The WIMPless Miracle and the DAMA Puzzle

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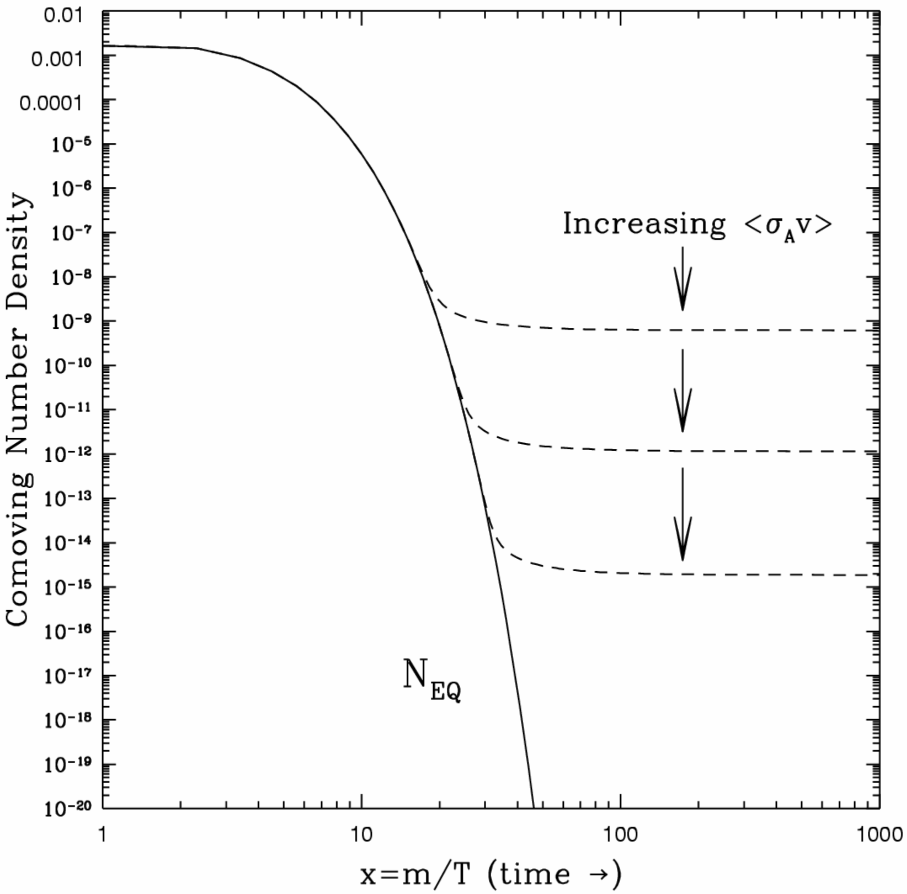
(0803.4196,0806.3746,0808.4151)

Relic Density

- matter in early universe in thermal equilibrium
- matter decouples because of the expansion of the universe
  - when particles can't find each other to interact, they decouple from equilibrium
- matter is non-relativistic at decoupling
- Boltzmann equation

$$\frac{d\eta}{dt} + 3H\eta = -\langle \sigma_{ann} \mathrm{v} \rangle \left(\eta^2 - \eta_{eq}^2 \right)$$

- x ~ 20 , $\rho \propto T^3 \left(M_p \langle \sigma v \rangle\right)^{-1}$



Y. Zeldovich (1965)
R. Scherrer, M. Turner (1986)
E. Kolb, M. Turner (1990)

WIMP miracle

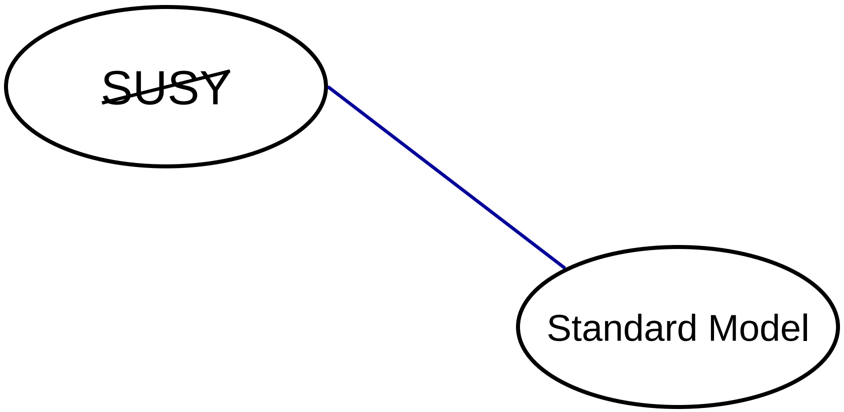
- knowing σ, we can figure out relic density
- to get observed DM density need σ ~ 1 pb
- stable matter with coupling and mass of the electroweak theory would have about right relic density for dark matter
  - WIMP miracle
- best theoretical idea for dark matter
- guide for most theory models and experimental searches
- but is this miracle really so miraculous?

A New Dark Matter Scenario

- common feature of beyond-the-Standard-Model physics
  - hidden gauge symmetries, particles
- arise in most theory frameworks
  - supersymmetry, string theory, GUTs, etc.
- possible dark matter candidates?
  - can get left over symmetries which stabilize particles
  - if stable, they contribute to dark matter
    - could be either good, or bad
- what are the dark matter implications for this scenario?

Setup

- the standard "low-energy SUSY" setup
  - one sector breaks supersymmetry
  - an energy scale is generated in Standard Model sector by gauge-mediation from the SUSY-breaking sector
  - this sets the mass of the W, Z, Higgs, etc.



