Semi-sterile neutrinos
+ some other fun stuff

Maxim Pospelov

University of Victoria/Perimeter Institute, Waterloo

MP: 2011, PRD.

MP, J. Pradler, 2012, PRD

See also Harnik, Kopp, Machado, 2012

H. An, MP, Pradler, 2012

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. Introduction. Semi-sterile neutrinos = sterile neutrinos + an extra force not present in the SM. Is there a place for "stronger-than-weak" forces? Kinetic mixing and baryon current portals.
2. New light ν states coupled via baryonic portal.
3. WIMP-like recoil, and inelastic scattering.
4. Specific signatures at CoGeNT, CRESST, DAMA, XENON

5. Non-standard WIMPs. Constraints on their charged excitations using double-beta decay experiments.
6. Conclusions

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.**

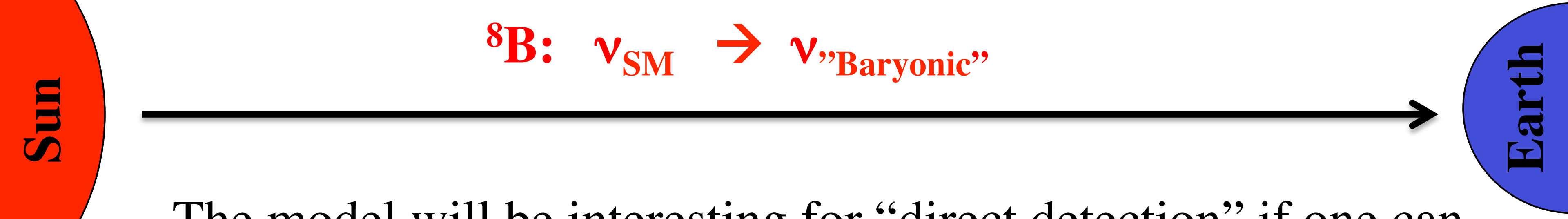
This is an example of **Neutrino oscillation portal.** (Papers by A. Nelson and collaborators from a ~ few years ago.)

As the extreme case for this idea, imagine that you have a 4th neutrino species, with mixing angle ~1, and $\Delta m^2 = 10^{-26}\ \mathrm{eV}^2$ 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

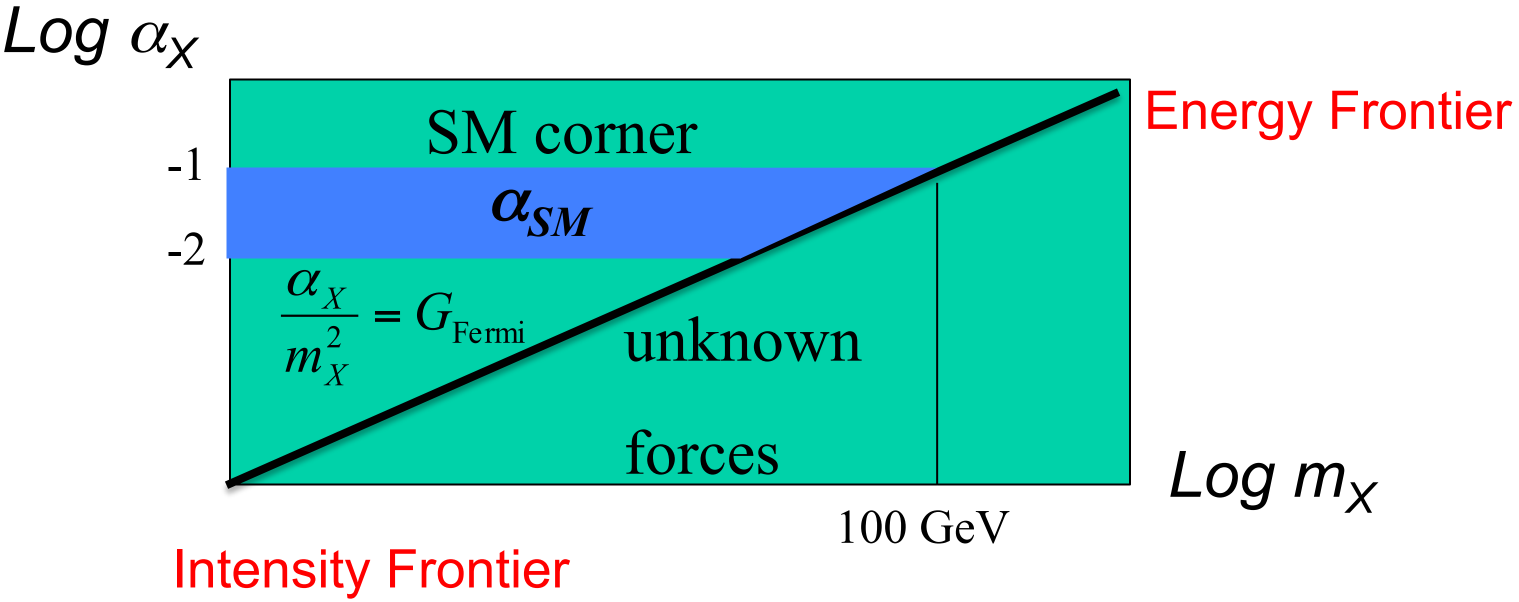
Scattering of ^{8}B neutrinos is very similar in shape to many "DM signals"… but about 10^{-4} from what is "needed". But a new state with stronger-than-weak elastic scattering rate can appear:


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

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.

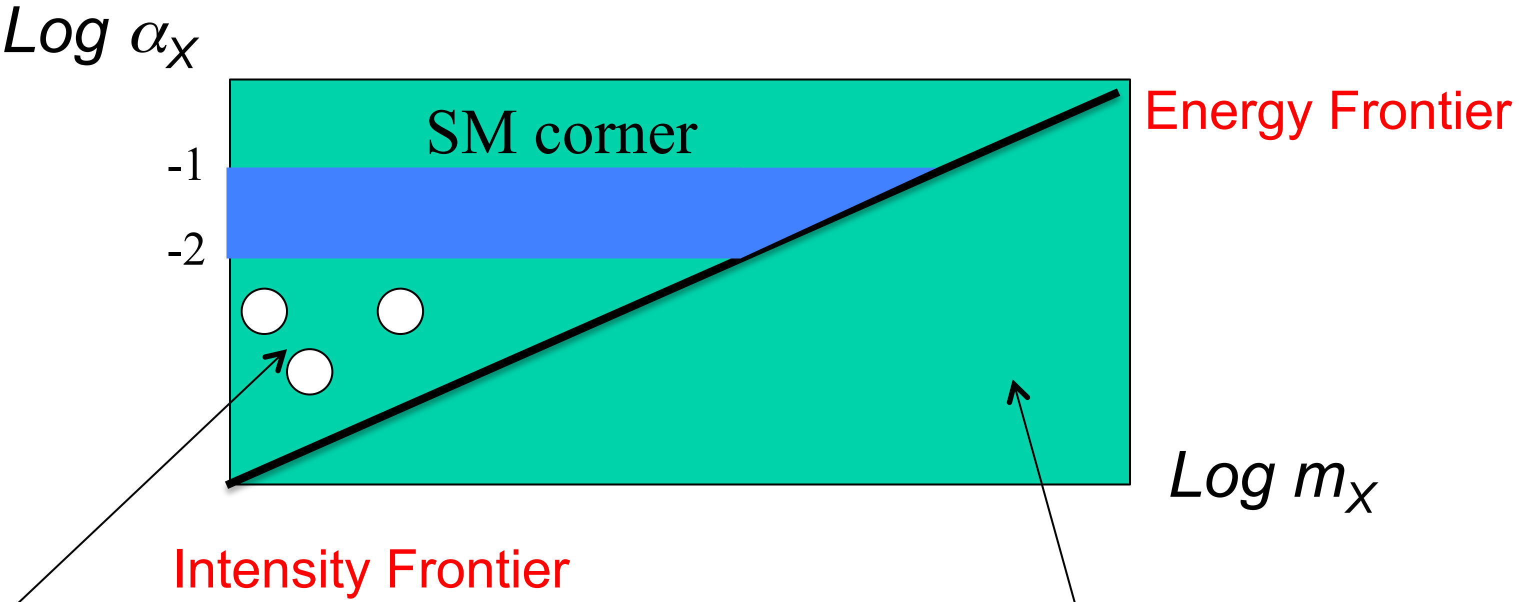
Intensity and Energy Frontiers



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

LHC can realistically pick up New Physics with $\alpha_X \sim \alpha_{SM}$, and $m_X \sim$ 1TeV, while having no success with $\alpha_X < 10^{-6}$, and $m_X \sim$ GeV.

