“Alternative” DM models – a review

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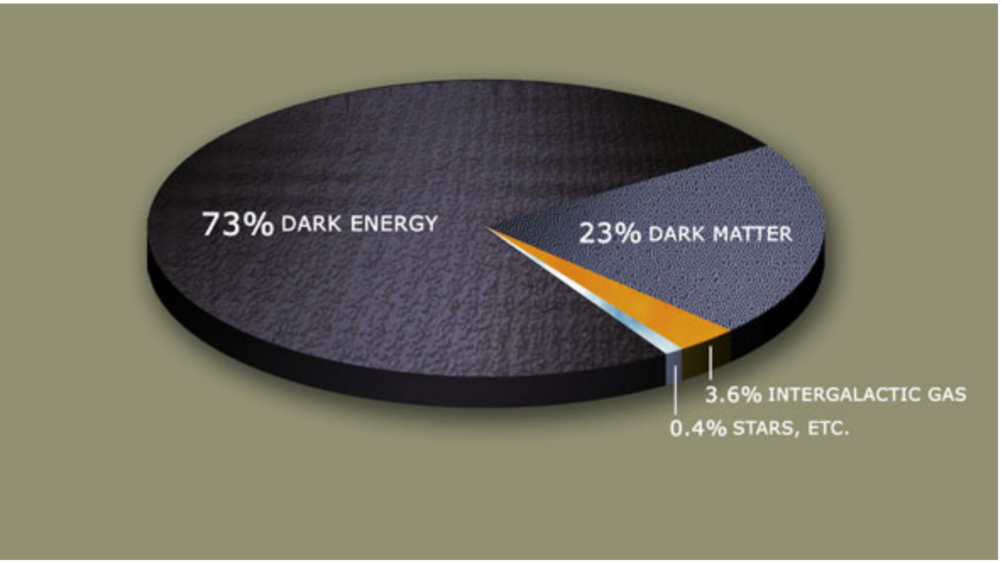
March 2012, Moriond meeting

Plan

P.S. The talk is solicited, and my interpretation of “unusual/ alternative” is anything but neutralino and axions.

1. Introduction. Rough classification of Dark Matter. Focus on WIMPs.
2. Simplest WIMPs. EW and Higgs mediation. *Significance of [possible] Higgs discovery for “light” WIMPs*.
3. Are we guaranteed to “see” WIMPs even with the best try of colliders/direct/indirect detection? *Snapshot of “secluded” WIMP ideas that led to the hunt for “dark forces”*.
4. Message for the direct detection community: keep your options open. Alternative uses of WIMP detectors: looking for *solar axions, exotic solar neutrinos, absorption of super-WIMPs, constraining the neutrino properties*.

2^{nd} missing mass problem – origin/nature of dark matter



In the era of precision cosmology we know that

1. There is substantial body of evidence for DM at different distance scales.
2. It is 6 times more abundant than baryons and contributes ~1/4 of the total energy budget.

The discovery of atomic nucleus created the 1^{st} missing mass problem of 1920s: Why A>Z or why is $M_{nucleus} > Z\, m_{proton}$? Led to the discovery of neutrons and the strong force.

Would the search for DM #2 lead to a similar spectacular discovery?

Simple classification of particle DM models

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

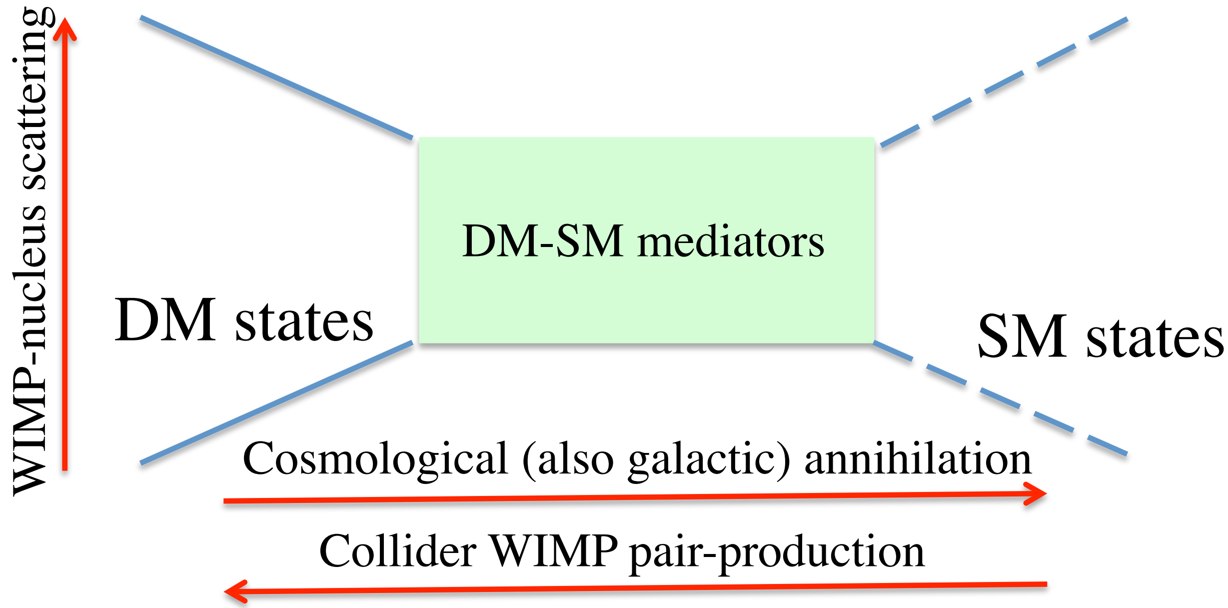
Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_{\gamma}=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **super-WIMPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_{\gamma}\sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Signatures can be completely different. EW Moriond → focus on WIMPs

WIMP paradigm



$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production? Not really…

EW mediation: Z bosons

First model of WIMPs constructed: heavy neutrino N annihilating to SM states via virtual Z. $NN \to Z^* \to SM$ for small m_N and $NN \to ZZ$, WW for m_N above di-boson threshold. (Lee; Weinberg; Zeldovich, Dolgov and Vysotsky, mid 70s). More generically, N could be split on two Majorana components N_1 and N_2, with Δm_N significantly modifying the pattern of scattering (Tucker-Smith, Weiner, 2000, and some earlier works).

Collider physics and direct detection provide complementary sensitivity to the model (Direct scattering is very sensitive to small Δm_N, while LEP I provides a very powerful constraint on $Z \to N_1 N_2$ from $Z \to$ invisible. In particular, models with $g_N > 0.3\, g_W$ are all gone after LEP irrespective of Δm_N.

