

Magnificent CEvNS 2023: Phenomenological and theoretical Perspectives

Manfred Lindner



Magnificent CEvNS 2023, Munich, Mar 22 – 24, 2023



**Carl Friedrich
von Siemens Stiftung**



Coherent Elastic ν -Nucleus Scattering: CEvNS

PHYSICAL REVIEW D

VOLUME 9, NUMBER 5

1 MARCH 1974

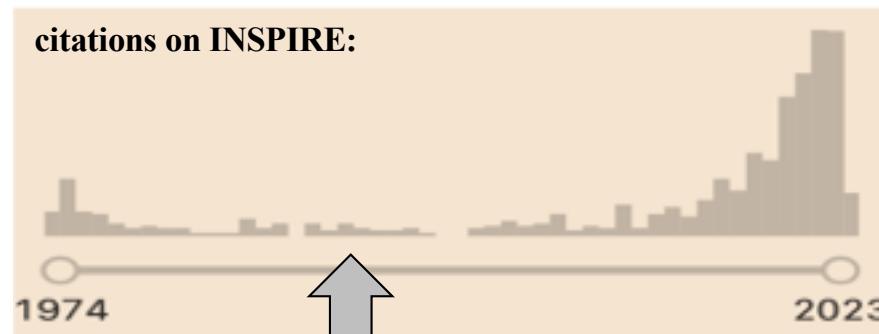
Coherent effects of a weak neutral current

Daniel Z. Freedman†

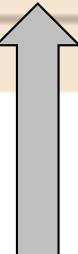
National Accelerator Laboratory, Batavia, Illinois 60510

and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

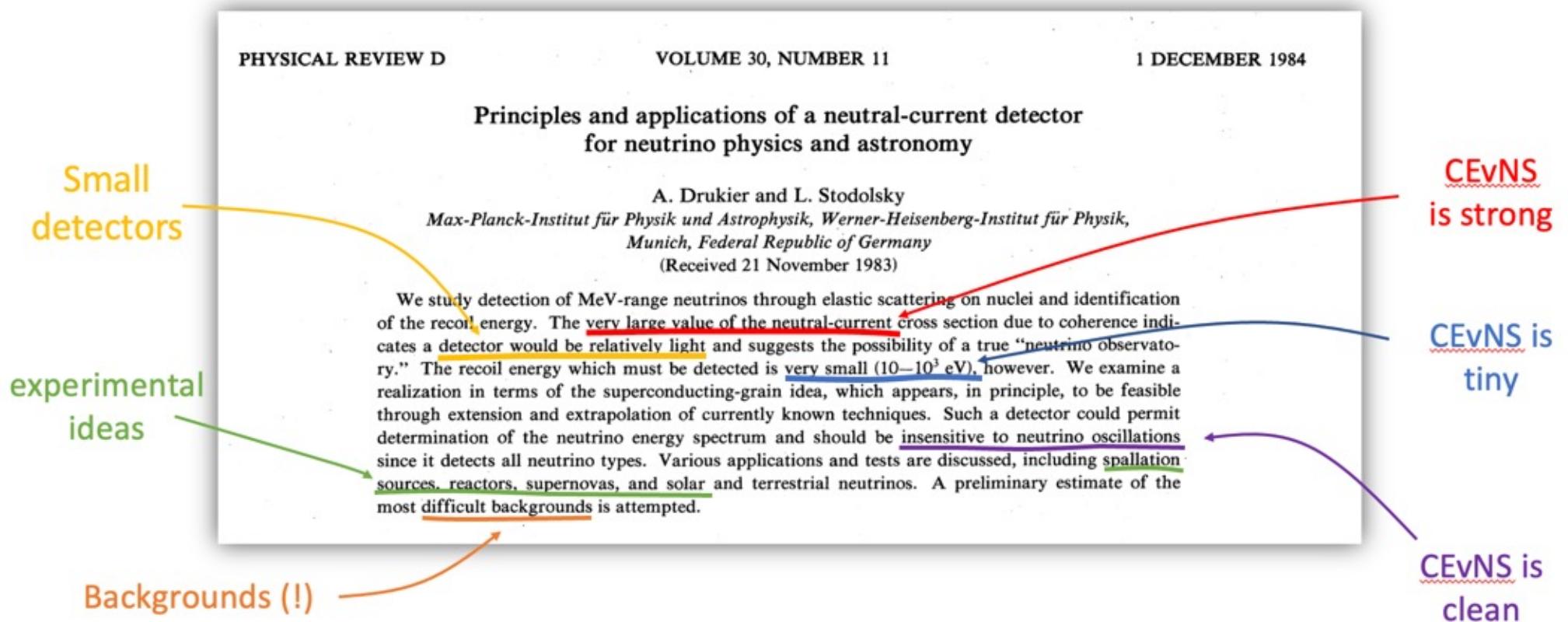
(Received 15 October 1973; revised manuscript received 19 November 1973)



- Implications for neutrino transport in supernovae
 - Large cross section important for understanding how neutrinos emerge from supernovae
 - neutron star formation
 - astro...



- Scattering on nucleons...
 - Spallation source... reactor neutrinos... detector properties...
 - BSM: NSI, vectors, scalars, ...
 - ...connections to DM...



