Thermal Relics and Galactic Dynamics of Dark Matter with Sommerfeld Enhancement

Hai-Bo Yu
UC Irvine

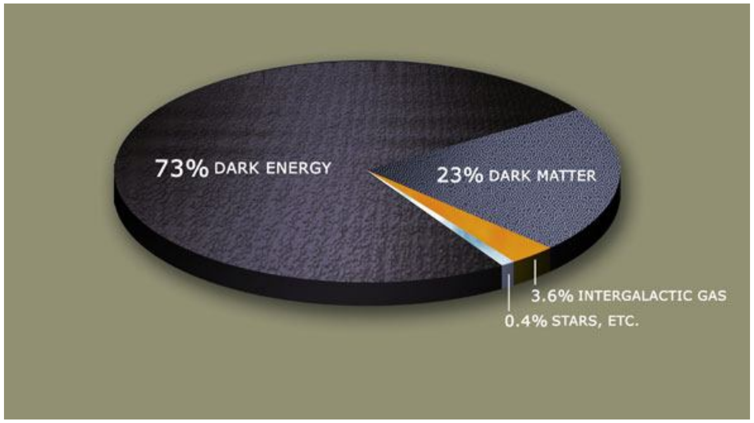
Pheno 2010

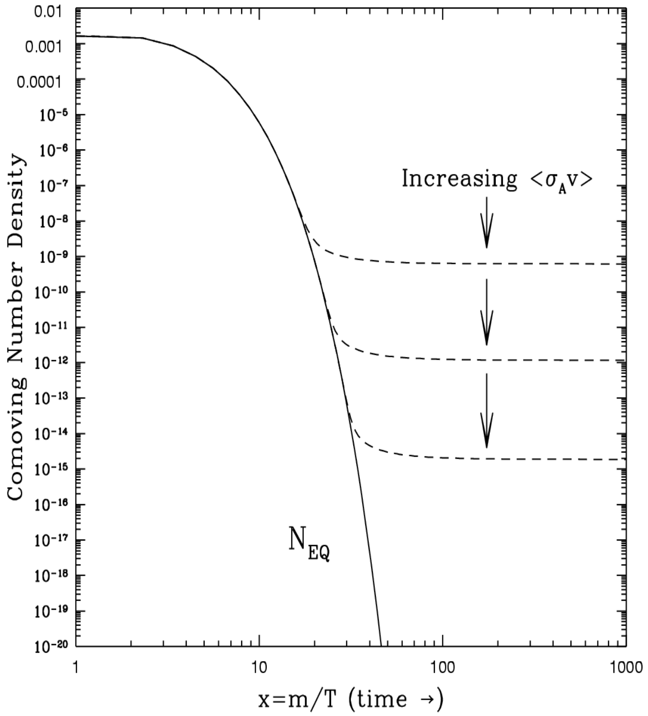
Feng, Kaplinghat and Yu (2009) PRL **arXiv:0911.0422** [hep-ph]
Feng, Kaplinghat and Yu (2010) **arXiv:1005.XXXX** [hep-ph]

Outline

- Motivations for dark matter with Sommerfeld enhancement
- Maximal enhancements with relic constraints
  - -Increased annihilation cross section
  - -possible non-thermal distribution
  - -Chemical re-coupling
- Galactic dynamics and halo shape constraints
- Conclusions

