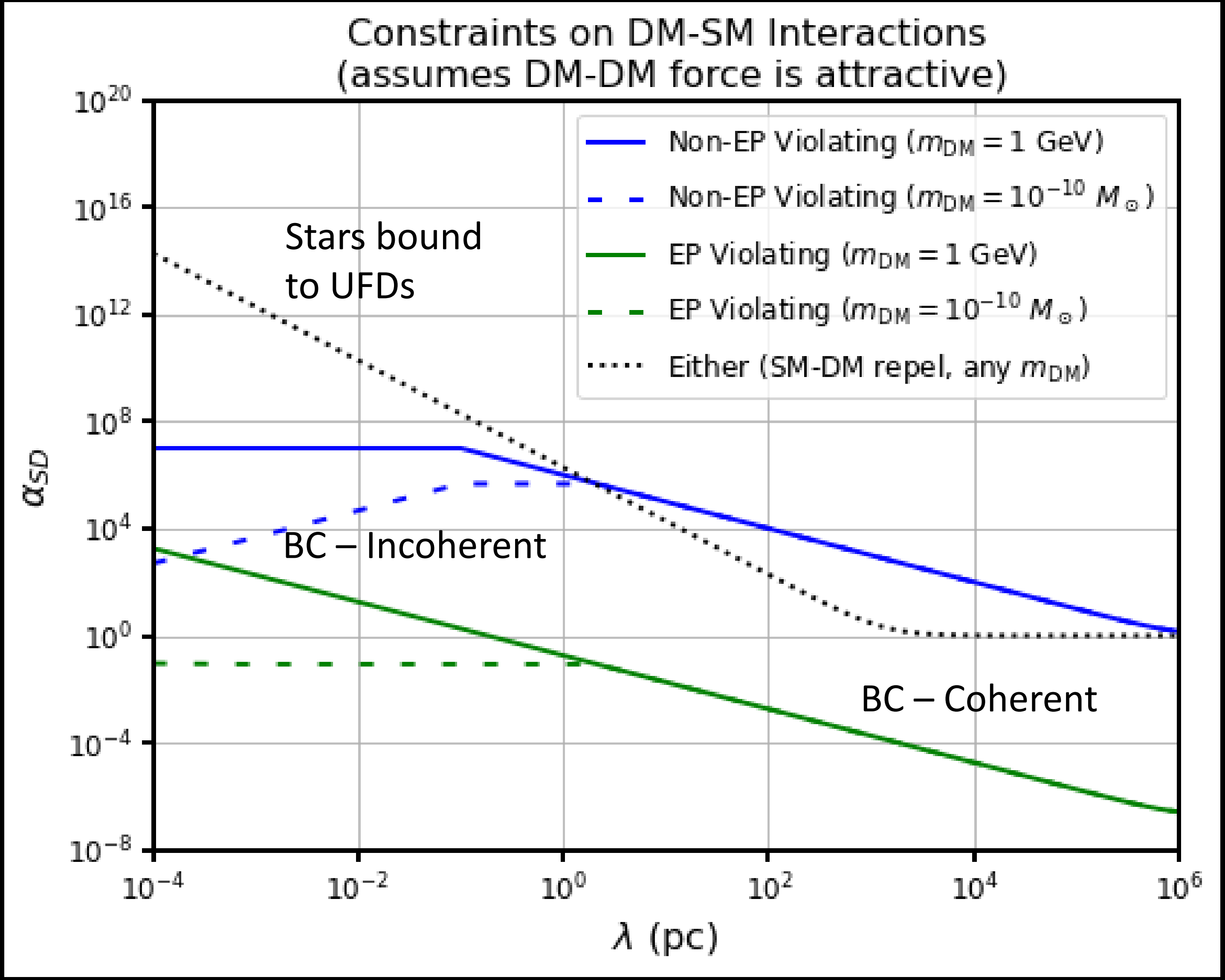
Existing constraints on long-range Standard Model self-interactions



$$\alpha_{SD} = \sqrt{\alpha_{SS}\alpha_{DD}}$$

EP violating constraints depend on exactly how much EP violation there is; I'll generally assume 1% for this talk

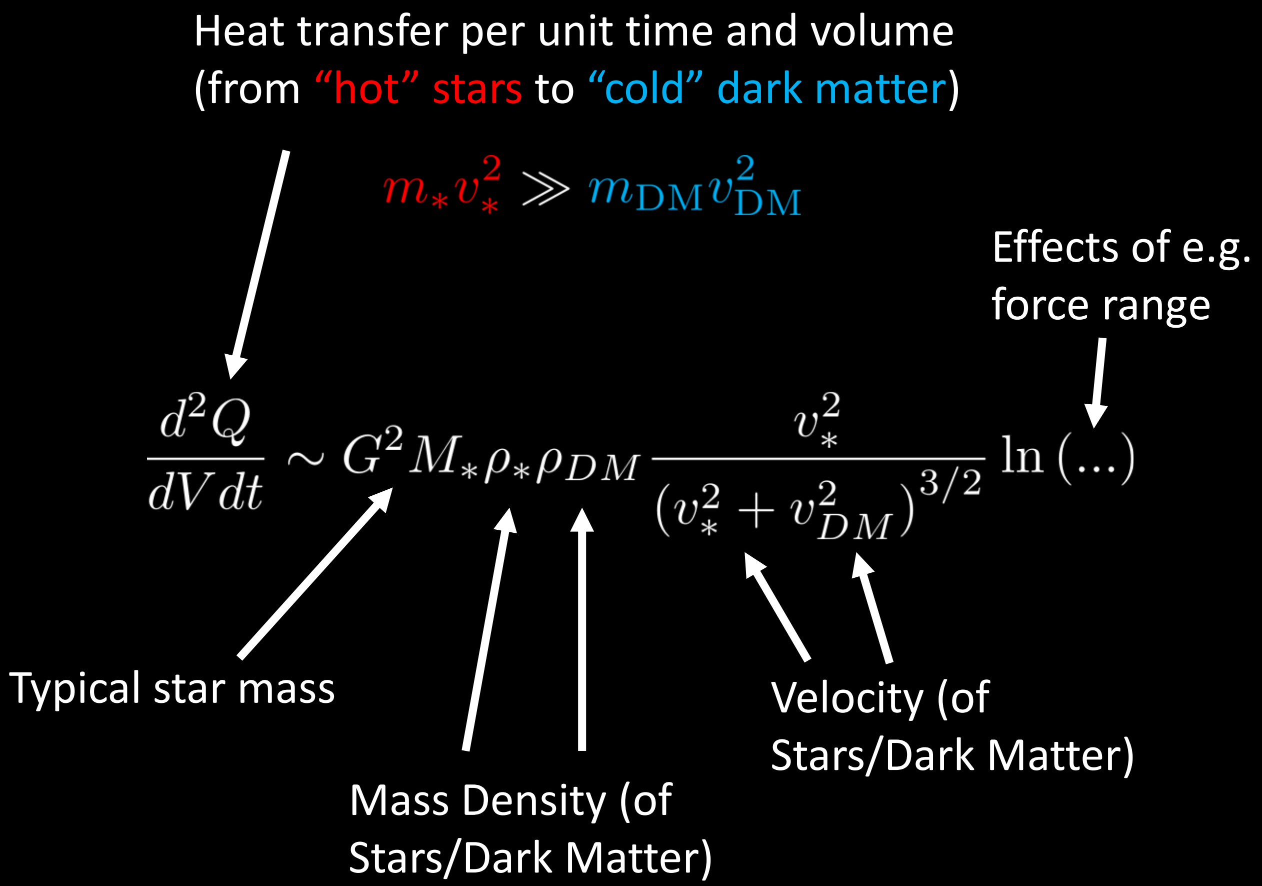
Combined constraints on long-range DM-SM interactions



Most constraints from

$$\alpha_{SD} = \sqrt{\alpha_{SS}\alpha_{DD}}$$

Dynamical friction is how galaxies gravitationally thermalize



Heat transfer per unit time and volume
(from “hot” stars to “cold” dark matter)

