Discovering Physics Beyond the Standard Model (again)

Saturday, Aug 15, 2009

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How we learn physics

- “You learn physics like this - first you see something and its very very confusing and you don’t understand anything. And then, sometime later, you see it again and you say ‘oh yes, yes, i’ve seen all this before!’ “

  John Bagger

Nuclear Physics B347 (1990) 1–11
North-Holland

NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

Howard GEORGI and Michael LUKE

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 17 April 1990

We identify and exemplify a new mechanism which leads to a nonzero magnetic moment for a neutrino, while suppressing the neutrino's mass. The mechanism requires that the contribution to the neutrino mass of the new particles that are responsible for its magnetic moment is approximately canceled by a contribution from neutral particles, related by a custodial SU(2) symmetry.

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly intriguing [3]. It is, of course, possible that this is an astrophysical problem rather than a particle physics problem. But that would require a synchronization of cycles of the interior of the sun with those of the convective layer, both in frequency and in *phase*. Thus it seems particularly interesting that there may be a particle physics explanation of this effect [4], involving a magnetic moment of the electron neutrino of the order of $10^{-11}\mu_B$.

How we discover physics beyond the standard

- First you see a result and insist that the data and/or assumptions are completely unreliable and should be ignored
- When it all works out, you say, "Yes, yes, we've known about this for some time"
  - Neutrino masses
  - Large mixing angles
  - Cosmological constant

What physics beyond the standard model?

Theory driven
Hierarchy problem:
SUSY, technicolor, RS, ADD, little Higgs

=> scale driven
i.e., we know there's a weak scale

Anomaly driven
solar neutrino problem
atmospheric neutrino anomaly
Cosmic acceleration
Galactic rotation curves
17 keV neutrino
LSND
PVLAS

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standard model physics

The next discovery

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The next discovery

- I really believe that the most likely thing we will discovery next is dark matter
  - Caveats:
    - Maybe not
    - Maybe not all
    - Maybe (probably) not what we were expecting

Era of data

- Cosmics: PAMELA, Fermi, ATIC, HESS, AMS, ACTs, WMAP, Planck...
- Direct: CDMS, DMTPC, XENON, LUX, CRESST, COUPP, PICASSO, KIMS...
- Production: LHC/Tevatron, Fixed Target, Beam dump

Most important thing about dark matter

No one knows anything about dark matter!*

*Except for the many things we know about dark matter

DM properties

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- None (who needs DM?)

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- Gas/brown dwarfs

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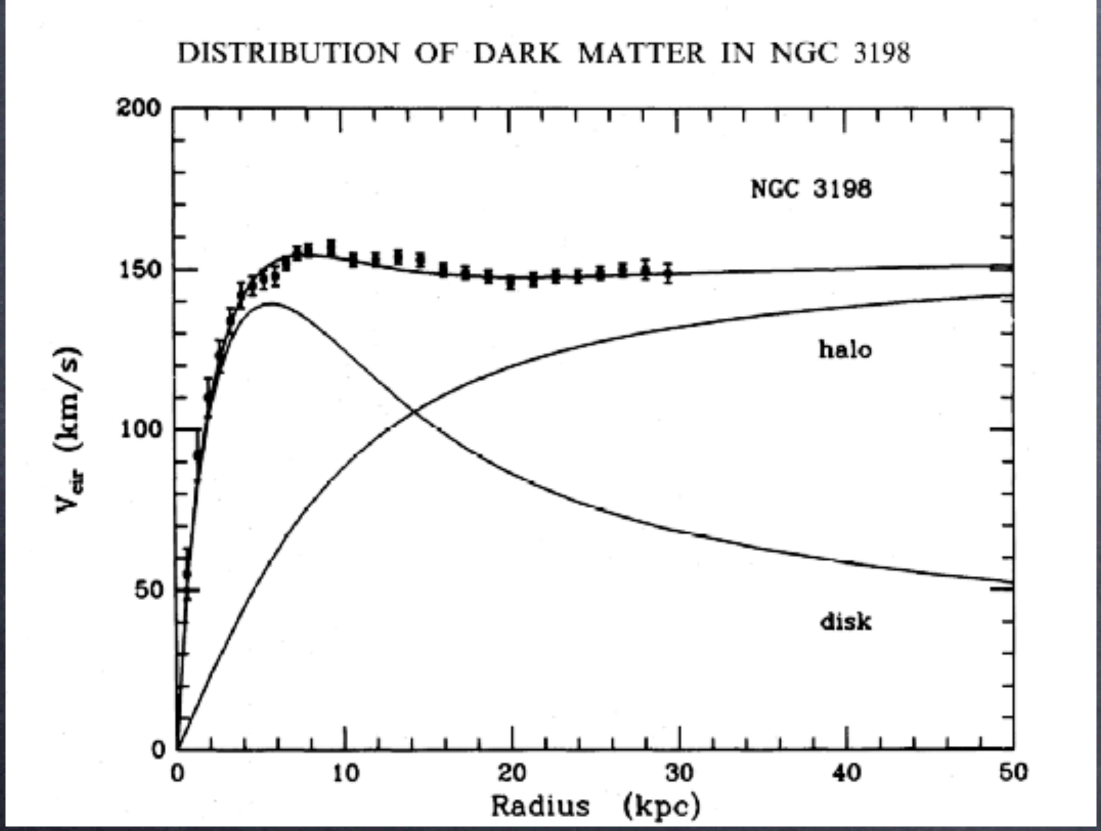
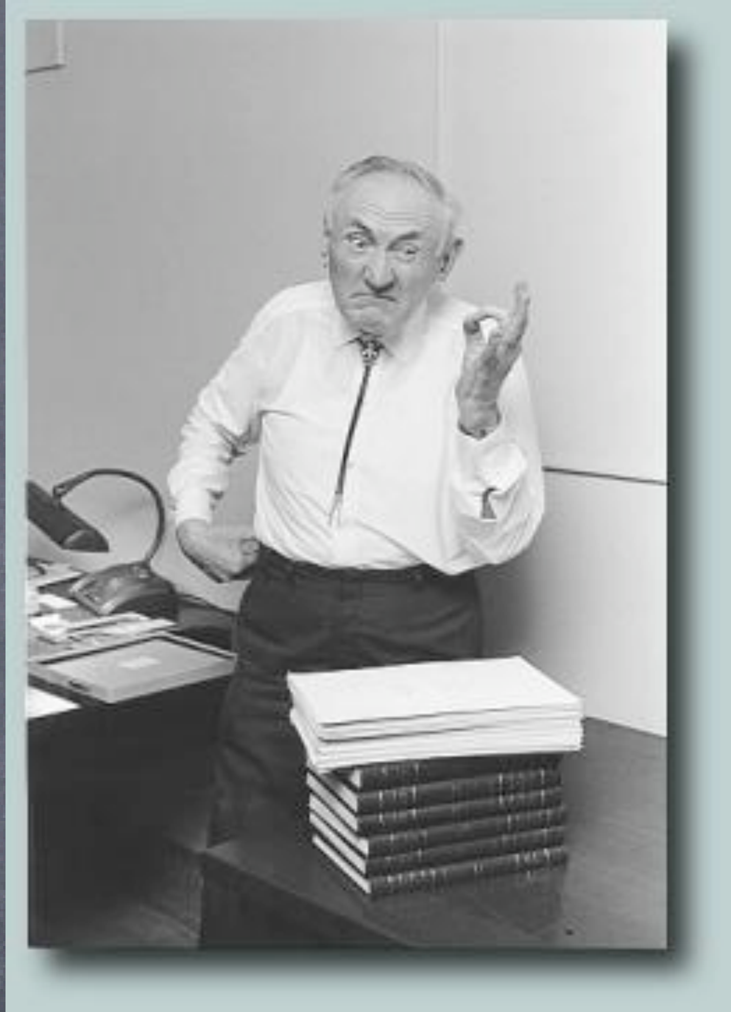
- neutralinos
- ...?

Evidence for DM

- Zwicky measuring galaxies in clusters
- Rubin (and previous)





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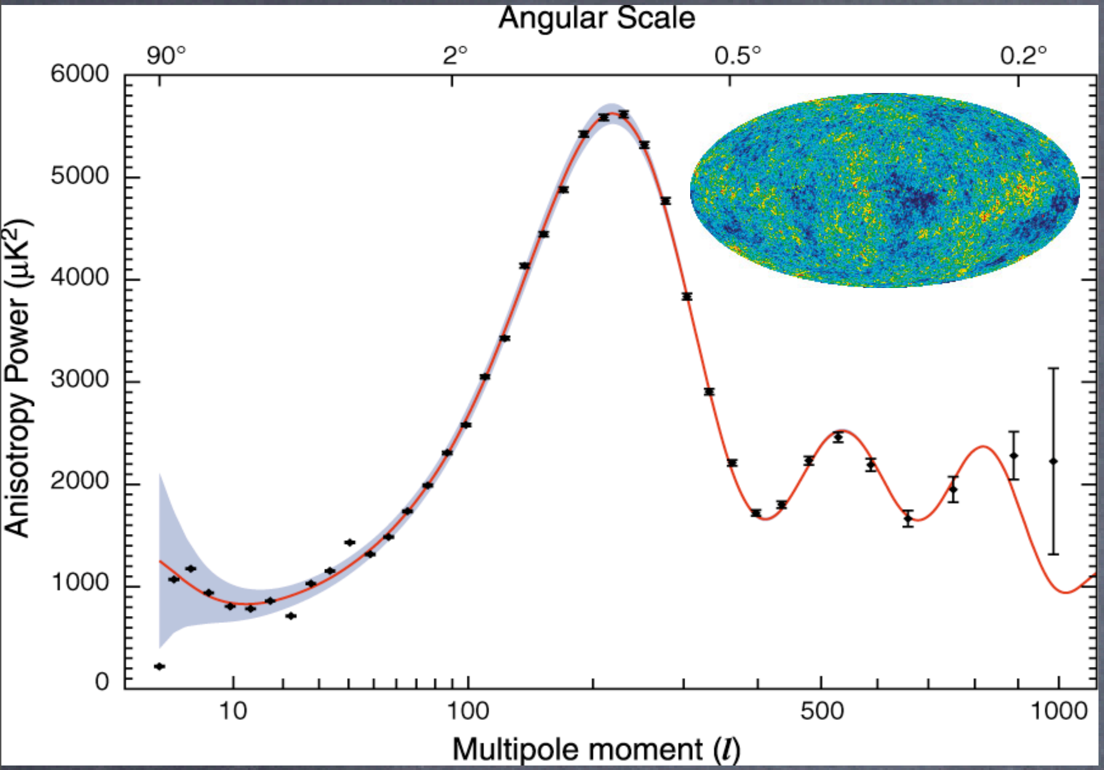

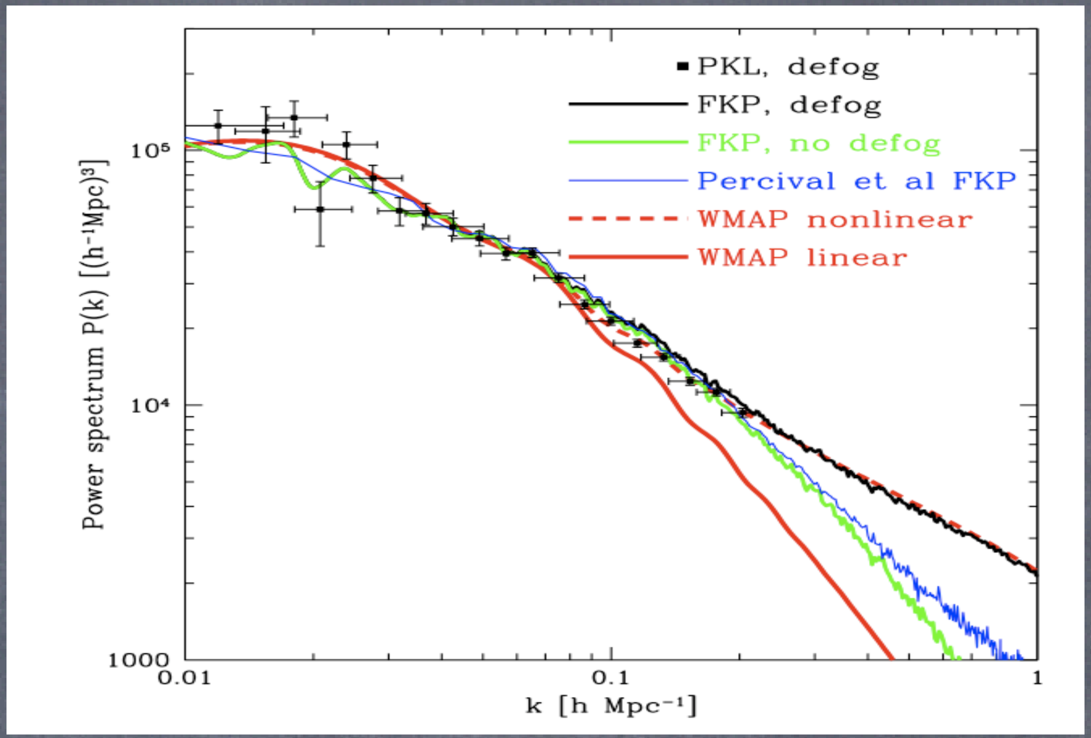

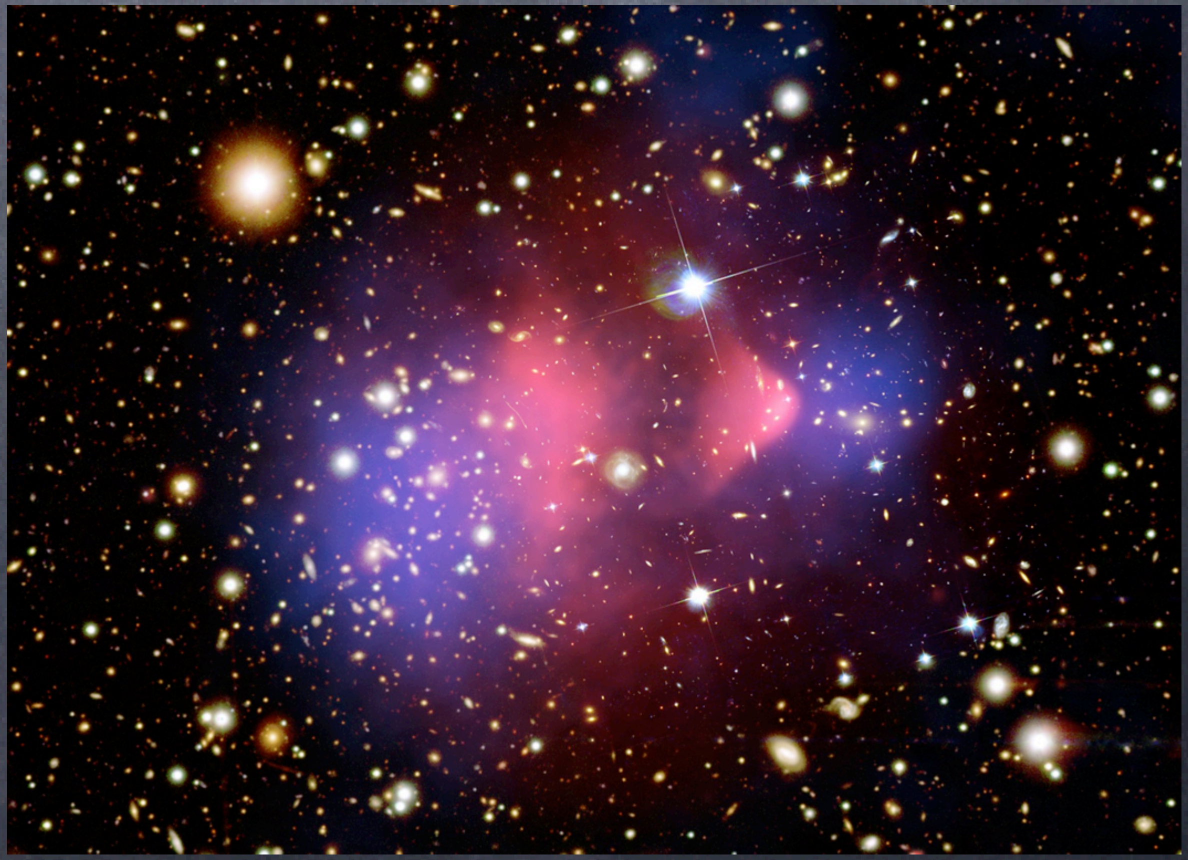

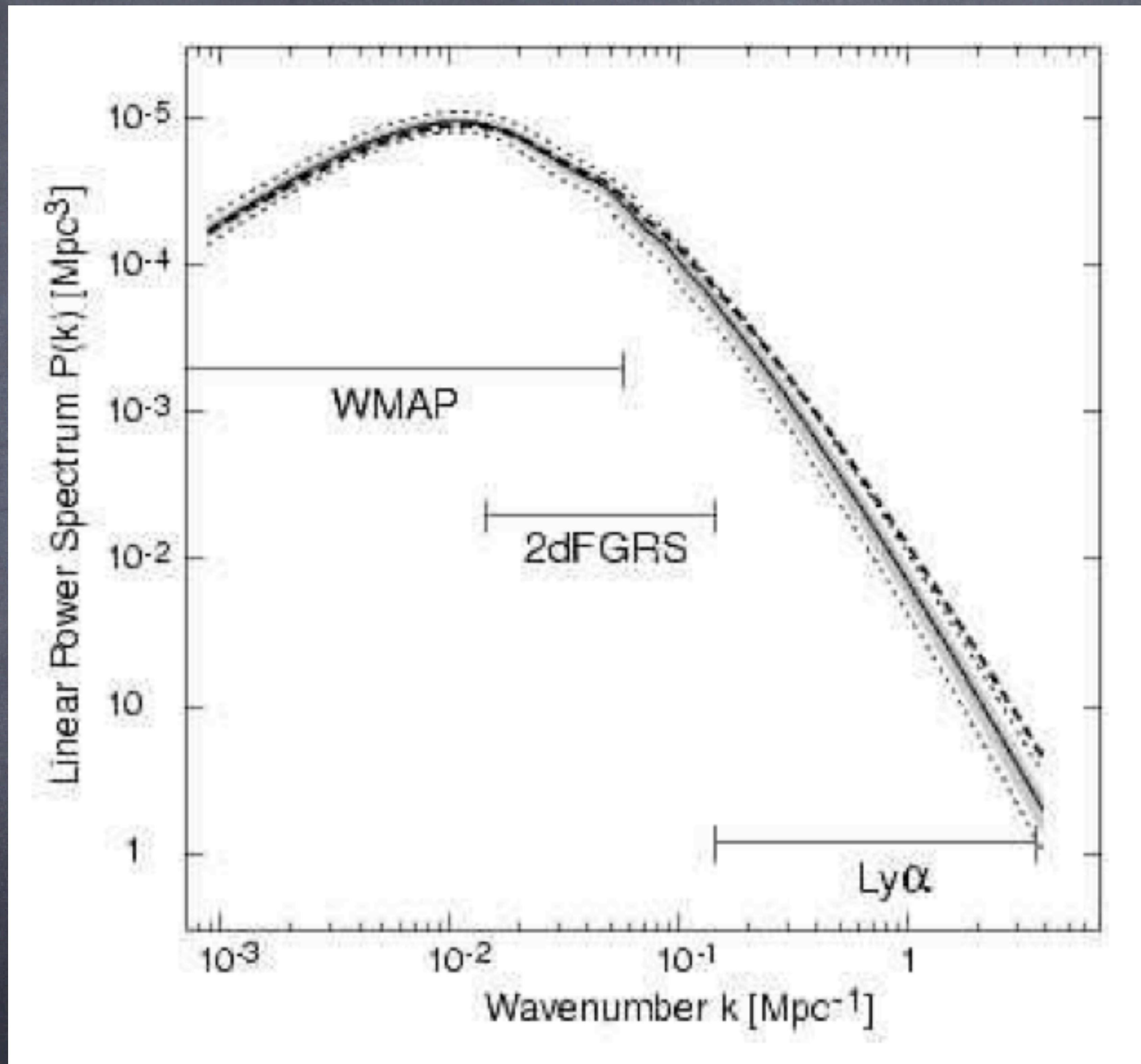
Linear Power Spectrum P(k) [Mpc3]
Wavenumber k [Mpc-1]
10-5
10-4
10-3
10-2
10
1
10-3
10-2
10-1
1
WMAP
2dFGRS
Lyα

Candidates for DM: Theory Motivated

Candidate		Motivation
axion	promote q to dynamical variable	strong CP problem
neutralino	mixture of Bino, Wino and up/down Higgsinos	hierarchy problem
sneutrino	partner of sneutrino (relic abundance and direct detecton problems)	hierarchy problem
LTOP	Little Higgs models, general BSM models	hierarchy problem
KKDM	First KK resonance, stabilized by KK parity	not the neutralino
axino	SUSY partner of axion	SCP+HP
4th gen	Another generation, but stable	first three generations
gravitino	LSP decays to gravitino, partner of graviton	HP+unpleasant childhood
LNSWP	Something stable and weak scale, why not?	The weak scale is there, DM is there

Also qballs, BHs, topological things, and whatever you are working on but I forgot to mention

Candidates for DM: “Exp” Motivated

Candidate	What is it	Motivation
SIDM	make DM strongly interacting (candidate?)	galaxy structure issues (cusps)
WDM	warm - keV sterile neutrino	substructure
Light DM	light (GeV) WIMP	DAMA
Spin-dependent DM	?	DAMA
iDM	Mixed sneutrino, split SU(2) doublet, new force	DAMA
MeVDM	DM with MeV mass	INTEGRAL
XDM	DM that upscatters with ~ GeV mass force	INTEGRAL, more recently PAMELA/Fermi...
Decaying DM	DM decays with long lifetime	PAMELA/Fermi

All these models are **wrong** except **at most** one

Precision Electroweak Studies

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Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
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	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	−0.7
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	−0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	−2.4
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$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
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A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
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	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		−0.3
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g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
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$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
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June 12, 2007 11:05

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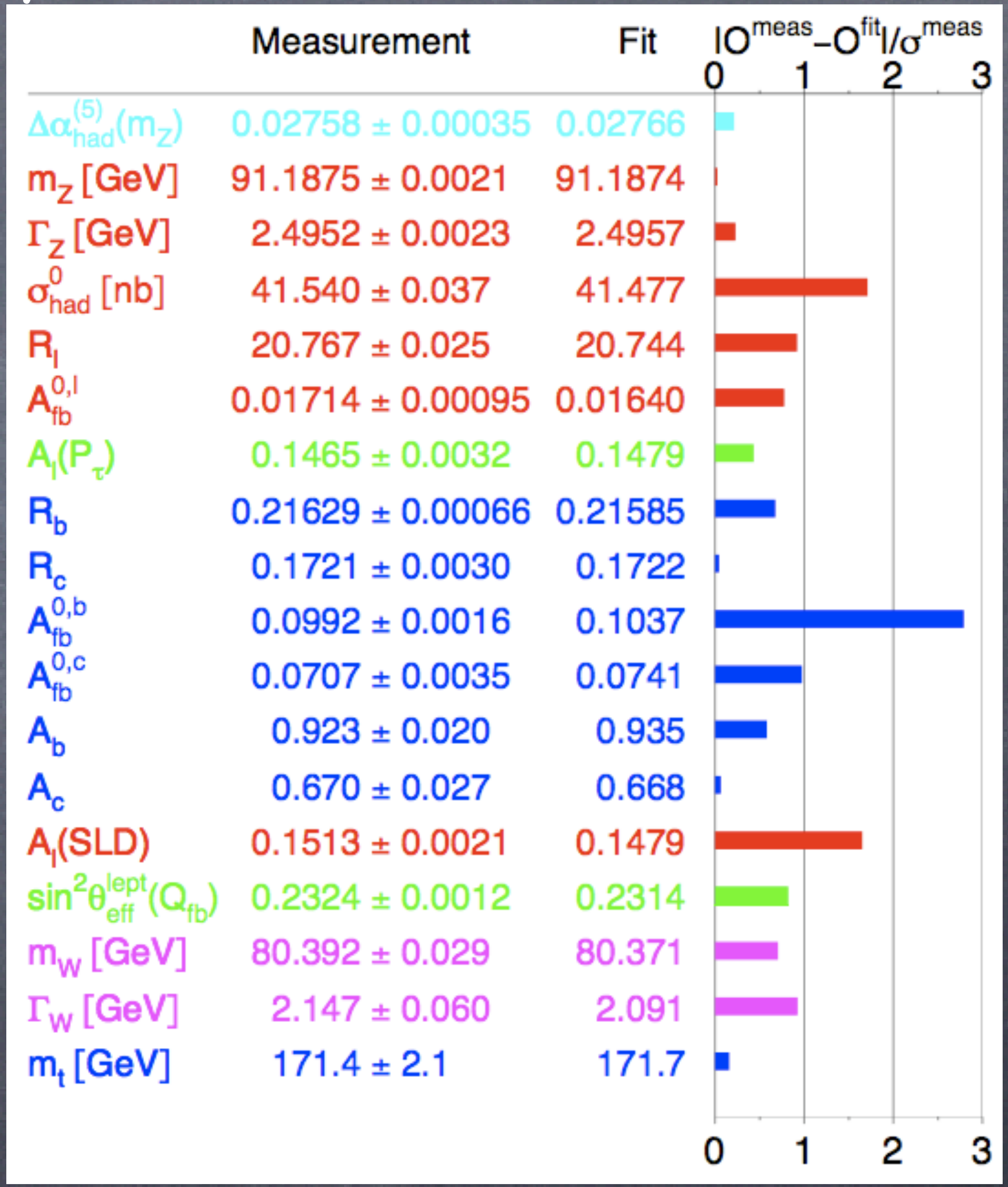

