Exploring ν signals in dark matter detectors

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in collaboration with:
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Outline

- Motivations
- Models
- Limits
- Modulation
- 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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Motivations

Solar neutrinos

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

Dark matter

- (Very) low threshold
- Small cross section
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Motivations

Solar neutrinos

- Low threshold
- Small cross section
- Low background
- Big detector
- Some unknowns, not much precision

Dark matter

- (Very) low threshold
- Small cross section
- Low background
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Make dark matter direct detection experiments multipurpose

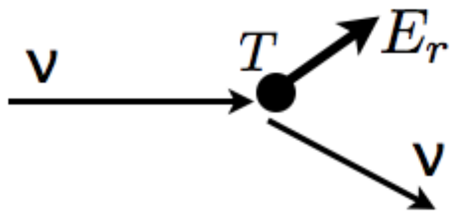
see also Pospelov 1103.3261, Pospelov Pradler 1203.0545

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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$s_w = \sin\theta_{weak}$ — neutrino energy — electron mass

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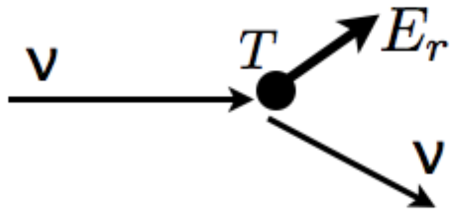

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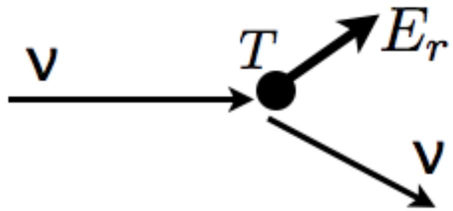

$$\frac{d\sigma_{\rm SM}^{\nu N}}{dE_r} = \frac{G_F^2 m_N F^2(E_r)}{2\pi E_\nu^2}\Big[(A^2 E_\nu^2 + 2AZ(2E_\nu^2(s_w^2 - 1) - E_r m_N s_w^2)$$

$$+ 4Z^2(E_\nu^2 + s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_N)) + s_w^2(E_r m_N - 2E_\nu^2)))\Big]$$

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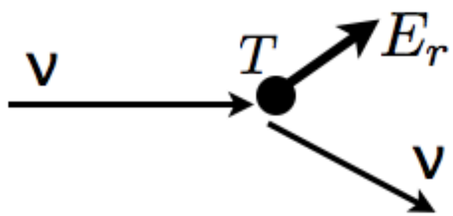

form factor

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mass number

$$+ 4Z^2(E_\nu^2 + s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_N)) + s_w^2(E_r m_N - 2E_\nu^2)))\Big]$$

atomic number — nucleus mass

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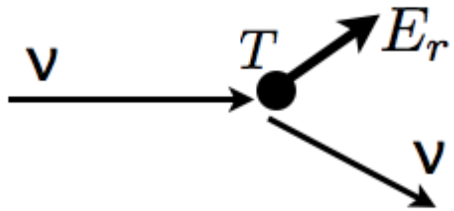

$$E_\nu^{\mathrm{min}} \approx \sqrt{m_T E_r/2}$$

form factor

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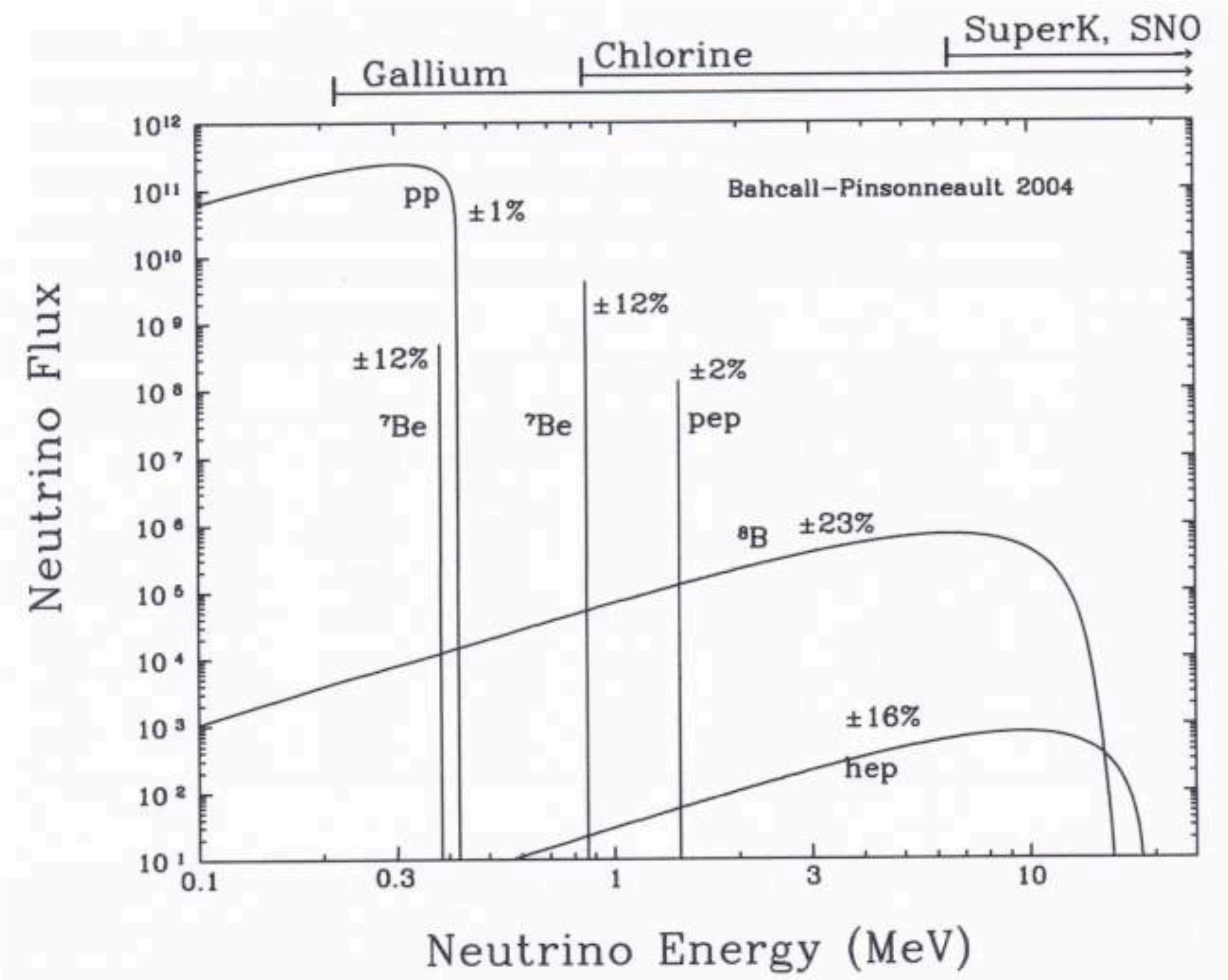

