Title: An Inverted Mass Hierarchy for Excited Dark Matter

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URL: http://pirsa.org/09020014

Abstract: Varied experimental results have recently sparked theoretical interest in the dark matter sector. I will review some of these results and the basic ideas in particle physics that might explain them, as well as some requirements for those models to work. Then I'll discuss a new model dark matter sector that can better explain many of the experimental results. I'll also mention the interesting cosmological history required in this type of model. Finally, if there's time, I'll discuss ongoing efforts at McGill to develop basic physics shared by many of the new dark matter models.

Inverted XDM

ARF

An Inverted Mass Hierarchy for Exciting Dark Matter

Andrew R. Frey

McGill University

0901.4327 and work in progress
with Fang Chen and Jim Cline

Outline

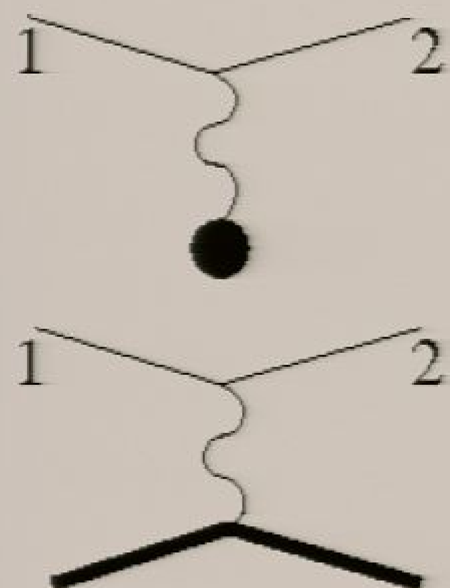
Hints About Dark Matter?

(*Chandra, Hubble, Magellan*)

Some Observations

- Direct detection
  - Seen at DAMA, not others?
  - Inelastic scattering?
- High energy $e^{\pm}$ in astrophysics
  - PAMELA, ATIC, & other observations
  - WMAP haze from synchotron
  - TeV scale DM decays or annihilations?
  - Alternately pulsars
- 511 keV photon line
  - INTEGRAL and older (40 yrs!)
  - Strong bulge component
  - DM decays or transitions?

Direct Detection



DAMA vs Others

- Collisions with nuclei
- Only seen at DAMA expts (possible candidates at others)
- Main difference = heavy nuclei
- Inelastic scattering favors heavy targets

$$\delta M \lesssim \mu v^2/2$$

- Need $\delta M \lesssim 100\ keV$

But...

- DAMA somewhat controversial
- I'll remain agnostic

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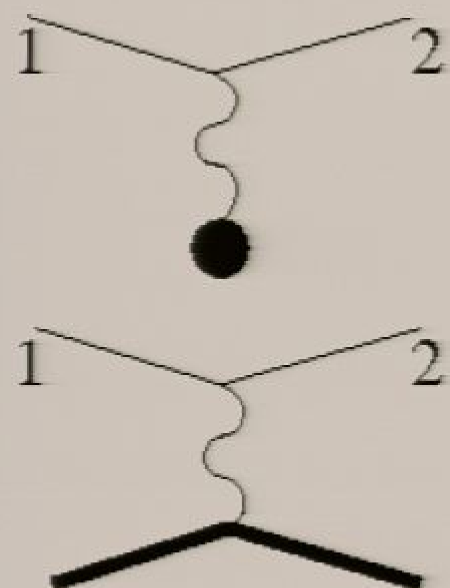

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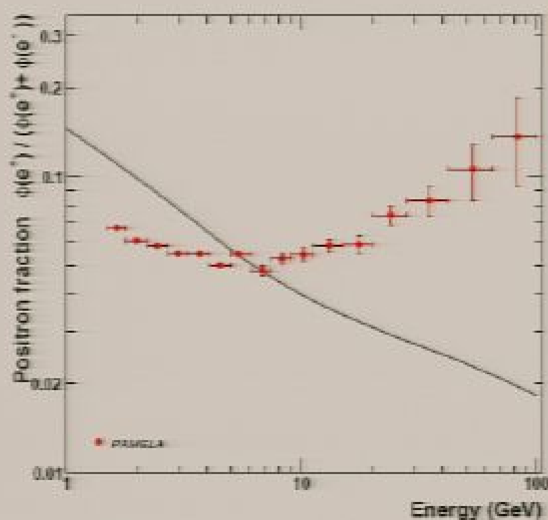
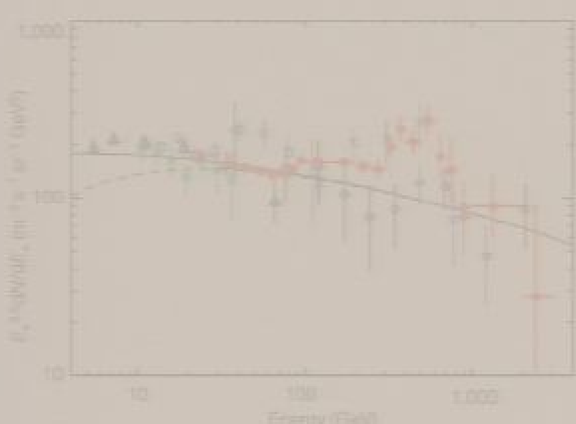
High Energy $e^{\pm}$



(*PAMELA*)

PAMELA

- Excess e^{+} fraction above $10\ GeV$
- Possibly:
  - Pulsars
  - $100+\ GeV$ DM Decay $\tau \sim 10^{26}\ s$
  - DM Annihilation $\sigma \sim 100 \times$WIMPy (leptophilic b/c no excess $\bar{p}$)



(*ATIC*)

ATIC/PPB-BETS, etc

- Excess $e^{\pm}$ at 100-800 GeV
- Distinct peak
- Consistent with PAMELA
- Similar explanations