The simple Picture

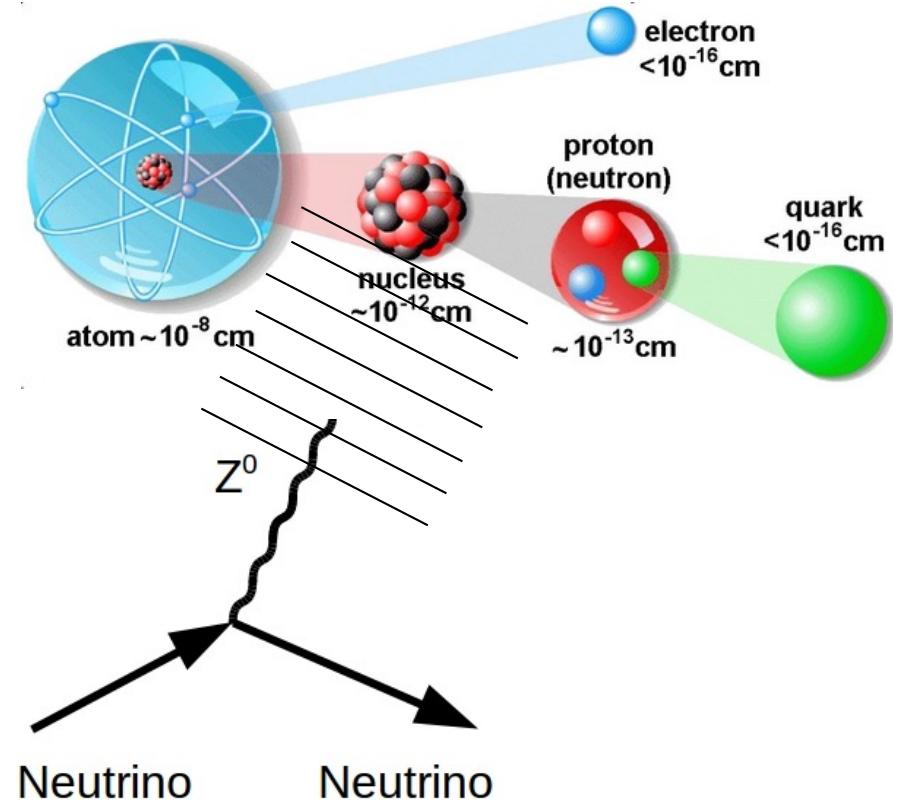
Z-exchange of ν with nucleus

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

→ sees mostly neutrons
 momentum ↔ wavelength

Very low momentum

→ nucleus recoils as a whole

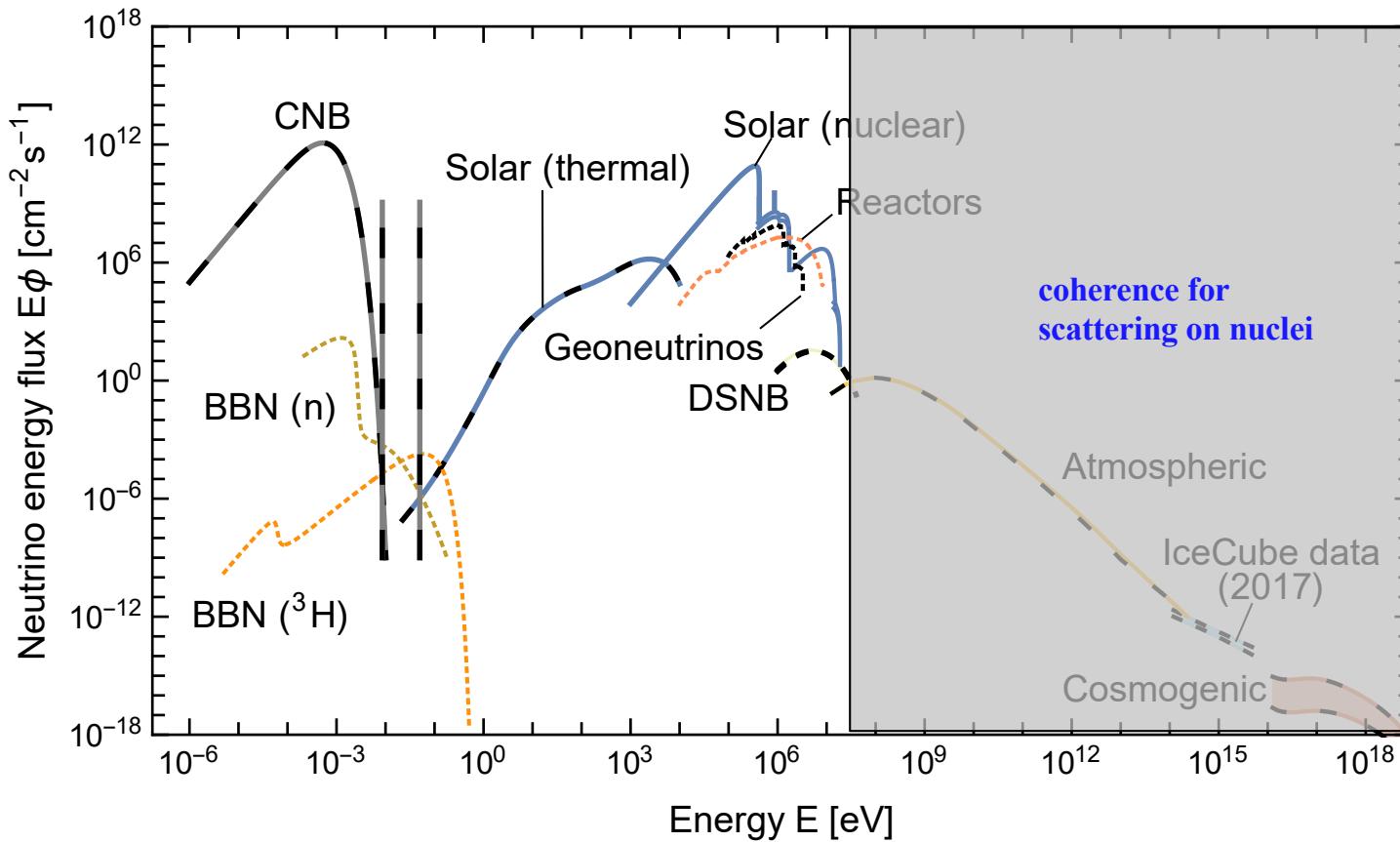


Coherence length $\sim 1/E \rightarrow E_\nu$ below O(50) MeV
 → low energy $E_\nu \leftrightarrow$ lower cross sections → very high flux!

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

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

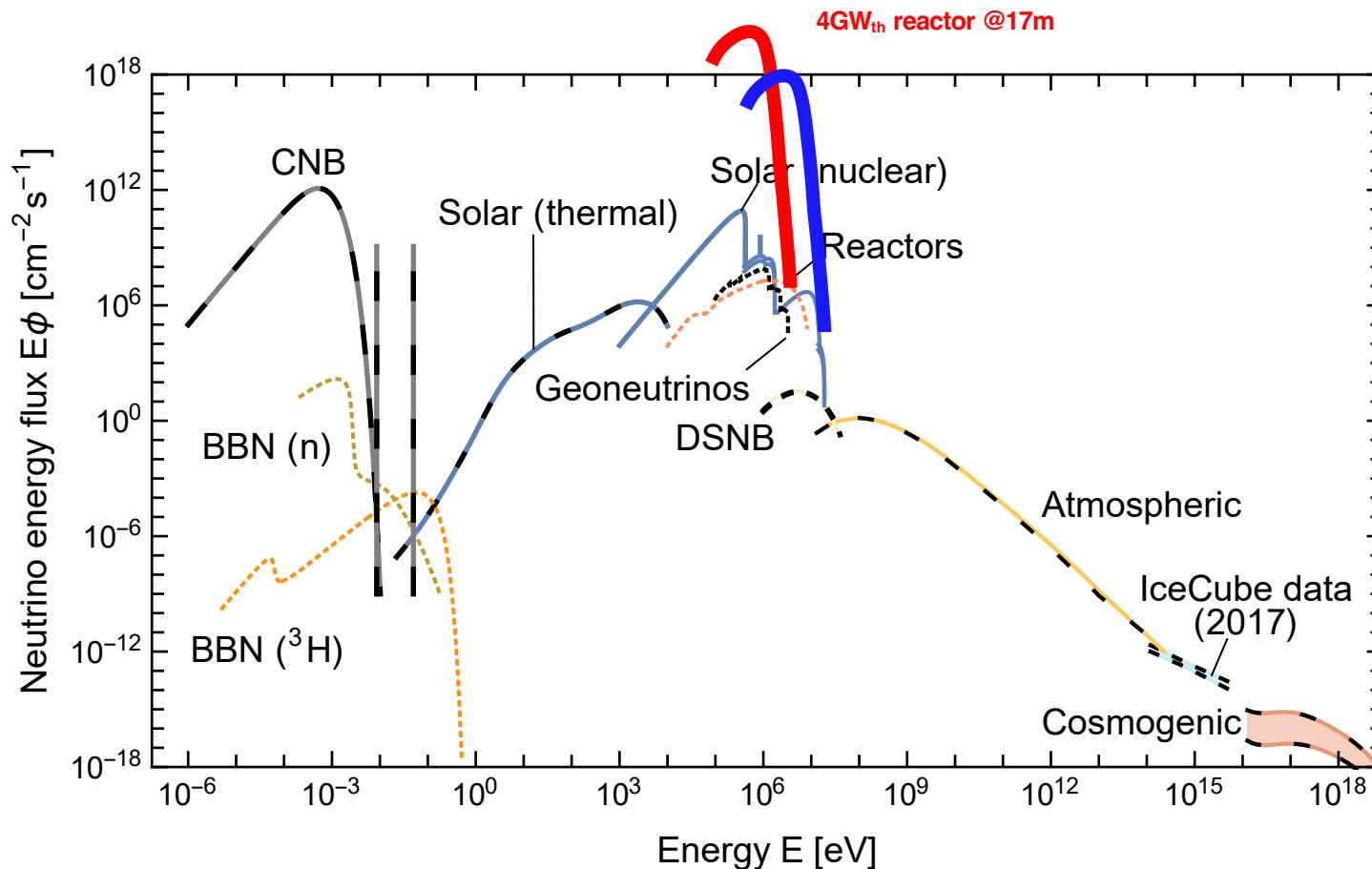
Sources: Flux \otimes Energy



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

Sources: Flux \otimes 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: \otimes detector size / backgrounds

N²: Coherence on large Scales \leftrightarrow Low E_ν

$$E_{rec}^{max} = \frac{2 \cdot E_\nu^2}{m_n \cdot A + 2 \cdot E_\nu} \approx \frac{2 \cdot E_\nu^2}{m_n \cdot A}$$

m_n = nucleon mass, $A=N+Z$

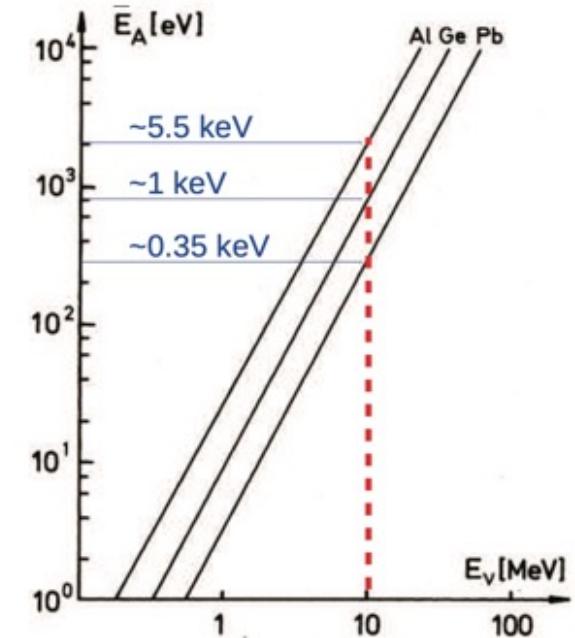
→ push-pull situation:

$$\sigma_{\nu A}^{tot} \propto N^2 \text{ vs. } E_{rec} \propto \frac{1}{(N+Z)}$$