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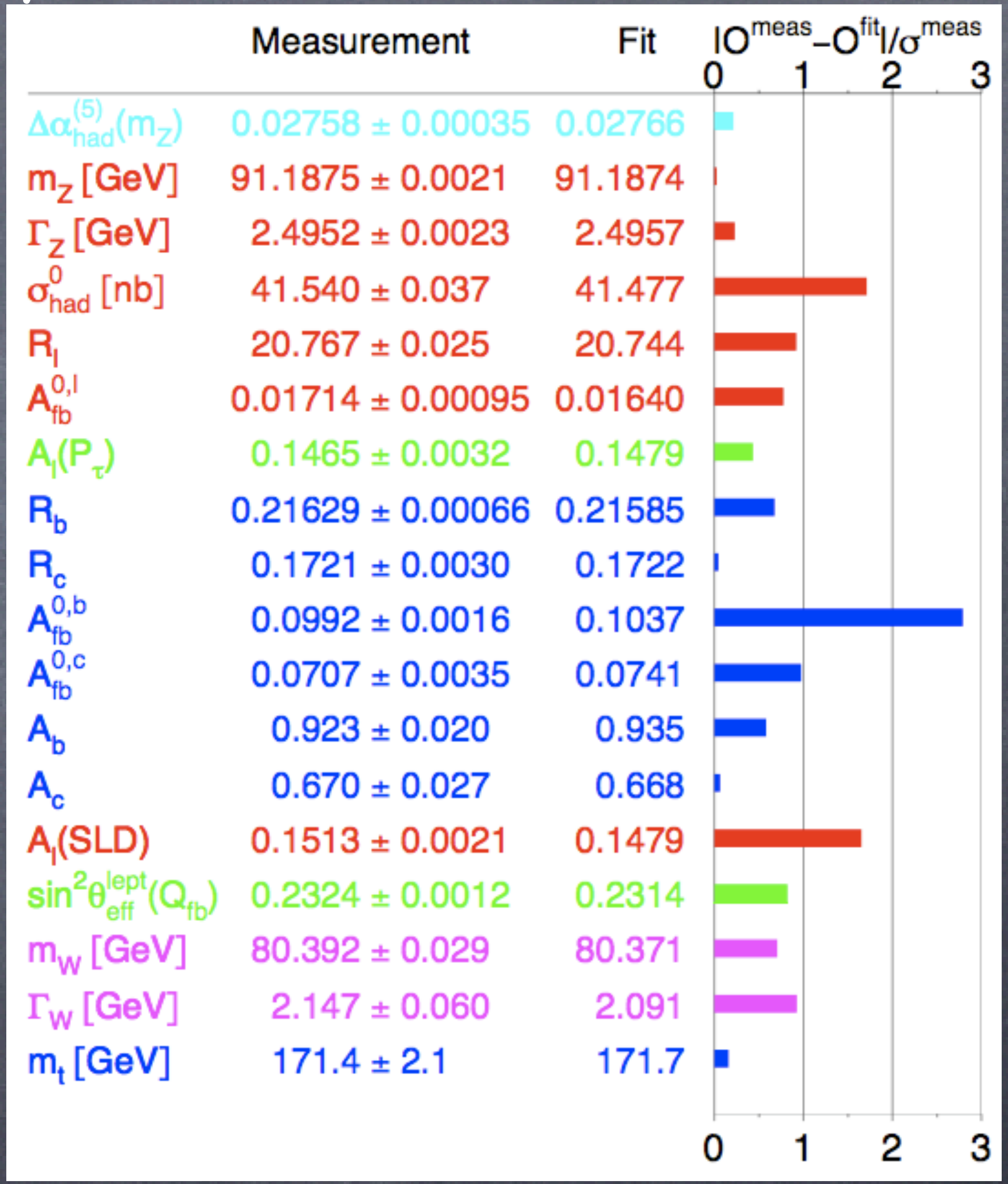
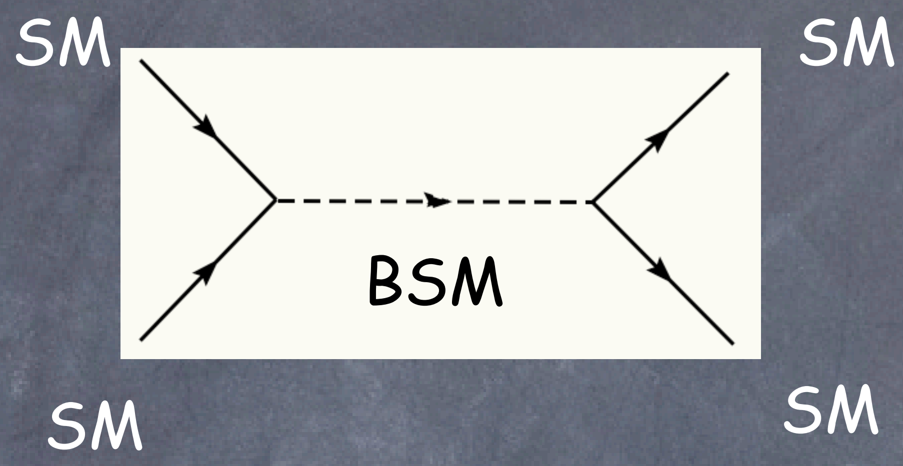


In general, new physics at the weak scale should have shown up in these precision studies

T-Parity (Cheng and Low)

- The problem arises from diagrams like



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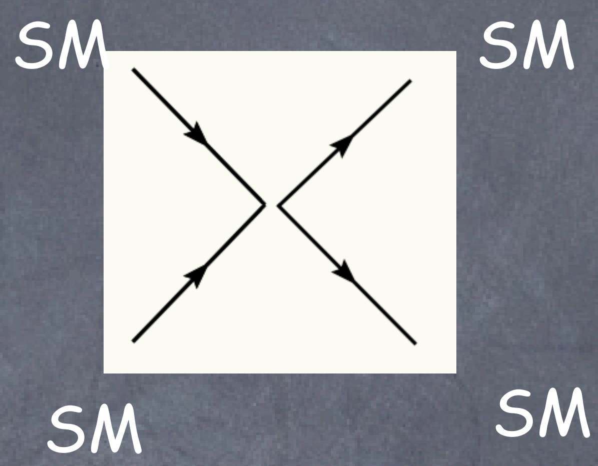

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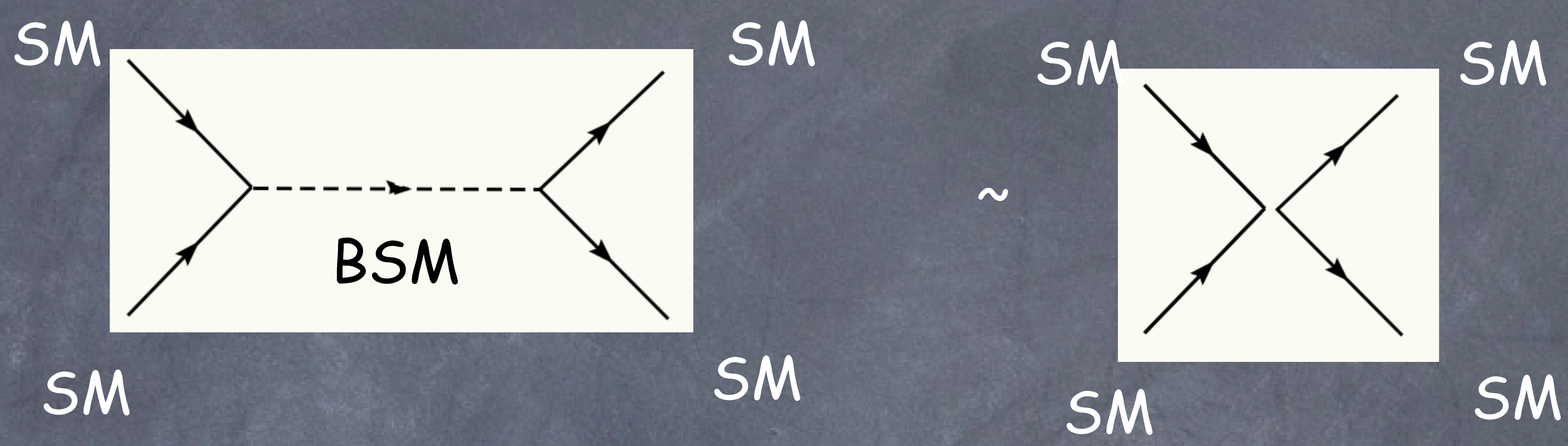

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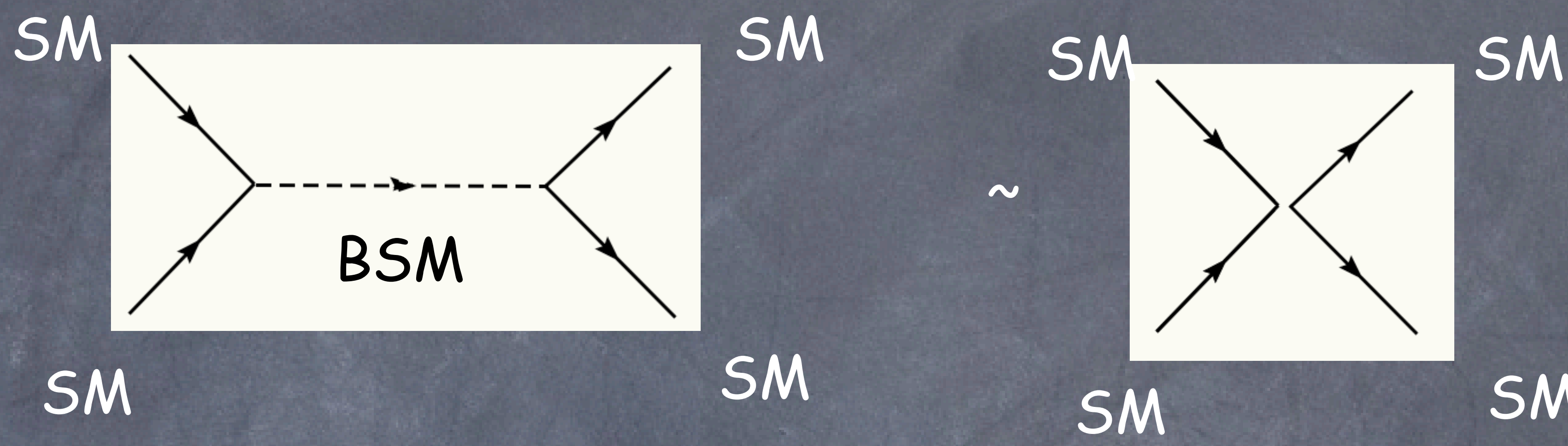

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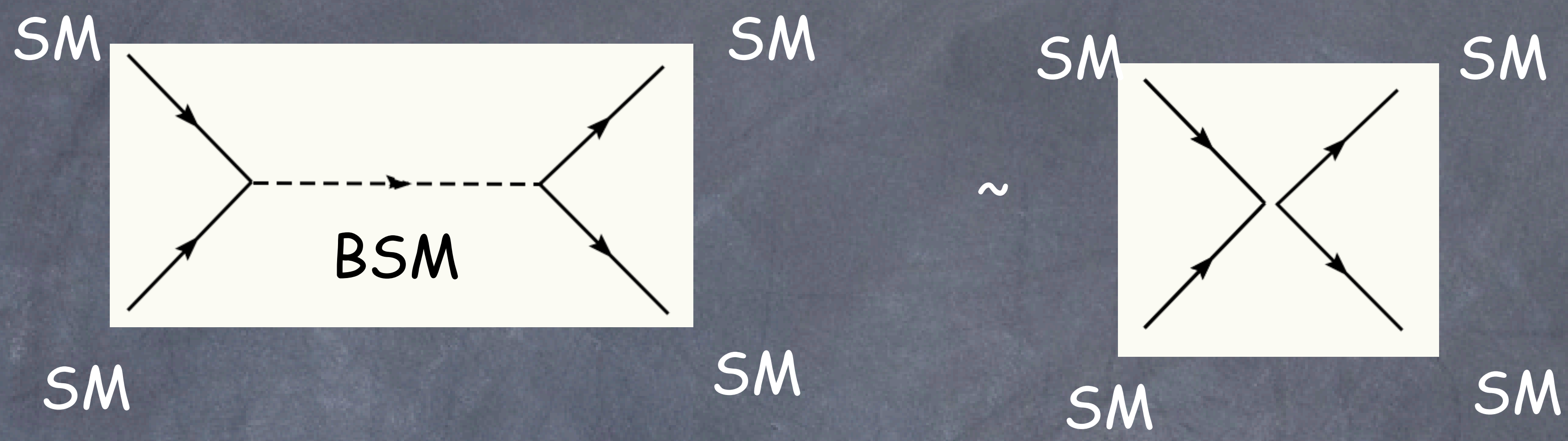

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$$\mathcal{L} \supset SM_1 SM_2 BSM$$

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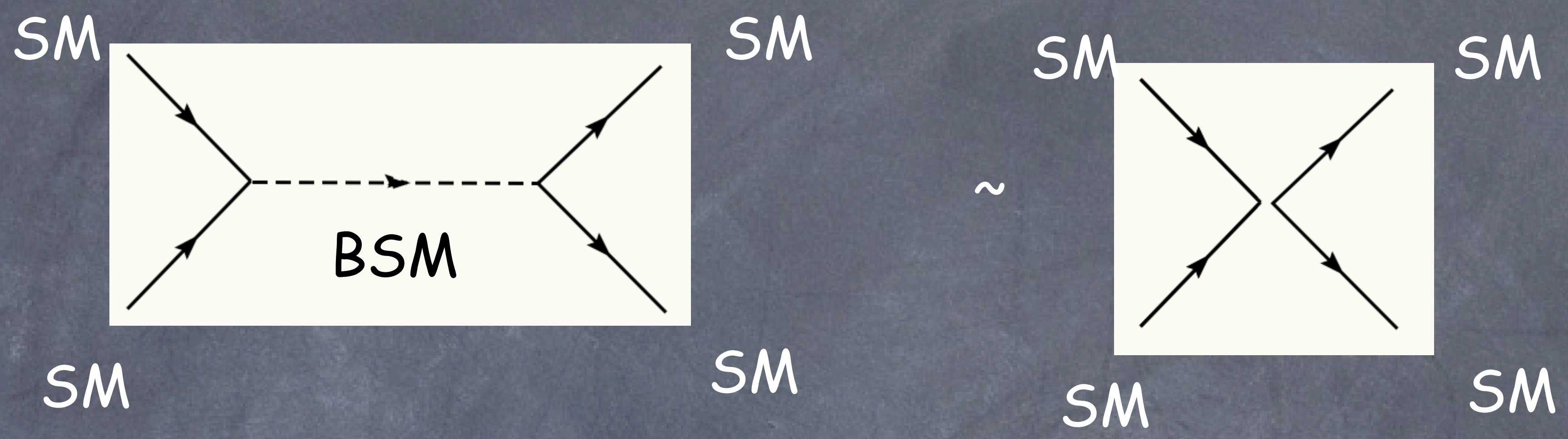

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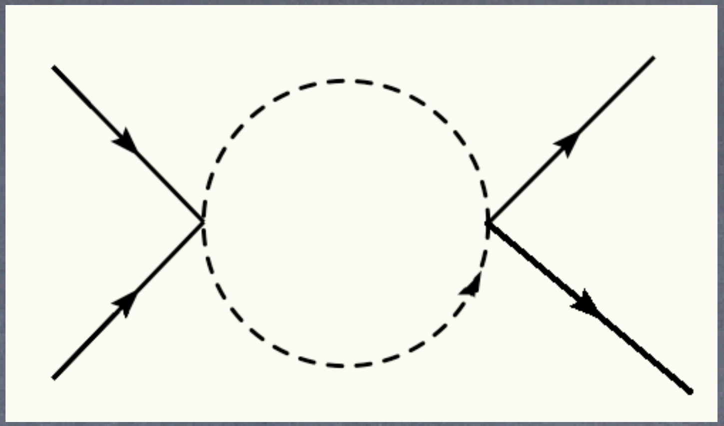
- Vertex comes from Lagrangian term

$$\mathcal{L} \supset SM_1 SM_2 BSM$$

- I.e., problem is presence of single BSM field
  - If only even numbers of BSM fields were allowed, this term is forbidden!

- Then process occurs via loop



loops smaller by ~ $1/16\pi^2$

enough to solve problem

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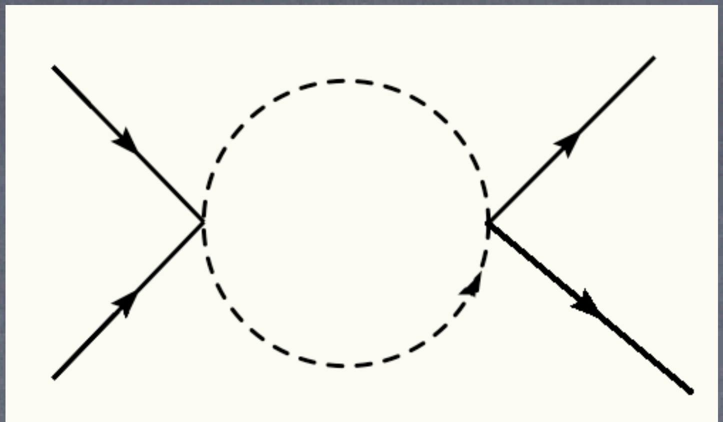


loops smaller by ~ $1/16\pi^2$

enough to solve problem

Introduce parity at weak scale => stable DM candidates

The WIMP

- early universe cheat sheet

$x = m/T$ time variable

$$n_R \sim T^3$$

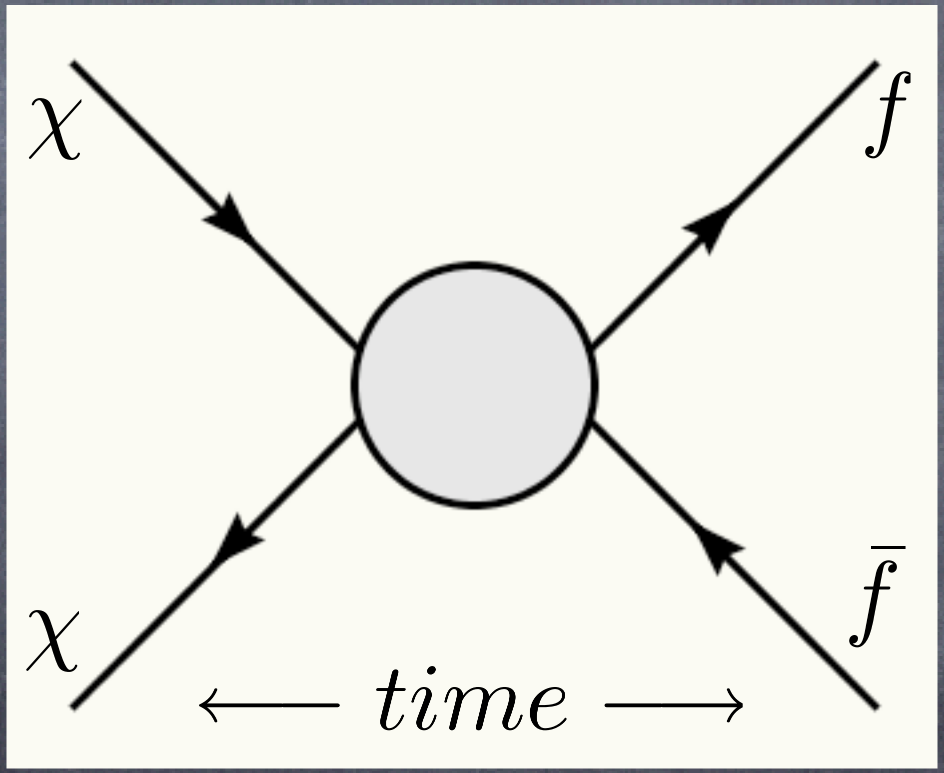
$$n_{NR} \sim (mT)^{3/2} e^{-m/T}$$

$$H \sim \frac{T^2}{M_{pl}} \quad \text{(radiation domination)}$$

NB: T= 1/time!

The WIMP “miracle”

assume thermal equilibrium $\chi\chi \leftrightarrow \bar{f}f$



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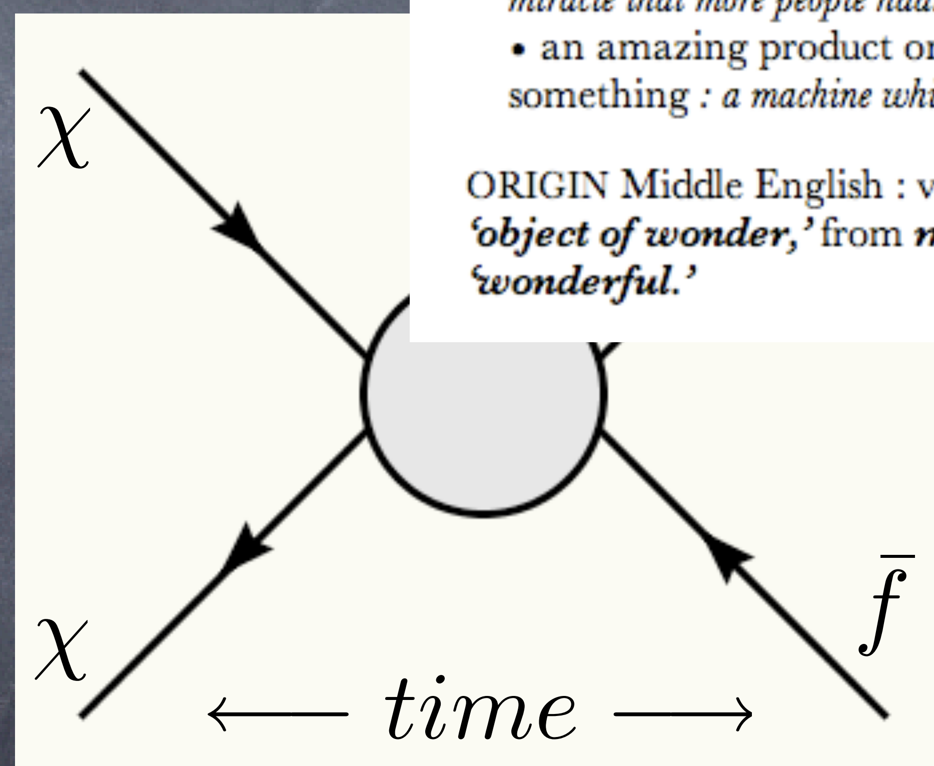
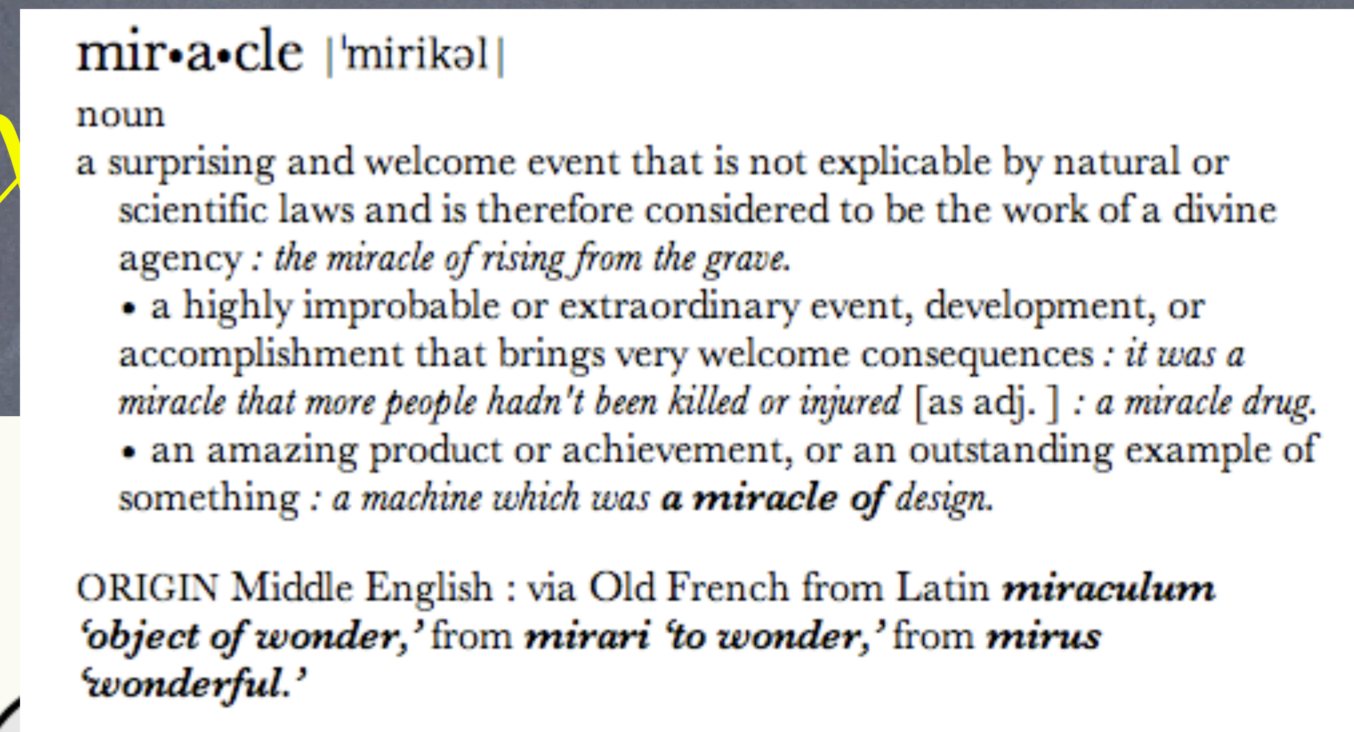




mir•a•cle |ˈmirikəl|

noun

a surprising and welcome event that is not explicable by natural or scientific laws and is therefore considered to be the work of a divine agency : *the miracle of rising from the grave.*

• a highly improbable or extraordinary event, development, or accomplishment that brings very welcome consequences : *it was a miracle that more people hadn't been killed or injured* [as adj.] : *a miracle drug.*

• an amazing product or achievement, or an outstanding example of something : *a machine which was* ***a miracle of*** *design.*

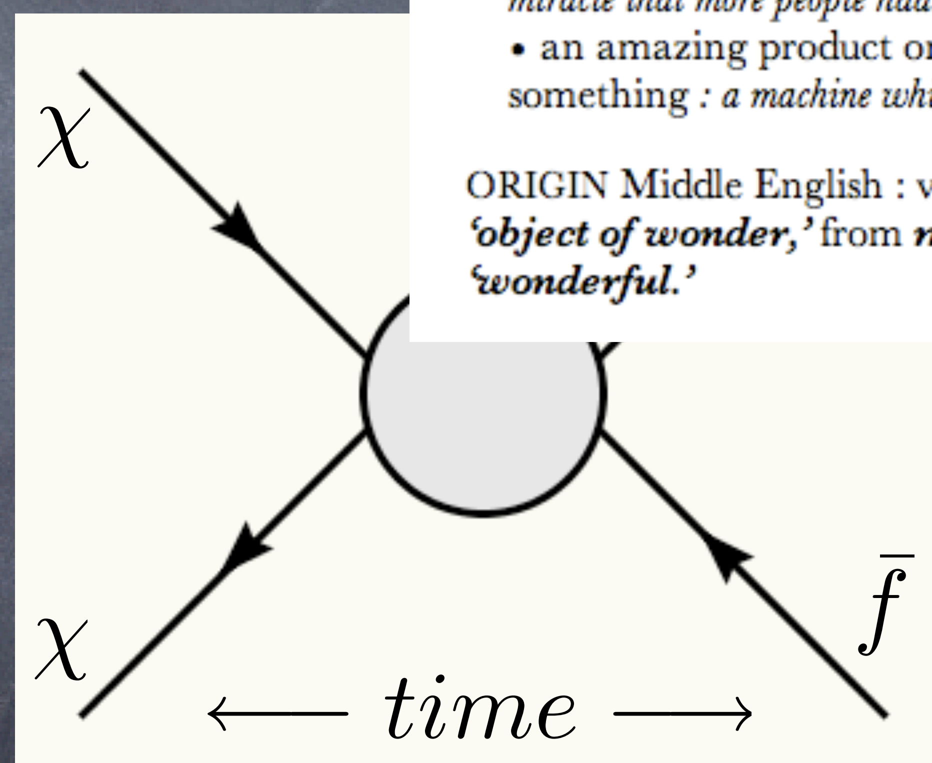
ORIGIN Middle English : via Old French from Latin ***miraculum*** ***'object of wonder,'*** from ***mirari 'to wonder,'*** from ***mirus*** ***'wonderful.'***

