Astrophysical Probes of Unification

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with

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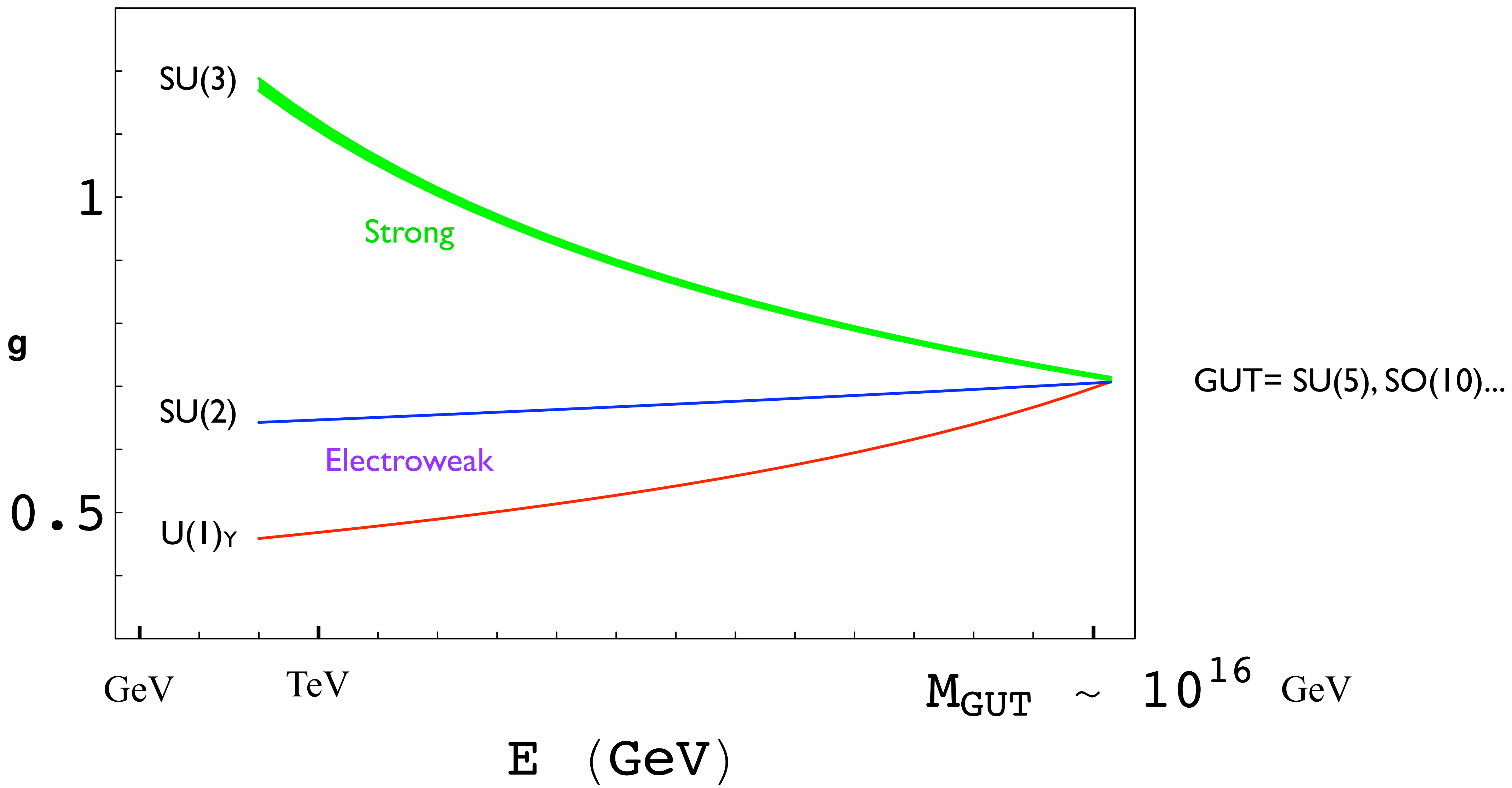
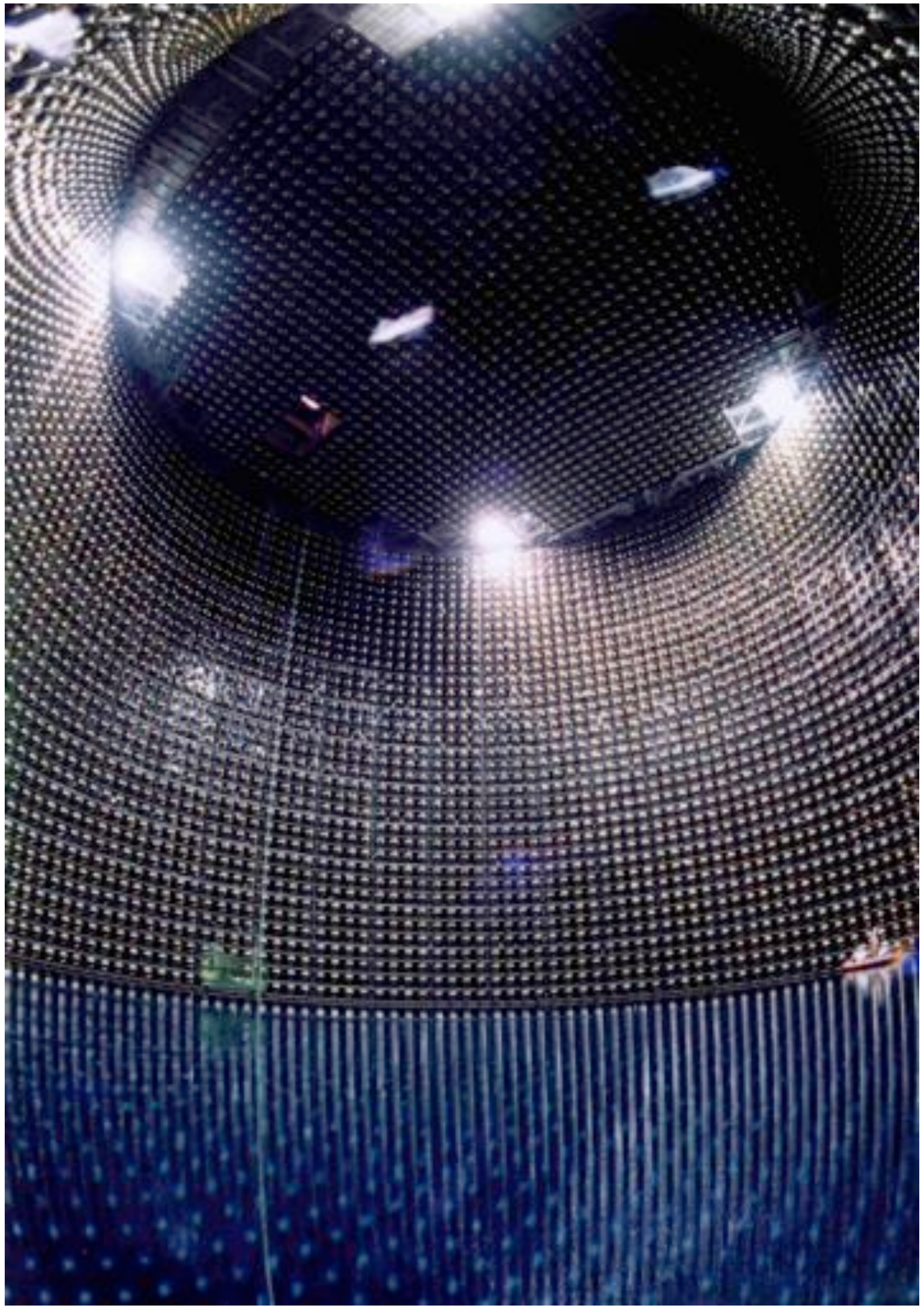
Supersymmetric Unification



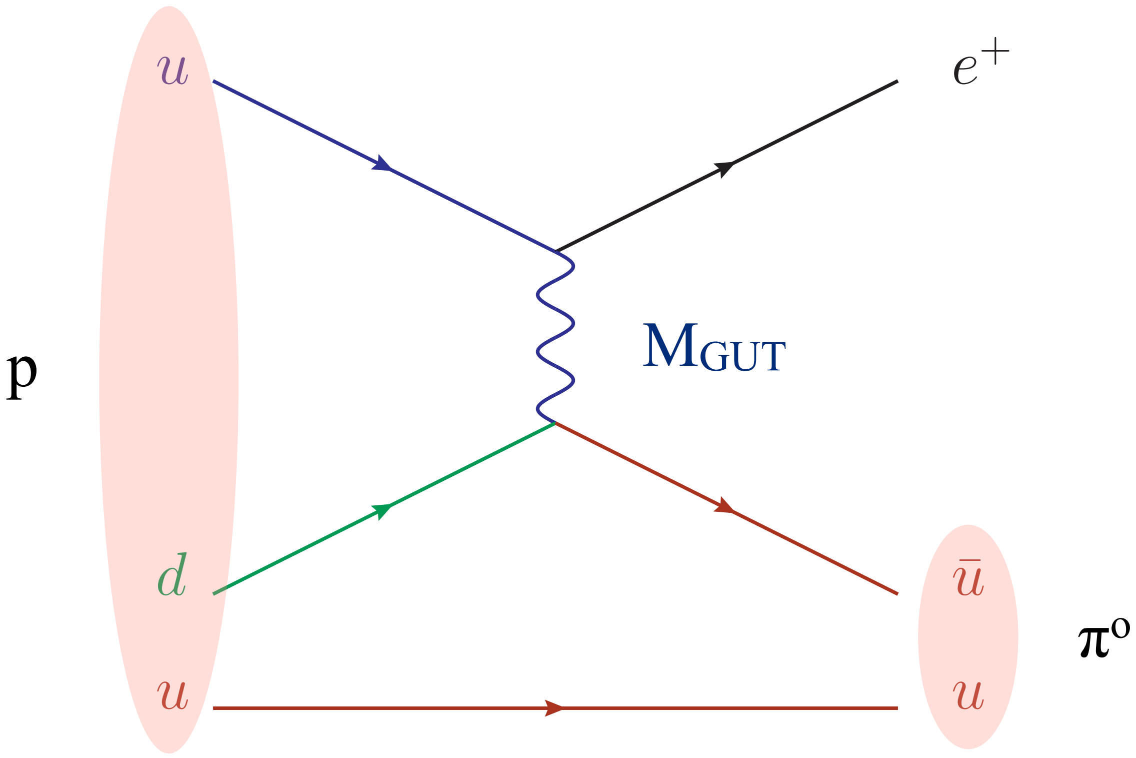
Suggests new scale $M_{GUT} \sim 10^{16}$ GeV

Low Energy Consequences?

Proton Decay



GUT physics destabilizes proton.



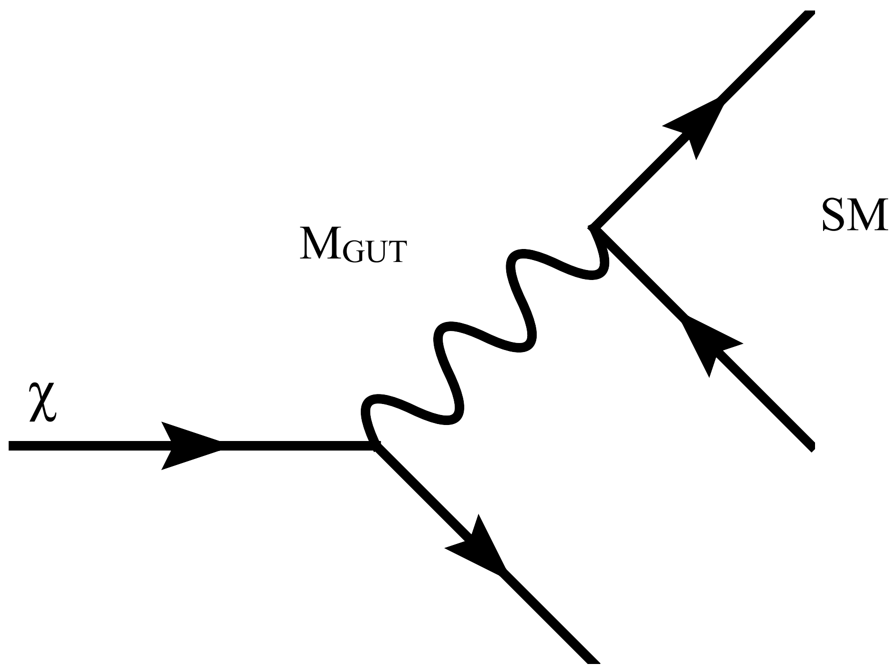
$$\tau \sim 8\pi \left(\frac{M_{GUT}}{2 \times 10^{16}\,\mathrm{GeV}} \right)^4 \left(\frac{1\,\mathrm{GeV}}{m_p} \right)^5 \sim 10^{43}\,\mathrm{s}$$

Other decays? Signatures?

