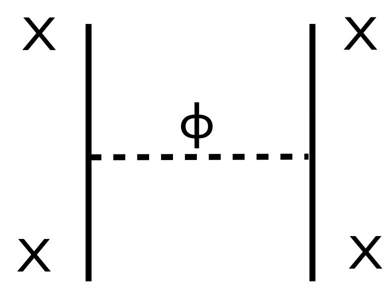
Beyond Collisionless Dark Matter:
From a Particle Physics Perspective

Hai-Bo Yu
University of Michigan, Ann Arbor

Aspen Winter Conference 2013

Recent Development



Contact interactions σ~constant

Spergel, Steinhardt (1999)

Massless mediators $\sigma \sim v^{-4}$

Ackerman, Buckley, Carroll, Kamionkowski (2008); Feng, Kaplinghat, Tu, HBY (2009)

WIMPless DM: Kumar, Feng (2008); Feng, Tu, HBY (2008)

Sub-GeV mediators σ~constant-v^{-4}

Feng, Kaplinghat, HBY (2009); Buckley, Fox (2009); Loeb, Weiner (2010)

DM models motivated by PAMELA anomalies: Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2009); Pospelov, Ritz (2009)

A complete study of the whole parameter space: Tulin, HBY, Zurek (2012) (2013)

Collisionless DM vs. SIDM

- Large scales: Great!
- Small scales (dwarf galaxies, subhalos)?

  cusp vs. core problem

  "too big to fail?" problem Boylan-Kolchin, Bullock, Kaplinghat (2011)
- These anomalies can be solved if DM is sufficiently self-interacting

  Recent simulation results

  Harvard group: Vogelsberger, Zavala, Loeb (2012); UCI group: Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas (2012)

  Due to baryons?

  Justin Read: "It is far from clear..."

Astrophysics Summary

- Evidence for DM self-interactions on dwarf galaxy scales

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

- Constraints: elliptical halo shapes; evaporation of subhalos; core collapse; Bullet Cluster

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

and $v \sim 1000$ km/s (cluster) Peter, Rocha, Bullock, Kaplinghat (2012)

Challenges

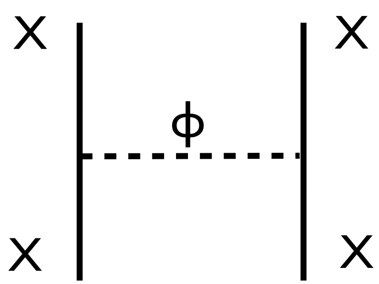
- A really large scattering cross section!

$\sigma \sim 1\mathrm{cm^2}\ (m_X/\mathrm{g}) \sim 2\times 10^{-24}\ \mathrm{cm^2}\ (m_X/\mathrm{GeV})$ $\sigma_{EW} \sim 10^{-36}\ \mathrm{cm^2}$

- How to avoid the constraints?

The original idea does not work well

Particle Physics of Dark Forces



- A light force mediator is necessary
- σ depends on DM velocities

Consider an extreme case where $m_X v >> m_\phi$, we have Coulomb scattering $\sigma \sim v^{-4}$

A complete study

$$\mathscr{L}_{\text{int}} = \begin{cases} g_X \bar{X}\gamma^\mu X \phi_\mu & \text{vector mediator} \\ g_X \bar{X} X \phi & \text{scalar mediator} \end{cases}$$

