# Interpretations of Possible Signals of Dark Matter

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University of Michigan
DPF 2009 at Wayne State
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# Outline

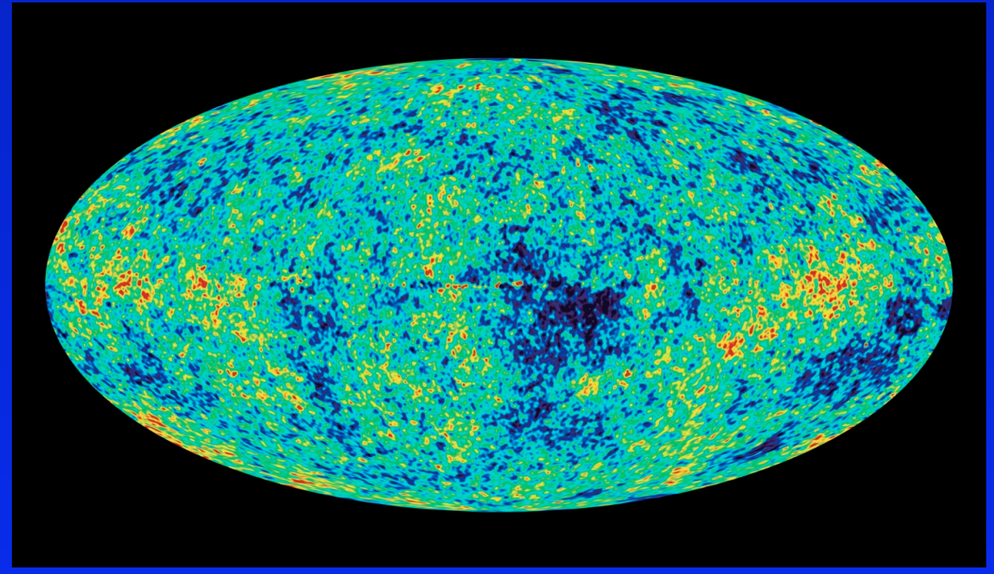
- Background
  - What do we ask for in Dark Matter?
- Indirect Detection
- Direct Detection
  - A puzzle
- Future?

# Two related Questions

- What can we learn about the Dark Matter?
- What can we learn about the history of the Universe?

# We know how much...

$$\Omega_{matter} h^2 = 0.1358 \pm 0.0037$$
$$\Omega_{baryon} h^2 = 0.02267 \pm 0.00059$$



WMAP+SN
+BAO

**Komatsu, et al. (WMAP) Astrophys.J.Suppl. 180:330-376,2009**

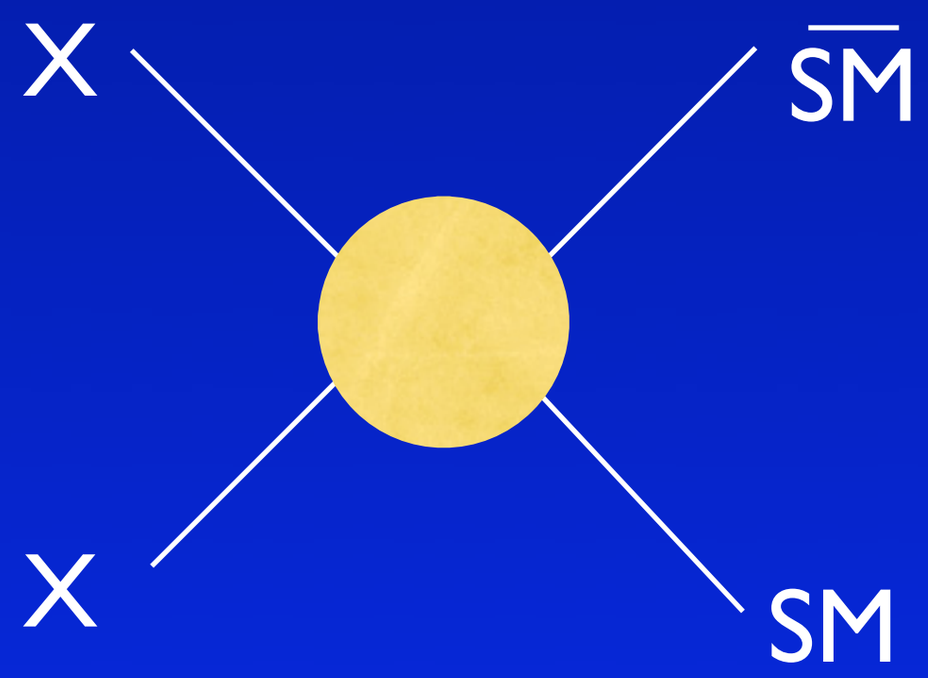
# New question: what is it?

# Calculate How Much Dark Matter...

Solve the Boltzmann equation in an expanding universe.

Annihilations try to maintain thermal equilibrium.

Expansion of the Universe prevents this.



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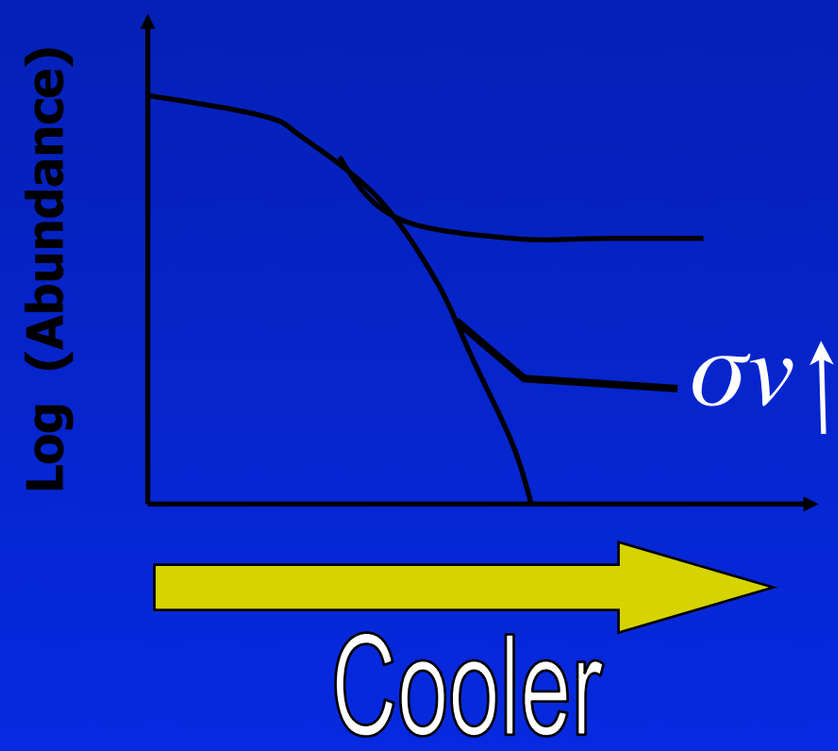


# For this talk

- We concentrate on the possibility of a particle at the weak scale, with non-gravitational interactions
- This omits, e.g., axions, SuperWIMPS...

# What is the Dark Matter?

- We know something about its mass.

$$\Omega h^2 \approx 10^{-9}\ \mathrm{GeV}^{-2}\left(\frac{M^2}{\alpha^2}\right)$$

- Coming to a collider near you?
- "The WIMP miracle"

# Minimal Theoretical Input

- We want it to be stable against decay:
- No terms linear in X in the Lagrangian

$$\mathcal{L} \not\supset X\, SM\, \overline{SM}$$

- Discrete symmetry e.g., X <-> -X

# Imposed by hand?

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4.$$

## (Extra Singlet)

Burgess; MacDonald; Davoudiasl

$$V(H_1, H_2) = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[ (H_1^\dagger H_2)^2 + h.c. \right] .$$

## (Inert Doublet Model)

Barbieri, Hall, Rychkov Phys.Rev.D74:015007,2006

# Possible, but a waste of the WIMP miracle

# Two Reasons to Expect New Physics BSM at the LHC

- Hierarchy Problem/ Electroweak Symmetry Breaking

$$\Delta m_h^2 = \frac{3 y_{top}^2}{8\pi^2}\Lambda^2$$

SUSY/Little Higgs/Extra Dim?

# What is the identity of that symmetry?

- Supersymmetry: R-Parity
  - imposed to avoid proton decay -- remnant of a GUT gauge symmetry?)
  - Ensures lighest supersymmetric particle can be stable.

# What is the identity of that symmetry?

- Extra Dimensions: KK-Parity
  - (remnant of 5-d Poincare invariance)
- Little Higgs with T-parity

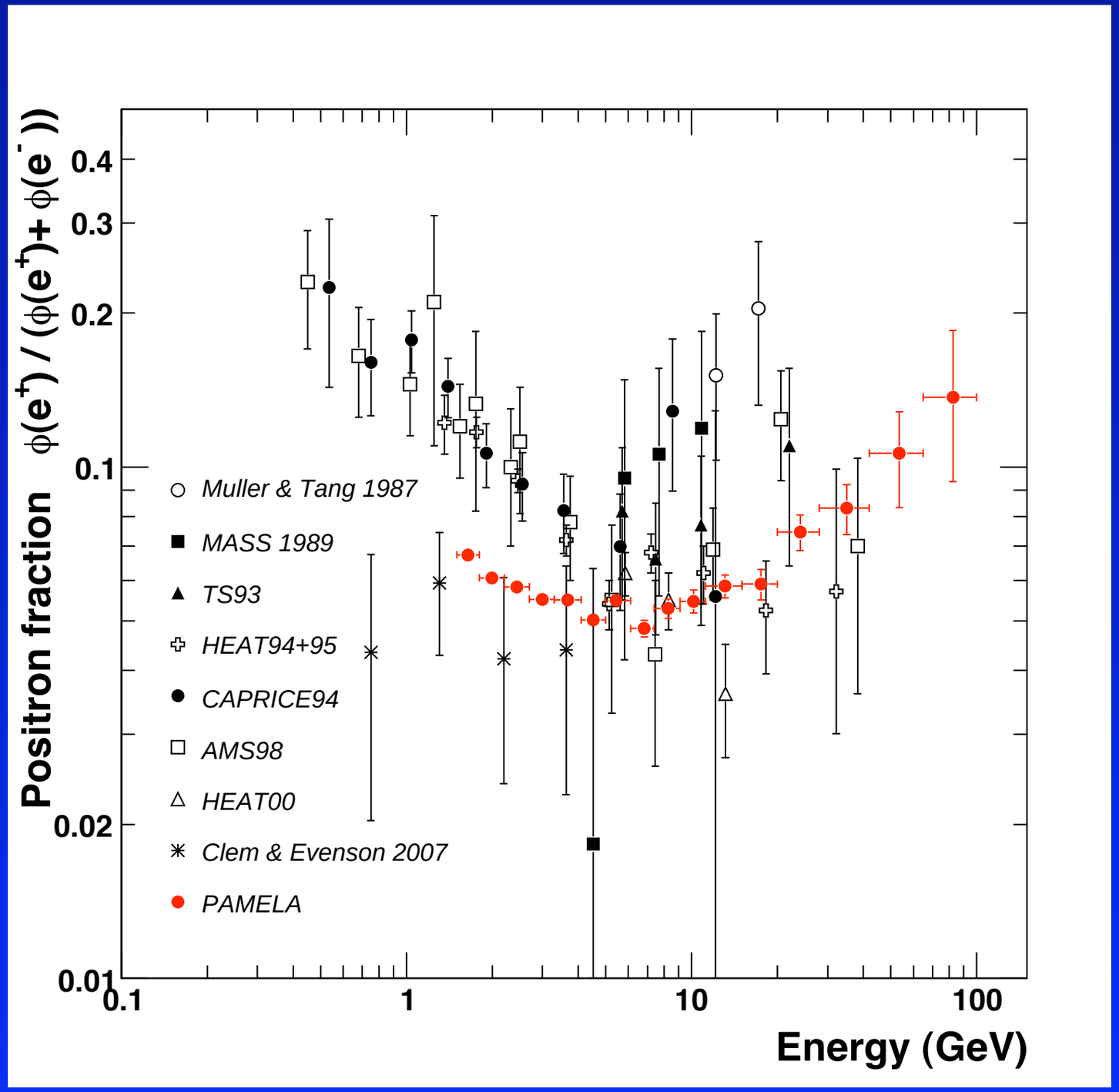
# The above story has some important on several assumptions

- “Boring”expansion
- Thermal History for DM

These assumptions have recently been challenged by data....

