Gravitational Slingshot as a Solution to Cold Dark Matter Cusp-Core Problem

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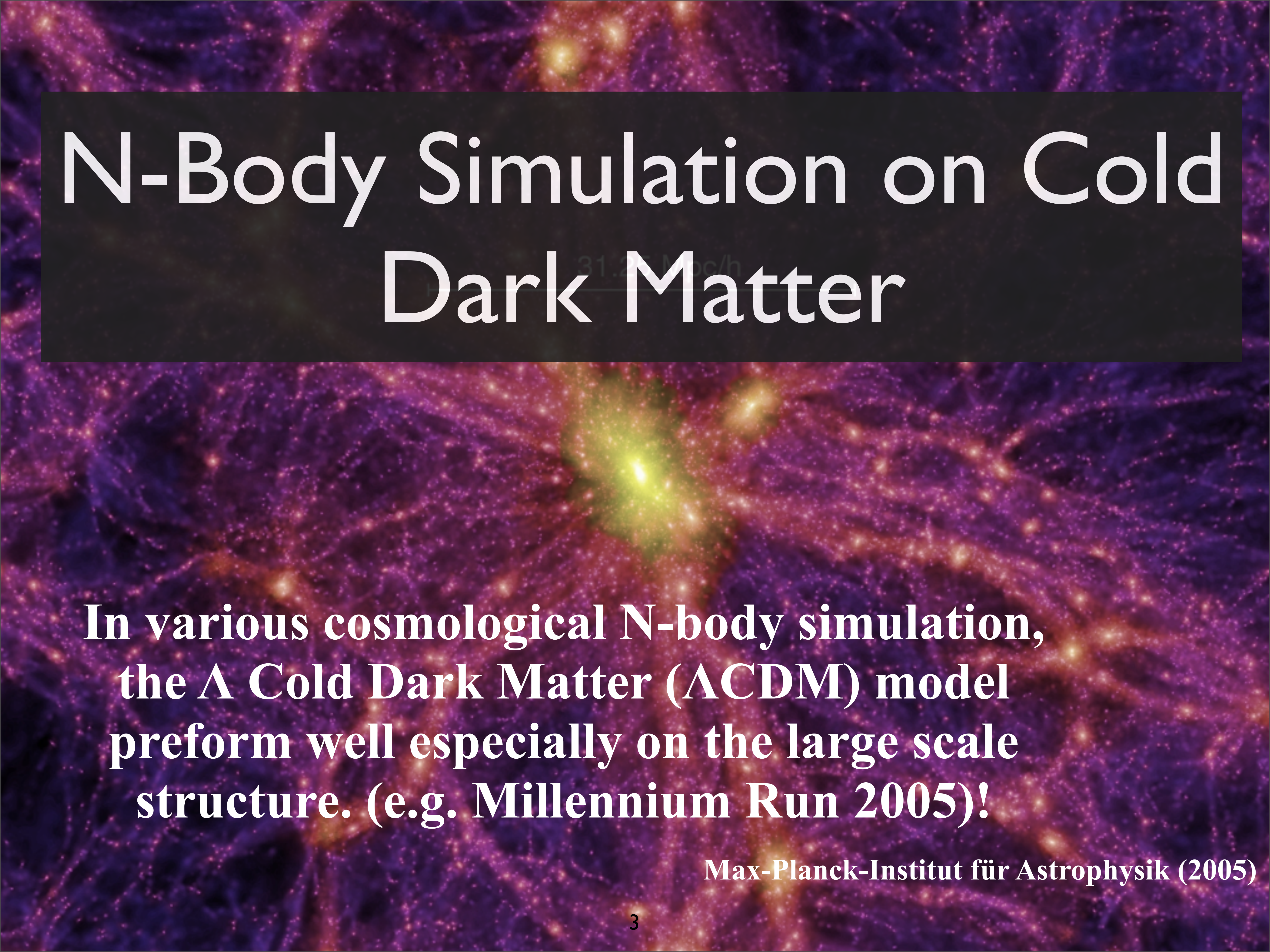
Dark Matter

- 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)!

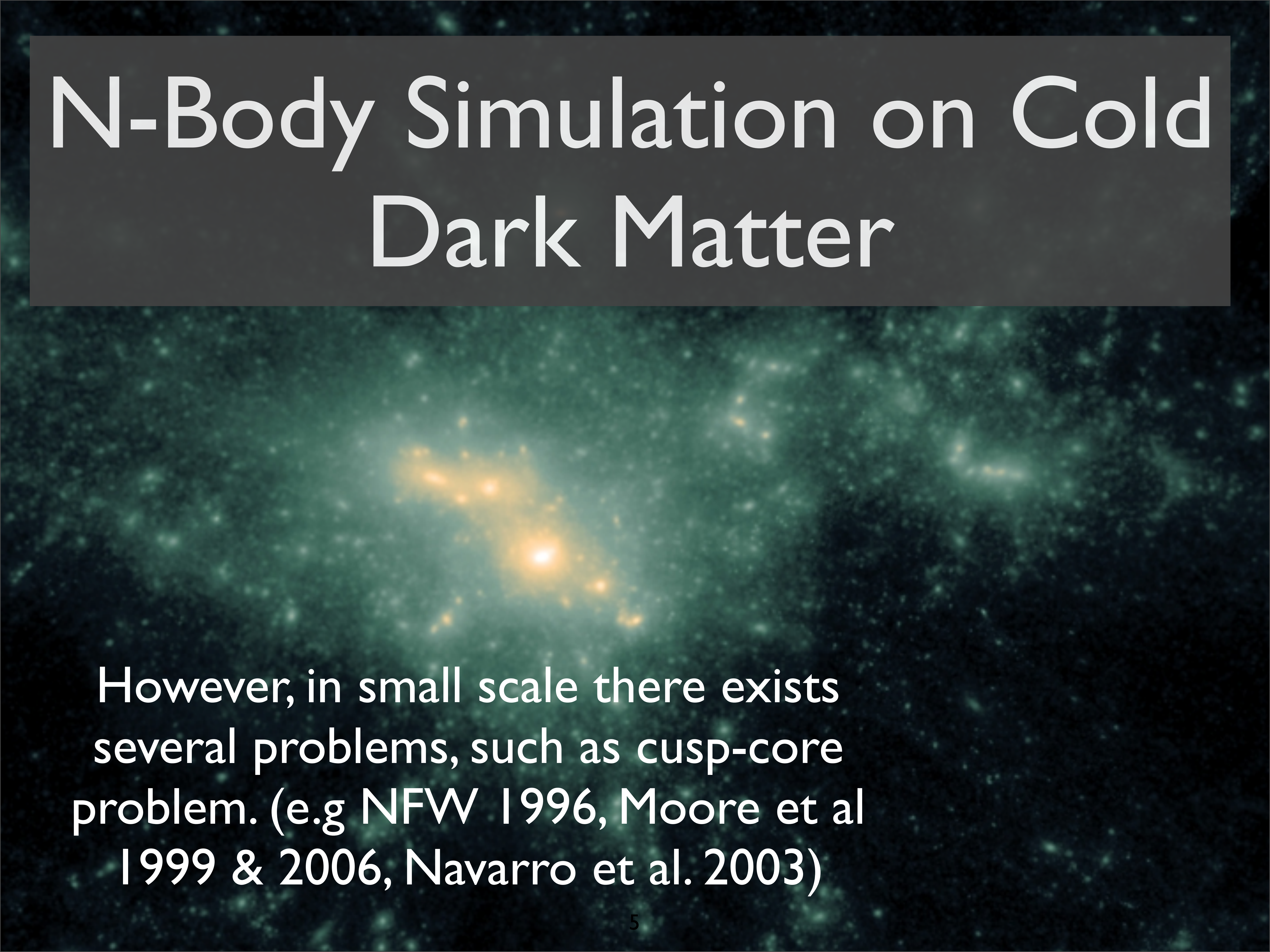
Max-Planck-Institut für Astrophysik (2005)

N-Body Simulation on Cold Dark Matter

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

Max-Planck-Institut für Astrophysik (2005)