LEP I was a big "reckoning day" for light Z-mediated Dark Matter.

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis(2000)

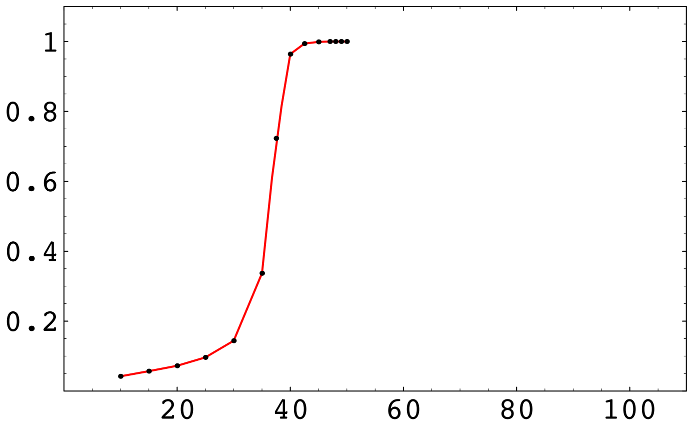
DM through the Higgs portal – *minimal model of DM*

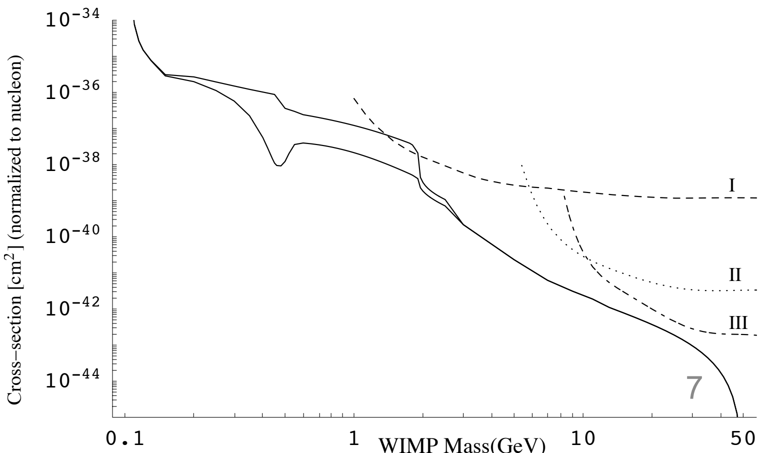
$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$

$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2}S^2h^2.$$

125 GeV Higgs is “very fragile” because its with is ~ y_b^2 – very small

R = $\Gamma_{\text{SM modes}}/(\Gamma_{\text{SM modes}}+\Gamma_{\text{DM modes}})$. Light DM can kill Higgs boson easily
(missing Higgs Γ: van der Bij et al., 1990s, Eboli, Zeppenfeld,2000)





There are many Higgs-mediated models that are invisible for DD yet lead to missing Higgs decay

Example: S – mediator, mixes with h; N – DM particles

$$\mathcal{L} = (H^\dagger H)(AS + \lambda S^2) + \beta S \bar{N} i\gamma_5 N$$

Combination $A\beta$ breaks CP, but in the dark sector. Annihilation cross section

$$\langle \sigma v \rangle_{\bar{N}N\to SM} \simeq \frac{3\lambda_h^2}{4\pi} \left(\frac{m_b}{m_h}\right)^2 \frac{m_N^2}{m_h^4} \sim 1 \text{ pb}$$

requires $\lambda_h^2 \sim 10 \times \left(\frac{20 \text{ GeV}}{m_N}\right)^2$

Suppression of Higgs visible widths, $R < 0.001$. Elastic cross sections are *hopeless*, suppressed by

$$\sigma_p^{\rm eq} \simeq \frac{1}{2\pi}(v/c)^2 \times \frac{g_{hpp}^2 \lambda_h^2 m_p^2}{m_h^4} \times \left(\frac{Am_p}{Am_p + m_N}\right)^2$$
$$\lesssim 10^{-48} \text{ cm}^2 \times \lambda_h^2. \quad (8$$

Tomorrow is a big reckoning day for the Higgs-mediated Dark Matter models

- A discovery of the SM(-like) Higgs with mass of ~ 125 GeV will wipe out many DM models with $m_{DM} < 50$ GeV that use Higgs particle for regulating its abundance in a fairly model-independent way. (this point was made repeatedly in recent literature Mambrini; Raidal, Strumia; X.-G. He, Tandean; Fox, Harnik, Kopp, Tsai; MP, Ritz; Lebedev; others…)

- Any theorist model-builder who wants to play with sub-50 GeV WIMPs may "run out of SM mediators" and will be then bound to introduce new mediation mechanisms, such as new [scalar] partners of SM fermions, new Higgses and/or new Z'. Light mediators have been also dubbed "dark forces".

- Existence of new mediator forces – especially light mediators – can change "usual" WIMP phenomenology in a profound way. (Fayet; Boehm; Finkbeiner, Weiner; MP, Ritz, Voloshin...)

Secluded WIMPs and Dark Forces

MP, Ritz, Voloshin; Finkbeiner and Weiner, 2007. Original model: Holdom 86

$$\mathcal{L}_{\rm WIMP+mediator} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

This Lagrangian describes an extra U(1)' group (**dark force**), and some matter charged under it. Mixing angle κ controls the coupling to the SM.

ψ – Dirac type WIMP; V_μ – mediator particle.

Two kinematic regimes can be readily identified:

- $m_{mediator} > m_{WIMP}$

  $\psi^+ + \psi^-$ -> virtual V^* -> SM states

κ has to be sizable to satisfy the constraint on cross section

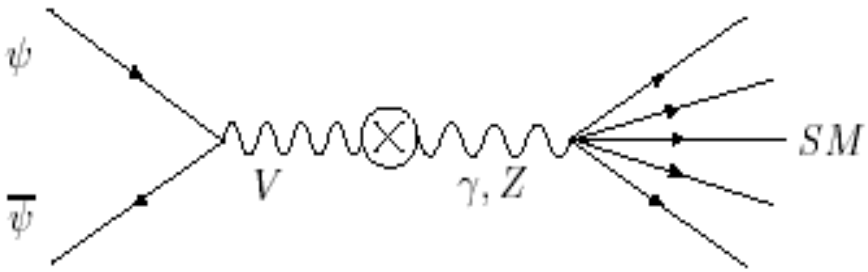
2. $m_{mediator} < m_{WIMP}$

   $\psi^+ + \psi^-$ -> on-shell V +V, followed by V -> SM states

There is almost no constraint on κ other than it has to decay before BBN. κ^2 » 10^{-20} can do the job.