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

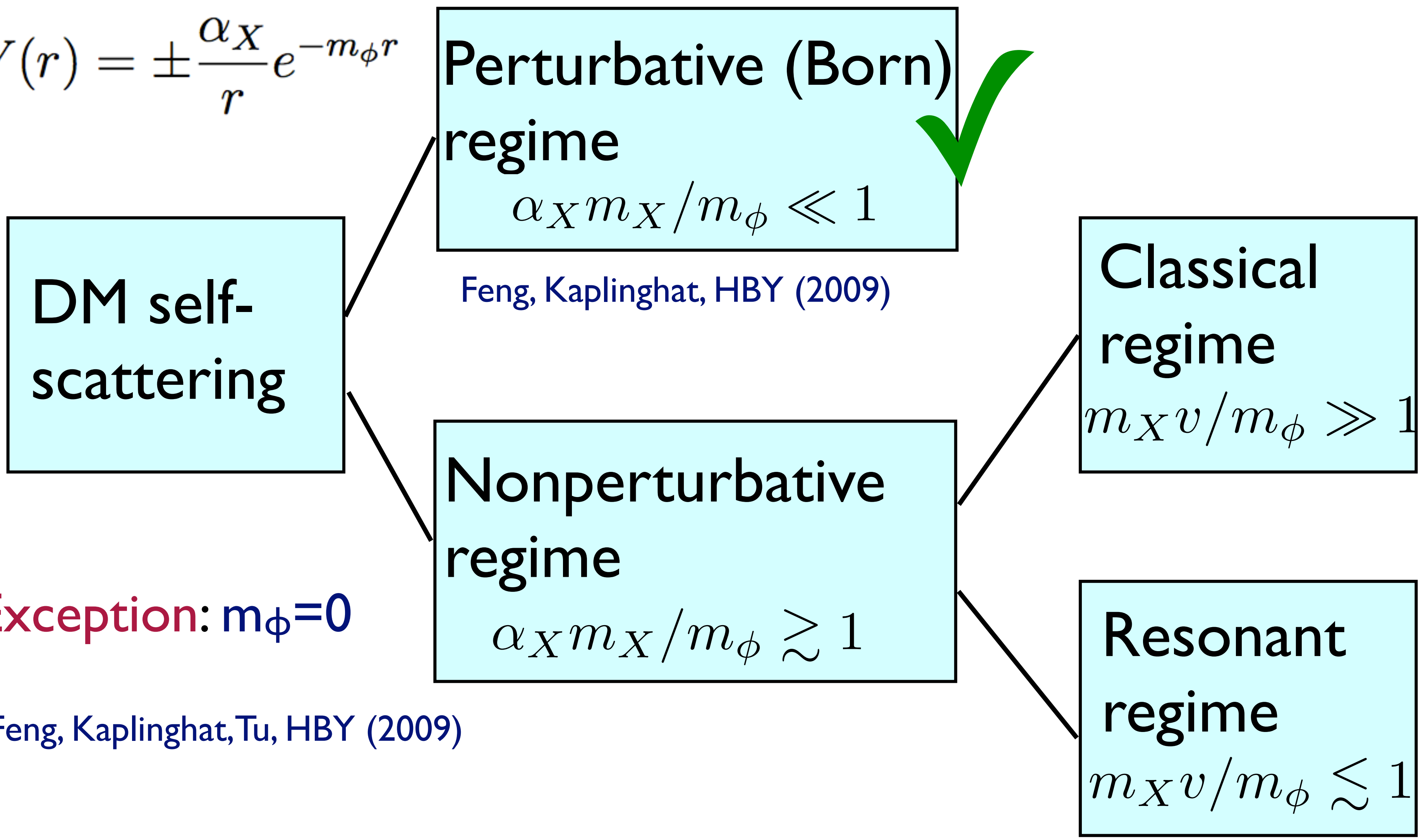
$$\alpha_X = g_X^2/(4\pi)$$

$$\sigma_T = \int d\Omega \,(1 - \cos\theta)\, \frac{d\sigma}{d\Omega}$$

Map out the parameter space (m_X, m_ϕ, α_X)

Scattering with a Yukawa Potential

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



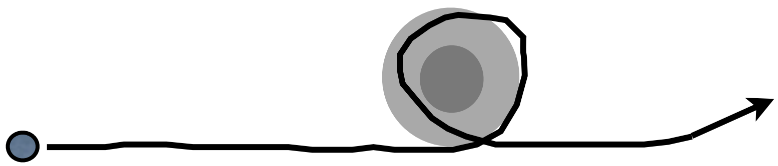
Feng, Kaplinghat, HBY (2009)

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

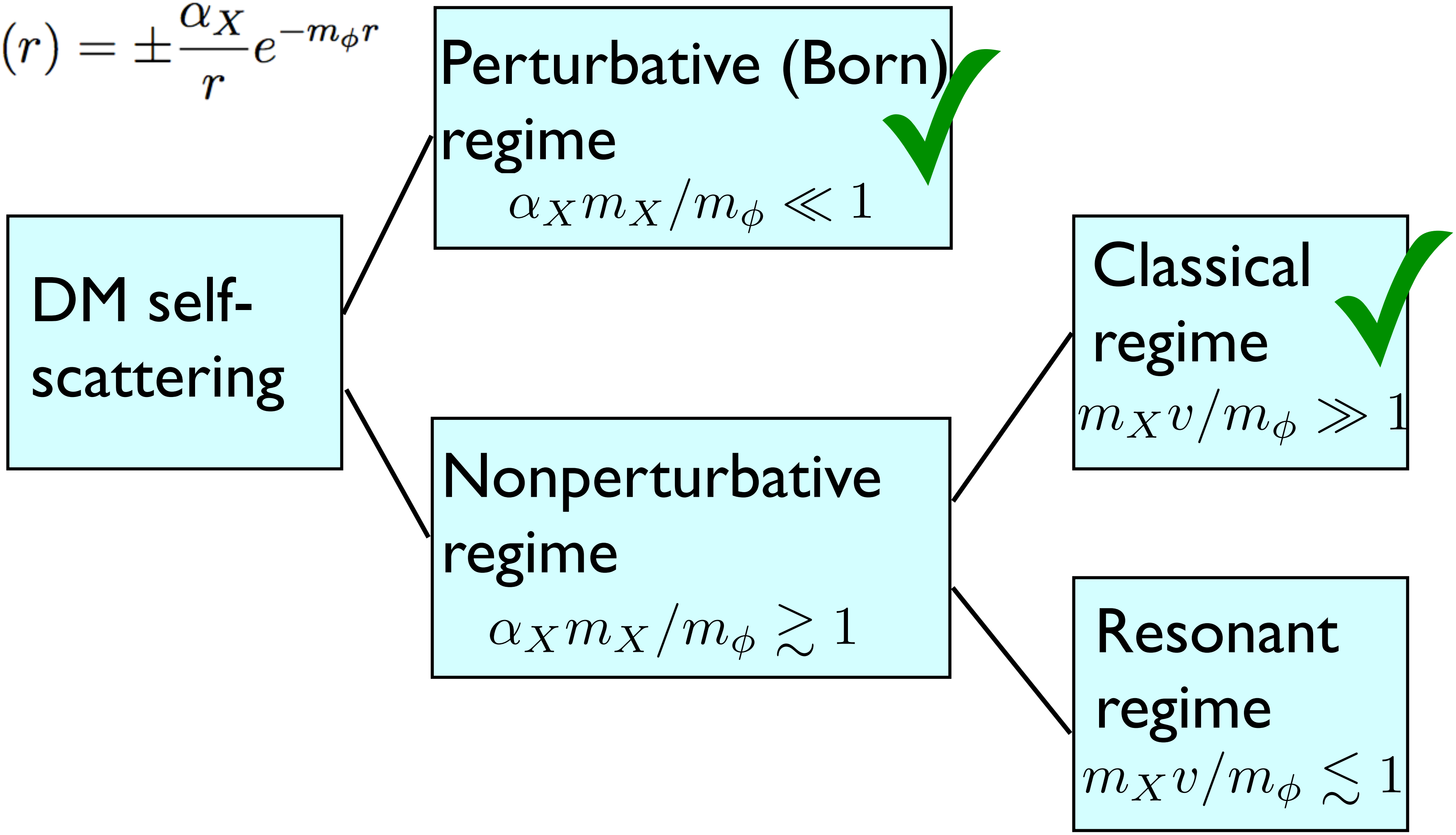
$\sigma_T \sim$ const at small v (saturated)