N-Body Simulation on Cold Dark Matter

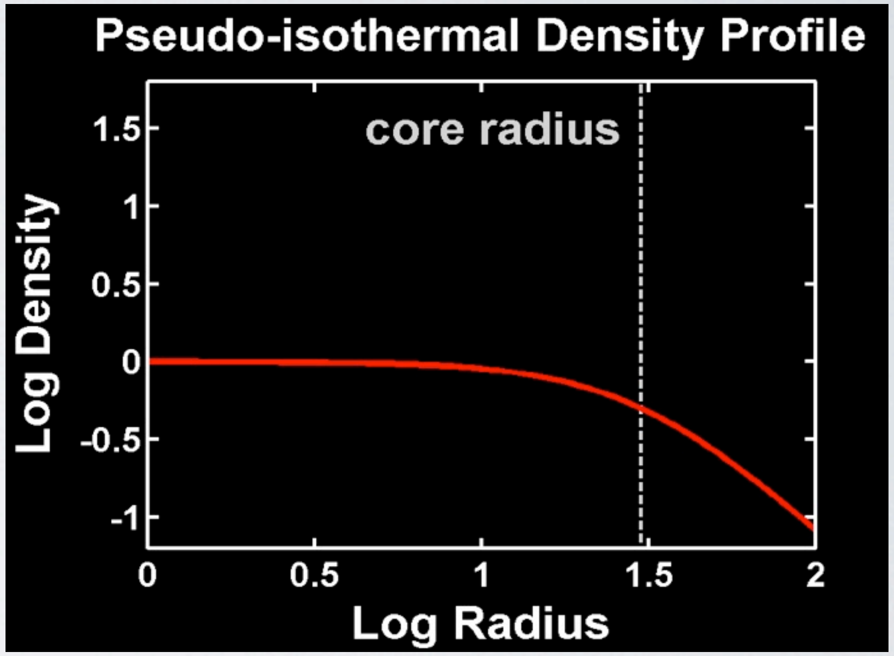


However, in small scale there exists several problems, such as cusp-core problem. (e.g NFW 1996, Moore et al 1999 & 2006, Navarro et al. 2003)

CUSP/CORE DENSITY PROFILE

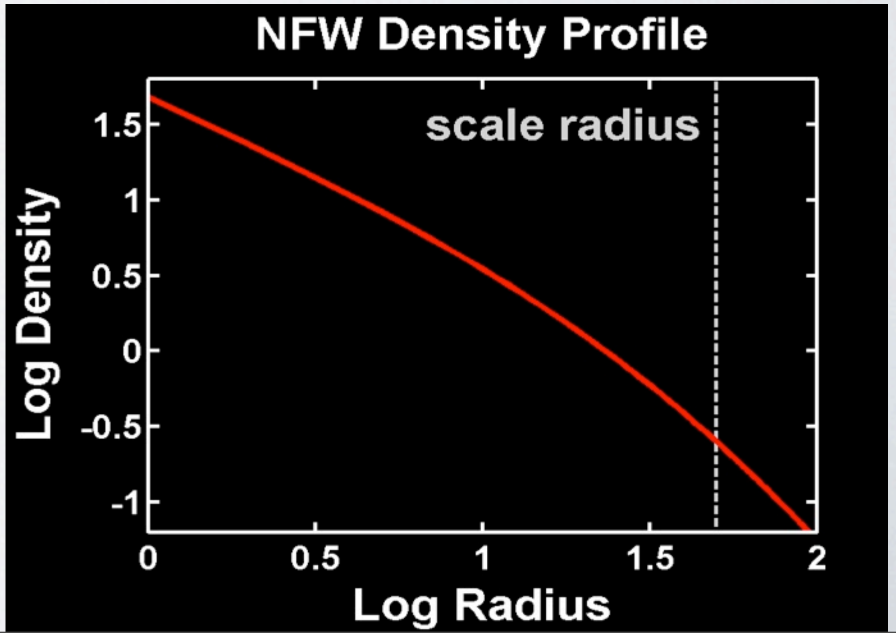
- Observation [*pseudo-isothermal* (PI)]: Core structure

