Inelastically Self-Interacting Dark Matter

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(work in preparation)

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Beyond CDM

- Several observational hints that the central regions of dark matter halos may be less concentrated than expected from N-body simulations. (See plenary talks tomorrow.)

- “Too big to fail” problem - massive dwarf-scale halos predicted in simulations do not appear to have observed counterparts. Observed most-massive dwarfs tend to have lower masses and central densities than predicted. We expect that such massive halos should always form stars and thus be observable.

- Studied in satellites of the Milky Way (Boylan-Kolchin et al 1103.0007) and M31 (Tolllerud et al 1403.6469), recent study on dwarfs in the Local Field (Garrison-Kimmel et al 1404.5313): all find this issue.

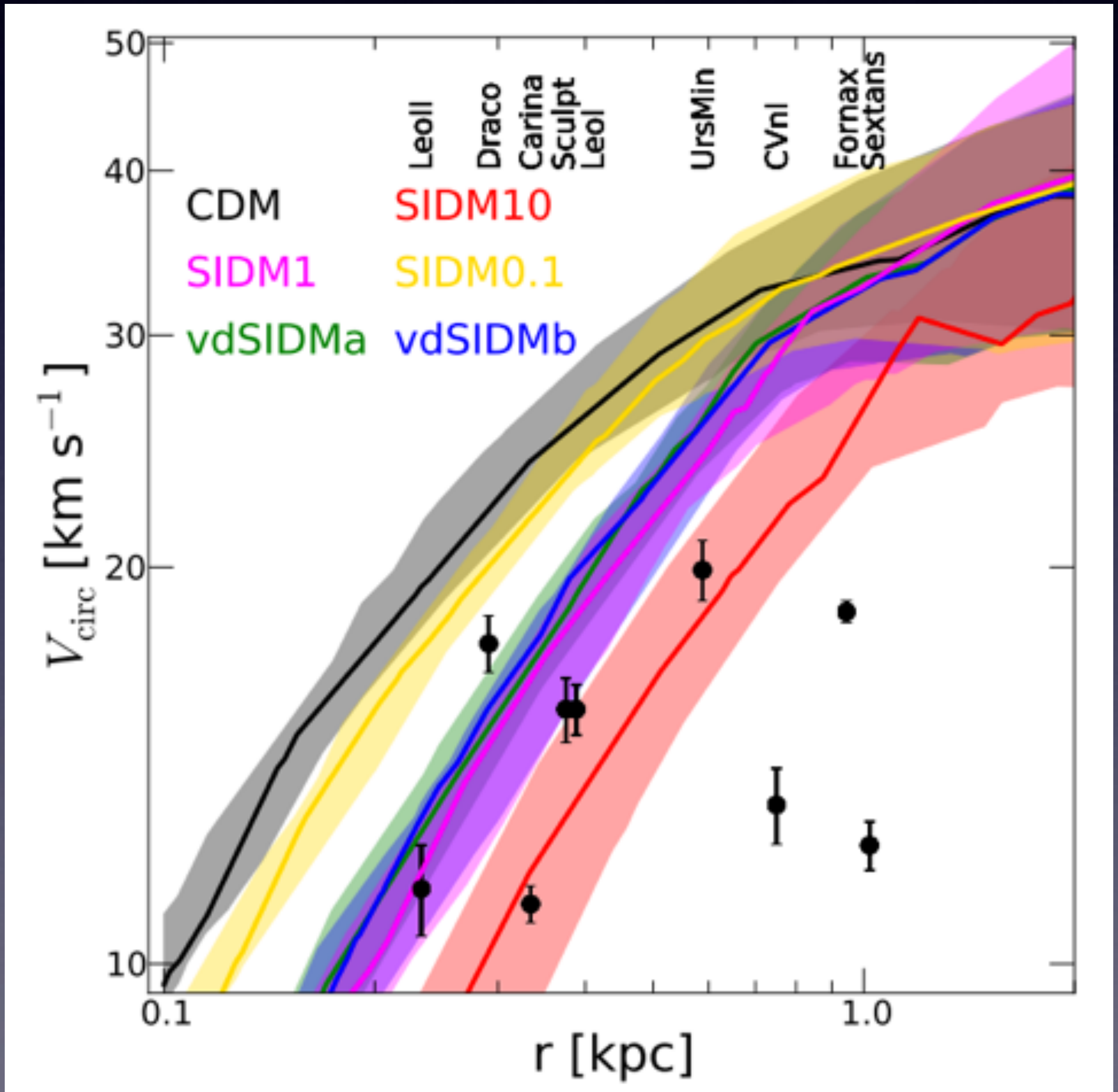
- “Cusp-core problem” - N-body simulations predict dark matter density should scale roughly as 1/r toward the center of halos (“NFW profile”), observations of dwarf galaxies and low-surface-brightness galaxies suggest a flatter profile (a “core”).

- Baryonic physics may resolve the discrepancies, but there are large uncertainties - e.g. choice of star formation history significantly affects results - and it is not clear if baryonic processes can explain the results from outside large galaxies.

