

Title: An Inverted Mass Hierarchy for Excited Dark Matter

Date: Feb 24, 2009 02:00 PM

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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

Outline

DM Hints

Boost Factors

Model

Future

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

Inverted XDM

ARF

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- 1 Hints About Dark Matter?
- 2 The Need for Boost Factors
- 3 An Inverted Model of Dark Matter
- 4 Future Directions

Hints About Dark Matter?

Inverted XDM

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DM Hints

Direct Detection

High-E e

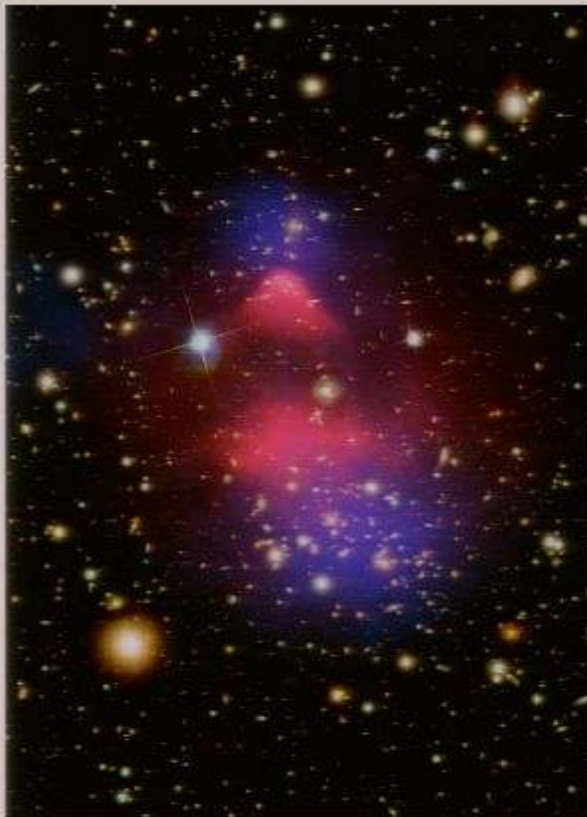
511 keV Line

Particle Physics

Boost Factors

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(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 synchrotron
 - 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

Inverted XDM

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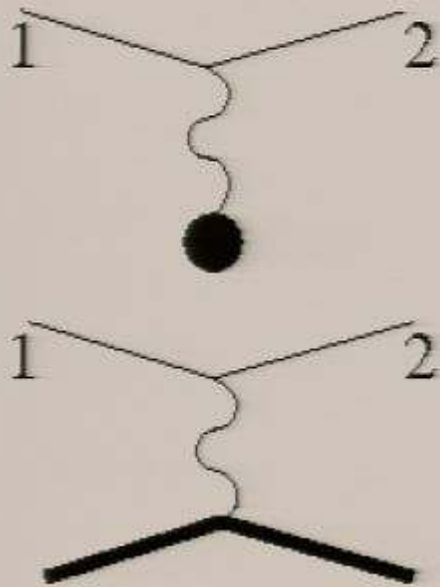
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DAMA vs Others

- 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 $\delta M \lesssim 100 \text{ keV}$

But...

- DAMA somewhat controversial
- I'll remain agnostic

Direct Detection

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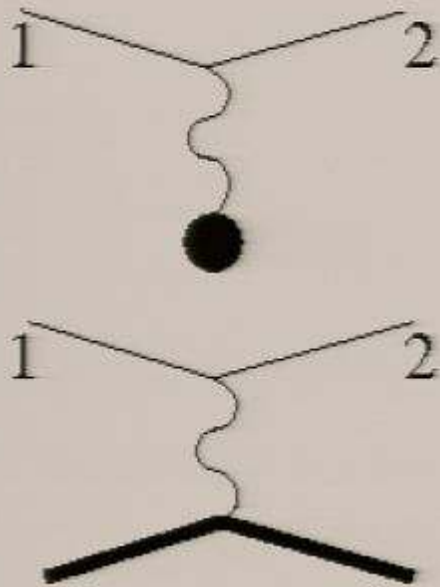
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High Energy e^\pm

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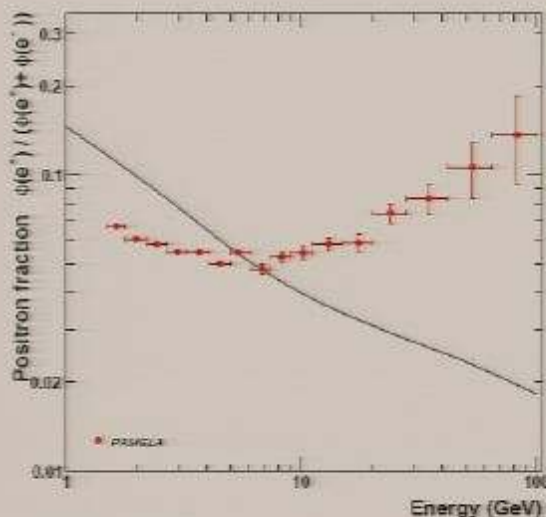
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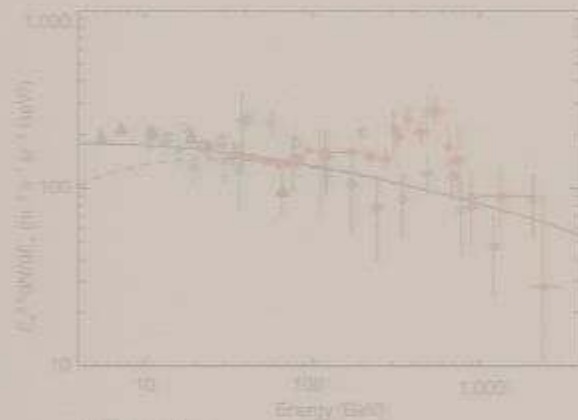
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(PAMELA)



