Goals

- Discuss scenarios where ID signals are suppressed or enhanced
- Develop an understanding of the range of possible particle energy spectra from DM annihilation or decay, & the implications for signal detectability
- Outline the diffusive propagation of (chaged) cosmic rays in our Galaxy & the effects of propagation on observed energy spectra

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Dream & nightmare scenarios for ID

Suppressed annihilation

* DM needs a partner to annihilate + partner abundance is suppressed at late times

- Simplest version: asymmetric DM

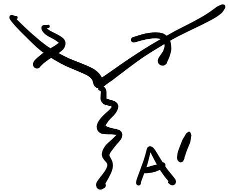
  annilations are DM + $\overline{\text{DM}}$ $\rightarrow$ SM

  Annihilation ~~xsec~~ xsec $\rightarrow$ standard thermal relic xsec

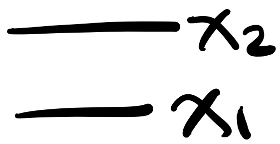
  All ~~..~~ anti-DM depleted early on

– Example 2: pseudo-Dirac DM

Start with model where DM = Dirac fermion w/ dark U(1) charge

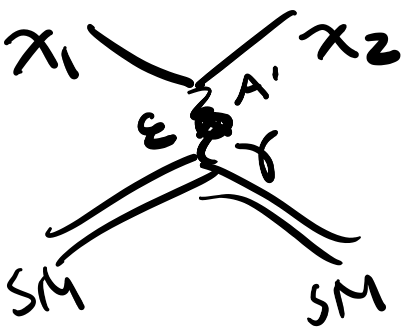


Add operator to $\mathcal{L}$ to split Dirac fermion into two nearly-degenerate Majorana fermions, χ_1 & χ_2 (masses m_1 & m_2)



Majorana fermions don't carry U(1) charge

Assume A' (→ dark U(1) gauge boson) mixes with SM U(1) with some mixing ε

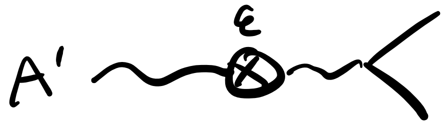


← dominant annihilation channel

Once $T \lesssim m_2 - m_1$, abundance of χ_2 will be Boltzmann suppressed

If A' is light,

⇒ suppresses ID signal



* Annihilation xsec suppressed at low velocities / low densities
  ↓
  - annihilation dominantly p-wave

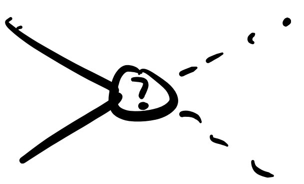
    annihilation of non-relativistic particles through a contact interaction scales as

    $\sigma v_{rel} \propto v_{rel}^{2L}$ where L = total orbital angular momentum for 2-body state

    $L=0$: "s-wave", σv_{rel} = constant w.r.t v_{rel}

    $L=1$: "p-wave" - can dominate if $L=0$ term vanishes

Example: Majorana fermion DM annihilating to real scalars



If CP is preserved, we need $\Delta L = 1$

CP $\quad (-1)(-1)^L \qquad (-1)^L$

If $L=0$ for initial state, ⇒ $S=0$ (antisymmetry) ⇒ $J=0$

Final state: $J=0, S=0$ ⇒ $L=0$

(Kumar & Marfatia 1305.1611)

- Kinematic suppression
  (e.g forbidden DM)

- Annihilation involving more than 2 particles
  - suppressed at low densities

- Also can have non-thermal production

Enhanced signals

- Example: Sommerfeld enhancement
  - induced by a long-range attractive potential
  - important when KE $\lesssim$ PE - i.e at low velocities
  → can also allow for bound-state formation
  - for a Coulomb-like potential, $V(r) = \frac{\alpha_D}{r}$
    [redacted] $mv^2 \lesssim \alpha_D^2 m$ corresponds to $v \lesssim \alpha_D$

