COHERENT bounds on light mediator models

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June 12th 2024

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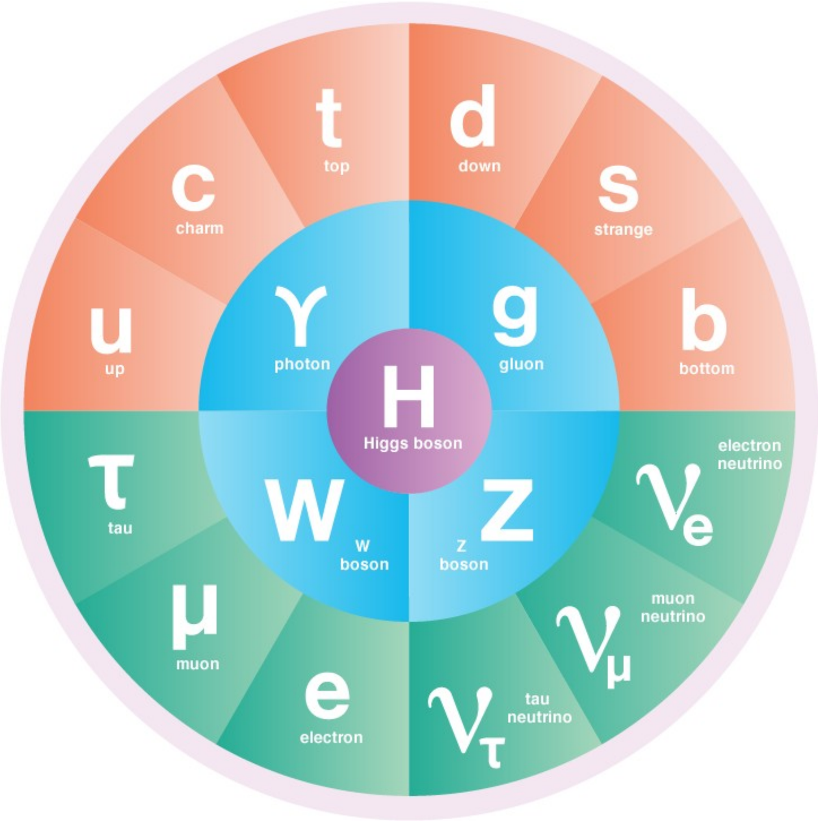
THE MAGNIFICENT CEνNS

Standard model neutrinos



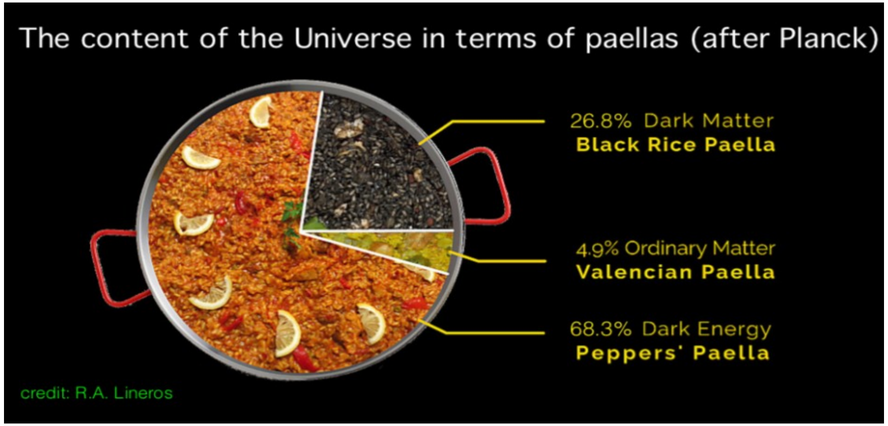
Neutrinos were predicted to explain the continuity of beta-spectra in 1930

Each charged lepton has a flavor neutrinos associated to them

Neutrinos belong to SU(2) doublets and are massless and neutral

We need physics beyond the standard model

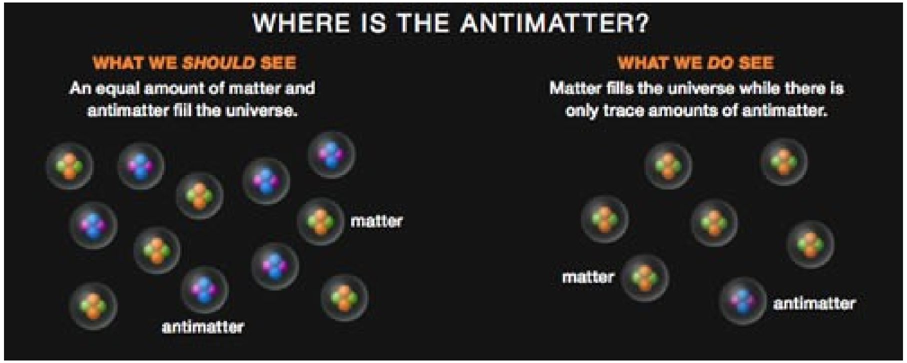
What are dark matter and dark energy?



The content of the Universe in terms of paellas (after Planck)

credit: R.A. Lineros

Baryon asymmetry of the universe?



WHERE IS THE ANTIMATTER?

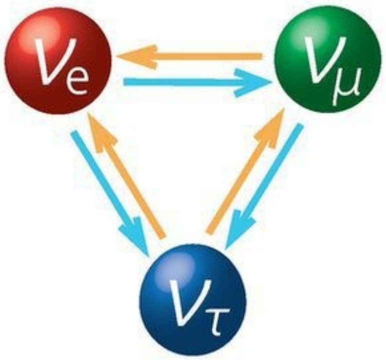
WHAT WE *SHOULD* SEE

An equal amount of matter and antimatter fill the universe.

