Astrophysical Probes of Unification

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work with
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P. Graham and S. Rajendran
(arXiv: 0812.2075 and ongoing work)

An Interesting Time

Interesting data is coming on several fronts:

* LHC and the Tevatron
* Cosmic Rays (PAMELA, ATIC, Fermi, IceCube)
* Primordial Nuclear Abundances (^{7}Li and ^{6}Li)
* DM Direct Detection (CDMS, XENON, CRESST, DAMA,...)
* Flavor Physics
* Neutrino Physics
* INTEGRAL
* CMB ("Haze", re-ionization, power spectrum...)
* EDMs
* .....

Non trivial links among various experiments - a broad picture of HEP.

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this talk

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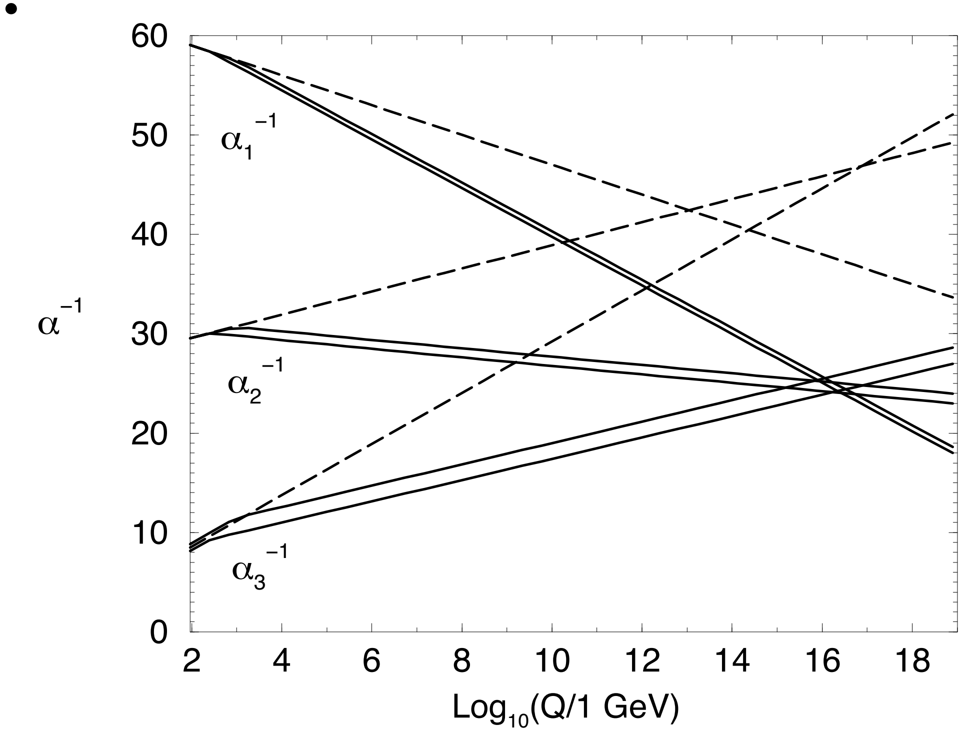
Non trivial links among various experiments - a broad picture of HEP.

Unification

* Supersymmetric Unification is an elegant and experimentally successful idea.

* Suggests new dynamics at high energies ~10^{16} GeV.

How can we probe such high scales?



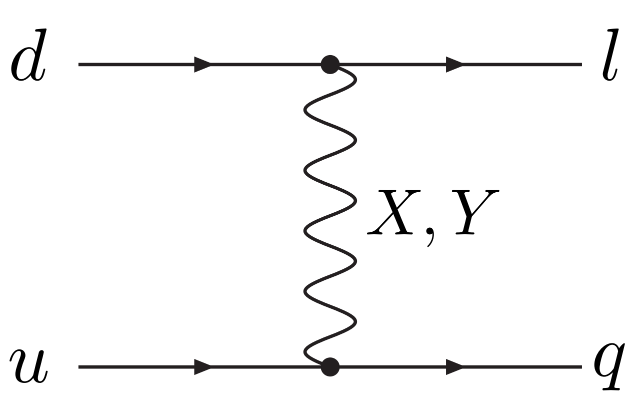
In analogy with the proton, **dark matter** (and other relics) may decay via GUT dynamics.

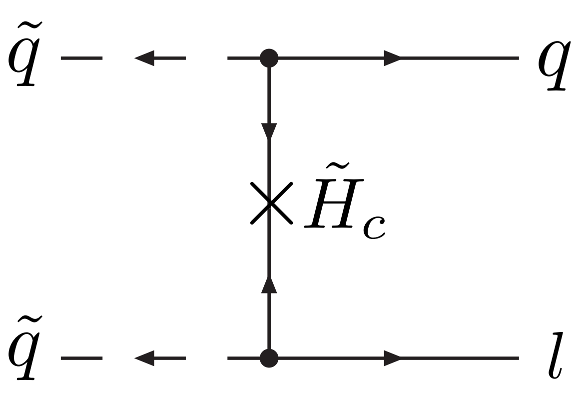
Leads to an interesting interplay between the LHC and potential astrophysical signals.

Probing Unification

- Baryon number is an (accidental) symmetry of the standard model. $U(1)_B$ forbids proton decay.
- Such global symmetries may well be violated by high scale dynamics.
- In GUTs, quarks and leptons are part of the same multiplet.

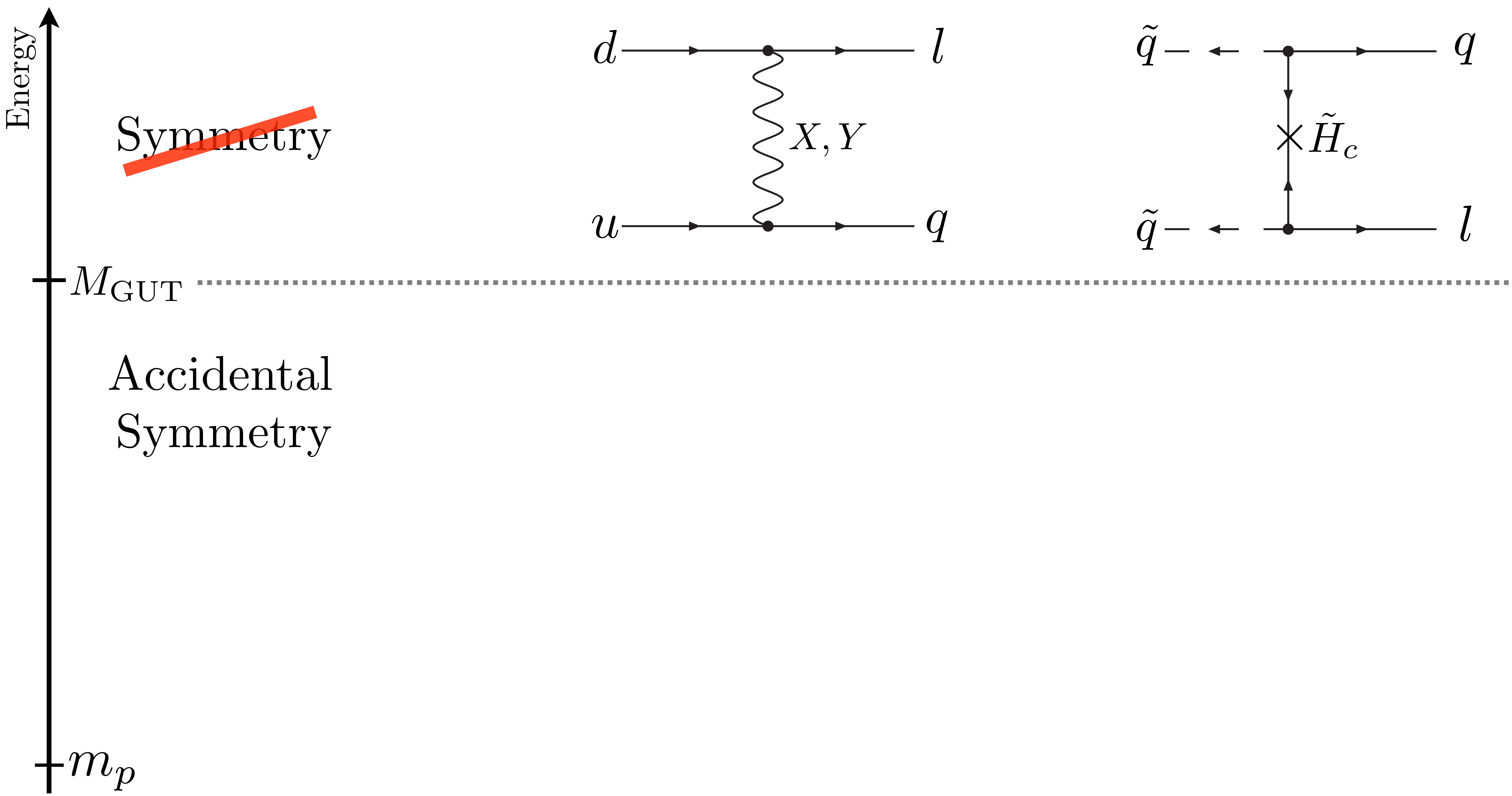
GUT interactions violate $U(1)_B$





Effective Theory

* The consequences of Unification can be tested at low energy by looking for proton decay.



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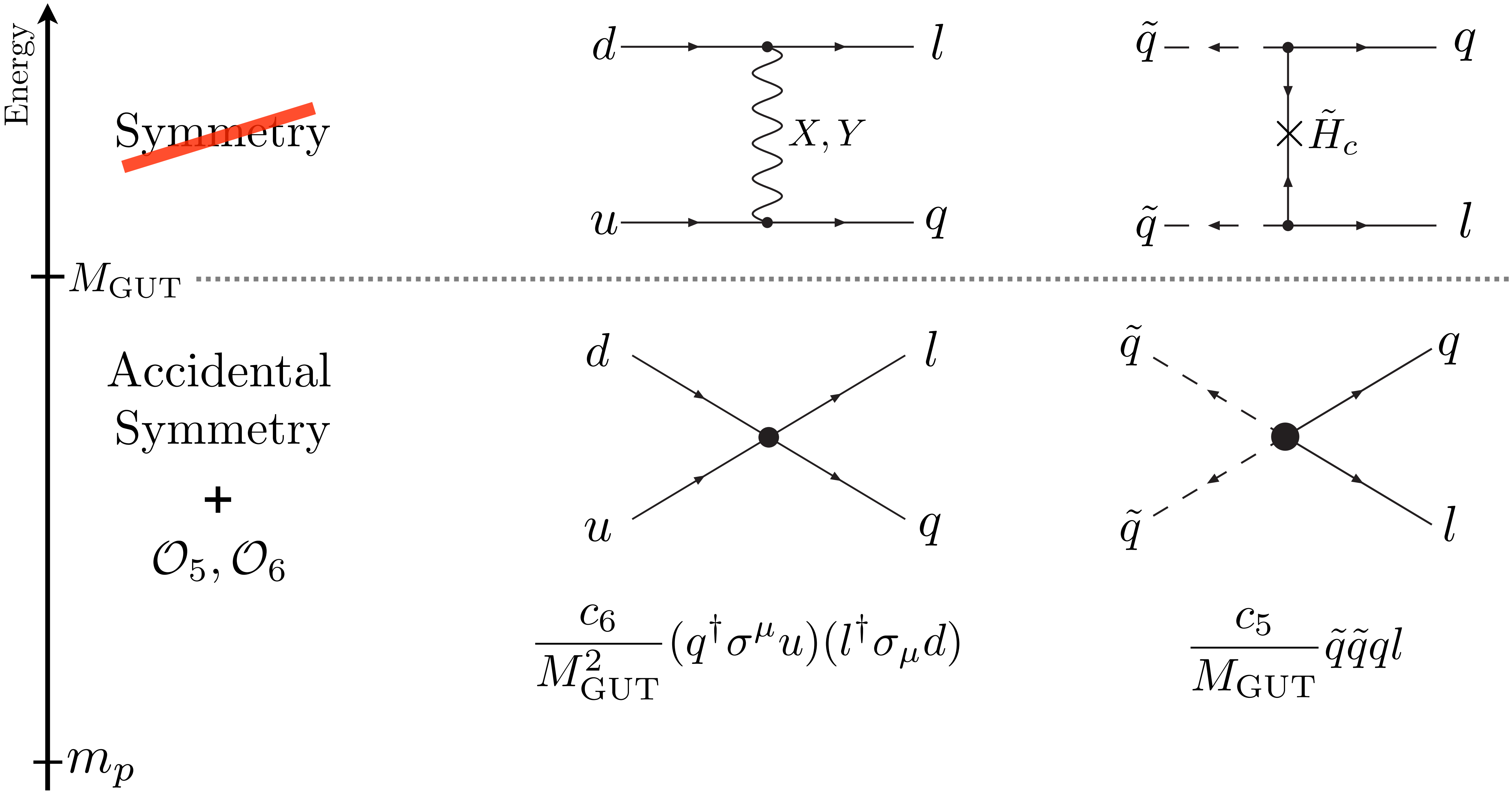

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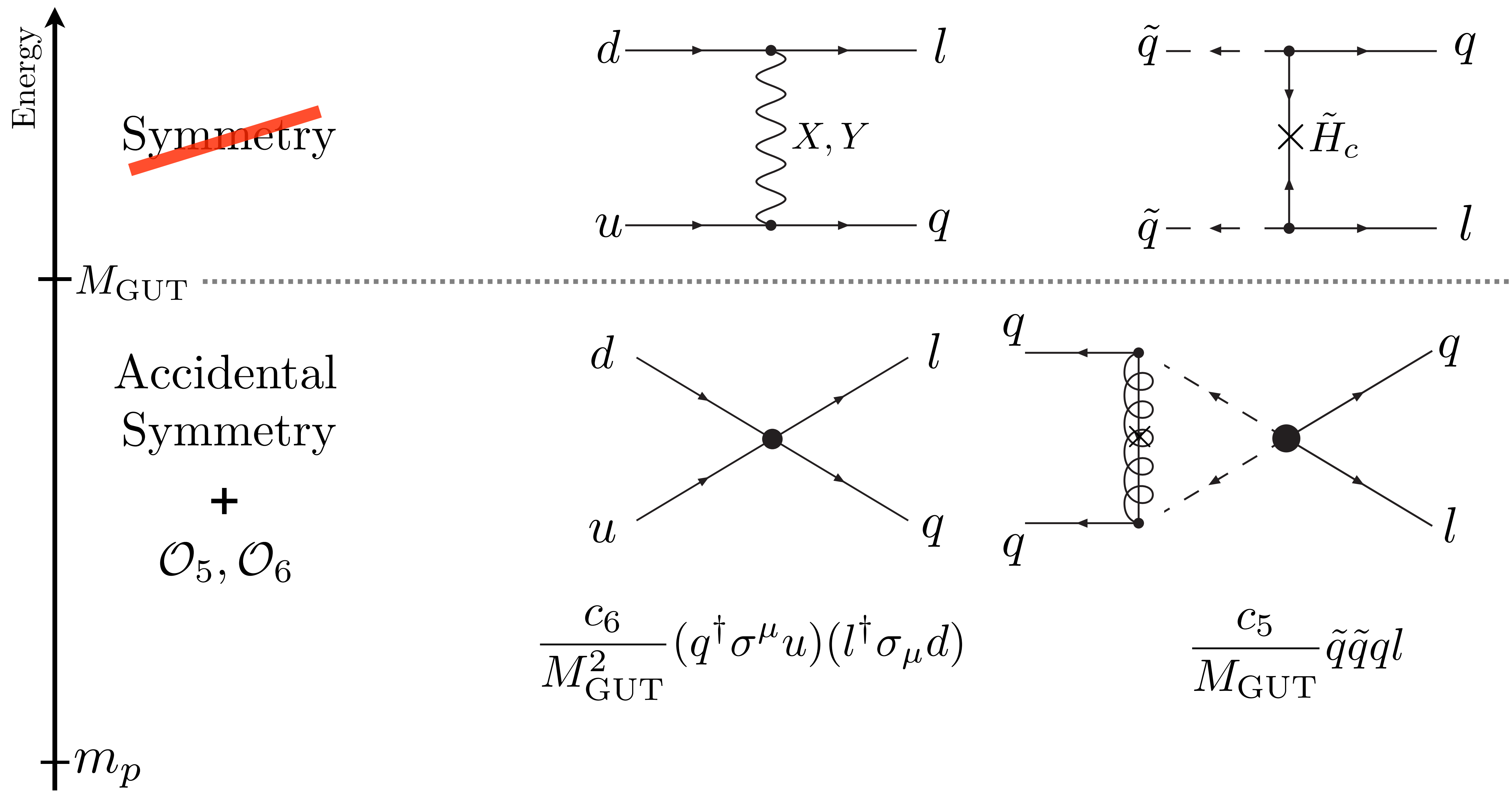