Not everything is known about SM corner



If you see new effects like e.g. $\mu \to eee$, it’ll be here (can be 1000 TeV or so, no real way to find out, and no pressing need for UV completion)

We are going to discuss some models where the interaction strength is above the SM Fermi-strength force. Is it possible for neutrinos? (Kinetically mixed dark photon, B-L force are no good)

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:

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

Comments on the model

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

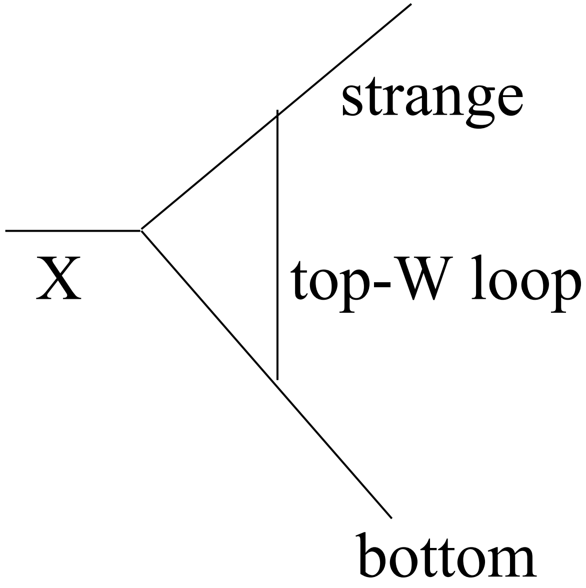
- Neutrino mass is not a problem: one could use the same set of RH neutrinos to [economically] introduce the mass in both sectors,

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

- Kinetic mixing will be developed radiatively, but κ ~ 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. I can leave it a-la Stuckelberg, and given a ~ 10 TeV cutoff, the tuning of m_V will be less than in the $\mathrm{Higgs}_{\mathrm{SM}}$

Why baryonic or EM currents are “safe” from flavor constraints

Conserved vector currents are uniquely positioned to avoid very strong flavor constraints . Axial vector portals, Higgs portals are potentially liable to very strong flavor constraints. Consider generic FCNC penguin-type loop correction.



For vector current, $G_F\, q^2$

For axial vector current, $G_F\, m_t^2$

There is extremely strong sensitivity to new scalars, pseudoscalars axial-vectors in rare K and B decays.There is no room for stronger-than-weak forces in these channels.

Oscillation of Solar neutrinos into ν_b

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

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

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:

$$\frac{dR}{dE_r} \simeq \frac{A^2 m_N}{2\pi} \times \frac{1}{2}\sin^2(2\theta_b) G_B^2 \Phi_{{}^8\mathrm{B}} \times I(E_r, E_0)$$

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

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

$$I(E_r, E_0) = \int_{E^{\min}(E_r)}^{\infty} dE \left(1 - \frac{(E^{\min})^2}{E^2}\right) \times f_{{}^8\mathrm{B}}(E) \times 2\sin^2\left[\frac{\pi E_0}{E}\right]$$

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:

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

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

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

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

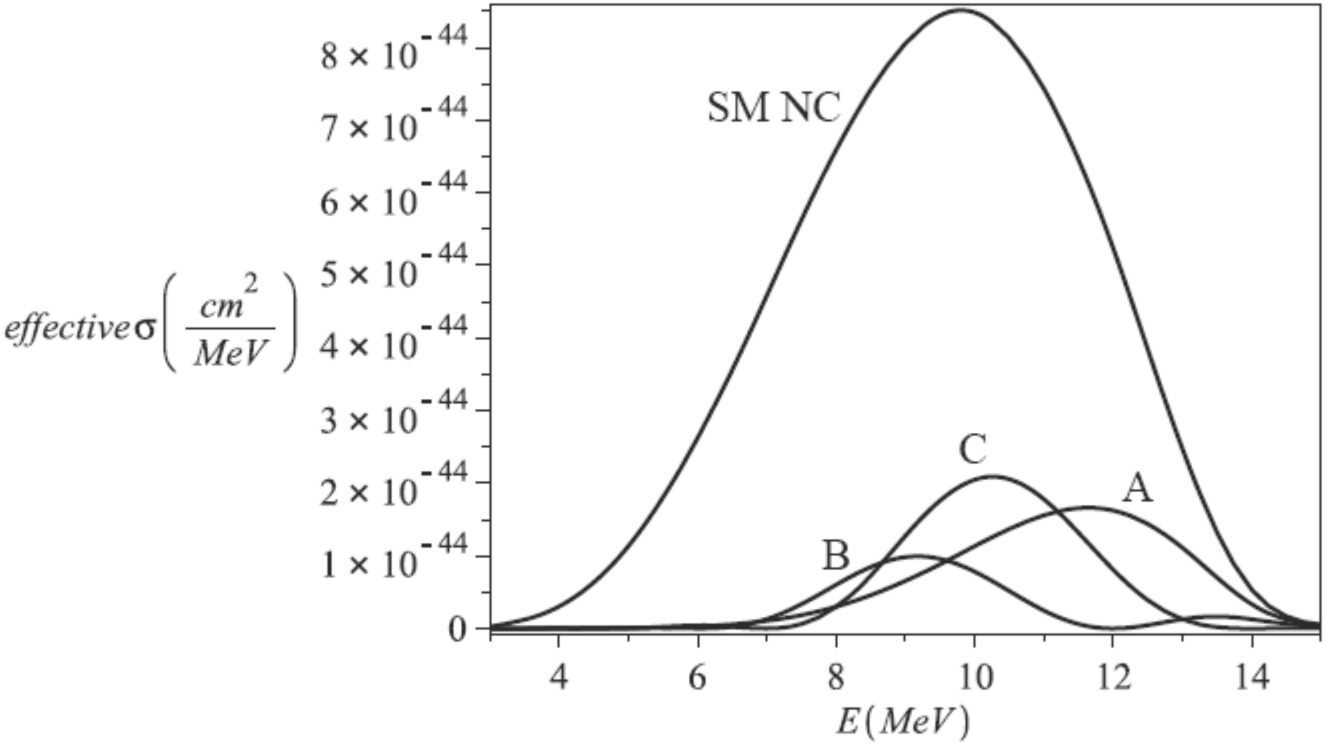
Importance of different couplings for elastic and inelastic scattering

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

$$R(4.4\text{ MeV}) \sim (0.05 - 0.15) \times \frac{\gamma\text{ injections}}{100\text{ tons} \times \text{day}} \times \frac{N_{\rm eff}^2}{10^4}.$$

Small signal but comparable to Boron8 SM neutrino ES.

