Exploring ν signals in dark matter detectors

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in collaboration with:
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arXiv:1202.6073

Outline

- Motivations
- Models
- Limits
- Modulation (very quick)
- Conclusions

Motivations

WHY { neutrino physics?
dark matter direct detection?
light mediators? }

Motivations

Solar neutrinos

- Low threshold

Dark matter

- (Very) low threshold

Motivations

Solar neutrinos

- Low threshold
- Small cross section

Dark matter

- (Very) low threshold
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Motivations

Solar neutrinos

- Low threshold
- Small cross section
- Low background

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Solar neutrinos

- Low threshold
- Small cross section
- Low background
- Big detector

Dark matter

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- Small cross section
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Motivations

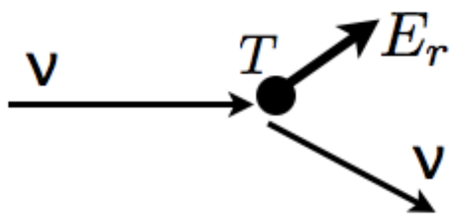
Solar neutrinos	Dark matter
- Low threshold	- (Very) low threshold
- Small cross section	- Small cross section
- Low background	- Low background
- Big detector	- Small detector

Make dark matter direct detection experiments multipurpose

see also Pospelov 1103.3261, Pospelov Pradler 1203.0545

Motivations

Standard signal

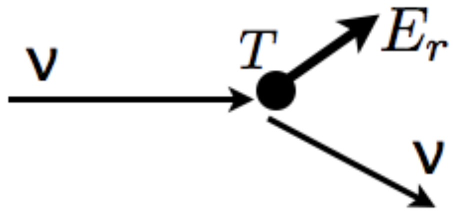


Motivations

Standard signal

$$\frac{d\sigma_{\rm SM}^{\nu_e e}}{dE_r} = \frac{G_F^2 m_e}{2\pi E_\nu^2}\left[4s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_e)) - 2s_w^2(E_r m_e - 2E_\nu^2) + E_\nu^2\right]$$

$$\frac{d\sigma_{\rm SM}^{\nu_{\mu,\tau} e}}{dE_r} = \frac{G_F^2 m_e}{2\pi E_\nu^2}\left[4s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_e)) + 2s_w^2(E_r m_e - 2E_\nu^2) + E_\nu^2\right]$$



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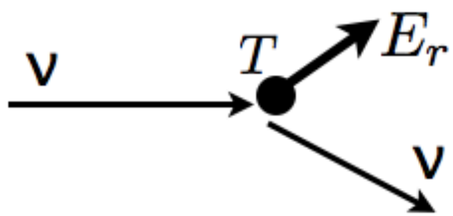

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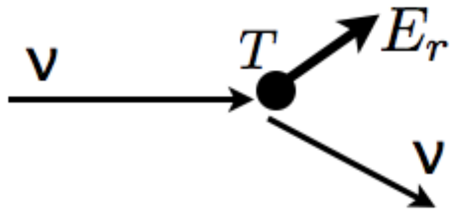

$$\frac{d\sigma^{\nu N}_{\rm SM}}{dE_r} = \frac{G_F^2 m_N F^2(E_r)}{2\pi E_\nu^2}\Big[(A^2 E_\nu^2 + 2AZ(2E_\nu^2(s_w^2 - 1) - E_r m_N s_w^2)$$
$$+ 4Z^2(E_\nu^2 + s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_N)) + s_w^2(E_r m_N - 2E_\nu^2)))\Big]$$

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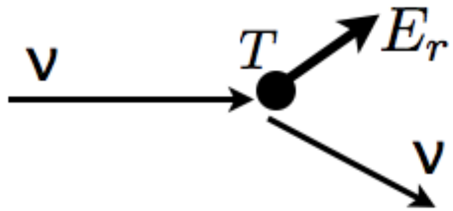

form factor

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mass number

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atomic number nucleus mass

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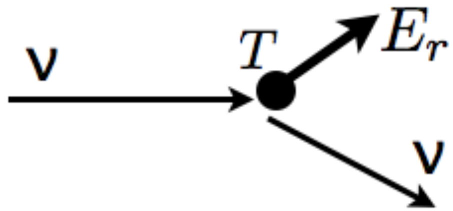

$$E_\nu^{\rm min} \approx \sqrt{m_T E_r/2}$$

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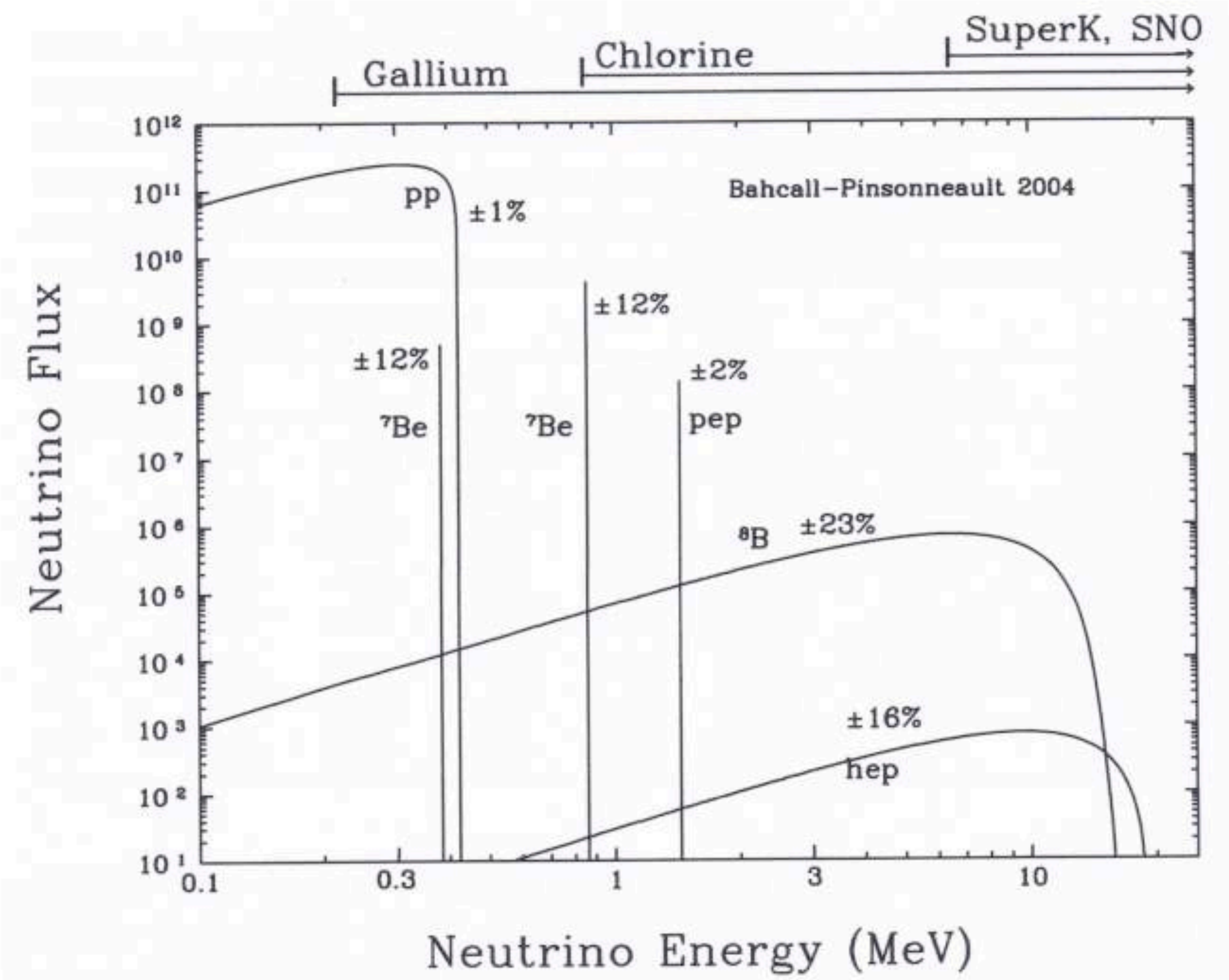
mass number — atomic number — nucleus mass

Motivations



Flux ($cm^{-2}s^{-1}MeV^{-1}$)

$^{8}B \sim 5 \times 10^{6}$

$^{7}Be \sim 5 \times 10^{9}$

pp $\sim 6 \times 10^{10}$

Solar model: BS05(OP)

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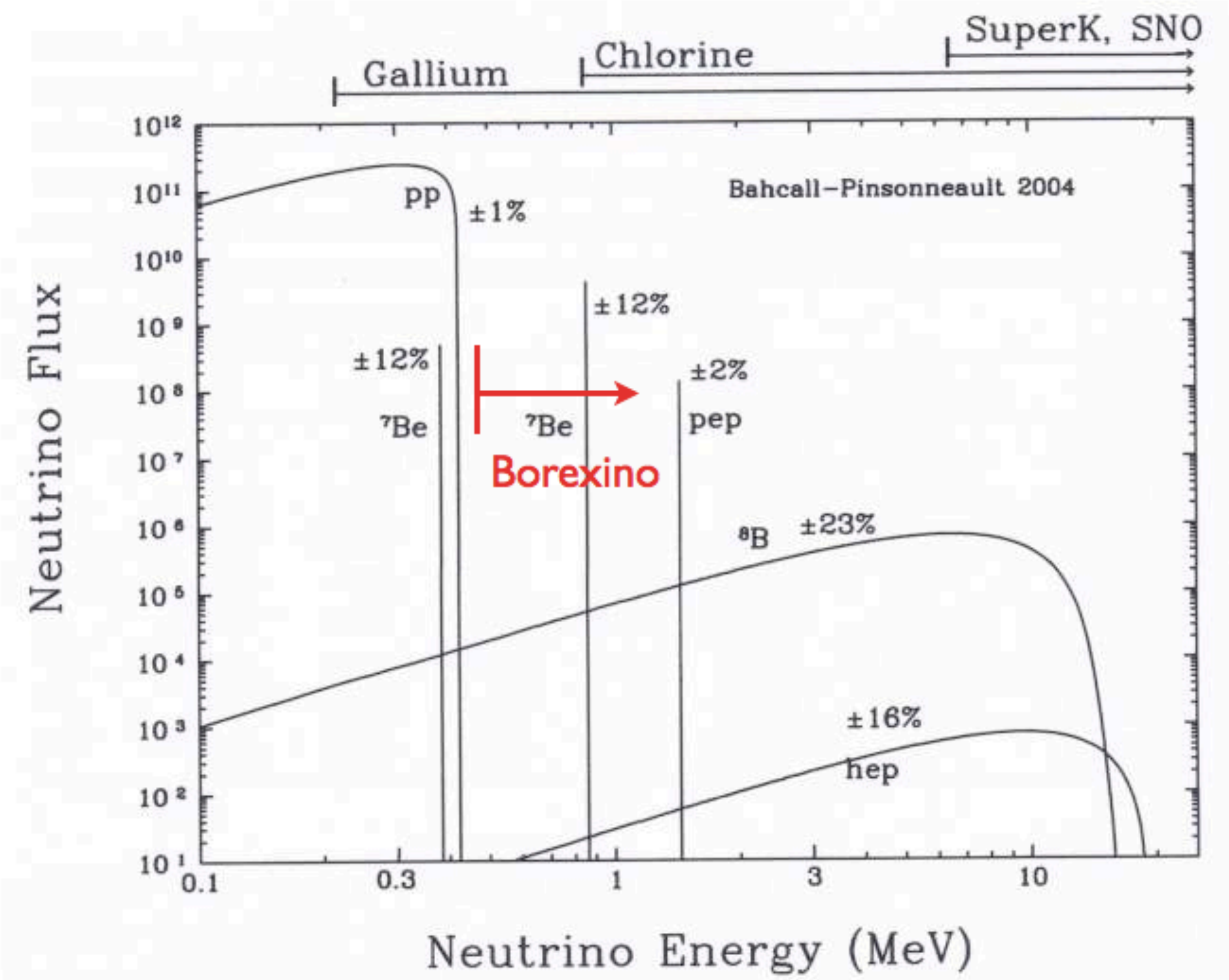

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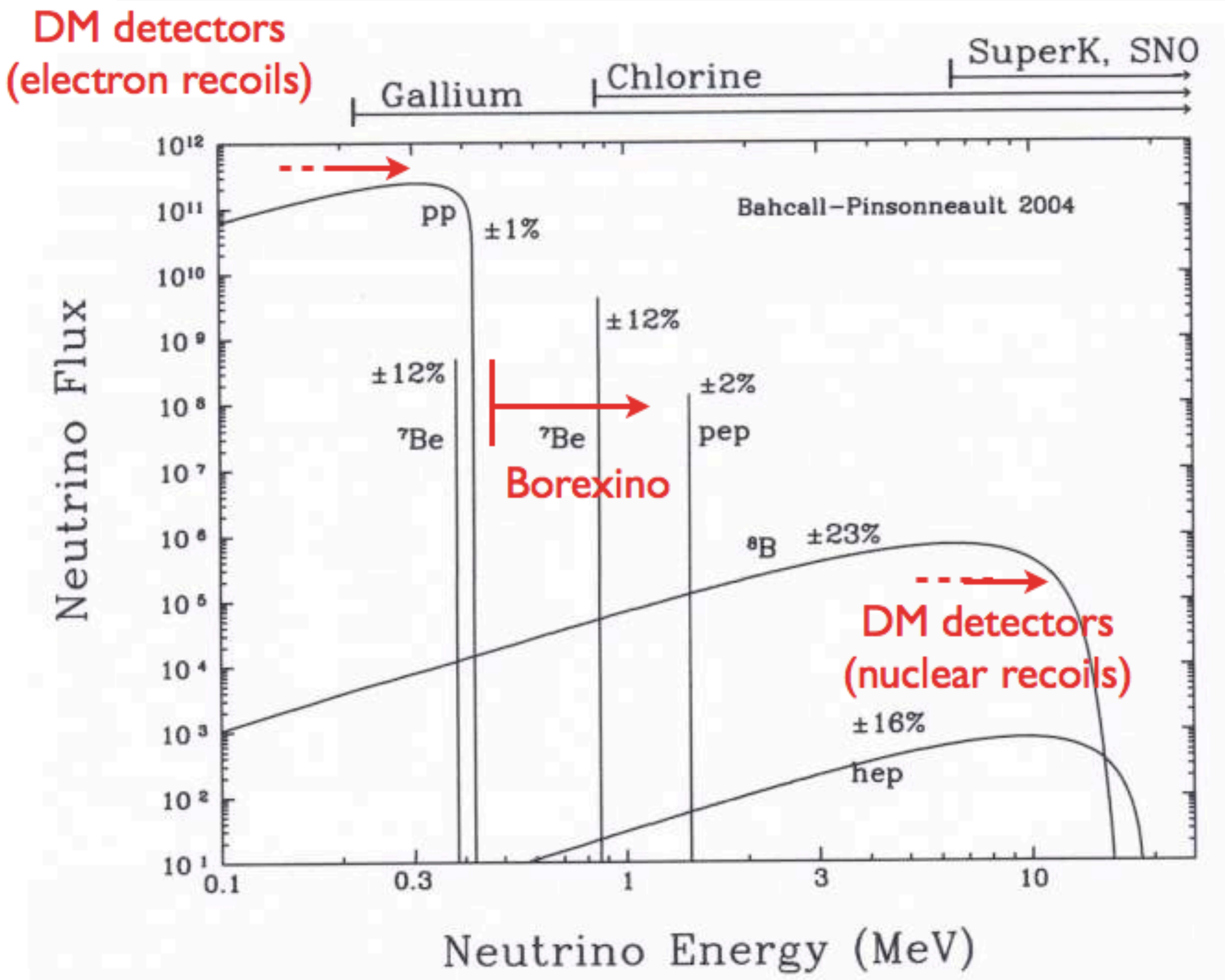

