Dark Matter as a Portal to New Physics
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Online

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asia pacific center for theoretical physics

Direct detection window to (light) new physics

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MultiDark
Multimessenger Approach for Dark Matter Detection

Outline

1. Direct (dark matter) detectors are **excellent probes for new physics**...

   SuperCDMS results on low-mass DM

   ... so good that they will soon start seeing (solar) neutrinos.

2. The resulting **neutrino floor** is sensitive to new neutrino physics.

   Supernovae constraints can determine how high it can be.

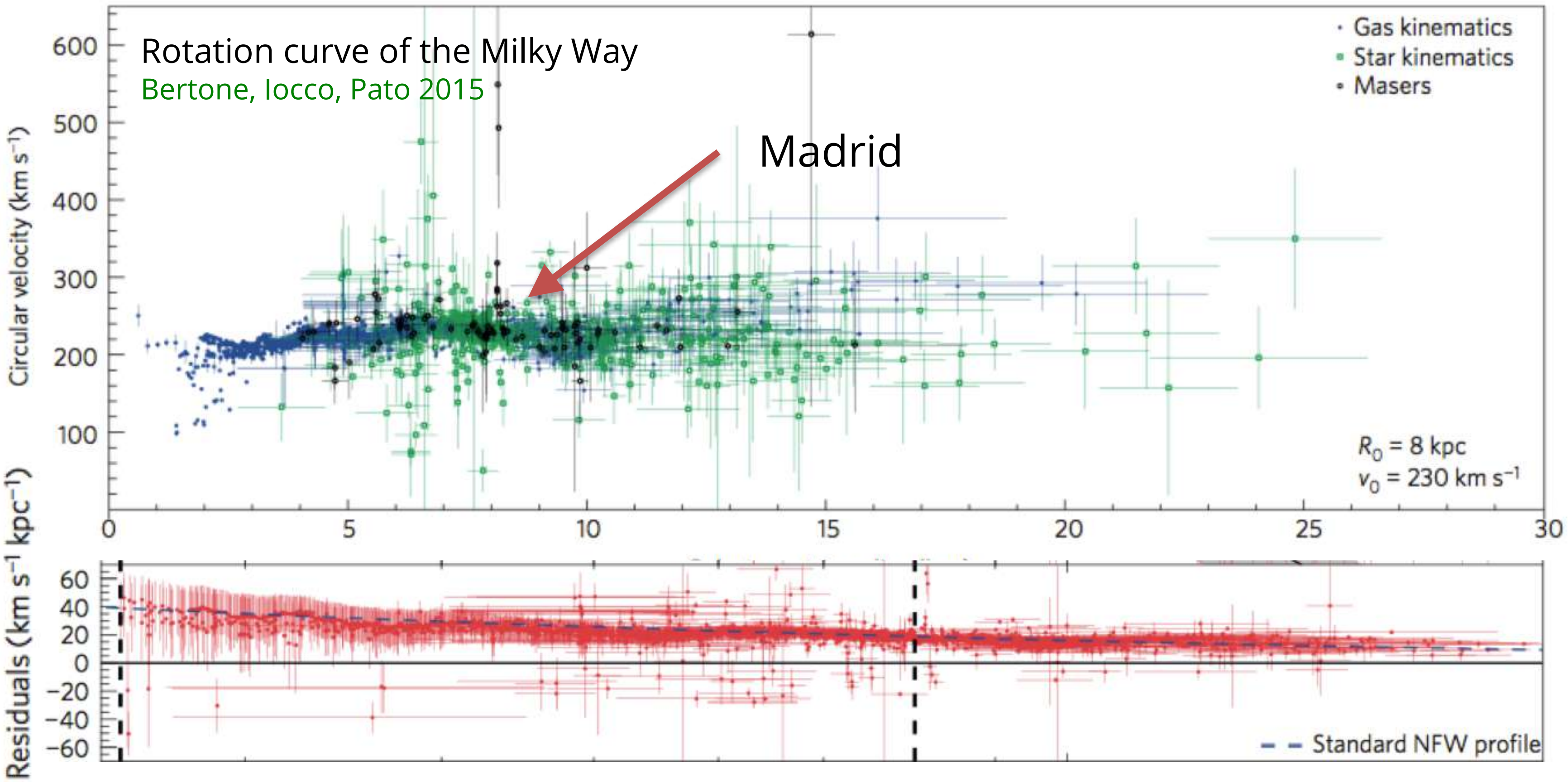
   DGC, Cermeño, Pérez-García, Reid (in progress)

3. Direct detection experiments can constrain new physics in the neutrino sector.

   Example in a gauged $U(1)_{L_\mu - L_\tau}$ and relation to the muon **anomalous magnetic moment.**

   Amaral, DGC, Foldenauer, Reid 2006.11225

There is Dark Matter in **Madrid**

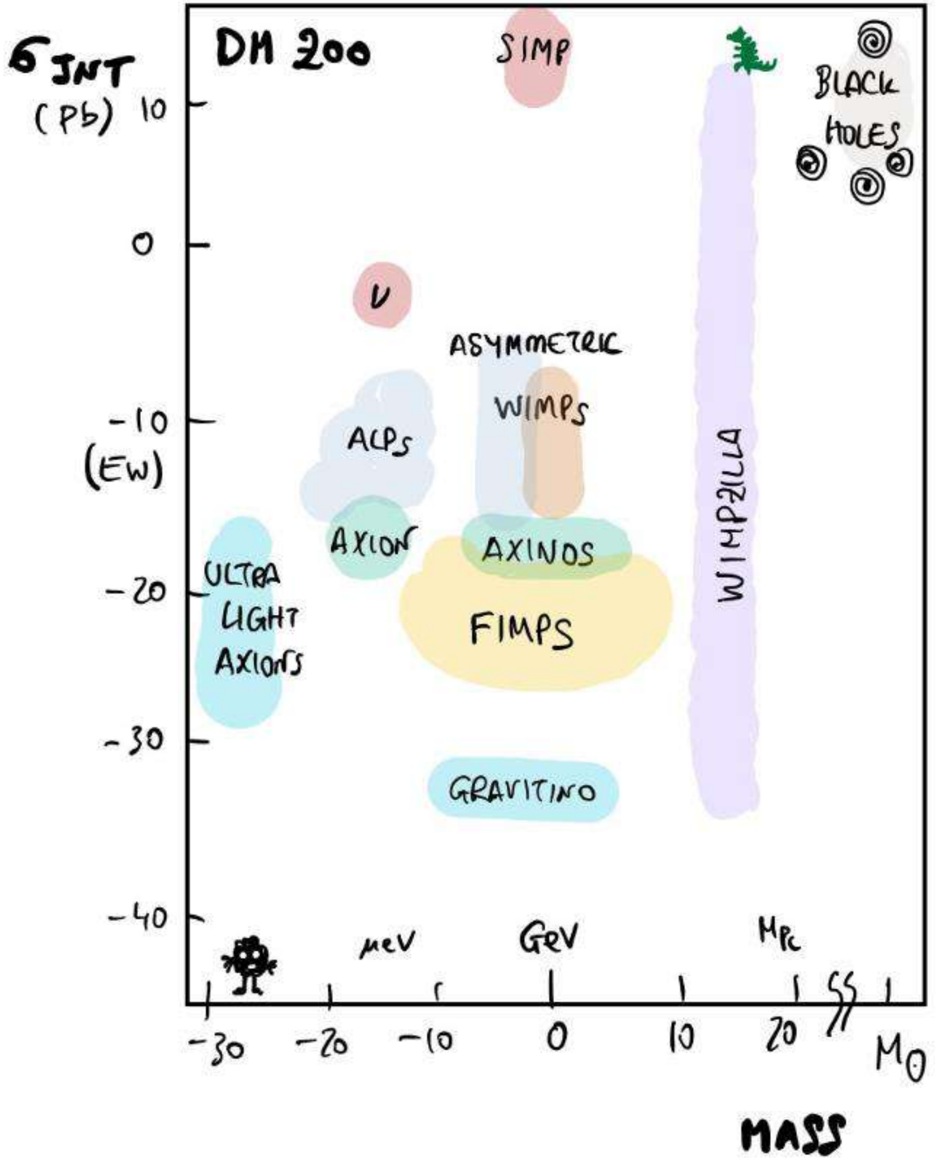


Rotation curve of the Milky Way

Bertone, Iocco, Pato 2015

Madrid

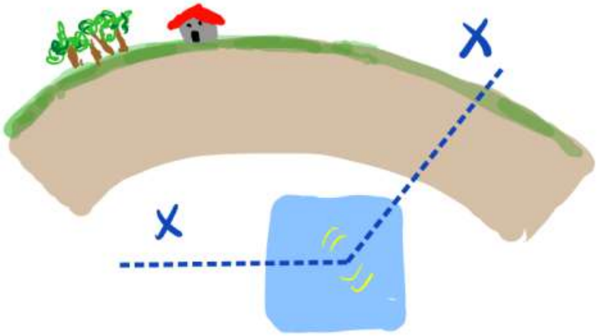
A theorist's PARADISE.... an experimentalist's PURGATORY



Direct Detection experiments

(Underground*) detectors to look for "invisibles"

- weakly-interacting (that traverse the Earth)
- Neutral (or millicharged)
- Cosmological or astrophysical origin
- Stable enough



Ionisation
Scintillation
Phonons (heat)
Bubble nucleation

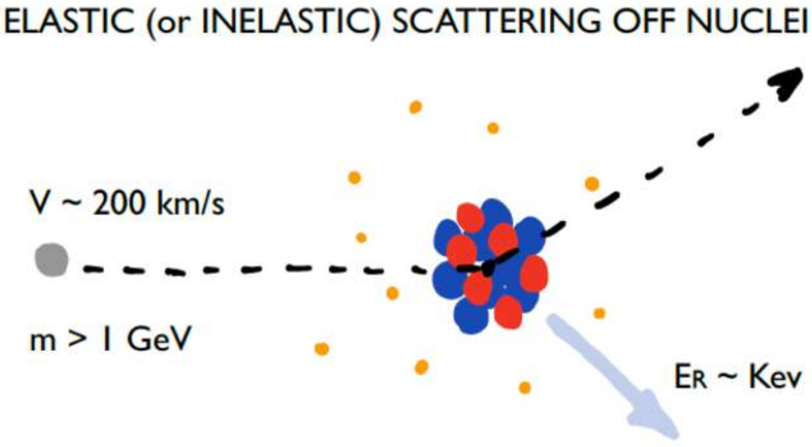
Interactions are (to say the least) rare

- Background attenuation (cleanliness + shielding)
- Increasing target size
- Increasing search window (**lower energy thresholds**)

Background/signal discrimination

- Discriminate nuclear recoils (NR) and electron recoils (ER)
- Morphology of the signal (energy spectrum)
- Time-dependence (modulations)
- Directionality

DIRECT DARK MATTER SEARCHES:
What can we measure?



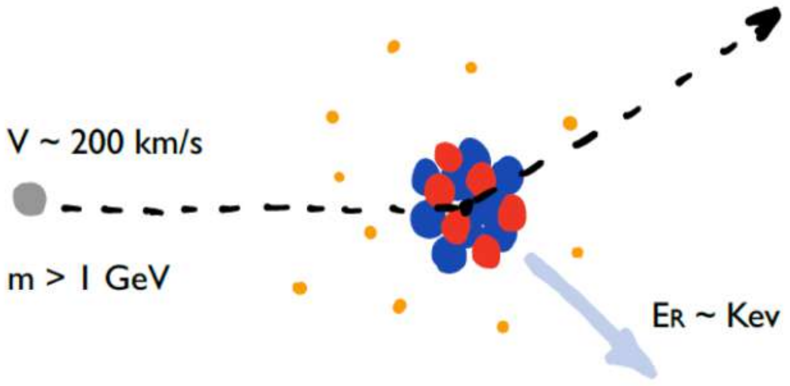
$$E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta^*)}{m_N}$$

NUCLEAR SCATTERING

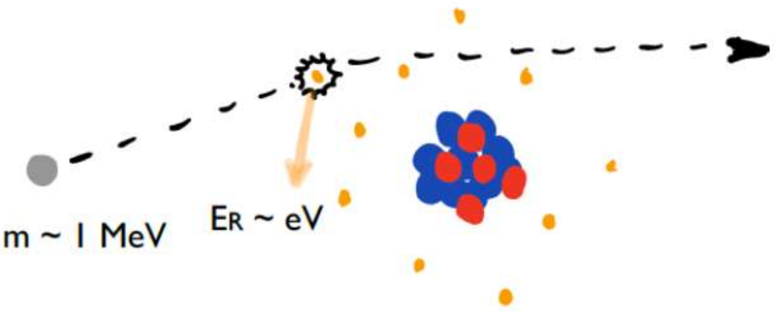
- “Canonical” signature
- Elastic or Inelastic scattering
- Sensitive to m >1 GeV

DIRECT DARK MATTER SEARCHES: What can we measure?

