Astrophysical Constraints on Interacting Dark Matter

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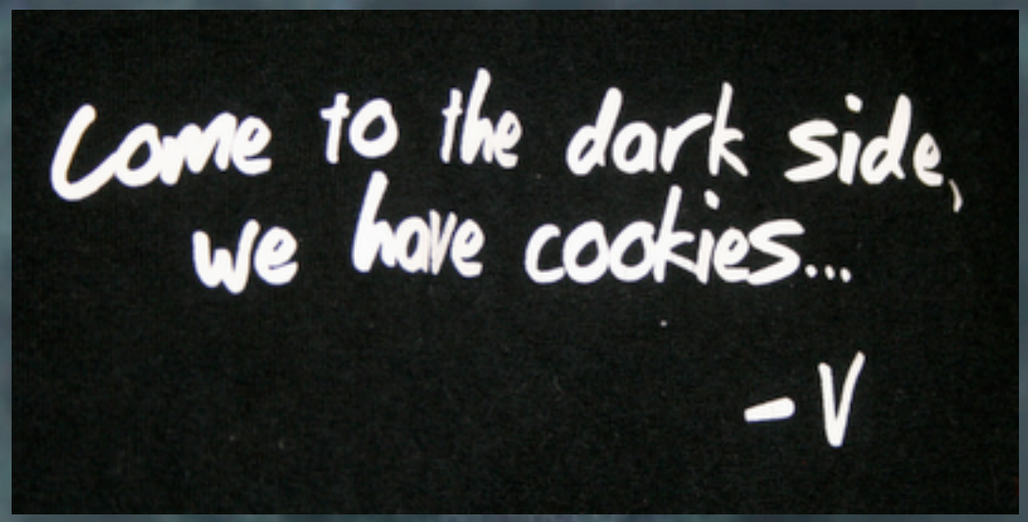
Does the Dark Sector need to be boring?



- WIMP DM fits the observations: $\langle \sigma v \rangle_{\rm thermal} \sim 3 \times 10^{-26} {\rm cm}^3/{\rm s}$
  - Thermal freeze-out with
  - No evidence of non-gravitational interactions
- PAMELA/Fermi/*etc.* anomalies might be from DM
  - Present-day cross-section inconsistent with $\langle \sigma v \rangle_{\rm thermal}$
  - Solutions to this often introduce new forces/ interactions to dark sector.

Complicated Dark Sectors

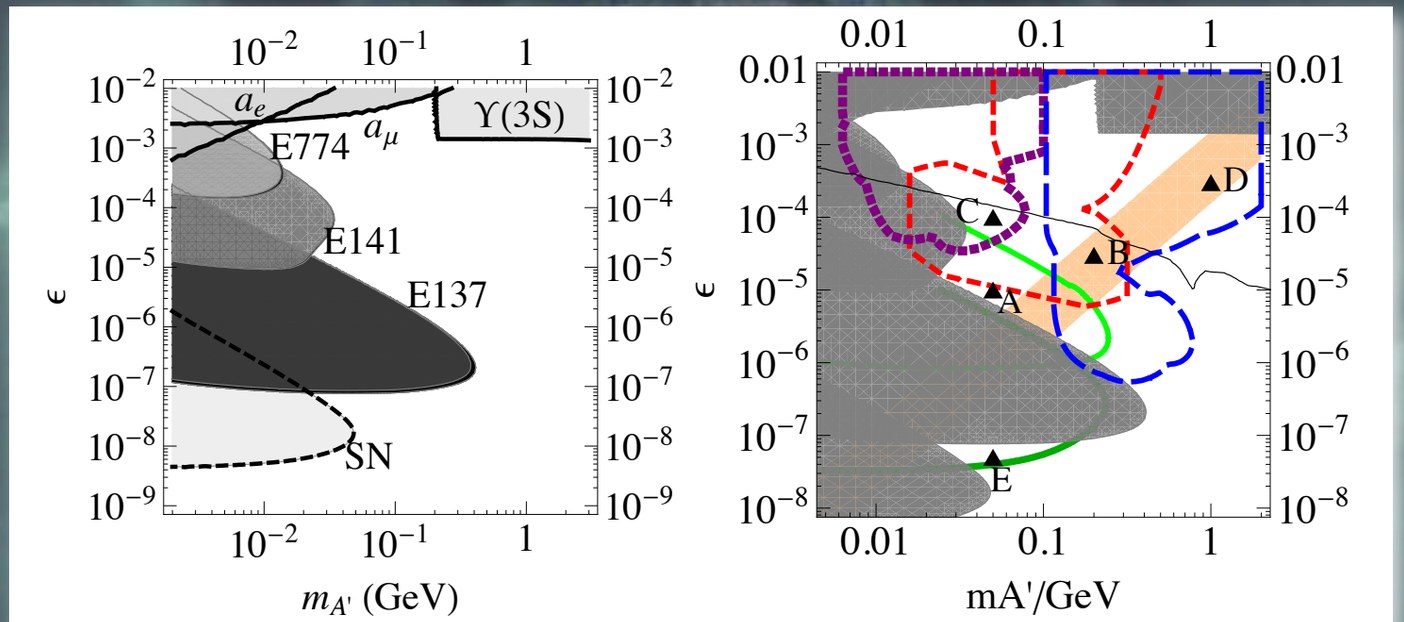
- New light bosons can give large annihilation enhancements
- Leptophilic DM explained through kinematics? or by some DM/leptogenesis connection?
- Dark forces can lead to bound states:
  - Inelastic DM?
  - WMAP haze?

