Impact of Gravitational Slingshot of Dark Matter on Galactic Halo Profiles

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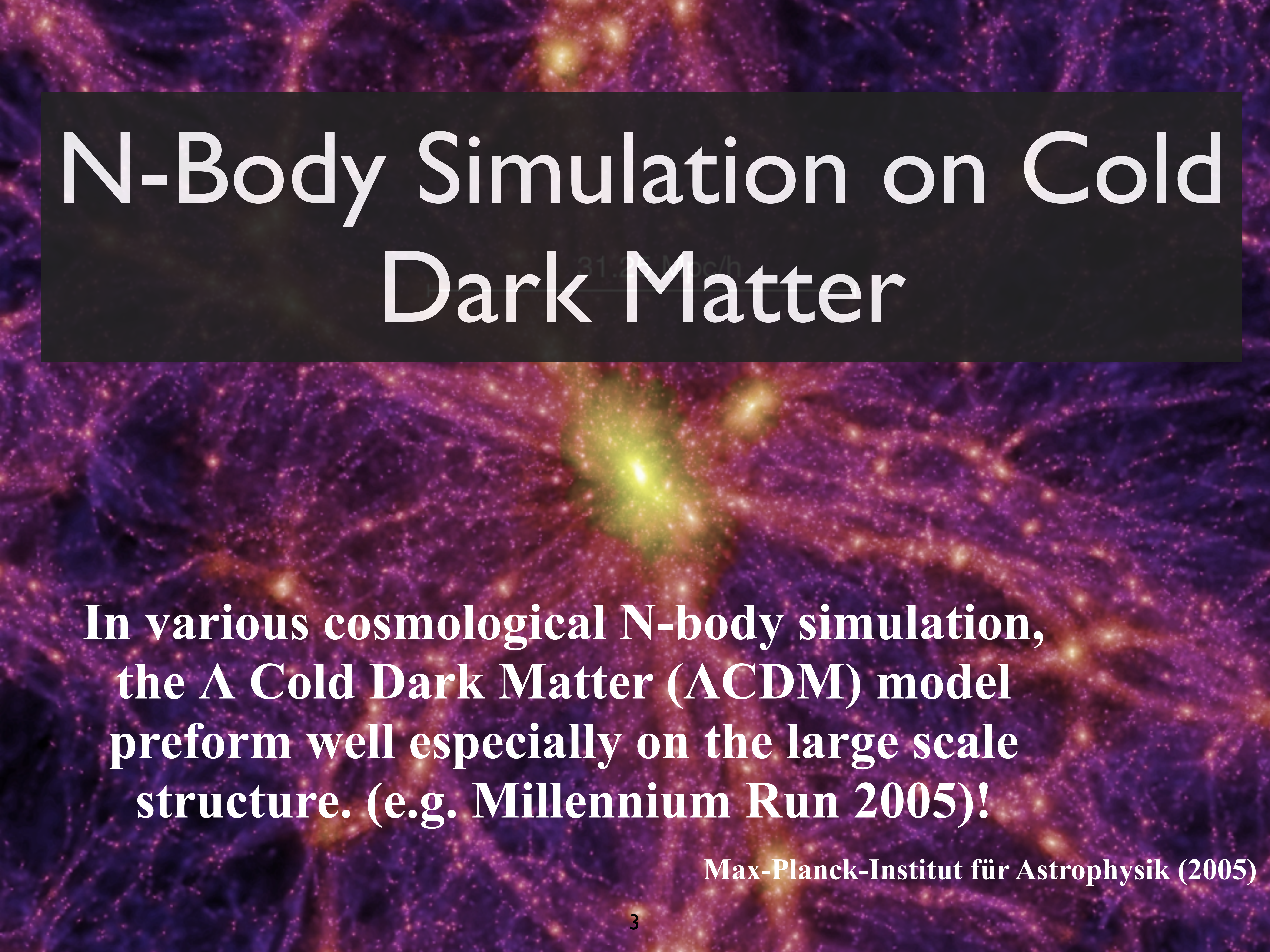
(ArXiv: 1412.2258)

East Asian Young Astronomers Meeting (EAYAM) @ NTU 2015.2.10

Dark Matter

- 84% of the matter is Dark(DM)
- DM interacts through gravity.
- Further DM interactions unobserved so far. Such couplings must be very weak, much weaker than weak interactions.



N-Body Simulation on Cold Dark Matter

In various cosmological N-body simulation, the Λ Cold Dark Matter (ΛCDM) model preform well especially on the large scale structure. (e.g. Millennium Run 2005)!

Max-Planck-Institut für Astrophysik (2005)

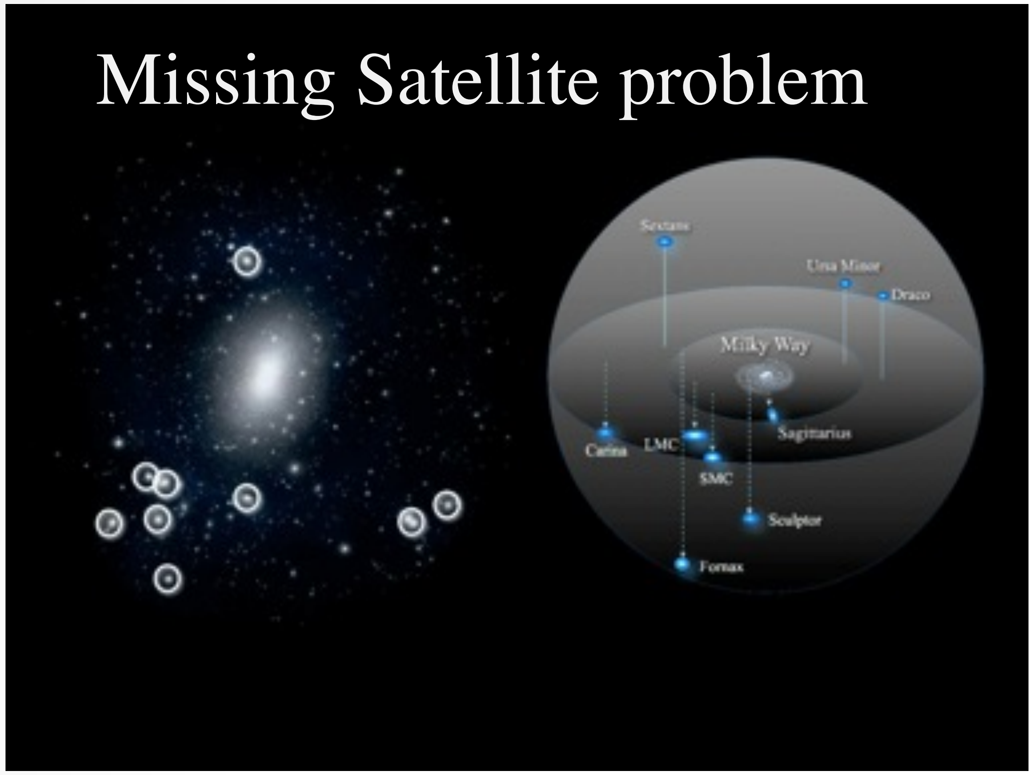
N-Body Simulation on Cold Dark Matter

- Collisionless
- Identical particle mass
- Extremely "heavy"(~10^7 solar mass)

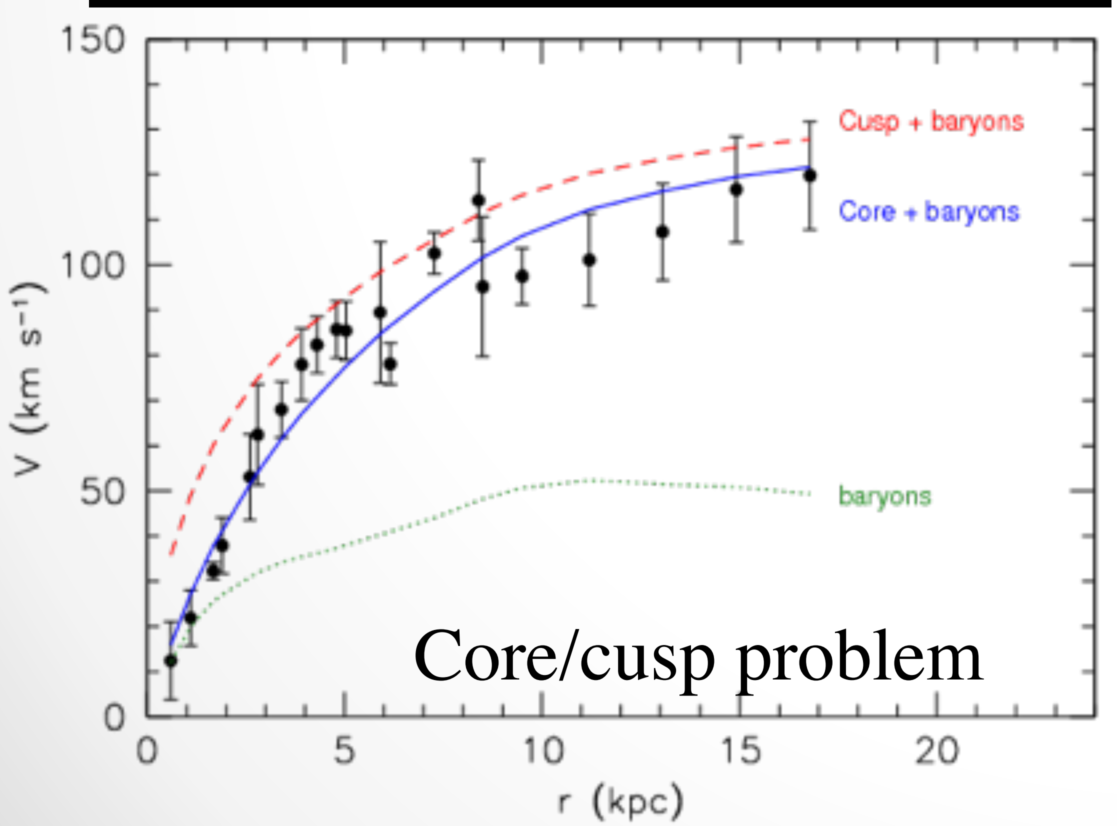
Max-Planck-Institut für Astrophysik (2005)