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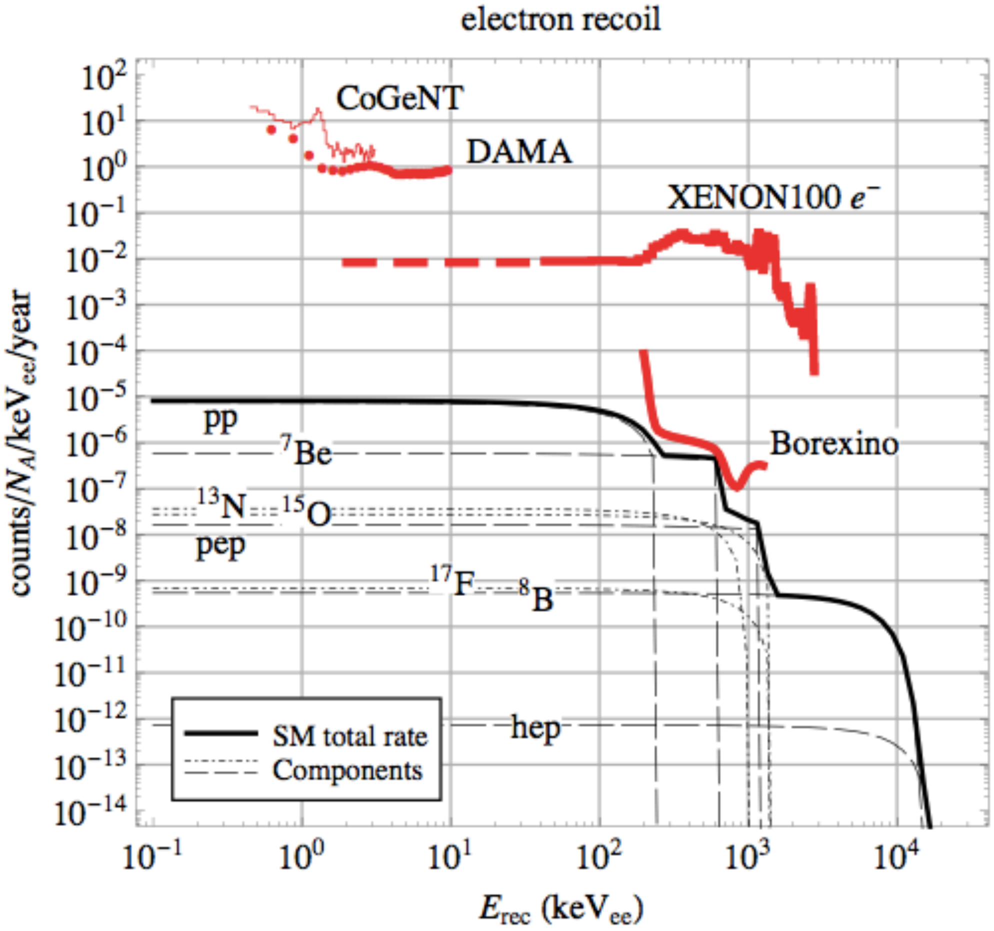

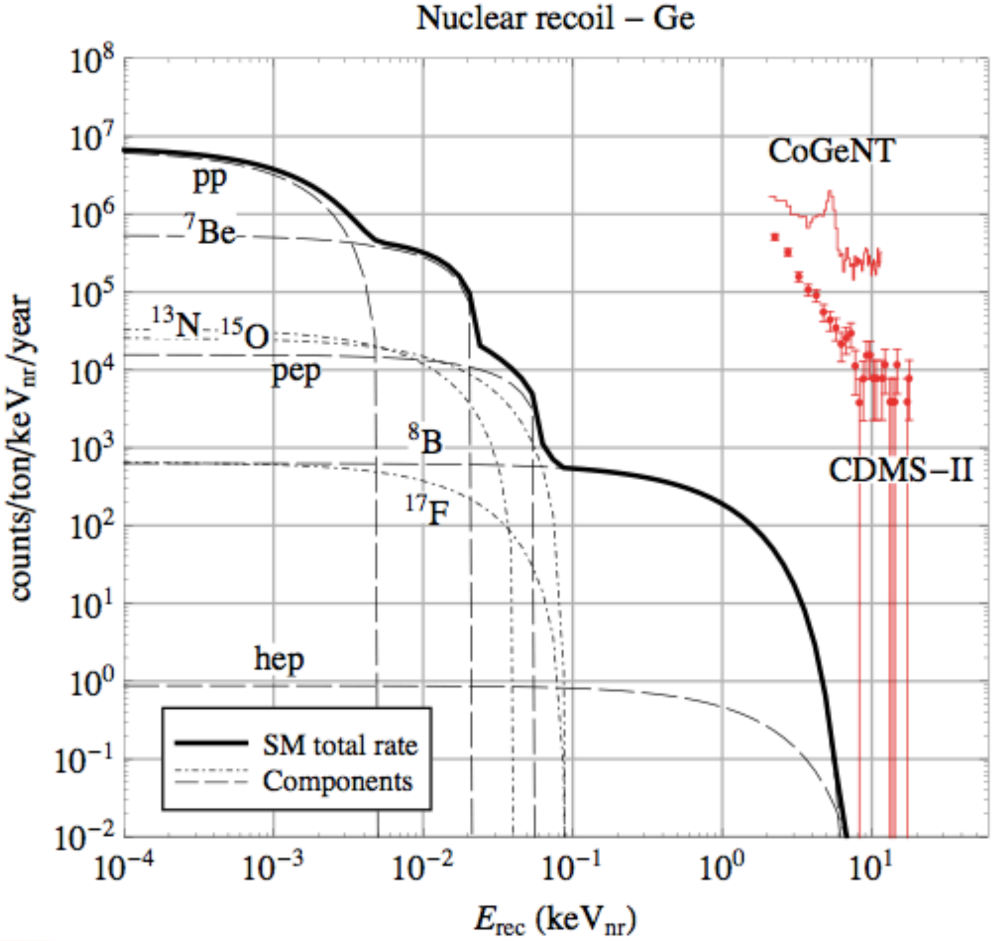

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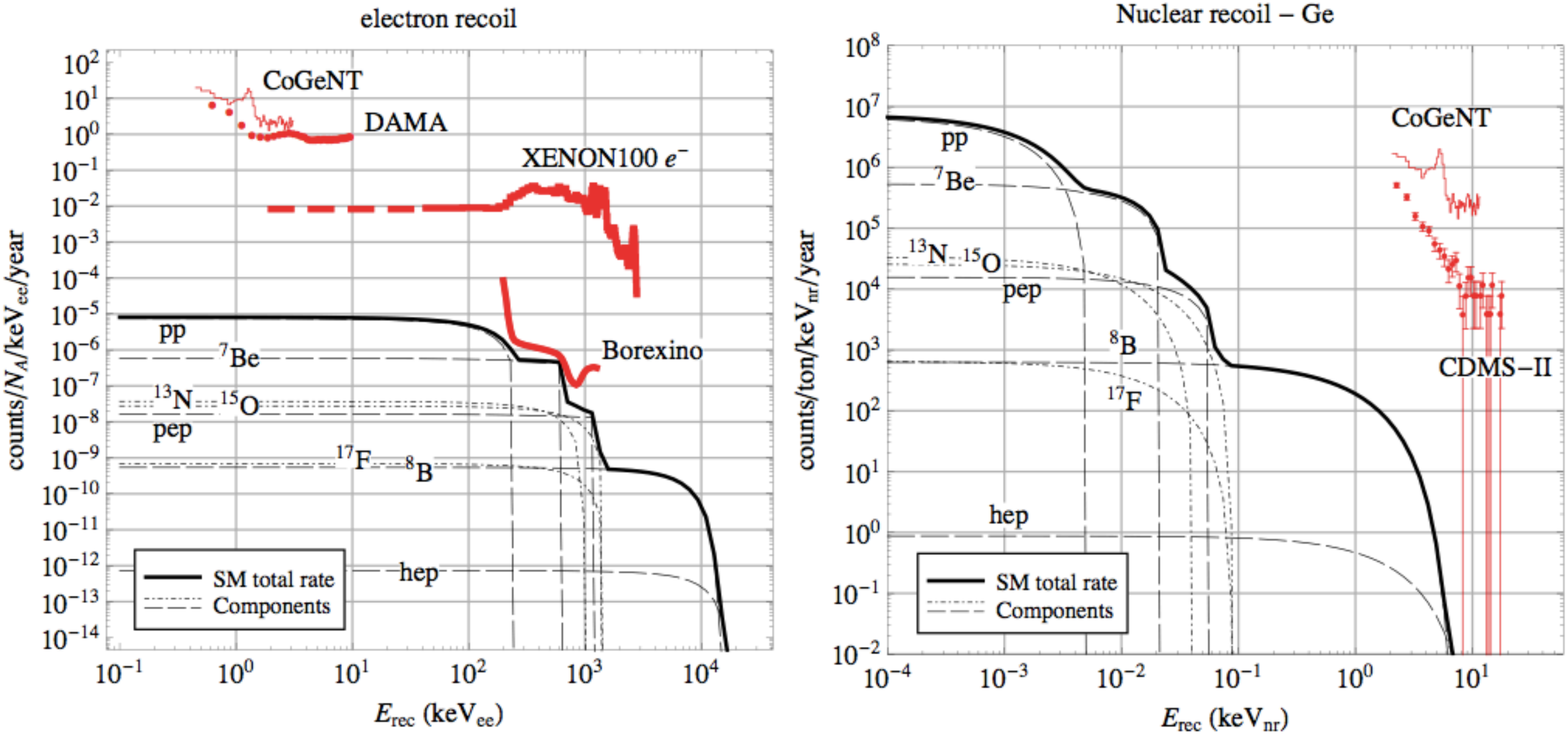
PLANCK May-30-2012 see also Gutlein et al 1003.5530 PAN Machado

Motivations



The standard solar ν signal is small. New physics?

Motivations

Non-standard neutrino magnetic moment

see, for instance, Marciano Sanda PLB 67 (1977), Kim PRD14 (1976), Beg et al PRD 17 (1978), Georgi Randall PLB 244 (1990), Czakon et al PRD 59 (1999), Mohapatra et al PRD 70 (2004), ...

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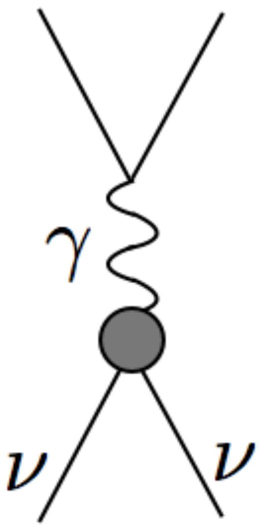
This could enhance the signal in dark matter direct detection experiments



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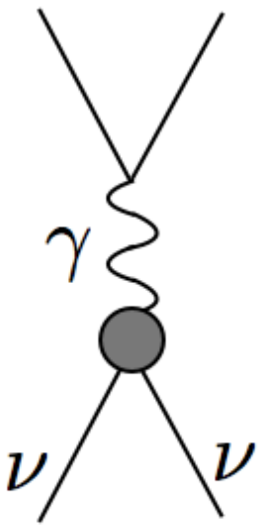

$$\sigma \sim \frac{1}{E_r} \longrightarrow$$ A low threshold means a higher rate!

Motivations

There can be new unknown weakly coupled light mediators with masses O(GeV) or less

see, for instance, Bjoren et al PRD 80 (2009), Arkani-Hamed et al PRD 79 (2009), Cheung et al PRD 80 (2009), ...

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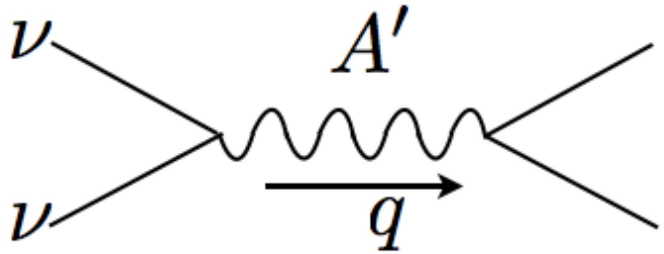

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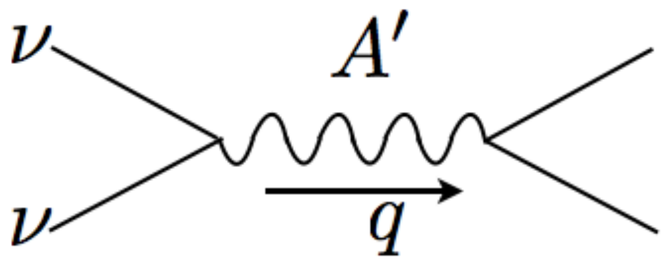

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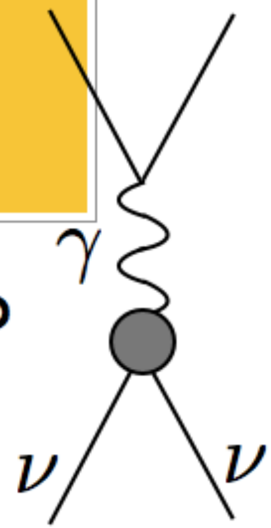
For light A', a low threshold means a higher rate!

Models

Neutrino magnetic moment
Gauged B-L
Sterile neutrinos and light A'
Barionic sterile neutrinos and gauged B
Electron scattering vs. nuclear scattering

Models

Non-standard neutrino magnetic moment



Perhaps the simplest type of new physics leading to enhanced scattering at low energies.

$$\mathcal{L}_{\mu_\nu} \supset \mu_\nu \, \bar{\nu}\sigma^{\alpha\beta}\partial_\beta A_\alpha \nu$$

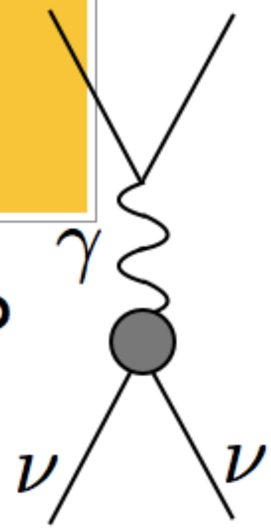
$$\frac{i}{2}[\gamma^\alpha, \gamma^\beta]$$

$$\sqrt{4\pi\alpha}/2m_e$$

$$\mu_\nu^{\rm std} = 3.2 \times 10^{-19} \mu_B \times (m_\nu/{\rm eV})$$

Models

Non-standard neutrino magnetic moment



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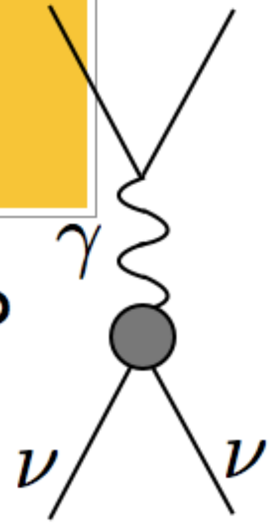

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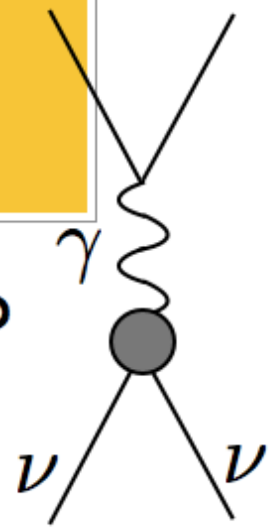

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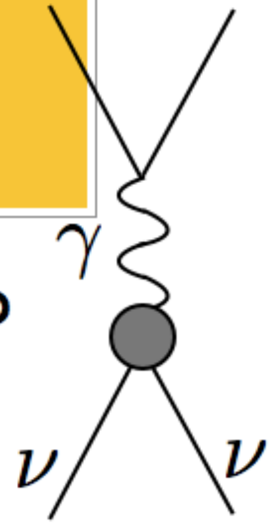

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For nuclear recoil

Models

Gauged $B-L$

$$\mathcal{L}_{B-L} \supset -g_{B-L}\,\bar{e}\gamma^\alpha A'_\alpha e + \frac{1}{3} g_{B-L}\,\bar{q}\gamma^\alpha A'_\alpha q - g_{B-L}\,\bar{\nu}\gamma^\alpha A'_\alpha \nu + \ldots$$

Dark photon

Neglect kinetic mixing (we will discuss it later).

