1. Probing non-standard neutrino physics with dark matter detectors

2. Probing non-standard WIMP physics with neutrino detectors

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MP: 2011 paper, PRD.

MP, J. Pradler, 2012, to appear in PRD

See also Harnik, Kopp, Machado , 2012

H. An, MP, Pradler, in progress

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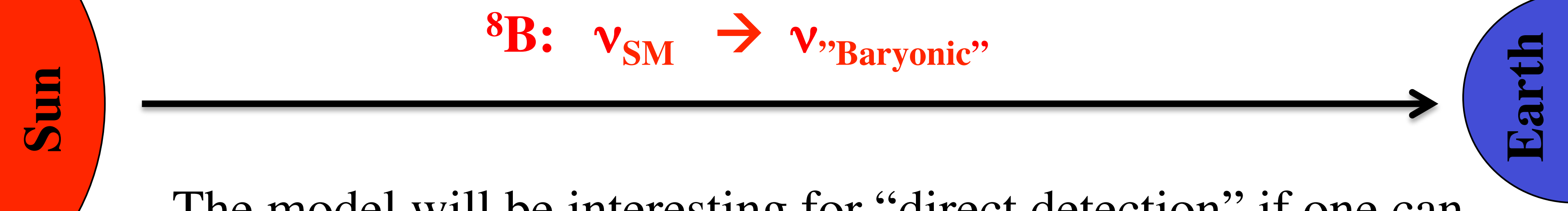
Main idea: **a very long baseline oscillation into a "semi-sterile" neutrino that has no charged current interactions but much enhanced baryon current can produce a light WIMP-like signal and evade other constraints.**

As the extreme case for this idea, imagine that you have a 4th neutrino species, with mixing angle ~1, and $\Delta m^2 = 10^{-26}$ eV^2 with a SM neutrino. Oscillation length for 10 MeV neutrino = Hubble scale, consequence for diffuse SN neutrino background. Does not interact – no chance to ever see it. But what if interacts more strongly than normal ν….?

Main Idea

In recent years a lot of *man*hours* was spent on the discussion of possible signals (keV-scale energy deposition) observed by some "direct DM detection" experiments. 99% of these discussions is inevitably centered around: *is it WIMP or is it background*? Could it be *anything else* that leads to O(keV) scale energy deposition? My answer: it could be different *new physics*, including solar neutrinos

Scattering of ^{8}B neutrinos is very similar in shape to many "DM signals"… but about 10^{-4} from what is "needed". But a new state with stronger-than-weak elastic scattering rate can appear:

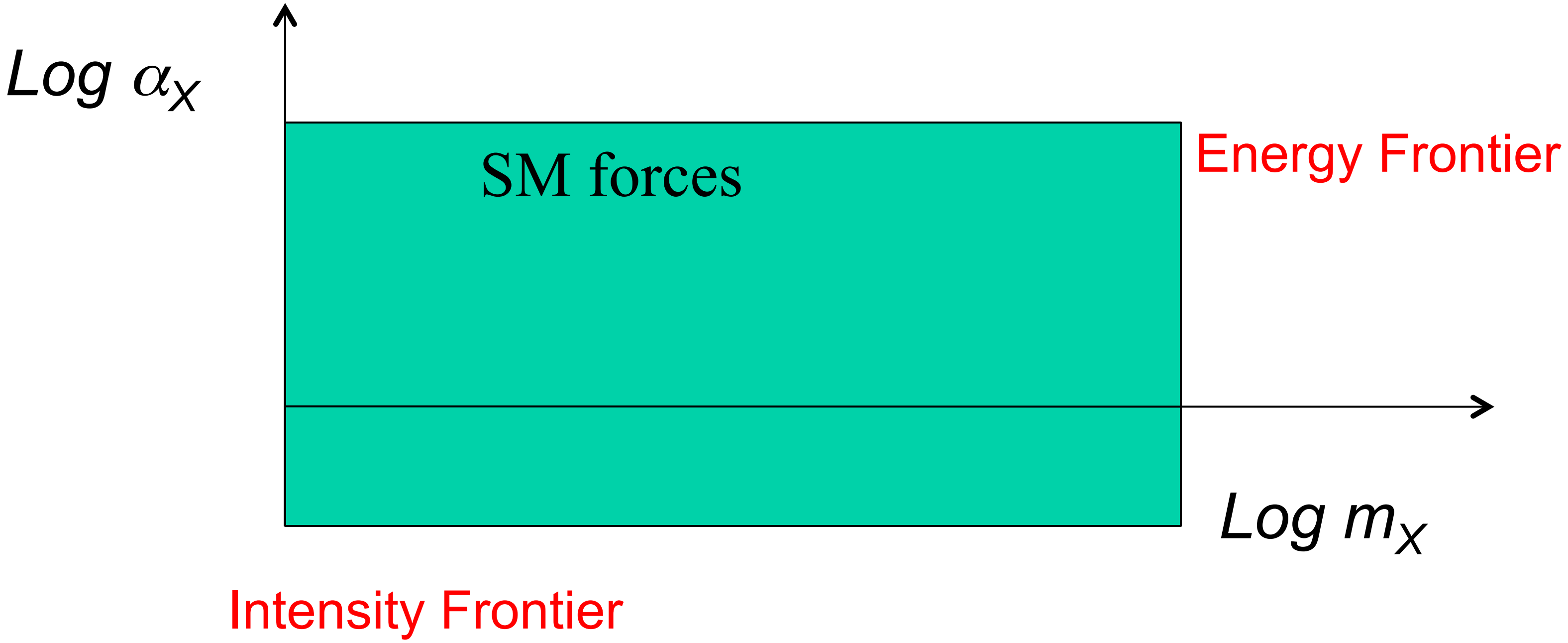


$^8\mathrm{B}$: $\nu_{\mathrm{SM}} \rightarrow \nu_{\text{"Baryonic"}}$

The model will be interesting for "direct detection" if one can

1. Enhance the coherent scattering rate by ~10^4
2. Hide this enhancement from the solar ν experiments.

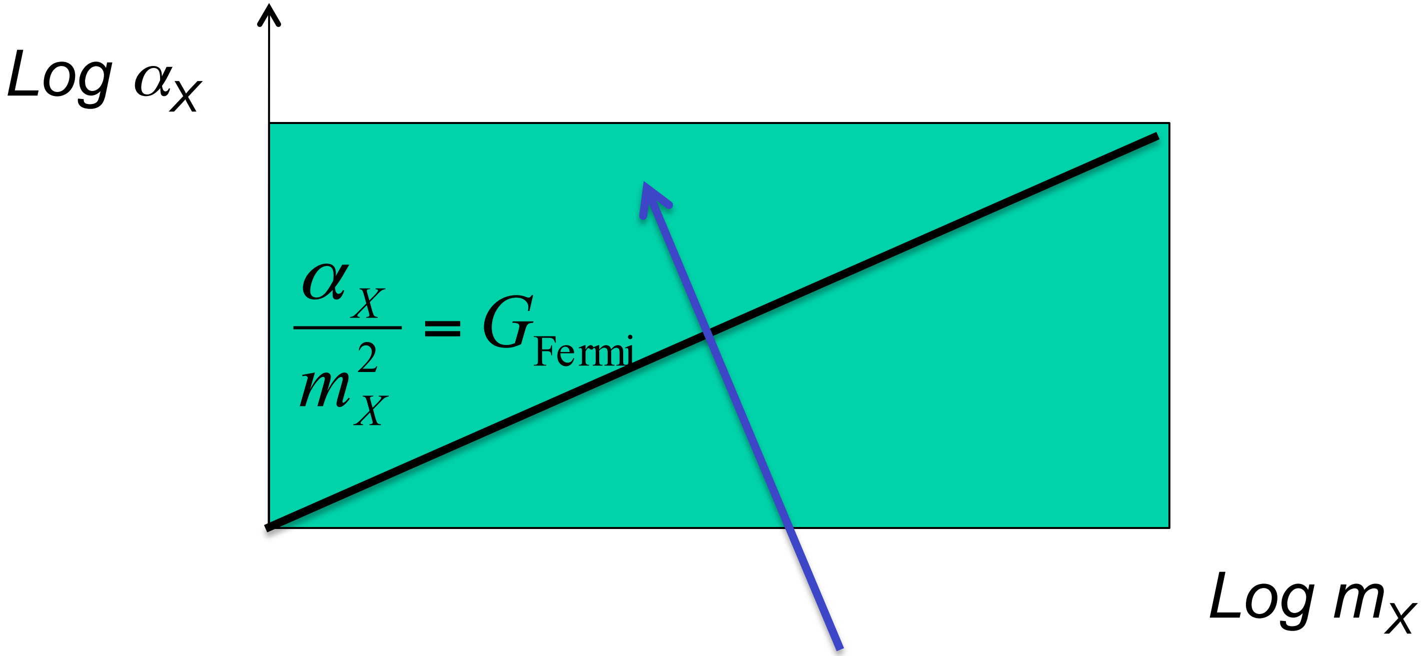
Intensity and Energy Frontiers



$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

LHC can realistically pick up physics with $\alpha_X \sim 1$, and $m_X \sim$ 1TeV, while have no success with $\alpha_X \sim 10^{-6}$, and $m_X \sim$ GeV.

Many models of MeV-GeV New Physics escape LHC *and* flavour constraints.



List of models that can be "stronger than weak"

1. **"Kinetically mixed" vector force.**
2. **Vector forces coupled to baryonic current.**
3. **Some exceptional lepton forces, such as gauged $\mu-\tau$, gauged μ_R, etc.**

The model

- 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:

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

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

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

Comments on the model

- “Stronger-than-weak” force, $N \sim 100$, implies $M_{\mathrm{mediator}} \ll M_Z$. The most safe place to hide it is below 100 MeV, where one can have $g_B \sim (10^{-2}-10^{-3})\,e$. This is not ruled out by any of the existing experiments.

- Neutrino mass is not a problem: one could use the same set of RH neutrinos to [economically] introduce the mass in both sectors,

$$\mathcal{L} = LH\mathbf{Y}N + \nu_{bL}\phi\mathbf{b}N + (h.c.) + \frac{1}{2}N\mathbf{M}_R N.$$

- Kinetic mixing will be developed radiatively, but $\kappa \sim$ loop factor, hence ok with recent constraints.

- The model has gauge anomaly (it is *B*, not *B-L*), but I can cancel it at the weak scale.

Oscillation of Solar neutrinos into ν_b

- Suppose the mass matrix is such that some part of the solar neutrinos oscillate into neutrino_b.

$$\Phi_{^8\mathrm{B}} = (5.69^{+0.173}_{-0.147}) \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}, \quad E_{\mathrm{max},^8\mathrm{B}} = 16.36\,\mathrm{MeV},$$
$$\Phi_{\mathrm{hep}} = (7.93 \pm 0.155) \times 10^3\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}, \quad E_{\mathrm{max,hep}} = 1.88\,\mathrm{MeV}.$$

18.8 MeV

At the Sun location we have ("+" is an appropriate mu-tau neutrino combination that participates in solar neutrino oscillations)

$$P_e(\mathrm{Sun}) \simeq \frac{1}{3}; \quad P_+(\mathrm{Sun}) \simeq \frac{2}{3}; \quad P_b(\mathrm{Sun}) = 0.$$

- At Earth's location one can easily have a more complicated mix:

$$P_b(\mathrm{Earth}) \simeq \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]$$
$$P_e(\mathrm{Earth}) \simeq \frac{1}{3}\left(1 - \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]\right)$$
$$P_+(\mathrm{Earth}) \simeq \frac{2}{3}\left(1 - \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]\right),$$

Elastic scattering signal

- There can be a considerable recoil signal from neutrino_b due to the coherent enhancement, and interaction strength that I took stronger-than-weak:

$$\frac{dR}{dE_r} \simeq \frac{A^2 m_N}{2\pi} \times \frac{1}{2} \sin^2(2\theta_b) G_B^2 \Phi_{sB} \times I(E_r, E_0)$$

$$\simeq 85 \, \frac{\text{recoils}}{\text{day} \times \text{kg} \times \text{KeV}} \times \left(\frac{A}{70}\right)^3 \times \frac{N_{\text{eff}}^2}{10^4} \times I(E_r, E_0).$$

Here $I(E_r)$ is the recoil integral given by

$$I(E_r, E_0) = \int_{E^{\min}(E_r)}^{\infty} dE \, \left(1 - \frac{(E^{\min})^2}{E^2}\right) \times f_{sB}(E) \times 2\sin^2\left[\frac{\pi E_0}{E}\right]$$

Effective interaction and enhancement of elastic channels

How much signal you would have is given by

Probability of oscillation * interaction strength

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

Despite N being very large, say a 100 or a 1000, standard neutrino detectors will have hard time detecting neutrino$_b$ because

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

The last formula is especially important because it allows to "hide" the enhancement of the elastic scattering from the dedicated neutrino experiments.

Signals of ν_b in "conventional" neutrino detectors

- Consider for example the deuteron breakup reaction, or Carbon excitation with subsequent energy release:

$$\begin{aligned} d+\nu_b &\rightarrow \nu_b+n+p \\ {}^{12}\mathrm{C}+\nu_b &\rightarrow \nu_b+{}^{12}\mathrm{C}^*(4.44\ \mathrm{MeV})\rightarrow \nu_b+{}^{12}\mathrm{C}+\gamma \end{aligned}$$

Because of the properties of baryonic currents the hadronic amplitude is quadratic in neutrino energy, and the signal is quartic:

$$\langle d|\exp(i\mathbf{q}\mathbf{r}^{(n)})+\exp(i\mathbf{q}\mathbf{r}^{(p)})|np\rangle$$

$$=2\langle d|np\rangle+i\mathbf{q}\cdot\langle d|\mathbf{r}^{(n)}+\mathbf{r}^{(p)}|np\rangle-\frac{q_kq_l}{2}\langle d|r_k^{(n)}r_l^{(n)}+r_k^{(p)}r_l^{(p)}|np\rangle=-\frac{q_kq_l}{4}\langle d|r_kr_l|np\rangle$$

