Coherent Neutrino Scattering, Searches for sterile States

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The XIX International Conference on Topics in Astroparticle and Underground Physics

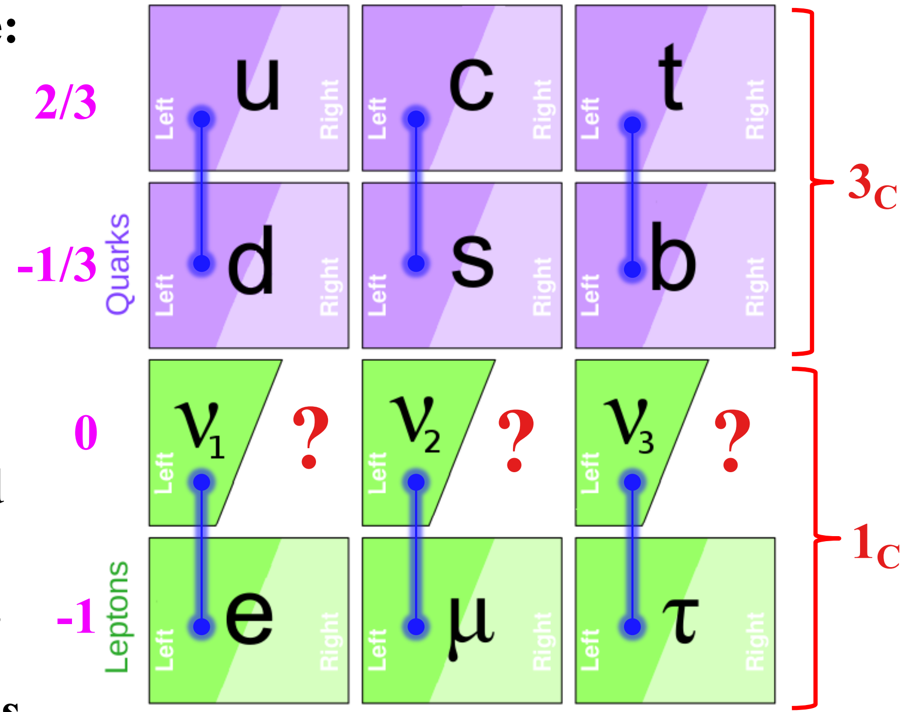
TAUP2025

TAUP XICHANG

Aug 24 – 30, 2025, Xichang, China

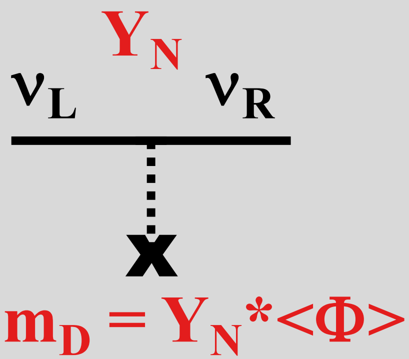
The Motivation for sterile Neutrinos

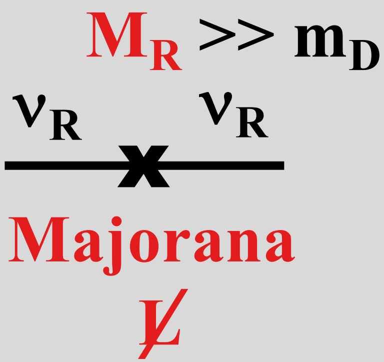
the Standard Model = facts learned from Nature:
- sucess of renormalizable QFT ➔ SM
- gauge group: **SU(3)c ⊗ SU(2)L ⊗ U(1)Y**
- **chiral** representations: $\mathbf{2_L}$ and $\mathbf{1_L}$, $\mathbf{3_C}$ and $\mathbf{1_C}$
- electric charge: **Q = T3 + Y/2**



questions:
- which representations? why generations?
- ν_R states appear missing? m_ν=0 ← not required
- **neutrino masses ➔ <u>simplest</u> option: add ν_R**
- beware: image is easily misleading: 1,2,3, GUTs

➔ **ν_R = (1_C, 1_L, Y=0) has important consequences**





6x6: see-saw ➔ block diagonalization

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R{}^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L{}^c \\ \nu_R \end{pmatrix}$$

- **3 active: ~m^2_D/M_R, 3 sterile ~ M_R**
- **expect tiny active/sterile mixings ~ m_D/M_R**

Constraints from Neutrino Oscillations

M_R very big ➔ ignore 6x6 picture ➔ 3x3 PMNS mixing matrix **U** of active neutrinos

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

3 x 3 unitarity:
$UU^+ = U^+U = 1$

normalization:

$$|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2 = 1 \quad (\alpha = e, \mu, \tau)$$

or

$$|U_{ei}|^2 + |U_{\mu i}|^2 + |U_{\tau i}|^2 = 1 \quad (i = 1, 2, 3)$$

orthogonality:

$$U_{\alpha 1}U^*_{\beta 1} + U_{\alpha 2}U^*_{\beta 2} + U_{\alpha 3}U^*_{\beta 3} = 0 \quad (\alpha, \beta = e, \mu, \tau, \alpha \neq \beta)$$

or

$$U_{ei}U^*_{ej} + U_{\mu i}U^*_{\mu j} + U_{\tau i}U^*_{\tau j} = 0 \quad (i, j = 1, 2, 3, i \neq j)$$

➔ **oscillations from active to sterile neutrinos would show up as 3x3 unitarity violation**

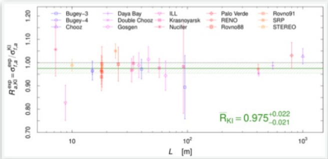
- **global 3ν oscillation fits work perfectly:**
- **fits without assumed unitarity also work very well ➔ at most ~1-3% deviation**

- **BARI group: Capozzi et al, PRD 104 (2021) 083031**
- **Valencia group: globalfit.astroparticles.es**
- **NuFIT: www.nu-fit.org**

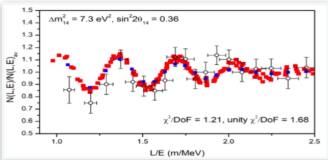
➔ **$U_{\alpha 4}$ expected to be small both from see-saw and 3x3 unitarity**

Old and newer Anomalies

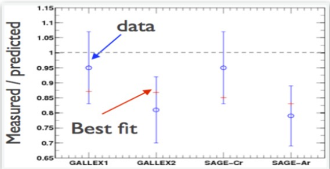
➔ results which neither fit into:
- a consistent 3+1 or 3+2, ... oscillation picture ➔ other mechanisms?
- cosmology (CMB+LSS, BBN, ...)



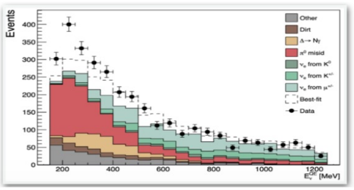
reactor anomaly (flux)
➔ probably resolved with improved fluxes
(origin of 5 MeV bump still open)



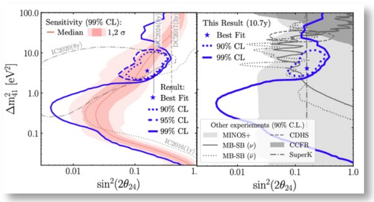
reactor spectra: **NEUTRINO-4** — **L/E oscillation pattern?**



Gallium anomaly:
GALLEX/GNO, SAGE, BEST



LSND, MiniBooNE



IceCube

oscillation rates with sterile ν's:
- **disappearance**
- **appearance**

P_{ee} $P_{e\mu}$

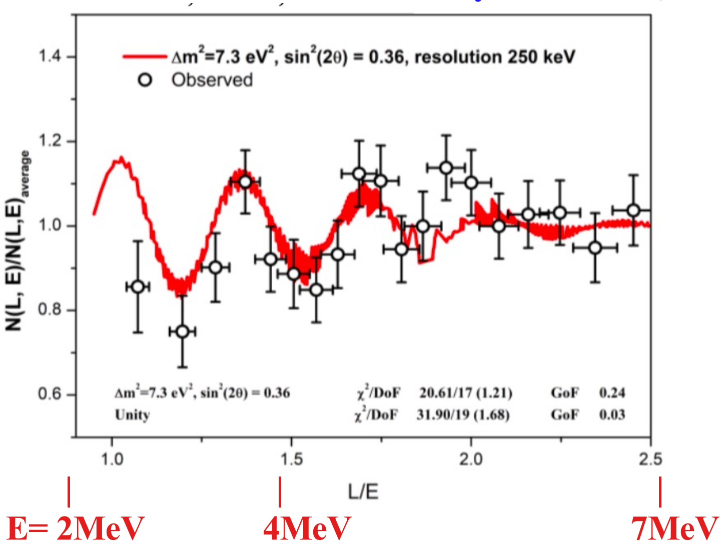
$P_{\mu e}$ $P_{\mu\mu}$

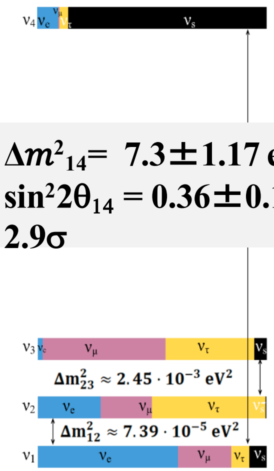
adding a 4th neutrino
➔ +2 parameters: $(U_{e4}, U_{\mu 4})$ + unitarity

NEUTRINO-4 ee

100 MW$_{thermal}$ @SM-3 reactor @Dimitrovgrad (Russia)
anti-neutrino detector (LS) @5m
ON/OFF measurement

Phys.Rev.D 104, 032003 (2021)





Δm^2_{14} = 7.3±1.17 eV²
$\sin^2 2\theta_{14}$ = 0.36±0.12
2.9σ

concerns / debates about:

- analysis
- energy resolution
- background
- …

➔ **oscillations: do not fit**
➔ **other explanations???**

other experiments with spectral information:

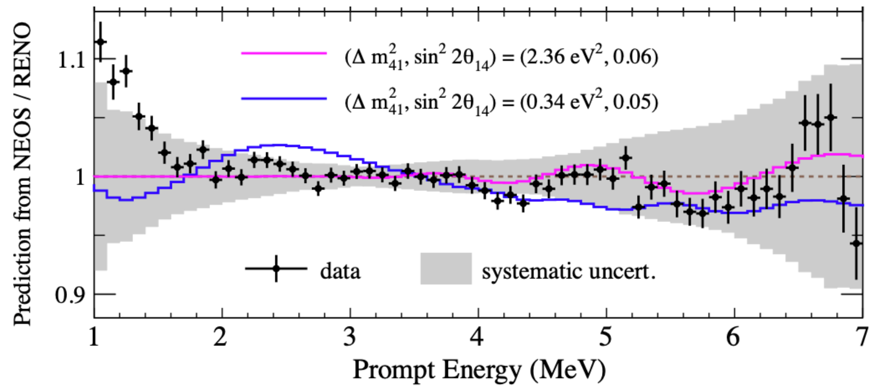
- **STEREO** (France), L = 9-11m
- **PROSPECT** (USA), L = 7-12m

} on-going combined analysis +Daya Bay ...stay tuned

- **DANSS** (Russia), L = 10.9-12.9m
- **SoLid** (Belgium), **PRD 111, 072005 (2025)**

➔ **no evidence**

- **NEOS** + RENO (Korea), commercial, L = 23.7 m



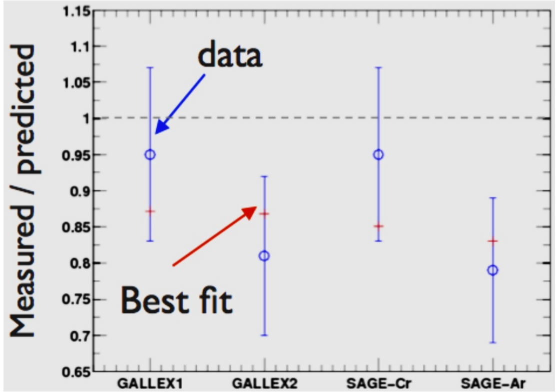
➔ **wiggles?** **PRD 105 (2022) L111101**
best fit $|\Delta m^2_{41}|$ =2.41eV² ; $\sin^2 2\theta_{14}$=0.08 (1σ)
➔ **combined with others... not significant**

experiments with near and far detector:
→ less reactor spectral uncertainties (bump, HE tail)

The Gallium Anomaly ee

$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$

calibrated with intense ^{51}Cr and ^{37}Ar sources
~20 years ago: **GALLEX/GNO** and **SAGE**
now: **BEST** (2022)



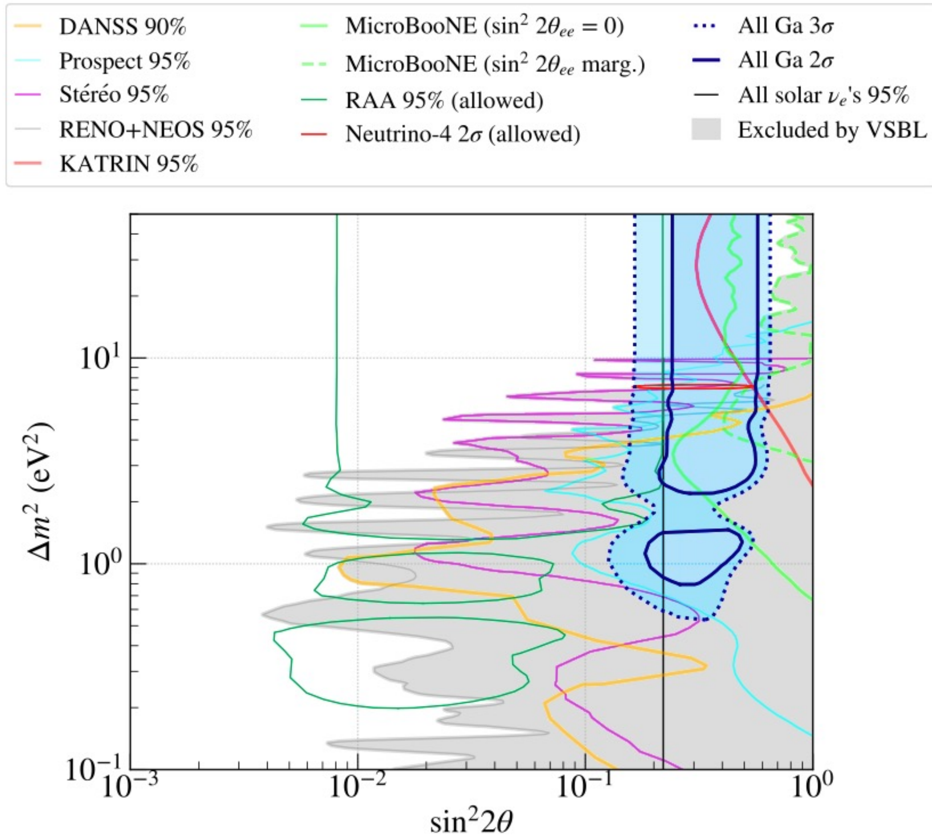
GALLEX
$$R_1(\mathrm{Cr}) = 0.953 \pm 0.11$$
$$R_2(\mathrm{Cr}) = 0.812 \pm 0.11$$

SAGE
$$R_3(\mathrm{Cr}) = 0.95 \pm 0.12$$
$$R_4(\mathrm{Ar}) = 0.79 \pm 0.095$$

BEST
$$R_5(\mathrm{I}) = 0.791 \pm 0.05$$
$$R_6(\mathrm{O}) = 0.766 \pm 0.05$$

➔ **0.80 ±0.05**
~ 4σ

PRC 105, 065502 (2022

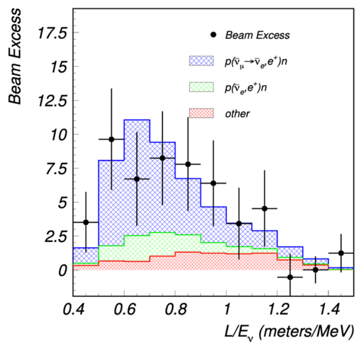


BEST confirms **GALLEX** and **SAGE** deficits
PRL 128, 232501 (2022)

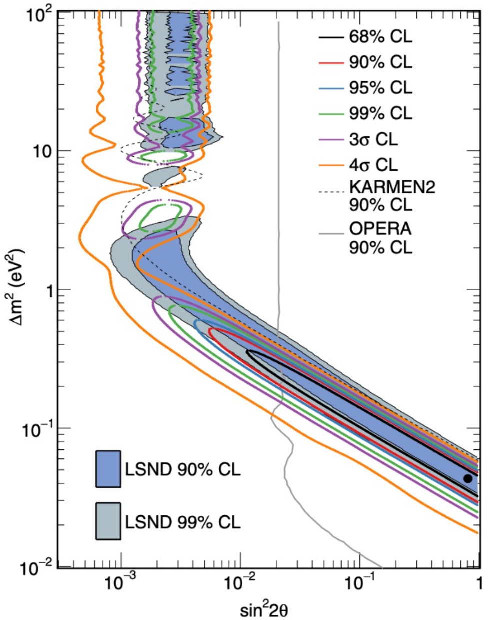
- **looks so far like a real effect**
- **oscillation into ν_s explanation excluded**
- **other physics? no known explanation**

LSND - MiniBooNE - MicroBooNE μe

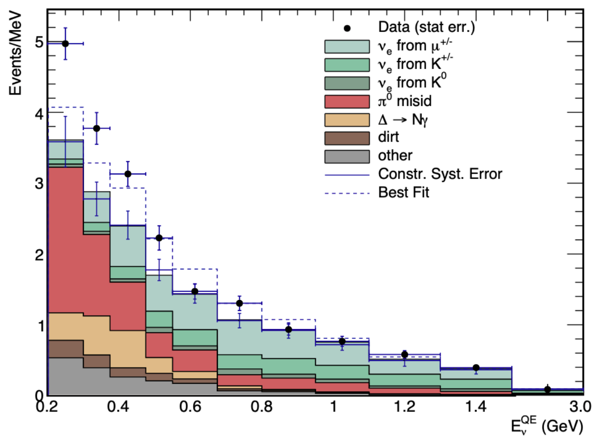
PRD 64:112007 (2001)

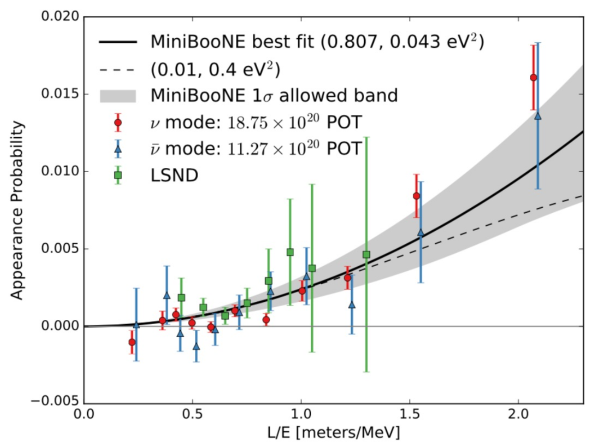


$\nu_\mu \rightarrow \nu_e$ appearance, ~30m
oscillation into ν_s ? → 3.8σ



PRL 121, 221801 (2018), PRD 103, 052002 (2021)