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Assume vector coupling: $\bar{\psi}\gamma^{\mu}\psi\, A'_{\mu}$

Models

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ν momentum and mass: heavy sterile neutrinos

models
A: $U(1)_{B-L}$

Models

Gauged $B - L$

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ν momentum and mass: heavy sterile neutrinos

Bounds: 5th force + astrophysics ⟶ $M_{A'} > 100$ MeV

models
A: $U(1)_{B-L}$

Models

Dark photon through kinetic mixing and ν_s

The A' coupling to SM particles is much smaller than its coupling to sterile neutrinos.

kinetic mixing — sterile is charged under U(1)'

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_s i\gamma^\mu \partial_\mu \nu_s + g'\bar{\nu}_s\gamma^\mu\nu_s A'_\mu$$
$$- \overline{(\nu_L)^c} m_{\nu_L}\nu_L - \overline{(\nu_s)^c} m_{\nu_s}\nu_s - \overline{(\nu_L)^c} m_{\text{mix}}\nu_s$$

These may be obtained from a seesaw

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B: $U(1)'+\nu_s$

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These may be obtained from a seesaw

σ is the same as before with $g_{B-L} \to \sqrt{\epsilon e g'}$

coupling to electrons

Models

Barionic ν_s and gauged barion number

models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$

Coupling to barions ⟶ weaker limits

σ is the same as before with $g_{B-L} \to g_B$

Models

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Coupling to barions ⟶ weaker limits

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Neutrino matter potential is very important

$$\uparrow V_{A'} = \frac{g_B^2}{\downarrow M_{A'}^2}(N_p + N_n)$$

Electron scattering

models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
C: $U(1)_B+\nu_s$

NMM, $U(1)_{B-L}$, and $U(1)' + \nu_s$ can lead to e^- scattering

Light or heavy sterile neutrinos

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Light or heavy sterile neutrinos

Heavy steriles: bounds from cosmology (X-ray flux from galaxy clusters and CMB) - skip it (see 1202.6073)

$\nu_s \to \gamma\nu_{\rm act}$ Smirnov Zukanovich-Funchal PRD 74 (2006), Nelson Walsh PRD 77 (2008), Feldman Nelson JHEP 0608 (2006)

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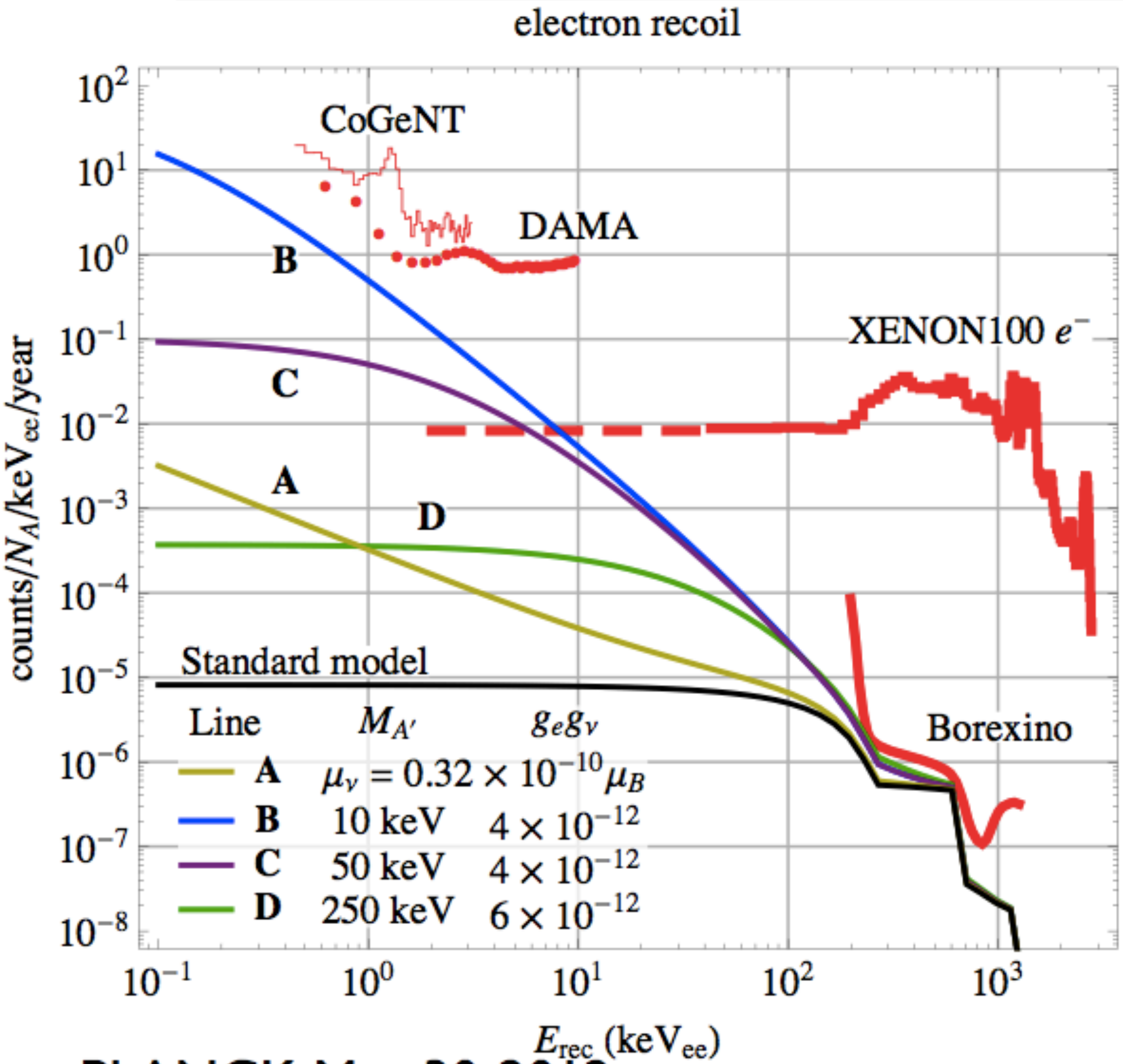

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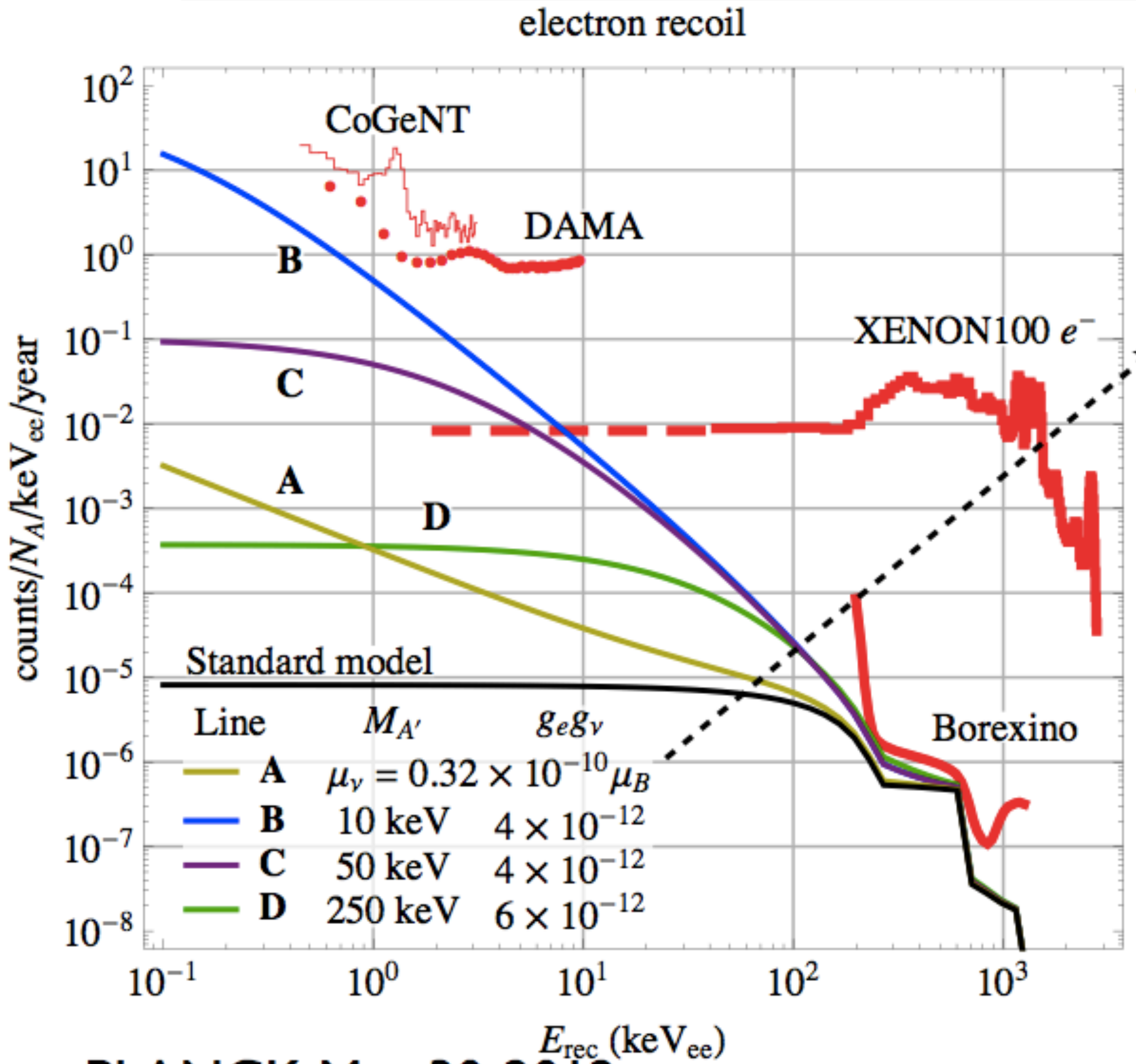

ν magnetic moment

Future DM detectors may enter this regime

XENON-1T, LUX, ZEPLIN, X-MASS, PANDA-X

Electron scattering

models
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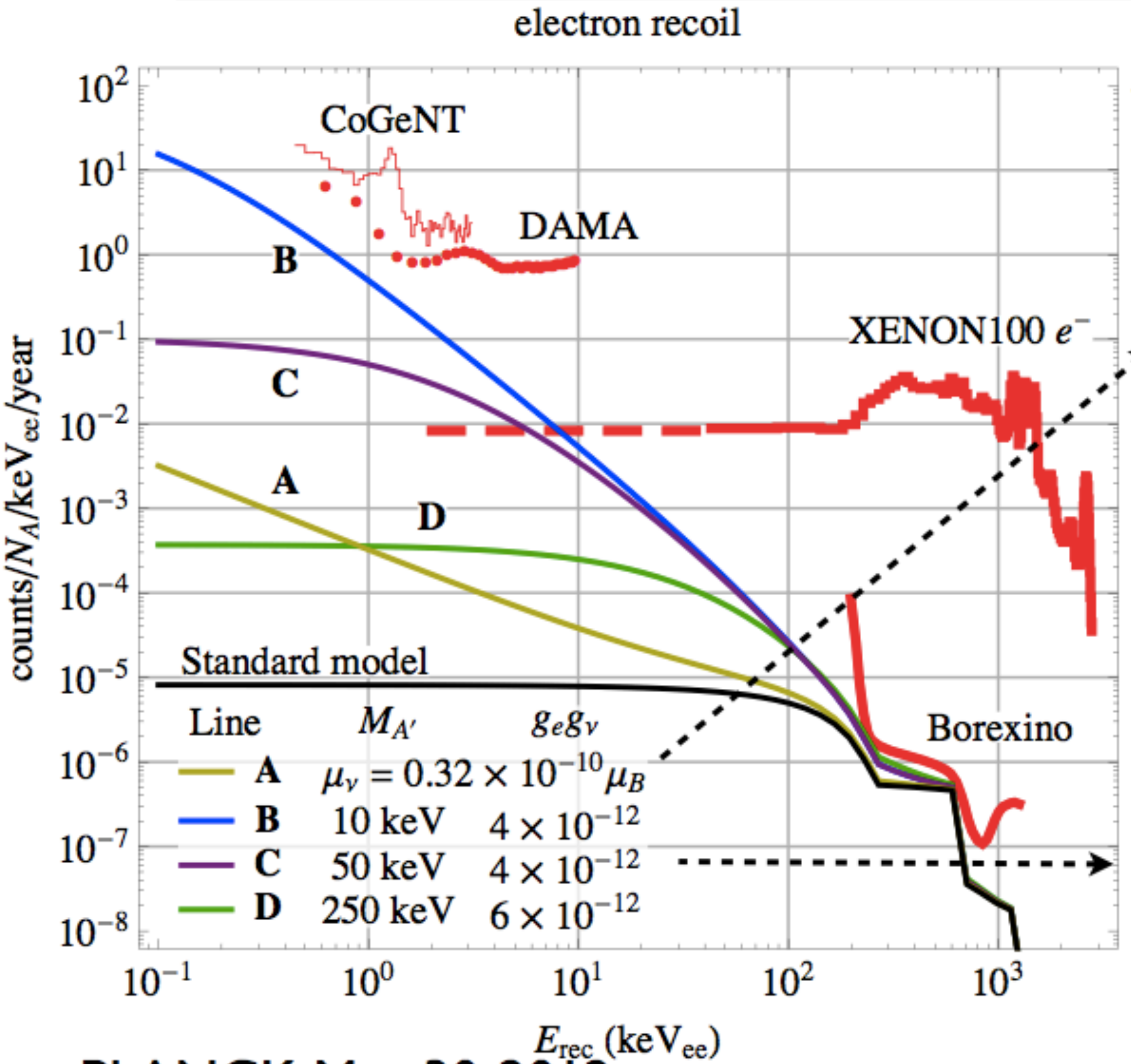

ν magnetic moment

Future DM detectors may enter this regime

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Curves B, C and D

$U(1)_{B-L}$: GEMMA, active ν

U(1)' + ν_s: richer, heavy ν_s

Nuclear scattering

models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
C: $U(1)_B+\nu_s$

NMM, $U(1)_{B\text{-}L}$, $U(1)' + \nu_s$, and $U(1)_{B} + \nu_s$ can lead to N scattering, but NMM is negligible

Low E_r ⟶ coherence ⟶ σ ~ (mass or atomic number)^2

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Low E_r ⟶ coherence ⟶ σ ~ (mass or atomic number)^2

Threshold $E_\nu^{\min} \approx \sqrt{m_T E_r/2}$:
keVnr E_r ⟶ MeV neutrinos ⟶ only high energy tail of ^{8}B component is important