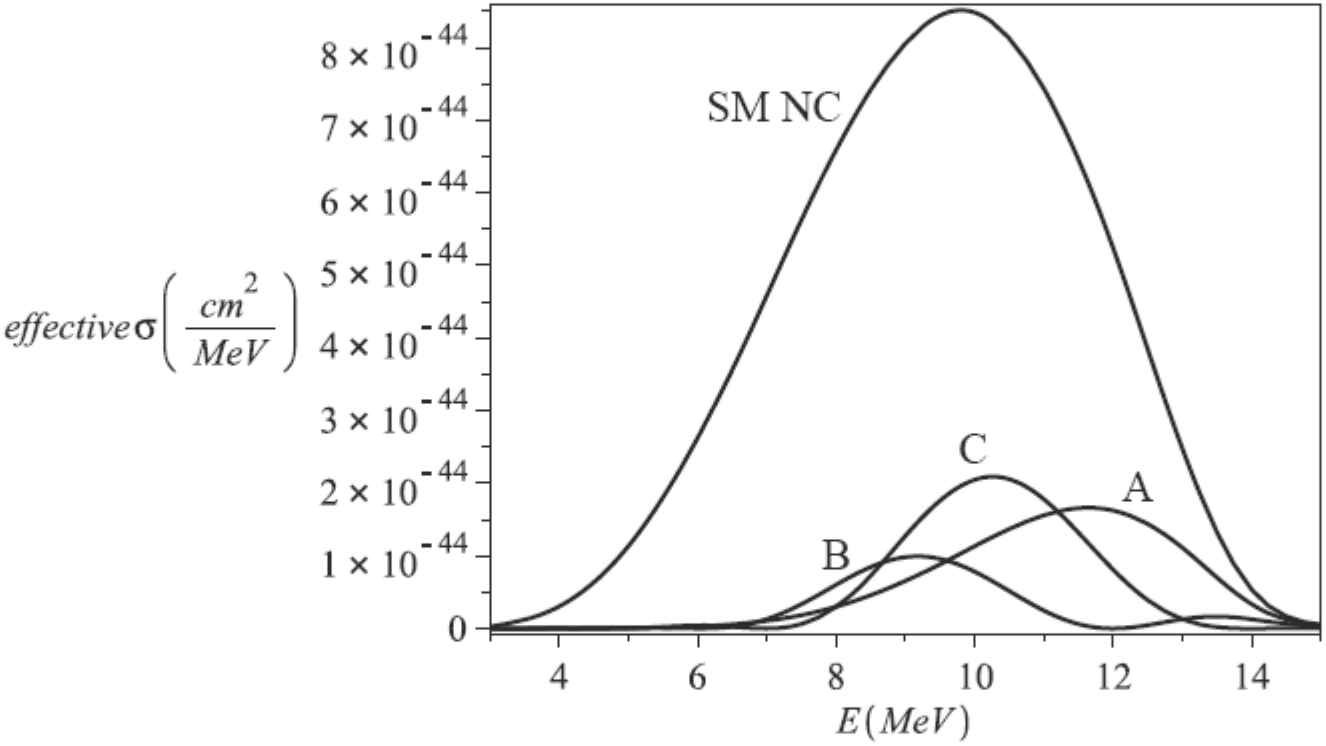
Importance of different couplings for elastic and inelastic scattering

coupling	Inelastic scattering	Elastic scattering
Isosinglet vector g_V^0	4 (looser)	1 (winner)
Isovector vector g_V^1	2-3	2
Isosinglet axial g_A^0	2-3	3-4
Isovector axial g_A^1	1 (winner)	3-4

If in SM iso-vector axial coupling would have been zero, there could not have been any SNO NC signal.

Inelastic processes are suppressed

- Even if coupling^2 is enhanced by 10000, the NCB process is just about 10% of the SM NC process at SNO (A,B,C are different choices of Δm^2)



Counting rate at BOREXINO

Counting rate at BOREXINO is not going to be very large either

$$R(4.4\ \mathrm{MeV}) \sim (0.05 - 0.15) \times \frac{\gamma\ \mathrm{injections}}{100\ \mathrm{tons} \times \mathrm{day}} \times \frac{\mathcal{N}_{\mathrm{eff}}^2}{10^4}.$$

Small signal but comparable to Boron8 SM neutrino ES.

P.S. the analysis of 4.4 MeV signature can be done by the

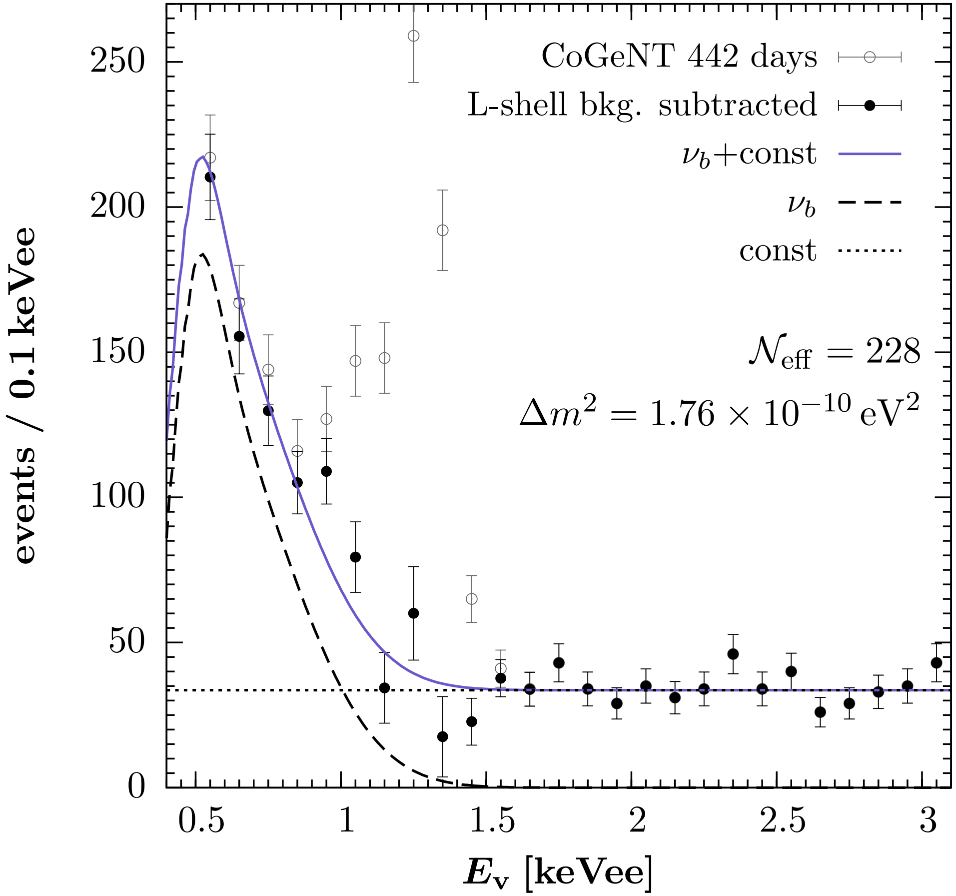
Borexino collaboration, as they know very well how it should look like (this line induced by neutron scattering is used in some calibration methods).

