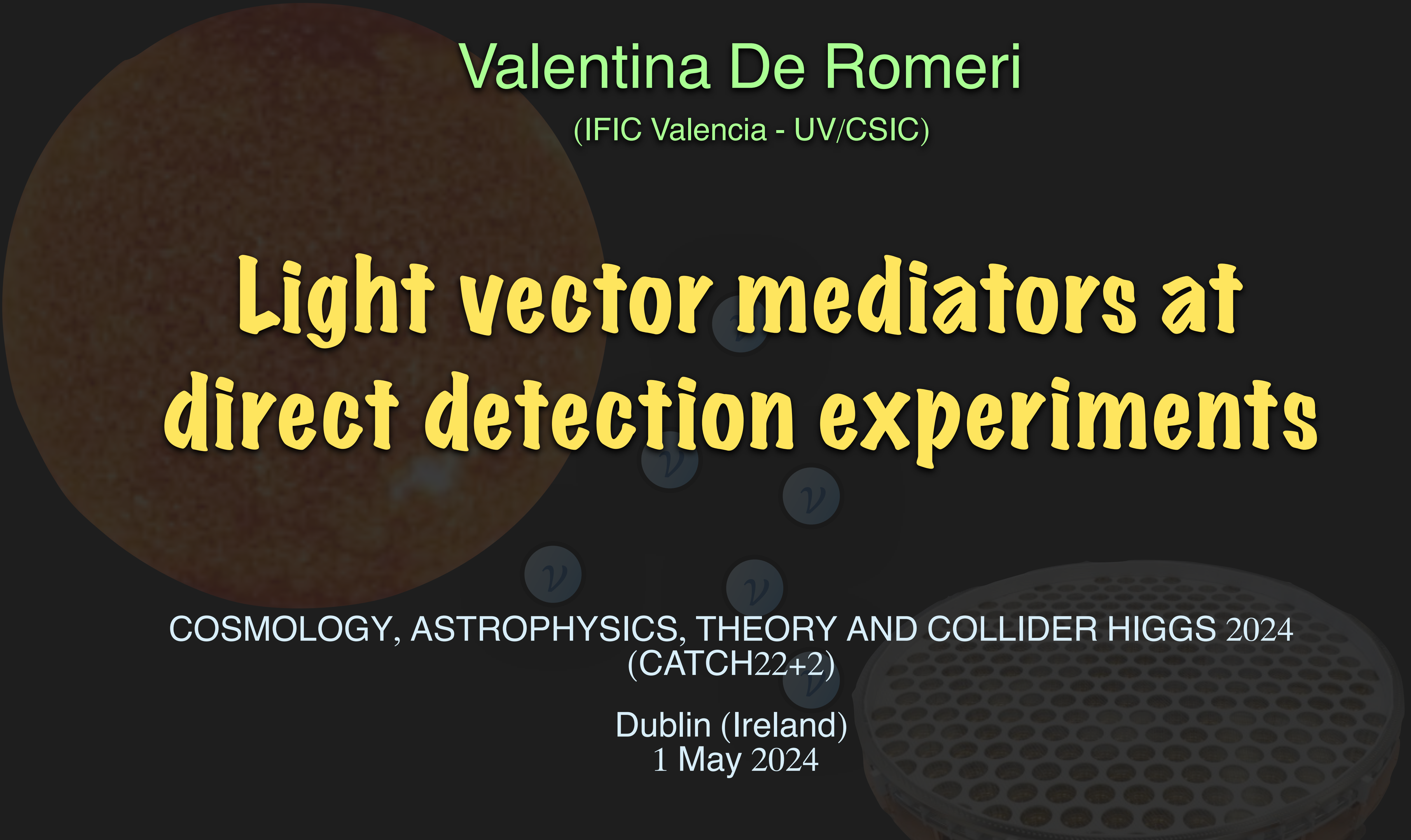
Valentina De Romeri

(IFIC Valencia - UV/CSIC)



Light vector mediators at direct detection experiments

COSMOLOGY, ASTROPHYSICS, THEORY AND COLLIDER HIGGS 2024
(CATCH22+2)

Dublin (Ireland)
1 May 2024

Based on VDR, Papoulias, Ternes [arXiv: 2402.05506, accepted for publication in JHEP]

DIRECT WIMP SEARCHES

If DM is made of particles that interact among themselves and with SM particles (e.g. WIMPs) we may hope to detect it.
One strategy:

DIRECT DETECTION
Which looks for energy deposited within a detector by the scattering of DM on the target

DIRECT WIMP SEARCHES

If DM is made of particles that interact among themselves and with SM particles (e.g. WIMPs) we may hope to detect it.
One strategy:

DIRECT DETECTION
Which looks for energy deposited within a detector by the scattering of DM on the target

Underground detectors look for "ghostly" particles:

- Neutral (or millicharged)
- Weakly-interacting
- Cosmological or astrophysical origin
- Long-lived enough

Scatterings are infrequent (if any!). Need:

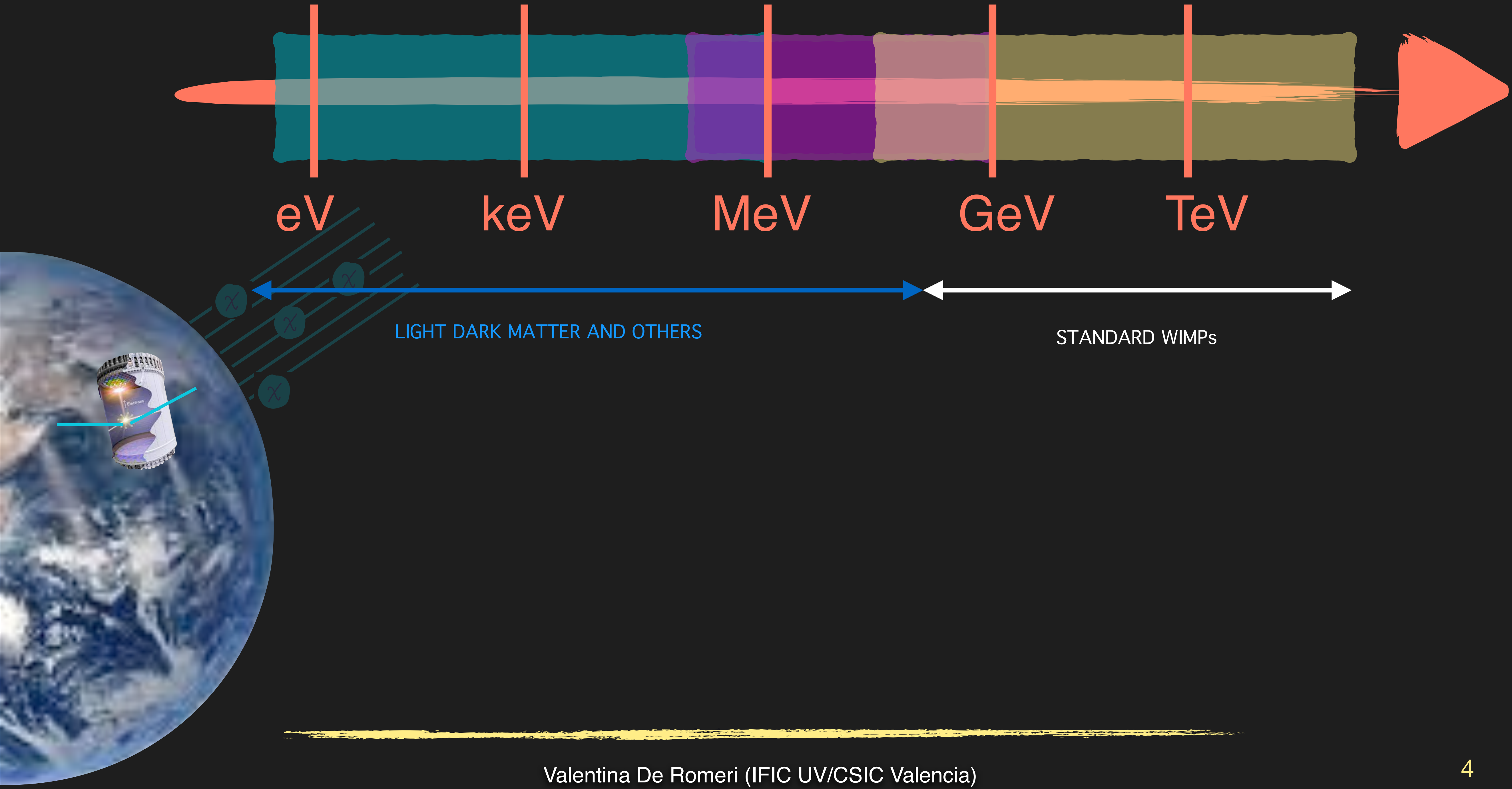
- Excellent background reduction
- Large exposure (time and volume)
- Low energy thresholds

DIRECT WIMP SEARCHES: signals

Electron absorption (very light DM)

Electron scattering (light WIMPs)

Nuclear scattering
Migdal effect (detect the ionization signal)