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

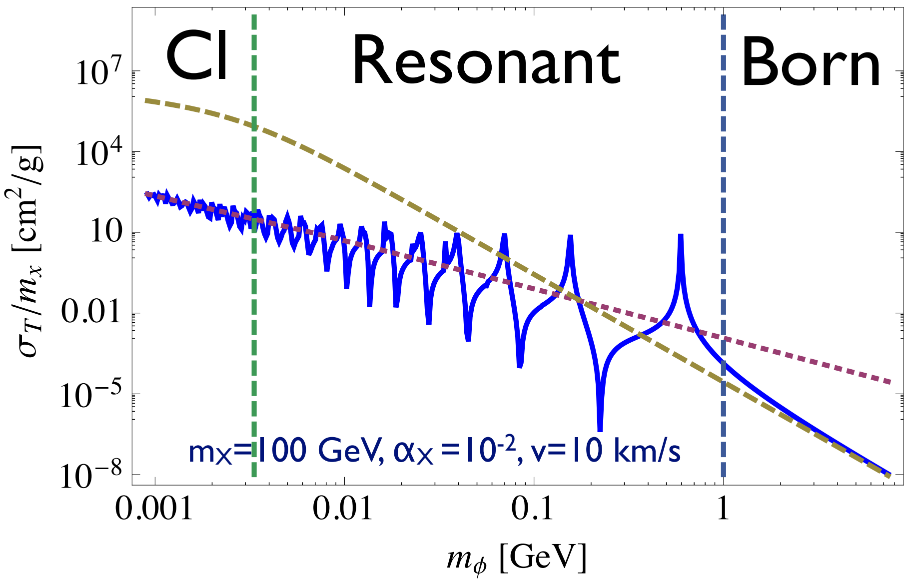
$$V(r) = \pm\frac{\alpha_X}{r}e^{-m_\phi r}$$

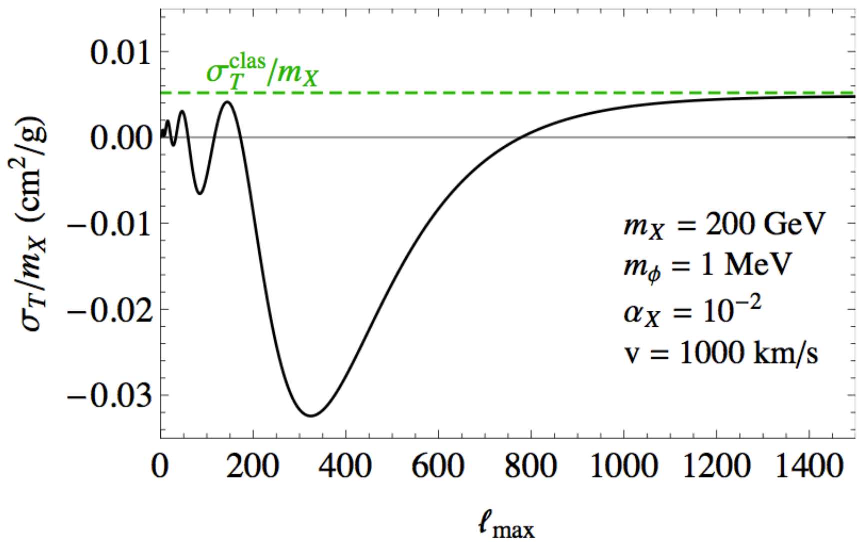


Numerical Approach

- Quantum mechanics 101-partial wave analysis

$$\frac{\sigma_T k^2}{4\pi} = \sum_{\ell=0}^{\infty} (\ell+1)\sin^2(\delta_{\ell+1} - \delta_\ell)$$





Solid: numerical; Dashed: Born; Dotted: plasma

"WIMPonium" Shepherda, Tait, Zaharijas (2009)