General comment about elastic scattering signal

- *Very similar to sub-10 GeV scale WIMPs.*
- Somewhat softer at the highest recoil, hence “safer” from strong Xe, Ge CDMS etc constraints where threshold is higher
- Has a chance of “explaining CoGeNT and/or CRESST signals”. Can be a correct magnitude and not too bad a spectral shape.
- Will show difference with the low-mass WIMPs if a lighter target (e.g. He) is used. Neutrinos will give more recoil on He, while WIMPs will give less.
- What about “DAMA modulation signal”? Last time we checked the Sun was closer to Earth in January – hence anti-modulation compared to DAMA. However, neutrino oscillation is a quantum [=nonmonotonic] phenomenon, and one can have a phase reversal.

Recoil in Germanium detectors: CoGeNT, CDMS

MP, J. Pradler, 2012

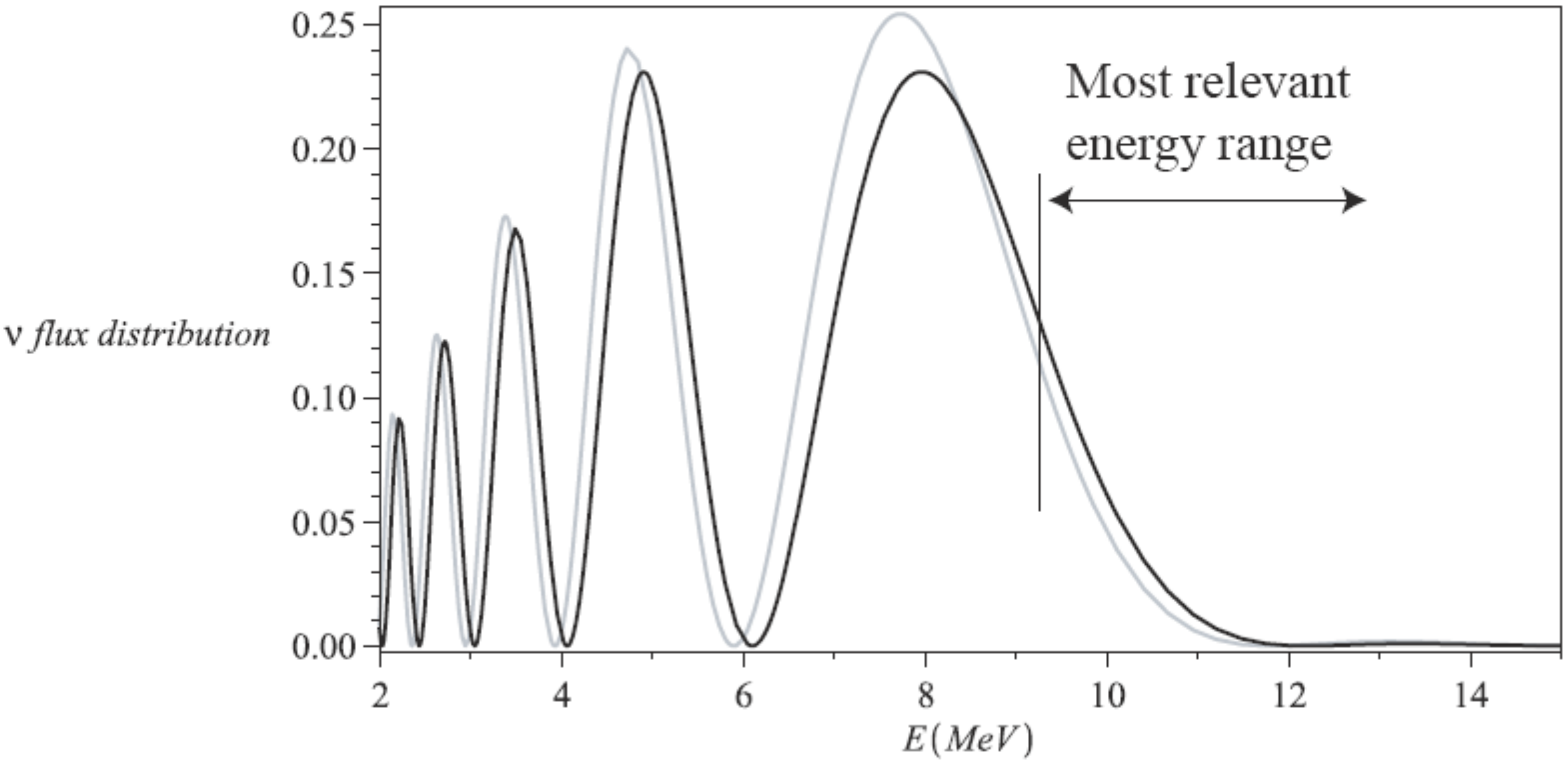


1. *You can put the model line through CoGeNT dots*. Probably not advisable as we learn that most of it [all of it?] is likely background

2. CDMS does not kill the "ν_b explanation" of CoGeNT

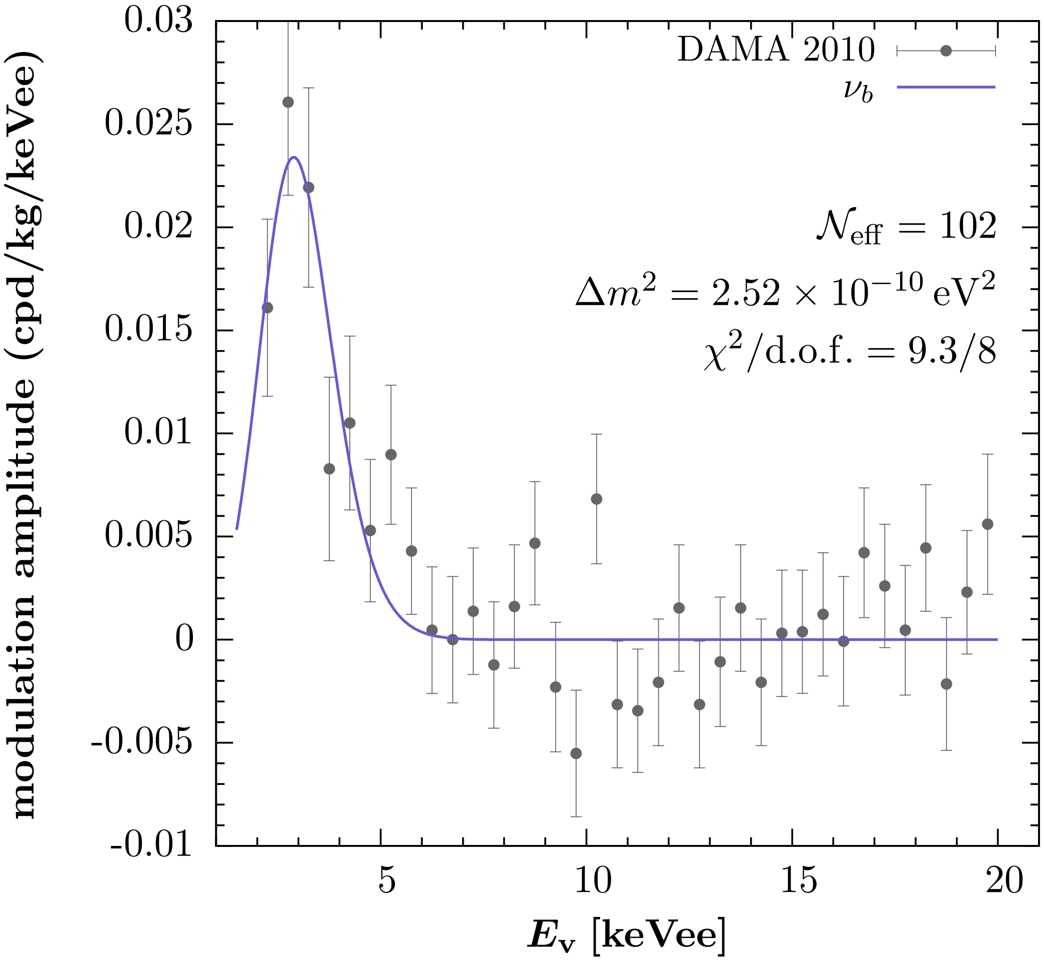
DAMA and "Just-So" phase reversal

- If oscillation length is comparable to the Earth-Sun distance, the phase can be reversed, and more neutrinos will arrive in July

