

Title: Bright Perspective for a Dark Sector

Date: Dec 04, 2008 02:00 PM

URL: <http://pirsa.org/08120022>

Abstract: Recent experimental results seem to require a dramatic change in our view of the dark matter sector. In this talk I will describe the reasons for this change and the ingredients required to describe the new data. I will present possible field theories that give rise to such phenomena and delineate the resulting collider signatures.

# Bright Perspectives from a Dark Sector

Itay Yavin

Princeton University

M. Baumgart, C. Cheung, J. T. Ruderman, L. T. Wang and I. Y. Coming out soon. . .  
Neal Weiner and I. Y. Coming out soon...

# Really Old News - 1933

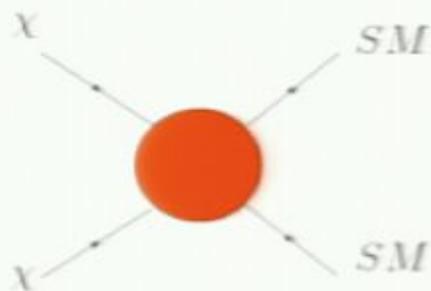
Zwicky discovered dark matter in the Coma cluster. By now, there are several cross-checks on the existence of dark matter.

A favorite candidate is a weakly interacting massive particle (WIMP)

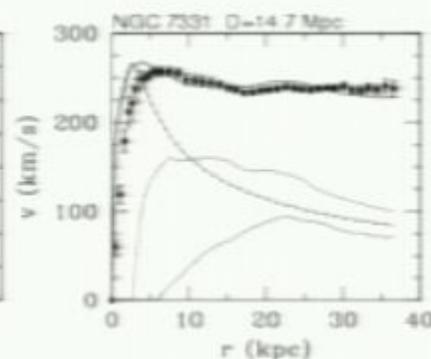
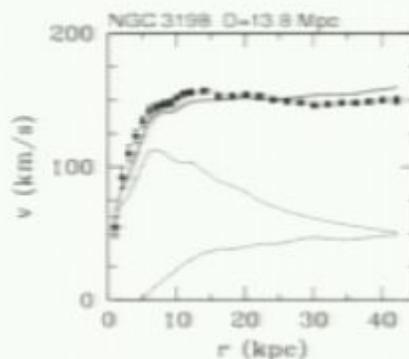
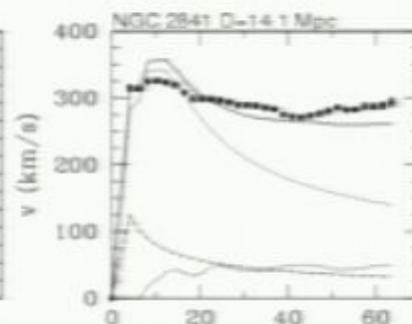
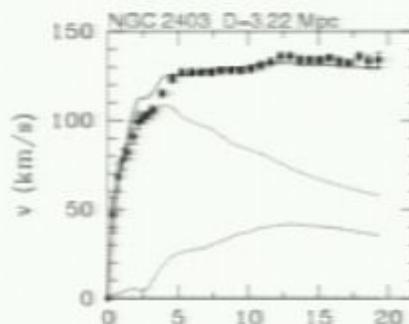
A WIMP density of

$$\rho_{\chi} = 0.3 \text{ GeV/cm}^3$$

A thermal relic with annihilation cross-section:



$$\langle \sigma v \rangle_{ann} = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

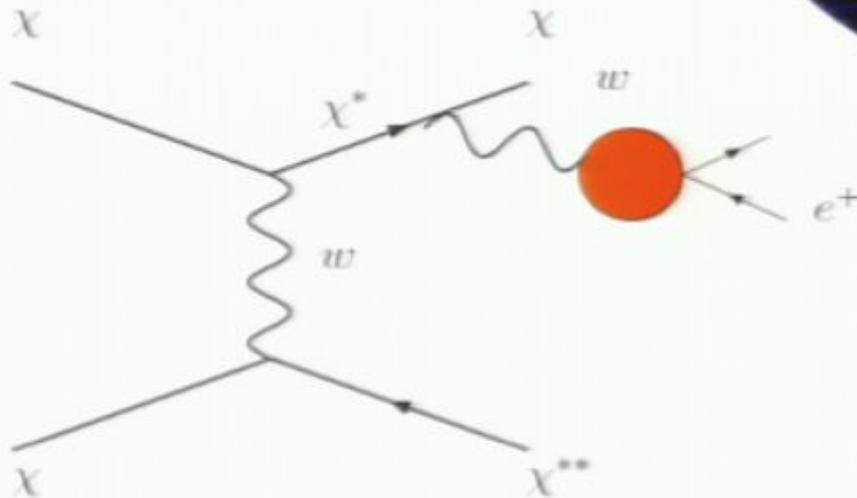
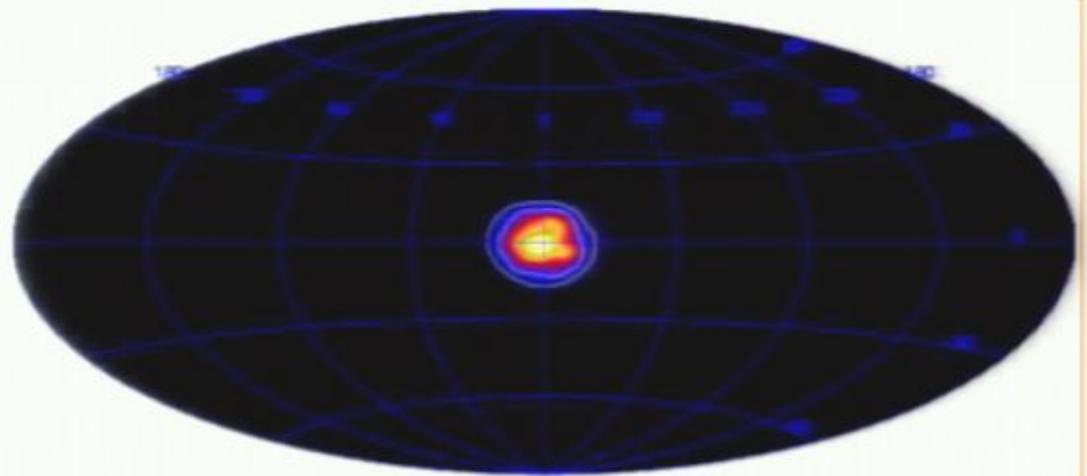


# Old News..., but a New Idea

In 1970 **Johnson et al.** observed the 511 keV line in gamma-rays from the galactic center. Leventhal pointed out positronium annihilation as a source, but the annihilation rate of  $7 \times 10^{42}$  pairs/s seemed too large.

Recently INTEGRAL greatly refined the measurement: **Weidenspointner et al.**

**Finkbeiner and Weiner** suggested eXcited Dark Matter:

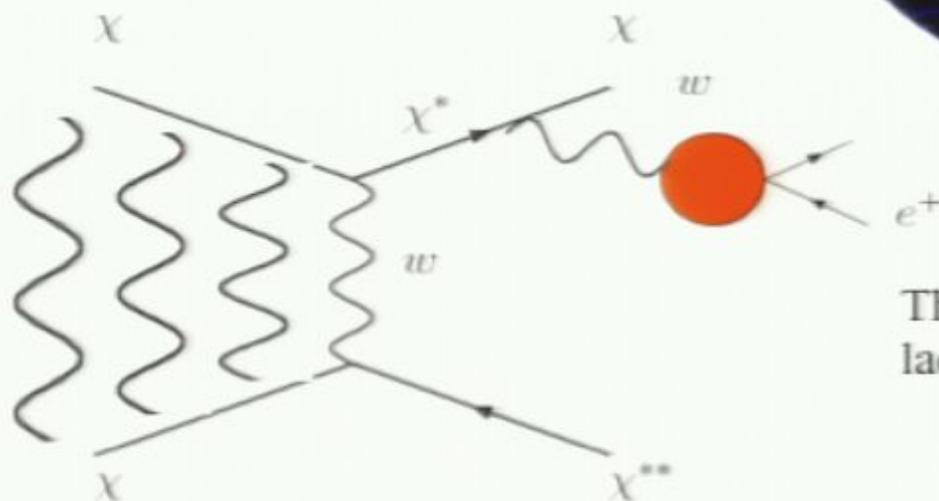
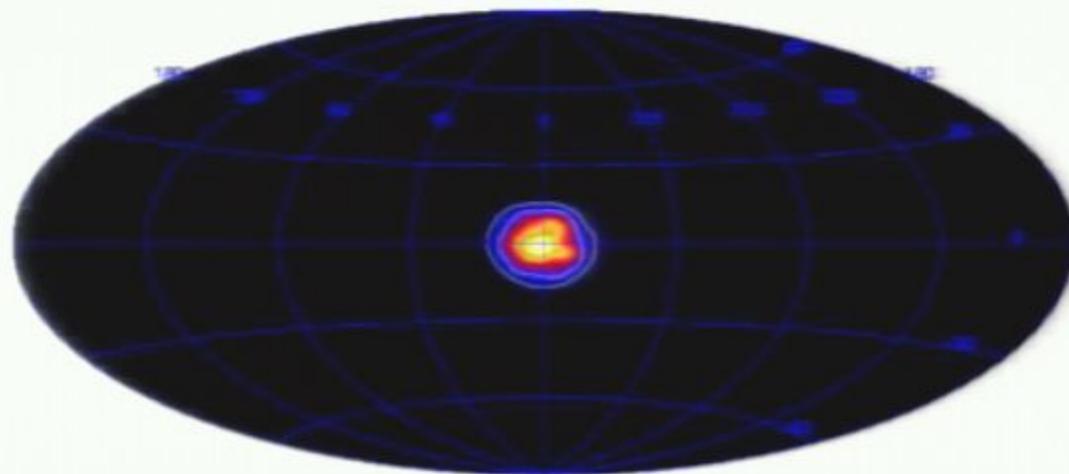


# Old News..., but a New Idea

In 1970 **Johnson et al.** observed the 511 keV line in gamma-rays from the galactic center. Leventhal pointed out positronium annihilation as a source, but the annihilation rate of  $7 \times 10^{42}$  pairs/s seemed too large.

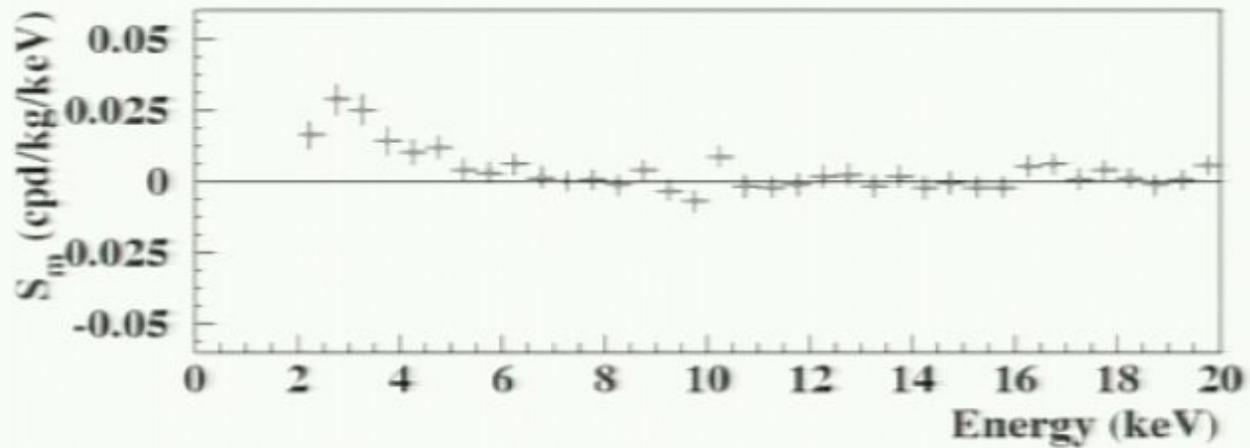
Recently INTEGRAL greatly refined the measurement: **Weidenspointner et al.**

**Finkbeiner and Weiner** suggested eXcited Dark Matter:

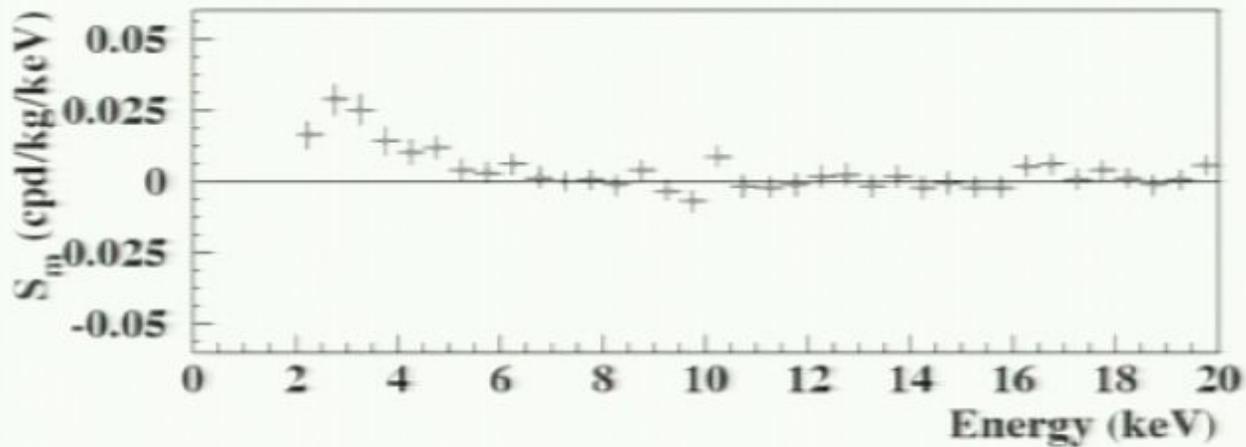


The cross-section is in fact enhanced by the ladder diagram.

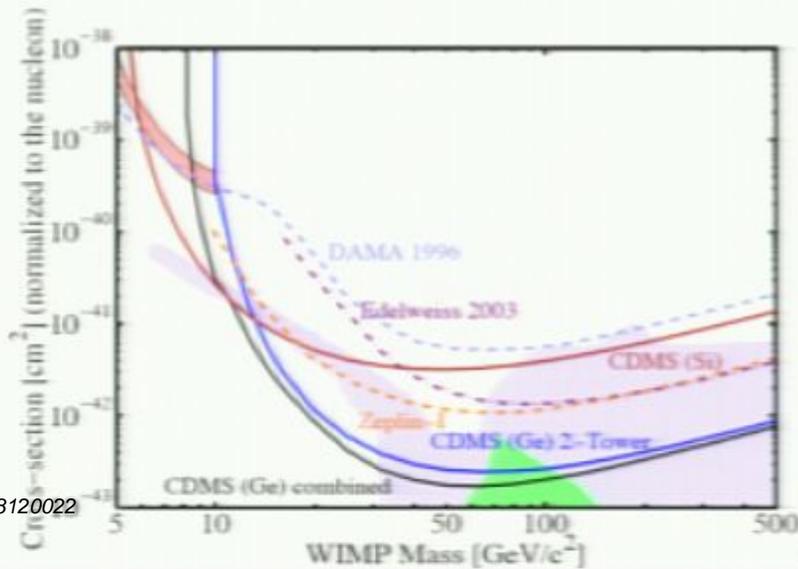
# Recent News - DAMA/LIBRA



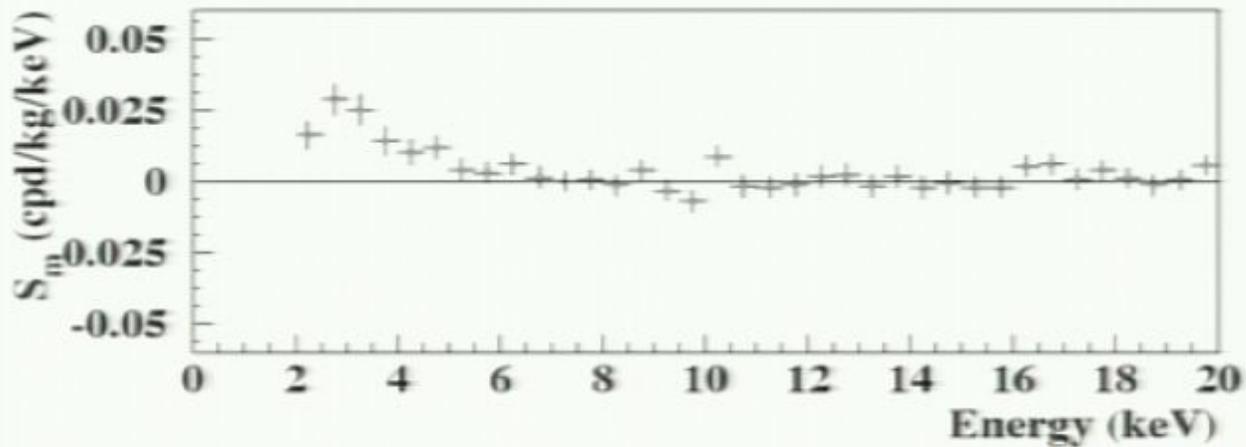
# Recent News - DAMA/LIBRA



Seems in conflict with, **CDMS**  
and **XENON** and others,

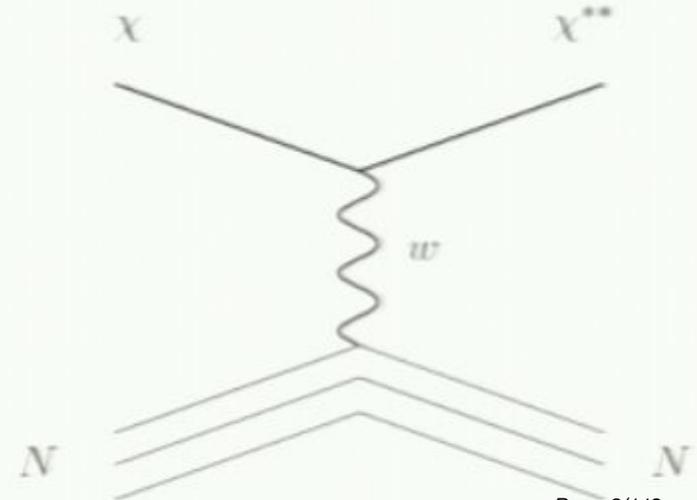
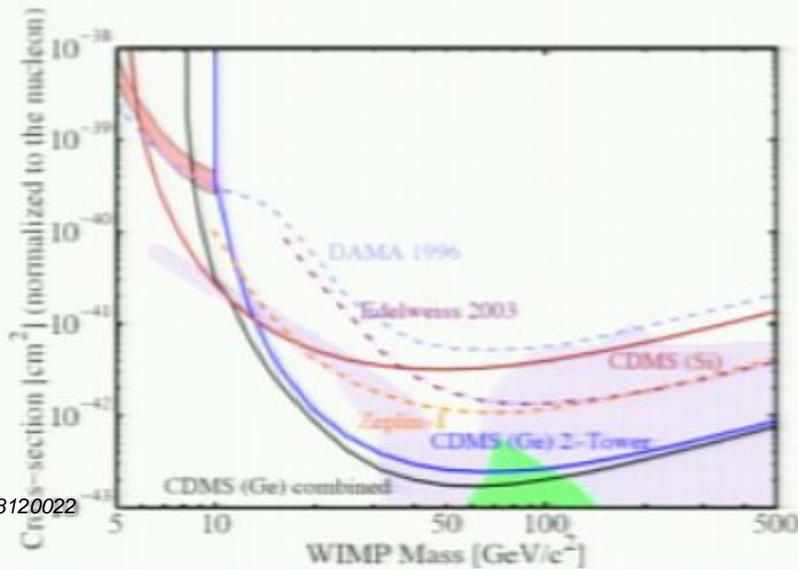


# Recent News - DAMA/LIBRA



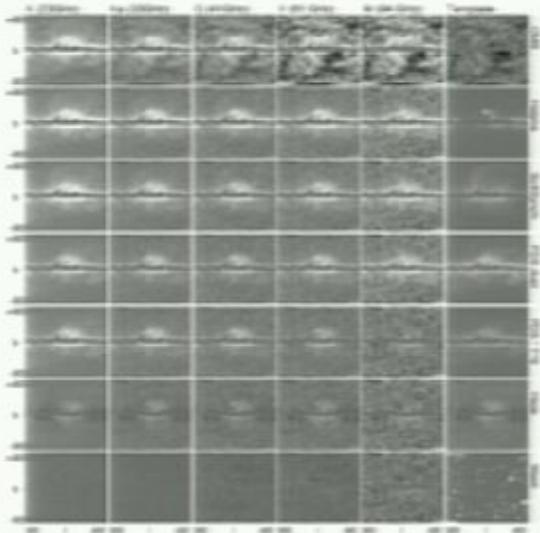
Seems in conflict with, **CDMS**  
and **XENON** and others,

But, **Smith and Weiner**  
suggested Inelastic Dark Matter:

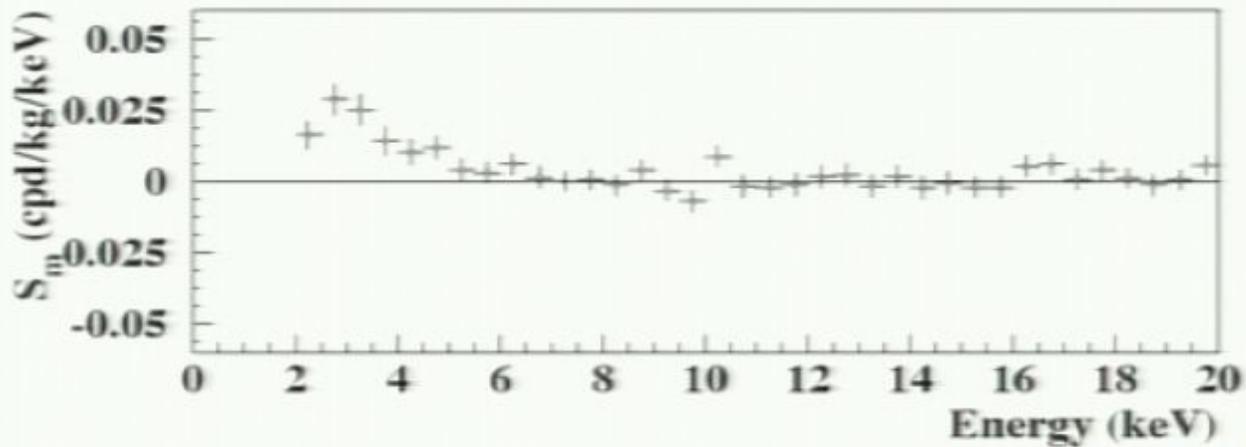


# Recent News - CMB Haze

**D. Finkbeiner** in 2003, found a component in the CMB which he could not subtract away. He termed it "Haze". This microwave haze is consistent with synchrotron radiation from high energy electron/positrons from the galactic center.