We have confirmed the analytical formula from plasma physics

Analytical Approach

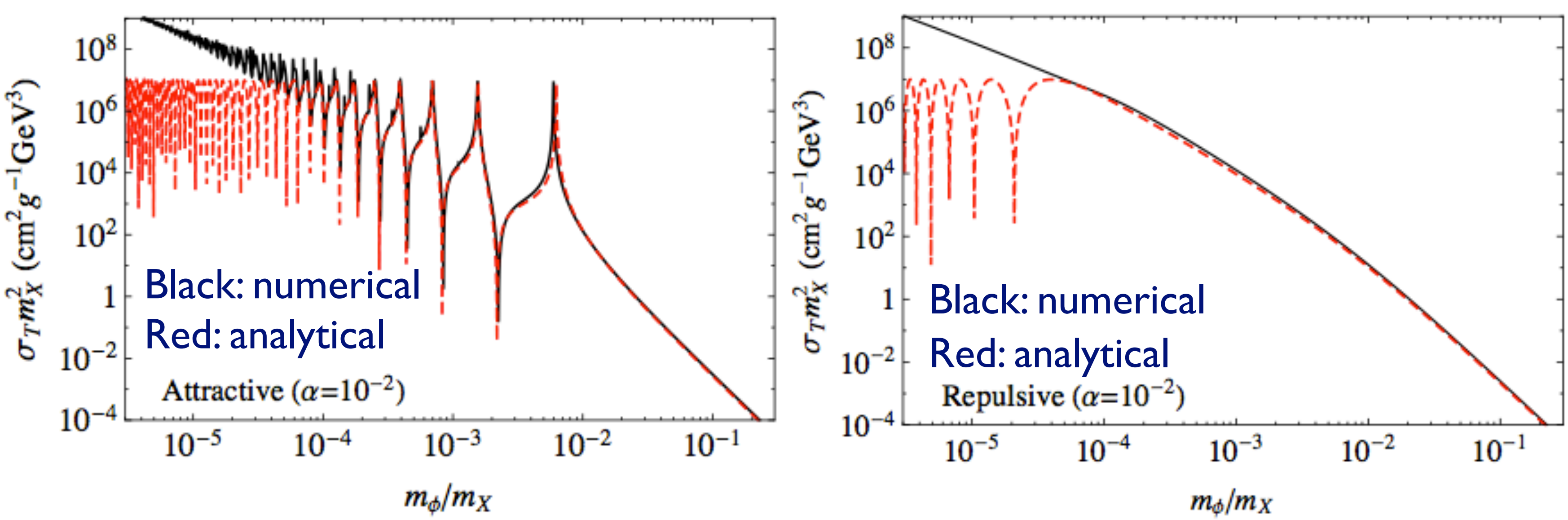
$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r} \longrightarrow V(r) = \pm \frac{\alpha_X \delta\, e^{-\delta r}}{1 - e^{-\delta r}}$$

Hulthén potential

$$\delta = \kappa m_\phi \qquad \kappa \simeq 1.6$$

The Schrödinger equation is solvable analytically for ell=0

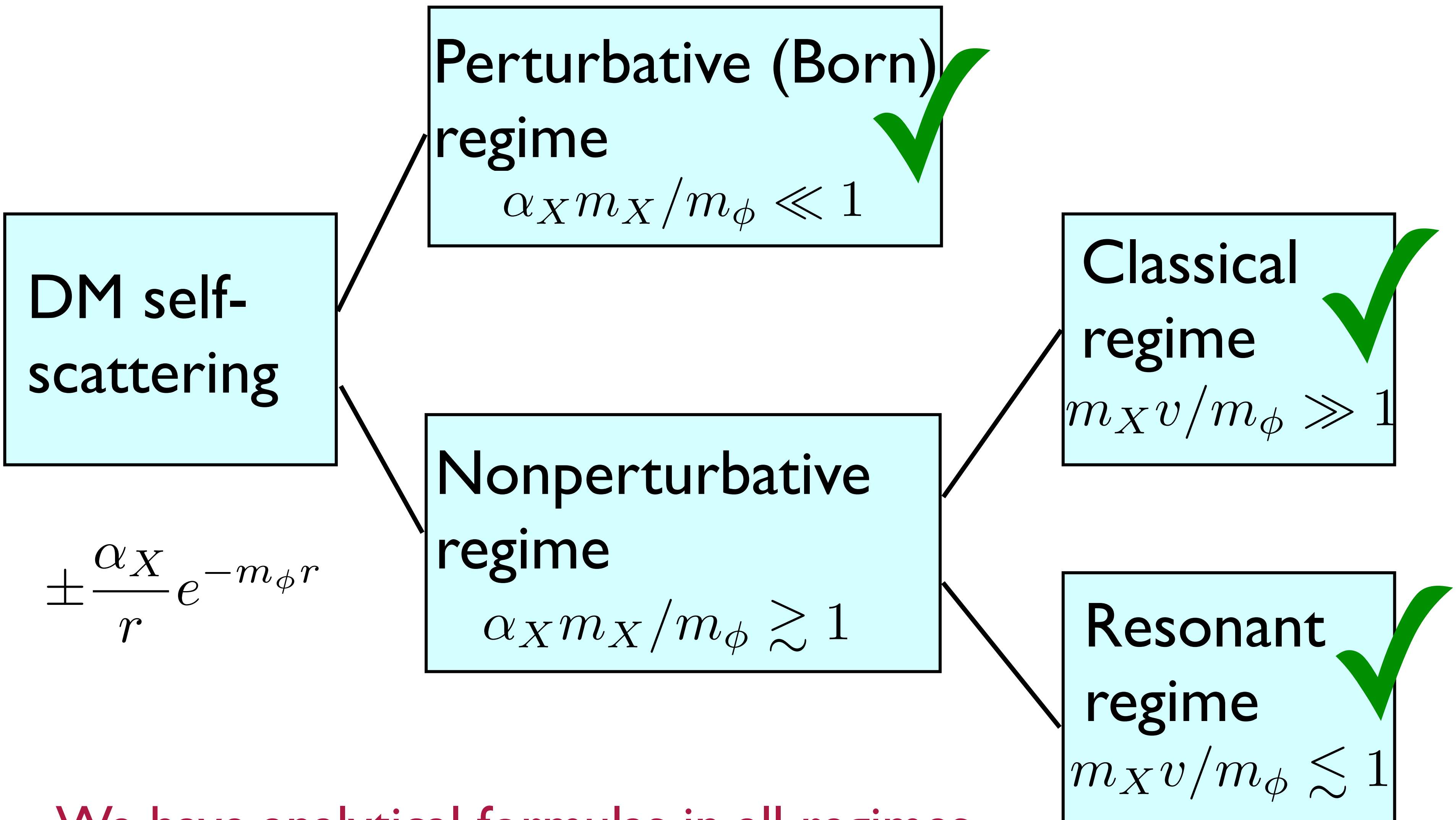
$$\sigma_T^{\text{Hulthén}} = \frac{16\pi}{m_X^2 v^2} \sin^2 \delta_0 \qquad \delta_0 = \arg\left(\frac{i\,\Gamma\left(\frac{i m_X v}{\kappa m_\phi}\right)}{\Gamma(\lambda_+)\Gamma(\lambda_-)} \right), \quad \lambda_\pm \equiv \begin{cases} 1 + \frac{i m_X v}{2\kappa m_\phi} \pm \sqrt{\frac{\alpha_X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