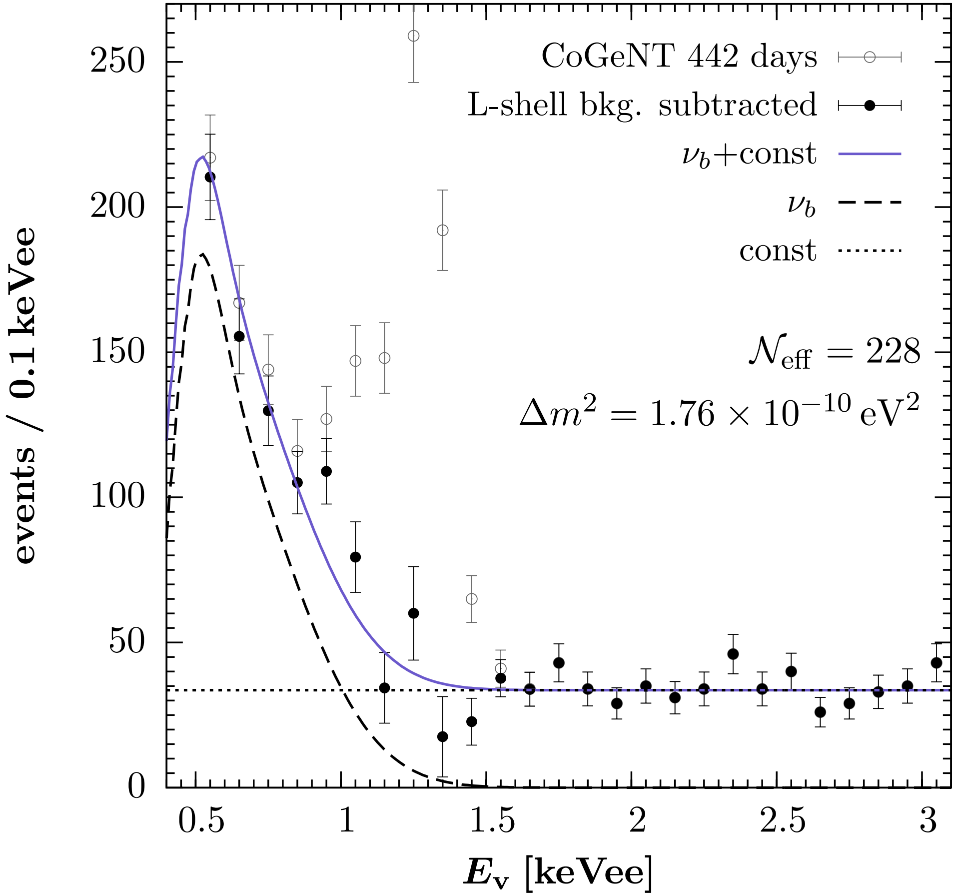
P.S. the analysis of 4.4 MeV signature can be done by the Borexino collaboration, as they know very well how it should look like (this line induced by neutron scattering is used in some calibration methods).

