Status and Perspectives of Coherent Elastic Neutrino Nucleus Scattering

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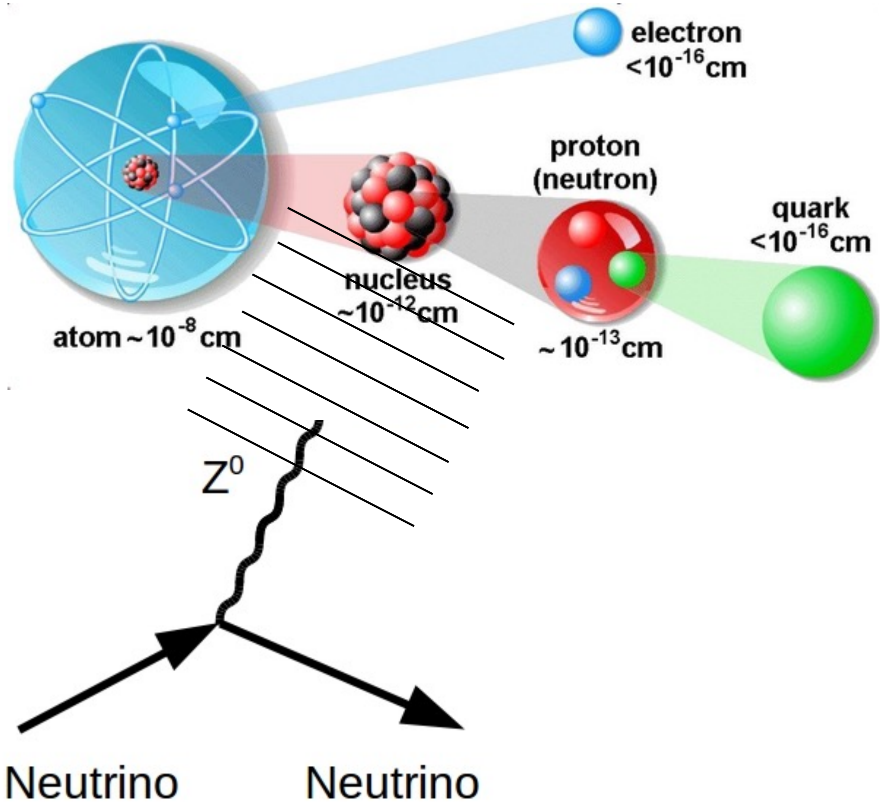
The simple Picture

Z-exchange of ν with nucleus

$$Q_w = N - (1 - 4\sin^2\theta_w)Z \quad \sim N$$

➔ sees mostly neutrons
momentum ←→ wavelength

Very low momentum
➔ nucleus recoils as a whole

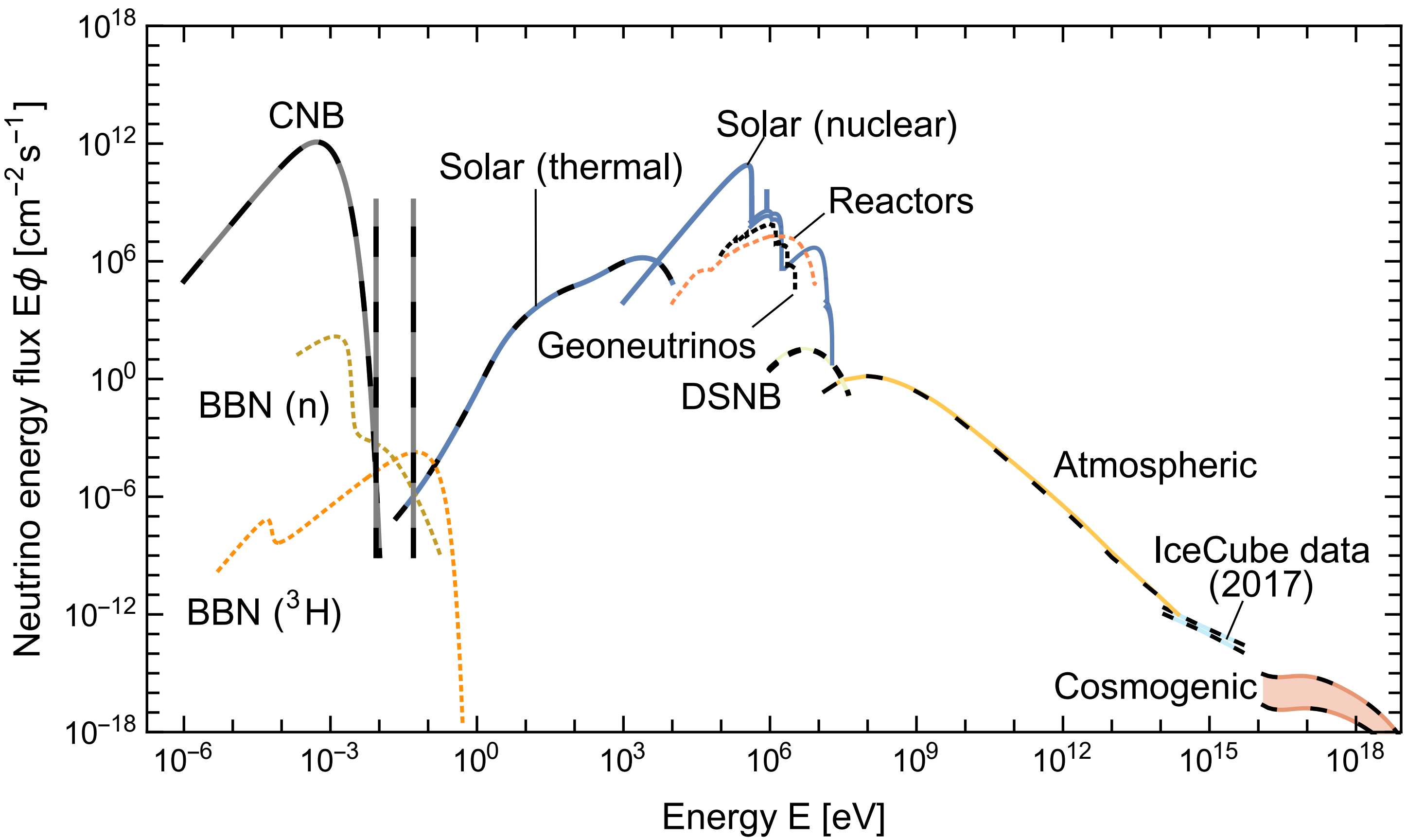


Coherence length ~ 1/E ➔ E_ν below O(50) MeV
➔ low energy E_ν ←→ lower cross sections ➔ very high flux!

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2) \sim N^2$$

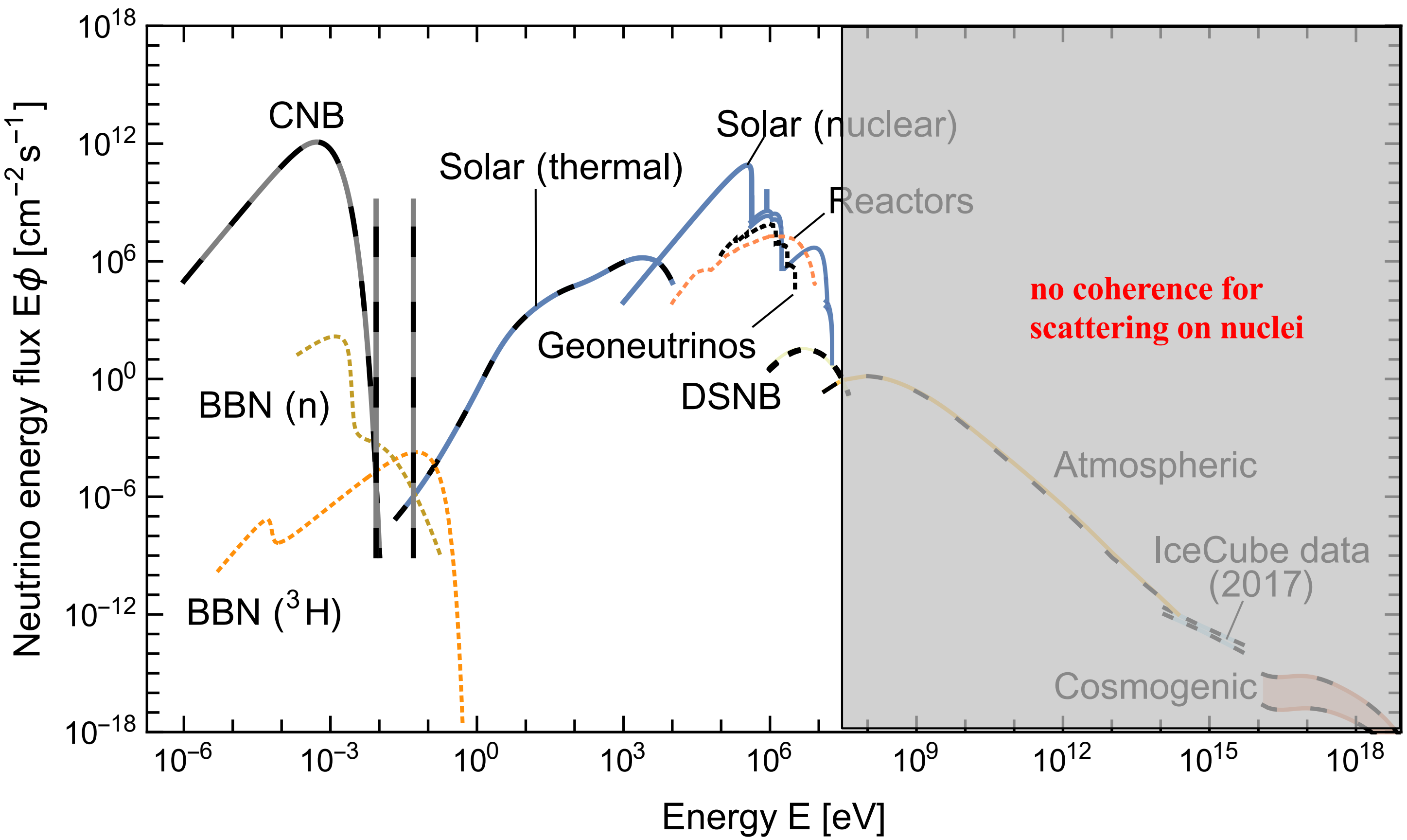
N ≃ 40 ➔ N^2 = 1600 ➔ detector mass 10t ➔ few kg

