Summary talk - Theory

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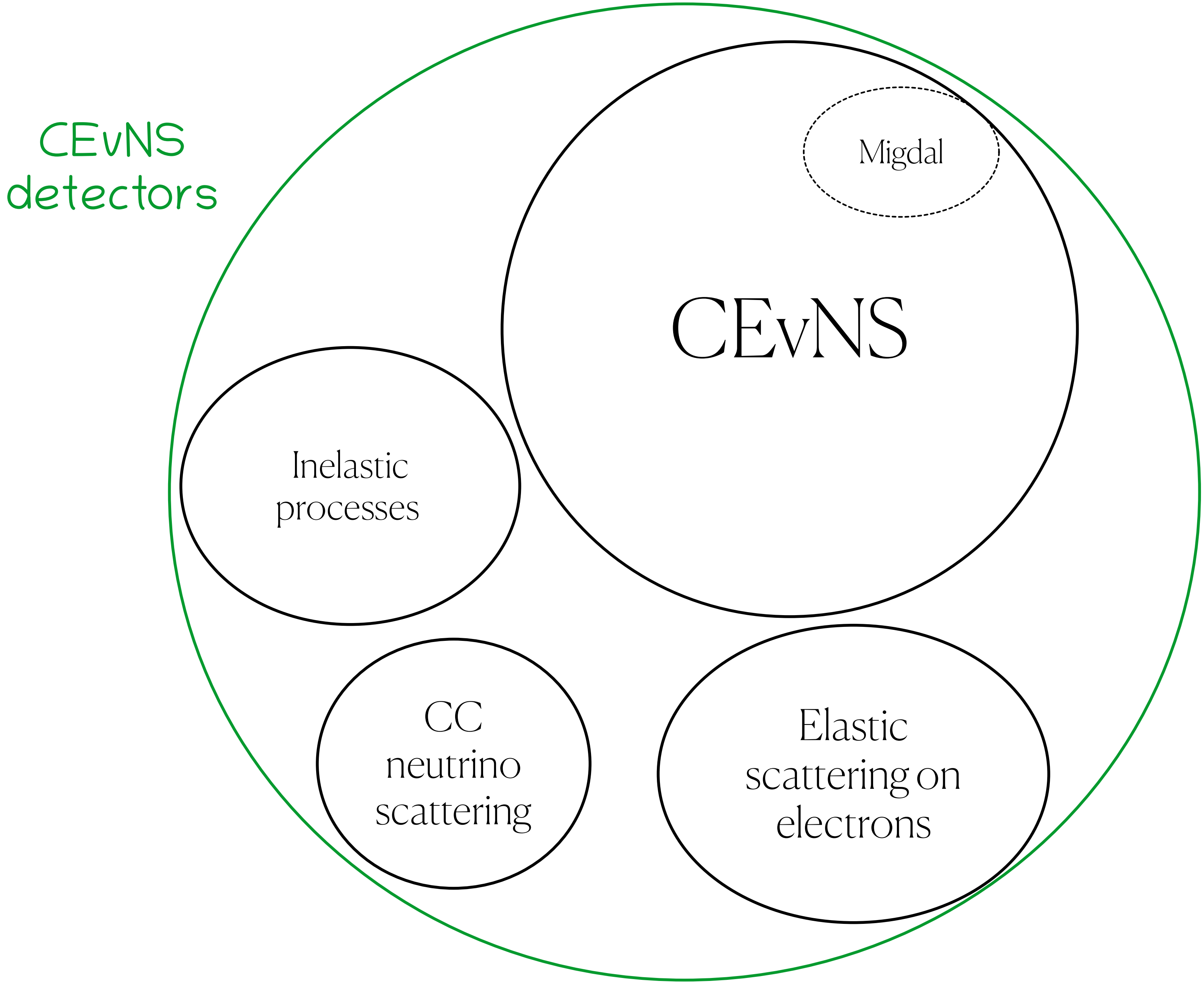
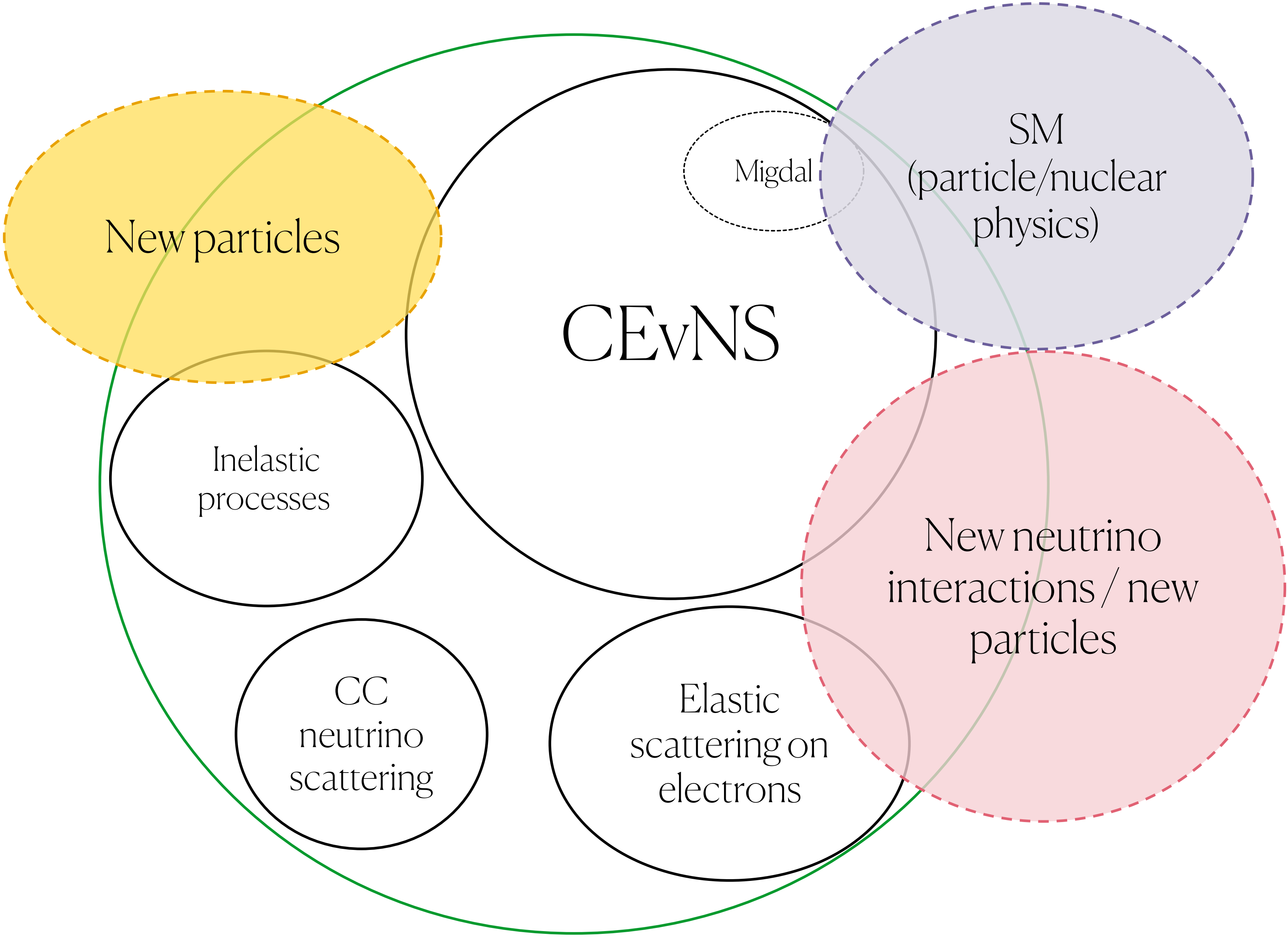
UAM-CSIC

6th Magnificent CEvNS Workshop
Valencia - June 14th, 2024

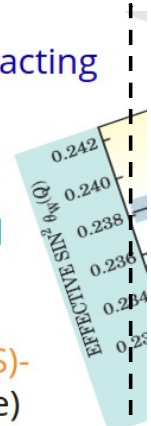

CEvNS detectors
Migdal
CEvNS
Inelastic processes
CC neutrino scattering
Elastic scattering on electrons


New particles
Migdal
SM
(particle/nuclear
physics)
CEvNS
Inelastic
processes
New neutrino
interactions / new
particles
CC
neutrino
scattering
Elastic
scattering on
electrons

(1) Standard Model

Neutron skin, weak angle, Rn, ...

- Atomic Parity Violation (APV): atomic electrons interacting with nuclei- **Cesium (Cs)** and **lead (Pb)** available.
- Parity Violation Electron Scattering (PVES): polarized electron scattering on nuclei- **PREX(Pb)** & CREX(Ca)
- Coherent elastic neutrino-nucleus scattering (CEνNS)- **Cesium-iodide (CsI),** argon (Ar) and germanium (Ge) available.

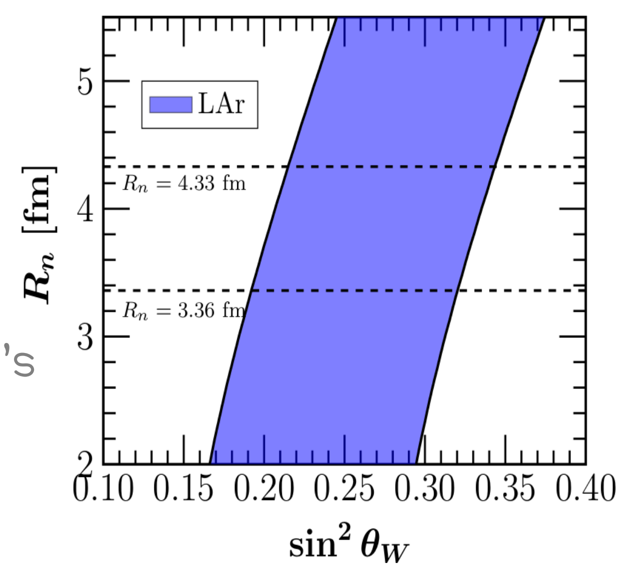


EW probes

$\sin^2\theta_W$ $\quad R_n \quad$ (Highly correlated)

$\sin^2\theta_W$ $\quad R_n \quad$ (Unavailable on Cs)

Mostly sensitive to R_n



Miranda's talk

Cadeddu's talk

Neutron skin, weak angle, Rn, ...

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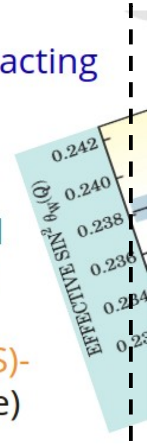

EW probes

$\sin^2\theta_W$ R_n (Highly correlated)

$\sin^2\theta_W$ R_n (Unavailable on Cs)

Mostly sensitive to R_n

Hadronic probes

New measurement from **proton-cesium elastic scattering at low momentum transfer** using an in-ring reaction technique at the **Cooler Storage Ring** (**CSRe**) at the Heavy Ion Research Facility in Lanzhou, which can be included in

First direct determination of ΔR_{np}

Cadeddu's talk

Neutron skin, weak angle, Rn, …

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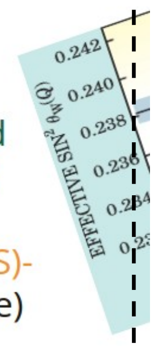
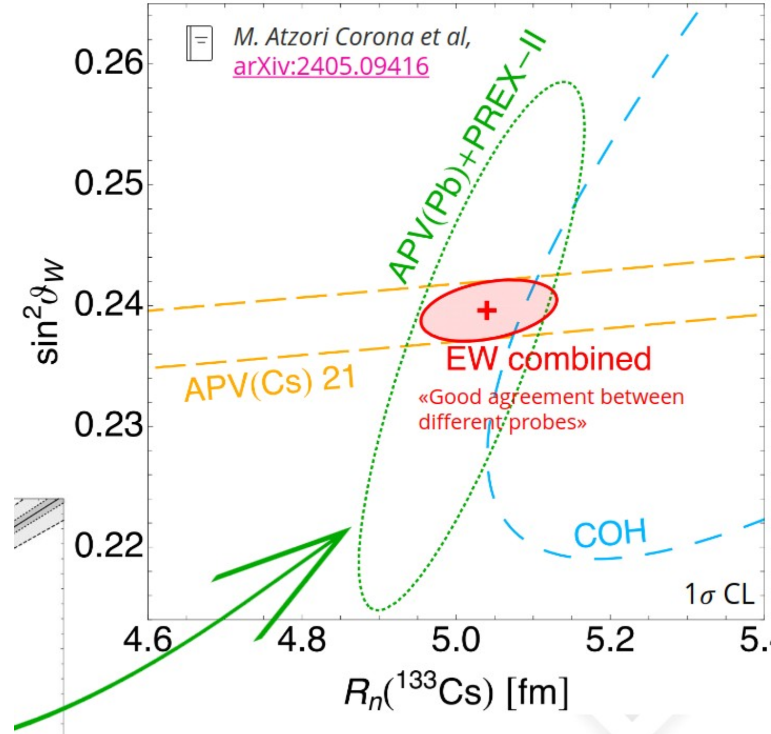


EW probes



✓ Pros: only electroweak probes used
❖ Cons: we should trust the theoretical nuclear models for the translation of R_n(Pb) to R_n(Cs)

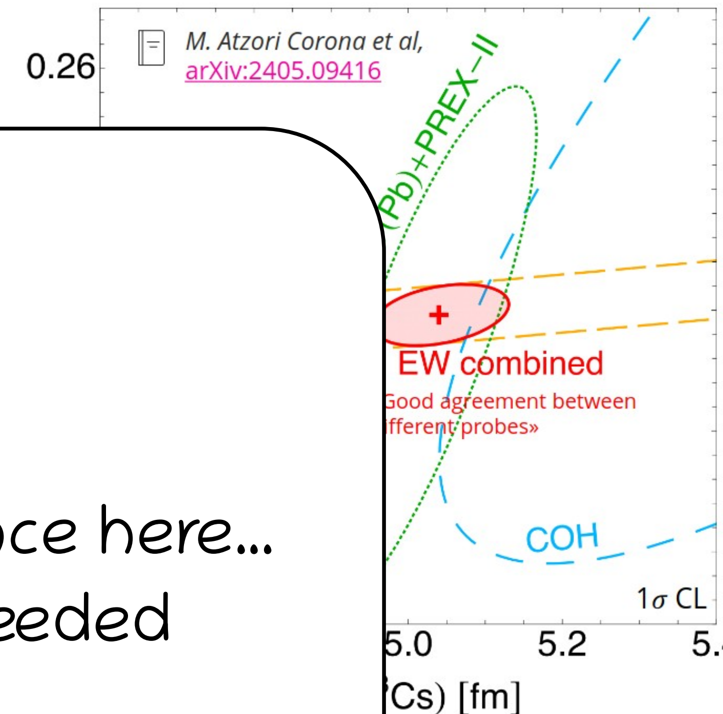
14

!

Cadeddu's talk

Neutron skin, weak angle, Rn, ...

- Atomic Parity Violation (APV): atomic electrons interacting with nuclei- **Cesium (**
- Parity Violation El… electron scatterin…
- Coherent elastic n… **Cesium-iodide (C…** available.



…eak probes used
…rust the theoretical
…for the translation of
R_n(Pb) to R_n(Cs)
14

Bottom line:

CEvNS can make a difference here...
but more precision is needed

!

Cadeddu's talk

Form factors

→ The nuclear form factor is a huge beast...

