The Sommerfeld Enhancement for Inelastic Dark Matter

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Based on TRS 0910.5713 and work in preparation,
in collaboration with
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Identification of Dark Matter, Montpellier, 29 July 2010

Context

- PAMELA and Fermi cosmic-ray anomalies motivate large DM annihilation cross sections (ten - few thousand * thermal relic value).
  - Sommerfeld enhancement proposed as mechanism for "boost factor" (BF).
  - Elegant simultaneous explanation for hard leptonic spectrum + no antiprotons, if DM annihilates to light force carriers (less than ~1 GeV) that then decay.

- However, Fermi pushes preferred DM mass to high scale (> 1 TeV). Large resonant peaks in Sommerfeld enhancement tend to occur at higher mediator/DM mass ratios. Can the Sommerfeld effect explain the full preferred "boost factor"?
  - Dent, Dutta & Scherrer; Zavala, Vogelsberger & White (2009): calculation of the effect of early-universe Sommerfeld enhancement on relic density of dark matter. Maximal BF ~ 500.
  - Feng, Kaplinghat & Yu (2010): specialize to mediator masses less than ~1 GeV, assume primary annihilation is to particle mediating Sommerfeld enhancement, careful relic density calculation. Maximal BF ~ 100-150.

- Parameter space also strongly constrained by the cosmic microwave background.

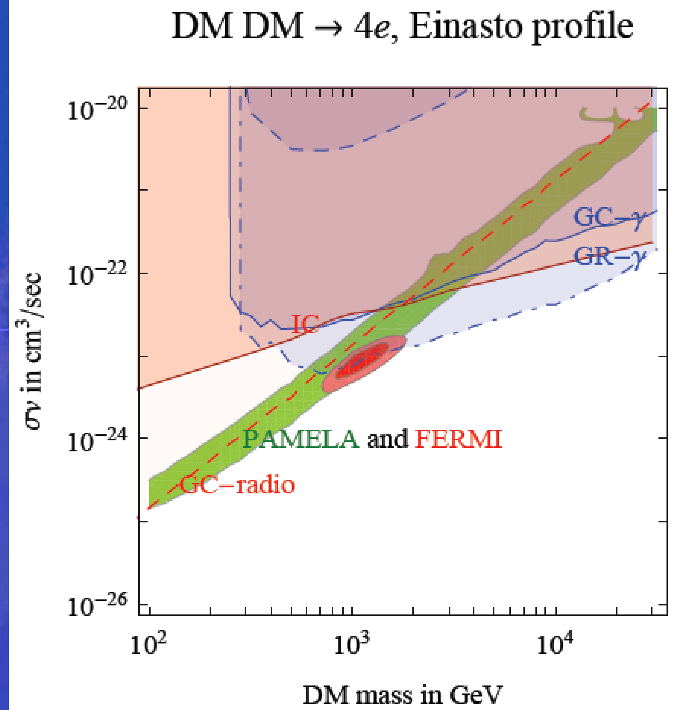
What do the data require?

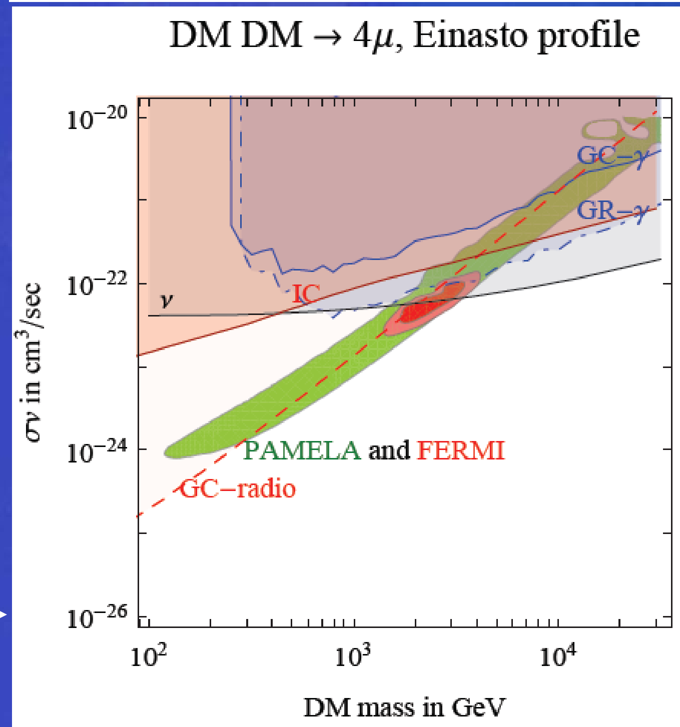
- Meade et al (followed by Feng et al):
  - 4-muon final state: 2.35 TeV, BF ~1500.
  - 4-electron final state: 1 TeV, BF ~200-300.
  - Variation in BFs due to different preferred mass (BF scales as ~m_χ), different amount of power into neutrinos.
  - Softer spectra favored by fits, but depends strongly on high-energy endpoint of spectrum.
  - Assumed local DM density of 0.3 GeV/cm^3; more recent studies suggest higher value, reduce required BF by factor of ~2+.

Increase in DM annihilation signal relative to ρ = 0.3 GeV/cm^3

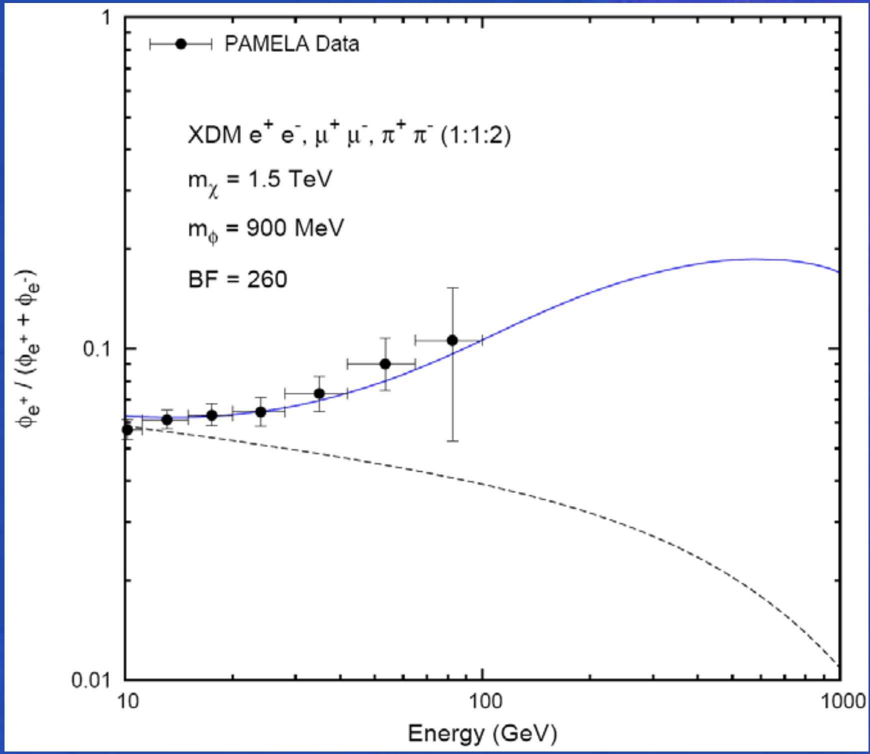
1	1.6	2.1	2.5	3.4
0.30	0.38	0.43	0.47	0.55