$$\frac{c_6}{M_{\rm GUT}^2}(q^\dagger \sigma^\mu u)(l^\dagger \sigma_\mu d)$$

$$\frac{c_5}{M_{\rm GUT}}\tilde{q}\tilde{q}ql$$

Effective Theory

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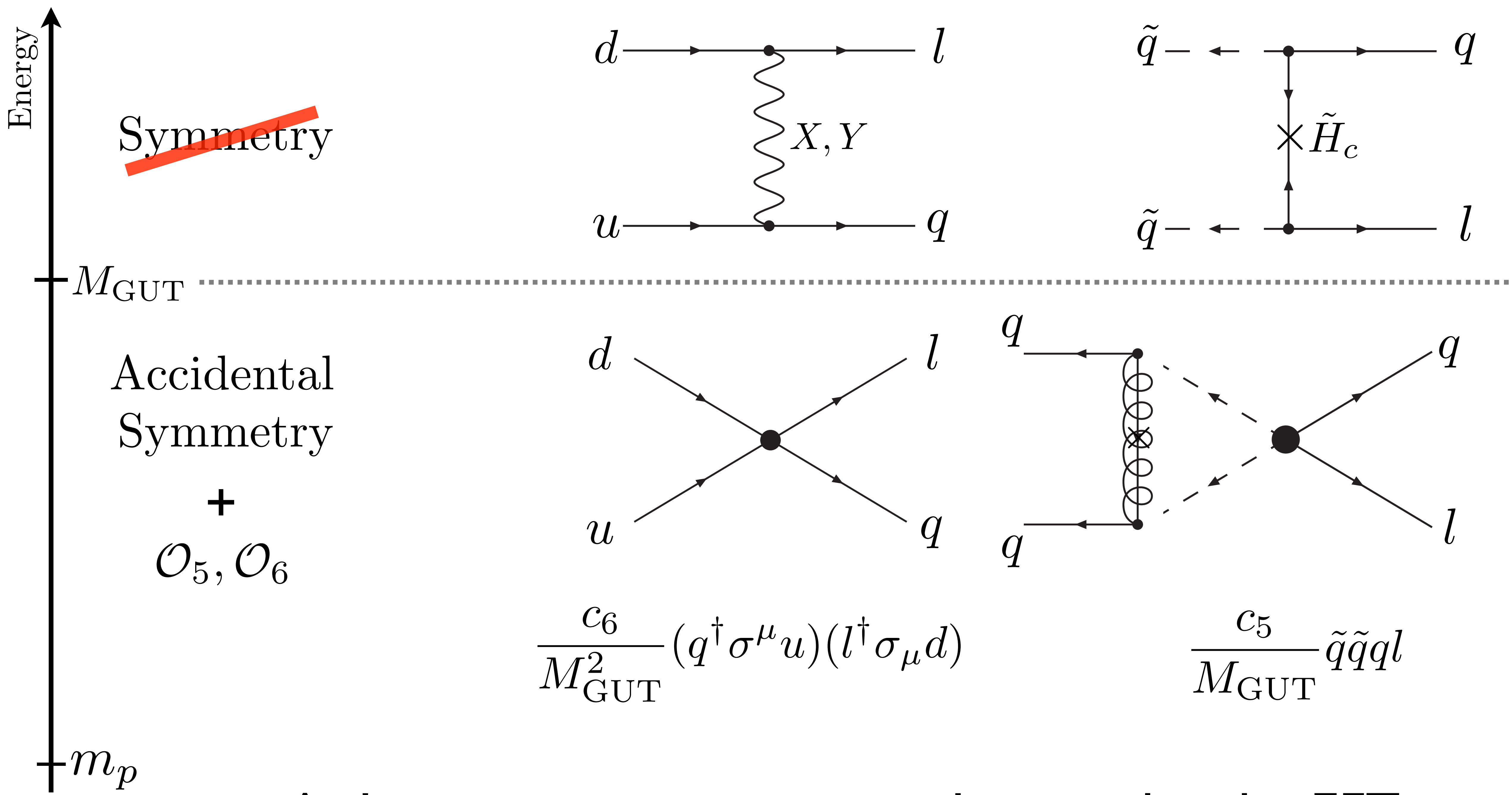

At low energies we can simply consider the EFT

Proton Decay

* Dimension five decay*

$$\tau_5 \propto \frac{8\pi}{c_5^2} \frac{M_{\rm GUT}^2}{\Lambda_{\rm QCD}^3} \sim 10^{37} \text{ sec}$$

* Dimension six decay

$$\tau_6 \sim \frac{8\pi}{c_6^2} \frac{M_{\rm GUT}^4}{\Lambda_{\rm QCD}^5} \sim 10^{42} \text{ sec}$$

* Experimental reach:

$$\tau_{\rm exp} \sim t_{\rm exp} N_{\rm protons} \sim (1 \text{ year}) \times \left(\frac{\text{kiloton}}{m_p}\right) \sim 10^{40} \text{ sec}$$

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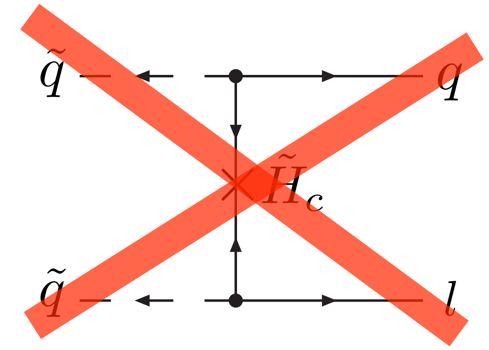

Highly constrained.

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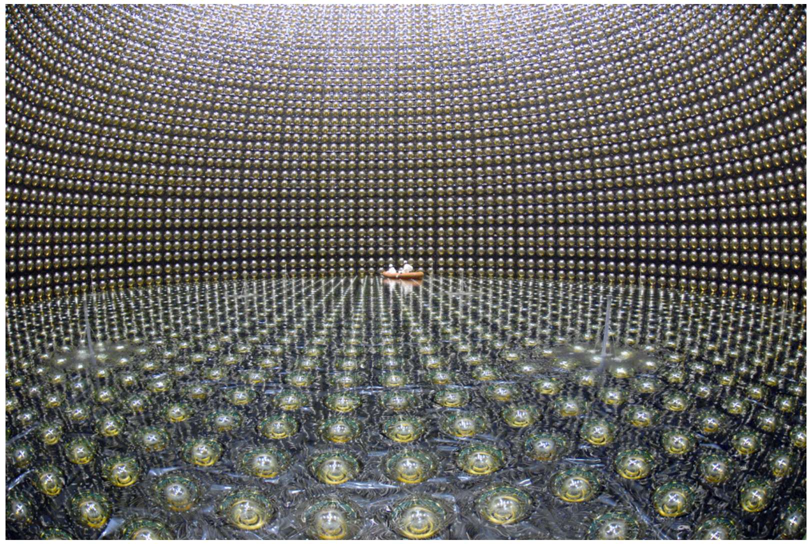

* Proton decay is constraining high energies by our ability to observe a **large number** of protons.
* Are there other "detectors" that have such a large exposure?

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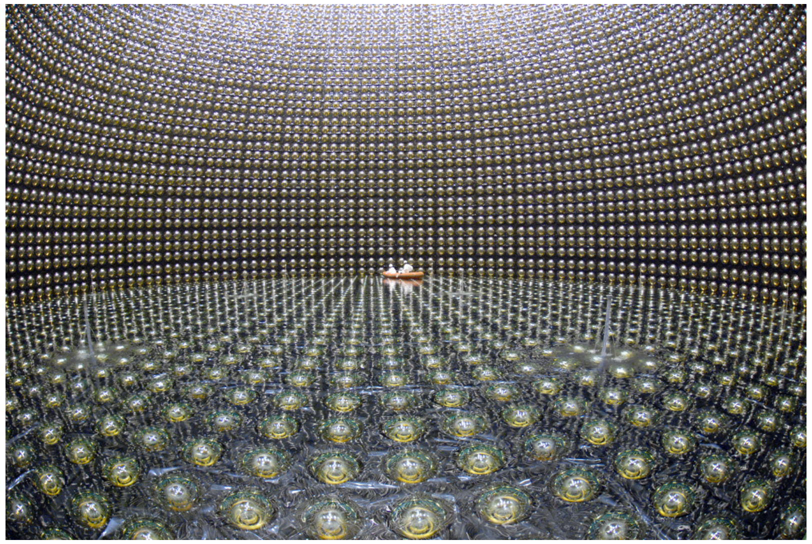

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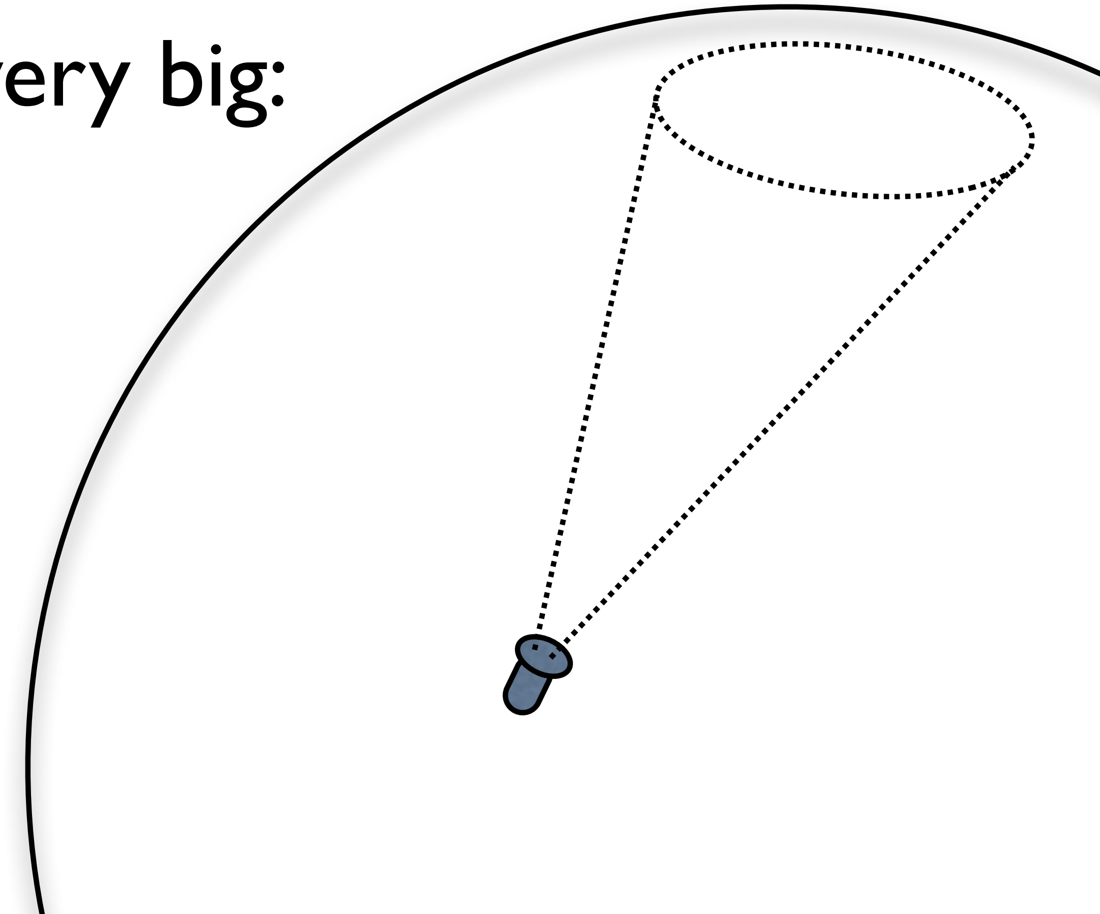
* Our **dark matter halo** is very big:



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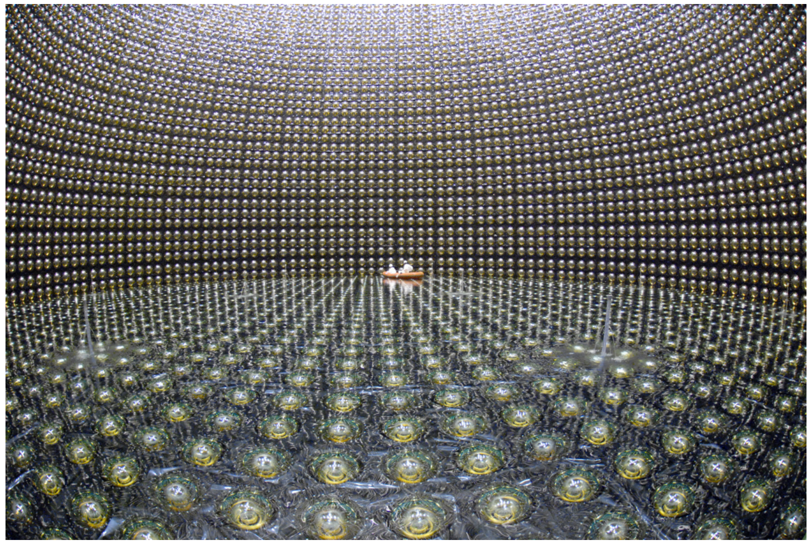
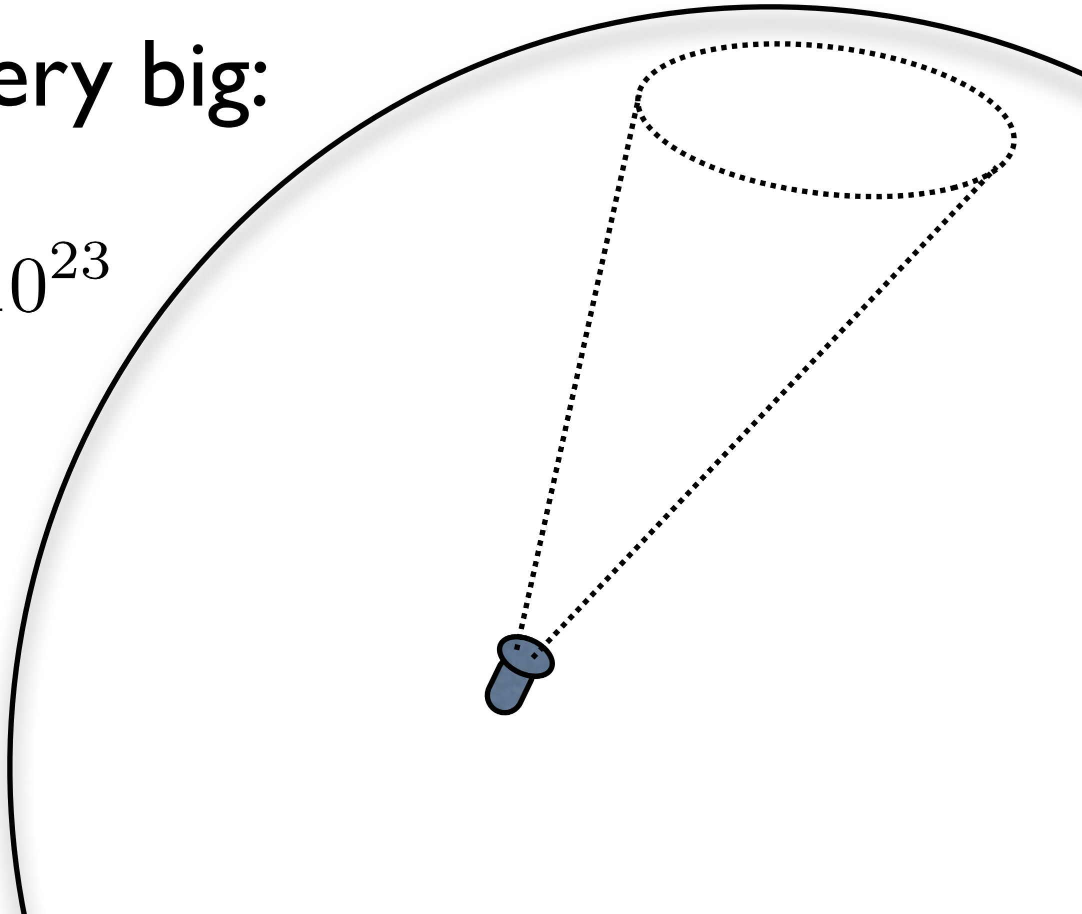


* Our **dark matter halo** is very big:

$$N_{\rm eff} \sim \int^{10\ {\rm kpc}} d^3 r \frac{(1\ {\rm m}^2)}{r^2} \frac{(0.3\ {\rm GeV\,cm}^3)}{m_{\rm DM}} \sim 10^{23}$$

$$\tau \sim 10^{23}(1\ {\rm day}) \sim 10^{28}\ {\rm sec}$$

would give O(100) events a year



Limits on Decaying DM

Decay channel	Extragalactic γ-rays EGRET	Galactic γ's HESS	antiprotons PAMELA	positrons PAMELA	neutrinos Super-K AMANDA, Frejus
$q\bar{q}$	4×10^{25} s	–	10^{27} s	–	–
e^+e^-	8×10^{22} s	2×10^{22} s $\sqrt{\frac{m_\psi}{\text{TeV}}}$ (K)	10^{24} s	2×10^{25} s $\left(\frac{\text{TeV}}{m_\psi}\right)$	3×10^{21} s $\left(\frac{m_\psi}{\text{TeV}}\right)$
$\mu^+\mu^-$	8×10^{22} s	2×10^{22} s $\sqrt{\frac{m_\psi}{\text{TeV}}}$ (K)	10^{24} s	2×10^{25} s $\left(\frac{\text{TeV}}{m_\psi}\right)$	3×10^{24} s $\left(\frac{m_\psi}{\text{TeV}}\right)$
$\tau^+\tau^-$	10^{25} s	10^{22} s $\sqrt{\frac{m_\psi}{\text{TeV}}}$ (K)	10^{24} s	10^{25} s $\left(\frac{\text{TeV}}{m_\psi}\right)$	3×10^{24} s $\left(\frac{m_\psi}{\text{TeV}}\right)$
WW	3×10^{25} s	–	3×10^{26} s	4×10^{25} s	8×10^{23} s $\left(\frac{m_\psi}{\text{TeV}}\right)$
$\gamma\gamma$	9×10^{24} s ($m_\psi = 100$ GeV) 2×10^{22} s ($m_\psi = 800$ GeV) 4×10^{23} s ($m_\psi = 3200$ GeV)	2×10^{24} s $\sqrt{\frac{m_\psi}{\text{TeV}}}$ (K) 5×10^{25} s $\sqrt{\frac{m_\psi}{\text{TeV}}}$ (NFW)	2×10^{25} s	8×10^{23} s $\left(\frac{\text{TeV}}{m_\psi}\right)$	–
$\nu\bar{\nu}$	8×10^{22} s	–	10^{24} s	10^{23} s	10^{25} s $\left(\frac{m_\psi}{\text{TeV}}\right)$

A search in many final states may allow distinguishing between final states.