Why self-interaction?

- Dark matter self-interaction with cross section $\sigma/m_\chi \sim 0.1\text{-}1\ cm^2/g$ could lower dark matter density in halo cores, as particles are scattered out of the dense cusp, and help resolve these issues.
- Potential to test these cross sections directly in galaxy clusters (e.g. W. Dawson, talk at "Debates on the Nature of Dark Matter" 2014).
- Important to understand how dark sector physics might affect observations, independent of any DM coupling to the Standard Model.

Example: too big to fail problem



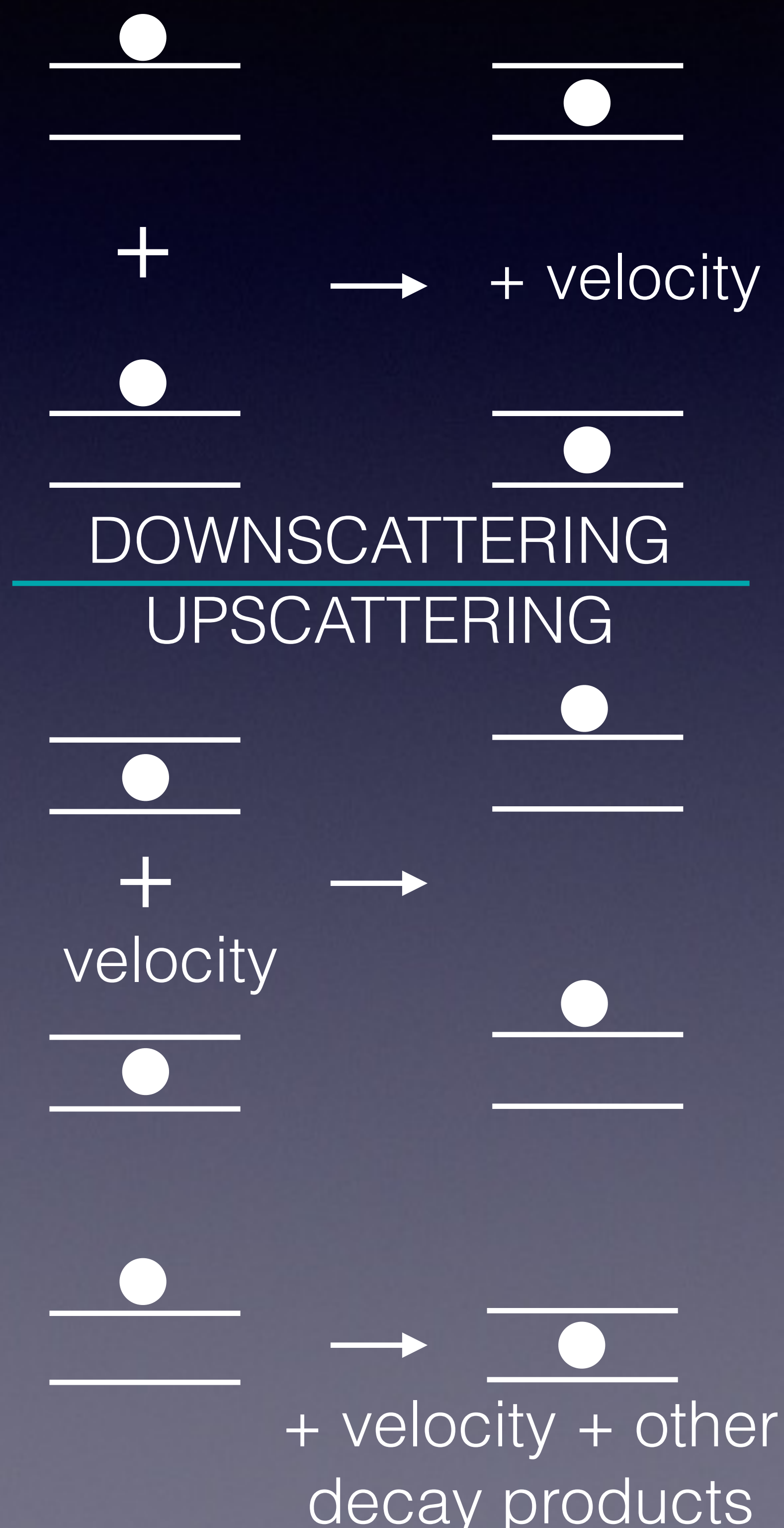
Zavala et al 1211.6426

Excited states

- Suppose that dark matter is multi-component. We will call the lightest stable state "dark matter". Other states may play an important role in phenomenology, especially if they are stable/metastable, and/or close in mass to the dark matter.
- Nearly-degenerate "excited states" for the DM naturally arise in models of expanded dark sectors where DM is part of a multiplet; also occur in composite dark matter models.
- Models of dark matter with nearly-degenerate excited states have interesting phenomenology and have been suggested in many contexts:
    - Scattering in direct detection experiments (Smith & Weiner 2001),
    - Indirect detection signatures of collisional excitations followed by decay to SM particles (e.g. Finkbeiner & Weiner 2007),
    - Decays from the excited state can help solve the "too big to fail" problem and flatten halo cores, by giving the decay products velocity "kicks" (e.g. Peter et al 2010) - if comparable to the circular velocity, these will deplete halos. Recently confirmed by simulation (Wang et al 1406.0527).