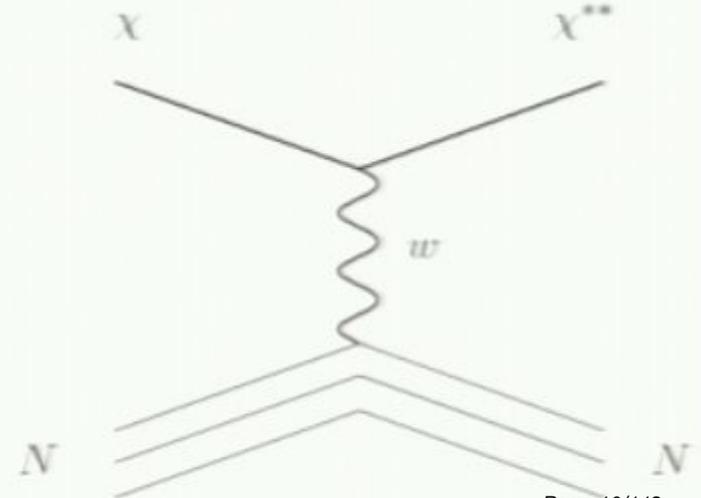
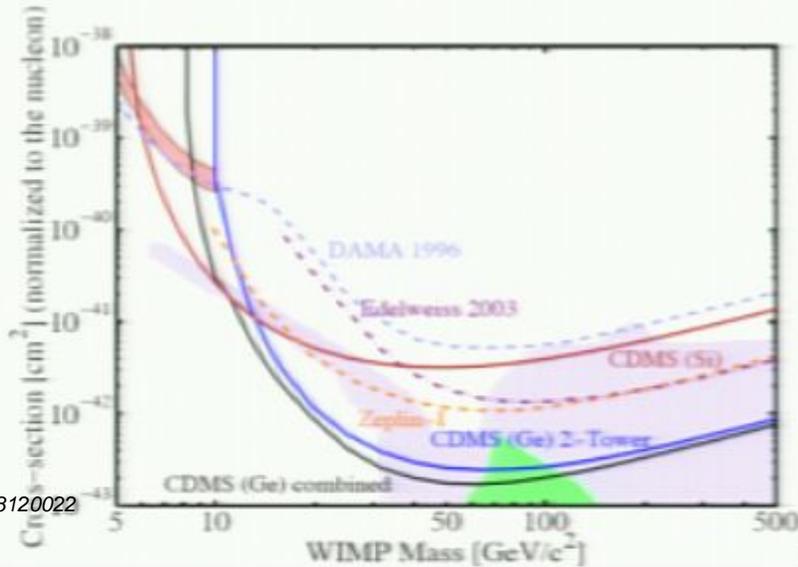


# Recent News - DAMA/LIBRA



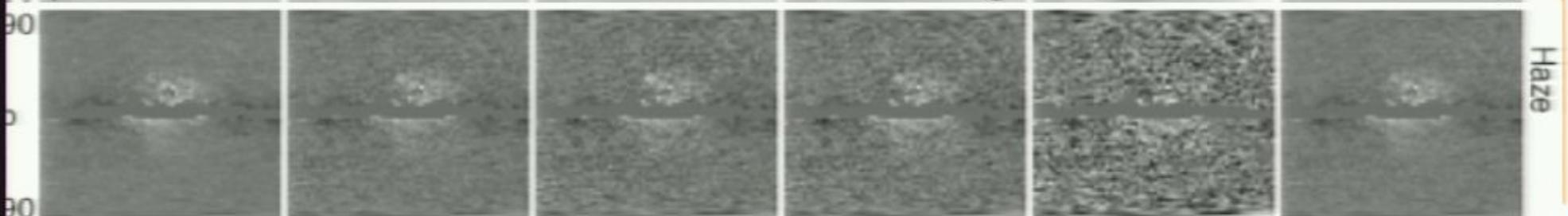
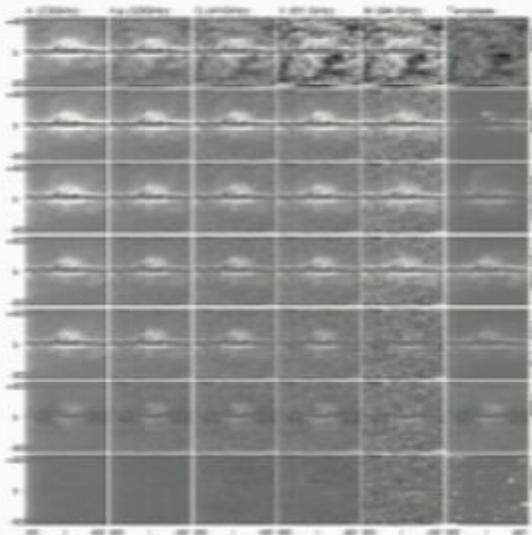
Seems in conflict with, **CDMS** and **XENON** and others,

But, **Smith and Weiner** suggested Inelastic Dark Matter:



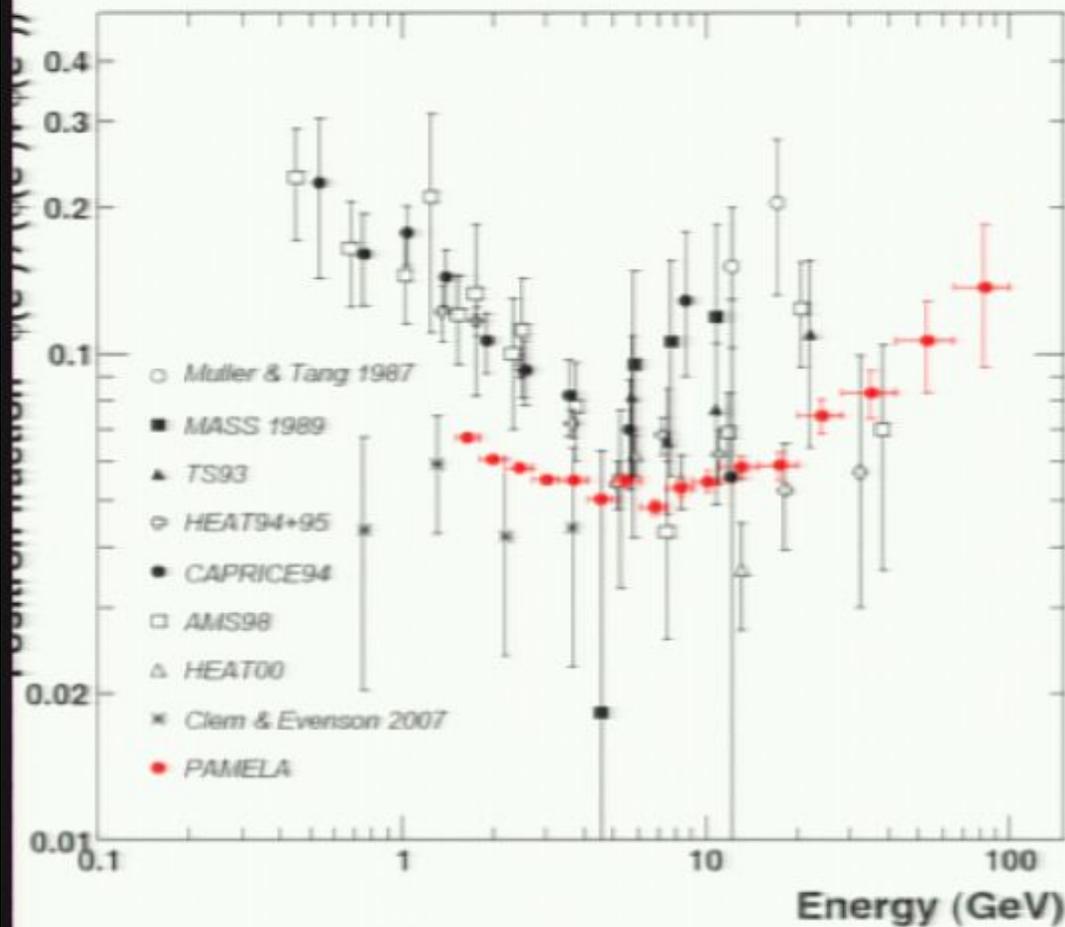
# Recent News - CMB Haze

**D. Finkbeiner** in 2003, found a component in the CMB which he could not subtract away. He termed it "Haze". This microwave haze is consistent with synchrotron radiation from high energy electron/positrons from the galactic center.

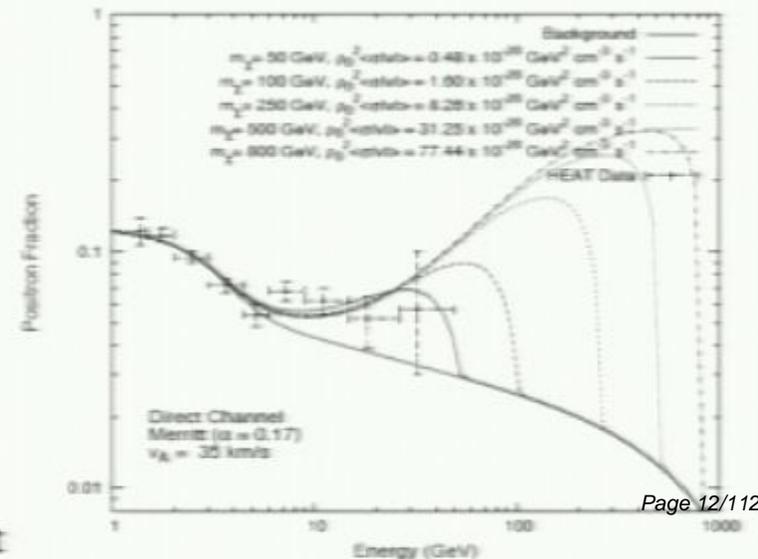
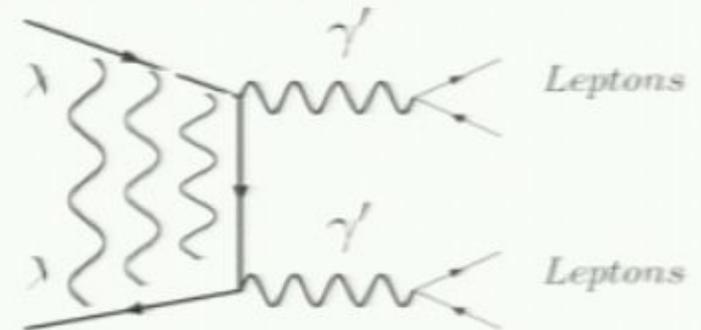


# News - PAMELA

In Oct. 2008, the **P**ayload for **A**nti-Matter **E**xploration and **L**ight-nuclei **A**strophysics reported a sharp raise in the positron content of cosmic rays from 10-50 GeV.

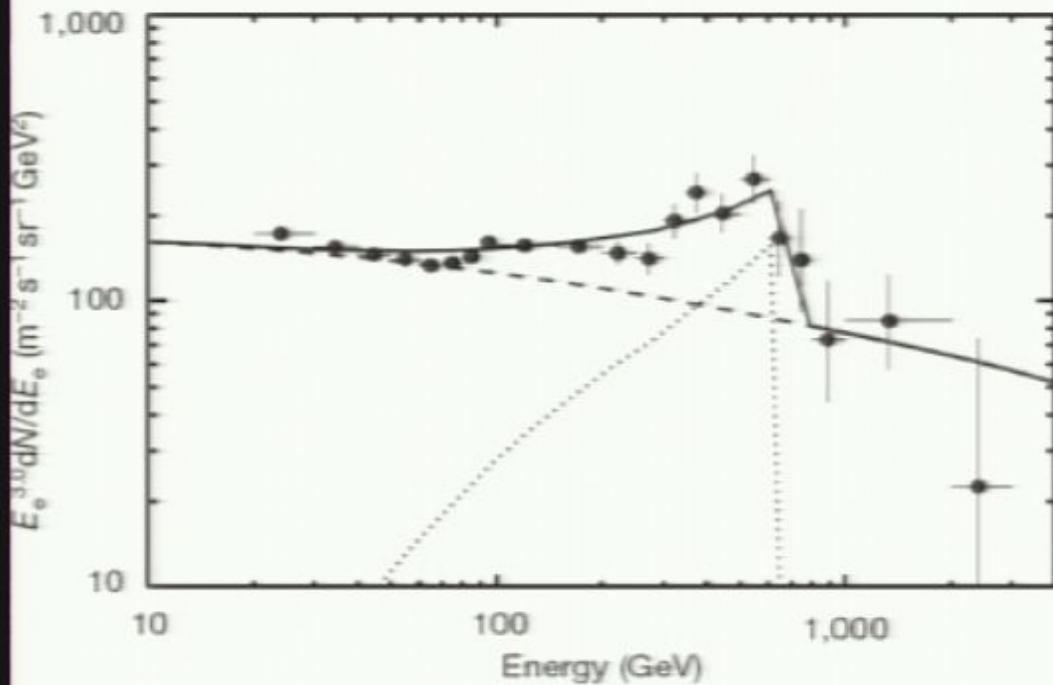


This was actually predicted by **Cholis, Goodenough and Weiner**

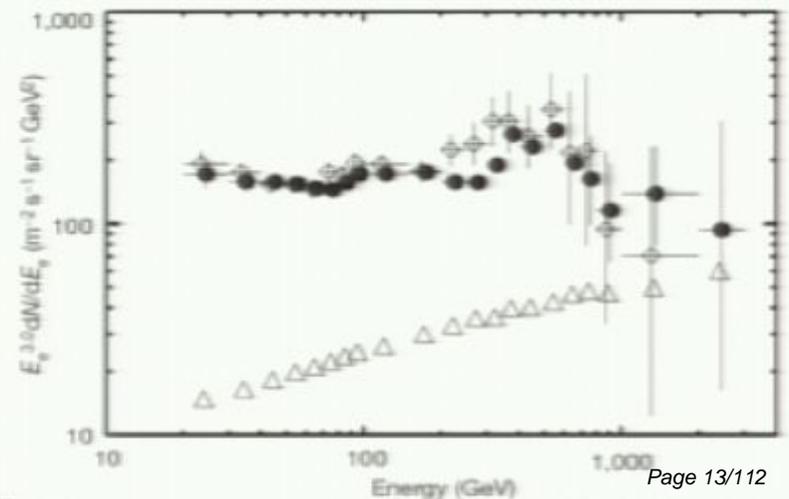
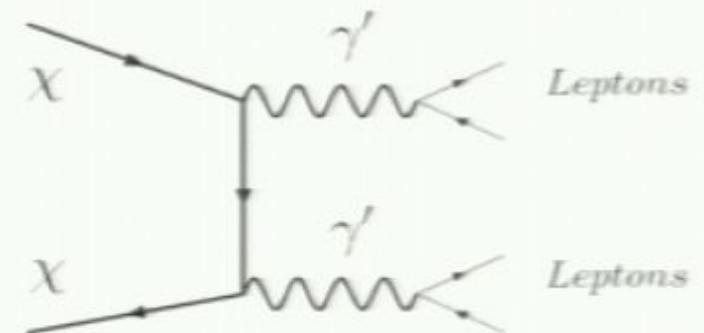


# News - ATIC

In Nov. 2008, the **A**dvanced **T**hin **I**onization **C**alorimeter reported an increase in the number of electrons/positrons content of cosmic rays at around 600-800 GeV



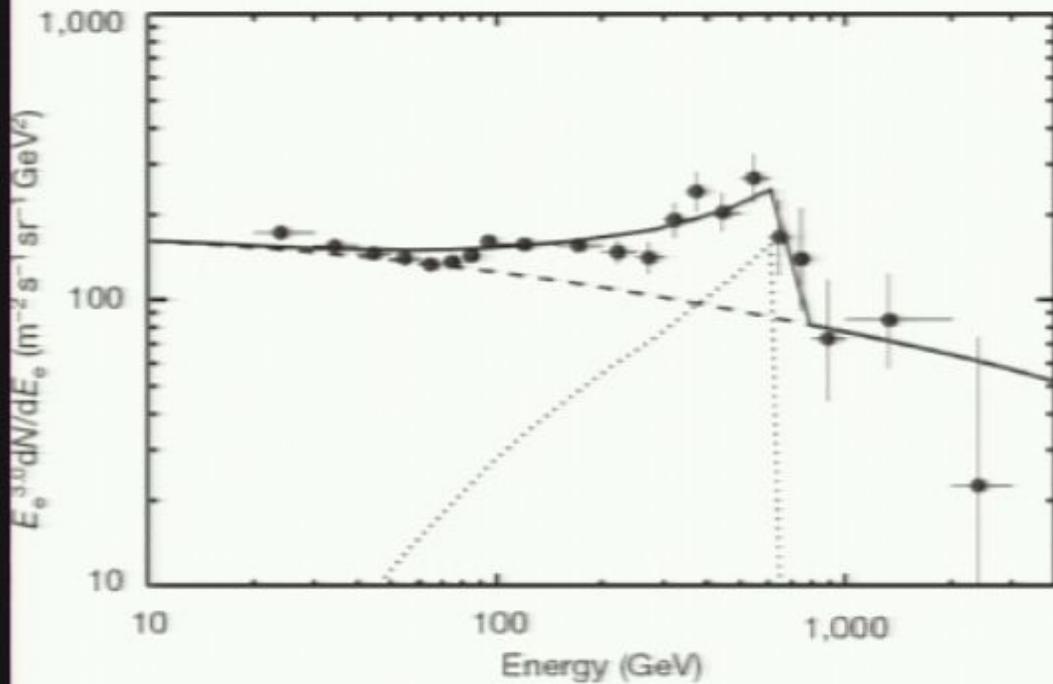
Background with the same shape???



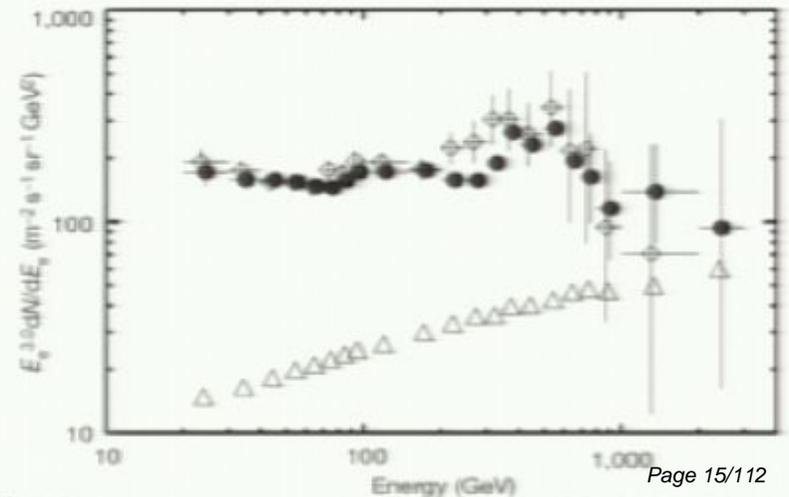
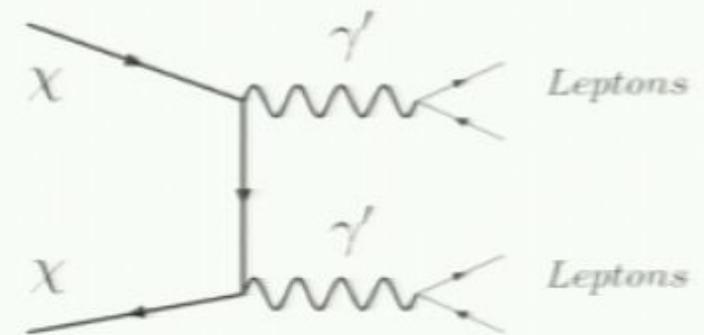
That was the Introduction. . .

# News - ATIC

In Nov. 2008, the **A**dvanced **T**hin **I**onization **C**alorimeter reported an increase in the number of electrons/positrons content of cosmic rays at around 600-800 GeV



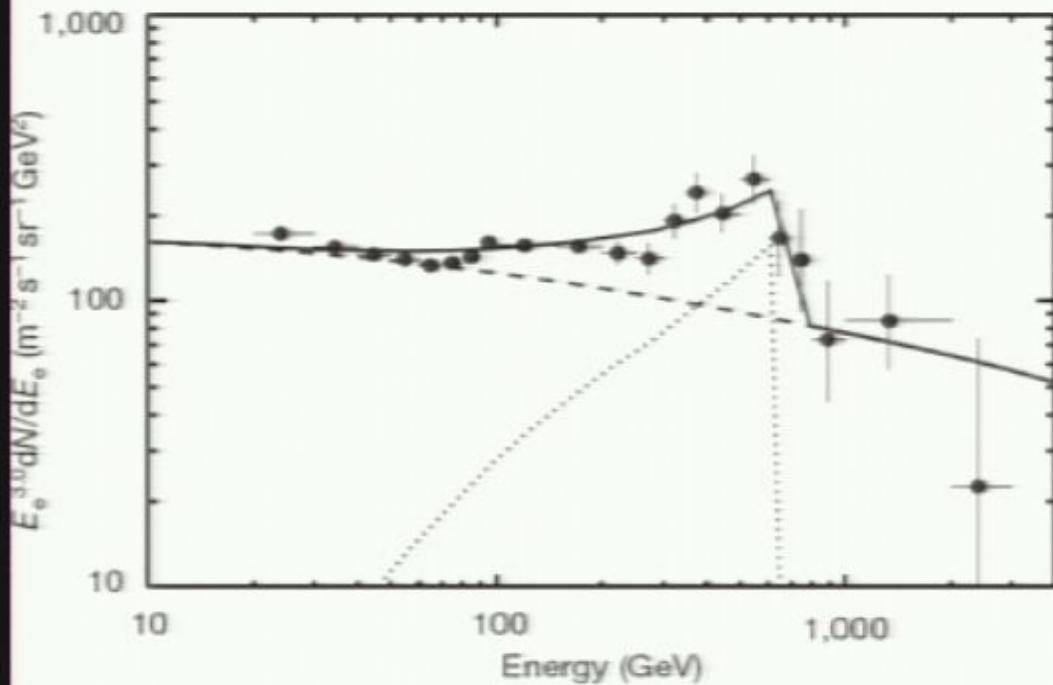
Background with the same shape???