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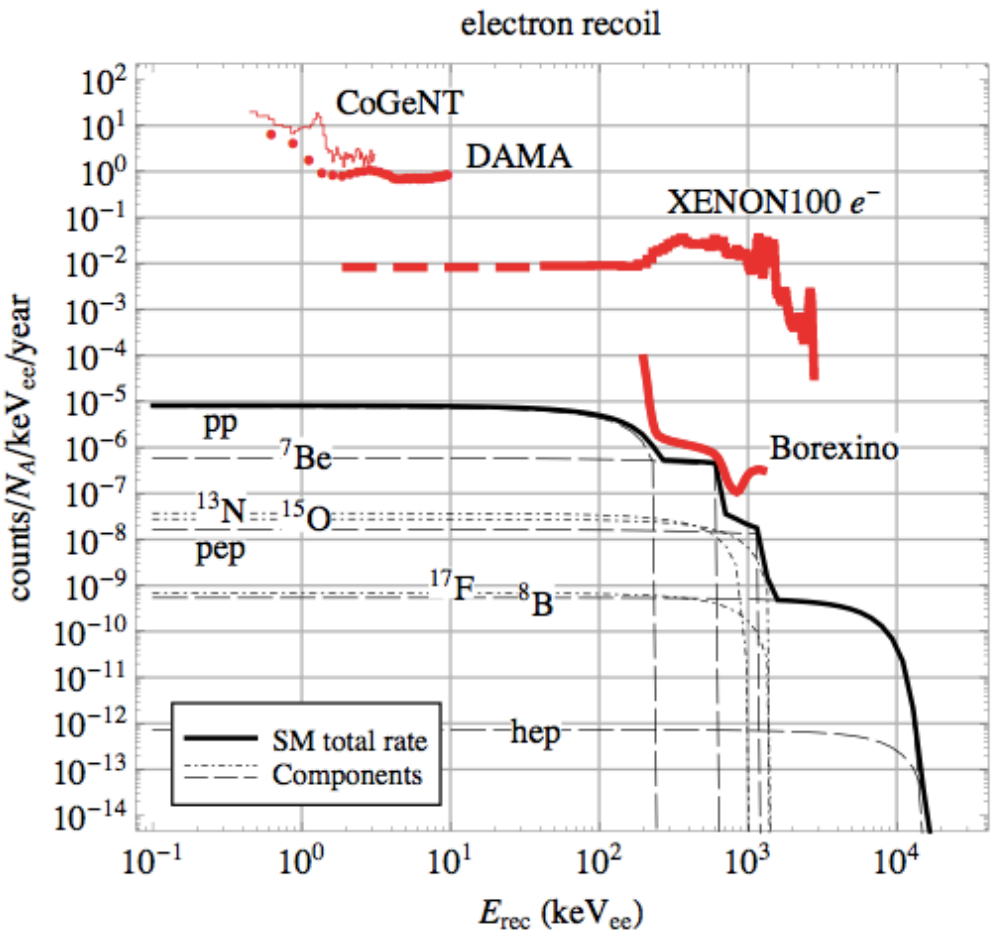
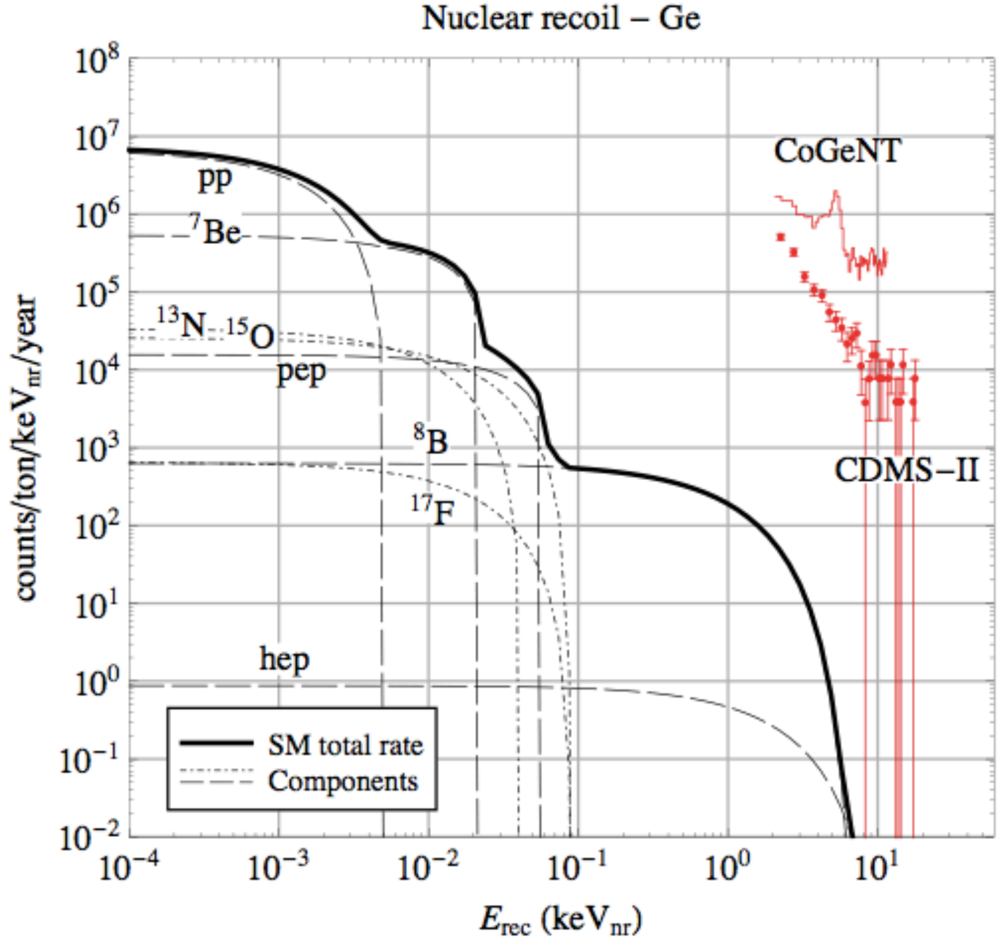
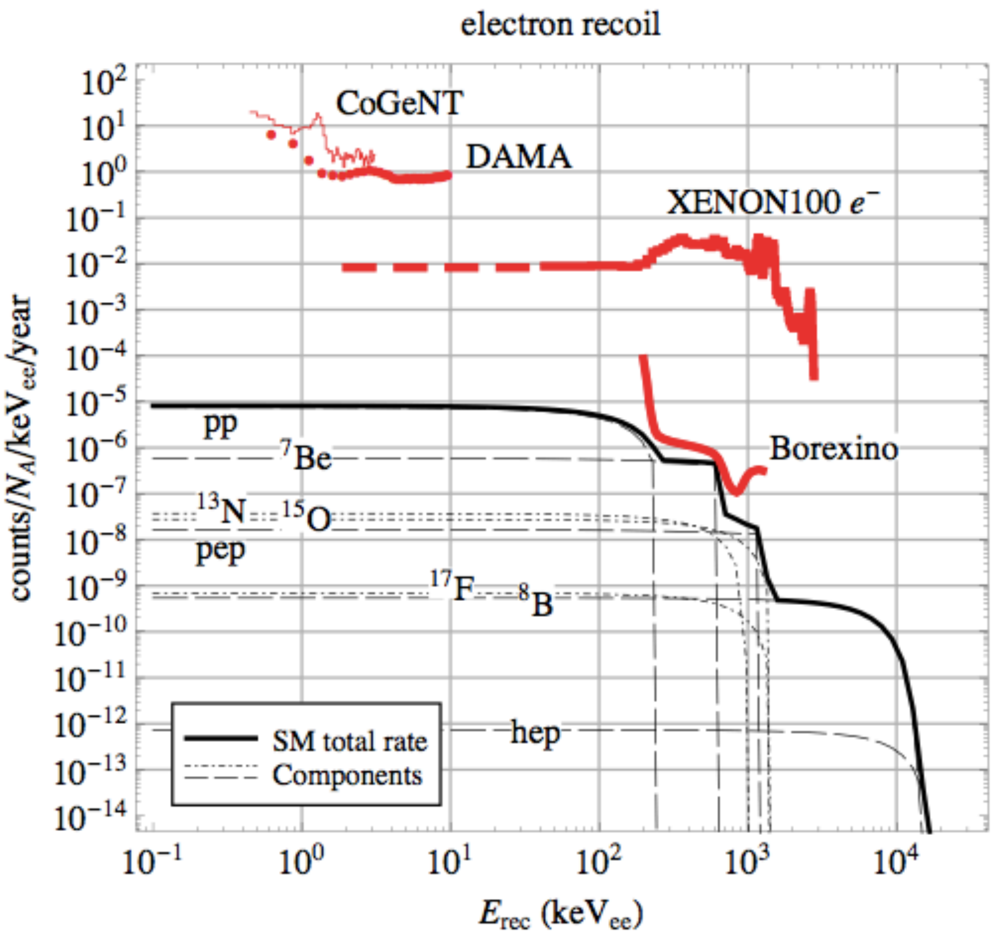
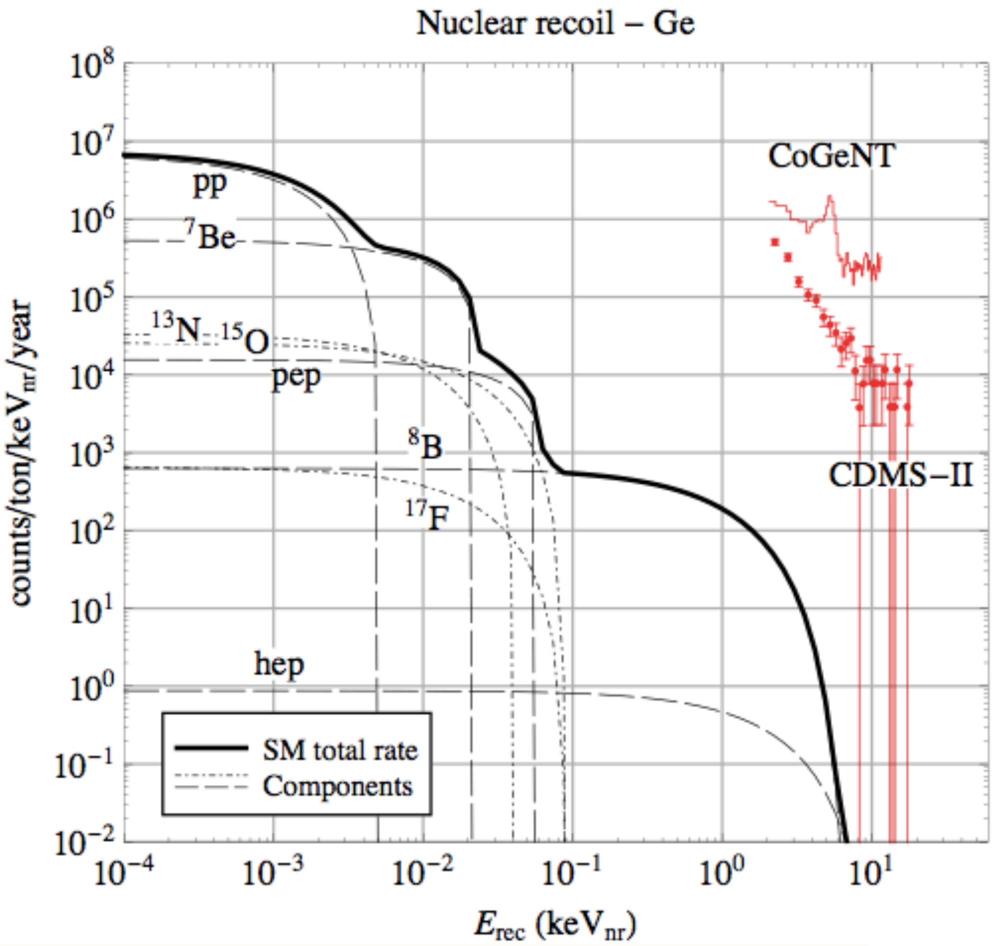




see also Gutlein et al 1003.5530

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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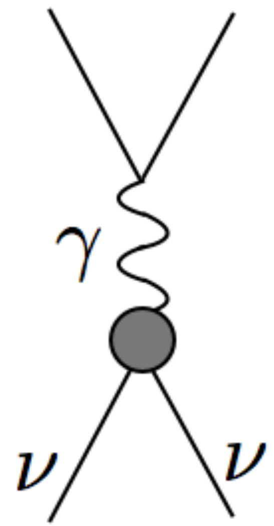
This could enhance the signal in dark matter direct detection experiments



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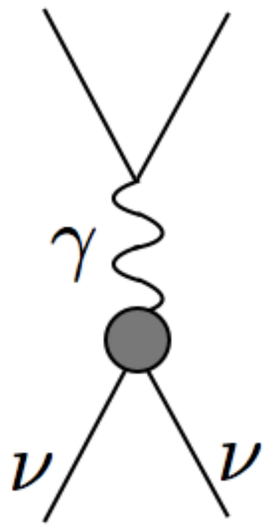

$$\sigma \sim \frac{1}{E_r} \longrightarrow$$ A low threshold means a higher rate!

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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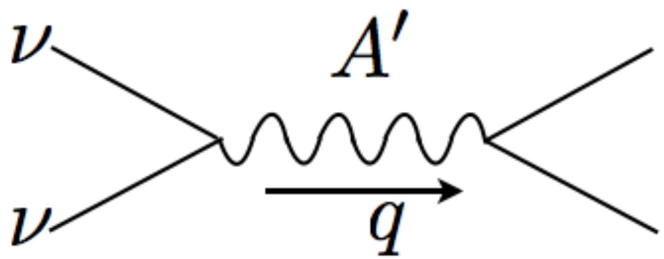

$$\sim \frac{1}{M_{A'}^2 - q^2} \qquad q^2 = -2E_r m_T$$

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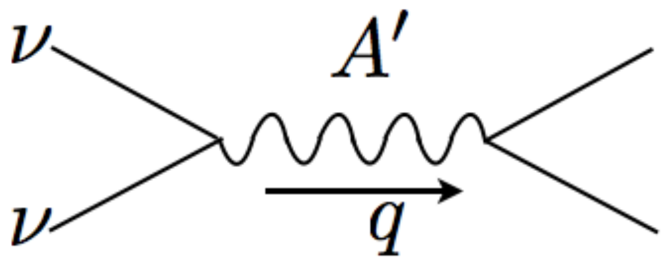


$$\sim \frac{1}{M_{A'}^2 - q^2} \qquad q^2 = -2E_r m_T$$

$$\sigma \sim \frac{1}{(M_{A'}^2 + 2E_r m_T)^2} \rightarrow$$

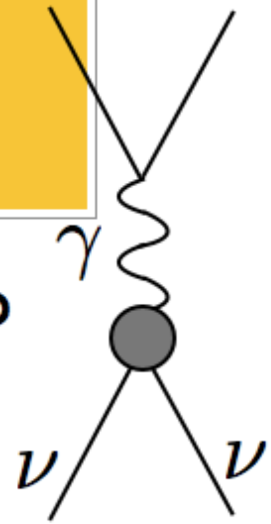
For light A', a low threshold means a higher rate!

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.

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

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

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

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

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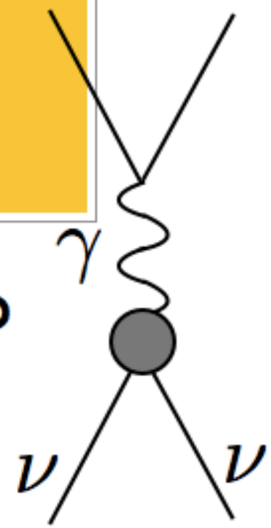

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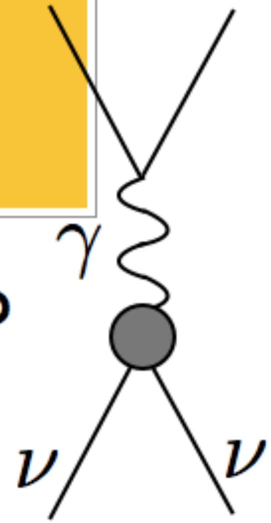

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Models

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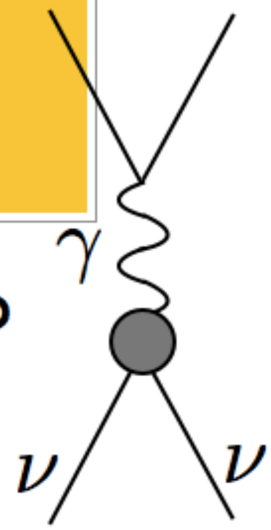

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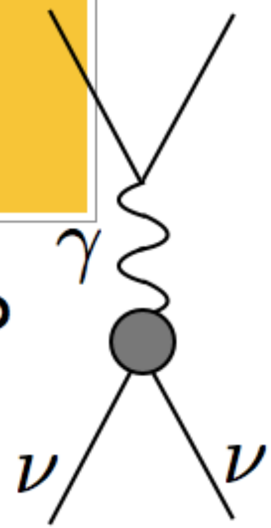

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For nuclear recoil

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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Dark photon

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The cross section depends mildly on the chiral structure of the A' couplings.

