Astrophysical constraints on non-standard coherent neutrino-nucleus scattering

Anna M. Suliga

with I. Tamborra
arXiv: 2010.14545

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Niels Bohr Institute,
University of Copenhagen

Ohio State CCAPP seminar

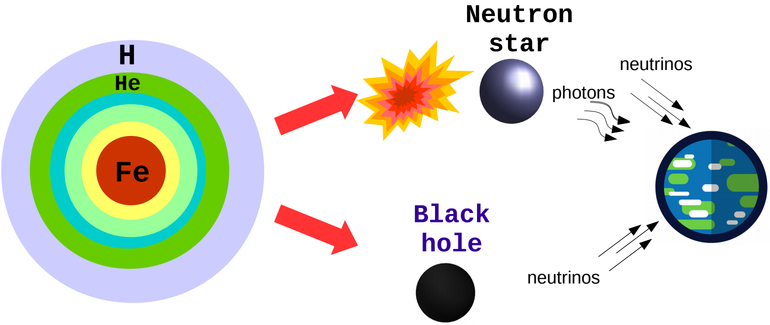
Overview

1. Astrophysical neutrino sources
2. Coherent neutrino-nucleus scattering
3. Event rates at future generation detectors
4. Sensitivity bounds on the mass and coupling of the new mediators
5. Non-standard coherent scattering in the supernova core
6. Conclusions

Astrophysical neutrino sources

Neutrinos:

- $\sim 10^{56}$ of them emitted from a single supernova
- can reveal the interior conditions of a collapsing star
- are the only messengers from the collapse to a black hole (+ GW)



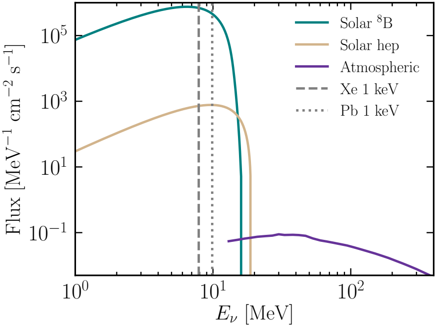
Solar and atmospheric neutrinos

Solar neutrinos

$$^{8}\mathrm{B} \to {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_e$$

$$^{3}\mathrm{He} + p \to {}^{4}\mathrm{He} + e^{+} + \nu_e$$

- neutrino energies up to ∼15 MeV



Atmospheric neutrinos

$$\pi^{+} \to \mu^{+} + \nu_\mu \text{ and } \pi^{-} \to \mu^{-} + \bar{\nu}_\mu$$

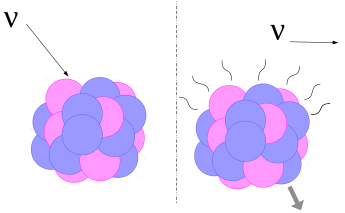
$$\mu^{+} \to e^{+} + \bar{\nu}_\mu + \nu_e \text{ and } \mu^{-} \to e^{-} + \nu_\mu + \bar{\nu}_e$$

- the highest neutrino energies among the considered sources
- high uncertainty $\sim 20\%$

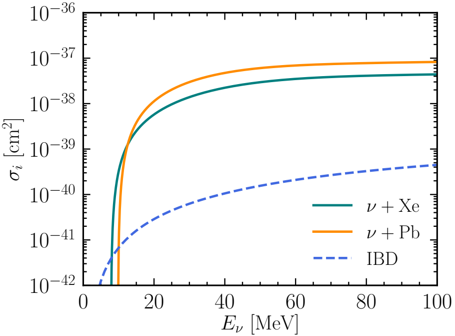
E. Vitagliano et al. arXiv: 1910.11878, M. Honda et al. arXiv: 1102.2688, J. L. Newstead et al. arXiv: 2002.08566

Coherent neutrino-nucleus scattering

Coherent elastic neutrino-nucleus scatterings (CEνNS)



$$\nu + T(A,Z) \to \nu + T(A,Z)$$



Cross section

$$\frac{d\sigma_{\text{SM}}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q), \;\; Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

- coherently enhanced by the square of the neutron number
- flavor insensitive
- coherent up to ~ 50 MeV