The WIMP "~~miracle~~"

assume thermal equilibrium

mir•a•cle |ˈmirikəl|
noun
a surprising and welcome event that is not explicable by natural or scientific laws and is therefore considered to be the work of a divine agency : *the miracle of rising from the grave.*
• a highly improbable or extraordinary event, development, or accomplishment that brings very welcome consequences : *it was a miracle that more people hadn't been killed or injured* [as adj.] : *a miracle drug.*
• an amazing product or achievement, or an outstanding example of something : *a machine which was* ***a miracle of*** *design.*

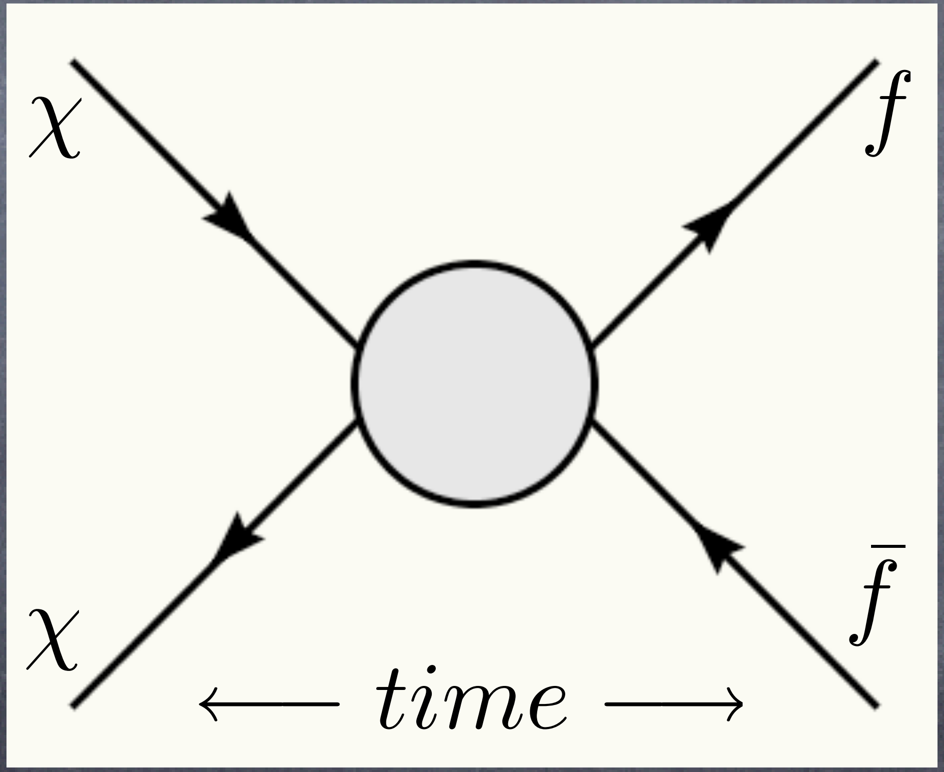
ORIGIN Middle English : via Old French from Latin ***miraculum*** ***'object of wonder,'*** from ***mirari*** ***'to wonder,'*** from ***mirus*** ***'wonderful.'***



The WIMP "~~miracle~~"

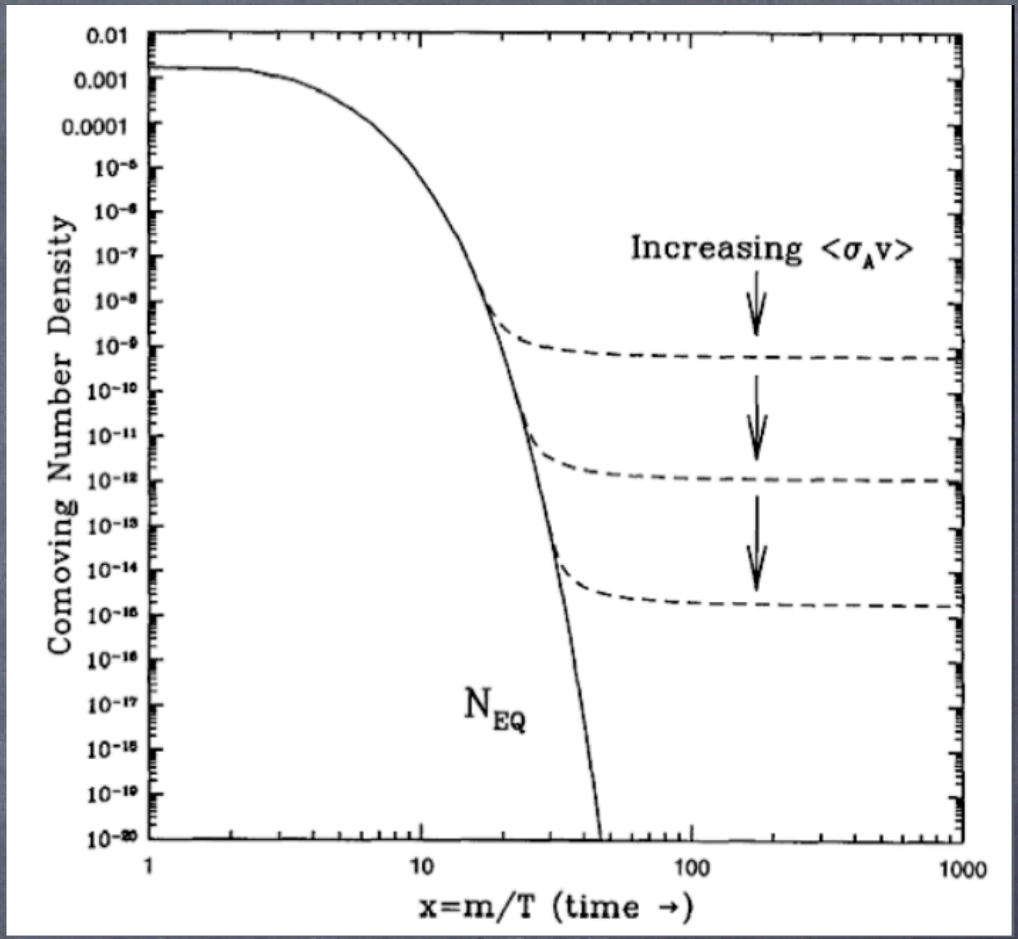
assume thermal equilibrium

$$\chi\chi \leftrightarrow \bar{f}f$$



assume thermal equilibrium $\chi\chi \leftrightarrow \bar{f}f$

When T<< M_{WIMP}, number density falls as $e^{-M/T}$



freezeout $T_f \to n < \sigma v >= H$

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$$n_{now} = n_f \frac{T_{now}^3}{T_f^3} \qquad \frac{n}{T^3}$$

dark matter per photon (is approximately constant)

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dark matter per photon (is approximately constant)

$$\frac{n_{now}}{T^3_{now}} \approx \frac{n_f}{T^3_f} = \frac{H_f}{T^3_f < \sigma v >} = \frac{T^2_f}{T^3_f M_{pl} < \sigma v >}$$

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$$n_{NR} \sim (mT)^{3/2} e^{-m/T} \qquad T_f = m/x_f \qquad x_f \sim \text{not infinity}$$

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$$\rho_{now} T_{now}^3 = \frac{m n_{now}}{T_{now}^3} \approx \frac{m m^2 x_f^3}{m^3 x_f^2 M_{pl} < \sigma v >}$$

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$$= \frac{x_f}{M_{pl} < \sigma v >}$$

just depends on cross section!

The WIMP not-miracle

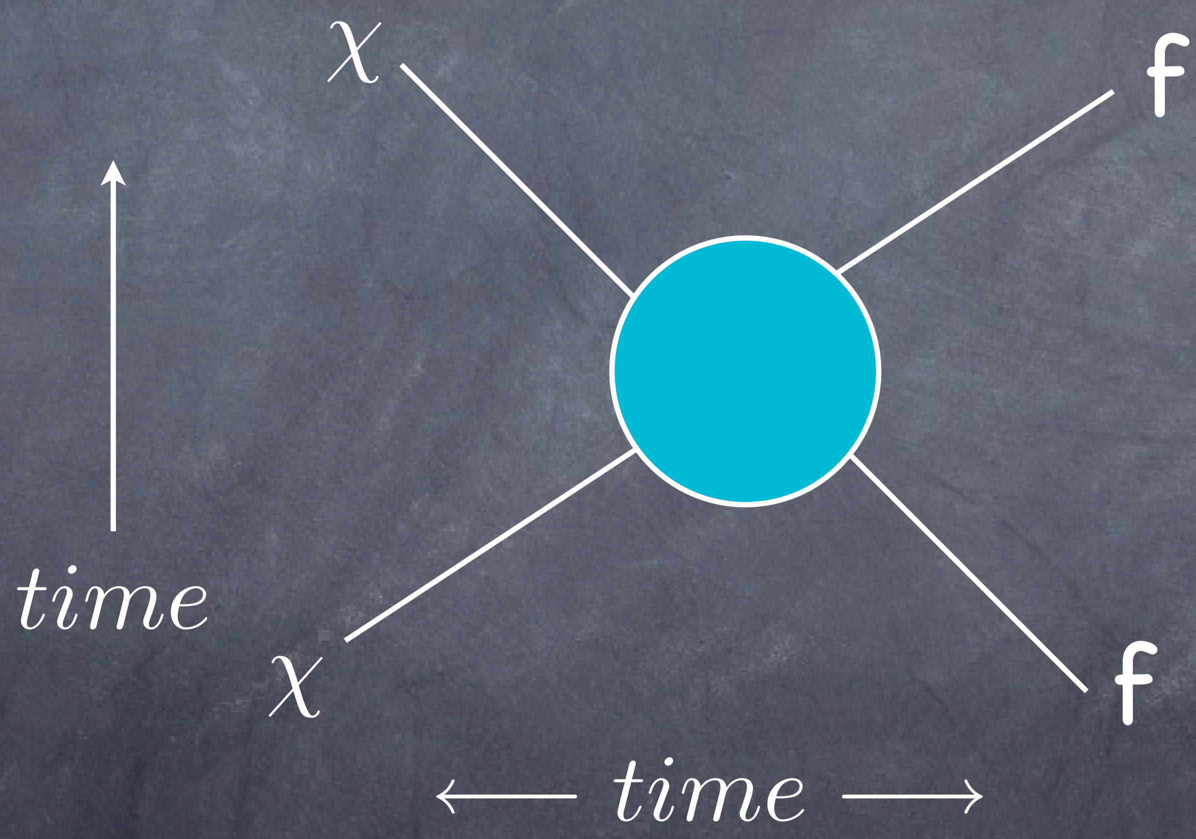
$$\Omega h^2 \approx 0.1 \times \left(\frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle} \right)$$

$$\approx 0.1 \times \left(\frac{\alpha^2/(100 \mathrm{GeV})^2}{\langle \sigma v \rangle} \right)$$

- Any weak- scale particle naturally freezes out within a few orders of magnitude of the correct cross section

- Three approaches with thermal DM

-Make it (colliders)
-Break it (indirect searches)
-Wait for it (direct searches)



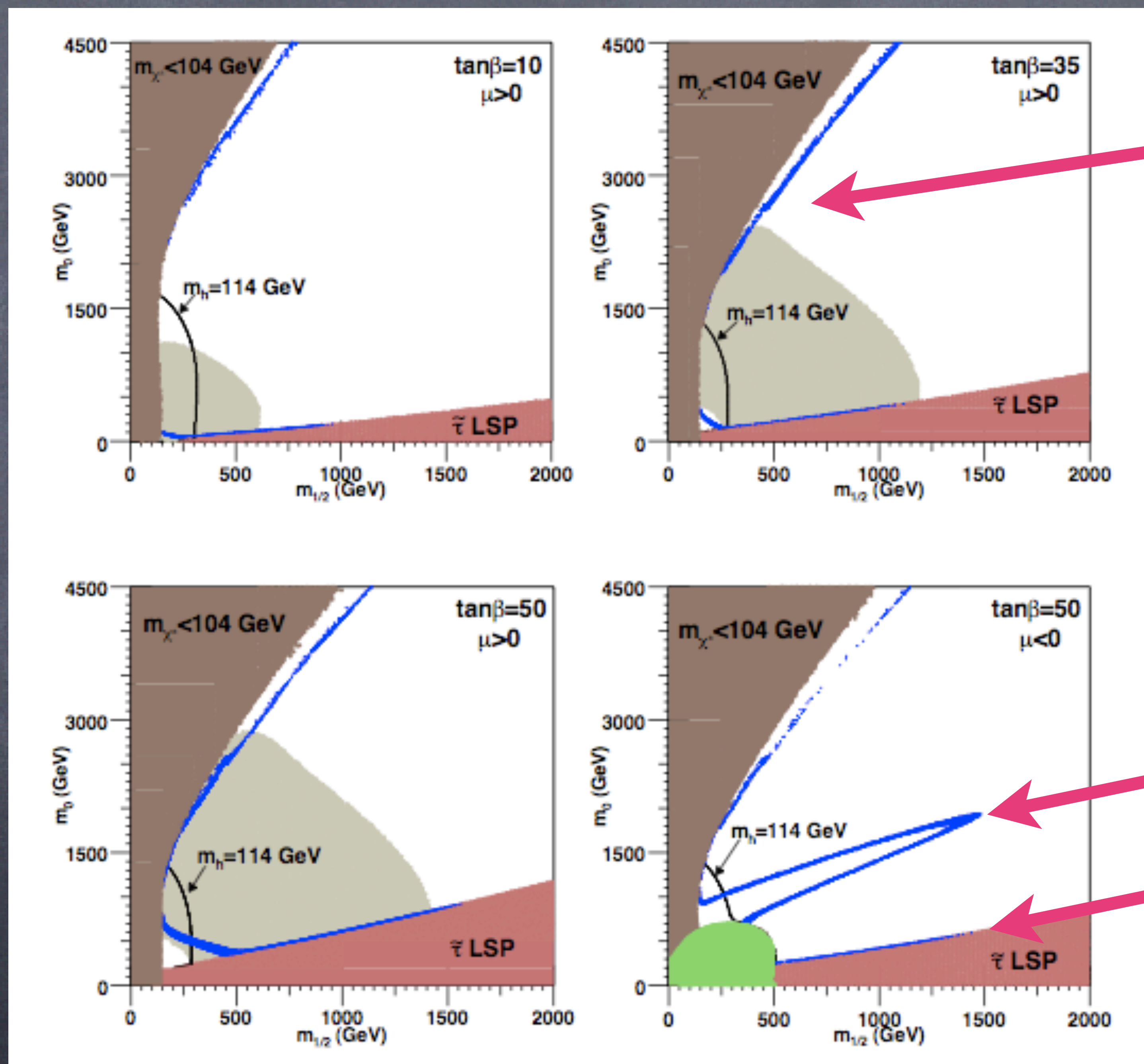
The neutralino

combination of Bino, Wino, up/down Higgsino (in MSSM)

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

$$\chi_{0,1,2,3} = \sum_{i=\tilde{B},\tilde{W},\tilde{H}_u,\tilde{H}_d} U_i \psi_i$$

typically “gaugino”-like or “Higgsino”-like



focus point

a funnel

coannihilation tail

The CMSSM/mSUGRA neutralino is not your friend

- Common logical path in mSUGRA*

LEP Higgs mass limit m_h>114.4 GeV

SUSY predicts m_h<m_Z

Need large radiative corrections to quartic to keep v=246 GeV

Large radiative corrections give contribution to Higgs mass

Cancel those corrections with large μ term

μ term is Higgsino mass

LSP is mostly Bino

Small elastic scattering cross sections

* No, not every point in mSUGRA, this is just an example

Anomalies and anomalies

- High Energy Electrons/Positrons: PAMELA (HEAT,AMS-01), ATIC, EGRET, WMAP
- Low energy positrons: INTEGRAL
- Direct detection: DAMA/LIBRA

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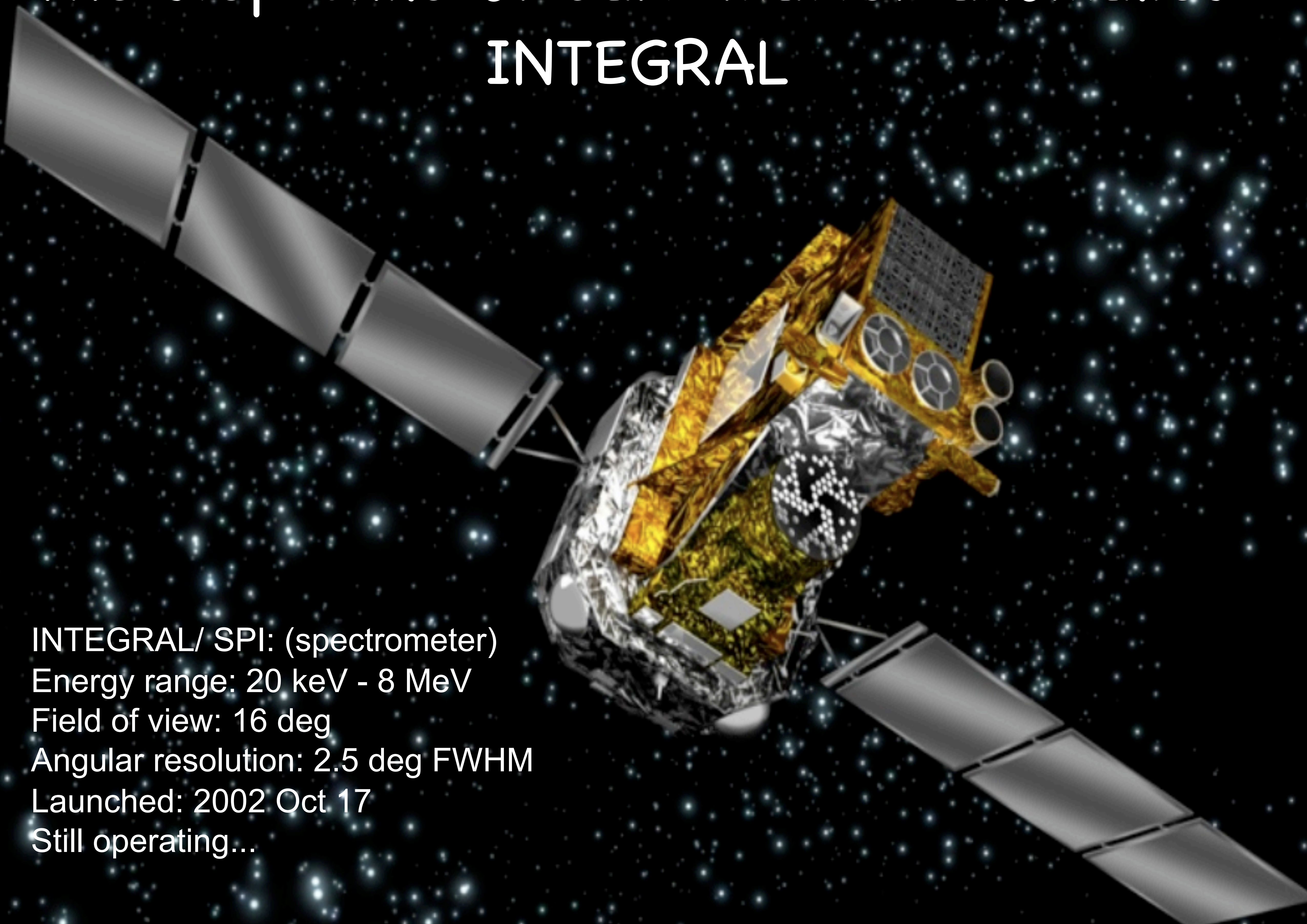
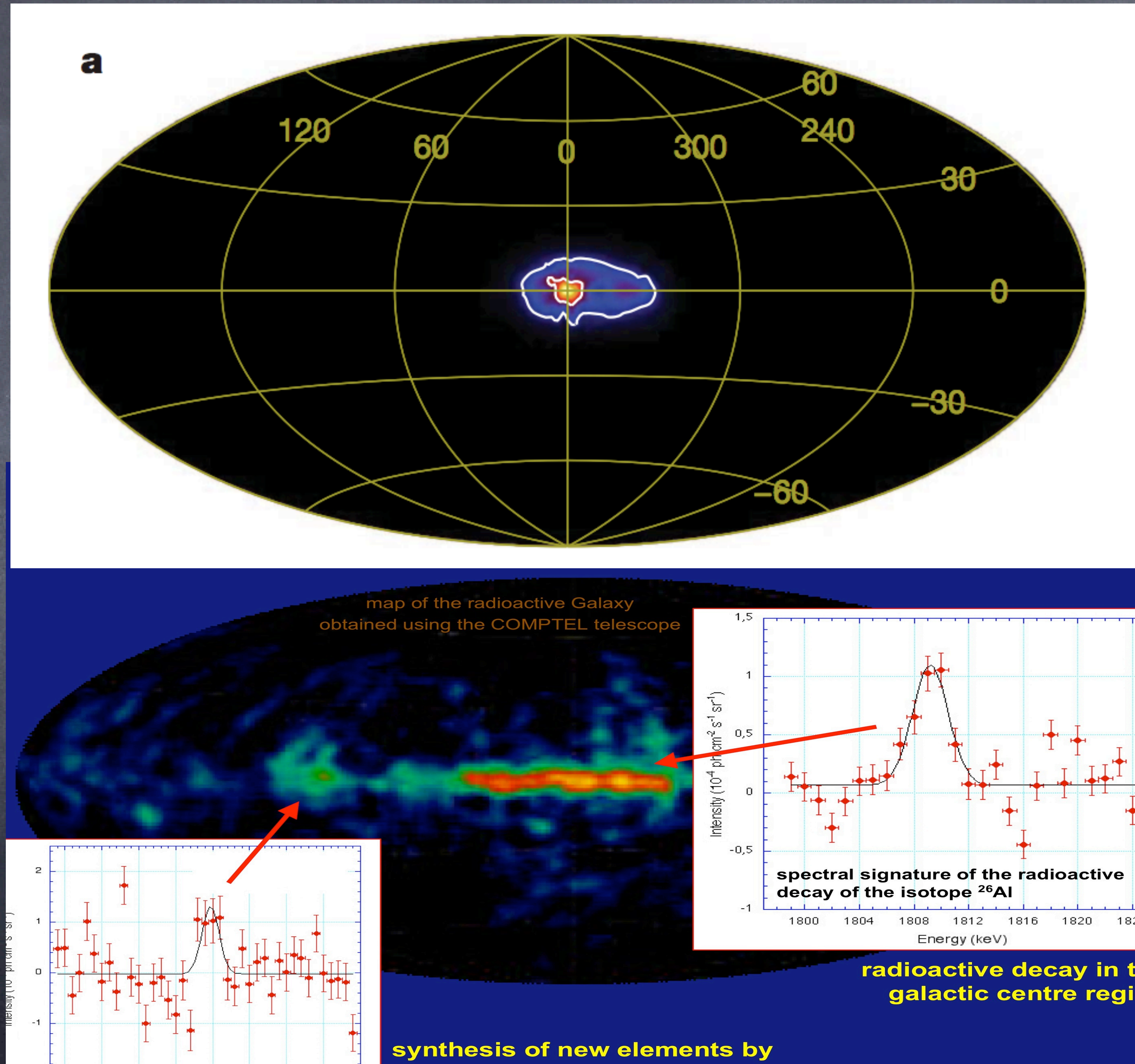
multiple indications

The step-child of dark matter anomalies: INTEGRAL



INTEGRAL/ SPI: (spectrometer)
Energy range: 20 keV - 8 MeV
Field of view: 16 deg
Angular resolution: 2.5 deg FWHM
Launched: 2002 Oct 17
Still operating...

distribution of the INTEGRAL 511 keV line



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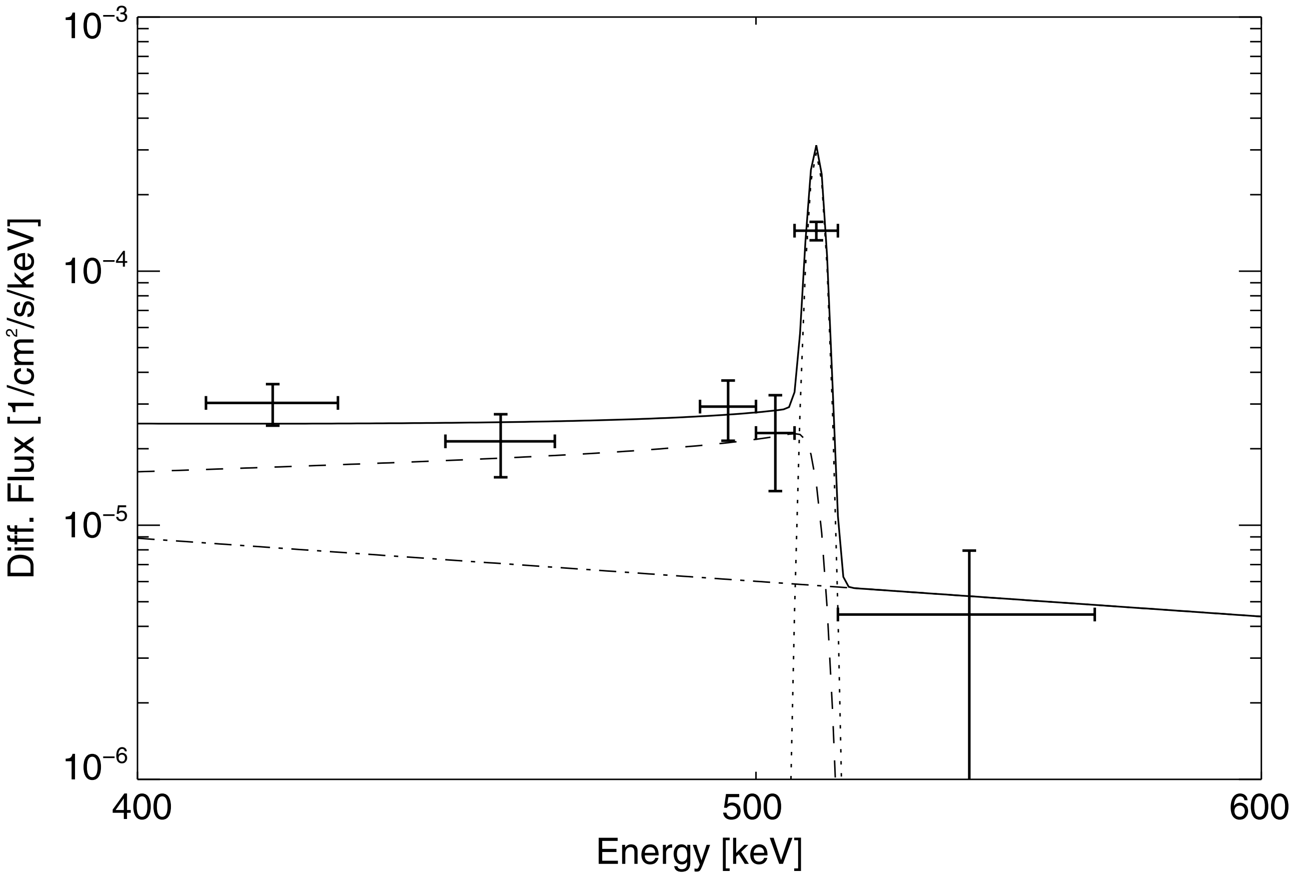


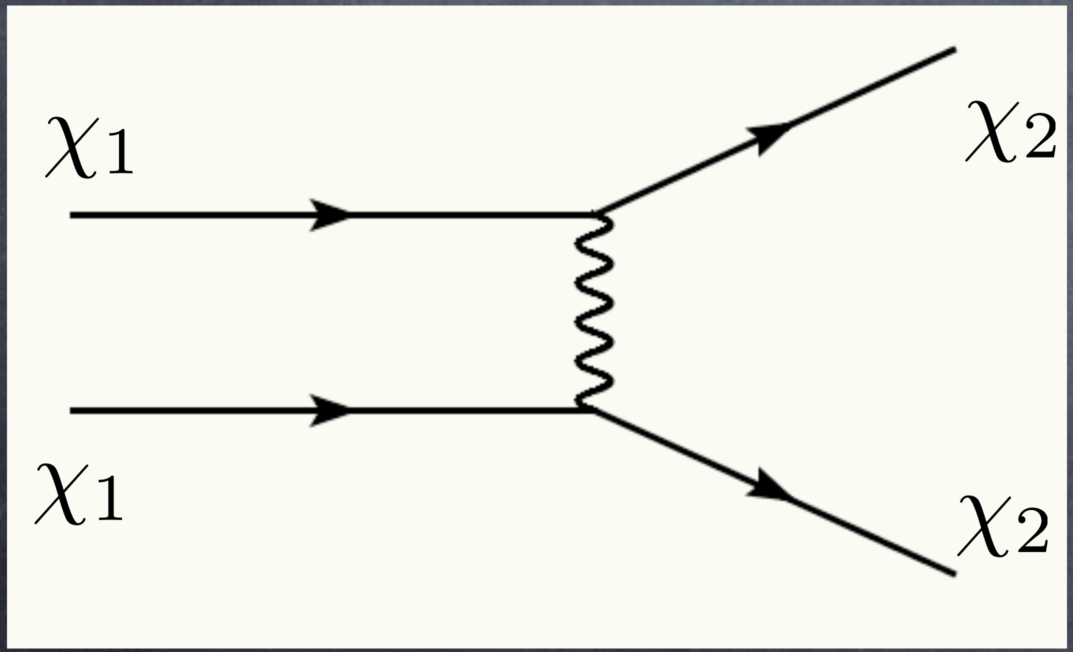
Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16°$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.

