# ν Signals of Dark Matter

## (and vice verse)

Roni Harnik, Fermilab

with Joachim Kopp and Pedro Manchado
JCAP 1207 (2012), 1202.6073

with Essig, Toro and Kaplan
PRD-82 (2010), 1008.0636

see related works by Maxim Pospelov and co.
0906.5614, 1103.3261, 1211.2258, 1203.0545

# DM vs. $\nu$ Detectors

* DM detectors (and searches for light resonances) share some features with $\nu$ detectors:
  - Large exposure (to a beam or any particle flying by).
  - Low backgrounds.
  - Low energy threshold.
* **Can they probe the same physics?**
  - Can DM detectors probe neutrinos? solar-ν's
  - Can ν detectors probe the dark sector? ν-Beams

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  - Can $\nu$ detectors probe the dark sector? $\nu$-beams

"Light NSI's" (a.k.a. light gauge boson)

(picking up from where Alex left off yesterday)

# DM Direct Detection

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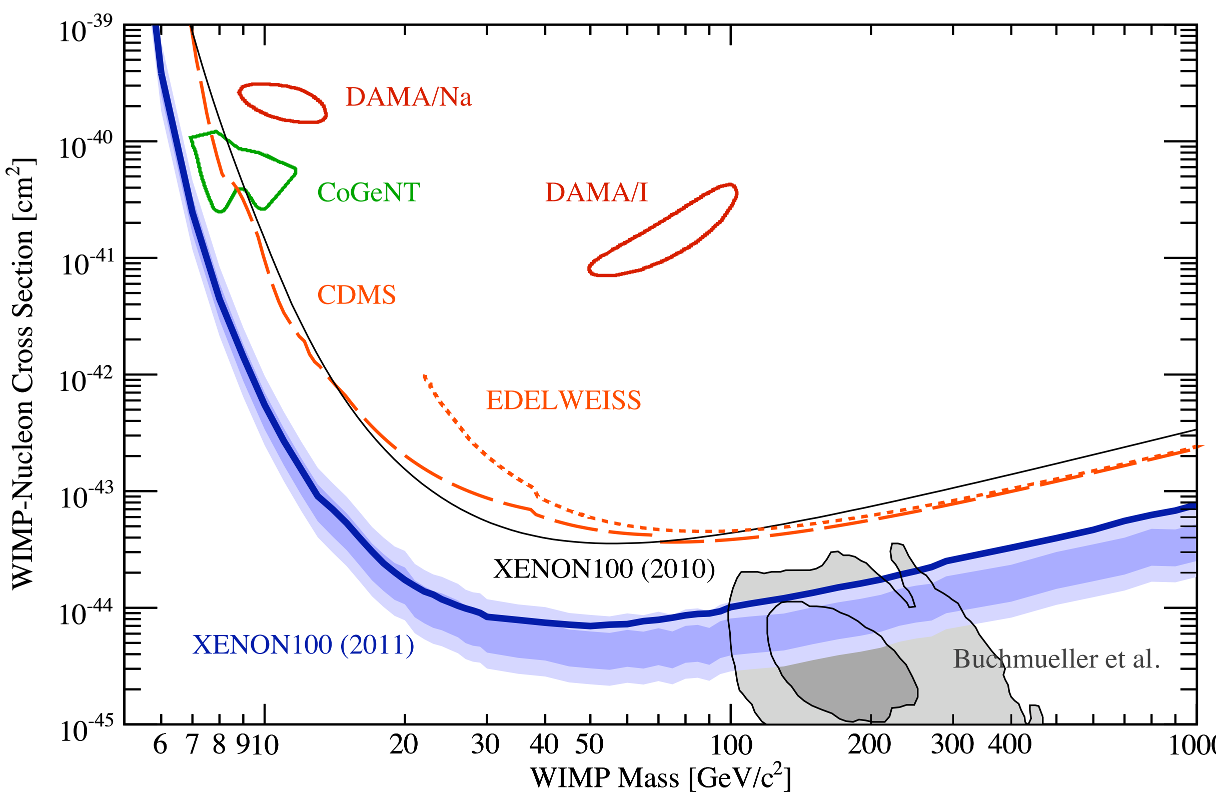
- A Heroic effort with remarkable results.
- Ultra-sensitive devices to detect the feeble kick of a WIMP deep underground.
- Endgame:
  **ν background:**




- Solar (low mass)
- Atmospheric (everywhere)

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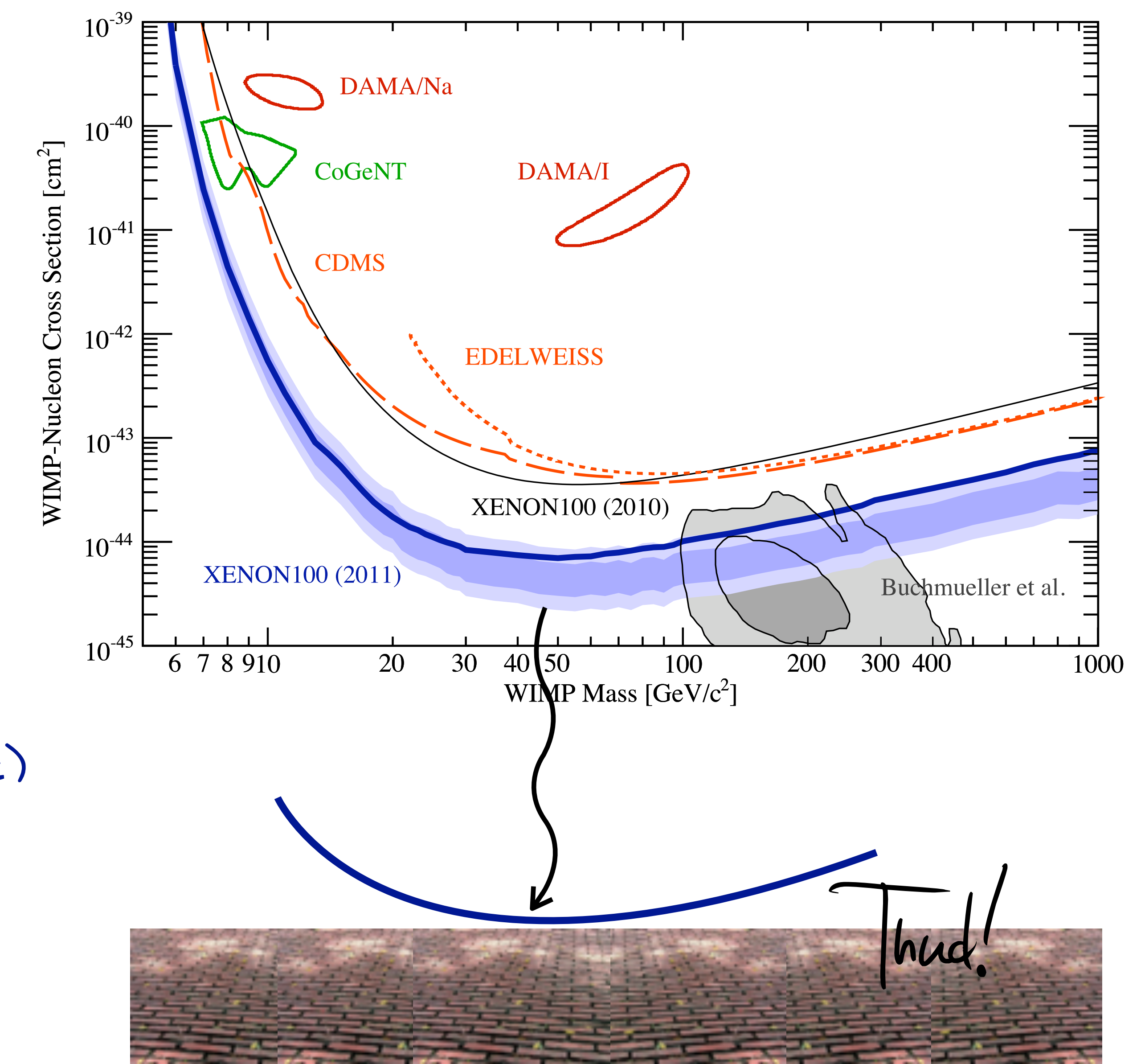
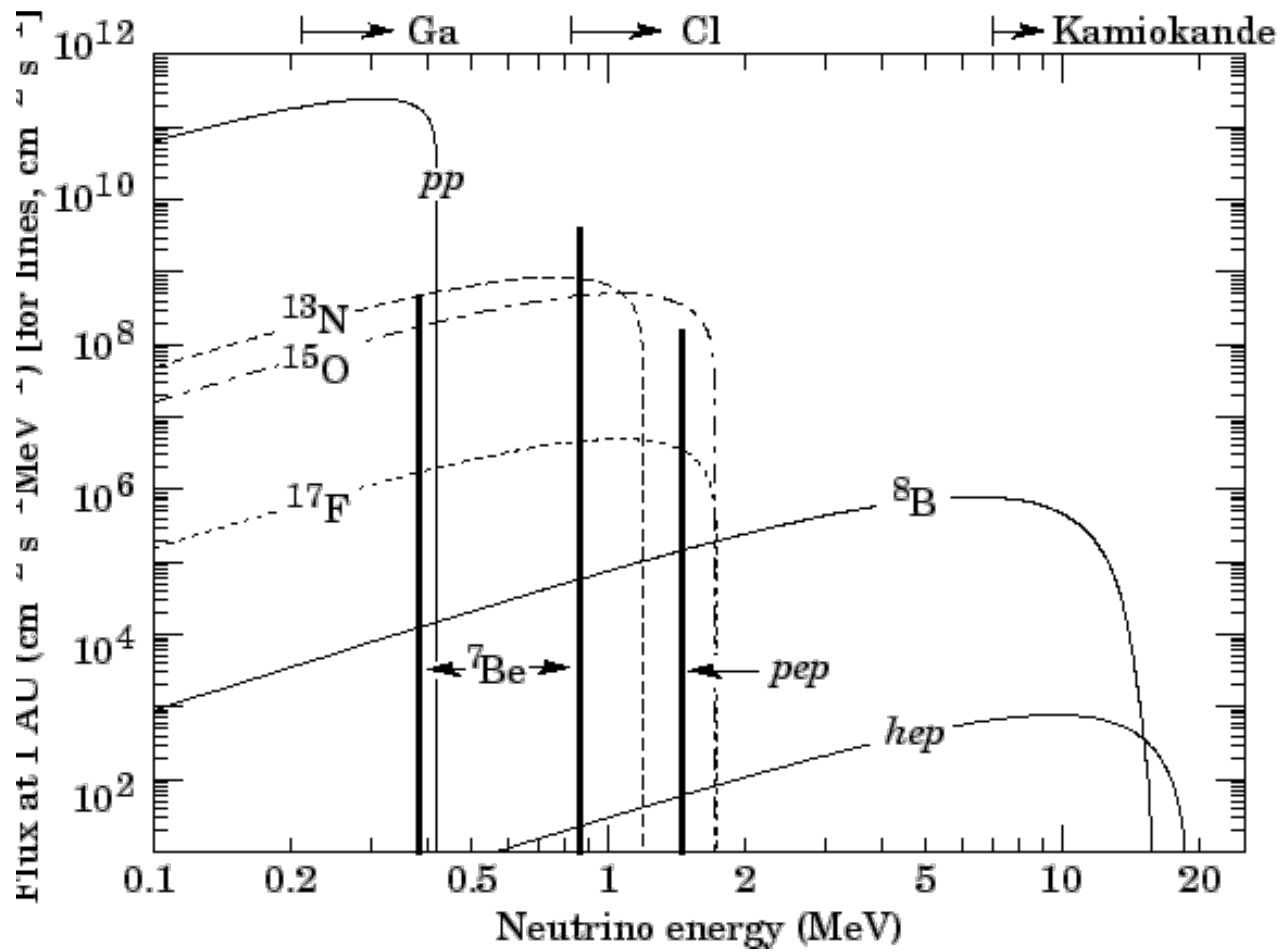


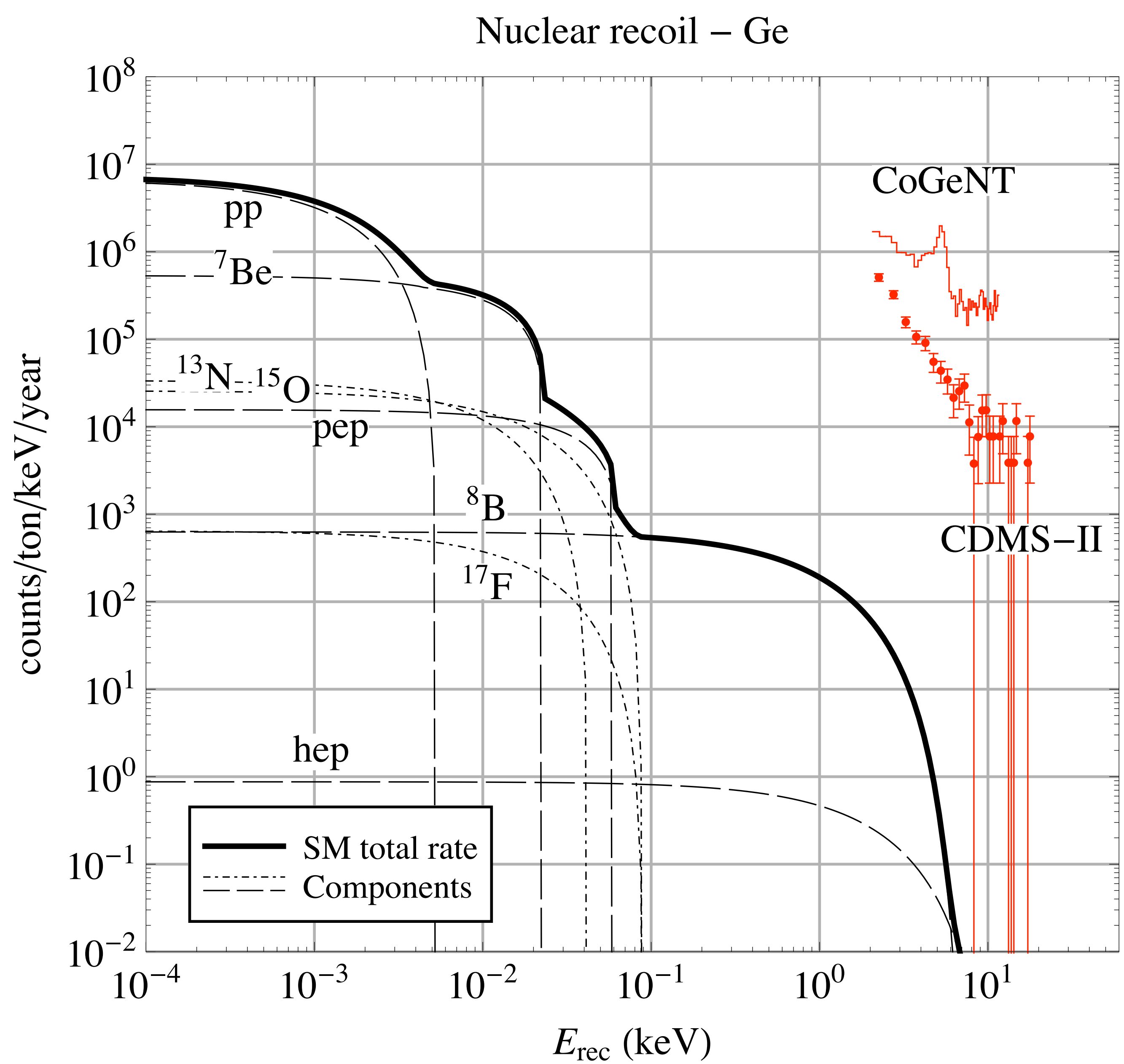
What does this look like
in a direct detection experiment?




$$\frac{dR}{dE_r} = N_T \int_{E_\nu^{\min}}^{\infty} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r} \, dE_\nu$$

# Spectrum

* For nuclear recoil:

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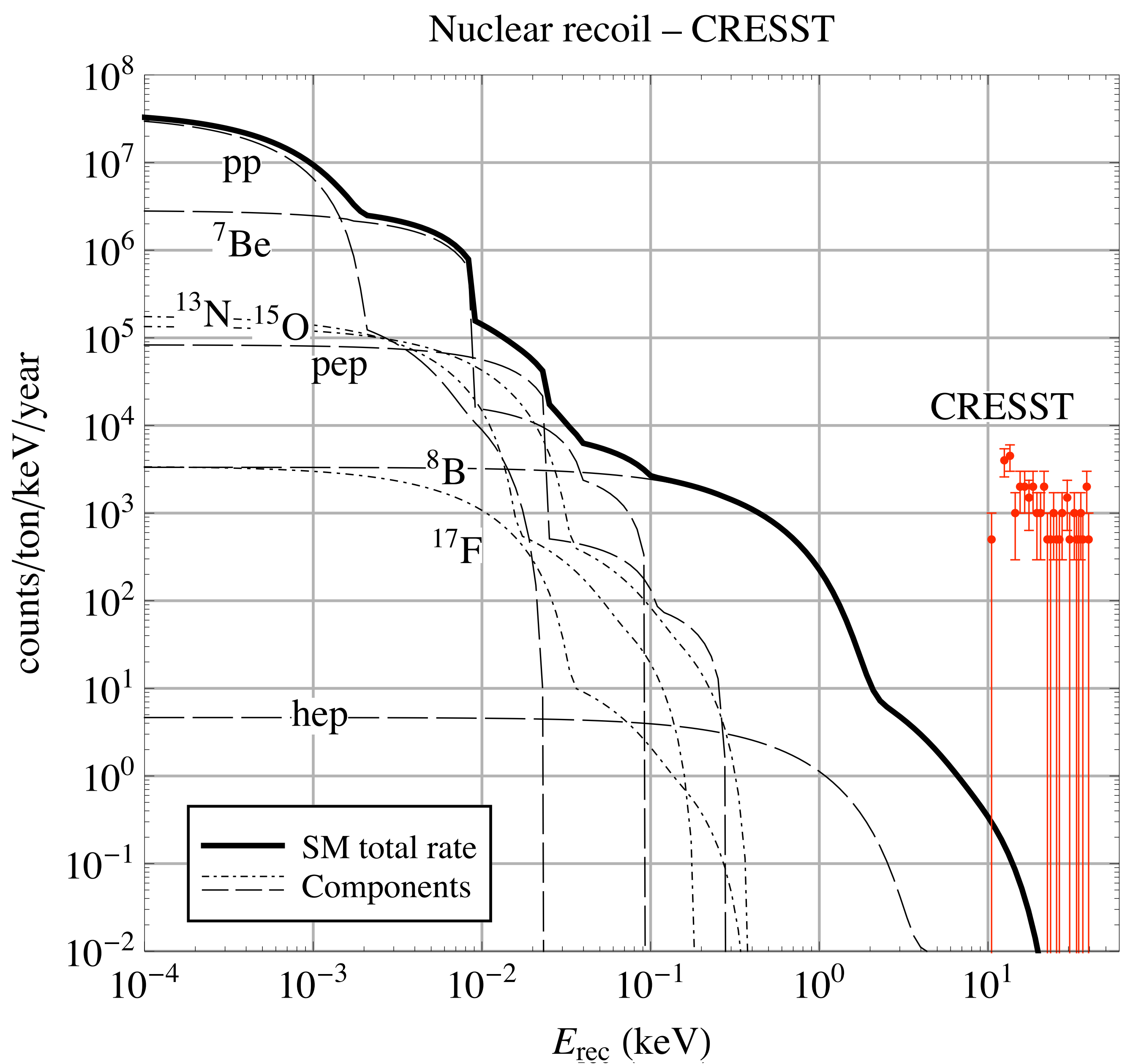


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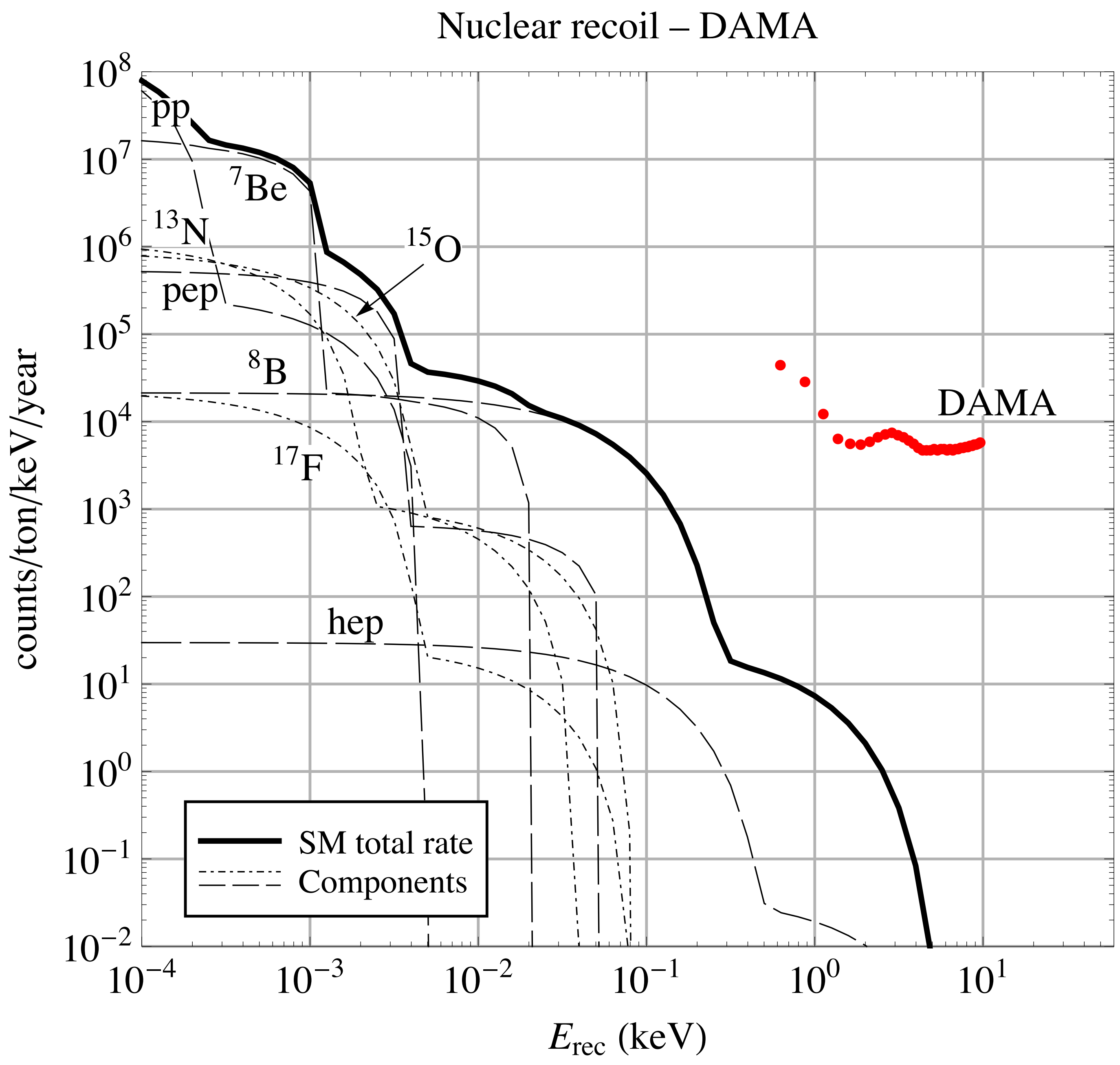


