Hidden Charged Dark Matter

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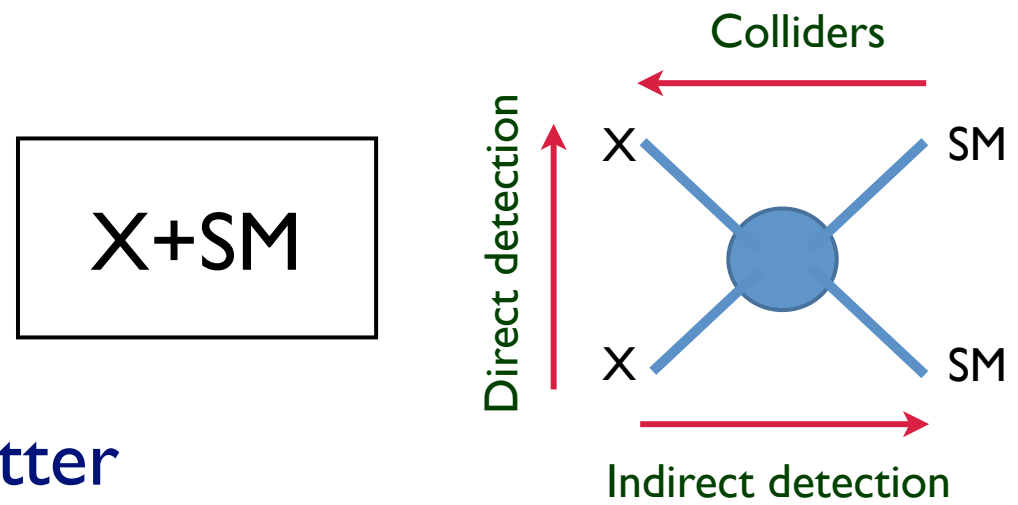
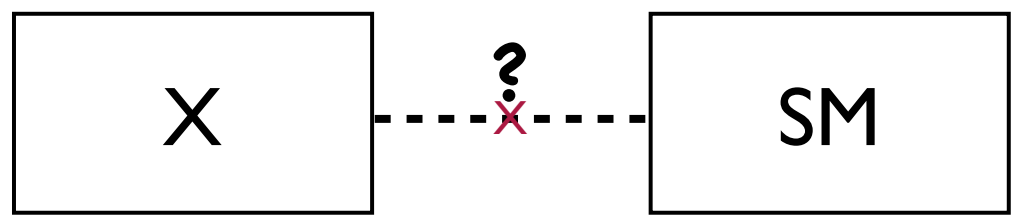
Dark Matter Candidates

- WIMPs: neutralinos, KK photons/neutrinos
- carry the weak interaction
- the WIMP miracle
- collisionless



- Hidden charged dark matter
- carry hidden quantum numbers
- can be SM singlet
- the WIMPless miracle
- self-interacting



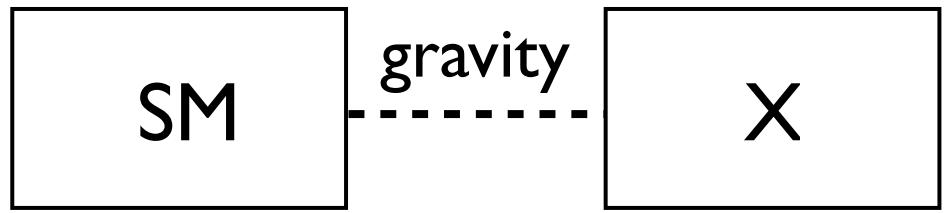
Pospelov, Ritz, Voloshin (2007); Hooper, Zurek (2008); Kumar, Feng (2008); Feng, Tu, HBY (2008); Ackerman, Buckley, Carroll, Kamionkowski (2008); Foot (2008); Feng, Kaplinghat, Tu, HBY (2009); Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2009); Pospelov, Ritz (2009); Shepherd, Tait, Zaharijas (2009); Cyr-Racine, Sigurdson (2012); Fan, Reece (2012)...

A Very Simple Example

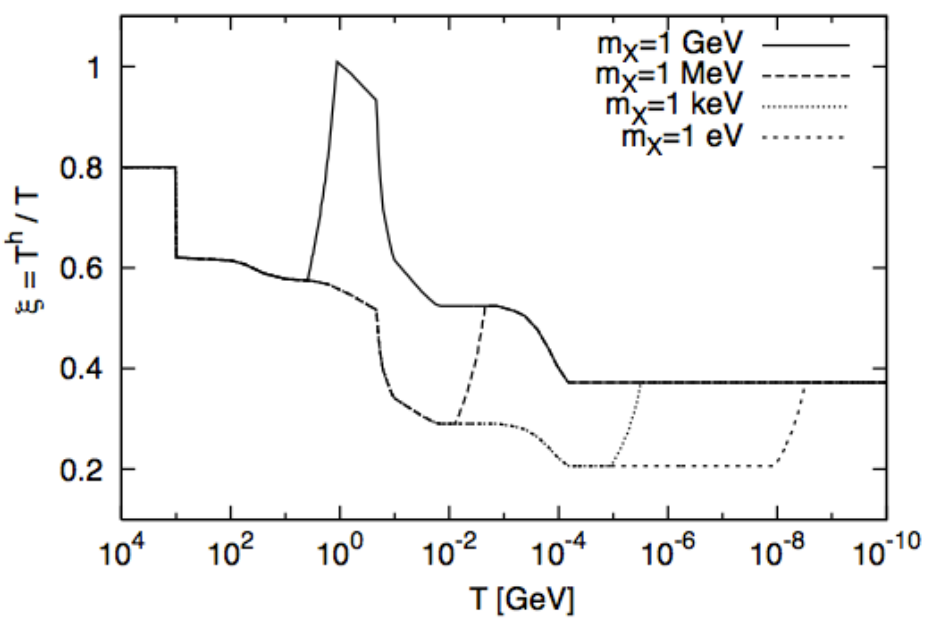
- Dark matter is charged under an unbroken $U(1)_X$

$$\mathcal{L} \supset g_X \bar{X} \gamma^\mu X \phi_\mu + m_X \bar{X} X$$

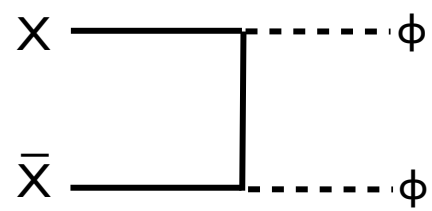
only two parameters (m_x, g_x)



- Two independent worlds



Feng, Tu, HBY (2008)



relic density

$$\Omega h^2 \sim \frac{1}{\langle \sigma_A v \rangle} \sim \frac{m^2}{g^4} \quad \text{If} \quad \frac{m_X}{g_X^2} \sim \frac{m_{\rm weak}}{g_{\rm weak}^2}$$

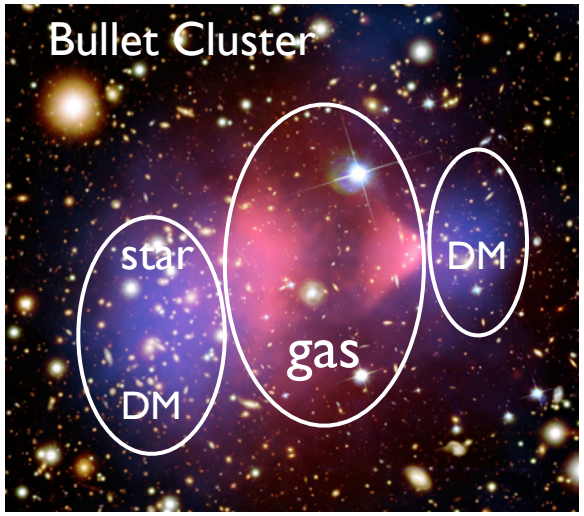
keep the WIMP miracle in the hidden sector