TeV Particle Decay

Hierarchy Problem, Dark Matter suggest new TeV particles.

Destabilized by GUT? Lifetimes?

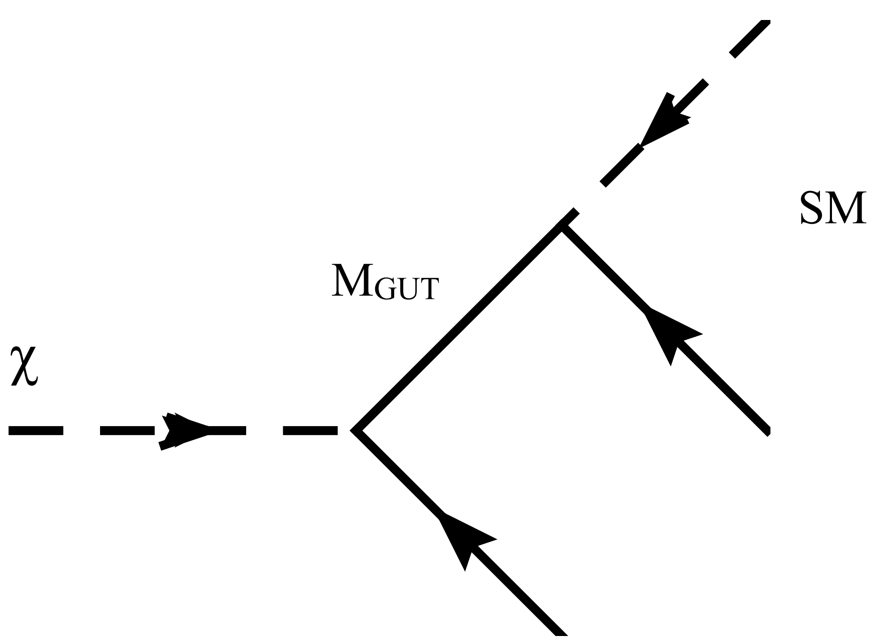


Cosmological

$$\tau \sim 8\pi \left(\frac{\mathrm{M_{GUT}}}{10^{16}\ \mathrm{GeV}}\right)^4 \left(\frac{\mathrm{TeV}}{m_\chi}\right)^5 = 3 \times 10^{27}\ \mathrm{s}$$

dim 6

Dark Matter?



More Rapid

$$\tau \sim 8\pi \left(\frac{\mathrm{M_{GUT}}}{10^{16}\ \mathrm{GeV}}\right)^2 \left(\frac{\mathrm{TeV}}{m_\chi}\right)^3 = 10\ \mathrm{s}$$

dim 5

Decays during BBN.

Outline

1. Dark Matter Decay
(and associated cosmic ray signals)

2. Decays during BBN
(primordial light element abundances)

3. Conclusions

Dark Matter Decay

Why Not?

Dark Matter around today.
Decay with cosmological lifetime.

All known stable particles (electrons, photons etc.) stabilized by gauge, space-time symmetries.

No known gauge symmetry associated with Dark Matter.

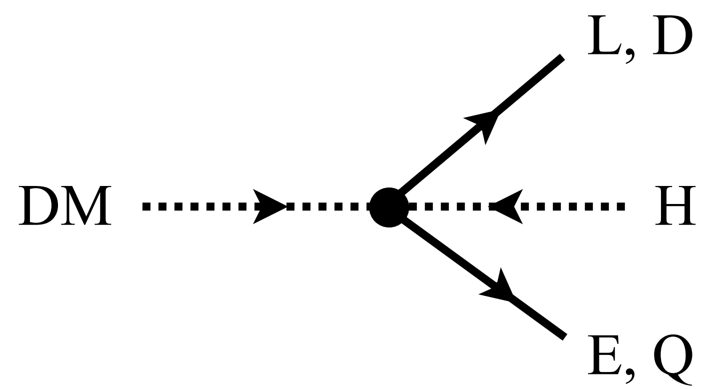
Protected by global symmetries?

Expect violations from quantum gravity or maybe GUT physics?

Possibilities for Decaying DM

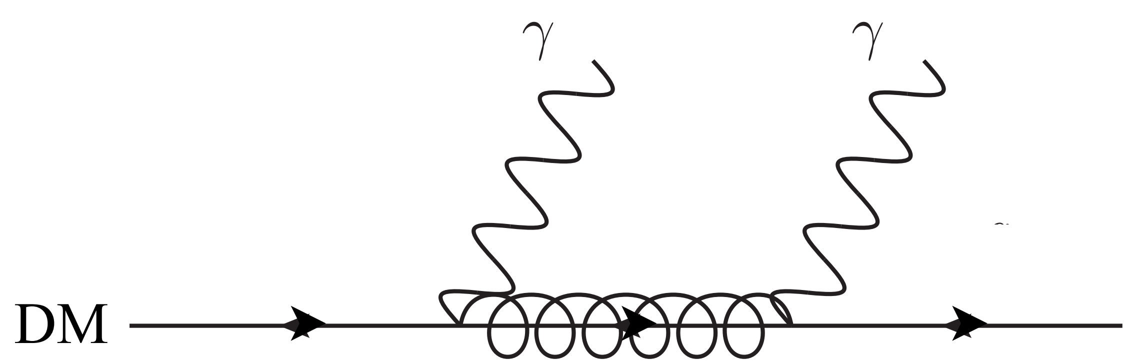
consider the possible decay modes allowed by standard model symmetries

$K \ni S^\dagger L H_u^\dagger E,\ S^\dagger D H_u^\dagger Q$



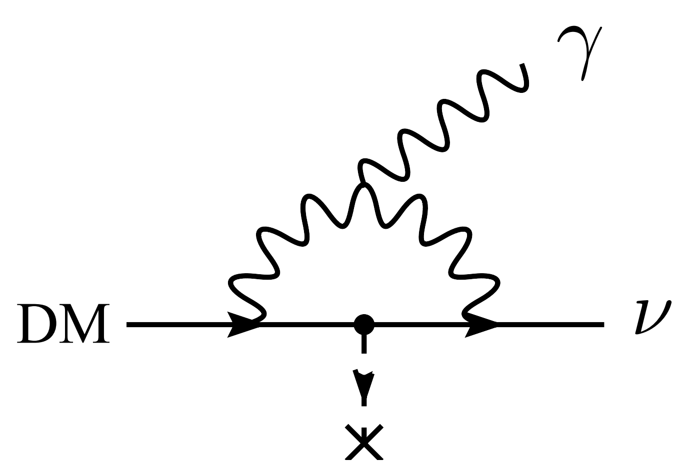
TeV leptons, quarks, or both

$\mathrm{W} \ni S^2 \mathcal{W}_\alpha \mathcal{W}^\alpha$



TeV photons (also W's...)

$\mathcal{L} \ni \frac{m_{SUSY}}{M_{GUT}^2} H_d \tilde{W} \not{\partial} \ell^\dagger$



monoenergetic photons and neutrinos

and more...

Signals of Dark Matter Decay

$$\tau \sim 10^{27}\ \mathrm{s} \left(\frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)^5 \left(\frac{\mathrm{M_{GUT}}}{10^{16}\ \mathrm{GeV}}\right)^4$$

DM decays yield flux of TeV cosmic rays ($e^{\pm}$, photons, neutrinos)

$$\int^{10\ \mathrm{kpc}} \frac{d^3r}{r^2}\frac{n_{\mathrm{DM}}}{\tau} \sim (10\ \mathrm{kpc}) \left(\frac{0.3}{\mathrm{cm}^3}\ \frac{\mathrm{GeV}}{m_{\mathrm{DM}}}\right) (10^{-28}\ \mathrm{s}^{-1})$$

$$\approx 10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

Such a flux could be observable.

E.g. in a satellite or balloon experiment (EGRET, PAMELA, ATIC, Fermi...):

$$\sim (1\ \mathrm{m}^2)(1\ \mathrm{yr})(1\ \mathrm{sr}) \approx 3 \times 10^{11}\ \mathrm{cm}^2\ \mathrm{s\ sr}$$

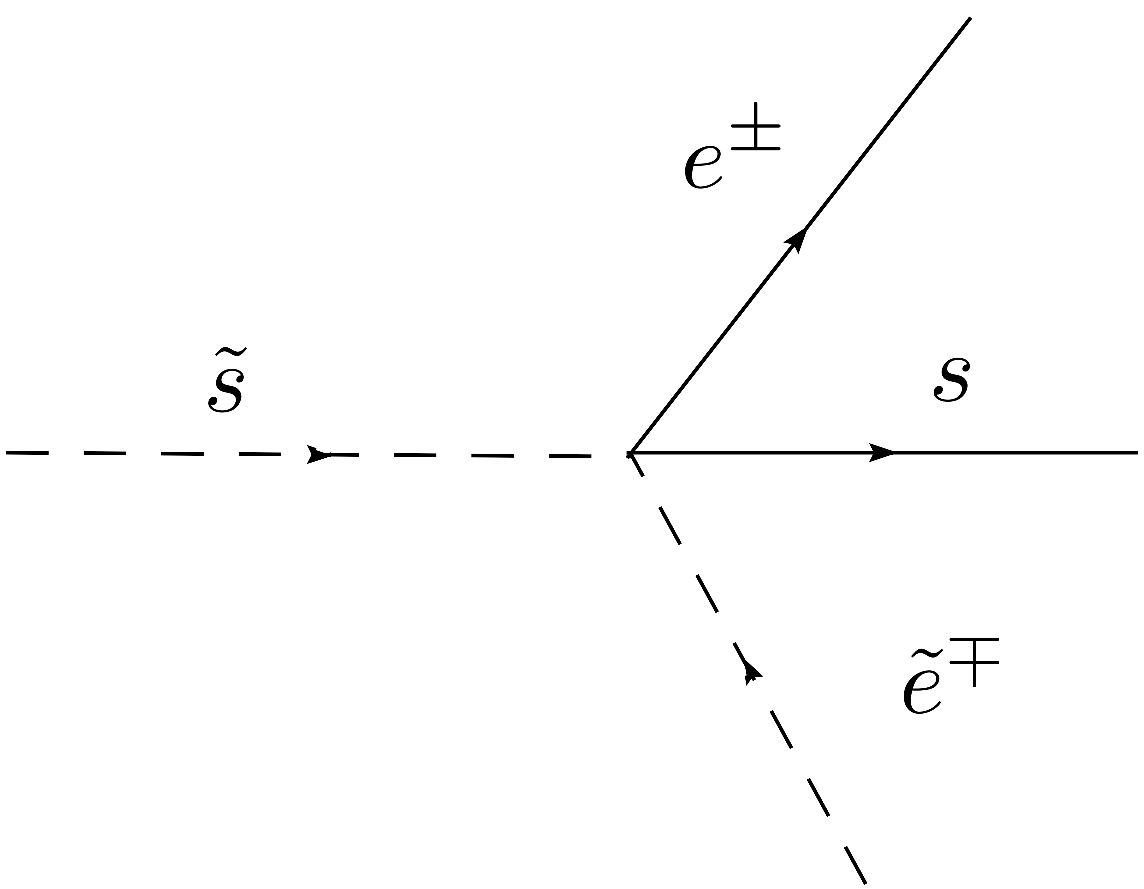
Dimension 6 Ubiquity

Introduce Dark Matter field S.

$$\int d^4\theta \, \frac{S^\dagger S \, O^\dagger O}{\Lambda^2} \qquad \begin{array}{rcl} O & = & \text{Any field,} \\ \Lambda & = & \text{Cut off } e.g.\ M_{pl},\, M_{GUT} \end{array}$$

Allowed by all symmetries.