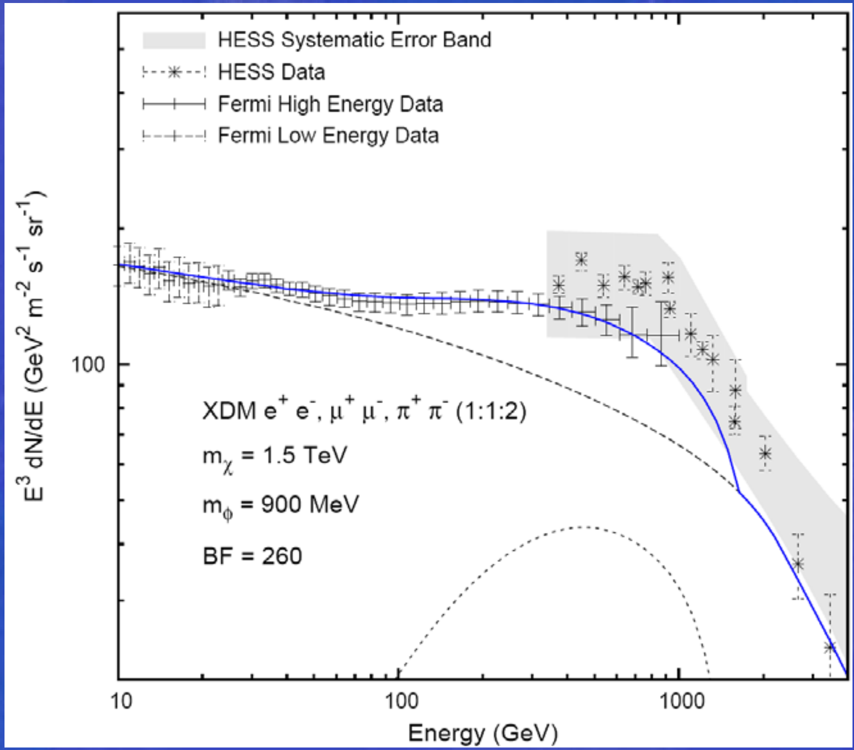
Catena & Ullio (0907.0018) Salucci et al (1003.3101) Pato et al (1006.1322)





Example curves from GALPROP

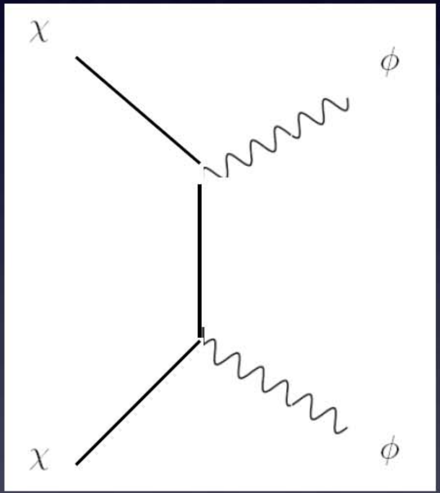




Target boost factors ~200-300 for ~1.5 TeV DM (with local density of 0.43 GeV/cm^3) annihilating to mixture of electrons + muons + charged pions, depending on branching ratios (and cosmic ray propagation parameters).

Model ingredients

- DM has some new U(1) gauge interaction, broken at the ~GeV scale by a dark Higgs h_D.
- Coupling to SM: U(1) gauge boson mixes kinetically with hypercharge (with a small mixing angle).
- Exchange of dark gauge bosons mediates an attractive force, giving Sommerfeld enhancement to annihilation at low velocities.



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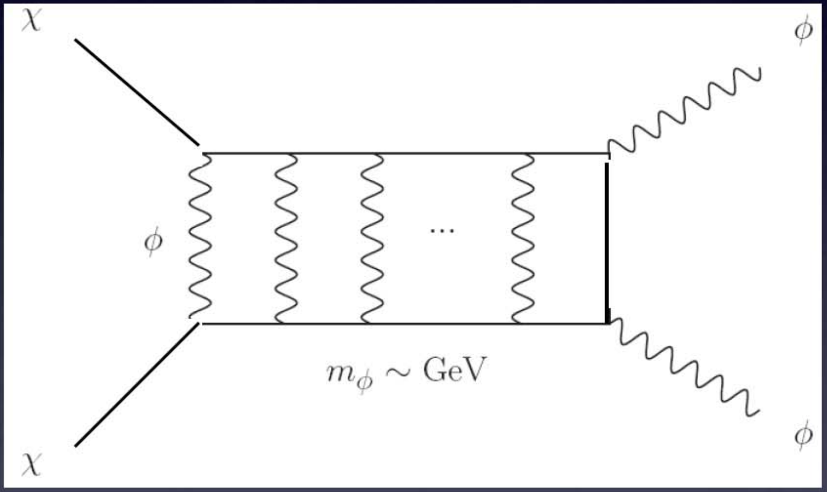