Searches for Dark Light

$$\mathcal{L} \supseteq \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} - m^2_{A'} A'^{\mu} A'_{\mu}$$

- Most searches assume a new broken $U(1)$ with kinetic mixing to the photon.

Bjorken *et. al.* 0906.0580



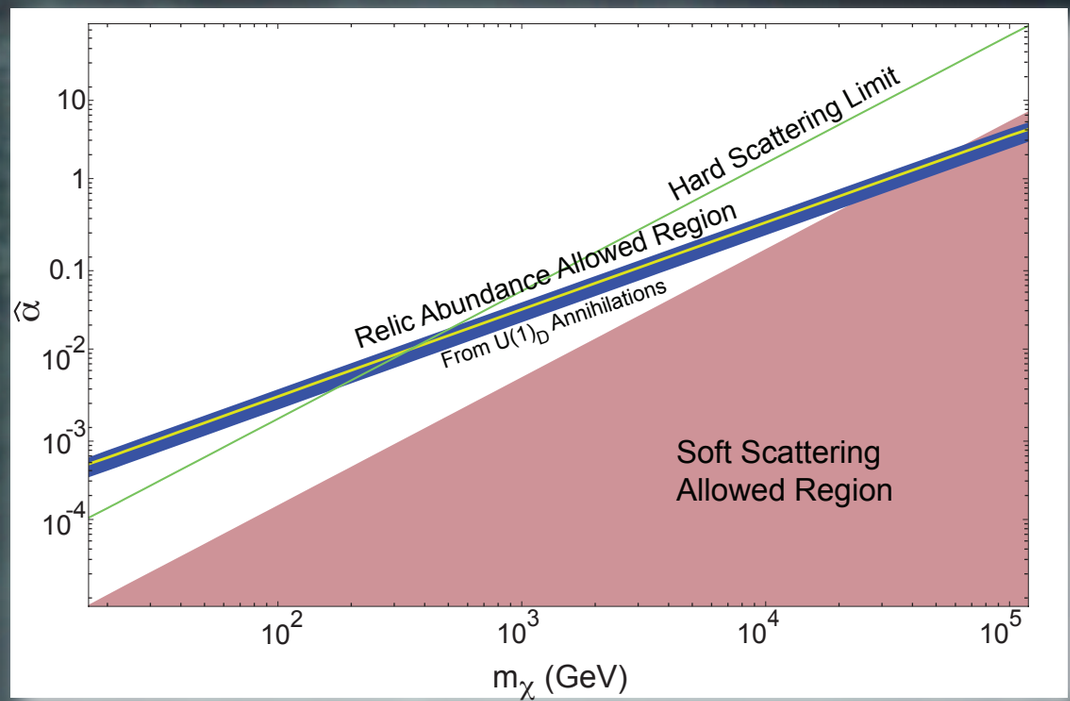
- Some constraints already exist, more possible using existing low-energy $e^- e^+$ beams.

A Different Approach

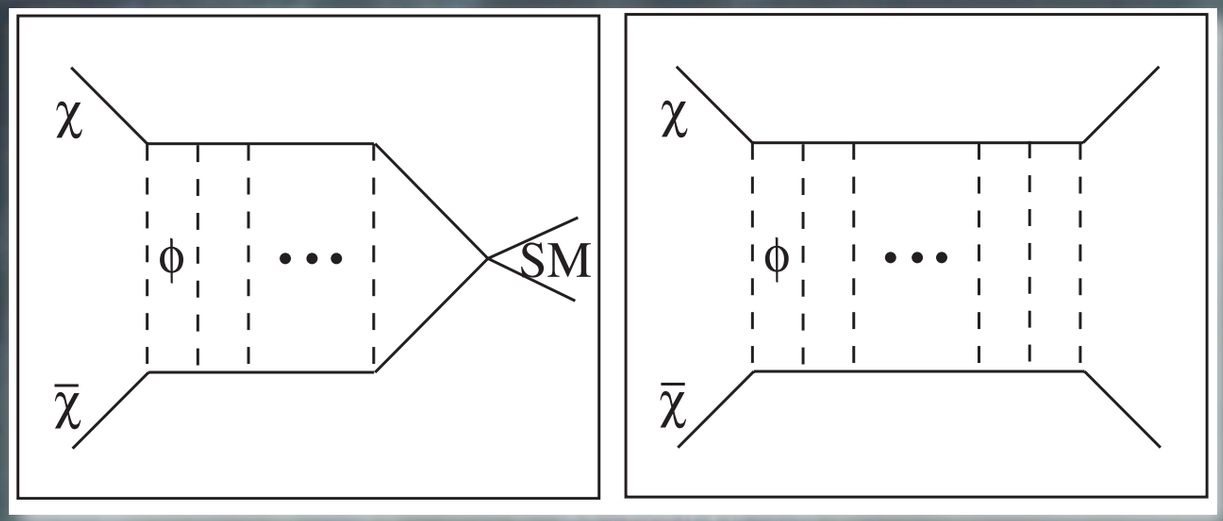
- Direct searches require model-dependent assumptions:
  - Gauge bosons rather than scalars
  - Dark photon - photon kinetic mixing
  - Coupling to SM fields
- Instead, look at DM-DM scattering mediated by the new dark force.
  - Constraints come from studies of galaxy formation and structure.
  - Avoids many of the assumptions above.