(ATIC)

PAMELA

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

ATIC/PPB-BETS, etc

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

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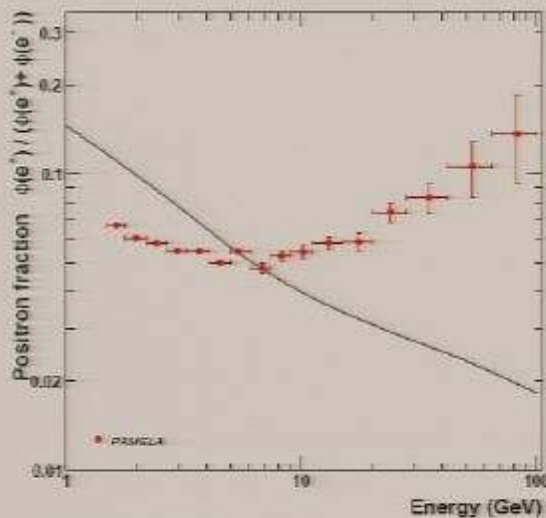
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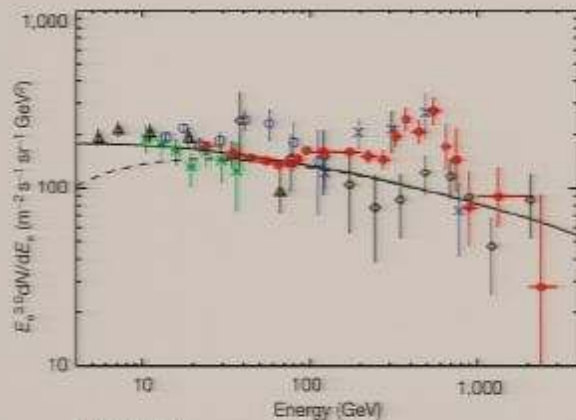
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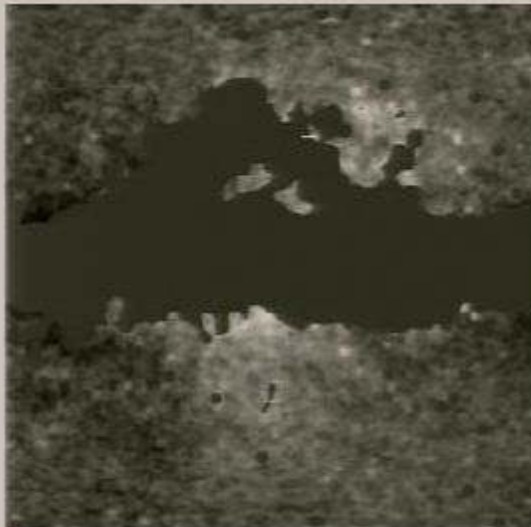
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(Finkbeiner et al from WMAP data)

WMAP Haze

- Excess microwaves at galaxy center (other foregrounds subtracted)
- Synchrotron of high energy e^\pm
- Consistent with DM annihilation

All require 100- to 1000-fold boost in cross-section for annihilation

High Energy e^\pm

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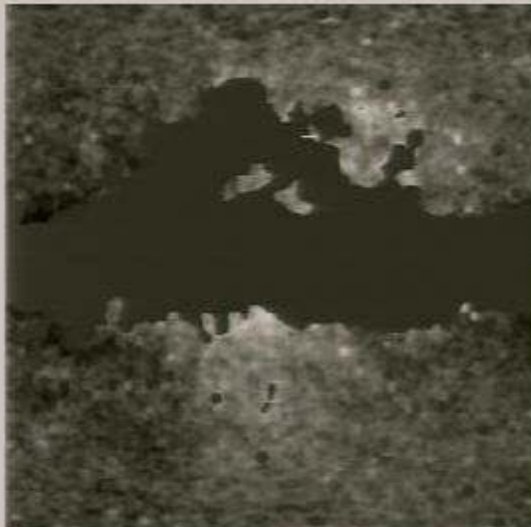
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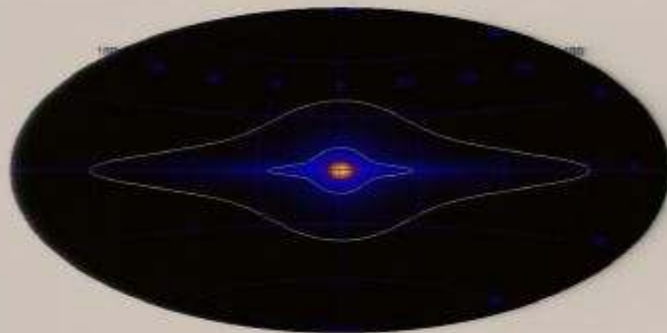
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511 keV Line