Dark Matter and WIMP miracle



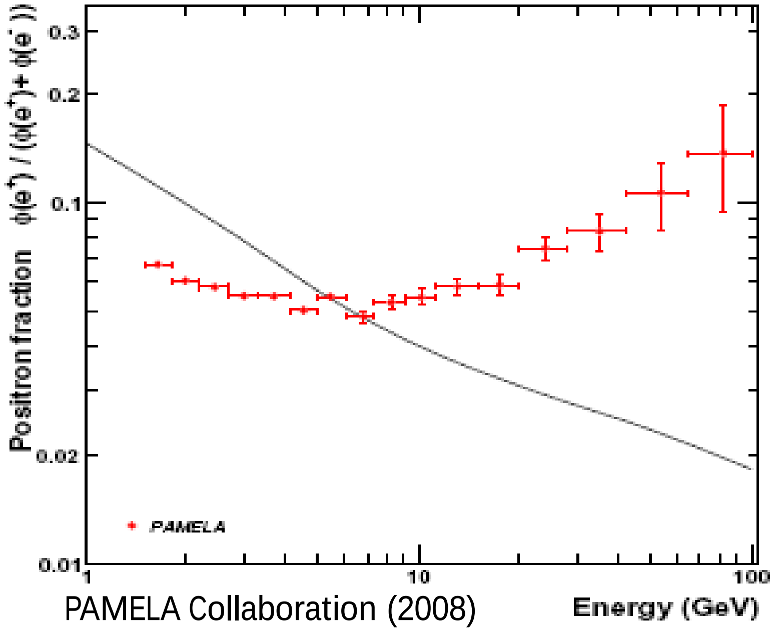


$$\Omega h^2 \simeq 0.1 \times \left(\frac{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_A v \rangle} \right)$$

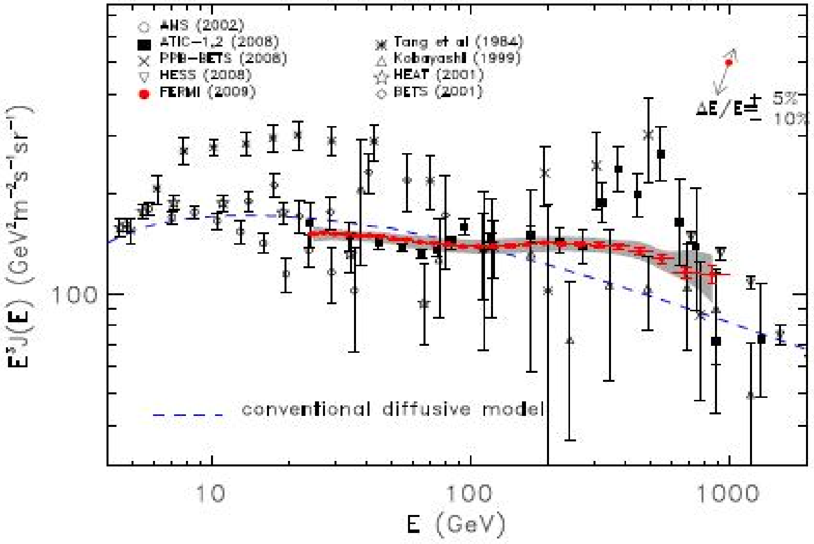
$$\langle \sigma_A v \rangle \sim \alpha^2 / m_X^2$$

$$m_X \sim 250 \mathrm{GeV},\ \alpha \sim 0.01,\ \ \langle \sigma_A v \rangle \sim 1.9 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

PAMELA and Fermi Results



PAMELA Collaboration (2008)



The Fermi LAT Collaboration (2009)

Astrophysical reasons?

- Pulsar, Supernova explosions, Cosmic ray propagation…

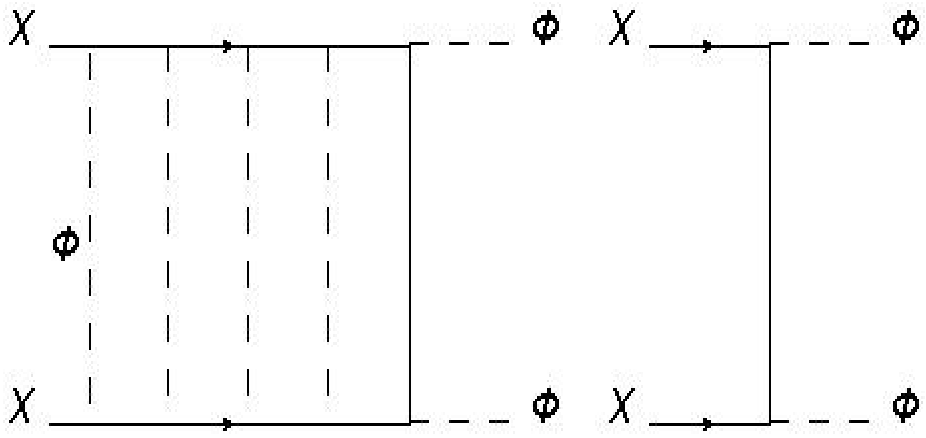
Dark matter

Advantages: Weak scale WIMP

Challenges: large annihilation cross section. one needs ~100-1000× (3.0×10^{-26}cm^3/s).