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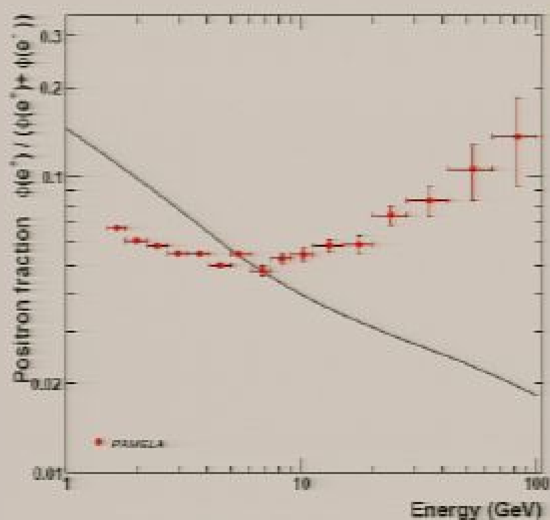

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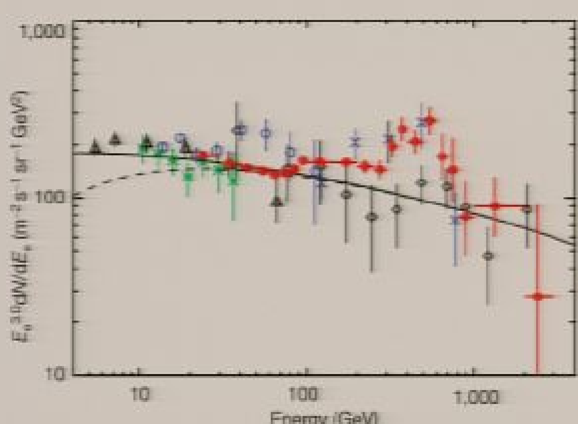

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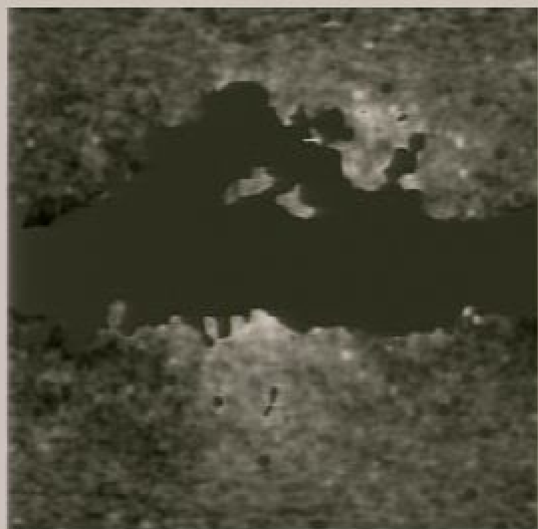

($Finkbeiner$ et al from WMAP data)

WMAP Haze

- Excess microwaves at galaxy center (other foregrounds subtracted)
- Synchotron of high energy $e^{\pm}$
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All require 100- to 1000-fold boost in cross-section for annihilation

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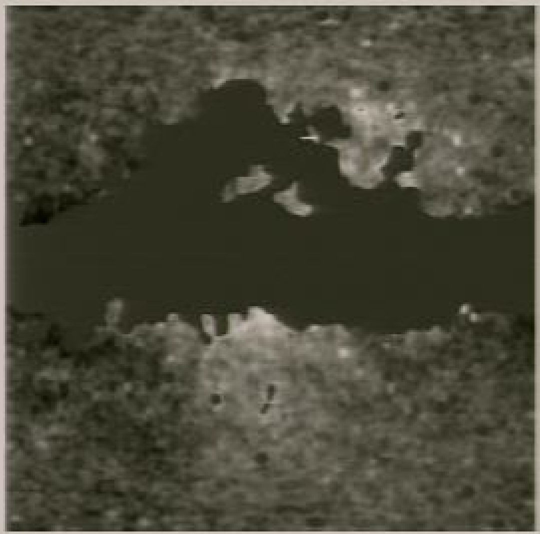

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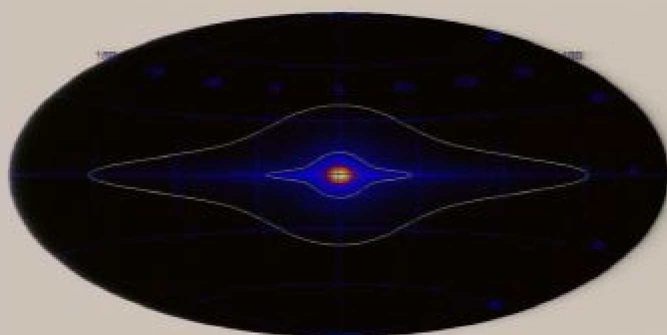
511 keV Line

Observed for almost 4 decades



(*INTEGRAL/SPI*)

INTEGRAL

- $e^{\pm}$ annihilation nearly at rest
- Dominant bulge component
- Possibly:
  - Super-/Hyper-/Novae (e^{+} escape?)
  - Light DM annihilation (cusps?)
  - Exciting DM

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- DM with 2 states $\delta M \gtrsim 2m_e$
- Requires boosted cross-section
- Variant spectra allowed

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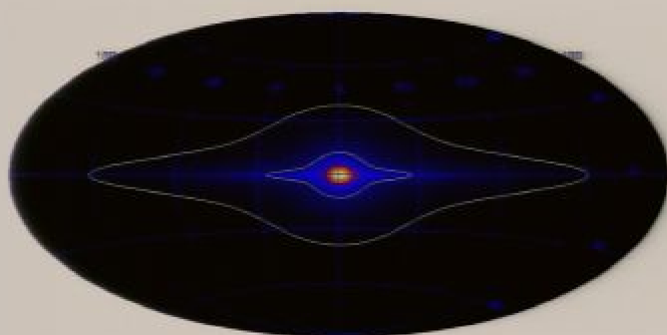

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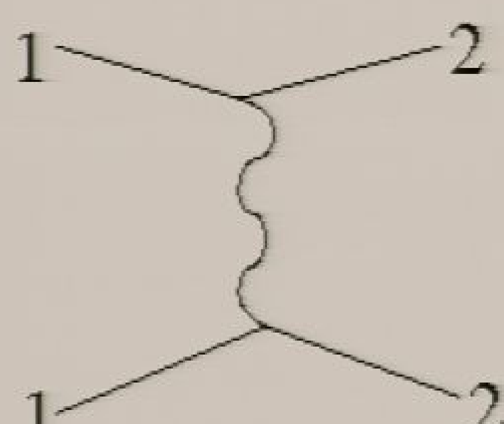