Observed for almost 4 decades



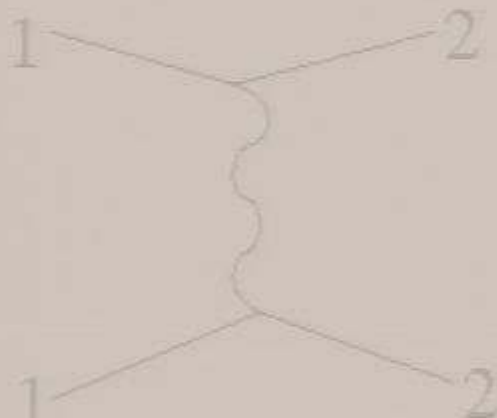
(INTEGRAL/SPI)

INTEGRAL

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

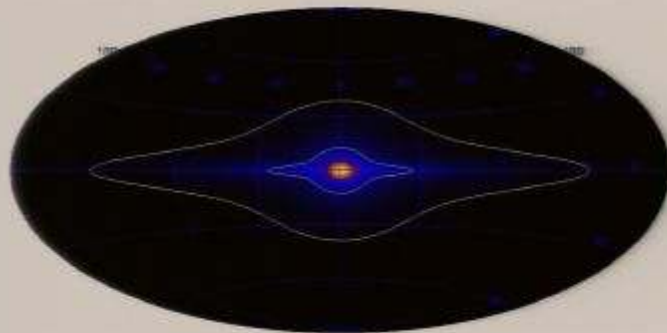
eXciting Dark Matter

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



511 keV Line

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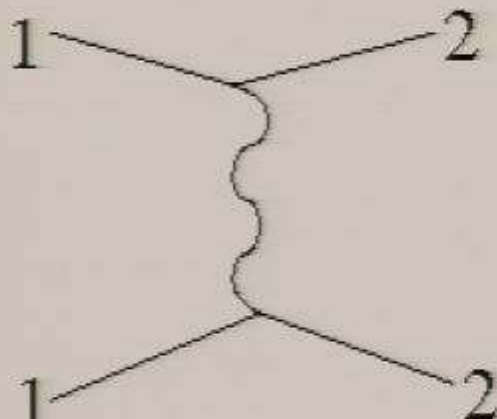
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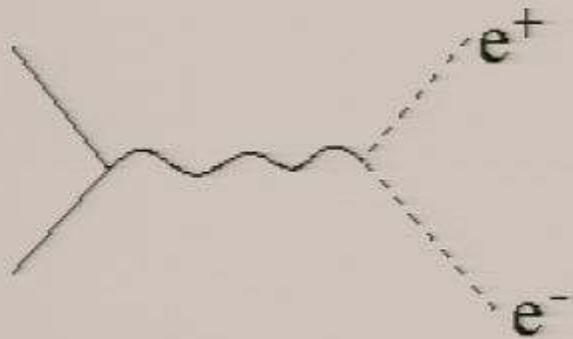
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Non-Abelian symmetry breaking key (*Arkani-Hamed et al*)



Leptophilia

- Gauge bosons naturally lighter
- Kinetic mixing with photon

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

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

Mass Splittings

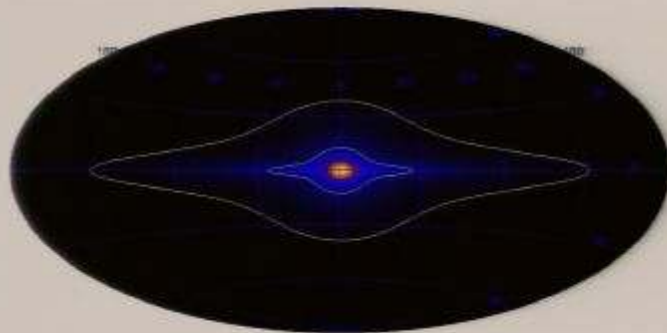
- Generated at 1-loop

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

- Naturally MeV , possibly 100 MeV

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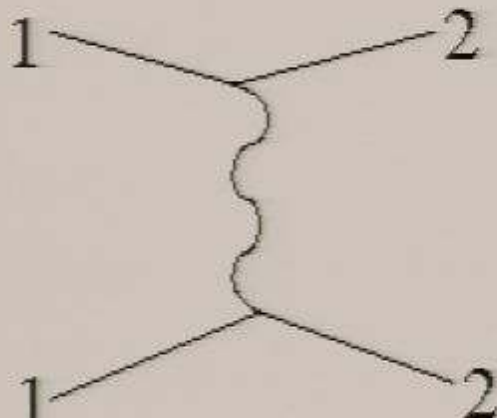
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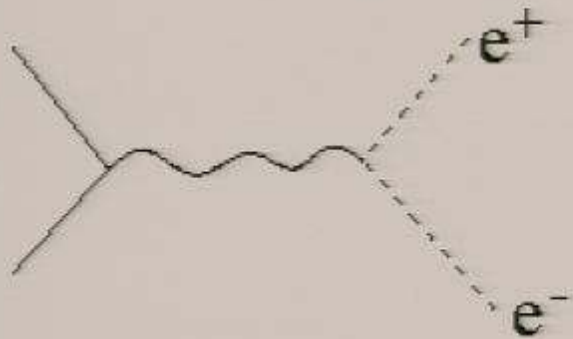
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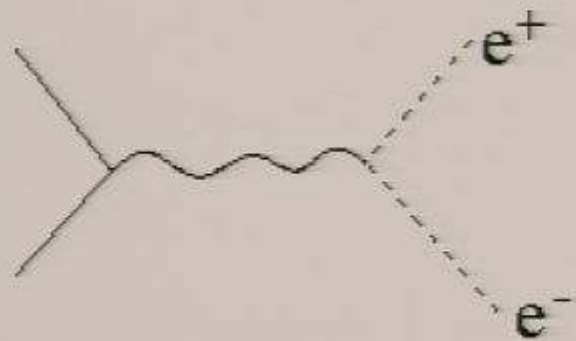
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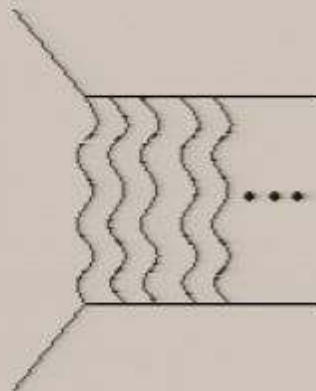
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Boost Factors