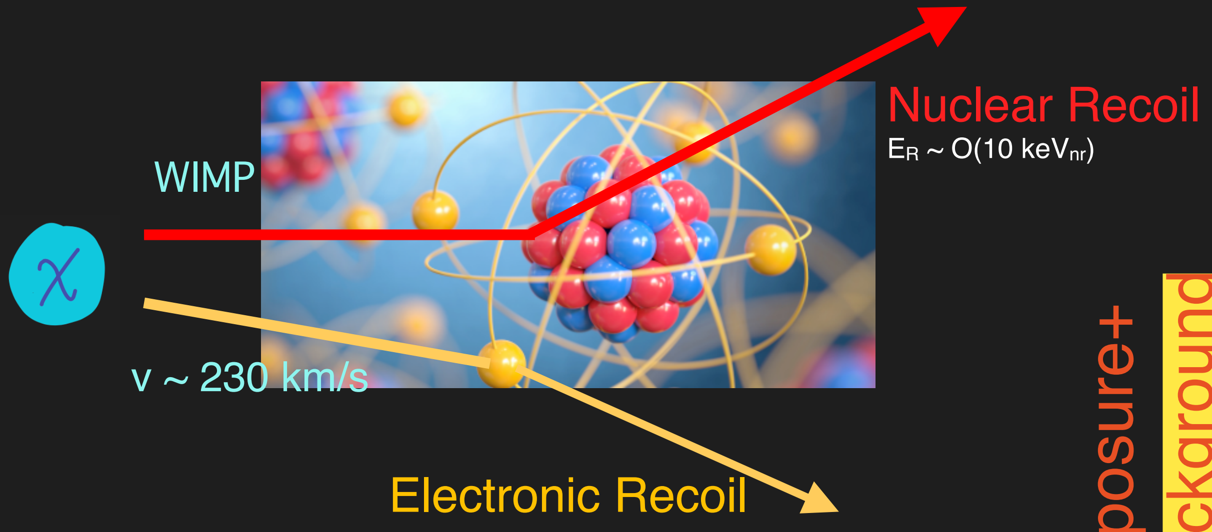


LIGHT DARK MATTER AND OTHERS

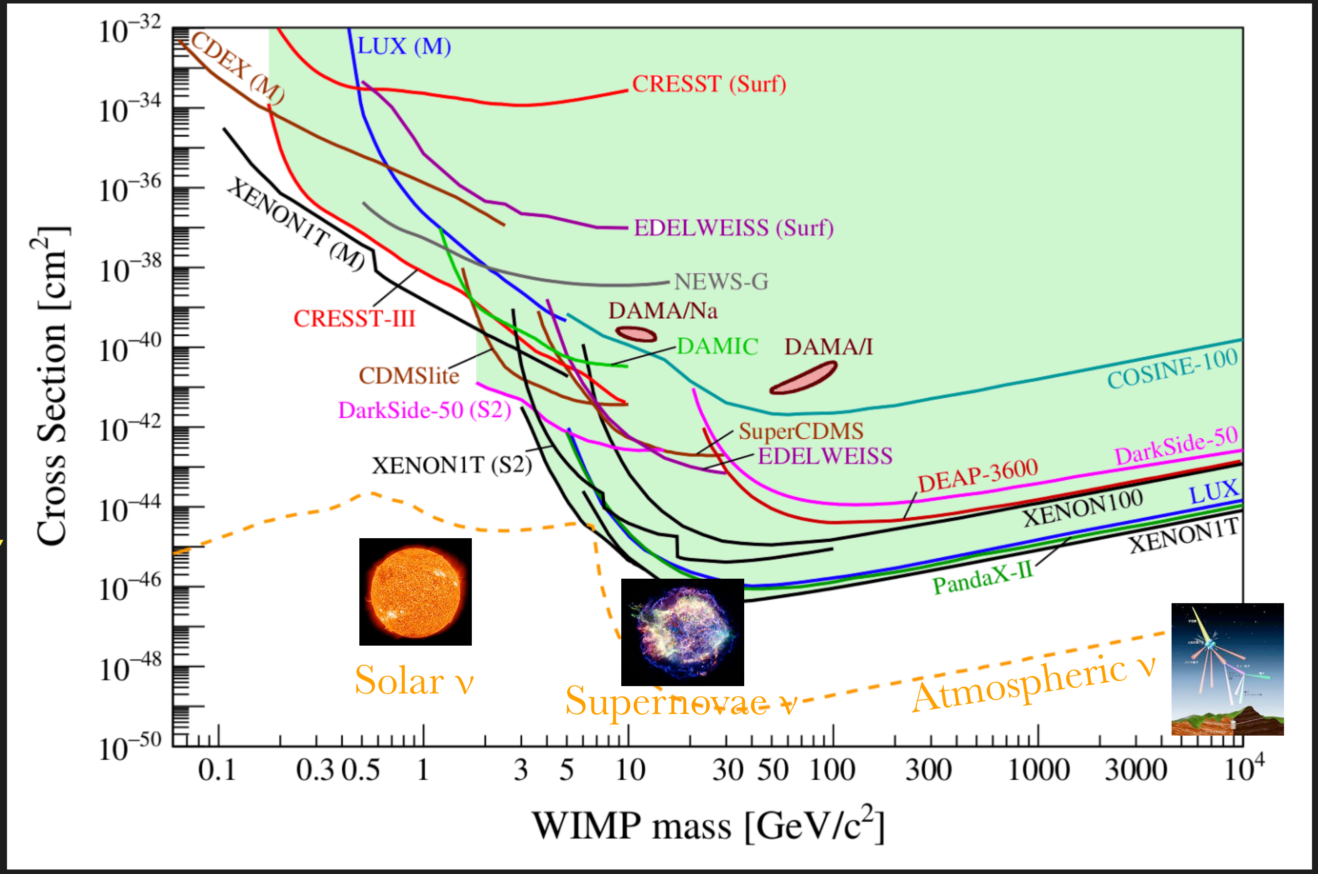
STANDARD WIMPs

DIRECT WIMP SEARCHES

DM-nuclei scattering:
spin-independent (strong bounds due to coherent enhancement) or spin-dependent (weaker bounds)



spin-independent WIMP-nucleon interactions



Exposure+
Background

Threshold

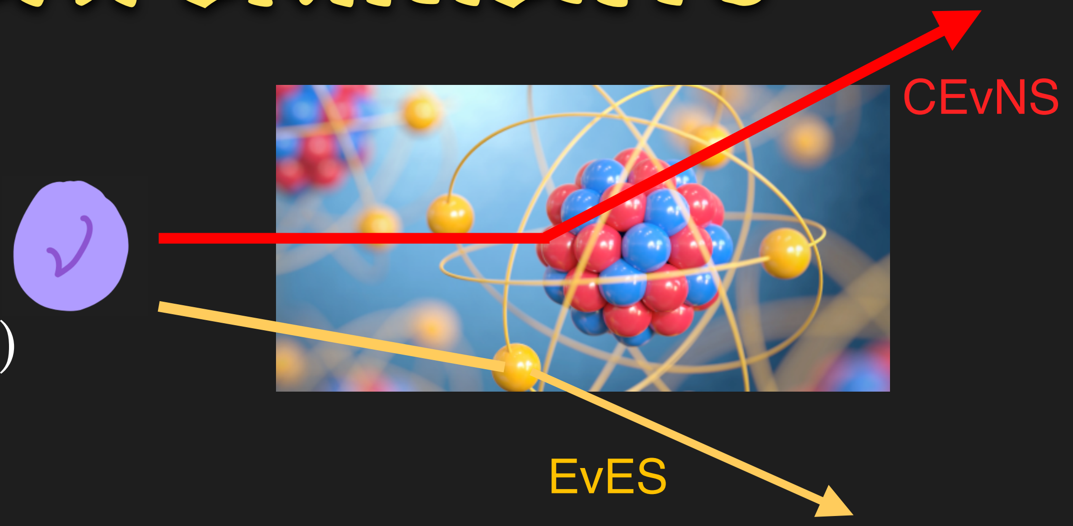
Direct Detection of Dark Matter – APPEC Committee Report 2021

NEUTRINOS IN DM DD EXPERIMENTS

Neutrinos can induce

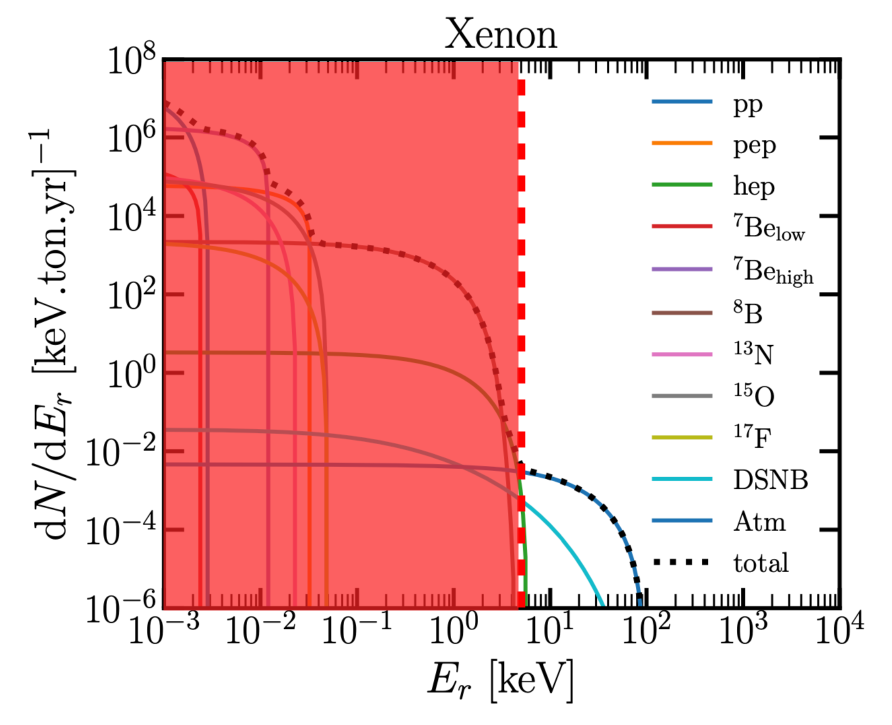
- elastic neutrino-electron scattering (EνES)
- coherent elastic neutrino-nucleus scattering (CEνNS)