A dream CEvNS detector:
assume a coherent 1 cm³ target

would require → $|\vec{q}| \lesssim q_0 \sim 10^{-5}$ eV

recoil energy → $E_{rec} \simeq \frac{q_0^2}{2M_{tot}} \sim 10^{-43}$ eV

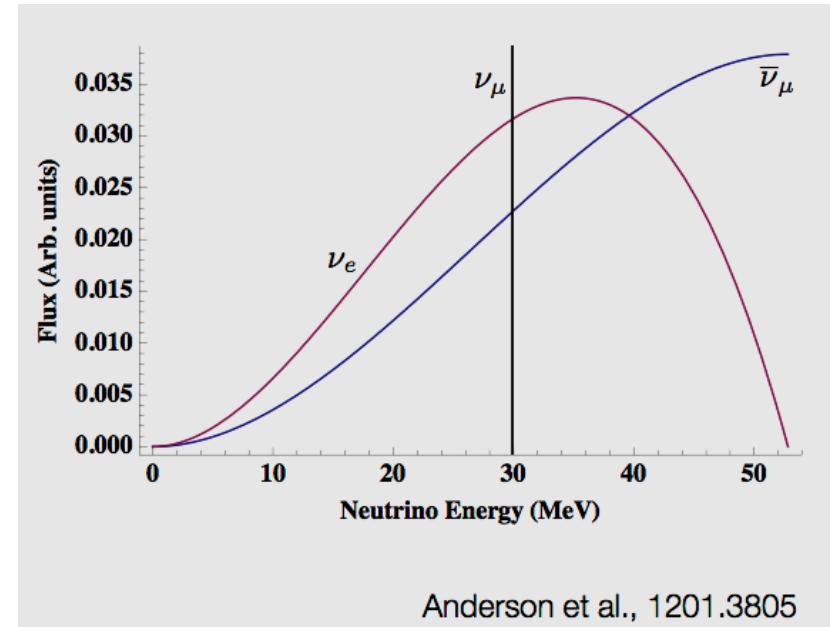


A.Drukier, L.Stodolsky, Phys.Rev.D 30 (1984) 11

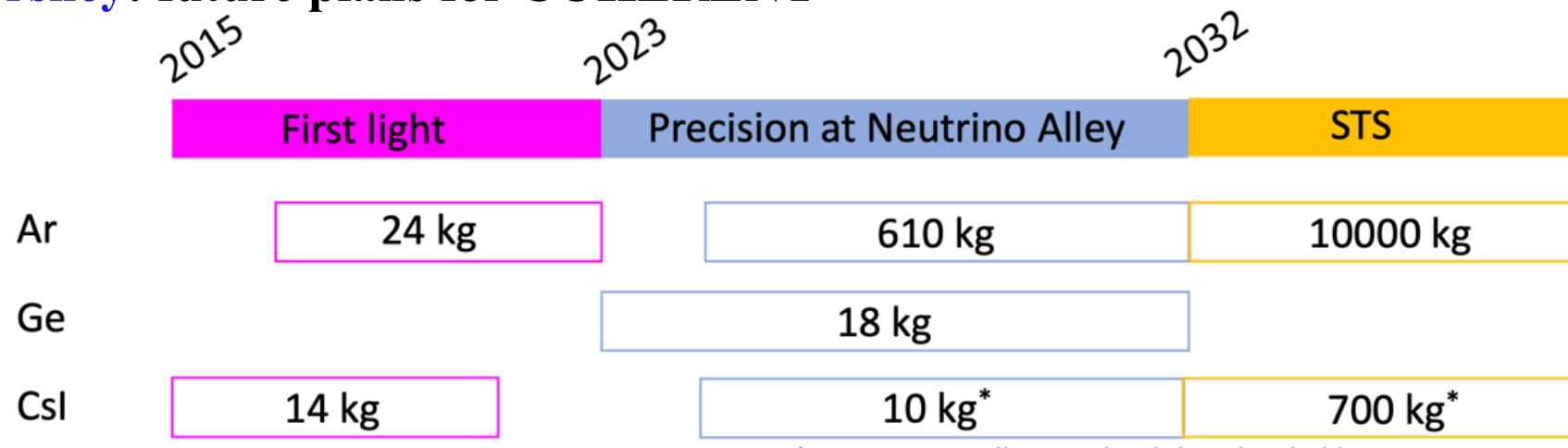
Experimental Paths

Low energy ν 's from accelerators:

- π -decay-at-rest (DAR) ν source
 - different flavors produced
 - relatively high recoil energies
- form factors...
- **1st observation by COHERENT**
- **aim at improved statistics (\simeq target mass)
bigger detectors, less background**



Pershey: future plans for COHERENT



→ more precision for CEvNS + dark matter...

Experimental Paths / 2

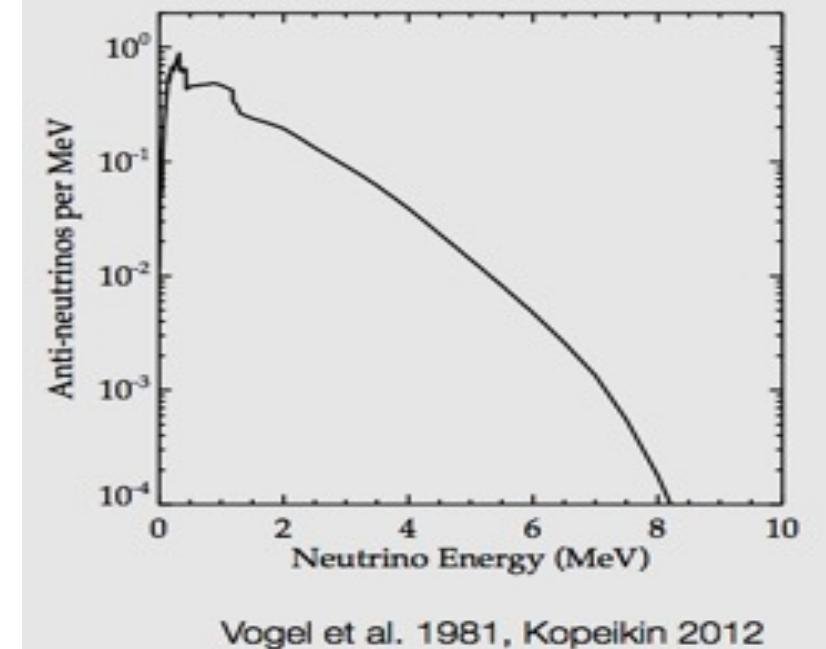
Reactors:

- lower ν energies than accelerators
- lower cross section → higher flux
- fully coherent \simeq no form factor
- SM deviations → BSM!

→ ...various experiments

CONUS within a factor of 2...

CONNIE, TEXONO, Ricochet, RED100, ...



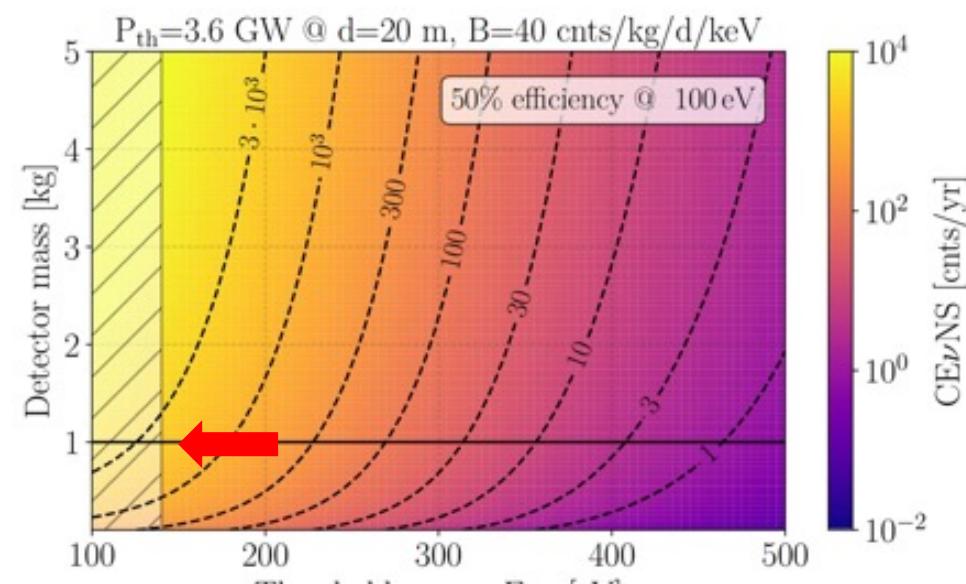
→ improvements:

Sanchez: CONUS → CONUS+

existing detector

+ improved threshold

→ get to the signal!

