New Models for Dark Matter

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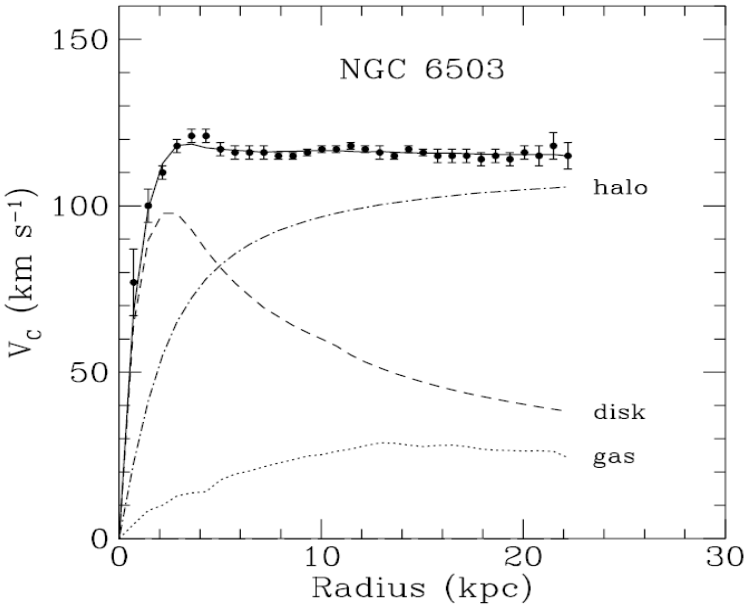
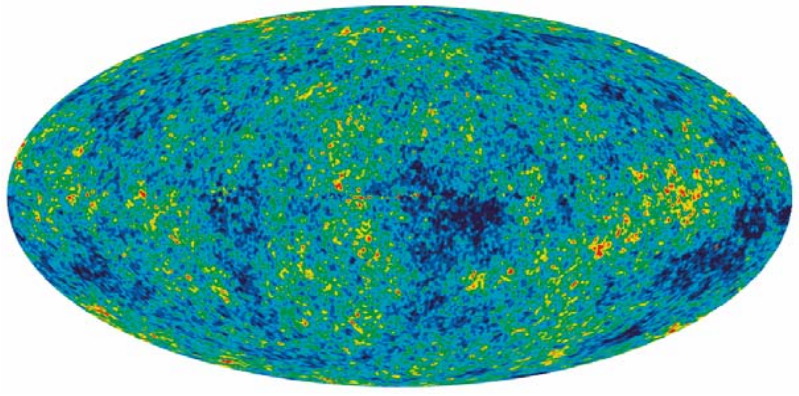
Dark Matter

Existence is well established

Rotation curves of galaxies



Cosmic microwave background radiation



$\Omega_b h^2 = 0.02273 \pm 0.00062$

$\Omega_M h^2 = 0.1099 \pm 0.0063$

$(h = 0.719 \, ^{+ 0.026}_{- 0.027})$

WMAP only (5 years)

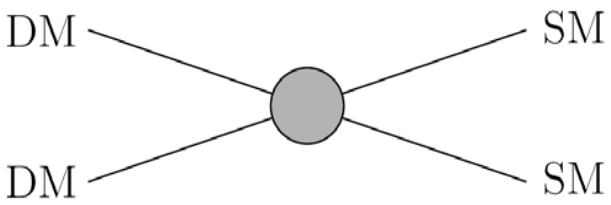
What is it?

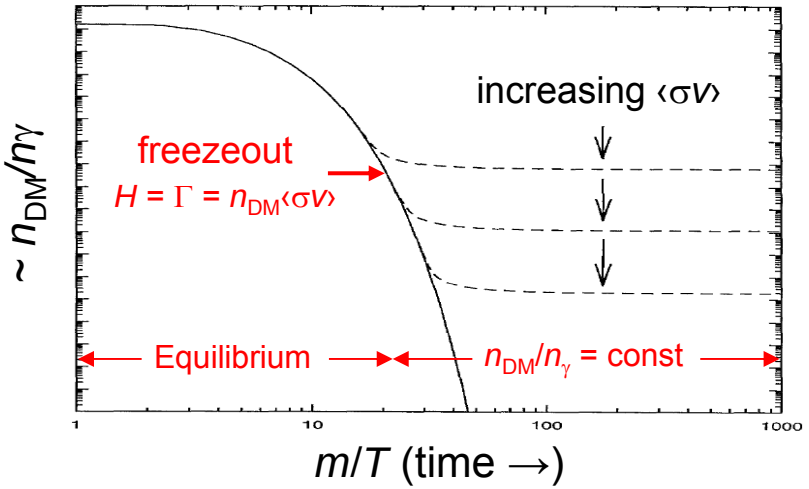
Model-independent knowledge quite limited

— wide range of mass and interaction strengths allowed

Connection to particle physics?