It is useful for simulations

Tulin, HBY, Zurek (2013)

Beyond Perturbation



We have analytical formulas in all regimes

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

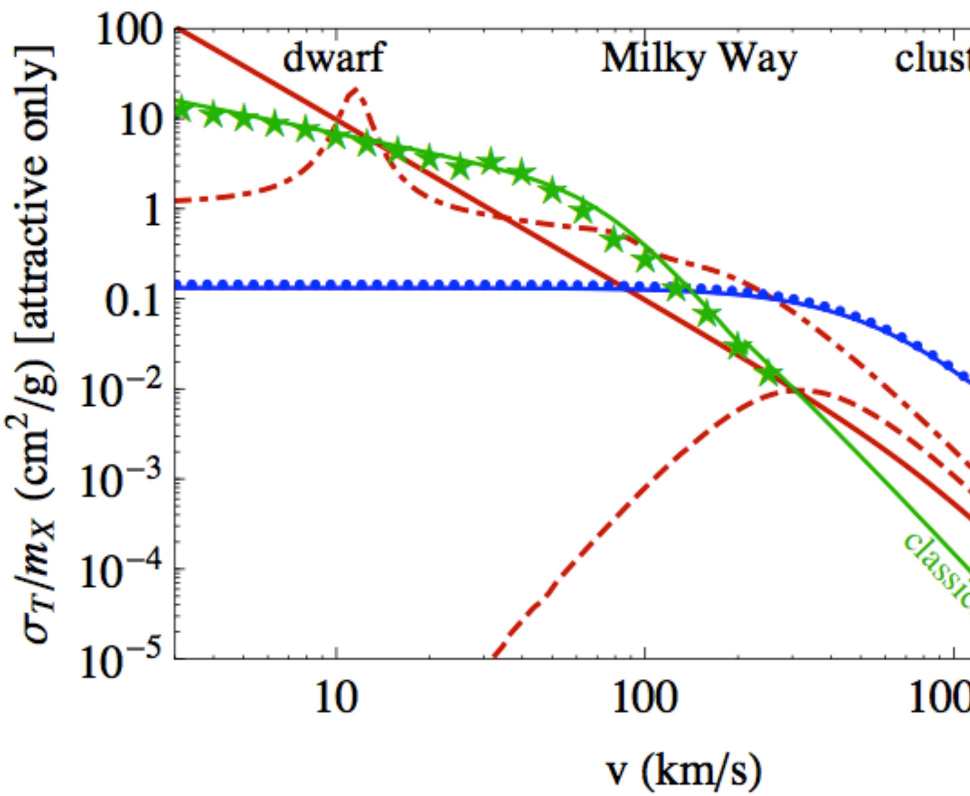
★: numerical

Resonant regime:

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

p-wave

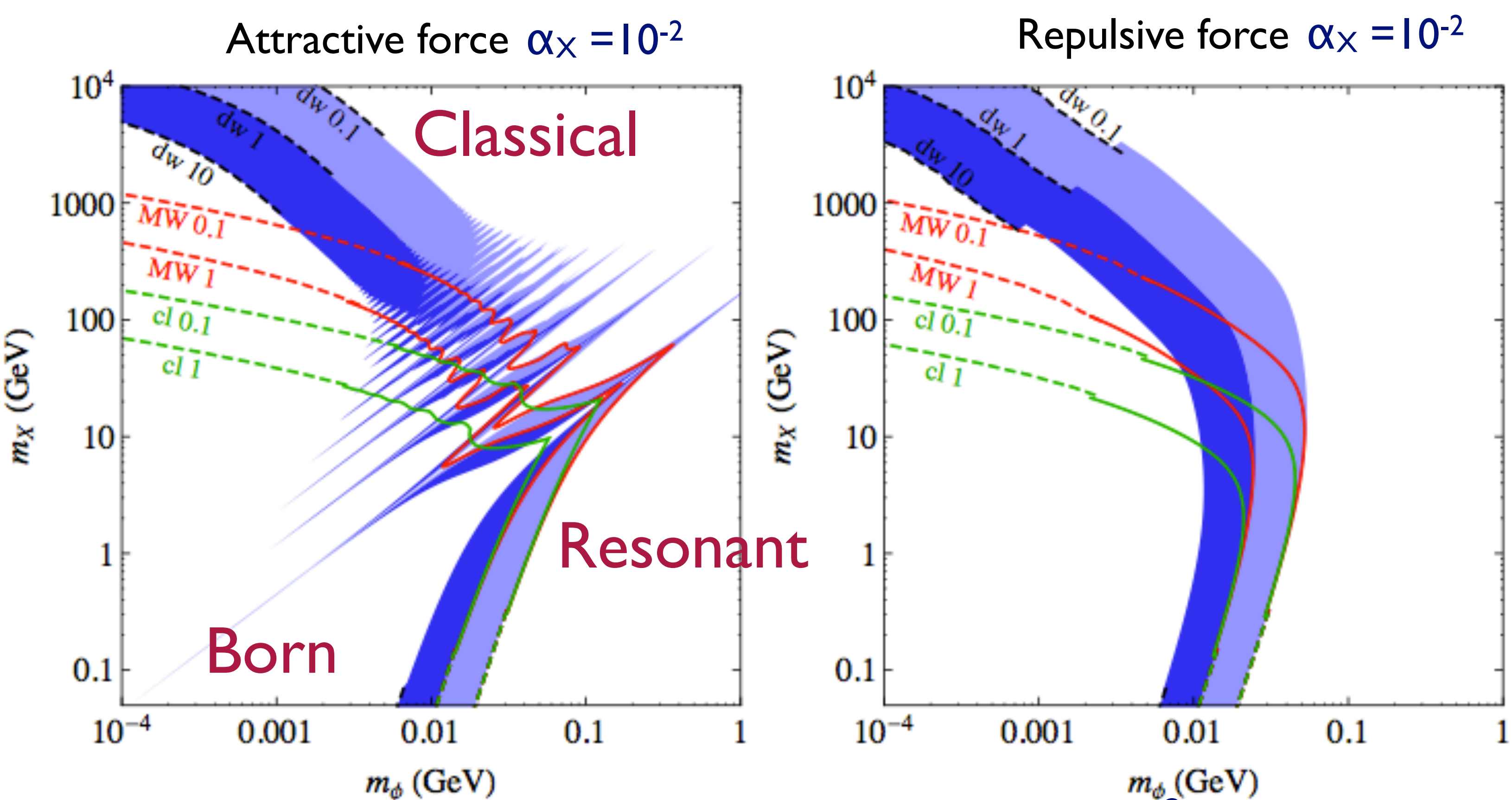
anti-resonance



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

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

Dark Force Parameter Space

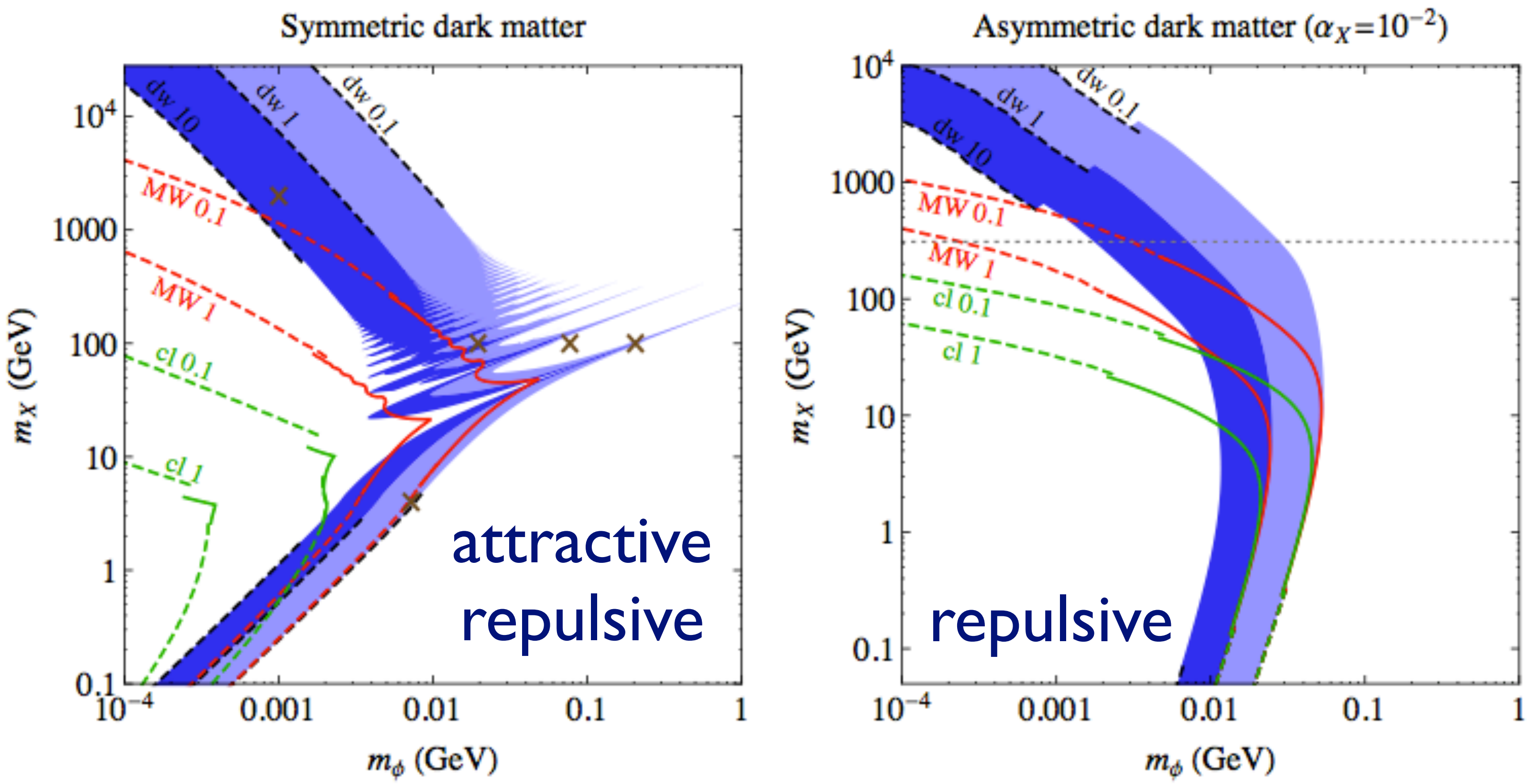


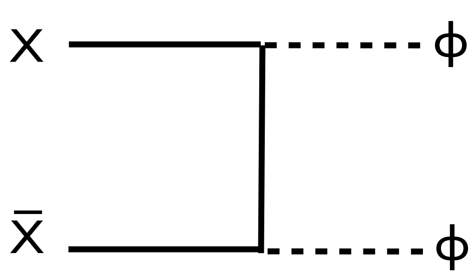
Contours show $\langle\sigma_T\rangle/m_X$ in cm^2/g