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

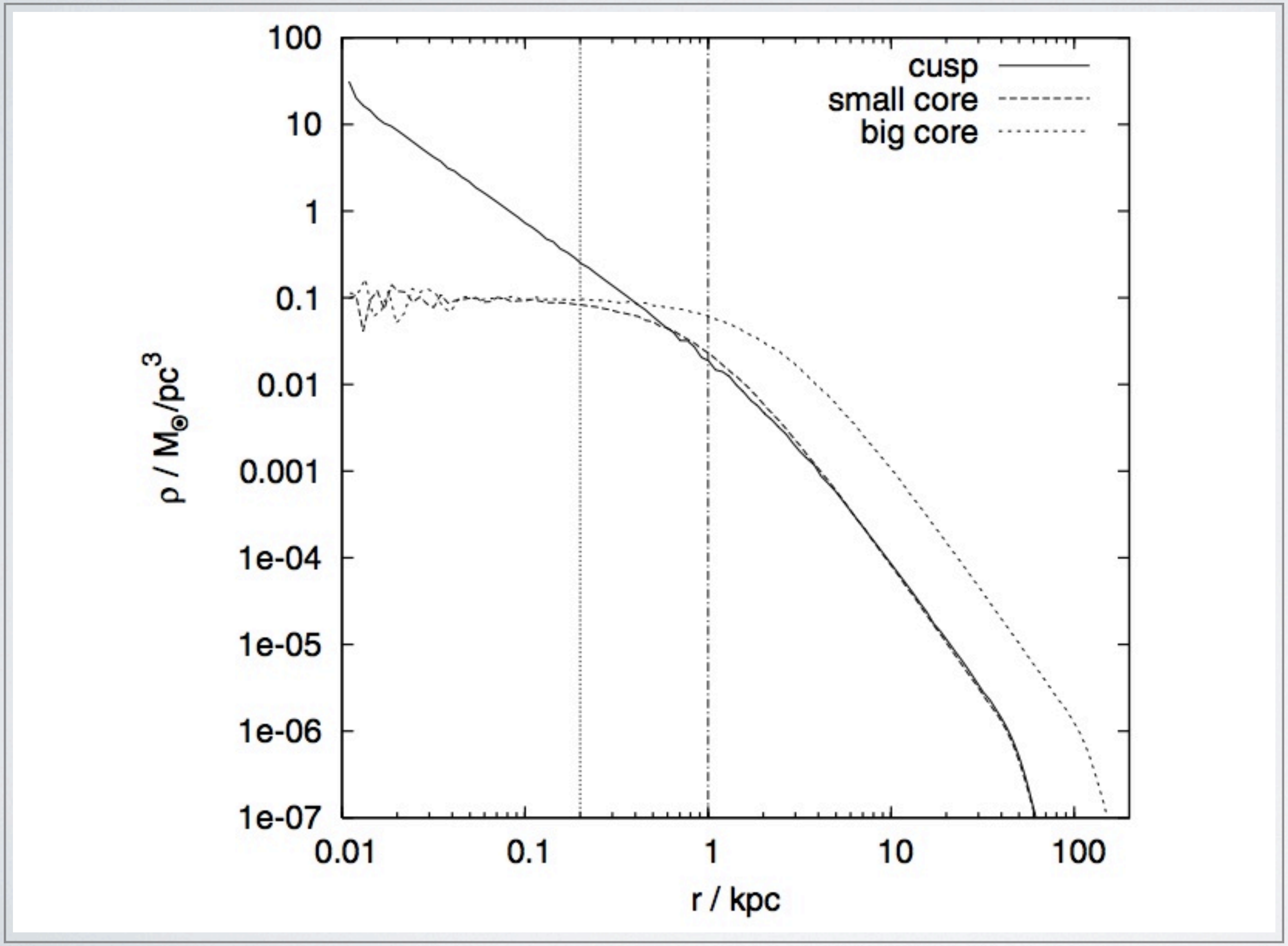


- Simulation [NFW profile]: Cusp structure

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



THE CUSPED PROBLEM



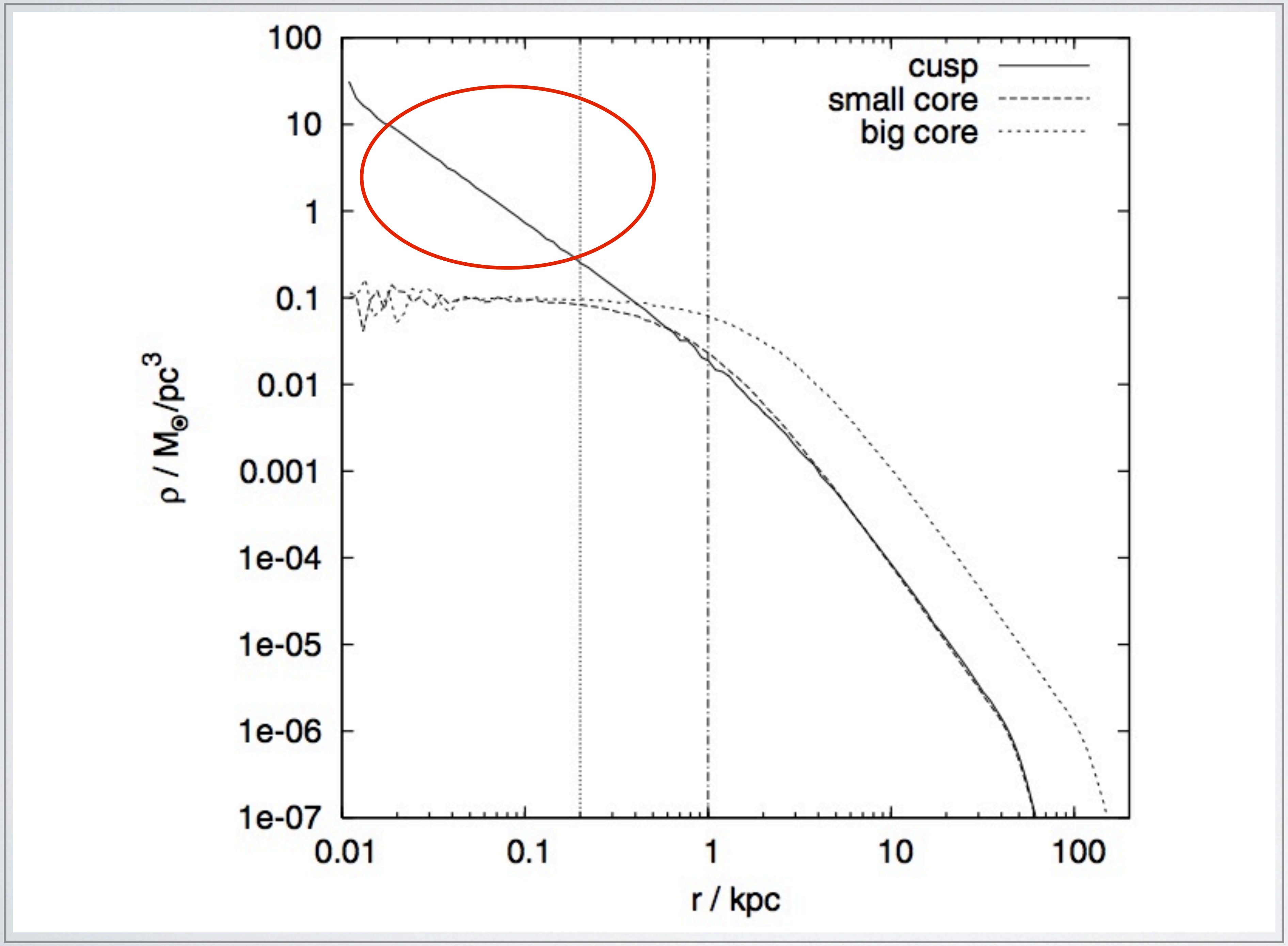
NFW Profile

$$\rho(r) = \frac{\text{constant}}{(r/a)(1+r/a)^2}$$

▲ Navarro, Frenk,& White

T. Goerdt et al. (2006)

THE CUSPED PROBLEM



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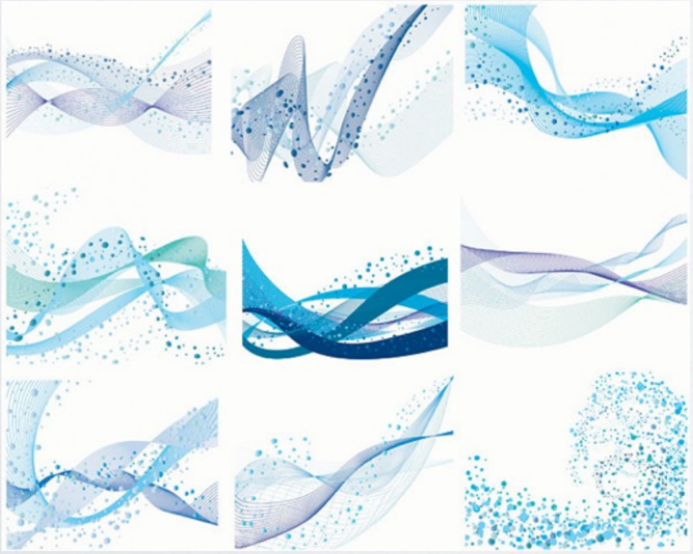
MISSING PHYSICS IN SIMULATION?

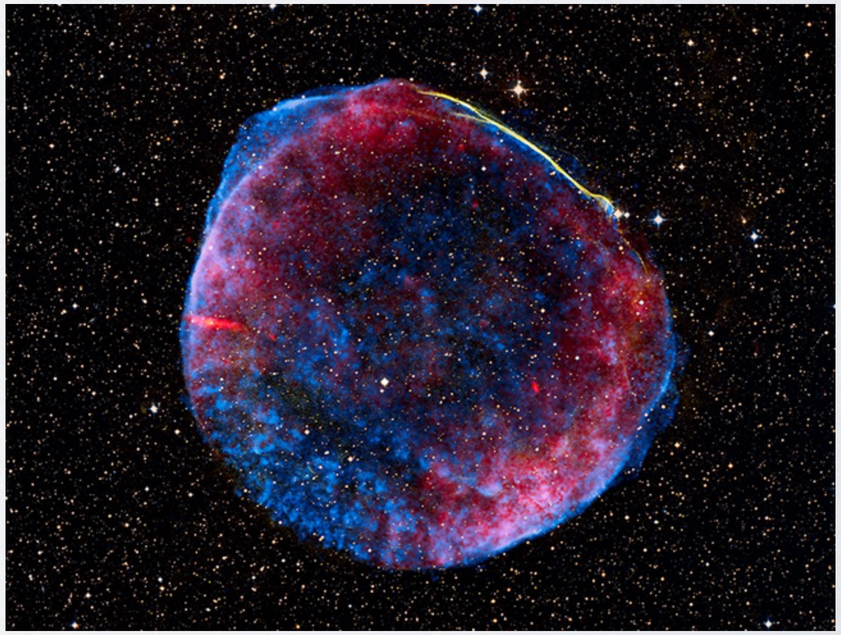
- Property of DM?
- Dynamical? [N-body only consider gravity]

PROPOSED SOLUTIONS

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

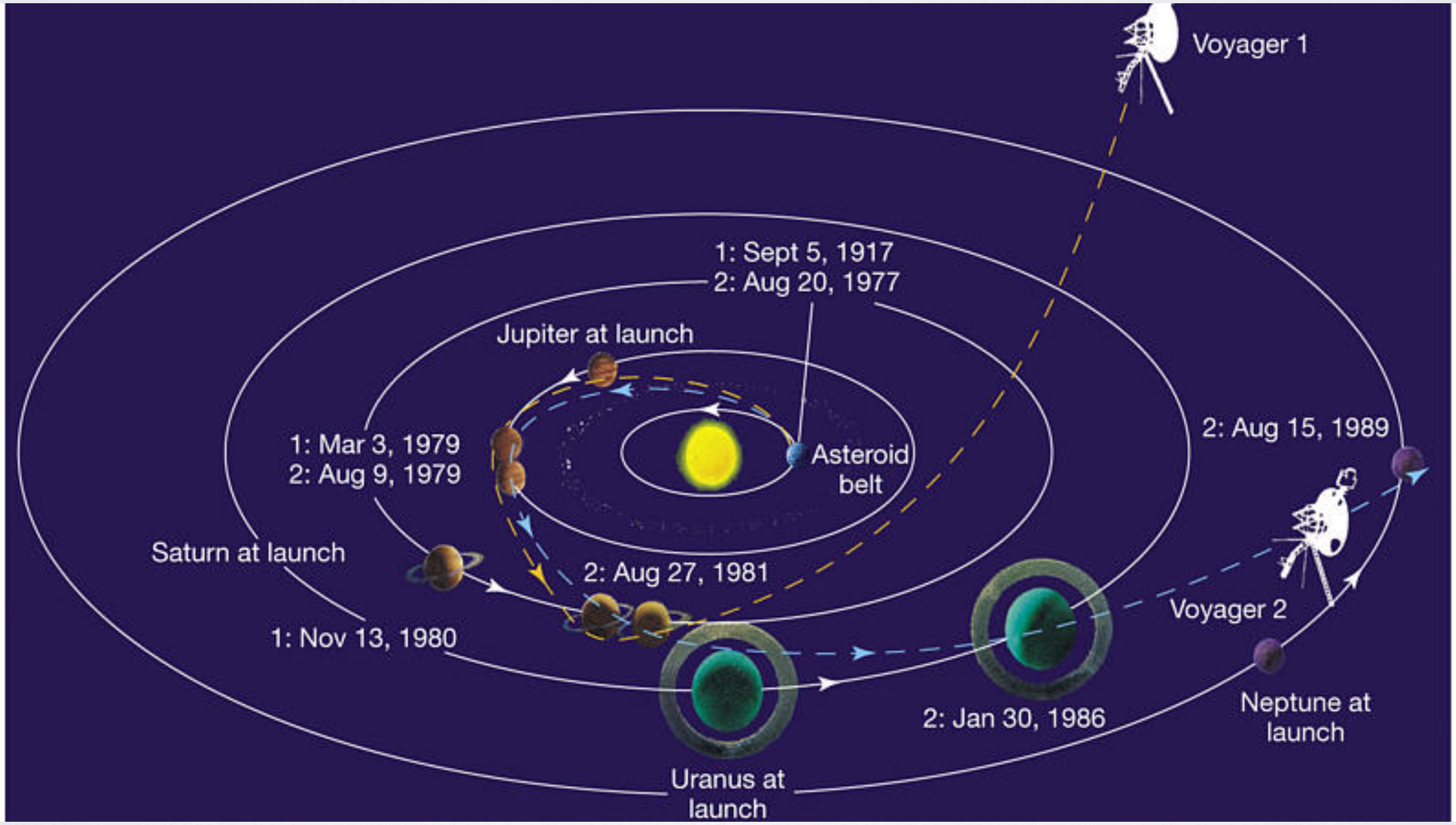


- Dynamical solutions
- **Supernova-driven outflows (F Governato et al. 2010)**
- Bar-driven dark halo evolution (MD Weinberg et al. 2002)
- **Gravitational Slingshot?**



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.