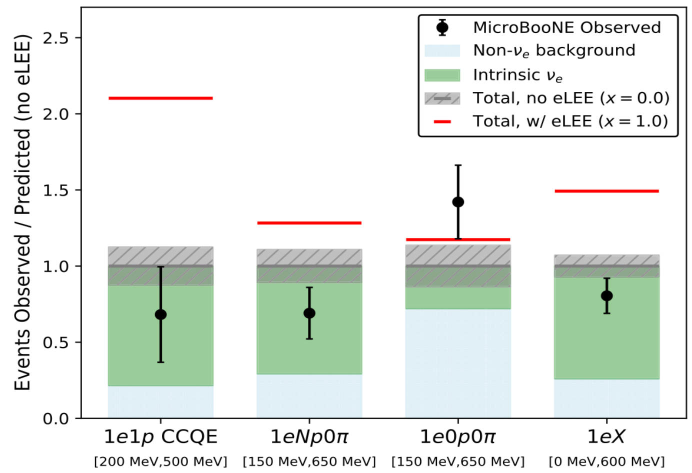




$\nu_\mu \rightarrow \nu_e$ appearance: 4.7σ
LSND + MiniBooNE: 6.1σ

PRL 128.241801 (2022)

inclusive and exclusive searches for ν_e CC



red = expected from **MiniBooNE**
→ **no excess of low-energy ν_e**

S. Martynenko @ NuDM24
MICROBOONE- Note-1127-PUB

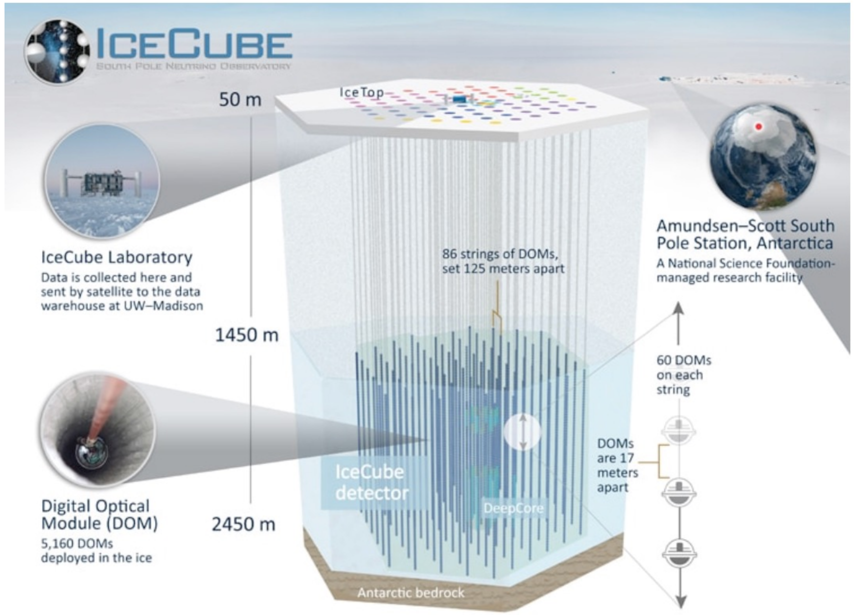
- ~65% more statistics
- new sideband constraints

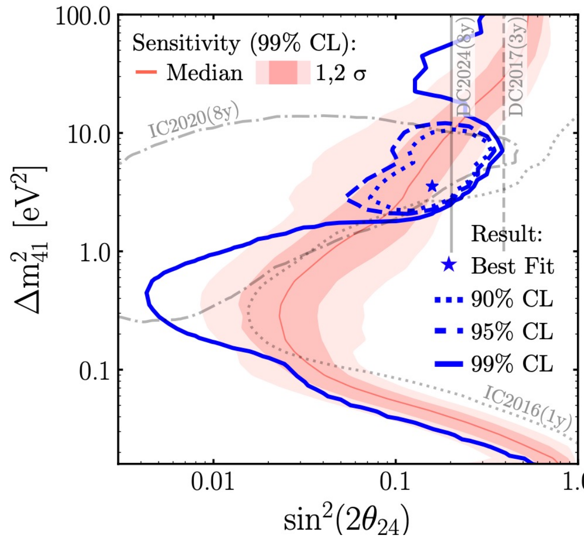
→ **no excess at > 99% CL**
oscillations: tension app. /disapp.

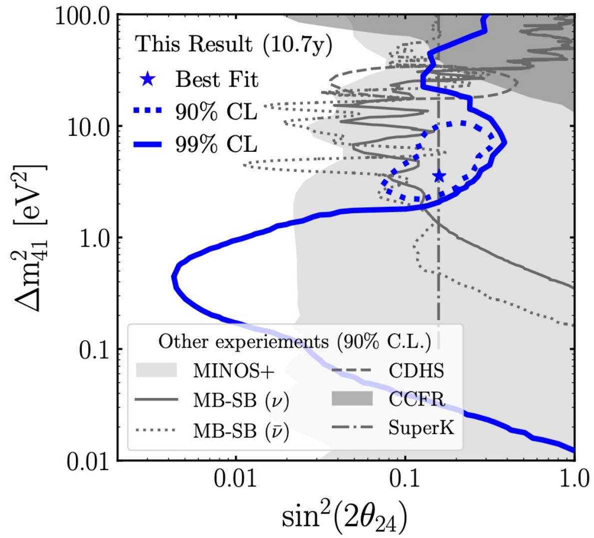
→ looking forward to FNAL SBN program

Atmospheric Neutrinos in ICECUBE μμ

- km^3 neutrino detector 1.5−2.5 km beneath the surface in the ice at the South Pole
- powerful sterile neutrino searches at both high (≥ 400 GeV) and low (≤ 60 GeV) energies
- **sensitive to ν_μ disappearance at eV^2**





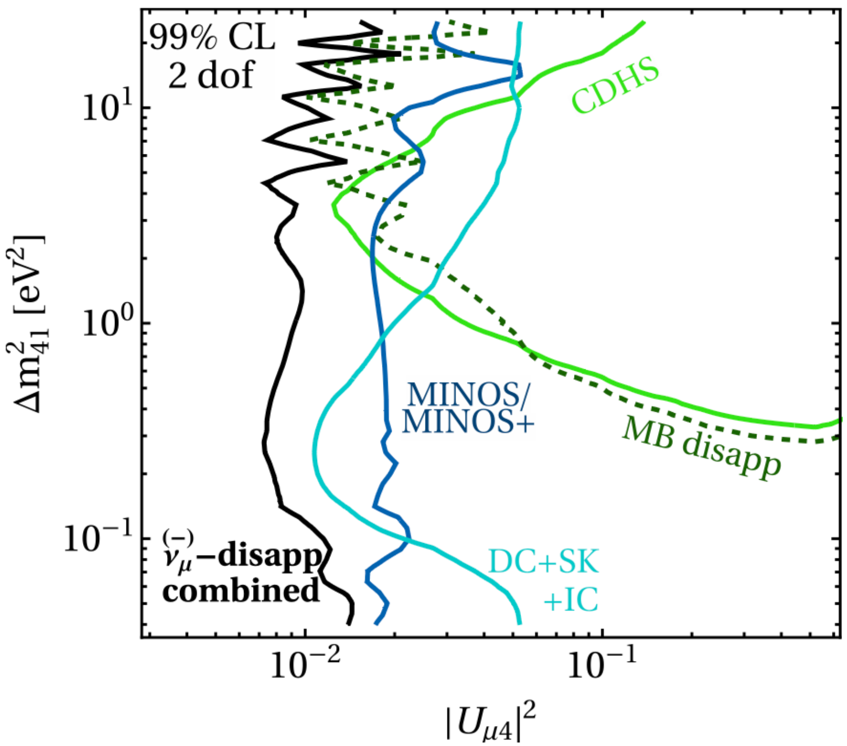


PRL 133 (2024) 20, 201804

- 3+1 sterile neutrino search using 10.7 years of IceCube data
- atmospheric ν_μ traversing Earth with 0.5-100 TeV
- best-fit for a 3+1 model: $\sin^2(2\theta_{24}) = 0.16$ and $\Delta m^2_{41} = 3.5$ eV^2
- **comparison to MINOS+ and others ➔ tension/unlikley**