Lepton modes.

Sommerfeld-enhanced annihilation

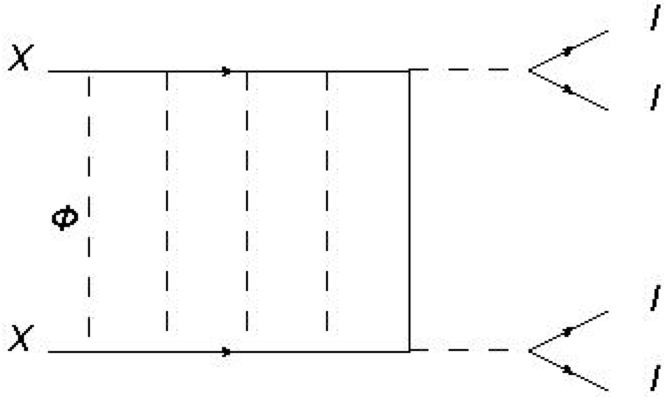


$$\sigma_A \to \sigma_{A0} S$$

$$S \sim \frac{\alpha}{v}$$

- Sommerfeld (1931), Hisano, Matsumoto and Nojiri (2003), Cirelli, Strumia and Tamburini (2007), Arkani-Hamed, Finkbeiner, Slatyer and Weiner (2008)…

•Introduce ~MeV-1GeV force carrier,
•Cross section is enhanced
•Hardronic modes are suppressed by kinematics



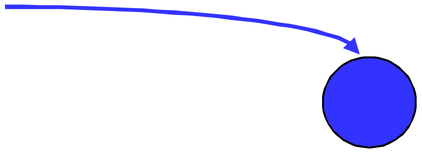
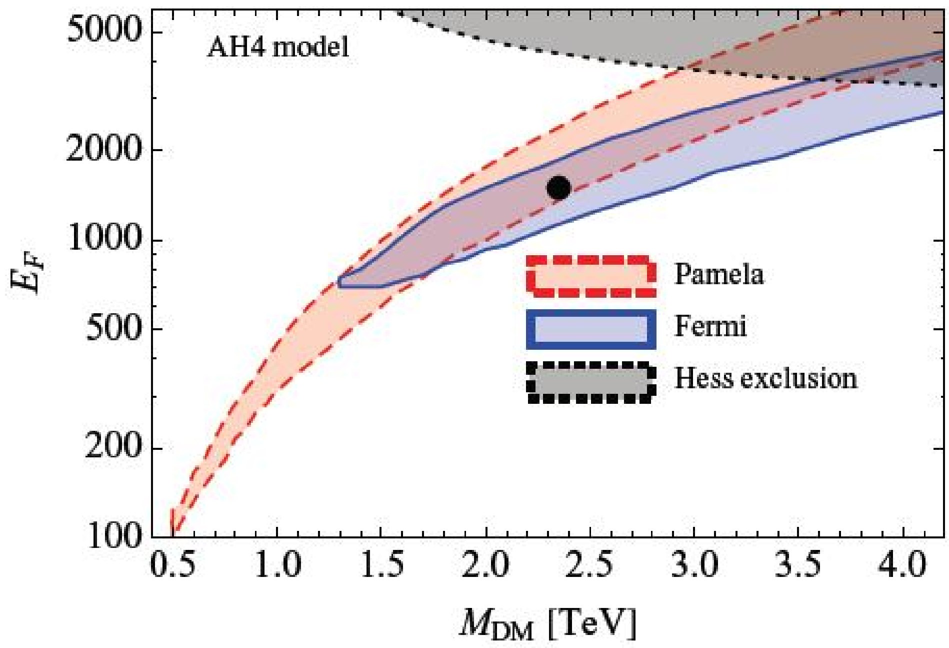