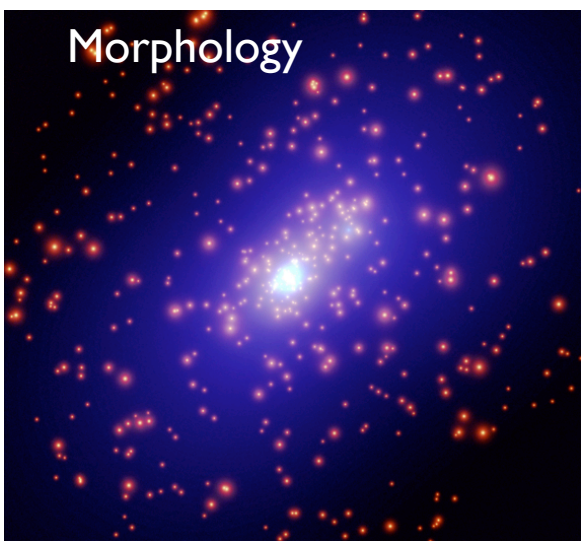
the WIMPless miracle

Feng, Kumar (2008)

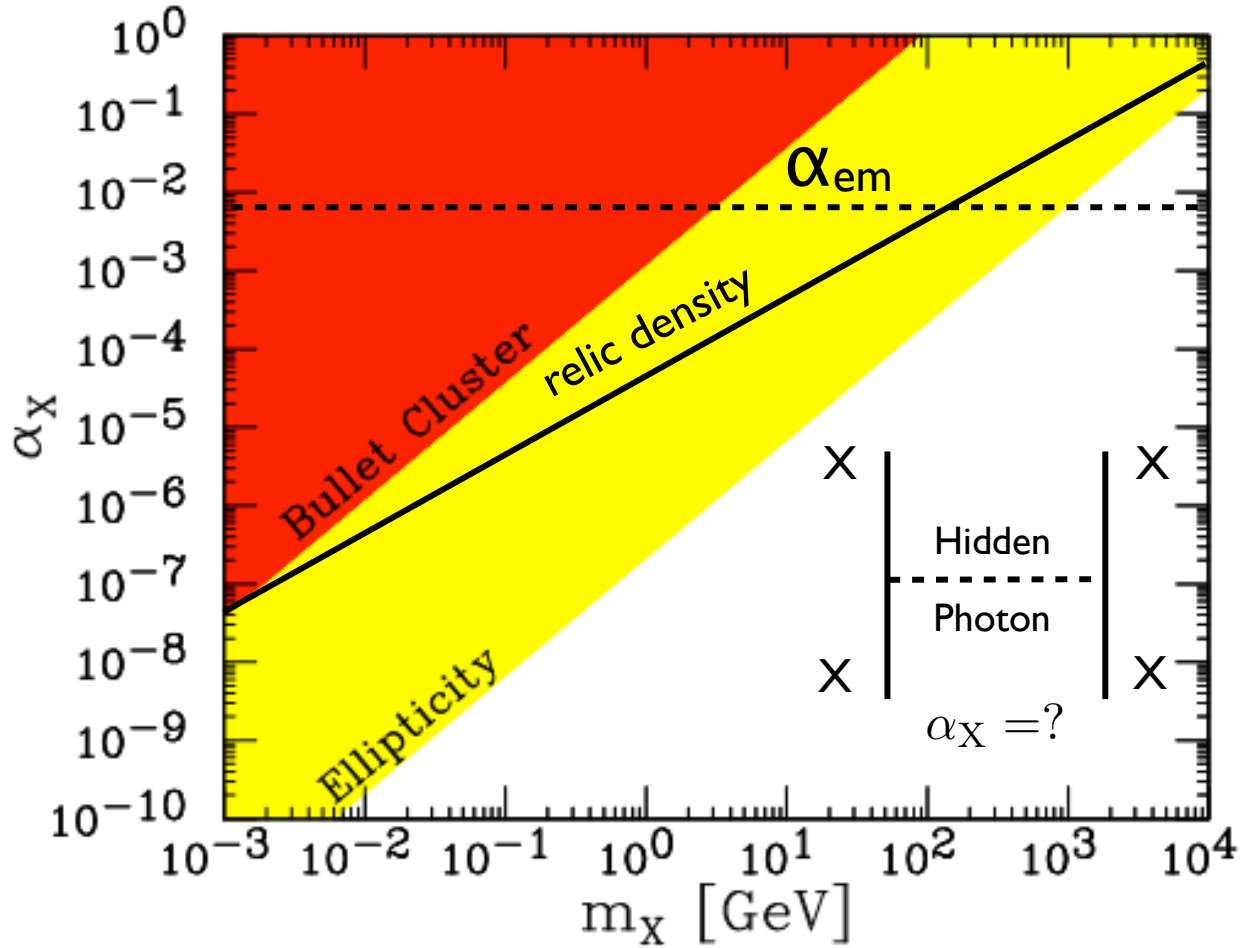
Limits on Hidden Charges

- Hidden photons mediate dark matter self-interactions





see Dawson`s talk



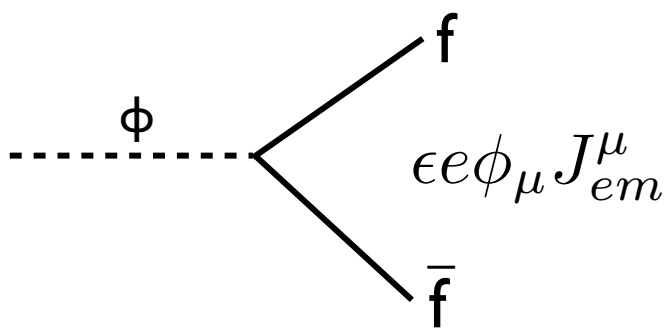
Feng, Kaplinghat, Tu, HBY (2009)

A Simple Example

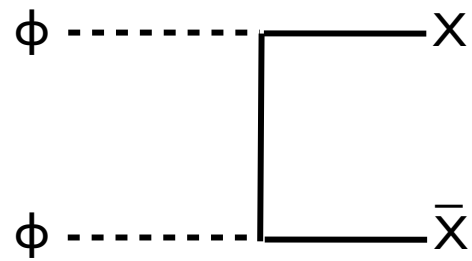
- Dark matter is charged under a broken $U(1)_X$
- $U(1)_X$ mixes with the SM $U(1)_Y$ through kinetic mixing

$$\mathcal{L} \supset g_X \bar{X}\gamma^\mu X \phi_\mu + m_X \bar{X} X + m_\phi^2 \phi^\mu \phi_\mu + \frac{\epsilon_Y}{2}\phi_{\mu\nu}B^{\mu\nu}$$