WHAT WE *DO* SEE

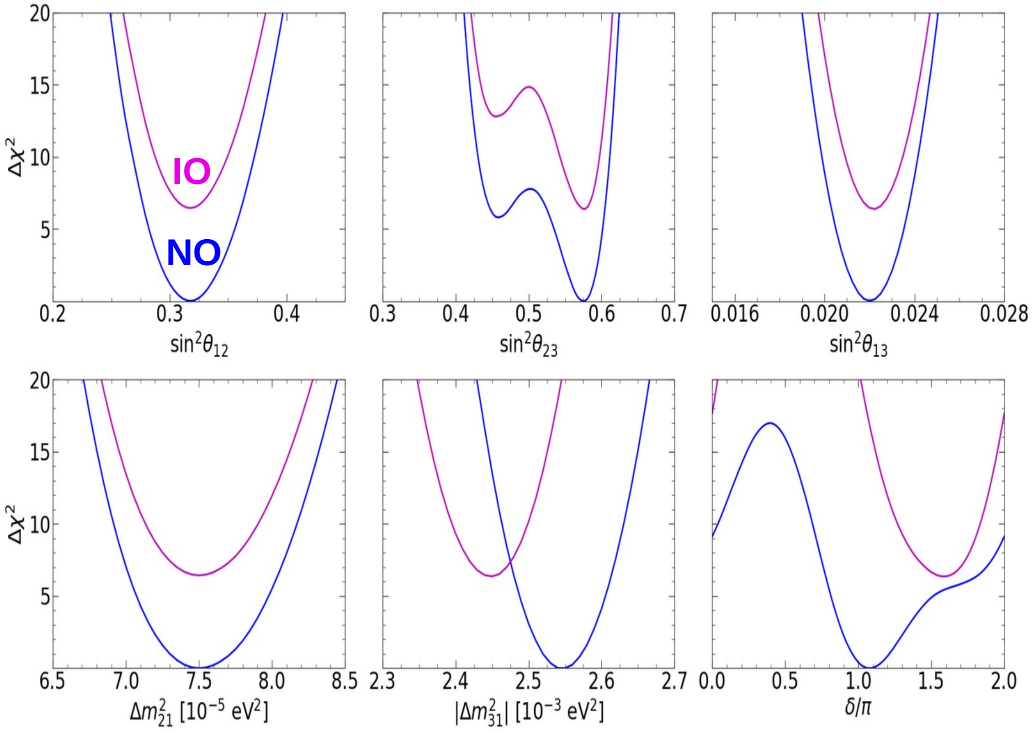
Matter fills the universe while there is only trace amounts of antimatter.

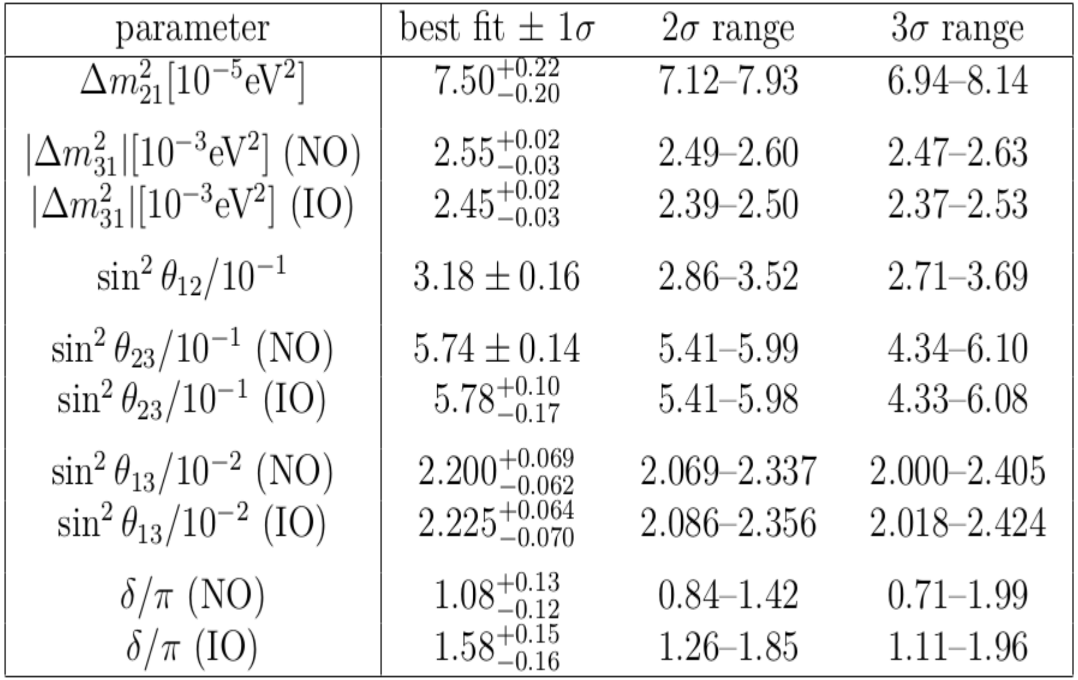
Neutrino oscillations?



Neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



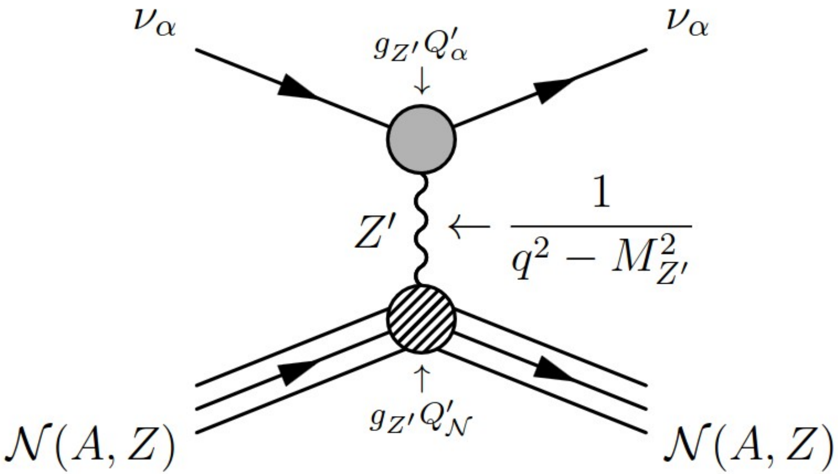


parameter	best fit ± 1σ	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

See also:
Bari - 2107.00532, PRD 2021

See also:
NuFit - 2111.03086, Universe 2021

Light vector mediators

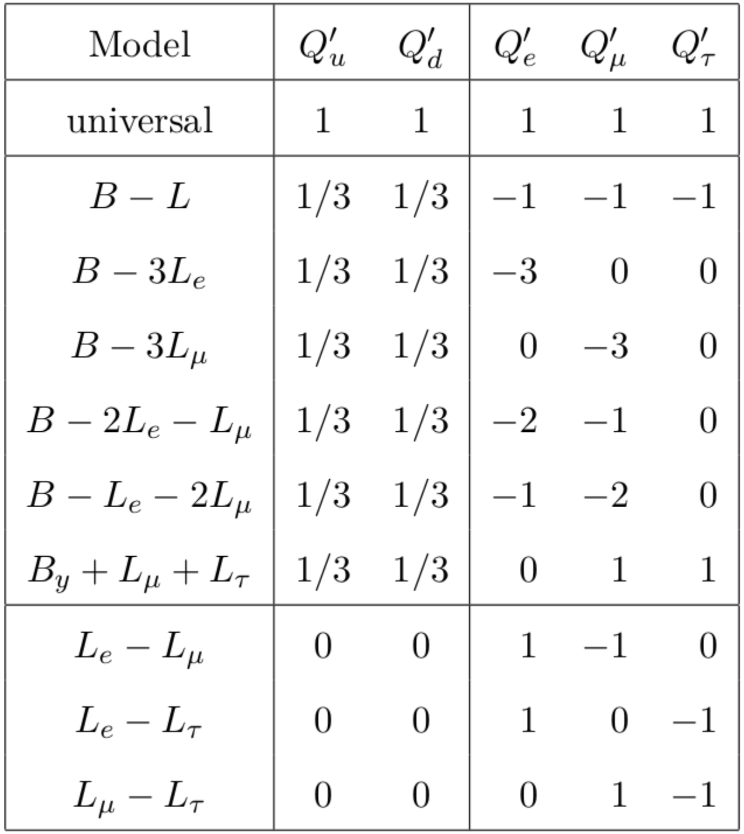


Some extensions of the Standard Model have new gauge bosons

Depending on the model the charges can be different for quarks and leptons

$$\mathcal{L}_{Z'}^{V} = -Z'_\mu \left[\sum_{\ell=e,\mu,\tau} g_{Z'}^{\nu_\ell V}\, \overline{\nu_{\ell L}} \gamma^\mu \nu_{\ell L} + \sum_{q=u,d} g_{Z'}^{qV}\, \overline{q} \gamma^\mu q \right]$$

Light vector mediators



Model	Q'_u	Q'_d	Q'_e	Q'_μ	Q'_τ
universal	1	1	1	1	1
$B-L$	$1/3$	$1/3$	-1	-1	-1
$B-3L_e$	$1/3$	$1/3$	-3	0	0
$B-3L_\mu$	$1/3$	$1/3$	0	-3	0
$B-2L_e-L_\mu$	$1/3$	$1/3$	-2	-1	0
$B-L_e-2L_\mu$	$1/3$	$1/3$	-1	-2	0
$B_y+L_\mu+L_\tau$	$1/3$	$1/3$	0	1	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

We consider U(1)’ models that are anomaly-free (except the universal one) if the SM is extended with three right-handed neutrinos

Possible explanation for neutrino masses and mixing

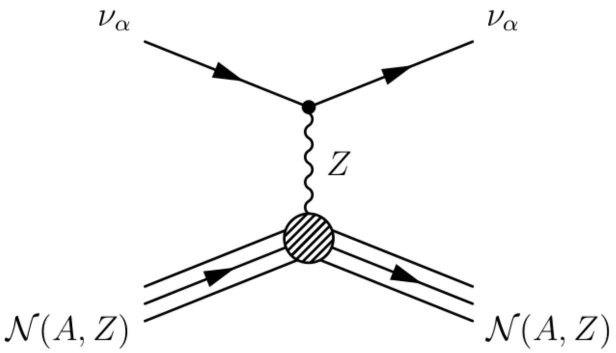
No direct coupling to nuclei for the L_α-L_β models

Atzori Corona et al, 2202.11002, JHEP 2022

Coherent elastic neutrino nucleus scattering

In the standard model we have

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\rm nr}}(E, T_{\rm nr}) = \frac{G_{\rm F}^2 M}{\pi}\left(1 - \frac{M T_{\rm nr}}{2E^2}\right)(Q_{\ell,{\rm SM}}^V)^2$$



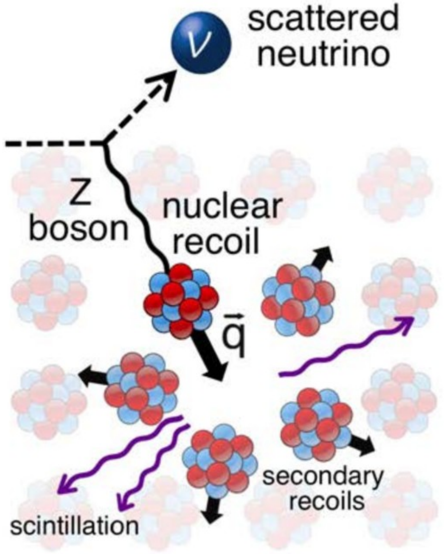
with the weak charge

$$Q_{\ell,{\rm SM}}^V = \left[g_V^p\,(\nu_\ell)\,Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]$$

$$g_V^p(\nu_e) = 0.0401, \qquad g_V^p(\nu_\mu) = 0.0318, \qquad g_V^n = -0.5094$$

The cross section scales with the neutron number squared

The form factors describe the loss of coherence for large momentum transfer



Coherent elastic neutrino nucleus scattering

In the standard model we have

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\rm nr}}(E,T_{\rm nr}) = \frac{G_{\rm F}^2 M}{\pi}\left(1-\frac{MT_{\rm nr}}{2E^2}\right)(Q^V_{\ell,\rm SM})^2 \qquad Q^V_{\ell,\rm SM} = \left[g_V^p\,(\nu_\ell)\,ZF_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]$$

