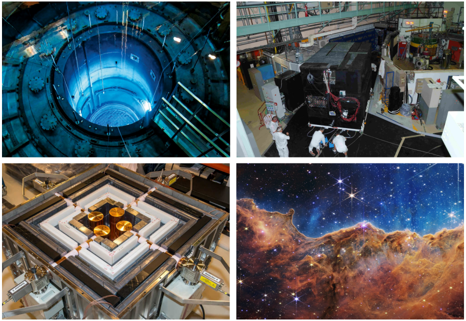
From nuclear reactor neutrinos
to nuclear fusion reactions in stars

Aurélie Bonhomme
IPHC/DRS/DNE



January 20, 2023

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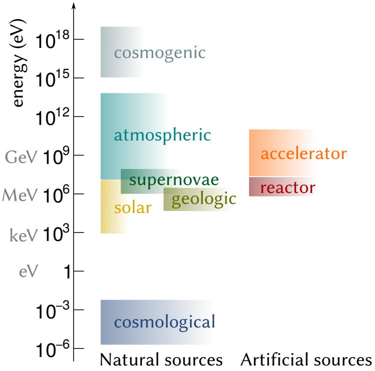
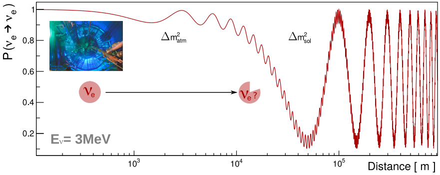
Experimental neutrino physics: history in a nutshell

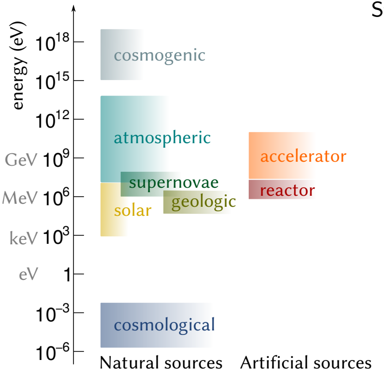


$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}_{\text{interaction}} = \underbrace{\mathrm{U_{PMNS}}}_{Mixing} \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}_{\text{propagation}}$$

- 1956: first detection! (reactor ν)
  IBD: p + $\bar{\nu}_e \rightarrow$ n + e^+: $\sigma \sim 6 \times 10^{-44} cm^2$
- 1962: ν exist in **different flavors:**
  leptonic flavors ν_e, ν_μ, ν_τ
- 1973: discovery of **weak neutral currents**
- 1998: Super-Kamiokande (atmospheric ν)
  2002: SNO – (solar *nu*)
  → awarded by the Nobel Prize 2015 "*for the discovery of neutrino oscillations, which shows that neutrinos have mass.*"



Experimental neutrino physics: a very promising program!



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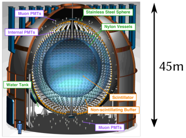
Still a lot of **open questions**:

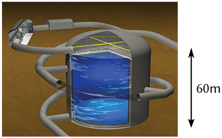
- Mass ordering?
  JUNO, KM3Net, HK, DUNE...
- CP violation?
  T2K/HK, DUNE
- Absolute mass? Nature?
  Katrin, Gerda, Cupid...
- Presence of sterile neutrino states? **STEREO**
- Non standard interactions? **CONUS**

Juno



20,000 tons of liquid scintillator

Hyper-Kamiokande



260,000 tons of water

Reactor neutrino experiments: power plants as intense sources

Fission of ^{235}U (+ ^{239}Pu, ^{238}U and ^{241}Pu):
$\bar{\nu}_e$ from (thousands of) β-decays of fission fragments (up to $\sim 10\,\mathrm{MeV}$)

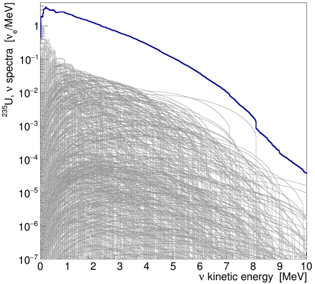
thermal power

isotopic fission fractions

$$S(E_\nu) = \frac{1}{4\pi L^2}\,\frac{W_{th}}{\sum_i \alpha_i E_i}\,\sum_i \alpha_i \,.\, S_i(E_\nu)$$

energy per fission

For each fission isotope i: $S_i(E_\nu) = \sum_j b_j E_{\beta\ j}(E_\nu)$



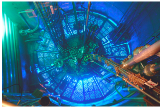
Experimentally:

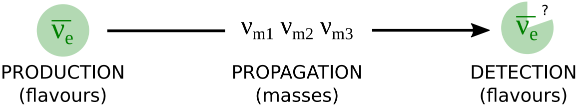
- Direct measure at reactors:
  Double Chooz, Daya Bay, RENO
  → measure of osc. param. θ_{13}
  → provide very precise reference measurements for comparison

Predictions:

- Summation method
  sum of all branches from nuclear databases
- Conversion method (HM) – reference
  data-driven approach, effective conversion of *virtual* β branches from e$^-$ to $\bar{\nu}_e$ spectrum

The Reactor Antineutrino Anomaly (RAA)





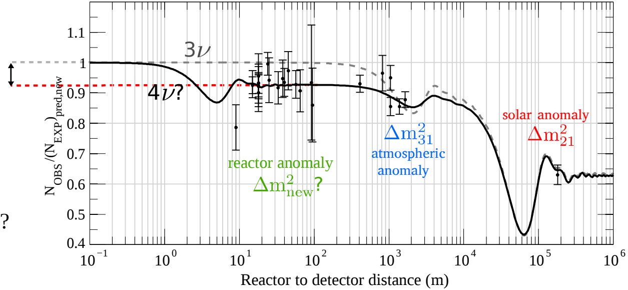
PRODUCTION
(flavours)

PROPAGATION
(masses)

DETECTION
(flavours)

$$\boxed{P_{\text{survival}}(L, E) = 1 - \sin^2(2\theta)\,.\,\sin^2(1.27\Delta m^2\,.\,L/E)}$$

~ 6 % deficit



- **Sterile neutrino ?**
- Wrong prediction ?

