The WIMPless Miracle

Jason Kumar
University of Hawaii

Collaborators

- Jonathan Feng
- John Learned
- Stefanie Smith
- Louis Strigari
  - 0803.4196, 0806.3746, 0808.4151, 0908.1768

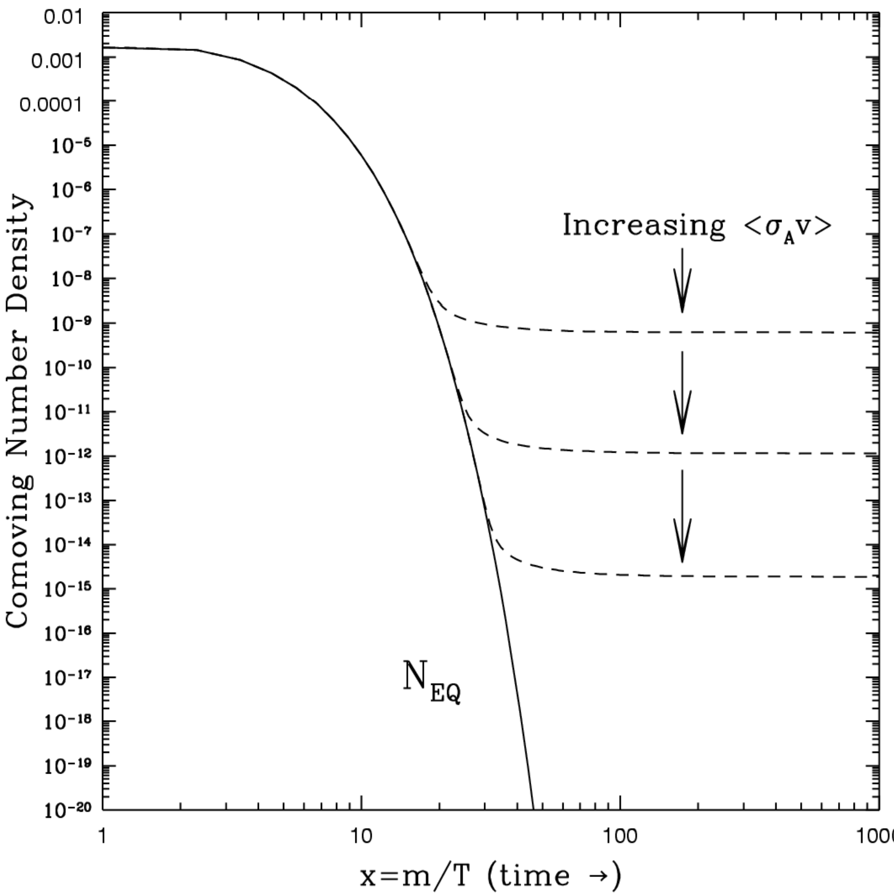
- Johan Alwall
- Danny Marfatia
- Shufang Su
- Fumihiro Takayama