Can forbid lower dim operators by symmetry



$$\tau_{\tilde{s}} \sim 10^{26}\,\mathrm{s} \left(\frac{\Lambda}{M_{GUT}}\right)^4 \left(\frac{\mathrm{TeV}}{m_{\tilde{s}}}\right)^5$$

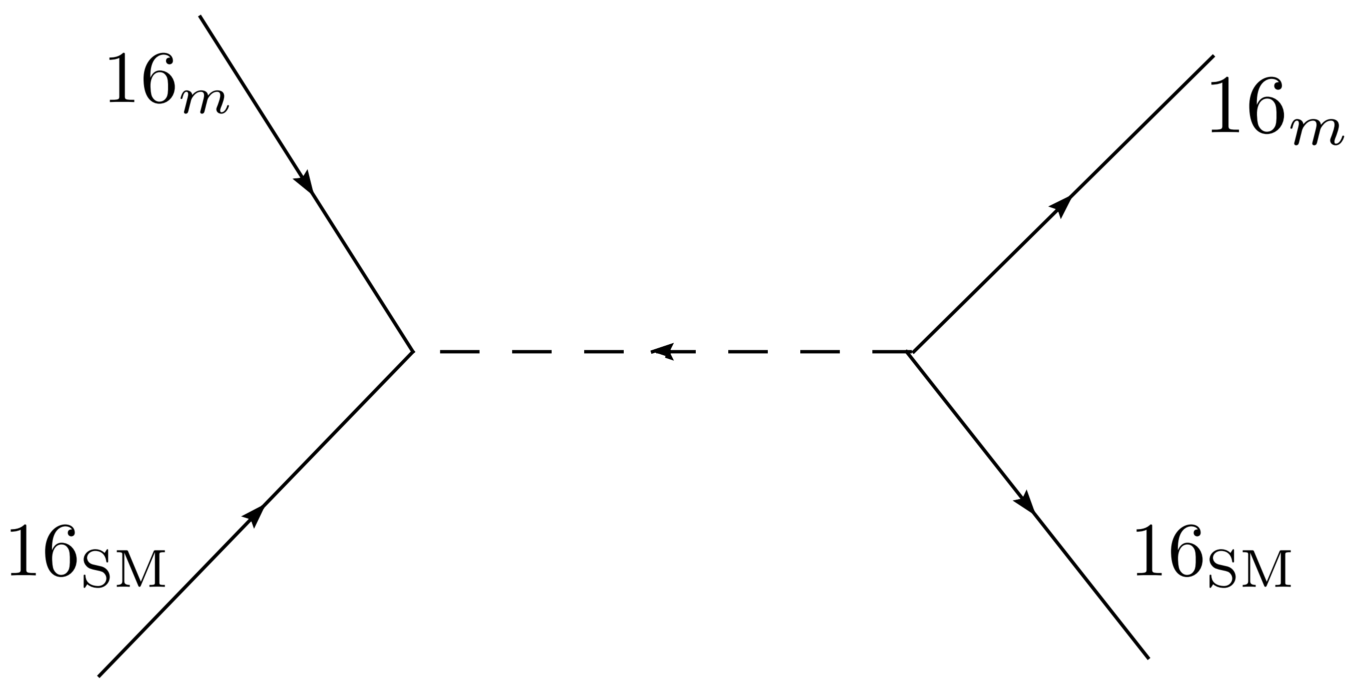
SO(10) Model

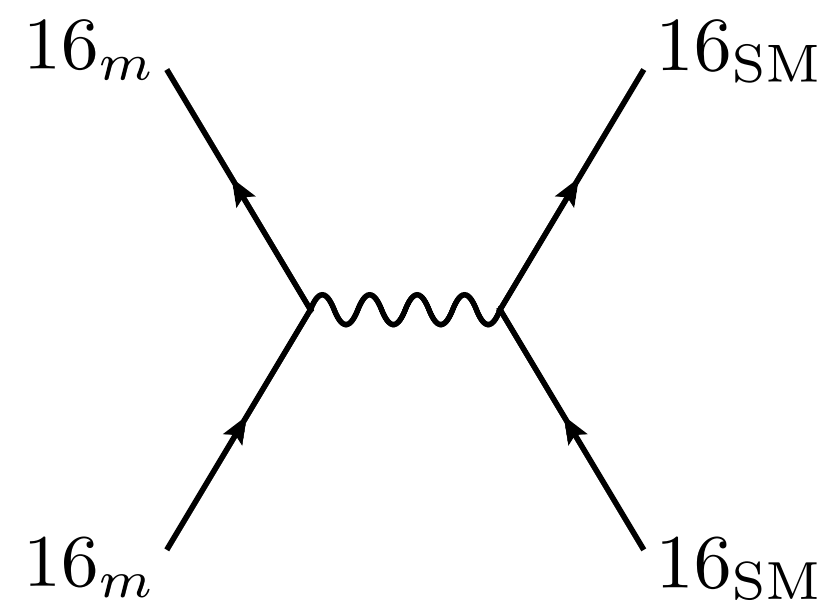
$$W_{\mathrm{MSSM}} = H16_{\mathrm{SM}}16_{\mathrm{SM}} + \mu HH$$

add one weak scale 16_{m} and one GUT scale 10_{GUT}

$$W' = \lambda 16_m 16_{\mathrm{SM}} 10_{\mathrm{GUT}}$$

integrating out 10_{GUT} and SO(10) gauge bosons generates dim 6 operators:



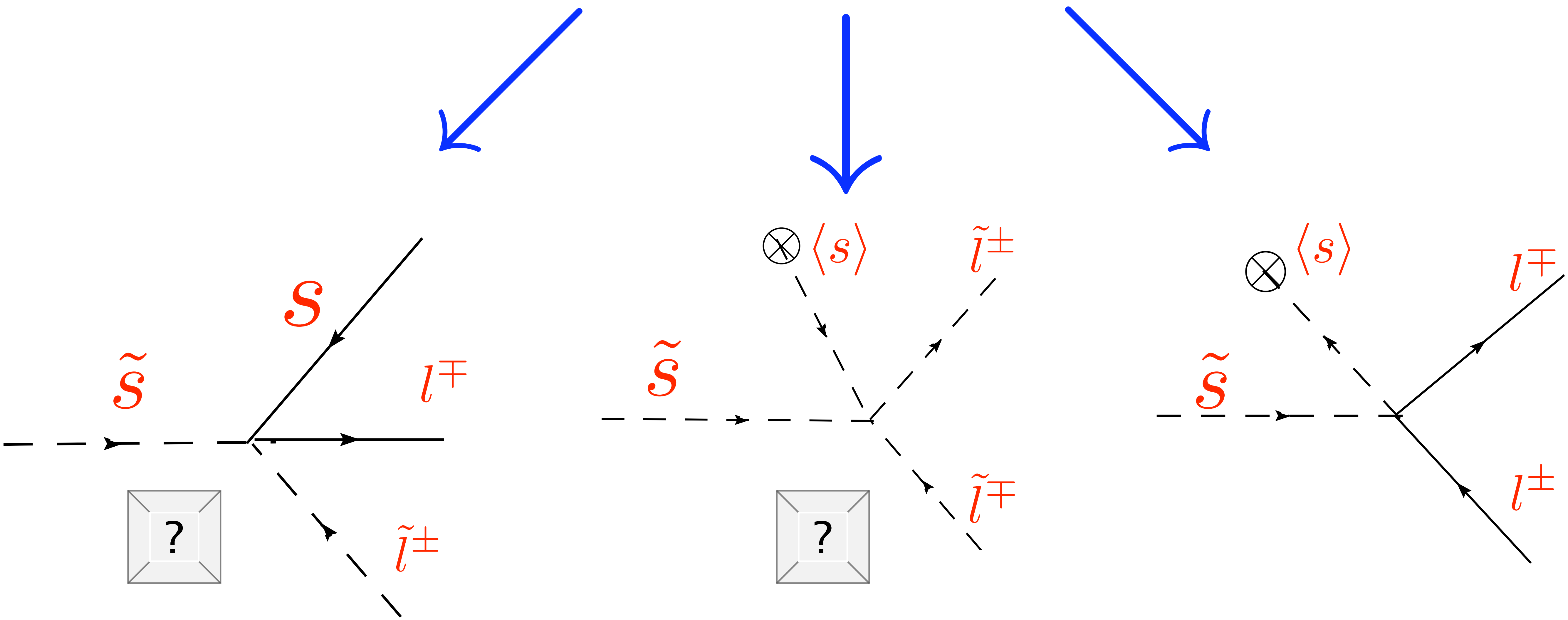


$$\int d^4\theta\, \lambda^4 \left(\frac{16_m^\dagger 16_m 16_{\mathrm{SM}}^\dagger 16_{\mathrm{SM}}}{M_{\mathrm{GUT}}^2} \right) \qquad \int d^4\theta\, g^4 \left(\frac{16_m^\dagger 16_m 16_{\mathrm{SM}}^\dagger 16_{\mathrm{SM}}}{M_{\mathrm{B\text{-}L}}^2} \right)$$

these yield dimension 6 operators for singlets, causing decays

Operator Phenomenology

$$\int d^4\theta \, \frac{S_m^\dagger S_m 16_{\rm SM}^\dagger 16_{\rm SM}}{M_{\rm GUT}^2}$$



$\tilde{s} \longrightarrow s l^\mp \tilde{l}^\pm$ $\quad$ $\tilde{s} \longrightarrow \tilde{l}^\mp \tilde{l}^\pm$ $\quad$ $\tilde{s} \longrightarrow l^\pm l^\mp$

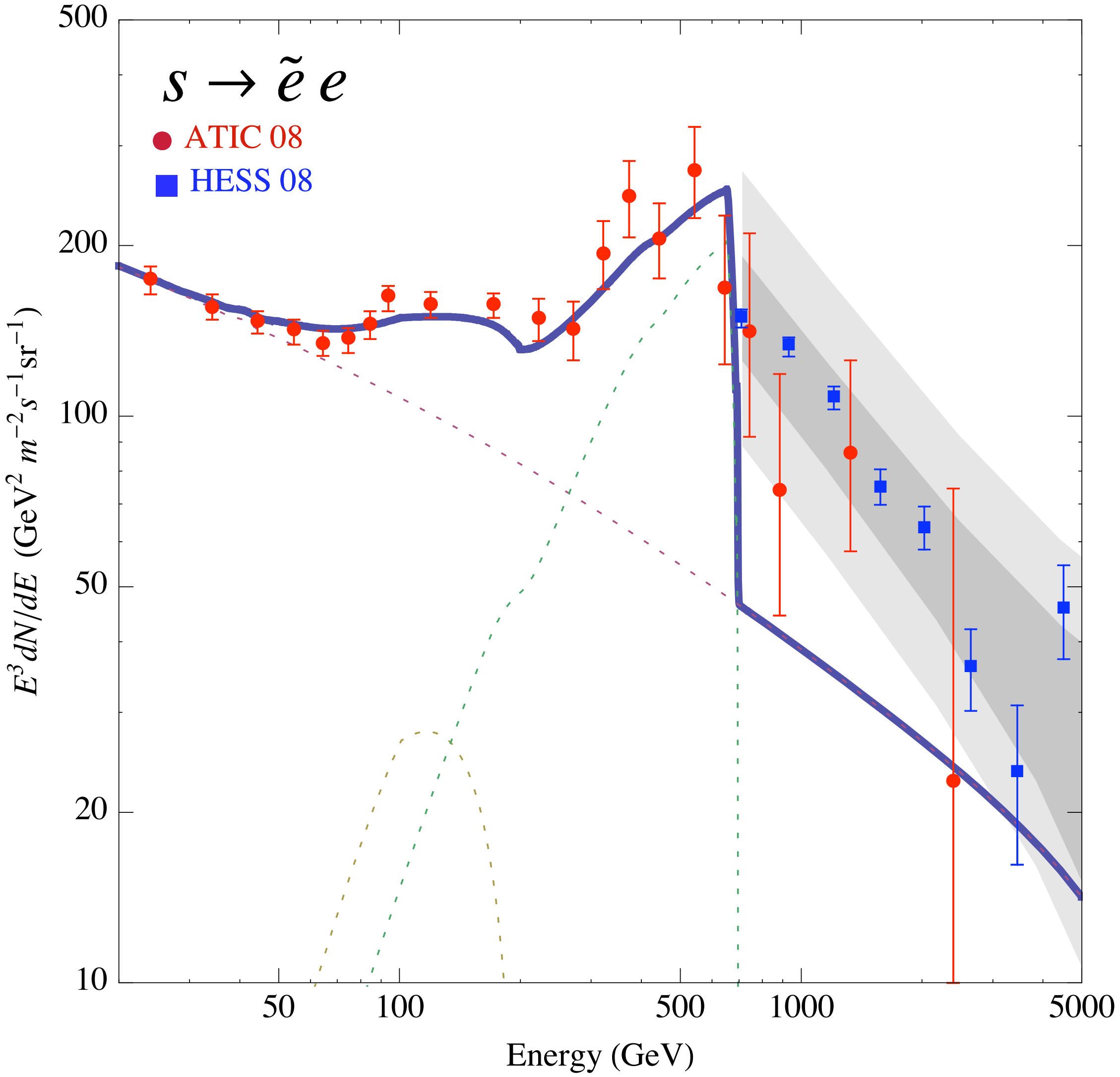
(helicity suppressed)

Superpartners always present in decay.

