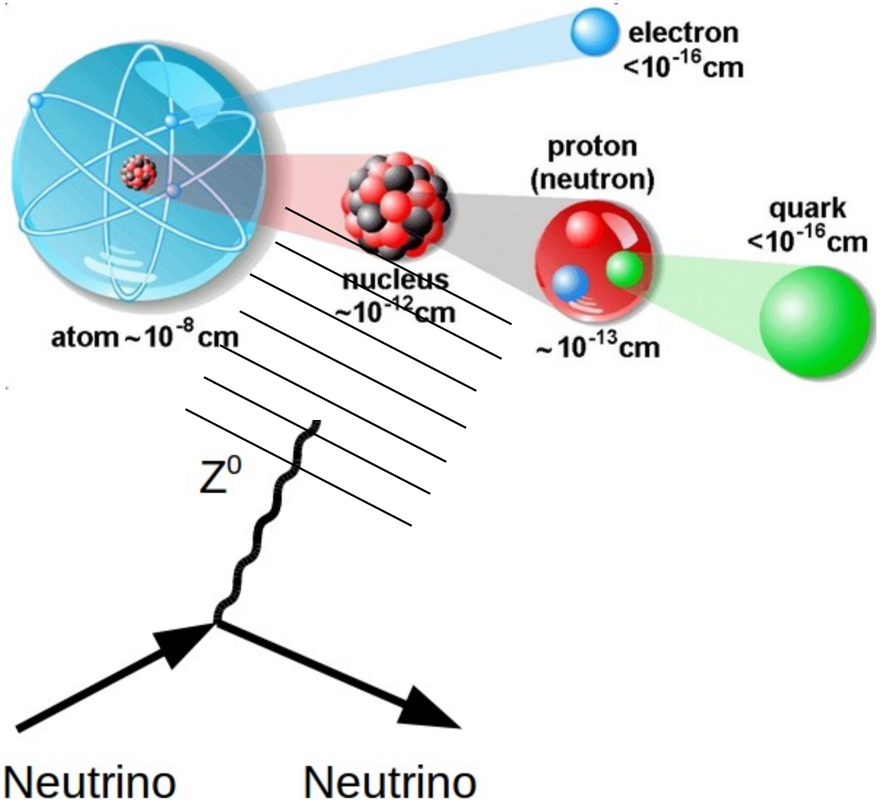
Status and Perspectives of Coherent Neutrino Scattering

Manfred Lindner

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

International Symposium on
Neutrino Physics and Beyond
NPB24, Feb. 19-21, 2024
HKUST Jockey Club, IAS, Hong Kong

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

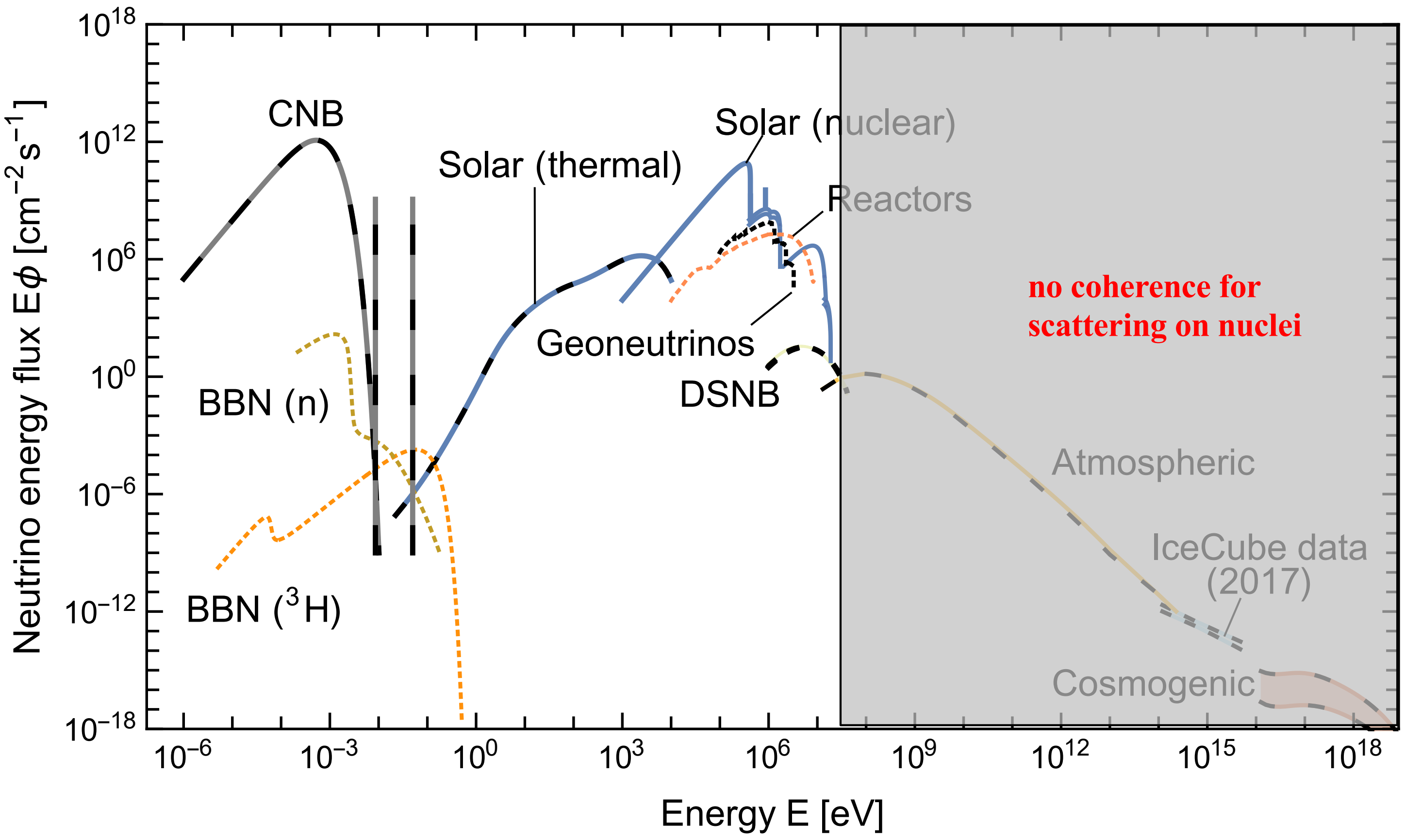
Coherence length ~ 1/E ➔ E_ν below O(50) MeV

➔ low energy E_ν ←→ lower cross sections ➔ very high flux!

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

$N \simeq 40$ ➔ $N^2 = 1600$ ➔ detector mass 10t ➔ few kg

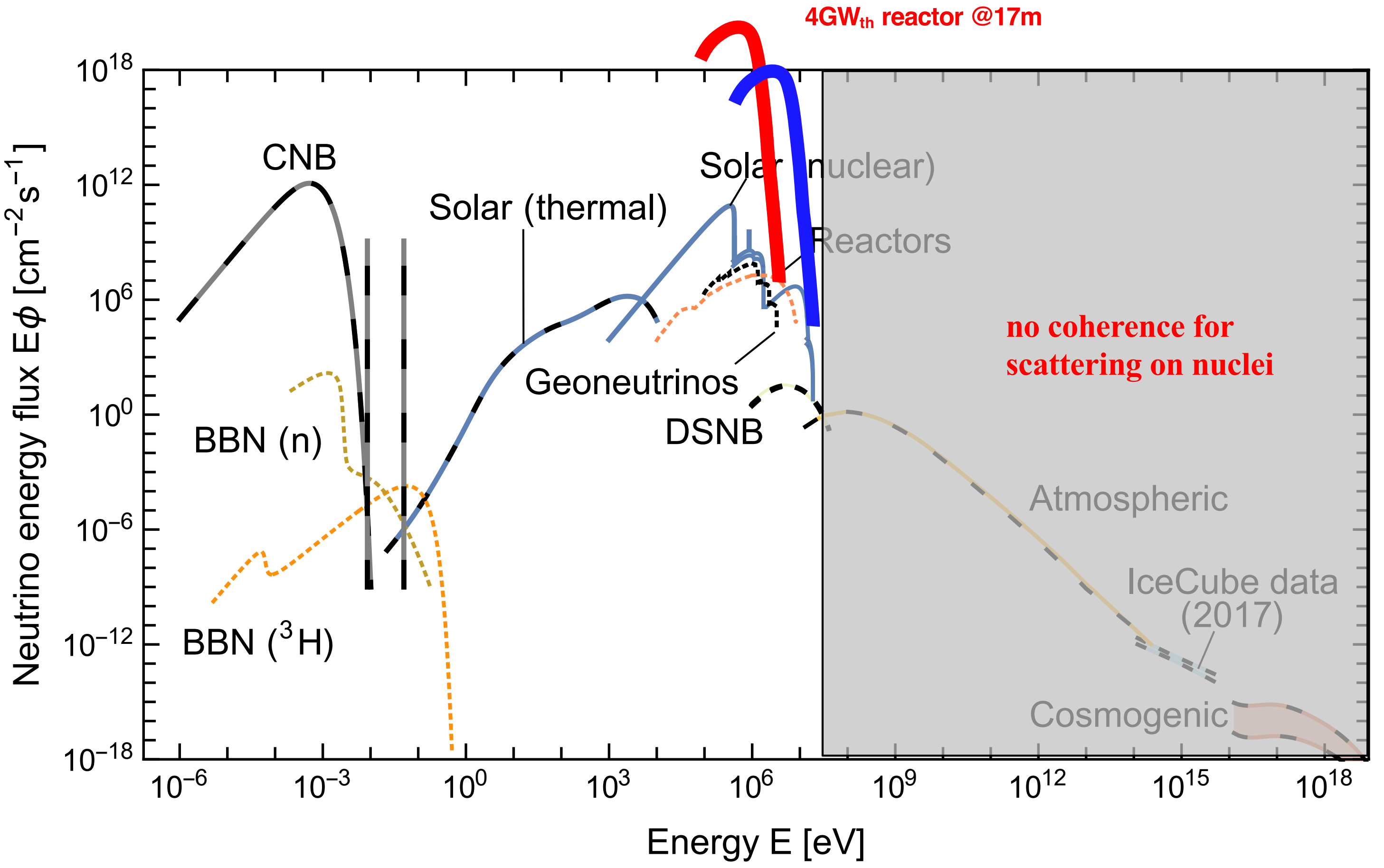
Sources: Flux ⊗ Energy



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

Sources: Flux ⊗ Energy

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



Vitagliano, Tamborra, Raffelt
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➔ event rates: ⊗ detector size 🡄🡆 backgrounds