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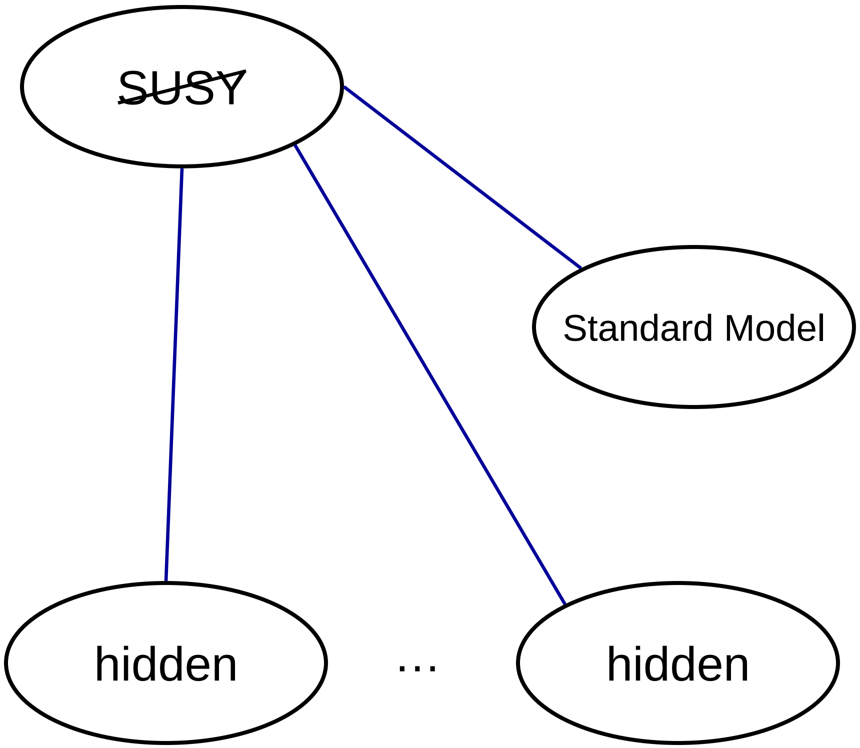
- we add to this extra gauge sectors, which behave in a qualitatively similar way
  - symmetry stabilizes particle at SUSY-breaking scale



Motivation

- hidden gauge sectors (several) arise typically in string theory and beyond-the-standard-model
- gauge-mediation provides an elegant solution to flavor-problem
- in string models like intersecting brane models, naturally have many sectors and lots of bifundamental matter
  - gauge mediators
  - extra sectors can leave global or discrete symmetries behind
- but even aside from these motivations, this is an interesting, reasonable and simple scenario

The Energy Scale

- gauge interactions determine energy scale in a known way
- F, M_{mess} set by dynamics of supersymmetry-breaking
  - same for all sectors
- in each sector, ratio of coupling to mass is approximately fixed
- same ratio determines annihilation cross-section
  - determines relic density (Scherrer, Turner; Kolb, Turner)
  - if WIMP miracle gets it right, so does every other sector

$$m_{scalar}^2 = \frac{g^4 N_{mess.}}{(4\pi)^4} \left(\frac{F}{m_{mess.}} \right)^2$$

see G. Giudice, R. Rattazzi (1998)

$$\frac{g_h^4}{m_h^2} \propto \left(\frac{m_{mess.}}{F} \right)^2 = const.$$

$$\Omega \propto \frac{1}{\langle \sigma v \rangle} \propto \left(\frac{g_h^4}{m_h^2} \right)^{-1} \propto \left(\frac{F}{m_{mess.}} \right)^2$$

Result

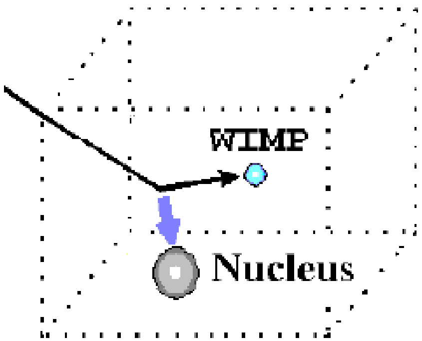
- we find in this scenario, a generic charged stable particle should have the right density (order of magnitude) to be dark matter
- maybe this is really a WIMPless miracle … any gauge sector with any coupling would have worked
- in fact, it should have worked for the MSSM in gauge-mediation
  - two stable particles → the LSP and the electron
  - first accident → electron Yukawa coupling is extremely (perhaps unnaturally) small
    - mass much lighter than "natural" scale (m_{top})
    - if electron mass were ~ m_{top}, would have the right relic density
  - second accident → in gauge mediation, the LSP is not gauge charged
- but in any other sector, a discrete symmetry can stabilize a hidden sector gauge charged particle
  - in the right ball-park for dark matter
  - distinct from gravity mediated result, where WIMPs really needed

Upshot

- a new well-motivated scenario for dark matter
- natural dark matter candidates with approximately correct mass density
- unlike "WIMP miracle" scenario, here dark matter candidate can have a range of masses and couplings
- opens up the window for observational tests, beyond standard WIMP range
- implications for cosmology, direct and indirect detection
  - such as the DAMA puzzle….

Detection Overview

- direct detection
  - DM scatters of nucleus in earth-based detector, and the recoil is measured
  - DAMA, CDMS, XENON10, CoGeNT, LUX, etc.