# PAMELA

Required cross section is much more than a thermal one $10^{-24}cm^3s^{-1}$

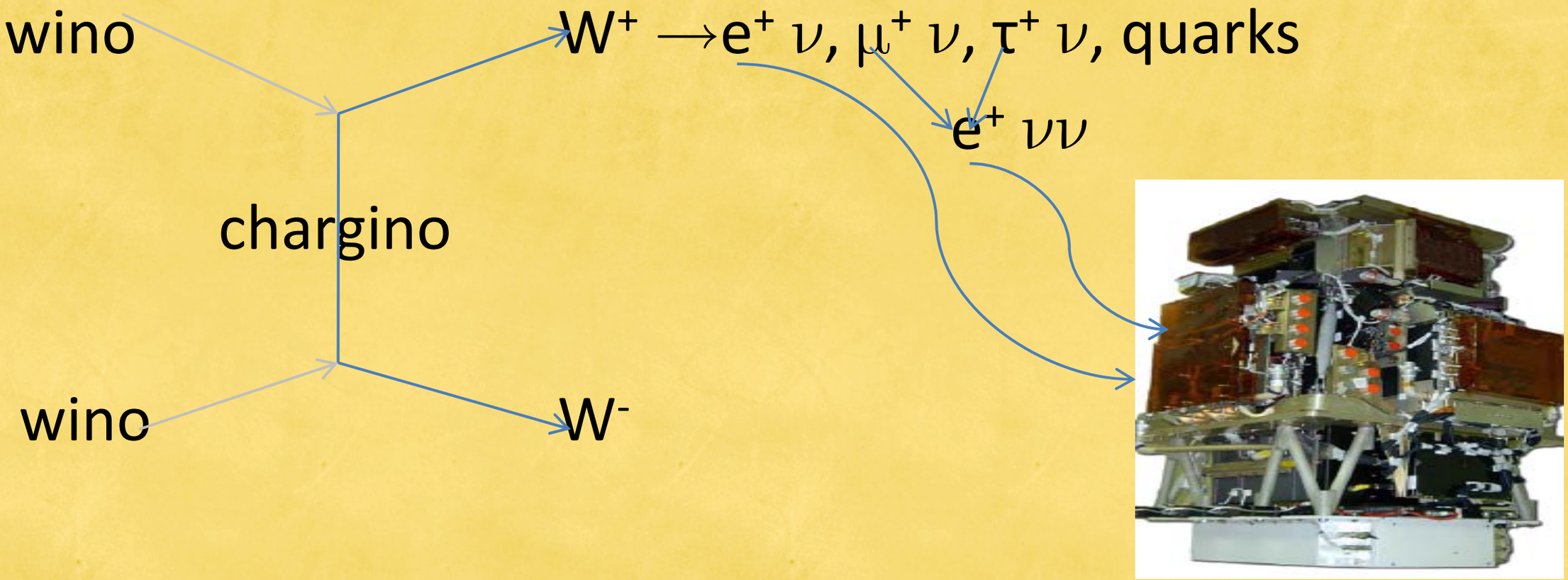



0810.4495

Nature 458:607-609,2009

# Non-thermal history

- Dark matter does not annihilate away to current abundance.
- Instead, it is populated at “late times” by decay of heavy field, e.g. modulus of string theory.
- Allows for WIMP with large cross section.
  - e.g. Randall/Moroi, Wino in ASMB




Kane at TeVPa

# How can we have thermal history?

- Something changes about Dark Matter annihilation between freeze-out and now.
- What changes?
  - velocity dependent cross section?
  - Properties of the DM (Cohen, Morrissey, AP, **Phys.Rev.D78:111701,2008**.)

# General Lesson

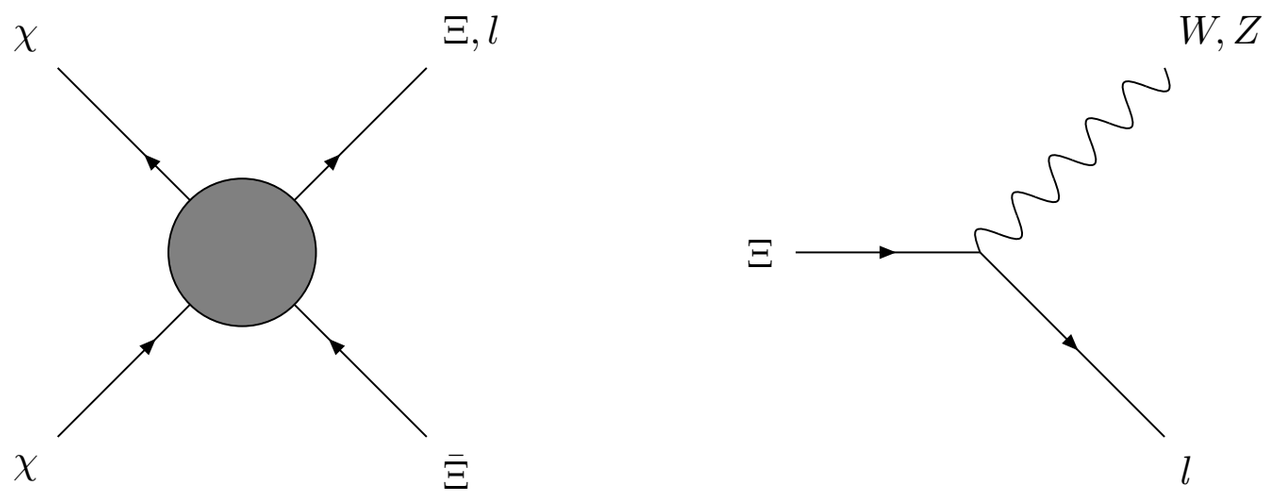
- If we measure annihilation cross-section (either by indirect detection + knowledge of halo, or by detailed measurements at a collider) and it does not match the WIMP miracle, we may discover a non-standard cosmology! (cf. BBN)

# Another puzzle

- No apparent excess in p-bars.
- So, annihilation to WW, ZZ, bb, cc, all not so great.
- (see however, Kane, Lu and Watson)

# Leptophilic Dark Matter

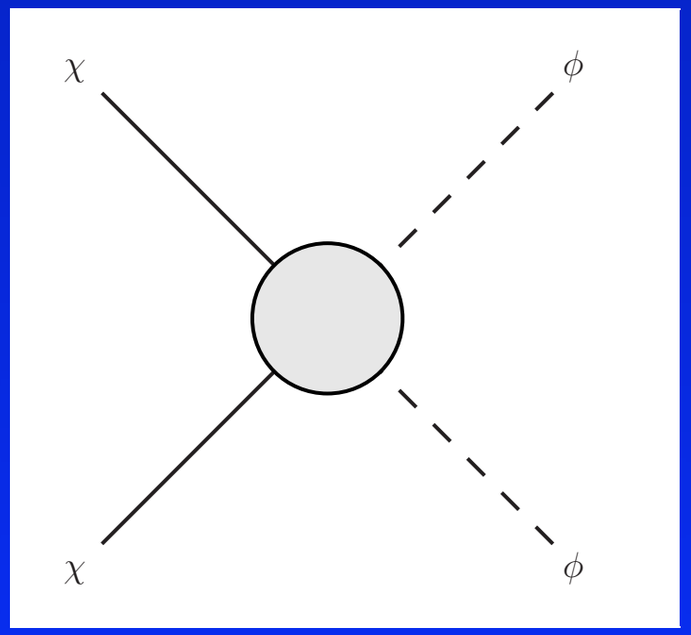
- Dynamics
  - Fox, Poppitz; Zurek; Phalen, AP, Weiner...many others




$$\mathcal{L} = \sum_i y_i \ell_i e_i^c h + \mu \bar{\Xi}\Xi + \epsilon_i \bar{\Xi}\ell_i + \tilde{y}_i \Xi e_i^c h + H.c.$$

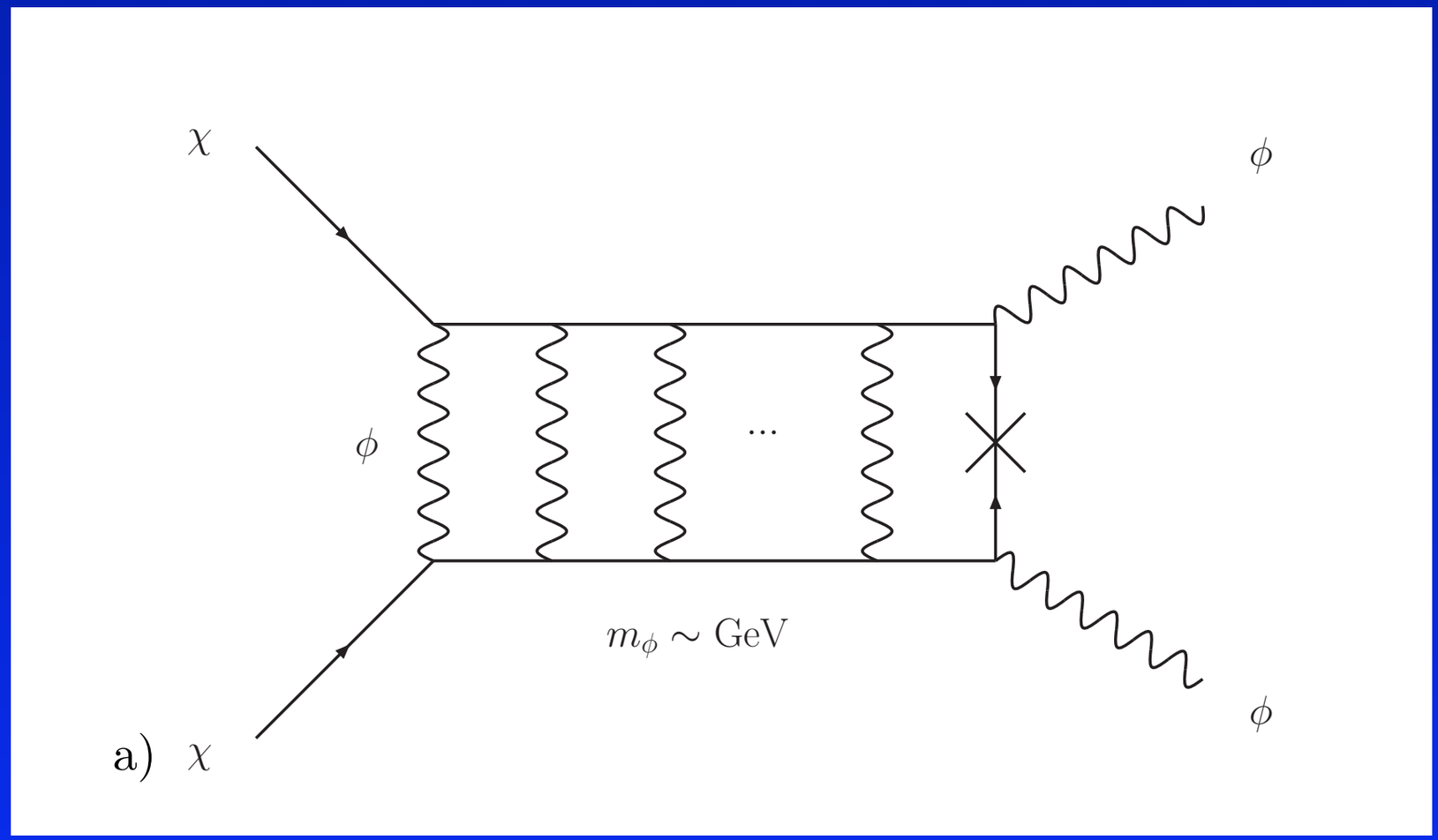
# Leptophilic Dark Matter

- Kinematics
  - Nomura, Thaler; Cholis, Finkbeiner, Goodenough, Weiner; Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Nelson, Spitzer,....many others




$$m_\phi < \mathrm{GeV}$$

# Sommerfeld Enhancement




Arkani-Hamed, Weiner, Slatyer, Finkbeiner

Phys. Rev. D79, 015014 (2009), 0810.0713.