Incomplete List of Reactor Experiments

CONNIE	Si CCDs	Brazil
CONUS	HPGe	Germany
NEWS-G	Ar+2%CH4	Canada
MINER	Ge/Si cryogenic	USA
NEON	NaI(Tl)	Korea
NUCLEUS	$CaWO_4$, Al_2O_3 cryogenic	Europe
νGEN	Ge PPC	Russia
RED-100	LXe dual phase	Russia
Ricochet	Ge, Zn, Al, Sn cryogenic	France
TEXONO	p-PCGe	Taiwan
Dresden II	PCGe	USA

➔ **CONUS+,** Switzerland

The CONUS Collaboration

Max-Planck-Institut für Kernphysik (MPIK), Heidelberg:
N. Ackermann, S. Armbruster, A. Bonhomme, H. Bonet, C. Buck, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, T. Rink, E. Sanchez-Garcia, H. Strecker
Former collaborators: T. Schierhuber, E. Van der Meeren, J. Henrichs, T. Hugle, J. Stauber
Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf: K. Fülber, R. Wink
Kernkraftwerk Leibstadt AG (KKL), Leibstadt: J. Wönckhaus, M. Rank

highest ν flux

➔ commerical power plant

Brokdorf, Germany NPP

3.9 GW thermal power

➔ very powerful anti-ν source

distance to core: 17m

➔ 2*10^{13} ν/cm^2/s

150 kW in ν's / m^2

Eur. Phys. J C79, 699 (2019)

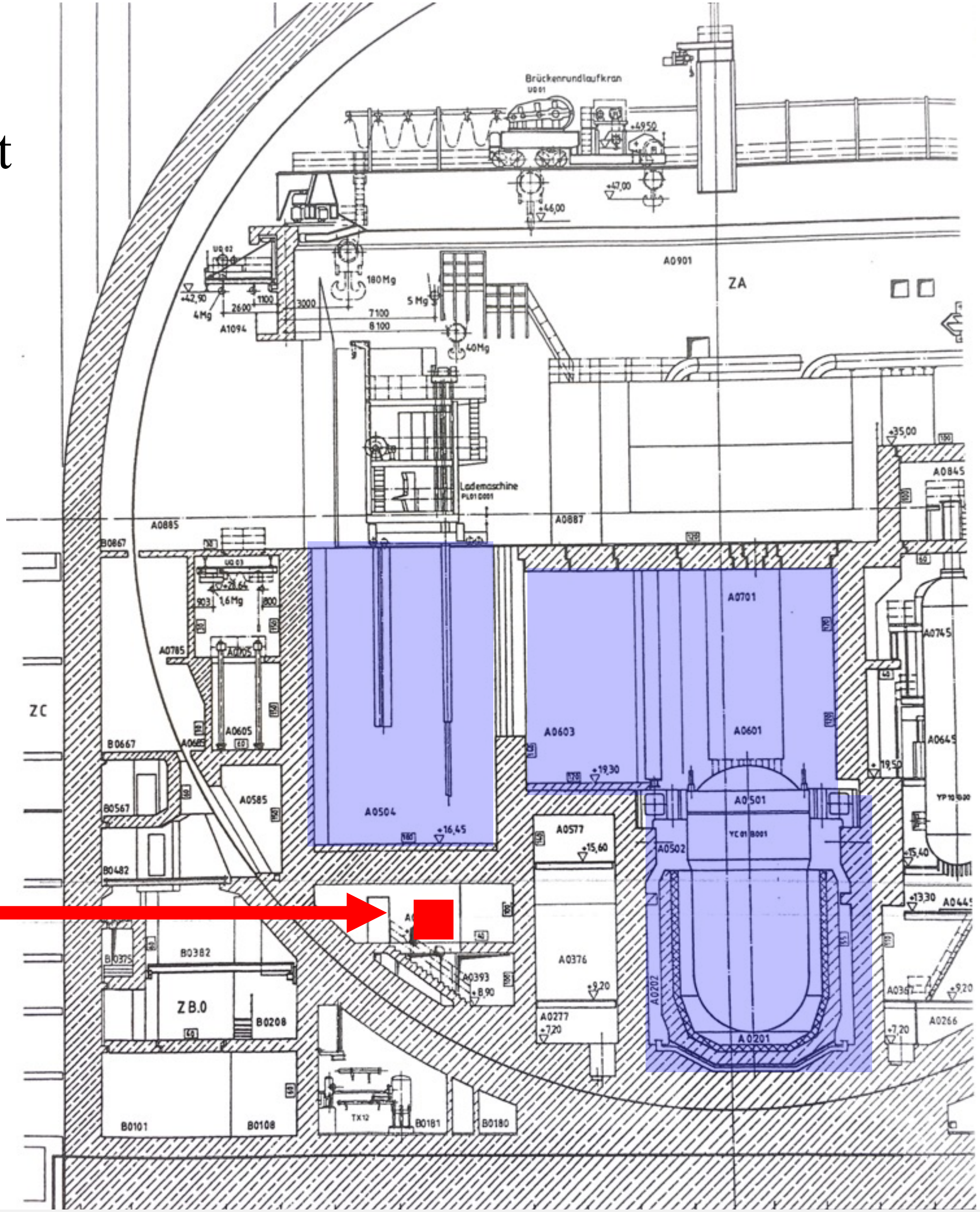
- must follow strict rules
  (allowed materials, ...)

+ full access during Covid

+ shutdown = off statistics!

➔ move to another reactor

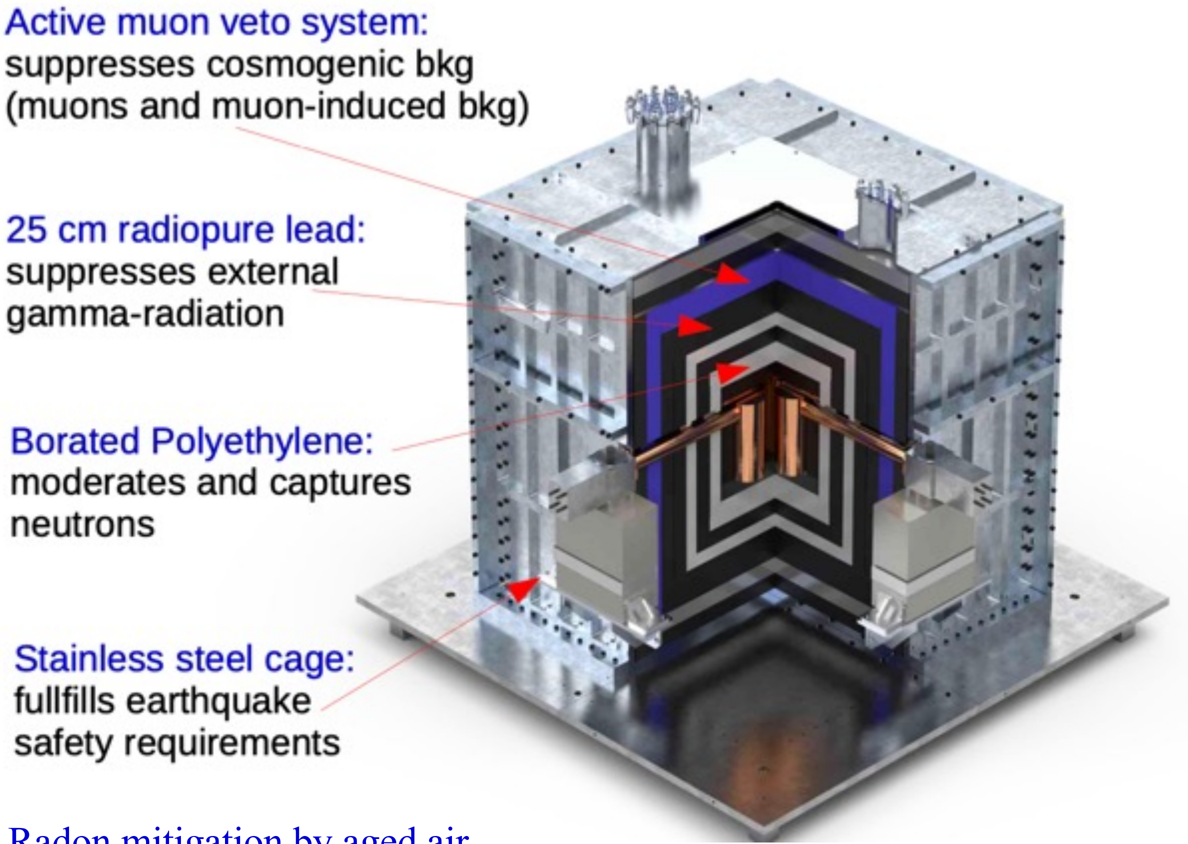
➔ improvements...: CONUS+



access at all times

The CONUS Detector

Special ``virtual depth” shield



Active muon veto system:
suppresses cosmogenic bkg
(muons and muon-induced bkg)