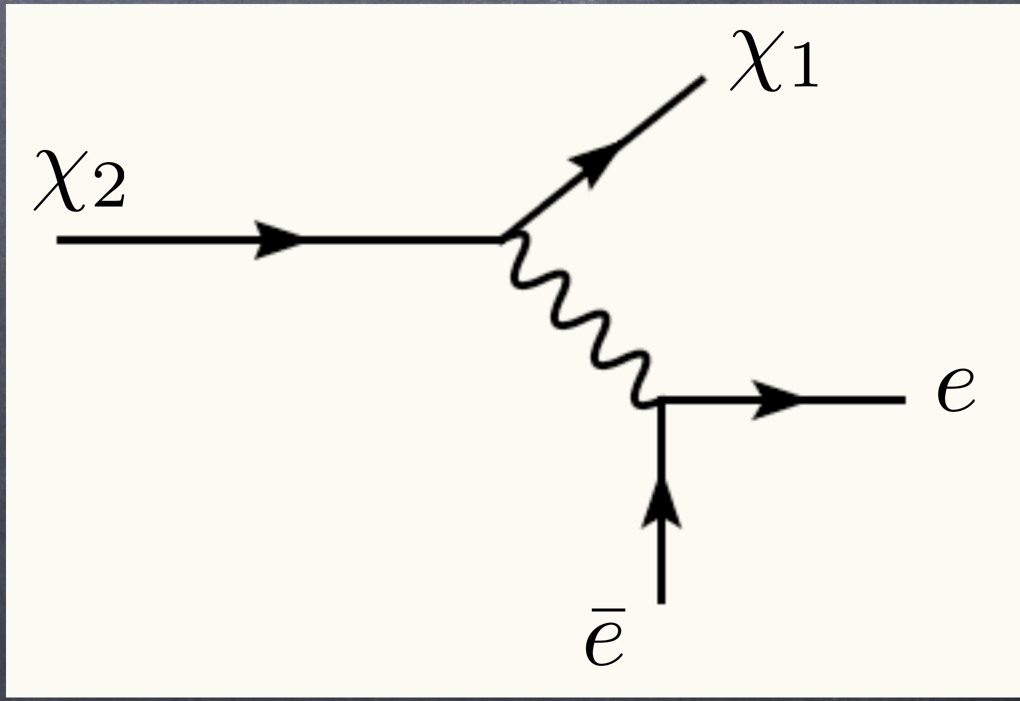
Must be injected with low energies to give narrow line shape

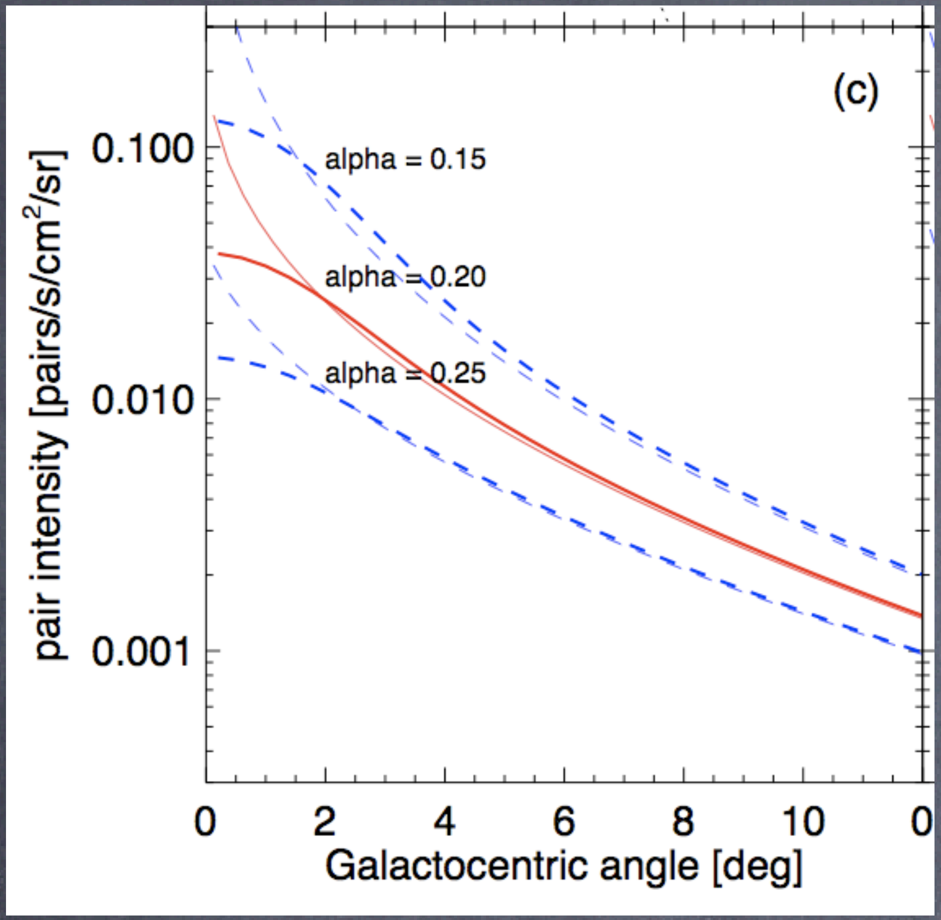
eXciting DM (XDM)

D.Finkbeiner, NW,
Phys.Rev.D76:083519,2007

- Suppose TeV mass dark matter has an excited state ~ MeV above the ground state and can scatter off itself into the excited state, then decay back by emitting e+e-







Need cross section near the geometric cross section, i.e.

$$\sigma \sim 1/q^2$$

Only possible if new force with mass less than q^2~ GeV^2 is in the theory

The NKOTB of dark matter anomalies: PAMELA

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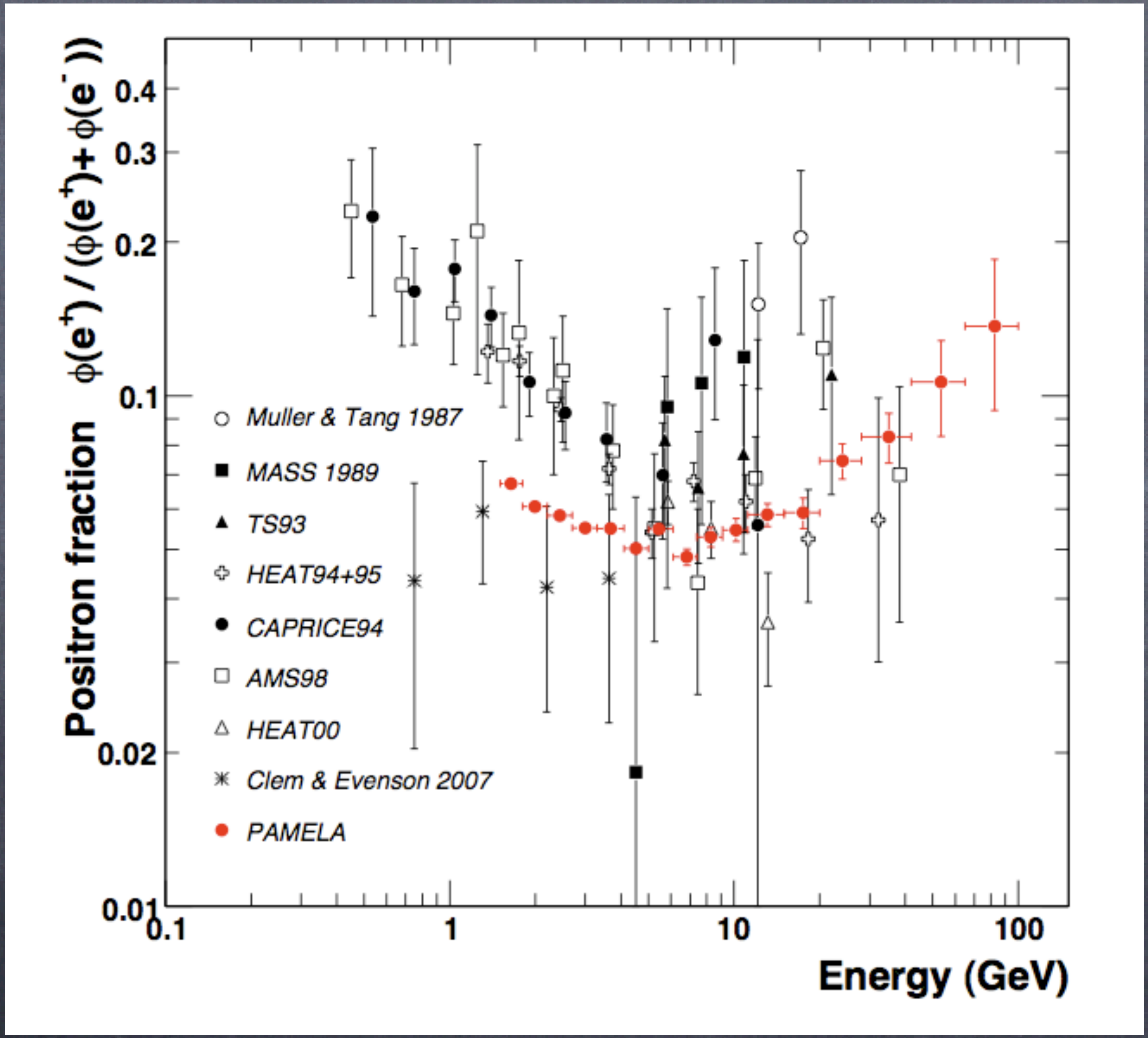
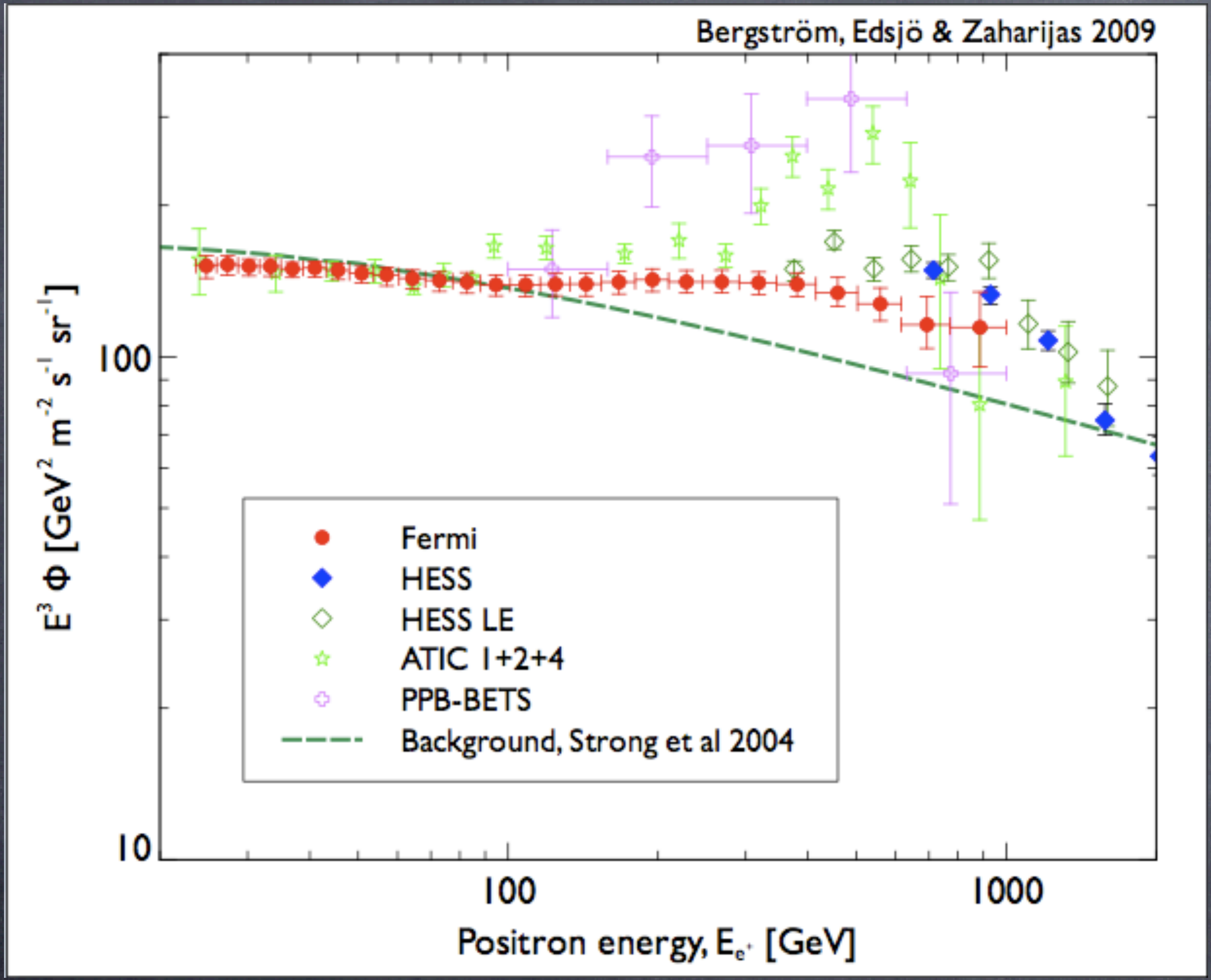
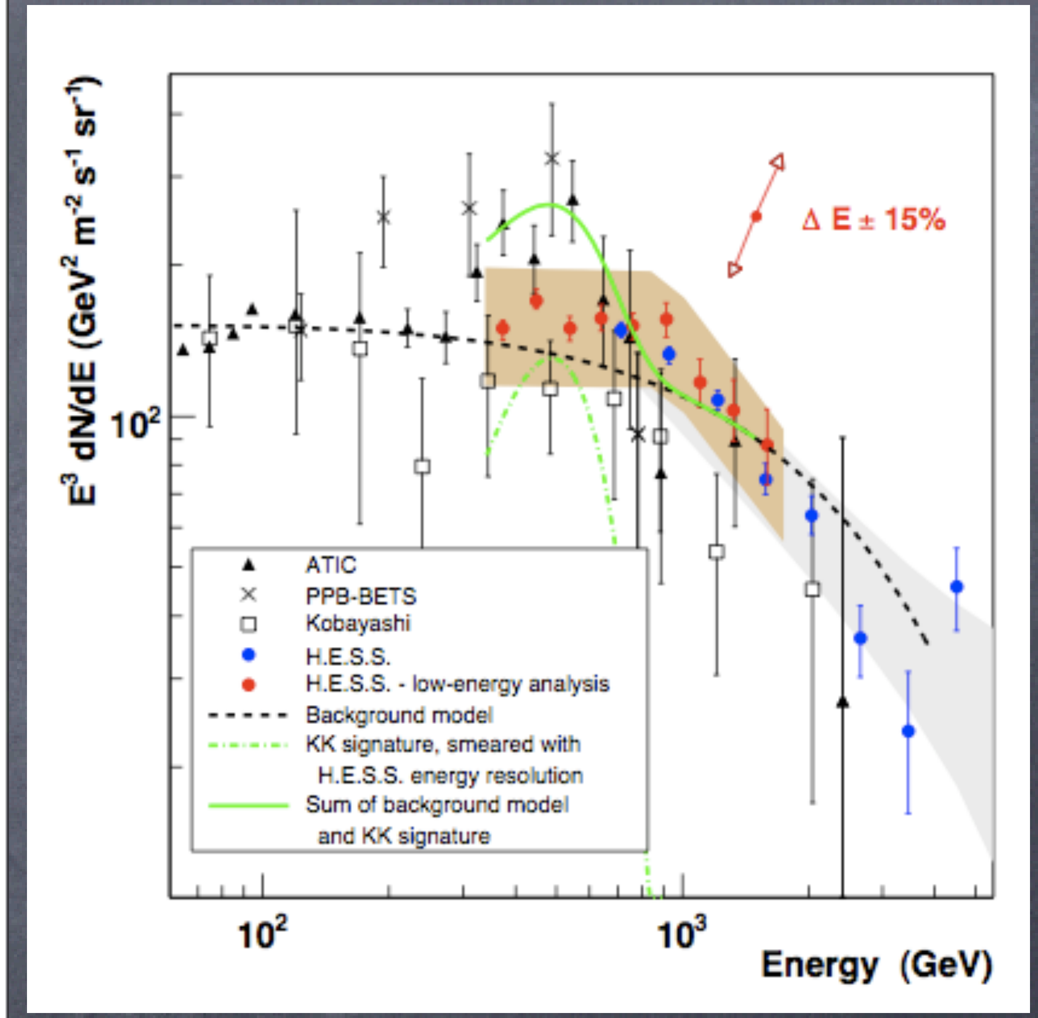
PAMELA



Positron fraction φ(e+) / (φ(e+)+φ(e-))
0.4
0.3
0.2
0.1
0.02
0.01
0.1
1
10
100
Energy (GeV)
Muller & Tang 1987
MASS 1989
TS93
HEAT94+95
CAPRICE94
AMS98
HEAT00
Clem & Evenson 2007
PAMELA

Fermi, HESS, ATIC, PPB-BETS





- **Harder** spectrum than expected - no break until ~ TeV

WIMP annihilations? Not so fast!

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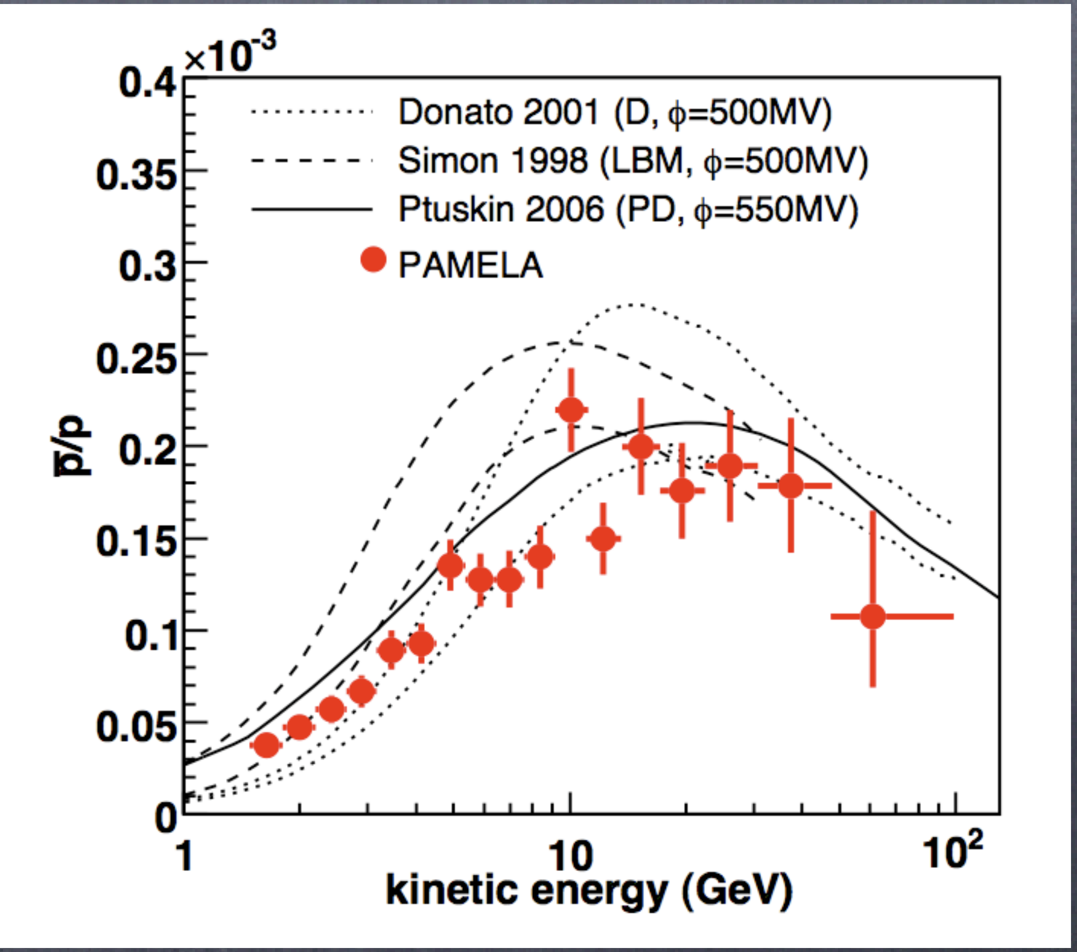

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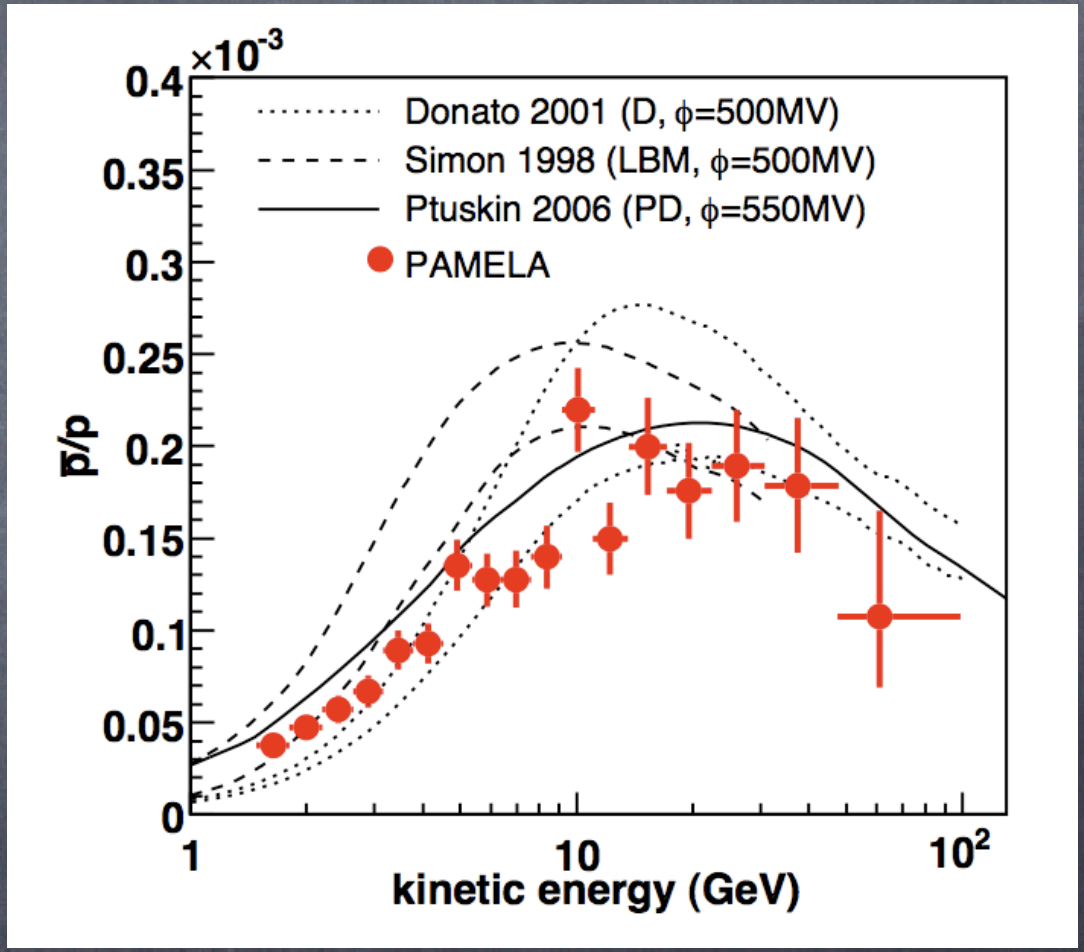

