ν Signals of Dark Matter

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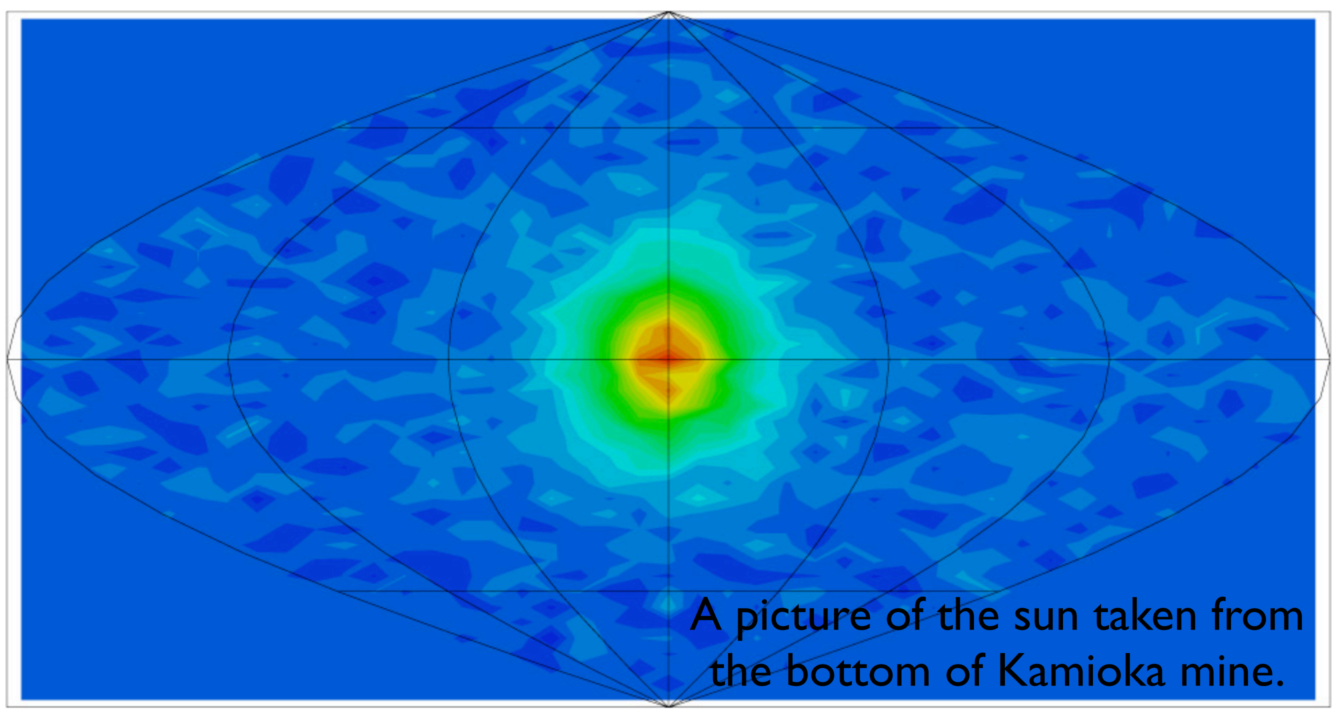
with Joachim Kopp and Pedro Manchado
1202.6073

See related works-
Pospelov 1103.3261
Pospelov and Pradler 1203.0545
yesterday's talk

Direct Detection

* In past decades direct detection collaborations have made a heroic (and successful!) effort in background reduction.

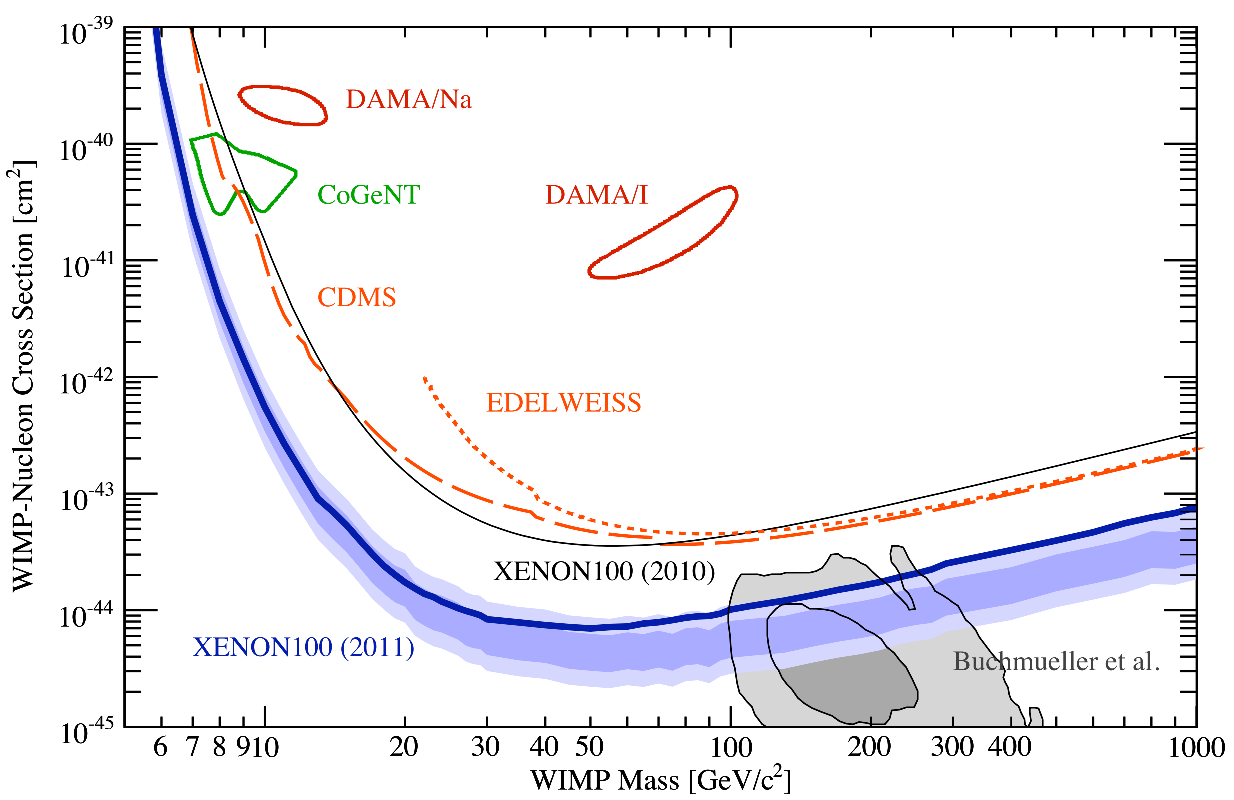
* Try as you might, these experiments are still completely exposed to the sun....



...in neutrinos!!!

Direct Detection

* The irreducible background from solar and atmospheric neutrinos will be the eventual end-game of direct detection.



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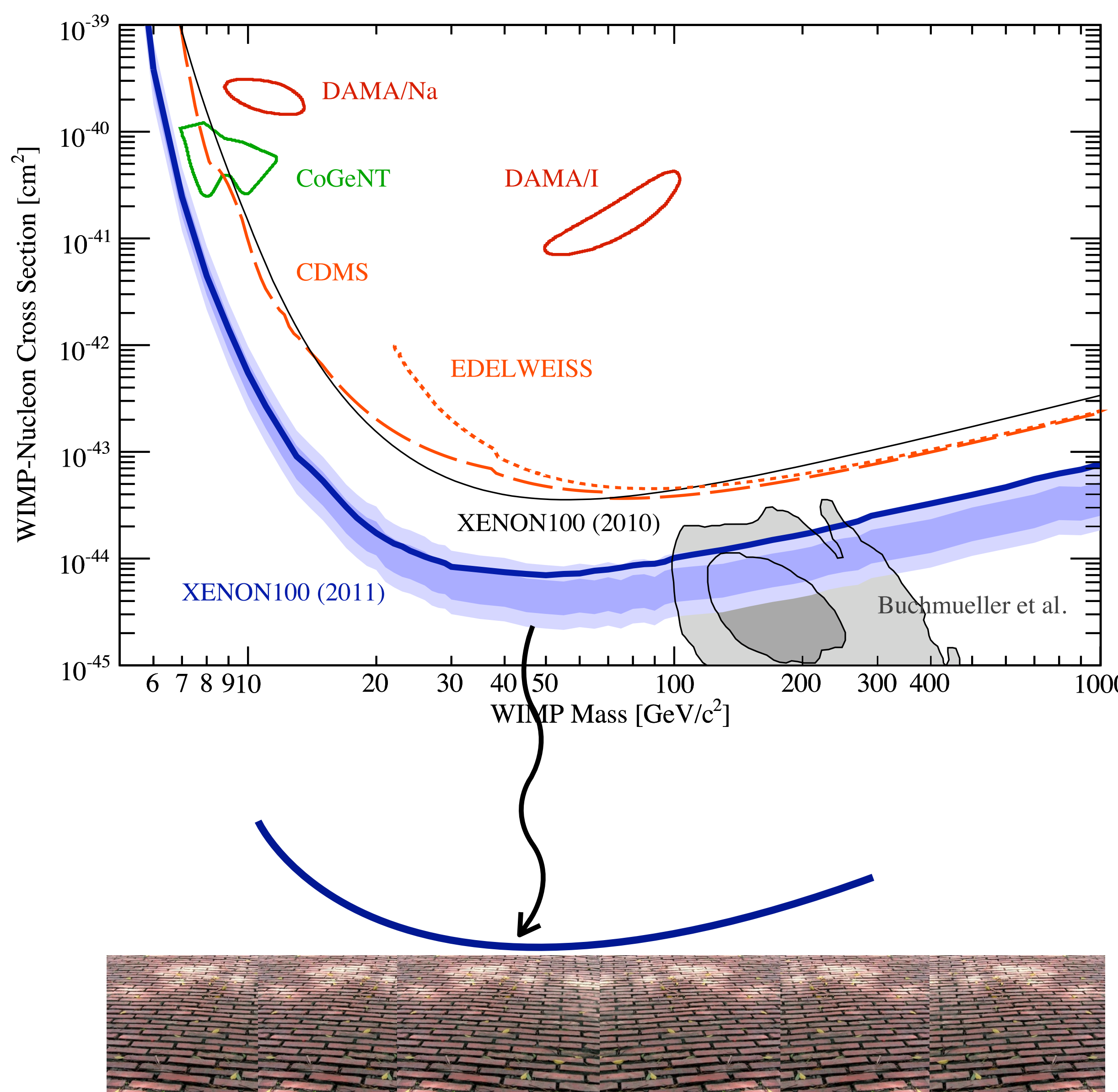
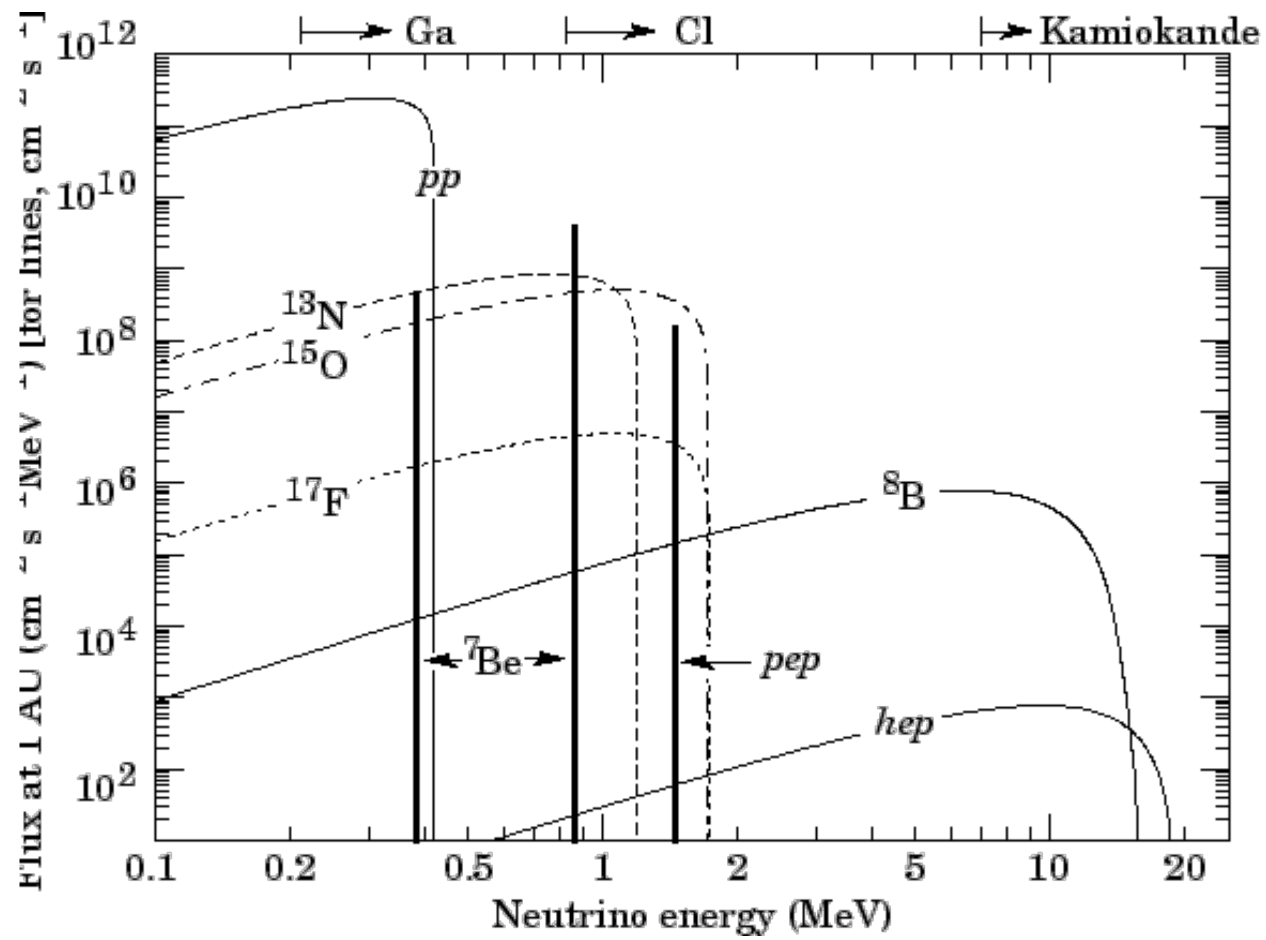


can this background be "raised" to be a signal?

What does this look like in a direct detection experiment?



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

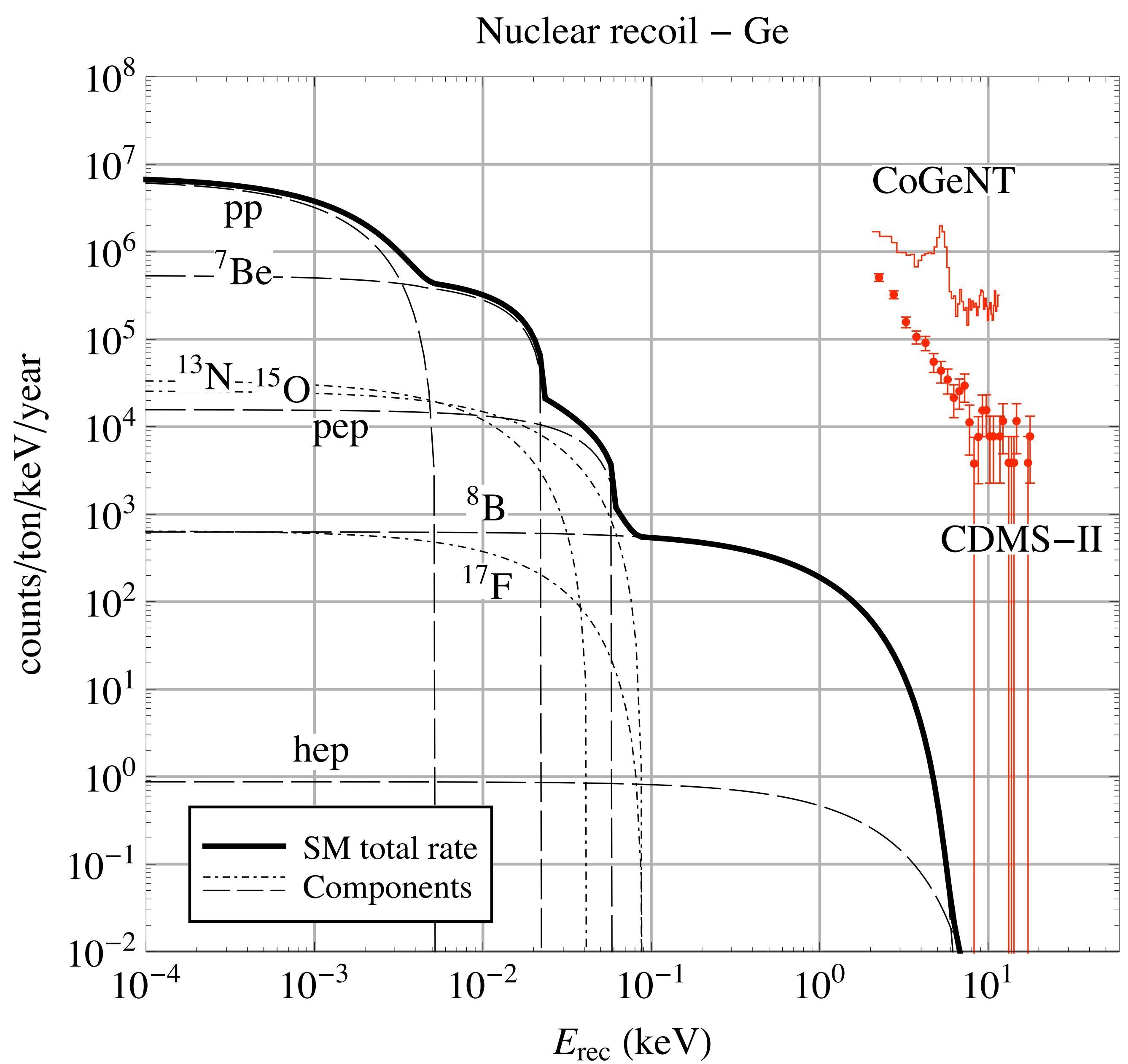
with $$E_\nu^{\min} = \frac{1}{2}\left(E_r + \sqrt{E_r^2 + 2E_r m_T}\right)$$

(relativistic version of $\frac{dR}{dE_R} = \frac{M_N N_T \rho_\chi \sigma_n}{2 m_\chi \mu_{ne}^2} F^2 \frac{(f_p Z + f_n (A-Z))^2}{f_n^2} \int_{v_{min}} \frac{f(v)}{v}$)

Spectrum

* For nuclear recoil:

  see Joseph Pradler's talk



* The scattering is coherent, $\propto A^2$.