ν-nucleus scattering detailed cross-section:

Incoherent

$$\frac{d\sigma_A}{dT} = \frac{G_F^2 m_A}{4\pi}\left(1 - \frac{m_A T}{2E_\nu^2} - \frac{T}{E_\nu}\right) Q_{\rm w}^2 \left|F_{\rm w}(\mathbf{q}^2)\right|^2 + \frac{G_F^2 m_A}{4\pi}\left(1 + \frac{m_A T}{2E_\nu^2} - \frac{T}{E_\nu}\right) F_A(\mathbf{q}^2)$$

Dominated by the first term, proportional to the weak form factor:

$$\begin{aligned} F_{\rm w}(\mathbf{q}^2) = \frac{1}{Q_{\rm w}} \Bigg[& \left(Q_{\rm w}^p \left(1 + \frac{\langle r_E^2\rangle^p}{6} t + \frac{1}{8m_N^2} t\right) + Q_{\rm w}^n \frac{\langle r_E^2\rangle^n + \langle r_{E,s}^2\rangle^N}{6} t \right) \mathcal{F}_p^M(\mathbf{q}^2) \\ & + \left(Q_{\rm w}^n \left(1 + \frac{\langle r_E^2\rangle^p + \langle r_{E,s}^2\rangle^N}{6} t + \frac{1}{8m_N^2} t\right) + Q_{\rm w}^p \frac{\langle r_E^2\rangle^n}{6} t \right) \mathcal{F}_n^M(\mathbf{q}^2) \\ & - \frac{Q_{\rm w}^p(1 + 2\kappa^p) + 2Q_{\rm w}^n(\kappa^n + \kappa_s^N)}{4m_N^2} t \mathcal{F}_p^{\Phi''}(\mathbf{q}^2) \\ & - \frac{Q_{\rm w}^n(1 + 2\kappa^p + 2\kappa_s^N) + 2Q_{\rm w}^p \kappa^n}{4m_N^2} t \mathcal{F}_n^{\Phi''}(\mathbf{q}^2) \Bigg], \qquad t = q^2 \end{aligned}$$

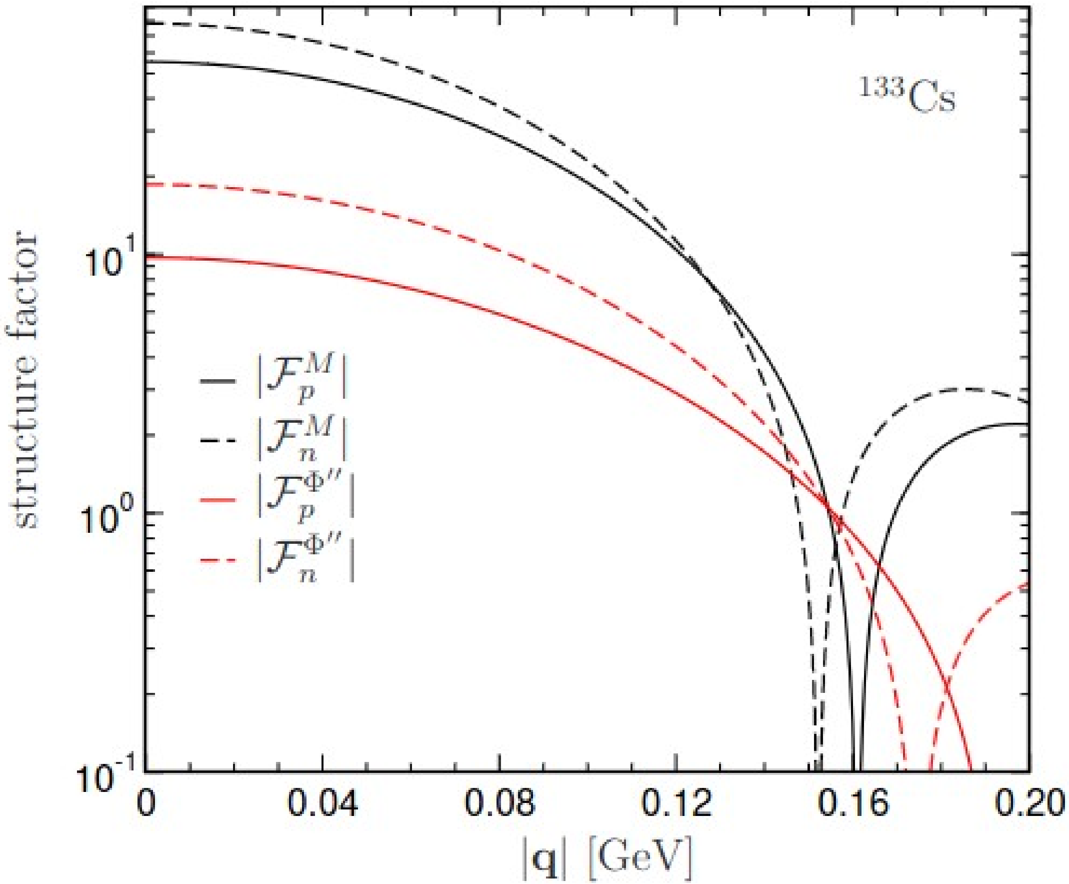
Coherent (first two lines)

Semi-coherent (last two lines)

Menendez's talk

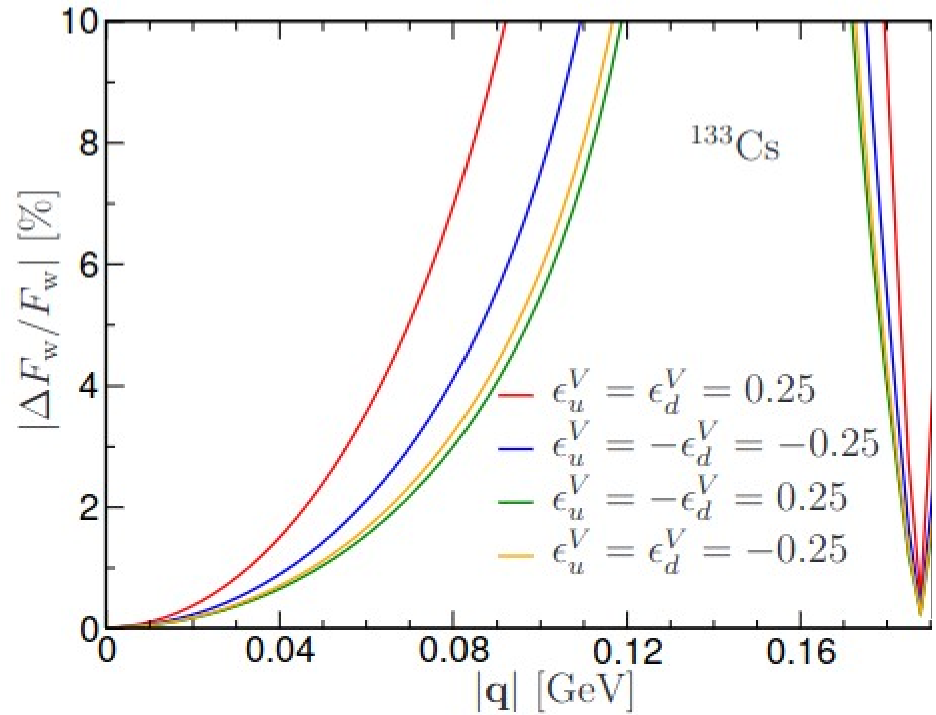
Form factors

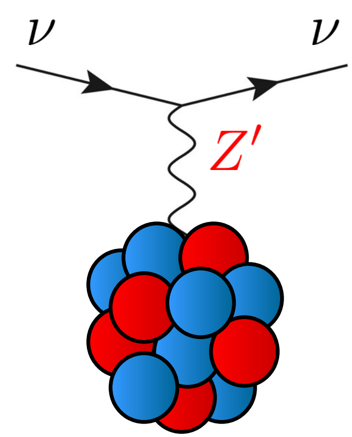
→ The nuclear form factor is a huge beast…



Hoferichter, JM, Schwenk, PRD102 074018 (2020)

The Q2-dependence gets modifications from BSM





Menendez's talk

Radiative corrections

Neutrino energy

Mass of the nucleus

SM vector proton coupling

SM vector neutron coupling

$$\frac{d\sigma^{CE\nu NS}(E_\nu, T_{nr})}{dT_{nr}} \cong \frac{G_F^2\, m_N}{\pi}\left(1 - \frac{m_N T_{nr}}{2E_\nu^2}\right)\left[g_V^p\left(\sin^2(\vartheta_W)\right) Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]^2$$

Nuclear recoil energy

Weinberg angle

Proton Form Factor

Neutron Form Factor

$$g_V^p(\nu_\ell) = \rho\left(\frac{1}{2} - 2\sin^2\vartheta_W\right) + 2\boxtimes_{WW} + \Box_{WW} - 2\phi_{\nu_\ell W} + \rho(2\boxtimes_{ZZ}^{uL} + \boxtimes_{ZZ}^{dL} - 2\boxtimes_{ZZ}^{uR} - \boxtimes_{ZZ}^{dR})$$

$$\phi_{\nu_\ell W} = -\frac{\alpha}{6\pi}\left(\ln\frac{M_W^2}{m_\ell^2} + \frac{3}{2}\right)$$

Not flavor universal anymore!

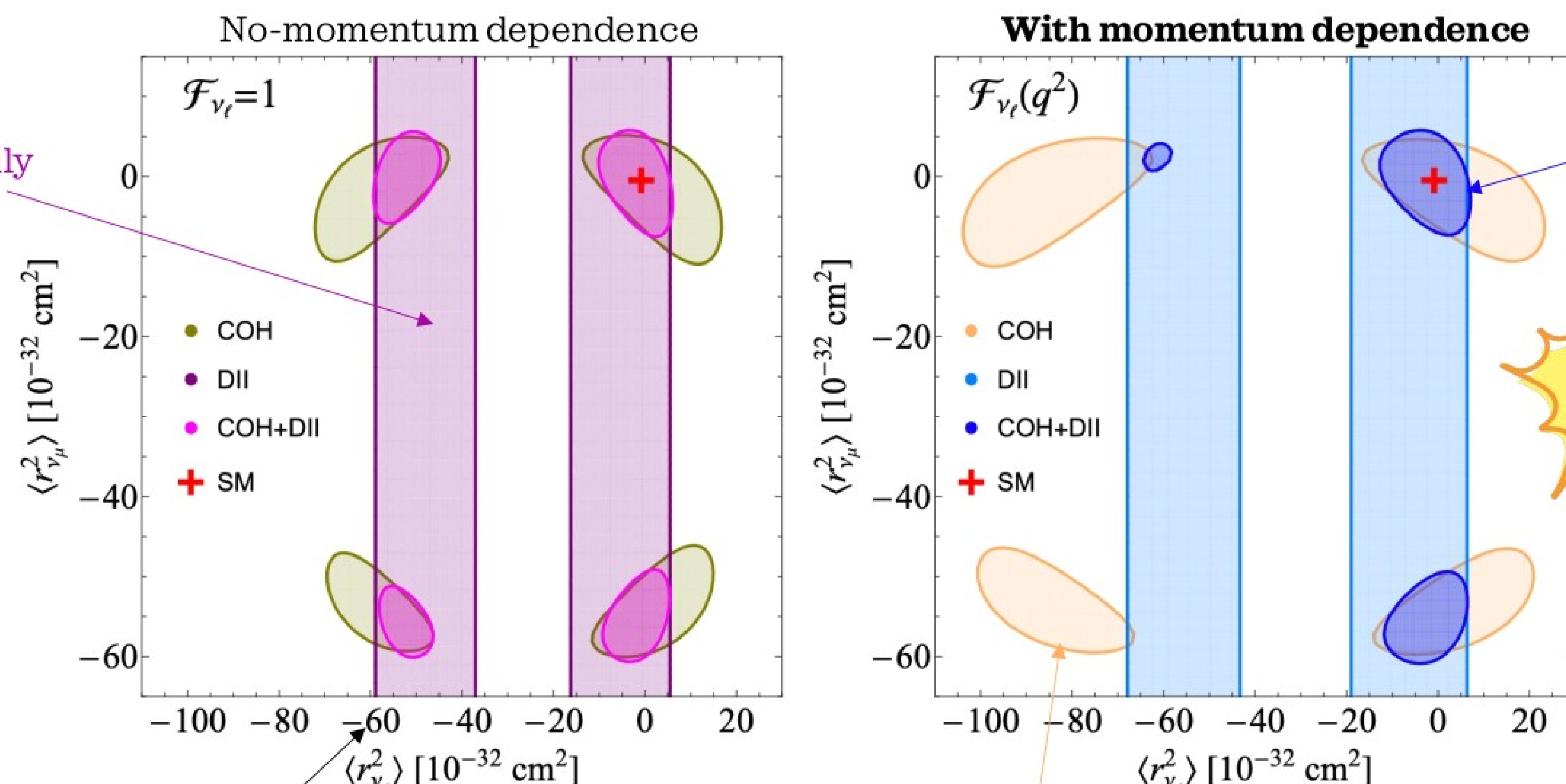
Correction tightly related to the definition of charge radius (defined at zero-momentum transfer)

Dordei's talk

Radiative corrections

However, CEvNS does **not** take place at zero momentum transfer...

Reactors are only sensitive to ν_e

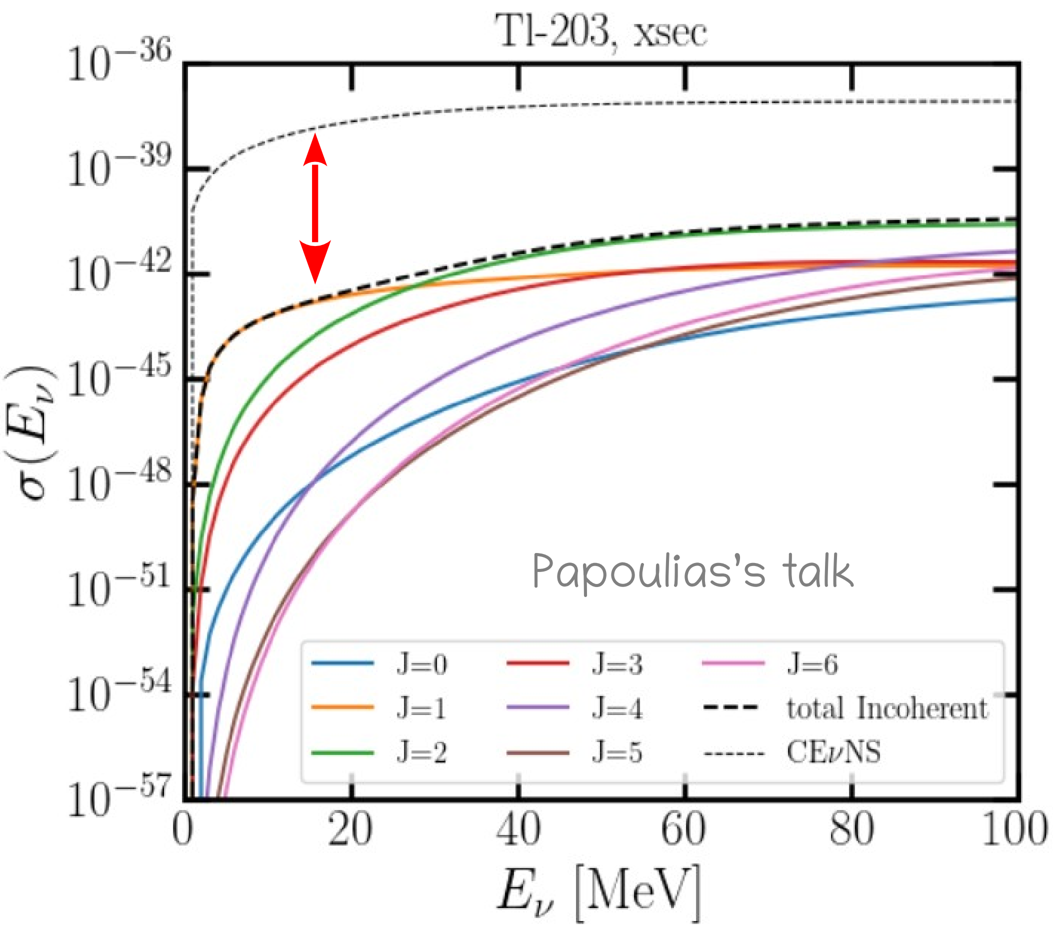


Muon
only r

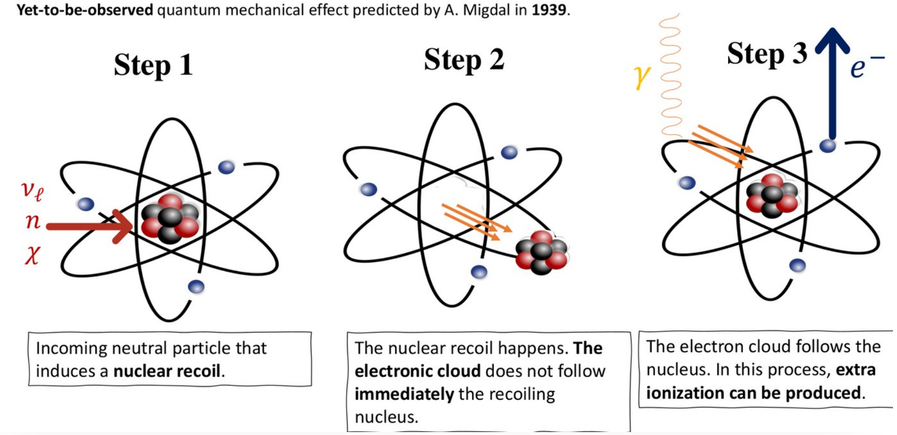
These largely negative values produce a degenerate cross-section

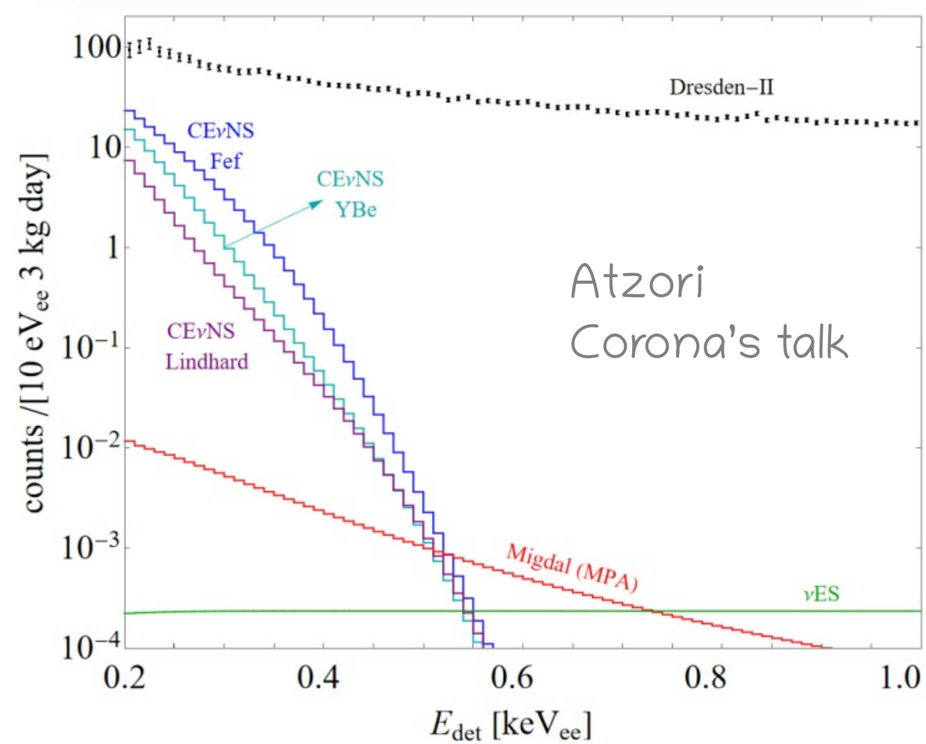
COHERENT results are more affected than reactors due to the larger momentum transfer.