Hisano, Matsumoto, Nojiri

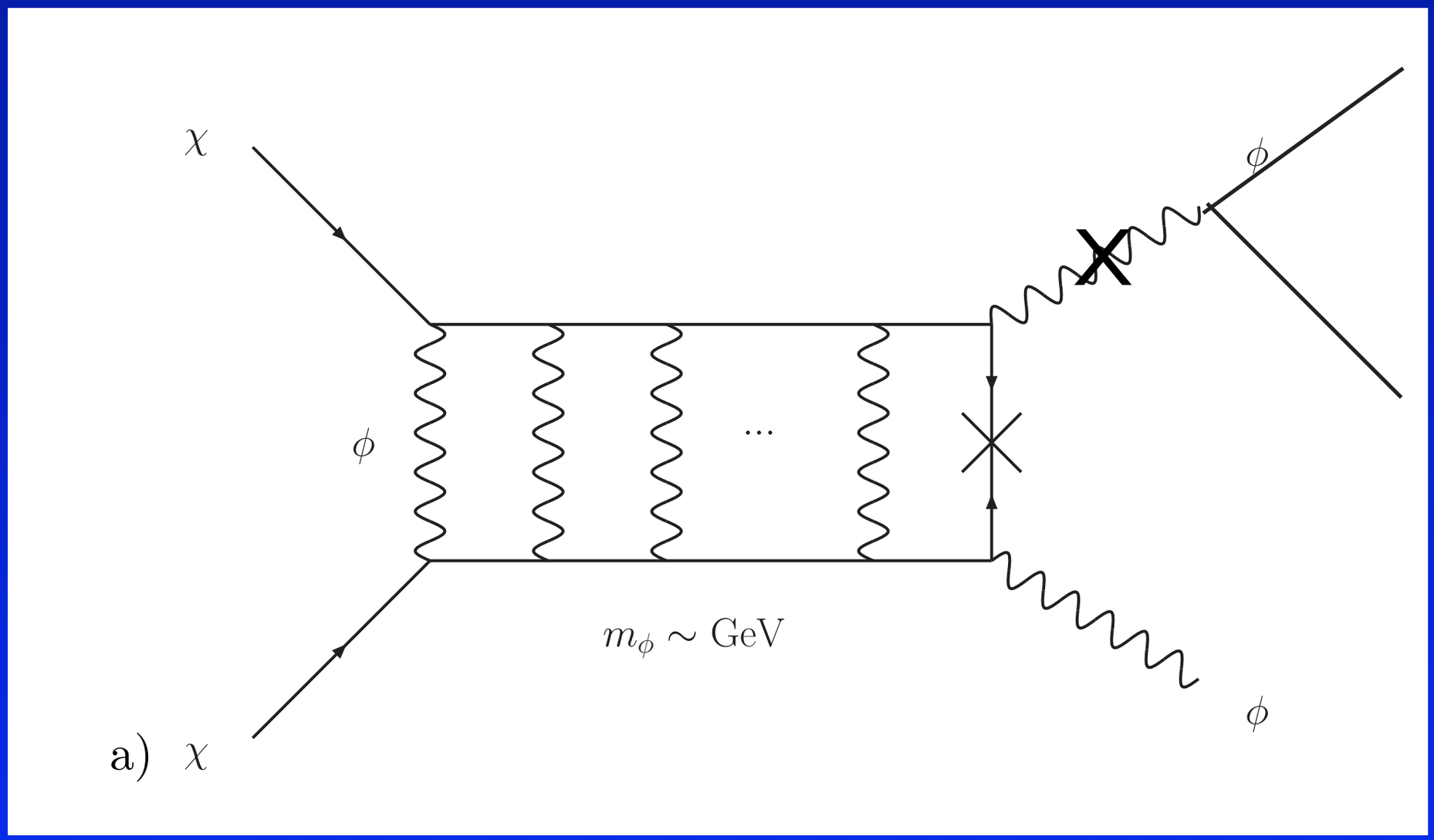
**Phys.Rev.Lett.92:031303,2004**.

# Dark Matter

- Gets its own force, e.g., $U(1)_{dark}$.
- U(1) mixes, e.g. with Z/gamma.

$$\mathcal{L} \supset \epsilon \phi^{\mu\nu} B_{\mu\nu}$$

Pospelov, et al. 0711.4866
Zurek 0811.4429
Morrissey, Poland, Zurek **JHEP 0907:050,2009**
**Cheung, et al. arXiv:0902.3246**
**Katz & Sundrum 0902.3271**
**Feng et al. 0905.3039**