Relic Density

- dark 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

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

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



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

WIMP miracle

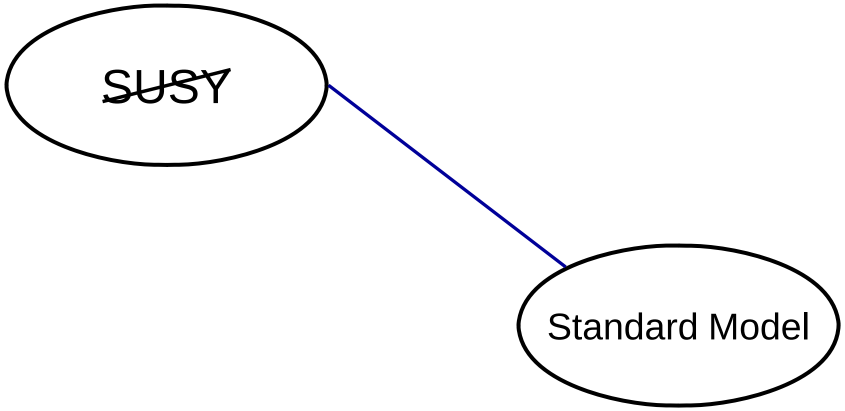
- knowing σ, we can figure out relic density
- to get observed DM density need σ ~ 1 pb
- stable matter with coupling and mass of the electroweak theory would have about right relic density for dark matter
  - WIMP miracle
- one of the best theoretical ideas for dark matter
- guide for most theory models 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
    - discrete, global, gauged?
  - 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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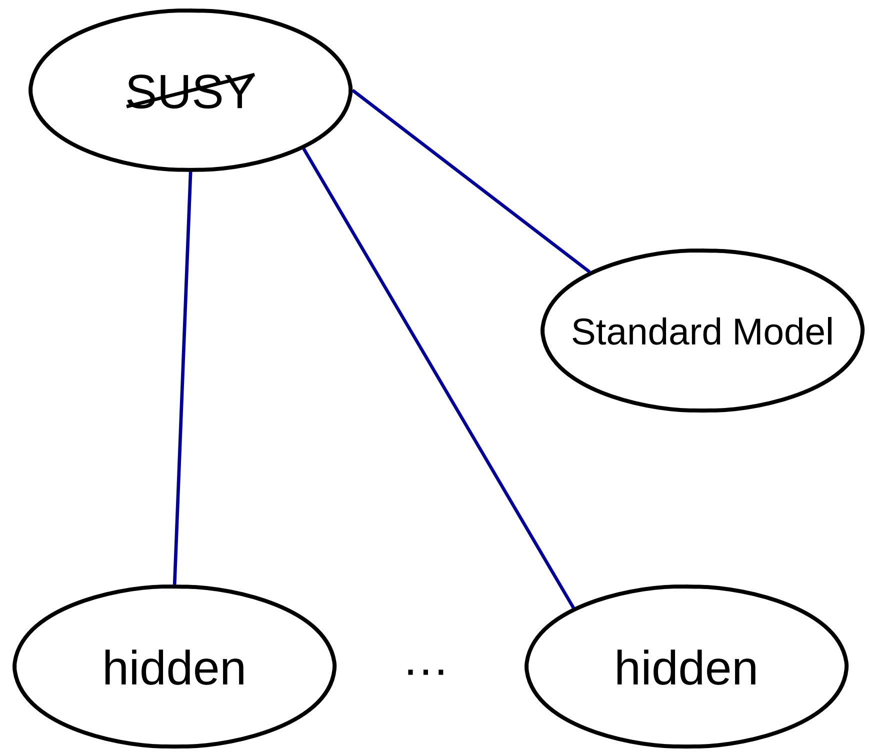
- we add to this extra gauge sectors, which behave in a qualitatively similar way
  - symmetry stabilizes particle at SUSY-breaking scale



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

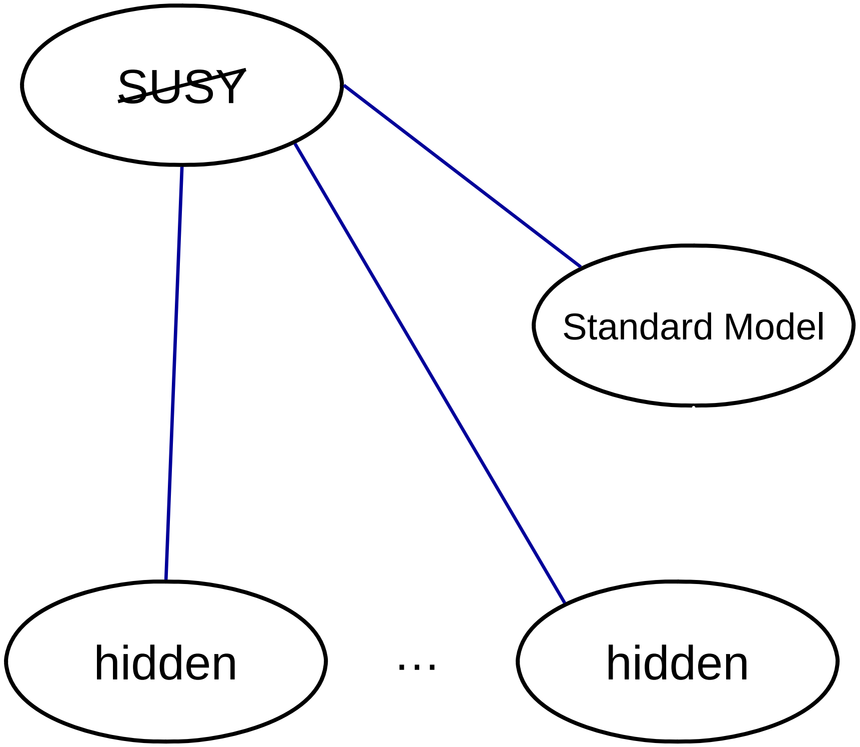
- we find in this scenario, a generic stable particle at soft-mass scale should have the right density (order of magnitude) to be dark matter
- maybe this is really a WIMPless miracle … any gauge sector with any coupling would have worked
- in fact, it should have worked for the MSSM in gauge-mediation
  - 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})
    - set by flavor physics which we don't understand
  - second accident → in gauge mediation, the LSP is not gauge charged
- but in any other sector, a discrete symmetry can stabilize a hidden sector particle at soft-mass scale
  - in the right ball-park for dark matter

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
  - multi-component easily follows from multiple hidden sectors
- implications for colliders, direct and indirect detection