Controversies on Galactic Scale

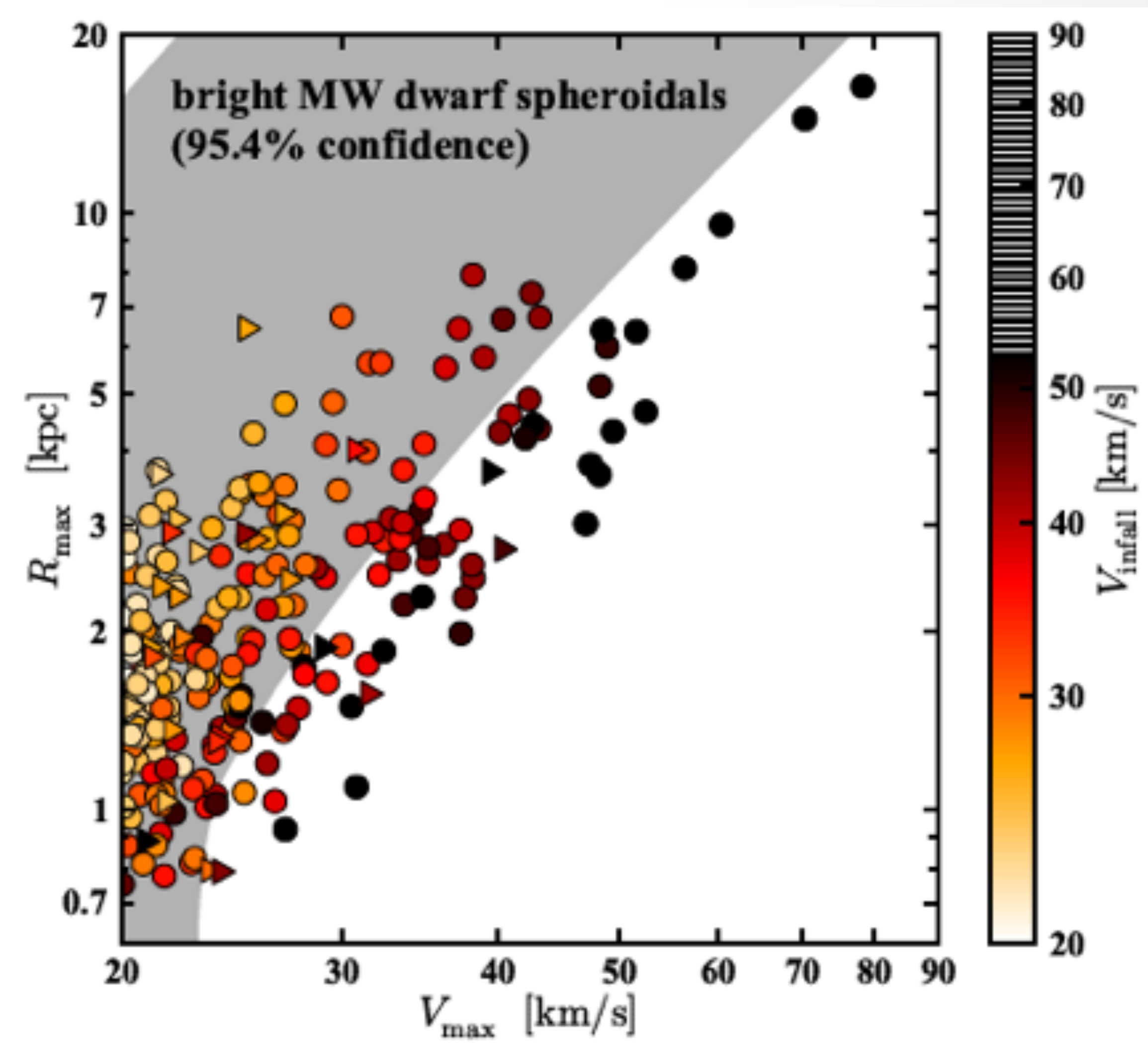
-- Comparison of Numerical Simulation & Observational Data



Missing Satellite problem



Core/cusp problem



Too Big to Fail problem

D. H. Weinberg et al. (2013) (arXiv:1306.0913)

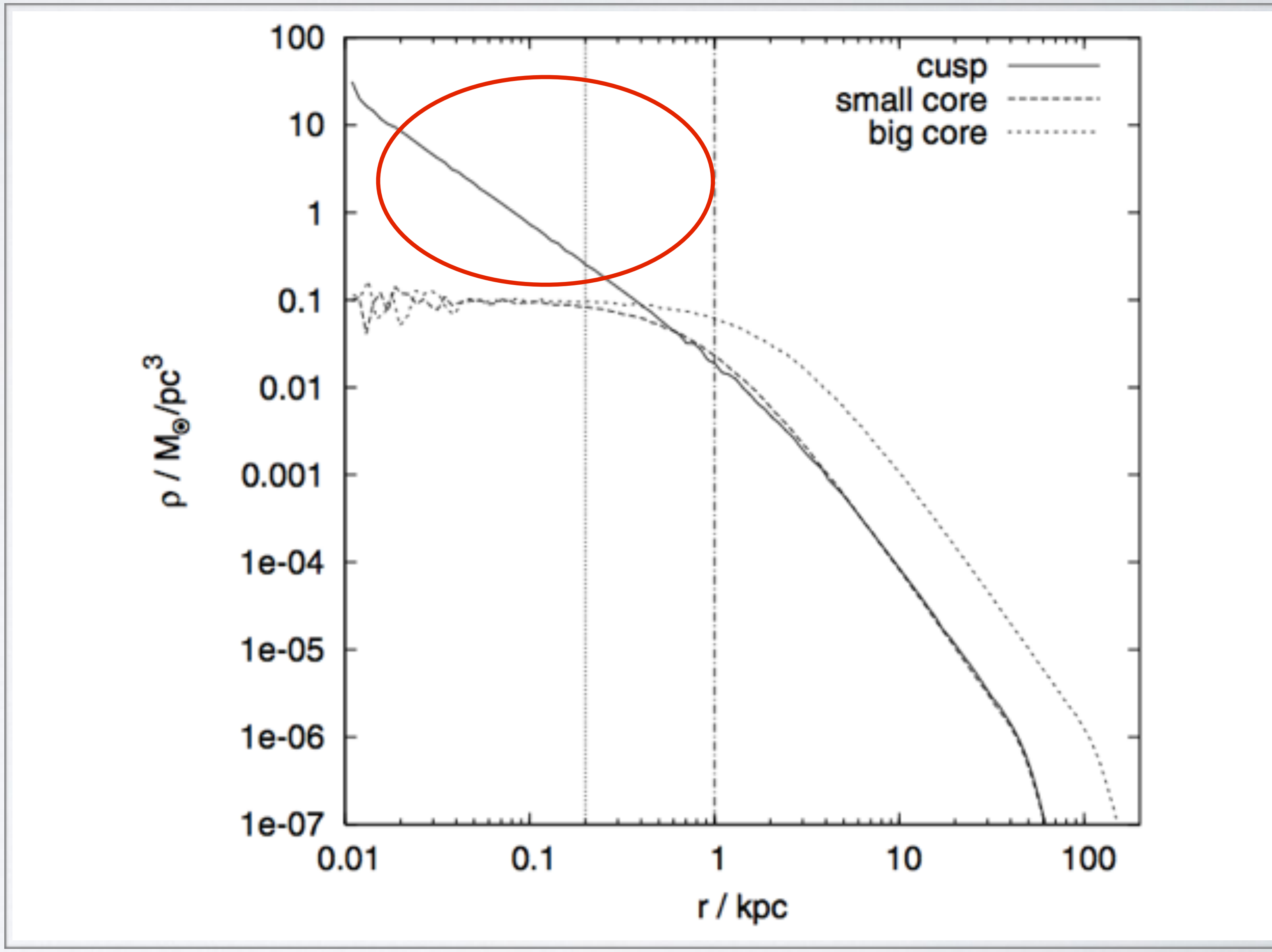
CUSP/CORE DENSITY PROFILE

- Observation [*pseudo-isothermal (PI)*]: Core structure

$$\rho_{\mathrm{PI}}(r) = \frac{\rho_0}{1 + (r/R_C)^2},$$

- Simulation [NFW profile]: Cusp structure

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_i}{(r/R_s)(1 + r/R_s)^2},$$



T. Goerdt et al. (2006)

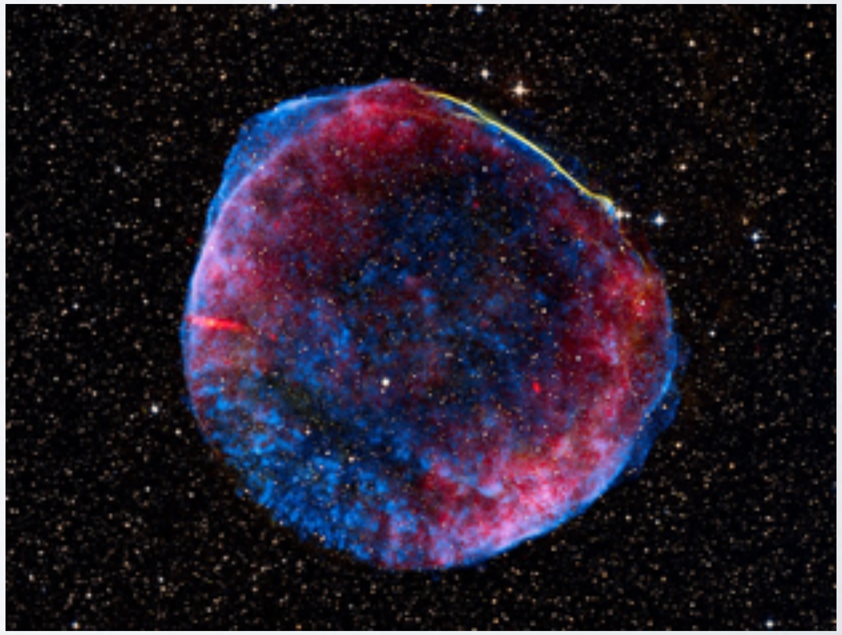
MISSING PHYSICS IN SIMULATION?