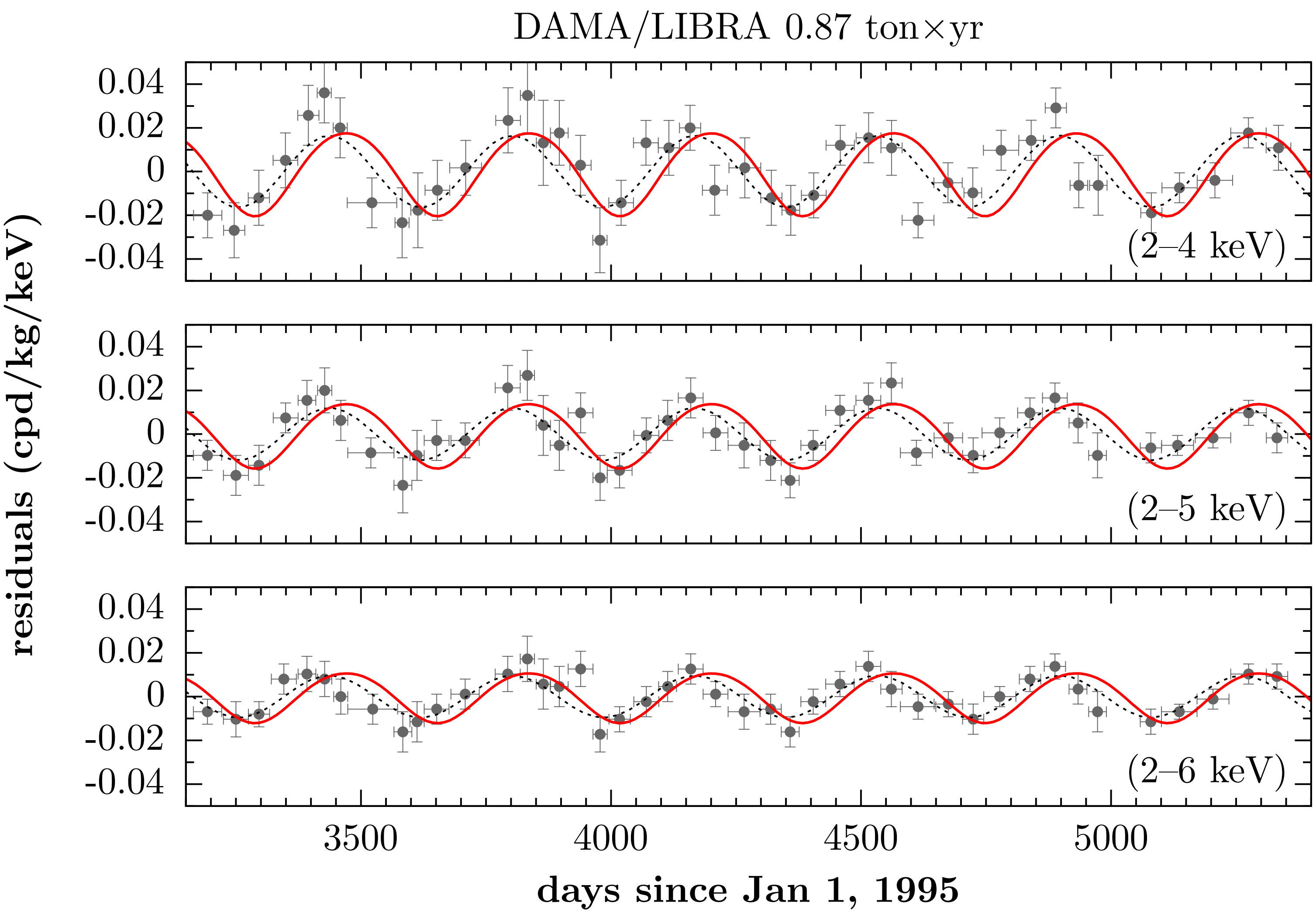


Fitting DAMA modulation amplitude

- Neglecting the phase offset of ~ 1 month, the fit of the ν_b model to DAMA modulation amplitude can be pretty decent. (Needless to say it is the scattering on Na)



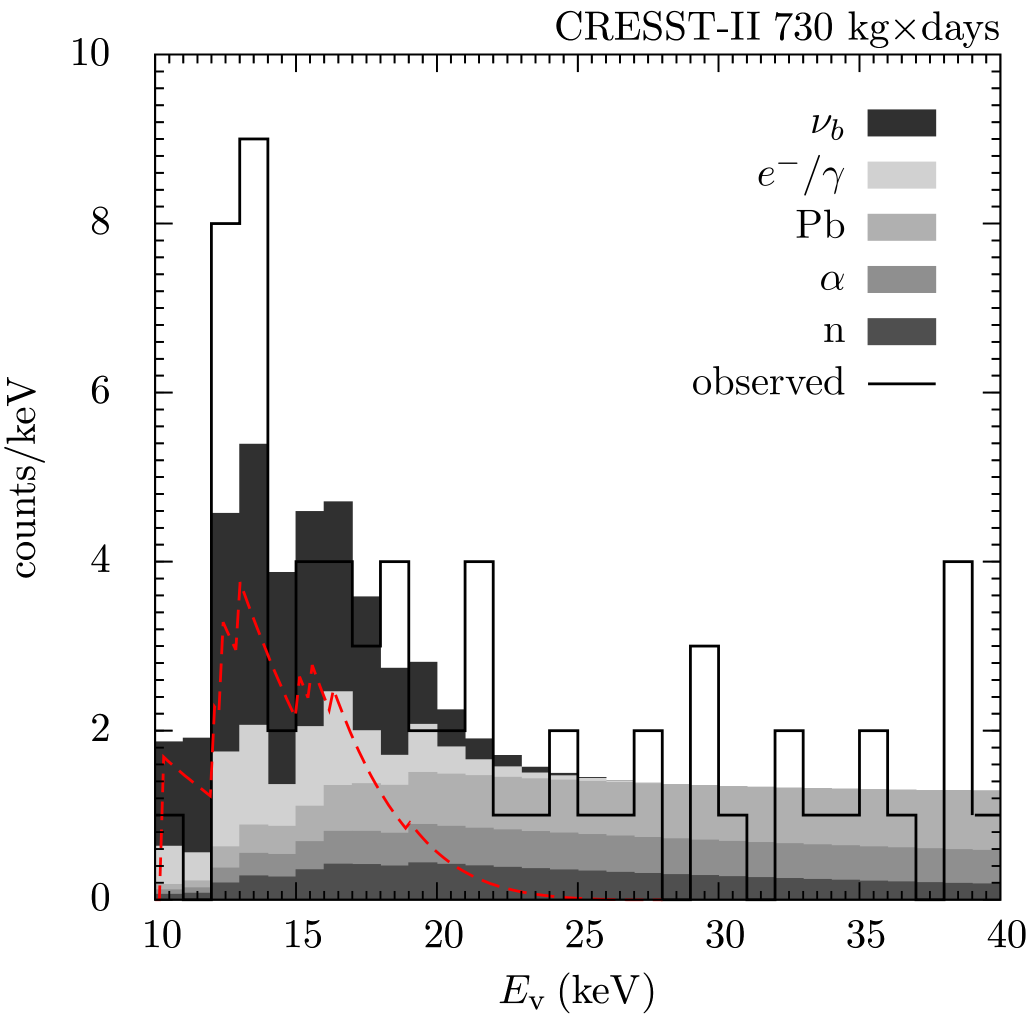
…But *July* is not *June*… The phase is off



