Dark Matter or Neutrino Recoil?

Interpretation of recent experimental results

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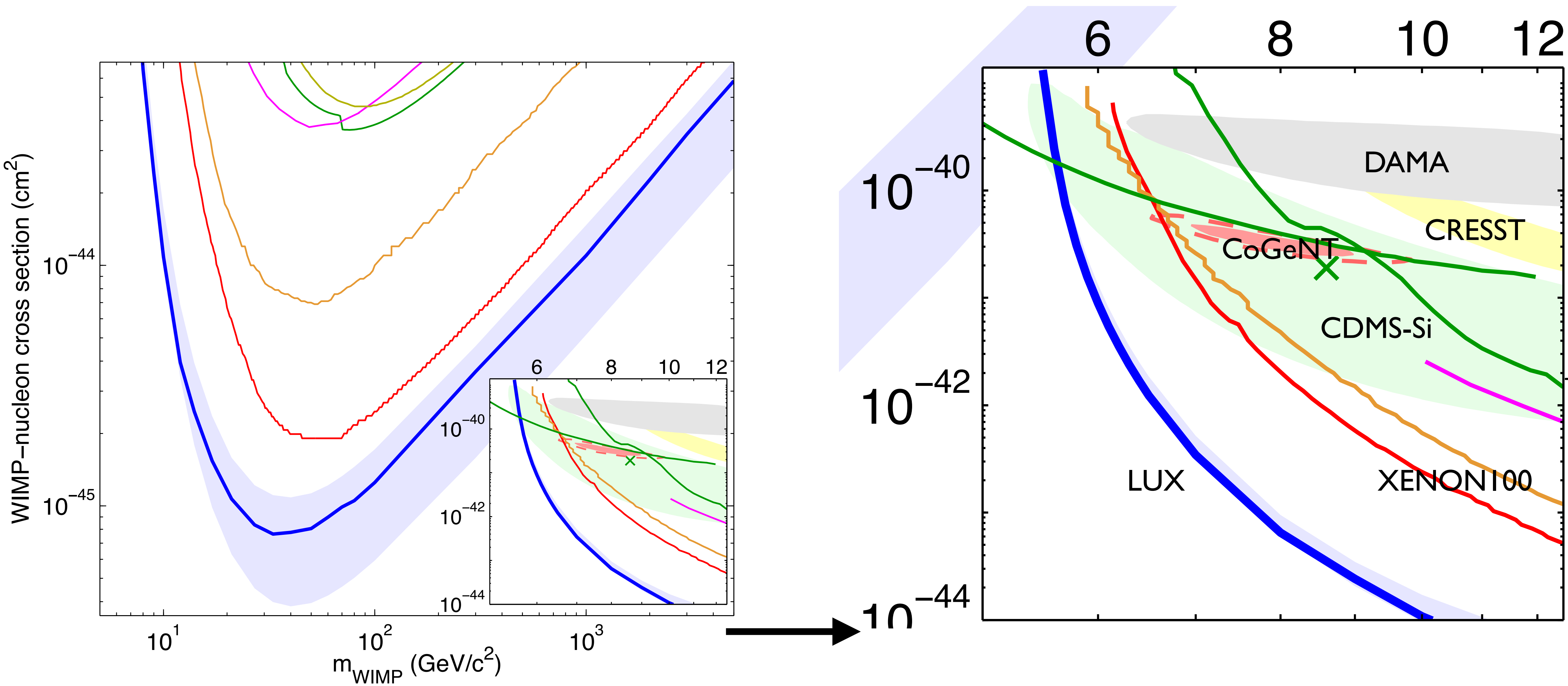
Johns Hopkins University

Aspen 2014

First LUX results

LUX collaboration, 2013



Time to rethink the 10 GeV elastic scattering DM paradigm.

=> see. K. Zurek's talk yesterday

Outline

- entertain a neutrino model that can explain the direct detection anomalies that are often interpreted in terms of light-DM. The model stands fairly unchallenged by LUX.

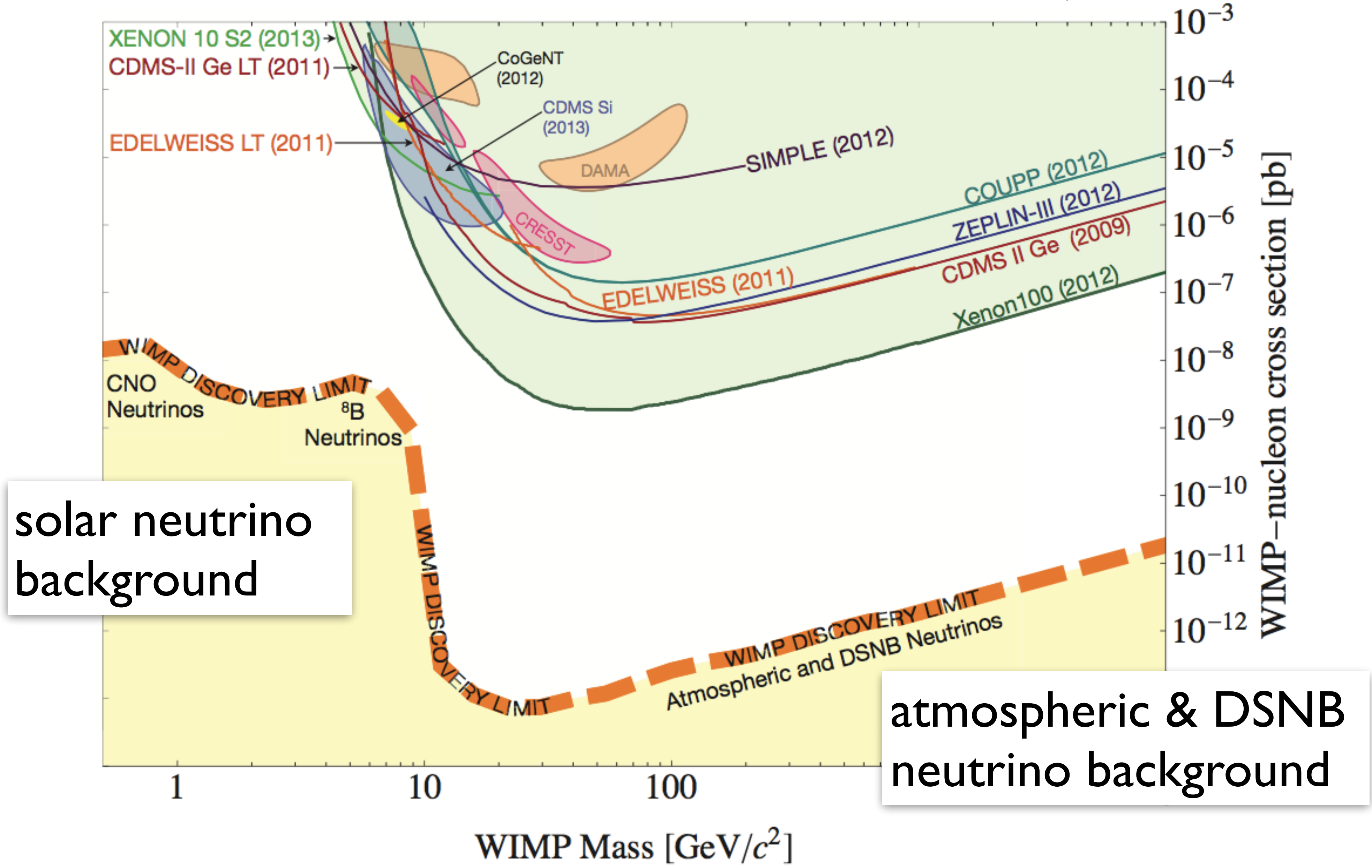
based on M.Pospelov, JP 2012 & 2013

- further astrophysical observables

preliminary explorations

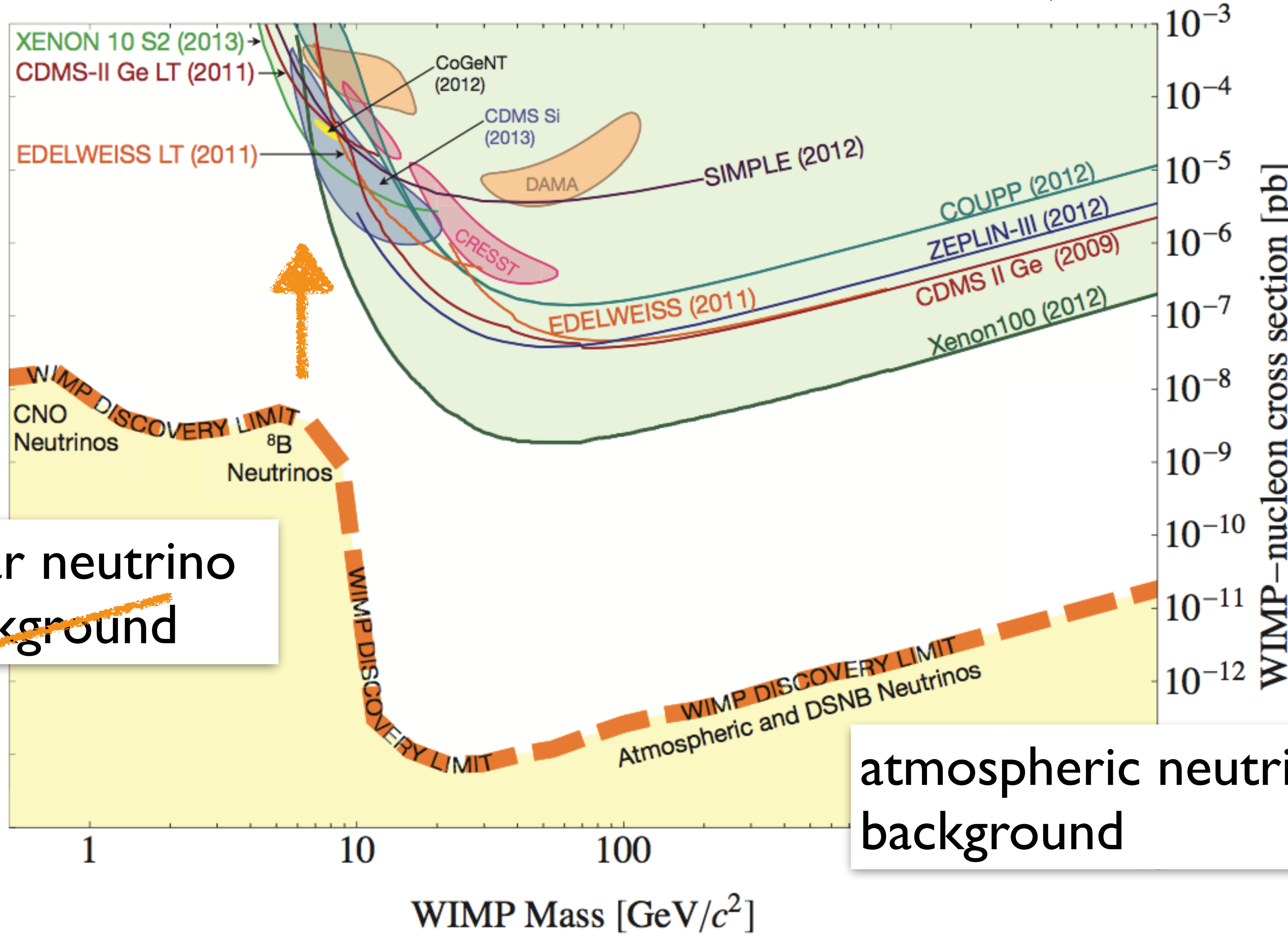
Direct detection - big picture

Snowmass 2013 / Billard et al, 2013



Direct detection - big picture

Snowmass 2013 / Billard et al, 2013



Can we lift that curve?

solar neutrino ~~background~~

signal

atmospheric neutrino background

Neutrino Physics with DD experiments

Pospelov (2011)
Harnik, Kopp, Machado (2012)
Pospelov, JP (2012)
Pospelov, JP (2013)

new neutrino

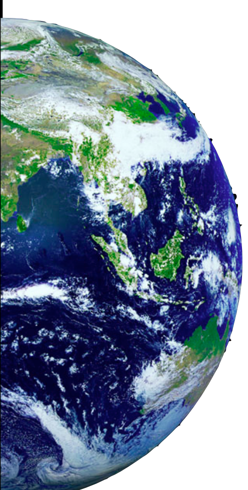
new force

$$\mathcal{L}_{\rm eff} = -G_B(\bar{\nu}_b\gamma^\mu\nu_b)J_{B,\mu}$$

baryon current

=> for MeV-scale ν_b NC-like coherent scattering on nuclei

$$E_R^{\rm max} = \frac{(2E_\nu)^2}{2m_N} = \mathcal{O}(\rm keV)$$



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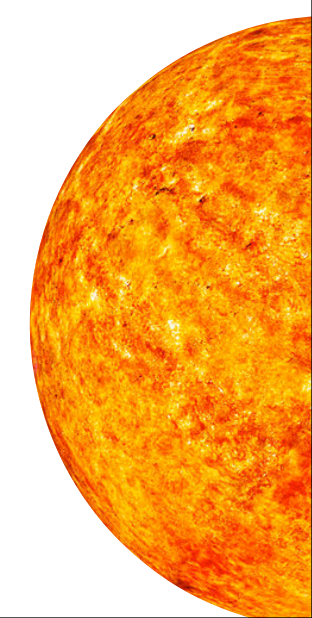

Neutrino Physics with DD experiments

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$$\mathcal{L}_{\text{eff}} = -G_B(\bar{\nu}_b\gamma^\mu\nu_b)J_{B,\mu}$$

baryon current

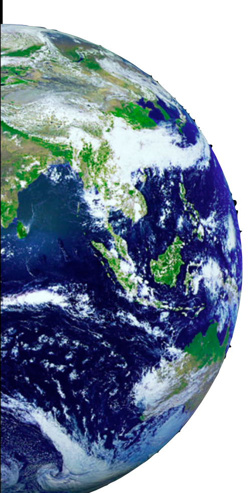
The scenario we have in mind:

1. stronger than weak interaction

$$G_B/G_F \gg 1$$

2. oscillation lengths

$$L_{\text{osc}} \gg 10^3\,\text{km}$$



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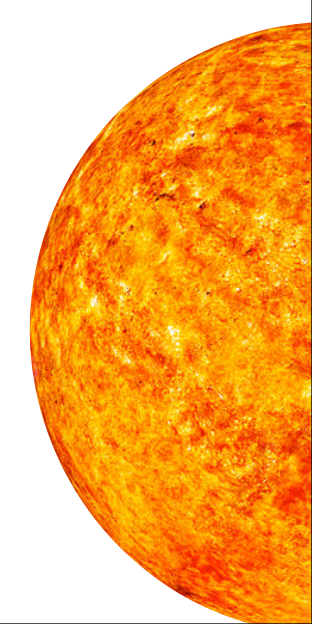


Enhanced interactions with J_B

- **crucial insight:**

$$\frac{\sigma_{\nu_b N}(\text{elastic})}{\sigma_{\nu_b N}(\text{inelastic})} \sim \frac{A^2}{E_\nu^4 R_N^4} \sim \mathcal{O}(10^8)$$

M. Pospelov, 2011

=> Dark Matter searches become competitive with neutrino experiments

=> D breakup in SNO does not constrain this scenario

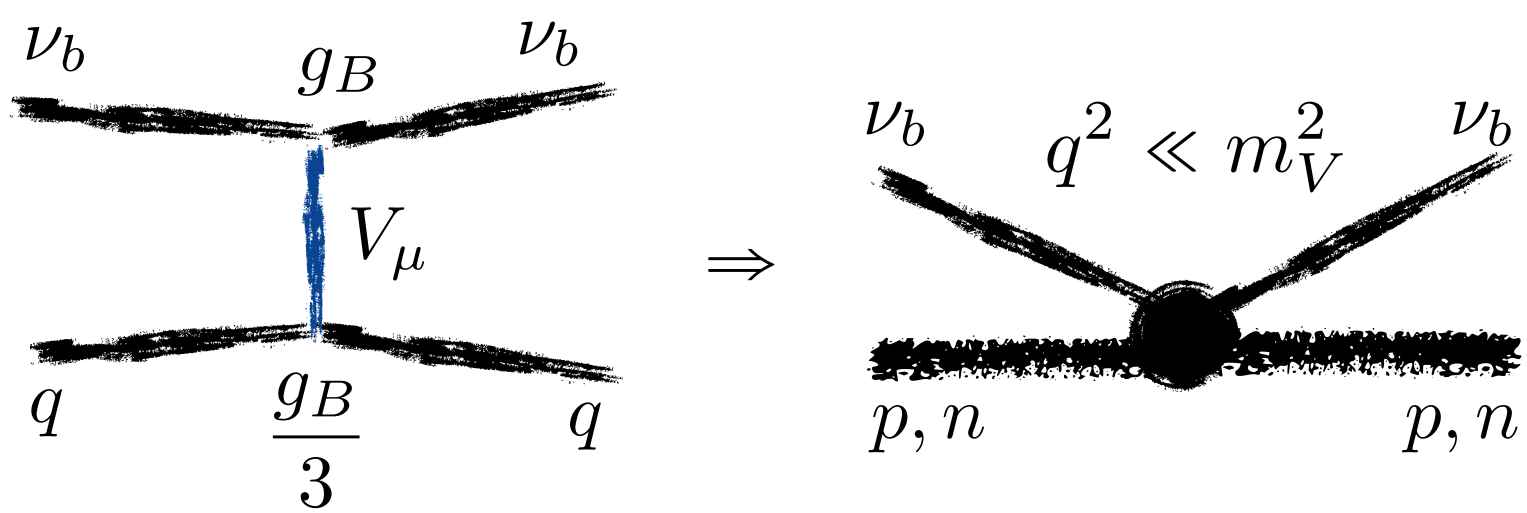
- Coherent neutrino nucleus scattering with $G_F^2(N/2)^2 \Rightarrow G_B^2 A^2$

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{8\pi} G_F^2 E_\nu^2 \left[Z(4\sin^2\theta_W - 1) + N\right]^2 (1+\cos\theta)$$

Enhanced interactions with J_B

- vector coupling of new left-handed neutrino ν_b to quarks

$$D_\mu \nu_b = (\partial_\mu + i q_\nu g_B V_\mu)\nu_b \qquad \not{D} = \not{D}^{\mathrm{SM}} + i\frac{g_B}{3}\gamma_\mu V^\mu$$



$$\frac{g_B^2}{m_V^2} \equiv G_B \gg G_F$$

"baryonic neutrino"

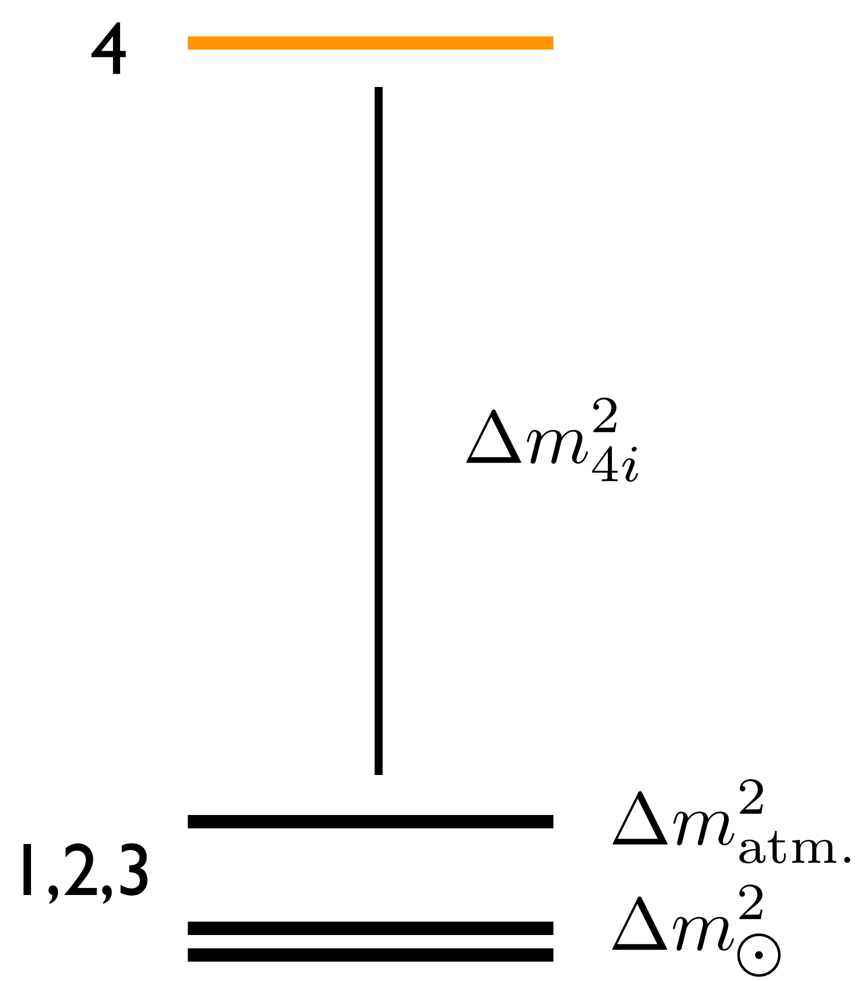
- $G_B/G_F \gg 1$ requires light mediator mass $m_V = \mathcal{O}(\mathrm{MeV} - \mathrm{GeV})$

Adding new light neutrinos

Δm^2: two limiting cases

- large splitting $|\Delta m^2_{4i}| \gg |\Delta m^2_{ij}|$

  short baseline anomalies
  (LSND, MiniBooNE, reactor)



Adding new light neutrinos

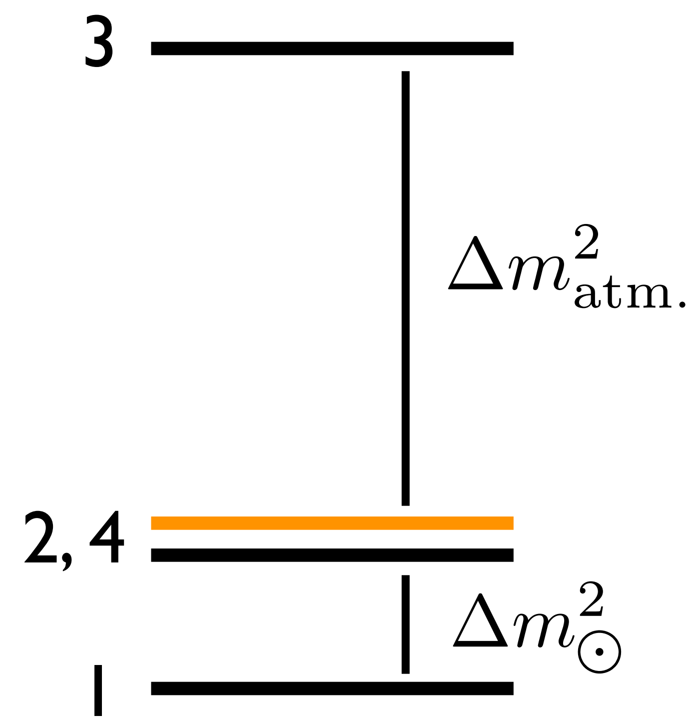
Δm^2: two limiting cases

- large splitting $|\Delta m^2_{4i}| \gg |\Delta m^2_{ij}|$

  short baseline anomalies
  (LSND, MiniBooNE, reactor)

- smaller than SM splitting with
  one neutrino *i*

  little considered in the recent literature,
  but can be used to conceal new interactions

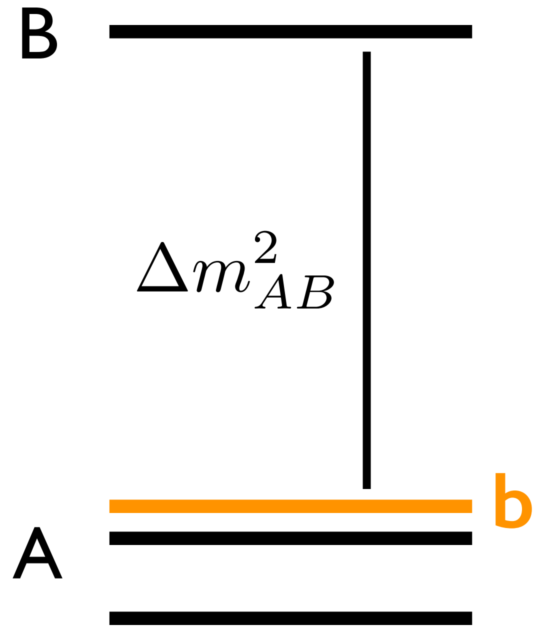


“Neutrino oscillation portal”

- appearance probability of “flavor” β

$$P_{\beta\alpha} = \left| \sum_k U^*_{\alpha k} U_{\beta k} \exp\left(-i \frac{\Delta m^2_{k1} L}{2E_\nu} \right) \right|^2$$

$$\simeq \sin^2\left(2\theta^{\rm eff}_{\beta\alpha}\right) \sin^2\left(\frac{\Delta m^2_{AB} L}{4E_\nu} \right) \qquad (\alpha \neq \beta)$$



- effective angle with the new state “b”

$$\sin^2\left(2\theta^{\rm eff}_{b\alpha}\right) = 4 \left| \sum_{k>A} U^*_{\alpha k} U_{bk} \right|^2$$

$$U = V_3 \times \prod_{i=1}^{3} R_{i4}(\theta_{i4})$$

- if all mixing angles $\theta_{b\alpha}$ between groups A and B for which a non-negligible phase ϕ_{AB} exists are zero, then $\sin^2(2\theta^{\rm eff}_{b\alpha}) = 0$

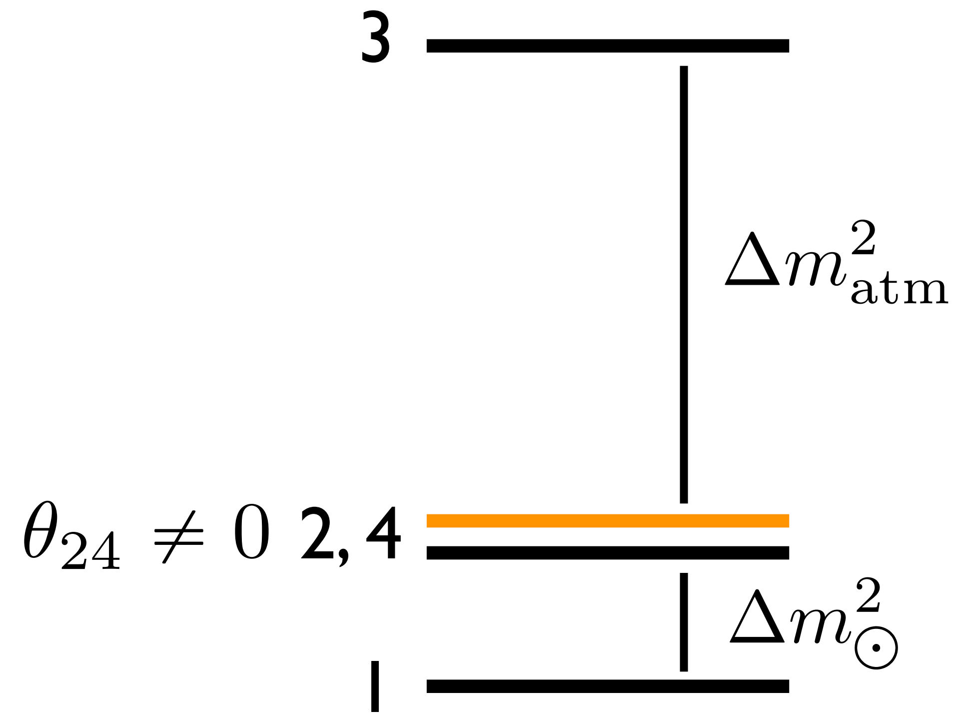
=> appearance of new flavor “b” is protected by small Δm^2

“Neutrino oscillation portal”

- in the following, consider the setup

$$n_2 = \cos\theta_{24} n_2^0 - \sin\theta_{24} n_4^0,$$
$$n_4 = \sin\theta_{24} n_2^0 + \cos\theta_{24} n_4^0$$

$$U = U_3 R^{24}(\theta_{24})$$



- considering small new angles $\theta_{i4} \lesssim 0.1$ keeps the standard oscillation picture largely intact

- $\Delta m^2 < 10^{-8}\,\mathrm{eV}^2$ guards new interaction from detection in terrestrial neutrino beams

$$P_{b\alpha} < 10^{-4} \quad \text{for} \quad L \leqslant 10^3\,\mathrm{km}, \qquad (E_\nu \geqslant 1\,\mathrm{MeV})$$

“Neutrino oscillation portal”

- portal may not guard new interactions on astrophysical baselines

$$L_{\mathrm{osc}} = \frac{4\pi E_\nu}{\Delta m^2} \approx 1\,\mathrm{AU}\left(\frac{10^{-10}\,\mathrm{eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)$$

- appearance of ν_b in the solar neutrino flux!