$$m_* v_*^2 \gg m_{\mathrm{DM}} v_{\mathrm{DM}}^2$$

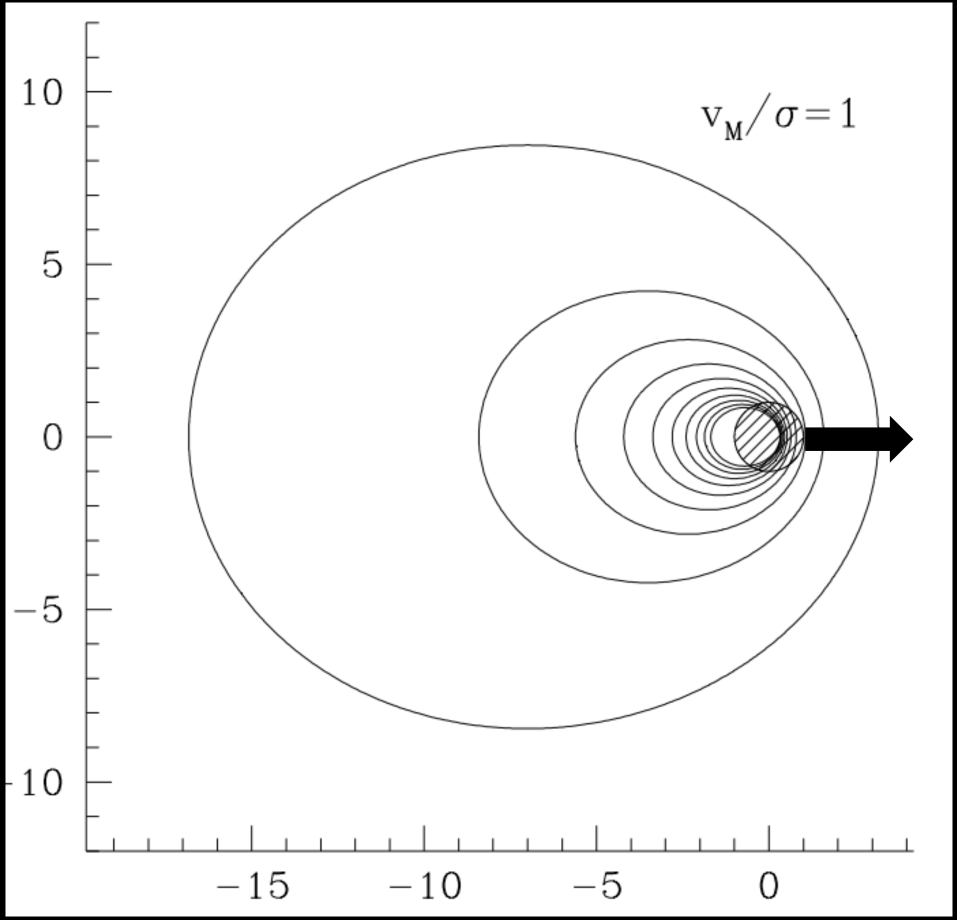
Effects of e.g.
force range

$$\frac{d^2Q}{dV\,dt} \sim G^2 M_* \rho_* \rho_{DM} \frac{v_*^2}{\left(v_*^2 + v_{DM}^2\right)^{3/2}} \ln\left(\ldots\right)$$

Typical star mass

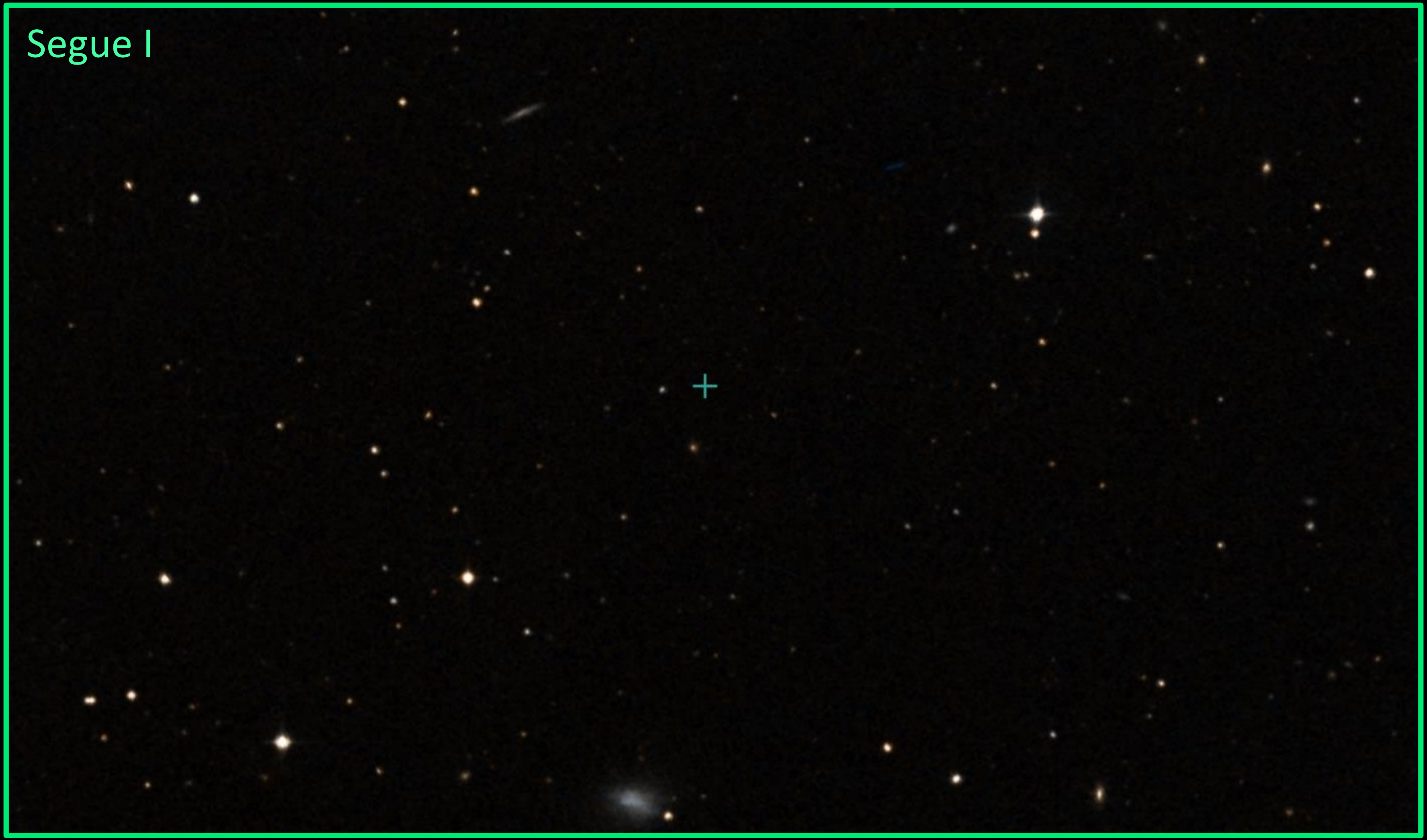
Mass Density (of
Stars/Dark Matter)

Velocity (of
Stars/Dark Matter)



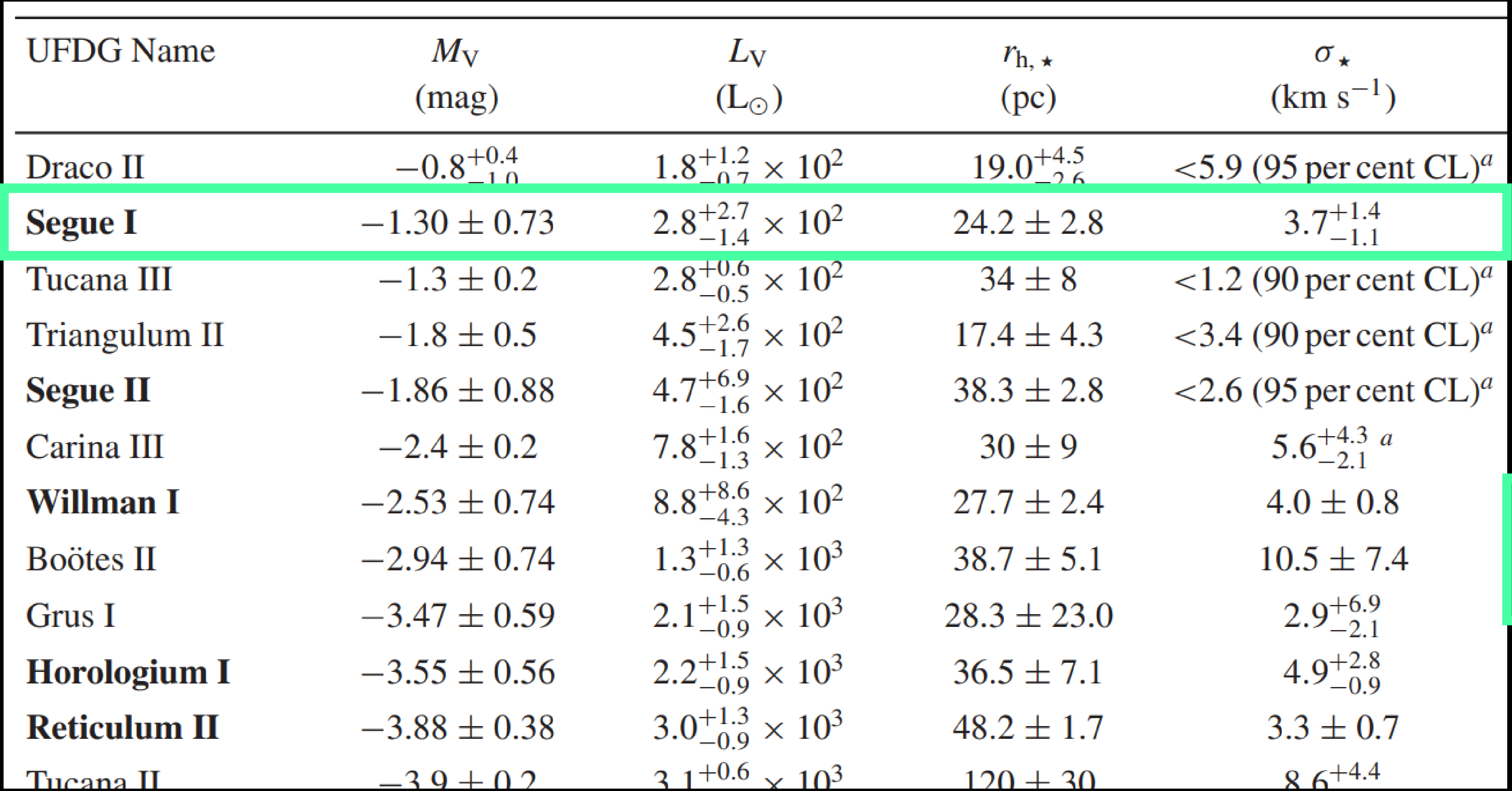
Binney, James and Tremaine, Scott. *Galactic Dynamics: Second Edition*, Princeton: Princeton University Press, 2008.
https://doi.org/10.1515/9781400828722

