# Coherent Elastic Neutrino-Nucleus Scattering: Theory, Experiment, and Astrophysics


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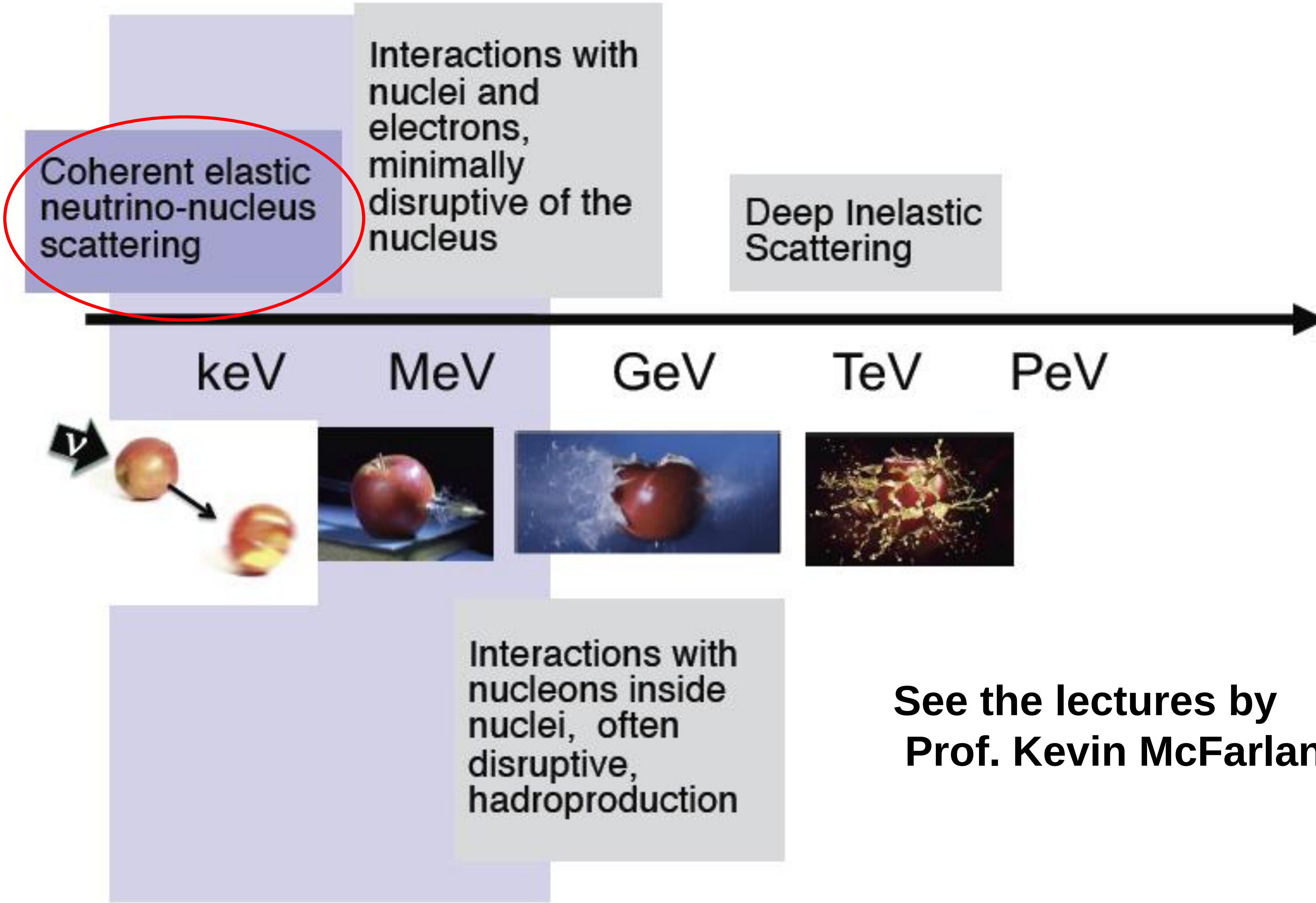
**@Beijing**

CCEPP Summer School 2021 on Neutrino Physics

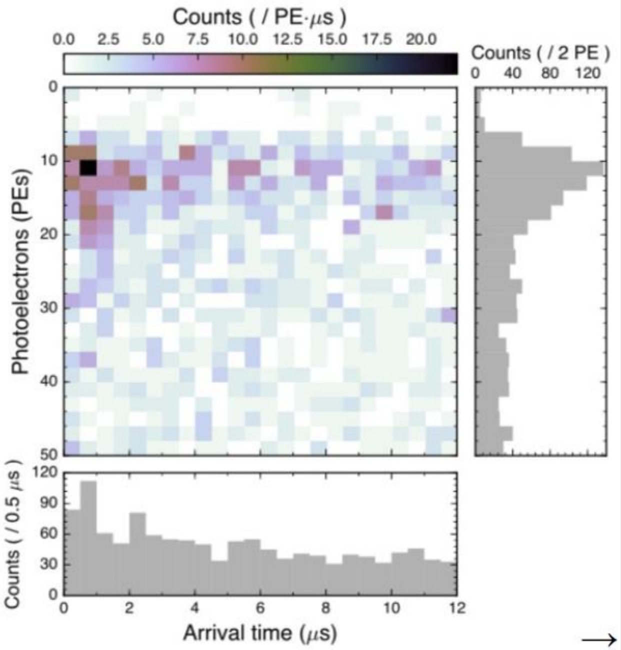
# Neutrino interactions over a range of energies




**See the lectures by Prof. Kevin McFarland**

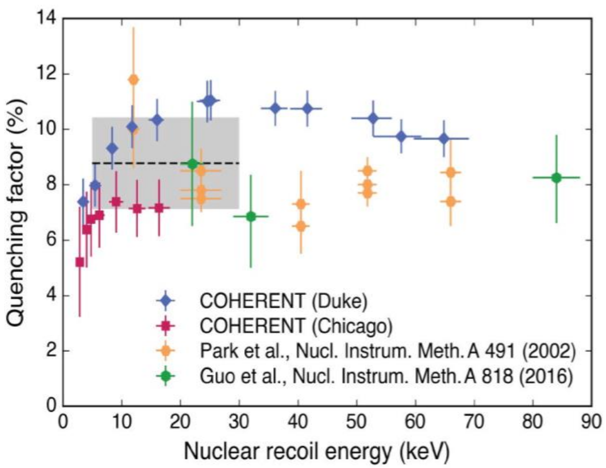
# Part D: Detection at Reactors

# Comparison with SM (6.7sigma)

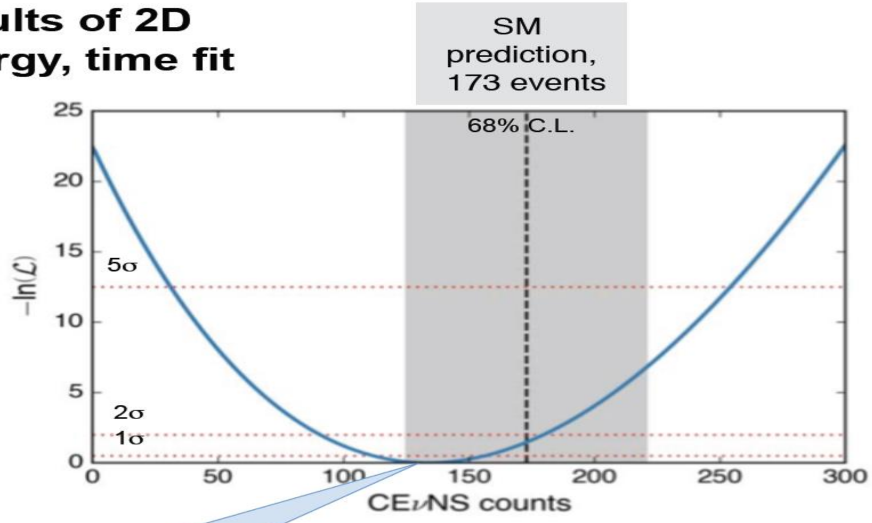



**Breakdown of systematics**

| Source of systematic | Contribution |
|---|---|
| Form factor (in CEνNS cross-section) | 5% |
| ν flux from SNS | 10% |
| Quenching factor | 25% |
| Det. efficiency | 5% |
| Source-detector baseline | Negligible |




**Results of 2D energy, time fit**




Best fit: **134 ± 22** observed events

No CEvNS rejected at 6.7σ, consistent w/SM within 1σ

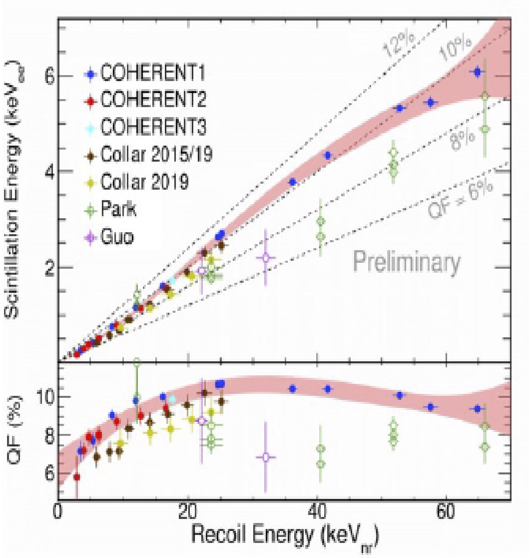
# New observation with CsI (2020)

- Continued data collection up to June 2019 → increased statistics by a factor > 2
- Refinements in the SSB characterization and beam power determination

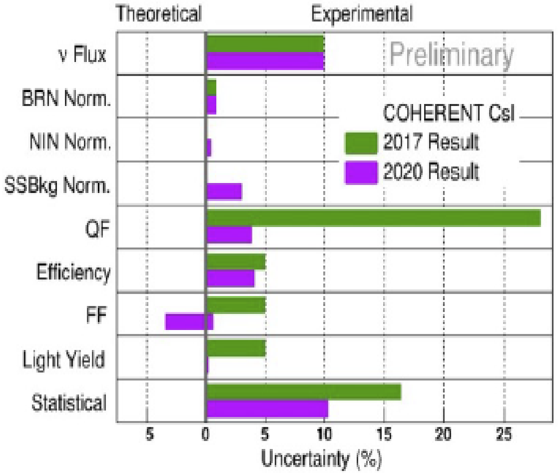
See A. Konovalov's talk

- Big work on re-measuring and understanding the QF

→ Unc. reduced to 3.6% in the new analysis !




- Updated measurement of CEvNS on CsI with new unc. budget !




| | |
|---|---|
| No-CEvNS rejection | 11.6 σ |
| SM CEvNS prediction | $333 \pm 11(\text{th}) \pm 42(\text{ex})$ |
| Fit CEvNS events | $306 \pm 20$ |
| Fit $\chi^2$/dof | 82.4/98 |
| CEvNS cross section | $169^{+30}_{-26} \times 10^{-40}$ cm$^2$ |
| SM cross section | $189 \pm 6 \times 10^{-40}$ cm$^2$ |

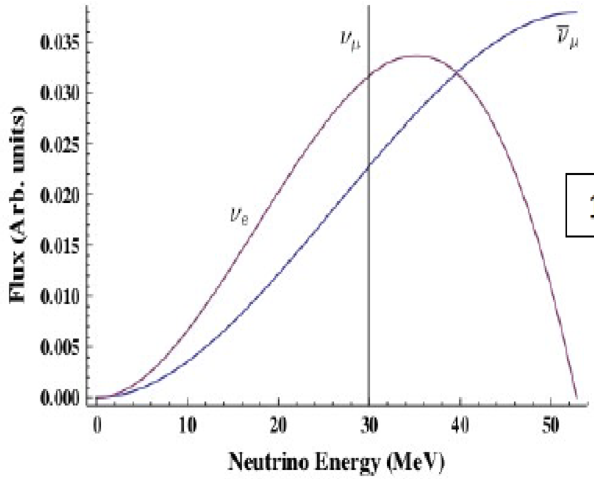
+ various searches of BSM physics...

See D. Pershey's talk

**From M. Vivier summary talk @Mag7s(2020)**

# Stopped-pion vs reactor neutrino sources

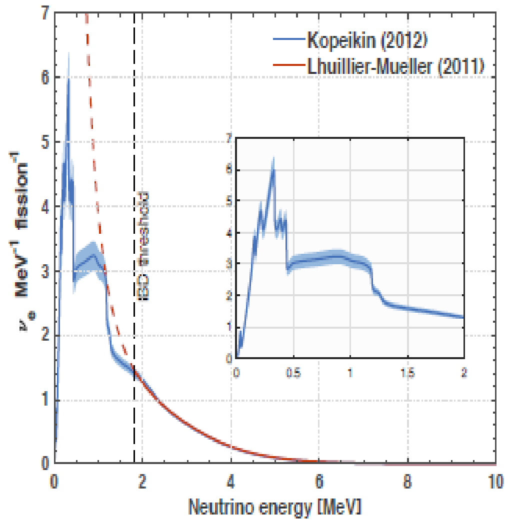
## Low energy neutrinos from accelerators




$10^7$-$10^8$ cm$^{-2}$ s$^{-1}$

- Pion–decay–at–rest (DAR) sources → multiple flavors
- Pulsed sources → high bck discrimination through timing
- Nuclear recoil energies ≥ 1–10 keV + not fully coherent
- High cross–section

## Reactor antineutrinos

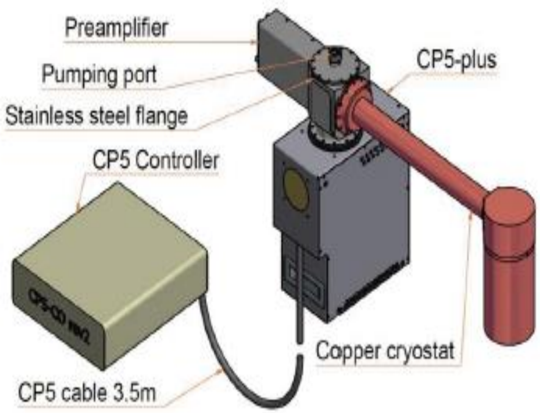



$10^{12}$-$10^{13}$ cm$^{-2}$ s$^{-1}$

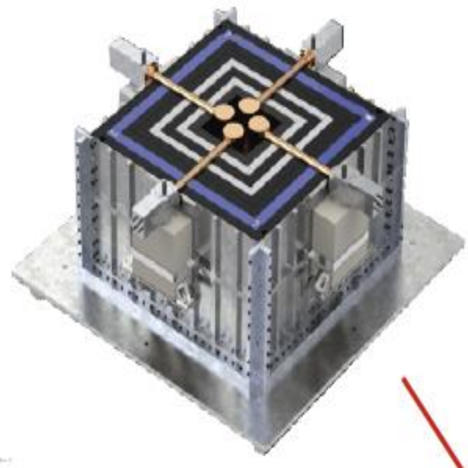
- Nuclear fission → single (electronic) flavor
- Continuous source → duty cycle important for bck mitigation
- Nuclear recoil energies ≲ 1 keV + fully coherent
- Lower cross–section, but compensated by much higher flux (depending on your threshold...)

# CONUS

4 x 1-kg p-type point contact HPGe




Passive & active shields



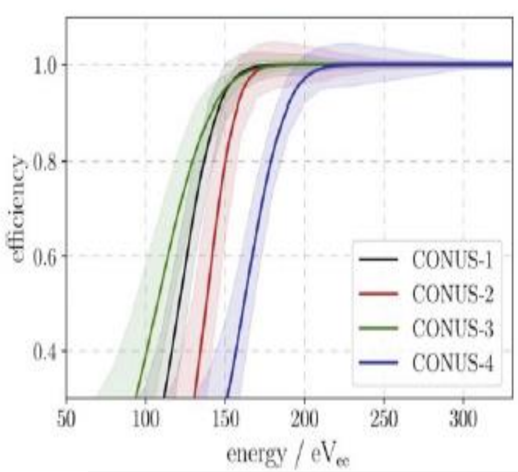
**Brokdorf reactor (Germany)**

- D = 17 m
- $P_{th}$ = 3.9 $GW_{th}$

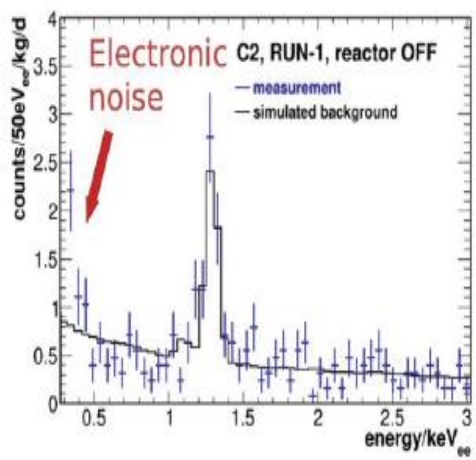
} ~ 2 x $10^{13}$ $cm^{-2}$ $s^{-1}$

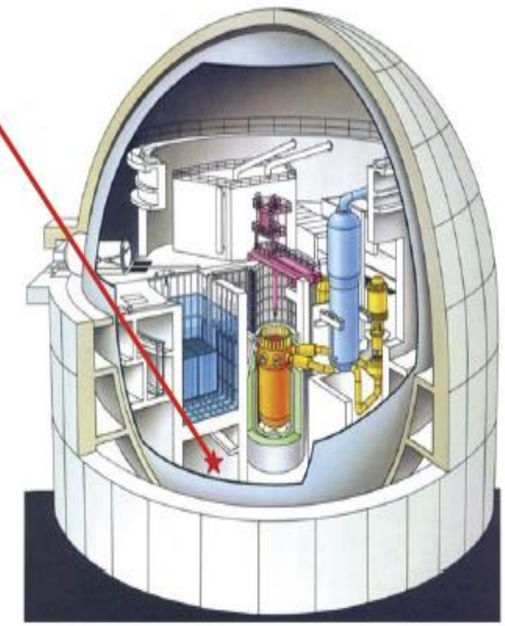
- Overburden = 10 → 45 m w.e

~ 300 $eV_{ee}$ threshold



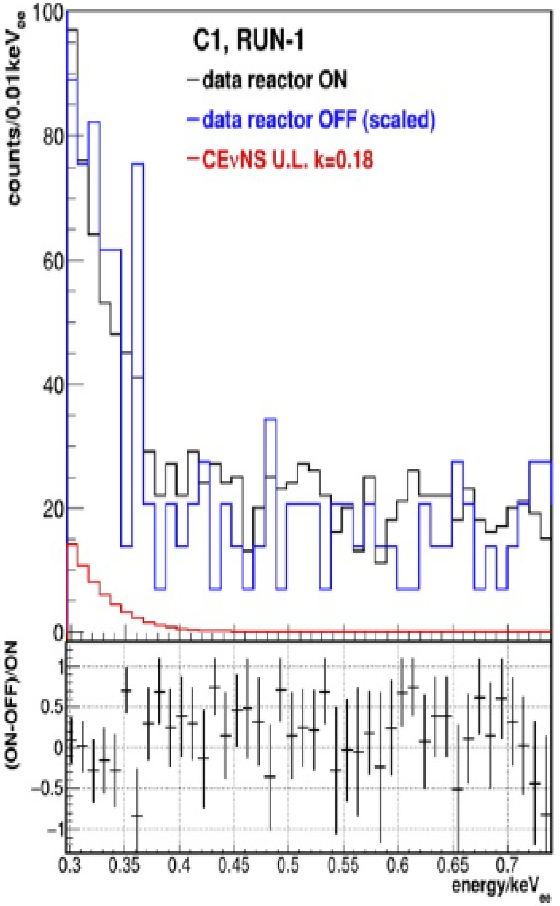

$10^4$ bck suppression → 10 dru @ 1 keV !



# CONUS

- Analysis of RUN–1 (2018) & RUN–2 (2019/2020) data → best UL on CEvNS with Ge !