Nuclear scattering

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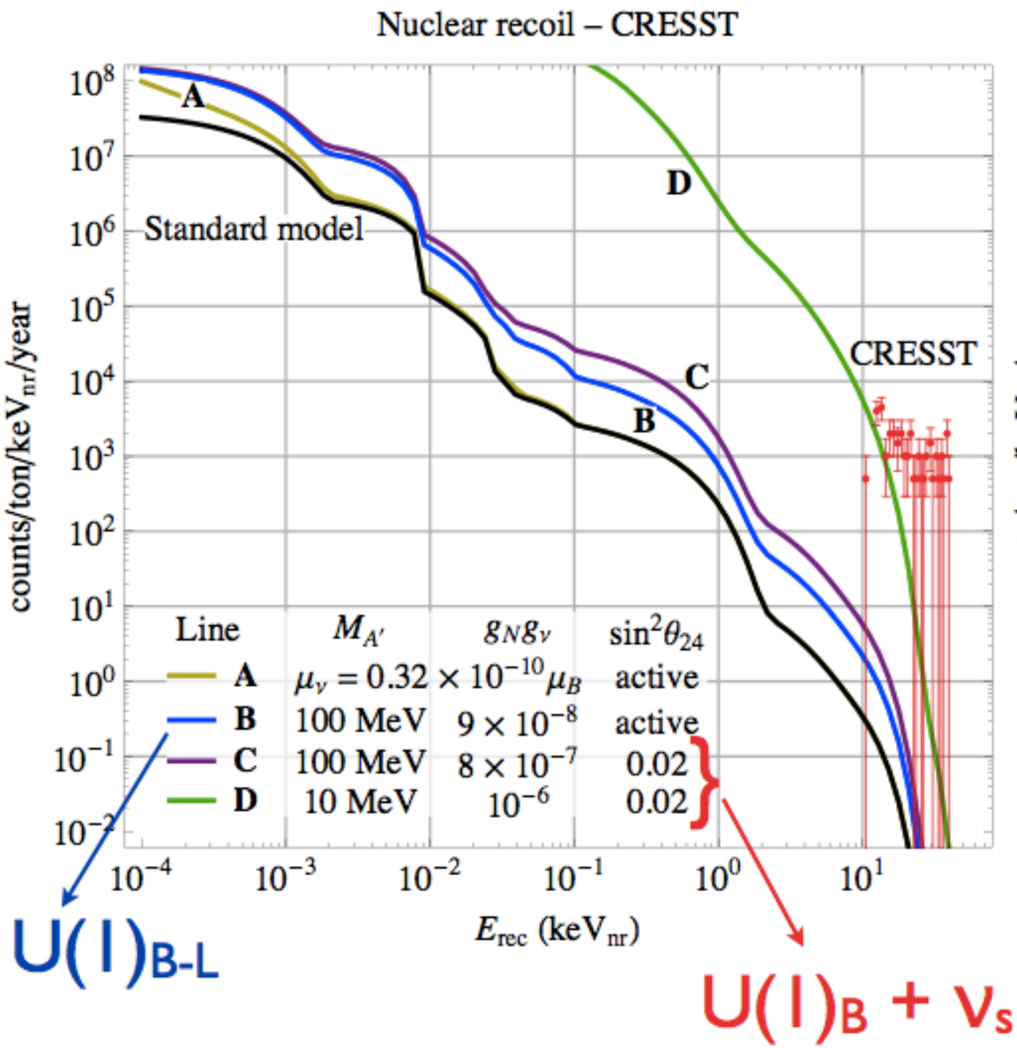

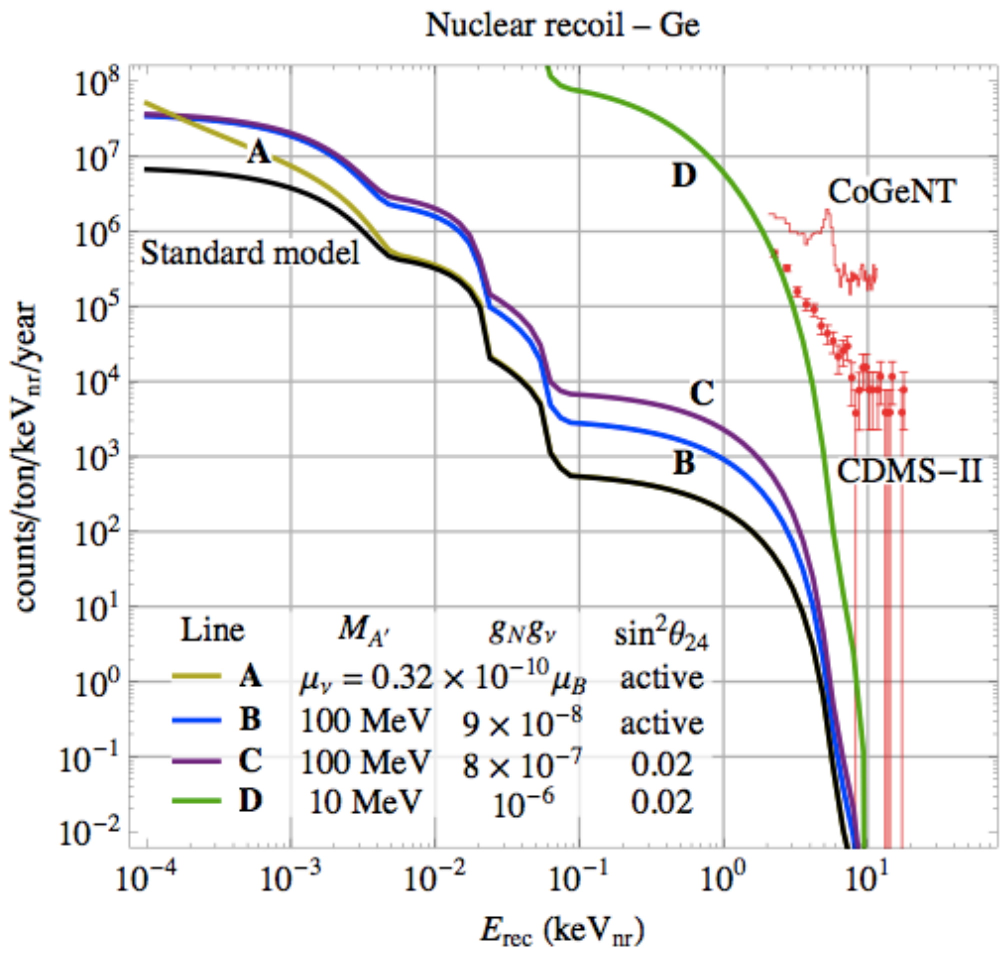

 see also Pospelov Pradler 1203.0545

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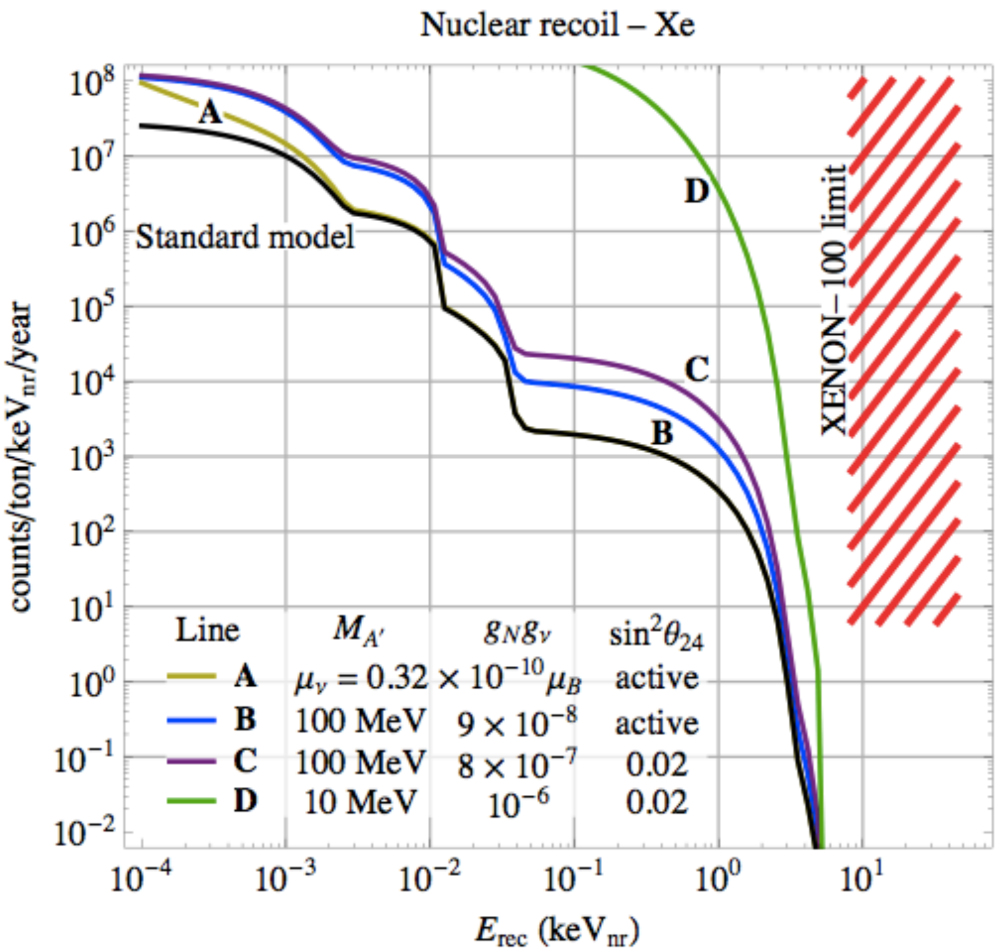

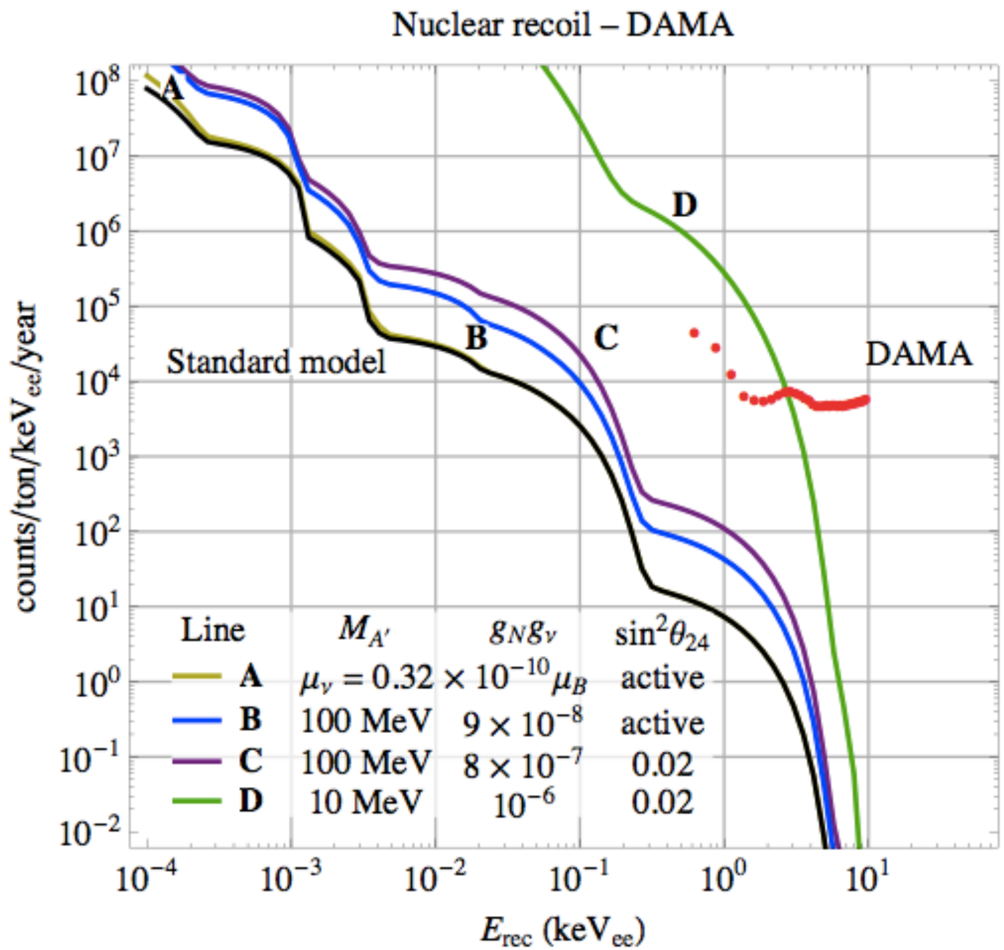

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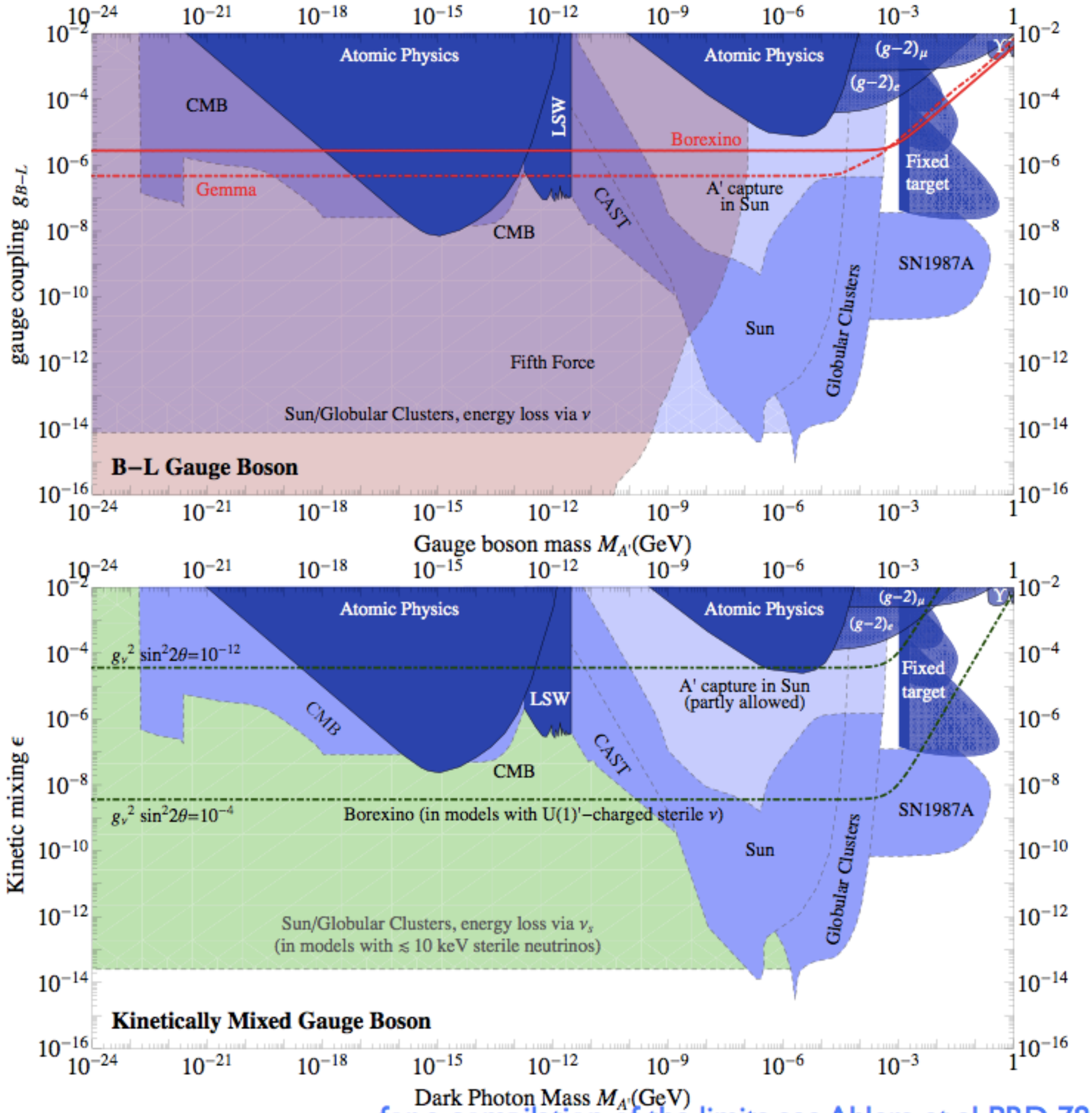
Limits