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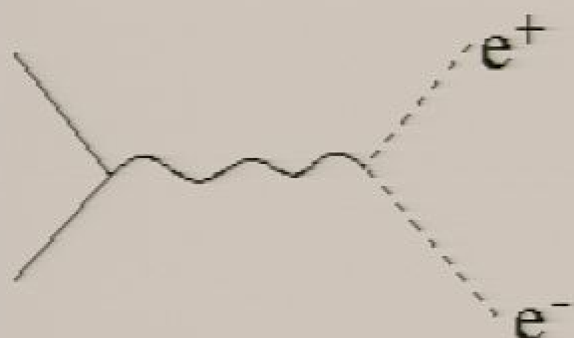
A Sketch of Particle Physics

Non-Abelian symmetry breaking key *(Arkani-Hamed et al)*



Leptophilia

- Gauge bosons naturally lighter
- Kinetic mixing with photon

$$\epsilon B_{\mu\nu} F^{\mu\nu}$$

- Resonant production at $\mu \lesssim 1\ GeV$ decays to $e^{\pm}$

Mass Splittings

- Generated at 1-loop

$$\delta M \sim \alpha\mu$$

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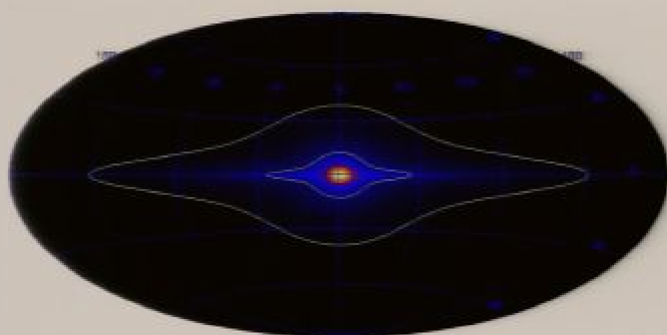

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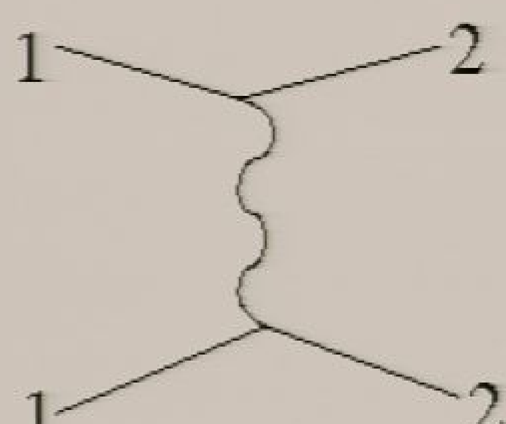

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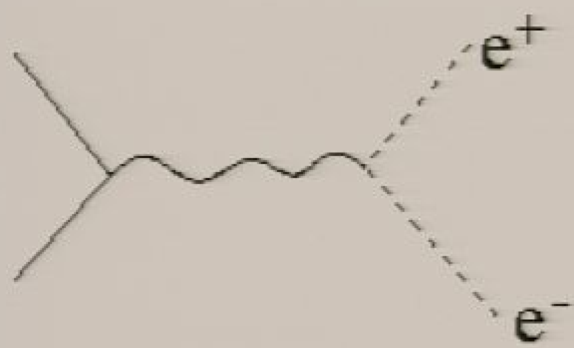

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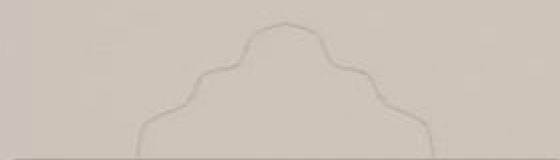

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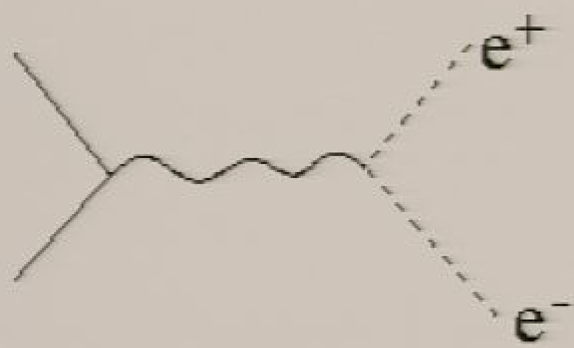

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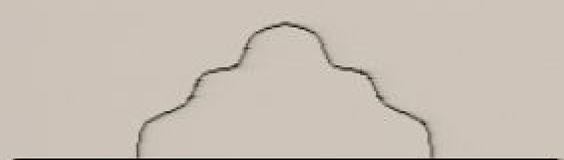

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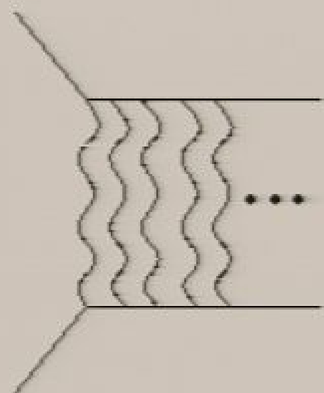

Boost Factors

- Uncertainty in DM density profile

$$\text{flux} \sim n^2 \langle \sigma v \rangle$$

- Or attraction of DM by gauge forces (Sommerfeld enhancement)

Putting It Together

- Production of $e^{\pm}$ only through light bosons
- XDM: MeV scale mass splitting through 1-loop
- iDM: 100 keV scale splitting through small 1-loop
- Not as reliant on hopes for DM clumping to boost

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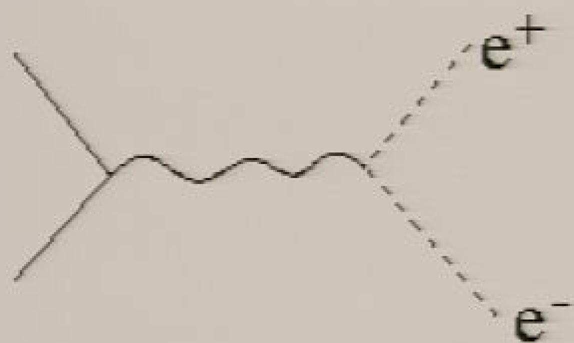