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

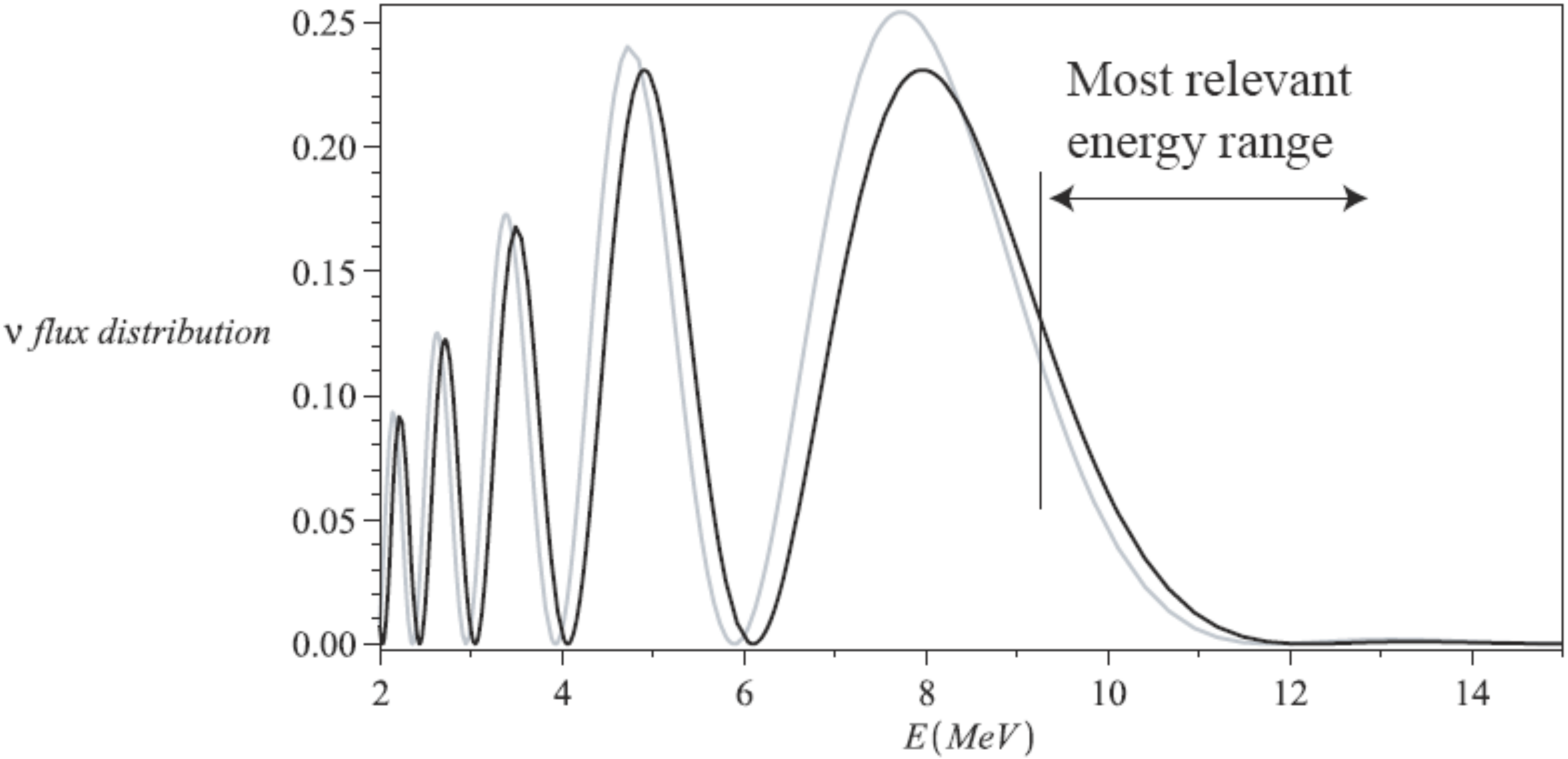
MP, J. Pradler, 2012



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

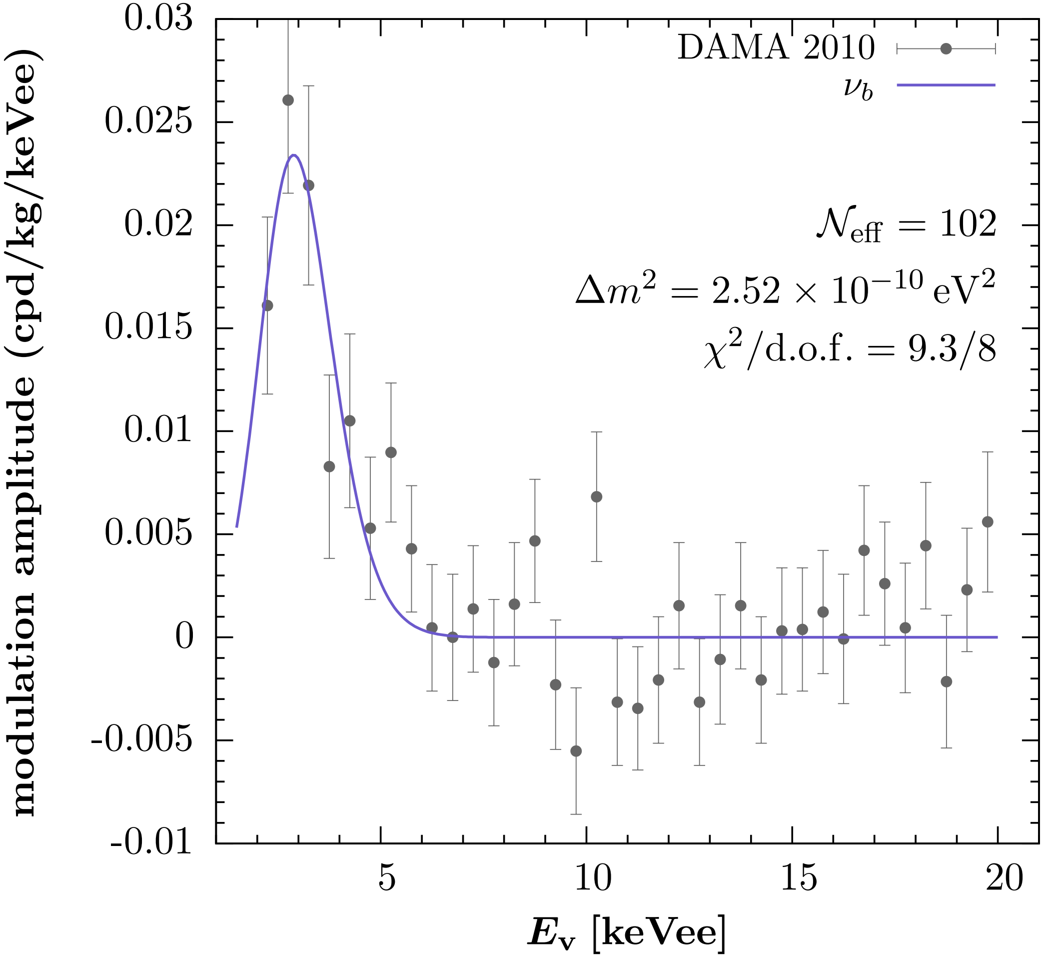
DAMA and "Just-So" phase reversal

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

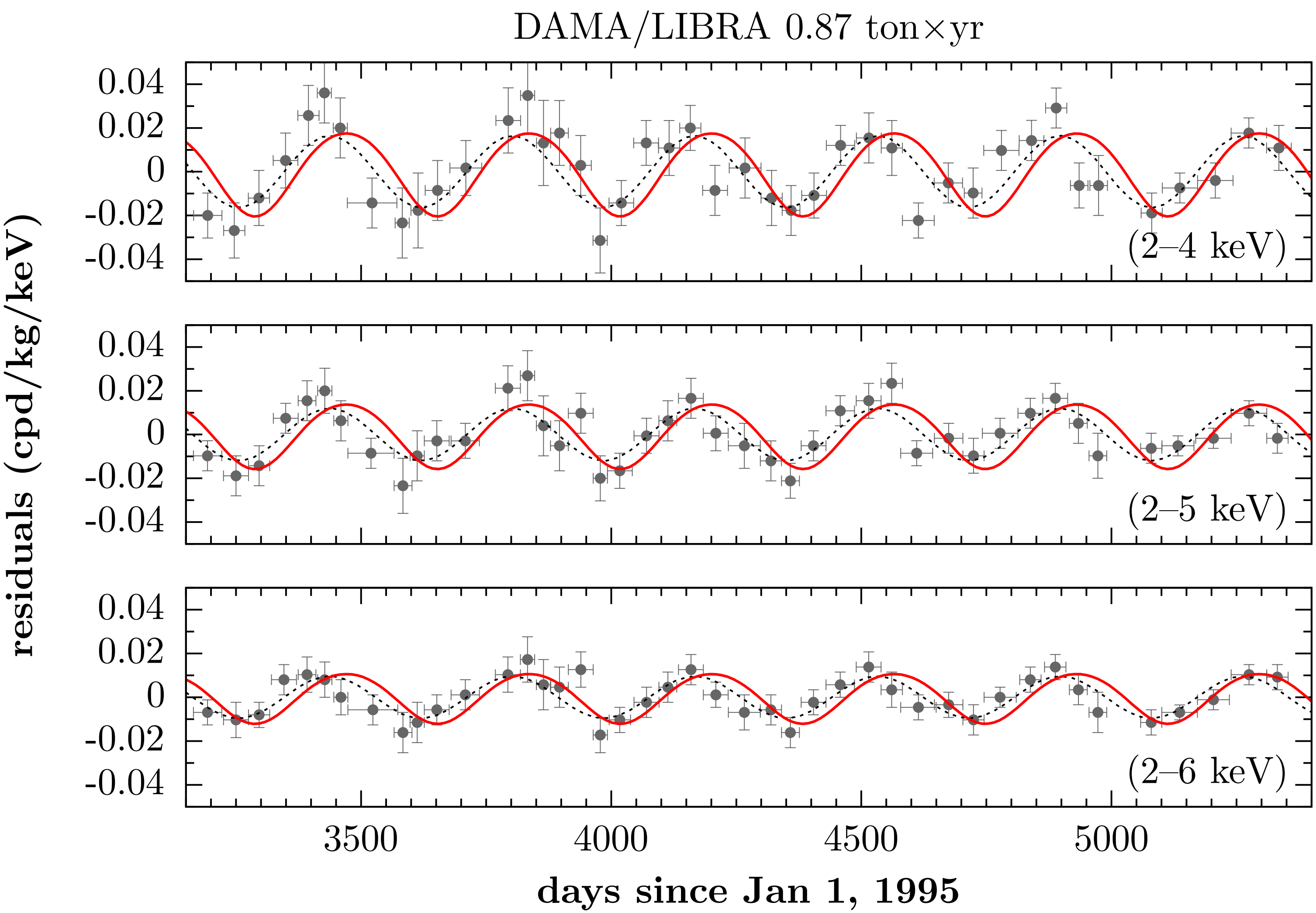


Fitting DAMA modulation amplitude

- 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)