25 cm radiopure lead:
suppresses external
gamma-radiation

Borated Polyethylene:
moderates and captures
neutrons

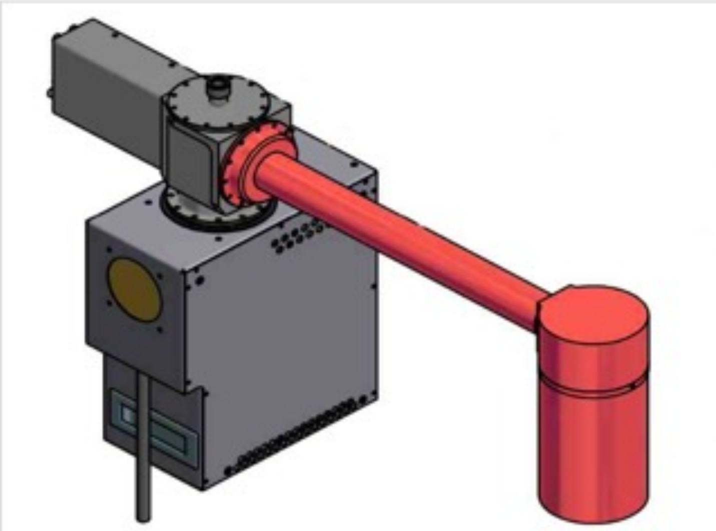
Stainless steel cage:
fullfills earthquake
safety requirements

Radon mitigation by aged air

total background suppression (w/o PSD) > 10^4 x

➔ low background conditions like in UG labs

Eur. Phys J. C83, 195 (2023)



CONUS-1 to -4 (C1-C4)

- intensive R&D with producer
- point-contact high purity Ge detector
- active mass: 3.72 kg
- low energy threshold: ~250 eV
- electrical PT cryocoolers at 85 K
- very low background components
- pulse shape discrimination (PSD)
- long cryostat arms

Eur. Phys J. C81, 267 (2021)

BSM Results Run 1-4

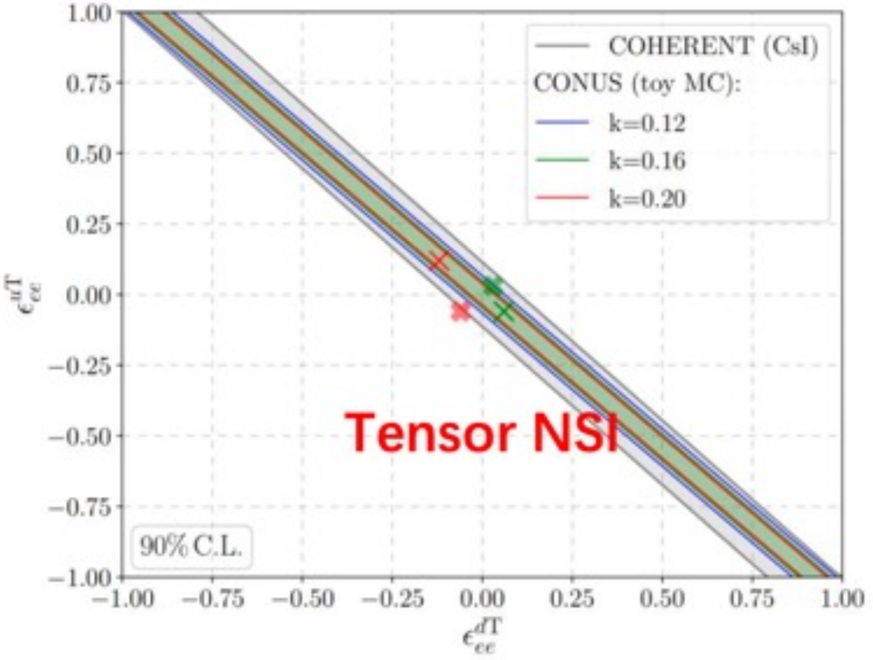
Fully coherent regime ➔ any deviation form SM = new physics:

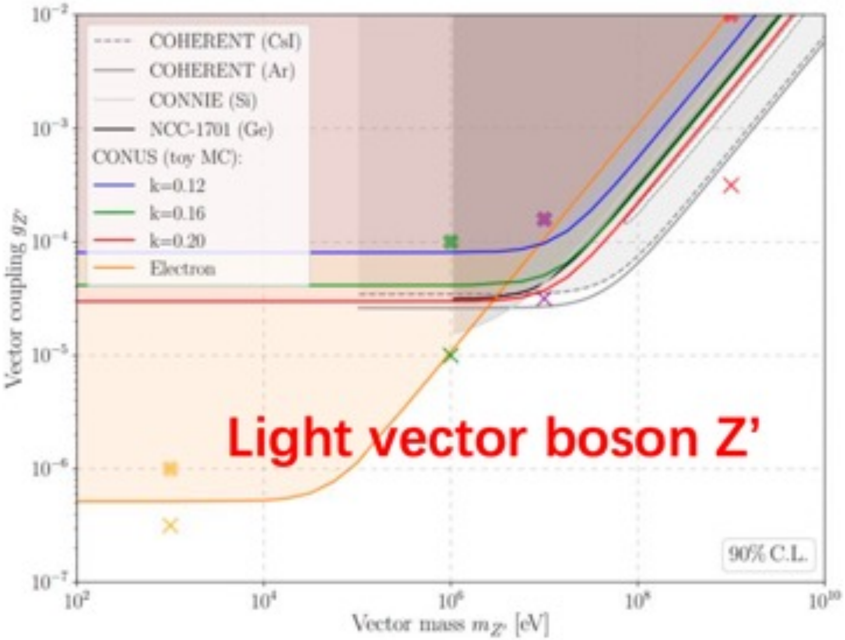
Tensor/Vector NSI (non-standard interactions): limits the coupling parameter space

Light vector boson: limits the mass-coupling parameter space

Neutrino millicharged: $|q_\nu| < 3.3 \times 10^{-12}\ e_0$

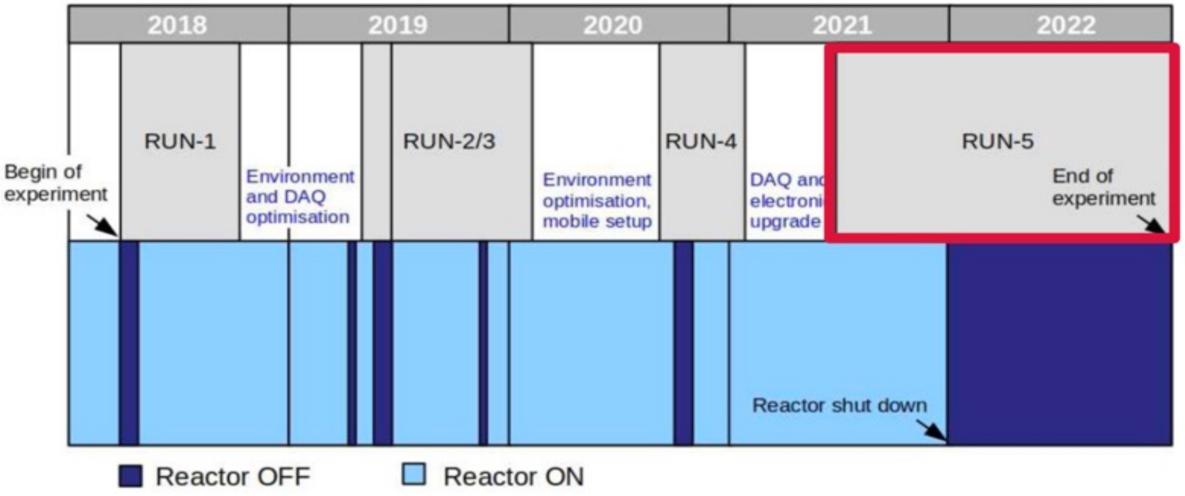
Neutrino magnetic moment: $\mu_\nu < 7.5 \times 10^{-11}\ \mu_B$