* The flux is low above threshold.

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

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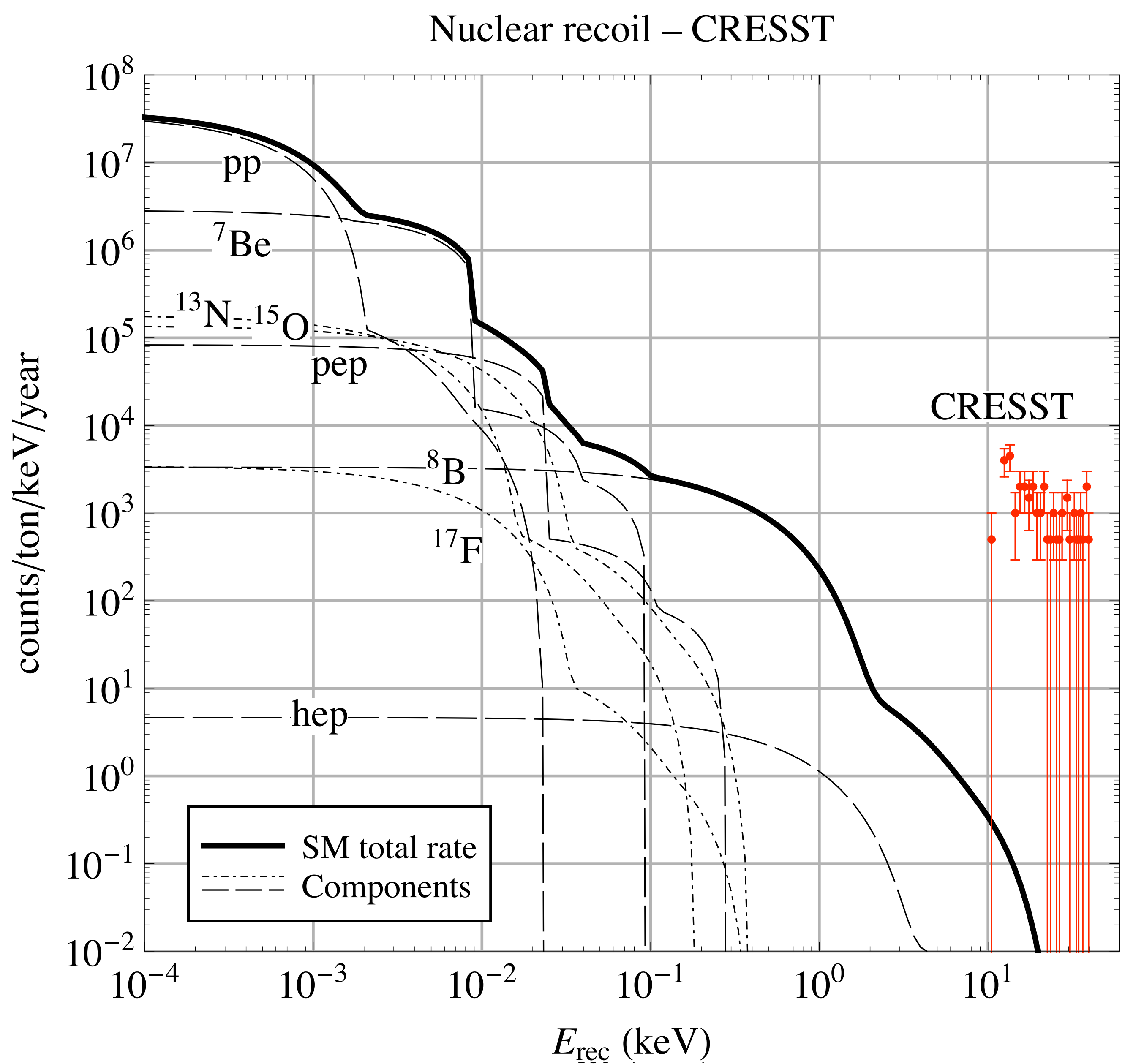

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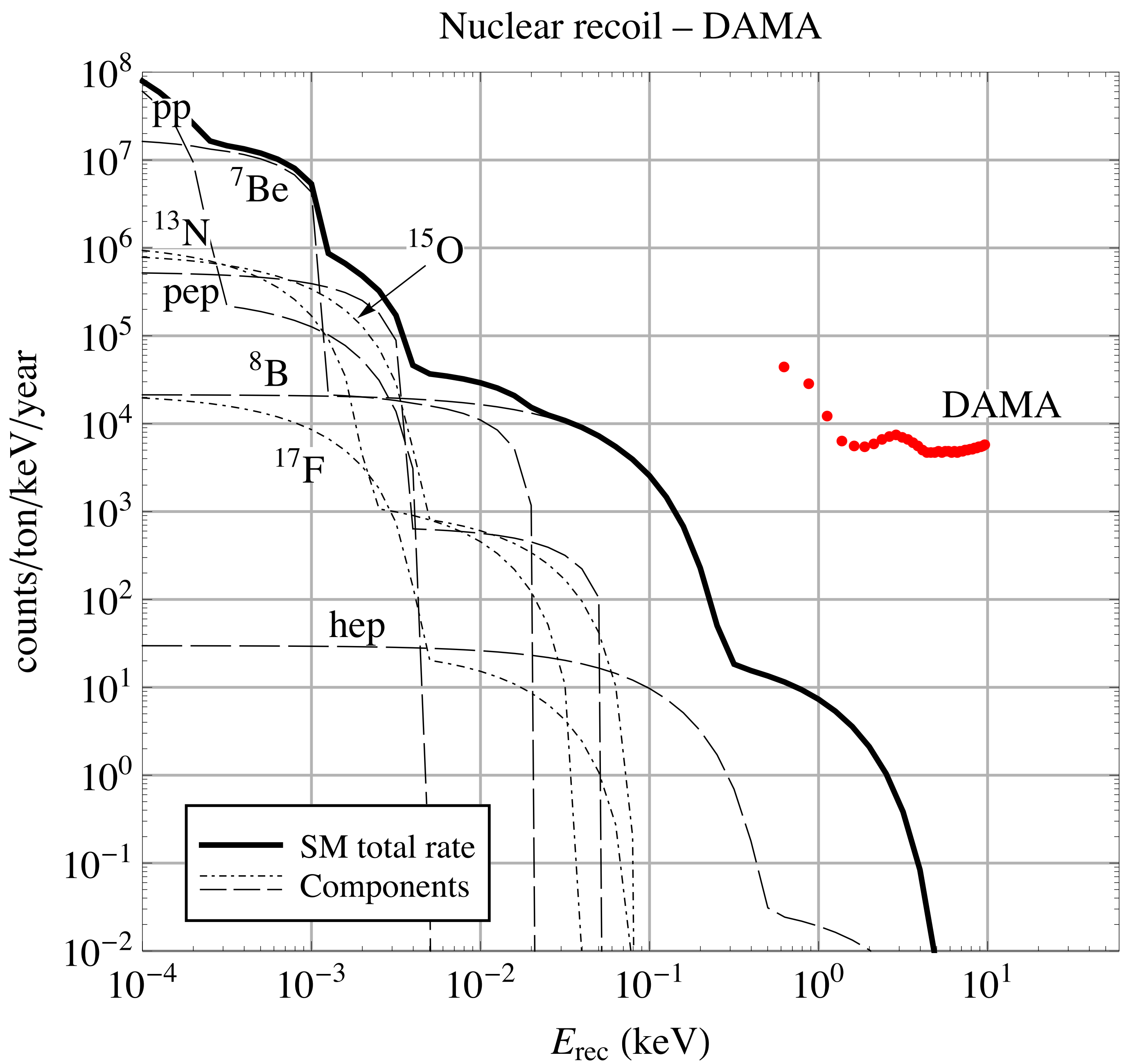
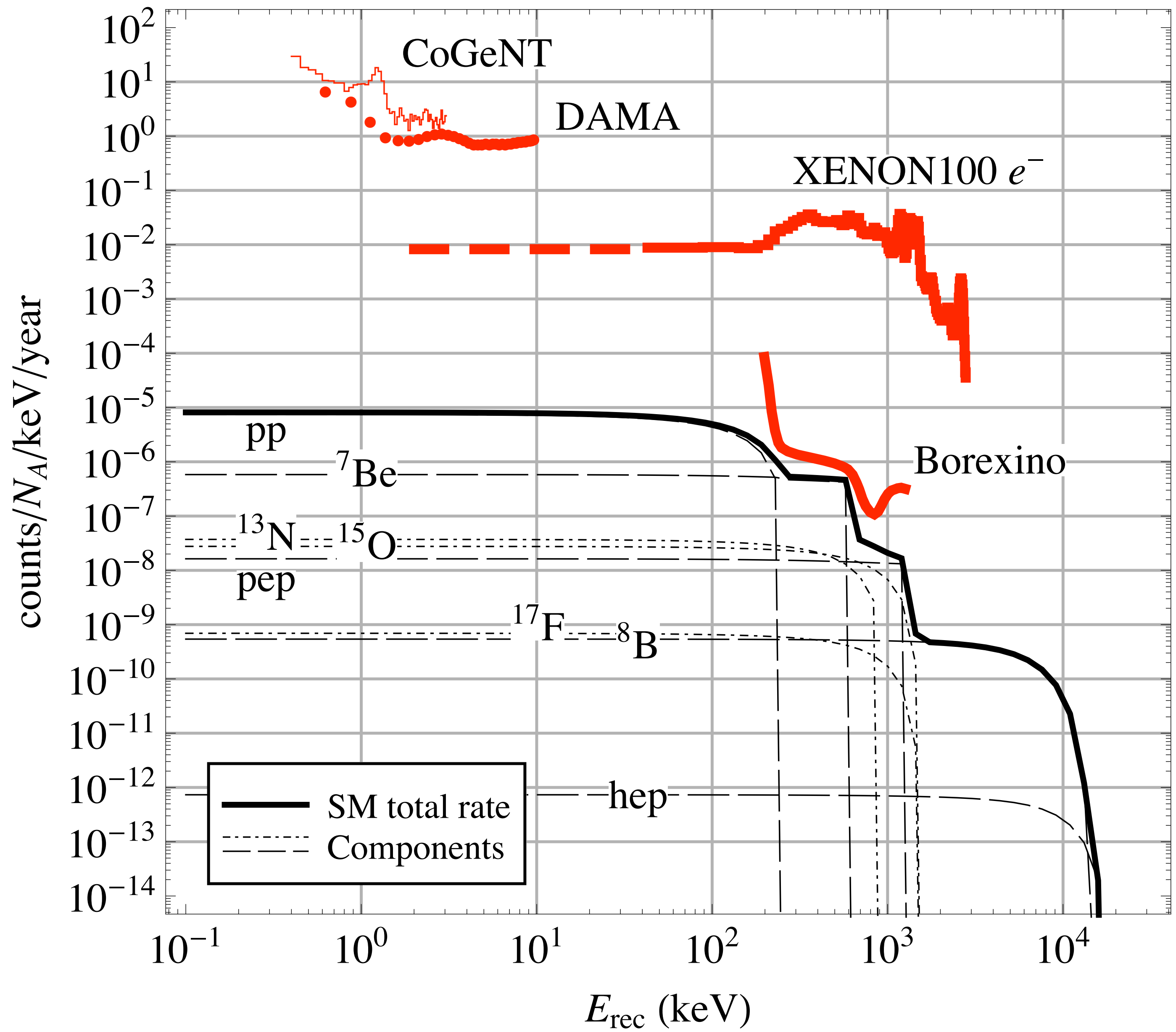


Spectrum

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

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

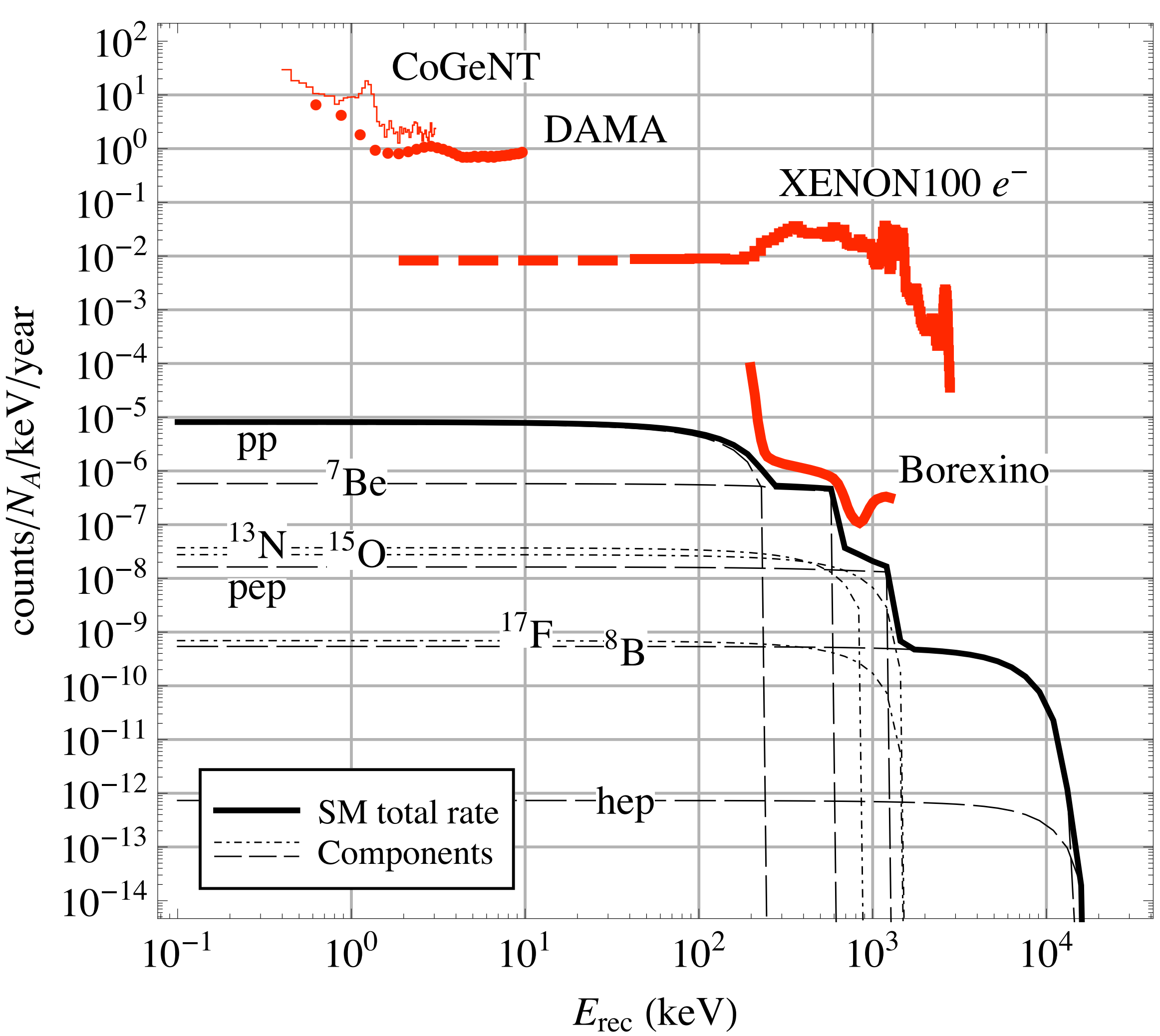
  - But, lower cross section, (phase space and coherence).