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Do not apply to model B

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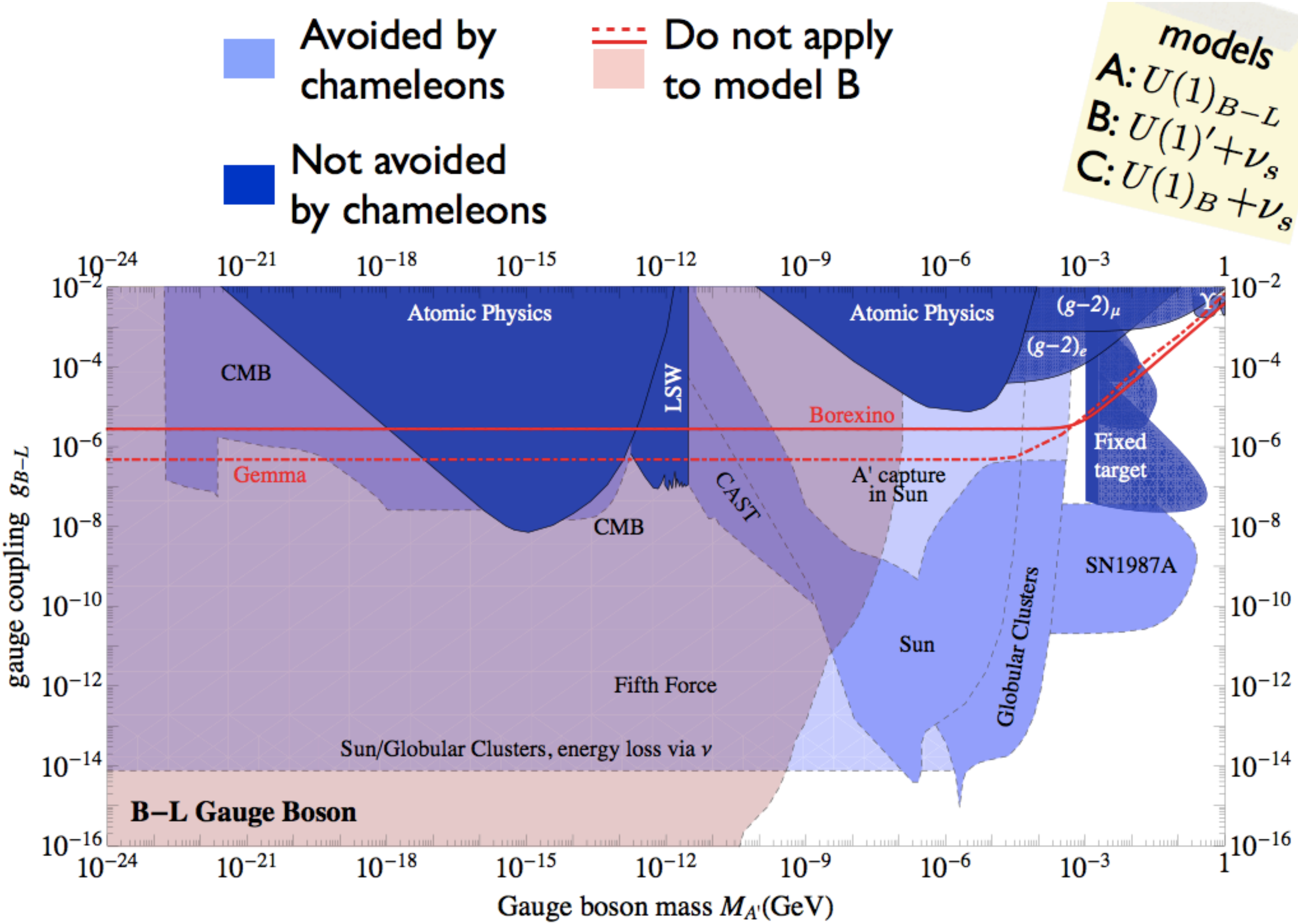

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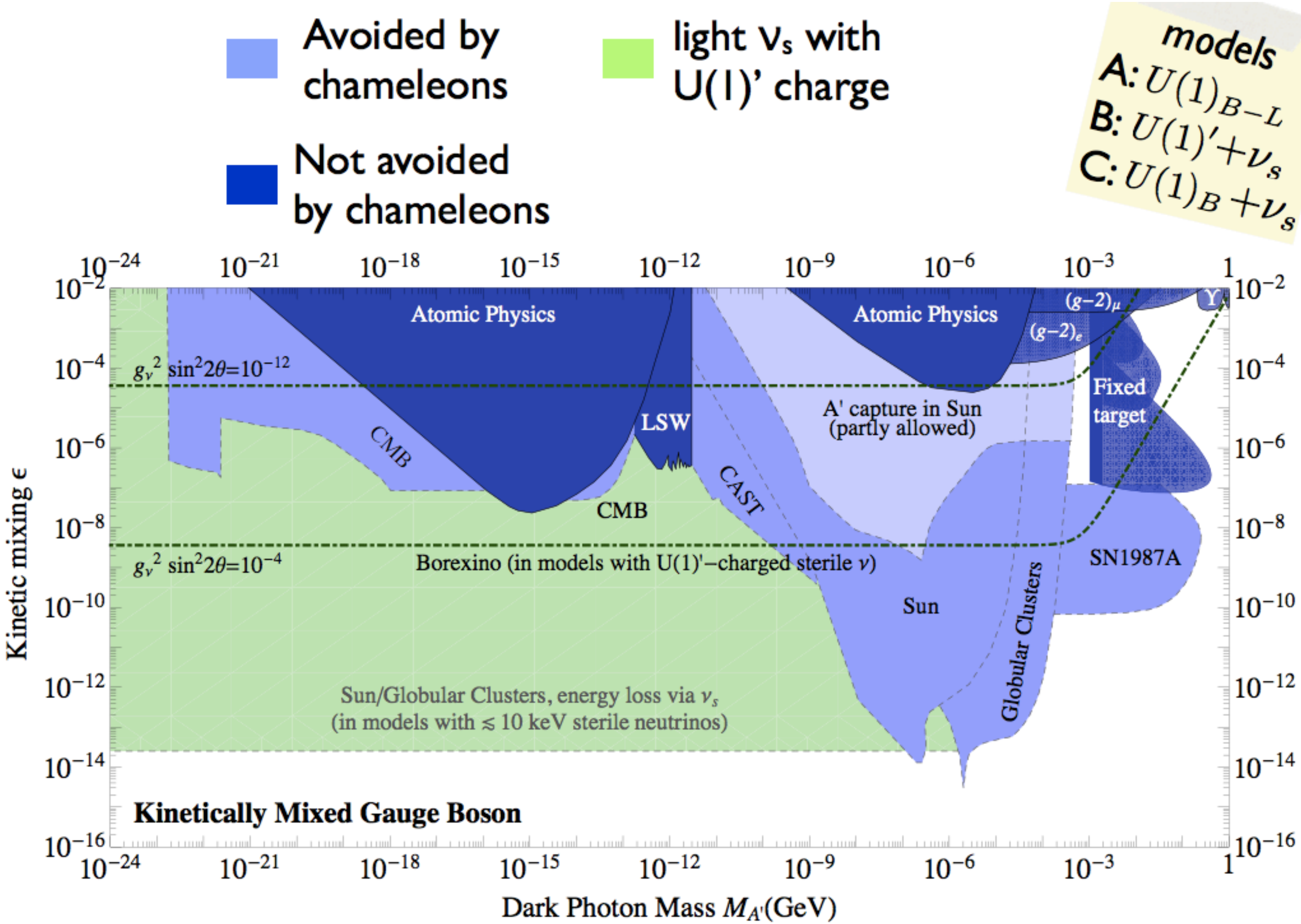

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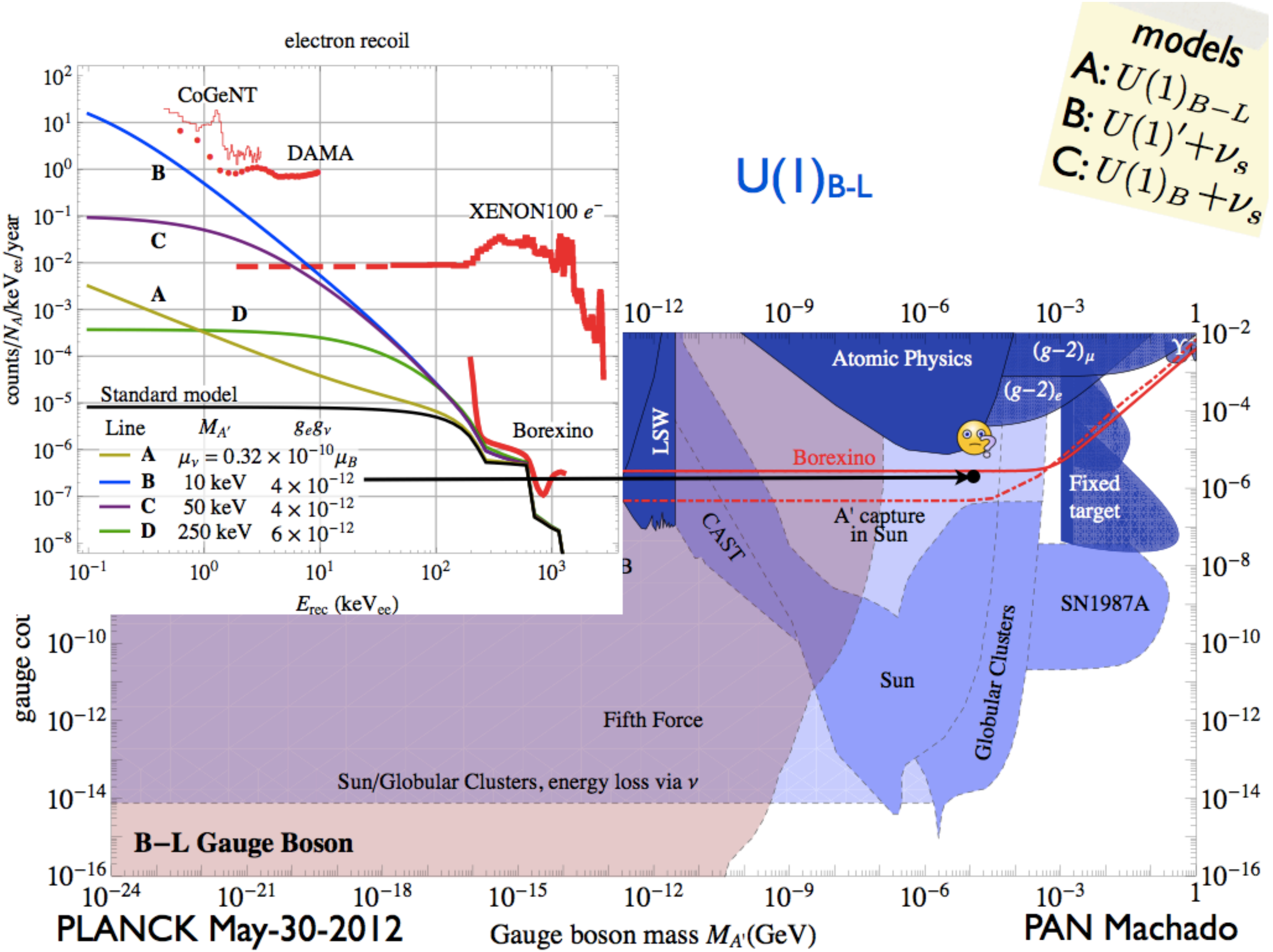
$U(1)_{B-L}$



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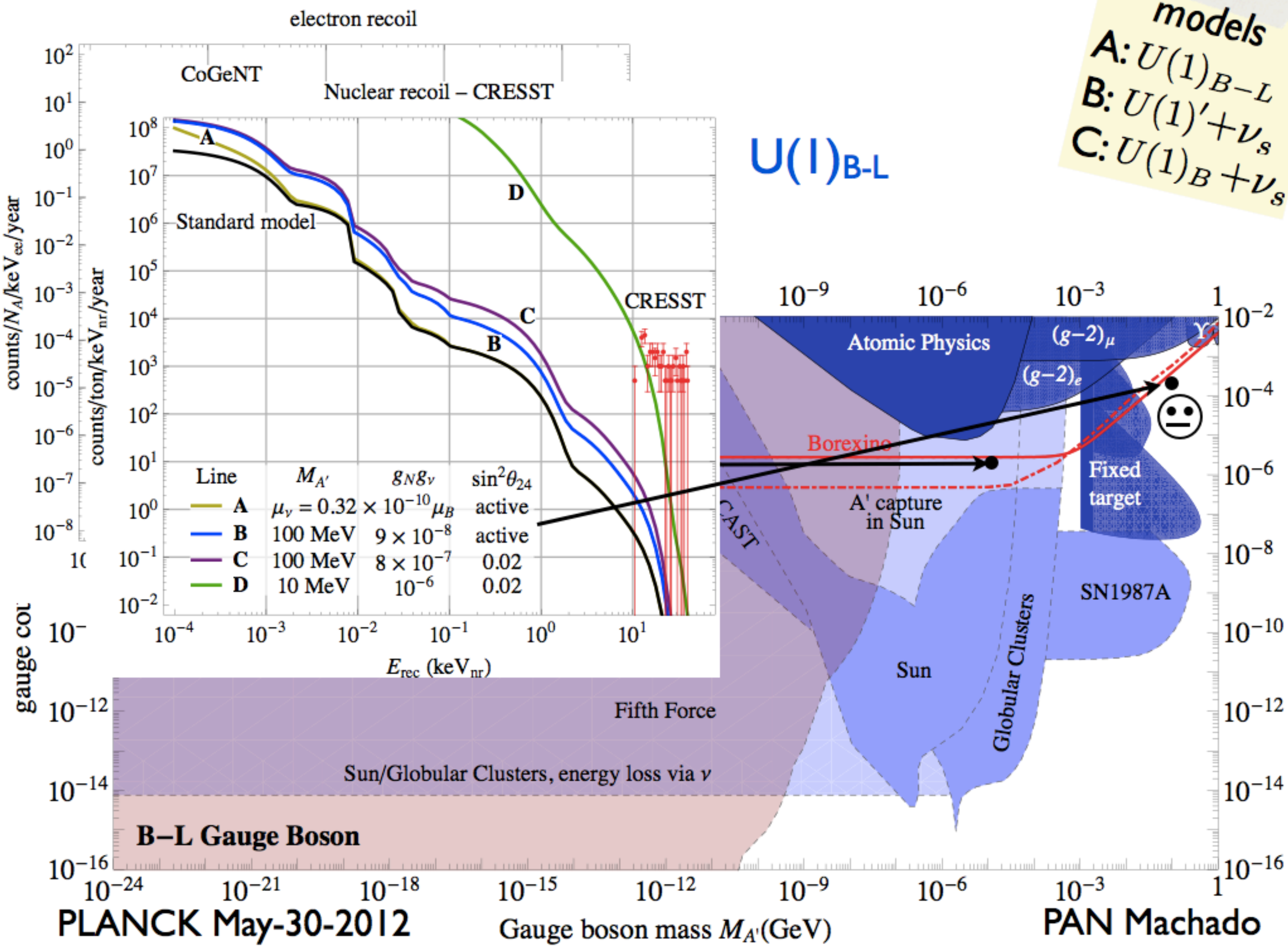