- 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

A Sketch of Particle Physics

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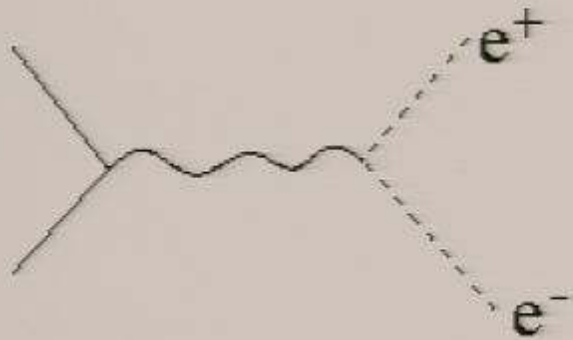
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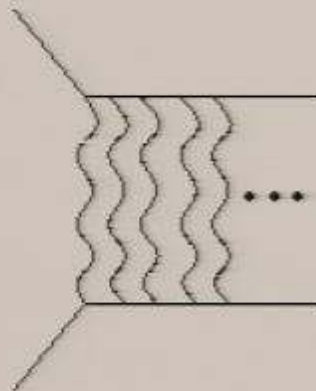
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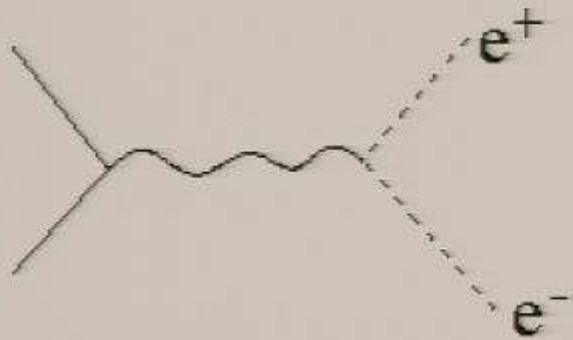
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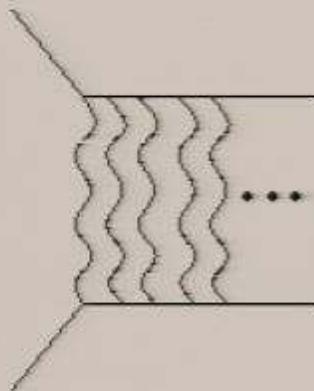
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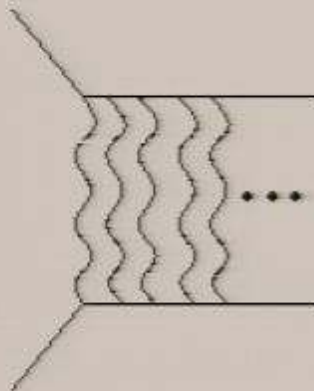
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The Need for Boost Factors

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Sommerfeld

XDM Difficulty

New Spectrum

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Annihilation Case

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

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

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

Review of Sommerfeld Enhancement

Inverted XDM

ARF

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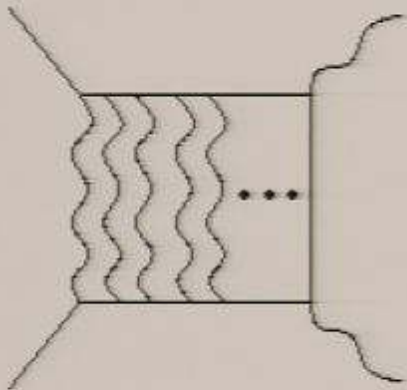
Sommerfeld

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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 $1/\mu$

Review of Sommerfeld Enhancement

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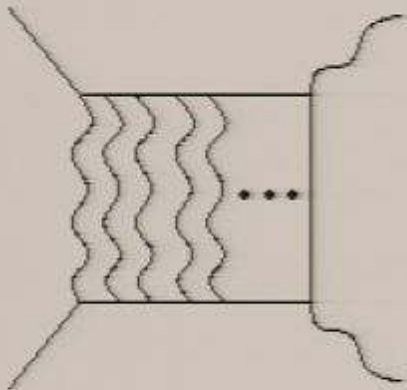
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A Difficulty for XDM