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

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We keep the neutrino momentum and mass, since later we will include heavy sterile neutrinos

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

Models

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Fifth force searches constrain the mass of the gauge boson to be above ~ 100 eV.
Thermal production in astrophysical objects "rule out" $1\,\mathrm{meV} \lesssim M_{A'} \lesssim 100\,\mathrm{MeV}$

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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These may be obtained from a seesaw

The cross section is the same as before, but with the replacement $g_{B-L} \to \sqrt{\epsilon e g'}$

coupling to electrons

Models

Barionic ν_s and gauged barion number

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

The limits are much weaker since the boson does not couples to leptons

The cross section is the same as before, but with the replacement $g_{B-L} \to g_B$ (and coherence factor)

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Neutrino matter potential is very important

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

Models

Barionic ν_s and gauged barion number

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

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

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Barionic ν_s and gauged barion number

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

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

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

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

$$\nu_s \to \gamma\nu_{act}$$

Heavy steriles - bounds from X-ray flux from galaxy clusters and CMB: avoid with low production in the early universe (low reheating temp.), chameleons, or fast invisible decay modes Smirnov Zukanovich-Funchal PRD 74 (2006), Nelson Walsh PRD 77 (2008), Feldman Nelson JHEP 0608 (2006)

Oscillation physics - production and modulation

Electron scattering

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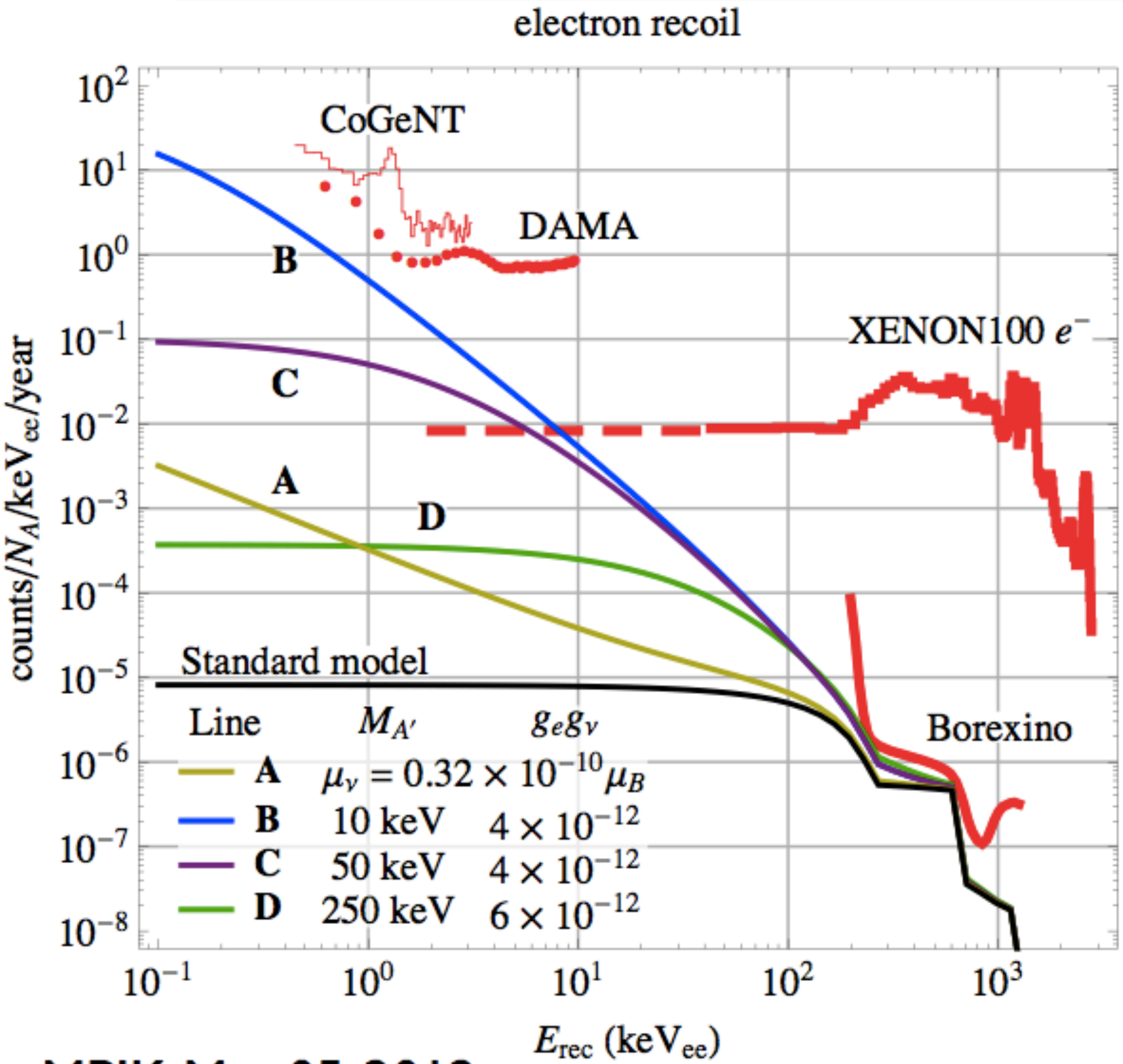

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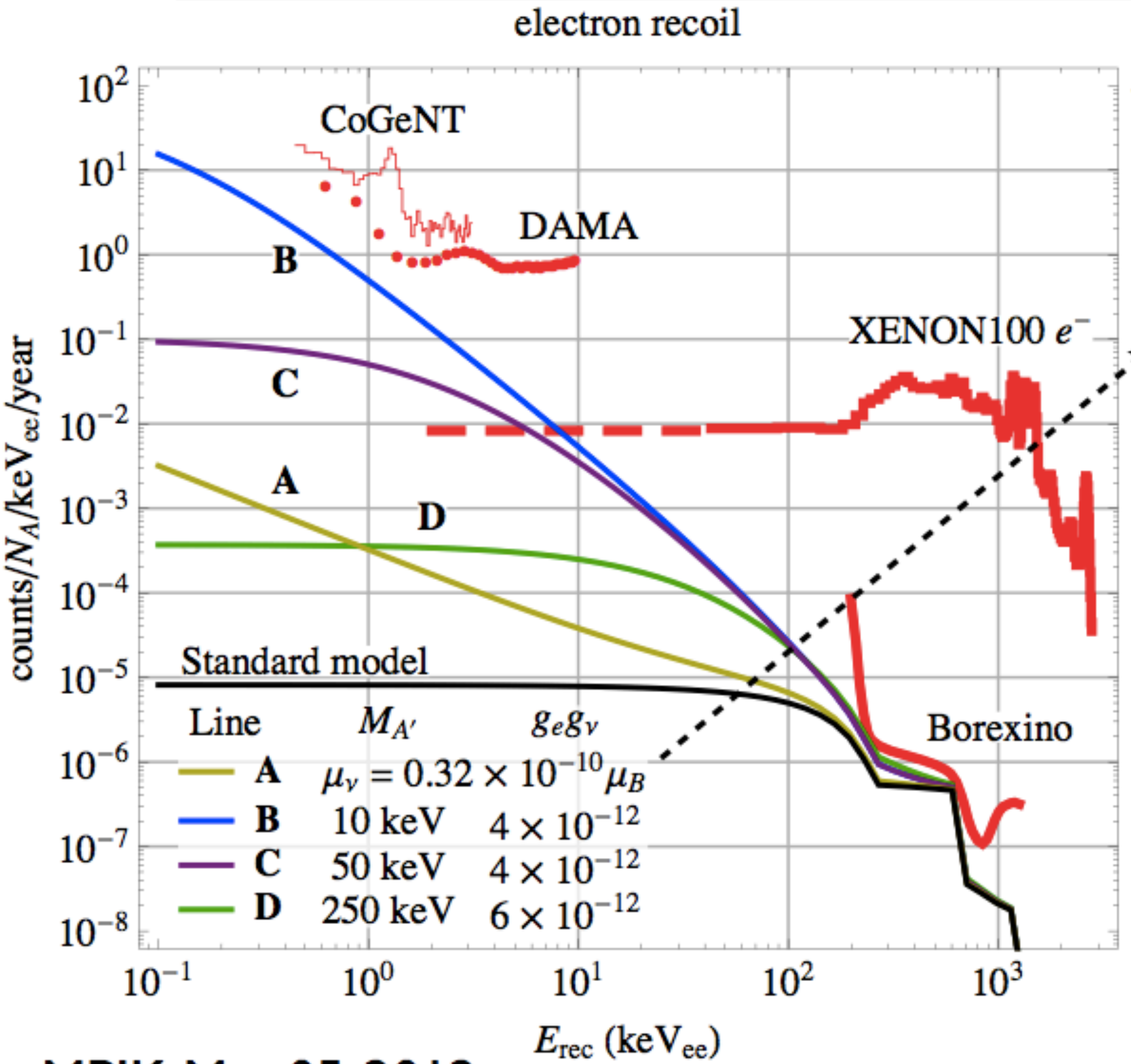

ν magnetic moment

Future DM detectors may enter this regime

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

Electron scattering

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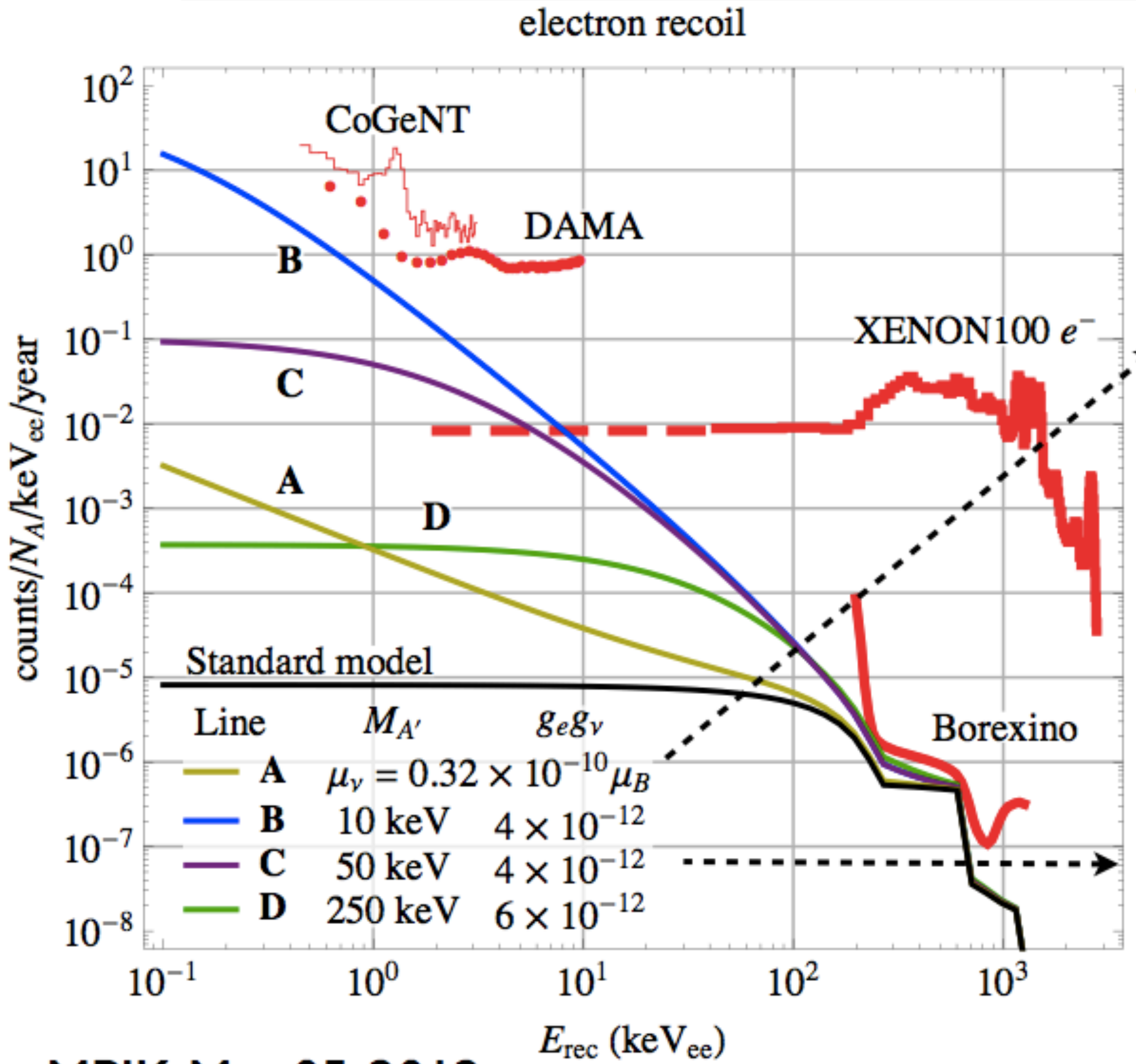