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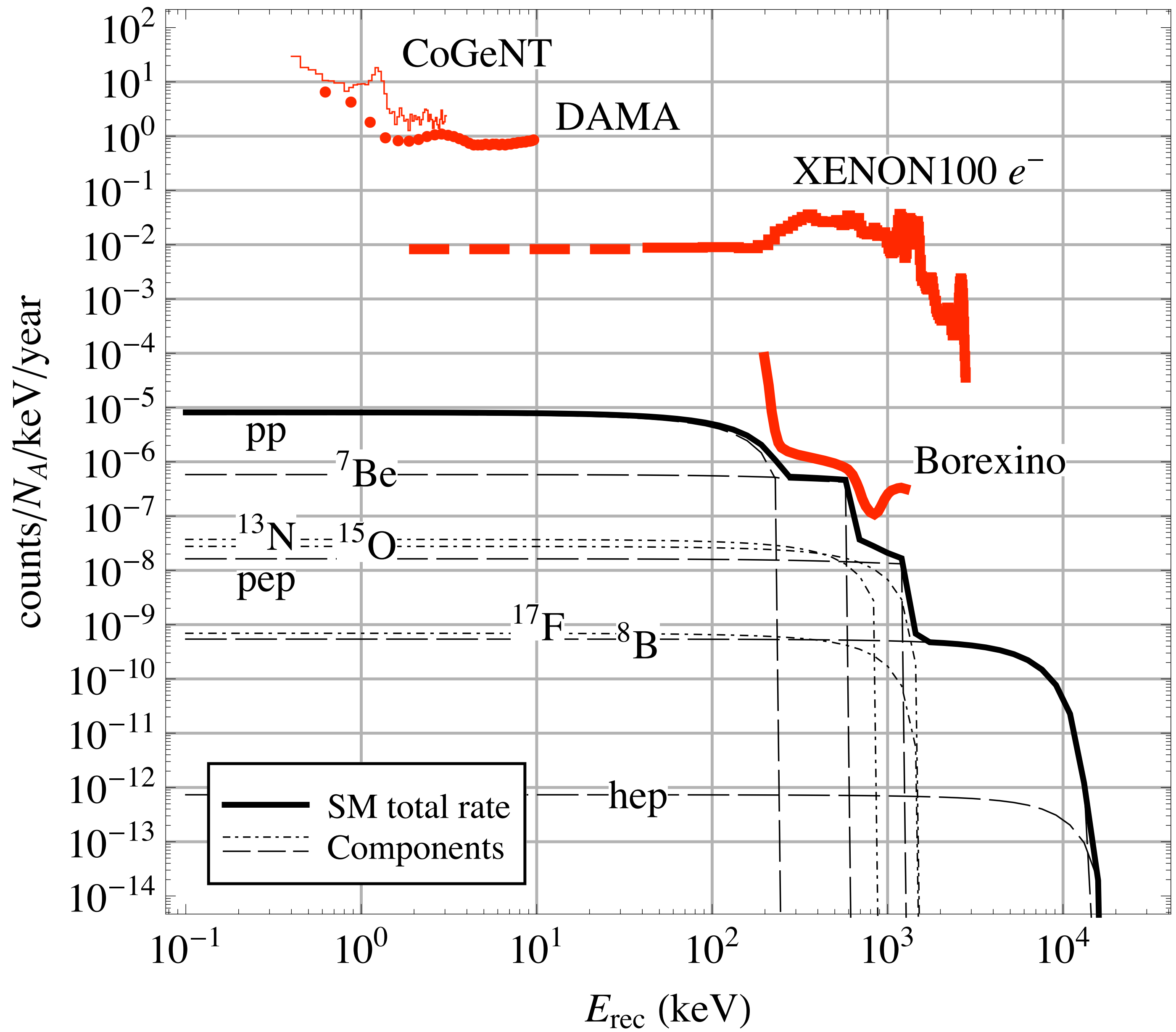
$$E_r^{\max} = \frac{2E_\nu^2}{m_T + 2E_\nu}$$

# Spectrum

* Electron recoil:
  - pp neutrinos are above threshold. High flux.

$$E_r^{\max} = \frac{2E_\nu^2}{m_T + 2E_\nu}$$

  - But, lower cross section, (phase space and coherence).




scattering on effectively free electrons.
All experiments in one plot!

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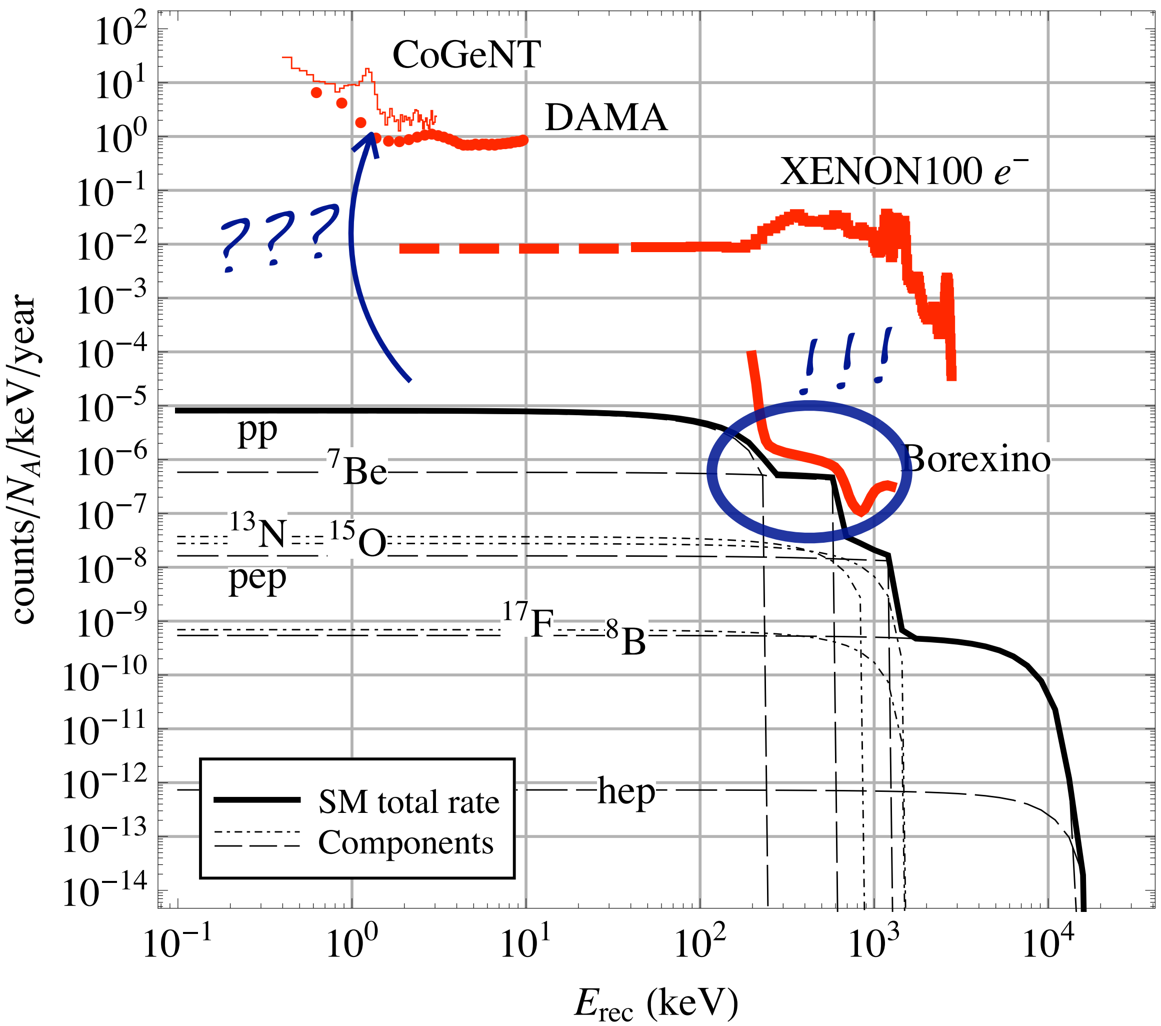

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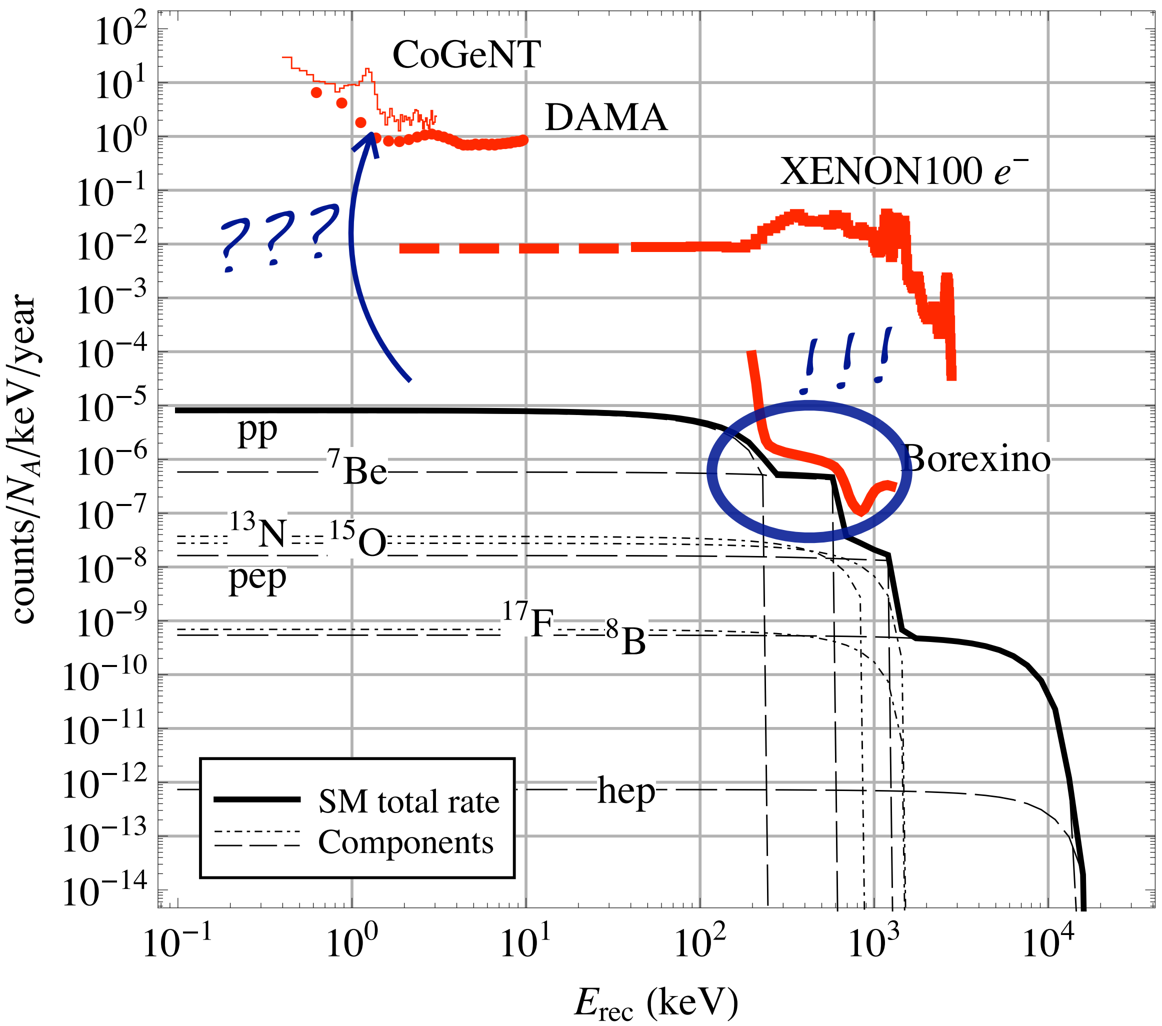


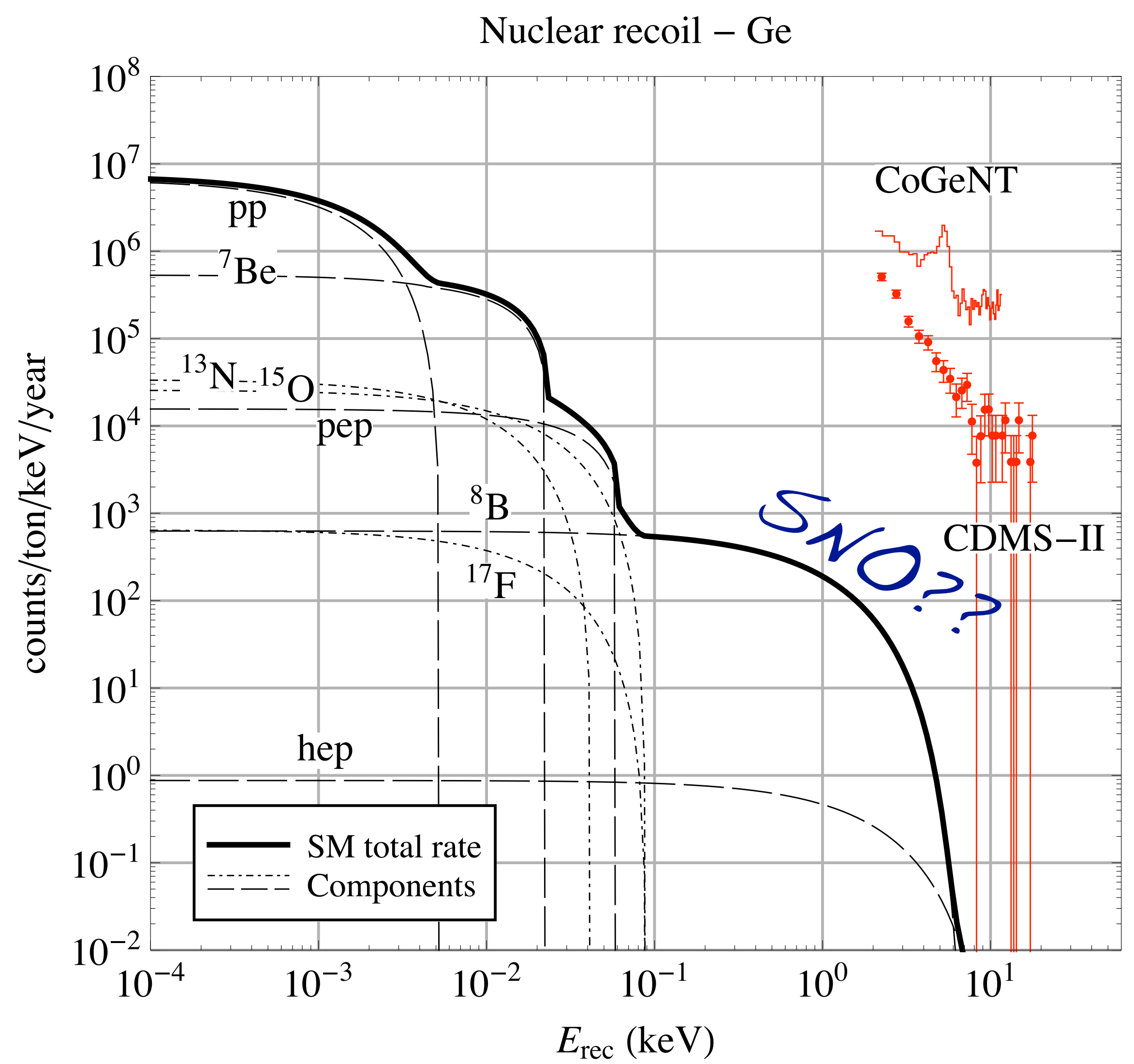

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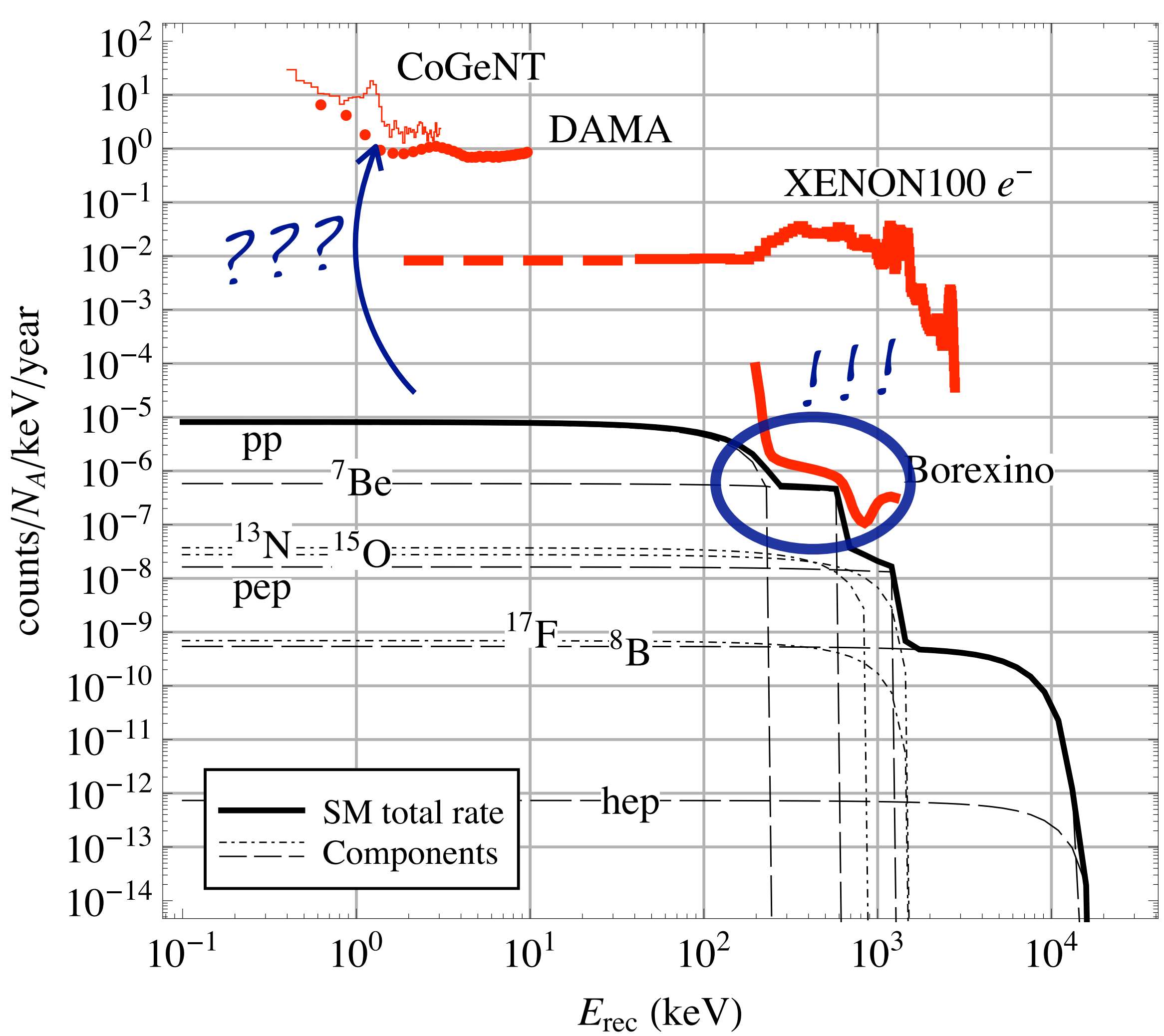


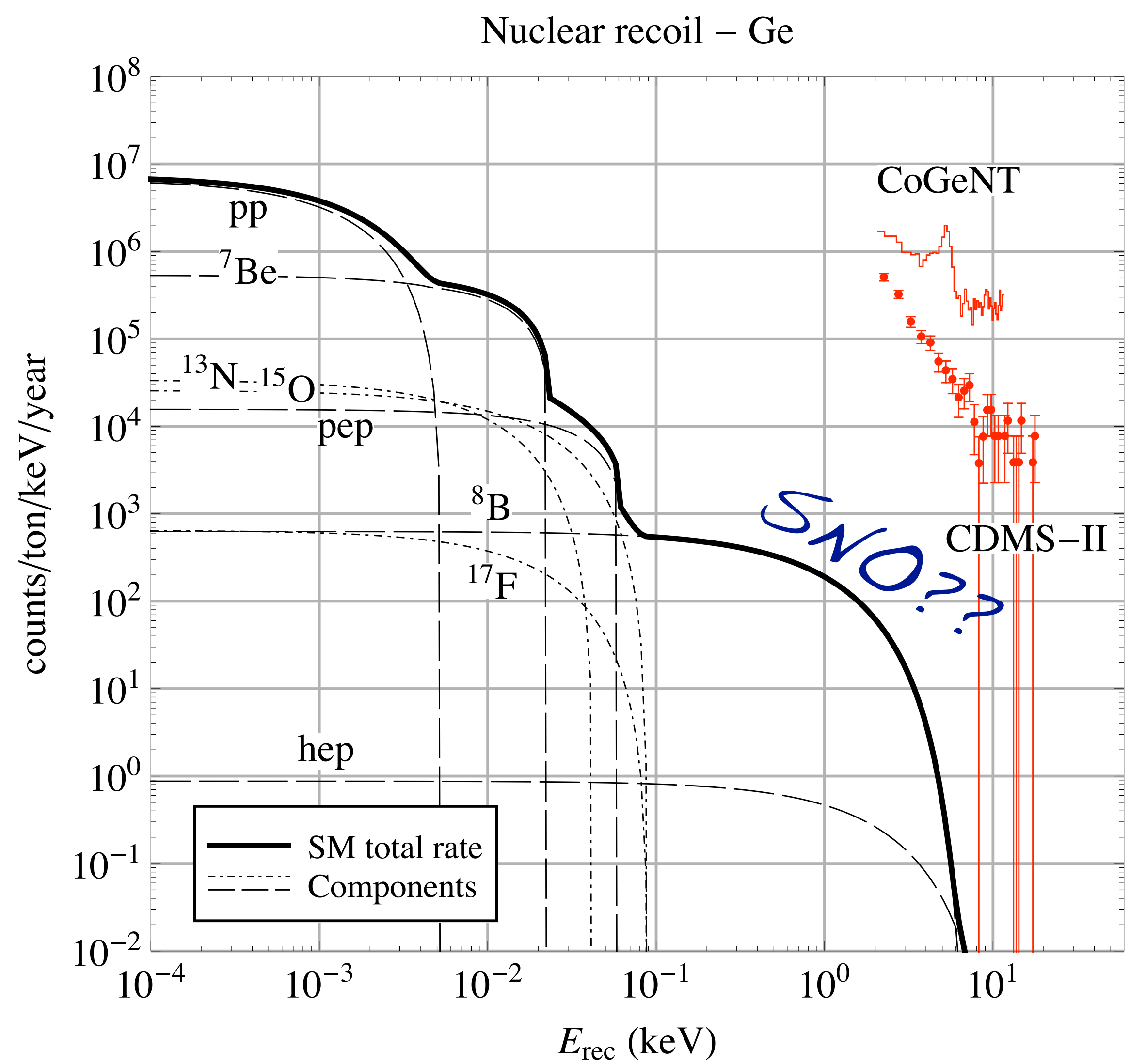


In this talk I’ll  more focus on e-recoil.