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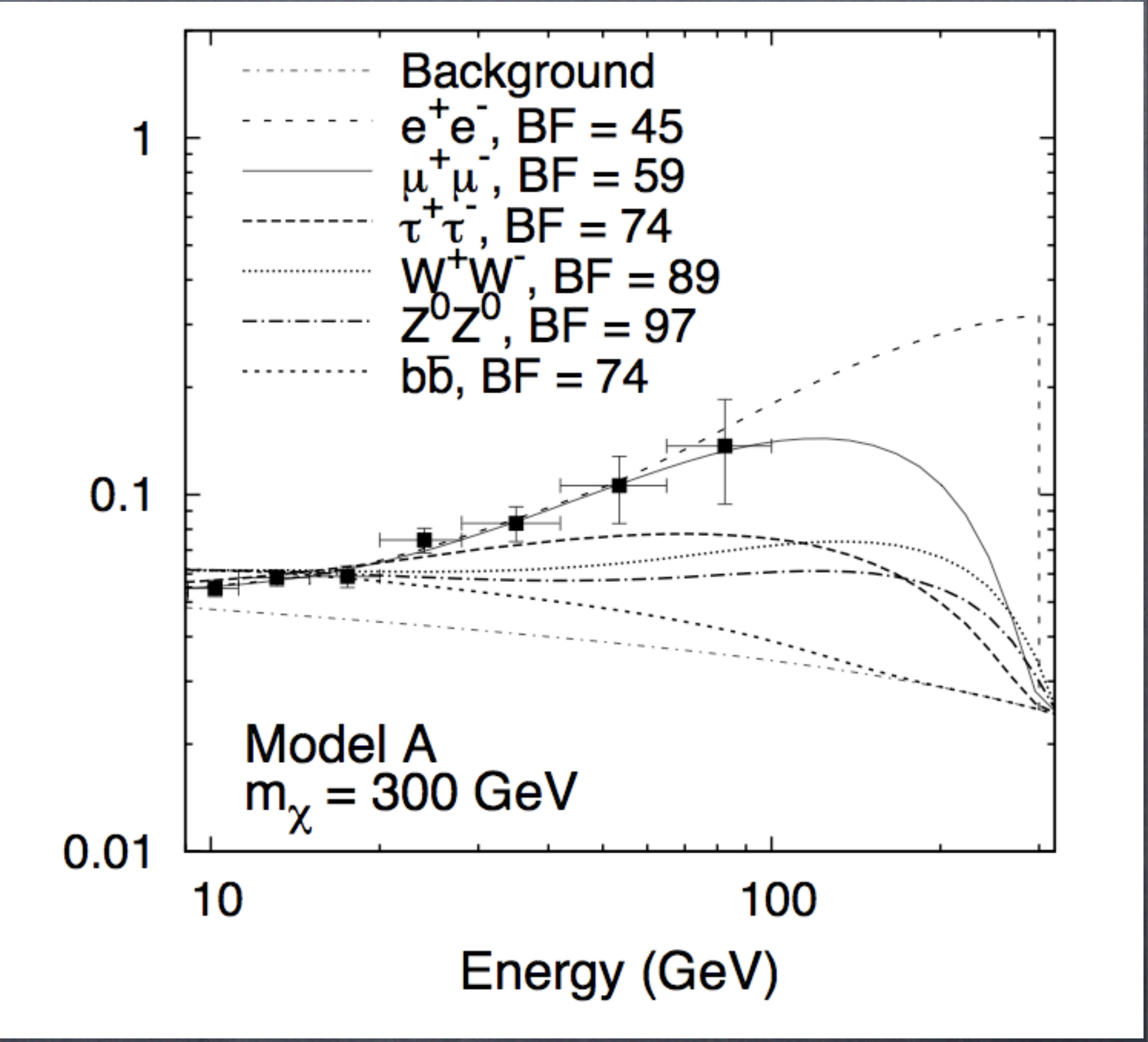

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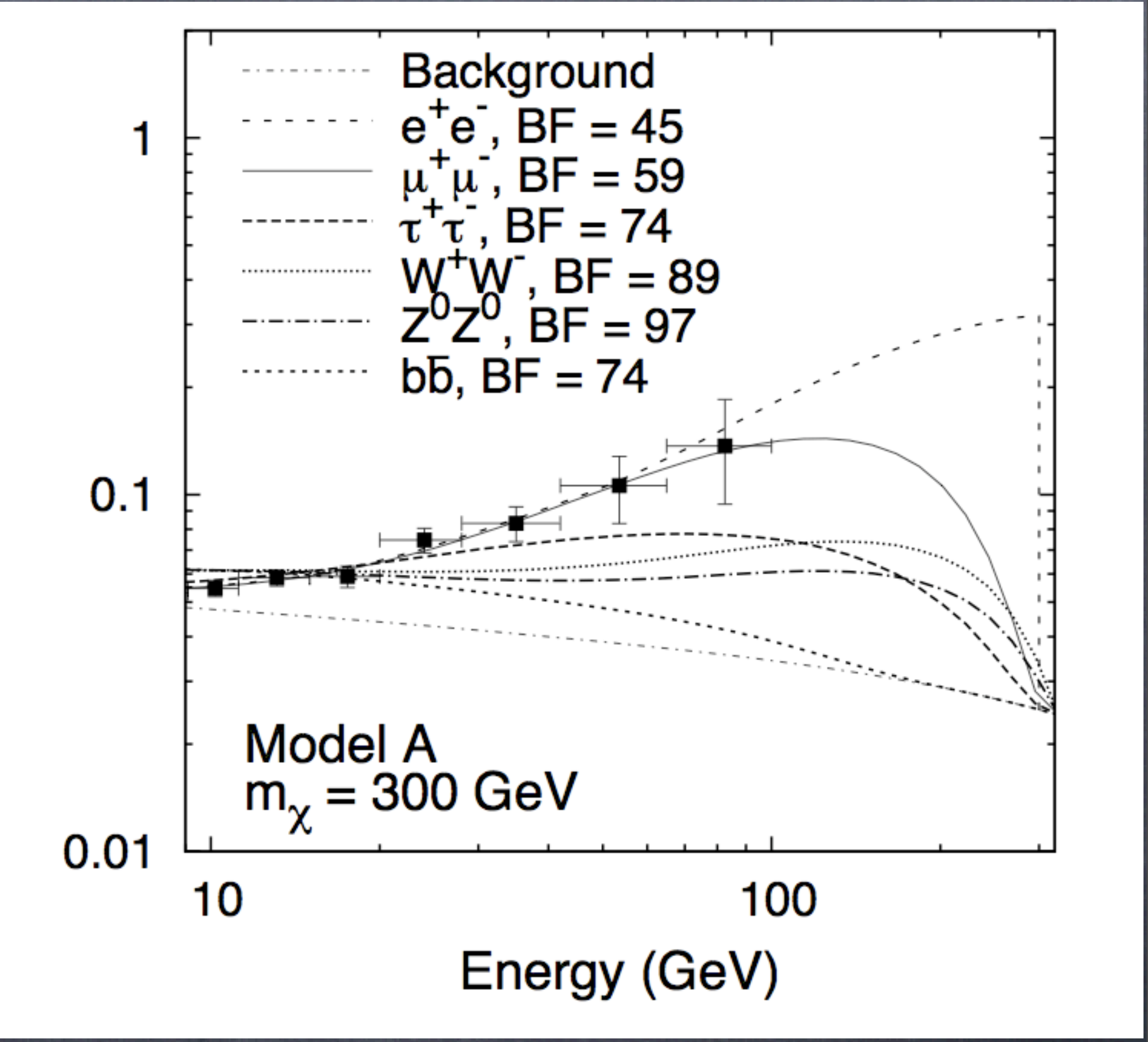

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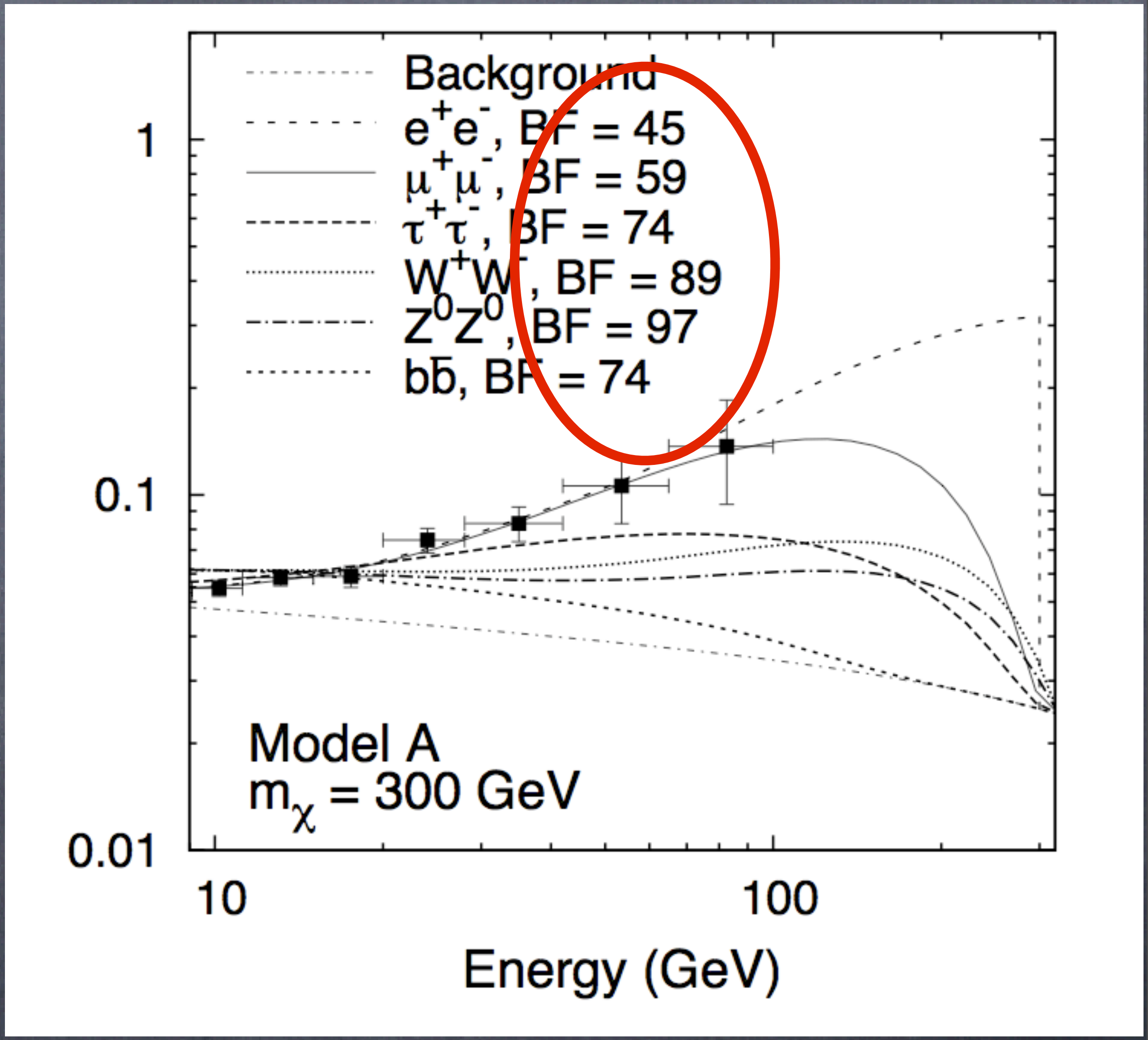

Explanations? (from DM)

- Issues to address
  - (1) Size of signal
  - (2) Hard positrons
  - (3) No antiprotons
- Dark matter could be produced non-thermally (gets 1, model build for 2/3)
- Dark matter could decay (gets 1, model build 2/3)
- Dark matter could interact through new, GeV scale force (gets 1,2,3, model build GeV scale)

New Dark Forces

- Revisit XDM setup: theory has light mediator Φ
- Mass must be below ~ GeV, what are consequences?

New forces = new annihilation modes

Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

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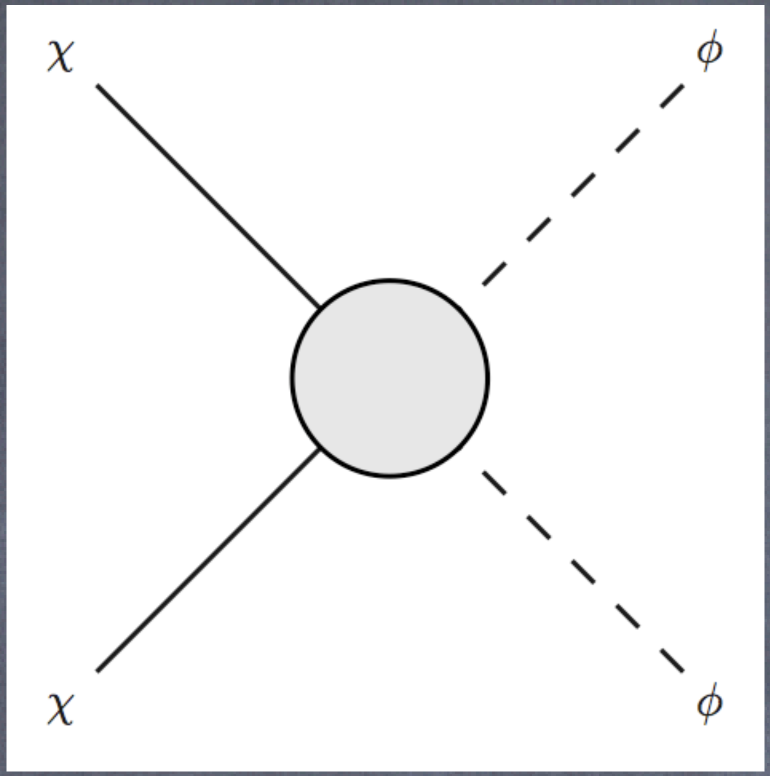

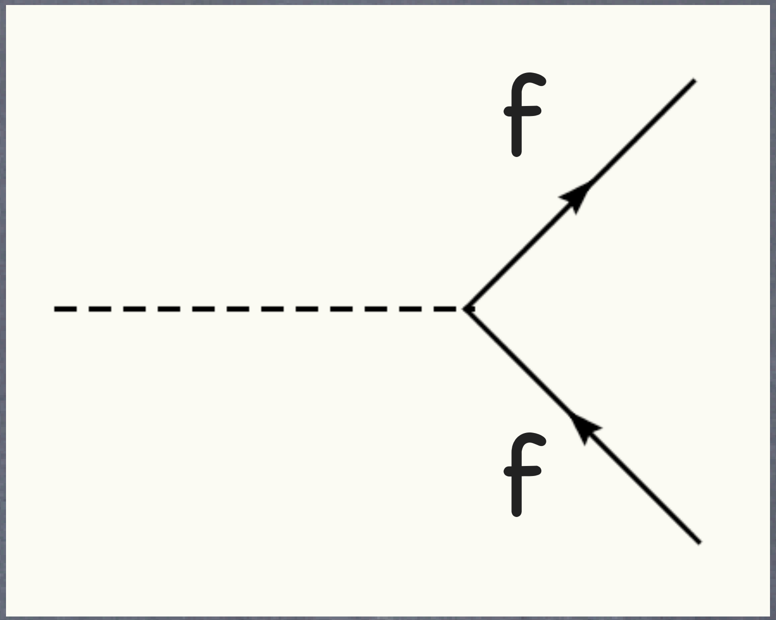

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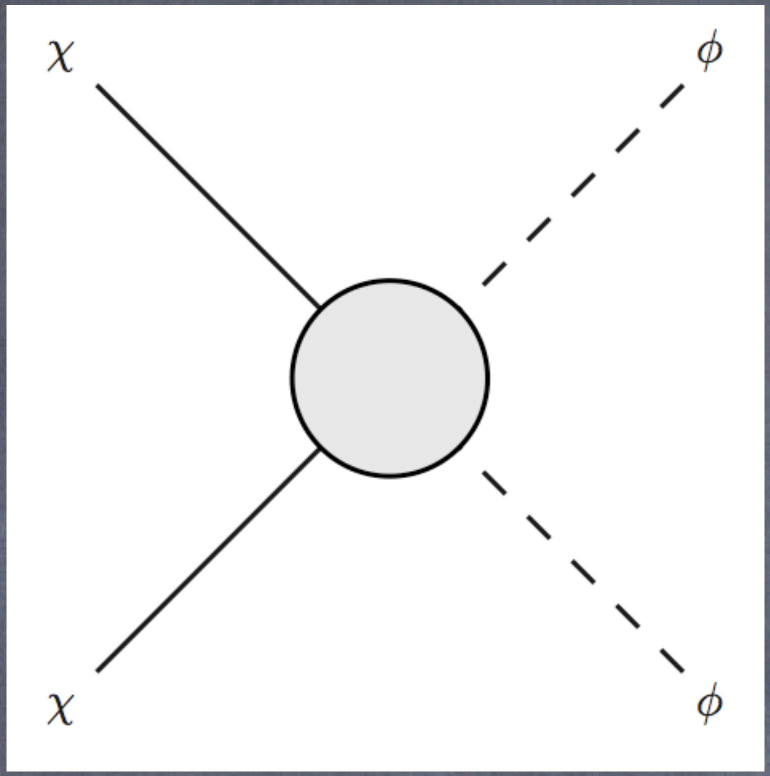

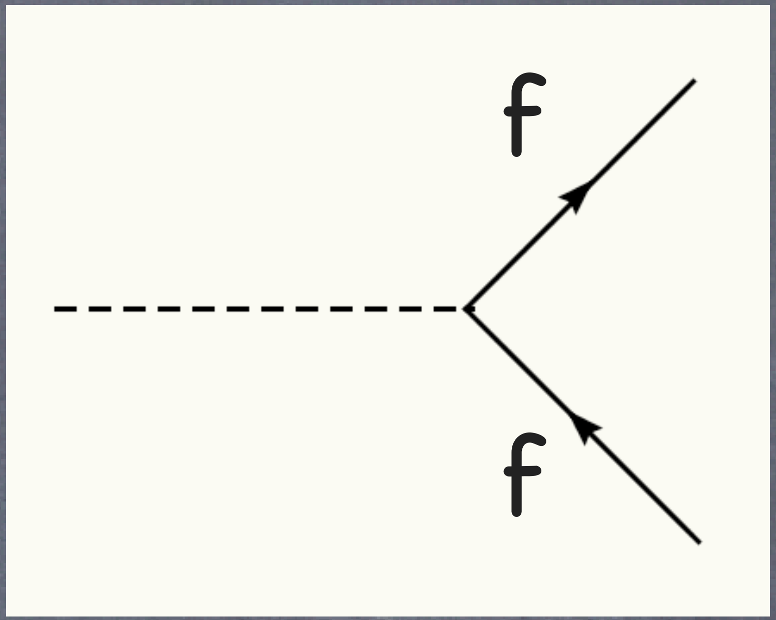

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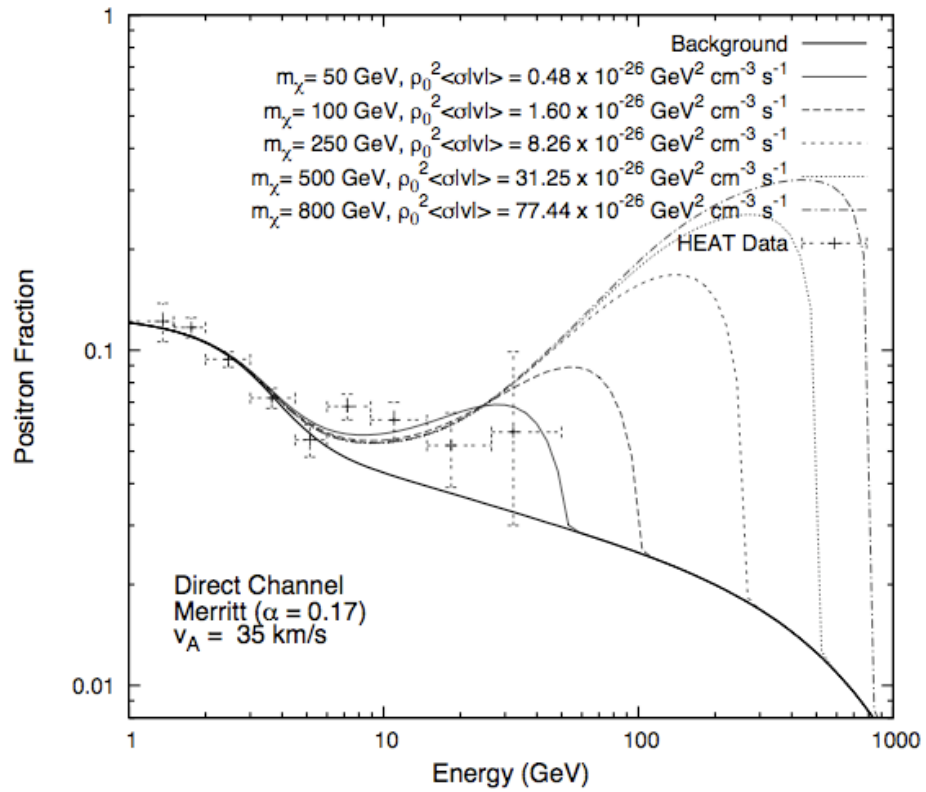

(c)Direct decay channel, $v_A = 35$ km/s

Cholis, Goodenough, NW, arxiv:0802.2922

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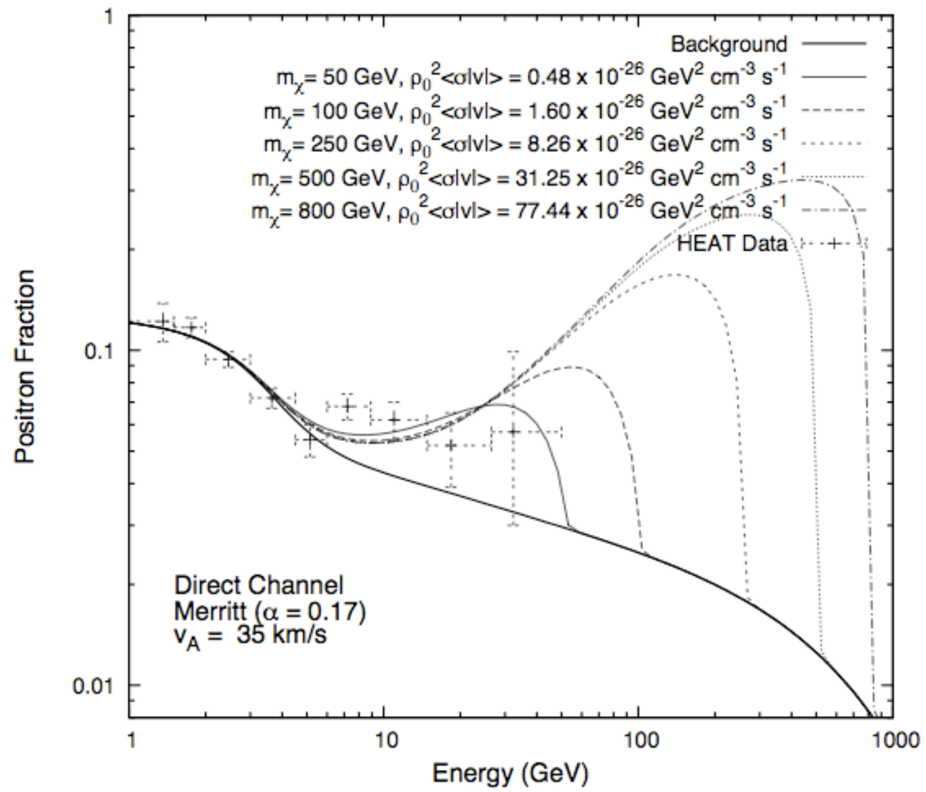

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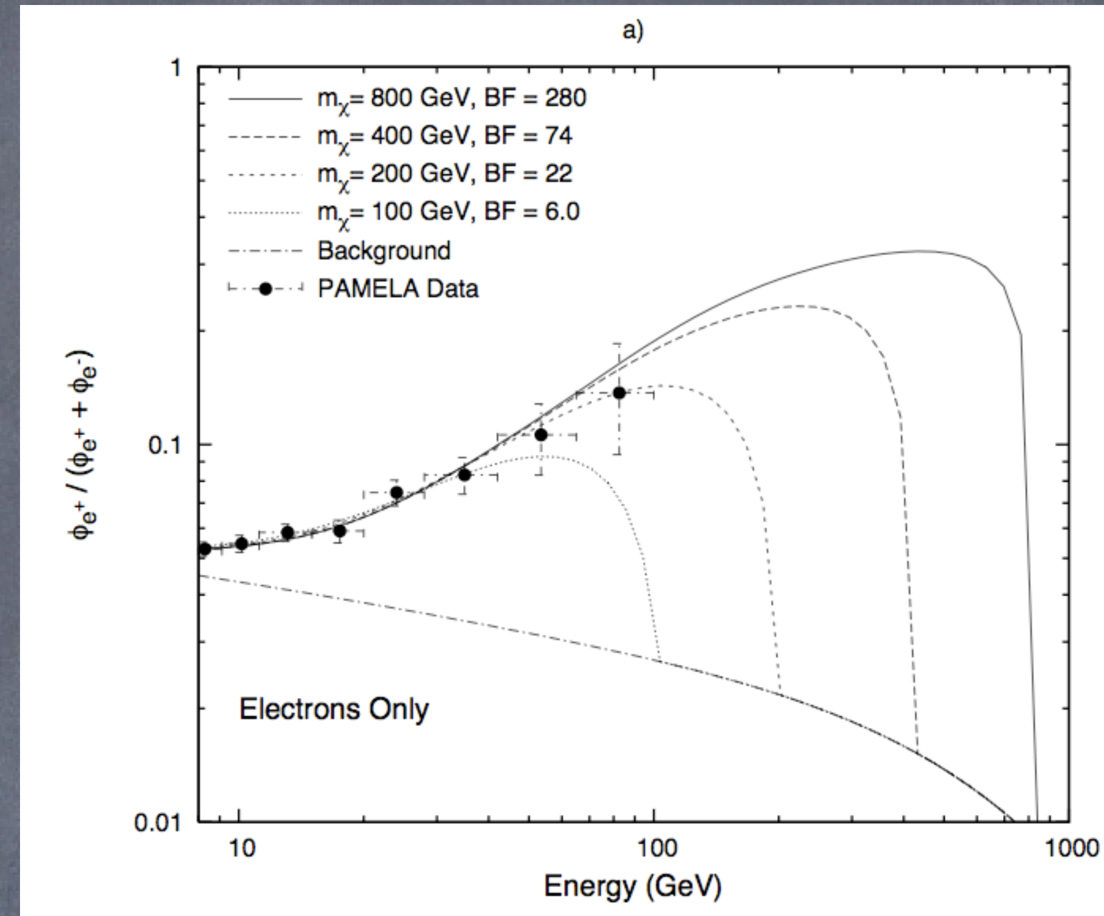

Cholis, et al, arxiv:0810.5344

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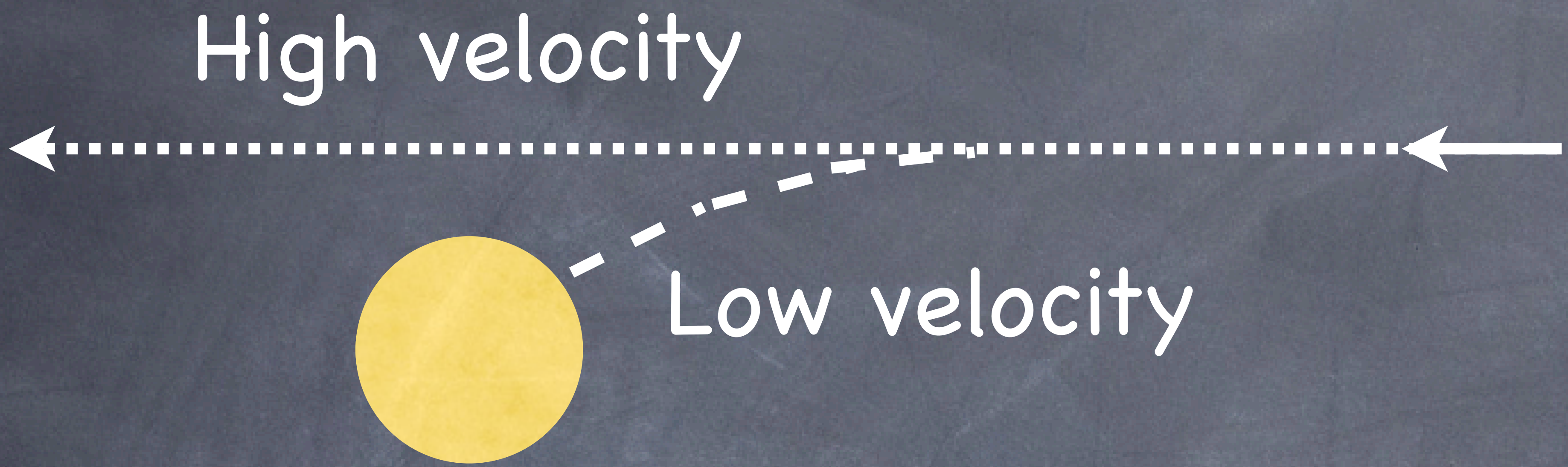
Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