- Property of DM?
- Dynamical? [N-body only consider gravity]

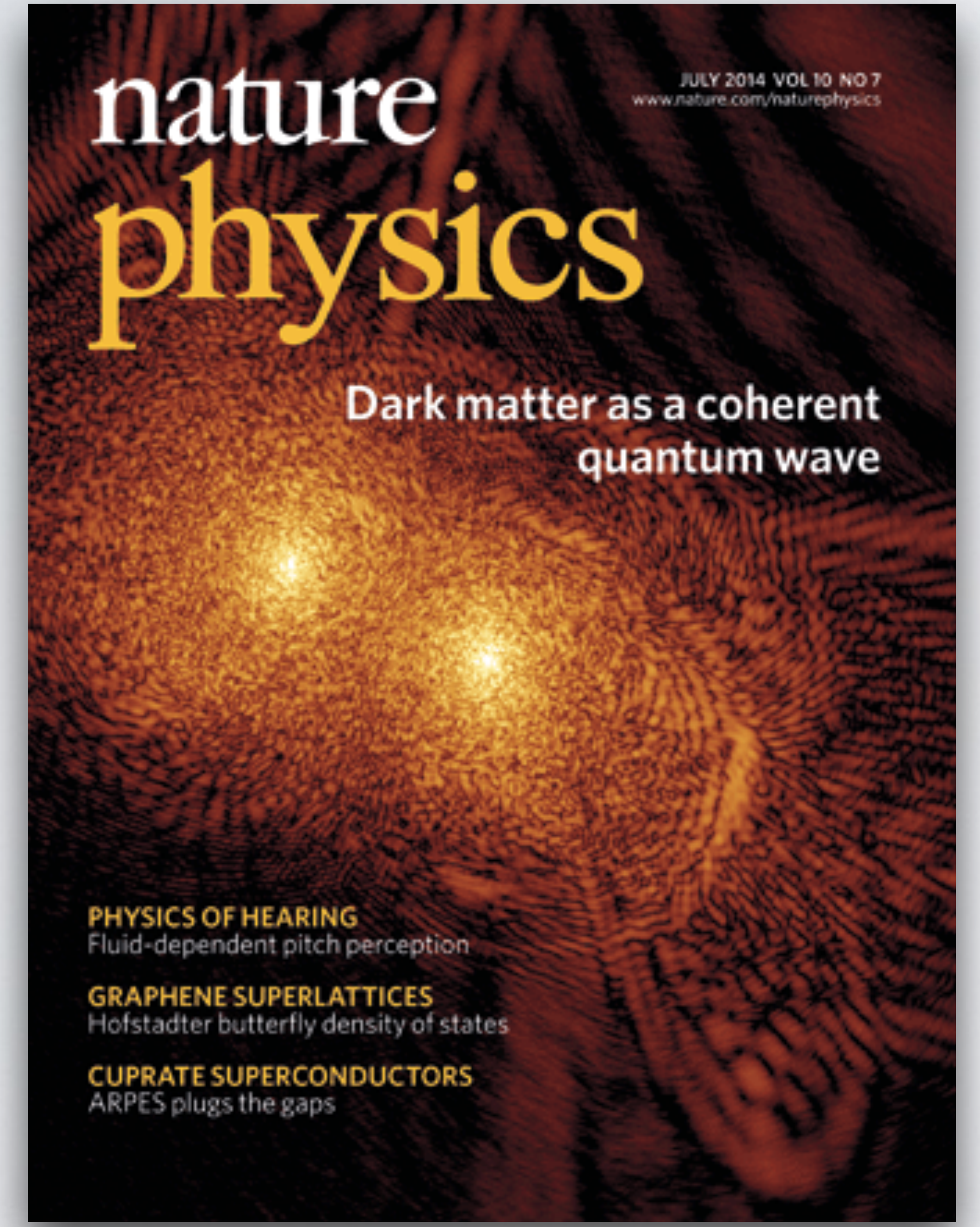
PROPOSED SOLUTIONS

- DM Model solutions
- Fuzzy/ψ(Wave-like) Dark Matter (Hu et al. 2000)
- Warm Dark Matter (Turok et al. 2001)
- Self-interacting Dark Matter (Spergel et al. 2000)

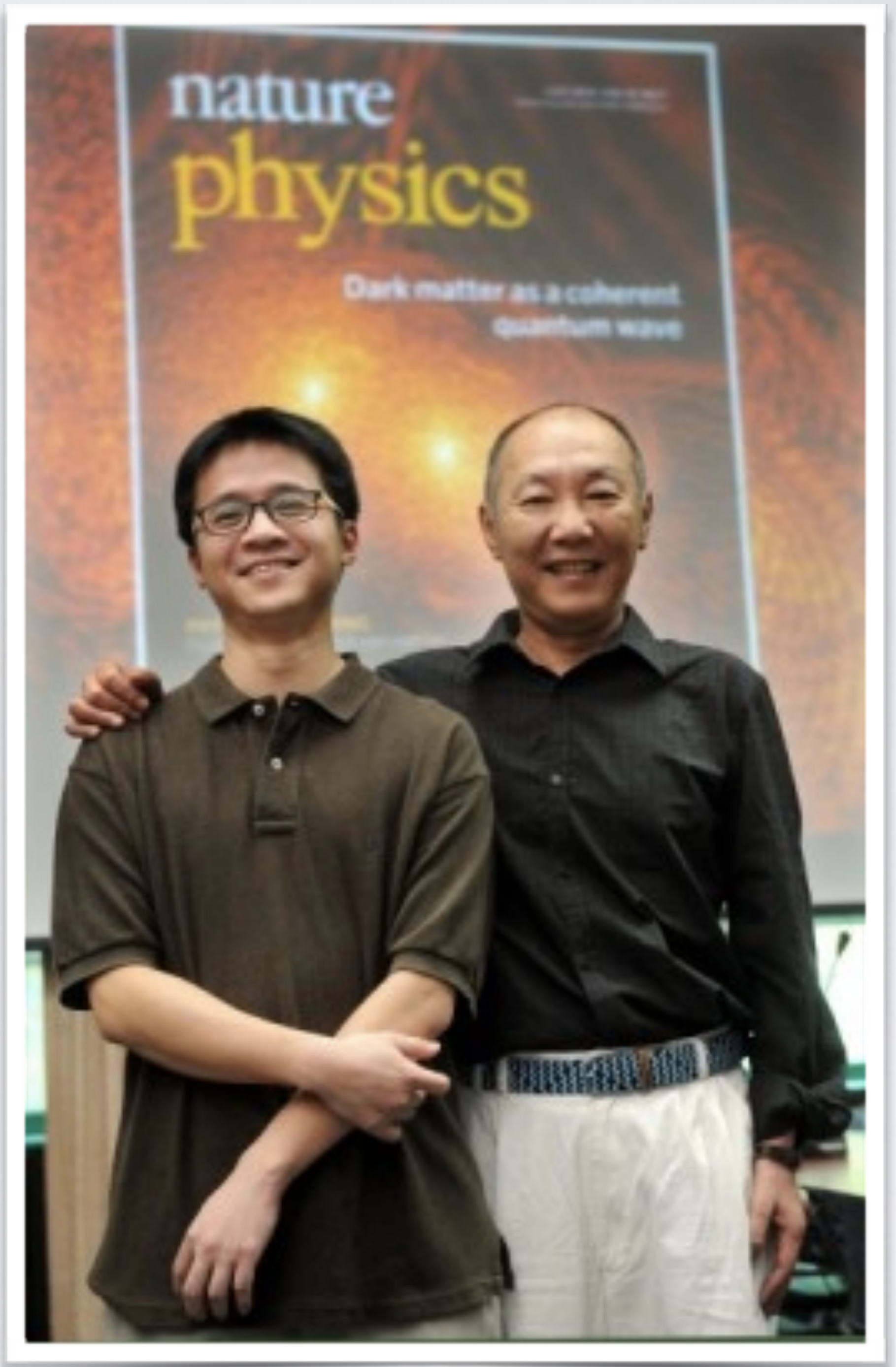
- Dynamical solutions
- **Supernova-driven outflows (F Governato et al. 2010)**
- Bar-driven dark halo evolution (MD Weinberg et al. 2002)
- **Gravitational Slingshot?**



ΨDM SIMULATION @ NTU



Cover of Nature Physics (2014)