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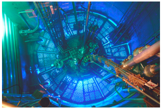

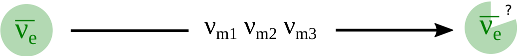

$\bar{\nu}_e$ —— $\nu_{m1}\ \nu_{m2}\ \nu_{m3}$ ⟶ $\bar{\nu}_e$?

PRODUCTION
(flavours)

PROPAGATION
(masses)

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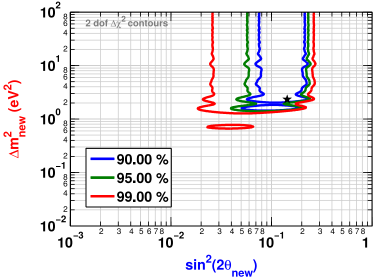

Phys. Rev. D **83**, 073006 (2011)

$L/E \sim 10\,\mathrm{m}/3\,\mathrm{MeV} \rightarrow \sim$ **1eV sterile neutrino**

Two new parameters: $\sin^2(2\theta_{new})$ and Δm^2_{new}

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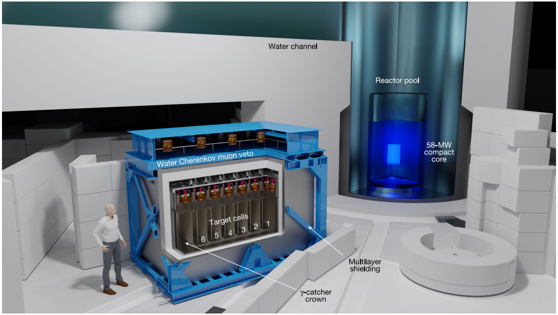
The STEREO experiment

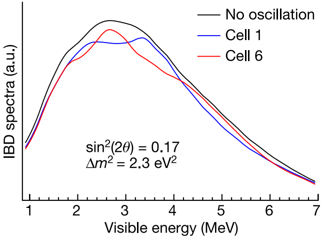
STEREO @ the ILL research facility, Grenoble:

- Data taking 2017-2020
- Pure ^{235}U $\bar{\nu}_e$ flux @10m
  58 MW$_{th}$ reactor core
  $10^{19}\ \bar{\nu}_e\ s^{-1}$

STEREO collaboration:
~30 scientists, 5 institutes



Nature **613**, 257–261 (2023)

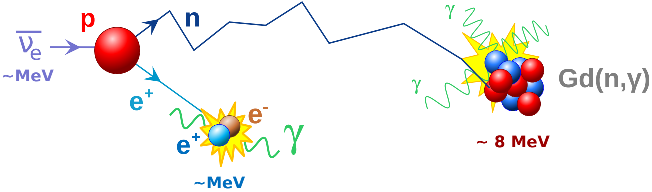


Designed for a relative measurement in 6 identical filled with Gd doped liquid scintillator

oscillation → energy distorsions

$\bar{\nu}_e$ detection principle

$\bar{\nu}_e$ signature: **I**nverse **B**eta **D**ecay (**IBD**) reaction: $\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$



Prompt
⇒ $\bar{\nu}_e$ **energy**

Delayed
⇒ **tagging**

STEREO challenges:

- ~ 400 $\bar{\nu}_e$/day: statistics, long-term measurement → stability
- see-level (15 m w.e. overburden) → cosmic background!
- precise energy measurement, comparison to MC → energy scale, detector response

Stability and precision of the energy scale

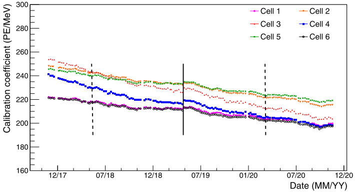
Phys. Rev. D **102** (2020) 5, 052002

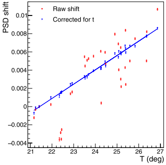
- Control of the detector response: calibration monitoring, correction of drifts, MC tuning

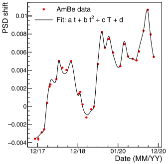
  → Reconstructed energy stable at 0.25 % level over three years of data taking

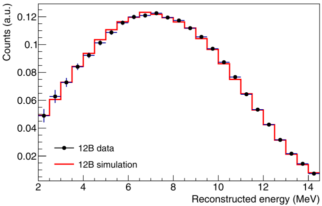
- Accurate control of the energy scale:

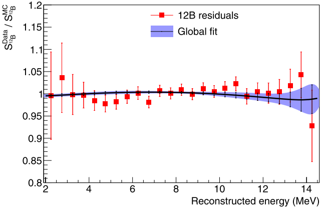
  → Distortions constrained at the percent level







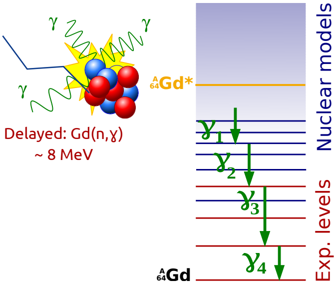




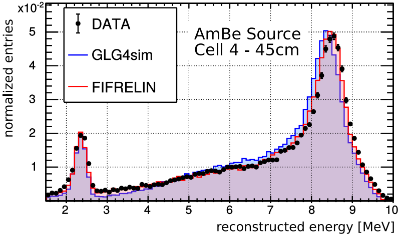
Improvement of the MC simulation

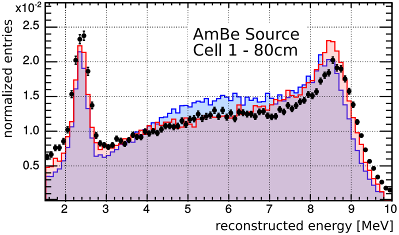
Eur. Phys. J. A **55** (2019) 10, 183

- Correct modelisation of Gd γ cascade of primary importance for small detectors
- Major improvement: collaboration with FIFRELIN → implement deexcitation of Gd isotopes using experimental data completed by nuclear models
- Systematic uncertainty from neutron detection: sub-percent level



