Probing long-range dark matter-baryon interactions in compact stellar systems

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Dark Side of the Universe 2025

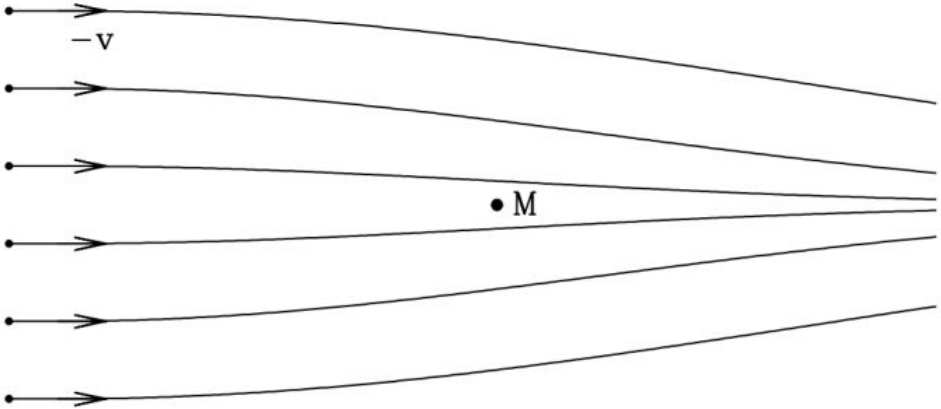
Based on 2408.01818 Yang Ma, ZW

Dynamical Friction

A perturber star in DM halo

DM closer to star when they pass behind

Creates a drag force on star



$$F_{\rm dyn} v_\star = -\frac{4\pi G^2 m_\star^2 \rho_{\rm DM}}{v_\star} \mathcal{G}(X) \ln\Lambda$$

$$\mathcal{G}(X) = \mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}} e^{-X^2}, \quad X = \frac{v_\star}{\sqrt{2}\sigma_{\rm DM}}$$

$$\ln\Lambda \equiv \ln(b_{\rm max}/b_{\rm min})$$

Chandrasekhar 1943

Adding a long-range interaction between DM and SM

$$V(r) = -\frac{GM_1M_2}{r}(1 + \tilde{\alpha}e^{-r/\lambda})$$

Models:

DM and SM couple to a massive mediator (gauged B-L, dark photon, …),

Asymmetric DM nuggets, 1406.2276, 1407.4121, 1707.02313, 1812.07573, 2010.07240…

and many more…

Adding a long-range interaction between DM and SM

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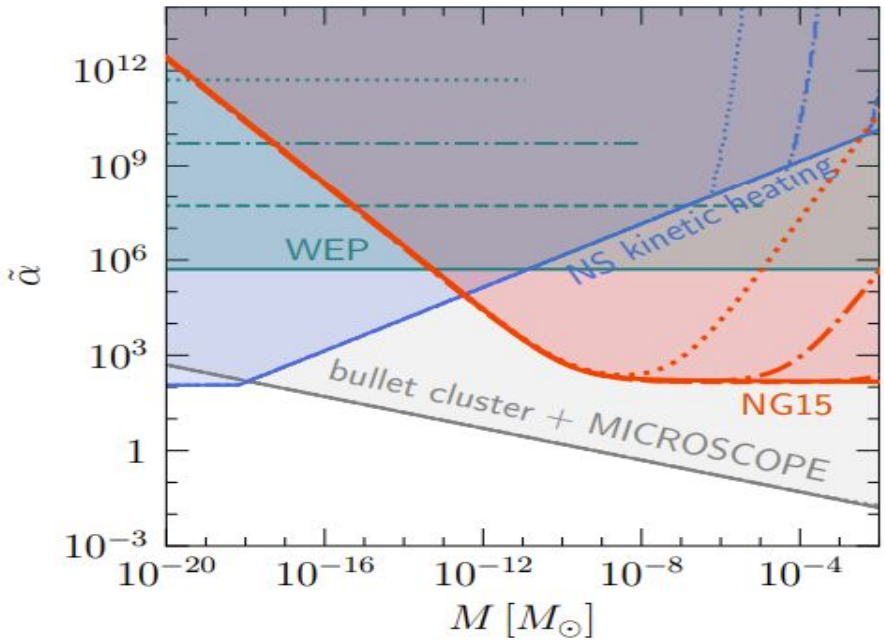
Constraints:



NANOGrav, 2306.16219

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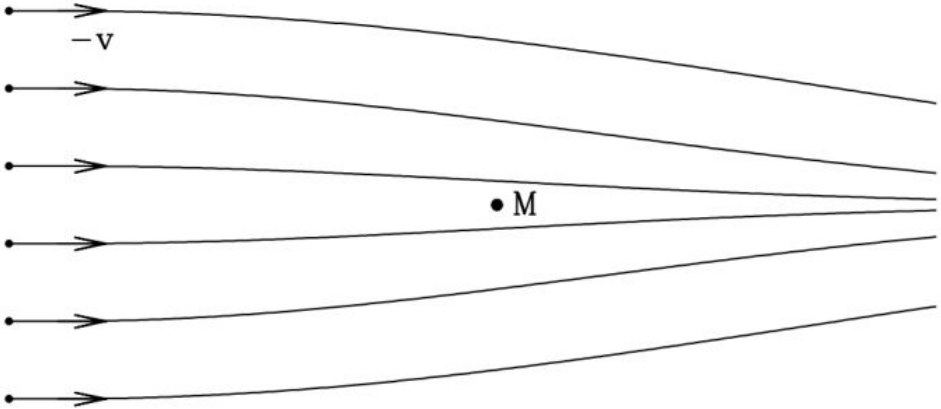

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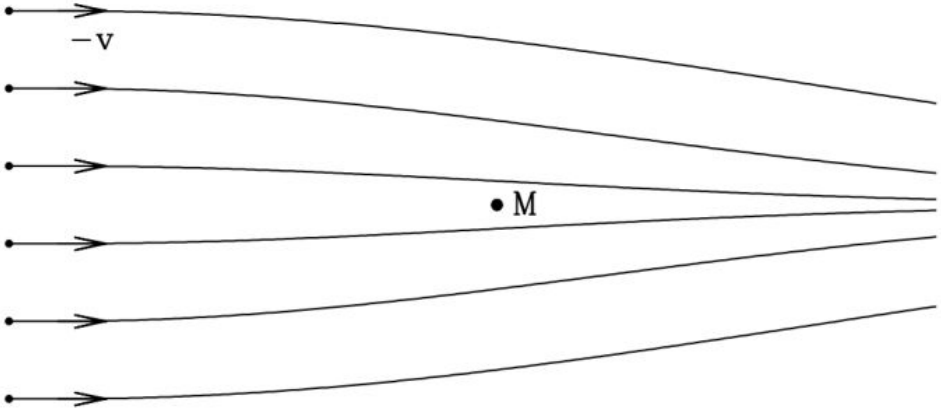

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$$\int_{b_{\rm min}}^{b_{\rm max}} \frac{(1+\tilde{\alpha}(1+b/\lambda)e^{-b/\lambda})^2}{b} \mathrm{d}b$$

Impact on star cluster

Potential energy of the cluster:

$$\frac{U}{M_\star} = -\beta_1 \frac{GM_\star}{r_h} + \beta_2 G\rho_{\rm DM} r_h^2 + u(\tilde{\alpha}, \lambda, r_h) + \text{const.}$$

self-gravity star-DM gravity star-DM long range

Contraction of star cluster

Dynamical friction -> loss rate of kinetic energy

$$F_{\rm dyn} v_\star = -\frac{4\pi G^2 m_\star^2 \rho_{\rm DM}}{v_\star} \mathcal{G}(X) \ln \Lambda$$

Potential energy

$$\frac{U}{M_\star} = -\beta_1 \frac{G M_\star}{r_h} + \beta_2 G \rho_{\rm DM} r_h^2 + u(\tilde{\alpha}, \lambda, r_h) + \text{const.}$$

Virial theorem:

$$\frac{{\rm d}r_h}{{\rm d}t} = \frac{2M_\star}{m_\star} \left(\frac{\partial U}{\partial r_h} \right)^{-1} \int dv_\star \, f(v_\star) F_{\rm dyn} v_\star$$