Sources: Flux ⊗ Energy



Vitagliano, Tamborra, Raffelt
Rev.Mod.Phys. 92 (2020) 45006
arXiv:1910.11878

Sources: Flux ⊗ Energy



Vitagliano, Tamborra, Raffelt
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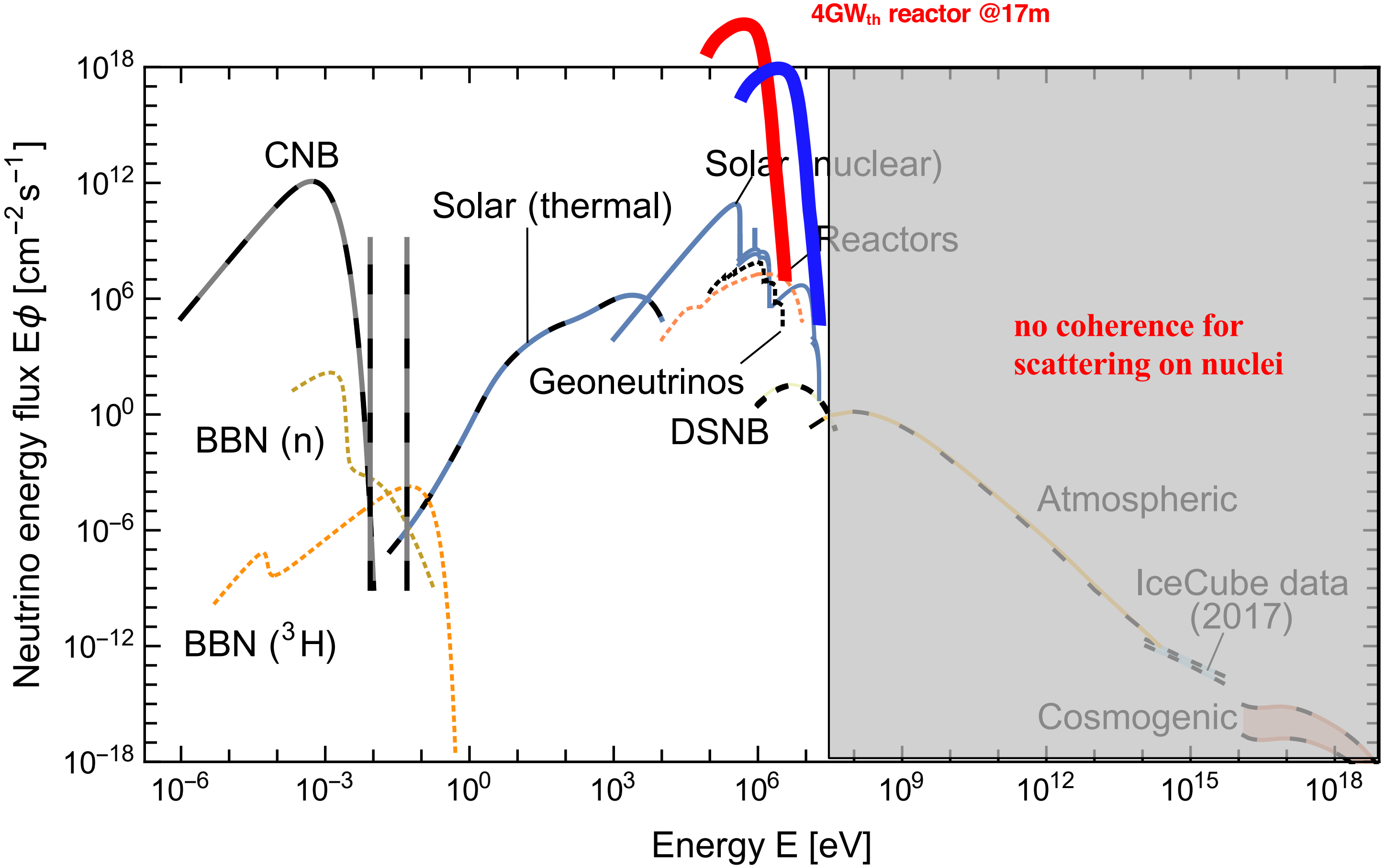
Sources: Flux ⊗ Energy

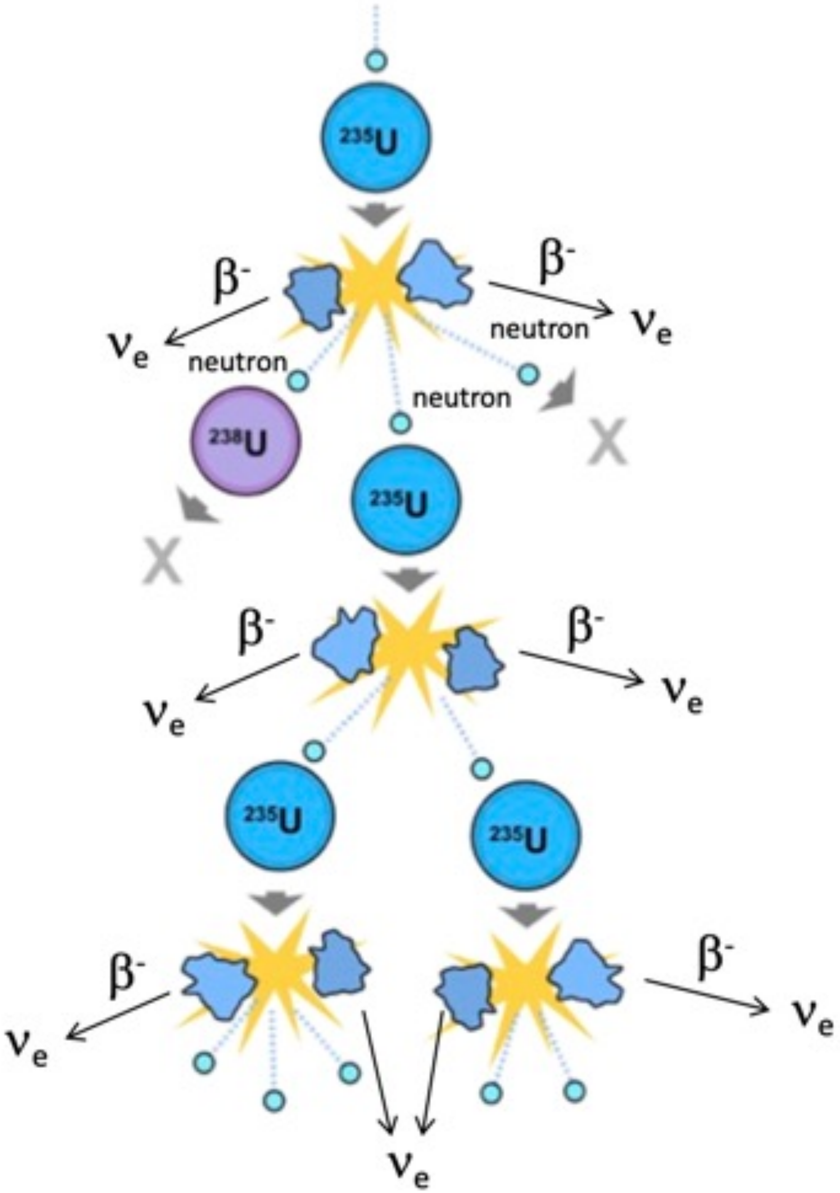
➔ very different close to a nuclear power reactor and in a stopped π-beam or a supernova

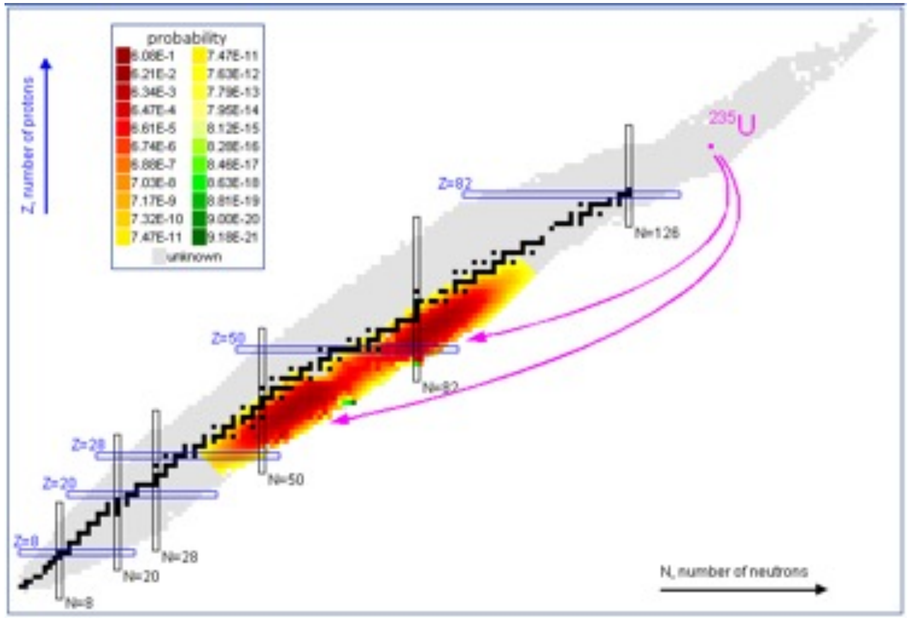


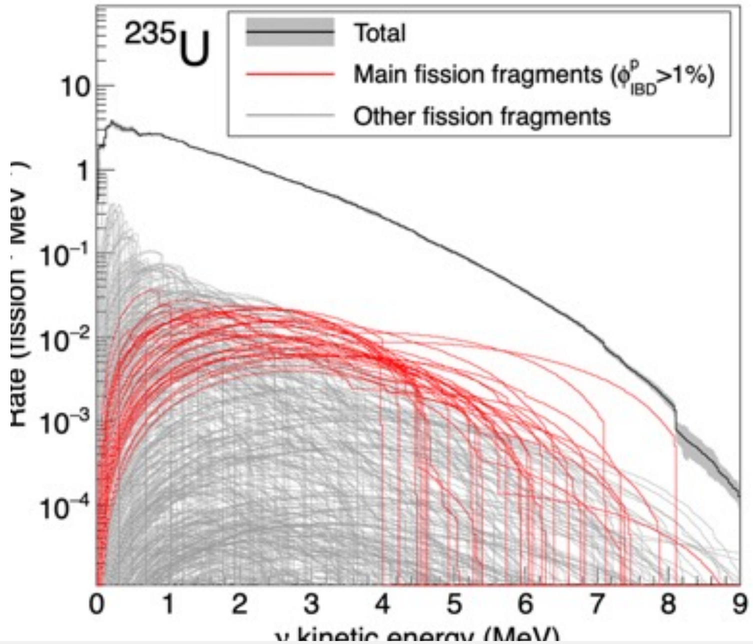
Vitagliano, Tamborra, Raffelt
Rev.Mod.Phys. 92 (2020) 45006
arXiv:1910.11878

➔ event rates: ⊗ detector size ⬅➔ backgrounds

Neutrinos from Nuclear Reactors







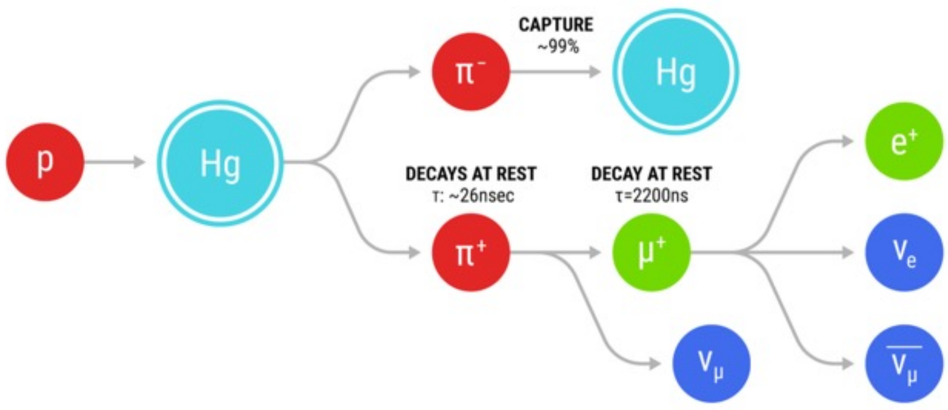
neutrinos for free

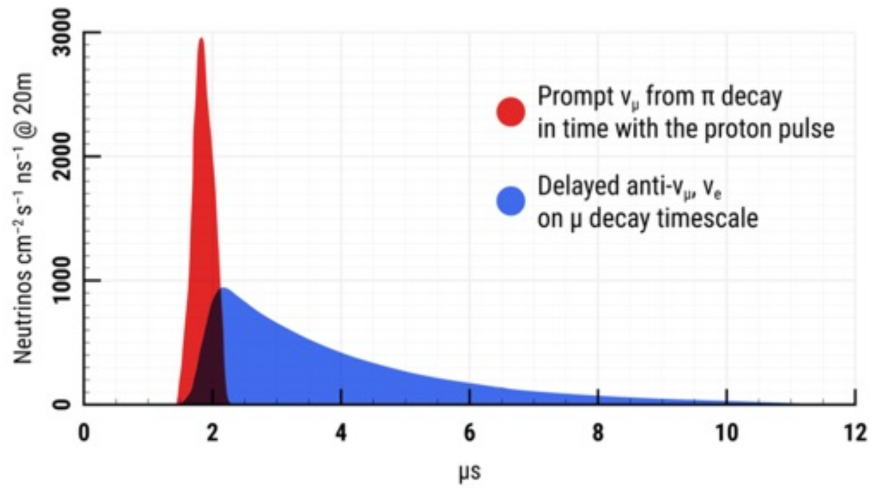
$4\pi \rightarrow 1/R^2$

huge flux: $4GW_{th}$

@20m: $150kW/m^2$

Pion Decay at Rest (π-DAR) and Supernovae

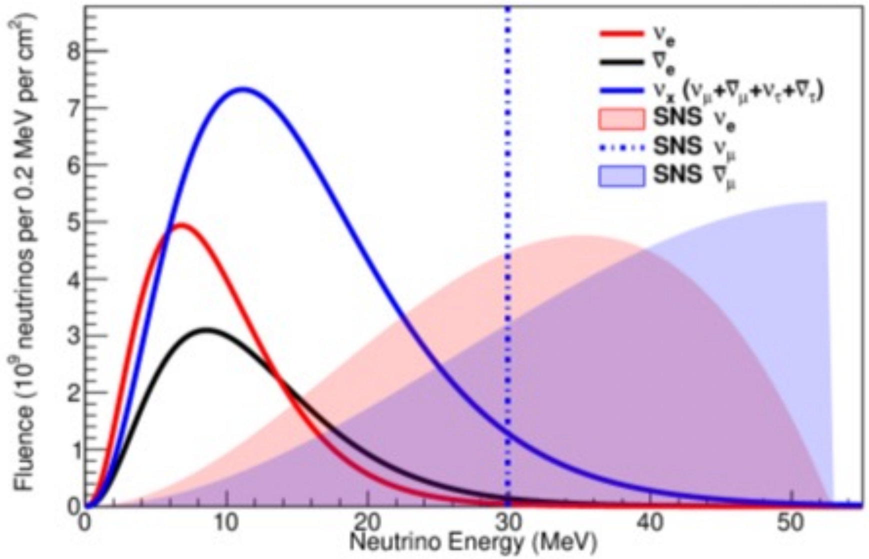




COHERENT collab

Pulsed source of ν_e and anti-ν_μ
- timing → background suppression
- up to 50MeV → partial coherence