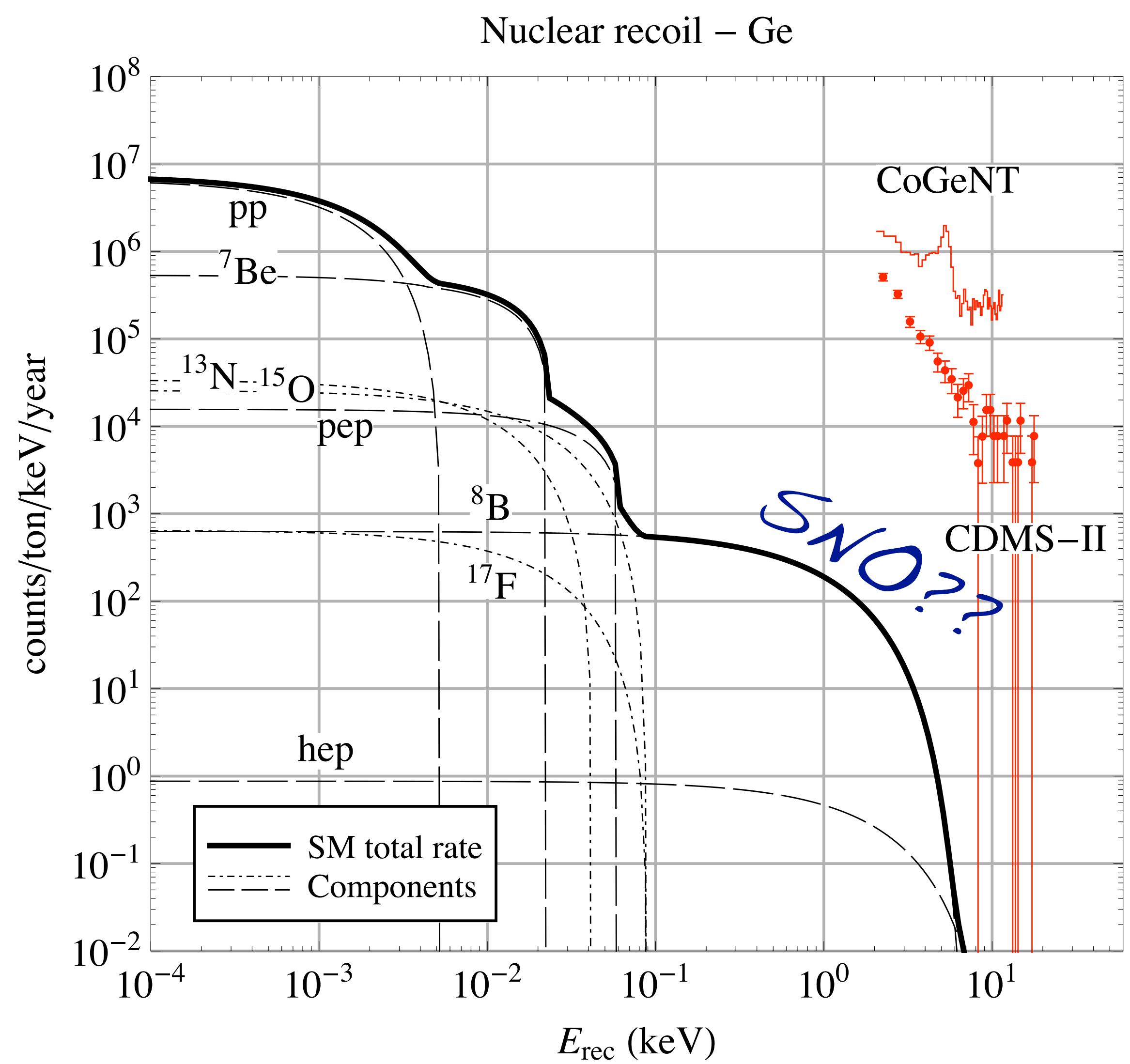


scattering on effectively free electrons.
All experiments in one plot!

New Physics?

* Can new physics in the neutrino sector "raise" this background and give interesting signals?





Since Joseph cover nuclear, I'll focus on e-recoil.

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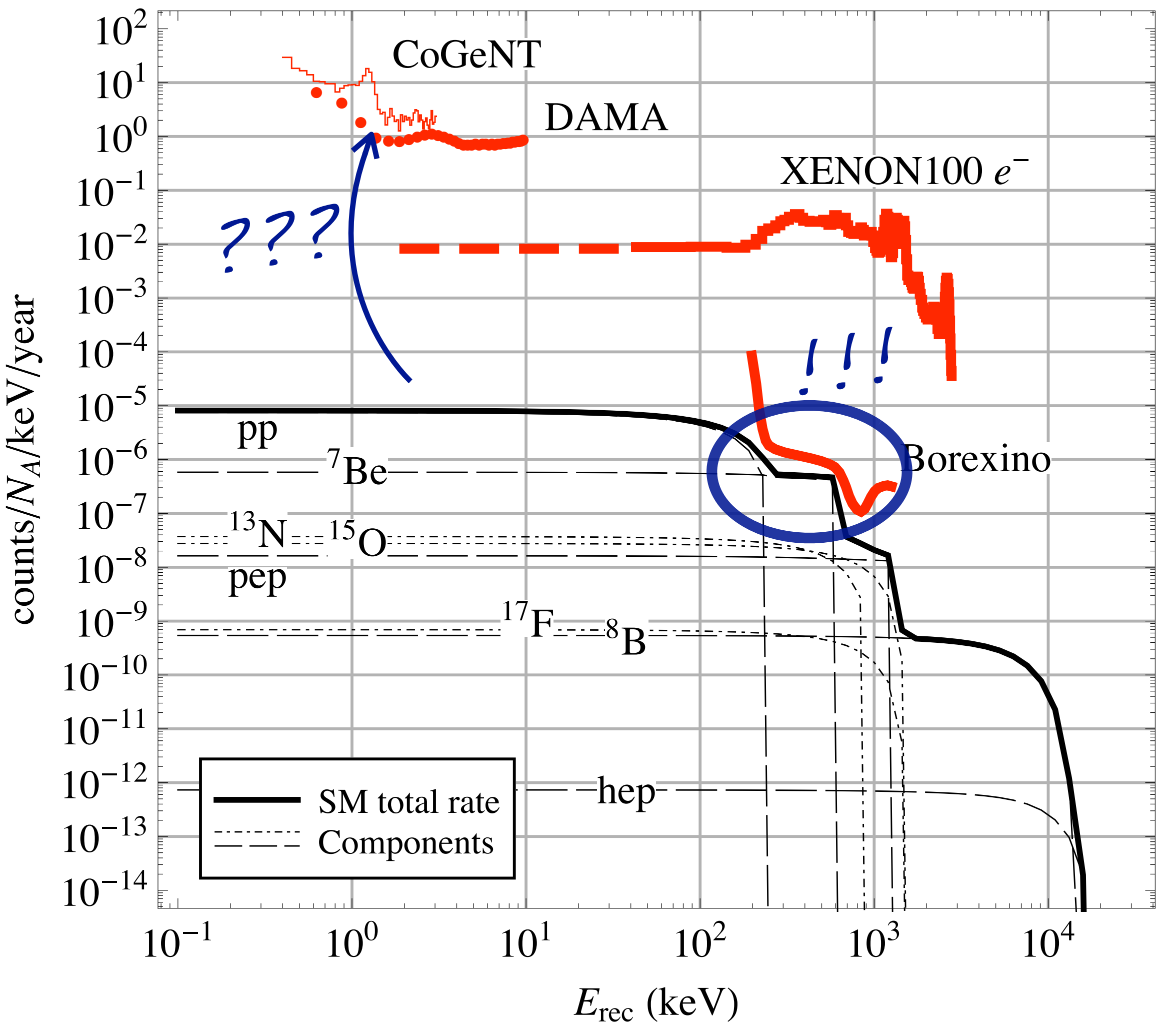

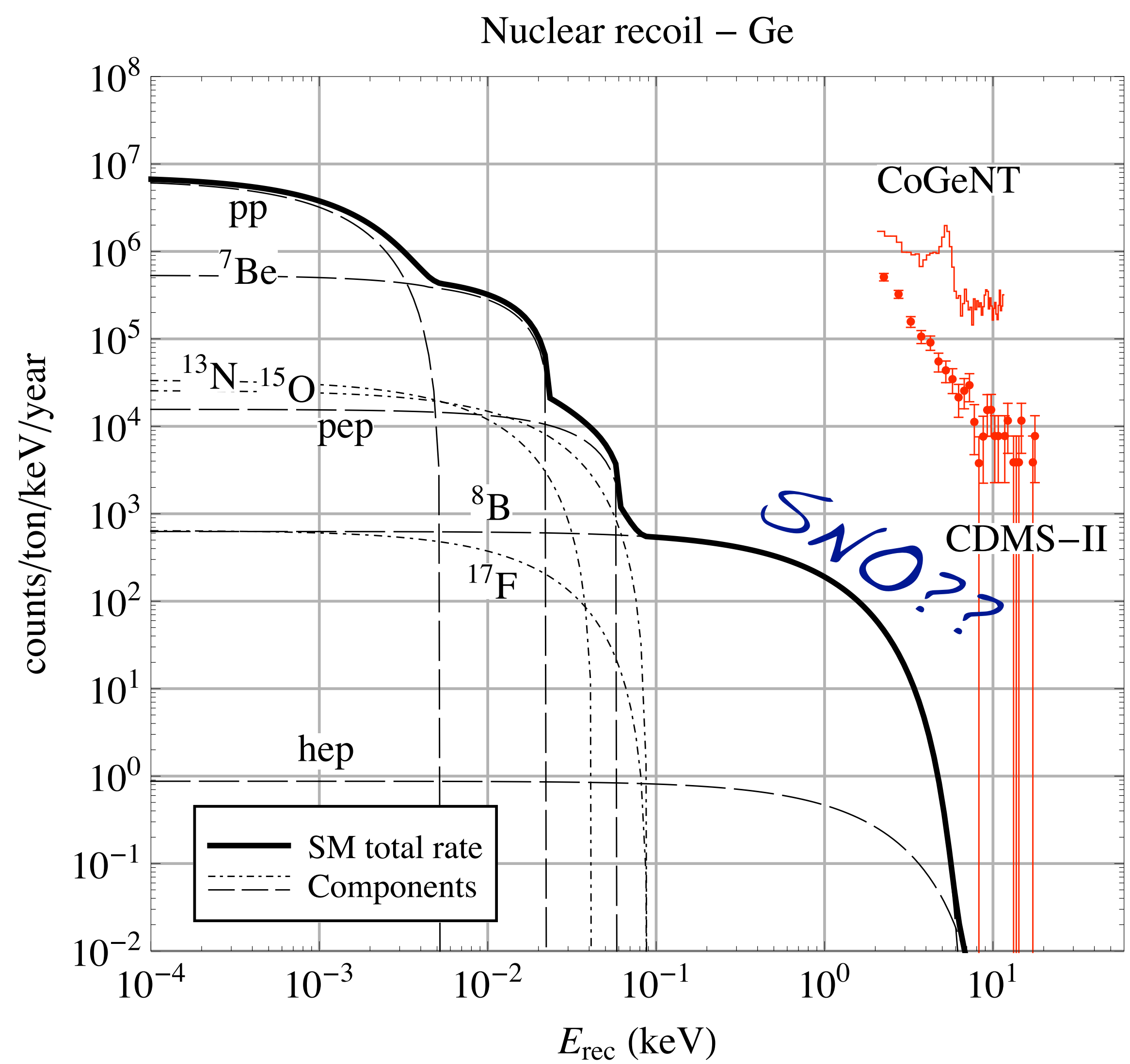

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Outline

* New light gauge bosons (A')
* Electron recoil
  - SM neutrinos or light steriles
  - Heavy steriles
* Potential sources of modulation-
  - Solar distance
  - Matter effects
  - Channeling
* Constraints on A's
* Conclusion.

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.

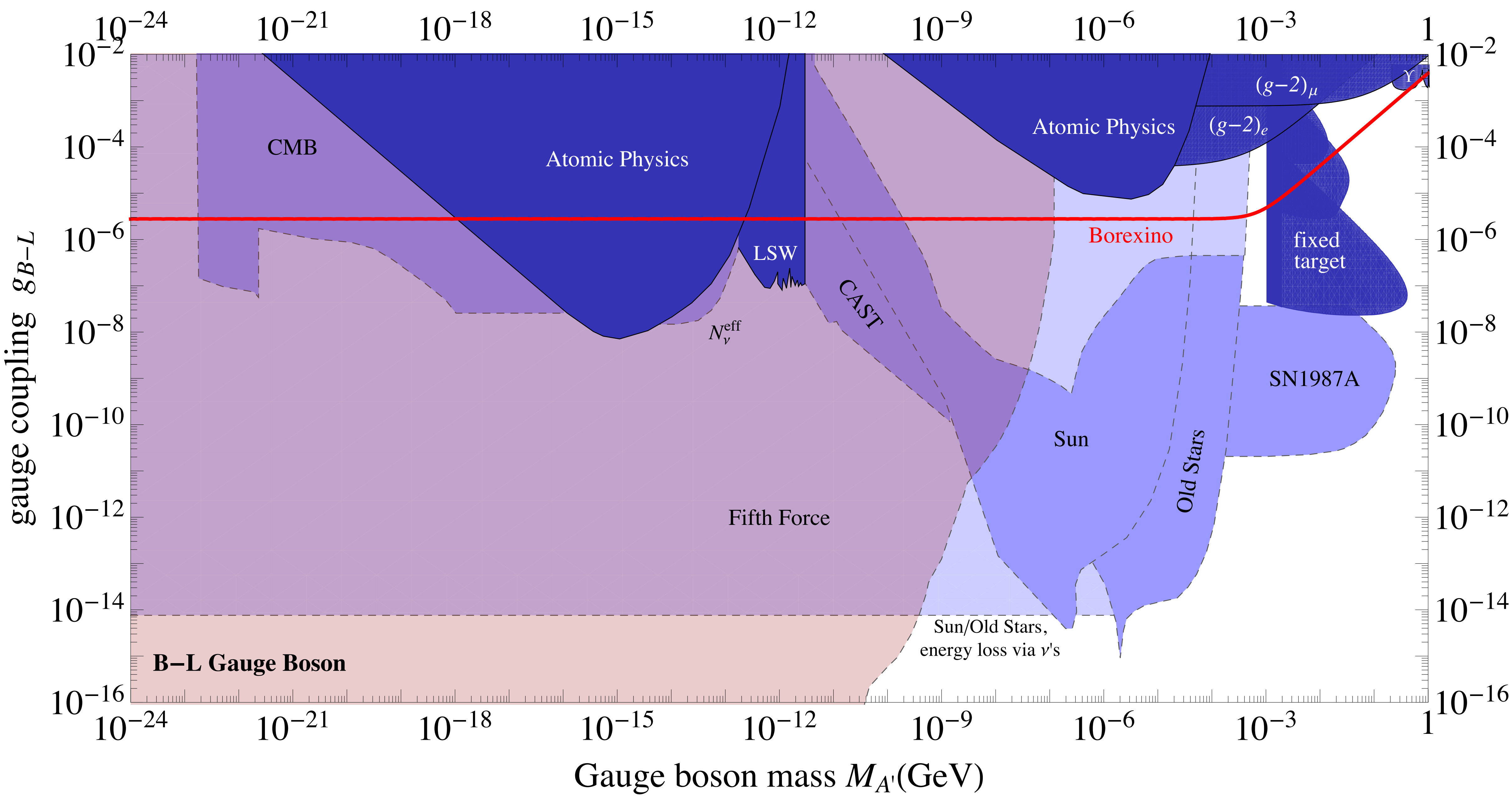
---

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

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

Parameter Space

* B-L is constrained. There are holes:



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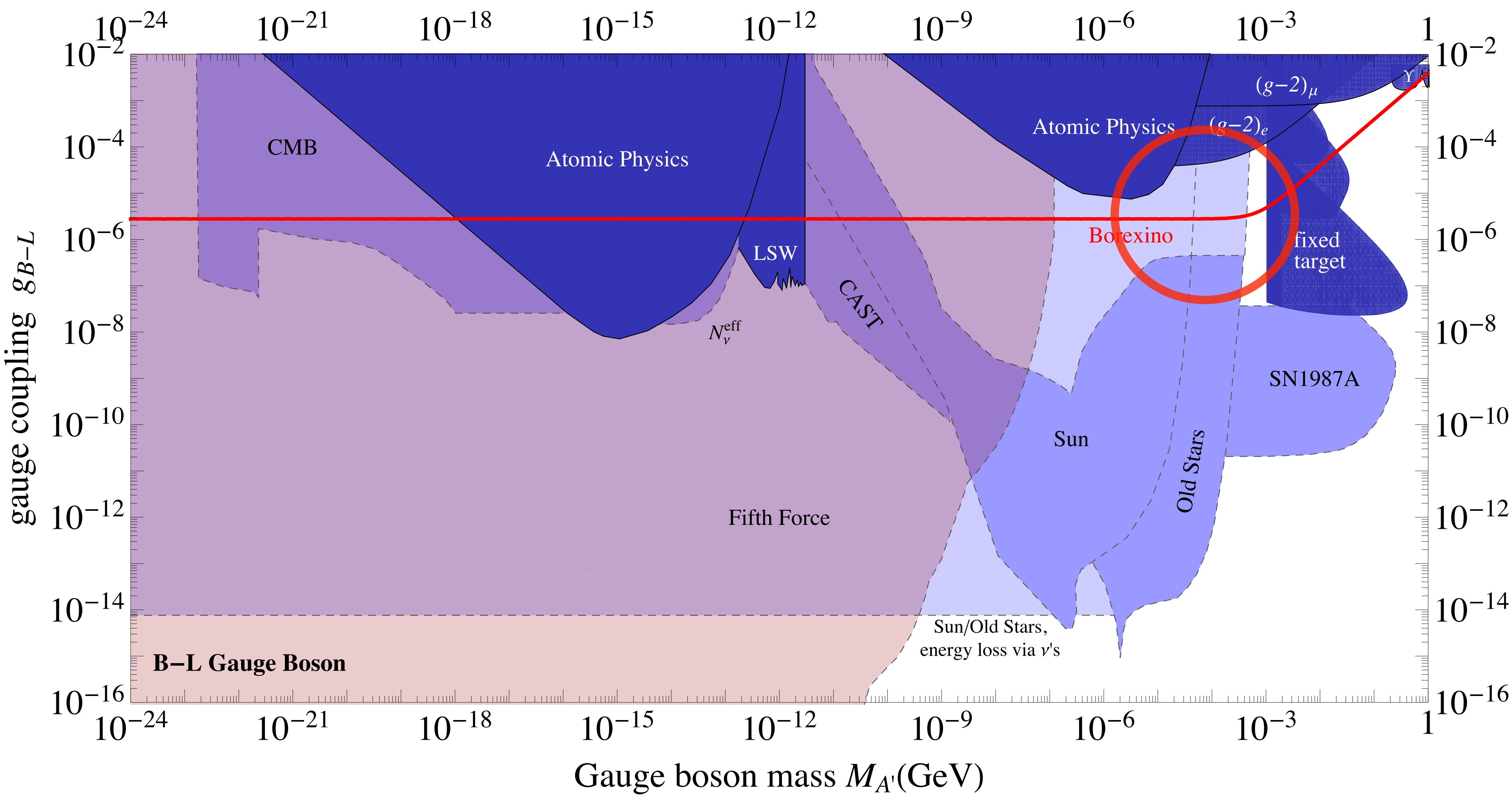

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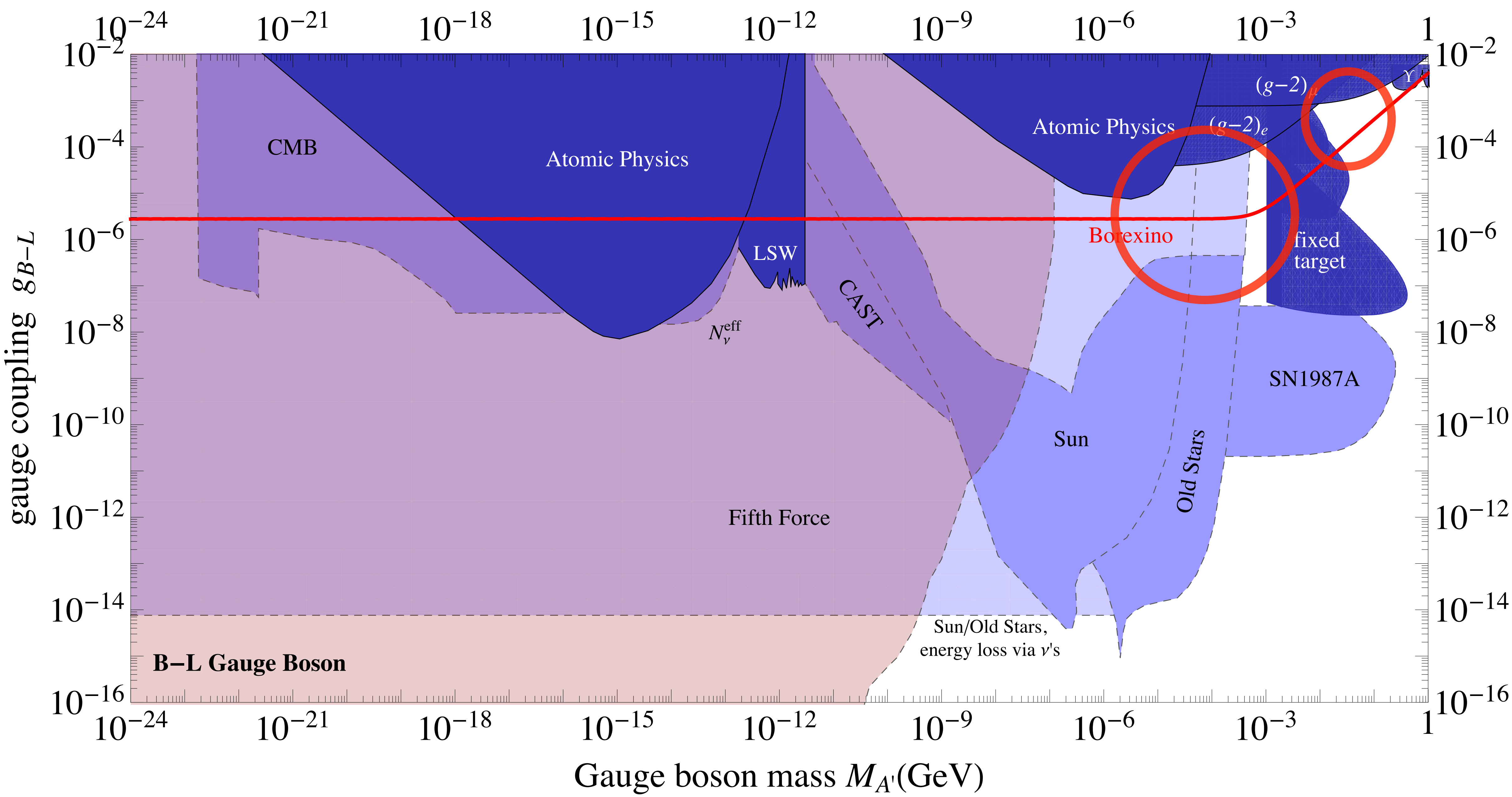

Parameter Space

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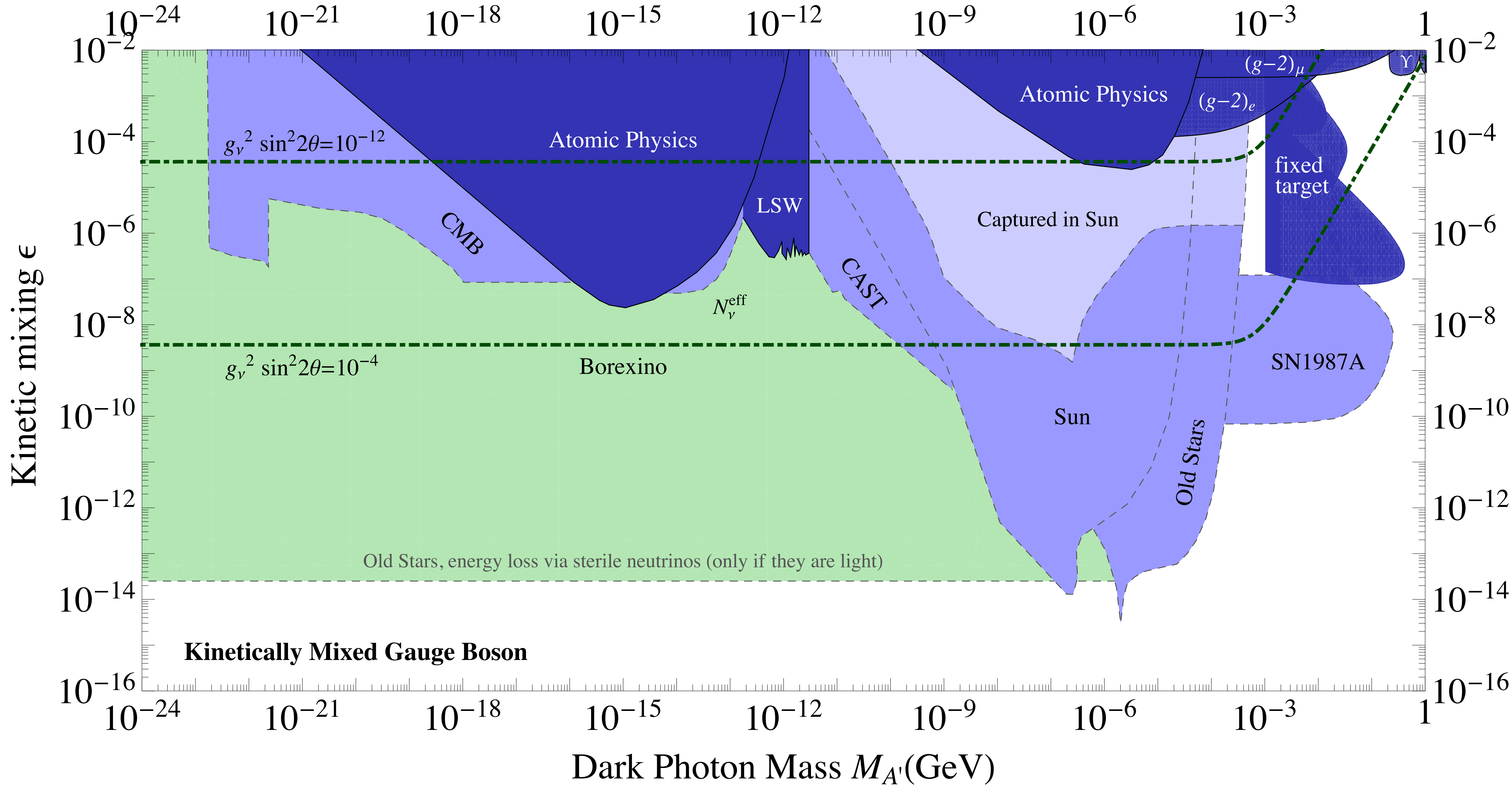

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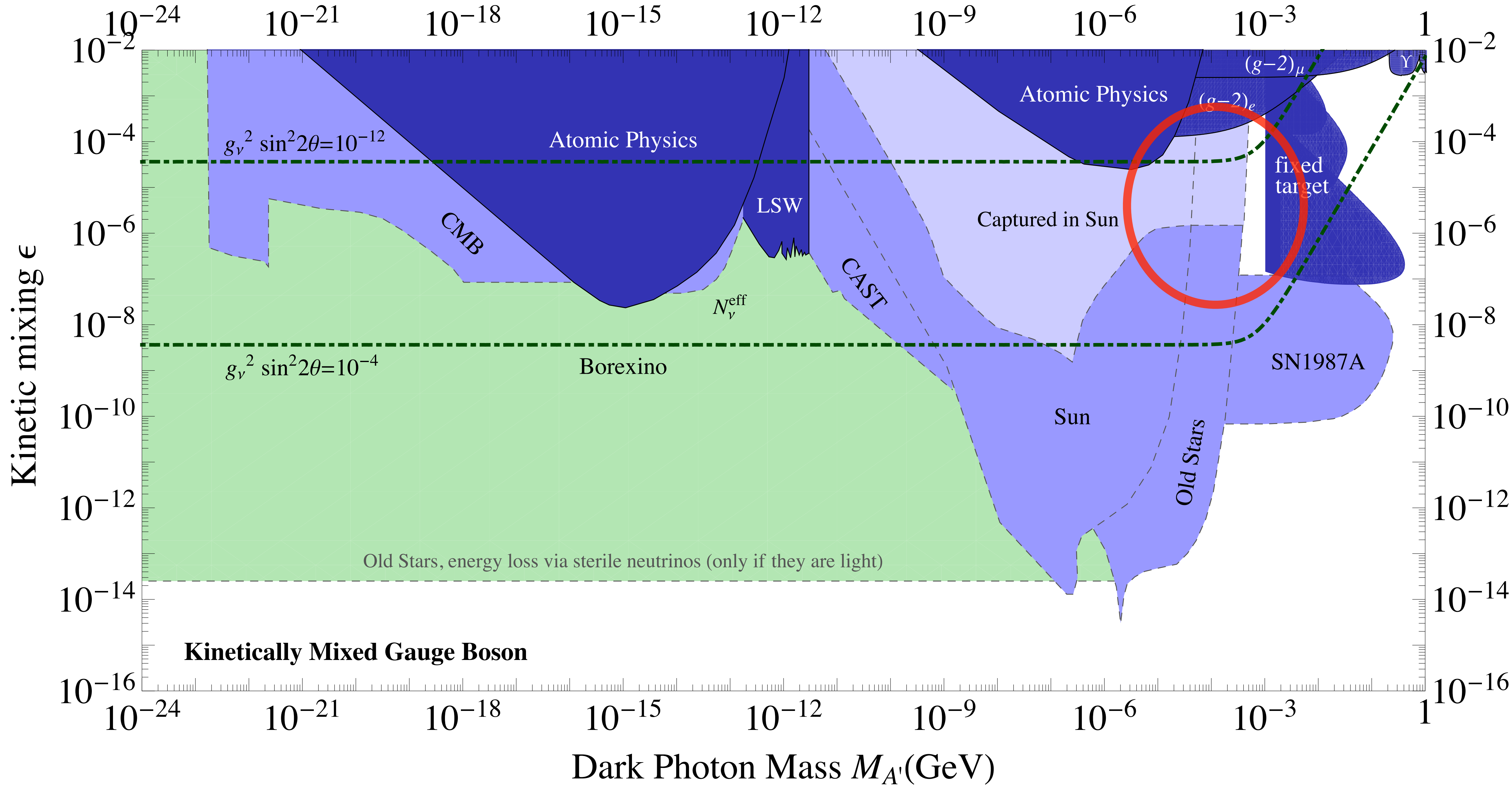

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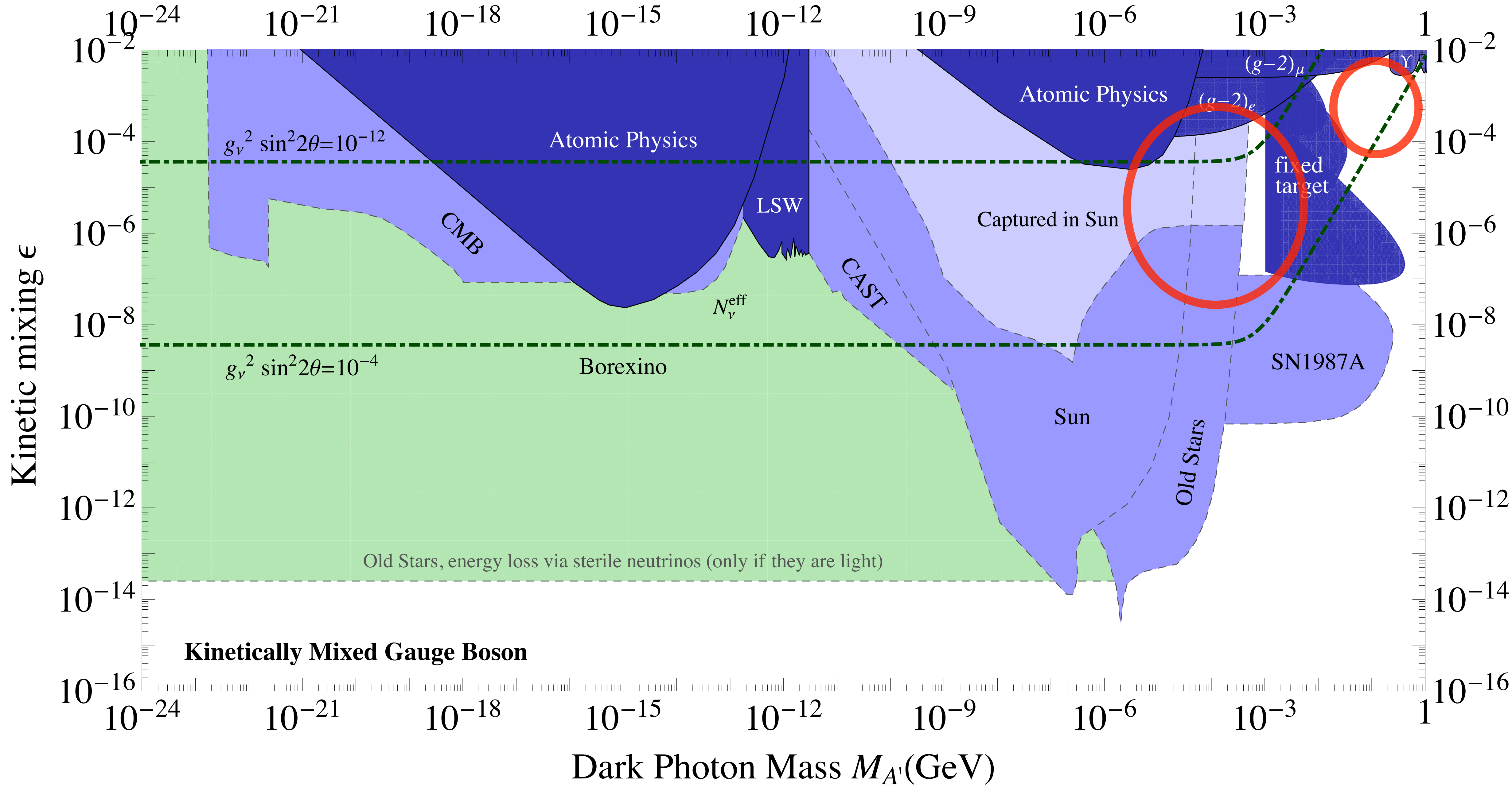