Flavor Structure: $M_{\text{B-L}}$ vs M_{GUT}

Universal

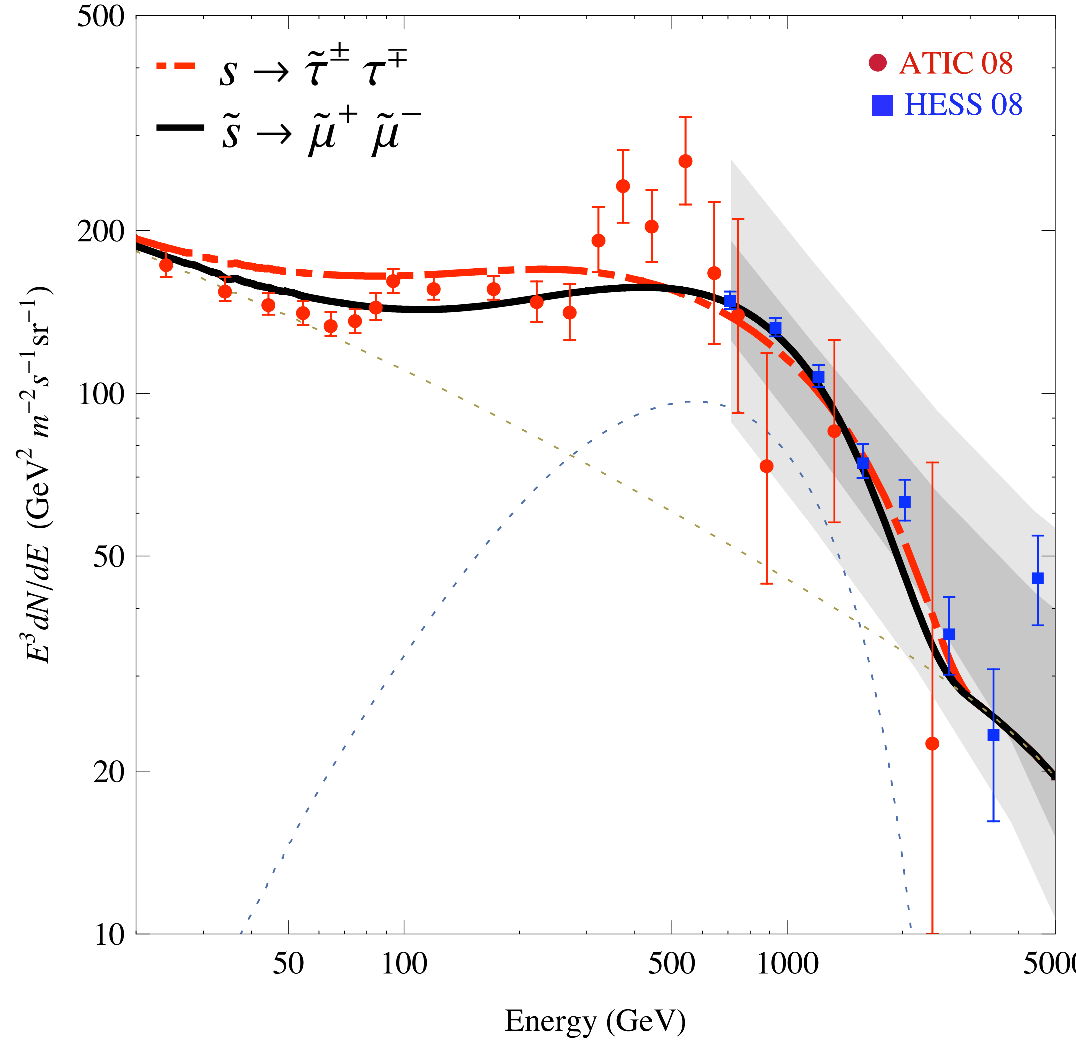
$(M_{\text{B-L}} < M_{\text{GUT}})$



$$\int d^4\theta\, g^4 \left(\frac{16_m^\dagger 16_m 16_{\text{SM}}^\dagger 16_{\text{SM}}}{M_{\text{B-L}}^2} \right)$$

Non-Universal

$(M_{\text{GUT}} < M_{\text{B-L}})$



$$\int d^4\theta\, \lambda^4 \left(\frac{16_m^\dagger 16_m 16_{\text{SM}}^\dagger 16_{\text{SM}}}{M_{\text{GUT}}^2} \right)$$

Hadronic Branching Fraction

PAMELA antiprotons $\implies \tau_{p^-} \gtrsim 10^{27}$ s

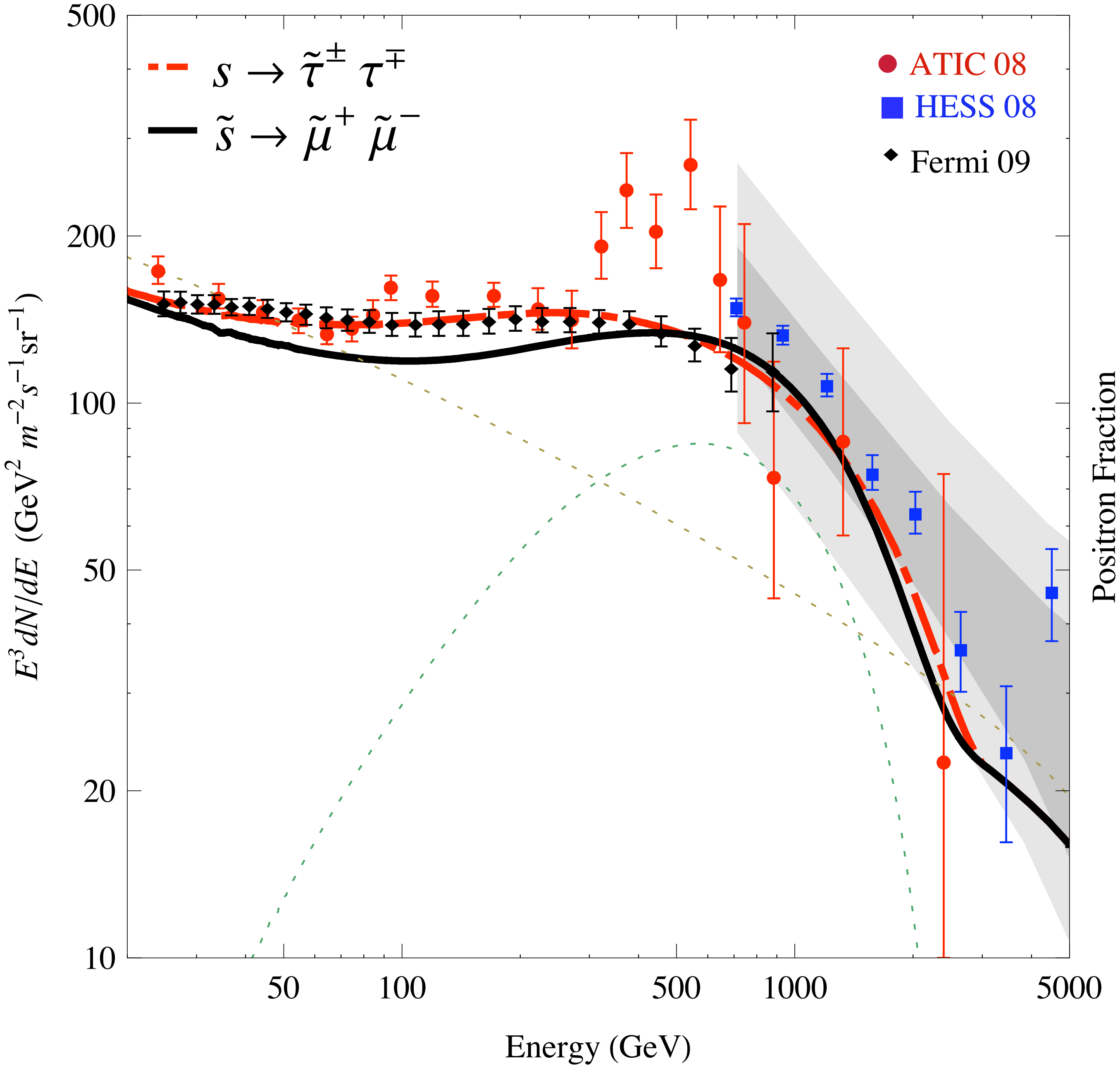
$$\text{Fraction} \sim \frac{\delta m^5}{M_{GUT}^4}$$

Superpartners always present in decay.

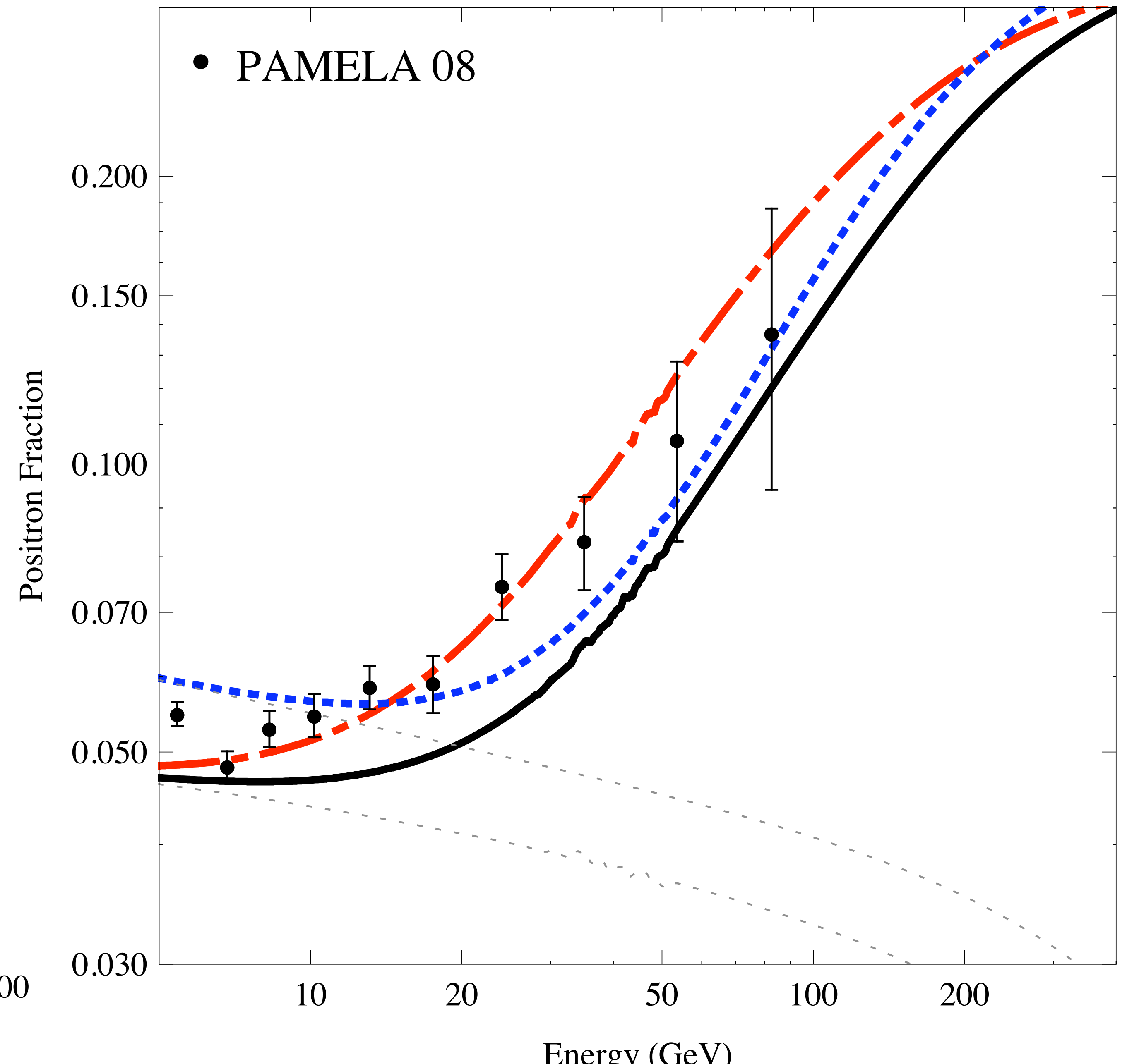
$\tilde{l}$ lighter than $\tilde{q} \implies$ lepton dominance.