- Spallation Neutron Source (**SNS**)
  Oak Ridge National Laboratory
- Under construction: ESS
  European Spallation Source, Sweden



Spectrum of a typical 10kpc galatice SN

Gallo Rosso, Vissani, Volpe, JCAP 04:040 (2018)

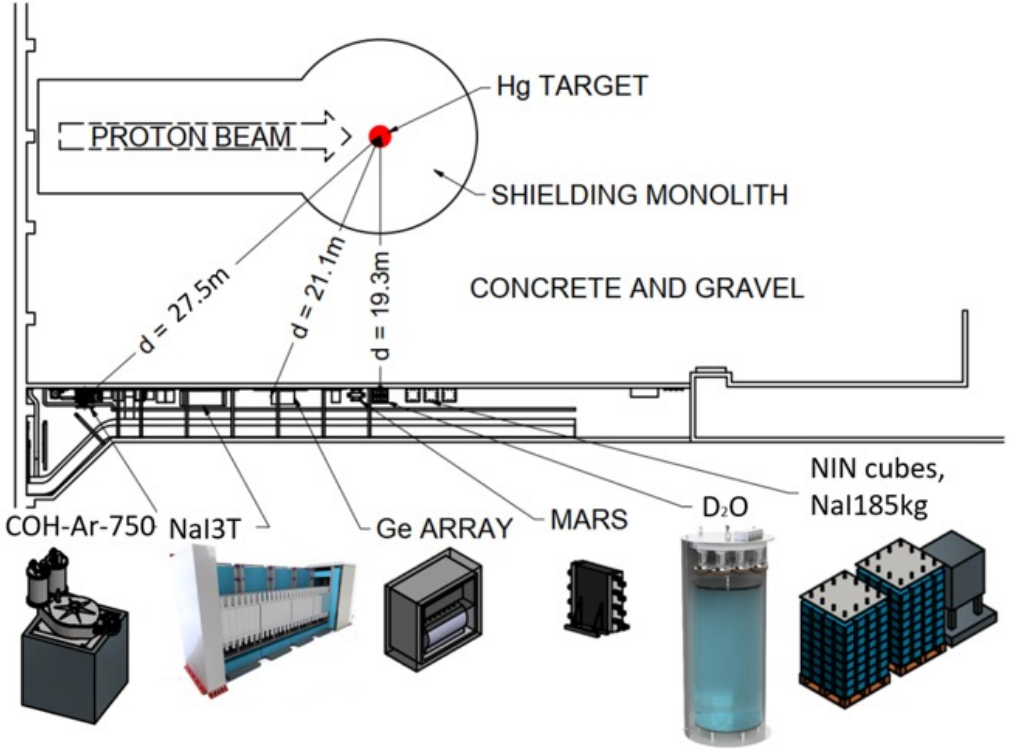
CEvNS Experiments

C. Bonifazi, Neutrino 2022

COHERENT

1974 CEνNS Prediction by D. Freedman
2017: First observation with the CsI[Na] detector

Neutrino Alley at Spallation Neutron Source (SNS)
at Oak Ridge National Laboratory, USA



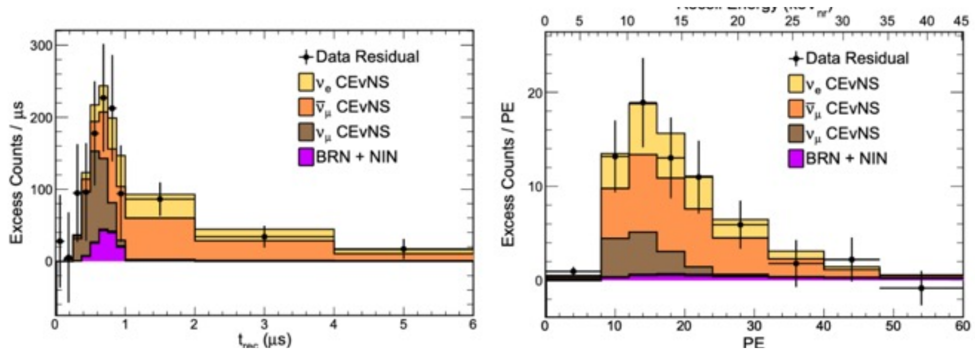
Pion decay at rest source:

- pulsed proton beam with 60 Hz
  ~10^{20} protons on target/d (POT)
  up to 1.7 MW power
  ➔ about 0.29 ν per POT
- background rejection via beam time structure

COHERENT

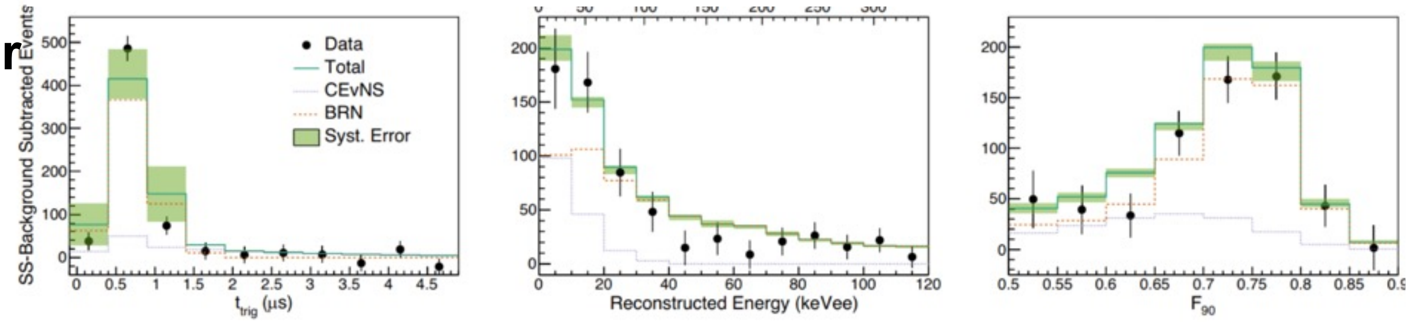
→ **CsI:** PRL 129 (2022) 081801

CsI improvements:
scintillator response model systematics



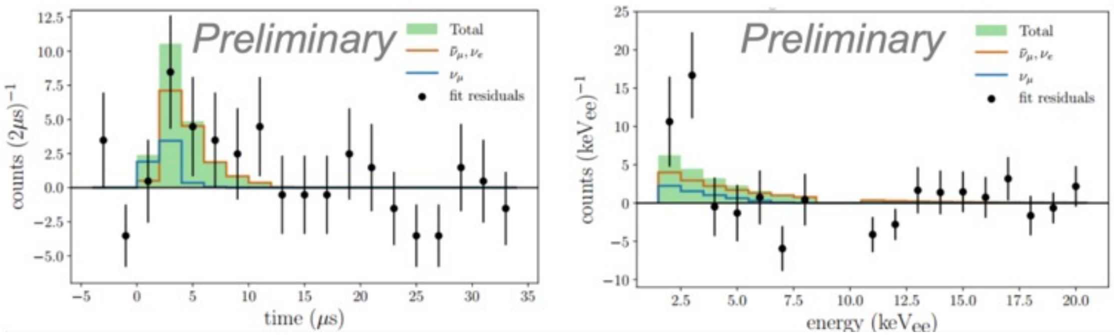
→ **Ar:** PRL 126 (2021) 012002

LAr single-phase detector
24.4 kg, 20 keV$_{nr}$ threshold
signal: 3.5σ significance



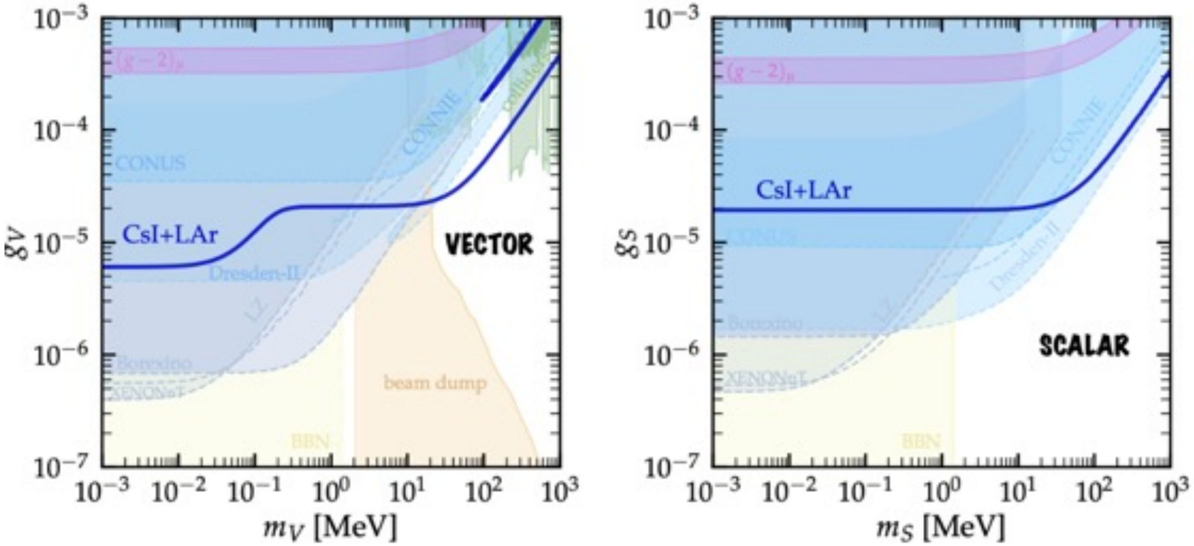
→ **Ge:** arXiv: 2406.13806

HPGe Germanium diodes
8 x 2.2kg semi coaxial
110-150 eV FWHM pulser resolution

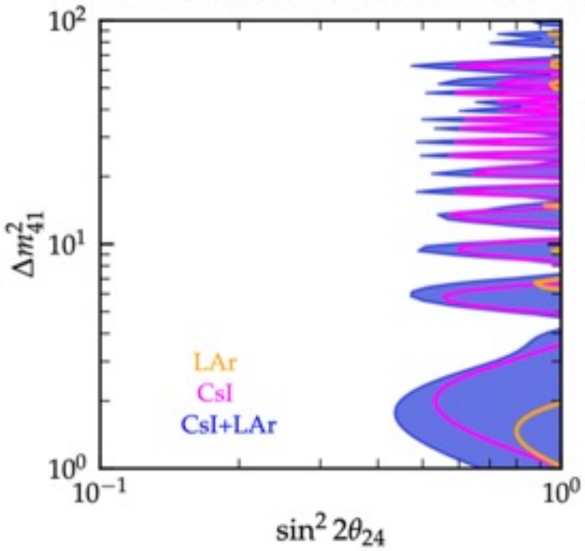


COHERENT

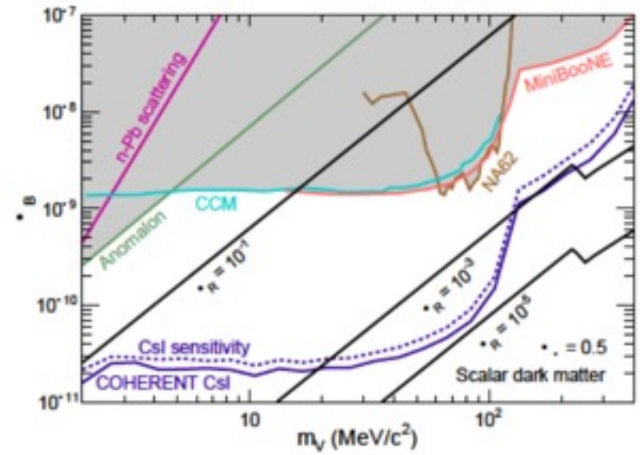
Limits on NSI with light vector and scalar mediators.