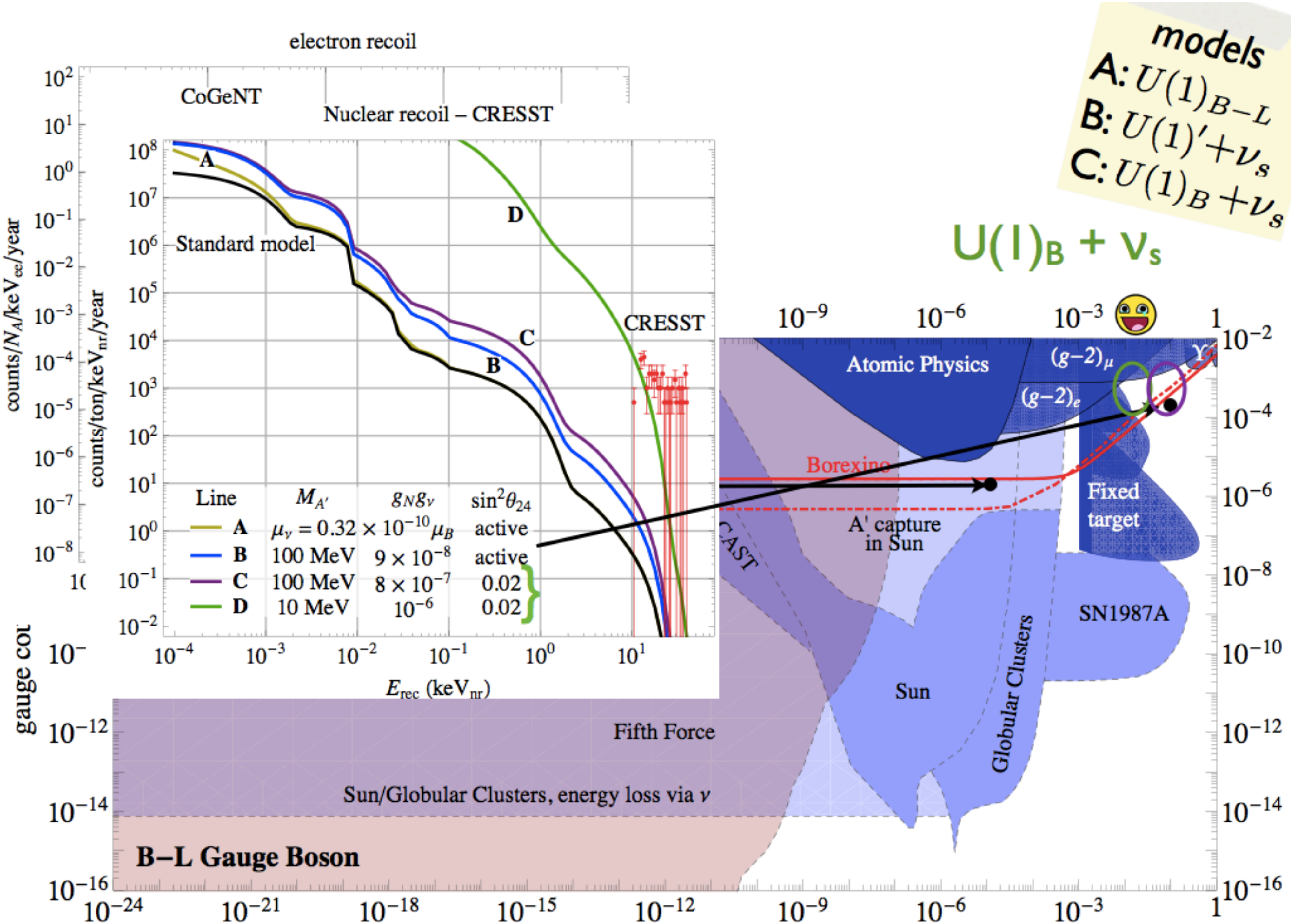

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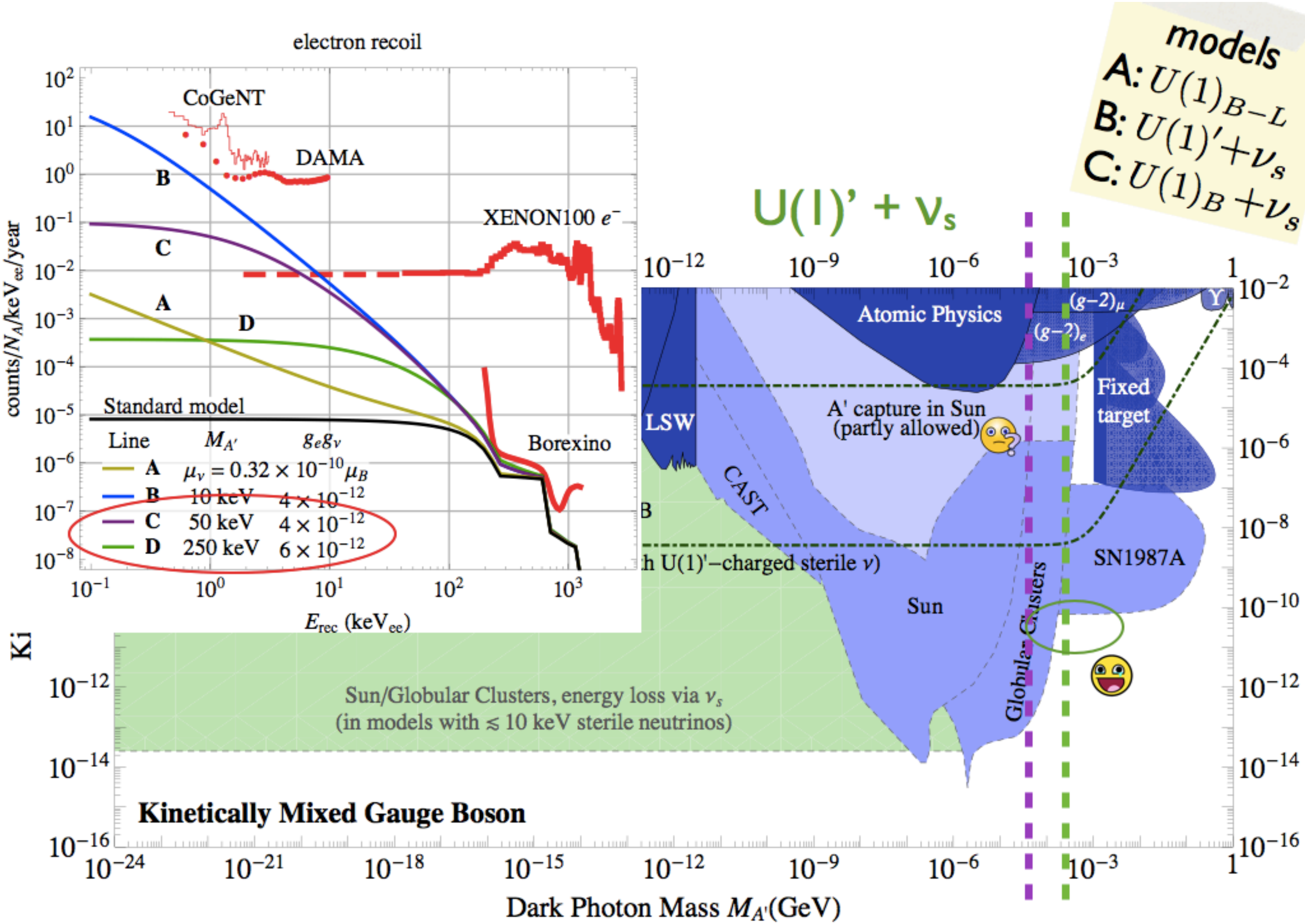
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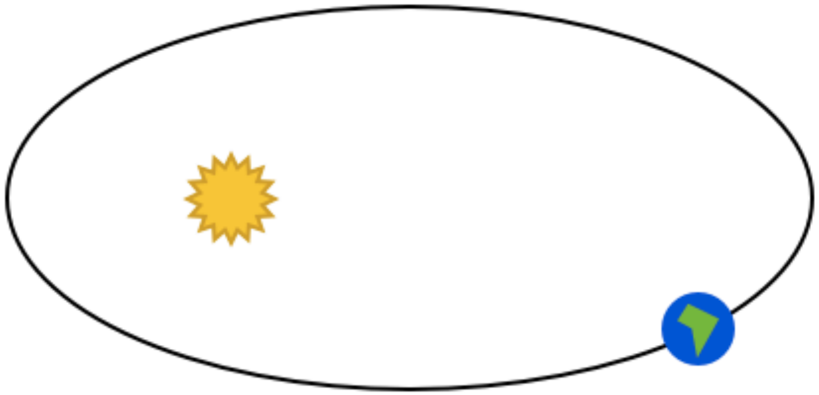
C: $U(1)_B+\nu_s$
U(1)' + ν_s
electron recoil
CoGeNT
DAMA
XENON100 e^-
Borexino
Standard model
Line $M_{A'}$ $g_e g_\nu$
A $\mu_\nu = 0.32 \times 10^{-10} \mu_B$
B 10 keV 4×10^{-12}
C 50 keV 4×10^{-12}
D 250 keV 6×10^{-12}
counts/N_A/keV$_{ee}$/year
E_{rec} (keV$_{ee}$)
Atomic Physics
$(g-2)_\mu$
$(g-2)_e$
Fixed target
A' capture in Sun (partly allowed)
LSW
CAST
SN1987A
Sun
Globular Clusters
Sun/Globular Clusters, energy loss via ν_s (in models with $\lesssim$ 10 keV sterile neutrinos)
Kinetically Mixed Gauge Boson
Dark Photon Mass $M_{A'}$(GeV)

Modulation

Modulation

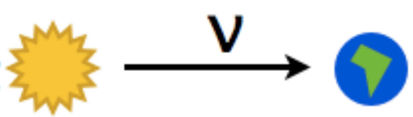
All in one slide

Earth's orbit

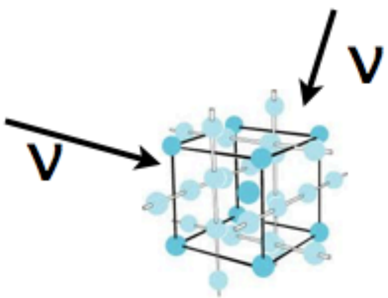


Oscillation physics

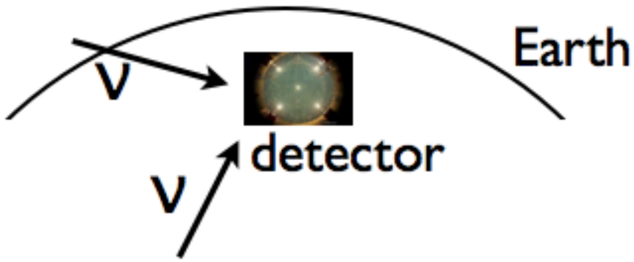
Vacuum:



Direction dependent quenching



Matter:



Modulation

All in one slide

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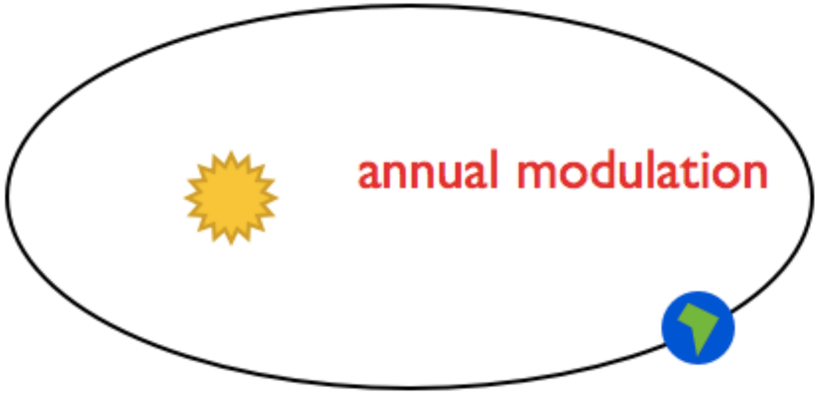

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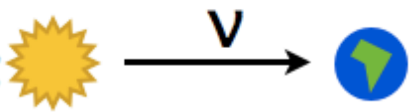
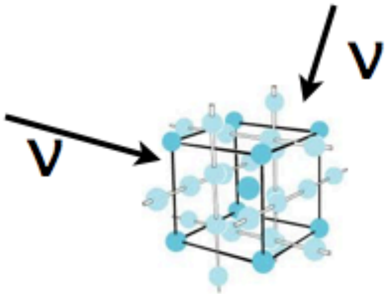
Vacuum: 

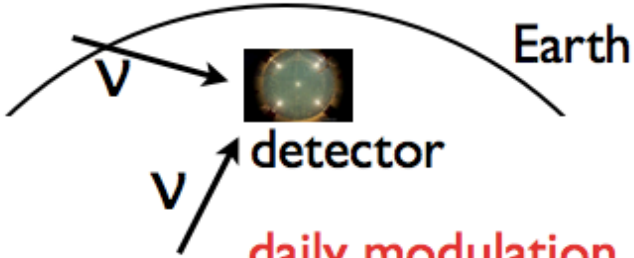
annual modulation

Direction dependent quenching



daily modulation

annual modulation

Matter: 

daily modulation

annual modulation

modulations can be used to distinguish models

Conclusions

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ν + DMDD $\longrightarrow$ rich phenomenology!

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ν + Light mediators $\longrightarrow$ $\uparrow\sigma$ @ low E_r for e^- and N

sterile ν charged under the gauge group [U(1)' or $U(1)_B$] avoid experimental $\longrightarrow$ $\uparrow\sigma$

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sterile ν charged under the gauge group [U(1)' or $U(1)_B$] avoid experimental $\longrightarrow$ $\uparrow\sigma$

Many modulations of the signal are possible

Conclusions

Non-standard signals from ν-e and ν-N scattering can be confused with DM scattering

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Thank you!

Backup

models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
C: $U(1)_B+\nu_s$

Models

Barionic ν_s and gauged barion number

In the limit of large potential

$$V_{A'} \gg \max_{j,k} |\Delta m^2_{jk}|/2E$$

the production in the Sun is negligible and the ν_s are produced via vacuum oscillations outside the Sun

Also, we cannot mess up the available fit to data (solar, terrestrial, day-night,...)

Last, if the new potential induces a MSW resonance, if possible, we can change the sign of Δm^2

Electron scattering

models
A: $U(1)_{B-L}$
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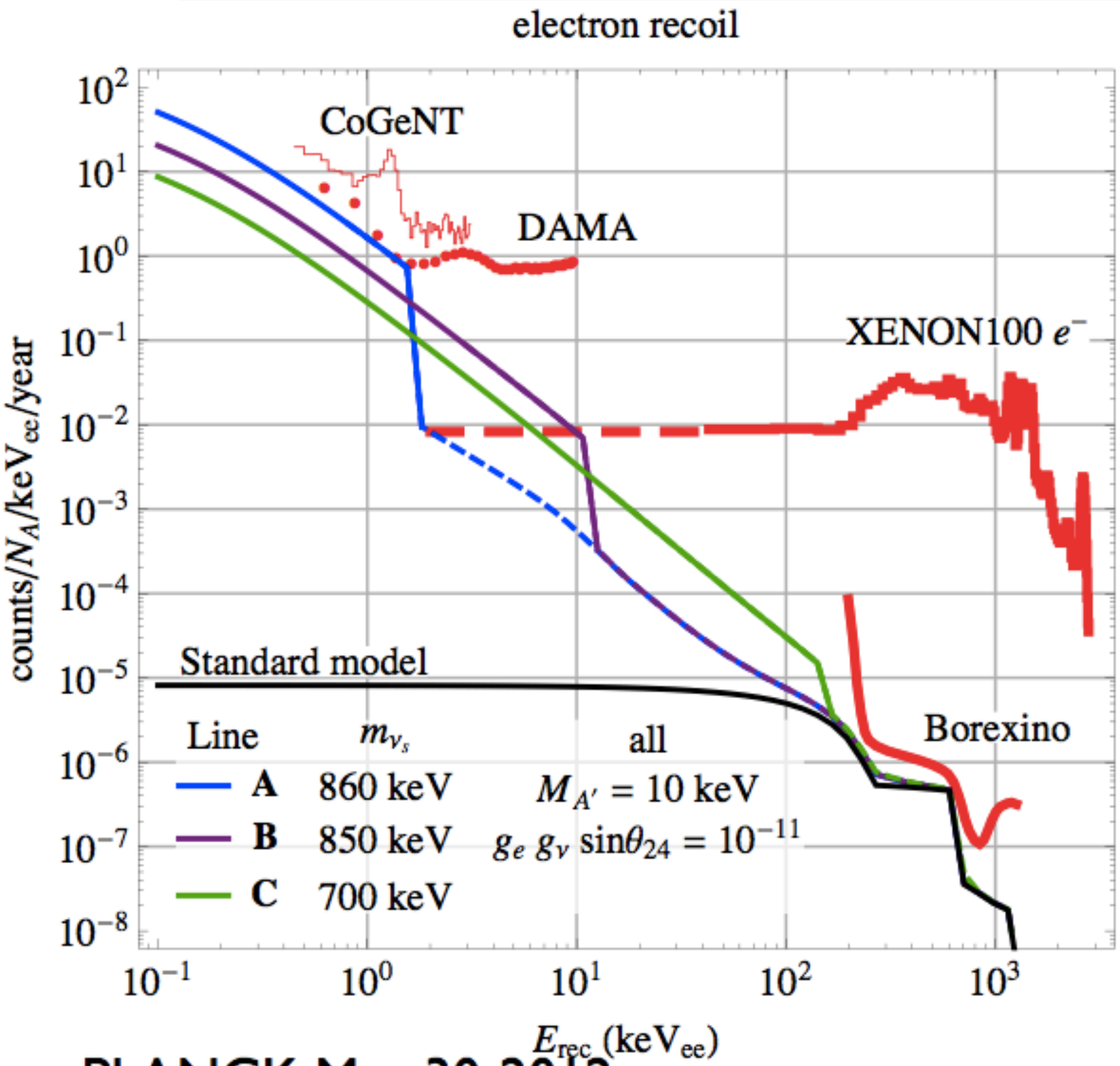