Detection Scenarios

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



Detection Scenarios

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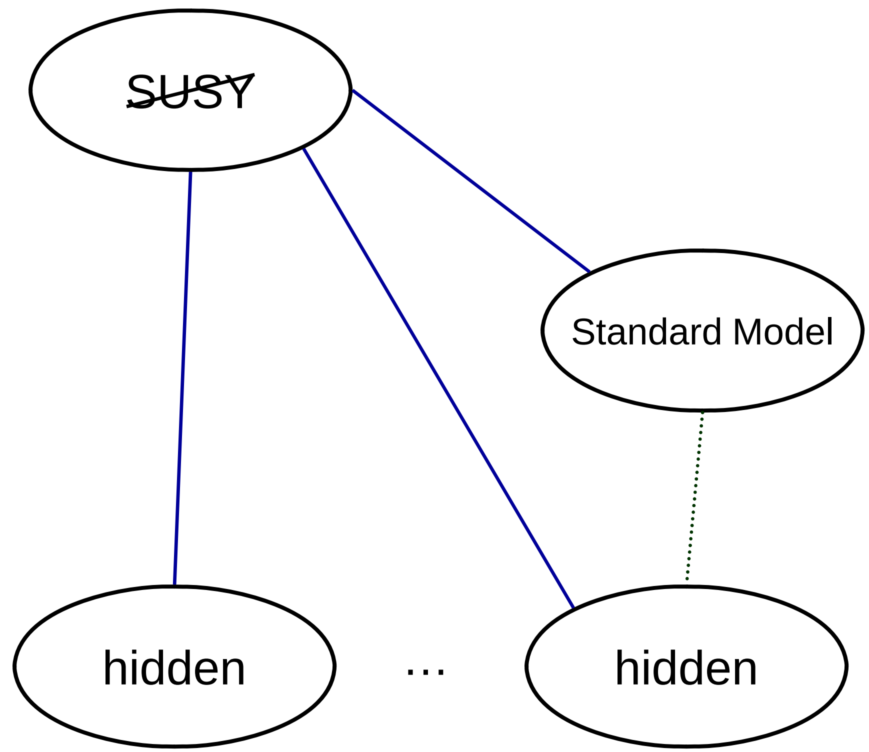
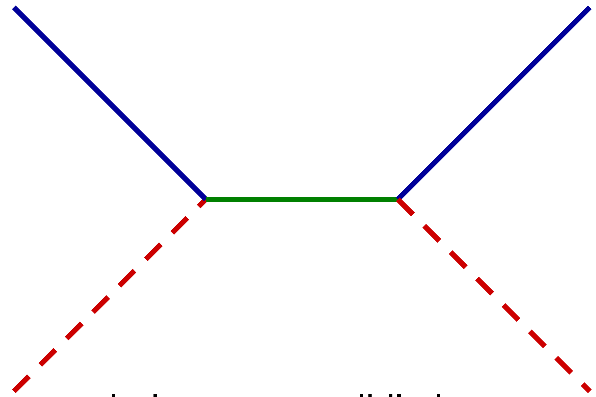
- but could have connectors between those sectors
  - exotics charged under both SM and hidden sector

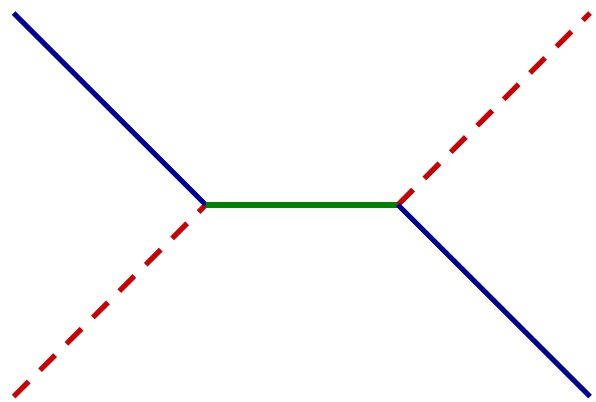


Yukawa coupling

- $W = \lambda X Y_L f_L + \lambda X Y_R f_R + m Y_L Y_R$
- f is a SM multiplet
- $Y_{L,R}$ are 4th generation-like connector particles
- allows both annihilation to and scattering from SM particle f, and collider production