GUT scale doublet-triplet splittings $\implies$ lepton dominance.

Fits



$m_{\tilde{s}} = 6$ TeV, $\tau = 7 \times 10^{25}$ s

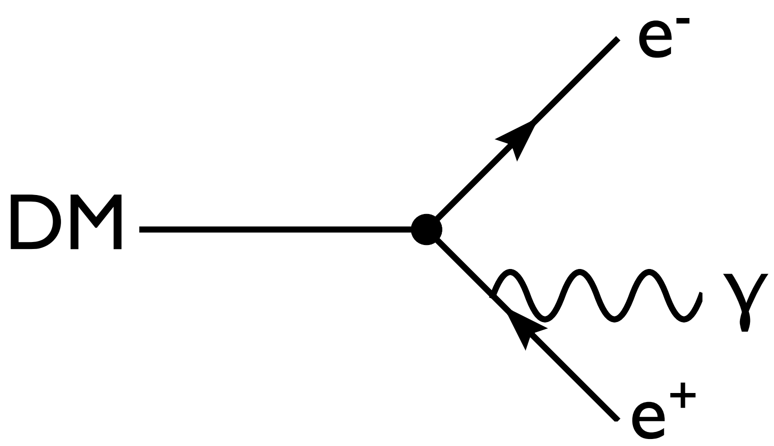


$m_s = 8$ TeV, $\tau = 1.2 \times 10^{26}$ s

Parameters: Mass, Lifetime, Decay Mode

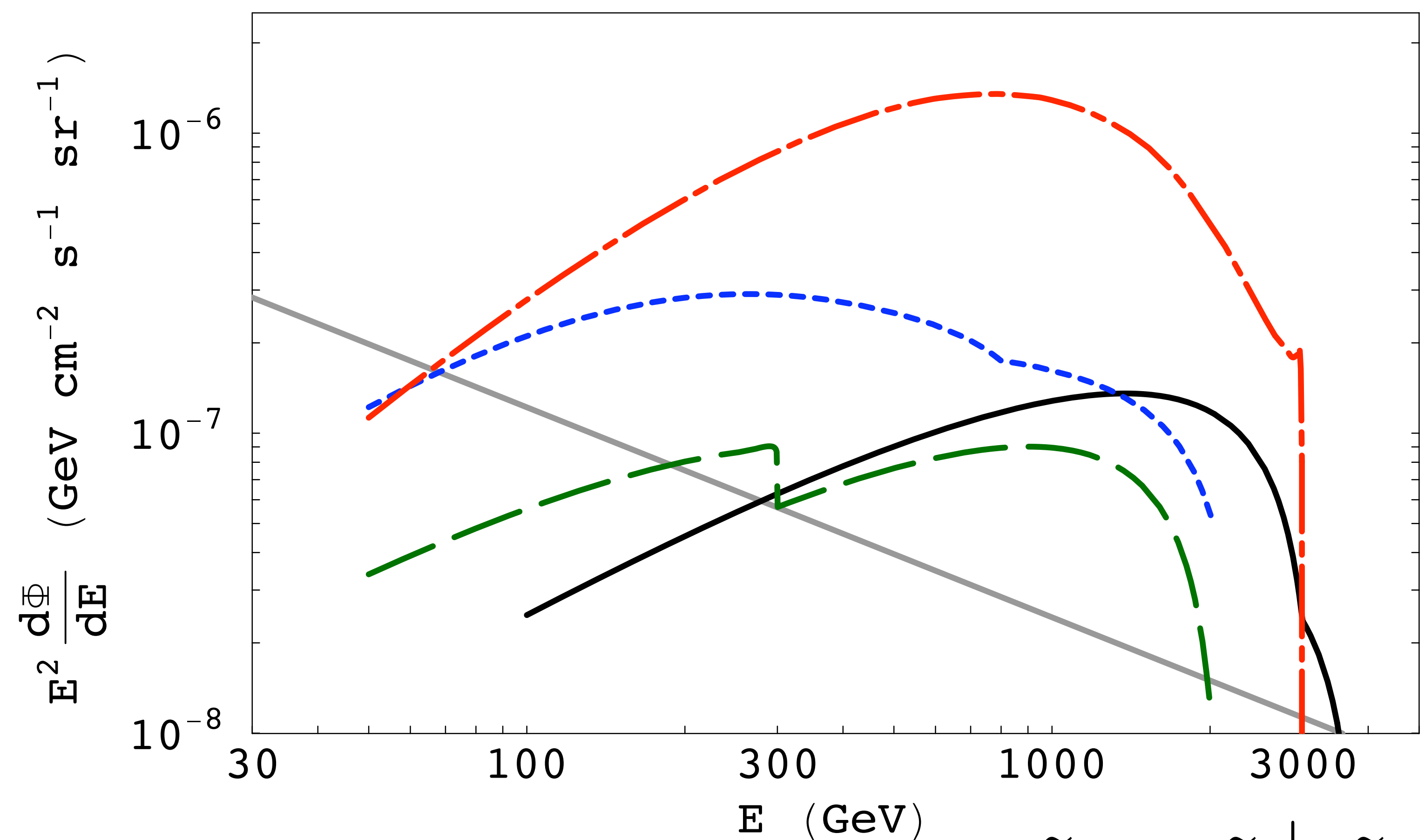
Other Explanations: Dark Matter annihilations, Astrophysics

Dark Matter Vs Astrophysics



$$\Gamma\left(e^+e^-\gamma\right) \sim \alpha\,\Gamma\left(e^+e^-\right)$$

Final State Radiation (FSR) independent of high energy physics model



$\tilde{s} \longrightarrow \tilde{\mu}^+\,\tilde{\mu}^-$

$s \longrightarrow \tilde{\tau}^{\pm}\,\tau^{\mp}$

$\tilde{s} \longrightarrow \tilde{l}_L^+\tilde{l}_L^-,\ \tilde{l}_R^+\tilde{l}_R^-$

γ-rays propagate freely in galaxy, point back to source

looking off plane of galaxy reduces galactic backgrounds more than signal from decays

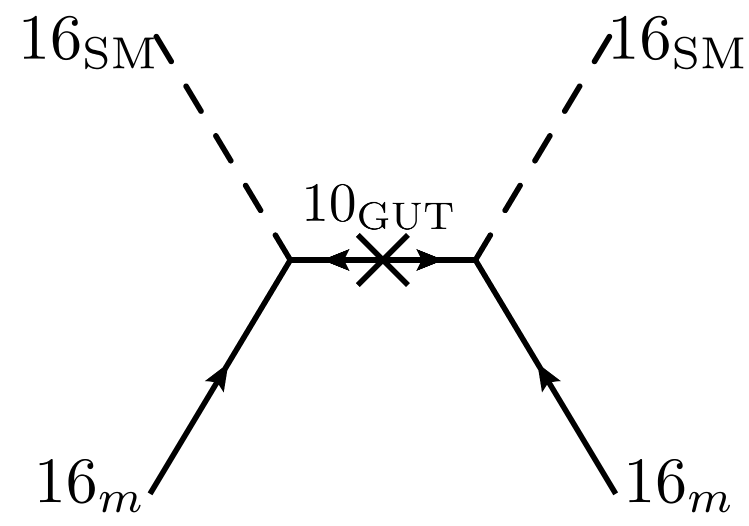
FSR gives a model-independent test of dark matter explanation of PAMELA/ATIC should be visible to Fermi (perhaps HESS?)

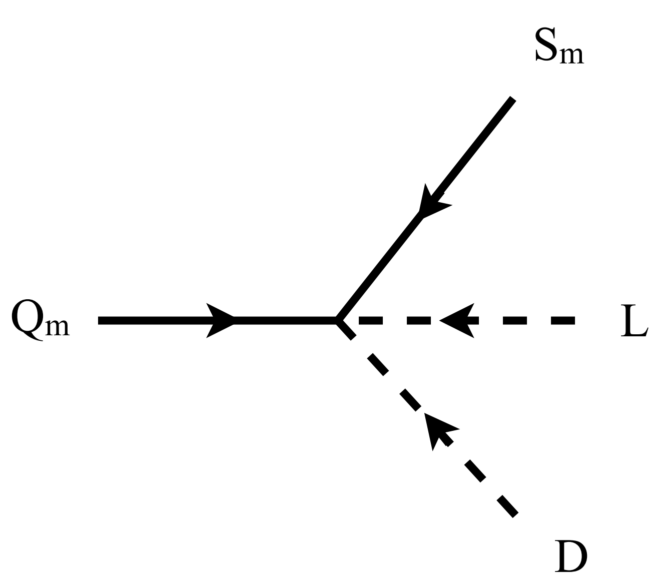
Relic Abundance

Mass term for 10_{GUT} generates

Dimension 5

$$\int d^2\theta \left(\frac{16_m 16_m 16_{\text{SM}} 16_{\text{SM}}}{M_{\text{GUT}}} \right)$$





Lifetime

$$\tau \sim 8\pi \frac{M_{\text{GUT}}^2}{m_\chi^3} = 10\ \text{s} \left(\frac{\text{TeV}}{m_\chi} \right)^3 \left(\frac{M_{\text{GUT}}}{2 \times 10^{16}\ \text{GeV}} \right)^2$$

Decays during BBN.

Generates relic abundance of S_m from decays of charged components of 16_m.

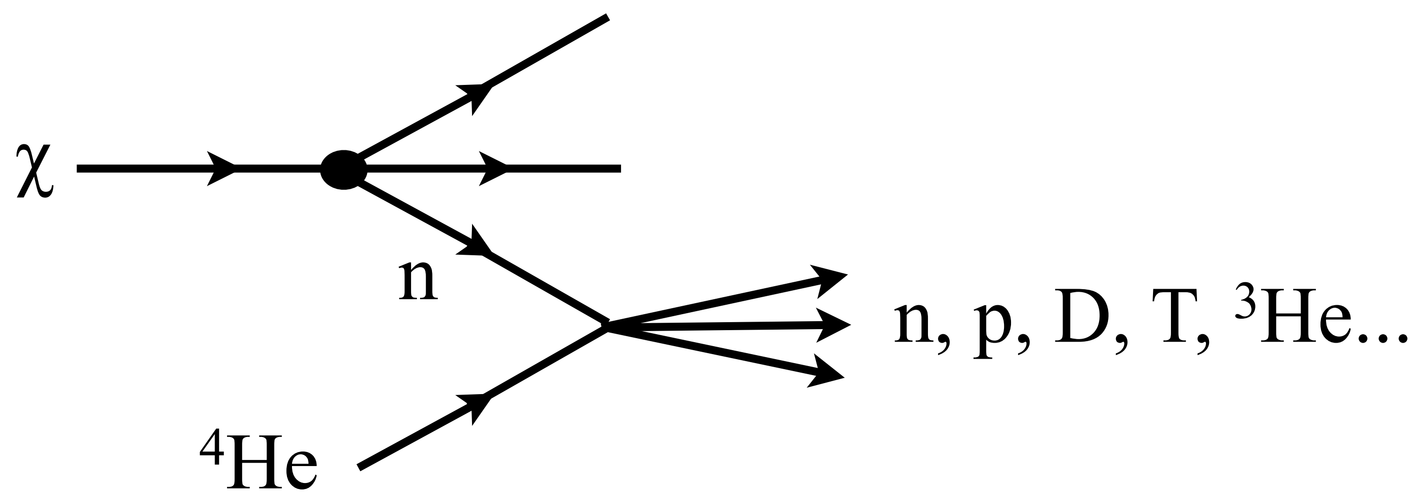
Decays During Nucleosynthesis

Big Bang Nucleosynthesis (BBN)

in universe ~ 100 - 1000 s many light elements are formed: ^{2}H, ^{3}He, ^{4}He, ^{7}Li...

abundances are well-predicted by SM and constrained by observations

Decays inject energy during BBN, can affect light element abundances



Li is a good probe of new physics due to its small abundance and low binding energy per nucleon

Lithium Anomalies

	$\frac{^7\mathrm{Li}}{\mathrm{H}}$	$\frac{^6\mathrm{Li}}{\mathrm{H}}$
Observed	$(1-2)\times 10^{-10}$	$(2-10)\times 10^{-12}$
BBN Predicts	$(5.2\pm 0.7)\times 10^{-10}$	10^{-14}

χ with $\Omega_\chi h^2 \sim 0.1$ decaying @ 1000 s solves both Li Problems.