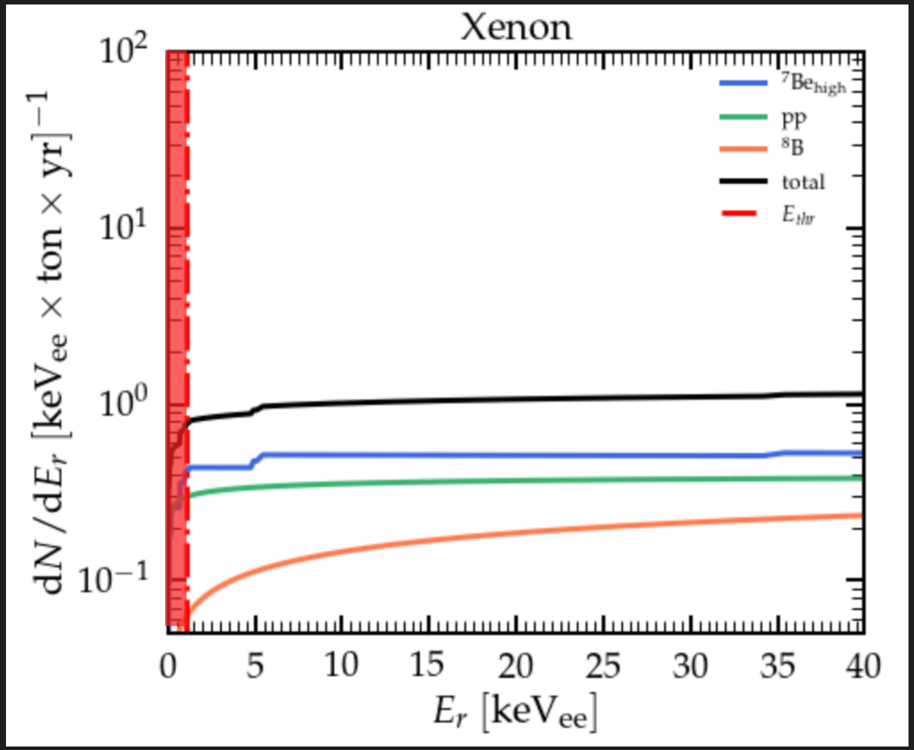
events in DM DD experiments.



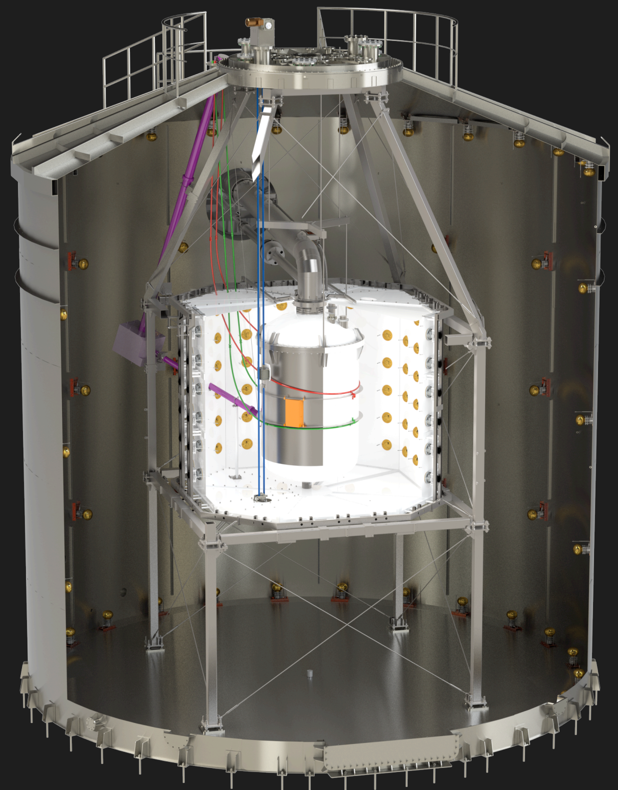
Due to threshold limitations, solar neutrinos are currently detected mainly through EνES.

Given the current detector technology, for EνES (CEνNS) only the pp and ^{7}Be (^{8}B) components of the total solar neutrino flux contribute significantly to the detectable event rates.





DM detectors can act as neutrino detectors:
low-threshold ($E_{thr} = 1$ keV) dual-phase liquid xenon (LXe) detectors are already sensitive to non-negligible fluxes of solar neutrinos via EvES.

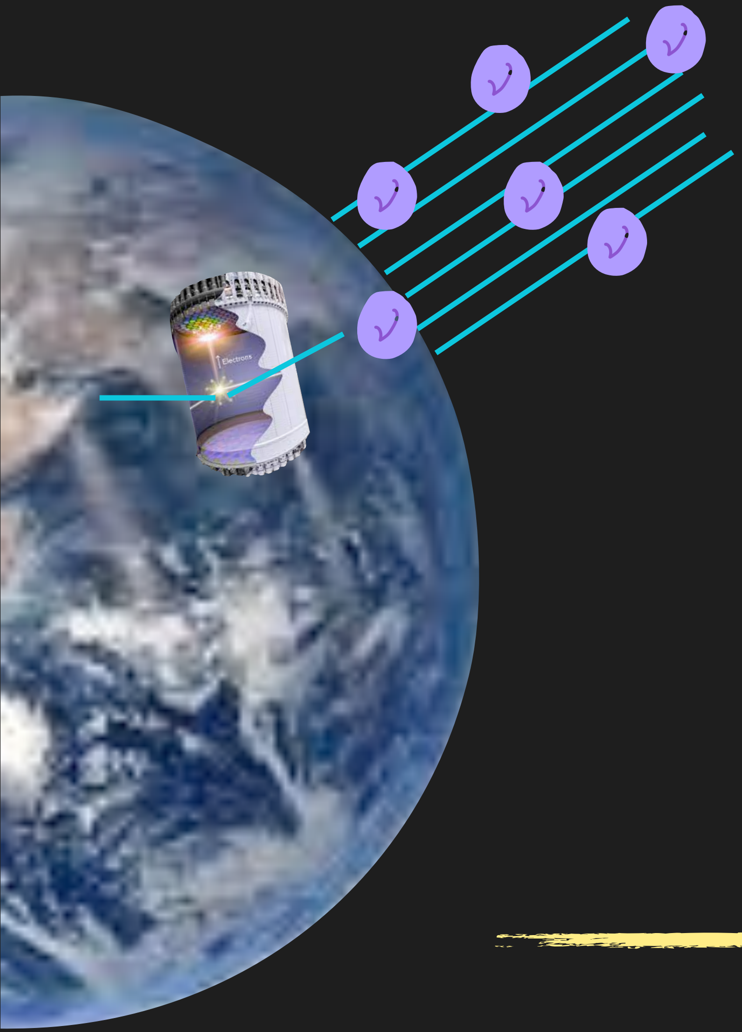


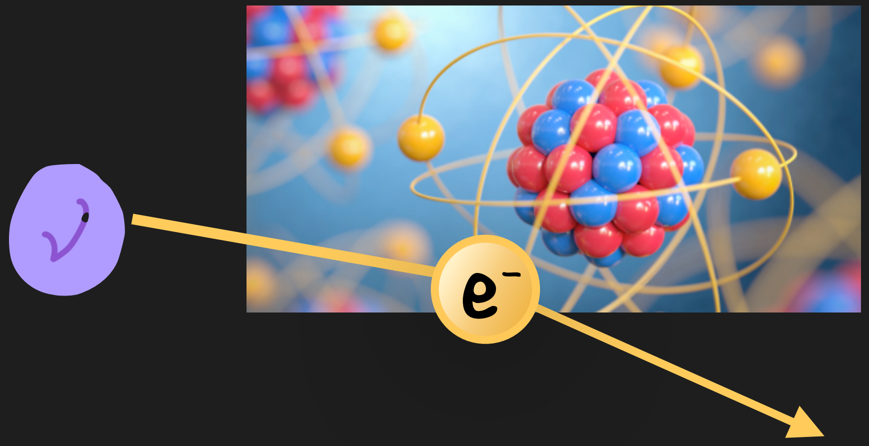
PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

XENON Collaboration, E. Aprile et al., Phys. Rev. Lett. 129 no. 16, (2022) 161805
LZ Collaboration, J. Aalbers et al., Phys. Rev. Lett. 131 no. 4, (2023) 041002
PandaX Collaboration, D. Zhang et al., Phys. Rev. Lett. 129 no. 16, (2022) 161804

ELASTIC NEUTRINO-ELECTRON SCATTERING

$$\left.\frac{d\sigma_{\nu_\alpha \mathcal{A}}}{dT_e}\right|^{\rm SM} = Z_{\rm eff}^{\mathcal{A}}(T_e)\frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2+(g_V-g_A)^2\left(1-\frac{T_e}{E_\nu}\right)^2-(g_V^2-g_A^2)\frac{m_e T_e}{E_\nu^2}\right]$$