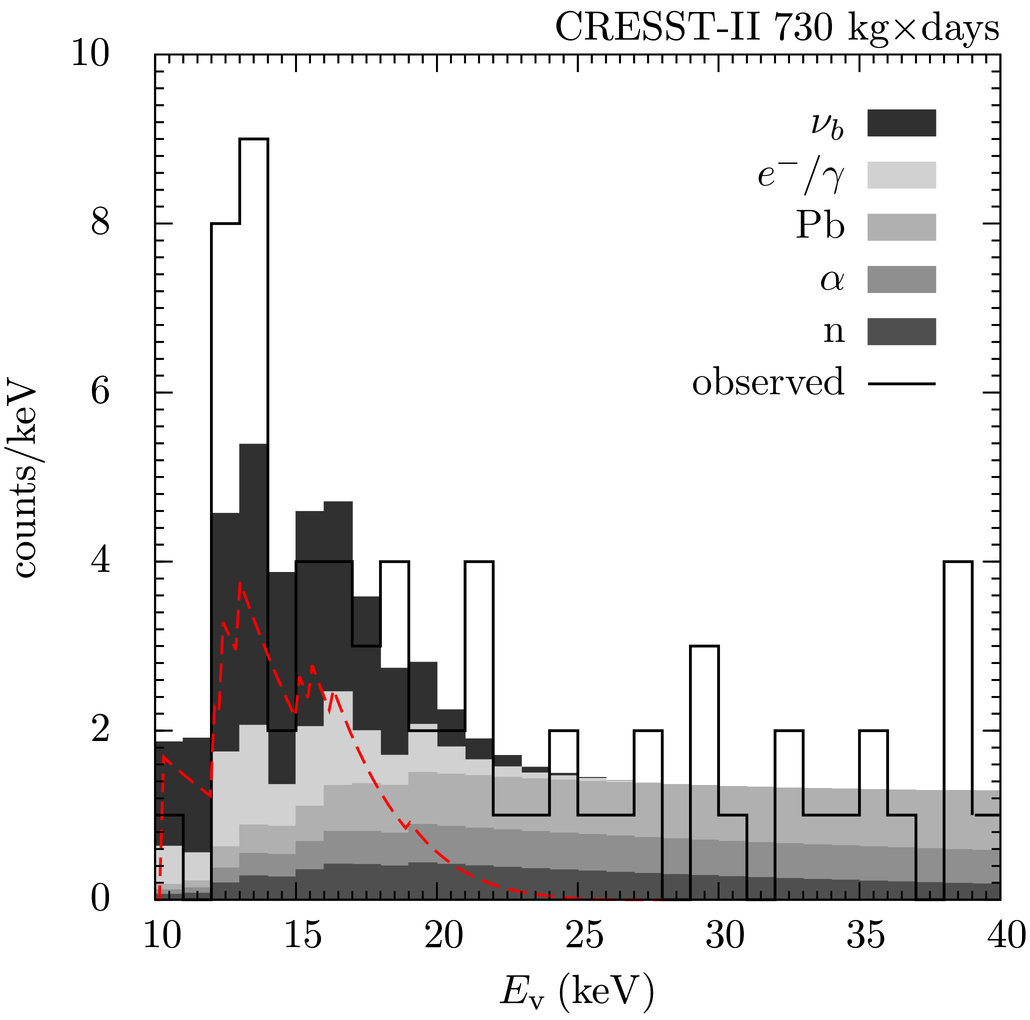
…But *July* is not *June*… The phase is off



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

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

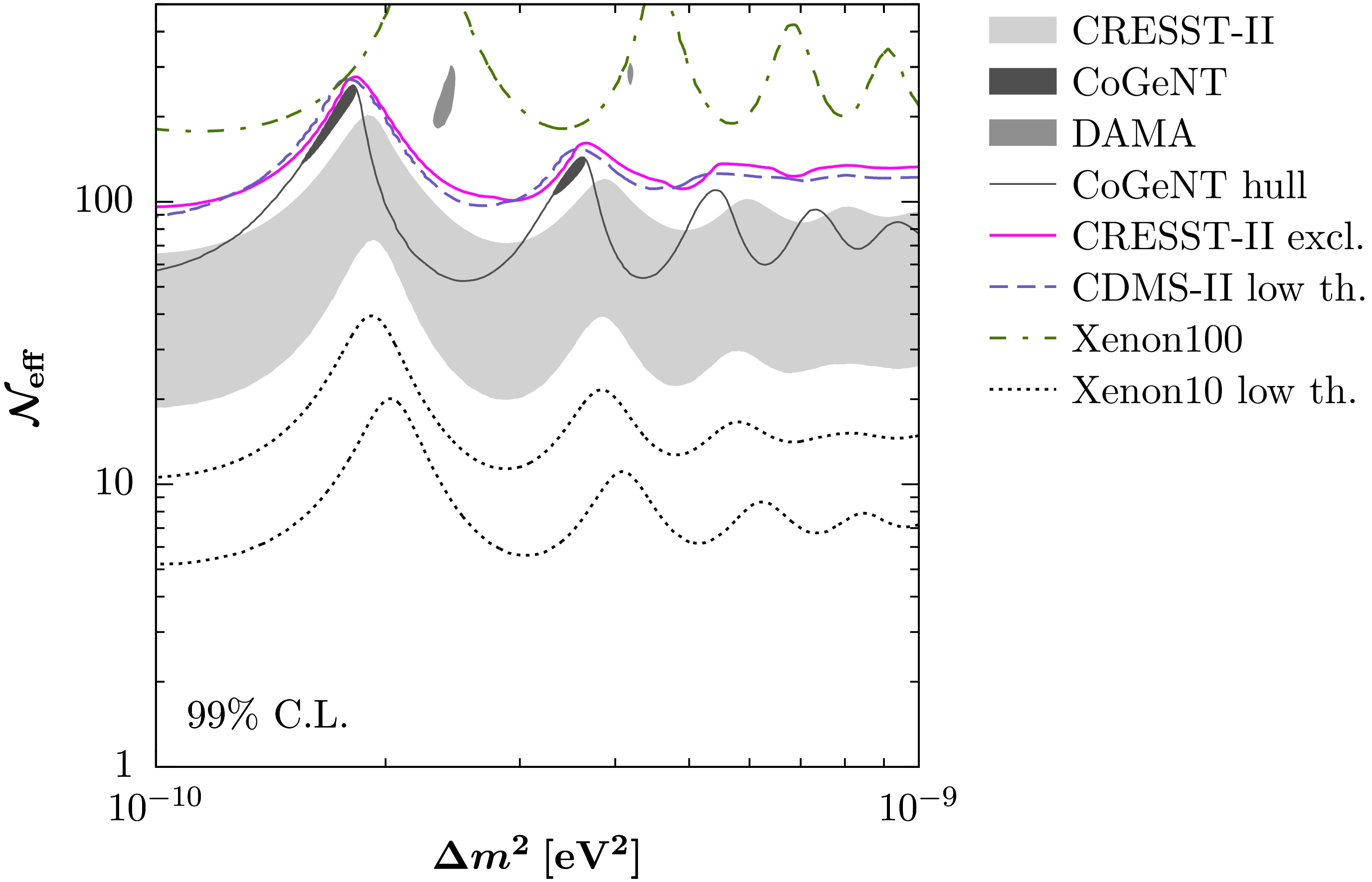
CRESST fit is not too bad…



Prefers slightly smaller N_{eff}

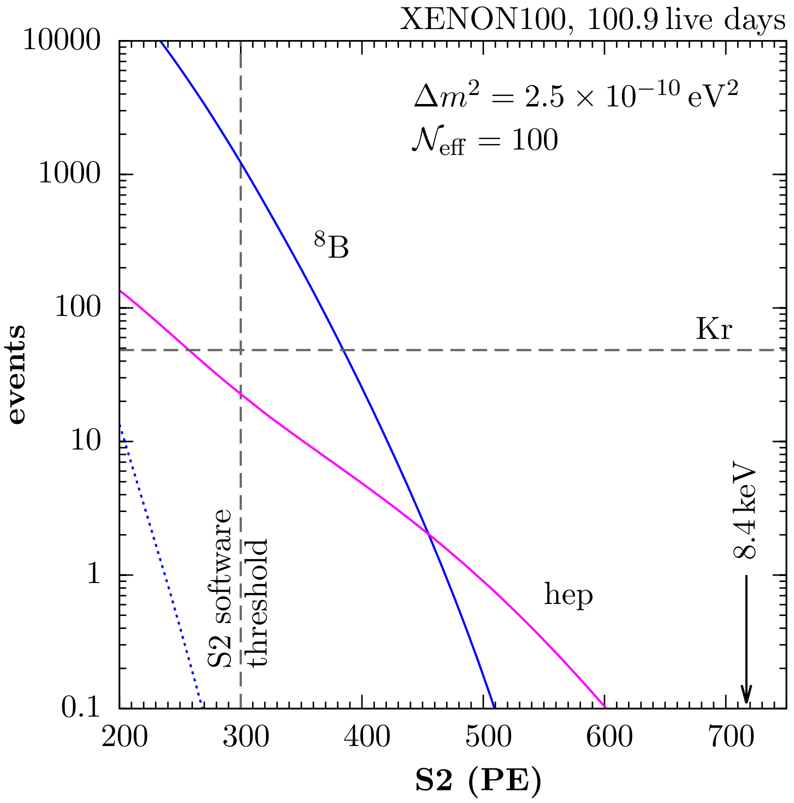
CRESST-II: $\Delta m_b^2 = 3 \times 10^{-10}\,\text{eV}^2, \quad \mathcal{N}_{\text{eff}} = 49, \quad \chi^2/n_d = 27.7/27,$