ν magnetic moment

Future DM detectors may enter this regime

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

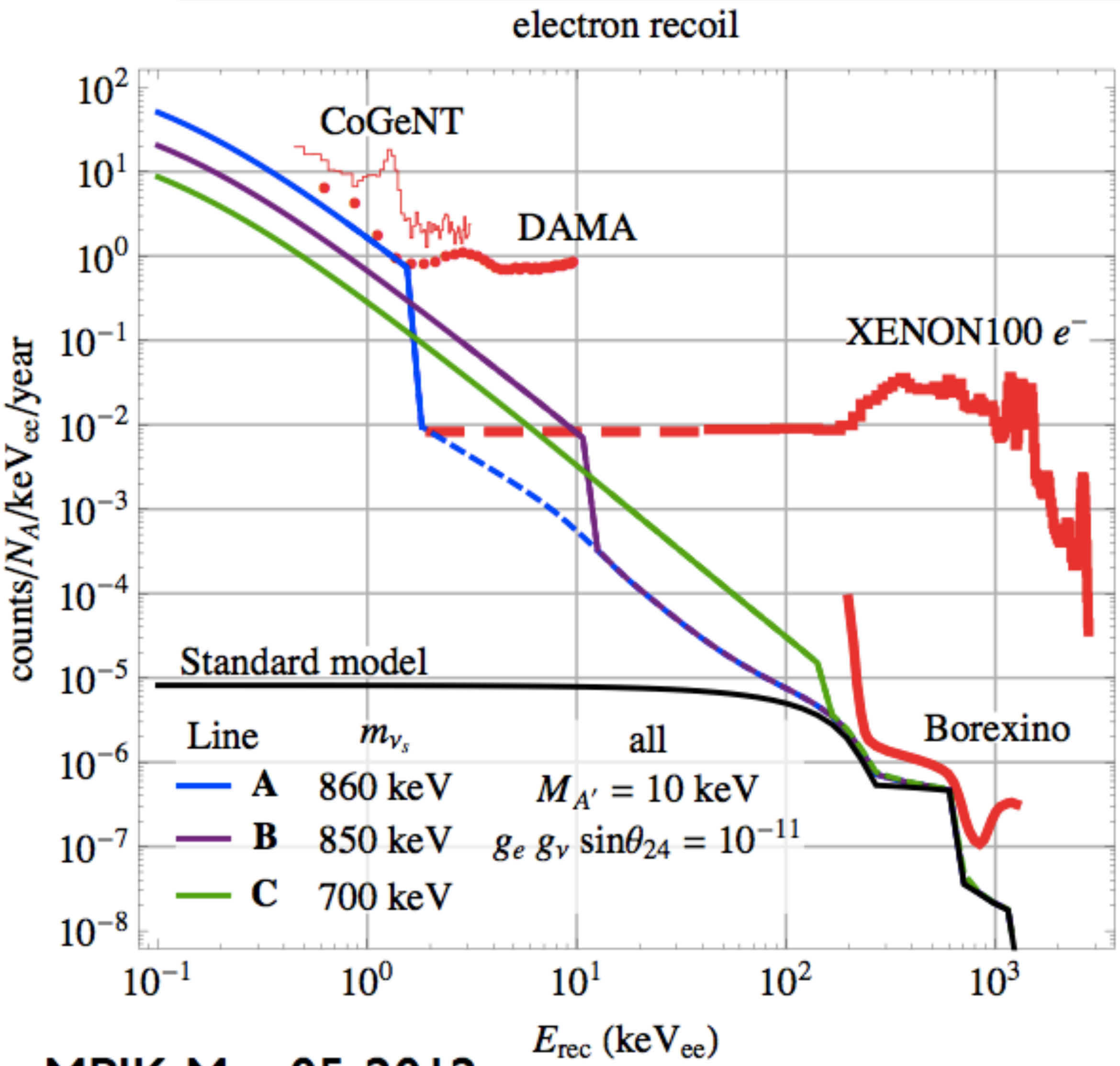
Curves B, C and D

$U(1)_{B-L}$: GEMMA, active ν

$U(1)' + \nu_s$: richer, heavy ν_s

Electron scattering

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



<u>All curves</u>

U(1)' + ν_s

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

Nuclear scattering

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

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

Low recoil energy: coherence - cross section is enhanced by the mass number

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Low recoil energy: coherence - cross section is enhanced by the mass number

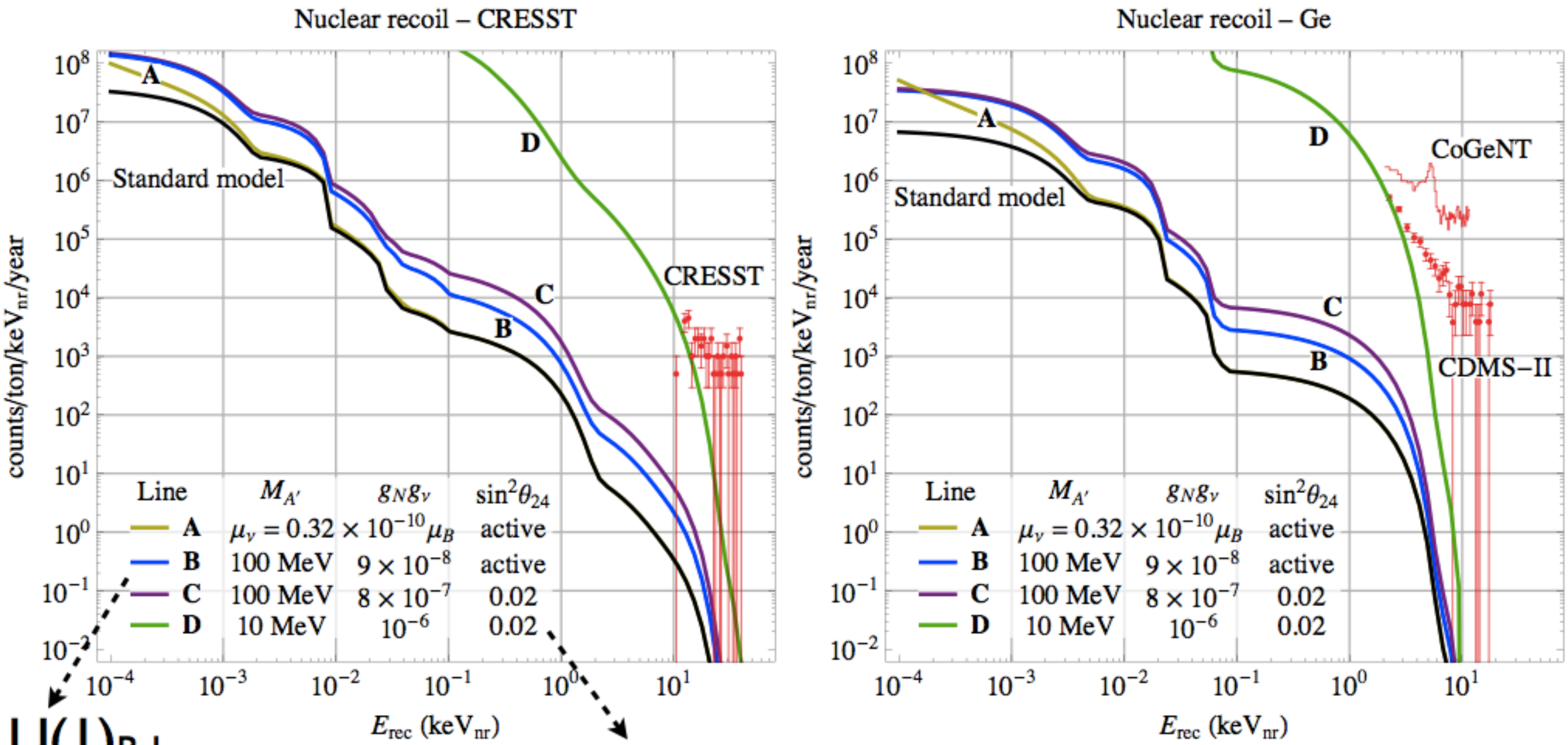
Threshold $E_\nu^{\min} \approx \sqrt{m_T E_r/2}$:
keVnr recoil needs MeV neutrinos – only high energy tail of ^8B component is important