- A lower bound on the mixing parameter $\epsilon \equiv \epsilon_Y \cos\theta_W$



$$\epsilon e \phi_\mu J^\mu_{em}$$



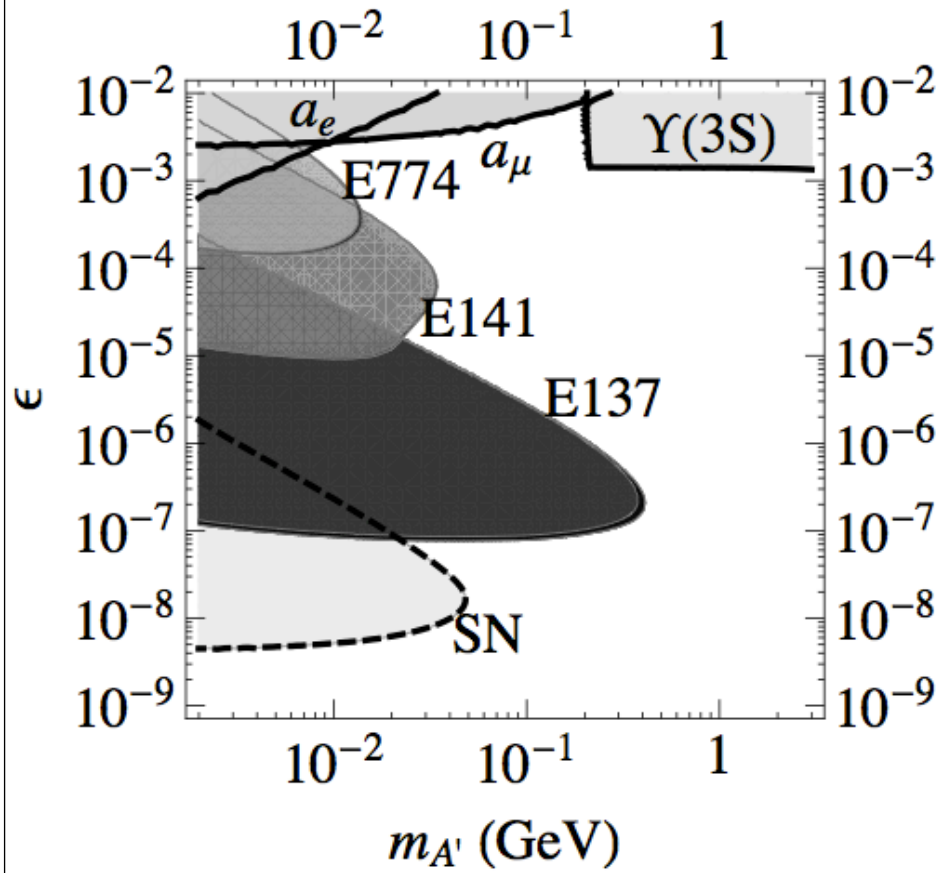
Γ_ϕ >H near freezeout

- the inverse decay keeps ϕ in the thermal equilibrium
- ϕϕ→XX produce dark matter

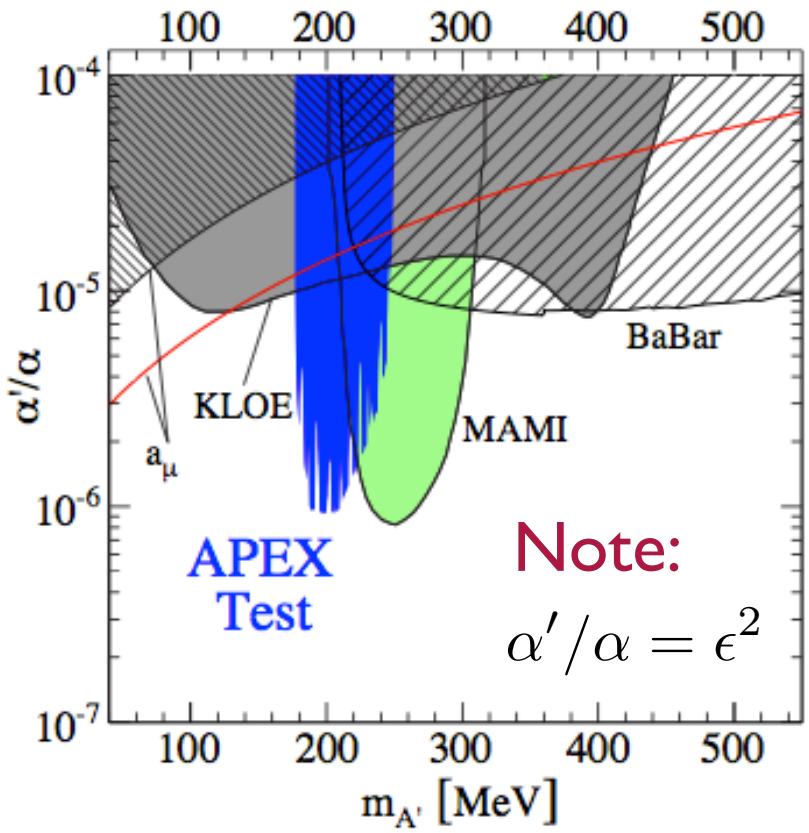
$$\epsilon \gtrsim 1.5 \times 10^{-5} \left[\frac{4}{\sum_f Q_f^2 N_c^f}\right]^{\frac{1}{2}} \left[\frac{\mathrm{GeV}}{m_\phi}\right] \left[\frac{m_X}{\mathrm{TeV}}\right]^{\frac{3}{2}}$$

Feng, Kaplinghat, HBY (2010)

Limits on Kinetic Mixing



Bjorken, Essig, Schuster, Toro (2009)



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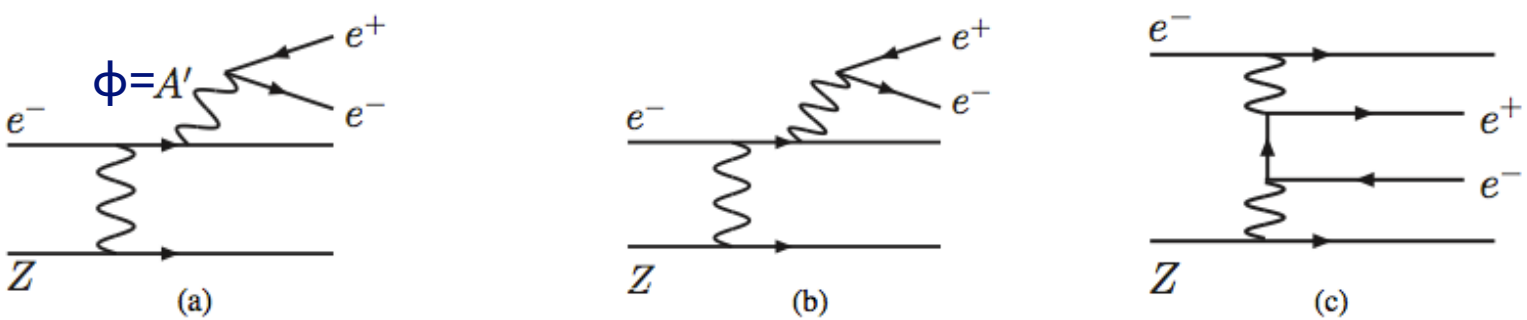
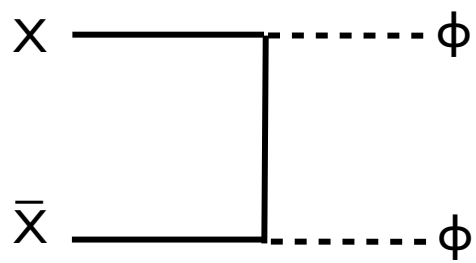


The Relic Density

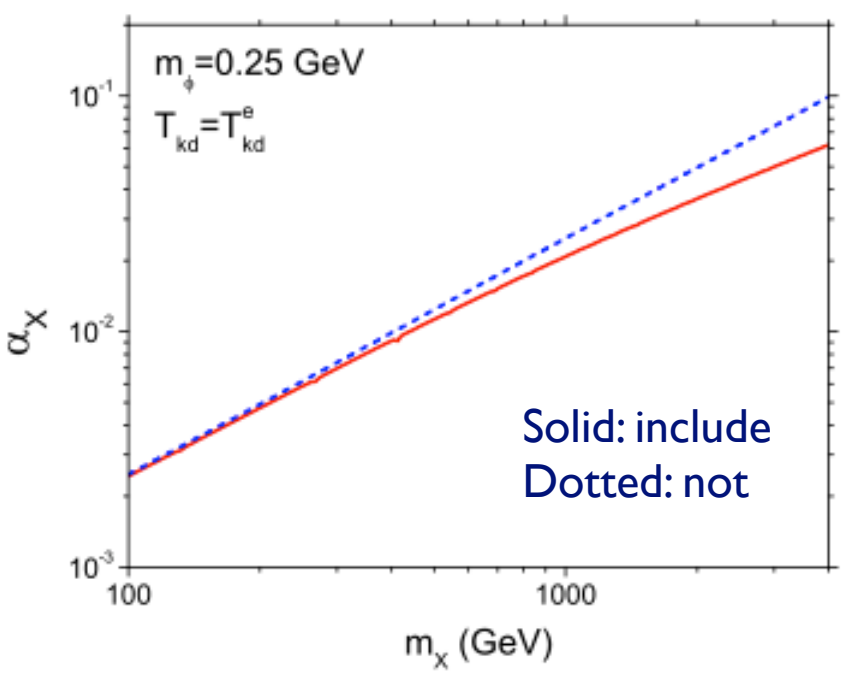
- Sommerfeld enhancements in the early Universe