New ideas

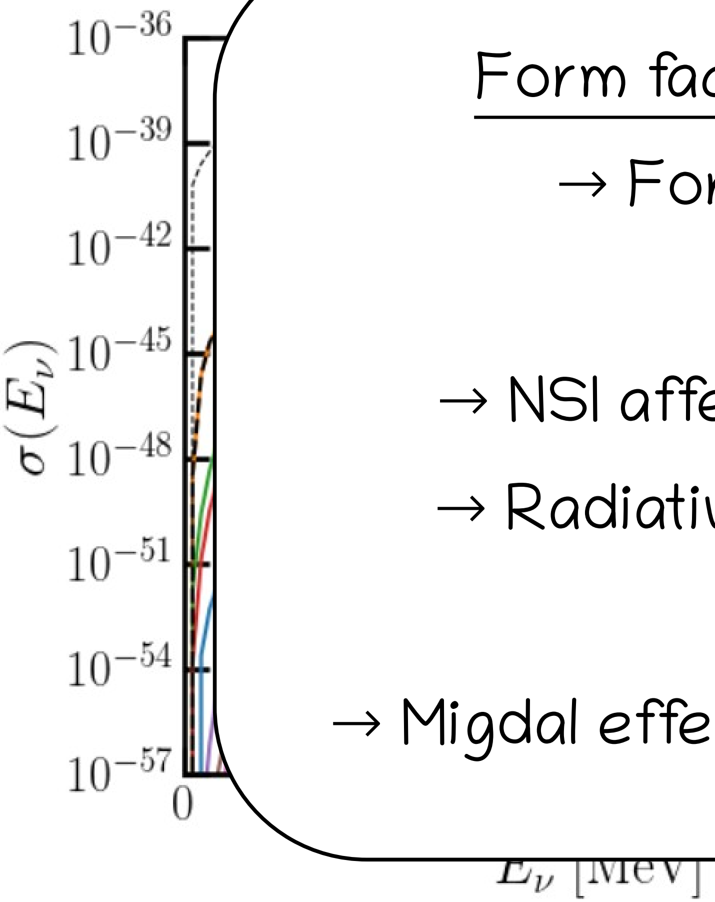


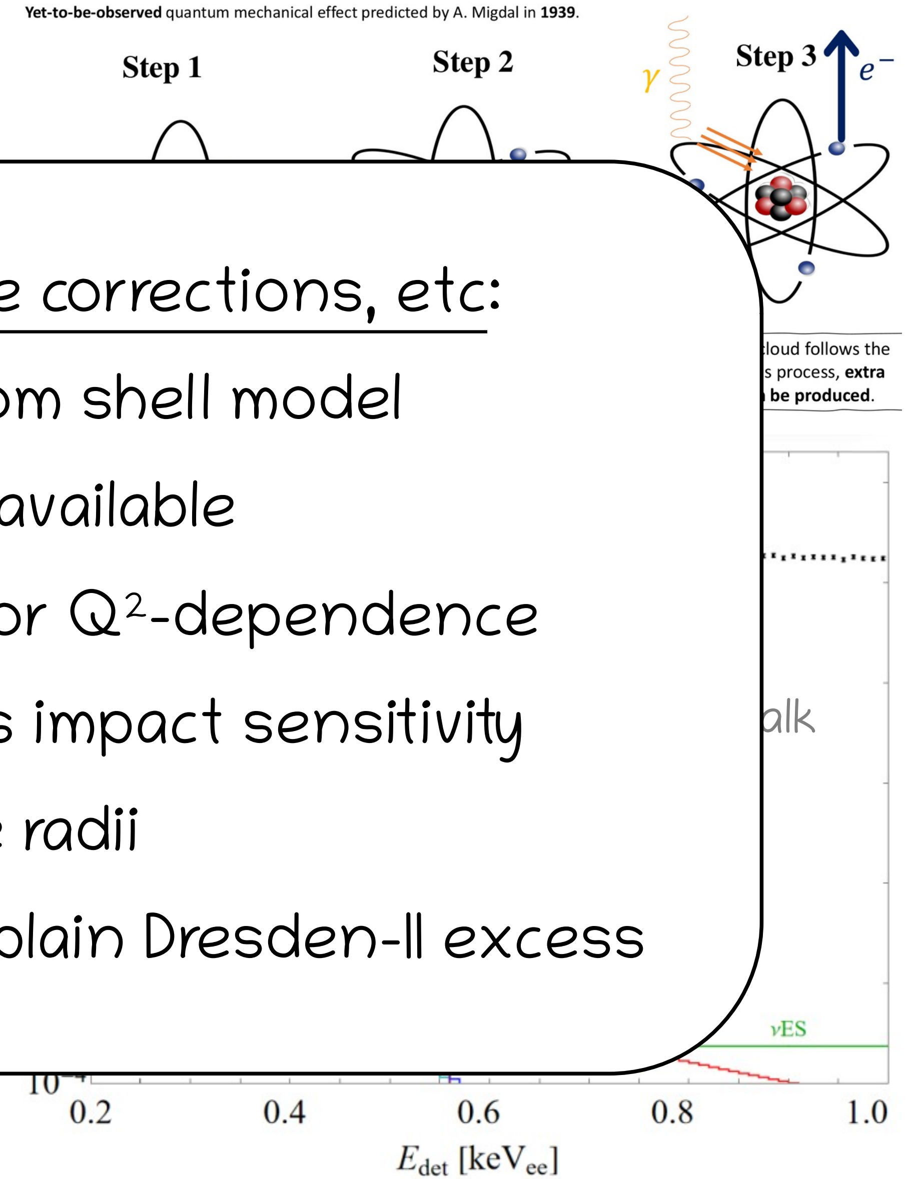
Yet-to-be-observed quantum mechanical effect predicted by A. Migdal in **1939**.





New ideas





Form factors, radiative corrections, etc:

→ Form factors from shell model calculations available

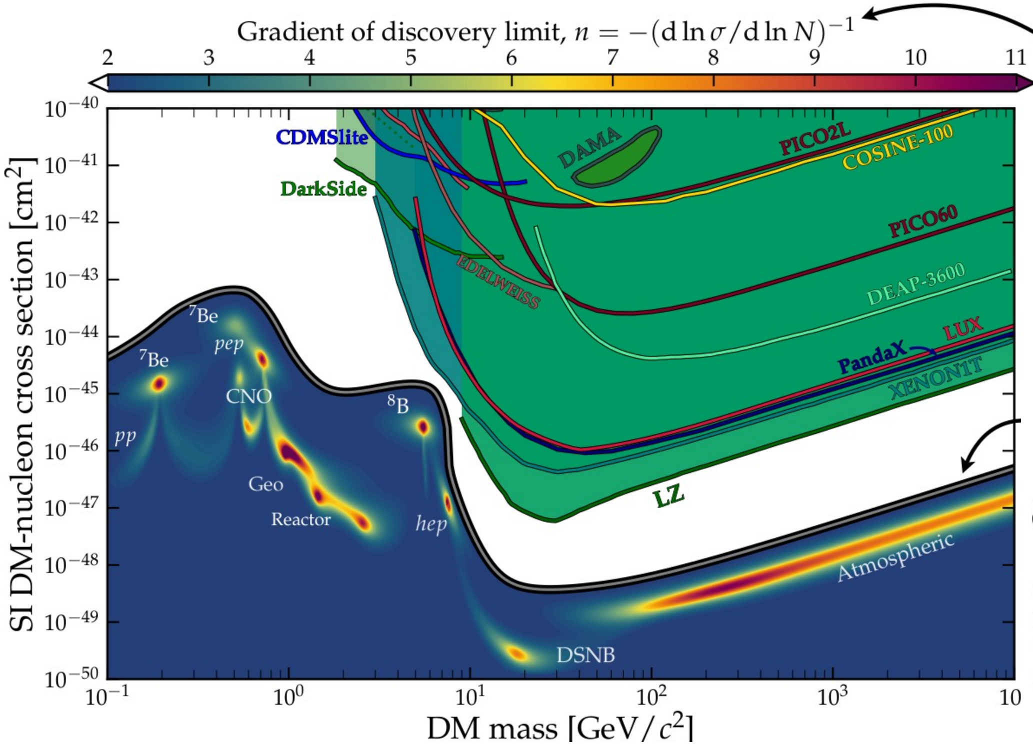
→ NSI affect Form factor Q^2-dependence

→ Radiative corrections impact sensitivity to charge radii

→ Migdal effect cannot explain Dresden-II excess

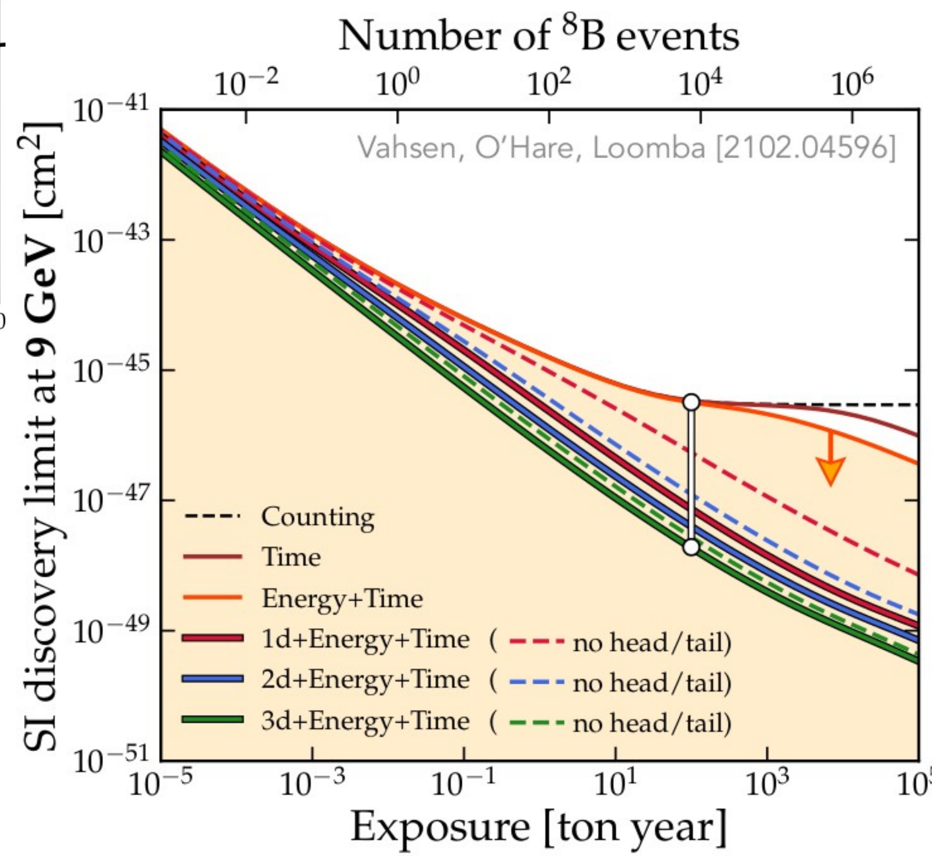
(2) New Physics in the neutrino sector

Neutrinos in Dark Matter Experiments

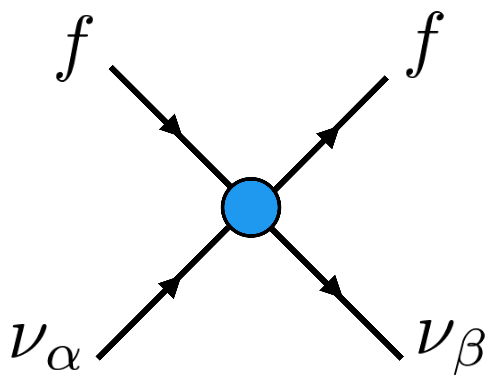


n parameterises the "fogginess" of the neutrino fog
→ this shows that the parameter space is not uniformly foggy everywhere

O'Hare's talk



Neutrinos in Dark Matter Experiments



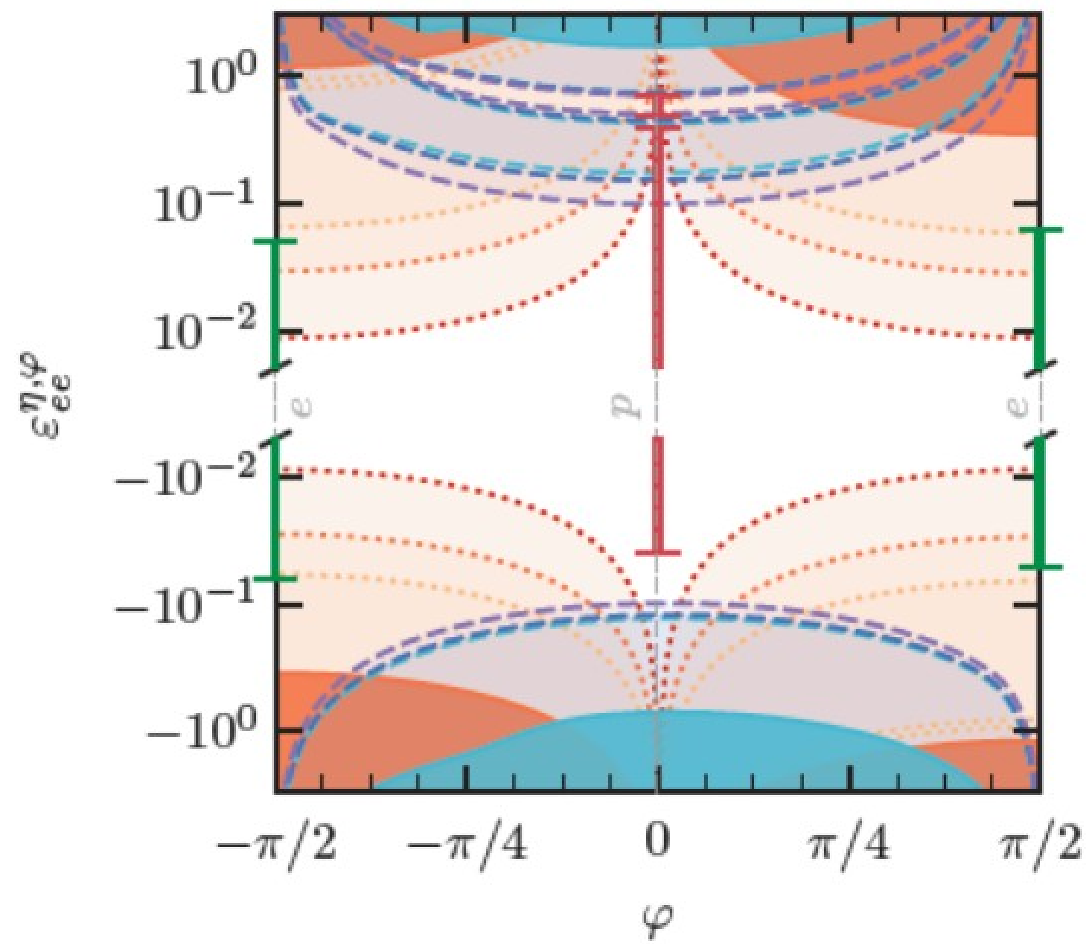
For solar neutrinos:

$$N_{ev} \propto \mathrm{Tr}\left[\rho\sigma\right]$$

Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea, 2204.03011

LZ, XENONnT, DARWIN

Amaral, Cerdeño, Cheek, Foldenauer, 2302.12846;

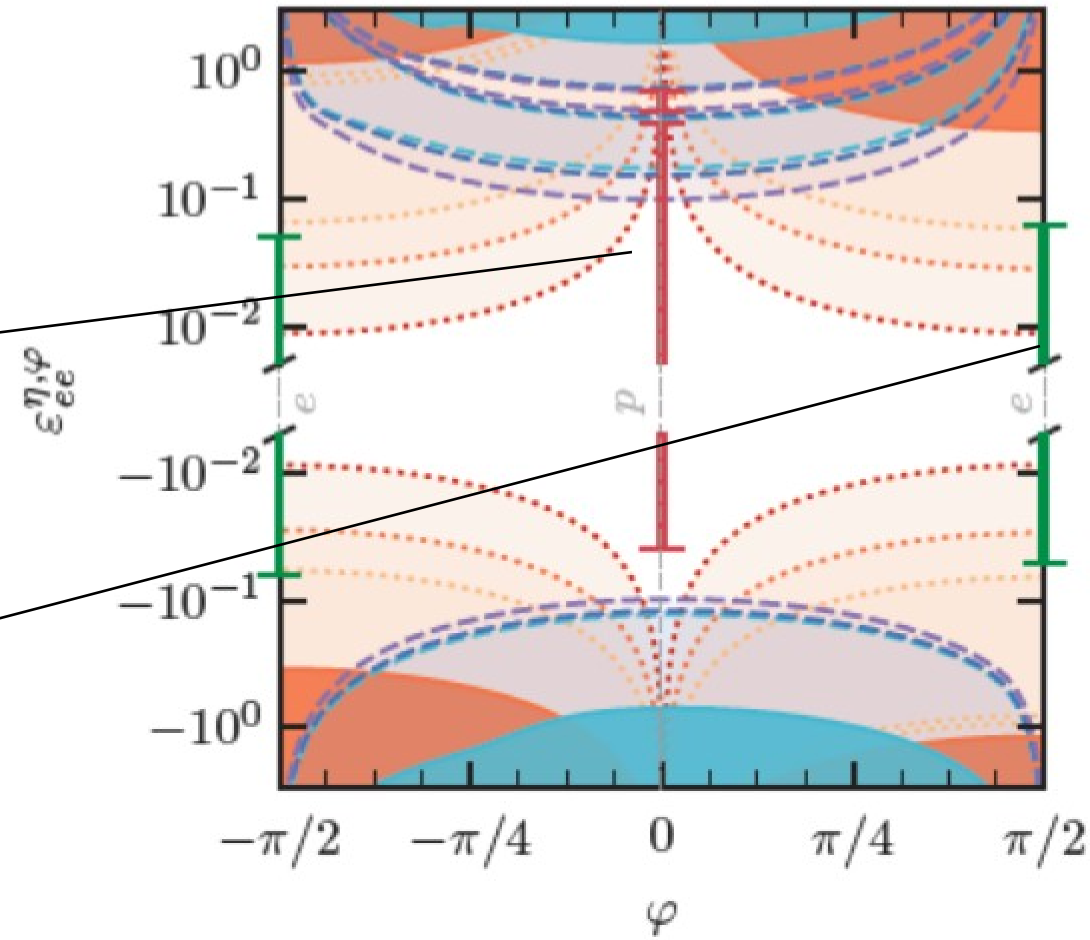


Cerdeño's talk

Neutrinos in Dark Matter Experiments

LZ, XENONnT, DARWIN

Amaral, Cerdeño, Cheek, Foldenauer, 2302.12846;