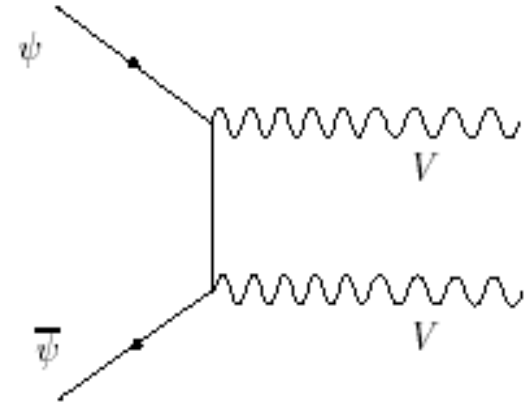
Two types of WIMPs

Un-secluded



Ultimately discoverable
Size of mixing*coupling is set by annihilation. Cannot be too small.

Secluded



Potentially well-hidden
Mixing angle can be 10^{-10} or so. It is not fixed by DM annihilation

You think gravitino DM is depressing, but so can be WIMPs

Indirect signatures of secluded WIMPs

Annihilation into a pair of V-bosons, followed by decay create boosted decay products.

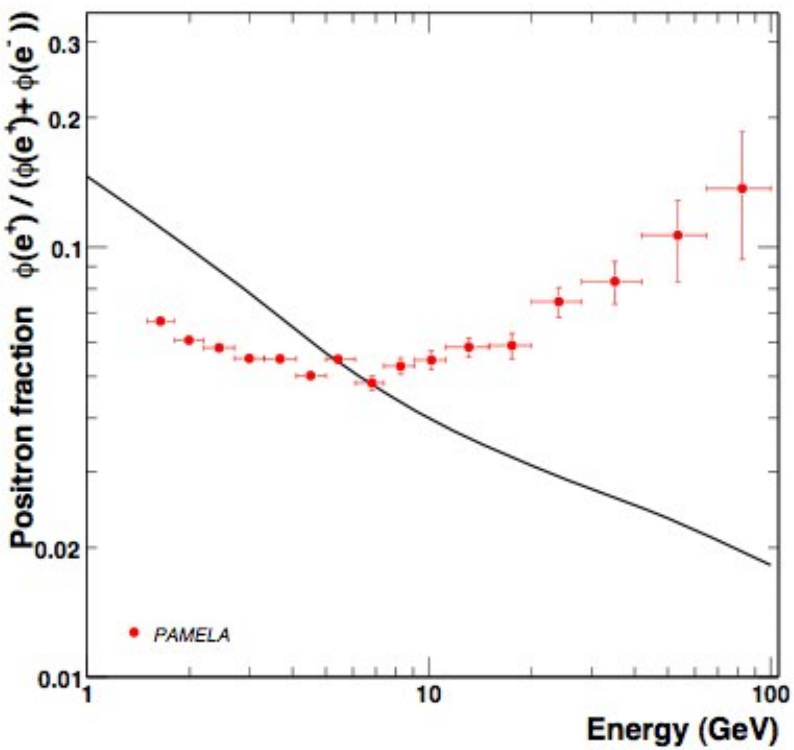
If m_V is under $m_{DM} v_{DM}$ **~ GeV, the following consequences are generic**

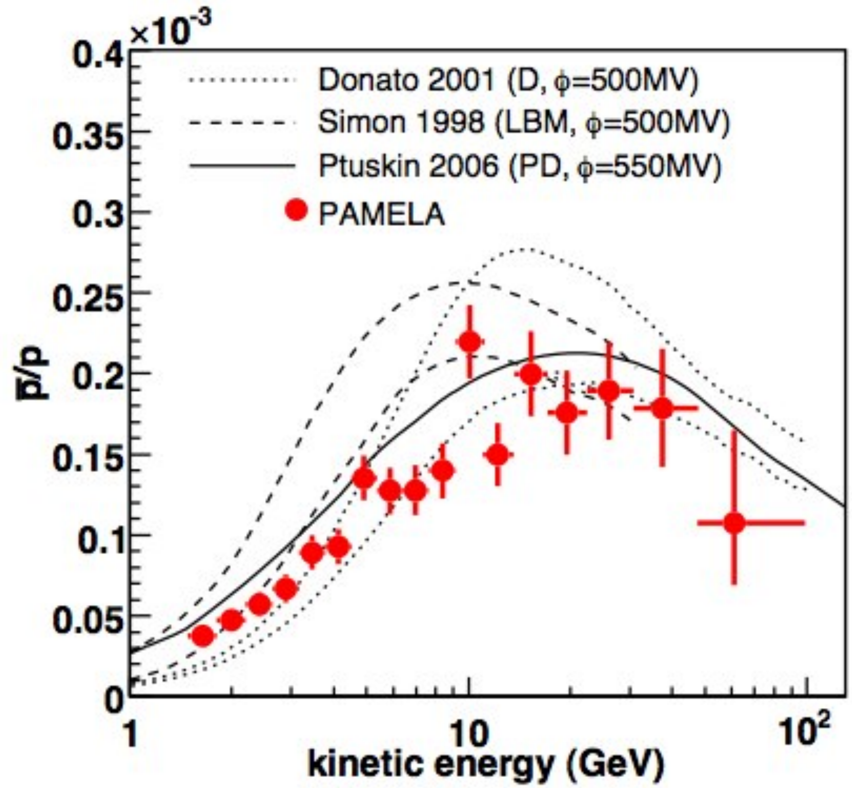
(Arkani-Hamed, Finkbeiner, Slatyer, Weiner; MP and Ritz, Oct 2008)

1. Annihilation products are dominated by electrons and positrons
2. Antiprotons are absent and monochromatic photon fraction is suppressed
3. The rate of annihilation in the galaxy, $\langle \sigma_{ann} v \rangle$, is enhanced relative to the cosmological $\langle \sigma_{ann} v \rangle$ because of the long-range *attractive* V-mediated force in the DM sector. (Sommerfeld and resonant enhancement)

Fits the PAMELA signature. [which can of course be explained by a variety of pure astrophysical mechanisms]

PAMELA positron fraction seem[ed] to be "abnormal"