$q^2 = -2E_r m_T \Rightarrow$ higher $M_{A'}$

Oscillation physics - production and modulation

Nuclear scattering

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

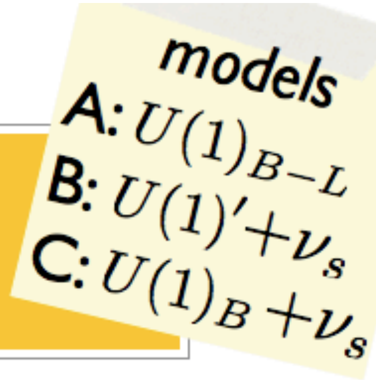


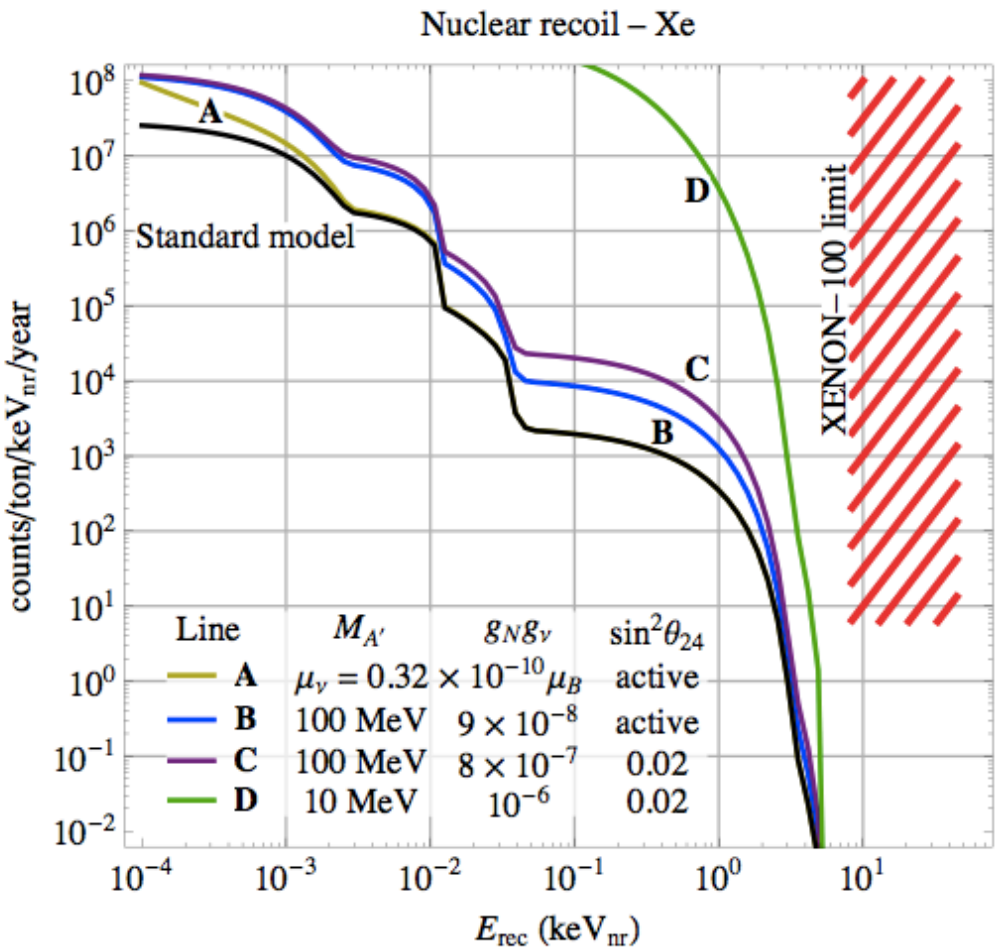
$U(1)_{B-L}$

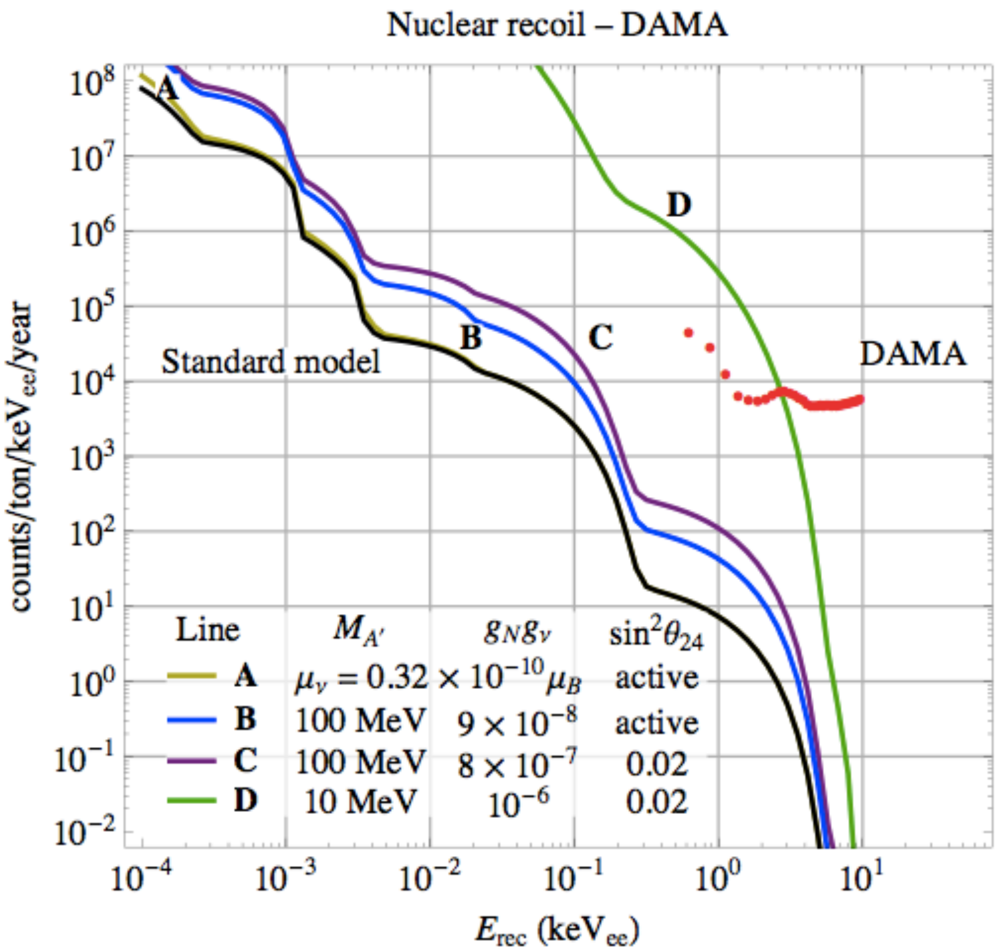
$U(1)_B + \nu_s$

see also Pospelov Pradler 1203.0545

Nuclear scattering







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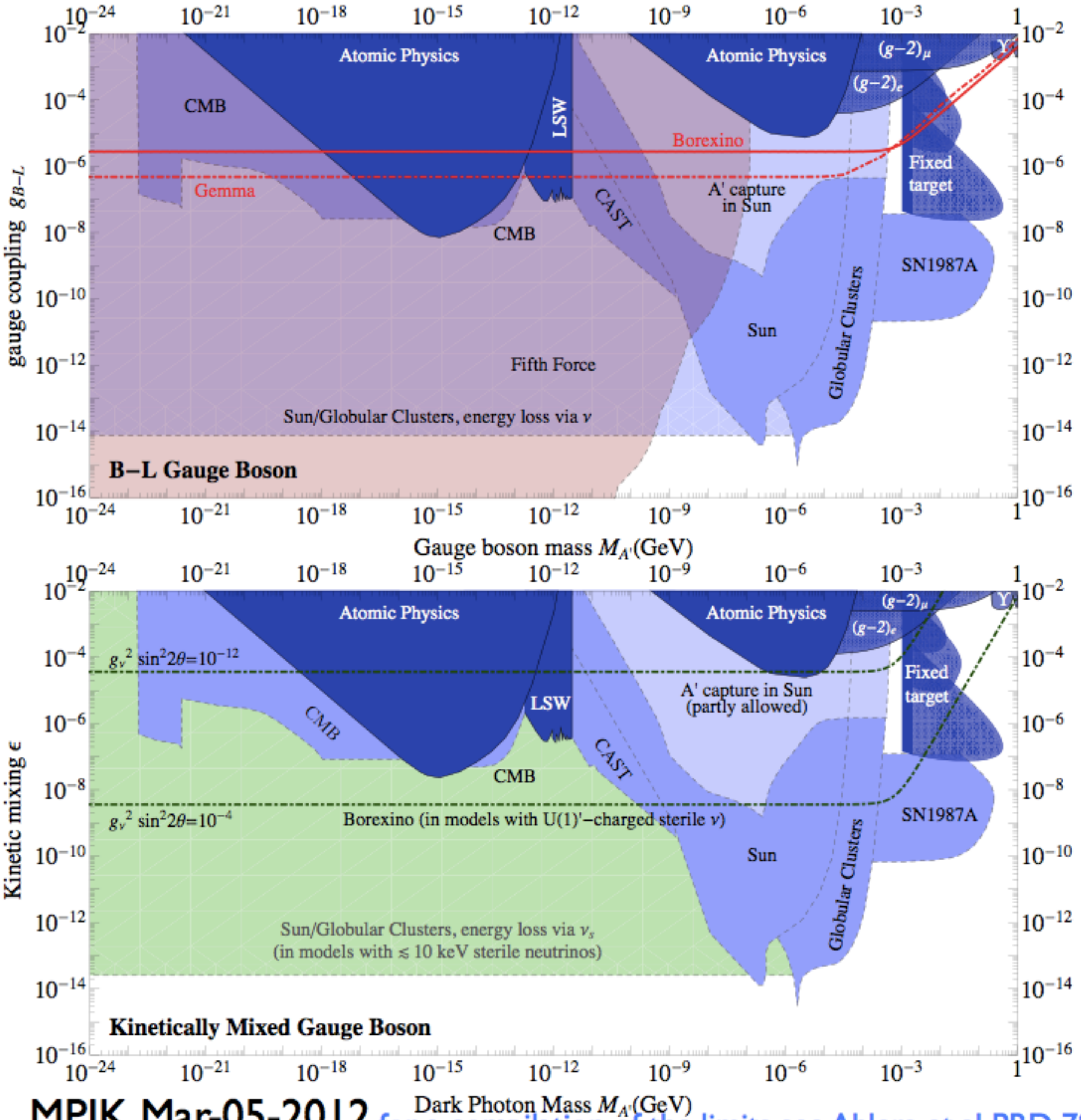
Limits



models
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Avoided by chameleons

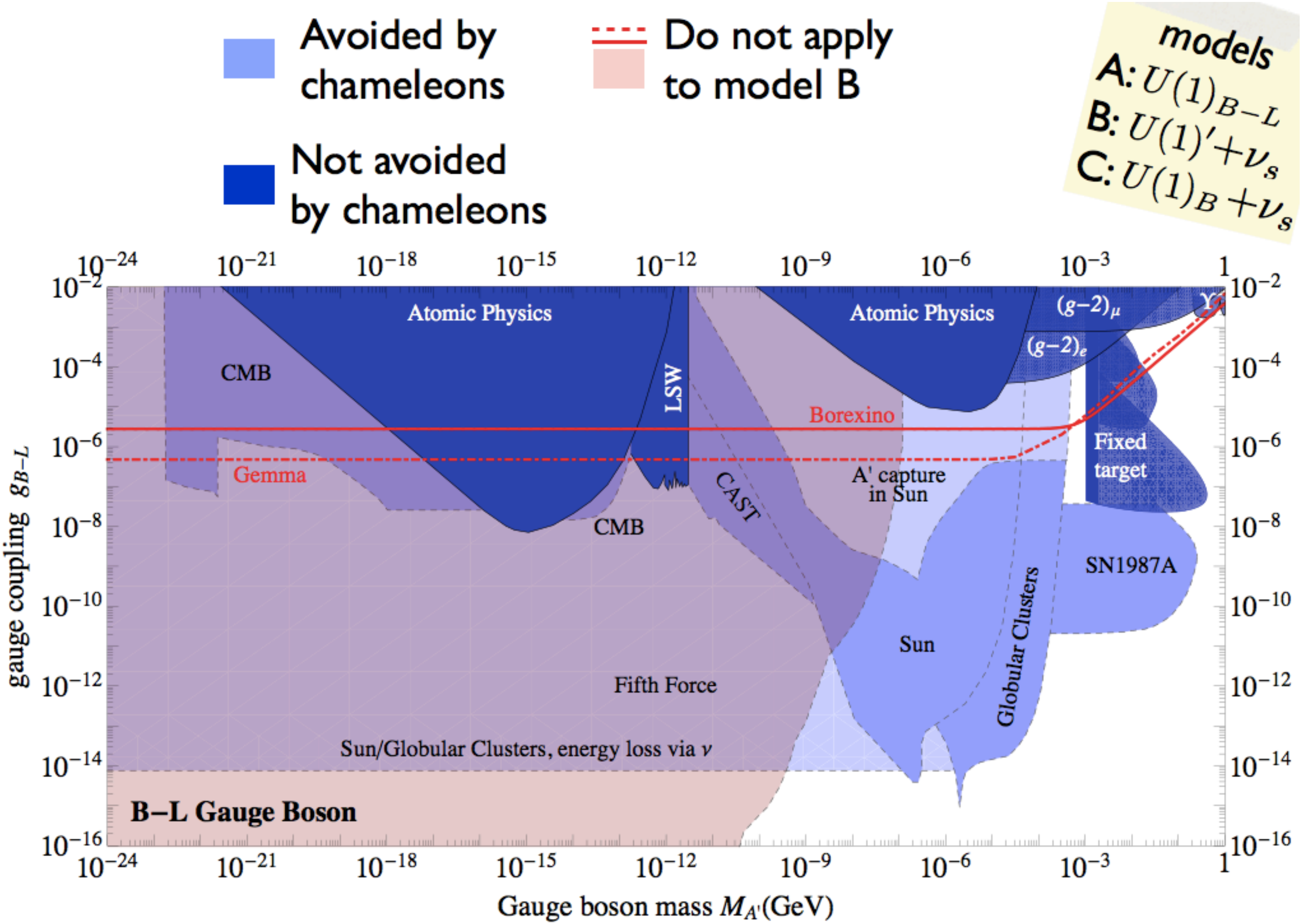
Not avoided by chameleons

Do not apply to model B

light ν_s with U(1)' charge

Go to
Bounds part 1
Bounds part 2
Bounds summary

MPIK Mar-05-2012 for a compilation of the limits see Ahlers et al PRD 78 (2008) PAN Machado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A' capture in Sun
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Sun/Globular Clusters, energy loss via ν
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gauge coupling g_{B-L}
Gauge boson mass $M_{A'}$(GeV)