Limits on sterile neutrino oscillations.

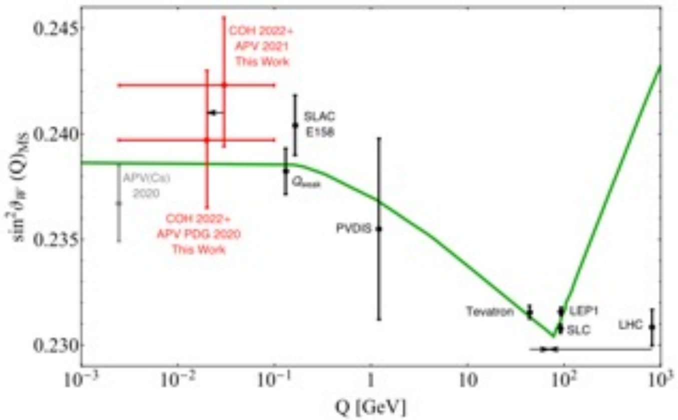


V. de Romeri et al, JHEP 04 (2023) 035



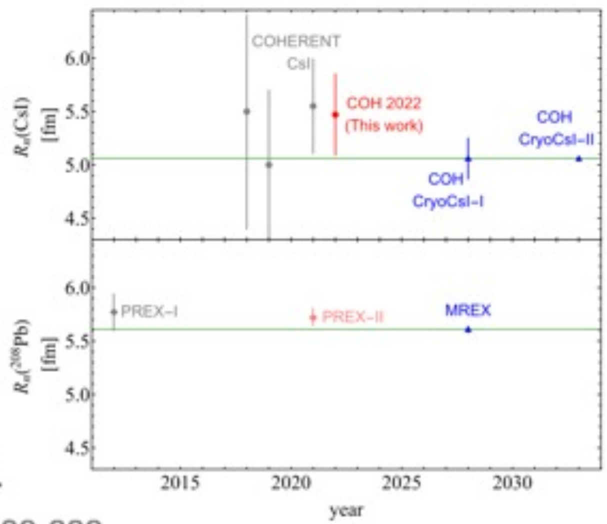
Limits on sub-GeV leptophobic dark matter.

COHERENT collab., PRD106 (2022) 5, 052004



Weak mixing angle measurement at low Q.

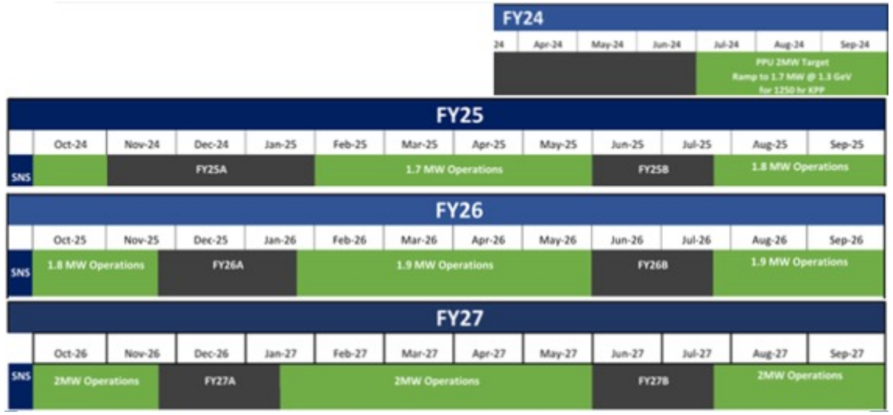
M. Corona et al, Eur. Phys. J. C (2023) 83:683



Neutron distribution radius.

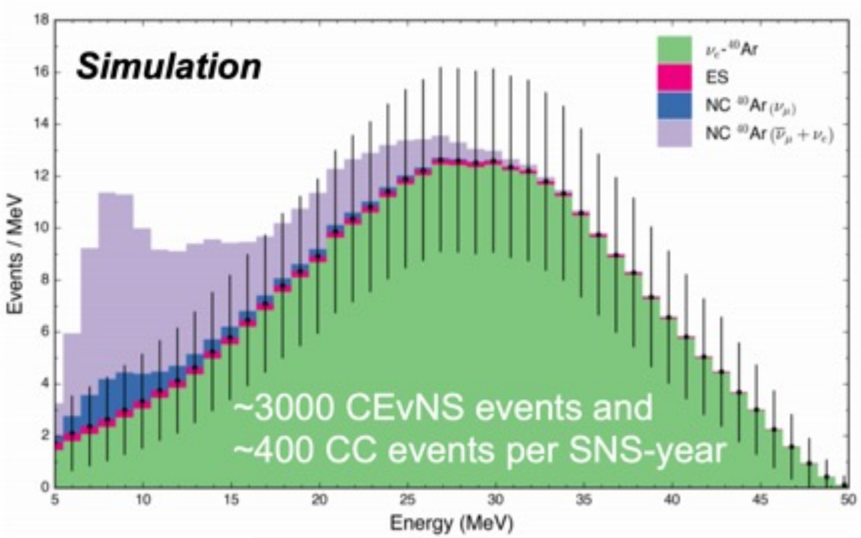
COHERENT Plans

Proton Power: Upgraded SNS
→ steadily increasing power
→2 MW



$D_2$0 detector
address leading systematic uncertainty

750-kg LAr target
expect ~3000 events/SNS/year



arXiv: 2204.04575

JINST 16 P08048 (2021)

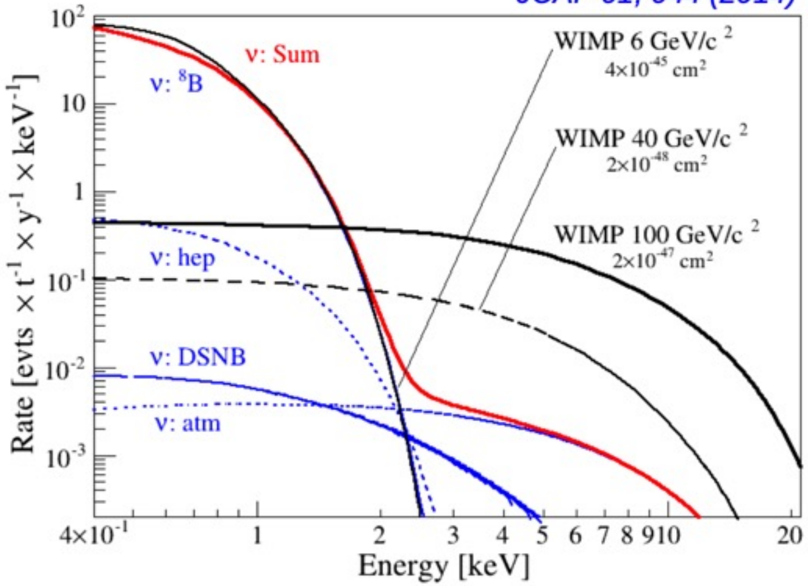
XENONnT (PandaX)

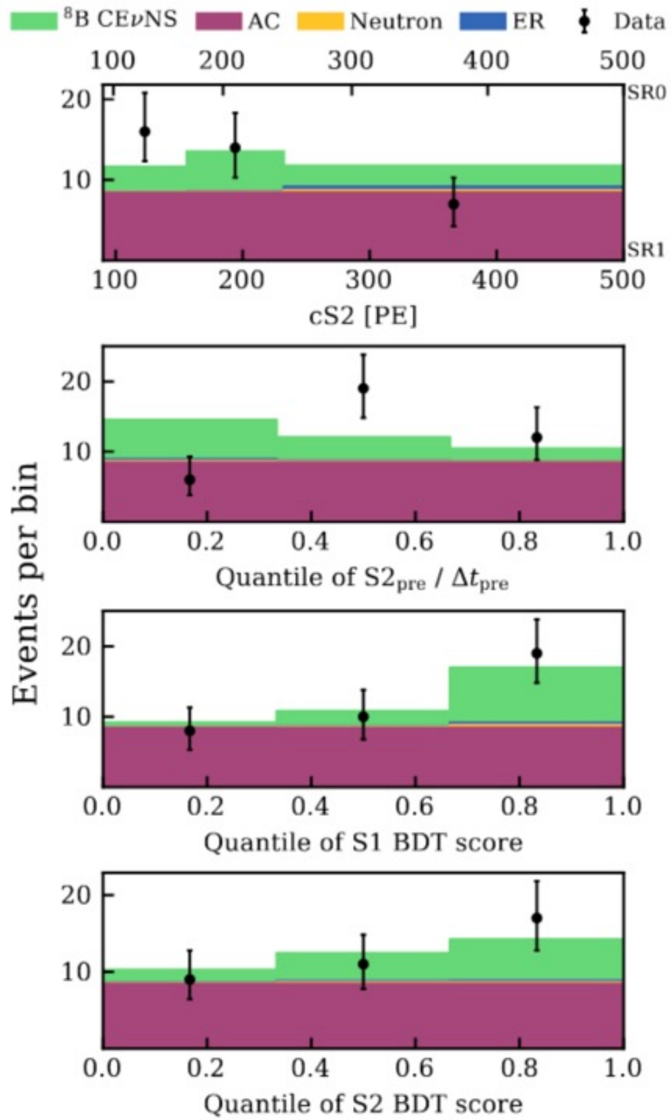
XENON

IDM2024 07/2024 arXiv:2408.02877, accepted by PRL

- First observation of CEνNS of astrophysical neutrinos with 2.7σ (3.2σ w/o $S2_{pre}/\Delta t_{pre}$)
- 11 events above backgrounds in 3.51 t×y exposure
- First step into the ultimate background for WIMP searches

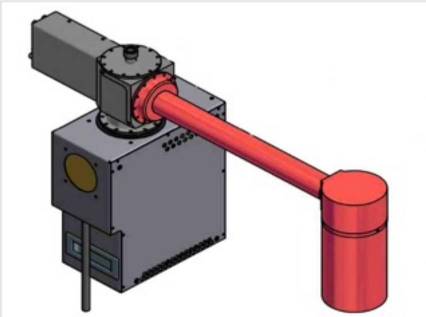
JCAP 01, 044 (2014)





also: some evidence seen in PandaX (2407.10892), LZ expected

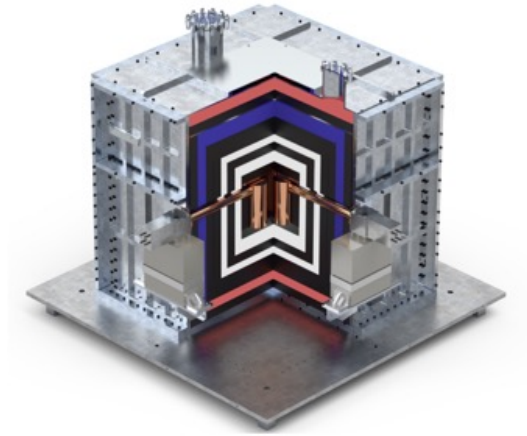
CONUS



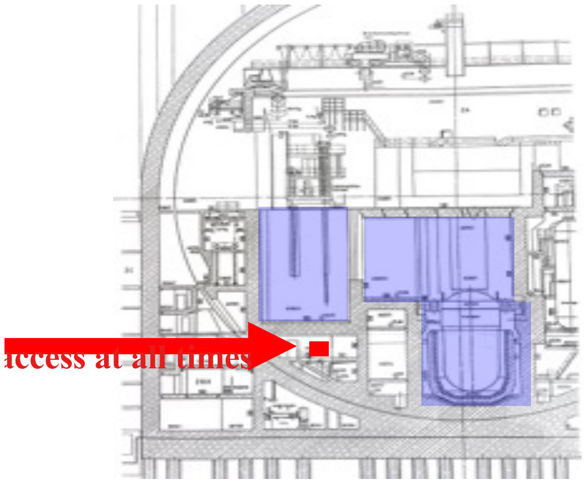
4x 1kg HPGe PPC

- active mass: 3.72 kg
- low energy threshold: ~250 eV
- electrical PT cryocoolers at 85 K
- pulse shape discrimination (PSD)
- special layerd shield