OSC+CEvNS global fit (marginalized)

Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.09109

Borexino results (one parameter at a time)

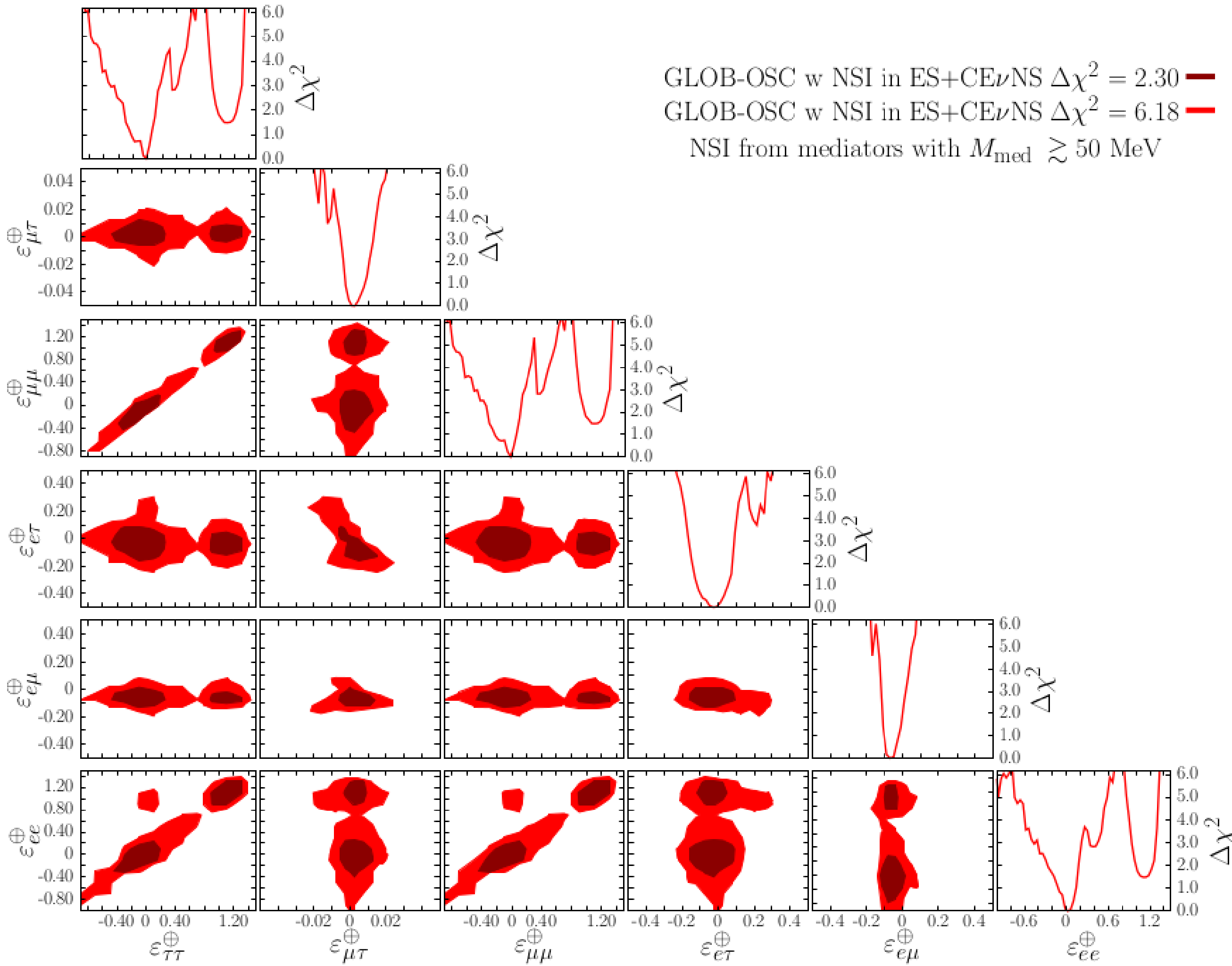
Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea, 2204.03011

Cerdeño's talk

Global fit to OSC + CEvNS

New results from OSC+CEvNS 2023 global fit:

Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea, 2305.07698

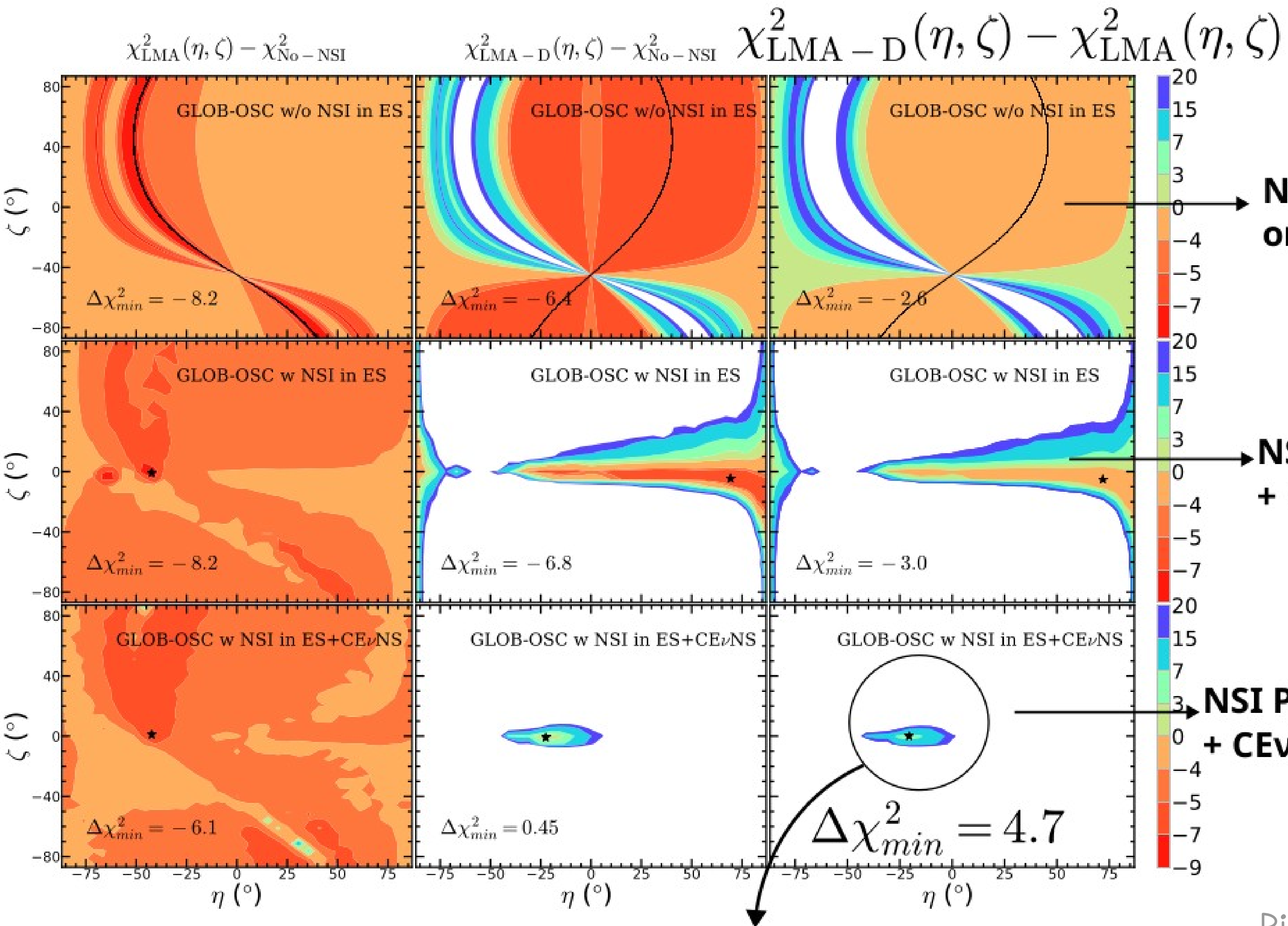


Ranges at 99% CL marginalized	
	GLOB-OSC w NSI in ES + CEνNS
$\varepsilon^{\oplus}_{ee}$	[-0.23, +0.25] ⊕ [+0.81, +1.3]
$\varepsilon^{\oplus}_{\mu\mu}$	[-0.29, +0.20] ⊕ [+0.83, +1.4]
$\varepsilon^{\oplus}_{\tau\tau}$	[-0.29, +0.20]⊕ [+0.83, +1.4]
$\varepsilon^{\oplus}_{e\mu}$	[-0.18, +0.08]
$\varepsilon^{\oplus}_{e\tau}$	[-0.25, +0.33]
$\varepsilon^{\oplus}_{\mu\tau}$	[-0.020, +0.021]

Pinheiro's talk

Global fit to OSC + CEνNS

Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea, 2305.07698



NSI Propagation only

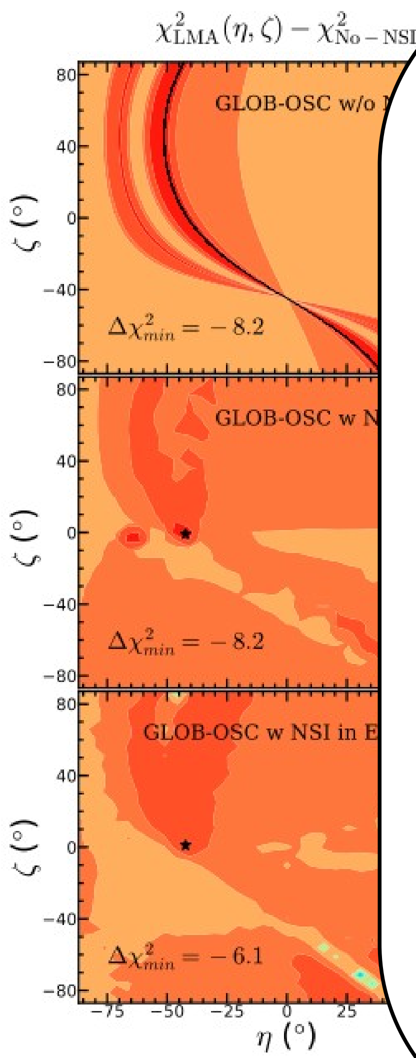
NSI Propagation + Electron Scattering

NSI Propagation+ES + CEνNS

LMA-D becomes disfavoured with respect to LMA

Pinheiro's talk

Global fit to OSC + CEνNS



lez-Garcia,
, Urrea,

agation

agation
n Scattering

tion+ES

ro's talk

respect to LMA

<u>NC-NSI:</u>

→ The inclusion of CEνNS data is crucial

→ Combination of different targets is key

→ → Dark Matter experiments will provide interesting results soon

→ worth looking into OSC + CEνNS + DMdd

NSI vs SMEFT

$$\mathcal{L}_{\rm NC} \supset 2\sqrt{2}G_F\left[\epsilon^{fL}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_L f) + \epsilon^{fR}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_R f)\right] + \textbf{h.c.}$$

Du's talk

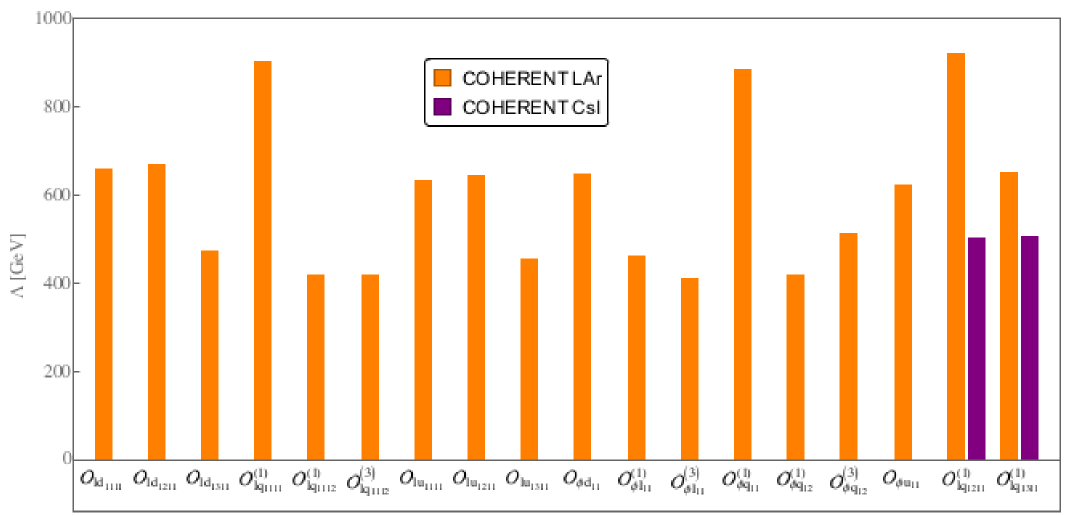
$$g_p^V = g_p^{V,\,\rm SM} + 3[c_{\ell q}] + [c^{(3)}_{\ell q}] + 2[c_{\ell u}] + [c_{\ell d}]$$

$$g_n^V = g_n^{V,\,\rm SM} + 3[c_{\ell q}] - [c^{(3)}_{\ell q}] + [c_{\ell u}] + 2[c_{\ell d}]$$

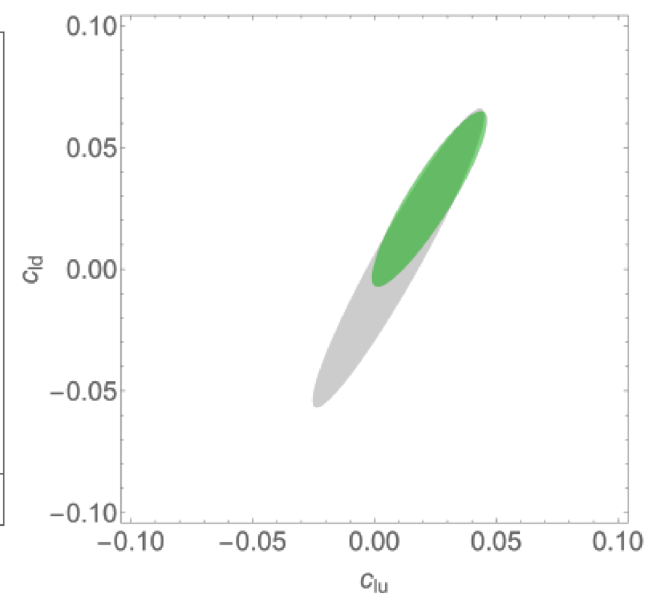
$$\mathcal{O}^{(1)}_{lq} = \left(\bar{l}_p\gamma^\mu l_r\right)\left(\bar{l}_s\gamma_\mu l_t\right)$$

$$\mathcal{O}^{(3)}_{lq} = \left(\bar{l}_p\gamma^\mu\tau^I l_r\right)\left(\bar{l}_s\gamma_\mu\tau^I l_t\right)$$

$$\mathcal{O}_{lQ} = \left(\bar{l}_p\gamma^\mu l_r\right)\left(\bar{Q}_s\gamma_\mu Q_t\right)$$



YD, Li, Tang, Vihonen, Yu, arXiv: 2106.15800



Breso-Pla, Falkowski, Gonzalez-Alonso, Monsalvez-Pozo, 2301.07036 (JHEP)

NSI vs SMEFT

$$\delta\mathcal{L}^{NC} \supset \frac{-1}{v^2}\cdot\left\{\sum_{X,X'}\left[\epsilon^{qq}_{XX'}\right]_{\alpha\beta}(\bar{\nu}_\alpha\Gamma_X\nu_\beta)(\bar{q}\Gamma_{X'}q)+\right.$$

$$\left.+\frac{1}{2}\left[\epsilon_F\right]_{\alpha\beta}\bar{\nu}_\alpha\sigma_{\mu\nu}P_L\nu_\beta F^{\mu\nu}+\text{h.c.}\right\}$$

$$\delta\mathcal{L}^{\pi} \supset -\frac{2V_{ud}}{v^2}\cdot\sum_{XX'}\left[\epsilon^{ud}_{XX'}\right]_{\alpha\beta}(\bar{\nu}_\alpha\Gamma_X l_\beta)\left(\bar{d}\Gamma_{X'}u\right)$$

$$\delta\mathcal{L}^{\mu} \supset -\frac{2}{v^2}\cdot\sum_{X,X'}\left[\rho_{XX'}\right]^{ab}_{\alpha\beta}\left(\bar{l}_\alpha\Gamma_X\nu_\beta\right)\cdot(\bar{\nu}_\alpha\Gamma_{X'}l_\beta)\,.$$