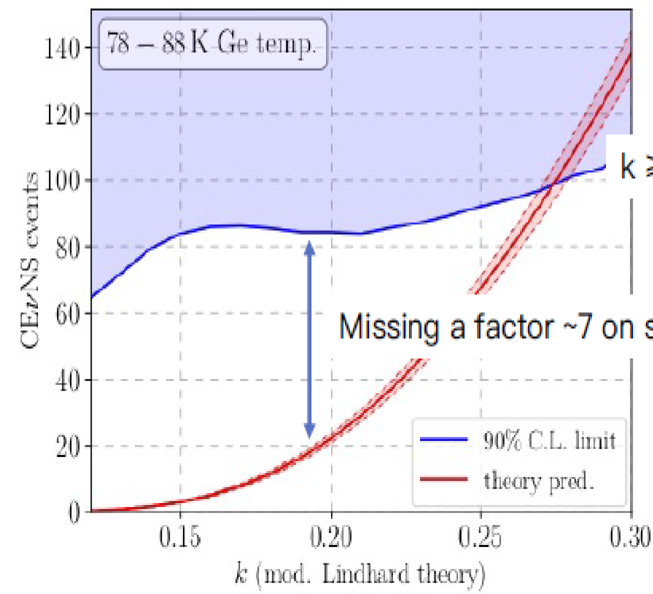



See J. Hakenmüller's talk

X 4

250/60 kg.d
ON/OFF data

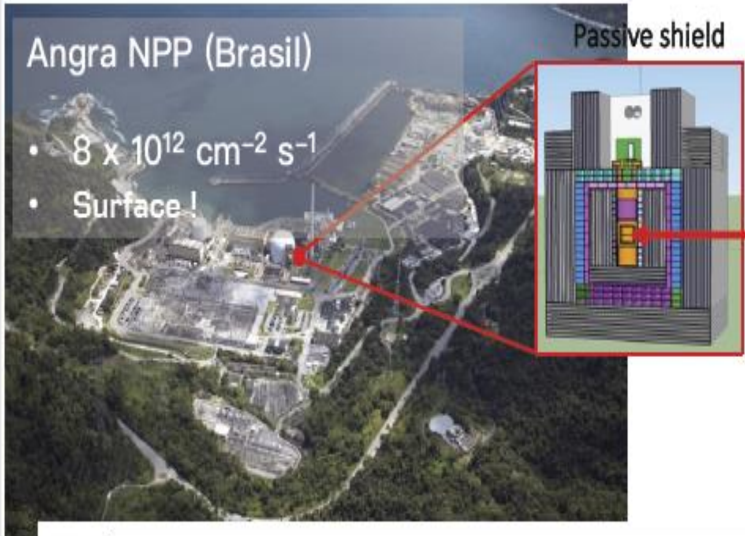
**Quenching matters !**




**Perspectives**

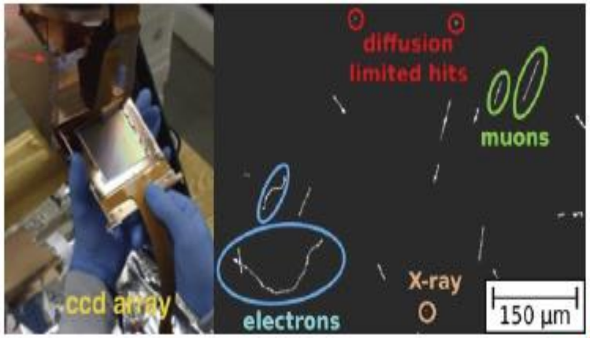
- New data + shutdown of KBR > 2021 → stat. unc ↓
- Improved analysis techniques → bck ↓ + sensitivity ↑

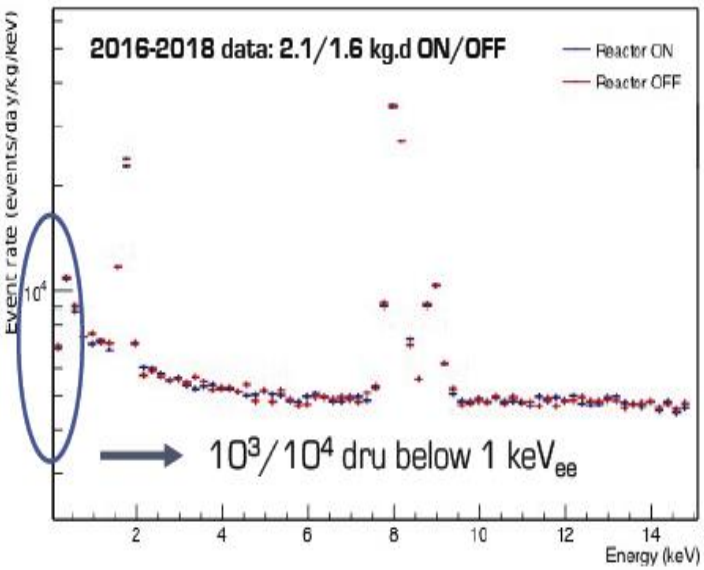
# CONNIE



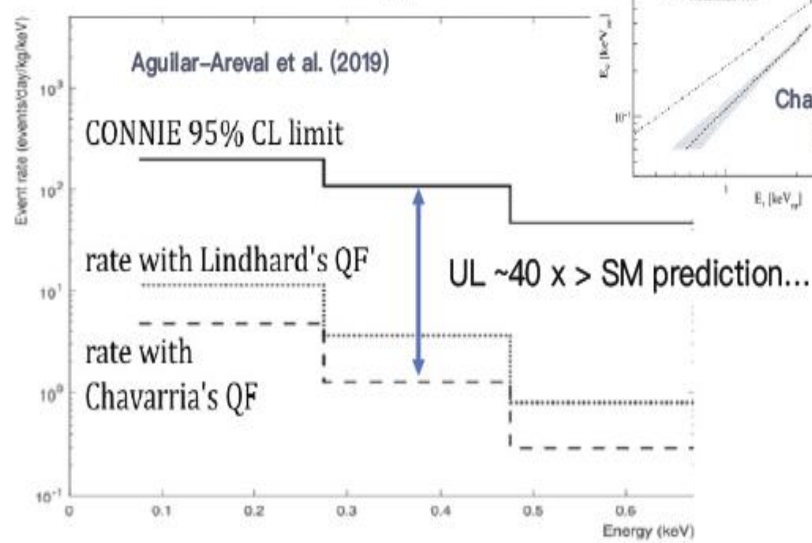

## Mpixels Si CCD array

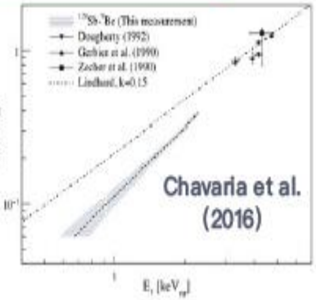
- Particle id.
- ~40 $eV_{ee}$ threshold
- Total mass ~ 70 g




**Quenching matters !**



# CONNIE

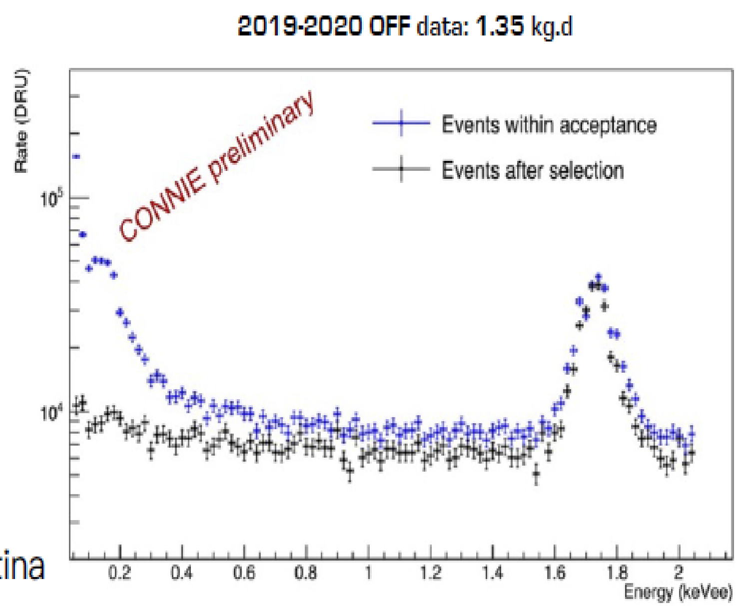
- New data (2019–2020) with many improvements in the analysis

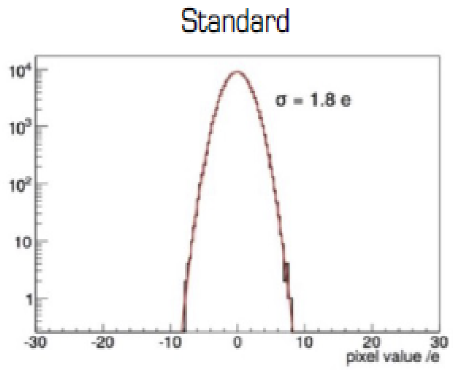
  → Unblinding of the ON data (1.5 kg.d) soon

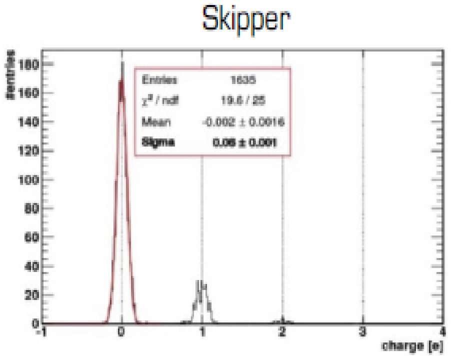
- Upgrade to a new readout system in 2021: **Skipper CCDs**
  - Multiple sampling of CCD pixels to reduce noise
  - Possibility to detect single e⁻
  - **Reduce threshold down to 7 $eV_{ee}$ !**

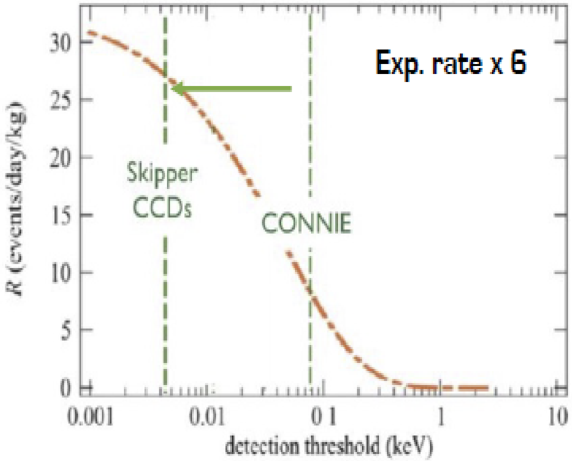
See P. Mota's & G. Fernandez-Moroni talks

- νIOLETA → SBL CEvNS program with kg-scale Skipper CCDs in Argentina



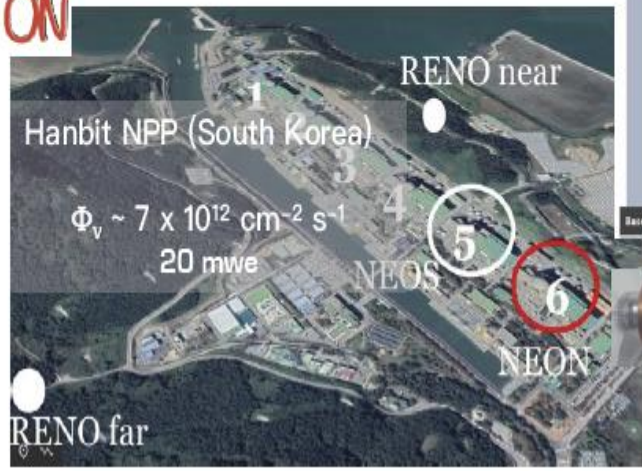



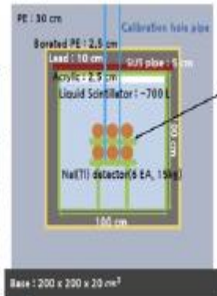



# Start physics run

## NEON

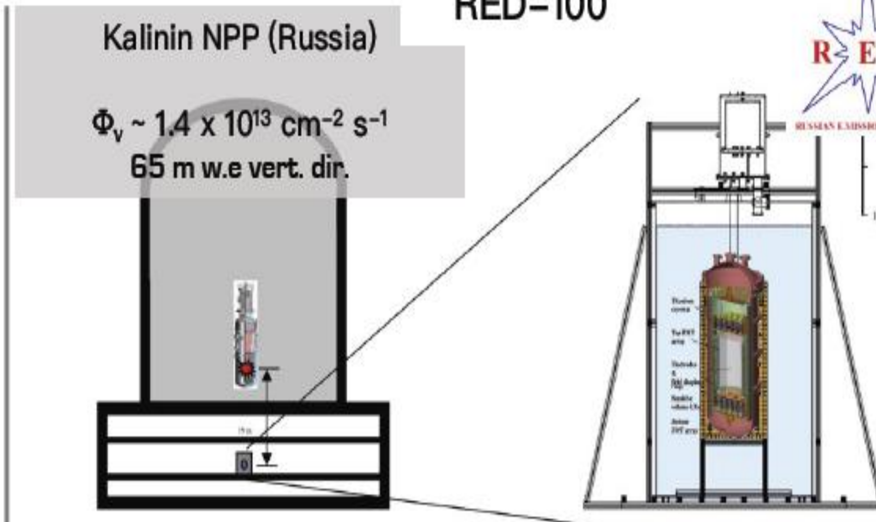



- Ultra-pure **NaI scint. crystals** (COSINE DM exp.)
- Optimized to reach low thr. → ~0.2–0.3 $keV_{ee}$
- QF needs to be characterized, prob. k ≤ 0.1–0.2
- Passive shield + active LS veto → ~ 10 dru ≤ a few keV
- Installation & commissioning at HNPP on-going

See HS. Lee's talk

## RED-100



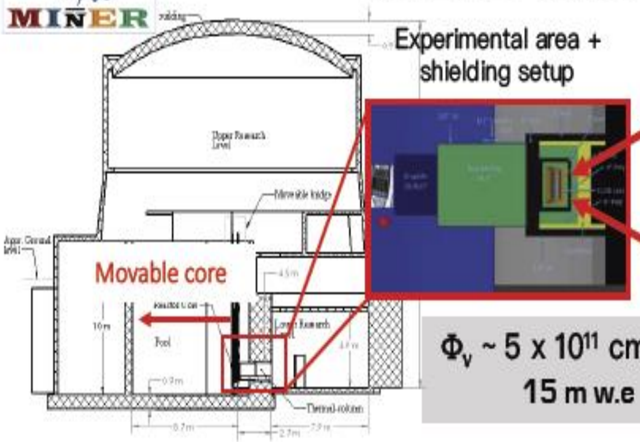

- **Dual-phase Xe TPC,** developed and tested at MEPHI
- Optimized to reach low thr. with SE detection cap.
- Passive shield, bck. characterization at KNPP on-going
- Spontaneous emission of SEs → main source of bck
- Installation & commissioning at KNPP right now

See D. Rudik's talk

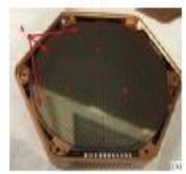
# Bolometric detectors

MINER

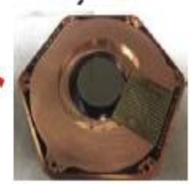
## MINER @ TAMU




HV



Hybrid



$\Phi_\nu \sim 5 \times 10^{11}$ cm$^{-2}$ s$^{-1}$
15 m w.e

- **Si & Ge superCDMS-style** detectors:
  - ➢ 100-g HV → 0.1 keV$_{NR}$ thr. with TNL amp. (no quenching !)
  - ➢ 100-g hybrid: collect separately prim. + TNL phonons to achieve ER/NR disc. down to 0.1 keV$_{NR}$
- Staged approach:

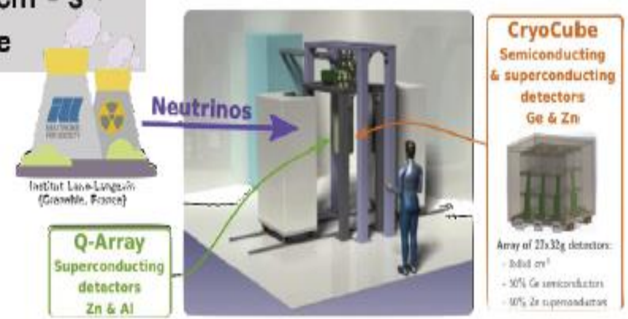
See R. Mahapatra's talk

  - ➢ Phase-1 (now): 2 x (3+1) HV/Hybrid Si. det
  - ➢ Phase-2 (2022): new hermetic shielding design (Icebox) + payload increase

RICOCHET

## RICOCHET @ ILL

$\Phi_\nu \sim 1.6 \times 10^{12}$ cm$^{-2}$ s$^{-1}$
15 m w.e




- **EDELWEISS-style** 30-g Ge semiconductor:
  - ➢ ~60 eV thr. demonstrated with phonon-only (no quenching !)
  - ➢ LN electronics R&D to push ER/NR discr. down to 50 eV
- **New superconducting Zn & Al det.** with ER/NR discr.
- 1-kg payload → 5σ detection in a couple of days
- Exp. site @ ILL characterized + shielding design on-going
- Deployment and physics run by 2023

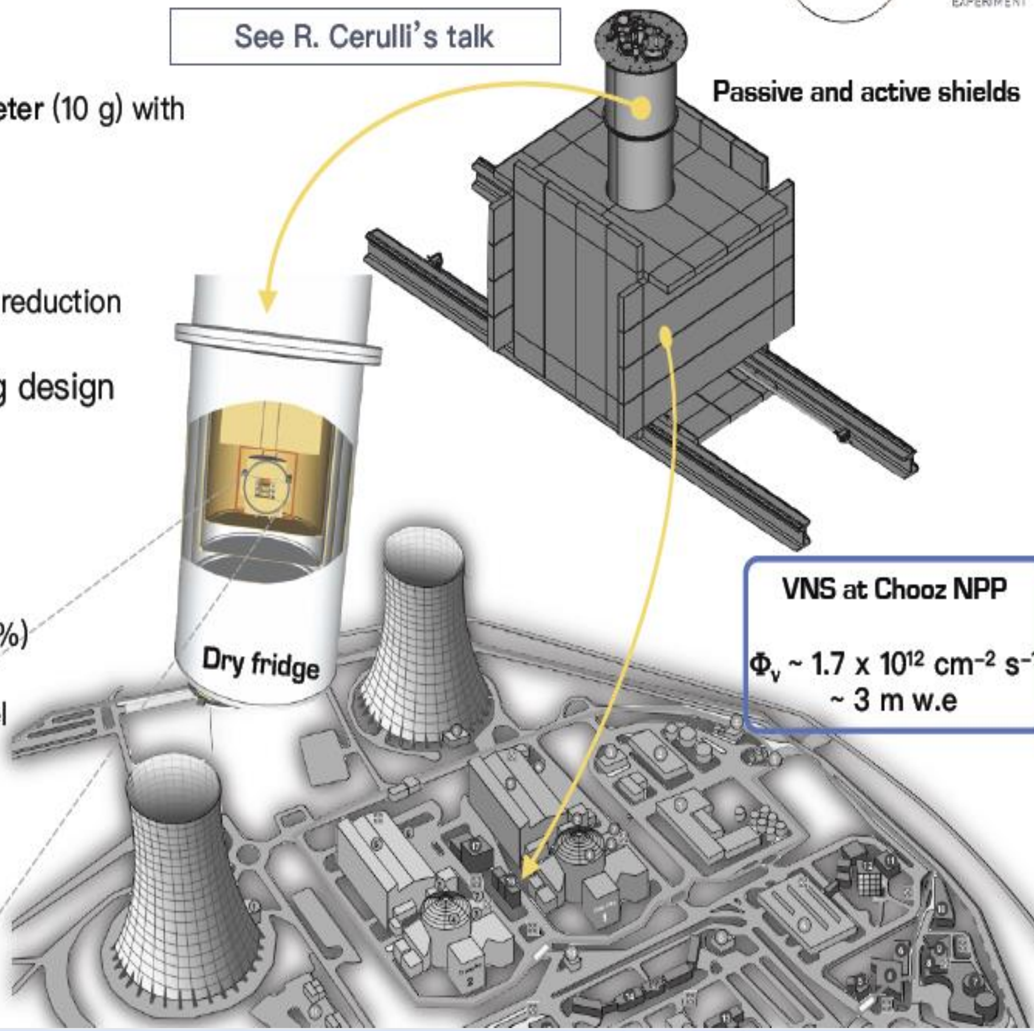
See T. Salagnac's talk

# NUCLEUS

## NUCLEUS

- Cryogenic detection at commercial reactors:
  - Array of $CaWO_4/Al_2O_3$ **gram-scale cryogenic calorimeter** (10 g) with low threshold: **20 eV demonstrated !**
  - Phonon readout only → **no quenching !**
  - Cryogenic Si and Ge **vetoes** → internal + external bck reduction
- Design phase: good progress on detector + shielding design
- Staged approach:
  - 2021: commissioning at TUM – bck. run
  - 2022: Chooz NPP – 1st physics run → CEvNS at O(10%)
  - 2023/2024: upgrade to kg-scale → CEvNS at ~% level

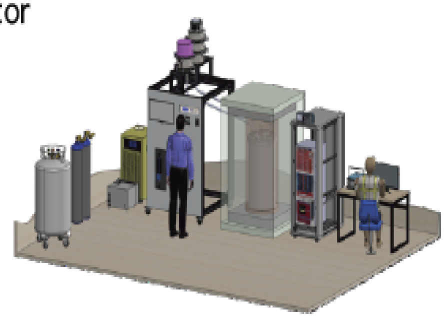
See R. Cerulli's talk




5 x 5 x 5 $mm^3$

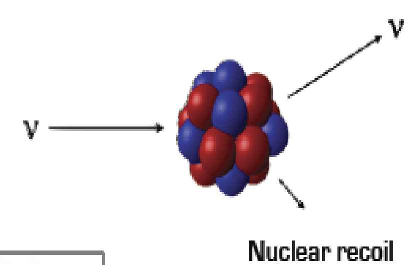
# Other proposals

- LXe det. operated in e⁻ couting mode
- R&D program to build a low bck. 10-kg det. reaching 0.3 $keV_{ee}$ thr.
- Aims at 5σ detection in ~40 days near a reactor

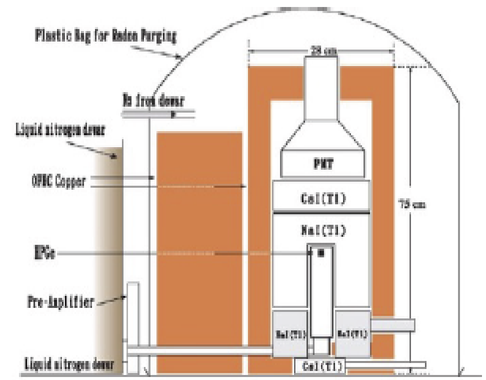


NUXE
Neutrino Detection with Xenon

TEXONO

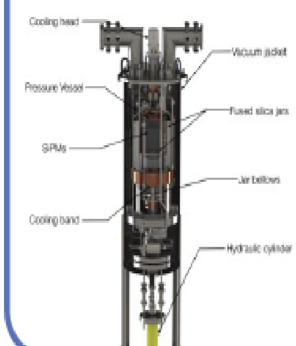



- Ge PPC with 0.2–0.3 $keV_{ee}$ thr.
- Kuo-sheng HPP (Taiwan), end of operation by 2022/2023
- Data taking with an upgraded 1.5-kg det.