ELASTIC (or INELASTIC) SCATTERING OFF NUCLEI



INELASTIC SCATTERING WITH ELECTRONS



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NUCLEAR SCATTERING

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ELECTRON SCATTERING

- Sensitive to light WIMPs

ELECTRON ABSORBPTION

- Very light (non-WIMP)

EXOTIC SEARCHES

- Axion-photon conversion in the atomic EM field
- Light Ionising Particles

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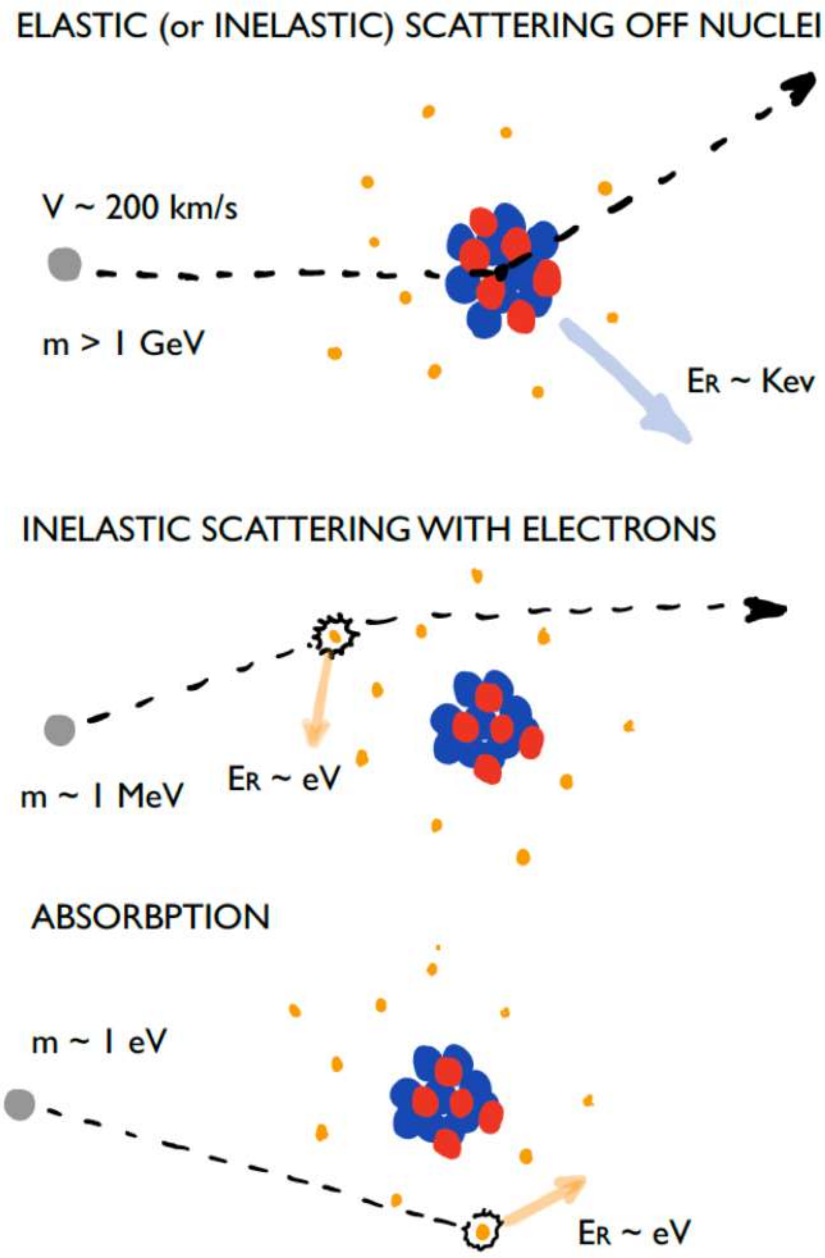

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Conventional direct detection approach (WIMPs)

$$N = \int_{E_T} \epsilon \frac{\rho}{m_\chi m_N} \int_{v_{\rm min}} v f(\vec{v}) \frac{d\sigma_{WN}}{dE_R} d\vec{v}\, dE_R$$

Particle (+ nuclear) Physics

The scattering cross section contains the details about the microphysics of the DM model

The most general case can be described by means of an Effective Field Theory

$$\mathcal{L}_{\rm int} = \sum_{i=1,15} c_i \chi^* \mathcal{O}_\chi \chi \Psi^*_N \mathcal{O}_i \Psi_N$$

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right] \left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

Discriminating a DM signal: ENERGY SPECTRUM

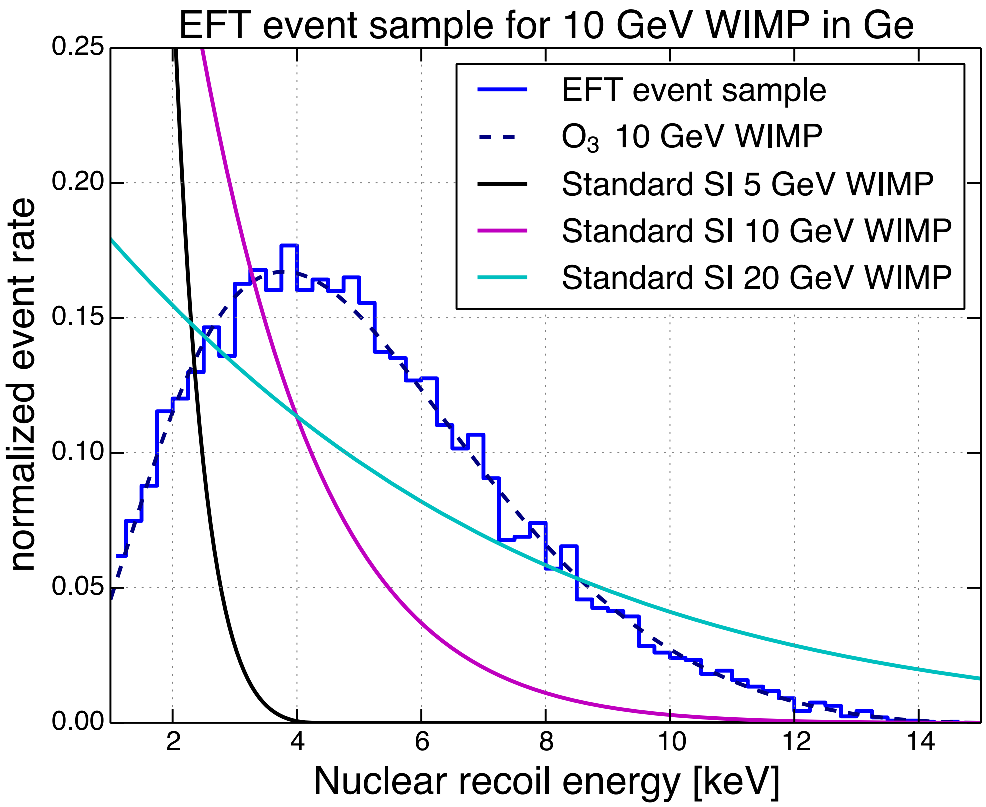
DM scattering would leave an **exponential signal** in the differential rate

The slope is dependent on the DM mass and the target mass

Light WIMPs expected at very low recoil energies

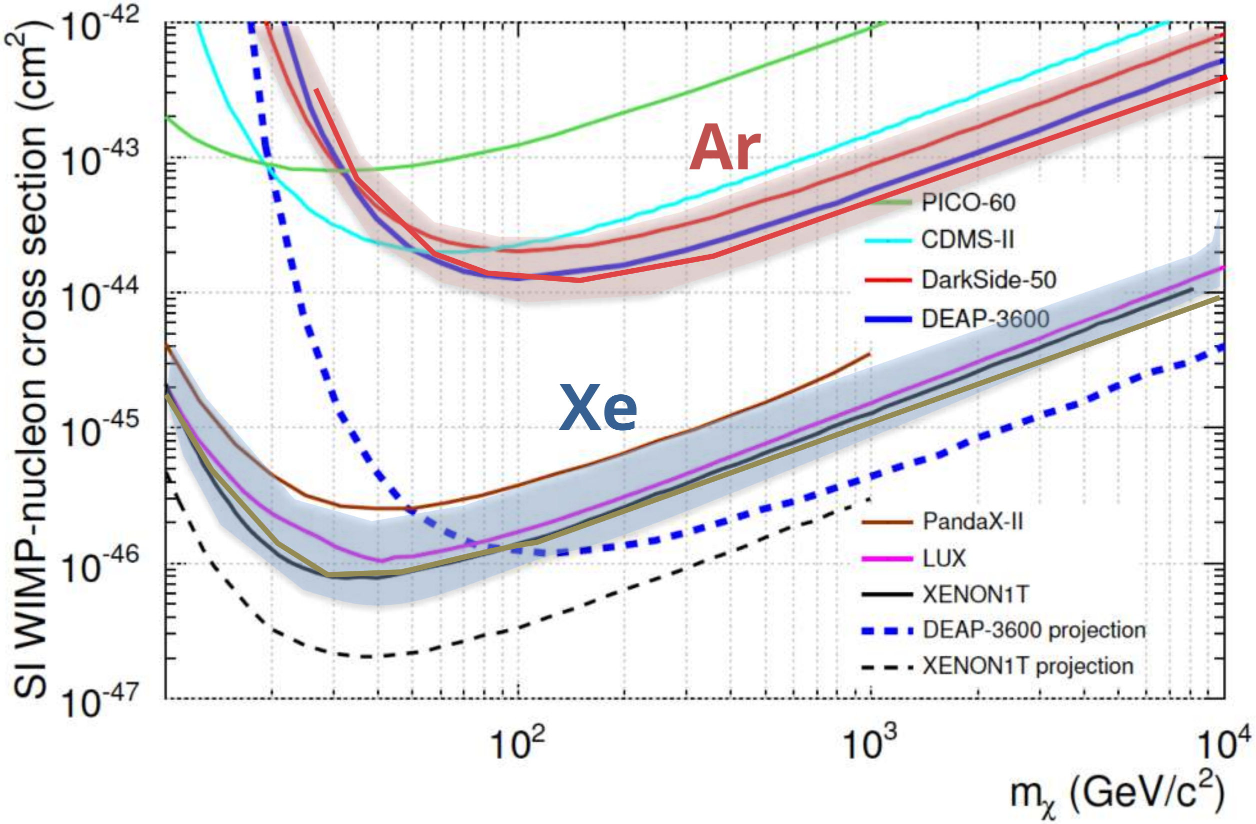
Favours light targets

Low-threshold searches



Constraints on the DM-nucleus scattering cross section

Single or double phase noble gas detectors excel in searches at large DM masses
XENON1T, LUX, Panda-X (Xe), DARKSIDE, DEAP (Ar)
Easily scalable



DARKSIDE 1802.07198
~10000 kg day

DEAP 1707.08042
9870 kg day

PANDAX 1708.06917
54000 kg day

LUX 1608.07648
33500 kg day

XENON1T 1805.12562
362000 kg day

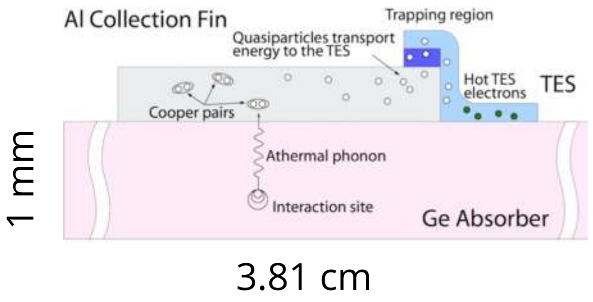
Constraints on low-mass WIMPs

CDMSlite, SuperCDMS, Edelweiss, CDEX (Ge), CRESST ($CaWO_4$), NEWS-G (Ne) complete the search for WIMPs at low masses.
Low-threshold experiments (with smaller targets) are probing large areas of parameter space

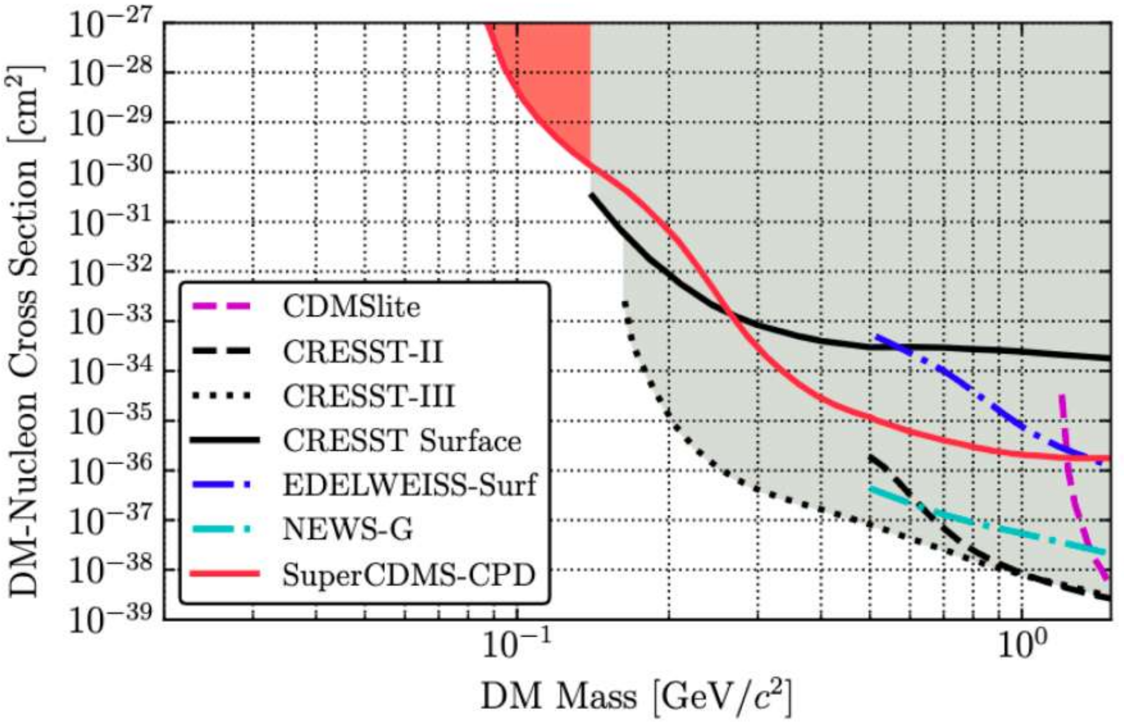
$\sigma_E = 4.92 \pm 0.01 \text{ eV}$ resolution
$E_T = 20.7 \text{ eV}$ threshold

9.9 g day exposure (SLAC Sep. 2018)