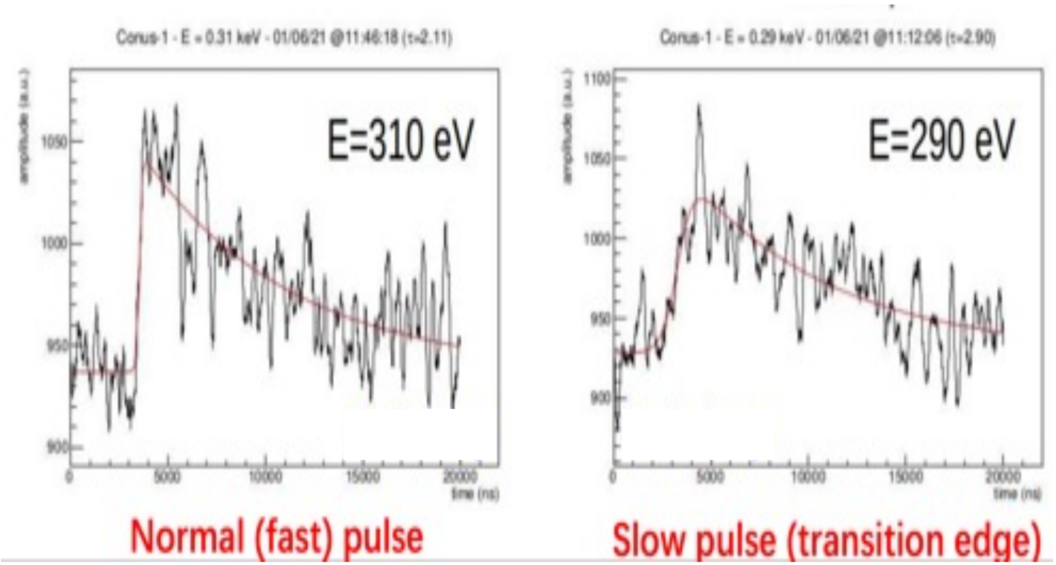
JHEP 05 (2022) 085

CONUS Run 5



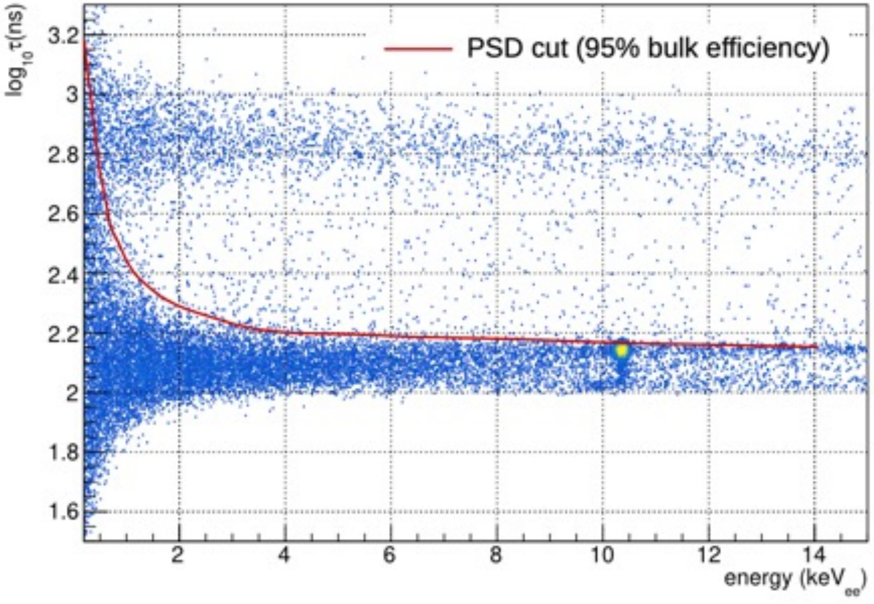
Energy thresholds:
C1: 220 eV_{ee}
C2: 210 eV_{ee}
C4: 210 eV_{ee}

added pulse shape discrimination
➔ remove slow pulses from close to the transition layer



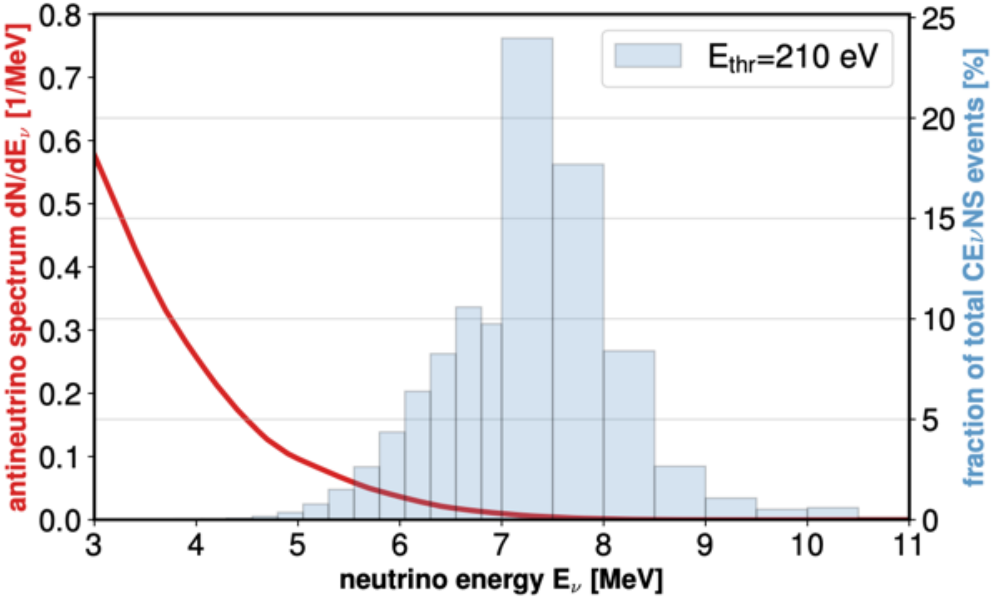
Normal (fast) pulse

Slow pulse (transition edge)



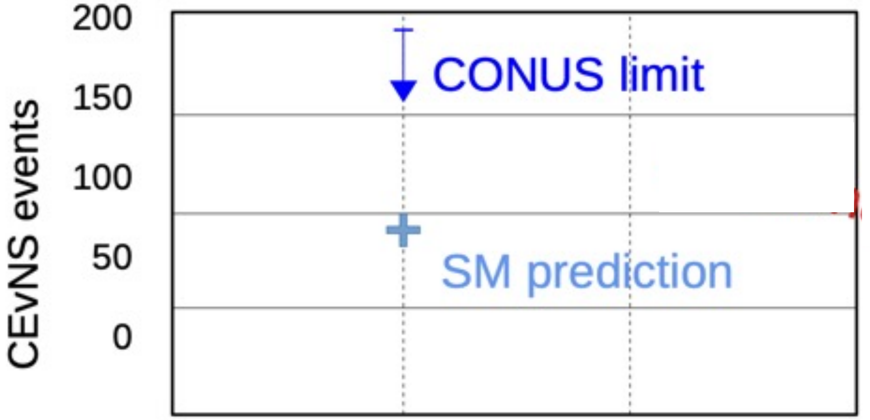
arXiv:2308.12105

CONUS Run 5 result



arXiv:2401.07684

Total exposure: 458d ON, 293d OFF



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

CONUS+

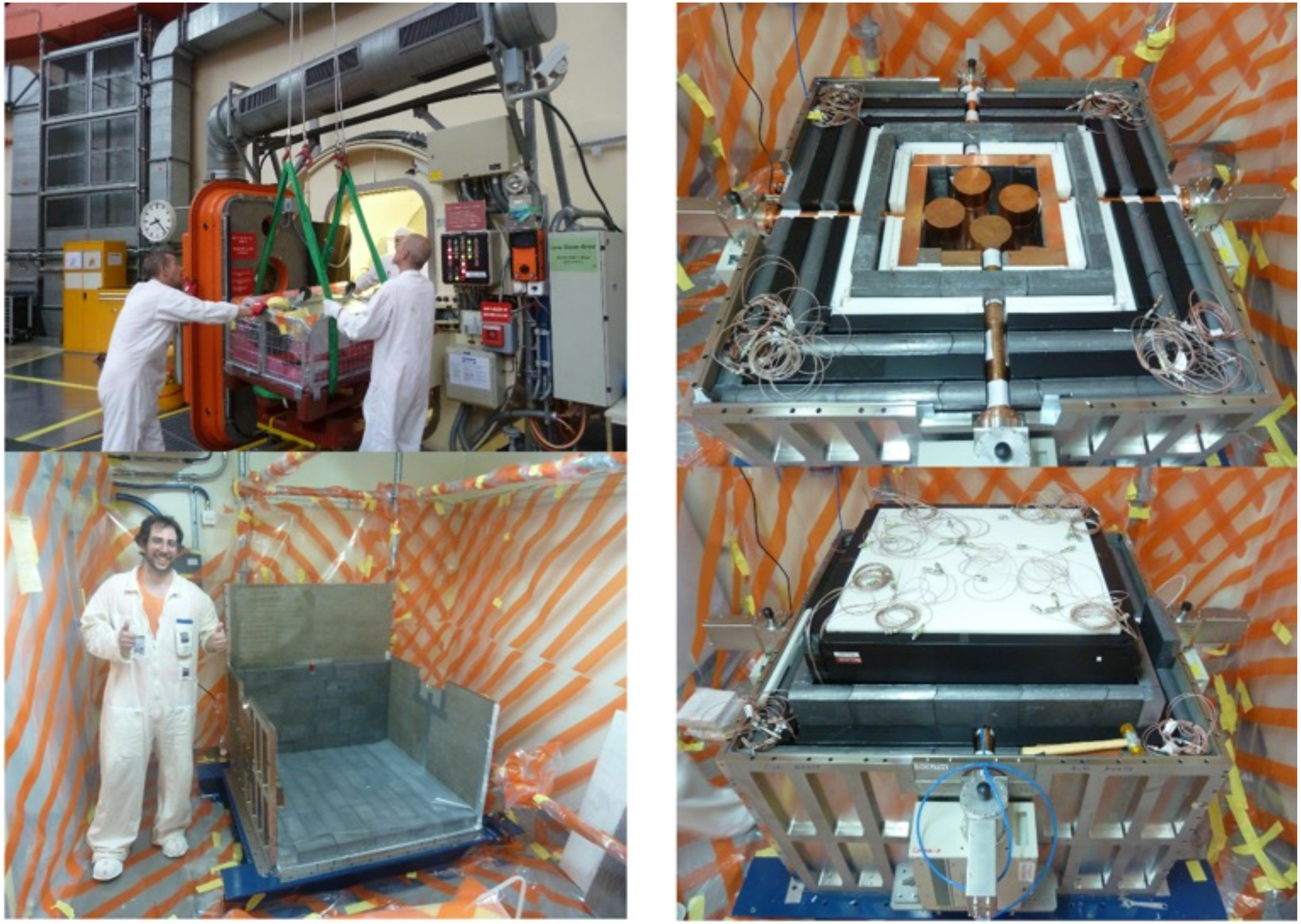
Brokdorf → Leibstadt,CH

Site characterisation (d=20.7 m):
- neutrons, muons, Radon, γ’s, ...