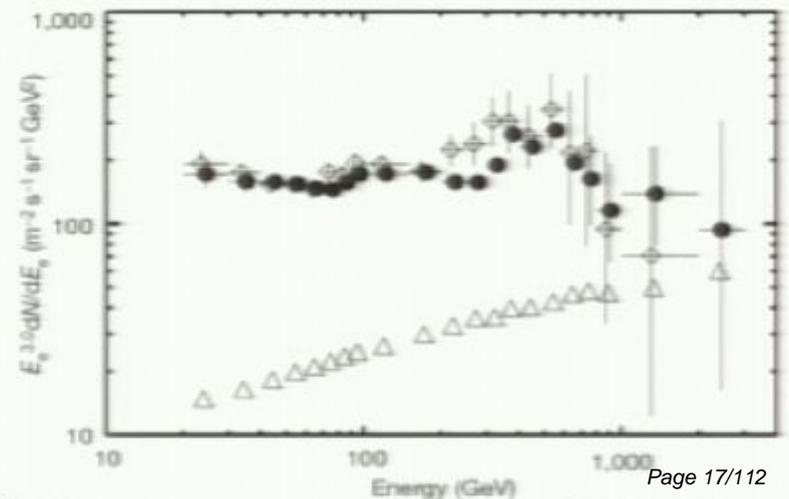
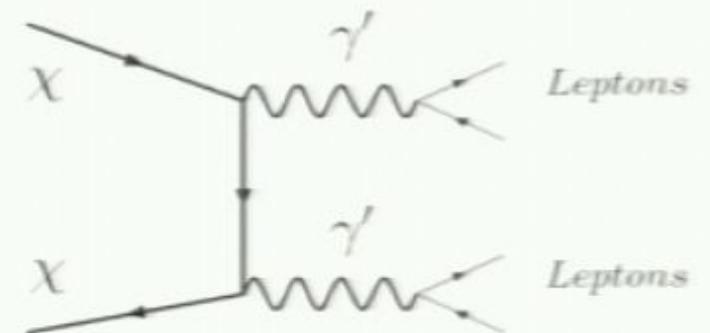
That was the Introduction. . .

# News - ATIC

In Nov. 2008, the **A**dvanced **T**hin **I**onization **C**alorimeter reported an increase in the number of electrons/positrons content of cosmic rays at around 600-800 GeV



Background with the same shape???



That was the Introduction. . .

# Content

- Model building for the Dark Sector
- Collider signatures
- DAMA model building
- Coll...probably not.

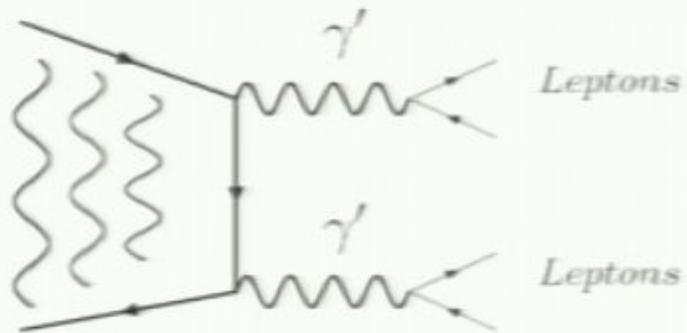
# “A Theory of Dark Matter”

Arkani-Hamed, Finkbeiner, Slyter and Weiner suggested a unified description:

# “A Theory of Dark Matter”

Arkani-Hamed, Finkbeiner, Slyter and Weiner suggested a unified description:

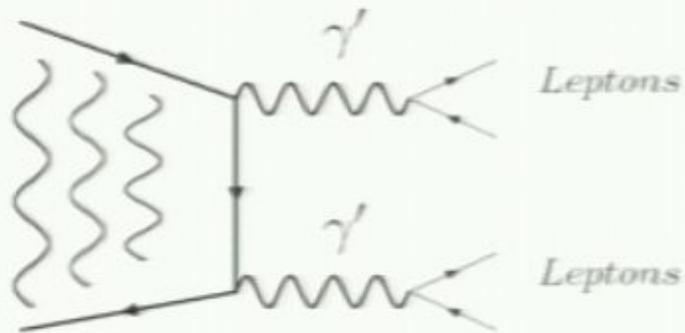
ATIC & PAMELA



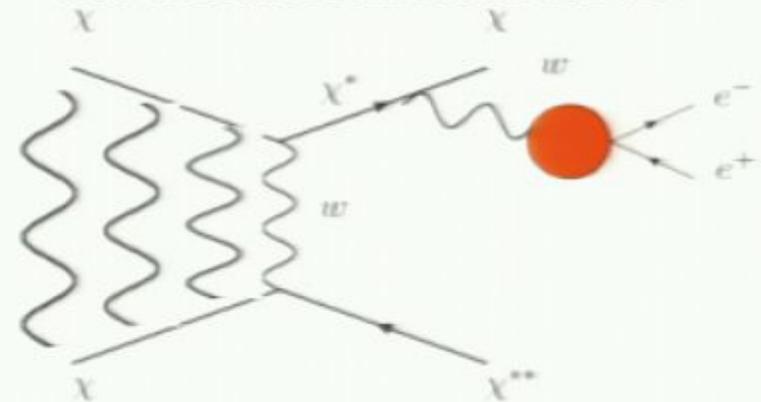
# “A Theory of Dark Matter”

Arkani-Hamed, Finkbeiner, Slyter and Weiner suggested a unified description:

ATIC & PAMELA



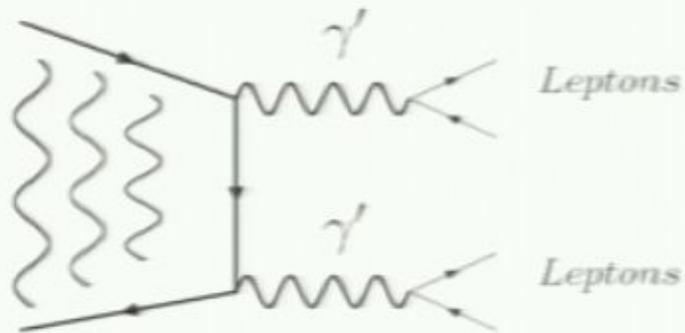
INTEGRAL & HAZE



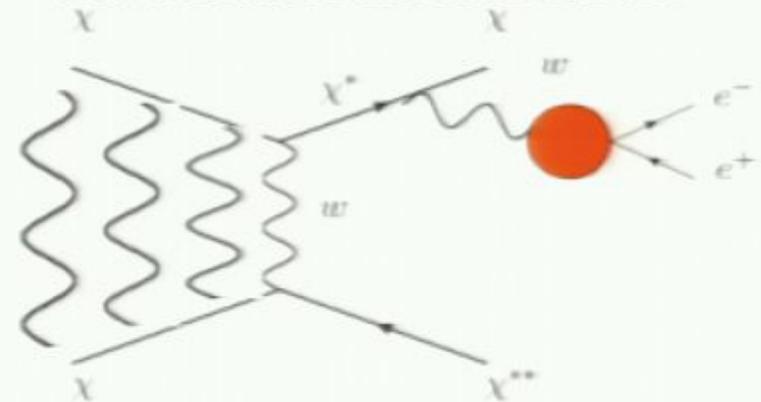
# “A Theory of Dark Matter”

Arkani-Hamed, Finkbeiner, Slyter and Weiner suggested a unified description:

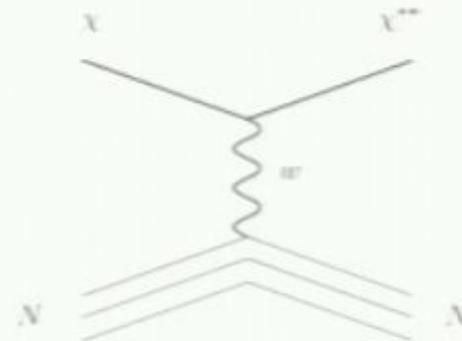
## ATIC & PAMELA



## INTEGRAL & HAZE



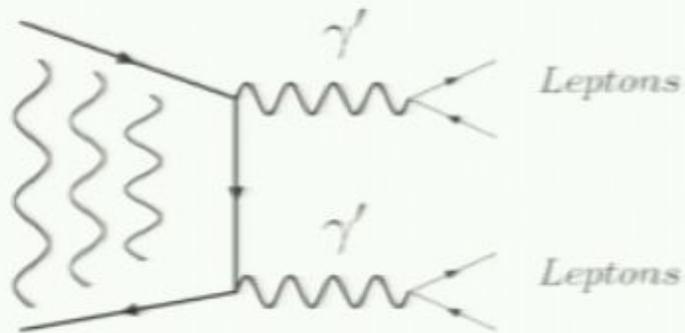
## Maybe even DAMA



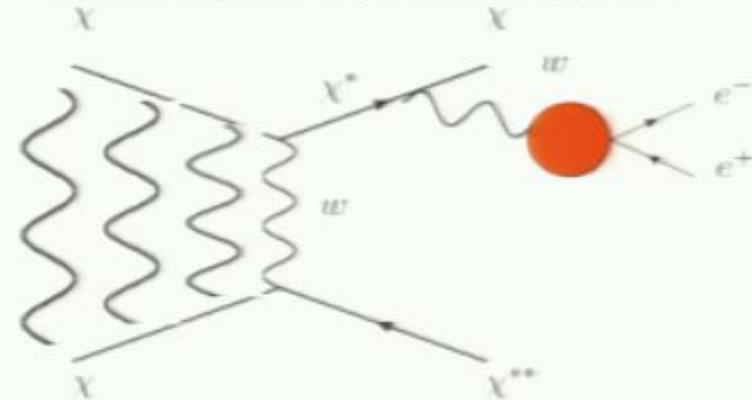
# “A Theory of Dark Matter”

Arkani-Hamed, Finkbeiner, Slyter and Weiner suggested a unified description:

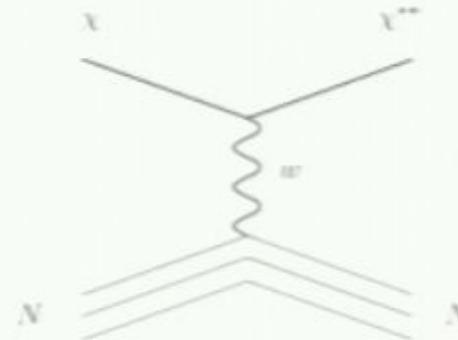
## ATIC & PAMELA



## INTEGRAL & HAZE



## Maybe even DAMA



TeV DM charged under a non-abelian gauge theory, weakly mixed with SM.

# Too Crazy? ? ?

Depends which observations you really believe. Each of the observations by themselves may have an astrophysical explanation within the SM. DAMA may be wrong.

# Too Crazy? ? ?

Depends which observations you really believe. Each of the observations by themselves may have an astrophysical explanation within the SM. DAMA may be wrong.

General theorem:

“If your theory explains all the experiments, it must be wrong because some of the experiments are wrong . . . ” - Anonymous.

# Too Crazy? ? ?

Depends which observations you really believe. Each of the observations by themselves may have an astrophysical explanation within the SM. DAMA may be wrong.

General theorem:

“If your theory explains all the experiments, it must be wrong because some of the experiments are wrong . . . ” - Anonymous.

But, in order to make progress, maybe better listen to Big Steve:

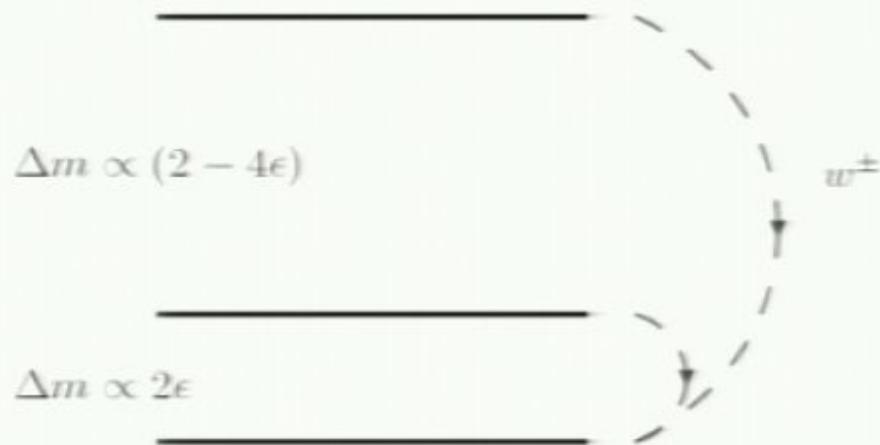
“Our mistake is not that we take our theories too seriously, but that we do not take them seriously enough”.

# Dark $SU(2) \times U(1)$

Dark matter is part of a dark  $SU(2) \times U(1)$  gauged matter multiplet which is completely broken. Consider for example an  $SU(2)$  triplet with  $Y = 1/2 - \epsilon$   
Break  $SU(2) \times U(1)$  down to  $U_{EM}(1)$

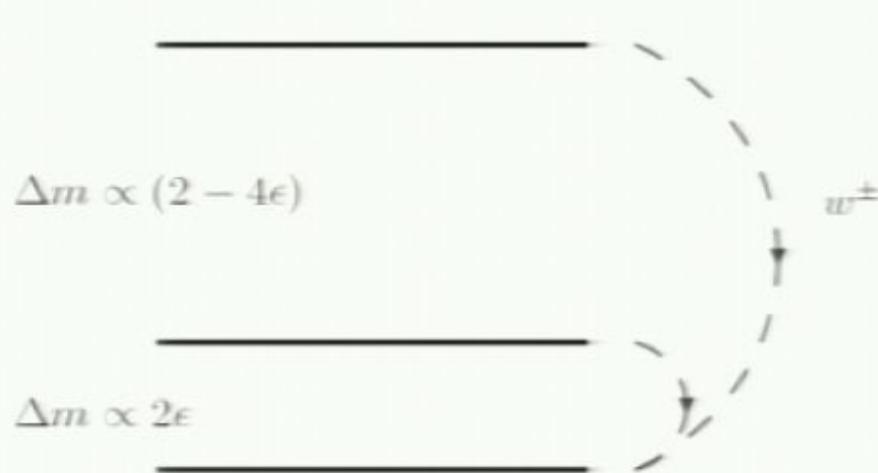
# Dark $SU(2) \times U(1)$

Dark matter is part of a dark  $SU(2) \times U(1)$  gauged matter multiplet which is completely broken. Consider for example an  $SU(2)$  triplet with  $Y = 1/2 - \epsilon$   
Break  $SU(2) \times U(1)$  down to  $U_{EM}(1)$



# Dark SU(2)xU(1)

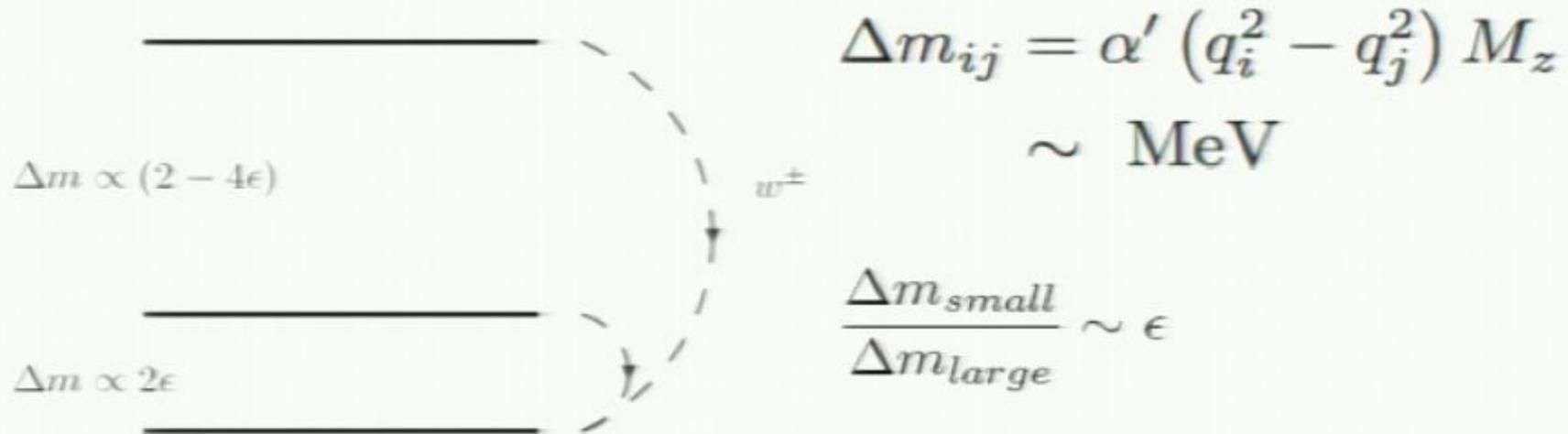
Dark matter is part of a dark SU(2)xU(1) gauged matter multiplet which is completely broken. Consider for example an SU(2) triplet with  $Y = 1/2 - \epsilon$   
Break SU(2)xU(1) down to U<sub>EM</sub>(1)



$$\Delta m_{ij} = \alpha' (q_i^2 - q_j^2) M_z$$
$$\sim \text{MeV}$$

# Dark SU(2)xU(1)

Dark matter is part of a dark SU(2)xU(1) gauged matter multiplet which is completely broken. Consider for example an SU(2) triplet with  $Y = 1/2 - \epsilon$   
 Break SU(2)xU(1) down to  $U_{EM}(1)$



The splittings are generated radiatively in the low energy theory.  
 Equally important is for all these states to be properly linked to each other.

# Kinetic Mixing (Holdom Effect)

The dark  $U(1)$  can kinetically mix with  $U_{EM}(1)$  so SM charged particles are now charged under the dark  $U(1)$ ,

$$\mathcal{L} \supset 2\epsilon F_{\mu\nu} f^{\mu\nu}$$

# Kinetic Mixing (Holdom Effect)

The dark  $U(1)$  can kinetically mix with  $U_{EM}(1)$  so SM charged particles are now charged under the dark  $U(1)$ ,

$$\mathcal{L} \supset 2\epsilon F_{\mu\nu} f^{\mu\nu}$$

Un-mixing,

$$A_\mu \rightarrow A_\mu + \epsilon a_\mu$$

# Kinetic Mixing (Holdom Effect)

The dark  $U(1)$  can kinetically mix with  $U_{EM}(1)$  so SM charged particles are now charged under the dark  $U(1)$ ,

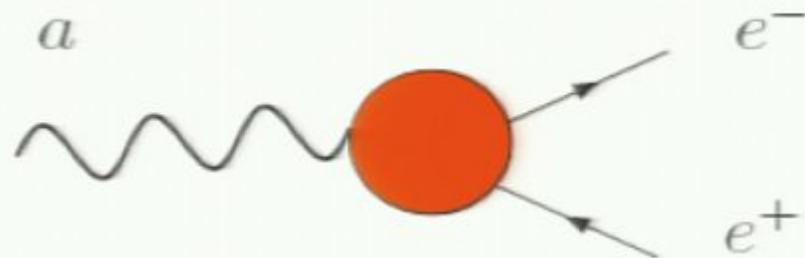
$$\mathcal{L} \supset 2\epsilon F_{\mu\nu} f^{\mu\nu}$$

Un-mixing,

$$A_\mu \rightarrow A_\mu + \epsilon a_\mu$$

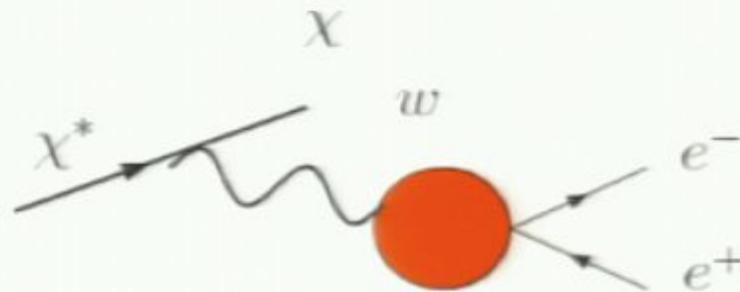
To get,

$$\epsilon q \bar{e} \gamma^\mu a_\mu e$$



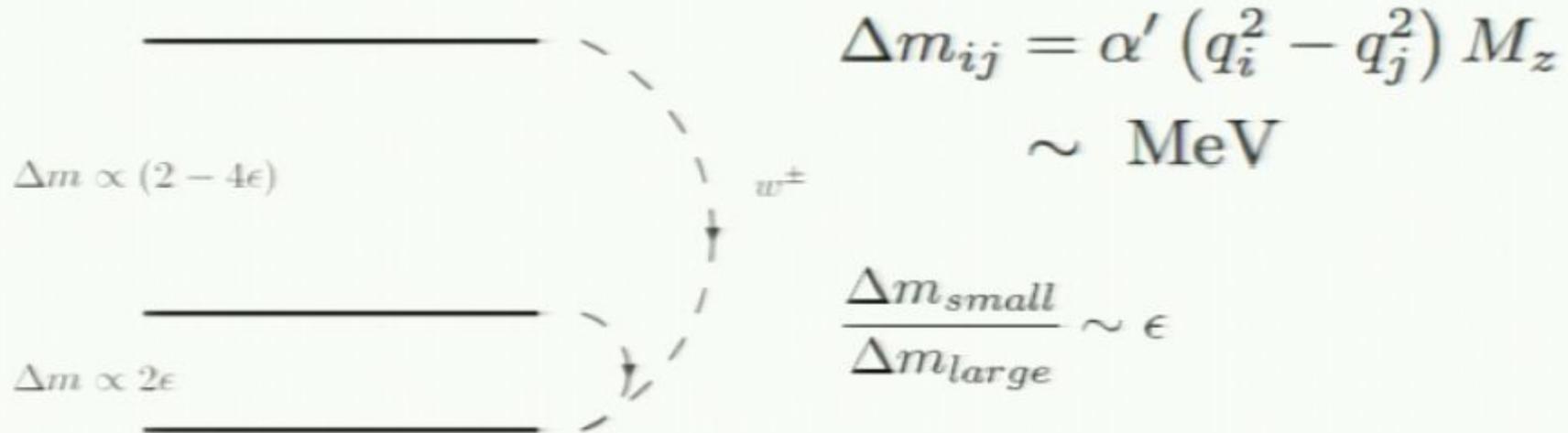
# Dark Charge Breaking

However, we also require the following process for INTEGRAL. Similar diagram is also needed for DAMA.



# Dark SU(2)xU(1)

Dark matter is part of a dark SU(2)xU(1) gauged matter multiplet which is completely broken. Consider for example an SU(2) triplet with  $Y = 1/2 - \epsilon$   
 Break SU(2)xU(1) down to  $U_{EM}(1)$



The splittings are generated radiatively in the low energy theory.  
 Equally important is for all these states to be properly linked to each other.