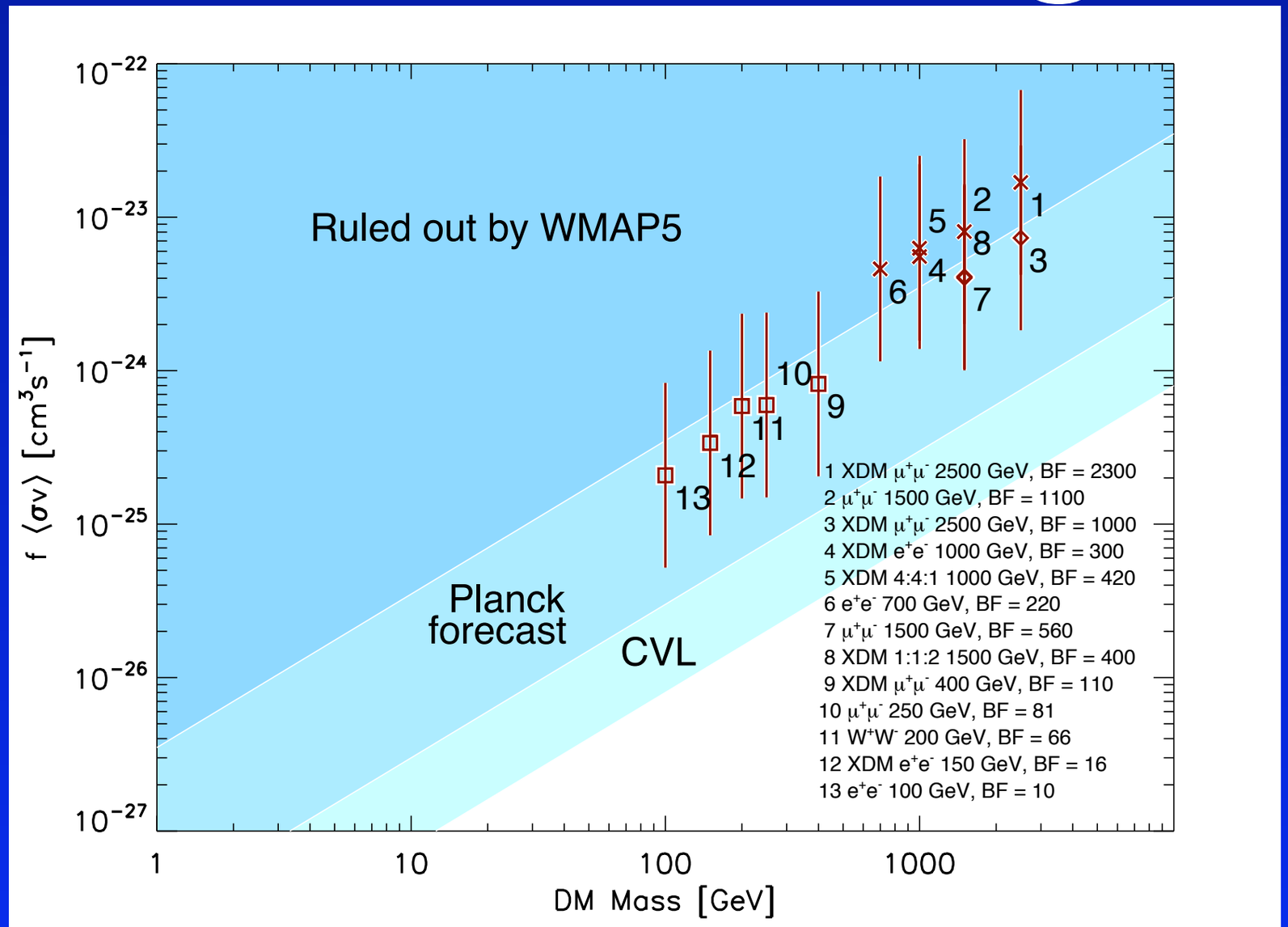



e/mu/pi

e/mu/pi

# CMB Constraints/Signal

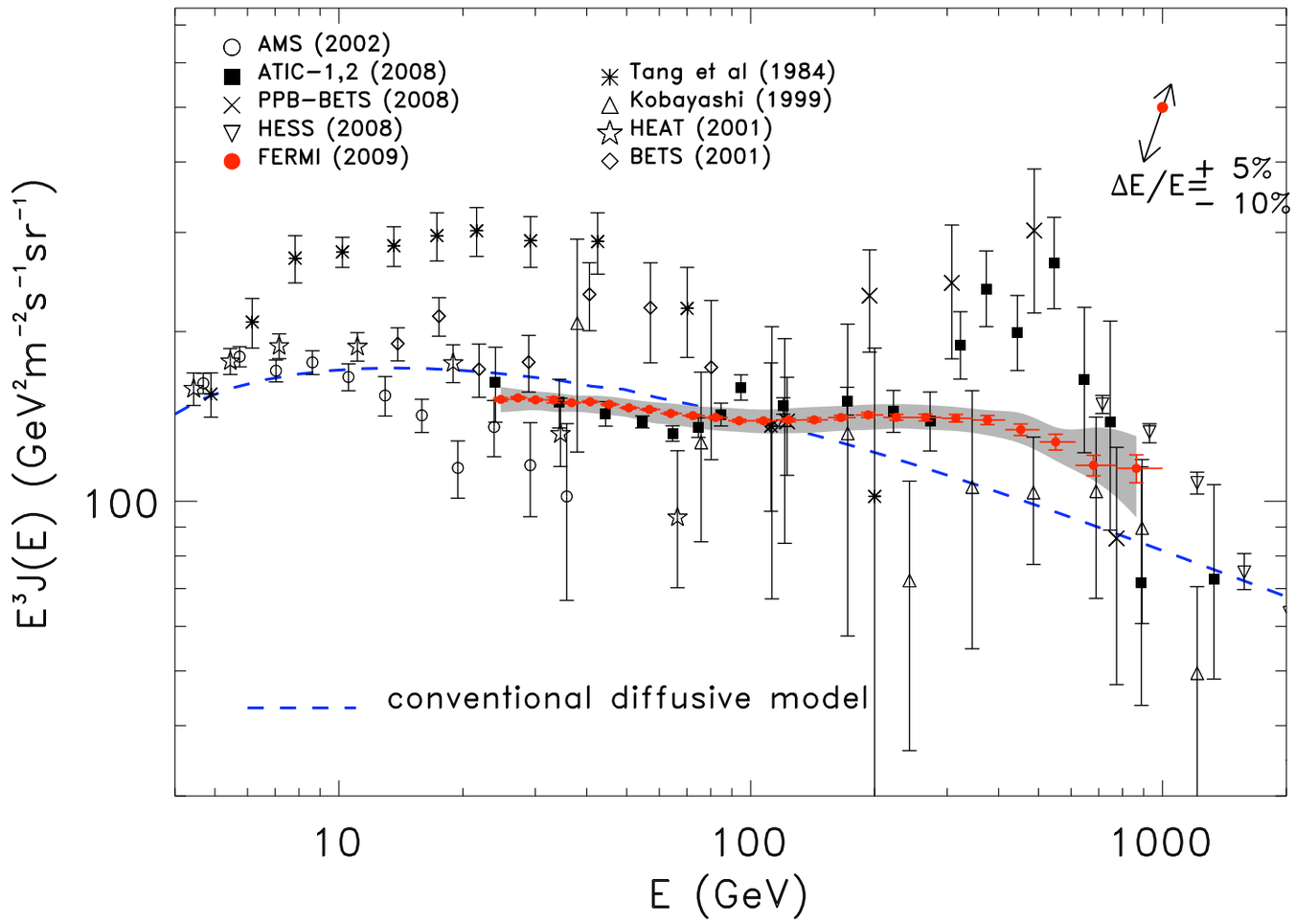
Slatyer, et al .arXiv:0906.119




Padamahaban and Finkbeiner 2005

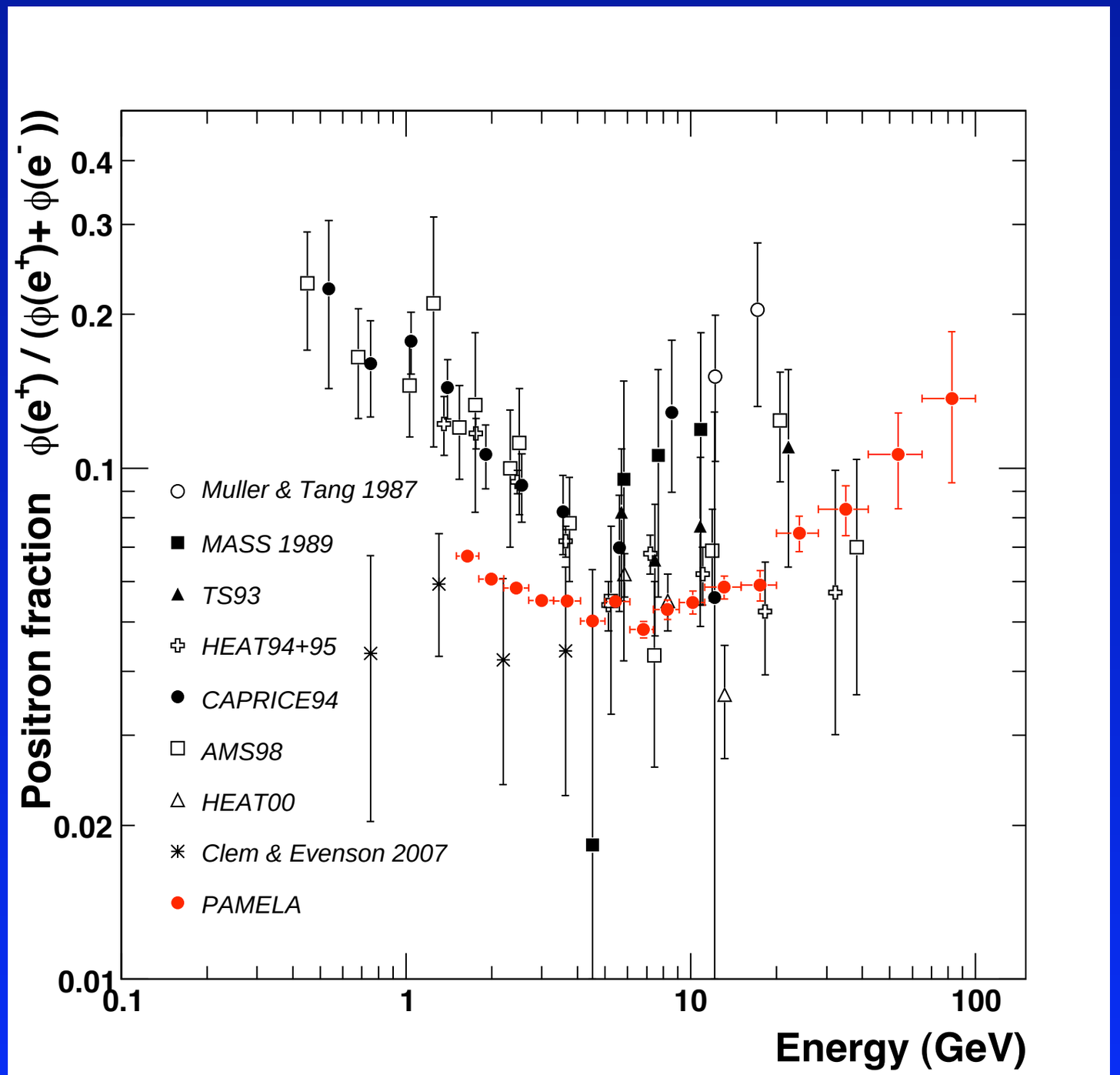
**Galli, et al., Phys.Rev.D80:023505,2009.**

# FERMI data for $e^- + e^+$




Fermi/LAT Collaboration Phys.Rev.Lett. 102:181101,2009

# PAMELA

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MCTP

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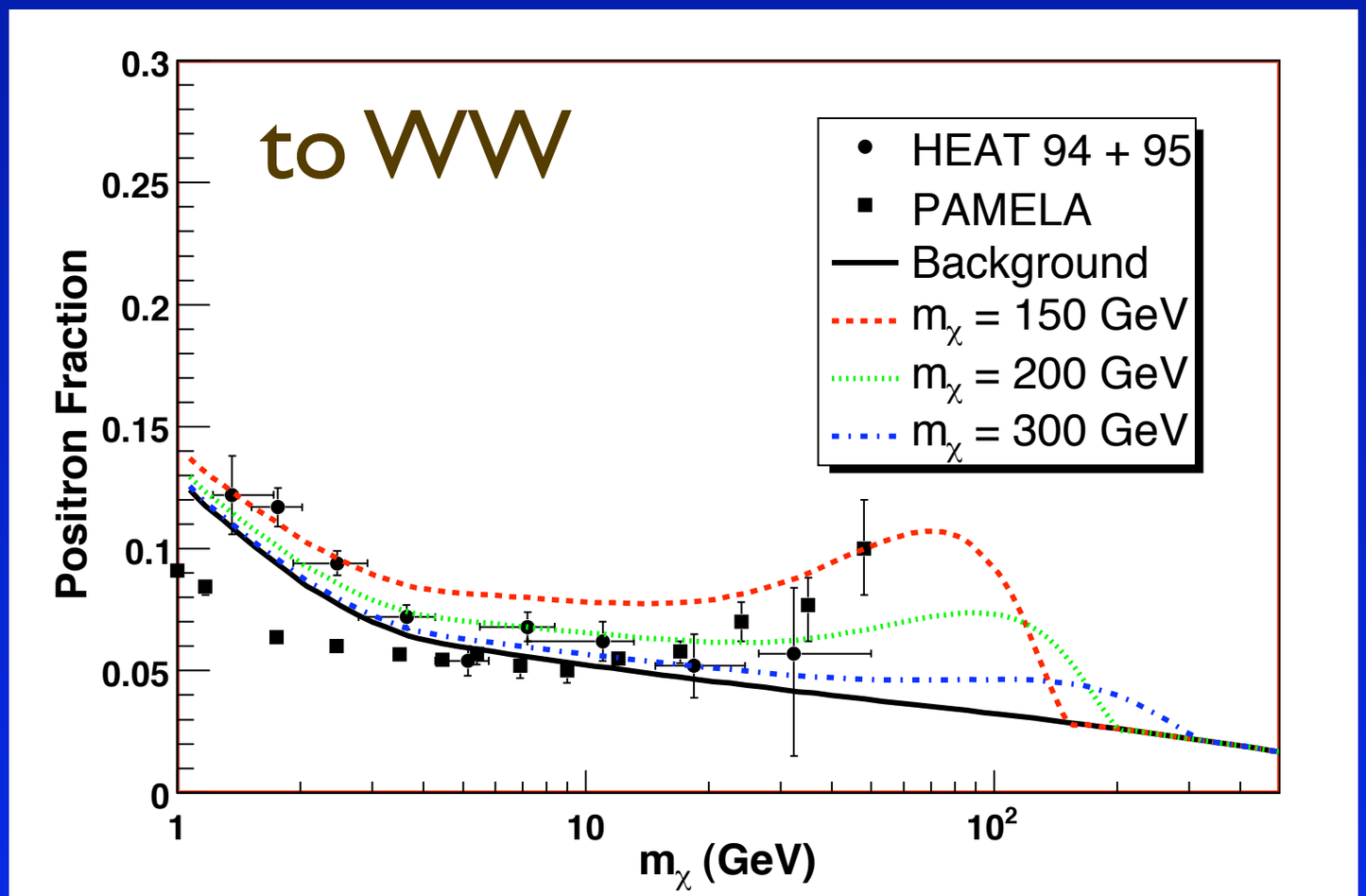
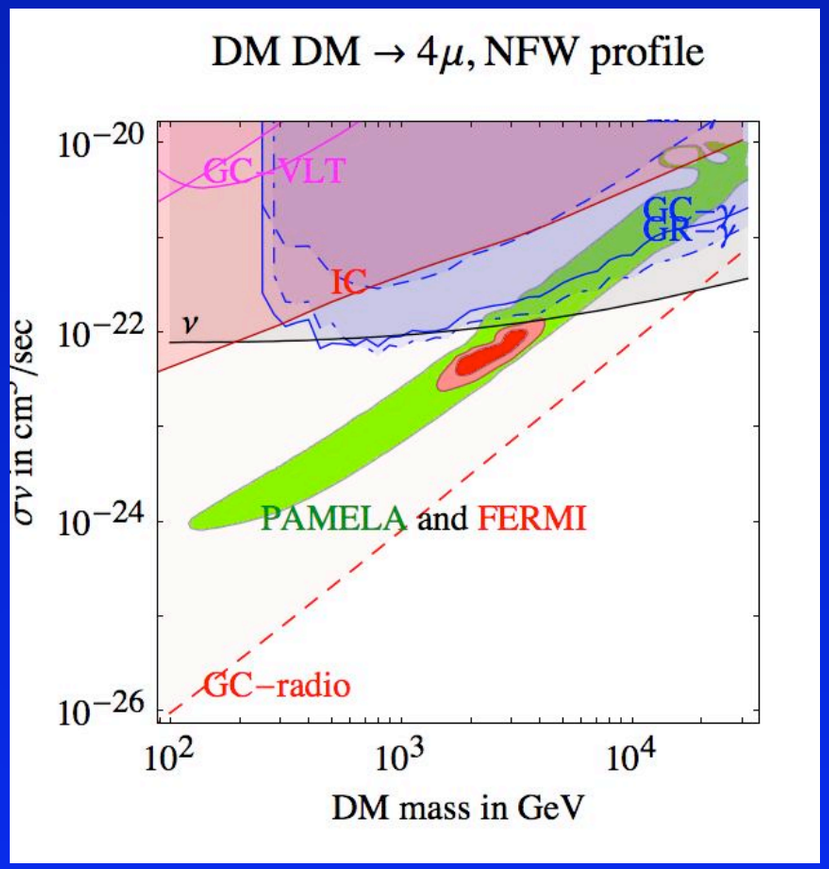
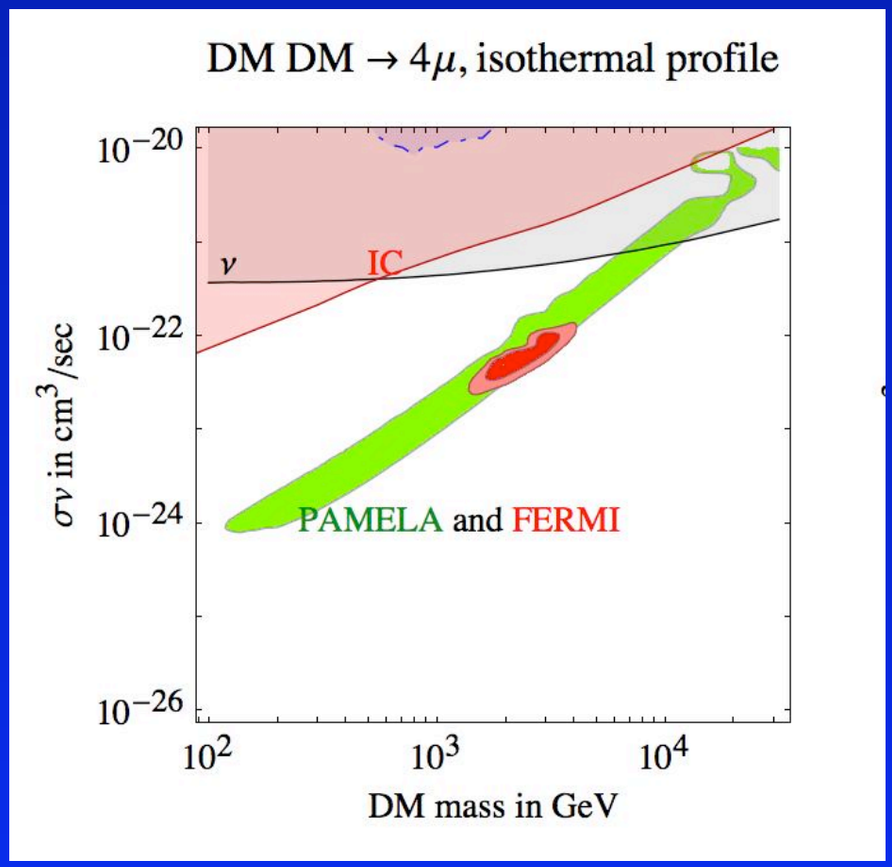

to WW
HEAT 94 + 95
PAMELA
Background
$m_\chi$ = 150 GeV
$m_\chi$ = 200 GeV
$m_\chi$ = 300 GeV
Positron Fraction
0.3
0.25
0.2
0.15
0.1
0.05
0
1
10
$10^2$
$m_\chi$ (GeV)

# Choices

- Assuming both PAMELA/FERMI correct
  - Surprising Astrophysics (two pieces?)
  - Surprising Heavy DM
  - DM + Astrophysics