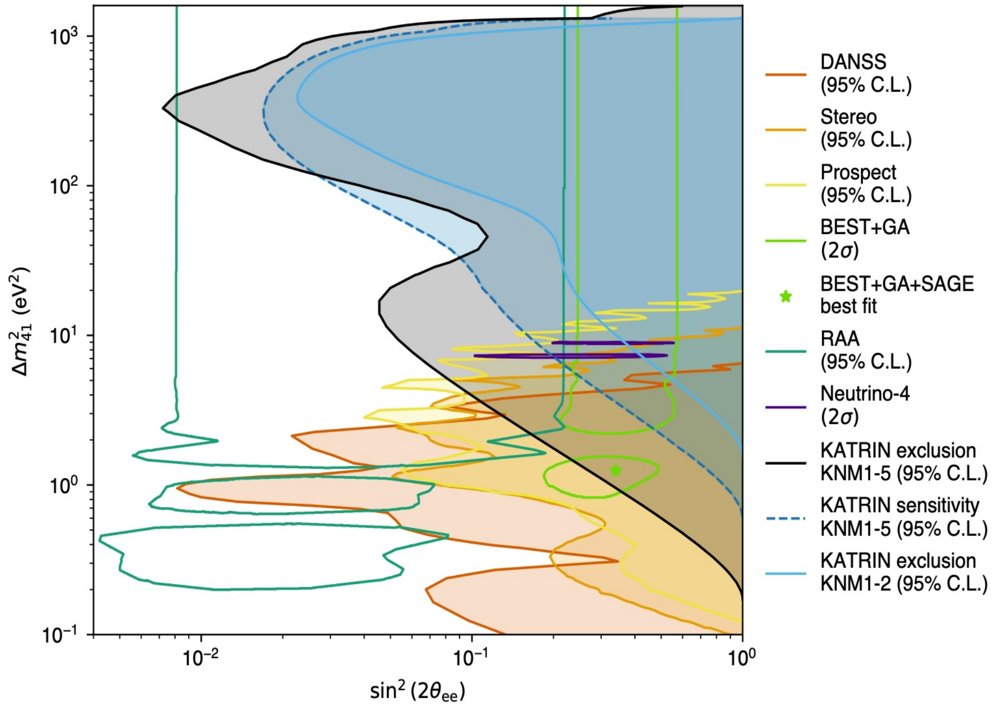
μμ Exclusion Limits ee

e,g, Dentler et al., JHEP 08 (2018) 010



a number of experiments with no hint for ν_μ disappearance

new result from KATRIN arXiv: 2503.18667



- **95% C.L. exclusion limits by KATRIN**

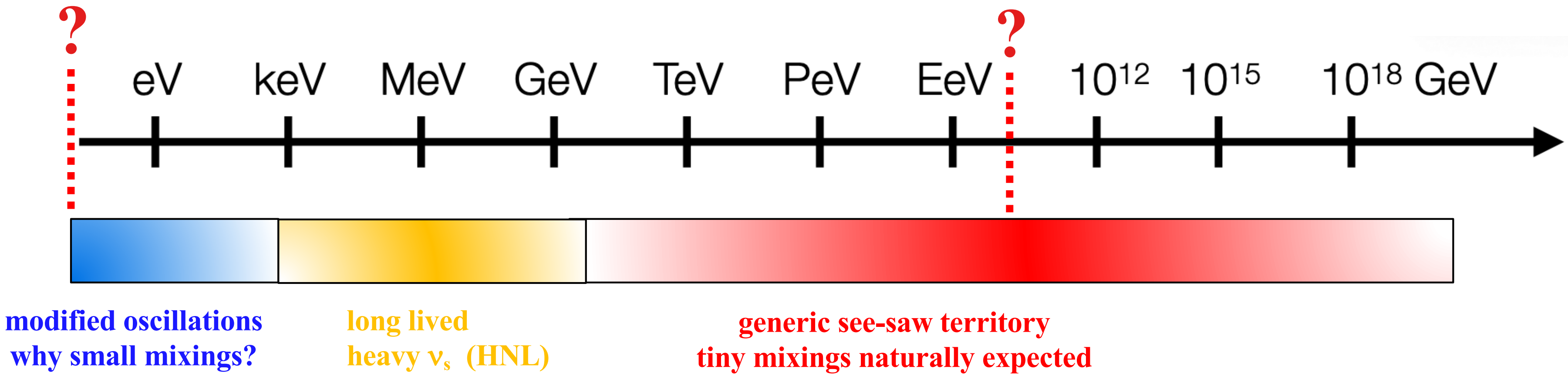
shown also:

- **DANSS**
- **STEREO**
- **Prospect**

anomalies do not fit to an oscillations interpretation

* reactor anomaly (RAA)
* gallium anomaly
* green star = best-fit BEST, GALLEX, SAGE
* Neutino-4 (purple)

Sterile Neutrinos: A Bigger Perspective



anomalies:

3+1 ➔ tension in data samples

3+2, 3+n ...???

persist? ➔ other mechanisms?

oscillation is an assumptions

➔ alternatives...

- decay
- NSI = short distance transition
- time dependent
- dark sectors
- ...

\+ **see-saw ←→ BAU**

←→ many other BAU mechanisms

\- 3^{rd} hierarchy problem if M_R too heavy

← improved EW fits with TeV-ish sterile ν_s,

← $\mathbf{M_R = g_Y \bullet <\phi>}$ with heavy $<\phi>$ and tiny g_Y

- many connections to BSM, dark sectors,...
- cosmology

  \- keV sterile neutrinos as dark matter

  \- DESI+Planck+CMB

  $\Sigma m_\nu < 0.064$eV, $\Delta N_{eff} = 3.23 \pm 0.34$ (SM=3.04)

➔ very important to clarify anomalies

sterile ν's: no clear sign, but still well motivated!

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

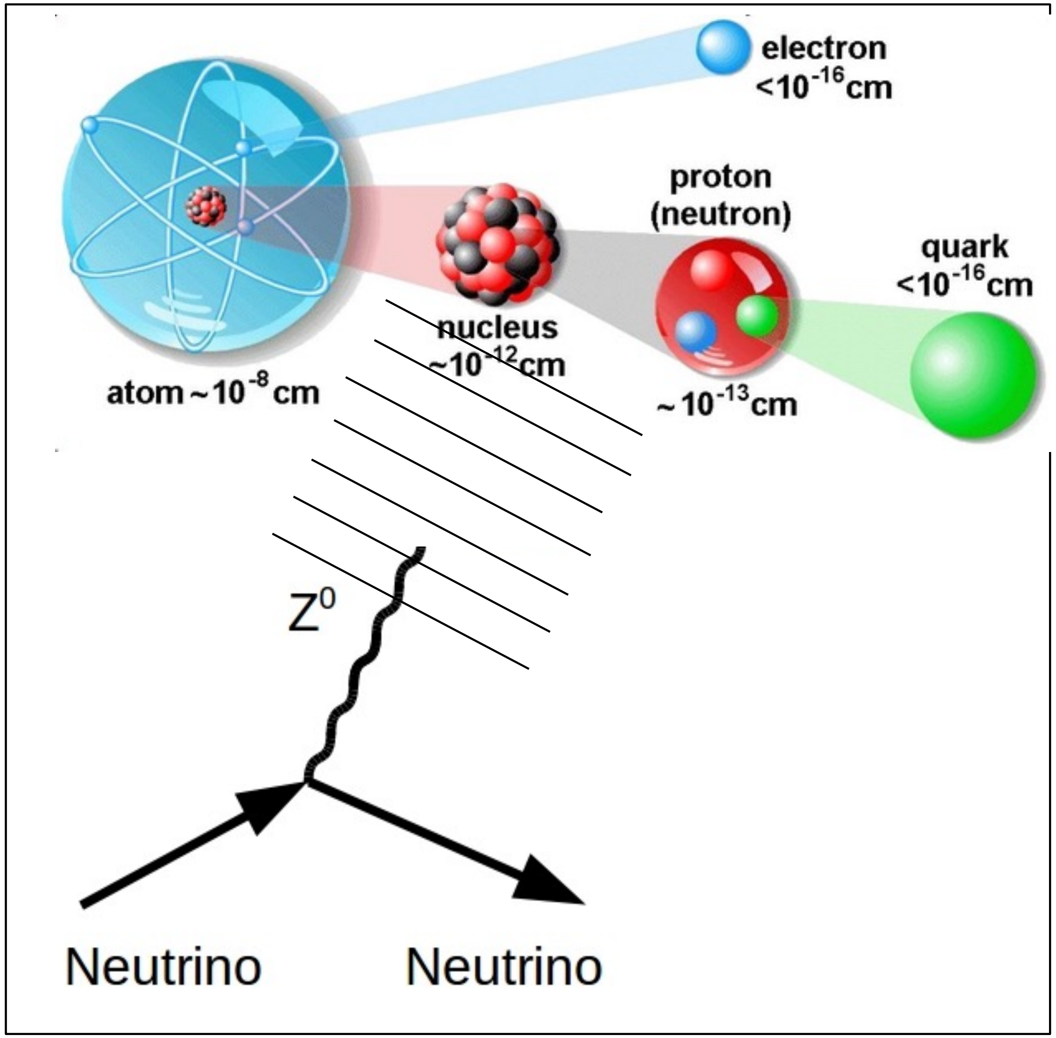
The simple picture:

1. ν-wavelength big enough
   → Z scattering @whole nucleus
2. small momentum transfer

   ➔ **coherent scattering**

- Coherence length ~ 1/E
  - E_ν below O(50) MeV
  - lower for full coherence

- cross section ~$(E_\nu)^2$
  → overcompensate:
  - very high ν flux
  - coherence ~ N^2



E.g. Germanium target:
N $\simeq$ 40-44 ➔ $N^2 \simeq$ 1600-1900 ➔ conventional detector mass 10t ←→ few kg

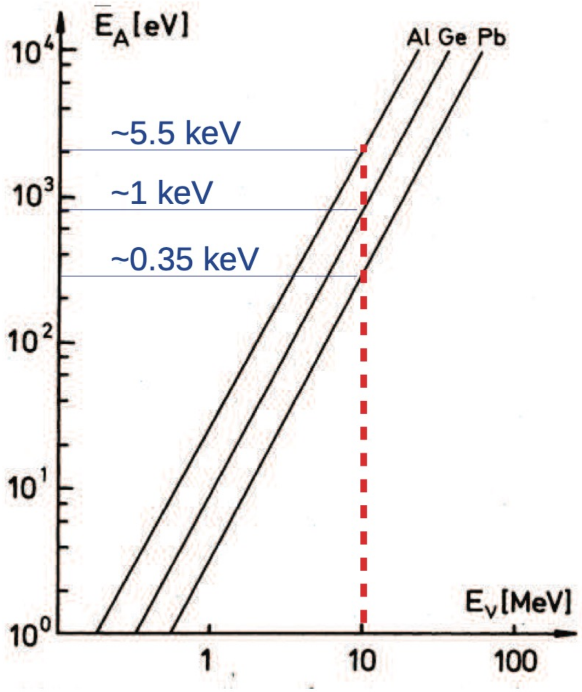
Z-scattering of ν with whole nucleus

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

$$Q_w = N - \underbrace{(1 - 4\sin^2\theta_w)}_{\simeq 0} Z \quad \sim \mathbf{N}$$