Dan Hooper
SUSY '07

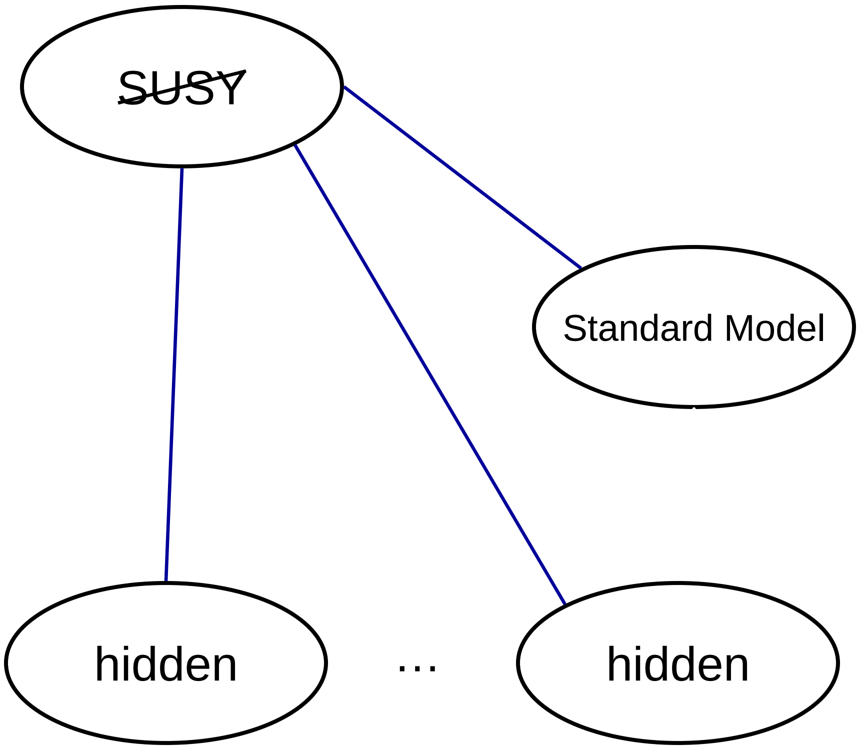
- indirect detection
  - DM annihilates to SM final states, which shower off γ, ν, e^+e^-
  - GLAST, PAMELA, ANTARES, Super-K, etc.

NASA website

- LHC

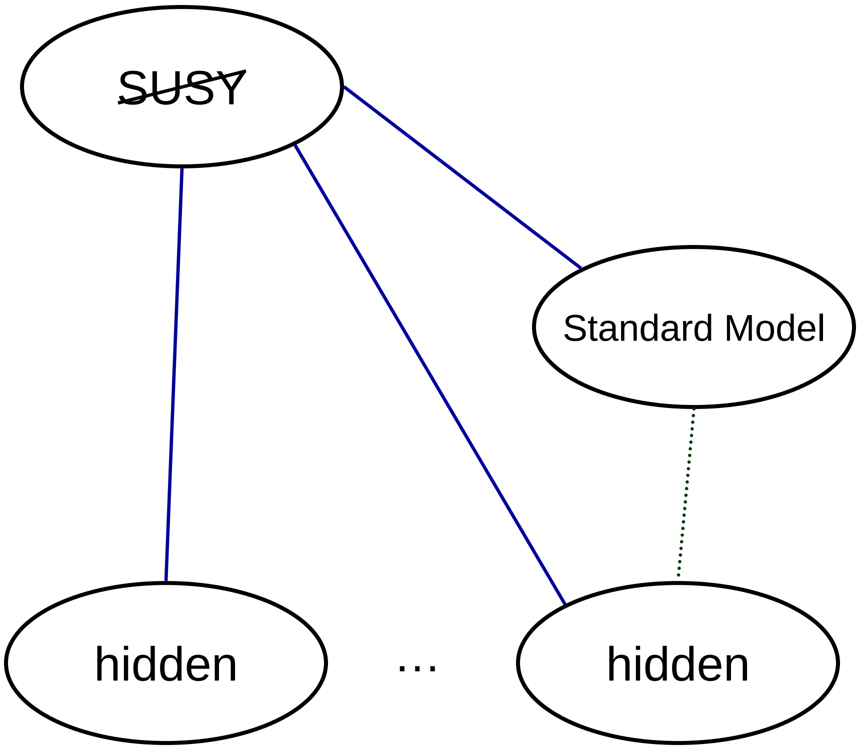
Detection Scenarios

- if no connection between SM and hidden sector…
  - no direct, indirect or collider signature
  - only gravitational



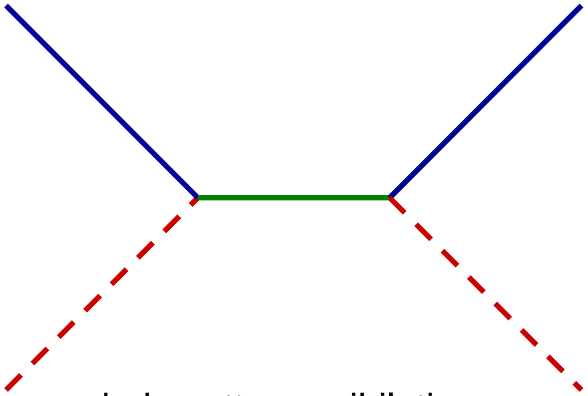
Detection Scenarios

- if no connection between SM and hidden sector…
  - no direct, indirect or collider signature
  - only gravitational
- but could have connectors between those sectors
  - either hidden sector DM charged also under SM
  - or exotics charged under both SM and hidden sector
- focus on the latter
  - more natural in IBM models, where hidden sector only gets SM coupling at loop level
  - more interesting signals