DM as a thermal relic of the early universe





Annihilation cross section determined

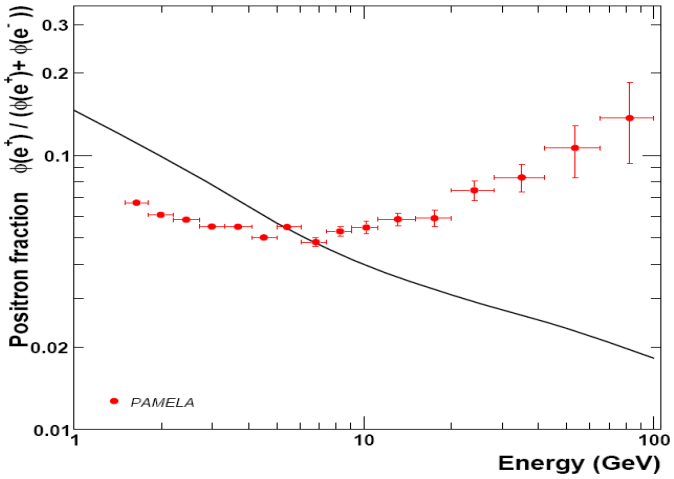
$$\Omega_{\rm DM}h^2 \simeq \frac{3\times10^{-27}\,{\rm cm}^3\,{\rm s}^{-1}}{\langle\sigma v\rangle} \Longrightarrow \langle\sigma V\rangle \sim \frac{g^2}{8\pi}\frac{1}{(\mathrm{TeV})^2}$$

weak interaction strength

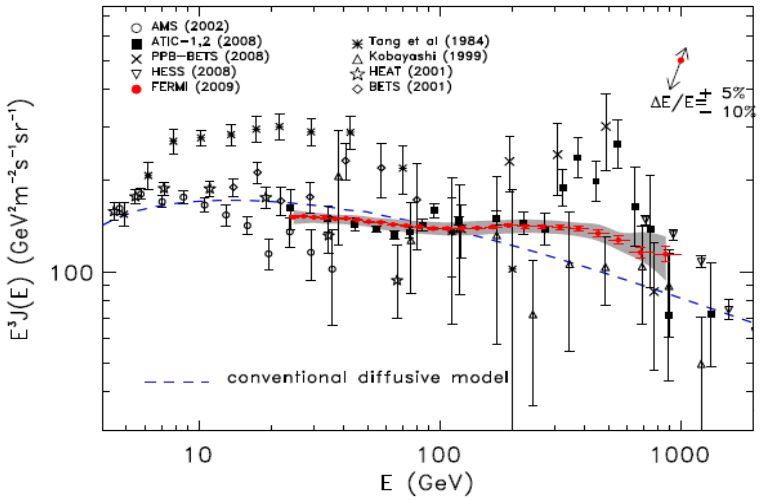
… Weakly Interacting Massive Particle (WIMP)

Hints?

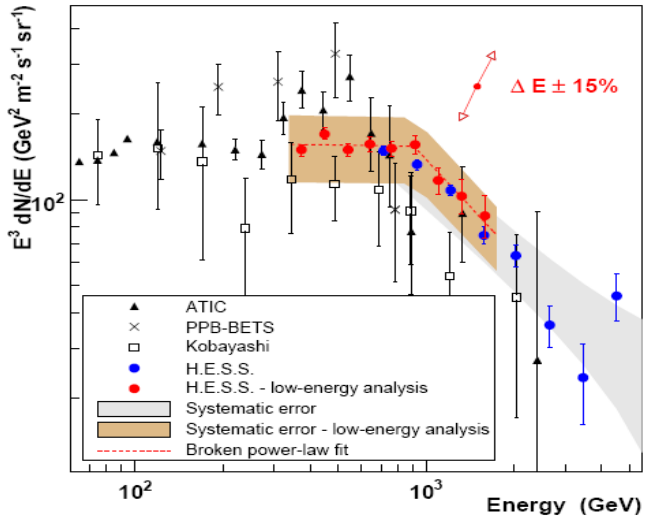
PAMELA



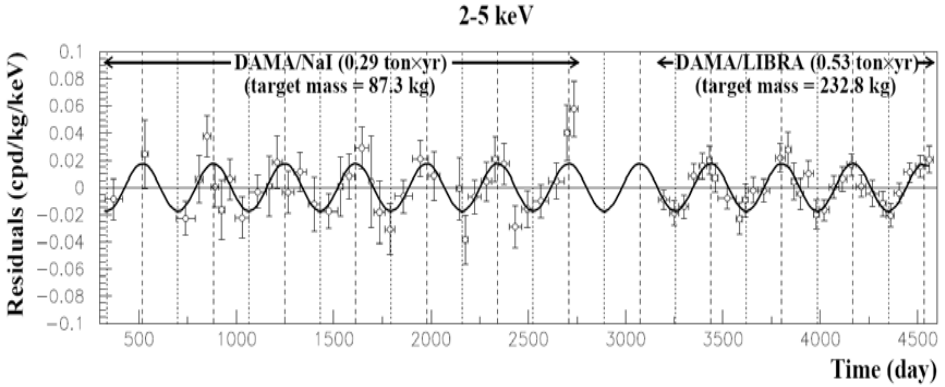
FERMI



H.E.S.S.