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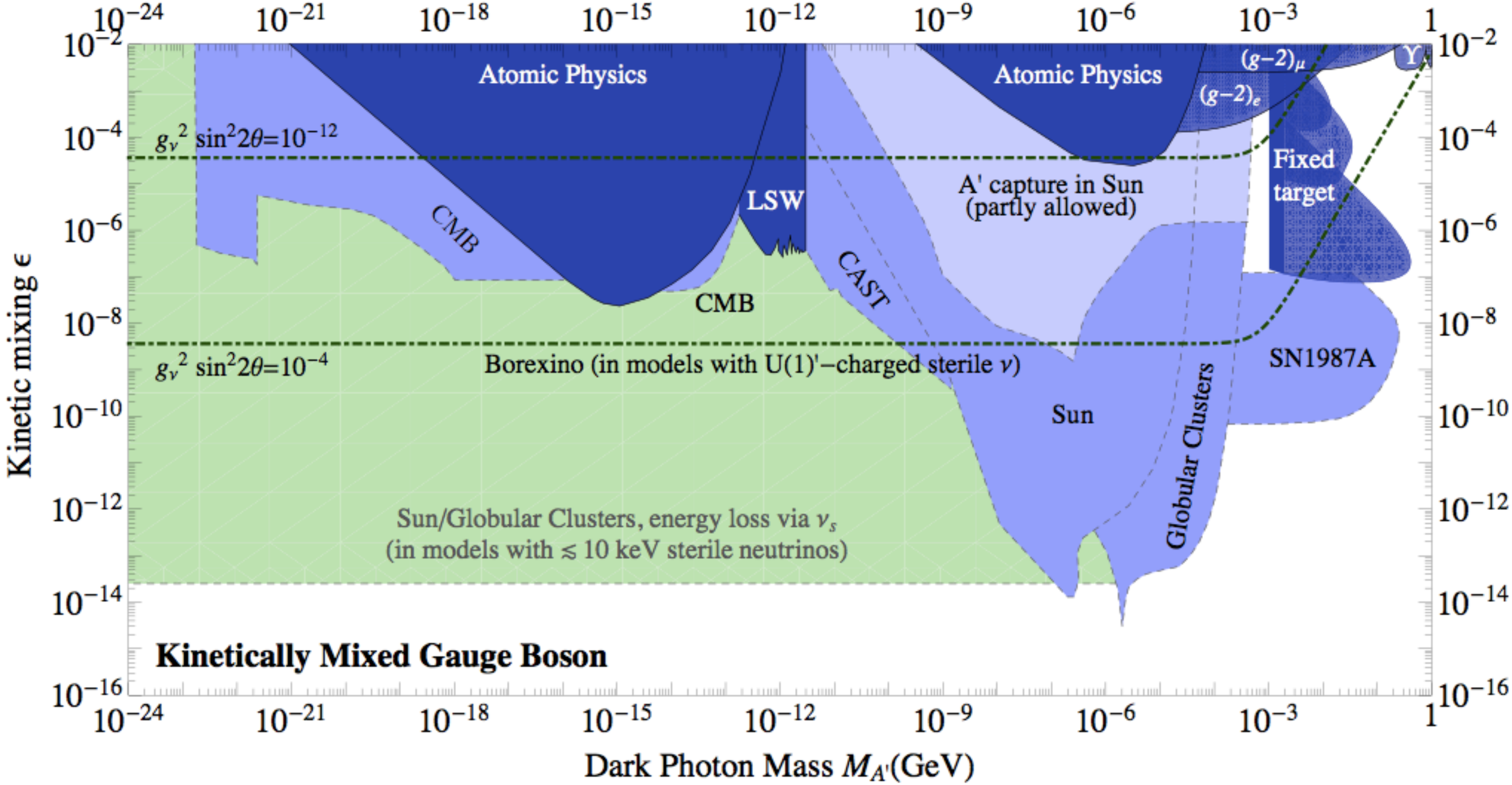

Bounds - I

models
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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)

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

Υ decays

$$\Upsilon \to \gamma A' \hookrightarrow \mu^+\mu^-$$

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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Atomic physics constraints

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

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)

Go to plot

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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

Go to plot

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

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

Cooling of stars in globular clusters

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

Bounds - II

models
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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)

Bounds - II

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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.

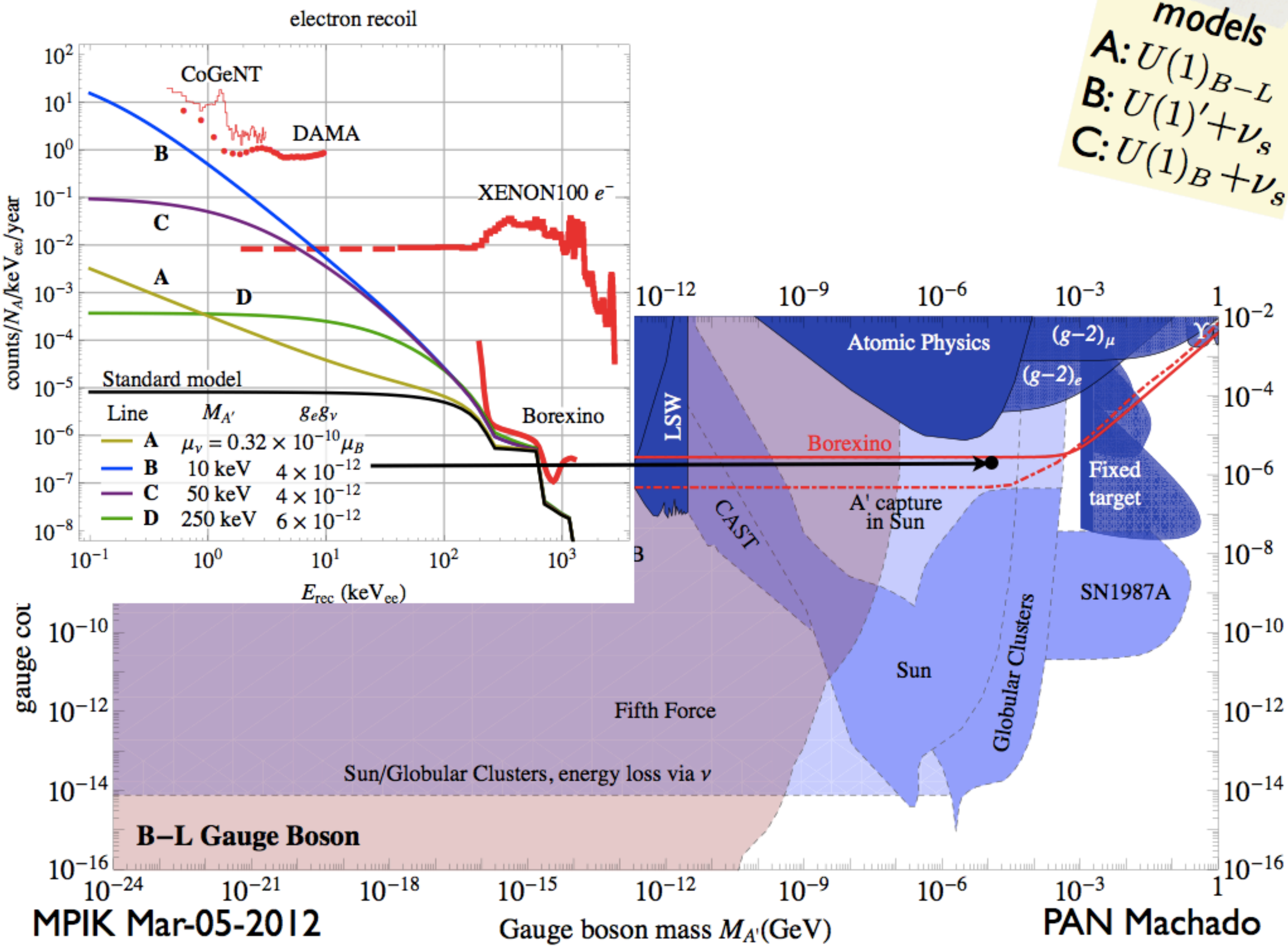
Bordag et al Phys Rept 353 (2001), Bordag et al *Advances in the Casimir effect* (2009), Adelberger et al PRL 98 (2007), Adelberger et al PPNP 62(2009)