Image: Feng

Fitting and tensions



Bergstrom et al. (2009)

$$m_\phi = 250\mathrm{MeV}$$

$$\phi \to \mu^+\mu^-$$

$$S \sim \frac{\alpha}{v} \qquad v \sim 10^{-3}$$

$$\alpha \sim 0.1 - 1$$

But from WIMP miracle, $\alpha \sim 0.01$

$$\Omega h^2 \sim 0.001 - 0.00001$$

Not enough thermal relics !

Feng, Kaplinghat and Yu (2009)

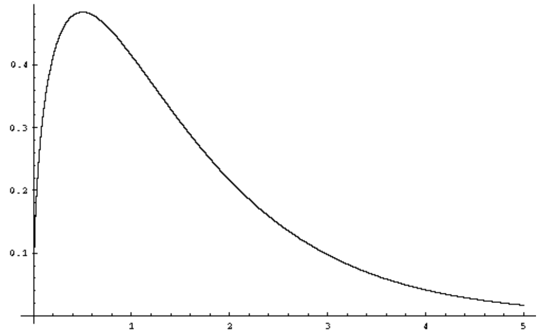
Careful treatment

- Annihilation is enhanced after freeze out

  Before Tkd $v \sim \sqrt{T}$, after Tkd $v \sim T$
- Resonance effects $S \sim \left(\frac{\alpha}{v}\right)^2$

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{\rm an} v_{\rm rel} \rangle \left(n_X^2 - n_X^{\rm eq\,2} \right)$$

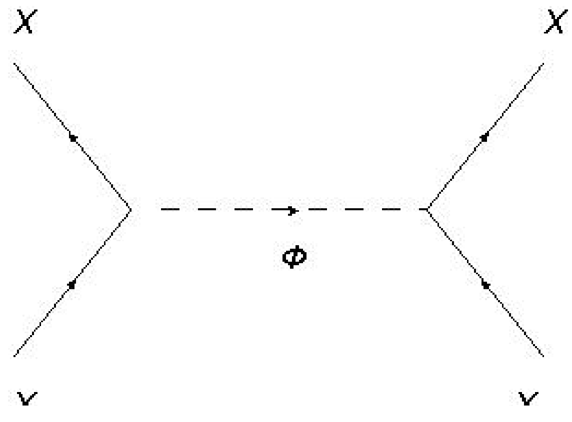
- Maxwell-Boltzmann distribution?

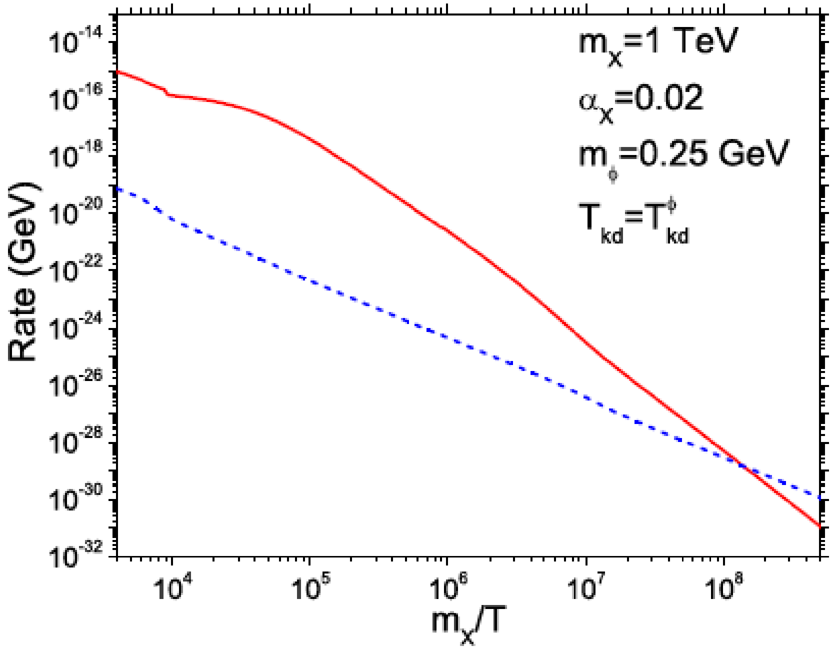


Slow particles annihilate with larger cross section.