- Scintillating LAr bubble chamber
- ER blind with ~40 $eV_{NR}$ achievable

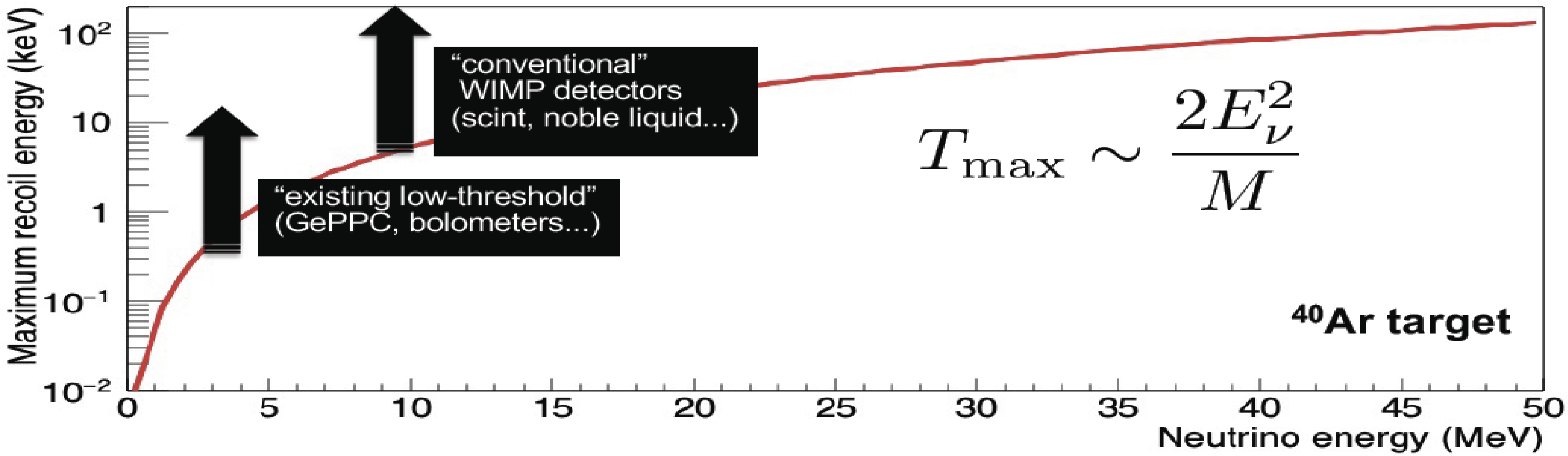
SBC

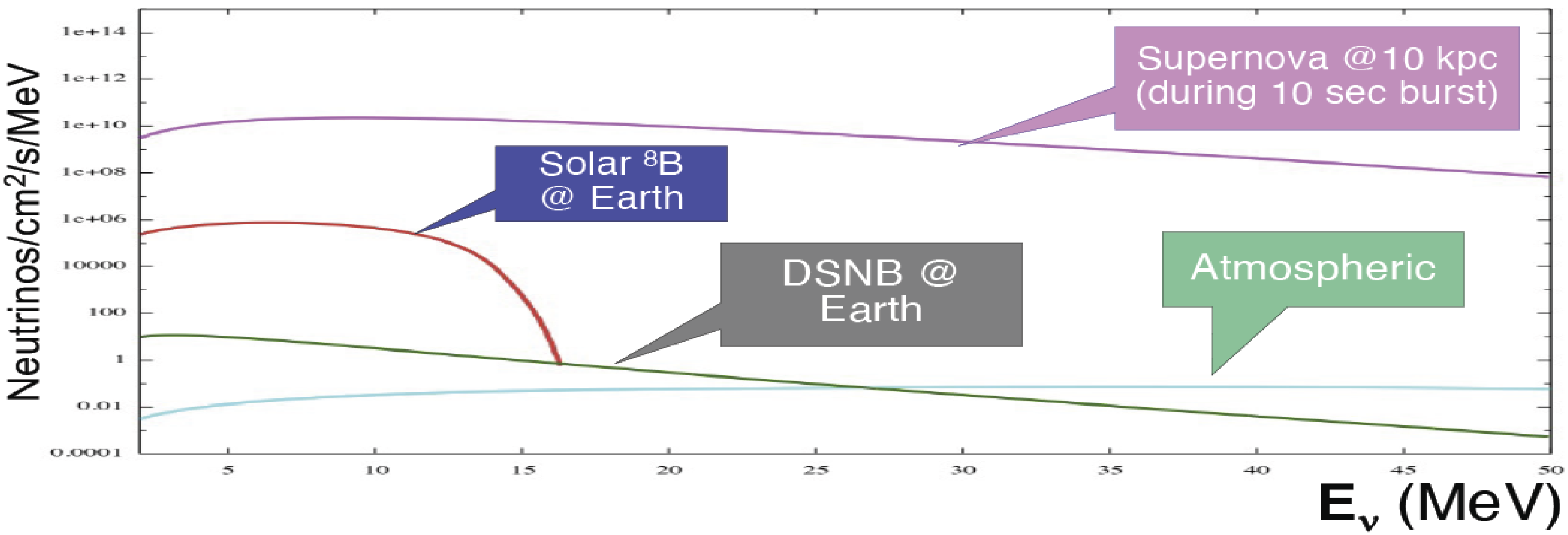



- ➢ Commissioning at FermiLAB
- ➢ WIMP program at SNOLAB (> 2022)
- ➢ CEvNS program at a reactor: ININ TRIGA (Mexico)?

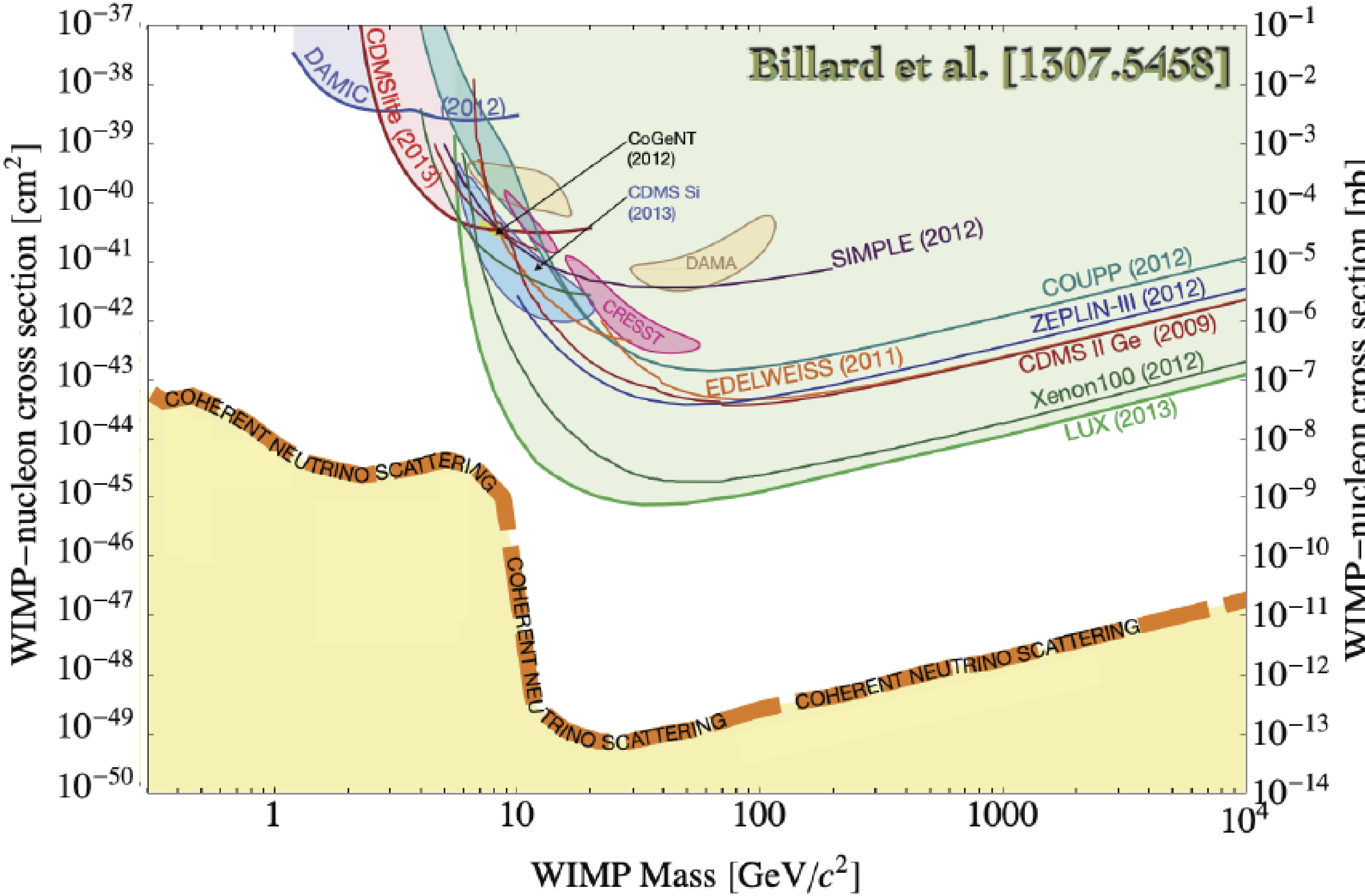
# Part E: Detection at DM exps.

# Detection of Natural sources

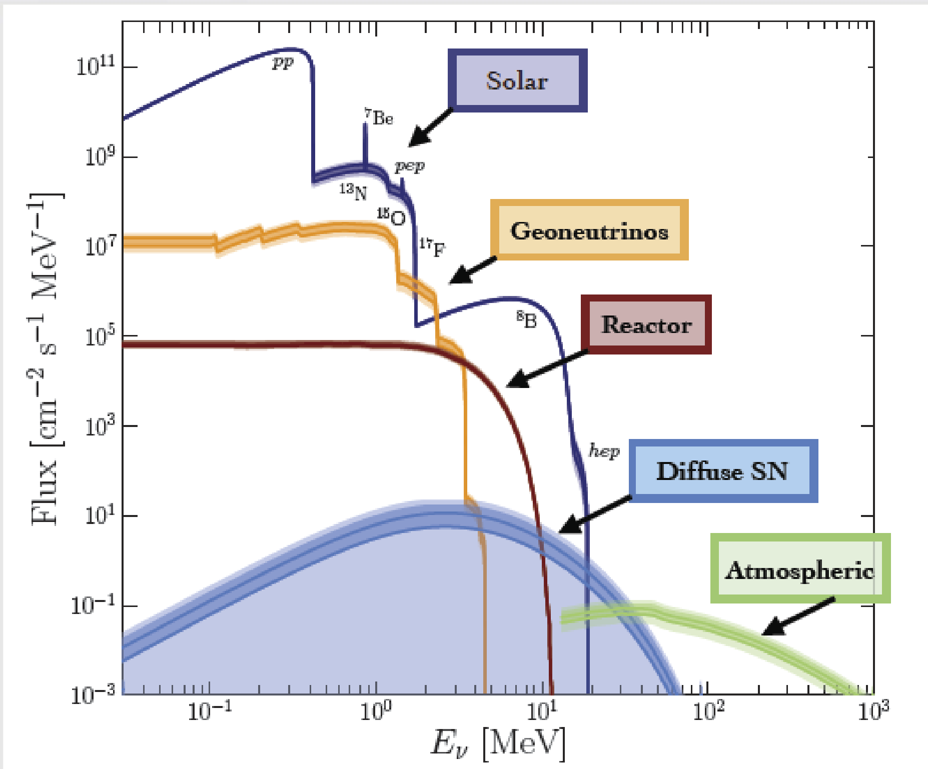


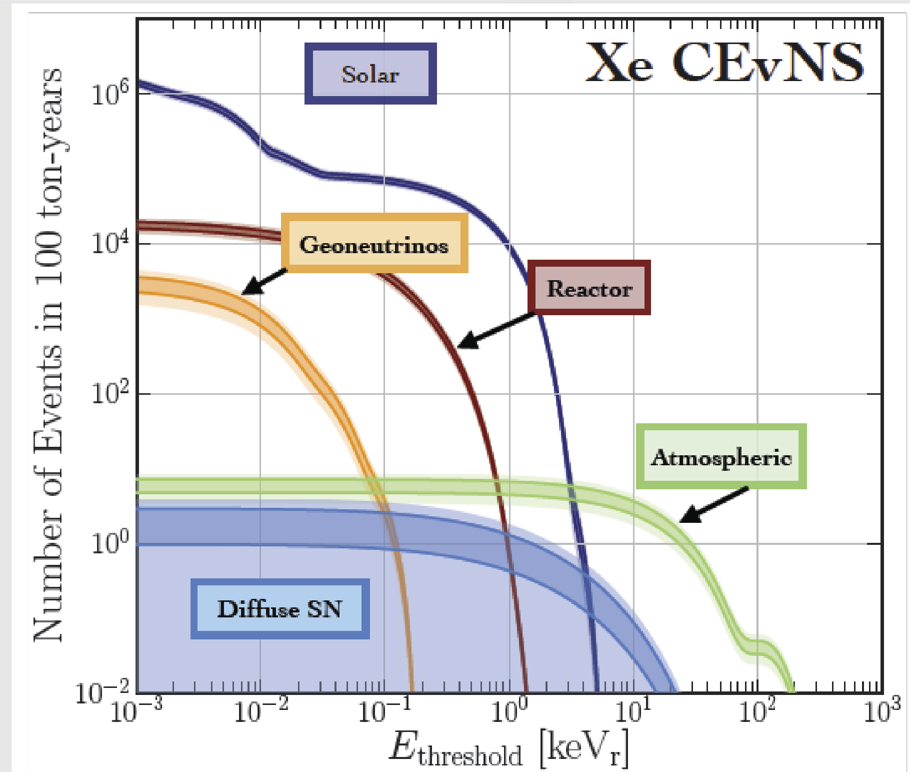



# Neutrino Floor



# Neutrino events at Xe DM exps.

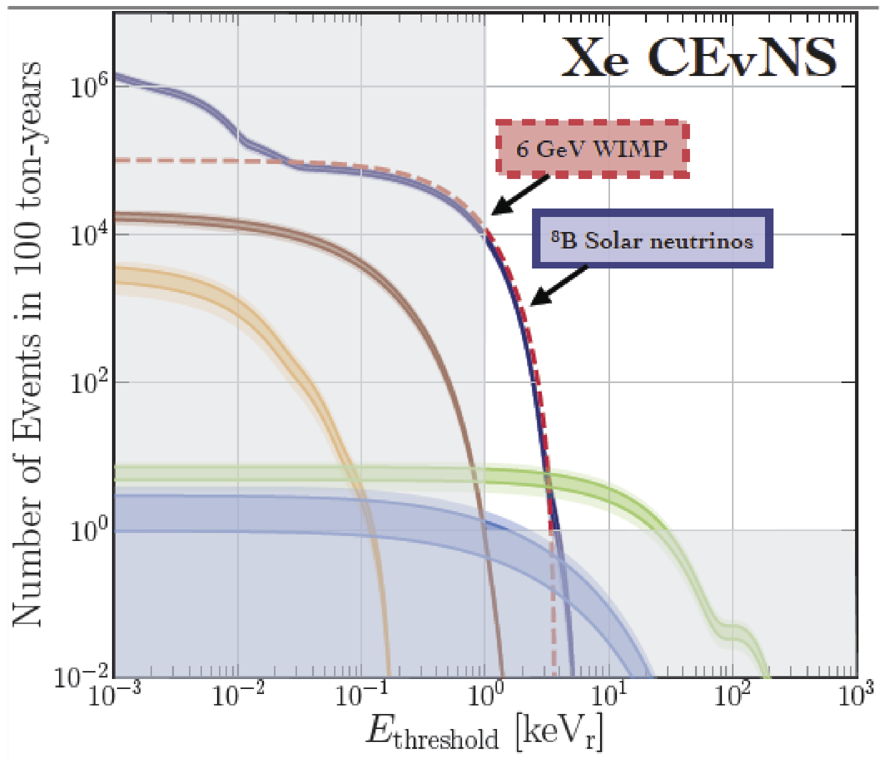


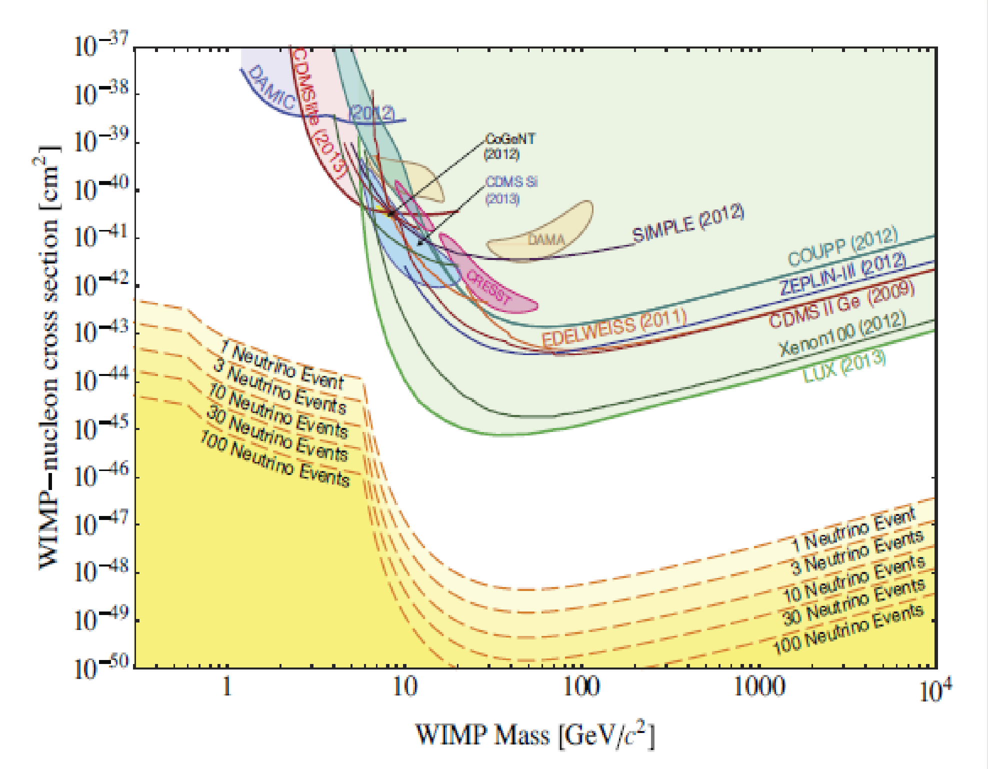




(1) Solar neutrinos dominate at low energies; while atmospheric neutrinos (DSNB) dominate at high energies.