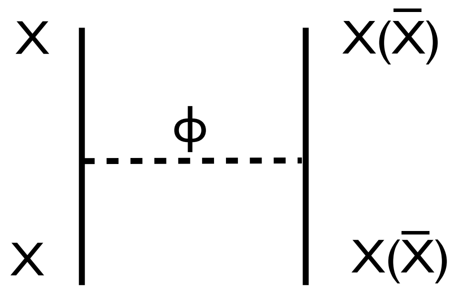
dw: dwarf (10 km/s)
MW: Milky Way (200 km/s)
cl: cluster (1000 km/s)

Blue region: Explain small scale anomalies

A Unified Model







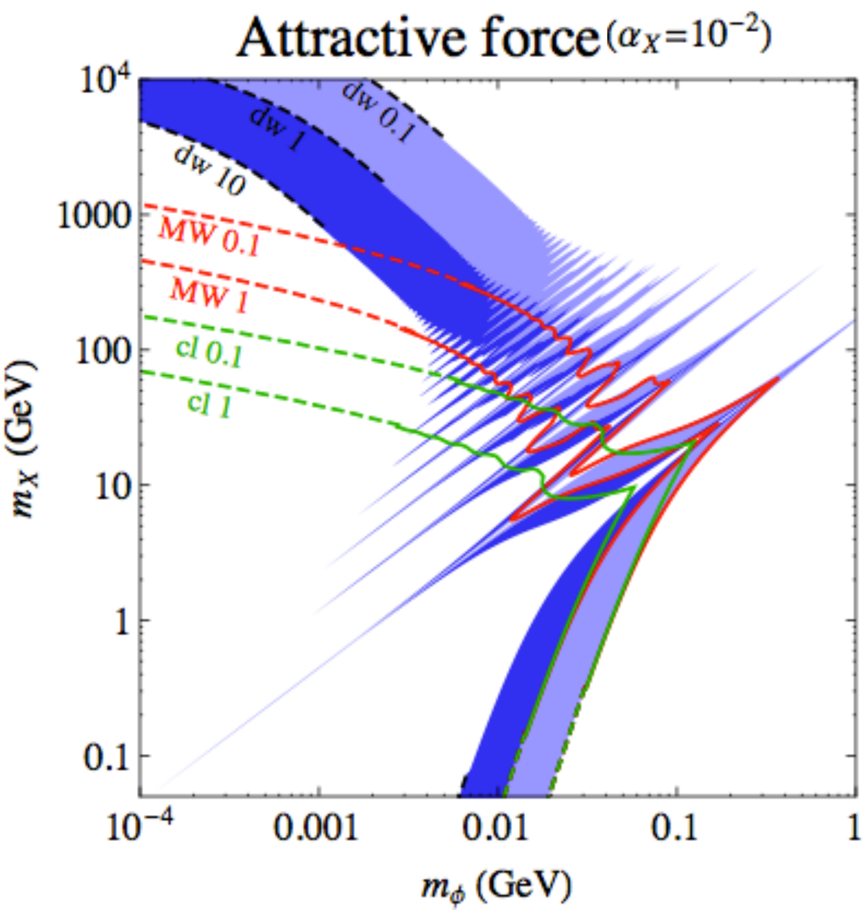
$$\langle \sigma v \rangle = \frac{\pi \alpha_X^2}{m_X}$$
$$\simeq 6 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$
$$\gtrsim 6 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