Ultrafaint dwarfs are excellent laboratories for SM-DM interactions



From SIMBAD and DSS: http://simbad.u-strasbg.fr/simbad/sim-id?Ident=%403785419&Name=NAME%20Segue%201&submit=submit

Ultrafaint dwarfs are excellent laboratories for SM-DM interactions



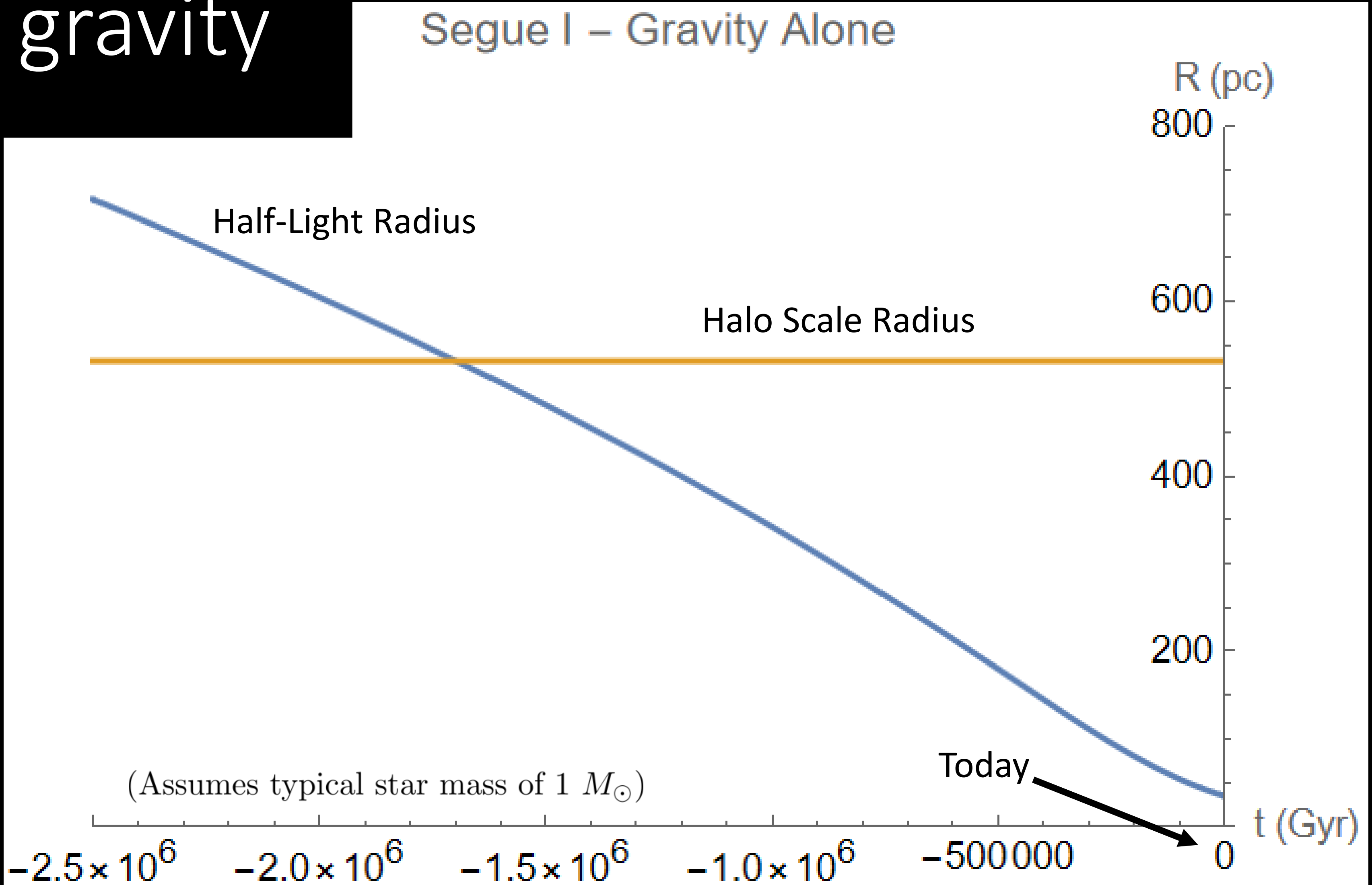
UFDG Name	M_V (mag)	L_V ($L_\odot$)	$r_{h,\star}$ (pc)	$\sigma_\star$ (km s^{-1})
Draco II	$-0.8^{+0.4}_{-1.0}$	$1.8^{+1.2}_{-0.7} \times 10^2$	$19.0^{+4.5}_{-2.6}$	<5.9 (95 per cent CL)[a]
Segue I	-1.30 ± 0.73	$2.8^{+2.7}_{-1.4} \times 10^2$	24.2 ± 2.8	$3.7^{+1.4}_{-1.1}$
Tucana III	-1.3 ± 0.2	$2.8^{+0.6}_{-0.5} \times 10^2$	34 ± 8	<1.2 (90 per cent CL)[a]
Triangulum II	-1.8 ± 0.5	$4.5^{+2.6}_{-1.7} \times 10^2$	17.4 ± 4.3	<3.4 (90 per cent CL)[a]
Segue II	-1.86 ± 0.88	$4.7^{+6.9}_{-1.6} \times 10^2$	38.3 ± 2.8	<2.6 (95 per cent CL)[a]
Carina III	-2.4 ± 0.2	$7.8^{+1.6}_{-1.3} \times 10^2$	30 ± 9	$5.6^{+4.3}_{-2.1}$ [a]
Willman I	-2.53 ± 0.74	$8.8^{+8.6}_{-4.3} \times 10^2$	27.7 ± 2.4	4.0 ± 0.8
Boötes II	-2.94 ± 0.74	$1.3^{+1.3}_{-0.6} \times 10^3$	38.7 ± 5.1	10.5 ± 7.4
Grus I	-3.47 ± 0.59	$2.1^{+1.5}_{-0.9} \times 10^3$	28.3 ± 23.0	$2.9^{+6.9}_{-2.1}$
Horologium I	-3.55 ± 0.56	$2.2^{+1.5}_{-0.9} \times 10^3$	36.5 ± 7.1	$4.9^{+2.8}_{-0.9}$
Reticulum II	-3.88 ± 0.38	$3.0^{+1.3}_{-0.9} \times 10^3$	48.2 ± 1.7	3.3 ± 0.7
Tucana II	-3.9 ± 0.2	$3.1^{+0.6} \times 10^3$	120 ± 30	$8.6^{+4.4}$