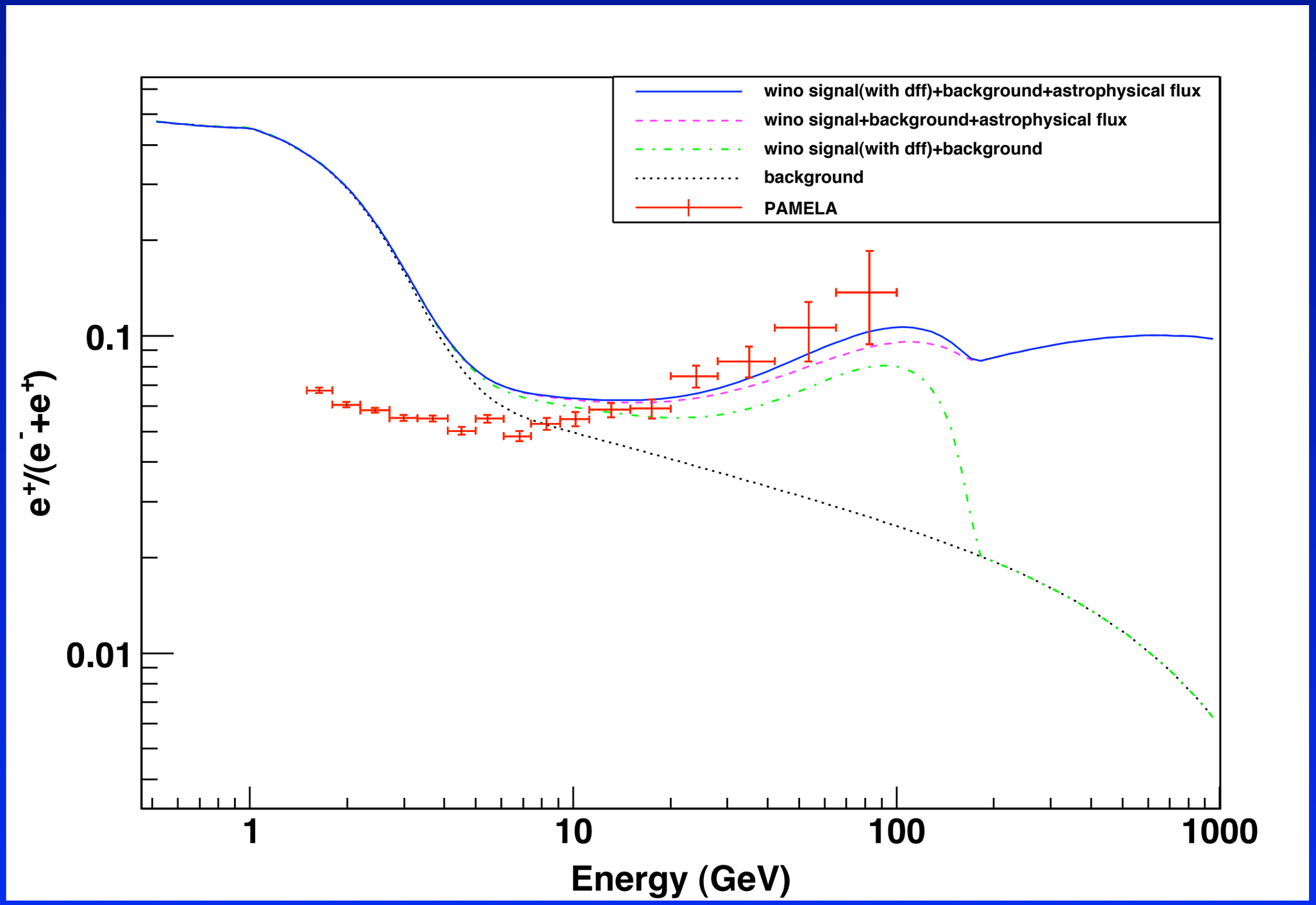
# Impact of Fermi




Meade, Papucci, Strumia, Volansky 0905.0480

# Non-Thermal Winos+Pulsars




## Kane, Lu, Watson

earlier related work: Grajek, Kane, Phalen, AP, Watson

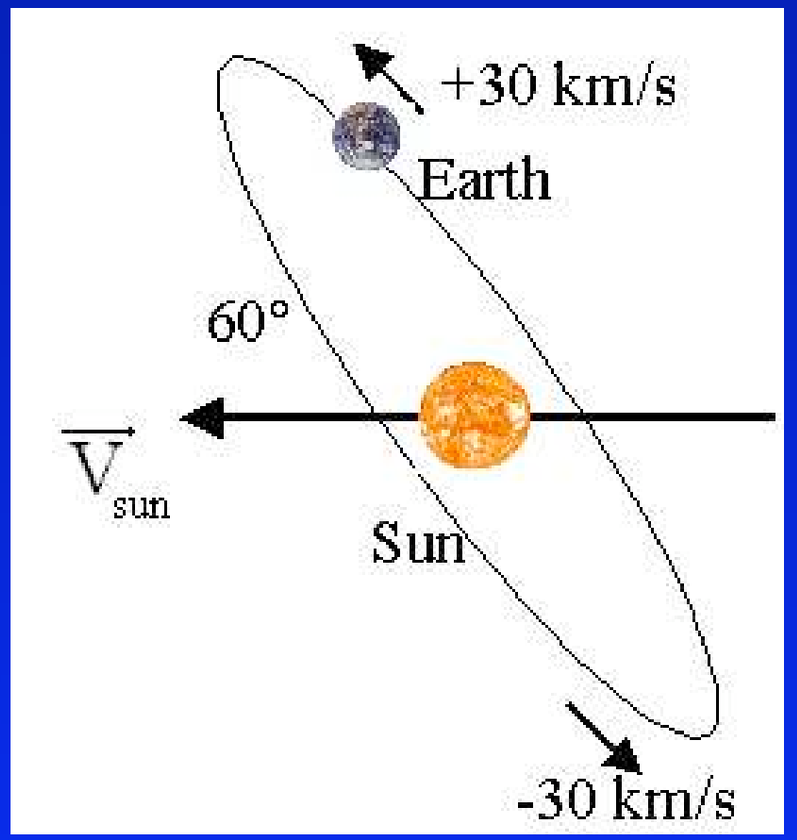
# Comments

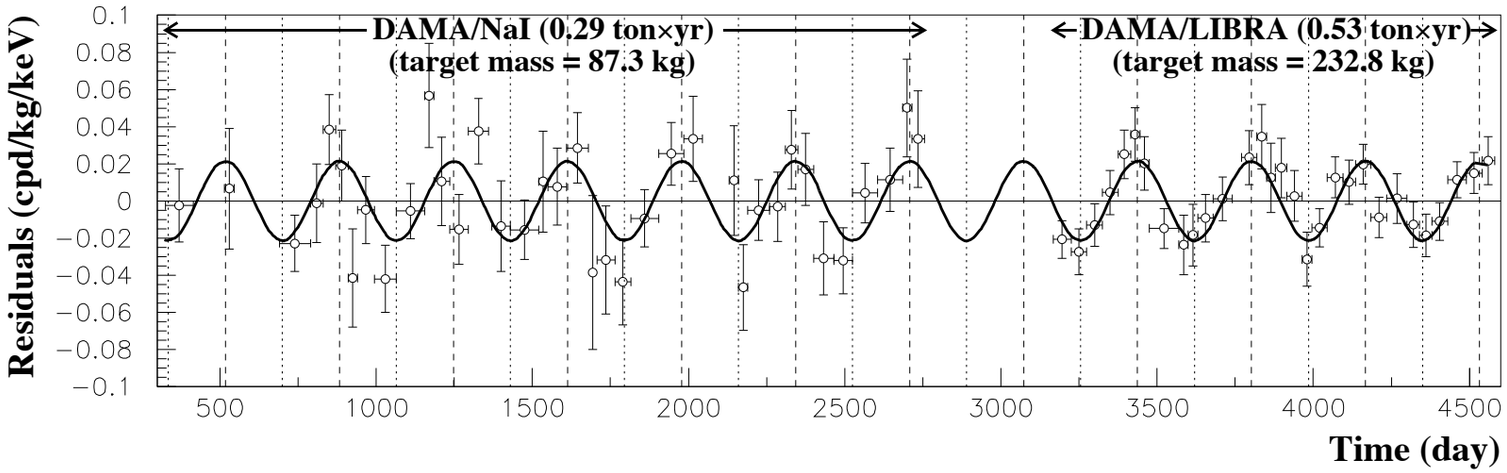
- If what we are seeing is not Dark Matter, then finding the DM in electrons/positrons may be impossible
- Finding it in Gammas will be challening

# Direct Detection?

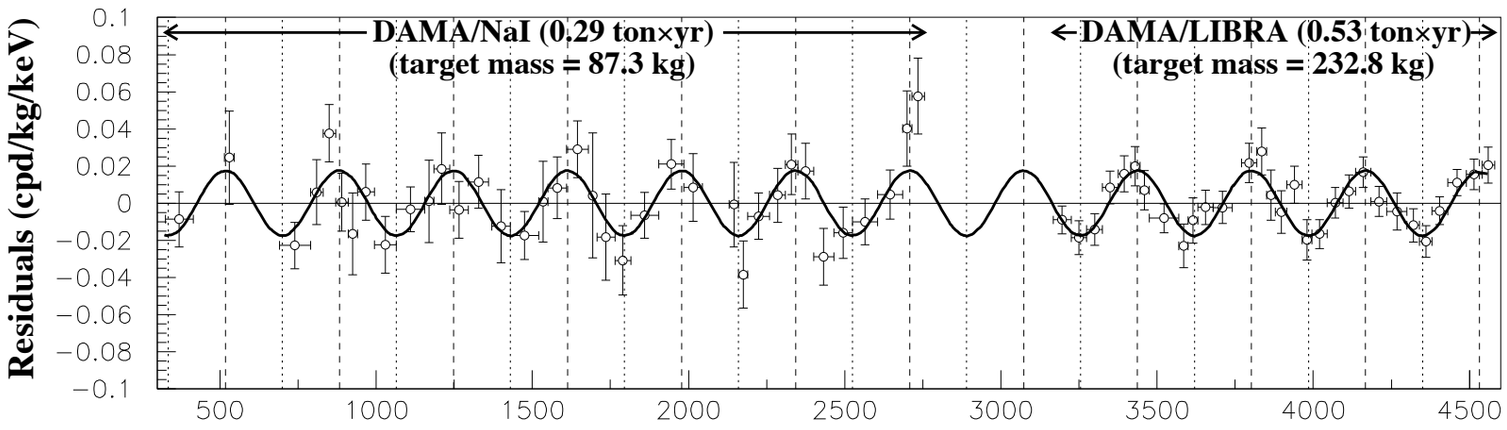
# Modulation Signature

- Modulation (Drukier, et al., Freese, et al.)