Sommerfeld Enhancement

High velocity

Arkani-Hamed, Finkbeiner, Slatyer, NW, '08; Pospelov, Ritz '08

Sommerfeld Enhancement



Arkani-Hamed, Finkbeiner, Slatyer, NW, '08; Pospelov, Ritz '08

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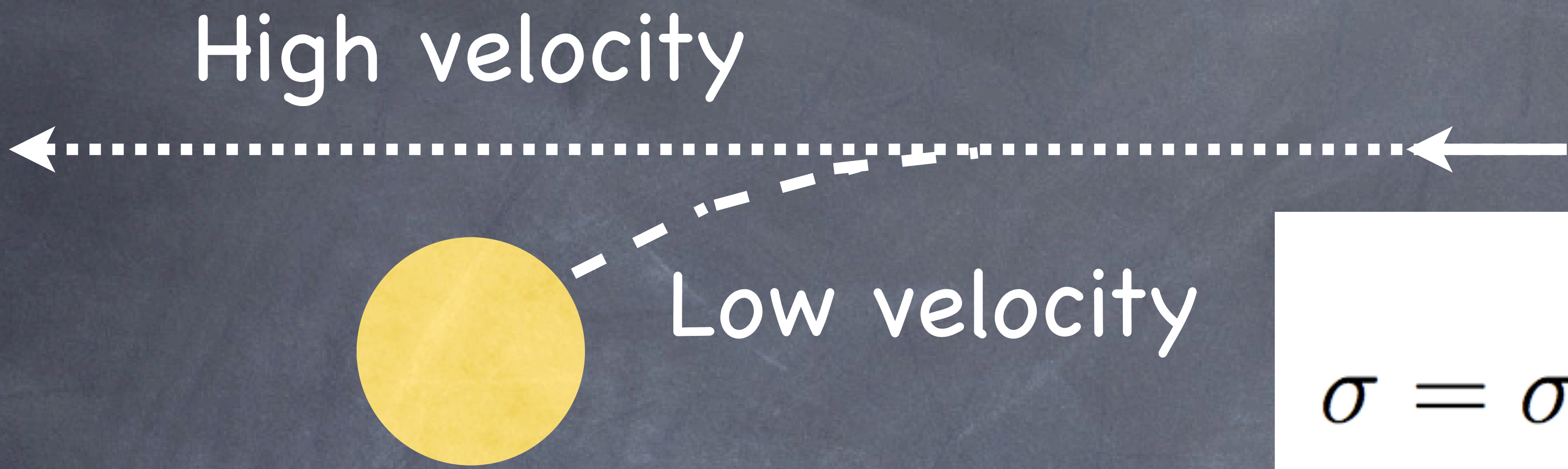
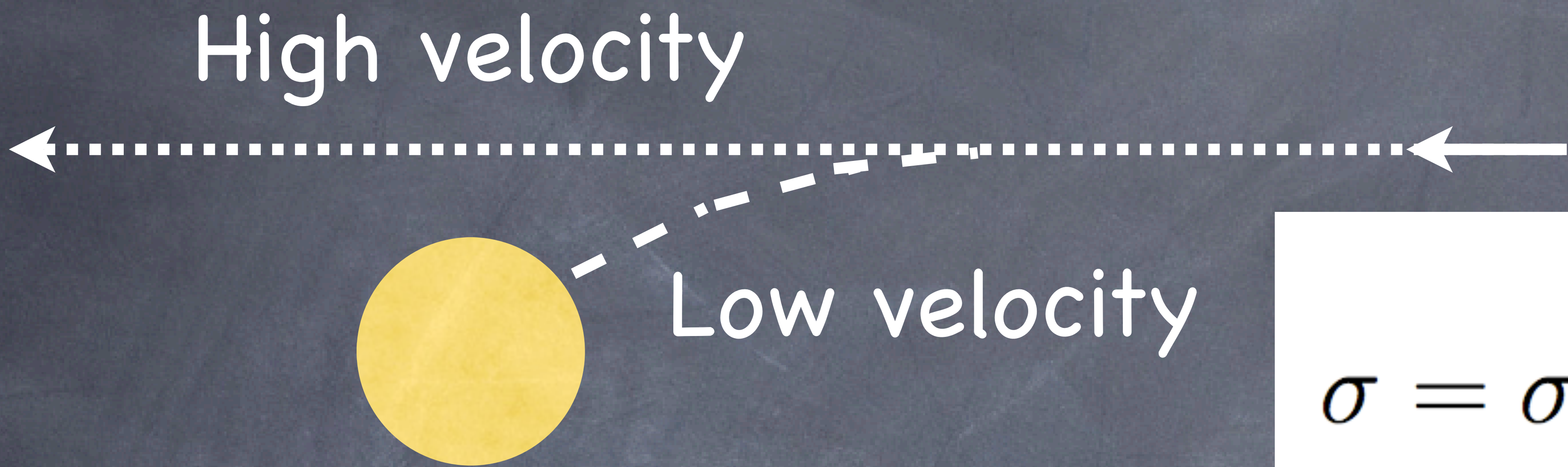


$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2}\right)$$

Arkani-Hamed, Finkbeiner, Slatyer, NW, '08; Pospelov, Ritz '08

Sommerfeld Enhancement



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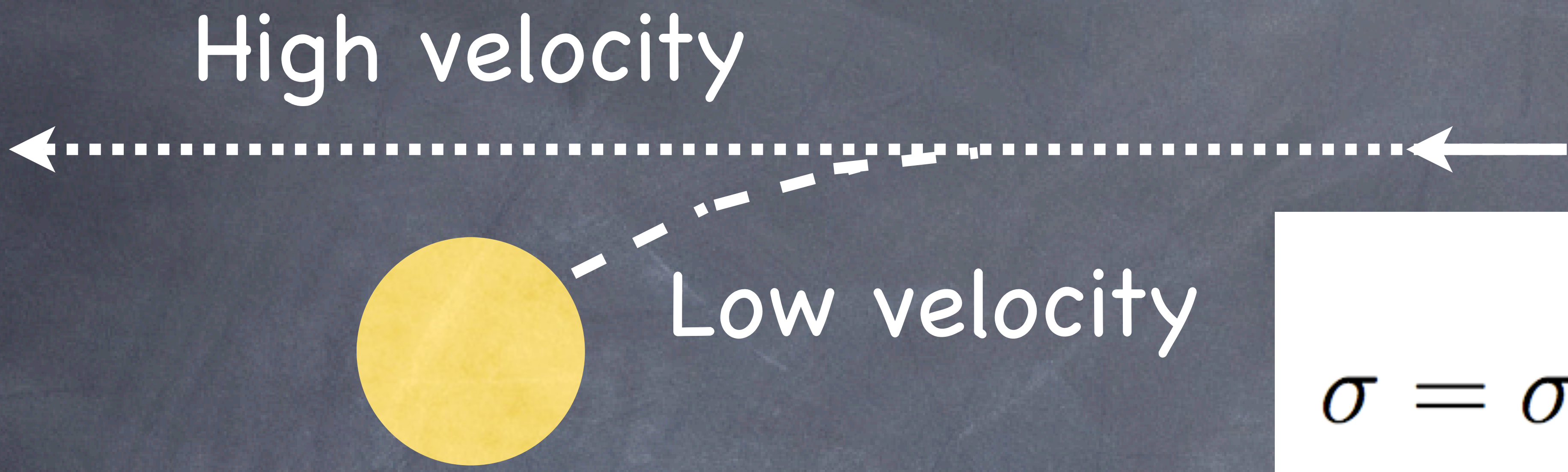
If particles interact via a "long range" force, cross sections can be much larger than the perturbative cross section

Arkani-Hamed, Finkbeiner, Slatyer, NW, '08; Pospelov, Ritz '08

Sommerfeld Enhancement



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If these signals arise from thermal dark matter, dark matter must have a long range force

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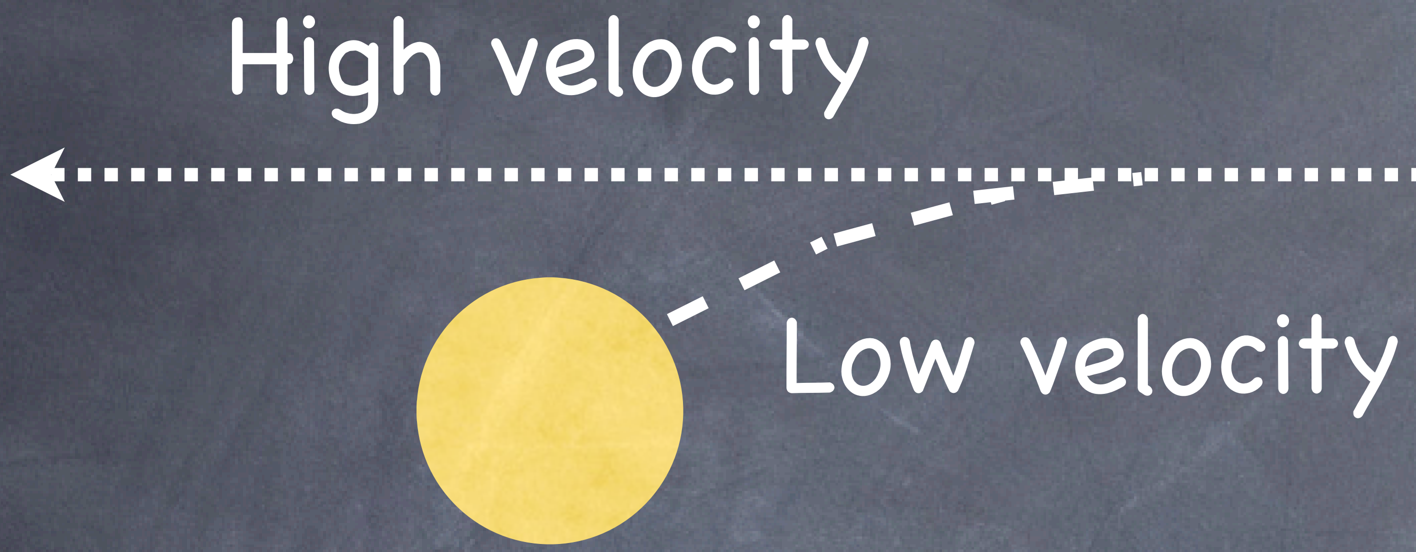

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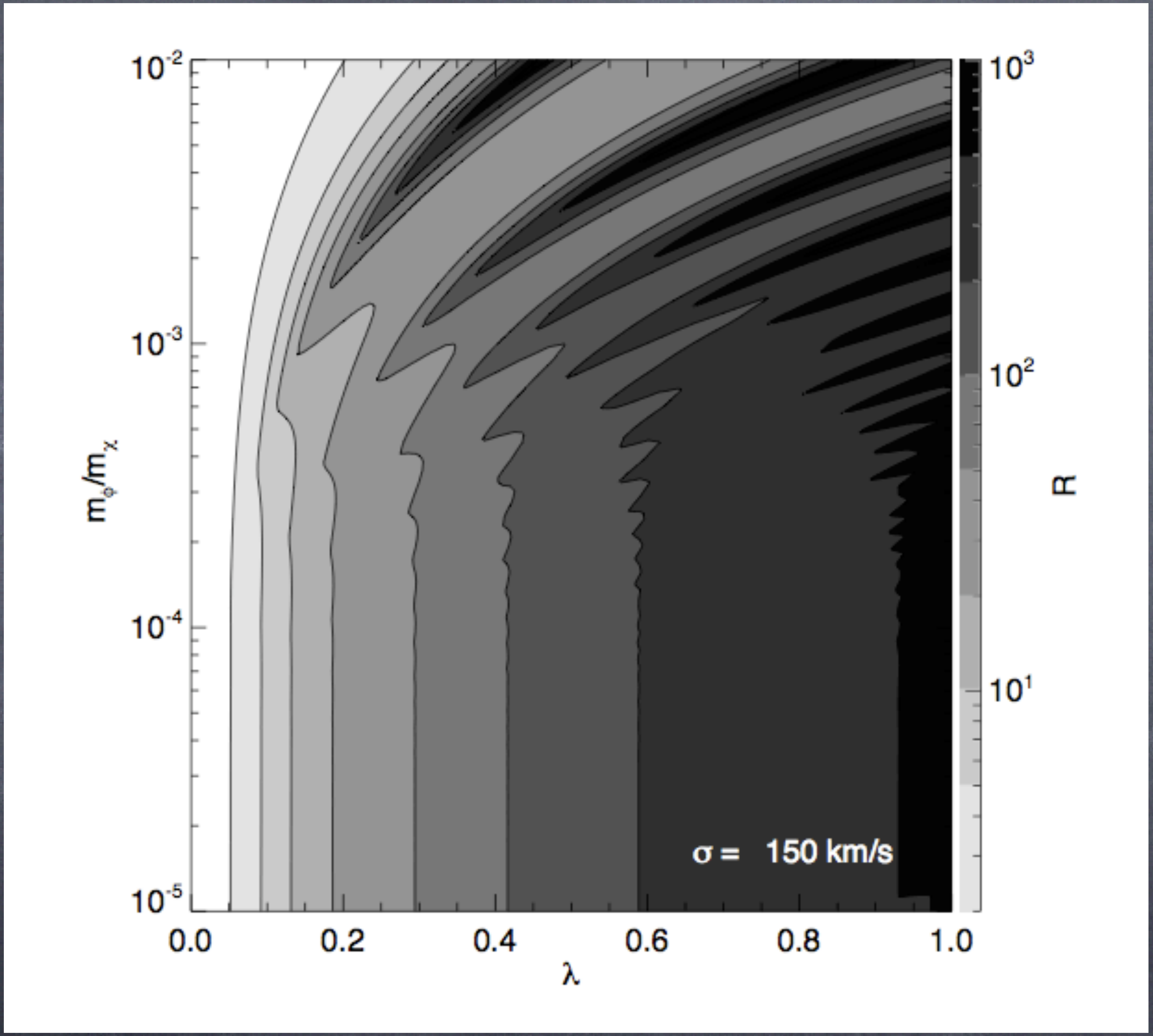
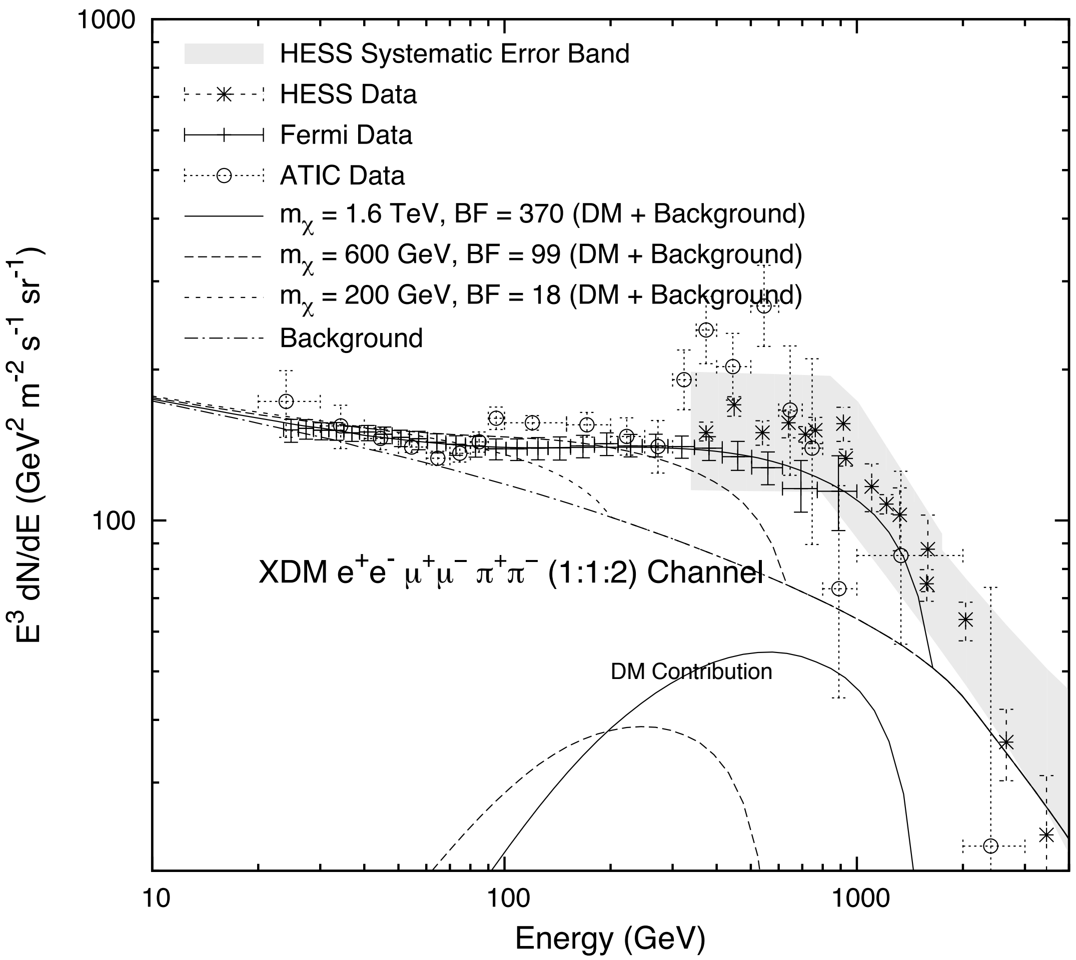
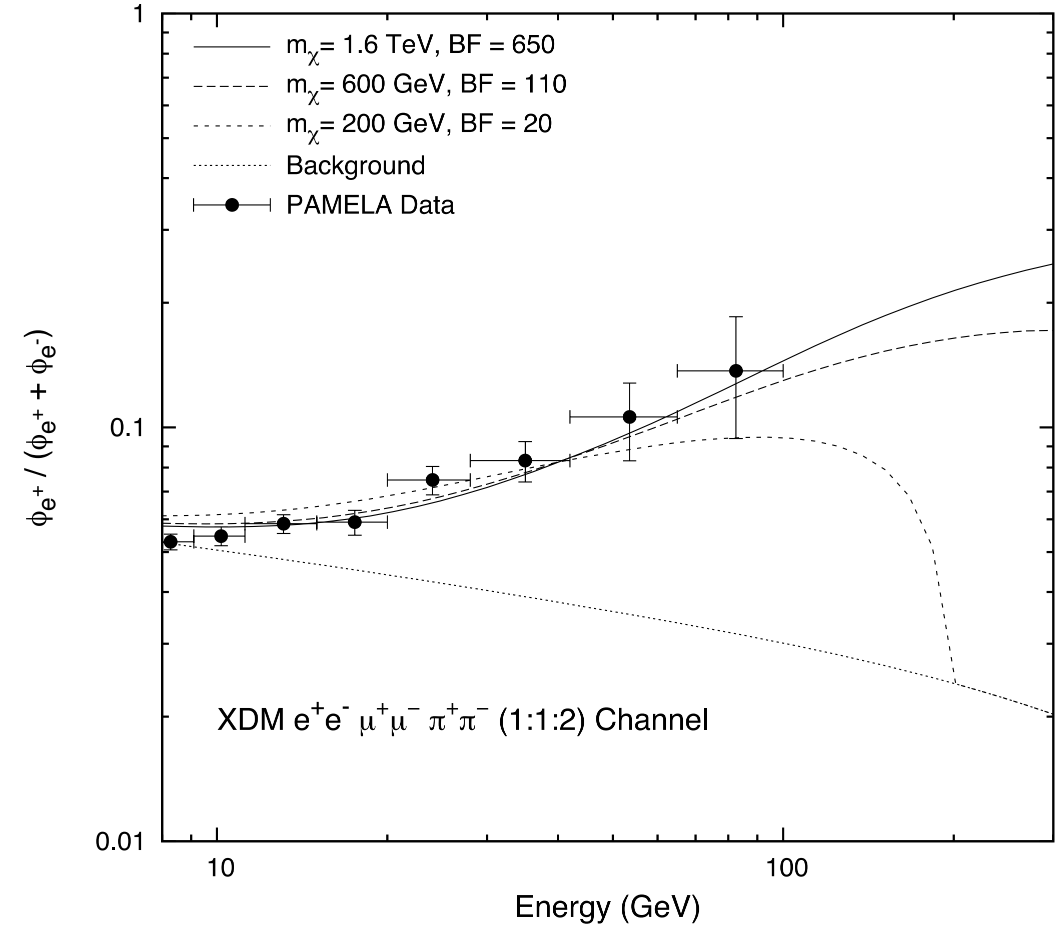
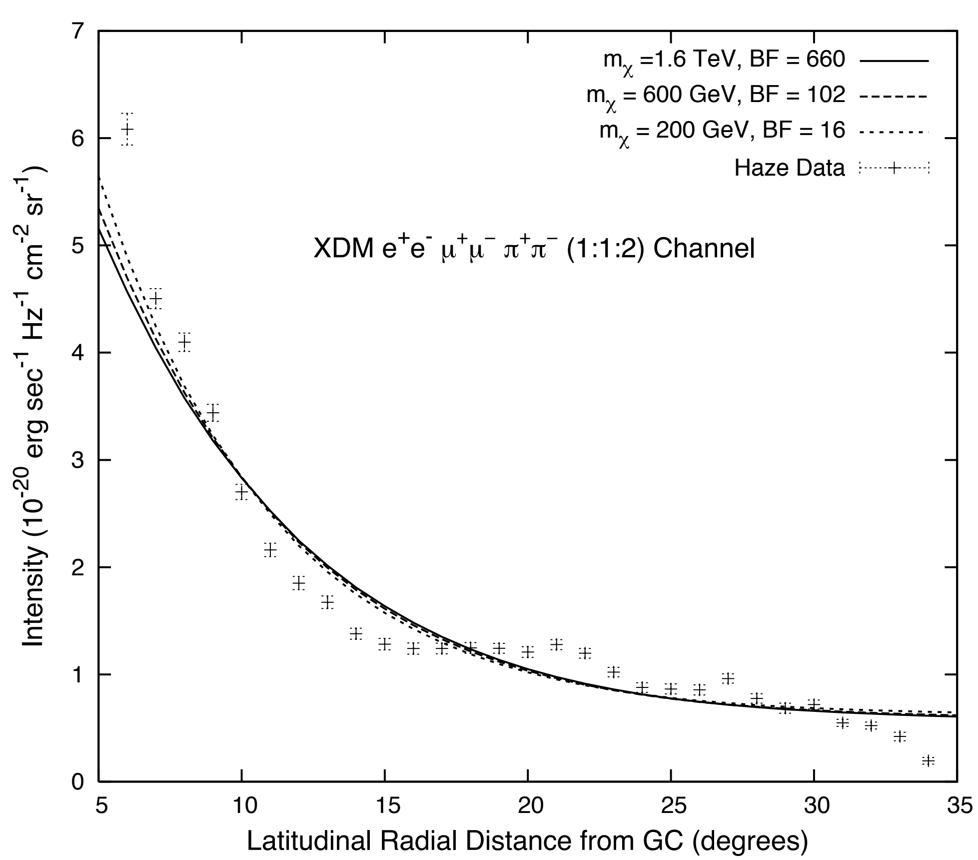
$$m_\phi^{-1} \gtrsim (\alpha M_{DM})^{-1}$$

Arkani-Hamed, Finkbeiner, Slatyer, NW, '08; Pospelov, Ritz '08


10^{-2}
10^{-3}
10^{-4}
10^{-5}
m_ϕ/m_χ
0.0
0.2
0.4
0.6
0.8
1.0
λ
10^3
10^2
10^1
R
σ = 150 km/s

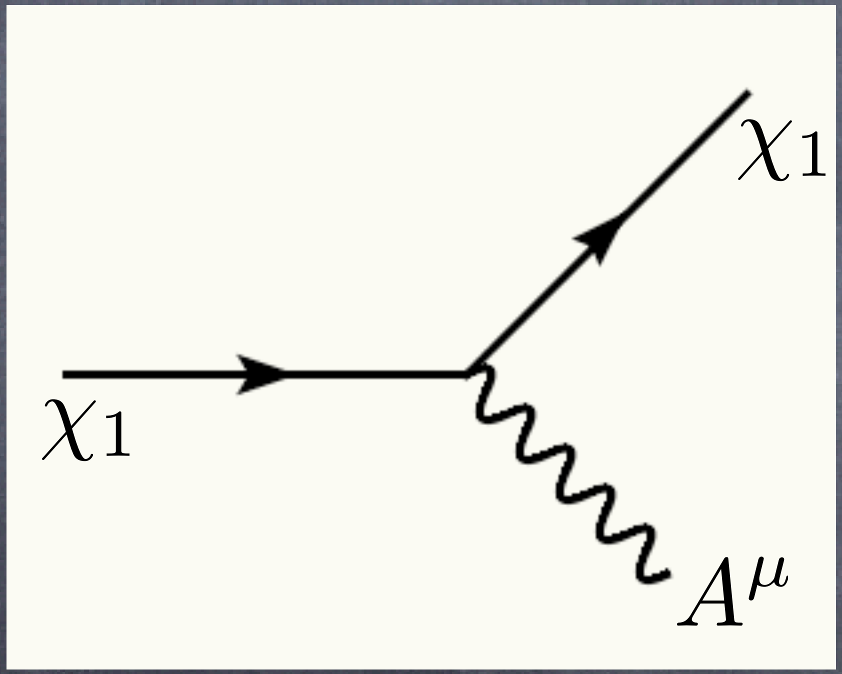

HESS Systematic Error Band
HESS Data
Fermi Data
ATIC Data
m_χ = 1.6 TeV, BF = 370 (DM + Background)
m_χ = 600 GeV, BF = 99 (DM + Background)
m_χ = 200 GeV, BF = 18 (DM + Background)
Background
XDM e^+e^- $\mu^+\mu^-$ $\pi^+\pi^-$ (1:1:2) Channel
DM Contribution
E^3 dN/dE (GeV^2 m^{-2} s^{-1} sr^{-1})
Energy (GeV)
1000
100
10
100
1000


m_χ= 1.6 TeV, BF = 650
m_χ= 600 GeV, BF = 110
m_χ= 200 GeV, BF = 20
Background
PAMELA Data
XDM e^+e^- $\mu^+\mu^-$ $\pi^+\pi^-$ (1:1:2) Channel
ϕ_{e^+} / (ϕ_{e^+} + ϕ_{e^-})
Energy (GeV)
1
0.1
0.01
10
100


m_χ =1.6 TeV, BF = 660
m_χ = 600 GeV, BF = 102
m_χ = 200 GeV, BF = 16
Haze Data
XDM e^+e^- $\mu^+\mu^-$ $\pi^+\pi^-$ (1:1:2) Channel
Intensity (10^{-20} erg sec^{-1} Hz^{-1} cm^{-2} sr^{-1})
Latitudinal Radial Distance from GC (degrees)
0
1
2
3
4
5
6
7
5
10
15
20
25
30
35