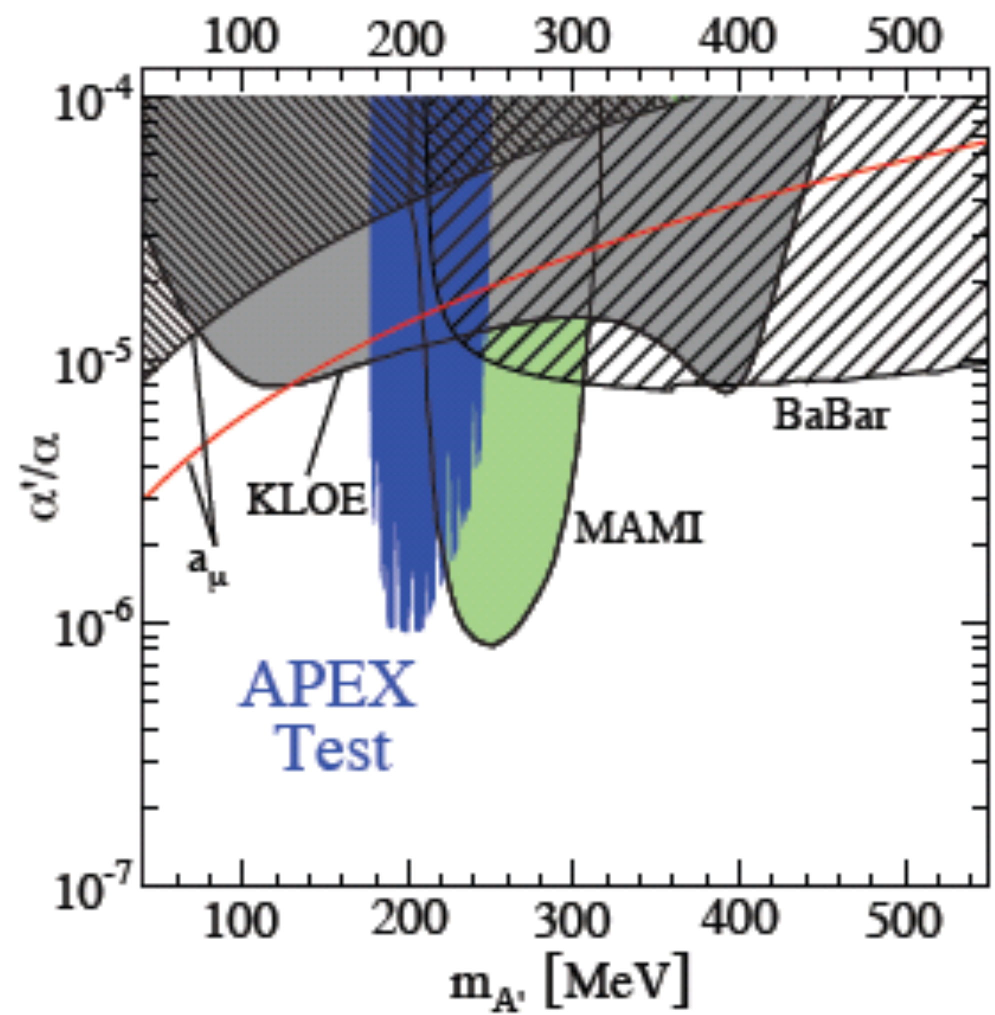
No surprises with antiprotons, but there is seemingly a need for a new source of positrons!

There is a "boost" factor of 100-1000 "needed" for the WIMP interpretation of PAMELA signal. E.g. SUSY neutralinos would not work, because the annihilation cross section is too small. Light dark force rectifies this problem.

Thinking about secluded WIMPs and dark forces have resulted in the brand new research program at the intensity frontier: searches of light (~ few GeV and lighter) mediators using colliders and fixed target experiments.

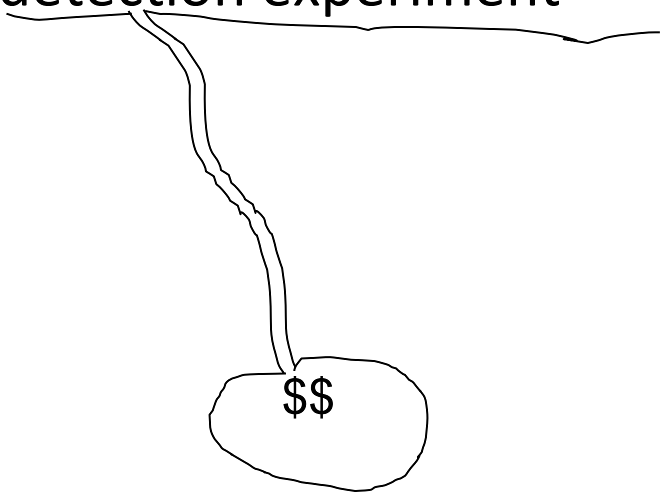
Recently, exclusion limits have become more stringent thanks to Mainz and Jlab experiments.

Such searches are motivated in their own right, independently from the DM theme and will be continued in the future.