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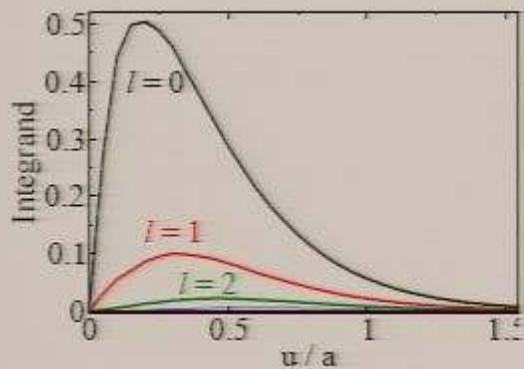
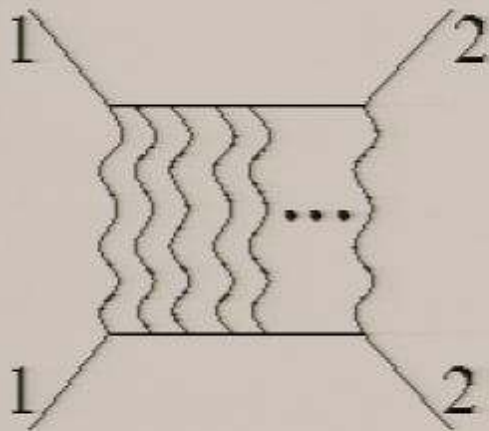
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Minimum Velocity

- 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

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Unitarity Limits

- For partial wave l , $\sigma_l \leq \pi(2l + 1)/M^2 v^2$
- 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

A Difficulty for XDM

Inverted XDM

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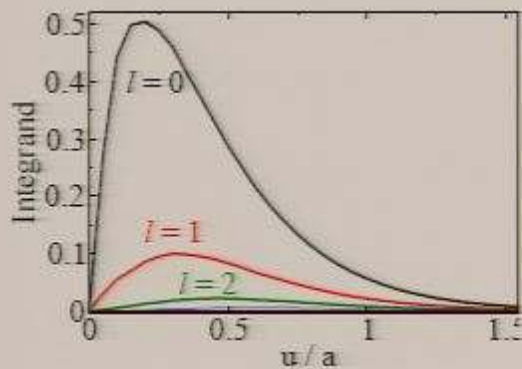
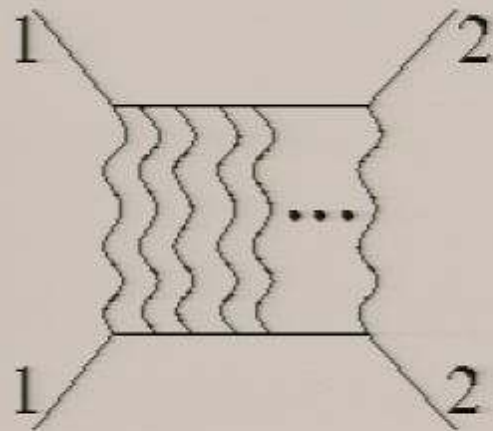
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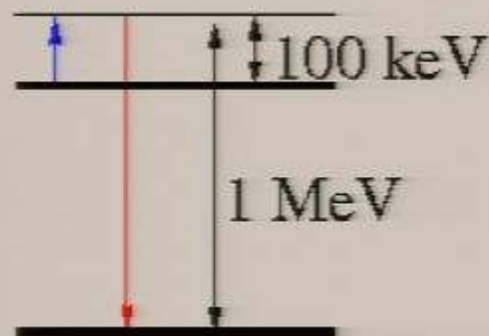
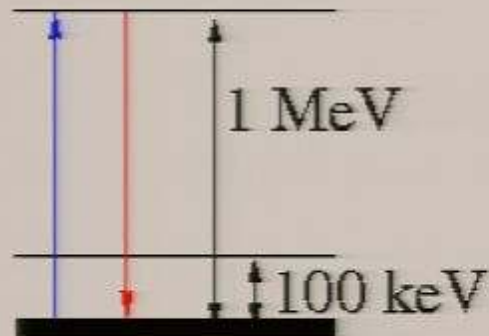
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Spectrum Inversion

- 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: $M \sim 500 \text{ GeV}$,
 $\delta M \sim 86 \text{ keV}$, $\mu \sim 120 \text{ MeV}$

Inverting the DM Spectrum

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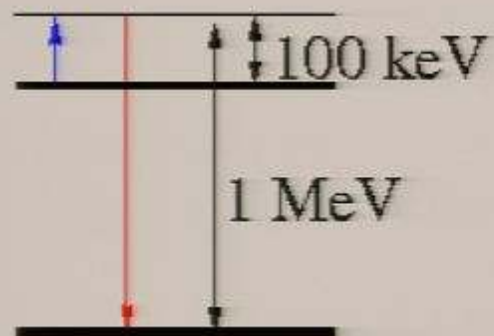
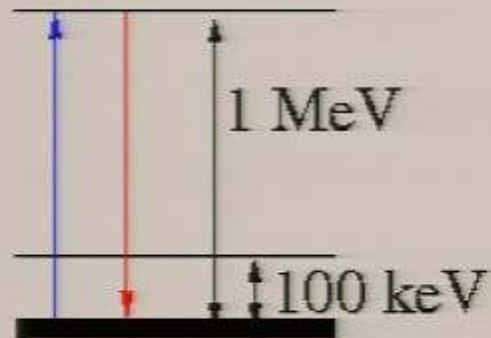
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An Inverted Model of Dark Matter