Age $\gtrsim 10$ Gyr

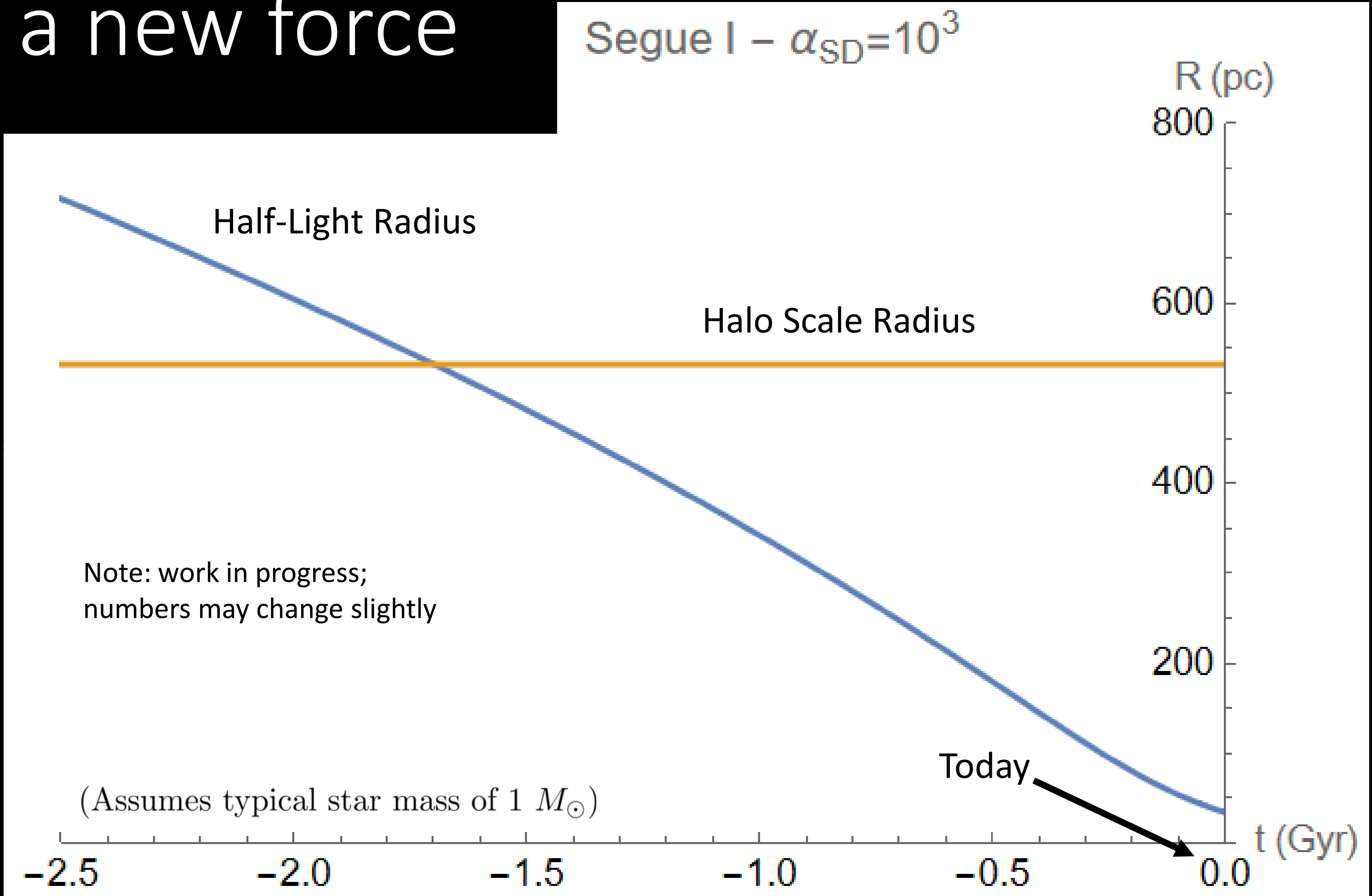
Density $\sim 1\ M_\odot/\mathrm{pc}^3$

https://web.archive.org/web/20210223225516id_/https://www.zora.uzh.ch/id/eprint/191094/1/staa170.pdf

Stellar evolution due to dynamical friction from gravity



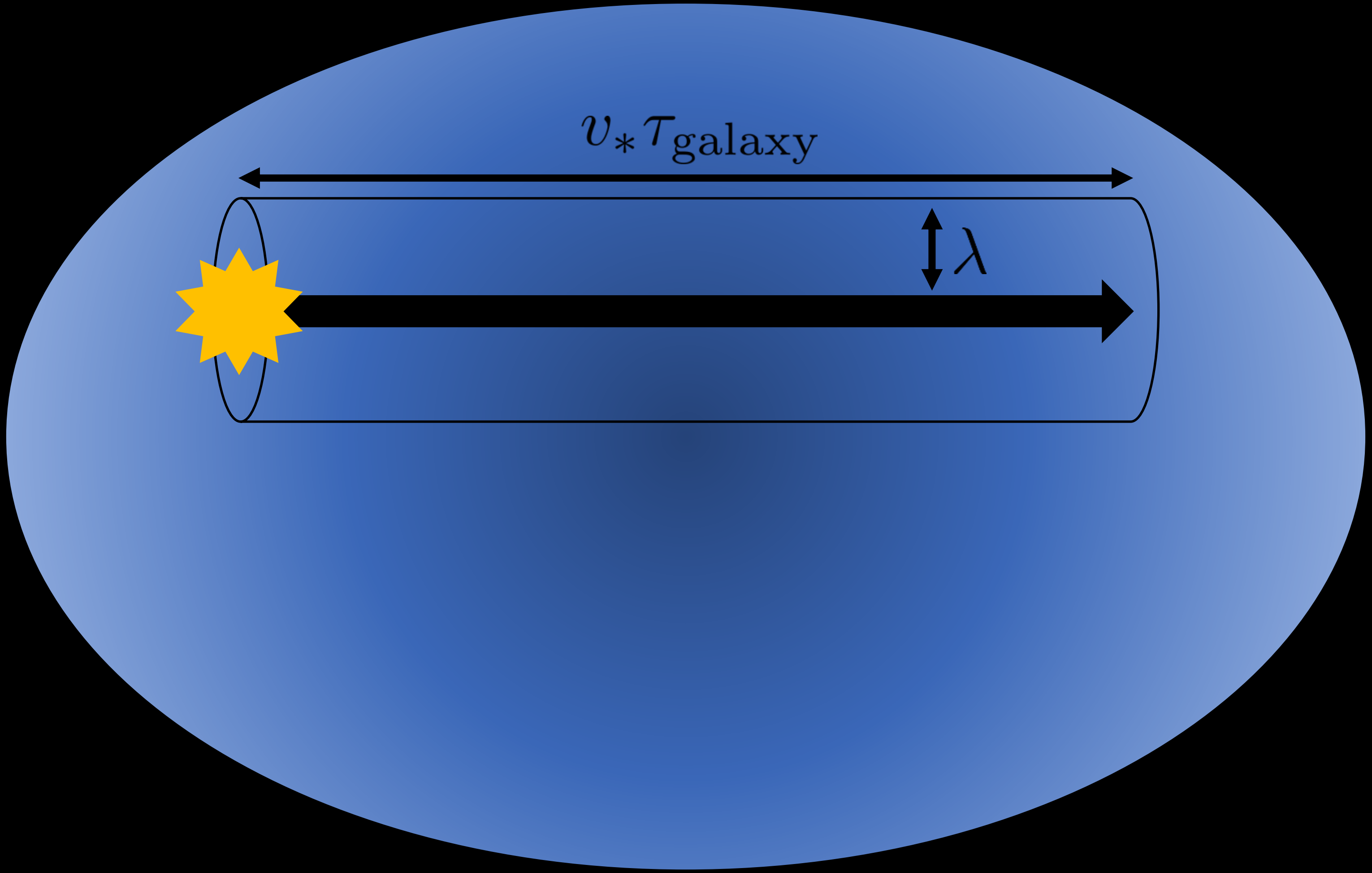
Stellar evolution due to dynamical friction from a new force



Note: work in progress;
numbers may change slightly

(Assumes typical star mass of 1 $M_\odot$)

Forces with range less than O(1 mpc) don't affect stellar evolution significantly



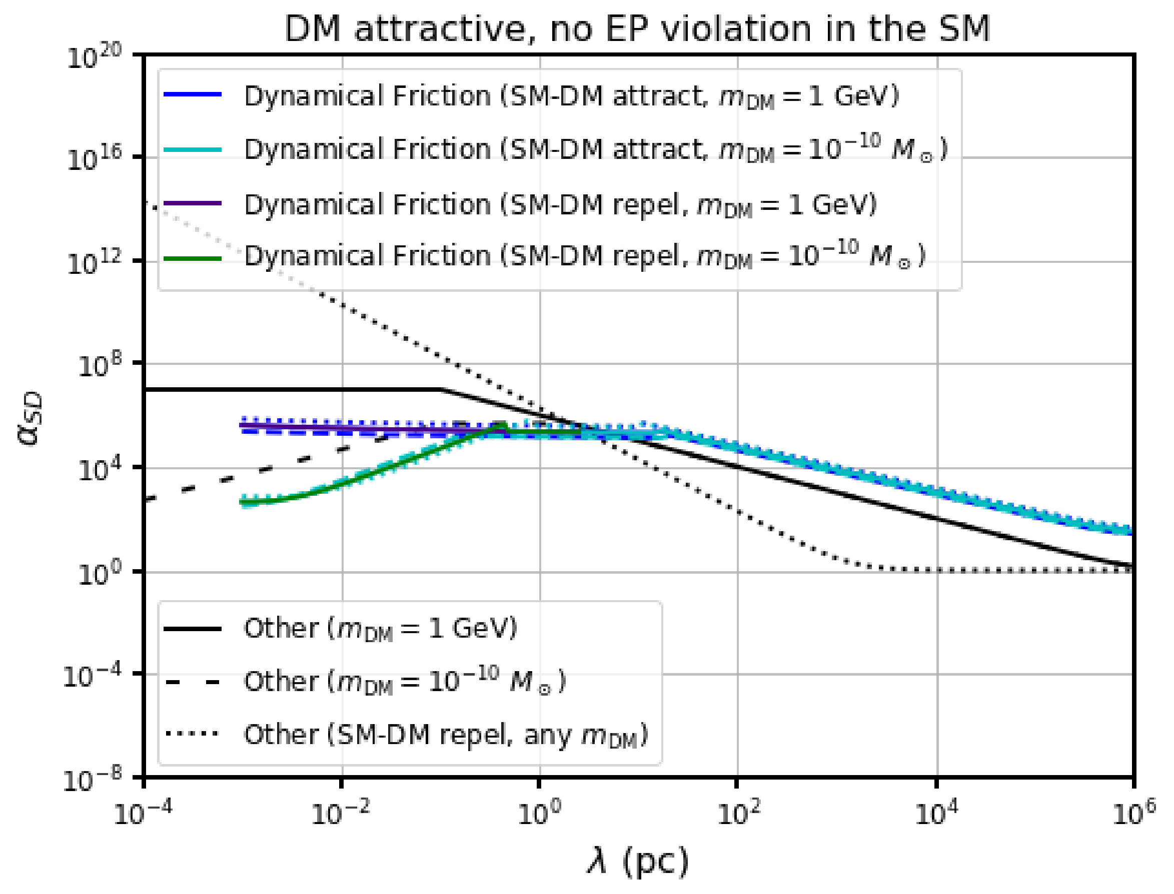
$$q_{\text{transfer}} \lesssim m_{DM} v_{\text{rel}}$$