=> coherent NC-type scattering in direct detection experiments

$$\frac{dR(t)}{dE_R} = N_T\left[\frac{L_0}{L(t)}\right]^2 \sum_i \Phi_i \int_{E_\nu^{\mathrm{min}}} dE_\nu\, \frac{df_i}{dE_\nu}\frac{d\sigma}{dE_R} P_b(t, E_\nu)$$

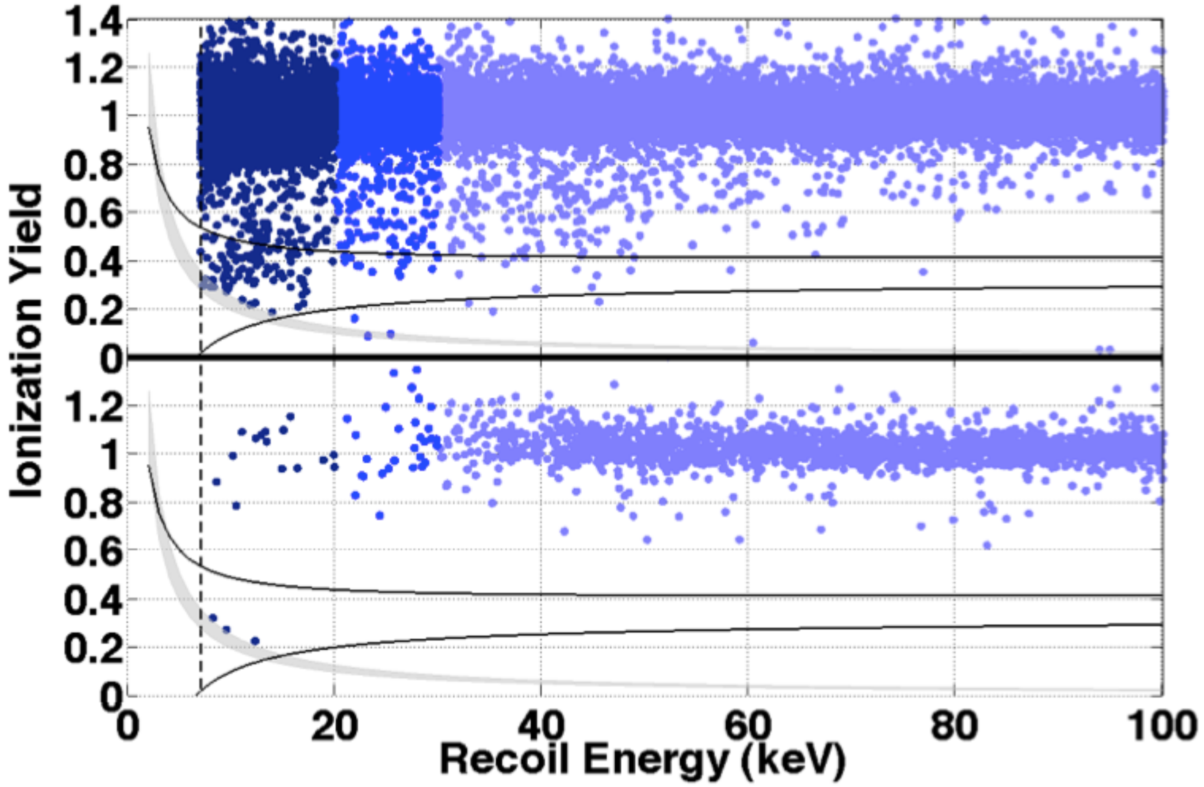
overall flux modulation

average over neutrino spectrum i

appearance probability

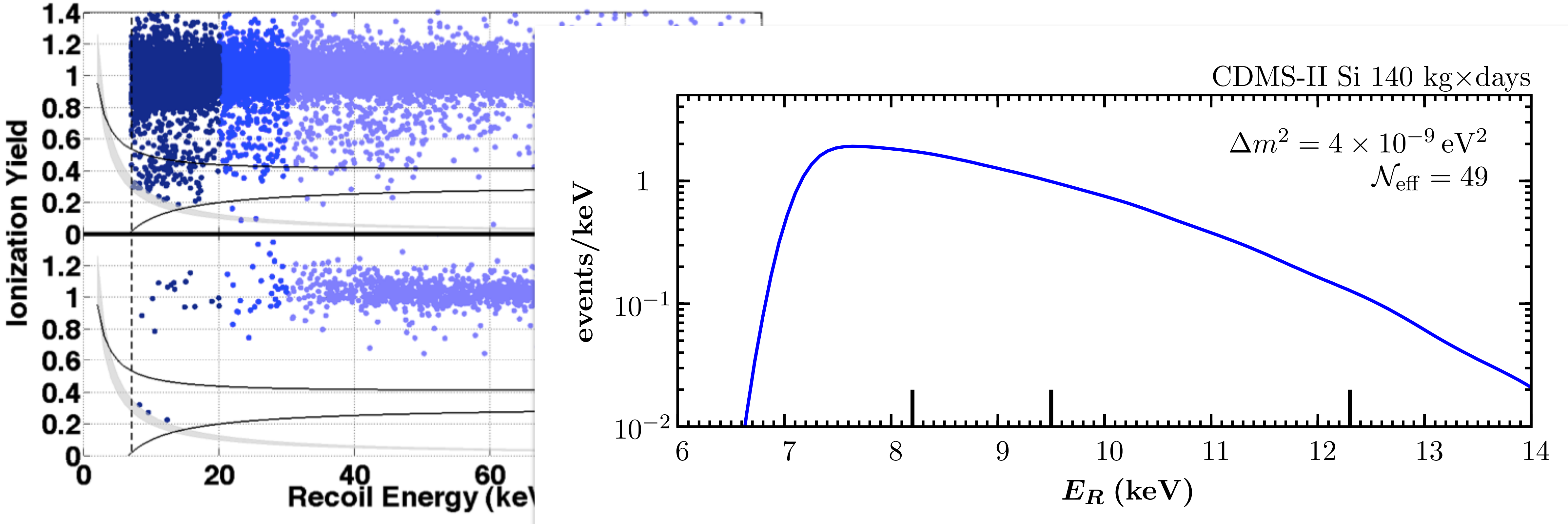
CDMS-Si 2013

3 events, 0.2% probability of
known background-only
hypothesis



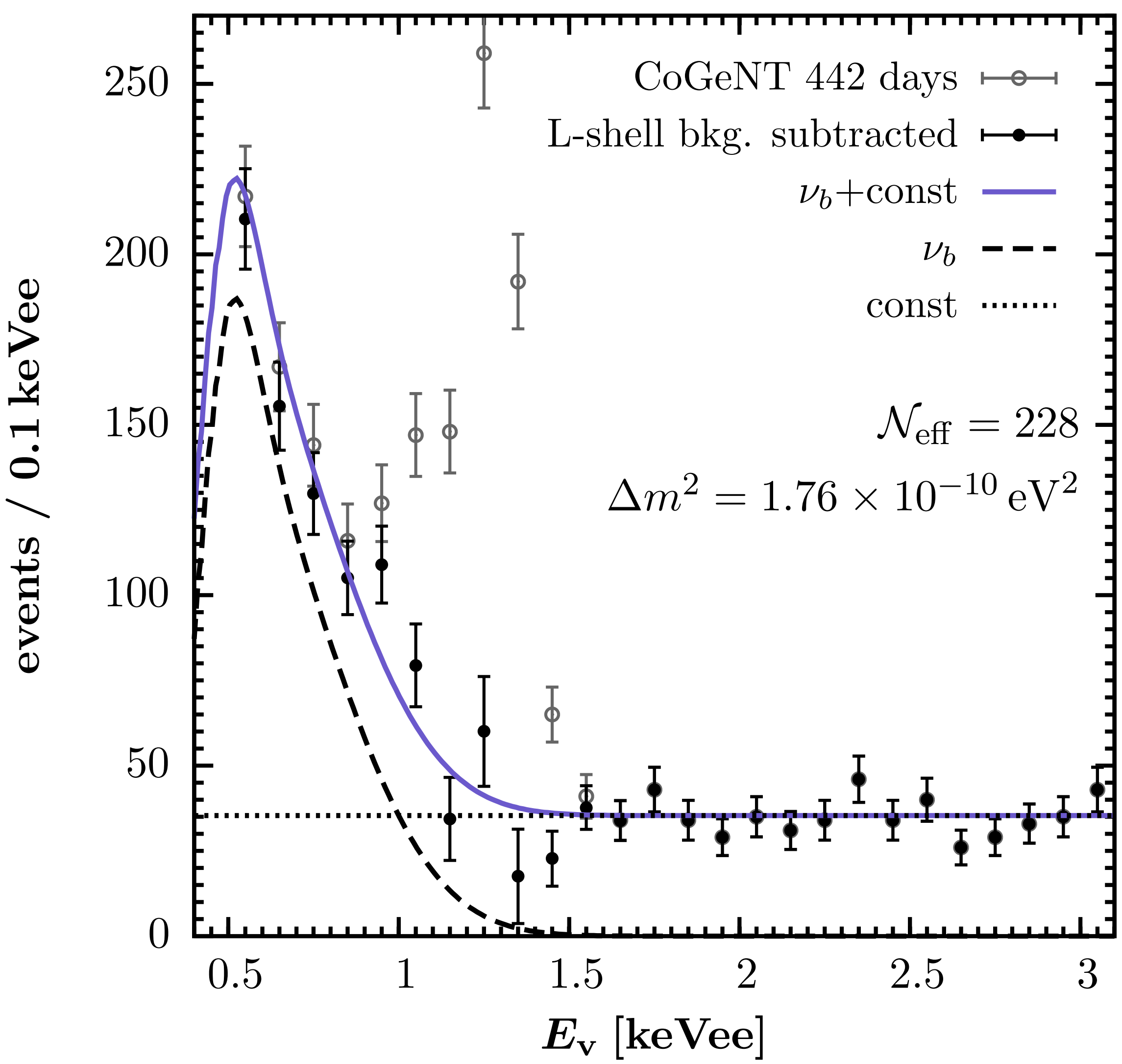
CDMS-Si 2013

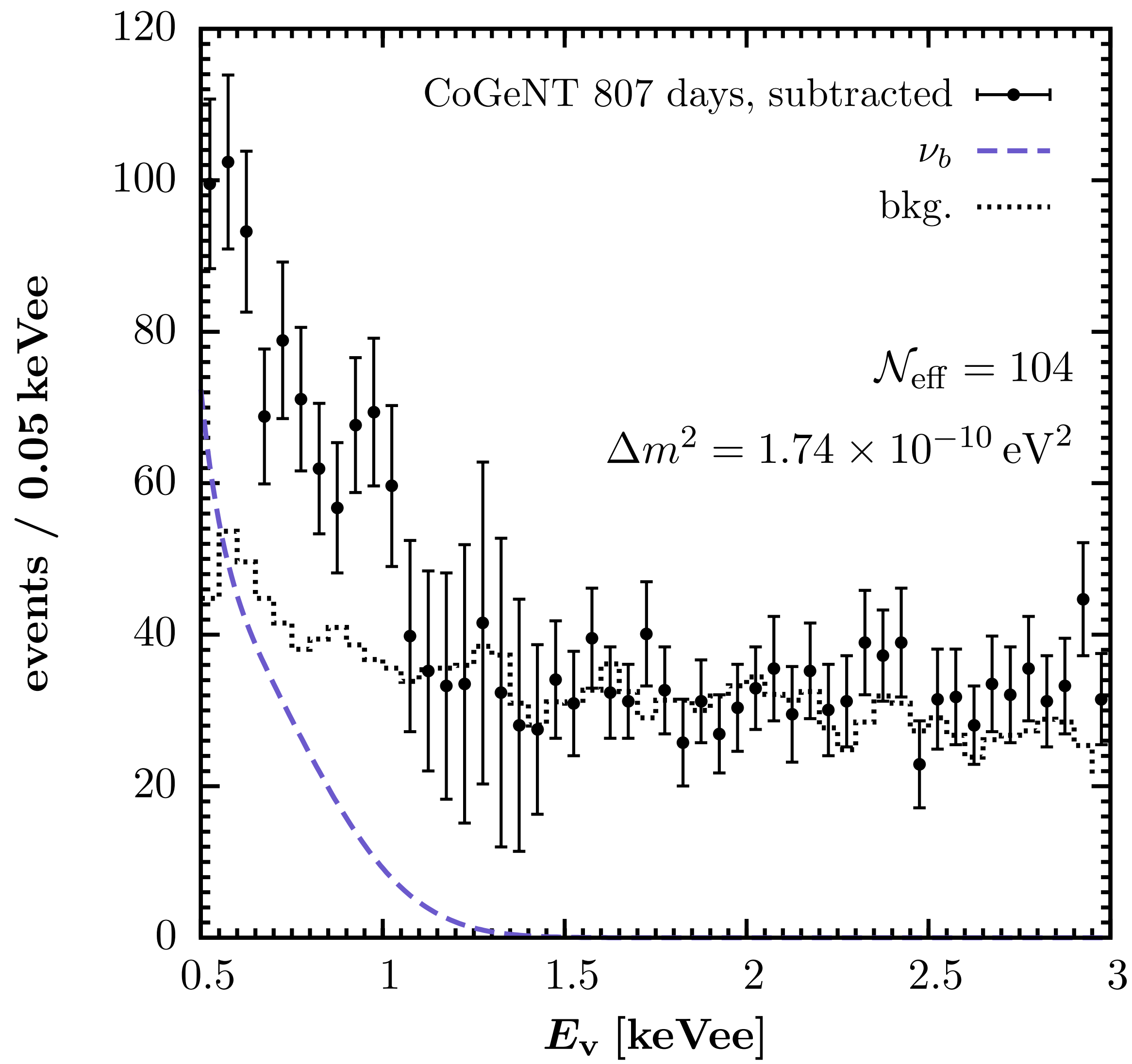
3 events, 0.2% probability of *known background-only* hypothesis



effective parameter: $\mathcal{N}_{\rm eff}^2 \equiv \frac{1}{2}\left(\frac{G_B}{G_F}\right)^2 \sin^2 2\theta_b \simeq 2\theta_b^2 \left(\frac{G_B}{G_F}\right)^2$