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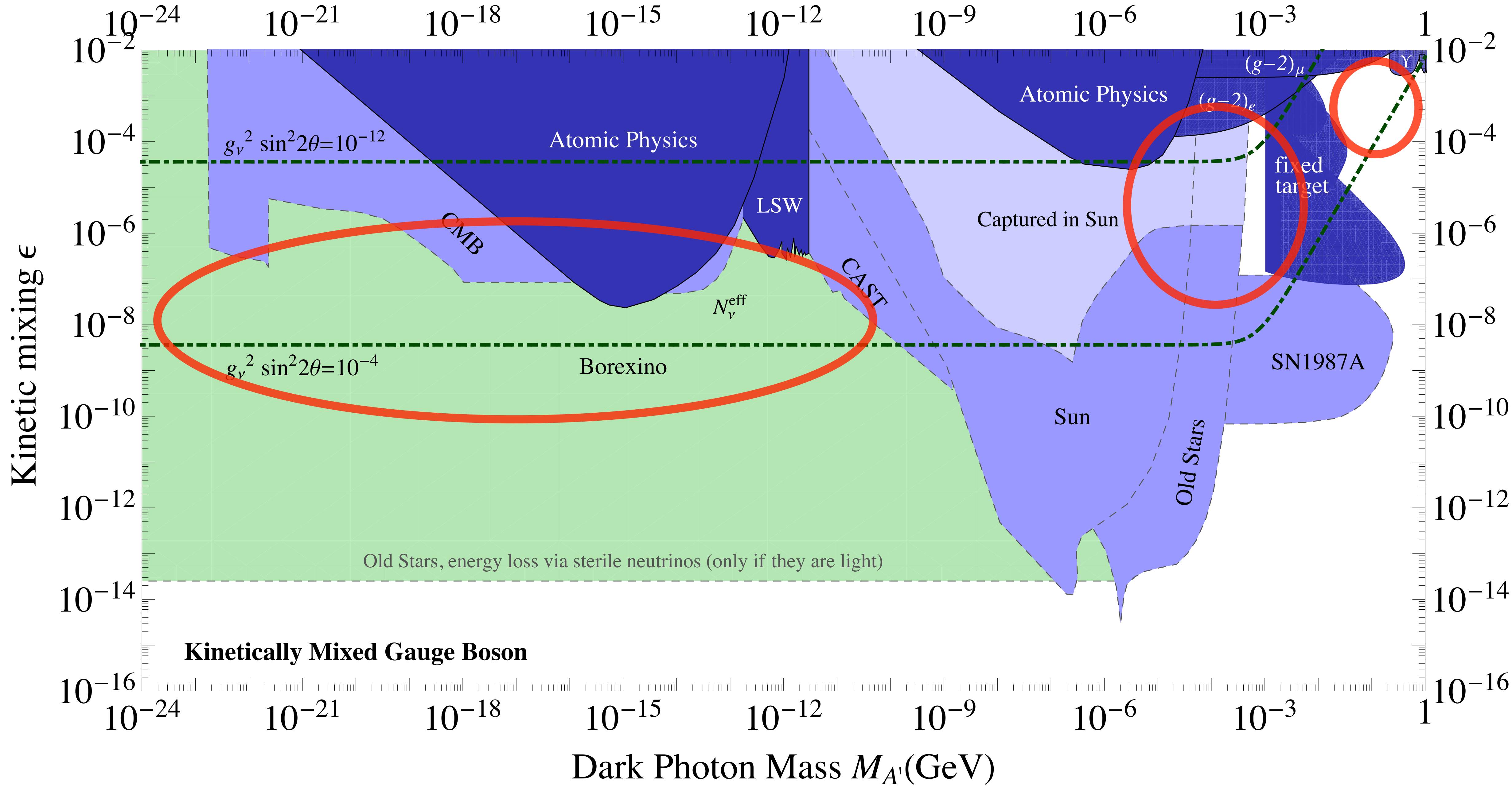

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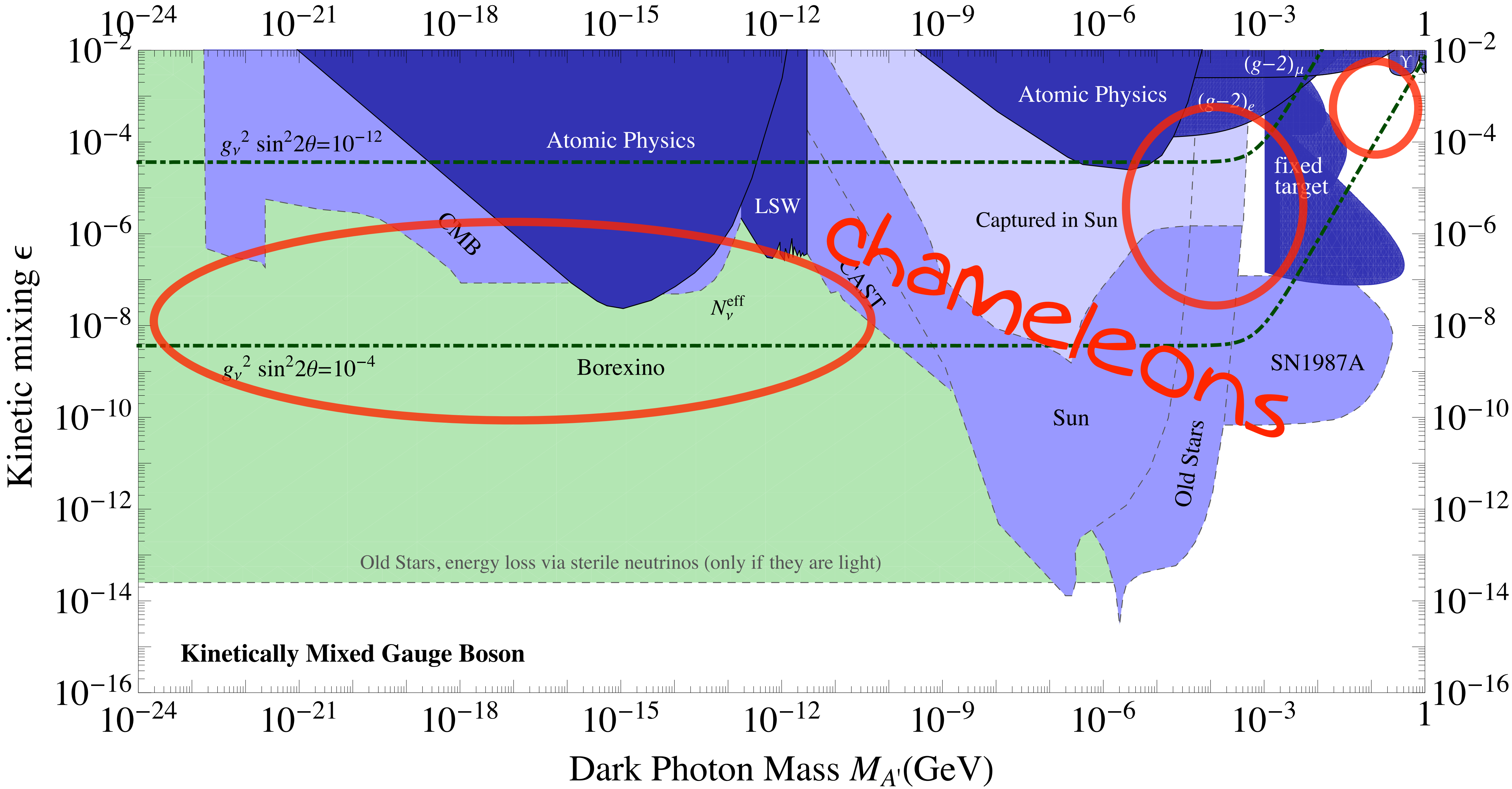

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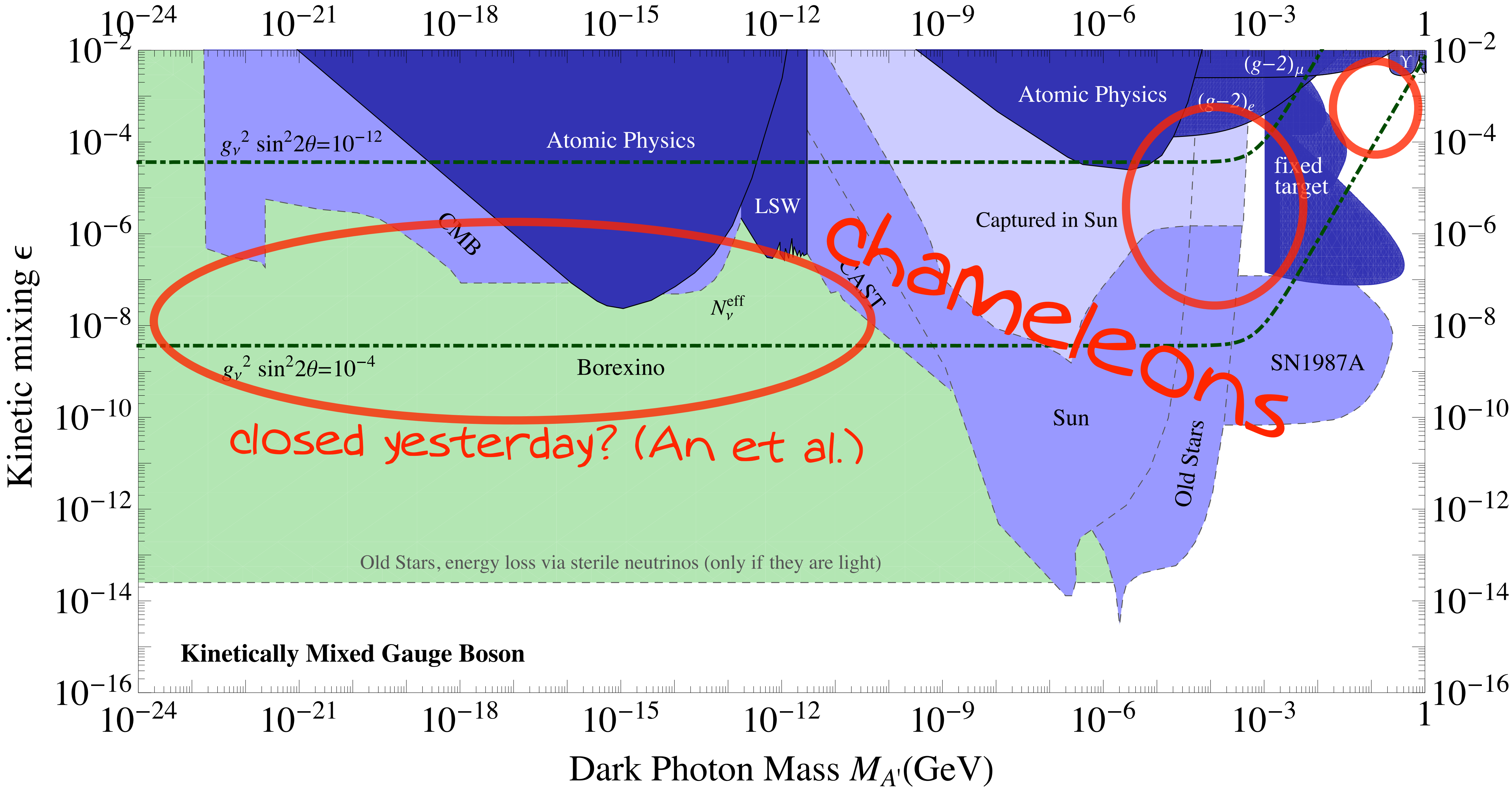
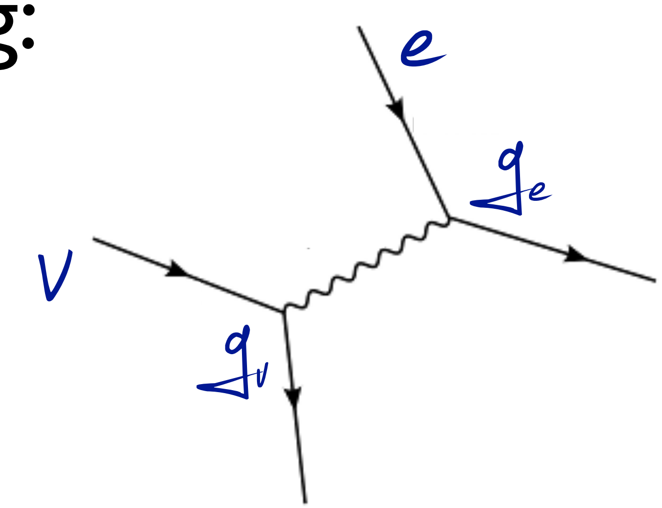


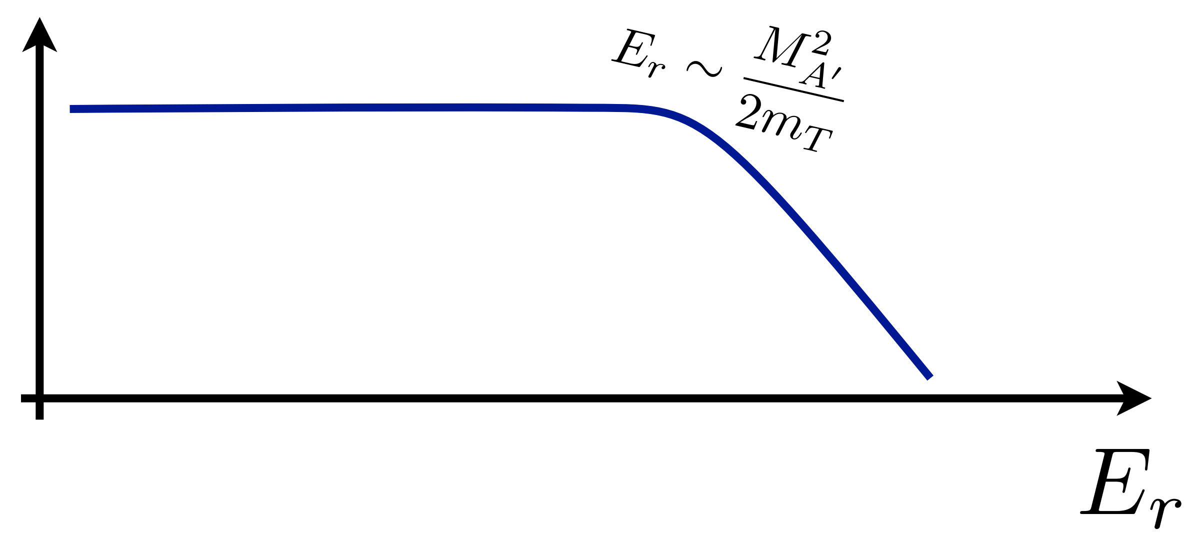
A Light Gauge Boson

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



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

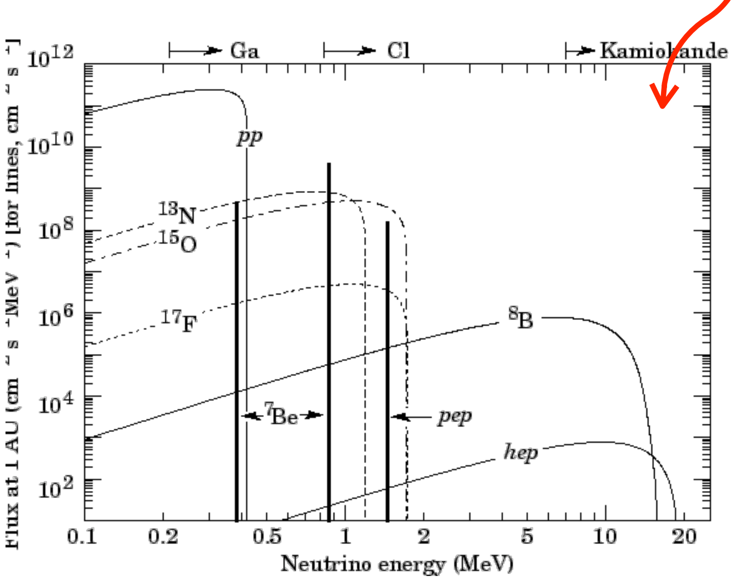
propagator: $q^2 - M^2$

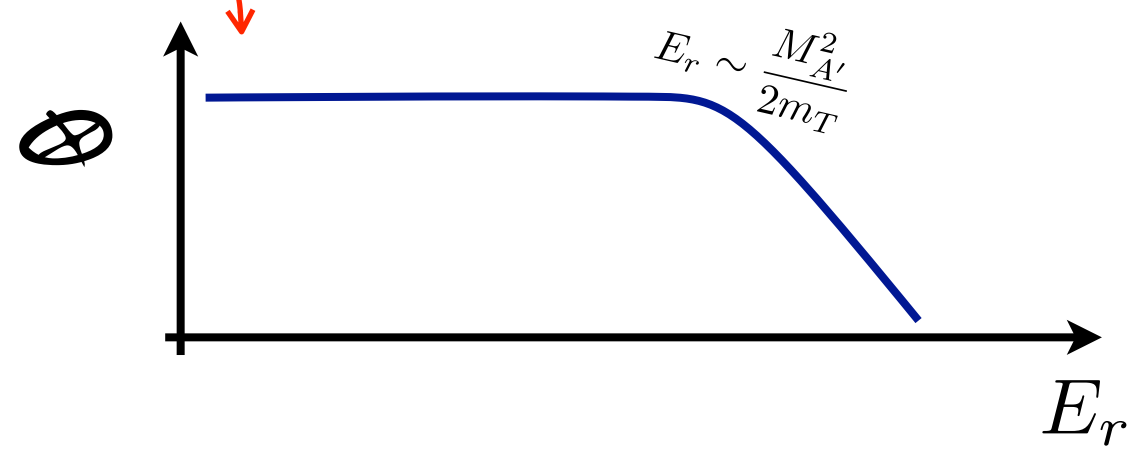


A Light Gauge Boson

- What does a direct detection experiment see? back to the master formula:

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

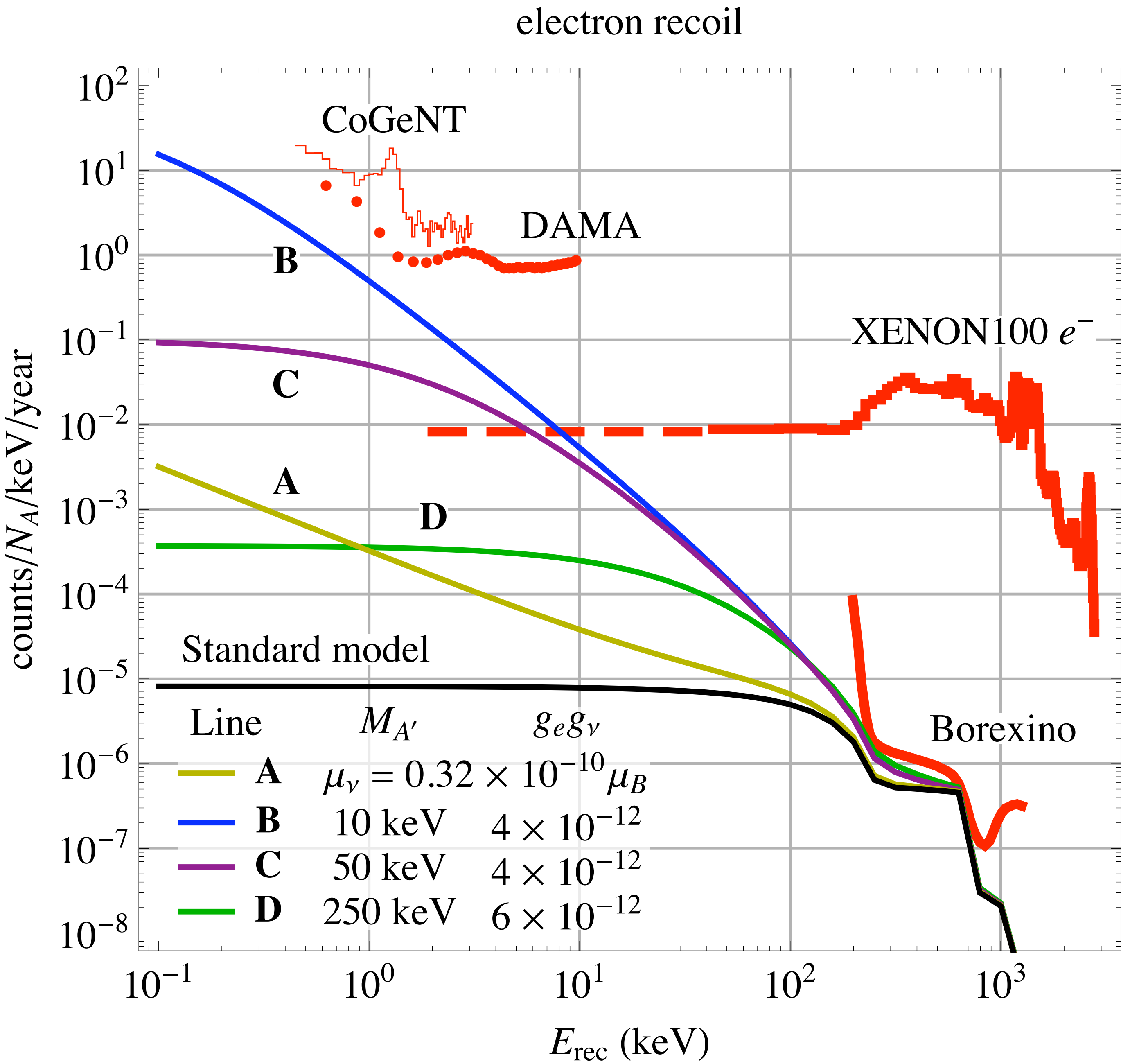




with $\quad E_\nu^{\min} = \frac{1}{2}\left(E_r + \sqrt{E_r^2 + 2E_r m_T}\right)$

CoGeNT or DAMA?

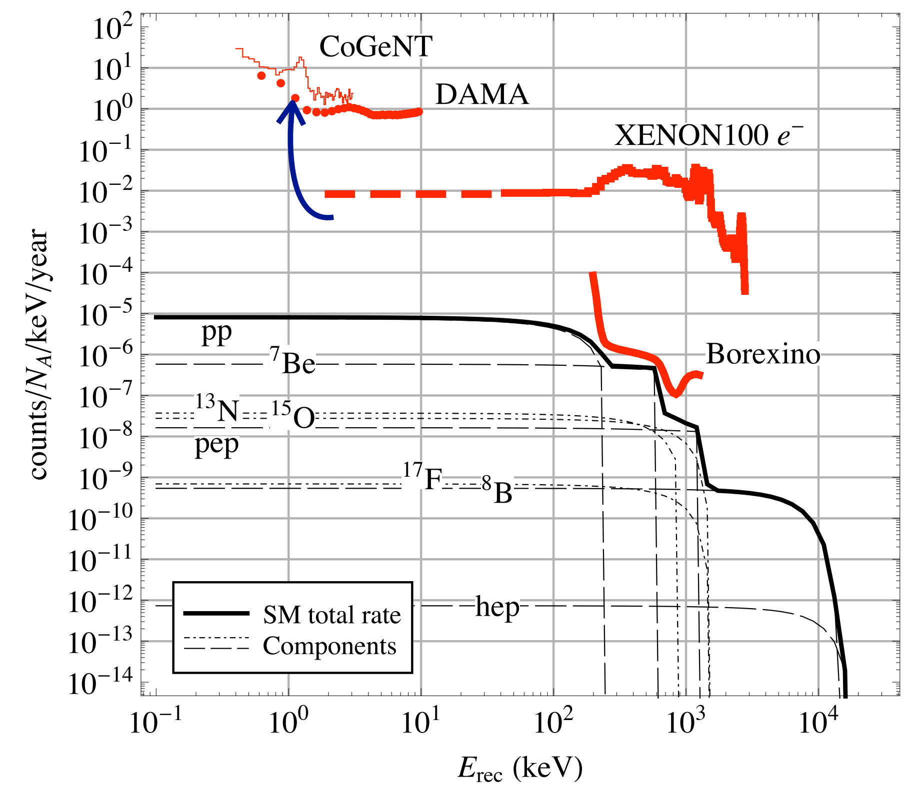
* If we want to do CoGent or DAMA there is clear tension with XENON100 (and also Borexino).



Heavy Sterile

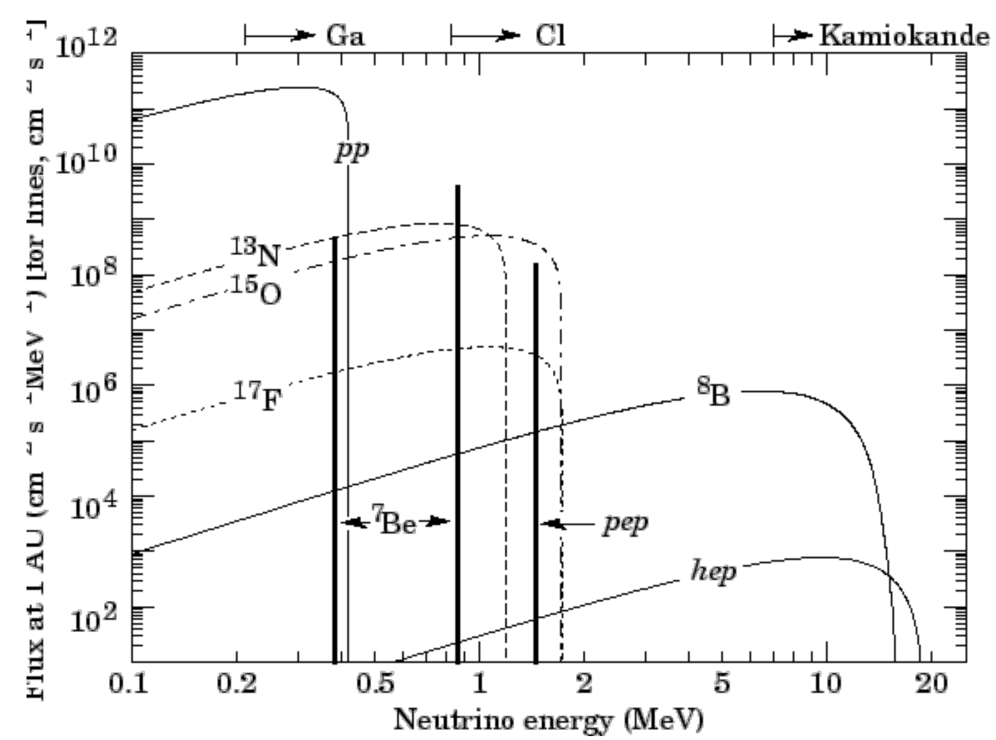
* Is there a way around XENON?

Can we get a sharp threshold?



* The solar flux has lines....

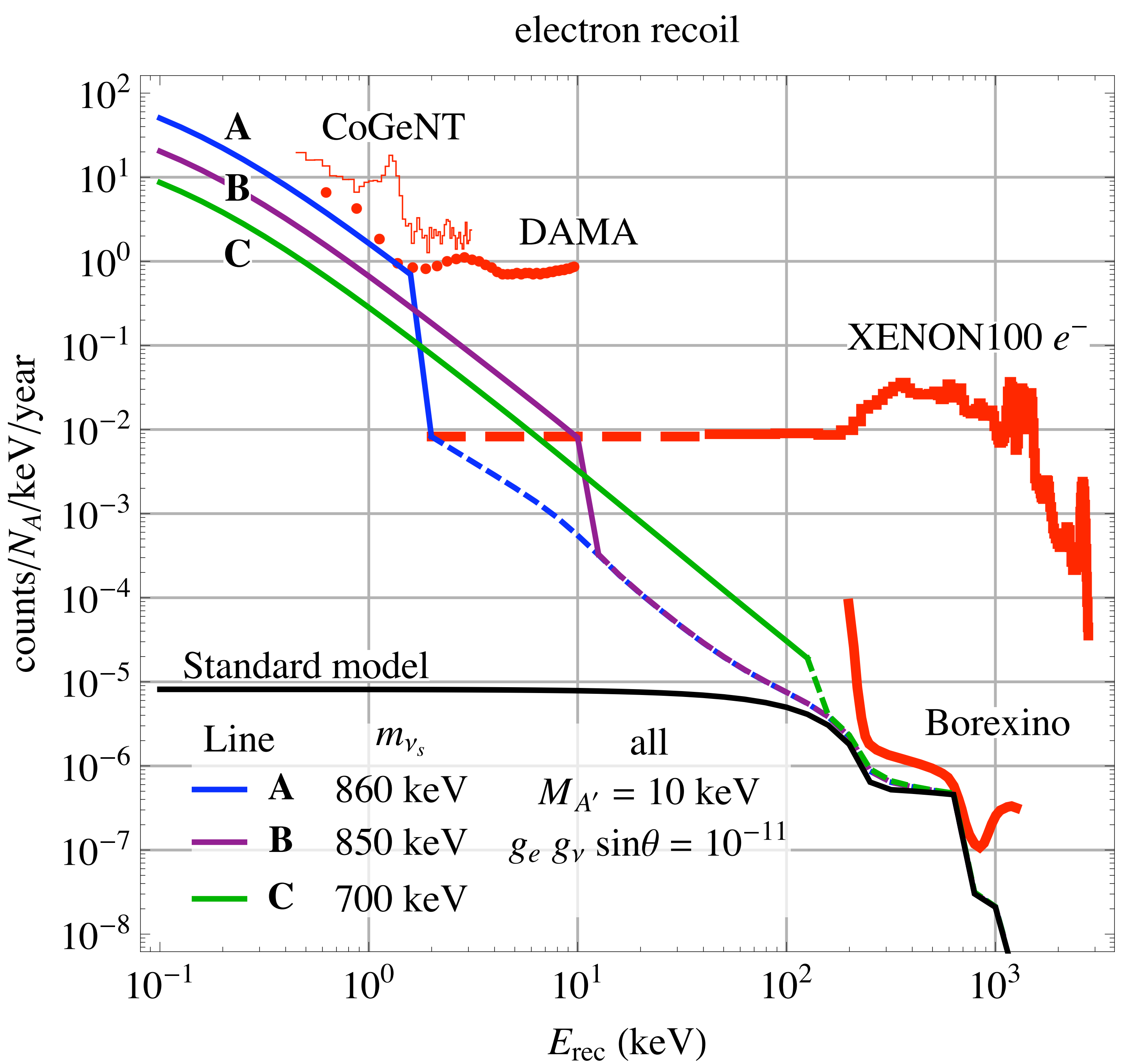
*A kinematic threshold near the ^{7}Be line. Its tuned...**



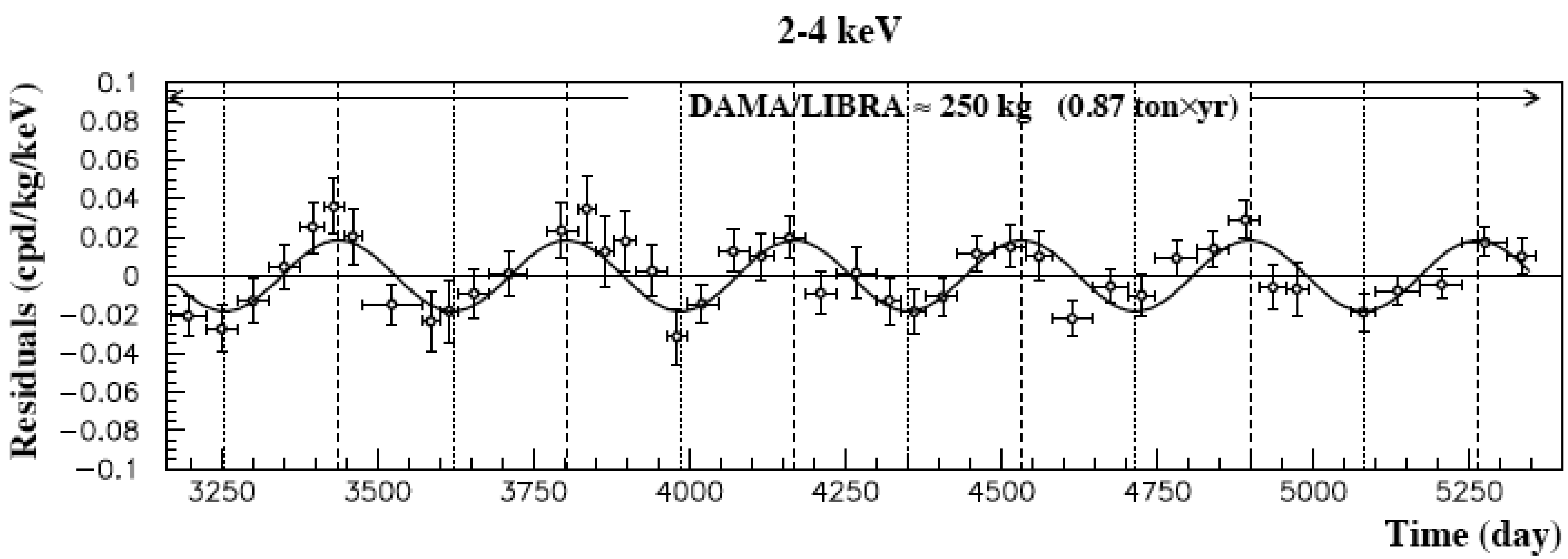
** I would like to thank IDM and its variants for the moral license to do this.*

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

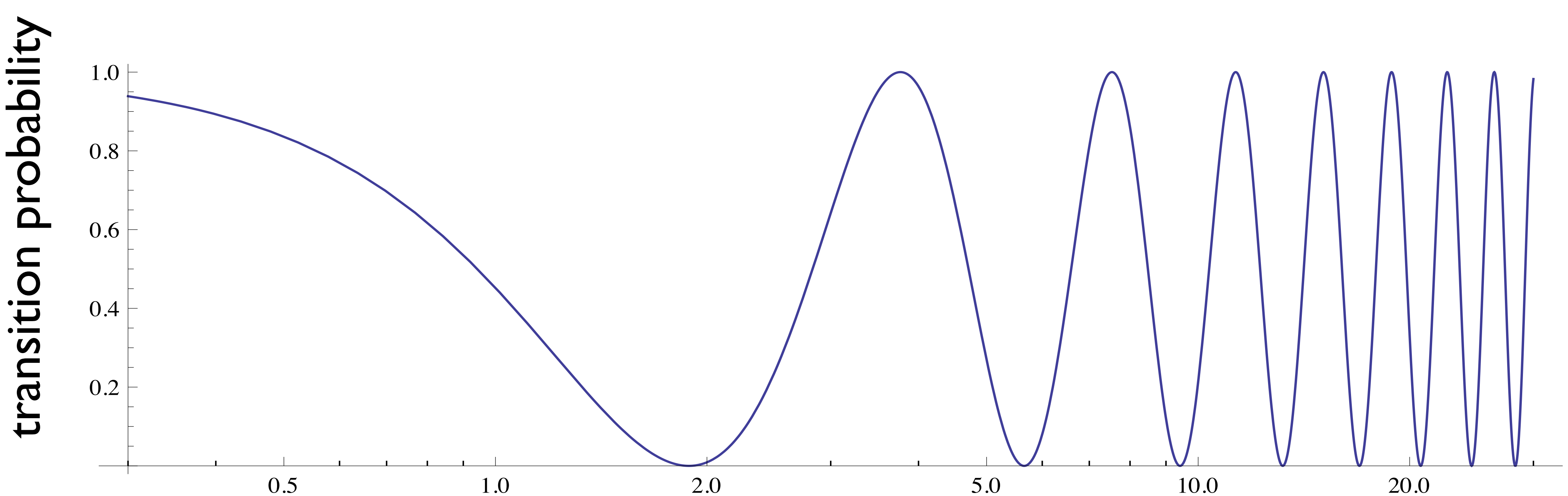
* Annual modulation is an iportant part of past and (hopefully) future anomalies.
* What modulation signals can the Sun produce?