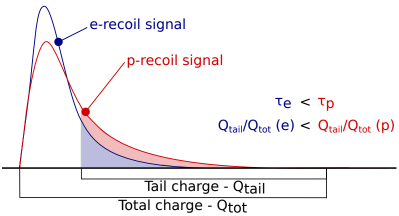
Delayed: Gd(n,ɣ)
~ 8 MeV





Correlated background and $\bar{\nu}_e$ extraction

Phys. Rev. D **102** (2020) 5, 052002



Pulse **S**hape **D**iscrimination (PSD) for prompt signal

- electron recoils (γ, $\bar{\nu}_e$ signal)
- proton recoils (fast neutrons...)

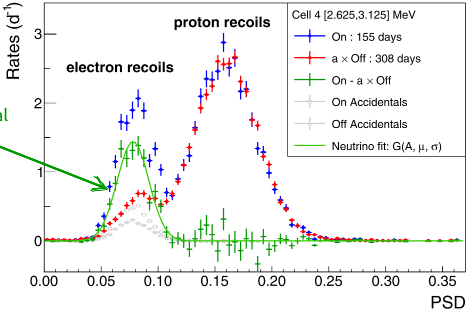
Correlated (cosmic) background:

- sensitive to environment
- stable in shape

→ build background model from reactor-off data

neutrino signal

S/B~1



$\bar{\nu}_e$ **signal extraction** from **reactor-on data**,
with **self-consistent background rescaling** for each cell, energy bin

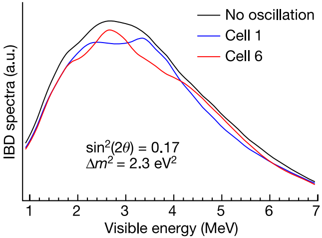
Oscillation analysis

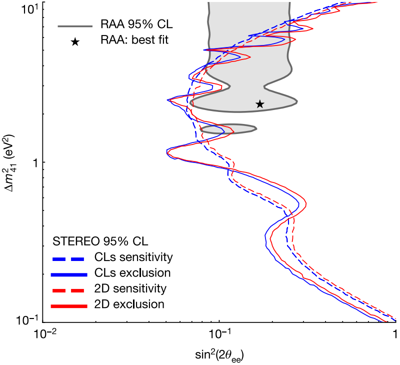
Nature **613**, 257–261 (2023)

Look for relative energy distortions between cells:

$$\chi^2 = \sum_{l}^{\text{Ncells}} \sum_{i}^{N_E} \left(\frac{\overset{\text{measured}}{\mathbf{D_{l,i}}} - \underset{\text{free norm}}{\phi_i}\, \overset{\text{simulated}}{\mathbf{M_{l,i}}}\big(\overset{\text{osc. params}}{\sin^2(2\theta), \Delta m^2_{41}}, \{\alpha\}\big)}{\sigma_{l,i}} \right) + \text{pulls}(\{\alpha\})$$

nuisance parameters (systematics)






Article

Nature | Vol 613 | 12 January 2023 | **257**

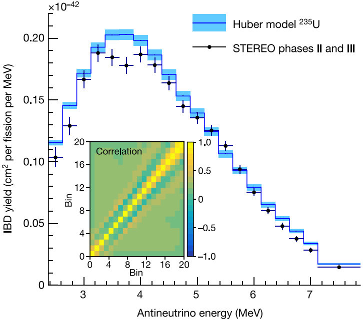
STEREO neutrino spectrum of ^{235}U fission rejects sterile neutrino hypothesis

https://doi.org/10.1038/s41586-022-05568-2 **The STEREO Collaboration***

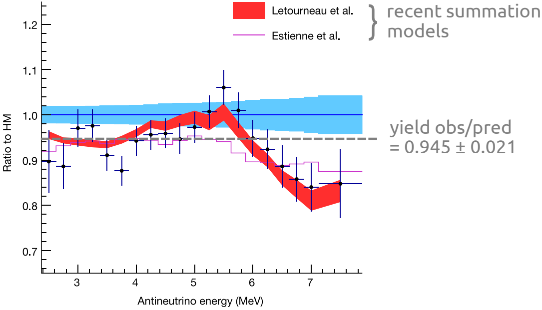
- Compatible no-oscillation hypothesis: p=0.52
- Scan method: $\Delta\chi^2$ distributions from pseudo-experiments
- Parameter space for a light sterile favored by RAA excluded

Spectral analysis: $\bar{\nu}_e$ from ^{235}U reference spectrum

Nature **613**, 257–261 (2023)



$\bar{\nu}_e$ spectra deconvoluted from detector response



} recent summation models

yield obs/pred = 0.945 ± 0.021

Ratio to HM prediction

Particle physics — **News & views**

Nuclear reaction rules out neutrino hypothesis

Jun Cao

An anomalous measurement from a nuclear reactor triggered a three-year campaign to find an elusive particle called the sterile neutrino. The search shows definitively that sterile neutrinos don't exist – but the anomaly persists. **See p.257**

i.e. a "nuclear explanation" for the reactor anomaly! (instead of a sterile neutrino...)