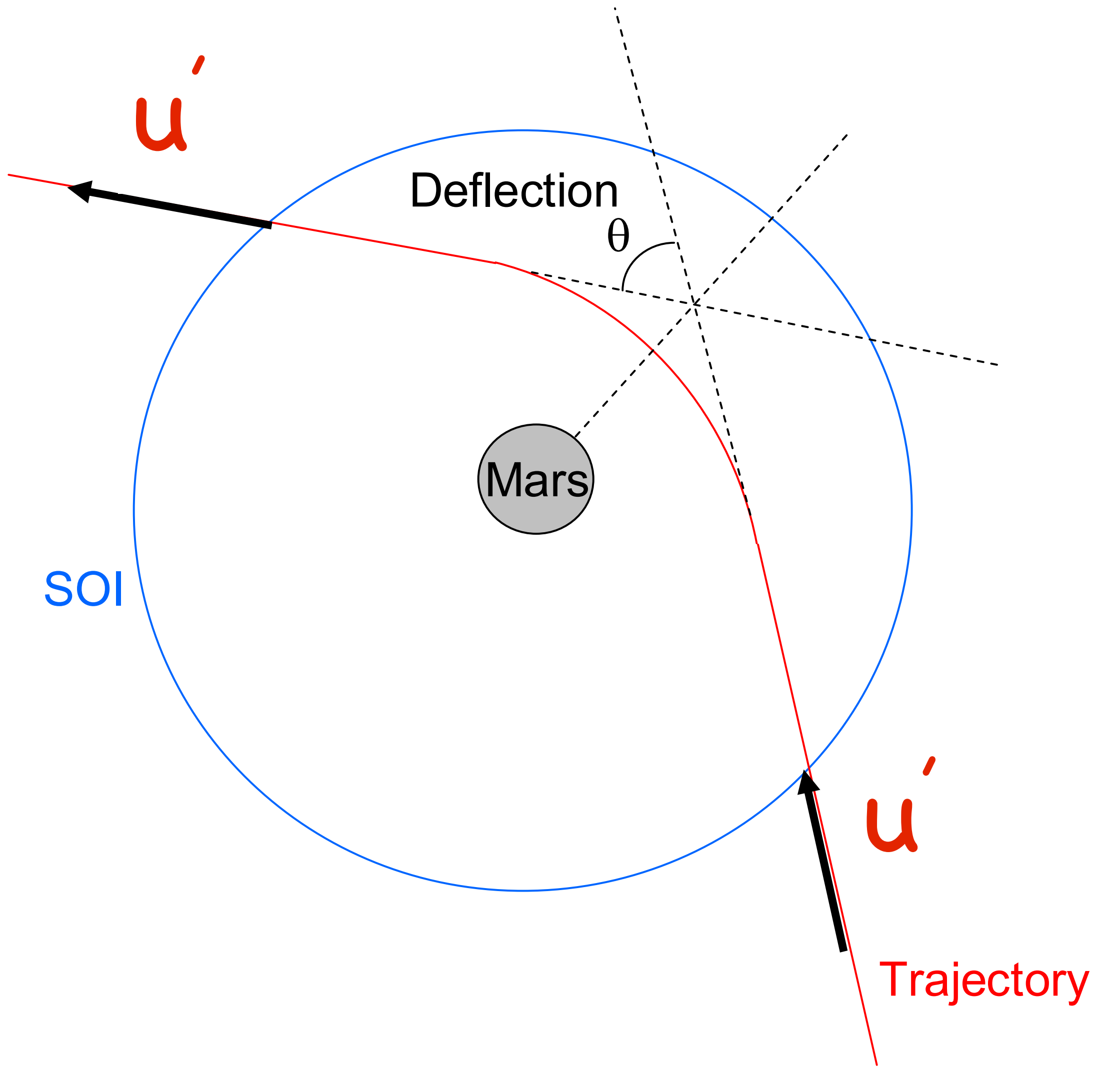


Stars in galaxy center

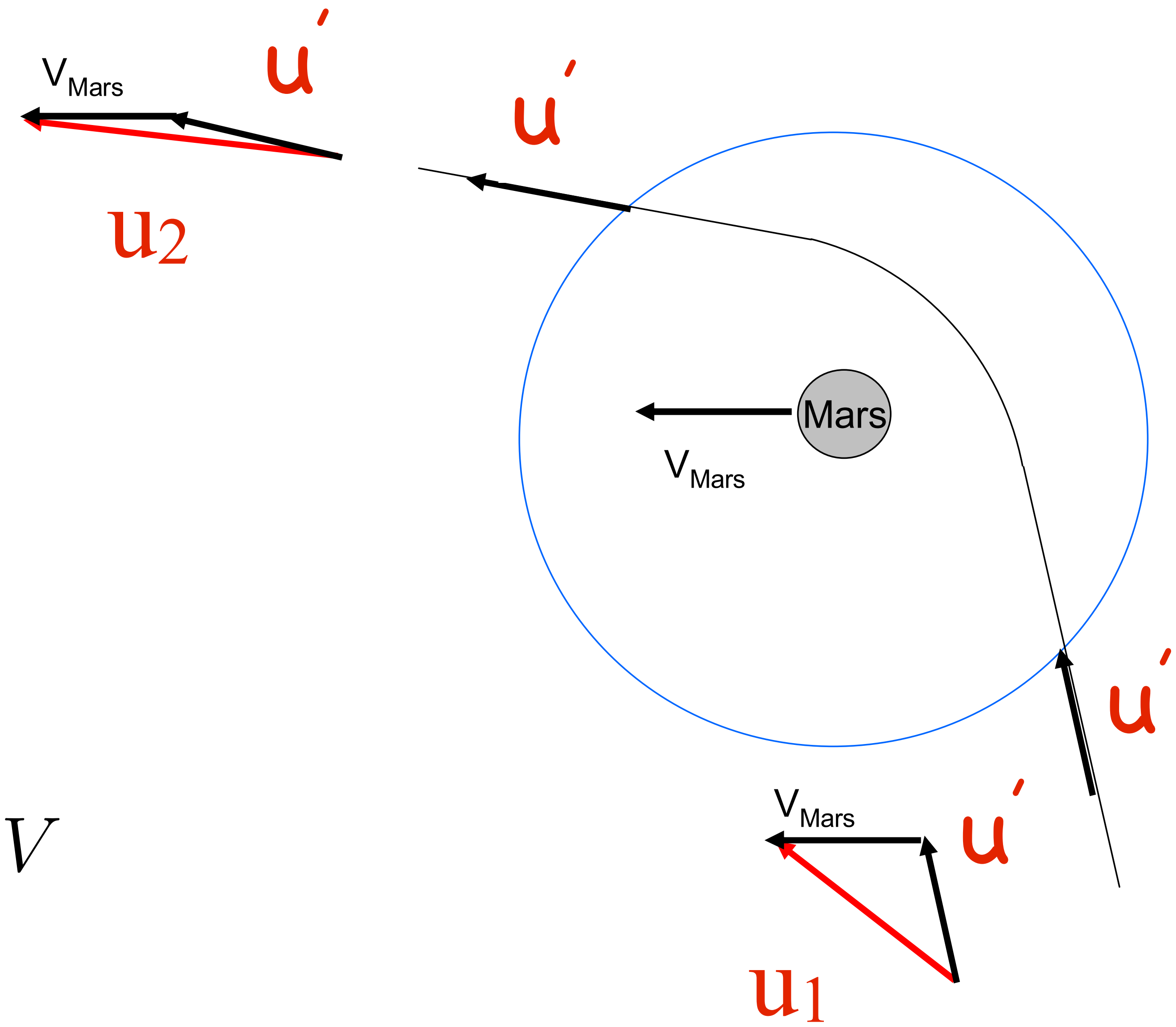
Galaxy center is where slingshot happens most often!

Star frame

- Sphere of Influence [SOI]
- Easy to solve the deflection angle
- [No Energy Gain in this frame!]