Time Scales

* A dark matter particle with a TeV mass may be decaying by a dim-6 GUT suppressed operator:

$$\tau_6 \sim 8\pi \frac{M_{\rm GUT}^4}{m^5} = 3 \times 10^{27}\ {\rm s} \left(\frac{\rm TeV}{m}\right)^5 \left(\frac{M_{\rm GUT}}{2 \times 10^{16}\ {\rm GeV}}\right)^4$$

In an interesting range for current and upcoming experiments!

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* There is wiggle room:

for $\tau_6 = 10^{26}$ sec, $m = $ TeV

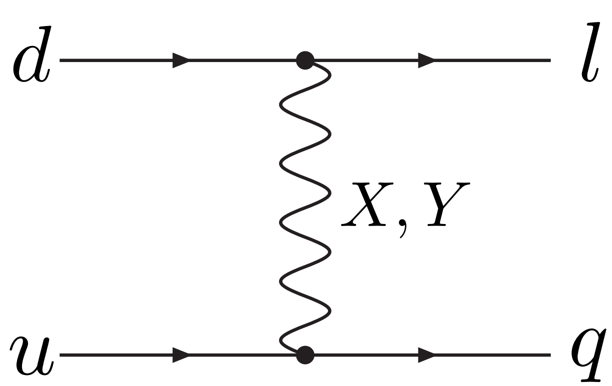
Number of Final State Particles	Scale M (GeV)
2	10^{16}
3	3×10^{15}
4	5×10^{14}
5	10^{14}

Outline

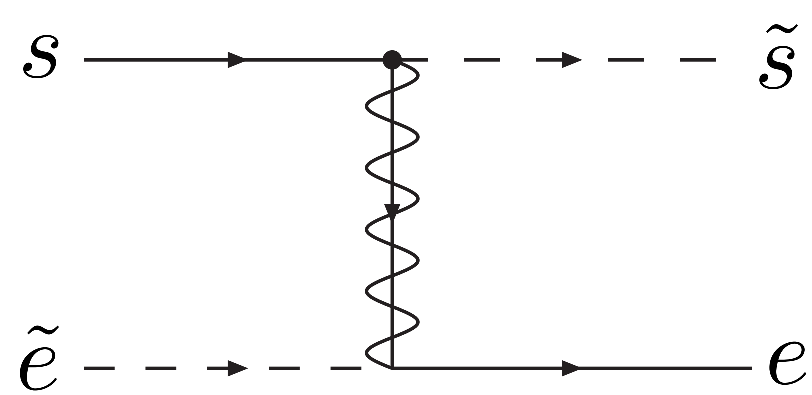
* **Dark matter decay** via GUT physics
  - Dim 6 Operators
  - Testing Unified theories
* **DM production**: dim 5 decay and BBN
* **A simple model**: SO(10)
  - Dim 5 & 6 decays
  - Dark matter decay to **superpatners** (!)
* **New and upcoming results**:
  - GUT interpretations of HESS, ATIC and PAMELA.
  - Predictions for other experiments.

Why Decaying DM?

- Dark matter may well be part of a different sector alongside ours.
- "DM-number" may be violated by interactions mediated by GUT scale particles



vs



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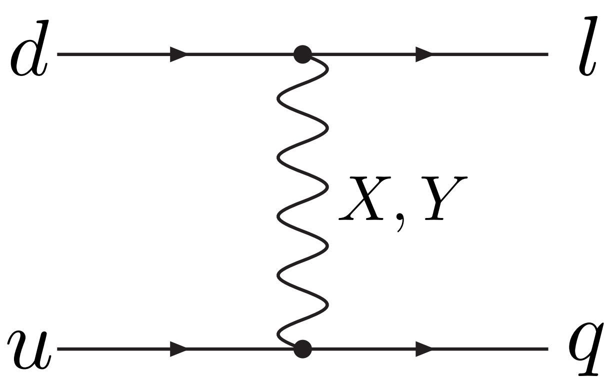


In our world baryons live "alongside" leptons, yet their individual numbers are violated only at the GUT scale (if GUTs are there). Why not DM?

Operator Analysis

* Add a singlet supermultiplet, S, to the MSSM. The singlet may be representative of a larger sector.

* Write dimension six operators that link S to the MSSM.

* Dimension 5 operators must be forbidden by symmetry.

* Many possible decays:

$s \to \mathrm{LSP}$ or $\mathrm{LSP} \to s$ or $\tilde{s} \to \mathrm{superpartners}$ or $\tilde{s} \to \mathrm{SM}$ or...

* Many possible operators.......

DM decay - Operators

Operator in SU(5)	Operator in MSSM	Final State	Lifetime (sec) ($M_{GUT} \sim 10^{16}$ GeV)	Mass Scale (GeV) (lifetime $\sim 10^{26}$ sec)
R-parity conserving				
$S^\dagger S 10^\dagger 10$	$S^\dagger S Q^\dagger Q,\ S^\dagger S U^\dagger U,\ S^\dagger S E^\dagger E$	leptons	10^{26}	10^{16}
$S^\dagger S H_{u(d)}^\dagger H_{u(d)}$	$S^\dagger S H_{u(d)}^\dagger H_{u(d)}$	quarks	10^{26}	10^{16}
$S^\dagger 10_f \bar{5}_f^\dagger 10_f$	$S^\dagger Q L^\dagger U, S^\dagger U D^\dagger E, S^\dagger Q D^\dagger Q$	quarks and leptons	5×10^{28}	10^{15}
$S^\dagger \bar{5}_f H_u^\dagger 10_f$	$S^\dagger L H_u^\dagger E,\ S^\dagger D H_u^\dagger Q$	leptons	10^{26}	10^{16}
$S^2 \mathcal{W}_\alpha \mathcal{W}^\alpha$	$S^2 \mathcal{W}_{EM} \mathcal{W}_{EM},\ S^2 \mathcal{W}_Z \mathcal{W}_Z$	γ (line)	10^{26}	10^{16}
Hard R violating				
$\bar{5}_f(\Sigma\bar{5}_f)\bar{5}_f(\Sigma\bar{5}_f)\bar{5}_f$	$DDDLL$	quarks and leptons	10^{37}	10^{13}
Soft R violating				
$\mathcal{L} \ni \frac{m_{SUSY}^4}{M_{GUT}^2} H_u \tilde{\bar{5}}_f$	$\frac{m_{SUSY}^4}{M_{GUT}^2} H_u \tilde{\ell}$	quarks	4×10^{30}	7×10^{14}
$\mathcal{L} \ni \frac{m_{SUSY}^3}{M_{GUT}^2} \tilde{H}_u \bar{5}_f$	$\frac{m_{SUSY}^3}{M_{GUT}^2} \tilde{H}_u \ell$	leptons	6×10^{32}	10^{14}
$\mathcal{L} \ni \frac{m_{SUSY}}{M_{GUT}^2} H_d \tilde{W} \not{\partial} \bar{5}_f^\dagger$	$\frac{m_{SUSY}}{M_{GUT}^2} H_d \tilde{W} \not{\partial} \ell^\dagger$	$\gamma + \nu$	2×10^{32}	10^{14}

Correlated Signals

- Once proton decay is discovered, we may begin to test the theory further by comparing the decay rates in various modes.

- Similarly in DM decay:
  We expect "GUT relations" among decays into different final states

$$\mathrm{DM} \rightarrow \bar{5}\text{'s} = \begin{pmatrix} D^c \\ L \end{pmatrix}$$

- D^c → hadrons
- L → leptons
- L → neutrinos

This may also depend on the SUSY spectrum - a strong tie to the LHC.

But how does singlet dark matter get produced?

Dimension 5 Decays

Dimension 5

* A dimension 5 decay gives a lifetime

$$\tau_5 \sim 8\pi \frac{M_{\rm GUT}^2}{m^3} = 7 \text{ s} \left(\frac{\rm TeV}{m}\right)^3 \left(\frac{M_{\rm GUT}}{2\times 10^{16}\text{ GeV}}\right)^2$$

* A relic that is decaying via dim-5 is **not DM**.
* **But**, the interesting range of 1-1000 seconds is probed by Big Bang nucleosynthesis.
* In fact, a relic decaying at 100-1000 seconds may be preferred to explain observations...

Lithium Problem

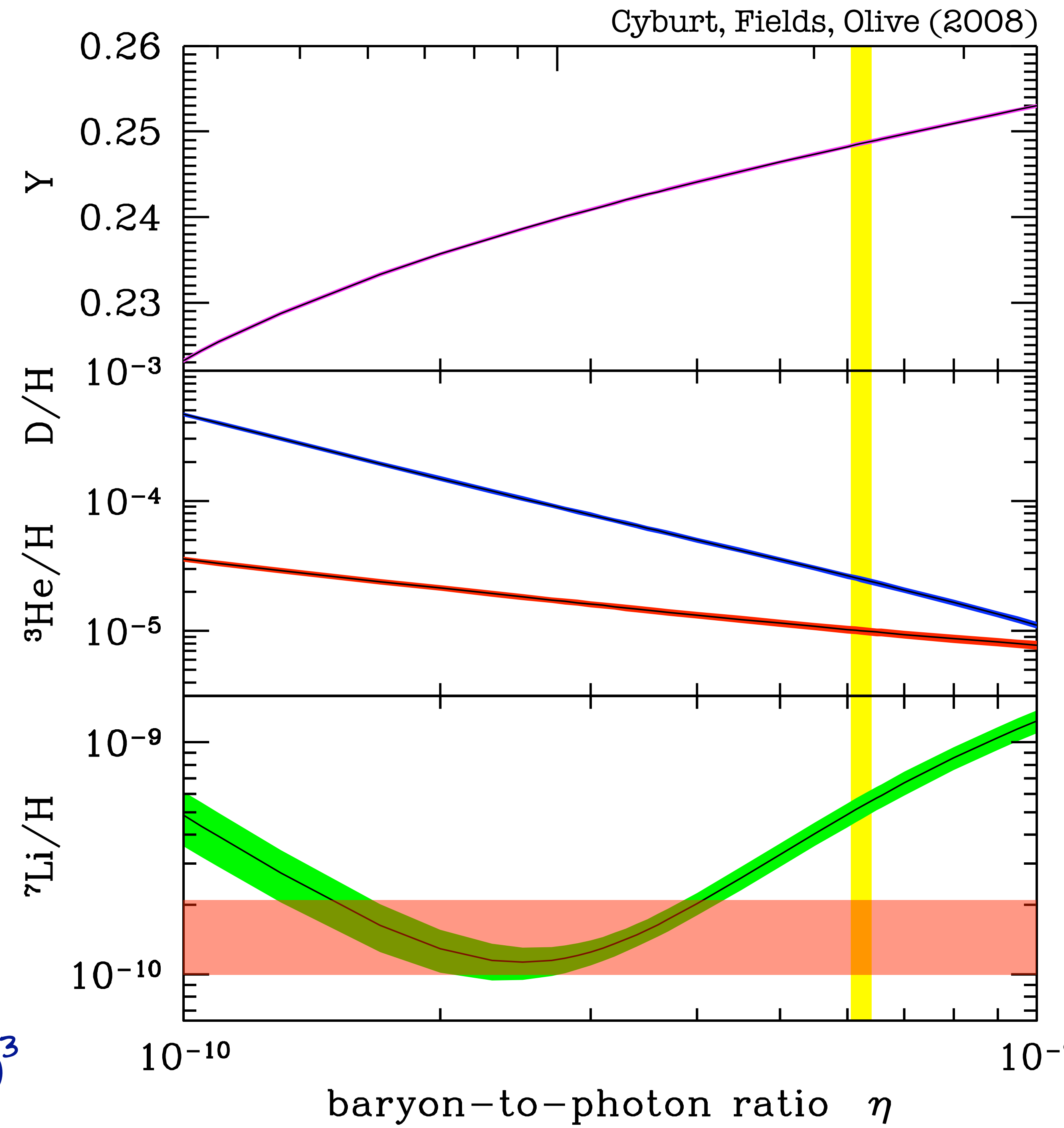
* Standard BBN nuclear abundances agree with observations.... with the exception of Lithium. Both ^{7}Li and ^{6}Li are observed in non-convecting stars

$$\left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{obs}} \sim 1 - 2 \times 10^{-10}$$

a factor 2-3 too low.

$$\left(\frac{^6\mathrm{Li}}{^7\mathrm{Li}}\right)_{\mathrm{obs}} \sim 0.05 \pm 0.02$$

a factor ~10^3 too high.



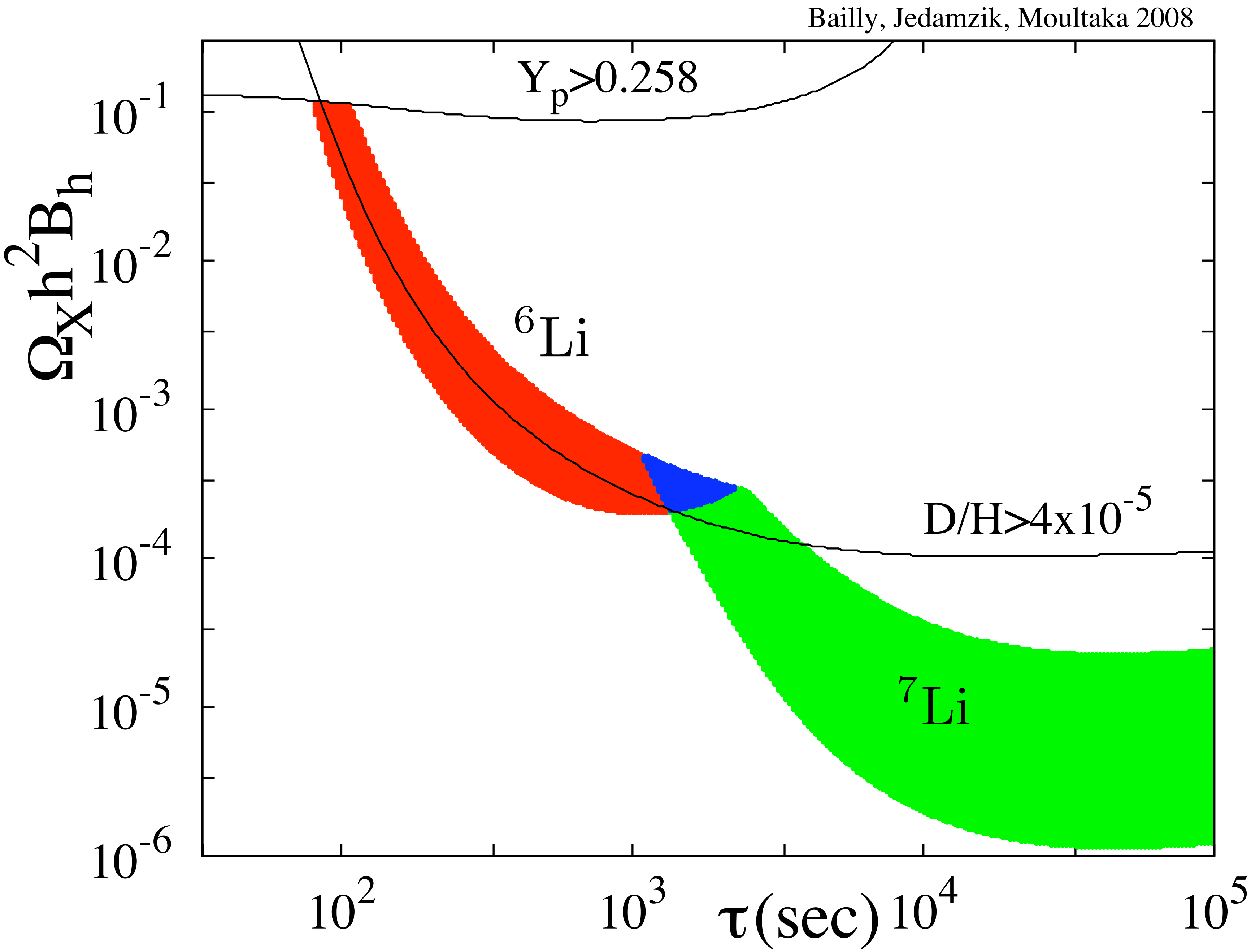
Lithium from Decays

Dimopulos et al. (88);
Feng, Rajaraman, Takayama (03);
Jedamzik et al (04,08);

* The Lithium abundance is very sensitive to energy dumped into the Universe during BBN.
* The energetic decay products can easily destroy ^{7}Li.
* They can also accelerate alpha particles which collide to produce ^{6}Li.
* Such a decay may be an opportunity to produce singlet dark matter (a.k.a SuperWIMP).

a detailed calculation shows.....