DAMA



Outline

- New signals in e^+/e^-
  - Dark matter annihilation
  - Dark matter decay
- DAMA signals

of course, could be astrophysics/experimental

— should not stop explorations until issues settled

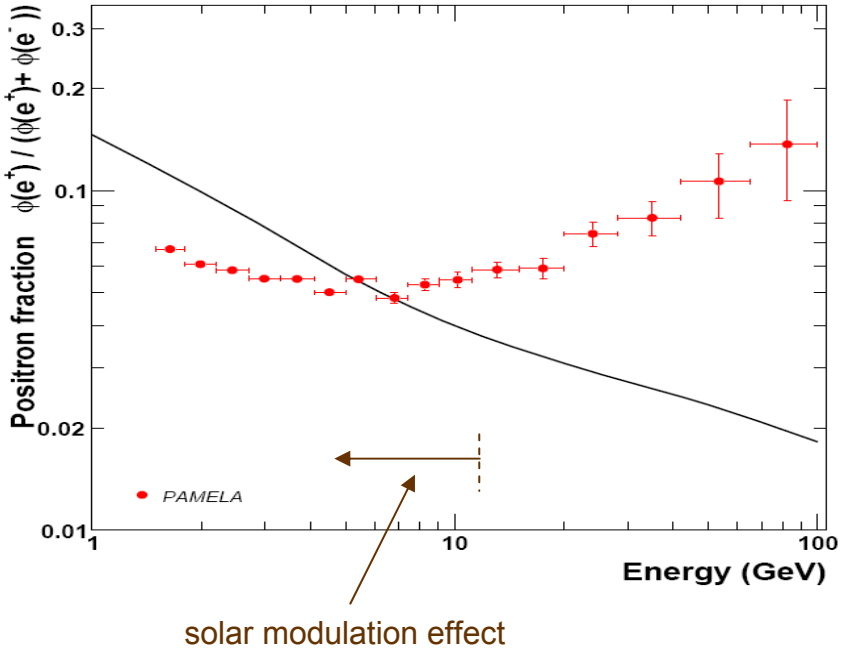
Potential strong implications for particle/astrophysics

… important opportunity

(cf. success of the standard model — gauge principle, quarks, leptons, …)

New Signals in e^+/e^-

PAMELA data



clear rise of the positron fraction above ~ 10 GeV

Adriani *et al.*, arXiv:0810.4995

— Astrophysics?

— Dark matter annihilation? cf. Cirelli's talk

— Dark matter decay? cf. Ibarra's talk

Dark Matter Annihilation

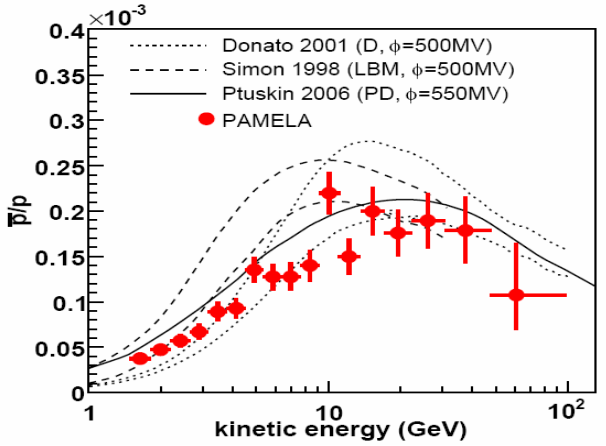
"Interesting"

— many other (astrophysical) signatures are "close" (WMAP haze, …)

Issues

- Leptonic final states:

  There is no "anomaly" in the antiproton data

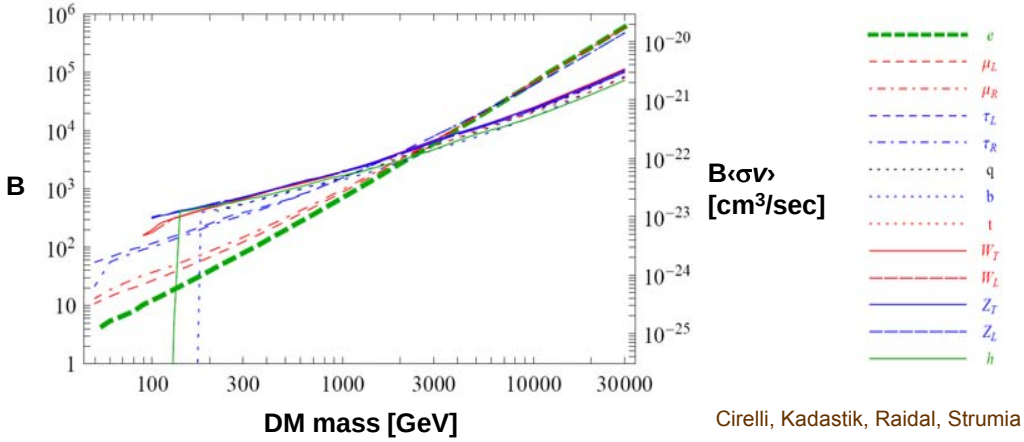


Adriani *et al.*, arXiv:0810.4994

- Large boost factor:

  Larger ‹σv› needed

$$\langle \sigma v \rangle = B \langle \sigma v \rangle_0$$



Cirelli, Kadastik, Raidal, Strumia

Various ways to obtain

Leptonic final states

— Kinematics Cholis, Goodenough, Weiner; …

— Couplings

Large boost factor

— Nonperturbative effects (Sommerfeld, boundstate) Hisano, Matsumoto, Nojiri, Saito; Pospelov, Ritz; …