Lab Frame

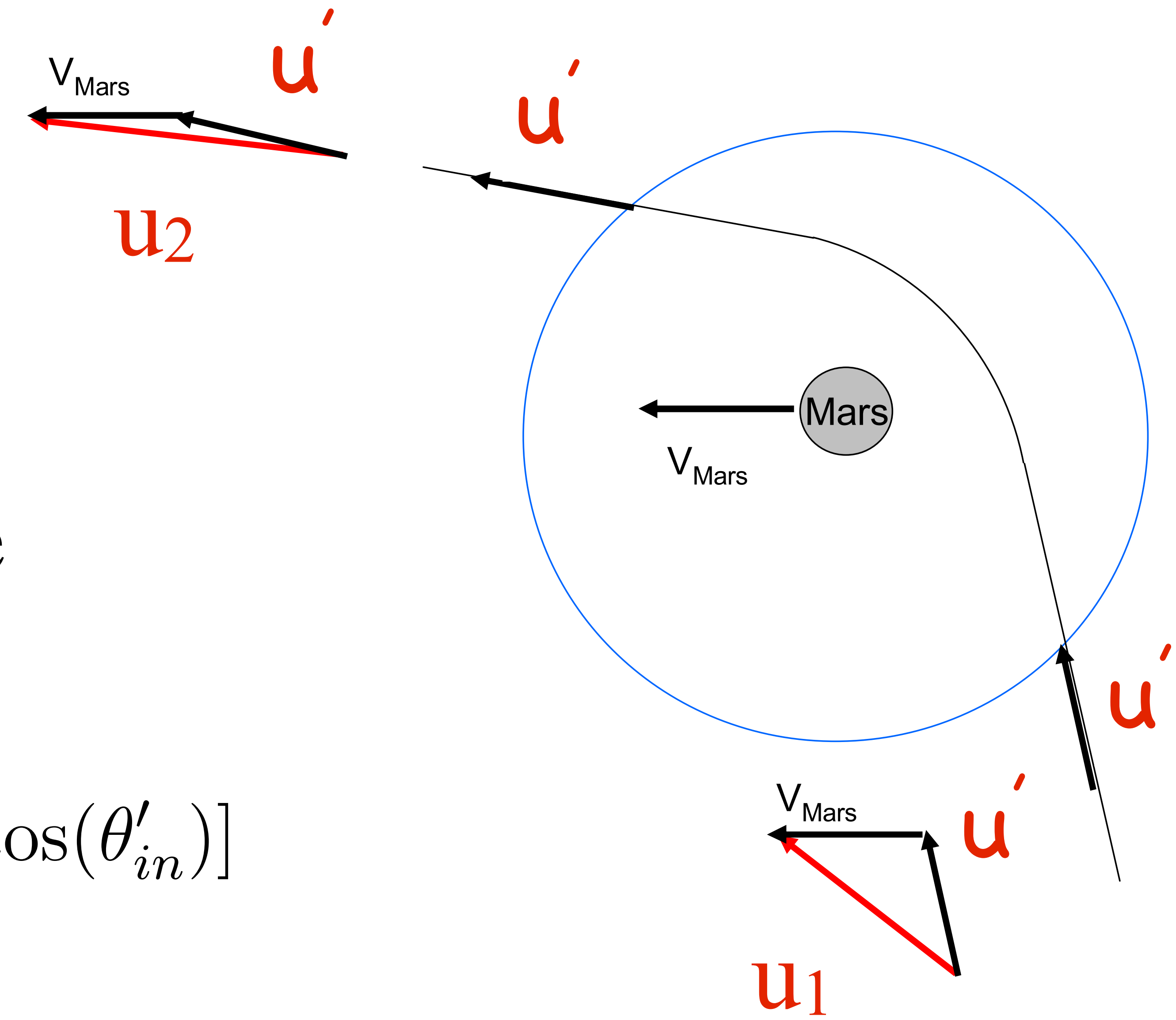


- The frame where we observe slingshot.

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

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

Lab Frame



- The frame where we observe slingshot.

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

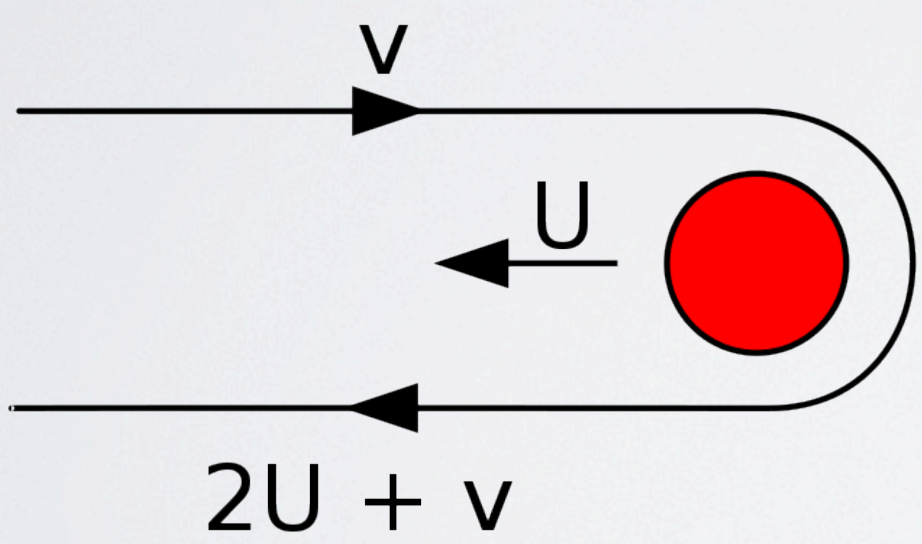
$$\Delta E_{sling} = \frac{1}{2}m[|u_2|^2 - |u_1|^2] = m(u_1 V cos\theta_{in} + V^2)(1 - cos\phi'_{def})$$

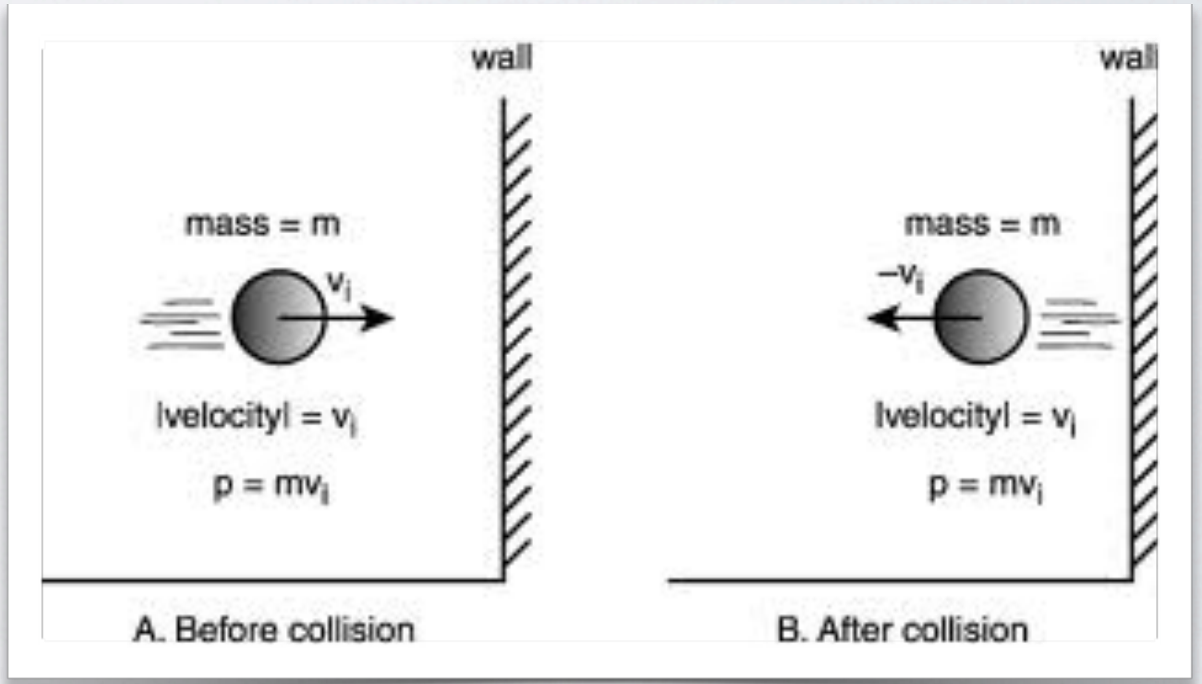
$$\langle \Delta E \rangle = \frac{\int nu' \frac{1}{2} m[|u_2|^2 - |u_1|^2] sin\theta d\theta d\phi}{\int nu' sin\theta d\theta d\phi}$$