Dr. Hsi-Yu Schive & Prof. Tzihong Chiueh

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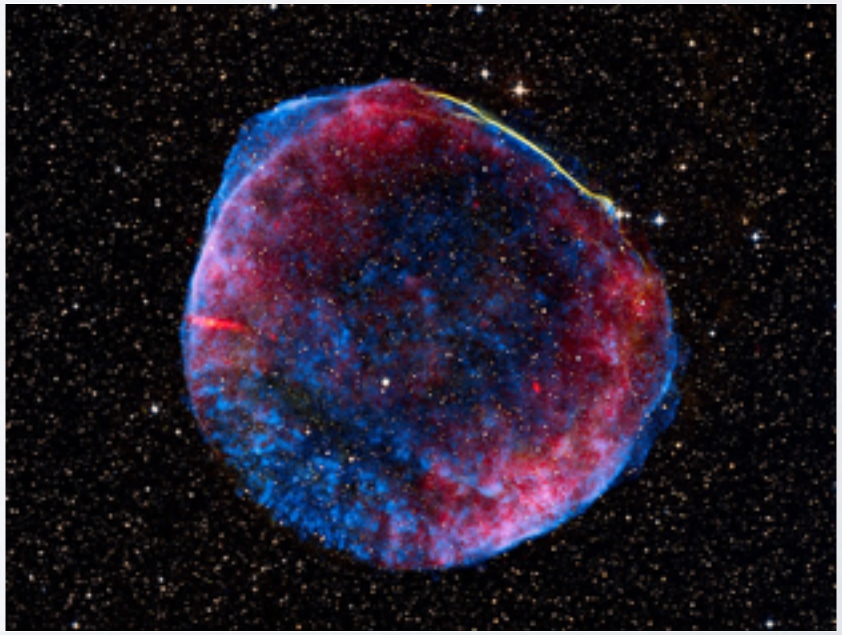
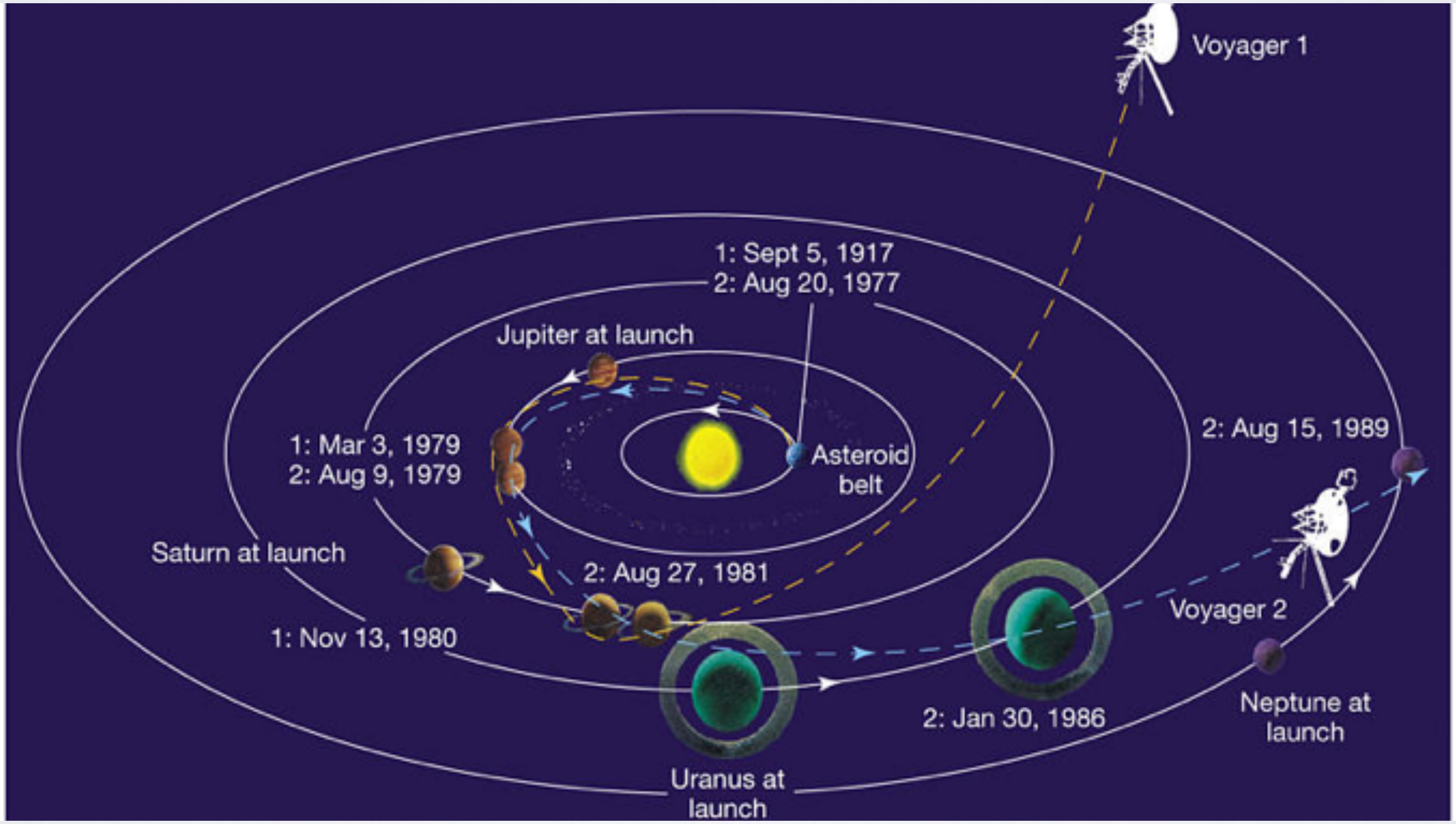


GRAVITATIONAL SLINGSHOT

The slingshot effect has been used effectively by NASA to send spacecraft to outer edges of the solar system. This phenomenon can be satisfactorily explained by Newtonian physics.



Stars in galaxy center

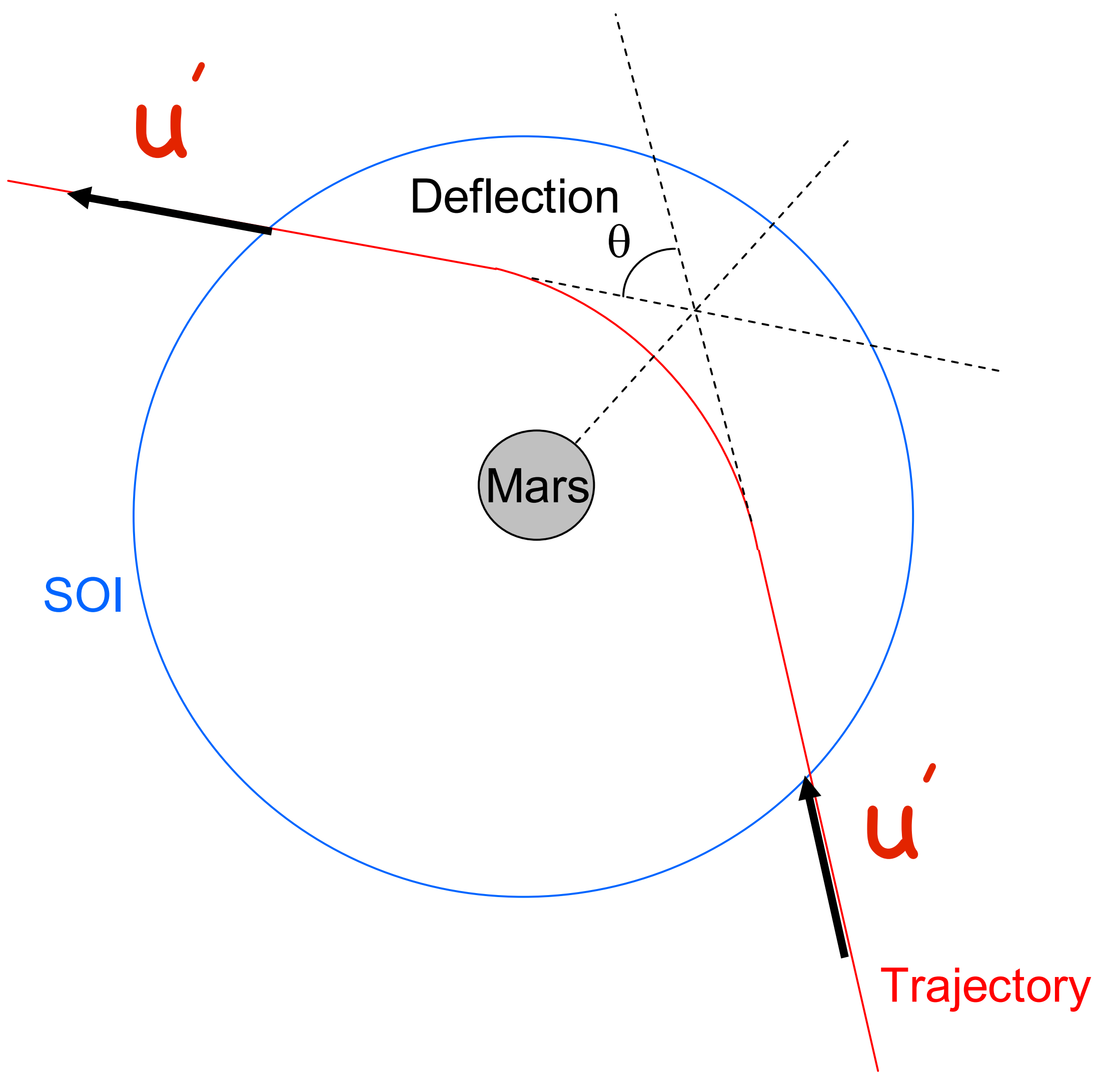
Galaxy center is where slingshot happens most often!

Star frame

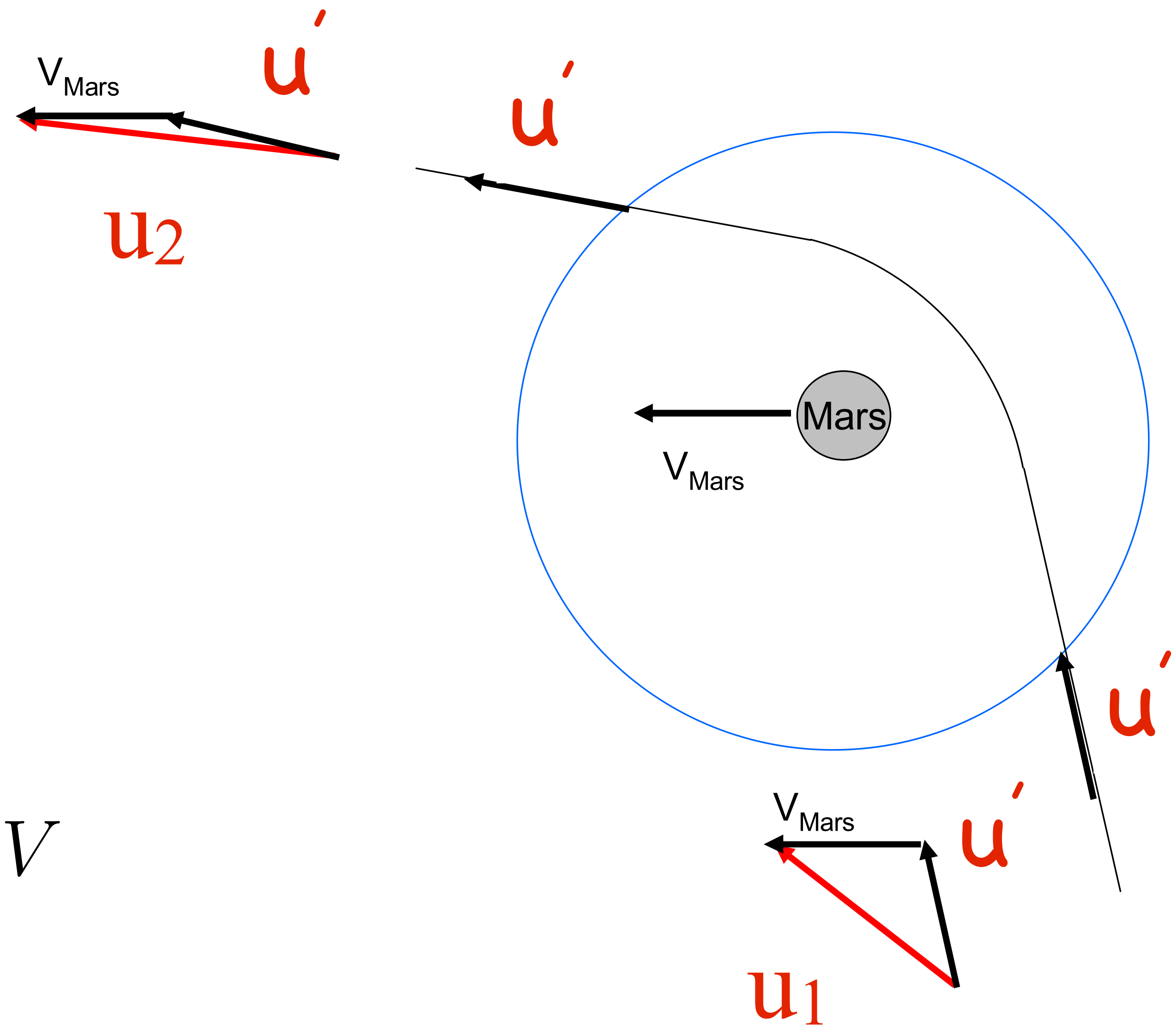
- Sphere of Influence [SOI]
- Easy to solve the deflection angle