dark matter annihilation



dark matter-nucleon scattering

Scattering from b-quarks

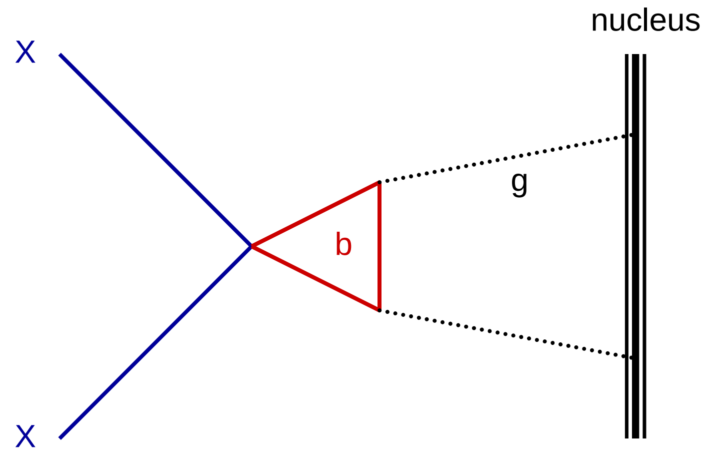
- assume WIMPless DM couples to 3rd generation quarks
  - assume coupling to other generations suppressed
  - reasonable FCNC solution
  - assume DM is scalar of X
    - working on fermionic DM now
- this gives a coupling to gluons in nucleus via loop of b-quarks
  - coupling via t-quarks suppressed by m_{top}
- can compute coupling via conformal anomaly (Shifman, Vainshtein, Zakharov)

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

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

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

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



New observational possibilities

- parameters are λ, m_Y, m_X

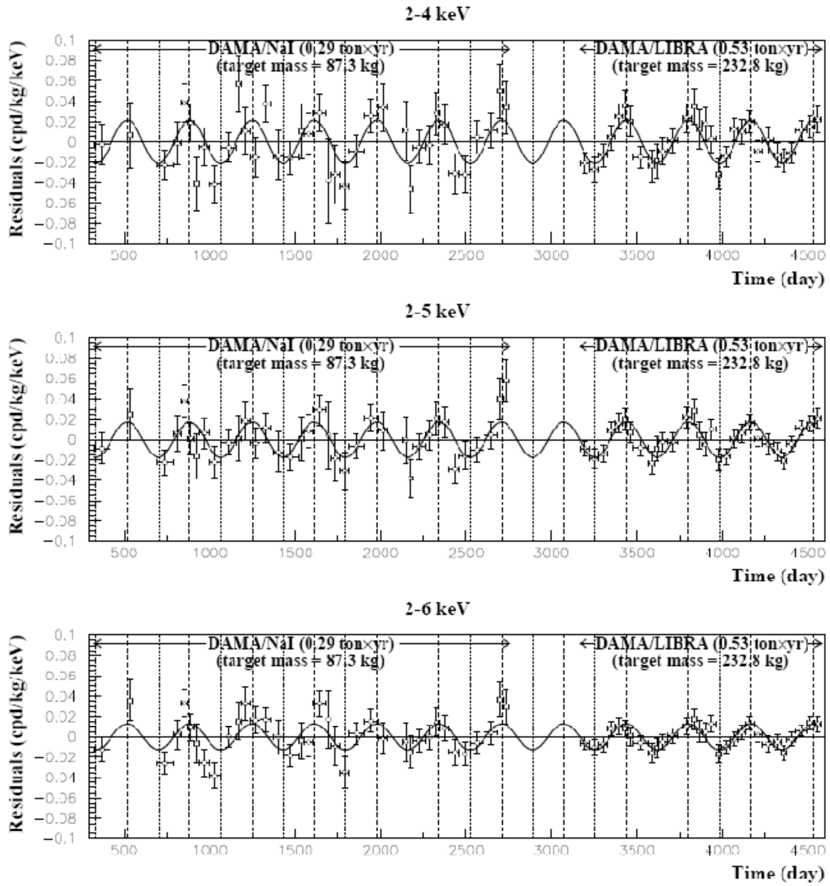
- $m_Y \sim 300 - 500$ GeV (Kribs, Plehn, Spannowsky, Tait)
  - constrained by precision electroweak data and direct tests

- low m_X
  - DAMA
  - (# density)^2 → indirect detection

- small λ
  - direct and indirect detection suffer
  - but collider possibilities may be good