<u>All curves</u>

U(1)' + ν_s

We have not taken into account 3 body kinematics (dashed lines)

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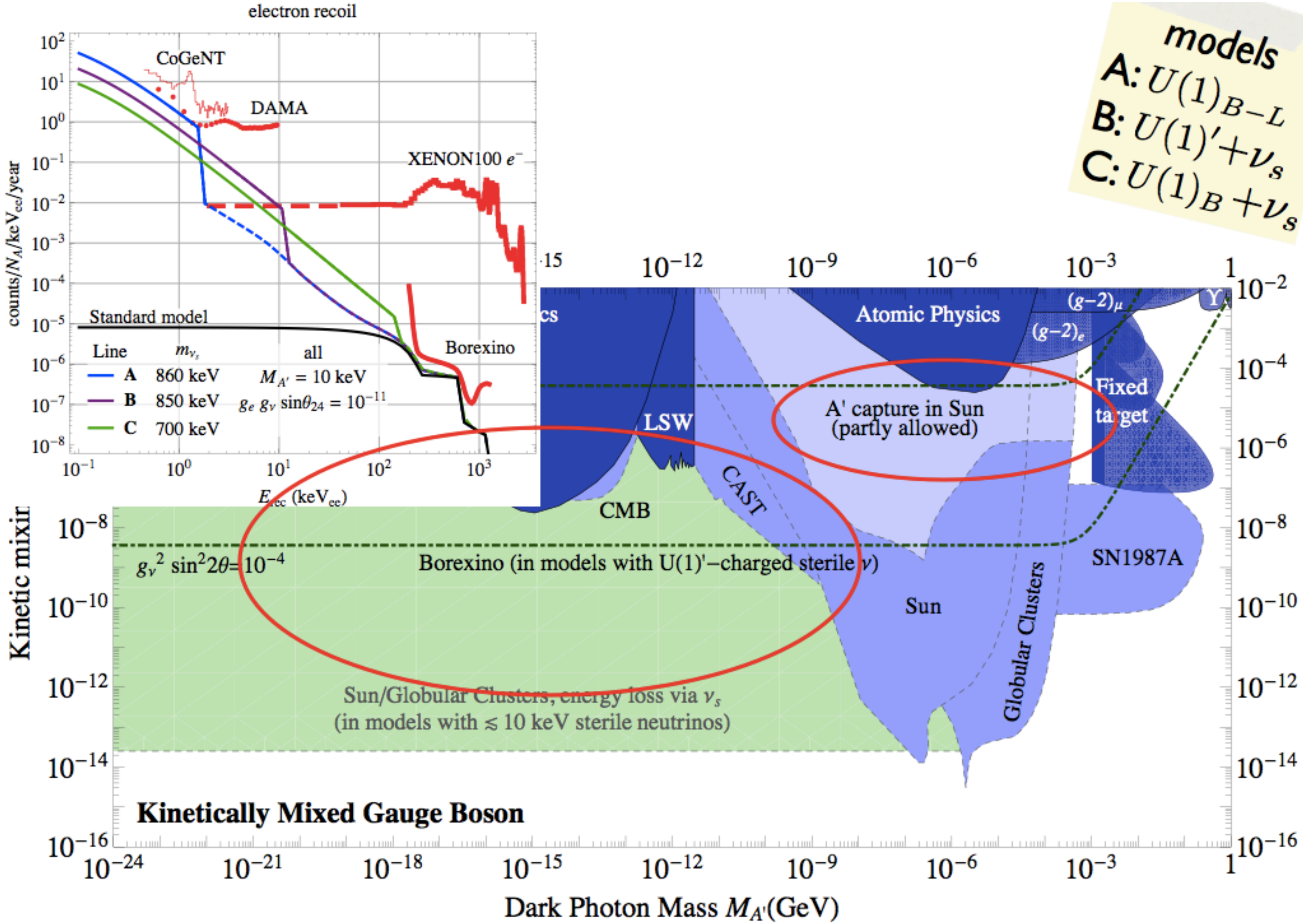

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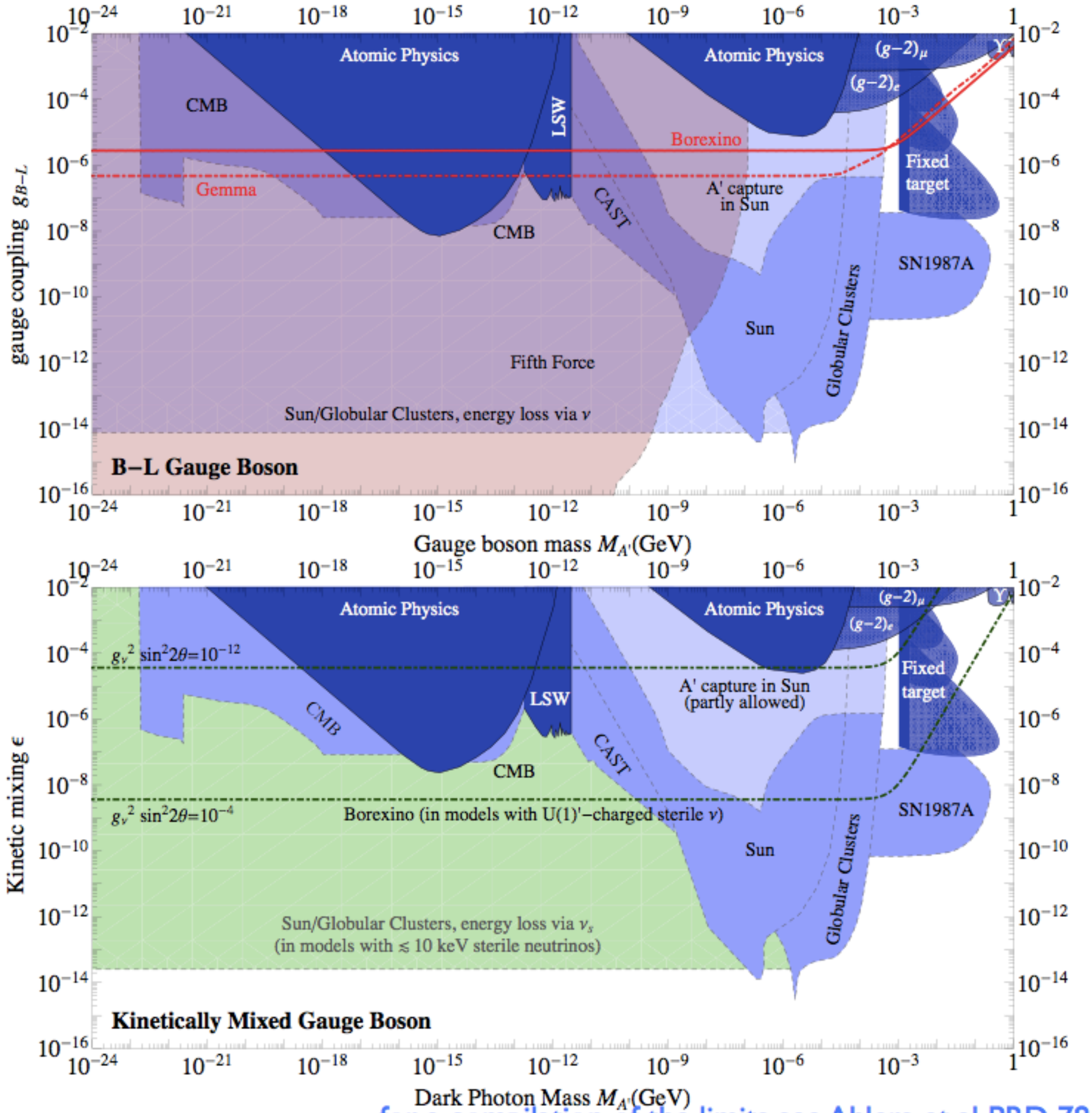

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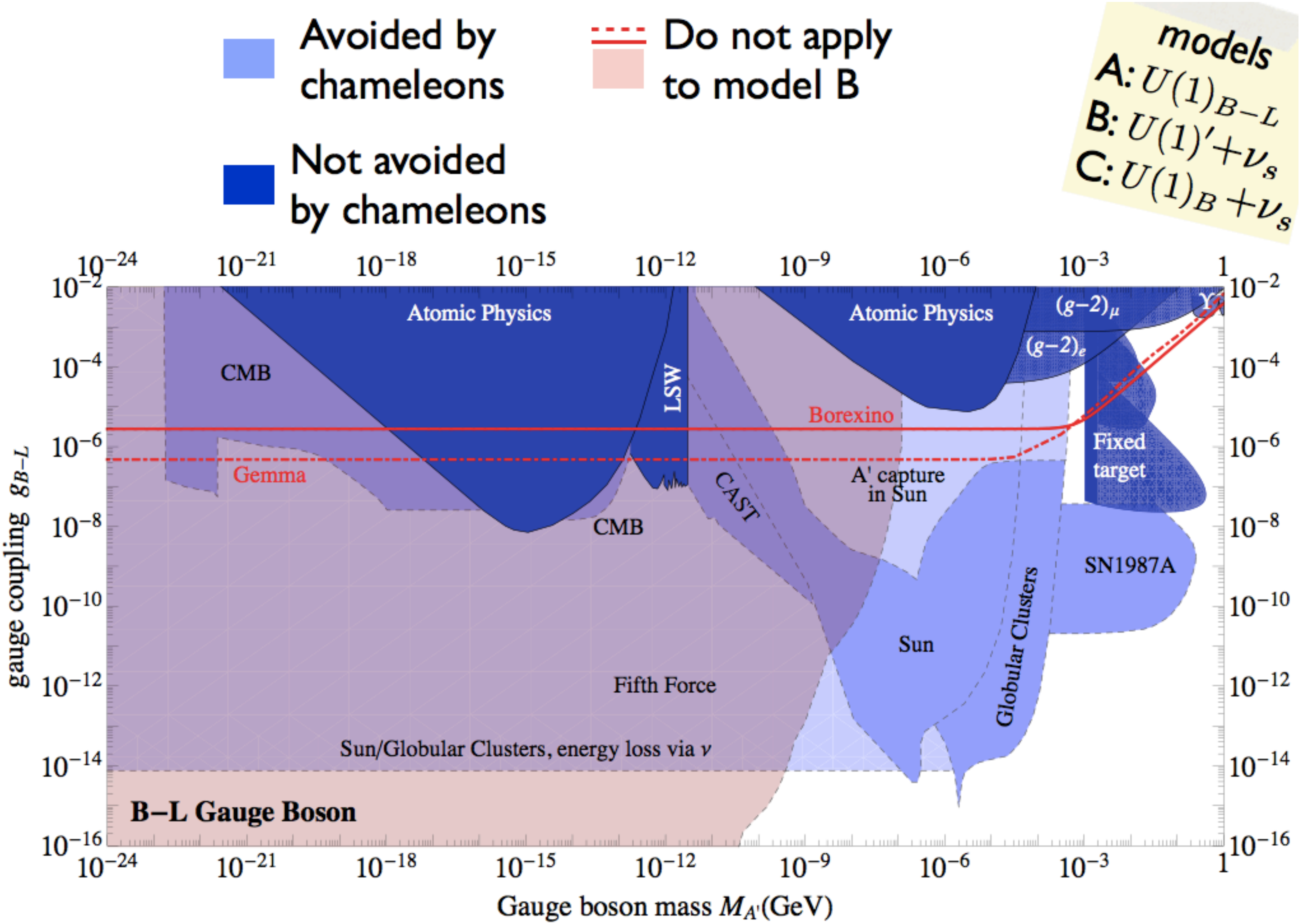

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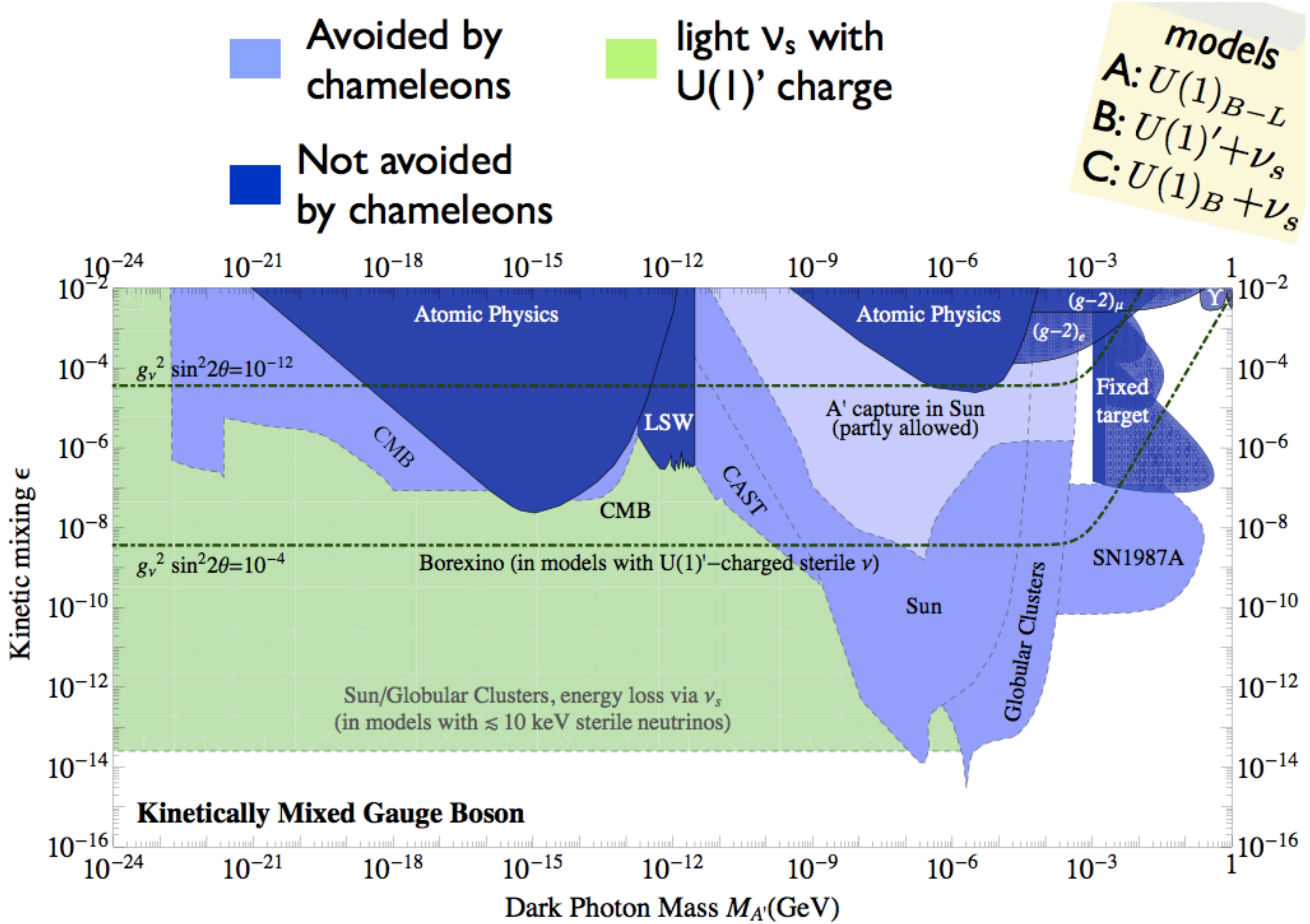

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models
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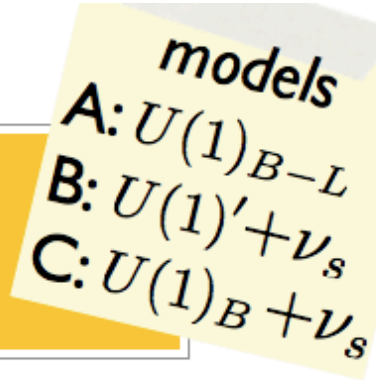
Bounds - I

Anomalous magnetic moment of the electron/muon

A new gauge boson coupling to leptons will contribute to it at one loop level. Applies to **A** and **B**, but not **C**.