Lithium from Decay



GUT scale
Dimension 5 decays
can fall anywhere
in this range.

May address the
Lithium problems.

Dimension 5 Operators

* A similar operator game may be played:

χ $SU(5)$ Rep.	Superpotential Terms	Kahler terms	Soft PQ breaking
Singlet	$\chi_e 10_f 10_f H_u$, $\chi_e 10_f \bar{5}_f H_d$, $\chi^2_{e,o} H_u H_d$, $\chi_o 10_f \bar{5}_f \bar{5}_f$, $\chi_e \mathcal{W}_\alpha \mathcal{W}^\alpha$	$\chi_e 10^\dagger_f 10_f$, $\chi_e H^\dagger_u H_u$, $\chi_o \bar{5}^\dagger_f H_d$	$\left(\frac{\mu}{M_{\rm GUT}}\right) \chi_e H_u H_d$ $\left(\frac{\mu}{M_{\rm GUT}}\right) \chi_o H_u \bar{5}_f$
$(5, \bar{5})$	$\chi_e H_u \bar{5}_f \bar{5}_f$, $\bar{\chi}_e H_u H_u H_d$, $\chi_o 10_f 10_f 10_f$, $\chi_o \bar{5}_f H_u H_d$	$\bar{\chi}^\dagger_e 10_f 10_f$, $\chi_o 10^\dagger_f H_u$	$\left(\frac{\mu}{M_{\rm GUT}}\right) \left(\chi^\dagger_e H_u,\ \bar{\chi}^\dagger_e H_d,\ \bar{\chi}^\dagger_o \bar{5}_f\right)$ $\mu \left(\frac{\mu}{M_{\rm GUT}}\right) \chi_o \bar{5}_f$
$(10, \bar{10})$	$\chi_e 10_f 10_f H_d$, $\bar{\chi}_e 10_f \bar{5}_f H_u$, $\bar{\chi}_o \bar{5}_f \bar{5}_f \bar{5}_f$, $\bar{\chi}_e \bar{5}_f \bar{5}_f H_d$	$\bar{\chi}^\dagger_e 10_f \bar{5}^\dagger_f$, $\bar{\chi}^\dagger_e \bar{5}_f \bar{5}_f$, $\bar{\chi}_o H_u \bar{5}^\dagger_f$	$\left(\frac{\mu}{M_{\rm GUT}}\right) \left(\chi^\dagger_o 10_f,\ \chi_e \bar{5}_f \bar{5}_f\right)$ $\mu \left(\frac{\mu}{M_{\rm GUT}}\right) \bar{\chi}_o 10_f$

The Lithium problem may imply new
meta-stable charged particle at the LHC!
(a.k.a super-WIMP phenomenology)

A Simple Model: SO(10)

An SO(10) Model

* Consider an SO(10) GUT model.
  Add a new $16, \overline{16}$ vector-like pair at a TeV.

* Three steps:

$$16_m = \begin{pmatrix} \bar{5}_m \\ \\ \\ 10_m \\ \\ \\ S_m \end{pmatrix}$$

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① Early Universe: WIMPS are produced thermally

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(1) Early Universe: WIMPs are produced thermally

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(2) 1000 sec: Dimension 5 decay, may affect Lithium

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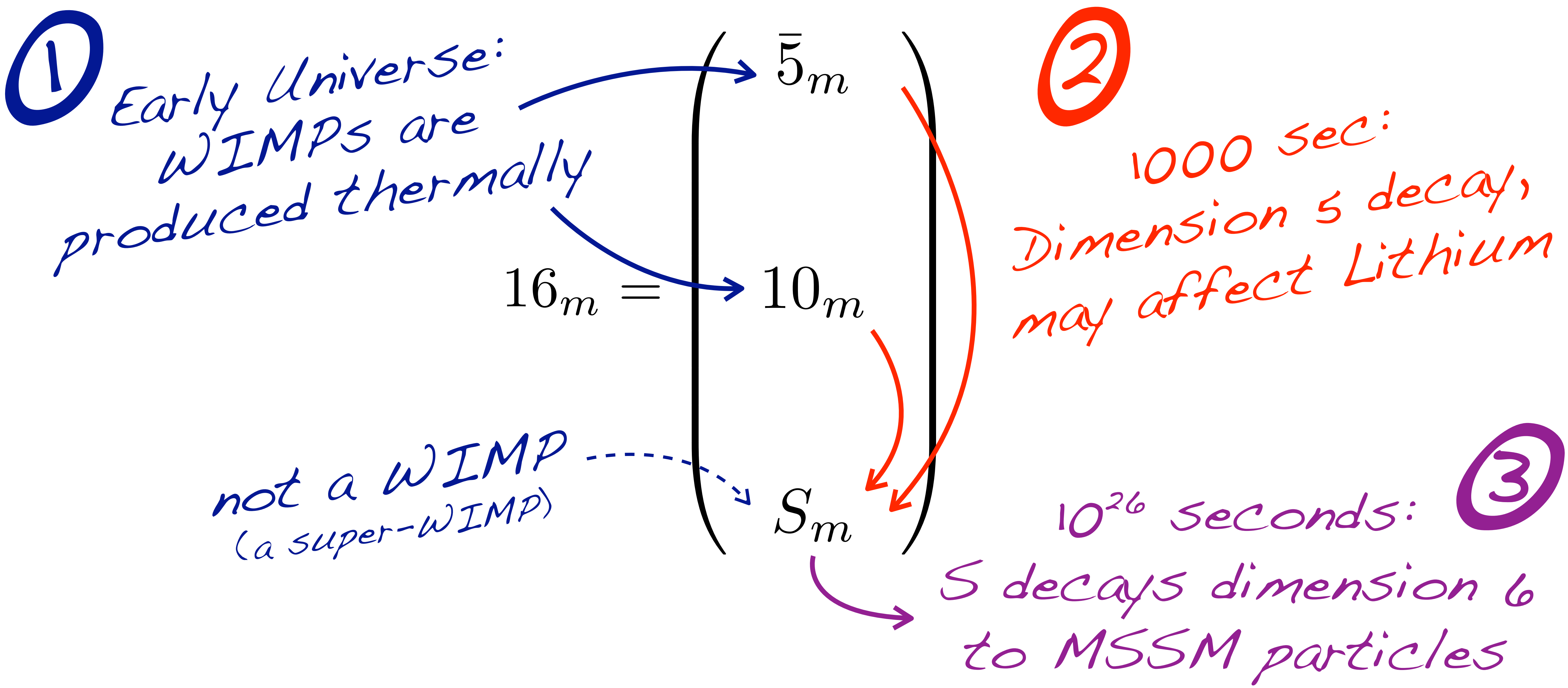


An SO(10) Model

* At the GUT scale introduce a 10 of SO(10)

$$W' = \lambda 16_m 16_f 10_{\rm GUT} + m 16_m \bar{16}_m + M_{\rm GUT} 10_{\rm GUT} 10_{\rm GUT}$$

* Integrate out $10_{\rm GUT}$ -

dim 5 $$\int d^2\theta \left(\frac{16_m 16_m 16_f 16_f}{M_{\rm GUT}} \right) \supset \int d^2\theta \left(\frac{10_m S_m \bar{5}_f \bar{5}_f}{M_{\rm GUT}} \right), \ldots$$

dim 6 $$\int d^4\theta \left(\frac{16_m^\dagger 16_m 16_f^\dagger 16_f}{M_{\rm GUT}^2} \right) \supset \int d^4\theta \left(\frac{S_m^\dagger S_m \, \bar{5}^\dagger \bar{5}}{M_{\rm GUT}^2} \right), \ldots$$

Flavor violating, matter only.

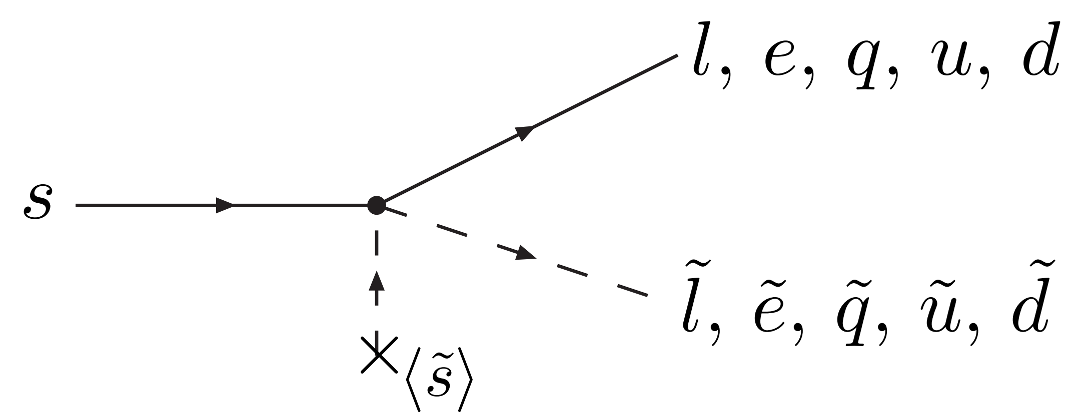
* Integrate out the B-L gauge multiplet

dim 6 $$\int d^4\theta \left(\frac{16_m^\dagger 16_m 16_f^\dagger 16_f}{M_{B-L}^2} \right) \supset \int d^4\theta \left(\frac{S_m^\dagger S_m \, \bar{5}^\dagger \bar{5}}{M_{B-L}^2} \right), \ldots$$

Flavor universal, matter & Higgs

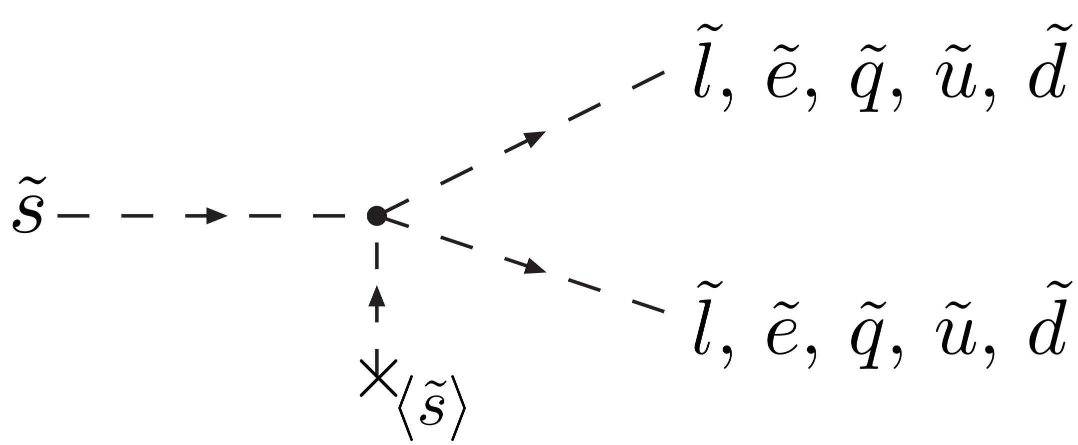
Decay to Superpartners

- Assume $\tilde{s}$ gets a vev of order TeV (of order its SUSY breaking soft mass).
- $\tilde{s}$ decay to fermions is helicity suppressed.



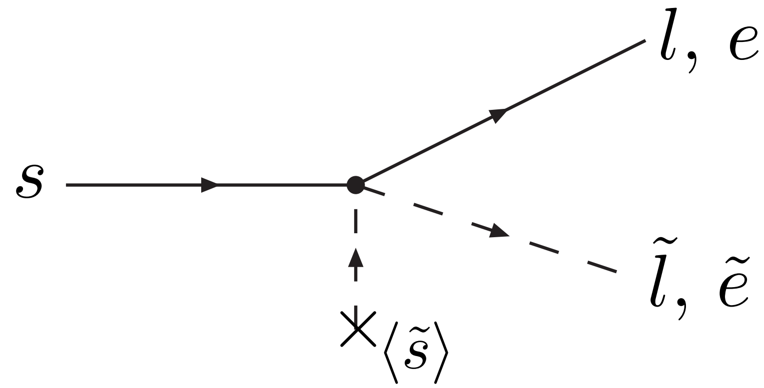
DM decays to superpartners!

Phase space: BR is sensitive to SUSY spectrum.

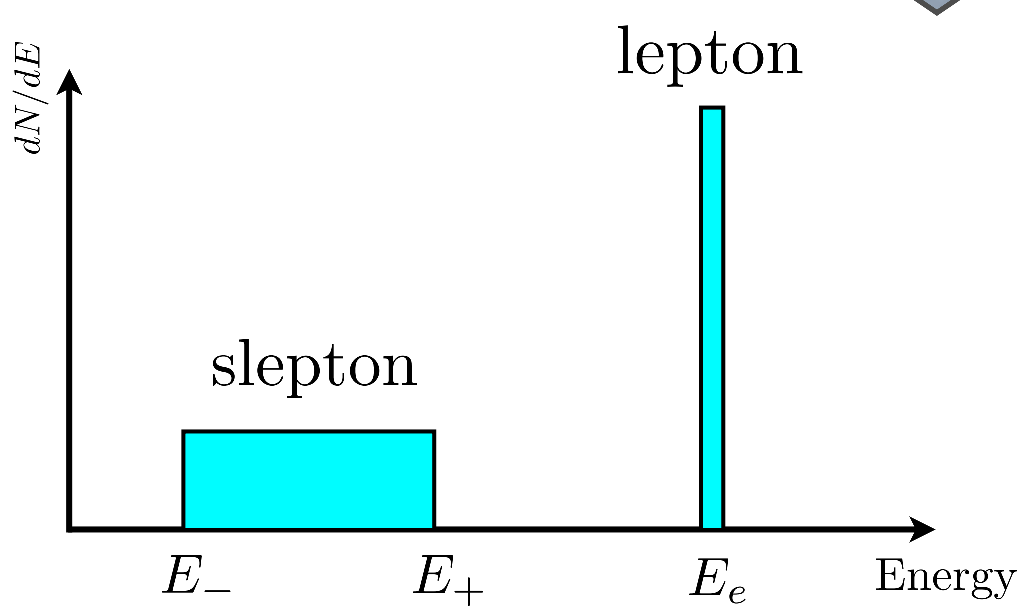


squarks are heavier than sleptons. Leptons dominate.