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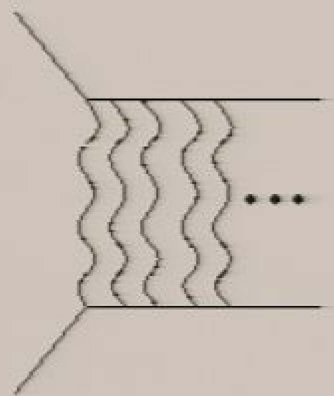

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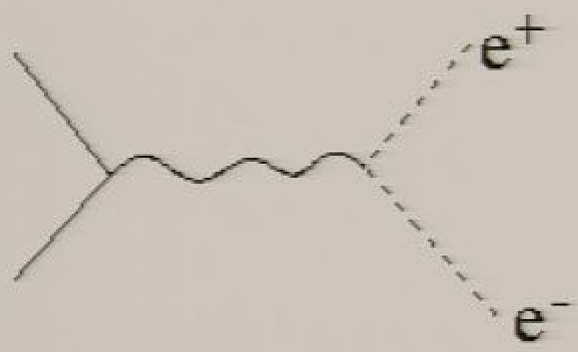

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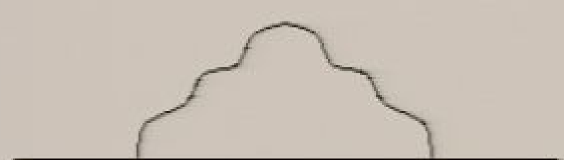

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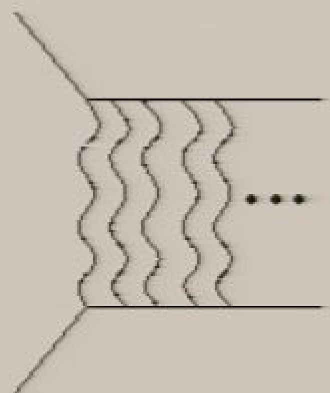

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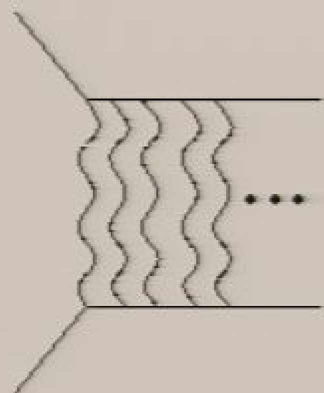

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The Need for Boost Factors

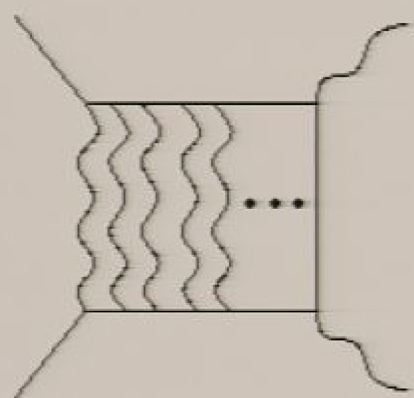
Annihilation Case

- Early universe cross-section ($v \sim 0.2$)

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \; cm^3/s$$

- In galaxy, $\langle v \rangle \sim 10^{-3}$, $\rho_{DM} \sim 0.35 \; GeV/cm^3$
- Excesses require $\langle \sigma v \rangle \sim 10^{-23} \; cm^3/s$
- Perturbatively $\langle \sigma v \rangle$ constant in v
- Boost at low velocity up to $\alpha M/\mu$

Review of Sommerfeld Enhancement



s-Wave Enhancement for Annihilation

- Annihilation local ($\ell \sim 1/M$)
  Only s-wave allowed
- Gauge force enhances wavefunction
  vs plane-wave $\sigma \sim \sigma_0 |\psi(0)|^2$
- Enhancement grows as α / v
  Saturates at $\sim \alpha M / \mu$
- Resonant enhancement if bound states

Higher Partial Wave

- Relevant for scattering/exciting
- Wavefunction in radius $1/\mu$

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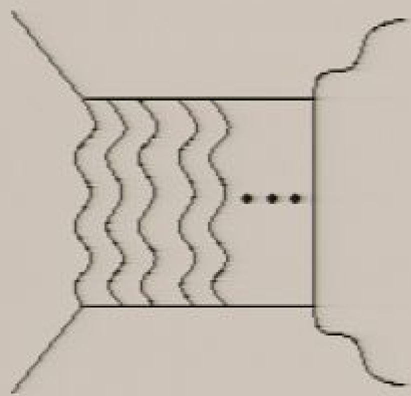

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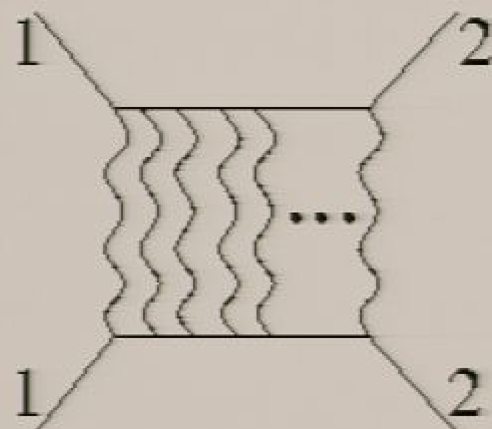

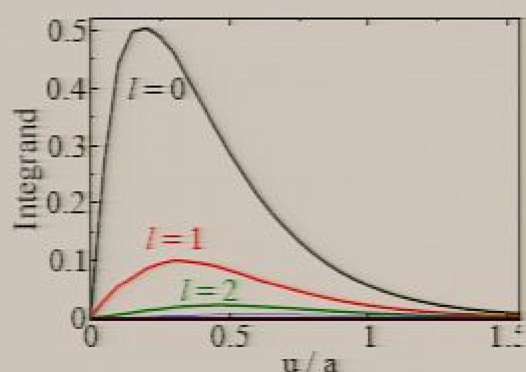

Minimum Velocity

- Excitation requires $v \geq \sqrt{2\delta M/M}$
- $\delta M \sim 2m_e$, $M \sim TeV$ gives $v \gtrsim 10^{-3}$ about RMS velocity
- Maxwell-Boltzmann suppression

$$\langle \sigma v \rangle \propto \int_{v_{min}}^{\infty} dv v e^{-3v^2/2v_{rms}^2}$$