Cruz Alzaga's lightning talk

See e.g., Breso-Pla, Falkowski, González-Alonso, et al, 2301.0036
Falkowski, Gonzalez-Alonso, Tabrizi, 1910.02971

NSI vs (SMEFT + ν_R)

$$\delta\mathcal{L}^{NC} \supset \frac{-1}{v^2}\cdot\left\{\sum_{X,X'}\left[\epsilon^{qq}_{XX'}\right]_{\alpha\beta}\left(\bar{\nu}_\alpha\Gamma_X\nu_\beta\right)\left(\bar{q}\Gamma_{X'}q\right)+\right.$$

$$\left.+\frac{1}{2}\left[\epsilon_F\right]_{\alpha\beta}\bar{\nu}_\alpha\sigma_{\mu\nu}P_L\nu_\beta F^{\mu\nu}+\text{h.c.}\right\}$$

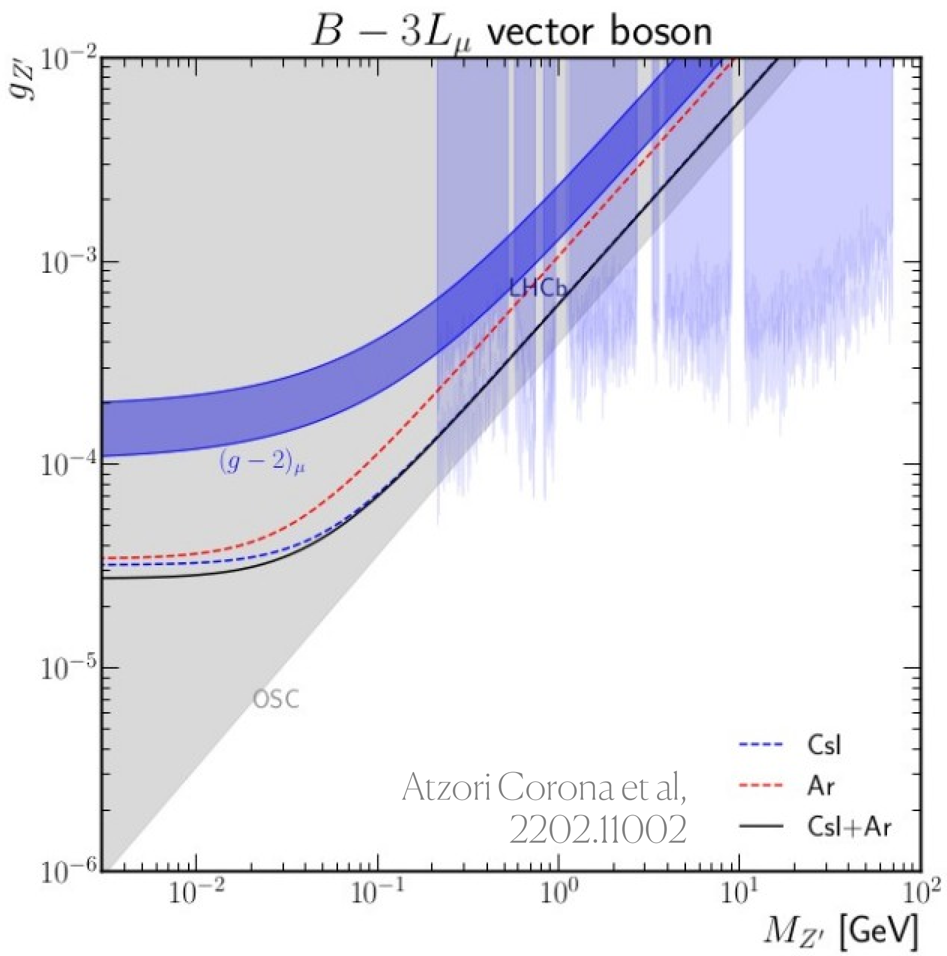
$$\delta\mathcal{L}^{\pi} \supset -\frac{2V_{ud}}{v^2}\cdot\sum_{XX'}\left[\epsilon^{ud}_{XX'}\right]_{\alpha\beta}\left(\bar{\nu}_\alpha\Gamma_X l_\beta\right)\left(\bar{d}\Gamma_{X'}u\right)$$

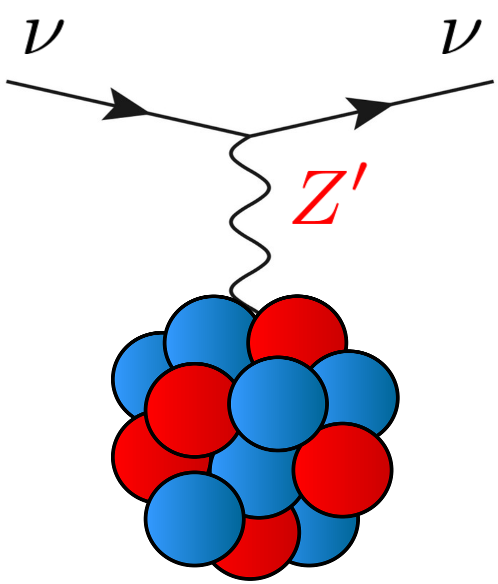
$$\delta\mathcal{L}^{\mu} \supset -\frac{2}{v^2}\cdot\sum_{X,X'}\left[\rho_{XX'}\right]^{ab}_{\alpha\beta}\left(\bar{l}_\alpha\Gamma_X\nu_\beta\right)\cdot\left(\bar{\nu}_\alpha\Gamma_{X'}l_\beta\right).$$

Cruz Alzaga's lightning talk

- **SM limit.** All charges except the vectorial ones vanish.
- **NP only in detection.** We obtain the same results as in previous works. ← NC-NSI - like
- **NP only in production.** Direct and indirect NP effects cancel out.
- **Linear NP terms.** There is no linear interference between the operators with RH-neutrinos and the ones present in the SM. We recover the linear limit of our previous work[1]. ← Effect in production cancel out; analysis can be recasted to NSI fit
- **Second order NP terms.** The number of charges is reduced to 9, since $(\tilde{Q}^{\mu}_{V})^2$ and $(\tilde{Q}^{\bar{\mu}}_{V})^2$ are affected by different NP terms in production at this order.

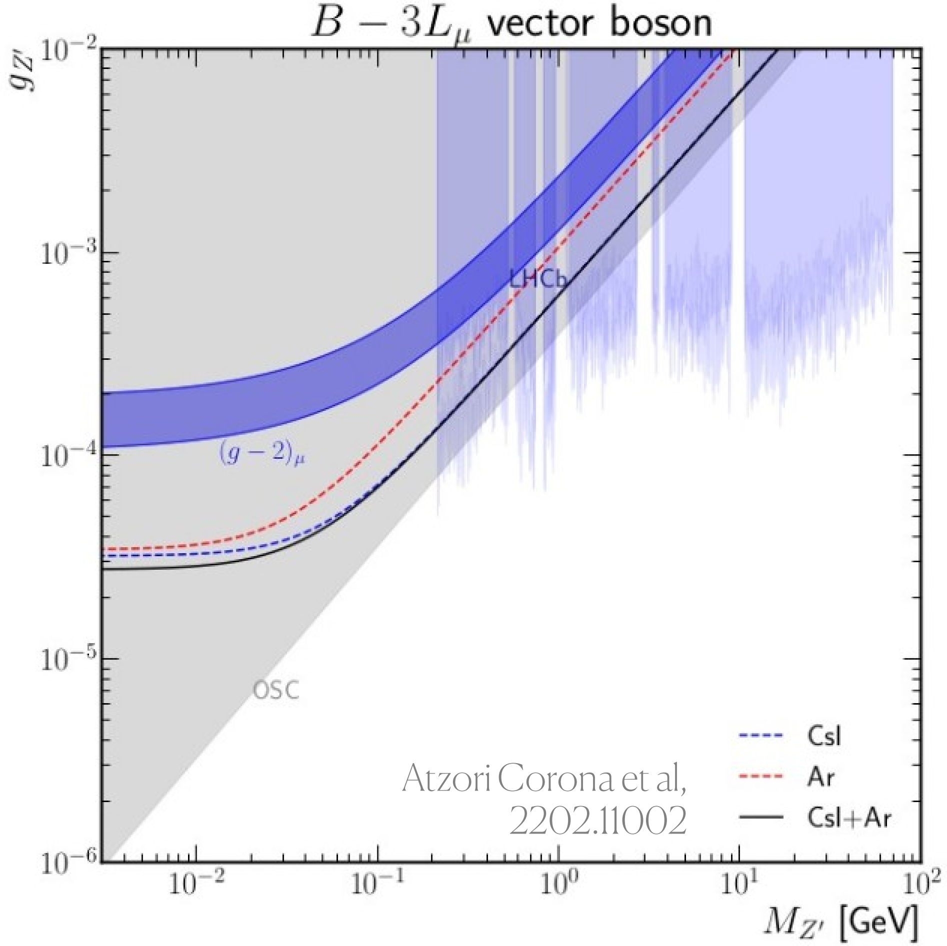
Light vector mediators

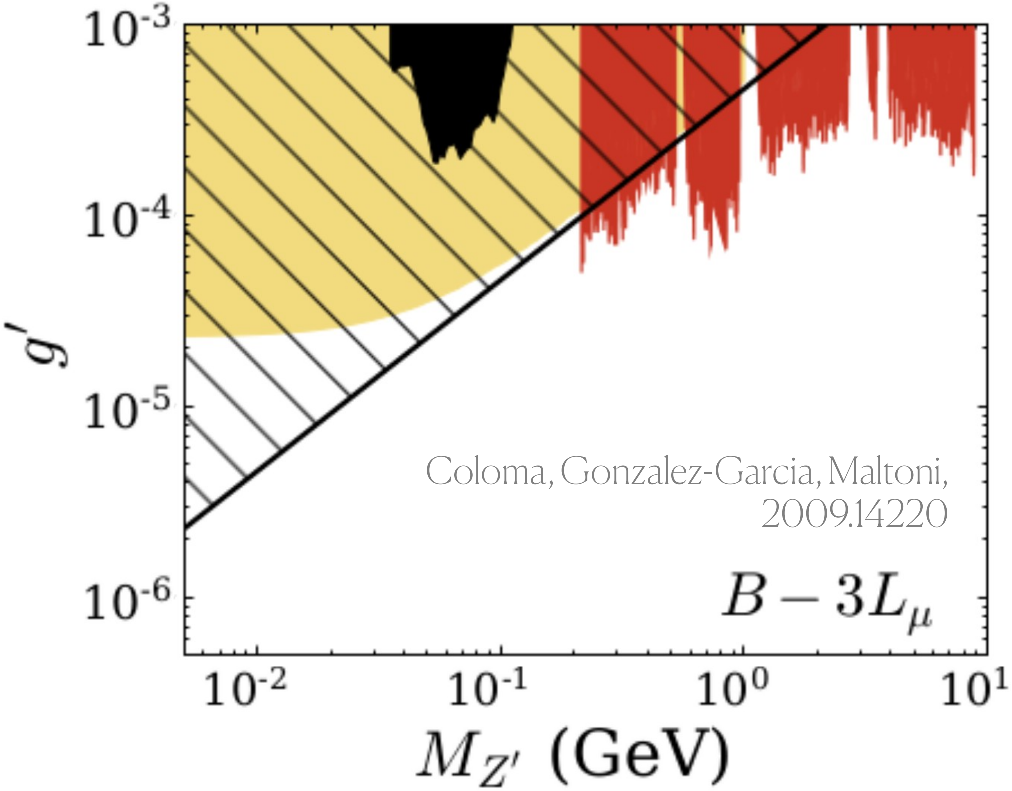




Ternes's talk

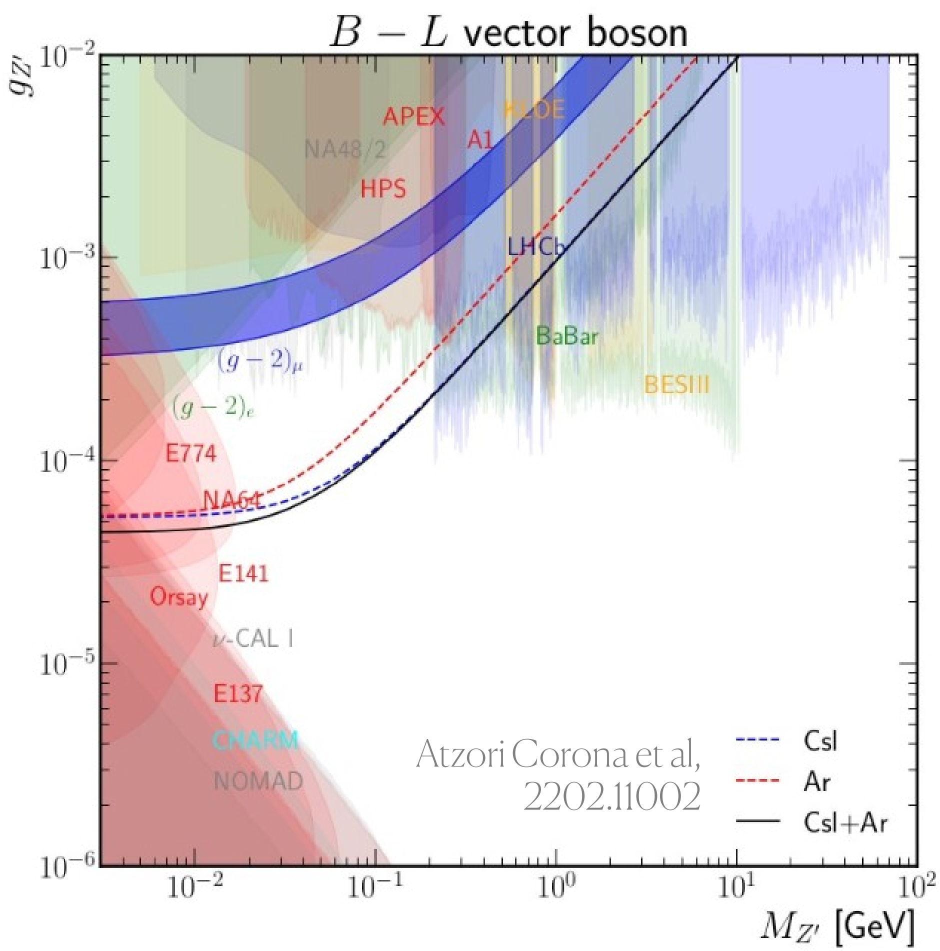
Light vector mediators



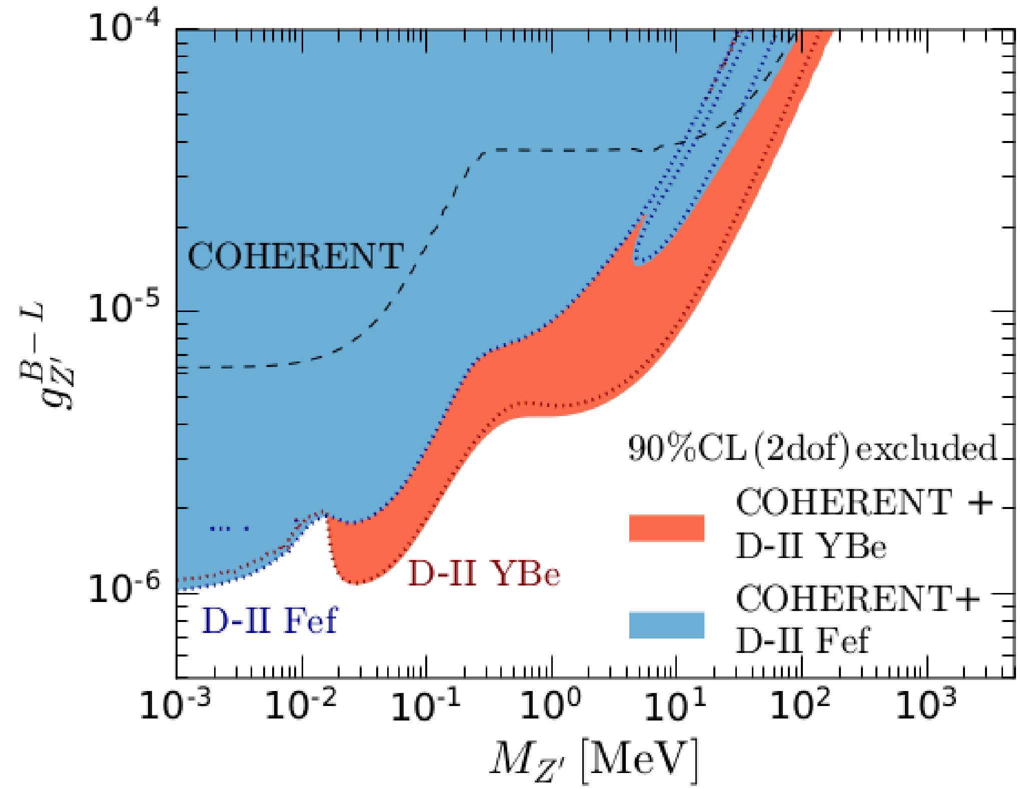


Ternes's talk

Light vector mediators



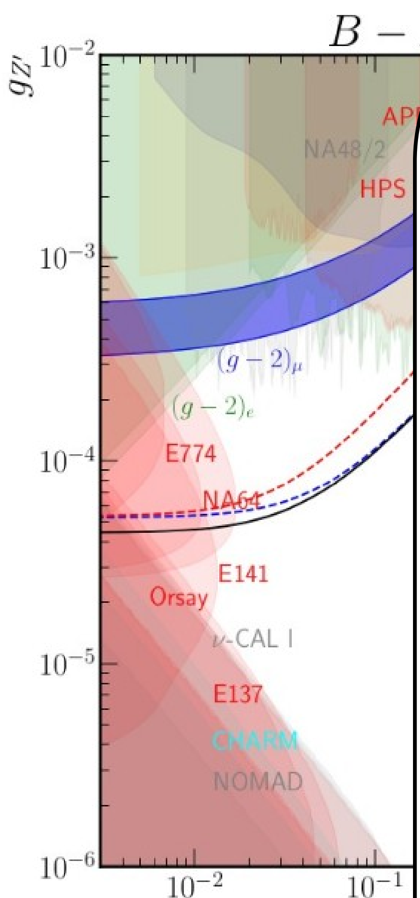
Atzori Corona et al, 2202.11002



Coloma, Esteban, Gonzalez-Garcia et al, 2202.10829

Ternes's talk

Light vector mediators



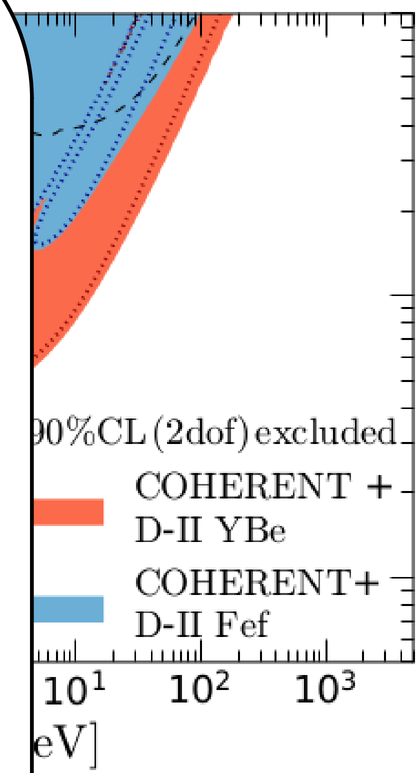
Ternes's talk

Light mediators:

→ No significant changes with more COHERENT data, nor combining nuclear targets

→ CEνNS data exclude possible explanations of $(g\text{-}2)_\mu$

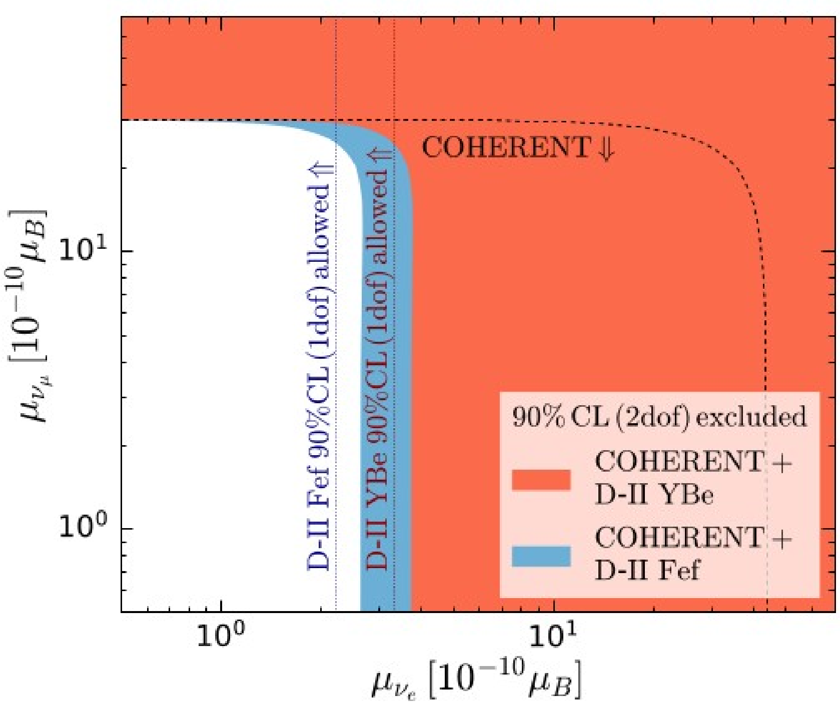
→ COHERENT sensitivity to scattering on e^-
Important at low masses



an, Gonzalez-Garcia et al, 2202.10829

Neutrino magnetic moments

Coloma, Esteban, Gonzalez-Garcia, et al,
2202.10829



Larizgoitia's lightning talk

→ Results confirmed independently by other groups
→ Again, no significant improvement from the use of latest CsI data

Atzori Corona, Cadeddu, Cargioli, et al, 2205.09484
De Romeri, Miranda, Papoulias, et al, 2211.11905

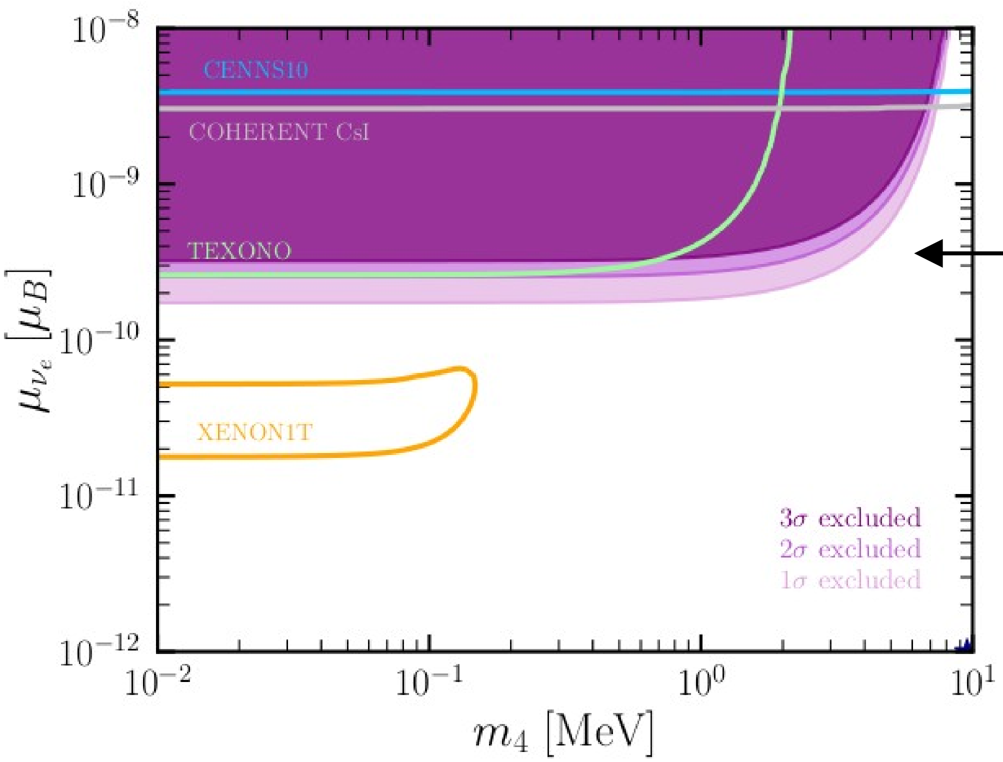
Li's & Miranda's talks

Experiment	Bounds	
CONUS	$\mu_{\bar{\nu}_e} \leq 7.5 \times 10^{-11} \mu_B$	CONUS Eur. Phys. J. **82** (2022) 813
Dresden II	$\mu_{\bar{\nu}_e} \leq 2.13 \times 10^{-10} \mu_B$	Atzori Corona et al JHEP09(2022) 164
COHERENT	$\mu_{\nu_e} \leq 3.8 \times 10^{-9} \mu_B$	de Romeri et al JHEP 04(2023) 035
COHERENT	$\mu_{\nu_\mu} \leq 2.6 \times 10^{-9} \mu_B$	de Romeri et al JHEP 04(2023) 035

Neutrino transition magnetic moments

Li's & Miranda's talks

$$\mathcal{L}_{\rm NDP} = \frac{d_\alpha}{2}(\bar{N}\sigma_{\mu\nu}\nu^\alpha F^{\mu\nu}) + {\rm h.c.}$$



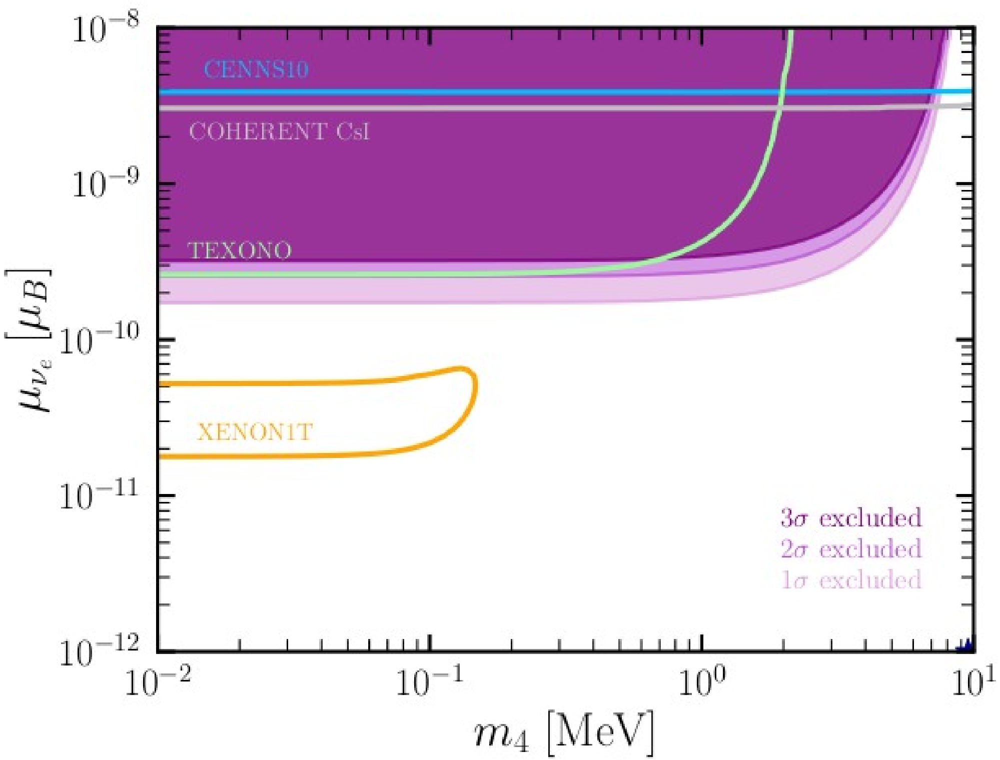
Miranda, Papoulias, Sanders, et al, 2109.09545

Aristizabal Sierra, de Romeri, Papoulias, 2203.02414

Neutrino transition magnetic moments

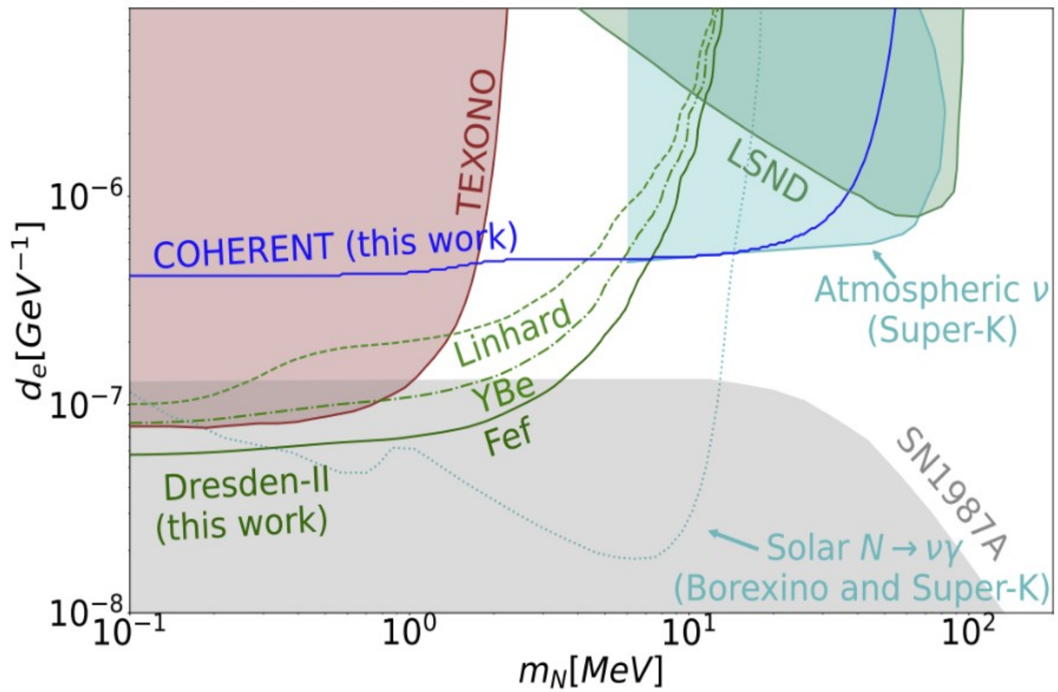
Li's & Miranda's talks

$$\mathcal{L}_{\rm NDP} = \frac{d_\alpha}{2}(\bar{N}\sigma_{\mu\nu}\nu^\alpha F^{\mu\nu}) + \text{h.c.}$$



Miranda, Papoulias, Sanders, et al, 2109.09545
Aristizabal Sierra, de Romeri, Papoulias, 2203.02414

→ Results also confirmed by other groups:

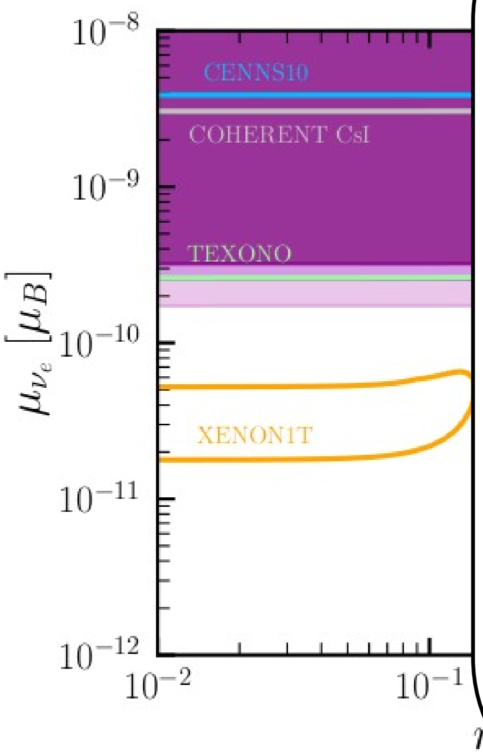


Li, Li, Xia, 2406.07477

Neutrino transition magnetic moments

Li's & Miranda's talks

$$\mathcal{L}_{\rm NDP} = \frac{d_\alpha}{2}(\bar{N}\sigma_{\mu\nu}\nu$$



Miranda, Papoulias, Sanders, ...
Aristizabal Sierra, de Romeri, Papoulias, 2203.02414

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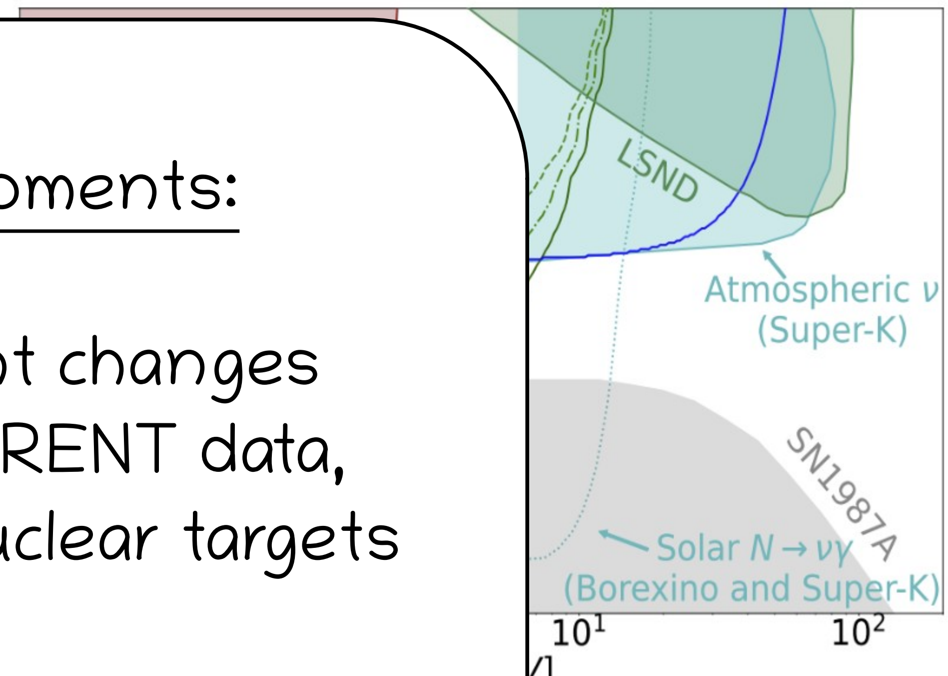