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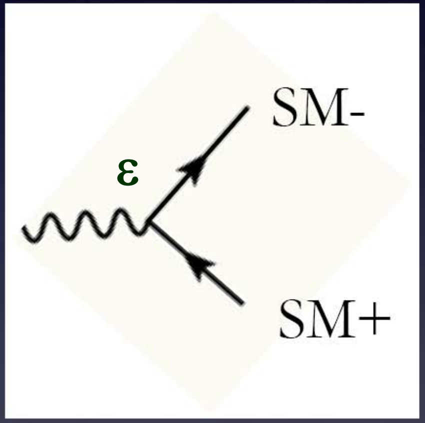
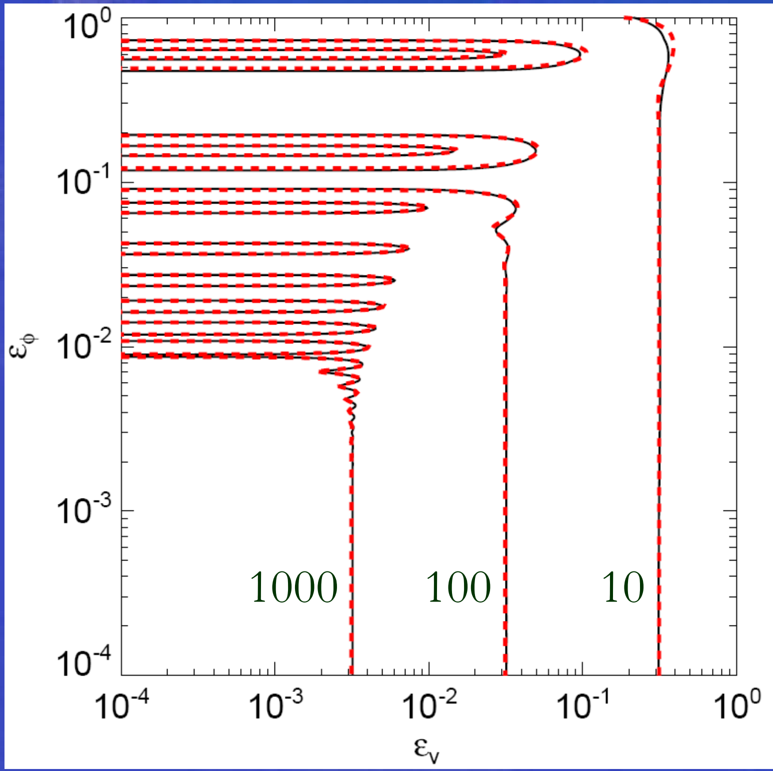


The Sommerfeld enhancement

- Enhancement to annihilation due to attractive force between DM particles; scales as 1/v for,
  $m_\phi/m_\chi < v < \alpha$.
  Saturates when $m_\phi/m_\chi \sim v$.

- Resonances occur at special values of $(m_\phi/m_\chi)/\alpha$; on these resonances the enhancement scales as $1/v^2$ and saturates later.

- Effect is much greater in the present-day Galactic halo ($v \sim 5*10^{-4}$) than at DM freezeout ($v \sim 0.3$). However, it can delay freezeout somewhat: this means the correct thermal relic density requires a smaller underlying annihilation cross section.



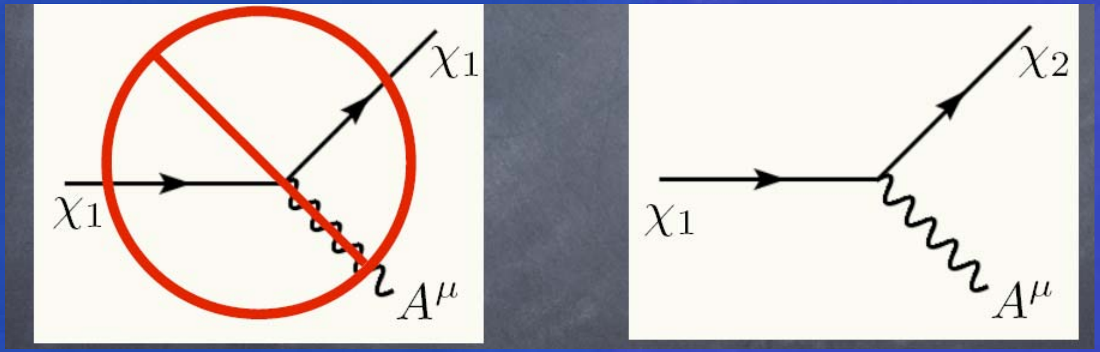
$\varepsilon_\phi = (m_\phi/m_\chi)/\alpha$, $\varepsilon_v = v/\alpha$
Contours are 10, 100, 1000.

Inelastic dark matter

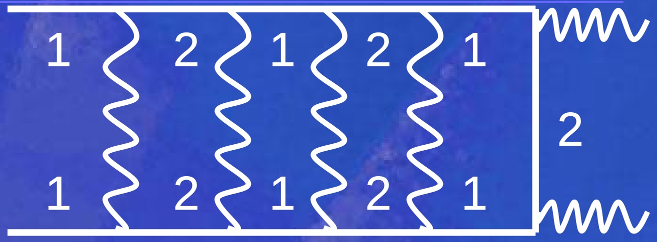
- Nearly-degenerate excited states are **natural** in this framework – experimental motivations from DAMA/LIBRA, INTEGRAL/SPI. However, all previous studies of Sommerfeld enhancement (in this class of models) **assume zero mass splitting**.

- Operator in example model: y $\chi\chi h_D{}^* h_D{}^*/\Lambda$,
Gives a small Majorana mass to DM at ~ GeV^2/ TeV ~ MeV.

- Mass eigenstates are 45° rotated from the gauge eigenstates
=> interactions between DM states and the gauge boson are purely off-diagonal.



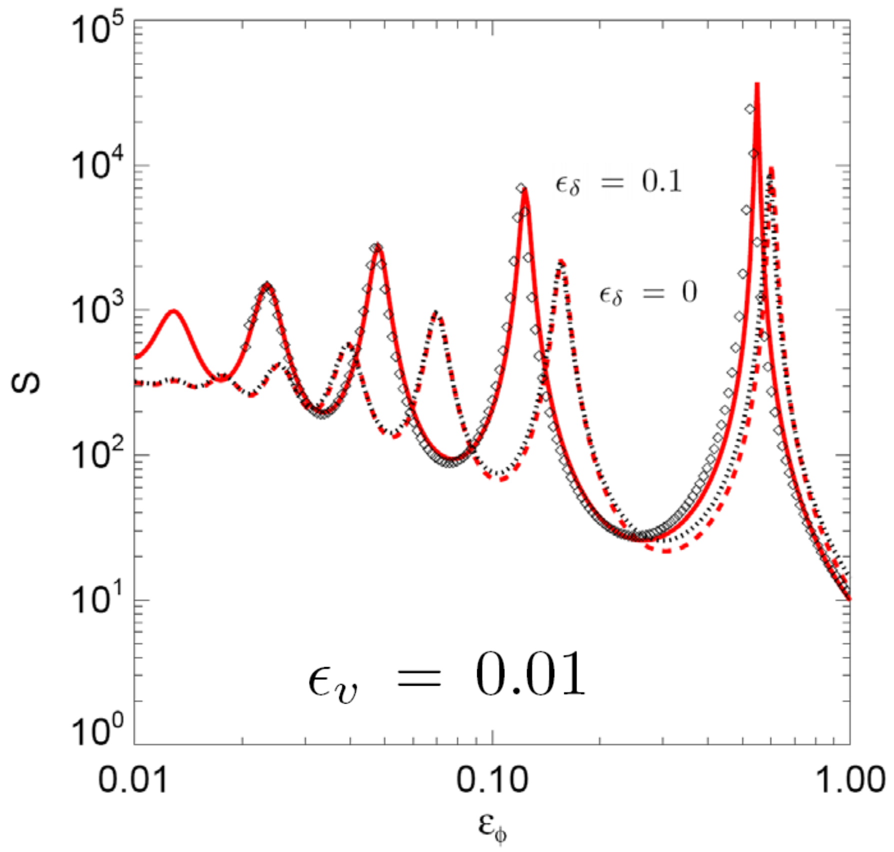
The Sommerfeld enhancement for iDM



- Ladder diagrams for Sommerfeld enhancement now involve excited state, even if particles begin in ground state.