- HM conversion spectra: overall 5 % normalization error of ^{235}U (+ power reactor experiments)
- Improved summation models: new TAGS nuclear data help!

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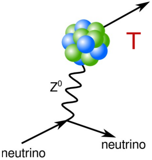
Coherent elastic neutrino-nucleus scattering (CEνNS)

2017: a newly experimentally accessible neutrino channel!

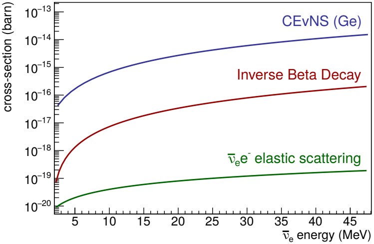


Coherent elastic neutrino-nucleus scattering (CEνNS)

$$\frac{\mathrm{d}\sigma}{\mathrm{dT}} = \frac{G_F^2}{4\pi}\underbrace{\left[\mathrm{N} - (1 - 4\sin^2\theta_w)Z\right]^2}_{\sim N^2}\underbrace{F^2(q^2)}_{\to 1}\ \mathrm{M}\left(1 - \frac{\mathrm{MT}}{2\mathrm{E}_\nu^2}\right)$$

- Low momentum transfer
  full **coherency** feature: $\sigma\ \alpha\ \mathbf{N}^2$
  $\sin^2(\theta_w) \sim 0.238$ at low energies and $\mathrm{F}(\mathrm{q}^2) \sim 1$
  fully coherent in Ge for $\mathrm{E}_\nu \lesssim 30\,\mathrm{MeV}$

- only experimentally accessible observable:
  low energy **recoil of the nucleus**!
  $\mathrm{T}_{\max}\ \alpha\ 1/\mathrm{A}$
  $\Rightarrow$ **very low energy threshold** required!



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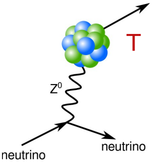

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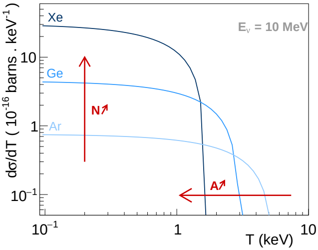

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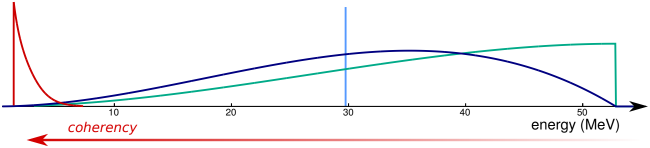
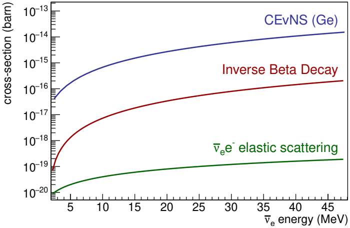
CEνNS already detected with **accelerator neutrinos**. What about **reactor neutrinos**?

?



$\bar{\nu}_e$ from β-decays of fissile isotopes

ν_μ, $\bar{\nu}_\mu$ and ν_e from π-decay at rest



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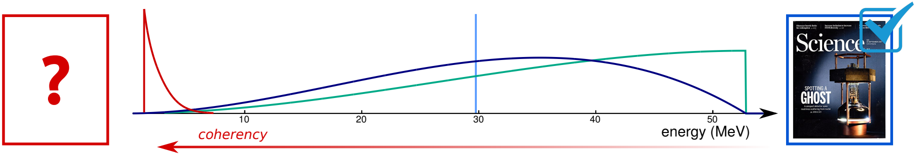

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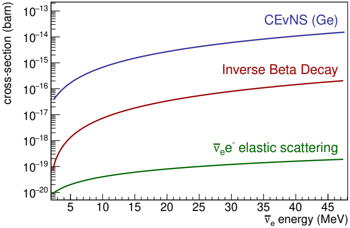

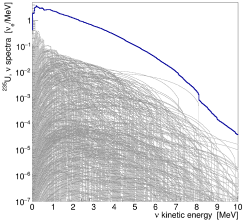

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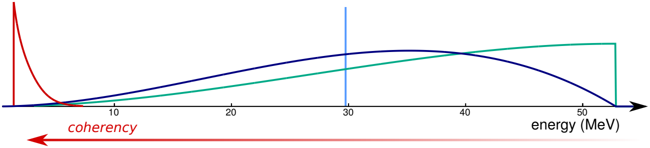

Science

SPOTTING A GHOST

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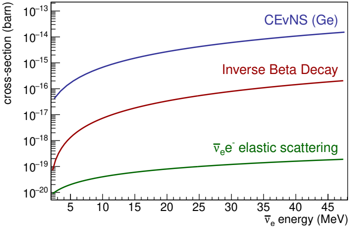

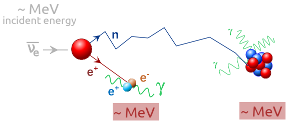

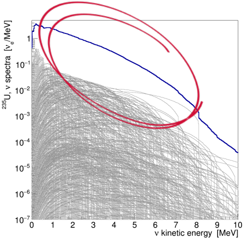

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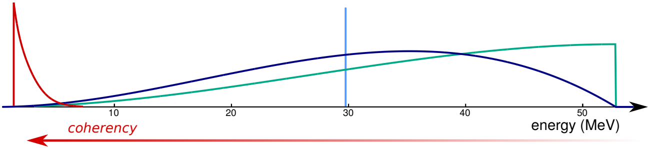

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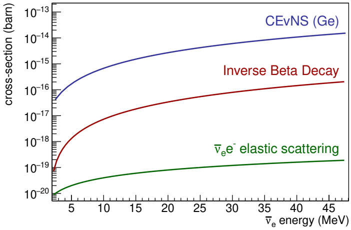
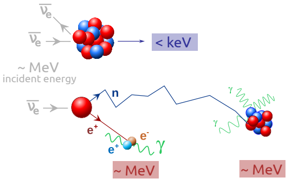
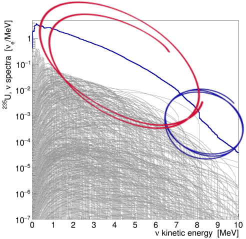






The CONUS experiment

CONUS @ the Brokdorf nuclear power plant (KBR), Germany:

- Data taking 2018-2022
- High $\bar{\nu}_e$ flux @17m from the 3.9 GW_{th} reactor core $10^{13}\ \bar{\nu}_e\ s^{-1}\mathrm{cm}^{-2}$

Reactor site: additional challenges: no fresh air (radon), limited access, no remote control...