— Nonthermal production

— Resonance effects Ibe, Murayama, Yanagida; …

— … (astrophysical...) cf. Hisano's talk

Various combinations possible

$\Longrightarrow$ not "standard" WIMPs

Let's see several realizations

→ particle physics implications

New (sub-)GeV scale dark sector

Arkani-Hamed, Finkbeiner, Slatyer, Weiner ('08)

DM ψ is charged under new gauge force mediated by X^μ

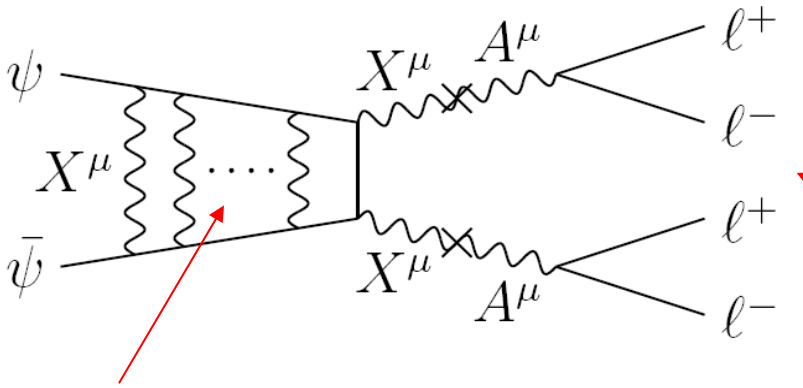
$m_\psi \sim 100\,\text{GeV} - 1\,\text{TeV}, \quad m_X \sim 100\,\text{MeV} - 1\,\text{GeV}$

existence of new sub-GeV dark sector

Dark gauge field X^μ mixes with photon A^μ

$$\mathcal{L} = \frac{\varepsilon}{2} X^{\mu\nu} F_{\mu\nu}$$

(ε naturally $O(10^{-3})$)



Nonperturbative enhancement

Leptonic final states

$m_\phi \lesssim 2m_\mu$: e^+e^-

$2m_\mu \lesssim m_\phi \lesssim 2m_\pi$: 50% e^+e^-, 50% $\mu^+\mu^-$

$2m_\pi \lesssim m_\phi \lesssim$ GeV: 40% e^+e^-, 40% $\mu^+\mu^-$, 20% $\pi^+\pi^-$

Tension with direct detection

$$\sigma_{\rm SI} \sim \left(\frac{\epsilon}{10^{-3}}\right)^2 \left(\frac{\alpha_{\rm Dark}}{137^{-1}}\right) \left(\frac{1\ {\rm GeV}}{m_X}\right)^4 10^{-37}\ {\rm cm}^2$$

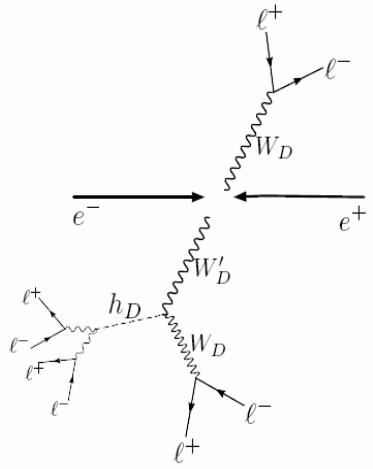
→ need splitting of $O(100\,\mathrm{keV}-\mathrm{MeV})$ in ψ? (→ DAMA?)

Dark gauge bosons

— Low energy e^+e^- collider

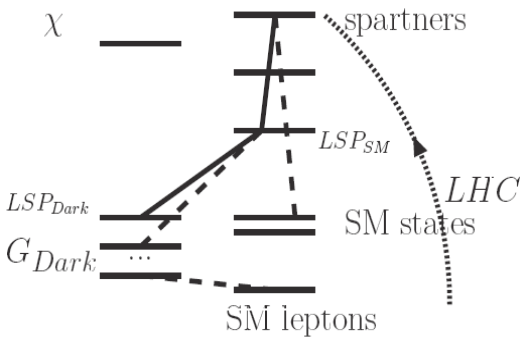
— High intensity deam-dump

Essig, Schuster, Toro; Reece, Wang; …



Lepton jets at the LHC

Arkani-Hamed, Weiner



Dark matter through the axion portal

Y.N., Thaler ('08)

DM talks to standard model through a light axion-like state(s)

simplest — DM and Higgs obtain masses from the same source

(symmetry breaking of $U(1)_X \leftrightarrow U(1)_{PQ}$)

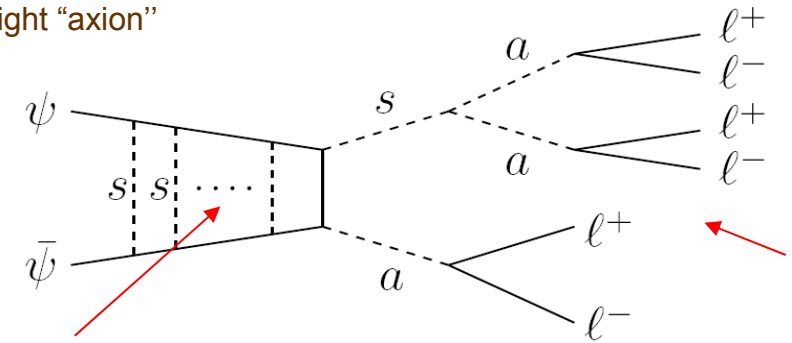
Minimal model (SUSY)