**How to convert the neutrino event spectra to the neutrino floor?**

# Neutrino Floor-II




**First, calculate the exposure required to generate n counts of CEνNS for a given minimum energy threshold. Second, compute the spin-independent WIMP-nucleon cross section for a fixed DM mass with the master formula:**

$$\sigma_n^0 = \frac{2.3}{n} \int_{E_R} \left( \frac{1}{m_N} \int_{E_\nu^{\min}} \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_\nu}{dE_R} \right) \left( \frac{\rho_{\rm DM} A^2}{2 m_{\rm DM} \mu_n^2} \int_{E_R}^{E_R^{\max}} F^2(E_R) dE_R \int_{v_{\min}} \frac{f(\vec{v})}{v} d^3 v \right)^{-1}$$

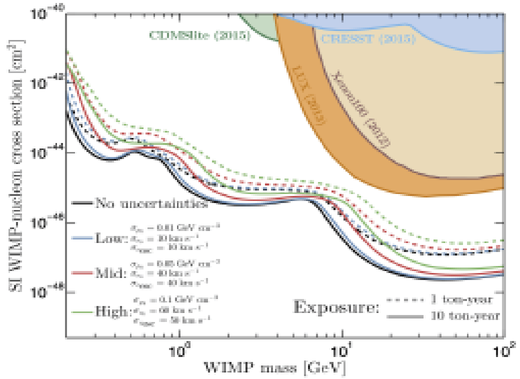
# Neutrino Floor Uncertainty

## Signal — Uncertainties — Background

### Astrophysical uncertainties

O'Hare [1604.03858]

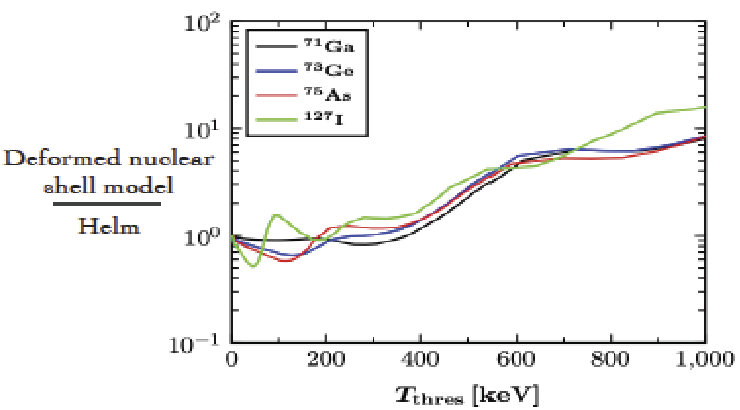
Astrophysical uncertainty in DM $f(v)$




### Nuclear physics uncertainties

Papoulias et al. [1804.11319]

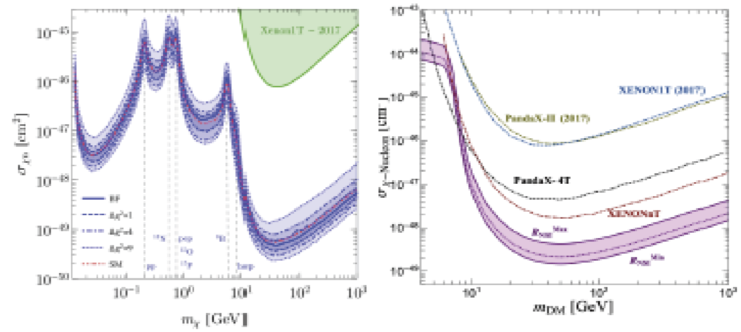
Nuclear form factors for DM / CEvNS




### Non-standard interactions

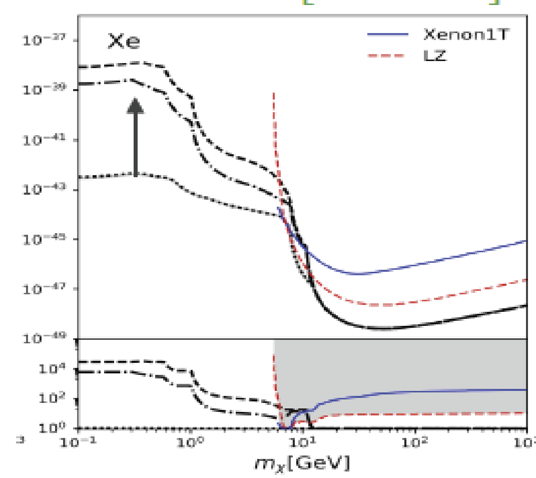
Aristizabal Sierra et al. [1712.09667]

Gonzalez-Garcia et al. [1803.03650]



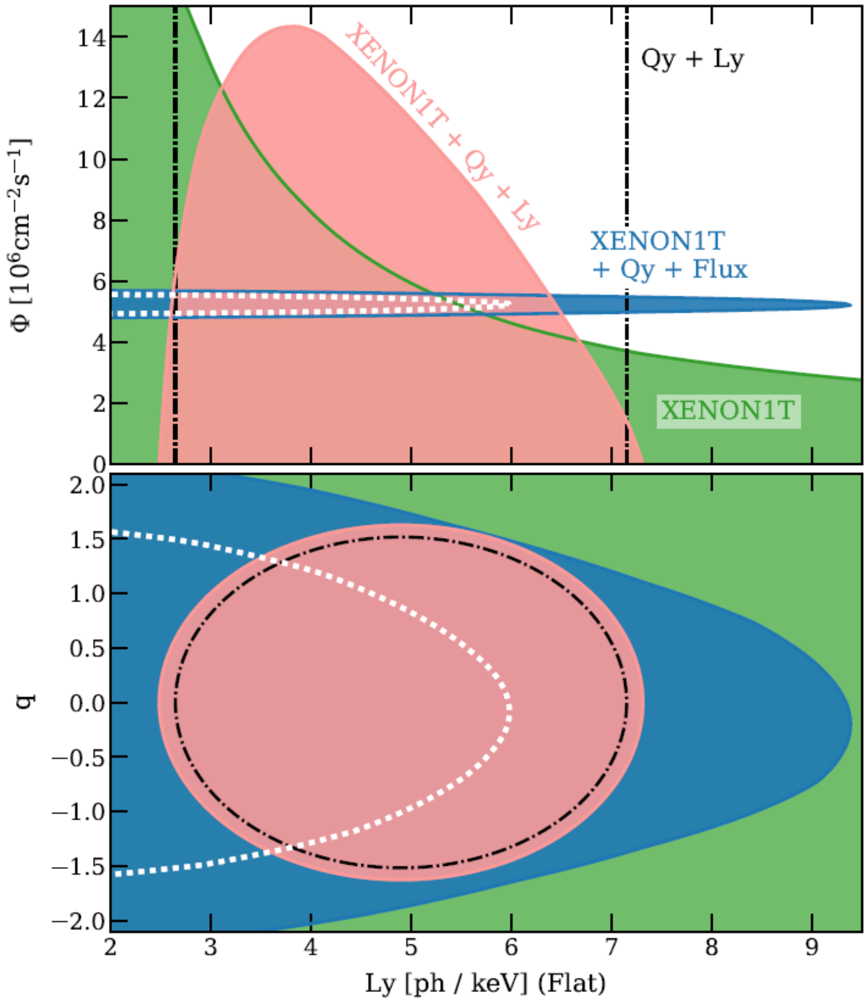

### New mediators

Boehm et al. [1809.06385]



# XENON-1T B8 neutrino search

*Phys.Rev.Lett.* 126 (2021) 091301, arXiv: 2012.02846



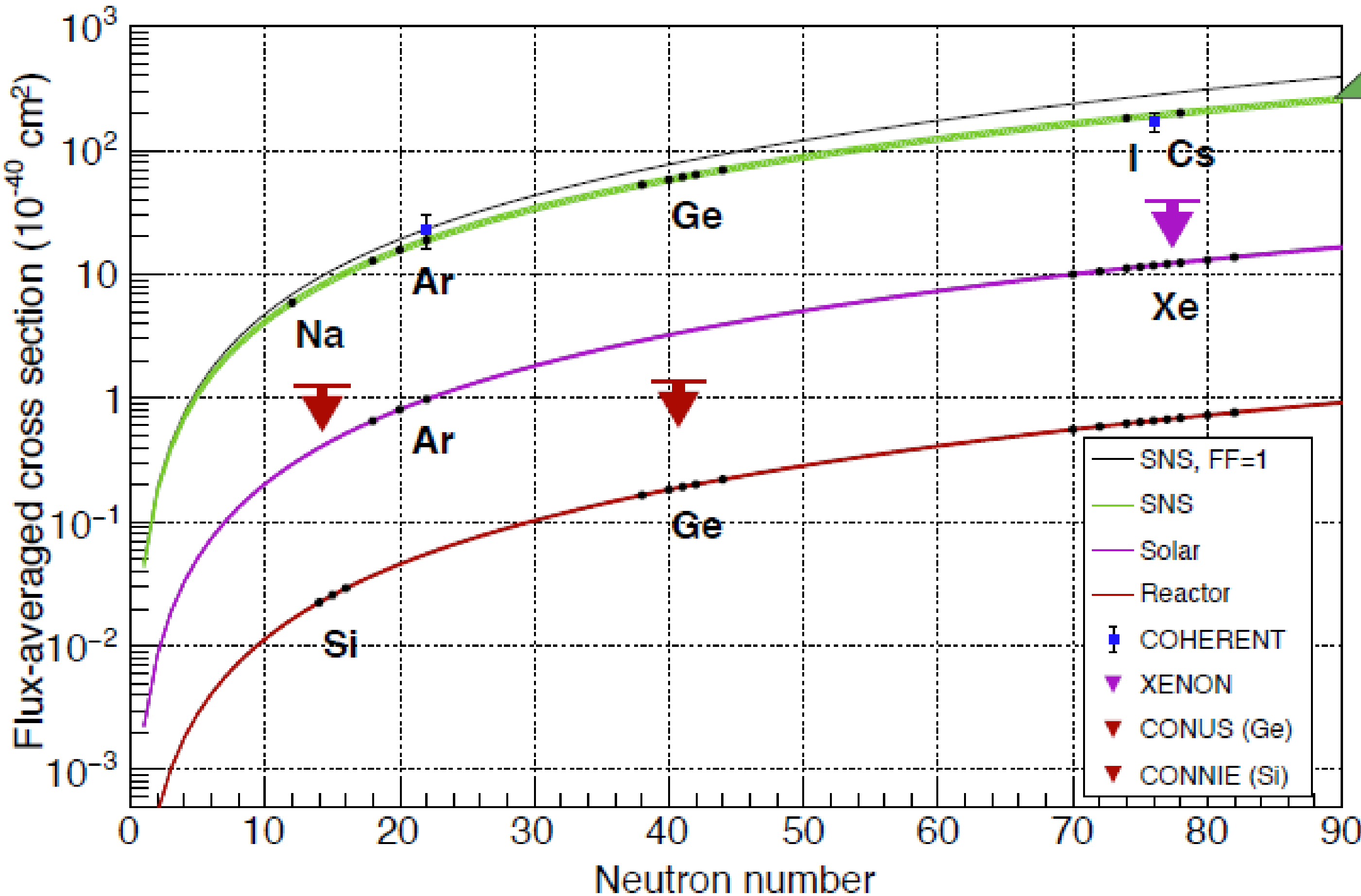

**(1) Energy threshold decreased from 2.6 keV to 1.6 keV**

**(2) Light yield & B8 flux normalization degenerated**

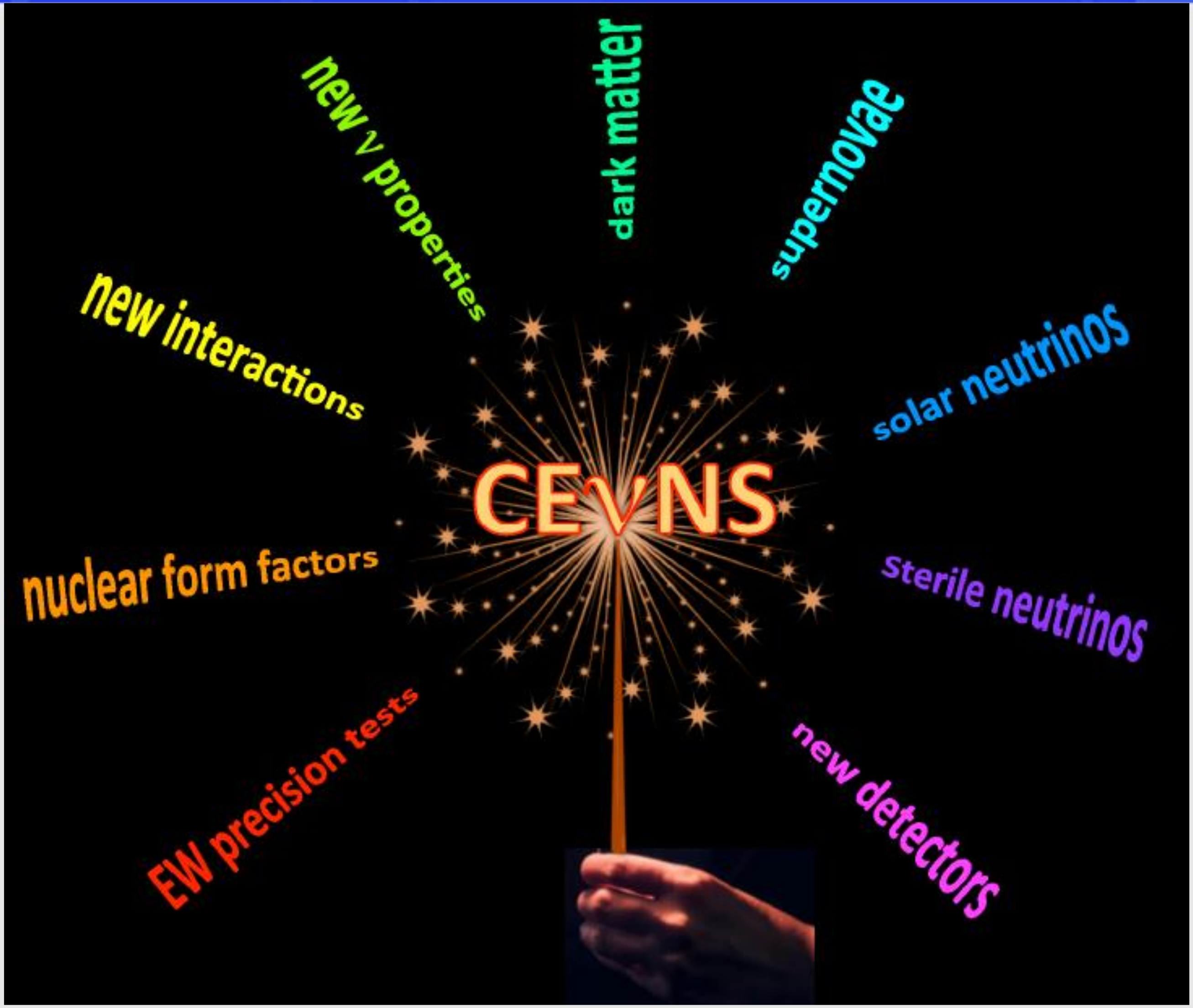
**(3) SSM flux : ~5X10$^6$**

# Summary of CEvNS searches

## Summary of CEvNS Results

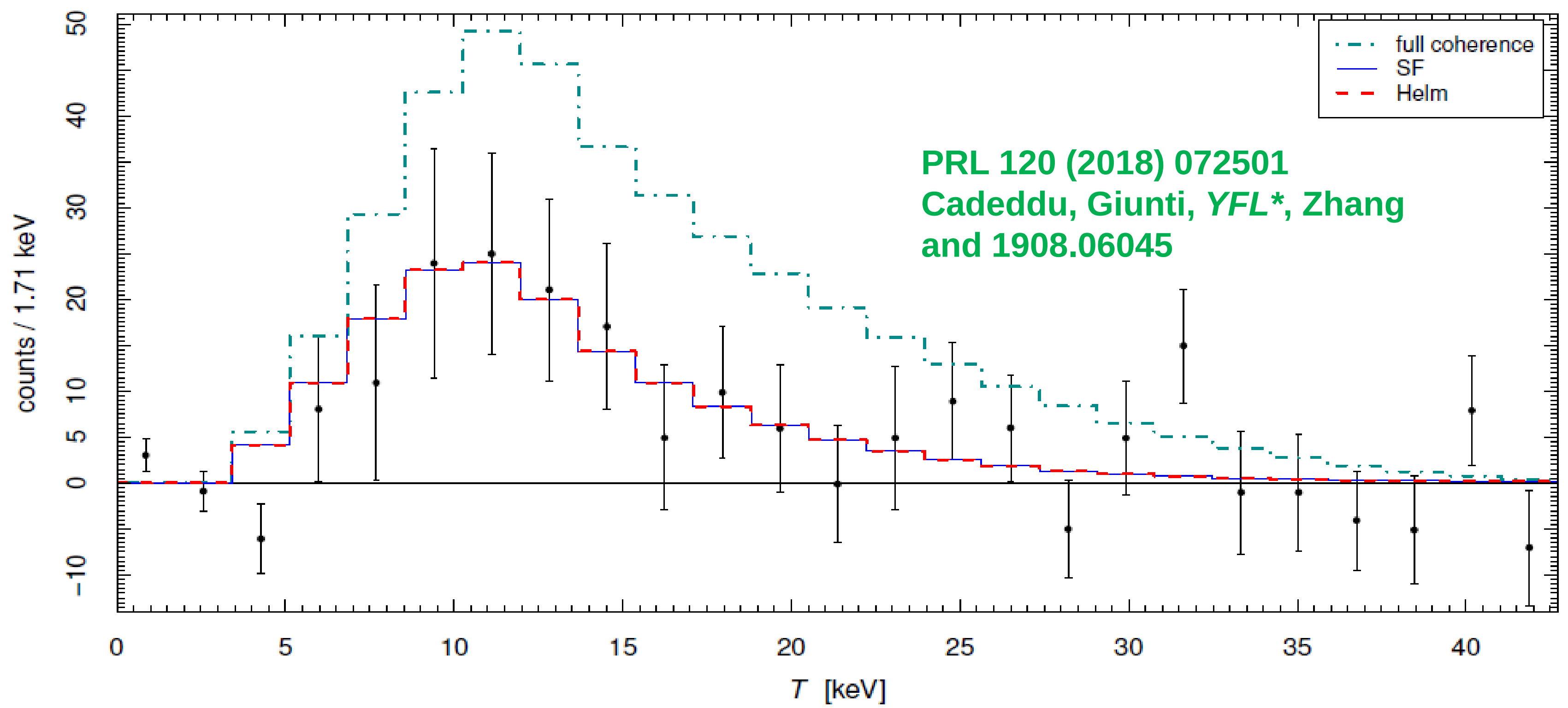



# Part F: Implications




E. Lisi@Neutrino 2018

# Test of Coherency condition




(1) **Full coherence → F(proton) = F(neutron) =1.**

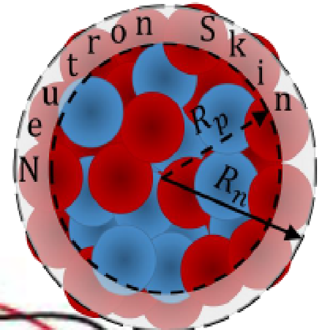
(2) **COHERENT data show 3.7 sigma evidence of the nuclear structure suppression of the full coherence**

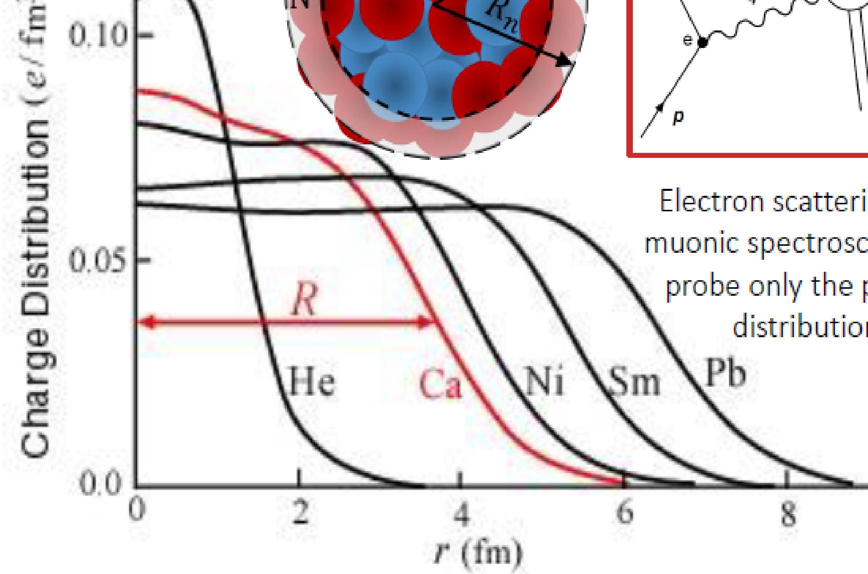
## What we (don't) know about nuclei

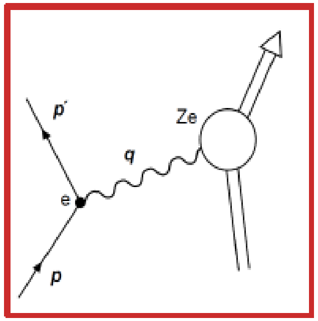
Most of the information we have on the nuclear size and nucleon's distribution inside the nuclei are mainly related to the electric charge and thus the protons.

$$R \cong 1.23\, A^{1/3}\ \text{fm}$$

This is because these information are extracted using the electron-nuclei scattering data that are sensitive only to the charge distribution.