When adding new vector mediators we need to replace

$$Q^V_{\ell,\rm SM+V} = Q^V_{\ell,\rm SM} + \frac{g_{Z'}^2 Q'_\ell}{\sqrt{2}G_F\left(|\vec{q}|^2+M_{Z'}^2\right)}\left[\left(2Q'_u+Q'_d\right)ZF_Z(|\vec{q}|^2) + \left(Q'_u+2Q'_d\right)NF_N(|\vec{q}|^2)\right]$$

or calculate the loop corrections

$$\left(\frac{d\sigma}{dT_{\rm nr}}\right)^{\nu_\ell-\mathcal{N}}_{L_\alpha-L_\beta}(E,T_{\rm nr}) = \frac{G_F^2 M}{\pi}\left(1-\frac{MT_{\rm nr}}{2E^2}\right)$$
$$\times\left\{\left[g_V^p\,(\nu_\ell) + \frac{\sqrt{2}\alpha_{\rm EM}g_{Z'}^2\left(\delta_{\ell\alpha}\varepsilon_{\beta\alpha}(|\vec{q}|)+\delta_{\ell\beta}\varepsilon_{\alpha\beta}(|\vec{q}|)\right)}{\pi G_F\left(|\vec{q}|^2+M_{Z'}^2\right)}\right]ZF_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right\}^2$$

$$\varepsilon_{\beta\alpha}(|\vec{q}|) = \int_0^1 x(1-x)\ln\left(\frac{m_\beta^2+x(1-x)|\vec{q}|^2}{m_\alpha^2+x(1-x)|\vec{q}|^2}\right)dx$$

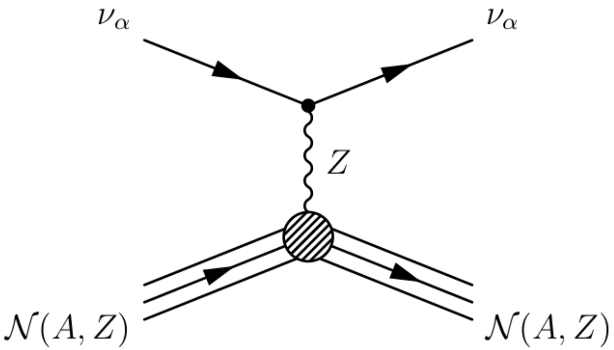
COHERENT

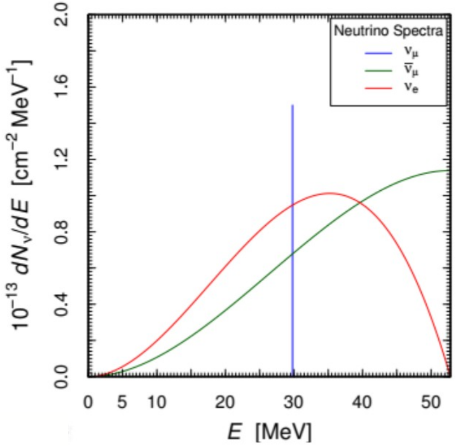
CEvNS was predicted in 1973! Freedman, PRD 1973

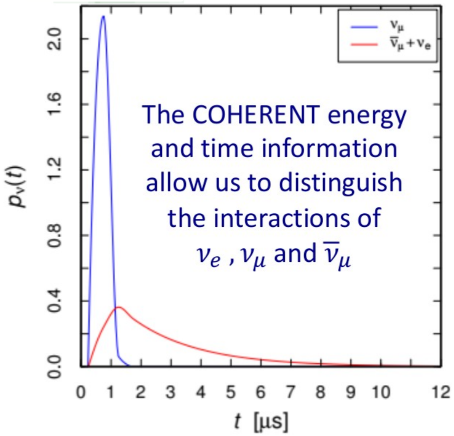
First observation of CEvNS in 2017 in the COHERENT experiment using neutrinos from decay of COHERENT, 1708.01294, Science 2017

$$\pi^+ \to \mu^+ + \nu_\mu$$

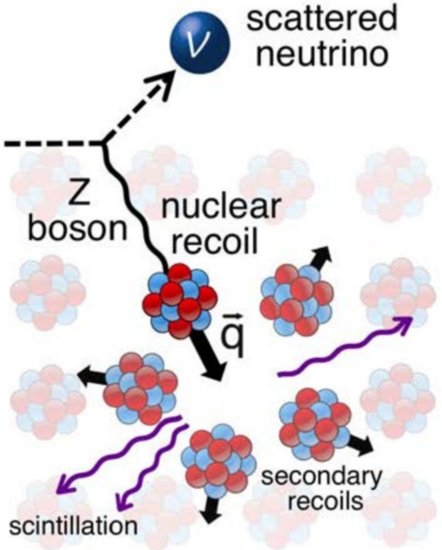
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$







The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ and $\bar{\nu}_\mu$



Cadeddu et al, 1810.05606, PRD 2018

COHERENT

Calculation is more complicated

$$N_i^{\mathrm{CE}\nu\mathrm{NS}} = N(\mathcal{N}) \int_{T_{\mathrm{nr}}^{i}}^{T_{\mathrm{nr}}^{i+1}} dT_{\mathrm{nr}}\, A(T_{\mathrm{nr}}) \int_{0}^{T'^{\mathrm{max}}_{\mathrm{nr}}} dT'_{\mathrm{nr}}\, R(T_{\mathrm{nr}}, T'_{\mathrm{nr}}) \int_{E_{\mathrm{min}}(T'_{\mathrm{nr}})}^{E_{\mathrm{max}}} dE \sum_{\nu=\nu_e,\nu_\mu,\bar{\nu}_\mu} \frac{dN_\nu}{dE}(E) \frac{d\sigma_{\nu-\mathcal{N}}}{dT_{\mathrm{nr}}}(E, T'_{\mathrm{nr}})$$

Detector effects (resolution, efficiency, quenching) must be taken into account when calculating the expected number of events

In the statistical analysis we must consider several sources of background and associated systematic uncertainties

$$\chi^2_{\mathrm{CsI}} = 2 \sum_{i=1}^{9} \sum_{j=1}^{11} \left[\sum_{z=1}^{4} (1+\eta_z) N_{ij}^{z} - N_{ij}^{\mathrm{exp}} + N_{ij}^{\mathrm{exp}} \ln \left(\frac{N_{ij}^{\mathrm{exp}}}{\sum_{z=1}^{4} (1+\eta_z) N_{ij}^{z}} \right) \right] + \sum_{z=1}^{4} \left(\frac{\eta_z}{\sigma_z} \right)^2$$