DAMA/LIBRA result

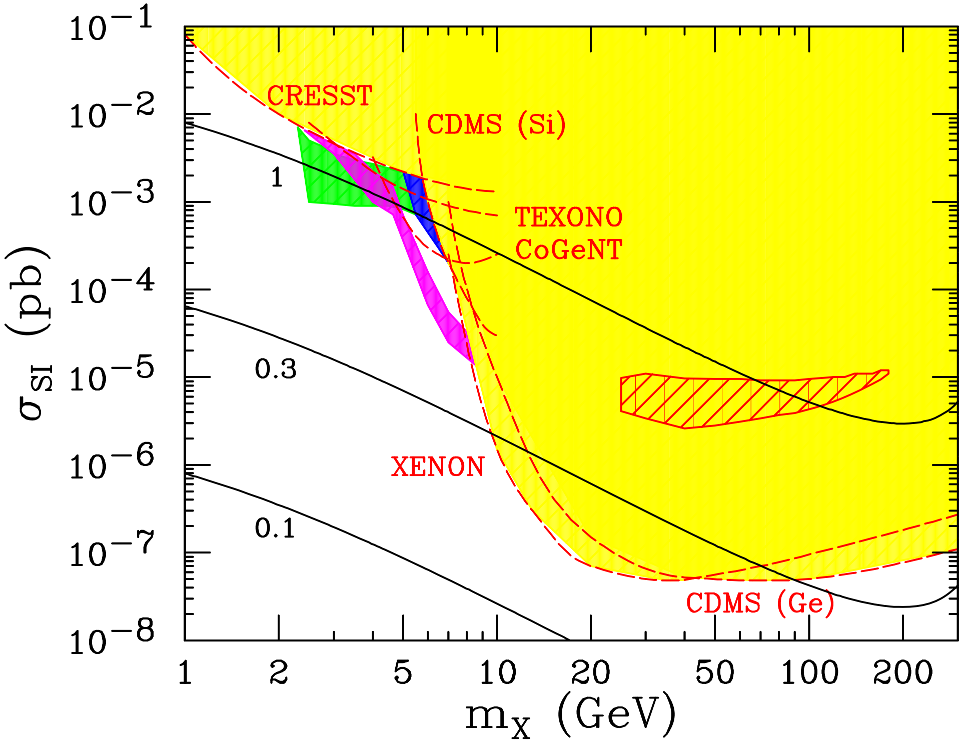
- NaI direct detection experiment
- large mass / large signal / large background
- uses annual modulation of signal to separate from background
- when earth and solar motion add, DM flux is maximized
  - larger signal
  - peaked ~ June 2
  - 8.2 σ effect



DAMA/LIBRA Collaboration arXiv:0804.2741

DAMA Annual Modulation Signal

- 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?



DAMA Annual Modulation Signal

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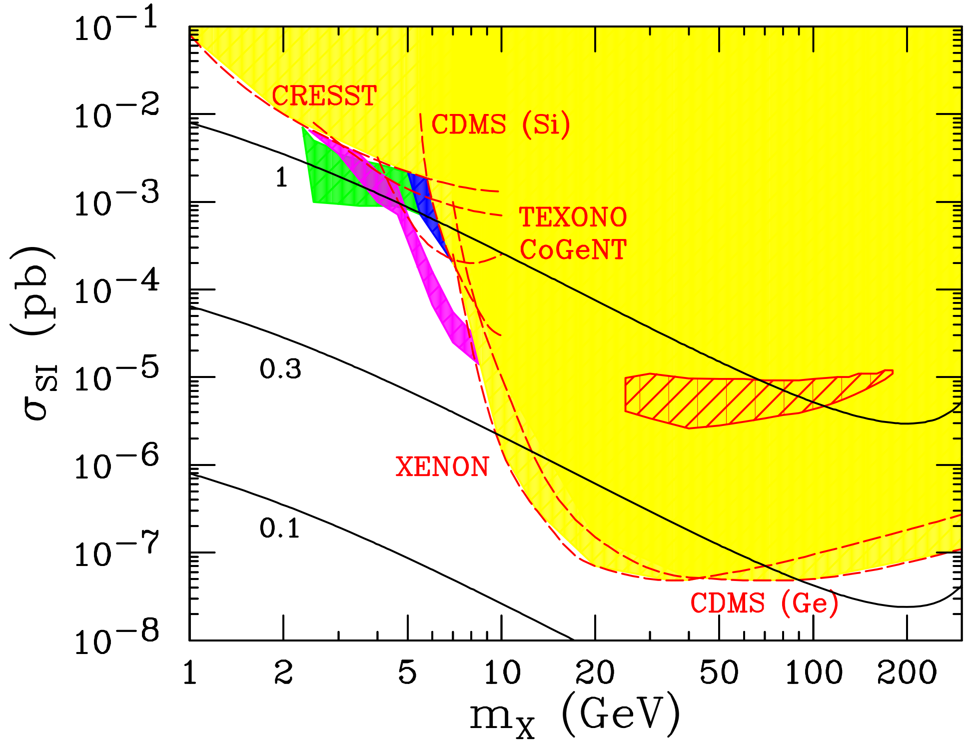

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DAMA Annual Modulation Signal