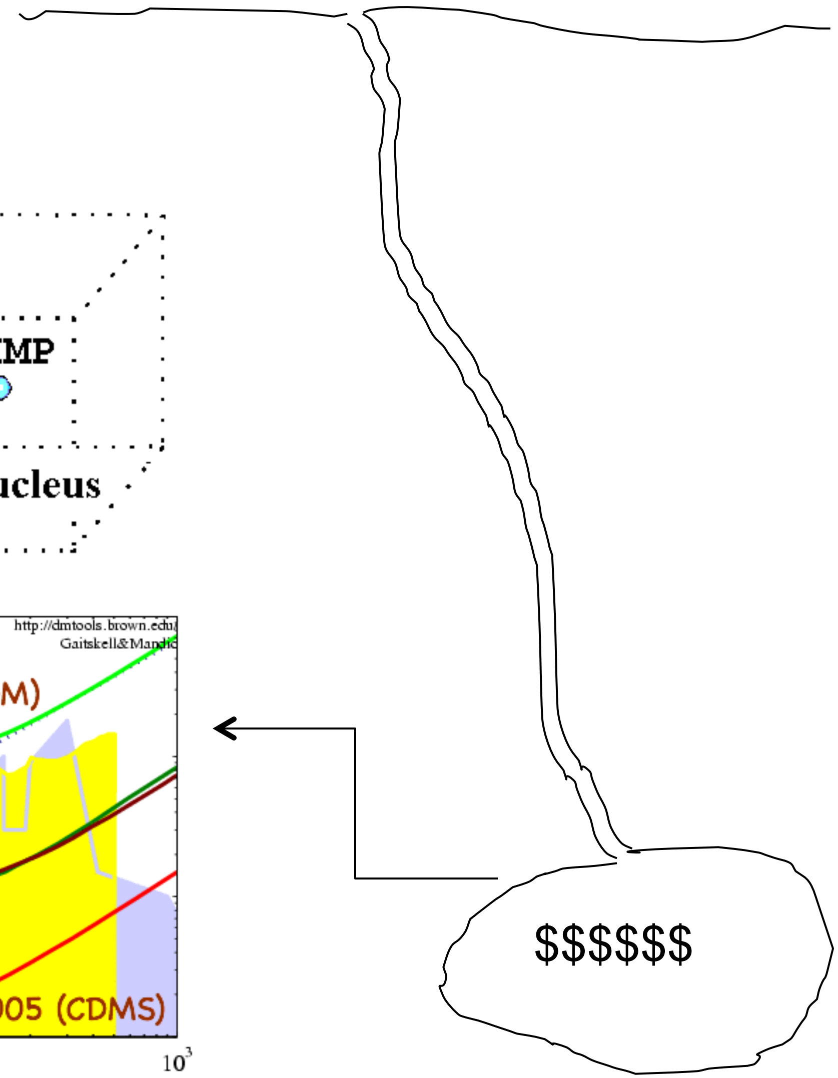


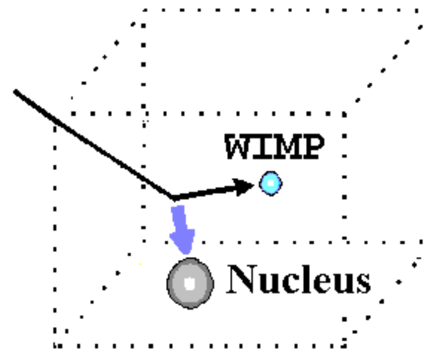
Currently all “direct DM detection” experiments search for the same thing

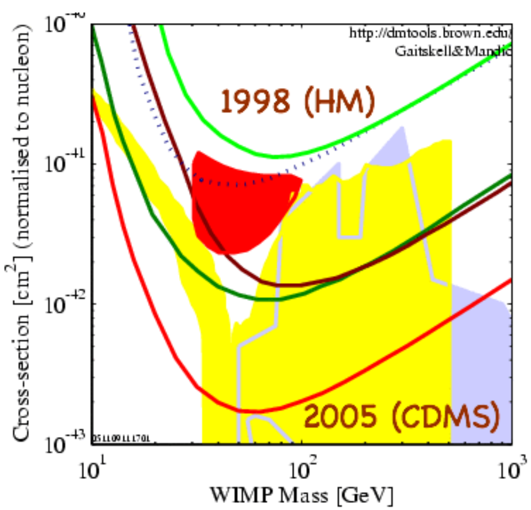
An average Dark Matter detection experiment



A more expensive DM experiment



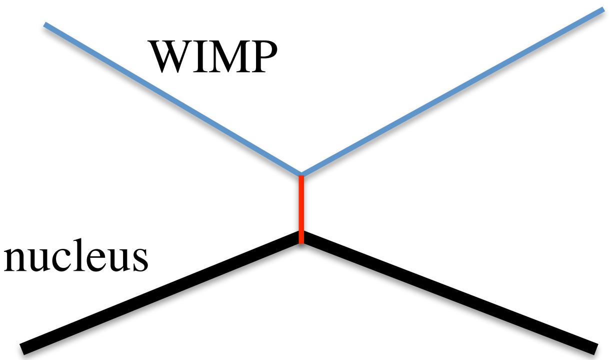




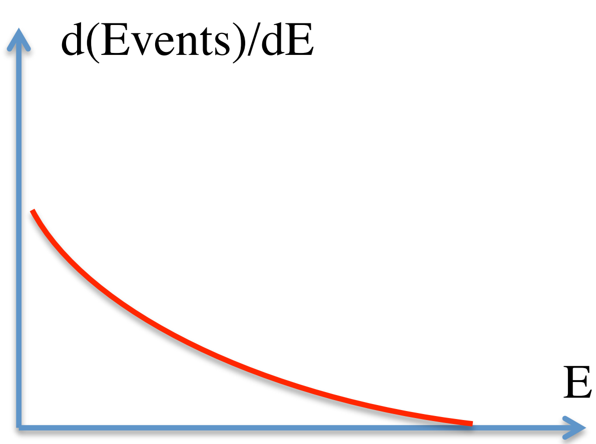
Diversifying physics output of direct detection exp’s is needed !!! (Take a cue from HEP exp’s)