D. Z. Freedman

Non-standard coherent neutrino-nucleus scatterings

$g = \sqrt{|g_{q,i} g_{\nu,i}|},\ g_{q,i} g_{\nu,i} > 0$

new vector mediator

Z'

new scalar mediator

ϕ

Lagrangian terms

$$\mathcal{L}^{Z'} = g_{\nu,Z'} Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{q} \gamma^\mu g_{q,Z'} q$$

$$\mathcal{L}^{\phi}_{\text{LNC}} = g_{\nu,\phi} \phi \bar{\nu}_R \nu_L + \phi \bar{q} g_{q,\phi} q$$

$$\mathcal{L}^{\phi}_{\text{LNV}} = g_{\nu,\phi} \phi \nu_L^c \nu_L + \phi \bar{q} g_{q,\phi} q$$

Cross sections

$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{G_F^2 m_T}{\pi} |\xi|^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q)$$

$$\xi = -\frac{Q_w}{2} + \frac{g_{\nu,Z'} Q'_w}{\sqrt{2} G_F (2 m_T E_r + m_{Z'}^2)}$$

$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{d\sigma_{\text{SM}}}{dE_r} + \frac{d\sigma_\phi}{dE_r}$$

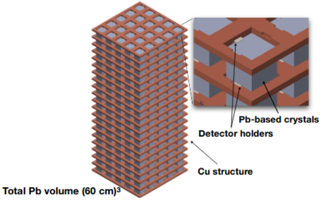
$$\frac{d\sigma_\phi}{dE_r} = \frac{(g_{\nu,\phi} g_{q,\phi} Q_s)^2}{2\pi (2 E_r m_T + m_\phi^2)^2} \frac{m_T^2 E_r}{2E_\nu^2} F^2(Q)$$

D. G. Cerdeno et al. arXiv: 1604.01025, Y. Farzan et al. arXiv: 1802.05171,
D. Aristizabal Sierra et al. arXiv: 1910.12437

Event rates at future generation detectors

Future generation CEνNS detectors

RES-NOVA (arXiv: 2004.06936)



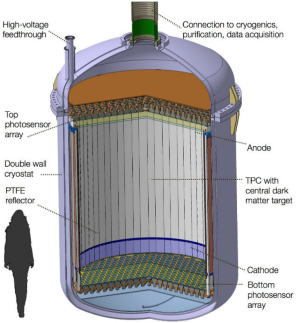
fiducial volume: 2.4 - 456 ton

target material: Pb

threshold: 1 keV

efficiency: 100%

DARWIN (arXiv: 1606.07001)



fiducial volume: 40 ton

target material: Xe

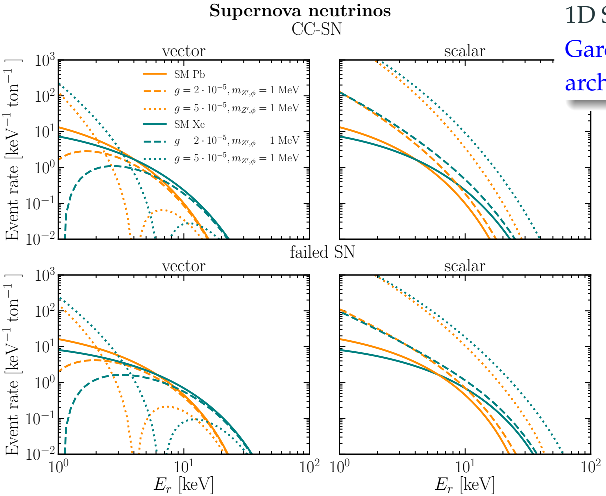
threshold: 1 keV

efficiency: XENON1T - 100%

Scattering rate

$$\frac{dR_{\nu N}}{dE_r dt} = N_T \, \epsilon(E_r) \int dE_\nu \, \frac{d\sigma_{\nu N}}{dE_r} \, \psi(E_\nu, t) \, \Theta(E_r^{\max} - E_r)$$