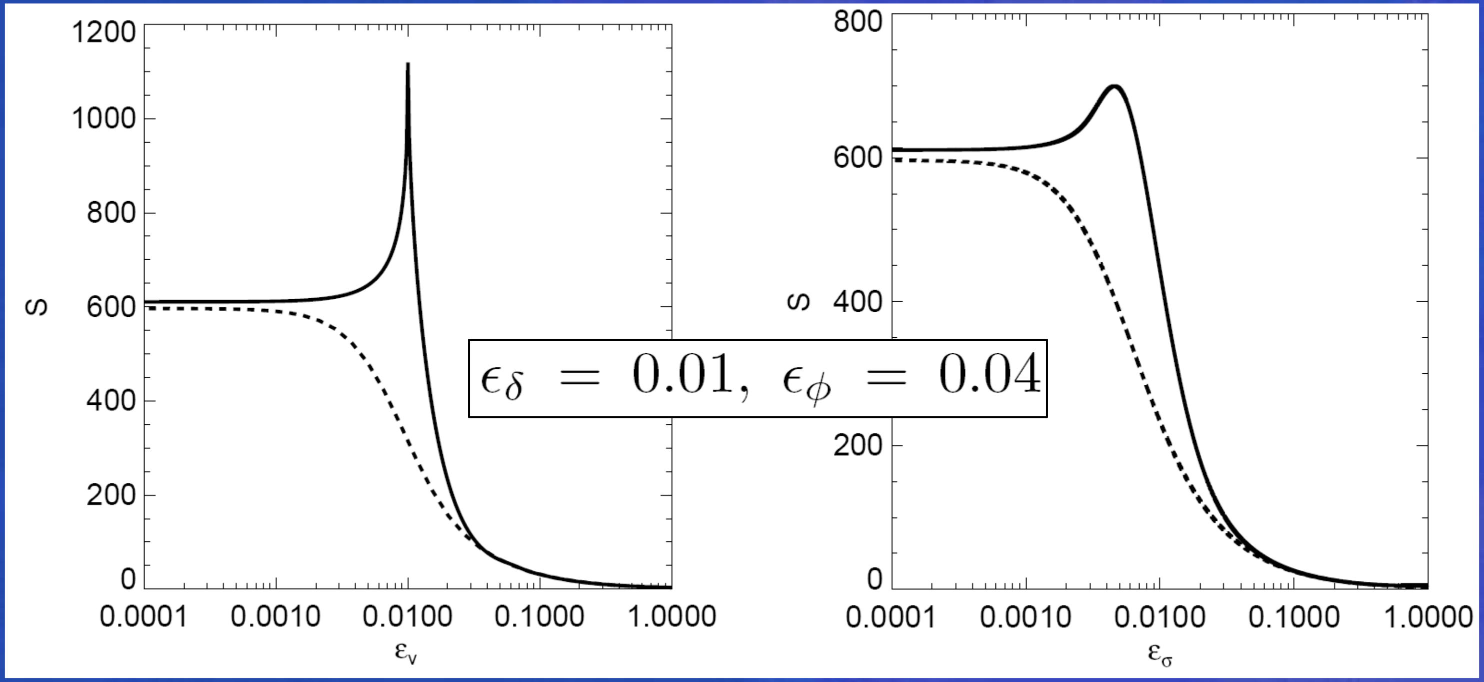
- Enhancement cuts off if $\delta > \alpha^2 m_\chi$ (potential energy of DM-DM system).

- However, if $\frac{1}{2} m_\chi v^2 < \delta < \alpha^2 m_\chi$, enhancement can actually be **increased**.
  - Resonances shift to lower m_ϕ.
  - Resonances increase in size (~4x).
  - Unsaturated, nonresonant enhancement larger by factor of 2 (but NOT saturated enhancement).



Red lines: semi-analytic approximation taken from TRS 0910.5713.

Velocity dependence of the Sommerfeld enhancement



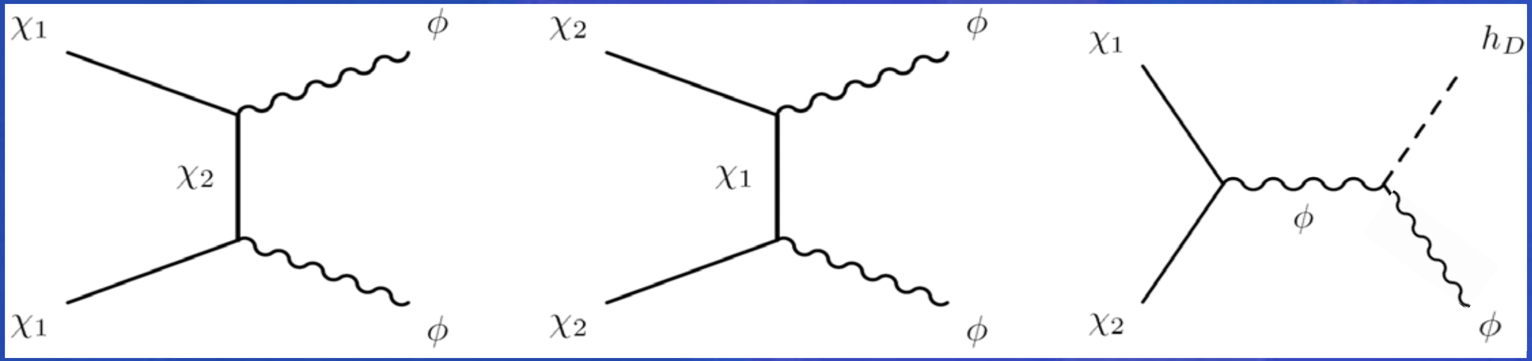
Unsmoothed | Smoothed by Maxwell-Boltzmann

Dotted line = elastic, solid line = inelastic.