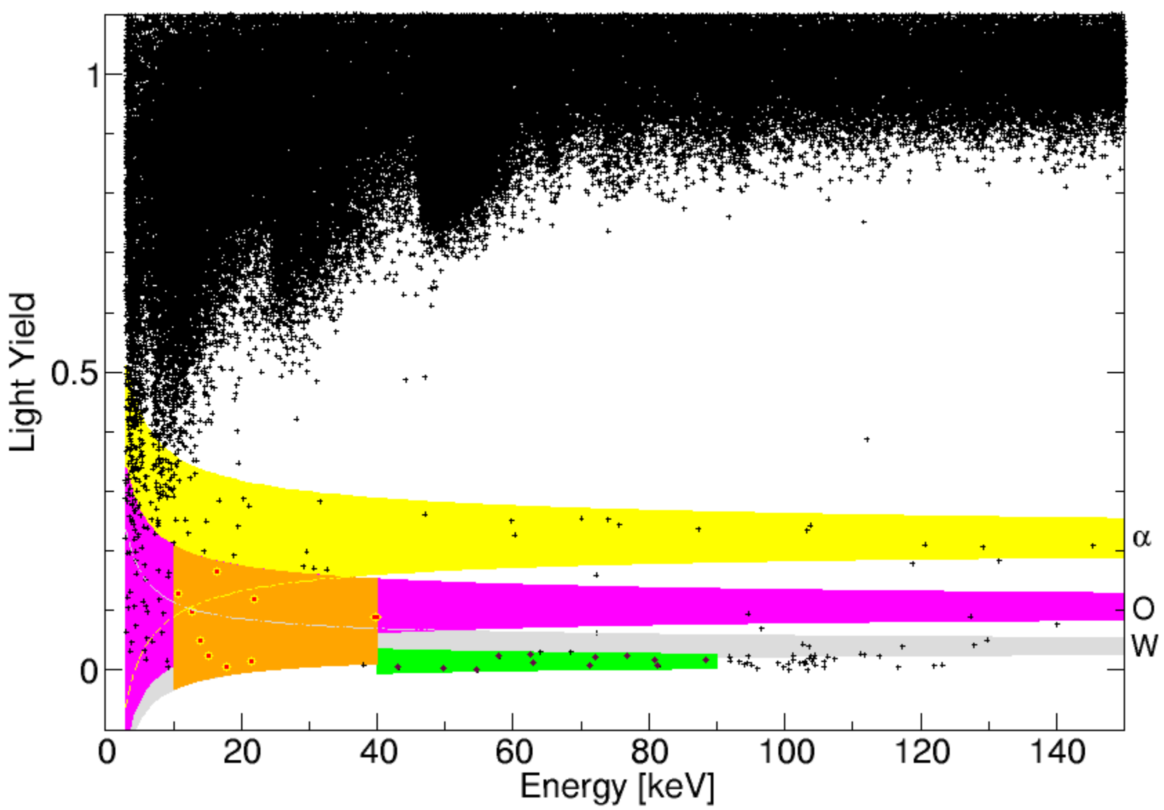
CoGeNT



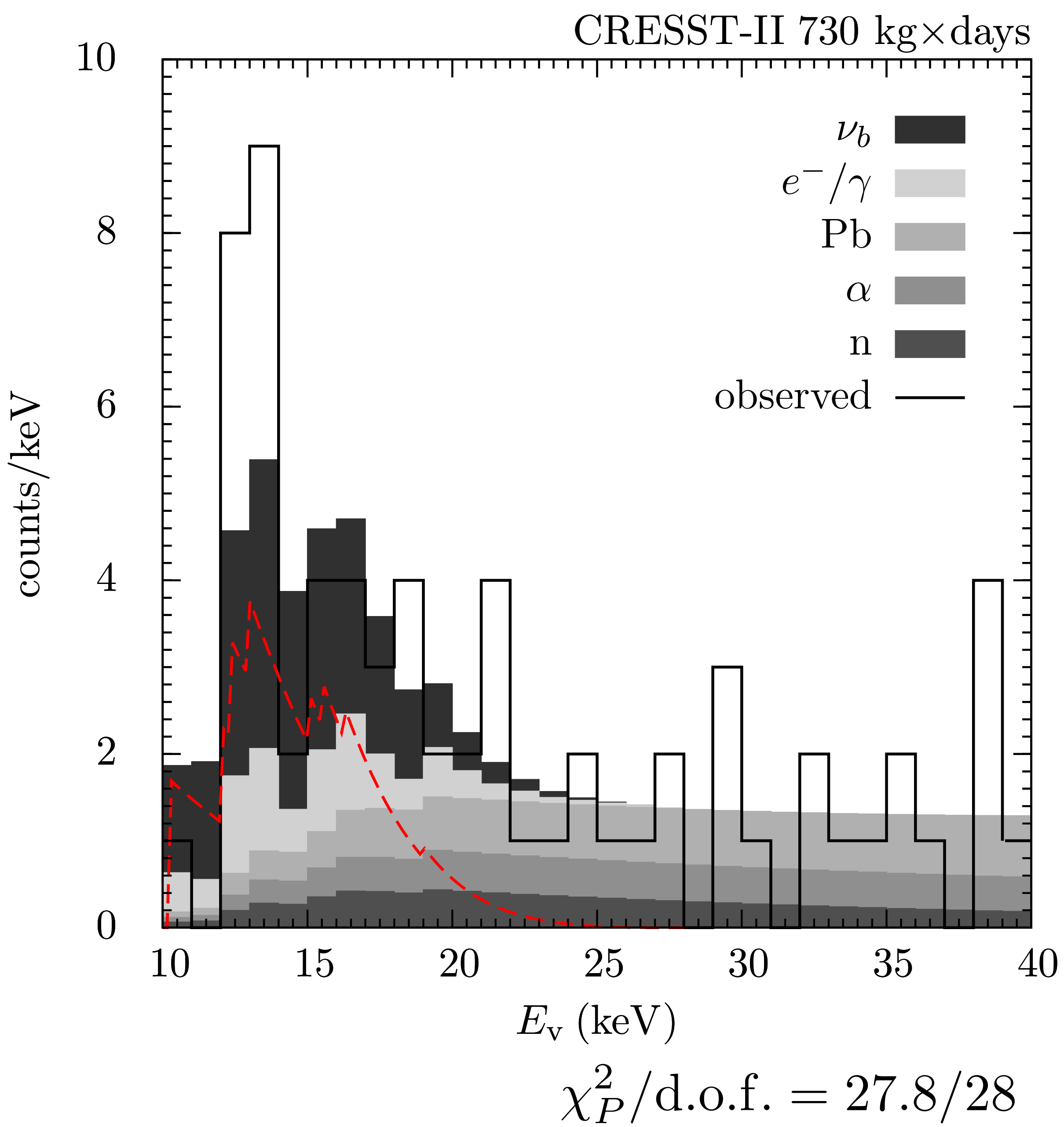


2012 $\Longrightarrow$ 2013

CRESST-II

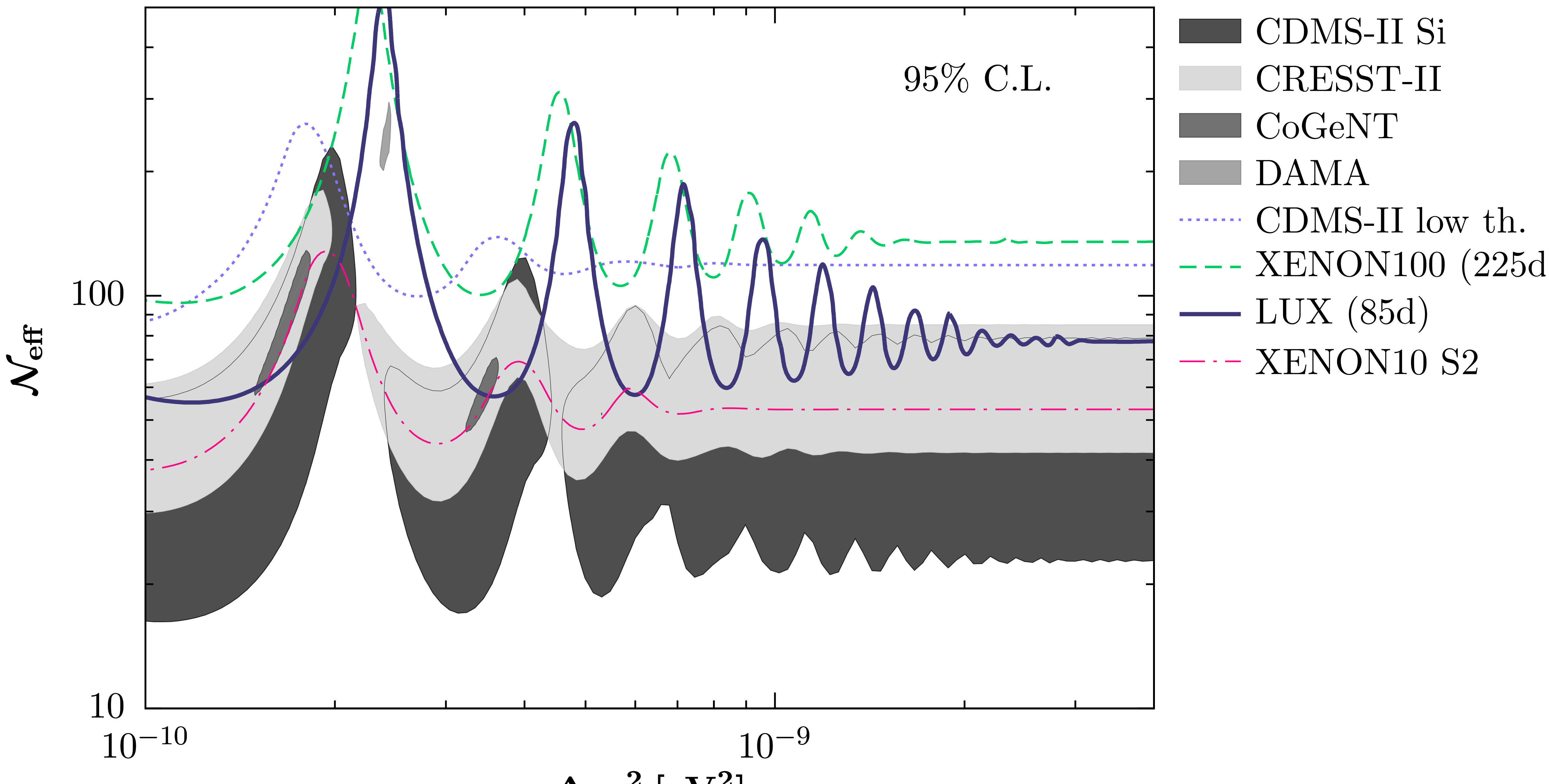


Angloher et al EPJC 2012



- 8 $CaWO_4$ crystals, 730kg days
- 67 events, only half understood as background