- Need many partial waves
  Only few contribute
- Difficult w/o very clumpy density
  Or modified velocity profile

A Difficulty for XDM

Unitarity Limits

- For partial wave l, $\sigma_l \leq \pi(2l+1)/M^2v^2$
- Optimal mass (with MB distribution) near 700 GeV
- Still requires density boost $\times 20$
- Yukawa potential keeps large l contribution small

Standard XDM has trouble

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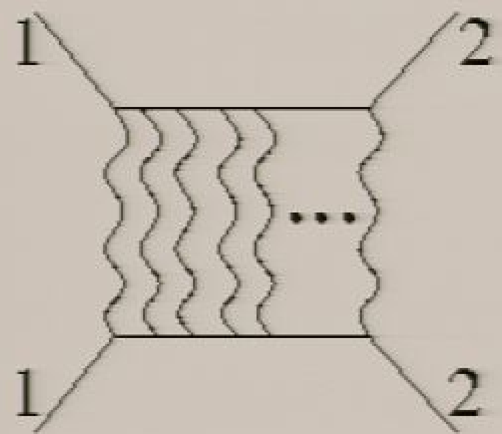

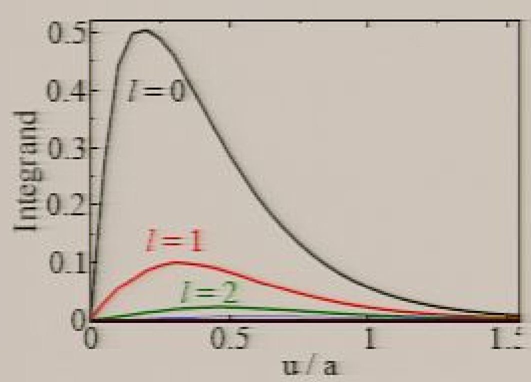

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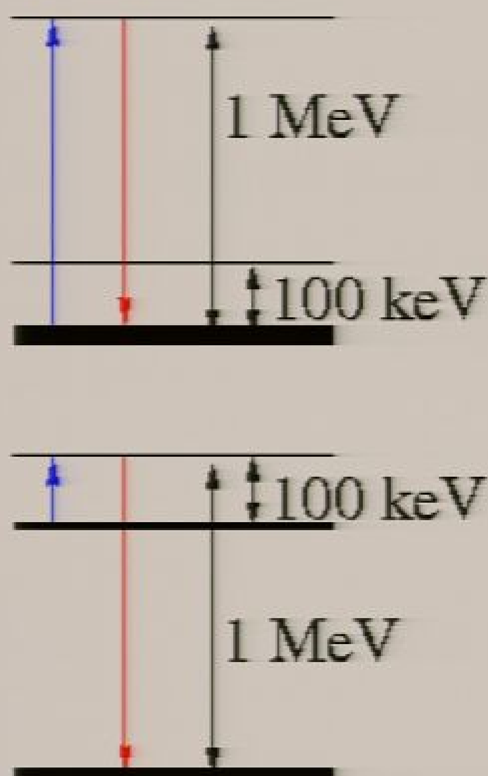

Spectrum Inversion

- Most models assume top spectrum
  Small gap just spectator
- But consider bottom spectrum
- Middle state has small gap to jump
  Then decay by $e^{\pm}$ pair

Inversion Benefits

- Minimum velocity smaller than RMS
  Reduces MB suppression
- More partial waves contribute
- Roughly optimized: $M \sim 500\ GeV$, $\delta M \sim 86\ keV$, $\mu \sim 120\ MeV$

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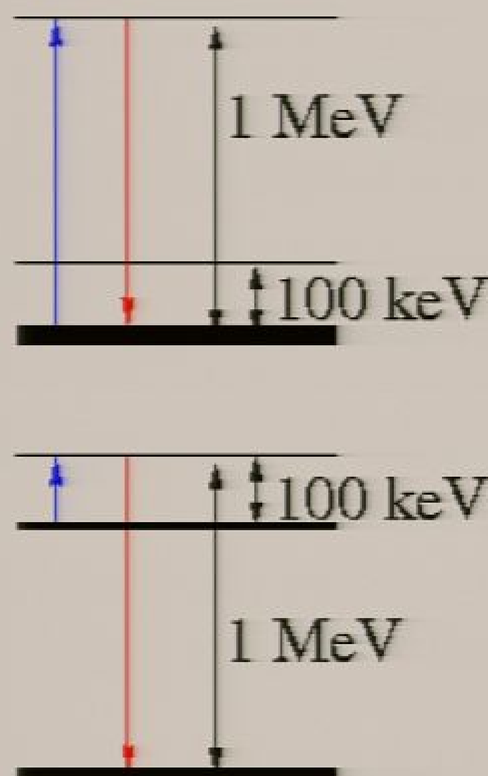

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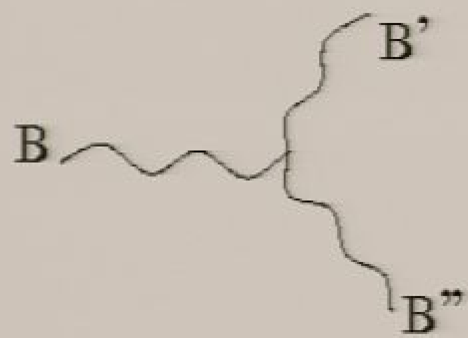
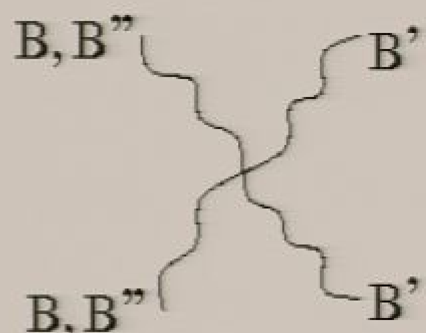
An Inverted Model of Dark Matter

Goals

- Engineer inverted DM spectrum for XDM
- Keep middle population stable
- Generate appropriate gauge boson mass & symmetry breaking
- Coupling to SM
  - XDM decay by $e^{\pm}$
  - Annihilation spectrum (broad and peaked)
- Find consistent cosmological history