Eur. Phys J. C81, 267 (2021)

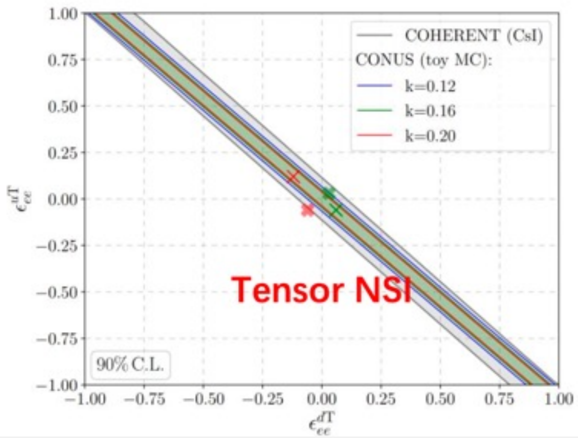


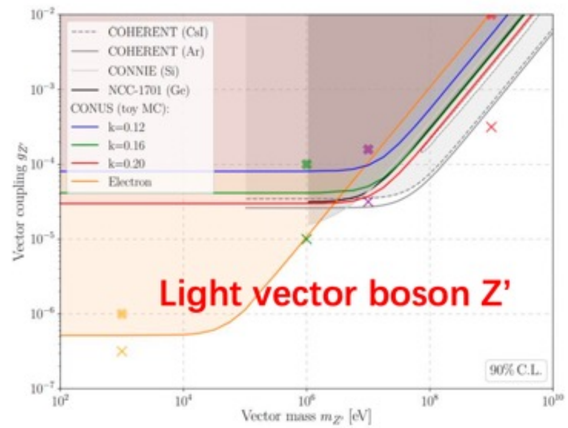
Brokdorf NPP:
3.9 GW, 17.1 m
5 runs
→ shutdown of NPP



BSM Results Run 1-4

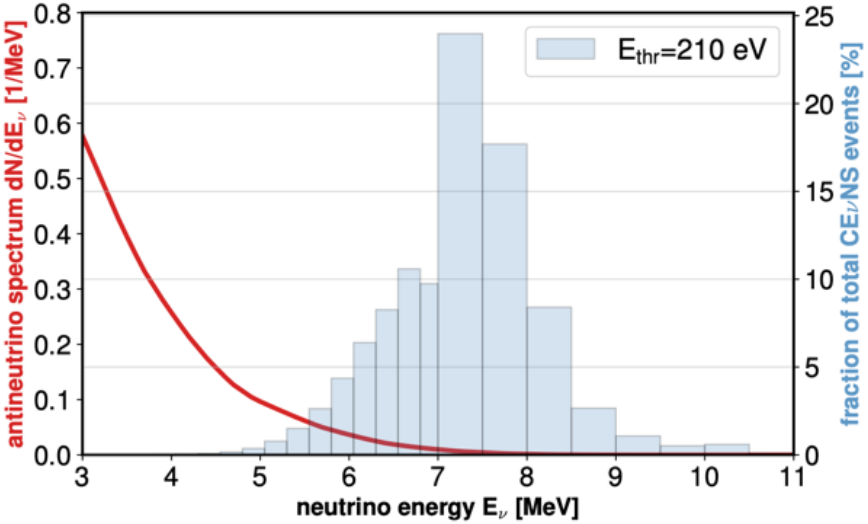
Tensor/Vector NSI (non-standard interactions): limits the coupling parameter space
Light vector boson: limits the mass-coupling parameter space
Neutrino millicharged: $|q_\nu| < 3.3 \times 10^{-12}\ e_0$
Neutrino magnetic moment: $\mu_\nu < 7.5 \times 10^{-11}\ \mu_B$

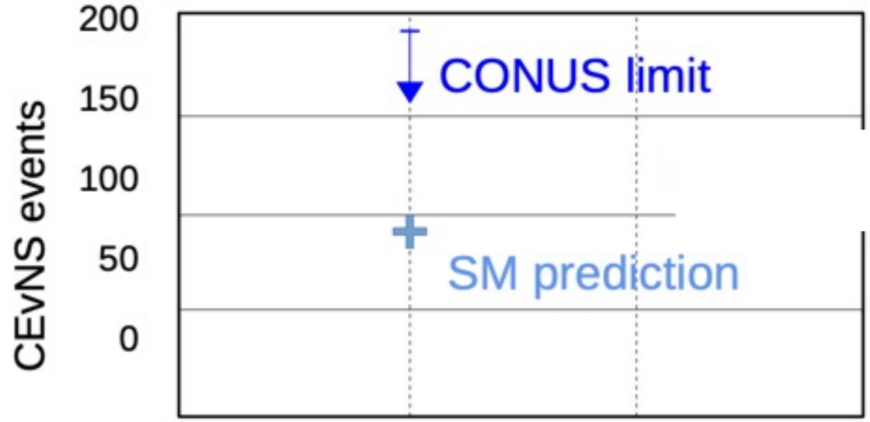




CONUS Run 5 result

Total exposure: 458d ON, 293d OFF





arXiv:2401.07684; PRL...

- combined limit (90% C.L.): **factor ~2** above predicted (Lindhard quenching with k=0.162)
- further slight improvements expected (PSD, additional statistics,…)

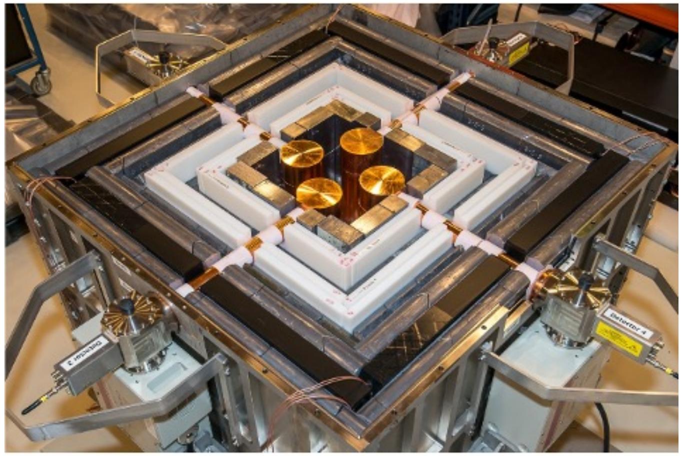
Best limit in the fully coherent regime as a function of the quenching parameter

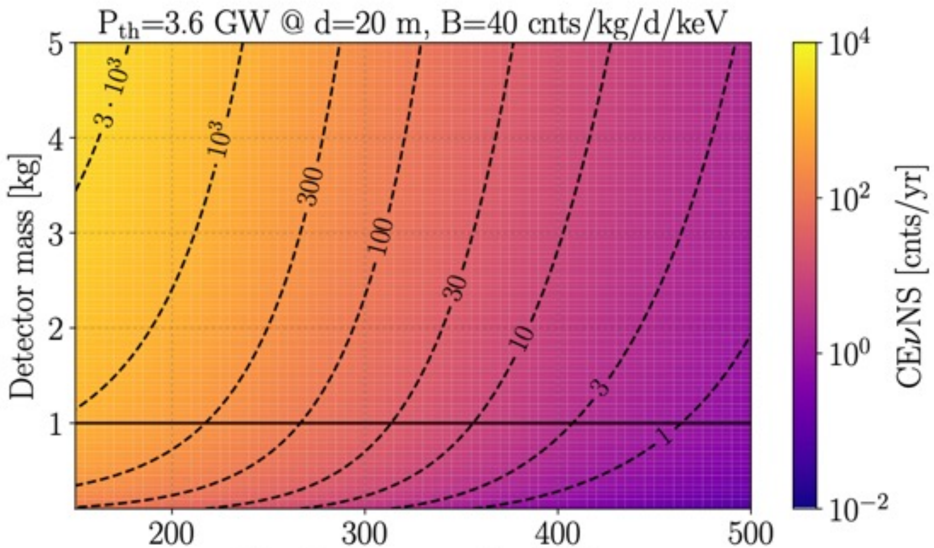
CONUS+

move to KKL Leibstadt: 3.6 GW, 20.7 m
site characterization (n, μ's, γ's, Radon,...)

Upgrades:

- ASIC readout
- water cooling
- pulse shape
- 150 eV_{ee} threshold
- **start of data taking 11/2023**
- **1st reactor off 05/2024**





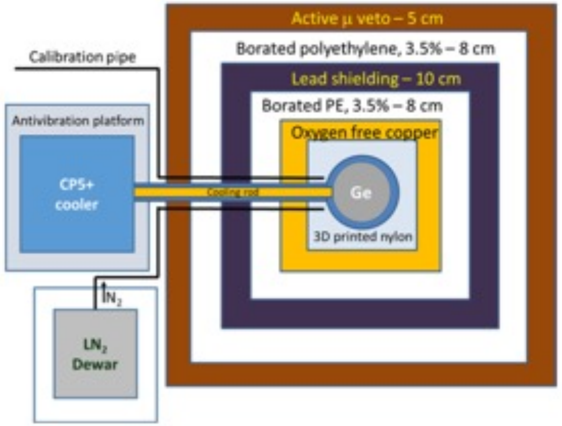
➔ **1 year of data being analyzed... ...stay tuned**

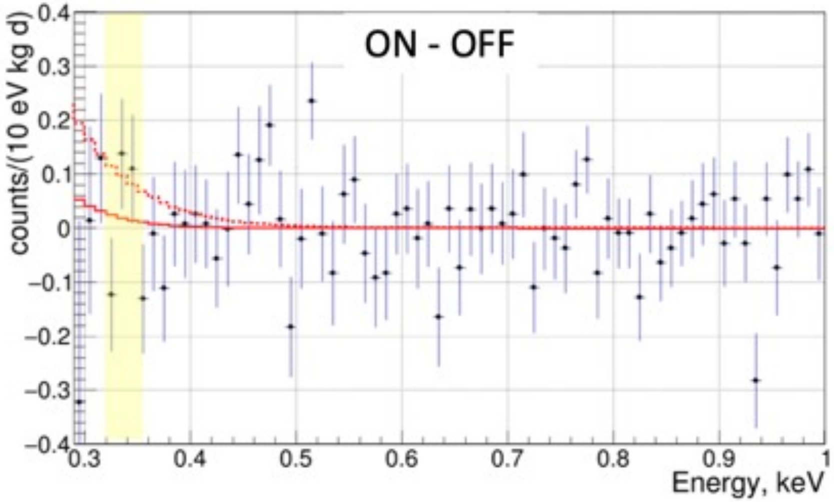
Another upgrade soon:
new 2.4 kg detectors
➔ mor emass
➔ even lower threshold

NuGEN

- Reactor neutrino experiment at 11 m from 3.1 GW_{th} the Kalinin reactor in Russia.
  - Flux 5 x 10^{13} $\bar{\nu}s^{-1}cm^{-2}$.
  - Distance to reactor can be varied 11-12 m.
- 1.5-kg p-type point contact High-Purity Germanium detector.
  - 50 m.w.e. overburden.
- Limits on CEνNS with 2021 and 2022 data.
  - Taking data with improved conditions since 2022.
  - Reduced background at low energy.