# Kinetic Mixing (Holdom Effect)

The dark  $U(1)$  can kinetically mix with  $U_{EM}(1)$  so SM charged particles are now charged under the dark  $U(1)$ ,

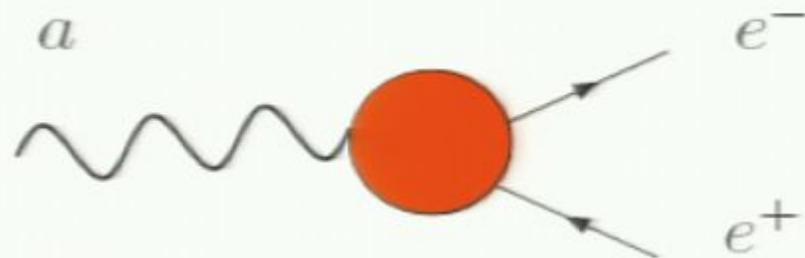
$$\mathcal{L} \supset 2\epsilon F_{\mu\nu} f^{\mu\nu}$$

Un-mixing,

$$A_\mu \rightarrow A_\mu + \epsilon a_\mu$$

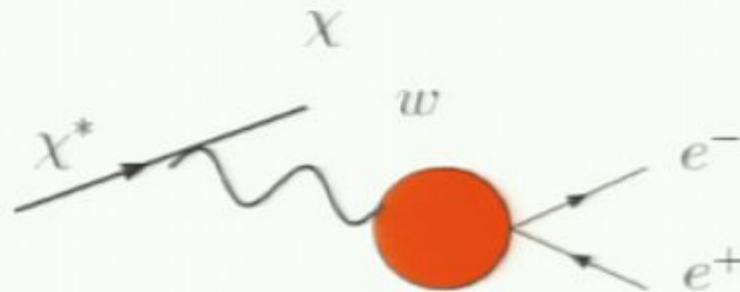
To get,

$$\epsilon q \bar{e} \gamma^\mu a_\mu e$$



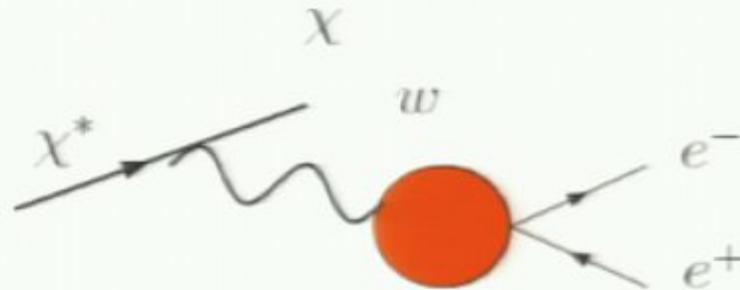
# Dark Charge Breaking

However, we also require the following process for INTEGRAL. Similar diagram is also needed for DAMA.



# Dark Charge Breaking

However, we also require the following process for INTEGRAL. Similar diagram is also needed for DAMA.

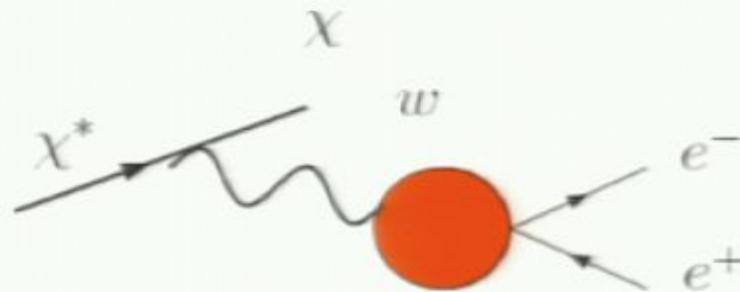


For that to happen we need the mass matrix of the gauge-bosons to have the form:

$$M_a^2 = \begin{pmatrix} m_a^2 & \delta_1 & \delta_2 & \delta_3 \\ \delta_1 & m_1^2 & 0 & 0 \\ \delta_2 & 0 & m_2^2 & 0 \\ \delta_3 & 0 & 0 & m_3^2 \end{pmatrix}$$

# Dark Charge Breaking

However, we also require the following process for INTEGRAL. Similar diagram is also needed for DAMA.



For that to happen we need the mass matrix of the gauge-bosons to have the form:

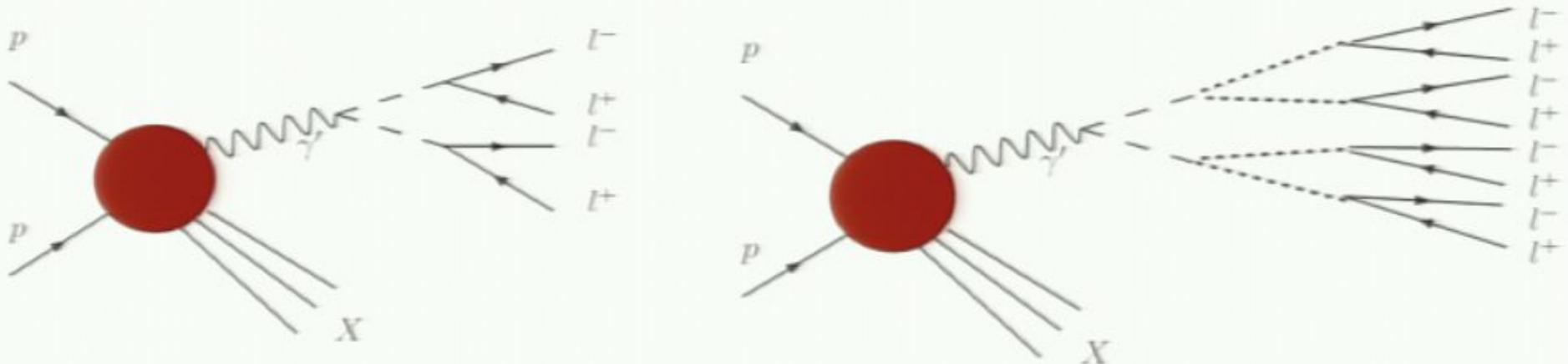
$$M_a^2 = \begin{pmatrix} m_a^2 & \delta_1 & \delta_2 & \delta_3 \\ \delta_1 & m_1^2 & 0 & 0 \\ \delta_2 & 0 & m_2^2 & 0 \\ \delta_3 & 0 & 0 & m_3^2 \end{pmatrix}$$

Breaking charge is not hard, but achieving this form requires custodial breaking as well.

# Collider Signatures

# Direct Production and “Lepton Jets”

The dark sector might be directly produced through prompt photon production processes.

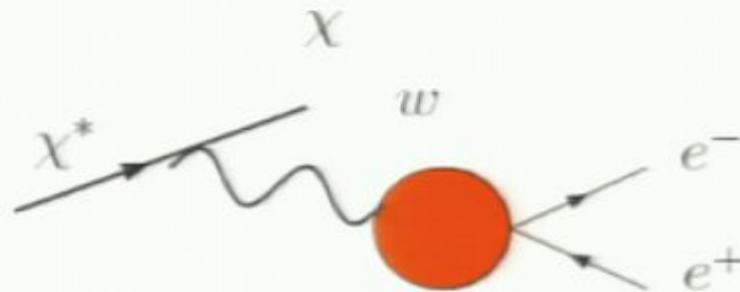


May have impact on lower energy experiments. **M. Pospelov** recently investigated the HyperCP peak at 214 MeV in connection with such a dark U(1). So far nothing new has been unearthed.

I will concentrate on Tevatron and LHC signatures.

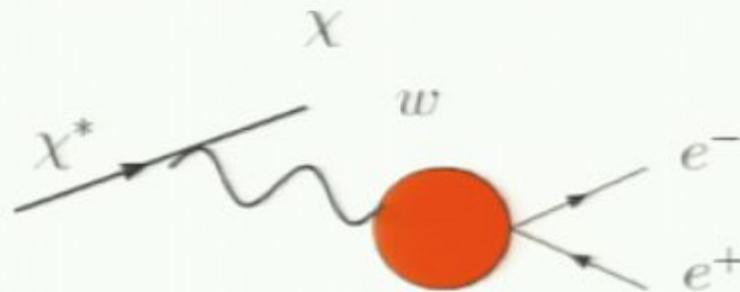
# Dark Charge Breaking

However, we also require the following process for INTEGRAL. Similar diagram is also needed for DAMA.



# Dark Charge Breaking

However, we also require the following process for INTEGRAL. Similar diagram is also needed for DAMA.

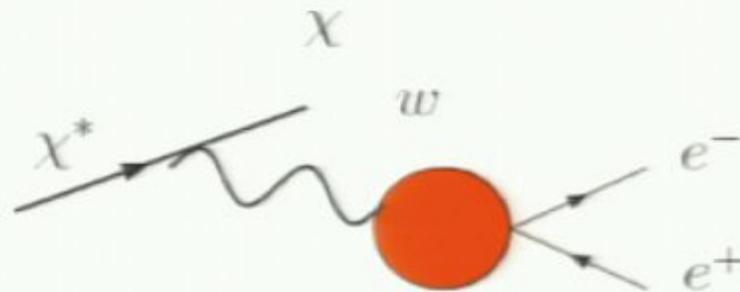


For that to happen we need the mass matrix of the gauge-bosons to have the form:

$$M_a^2 = \begin{pmatrix} m_a^2 & \delta_1 & \delta_2 & \delta_3 \\ \delta_1 & m_1^2 & 0 & 0 \\ \delta_2 & 0 & m_2^2 & 0 \\ \delta_3 & 0 & 0 & m_3^2 \end{pmatrix}$$

# Dark Charge Breaking

However, we also require the following process for INTEGRAL. Similar diagram is also needed for DAMA.



For that to happen we need the mass matrix of the gauge-bosons to have the form:

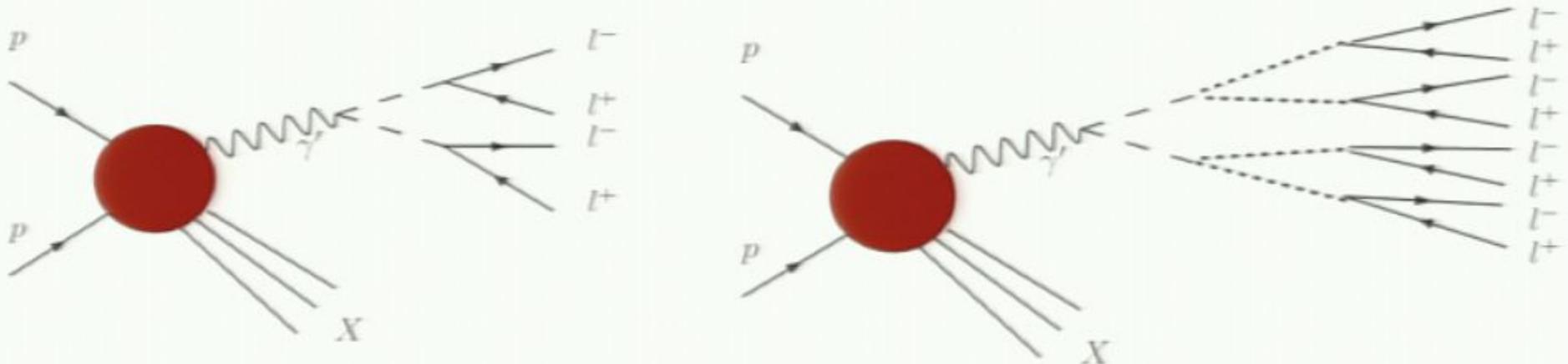
$$M_a^2 = \begin{pmatrix} m_a^2 & \delta_1 & \delta_2 & \delta_3 \\ \delta_1 & m_1^2 & 0 & 0 \\ \delta_2 & 0 & m_2^2 & 0 \\ \delta_3 & 0 & 0 & m_3^2 \end{pmatrix}$$

Breaking charge is not hard, but achieving this form requires custodial breaking as well.

# Collider Signatures

# Direct Production and “Lepton Jets”

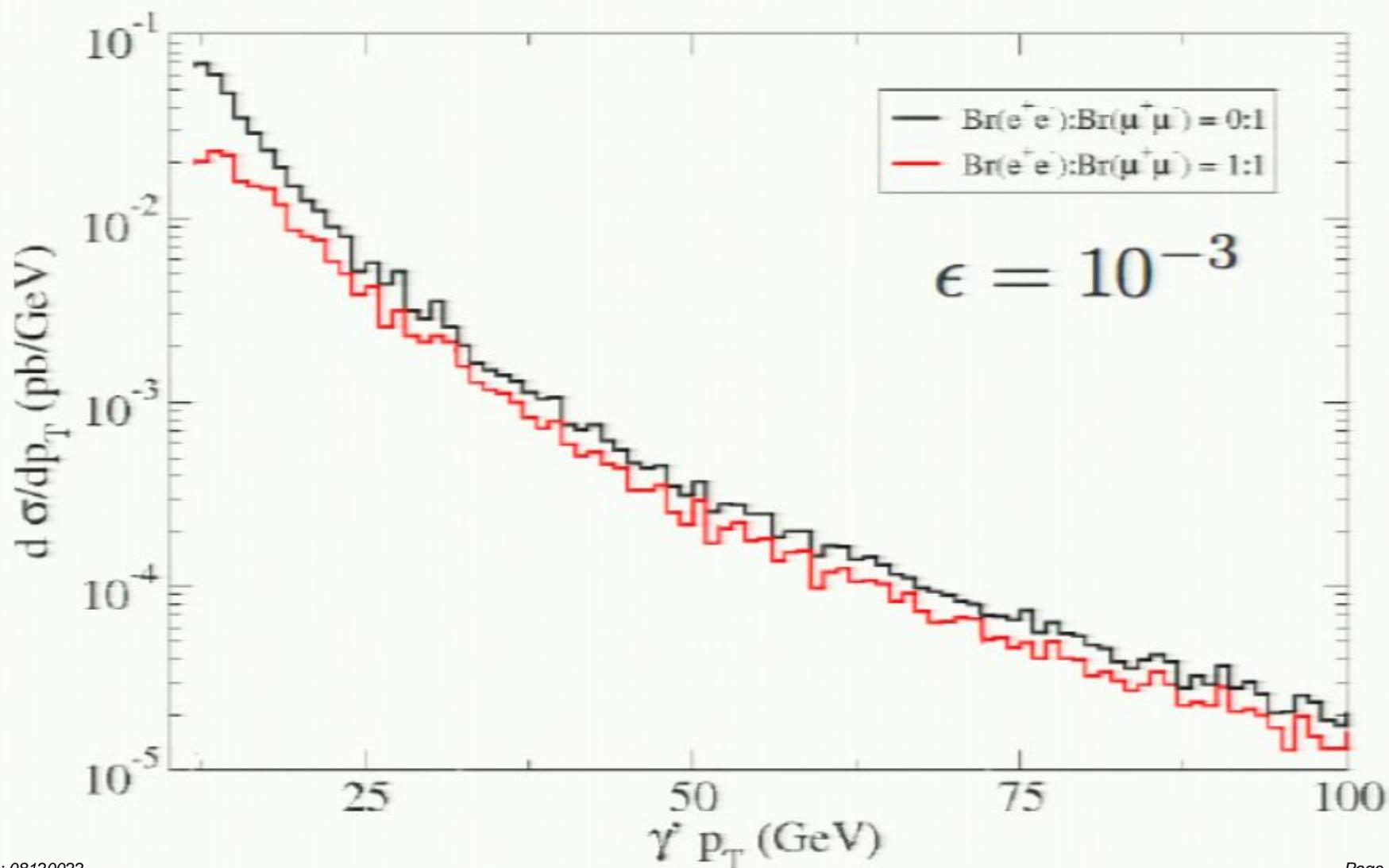
The dark sector might be directly produced through prompt photon production processes.



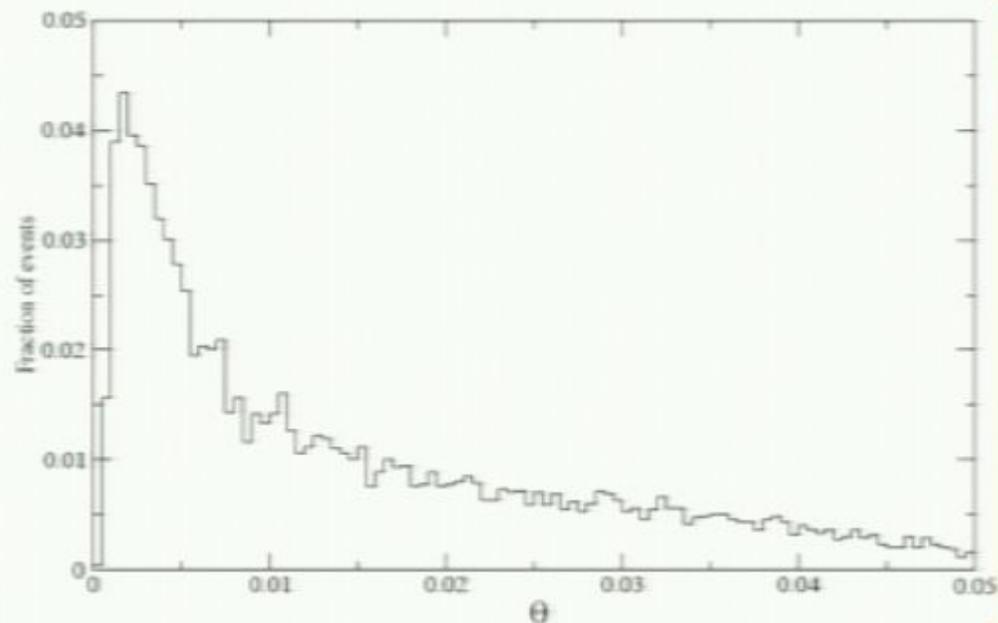
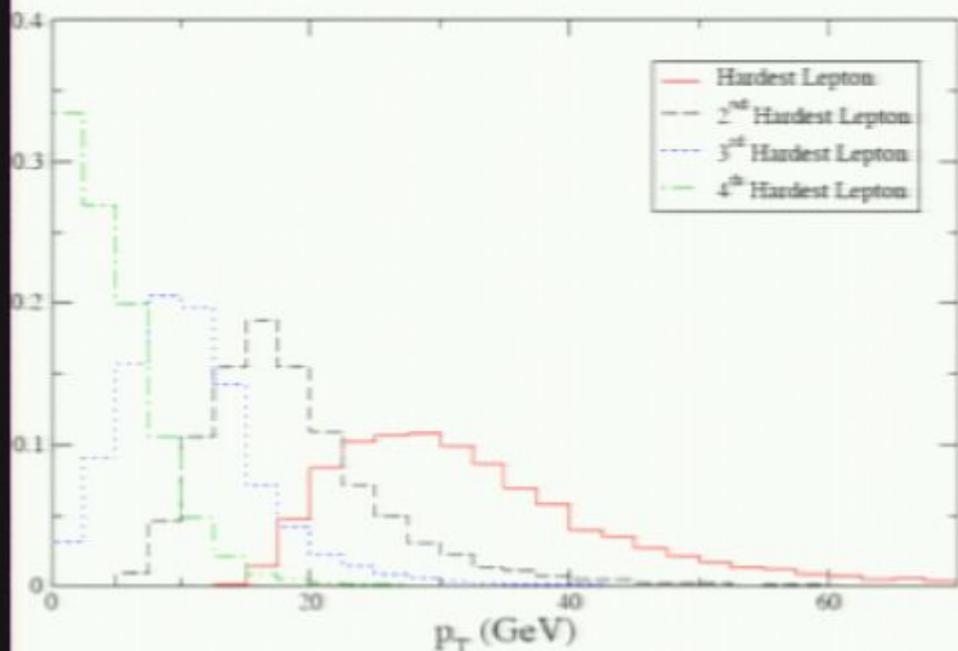
May have impact on lower energy experiments. **M. Pospelov** recently investigated the HyperCP peak at 214 MeV in connection with such a dark U(1). So far nothing new has been unearthed.

I will concentrate on Tevatron and LHC signatures.

# XSec at Tevatron and LHC



# Lepton Distributions



Both ATLAS and CMS can easily trigger on such events. However:

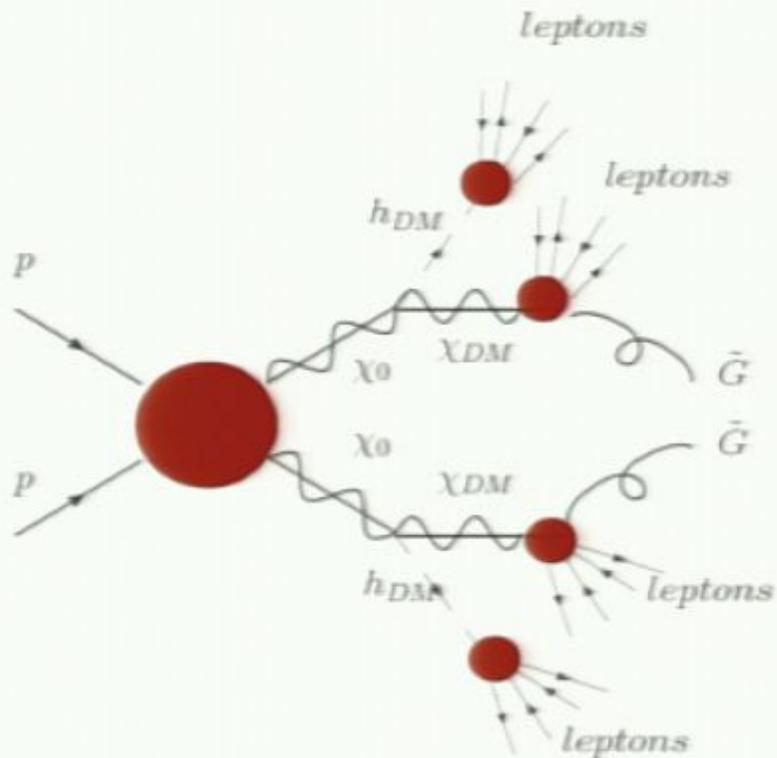
- Large background from  $J/\psi$  and  $K, \pi$  in flight decay. Needs  $> 2$  leptons.
- Angular resolution is mrad for single hits in CMS. Will be able to resolve multiple hits with 10 mrad separation? **Work in progress with V. Halyo**

# Supersymmetry's little helper

MSSM LSP pair production is very hard to trigger on. With the lepton jets at the bottom of every event, the task is considerably easier.