$\mathrm{DM} \to e\tilde{e}$



monoenergetic electron
+
monoenergetic selectron
(decays to electron+LSP)



$$E_e = \frac{m_s^2 - m_{\tilde{e}}^2}{2m_s}$$

$$E_- = \frac{m_s(m_{\tilde{e}}^2 - m_{LSP}^2)}{2m_{\tilde{e}}^2}$$

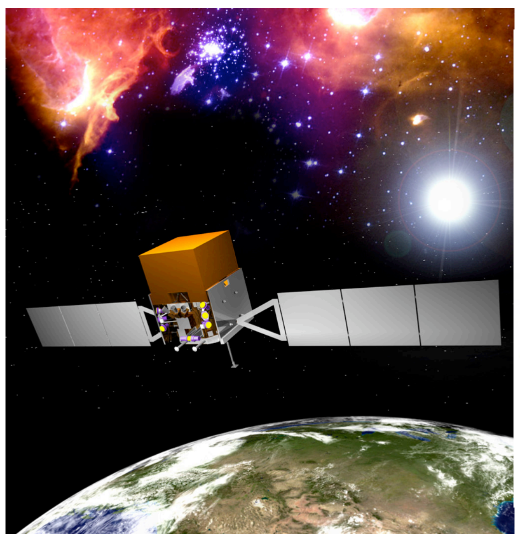
$$E_+ = \frac{m_{\tilde{e}}^2 - m_{LSP}^2}{2m_s}$$

May produce non trivial spectral features.

Related to SUSY spectrum measured at LHC.

New Data is Coming

* We are entering a golden age in cosmic ray measurements

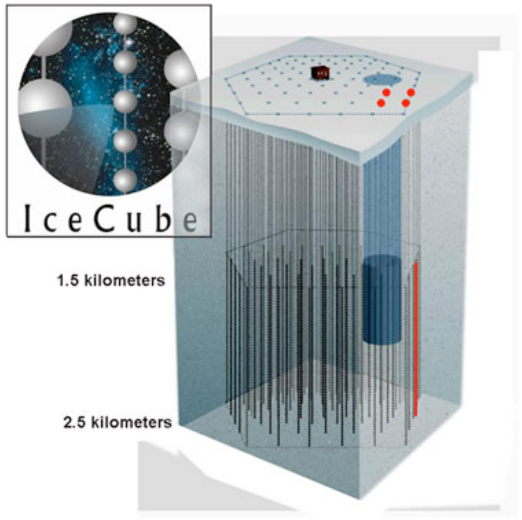


Fermi (GLAST)

PAMELA

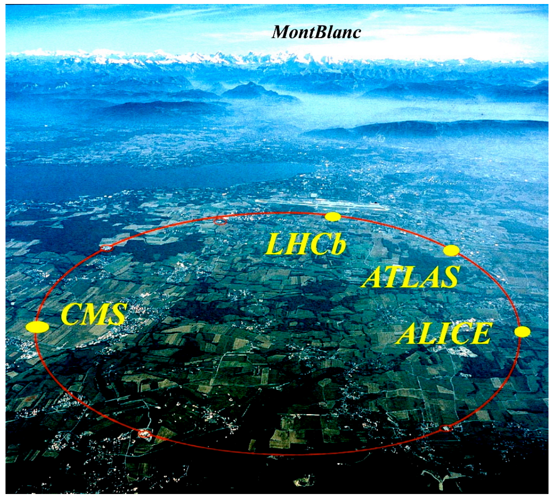
HESS

ATIC



IceCube

* Spectra of Higgs and SUSY particles may be available soon:

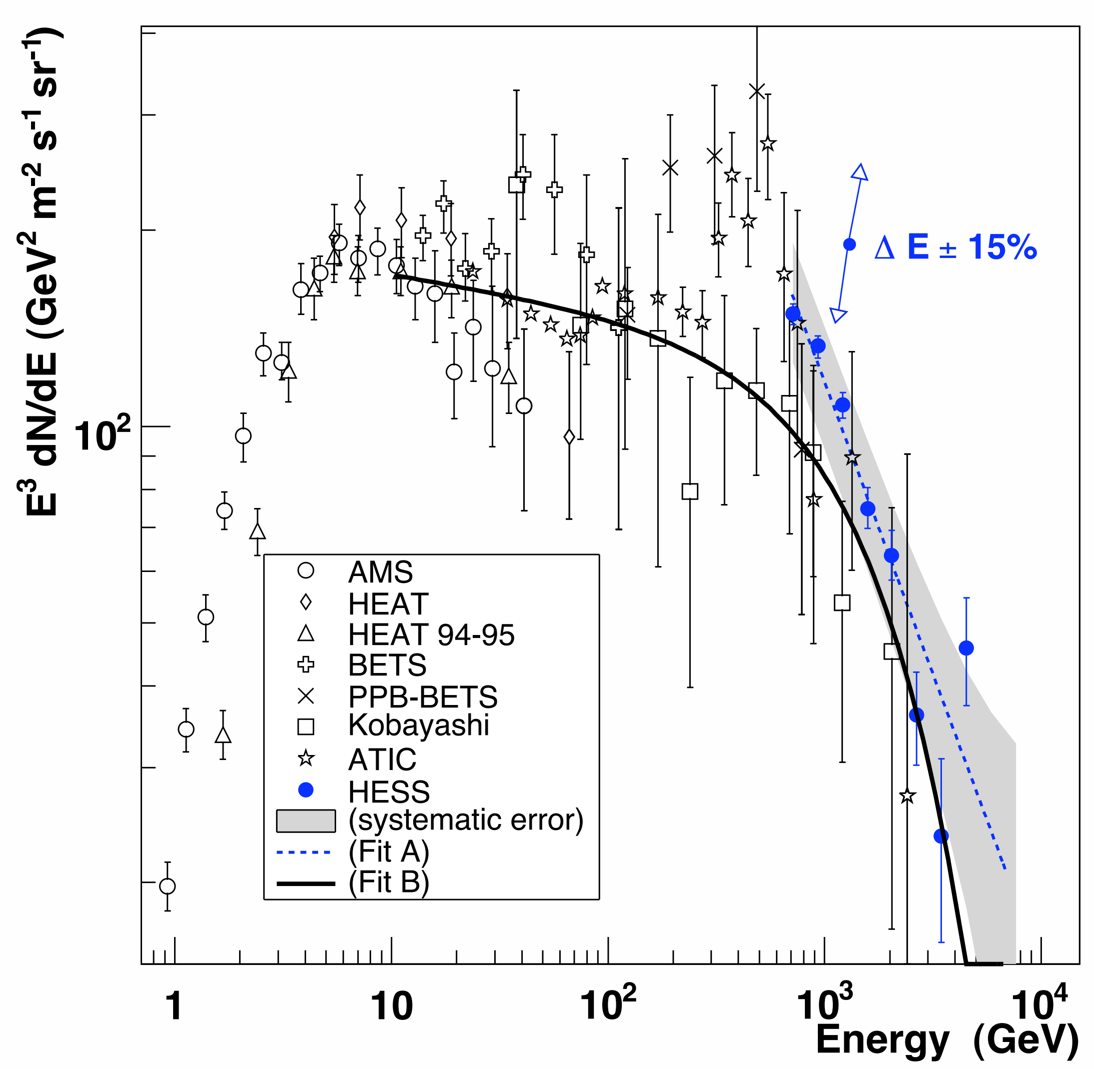


LHC

Tevatron

HESS

- HESS has measured the electron+positron (+gamma) flux at very high energies.
- Including systematics: may be interpreted as background, or as the "high end" of a signal.
- Caution should be taken when combining date from several experiments....



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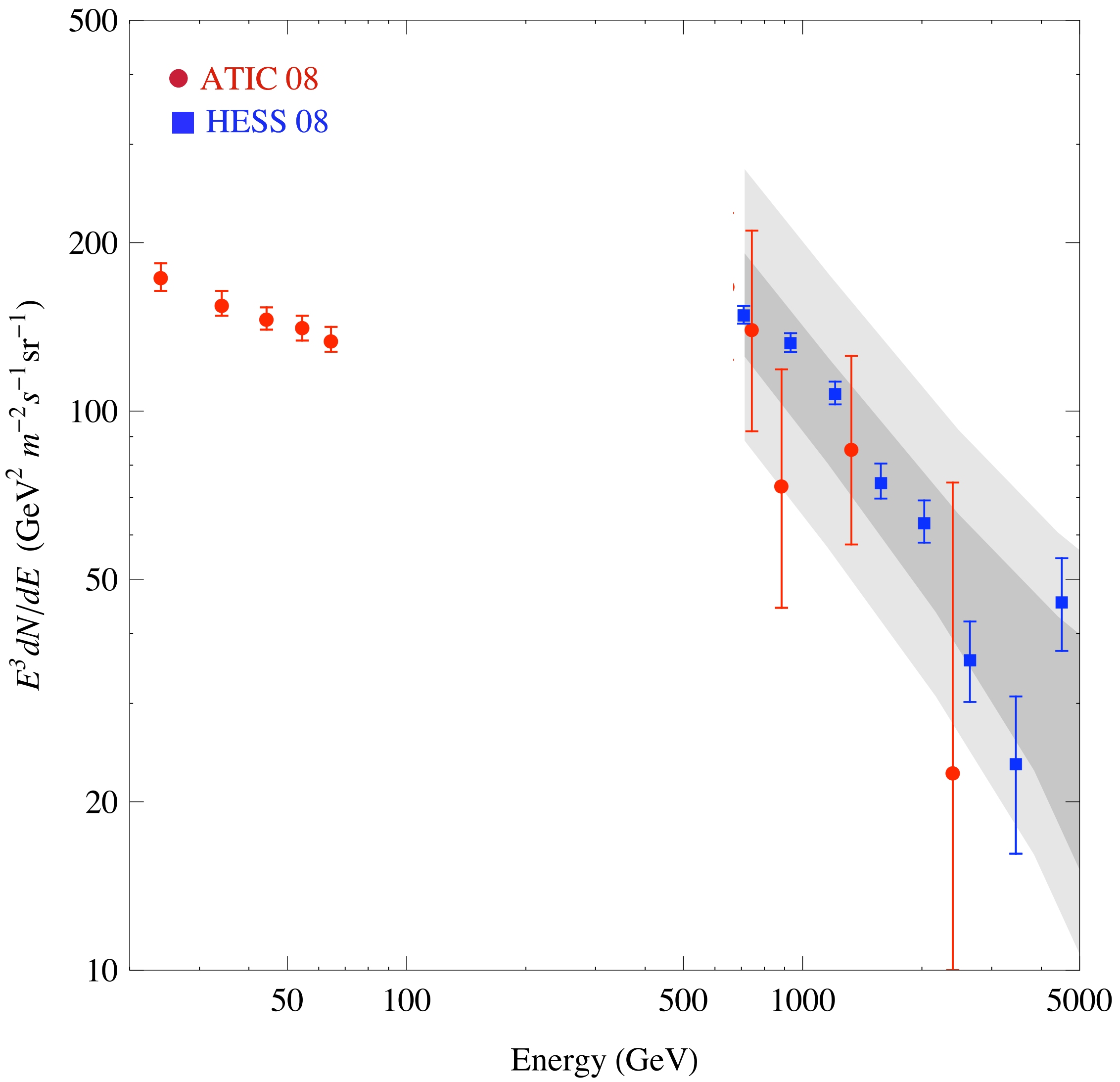

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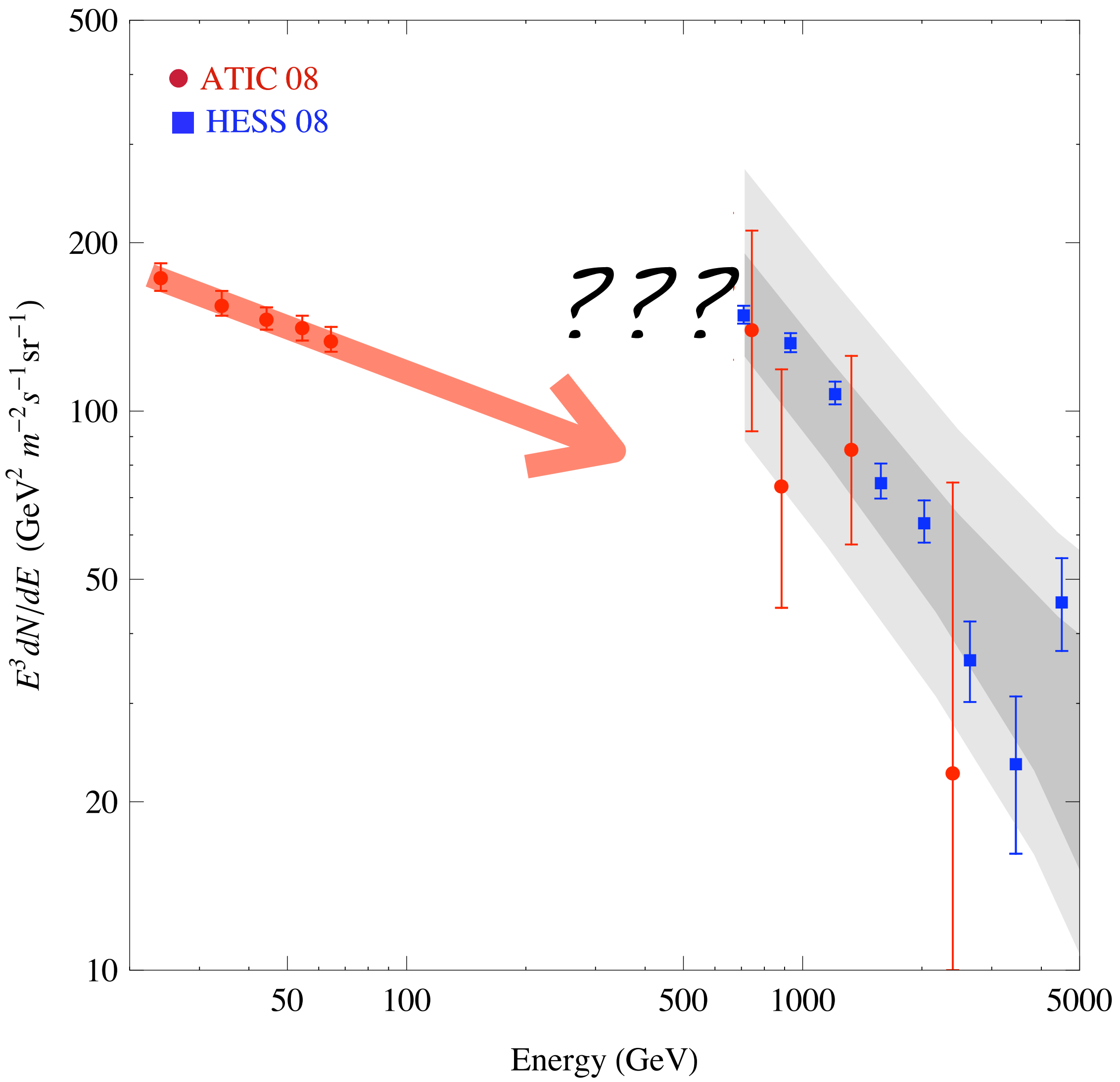
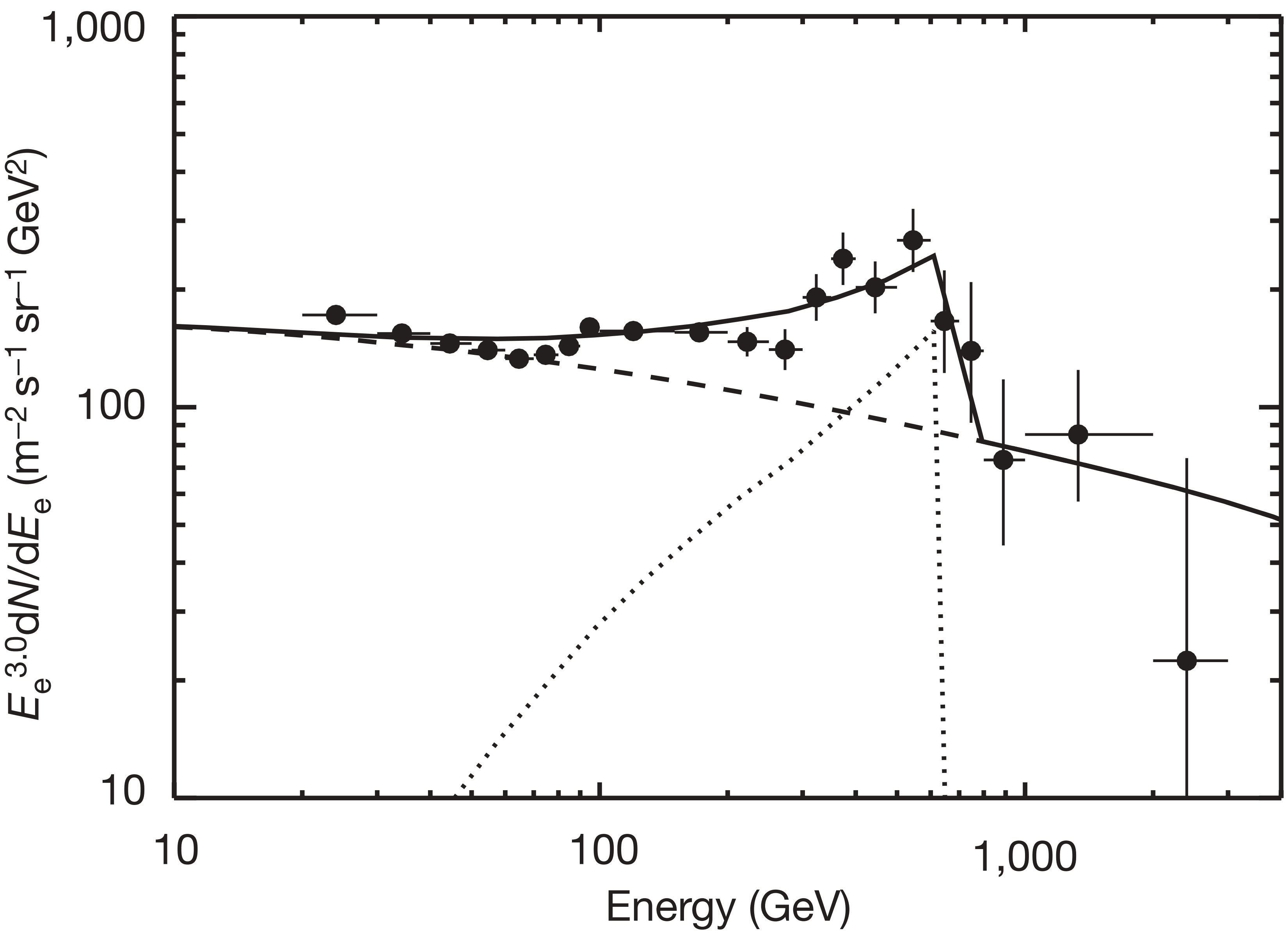


Caution!