Atzori Corona et al, 2202.11002, JHEP 2022
Atzori Corona et al, 2205.09484, JHEP 2022

COHERENT

Data included

CEvNS on CsI scintillating crystal

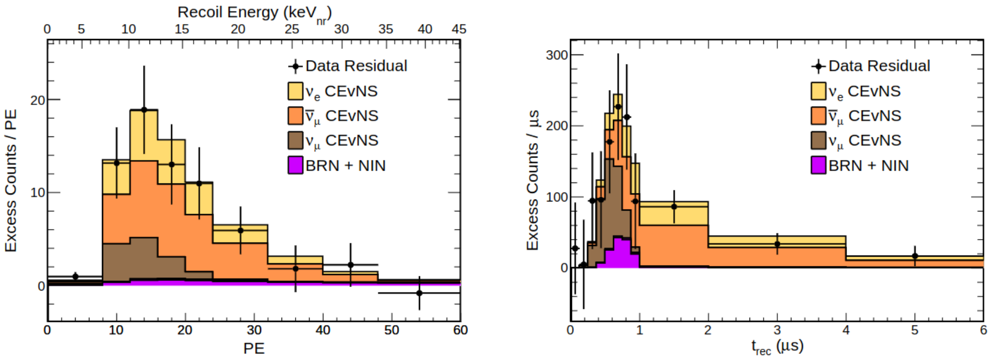
306 ± 20 events, $> 11\sigma$

consistent with SM

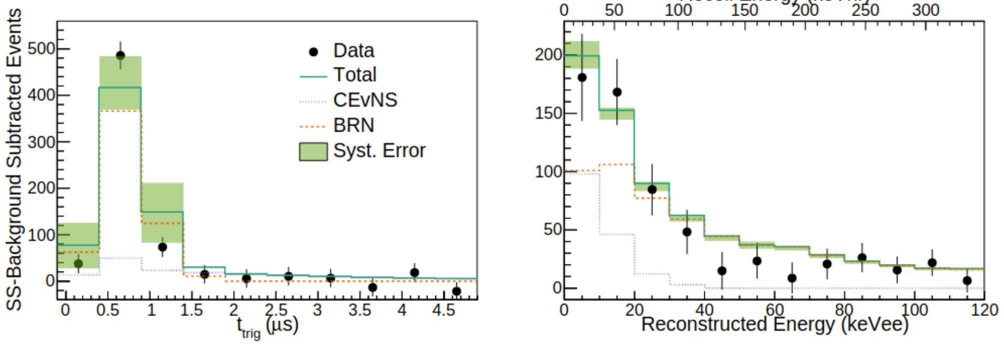
Data included

CEvNS on liquid argon