Scattering vs absorption

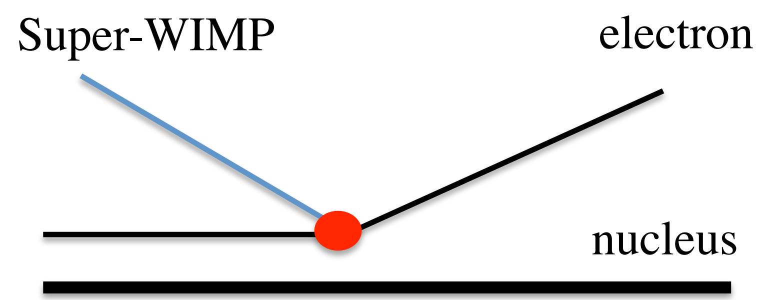
WIMP-nucleus scattering



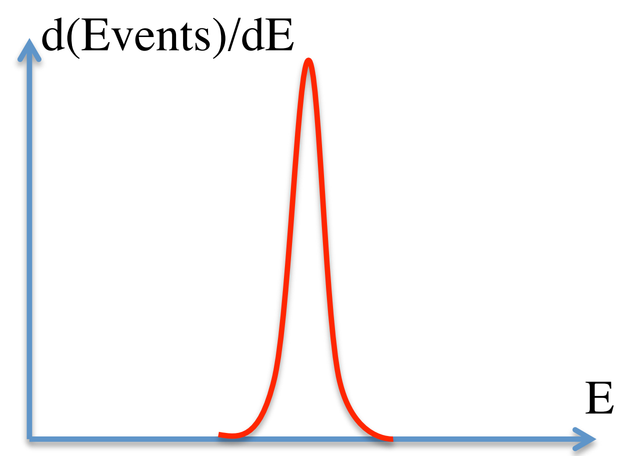
Signal: ionization + phonons/light



Atomic absorption of super-WIMPs

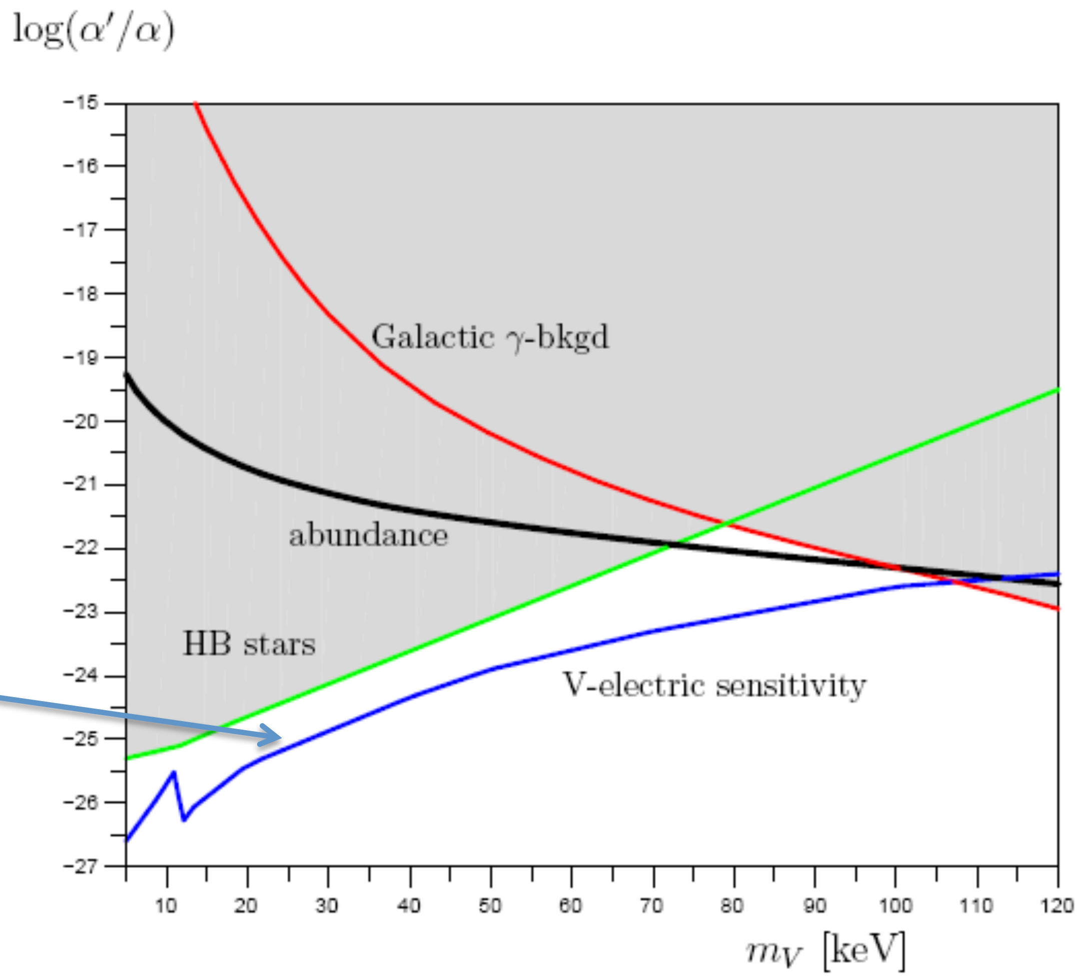


Ionization at $E = m_{superWIMP}$



Absorption of vector DM

Very "approximate", proper Experimental analysis is needed



Direct detection search of Vector super-WIMP is competitive with other constraints. MP, Ritz, Voloshin, 2008.

See also Postma, Redondo, 2008, for the in-depth analysis of the same model.

Axions from the Sun

Sun can emit exotic nearly massless particles (axions, "dark vectors", pico-charge particles etc), which lead to the ionization signal in DM detectors. (F.Avignone et al, from 1980s).

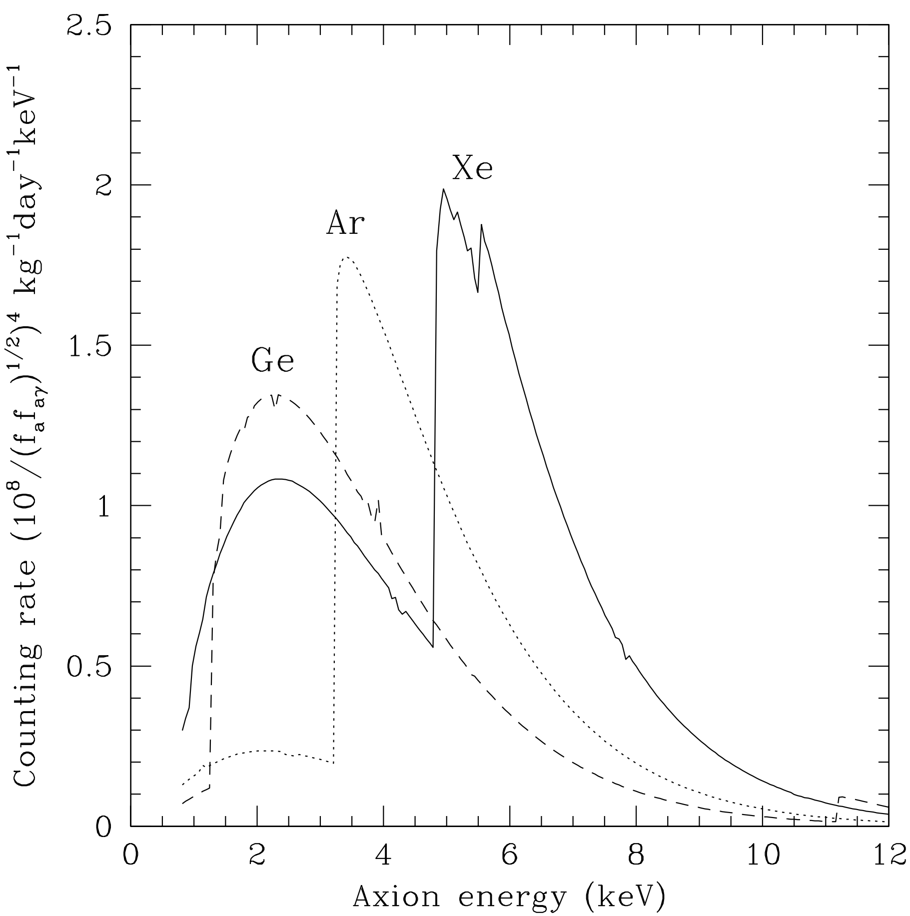


FIG. 4: Counting rate for the axio-electric effect for Ar, Ge and Xe as a function of axion energy.