$W = \lambda S H_u H_d + \xi S \Psi \bar{\Psi}$ (DM) $\xrightarrow{\text{SUSY breaking}}$ $\langle S \rangle \neq 0$

$m_{\text{weak}} \sim \lambda \langle S \rangle, \; m_\Psi \sim \xi \langle S \rangle$

$S \to s + i a$

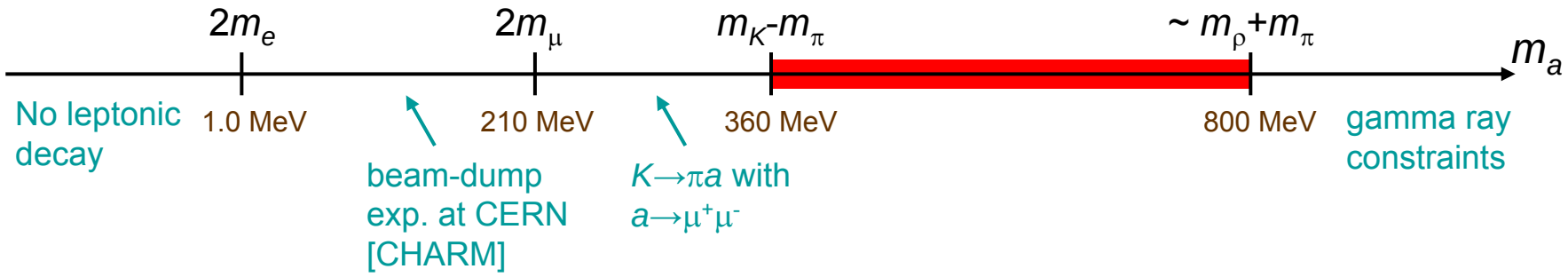
~GeV scalar — light "axion"



Leptonic final states

Nonperturbative enhancement

Axion mass



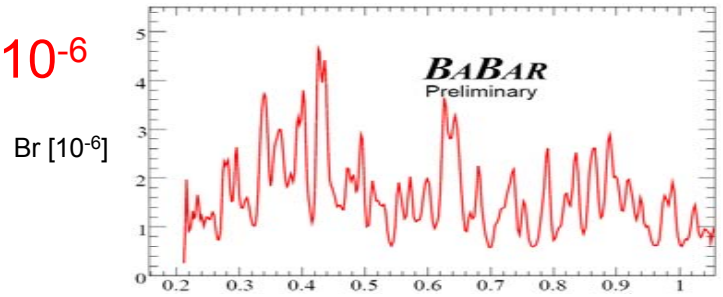
$360\ \text{MeV} \lesssim m_a \lesssim 800\ \text{MeV} \Longrightarrow a \to \mu^+\mu^- \quad (\ell = \mu)$

Satisfy all constraints

$m_{\rm DM}$	λ	$\tan\beta$	m_S^2	f_a	μ_H	A_λ	$m_{H_u}^2$	$m_{H_d}^2$	m_s	τ_s	$\mathrm{Br}(s\to f\bar{f})$	$m_{\tilde{s}}$	$m_{3/2}$	$\tau_{\tilde{s}}$	m_a	τ_a	$\sigma_{\rm SI}$ [cm^2]
1000	0.25	2.0	-6.8^2	1100	270	650	110^2	530^2	34	$4\cdot10^{-21}$	$f=b:3\%$	5.5	10 eV	$2\cdot10^{-5}$	0.7	$8\cdot10^{-15}$	$3\cdot10^{-43}$
1200	0.10	4.0	-6.3^2	1200	120	430	-69^2	440^2	5.6	$1\cdot10^{-18}$	$f=\tau:5\%$	1.2	5 eV	0.02	0.4	$1\cdot10^{-14}$	$4\cdot10^{-43}$
3000	0.18	2.0	-3.3^2	1800	330	820	150^2	660^2	25	$3\cdot10^{-20}$	$f=b:0.1\%$	2.3	10 eV	$3\cdot10^{-3}$	0.7	$2\cdot10^{-14}$	$3\cdot10^{-43}$

B-factory signals

$\mathrm{Br}(\Upsilon\to\gamma a) \sim 10^{-6}$



BaBar collab., arXiv:0902.2176

LHC signals

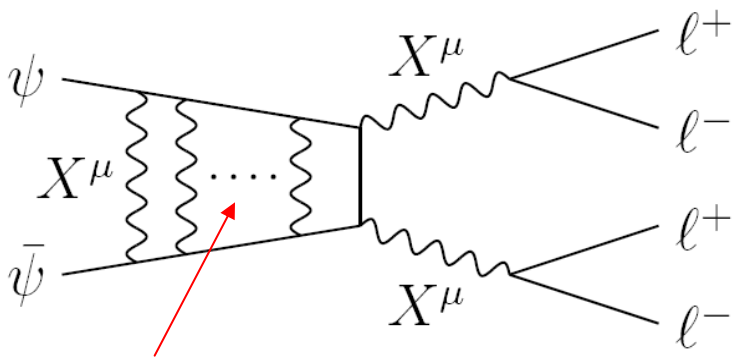
- $h \to aa \to 4\mu$
- pairs/quartets of collimated μ's