$$E_r^{\max} = \frac{2E_\nu^2}{m_T + 2E_\nu}$$

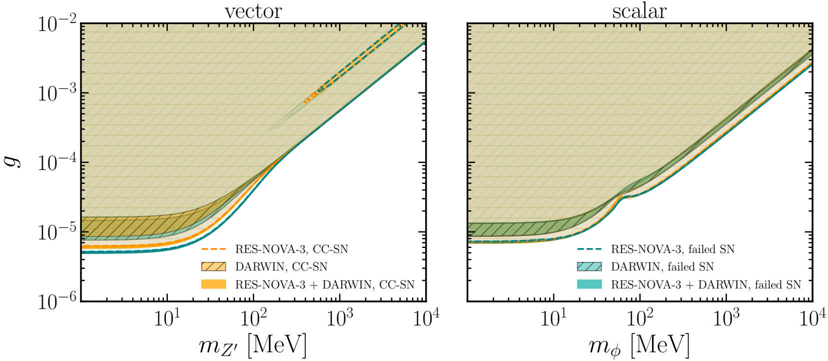


1D SN models
Garching group archive

- Failed SN: hotter neutrino spectrum → longer recoil spectrum
- Heavier target: higher number of events but shorter recoil spectrum

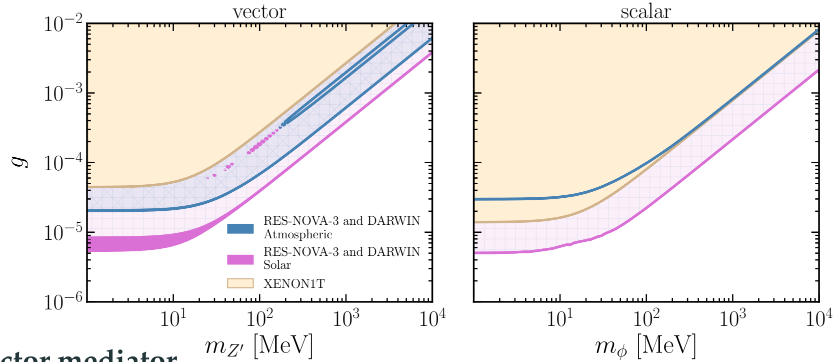
Sensitivity bounds on the mass and coupling of the new mediators

Results supernova neutrinos



- failed SN: higher number of events → better constraints
- RES-NOVA-3 drives the limits due to to higher volume
- vector mediator small unconstrained region due to the interference term
- limits on the vector mediator better for low mediator masses

Results solar and atmospheric neutrinos

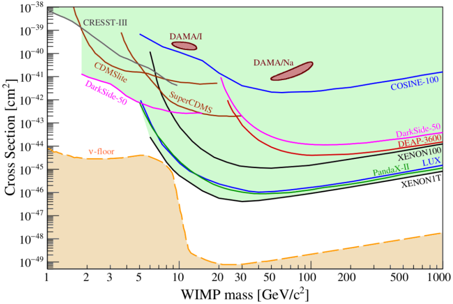


Vector mediator

- Solar neutrinos: bounds driven by Xe based detector
- Atmospheric neutrinos: bounds driven by Pb detector

Scalar mediator

- Bounds driven by Pb detector



M. Schumann, arXiv:1903.03026

neutrino floor

unavoidable background

in the future dark matter detectors

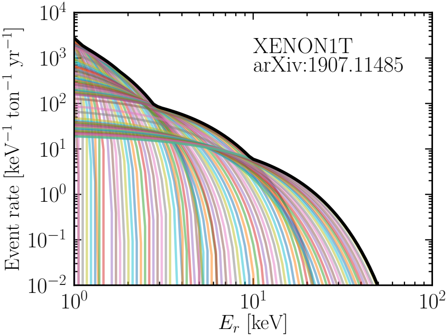
WIMP's limits

on the mass and cross section

↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓

limits on the mass and coupling

of the non-standard mediators



J. Aalbers et al. wimprates, E. Aprile et al. arXiv: 1907.11485

Non-standard coherent scattering in the supernova core

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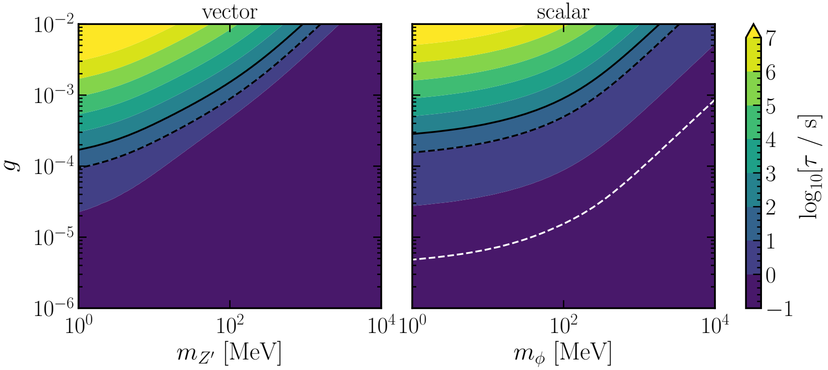
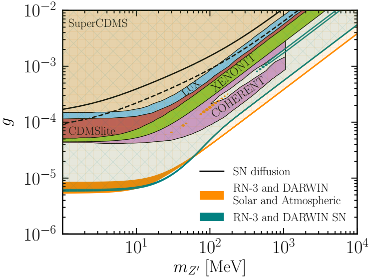