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Particle Content

Higgsing

Signatures

Cosmology

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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

Inverted XDM

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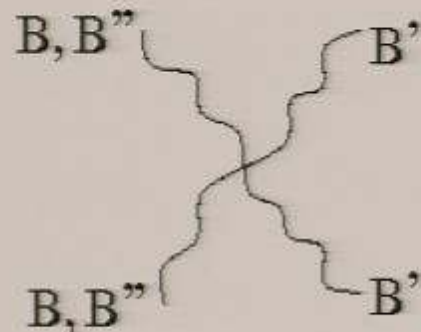
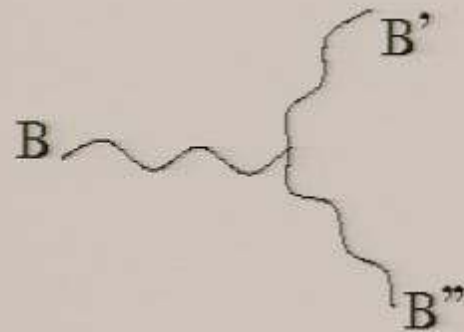
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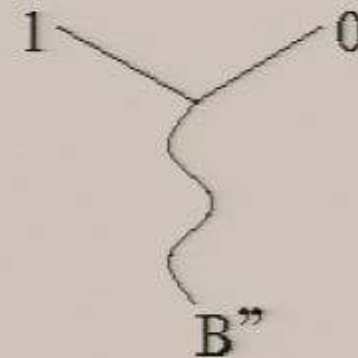
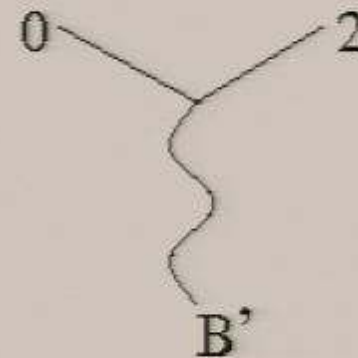
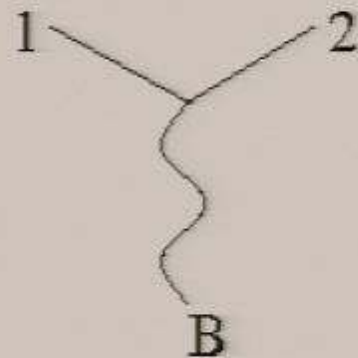


$SU(2)$ Gauge and DM Sector

- Adjoint as $SO(3)$ vector

$$B_{\mu}^a = (B_{\mu}, B'_{\mu}, B''_{\mu})$$

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



Particle Content and Interactions

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Higgs Sector

- Adjoint Δ^a :

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

- 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 :

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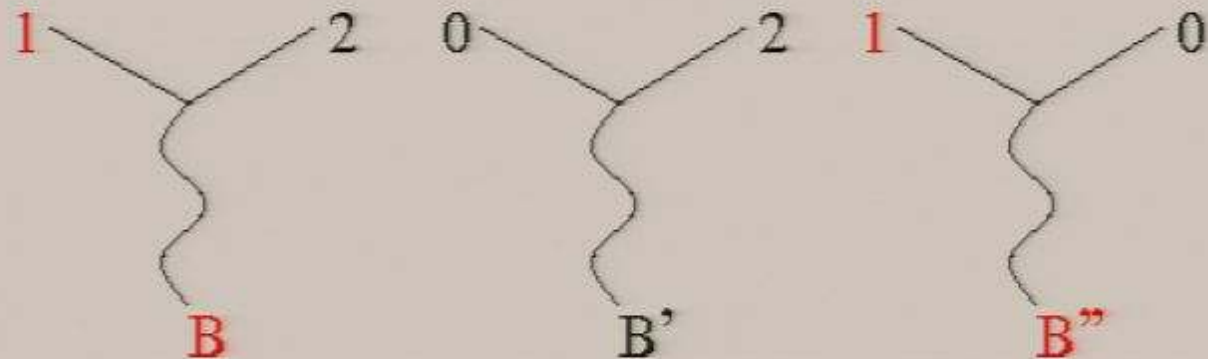
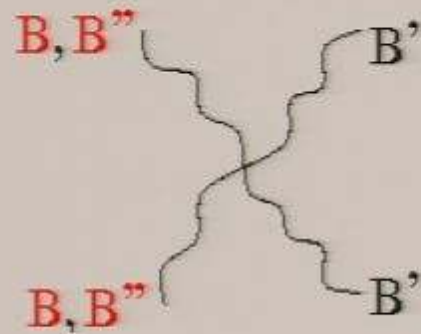
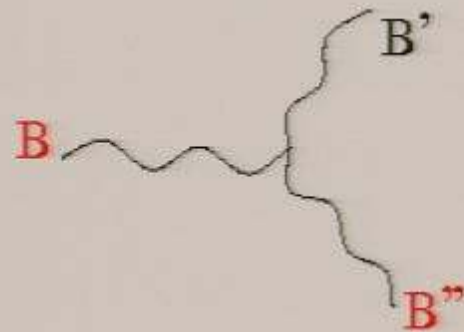
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$$V = \lambda_1 \left(\Sigma^{ab} \Sigma^{ab} - 2\Sigma^2 \right)^2 + \lambda_2 \left(\Delta^a \Delta^a - \Delta^2 \right)^2 + \lambda_3 \Delta^a \Sigma^{ab} \Sigma^{bc} \Delta^c \\ + \lambda_4 \Delta^a \Sigma^{ab} \Delta^b + \lambda_5 \Sigma^{ab} \Sigma^{bc} \Sigma^{ca}$$