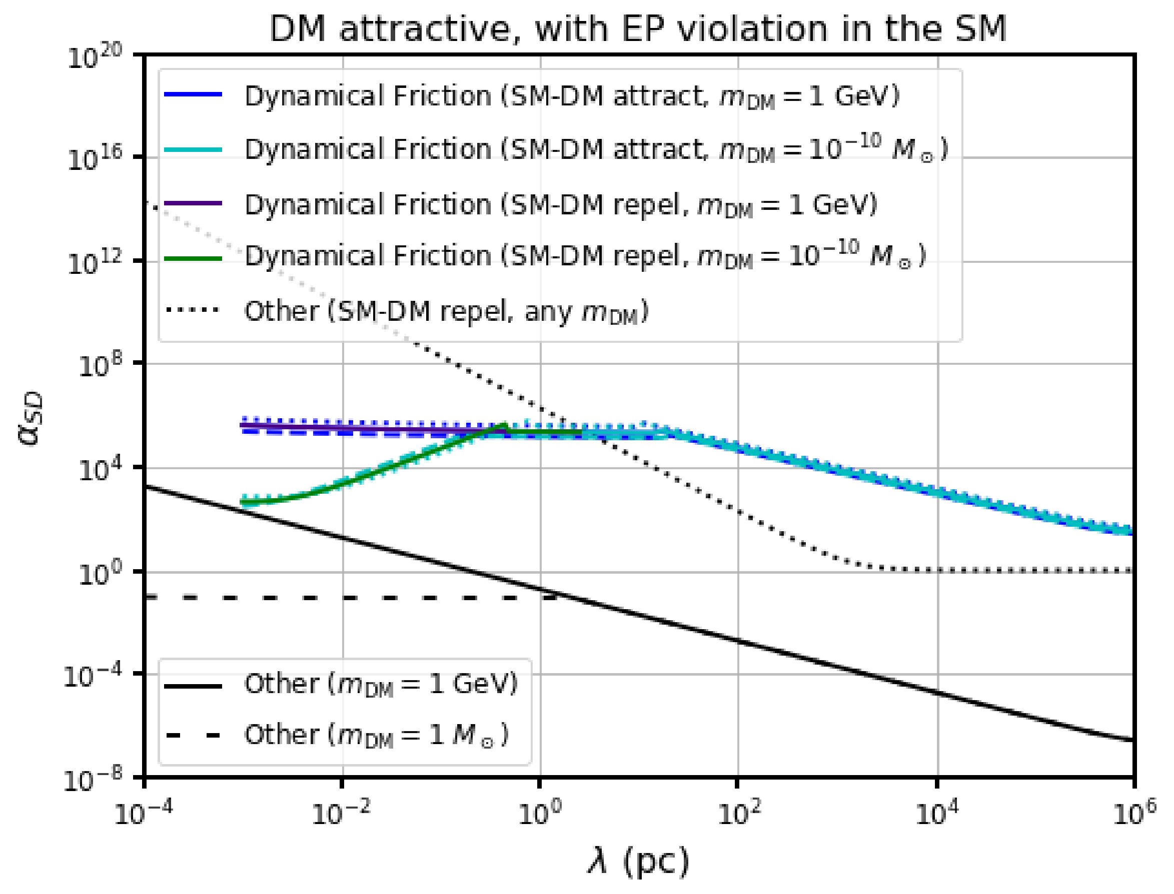
$$\Downarrow$$

$$\pi \lambda^2 v_{\text{rel}} \tau_{\text{galaxy}} \rho_{DM} \gtrsim m_*$$

for order-1 effects

Constraints: dark matter self-attractive





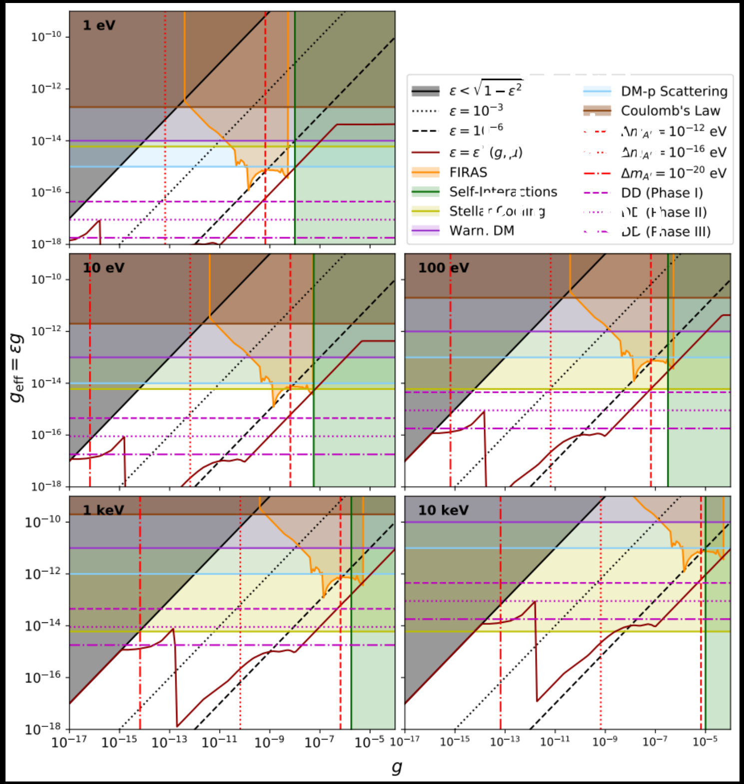
Summary

- Dark matter can have long-range interactions with itself or with the Standard Model

- Long-range self-interactions of DM can be constrained by observations of the collision velocity and final mass distribution of the Bullet Cluster

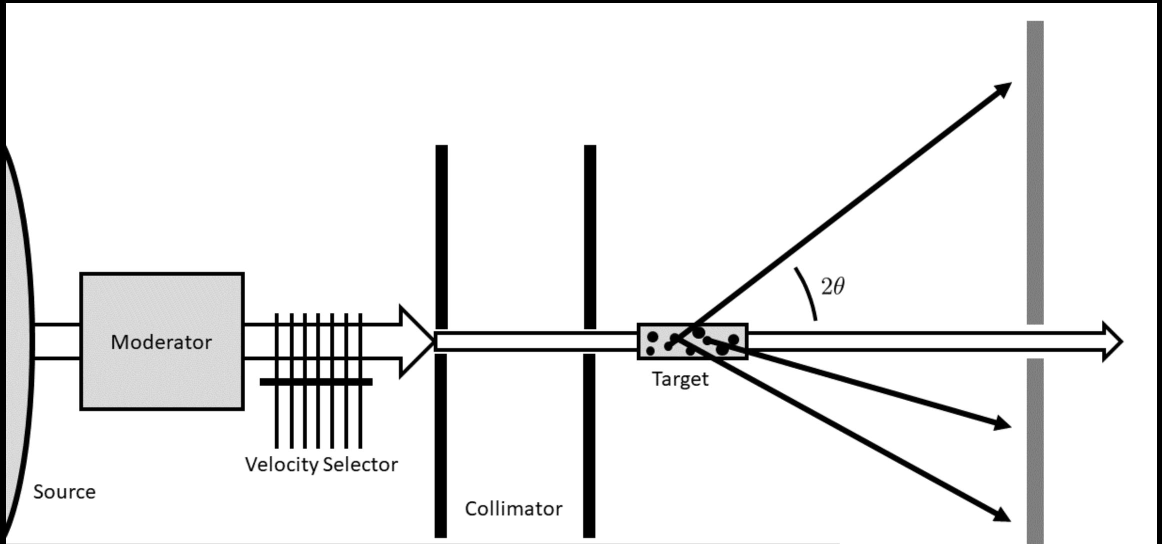
- Long-range interactions with the SM could lead to observable changes to the star distributions of ultrafaint dwarf galaxies