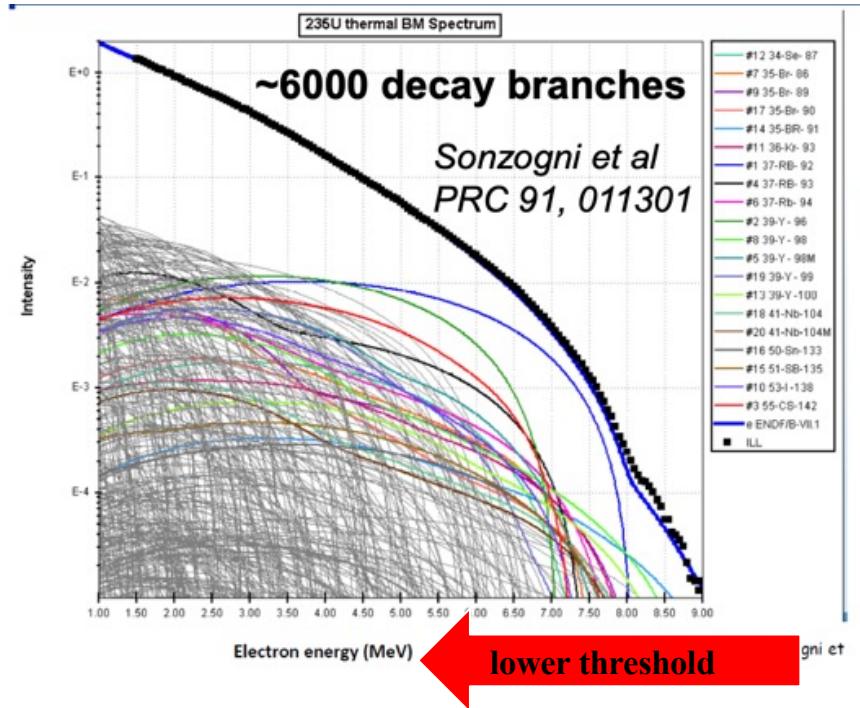


Experimental Paths / 3

Fully exploit the reactor neutrino flux

- significantly **lower threshold** based on cryogenic bolometers: CaWO₄ and Al₂O₃
- technology evolving \leftrightarrow excess... ?
- advantage: much smaller mass to see effect
- maximal detector mass? \leftrightarrow high statistics

Nucleus, others...



Getting closer to powerful reactors?

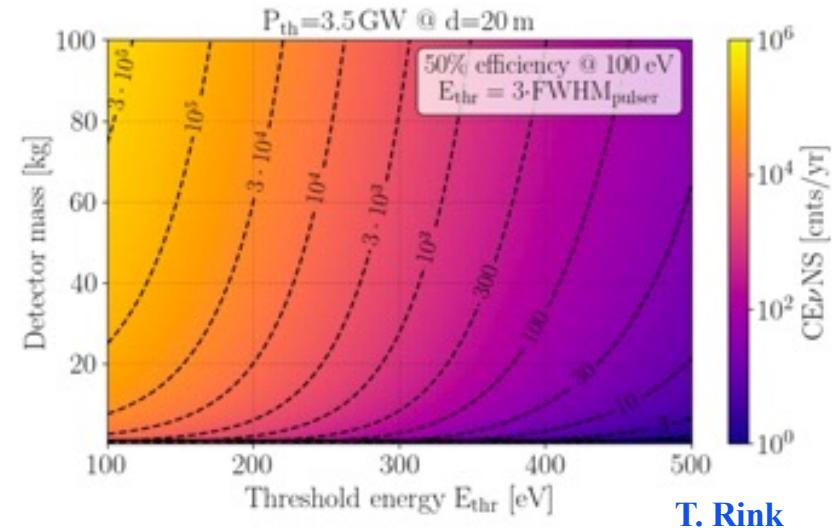
- many things are not allowed (access, many materials, network, ...)
 - \rightarrow requires \sim order of magnitude bigger detector if you are forced to go outside
 - \rightarrow less overburden...
- too close: increased backgrounds (neutrons, gammas, contaminations, access,...)
- research reactors: easier, but flux $\sim P/R^2$ is lower

Experimental Paths / 4

Lower threshold + increased mass

- improved kg size or multi kg Ge detectors ...
- ~ existing or mildly extrapolated technology
- reasonable assumptions on background etc.
- 3kg detectors in a 4x4x2 array

→ O(100kg) with lower threshold seems doable
→ high statistics!



T. Rink

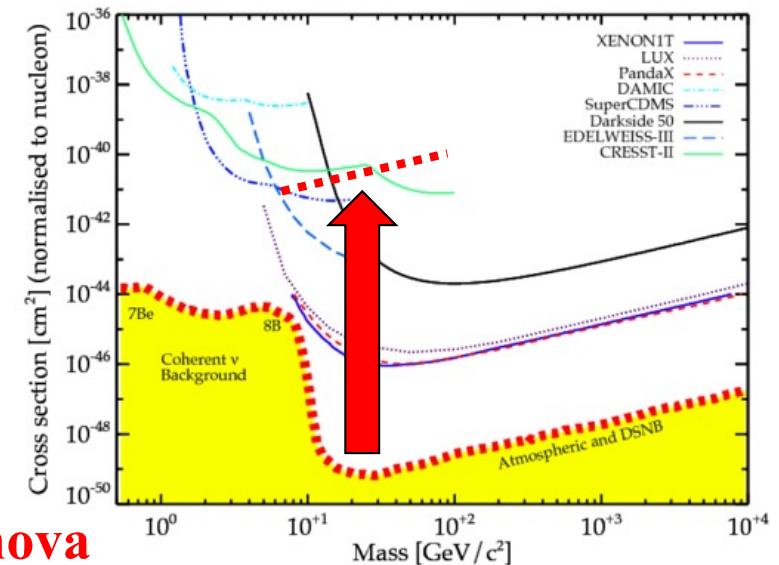
Less flux @ huge detectors...

- solar neutrinos @DM detectors
- flux $\simeq 10^{-xx} \leftrightarrow$ detector $\simeq 10^{+xx}$
- LXe DM detectors with tons of mass,
very clean, low thresholds...

XENONnT, LZ, DARWIN, XLZD, ...

In addition: vES

In addition (for patient people): A galactic supernova



Experimental Paths / 5

Important: Signal to background

- high statistics means ~ thousand's of events → detector size
- backgrounds (natural, environmental)

→ how to get the required S/B for a larger detector?

Today two main techniques (long term may be different ↔ R&D efforts)

- growing crystals (it's also a purification process)
- liquid noble gas detectors (getter in loop, distillation, surface/volume)

In all cases:

- need clean detector instrumentation
- shield external/environmental backgrounds (neutrons, gammas, cosmics...)

And the winner is:

**Whoever gets the biggest event rate with lowest background
...for different targets and energies...**

↔ physics potential beyond seeing the expected SM effect

What is it good for?

Detecting CEvNS: An expected SM process already observed by COHERENT
Why more statistics? Why bother?

- 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
- Measurements 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

Any Idea where BSM should show up?

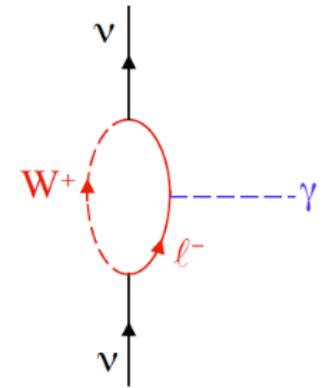
Neutrino magnetic Moment in the SM + ν_R

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

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:

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

→ limits from CEvNS (and others) are much weaker

→ BSM models significantly enhance μ_ν

e.g. MSSM with L violation by R-parity violation $\sim \lambda'$

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

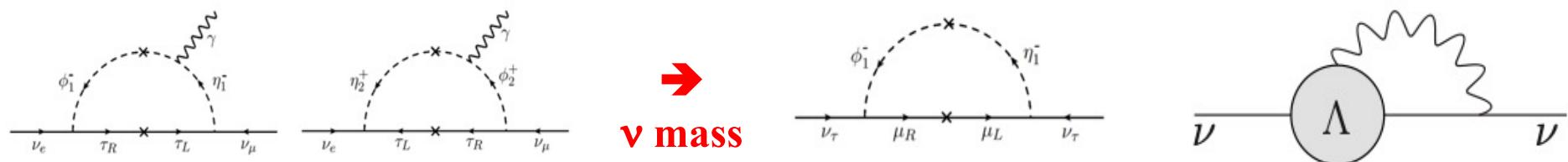
BUT → $\mu_\nu \leq 10^{-13} \mu_B$

$A_\ell \leftrightarrow$ SUSY breaking
trilinear coupling
 $M_{\tilde{\ell}} \leftrightarrow$ slepton mass