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 $\mu > \mu'$

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

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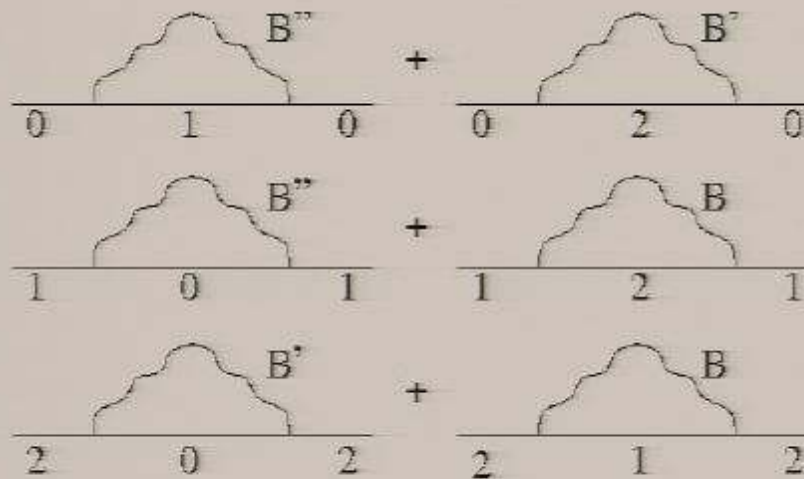
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DM Mass Splittings

- 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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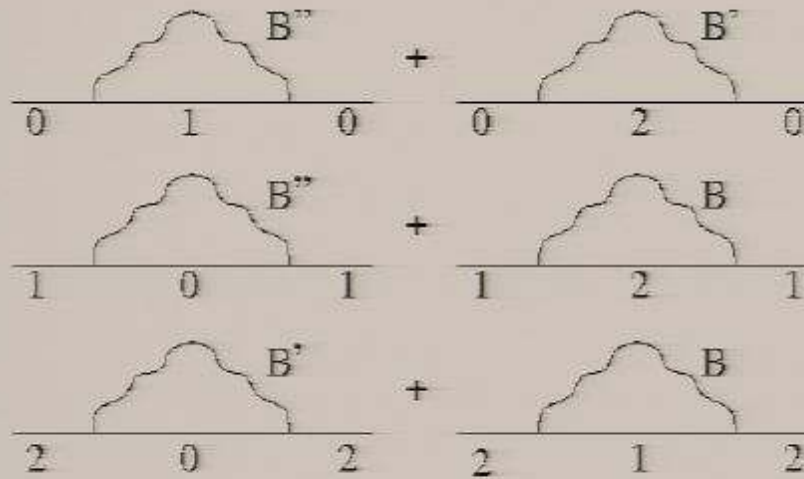
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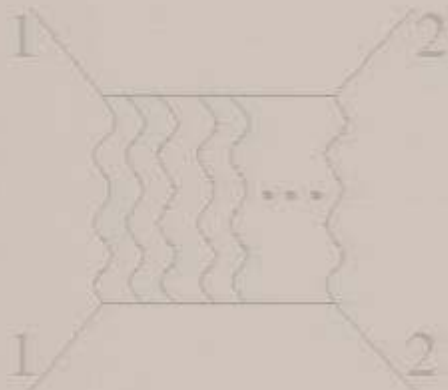
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Coupling to SM

- B' couples to hypercharge
- Kinetic diagonalization

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

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

XDM and e^\pm pairs

- Enhanced $\chi^1 \chi^1 \rightarrow \chi^2 \chi^2$ scattering
- χ^2 decays
 - Dominantly $\chi^2 \rightarrow e^+ e^- \chi^0$
 - Suppressed $\chi^2 \rightarrow \gamma \chi^0$

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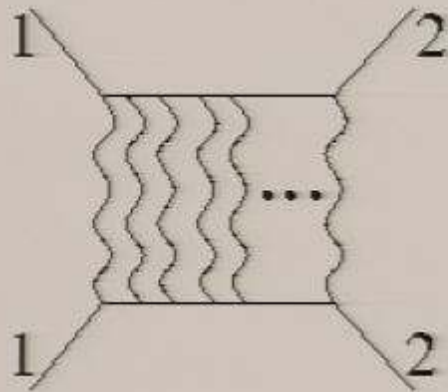
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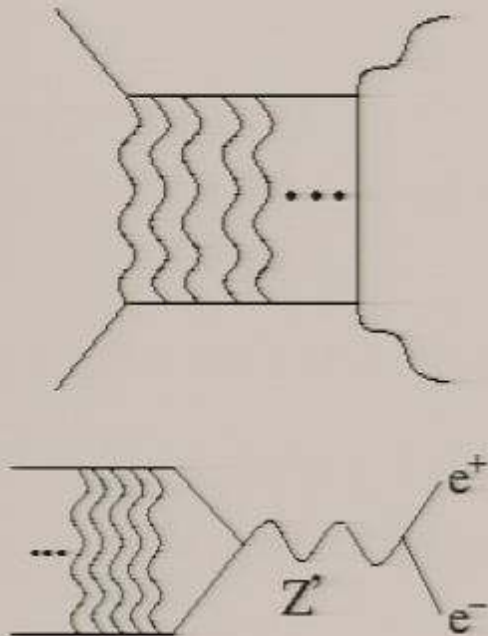
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Annihilation