- prolonged diffusion time → possible change in the star's fate
- prolonged diffusion time → changed duration of the neutrino signal
- LNC scalar mediator → new cooling channel due to ν_R

Conclusions

Conclusions

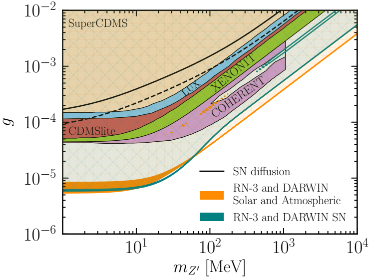


Future dark matter (CEνNS) detectors

- sensitive to astrophysical neutrinos
- flavor insensitive neutrino channel
- high cross section & low thresholds
- open an extra window to probe New Physics
- promise to place most competitive bounds on new mediators

Core-collapse supernovae

- non-standard mediators affect the diffusion time of neutrinos
- scalar LNC mediator $\rightarrow$ new cooling channel



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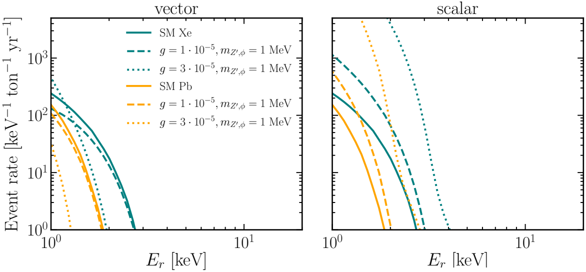
Thank you!

Backup slides

Event rates for solar and atmospheric neutrinos

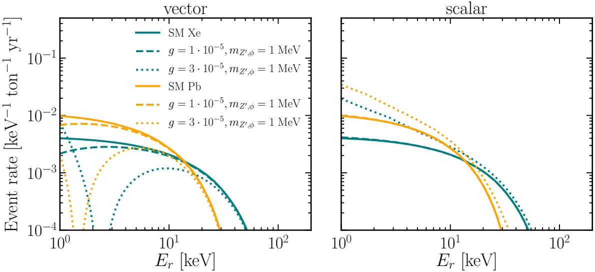
Solar neutrinos



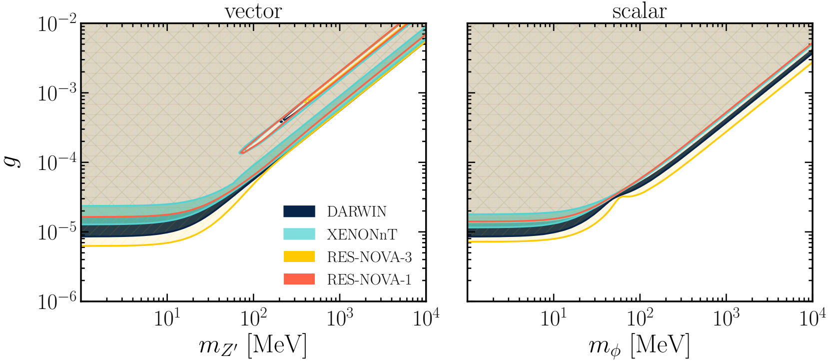
- small neutrino energies
  short recoil spectrum
- small neutrino energies
  Xe detector favored

Atmospheric neutrinos

- high neutrino energies
  longest recoil spectrum
- high neutrino energies
  Pb detector favored