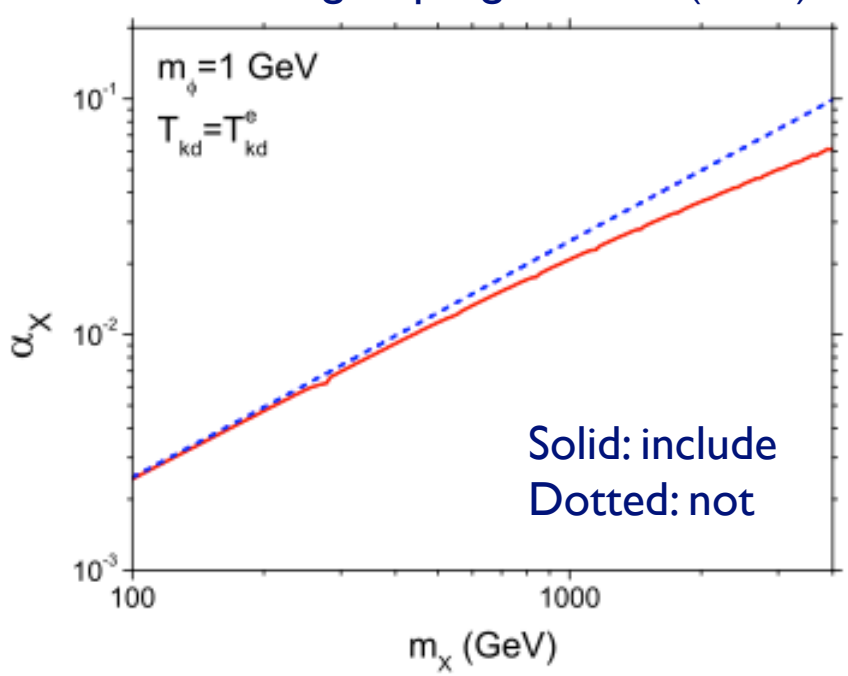


$$(\sigma_{\rm an} v_{\rm rel})_0 = \frac{\pi \alpha_X^2}{m_X^2}$$

to determine α_X

Feng, Kaplinghat, HBY (2010)

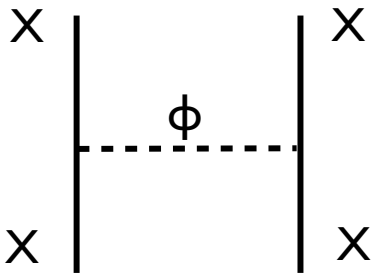




The Sommerfeld effect in the early Universe can lead to an O(1) suppression factor on α_X for the dark matter mass larger than ~1 TeV

Self-interactions

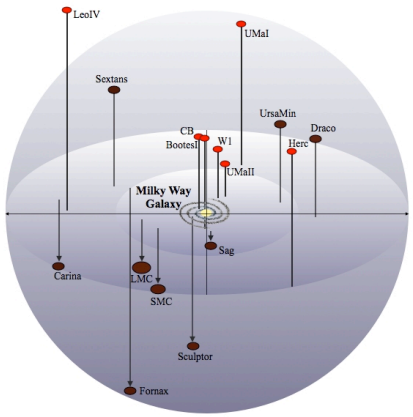
- WIMPs are typical collisionless cold dark matter
- Hidden charged dark matter can have large self-interactions



$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$

Three parameters (m_X, m_ϕ, α_X)

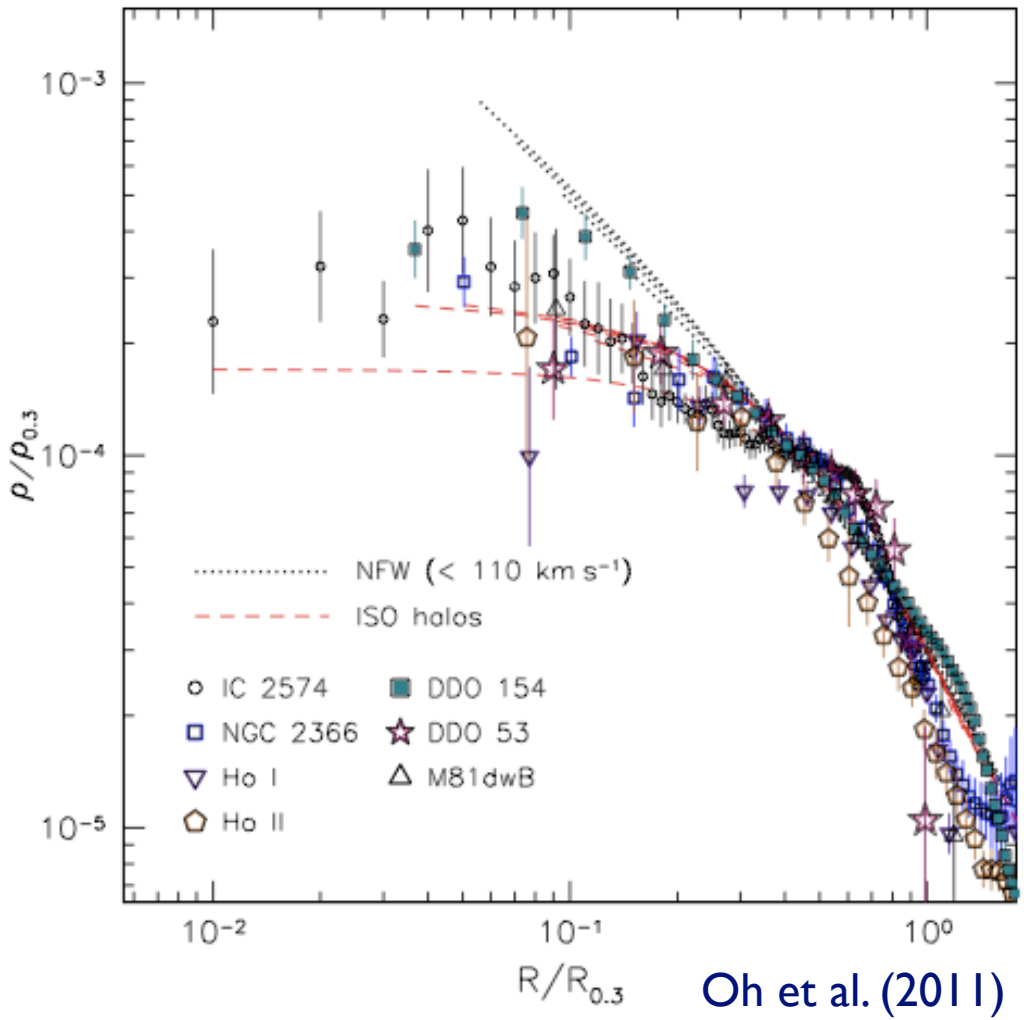
- Dark matter self-interactions through a Yukawa potential are important
  - have important impact on dark matter dynamics
  - can provide a solution to small scale anomalies



see Annika`s talk; Boylan-Kolchin`s talk

Core VS. Cusp Problem

- THINGS (dwarf galaxy survey)