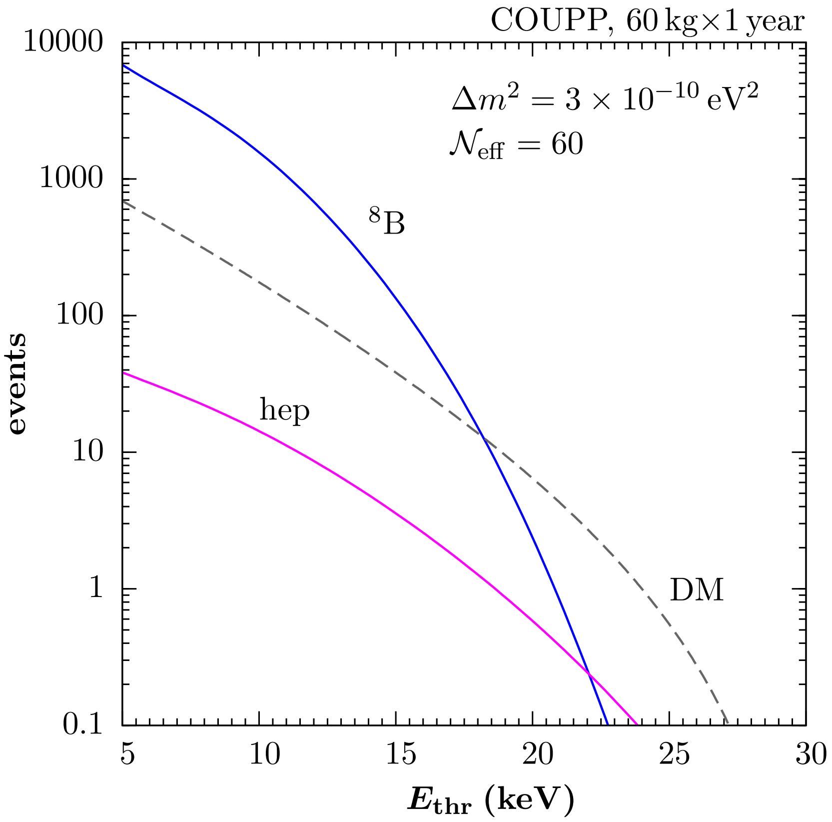
Putting things together on N_{eff}-Δm^2 plot



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 I

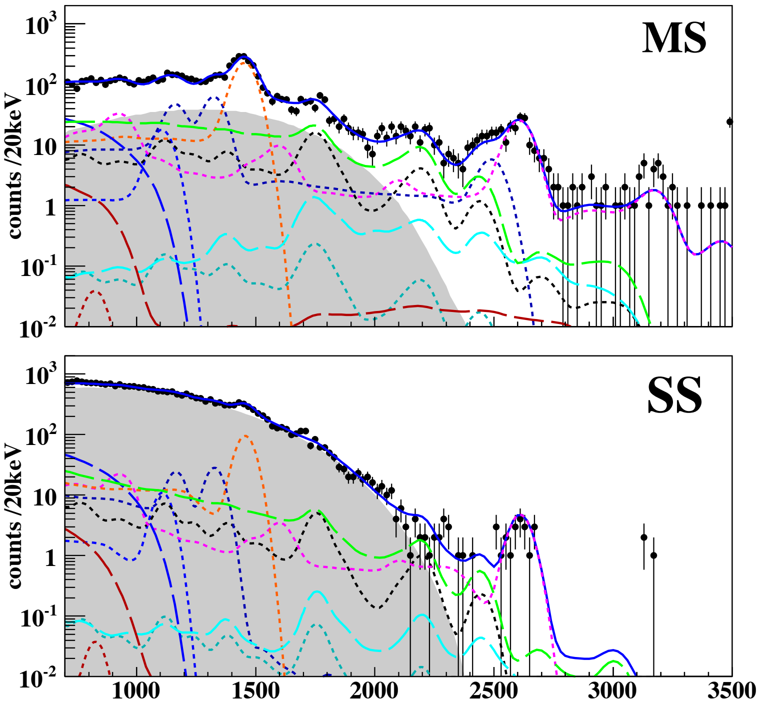
- A lot of work has been done on active → sterile neutrino oscillations. What about "semi-sterile", when new states have stronger-than-SM interactions in neutral channels?
- I have presented a model that takes solar neutrinos and transforms them into "baryonic neutrinos" – those that have much stronger 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.
- The model considered here is "the tip of the iceberg" – there are equally interesting models where "oscillation portal" is combined with stronger-than-G_F "dark force" interactions.
- Finally, so-called "non-standard neutrino interactions", with O(0.1)*(ν current)*(quark current) is all about dark force.

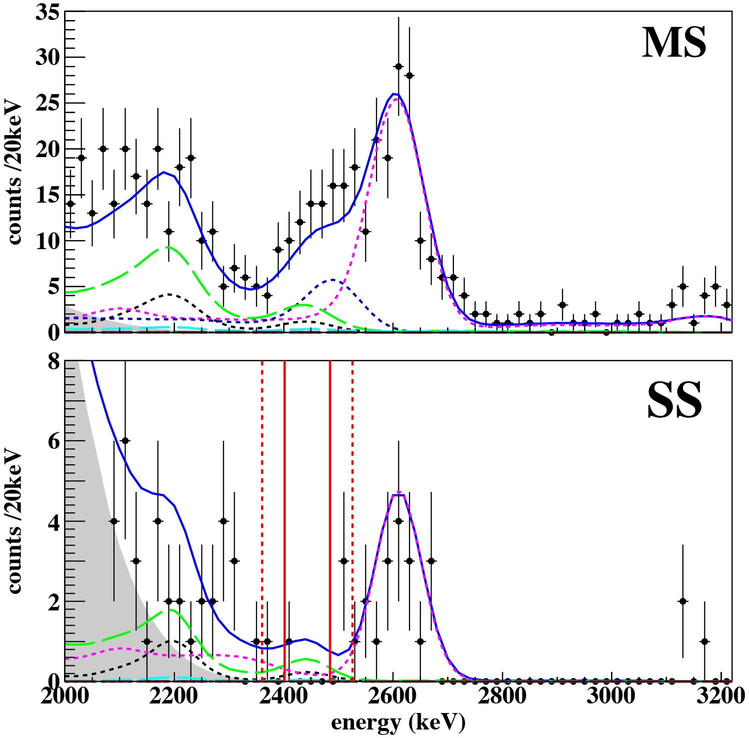
Part II: DM with a charged relative

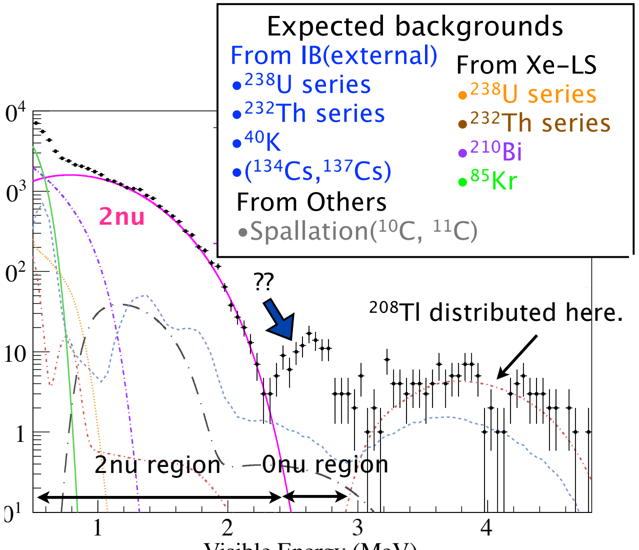
- An example presented in Part I is about the new states/new forces, where the DM direct detection experiments can say somethinn really non-trivial about neutrino models.