Inelastic self-interaction

- Nearly-degenerate excited state => novel scattering kinematics.
- Similar to decays from the excited state, collisional de-excitation of a long-lived population in the excited state will confer velocity kicks, depleting dense regions of halos (e.g. Loeb & Weiner 2011) and naturally producing cores.
- Collisional up-scattering might have the opposite effect, setting constraints on models that invoke it.
- Has not yet been studied in simulations or detailed calculations, only simple estimates of its effects.



A simple inelastic model

- Ingredients:
  - Pseudo-Dirac fermion dark matter (Dirac at high energies, split into nearly-degenerate Majorana fermions at low energies).
  - Long-range interaction mediated by a dark U(1), dark gauge boson denoted ϕ.
  - Since Majorana fermions don't carry conserved charge, low-energy interaction is purely off-diagonal in the mass eigenstate basis - $\phi\chi_1\chi_2$ but not $\phi\chi_1\chi_1$.
  - Scatterings thus couple $\chi_1\chi_1$ to $\chi_2\chi_2$, and $\chi_1\chi_2$ to $\chi_2\chi_1$ - the latter is always elastic scattering, the former is inelastic and described by the matrix potential:

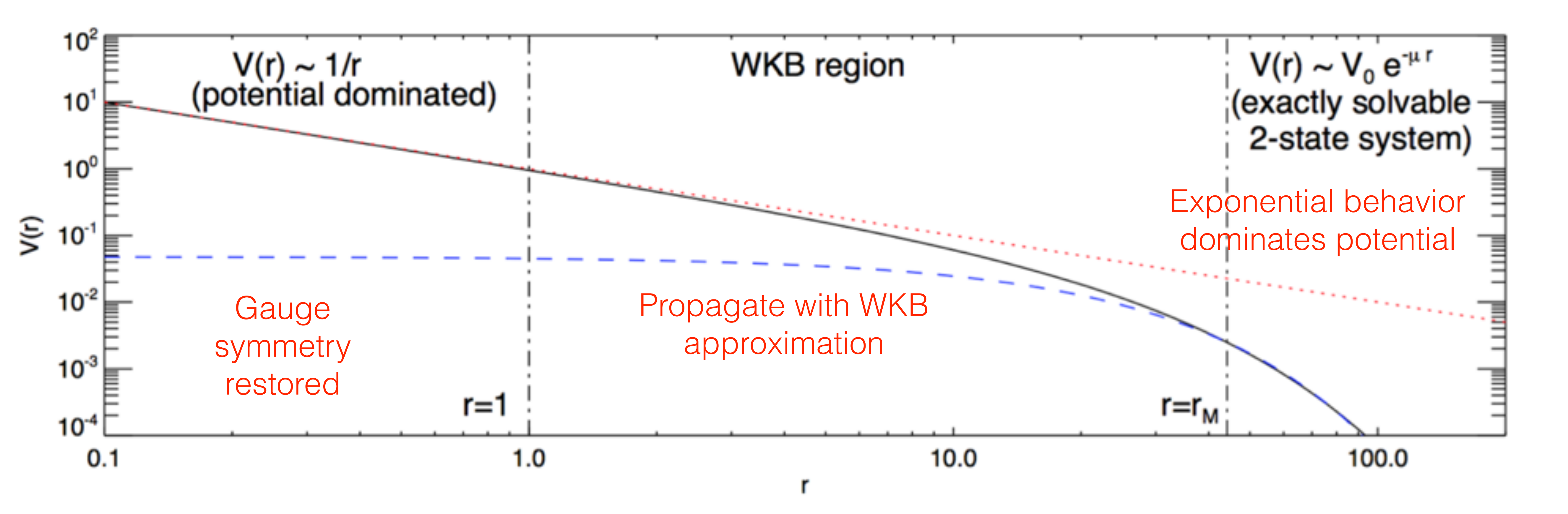
$$V(r) = \begin{pmatrix} 0 & -\hbar c\alpha \frac{e^{-m_\phi c r/\hbar}}{r} \\ -\hbar c\alpha \frac{e^{-m_\phi c r/\hbar}}{r} & 2\delta c^2 \end{pmatrix}$$

Yukawa-like potential   mass splitting

- Goal: develop analytic expression for scattering in this system, to build intuition and as a concrete physical example for incorporation into simulations.