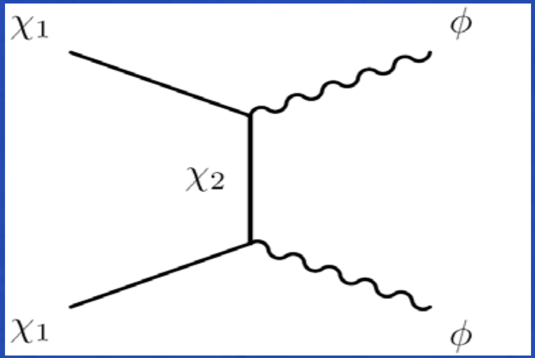
Similar saturation behavior, inelastic case is enhanced at intermediate velocities.

Self-annihilation vs co-annihilation

- Early universe: ½ χ_1, ½ χ_2



- Present-day halo: χ_1 only

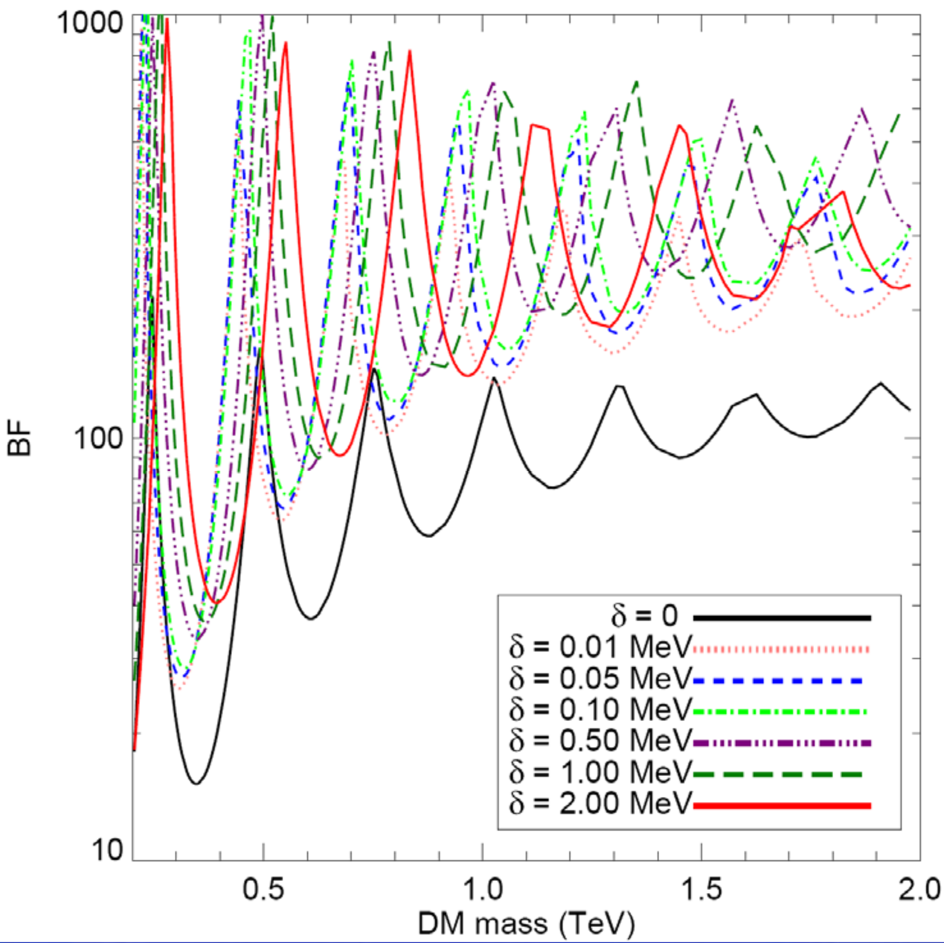


(Caveat: this is for s-wave annihilation, there is also a p-wave suppressed channel in the minimal model that can be important at freezeout in some parts of parameter space.)

- Annihilation in present day is **enhanced** if $\chi_1\chi_1$ annihilation more efficient than $\chi_1\chi_2$. For the minimal model, the factor is 1.6. (Unrelated to Sommerfeld effect!)

Boost factor in the present day

- Define $BF = \dfrac{\langle \sigma v \rangle_{present}}{3{*}10^{-26}\ cm^3/s}$.
- For several SM final states (m_ϕ held constant), compute BF as a function of m_χ, adjusting α_D to obtain correct relic density.
- Compute relic density by solving Boltzmann equation for two-state system, including upscattering, downscattering, decay of excited state, and differing annihilation rates.



m_ϕ = 900 MeV, 1:1:2 e:μ:π

Constraints from the cosmic microwave background

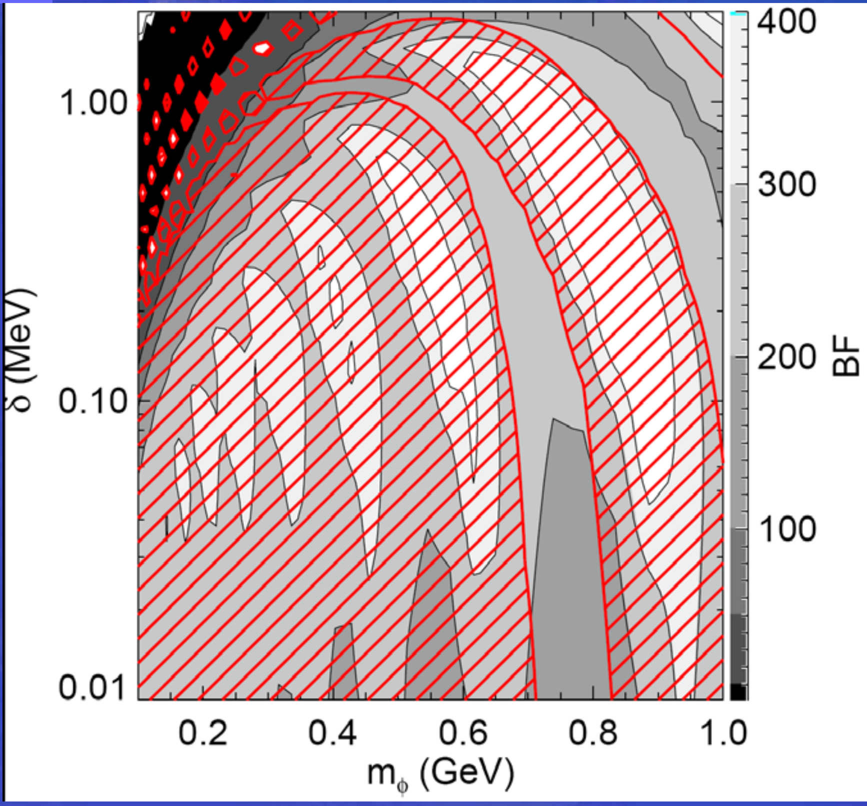
- High-energy electrons and photons injected around the redshift of last scattering give rise to a cascade of secondary photons and electrons, which modify the cosmic ionization history and hence the CMB.