ATIC

A balloon experiment measuring the combined electron+positron flux:



One bump or two?

Note! Astrophysical explanations have been proposed.

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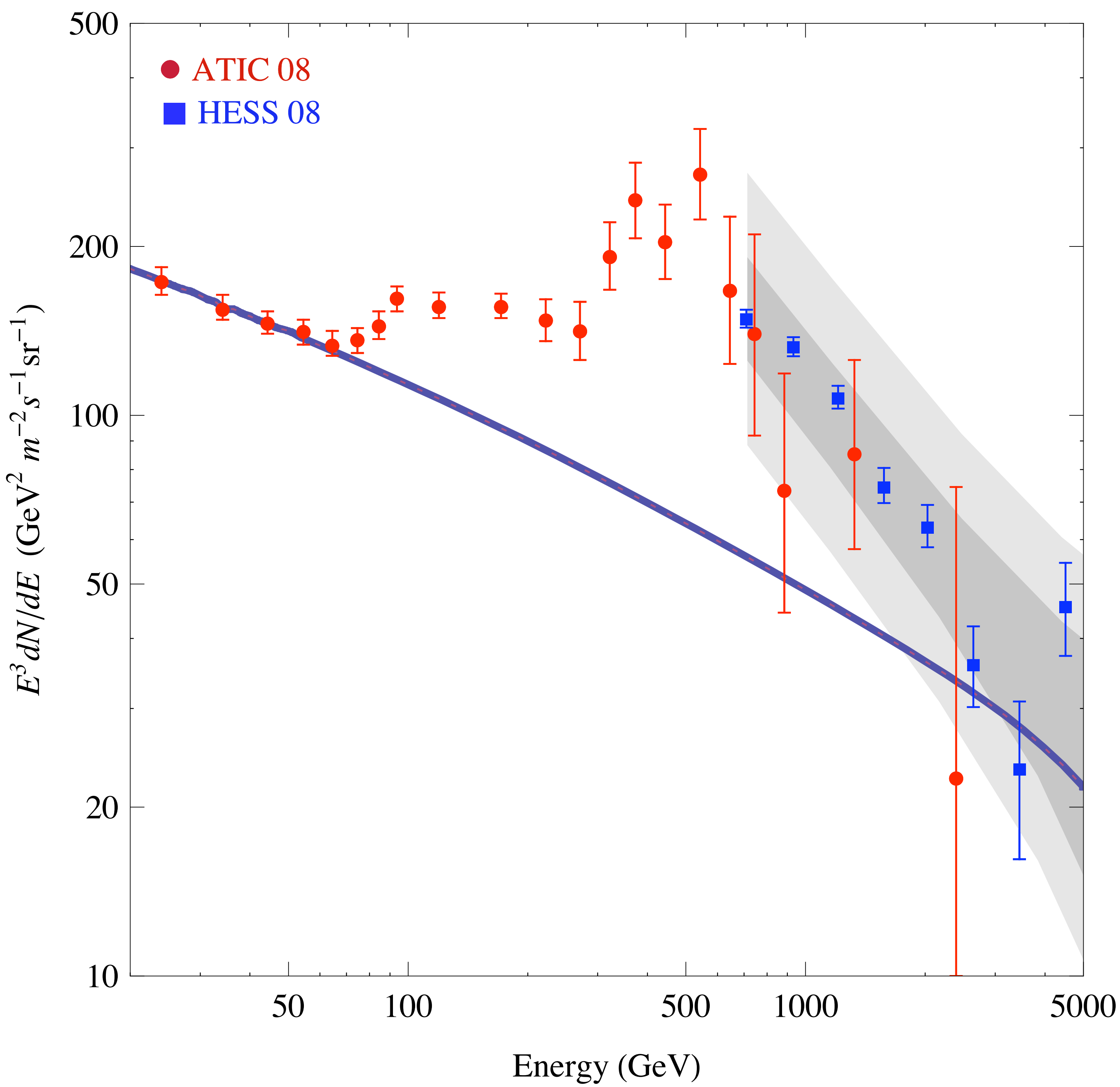

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Caution!

* It is important to consider ATIC and its spectral features with caution.
  - Systematic uncertainties.
  - Astrophysical sources.
* Luckily, Fermi and PAMELA will confirm/refute this shape.
* A double feature may survive. If so, how do we interpret it?

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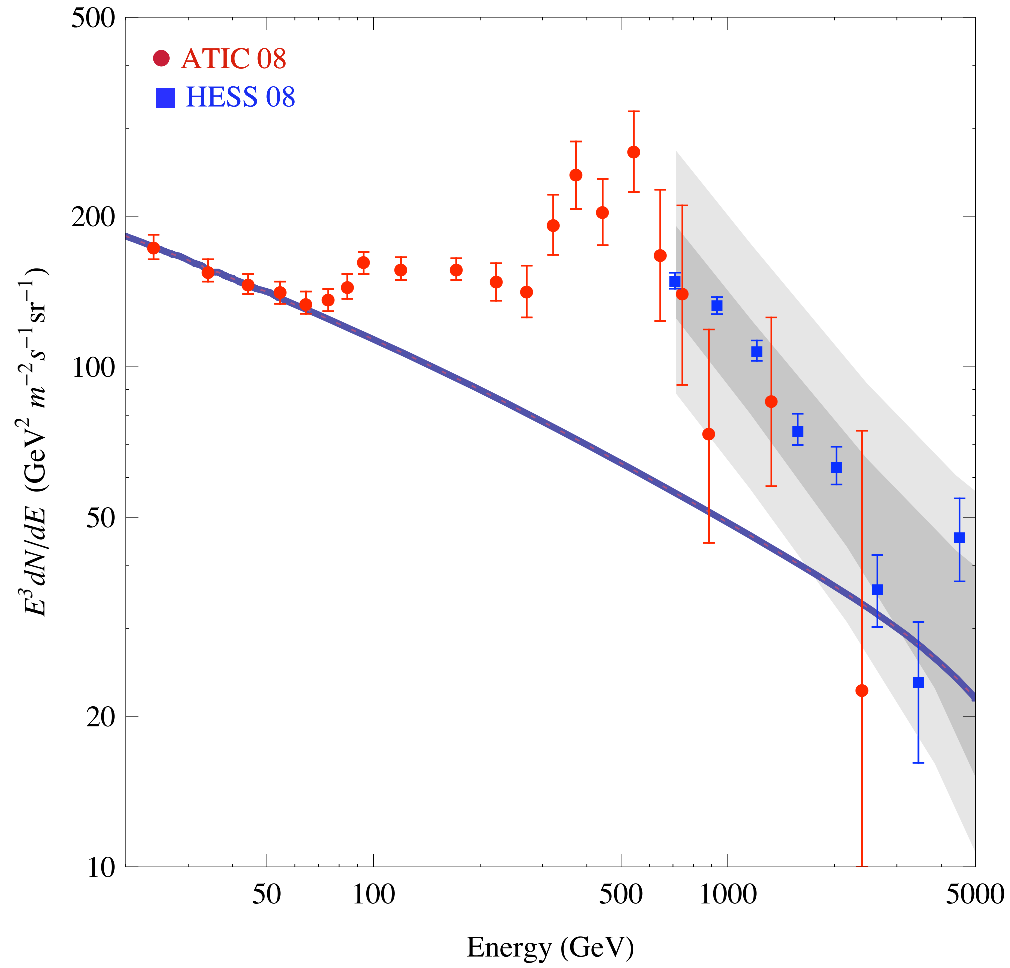
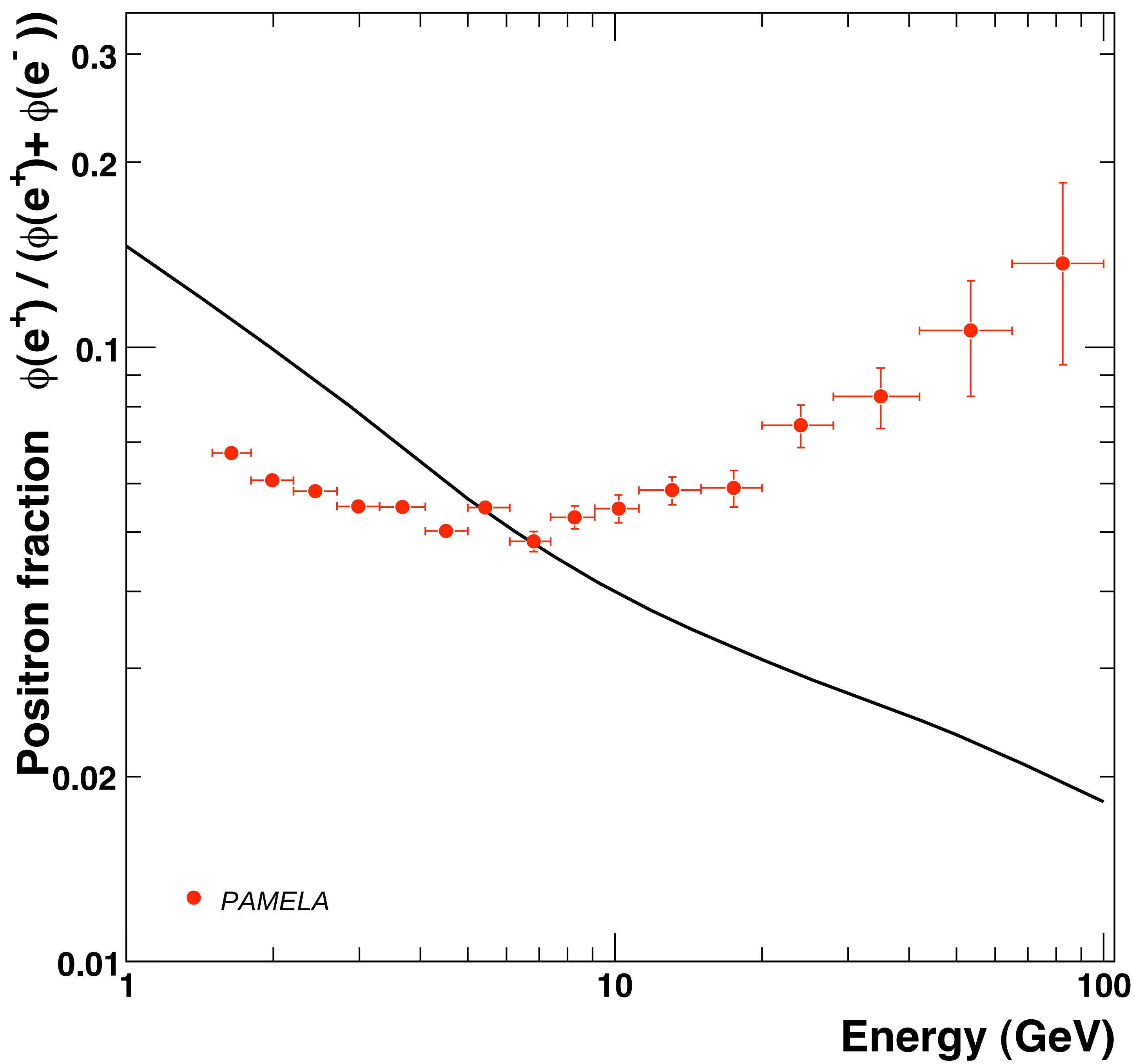


PAMELA

A satellite experiment. Measured the positron fraction in cosmic rays. Confirmed a hint of an excess seen by HEAT.



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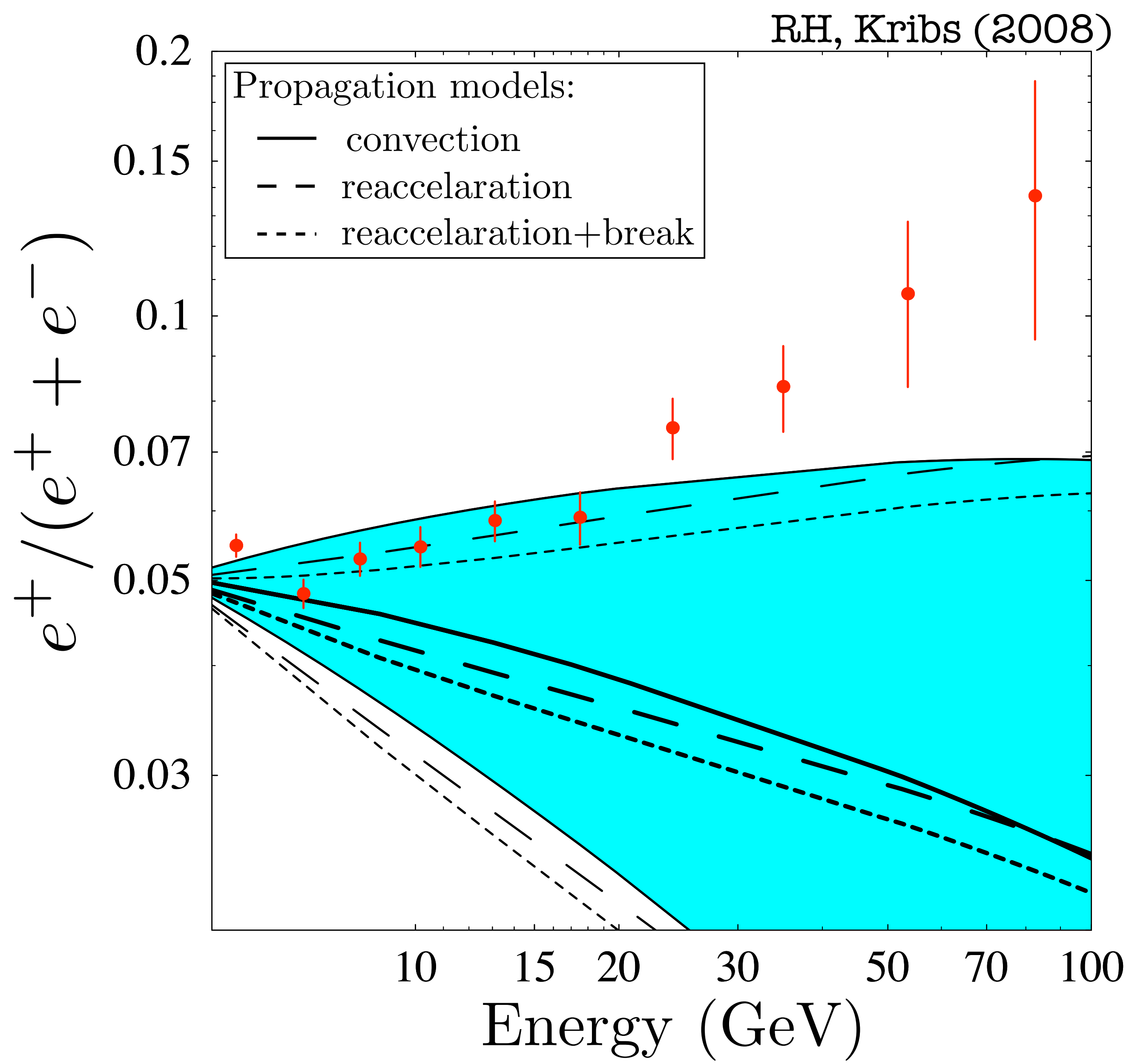
PAMELA