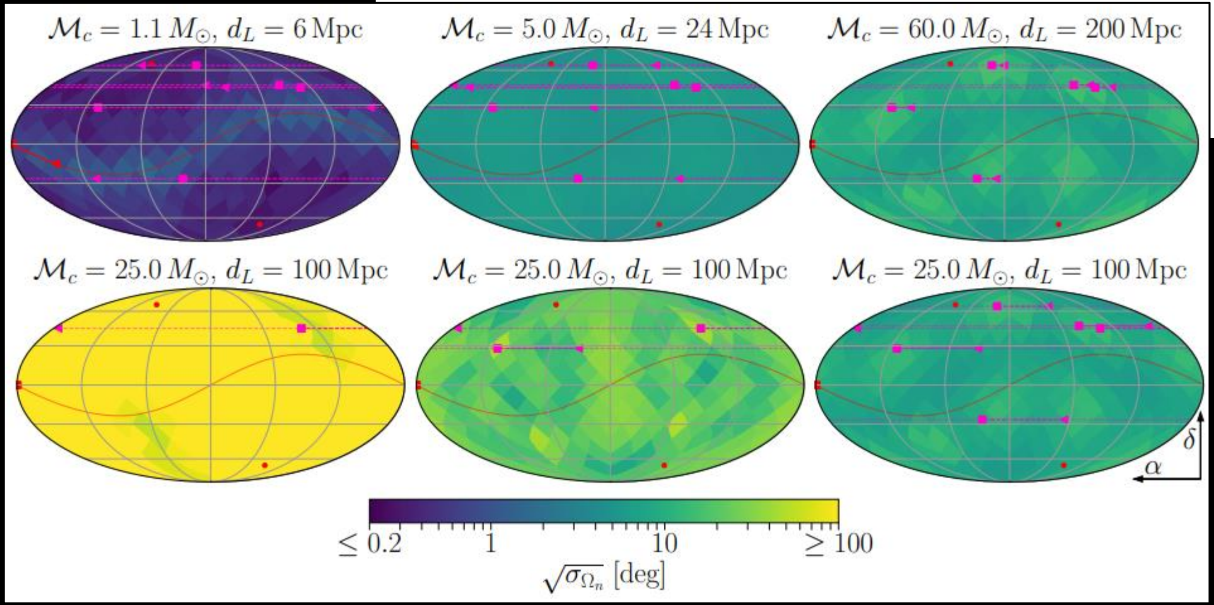
Other projects you can ask me about



Ultralight Millicharged Dark Matter

Searching for Short-Range New Forces with Coherent Neutron Scattering





Parameter Reconstruction for Midband Gravitational Wave Detectors

Questions?

Backup Slides

Many models of dark matter include new interactions with the Standard Model

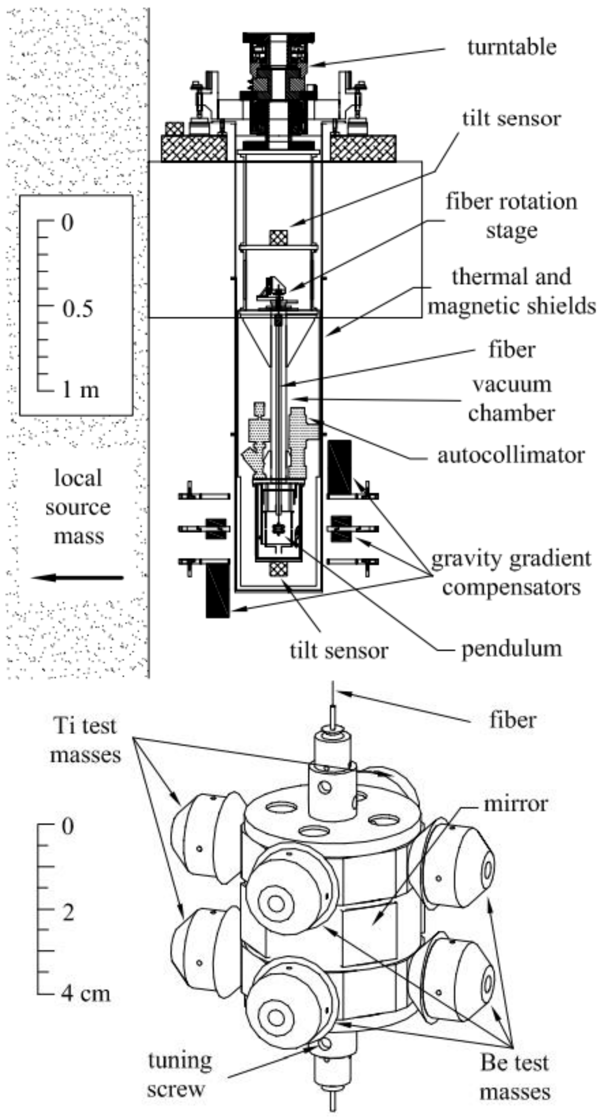
- Dark matter is only *required* to interact gravitationally, but many reasons to consider other interactions with the SM:
  - No (known) symmetries prohibiting this
  - Dark matter self-interactions
  - Similar amounts of dark matter and SM
  - Production mechanisms

- And, in any case, studying DM is pretty hopeless otherwise

Constraints on equivalence principle violation directed towards the MW center

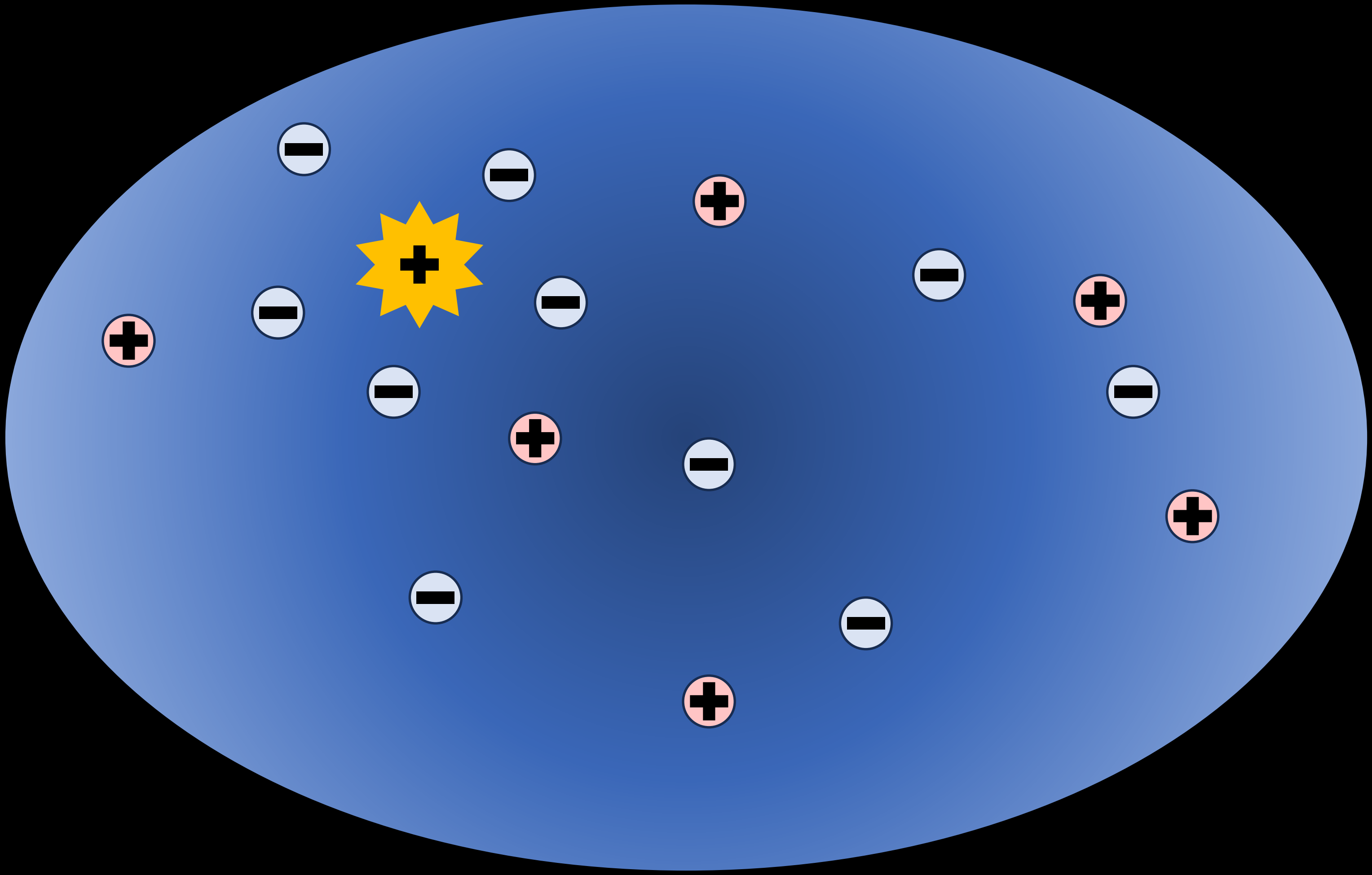
- Torsion balances can look for equivalence-principle violating forces
- Looking towards the MW center tests new DM-SM forces, giving

$$\alpha_{\rm SD} \lesssim 10^{-2}\left(1+\left(\frac{10\ \rm kpc}{\lambda}\right)^2\right)$$