For $v \ll \alpha_D$, $\sigma v_{rel} = S\, \sigma v_{rel}$

$$S \approx \frac{2\pi\alpha_D}{v_{rel}} \quad \text{for } L=0$$

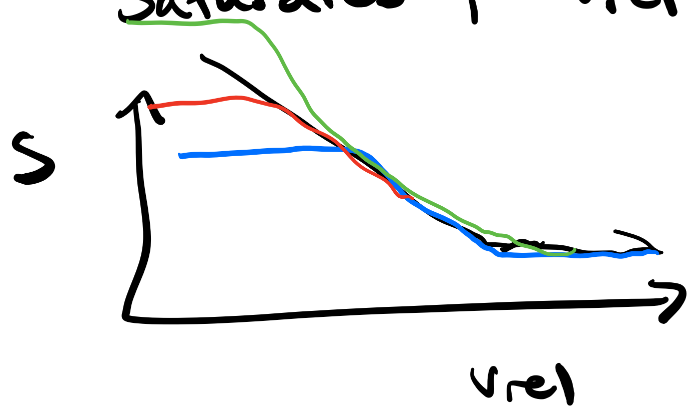
$$S \propto \left(\frac{\alpha_D}{v_{rel}}\right)^{2L+1}$$

- In practice, usually force carrier has a mass $m_{A'}$

Large S still possible $\frac{1}{m_{A'}} \gtrsim$ Bohr radius $\sim \frac{1}{\alpha_D m_\chi}$

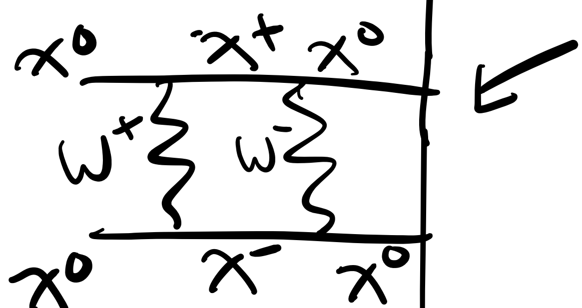
Then enhancement is Coulomb-like for $v_{rel} \gtrsim \frac{m_{A'}}{m_\chi}$

Saturates for $v_{rel} \lesssim \frac{m_{A'}}{m_\chi}$



- Bound state formation

- Temperature-dependent resonance effects



Energy spectra

Step 1 in translating a model to a prediction for observation:

DM physics $\longrightarrow$ rate of SM particles produced $\longrightarrow$ rate of <u>stable</u> SM particles

↑ Pythia, Herwig, PPPC4DMID

Roughly 4 categories of SM states for ID purposes:

spectrum of e^+e^-, γ, ν, $\bar{\nu}$, p, $\bar{p}$, heavier (anti) nuclei

(1) quarks, gauge bosons, τ leptons

→ quarks → hadronization

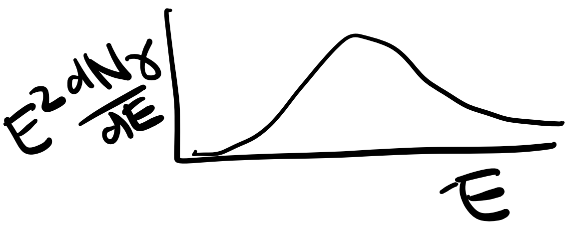
→ copious production of pions + heavier hadrons if enough COM energy