“Athermal” Silicon detector on surface

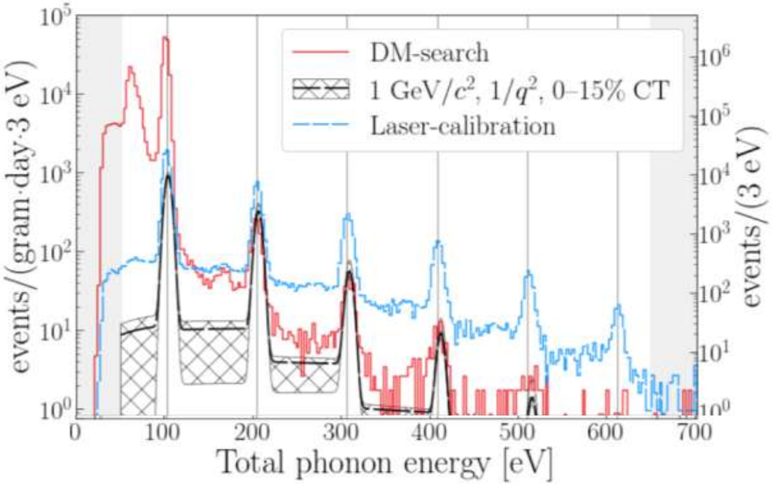


SuperCDMS 2007.14289

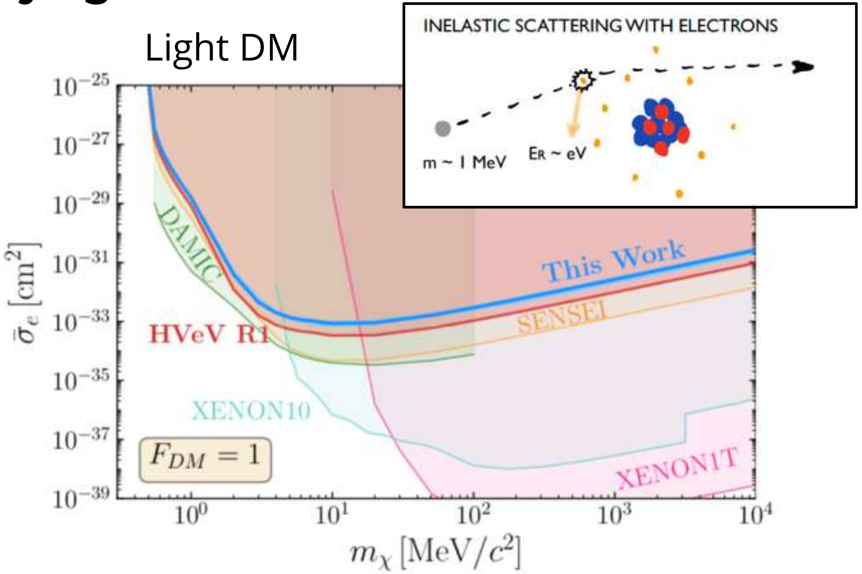


Electron recoils allow to probe very light DM

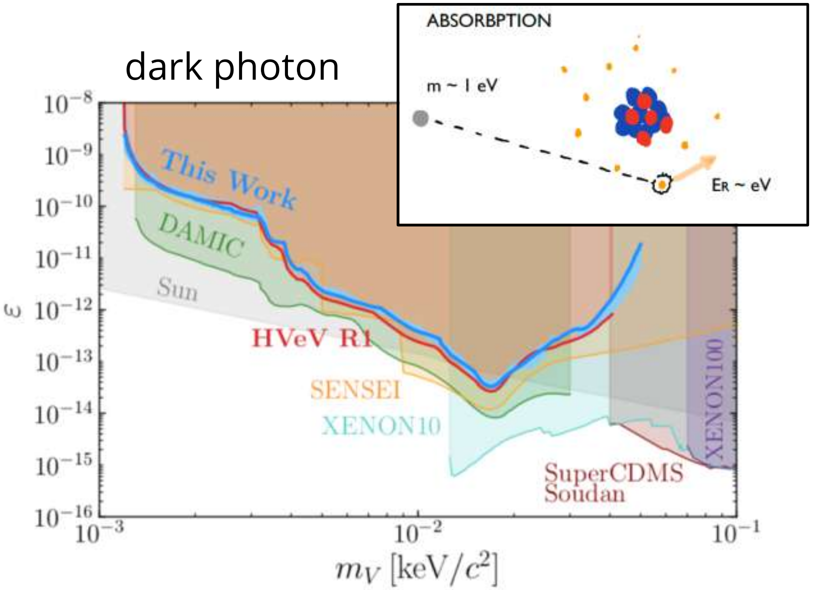
SuperCDMS (HVeV)
2005.14067



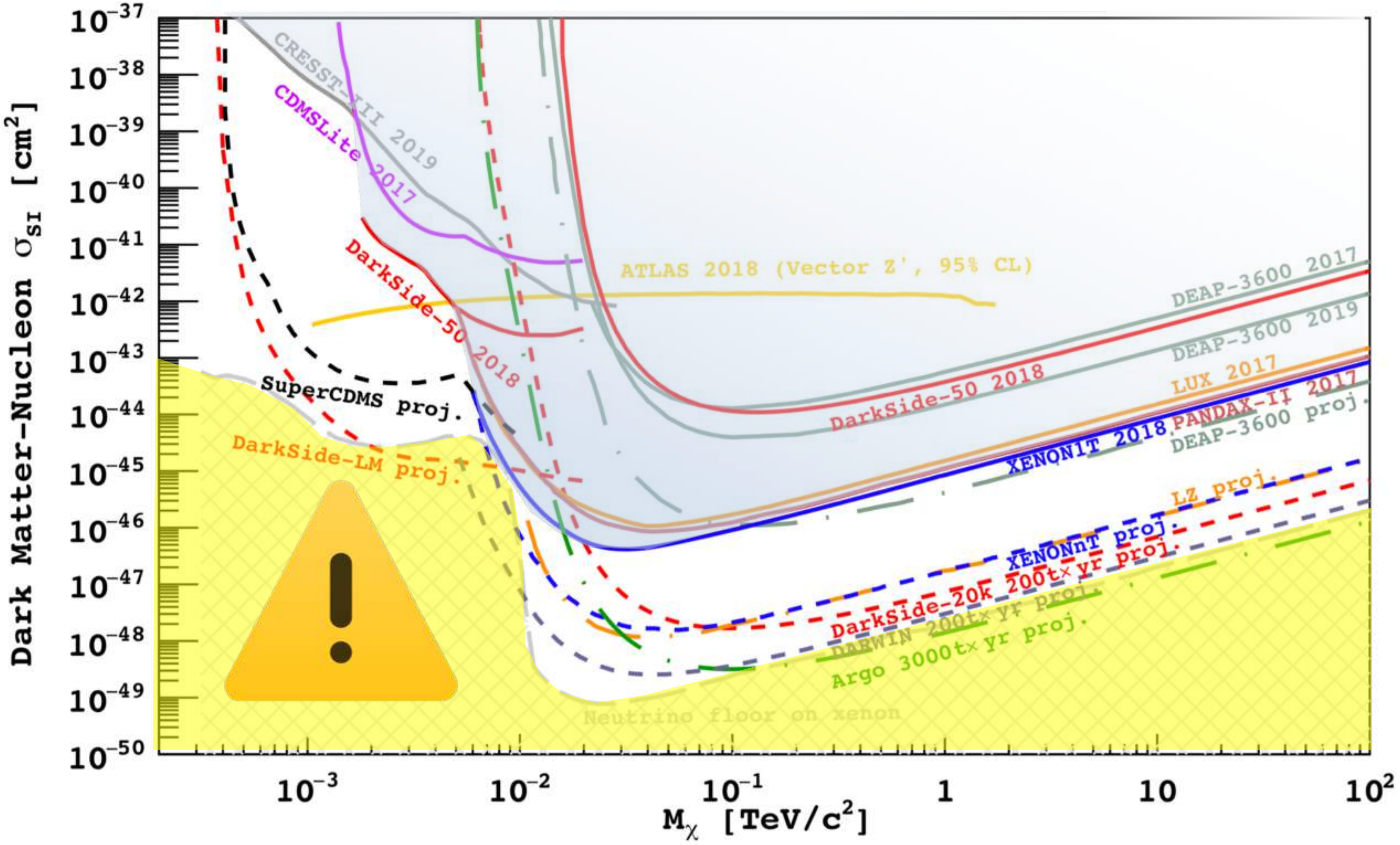
Light DM



dark photon

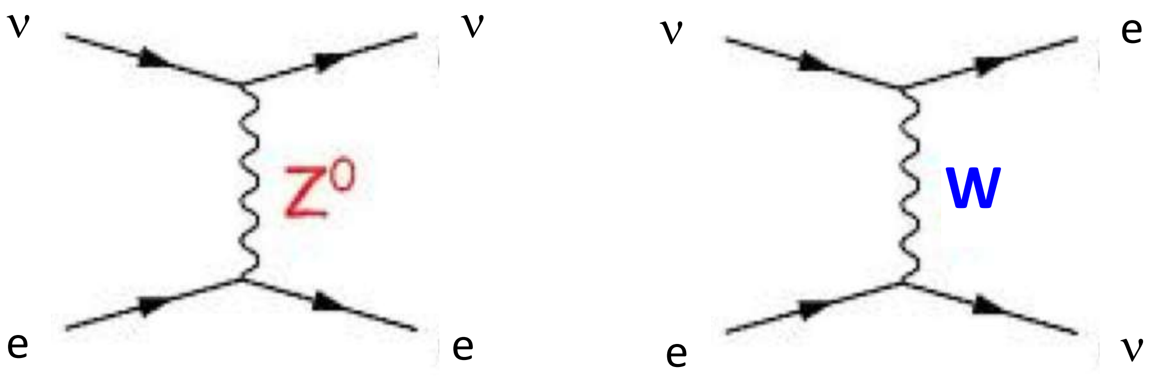


Prospects for the next 5-10 yrs

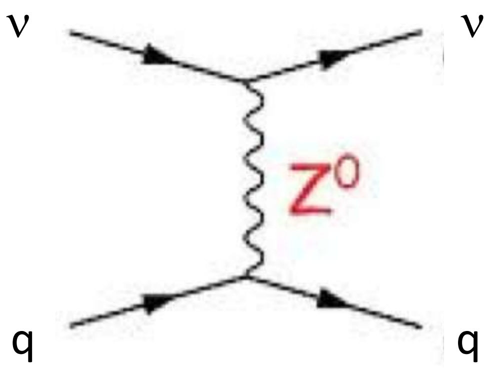


Neutrinos can be observed in direct detection experiments

Exchange of W and Z bosons with electrons



Exchange of a Z boson with the nucleus (Coherent scattering)



Neutrinos in direct detection experiments

$$N = \varepsilon \, n_T \int_{E_{\rm th}}^{E_{\rm max}} \sum_{\nu_\alpha} \int_{E_\nu^{\rm min}} \frac{d\phi_{\nu_e}}{dE_\nu} \, P(\nu_e \to \nu_\alpha) \, \frac{d\sigma_{\nu_\alpha T}}{dE_R} \, dE_\nu dE_R$$

Neutrino-Electron scattering (ER)

$$\frac{d\sigma_{\nu e}}{dE_R} = \frac{G_F^2 m_e}{2\pi}\left[(g_v + g_a)^2 + \quad (g_v - g_a)^2 \left(1 - \frac{E_R}{E_\nu}\right)^2 + (g_a^2 - g_v^2)\frac{m_e E_R}{E_\nu^2}\right]$$

Coherent Neutrino-Nucleus scattering (NR)

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

$$Q_v = N - (1 - 4\sin^2\theta_W)Z$$

The form factor is the same as in WIMP-nucleus scattering.

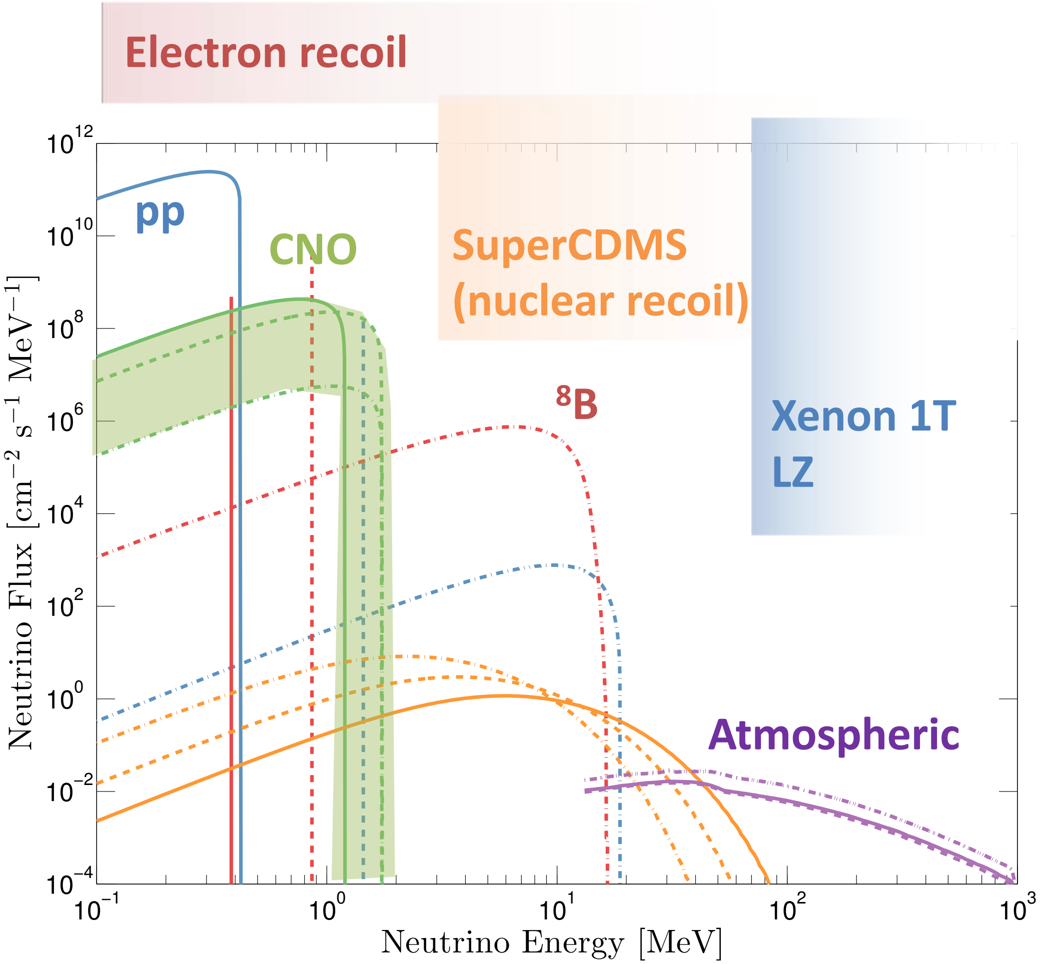
The spectrum differs as it depends on neutrino flux.