Detector improvements:
- improved energy resolution
- lower thresholds
- better trigger efficiency
- improved muon veto

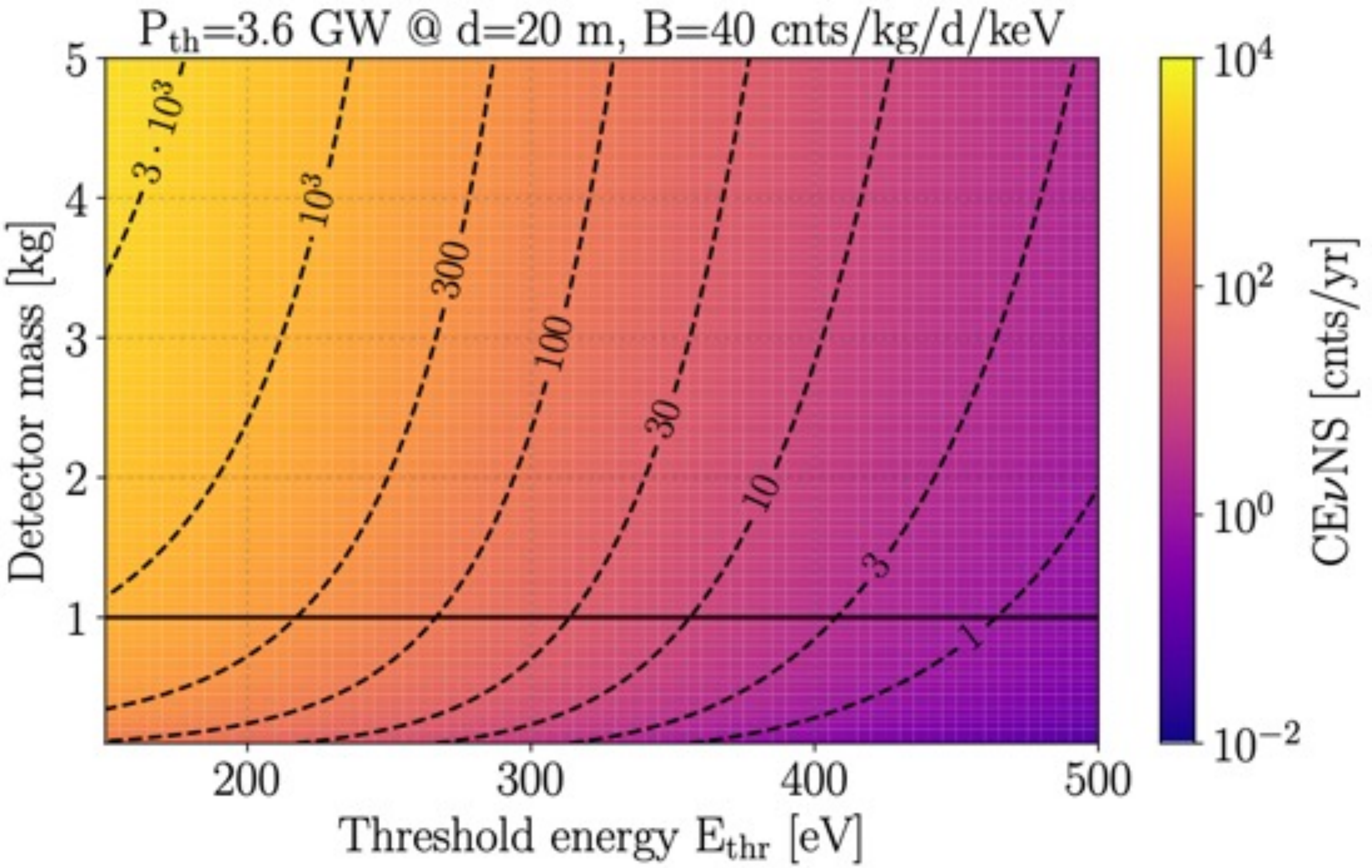
Foreseen 2024: mass 4 → 10kg

Installation Summer 2023



➔ **start of data taking: Nov. 11, 2023**

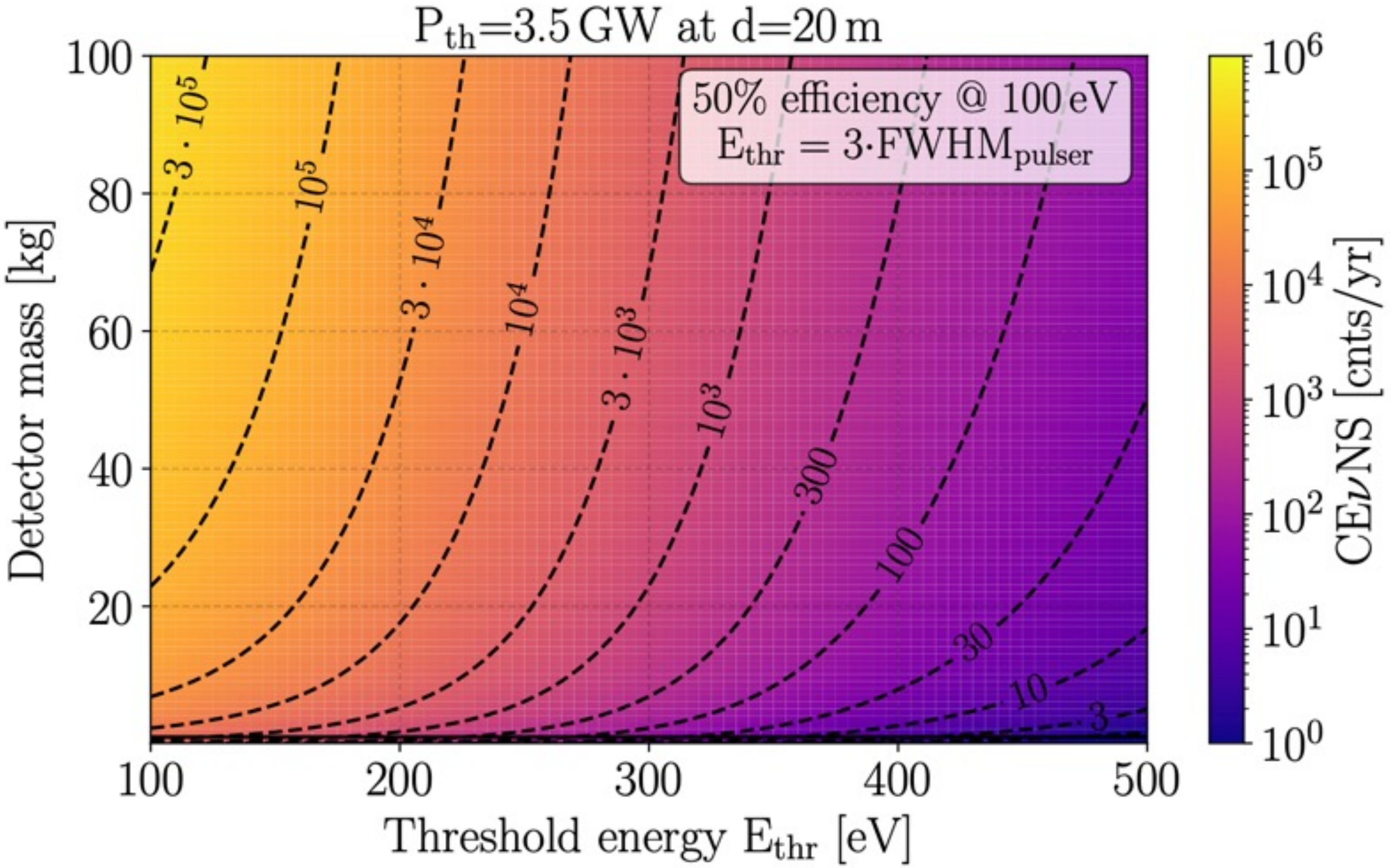
Expected Event Rate per Year



expectation compared to CONUS: x10

➔ CEνNS signal expected around the corner!

Scaling to larger Detector Masses



➔ **technology for high statistics exists!**

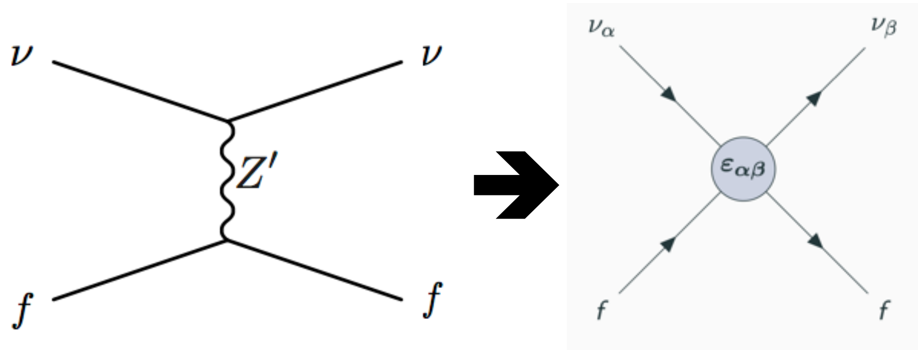
What is CEvNS good for?