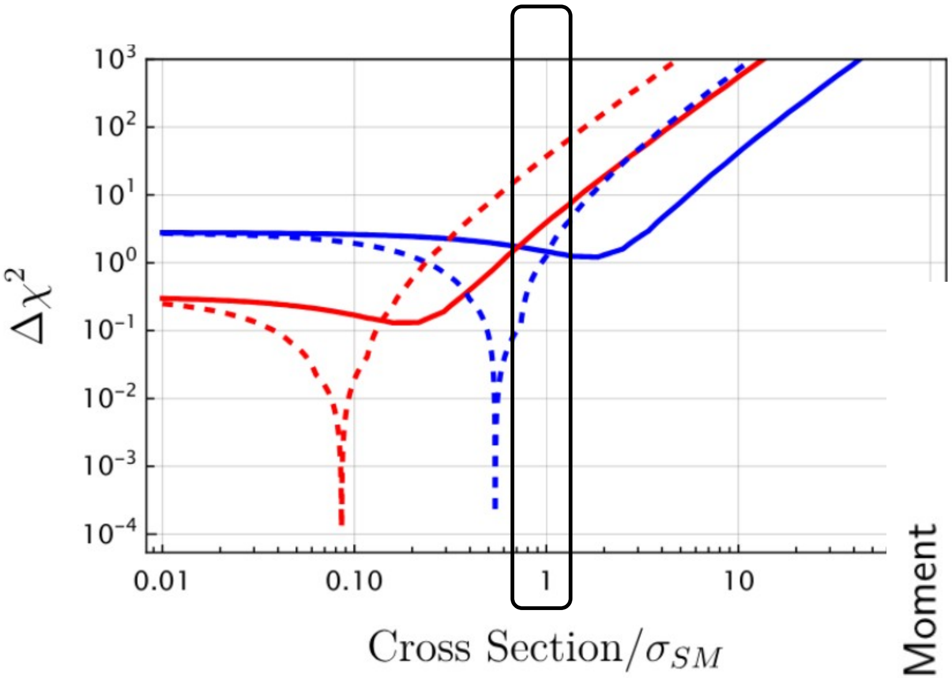
Li, Li, Xia, 2406.07477

Magnetic moments:

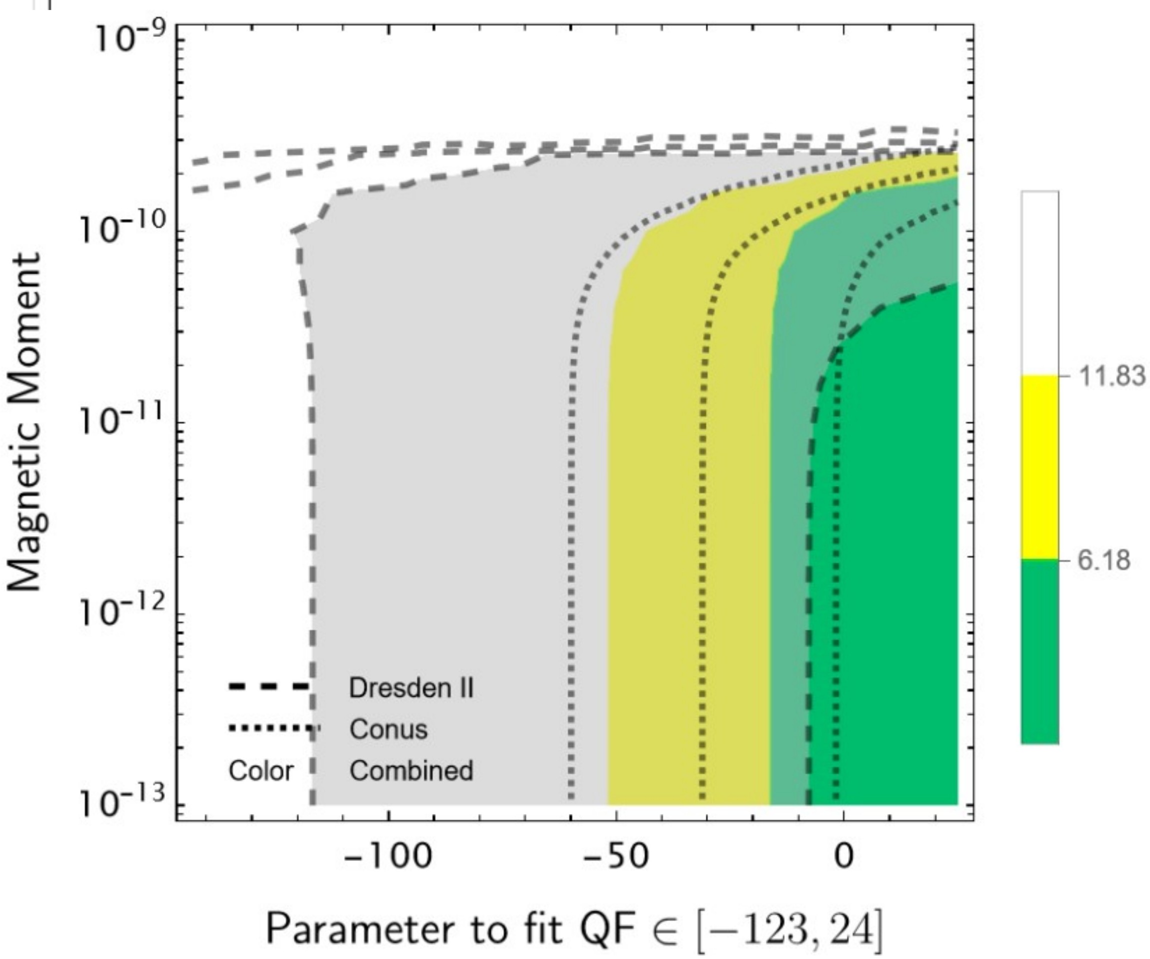
→ No significant changes with more COHERENT data, nor combining nuclear targets

→ Dresden-II limits stronger (much lower threshold)

Neutrino magnetic moments vs QF



Huber's talk



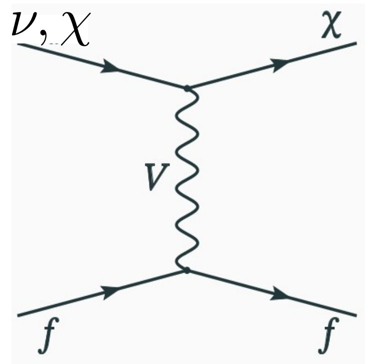
→ While CONUS seems to favor Lindhard, Dresden-II remains OK-ish

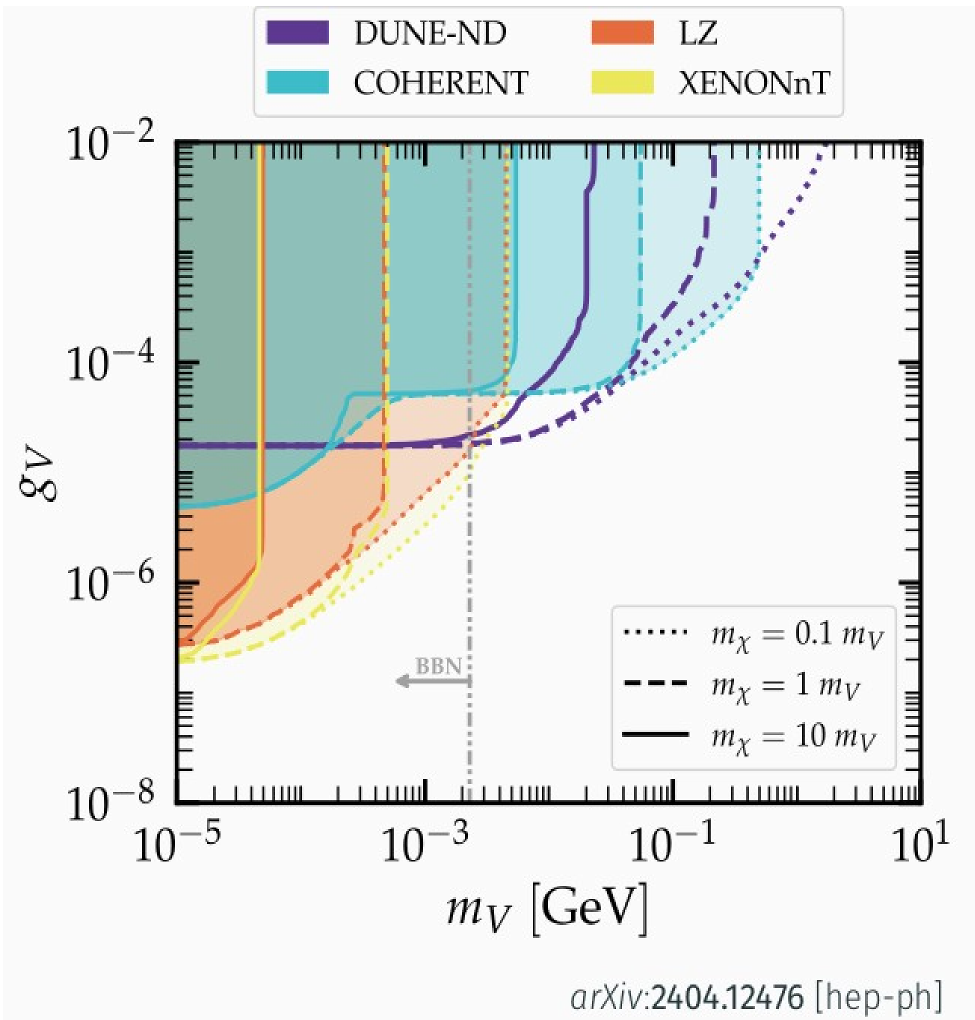
→ An incorrect QF significantly affects the limits on BSM physics manifesting at low energies (!!)