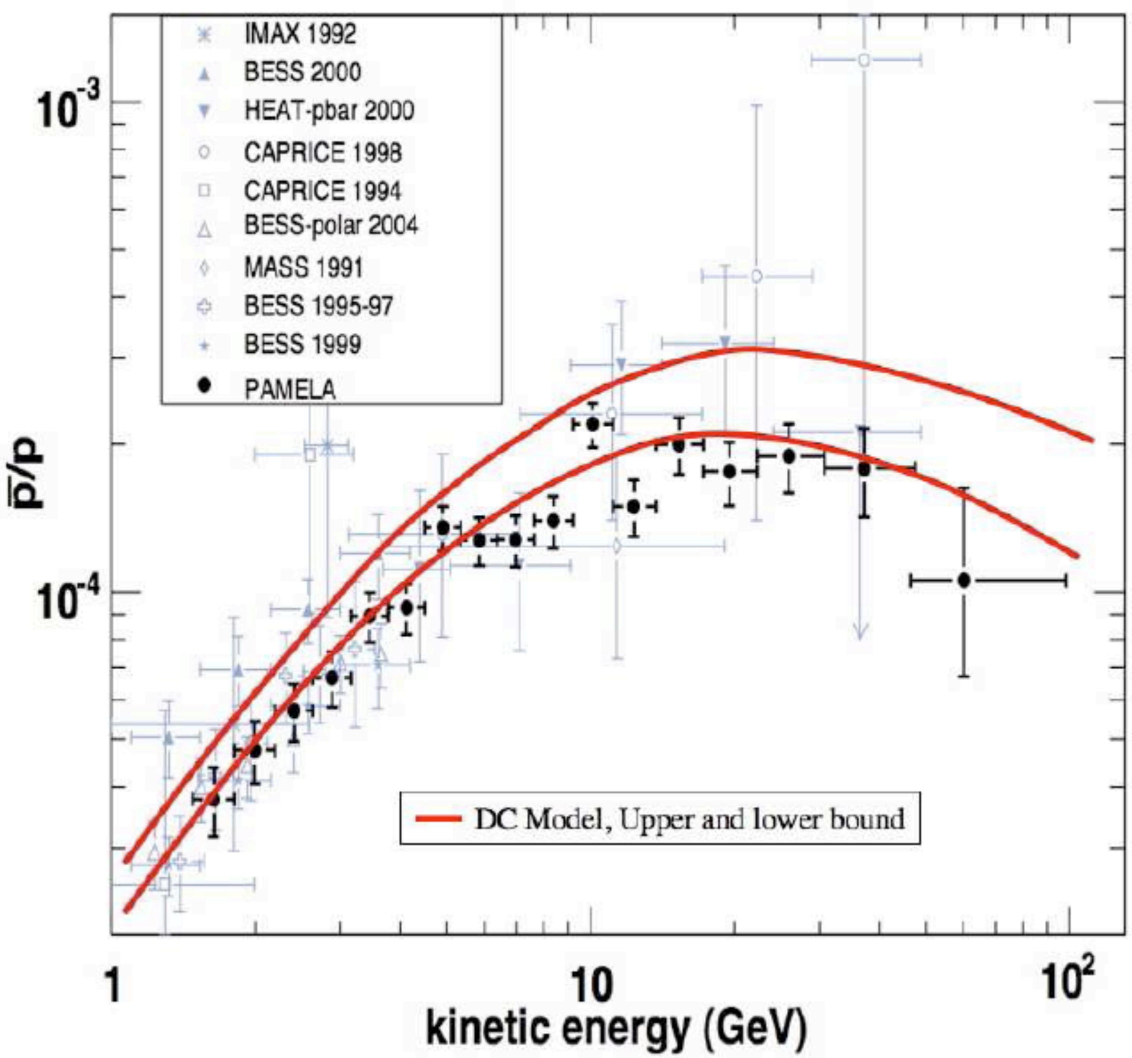
* Uncertainties on the background are large an difficult to quantify.

  But, the shape of the PAMELA spectrum qualitatively disagrees with backgrounds.



Anti-Protons

* No excess is seen up to ~100 GeV:



?

Note:
Protons loose energy more slowly.

A signal at high energies may still come up.

Potential to test GUT relations b/w hadronic and leptonic decays

Annihilation or Decay

* These anomalies are commonly interpreted as DM annihilations (as well as astrophysics).
* The rate $n^2\sigma v$ required to explain the signal is high compared to what is expected for SUSY WIMPs.
* Even for more efficient annihilators (e.g. Dirac DM) a "boost factor" of a couple hundred (at least) is required to explain ATIC.
* This may occur either from DM clumping or a Sommerfeld enhancement.
* For decays the signal rate is simply $n\Gamma$. :-)

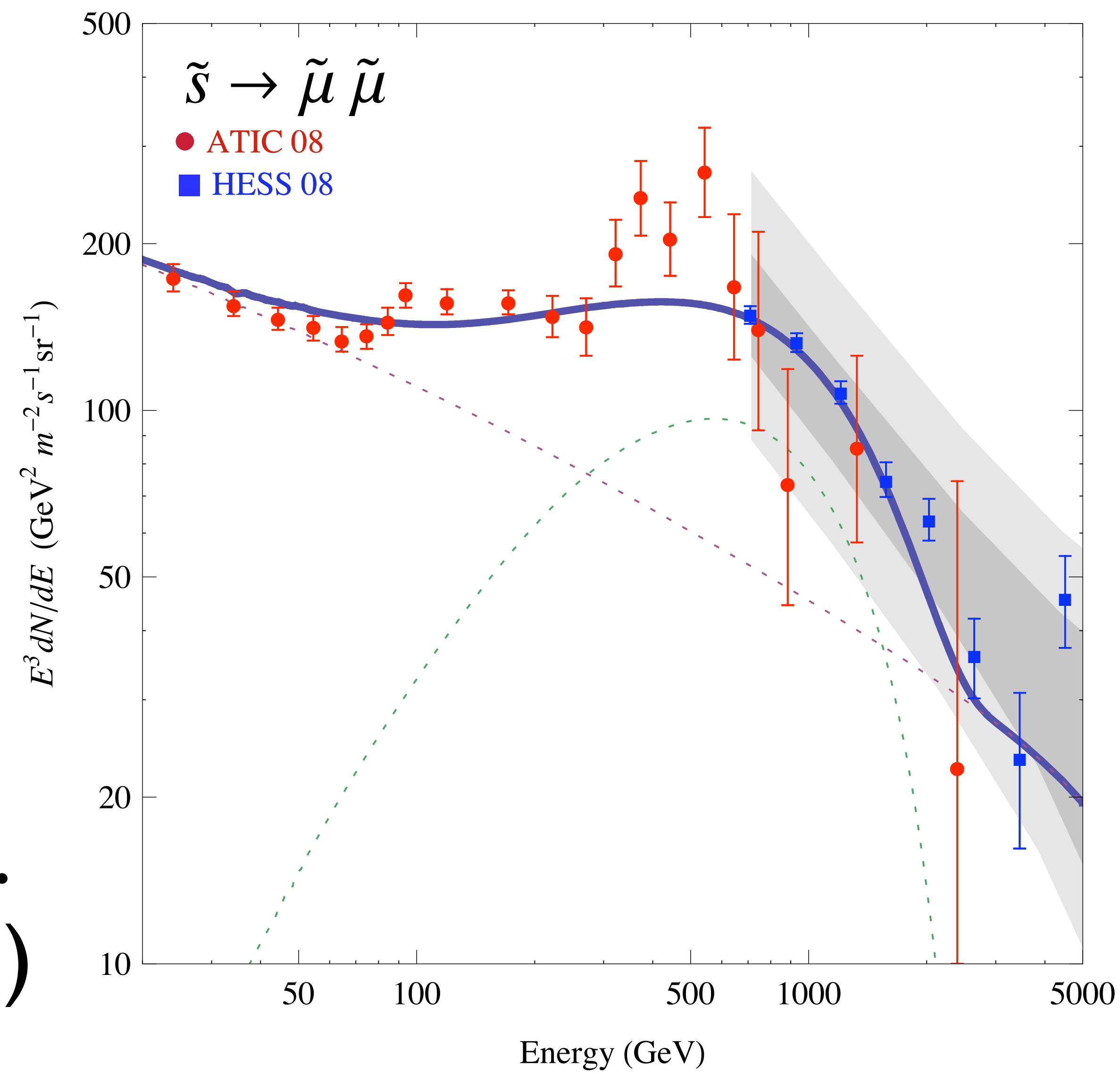
Even if all these are shown to be astrophysics
it is interesting to consider how
GUT physics may show up...

Possible GUT Scale Interpretations and Correlated Signals

HESS and smuons

* A decay to smuons may produce a soft feature that may interpolate low energy data with HESS.

* Can generically occur if DM decays via dim 6 flavor violating operators. (selectrons are supressed)



* A similar feature can come from $s \longrightarrow \tau\tilde{\tau}$ (though the photon signal is different in this case).

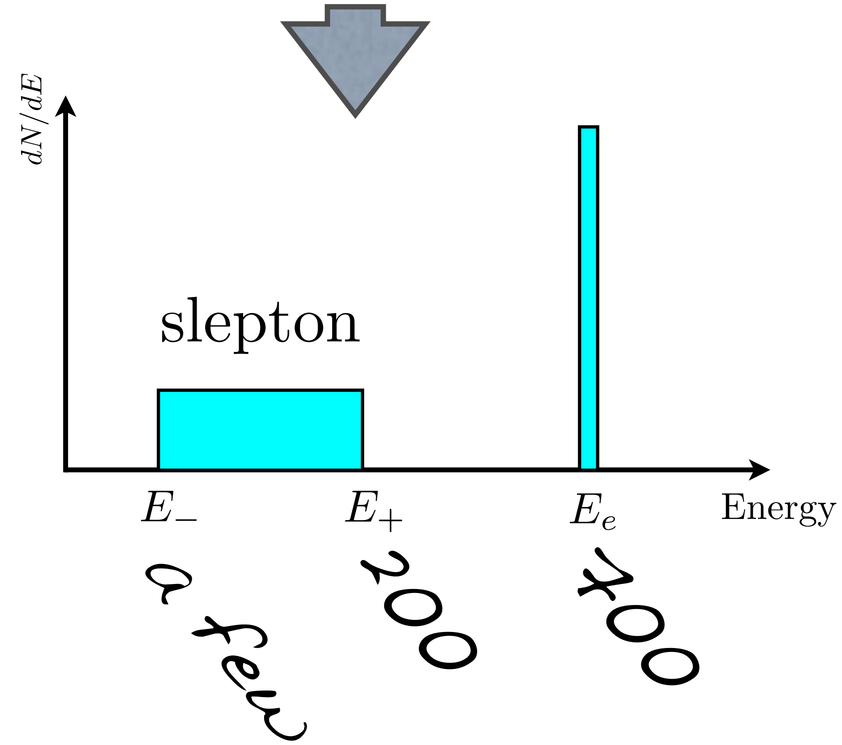
$\mathrm{DM} \to l\,\tilde{l}$ and $\tilde{l}\,\tilde{l}$

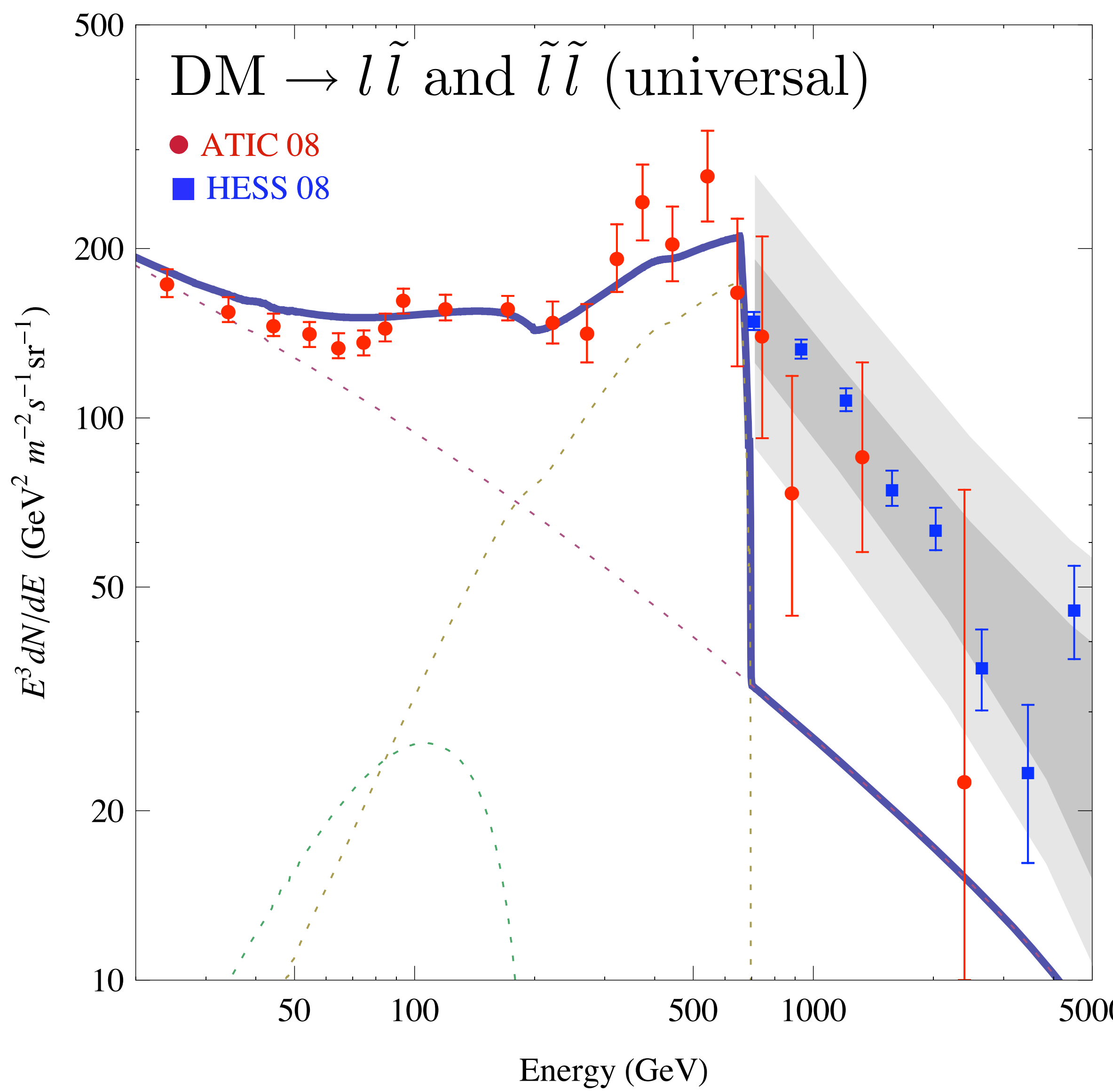
* The ATIC shape resembles DM → lepton+slepton e.g. via a “B-L” operator.

$m_s \sim m_{\tilde{s}} \sim 1400\ \mathrm{GeV}$

$m_{\tilde{l}} \sim 155\ \mathrm{GeV}$

$m_{LSP} \sim 130\ \mathrm{GeV}$

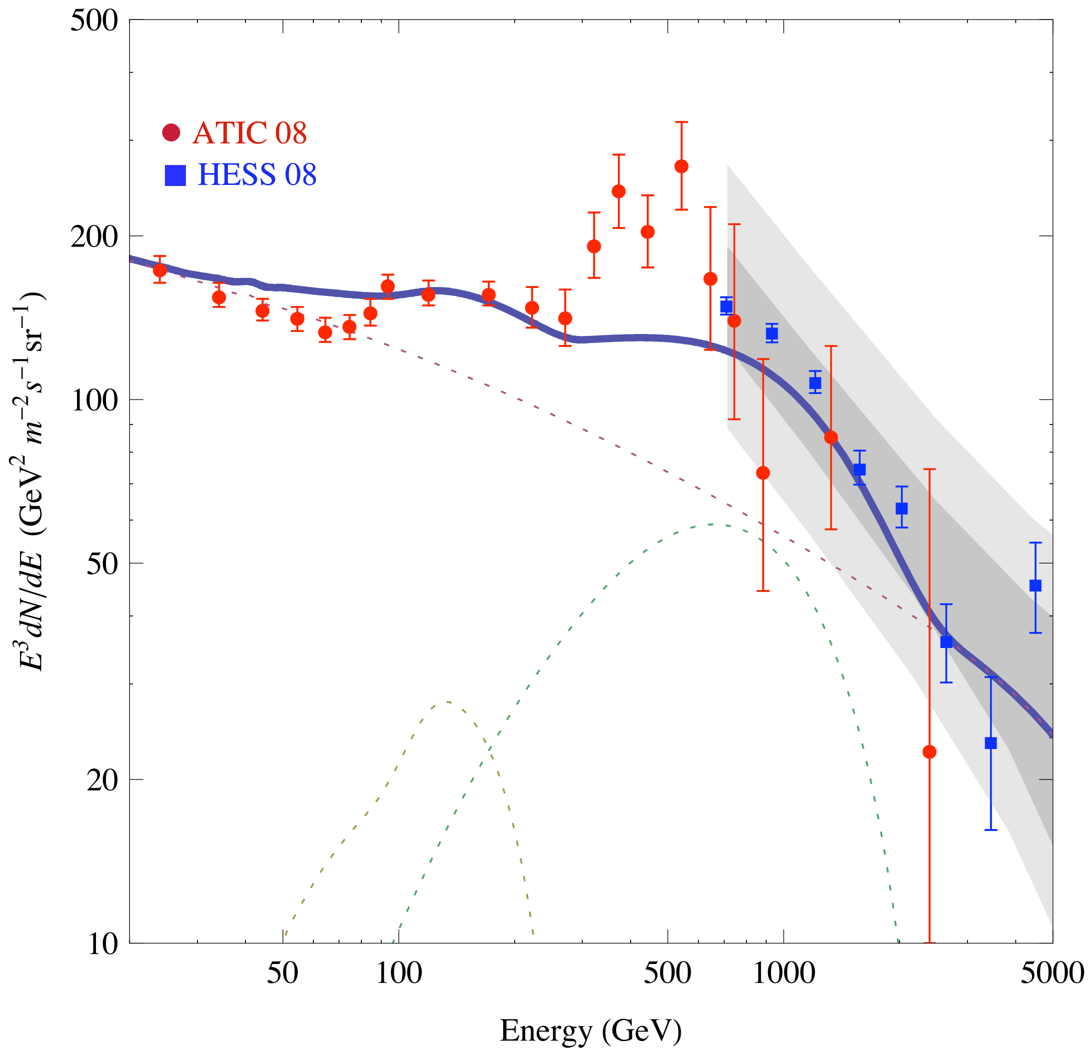




To be cross checked by Fermi, PAMELA **and LHC**

Double Features

* Softer double features are also generic.