Dark Matter Scattering

- Strength of long-range dark forces limited by repeated soft-scattering in galactic halos (Ackerman *et. al.* 0810.5126, Feng *et. al.* 0905.3039)
- Halo DM constrained to exchange less than $\mathcal{O}(1)$ of K.E. over dynamical time.
- Short-range forces lack 'Coulomb logarithm' but can still have Sommerfeld-like enhancements of scattering.



Sommerfeld Enhancement



- Presence of ϕ-induced potential alters ψ at both origin (annihilation) and infinity (scattering).
- Calculation can be approached classically (Feng *et. al.* 0911.0422) or through quantum mechanics (MRB & Fox 0911.3898)
- In QM, resonances in spectrum give large enhancements to both processes when $E_{\rm res.} \approx K.E.$

QM Scattering

MRB & Fox 0911.3898

- Solve Schrödinger equation with potential

$$V(r) = -\frac{\alpha}{r} e^{-m_\phi r} \quad \text{and B.C.} \quad R_\ell \to \alpha m_\chi \sin\left(\frac{kr}{2} - \frac{\pi\ell}{2} + \delta_\ell\right)$$

- Scattering cross section $\sigma = \frac{4\pi}{k^2} \sum_\ell (2\ell+1) \sin^2 \delta_\ell$
- Can only solve for finite number of ℓ values:

$$\ell_{\max} = k b_{\max} \quad \text{where} \quad K.E. = V(b_{\max})$$

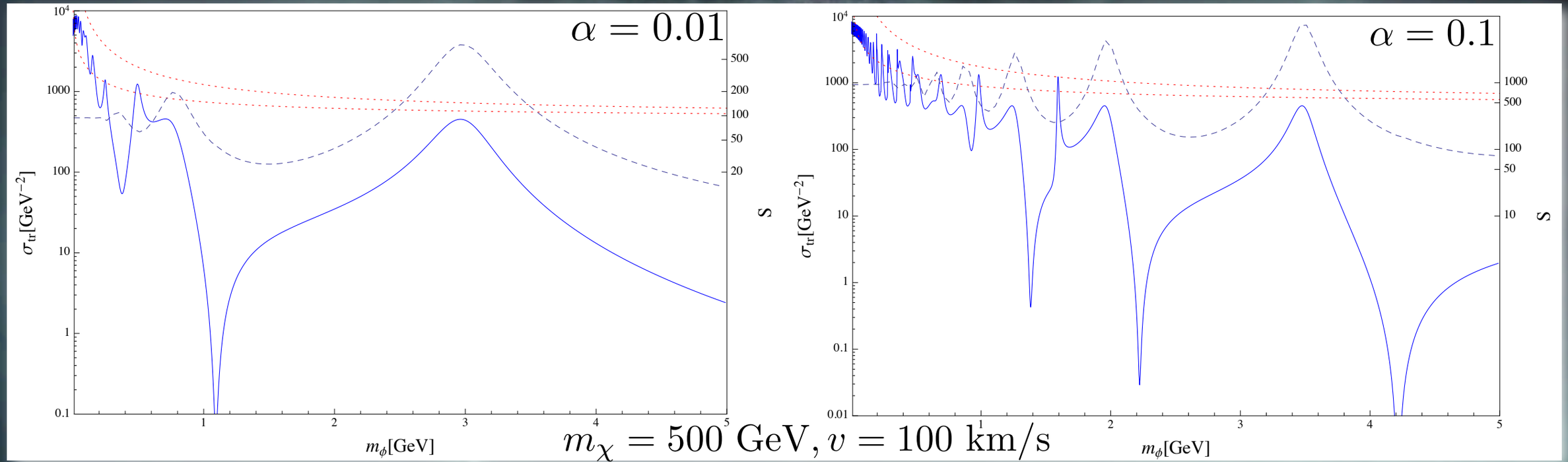
- Use transfer cross section to avoid low-energy divergence:

$$\sigma_{\rm tr} = \int d\Omega (1 - \cos\theta) \frac{d\sigma}{d\Omega}$$

QM Scattering

- Can make approximation that $\sin\delta_\ell \to 1$ for $\ell \leq \ell_{\rm max}$

$$\sigma_{\rm approx.} = \frac{4\pi}{m_\chi^2 v^2}(1+\ell_{\rm max})^2 \quad \sigma_{\rm tr,approx.} = \frac{4\pi}{m_\chi^2 v^2}(1+\ell_{\rm max})$$