It is formally ~5σ away from the DAMA phase.

NB: Similarly DAMA explanation by muons is also a bad fit, Chang, Pradler, Yavin

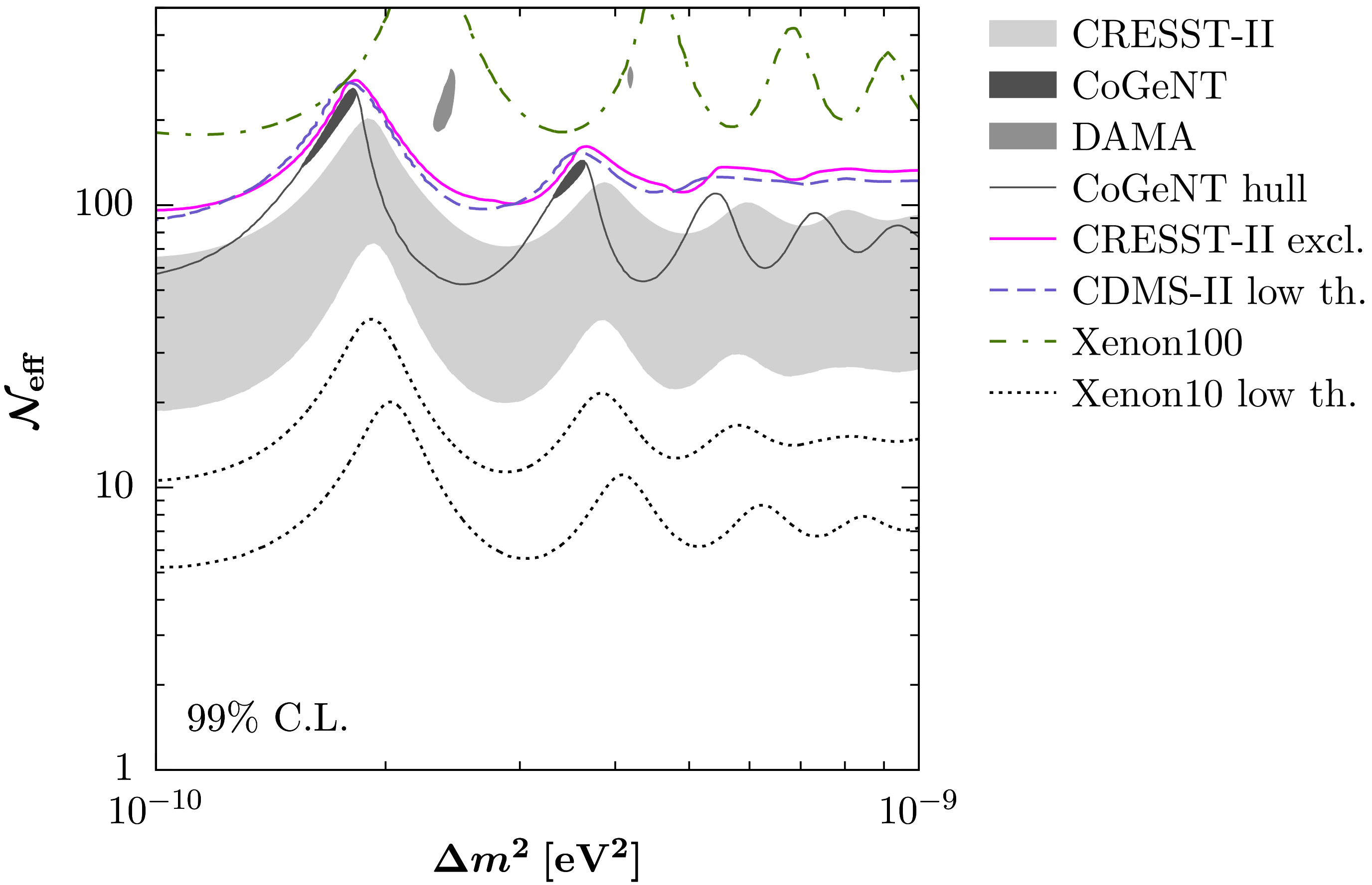
CRESST fit is not too bad…



Prefers slightly smaller N_{eff}

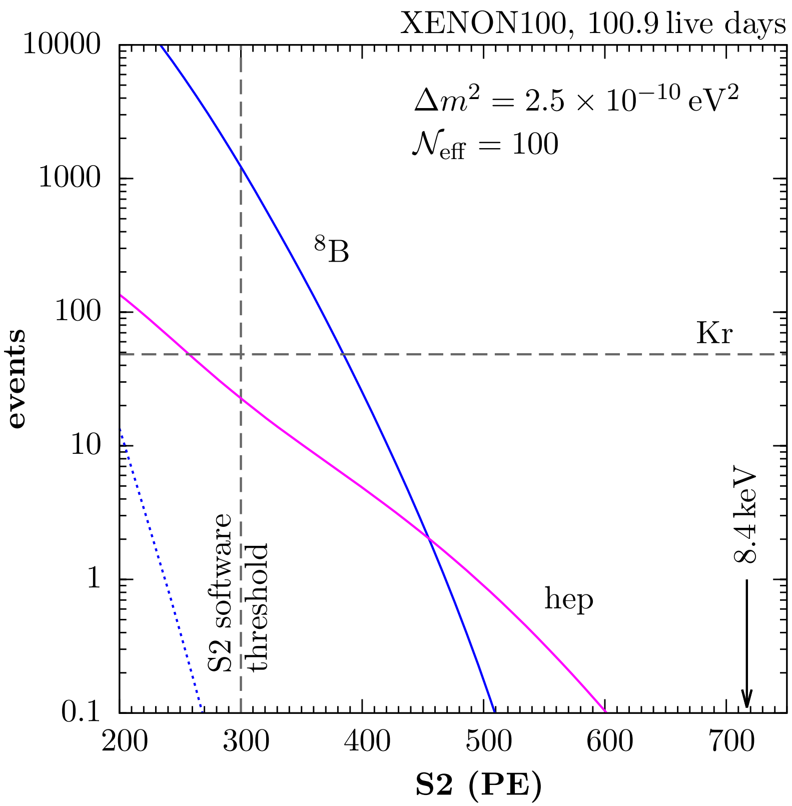
$$\text{CRESST-II:} \quad \Delta m_b^2 = 3 \times 10^{-10}\,\text{eV}^2, \quad \mathcal{N}_{\text{eff}} = 49, \quad \chi^2/n_d = 27.7/27,$$