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



→ 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 \rightarrow impact on $m_\nu \leftrightarrow \mu_\nu$ relation

[K.S. Babu, S. Jana, ML, JHEP 10 \(2020\) 040](#)

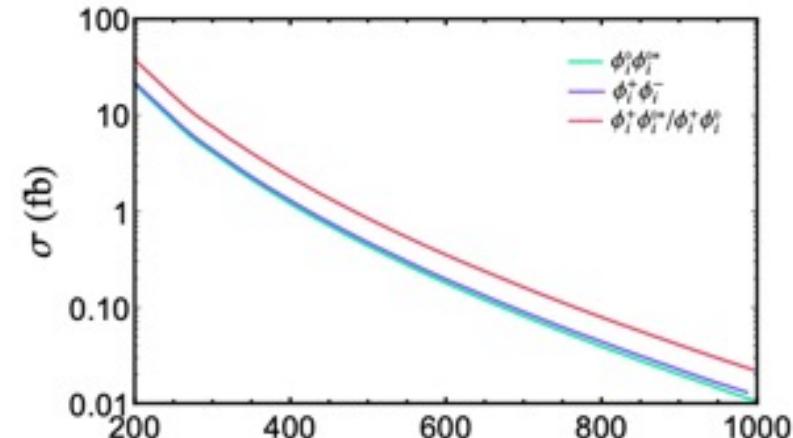
Horizontal $SU(2)_H$ broken by muon Yukawa coupling

Main point:

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

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

\rightarrow LHC prospects
 \rightarrow HEP / CEvNS 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 v_R): $q_v=0$ ← consequence of charge quantization

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

U(1)_Y gauge invariance
of Yukawa couplings

$$\Rightarrow \begin{aligned} Y_e &= Y_L - 1 \\ Y_u &= Y_Q + 1 \\ Y_d &= Y_Q - 1 \end{aligned}$$

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

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

$$\text{From this follows: } 0 = \text{Tr}[Y^3] = (Y_L + 1)^3 \implies Y_L = -1 \quad \boxed{\rightarrow q_v = 0}$$

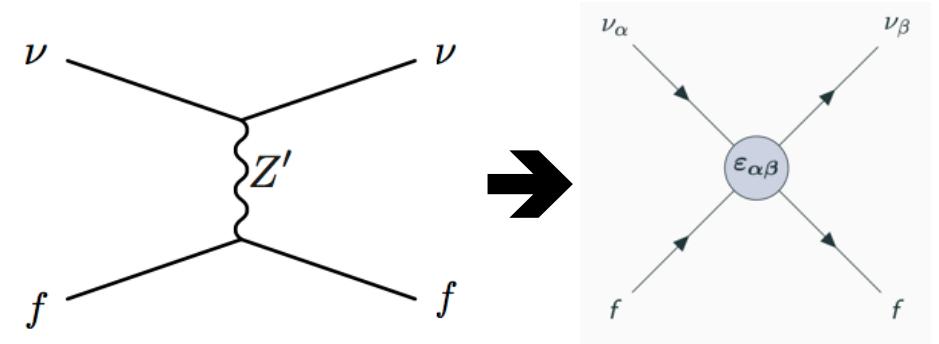
$$\text{With } v_R: \quad \text{Tr}[Y^3] = (Y_L + 1)^3 - (Y_L + 1)^3 = 0 \quad \rightarrow q_v \neq 0 \text{ allowed}$$

Other v -mass mechanisms, GUTs...

But: Current CEvNS limits are much weaker than the best limit above...

BSM Physics as NSI's

NSI's \leftrightarrow BSM at high scales
 ... which is integrated out
 Z' , new scalars, ... $\rightarrow \epsilon_{ij}$



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

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

Barranco et al. 2005

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

**→ Competitive method to test TeV scales
 $\epsilon = 0.01 \leftrightarrow$ TeV scales**

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 :
$$\frac{d\sigma_\phi}{dT} = \frac{g_\phi^4 (14N + 15.1Z)^2 M^2 T}{4\pi E_\nu^2 (2MT + m_\phi^2)^2}$$

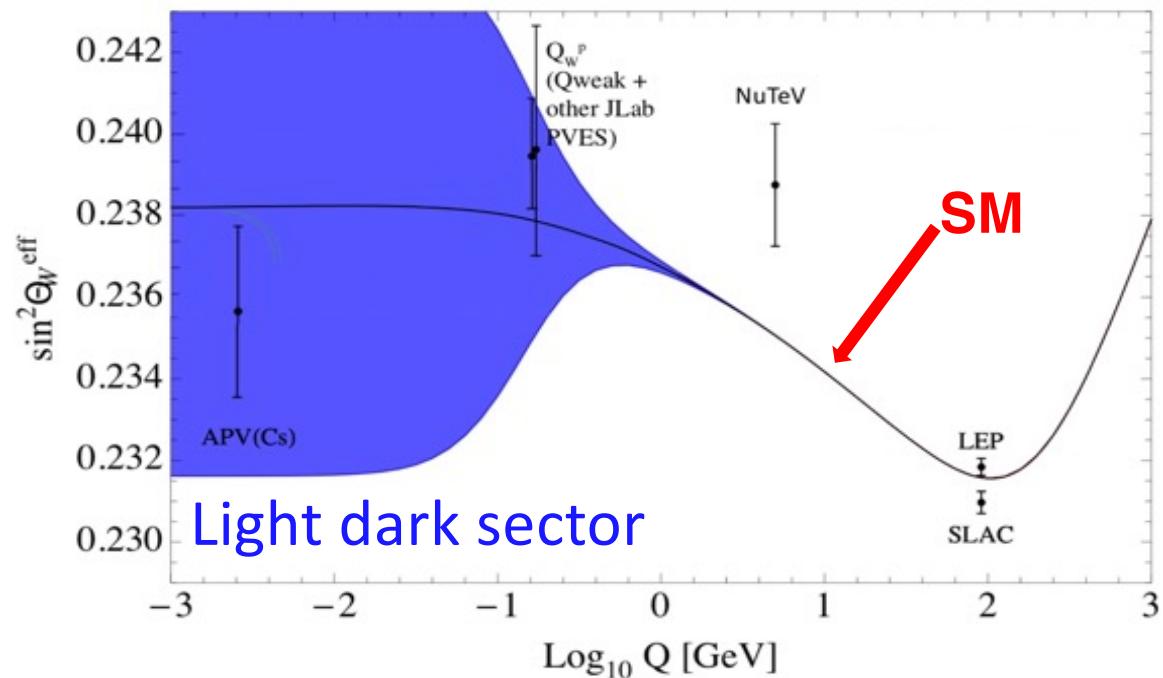
- light vector boson Z':
$$\frac{d\sigma_{Z'}}{dT} = \left(1 - \frac{3g_Z^v g_Z^q (Z+N)}{\sqrt{2} G_F Q_{SM} (2MT + m_{Z'}^2)} \right)^2 \frac{d\sigma_{SM}}{dT}$$

→ often connected to dark sector = DM

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

CEvNS 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



Beware – models often in conflict with other measurements:

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

Nuclear Structure with coherent Scattering

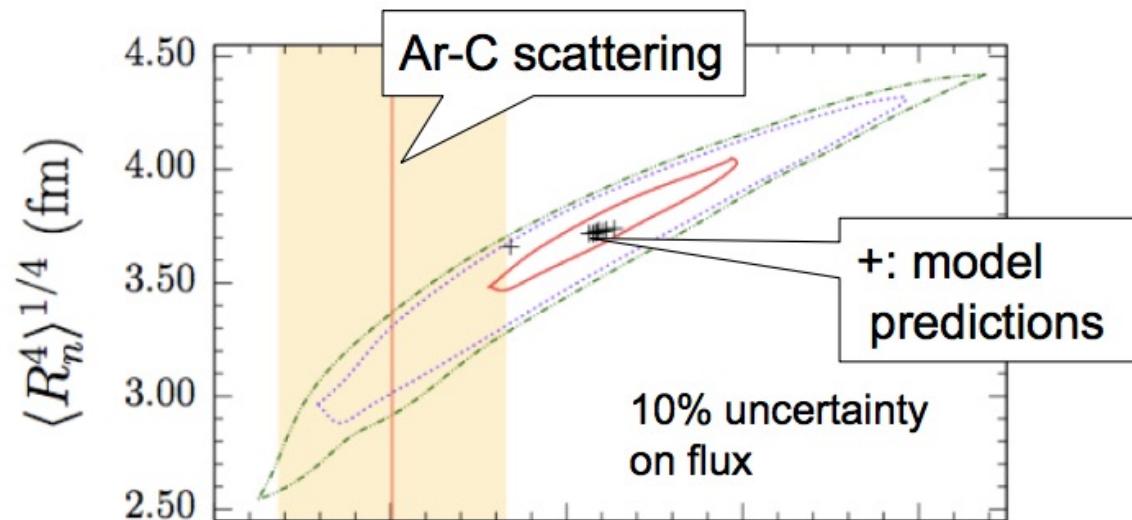
Remember: DAR sources close to de-coherence \leftrightarrow combine with reactor measurements