CONUS collaboration:
17 scientists (MPIK, KBR)

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Preussen Elektra

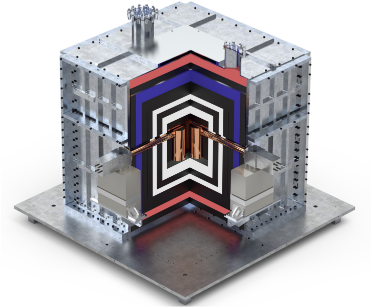
PTB
Messen • Forschen • Wissen
scientific cooperation

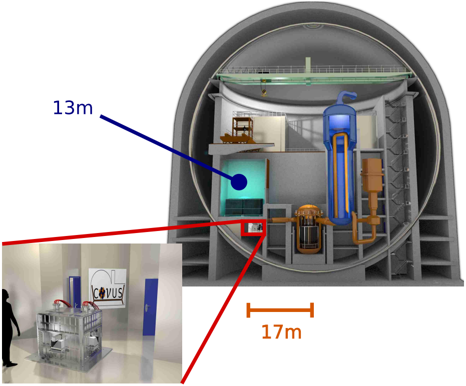
The CONUS experiment

Eur. Phys. J. C **81** (2021) 3, 267

4 p-type point contact HPGe (1kg each)

- very low background components
- pulser resolution (FWHM) $< 85\,\text{eV}_{\text{ee}}$ $\rightarrow$ threshold $\lesssim 300\,\text{eV}_{\text{ee}}$
- electric cryogenic cooling





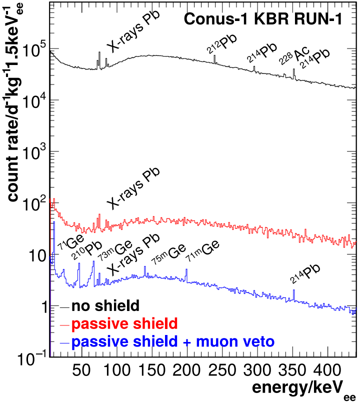
Passive + active shield

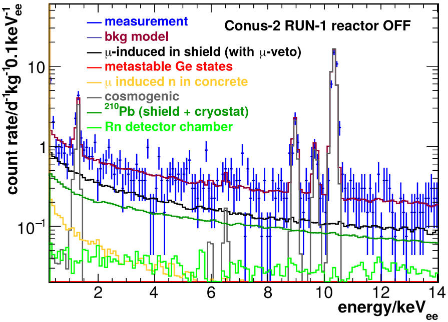
- Lead with low ^{210}Pb content
- Borated PE, pure PE
- Active μ-veto (plastic scintillator)

Background suppression

Eur. Phys. J. C **79** (2019) 699, arXiv:2112.09585 (2021)

- External natural radioactivity and cosmogenic background: reduced by 10^4
- Negligible reactor-correlated background inside shield
- Residual background well understood, fully described by MC simulations



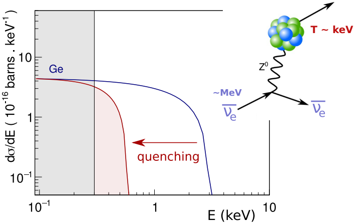


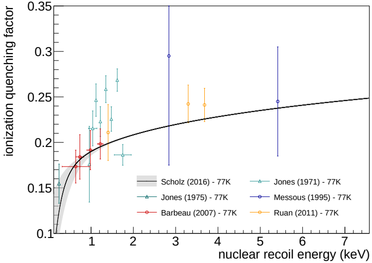
Background level in [0.5 – 1] keV$_{ee}$:
10 counts/kg/d/keV$_{ee}$, **stable**

Detector response: quenching

- Last piece needed for a correct data interpretation: detector response: quenching
  HPGe: **measure ionization energy only**

  → precise knowledge needed!





Ionization quenching factor: $E_{ioniz}/E_{nucl.rec.}$

- Extensively measured for 10-100 keV
  Data lacking in the keV range
- Lindhard model: Q(E) = f(**k**)
  Validity at low energy? kinematic cutoff, enhancement, temperature dependence...?

