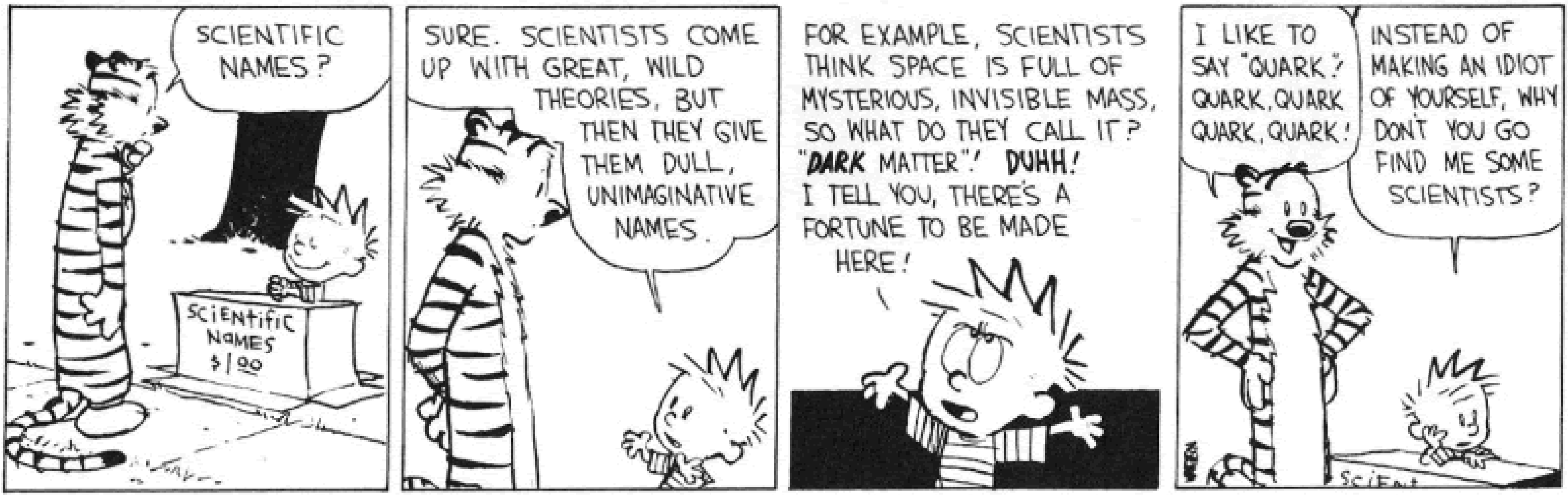
The Impact of the Phase-space Density on the Indirect Detection of Dark Matter



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The Problem and Goal

- Galactic dark matter (DM) halos
  - Velocity measurements
  - Structure formation
- Indirectly detect?
- WIMPs may self-annihilate into SM particles
- The interaction rate depends on the velocity of annihilating particles
- What can we know, or what should we assume about the velocity distribution?

Flux from Annihilation

Interaction rate

J-factor
The “where”

$$\Phi_\gamma(\psi) = \frac{N_\gamma \langle \sigma v \rangle}{4\pi m_\chi^2} \times \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \rho^2[r(s)]\ \mathrm{d}s$$

Particle physics
The “what”

Spacial density

Importance of Velocity

- The interaction rate is a thermal average of a function of velocity

$$\langle \sigma v \rangle \simeq a + b\langle v^2 \rangle + O(\langle v^4 \rangle)$$

- Sommerfeld enhancement arises if there is a light boson that mediates a force between DM particles
    - Multiplicative change of somewhere between v^{-1} and v^{-2}
- Calculating averages in general requires knowledge of the relative velocity distribution

J. L. Feng, M. Kaplinghat, H. Yu, *Sommerfeld Enhancements for Thermal Relic Dark Matter* (arXiv:1005.4678)

Standard Method

- We do not know the velocity distribution of the DM particles; we assume only the density
- Standard to assume a Maxwell-Boltzmann distribution (MB)

$$f_{MB}(v) = (2\pi\sigma_v)^{-3/2} e^{-v^2/2\sigma_v^2}$$

- Velocity dispersion σ_v may be taken as constant but is generally a function of position
  - Given by Jeans equation
  - Robertson & Zentner (arXiv:0902.0362)
- Velocity distribution is MB only for a very particular density profile (singular isothermal sphere)