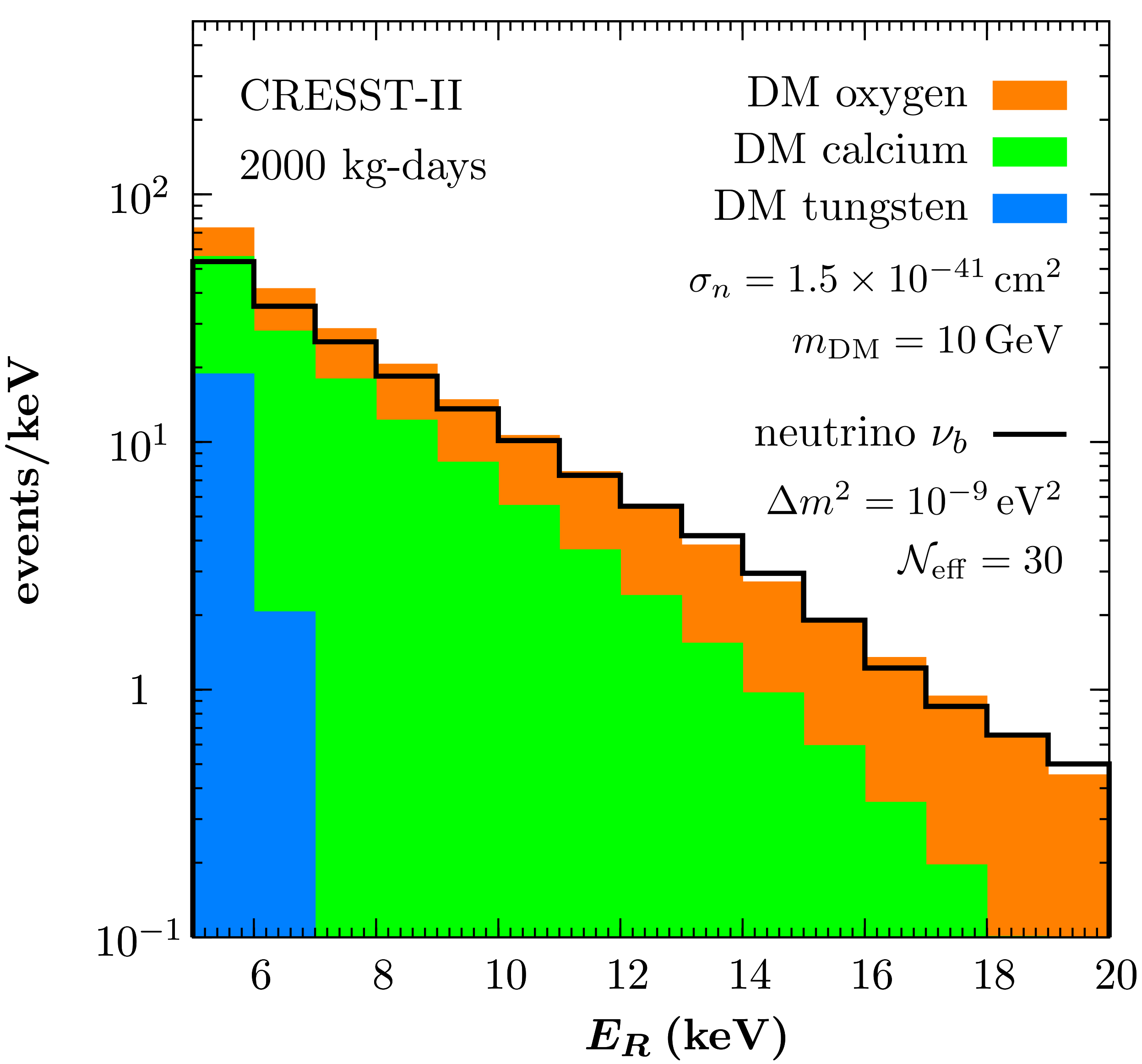
A joint explanation of anomalies*



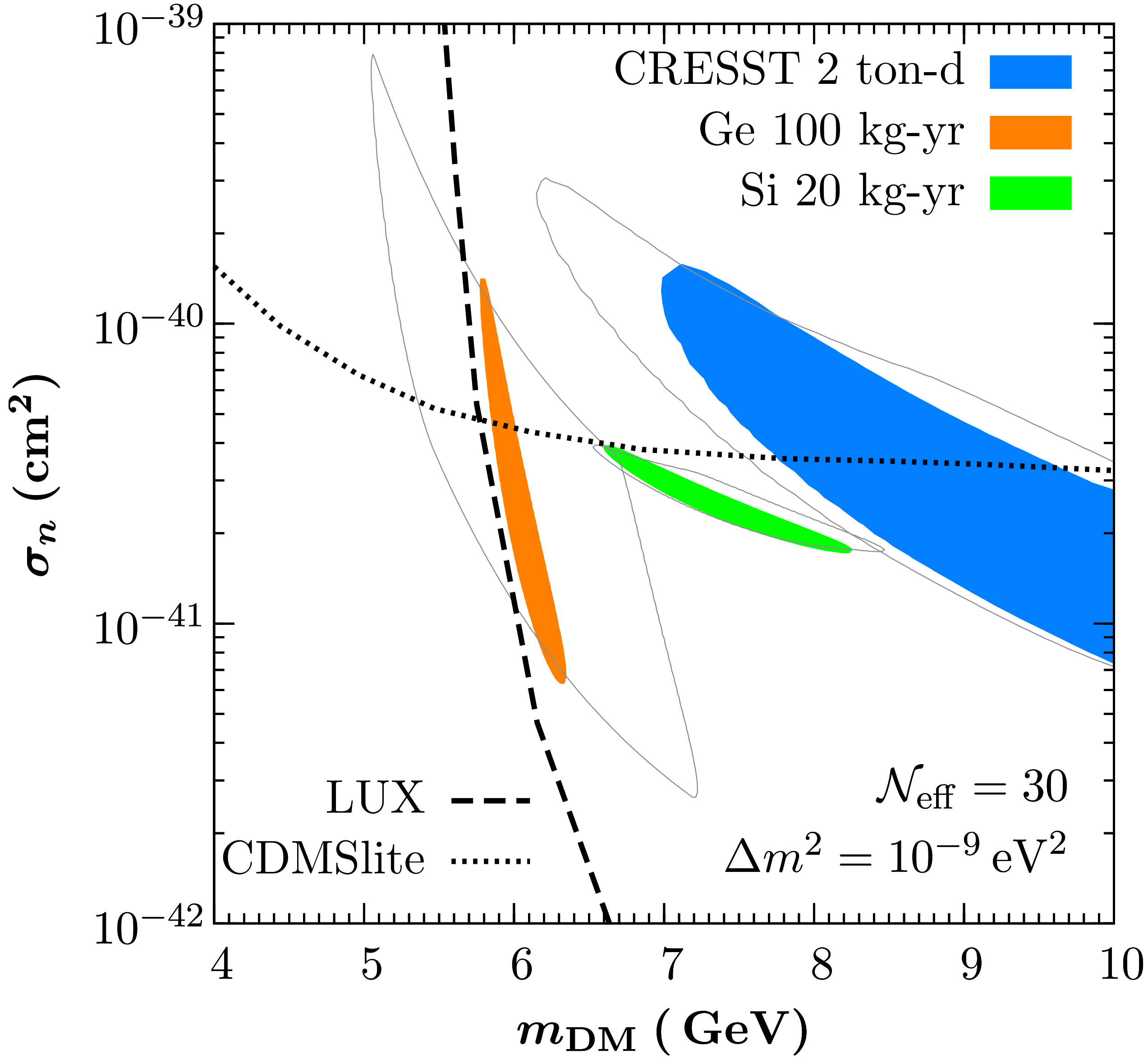
*except DAMA

Light DM vs. ν_b

signals look alike



DM interpretation of a ν_b signal



=> complementary targets needed

Inelastic signals

1311.5347

- C-excitation in Borexino

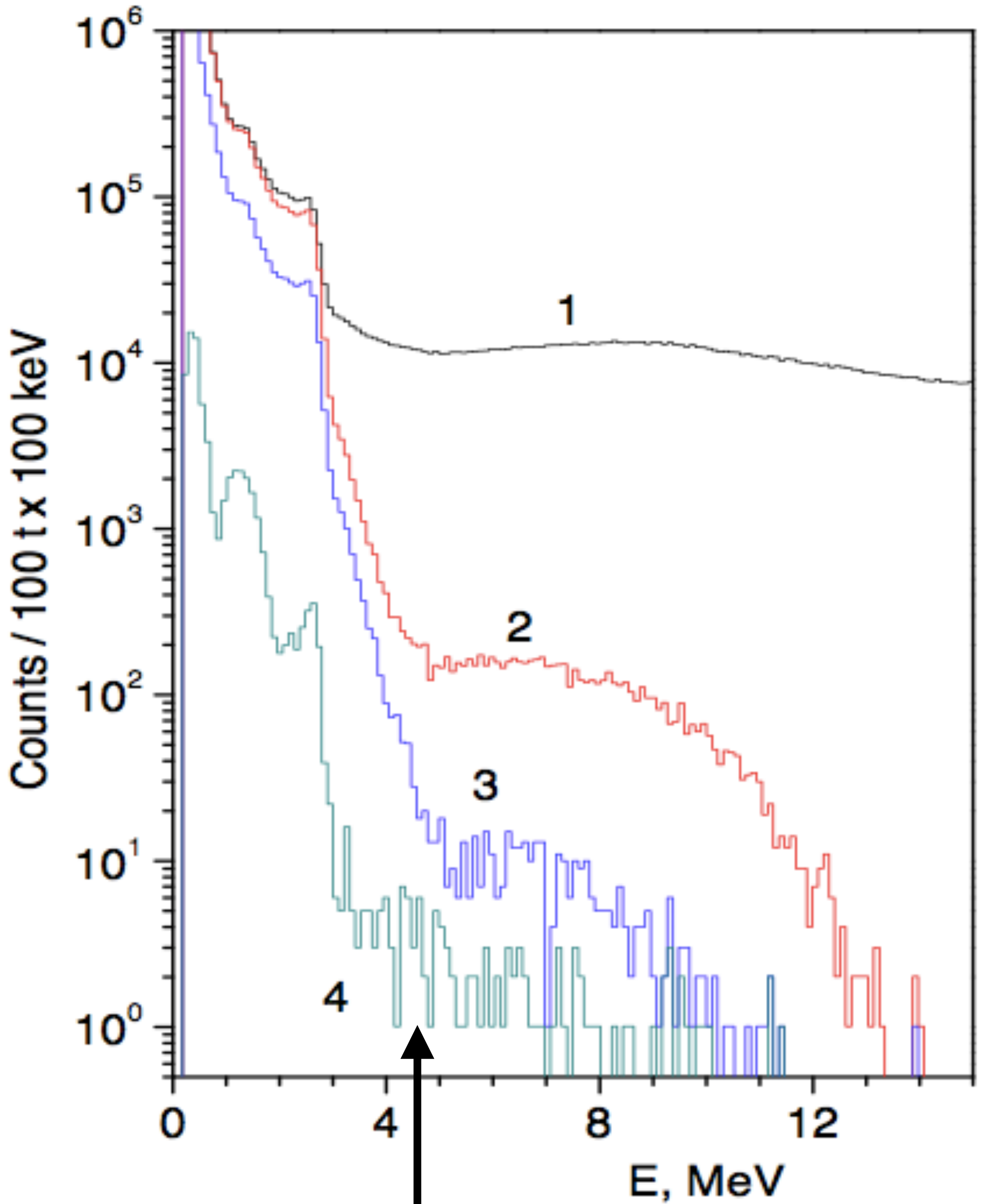
$$^{12}\mathrm{C} + \nu_b \ \rightarrow \ \nu_b +^{12}\mathrm{C}^*(4.44\ \mathrm{MeV}) \rightarrow \nu_b +^{12}\mathrm{C} + \gamma$$

- "**by-eye**" sensitivity:

$$R_{\rm obs} \sim \frac{6\,\mathrm{events}}{100\,\mathrm{ton}\times 442\,\mathrm{days}}$$

subtract 8B ES bkg. by eye $6 \rightarrow 3$
& use estimate from Pospelov 2011
on excitation cross section

$$\mathcal{N}_{\rm eff} \lesssim 30 - 40 \ (90\%\mathrm{C.L.})$$



C-line would show up here

Inelastic signals

1311.5347

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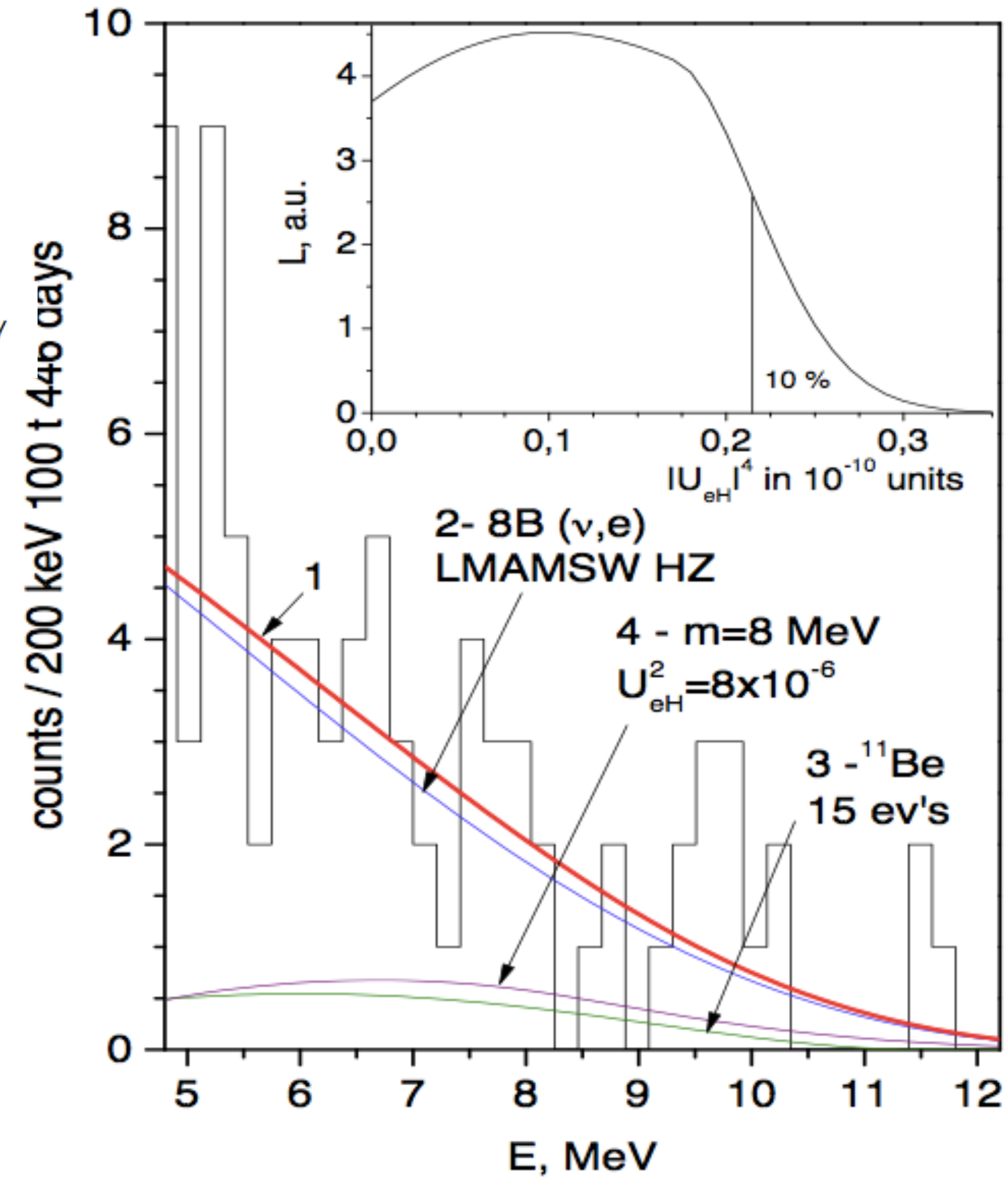
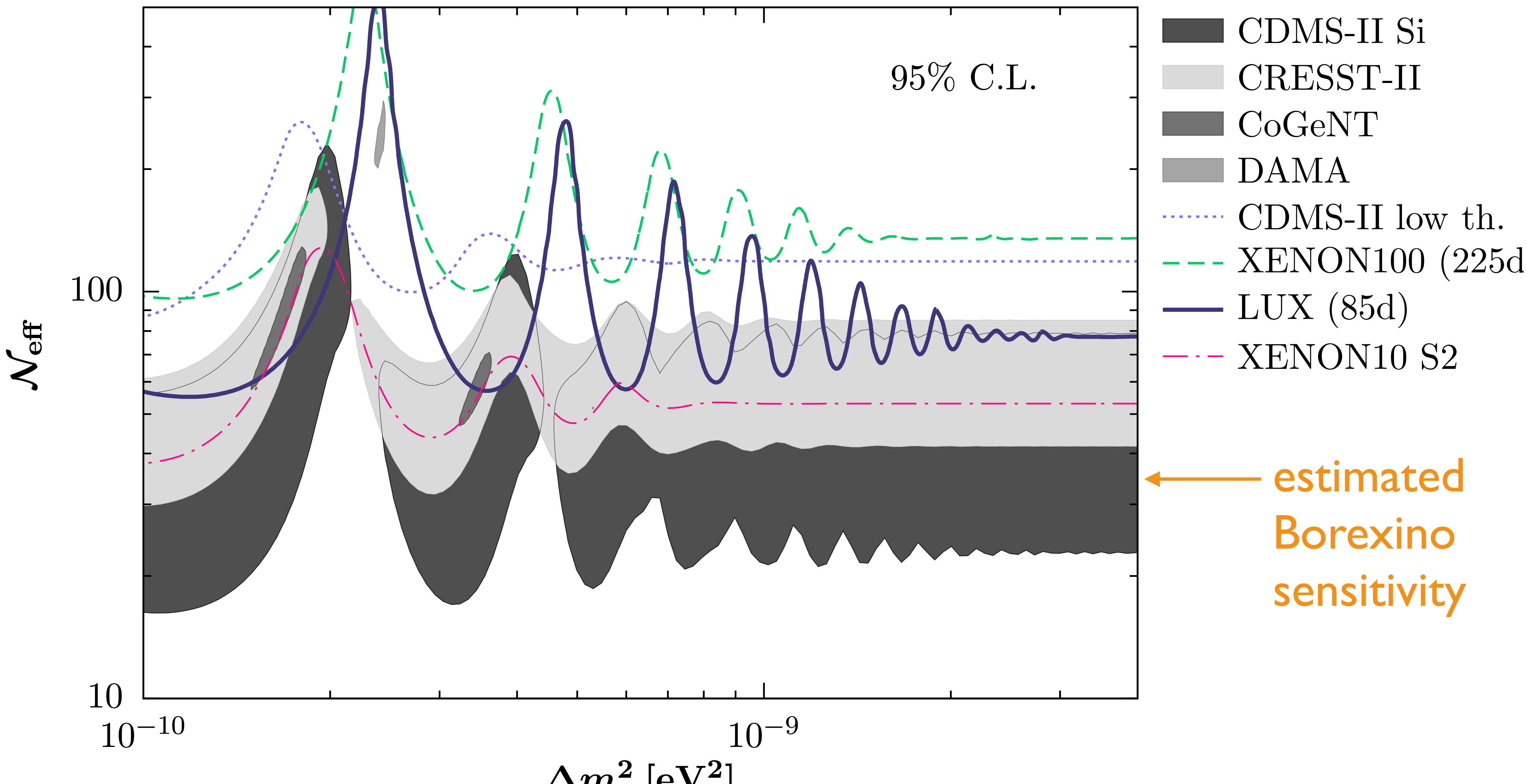