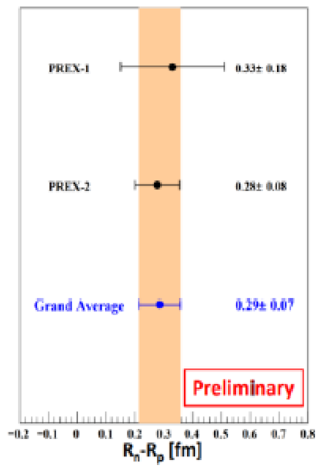

Electron scattering and muonic spectroscopy can probe only the proton distribution

### Parity violation in electron scattering

$^{208}$Pb PREX-II

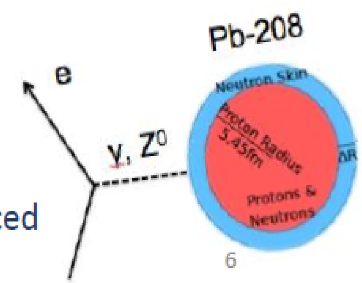
$$R_n - R_p = 0.278 \pm 0.078\ \text{fm}$$

See Reed's talk




Measuring the elastic differential cross sections for incident electrons of +/- helicity we are able to "select" the Z coupling to neutron.

$$A_{PV} = \left(\frac{d\sigma_+}{d\Omega} - \frac{d\sigma_-}{d\Omega}\right) \Big/ \left(\frac{d\sigma_+}{d\Omega} + \frac{d\sigma_-}{d\Omega}\right)$$




It is sensitive to the parity-violating term induced by the weak interaction.

From summary talk @Mag7s(2020)

# Proton Distributions of Cs & I

- The charge radii of $^{133}$Cs and $^{127}$I have been determined with muonic atom spectroscopy: [Angeli, Marinova, ADNDT 99 (2013) 69]

$$R_c(^{133}\mathrm{Cs}) = 4.8041 \pm 0.0046\,\mathrm{fm}$$

$$R_c(^{127}\mathrm{I}) = 4.7500 \pm 0.0081\,\mathrm{fm}$$

- Radius of the proton distribution: $R_p^2 = R_c^2 - \frac{N}{Z}\langle r_n^2 \rangle_c$

[Ong, Berengut, Flambaum, arXiv:1006.5508; Horowitz et al, arXiv:1202.1468]

- Squared charge radius of the neutron:

$$\langle r_n^2 \rangle_c = -0.1161 \pm 0.0022\,\mathrm{fm}^2$$ [PDG 2018]

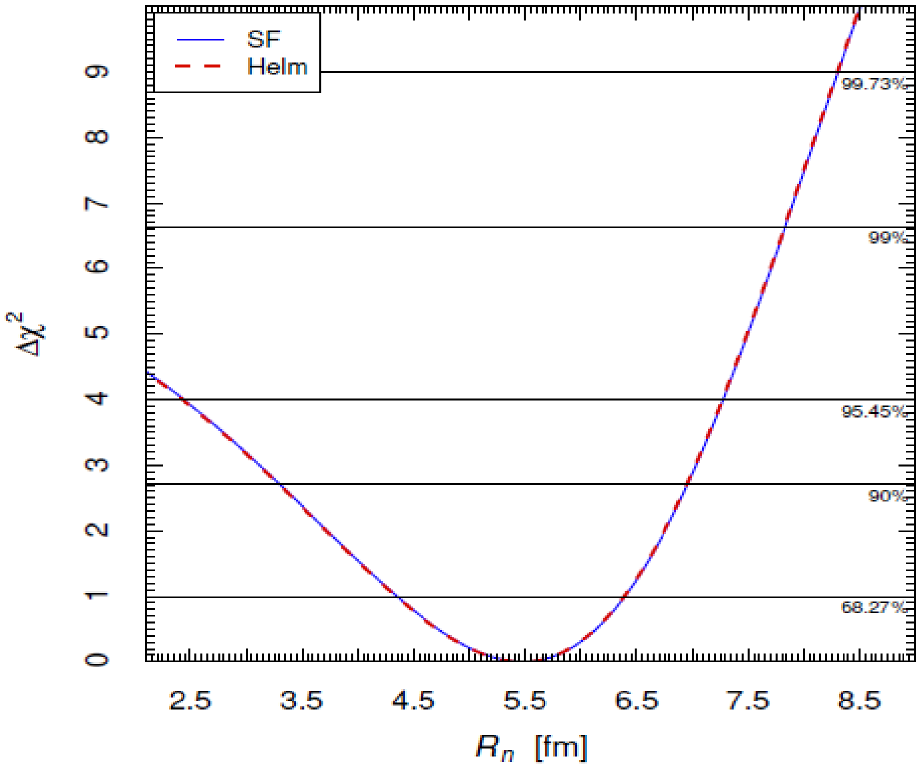
- Radii of the proton distributions of $^{133}$Cs and $^{127}$I:

$$R_p(^{133}\mathrm{Cs}) = 4.821 \pm 0.005\,\mathrm{fm}$$

$$R_p(^{127}\mathrm{I}) = 4.766 \pm 0.008\,\mathrm{fm}$$

# Neutron Distributions of Cs & I

- Fit of the 2017 COHERENT CsI data to get $R_n(^{133}\text{Cs}) \simeq R_n(^{127}\text{I})$:




First determination of $R_n$ with neutrino-nucleus scattering:

$$R_n(\text{CsI}) = 5.5^{+0.9}_{-1.1}\ \text{fm}$$

[Cadeddu, Giunti, Li, Zhang, arXiv:1710.02730]

- With new 2020 COHERENT CsI data: [Pershey @ Magnificent CE$\nu$NS 2020]

$$R_n(\text{CsI}) = 5.55 \pm 0.44\ \text{fm}$$

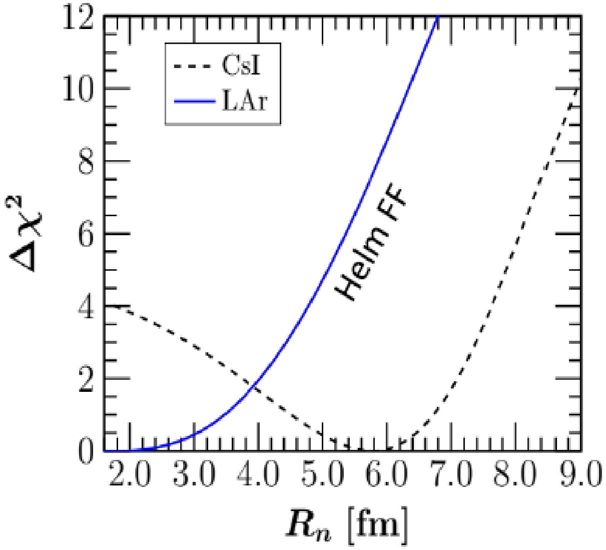
[Cadeddu et al, arXiv:2102.06153]

# What about Argon?

## First argon constraints on neutron radius

Using COHERENT CENNS-10 [arXiv:2003.10630]

[O. G. Miranda et al. arXiv:2003.12050v3]

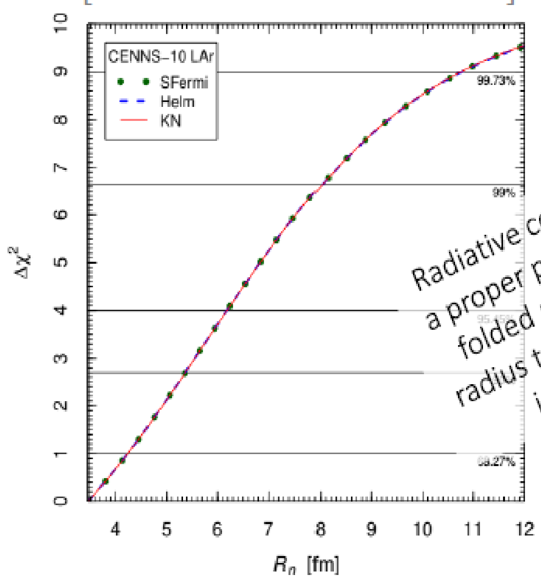



$$\chi^2(X) = \min_{\alpha}\left[\frac{(N_{\rm meas} - N_{\rm theor}(X)[1+\alpha])^2}{\sigma_{\rm stat}^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2\right]$$

$R_n < 4.33$ fm @90 % CL

Single energy bin analysis for LAr

[M. C. et al. arXiv:2005.01645v2]



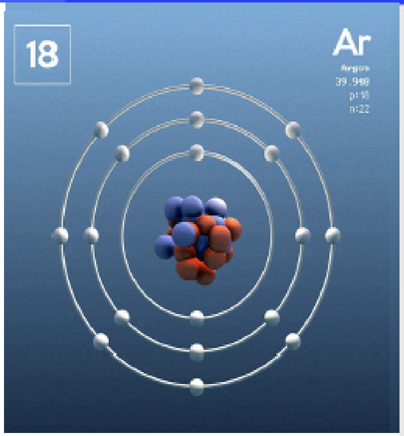

Radiative corrections and a proper point-neutron vs folded proton/neutron radius treatment included in the analysis!

$$R_p = 3.448 \pm 0.003 \text{ fm}$$

$$R_n(^{40}\text{Ar}) < 4.2\,(1\sigma),\ 6.2\,(2\sigma),\ 10.8\,(3\sigma) \text{ fm}$$

These bounds are in agreement with the nuclear model predictions, but unfortunately they are too weak to allow us a selection of the models.

**From summary talk @Mag7s(2020)**




Theoretical values for Ar in [fm] with Skyrme-Hartree-Fock (SHF) and relativistic mean field (RMF) nuclear models.

| Interaction | | $R_p^{\rm point}$ | $R_n^{\rm point}$ |
|---|---|---|---|
| Sky3D | | | |
| SkI3 | [37] | 3.33 | 3.43 |
| SkI4 | [37] | 3.31 | 3.41 |
| Sly4 | [38] | 3.38 | 3.46 |
| Sly5 | [38] | 3.37 | 3.45 |
| Sly6 | [38] | 3.36 | 3.44 |
| Sly4d | [39] | 3.35 | 3.44 |
| SV-bas | [40] | 3.33 | 3.42 |
| UNEDF0 | [41] | 3.37 | 3.47 |
| UNEDF1 | [42] | 3.33 | 3.43 |
| SkM* | [43] | 3.37 | 3.45 |
| SkP | [44] | 3.40 | 3.48 |
| DIRHB | | | |
| DD-ME2 | [45] | 3.30 | 3.39 |
| DD-PC1 | [46] | 3.30 | 3.39 |

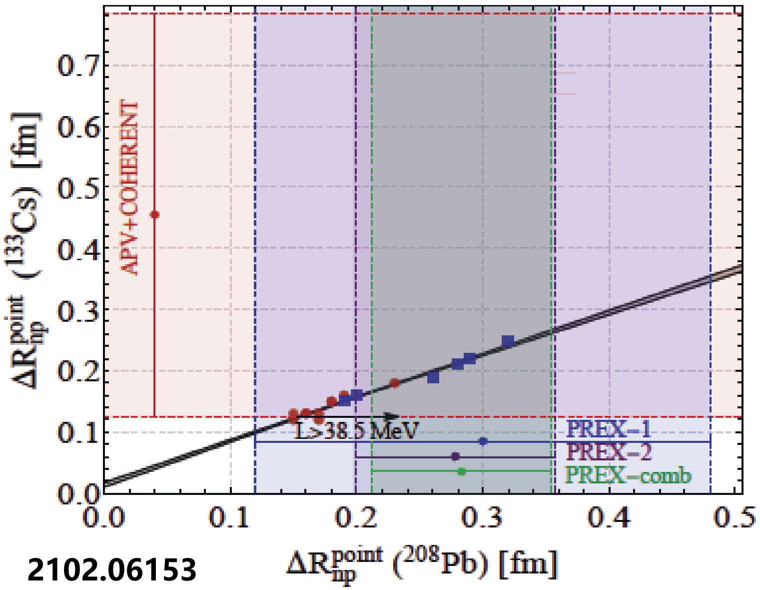
[arXiv:2005.01645v2] 10

# Neutron Distributions of Cs & I

- Neutron form factor is the Fourier transform of the neutron distribution
- **First measurement of neutron radius with neutrinos, pure weak NC measurement!**
- neutron skin → the nuclear Equation of State (EOS)→ neutron star radius

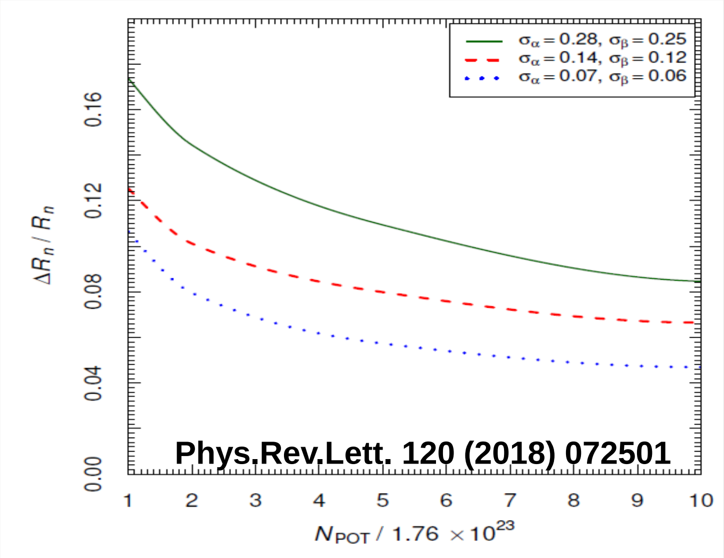
$$R_n(\mathrm{CsI}) = 5.55 \pm 0.44\,\mathrm{fm}$$

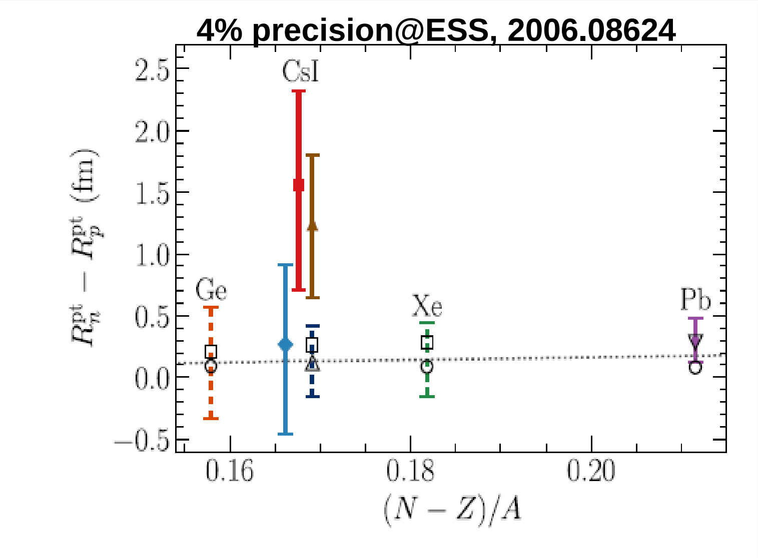
- The uncertainty is large, but it can be improved in future.
- Predictions of nuclear models: $R_n(\mathrm{CsI}) \approx 4.9 - 5.1\,\mathrm{fm}$
- A large $R_n$ has important implications for:
  - Nuclear physics: a larger pressure of neutrons
  - Astrophysics: a larger size of neutron stars

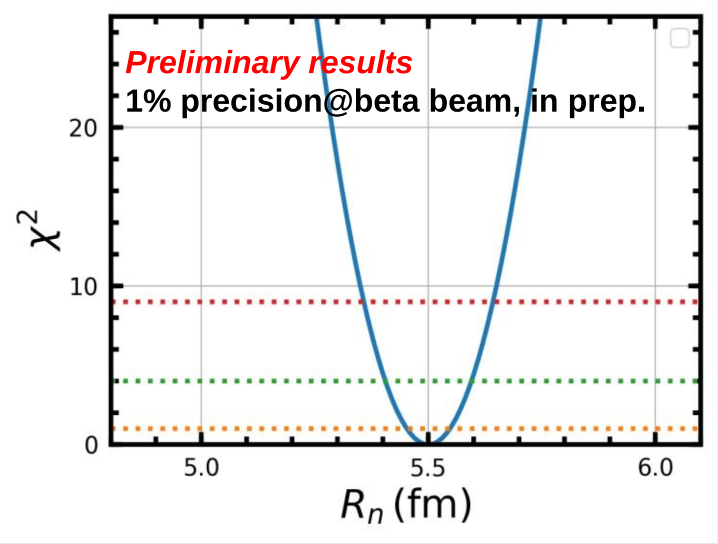



2102.06153

# Future prospects




- **DAR neutrino source: ~4% precision**
- **Still not good enough for the neutron skin**
- **Low energy beta beam:**