- An example in Part II is where you have unexpected sensitivity to DM physics using neutrino experiments (and not via the annihilation neutrino from the Sun).

Part II: new pieces of data in ν-physics





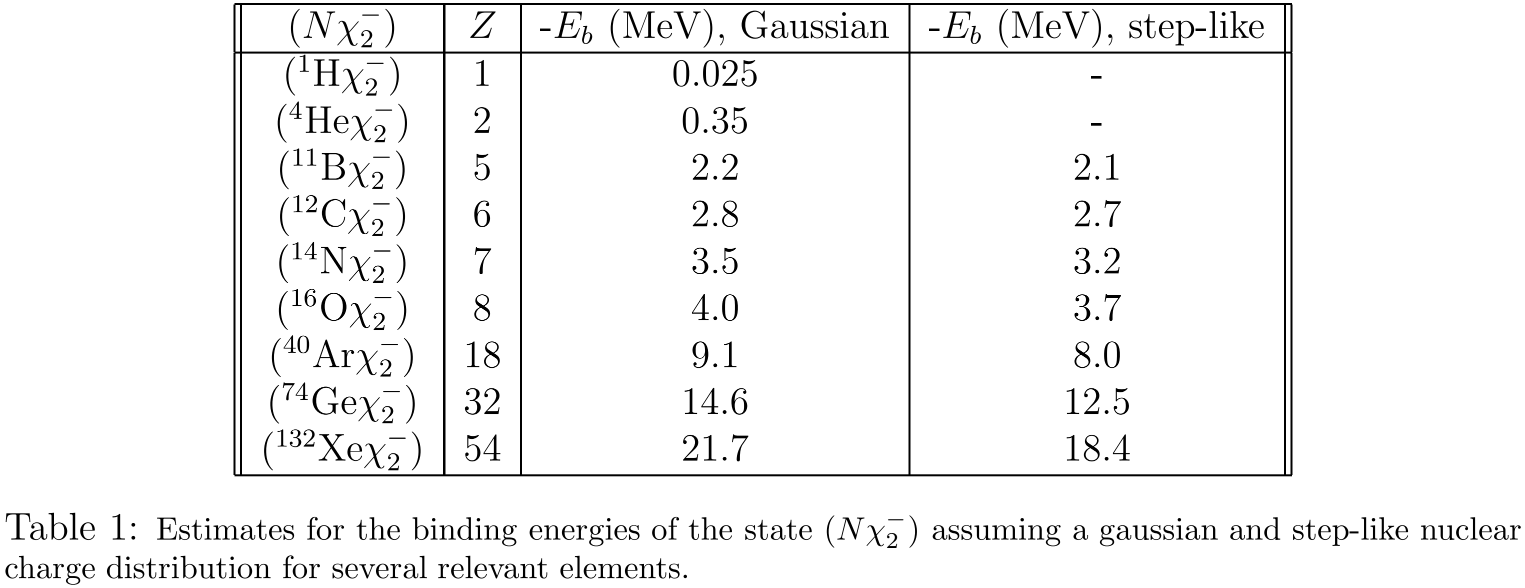


First time there is a wide energy coverage of energy release in ^{136}Xe. This allows to study/set constraints on Dark Matter sector where the neutral states are accompanied by excited charged states.

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

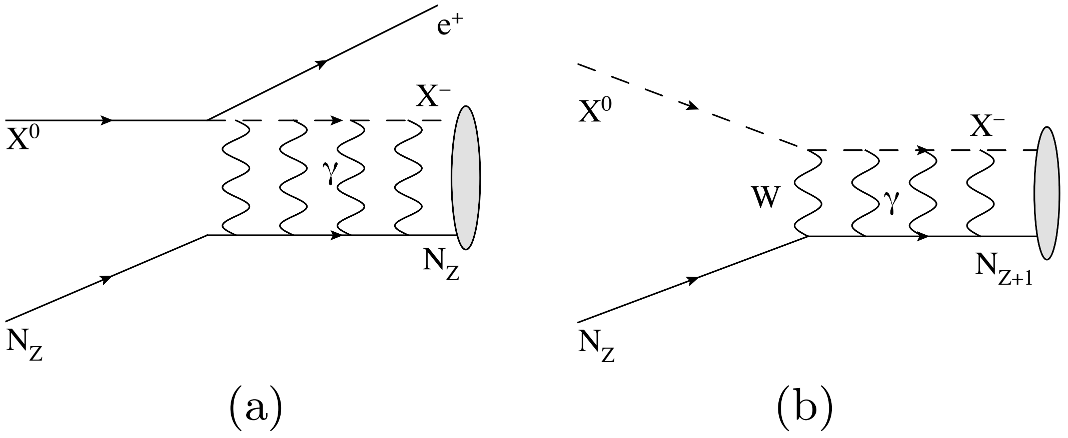
Same spin: $\chi_1^0 + N^{(Z)} \rightarrow (N^{(Z+1)}\chi_2^-)^* \rightarrow (N^{(Z+1)}\chi_2^-) + (\gamma, n, \ldots).$

New analysis

- H. An, J. Pradler, and MP, 2012

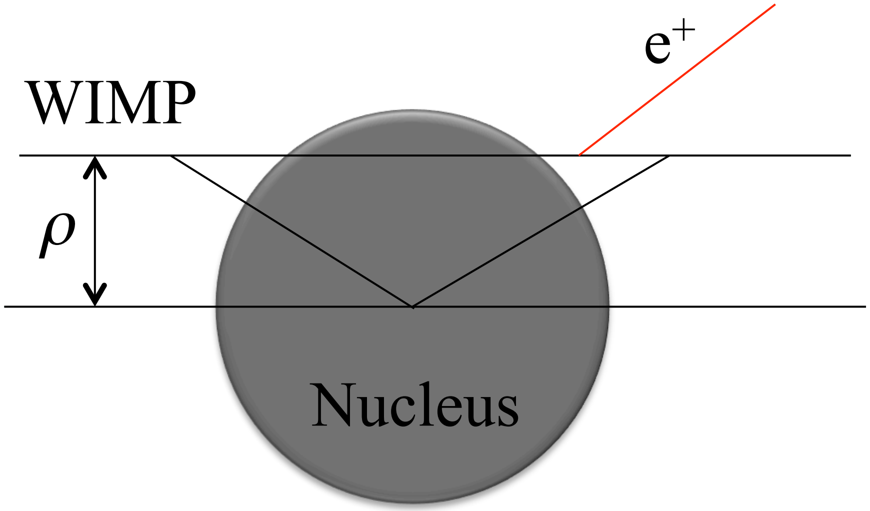
$$\text{Case A:} \quad N_Z + X^0 \to (N_Z X^-) + e^+,$$

$$\text{Case B:} \quad N_Z + X^0 \to (N_{Z+1} X^-)\ ,$$



Calculations in case A are much simpler. They can be performed in semi-classical approximation. Case B is more complicated. But if the energy release is significant, one can use Fermi model for the nucleus

Semi-classical calculation for case A



The cross section can be calculated by summing 2πρdρ multiplied by probability of emitting a positron along the classical trajectory. (Similar to Kramers' calculation of molecular formation rates)

Works as long as the Number of available QM final states of Nucleus + Charged WIMP >> 1.