FIG. 4. The Borexino spectrum in the $(4.8 - 12.8)$ MeV

A joint explanation of anomalies*



*except DAMA

Neutrino oscillation portal

- portal does not guard new interactions on astrophysical baselines

$$L_{\rm osc} = \frac{4\pi E_\nu}{\Delta m^2} \approx 1\,\mathrm{AU}\left(\frac{10^{-10}\,\mathrm{eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)$$

$$\downarrow \qquad\qquad \downarrow$$

$$L_{\rm osc} = \frac{4\pi E_\nu}{\Delta m^2} \approx 1\,\mathrm{kpc}\left(\frac{10^{-10}\,\mathrm{eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{1\,\mathrm{PeV}}\right)$$

- **Are IceCube's recent measurements of non-atmospheric highest energy neutrino flux affected by the new state?**

IceCube
high energy neutrino flux

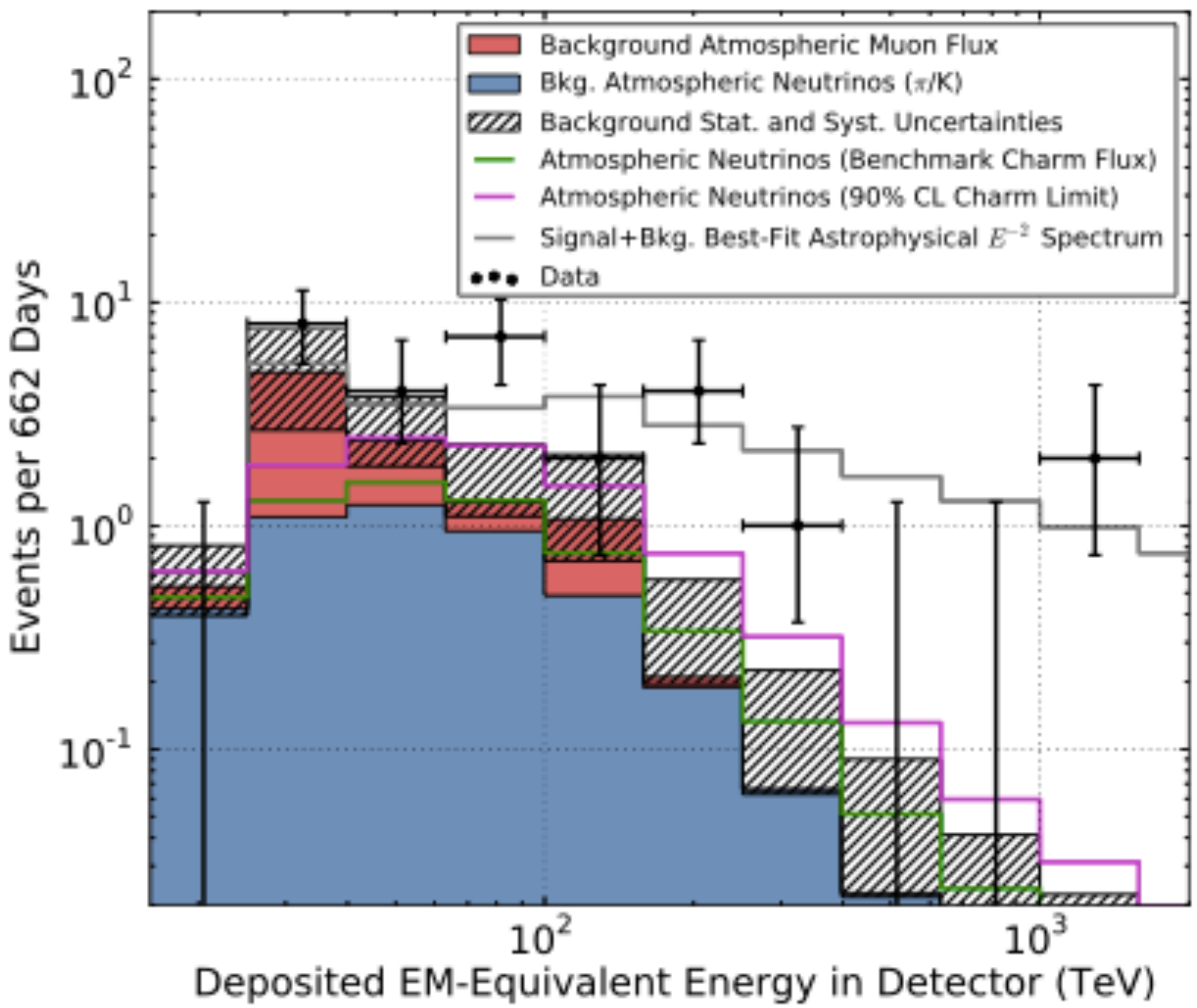
- IceCube IC-79/IC-86 2 year data

  2 events at PeV energy

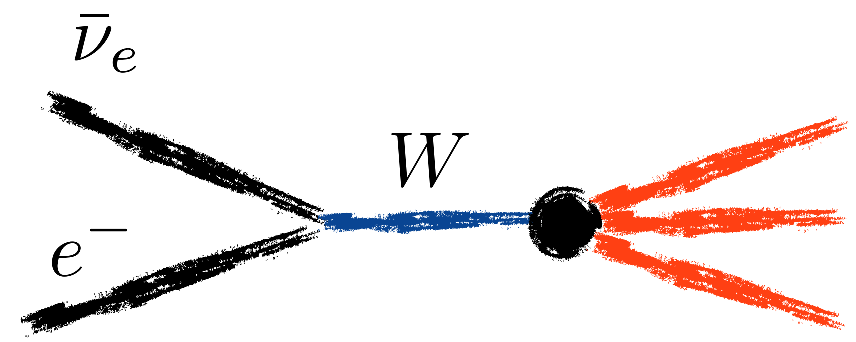
  26 more event 20-200 TeV

- Highest energy neutrino events ever observed

IceCube 2013



IceCube
reported features



Glashow resonance

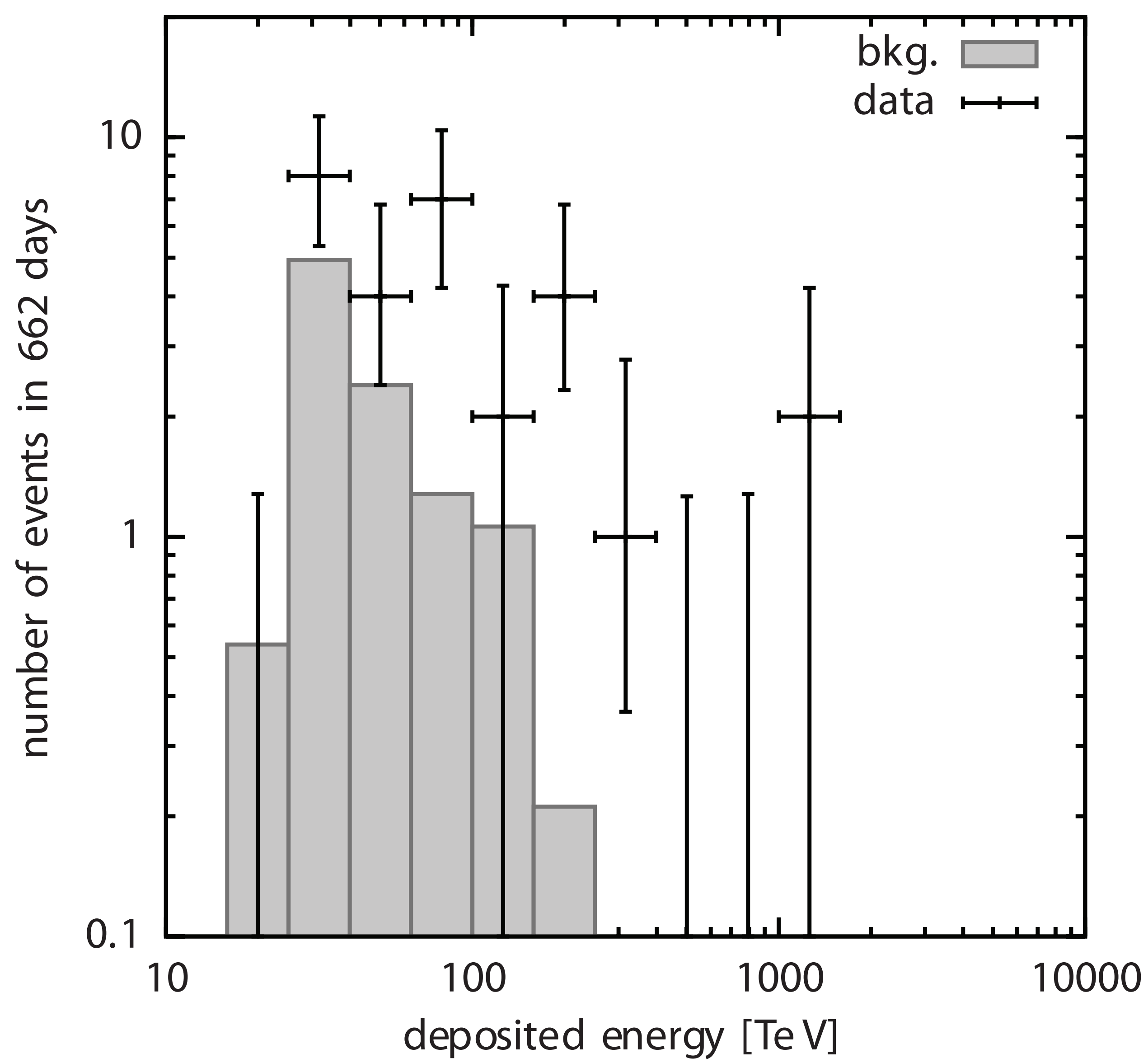
- atmospheric origin excluded (4σ)
- consistent with isotropic flux

$$E^2\Phi(E) \simeq 10^{-8}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

- **potential cutoff above ~ 2 PeV?**

where is the "Glashow resonance" @ 6.3 PeV? $m_W = \sqrt{2m_eE_\nu}$

(3-6 events are missing)



IceCube 2013

A new window into neutrino physics?

The measurements of the high-E neutrino flux will primarily educate us about the origin of high-E cosmic rays.

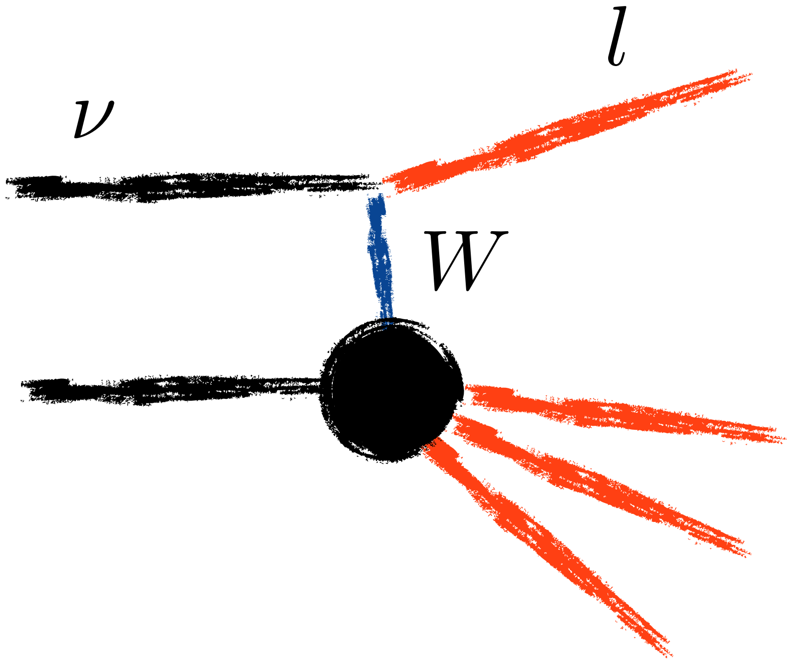
see, e.g., Murase et al., Laha et al., W. Winter

But IceCube, at those energies, may also tell us more about new physics in the neutrino sector. Can we:

- induce signals in excess of the Waxman-Bahcall bound?
- "suppress" events in the Glashow resonance region / spectral cut off?
- change observables like shower/track ratio or sky-distribution?
- relax the relation between diffuse gamma rays and nu-flux?