# New Physics Models

* Many models with new light gauge boson:
  - A light **B-L** gauge boson
  - Kinetically mixed U(1) (a.k.a **dark photon**).
* New **sterile** neutrinos can also come in handy. Can be emitted by the sun via mixing or oscillation.

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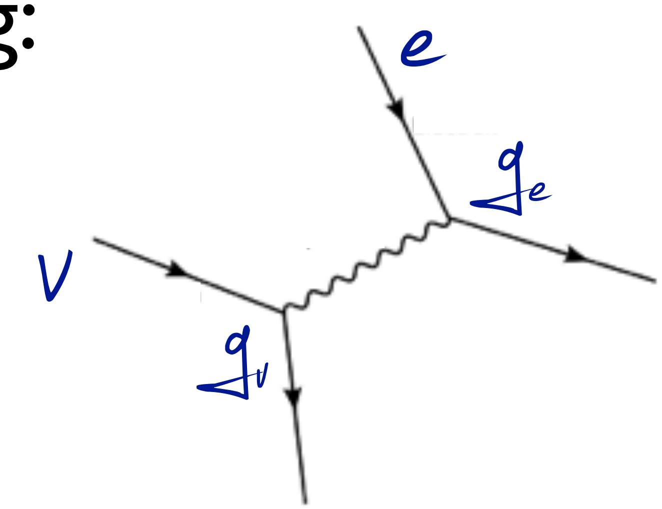
* Another "new" gauge boson that can couple to neutrinos is the **photon**.

  a magnetic dipole moment: $\mu_\nu \, \bar{\nu}\sigma^{\mu\nu}\nu \, F_{\mu\nu}$

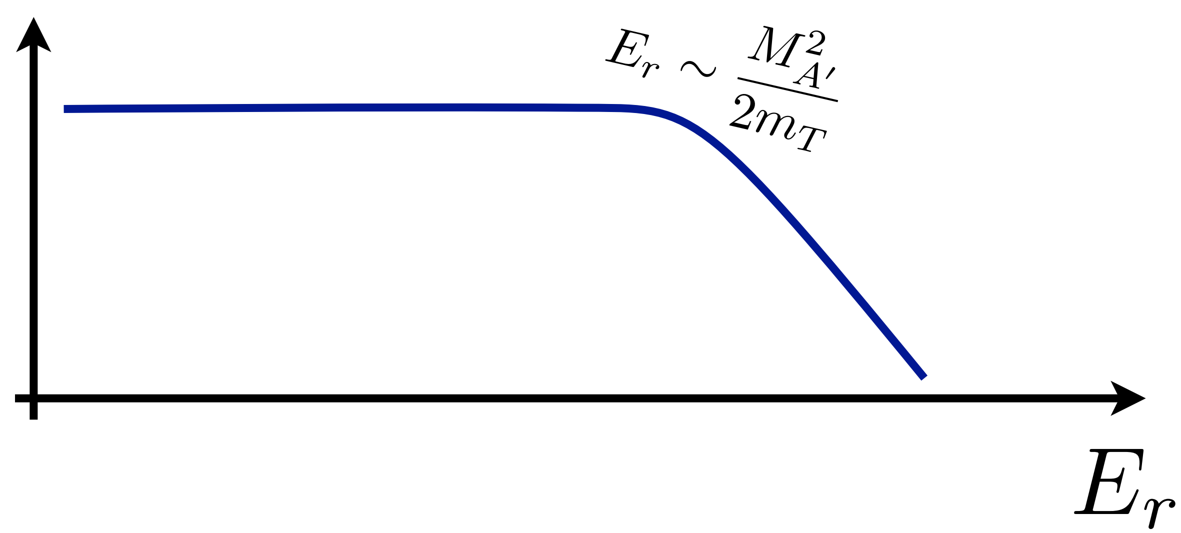
# A Light Gauge Boson

* The exchange of A' contributes to neutrino-nucleus and neutrino-electron scattering:




$$\frac{d\sigma}{dE_r} = \frac{g_\nu^2 g_T^2 m_T}{4\pi p_\nu^2 (M_{A'}^2 + 2E_r m_T)^2}\left[2E_\nu^2 + E_r^2 - 2E_r E_\nu - E_r m_T - m_\nu^2\right]$$

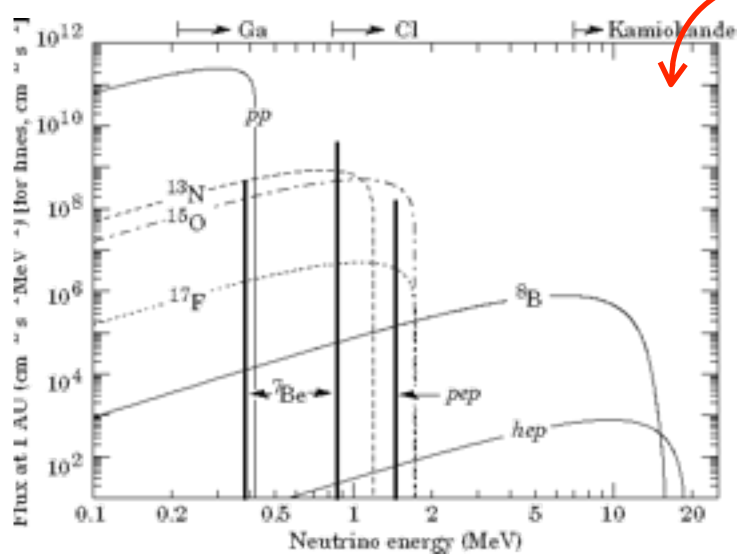
propagator: $q^2 - M^2$



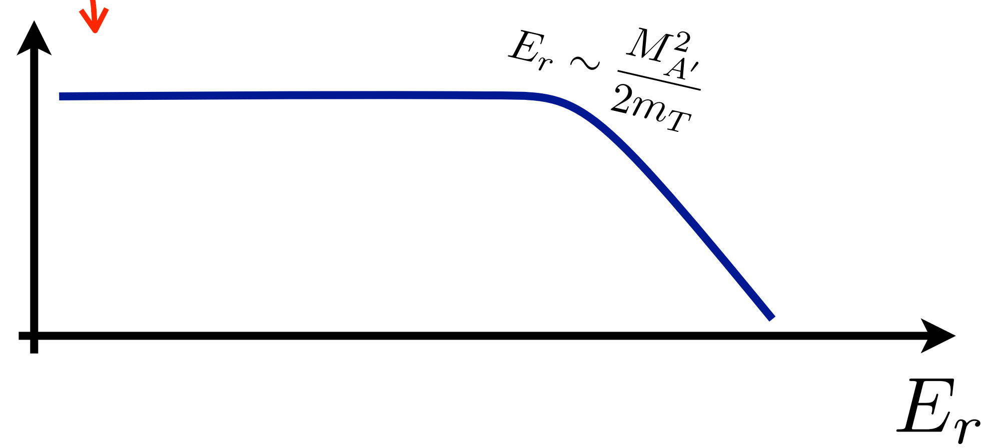
# A Light Gauge Boson

- What does a direct detection experiment see?

$$\frac{dR}{dE_r} = N_T \int_{E_\nu^{\min}}^{\infty} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r} \, dE_\nu$$




$\otimes$

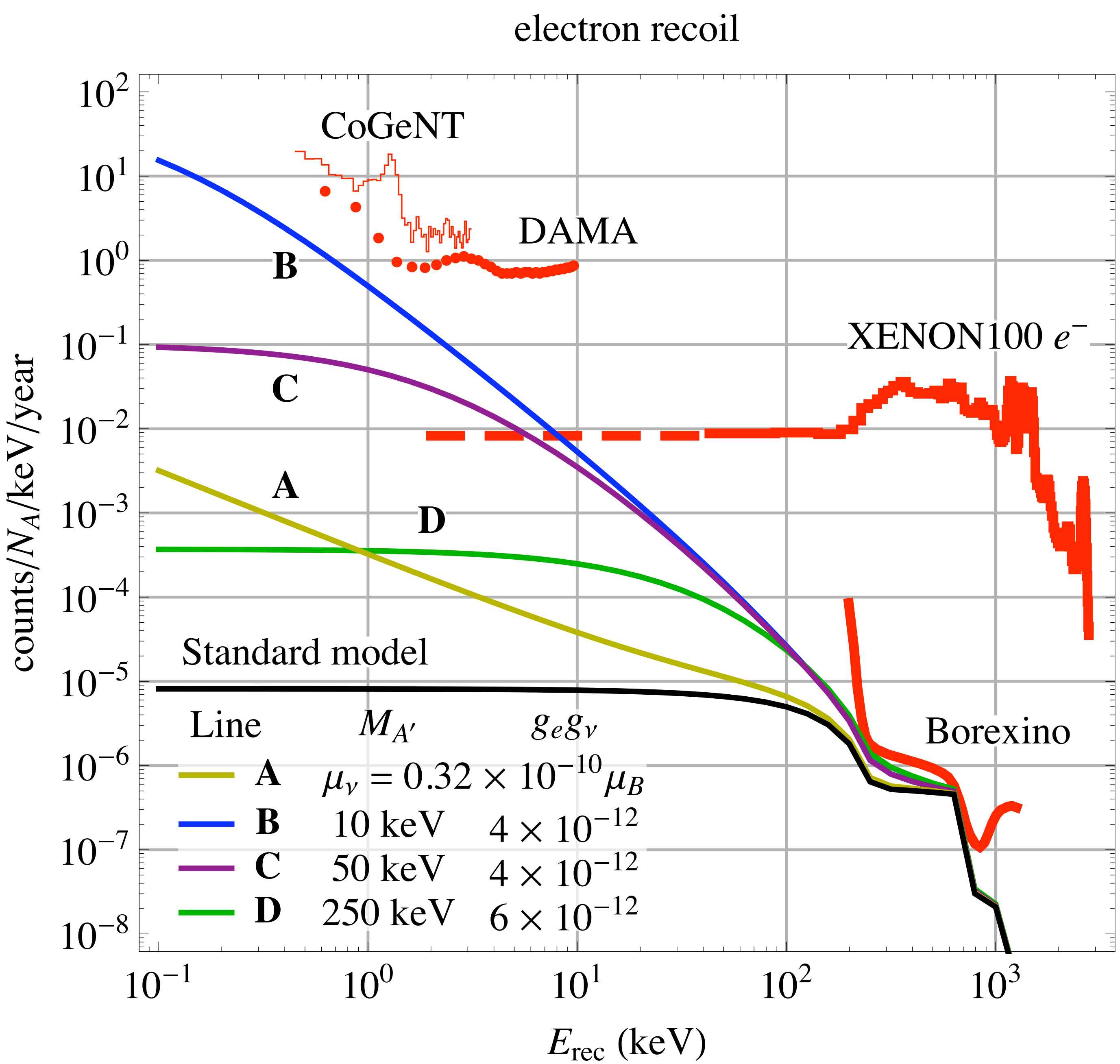



with $\quad E_\nu^{\min} = \frac{1}{2}\left(E_r + \sqrt{E_r^2 + 2E_r m_T}\right)$

# Sample Spectra

* Oh the wonderful things you can do...

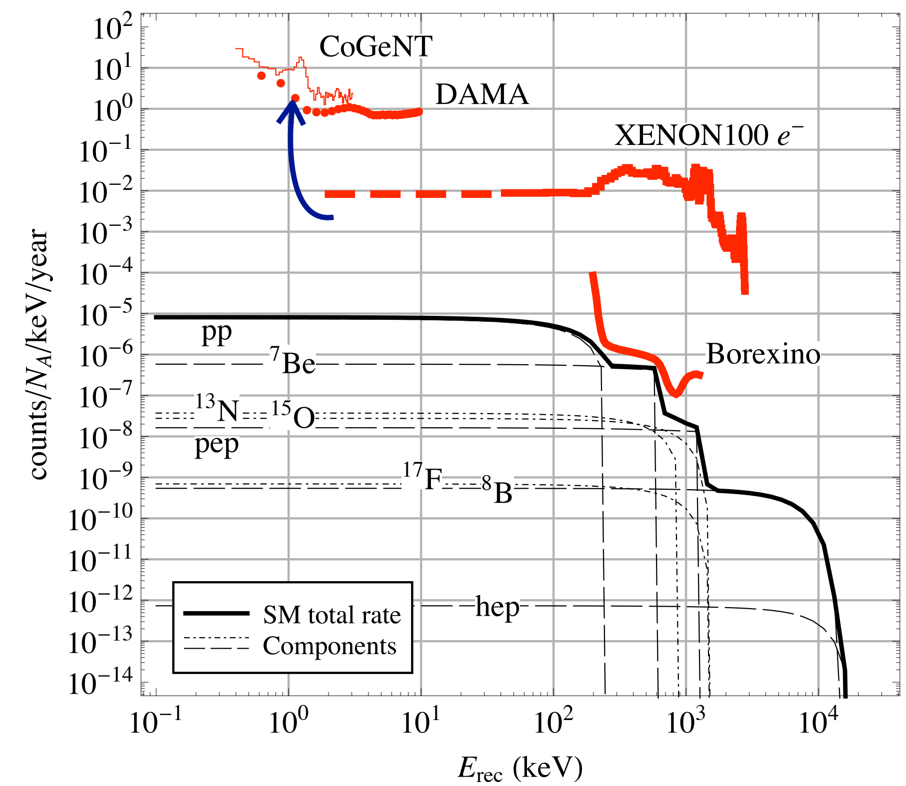
* If we want to do CoGent or DAMA there is clear tension with XENON100 (and also Borexino).



# Heavy Sterile

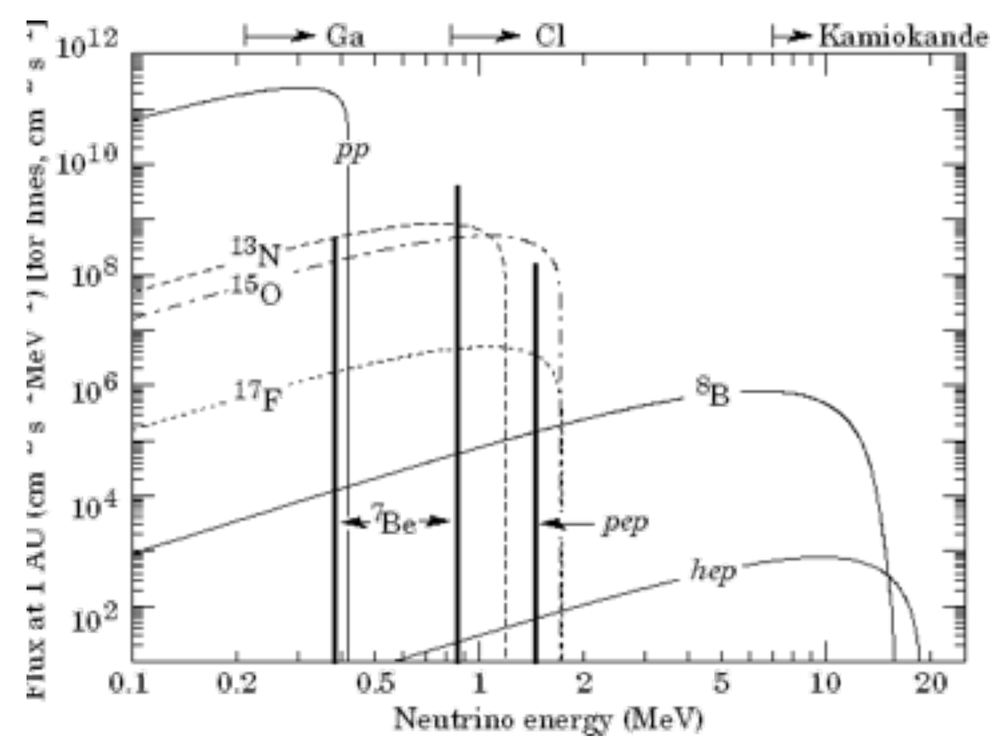
* Is there a way around XENON?

*Can we get a sharp threshold?*




* The solar flux has lines....

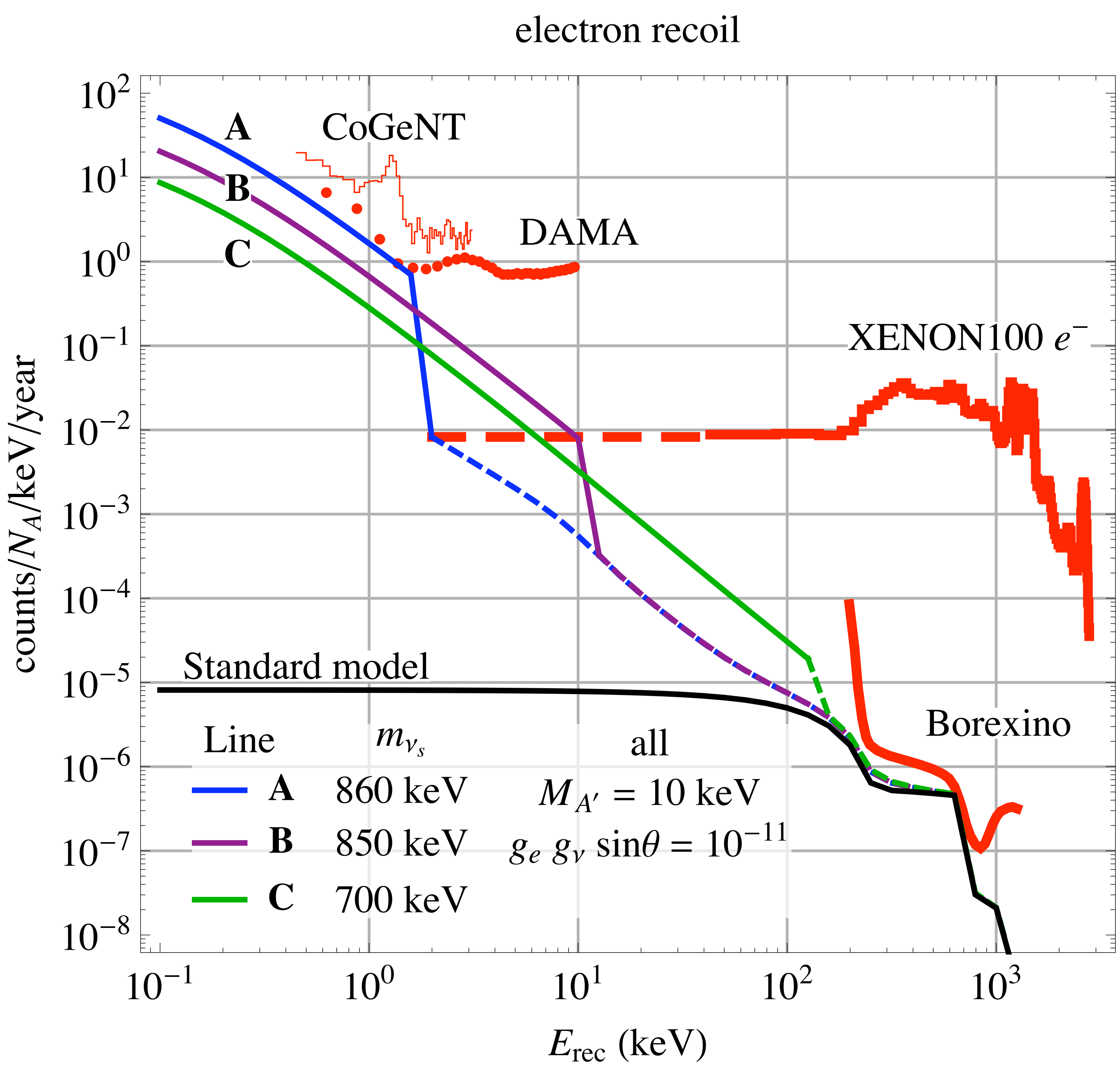
*A kinematic threshold near the $^7$Be line...**



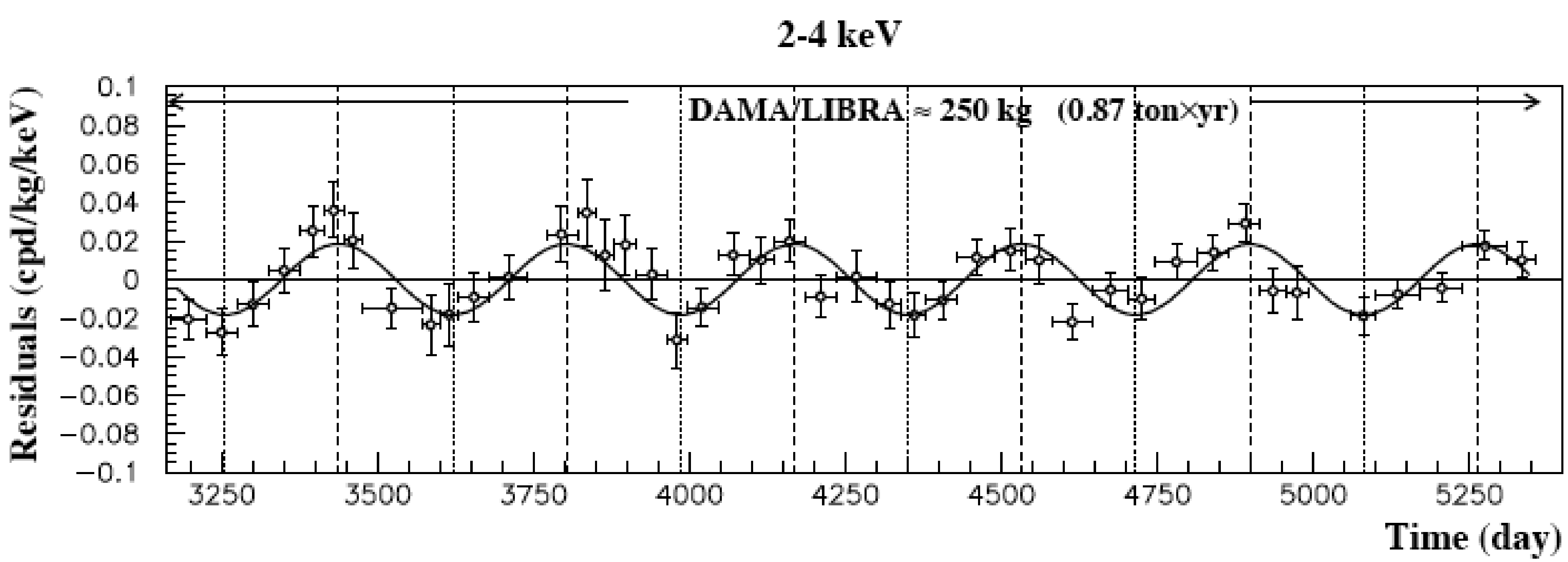

* *I would like to thank IDM and its variants for the moral license to do this.*

# Heavy Sterile

* Interesting spectra can arise:



# Modulation


2-4 keV
DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
3250
3500
3750
4000
4250
4500
4750
5000
5250
Time (day)

# Modulation and the Sun

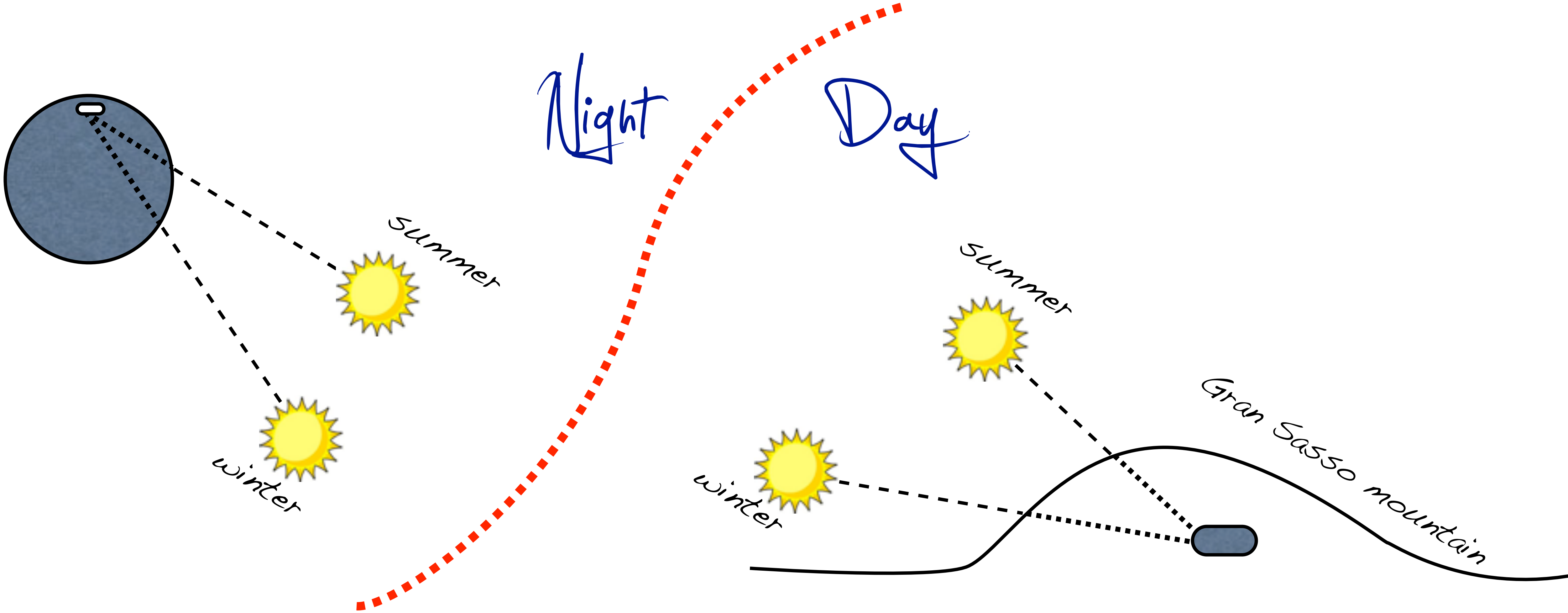
* Annual modulation is an important part of the direct detection program (e.g. DAMA, CoGeNT?).
* Many possibilities for modulation from the Sun:
  - Earth sun distance.
  - Just-so.
  - Mater effects.
  - ....
* Gives a rich phenomenology:
  - daily.
  - annually.

# Matter Effects

* The new gauge boson can lead to new "MSW-like" matter effects: $$V_{\rm matter} = \frac{g_\nu}{M_{A'}^2}(g_e n_e + g_p n_p + g_n n_n)$$
* Oscillations in matter can be *very* different from those in vacuum.
* **Day-night** asymmetry due to an oscillation b/w among sterile species in matter. This asymmetry can be large.
* The matter oscillation length, $L_{\rm osc} = 4\pi E/\Delta m^2$ , can be anywhere between a kilometer and the earth radius.

# Zenith Angles

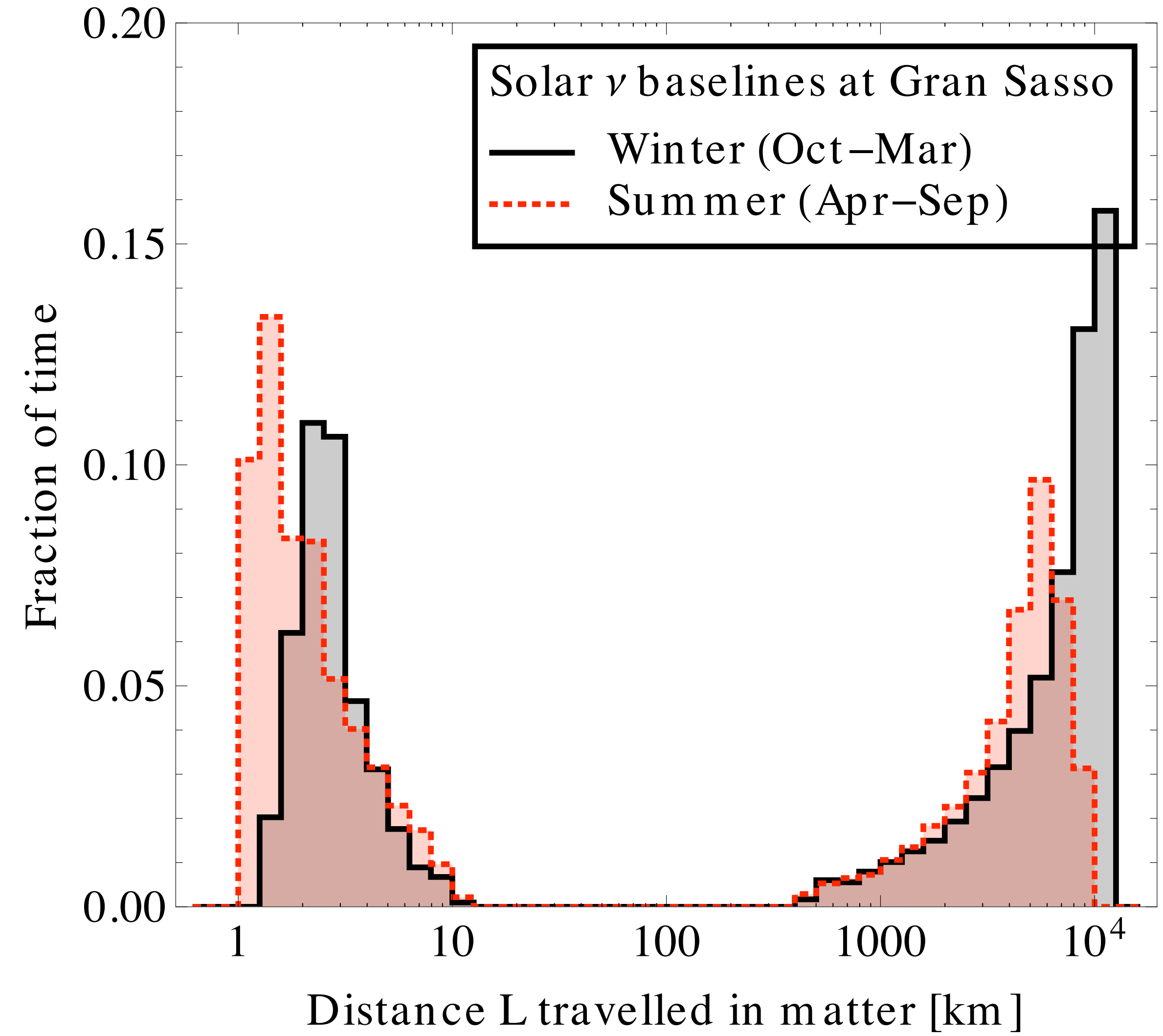
* At noon, the sun is high in the sky in summer. Low in winter.
* At midnight, the Sun is lower *below* the horizon in winter. Higher in summer.



# Zenith Angle

* The average baseline in rock for solar neutrinos going to Gran Sasso **modulates**:

annual modulation can be much stronger asymmetry in daylight hours.




* A strong daily modulation is induced here too.

# Searching for Light States with neutrino Beams

e.g. Dark Photons and Axions.

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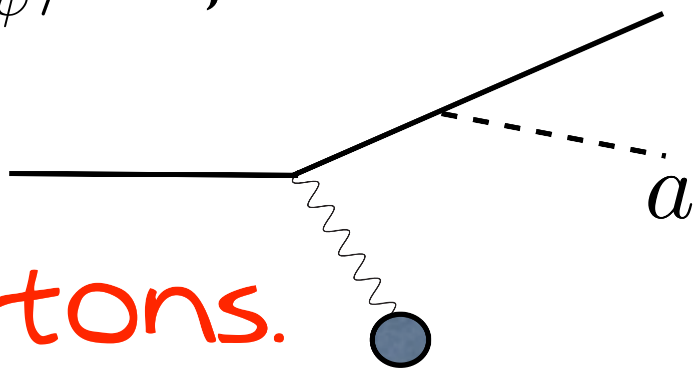
**Neutrino beams are "staged beam dumps":**

You dump the beam in stages, and you can do interesting physics at every stage.

(this is the DOE definition of "staged").

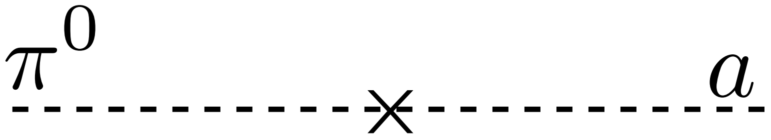
# Axion - Production

* **"a-sstrahlung":**
  rule of thumb - for every bremsstrahlung photon there is a small probability, $m_\psi^2/F^2$, to emit an axion instead.



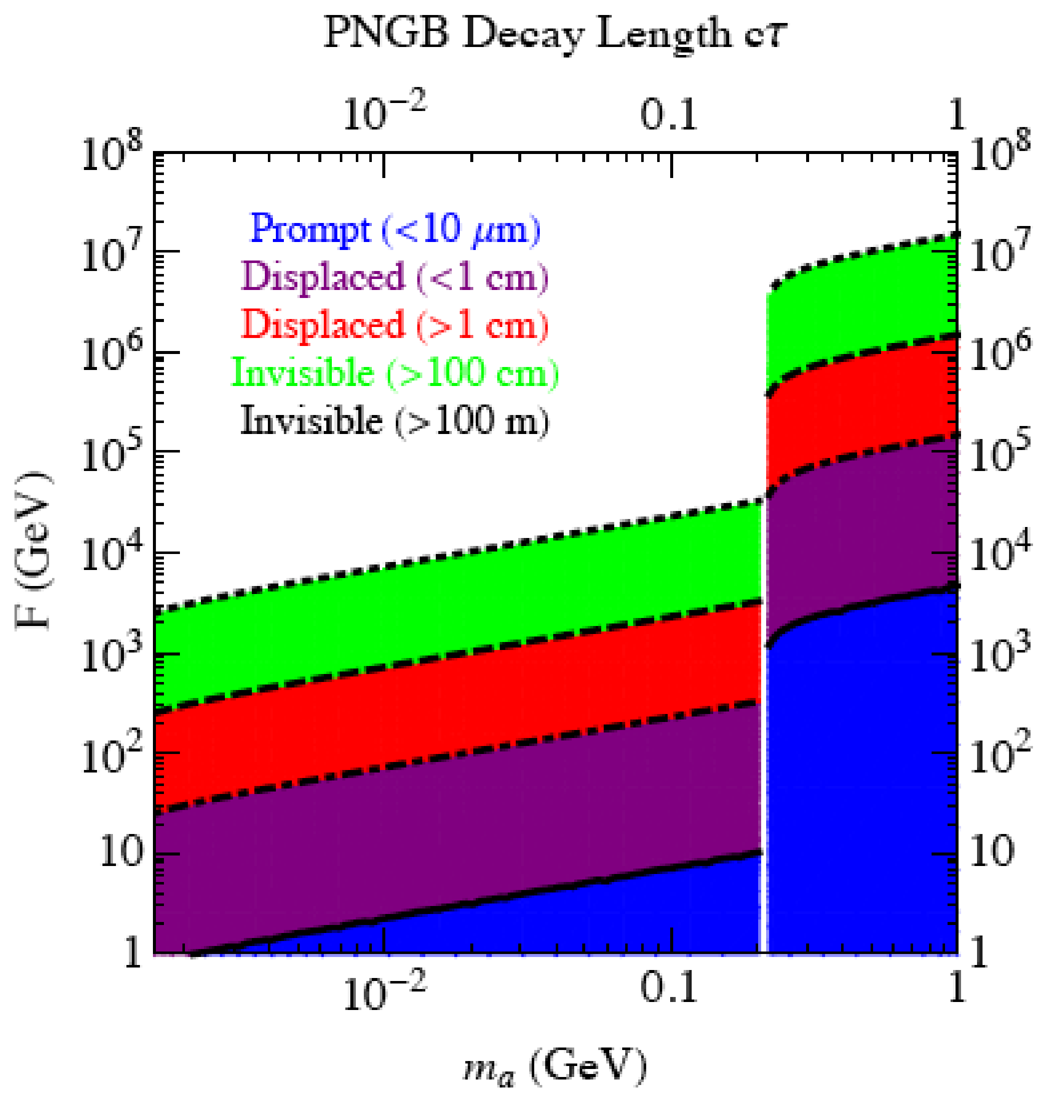

same for dark photons.

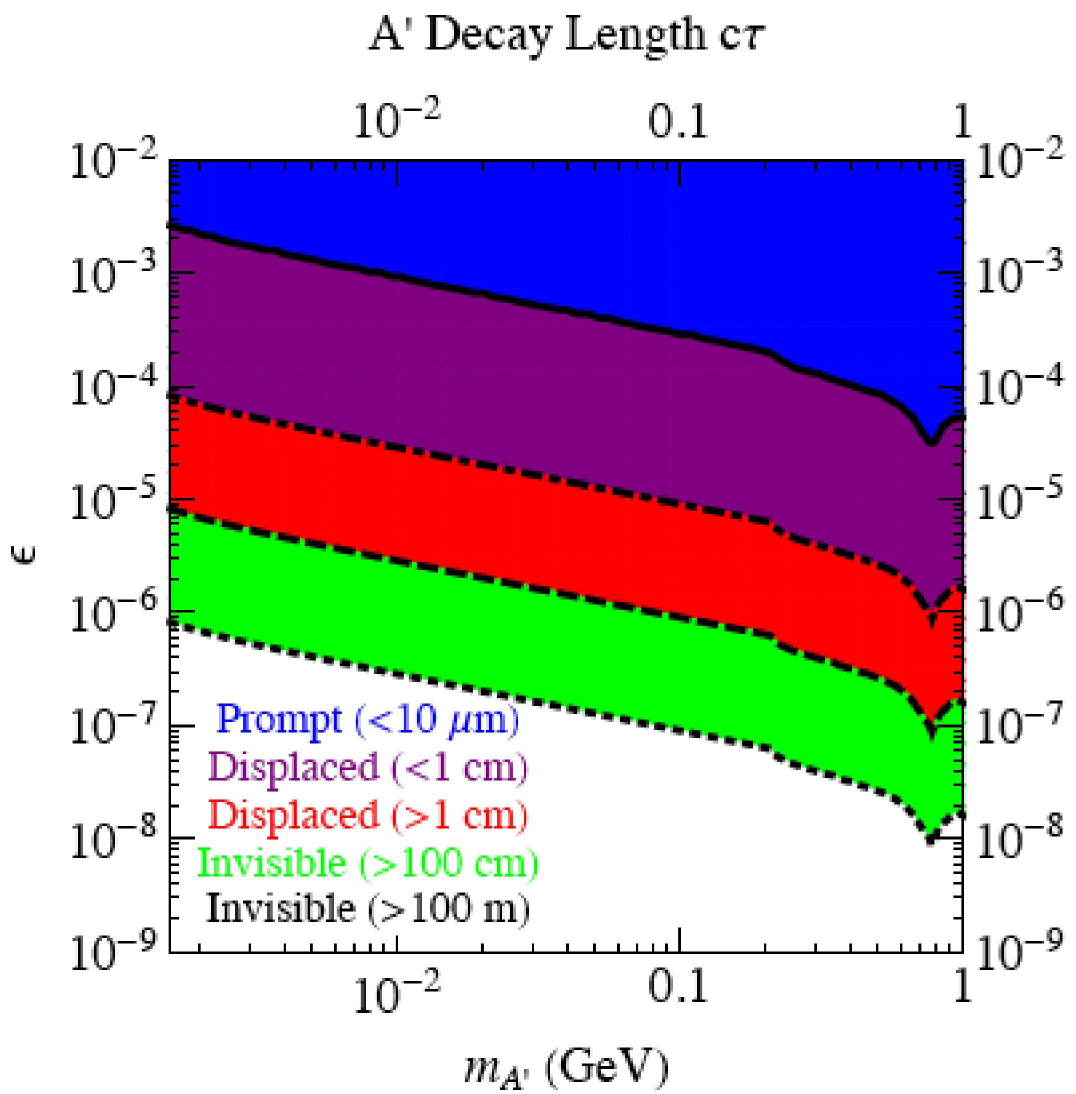
* **Mixing with a pion:**
  Every produced pion can be an axion instead, with a some small probability $\sim f_\pi^2/F^2$.



# Decay

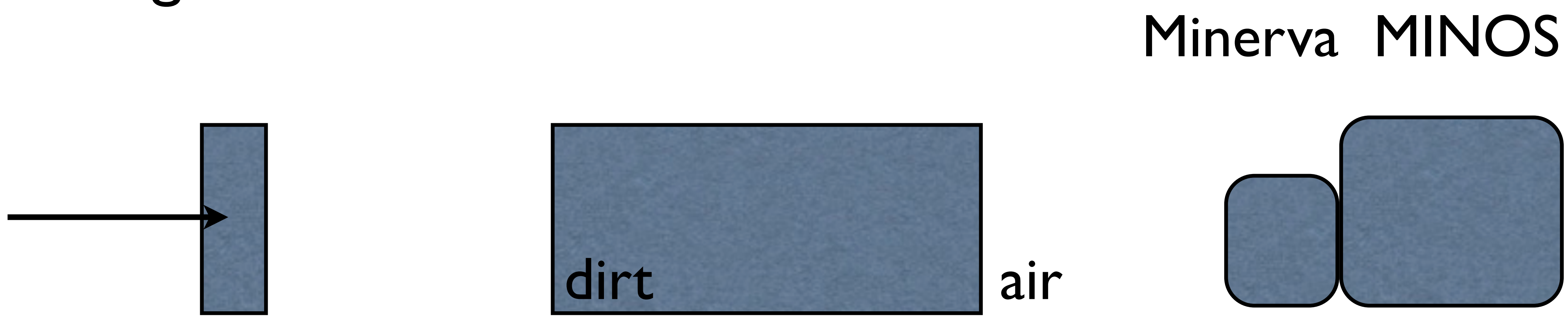
* Decay lengths can be either long (>100m) or short (prompt).