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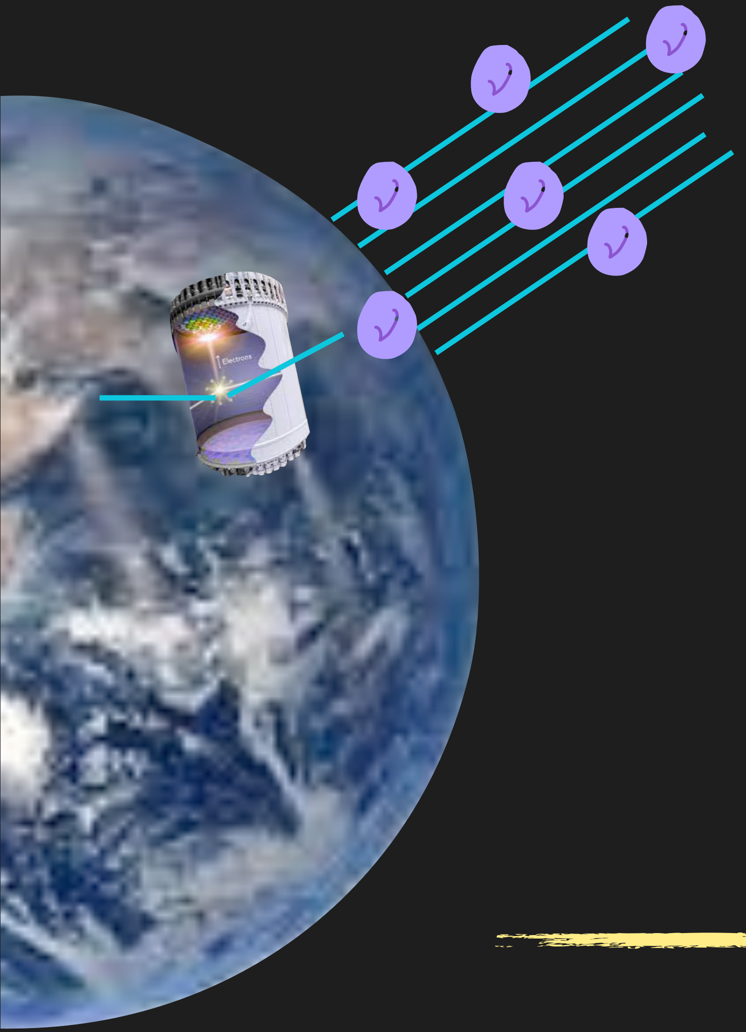
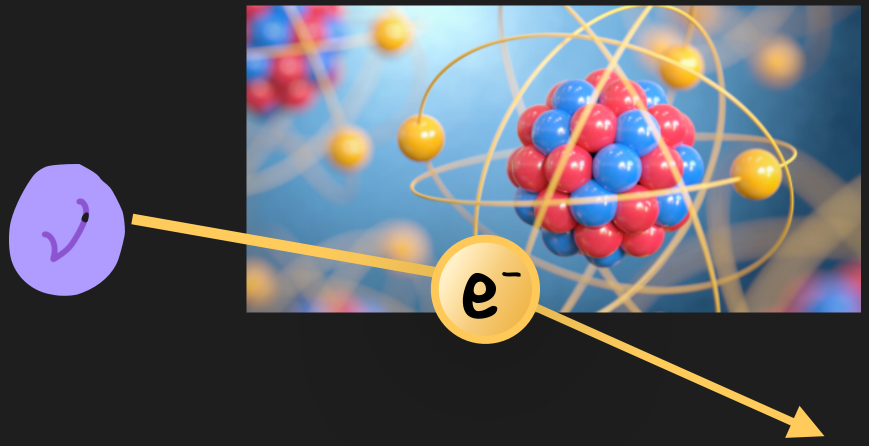
effective number of electrons that can be ionized





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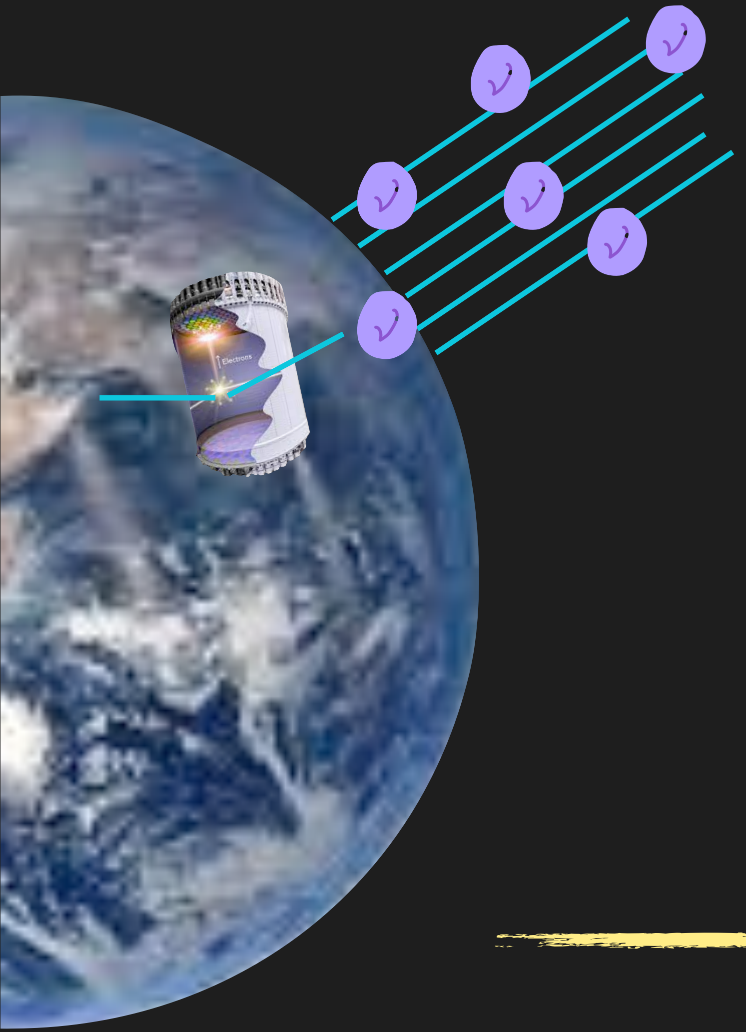
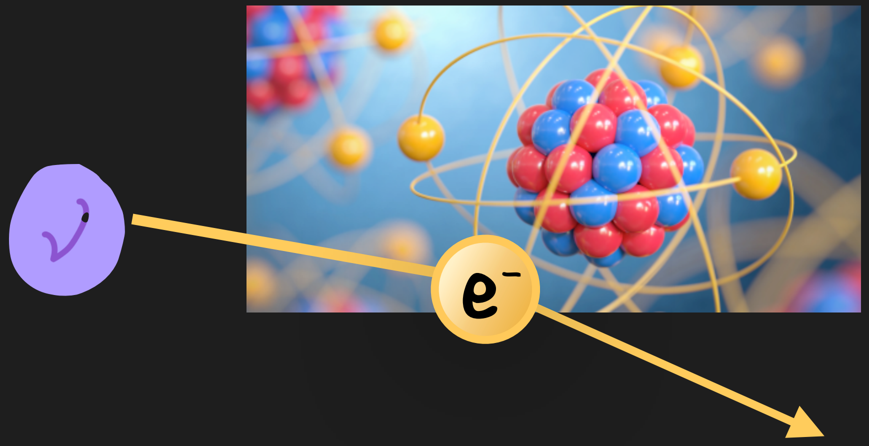
$$\frac{d\sigma_{\nu_\alpha \mathcal{A}}}{dT_e}\bigg|^{\mathrm{SM}} = Z^{\mathcal{A}}_{\mathrm{eff}}(T_e)\frac{G_F^2 m_e}{2\pi}\left[(\boxed{g_V}+\boxed{g_A})^2+(g_V-g_A)^2\left(1-\frac{T_e}{E_\nu}\right)^2-(g_V^2-g_A^2)\frac{m_e T_e}{E_\nu^2}\right]$$

$g_V = 2\sin^2\theta_W - 1/2 + \delta\alpha e$

$g_A = -1/2 + \delta_{\alpha e}$



For electron neutrinos both neutral and charged currents are relevant; for muon and tau flavors, only neutral current.



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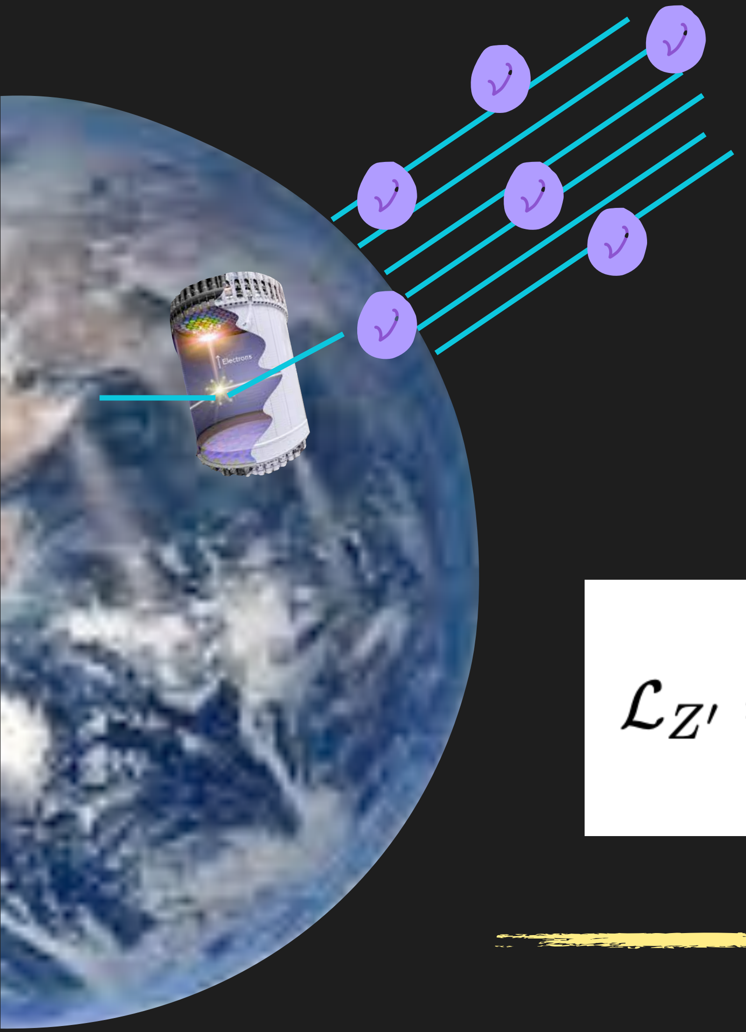
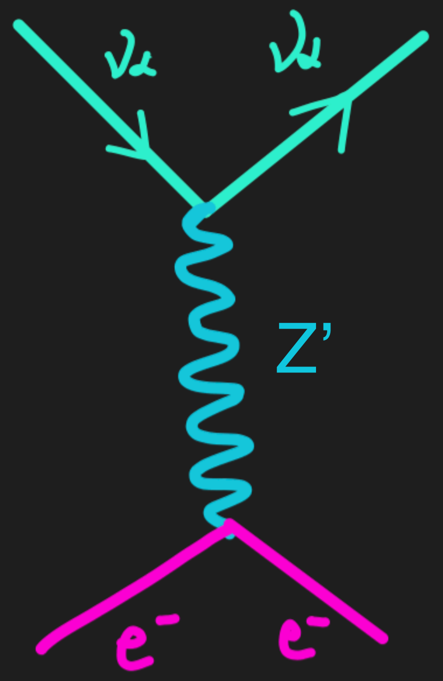


$$g_V \to g_V^{\mathrm{SM}} + \frac{(g_{Z'})^2 Q_{Z'}^{e} Q_{Z'}^{\nu_\alpha}}{\sqrt{2}G_F(2m_eT_e+m_{Z'}^2)}$$



$$\mathcal{L}_{Z'} = \boxed{g_{Z'}} Z'_\mu\left(\boxed{Q_{Z'}^{f}}\bar{f}\gamma^\mu f + \sum_\alpha \boxed{Q_{Z'}^{\nu_\alpha}}\bar{\nu}_{\alpha,L}\gamma^\mu \nu_{\alpha,L}\right) + \frac{1}{2}m_{Z'}^2 Z'^\mu Z'_\mu$$