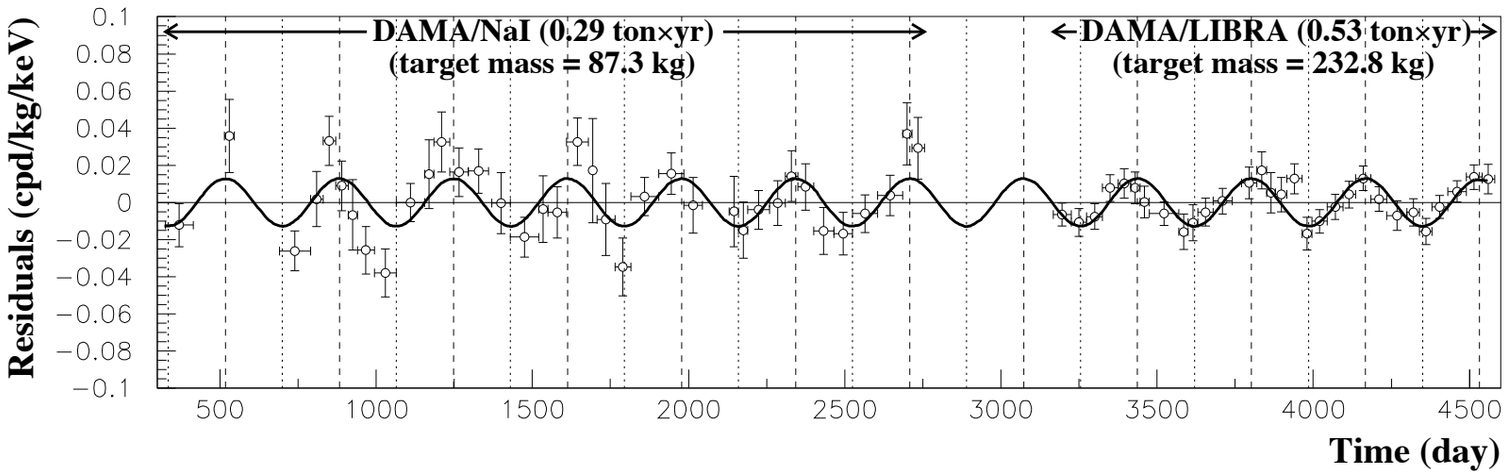





2-5 keV




2-6 keV




# DAMA/LIBRA from 0804.2741

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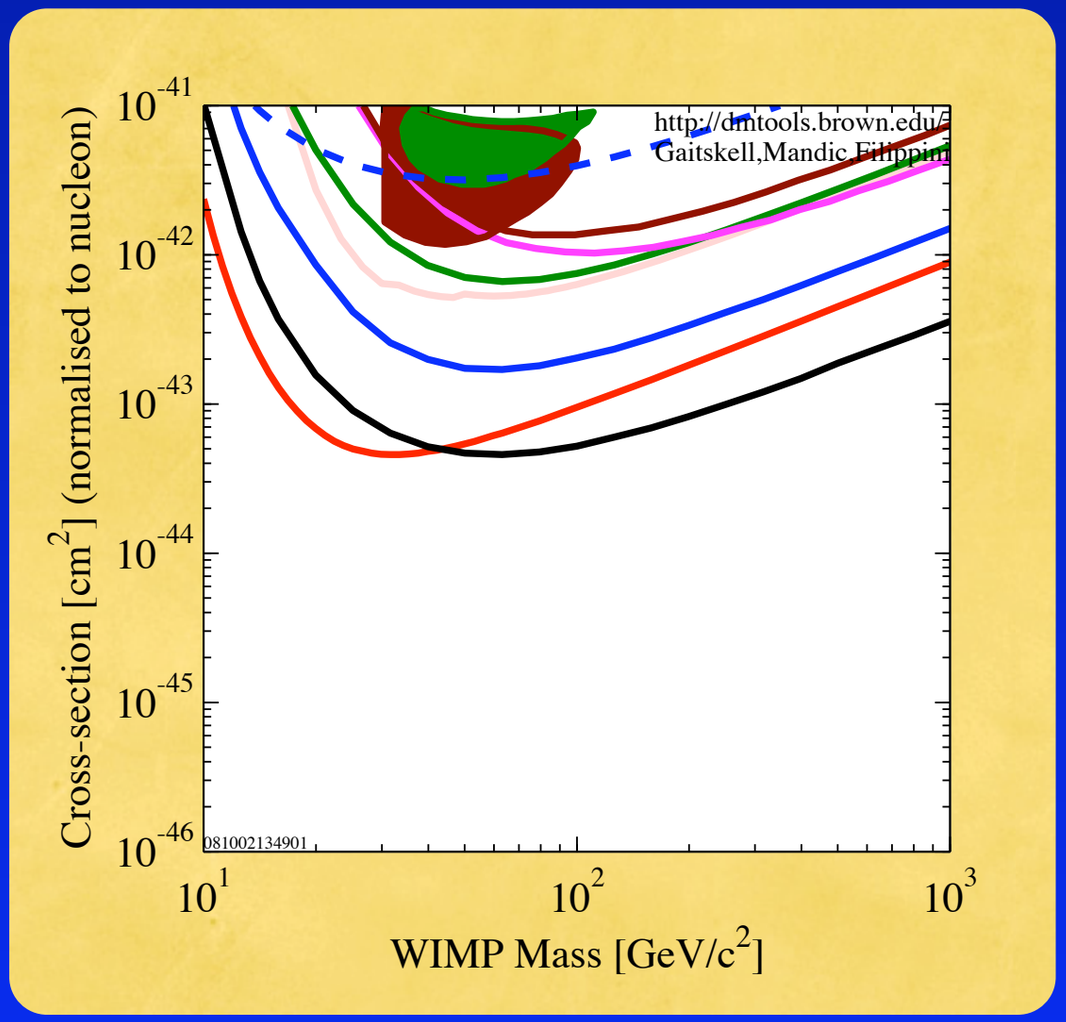
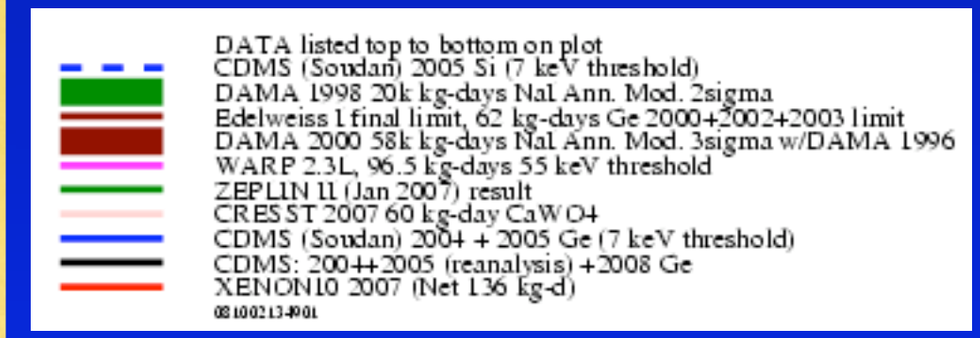
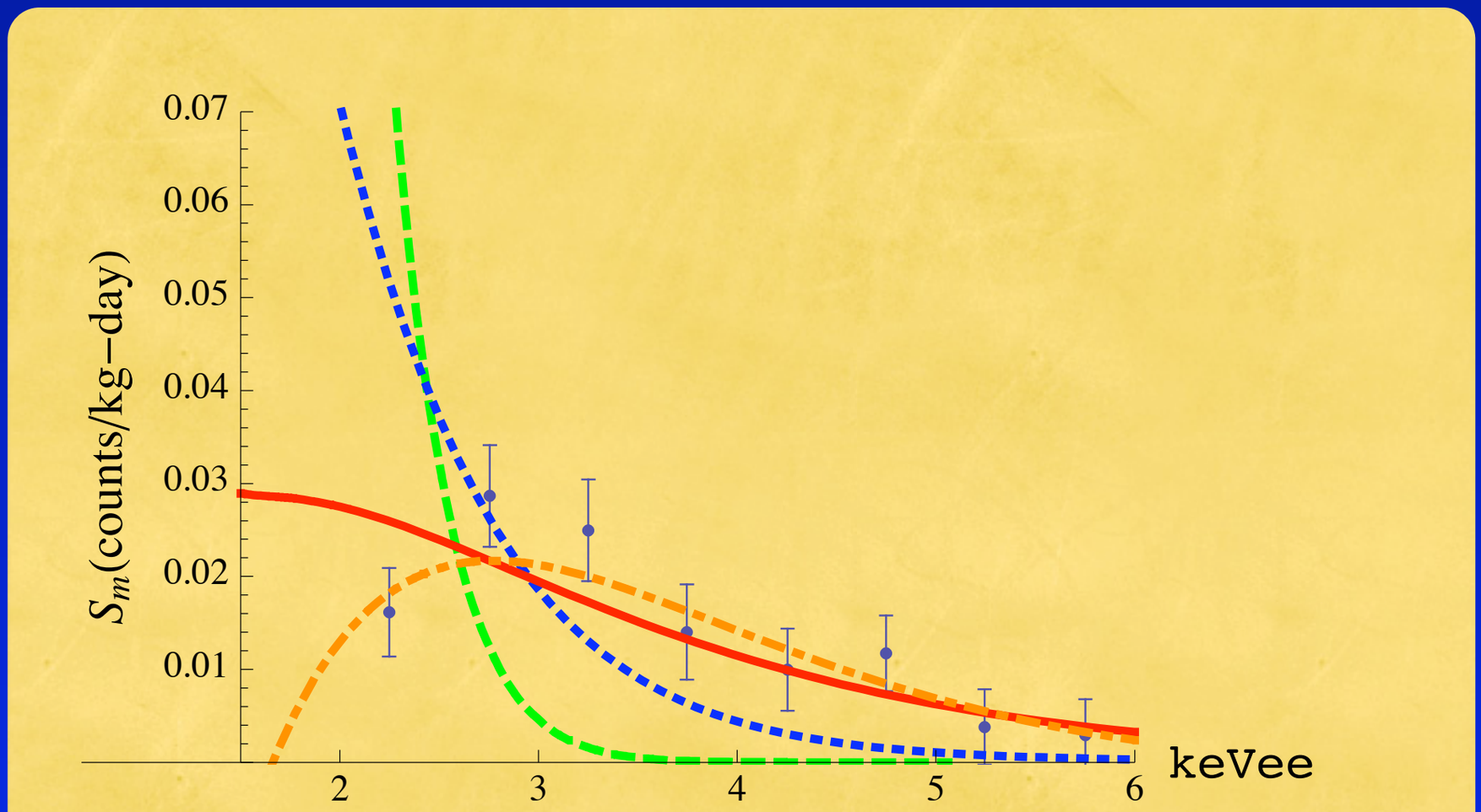
# DAMA vs. Others