- neutrons dominate: $\sigma \sim N^2$ → enhancement
- form factor $F(Q^2)$ ←→ size of nucleus
- form factor matters for E_ν = 20-50 MeV
- $F(Q^2)$ → 1 for $E_\nu \ll 50$ MeV
- kinematics:

  M: mass of nucleus
  E_ν: neutrino energy
  T: nuclear recoil energy
  θ: scattering angle

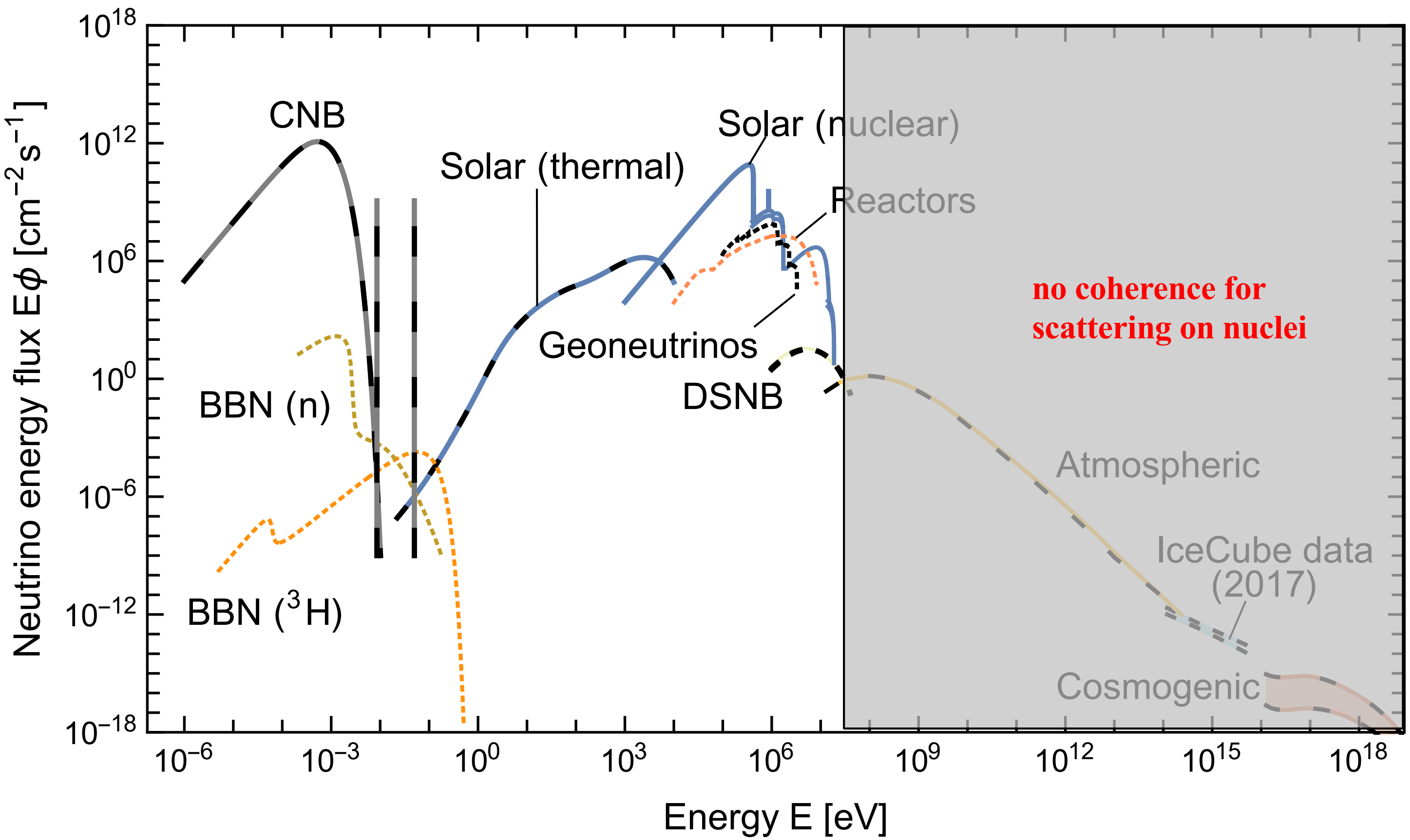


A.Drukier, L.Stodolsky, Phys.Rev.D 30 (1984) 11

$$|\vec{q}| = \sqrt{2MT} = \sqrt{2E_\nu^2(1-\cos\theta)}$$

→ very small momentum transfer

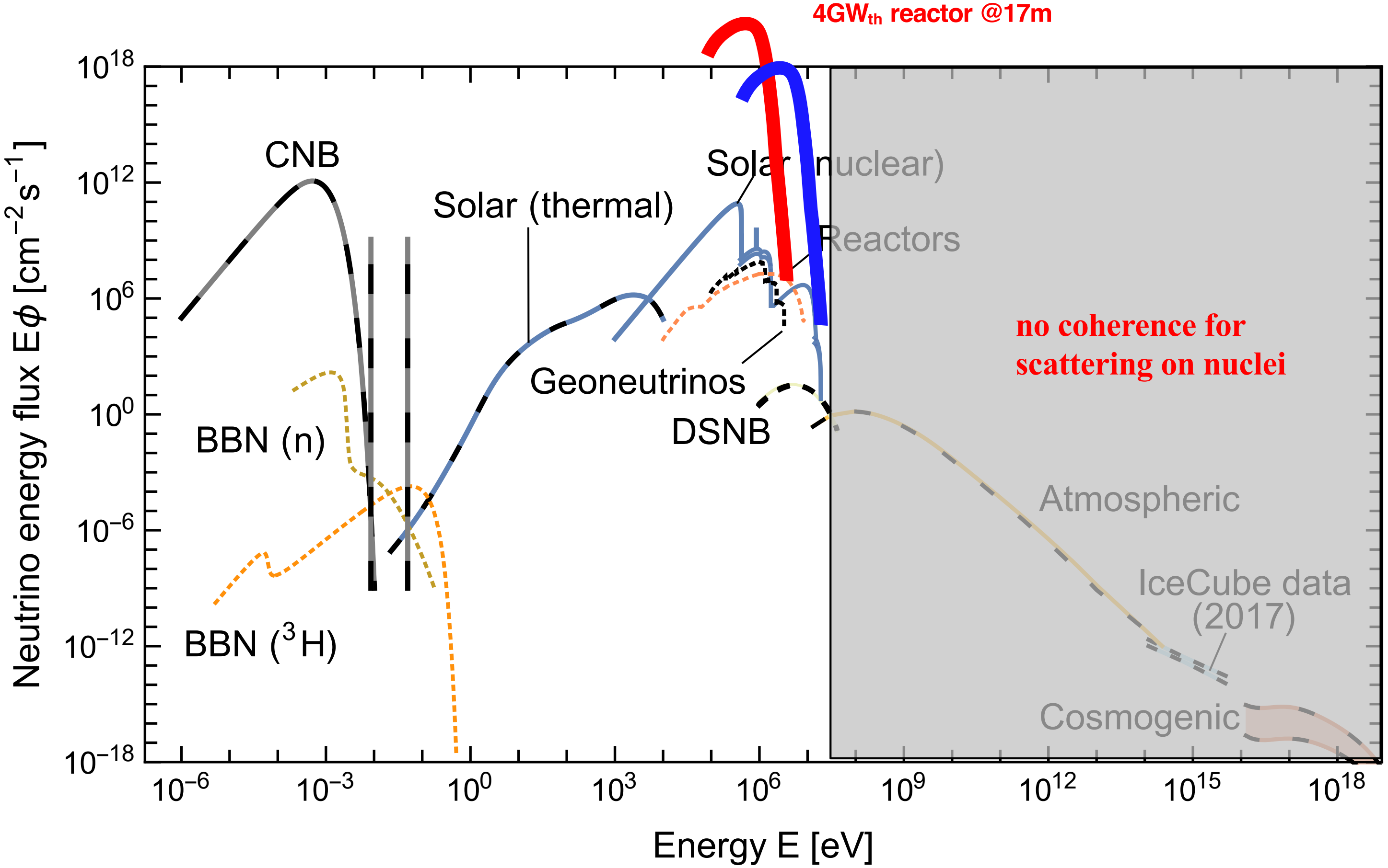
Neutrino Sources: Flux ⊗ Energy



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

Neutrino Sources: Flux ⊗ Energy

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

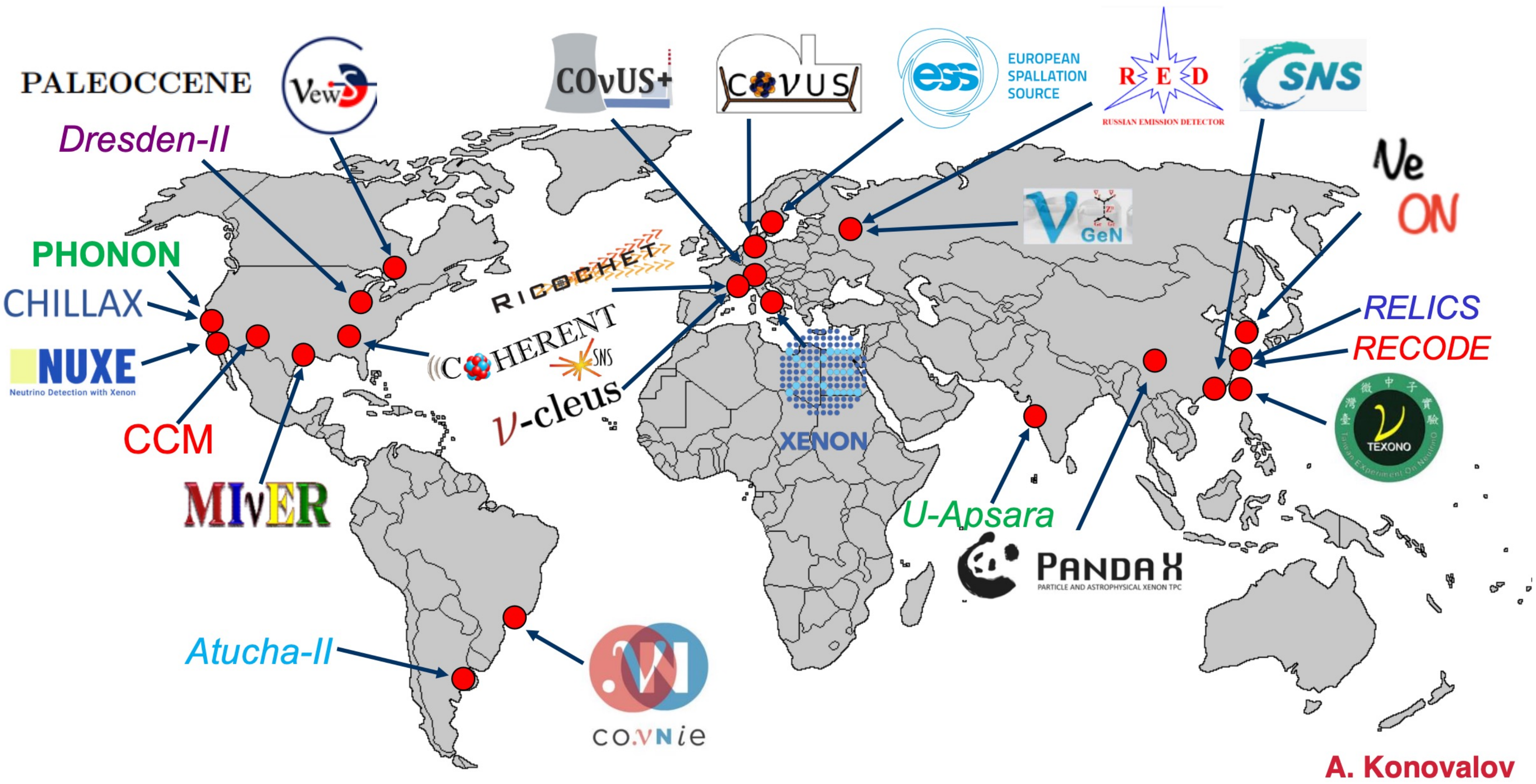


Vitagliano, Tamborra, Raffelt
Rev.Mod.Phys. 92 (2020) 45006
arXiv:1910.11878