gr-qc/0712.0607

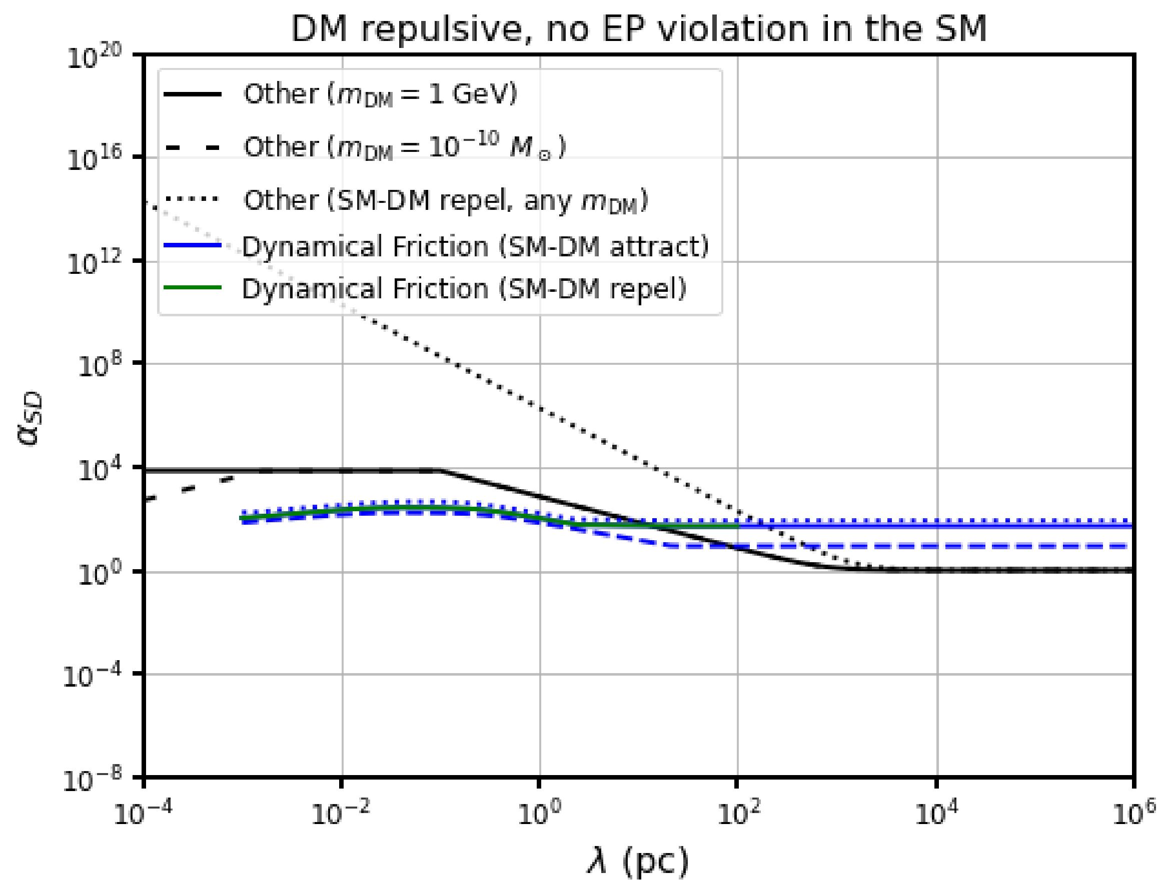
If dark matter has mixed charge signs, Debye screening limits the new force's range