  **gamma=20, $^6$He**

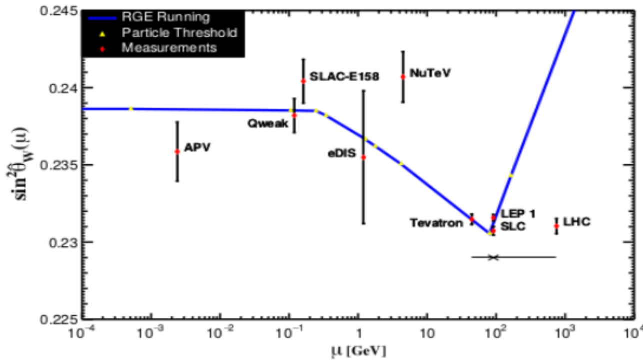
  **$10^{12}$ injected ions**

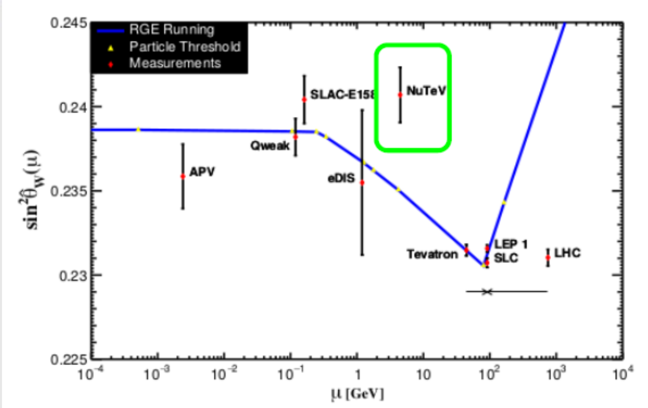
  **hundreds kg detector x 5 years**

**Towards 5-sigma measurement of the skin**

# EW precision tests: weak mixing angle

The value of $\sin^2\theta_w$ depends on the energy scale



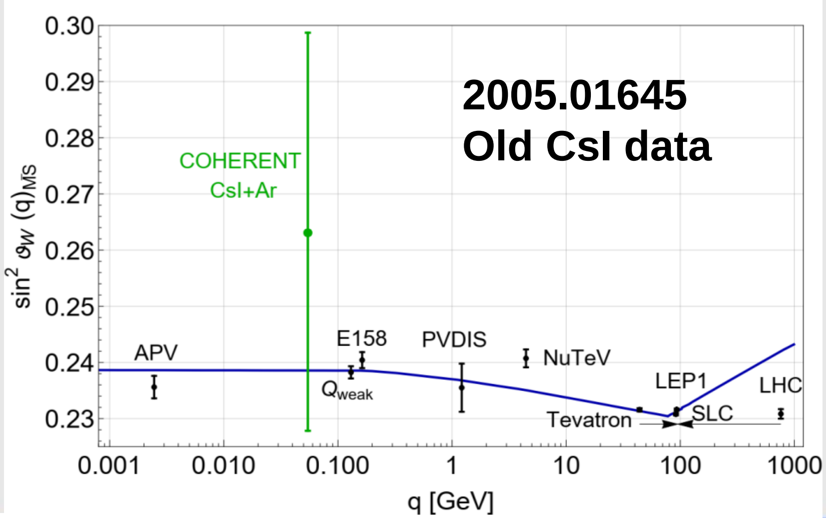

In the $\overline{MS}$ renormalization scheme

$$\sin^2\theta_w = \frac{g'^2}{g^2+g'^2}$$

- g is the $SU(2)_L$ coupling constant
- g' is the $U(1)_Y$ coupling constant

NuTeV determined $\sin^2\theta_w$ by the Paschos-Wolfenstein ratio

$$R^- = \frac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\overline{\nu} N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\overline{\nu} N}}$$

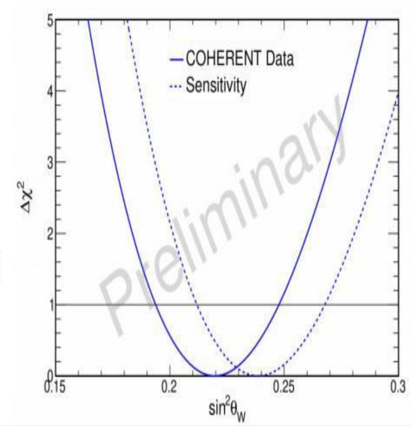



## New CsI data

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi} Q_W^2 \left(1 - \frac{MT}{E_\nu^2} + \left(1 - \frac{T}{E_\nu}\right)^2\right)$$

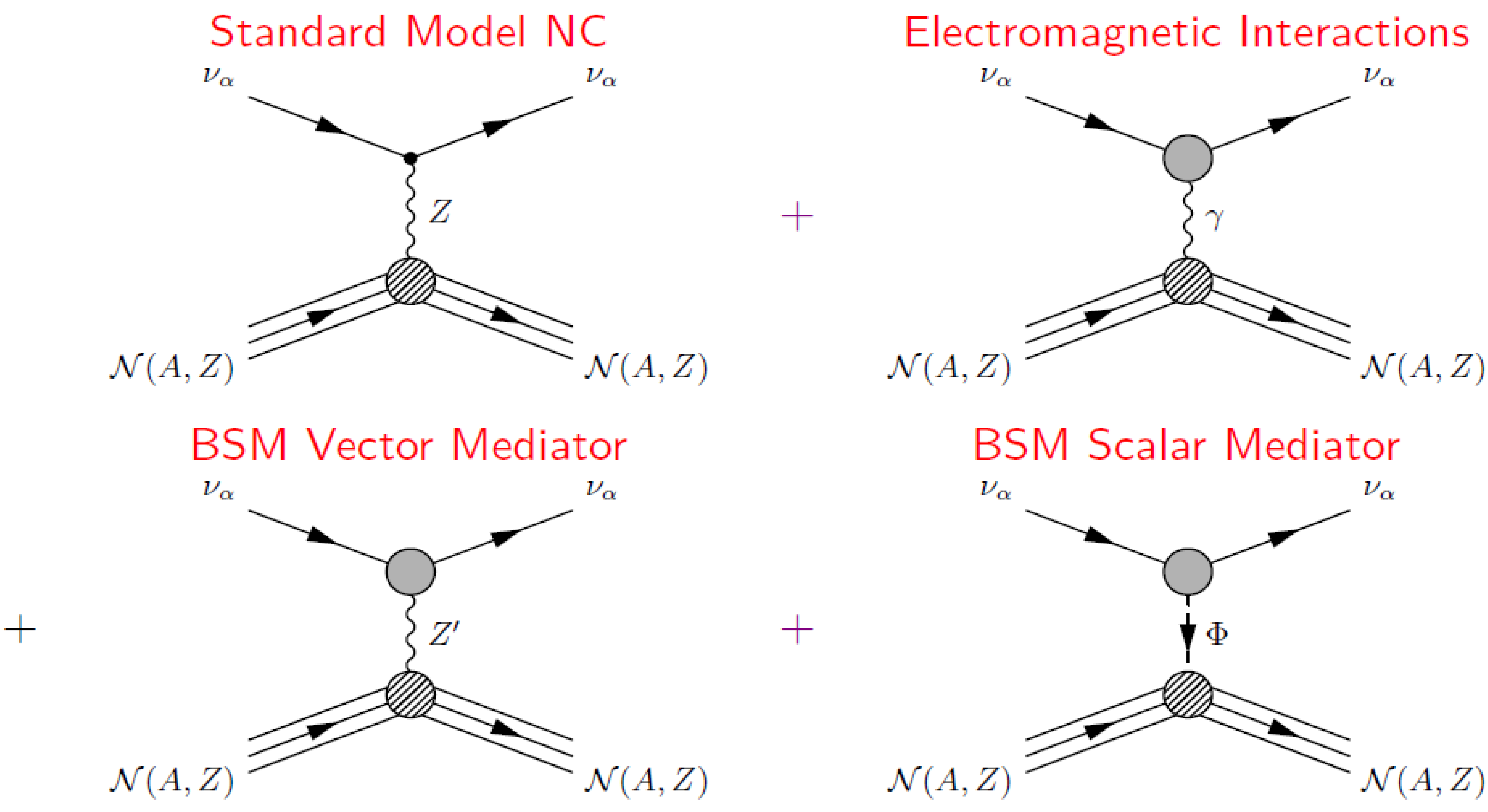
$$Q_W = (1 - 4\sin^2\theta_W) Z F_Z(Q^2) - N F_N(Q^2)$$

- The expression for the weak charge gives CEvNS sensitivity to determine $\sin^2\theta_W$ at low-$Q^2$
  - $\sin^2\theta_W = 0.220^{+0.028}_{-0.027}$




***Radiative corrections to be included***

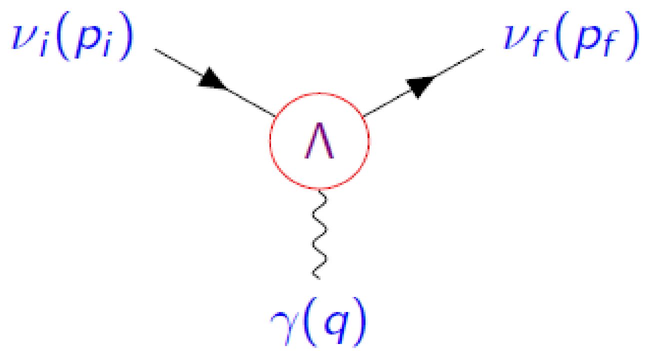
# BSM Neutrino Interactions with CEvNS



# Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:




$$\langle \nu_f(p_f) | j_{\mu}^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_{\mu}^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_{\mu}(q) = \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^{\nu} \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors: charge ($F_Q$), anapole ($F_A$), magnetic ($F_M$), electric ($F_E$)

$q^2 = 0 \quad \Longrightarrow$ $q$, $a$ (helicity-conserving); $\mu$, $\varepsilon$ (helicity-flipping)

# Electromagnetic Vertex Function

$$\Lambda_\mu(q) = (\gamma_\mu - q_\mu \not{q}/q^2)\,[F_Q(q^2) + F_A(q^2) q^2 \gamma_5] - i\sigma_{\mu\nu} q^\nu\,[F_M(q^2) + i F_E(q^2)\gamma_5]$$

Lorentz-invariant form factors: charge ($F_Q$), anapole ($F_A$), magnetic ($F_M$), electric ($F_E$)

$q^2 = 0 \Longrightarrow$ $q$, $a$, $\mu$, $\varepsilon$

- Hermitian form factors: $F_Q = F_Q^\dagger$, $F_A = F_A^\dagger$, $F_M = F_M^\dagger$, $F_E = F_E^\dagger$

- Majorana neutrinos: $F_Q = -F_Q^T$, $F_A = F_A^T$, $F_M = -F_M^T$, $F_E = -F_E^T$

no diagonal charges and electric and magnetic moments in the mass basis

- For left-handed ultrarelativistic neutrinos $\gamma_5 \to -1 \Rightarrow$ The phenomenology of the charge and anapole are similar and the phenomenology of the magnetic and electric moments are similar.

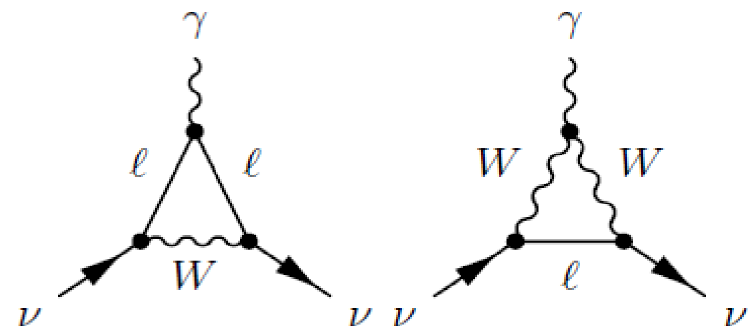
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.

# Neutrino Charge Radius

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$




- $$F(q^2) = \cancel{F(0)} + q^2 \left.\frac{dF(q^2)}{dq^2}\right|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots$$

- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\mathrm{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m_\ell^2}{m_W^2}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\mathrm{SM}} = -8.2 \times 10^{-33}\,\mathrm{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\mathrm{SM}} = -4.8 \times 10^{-33}\,\mathrm{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\mathrm{SM}} = -3.0 \times 10^{-33}\,\mathrm{cm}^2$$

# Neutrino Charge Radius

- Neutrino charge radii contributions to $\nu_\ell$–$\mathcal{N}$ CE$\nu$NS:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\Bigg\{\Bigg[\underbrace{-\frac{1}{2}}_{g_V^n} N F_N(|\vec{q}|^2)$$

$$+\Bigg(\underbrace{\frac{1}{2} - 2\sin^2\vartheta_W}_{g_V^p \simeq 0.023} - \frac{2}{3}\, m_W^2 \sin^2\vartheta_W \langle r^2_{\nu_{\ell\ell}}\rangle\Bigg) Z F_Z(|\vec{q}|^2)\Bigg]^2$$

$$+\frac{4}{9}\, m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell'\neq\ell} |\langle r^2_{\nu_{\ell'\ell}}\rangle|^2\Bigg\}$$

- In the Standard Model there are only diagonal charge radii $\langle r^2_{\nu_\ell}\rangle \equiv \langle r^2_{\nu_{\ell\ell}}\rangle$ because lepton numbers are conserved.
- Diagonal charge radii generate the coherent shifts

$$\sin^2\vartheta_W \to \sin^2\vartheta_W \left(1 + \frac{1}{3} m_W^2 \langle r^2_{\nu_\ell}\rangle\right) \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$$

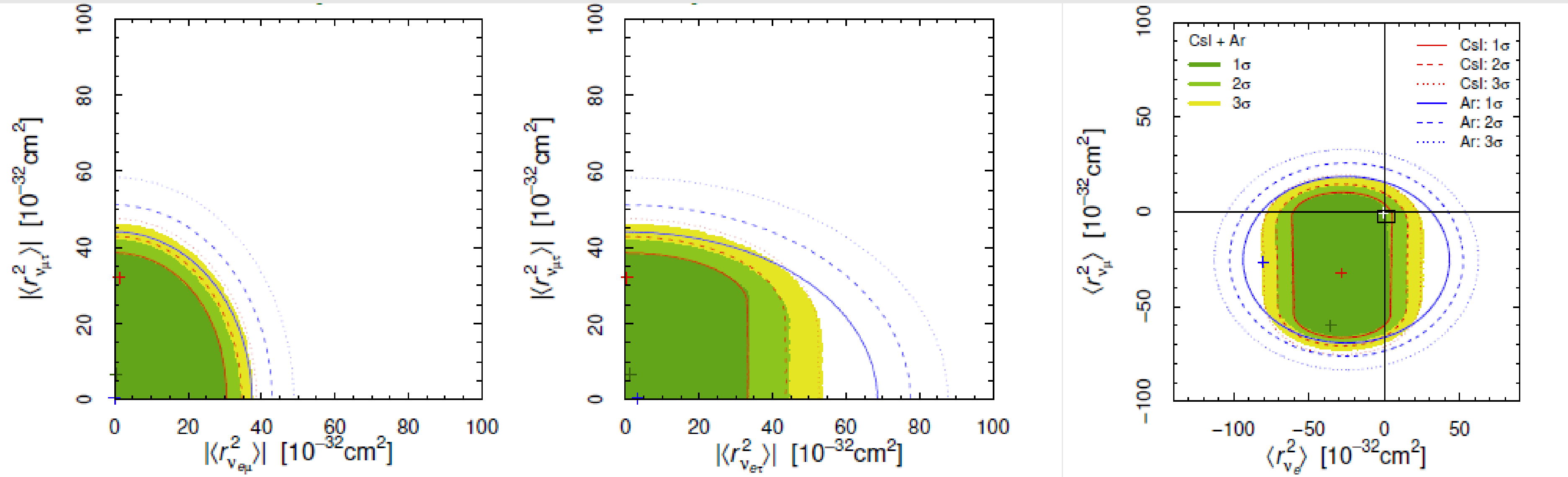
- Transition charge radii generate the incoherent contribution

$$\frac{4}{9}\, m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell'\neq\ell} |\langle r^2_{\nu_{\ell'\ell}}\rangle|^2 \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \sum_{\ell'\neq\ell} \nu_{\ell'\neq\ell} + \mathcal{N}$$

[Kouzakov, Studenikin, PRD 95 (2017) 055013, arXiv:1703.00401]

# COHERENT constraints on neutrino charge radii

| Method | Experiment | Limit [cm$^2$] | CL | Year |
|---|---|---|---|---|
| Reactor $\bar{\nu}_e\, e^-$ | Krasnoyarsk | $\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$ | 90% | 1992 |
| | TEXONO | $-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$ | 90% | 2009 |
| Accelerator $\nu_e\, e^-$ | LAMPF | $-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$ | 90% | 1992 |
| | LSND | $-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$ | 90% | 2001 |
| Accelerator $\nu_\mu\, e^-$ | BNL-E734 | $-5.7 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 1.1 \times 10^{-32}$ | 90% | 1990 |
| | CHARM-II | $\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$ | 90% | 1994 |



# Neutrino Magnetic and Electric Moments

- Extended Standard Model with right-handed neutrinos and $\Delta L = 0$:

$$\mu_{kk}^{\mathrm{D}} \simeq 3.2 \times 10^{-19} \mu_{\mathrm{B}} \left( \frac{m_k}{\mathrm{eV}} \right) \qquad \varepsilon_{kk}^{\mathrm{D}} = 0$$

$$\left. \begin{array}{c} \mu_{kj}^{\mathrm{D}} \\ i\varepsilon_{kj}^{\mathrm{D}} \end{array} \right\} \simeq -3.9 \times 10^{-23} \mu_{\mathrm{B}} \left( \frac{m_k \pm m_j}{\mathrm{eV}} \right) \sum_{\ell=e,\mu,\tau} U_{\ell k}^{*} U_{\ell j} \left( \frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

- Extended Standard Model with Majorana neutrinos ($|\Delta L| = 2$):

$$\mu_{kj}^{\mathrm{M}} \simeq -7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k + m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Im} \left[ U_{\ell k}^{*} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

$$\varepsilon_{kj}^{\mathrm{M}} \simeq 7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k - m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Re} \left[ U_{\ell k}^{*} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

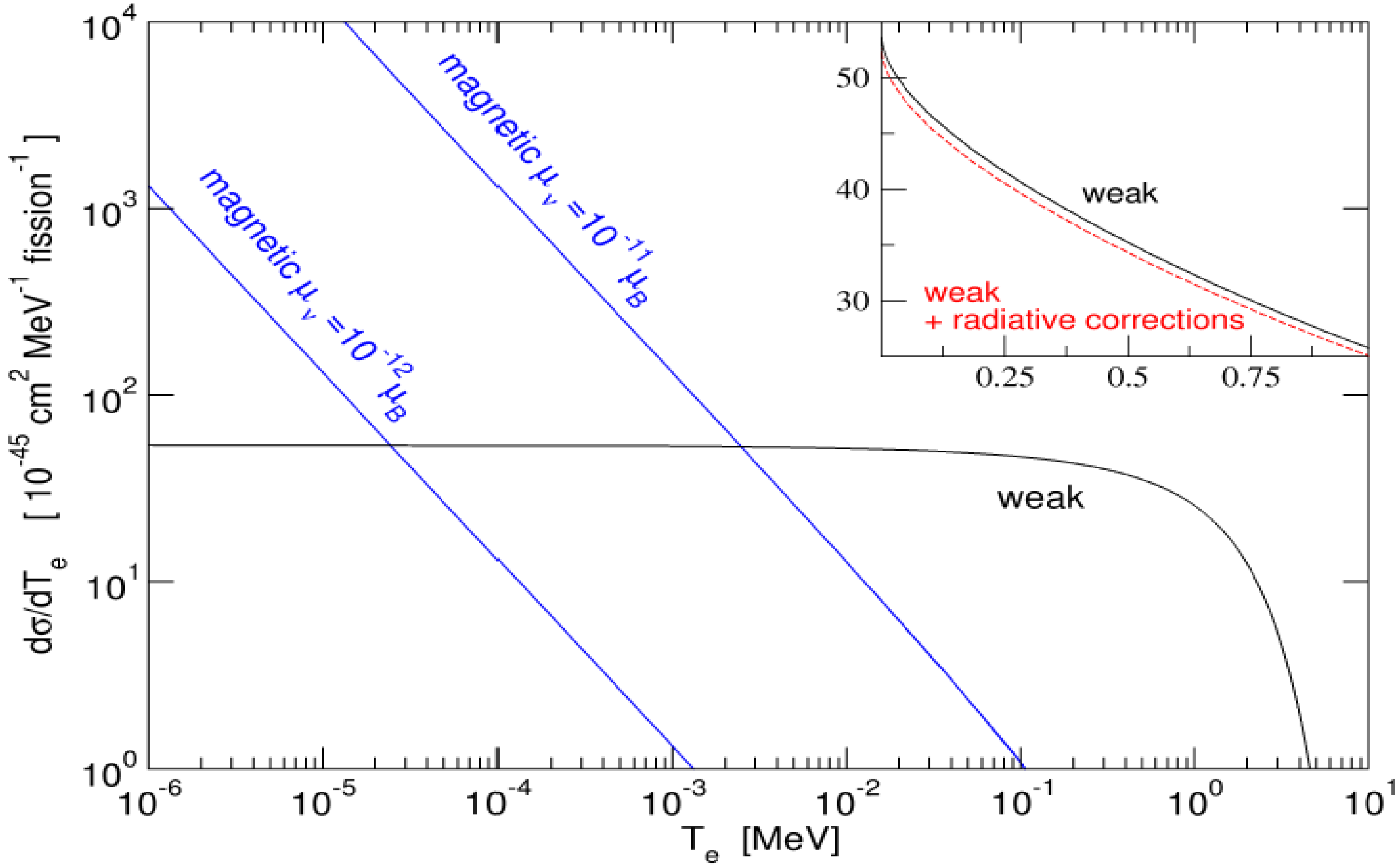
[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