$$\theta_{\text{defl}} = 2\tan^{-1}\left(\frac{GM}{bv^2}\right).$$

- [No Energy Gain in this frame!]



Lab Frame



- The frame where we observe slingshot.

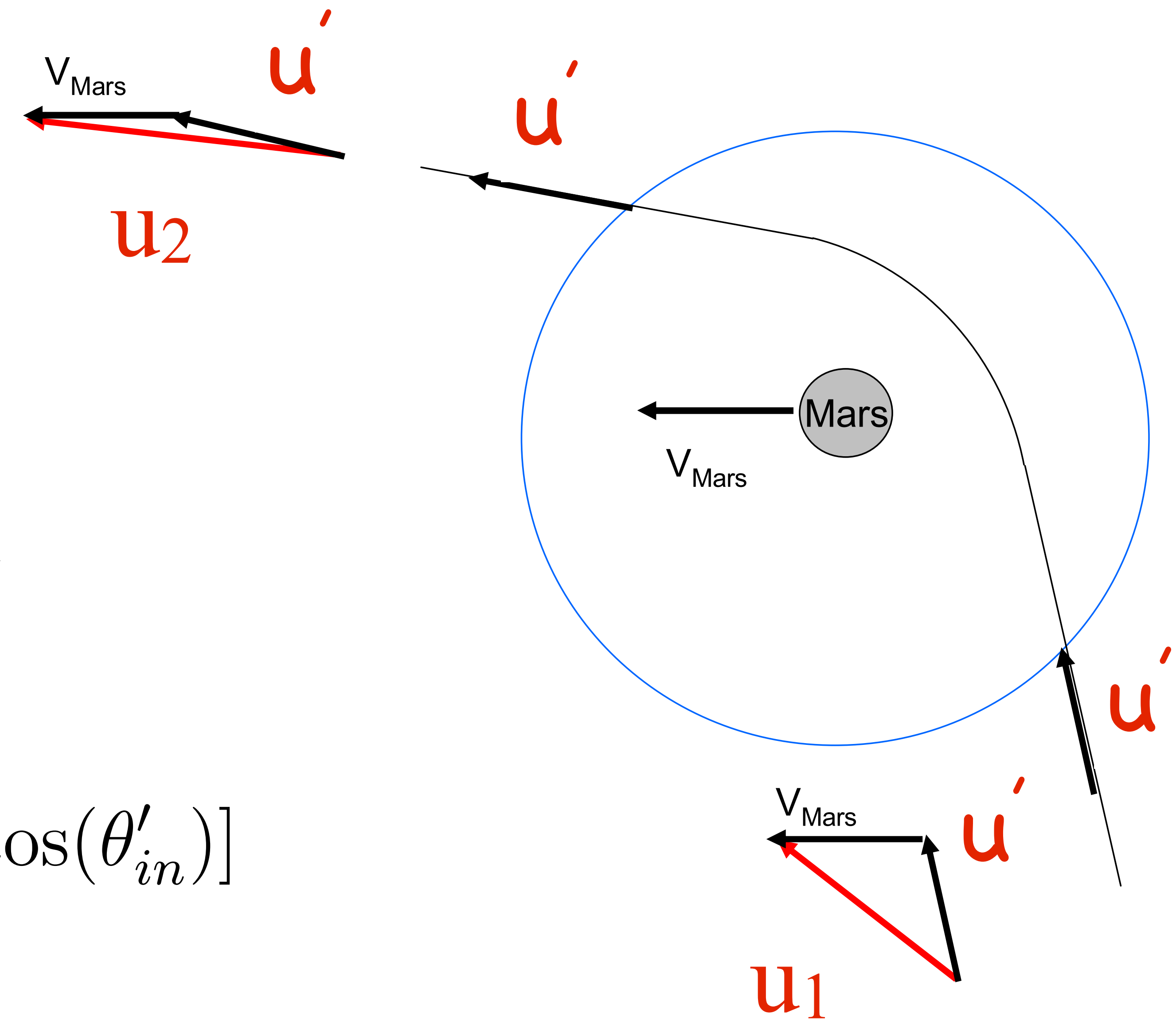
$$u' \cos\theta'_{in} = u_1 \cos\theta_{in} + V$$

$$u' \sin\theta'_{in} = u_1 \sin\theta_{in}$$

$$u' \cos\theta'_{out} = u' \cos(\theta'_{in} + \phi'_{def}) = u_2 \cos\theta_{out} + V$$

$$u' \sin\theta'_{out} = u' sin(\theta'_{in} + \phi'_{def}) = u_2 \sin\theta_{out}$$

Lab Frame



- The frame where we observe slingshot.

$$\Delta E_{sling} = mu'V[\cos(\theta'_{out}) - \cos(\theta'_{in})]$$

$$\Delta E_{sling} = \frac{1}{2}m[|u_2|^2 - |u_1|^2] = m(u_1 V cos\theta_{in} + V^2)(1 - cos\phi'_{def})$$

$$\frac{dE}{dt} = \frac{\int_{b_{min}}^{b_{max}} bdb \int d\Omega_{in} \Delta E\, n_* \sigma v_{rel}}{\int_{b_{min}}^{b_{max}} bdb \int d\Omega_{in}},$$

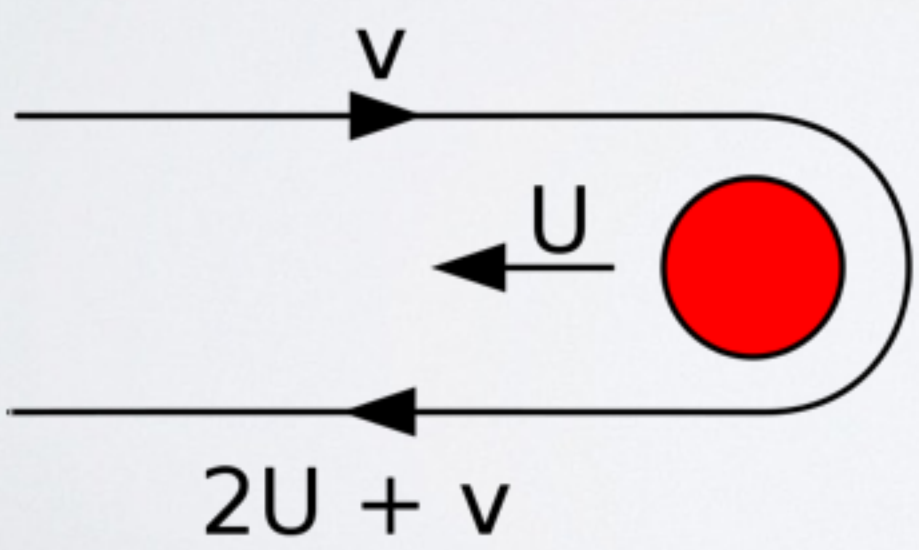
$$\frac{dE}{dt} = \frac{m_\chi V_*^2}{\tau}$$