$$R_{\rm Ar} \simeq 5.0 \left(\frac{10^8 \rm GeV}{(f_a f_{a\gamma})^{1/2}}\right)^4 \rm kg^{-1} day^{-1},$$

$$R_{\rm Ge} \simeq 5.2 \left(\frac{10^8 \rm GeV}{(f_a f_{a\gamma})^{1/2}}\right)^4 \rm kg^{-1} day^{-1},$$

$$R_{\rm Xe} \simeq 8.2 \left(\frac{10^8 \rm GeV}{(f_a f_{a\gamma})^{1/2}}\right)^4 \rm kg^{-1} day^{-1}.$$

Counting rates in the DM detectors can provide sensitivity to axion couplings complementary to e.g. CAST. Derevianko et al, 2010

Emission of other exotic light states and their signals at DM detectors need to be studied

Probing non-standard neutrinos from the Sun with Dark Matter detectors

MP, 2011; Harnik et al, MP, Pradler, 2012

- If there is a 4th neutrino, *sterile under standard EW interactions, but very interactive via new baryonic currents* unexpected phenomenological consequences show up:

1. *Signals at direct Dark Matter detectors at low recoil*
2. New "neutral-current-like" events at fixed targets/neutrino beams
3. New signatures at neutrino detectors
4. ….

The model of "baryonic neutrino"

- Consider a new "neutrino-like" particle coupled to baryonic currents:

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \bar{\nu}_b\gamma_\mu(i\partial_\mu + g_l V_\mu)\,\nu_b + \sum_q \bar{q}(i\not{D}_{SM} + \frac{1}{3}g_b\gamma_\mu V_\mu)q + \mathcal{L}_m.$$

At the nucleon level we have a isosinglet vector current:

$$\frac{1}{3}V_\mu g_b \sum_q \bar{q}\gamma_\mu q \;\to\; g_b V_\mu(\bar{p}\gamma_\mu p + \bar{n}\gamma_\mu n) + \ldots$$

These properties *suppress* standard neutrino signals and *enhance* the elastic recoil. Let us introduce an analogue of Fermi constant:

$$\mathcal{L}_{NCB} = G_B \times \bar{\nu}_b\gamma_\mu\nu_b J_\mu^{(0)}; \quad G_B = \frac{g_l g_b}{m_V^2} \equiv \mathcal{N} \times \frac{10^{-5}}{\mathrm{GeV}^2}.$$

Suppose the masses and mixings are such that some part of the solar ^{8}B neutrinos oscillate into ν_b.

$$P_b(\mathrm{Earth}) \simeq \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]$$

Effective interaction and enhancement of elastic channels

How much signal you would have is given by

Probability of oscillation * interaction strength

$$\mathcal{N}_{\rm eff}^2 = \mathcal{N}^2 \times \frac{1}{2} \times \sin^2(2\theta_b),$$

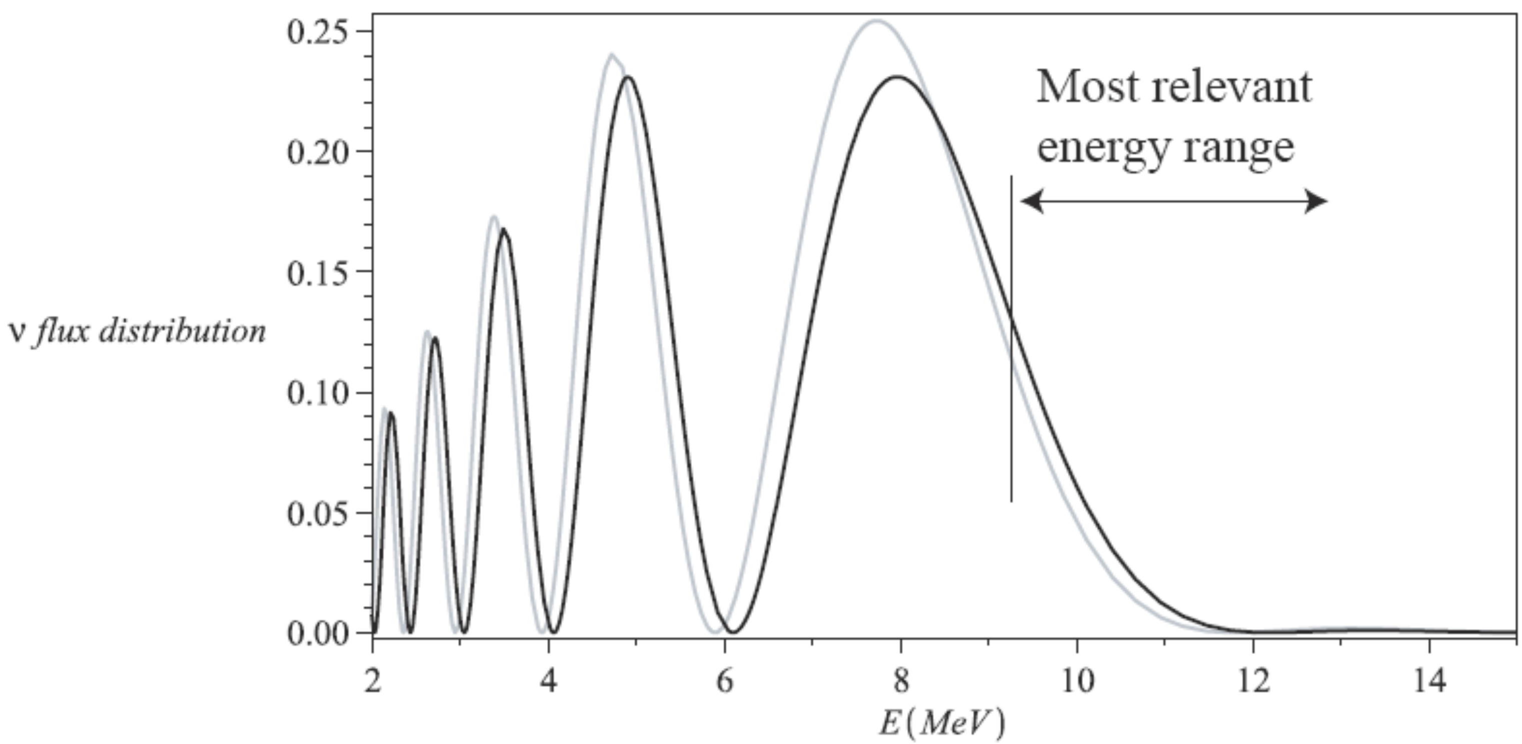
Despite N being very large, say a 100 or a 1000, standard neutrino detectors will have hard time detecting ν_b because nuclear excitations and deuteron breakup due to iso-singlet vector are extremely inefficient

$$\frac{\sigma_{\nu_b-{\rm Nucl}}({\rm elastic})}{\sigma_{\nu_b-{\rm Nucl}}({\rm inelastic})} \sim \frac{A^2}{E_\nu^4 R_N^4} \sim 10^8,$$