Still collecting data, more data expected to come soon

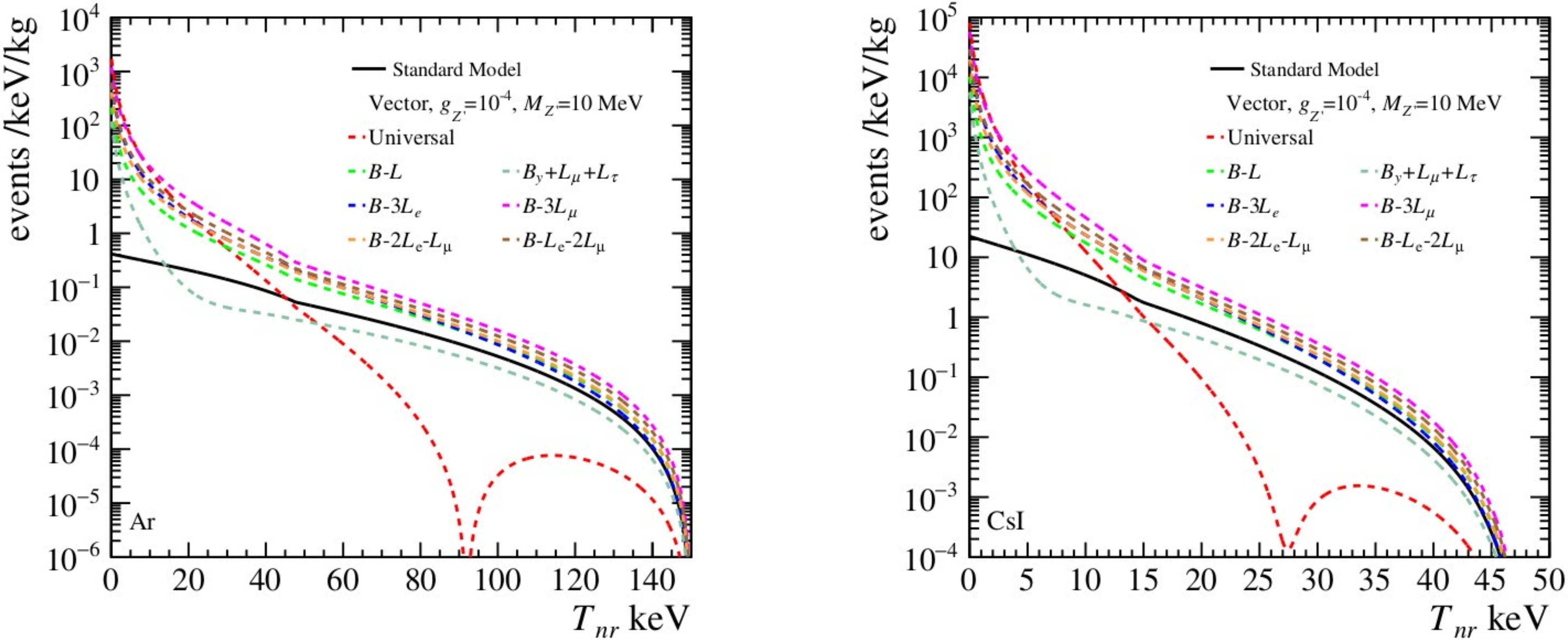


COHERENT, 2110.07730, PRL 2022



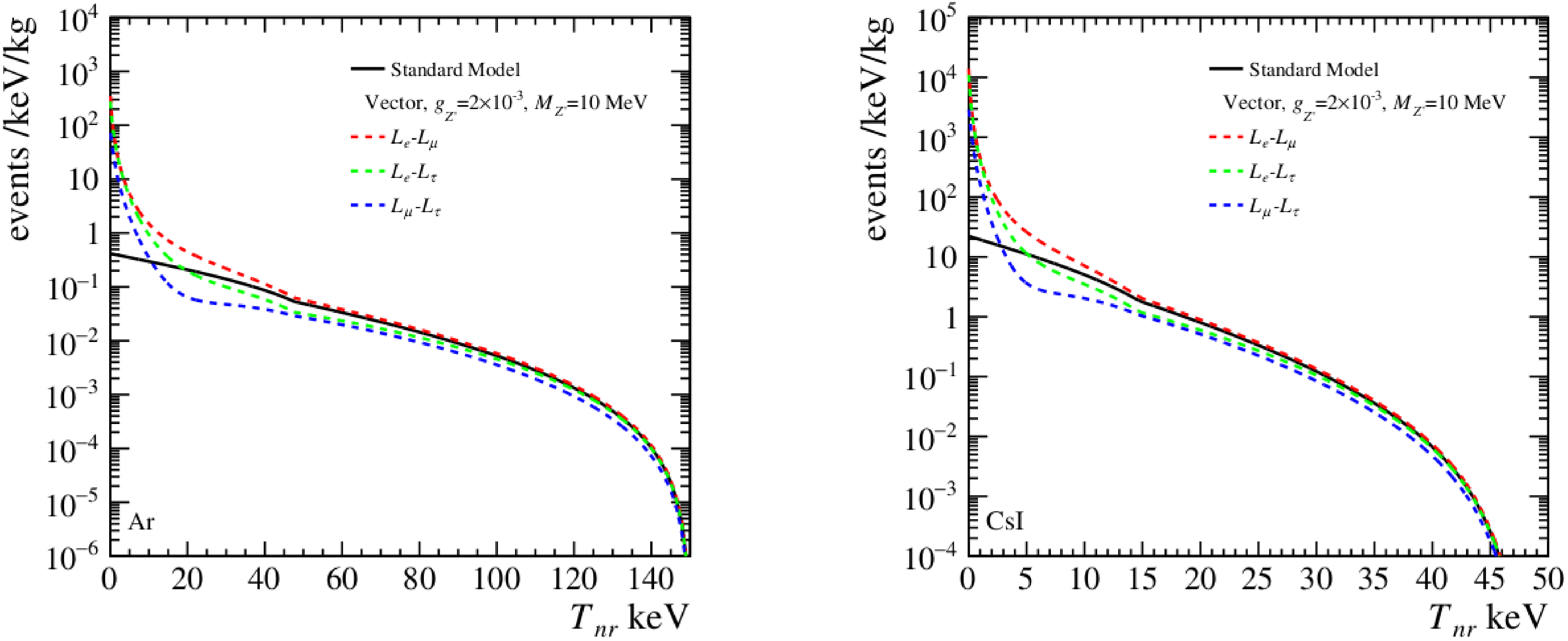
COHERENT, 2003.10630, PRL 2021

Event rates



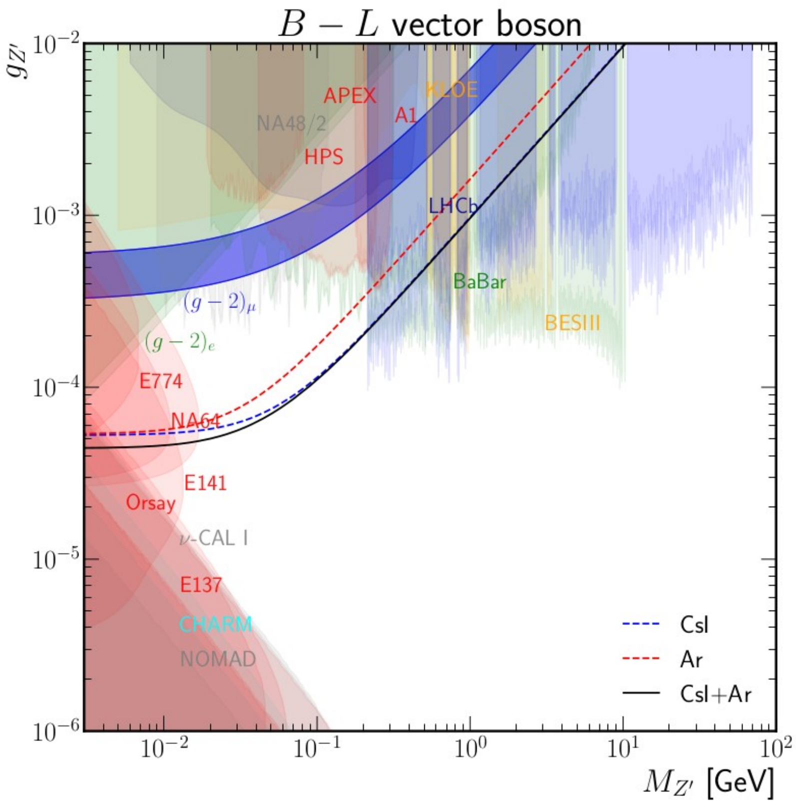
Atzori Corona et al, 2202.11002, JHEP 2022