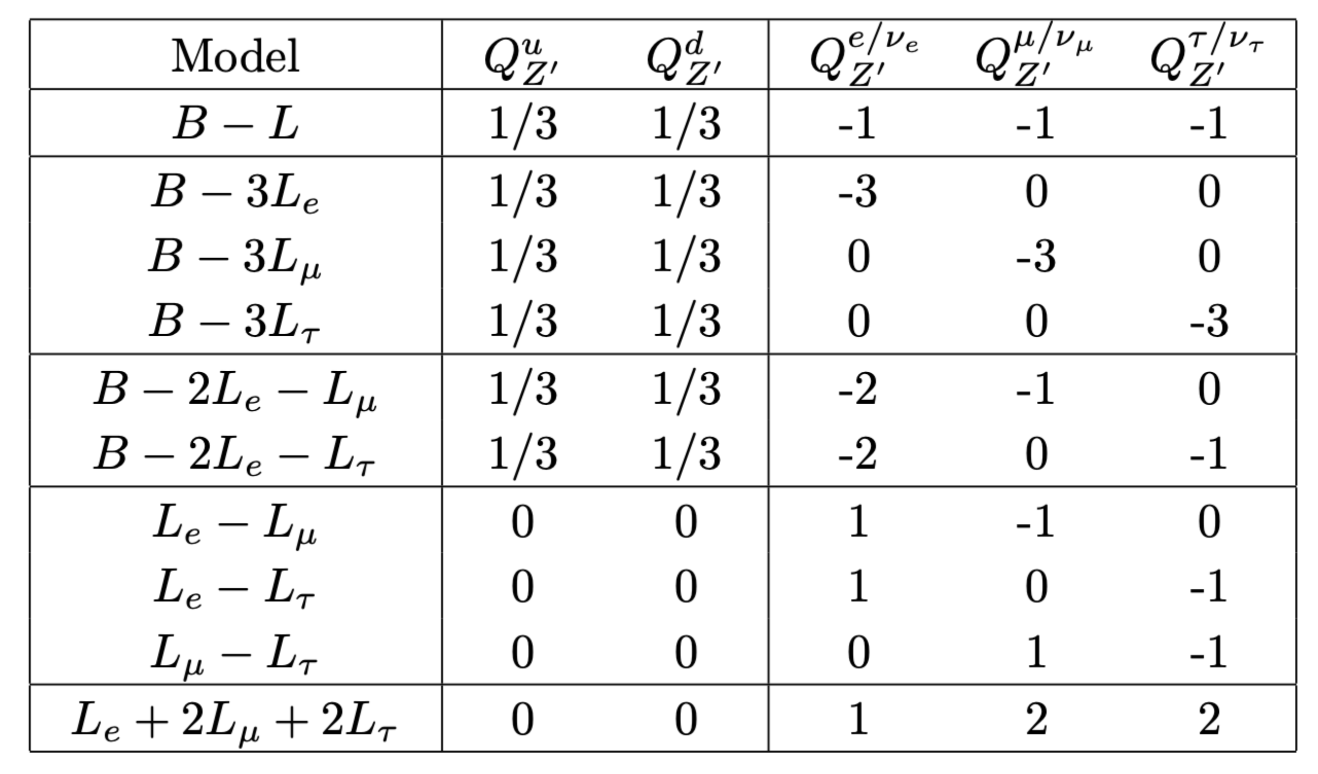
LIGHT VECTOR MEDIATORS

Universal Z′ model in which all the standard fermions have the same charge: not anomaly-free.
It can be extended with new non-standard particles to make it anomaly-free.

We consider U(1)’ models that are anomaly-free.
In some cases the SM is extended with the introduction of three right-handed neutrinos
➜ Possible explanation for neutrino masses and mixings

There is an infinite set of anomaly-free U(1)′ gauge groups generated by

$$c_1 B_1 + c_2 B_2 + c_3 B_3 - c_e L_e - c_\mu L_\mu - c_\tau L_\tau$$



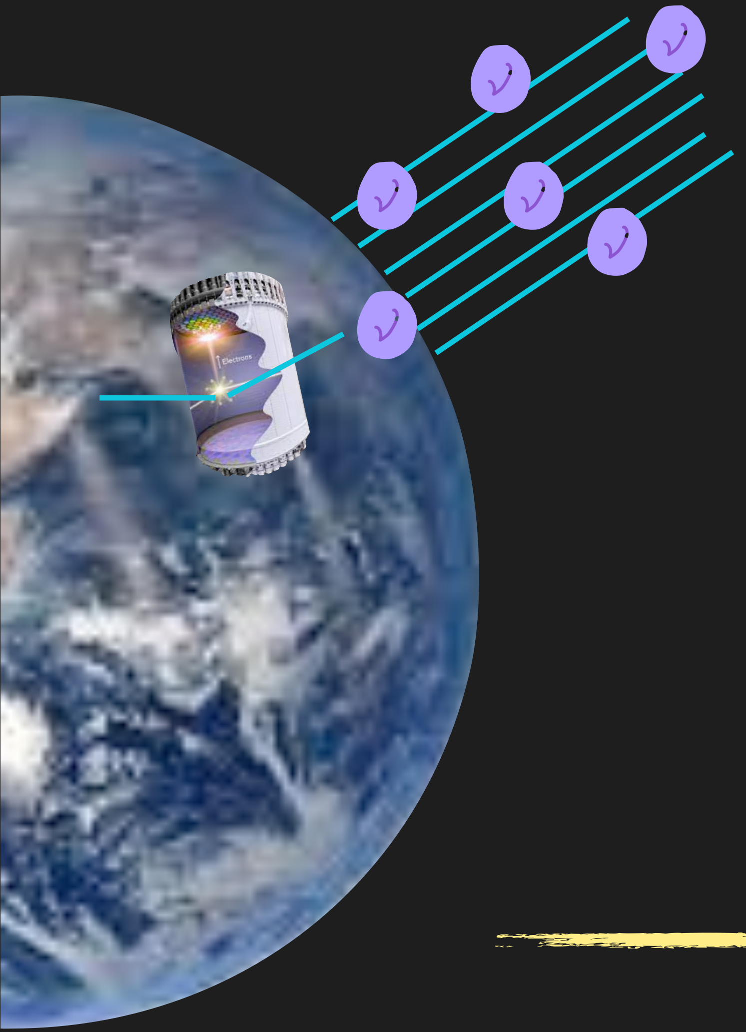
Model	$Q^u_{Z'}$	$Q^d_{Z'}$	$Q^{e/\nu_e}_{Z'}$	$Q^{\mu/\nu_\mu}_{Z'}$	$Q^{\tau/\nu_\tau}_{Z'}$
$B-L$	1/3	1/3	-1	-1	-1
$B-3L_e$	1/3	1/3	-3	0	0
$B-3L_\mu$	1/3	1/3	0	-3	0
$B-3L_\tau$	1/3	1/3	0	0	-3
$B-2L_e-L_\mu$	1/3	1/3	-2	-1	0
$B-2L_e-L_\tau$	1/3	1/3	-2	0	-1
L_e-L_μ	0	0	1	-1	0
L_e-L_τ	0	0	1	0	-1
$L_\mu-L_\tau$	0	0	0	1	-1
$L_e+2L_\mu+2L_\tau$	0	0	1	2	2

See e.g.
Paul Langacker Rev. Mod. Phys. 81, 1199–1228 (2009)
de la Vega+ JHEP 09 (2021) 146
Atzori Corona+ JHEP 05 (2022) 109
T. Han+ JHEP 11 (2019) 028
Coloma+ JHEP 01 (2021) 114
…