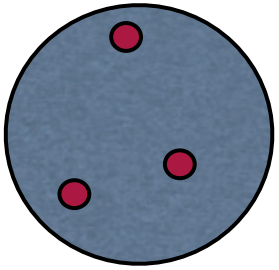
Oh et al. (2011)

density profile: $\rho \sim r^{\alpha}$

predicted: $\alpha \sim -1$

observed: $\alpha = -0.29 \pm 0.07$

- Observed central density shows flattened cores
- N-body simulations predict cusps



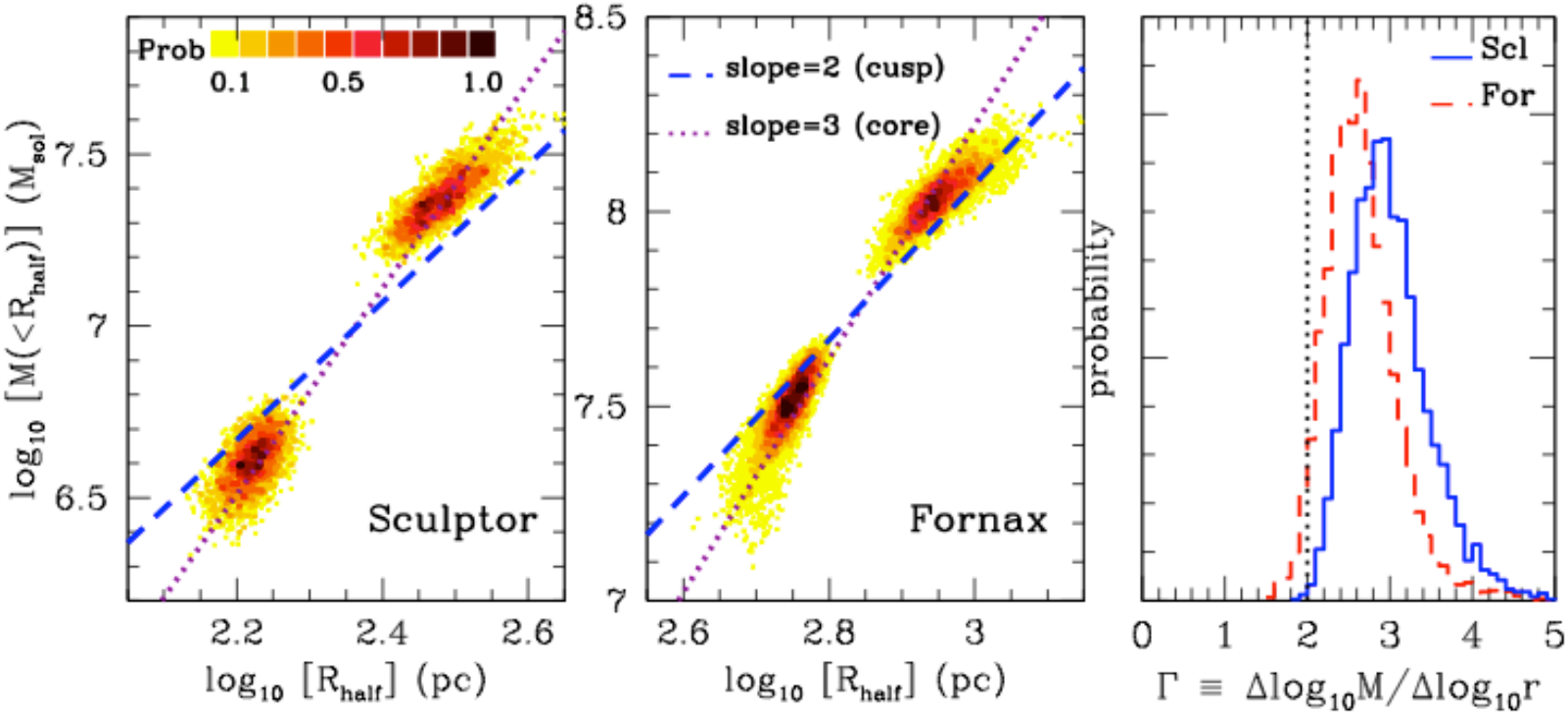
$$V \sim \sqrt{\frac{GM_<}{r}}$$

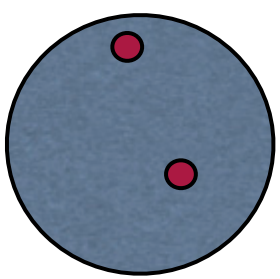
$$M_< \sim \int \rho r^2 dr$$

Core VS. Cusp Problem

- Milky Way dwarf galaxies

Walker, Penarrubia (2011)





$$V \sim \sqrt{\frac{GM_<}{r}}$$

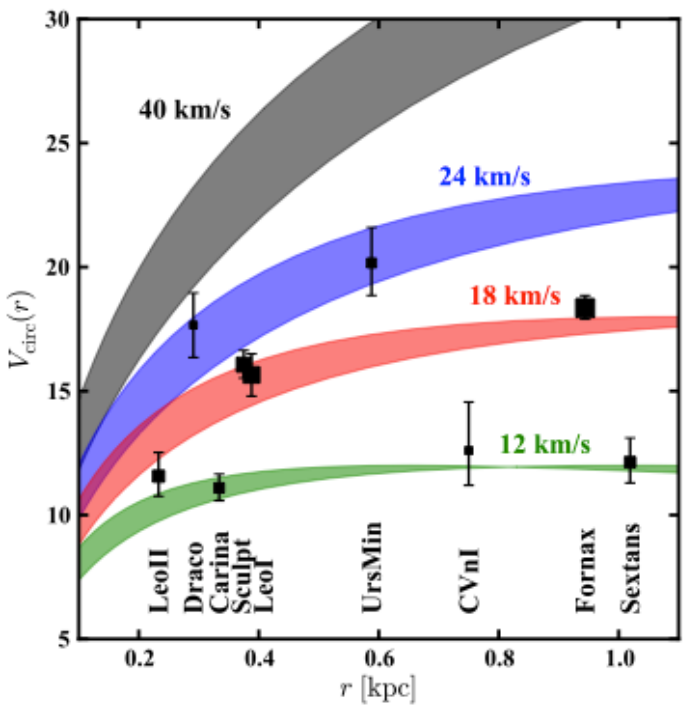
cusp $\rho \sim r^{-1} \rightarrow M \sim \int \rho d^3r \sim r^2$