James Binney and Scott Tremaine, *Galactic Dynamics*

Calculating the Distribution Function

- The phase-space density tells us everything
- Assuming a density profile and equilibrium (and isotropy, but...), Eddington's formula offers a way to calculate the DF
- We also take a model of the galactic disk and bulge
  - Contributes to potential seen by DM particles

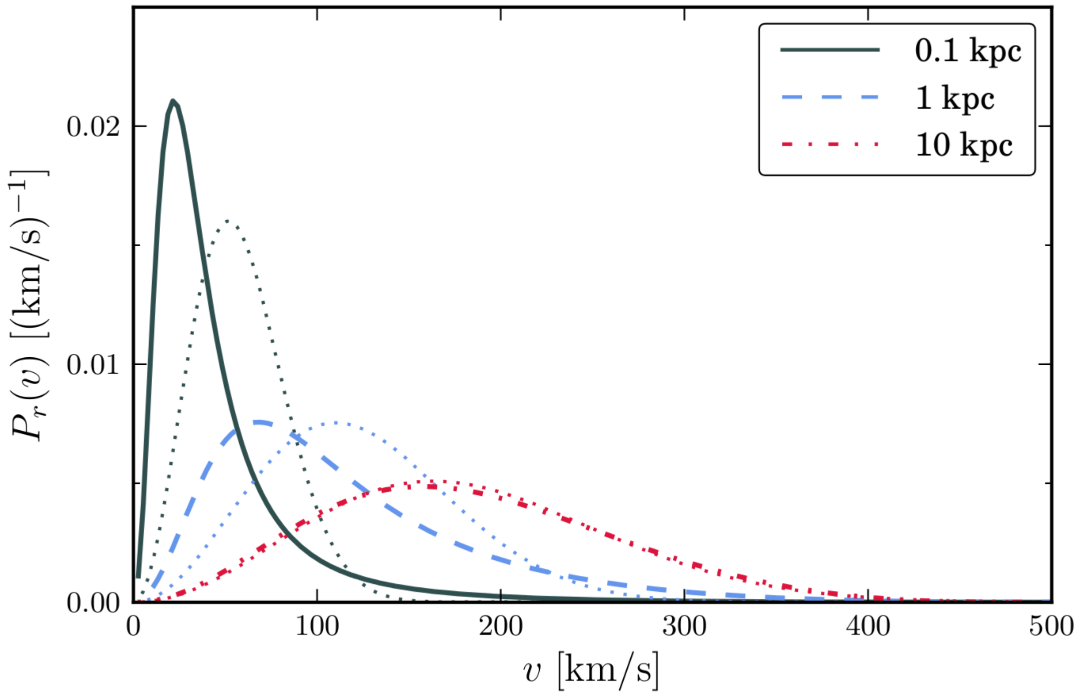