ELASTIC NEUTRINO-ELECTRON SCATTERING: LEPTOPHILIC MODEL L_μ-L_τ

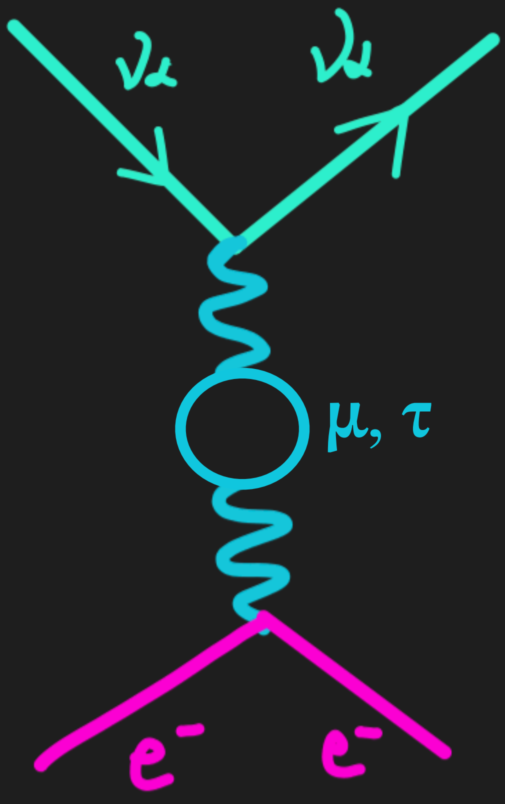
$$\left.\frac{d\sigma_{\nu_\alpha \mathcal{A}}}{dT_e}\right|^{\rm SM} = Z^{\mathcal{A}}_{\rm eff}(T_e)\frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2+(g_V-g_A)^2\left(1-\frac{T_e}{E_\nu}\right)^2-(g_V^2-g_A^2)\frac{m_eT_e}{E_\nu^2}\right]$$

There is no direct coupling to electrons
So the new contribution arises at the one-loop level:



$$g_V \to g_V^{\rm SM} - \frac{\sqrt{2}\alpha_{\rm em} g_{Z'}^2(\delta_{\alpha\mu}-\delta_{\alpha\tau})}{\pi G_F(2m_eT_e+m_V^2)}\boxed{\epsilon_{\tau\mu}(|\vec{q}|)}$$

$$\sim \frac{1}{6}\ln\left(\frac{\mathrm{m}_\tau^2}{\mathrm{m}_\mu^2}\right)$$



DATA ANALYSIS: XENONnT, LZ & PANDAX

$$R_k^{\mathrm{E}\nu\mathrm{ES}} = \mathcal{N} \int_{T_e^k}^{T_e^{k+1}} dT_e \underset{\text{Efficiency}}{A(T_e)} \int_0^{T_e'^{\,\mathrm{max}}} dT_e' \; R(\overset{\text{Reconstructed E}}{T_e}\,\underset{\text{True E}}{T_e'}) \sum_{i=pp,{}^7\mathrm{Be}} \int_{E_\nu^{\mathrm{min}}}^{E_{\nu,i}^{\mathrm{max}}} dE_\nu \sum_\alpha \Phi^i_{\nu_\alpha}(E_\nu) \underset{\text{EvES xsec}}{\frac{d\sigma_{\nu_\alpha \mathcal{A}}}{dT_e'}}$$

- $\mathcal{N} = \varepsilon N_T$ is a normalization constant that takes into account the exposure

$\varepsilon = \{1.16, 0.90, 0.63\}$ ton × year for XENONnT, LZ and PandaX-4T

- Main contributions from pp and ^{7}Be neutrinos. Produced as electron neutrinos, they oscillate into other flavors
- LZ and PandaX-4T: Poissonian least-squares function; XENONnT: χ^2 analysis

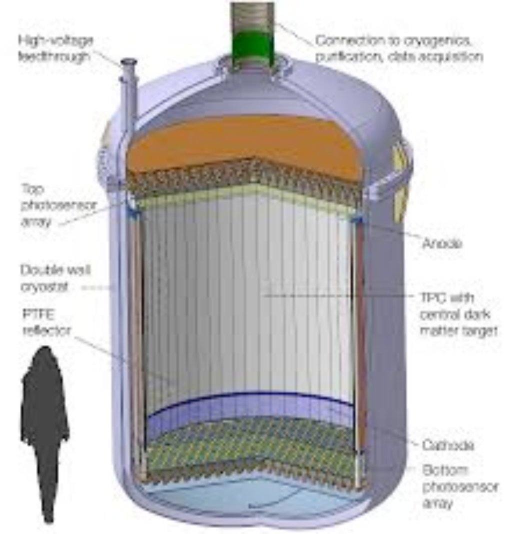
Total number of events include backgrounds

$$R_k^X = R_k^{\mathrm{E}\nu\mathrm{ES}} + \sum_i R_k^i$$

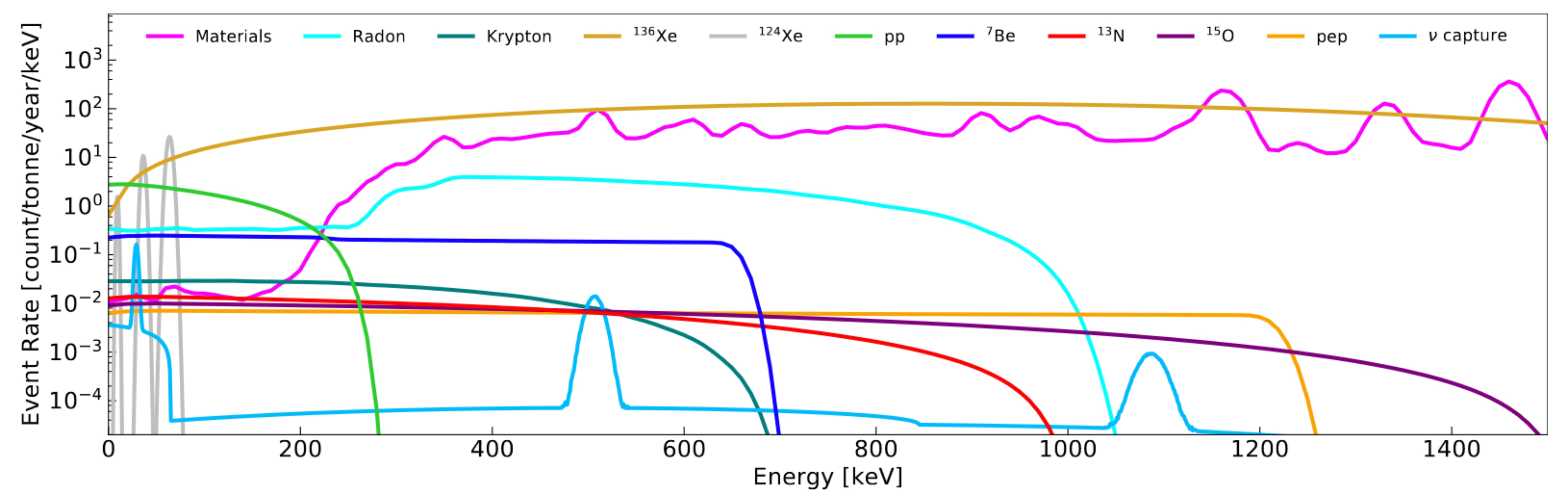
DATA:
XENON Collaboration, E. Aprile et al., Phys. Rev. Lett. 129 no. 16, (2022) 161805
LZ Collaboration, J. Aalbers et al., Phys. Rev. Lett. 131 no. 4, (2023) 041002
PandaX Collaboration, D. Zhang et al., Phys. Rev. Lett. 129 no. 16, (2022) 161804

EFFICIENCIES:
XENON Collaboration, E. Aprile et al., Phys. Rev. Lett. 129 no. 16, (2022) 161805
LZ Collaboration, J. Aalbers et al., arXiv:2307.15753
PandaX Collaboration, D. Zhang et al., Phys. Rev. Lett. 129 no. 16, (2022) 161804

SENSITIVITY AT DARWIN

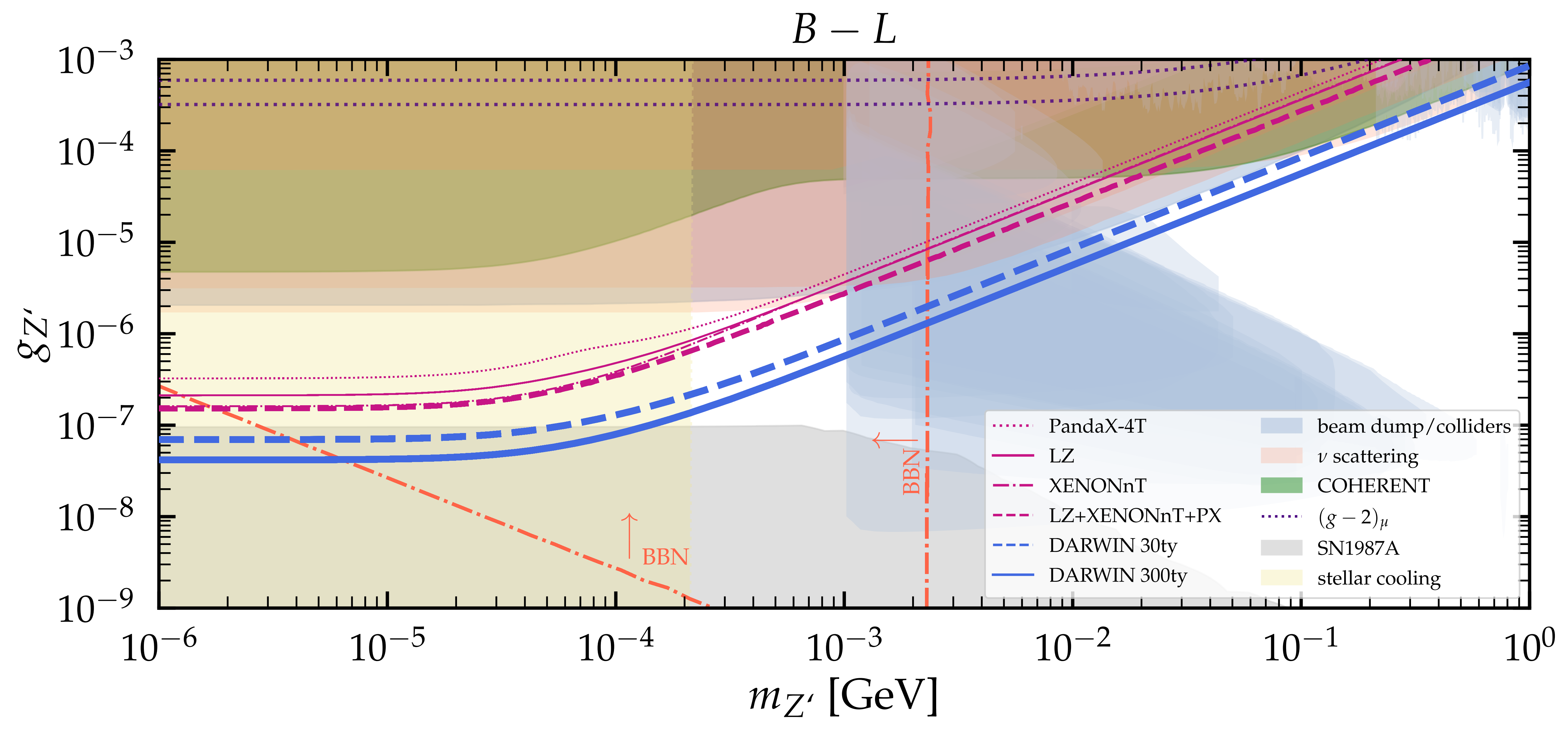


- Same analysis as for current experiments
- We also include the contributions from solar N, O and pep neutrinos
- We use the same resolution function and detector efficiency as for XENONnT
- We consider exposures of 30 ton × years and 300 ton × years.