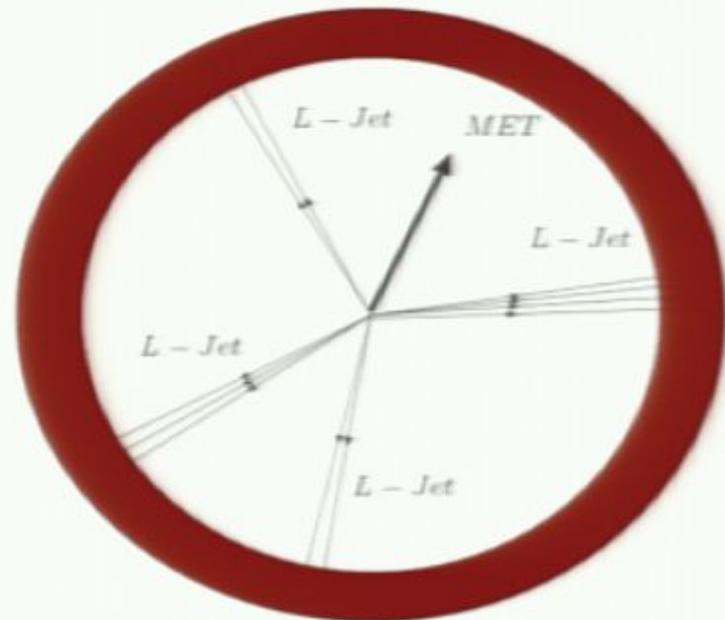
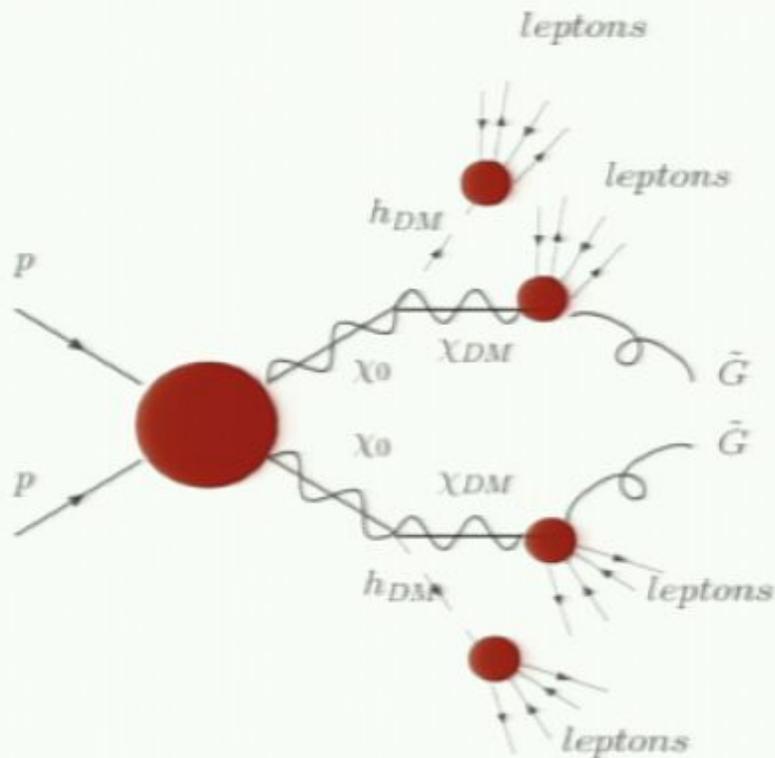
# Supersymmetry's little helper

MSSM LSP pair production is very hard to trigger on. With the lepton jets at the bottom of every event, the task is considerably easier.

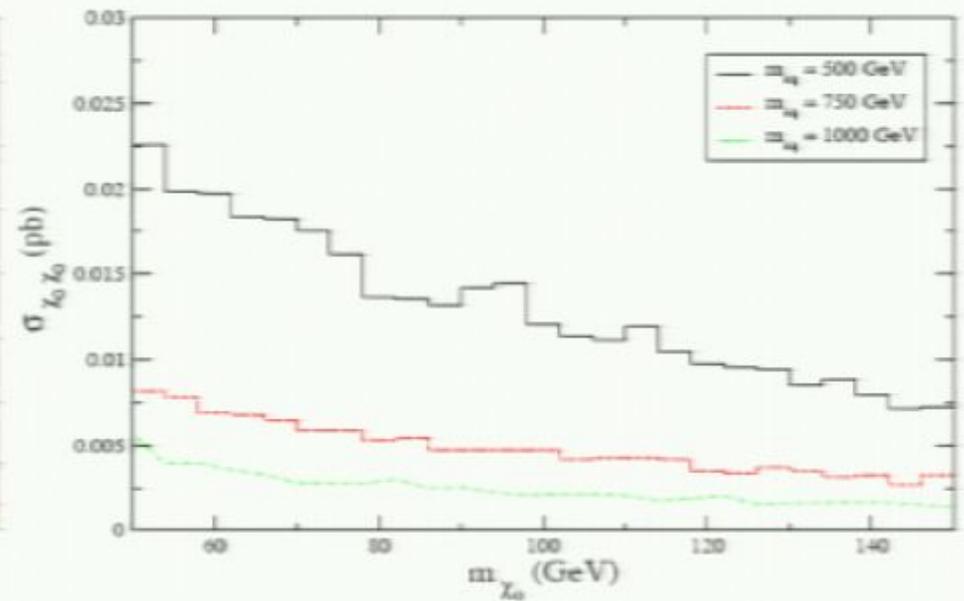
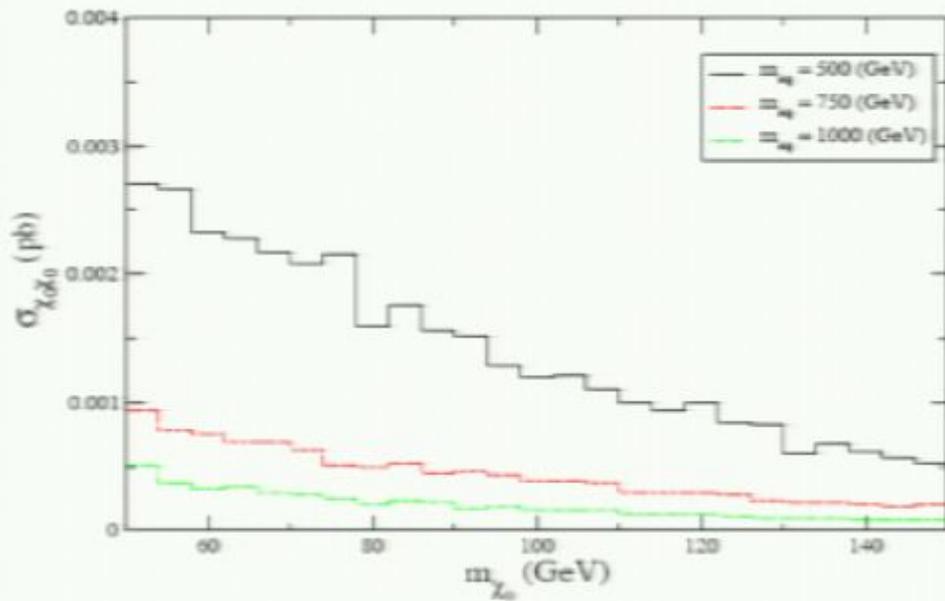


# Supersymmetry's little helper

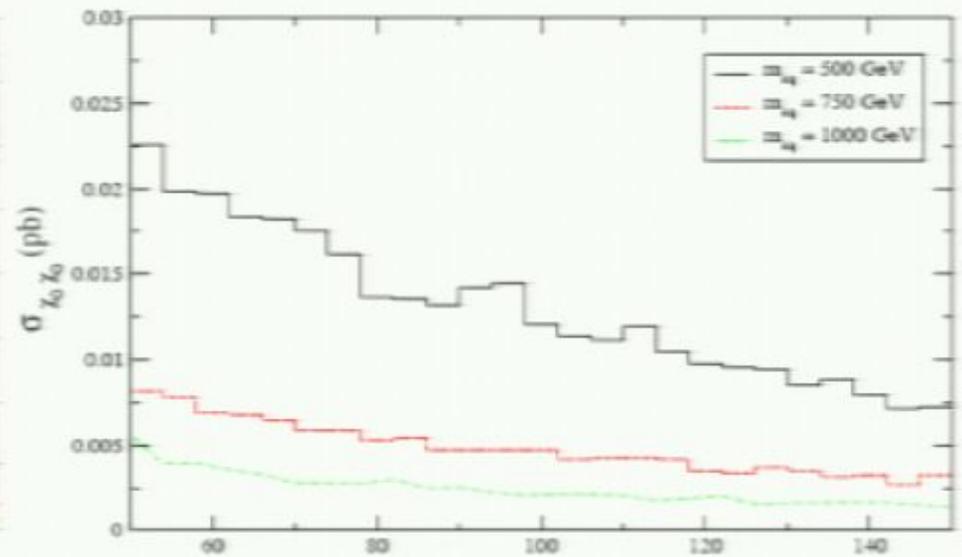
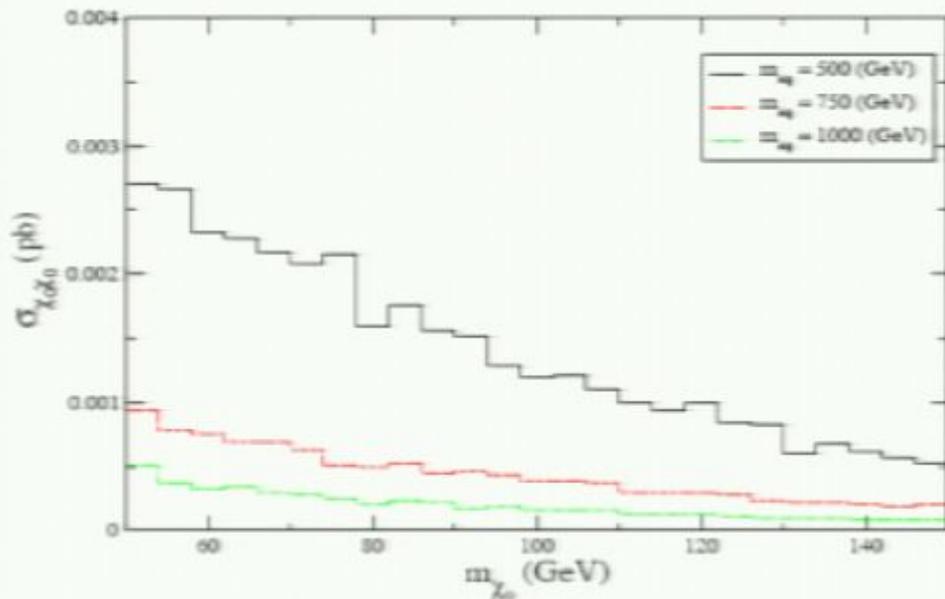
MSSM LSP pair production is very hard to trigger on. With the lepton jets at the bottom of every event, the task is considerably easier.



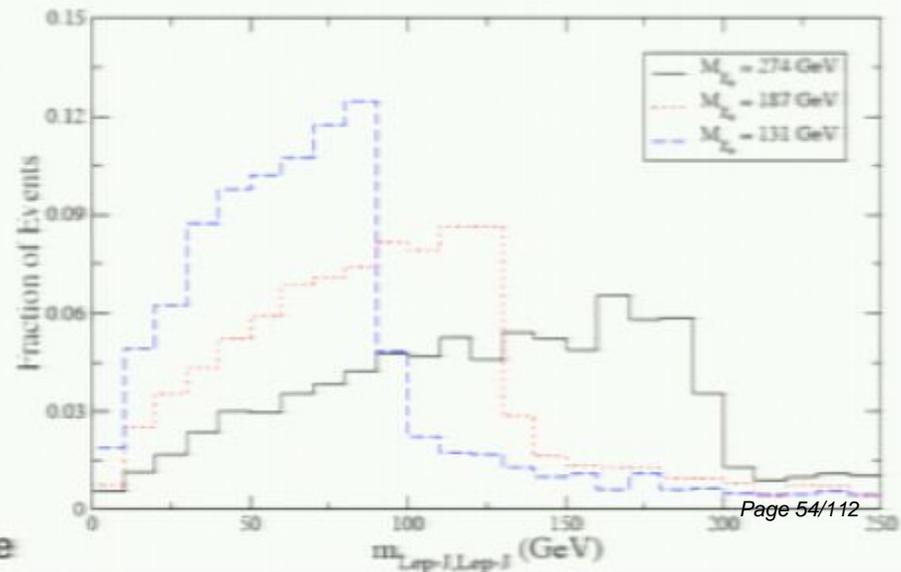
# Tevatron & LHC Reach.



# Tevatron & LHC Reach.



Can reconstruct LSP mass with a histogram of the invariant mass of every lepton jet pair.

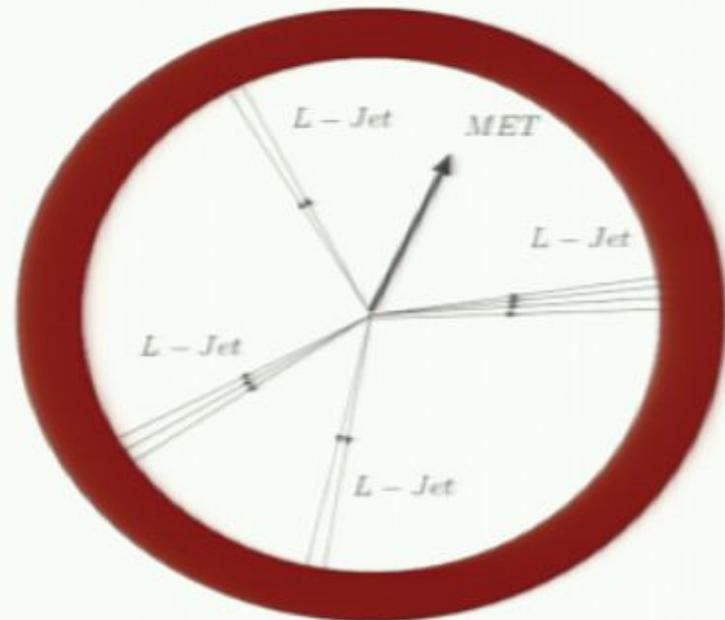
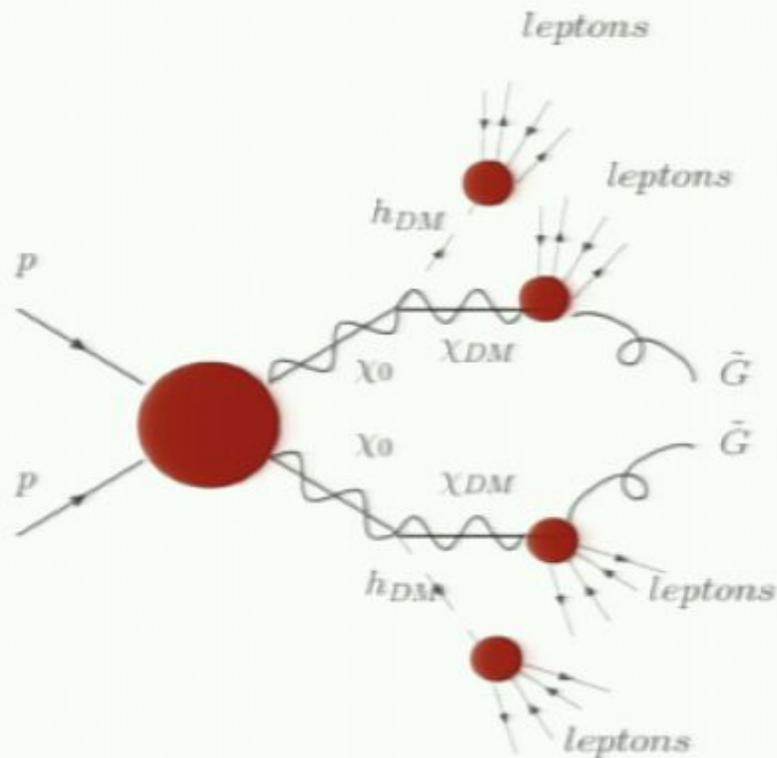


# Supersymmetry's little helper

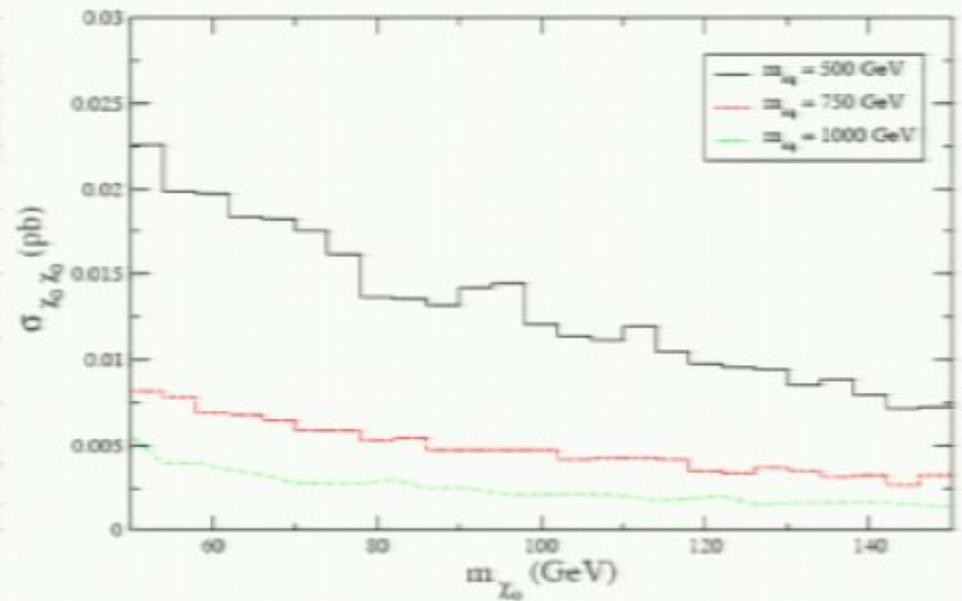
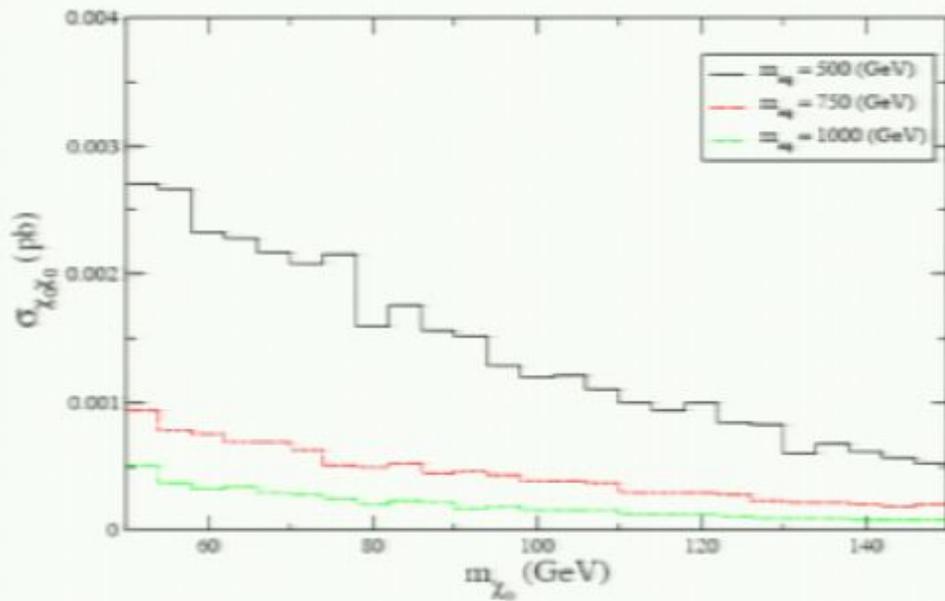
MSSM LSP pair production is very hard to trigger on. With the lepton jets at the bottom of every event, the task is considerably easier.

# Supersymmetry's little helper

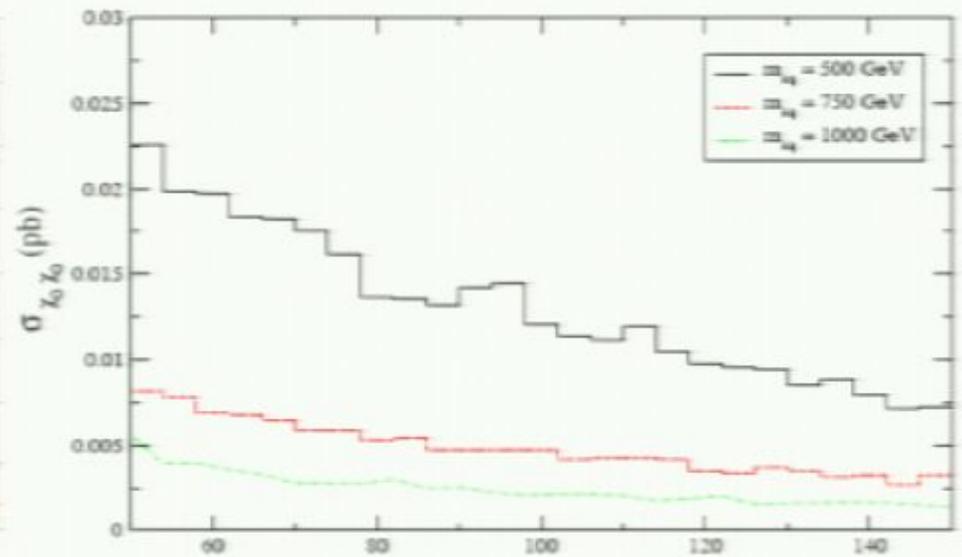
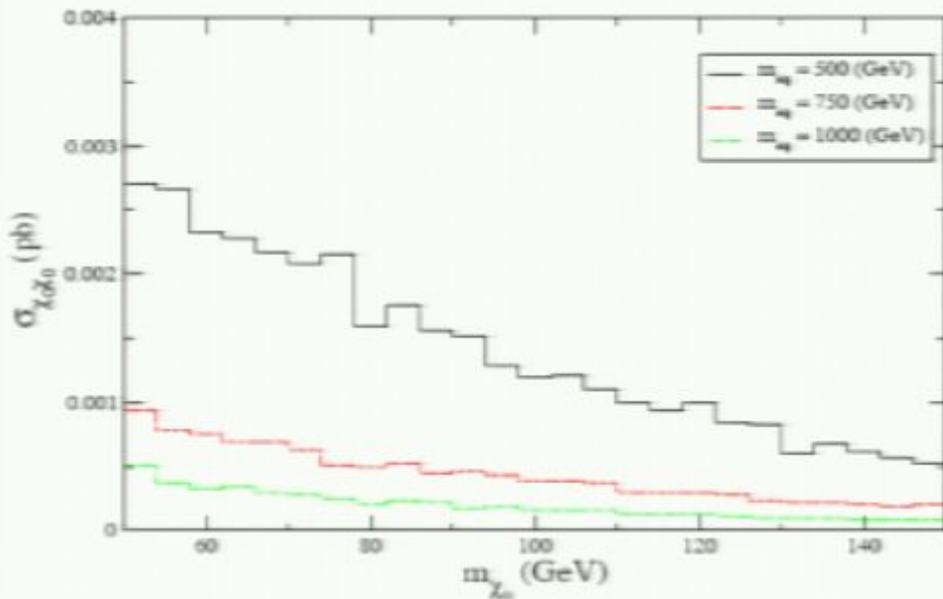
MSSM LSP pair production is very hard to trigger on. With the lepton jets at the bottom of every event, the task is considerably easier.