Eddington's Formula

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2}$$

$$\rho(r) \equiv \int \mathrm{d}^3 v f(\Psi(r) - v^2/2)$$

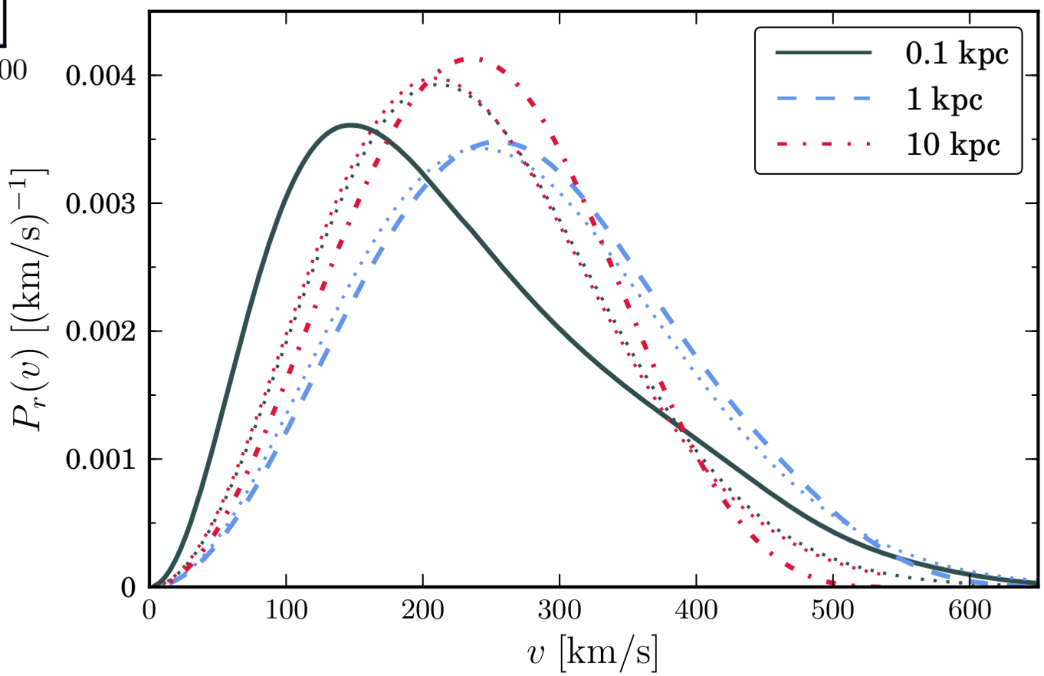
James Binney and Scott Tremaine, *Galactic Dynamics*

Galactic NFW Halo – DM Vel. Dist.



Deviation from MB
at small radii

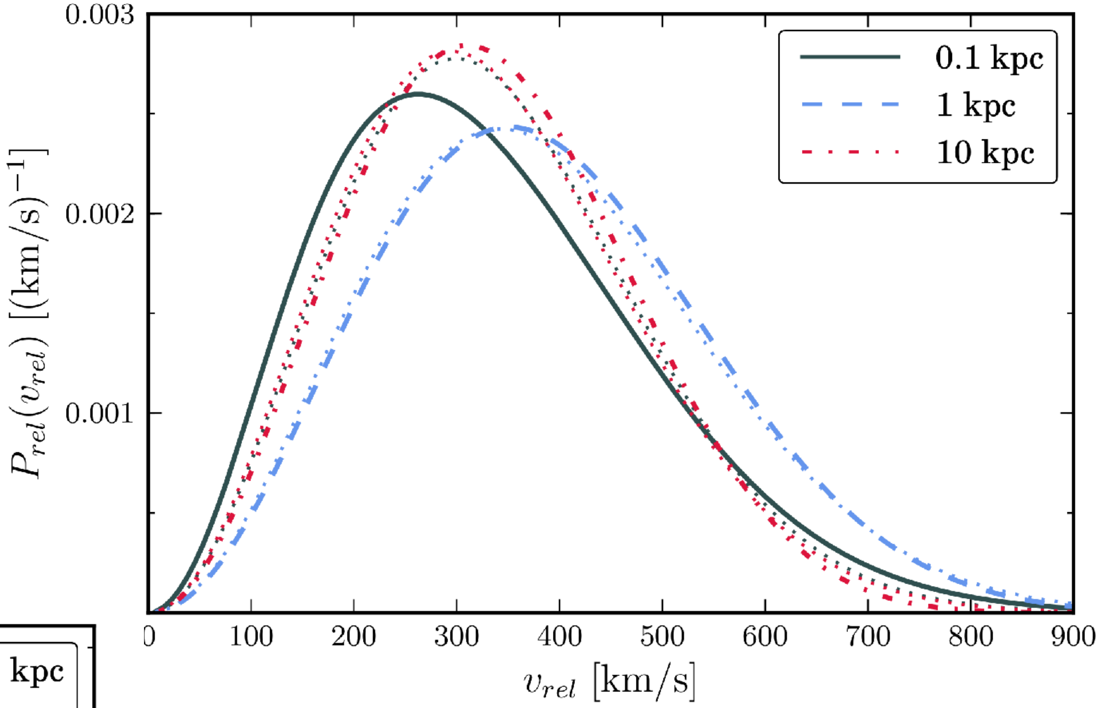
Baryonic potential
lessens the departure