nuGEN collab., PRD 106 (2022) 5, L051101





A. Lubashevskiy, Magnificent CEνNS 2023

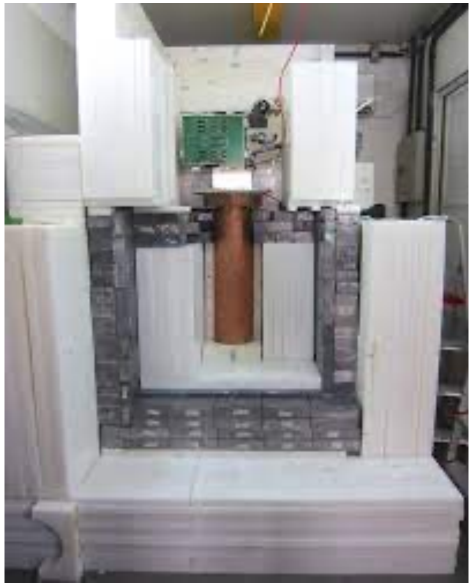
I. Nasteva, NEUTRINO2024

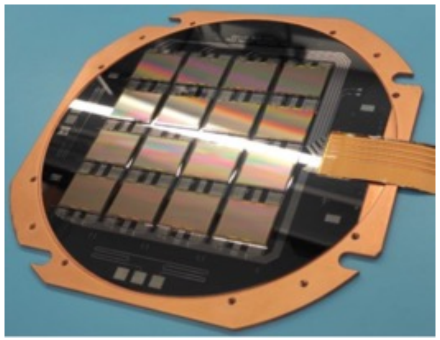
CONNIE

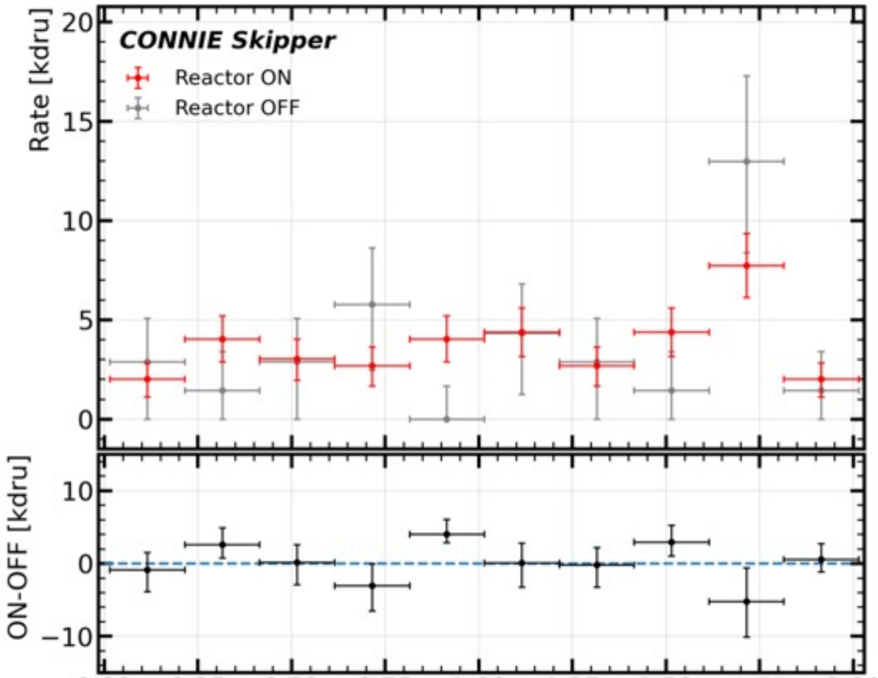
Angra 2 reactor (Brazil)
3.95 GWth, 30m
Skipper CCD Array - 15eV$_{ee}$ threshold, single e$^-$ resolution

CEvNS search:
14.9 g*days ON and 3.5 g*days OFF
➔ limit: 76 ⊗ SM
➔ limits on millicharged particles

arXiv:2403.15976



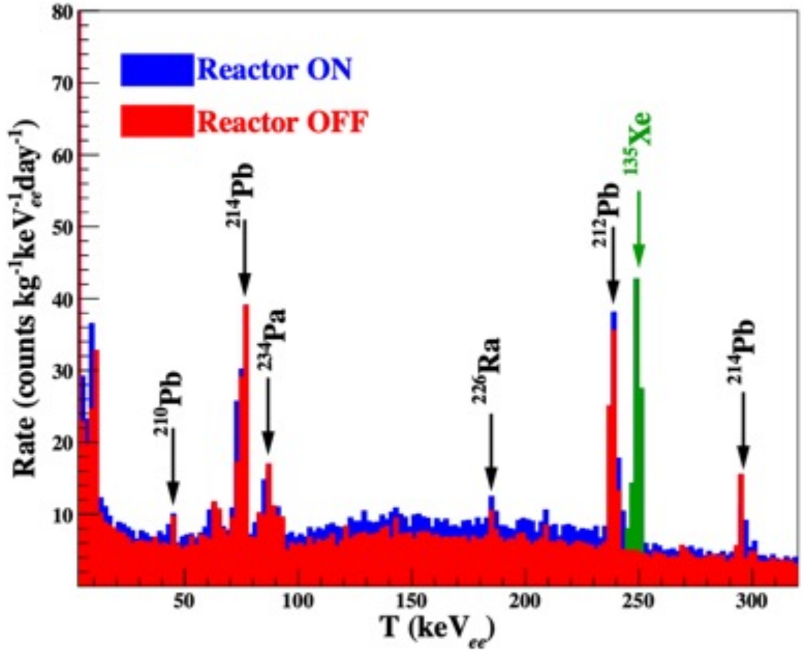




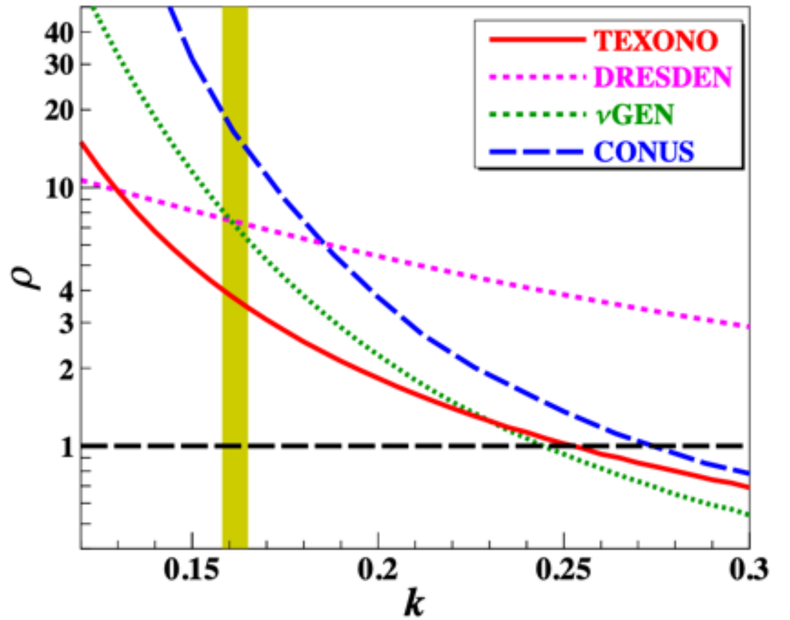
TEXONO / Sanmen

KuoSheng NPP (Taiwan)
2.9 GW, 28m, since ~2003

Upgrade to electro cooled HPGe, 200 eV thresho
Working on updated analysis
TAUP: DOI: https://doi.org/10.22323/1.441.0226

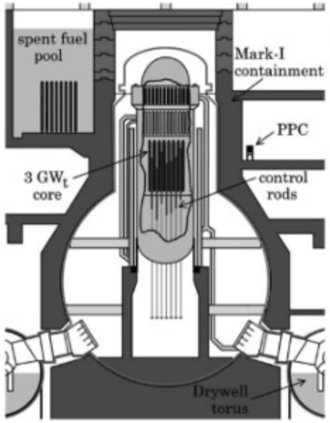


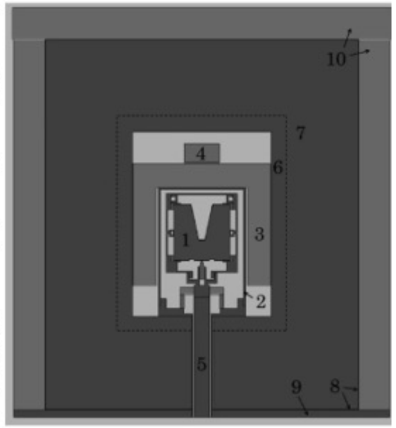
New site / collaborations
Sandmen NPP (China)
3.4 GW, 7m, 11m, 22m
RECODE: PPC HPGe ~160eV$_{ee}$ threshold
- 1kg / 10kg scales, based on CDEX1, CDEX10
- first physics: 2025
RELICS: LXe
- 32kg fiducial mass
- 2-phase LXe



NCC-1701

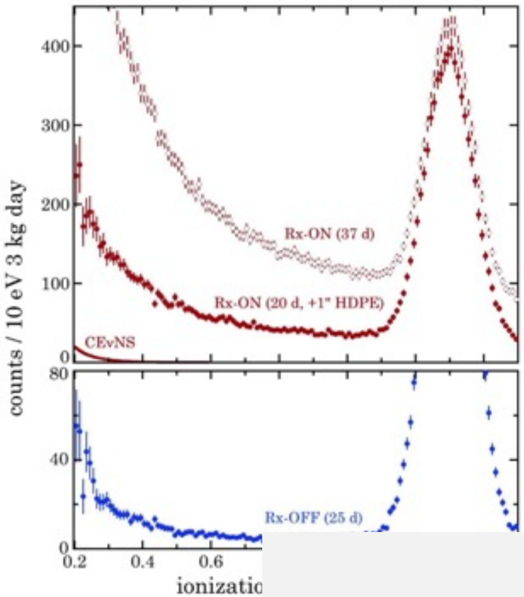
Dresden-II NPP (USA)
2.96 GW_{th}, 8m
3kg HPGe
200 eV_{ee}
ν-flux: 8.1 ⊗ 10^{13} ν/cm²/s





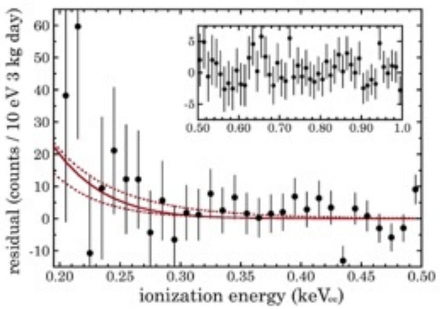
claim excess in reactor-on data

- depends a lot on quenching factor ←→ CONUS quenching factor
- CONUS should have seen a signal if NCC-1701 QF were correct
- Migdahl effect → orders of magnitude weaker Giunti et al: 2307.12911
- backgrounds (neutrons!)

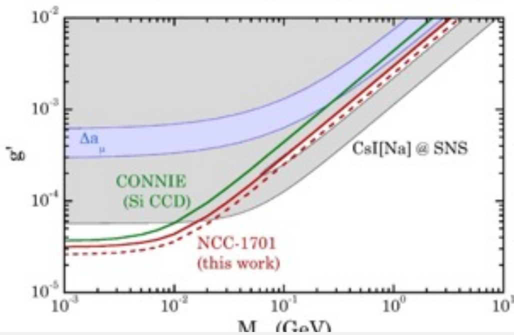


Epithermal neutrons dominate low energies.