Event rates



Atzori Corona et al, 2202.11002, JHEP 2022

Exclusion limits for selected models

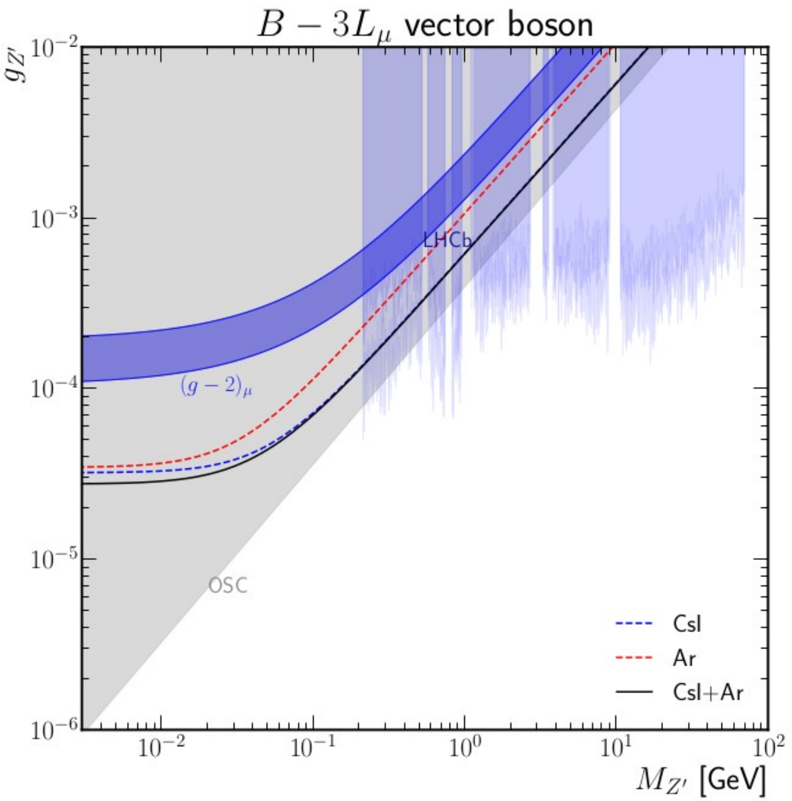


Very popular light vector mediator model with a lot of literature

COHERENT data exclude the preferred region from g-2

Atzori Corona et al, 2202.11002, JHEP 2022

Exclusion limits for selected models

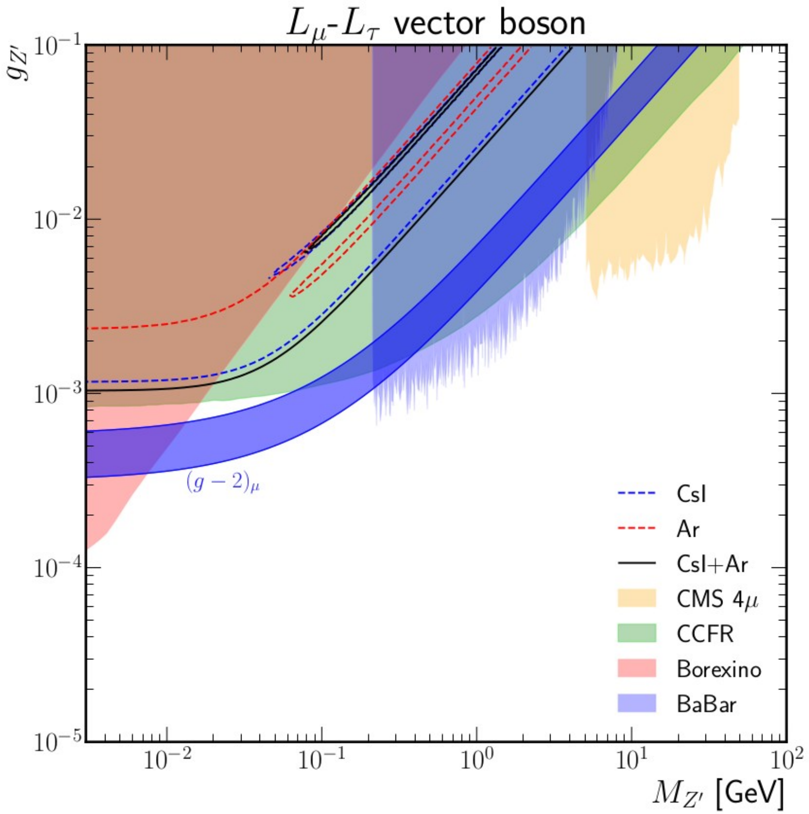


The bounds on the other models are of similar strength

Sometimes other bounds apply, which can be stronger or weaker than COHERENT bounds

Atzori Corona et al, 2202.11002, JHEP 2022

Exclusion limits for selected models



For the L_α-L_β models the couplings are generated only at loop level and the bounds become weaker

COHERENT can not exclude the preferred region from g-2

Atzori Corona et al, 2202.11002, JHEP 2022

Conclusions

Neutrino scattering experiments provide powerful tools for SM tests and BSM searches

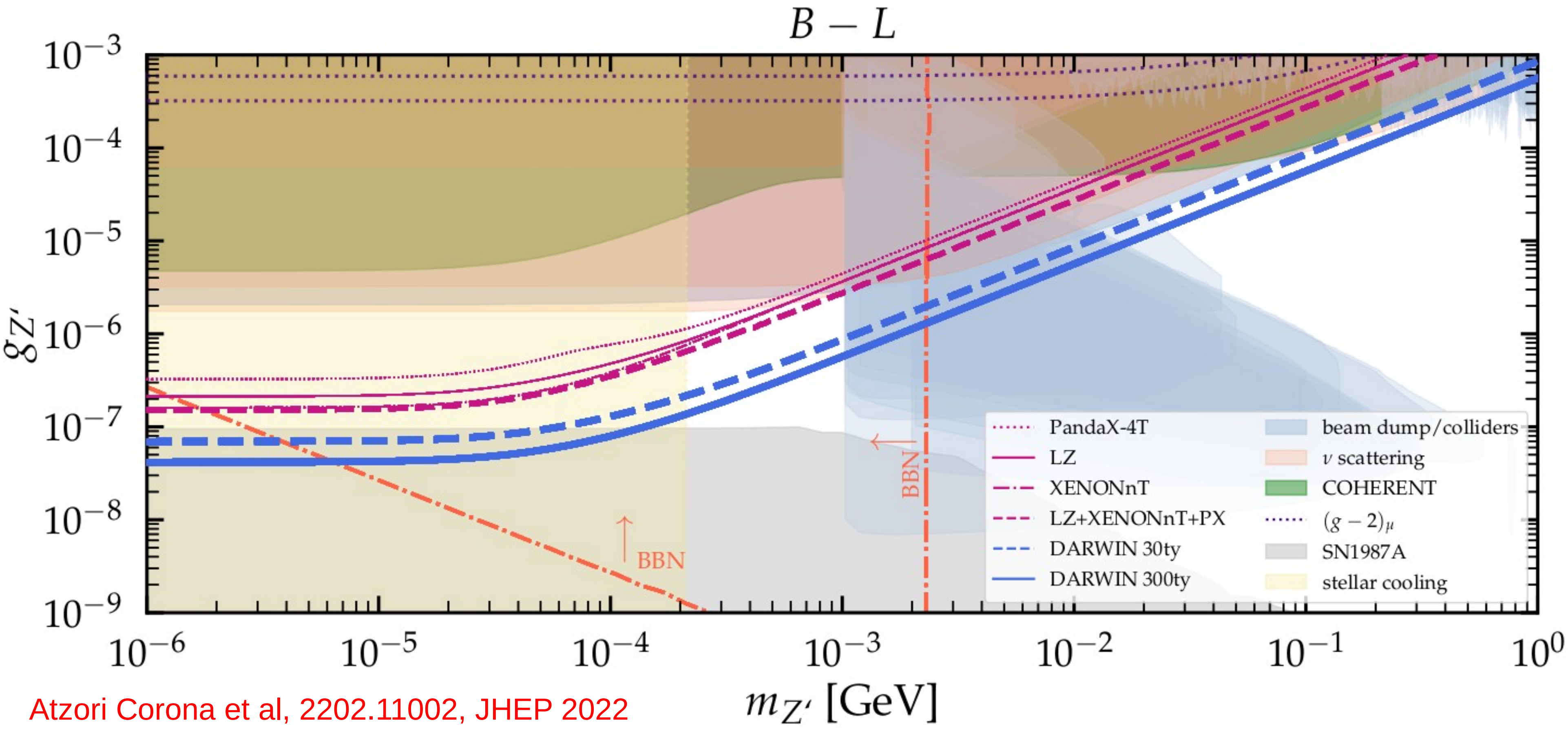
COHERENT data can be used to bound the parameter space for many classes of light vector mediator models