IceCube event topologies

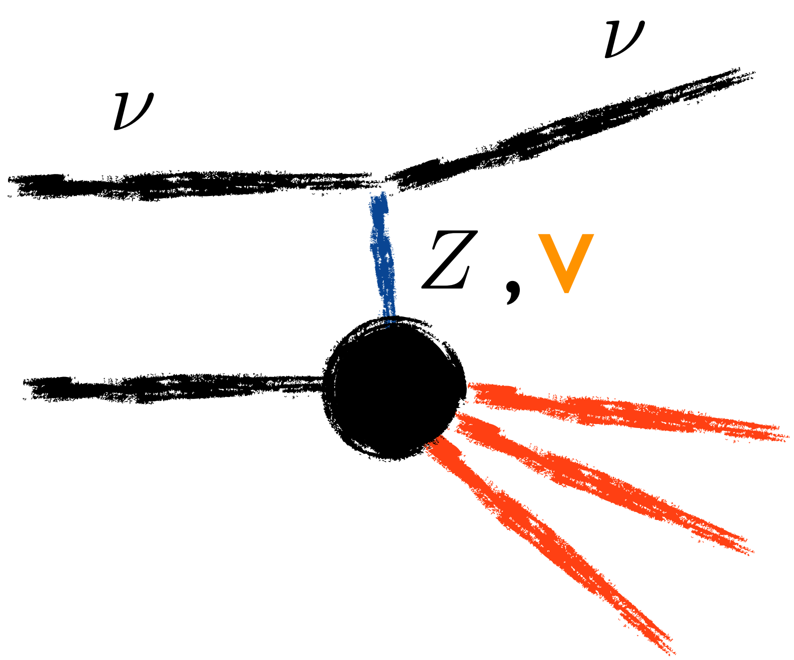
CC



ν_μ ...tracks

$\nu_{e,\tau}$ ...showers
(for sub-PeV ν_τ)

NC **+ NCB**

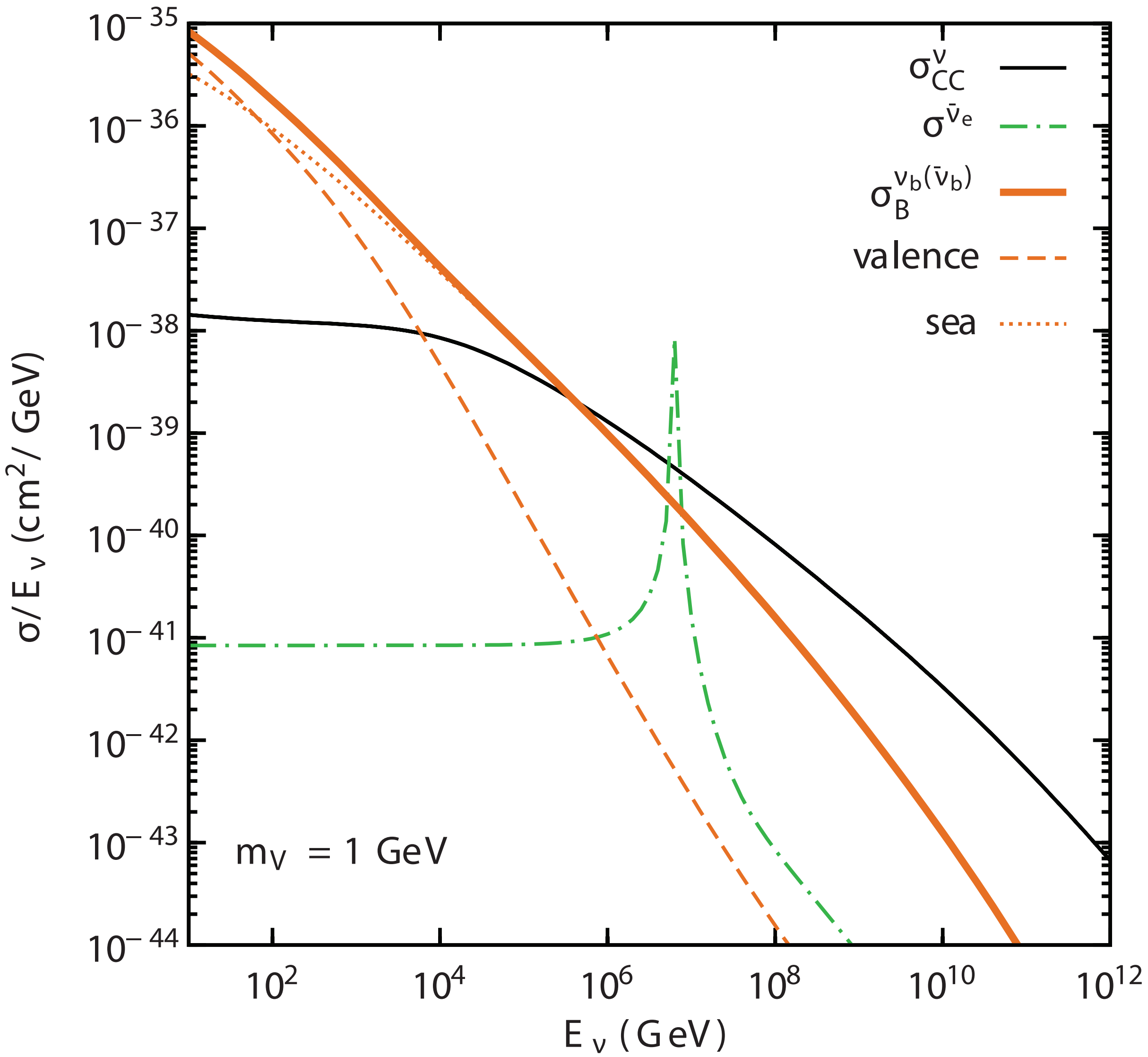


ν_x ... showers
~ 40% of E_ν deposited

+ additional shower events
XX% of E_ν deposited

DIS cross section

$$\frac{d^2\bar{\sigma}_B}{dxdy} = \frac{G_B^2 q_B^2}{2\pi} \frac{E_\nu m_\mathcal{N}}{(1+Q^2/m_V^2)^2} \times (\text{"Baryonic Form Factor"})$$



$G_B = 200 G_F$

- A new light mediator V cuts off cross section at lower energies

=> less PeV for more TeV events

=> effective suppression of events in the Glashow resonance region!

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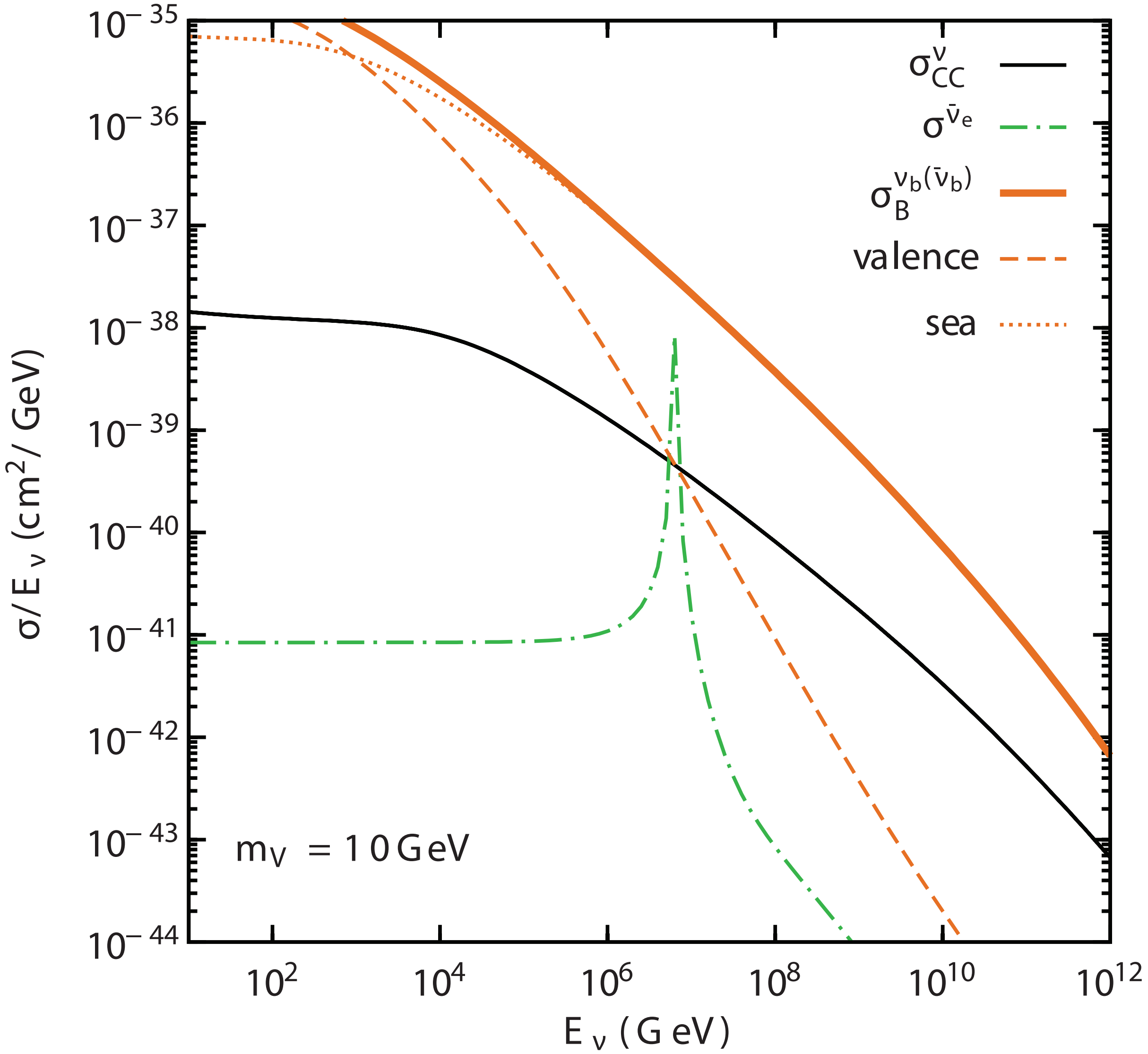

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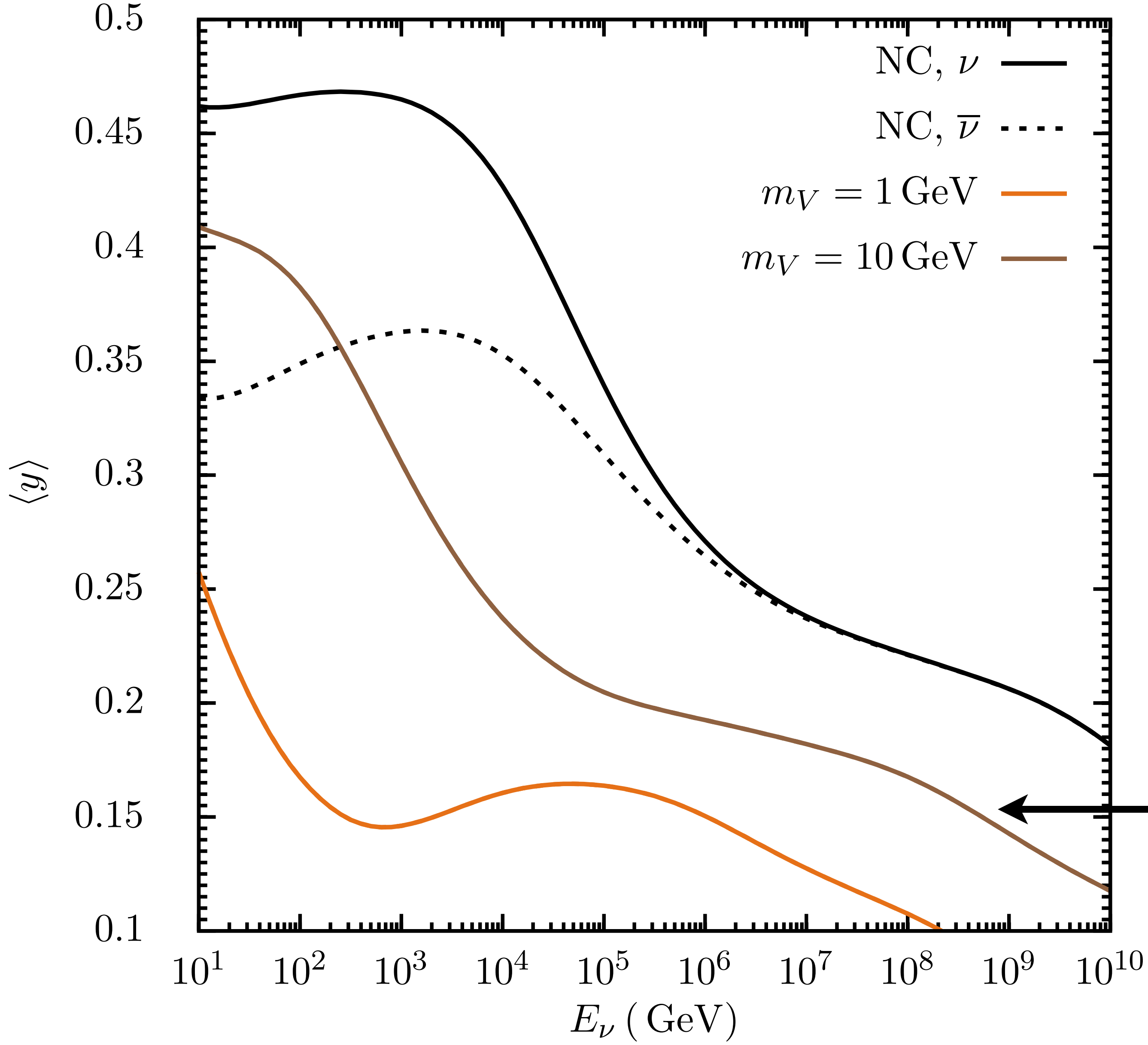
DIS average inelasticity