- Robust constraints from WMAP5 require,

$$\frac{\langle \sigma v \rangle_{z\sim1000}}{3*10^{-26}\ \mathrm{cm}^3/\mathrm{s}} < (120/f)\ (m_\chi/1\ \mathrm{TeV})$$

  f is an efficiency factor depending on the SM final state:

  e^+e^-: f~0.7, $\mu^+\mu^-$: f~0.24, $\pi^+\pi^-$: f~0.2



Example: effect of CMB constraints on parameter space for 1.2 TeV DM. Red-hatched = ruled out by CMB.

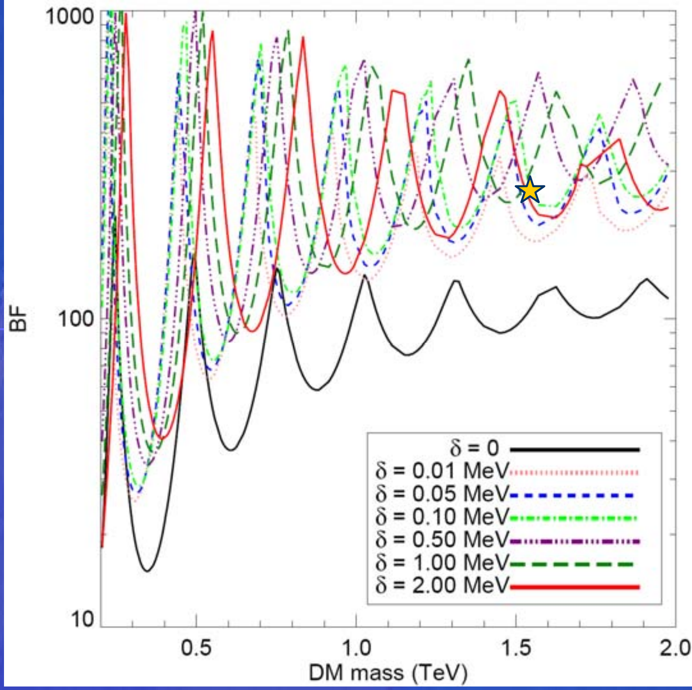
Example benchmark

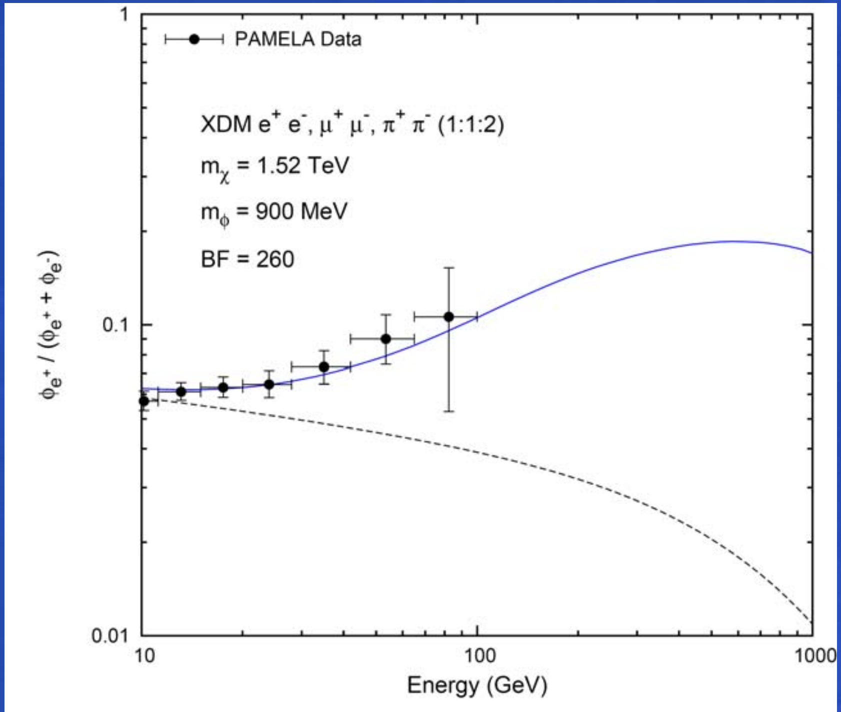
$\alpha = 0.037$ $m_\chi = 1520$ GeV

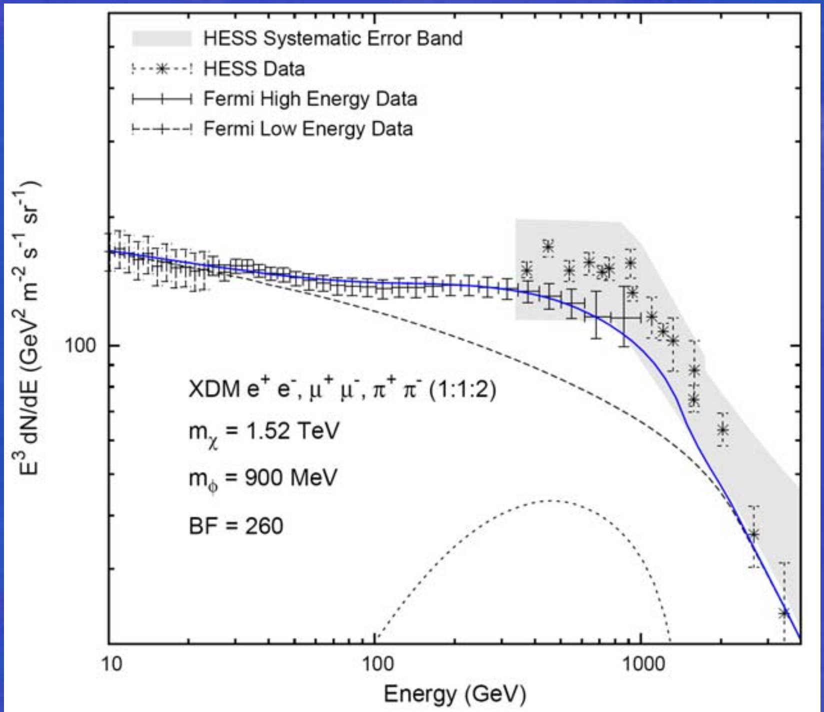
$m_\phi = 900$ MeV $\delta = 1.1$ MeV

Local BF = 260 Saturated BF = 365

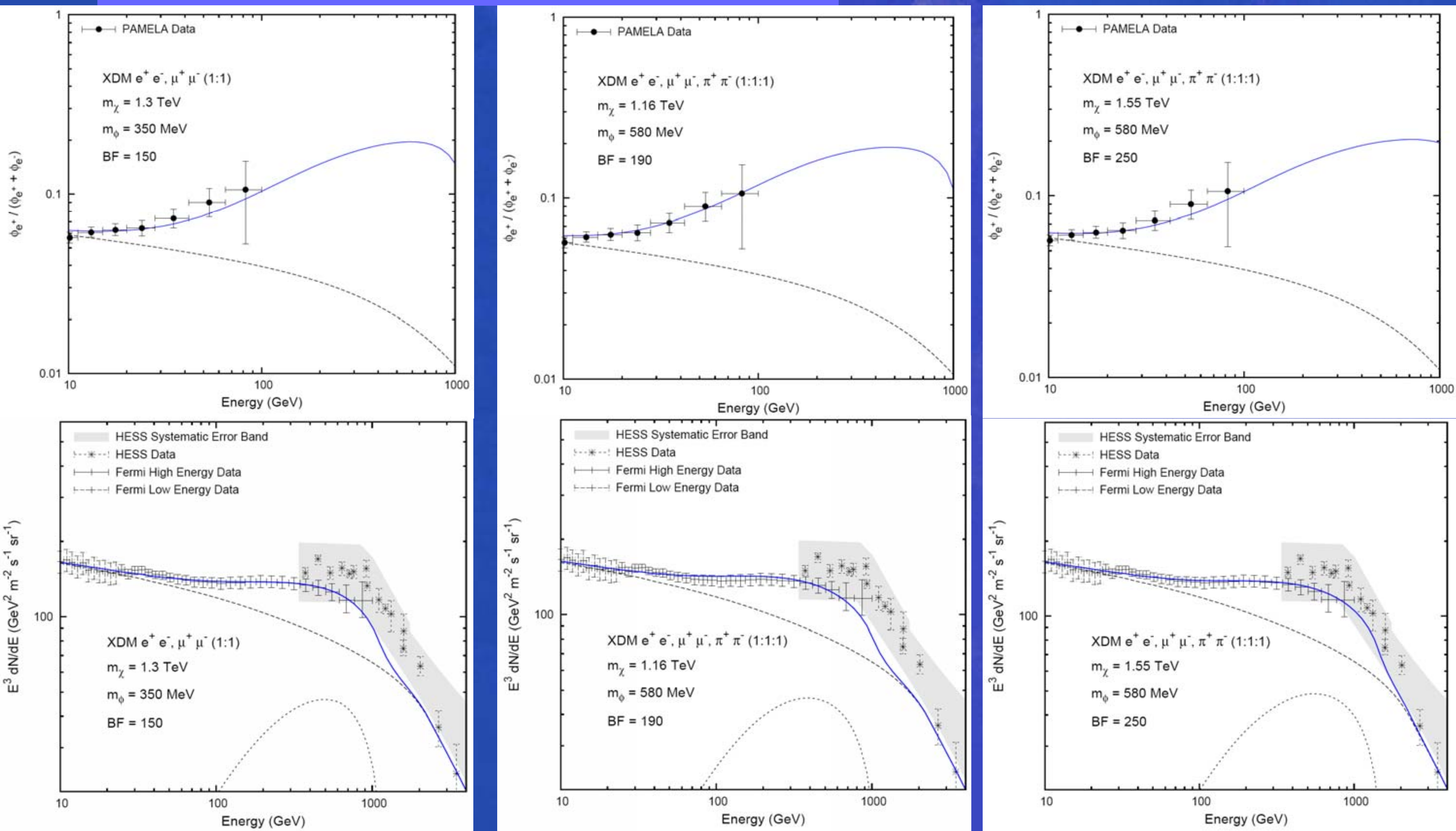
CMB limit = 545







More benchmarks at different mediator / DM masses



Conclusions

- Models of a light dark sector coupled to the Standard Model via kinetic mixing can fit the PAMELA/Fermi cosmic ray anomalies well, with required boost factors of order 100-300 and DM masses of 1-1.5 TeV, depending on the light gauge boson mass.