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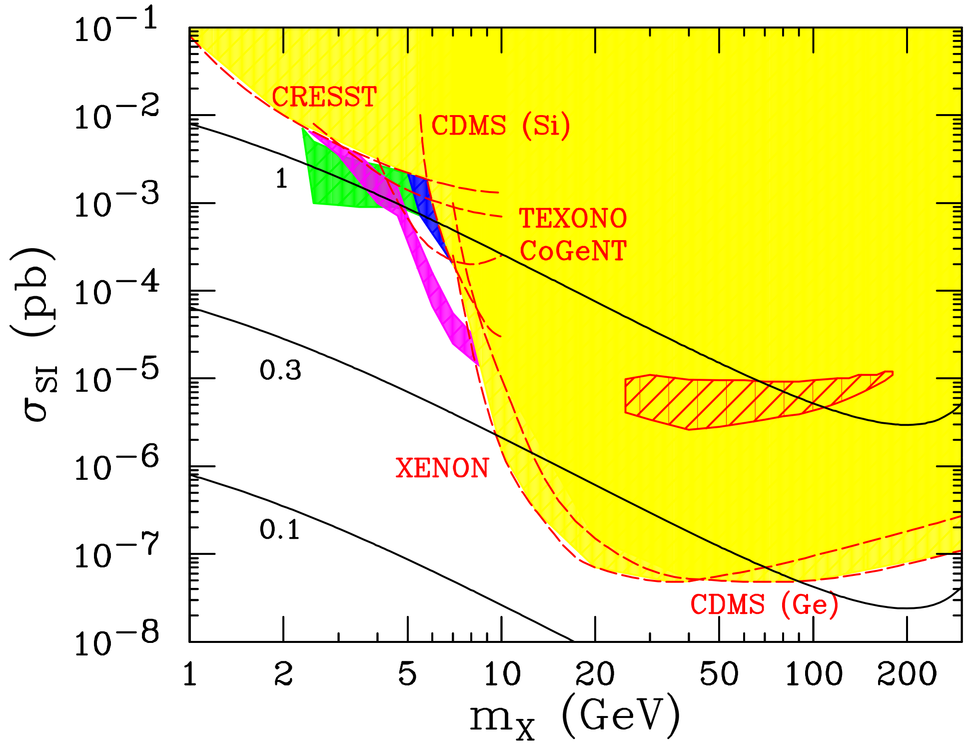
- why do other experiments not see it? low mass?
  - low recoil energy
  - particle physics uncertainties
    - channeling effect, etc.
      (Petriello, Zurek)
  - astrophysics uncertainties
    - dark matter streams, etc.
      (Gelmini, Gondolo)
- what theory model could generate a signal in that region of parameter space?