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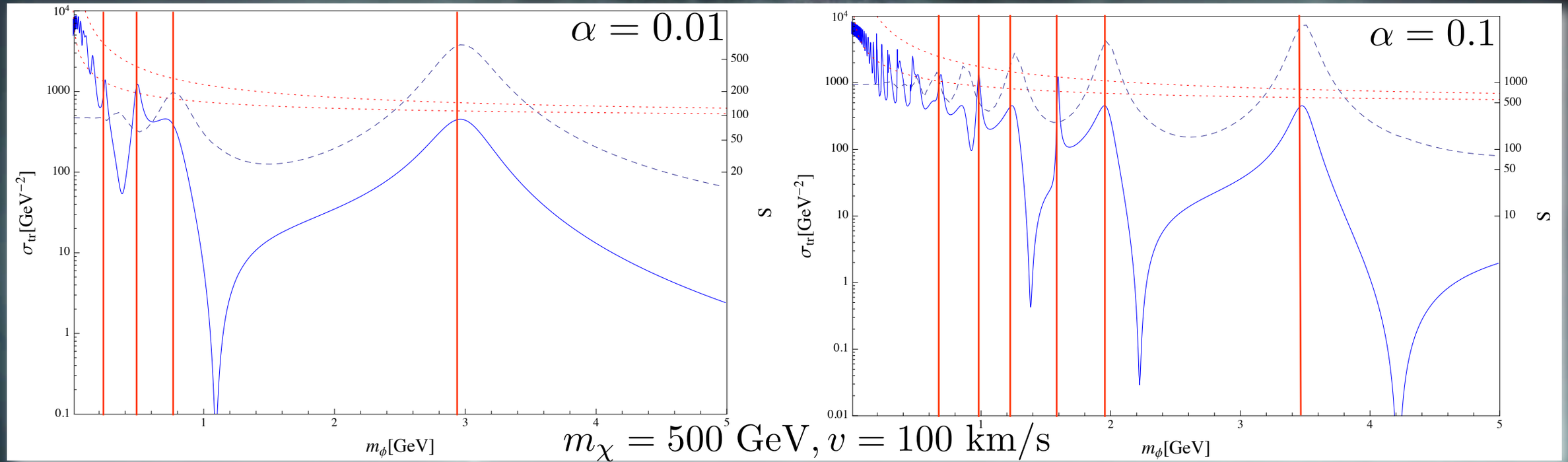


Resonance when $\sin\delta_\ell = 1$

Classical Scattering

Feng, Kaplinghat & Yu 0911.0422

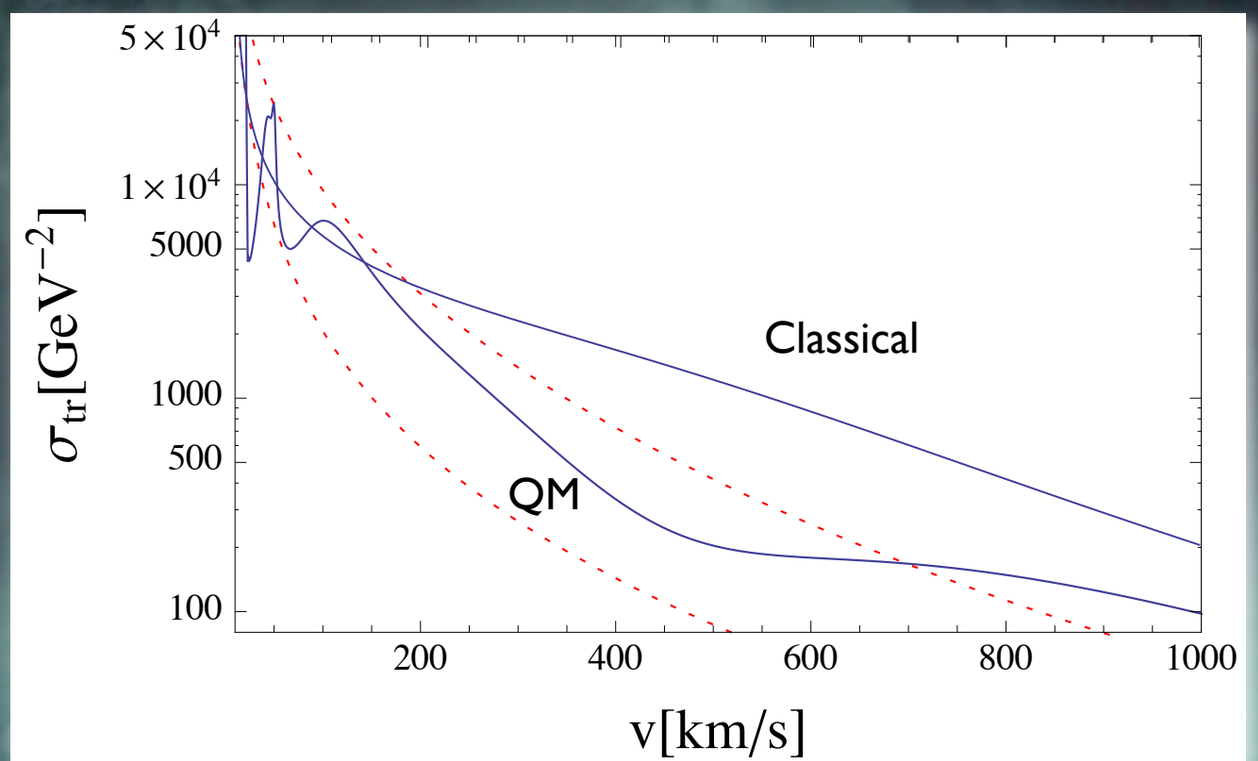
- Classical calculations from plasma physics applicable:

$$\sigma_{\rm tr} \approx \frac{4\pi}{m_\phi^2}\beta^2 \ln\left(1+\beta^{-1}\right), \beta < 0.1$$

$$\sigma_{\rm tr} \approx \frac{8\pi}{m_\phi^2}\frac{\beta^2}{1+1.5\beta^{1.65}}, 0.1 < \beta < 1000$$

$$\beta \equiv \frac{2\alpha m_\phi}{m_\chi v_{\rm rel}^2}$$

Classical calculation analytic, easier to work with.
Misses resonant behavior present in full QM formula.



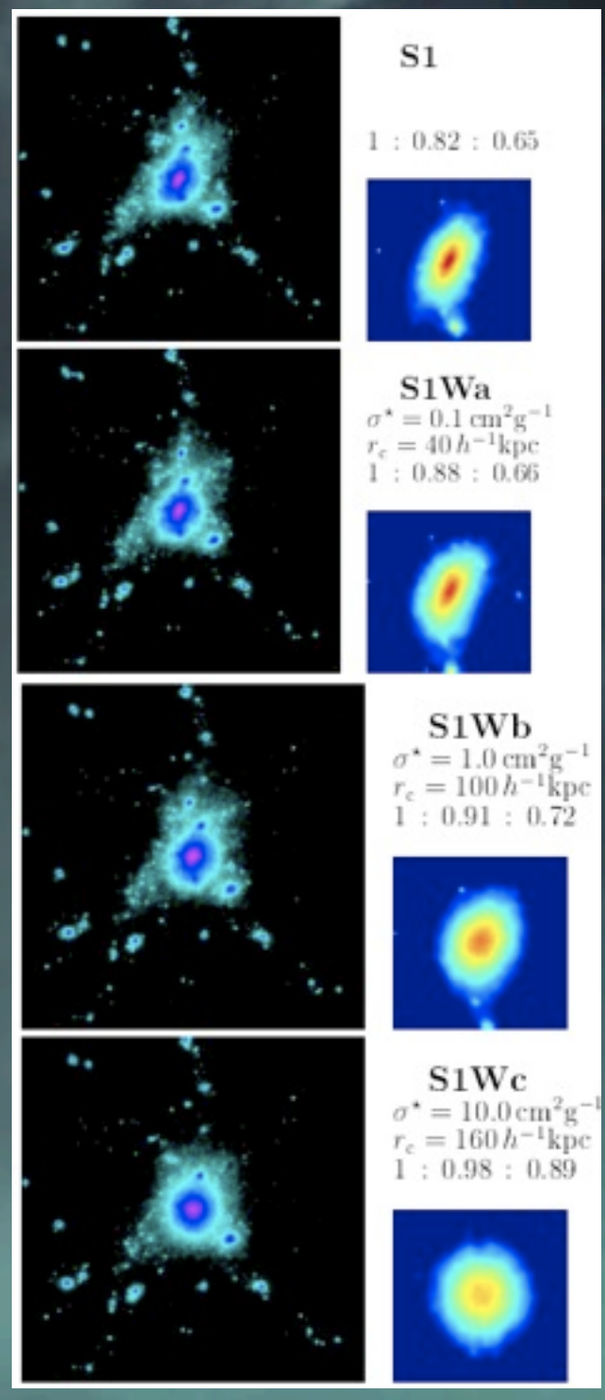
Galactic Dynamics

- Bound placed on $\sigma_{\rm tr}/m_\chi$
  - Work in units of $\mathrm{cm}^2/\mathrm{g} = 2 \times 10^{-4}\ \mathrm{GeV}^{-3}$
- Generally, DM cannot exchange $\mathcal{O}(1)$ of its kinetic energy in lifetime of the system.
  - As ϕ -enhanced scattering has $\sigma_{\rm tr} \propto v^{-\alpha}$, we want the strongest bound on $\sigma_{\rm tr}/m_\chi$ for systems with the lowest velocity.
- Note that almost all bounds assume hard-sphere scattering: *i.e.* velocity-independent