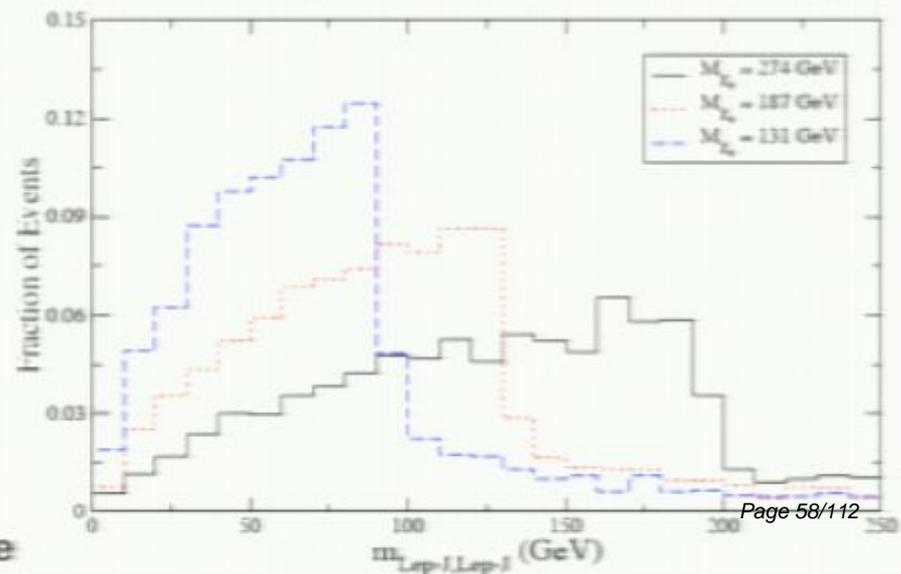
# Tevatron & LHC Reach.



# Tevatron & LHC Reach.

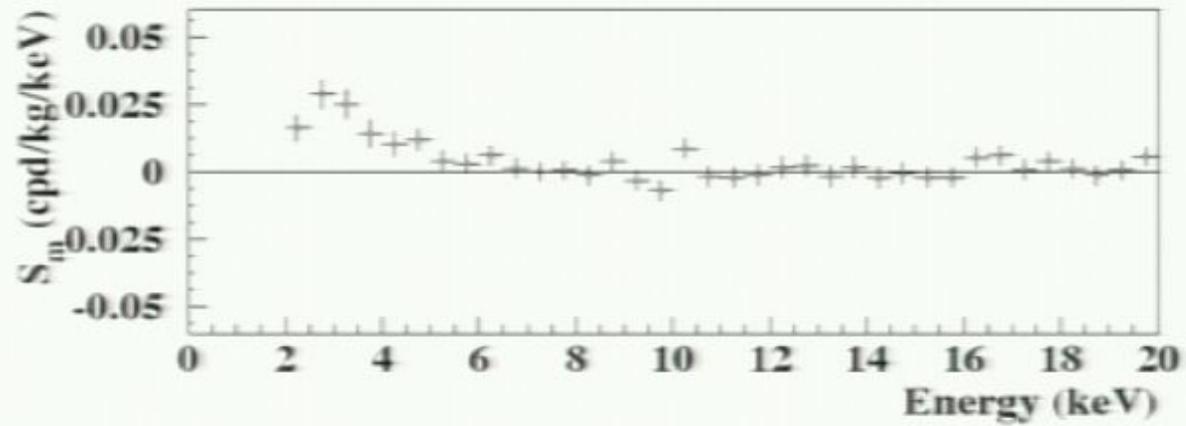


Can reconstruct LSP mass with a histogram of the invariant mass of every lepton jet pair.

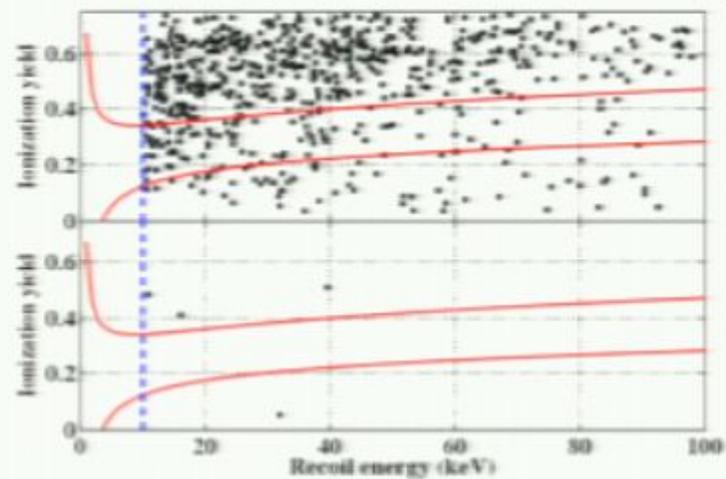
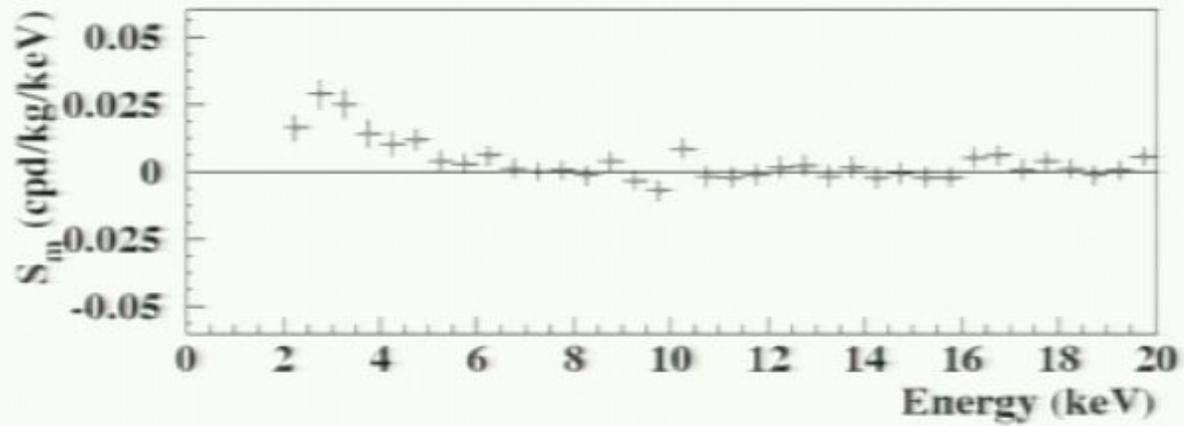


# DAMA's Signal

# DAMA/LIBRA

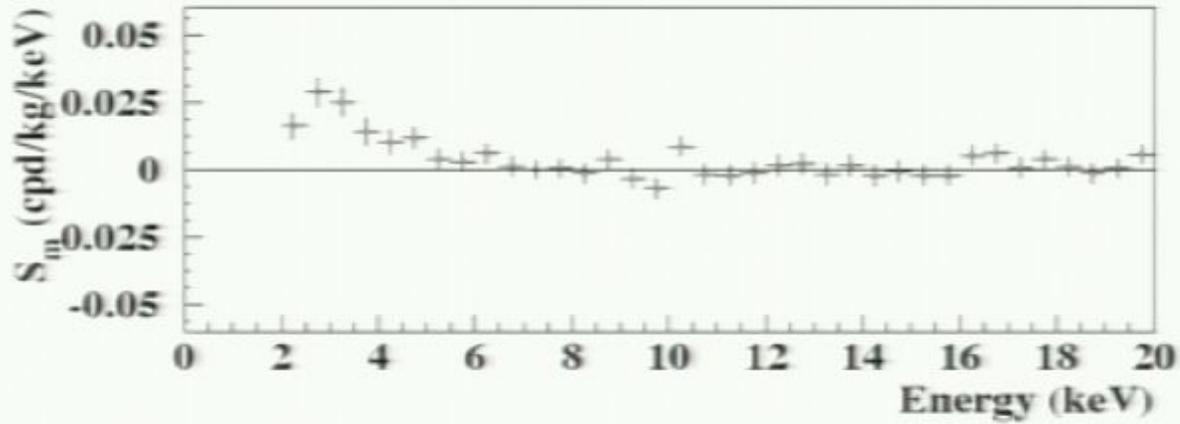


# DAMA/LIBRA

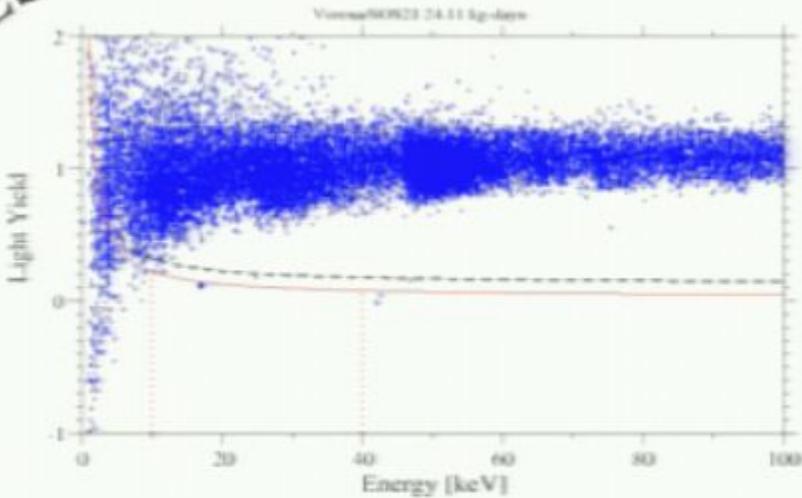


CDMS

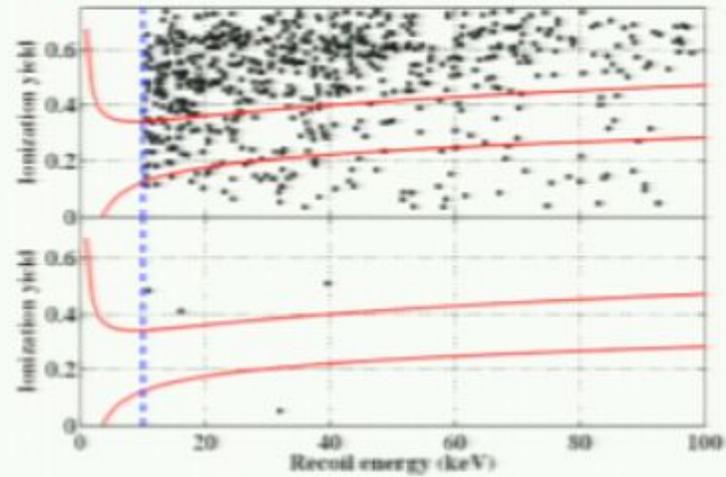
# DAMA/LIBRA



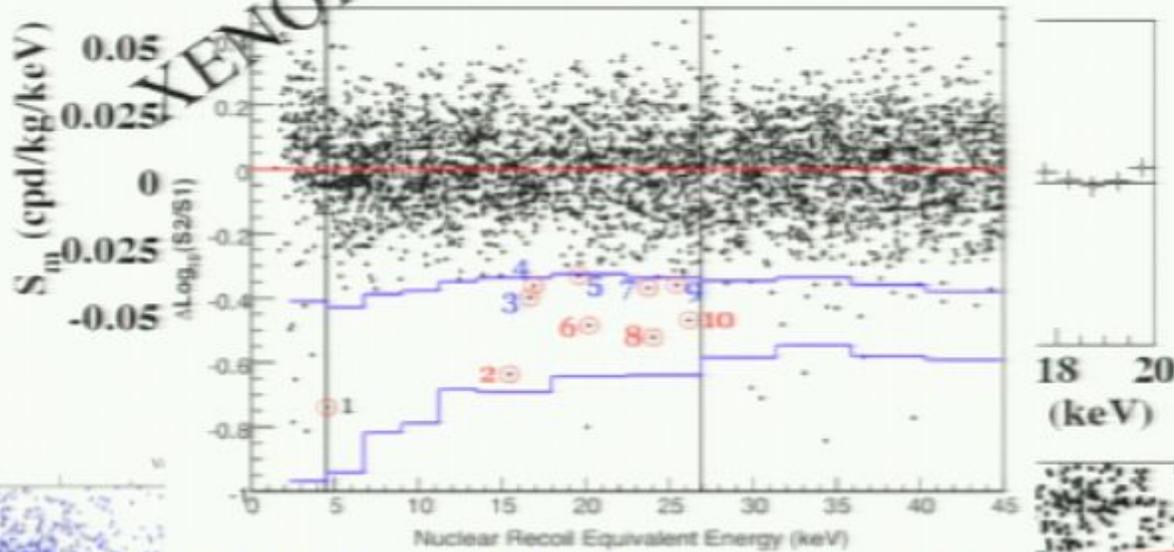
CRESST



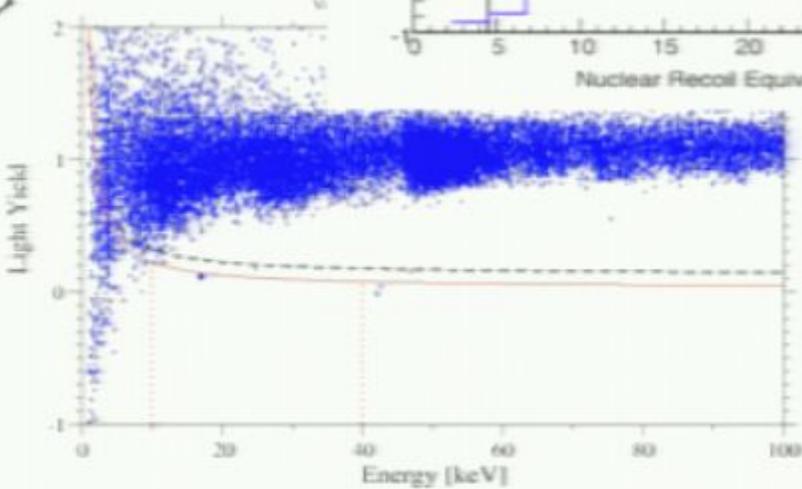
CDMS



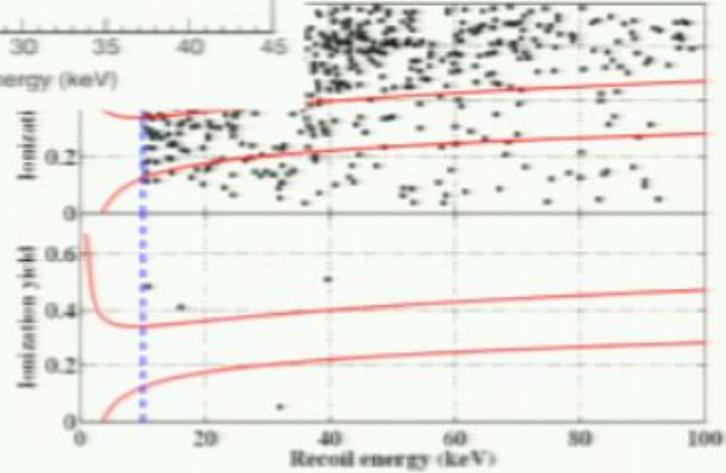
# DAMA/LIBRA



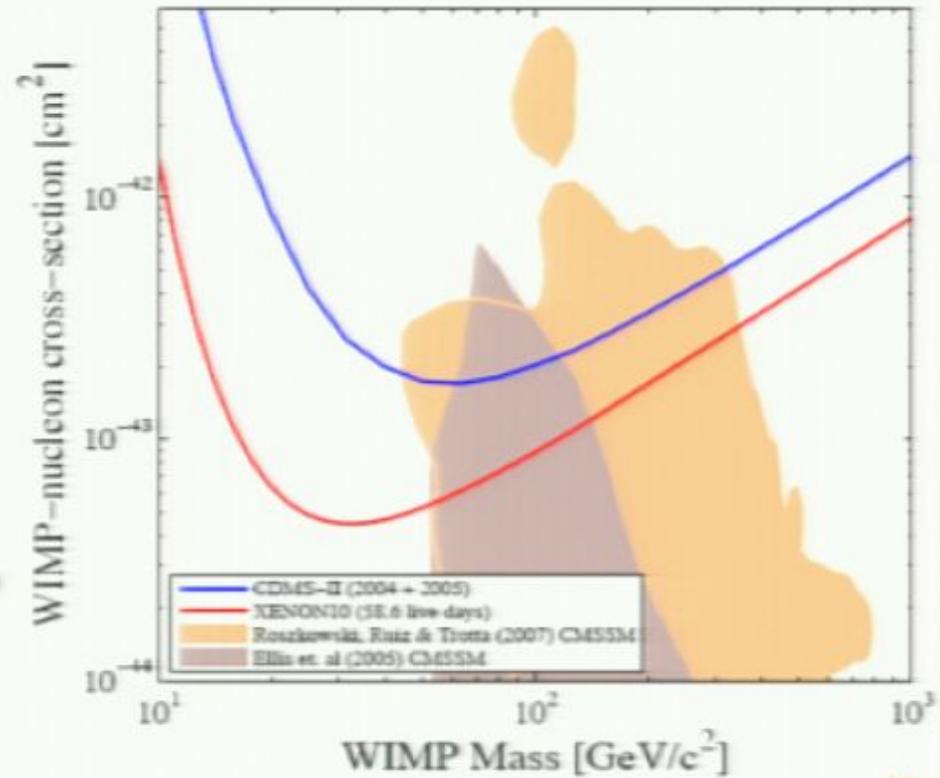
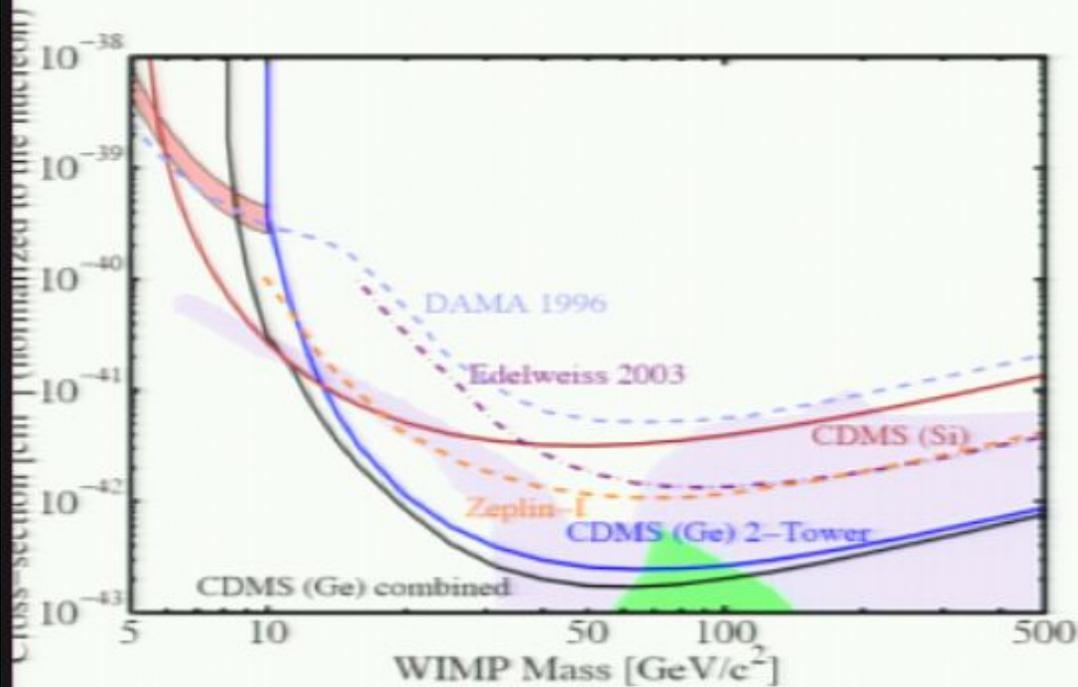
CRESST



CDMS

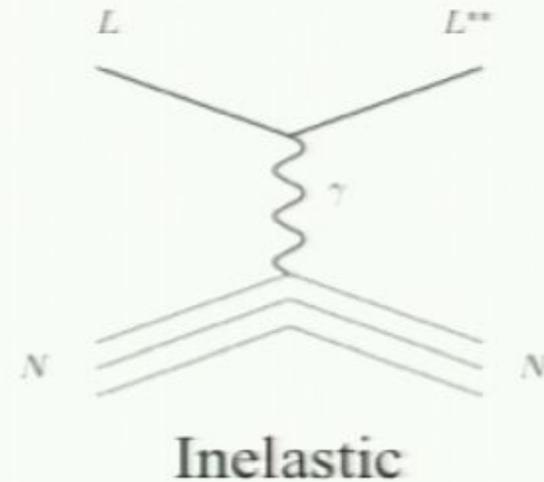
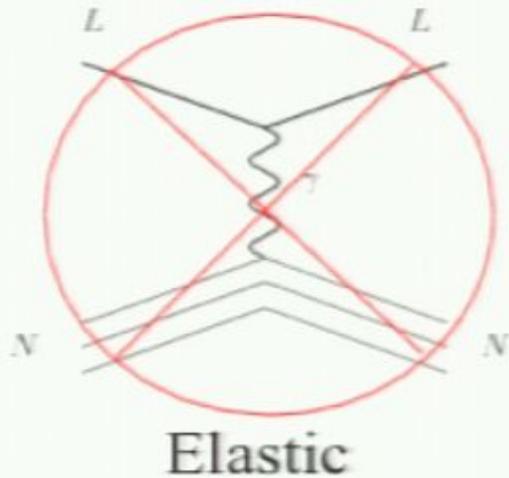


# Other Experiments



# Nuclear Recoil

Inelastic DM (**Smith & Weiner**) requires the WIMP to recoil inelastically against the nucleus.