# Proton Beam Dumps

* Every neutrino beam starts with protons striking a target:



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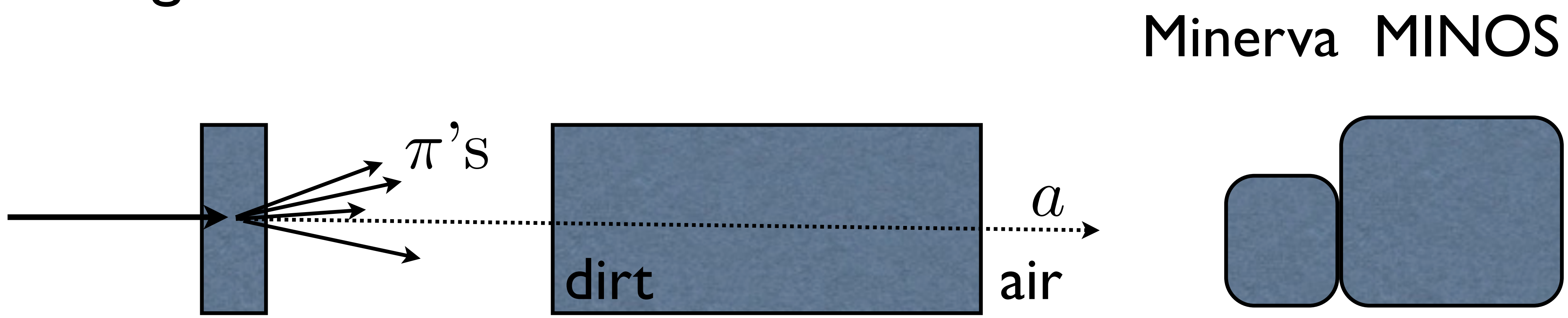

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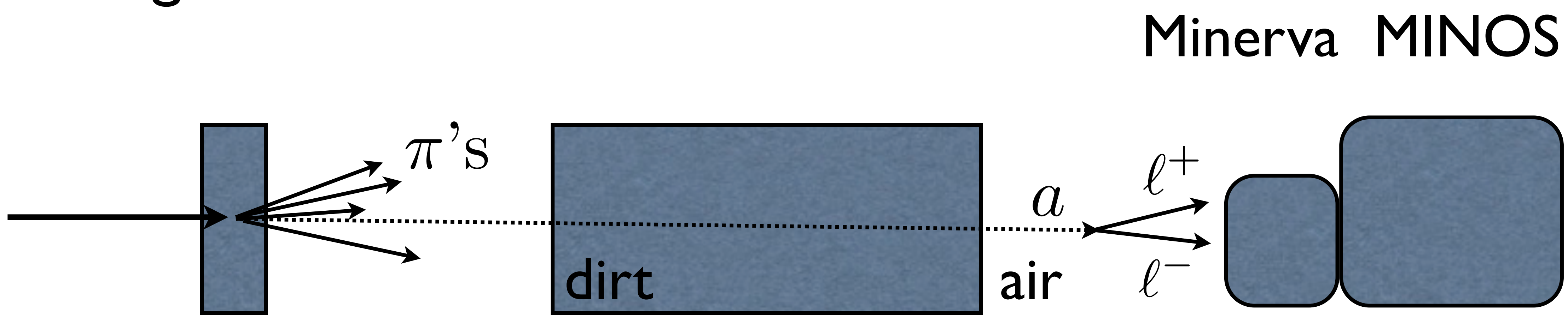

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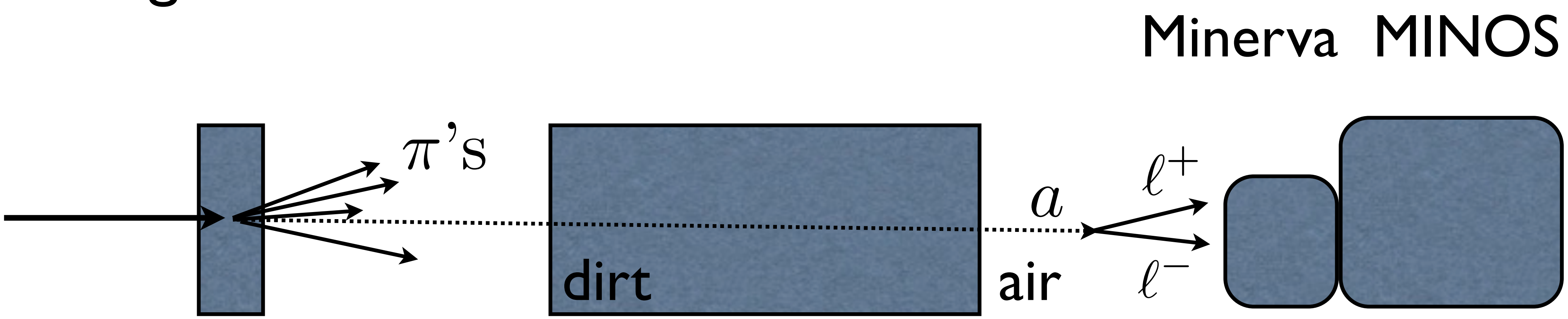



**Signal:**

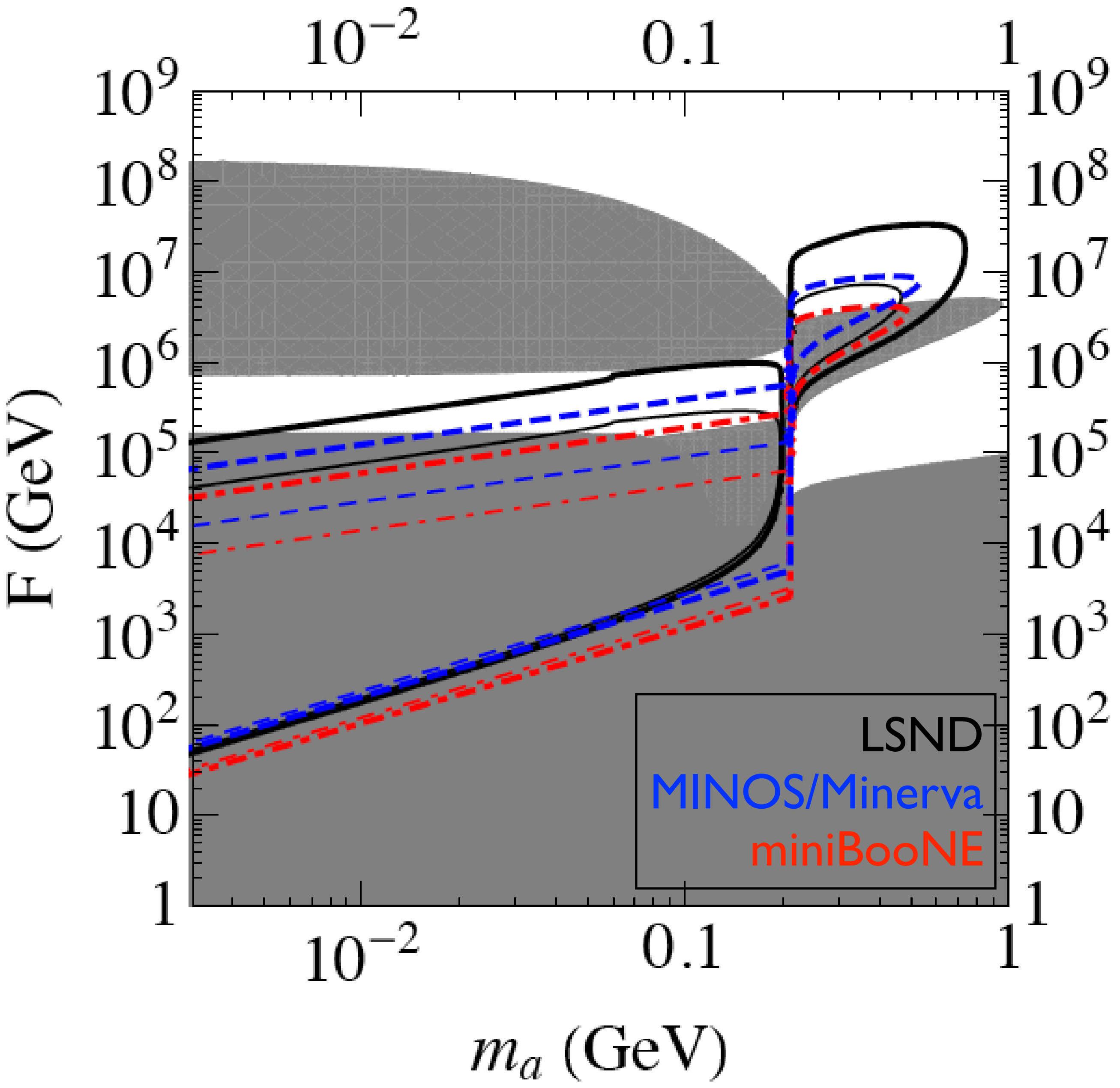
* **lepton (or photon) pair in near detector originating from a single point in air.**
* **Reconstruct a mass peak.**

*Low backgrounds.*

*MINOS & Minerva are complementary!*

# Limits

* Gap b/w CHARM and SN partially closes.
* LSND dominates thanks to number of protons on target.
* Future facilities can close the gap?



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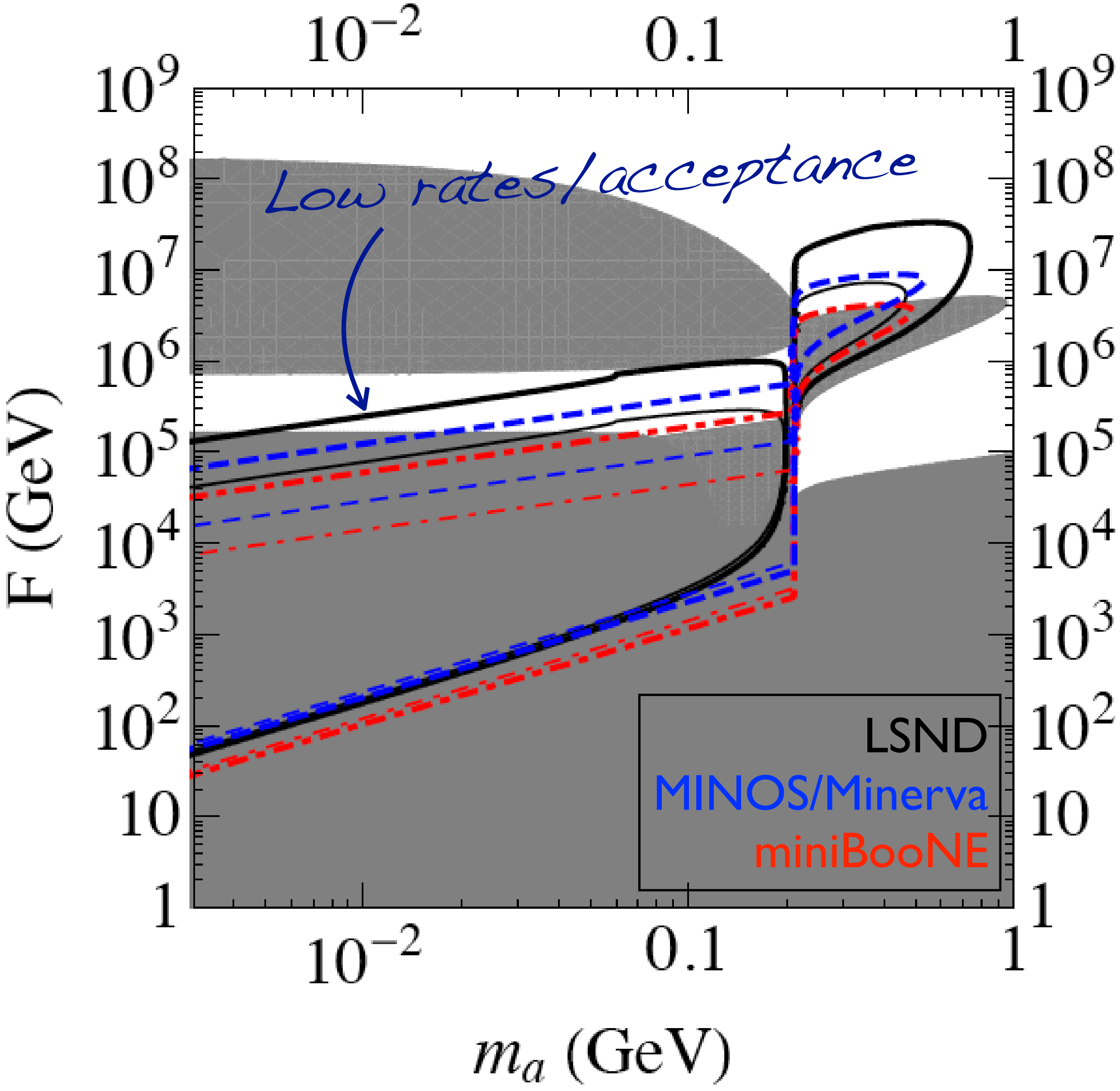

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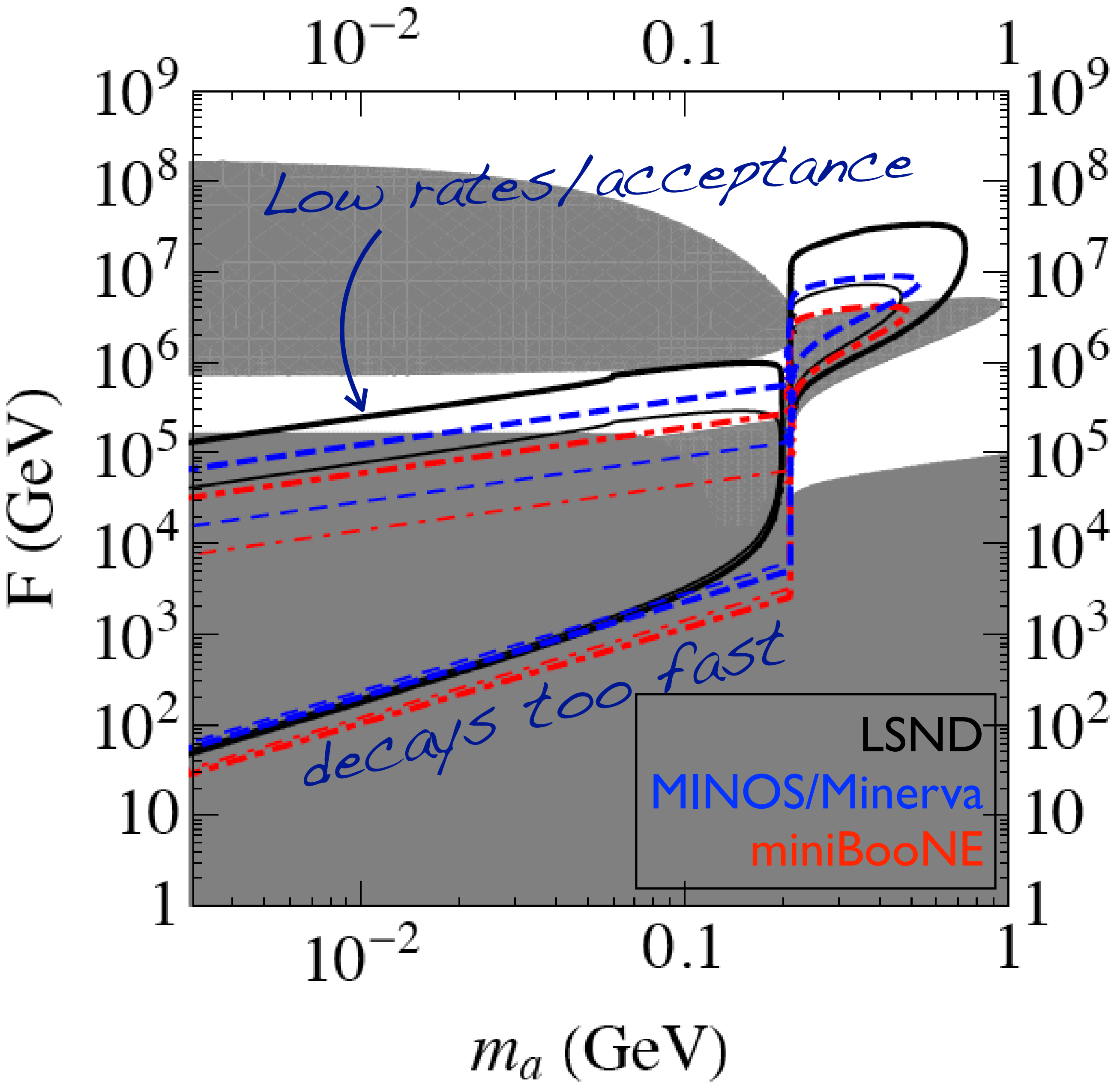
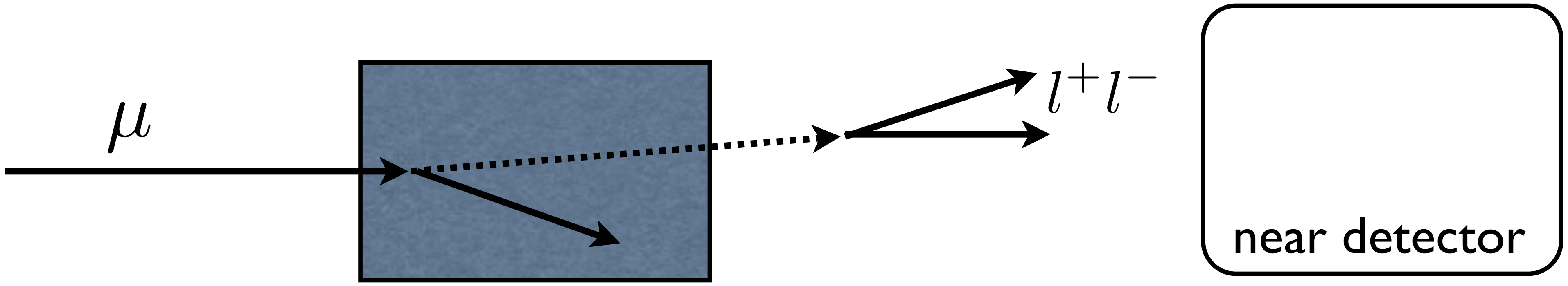


# Muon Beam Dumps

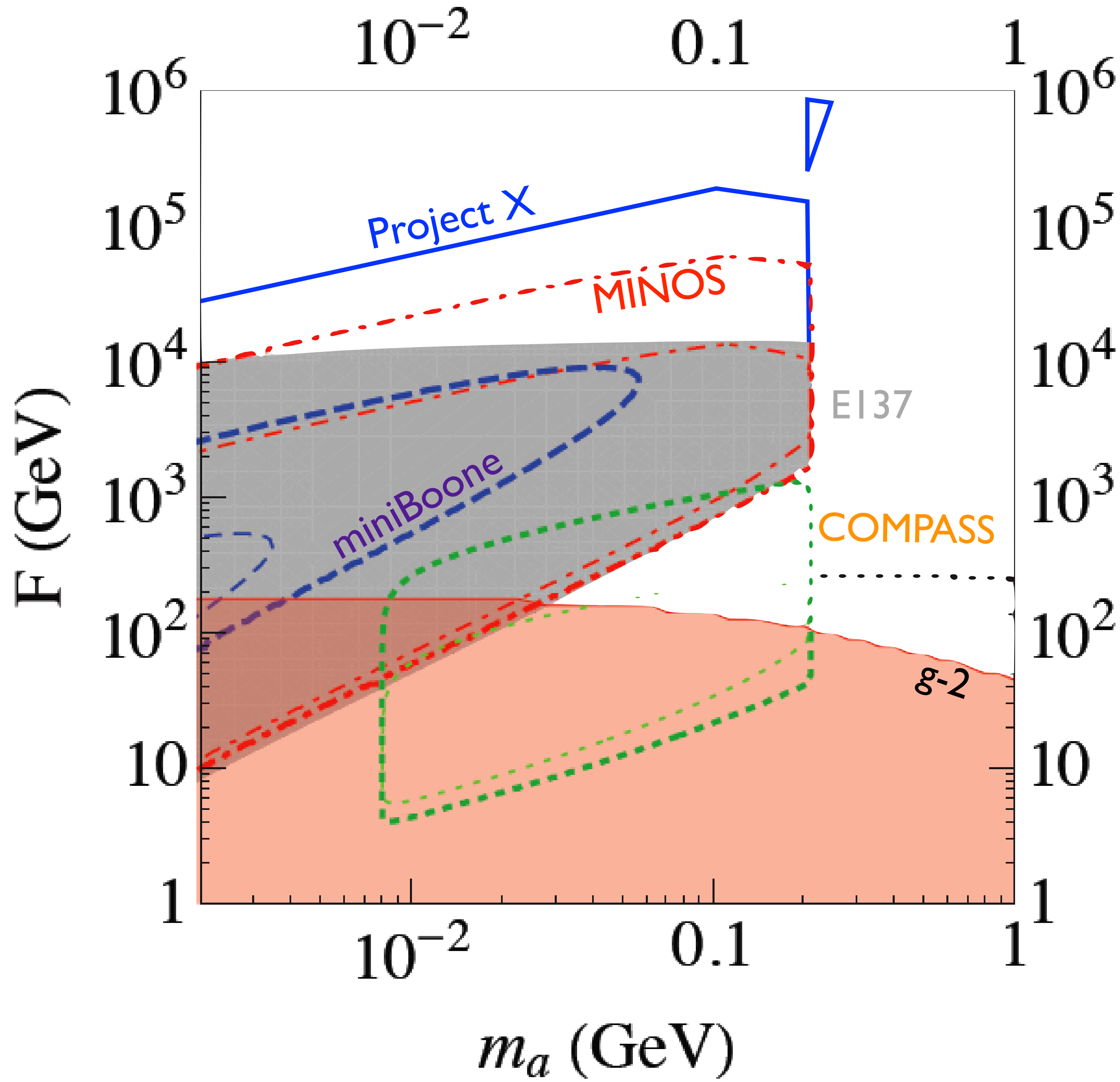
* Neutrino beams are also muon beam dumps.
* **NuMI is also the worlds most intense muon beam!**




* Muons have advantages:
  - Probe leptophic states.
  - Axion couple to mass.
  - Muon g-2 anomaly...?

# Limits

* MIMOS/Minerva do well (compare to E137).
* Naive Project-X projection ($N_{mu}$=MINOS x 10) is obviously better!



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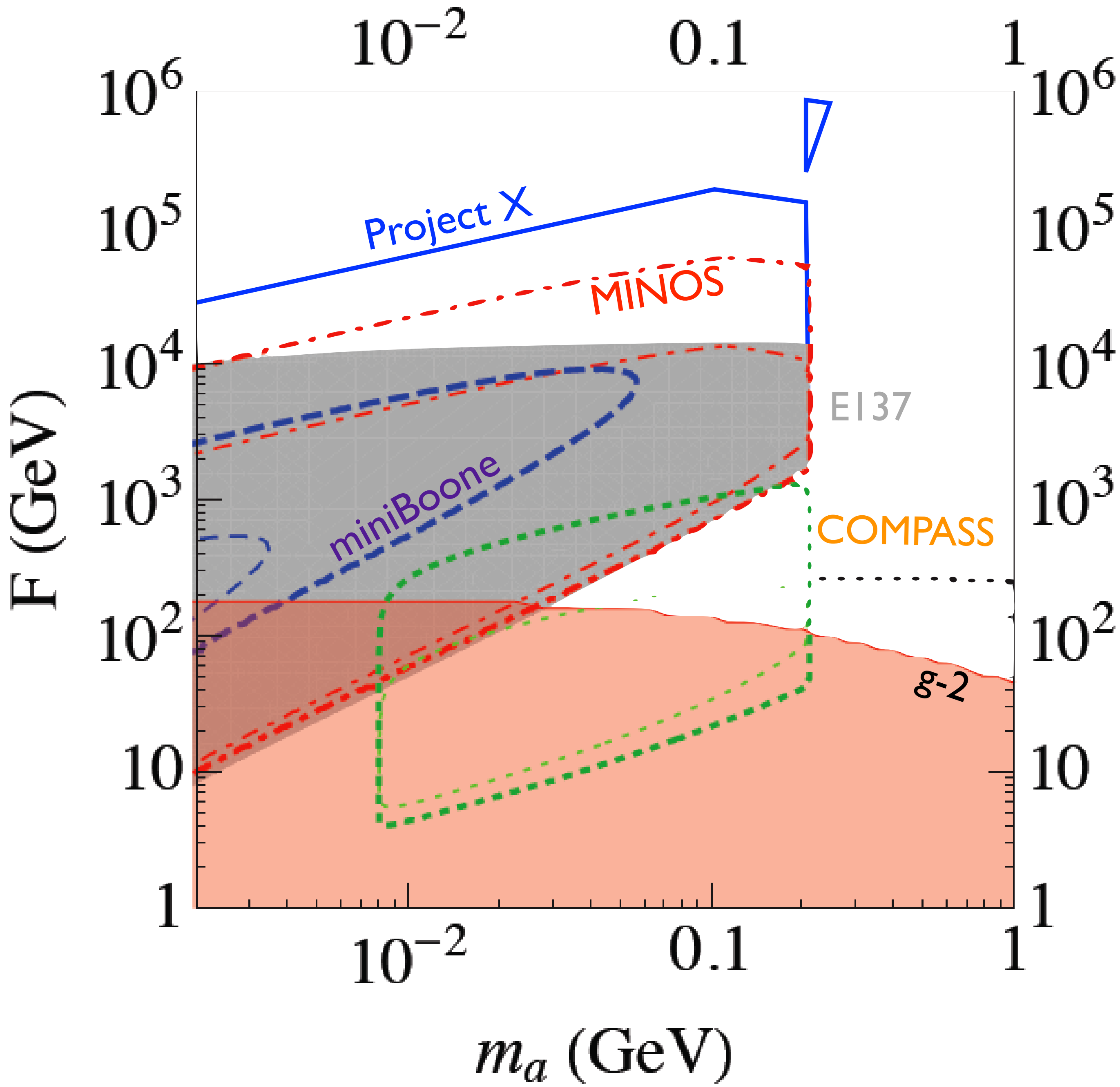



COMPASS, a muon fixed target experiment, Can close the gap.
(Instrument the NuMI muon monitor???)