Neutrino fluxes

- **Solar neutrinos**
  dominate at low energy – the leading contribution is the pp chain below 1 MeV

- **Atmospheric neutrinos**
  contribute at higher energies but at a much smaller rate

- **Diffuse Supernovae Background**
  relevant around ~20-50 MeV



Experimental response to CNNS

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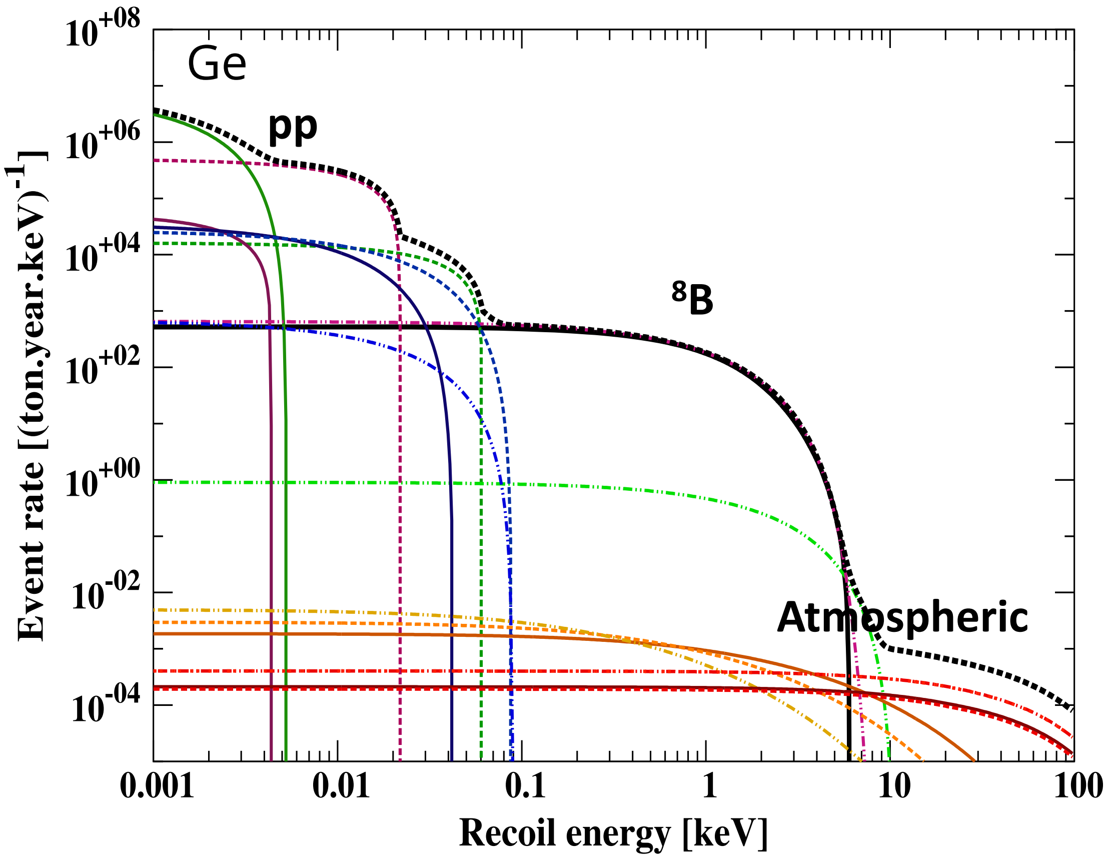
Ruppin, Billard, Figueroa-Feliciano, Strigari 2014



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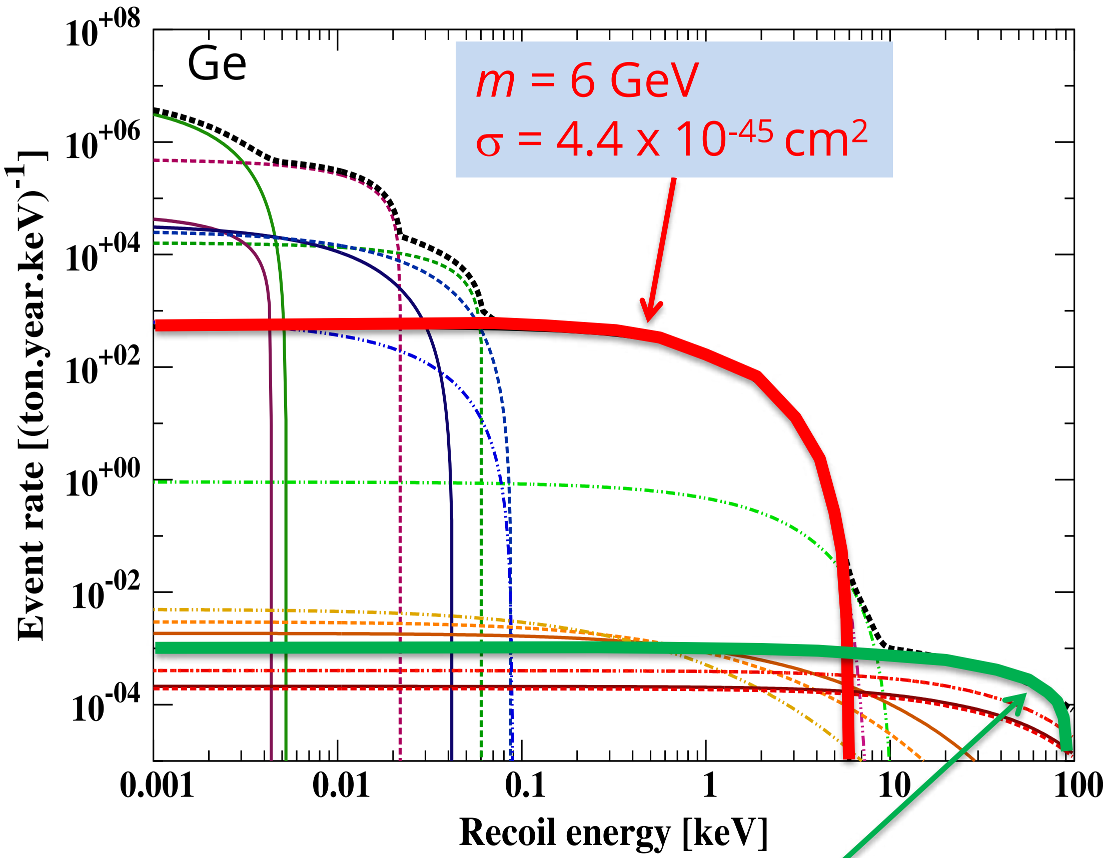


m = 6 GeV
σ = 4.4 x 10^{-45} cm^2

m > 100 GeV
σ ~ 10^{-47} cm^2

Background for DM experiments

Future dark matter experiments will be sensitive to this SM process, limiting the reach for DM searches (Neutrino Floor)

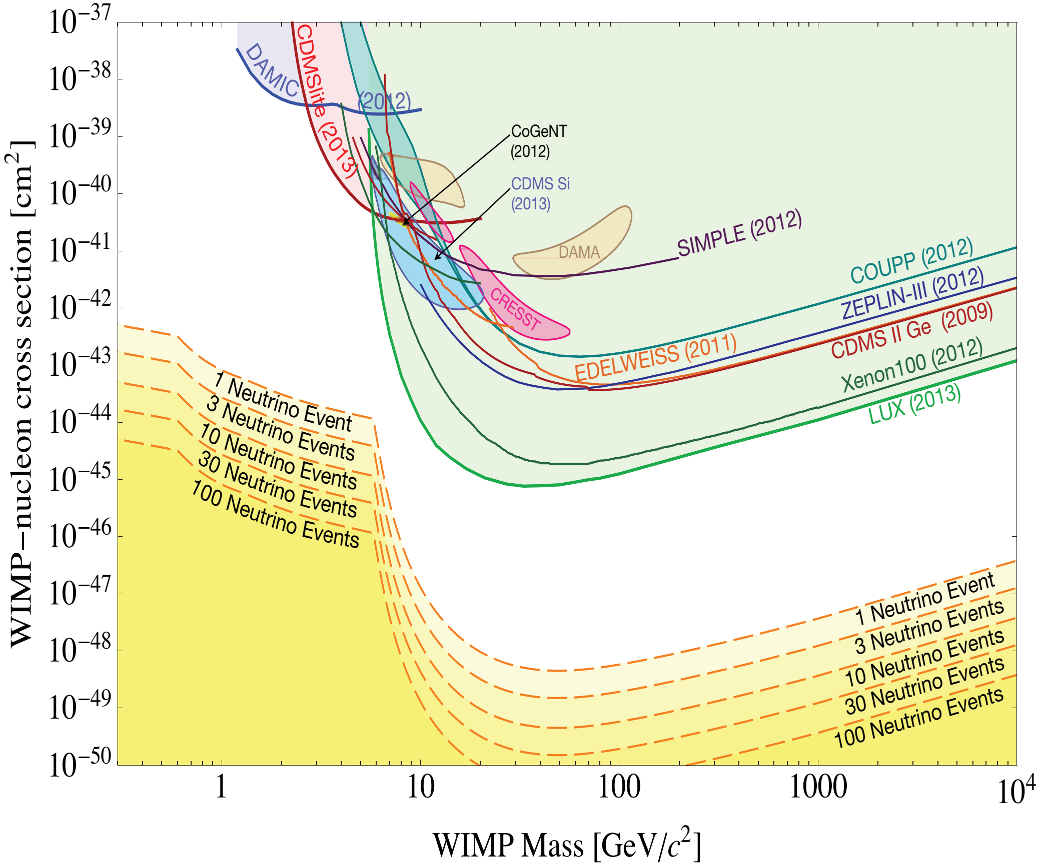
Going beyond the neutrino floor:

- Spectral analysis
- Annual modulation

  Billard et al. 1307.5458
  Davis 1412.1475
- Combination of complementary targets

  Ruppin et al. 1408.3581
- Directional detection

  Grothaus et al. 1406.5047
  O'Hare et al. 1505.08061



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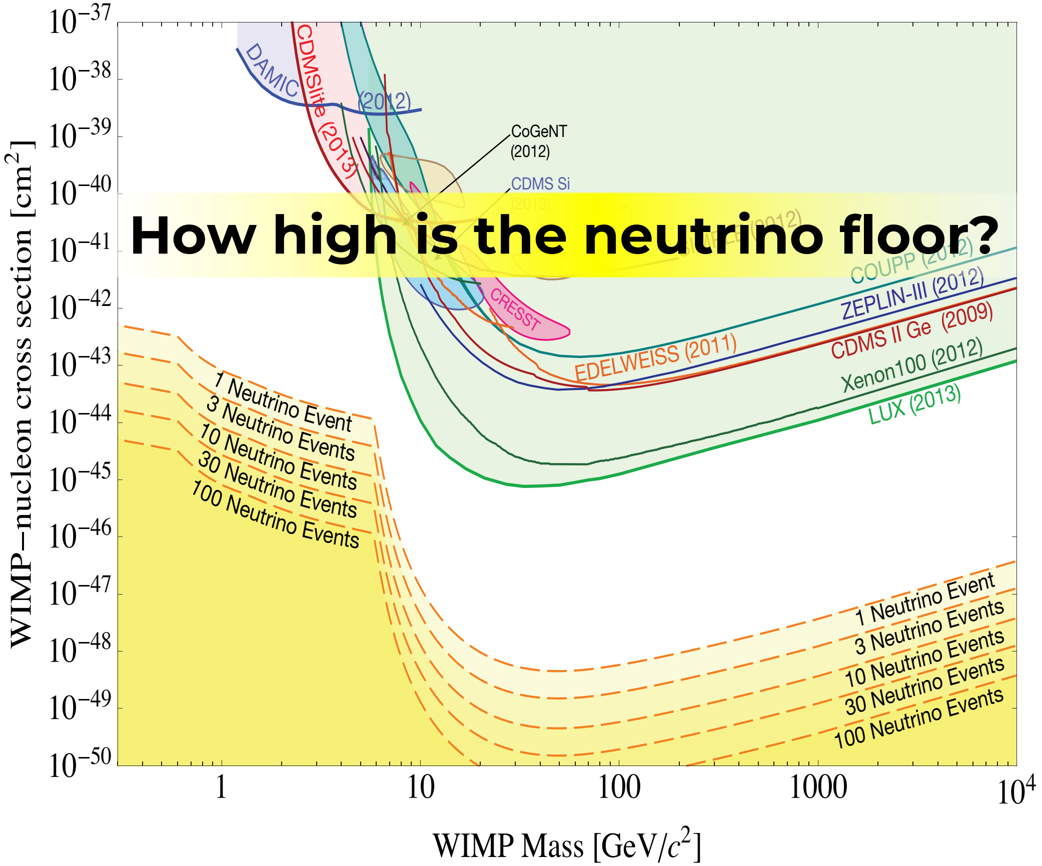


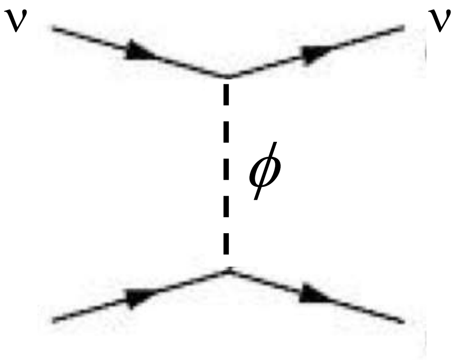
How high is the neutrino floor?