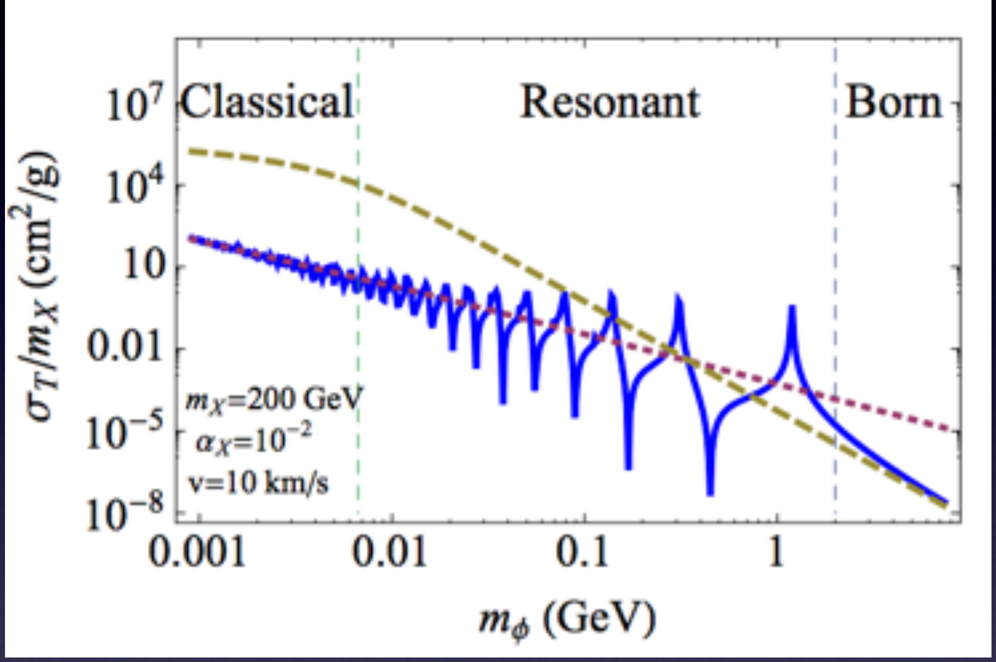
A semi-analytic solution

- This model was analyzed in 2009 in the context of dark matter annihilation - solving the Schrodinger equation is (semi-)analytically tractable, can be used as a toy model to study the non-perturbative effects of the excited state. (Found shifts in the resonance structure + enhanced annihilation.)
- Current work (to appear): extend the calculation to the case of scattering.



Scattering regimes

Tulin, Yu & Zurek 1302.3898



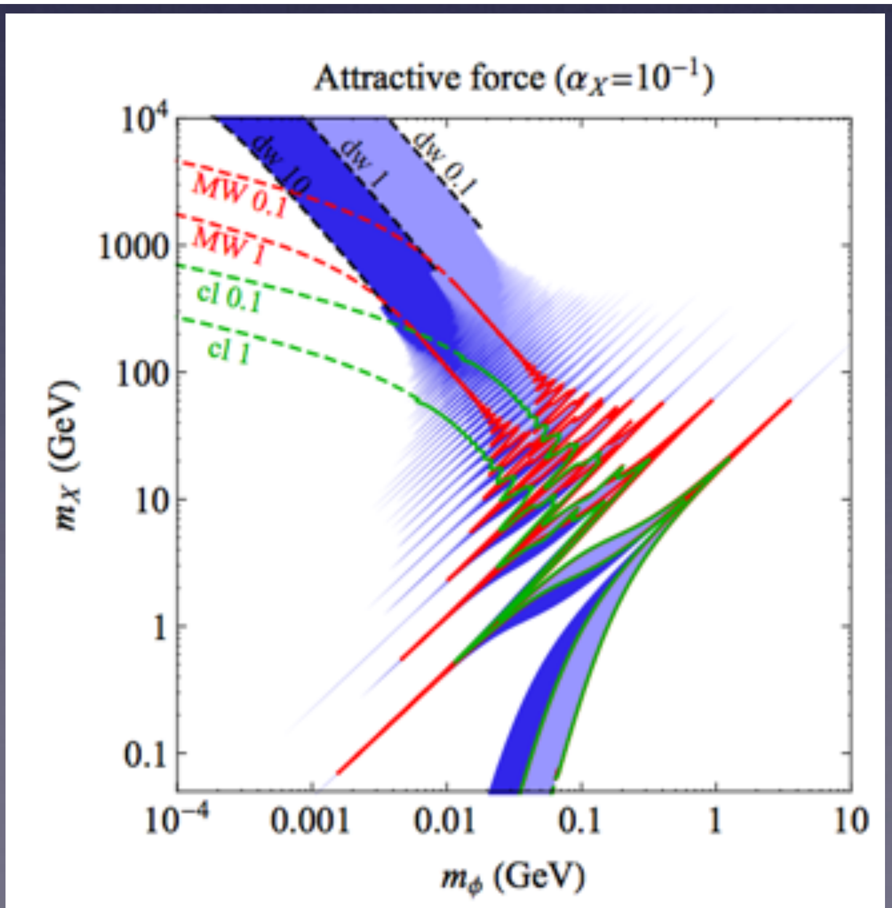
- Classical - large number of partial waves must be taken into account. Holds at high velocities relative to force carrier mass ($v/c > m_\phi/m_\chi$).

- Perturbative - Born approximation / Feynman diagrams are appropriate, holds for $\alpha < m_\phi/m_\chi$ or $\alpha < v/c$.