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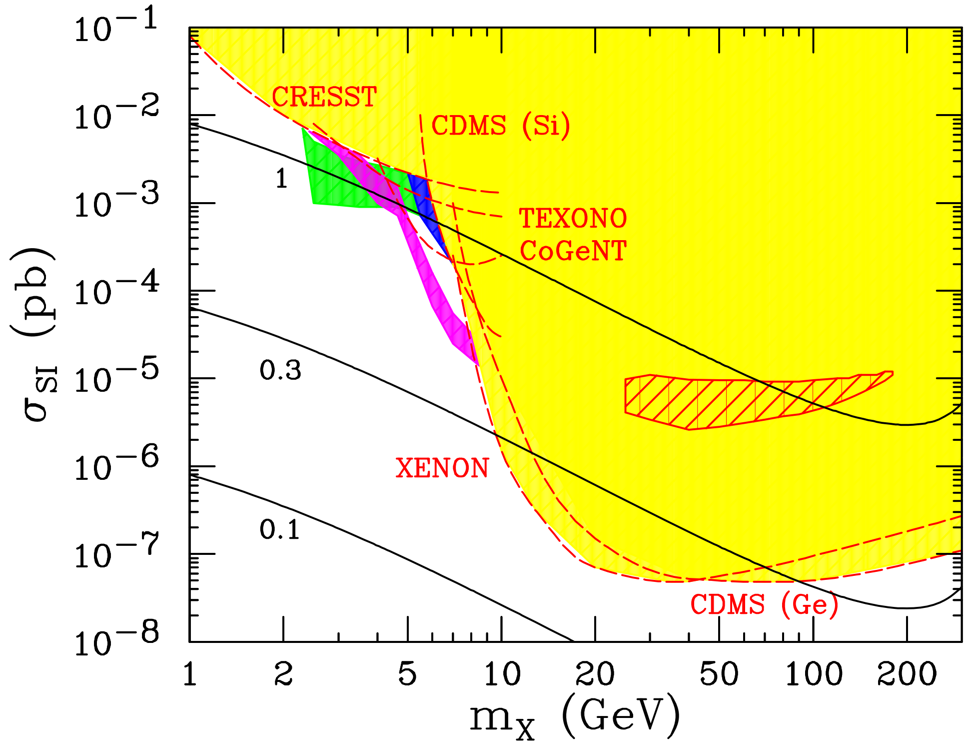
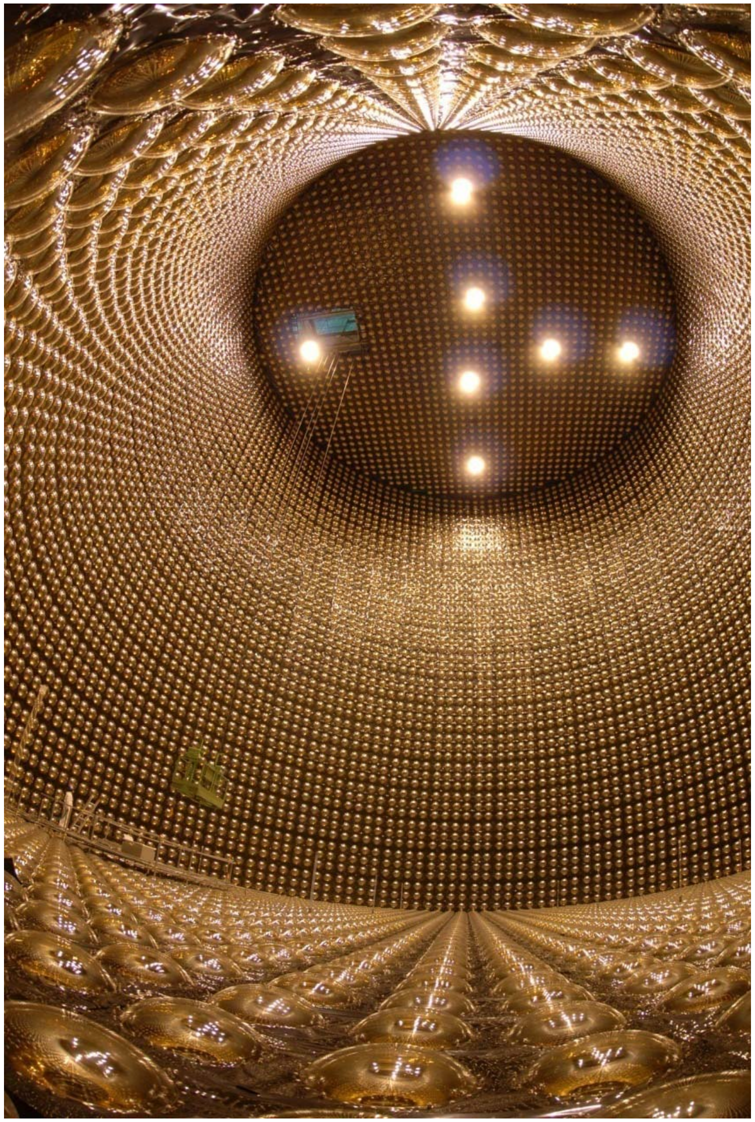
  - astrophysics uncertainties
    - dark matter streams, etc. (Gelmini, Gondolo)
- what theory model could generate a signal in that region of parameter space?
  - WIMPless dark matter with $m_X \sim$ 5-10 GeV, $\lambda \sim 0.5$



Testing at neutrino experiments

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

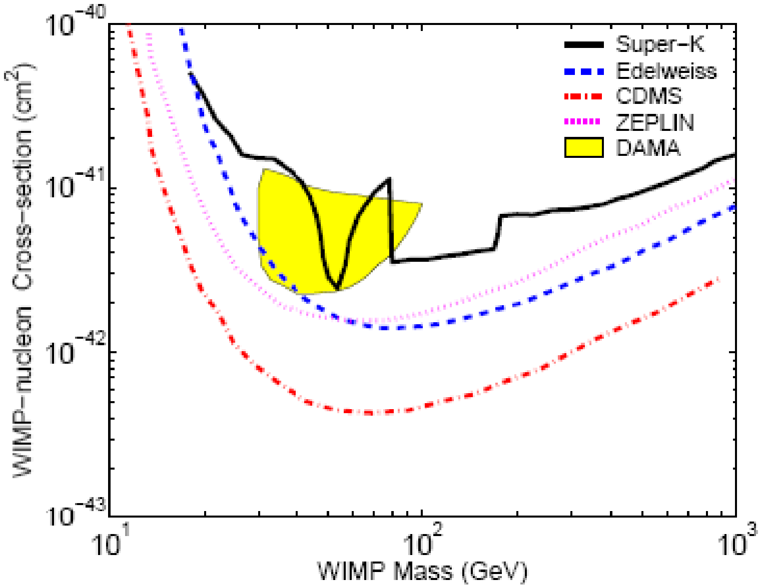
- need another experiment to figure out what DAMA is seeing
- direct detection experiment
  - need low threshold
  - if DAMA result comes from earth-specific physics, won't know
- indirect detection experiment
  - model-dependent relation to DAMA
- neutrino detectors….
  - model-independent, but very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



Super-Kamiokande

How neutrino detectors set limits….