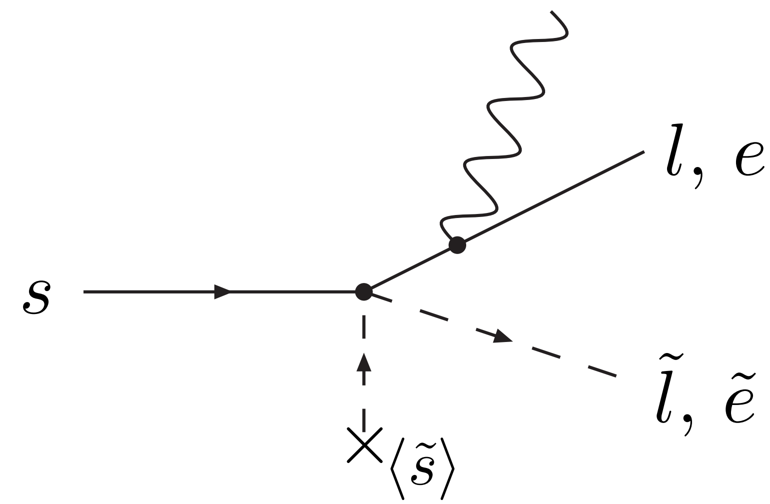


etc.

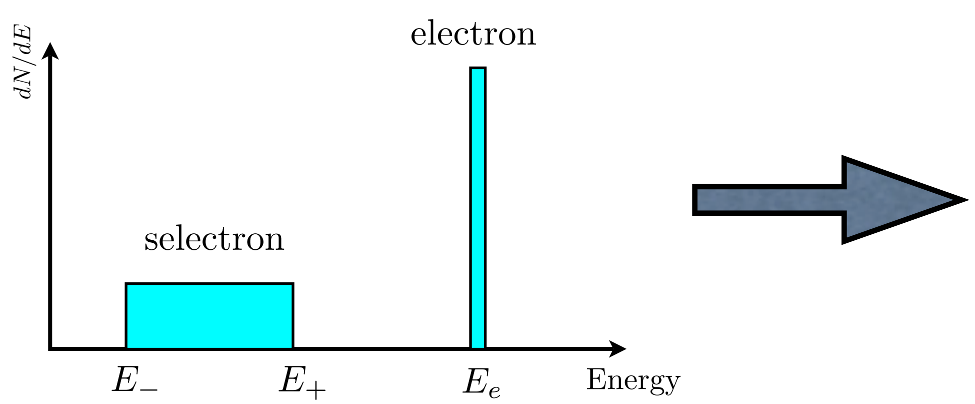
Final State Radiation

* Cosmic ray electrons are not enough to make a strong case. What else can we predict?
* Photons have much less propagation uncertainty.

Final state radiation:



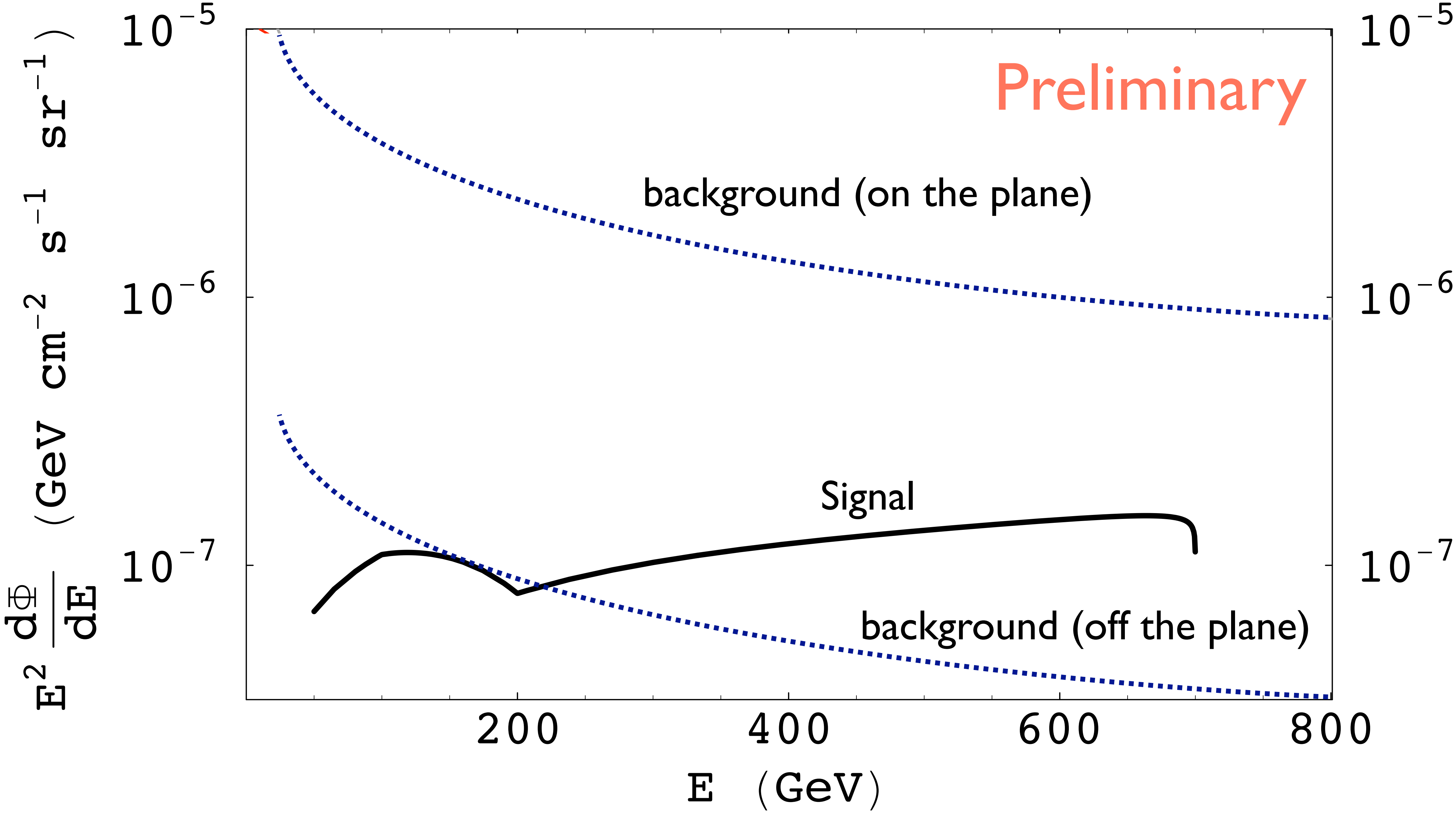
* FSR spectrum is independent of microphysics. Depends only on injection spectrum.



....

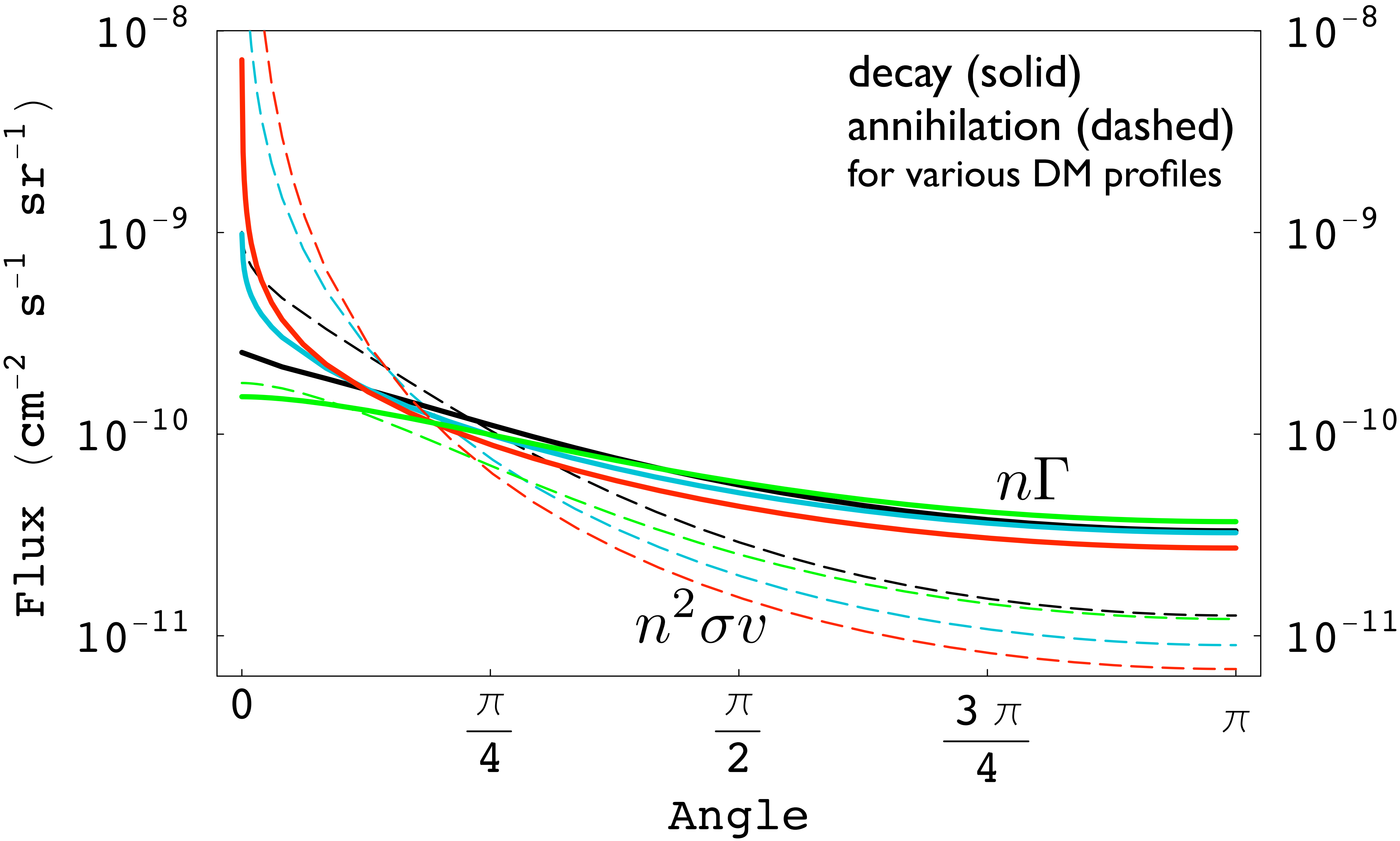
Fermi - Spectrum

Fermi may confirm the two bump structure:



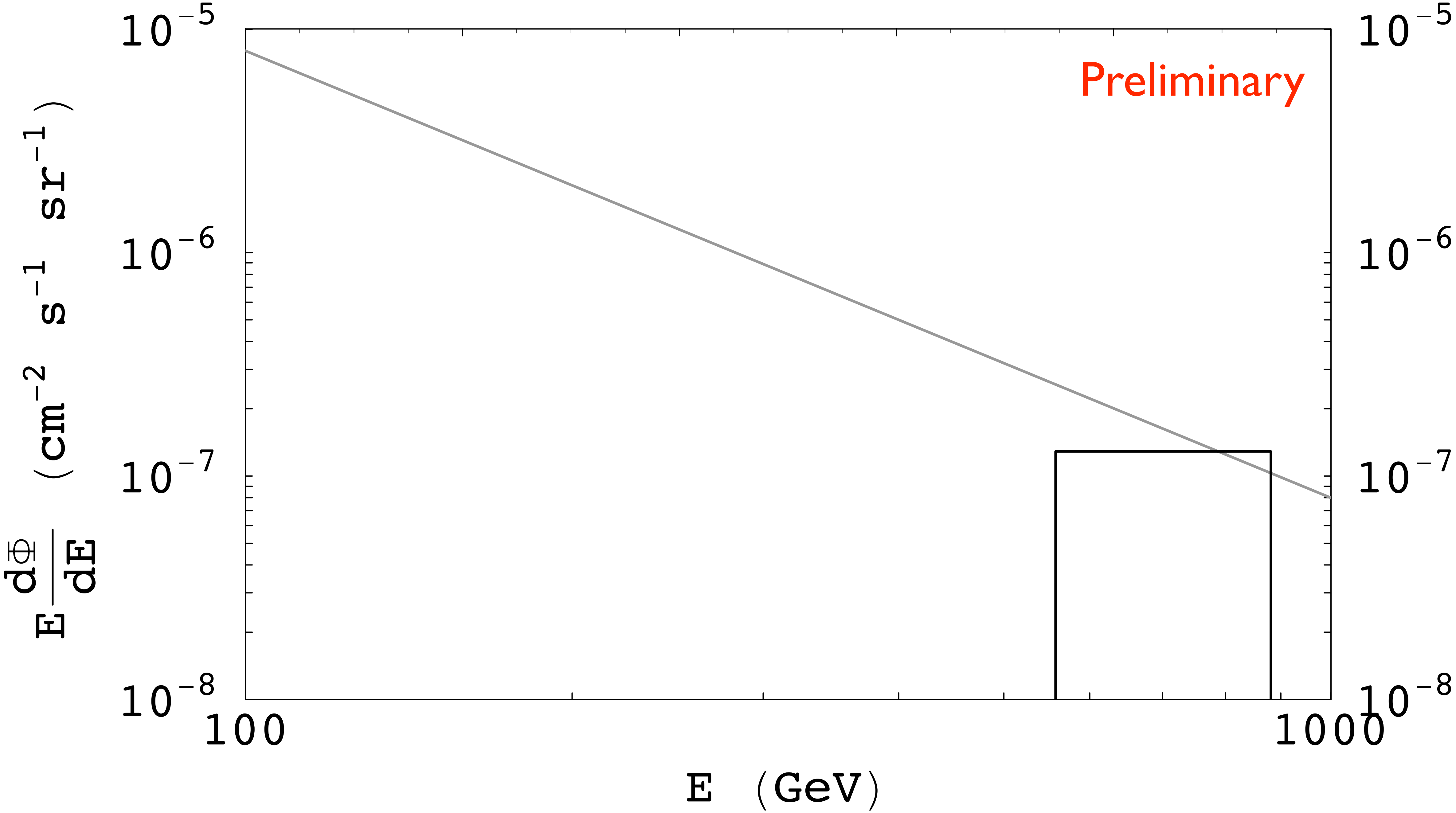
Fermi - Annihilation vs. Decay

* Photon flux vs. angle off the galactic plane:



Neutrinos - IceCube

* Mono energetic neutrinos at the ATIC "edge":



Conclusions

* Astrophysical searches for late decaying particles may complement proton decay in probing the GUT scale.

* Dark matter may generically decay to superpartners:

    - **Branching fractions** sensitive to GUT scale operators and to SUSY spectrum.

    - **Spectral features** may also teach us about superpartner masses.

* These interpretations of the data will be tested soon by **the LHC** and **a new generation of cosmic ray experiments.**