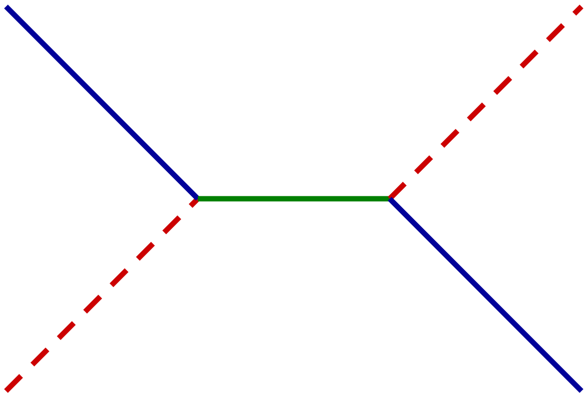


Yukawa coupling

- $W = \lambda X Y_L f_L + \lambda X Y_R f_R + m Y_L Y_R$
- f is a SM multiplet
- $Y_{L,R}$ are 4th generation-like connector particles
- allows both annihilation to and scattering from SM particle f
- new signatures at small mass
  - direct detection signal
  - number density larger
    - strong indirect detection possibilities
    - signal $\propto$ (# density)^2



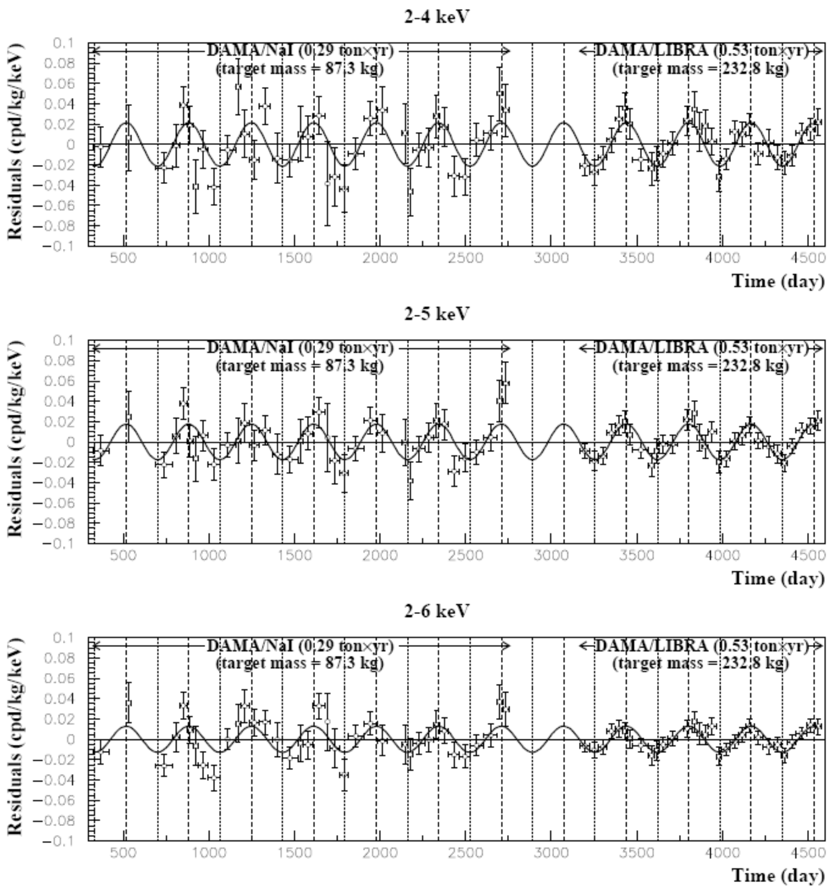
dark matter annihilation



dark matter-nucleon scattering

DAMA/LIBRA result

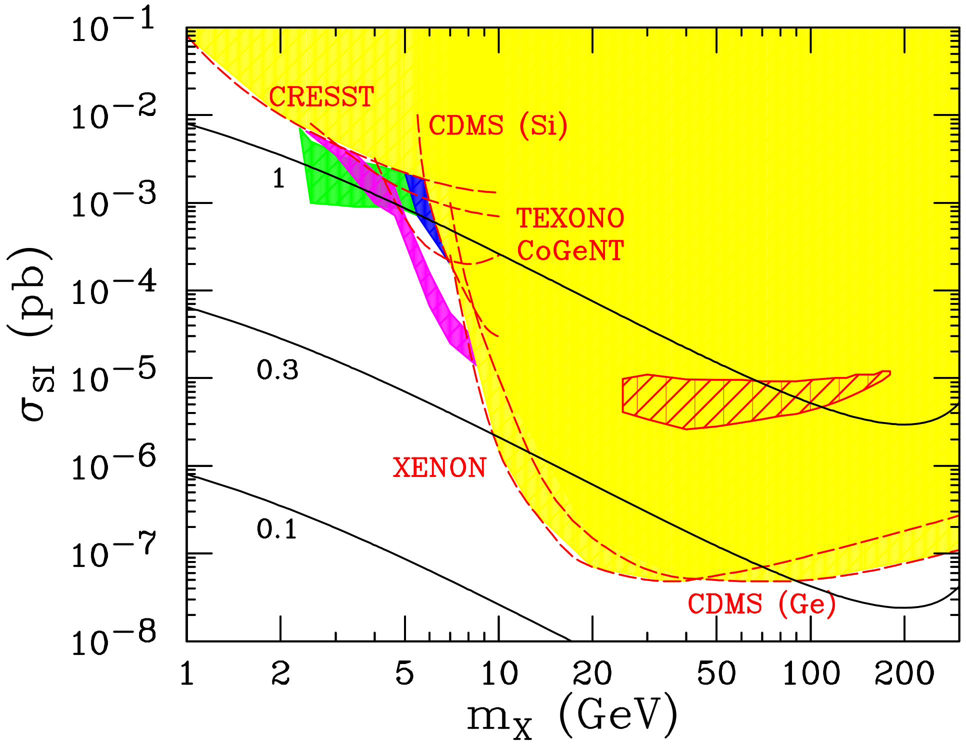
- NaI direct detection experiment
- large mass / large signal / large background
- uses annual modulation of signal to separate from background
- when earth and solar motion add, DM flux is maximized
  - larger signal
  - peaked ~ June 2
  - 8.2 σ effect



DAMA/LIBRA Collaboration arXiv:0804.2741

Issues

- is the experimental result really a DM signal?
- why do other experiments not see it?
- what theory model could generate a signal in that region of parameter space?