# Neutrino Electron Scattering

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\text{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_\text{B}}\right)^2$$



# Experimental Bounds

| Method | Experiment | Limit [$\mu_B$] | CL | Year |
|---|---|---|---|---|
| Reactor $\bar{\nu}_e\, e^-$ | Krasnoyarsk | $\mu_{\nu_e} < 2.4 \times 10^{-10}$ | 90% | 1992 |
| | Rovno | $\mu_{\nu_e} < 1.9 \times 10^{-10}$ | 95% | 1993 |
| | MUNU | $\mu_{\nu_e} < 9 \times 10^{-11}$ | 90% | 2005 |
| | TEXONO | $\mu_{\nu_e} < 7.4 \times 10^{-11}$ | 90% | 2006 |
| | GEMMA | $\mu_{\nu_e} < 2.9 \times 10^{-11}$ | 90% | 2012 |
| Accelerator $\nu_e\, e^-$ | LAMPF | $\mu_{\nu_e} < 1.1 \times 10^{-9}$ | 90% | 1992 |
| Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$ | BNL-E734 | $\mu_{\nu_\mu} < 8.5 \times 10^{-10}$ | 90% | 1990 |
| | LAMPF | $\mu_{\nu_\mu} < 7.4 \times 10^{-10}$ | 90% | 1992 |
| | LSND | $\mu_{\nu_\mu} < 6.8 \times 10^{-10}$ | 90% | 2001 |
| Accelerator $(\nu_\tau, \bar{\nu}_\tau)\, e^-$ | DONUT | $\mu_{\nu_\tau} < 3.9 \times 10^{-7}$ | 90% | 2001 |
| Solar $\nu_e\, e^-$ | Super-Kamiokande | $\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}$ | 90% | 2004 |
| | Borexino | $\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 2.8 \times 10^{-11}$ | 90% | 2017 |

[see the review Giunti, Studenikin, arXiv:1403.6344]

- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_B$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_B$ discovery $\Rightarrow$ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

# CEvNS

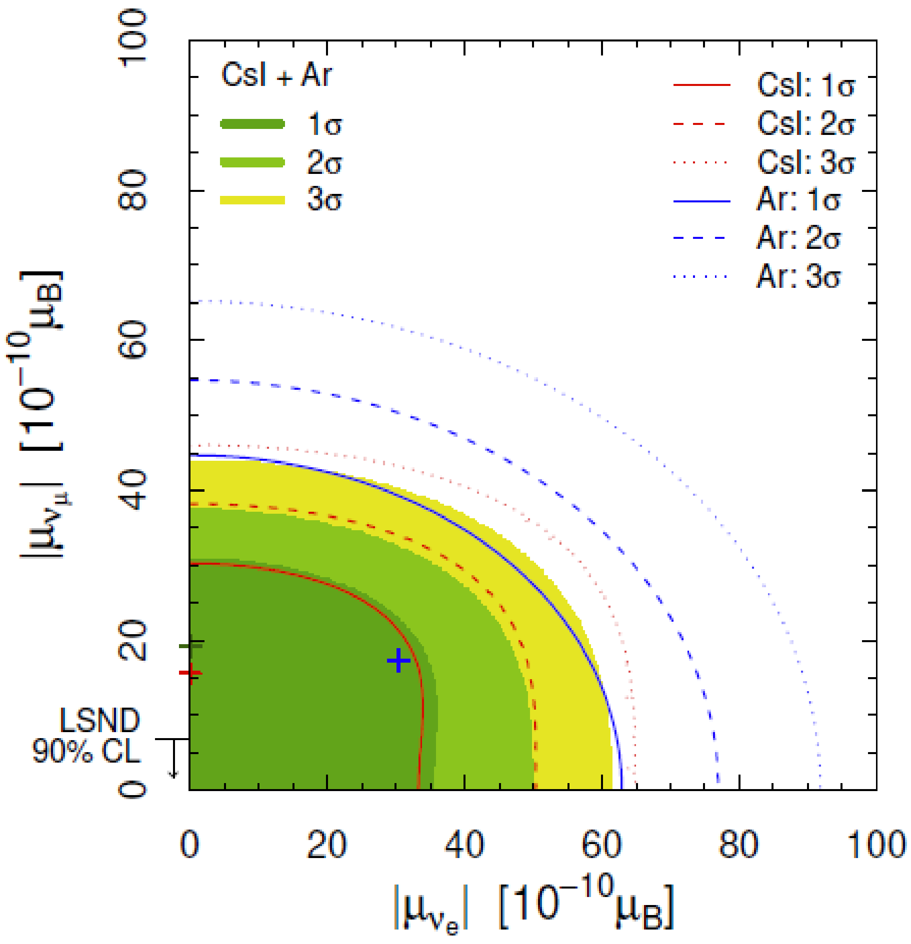
- Neutrino magnetic (and electric) moment contributions to CE$\nu$NS
$\nu_\ell + \mathcal{N} \to \sum_{\ell'} \nu_{\ell'} + \mathcal{N}$:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(|\vec{q}|^2) + g_V^p Z F_Z(|\vec{q}|^2)\right]^2 + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} \frac{|\mu_{\ell\ell'}|^2}{\mu_B^2}$$

- The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity.

- The $m_e$ is due to the definition of the Bohr magneton: $\mu_B = e/2m_e$.

# COHERENT constraints on ν magnetic moments




- The sensitivity to $|\mu_{\nu_e}|$ is not competitive with that of reactor experiments:

$$|\mu_{\nu_e}| < 2.9 \times 10^{-11}\,\mu_B \quad (90\%\ \mathrm{CL})$$

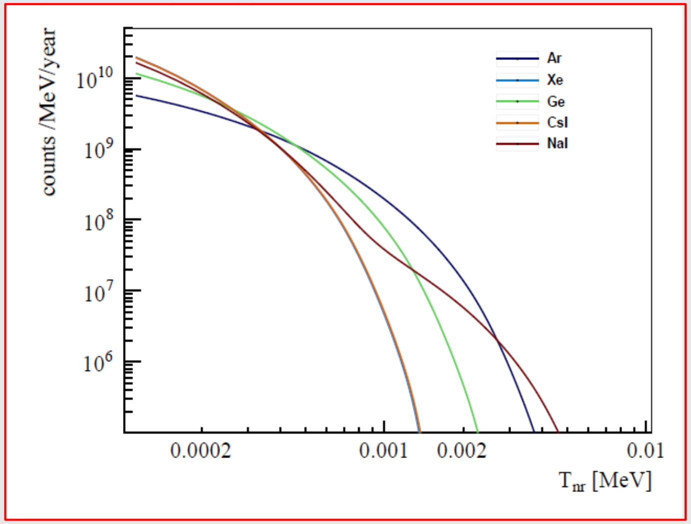
[GEMMA, AHEP 2012 (2012) 350150]

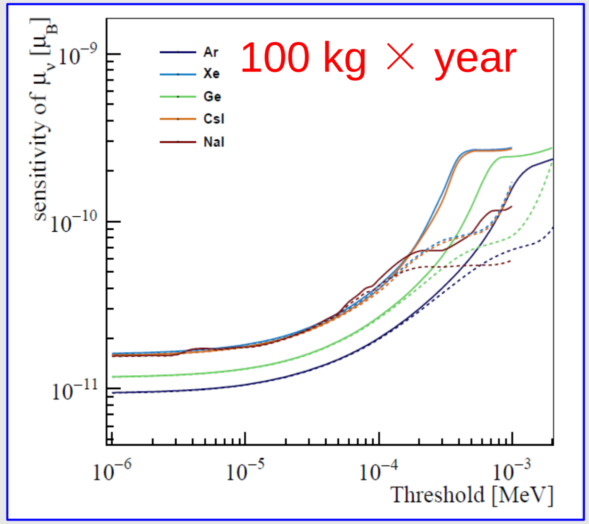
- The constraint on $|\mu_{\nu_\mu}|$ is not too far from the best current laboratory limit:

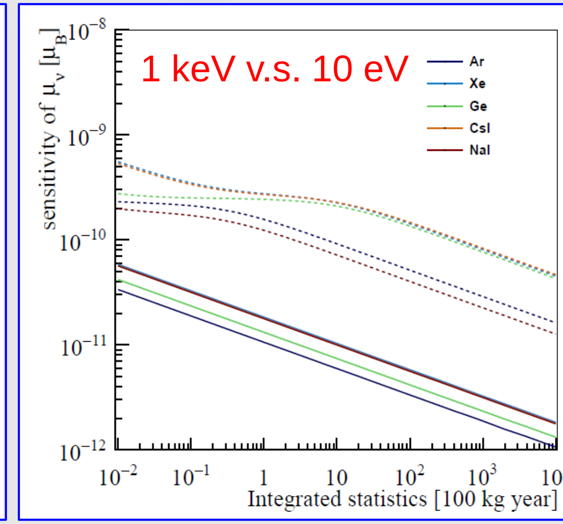
$$|\mu_{\nu_\mu}| < 6.8 \times 10^{-10}\,\mu_B \quad (90\%\ \mathrm{CL})$$

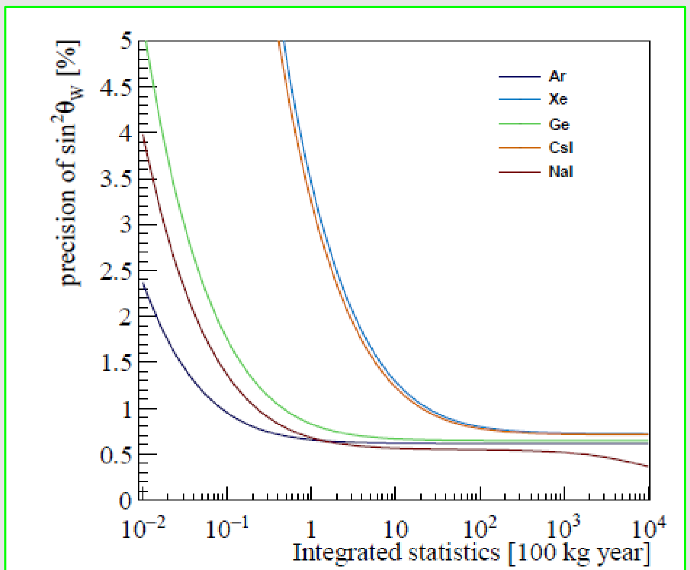
[LSND, PRD 63 (2001) 112001]

# Physics reaches@Reactors



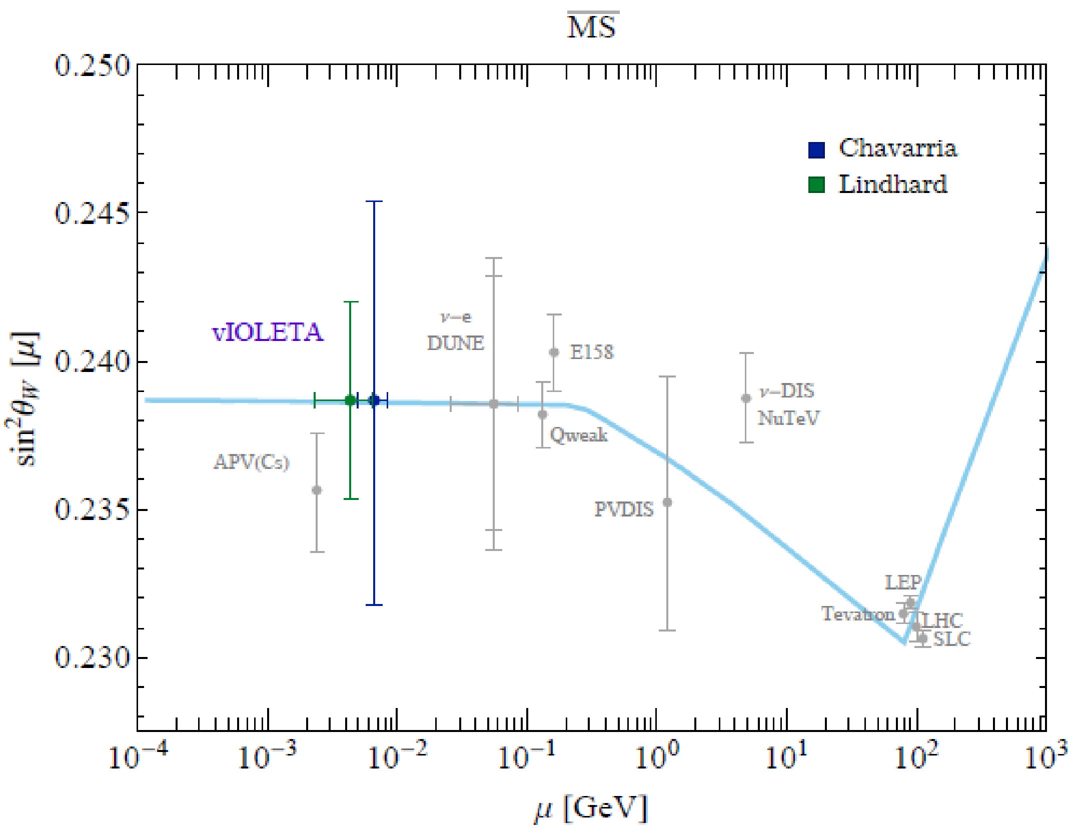




## Particle physics probe@low energies (from PhD thesis of Y.Y. Zhang)

- **Weak mixing angle: at the level of 1%**
- **Magnetic moments: $10^{-10}$~$10^{-12}$ : Threshold**
- **Probe for other new ν interactions**

# Physics reaches@Reactors




$\delta \sin^2\theta_w \sim 1.4\%$ Linhard ($\langle Q^2 \rangle \sim 4.3$ MeV)
$\delta \sin^2\theta_w \sim 2.8\%$ Chavarria ($\langle Q^2 \rangle \sim 6.6$ MeV)

Ivan Martinez Soler (Fermilab and Northwestern U.)

**DUNE** can also measure $\sin^2\theta_w$ Phys.Rev.Lett. 125 (2020) 5, 051803

**Detector: Skipper CCD**

**Detector configuration:**

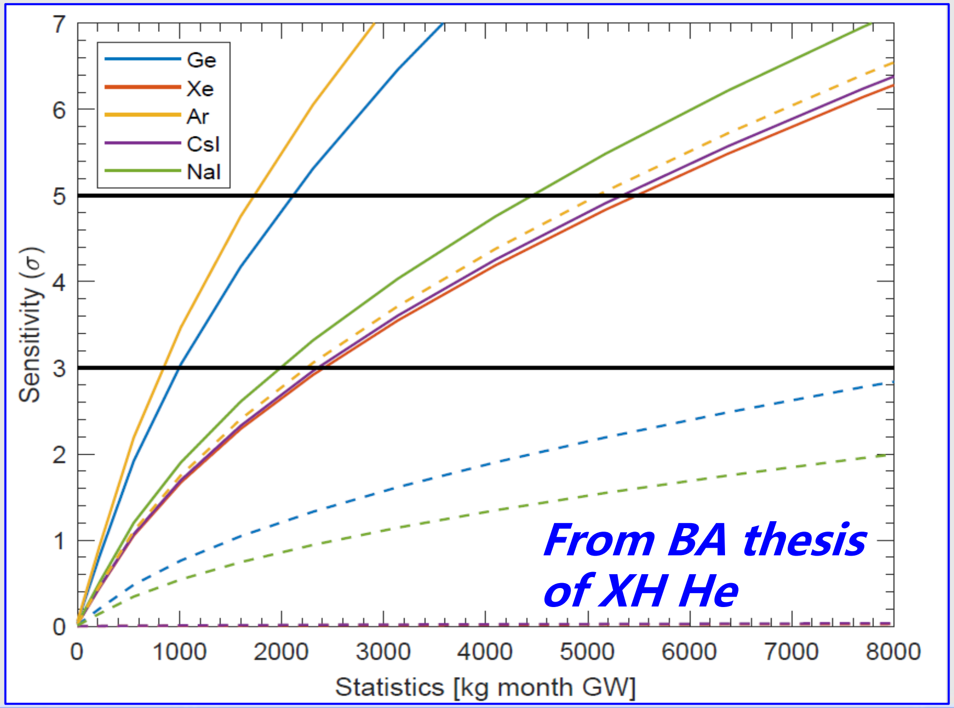
- Distance: 12 m
- Mass: 1 kg
- Reactor Power: 2 GW
- Time: 3 years
- Reactor-off: 45/days per year
- $\sigma_Q = 0\%$

**Keys: energy threshold, quenching**

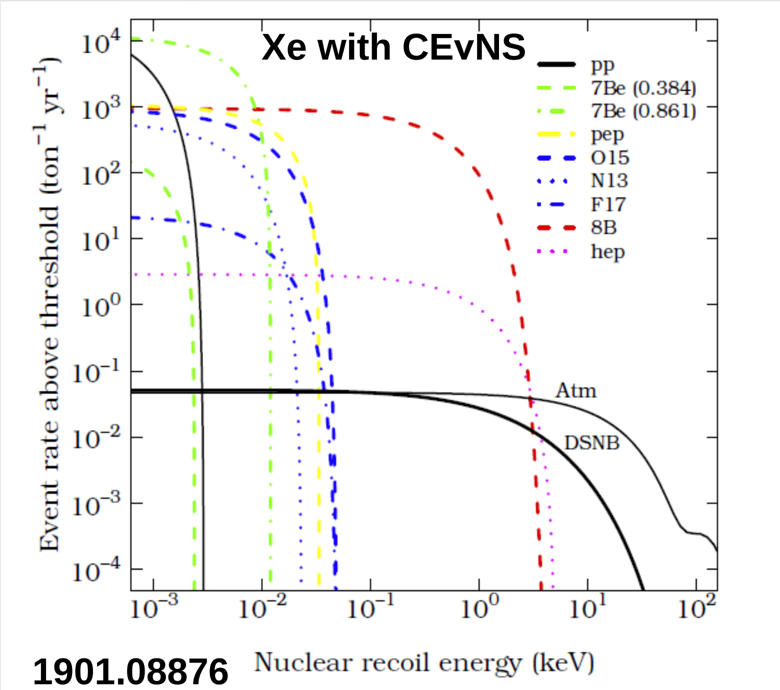
# Reactor monitoring with CEvNS

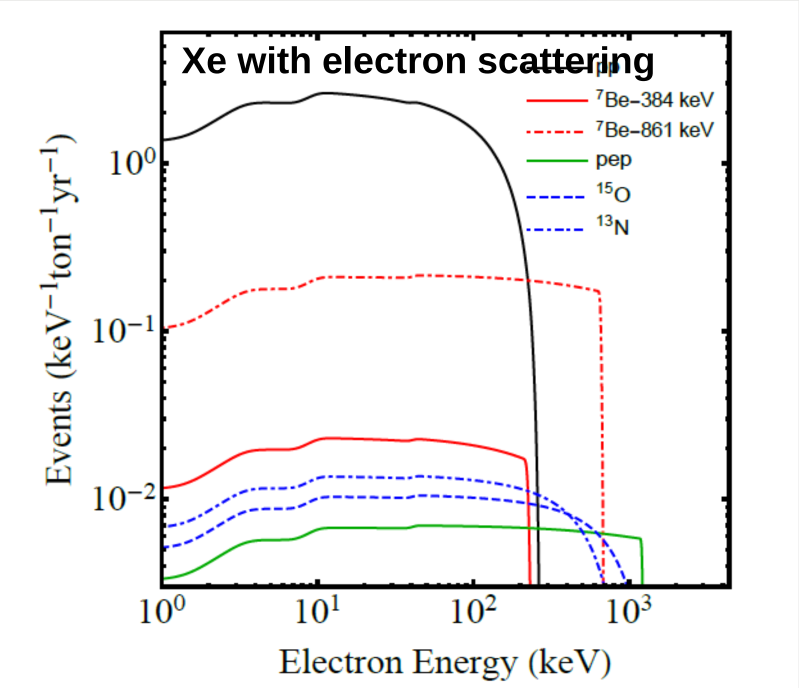
## Monitoring Pu239 production@reactors: (2% fission fraction/month)