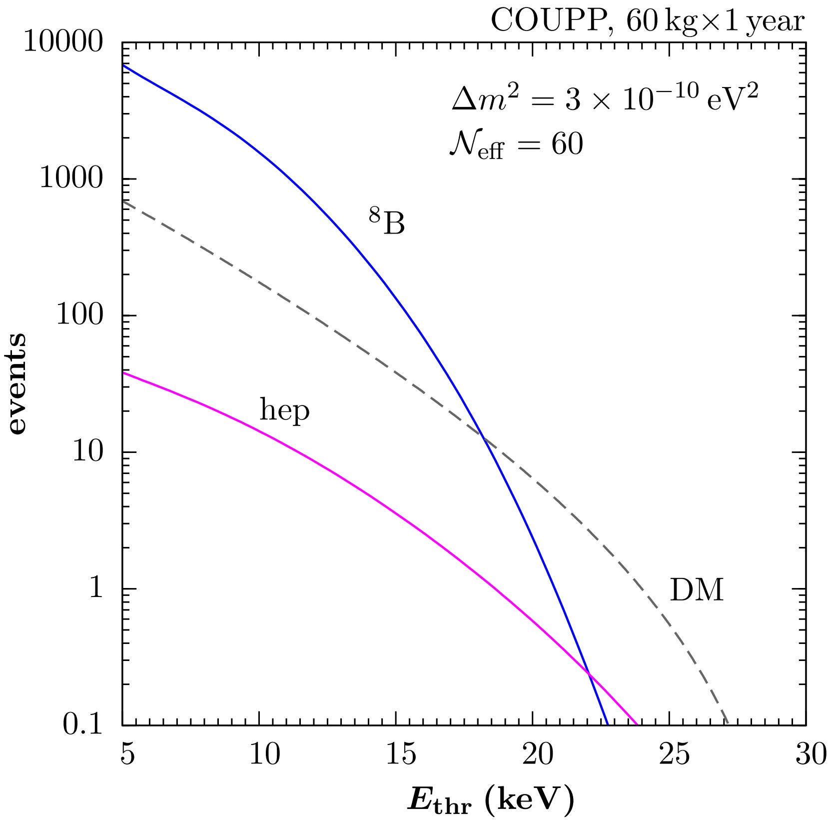
Putting things together on N_{eff}-Δm^2 plot



Strongest constraints on N_{eff} are from Xenon-10 ionization-only analysis – but it is the most uncertain as well. All-in-all the model is not doing much "worse" than 10-GeV WIMPs…

Future? Xenon-100 low threshold and COUPP





The model is more predictive than WIMPs. You cannot change spectral profile much, or modify interactions to n/p at will. If it is nature's choice, ν_b model with Neff ~ O(100) will be seen soon.

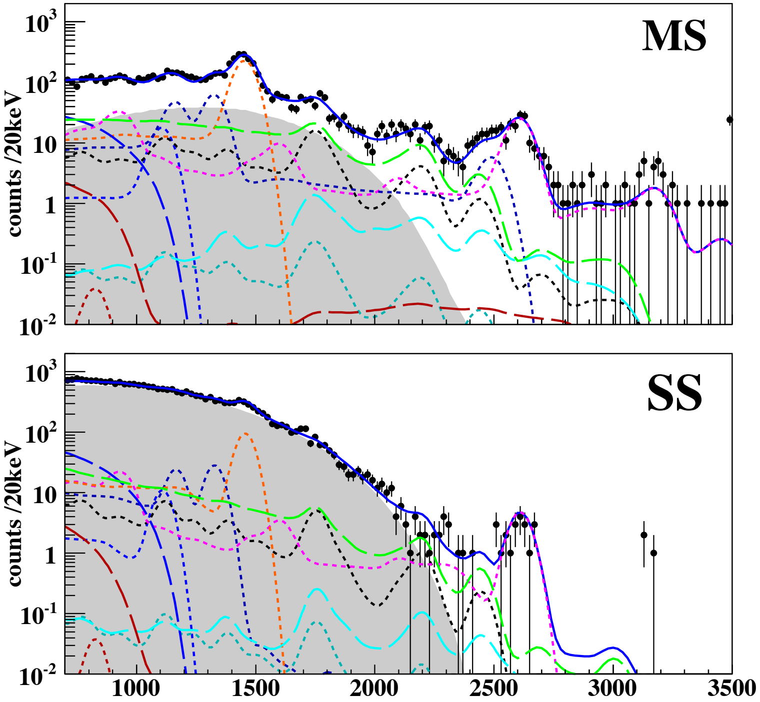
Possible avenues to search for neutrino_b and new baryonic currents

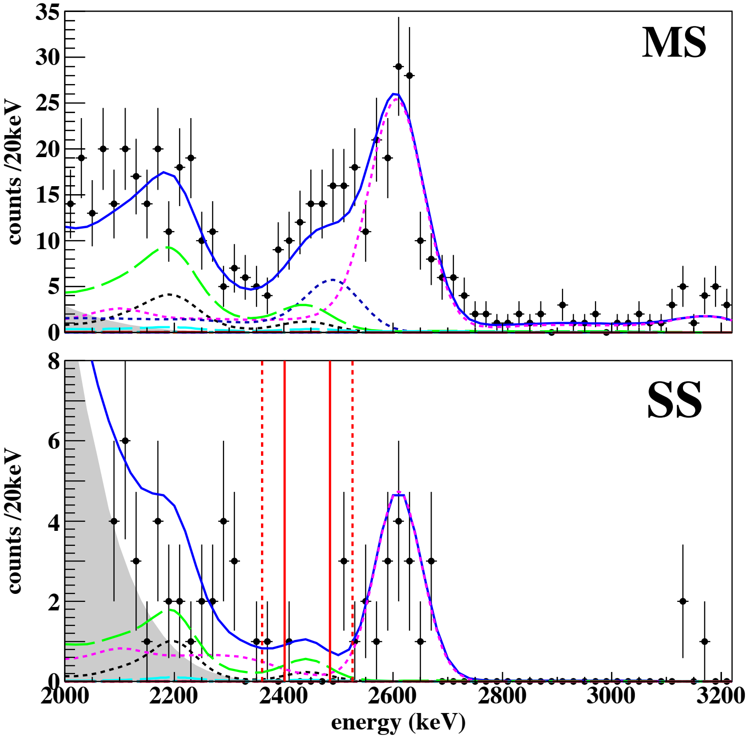
- *Hadron colliders*: If G_B/G_F is fixed at a 100 or so, Tevatron experiments will produce an *upper* bound on vector mass.
- *Neutrino oscillations*: Matter effects for (anti)neutrino_b can be significant. In light of latest developments in neutrino physics, the 4th one may not be an unwelcome addition.
- *Neutrino beams*: Ample opportunities to produce neutrino_b in hadronic cascades (T2K, MiniBoone type of experiments) and detect them using the "NC-like" scattering on nucleons in near detectors. Similar to *light DM beam* idea
- *Cosmology*: a departure from N_neutrino = 3 is expected. Better CMB probes are forthcoming.
- *Rare decays*: New precision tests of K-> pi nu nu may detect extra energy sinks.