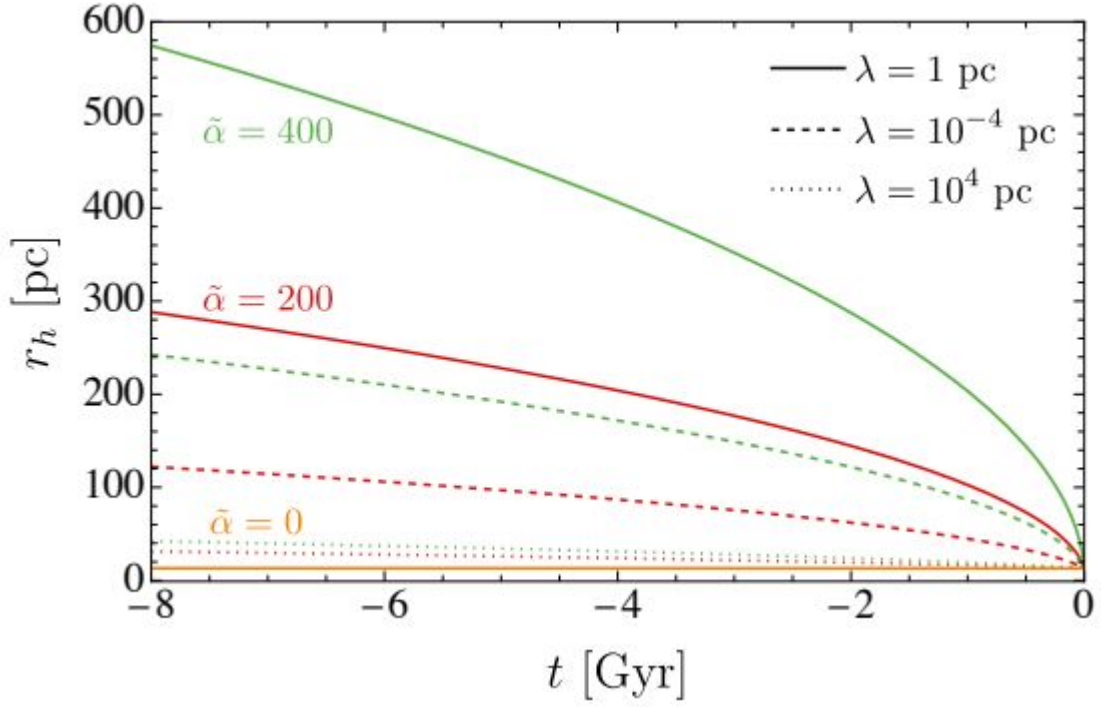
Star cluster in Eridanus II

Ultrafaint dwarf galaxy Eri II hosts a globular cluster at center

Eri II R_h (pc)	277 ± 14	
Cluster r_h (pc)	13 ± 1	
$M_\star$ $(M_\odot)$	[2000, 6000]	
Cluster age $t_{\rm age}$ (Gyr)	[3, 12]	
$\sigma_{\rm DM}^{\rm 1D}$ (km/s)		$10.3^{+3.0}_{-3.2}$
$\sigma_\star^{\rm 1D}$ (km/s)		$2.3^{+5.3}_{-2.3}$
$\rho_{\rm DM}$ $(M_\odot/{\rm pc}^3)$		$7.1^{+6.4}_{-3.7}$

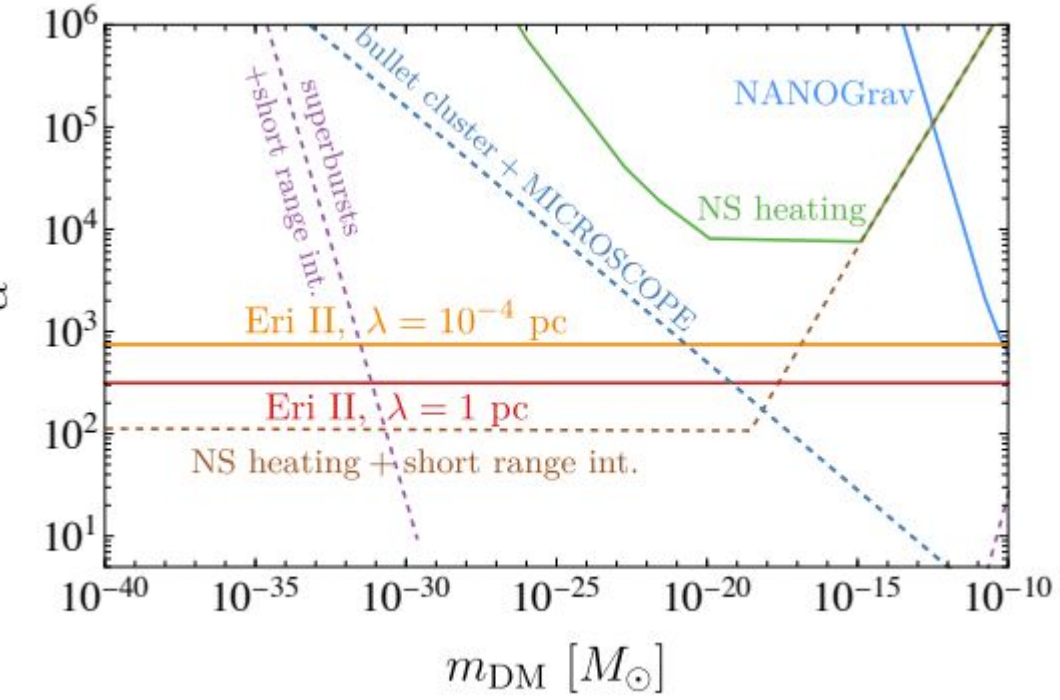
Crnojevic et al 2016
Zoutendijk et al 2020