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

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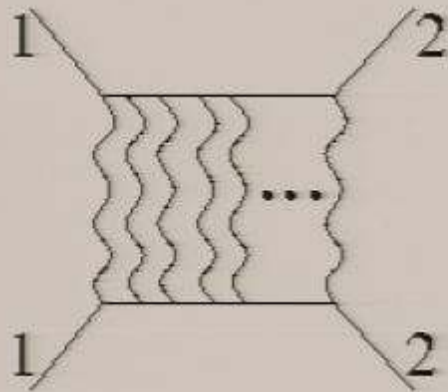
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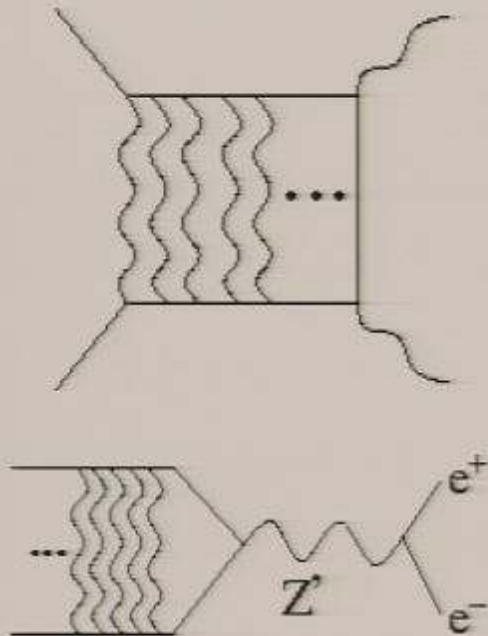
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DM Thermal Relic Density

- Freeze-out density $\sim 1/\sigma$
- χ abundance too high
- Either increase gauge coupling
Or introduce new Z'
- Z' would add to ATIC peak

Gauge & Scalar Relics

- Similar but lower mass propagators
- Negligible abundances
- Signals entirely too weak

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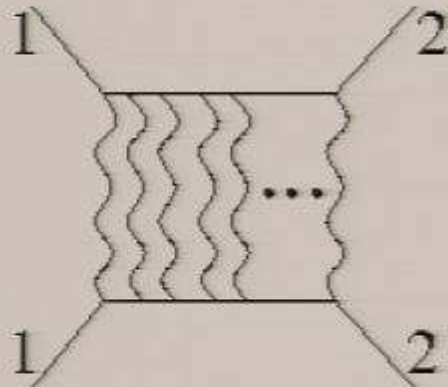
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Kinetic Equilibration

- Consider $\chi\chi \leftrightarrow \chi\chi$ scattering
Equilibrium at low KE depletes χ^1
- At $KE \sim 2m_e$, $v \sim 10^{-3}$
Sommerfeld enhanced
- Note $p \propto a^{-1} \propto T$
So $\langle\sigma v\rangle \propto 1/v \propto 1/T$, $n\langle\sigma v\rangle \propto H$
- More p removes equilibration

Nonthermal Generation

- Take $m_S \sim \langle S \rangle \sim \Lambda$
- Thermal WIMP abundance
- Induced Yukawa with χ
- Decay rate:
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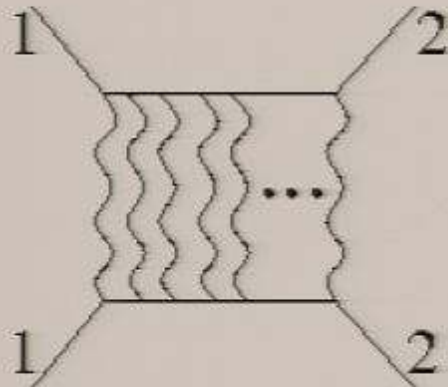
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Quantum Mechanics

- 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?

Cosmology

- Advantages of nonthermal generation?
- More detailed calculation of signals

Dark matter is exciting right now!

Cosmology of DM Sector

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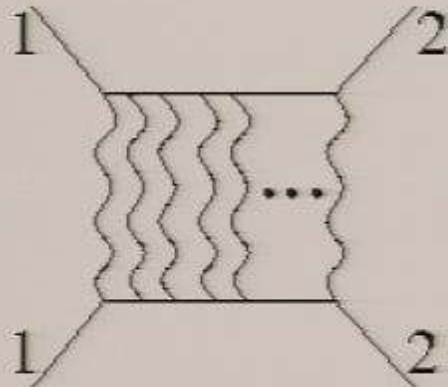
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