# Concluding

* **Dark matter** and **neutrino** experiments share some features: low backgrounds, large exposure, low thresholds.

* Both are completely exposed to the sun... in neutrinos.

* New physics connecting the SM to neutrinos can lead to **interesting direct detection signals**.

* Neutrino beams are **beam dumps**.
  Can look for new physics from various sources:
    - Proton dumps (and meson decays).
    - Muon Dumps.

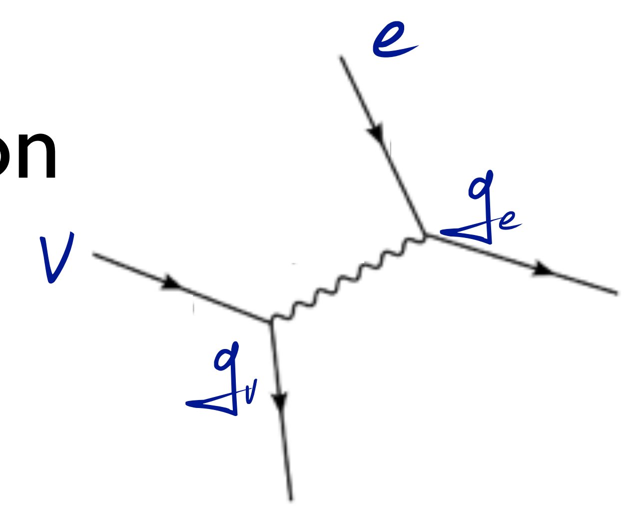
* Signal: **lepton or photon pairs** in near detectors.

# Deleted Scenes

(and various constraints on dark photons and axions)

# Steriles and A's

* We would like to dial couplings of electron neutrino to the A' independently.
* For B-L we cannot do this.

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* Example - a kinetically mixed A' and new "sterile" neutrinos charged under it:

effectively, $g_{nu} \gg g_e$.

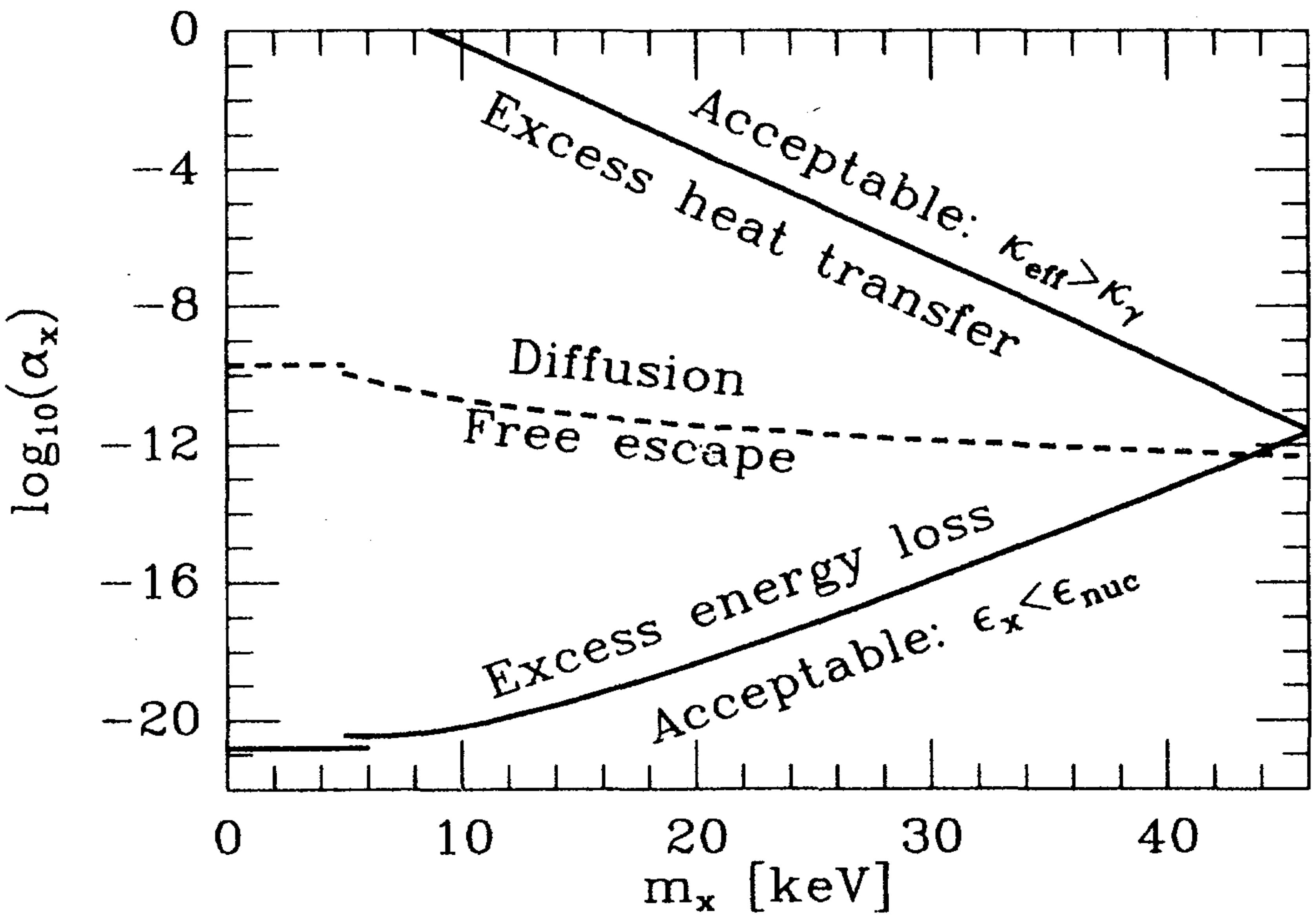
$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_{sL} i\partial\!\!\!/ \nu_{sL} + g'\bar{\nu}_{sL}\gamma^\mu \nu_{sL} A'_\mu$$
$$- Y_\nu \bar{L}\tilde{H}\nu_R - Y_s \bar{\nu}_{sL} H' \nu_R - \frac{1}{2}\overline{(\nu_R)^c} M_R \nu_R - h.c. \, .$$

* Steriles are produced in the sun through mixing with neutrinos or through oscillations outside the sun.

more knobs for a model builder to turn.

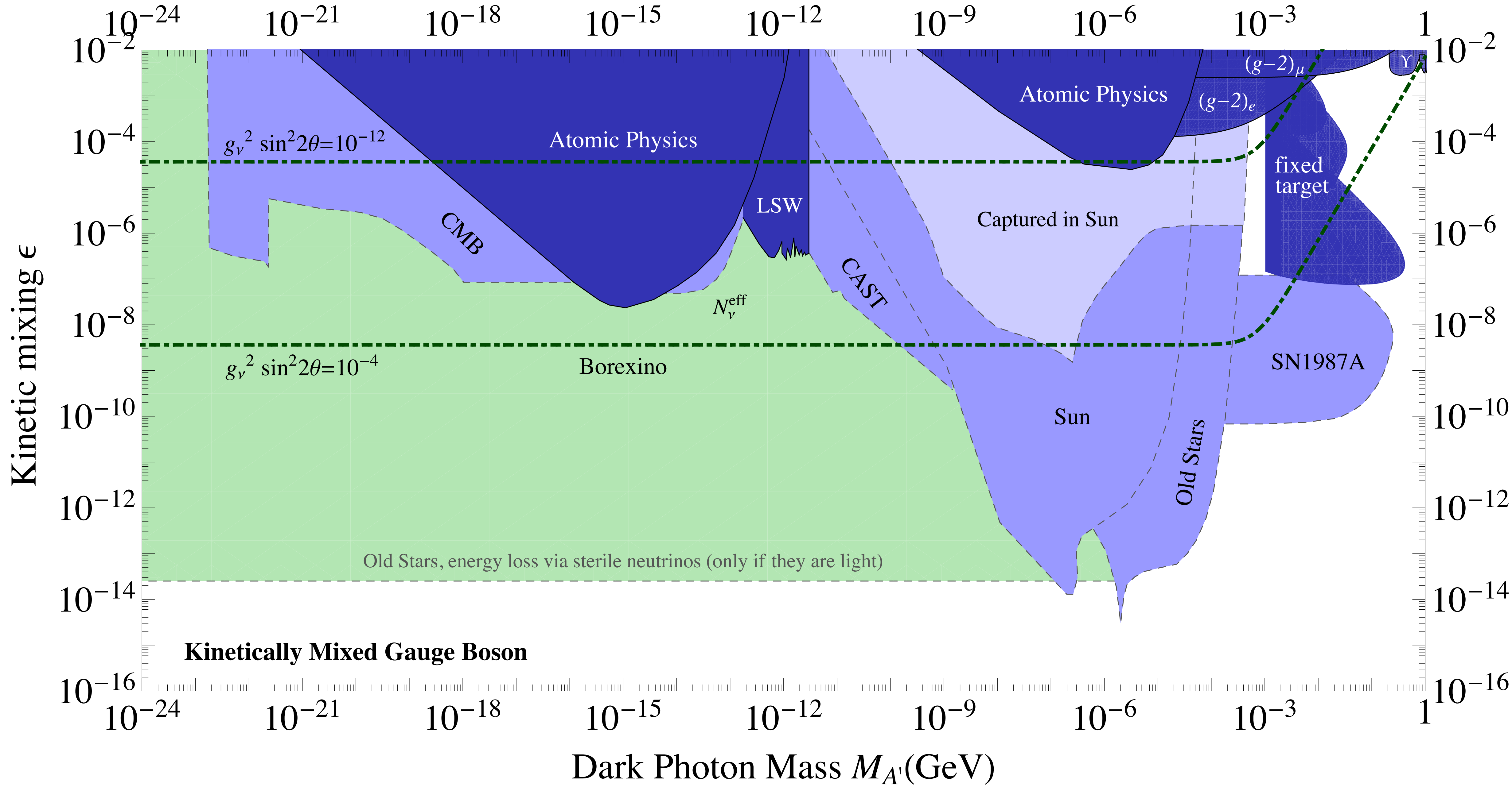
# Solar Bounds

- Raffelt-Starkman: energy transfer in the sun.



# Parameter Space

* Many constraints on the parameter space of A's



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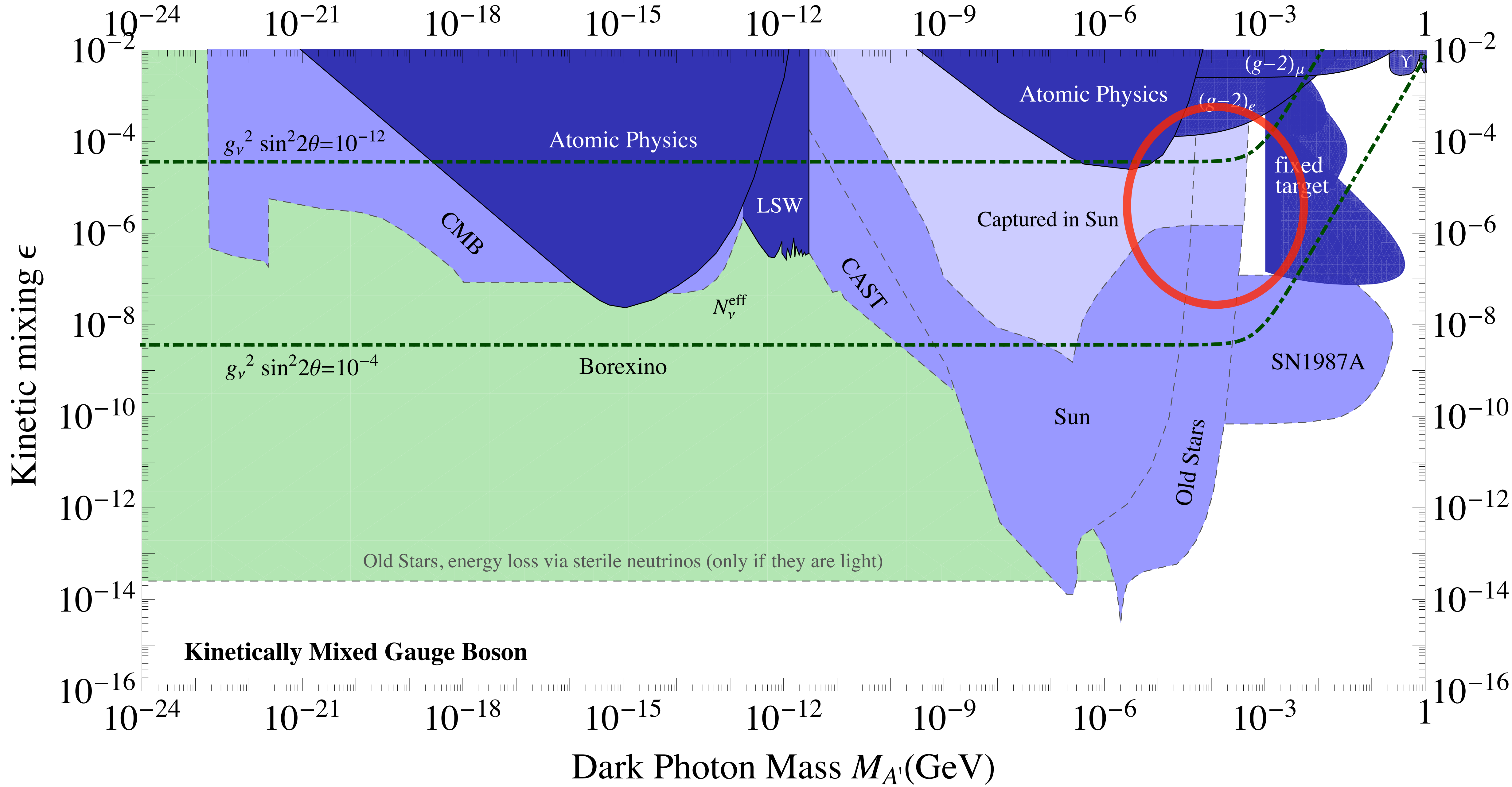

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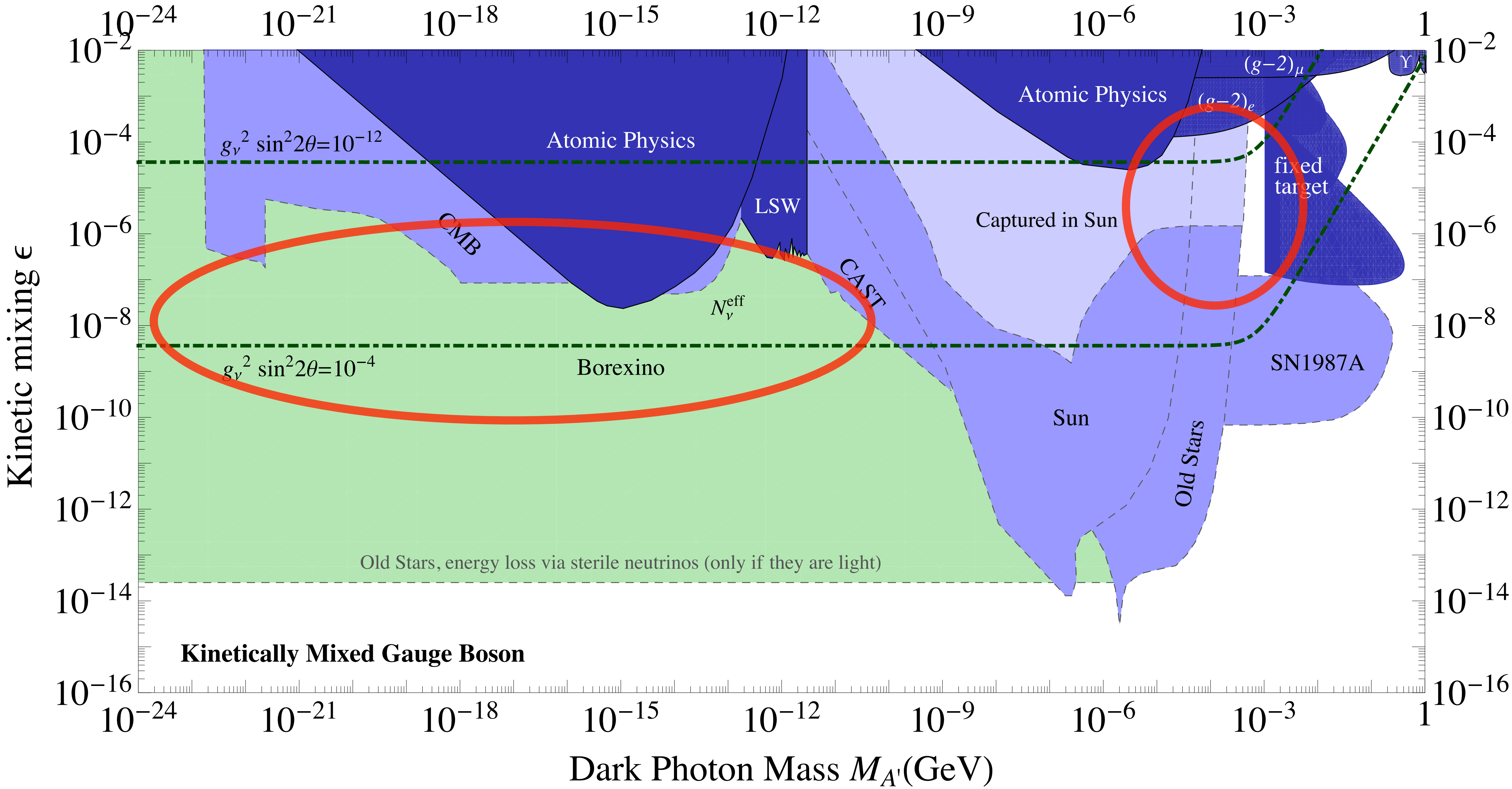

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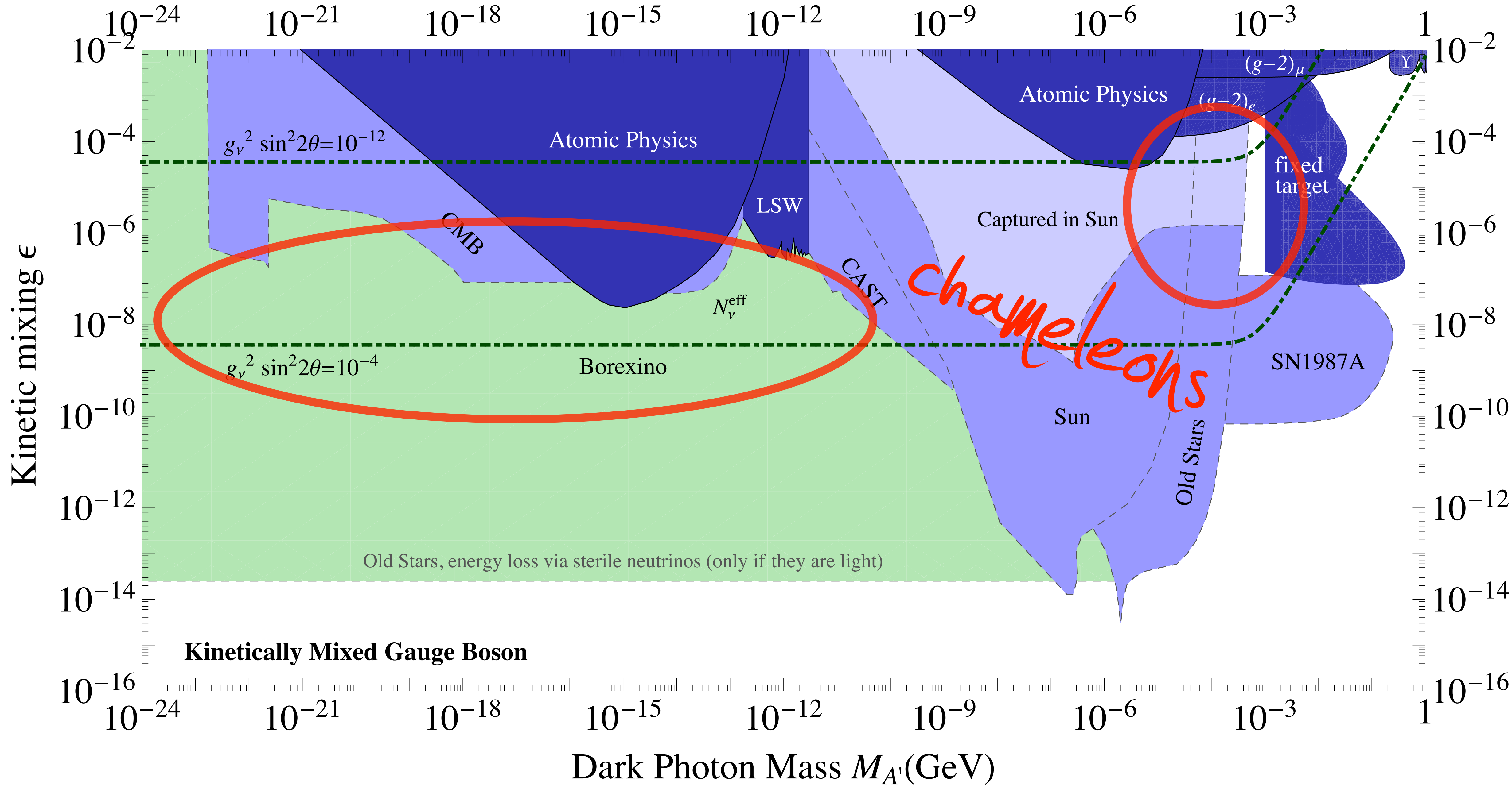