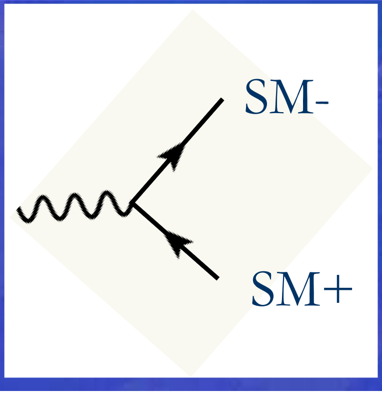
- These boost factors can be achieved by Sommerfeld enhancement alone, without violating constraints from the CMB, in models where the DM possesses a nearly-degenerate excited state and has the right thermal relic density, in contrast to recent claims in the literature for the elastic case. The CMB limits are very stringent, ruling out many regions of parameter space that give the correct thermal relic density.

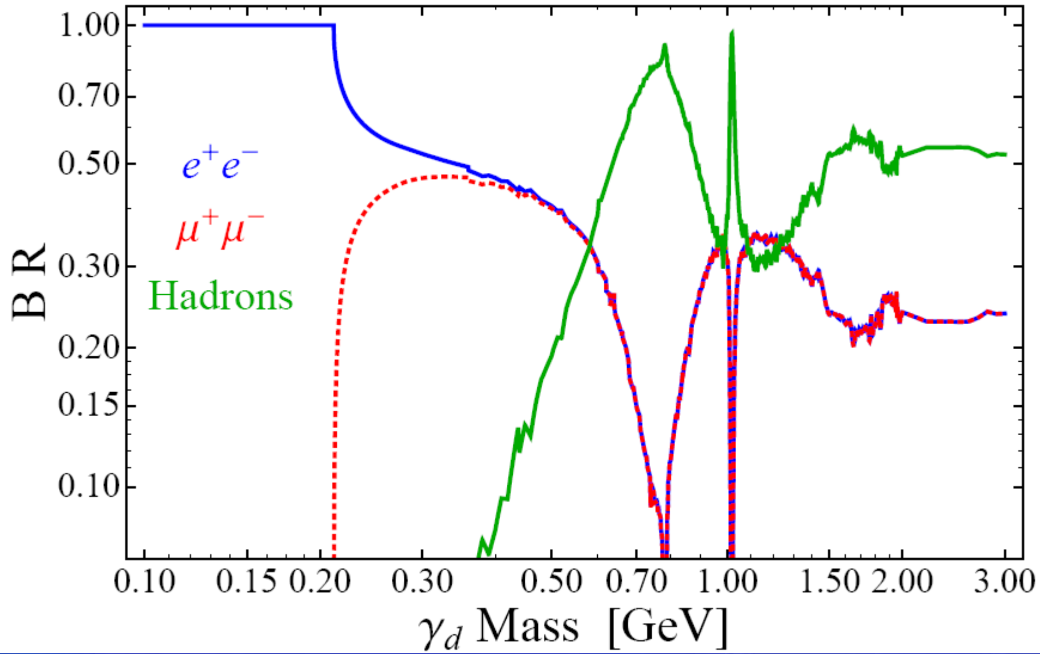
- In purely elastic models, there is tension at the O(2) level for thermal relic DM, with the situation being worse for larger DM masses and mediators with small decay branching ratios to electrons. However, there are significant astrophysical uncertainties in the required enhancement.