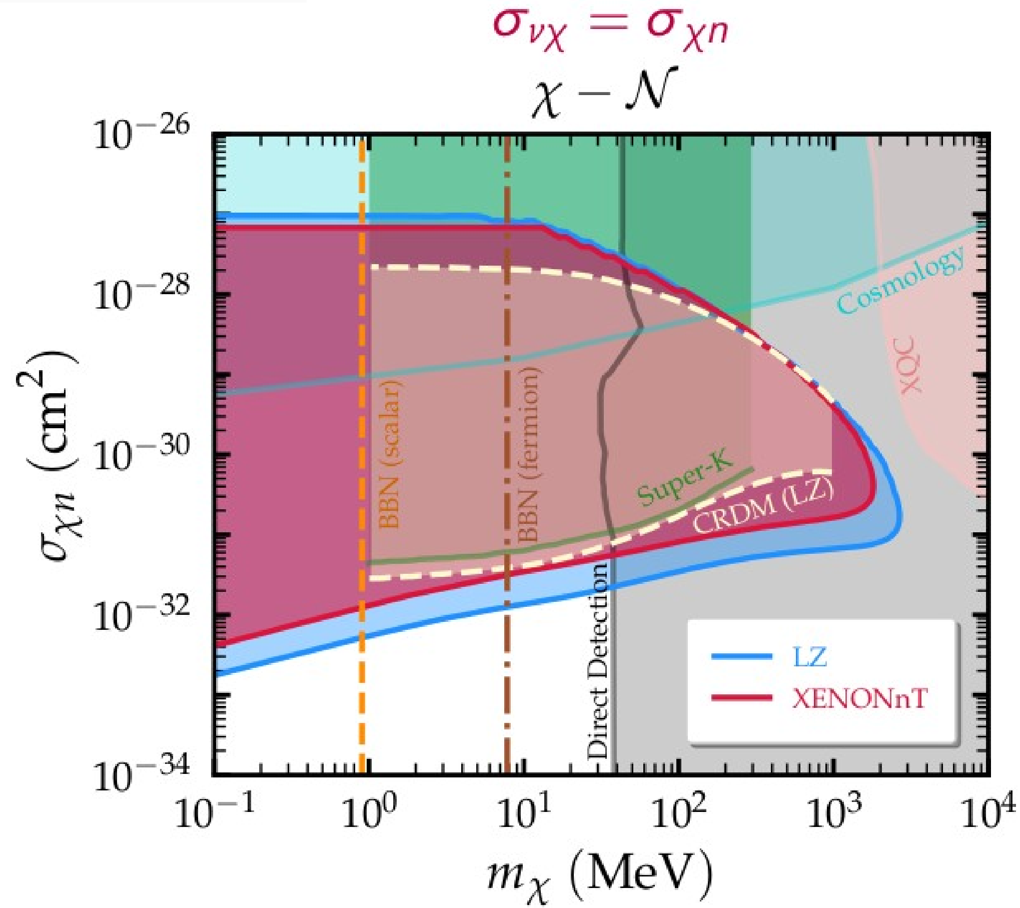
(3) Searches for new particles

Coherent scattering of new particles

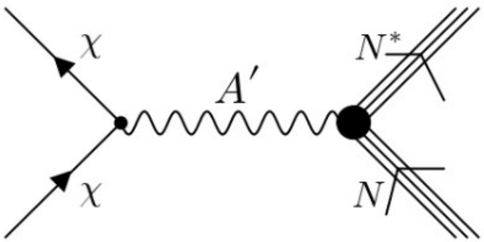
Muñoz Candela's &
Majumdar's talks

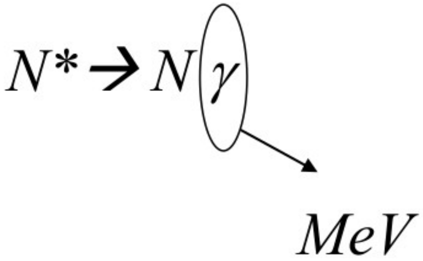




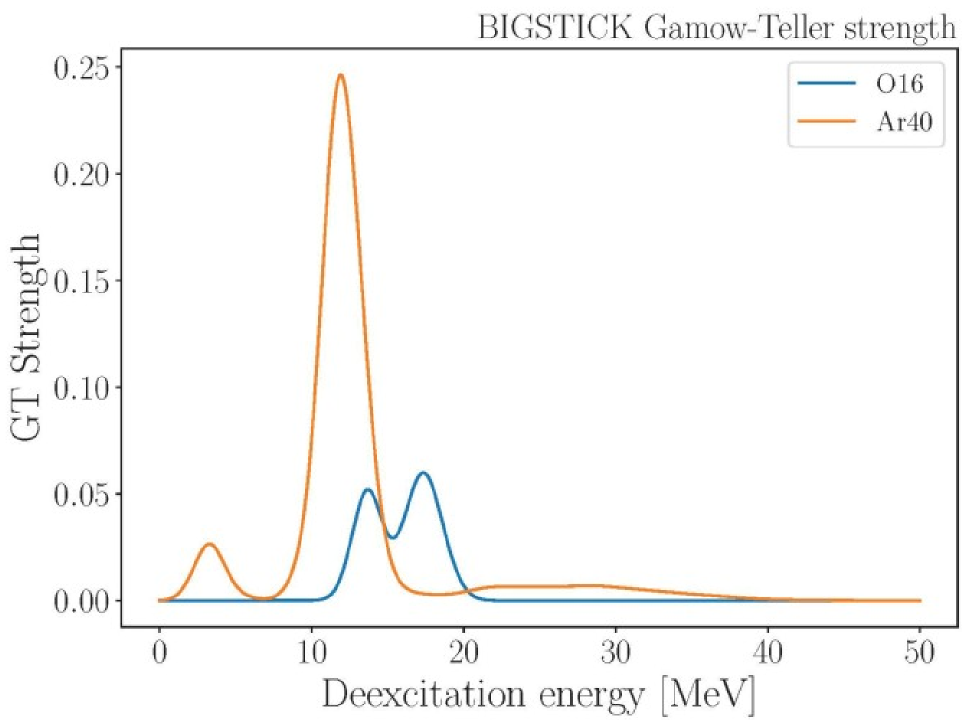


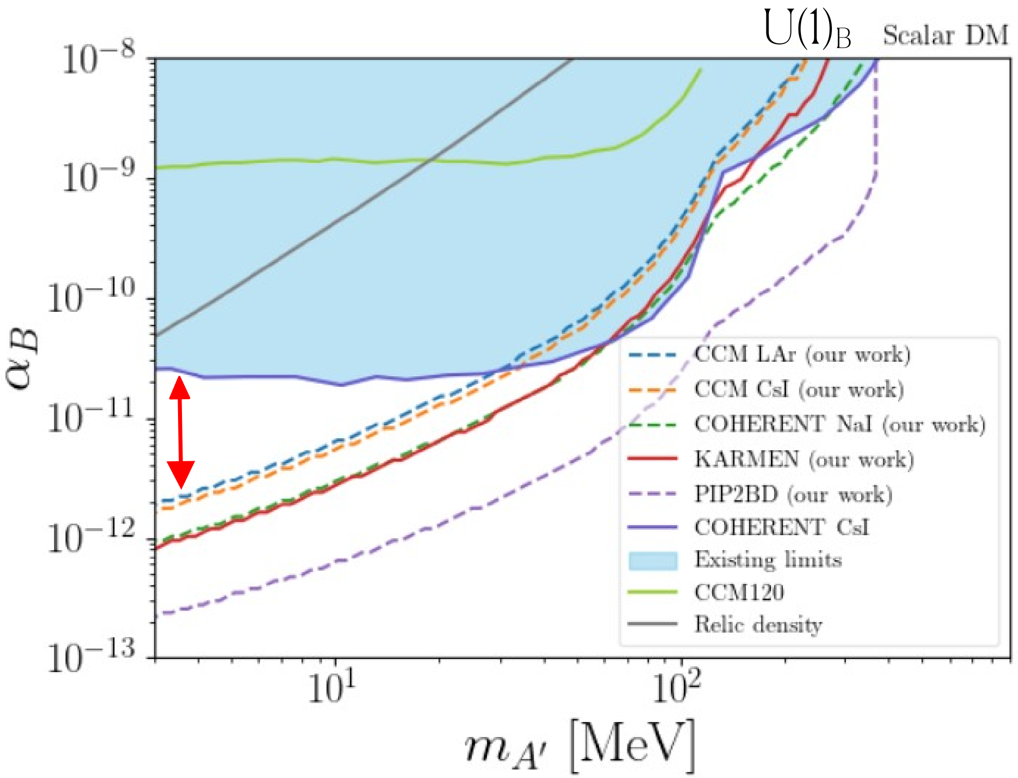
Inelastic Dark Matter signals





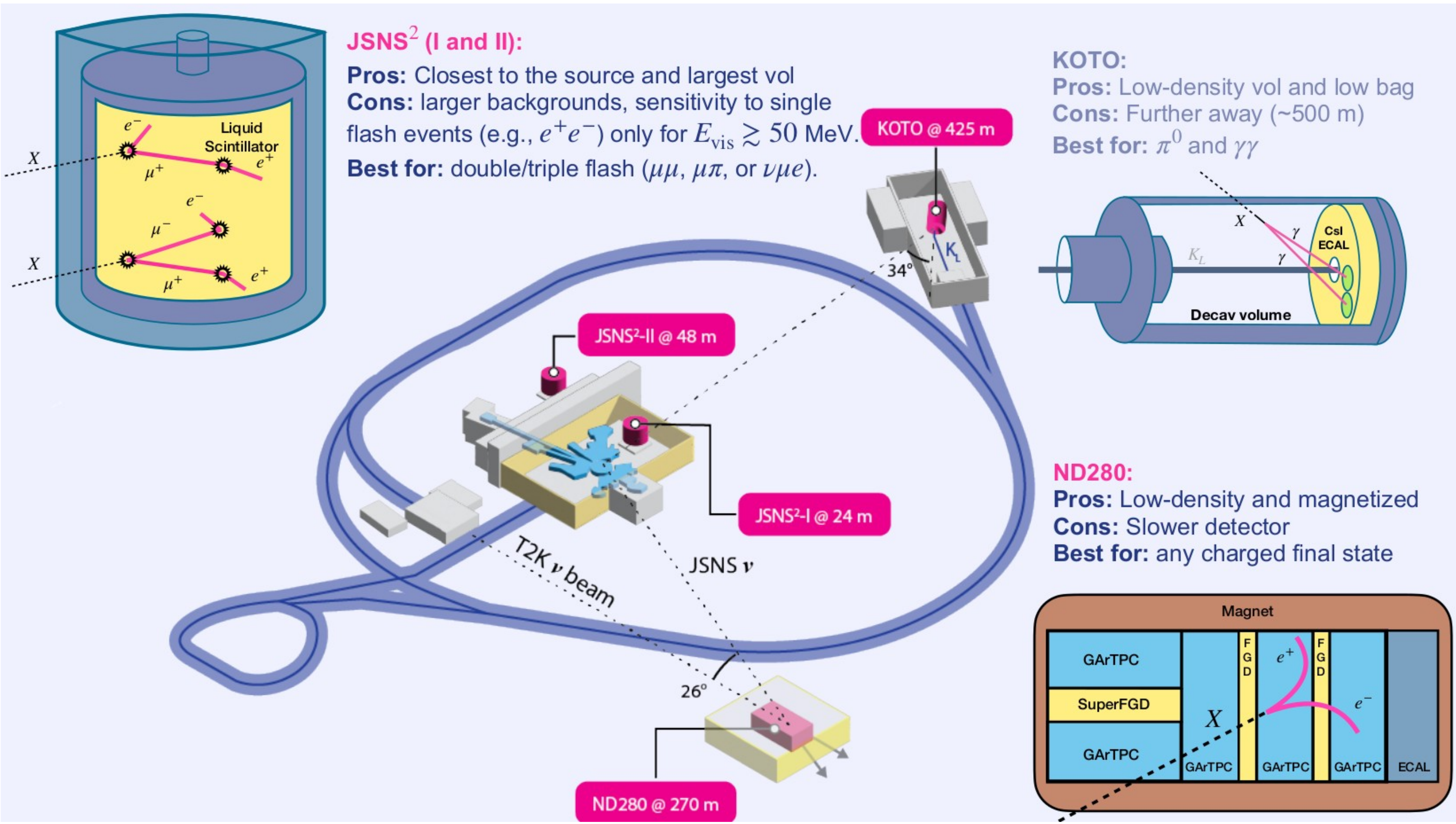
Dutta's talk





Long-lived particles @ Spallation Sources

Hostert's talk

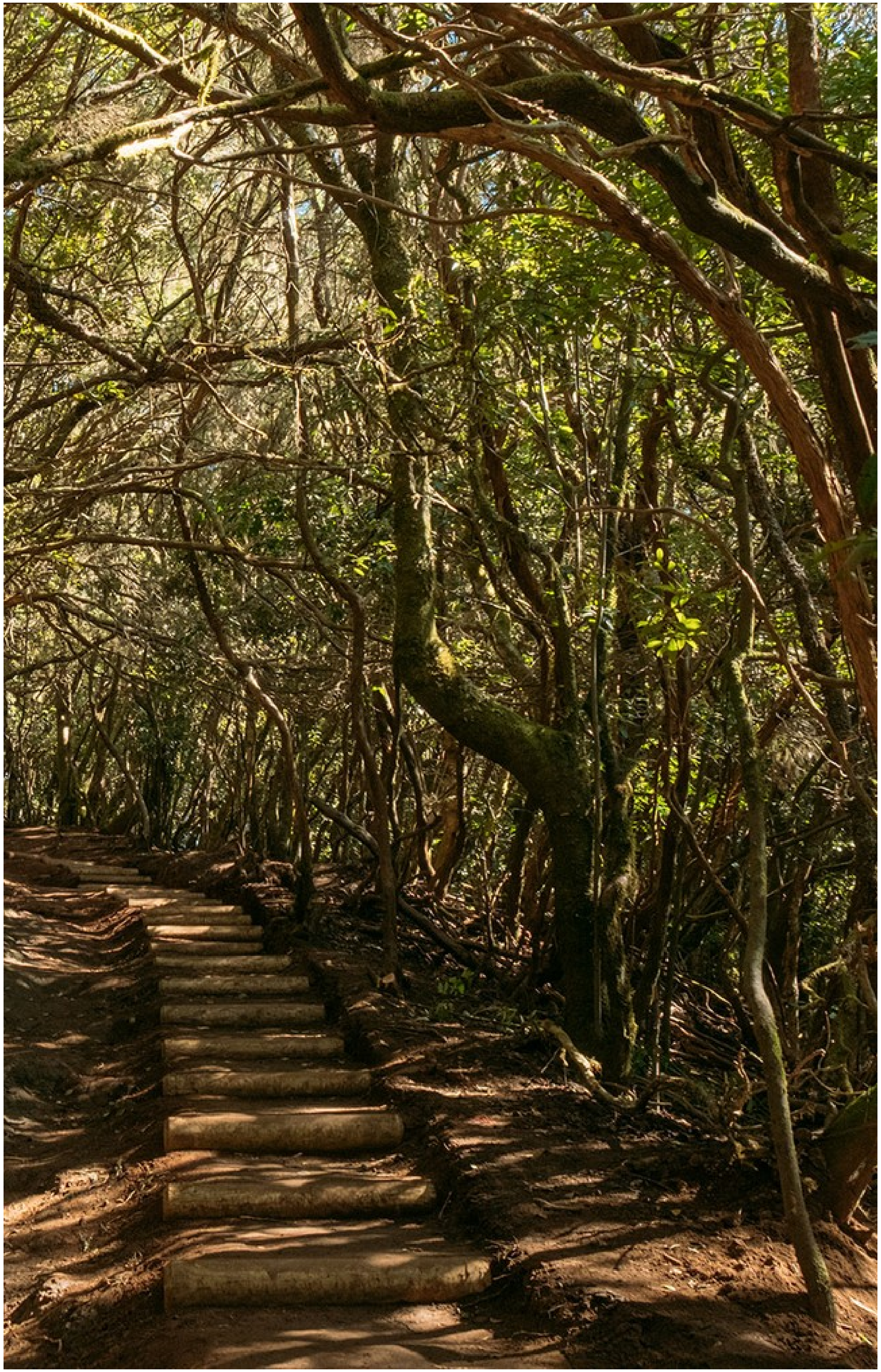


Long-lived particles @ Spallation Sources

Hostert's talk

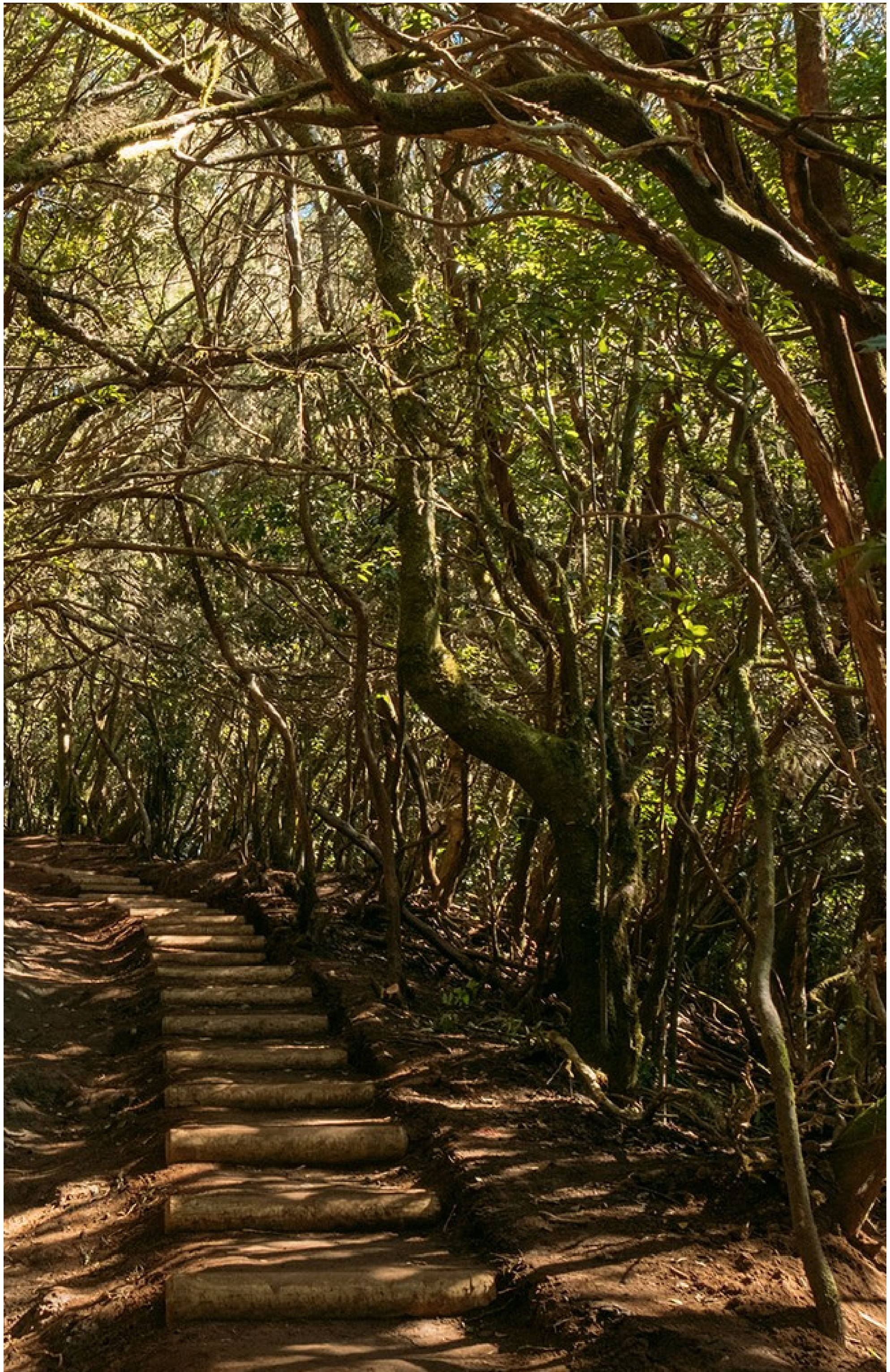
Model	Production	Decay	Timing signature	J-PARC Detector
Heavy Neutral Leptons	$\mu^+ \to e^+ \nu N$	$N \to \nu e^+ e^-$		ND280
	$\pi^+/K^+ \to \ell N$	$N \to \nu e^+ e^-$		ND280
		$N \to \nu \mu^+ e^- / \pi^+ e^-$		JSNS^2 and ND280
		$N \to \nu \mu^+ \mu^- / \pi^+ \mu^-$		JSNS^2 and ND280
		$N \to \nu \pi^0$		KOTO
Higgs Portal Scalar	$K^+ \to \pi^+ S$	$S \to e^+ e^-$		ND280
		$S \to \mu^+ \mu^- / \pi^+ \pi^-$		JSNS^2 and ND280
		$S \to \pi^0 \pi^0$		KOTO
Muon Portal Scalar	$\mu^+ \to e^+ \nu \nu S_M$	$S_M \to \gamma\gamma$		KOTO
ALP: Higgs Coupling	$K^+ \to \pi^+ a_\phi$	$a_\phi \to e^+ e^-$		ND280
		$a_\phi \to \mu^+ \mu^-$		JSNS^2 and ND280
ALP: Flavor Violating	$\mu^+ \to e^+ a_{FV} (\gamma)$	$a_{FV} \to e^+ e^-$		ND280
ALP: Weak Violating	$\pi^+ \to e^+ \nu_e a_{WV}$	$a_{WV} \to e^+ e^-$		ND280

→ Maybe worth exploring also at SNS, LANSCE, ESS!



To summarize...

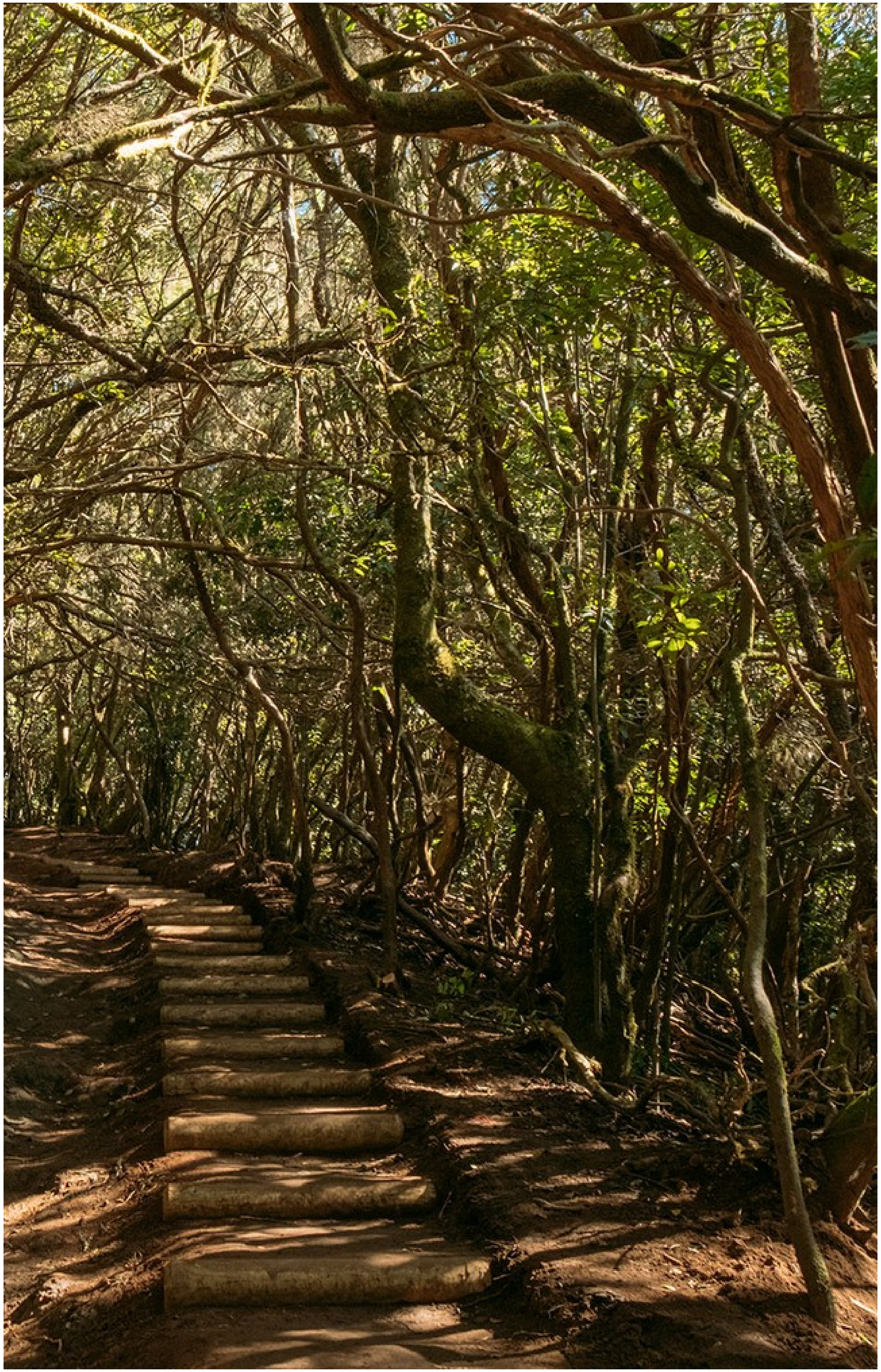
Macizo de Anaga,
Tenerife



To summarize...

- COHERENT (Spallation Source)
  - CsI
  - Ar
  - More to come! Ge, Na, ...
- CEvNS at Reactors
- CEvNS from astrophysical sources
- Increased precision
  - Quenching Factor
  - Nuclear Form Factors
  - Improved flux uncertainties
  - Radiative Corrections
- Not only CEvNS!
  - elastic scattering on electrons; CC neutrino scattering; inelastic signals, de-excitation photons, decays of long-lived particles...

Macizo de Anaga,
Tenerife



Macizo de Anaga,
Tenerife

To summarize...

- A high reward awaits at the top:
  - Neutron skin
  - Weak mixing angle
  - NSI / SMEFT
  - Sterile neutrinos
  - ALPs
  - Dark fermions/dark matter
  - ...

→ We are just getting started!

Thanks!

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