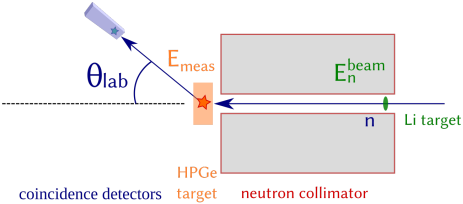
→ dedicated effort to measure it directly at low energy: **Quench'inGe** setup @ PTB (2020)

Ionization quenching factor: direct measurement

CEνNS data interpretation crucially relies on the quenching factor
→ **Quench'inGe** at the PIAF accelerator facility (PTB, Germany)

Direct, model-independent meas.
using neutrons (nuclear recoils):

$$\boxed{\mathbf{Q} \equiv \frac{\mathbf{E^{meas}_{ioniz}}}{\mathbf{E_{nr}}(\theta_{\mathbf{lab}}, \mathbf{E_n})}}$$



Pulsed monoenergetic neutron beams
from proton beam via Li(p,n)

- 250-800 keV neutrons
  →∼ keV recoils in Ge
- ∼ $10^3 n \cdot cm^{-2} \cdot s^{-1}$ on Ge target
- 3 % width @ 500keV

PTB
Messen ▪ Forschen ▪ Wissen
scientific cooperation

Ionization quenching factor: direct measurement

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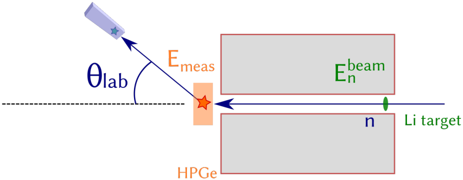
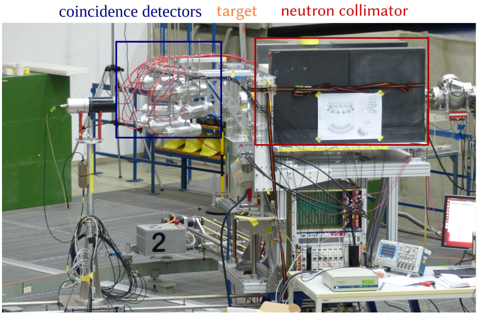




Experimental setup (Oct. 2020):

- Neutron collimation
  ⌀ 35 mm beam at HPGe target
- Dedicated thin HPGe target
  no material on beam axis
  FWHM: 135 eV @ 5.9 keV
- Liquid scintillators (LS) array
  low energy threshold, good PSD
  ∼ 70 % neutron detection eff.

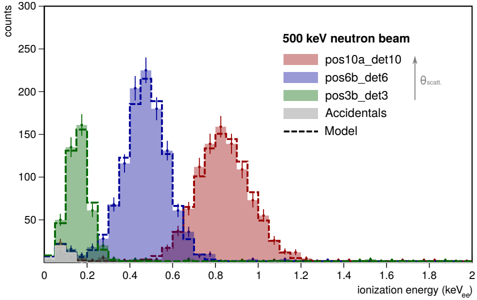
Ionization quenching factor: direct measurement

Eur. Phys. J. C **82** (2022) 9, 815

Data analysis: signal selection via triple coincidence:
beam stop – target HPGe – LS detectors

$$\boxed{\mathbf{Q} \equiv \frac{\mathbf{E}_{\mathbf{ioniz}}^{\mathbf{meas}}}{\mathbf{E}_{\mathbf{nr}}(\theta_{\mathbf{lab}}, \mathbf{E}_{\mathbf{n}})}}$$

- $\mathbf{E}_{\mathbf{ioniz}}^{\mathbf{meas}}$: **ionization energy**
  energy scale: Fe-55 + Ge activation lines
  precise modeling of detector response
- $\mathbf{E}_{\mathbf{nr}}(\theta_{\mathbf{lab}}, \mathbf{E}_{\mathbf{n}})$: **nuclear recoil energy**
  $\mathbf{E}_{\mathbf{n}}$ from time-of-flight
  scattering angles ($\theta_{\mathbf{lab}}$) at the 1° level



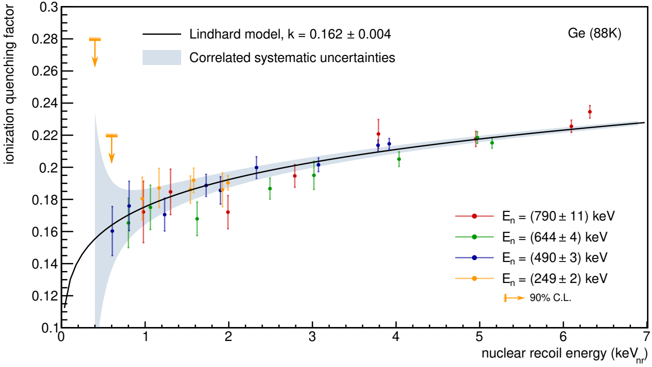
∼16 h beam exposure:

- beam energy varied between 250 keV – 800 keV
- angles varied between 18° and 45°

→ probe nuclear recoils between 0.4 and 6 keV

Ionization quenching factor: results

Eur. Phys. J. C **82** (2022) 9, 815

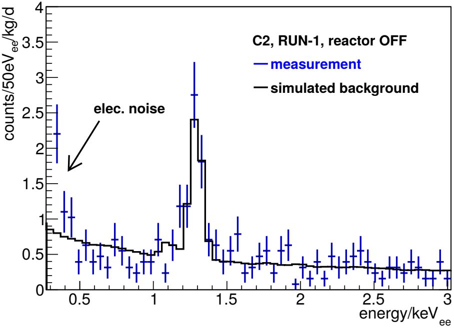


- All data set ($\neq$ beam energies, $\neq$ LS detectors...) compatible with each other
- Systematic uncertainties included: geometry, detector response, beam energy
- Data compatible with Lindhard model: $k = 0.162 \pm 0.004$ (stat+syst)

Data selection and analysis overview

Data quality cuts:

- Discard high temperature variations periods
- Discrimination of microphonic and spurious events via time difference



Region Of Interest (ROI):

- Trigger efficiency ∼100 %
- Electronic noise component described by an exponential, contribution $< 4\times$ MC

Run-1+2 exposure:

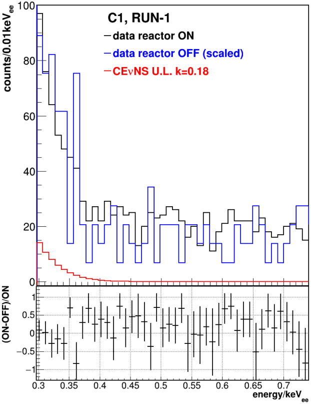
248.7 kg d (reactor-on)
58.8 kg d (reactor-off)