DARWIN Collaboration, Eur. Phys. J. C 80 no. 12, (2020) 1133

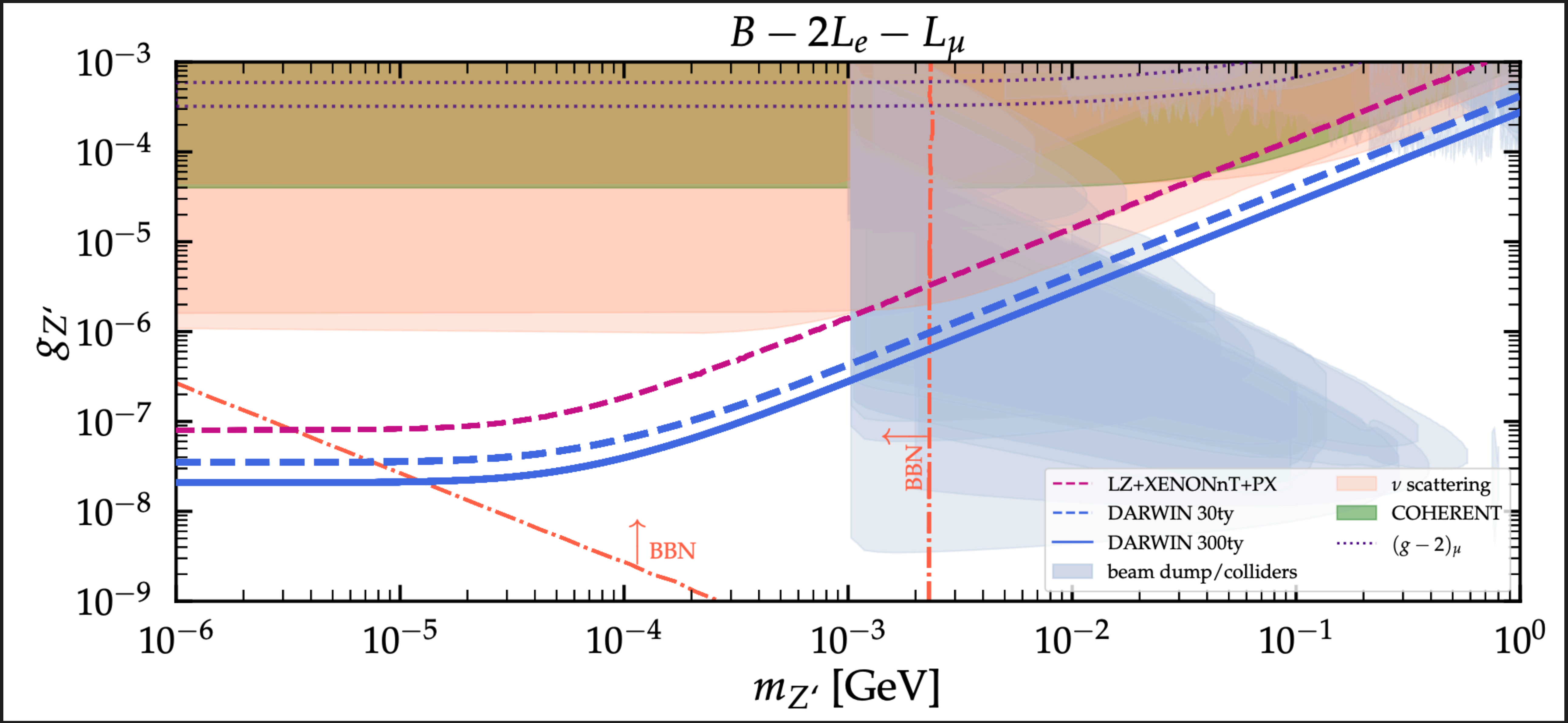
B-L MODEL



VDR, Papoulias, Ternes 2402.05506

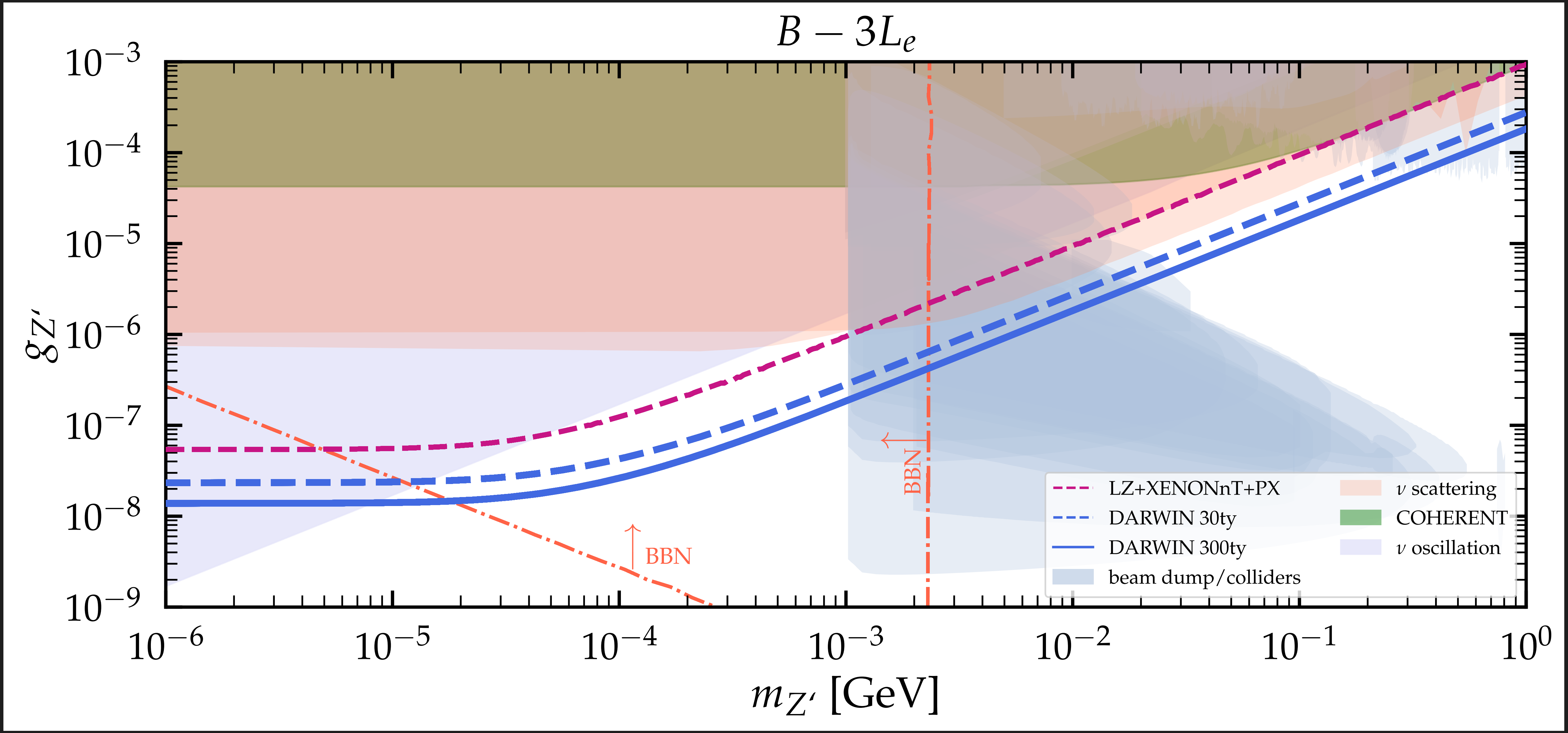
DarkCast: Ilten+ JHEP 06 (2018) 004
COHERENT: M. Atzori Corona+ JHEP 05 (2022) 109, P. Melas+ JHEP 07 (2023) 190
NA64 Collaboration Phys. Rev. Lett. 129 no. 16, (2022) 161801
BBN: G.-y. Huang+ Phys. Rev. D 97 no. 7, (2018) 075009
Li & Xu JCAP 09 (2023) 009
SN: J. H. Chang+ JHEP 01 (2017) 107