➔ event rates: flux ⊗ detector size ⊗ time ←→ backgrounds

➔ sources: beams, reactors, Sun, supernovae

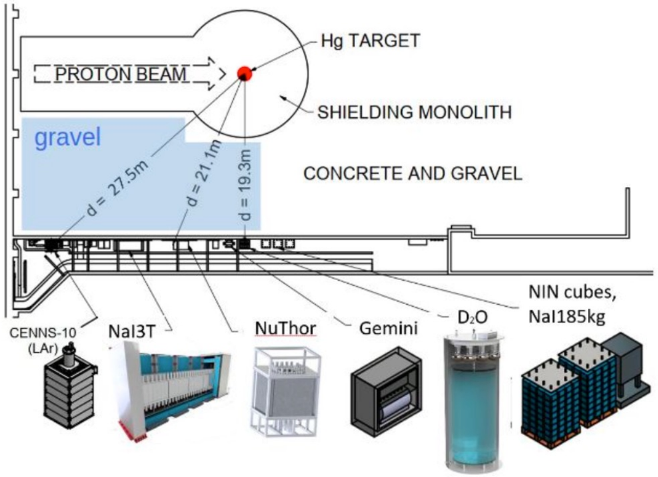
CEvNS Projects in the World

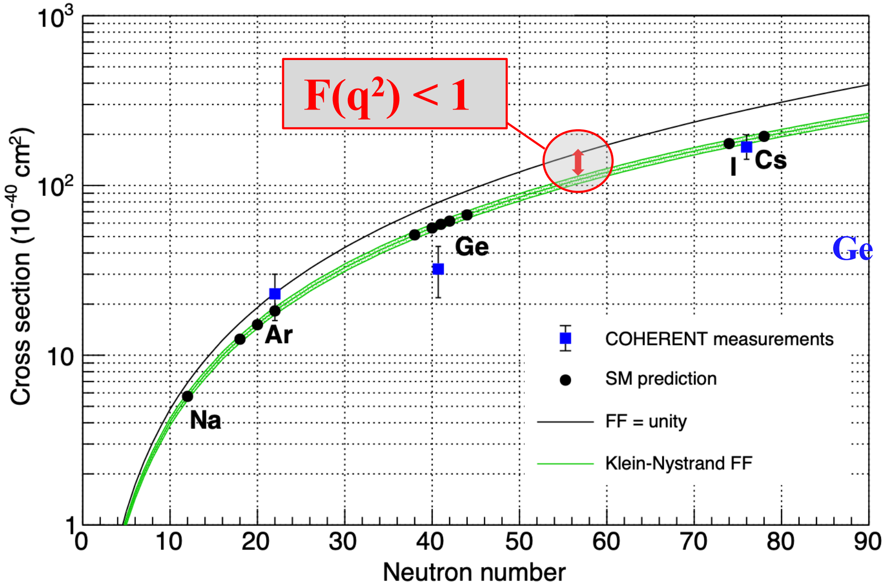


1974 –D. Freedman: coherent scattering of neutrinos on the whole nucleus (CEνNS)
2017 – observation by COHERENT in stopped π-beams ←→ F(q²) - not fully coherent
2024 – solar ^{8}B neutrinos by XENONnT and PandaX
2025 – CONUS+ with reactor neutrinos

COHERENT

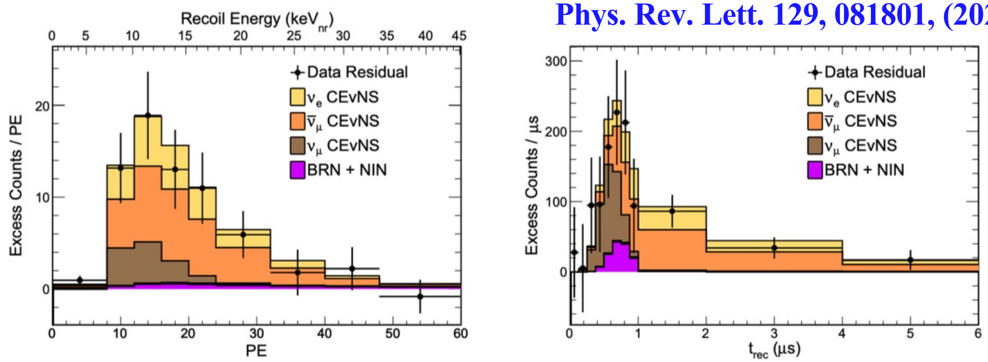
Spallation Neutron Spource (SNS)
@Oak Ridge National Laboratory, USA





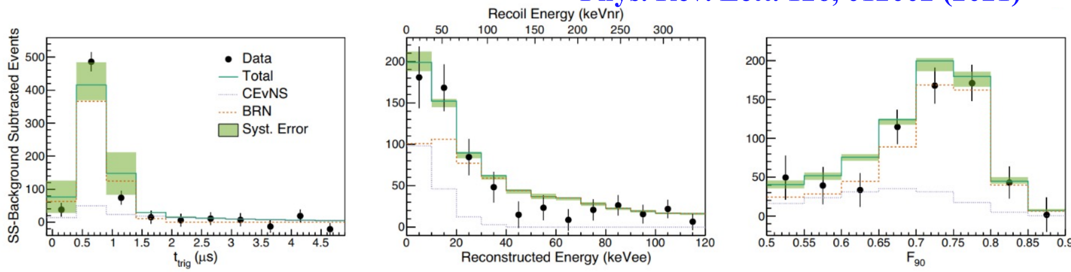
Phys. Rev. Lett. 129, 081801, (2022)

CsI



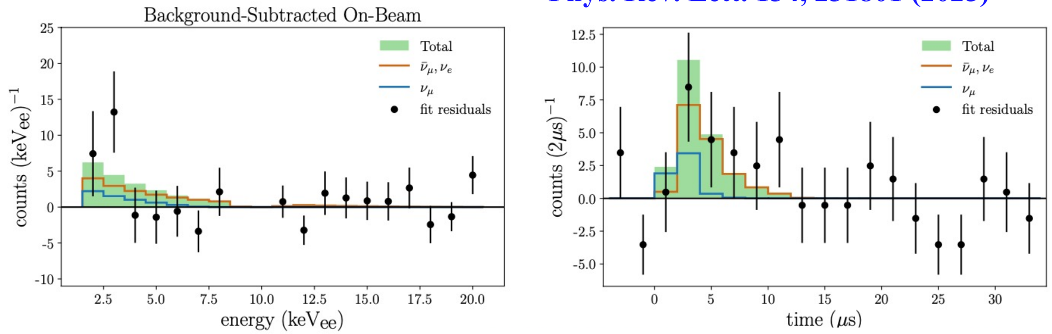
Phys. Rev. Lett. 126, 012002 (2021)

Ar



Phys. Rev. Lett. 134, 231801 (2025)