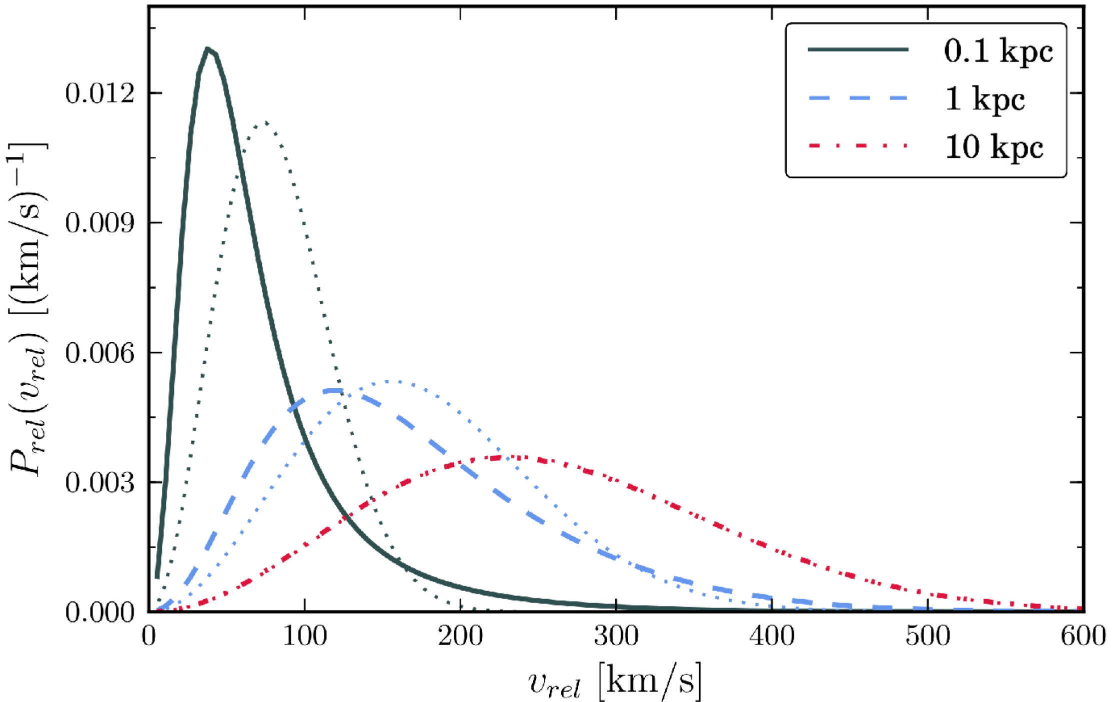


Relative Velocity Distribution

$$f_{\mathrm{rv}}(v_{\mathrm{rel}}) = 4\pi v_{\mathrm{rel}}^2 \, 2\pi \int_0^\infty \mathrm{d}v_{\mathrm{cm}} \, v_{\mathrm{cm}}^2 \int_{-1}^{1} \mathrm{d}z \cdot \\ \cdot f_v\left(|\mathbf{v}_{\mathrm{rel}}/2 + \mathbf{v}_{\mathrm{cm}}|\right) \cdot f_v\left(|\mathbf{v}_{\mathrm{rel}}/2 - \mathbf{v}_{\mathrm{cm}}|\right)$$