* **Many possibilities for modulation:**
  - daily.
  - annually.
  - even semi-annually.

Elliptical Orbit & Just-So

- We are on an elliptical orbit. Wikipedia:
  - Closest to the Sun on **Jan 3rd** (wrong phase for DAMA).
  - The amplitude is 1.6% (flux is double that).
- Introduce oscillation on AU scale (with sterile):

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



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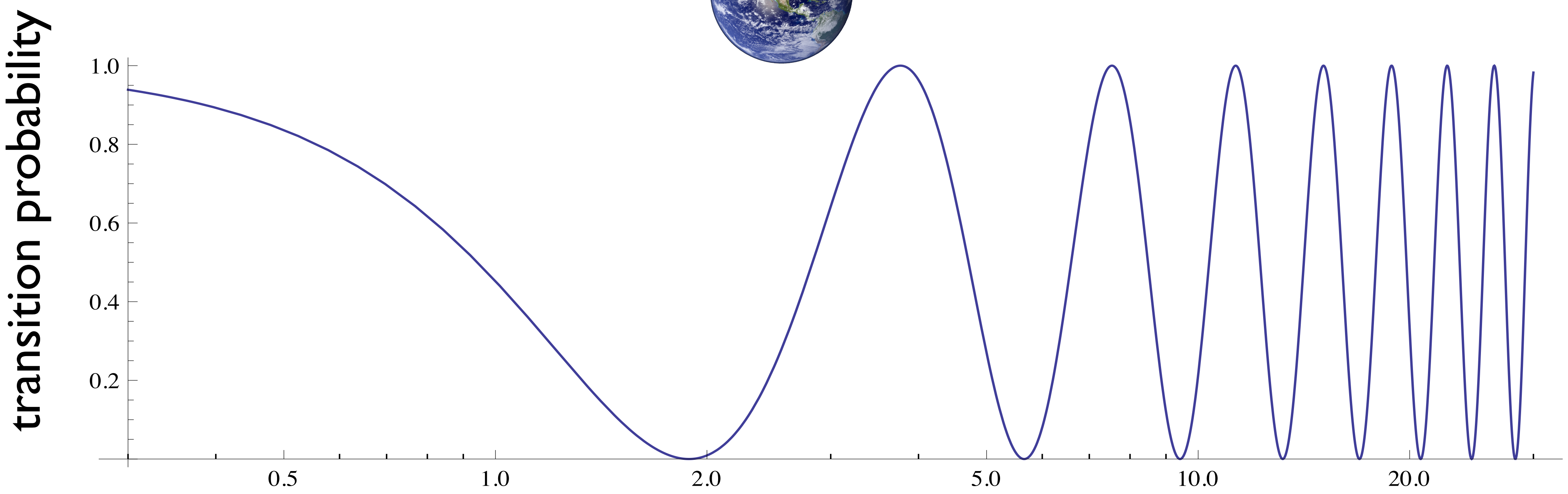

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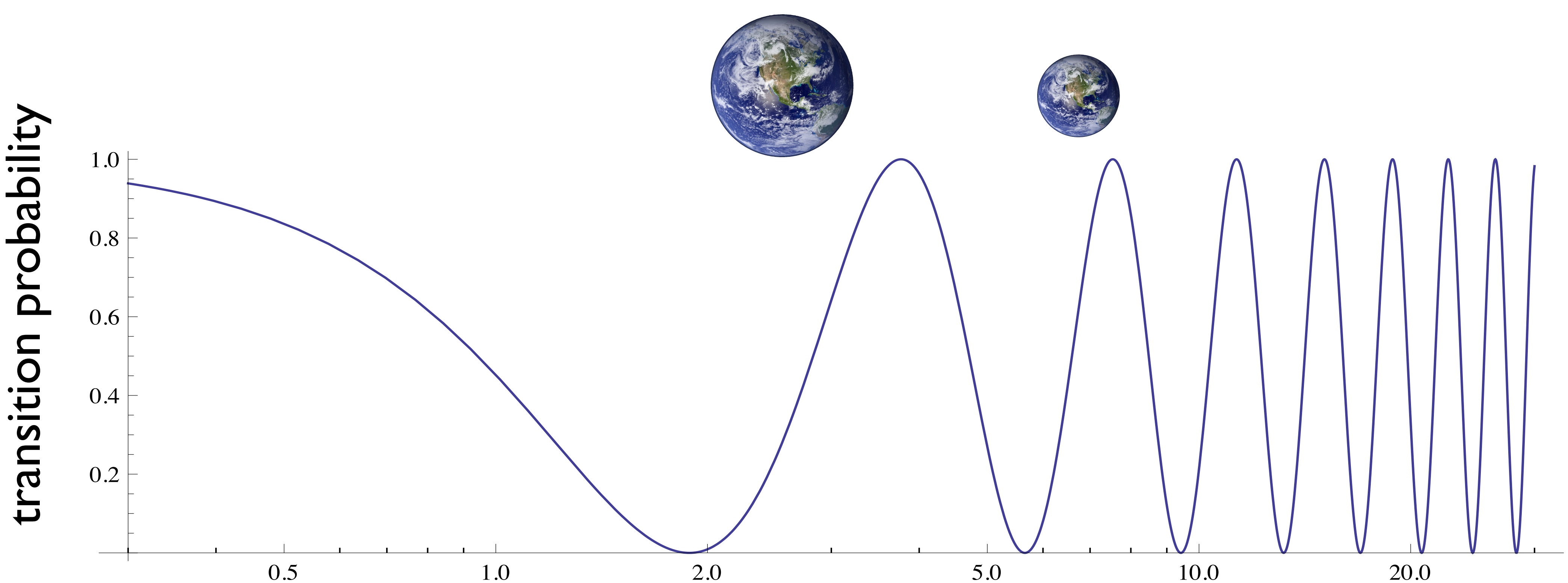

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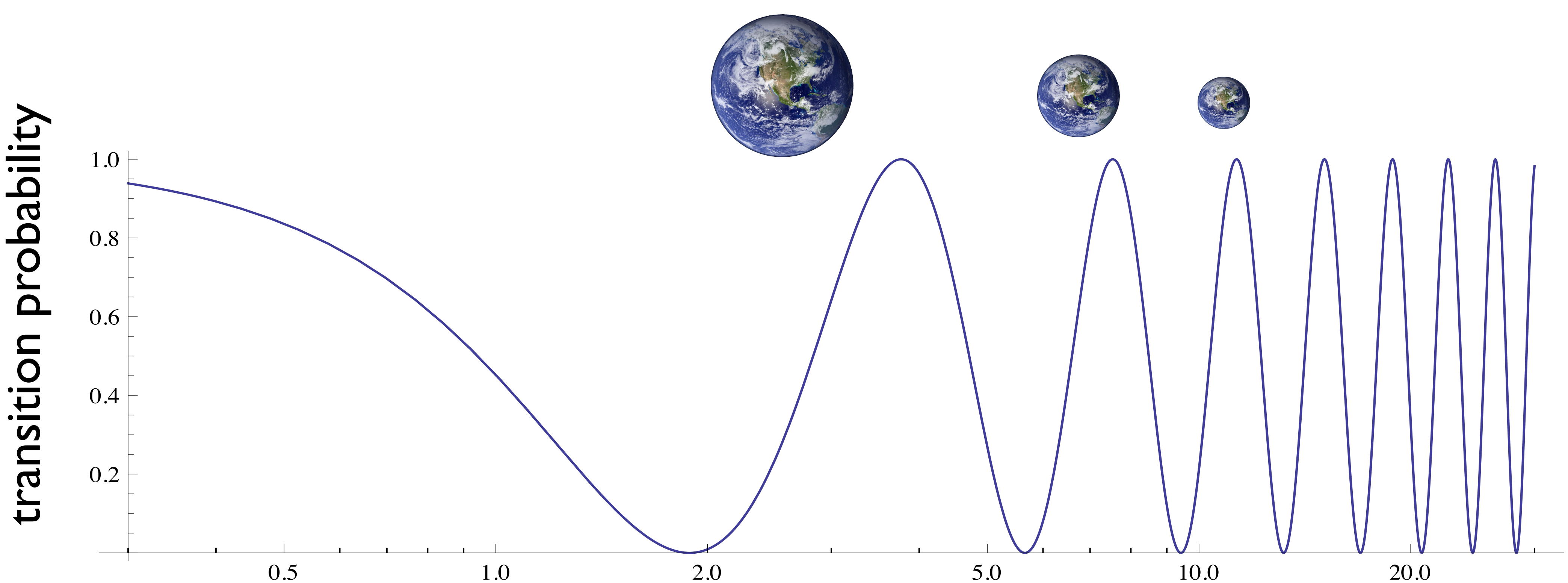
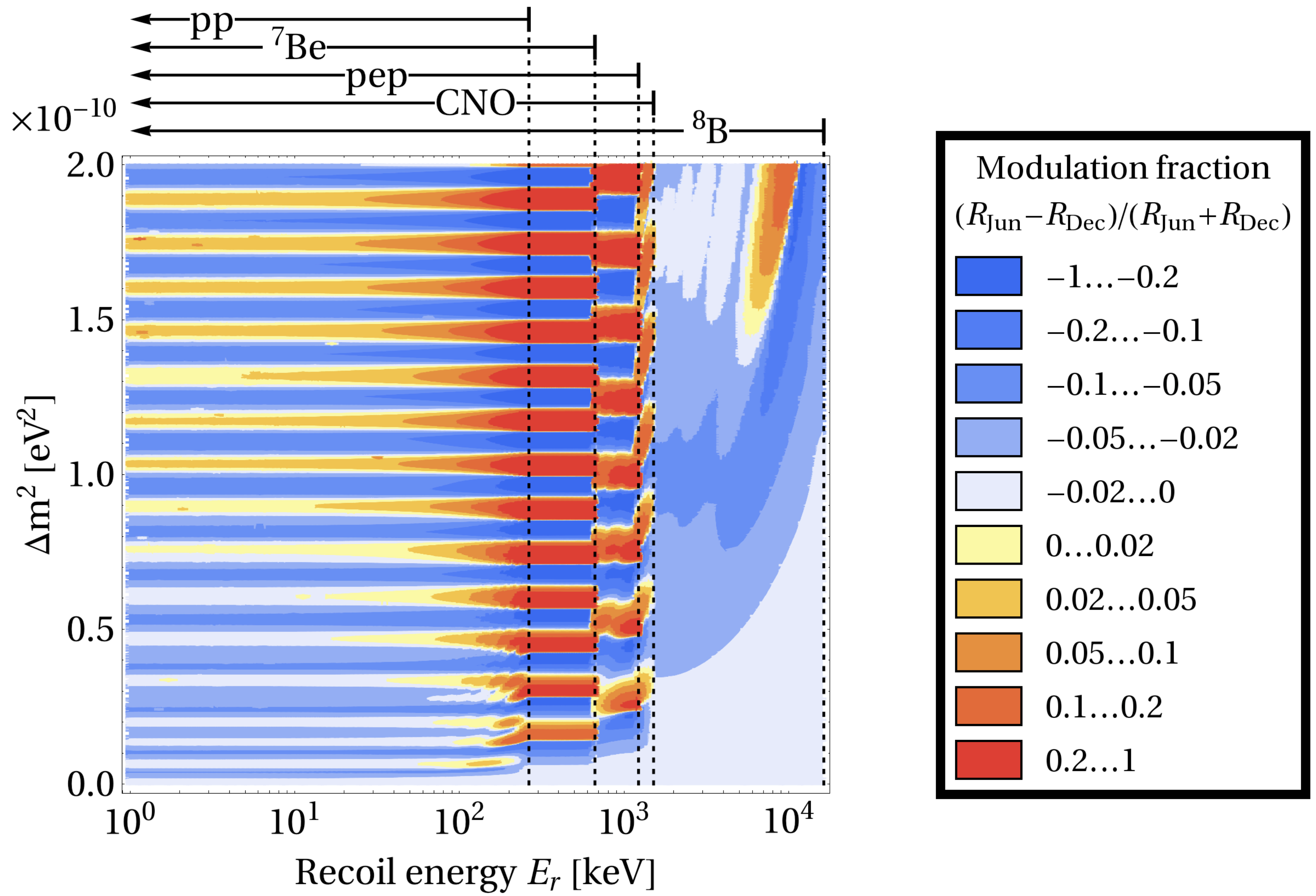


Just-So

* A variety of modulation amplitudes are possible



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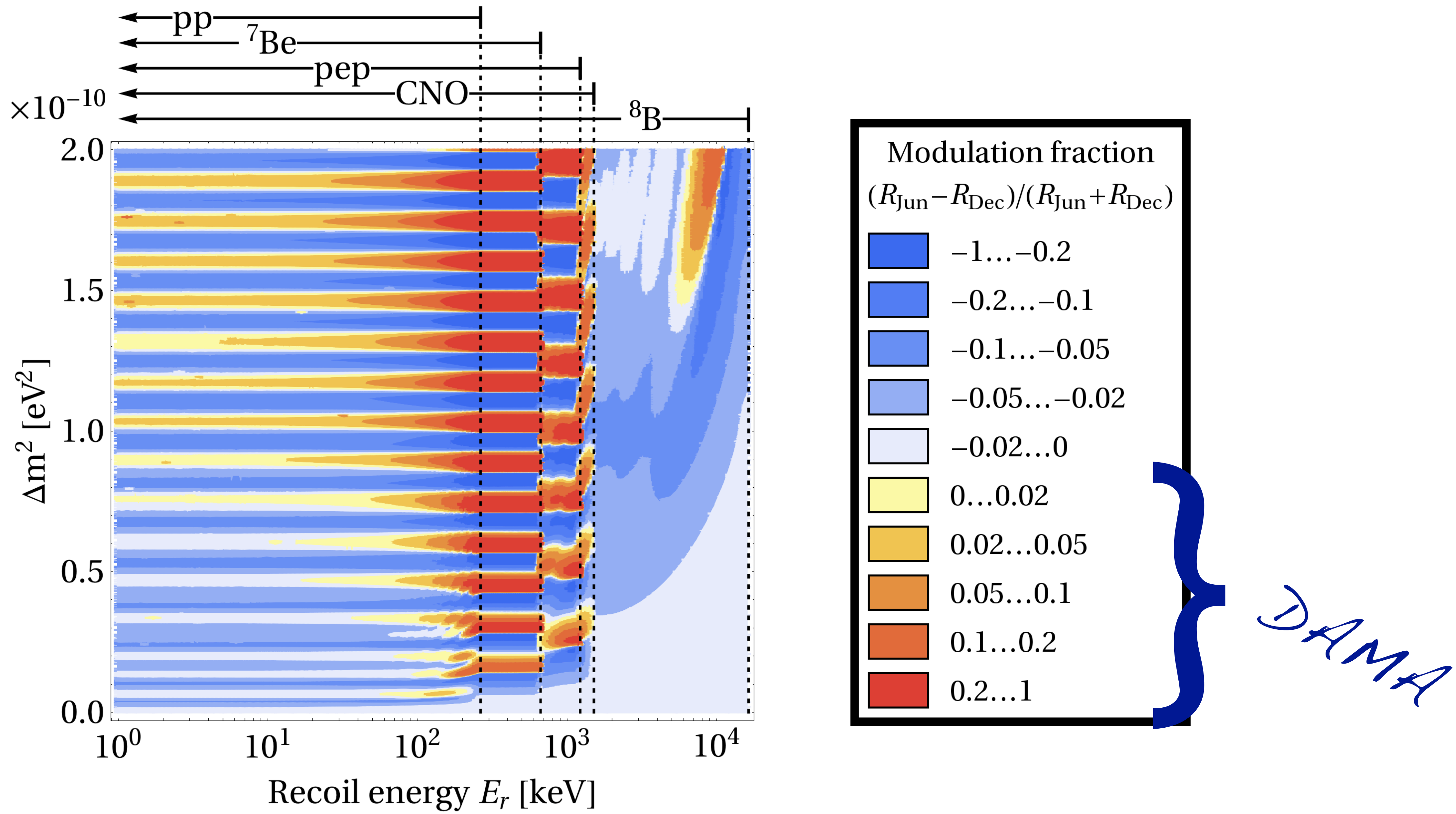