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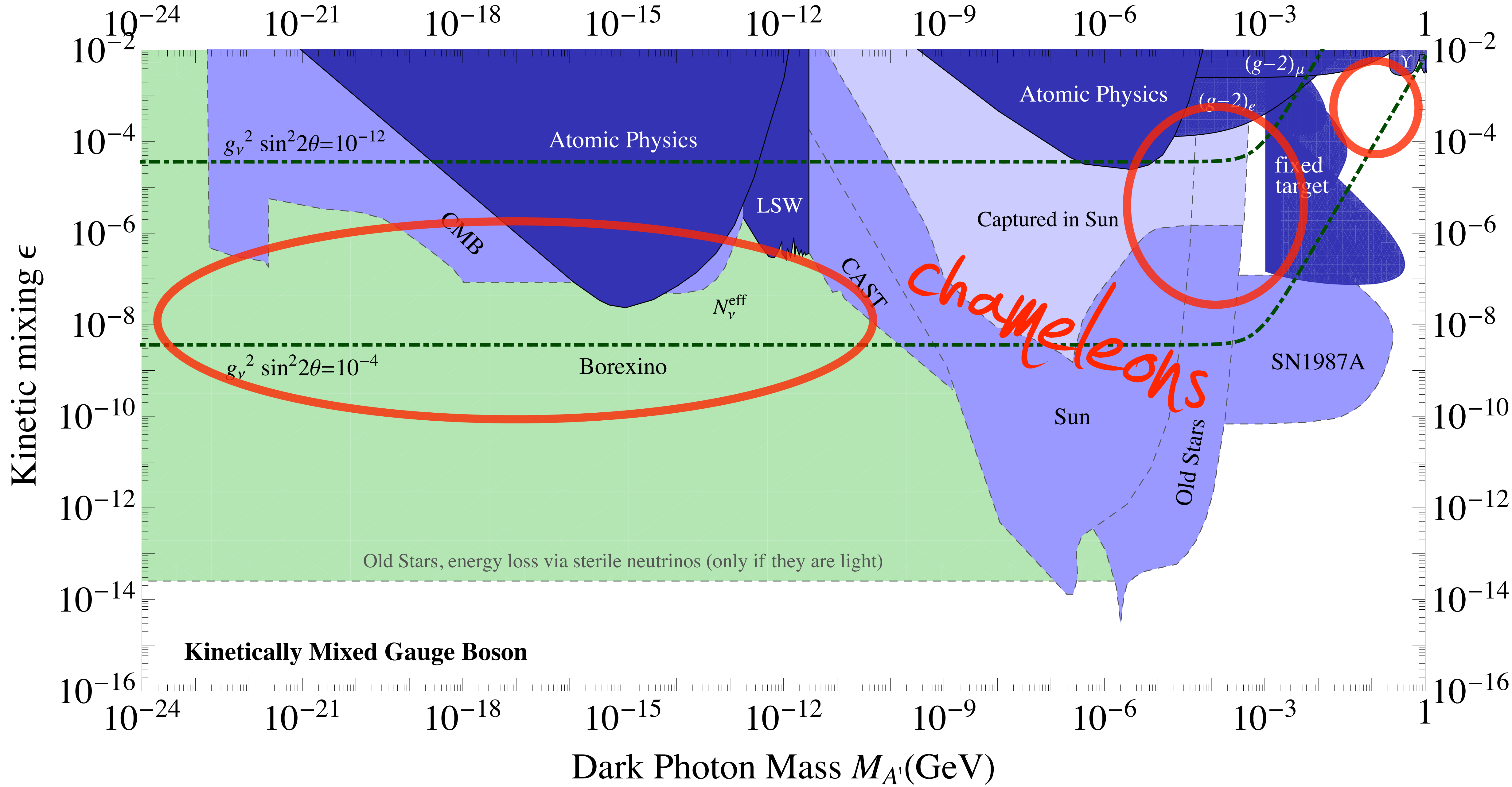
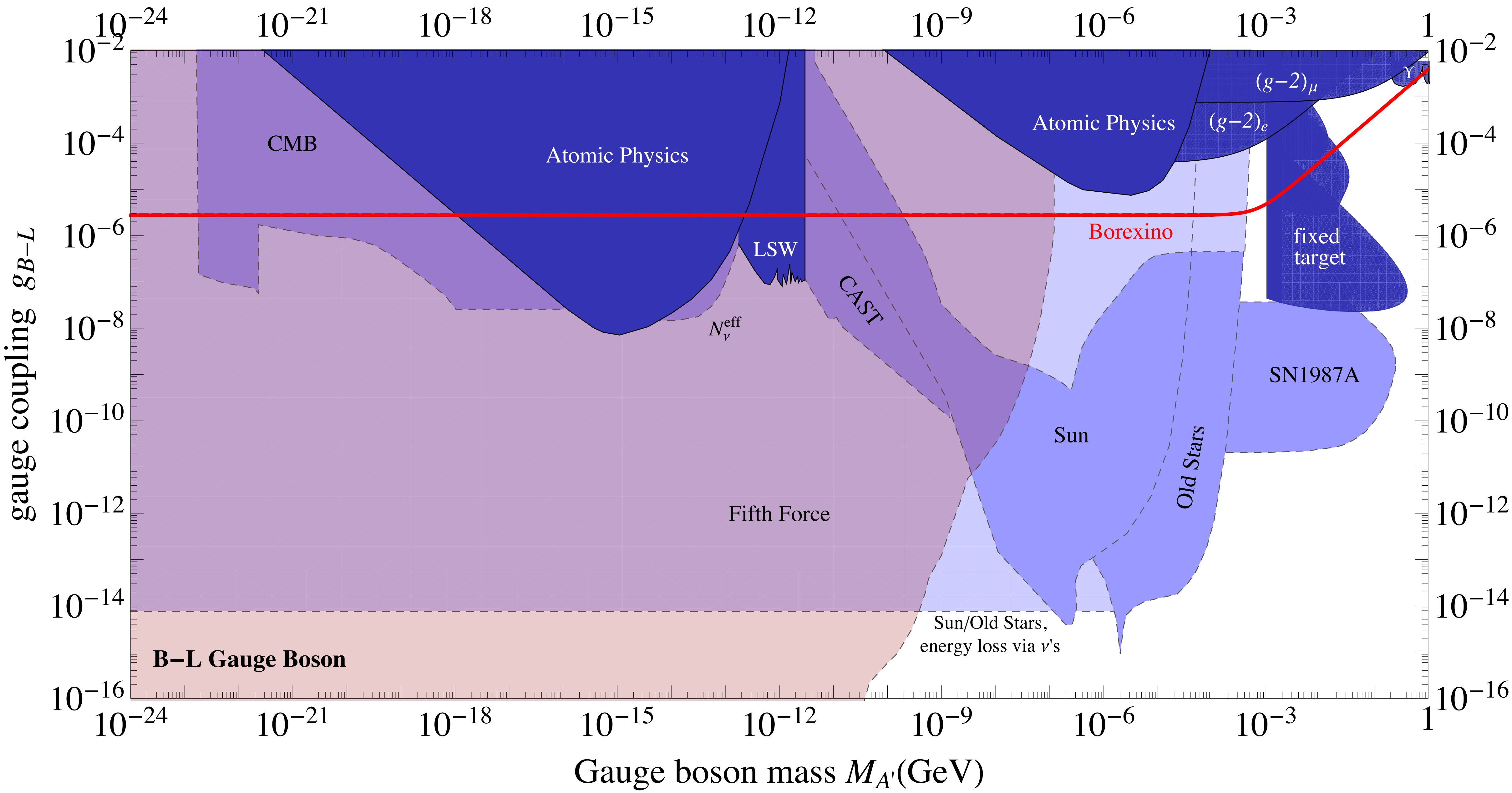


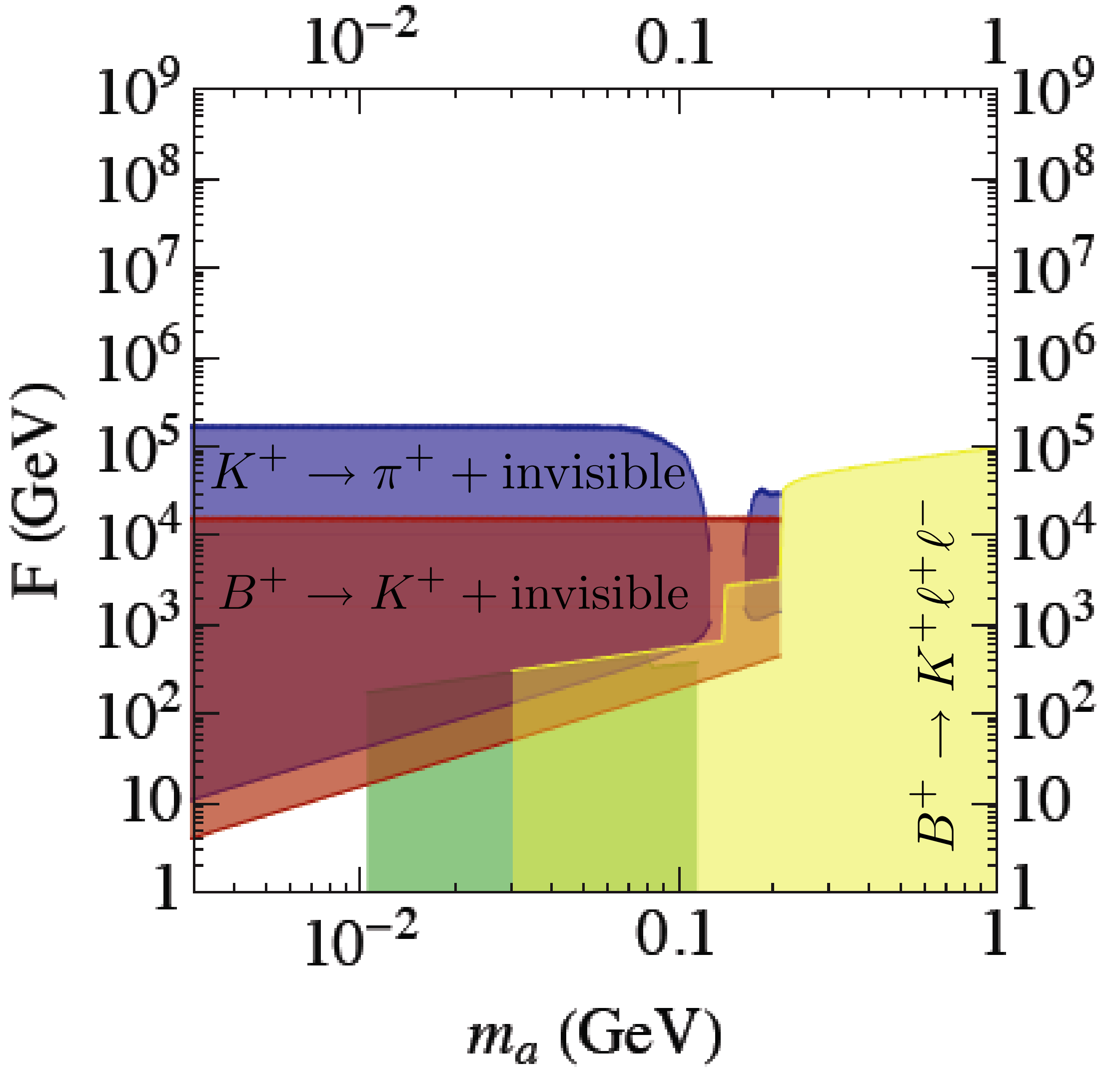
# Parameter Space

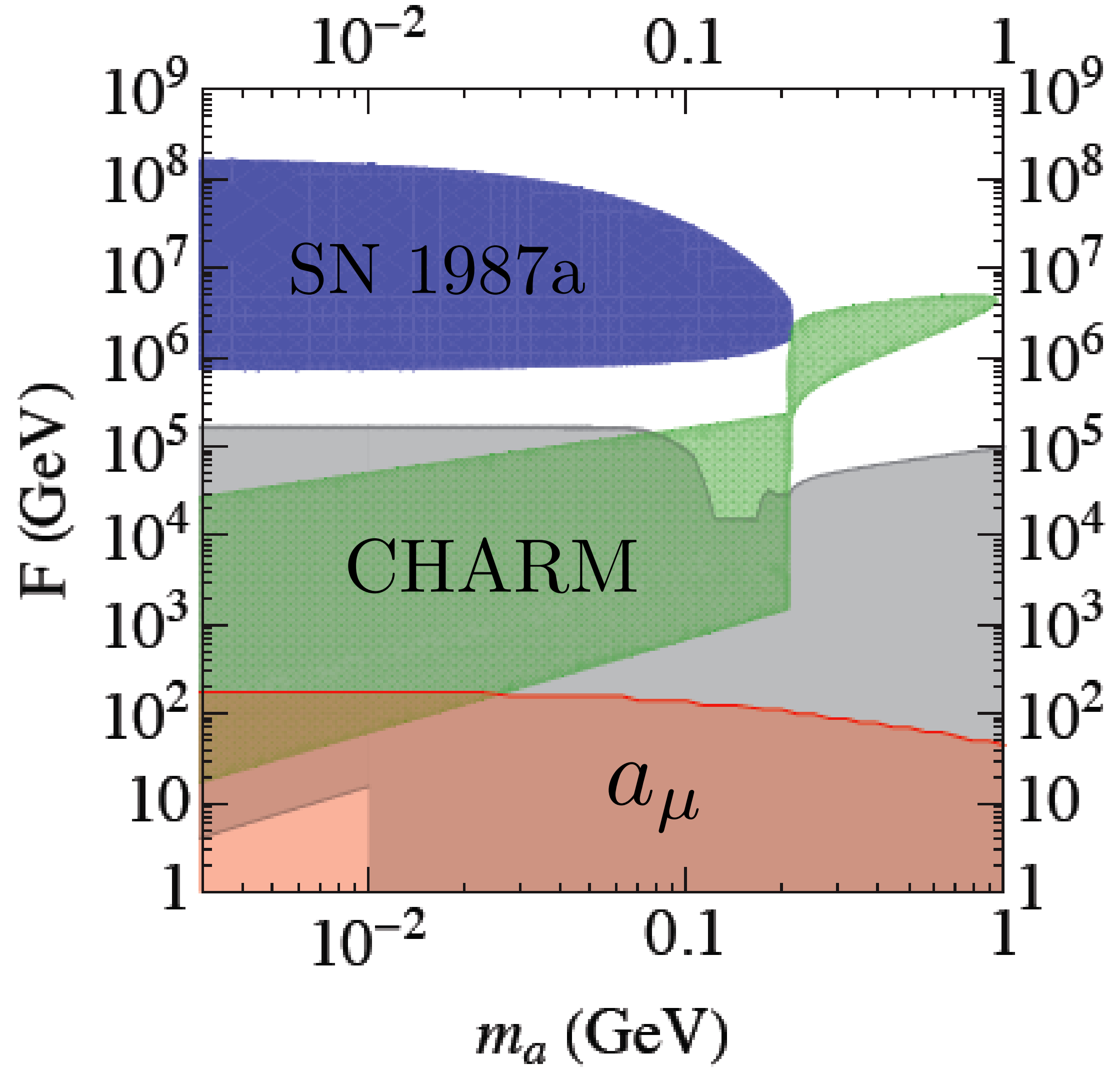
* A B-L gauge boson is more constrained:



# Axion - existing limits

- Limits on axions come from flavor, g-2, SN 1987a, and from CHARM (beam dump at CERN).




Note: g-2 is negative.

But could turn positive at 2-loops if it couples to tau.

# Nuclear Recoil

# Nuclear Recoil

- The situation is very different w/ nuclear recoil.
- SNO has measured Boron 8 neutrinos through deuterium dissociation.
- SNO is probing a momentum transfer that is only a factor of a few higher than DAMA or CoGent.

- A light mediator does not buy you much.

But...

# Nuclear Recoil

* Deuterium dissociation is an inelastic process.
* The standard model rate at SNO is dominated by the axial-vector component of the Z interaction.
* The vector component is suppressed by....

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

understanding this is in progress.

1103.3261

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Pospelov:

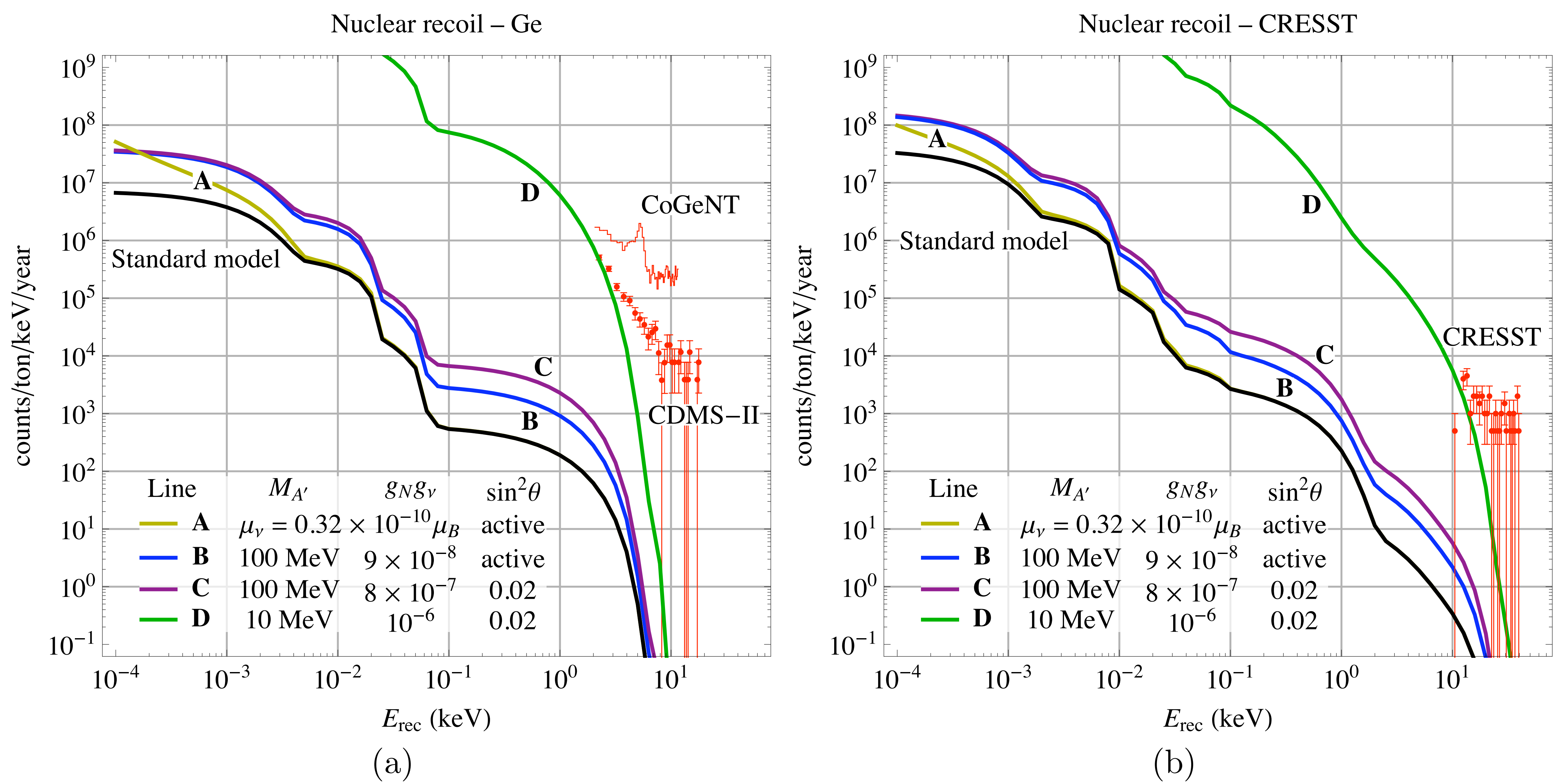
$$\langle d|\exp(i\mathbf{q}\mathbf{r}^{(n)}) + \exp(i\mathbf{q}\mathbf{r}^{(p)})|np\rangle$$

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

1103.3261

# Nuclear recoil

* Interesting spectra are achievable:



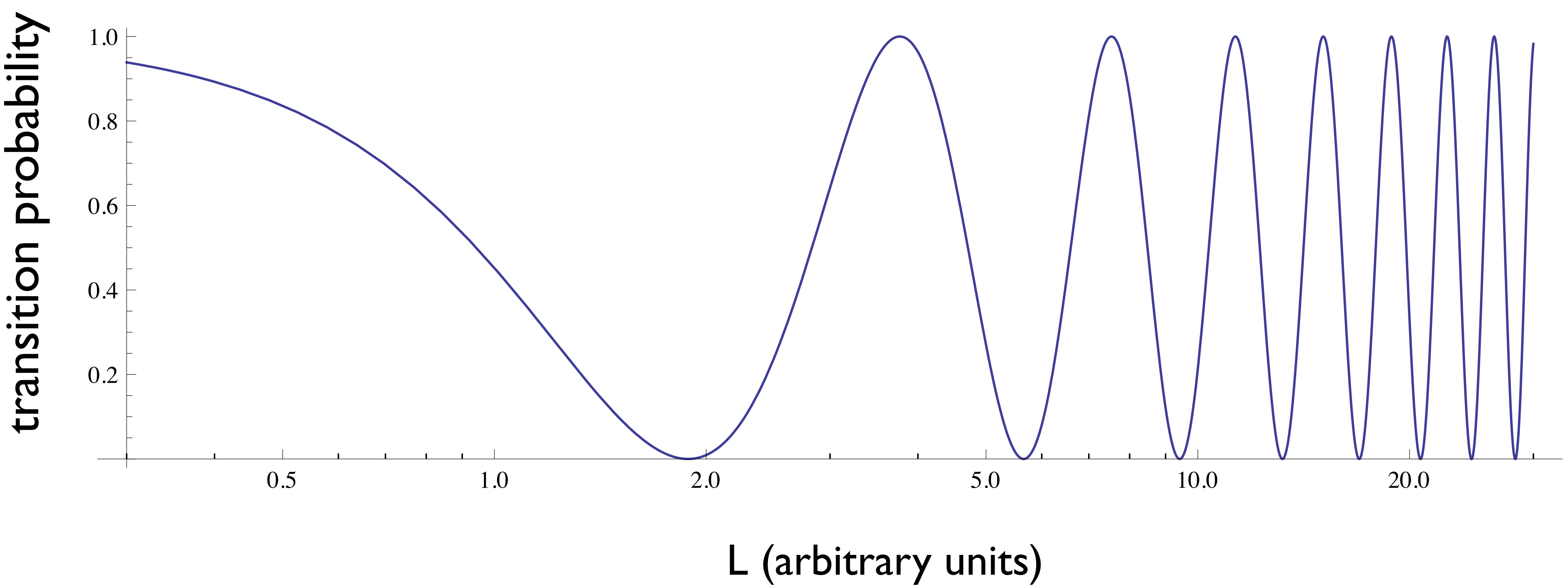

SNO constraints may still be too much....(in progress)

# Other Modulation Scenarios

# Just-So

* Introduce a vacuum oscillation between sterile and active neutrinos.