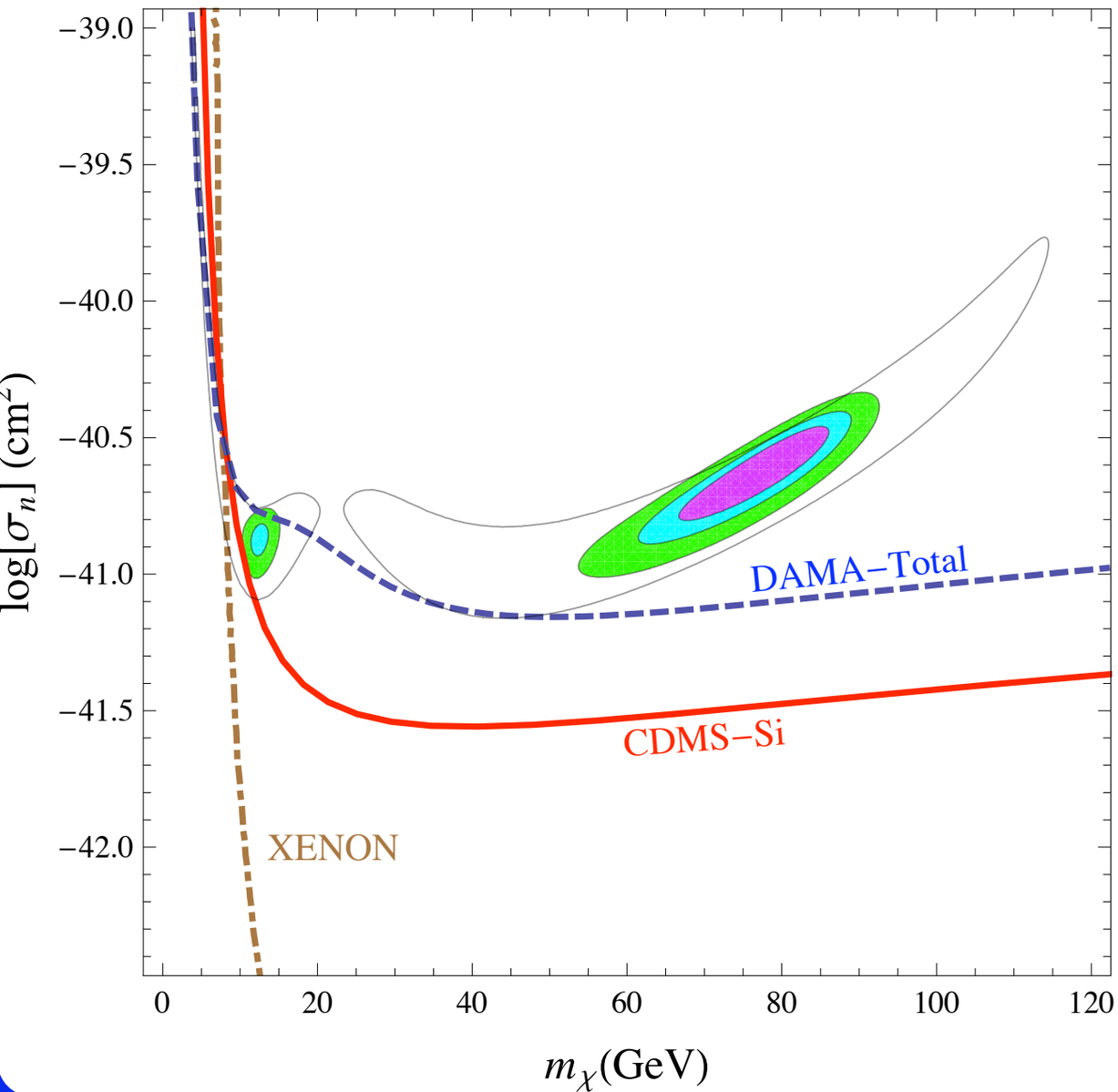



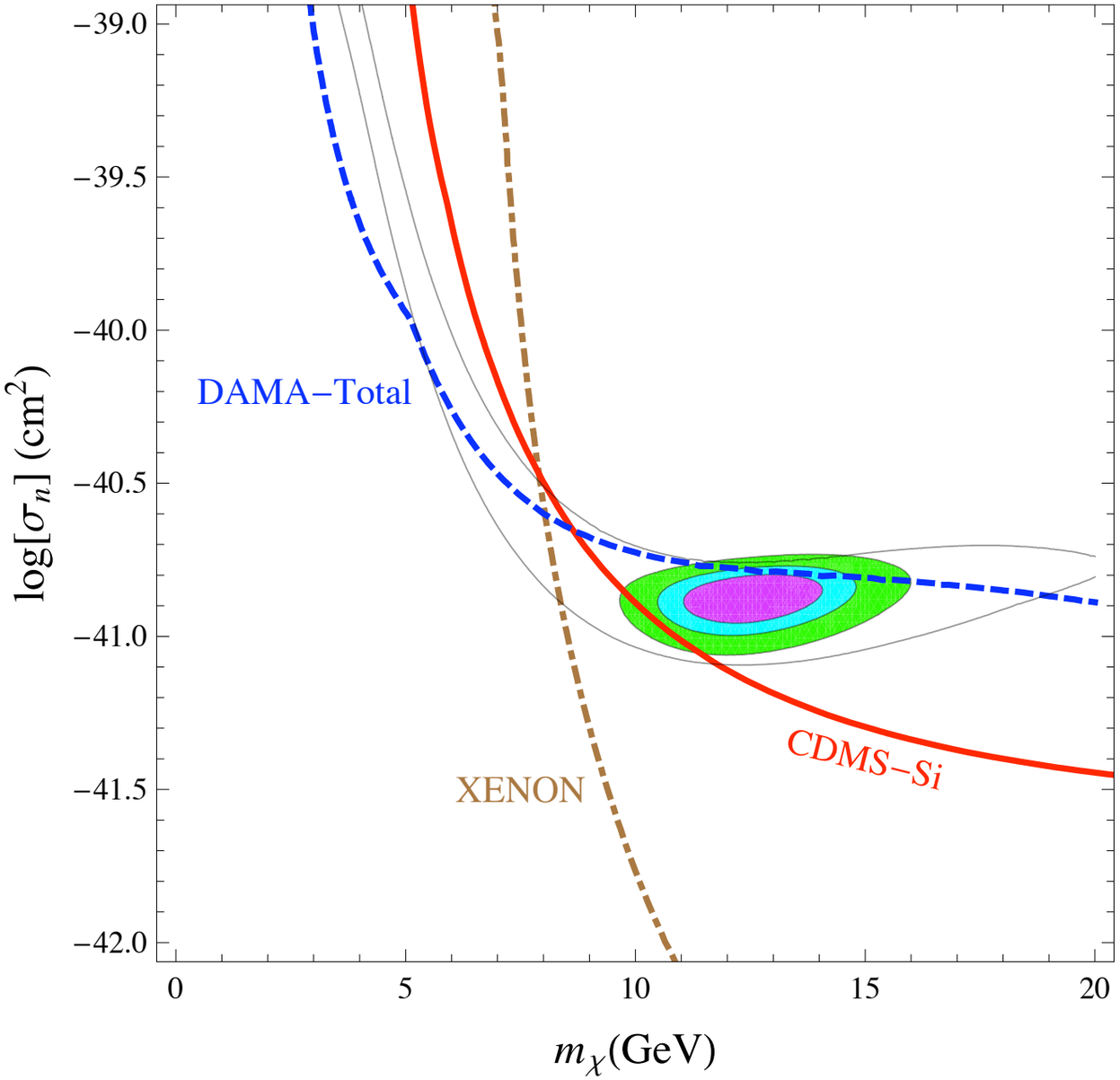
# Energy Spectra




S. Chang, AP, N. Weiner

# Spin Independent




S. Chang, AP, N. Weiner.
See also Freese, Gelmini, Gondolo, Savage;
Zurek, Petriello

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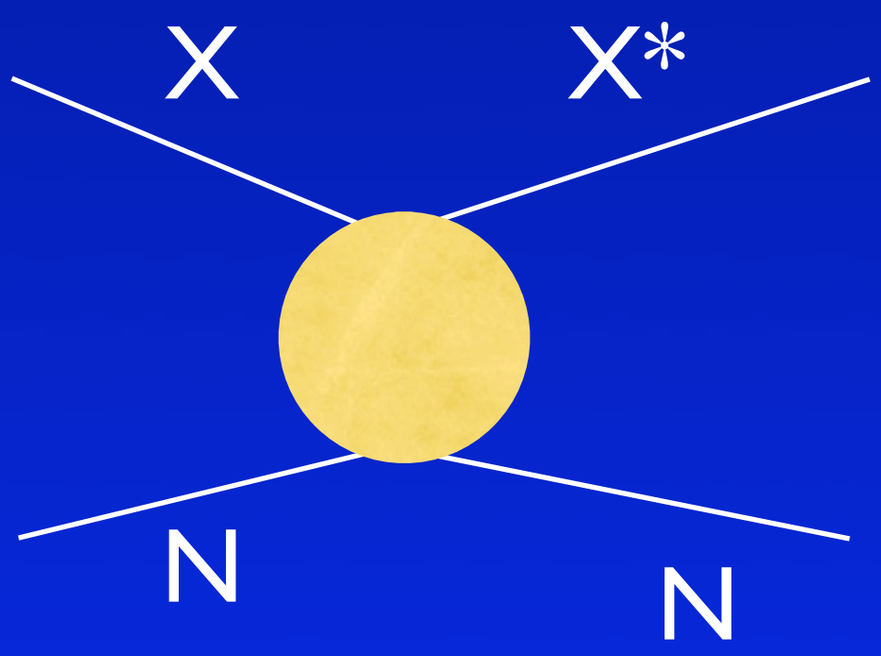
# Spin Dependent

- Savage, Gondolo, Gelmini and Freese (arXiv:0808.3607)
- Further constrainted by COUPP and PICASSO
- Also constrained from Capture on Sun

# Inelastic Dark Matter



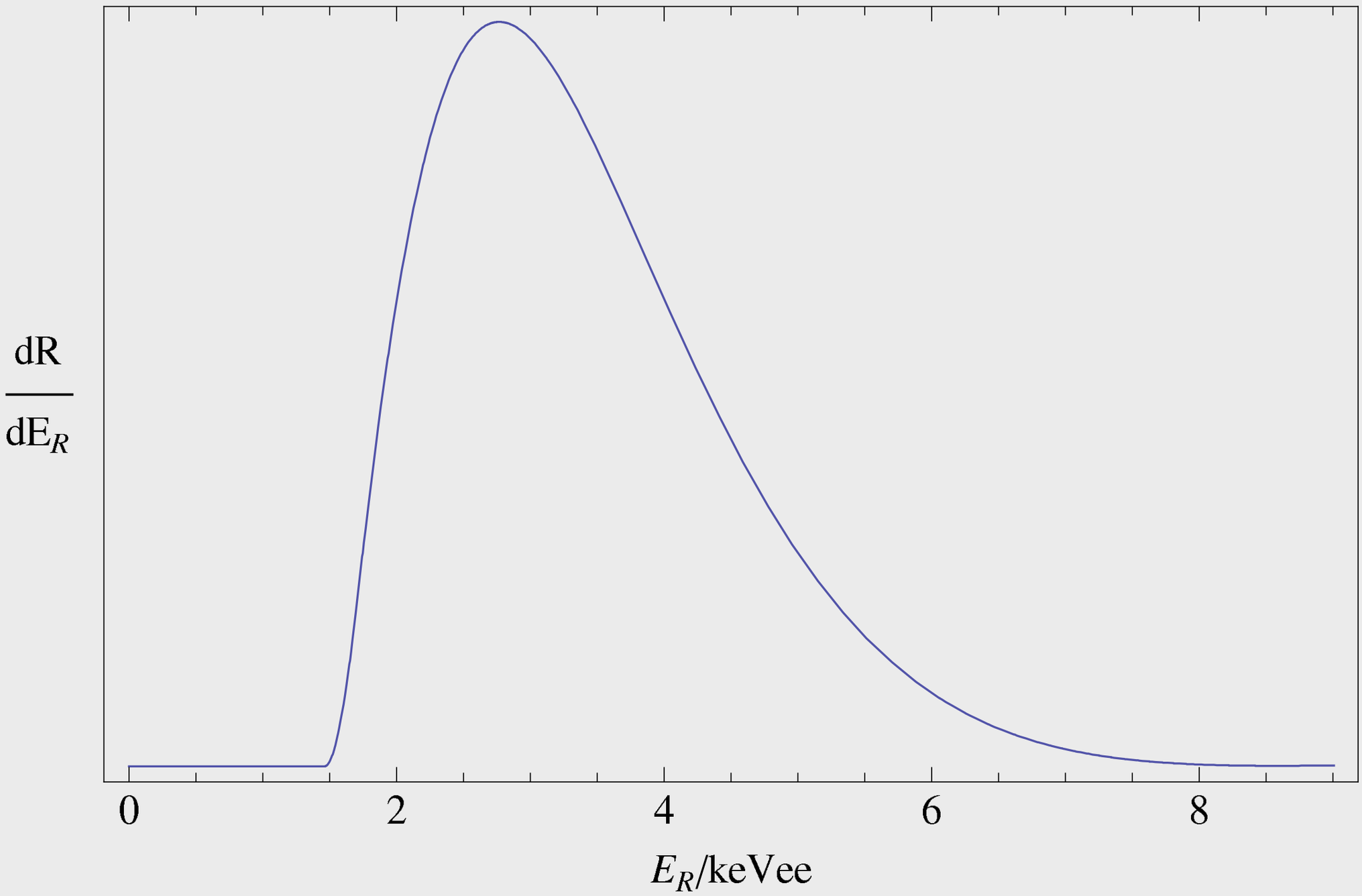

$$M_{X^*} - M_X = \delta \sim 100\,keV$$

Weiner/Tucker-Smith

**Phys.Rev.D64:043502,2001**.

# Many implementations.

- Sneutrinos (Weiner/Tucker-Smith)
- Slightly Split Dirac Fermion
- Inert Doublet (0907.0430v1, Ariana, Ling, Tytgat)
- Non-Abelian Multiplet (Arkani-Hamed, Weiner, Finkbeiner, Slatyer)