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

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

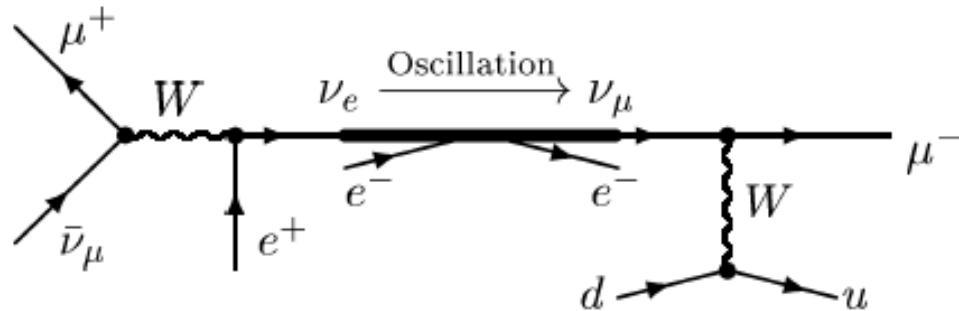
Fit recoil **spectral shape** to determine the $F(Q^2)$ moments
(requires very good energy resolution, good systematics control)

Example:
tonne-scale
experiment
at π DAR source



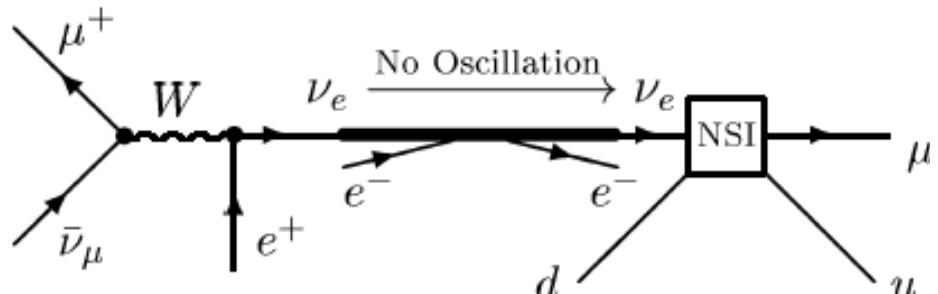
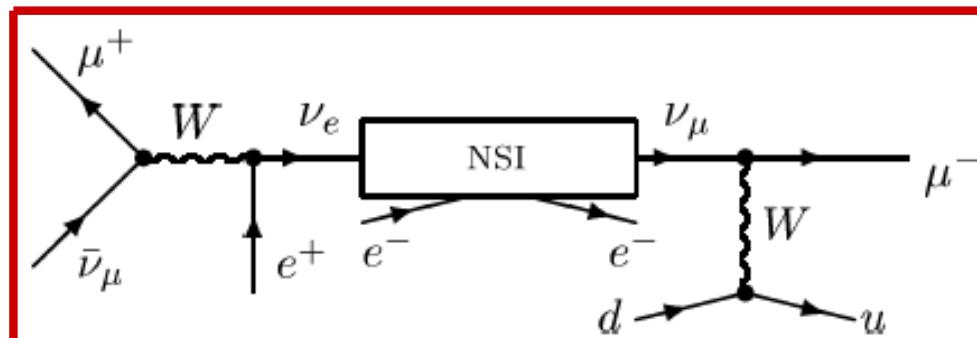
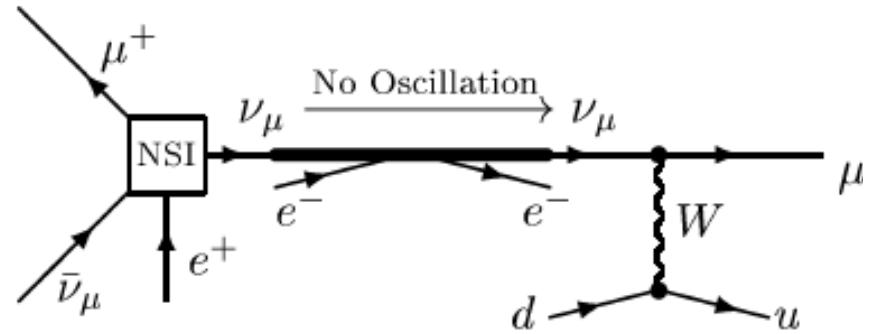
NSI's interfere with Oscillations

the “golden” oscillation channel



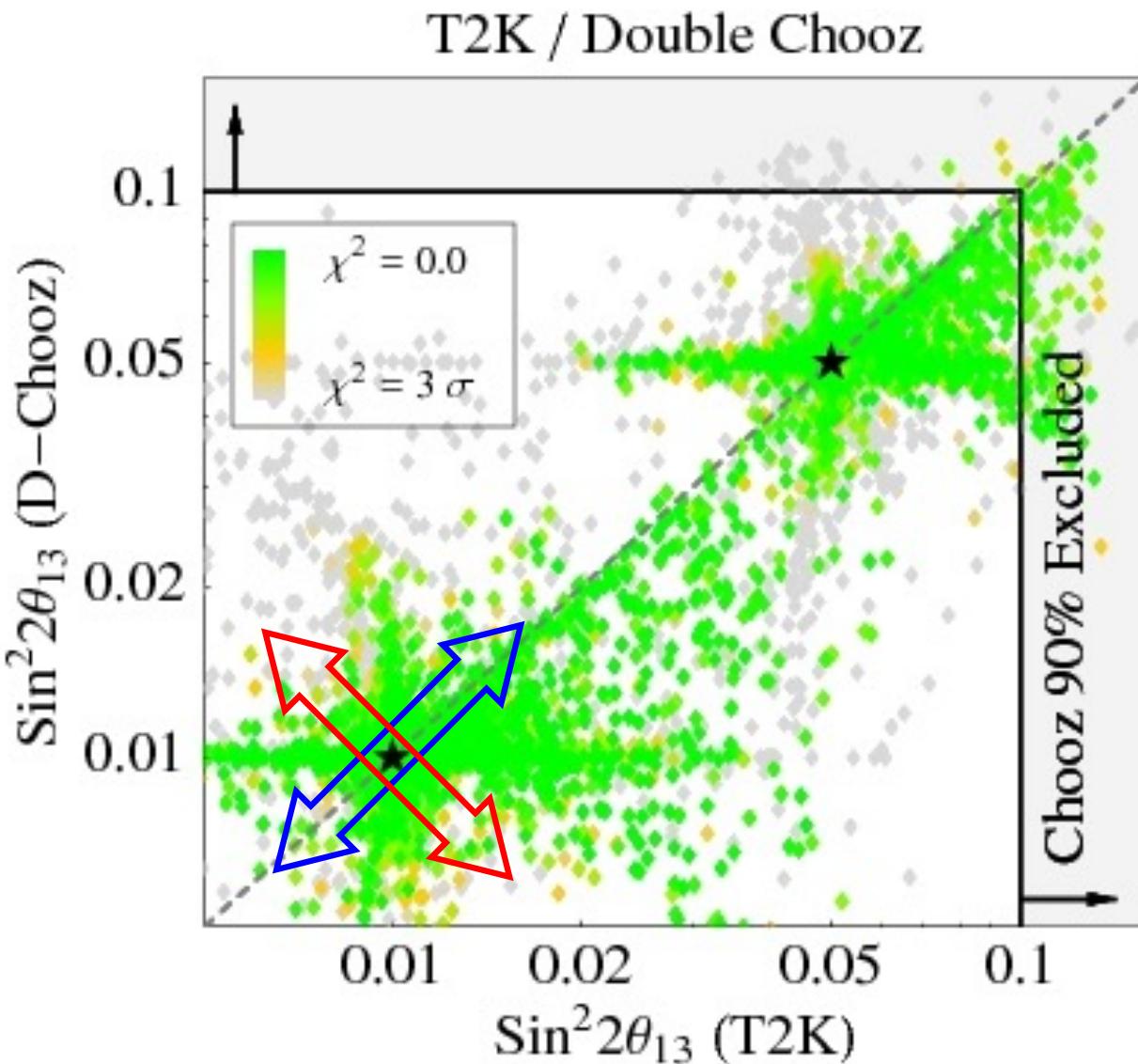
(a)

NSI contributions to the “golden” channel



note: interference in oscillations $\sim \epsilon$ \longleftrightarrow FCNC effects $\sim \epsilon^2$

NSI: Offset and Mismatch in θ_{13}



Kopp, ML, Ota, Sato (2007)

Redundant measurements:

Double Chooz + T2K

*=assumed ‘true’ values of θ_{13}

scatter-plot: ϵ values random

- below existing bounds
- random phases

NSIs can lead to:

- offsets
- mismatch

→ redundant measurements.