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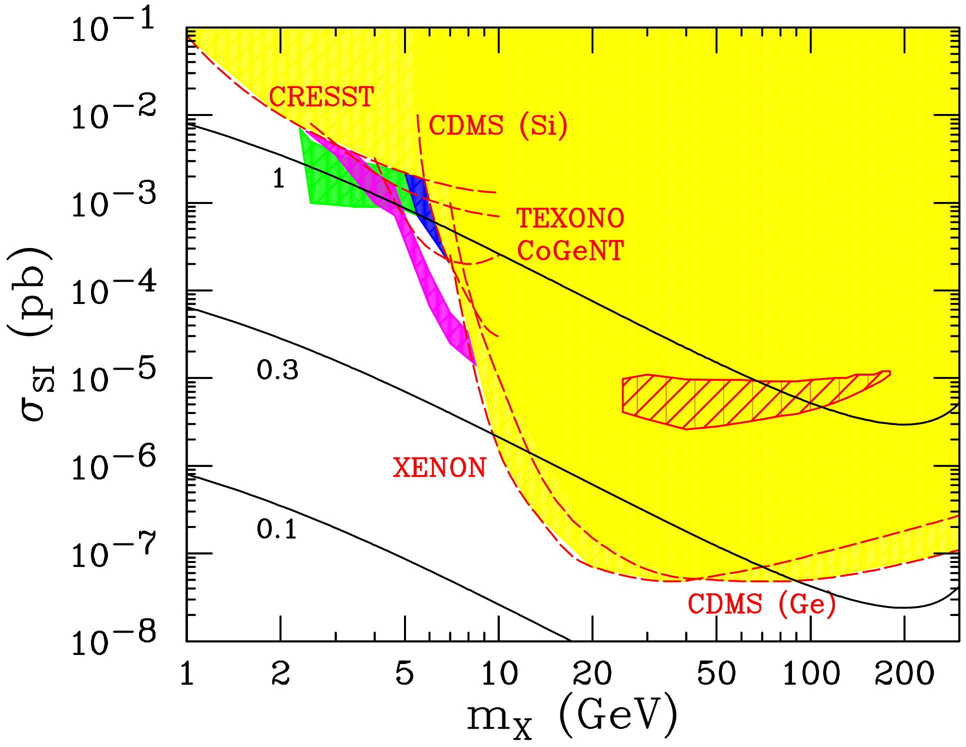

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  - low recoil energy
  - particle physics uncertainties
    - channeling effect, etc.
  - astrophysics uncertainties
    - dark matter streams, etc. (Gelmini, Gondolo)
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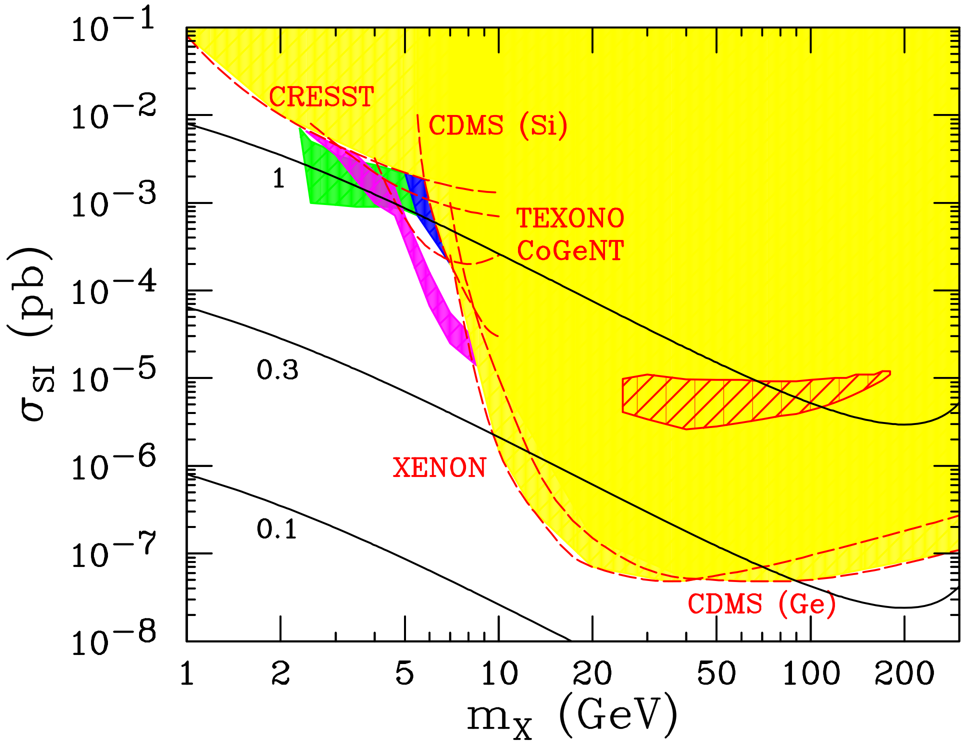