→ Simultaneous likelihood fit (ON/OFF) for all detectors & runs

- signal prediction: CEνNS (theory), reactor spectrum
- background description: MC + electronic noise
- nuisance parameters for systematic uncertainties

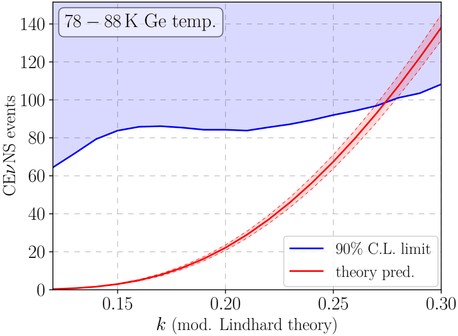
First CEνNS constraint from CONUS

Phys. Rev. Lett. **126**, 041804 (2021)



Best CEνNS limit at reactor:

$< 0.4\ \mathrm{d}^{-1}\mathrm{kg}^{-1}$ (90 % C.L.)

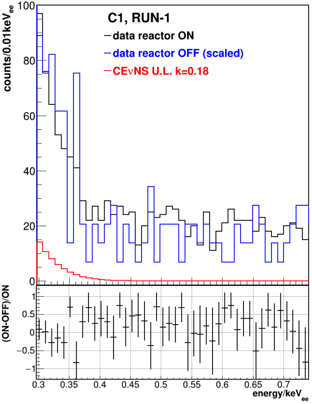


CONUS upper limit for k = 0.16: 85 counts (17 times above expectation)

→ challenge for the detection of CEνNS at reactor and for CONUS!

First CEνNS constraint from CONUS

Phys. Rev. Lett. **126**, 041804 (2021)



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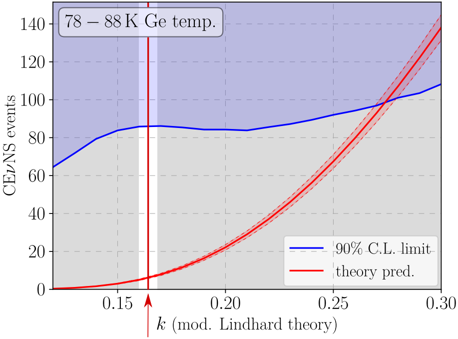


PTB measurement

CONUS upper limit for $k = 0.16$: 85 counts (17 times above expectation)

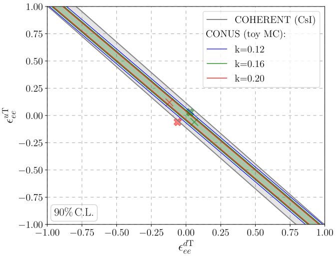
→ challenge for the detection of CEνNS at reactor and for CONUS!

Searches for new physics

J. High Energ. Phys. **85** (2022), *Eur. Phys. J. C* **82**, 813 (2022)

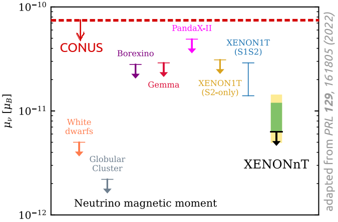
Imprints of new physics through the modification of the CEνNS cross-section
$\rightarrow$ look for experimental signatures in CONUS data!

- Non-standard neutrino-quark interactions (NSIs): extension of the neutral current with new mediators (at reactor: sensitive to ε^{d}_{ee} and ε^{u}_{ee})
  - vector case: $Q_W \mapsto Q_{NSI}(\{\varepsilon^{q}_{\alpha\beta}\})$
  - tensor case: higher end point
    $\rightarrow$ competitive limits (low background)



- Light mediators: simplified models using universal couplings, CONUS sensitive to low mediator masses

- Neutrino electromagnetic properties: from $\bar{\nu}_e$-electron scattering channel: $\mu_\nu < 7.5 \cdot 10^{-11}\,\mu_B$ (90% C.L.).



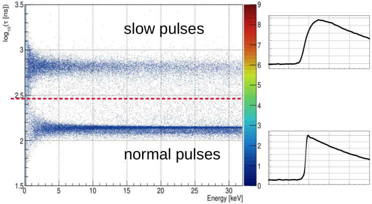
adapted from *PRL* **129**, 161805 (2022)

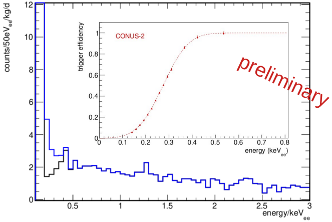
Perspectives for CONUS and CEνNS at reactor site

Promising last CONUS dataset (Run5, 2020–2022):

- Extended statistics:
  - – improved stability conditions
  - – exceptionally long reactor-OFF dataset in 2022
- New acquisition system:
  - – Pulse Shape Discrimination (surface vs. bulk):
    $\rightarrow$ 20 % additional background rejection!
  - – Lower energy threshold ($\lesssim 250\,\mathrm{eV}$)

$\rightarrow$ significantly improved sensitivity (CEνNS, BSM), publications coming soon!





- + exploring new reactor sites

Summary on neutrino physics

- **Hints for light sterile neutrino(s) at the eV scale (short baselines):**
  - Reactor Antineutrino Anomaly → $\sim 1\,\text{eV}$ excluded by STEREO (and others)
  - Gallium anomaly: higher Δm^2 regions? (recently revived by BEST?)
  - Accelerator SBL anomalies (LSND, MiniBoone): wait for final MicroBoone results...