Particle Content and Interactions



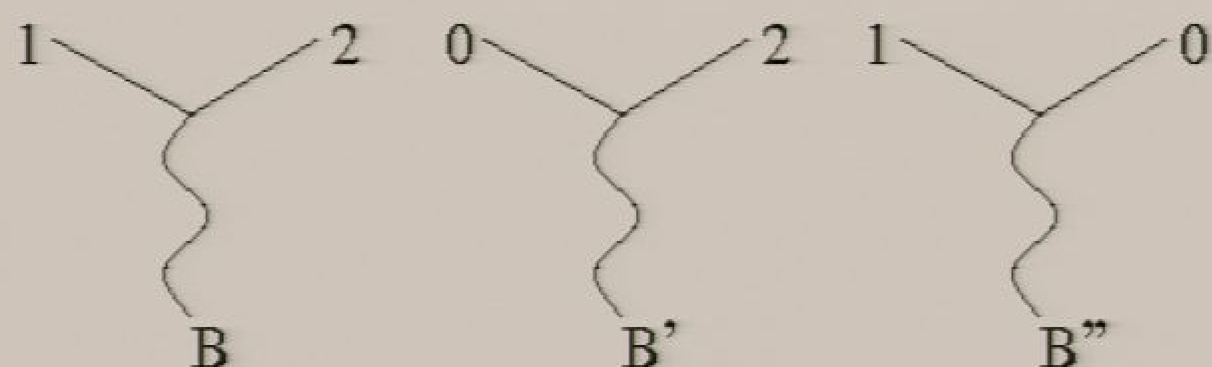


$SU(2)$ Gauge and DM Sector

- Adjoint as $SO(3)$ vector

$$B^a_\mu = (B_\mu, B'_\mu, B''_\mu)$$

- Majorana fermion DM χ^a
- "Bare" mass $\sim 500\ GeV$
- Interactions as shown
- $\mathbb{Z}_2$ symmetry



Particle Content and Interactions

Higgs Sector

- Adjoint Δ^a:

$$(\Delta^a/\Lambda)B^a_{\mu\nu}Y^{\mu\nu}$$

- 5-plet Σ^{ab}:

$$h\Sigma^{ab}\bar{\chi}^a\chi^b$$

- Both add to B^a masses

Cosmological Sector

- Heavy $U(1)$ Z' (maybe) Coupled to e_R
- Heavy scalar S:

$$(S^2/\Lambda_{GUT})\bar{\chi}^a\chi^a$$

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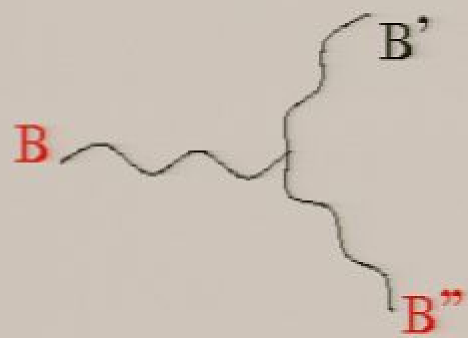

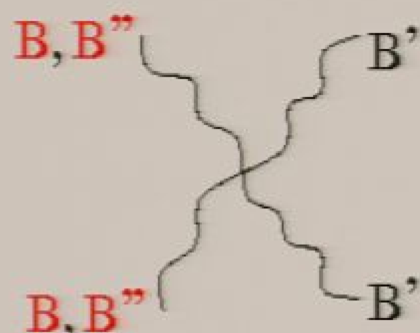

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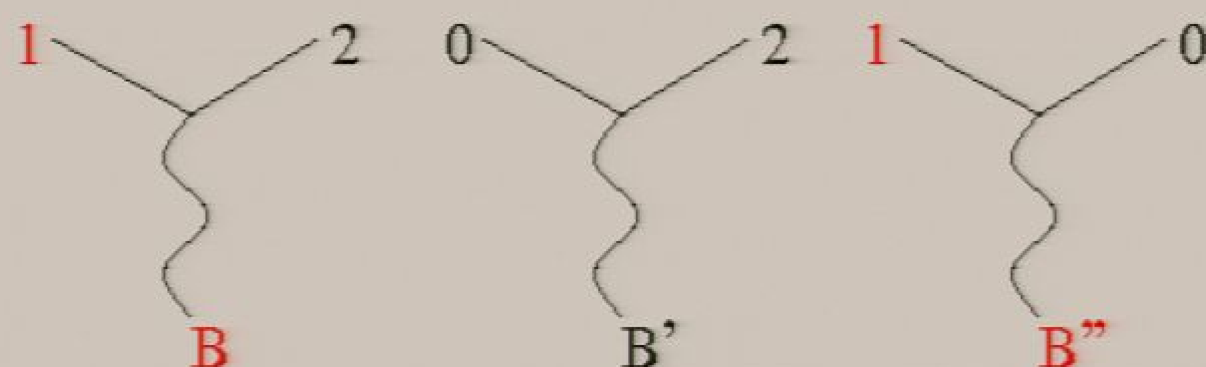

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$$h\Sigma^{ab}\bar{\chi}^a\chi^b$$

- Both add to B^a masses

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- Heavy $U(1)$ Z' (maybe) Coupled to e_R
- Heavy scalar S:

$$(S^2/\Lambda_{GUT})\bar{\chi}^a\chi^a$$

Particle Content and Interactions

Higgs Sector

- Adjoint Δ^a:

$$(\Delta^a/\Lambda)B^a_{\mu\nu}Y^{\mu\nu}$$

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ARF

Symmetry Breaking

$$V = \lambda_1 \left(\Sigma^{ab}\Sigma^{ab} - 2\Sigma^2\right)^2 + \lambda_2 \left(\Delta^a\Delta^a - \Delta^2\right)^2 + \lambda_3 \Delta^a \Sigma^{ab}\Sigma^{bc}\Delta^c$$

$$+\lambda_4 \Delta^a \Sigma^{ab} \Delta^b + \lambda_5 \Sigma^{ab}\Sigma^{bc}\Sigma^{ca}$$