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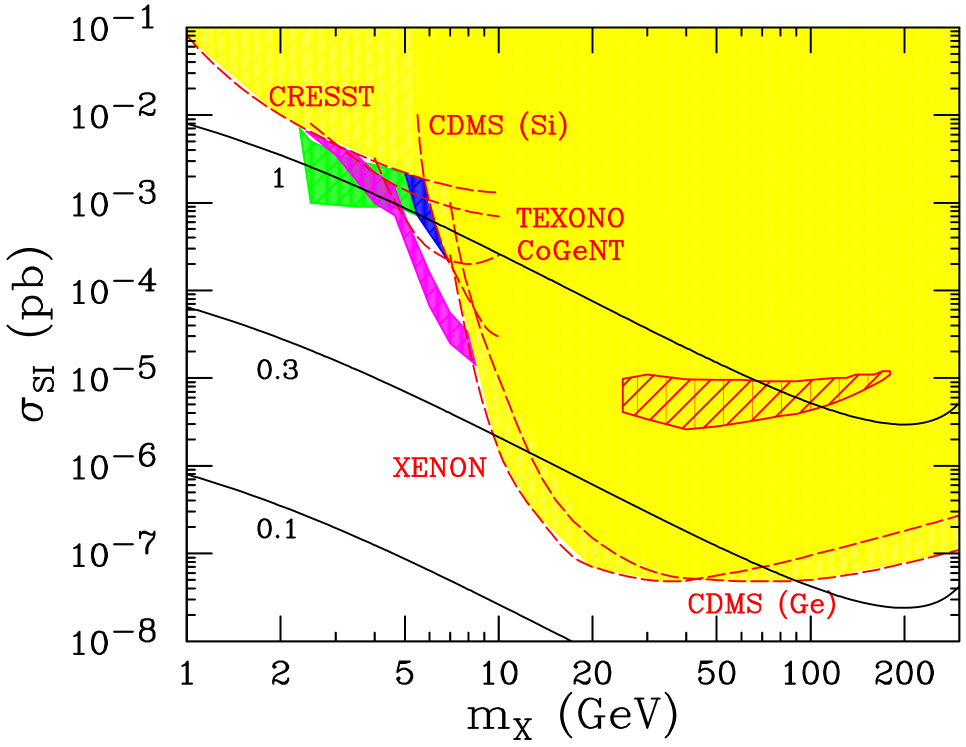
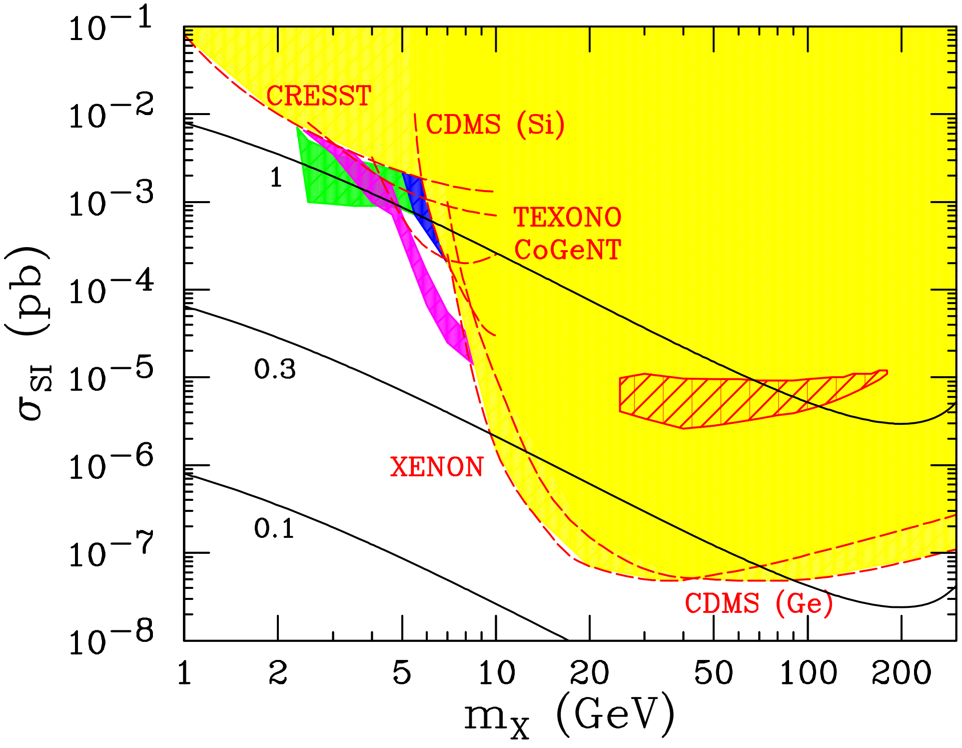
  - we address this with WIMPless dark matter



How can DAMA be consistent with other experiments?

- dark matter mass estimates depend on kinematics of non-relativistic scattering
- recoil energy threshold for experiment gives you a cutoff on mass sensitivity
- channeling effect
  - crystalline scintillators
  - some recoiling nuclei lose no energy to phonons, only to electrons
- dark matter streams
  - changes halo velocity as seen at earth
- more complicated (CPW,FS,SGGF)



WIMPless Model

- we now have a dark matter model which seems to naturally give us the right relic density, but at a variety of mass scales
  - no theory prediction now for the mass scale

- let's treat the DAMA/LIBRA signal as an experimental hint for where the DM mass scale is

- can a consistent WIMPless model to fit this experimental hint?