Bailly, Jedamzik, Moultaka 2008

Caveats

Stars may reprocess ^{7}Li

Turbulence in stellar atmospheres could appear to be ^{6}Li

Operator Analysis of Dim 5 Decays

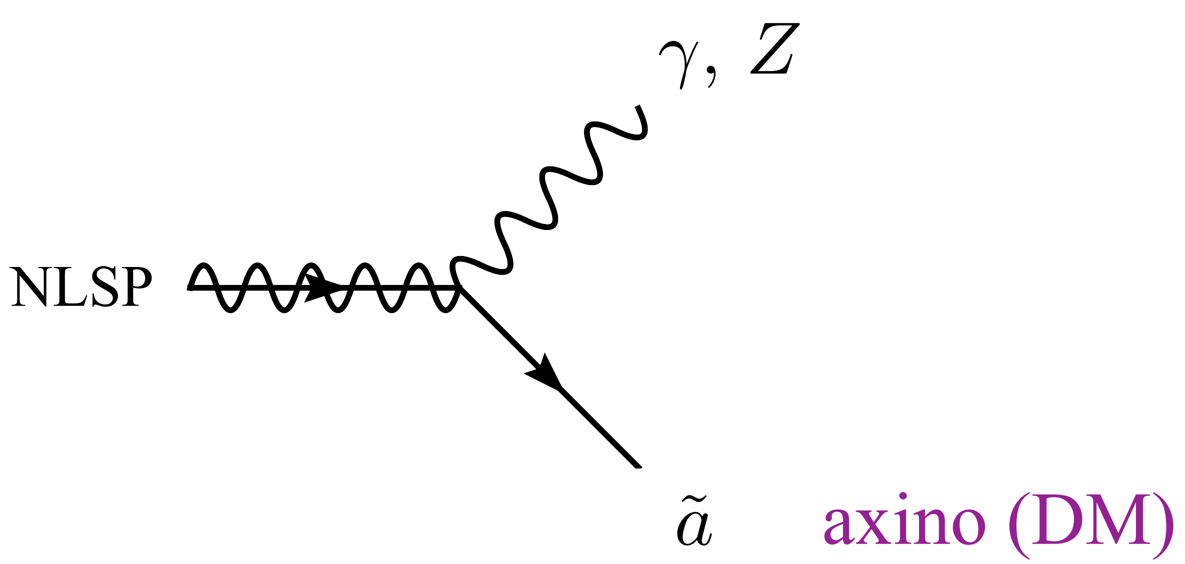
$$\tau \sim 8\pi \frac{M_{\rm GUT}^2}{m_\chi^3} = 10 \text{ s} \left(\frac{\rm TeV}{m_\chi}\right)^3 \left(\frac{M_{\rm GUT}}{2\times 10^{16} \text{ GeV}}\right)^2$$

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

Decays @ 10 - 1000 s Generic!

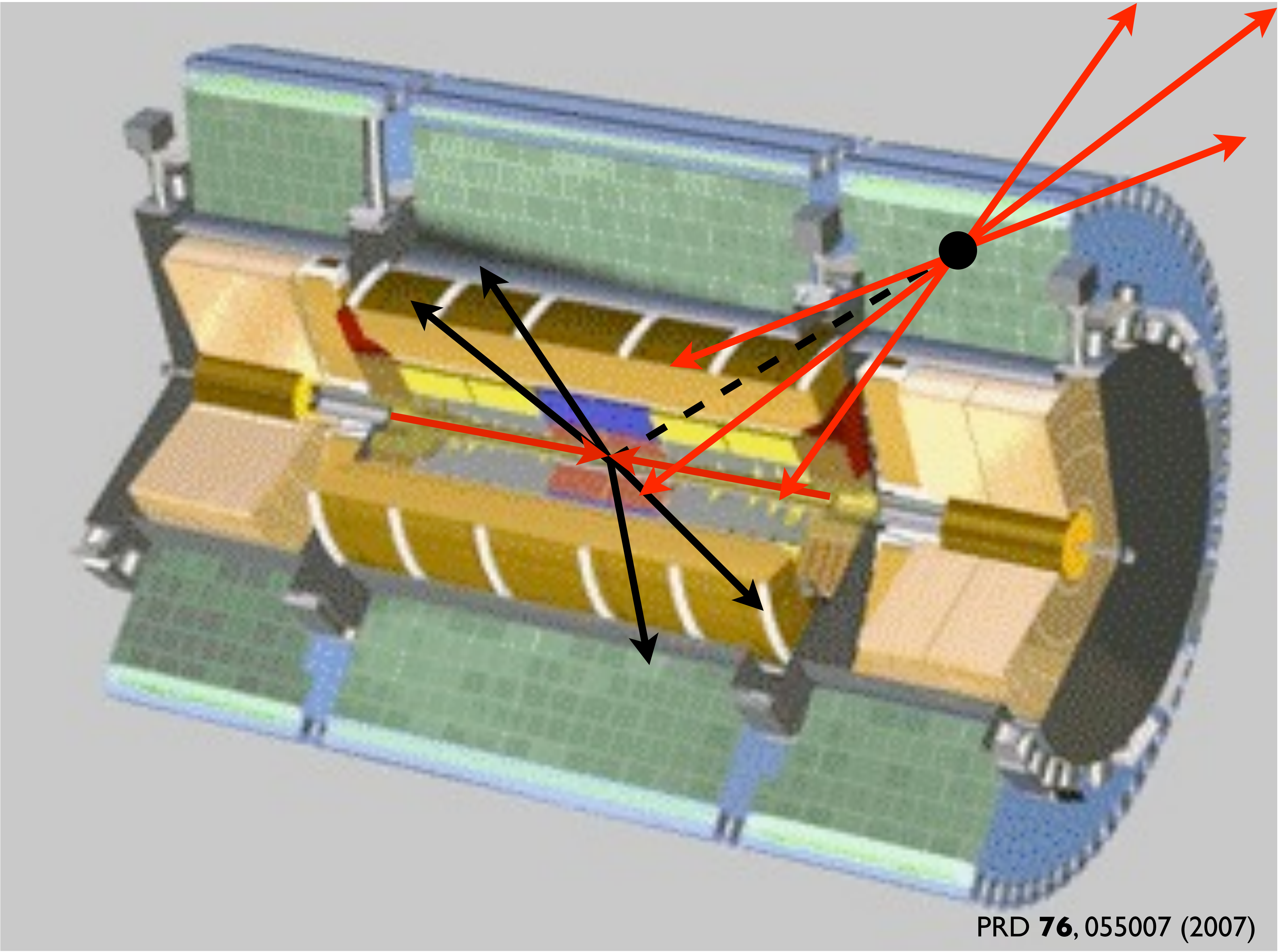
The Axion

$$W \ni \frac{\alpha}{4\pi}\frac{a}{f}\mathcal{W}_\alpha \mathcal{W}^\alpha$$



if such a decay produces the DM it may be Warm (WDM) not Cold (CDM)
affects structure formation

Late-Decaying Particles at the LHC



charged or colored particles will stop in the detectors and decay out of time

the LHC could see the decay of the particle which explains the Li problems

Conclusions - An Era of Data?

GUT physics can cause dark matter to decay

- potentially observable cosmic rays

GUT physics can also cause late-decays during BBN

- possibly observable effect on primordial light element abundances

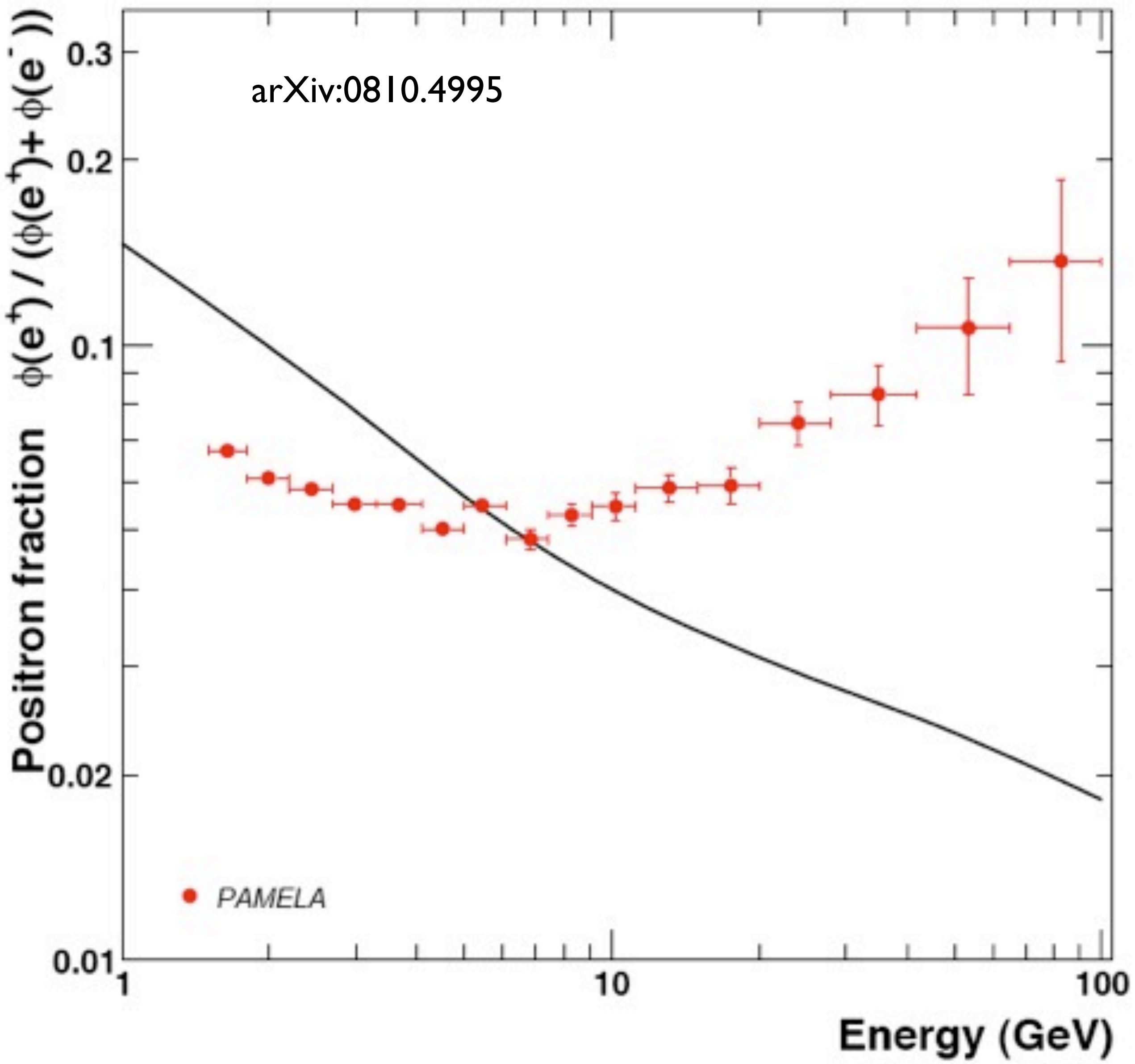
As an example, if PAMELA/ATIC and Li anomalies are evidence of new physics, correlated signals could be seen soon