SLINGSHOT MECHANISM AS A SOLUTION TO THE CUSP-CORE PROBLEM

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

- Slingshot is similar to 2nd-order Fermi acceleration





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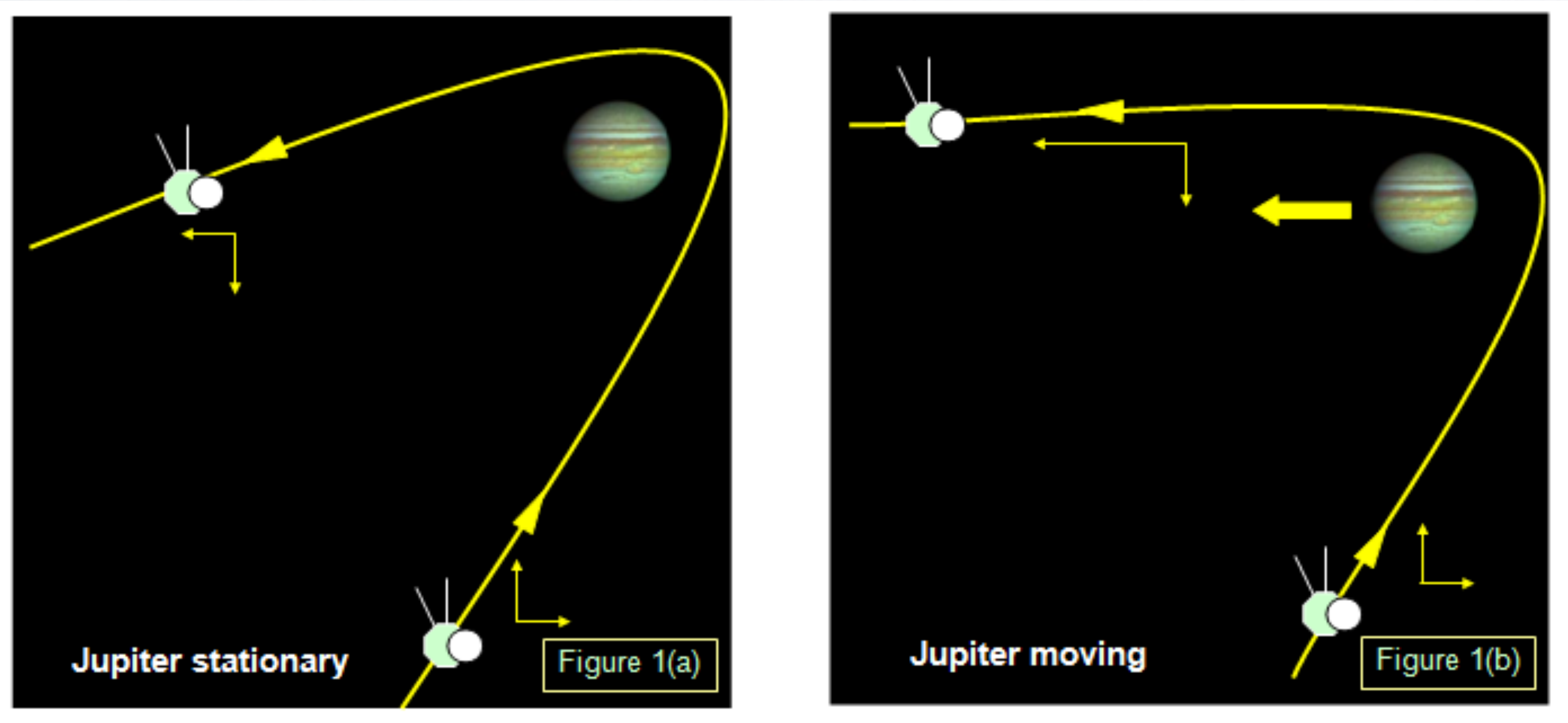
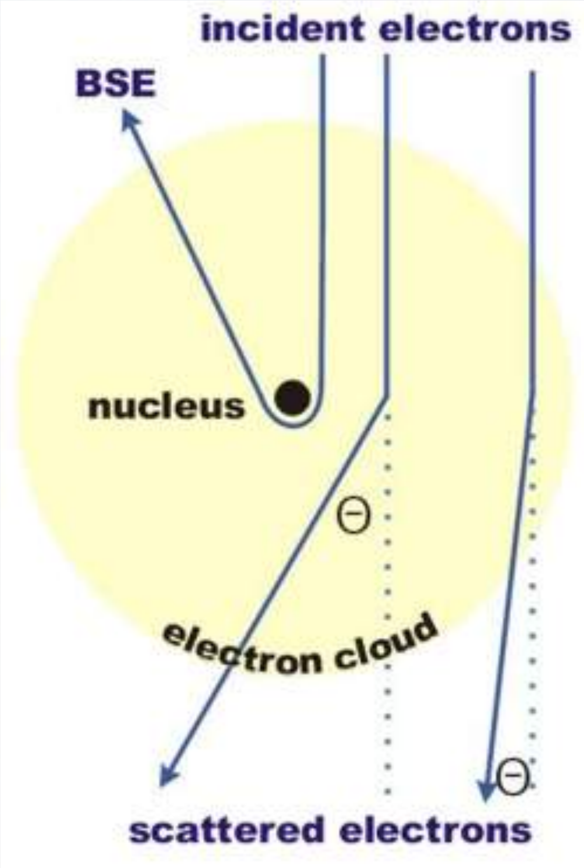
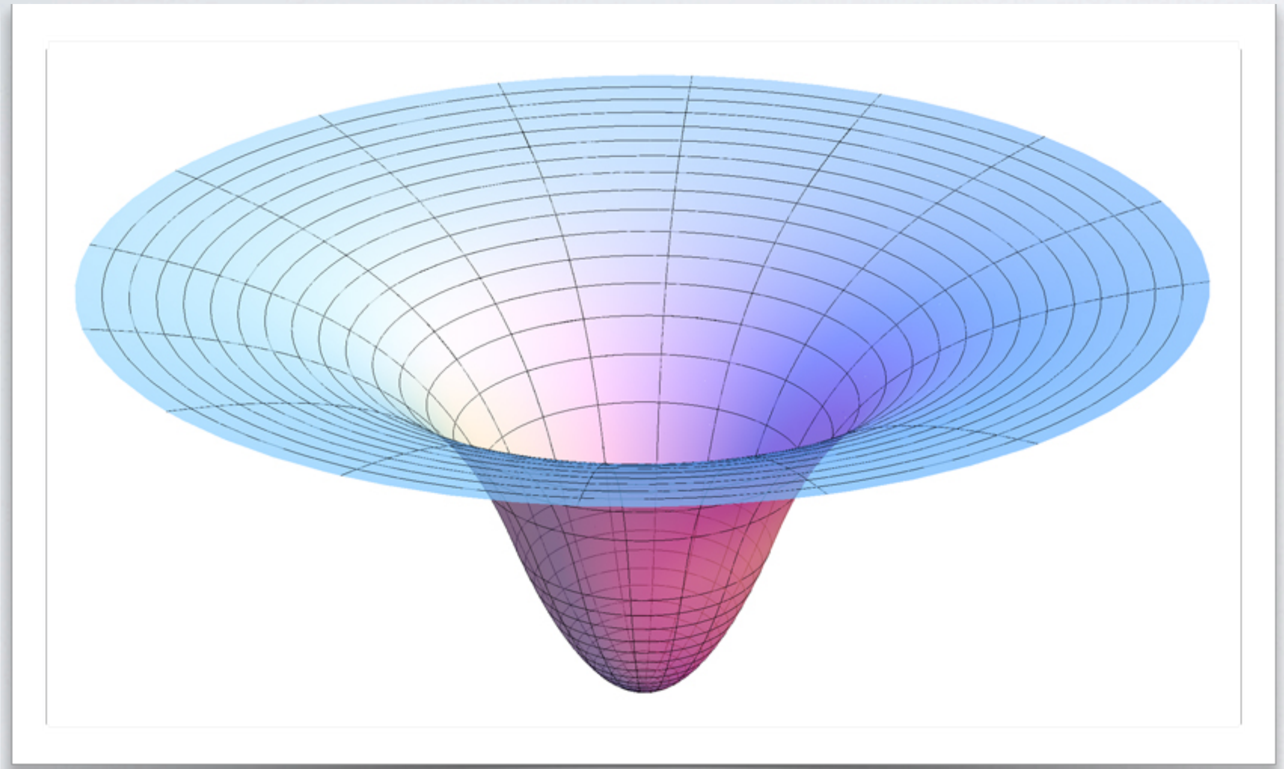
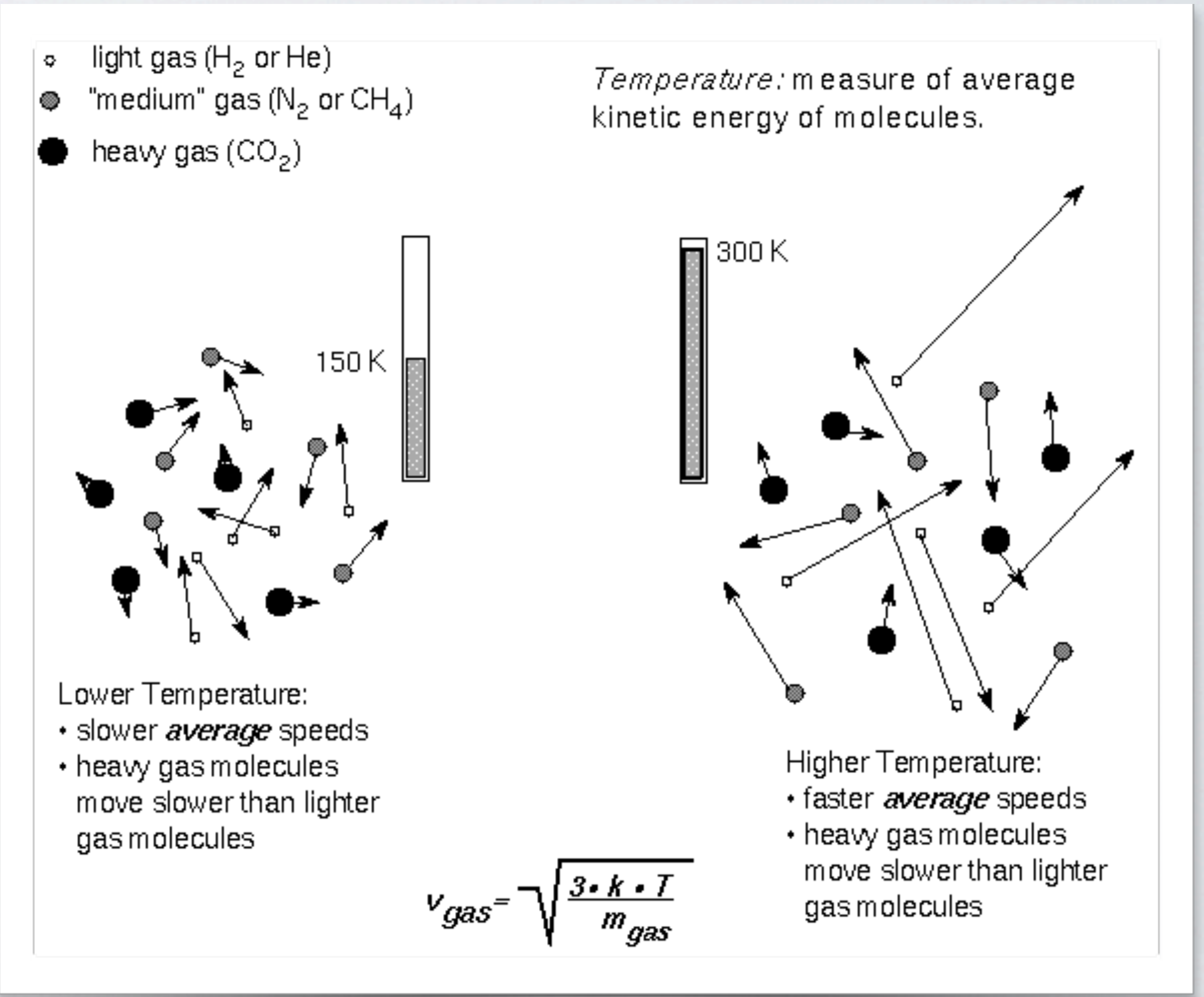