Leptophilic dark matter

Fox, Poppitz ('08); also Cirelli, Kalastik, Raidal, Strumia ('08)

New U(1) gauge force under which
only DM and leptons are charged

- U(1) is broken at $O(1-10$ GeV)
- $g_\ell < 10^{-3}$ ($\ll g_\psi \sim O(1)$)



Leptonic final states

$e+\mu$, $e+\tau$, or $\mu+\tau$

Nonperturbative
enhancement

→ neutrino flux from the sun/earth

Astrophysical constraints

Photons (galactic center region, dwarf galaxies, …)

Bell, Jacques; Bertone, Cirelli, Strumia, Taoso; Bergstrom, Bertone, Bringmann, Edsjo, Taoso; Mardon, Y.N., Stolarski, Thaler; Meade, Papucci, Volansky; …

Neutrinos

Hisano, Kawasaki, Kohri, Nakayama; Liu, Yin, Zhu; Mardon, Y.N., Stolarski, Thaler; Meade, Papucci, Volansky; …

… nontrivial but model dependent (astrophysics, particle physics)

… cascade helps

diffuse gamma

Kamionkowski, Profumo; ...

BBN

Hisano, Kawasaki, Kohri, Moroi, Nakayama; ...

CMB

Galli, Iocco, Bertone, Melchiorri; ...

… boost factor “saturated”

Dark Matter Decay

DM sector (typically) more isolated — safer (ρ^2 v.s. ρ)

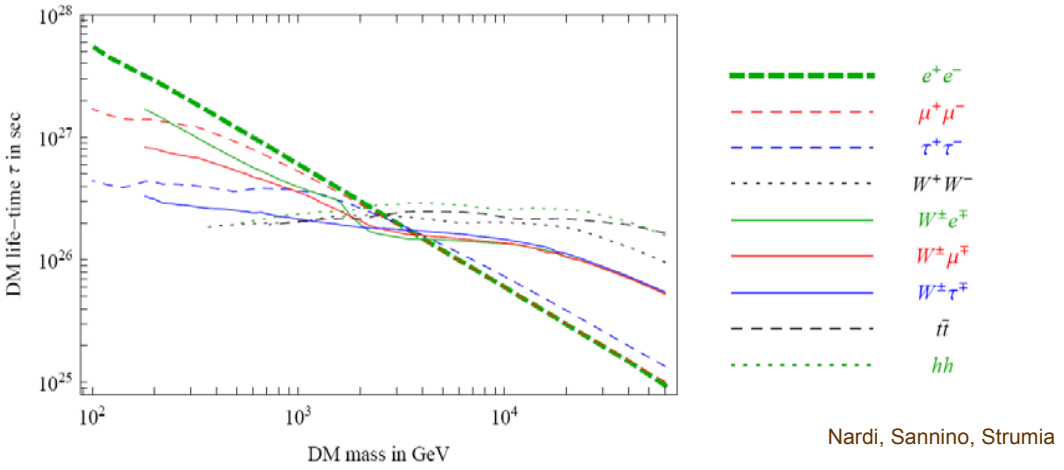
Issues

- Leptonic final states:

  — to a lesser extent

- Lifetime:

$\tau \sim 10^{26}$ sec



Nardi, Sannino, Strumia

… Dimension-6 operators (GUT scale physics)

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

Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran; Nardi, Sannino, Strumia; …

Singlet dark matter with SUSY

Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran ('08)