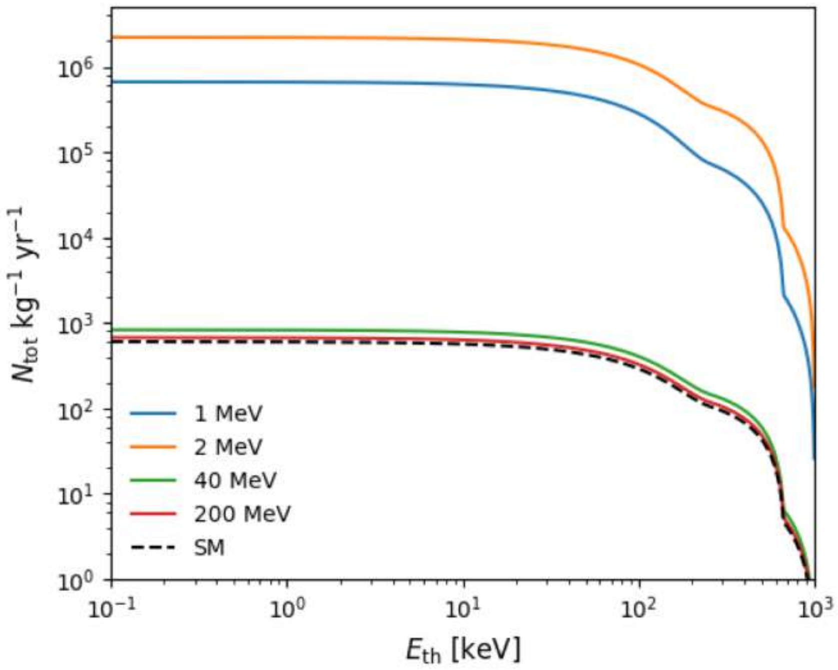
2- How high is the neutrino floor?

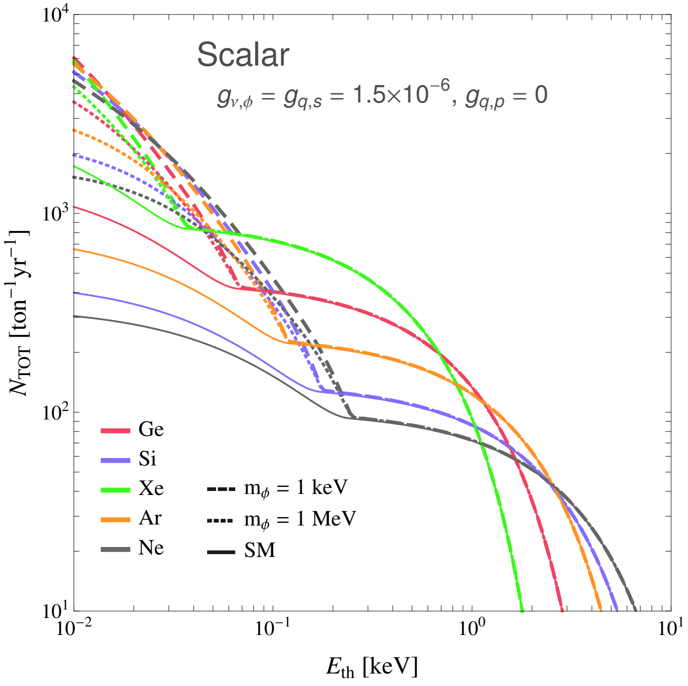

New neutrino physics
Z’
Neutrino floor

New SCALAR mediator

$$\begin{aligned}\mathcal{L} = \; & (g_{\nu,\phi}\,\phi\bar{\nu}_R\nu_L + h.c.) \\ & + \phi\bar{\ell}g_{\ell,s}\ell + \phi\bar{q}g_{q,s}q\end{aligned}$$







Cerdeño, Fairbairn, Jubb, Machado, Vincent, Boehm 2016

How high is the neutrino floor?

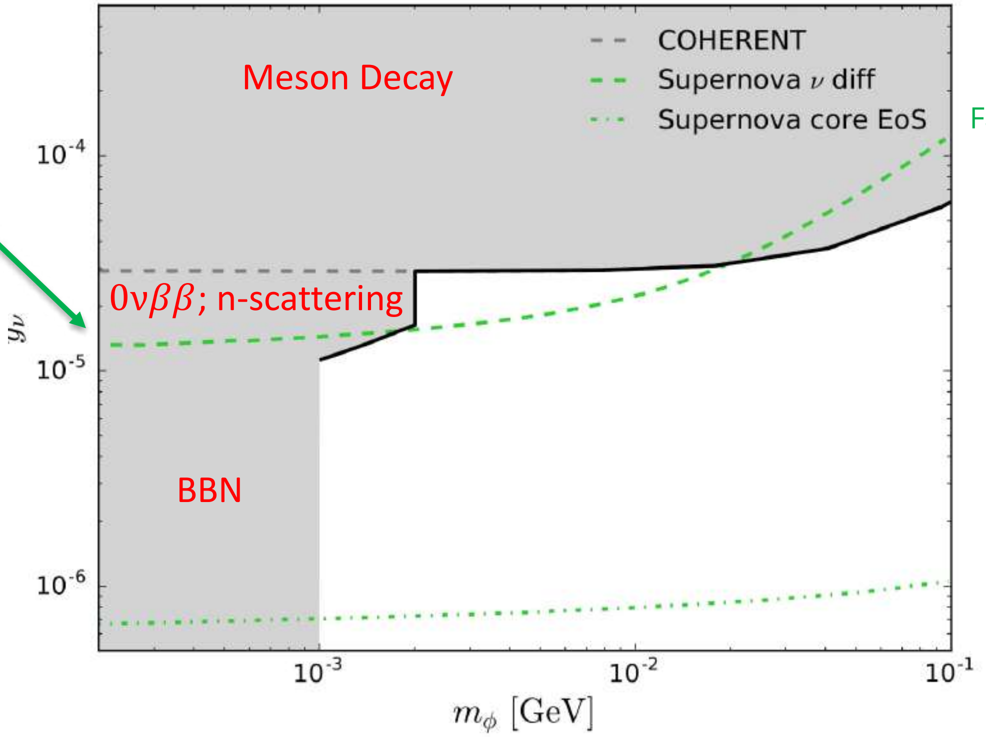
If we allow for new physics in the neutrino sector, the neutrino floor is actually ABOVE the SM one.

Scalar-mediated models

$$\mathcal{L} = -y_\nu \bar{\nu}_L^c \phi \nu_L - \sum_{f \neq \nu} y_f \bar{f} \phi f - \sum_{f \neq \nu} y_f^5 \bar{f} \phi i \gamma_5 f + \text{h.c.}\ ,$$

Boehm, Cerdeño, Machado, Olivares, Reid 2018

Constraints on neutrino diffusion in SN



Farzan et al. 1802.05171

Constraint is estimated to produce similar effects than SM

Does not incorporate the Majorana nature of neutrinos

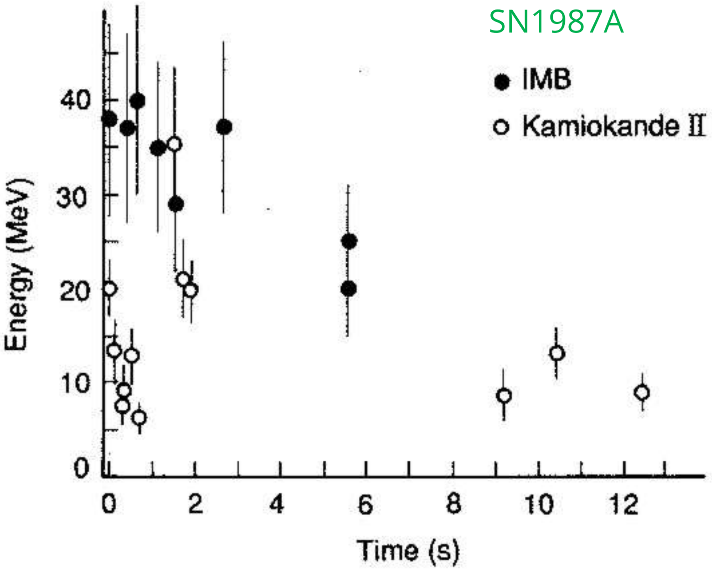
No medium effects are considered

Neutrino mean free path inside a proto Neutron Star

During the final phases of core collapse supernovae (and after the initial burst), neutrinos are still trapped within the nascent proto neutron star (radius ~10 km) and are emitted as it cools down (Kevin-Helmholtz cooling).

Observation of SN1987A suggests that these neutrinos are observed for

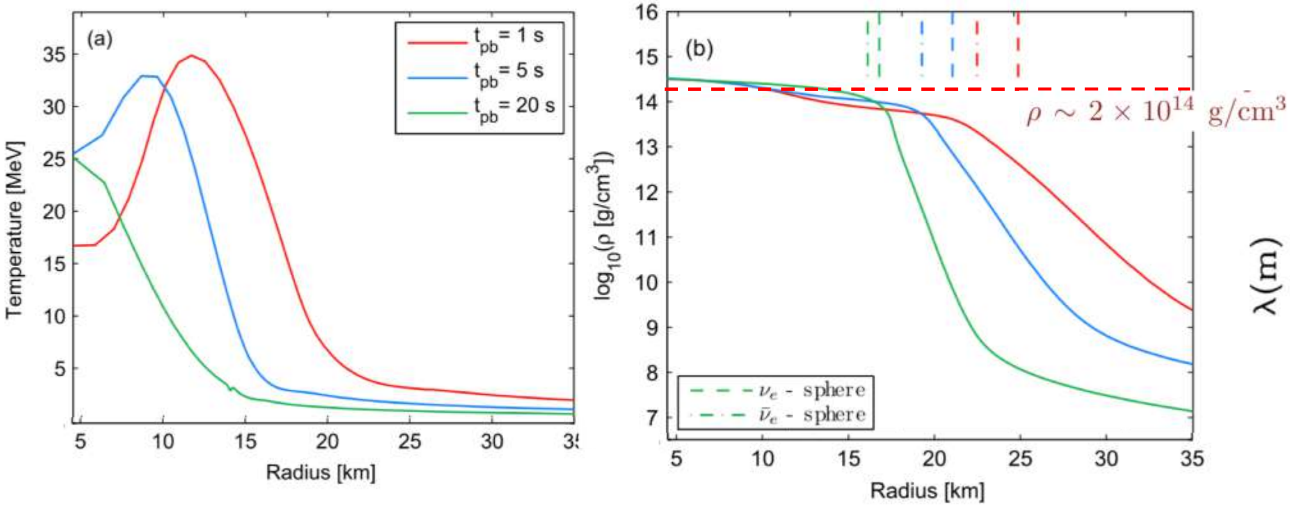
$$\Delta t \sim 10 \text{ s}$$



This is consistent with SM Dirac neutrinos, but new physics contributions can alter the neutrino mean free path leading to $\Delta t > 10 \text{ s}$

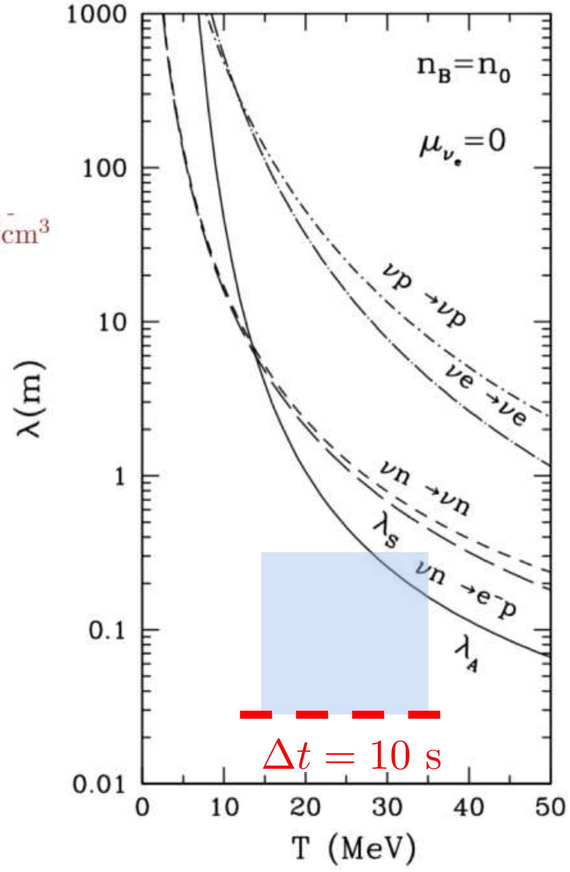
Neutrino mean free path inside a proto Neutron Star

The pNS has a radius of ~ 10 km, **a density several times the nuclear saturation**, and a typical temperature of 15-35 K



Fischer, Martínez Pinedo, Hempel, Liebendörfer 2012

Reddy, Prakash, Lattimer 1997



The main scattering process to consider in the LNV scalar model is

$$\nu n \to \nu n$$

(there are fewer protons and electrons)

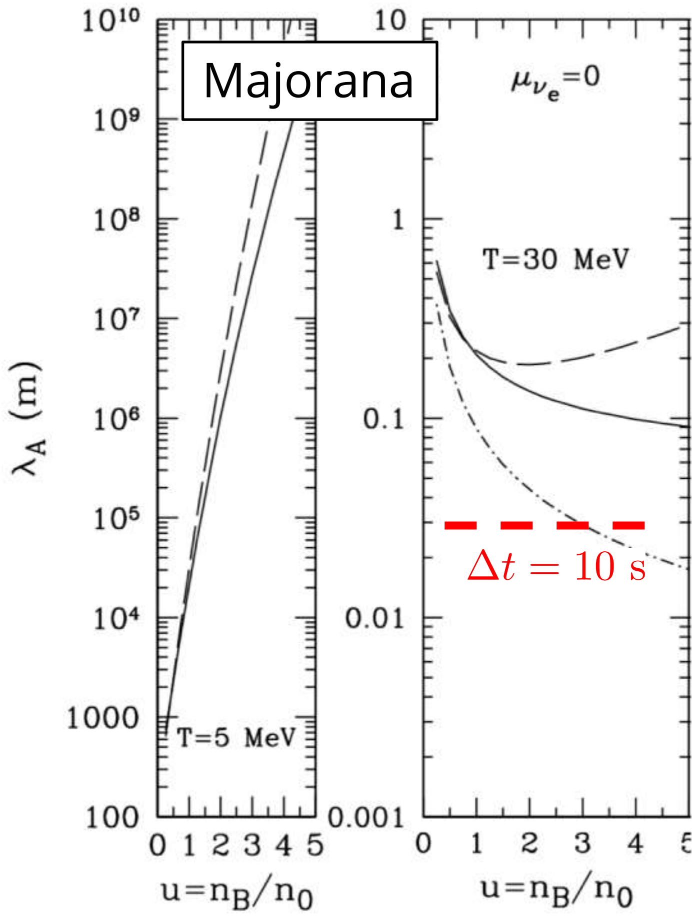
$$\lambda = \left(\frac{\sigma}{V}\right)^{-1}$$

Neutrino mean free path inside a proto Neutron Star

$$\frac{d\sigma}{V} = \int \frac{|\overline{\mathcal{M}}|^2}{8(2\pi)^4|\vec{k}|\sqrt{(pk)^2}}\,|\vec{p}|\,\mathcal{F}(E_N, E'_N, E'_\nu)\,\delta(\cos\theta - \cos\theta^0)\,d\phi_{13}\,d|\vec{q}|\,dq_0\,d|\vec{p}|\,d\cos\theta,$$

$$\mathcal{F}(E_N, E'_N, E'_\nu) = f_N(E_N)(1 - f_N(E'_N))(1 - f_\nu(E'_\nu)).$$

Reddy, Prakash, Lattimer 1997



We have computed the neutrino mfp for a relevant range of T, n, and E_ν and considering the **effective values for the nucleon mass and chemical potential.**

Our preliminary results suggest that Majorana neutrinos are less constrained than Dirac ones.