Spectrum after subtraction of modeled epithermal neutron component



Limit for low-mass vector mediators



More Upcoming or R&D

I. Nasteva, NEUTRINO2024

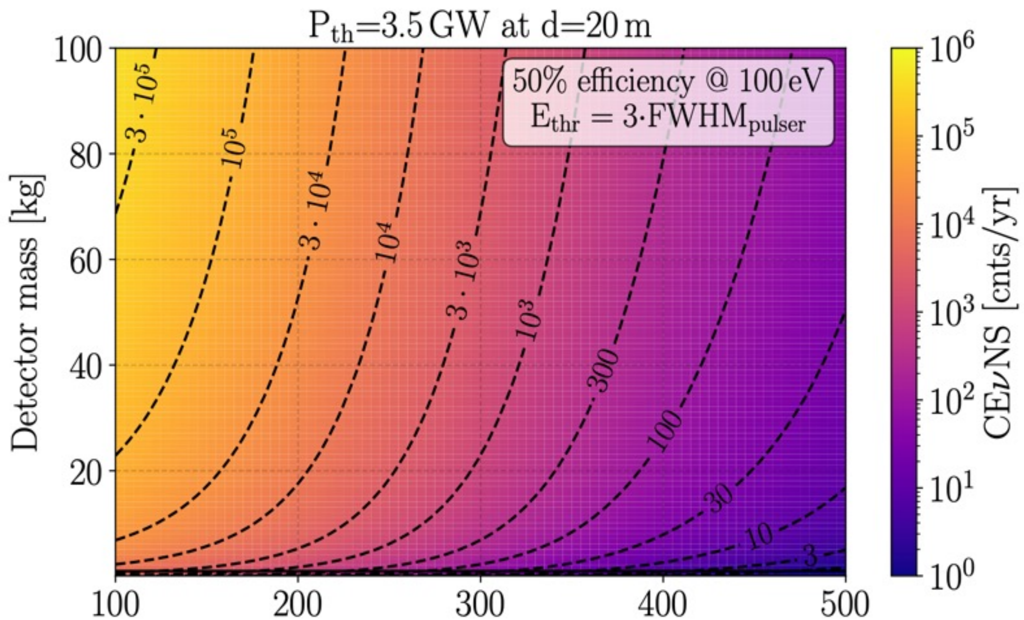
Experiment	Detector	Mass	Threshold	Reactor/ source	Distance to source	Thermal power	Neutrino flux ν/cm^2/s	Location
COHERENT	CsI, Ar, Ge, NaI	15-185 kg	6.5-20 keVnr	πDAR	19-28 m		4.3*10^7	USA
nuESS*	CsI, Ge, Xe, Ar			πDAR				Sweden
CICENNS*	CsI(Na)	300 kg	2 keVnr	πDAR	10.5 m		2*10^7	China
Atucha-II	Si CCDs	2.5 g	40 eVee	Atucha-II	12 m	2 GW$_{th}$	2*10^{13}	Argentina
BULLKID*	Si/Ge cryogenic	20 g	160 eV					Italy
CONNIE	Si CCDs	0.5 g	15 eVee	Angra-II	30 m	3.9 GW$_{th}$	7.8*10^{12}	Brazil
CONUS	HPGe	3.74 kg	210 eVee	Brokdorf	17 m	3.9 GW$_{th}$	2*10^{13}	Germany
CONUS+	HPGe	3.74 kg	150 eVee	Leibstadt	20.7 m	3.6 GW$_{th}$	1.45*10^{13}	Switzerland
MINER*	Ge, Si, Al_2O_3 cryogenic	1 kg	100 eVnr	TRIGA / HFIR*	2-10 m	1 MW$_{th}$	~1*10^{12}	USA
NCC-1701	HPGe	3 kg	200 eVee	Dresden-II	8 m	2.96 GW$_{th}$	8.1*10^{13}	USA
NEON	NaI(Tl)	16.7 kg	200 eVee	Hanbit	23.7 m	2.815 GW$_{th}$	~1*10^{13}	Korea
NEWS-G3*	Ar+2%CH4			tbc				Canada
NUCLEUS*	$CaWO_4$, Al_2O_3 cryogenic	10 g	20 eVnr	Chooz	77 m, 102 m	2x2.45 GW$_{th}$	1.7*10^{12}	France
NUXE*	LXe	10 kg		tbc				
nuGEN	HPGe	1.4 kg	200 eVee	Kalinin	11-12 m	3.1 GW$_{th}$	5.4*10^{13}	Russia
RED-100	LXe, Lar*	200 kg		Kalinin	19 m	3.1 GW$_{th}$	1.35*10^{13}	Russia
RECODE*	HPGe	1-2,10 kg	160 eVee	Sanmen	11, 22 m	3.4 GW$_{th}$	Up to 5.6*10^{13}	China
RELICS*	LXe	50 kg	1 keVnr	Sanmen	22 m	3.4 GW$_{th}$	1.4*10^{13}	China
Ricochet*	Ge, Zn, Al, Sn cryogenic	680 g	160 eVee, 300 eVnr	ILL-H7	8.8 m	58 MW$_{th}$	1.6*10^{12}	France
SBC*	Ar	10 kg	100 eVee	tbc				USA
TEXONO	HPGe	1.43 kg	200 eVee	Kuo-Sheng	28 m	2.9 GW$_{th}$	6.4*10^{12}	Taiwan

Future

- CEνNS prediction 1974 (Freedman)
- 1st observation: COHERENT 2017
- 2024: CEνNS of solar neutrinos @XENONnT
- ... CEνNS signal of reactor neutirnos around the corner...

➔ **foreseeable high statistics CEνNS future**

- pi-DAR:
  - larger detectors
  - more intense breams
- solar neutrinos:
  - next generation LXe dark matter detectors (XLZD)
- reactor: upscaling of existing CONUS technology:



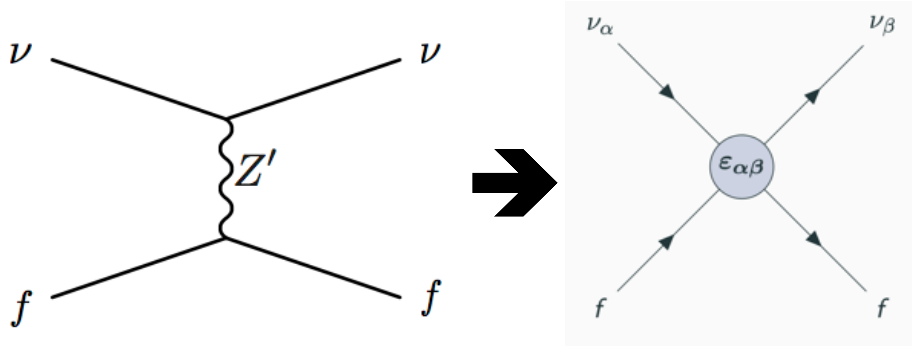
What is CEvNS good for?

High statistics CEvNS experiments touch many interesting topics:

- Large cross sections → small neutrino detectors → faster progress, applications
- Clean SM predictions for cross sections → BSM sensitivity
- Sensitivity to neutrino magnetic moment and $\langle r_\nu^2 \rangle$ → BSM sensitivity
- Possibility to measure $\sin^2\theta_W$ at low energies → BSM sensitivity
- Masurements of neutron formfactors (nuclear structure) → unique
- Nuclear reactor monitoring (non-proliferation) → applications
- Precision flavor-independent neutrino flux measurements for oscillation experiments → synergy with other experiments
- Sterile neutrino searches → BSM
- Energy transport in supernovae → important for next SN
- SN neutrino detection → SNEWS, pointing, ...
- Input for dark matter direct detection (neutrino floor) → solar neutrinos
- dark matter physics → BSM

BSM Physics as NSI's

NSI's ←→ BSM at high scales
... which is integrated out
Z', new scalars, … → ε_{ij}



$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{\left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 + \sum_{\alpha=\mu,\tau}\left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV})\right]^2\right\}$$

Barranco et al. 2005

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

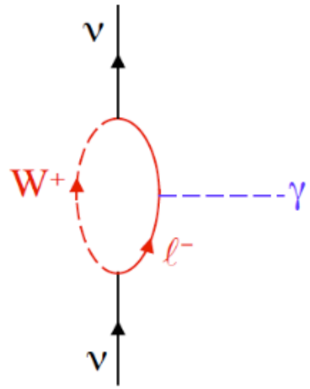
→ Competitive method to test TeV scales
ε = 0.01 ←→ TeV scales

Neutrino magnetic Moment in the SM + ν_R

Dirac: $$\mathcal{L} \supset \mu_\nu \overline{\nu}_L \sigma_{\mu\nu} \nu_R F^{\mu\nu} + m_\nu \overline{\nu}_L \nu_R + \text{H.c.}$$

μ_ν and ν mass operators have the same chiral structure

➔ μ_ν typically proportional to m_ν



SM+ν_R: $$\mu_\nu = \frac{eG_F m_\nu}{8\sqrt{2}\pi^2} = 3 \times 10^{-20} \mu_B \left(\frac{m_\nu}{0.1 \text{ eV}}\right)$$

Transition mag. moment for Majorana ν's:

$$\mu_{ij} = -\frac{3eG_F}{32\sqrt{2}\pi^2}(m_i \pm m_j) \sum_{\ell=e,\mu,\tau} U^*_{\ell i} U_{\ell j} \frac{m_\ell^2}{m_W^2}$$ ➔ $O(10^{-23})\ \mu_B$

➔ many BSM models significantly enhance μ_ν

e.g. MSSM with L violation by R-parity violation ~ λ'

$$\mu_\nu \sim \lambda'^2/(16\pi^2) m_\ell^2 A_\ell / M_{\tilde{\ell}}^4$$

A_l ←→ SUSY breaking trilinear coupling

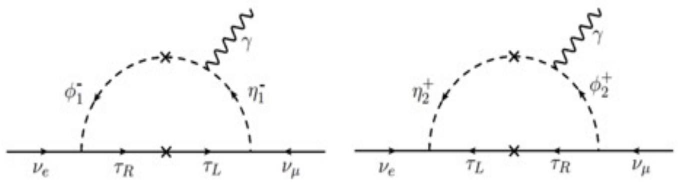
$M_{\tilde{\ell}}$ ←→ slepton mass

BUT ➔ $\mu_\nu \leq 10^{-13}\ \mu_B$

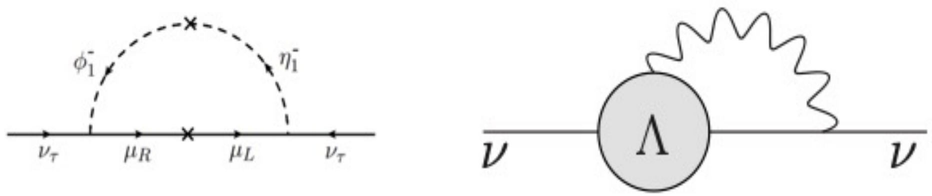
Rather general: TeV-ish BSM models allow/predict $\mu_\nu \leq 10^{-13}\ \mu_B$

Pushing higher often leads to two problems:

- light new particles that should have been discovered
- intrinsic relation between magnetic moment and radiative neutrino masses



➔ ν mass



➔ neutrino mass shifts which are much bigger than allowed w/o fine-tuning

➔ observation would be a major discovery ←→ flavour!