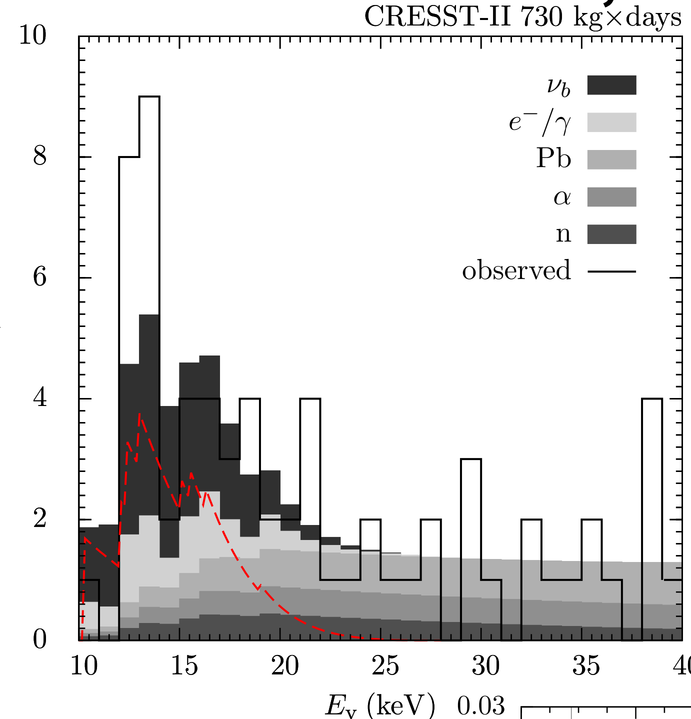
For calculation of the neutron signal at SNO and C(4.4 MeV) signal at Borexino, see, MP, 2011. Large G_B → light-ish mediator

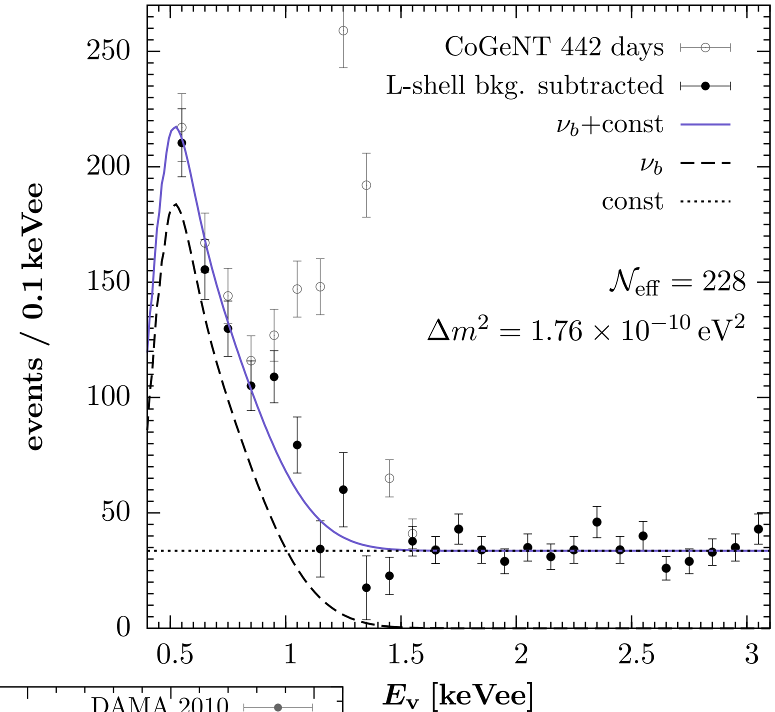
“Just-so” phase reversal

- If oscillation length is comparable to the Earth-Sun distance, the phase can be reversed, and more neutrinos will arrive on the 4^{th} of July. ν_B *Boron-8 neutrino spectrum with “just so” Δm. One can get within one month from DAMA/LIBRA modulation.*

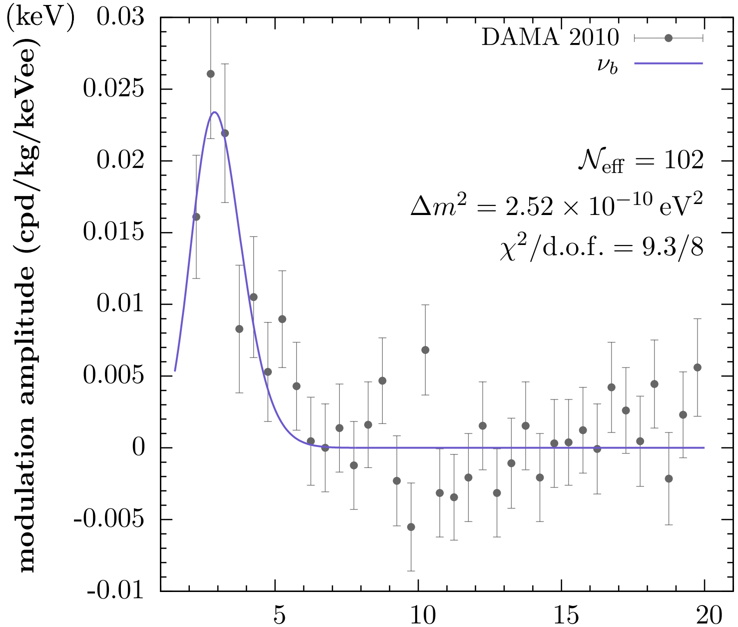


CRESST, CoGeNT, DAMA [amplitude]





In many instances ν_b model is doing as good or better than light DM (except DAMA phase) MP, Pradler



"Baryonic neutrino" is a legitimate piece of new physics that can be searched with exactly the same instruments/types of signal.

Conclusions

1. *Tomorrow [or may be later this year], many models of sub-50 GeV WIMPs that live off SM Higgs mediation and lead to the suppression of the visible Higgs decay modes may end up dead – if the Higgs is discovered.*

2. Secluded models of WIMPs – with the annihilation to metastable mediators with subsequent decay to SM states – decouples annihilation from scattering or collider signals. Light mediators help to "explain" PAMELA etc anomalies by boosting the cross section. Most importantly, thinking of these issues re-ignited experimental interest to searches of "dark forces" at around and below GeV.

3. *Do we get our money worth with direct detection experiments where often the sole focus is σ-m plot? How about axion physics, superweak DM, non-standard solar neutrino signals… The latter can even be entertained as an explanation for various anomalies in direct detection.*