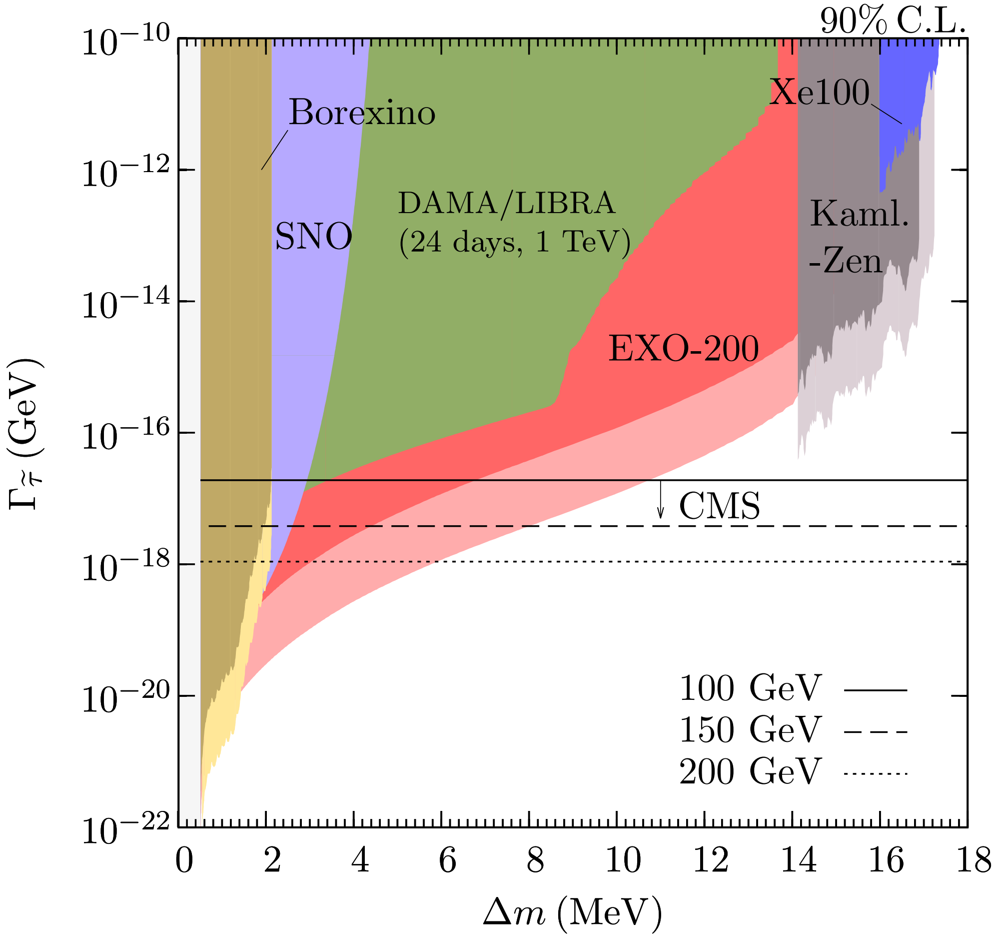
$$\sigma_A v \simeq (|g_{eL}|^2 + |g_{eR}|^2)/(8\pi m_\chi) \times \sum_{n,l} B_{n,l},$$

$$B_{n,l} \simeq \left(E_B^{(n,l)} - \Delta m - m_e\right) \sqrt{(E_B^{(n)} - \Delta m)^2 - m_e^2}$$

$$\times \int d^3 r_1 d^3 r_2 \, \phi^*_{n,l}(\vec{r}_1) \phi_{n,l}(\vec{r}_2) e^{i\mu \vec{v}\cdot(\vec{r}_1 - \vec{r}_2)}.$$

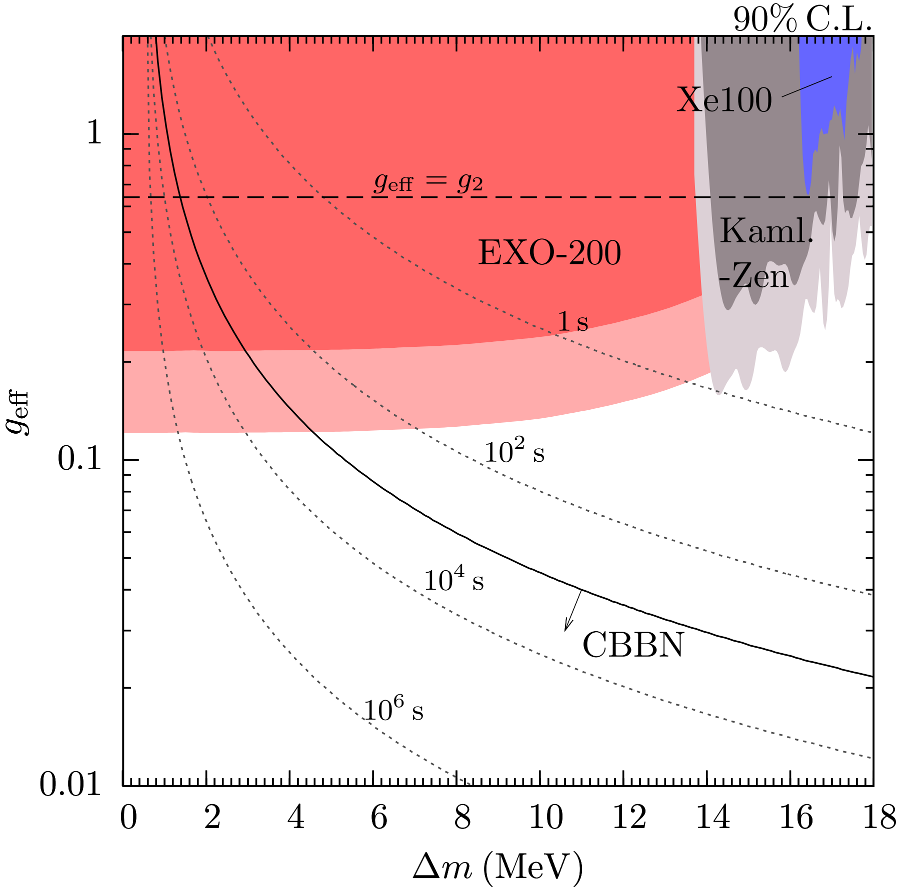
$$\sum_{n,l} B_{n,l} \simeq \int_{|\vec{r}|<r_b} d^3\vec{r} \sqrt{(V(|\vec{r}|) + \Delta m)^2 - m_e^2} (V(|\vec{r}|) + \Delta m + m_e).$$

Constraints for case A, M_{DM} = 100 GeV, 1 TeV



- Constraints are formulated in terms of the lifetime(width) for Charged DM → Neutral WIMP in vacuum. Corresponds to the sensitivity to the chi^0-chi$^-$-e$^+$ coupling at O(10^{-5}) level. If such model is reality, DM will leave charged tracks at the LHC.

Constraints for case B, M_{DM} = 100 GeV, 1 TeV



Rates are estimated using similar semi-classical idea: during the fly-by, there is a probability of chi^0 + neutron → chi^- + proton. Orthogonal constraints are provided by the [Catalyzed] Big Bang Nucleosynthesis.

Conclusions II

- A possibility that the DM can have a charged cousin within 20 MeV mass can be limited rather sensitively with the neutrino-less double beta decay experiments (first results on limiting energy release in O(MeV) region using heavy elements)

- Both models (same spin; different spin) are constrained. Constraints are orthogonal to the LHC, (and typically stronger where there is overlap). These are first "direct detection" constraints on charged excitations of dark matter.

- 0n2b experiments may start thinking about analyzing this type of signatures, e.g. almost monochromatic energy release at some "odd place".