- want $m_X \sim$ 2-10 GeV, $g \sim 0.1$
- $\sigma_{SM} \sim 10^{-38-41}\ \text{cm}^2 \propto \lambda^4/m_Y^2$
- scaling gives us hints for indirect and collider searches

Scattering from b-quarks

- assume WIMPless DM couples to 3rd generation quarks
  - coupling to other generations can be Cabibbo-suppressed
- this gives a coupling to gluons in nucleus via loop of b-quarks
  - coupling via t-quarks suppressed by m_{top}
- can compute coupling via conformal anomaly (Shifman, Vainshtein, Zakharov)

$$\sigma_{SI} = \frac{\lambda^4}{4\pi} \frac{m_N^2}{(m_N + m_X)^2} \frac{\left[ZB_b^p + (A-Z)B_b^n\right]^2}{A^2 (m_X - m_Y)^2}$$

$$\propto \frac{\lambda^4}{m_Y^2}$$

$$B_b^{p,n} \sim \frac{2}{27} \frac{m_p f_g^{p,n}}{m_b}$$

$$f_g^{p,n} \sim 0.8$$

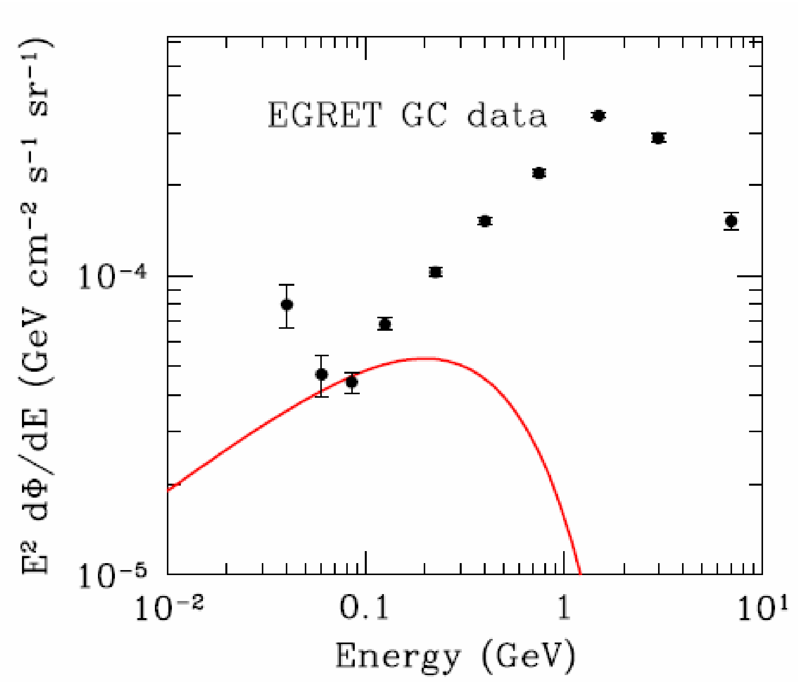
$$m_Y \sim 400\,\mathrm{GeV}$$

$$\lambda \sim 0.5$$

Gamma ray signal

- b-quarks shower off gamma rays which can be probed at GLAST
- pick a point consistent with DAMA/LIBRA signal
  - m_Y ~ 400 GeV, m_X ~ 6 GeV
  - $\langle \sigma_{SM} v \rangle$ ~ 7 pb
    - little large, but close enough (Feng, Tu, Yu)
- assume $\rho \propto 1 / r^{0.8}$
- spectrum peaks at $m_X/25$ (Baltz, Taylor, Wai)
  - internal brem. (peak near m_X) suppressed by high mass final state
- tough signal, but not impossible

$$\sigma_{SM} v = \frac{\lambda^4}{4\pi} \frac{m_Y^2}{\left(m_Y^2 + m_X^2\right)^2} \sqrt{1 - \frac{m_b^2}{m_X^2}} \propto \frac{\lambda^4}{m_Y^2}$$



Collider signature

- collider searches for 4th generation quarks
  - constrained by direct limits from Tevatron
  - precision electroweak constraints from LEP

- would require $m_Y > \sim 260$ GeV

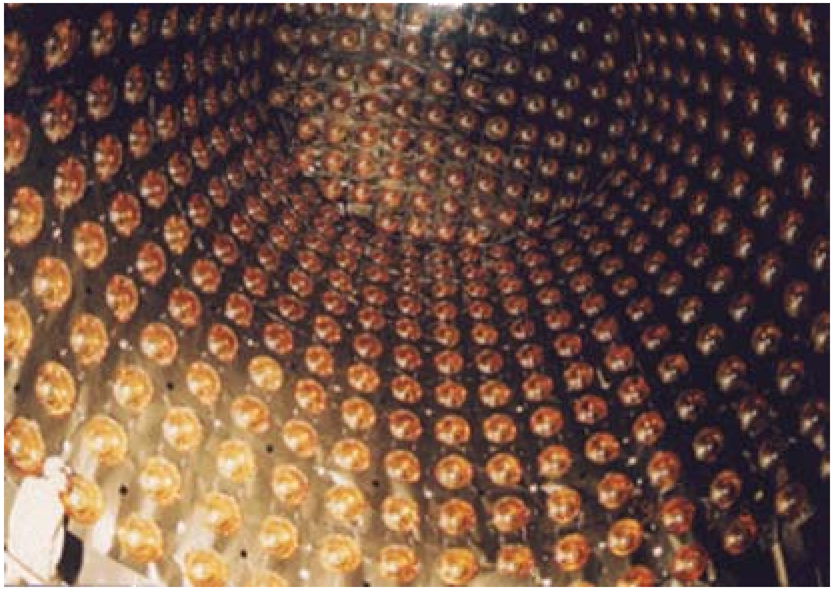
- but exotic quarks in the mass range 300-500 GeV are possible and can be detected at LHC (Kribs, Plehn, Spannowsky, Tait)
  - consistency check for WIMPless model of DAMA/LIBRA signal

- exotics usually require higher mass Higgs for consistency with precision EW
  - interesting correlation with Higgs searches

Corroborating at Super-K

(see also Hooper, Petriello, Zurek, Kamionkowski; Savage, Gelmini, Gondolo, Freese)