Scalar VEVs

- $\langle \Delta^1 \rangle = \Delta$, $\langle \Delta^{0,2} \rangle = 0$
- $\langle \Sigma^{01} \rangle = \langle \Sigma^{12} \rangle = 0$ for $\lambda_3 \Delta^2 \gtrsim \lambda_5 \Sigma$
- $\langle \Sigma^{11} \rangle$ fixed, take small
- $\langle \Sigma^{00} \rangle \sim \Sigma$, $\langle \Sigma^{02} \rangle = 0$

Gauge Boson Masses

- $\mu = \mu'' = g\sqrt{2\Sigma^2 + \Delta^2}$
- $\langle \Sigma^{11} \rangle$ gives splitting
- $\mu' = g2\sqrt{2}\Sigma$
- Take $\Delta > \sqrt{6}\Sigma$
  So $\mu > \mu'$

$$\Delta \sim 10\ GeV\ ,\ \Sigma \sim GeV \Rightarrow \mu \sim GeV\ ,\ \mu' \sim 100\ MeV$$

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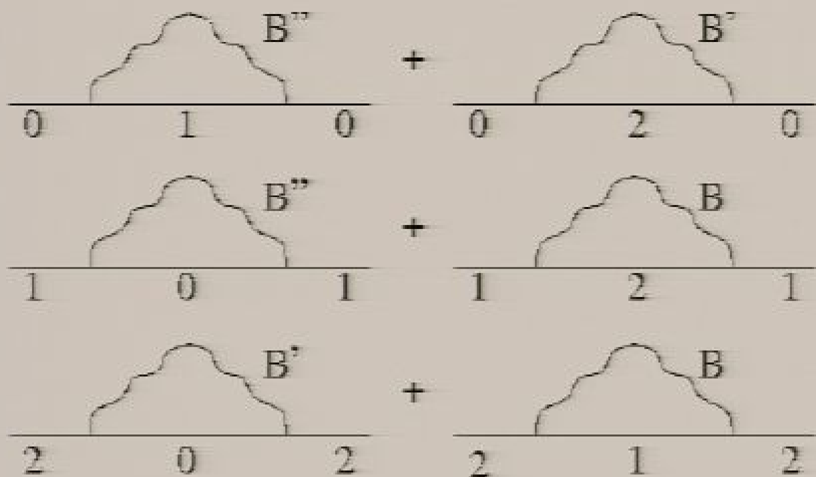

DM Mass Splittings

- χ^1 split from χ^0, χ^2 by loops
- Yukawa splits χ^0, χ^2

$$\delta M \sim 2h\Sigma \sim MeV$$

- Plus splitting from $\langle \Sigma^{11} \rangle$

Mass eigenbasis:

$$\begin{bmatrix} M_2 \\ M_1 \\ M_0 \end{bmatrix} = M + \alpha\mu + \begin{bmatrix} h\Sigma - \frac{1}{2}\alpha(\mu - \mu') \\ 0 \\ -h\Sigma - \frac{1}{2}\alpha(\mu - \mu') \end{bmatrix}$$

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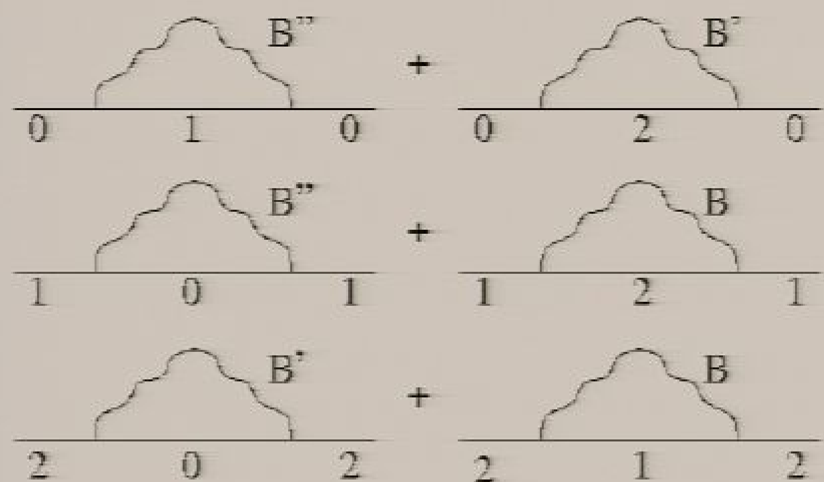

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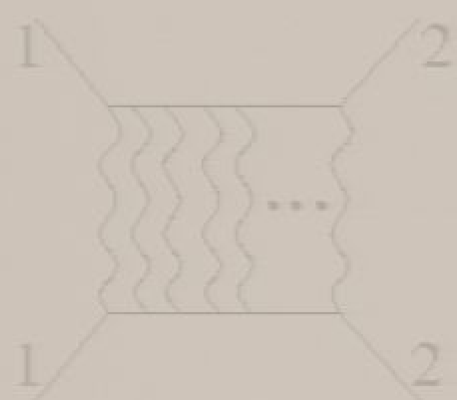
Excitation and Annihilation Signatures

Coupling to SM

- B' couples to hypercharge
- Kinetic diagonalization

$$B' = \tilde{B}' + (\Delta/\Lambda)\sin\theta_W \tilde{Z} + \cdots$$

- No iDM for DAMA (due to $\mathbb{Z}_2$)



XDM and $e^{\pm}$ pairs

- Enhanced $\chi^1\chi^1 \to \chi^2\chi^2$ scattering
- χ^2 decays
  - Dominantly $\chi^2 \to e^+e^-\chi^0$
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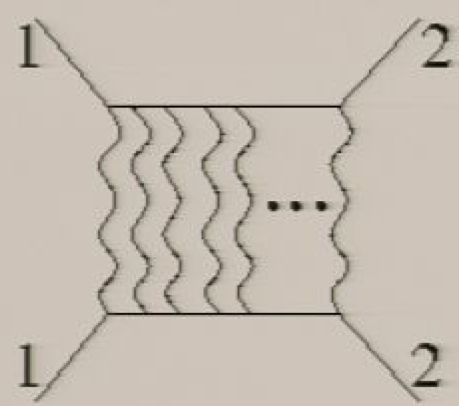