Fix α_X

Tulin, HBY, Zurek (2012)

Experimental Test

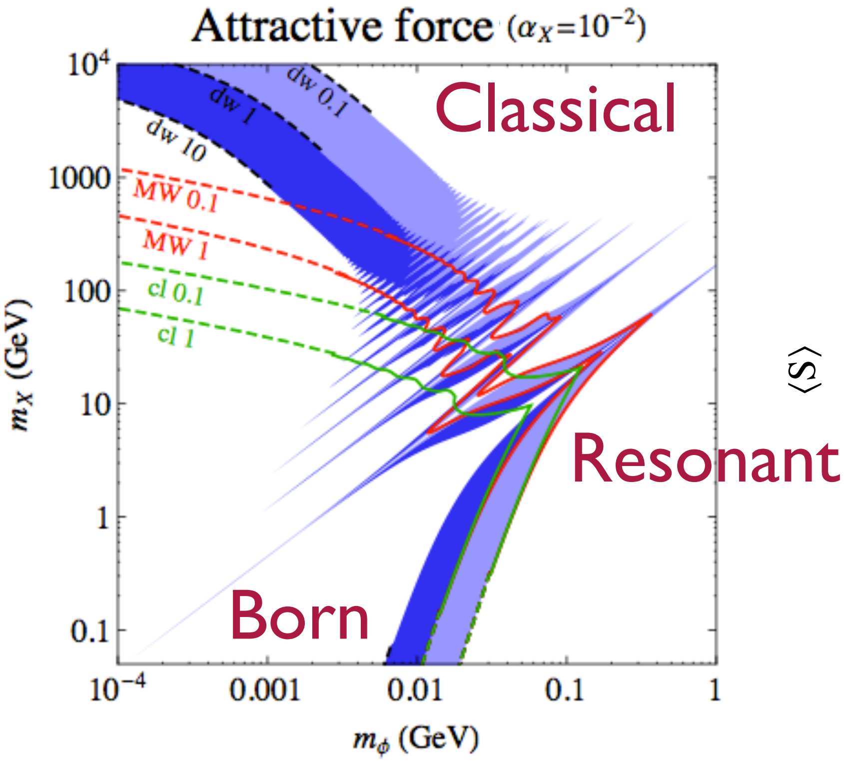
- DM density profiles on different scales

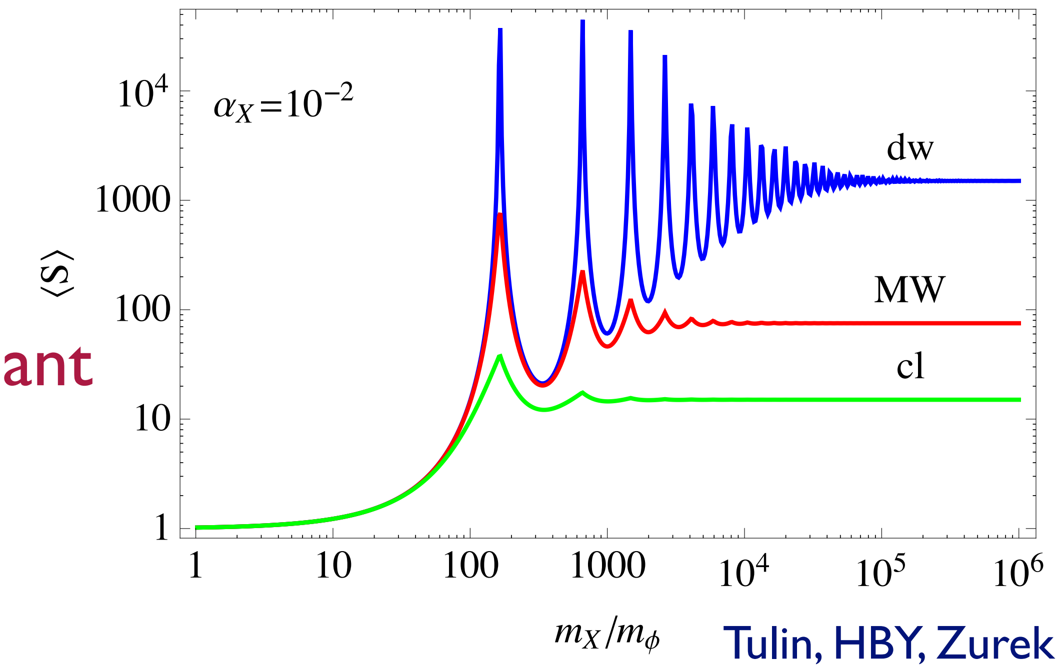


- In the Born regime, σ_T does not depend on DM velocities
- If we also observe DM cores in clusters, the Born regime is preferred

Experimental Test

- Implications for indirect detection





Tulin, HBY, Zurek (2013)

- The light mediator can also lead to Sommerfeld enhancements for DM annihilation
- The resonant conditions are the same for both scattering and annihilation

$<S>_{dw}/<S>_{MW}$

Born regime: O(1)

Resonant regime: O(100)

Classical regime: O(10)

Conclusions

- Considered "nuclear physics" of dark matter
- Solved the scattering problem with a Yukawa potential completely
- Light dark forces can (with one coupling α_X)
  - Explain anomalies on dwarf galaxy scales
  - Satisfy bounds on Milky Way and cluster scales
  - Provide the correct DM relic density
- This scenario is testable