Relative Velocity Distribution

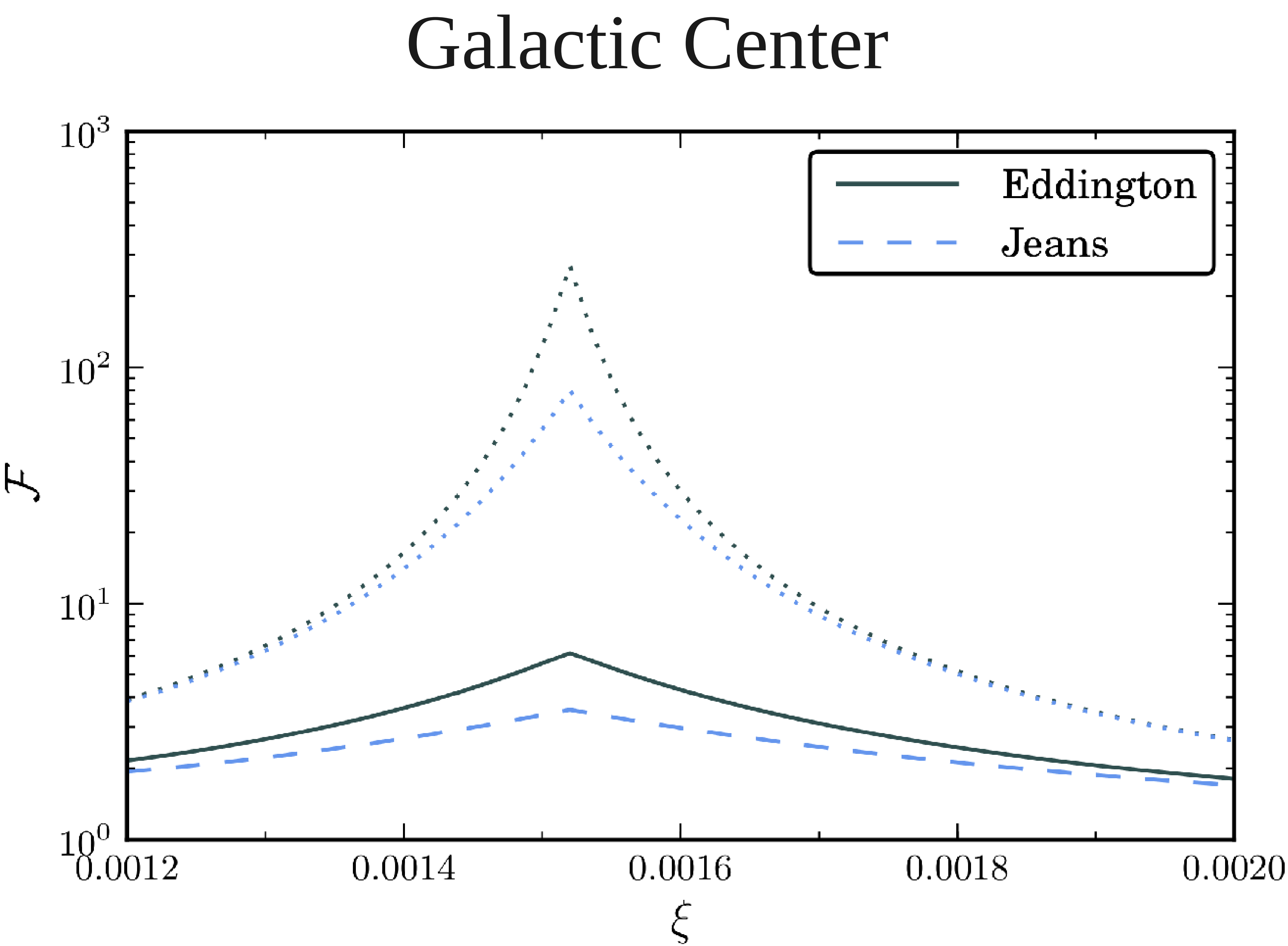




J-factors

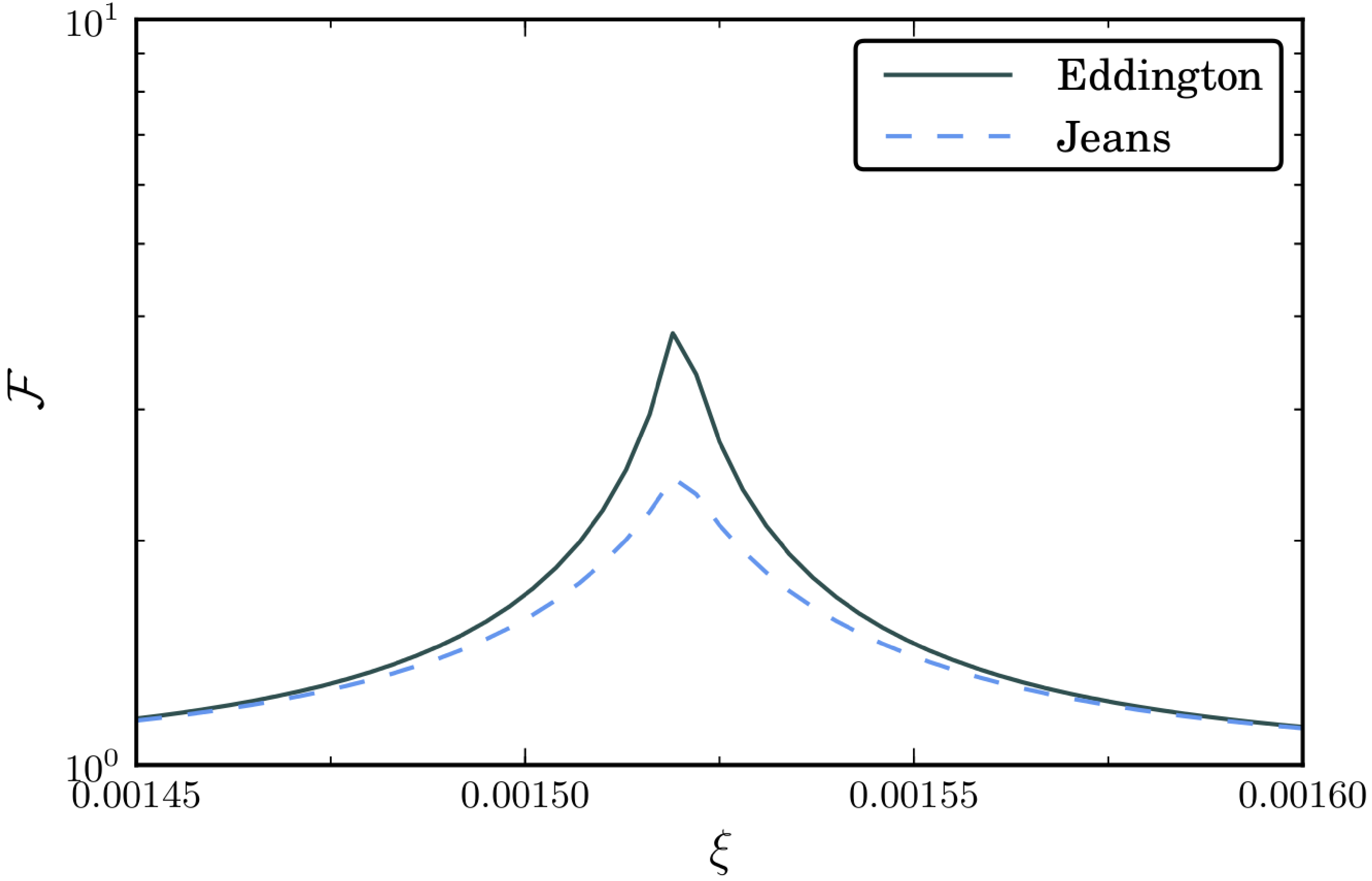
- With the relative velocity distribution, we can calculate an arbitrary interaction rate:
  - Relative velocity dispersion (p-wave)
  - Pure *s*-wave interactions unchanged except at resonances
  - **Sommerfeld enhancement**
- Radial dependence of $<\sigma v>$ means it must enter the line-of-sight integral

$$J(\psi) \propto \int \mathrm{d}l \, \frac{\langle \sigma(v) v \rangle (l)}{\langle \sigma v \rangle_0} \, \rho_\chi^2(l)$$