  Straightforward to generalize to inelastic case.

- Resonant - s-wave scattering dominates, zero-energy bound states in the spectrum lead to sharp resonances and anti-resonances. Important for $v/c < m_\phi/m_\chi < \alpha$ - often relevant in dwarf galaxies.

  Subject of this work.



Cross sections

- Resonance structure is captured by angle ϕ. This angle is defined in terms of a numerical integral, detailed expression in TRS 0910.5713, approximately:

$$\varphi \approx -\sqrt{2\pi/\epsilon_\phi}$$

$$\sigma_{\mathrm{gr}\to\mathrm{gr}} = \frac{\pi}{\epsilon_v^2}\left|1+\left(\frac{V_0}{4\mu^2}\right)^{-\frac{2i\epsilon_v}{\mu}}\left(\frac{\Gamma_v}{\Gamma_v^*}\right)\left[\frac{\cosh\left(\frac{\pi(\epsilon_\Delta+\epsilon_v)}{2\mu}\right)\sinh\left(\frac{\pi(\epsilon_v-\epsilon_\Delta)}{2\mu}+i\varphi\right)}{\cosh\left(\frac{\pi(\epsilon_\Delta-\epsilon_v)}{2\mu}\right)\sinh\left(\frac{\pi(\epsilon_\Delta+\epsilon_v)}{2\mu}-i\varphi\right)}\right]\right|^2$$

$$\sigma_{\mathrm{ex}\to\mathrm{ex}} = \frac{\pi}{\epsilon_\Delta^2}\left|1+\left(\frac{V_0}{4\mu^2}\right)^{-\frac{2i\epsilon_\Delta}{\mu}}\left(\frac{\Gamma_\Delta}{\Gamma_\Delta^*}\right)\left[\frac{\cosh\left(\frac{\pi(\epsilon_\Delta+\epsilon_v)}{2\mu}\right)\sinh\left(\frac{\pi(\epsilon_\Delta-\epsilon_v)}{2\mu}+i\varphi\right)}{\cosh\left(\frac{\pi(\epsilon_\Delta-\epsilon_v)}{2\mu}\right)\sinh\left(\frac{\pi(\epsilon_\Delta+\epsilon_v)}{2\mu}-i\varphi\right)}\right]\right|^2$$

$$\sigma_{\mathrm{gr}\to\mathrm{ex}} = \frac{2\pi\cos^2\varphi\,\sinh\left(\frac{\pi\epsilon_v}{\mu}\right)\sinh\left(\frac{\pi\epsilon_\Delta}{\mu}\right)}{\epsilon_v^2\cosh^2\left(\frac{\pi(\epsilon_\Delta-\epsilon_v)}{2\mu}\right)\left(\cosh\left(\frac{\pi(\epsilon_v+\epsilon_\Delta)}{\mu}\right)-\cos(2\varphi)\right)}$$

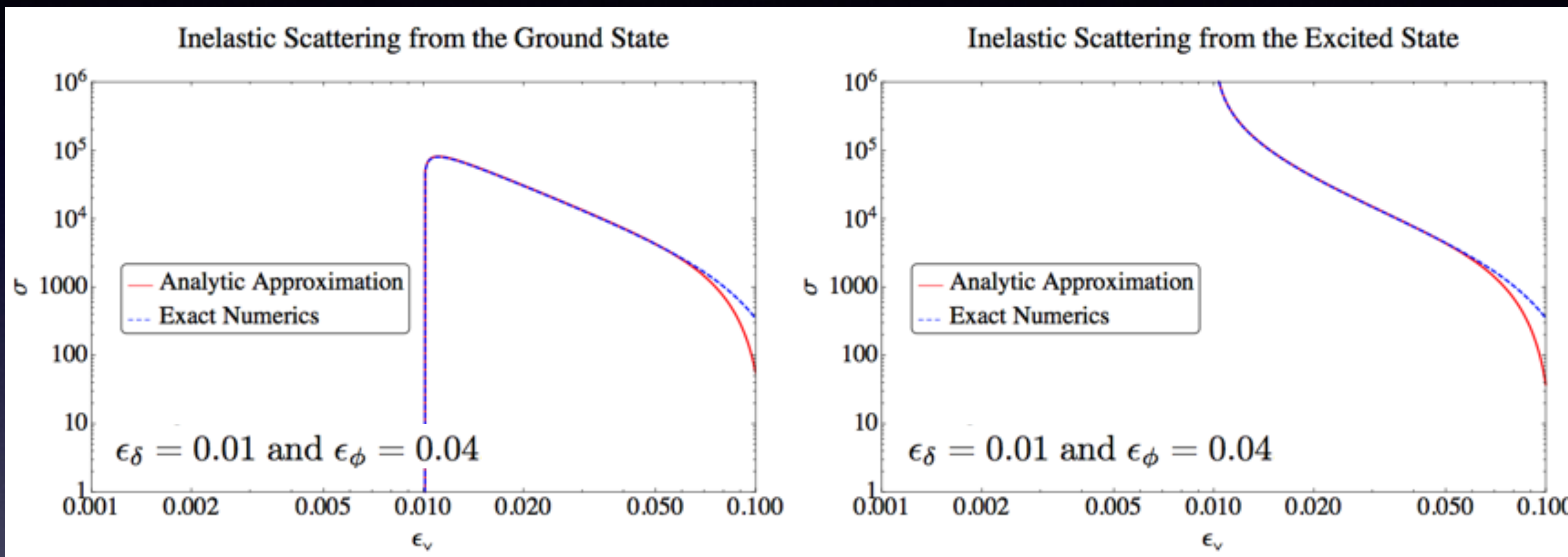
$$\sigma_{\mathrm{ex}\to\mathrm{gr}} = \frac{2\pi\cos^2\varphi\,\sinh\left(\frac{\pi\epsilon_v}{\mu}\right)\sinh\left(\frac{\pi\epsilon_\Delta}{\mu}\right)}{\epsilon_\Delta^2\cosh^2\left(\frac{\pi(\epsilon_\Delta-\epsilon_v)}{2\mu}\right)\left(\cosh\left(\frac{\pi(\epsilon_v+\epsilon_\Delta)}{\mu}\right)-\cos(2\varphi)\right)}$$