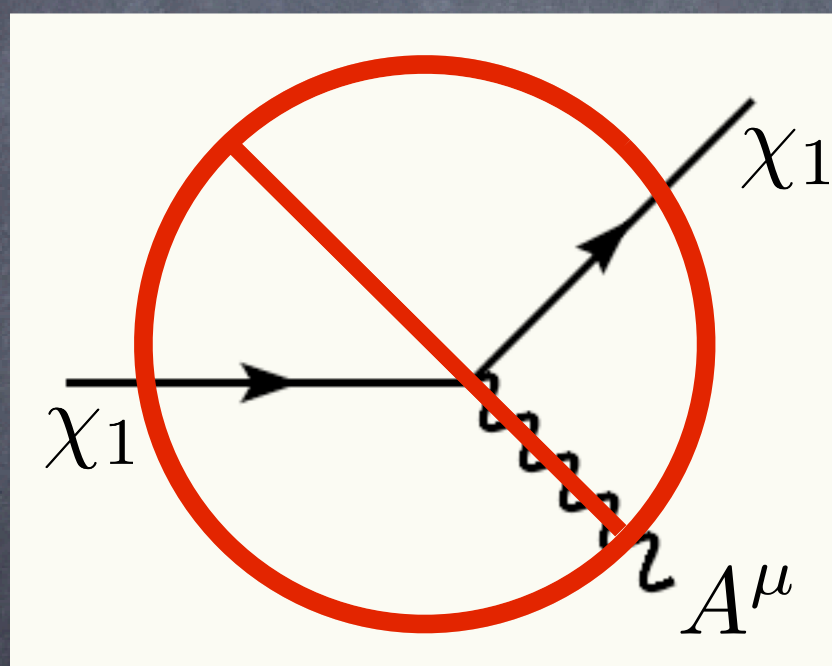
Consider vector interaction

$\chi_1 \sigma_\mu \chi_1 A^\mu$



Consider vector interaction

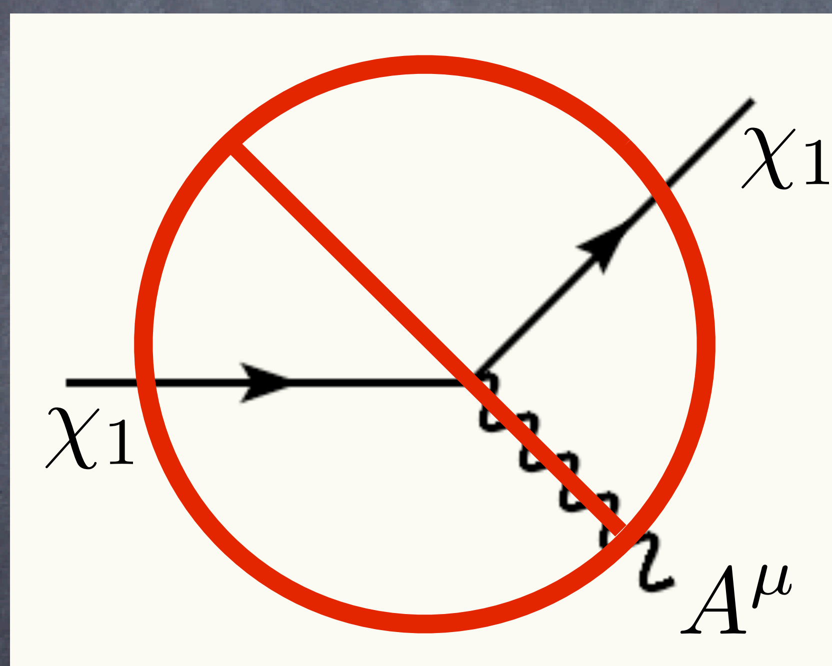
$\cancel{\chi_1 \sigma_\mu \chi_1 A^\mu}$

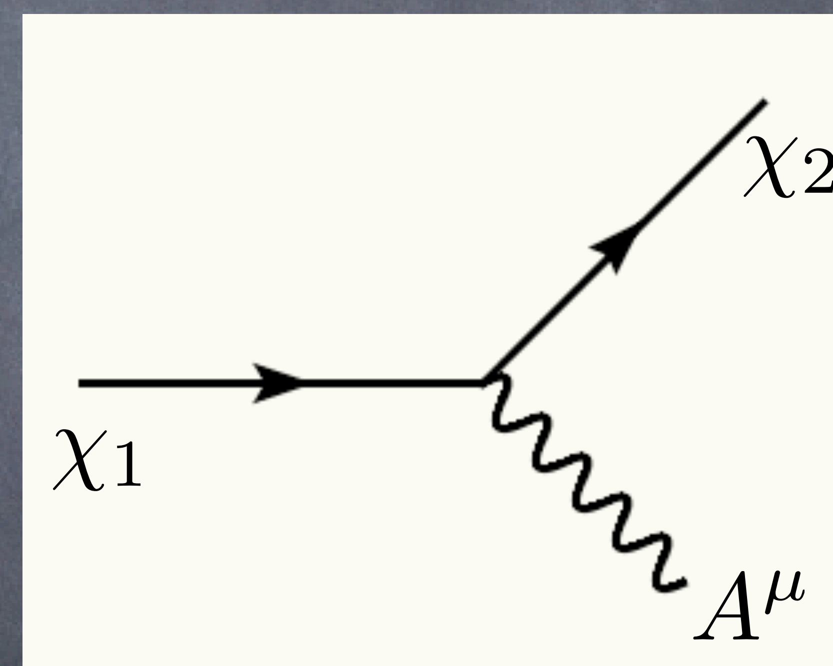


Consider vector interaction

$\cancel{\chi_1\sigma_\mu\chi_1 A^\mu}$

$\chi_1\sigma_\mu\chi_2 A^\mu$

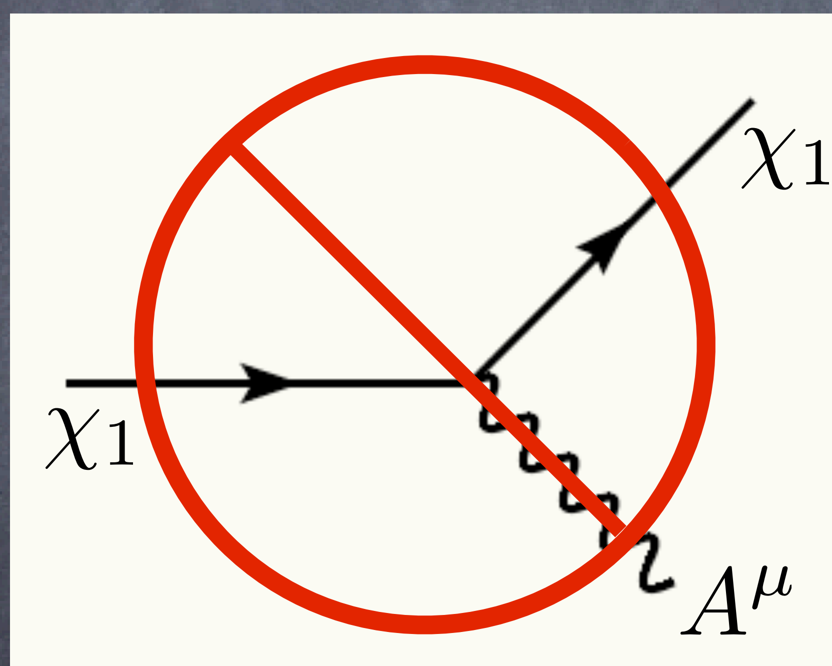


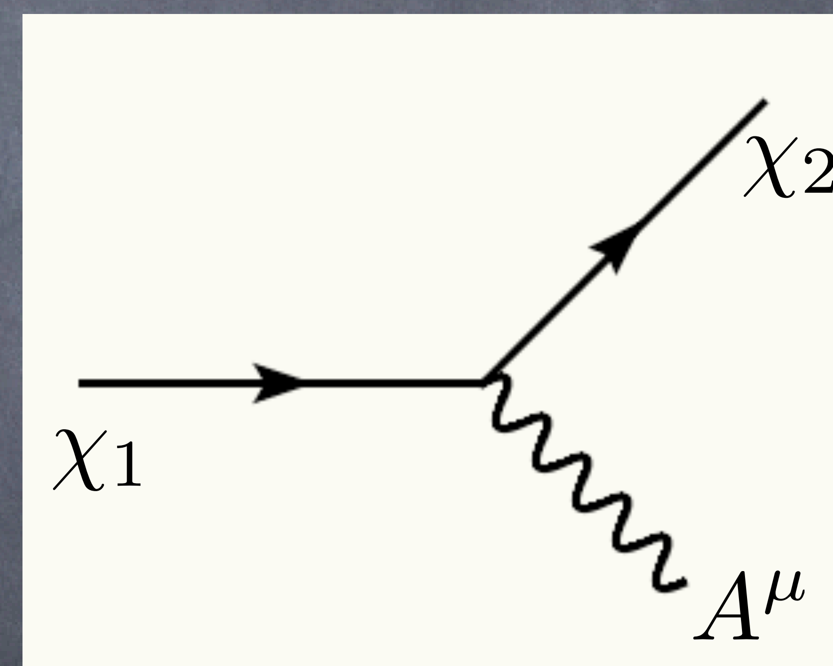


Consider vector interaction

$\cancel{\chi_1\sigma_\mu\chi_1 A^\mu}$

$\chi_1\sigma_\mu\chi_2 A^\mu$



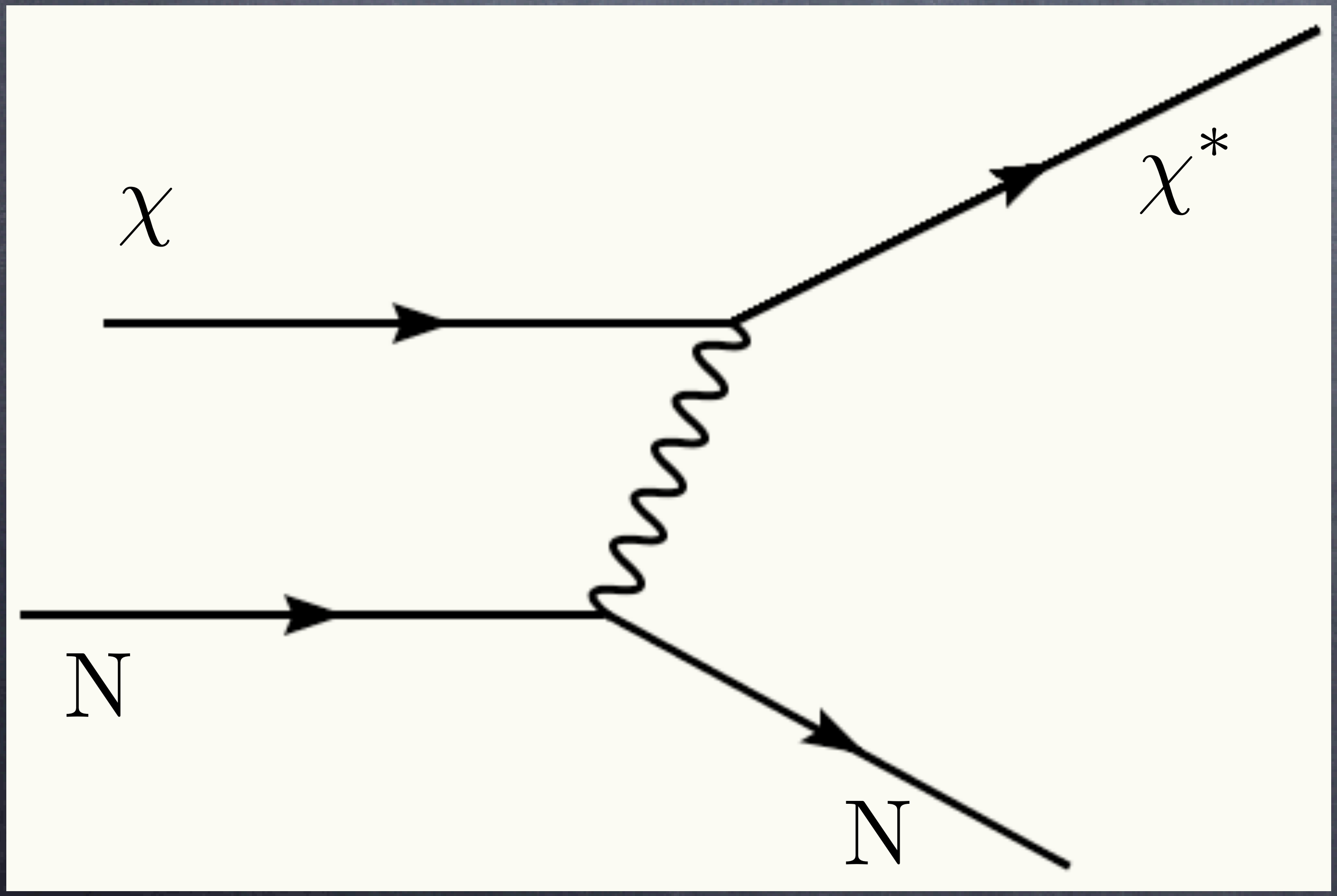


Vector interactions for massive WIMPs ($M_{DM}>M_{force}$) **always** require multiple states interaction is off-diagonal

"Inelastic" dark matter

D.Tucker-Smith, NW, **Phys.Rev.D64:043502,2001;Phys.Rev.D72:063509,2005**

- DM-nucleus scattering must be inelastic
- If dark matter can only scatter off of a nucleus by transitioning to an excited state (100 keV), the kinematics are changed dramatically



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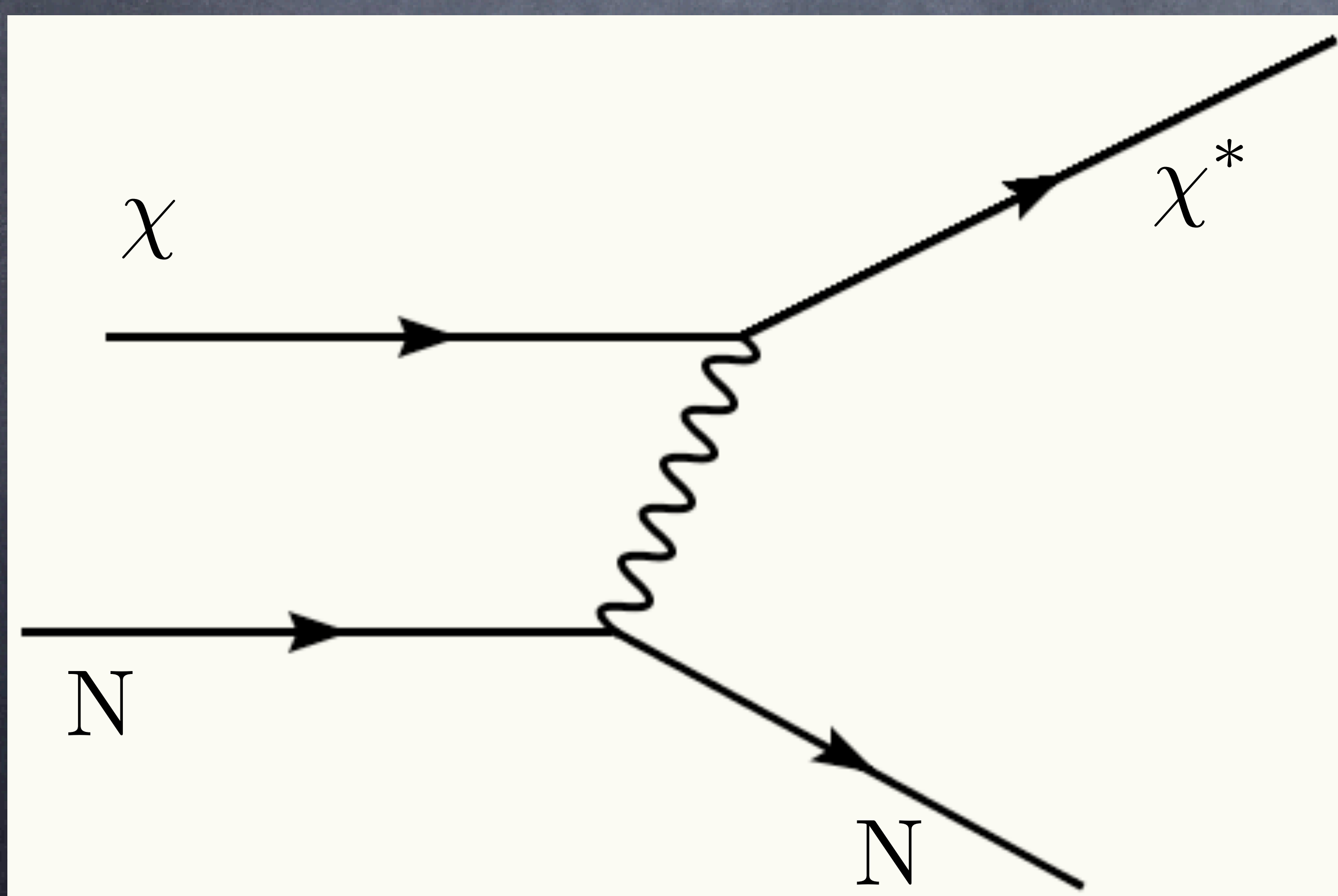


$$\frac{v^2 \mu_{\chi N}}{2} > \delta$$

- Nice because same GeV mediator gives all aspects of the anomalies (size, leptons, no antiprotons)
- Non-Abelian or multi-state models give natural explanation for all anomalies (INTEGRAL, DAMA, and e+e-)

Simplest mediator models

$$\epsilon F_{\mu\nu}^{dark} F_{EM}^{\mu\nu}$$

massless case Holdom, PLB '86

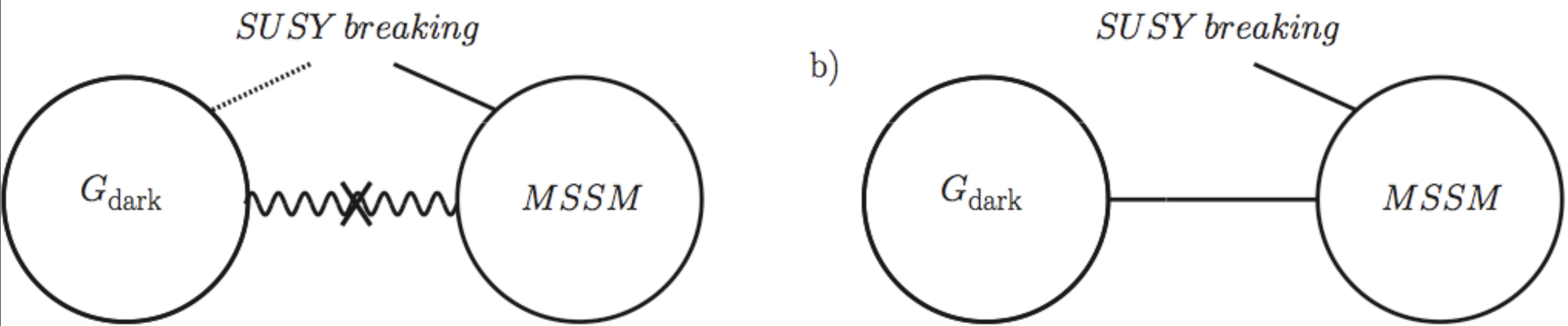
- Couples (massive) "dark photon" to charge
- Can introduce Abelian or non-Abelian
- Decays into electrons, muons, pions
- Also mixes with rho meson => larger BR

$$\phi \longrightarrow \pi^+\pi^-$$

Finding DM at the LHC

- Ordinary SUSY WIMPs: use cascades to LSP, look for missing energy
- What here?

What is this WIMP?



- Fits nicely into SUSY (esp gauge mediation)
- fm scale easily generated (mSUSY/16pi^2)

In SUSY

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Dark} + \mathcal{L}_{mix}$$

$$\mathcal{L}_{mix} = -\frac{1}{2}\epsilon f^{\mu\nu}_{Dark} F^{\mu\nu}$$

$$\epsilon' \bar{\eta} \bar{\sigma}^{\mu} \partial_{\mu} \chi_0$$

LSP_{SM} is weakly mixed with LSP_{dark}

New Collider Pheno: Lepton Jets

- Production of G_{dark} states, yield boosted, highly collimated leptons ("lepton jets")

Arkani-Hamed, NW, '08; Baumgart, Cheung, Ruderman, Wang, Yavin, ` 09; Bai, Han '09

cf "Hidden Valley" models, Strassler and Zurek '06

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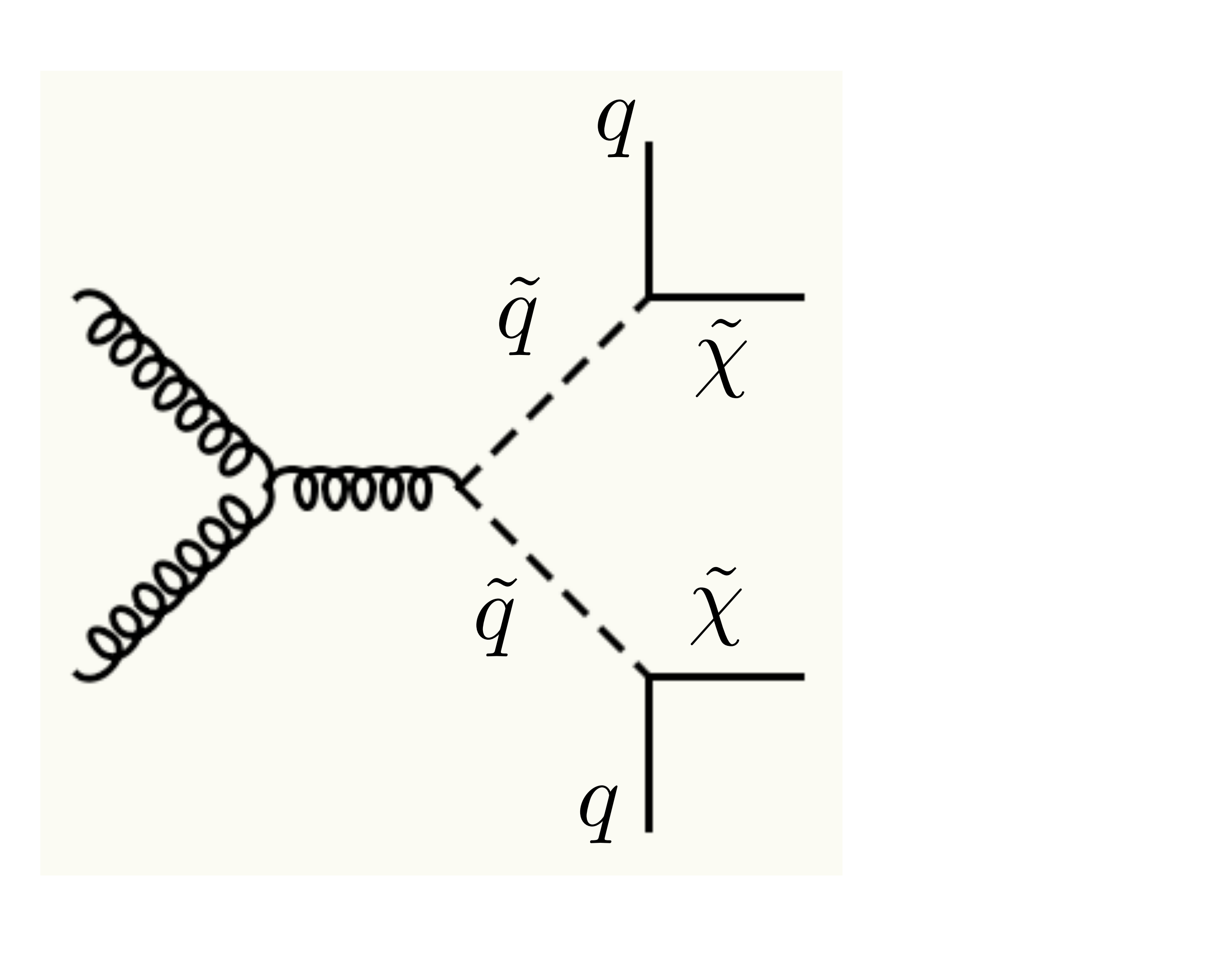

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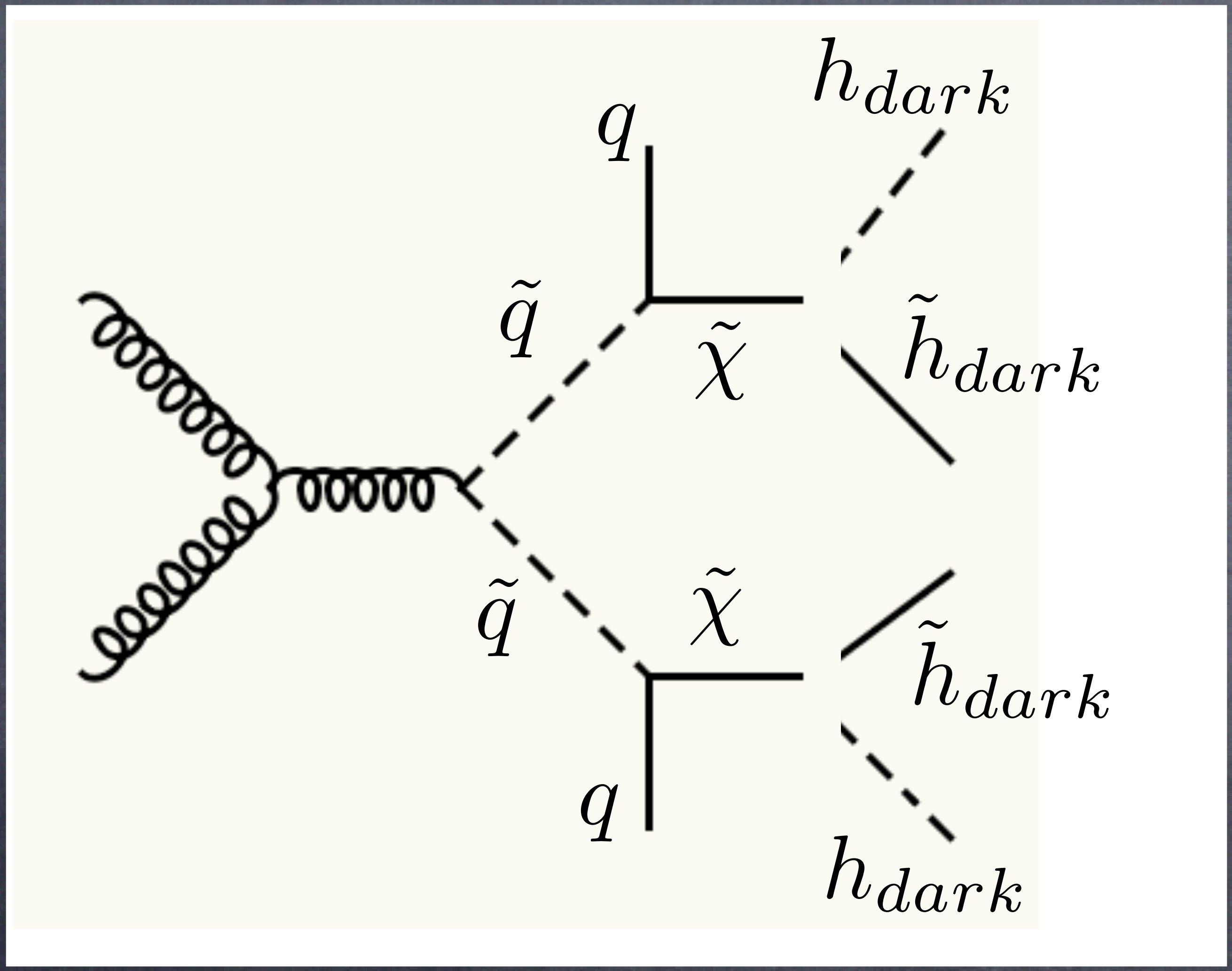
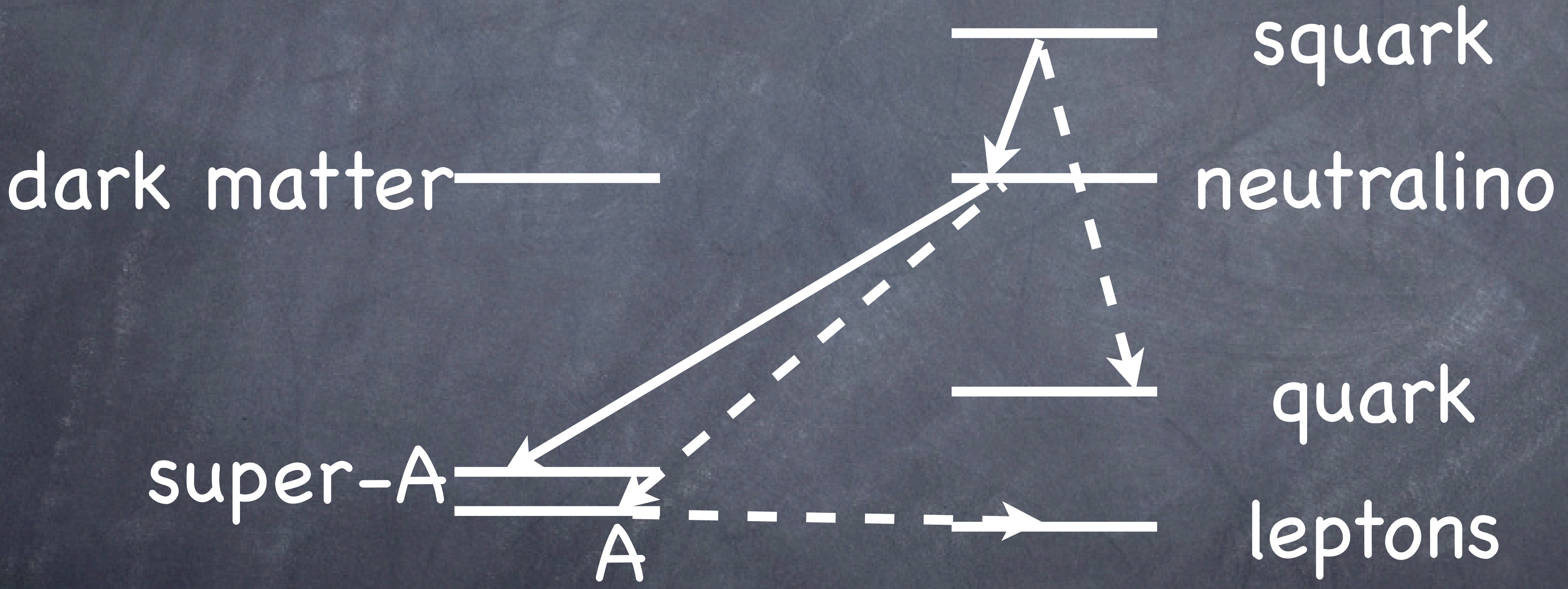


kinetic mixing induces decay LSP_{SM}->LSP_{dark}

cf "Hidden Valley" models, Strassler and Zurek '06

LHC?