core $\rho \sim const \rightarrow M \sim \int \rho d^3r \sim r^3$

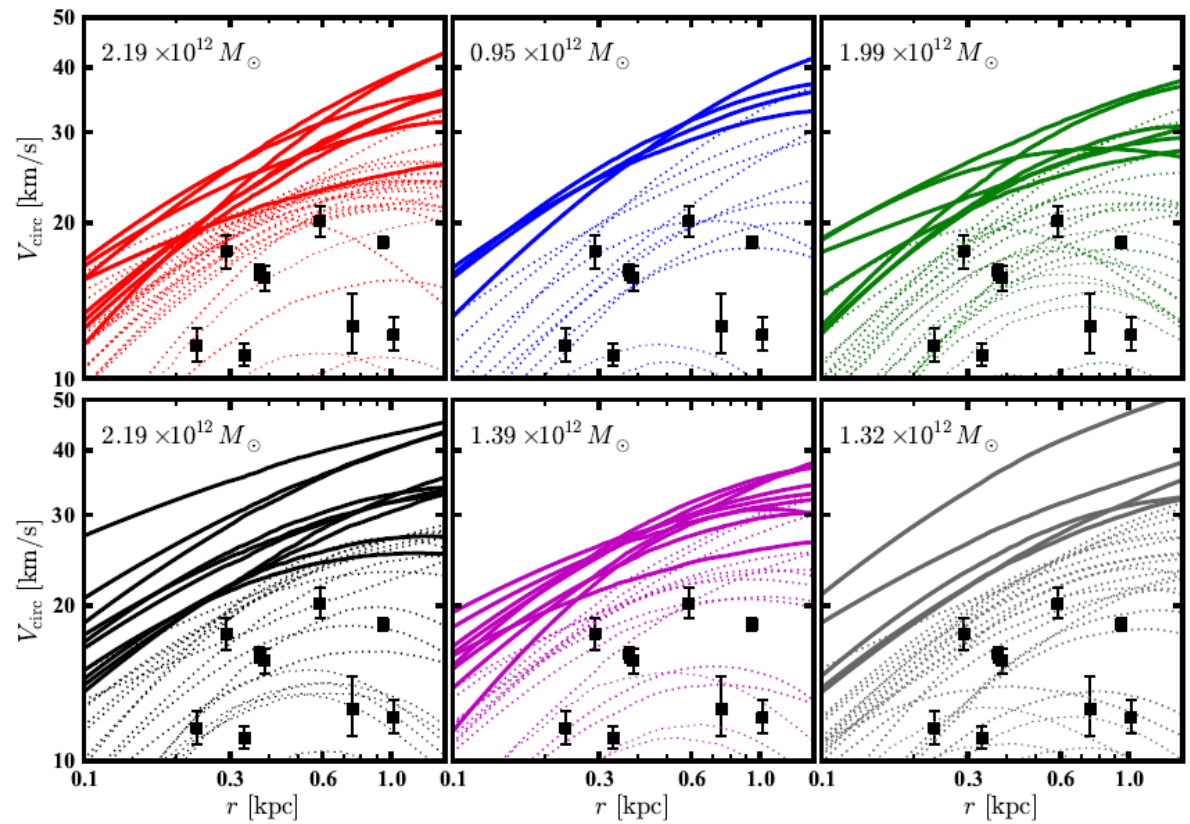
Two groups of stars as test particles

Too Big to Fail Problem

- Milky Way dwarf galaxies Boylan-Kolchin, Bullock, Kaplinghat (2011)



$$V \sim \sqrt{\frac{GM_<}{r}}$$

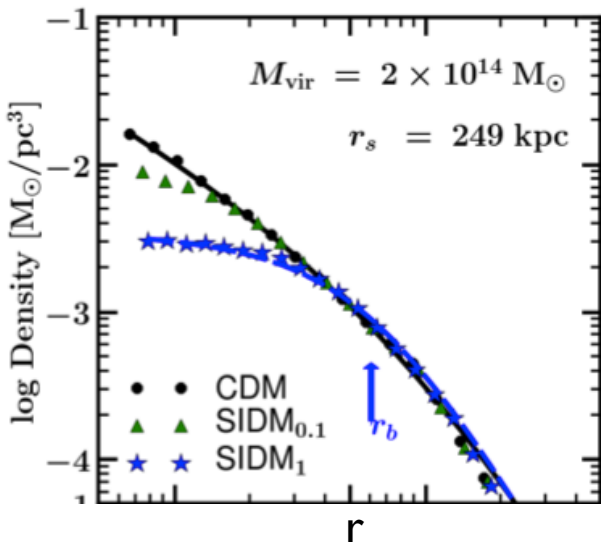


- Most massive subhalos in collisionless CDM simulations are too dense to host observed galaxies in the Milky Way
- These predicted most massive subhalos are "too big to fail" in forming stars

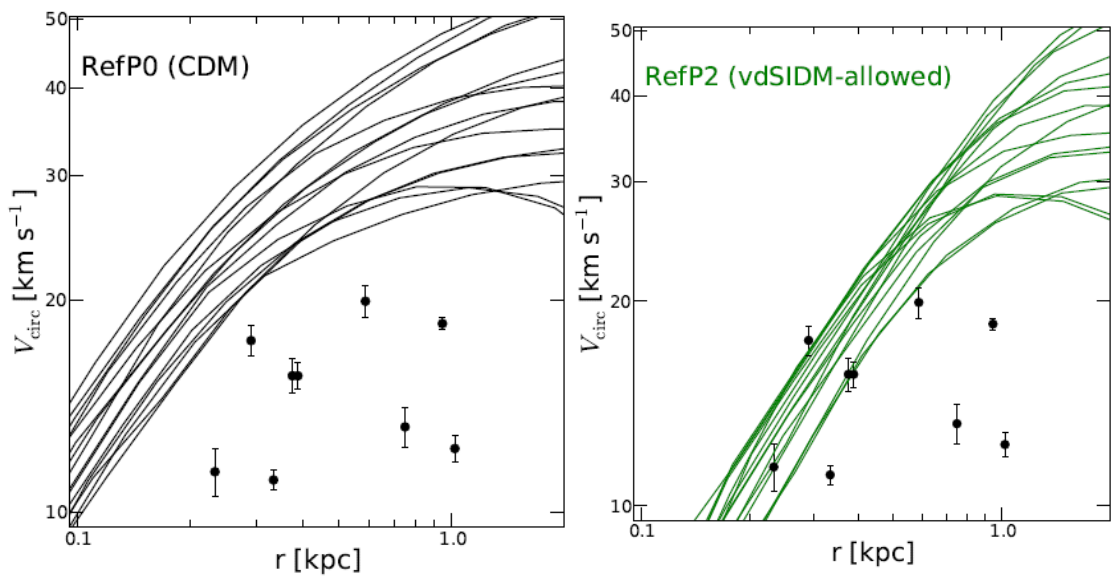
Self-interacting Dark Matter

- All these small scale anomalies can be solved if DM is sufficiently self-interacting

Spergel, Steinhardt(1999)



Rocha, Peter, Bullock, Kaplinghat, et al. (2012)



Vogelsberger, Zavala, Loeb (2012)

DM self-interactions lead to cores

DM self-scattering moves predicted circular velocities into (closer) alignment with MW dwarf galaxies

Astrophysics Summary

- Evidence for DM self-interactions on dwarf galaxy scales

  $\sigma/m_X \sim 0.1 - 10\ \mathrm{cm}^2/\mathrm{g}$ for $v \sim 10$ km/s

- Constraints: elliptical halo shapes and the Bullet Cluster

  $\sigma/m_X < 0.1 - 1\ \mathrm{cm}^2/\mathrm{g}$ for $v \sim 100$ km/s (MW)
  and $v \sim 1000$ km/s (cluster)

Peter, Rocha, Bullock, Kaplinghat (2012)

Challenges

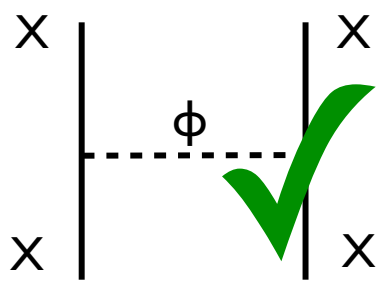
- A really large scattering cross section!

  $\sigma \sim 1\mathrm{cm}^2\,(m_X/\mathrm{g}) \sim 2\times10^{-24}\ \mathrm{cm}^2\,(m_X/\mathrm{GeV})$ $\quad \sigma_W \sim 10^{-36}\ \mathrm{cm}^2$

- How to avoid the constraints?