DGC, Cermeño, Pérez-García, Reid (in progress)

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Fermi-blocking term:

$$\mathcal{F}(E_N, E'_N, E'_\nu) = f_N(E_N)(1 - f_N(E'_N))(1 - f_\nu(E'_\nu)).$$

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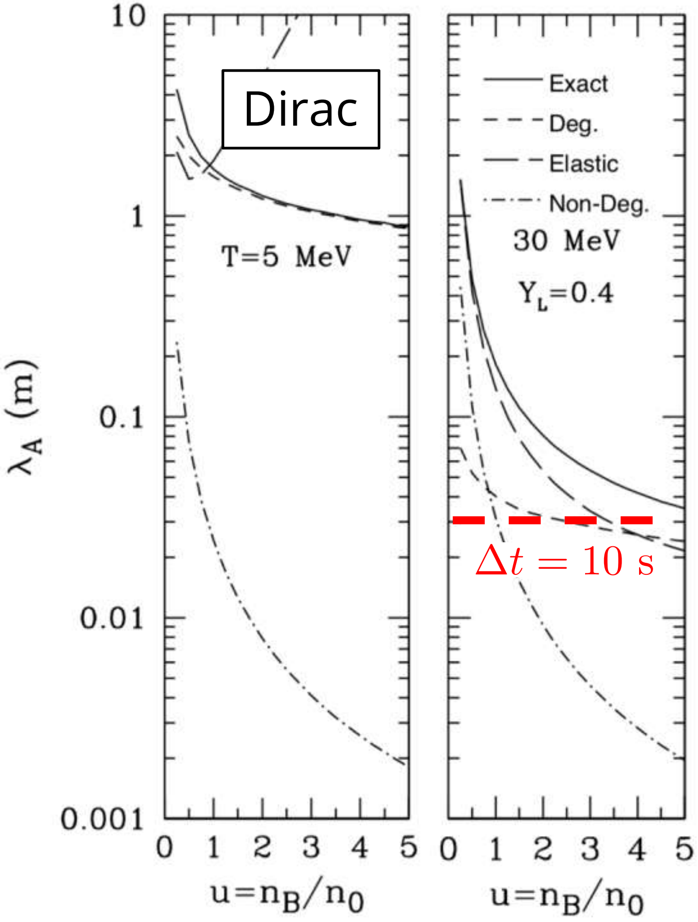

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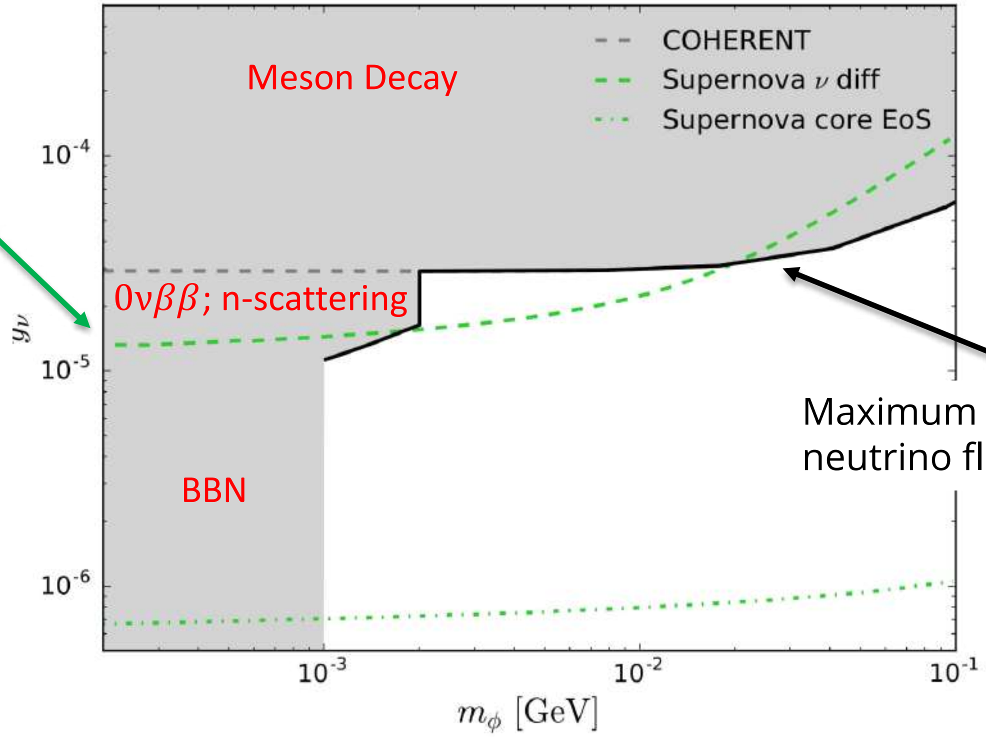

This line is shifted to larger values of the coupling

Maximum contribution to the neutrino floor

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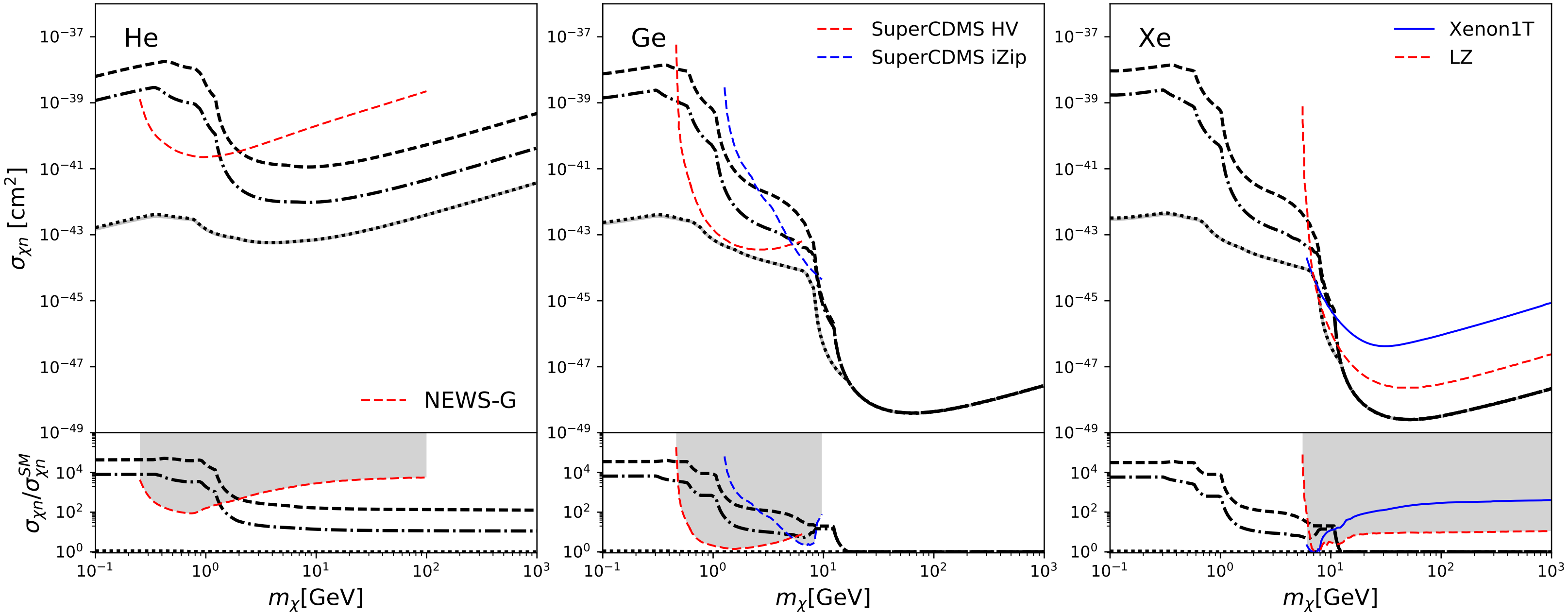
Scalar-mediated models

Boehm, Cerdeño, Machado, Olivares, Reid 2018



The neutrino floor can be orders of magnitude higher than in the SM

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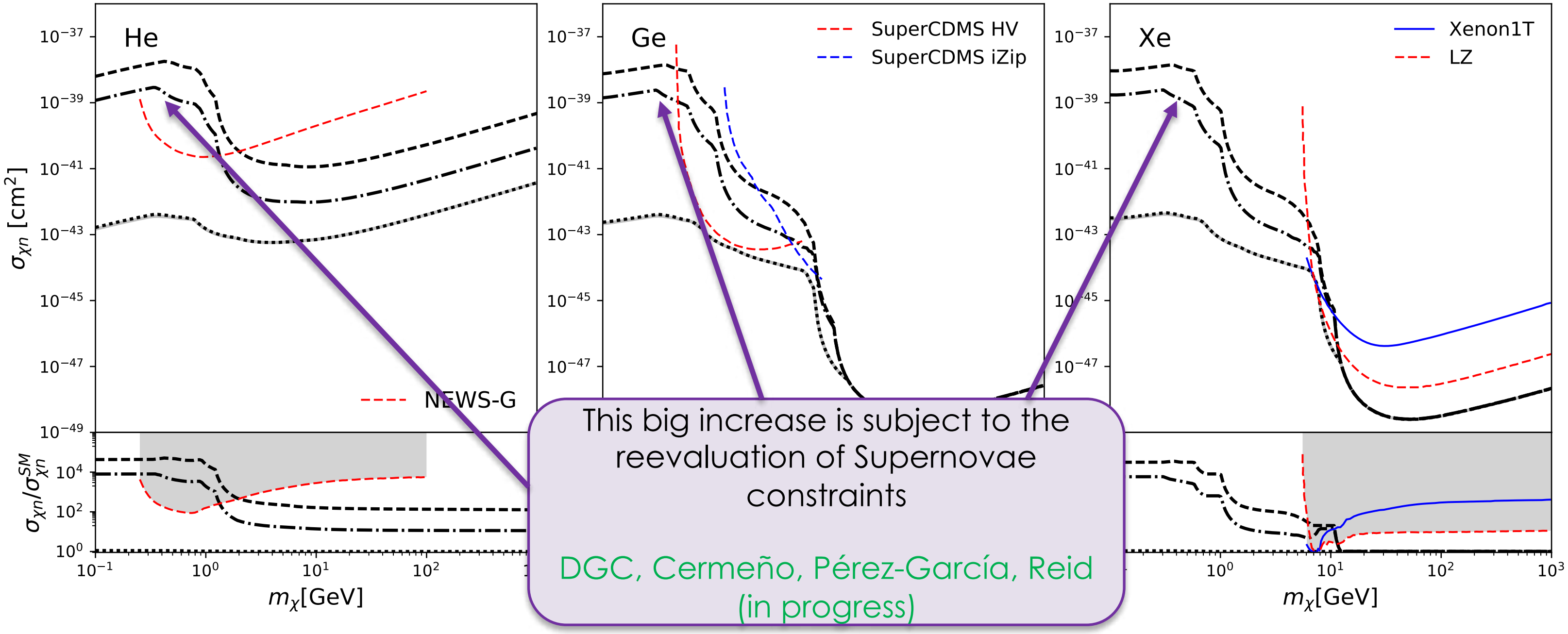


This big increase is subject to the reevaluation of Supernovae constraints

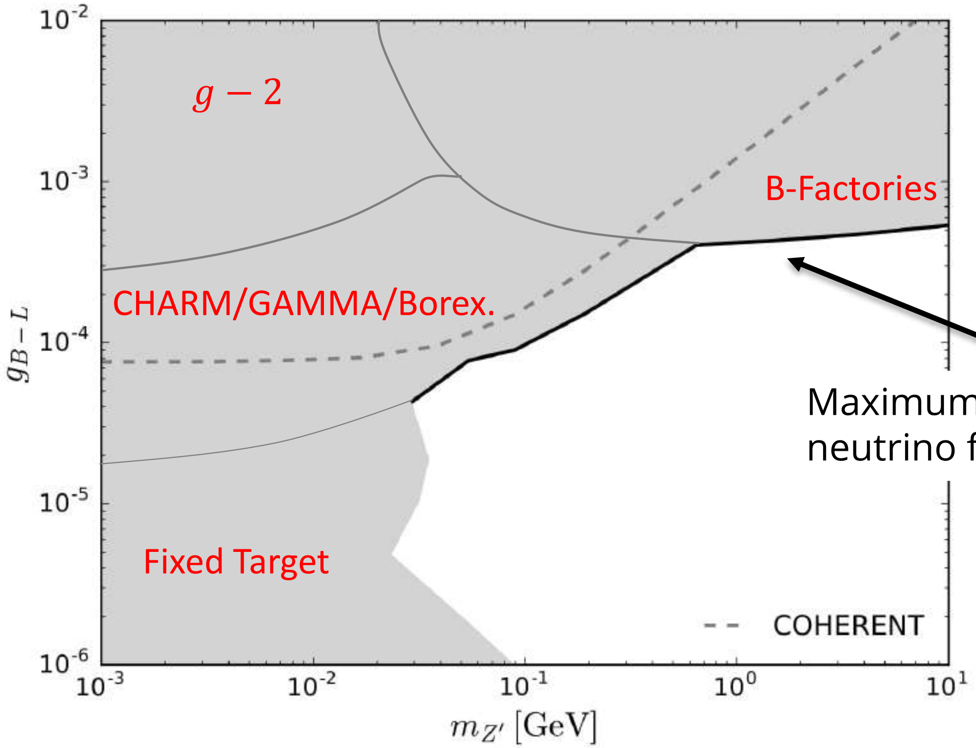
DGC, Cermeño, Pérez-García, Reid (in progress)

The neutrino floor can be orders of magnitude higher than in the SM

New VECTOR mediator

This model is subject to stringent constraints from colliders, neutrino experiments, and astrophysics.