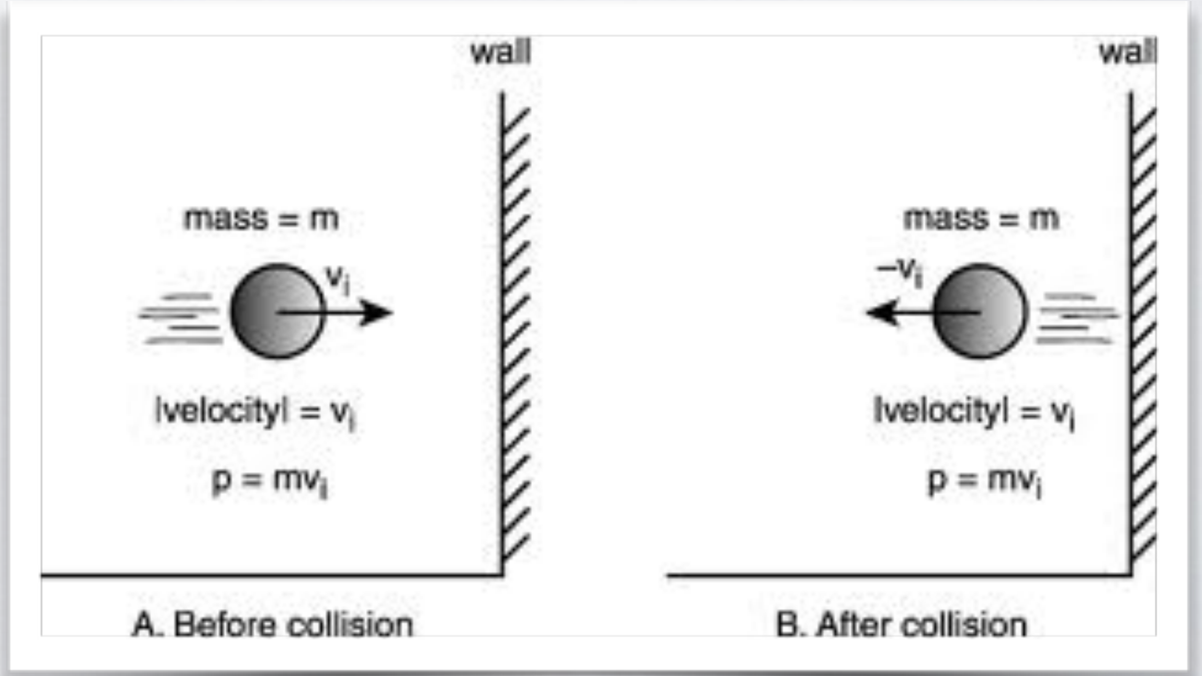
ANALOGUE: ELASTIC COLLISION

- **Slingshot is similar to elastic collision and scattering**

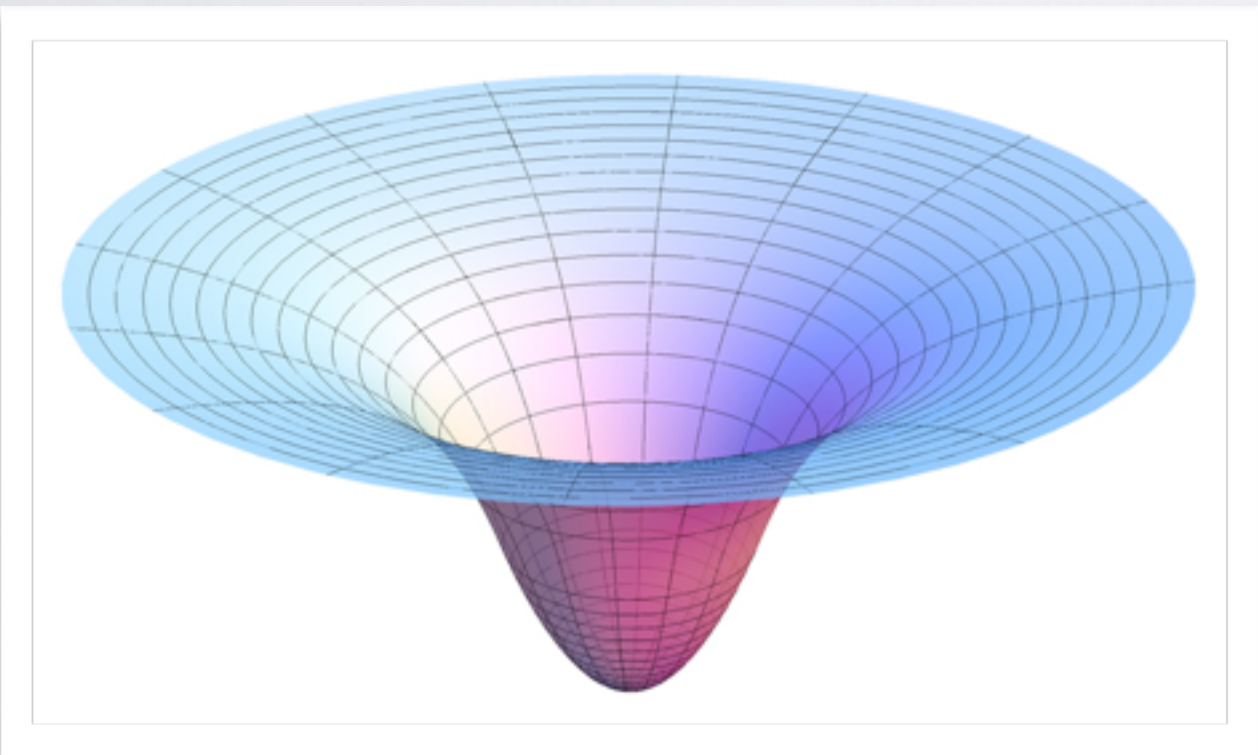
- Slingshot is similar to 2nd-order Fermi acceleration

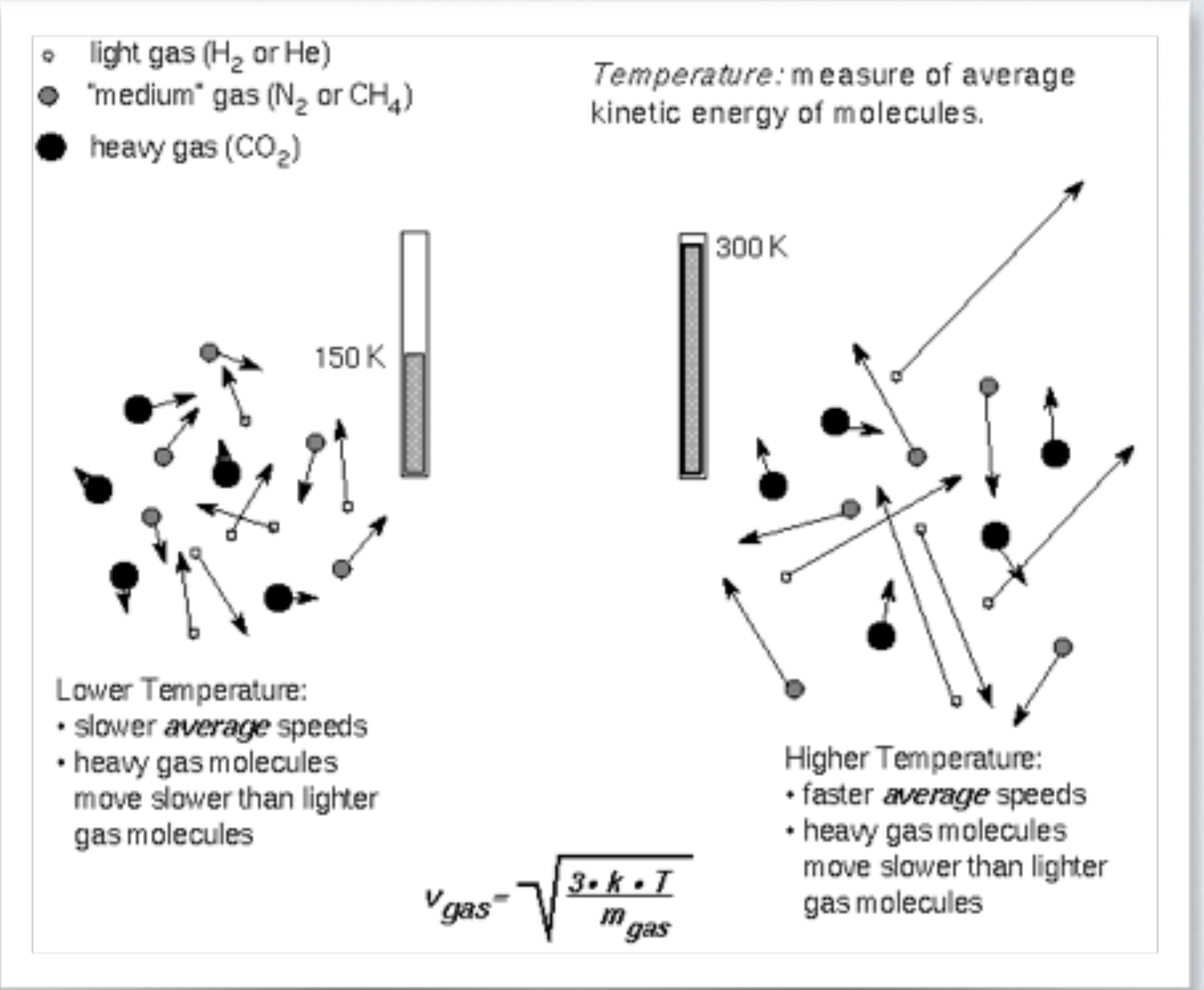
- Slingshot is dynamical friction (for heavier object)





ANALOGUE: PARTICLES IN A BOX

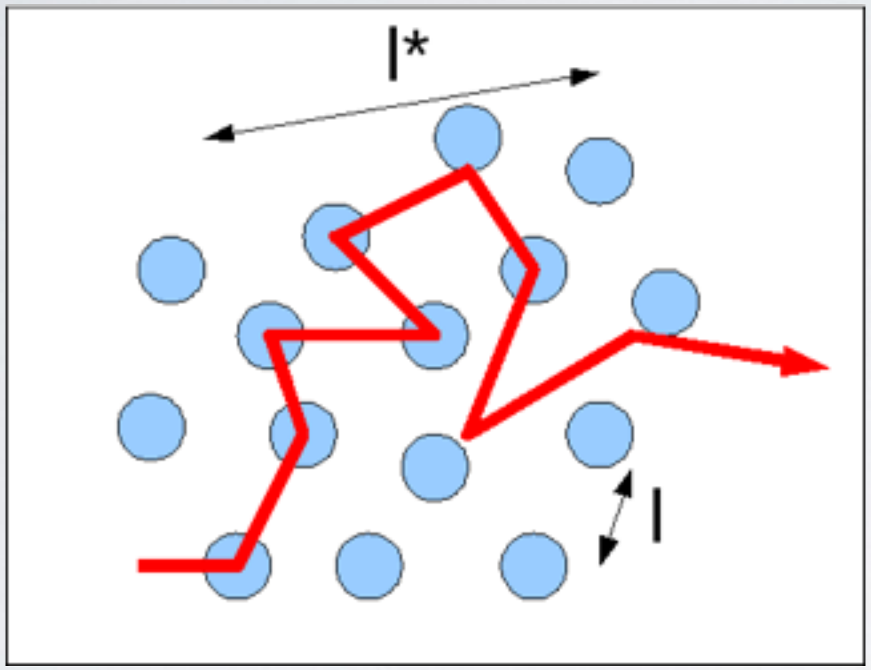


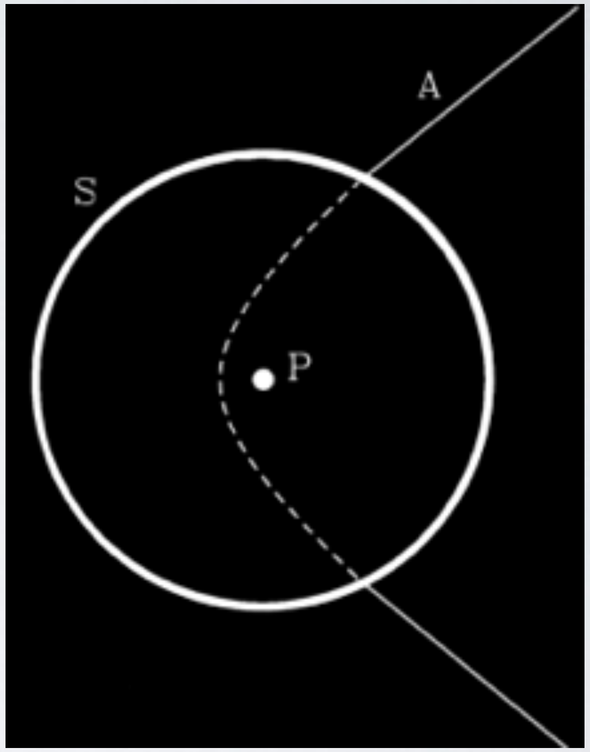


Light object goes faster!