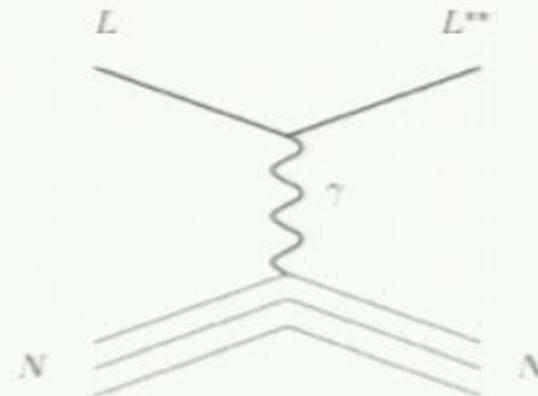


# Nuclear Recoil

Inelastic DM (**Smith & Weiner**) requires the WIMP to recoil inelastically against the nucleus.



Elastic



Inelastic

$$\beta_{min} = \sqrt{\frac{1}{2m_N E_R} \left( \frac{m_N E_R}{\mu} + \varepsilon \right)}$$

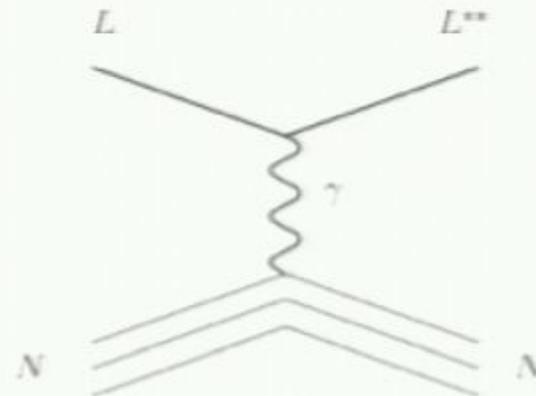
$m_N$  - Nucleus mass

# Nuclear Recoil

Inelastic DM (**Smith & Weiner**) requires the WIMP to recoil inelastically against the nucleus.



Elastic



Inelastic

$$\beta_{min} = \sqrt{\frac{1}{2m_N E_R} \left( \frac{m_N E_R}{\mu} + \mathcal{E} \right)}$$

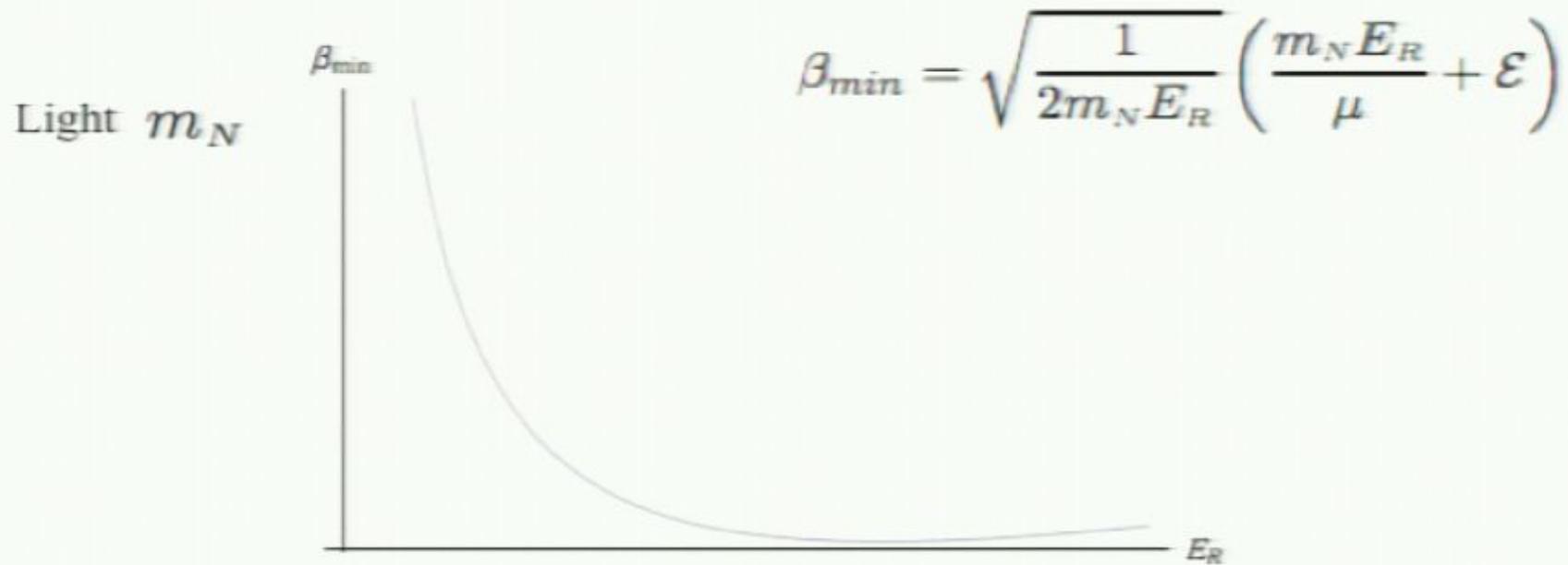
$m_N$  - Nucleus mass

$\mathcal{E}$  - Excitation Energy

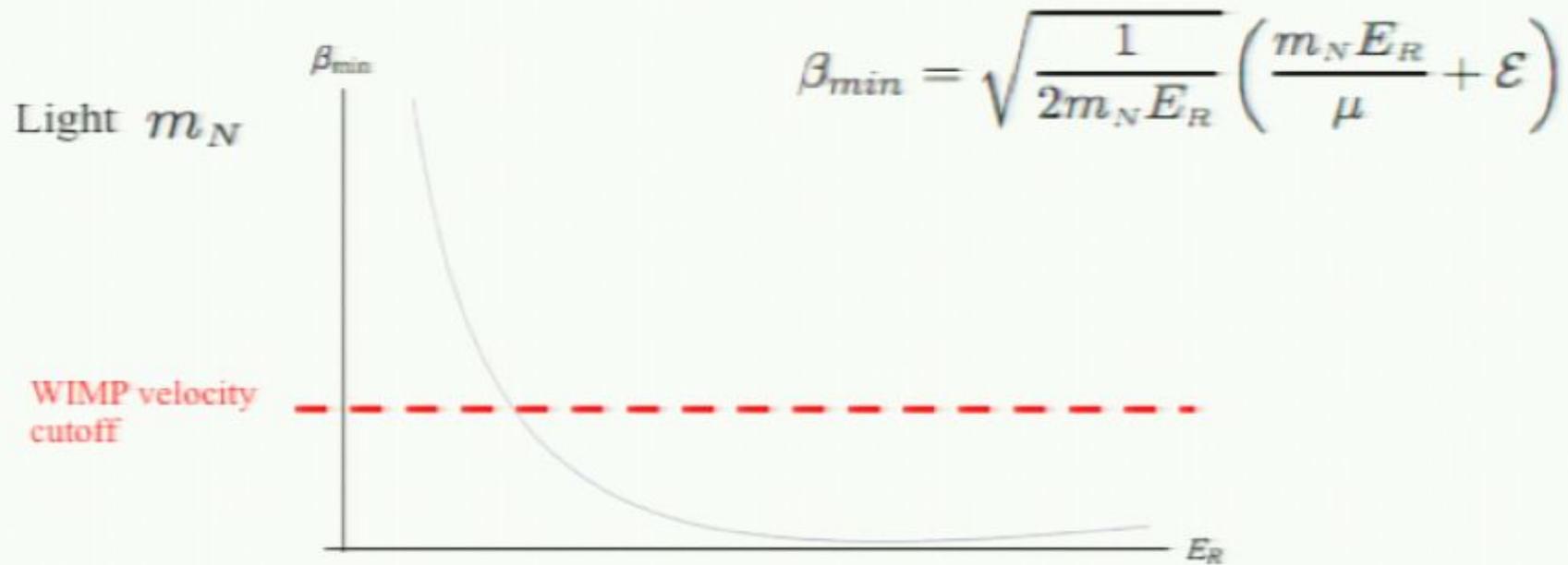
$E_R$  - Recoil Energy

$\mu$  - Nucleon-WIMP reduced mass

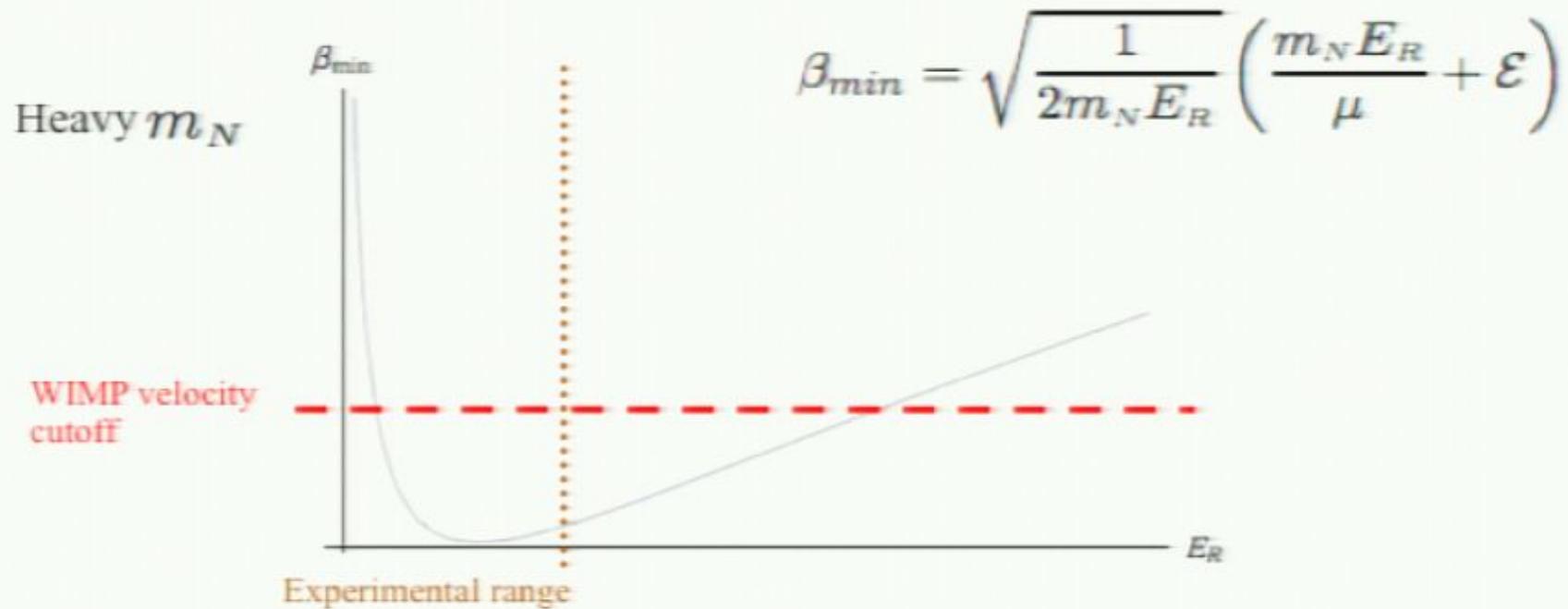
# Inelastic Transitions



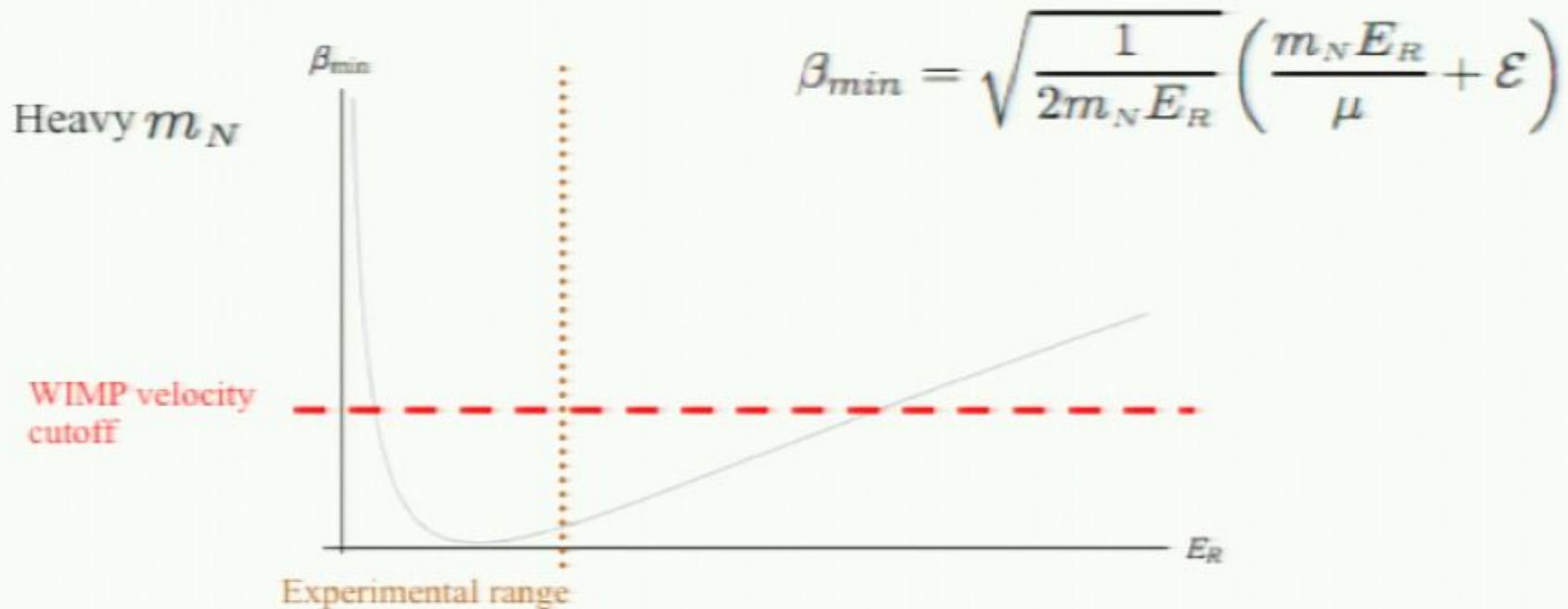
# Inelastic Transitions



# Inelastic Transitions

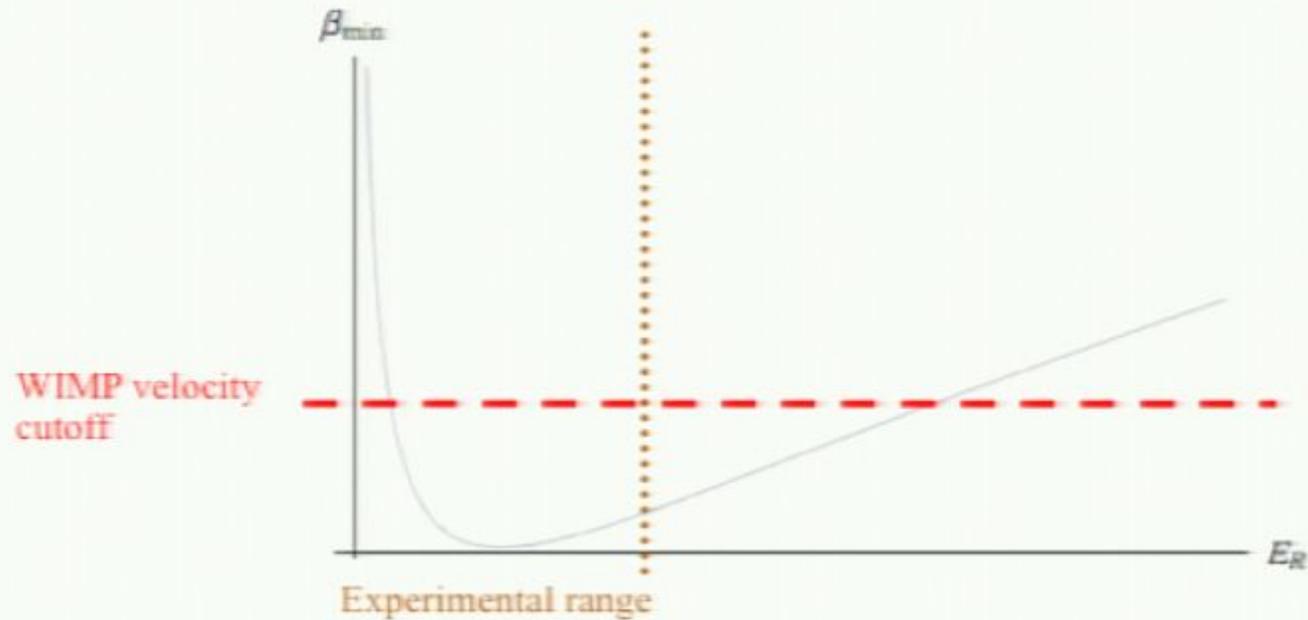


# Inelastic Transitions

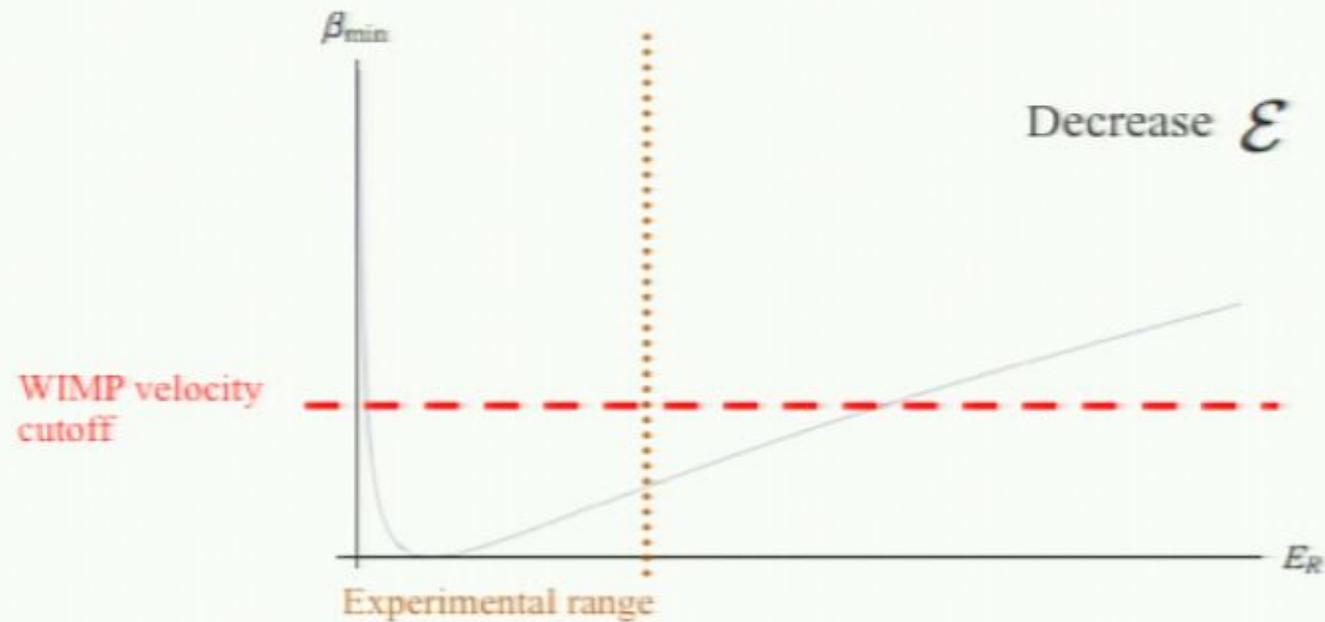


- 1) Light element experiments may not see anything.
- 2) The spectrum of events has a maximum.
- 3) Probing the tail of the Boltzmann distribution ---> large modulations.

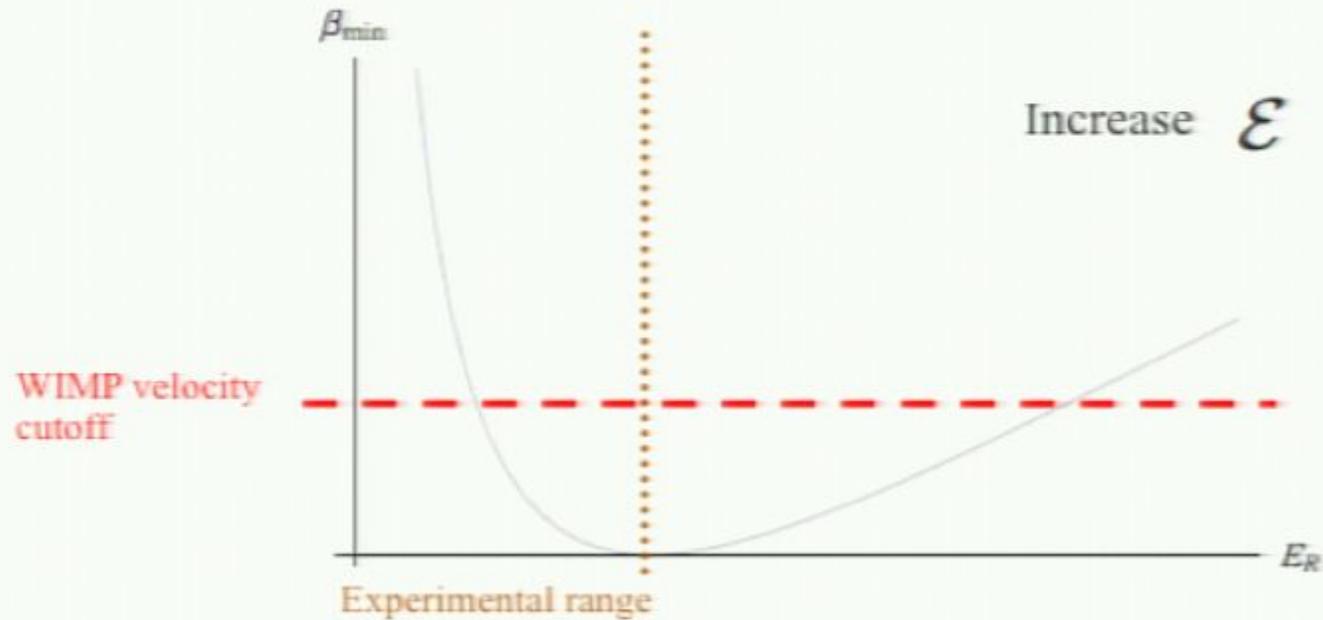
# Excitation Energy



# Excitation Energy

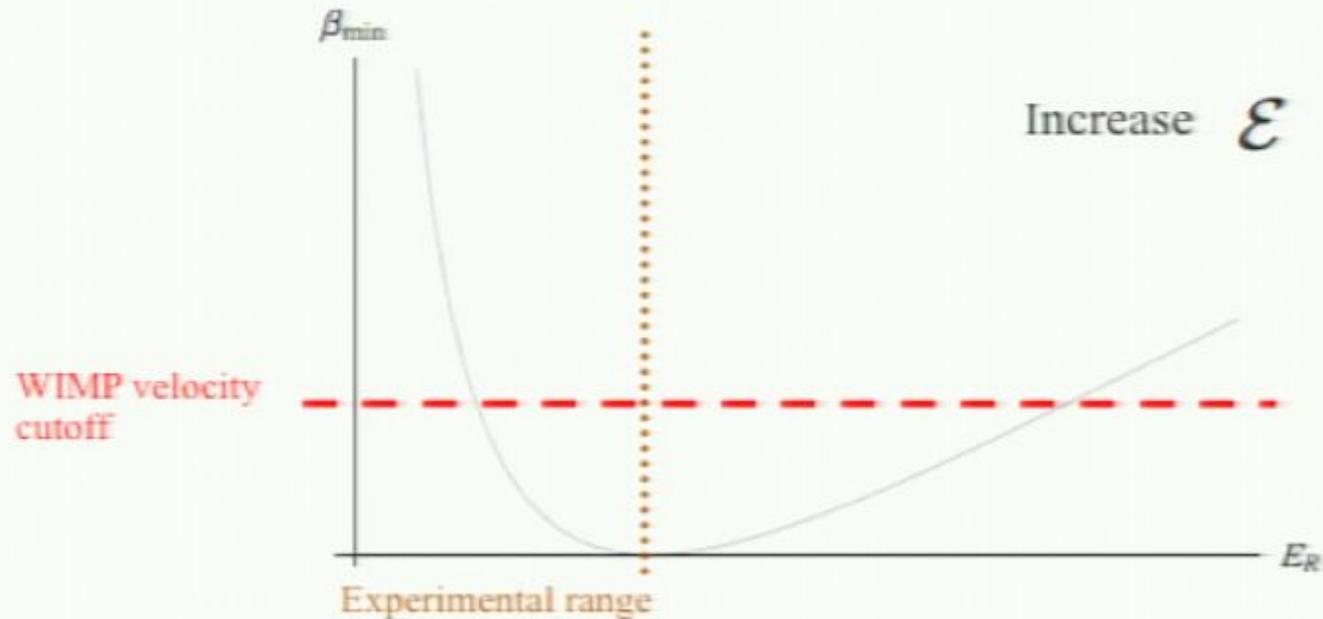


# Excitation Energy



$\epsilon$  Has to be chosen carefully. Too small and we are back to the elastic case. Too large and there is no signal for DAMA.