BONUS SLIDES

Final SM states for DM annihilation

- If SM coupling is via kinetic mixing, dark gauge boson ϕ couples dominantly to charge: the coupling through the Z is suppressed by m_ϕ^4/m_Z^4.
- Thus the ϕ decays to kinematically accessible charged SM final states, depending on its mass.

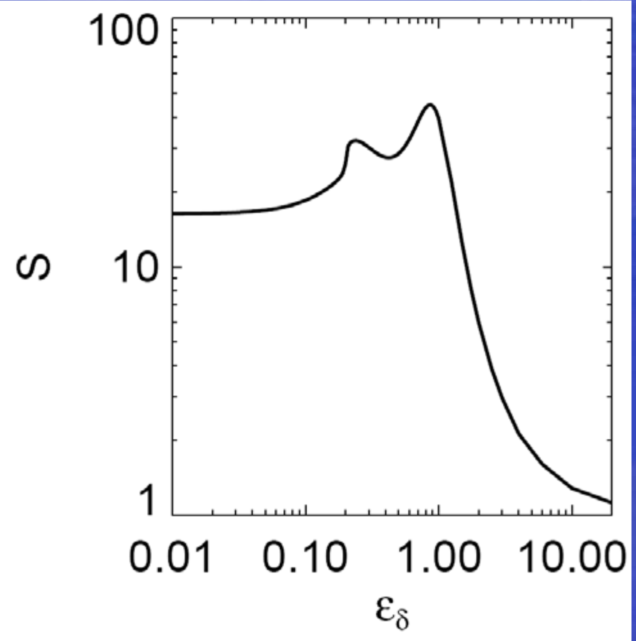




Falkowski, Ruderman, Volansky and Zupan, 1002.2952

How does inelasticity affect the Sommerfeld enhancement?

- Pure off-diagonal interaction: $|11\rangle$ and $|22\rangle$ states couple to each other, not to $|12\rangle$.



- Initial question: does the Sommerfeld enhancement turn off when kinetic energy << mass splitting?
- NO, however, it does cut off if the kinetic energy + potential energy $\sim \alpha^2 m_\chi << \delta$.

Why the factor of 2?

- This can be understood in the quantum mechanics picture, in terms of the evolution of the eigenstates with r.
- In the adiabatic / large δ limit, a state initially in the lower-energy eigenstate at infinity (ground state) will smoothly transform into the lower-energy eigenstate at small r, which experiences an attractive potential.
- In the diabatic / small δ limit, the small-r state corresponding to either asymptotic eigenstate will be an even mixture of attracted and repulsed components (i.e. lower- and higher-energy eigenstates).

r → ∞

$$\psi_+ \approx \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \psi_- \approx \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\lambda_+ \approx \frac{l(l+1)}{r^2} - \epsilon_v^2 + \epsilon_\delta^2 + \frac{V(r)^2}{\epsilon_\delta^2}$$

$$\lambda_- \approx \frac{l(l+1)}{r^2} - \epsilon_v^2 - \frac{V(r)^2}{\epsilon_\delta^2}$$

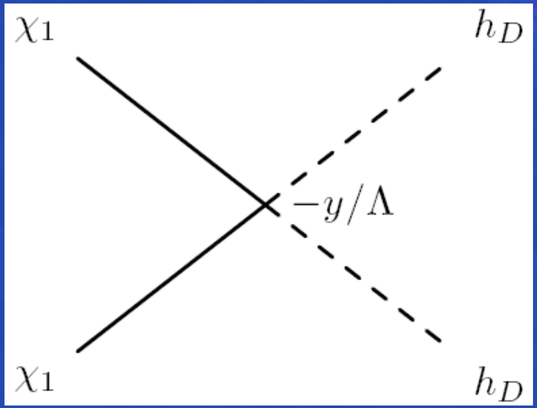
r → 0

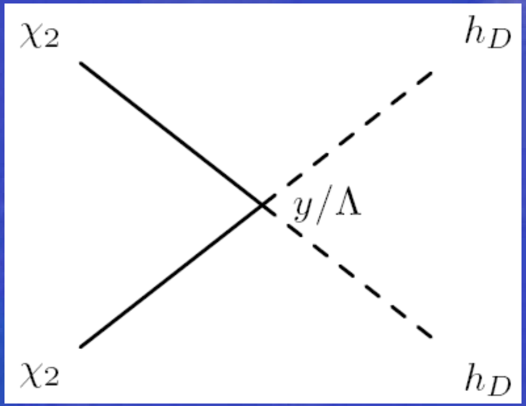
$$\psi_\pm \approx \frac{1}{\sqrt{2}} \begin{pmatrix} \mp 1 \\ 1 \end{pmatrix}$$

$$\lambda_\pm \approx \frac{l(l+1)}{r^2} - \epsilon_v^2 + \frac{\epsilon_\delta^2}{2} \pm V(r)$$

Annihilation from the mass splitting operator

- In this specific realization of this class of models, there is also a more model-dependent annihilation channel, from the operator generating the mass splitting,





- $(\sigma\ v)_{\mathrm{splitting}} \sim S_{\mathrm{rep}}\ v^2\ (m_\chi \delta / m_\phi{}^2)^2\ (\sigma v_{\mathrm{rel}})_{11}$
- Highly velocity suppressed (p-wave, + Sommerfeld effect *suppresses* annihilation), negligible in present day – but can be important, even dominant, at freezeout, especially for large δ + small m_ϕ.