credit: astronomynotes.com

MEAN FREE PATH



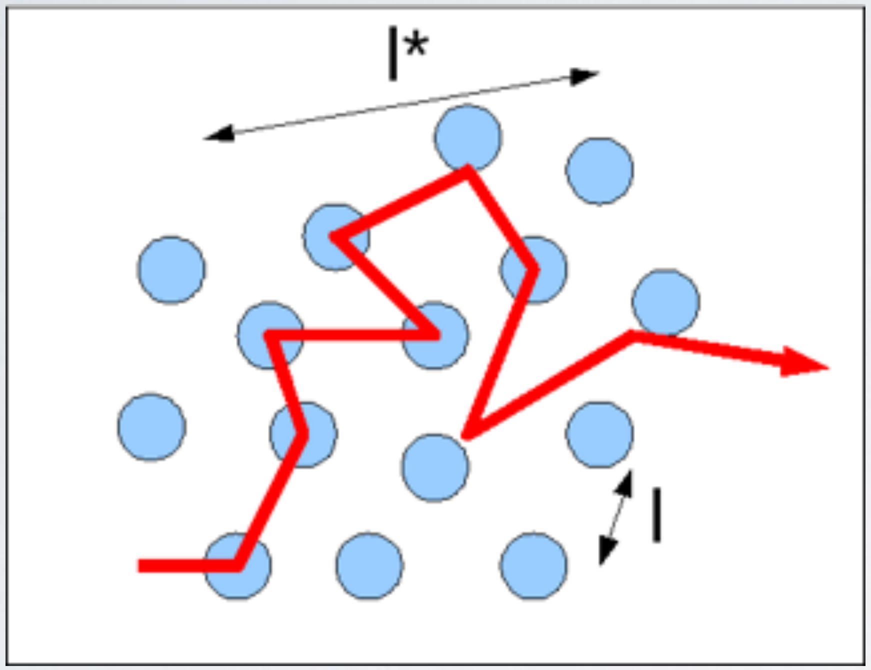


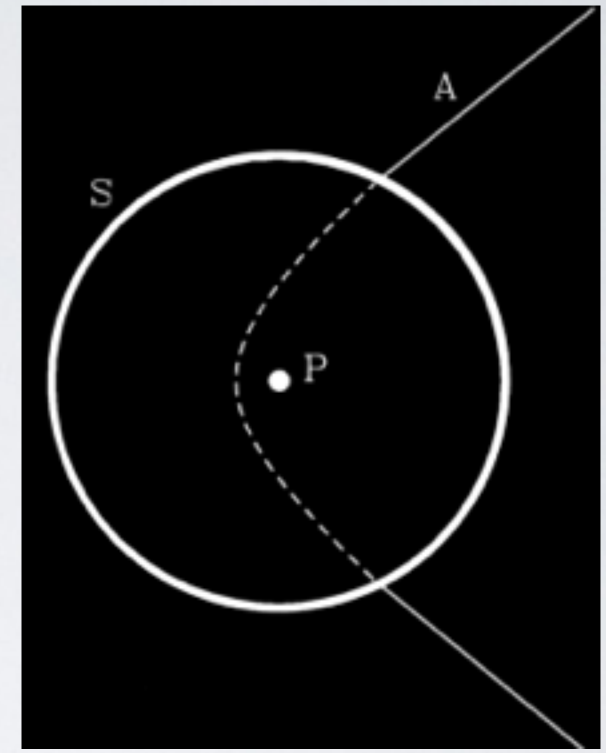
$$\ell = (\sigma n)^{-1}$$

Where ℓ is the mean free path, n is the number of target particles per unit volume, and σ is the effective cross sectional area for collision.

In our case, the n is the number of stars per unit volume, and σ is the effective surface of influence of a star for slingshot.

MEAN FREE PATH





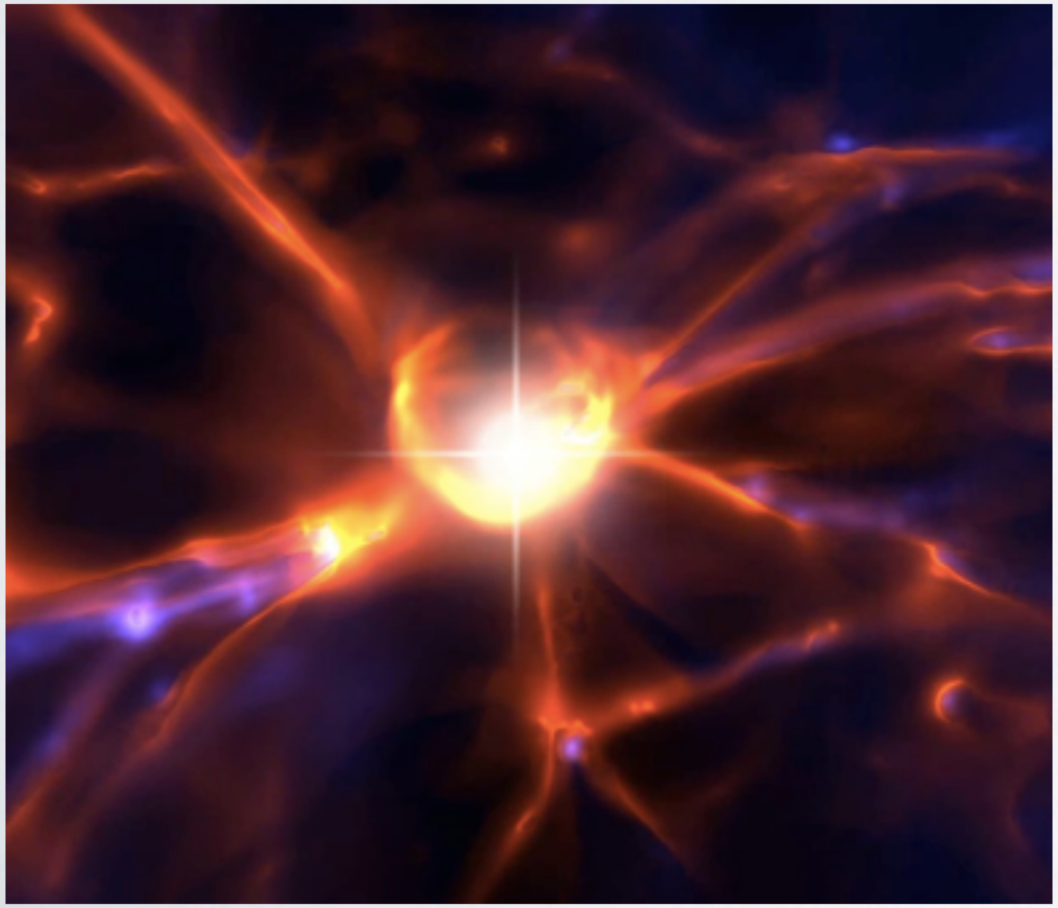
$$\sigma = \pi b_{max}^2$$

We set $b_{max} = \min(b_C; n^{-1/3})$, the smaller of either (1) the Coulomb distance b_C where the stellar potential equals the mean galactic potential, or (2) the mean interstellar distance $n^{-1/3}$.

MASSIVE STAR & SLINGSHOT

$$\ell = (\sigma n)^{-1}$$

$$\theta_{\text{defl}} = 2\tan^{-1}\left(\frac{GM}{bv^2}\right).$$

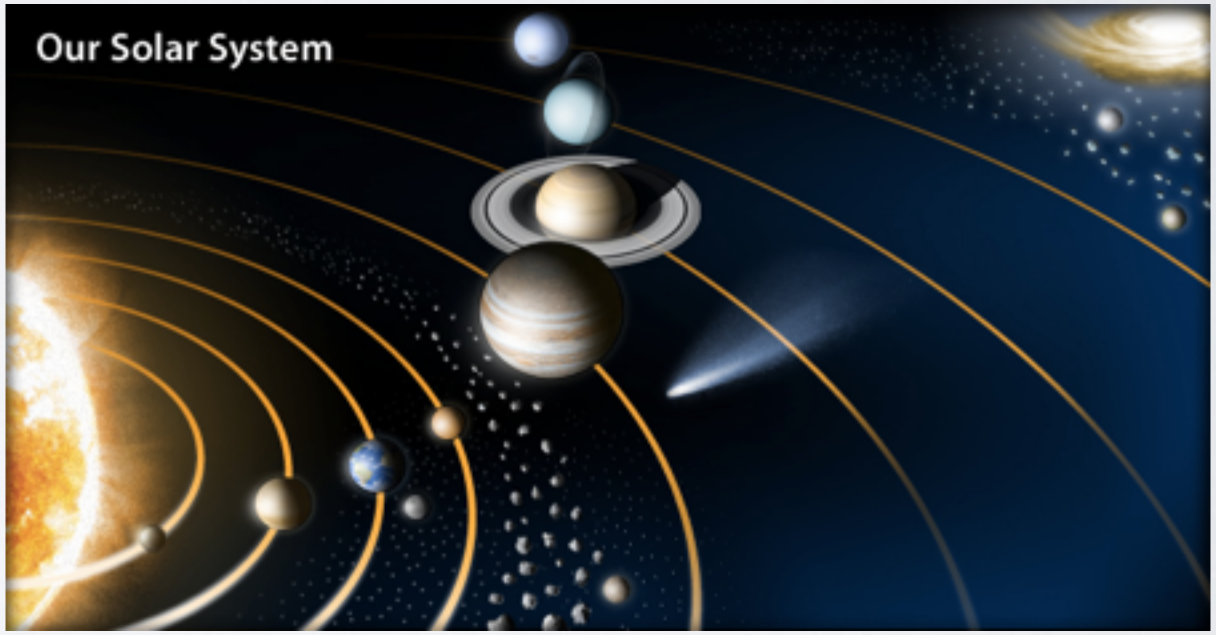


- The more massive the object is, the more efficient the slingshot effects the distribution of DM.