This preferentially depletes the low velocity population and may distort the phase space distribution.

Self-Scattering and thermal distribution



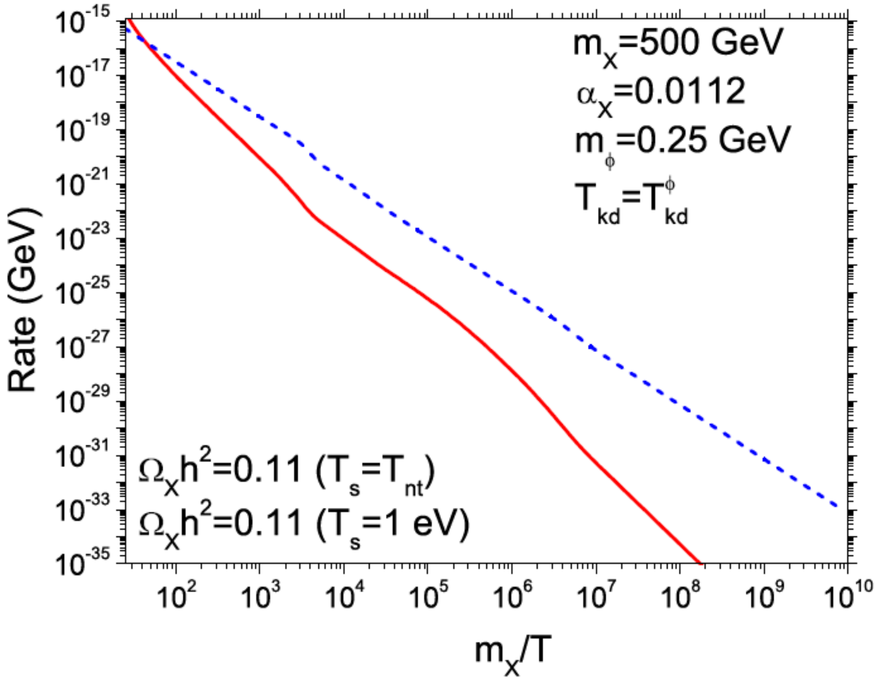


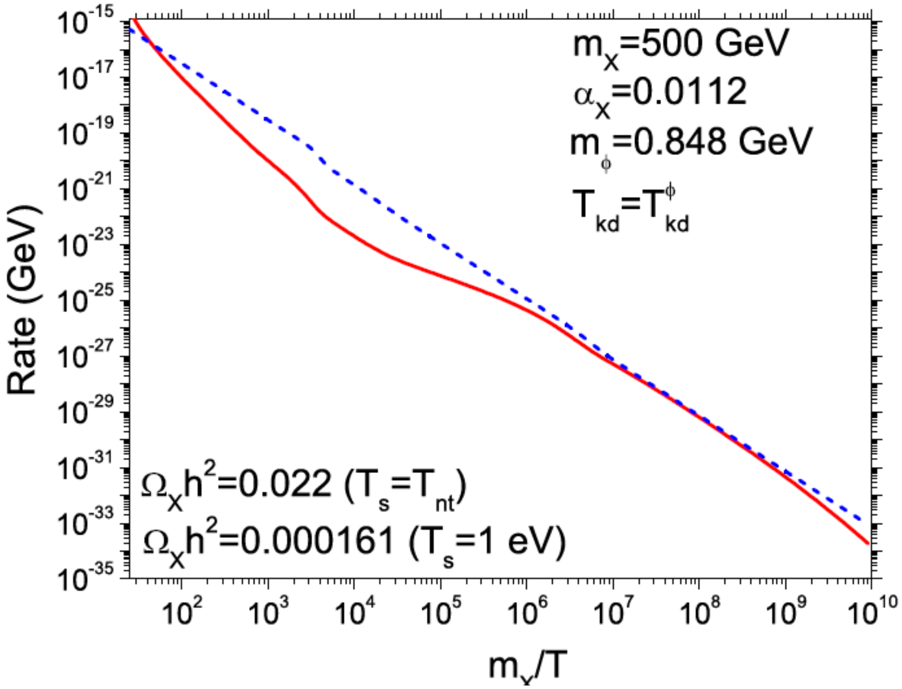
Feng, Kaplinghat and Yu (2010)