Boehm, Cerdeño, Machado, Olivares, Reid 2018



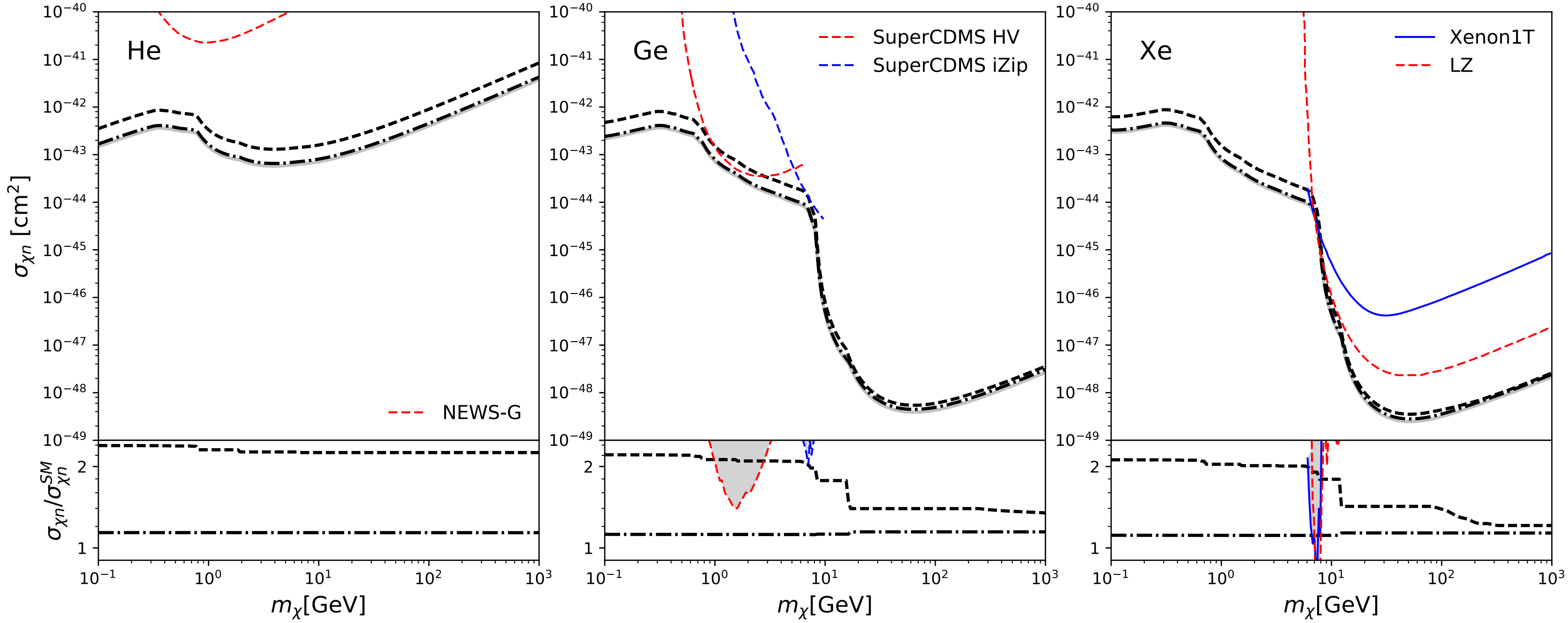
Maximum contribution to the neutrino floor

How high is the neutrino floor?

If we allow for new physics in the neutrino sector, the neutrino floor is actually ABOVE the SM one.

Vector-mediated models

Boehm, Cerdeño, Machado, Olivares, Reid 2018



The neutrino floor can be approximately 2 times higher than in the SM

3- Probing new physics in the neutrino sector with direct detection

$U(1)_{L_\mu - L_\tau}$

Gauging the difference between two lepton-flavour numbers is anomaly-free within the SM – no need for extra fermions.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\alpha\beta} X^{\alpha\beta} - \frac{\epsilon_Y}{2} B_{\alpha\beta} X^{\alpha\beta} - \frac{M_X^2}{2} X_\alpha X^\alpha - g_{\mu\tau}\, J_\alpha^{\mu-\tau} X^\alpha \,,$$

$$J_\alpha^{\mu-\tau} = \bar{L}_2 \gamma_\alpha L_2 + \bar{\mu}_R \gamma_\alpha \mu_R - \bar{L}_3 \gamma_\alpha L_3 - \bar{\tau}_R \gamma_\alpha \tau_R \,,$$

A massive hidden photon is generated with kinetic coupling to the SM photon. Thus, we can write the interactions of the hidden photon as

$$\mathcal{L}_{f A'} = -c_f\, \bar{f} \gamma^\alpha f\, A'_\alpha$$

f	e	ν_e	μ, ν_μ	τ, ν_τ	q_d	q_u
c_f	$\epsilon\, e$	0	$g_{\mu\tau}$	$-g_{\mu\tau}$	$\frac{1}{3}\epsilon\, e$	$-\frac{2}{3}\epsilon\, e$

The new gauge boson does not have couplings to electrons or quarks at leading order. Collider constraints are easily evaded.

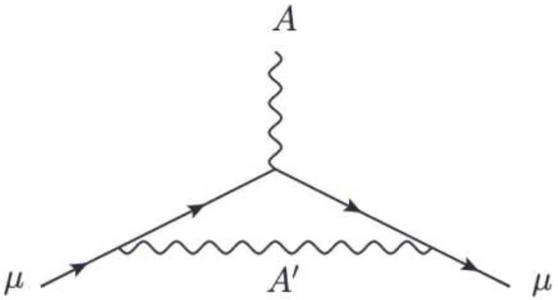
$U(1)_{L_\mu - L_\tau}$

- This construction can account for the observed discrepancy in the muon anomalous magnetic moment.

Ma, Roy, Roy PLB525(2002)106
Harigaya et al. JHEP03(2014)105

$$a_\mu^{\text{exp}} = 116\ 592\ 089(63) \times 10^{-11}$$

$$a_\mu^{\text{SM}} = 116\ 591\ 810(43) \times 10^{-11}$$

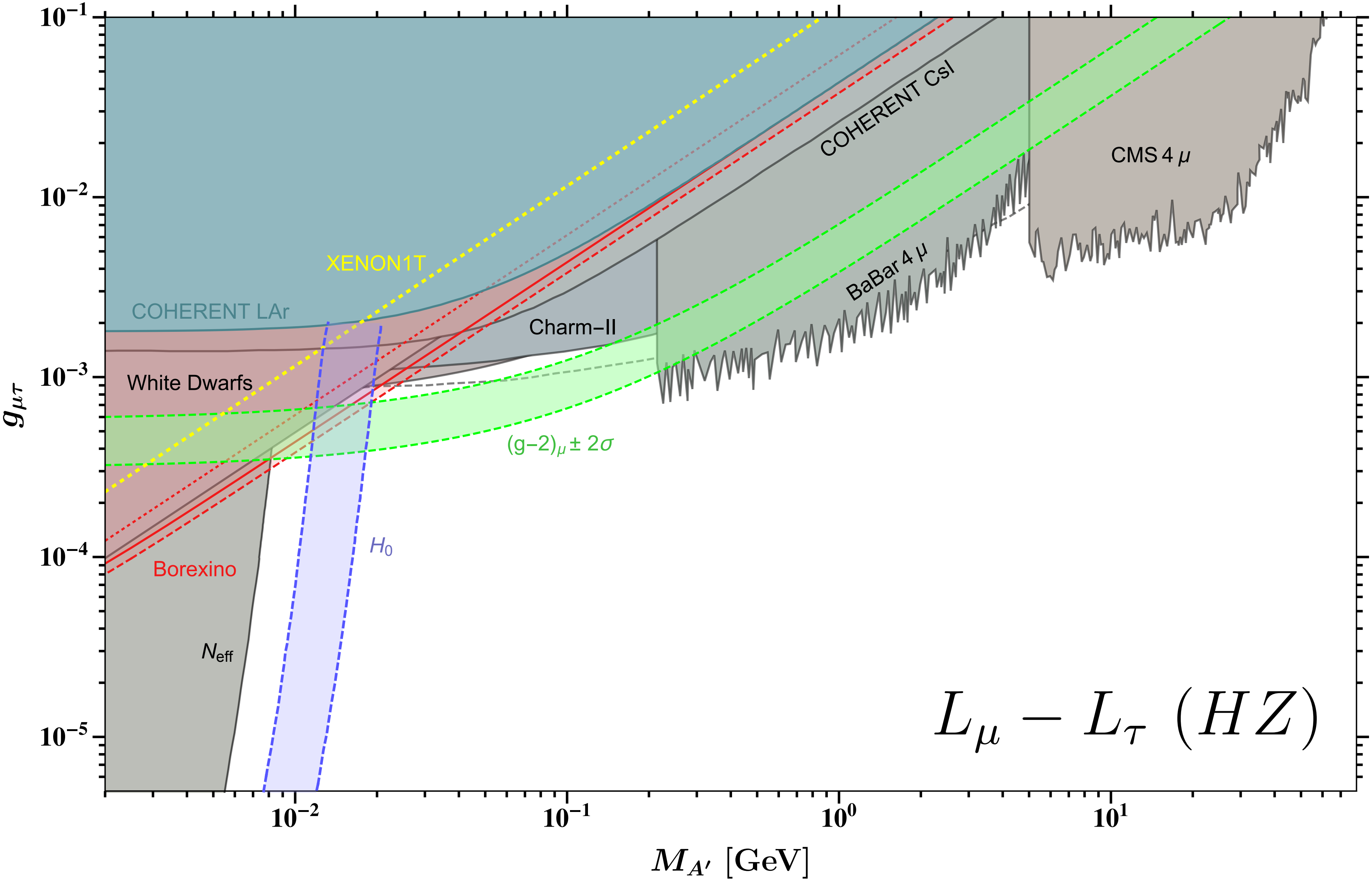


- The new gauge boson can significantly alleviate the 3σ deviation of local measurements of the Hubble parameter from the value inferred from CMB data

Bernal, Verde, Riess JCAP 10 (2016) 019

$$\Delta N_{\text{eff}} \sim 0.4$$

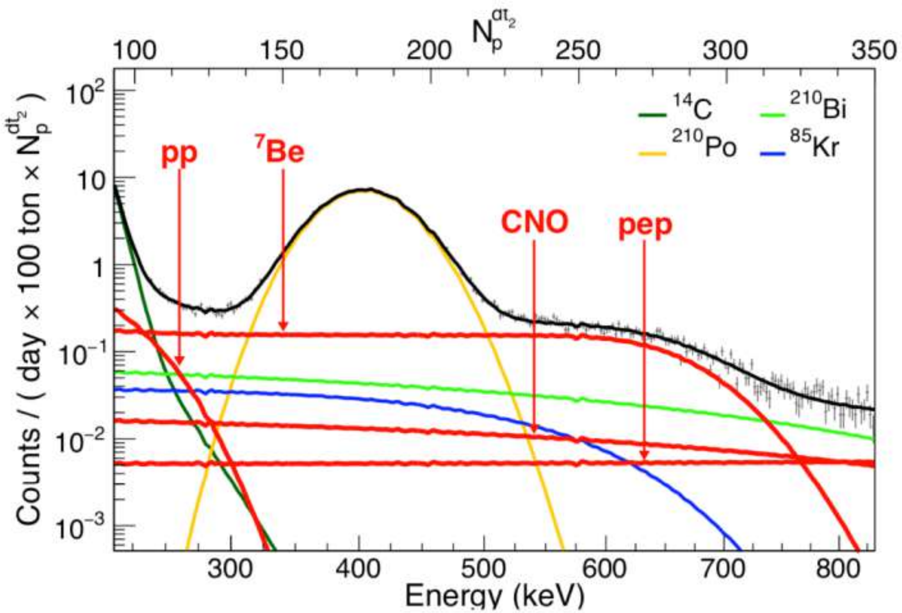
Amaral, DCG, Foldenauer, Reid; 2006.11225



Other **Constraints**

Phase II [Borexino; PRD 100, 082004]

Phase I [Borexino; PRL 107, 141302]



BOREXINO

Borexino has measured the neutrino spectrum with great precision, especially the 7Be flux

Bounds on ν-e couplings

COHERENT

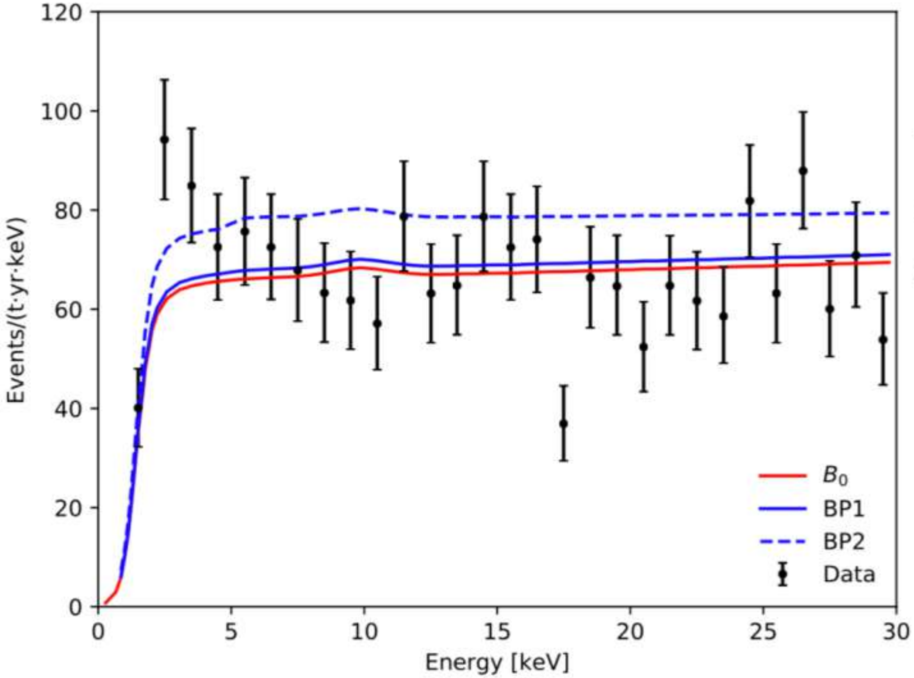
COHERENT has measured neutrino-nucleus coherent scattering on two targets (CsI and Lar). Both observations are consistent with the SM.