B -2Le-Lμ MODEL



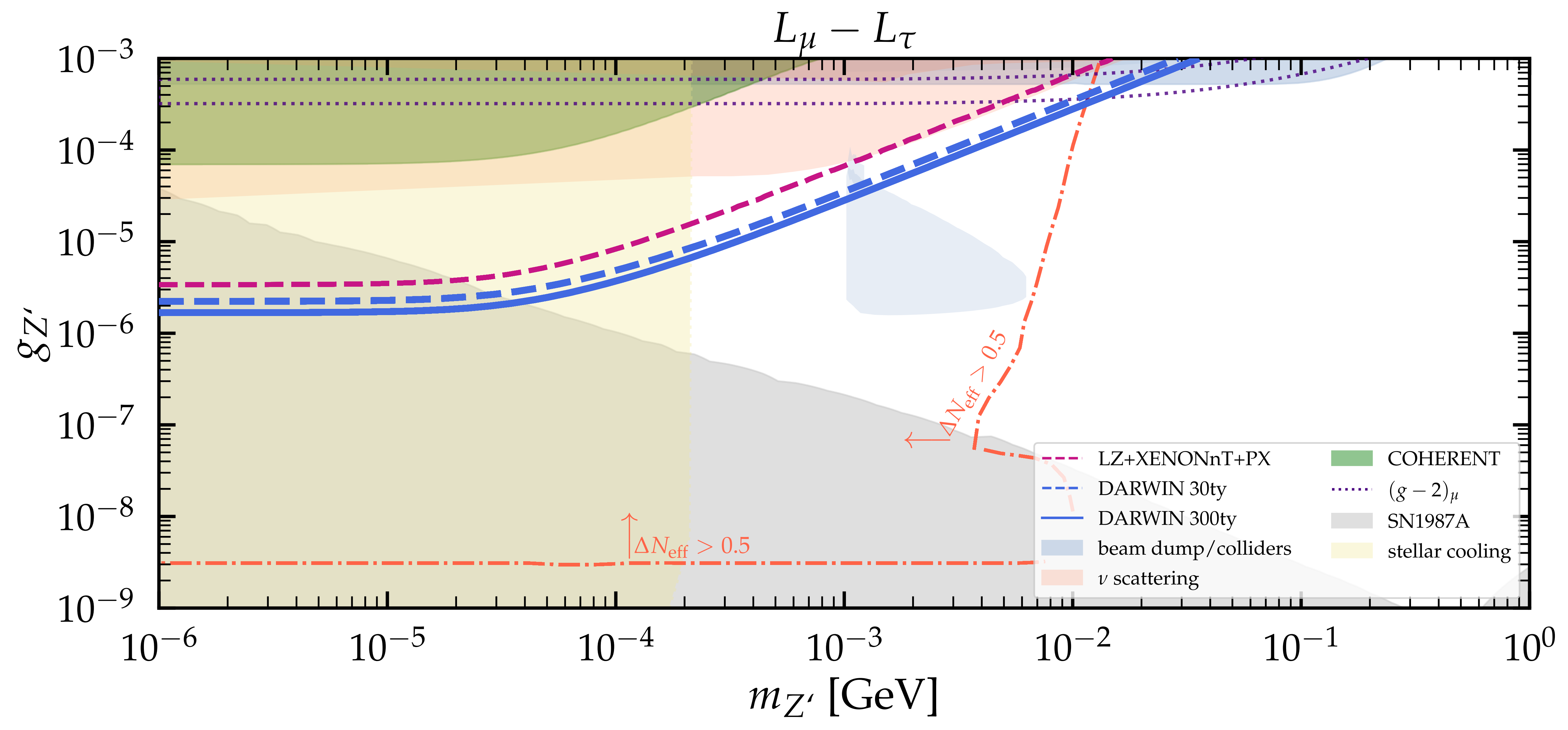
VDR, Papoulias, Ternes 2402.05506

B -3Le MODEL



VDR, Papoulias, Ternes 2402.05506

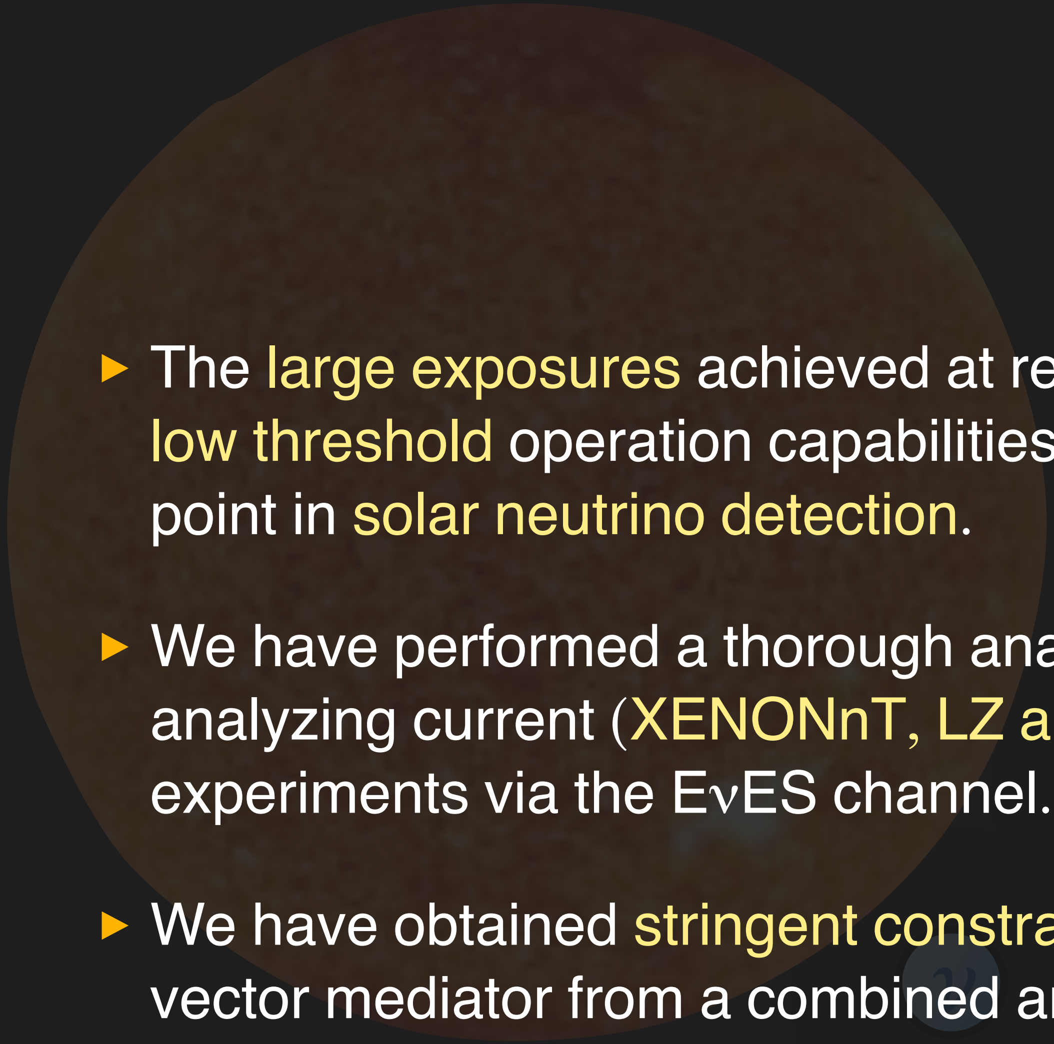
$L\mu$ -$L\tau$ MODEL



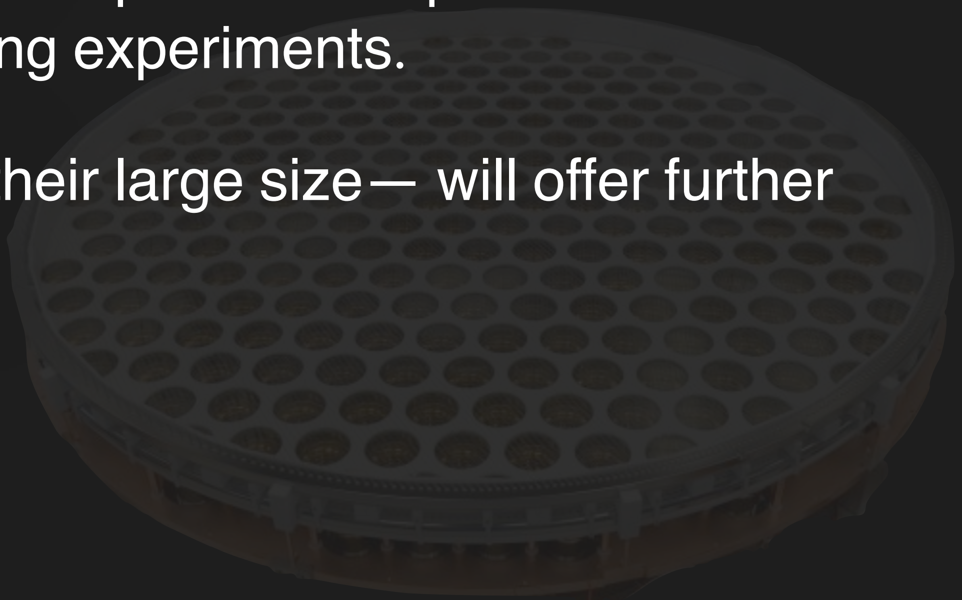
VDR, Papoulias, Ternes 2402.05506

∆Neff: M. Escudero+ JHEP 03 (2019) 071
COH: Melas+ JHEP 07 (2023) 190
NA64: Andreev+ arXiv:2401.01708 [hep-ex]
Oscillations: Coloma et al., JHEP 01 (2021) 114
SN: Croon et al. JHEP 01 (2021) 107

SUMMARY



- The large exposures achieved at recent DM DD experiments, combined with the very low threshold operation capabilities of recent and future detectors, mark a turning point in solar neutrino detection.
- We have performed a thorough analysis of compelling, anomaly-free U(1)' models, by analyzing current (XENONnT, LZ and PandaX-4T) and future (DARWIN) DM DD experiments via the EνES channel.
- We have obtained stringent constraints on the relevant parameter space of the new vector mediator from a combined analysis of ongoing experiments.
- Future DM DD experiments like DARWIN —given their large size— will offer further improvements.



SUMMARY

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Thank you!