$$\epsilon_v \equiv \frac{v}{c\alpha}, \quad \epsilon_\delta \equiv \sqrt{\frac{2\delta}{m_\chi\alpha^2}}, \quad \epsilon_\phi \equiv \frac{m_\phi}{\alpha m_\chi}, \quad \epsilon_\Delta \equiv \sqrt{\epsilon_v^2-\epsilon_\delta^2} \quad \mu, V_0 \sim \epsilon_\phi$$

Sufficient conditions for validity:

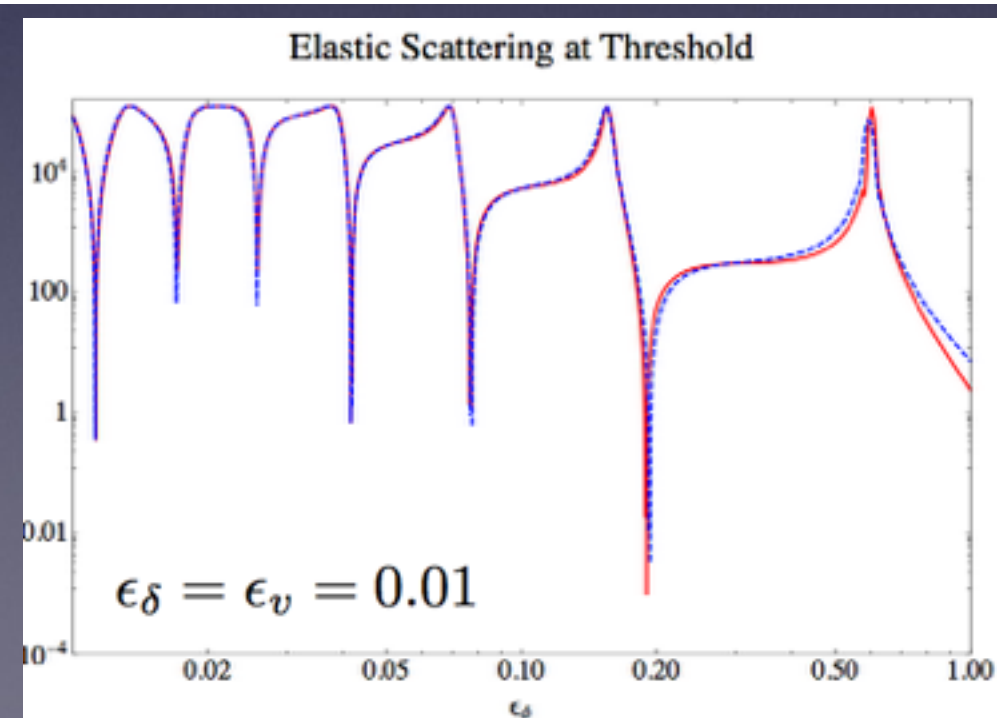
$$v \lesssim \alpha, \quad m_\chi v \lesssim m_\phi \lesssim \alpha m_\chi, \quad \delta \lesssim \alpha m_\phi, \alpha^2 m_\chi$$

Comparison to numerics



- Excellent agreement with numerical calculations.

- Pronounced resonances and anti-resonances at particular values of the mediator mass.