ANALOG: PARTICLES IN A BOX

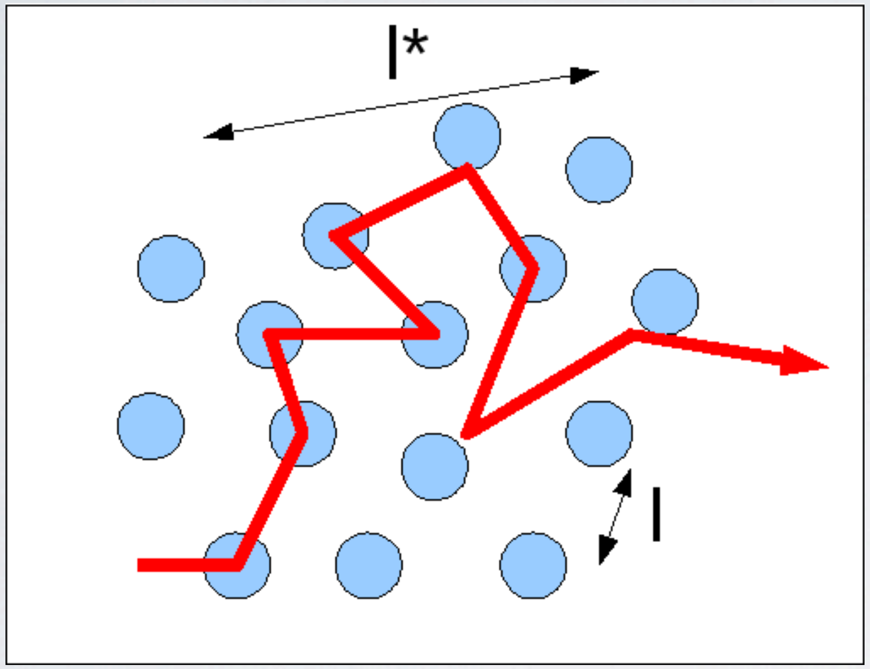


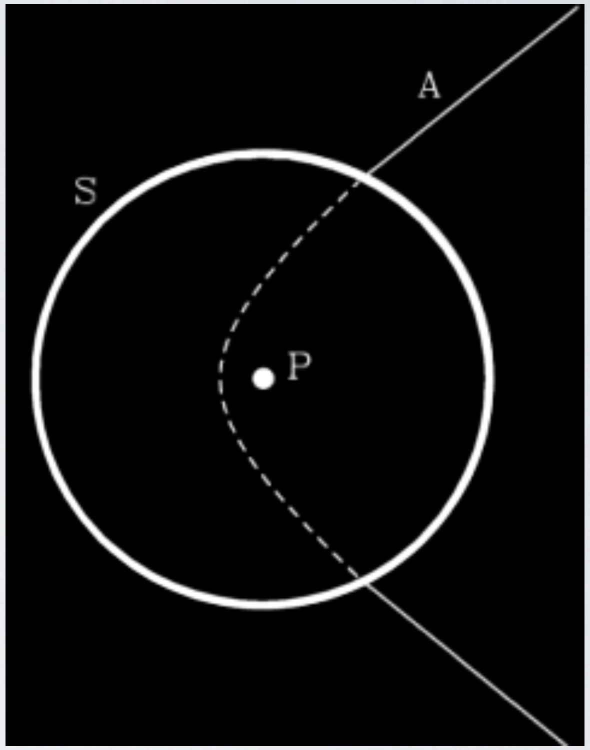


Light object goes faster!

credit: astronomynotes.com

MEAN FREE PATH





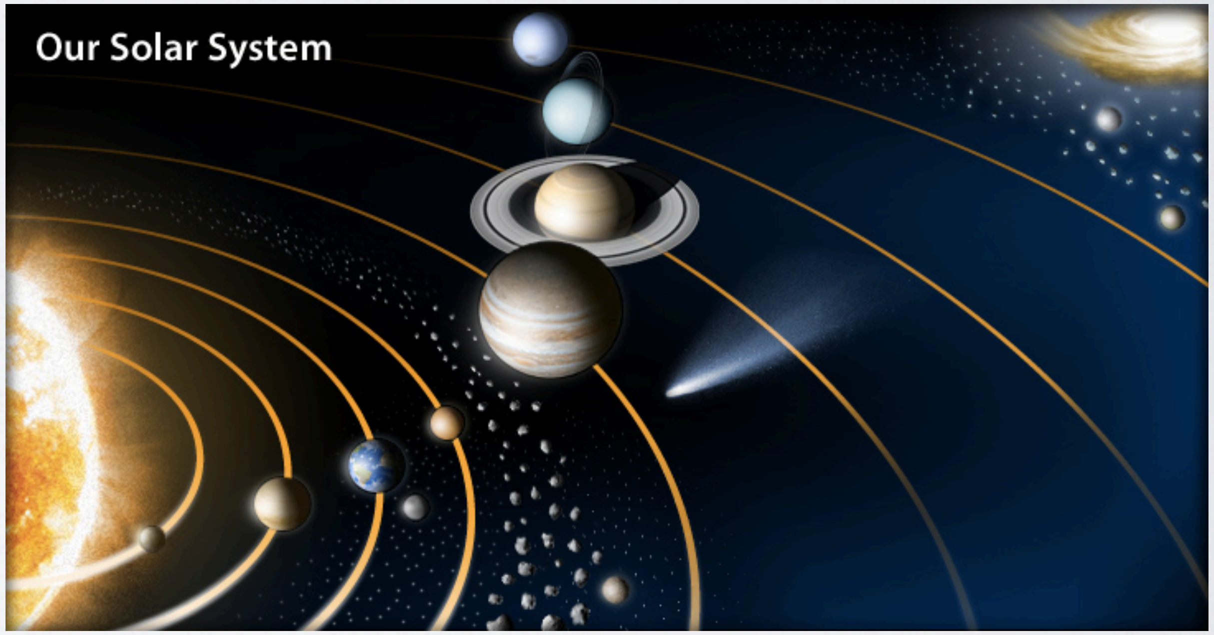
$$\ell = (\sigma n)^{-1}$$

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.