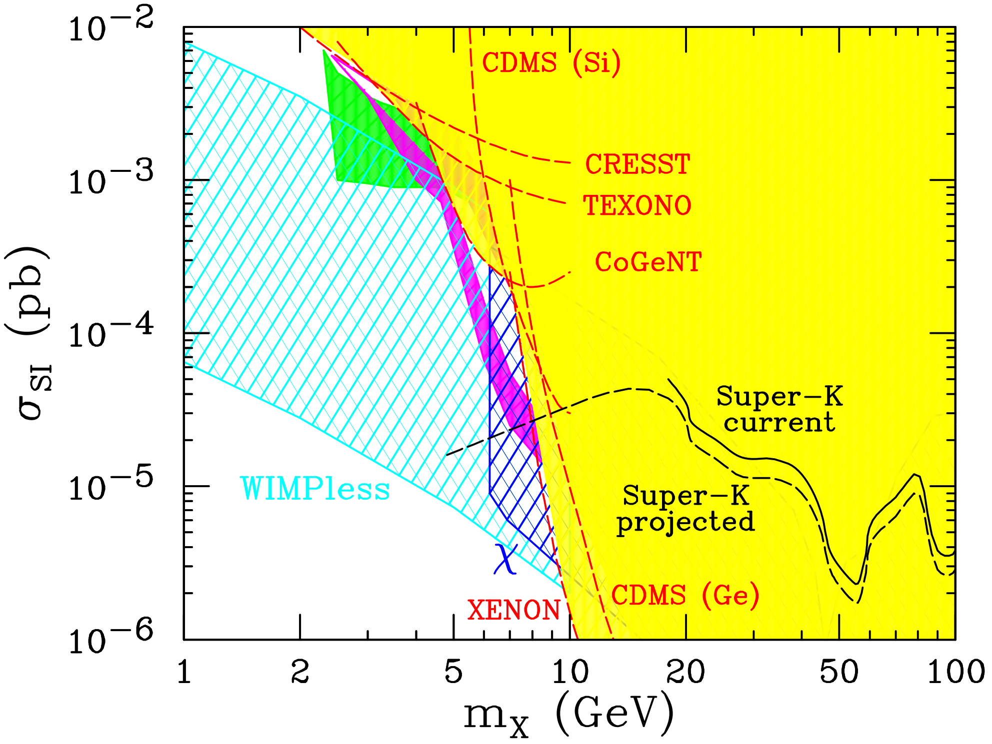
- sun/earth capture DM by elastic scattering
  - higher density/annihilation rate
  - νs get out
- if sun is in equilibrium, annihilation rate = capture rate
  - capture rate $\propto \sigma_{\text{DM-nucleon}} / m_{DM}$
- if ν detector can bound $XX \rightarrow \nu\nu$ flux, can then bound $\sigma_{\text{DM-nucleon}}$
- Super-K sensitive to low E_ν
  - good for DAMA
  - model-independent (largely)
- liquid scintillator detectors may be even better



Desai, et al., hep-ex/0404025

Super-K bounds….

- ν_μ convert to μ in/near detector, and μ detected at Super-K
- background = atmospheric ν
- old bound from throughgoing μ
  - pass all the way through detector
- >18 GeV limit → >90% of μ are throughgoing
- for 5 - 10 GeV range, mostly fully-contained events
  - μ form in detector and stop there
- can also get potential bounds from ν_e



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

Collider signature

- collider searches for $Y_{L,R}$ → 4^{th} generation-like quarks
  - constrained by direct limits from Tevatron
  - precision electroweak constraints from LEP

- would require $m_Y > \sim 260$ GeV
  - best range ~ 300 – 500 GeV

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

- interesting new possibility at small λ
  - direct and indirect detection go bad, but colliders might do well

Jets + missing E_T signal

- can produce pp→YY through QCD processes
  - no λ dependence

- only decay channel could be YY → X b X b
  - Y has same hidden charge as X
  - di-b-jet + missing E_T
  - also $Y_L^t Y_L^t$ → X t X t (, $Y_L^b W^+$ $Y_L^b W^+$) → jets + missing E_T

- λ affects Y lifetime
  - if very small → Y reaches detector
  - if not too small → displaced Y decay vertex
  - also affects branching fraction of $Y_L^t \rightarrow Y_L^b\ W^+$
- either way, striking signal in region where direct and indirect detection has trouble
- can potentially see at Tevatron → better at LHC

Conclusion

- new theoretical window for dark matter
  - dark matter with right relic density at wide range of masses
- possible explanation for results of DAMA/LIBRA
- interesting corroborative checks at LHC and Tevatron
- possible to corroborate WIMPless (and other) models for DAMA/LIBRA very soon at Super-Kamiokande
  - new possibilities with liquid scintillators and ν_e

Mahalo…!