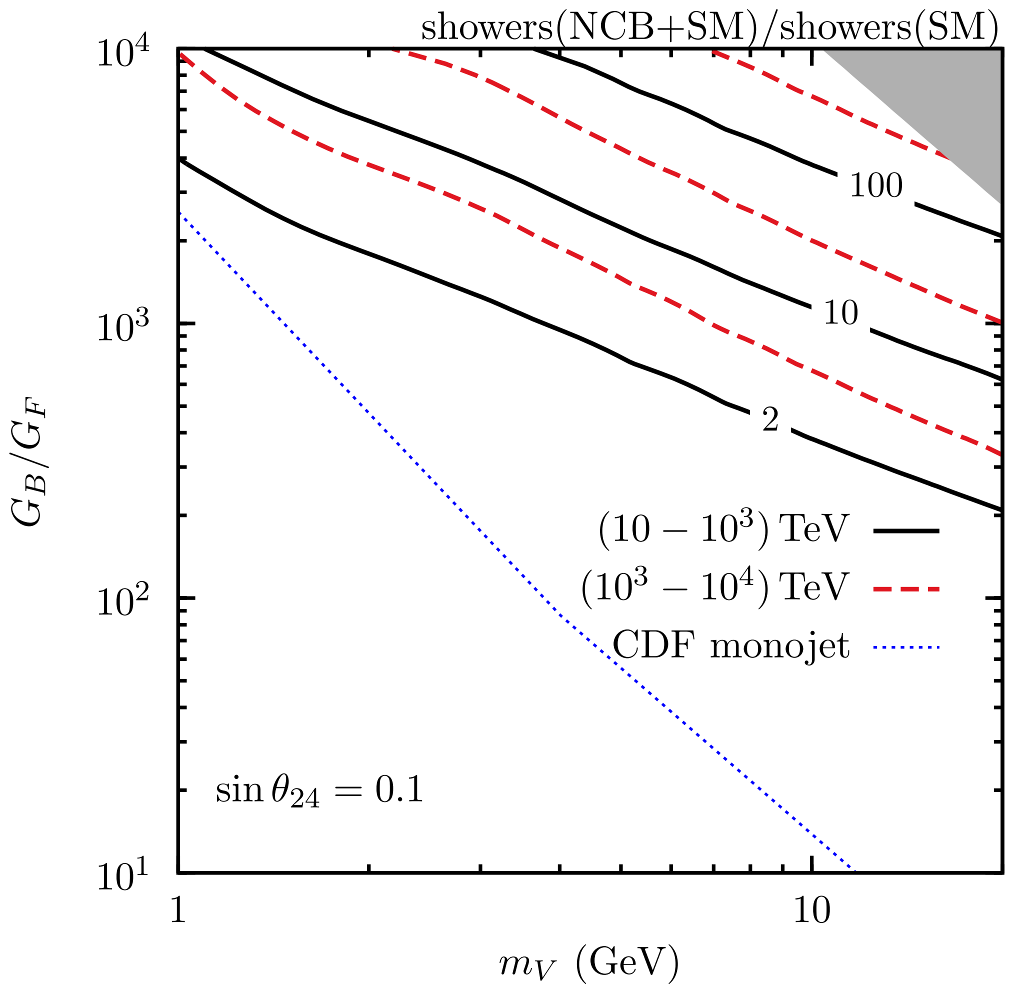
$$y = \frac{E_\nu - E'_\nu}{E_\nu}$$

$\langle y \rangle E_\nu$ ...average energy deposited in the detector

baryonic scatterings are *softer* than NC

=> heavier mediators are favored!

IceCube observable shower/track ratio



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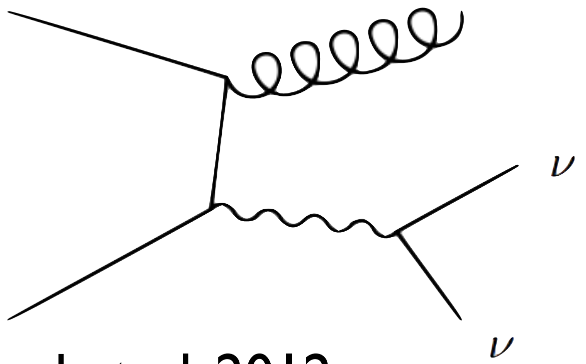
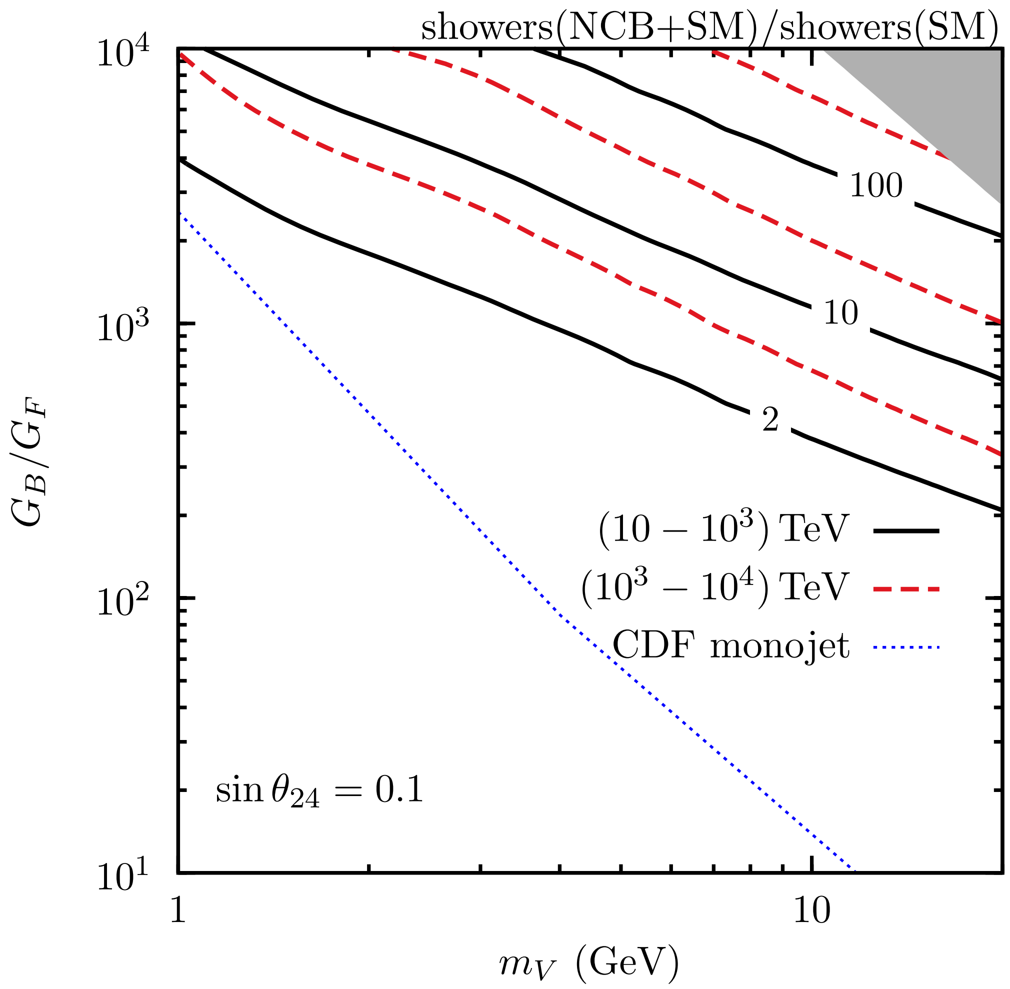
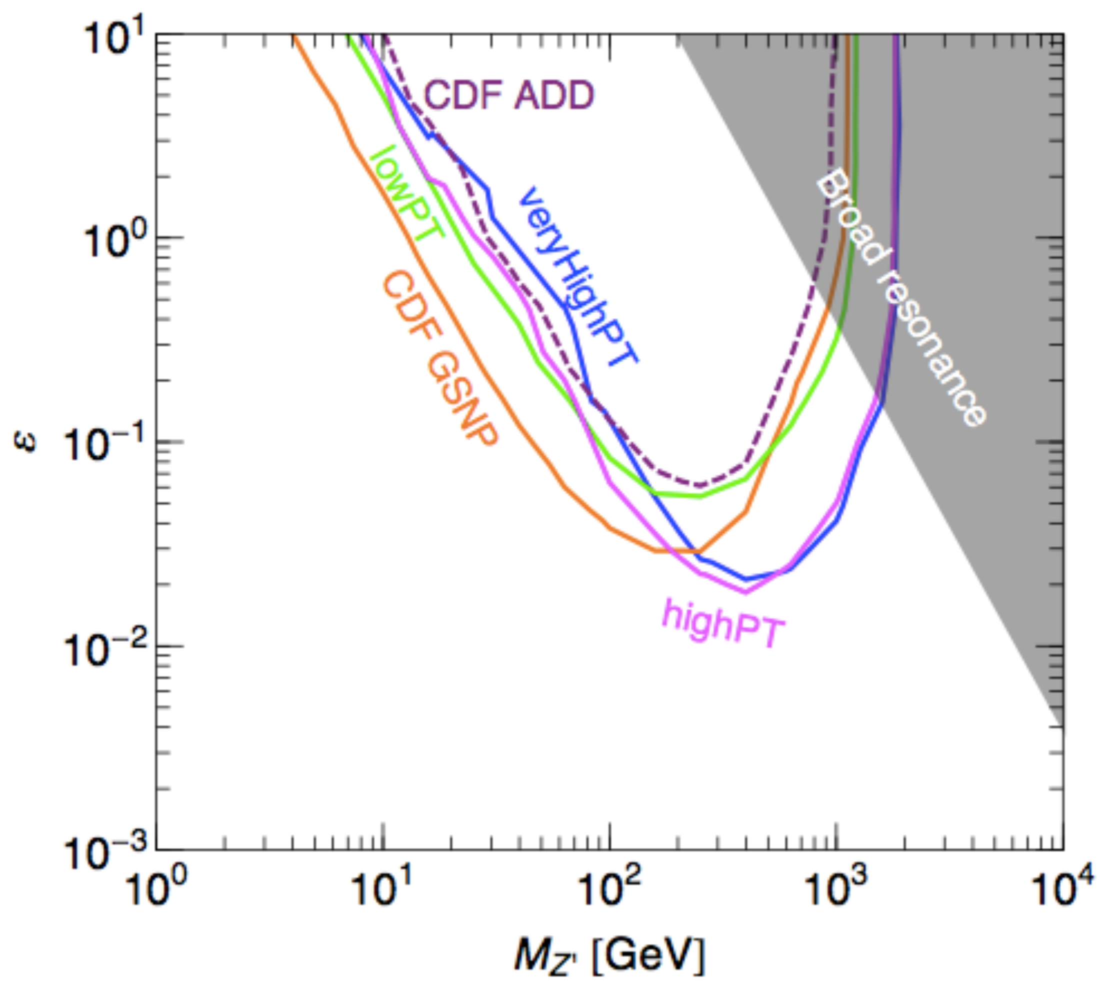




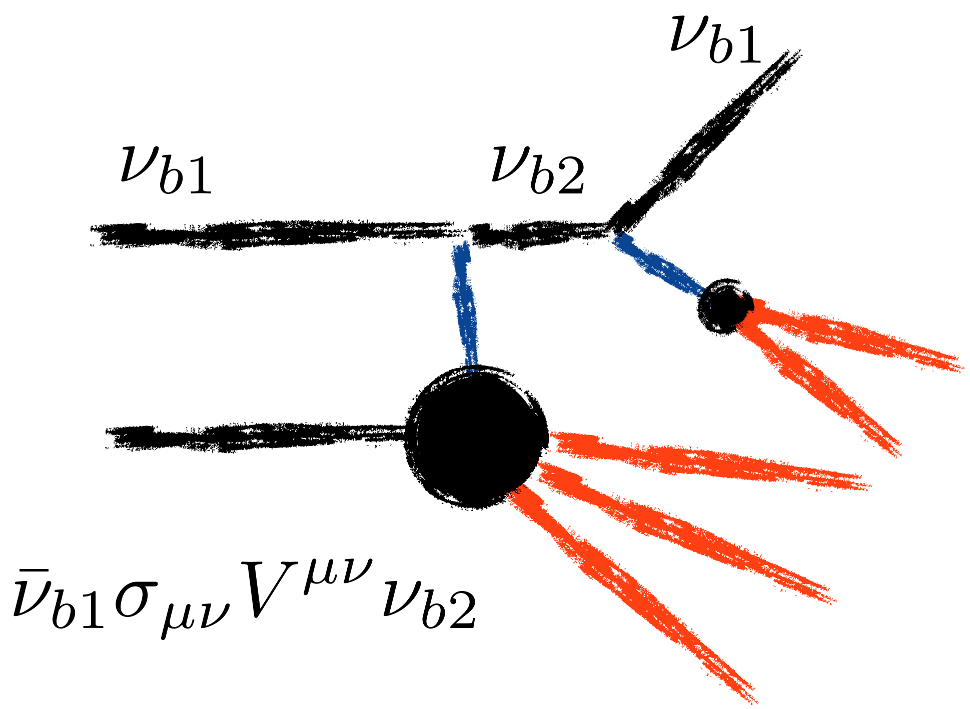
Friedland et. al, 2012



combination of largish vector masses together with large coupling is excluded by collider monojet constraints.

IceCube further avenues

=> we can entertain variants of the model and increase the energy deposition in the scattering, e.g.



If a "neutrino oscillation portal" would be operative, astrophysical signals may be the only means to probe such an extended neutrino sector.

(work in progress)

Summary

- “neutrino oscillation portal” guards enhanced interactions of new “sterile” neutrinos
- A new neutrino that couples with stronger-than-weak interactions to quarks provides alternative explanation to the dark matter direct detection anomalies; model “wins” when compared to10 GeV-ish DM explanations.
- variants of the model may also have interesting implications for the recent non-atmospheric (sub)-PeV IceCube neutrino observations

Outlook

- Using the "neutrino oscillation portal" we may, e.g. combine ν_b with eV-scale sterile neutrino scenario; joint explanation of DM anomalies and neutrino short-baseline anomalies possible?
- Laboratory searches of ν_b: on-shell production of baryonic vector V_μ in fixed targets
- early Universe:

  => $N_{\rm eff}$ little affected (see also Kopp & Dasgupta 2013)

  => coherent flavor transformation?

  For $\Delta m^2 = \mathcal{O}(10^{-10})\,\mathrm{eV}^2$ MSW condition met at $T \sim \mathrm{MeV}$

  effects on BBN yields of light elements?