Millicharges

Strongest limit from the neutrality of matter
G. Bressi et al., PRA 83 (2011) 5, 052101

$$q_\nu \leq \times 10^{-21} e$$

text book SM (w/o ν_R): $q_\nu=0$ ← consequence of charge quantization

$$Q = I_3 + \frac{Y}{2}$$

U(1)Y gauge invariance of Yukawa couplings ➔

$$Y_e = Y_L - 1$$
$$Y_u = Y_Q + 1$$
$$Y_d = Y_Q - 1$$

quarks with 3 colors → $SU(2)_L$ triangle anomaly cancellation ➔ $Y_Q = -Y_L/3$

$U(1)_Y$ triangle anomaly canc. ➔ $0 = \mathrm{Tr}\left[Y^3\right] = 2Y_L^3 + 6Y_Q^3 - Y_e^3 - 3\left(Y_u^3 + Y_d^3\right)$

From this follows: $0 = \mathrm{Tr}\left[Y^3\right] = (Y_L+1)^3 \implies Y_L = -1$ ➔ $q_\nu = 0$

With ν_R: $\mathrm{Tr}\left[Y^3\right] = (Y_L+1)^3 - (Y_L+1)^3 = 0$ ➔ **$q_\nu \neq 0$ allowed**

Other ν-mass mechanisms, GUTs…

But: Current CEνNS limits are much weaker than the best limit above…

Nuclear Structure with coherent Scattering

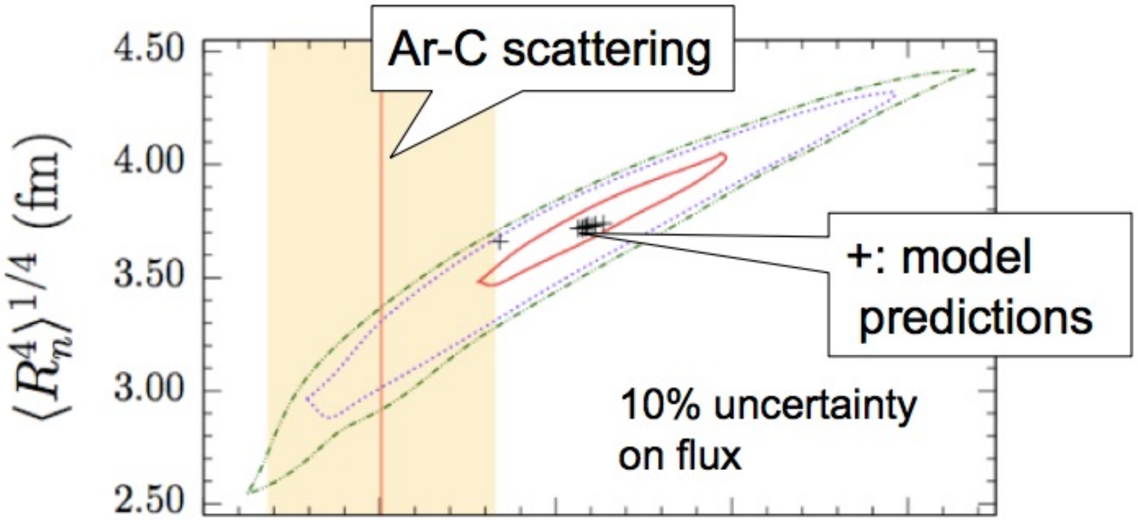
DAR sources partially coherence ⇔ combine with reactor measurements

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi}\left(1-\frac{MT}{2E^2}\right)\left[N F_N(q^2) - Q_W Z F_Z(q^2)\right]^2$$

Nuclear form factors $F_{N,Z}(q)$ ~ Fourier transforms of N & P densities
➔ resolve nuclei (neutrons) in neutrino light

Fit recoil ***spectral shape*** to determine the $F(Q^2)$ moments
(requires very good energy resolution,good systematics control)

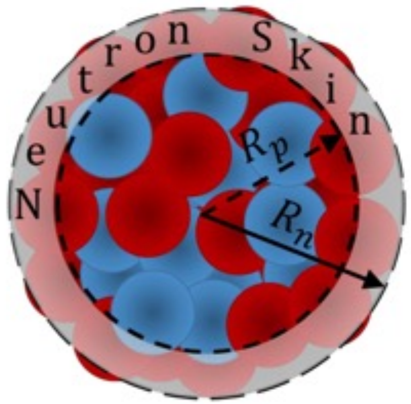
Example:
tonne-scale
experiment
at πDAR source



Nuclear Models and NSI's

Klein-Nystrand form factor

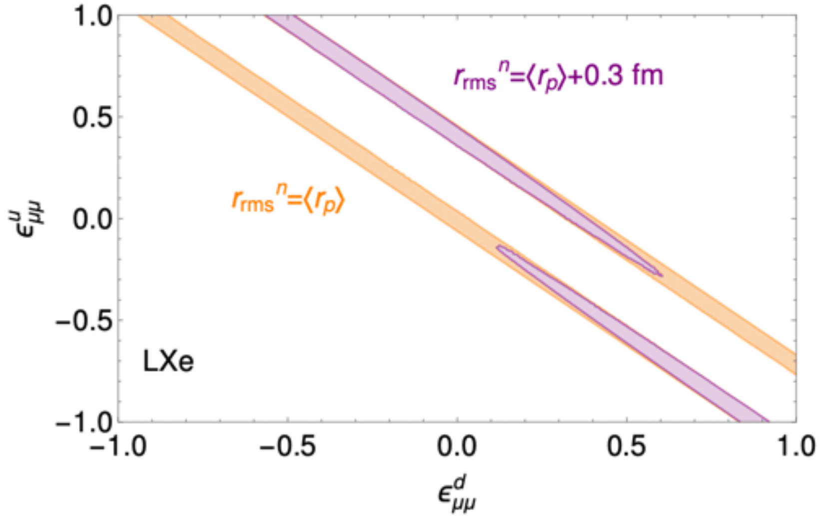
$$F_W(|\vec{q}|^2) = 3\frac{j_1(|\vec{q}|R_A)}{|\vec{q}|R_A}\left(\frac{1}{1+|\vec{q}|^2a_k^2}\right)$$

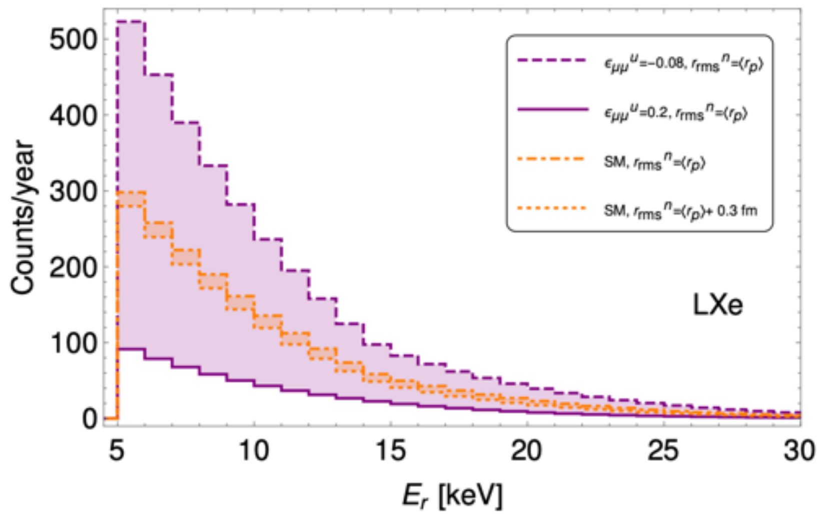


➔ **relies on a surface-diffuse distribution**
folding a short-range Yukawa potential with range a_k over a hard sphere distribution with radius R_A

$$\langle r^2\rangle_{\mathrm{KN}} = \frac{3}{5}R_A^2 + 6a_k^2$$

Aristizabal Sierra, Liao, Marfatia, JHEP 06 (2019) 141
allowed regions in the NSI case and for two choices of the rms neutron radius





New Bosons

Heavy: ➔ partially covered by NSI's (being integrated out...)
➔ interactions of new heavy bosons with SM bosons

Light: ➔ simplified models

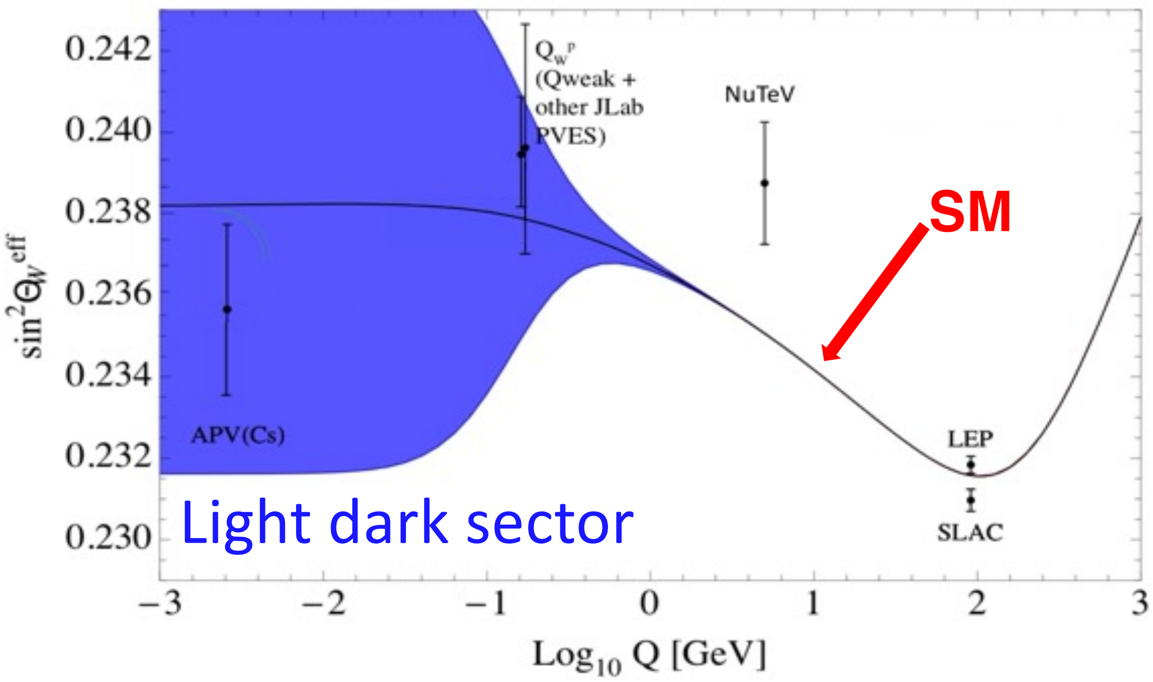
- new light scalar/vector mediators
- universal couplings
- light scalar boson ϕ : $$\frac{d\sigma_\phi}{dT} = \frac{g_\phi^4 (14N + 15.1Z)^2 M^2 T}{4\pi E_\nu^2 (2MT + m_\phi^2)^2}$$
- light vector boson Z': $$\frac{d\sigma_Z'}{dT} = \left(1 - \frac{3 g_Z^{\nu}{}' g_Z^{q}{}' (Z+N)}{\sqrt{2} G_F Q_{SM} (2MT + m_Z^2{}')}\right)^2 \frac{d\sigma_{SM}}{dT}$$

➔ **often connected to dark sector = DM**

Precise Measurement of $\sin^2\theta_W$ at low E

CEνNS cross-section:
$\sigma \sim N - [(1 - 4 \cdot \sin^2\theta_W)\, Z]^2$

SM: running $\sin^2\theta_W$
→ sensitivity to light particles in loops



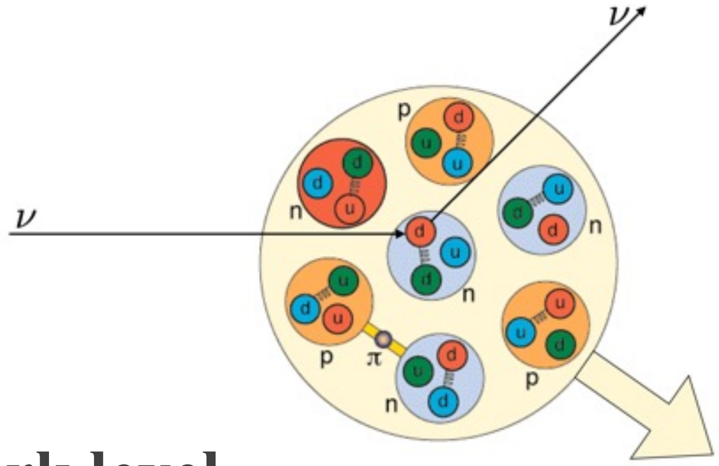
<u>Beware – models often in conflict with other measurements:</u>

- **g-2**
- **dark matter searches**
- **astroparticle physics**
- **...**

Even more fundamental...

Elementary reaction: neutrinos interact with quarks via Z exchange

requirements:
absence of individual recoil
scattering in phase



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- **Form factors and x-sections ←→ quark level ←→ limitations of factorization σ ⊗ F(q^2)**
- **CEνNS in QFT → conceptually very interesting questions**
  see e.g. **Akhmedov, Arcadi, ML, Vogl, JHEP 1810 (2018) 045, arXiv:1806.10962**
  - role of the recoil of constituents in quantized picture
  - semi-classical factorization of QFT process into (cross-section) * F(q^2) ?
- **coherence length in QFT approach**
  Egorov, Volobuev: 1902.03602

Summary

- **CEνNS has become a hot topic ⇔ many physics topics**

citations of original paper
by D. Freedman

- **Outlook:**
  - further observations of CEνNS in the pipeline
  - higher statistics → growing precision (good time-scales & costs)
  - growing number of studies discussing BSM scenarios
  - interplay of HEP, astroparticle analyses (DM...) and nuclear physics

➔ rising experimental and theoretical activity!