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 profile

$$\langle \Delta E \rangle \simeq F(u_\chi, V_*) m V_*^2.$$

$$\rho(r,T) \simeq \frac{\rho_i R_s}{r + 3r_0 \ln[1 + \frac{C_0 T}{r_0} e^{-r/r_0}]},$$

Preliminary result

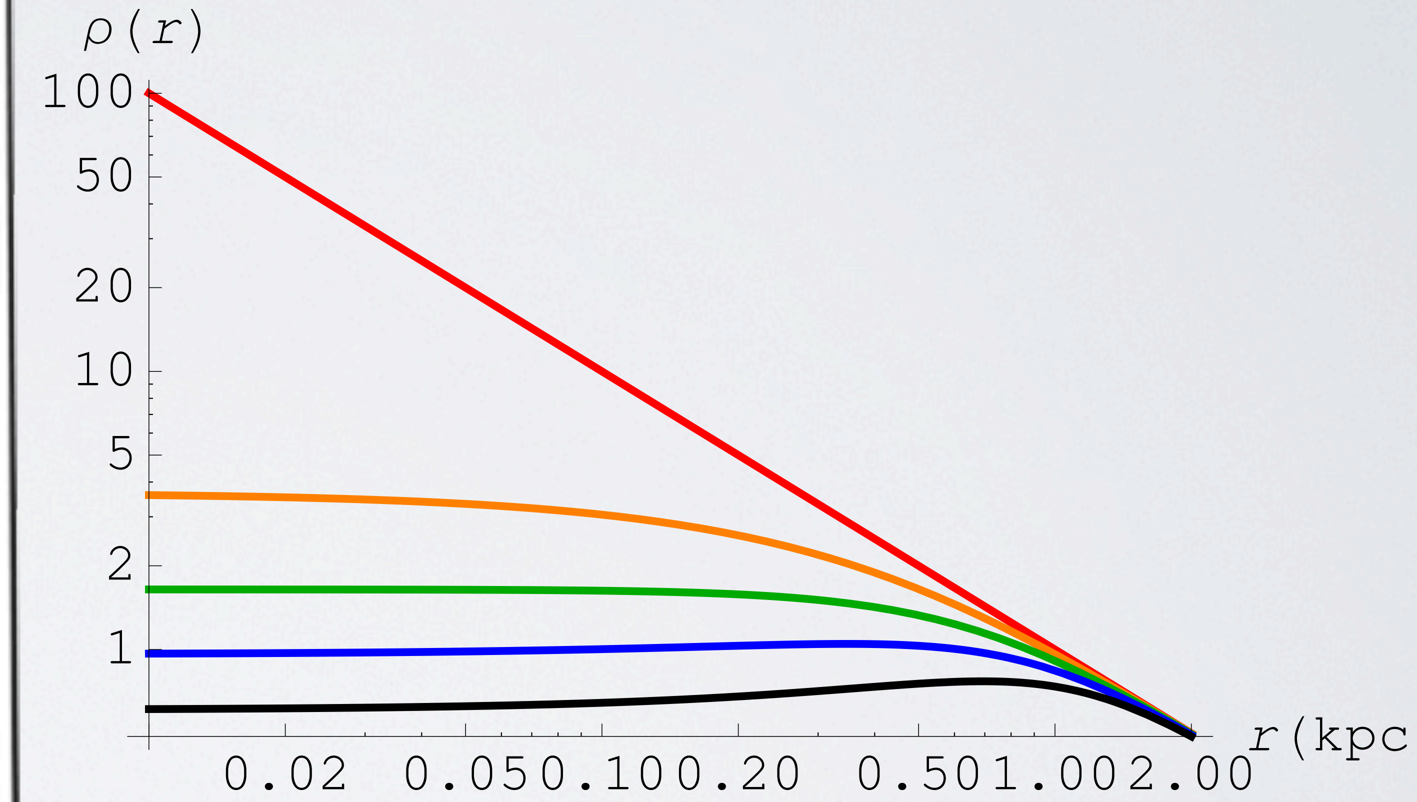
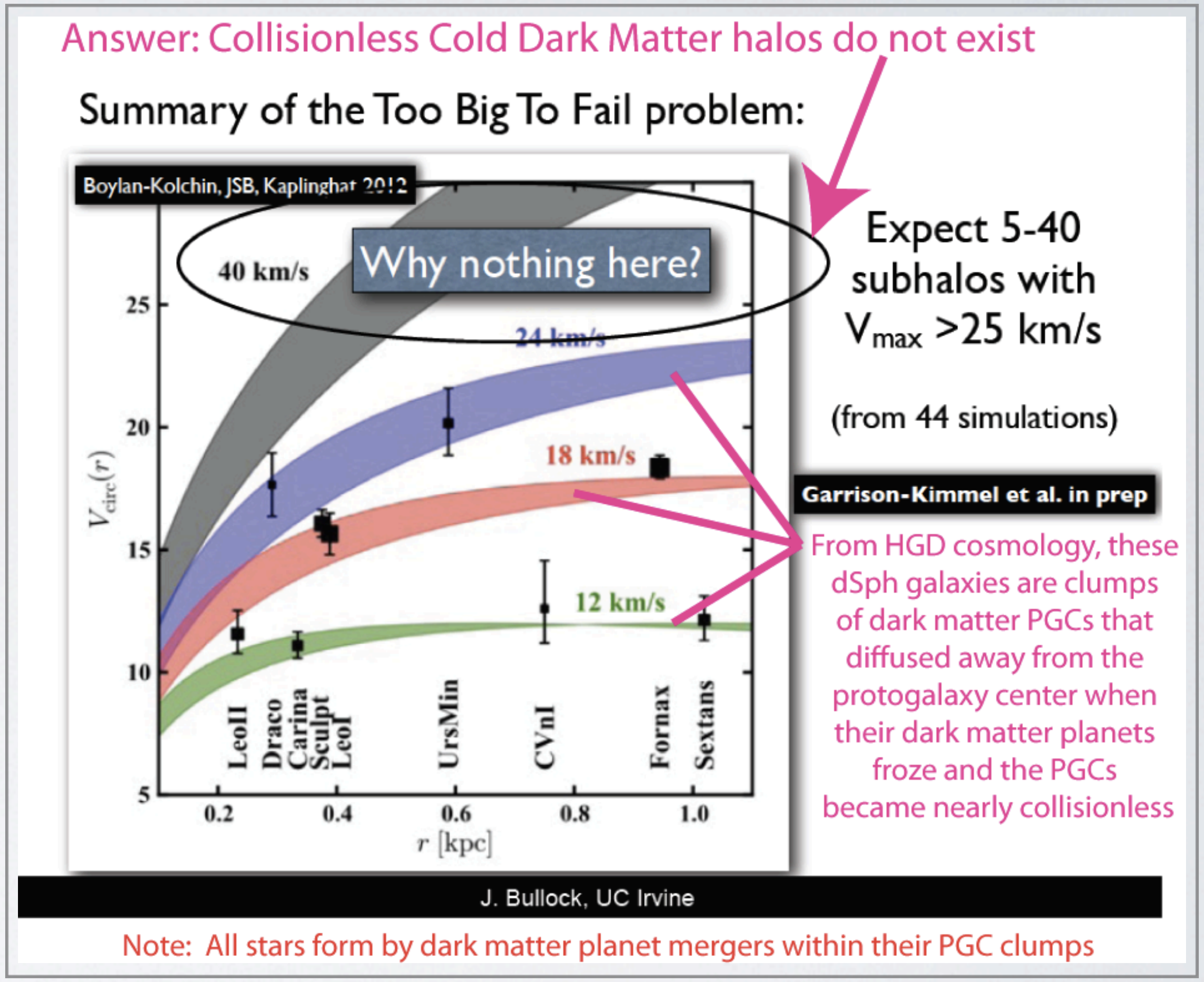


FIG. 2. DM density profile in the inner part of the galaxy. Red line represents the original NFW profile ($T = 0$ yrs). Other curves correspond 10^8 years, $2.5 * 10^8$ years, $5 * 10^8$ years, 10^9 years, as shown.

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.
- Slingshot naturally solve the cusp-core problem.
- Slingshot effect provides a natural mechanism to alleviate other CDM small scale problems.