→ over-constraining!

↔ flavour symmetries: are we explaining the correct numbers?

More Phenomenology / Theory / Applications

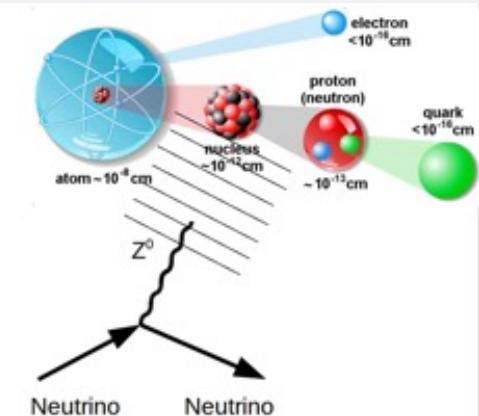
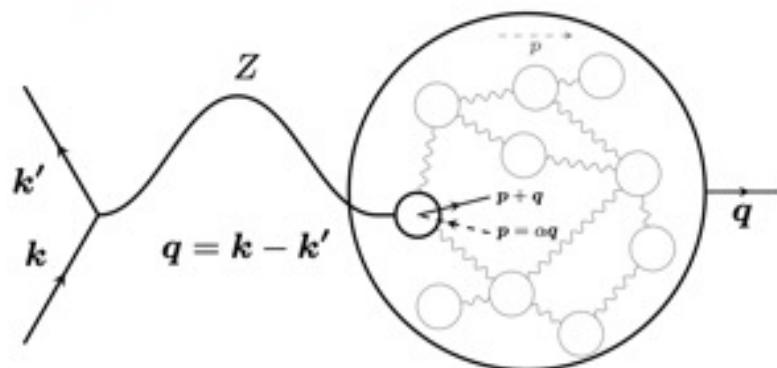
- many connections to dark matter models
- search / limits for dark particles
- producing new fermion with CEvNS
- effects of CP violating parameters on CEvNS processes
- ...

The need for theoretical Improvements

Question: Does the simple picture of CEvNS adequately describe the process?

Answer: It depends on the required precision!

→ nucleus made of protons and neutrons



requirements:

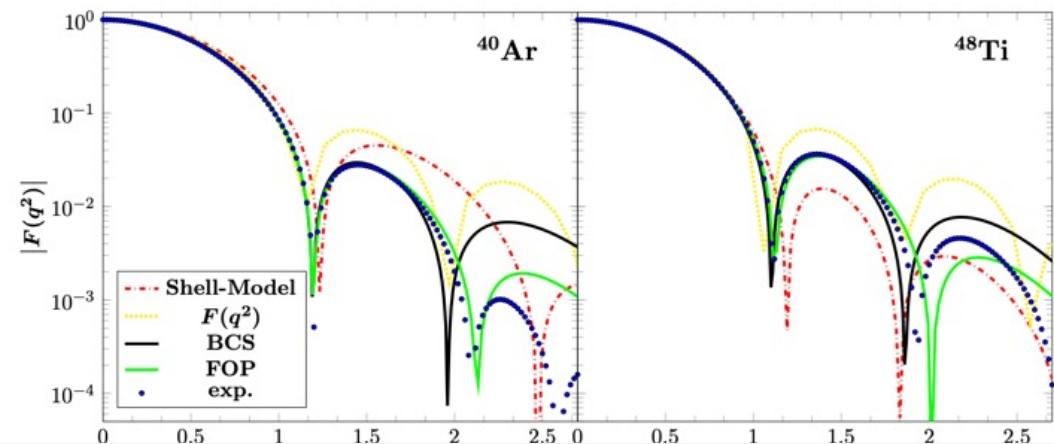
absence of individual recoil

↔ nuclear structure, binding
scattering in phase

↔ is the form factor picture sufficient

significant nuclear uncertainties
e.g. Papoulias, Kosmas
Adv.High Energy Phys. (2015) 763648

a task for theory and experiment

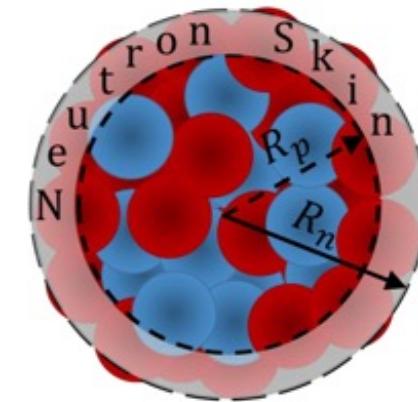


Nuclear Models and NSI's

Klein-Nystrand form factor

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

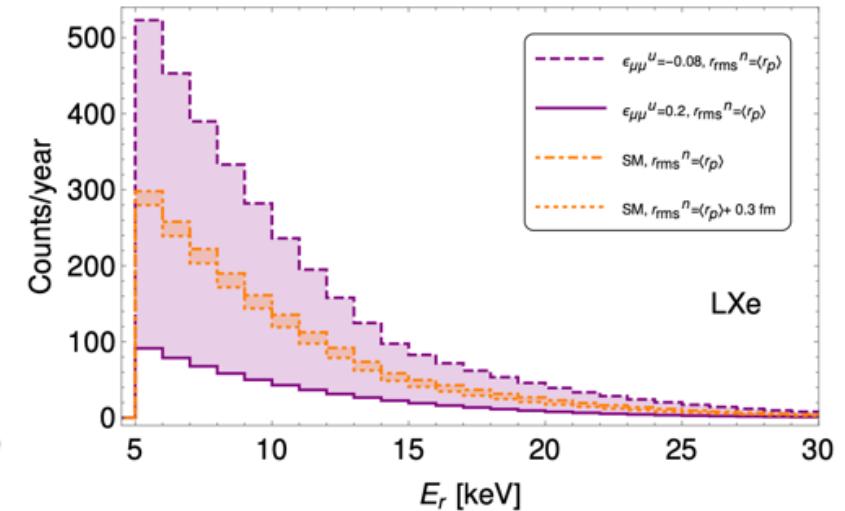
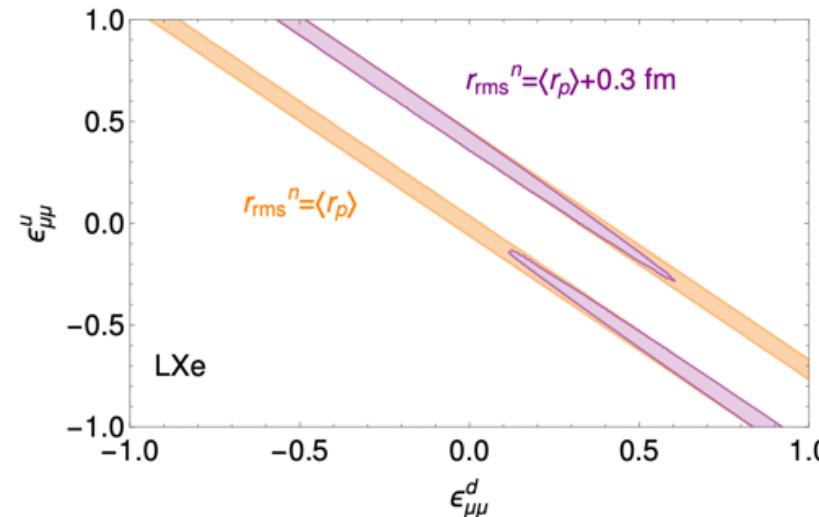
→ relies on a surface-diffuse distribution
 folding a short-range Yukawa potential with range a_k
 over a hard sphere distribution with radius R_A