Time evolution of half-light radius



Limits on coupling of long-range interaction

$$\tilde{\alpha} \leq 314.5, \quad \text{for} \quad \lambda = 1\,\text{pc},$$
$$\tilde{\alpha} \leq 747.1, \quad \text{for} \quad \lambda = 10^{-4}\,\text{pc}$$



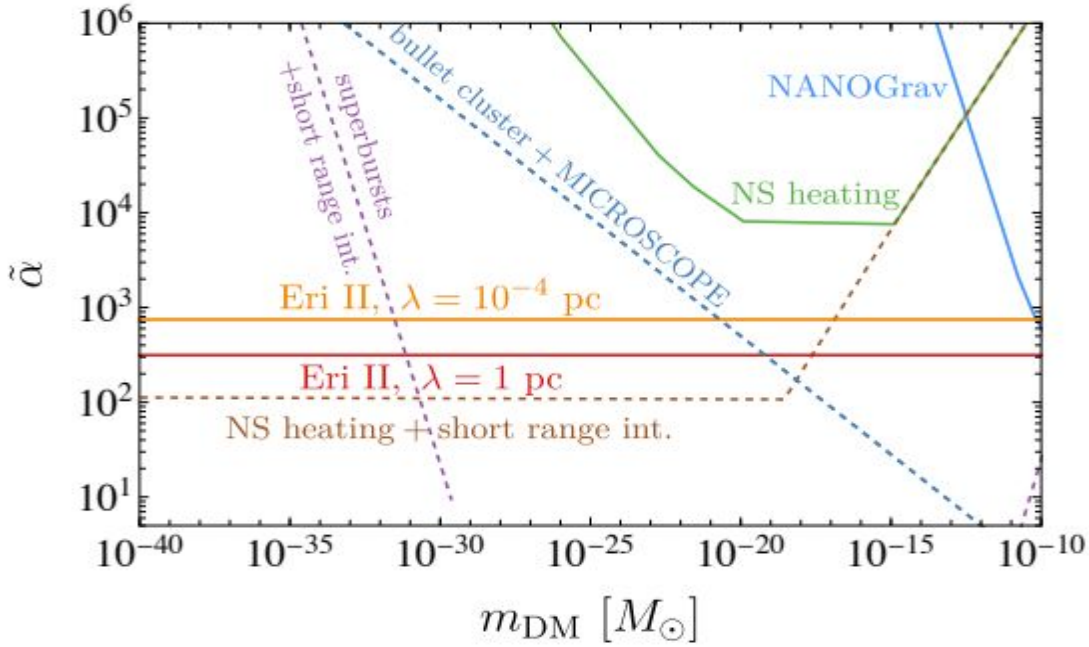
Many UFDs host compact stellar systems

Name	r_h † pc	L_V $L_\odot$	$\overline{\rho}_{1/2}$ $M_\odot\,\mathrm{pc}^{-3}$	σ_* $\mathrm{km\,s}^{-1}$
Wil I	25 ± 6	1000	4	$4.3^{+2.3}_{-1.3}$
Seg I	29^{+8}_{-5}	300	3	3.9 ± 0.8
Seg II	35 ± 3	900	1	$3.4^{+2.5}_{-1.2}$
Ret II	$32^{+2}_{-1}/55^{+5}_{-5}$	1500*	2	$3.2^{+1.6}_{-0.5}$
Hor I	$30^{+4}_{-3}/60^{+76}_{-30}$	2000*	5	$4.9^{+2.8}_{-0.9}$
Pic I	$29^{+9}_{-4}/43^{+153}_{-21}$	2000*		
Pho II	$26^{+6}_{-4}/33^{+20}_{-11}$	1500*		
Ind I	$37^{+13}_{-8}/12^{+2}_{-2}$	1000*		
Eri III	$14^{+13}_{-3}/11^{+8}_{-5}$	500*		
Dra II	19^{+8}_{-6}	1000		

Brandt, 1605.03665

Conclusions

- Long-range interaction enhances dynamical friction
- Drives compact stellar systems to contract in time
- Coupling < O(100)



Thank you!