# Excitation Energy



$\epsilon$  Has to be chosen carefully. Too small and we are back to the elastic case. Too large and there is no signal for DAMA.

- 1) Why  $\epsilon \sim m_{\chi} \beta_{rot}^2 \sim 100 \text{keV}$
- 2) Why is the elastic channel absent?

# Density of States

Both questions can be answered if the WIMPs are endowed with some density of states which grows with energy,

# Density of States

Both questions can be answered if the WIMPs are endowed with some density of states which grows with energy,

$$g_n(\mathcal{E}) = \frac{n}{\mathcal{E}_0^n} \mathcal{E}^{n-1}$$

$\mathcal{E}_0$  Some new scale, can be much larger than 100 keV

# Density of States

Both questions can be answered if the WIMPs are endowed with some density of states which grows with energy,

$$g_n(\mathcal{E}) = \frac{n}{\mathcal{E}_0^n} \mathcal{E}^{n-1}$$

$\mathcal{E}_0$  Some new scale, can be much larger than 100 keV

- 1) Excitation energy is determined by the highest kinetic energy available.
- 2) Elastic scattering is “state” space suppressed.

# Event Rate

The differential event rate is now a convolution of the usual differential rate formula with the DOS,

$$\frac{dR}{dE_R} = \frac{N_T m_N \rho_\chi \sigma_n}{2m_\chi \mu_n^2} A^2 F^2(E_R) \left( \frac{n}{\mathcal{E}_0^n} \int \mathcal{E}^{n-1} d\mathcal{E} \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv \right)$$

# Event Rate

The differential event rate is now a convolution of the usual differential rate formula with the DOS,

$$\frac{dR}{dE_R} = \frac{N_T m_N \rho_\chi}{2m_\chi} \frac{\sigma_n}{\mu_n^2} A^2 F^2(E_R) \left( \frac{n}{\mathcal{E}_0^n} \int \mathcal{E}^{n-1} d\mathcal{E} \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv \right)$$

Can be done exactly,  
including the escape velocity

(Throughout, I will assume  $v_{esc} = 500$  km/s)

# Event Rate

The differential event rate is now a convolution of the usual differential rate formula with the DOS,

$$\frac{dR}{dE_R} = \frac{N_T m_N \rho_\chi}{2m_\chi} \frac{\sigma_n}{\mu_n^2} A^2 F^2(E_R) \left( \frac{n}{\mathcal{E}_0^n} \int \mathcal{E}^{n-1} d\mathcal{E} \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv \right)$$

Numerical evaluation

Can be done exactly,  
including the escape velocity

(Throughout, I will assume  $v_{esc} = 500$  km/s)

# Event Rate

The differential event rate is now a convolution of the usual differential rate formula with the DOS,

$$\frac{dR}{dE_R} = \frac{N_T m_N \rho_x \sigma_n}{2m_x \mu_n^2} A^2 F^2(E_R) \left( \frac{n}{\mathcal{E}_0^n} \int \mathcal{E}^{n-1} d\mathcal{E} \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv \right)$$

Numerical evaluation

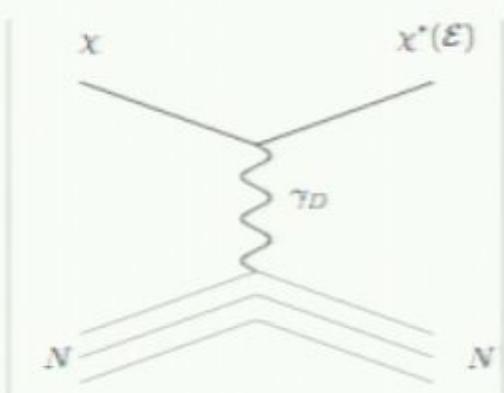
Can be done exactly,  
including the escape velocity

(Throughout, I will assume  $v_{esc} = 500$  km/s)

Define  $\frac{\sigma_n}{\mu_n^2} \equiv G^2$  where  $G = \alpha_{DF}/M_{DF}^2$

# Overall Scale

The inelastic signal scales like,

$$\frac{dR}{dE_R} \sim \frac{n}{\mathcal{E}_0^n} \int d\mathcal{E} \mathcal{E}^{n-1} \left| \begin{array}{c} \chi \\ \chi^*(\mathcal{E}) \\ \gamma_D \\ N \\ N \end{array} \right|^2 \sim \frac{G^2}{\mathcal{E}_0^n}$$


# Overall Scale

The inelastic signal scales like,

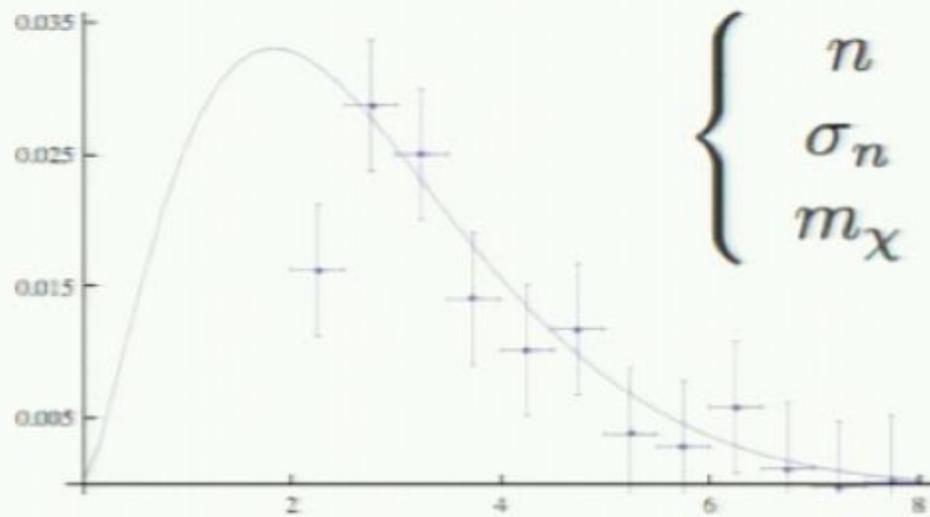
$$\frac{dR}{dE_R} \sim \frac{n}{\mathcal{E}_0^n} \int d\mathcal{E} \mathcal{E}^{n-1} \left| \begin{array}{c} \chi \\ \chi^*(\mathcal{E}) \\ \gamma_D \\ N \\ N \end{array} \right|^2 \sim \frac{G^2}{\mathcal{E}_0^n}$$

DAMA requires a scattering cross-section of about  $10^{-40} \text{ cm}^2$ . That translates to the following scaling of the parameters,

$$\mathcal{S} \left( \sqrt{G} \times 2 \text{ TeV} \right)^4 \left( \frac{100 \text{ keV}}{\mathcal{E}_0} \right)^n$$

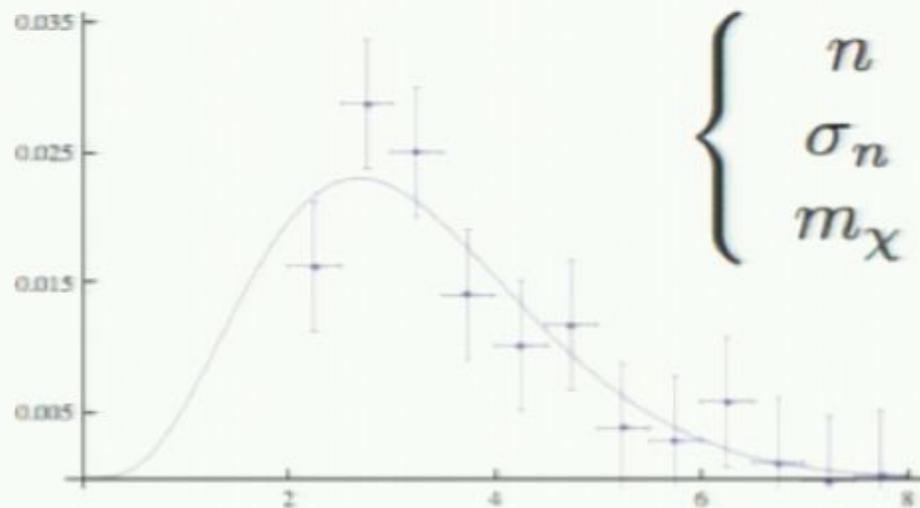
$\mathcal{S}$  Is an order unity number which is fixed by fitting the DAMA modulation signal.

# Fit to DAMA



$$\left\{ \begin{array}{l} n = 3 \\ \sigma_n = 4.0 \times 10^{-40} \text{ cm} \\ m_\chi = 150 \text{ GeV} \end{array} \right.$$

# Fit to DAMA

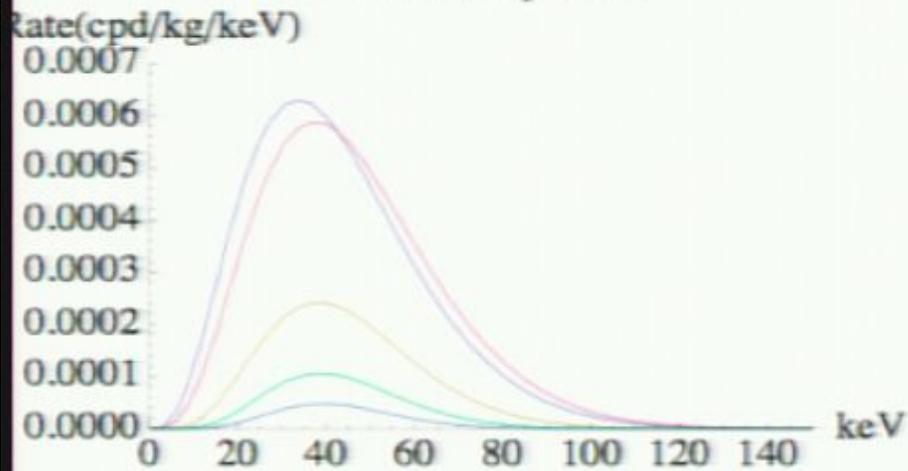


$$\left\{ \begin{array}{l} n = 9 \\ \sigma_n = 3.7 \times 10^{-40} \text{ cm} \\ m_\chi = 85 \text{ GeV} \end{array} \right.$$

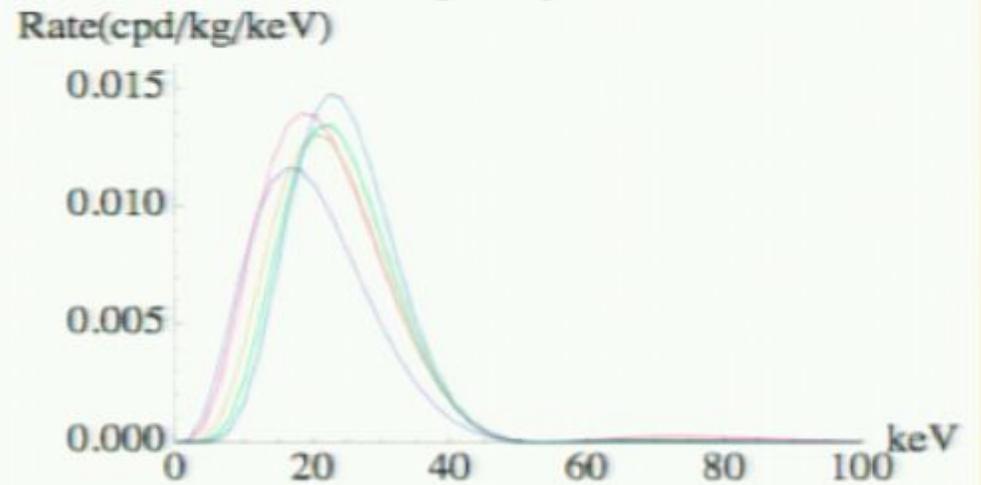
With a steep DOS we can fit the DAMA modulation data and escape the bounds from other direct detection experiments.

# Spectrum

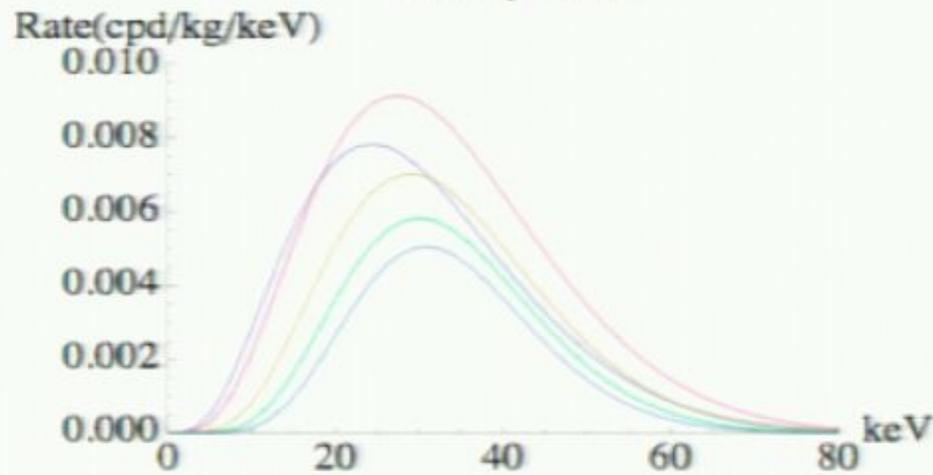
Germanium Spectrum



Tungsten Spectrum



Xenon Spectrum

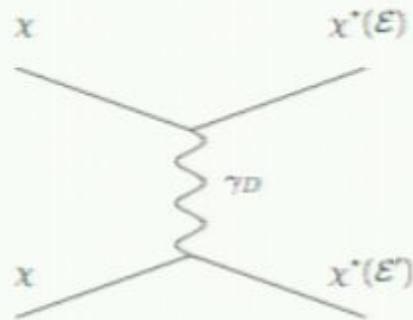


# Comparison with other Exp.

$m_\chi$ GeV	$n$	DAMA 2 – 6 keVee $10^{-2}$ dru	XENON 4.5 – 45 keV counts	CDMS 10 – 100 keV counts	ZEPLIN 5 – 20 keVee counts	KIMS 3 – 8 keVee $10^{-2}$ dru	CRESST 12 – 60 keV counts
exp		$1.31 \pm 0.16$	24 (31.6)	2 (5.3)	29 (37.2)	$5.7 \pm 3.27$	7 (11.3)
342	3	1.45	68	43	48	28	21
116	6	1.45	31	11	24	14	13
88	9	1.44	20	3	16	9.0	11
78	12	1.42	14	1	12	6.5	11
73	15	1.40	11	0.5	10	5.1	11
70	18	1.37	10	0.2	8	4.0	12

For a shallow DOS there is too much pollution from the elastic scattering and the bounds from CDMS become relevant. With a steep DOS, CRESST offers the most stringent bounds.

# Strong Coupling



# Examples with a Steep DOS

Large ( $n$ ) extra dimensions with a toric geometry. The number of states above the compactification scale grows with energy,

$$N(\mathcal{E}) \sim (\mathcal{E}R)^n$$

# Examples with a Steep DOS

Large ( $n$ ) extra dimensions with a toric geometry. The number of states above the compactification scale grows with energy,

$$N(\mathcal{E}) \sim (\mathcal{E}R)^n$$

For a general compact manifold of dimension  $n$ , there is a theorem in mathematics, known as “**Weyl’s Law**”, which gives the number of eigenvalues of the Laplacian operator below some number,  $\lambda$ .

$$N(\lambda) = \frac{\text{vol}(\mathcal{M})}{(4\pi)^{n/2}\Gamma(n/2 + 1)} \lambda^{n/2} + \mathcal{O}\left(\lambda^{(n-1)/2}\right)$$

# Bound States

Another possibility is to form bound states with a fairly flat potential.  
Consider the Schrodinger equation:

$$\left( -\frac{1}{2m} \nabla^2 + V(\vec{r}) \right) \psi(\vec{r}) = E \psi(\vec{r})$$

# Bound States

Another possibility is to form bound states with a fairly flat potential.  
Consider the Schrodinger equation:

$$\left( -\frac{1}{2m} \nabla^2 + V(\vec{r}) \right) \psi(\vec{r}) = E\psi(\vec{r})$$

E.g. Harmonic Oscillator, 

$$E_{HO} = \omega (n_1 + \dots + n_d + d/2)$$

# Bound States

Another possibility is to form bound states with a fairly flat potential.  
Consider the Schrodinger equation:

$$\left( -\frac{1}{2m} \nabla^2 + V(\vec{r}) \right) \psi(\vec{r}) = E \psi(\vec{r})$$

E.g. Harmonic Oscillator, 

$$E_{HO} = \omega (n_1 + \dots + n_d + d/2) \quad \Rightarrow \quad N(\mathcal{E}) \sim \mathcal{E}^d$$

But, selection rules will forbid transitions.

# Bound States

Another possibility is to form bound states with a fairly flat potential.  
Consider the Schrodinger equation:

$$\left( -\frac{1}{2m} \nabla^2 + V(\vec{r}) \right) \psi(\vec{r}) = E \psi(\vec{r})$$

E.g. Harmonic Oscillator, 

$$E_{HO} = \omega (n_1 + \dots + n_d + d/2) \quad \Rightarrow \quad N(\mathcal{E}) \sim \mathcal{E}^{\times}$$

But, selection rules will forbid transitions. Consider only s states.

E.g. s states for a string potential,

$$V(r) = T r \quad \Rightarrow \quad N(\mathcal{E}) \sim \left( \frac{m^{1/2}}{T} \right) \mathcal{E}^{3/2}$$

# Cwikel-Lieb-Rosenblum Estimate

Another useful theorem in mathematics provides an estimate for the number of bound states below some energy,  $\mathcal{E}$

$$N(\mathcal{E}) < L_{0,d} \int (\mathcal{E} - V(\vec{x}))^{d/2} d^d x$$

# Cwikel-Lieb-Rosenblum Estimate

Another useful theorem in mathematics provides an estimate for the number of bound states below some energy,  $\mathcal{E}$

$$N(\mathcal{E}) < L_{0,d} \int (\mathcal{E} - V(\vec{x}))^{d/2} d^d x$$

So we can obtain a very steep DOS by considering very flat potentials.

$$N(\mathcal{E}) < \int (\mathcal{E} - cr^\xi)^{d/2} d^d r \sim \mathcal{E}^{d(\frac{1}{\xi} + \frac{1}{2})}$$

# Cwikel-Lieb-Rosenblum Estimate

Another useful theorem in mathematics provides an estimate for the number of bound states below some energy,  $\mathcal{E}$

$$N(\mathcal{E}) < L_{0,d} \int (\mathcal{E} - V(\vec{x}))^{d/2} d^d x$$

So we can obtain a very steep DOS by considering very flat potentials.

$$N(\mathcal{E}) < \int (\mathcal{E} - cr^\xi)^{d/2} d^d r \sim \mathcal{E}^{d(\frac{1}{\xi} + \frac{1}{2})}$$

In particular, a log potential will produce an exponentially growing DOS.  
A flat potential which is lifted only at loop level can produce a log potential.

# Missing Pieces

# Missing Pieces

- What is the cosmology of such a WIMP?

# Missing Pieces

- What is the cosmology of such a WIMP?
- Can this have any relation to “a theory of dark matter”.

# Missing Pieces

- What is the cosmology of such a WIMP?
- Can this have any relation to “a theory of dark matter”.
- What happens above the strong scale? (QCD...)

# Missing Pieces

- What is the cosmology of such a WIMP?
- Can this have any relation to “a theory of dark matter”.
- What happens above the strong scale? (QCD...)

## Future Data

# Missing Pieces

- What is the cosmology of such a WIMP?
- Can this have any relation to “a theory of dark matter”.
- What happens above the strong scale? (QCD...)

## Future Data

- More XENON experiments are underway.

# Missing Pieces

- What is the cosmology of such a WIMP?
- Can this have any relation to “a theory of dark matter”.
- What happens above the strong scale? (QCD...)

## Future Data

- More XENON experiments are underway.
- CRESST should have better bounds.

# Conclusions

# Conclusions

- New observations warrant the construction of Concordance models for the dark sector.

# Conclusions

- New observations warrant the construction of Concordance models for the dark sector.
- Some *preliminary* generic predictions for the LHC.

# Conclusions

# Conclusions

- New observations warrant the construction of Concordance models for the dark sector.

# Conclusions

- New observations warrant the construction of Concordance models for the dark sector.
- Some *preliminary* generic predictions for the LHC.

# Conclusions

- New observations warrant the construction of Concordance models for the dark sector.
- Some *preliminary* generic predictions for the LHC.
- DAMA hint that dark matter may a complicated composite state.