Parametrics for scattering from the excited state

In the limit of low velocity:

$$\sigma_{\mathrm{ex}\to\mathrm{gr}}\, v_{\mathrm{ex}} \propto \frac{1}{m_\phi^2}\sqrt{\frac{\delta}{m_\chi}}\ \text{off-resonance}, \quad \frac{1}{m_\chi \delta}\sqrt{\frac{\delta}{m_\chi}}\ \text{near-resonance}$$

$$\sigma_{\mathrm{ex}\to\mathrm{ex}} \propto \frac{1}{m_\phi^2}\ \text{off-resonance}, \quad \frac{1}{m_\chi \delta}\ \text{near-resonance}.$$

Perturbative result:

$$\sigma v \approx \frac{4\pi\alpha^2 m_\chi^2 \sqrt{2\delta/m_\chi}}{m_\phi^4}$$

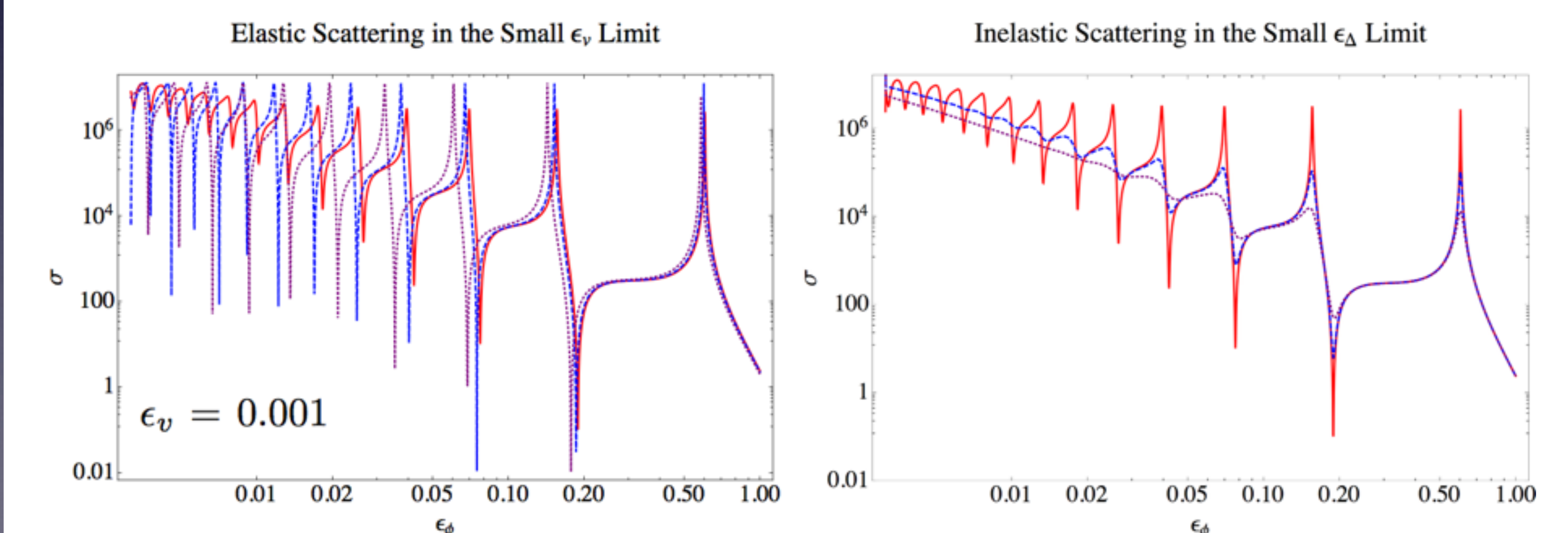
$$\sigma \approx \frac{\pi\, \alpha^4\, m_\chi^4}{m_\phi^6}.$$

- At low velocities, the cross section for elastic scattering approaches (parametrically) the geometric cross section $1/m_\phi^2$, away from resonances. On resonance, for excited-state scattering, the cross section is instead bounded by the mass splitting - suppresses resonances relative to ground-state scattering, which formally diverges as $1/v^2$.
- Downscattering: σv approaches a constant value, as in the perturbative case, due to phase space. Cross section in this limit has the same parametric scaling as elastic scattering cross section (from the excited state), except for the phase space factor.
- In both cases, the non-perturbative cross section is smaller than the naive perturbative (tree level) cross section, in the regime $m_\phi << \alpha m_\chi$, by a factor $(m_\phi/\alpha m_\chi)^2$.

Impact of the mass splitting

- For ground-to-ground scattering, qualitative results are similar to the one-state case, although the resonances shift position. Cross section scales as $1/m_{\phi}^2$ at small v away from resonances, although there is a large prefactor.

- For downscattering, similar considerations hold, although a large mass splitting damps the resonances rather than shifting them. Thus resonances occur for different parameters, for slow-moving particles in the ground and excited states.



$\epsilon_\delta = 0$ (solid, red), $\epsilon_\delta = 0.01$ (dashed, blue), and $\epsilon_\delta = 0.03$ (dotted, purple)

Astrophysics implications

- Can generically obtain interesting cross sections (0.1-1 cm^2/g) for elastic scattering and downscattering.