For models which couple only to leptons COHERENT bounds are not competitive with other probes


electron-neutrino
ν_e
muon neutrino
ν_μ
tau-neutrino
ν_τ

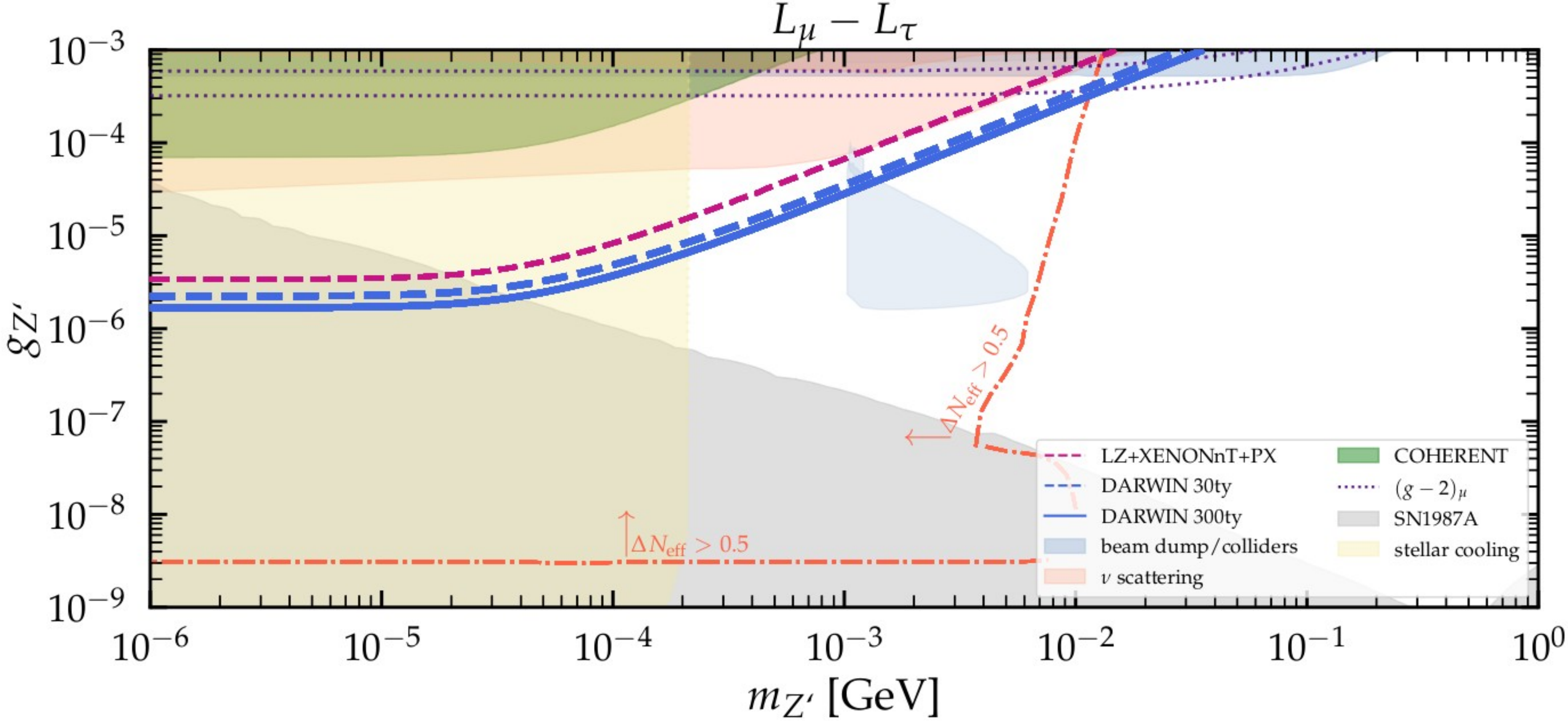
Thank you!

Exclusion limits from DMDD experiments



Atzori Corona et al, 2202.11002, JHEP 2022
De Romeri et al, 2211.11905, JHEP 2023
De Romeri, Papoulias, Ternes, 2402.05506, JHEP 2024

Exclusion limits from DMDD experiments



Atzori Corona et al, 2202.11002, JHEP 2022
De Romeri, Papoulias, Ternes, 2402.05506, JHEP 2024

Christoph Ternes