- **With 200 kg x 4GW@30 m**
- **Best performance with (light) Argon detector**
- **@1 keV: 2.5 month for 3-sigma, 6 month for 5-sigma**
- **@500 eV: 1 month for 3-sigma, 2 month for 5-sigma**



# Solar neutrinos




- **1 keV threshold NR (ER) will enable a collection around 500-1000 (several) events per ton*year**

- **A better than SNO neutral current measurement (1%) is achievable**

- **Test standard solar model**

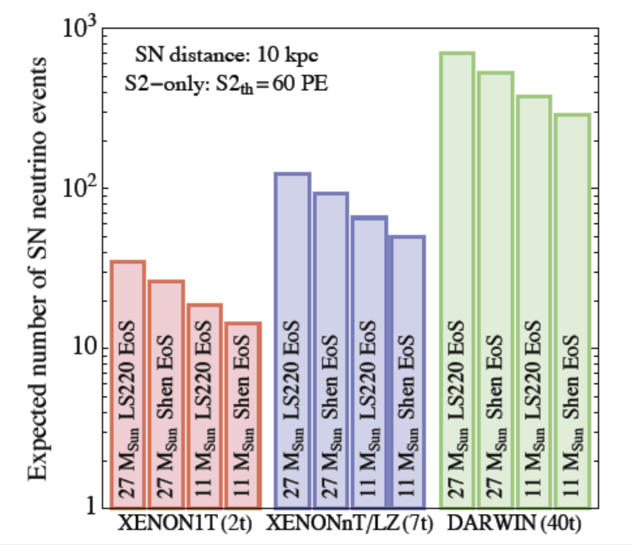
- **400 pp events per ton*year → ~1% flux accuracy to test luminosity and th(12)**

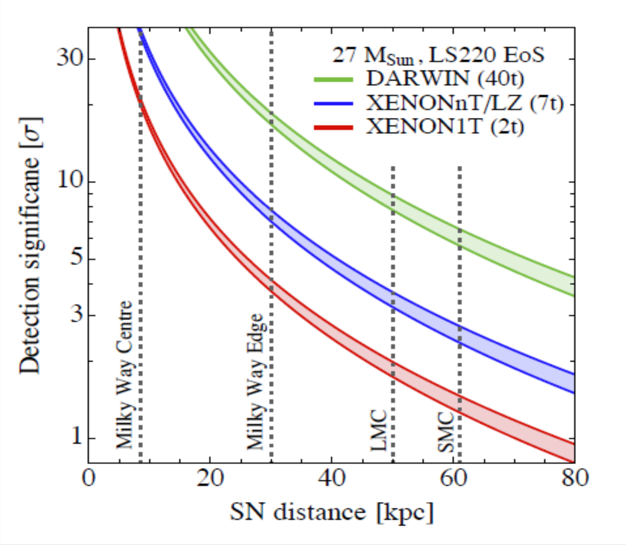
# Supernova neutrinos

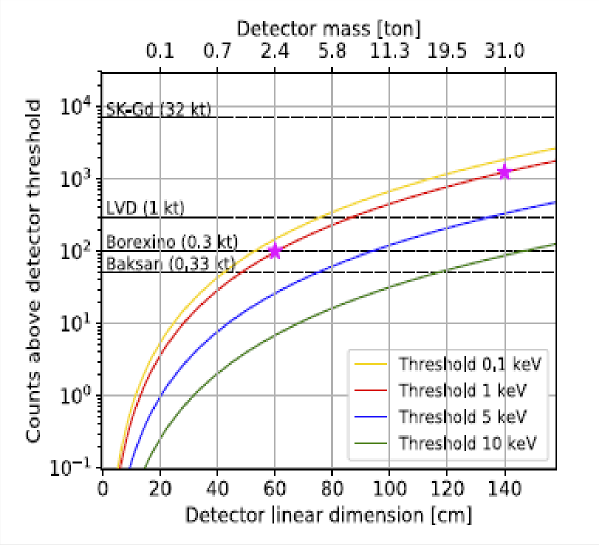
**Three ways of supernova neutrino observation using NC interactions**

- **At JUNO: neutrino-proton scattering (~2000 evts @10 kpc)**

- **At Dark Matter experiments: *1606.09243***



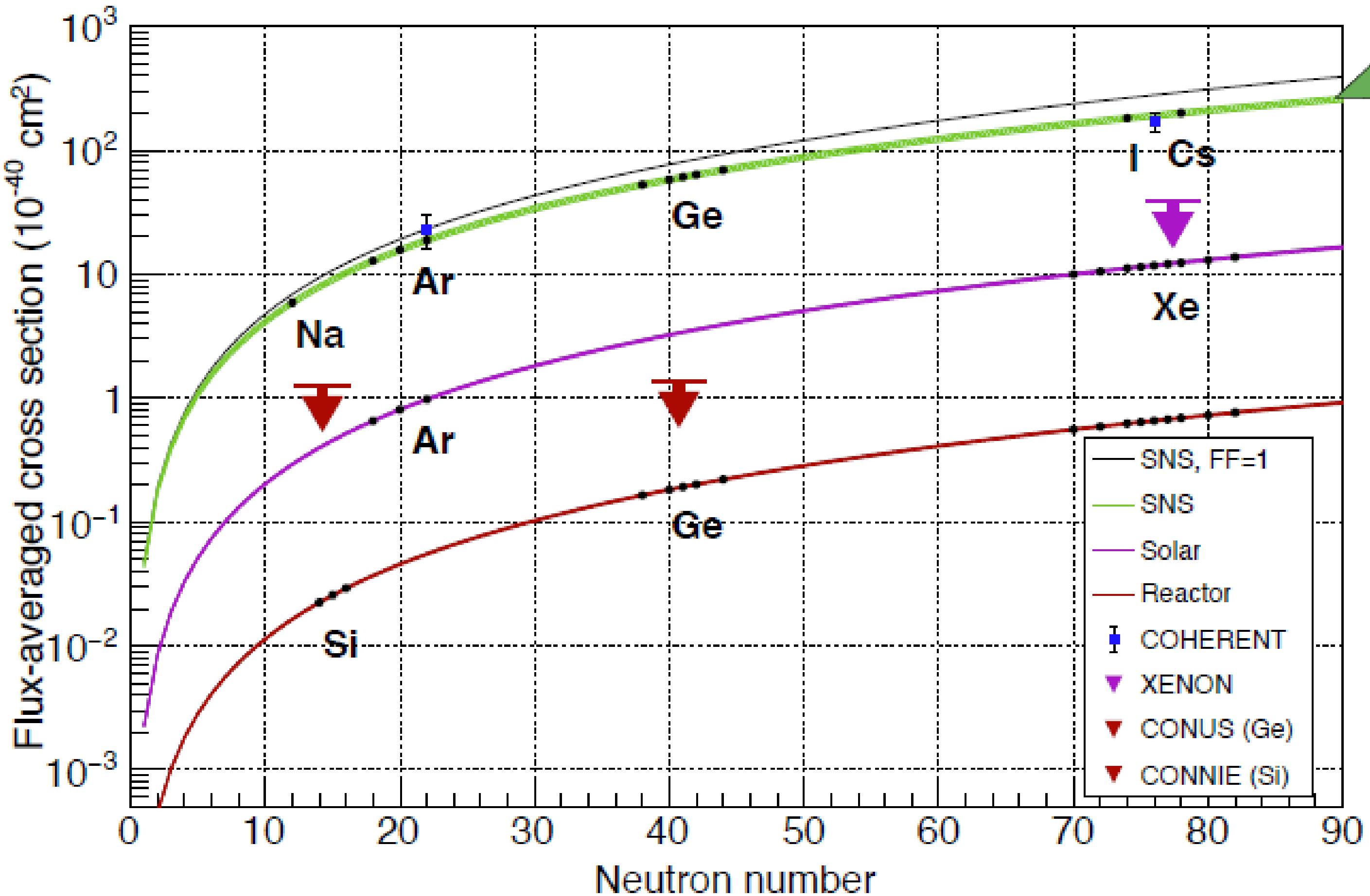




- **Neutrino observatory based on archaeological lead: *2004.06936***

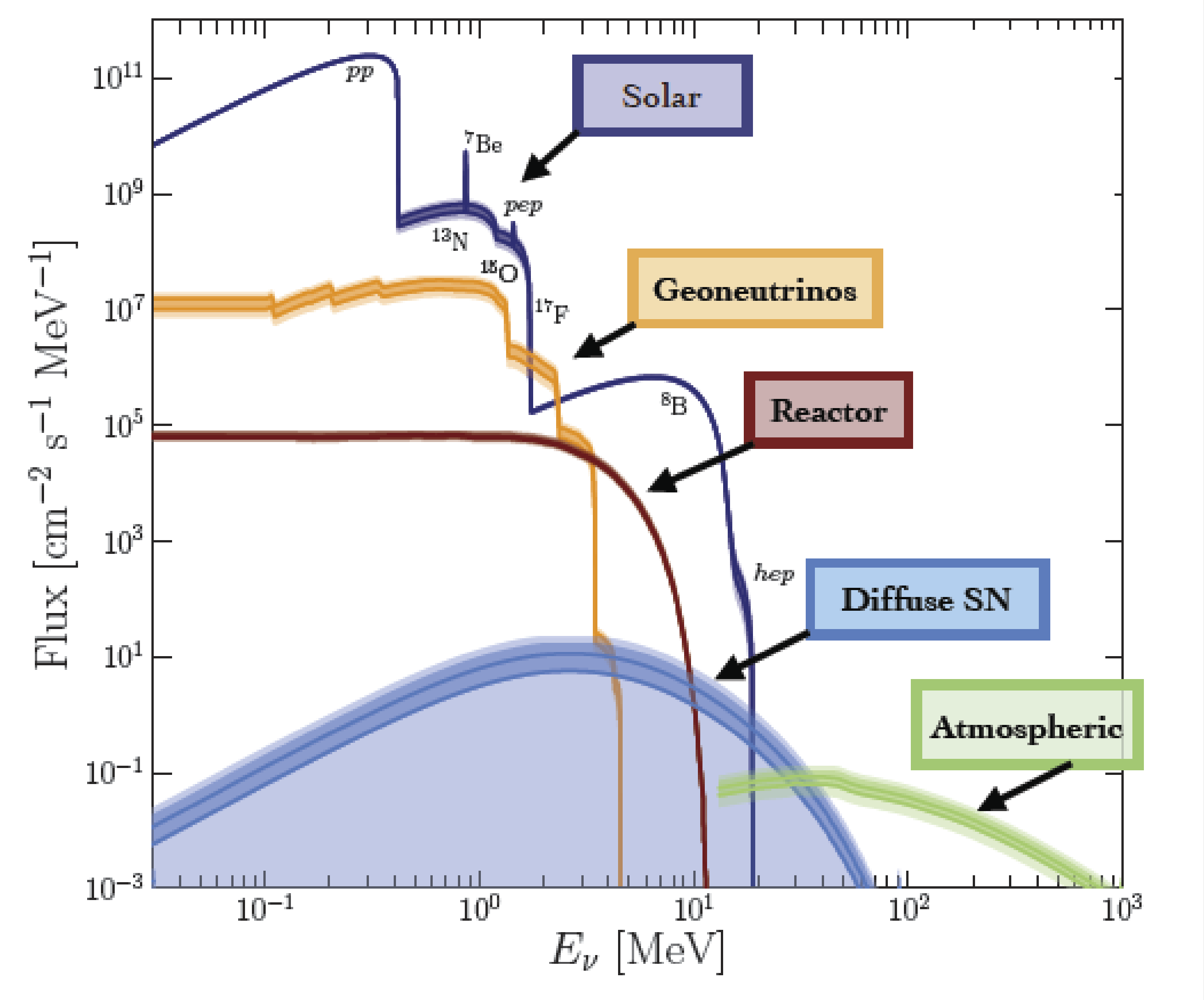
  ***The RES-NOVA project***

# What is for future?

## Summary of CEvNS Results




# What is for future?



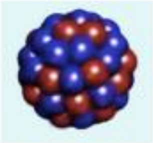
# What is for tomorrow?

**CEvNS: what's it good for?**

① So
② Many **!** (not a complete list!)
③ Things

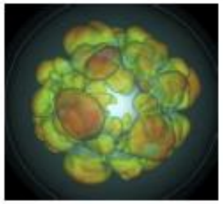
CEvNS as a **signal**
for signatures of *new physics*

CEvNS as a **signal**
for understanding of "old" physics

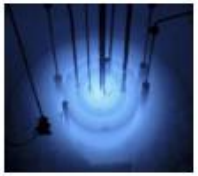


CEvNS as a **background**
for signatures of new physics


CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**



# Backup

# How to detect this process?

- **How to detect the CEνNS process:**
- **We need an intensive source and a sensitive detector.**
- **Natural sources versus Man-Made sources:**

**(a) Solar neutrinos, atmospheric neutrinos, supernova neutrinos**
**(b) Reactor neutrinos, accelerator neutrinos**

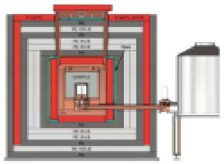
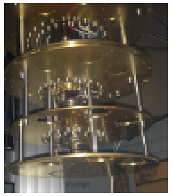
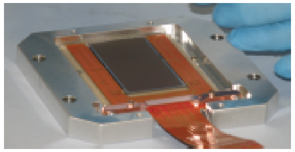
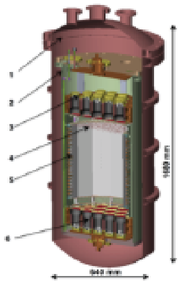
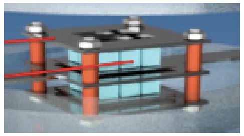
- **Sensitive detectors:**

**(a) Thanks to thirty years developments of dark matter detection techniques, we are approaching to the low threshold frontier of the keV level.**

**Promising prospective for the CEνNS detection !**

# CEνNS Experiments at Reactors

| Experiment | Technology | Location |
|---|---|---|
| **CONUS** | HPGe | Germany |
| **Ricochet** | Ge, Zn bolometers | France |
| **CONNIE** | Si CCDs | Brazil |
| **RED** | LXe dual phase | Russia |
| **Nu-Cleus** | Cryogenic $CaWO_4$ , $Al_2O_3$ calorimeter array | Europe |
| **MINER** | Ge iZIP detectors | USA |


Novel low-background, low-threshold technologies

# Implications: overview

- What can we do using the new CEνNS measurements:
- Testing the coherency
- Neutron radius measurements
- Testing properties of neutrino interactions

  Nonstandard interactions,
  Neutrino electromagnetic properties

- New physics at low threshold frontiers,

  Z prime, 1708.04255, 1803.01224, 1812.04067, 1903.10666, etc.
  scalar mediator, 1802.05171, 1804.03660, etc.
  dark photon, 1710.10889, 1906.10745, etc.
  Neutrino floor, 1710.10889, 1809.06385, 1904.11214 etc.
  and many other aspects

# Why study the neutron radius?

(a) The neutron radius and neutron skin are strongly correlated to the nuclear Equation of State (EOS), the slope of bulk symmetry energy, and other nuclear quantities.

(b) A larger neutron skin would suggest a stiffer EOS and imply a larger neutron star radius, which is related to the gravitational binding energy of core collapse supernovae.

(c) With the first observation of binary neutron star inspiral at Advanced LIGO and Advanced Virgo, one can infer the tidal deformability parameter, which is also related to the neutron star EOS and to the neutron skin.

(d) Information on the nuclear neutron density radius is also important for a precise determination of the background due to coherent elastic neutrino-nucleus scattering in dark matter detectors (e.g., 133Cs and 127I have similar atomic and mass numbers to that of Xenon).

# Nuclear Form Factors

- **Form factor** describes the interaction of extended objects beyond the point-like particles.

- **Taking the charge distribution (Coulomb scattering) as an example:**

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{point-like}} |F(q^2)|^2$$

$$F(q^2) \equiv \frac{1}{Ze} \int e^{\frac{-i\mathbf{q}.\mathbf{R}}{\hbar}} \rho(\mathbf{R}) d\tau \Rightarrow F(q^2) = \frac{4\pi\hbar}{Zeq} \int R\rho(R) \sin\left(\frac{qR}{\hbar}\right) dR$$

- **Here for weak interaction of protons and neutrons:**

$$F_Z(q^2) = \frac{4\pi}{Z} \int \rho_p(r)\, j_0(qr)\, r^2 dr$$

- **How to obtain the form of form factors:**

  **a) calculated with nuclear structure models** ***arXiv:1502.02928***

  **b) using analytical expressions with effective parameters**

  **c) directly taken from experimental data**

# Nuclear Form Factors

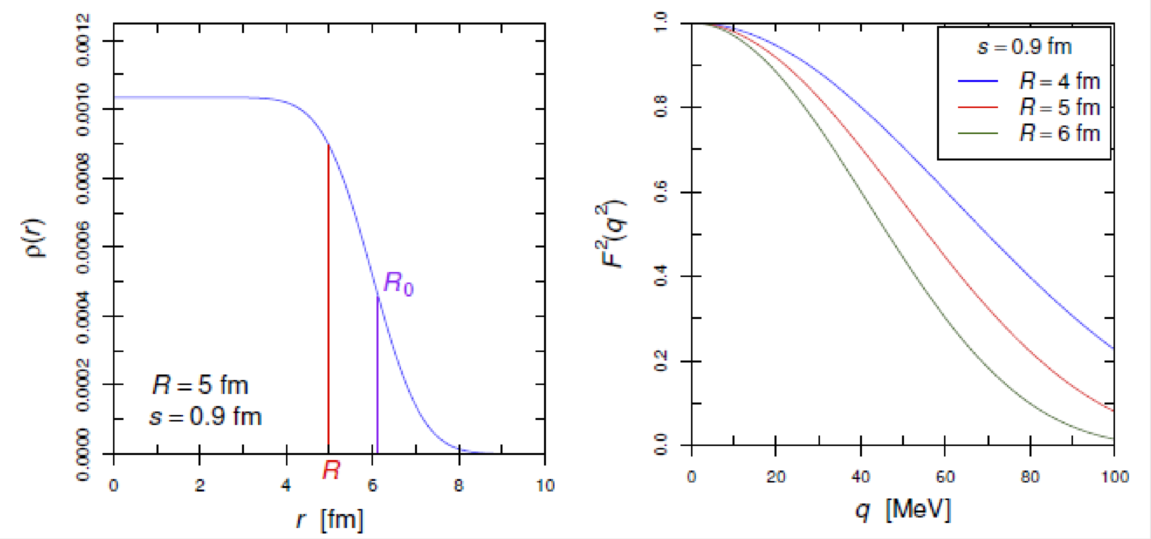
- **Analytical expressions of form factors:**

a) **symmetrized Fermi form factor** ***Phys. Rev. C94, 034316 (2016)***
b) **Helm form factor** ***Phys. Rev. 104, 1466 (1956)***
c) **Klein-Nystrand form factor** ***Phys. Rev. C60, 014903 (1999)***

- **We choose the Helm form factor:**

$$F_N^{\rm Helm}(|\vec{q}|^2) = 3\,\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0}\,e^{-|\vec{q}|^2 s^2/2}$$

Rms radius: $R^2 = \langle r^2 \rangle = \frac{3}{5}R_0^2 + 3s^2$ Surface thickness: $s \simeq 0.9\,\mathrm{fm}$




**Helm form factor:**

**Obtained from a convolution of a sphere with constant density with radius $R_0$ and a Gaussian density with standard deviation *s*.**