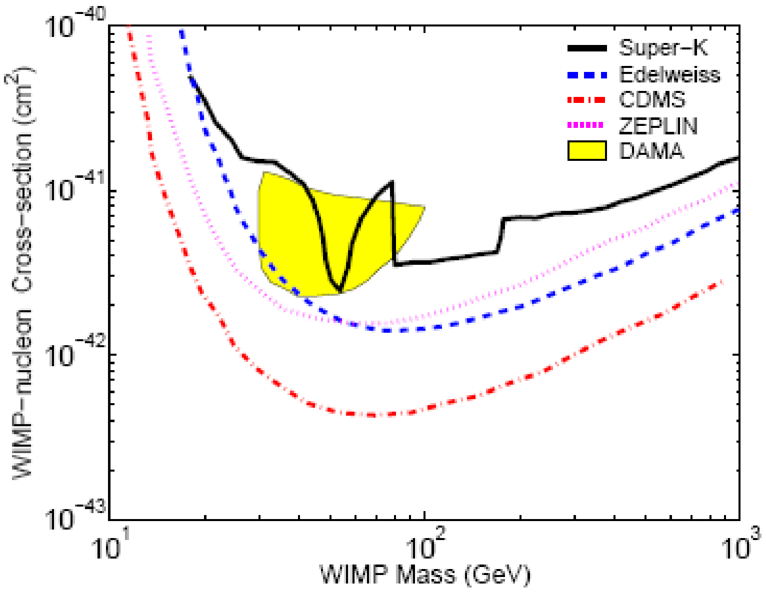
- need another experiment to figure out what DAMA is seeing
- direct detection experiment
  - need low threshold
  - if DAMA result comes from earth-specific physics, won't know
- indirect detection experiment
  - model-dependent relation to DAMA
- Super-Kamiokande
  - model-independent, but very different from direct detection tests
  - low threshold



Super-Kamiokande

How Super-K can set limits….

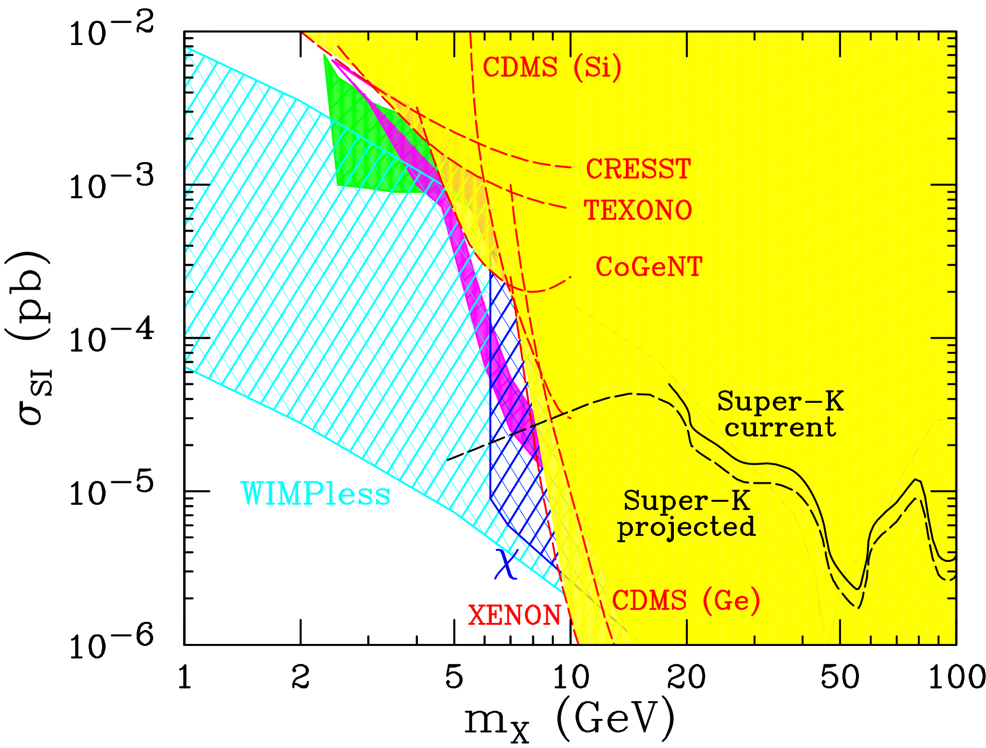
- sun/earth capture DM by elastic scattering
  - absorb energy
- capture yields higher density
  - higher DM annihilation rate
  - νs get out
- if sun is in equilibrium, annihilation rate = capture rate
  - capture rate $\propto \sigma_{\text{DM-nucleon}}$
- if Super-K can bound XX→$\nu\nu$ flux, can then bound $\sigma_{\text{DM-nucleon}}$
- Super-K sensitive to low E_ν
  - good for DAMA
  - model-independent (largely)



Desai, et al., hep-ex/0404025

Super-K bounds….

- ν_μ convert to μ in/near detector, and μ detected at Super-K
- if data matches atmospheric ν background
  - statistical uncertainty bounds ν flux contribution from XX→$\nu\nu$
- old bound from throughgoing μ
  - pass all the way through detector
- >18GeV limit → >90% of μ are TG
- for 5-10GeV range, mostly fully-contained events
  - μ form in detector and stop there



projected Super-K bounds using fully-contained events and 3000 live days, plus WIMPless and neutralino (Bottino, et al) predictions

Conclusion

- new theoretical window for dark matter
  - can address dark matter at low mass

- possible explanation for results of DAMA/LIBRA

- interesting corroborative checks at LHC, and possibly at GLAST

- possible to corroborate WIMPless (and other) models for DAMA/LIBRA very soon at Super-Kamiokande

Mahalo…!