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

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

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



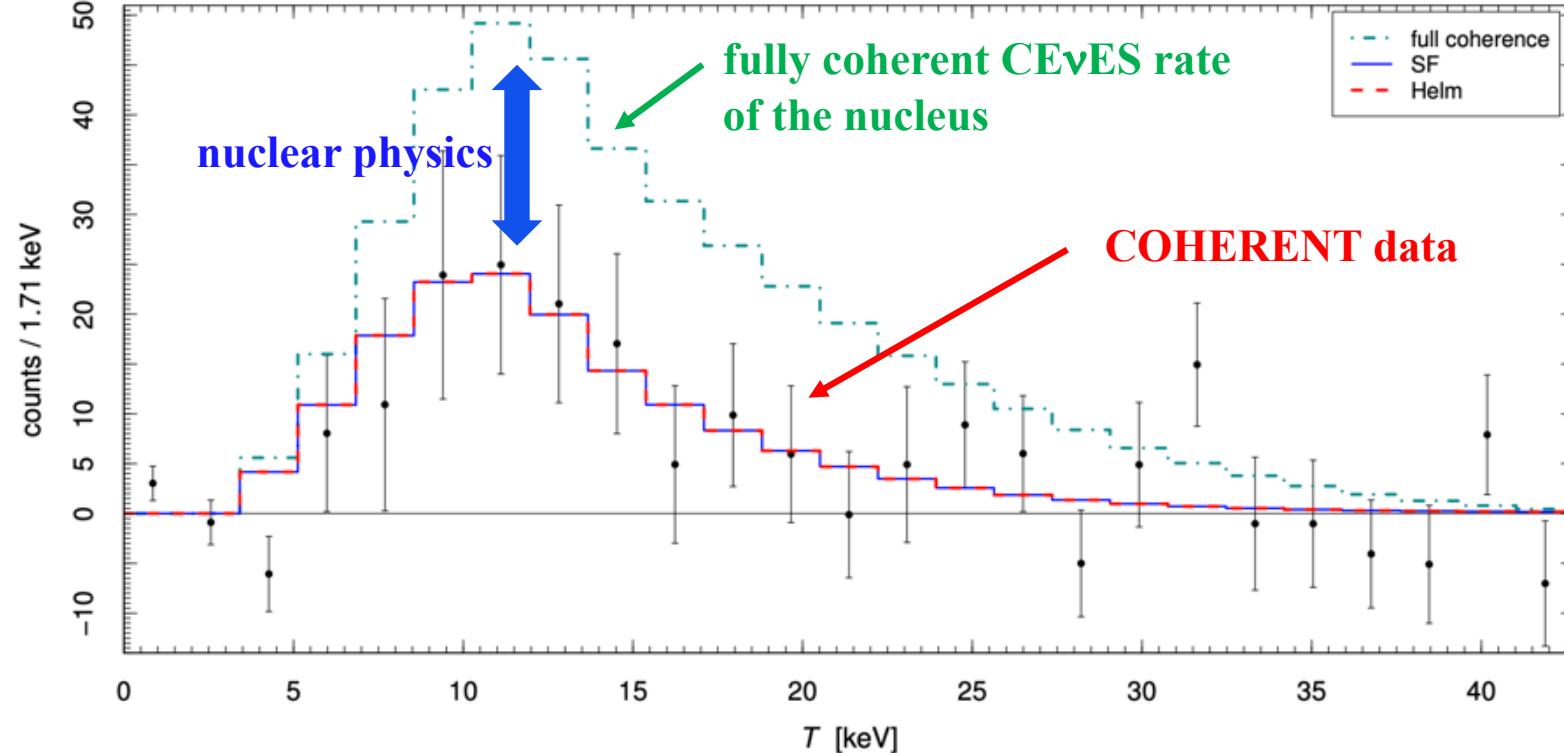
CsI Neutron density Distribution @COHERENT

$$\frac{d\sigma_{\nu-N}}{dT}(E, T) \simeq \frac{G_F^2 M}{4\pi} \left(1 - \frac{MT}{2E^2}\right) \times [NF_N(q^2) - \epsilon ZF_Z(q^2)]^2$$

Form factors are Fourier transform of the nuclear p,n densities

Cadeddu, Giunti, Li, Zhang, PRL120, 072501 (2018)

symmetrized Fermi (SF) (solid blue)
Helm (red dashed)



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

$$\Delta R_{np} \simeq 0.7^{+0.9}_{-1.1} \text{ fm.}$$

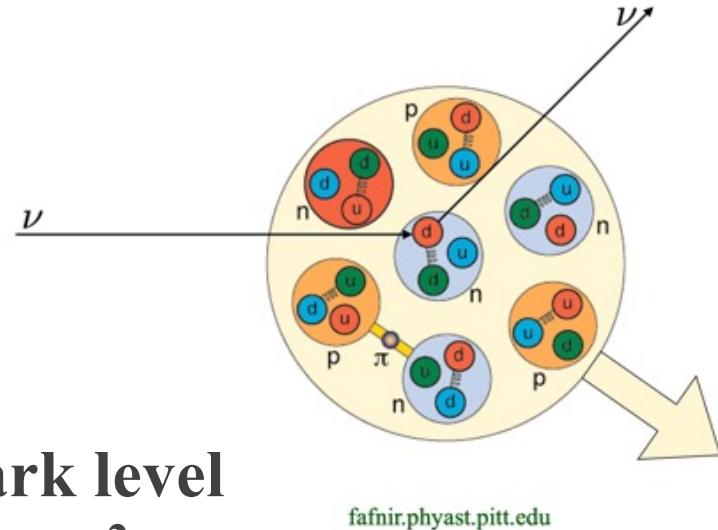
What if high precision data deviate?

Even more fundamental...

Elementary reaction: neutrinos interact with quarks via Z exchange

requirements:

absence of individual recoil
scattering in phase

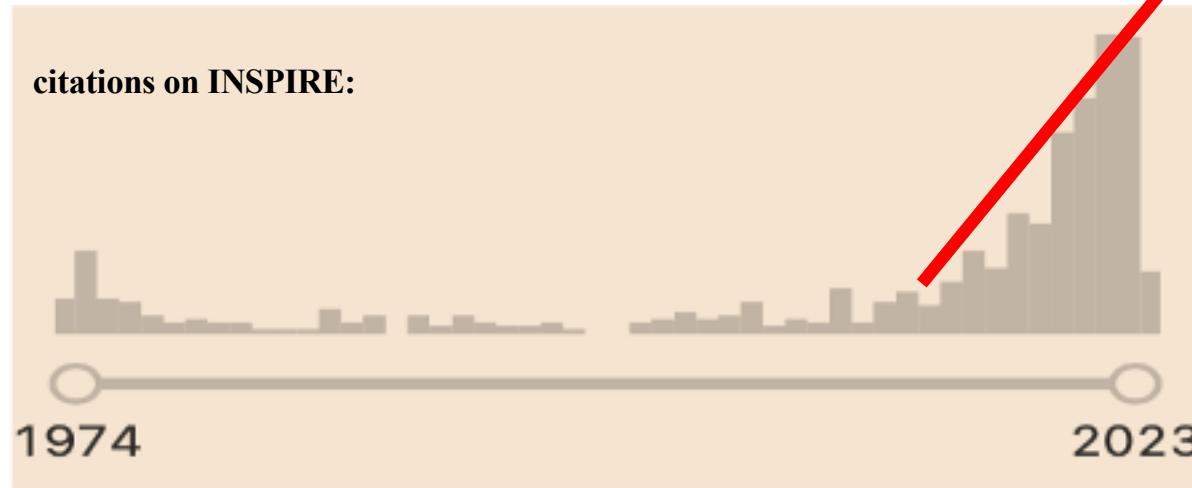


fafnir.phyast.pitt.edu

- Form factors and x-sections \leftrightarrow quark level
 \leftrightarrow limitations of factorization $\sigma \otimes F(q^2)$
- CEvNS in QFT \rightarrow 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](#)

Conclusions

- CEvNS is a hot topic



- **One can expect**
 - further observations of CEvES
 - higher statistics → growing precision
 - growing number of studies discussing BSM scenarios
 - interplay of CEvES, HEP, astroparticle analyses (DM...)
 - **We need both more experimental and theoretical activity!**
 - **A prediction →more exciting Magnificent CEvES Workshops**



**Carl Friedrich
von Siemens Stiftung**



Nymphenburg Castle & Park



Local Organizing Committee
Raimund Strauss (Co-chair)
Victoria Wagner (Co-chair)



THE MAGNIFICANT SERvANTS

Andreas Erhart
Margarita Kaznacheeva
Angelina Kinast
Paola Mucciarelli
Tobias Ortmann
Luca Pattavina
Lilly Peters
Petra Riedel
Johannes Rothe
Nicole Schermer
Sabine Wenzel
Alexander Wex