  $\sigma \sim \mathrm{const}$

Spergel, Steinhardt(1999)



$$V(r) = \pm\frac{\alpha_X}{r}e^{-m_\phi r}$$

Scattering with a Yukawa Potential

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$

DM self-scattering

Perturbative (Born) regime

$\alpha_X m_X / m_\phi \ll 1$

Feng, Kaplinghat, HBY (2009)

Non-perturbative regime

$\alpha_X m_X / m_\phi \gtrsim 1$

Classical regime

$m_X v / m_\phi \gg 1$

Resonant regime

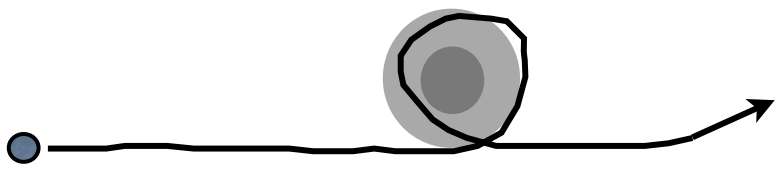
$m_X v / m_\phi \lesssim 1$

Exception: $m_\phi = 0$

Feng, Kaplinghat, Tu, HBY (2009)

Classical Regime

- Classical approximation from plasma physics



Charged-particle scattering in plasma

$$\pm\frac{\alpha_X}{r}e^{-m_\phi r} \qquad \alpha_X = \alpha_{\rm EM}$$

$$m_\phi = \text{Debye photon mass}$$

Attractive

Khrapak et al. (2003) (2004)

$$\sigma_T^{\rm clas} \approx \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 \ln\left(1+\beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2/\left(1+1.5\beta^{1.65}\right) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \beta \gtrsim 10^3 \end{cases}$$

Repulsive

$$\sigma_T^{\rm clas} \approx \begin{cases} \frac{2\pi}{m_\phi^2}\beta^2 \ln\left(1+\beta^{-2}\right) & \beta \lesssim 1 \\ \frac{\pi}{m_\phi^2}\left(\ln 2\beta - \ln\ln 2\beta\right)^2 & \beta \gtrsim 1 \end{cases}$$

$$\beta \equiv 2\alpha_X m_\phi/(m_X v^2)$$

$\sigma_T \sim v^{-4}$ at large v

$\sigma_T \sim$const at small v (saturated)

Apply to DM: σ_T is enhanced on dwarf scales compared to larger scales

Feng, Kaplinghat, HBY (2009); Loeb, Weiner (2010); Vogelsberger, Loeb, Zavala (2012)

Beyond Perturbation

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$

DM self-scattering

Perturbative (Born) regime ✓

$\alpha_X m_X / m_\phi \ll 1$

Nonperturbative regime

$\alpha_X m_X / m_\phi \gtrsim 1$

Classical regime ✓

$m_X v / m_\phi \gg 1$

Resonant regime

$m_X v / m_\phi \lesssim 1$

Resonant Regime

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r} \longrightarrow V(r) = \pm \frac{\alpha_X \delta\, e^{-\delta r}}{1 - e^{-\delta r}}$$

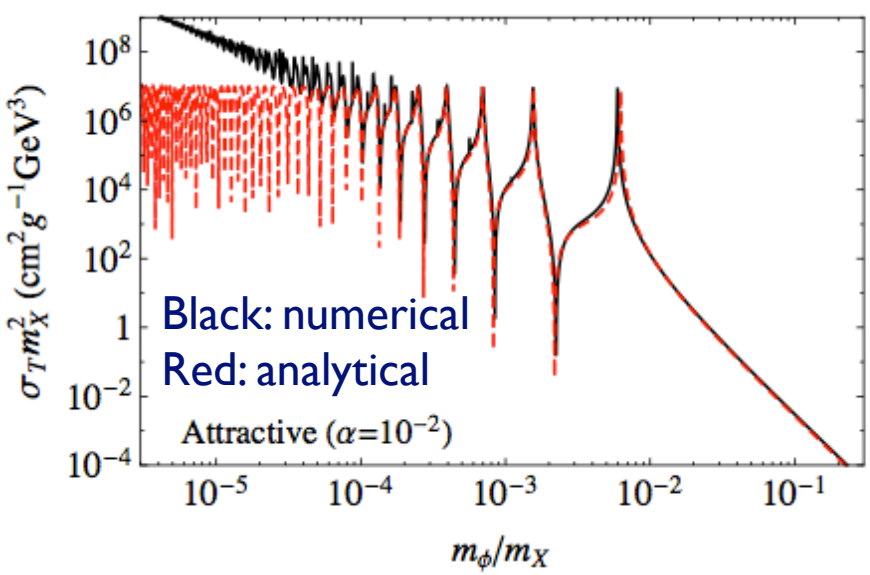
$$\delta = \kappa m_\phi$$

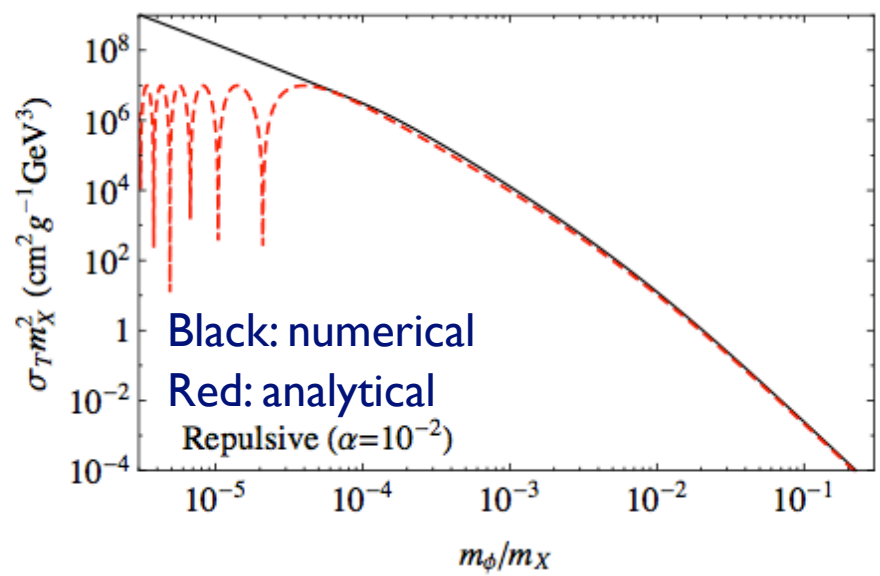
$$\kappa \simeq 1.6$$

Hulthén potential

The Schrödinger equation is solvable analytically for ell=0

$$\sigma_T^{\text{Hulthén}} = \frac{16\pi}{m_X^2 v^2} \sin^2 \delta_0 \qquad \delta_0 = \arg\left(\frac{i\,\Gamma\left(\frac{i m_X v}{\kappa m_\phi}\right)}{\Gamma(\lambda_+)\Gamma(\lambda_-)} \right), \quad \lambda_\pm \equiv \begin{cases} 1 + \frac{i m_X v}{2\kappa m_\phi} \pm \sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} - \frac{m_X^2 v^2}{4\kappa^2 m_\phi^2}} & \text{attractive} \\ 1 + \frac{i m_X v}{2\kappa m_\phi} \pm i\sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} + \frac{m_X^2 v^2}{4\kappa^2 m_\phi^2}} & \text{repulsive} \end{cases}$$





"WIMPonium" Shepherda, Tait, Zaharijas (2009)

Tulin, HBY, Zurek (2012) (2013)

Beyond Perturbation

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$

DM self-scattering

Perturbative (Born) regime
$\alpha_X m_X / m_\phi \ll 1$

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Classical regime
$m_X v / m_\phi \gg 1$

Resonant regime
$m_X v / m_\phi \lesssim 1$

We have analytical formulas in all regimes
We have verified these formulas numerically

Velocity Dependence

- σ_T has a rich structure

Tulin, HBY, Zurek (2012)