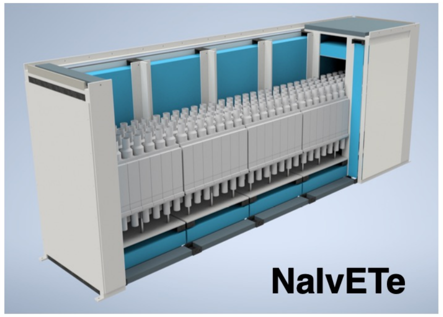
Ge



Future COHERENT

- continue data taking ➔ improvements to come
- on-going upgrades

- SNS Proton Power Upgrade complete
- Ge acquiring 6x statistics in 2025 as PRL release, lower thresholds and backgrounds
- $D_2$0 addressing leading syst. uncertainty
- 750-kg LAr target commissioning at ORNL now; will see ~5000 events/year
- 2.4 tn NaIvETe (NaI) taking data in 2025
- Cryo-CsI R&D in progress
- NuThor observed ν-induced fission
- Pb glass 22 tn detector for inelastic in the works

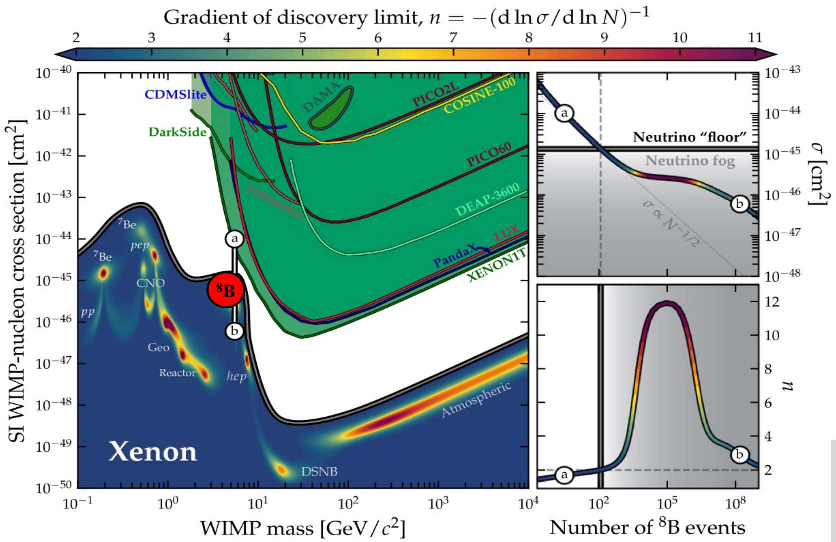


➔ **towards precision CEνNS**

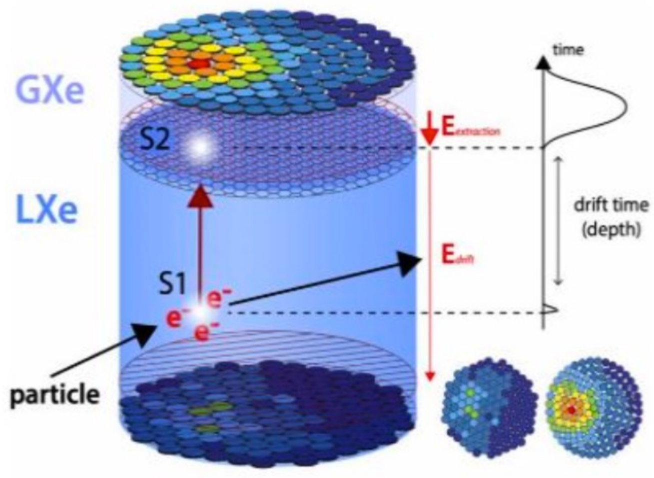
XENONnT and PandaX

- solar neutrinos (^{8}B)
- atmospheric neutrinos

➔ "neutrino fog" in DM experiments



O'Hare, PRL 127 (2021) 251802



XENONnT - 2.7σ
PRL 133, 191002 (2024)

lowered S1,S2 thresholds
NR signals as low as 0.5 keV
exposure 3.51 t × yr
best-fit: 10.7+3.7−4.2 ^{8}B events

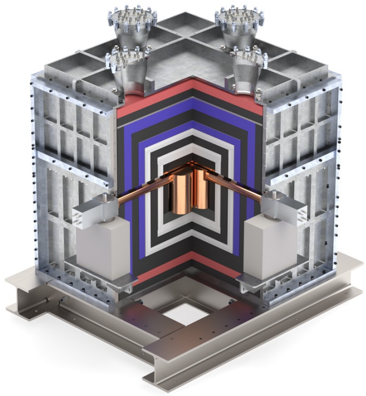
PandaX-4T - 2.6σ
PRL 133, 191001 (2024)

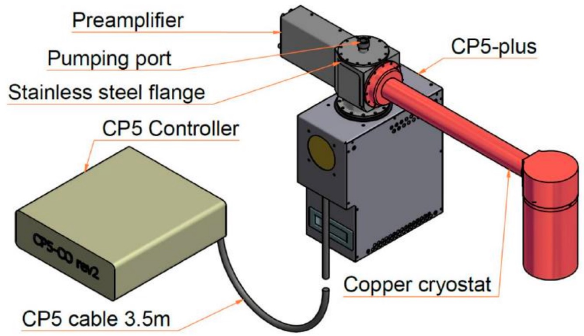
2 channels (paired S1-S2, US2)
thresholds of 1.1 and 0.33 keV
1.20 and 1.04 t × yr
3.5±1.3 (paired) ; 75±28 (US2)

future: +LZ, more statistics

long term: XLZD, PandaxT ➔ precision CEνNS

CONUS+

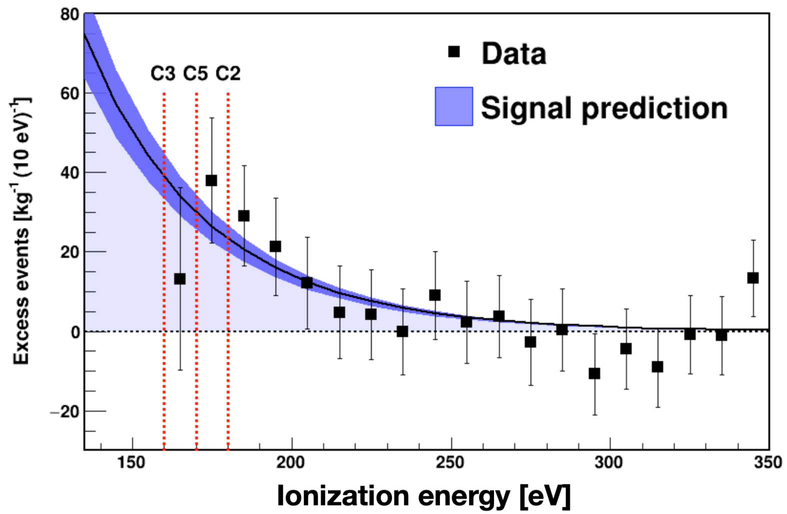




Leibstadt nuclear power plant, CH (KKL)

3.6 GW_{th} , 20.7m → flux: $1.45*10^{13}$ ν/cm²/s

- sophisticated shield → ``virtual depth”
- improved veto systems
- extensive bckg measurements (n, μ‘s, materials,...)
- 4 × 1kg low bckg point-contact HPGe detectors
- pulse shape discrimination (slow pulses)
- ASIC electronics (improved low E trigger efficiency)
- reduced point contact size & bonding technology
- lower threshold: **~250 → 160 eV**
- very sophisticated & well tested bckg model
- **$F(Q^2) = 1$ → deviations → BSM**



Nature 643, 1229 (2025)

395 ± 106 CEvNS events → 3.7σ

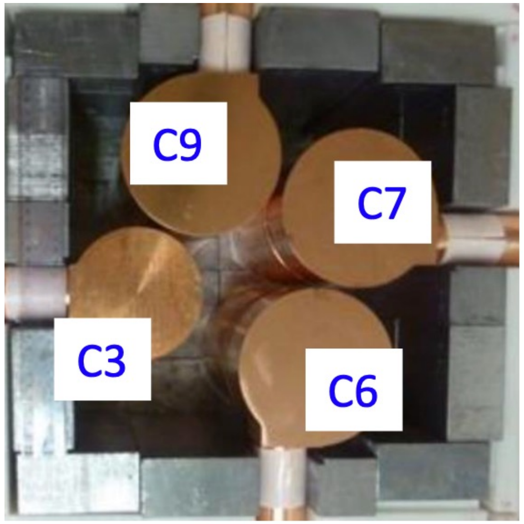
1st detection of CEvNS with reactor ν’s!

Comparison of CEνNS Results

Experiment	Target	Source	Neutrino energy	Flux $[cm^{-2}s^{-1}]$	Data [counts]	Data/ SM prediction	Significance of null hypothesis rejection
COHERENT	Cs	Accelerator	10 – 50 MeV	$5 * 10^7$	306^{+20}_{-20}	$0.90^{+0.14}_{-0.14}$	$11.6\,\sigma$
COHERENT	Ar	Accelerator	10 – 50 MeV	$5 * 10^7$	140^{+40}_{-40}	$1.22^{+0.49}_{-0.49}$	$3.5\,\sigma$
COHERENT	Ge	Accelerator	10 – 50 MeV	$5 * 10^7$	21^{+7}_{-6}	$0.59^{+0.26}_{-0.24}$	$3.9\,\sigma$
XENONnT	Xe	Sun (^{8}B)	< 15 MeV	$5 * 10^6$	11^{+4}_{-2}	$0.90^{+0.65}_{-0.67}$	$2.73\,\sigma$
PandaX-4T	Xe	Sun (^{8}B)	< 15 MeV	$5 * 10^6$	4^{+1}_{-1}	$1.25^{+0.69}_{-0.69}$	$2.64\,\sigma$
CONUS+	Ge	Reactor	< 10 MeV	$1.5 * 10^{13}$	395^{+106}_{-106}	1.14^{+036}_{-036}	$3.7\,\sigma$