Galactic Dynamics

System	$v(\mathrm{km/s})$	$\sigma_{\mathrm{tr}}/m_\chi \mathrm{cm}^2/\mathrm{g}$
Bullet Cluster	1000	1.25
Galactic Evaporation	1000	0.3
Elliptic Clusters	1000	0.02
Dwarf Evaporation	100	0.1
Black Hole Growth	100	0.02
Mean Free Path	$44 - 2400$	$0.01 - 0.6$
Dwarf Galaxies	10	0.1

Yoshida *et. al.* astro-ph/0006134



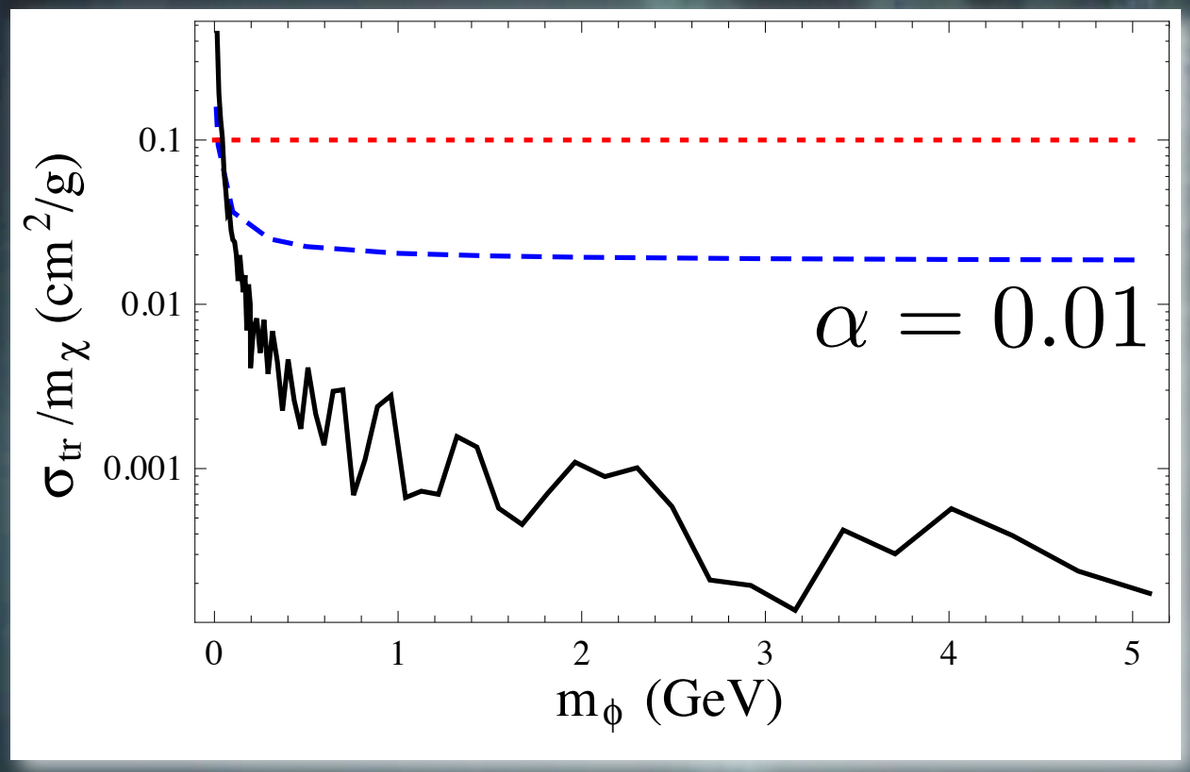
Dwarf Galaxy Bounds

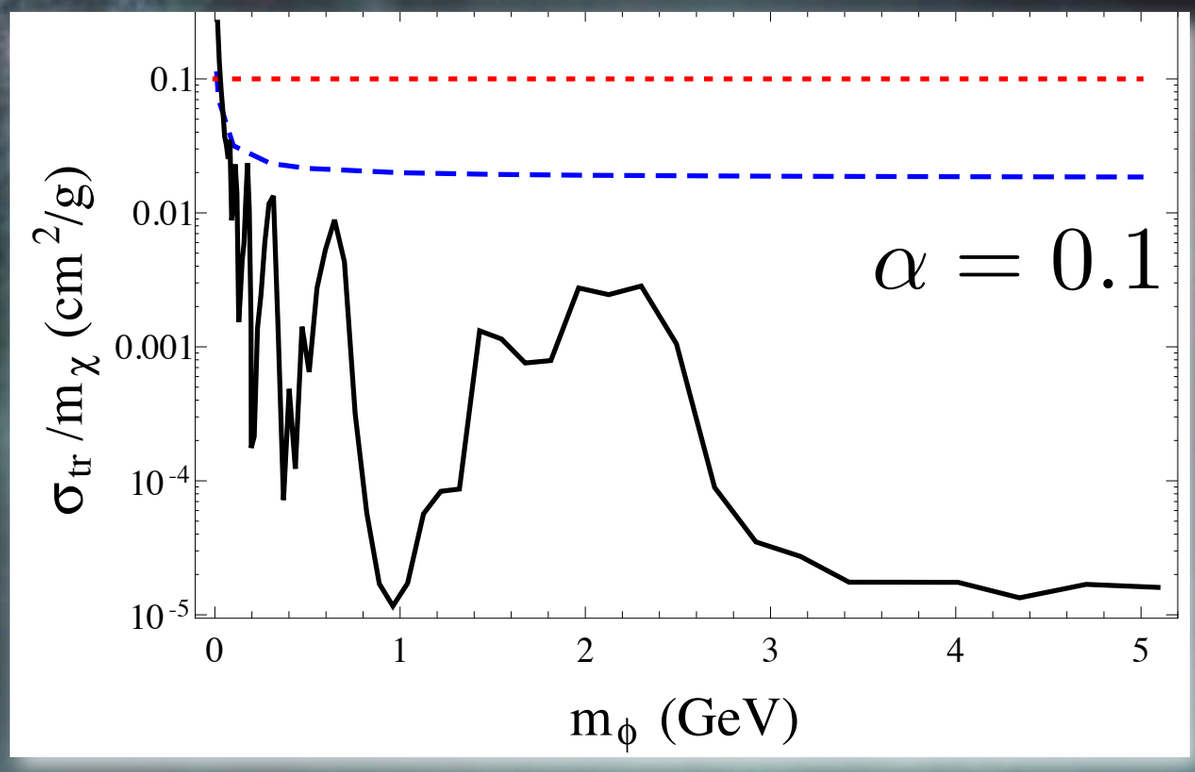
- Dwarf galaxies weakly bound, so $v \sim 10\ \mathrm{km/s}$
- Shown by Spergel & Steinhardt (astro-ph/9909386) that increased DM scattering reduced number of dwarf galaxies and the cuspiness of dwarf halos.
- Originally thought that this was necessary to solve "missing satellite problem."
- This is now solved by tidal stripping and photo-ionization effects, forcing the DM scattering effect to be small.

Placing Bounds

- Integrate over a Maxwell-Boltzmann distribution

$$\langle \sigma_{\rm tr} \rangle = \int f(\vec{v}_1) f(\vec{v}_2) \frac{d\sigma_{\rm tr}}{d\Omega}(\vec{v}_1 - \vec{v}_2) d\vec{v}_1 d\vec{v}_2 d\Omega$$