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

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

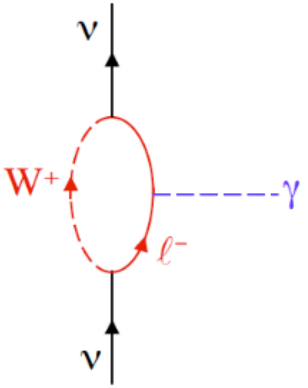
→ Competitive method to test TeV scales
ε = 0.01 ←→ TeV scales

Neutrino magnetic Moment in the SM + ν_R

Dirac:

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

μ_ν and ν mass operators have the same chiral structure
➔ μ_ν typically proportional to m_ν



SM+ν_R:

$$\mu_\nu = \frac{e G_F m_\nu}{8\sqrt{2}\pi^2} = 3 \times 10^{-20} \mu_B \left(\frac{m_\nu}{0.1\ \mathrm{eV}} \right)$$

Transition mag. moment for Majorana ν's:

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

➔ O(10^{-23}) μ_B

➔ **many BSM models significantly enhance μ_ν**

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

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

A_l ←→ SUSY breaking trilinear coupling

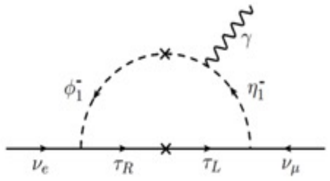
$M_{\tilde\ell}$ ←→ slepton mass

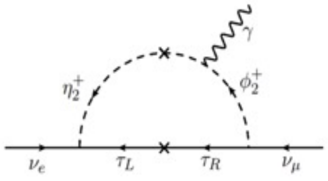
BUT ➔ $\mu_\nu \leq 10^{-13}\ \mu_B$

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

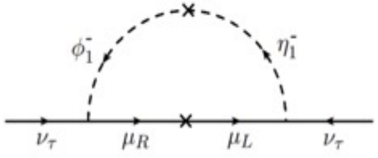
Pushing higher often leads to two problems:

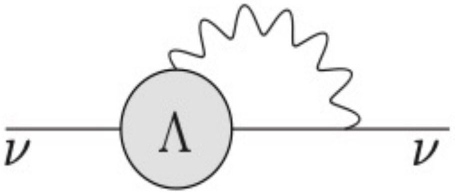
- **light new particles that should have been discovered**
- **intrinsic relation between magnetic moment and radiative neutrino masses**





➔ **ν mass**





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

➔ **observation would be a major discovery ←→ flavour!**

But: Flavour symmetries can unlock mass/magnetic moment link

See e.g.: **ML, B. Radovčić, J. Welter, JHEP 07 (2017) 139**

symmetries for ν mass patterns ➔ impact on m_ν ←→ μ_ν relation

K.S. Babu, S. Jana, ML, JHEP 10 (2020) 040

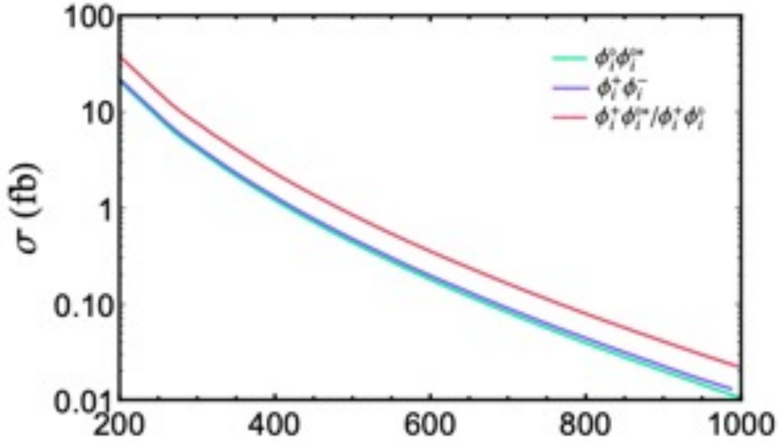
Horizontal $SU(2)_H$ broken by muon Yukawa coupling

Main point:

$$\mathcal{L}_{\text{mag.}} = (\nu_e^T \ \ \nu_\mu^T) C^{-1} \sigma_{\mu\nu} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} F^{\mu\nu} \quad \Leftrightarrow \quad \mathcal{L}_{\text{mass}} = (\nu_e^T \ \ \nu_\mu^T) C^{-1} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$\mathcal{L}_{\text{mass}}$ is not invariant ➔ $m_\nu = 0$ in the $SU(2)_H$ limit while μ_ν is allowed + corrections ➔elegantly generates the correct ν mass scale

- ➔ **LHC prospects**
- ➔ **HEP / CEνES interplay**



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

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

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

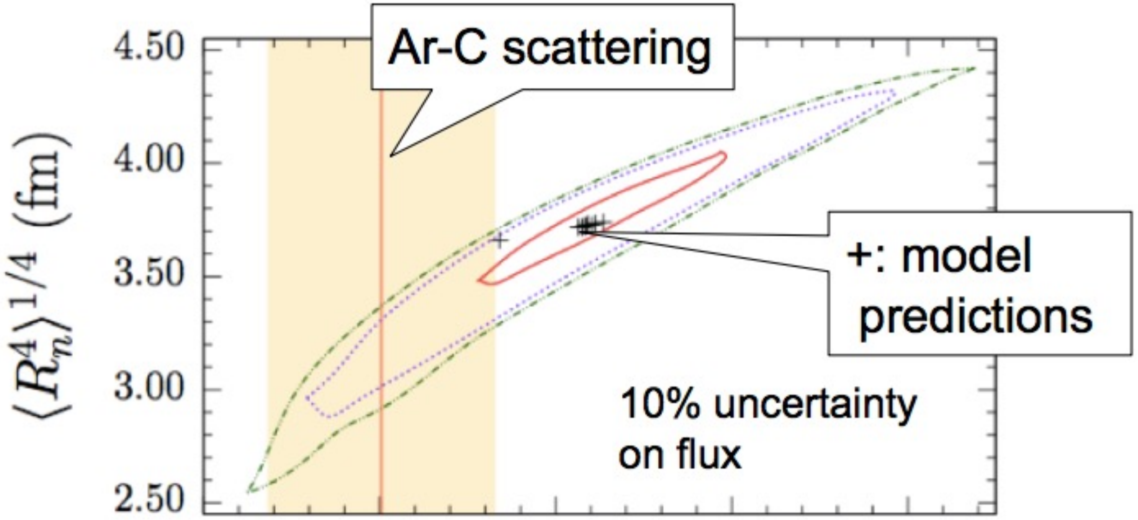
Nuclear form factors $F_{N,Z}(q)$ ~ Fourier transforms of N & P densities

→ 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



Conclusions

- **CEνNS is becoming hot topic ⇔ many theoretical connections**

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

➔ rising experimental and theoretical activity!

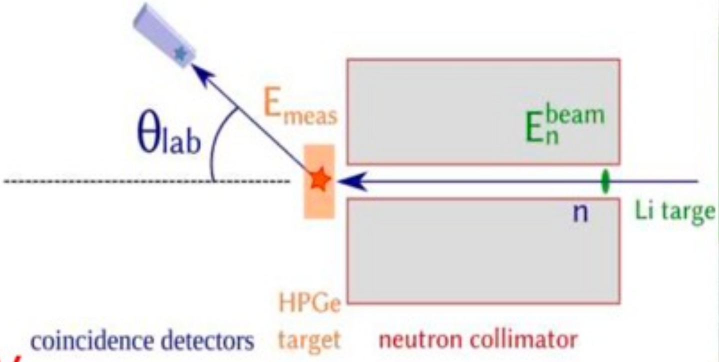
BACKUP

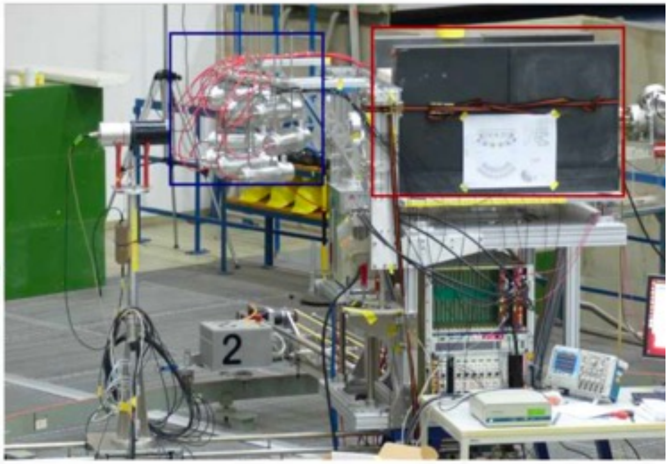
CONUS Quenching Measurement

Measurement at PTB:

Method:

- purely kinematics
  → model-independent
- triple time coincidence
- angles 18-45°
  (1° precision)
- monoenergetic neutron beam:
  energies 250 - 800 keV
  → nuclear recoils: (0.4, 6.3) keV





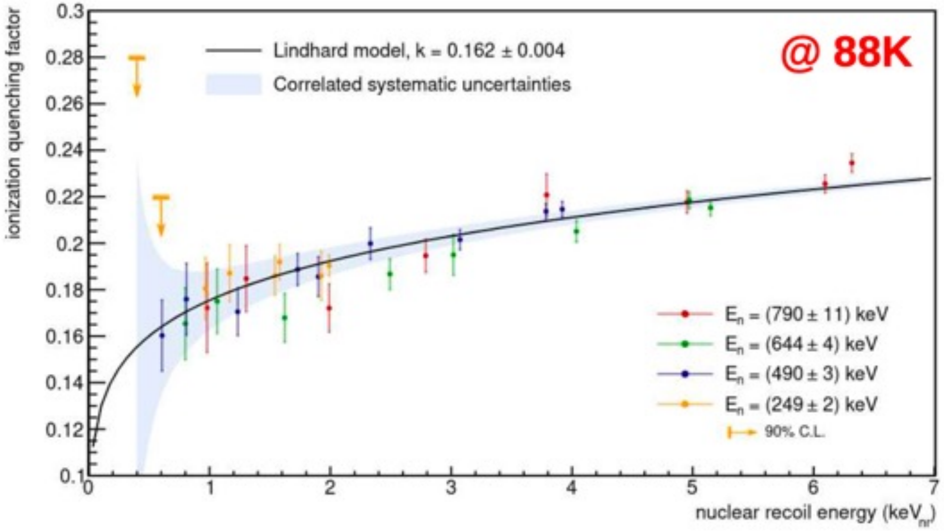
Main result:

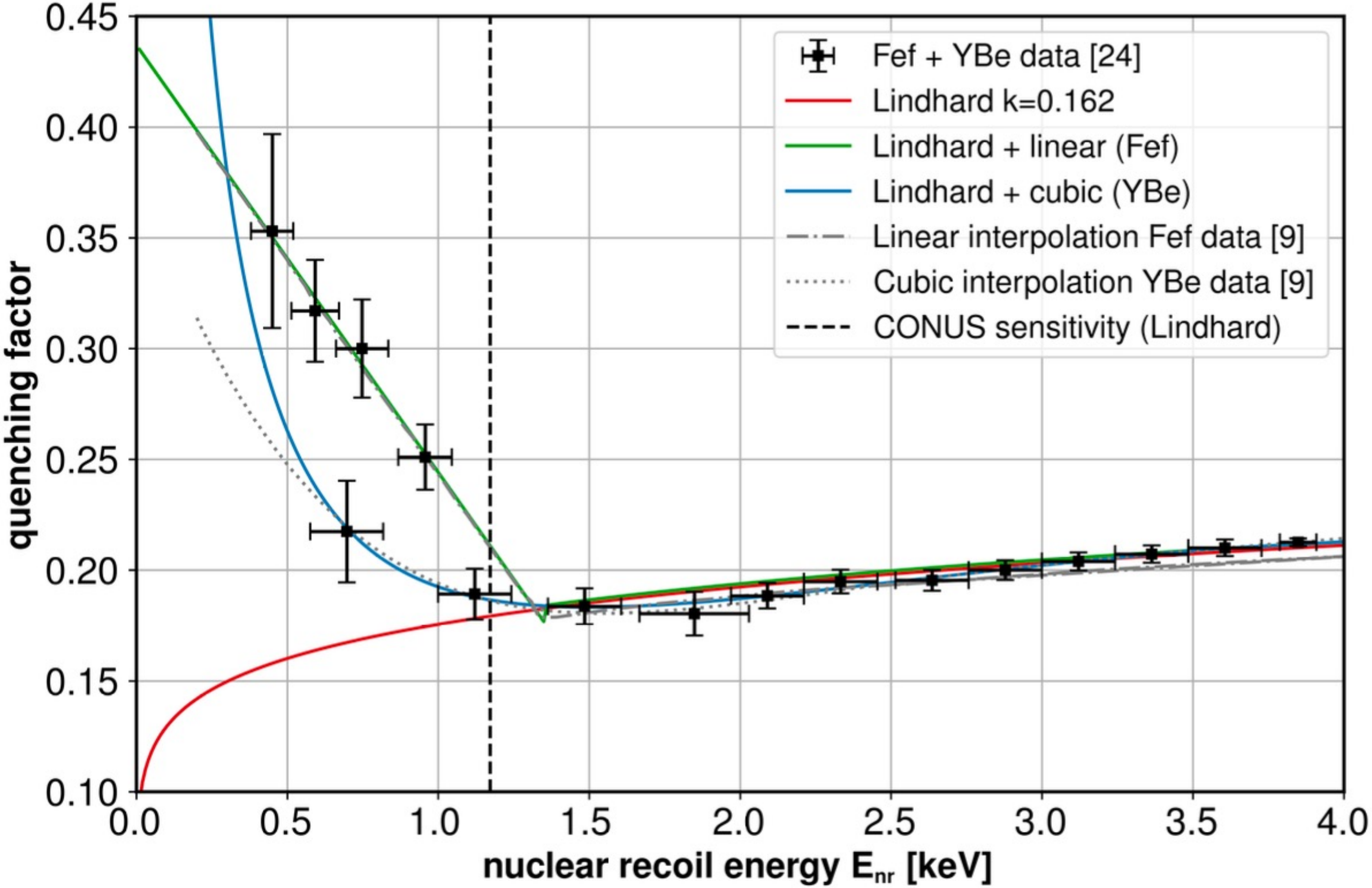
k=0.162+-0.004 (stat.+syst.)

→ precision at +-2.5% !

→ confirm validity of Lindhard theory !

→ CEvNS detection even more challenging

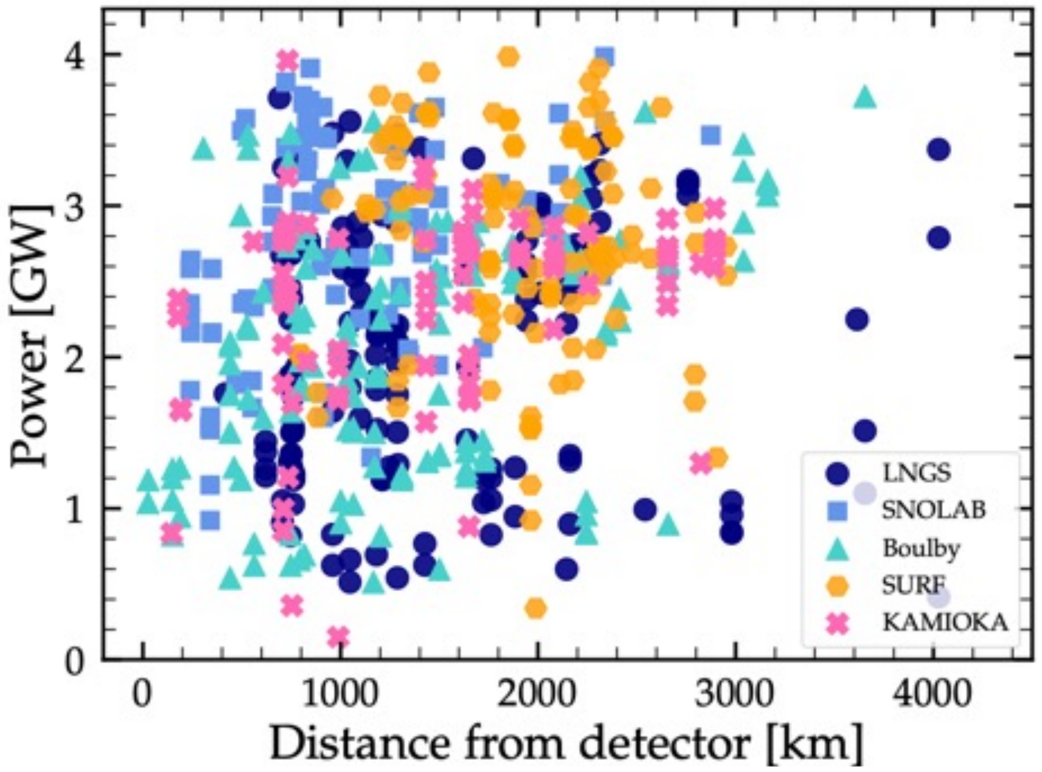


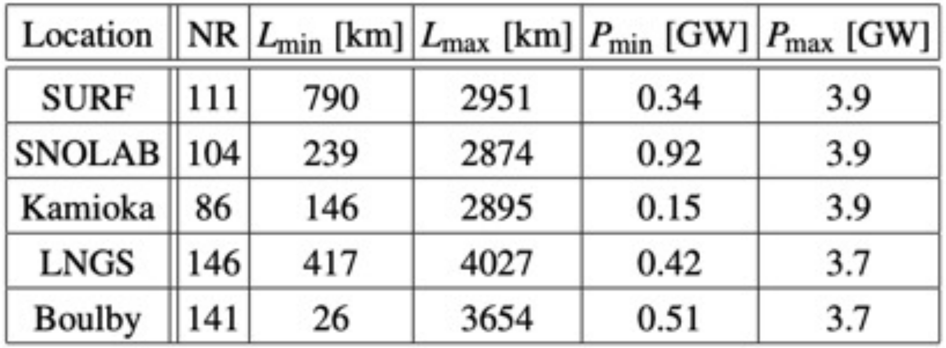

Fef + YBe data [24]
Lindhard k=0.162
Lindhard + linear (Fef)
Lindhard + cubic (YBe)
Linear interpolation Fef data [9]
Cubic interpolation YBe data [9]
CONUS sensitivity (Lindhard)
quenching factor
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
nuclear recoil energy E_{nr} [keV]

Nuclear Reactors and DM Detectors

NPP and underground labs

S. Sierra, V. De Romeri, Ch. Ternes: 2402.06416





Location	NR	$L_{\min}$ [km]	$L_{\max}$ [km]	$P_{\min}$ [GW]	$P_{\max}$ [GW]
SURF	111	790	2951	0.34	3.9
SNOLAB	104	239	2874	0.92	3.9
Kamioka	86	146	2895	0.15	3.9
LNGS	146	417	4027	0.42	3.7
Boulby	141	26	3654	0.51	3.7

XLZD-like detector →rate per year:

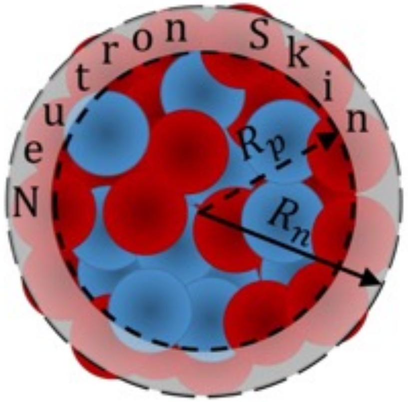
0.1 keV threshold:
16 (SURF)
44 (LNGS)
82 (Kamioka)
124 (SNOLAB)
733 (Boulby)

0.3 keV threshold: factor 1/7

➔ cannnot be ignored...