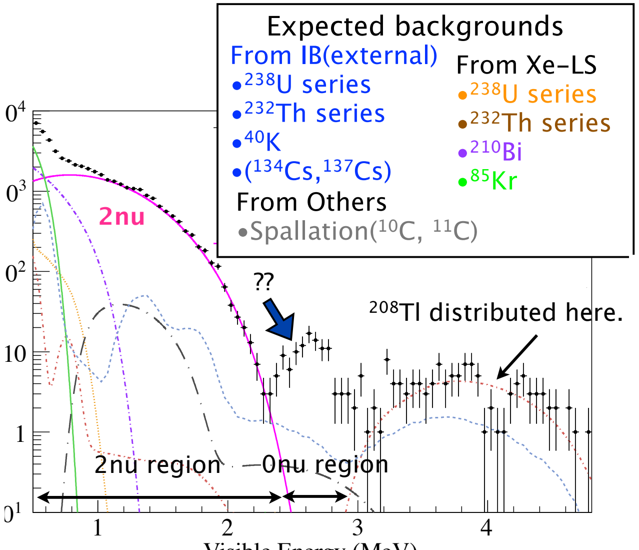
Conclusions

- A lot of work has been done on active → sterile neutrino oscillations. What about "semi-sterile", when new states have stronger-than-SM interactions in neutral channels?
- I have presented a model that takes solar neutrinos and transforms them into "baryonic neutrinos" – those that have much stronger coupling to baryon current than the SM ν's.
- In this model "little guys" (= "DM" experiments) can compete and surpass in sensitivity the "big guys" (= neutrino experiments). Many DM anomalies can be explained within this model if the enhancement of interaction amplitude relative to SM is O(100). (~1 month discrepancy with DAMA phase will remain). The signal is reminiscent of ~10 GeV WIMPs but is far more predictive.

Part II: new pieces of data in ν-physics





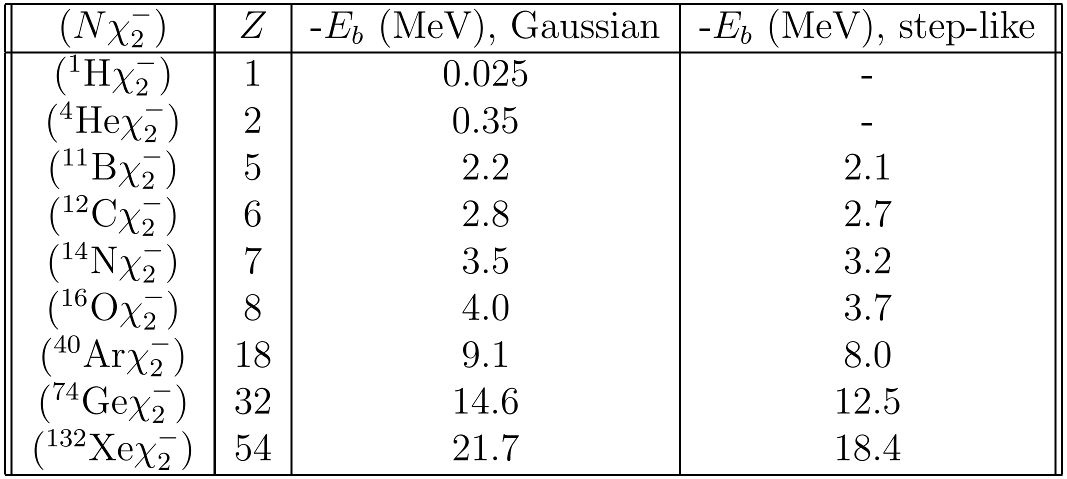


First time there is a wide energy coverage of energy release in ^{136}Xe. This allows to study/set constraints on Dark Matter sector where the neutral states are accompanied by excited charged states.

WIMP-nucleus “recombination”

- Quasi-degenerate χ^0-$\chi^\pm$ WIMP particles with Δm in ~ MeV range. New signatures due to χ-nucleus binding, MP, Ritz (2008).

Charged particles are unstable in vacuum but can be stable when attached to a nucleus depending on mass splitting.



$(N\chi_2^-)$	Z	-E_b (MeV), Gaussian	-E_b (MeV), step-like
$(^1\mathrm{H}\chi_2^-)$	1	0.025	-
$(^4\mathrm{He}\chi_2^-)$	2	0.35	-
$(^{11}\mathrm{B}\chi_2^-)$	5	2.2	2.1
$(^{12}\mathrm{C}\chi_2^-)$	6	2.8	2.7
$(^{14}\mathrm{N}\chi_2^-)$	7	3.5	3.2
$(^{16}\mathrm{O}\chi_2^-)$	8	4.0	3.7
$(^{40}\mathrm{Ar}\chi_2^-)$	18	9.1	8.0
$(^{74}\mathrm{Ge}\chi_2^-)$	32	14.6	12.5
$(^{132}\mathrm{Xe}\chi_2^-)$	54	21.7	18.4

Table 1: Estimates for the binding energies of the state $(N\chi_2^-)$ assuming a gaussian and step-like nuclear charge distribution for several relevant elements.

If Δm < 18 MeV, there will be a signature of “recombination” with ^{136}Xe

Different spin: $\chi_1^0 + N \rightarrow (N\chi_2^-) + e^+$

Same spin: $\chi_1^0 + N^{(Z)} \rightarrow (N^{(Z+1)}\chi_2^-)^* \rightarrow (N^{(Z+1)}\chi_2^-) + (\gamma, n, \ldots).$

Application to simplest case

- Consider $\chi_1^0 + N \to (N\chi_2^-) + e^+$ caused by $\mathcal{L} = g\chi_1\bar{e}\chi_2^- + \text{h.c.}$

The rate can be calculated almost exactly, but here is the parametric estimate for Δm ~10 MeV "recombining" on ^{136}Xe:

$$\sigma v \sim 0.1\, g^2\, (Z\,\alpha)^2\, R_N/m_\chi \sim g^2\, (TeV/m_\chi)\, 10^{-21}\, cm^3\, /\, sec$$

Current experimental sensitivity of EXO-200 above 2.6 MeV is better than ~ O(20) counts/(10^4 kg days) → $\sigma v < 10^{-29}\, cm^3 / sec\, (m_\chi/TeV)$.
This leads to the conclusion that $g^2 < 10^{-8}\, (m_\chi/TeV)^2$, or translating it to the lifetime of a sub-TeV free $\chi^\pm$ particle, one gets
$\tau > 2\,\pi\, m_\chi /\, \Delta m^2/g^2 > 10^{-8}$ *seconds*

Stable enough to create charged tracks at LHC detectors.

Conclusion: EXO-200 data have sensitivity to DM models that are otherwise very difficult for collider/elastic scattering DM detection.