Born regime: σ_T~const below MW scales

Classical regime: σ_T increases on small scales

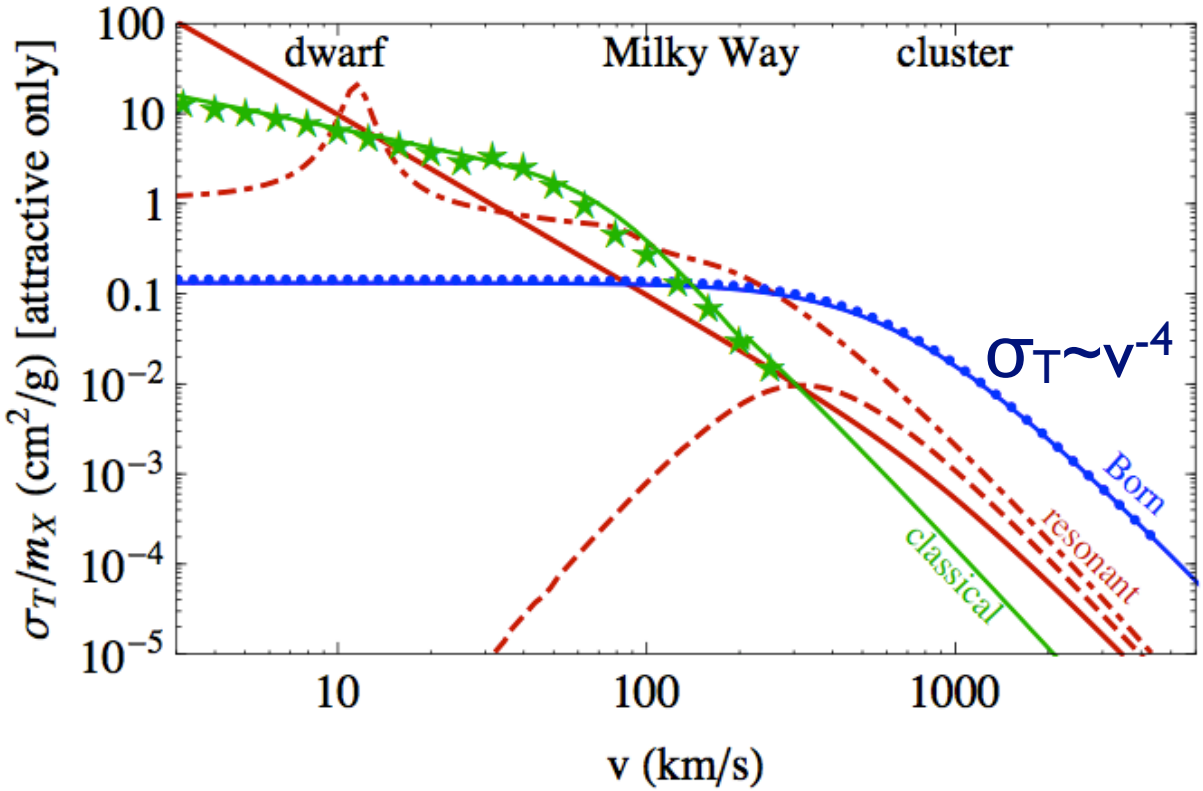
★: numerical

Resonant regime:

s-wave: $\sigma_T \sim v^{-2}$

p-wave

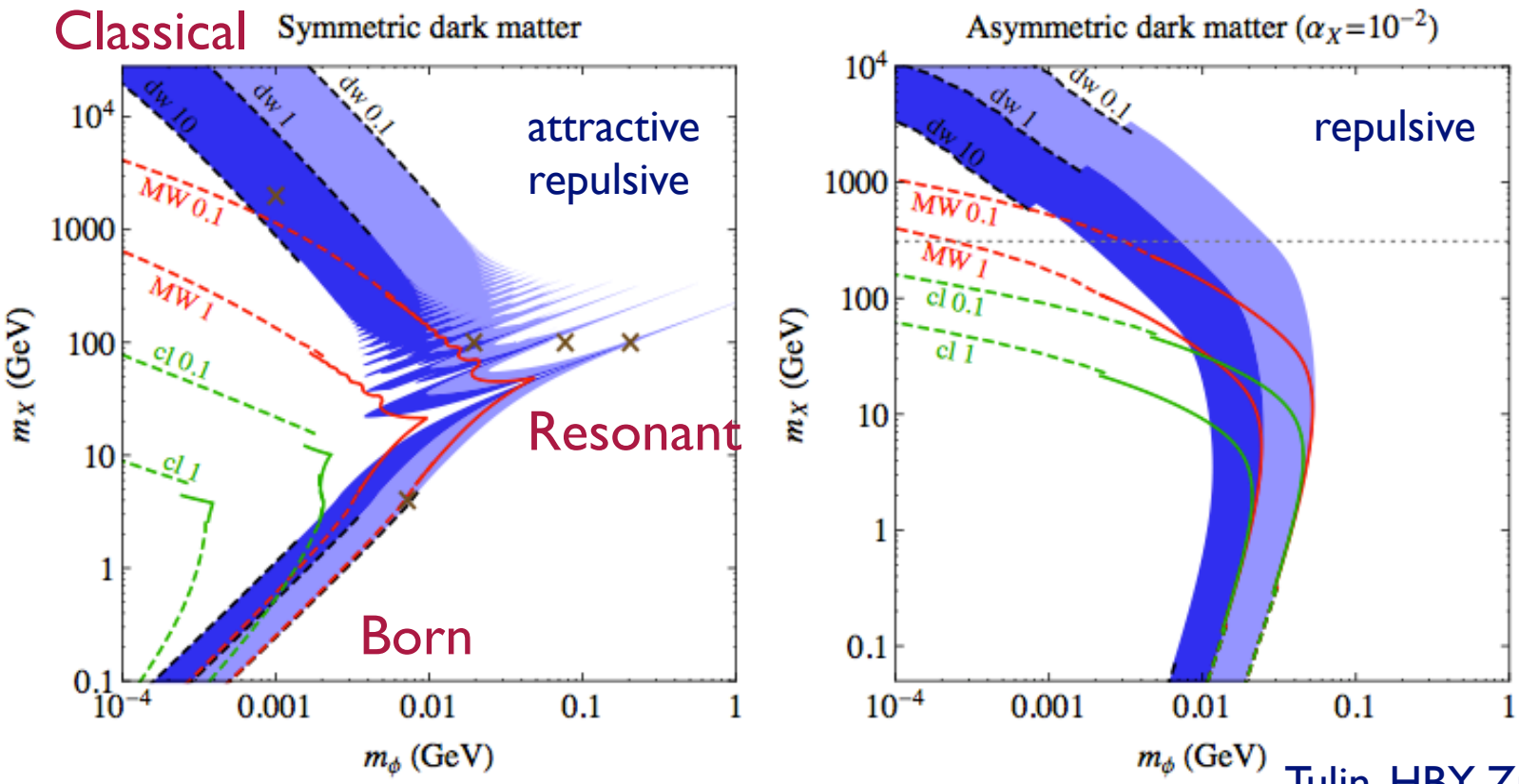
anti-resonance



- In many cases, σ_T is enhanced on dwarf scales
- This helps us avoid constraints on MW and cluster scales

in contrast to σ_T ~const as originally proposed

A Unified Model



Tulin, HBY, Zurek (2012)

Fix α_X by the relic density, contours show $\langle\sigma_T\rangle/m_X$ in cm^2/g

dw: dwarf (10 km/s)
MW: Milky Way (200 km/s)
cl: cluster (1000 km/s)

Blue regions: Solve the small scale anomalies

Summary

- Hidden charged dark matter is beyond the WIMP paradigm
- It has various new features: different thermal histories, different experimental signatures, Sommerfeld enhancements and self-interactions
- It provides a solution to the small scale anomalies