- For example, the Population III star has mass around 100 solar mass, and they may turn into a 40 solar mass BH when they died. (Abel et al. 2002, Zhang et al. 2008)

TIME EVOLUTION OF DM DENSITY PROFILE

- Circular orbit model
- Dark matter will move to higher orbits as time evolve [due to slingshot].



Orbits of Solar system.

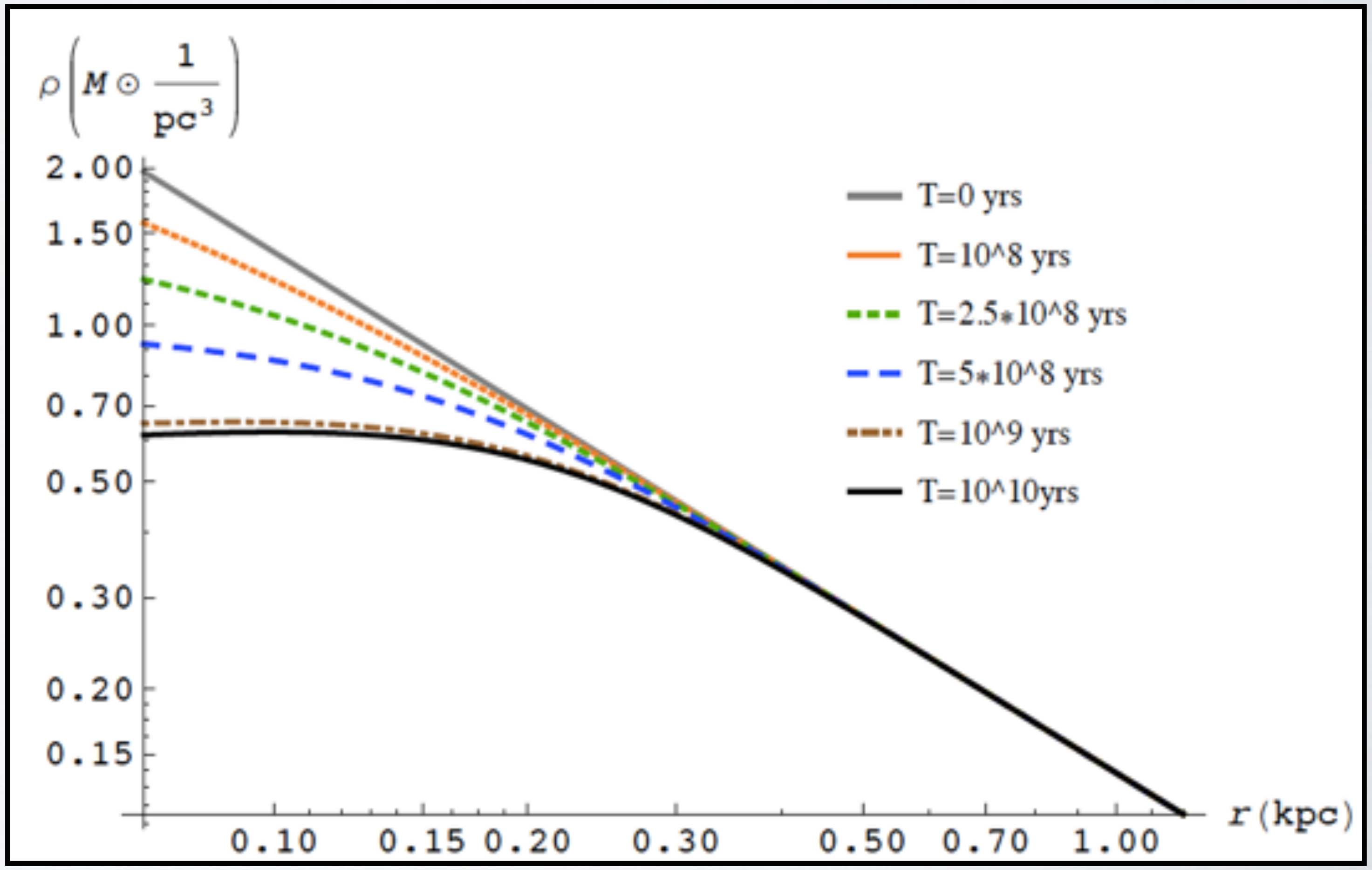
Credit: NASA

Time evolution of DM density

	$M_* \; [M_\odot]$	V_*, u_χ [m/s]	n_0 $[\mathrm{pc}^{-3}]$	R_e[kpc]	τ [years]
early MW	100	10^5	10	0.2	10^{10}
late MW	1	10^5	10^3	0.2	10^{12}
early dwarf	100	2×10^4	0.5	0.1	10^9
late dwarf	1	2×10^4	50	0.1	10^{11}

$$n_*(r) = n_0 e^{-r/R_e}$$

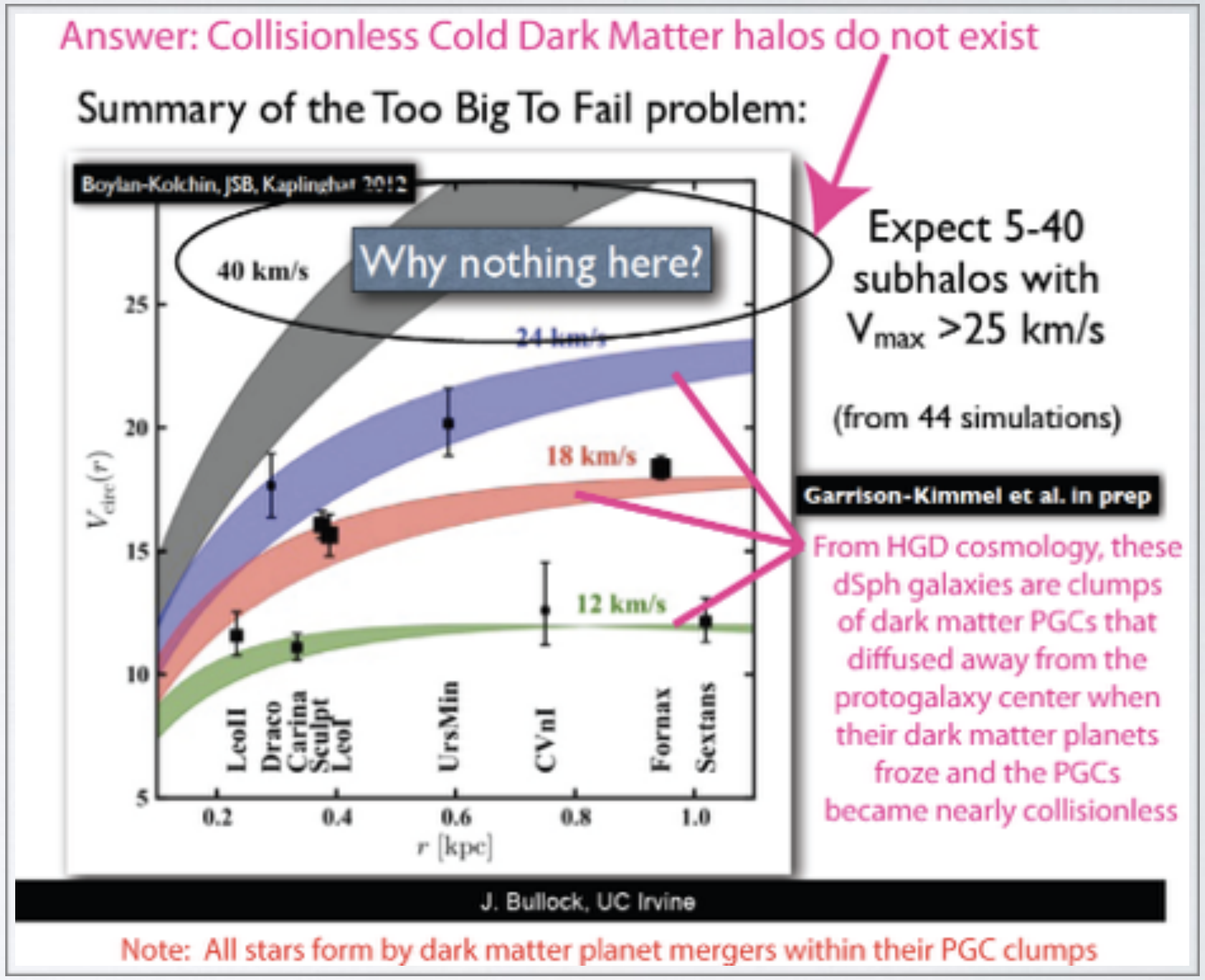
$$\rho(r,t) \simeq \frac{\rho_i R_s}{r + 3R_e \ln\left(1 + \frac{v_0 t}{R_e} e^{-r/R_e}\right)},$$



Chen, Duh, Labun & Lin (2014)

OTHER IMPLICATION

- Missing Satellites Problem
- Too Big To Fail Problem



M Boylan-Kolchin et al. (2011)

SUMMARY

- Slingshot effect is not resolved in N-Body simulations due to: (1)Resolution limit (2) The absence of stars in many simulations.
- Works (DM) model independently. Slingshot may alleviate the cusp-core problem.
- Will change the DM distribution function at early times.
- Slingshot effect may also provides a natural mechanism to alleviate other CDM small scale problems.