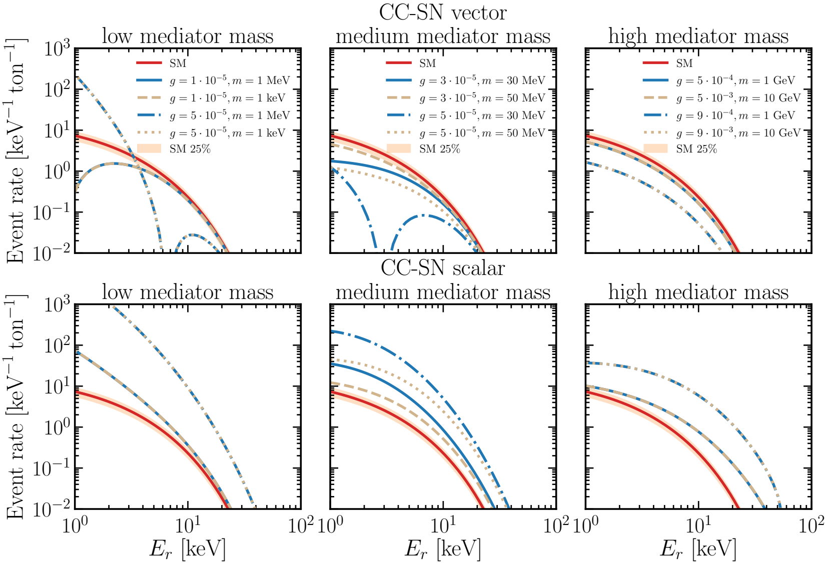


Results supernova neutrinos

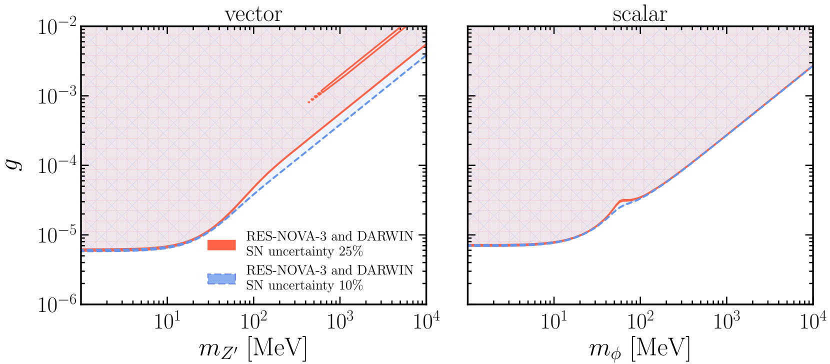


- smaller detector volumes relax the constraints
- vector mediator small unconstrained region due to the interference term
- RES-NOVA-1 worse than XENONnT due to the smaller volume

Mediator mass dependence



SN uncertainty



Non-standard coherent scattering in the supernova core

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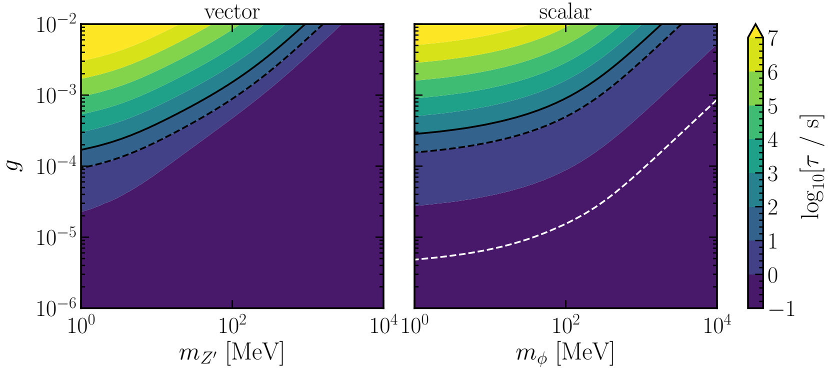

- mean-free path

$$\lambda_{\nu_\beta} = \sum_{CC,NC} \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta}) E^2_{\nu_\beta}}{n_t \int dE_{\nu_\beta} f(E_{\nu_\beta}) E^2_{\nu_\beta} \sigma_i(E_{\nu_\beta})}$$

- diffusion time

$$\tau_{\nu_\beta} = \int_{R_1}^{R_2} dr \frac{r}{\lambda_{\nu_\beta}(r)}$$

- number of scatters

$$N = \int_0^{R_2} \frac{2r}{\lambda(r)^2}\, dr$$

$R_1 = 10$ km

$R_2 = 40$ km