Go to plot

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	✓	✗	✓



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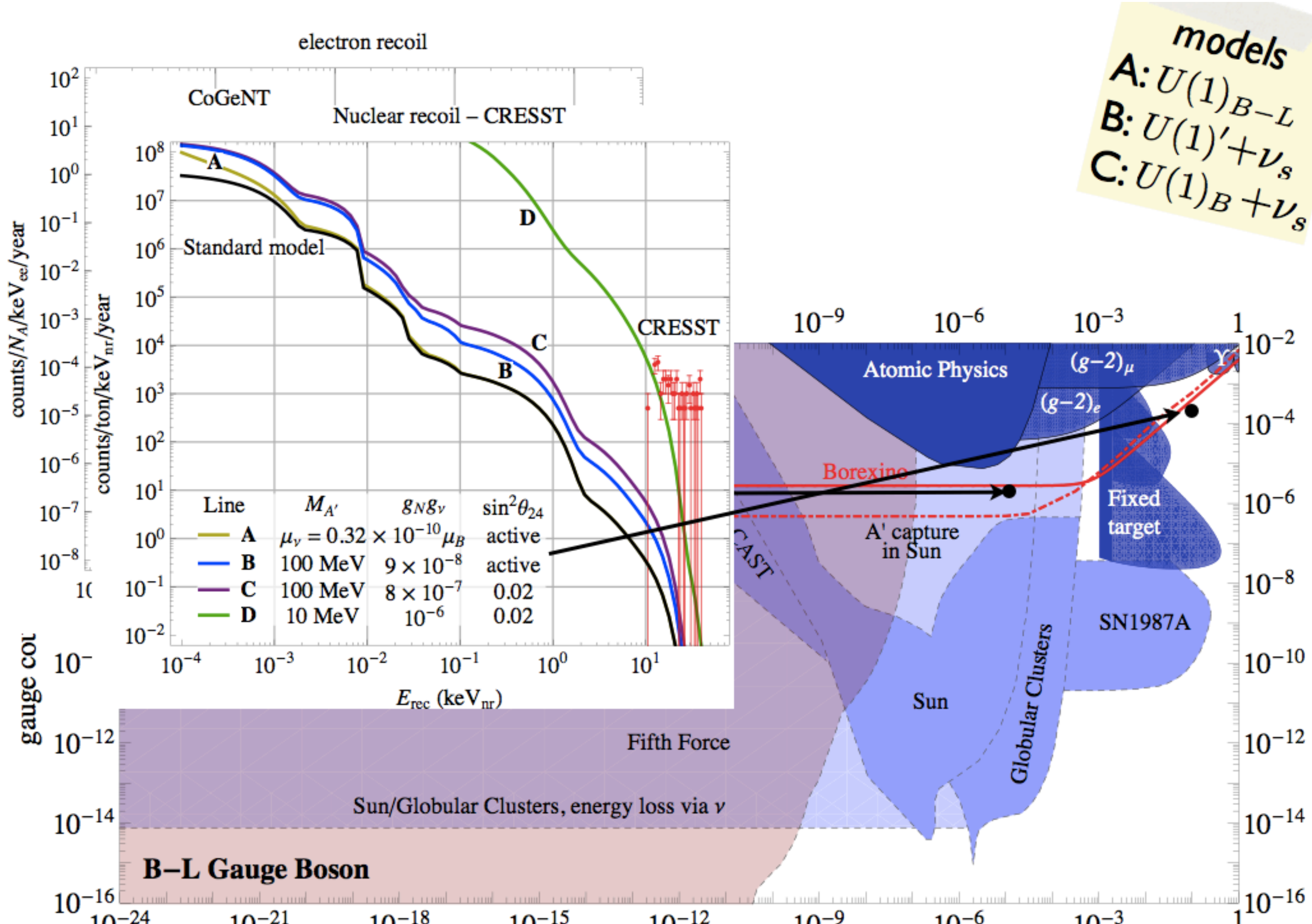
models
A: $U(1)_{B-L}$
B: $U(1)'+\nu_s$
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electron recoil
CoGeNT
Nuclear recoil – CRESST
Standard model
CRESST
counts/N_A/keV$_{ee}$/year
counts/ton/keV$_{nr}$/year
E_{rec} (keV$_{nr}$)
Line | $M_{A'}$ | $g_N g_\nu$ | $\sin^2\theta_{24}$
A | $\mu_\nu = 0.32 \times 10^{-10}\mu_B$ | active
B | 100 MeV | 9×10^{-8} | active
C | 100 MeV | 8×10^{-7} | 0.02
D | 10 MeV | 10^{-6} | 0.02
Atomic Physics
$(g-2)_\mu$
$(g-2)_e$
Borexino
A' capture in Sun
Fixed target
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Sun/Globular Clusters, energy loss via ν
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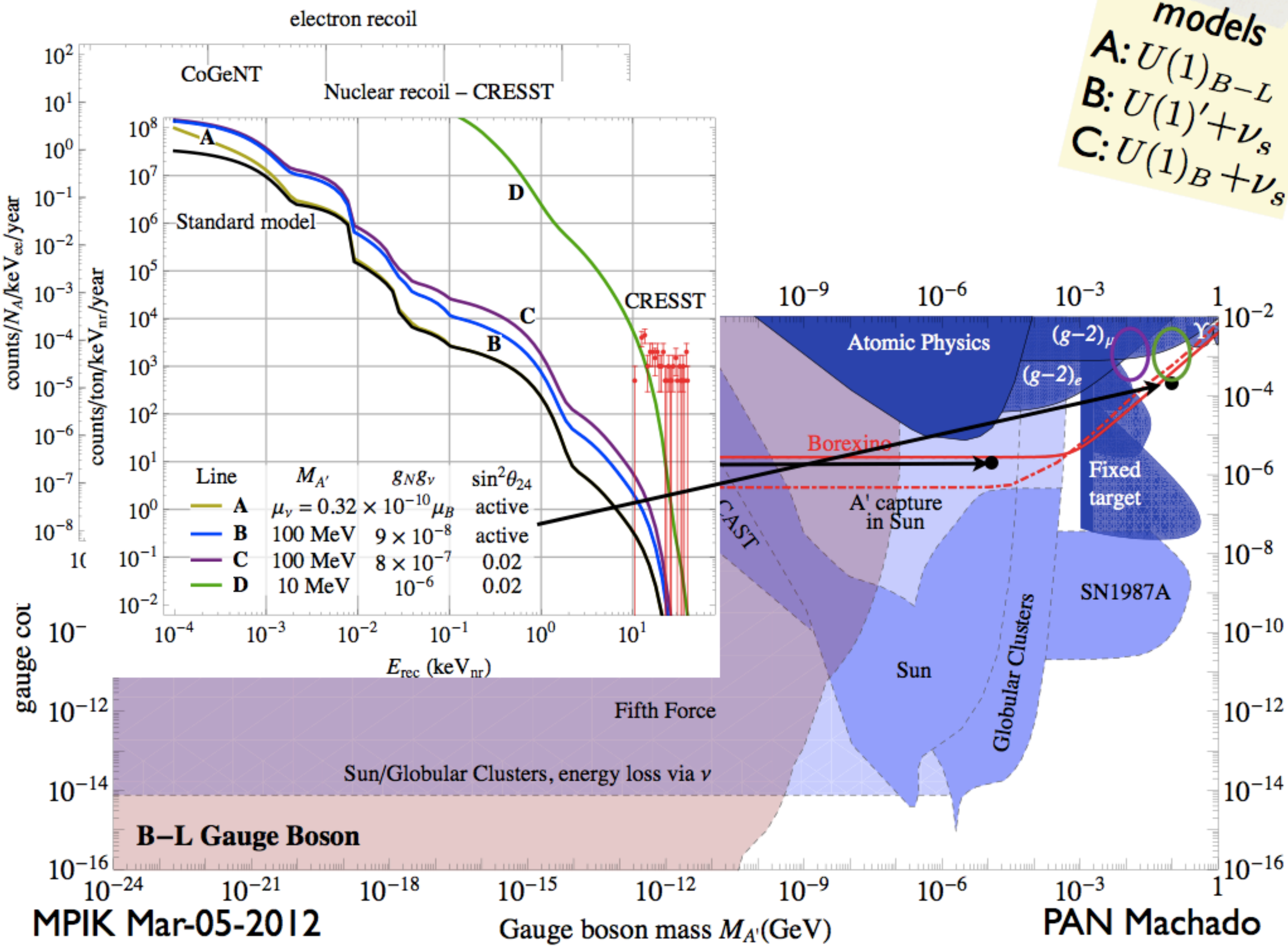

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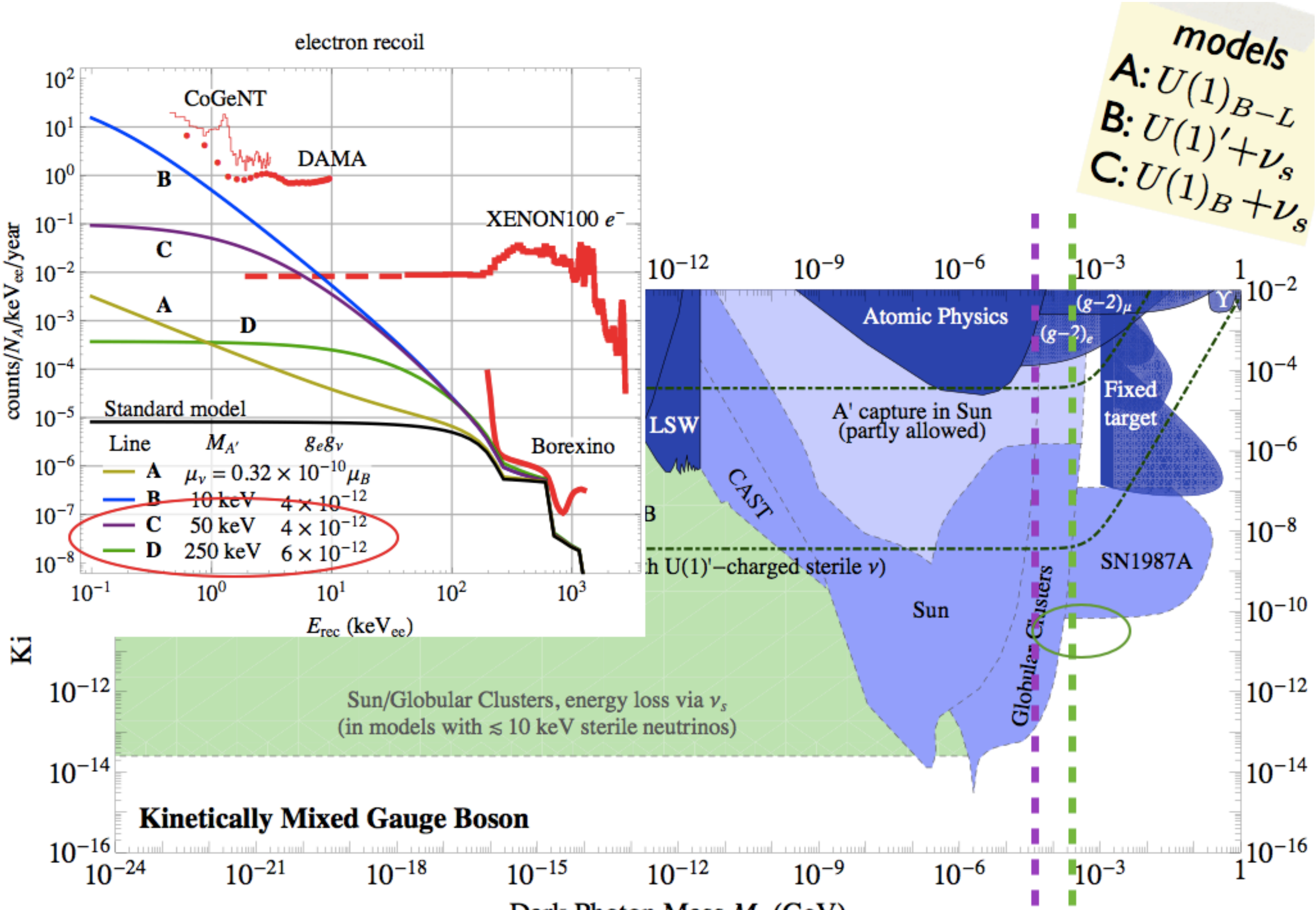