Pospelov PRD 80 (2009), Bennett et al. PRD 73 (2006)

Bounds - I



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Fixed target experiments

Shot electrons and protons in a target. If a dark photon is produced, it can decay into an electron-positron pair. Threshold: $2m_e$. Applies to **A** and **B**. For **C**, should be loop suppressed. For **B**, the presence of steriles can reduce e^+e^- BR and weaken the bound.

Bjorkenet al PRD 80 (2009), Batell et al PRD 80 (2009), Essig et al PRD 82 (2010)

Bounds - I

models
A: $U(1)_{B-L}$
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Υ decays

$$\Upsilon \rightarrow \gamma A' \;\hookrightarrow \mu^+ \mu^-$$

This decay is constrained by B-factories. Applies directly to **B**, unless A' to ν_s first. To **A** it gets modified by O(1). Not **C**.

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Changes in the Coulomb force at atomic distance scales are measured. **A** and **B** but not **C**.

Bartlett Loegl PRL (1988)

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Light shining thru walls

Shot a laser onto an opaque wall and search for a photon behind it. **A** and **B** but not **C**.

Ahlers et al PRD 77 (2008)

Bounds - I

models
A: $U(1)_{B-L}$
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GEMMA

The Germanium Experiment on measurement of Magnetic Moment of Antineutrino searches for anomalous neutrino-electron scattering rates at low recoil energies. Applies to **A**, **B** if there are heavy enough steriles, but not **C**.

Beda et al PPNL 7 (2010)

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Beda et al PPNL 7 (2010)

Borexino

Search for anomalous neutrino-electron scattering rates with solar neutrinos. **A** and **B** but not **C**.

Borexino Collaboration 1104.1816

Bounds - II

models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
C: $U(1)_B+\nu_s$

Supernova 1987A

A dark photon produced in the SN core takes away the SN energy. The A' emission is mainly due to A' radiation off protons and neutrons, so it applies to all models here.

Dent et al 1201.2683

Bounds - II

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Supernova 1987A

A dark photon produced in the SN core takes away the SN energy. The A' emission is mainly due to A' radiation off protons and neutrons, so it applies to all models here.

Dent et al 1201.2683

Solar constraints

The A' is thermally produced in the Sun by emission off electrons (conversion of plasma excitations - resonance). **A** and **B** (and **C**?). If A' couples to ν, they escape leading to energy loss (minicharged limits). These can be evaded if the A' couples only to ν_s heavy enough.

Redondo JCAP 0807 (2008), Raffelt Starkman PRD 40 (1989)

Bounds - II

models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
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Cooling of stars in globular clusters

Similar to Solar constraints. **A** and **B** (and **C**?).

Bounds - II

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C: $U(1)_B + \nu_s$

Cooling of stars in globular clusters

Similar to Solar constraints. **A** and **B** (and **C**?).

CAST experiment

Helioscope looking for photons in a dark shielded cavity. The photons are produced in the Sun, oscillate to dark photons, enter the cavity and oscillate back. **A** and **B** (and **C**?). Can be avoided if dark photons decay before reaching the Earth.

CAST Collaboration JCAP 0902 (2009)

Bounds - II

models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
C: $U(1)_B+\nu_s$

CMB constraints (FIRAS)

The A' mix with the photon in a frequency dependent way and this attenuates the black body spectrum of the CMB. **A** and **B** (and **C**?).

Mirizzi et al JCAP 0903 (2009), Fixsen et al Astrophys J 473 (1996)

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Fifth force searches

Test of gravitational, Casimir, and Van der Waals forces on small distances. Applies to **A** and **C** but not **B**, since the test bodies are electrically neutrals.

Bordag et al Phys Rept 353 (2001), Bordag et al *Advances in the Casimir effect* (2009), Adelberger et al PRL 98 (2007), Adelberger et al PPNP 62(2009)

Bounds - summary

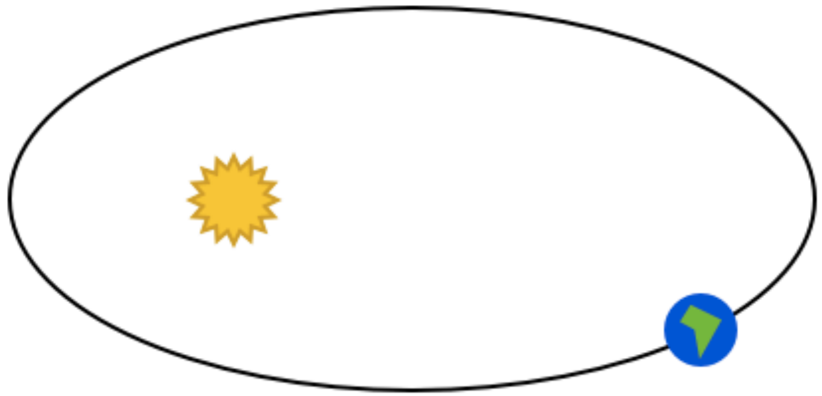
models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
C: $U(1)_B+\nu_s$

	$U(1)_{B-L}$	$U(1)'$ kin mix	$U(1)_B+\nu_s$
g – 2	✓	✓	✗
Fixed Target	✓	✓	✗
Υ	✓	✓	✗
Atomic physics	✓	✓	✗
Sun/Clusters/CAST	✓	✓	?
SN1987A	✓	✓	✓
LSW	✓	✓	✗
CMB	✓	✓	?
Borexino	✓	only if ν_s exist	✗
GEMMA	✓	✗	✗
Fifth force	✓	✗	✓

Modulation

Earth-Sun distance

Earth's orbit is elliptical



Perihelion - Jan 3rd - 0.983 AU
Aphelion - July 4th - 1.017 AU

Modulated amplitude of 3%

Opposed to the one seen in DAMA

Modulation

Neutrino oscillations in vacuum

If Δm^2 O(10^{-10}eV^2), the osc. legth is comparable to the Earth-Sun distance, leading to annual mod.

Pospelov 1103.3261

This could overcompensate the contribution to the modulation due to the Earth-Sun distance

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Pospelov 1103.3261

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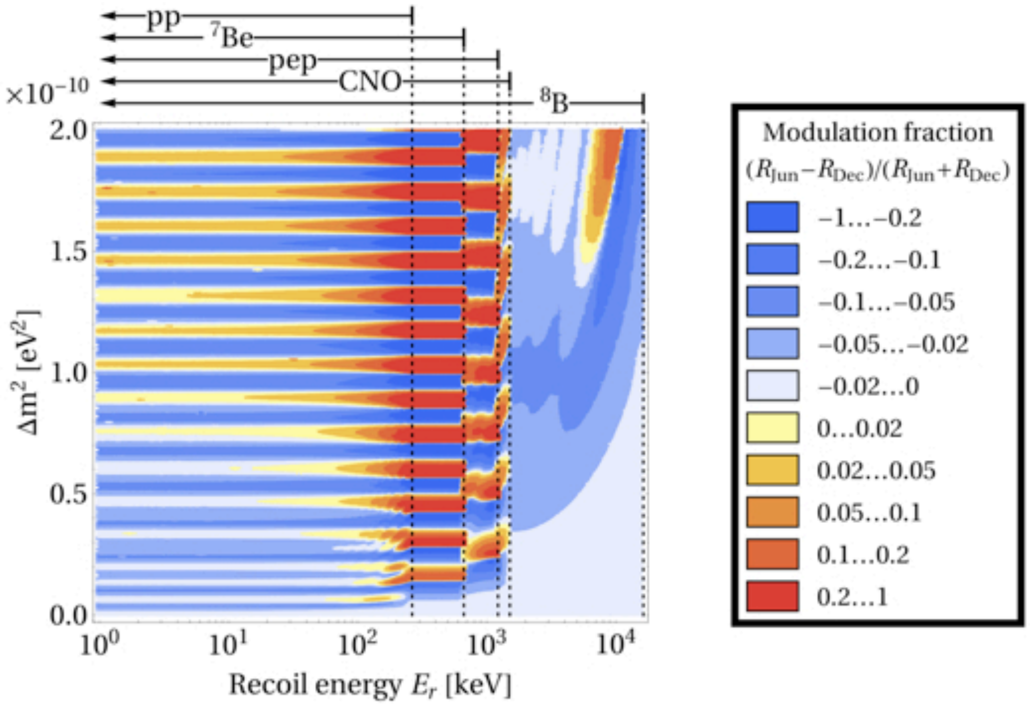
R is the count rate in Jun or Dec



Modulation

Diurnal and annual modulation from Earth matter effects

models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
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$U(1)_B$ + 2 barionic sterile neutrinos

Strong matter effect → day-night asymmetry (sterile sector)

The annual change in the length of the day will lead to annual modulation and daily modulation

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Strong matter effect → day-night asymmetry (sterile sector)

The annual change in the length of the day will lead to annual modulation and daily modulation

distinguish this scenario from the others

L_{osc} ~ 1 km + large matter potential + resonance: even the depth of the detector will be important...

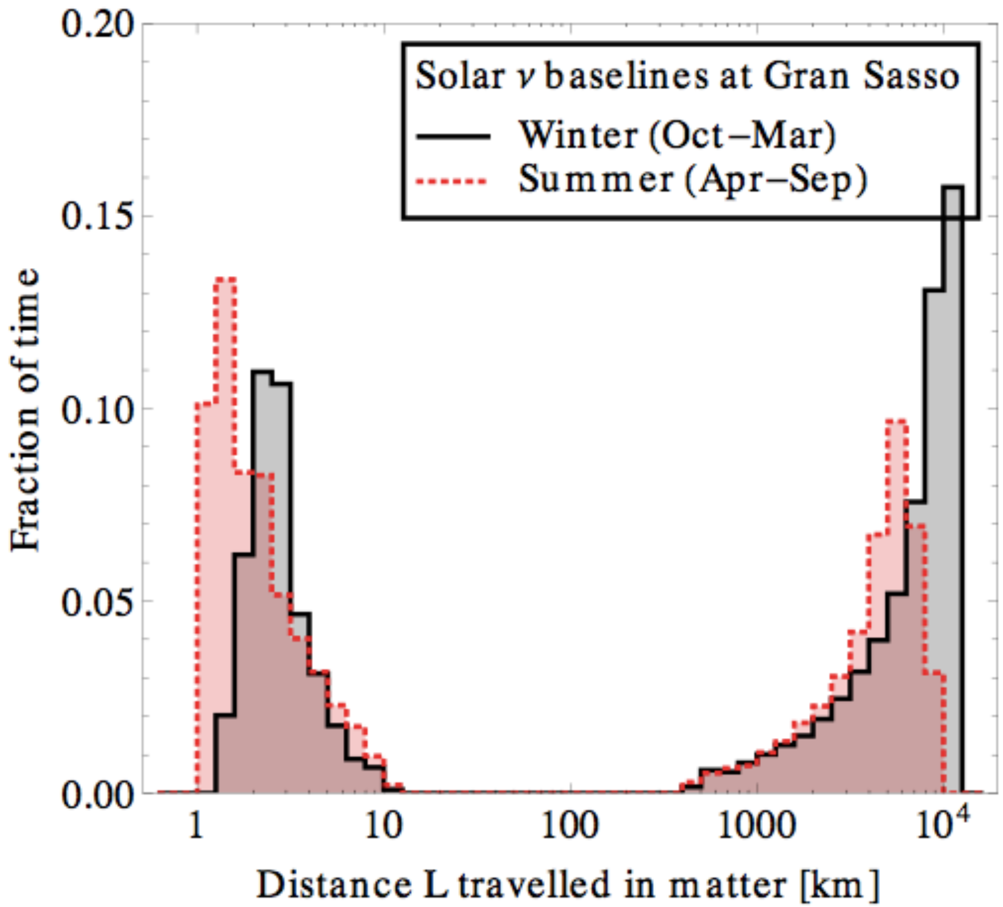
Modulation

Zenith angle dependency of Earth matter effects

The daily average distance that the neutrino travels in the Earth modulates annually

If $L_{osc} \sim O(km)$ or $O(R_{earth})$ the oscillation probability can modulate during the year (and daily)

In the first case, the modulation pattern depends on local topograph



Plot done in Mathematica 8. Data taken from:
NASA and J A Program http://asterweb.jpl.nasa.gov/gdem.asp
R. Bellotti et al PRD 42 (1990)

Modulation

Direction dependent quenching factors

The response of a solid state detector to nuclear recoils can be sensitive to the direction in which the recoil nucleus is traveling with respect to the crystal axes

Bozorgnia et al 1006.3110, 1008.3676, 1009.3325, 1011.6006, 1101.2876

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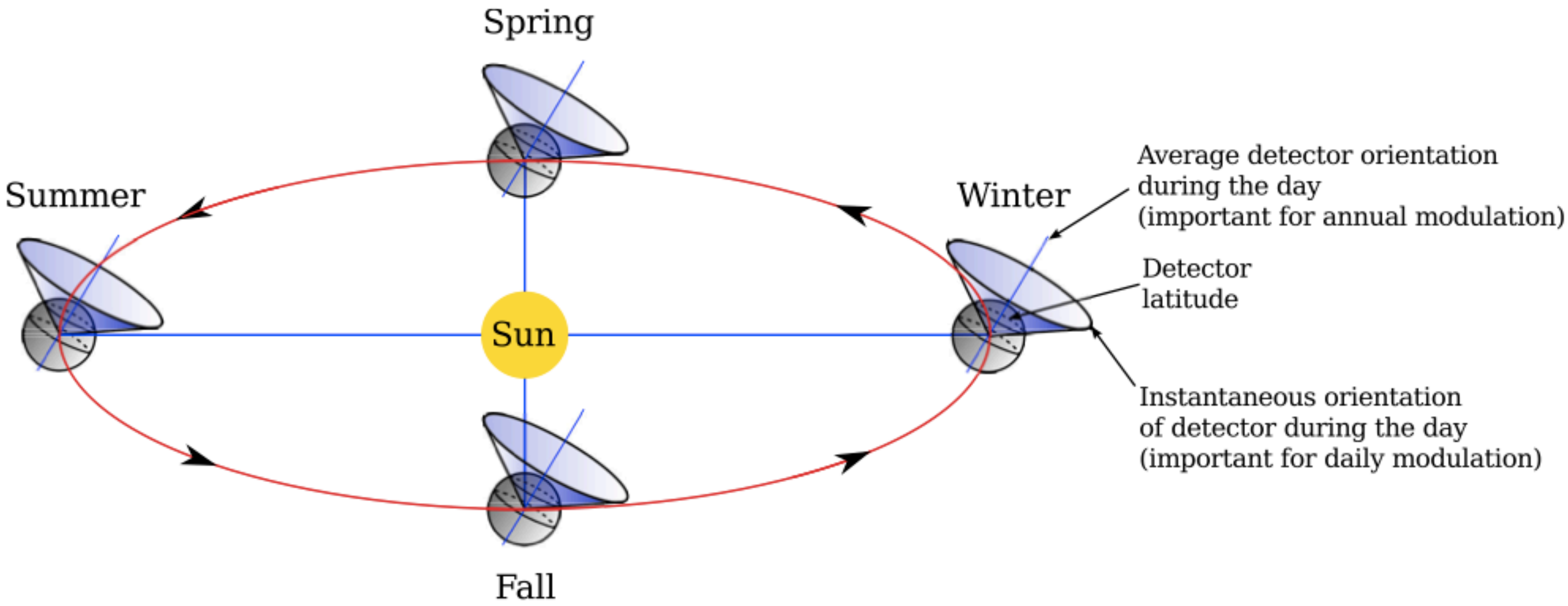
Many detectors only detect electronic excitations, so the quenching factor in the former case is larger

Modulation

Direction dependent quenching factors



Daily and annual modulation should be present, but other modulation frequencies can be also possible