➔ could be a feature with a very close NPPs turing on or off

Nuclear Models and NSI's



Klein-Nystrand form factor

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

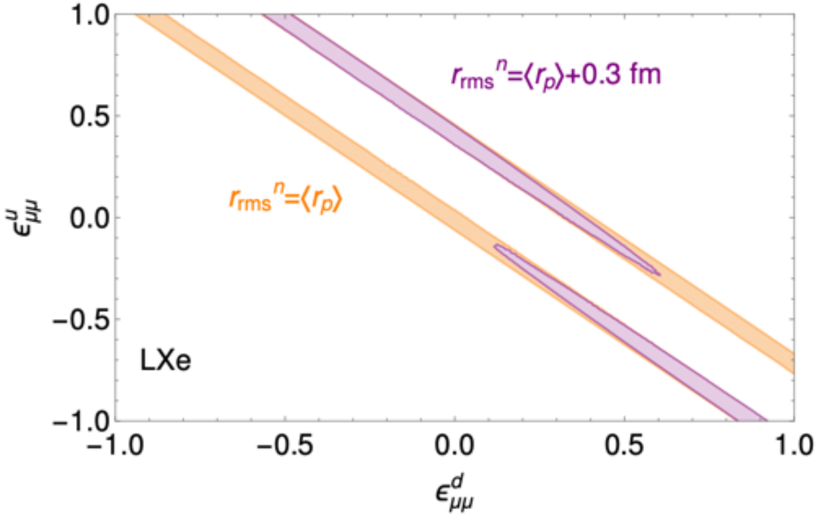
➔ **relies on a surface-diffuse distribution**

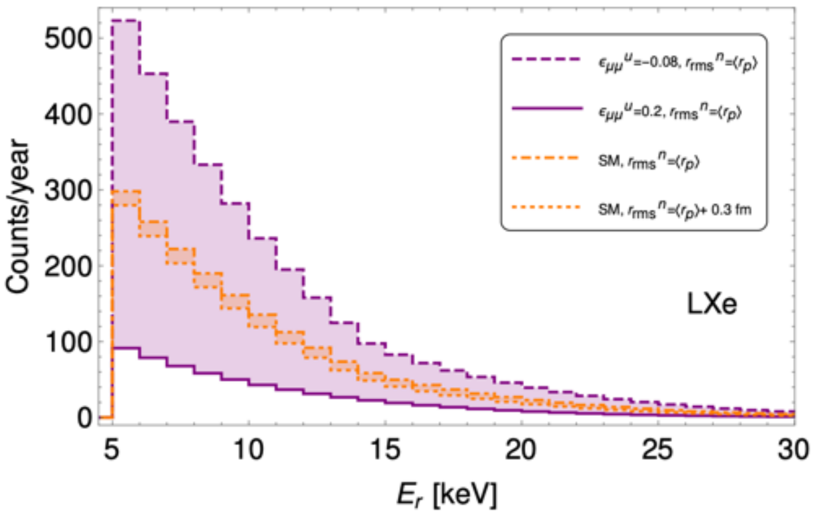
folding a short-range Yukawa potential with range a_k
over a hard sphere distribution with radius R_A

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

Aristizabal Sierra, Liao, Marfatia, JHEP 06 (2019) 141

allowed regions in the NSI case and for two choices of the rms neutron radius

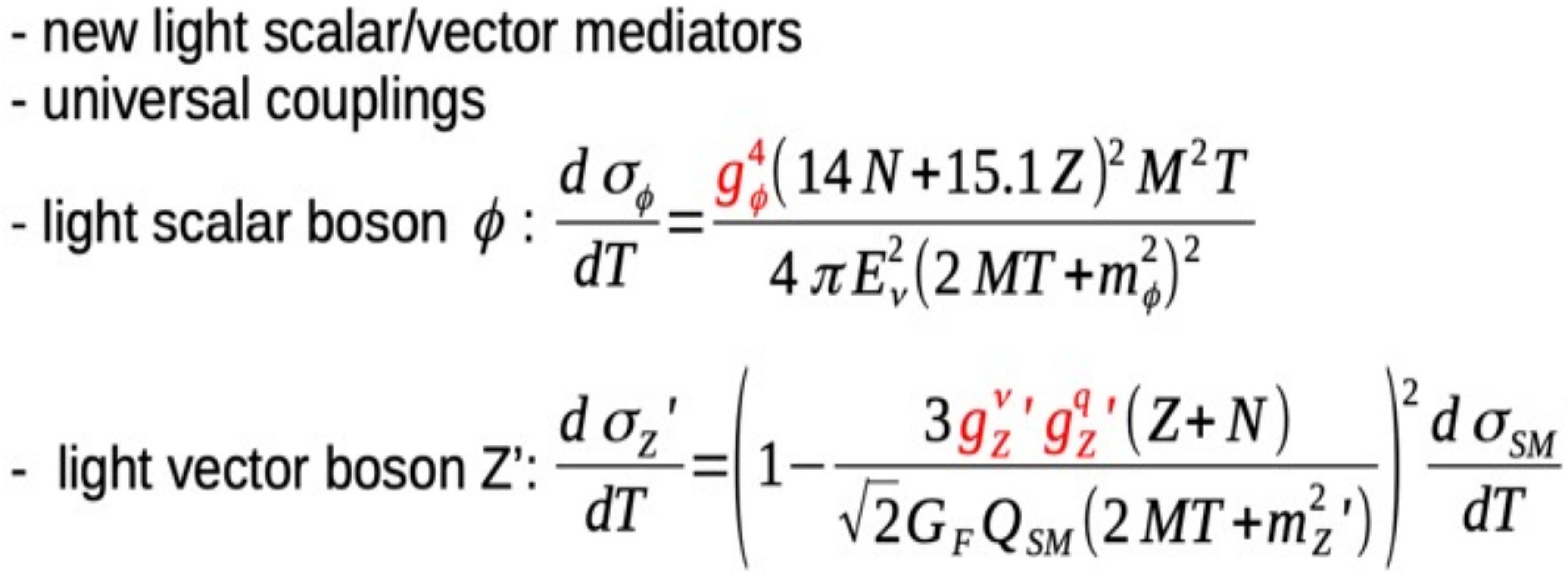




New Bosons

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':

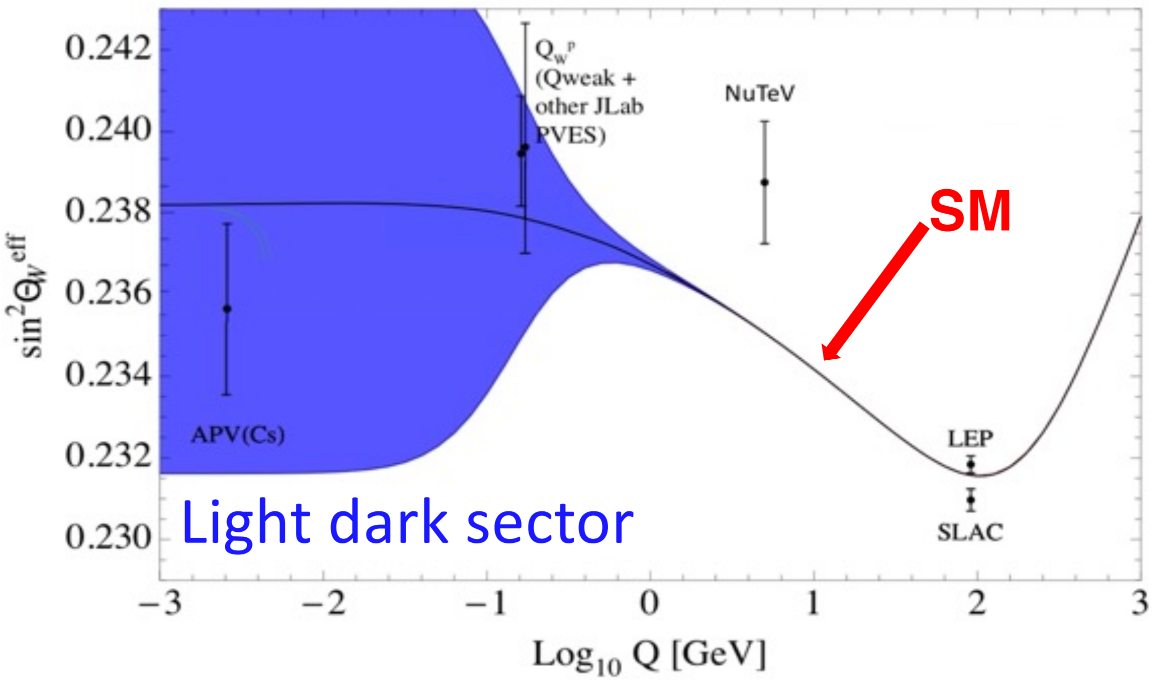
$$\frac{d\sigma_Z{}'}{dT} = \left(1 - \frac{3 g_Z^{\nu}{}' g_Z^{q}{}' (Z+N)}{\sqrt{2} G_F Q_{SM} (2MT + m_Z^2{}')}\right)^2 \frac{d\sigma_{SM}}{dT}$$

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

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

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

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

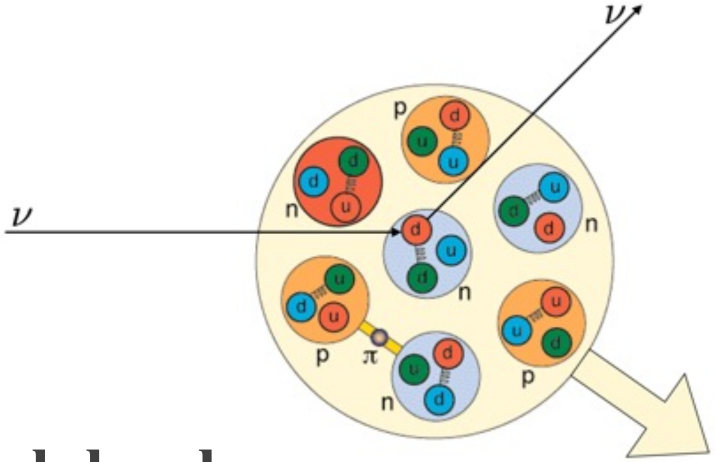


<u>Beware – models often in conflict with other measurements:</u>

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

Even more fundamental...

Elementary reaction: neutrinos interact with quarks via Z exchange



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requirements:
absence of individual recoil
scattering in phase

- **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