- **Search for CEνNS at reactors: rich physics program with small experiments!**
  - First detection still pending!
  - Opens new possibilities to explore BSM physics
  - Complementary approaches and technologies
  - Synergies with dark matter searches

- **The yet unexplored sub-keV region:**
  - Quenching factor crucial, recent tensions, renewed interest!
  - Unknown backgrounds: systematic *low energy excess* to be understood

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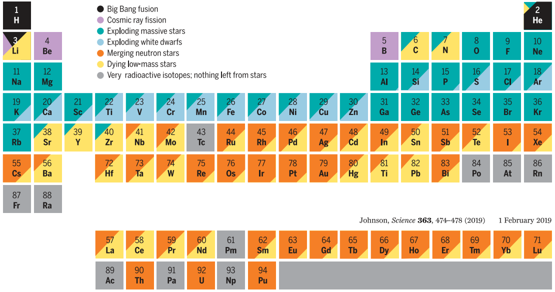
Table of Contents

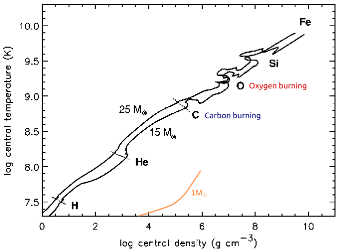
Nucleosynthesis and massive stars

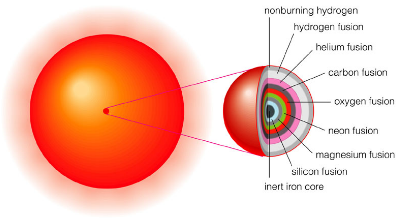
- Synthesis of elements: lives and deaths of stars
- Massive stars: succession of burning phases, shell structure
- Stellar evolution driven by nuclear reactions

The evolving composition of the Universe



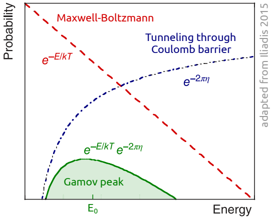
Johnson, *Science* **363**, 474–478 (2019) 1 February 2019

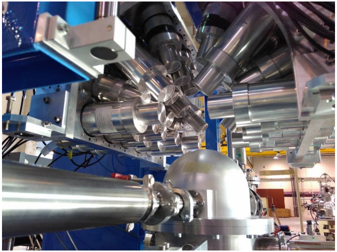




The STELLA experiment and the ^{12}C+^{12}C case

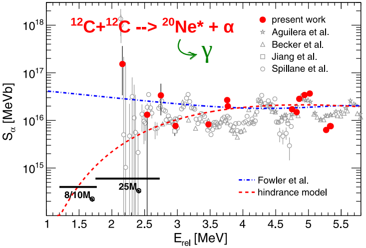
- ^{12}C+^{12}C: the first fusion to be considered for massive stars!
- Astrophysical region of interest: *the Gamov window*
  → extremely low cross-sections! ($\lesssim$ pb!)
  Challenges: beam intensity, stability, background, efficiency
- STELLA: direct measurement with coincidence between charged particles and deexcitation gammas
- Strong nuclear structure effects:
  → Hindrance? Clusters? Adsley *et al.* PRL **129**, 102701 (2022)
  → Astrophysical impact? Monpribat *et al.* A&A **660** (2022)





STELLA at Andromède, Orsay

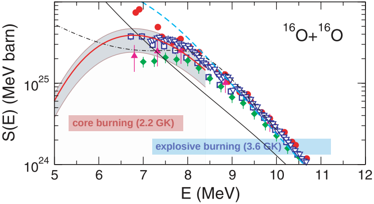
PHYSICAL REVIEW LETTERS **124,** 192701 (2020)



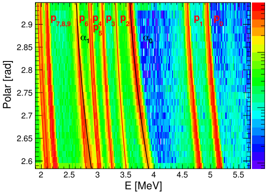
Astrophysical factor $S = E\sigma(E)exp(2\pi\eta)$

The next steps with STELLA: ^{12}C+^{16}O and ^{16}O+^{16}O

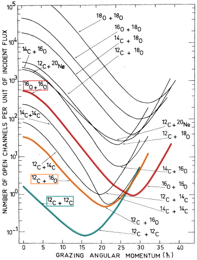
- Next natural reactions of astrophysical relevance:
  - ^{12}C+^{16}O: e.g. late carbon burning phase
  - ^{16}O+^{16}O: the next binary fusion
- Nuclear physics: fusion hindrance? Resonances?
- Scarce data in the relevant Gamov window...



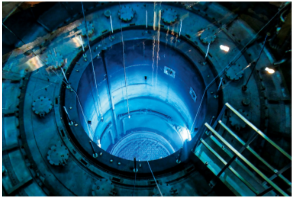
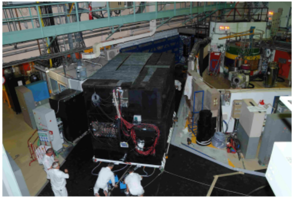
→ **Measure with STELLA!** Additional challenge: increasing complexity of exit channels:



^{12}C + ^{12}C	**^{12}C + ^{16}O**	**^{16}O + ^{16}O**
^{20}Ne + α	^{24}Mg + α	^{28}Si + α
^{23}Na + p	^{27}Al + p	^{31}P + p
^{23}Mg + n	^{27}Si + n	^{31}S + n
^{16}O + 2α	^{25}Mg + 2p	^{30}Si + 2p
	^{20}Ne + 2α	^{24}Mg + 2α
	^{23}Na + αp	^{27}Al + αp
		^{30}P + d
		^{30}P + np



- Charged particle detectors upgrade: improved angular coverage, adapted thickness (higher energies), resolve complex final states
- Additional beam focusing element for an optimal beam spot size

Thank you for your attention!