- What happens if these states are produced at the LHC?



N.Arkani-Hamed, NW, arXiv:0810.0714

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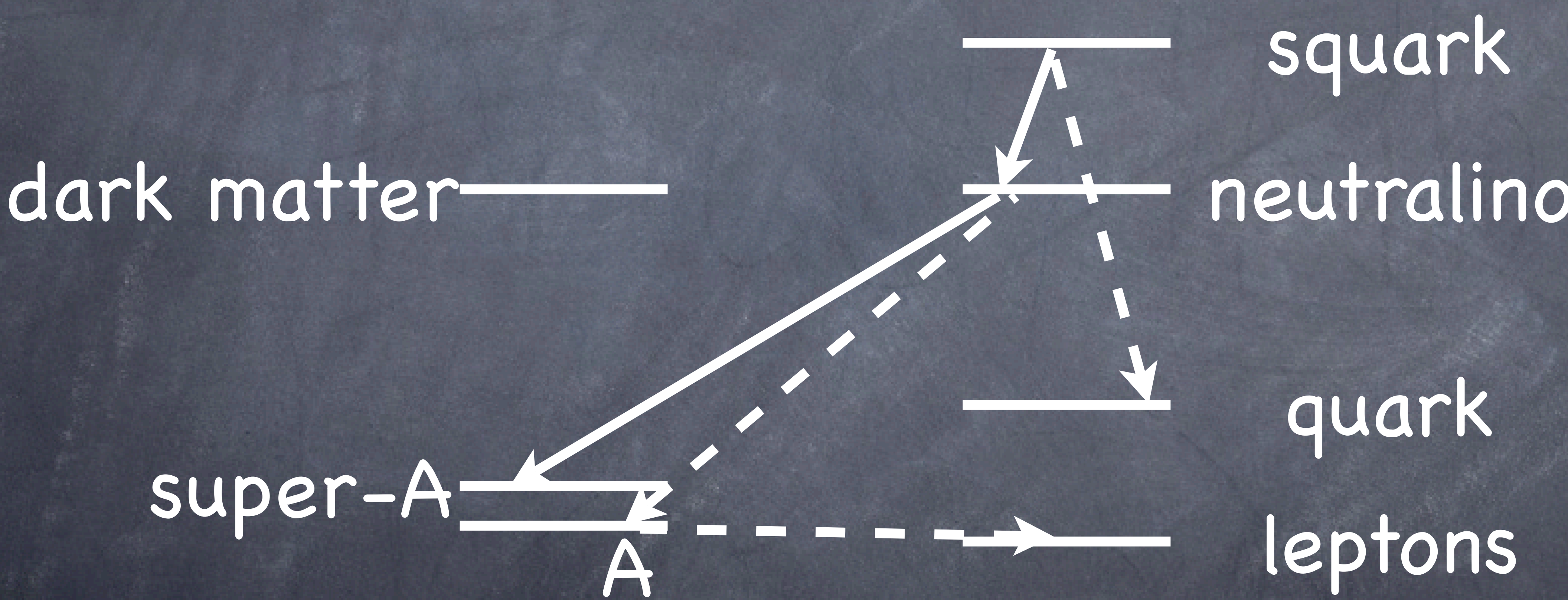

$$\tau \sim (\alpha \epsilon^2 m_{Z_{Dark}} N_{decaychannels})^{-1} \sim (\frac{10^{-7}}{\epsilon})^2 cm$$

N.Arkani-Hamed, NW, arXiv:0810.0714

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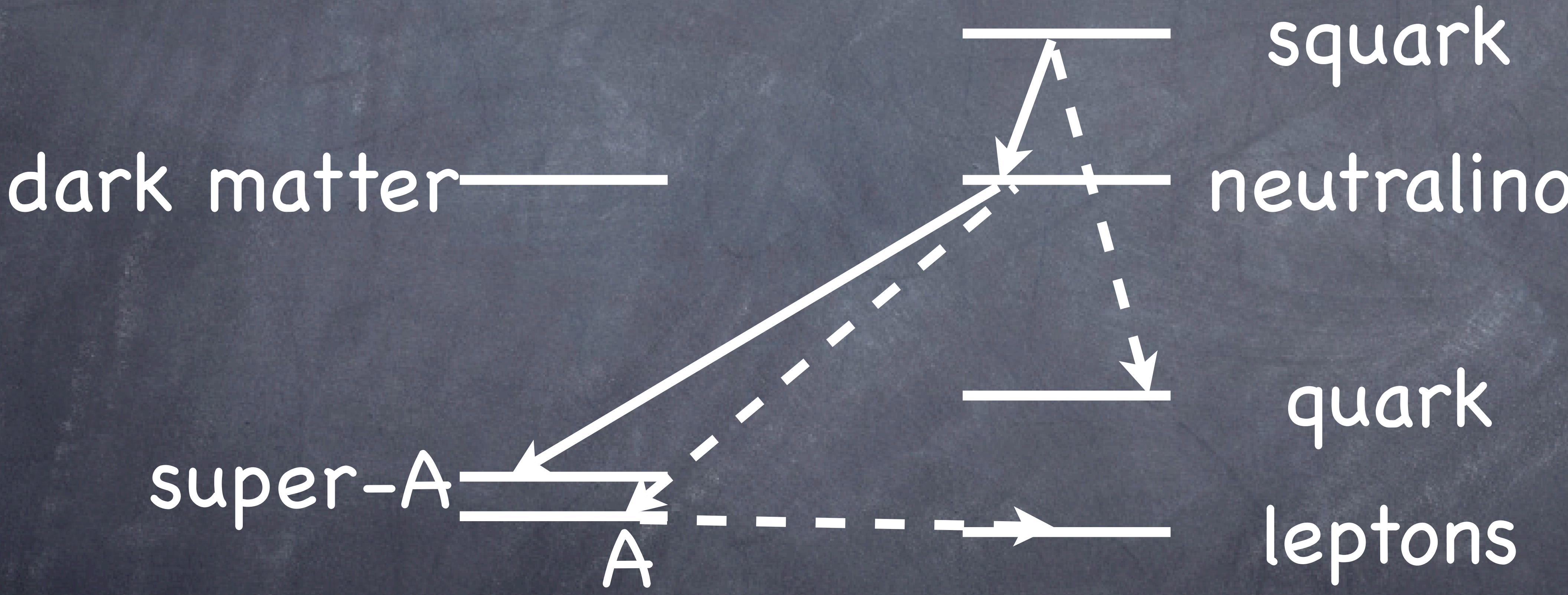
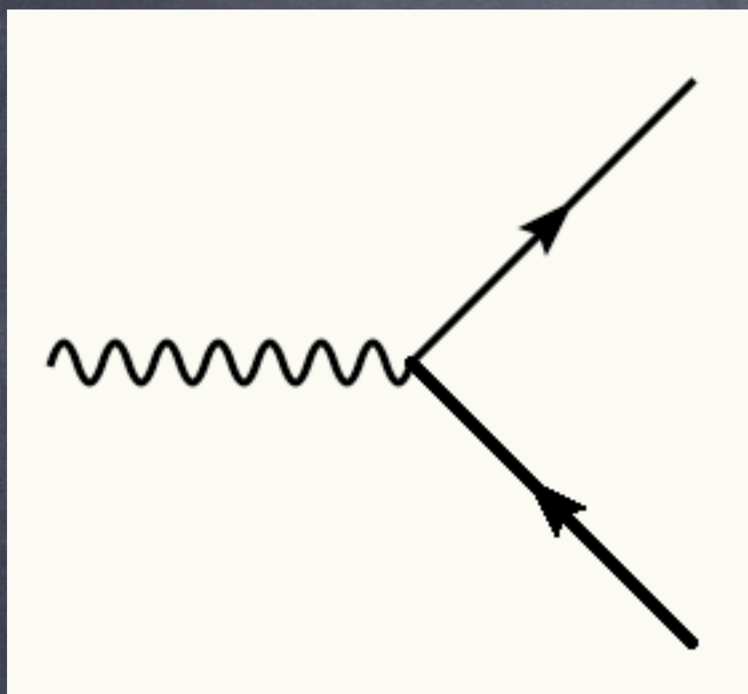


invariant mass ~GeV

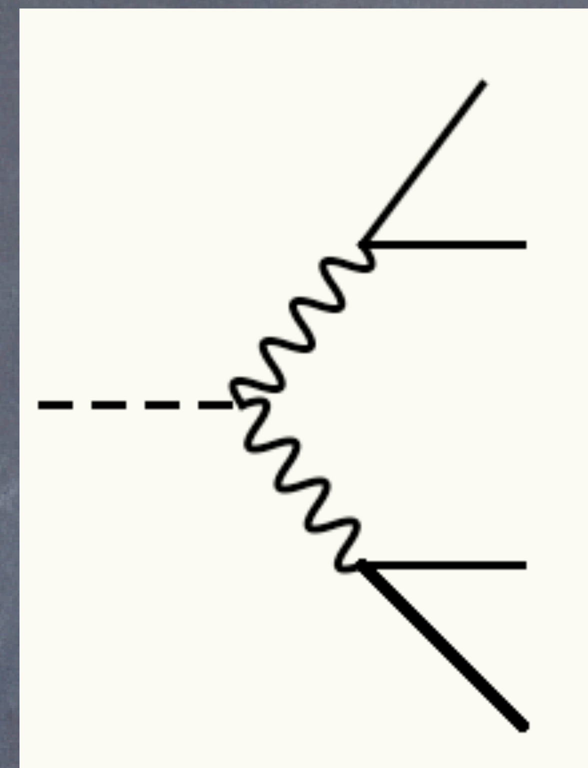
$$\tau \sim (\alpha\epsilon^2 m_{Z_{Dark}} N_{decaychannels})^{-1} \sim (\frac{10^{-7}}{\epsilon})^2 cm$$

N.Arkani-Hamed, NW, arXiv:0810.0714

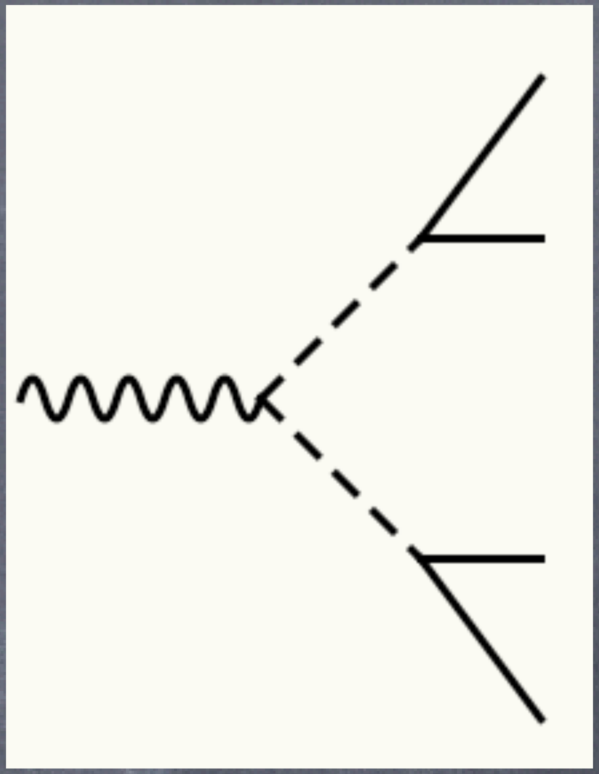
What kind of lepton jets?



Prompt/ displaced, resonance



Prompt/ displaced, non-resonance

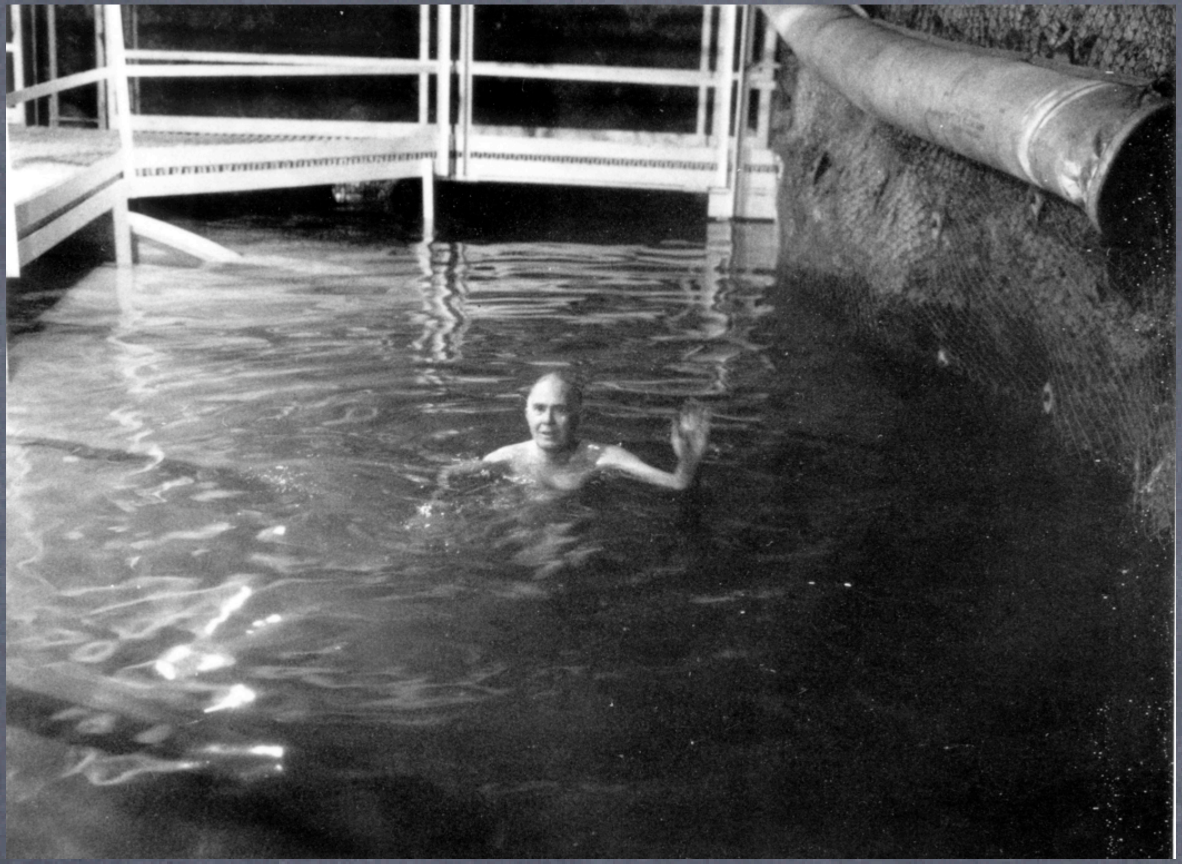


Displaced/ invisible, non-resonance

- Multiple types of objects can exist in the same theory (so not either/or)

- Missing Energy Signatures no longer **key** signal of DM sector
  - May nonetheless be present
- High energy, high multiplicity leptonic objects with low invariant mass may be signal of dark matter and new dark forces

Historical Perspective



VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M.D. Messier,[2] K. Scholberg,[2] J.L. Stone,[2] L.R. Sulak,[2] C.W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P.G. Halverson,[4,*] J. Hsu,[4] W.R. Kropp,[4] L.R. Price,[4] F. Reines,[4] M. Smy,[4] H.W. Sobel,[4] M.R. Vagins,[4] K.S. Ganezer,[5] W.E. Keig,[5] R.W. Ellsworth,[6] S. Tasaka,[7] J.W. Flanagan,[8,†] A. Kibayashi,[8] J.G. Learned,[8] S. Matsuno,[8] V.J. Stenger,[8] D. Takemori,[8] T. Ishii,[9] J. Kanzaki,[9] T. Kobayashi,[9] S. Mine,[9] K. Nakamura,[9] K. Nishikawa,[9] Y. Oyama,[9] A. Sakai,[9] M. Sakuda,[9] O. Sasaki,[9] S. Echigo,[10] M. Kohama,[10] A.T. Suzuki,[10] T.J. Haines,[11,4] E. Blaufuss,[12] B.K. Kim,[12] R. Sanford,[12] R. Svoboda,[12] M.L. Chen,[13] Z. Conner,[13,‡] J.A. Goodman,[13] G.W. Sullivan,[13] J. Hill,[14] C.K. Jung,[14] K. Martens,[14] C. Mauger,[14] C. McGrew,[14] E. Sharkey,[14] B. Viren,[14] C. Yanagisawa,[14] W. Doki,[15] K. Miyano,[15] H. Okazawa,[15] C. Saji,[15] M. Takahata,[15] Y. Nagashima,[16] M. Takita,[16] T. Yamaguchi,[16] M. Yoshida,[16] S.B. Kim,[17] M. Etoh,[18] K. Fujita,[18] A. Hasegawa,[18] T. Hasegawa,[18] S. Hatakeyama,[18] T. Iwamoto,[18] M. Koga,[18] T. Maruyama,[18] H. Ogawa,[18] J. Shirai,[18] A. Suzuki,[18] F. Tsushima,[18] M. Koshiba,[19] M. Nemoto,[20] K. Nishijima,[20] T. Futagami,[21] Y. Hayato,[21,§] Y. Kanaya,[21] K. Kaneyuki,[21] Y. Watanabe,[21] D. Kielczewska,[22,4] R.A. Doyle,[23] J.S. George,[23] A.L. Stachyra,[23] L.L. Wai,[23,‖] R.J. Wilkes,[23] and K.K. Young[23]
(Super-Kamiokande Collaboration)

VOLUME 54, NUMBER 17 PHYSICAL REVIEW LETTERS 29 APRIL 1985

Evidence of Heavy-Neutrino Emission in Beta Decay

J. J. Simpson
Department of Physics and Guelph-Waterloo Program for Graduate Work in Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada
(Received 18 February 1985)

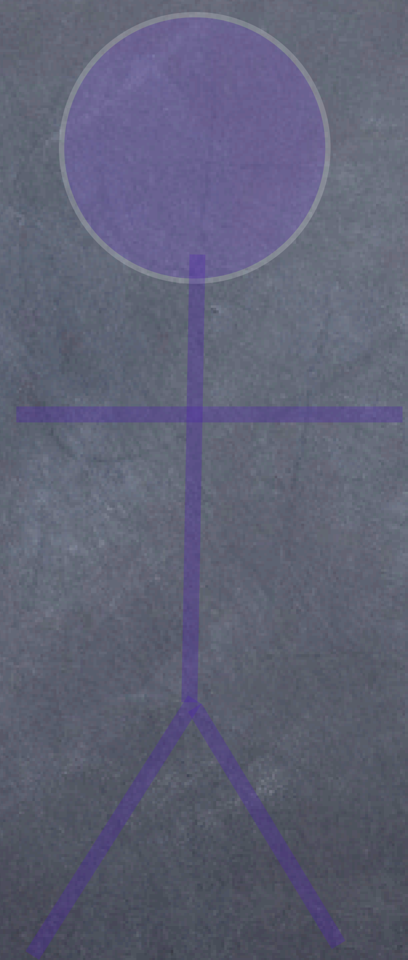
The observation of a distortion of the β spectrum of tritium is reported. This distortion is consistent with the emission of a neutrino of mass about 17.1 keV and a mixing probability of 3%.

PACS numbers: 23.40.Bw, 14.60.Gh, 27.10.+h

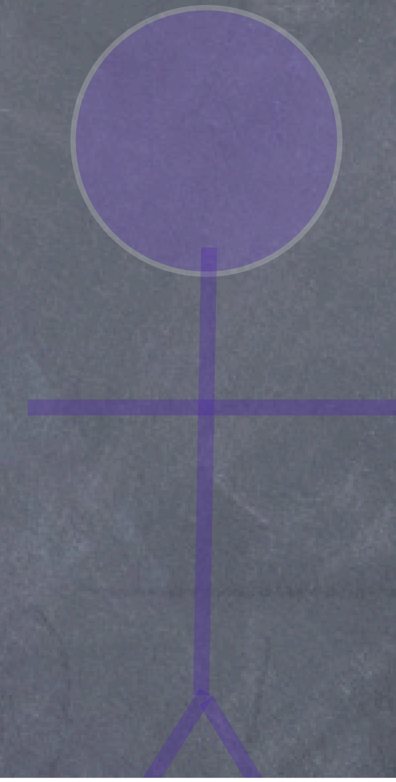
There is considerable interest today in whether neutrinos have mass or not. Since it has been known for some time that the energy spectra of β particles will

on the Mo $K\alpha$ x rays. The x rays which were incident upon the detector through the slot in an x-ray chopper wheel intermittently with a period of a minute were

Mr. Dark Matter



The future of high energy physics?

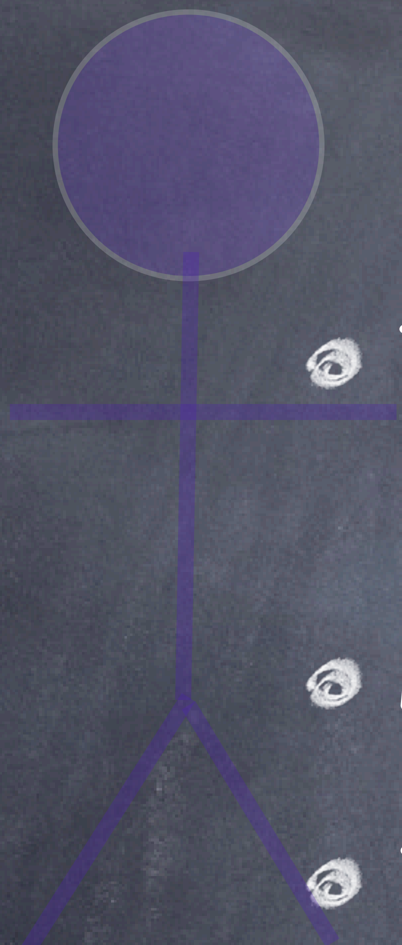


New physics (SUSY, etc)

↑ energy frontier

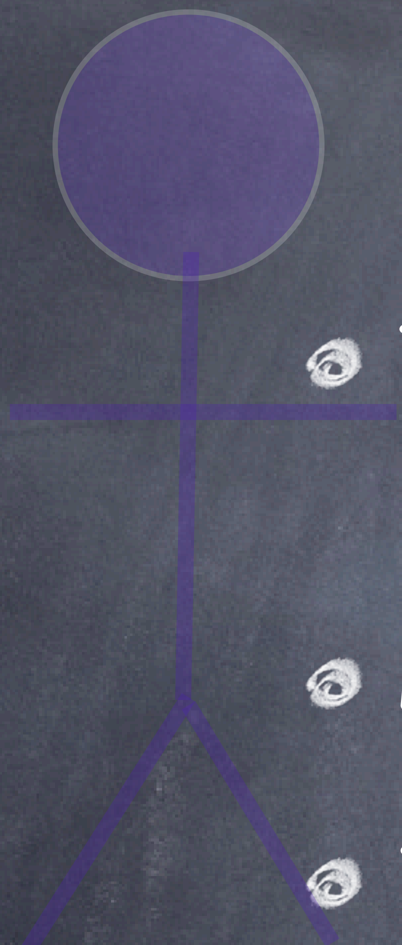
Standard model → Dark sector

luminosity frontier



- There are many anomalies out there, and maybe some have something to do with DM
- Maybe not
- Regardless, the range of DM models reminds us how little we really know about these things
- Experimental question: Fermi/GLAST, Planck, PAMELA, LHC, future DM detection experiments will answer all of these

Rethinking beyond the standard model



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Thank you very much!