$$P_{1\to 2} \sim \sin^2 2\theta \sin^2 \frac{\Delta m_{12}^2 L}{2E_\nu}$$



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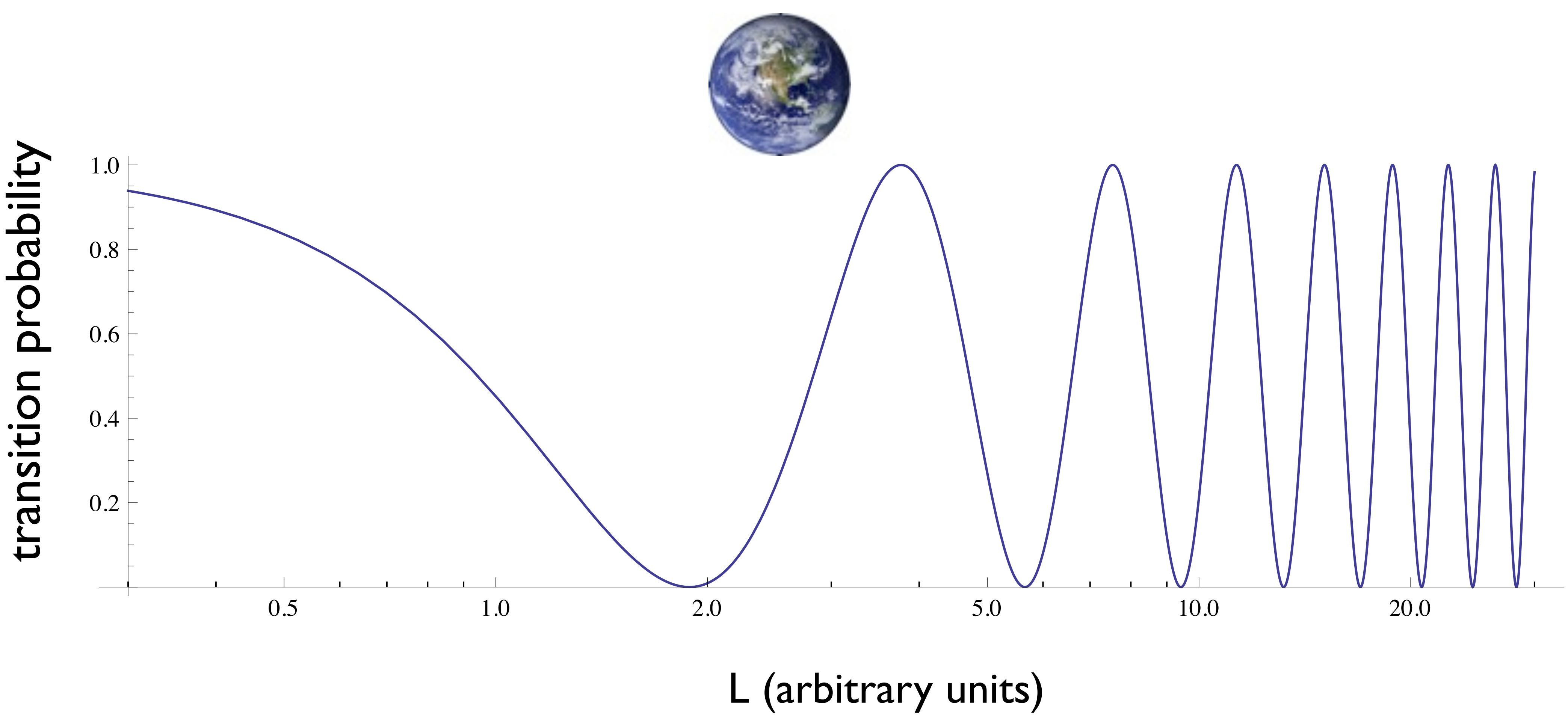

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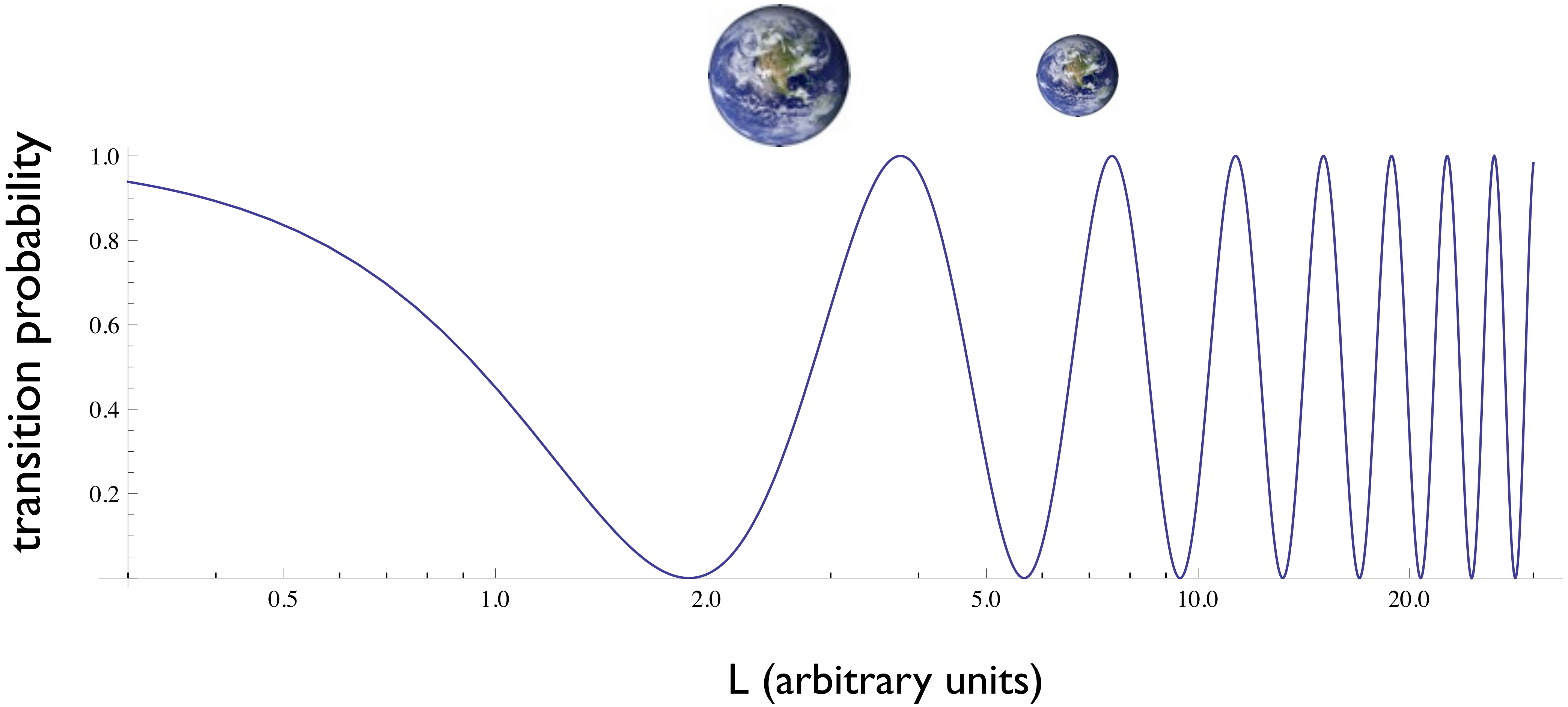

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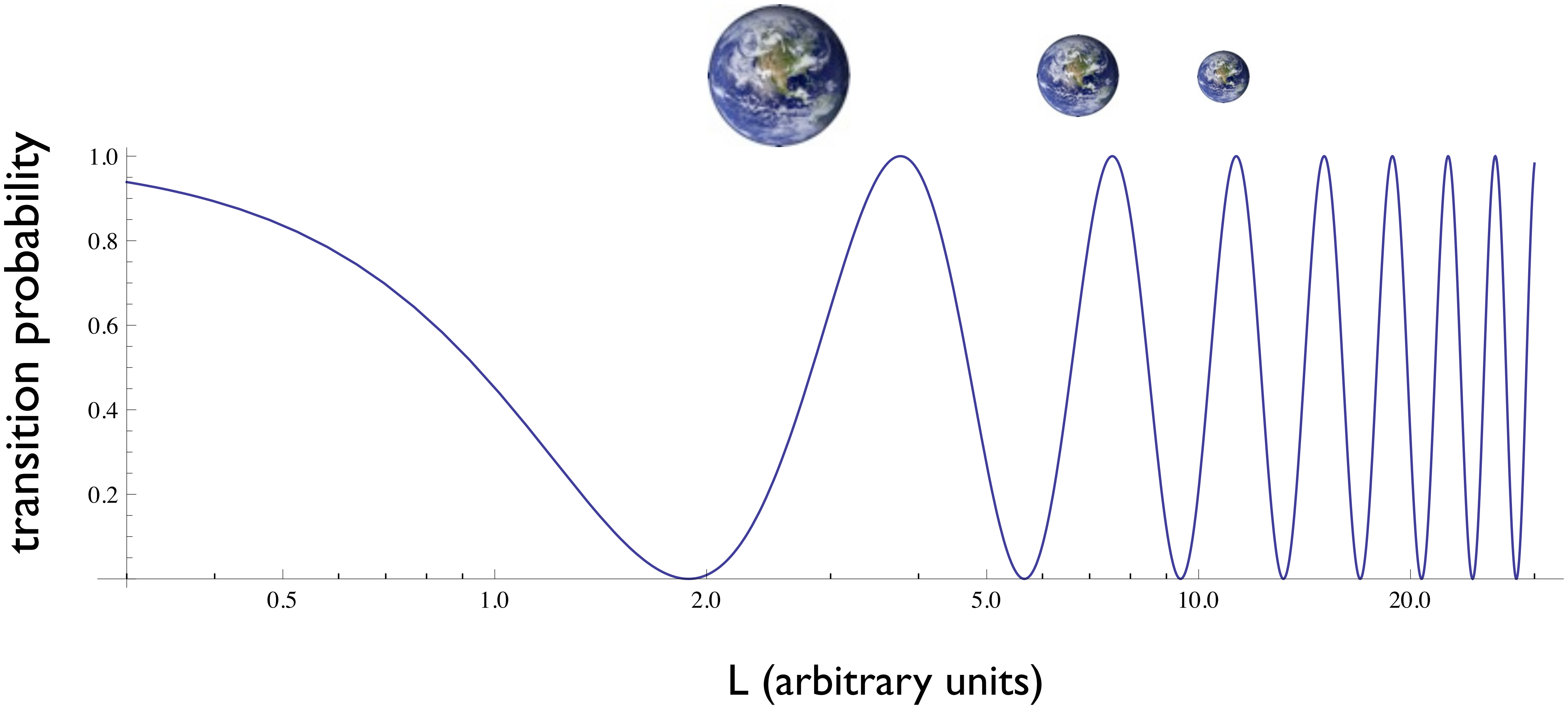
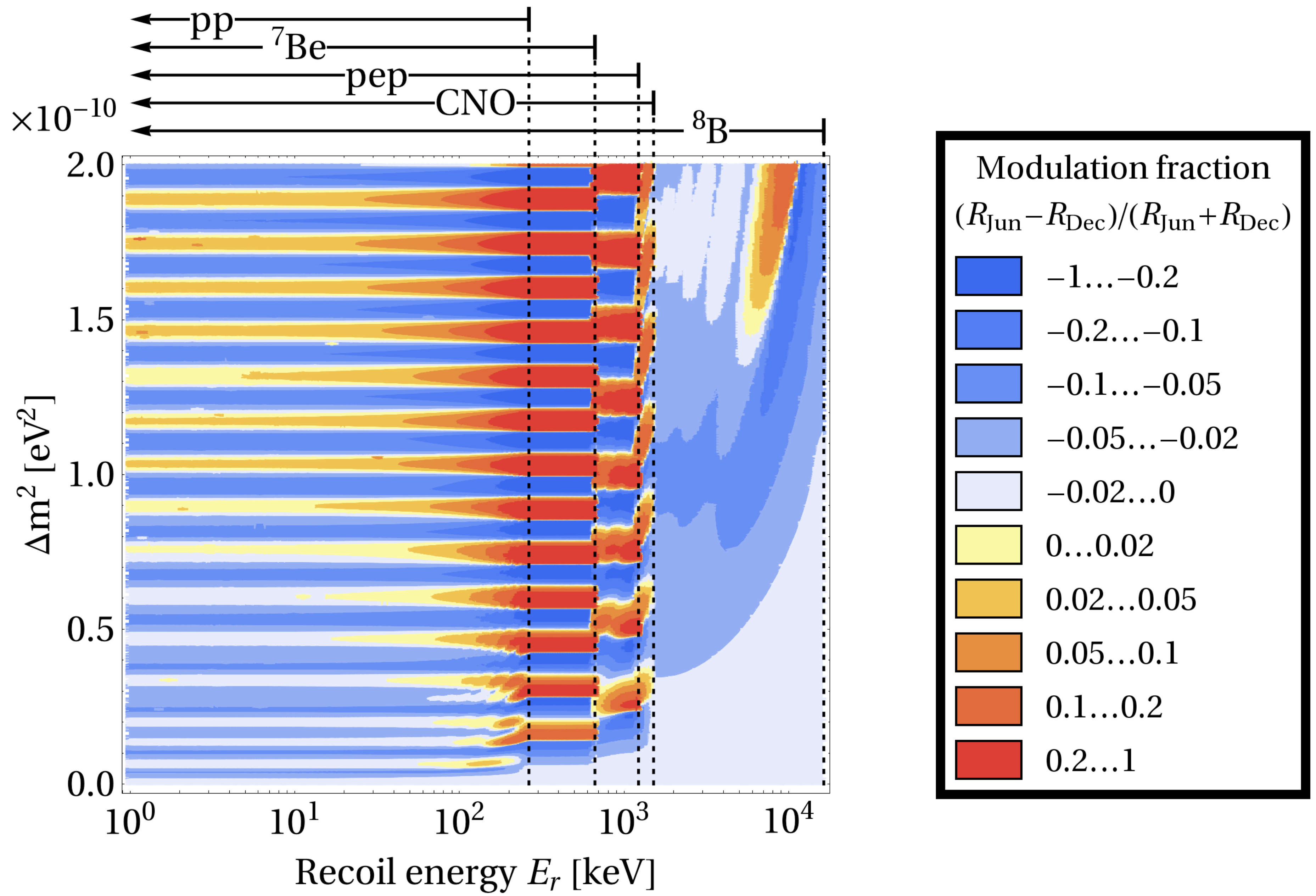


# Just-So

* A variety of modulation amplitudes are possible



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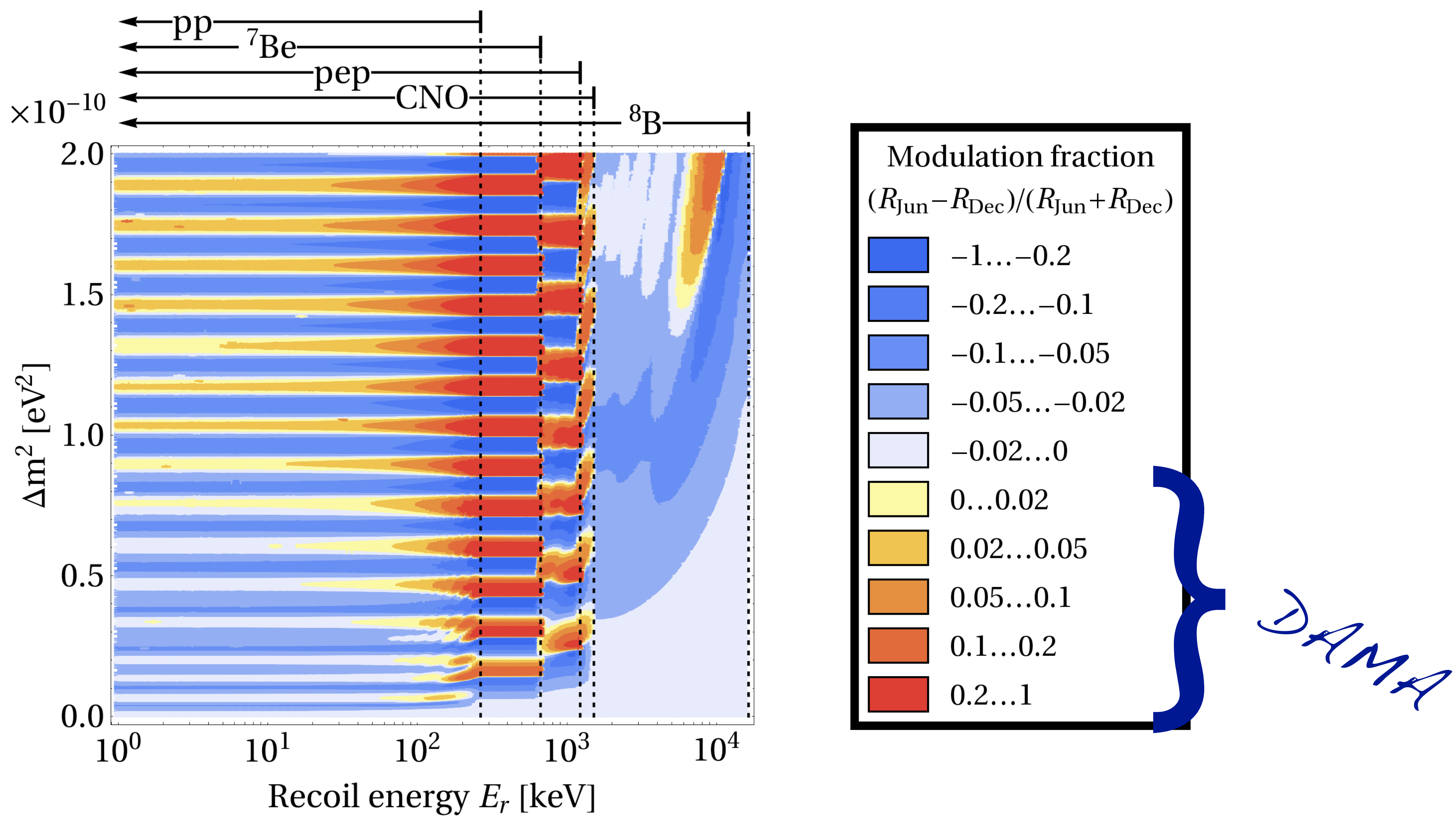
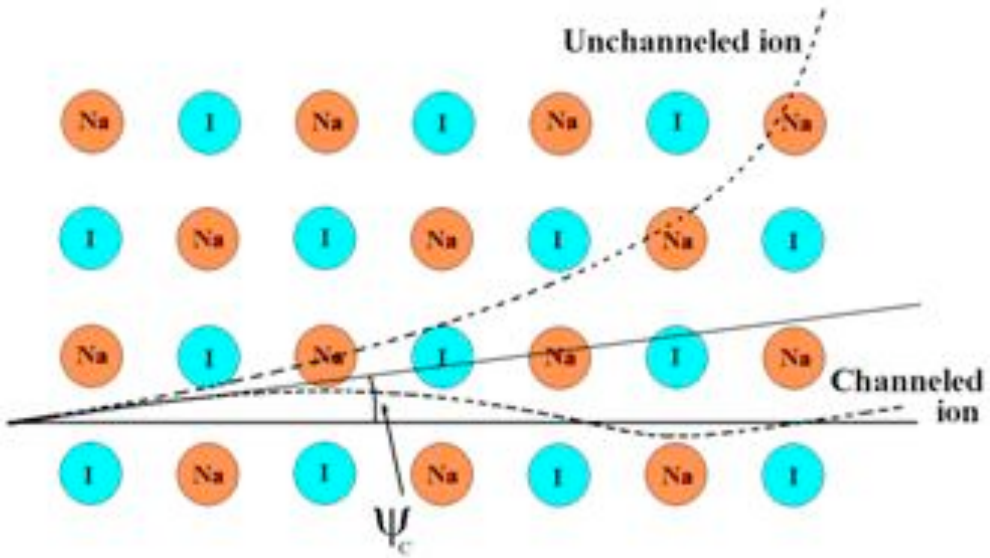


# Channeling

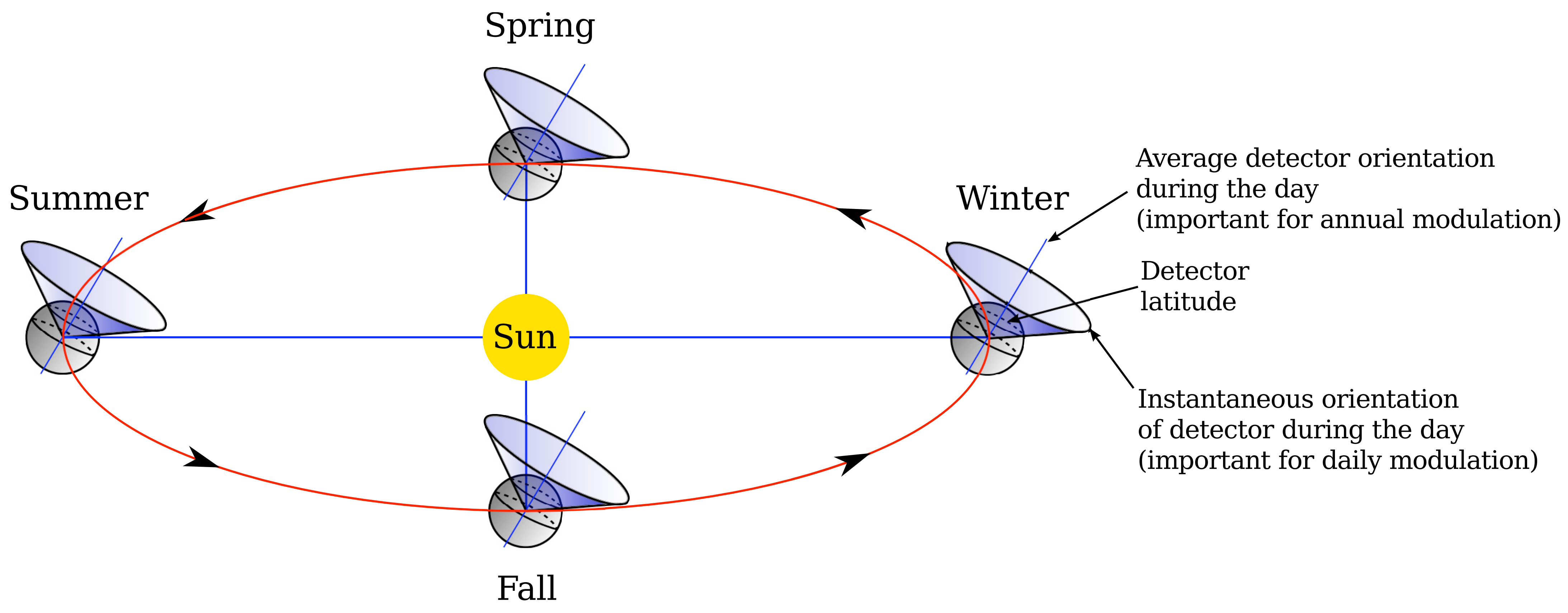
* The dark matter signal is isotropic to zeroth order.
* A signal coming from the sun is maximally anisotropic.
* Imagine channeling in crystals occurs:




* A highly angle dependent effect $\longrightarrow$ modulation!

# Channeling

* This can lead to a daily modulation, as well as a annual or semi-annul modulation.



# Absorption

* If the sterile scattering cross section is high, its m.f.p may be smaller than earth radius.
* Neutrinos are captured during the night, but reach the detector during the day.
* Steriles can still be produced via oscillation outside the sun.
* The sterile flux may still be adjusted to fit the signal strength in direct detection.