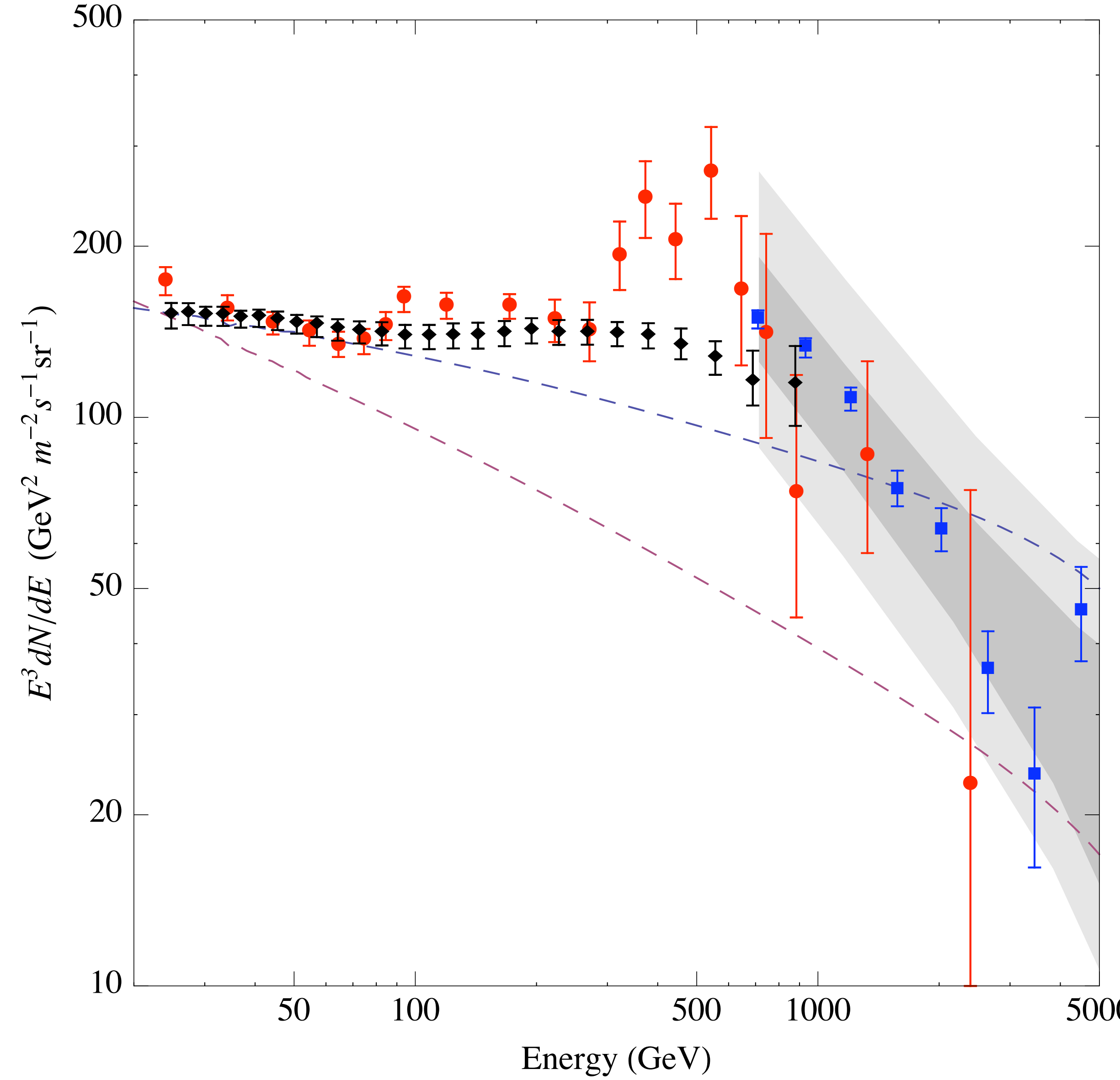
- Fermi should see gamma-rays from decaying (or annihilating) dark matter
- LHC could see late-decays of the particle responsible for Li

Hints?

PAMELA

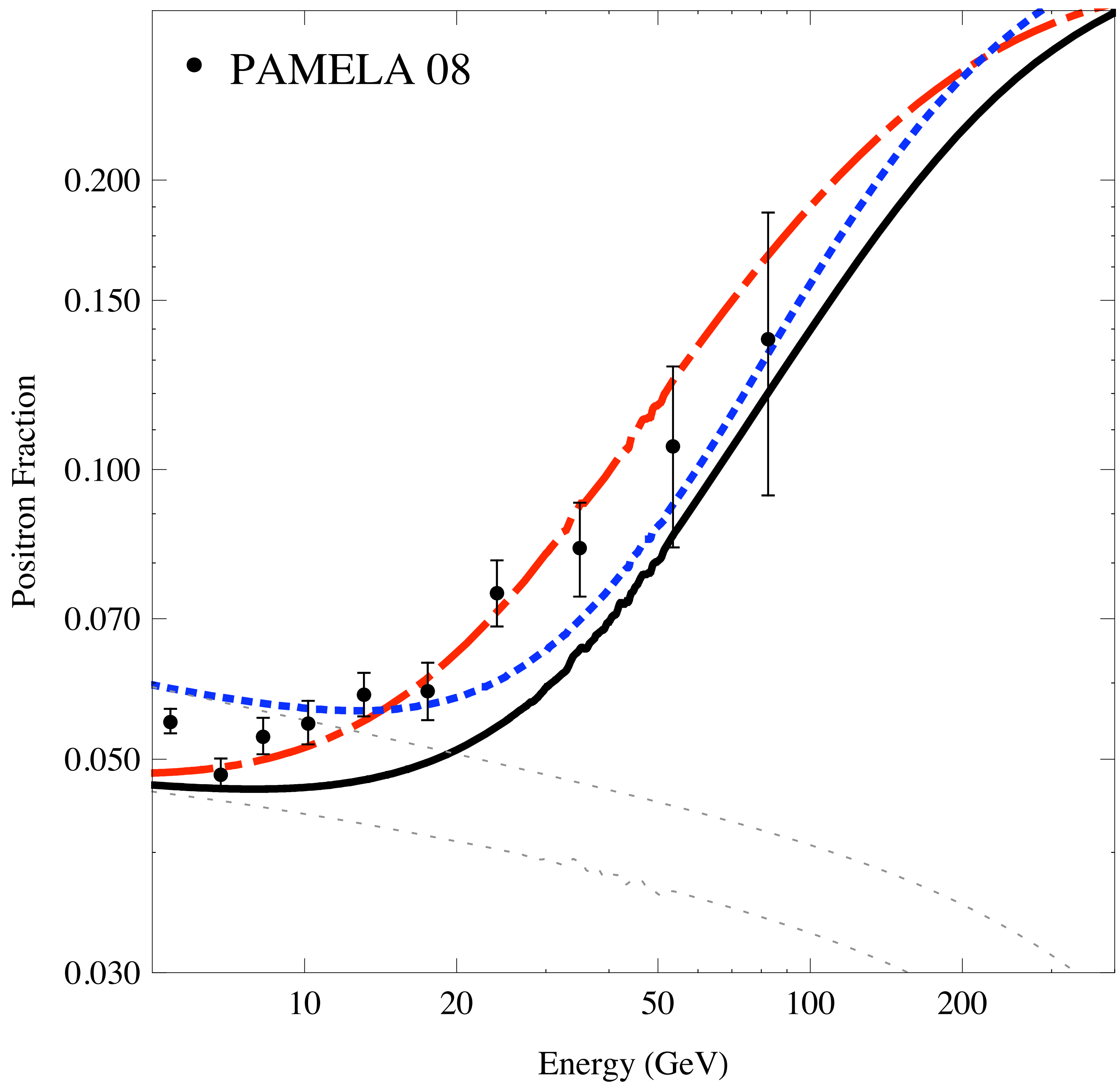
Fermi, HESS, ATIC





distinguish e^+ and p?

Fit with Dark Matter Decay?



PAMELA 08
0.200
0.150
0.100
0.070
0.050
0.030
Positron Fraction
10
20
50
100
200
Energy (GeV)

Limits on Decaying Dark Matter

Decay channel	γ-rays EGRET	Galactic γ-rays HESS	antiprotons PAMELA	positrons PAMELA	neutrinos Super-K, Frejus AMANDA
$q\bar{q}$	4×10^{25} s	–	10^{27} s	–	–
e^+e^-	8×10^{22} s	2×10^{22} s (K)	10^{24} s	2×10^{25} s	3×10^{21} s
$\mu^+\mu^-$	8×10^{22} s	2×10^{22} s (K)	10^{24} s	2×10^{25} s	3×10^{24} s
$\tau^+\tau^-$	10^{25} s	10^{22} s (K)	10^{24} s	10^{25} s	3×10^{24} s
WW	3×10^{25} s	–	3×10^{26} s	4×10^{25} s	8×10^{23} s
$\gamma\gamma$	10^{22-25} s	2×10^{24} s (K) 5×10^{25} s (NFW)	2×10^{25} s	8×10^{23} s	–
$\nu\bar{\nu}$	8×10^{22} s	–	10^{24} s	10^{23} s	10^{25} s

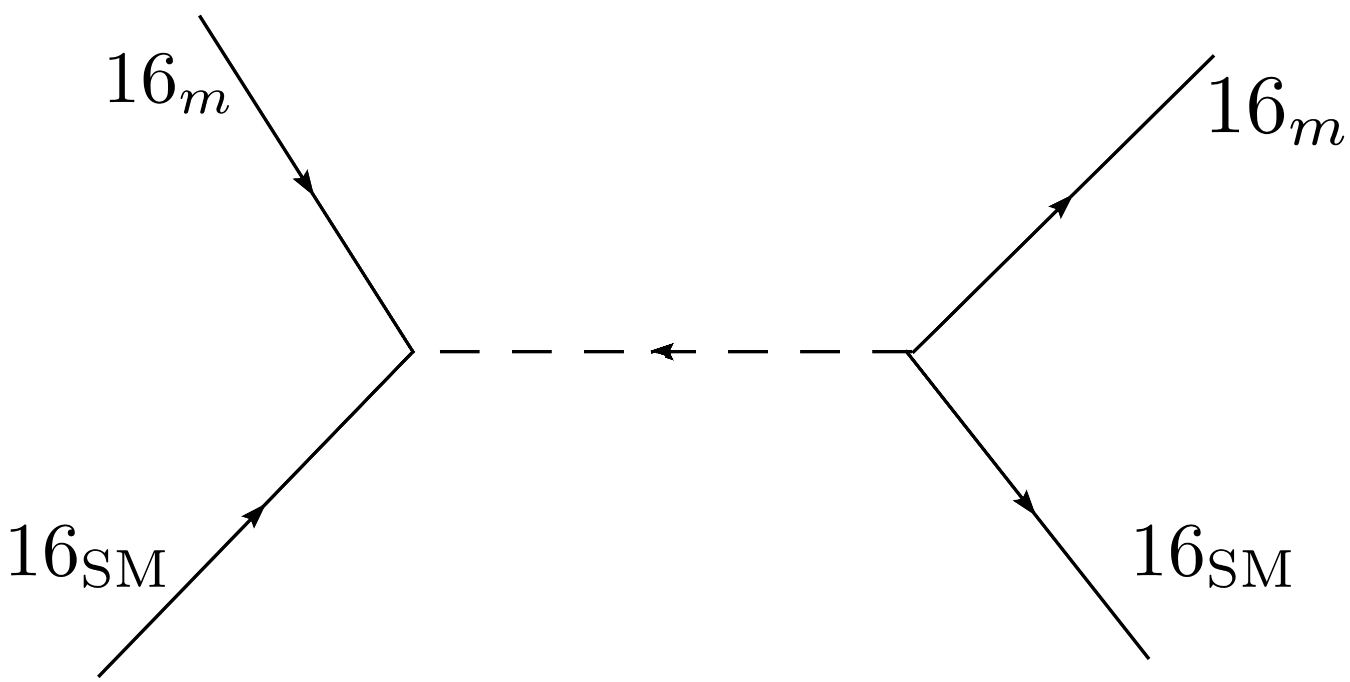
SO(10) Model

$$W_{\mathrm{MSSM}} = H 16_{\mathrm{SM}} 16_{\mathrm{SM}} + \mu H H$$

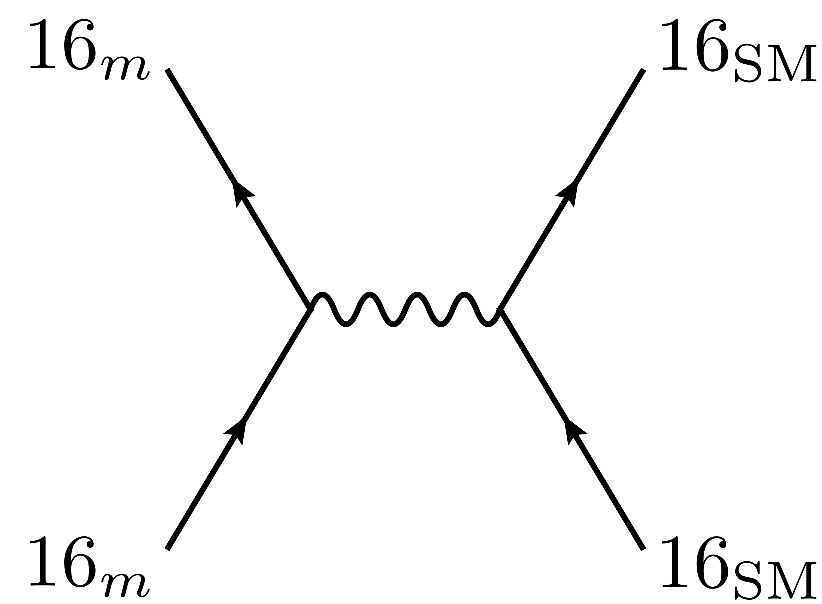
add one weak scale 16_{m} and one GUT scale 10_{GUT}