➔ all will collect more statistics ; longer term ➔ expect precision

Future of CONUS+

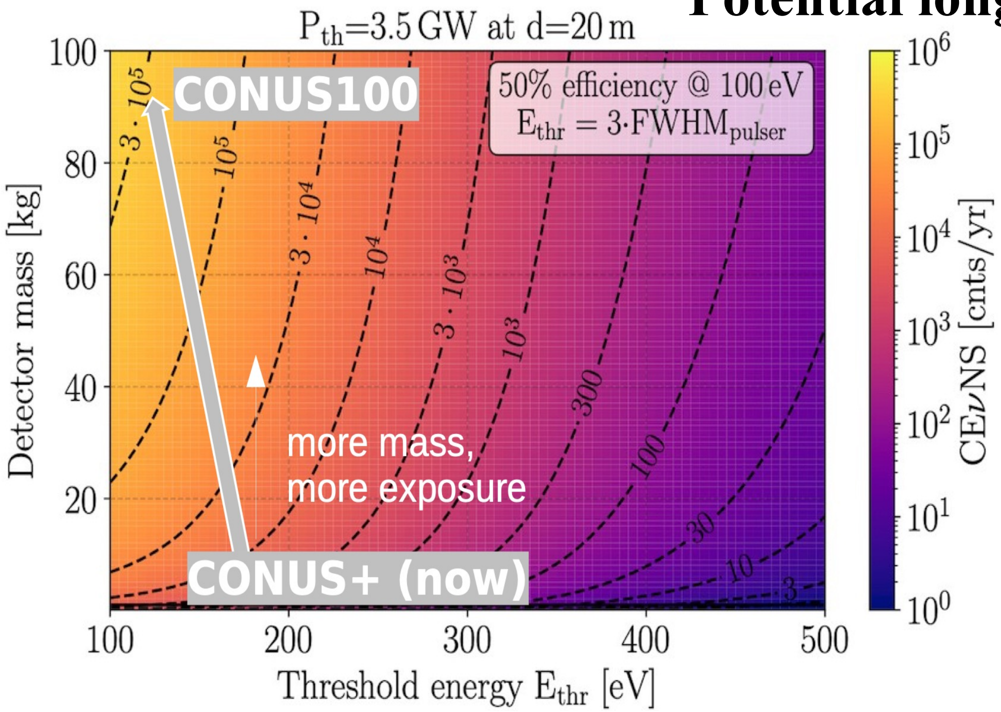


- new 2.4 kg PPC Ge detectors 3 kg → 1+3*2.4 = 8.2 kg
- various improvements (background, threshold, ...)
- installed in 11/2024
- taking data → improved results O(1yr)

➔ **improved CEνNS results on shorter time scales**

Potential long term potential of established technology

ML, T. Rink, M. Sen, JHEP 08 (2024) 171



- scaling to O(100kg) Germanium
- even lower threshold seems feasible
- 5 years of operation

→ **500.000 events in 5y conceivable**

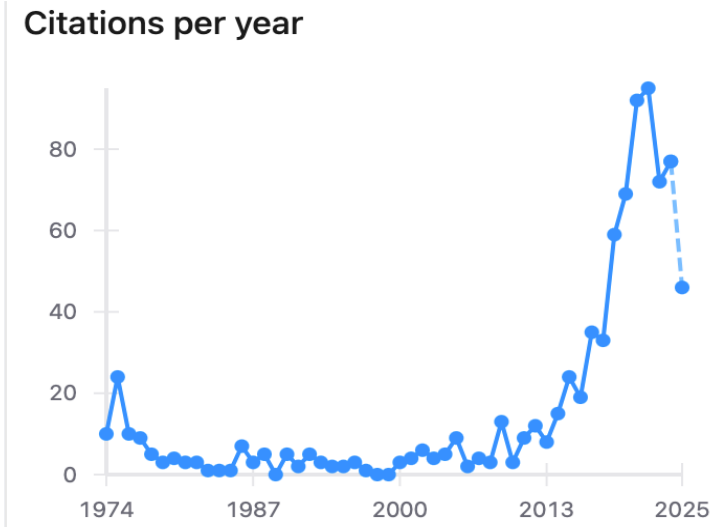
➔ **precision CEνNS physics**

Many interesting CEvNS Topics

- clean SM cross sections
- $\sin^2\theta_W$ at low energies
- Sterile neutrino searches
- ν magnetic moment, $\langle r_\nu^2 \rangle$
- ν millicharges
- NSI operators
- Tests of lepton universality

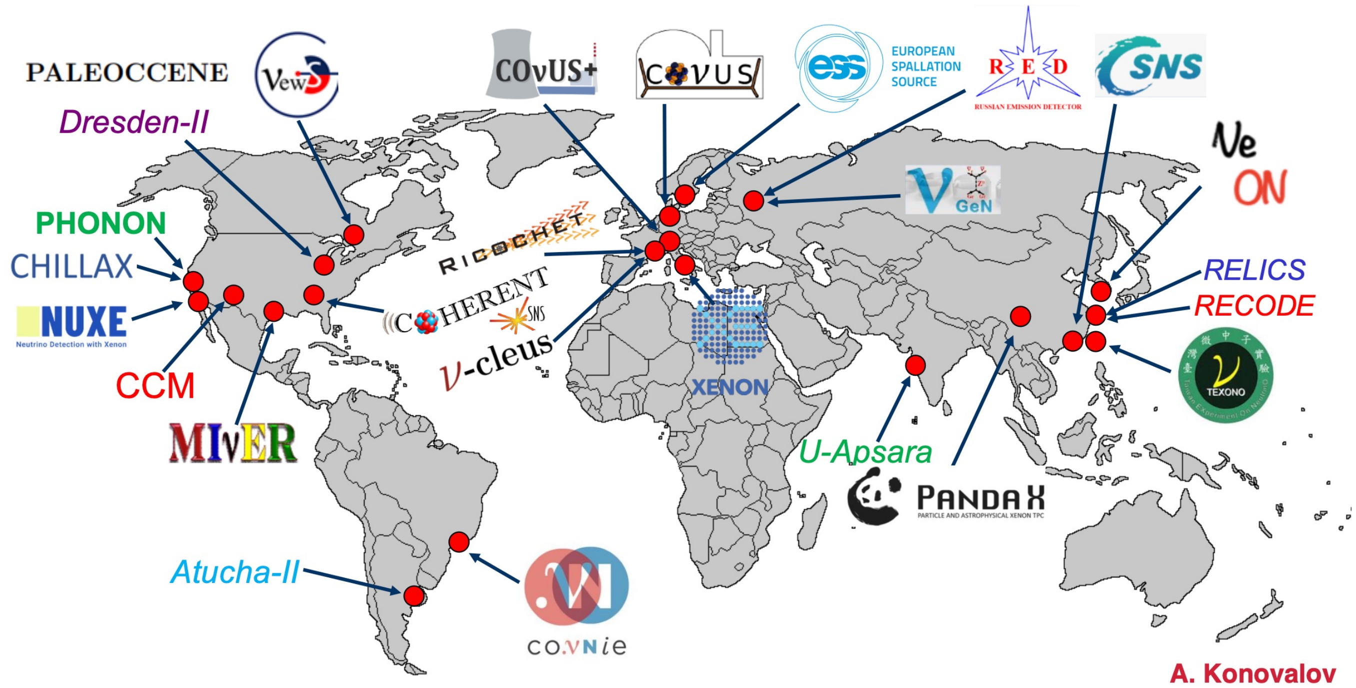
} unique BSM sensitivity

D.Z. Freedman, PRD9, 1389 (1974)



- Connections to models of dark matter
- Measurements of neutron formfactors (nuclear structure) → unique
- Nuclear reactor monitoring (non-proliferation) → applications
- Flux & spectral measurements → synergy w. oscillation experiments
- CEvNS & energy transport in supernovae → important for next SN
- SN neutrino detection → SNEWS, pointing, ...
- Connection to dark matter direct detection (ν floor) → solar ν's

Other CEνNS Experiments



various very promising other technologies & experiments

→ very interesting, healthy & motivating competition

→ see parallel sessions for status & details: .....

➔ moving to precision CEνNS physics

very interesting potential to test / discover BSM physics

Conclusions

Sterile neutrinos: many reasons - very well motivated: simple see-saw + many variants

- **so far limits assuming oscillations (ee, μμ, μe)**
- **anomalies which do not fit into an oscillation picture**
  → might hint some other new physics or might go away
  → very important to clarify
- **constraints from cosmology and astrophysics**

CEvNS: finally observed O(50) years after invention

- COHERENT (stopped π beam)
- XENONnT and PandaX-4T (solar ^{8}B ν's)
- CONUS+ (reactor neutrinos)

} improved results to come
+ other experiments coming online

- so far consistent with SM expectations → already very interesting BSM limits
- all aim at upgrades which will lead to significantly increased statistics
  → moving towards an aera of precision neutrino physics

ν masses: 1st BSM physics → much more than masses & mixings

More Details in Parallel Talks

sterile neutrinos

Gallium anomaly:	CIUFFOLI, Emilio BENATO, Giovanni JI, Xiangpan
MicroBooNE:	LUO, Xiao JI, Xiangpan
KATRIN:	MOHANTY, Shailaja NAVA, Andre
DANSS:	ALEKSEEV, Igor SVIRIDA, Dmitry
Daya Bay:	LI, Ruhui
SBND:	WESTER, Thomas
LiF crystals:	WOO, KyungRae
Jinping Neutrino Experiment (JNE):	ZHU, Yutao

CEνNS

nuGeN:	LUBASHEVSKIY, Alexey
NUCLEUS:	BOSSIO, Elisabetta
CONNIE:	AGUILAR-AREVALO, Alexis
XENON:	LI, Shengchao LIU, Kexin
COHERENT:	LIU, Jing
RED-100:	KOZLOVA, Ekaterina
Ga-anomaly:	BENATO, Giovanni
RELICS:	XIE, Lingfeng
NR tracking:	CARATELLI, David
CONUS+:	LINDNER, Manfred