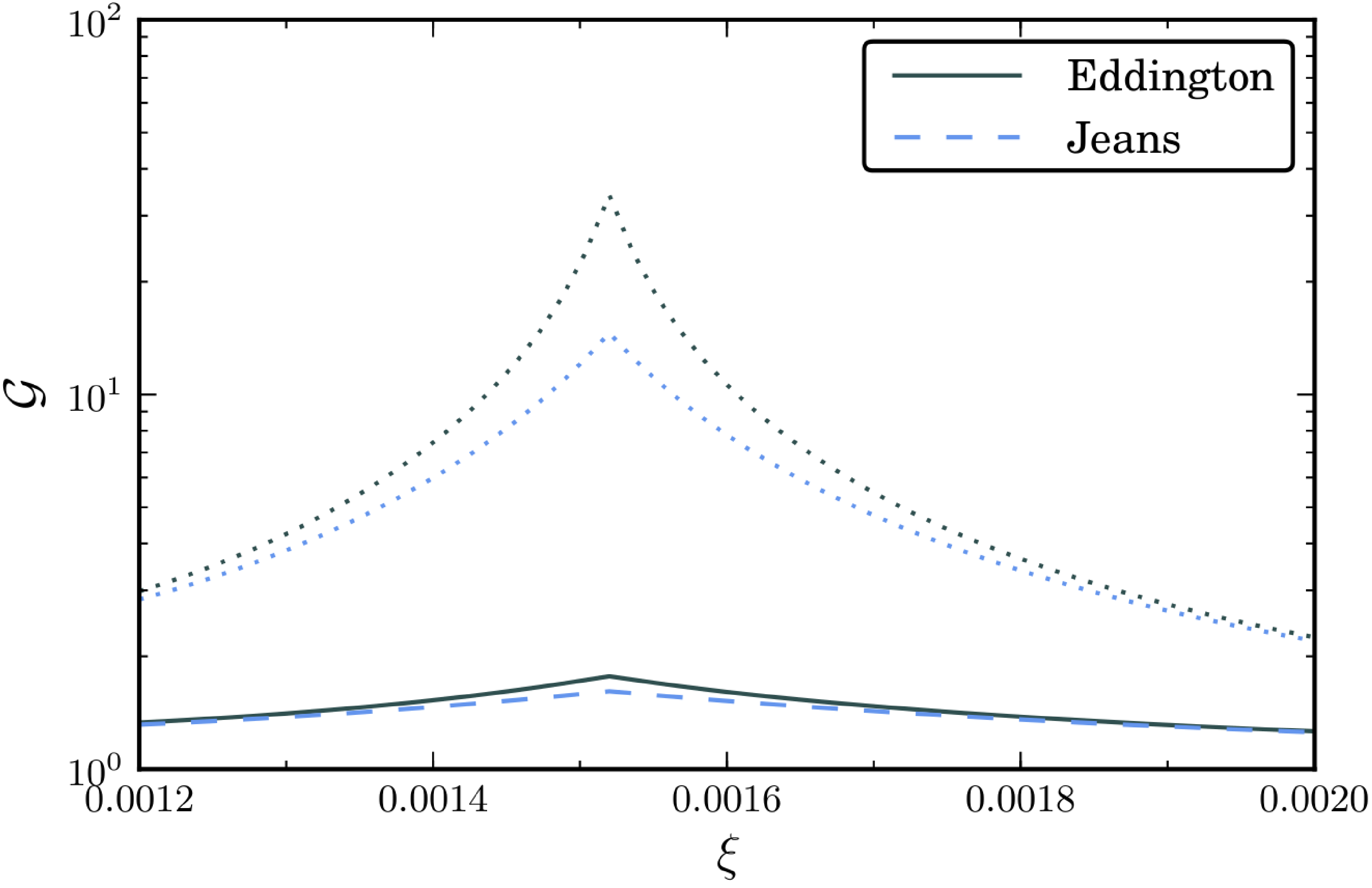


Galactic Center
Eddington
Jeans
$\mathcal{F}$
ξ
10^3
10^2
10^1
10^0
0.0012
0.0014
0.0016
0.0018
0.0020

Dwarf Spheroidal Draco (NFW)



Synchrotron/IC Signal



Other Enhancements

- *s*-wave resonance in NMSSM
  - Exchange of a pseudoscalar Higgs
  - Little variation at low velocities, so a weak dependence on the (galactic) distribution shape
- *p*-wave interaction may not require this detailed analysis
  - Relative velocity dispersion seems to follow same relation to single-particle dispersion that MB does
  - Jeans equation suffices

Further details and future work

- Einasto and Burkert profiles also considered
- Central black hole – arXiv:1305.2619
- An extragalactic diffuse DM signal?
  - Add up luminosities of halos of all shapes, sizes, distances
- Anisotropy
  - Eddington-like equations derived for some forms of $\beta(r)$
- Pseudo-phase-space density follows a power law?
  - Dehnen & McLaughlin
  - Campbell & Dutta

Thank You!

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"All models are wrong, but some are useful."
-- G.E.P. Box