- The Light force carrier also mediates dark matter self-scattering.
- Self-scattering can maintain dark matter thermal distribution in early Universe.
- Bounds from observed elliptical halo shape. Feng, Kaplinghat and Yu (2009), Buckley and Fox (2009).

$$T_{\rm nt} \sim 20\ {\rm keV} \left[\frac{m_\phi}{250\ {\rm MeV}}\right] \left[\frac{m_X}{1\ {\rm TeV}}\right]^{\frac{3}{4}} \left[\frac{T_{\rm kd}}{250\ {\rm MeV}}\right]^{\frac{1}{4}} \left[\frac{\kappa}{800}\right]^{-\frac{1}{2}}$$

Resonance and Chemical Recoupling



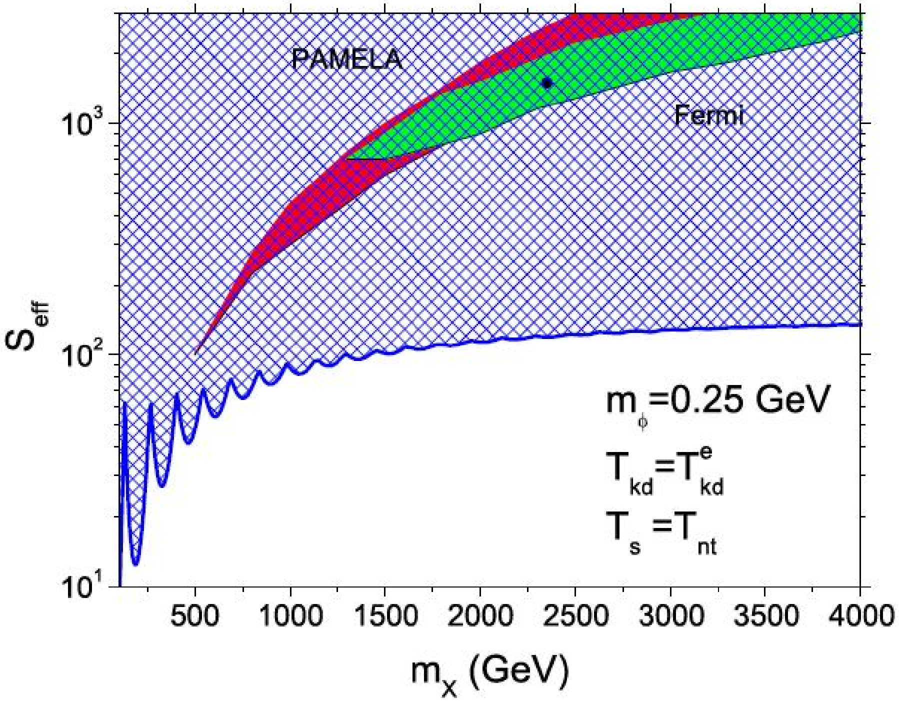


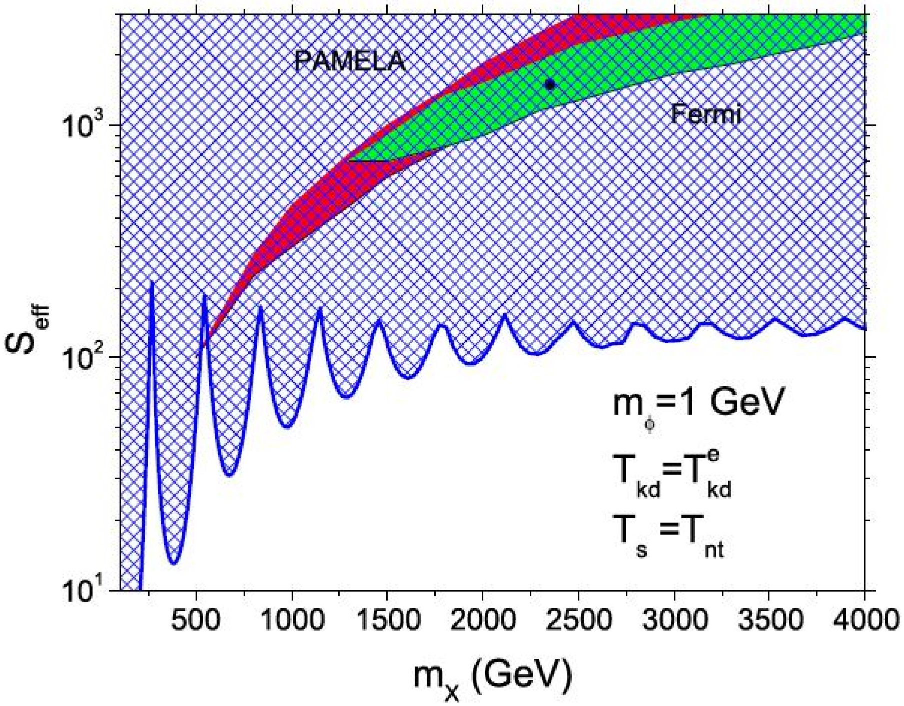
$$H \sim T^2 \qquad \Gamma_{\rm an} = n_X \langle \sigma_{\rm an} v_{\rm rel} \rangle \qquad n_X \sim T^3$$

$$\langle \sigma_{\rm an} v_{\rm rel} \rangle \sim v^{-2} \sim T^{-2}, \;\; \Gamma_{\rm an} \sim T$$

Contrary to naïve expectations, enhancement is **NOT** maximized by sitting exactly at resonance.

Maximal enhancement with optimized parameter choices





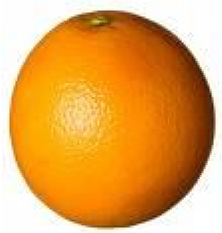
- Different modes (4e, 2mu+2e…)
- Astrophysics uncertainties