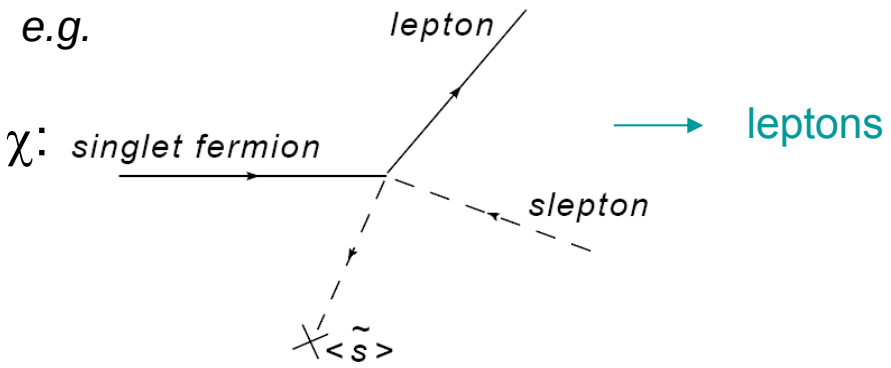
- Leptonic final states

  — GUT-scale physics

  $m_\chi > m_\ell$

  — kinematics

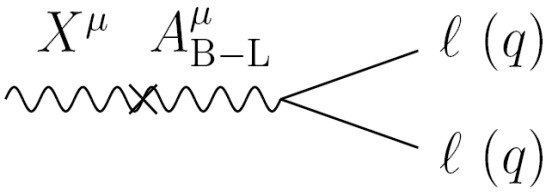
  $m_\chi < m_\ell$



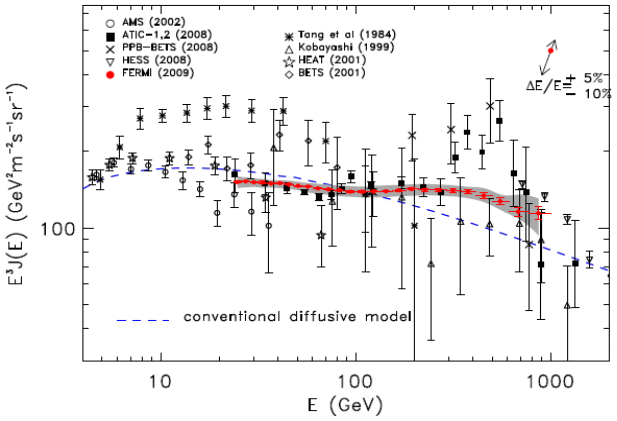
Hidden gauge boson

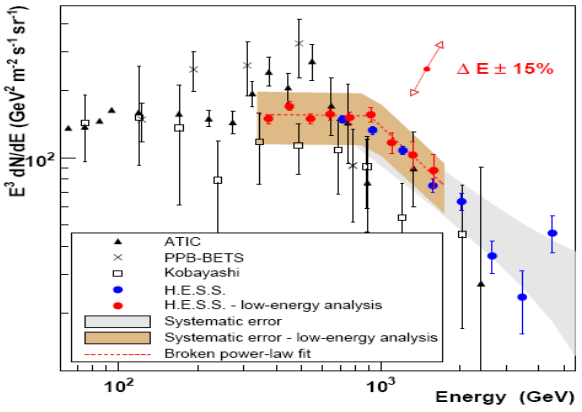
Chen, Nojiri, Takahashi, Yanagida ('08)

— gauge charges (couplings)



New FERMI/H.E.S.S. Data

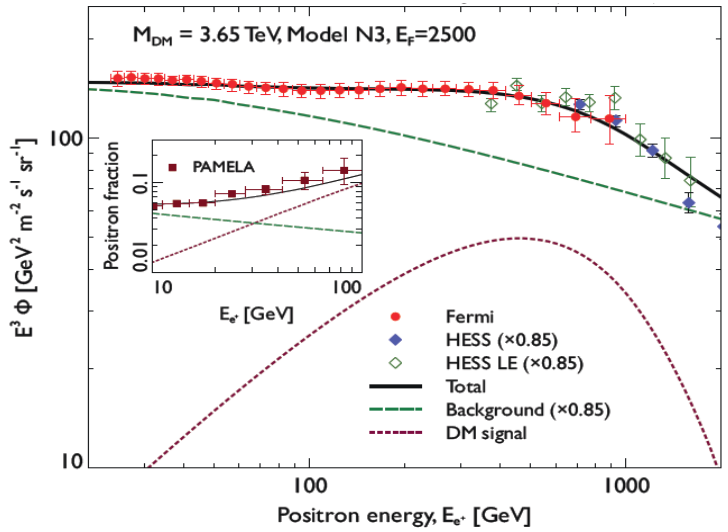


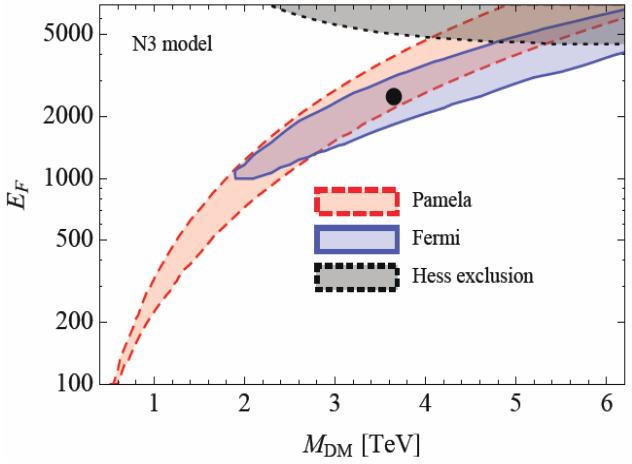


Smooth spectrum ~ TeV (μ, τ, cascades, …)

(or m_χ « TeV)

e.g. Axion portal





Bergström, Edsjö, Zaharijas

… relatively simple setup/models explain data

True story?

→ We don't know

… future data will tell

(anisotropy, gamma ray, …)

Motivates new signatures to look at

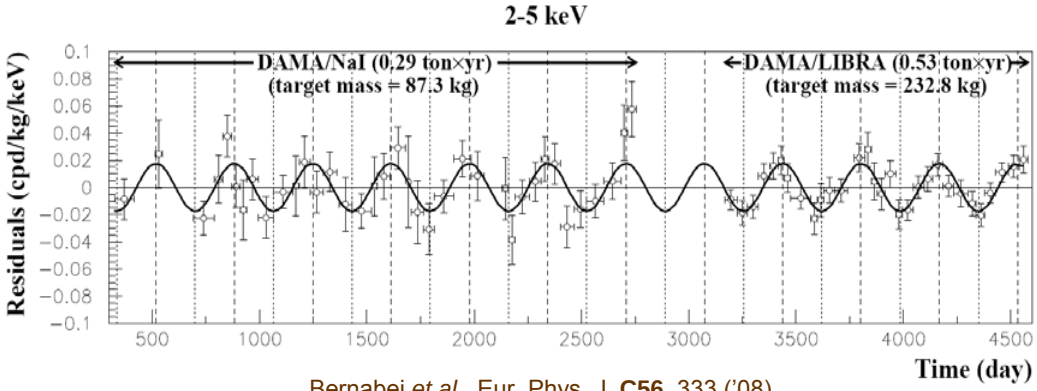
- Low energy (e.g. ~ GeV) dark/hidden sector
- Light axion-like states
- …