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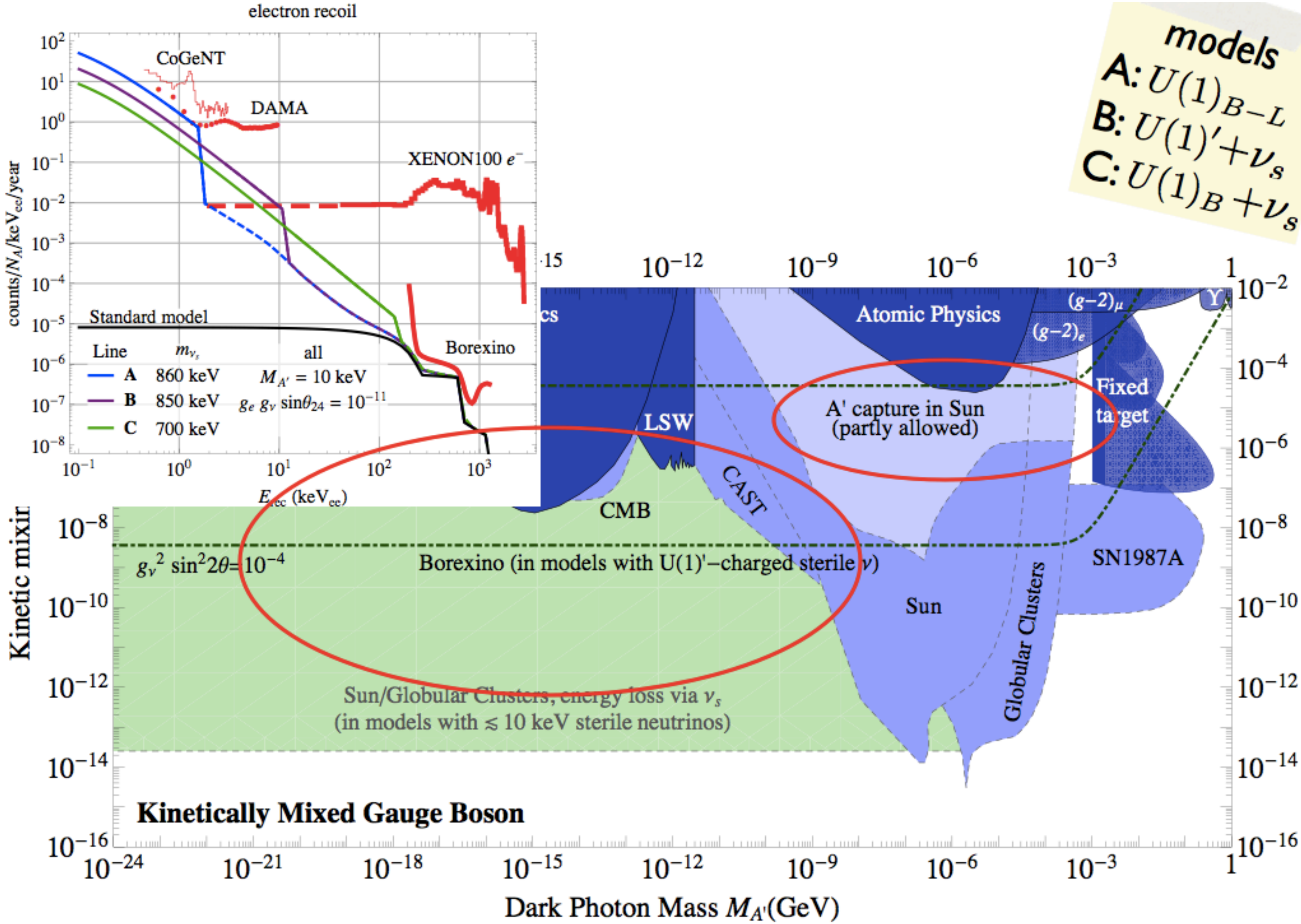

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Modulation

Earth-Sun distance
Neutrino oscillations in vacuum
Earth matter effects
Absorption in the Earth
Direction dependent quenching factor

Modulation

Earth-Sun distance

Earth's orbit is elliptical

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

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Earth-Sun distance

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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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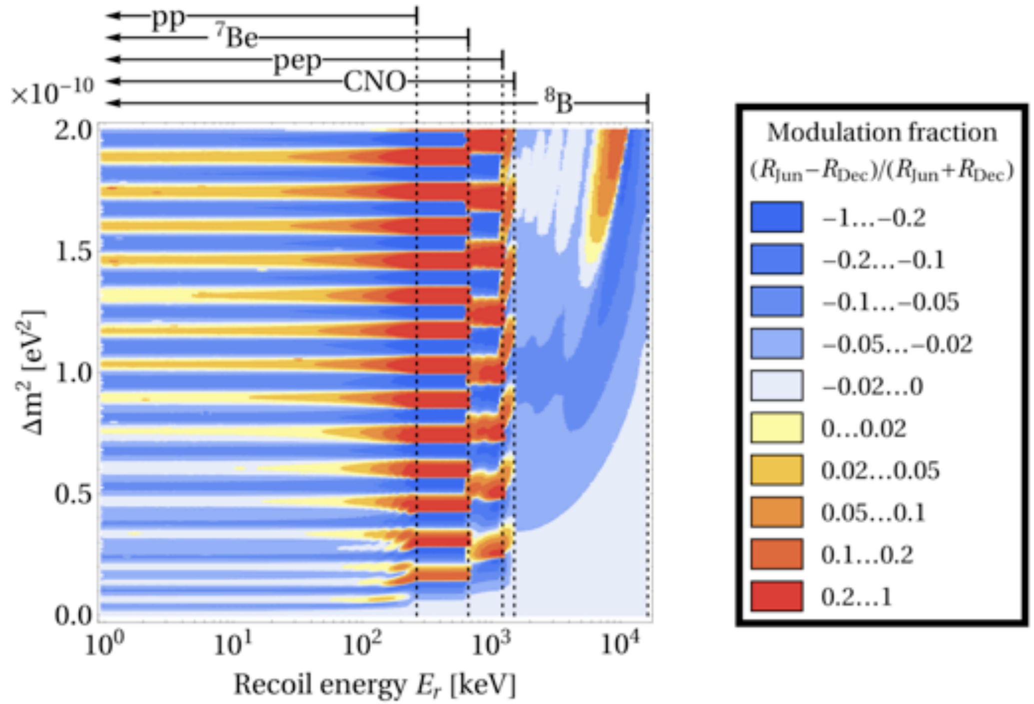
R is the count rate in Jun or Dec



Modulation

Diurnal and annual modulation from Earth matter effects

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A: $U(1)_{B-L}$
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$U(1)_B$ + 2 steriles

Strong matter effects can lead to day-night asymmetry

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

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

The daily modulation modulation could be used to distinguish this scenario from the others

If $L_{osc} \sim 1$ km and large matter potential, there can be a resonance, and then even the depth of the detector will be important...

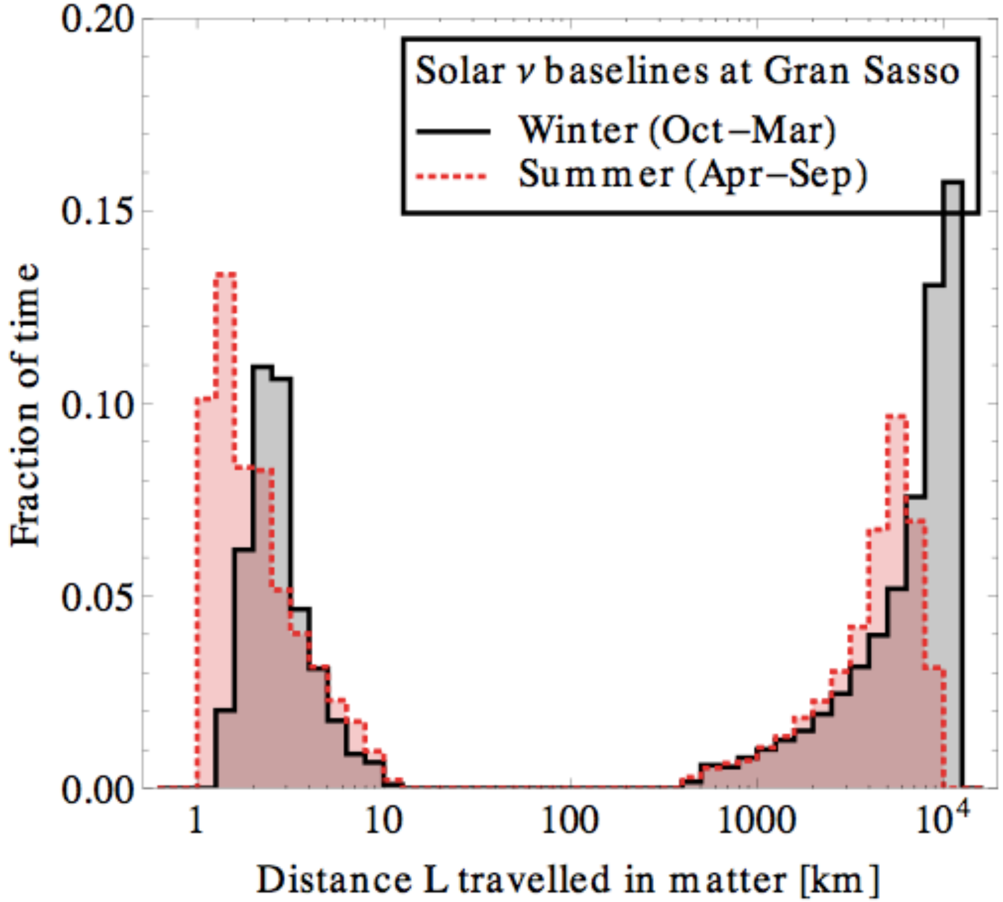
Modulation

Zenith angle dependency of Earth matter effects

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

If L_{osc} ~ 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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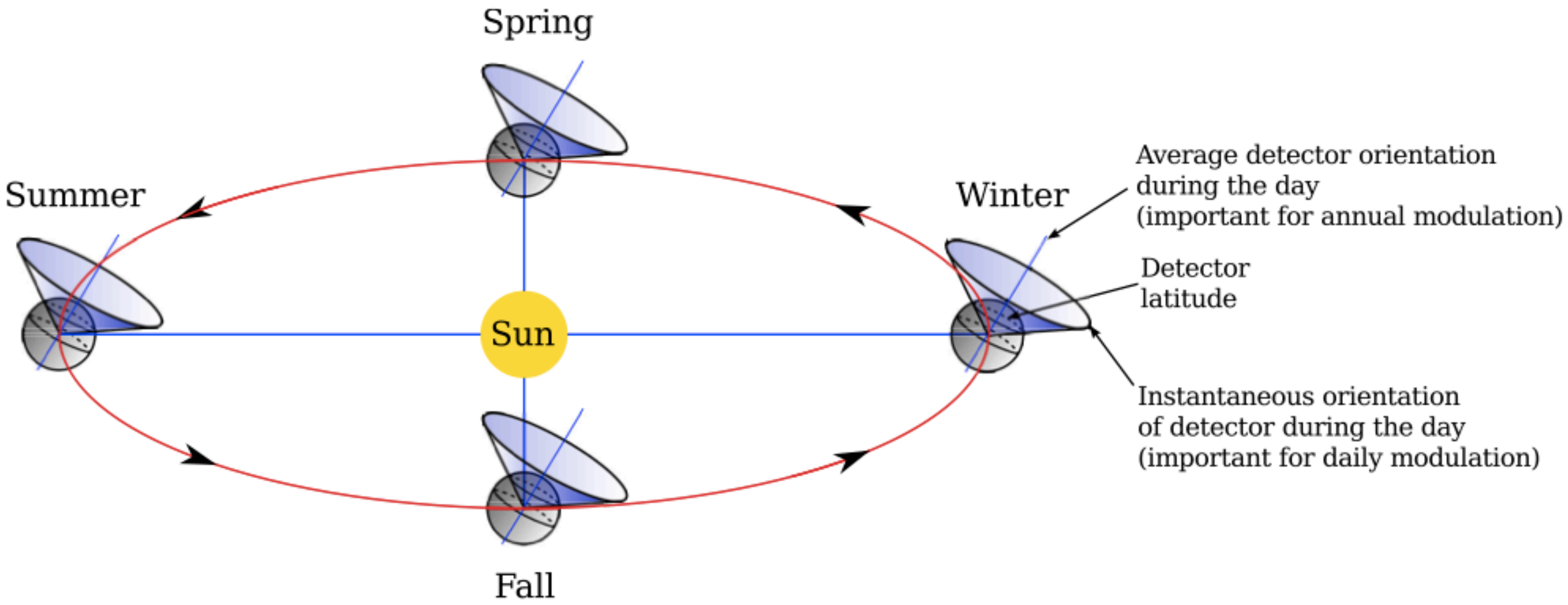
Many detectors only detect electronic excitations, so the quenching factor in the former case is larger

Modulation

Direction dependent quenching factors



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

Conclusions

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There is a rich phenomenology of standard and non-standard solar neutrino signals in dark matter direct detection experiments

Light mediators can lead to neutrino-electron and neutrino-nuclear scattering rates much higher than in the SM, specially if there are sterile neutrinos charged under the gauge group, without violating any experimental bound

Also, interesting signal modulations can arrive in these types of models

Conclusions

Because of their low threshold, DM experiments can be complementary to dedicated neutrino experiments when searching for new physics

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Thank you!