- Different sources for PAMELA and Fermi
- More complicated models

Astrophysical consequences of self-interaction of dark matter

- Kinetic decoupling, small scale formation, bound state formation, the Bullet Cluster, halo shape [see Feng, Kaplinghat, Tu and Yu (2009)].

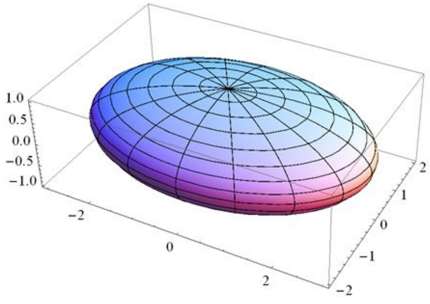
Morphology of dark matter halo with self-interacting dark matter:

- If self-interactions are rapid enough, they lead to
  - isotropic velocity dispersion.
  - spherical halo.
  - isothermal halo.



- These expectations are from simulations of scattering in the hard sphere limit. [Dave et al. (2000), Yoshida et al. (2000), Moore et al. (2000), Craig et al (2001), Kochanek et al. (2001)]

- Many elliptical galaxies show clear evidence for flattened, tri-axial dark matter halos.



$$m_\phi > 30 \text{ MeV}$$

Feng, Kaplinghat and Yu (2009)

From wikipedia.com

Summary

- Cosmic ray excesses motivate dark matter with Sommerfeld enhancement.
- It has interesting thermal history and galactic dynamics.
- Thermal relic constraints disfavor this explanation.