… something we could do, but didn't focus

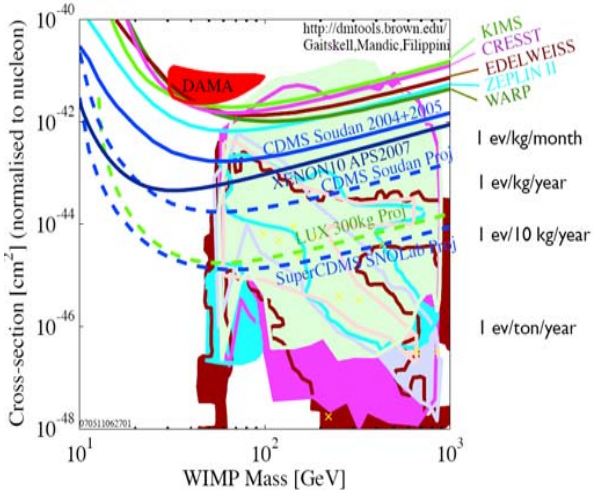
→ discovery?

DAMA signals

DAMA annual modulation



Bernabei *et al.*, Eur. Phys. J. **C56**, 333 ('08)

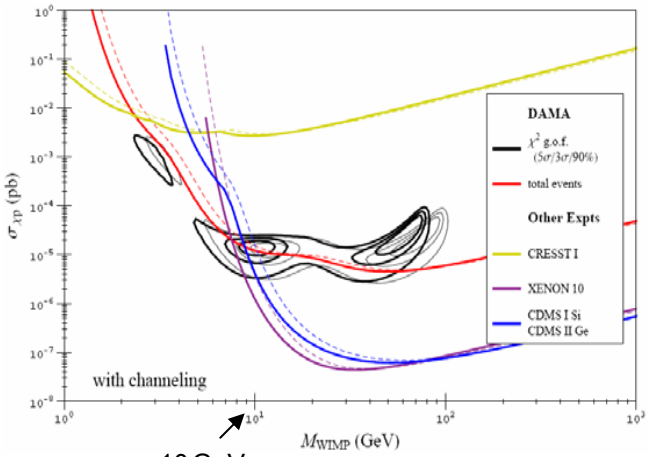


Possible explanations

— light (~ 10 GeV) dark matter

— electron recoil ← "marginal"

— inelastic dark matter

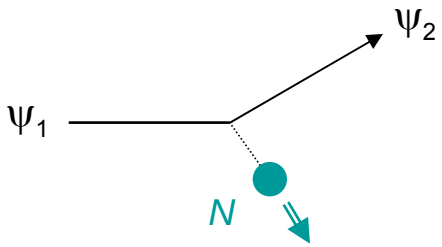


Savage, Freese, Gondolo, Spolyar

Inelastic dark matter

Smith, Weiner ('01)

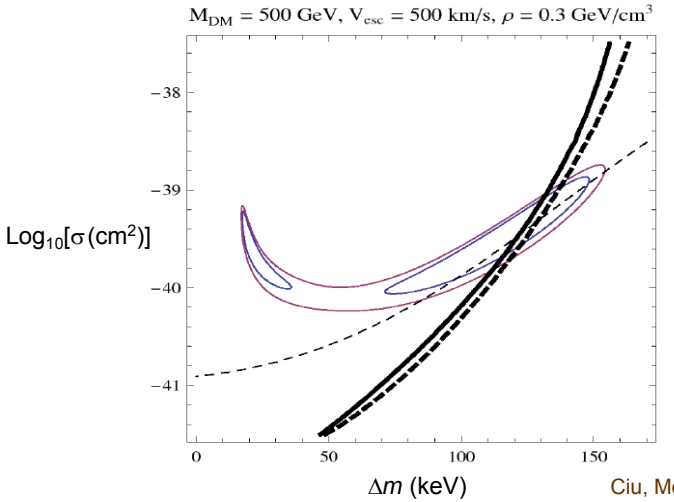
Two dark states with $\Delta m \sim O(100\,\mathrm{keV})$



… scatters (only) inelastically

The minimum velocity depends on nuclei

$$v_{\min} \simeq \frac{1}{\sqrt{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \Delta m \right)$$



Ciu, Morrissey, Poland, Randall

Naturally obtained via symmetry breaking

e.g. $\mathcal{L} = M \psi \bar{\psi} + m (\psi \psi + \bar{\psi} \bar{\psi})$ $\quad m \ll M$

Conclusions

Dark Matter

→ We must/want to know what it is

Hints?

— PAMELA, FERMI, H.E.S.S., DAMA, …

If any of these results is associated with DM,

DM cannot be "standard" (except possibly PAMELA)

absolutely-stable, thermally produced, weakly interacting, vanilla dark matter

Physics of dark matter may be much richer than imagined

… tremendous implication and particle/astrophysics

Clearly an exciting time! — in many respects!