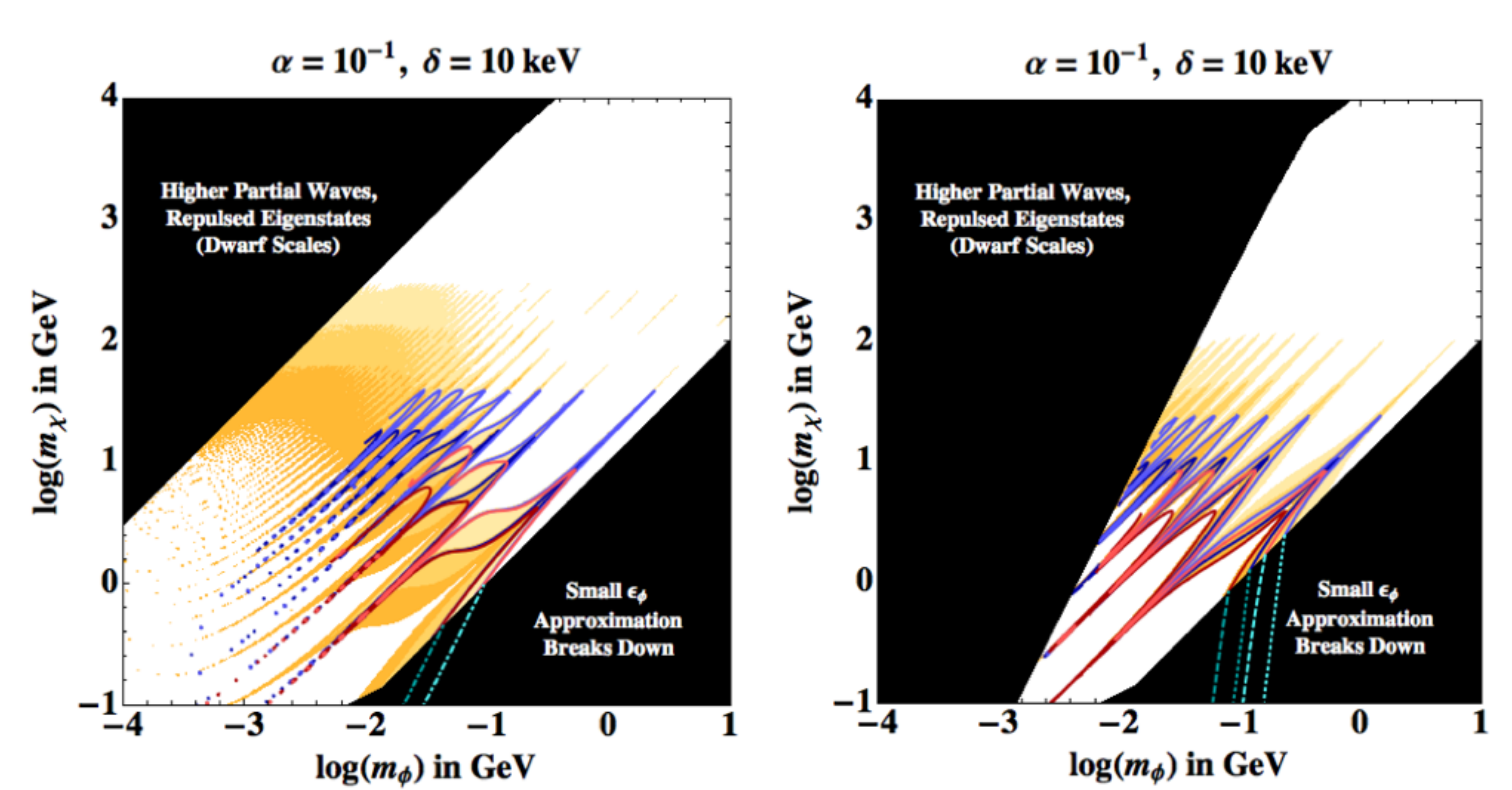
- Favored region generally corresponds to DM masses of 10-100 GeV and mediator masses of 1-100 MeV. (Higher DM masses and lower mediator masses correspond to the classical region; lower DM masses and higher mediator masses to the perturbative region.)

- A significant resonant region requires $v \ll \alpha$; for light DM masses coupled to a dark photon, this condition likely requires asymmetric dark matter, a non-thermal production mechanism, or this component of DM to be sub-dominant. (A significant excited state population may require a non-thermal production mechanism in any case.)

- Difficult to get large enough upscattering cross sections in dwarfs that modifications to halo structure would be expected, even for mass splittings as small as 100 eV.

Example

Ground-ground scattering | Downscattering



Conclusions

- Dark matter self-interactions, and downscattering of a relic population of dark matter in an excited state, can have interesting phenomenological implications.

- We have developed a simple semi-analytic approximation for s-wave scattering of dark matter interacting via a long-range “dark force”, where the scattering can be inelastic, applicable to the non-perturbative resonant regime.

- In this regime the effects of the excited state on elastic scattering in the ground state are subtle, with the main effect being shifting of the resonances and anti-resonances.

- Downscattering from the excited state has the expected $\sigma \sim 1/v$ dependence due to phase space, and so is significantly enhanced in dwarfs relative to MW-size galaxies and clusters (even more so than elastic scattering). The overall cross section is enhanced by phase space relative to elastic scattering, but the resonance structure is damped.

- Downscattering cross sections corresponding to ~1 scattering per particle per dynamical time of a dwarf galaxy are obtained for similar parameters to the elastic case.