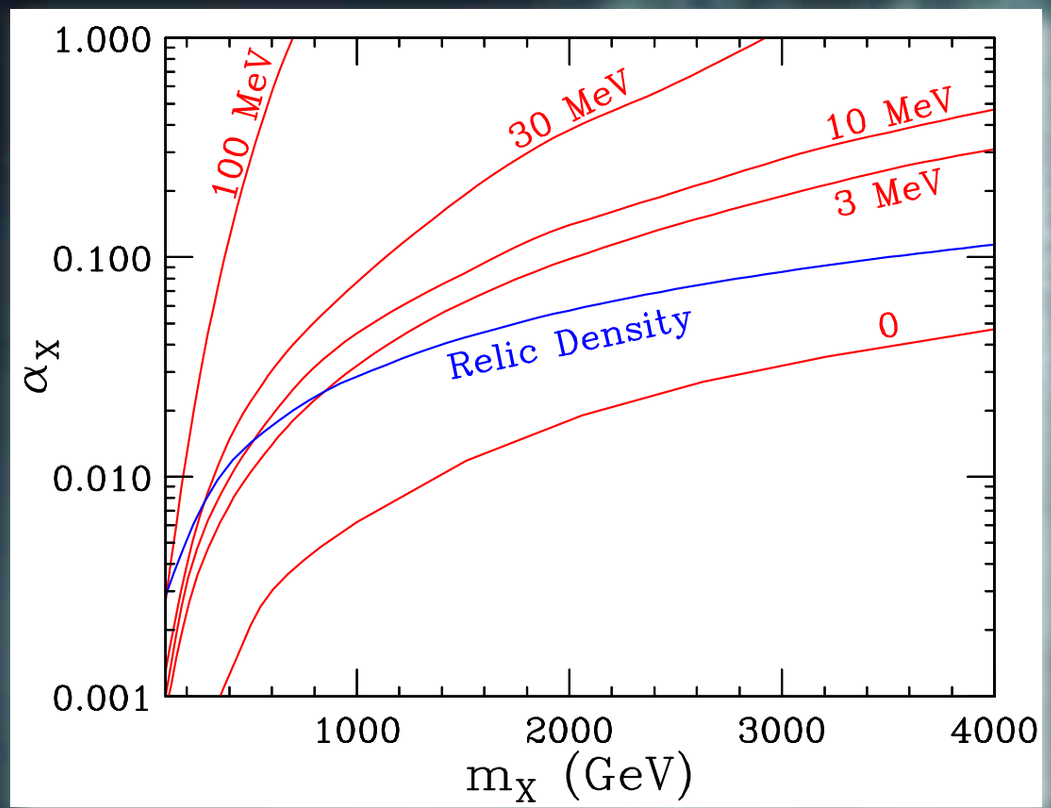


$$m_\chi = 500 \text{ GeV}, v_0 = 10 \text{ km/s}$$

MRB & Fox 0911.3898

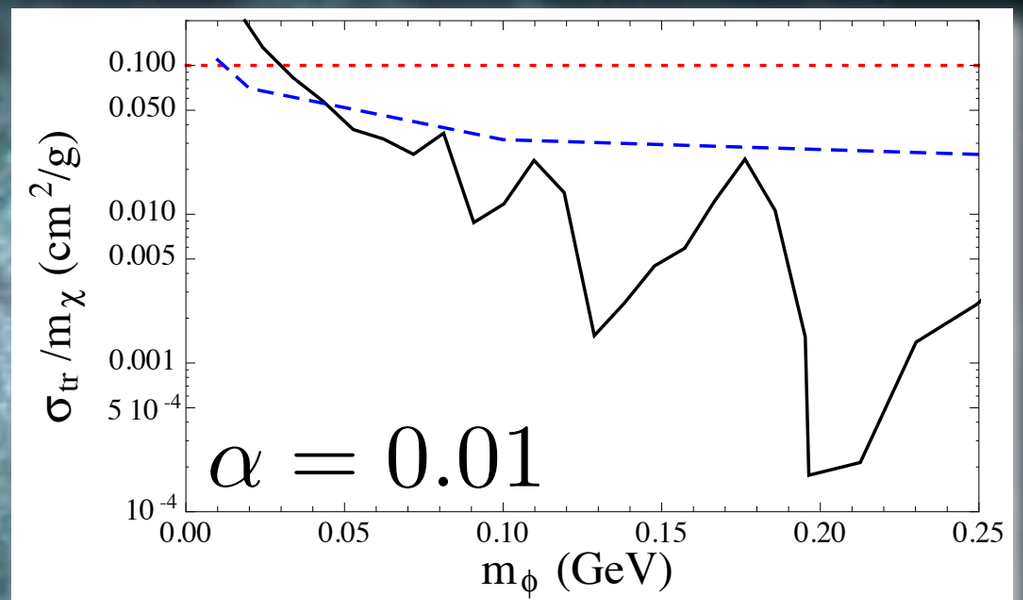
Placing Bounds

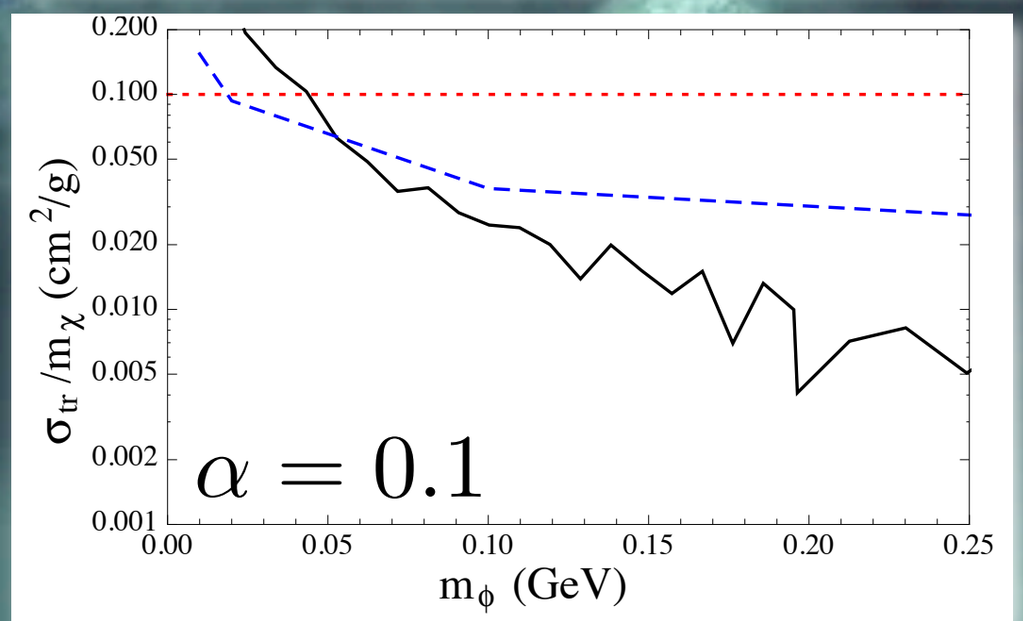
Classical bounds from $v_0 \sim 100$ km/s systems



Feng, Kaplinghat & Yu 0911.0422

QM: $v_0 = 10$ km/s





MRB & Fox 0911.3898

Conclusions

- Current bounds exclude $m_\phi \lesssim 50$ MeV, cannot exclude many interesting dark force models
  - These bounds derived from v-independent σ
  - Possible to improve with future simulations?
    - Keep in mind, many bounds non-linear
- Resonant behavior can have surprisingly large effects, especially in large m_ϕ regime
- Interesting effects from dark forces on nucleon/DM scattering?

Background provided by A. Brooks, F. Governato, and the U. Washington's *N*-Body Shop.