One can derive bounds on new ν-N couplings

Other **Constraints**

XENON1T

No excess over the observed measurement also leads to bounds on ν-e couplings



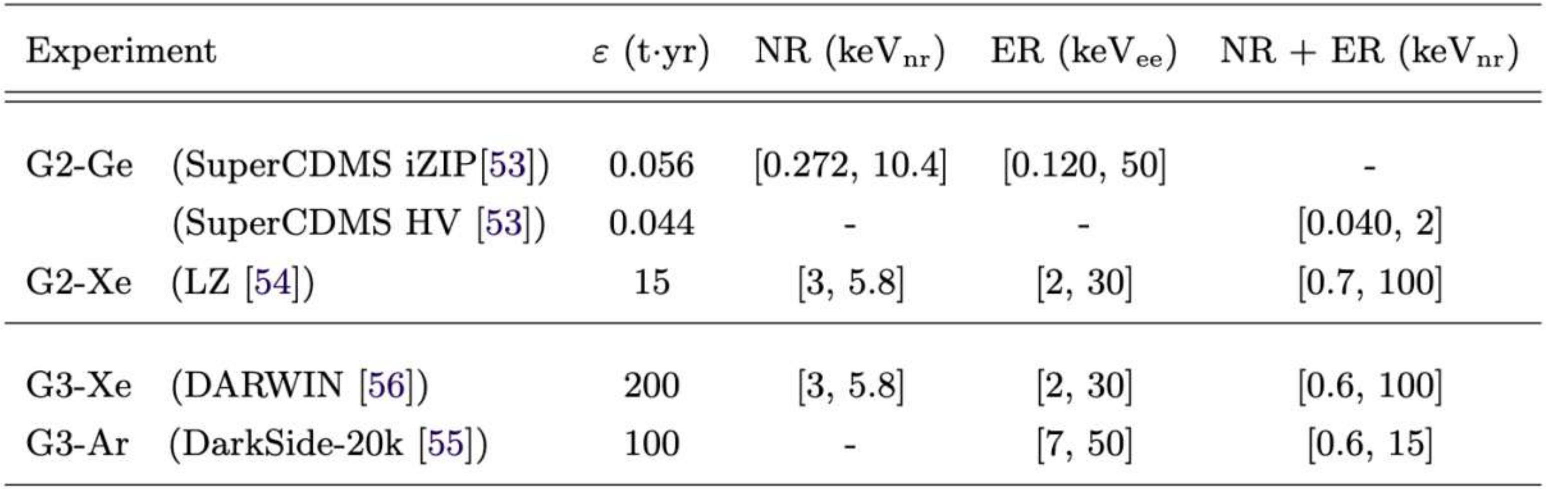
$$M_{A'} = 15 \text{ MeV}$$

$$g_{\mu\tau} = 1.7 \times 10^{-3}$$

$$g_{\mu\tau} = 5.6 \times 10^{-4}$$

Next Generation direct detection experiments

We consider idealized versions of next generation of experiments, based on proposed detectors

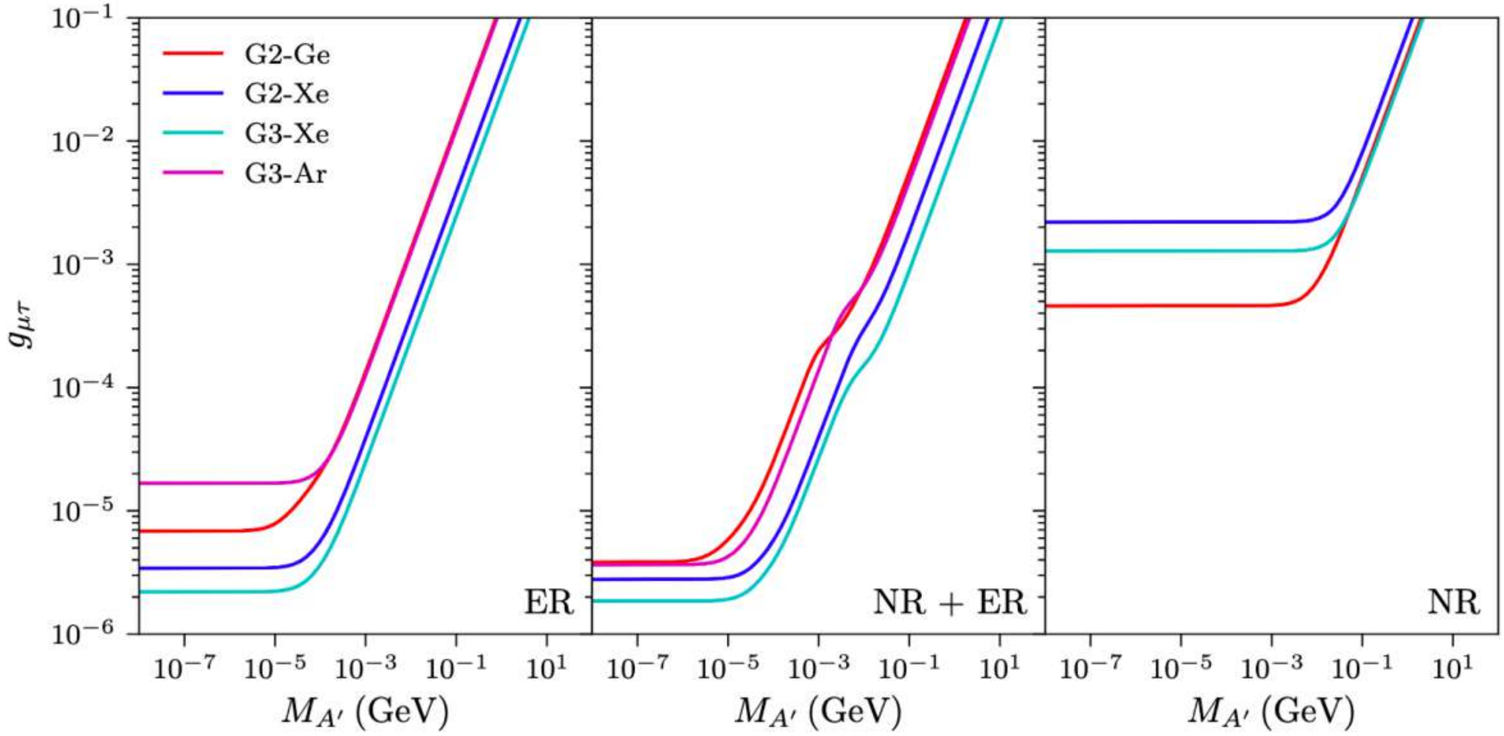


Experiment		ε (t·yr)	NR ($\mathrm{keV_{nr}}$)	ER ($\mathrm{keV_{ee}}$)	NR + ER ($\mathrm{keV_{nr}}$)
G2-Ge	(SuperCDMS iZIP[53])	0.056	[0.272, 10.4]	[0.120, 50]	-
	(SuperCDMS HV [53])	0.044	-	-	[0.040, 2]
G2-Xe	(LZ [54])	15	[3, 5.8]	[2, 30]	[0.7, 100]
G3-Xe	(DARWIN [56])	200	[3, 5.8]	[2, 30]	[0.6, 100]
G3-Ar	(DarkSide-20k [55])	100	-	[7, 50]	[0.6, 15]

ER: used projected background models for SuperCDMS (Ge) and Xenon (Xe)

NR: assumed background free (Xenon) and background model for SuperCDMS (High Voltage)

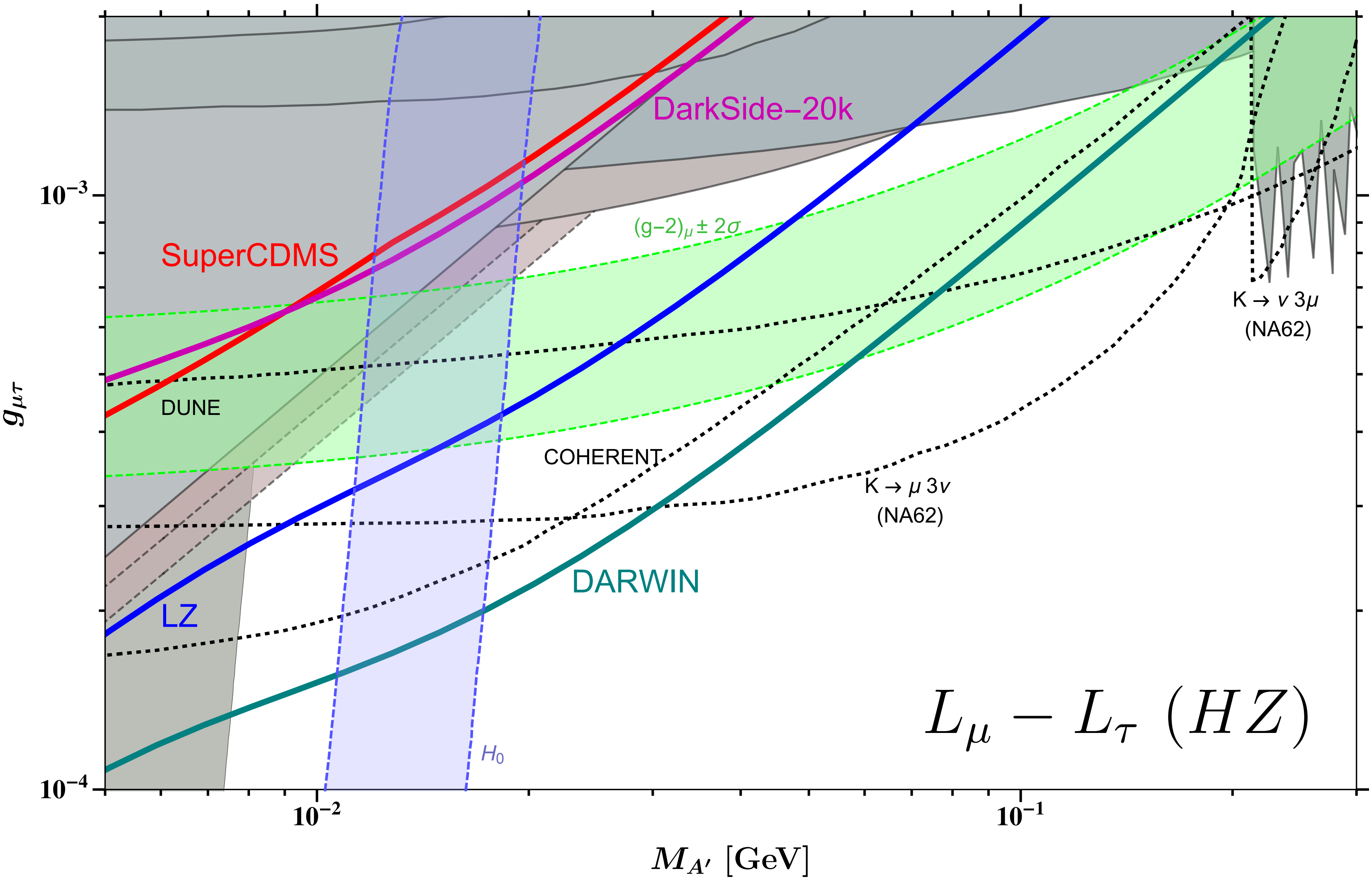
Assuming no observation, we derive upper bounds on the coupling



ER: favours large detectors (more electrons) but the background is a limiting factor

NR: low thresholds are favoured, but the performance is optimized at masses around 10 MeV

Amaral, DCG, Foldenauer, Reid; 2006.11225



Summary

- Direct (dark matter) detectors are excellent probes of the light invisible sector (e.g., dark matter and neutrinos)

- Can observe neutrinos through electron and nuclear recoils and probe new physics in this sector

  - The neutrino floor is higher than expected, especially at low masses. But dependent on (supernova) constraints

  - Gauged U(1)L_μ-L_τ could provide a solution to the muon anomalous magnetic moment and solve the tension in H_0

    Xenon based experiments are competitive to probe remaining regions of the parameter space