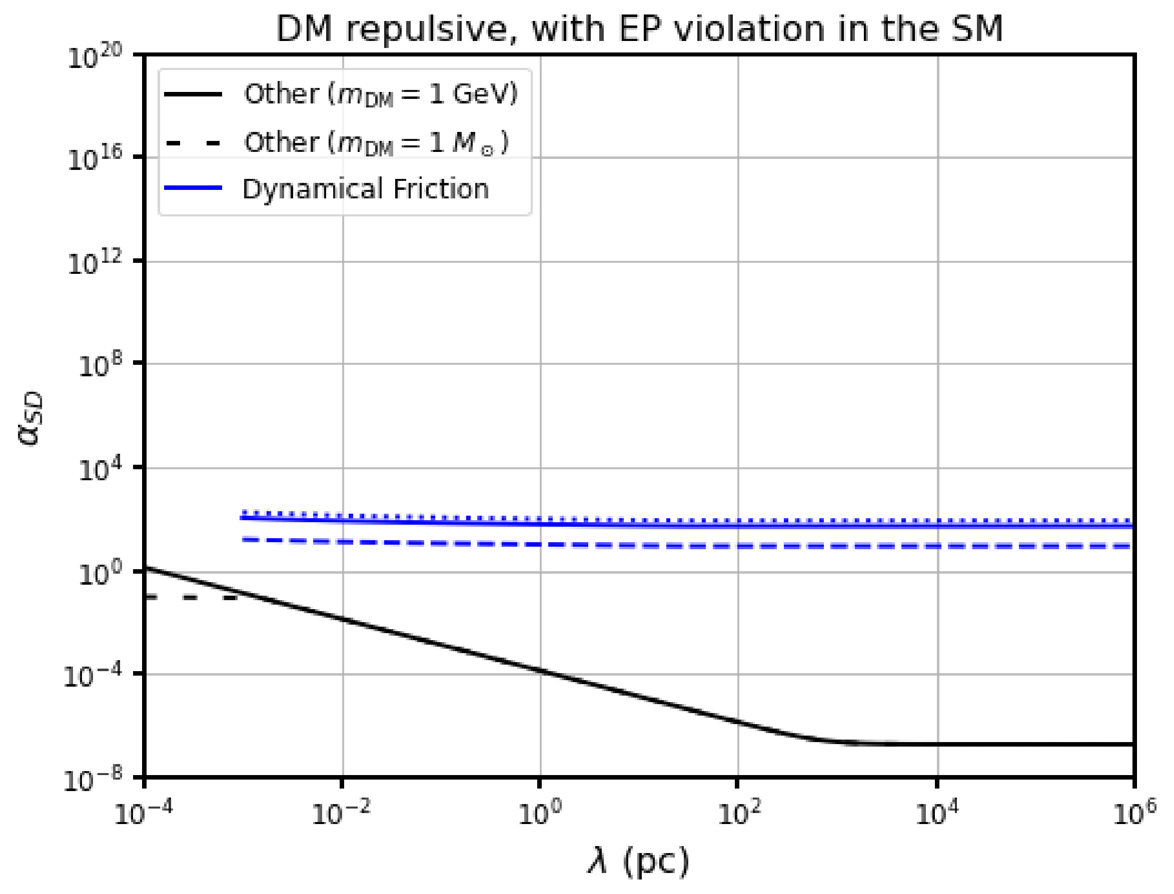


$$\lambda_D \sim \sqrt{\frac{v_{DM}^2}{4\pi\alpha_{DD} G \rho_{DM}}}$$

$$\sim 1 \text{ mpc} \left(\frac{\alpha_{DD}}{10^{10}}\right)^{-1/2}$$

Constraints: dark matter self-repulsive


DM repulsive, no EP violation in the SM

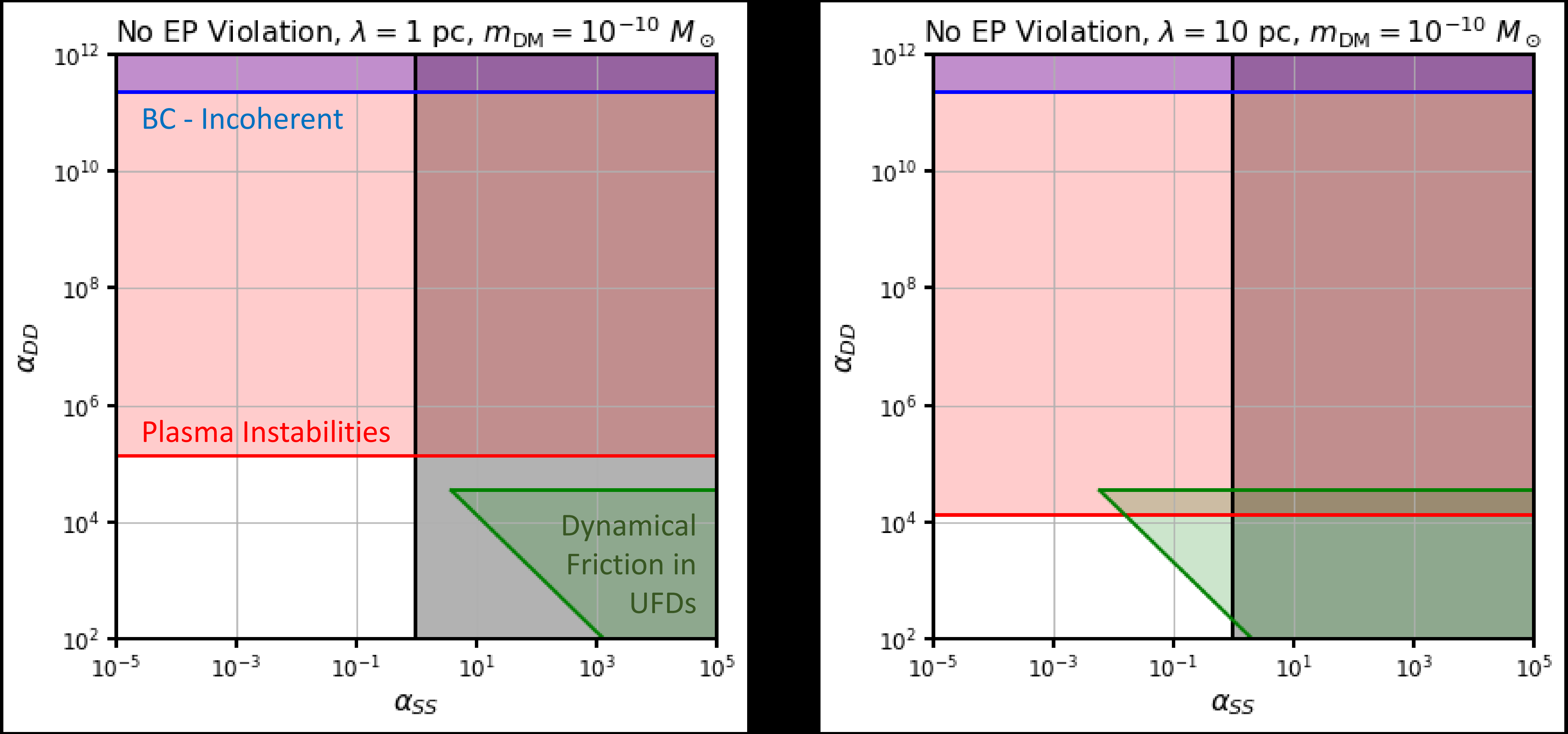

DM repulsive, with EP violation in the SM

Plasma instabilities in dark matter halos

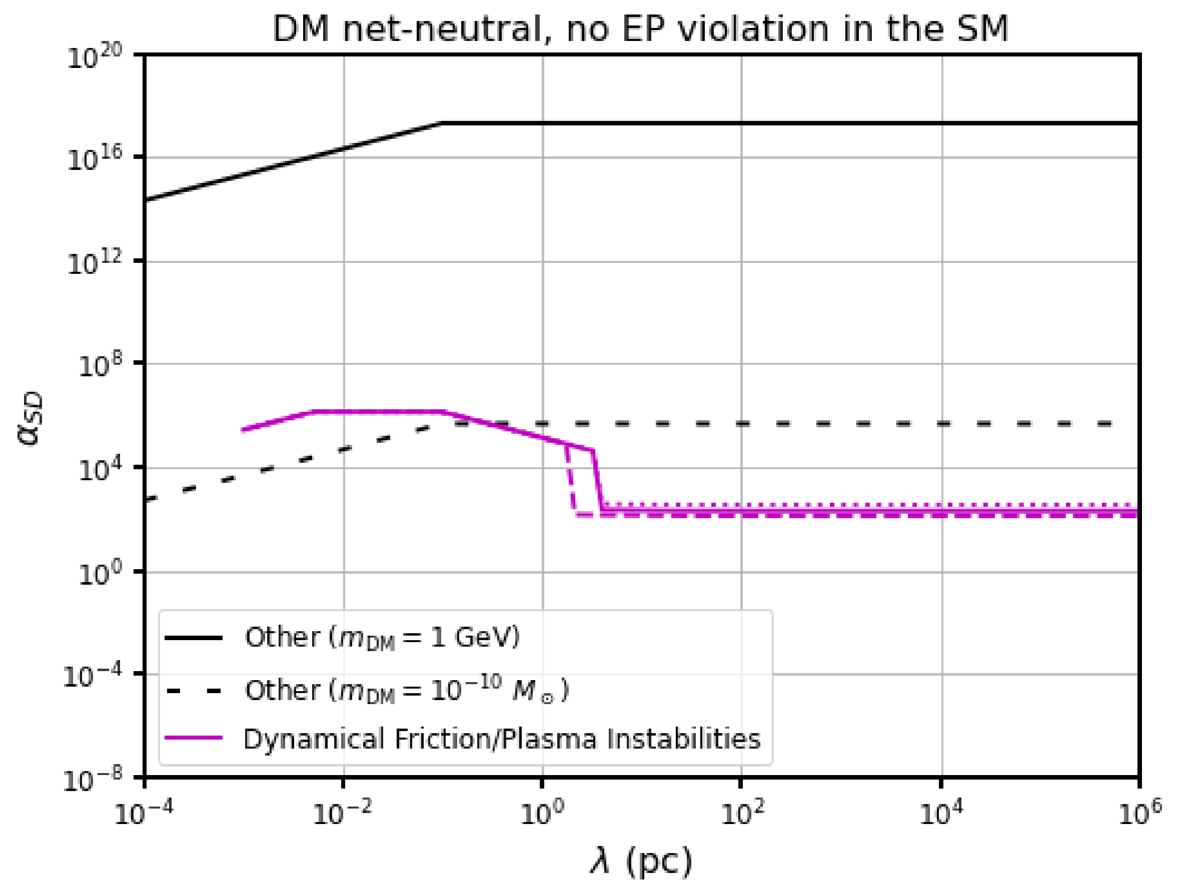
- Long-range self-interactions of mixed-charge DM can lead to exponentially growing plasma instabilities in
    - The Bullet Cluster
    - Subhalos
- Not currently constrained, but could have large effects that might be detectable in the future

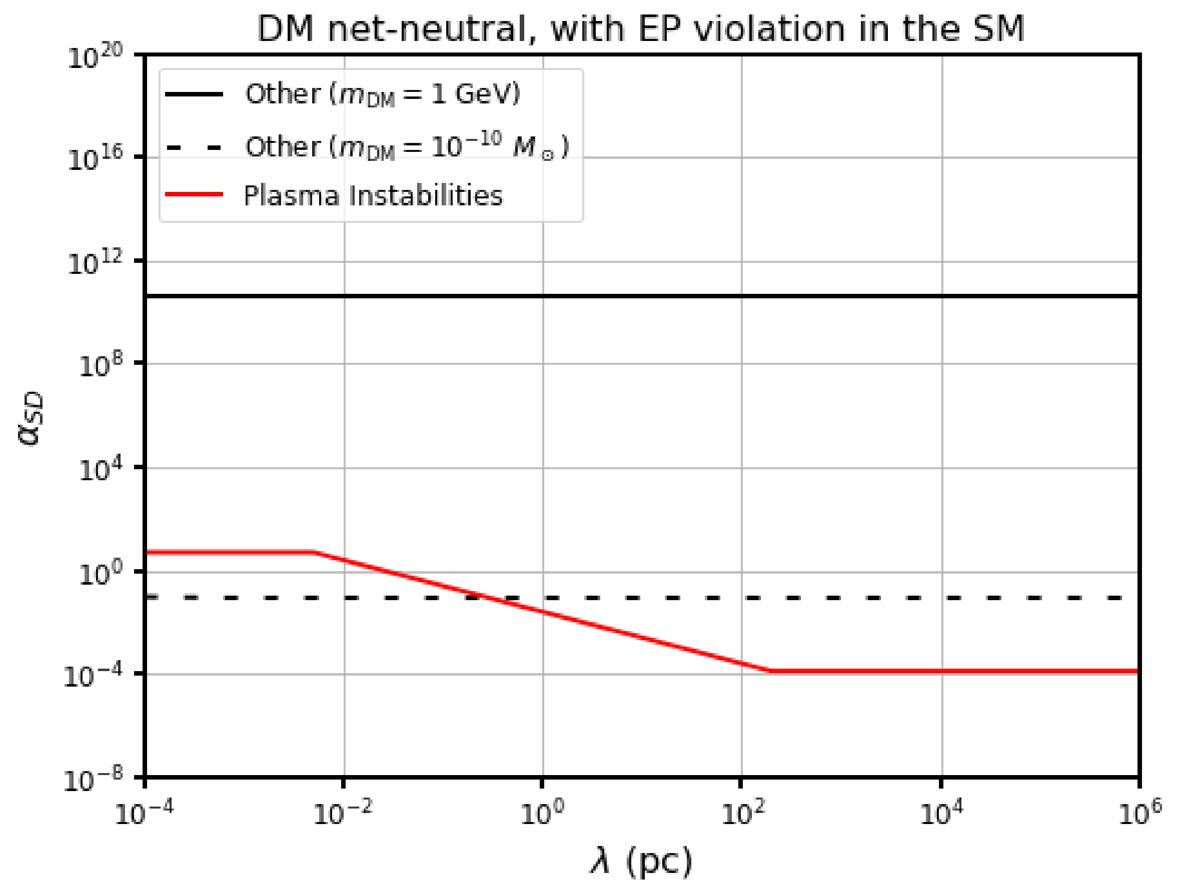
Journal of Cosmology and Astroparticle Physics **11** (2020) 034

Constraints: dark matter net-neutral



Constraints: dark matter net-neutral





Dynamical friction also leads to anomalous acceleration of planets and satellites

Acceleration from
dynamical friction

Mass of star
(or planet, etc.)

$$\frac{dv_*}{dt} \sim -G^2 \boxed{M_*} \rho_* \rho_{DM} v_* \left(\frac{v_*}{v_{DM}}\right)^3 \ln\left(\ldots\right)$$

Differential acceleration between the Sun and a satellite could give similar limits to UFDs

gr-qc/1508.06273