Matter Effects

- The new gauge boson can lead to new "MSW-like" matter effects:
$$V_{\text{matter}} = \frac{g_\nu}{M_{A'}^2}(g_e n_e + g_p n_p + g_n n_n)$$

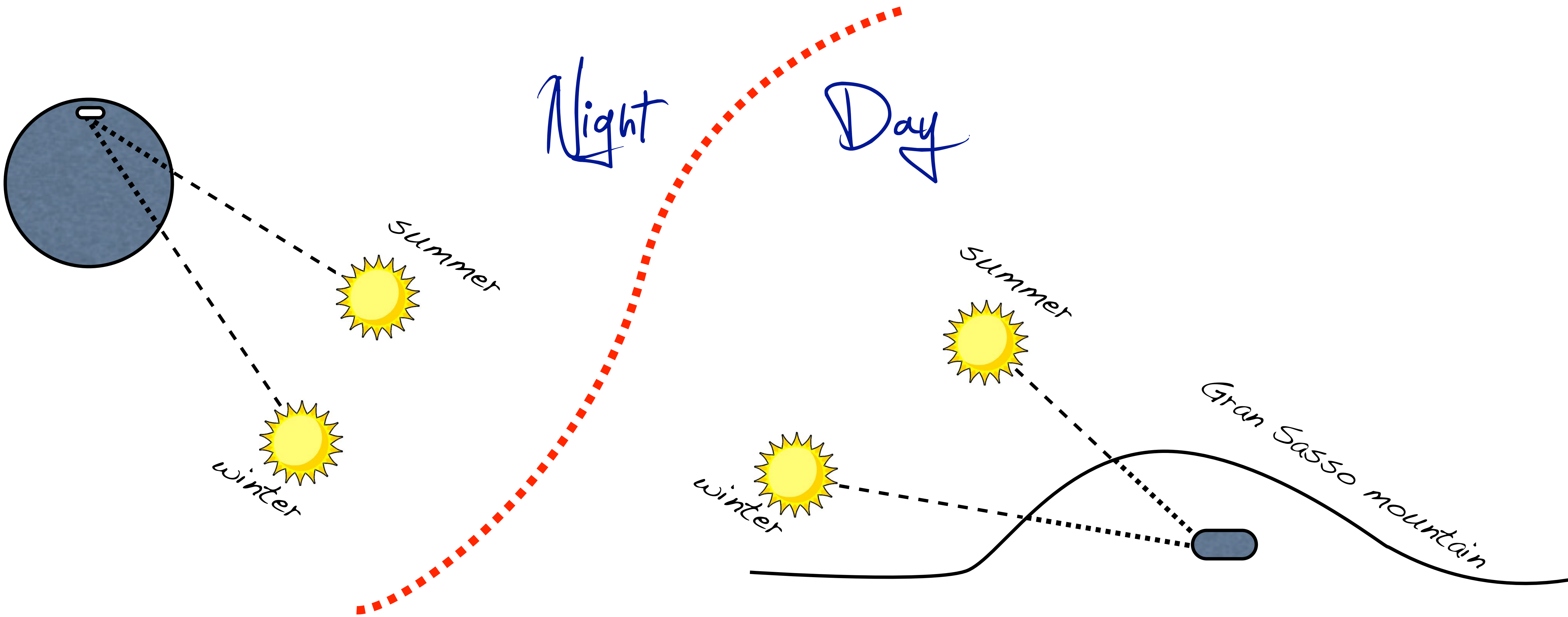
- Active-sterile oscillations in matter can be *very* different from those in vacuum.

- **Day-night asymmetry** due to an oscillation b/w among sterile species in matter. This asymmetry can be large.

- The matter oscillation length, $L_{\text{osc}} = 4\pi E/\Delta m^2$, can be anywhere between a kilometer and the earth radius.

Zenith Angles

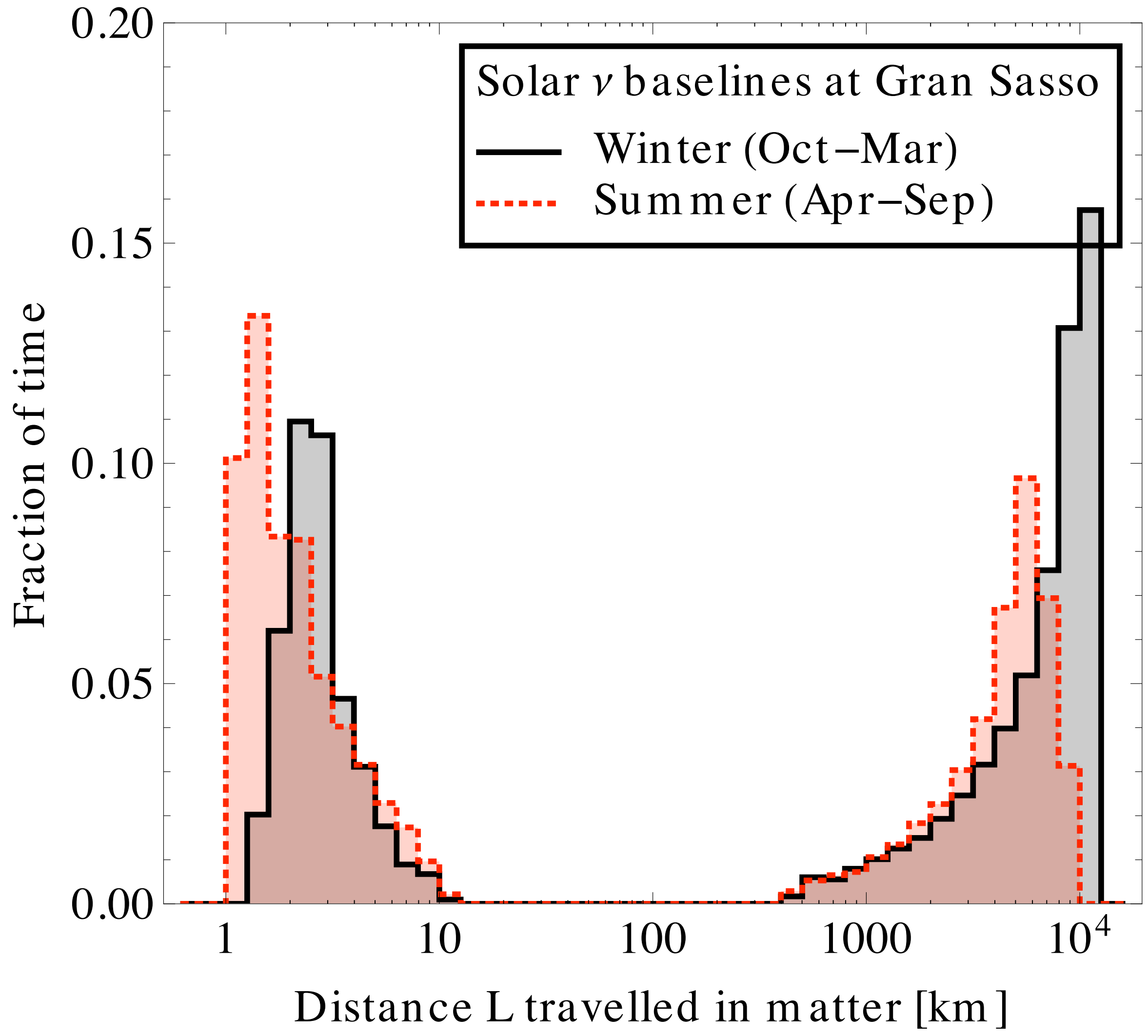
* At noon, the sun is high in the sky in summer. Low in winter.
* At midnight, the Sun is lower *below* the horizon in winter. Higher in summer.



Zenith Angle

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

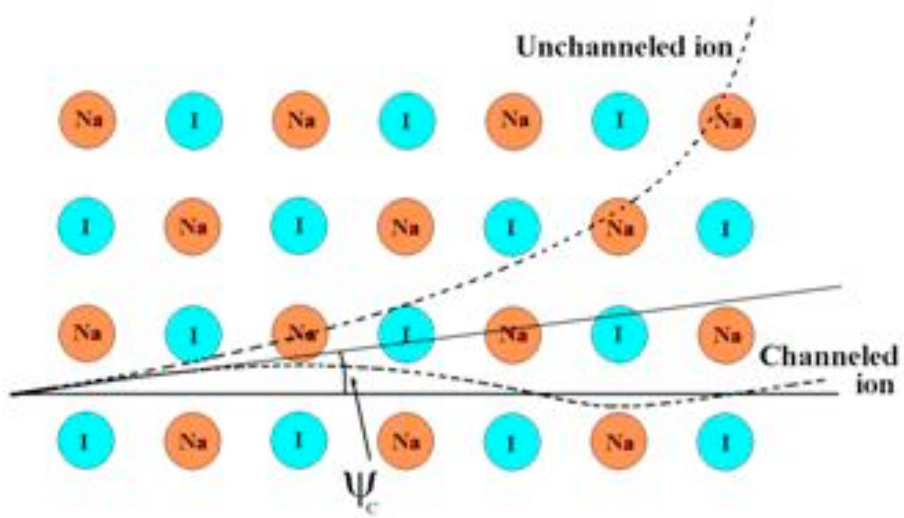
annual modulation can be much stronger asymmetry in daylight hours.



- A strong daily modulation is induced here too.

Channeling

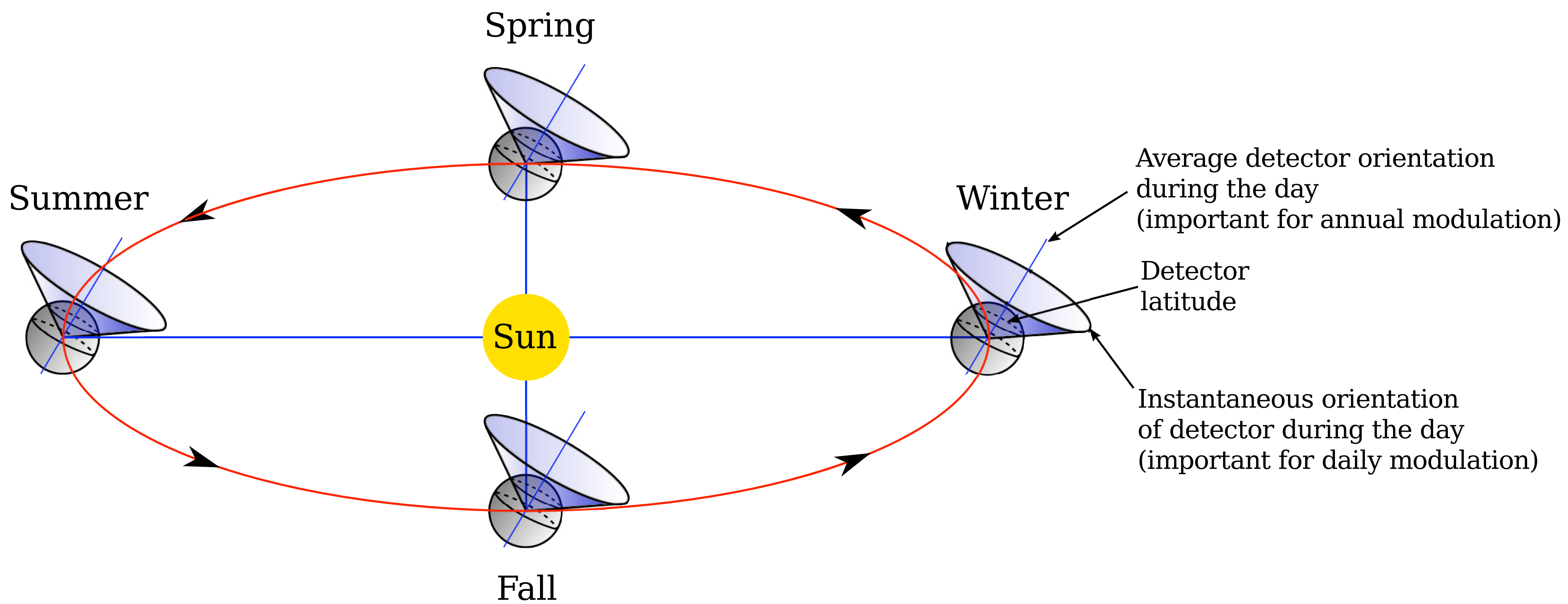
- The dark matter signal is isotropic to zeroth order.
- A signal coming from the sun is maximally anisotropic.
- Imagine channeling occurs in some target crystals:



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

Channeling

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



Concluding

* **Dark matter** and **neutrino** experiments share some features: low backgrounds, large exposure, low thresholds.
* They can probe similar physics.
* New physics connecting the SM to neutrinos can lead to **interesting direct detection signals**:
  - New light gauge bosons.
  - Neutrino dipole moments.
* Many possibilities for rich **modulation** signals.

Deleted Scenes

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:

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

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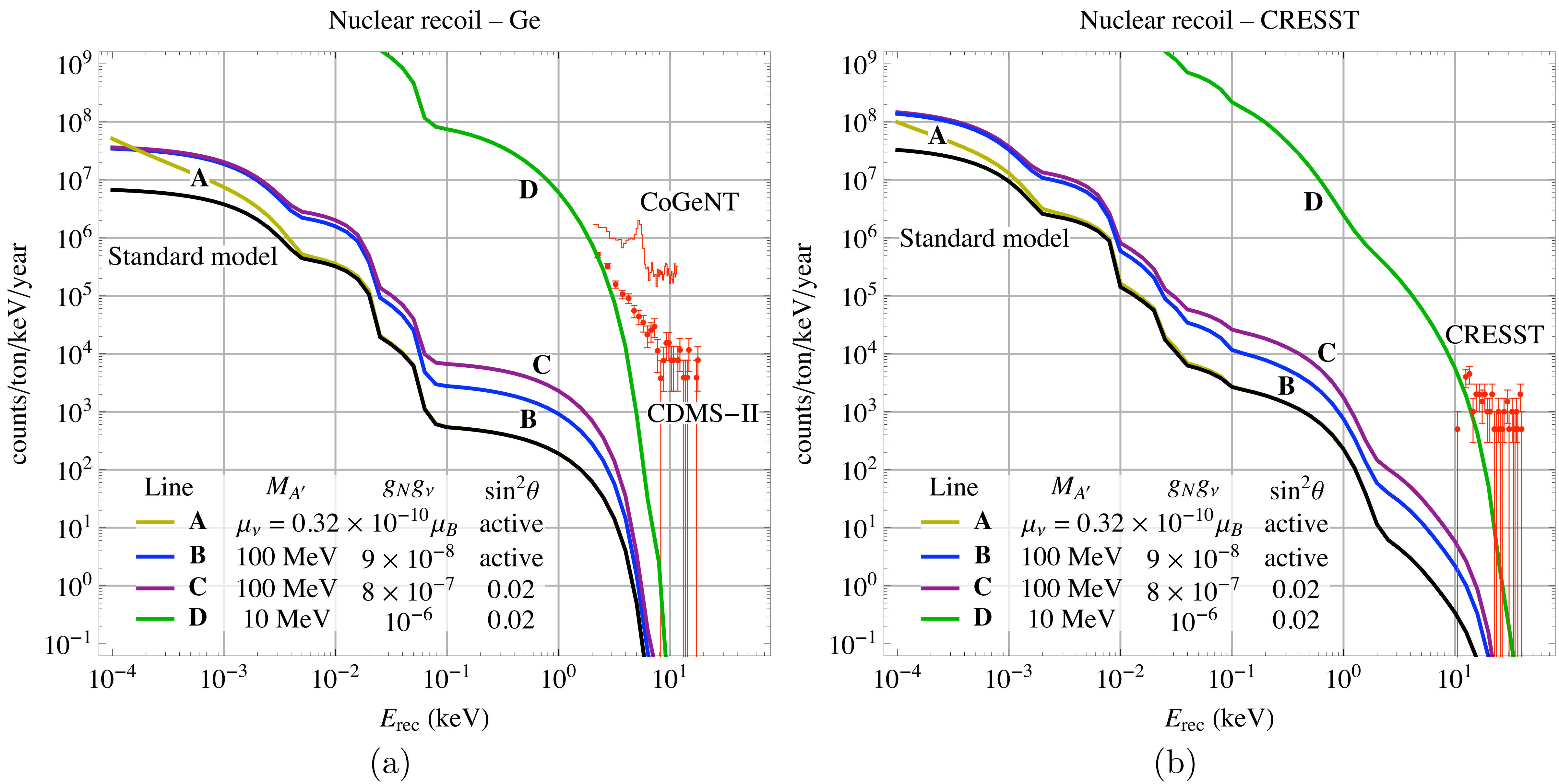
Nuclear recoil

- Interesting spectra are achievable:



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

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.