Chang, Kribs, Tucker-Smith, Weiner

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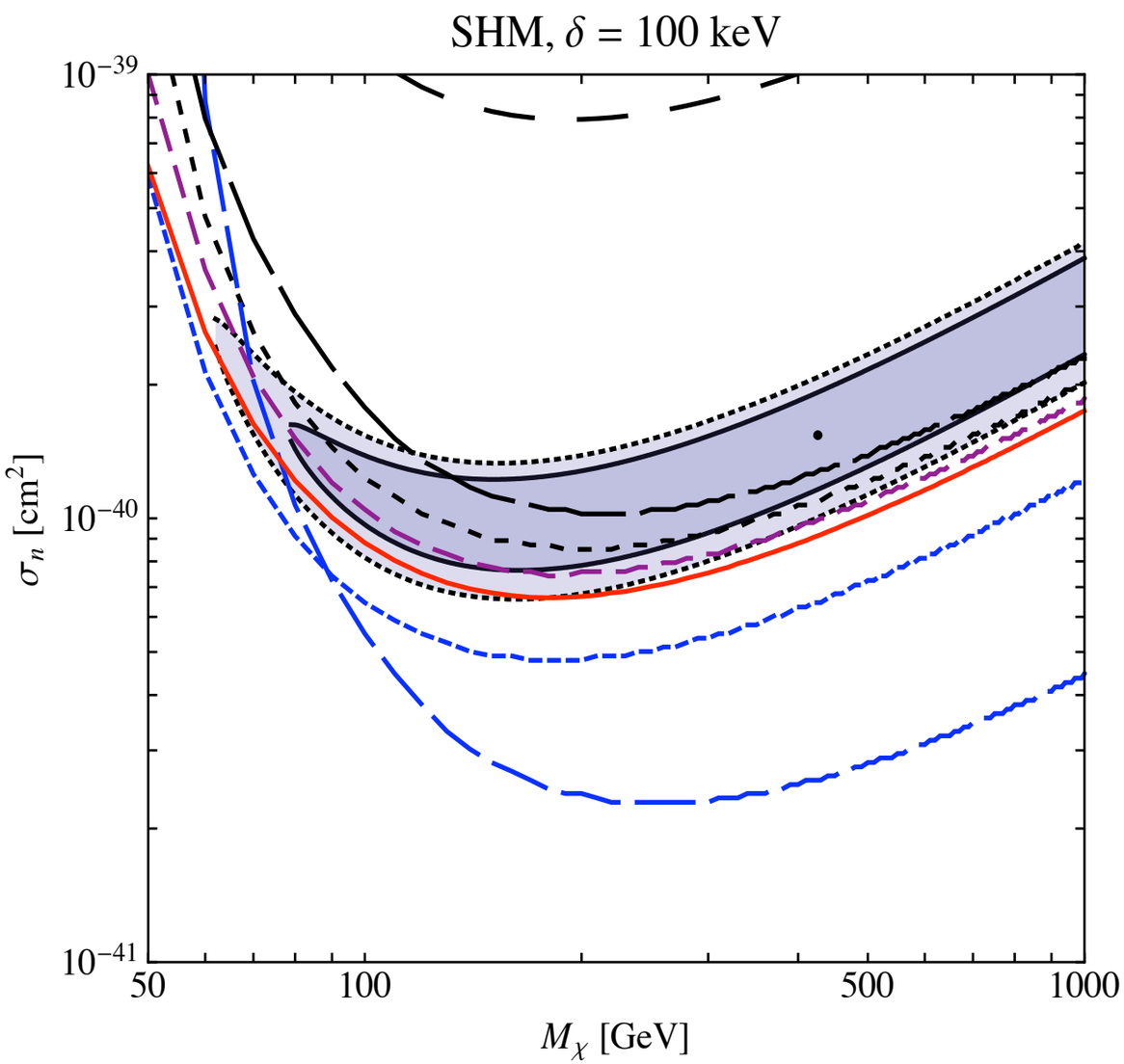
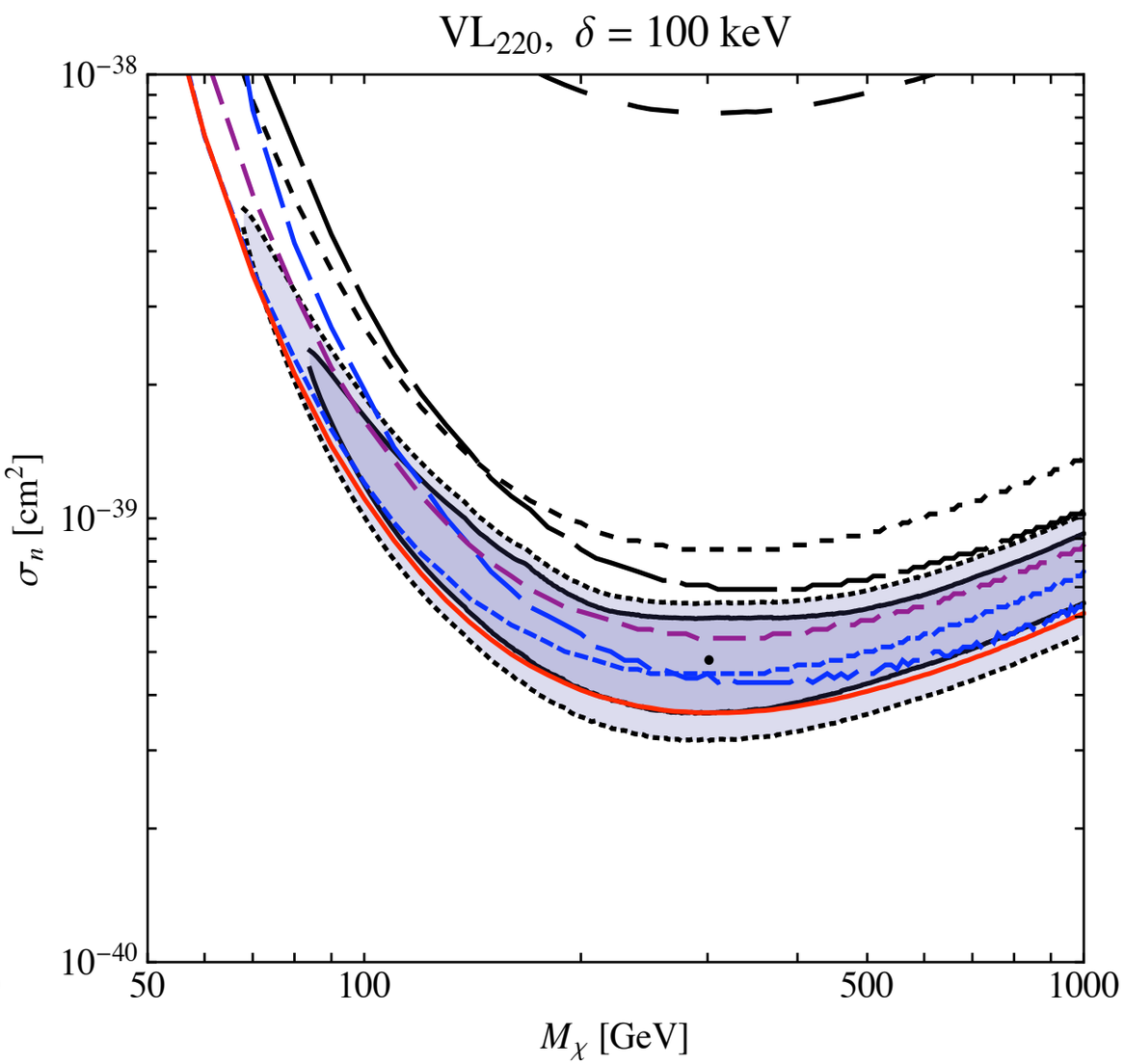
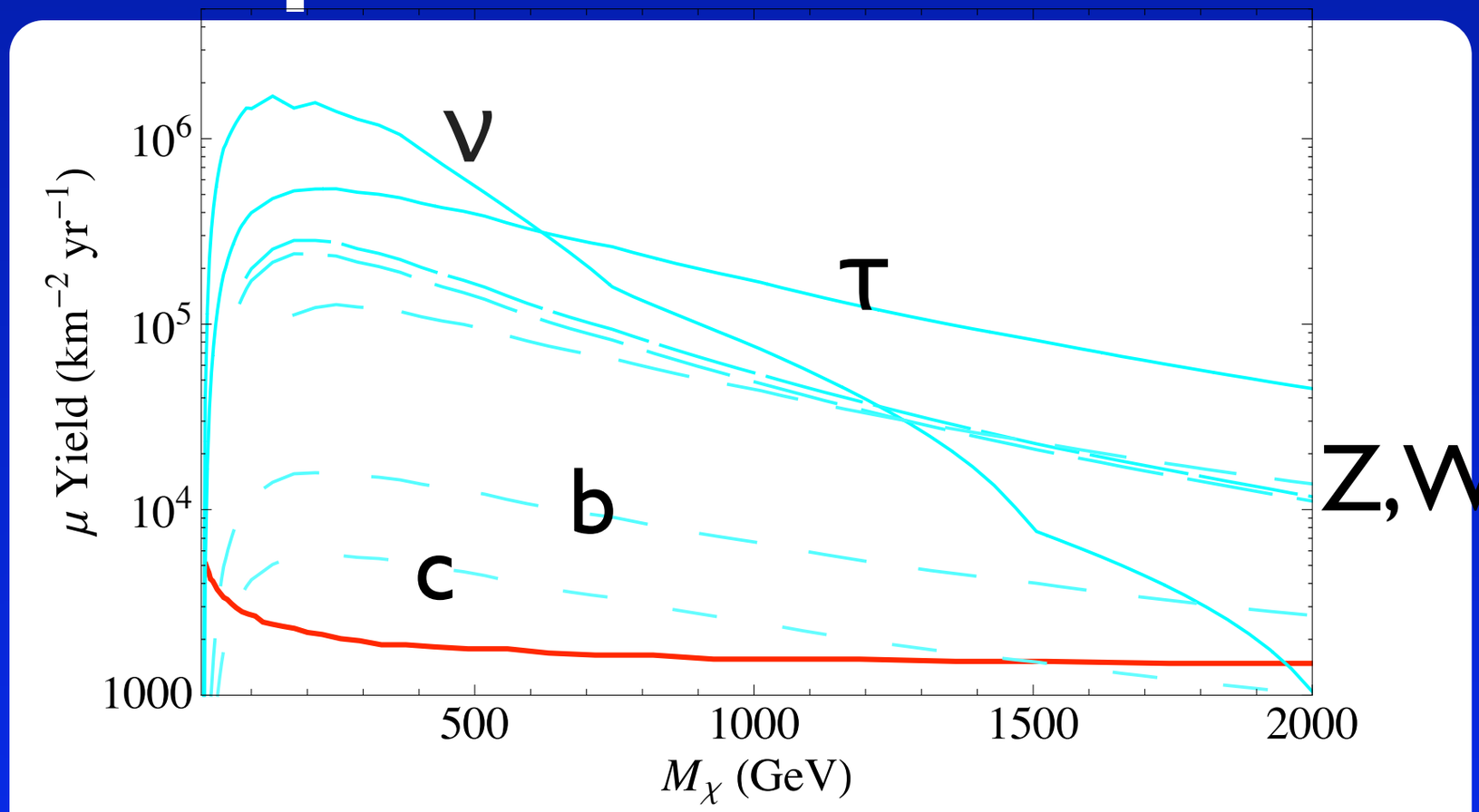


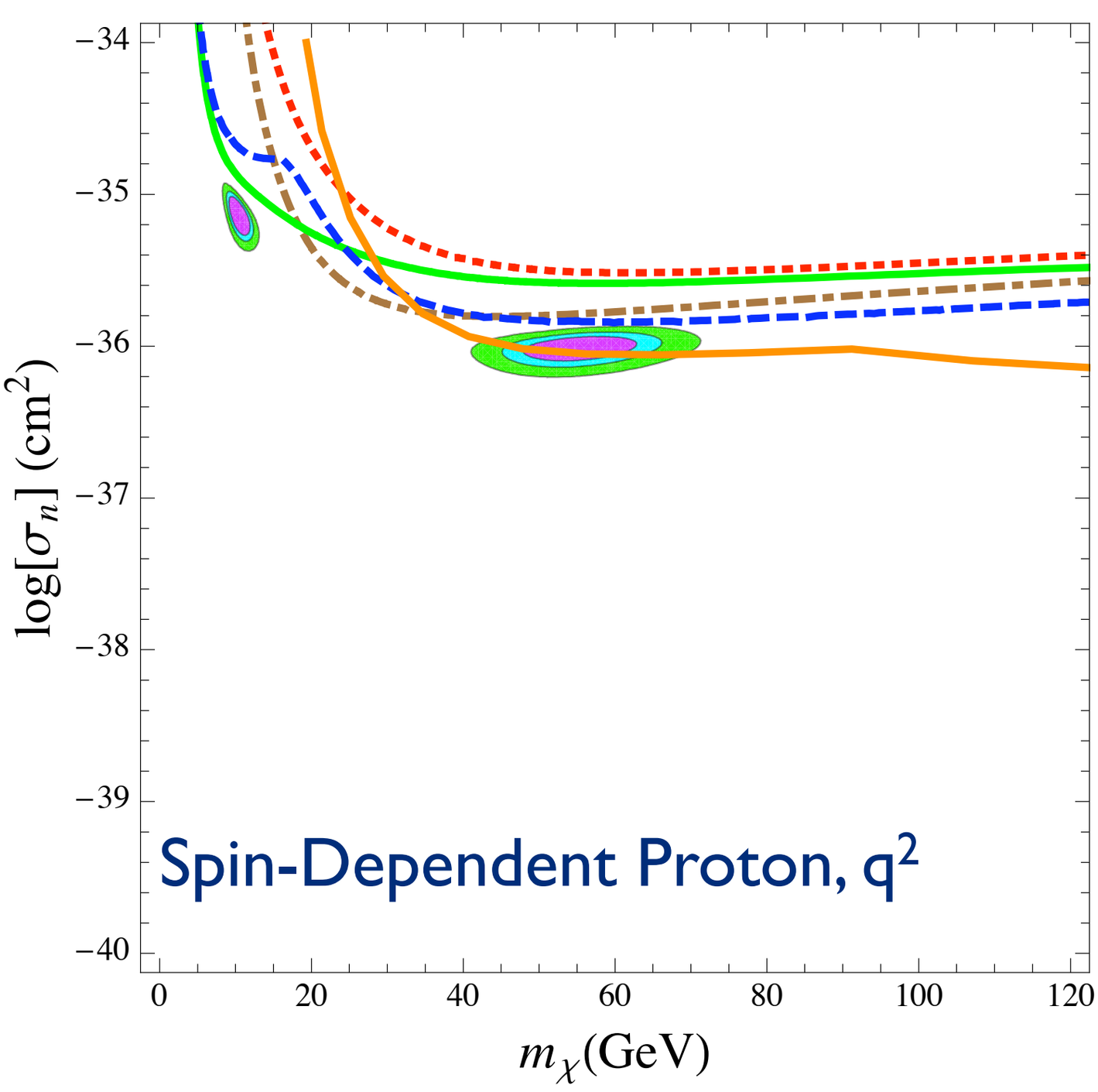

**John March-Russell, et al., JHEP 0905:071,2009**

See also Hoberg, Winkler, arXiv:0907.3940v1

# Constrained by Capture on Sun




- S. Nussinov, L.T. Wang, I. Yavin, **arXiv:0905.1333**
- **See also, Menon, Morris, AP, Weiner arXiv:0905.1847**




Chang, Pierce, Weiner (in preparation)

# General Lesson

- Useful to go beyond the simplest candidates (and recoild spectra). Don't want to miss a signal.

# Conclusions

- Dark Matter Experiments have presented some tantalizing clues
- Dark Matter that could explain current data are not your father's WIMP. A rich Dark Sector?
- Data from FERMI (dwarf spheroidals, Inverse Compton...) , Direct Detection, and Colliders will be crucial in building an understanding.