π^0, π^+ π^- → (anti) neutrinos, e^+e^-

↳ copious neutrino & charged lepton

$\gamma\gamma$

↳ copious continuum photons

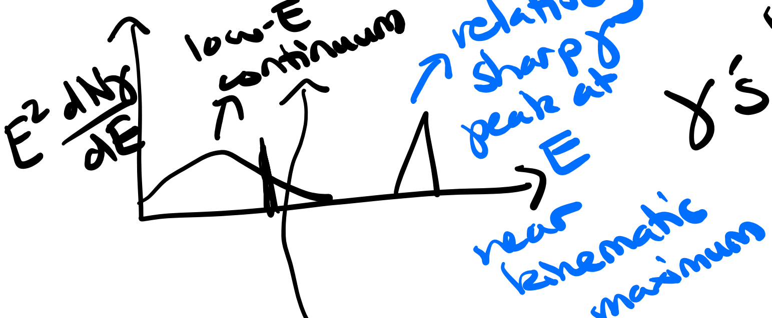


- antiprotons/protons
- (anti) deuterons
- (anti) nuclei

increasing mass ↓ theoretically challenging

(2) $e^\pm$, $\mu^\pm$ → copious charged leptons, maybe neutrinos, γ's only from 3-body states or secondaries

↓ photons emitted as charged particles travel through galaxy

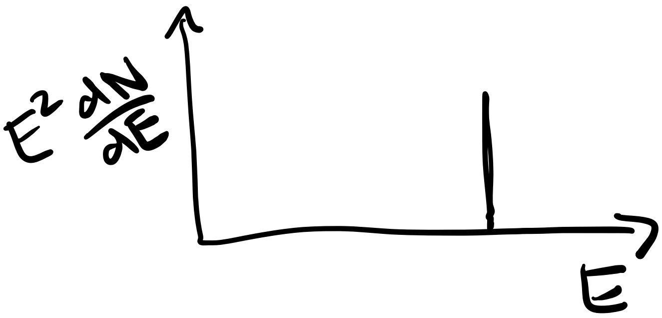


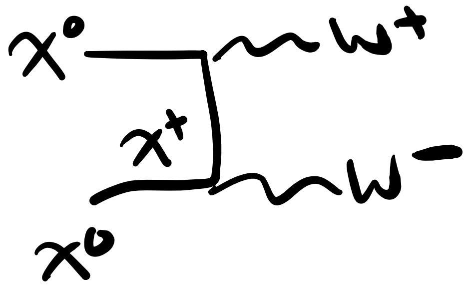
+ 511 keV photons from e^+ annihilation

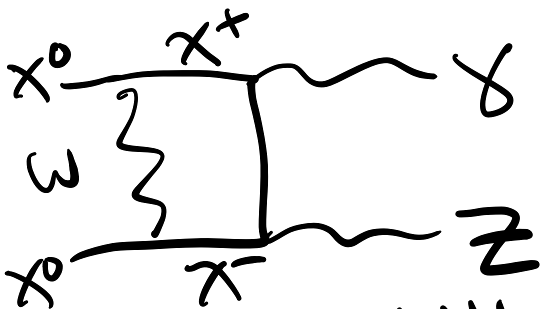
(3) $\gamma\gamma$, γX – direct annihilation/decay to line photons

Spectral line – no backgrounds at γ-ray energies

But expected to be small (e.g. 1-loop-suppressed) as DM is dark



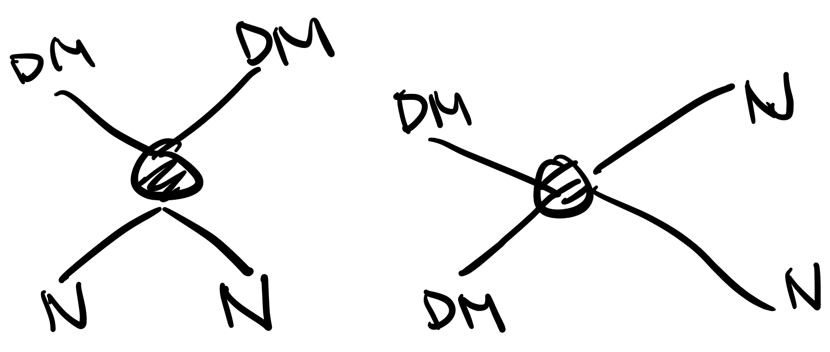




(4) Neutrinos only – difficult to observe (although rate can be enhanced from solar capture)

At high (TeV+) DM masses, sensitivity from IceCube, ANTARES

At high energies, radiation of W/Z is important



Dark sector cascades: Elor et al 1511.08787