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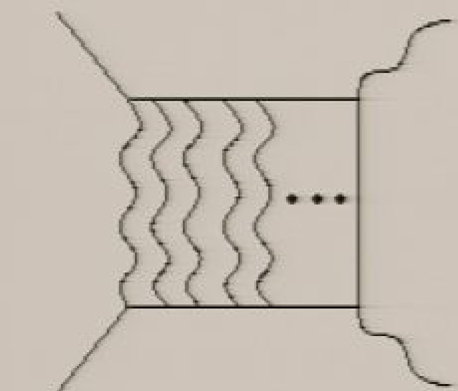

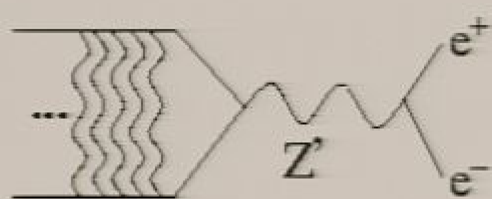

Annihilation

- $\chi^0\chi^0$ or $\chi^1\chi^1$ as before
- B' produced dominantly on-shell
  Hence only $e^\pm$
- Two $e^\pm$ pairs, so broad spectrum
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- Much sharper spectrum
- ATIC peak?

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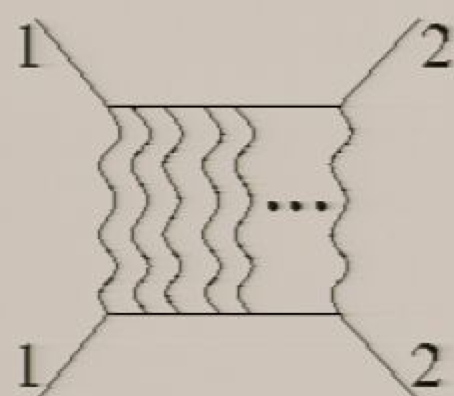

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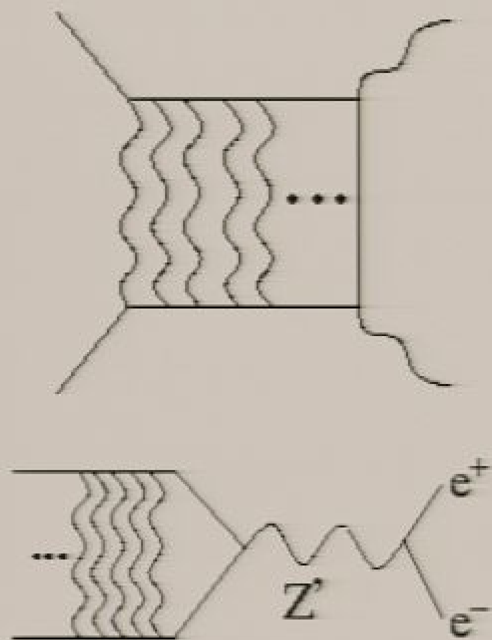

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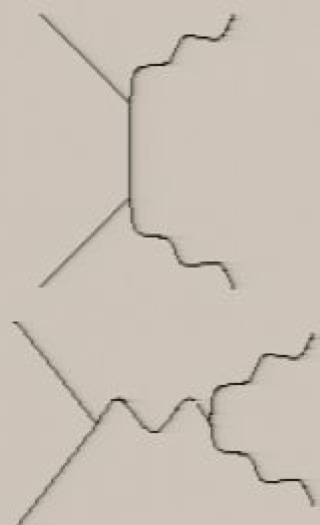
Cosmology of DM Sector



DM Thermal Relic Density

- Freeze-out density $\sim 1/\sigma$
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- Either increase gauge coupling
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Gauge & Scalar Relics

- Similar but lower mass propagators
- Negligible abundances
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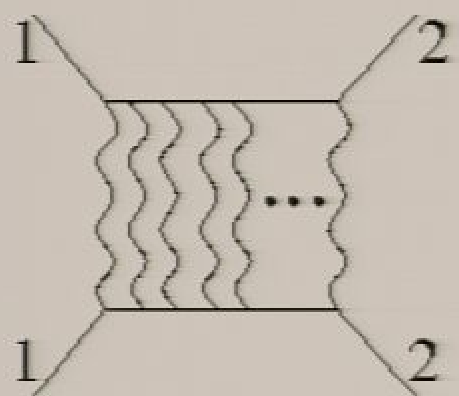

Kinetic Equilibration

- Consider $\chi\chi \leftrightarrow \chi\chi$ scattering
  Equilibrium at low KE depletes χ^1
- At KE$\sim 2m_e$, $v \sim 10^{-3}$
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- Note $p \propto a^{-1} \propto T$
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Nonthermal Generation

- Take $m_S \sim \langle S \rangle \sim \Lambda$
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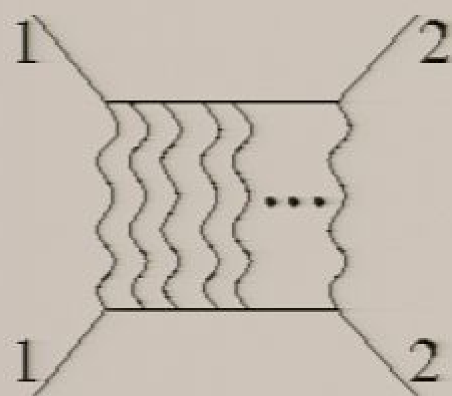

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- Improved studies of multistate Sommerfeld enhancement WKB when numerics are too difficult

Particle Physics

- More detailed exploration of the model
- Can other reps work for iDM?

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Dark matter is exciting right now!

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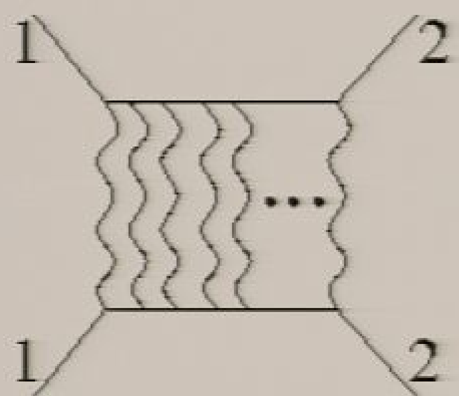

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