$$W' = \lambda 16_m 16_{\mathrm{SM}} 10_{\mathrm{GUT}}$$

integrating out 10_{GUT} and SO(10) gauge bosons generates dim 6 operators:



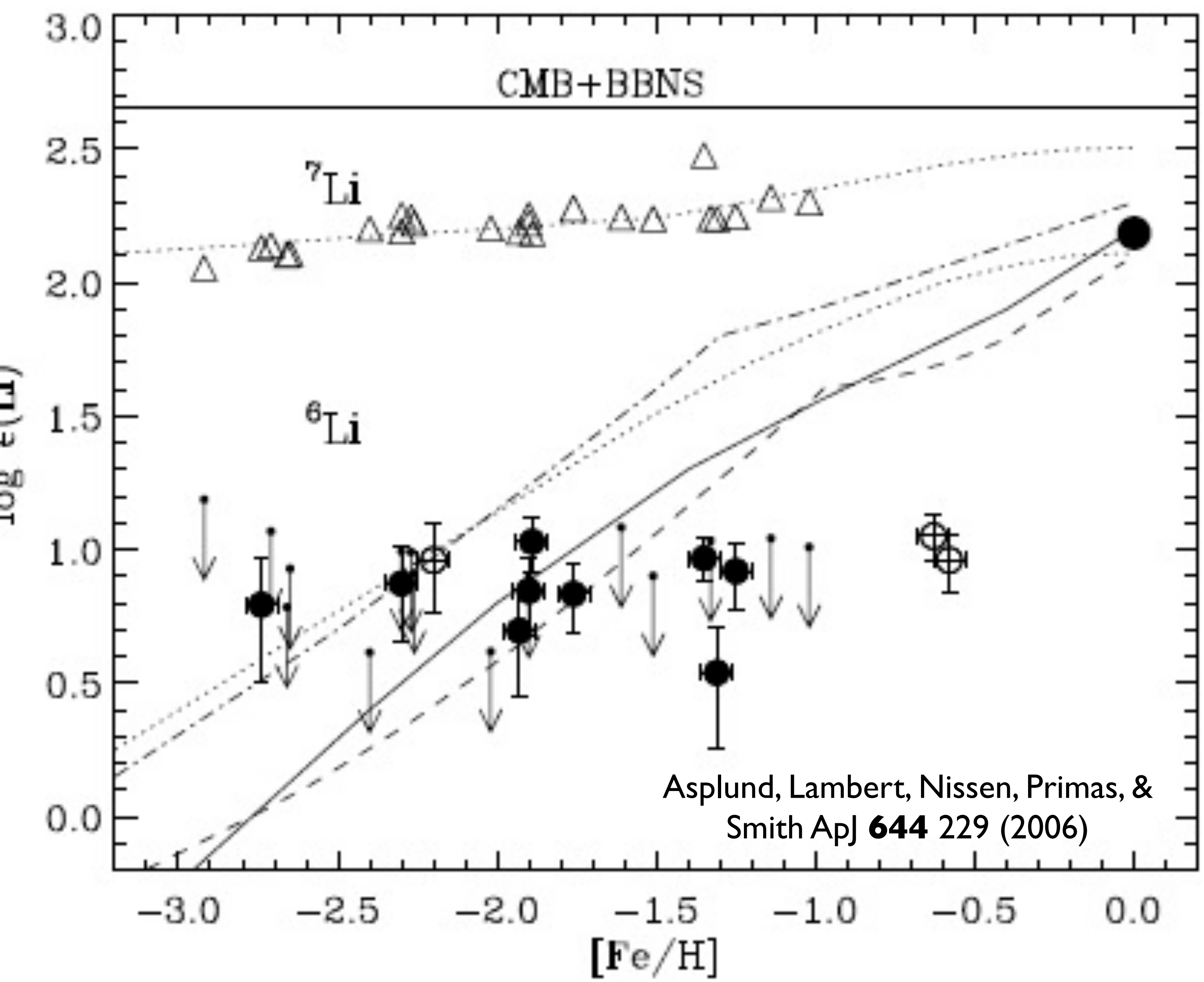
$$\int d^4\theta\, \lambda^4 \left(\frac{16_m^\dagger 16_m 16_{\mathrm{SM}}^\dagger 16_{\mathrm{SM}}}{M_{\mathrm{GUT}}^2} \right)$$



$$\int d^4\theta\, g^4 \left(\frac{16_m^\dagger 16_m 16_{\mathrm{SM}}^\dagger 16_{\mathrm{SM}}}{M_{\mathrm{B\text{-}L}}^2} \right)$$

these yield dimension 6 operators for singlets, causing decays

Lithium Observations



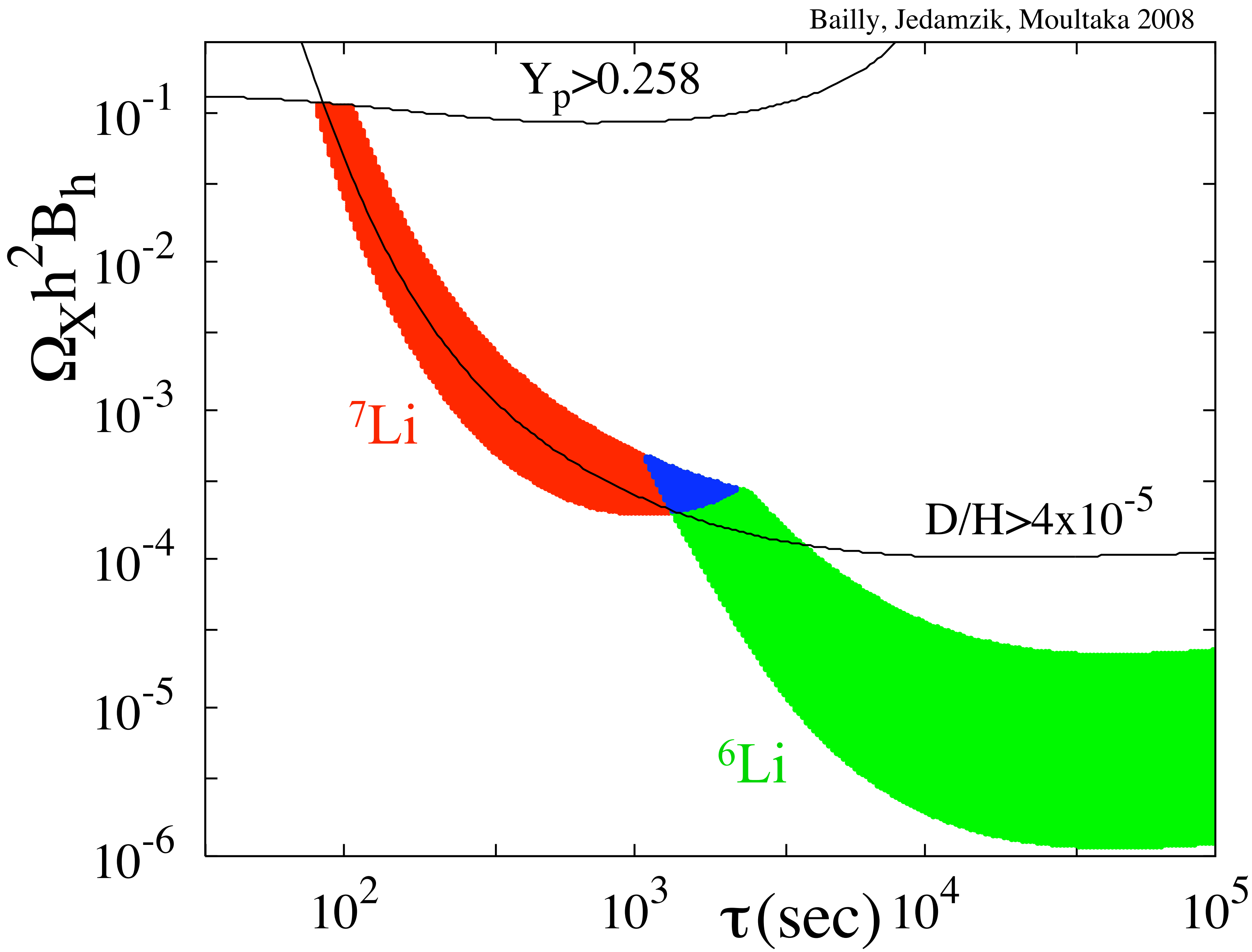
Spite Plateaus imply primordial abundance

Stars may reprocess ^{7}Li

Turbulence in stellar atmospheres could appear to be ^{6}Li

Deficit of ^{7}Li and excess ^{6}Li rules out any single solution to both Li problems except for physics beyond the Standard Model

A Late-Decay Solves the Lithium Problems



Ω_χ = abundance of decaying particle

B_h = hadronic branching fraction

$$m_\chi \sim 1 \text{ TeV} \implies \Omega_\chi h^2 \sim 0.1$$

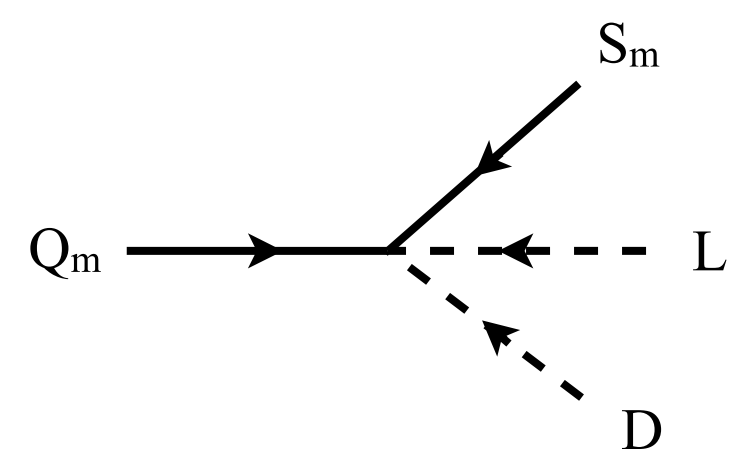
Deficit of ^{7}Li and excess ^{6}Li rules out any single solution to both Li problems except for physics beyond the Standard Model

SO(10) Model Timeline

$$\int d^2\theta \left(\frac{16_m 16_m 16_{\rm SM} 16_{\rm SM}}{M_{\rm GUT}} \right) \qquad \int d^4\theta \left(\frac{16_m^\dagger 16_m 16_{\rm SM}^\dagger 16_{\rm SM}}{M_{\rm GUT}^2} \right)$$

early: gauge interactions generate relic abundance of non-neutral components of 16_m

at 100 s: all components of 16_m decay to singlet S_m



at 10^{27} s: scalar S_m decays to fermion S_m (or vice-versa)