The reactor antineutrino anomaly and low energy threshold neutrino experiments

Estela Garcés
CINVESTAV-México

Based on: ArXiv-hep-ph/1708.09518
B. C. Canas,E. A. G., O. G. Miranda, and A. Parada

Outline

- I. INTRODUCTION
- II. ANTINEUTRINO ELECTRON SCATTERING MEASUREMENT (+Gallium)
- III. PERSPECTIVES FOR COHERENT ELASTIC NEUTRINO NUCLEUS SCATTERING IN REACTOR EXPERIMENTS
- IV. CONCLUSIONS

Neutrino oscillations

Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

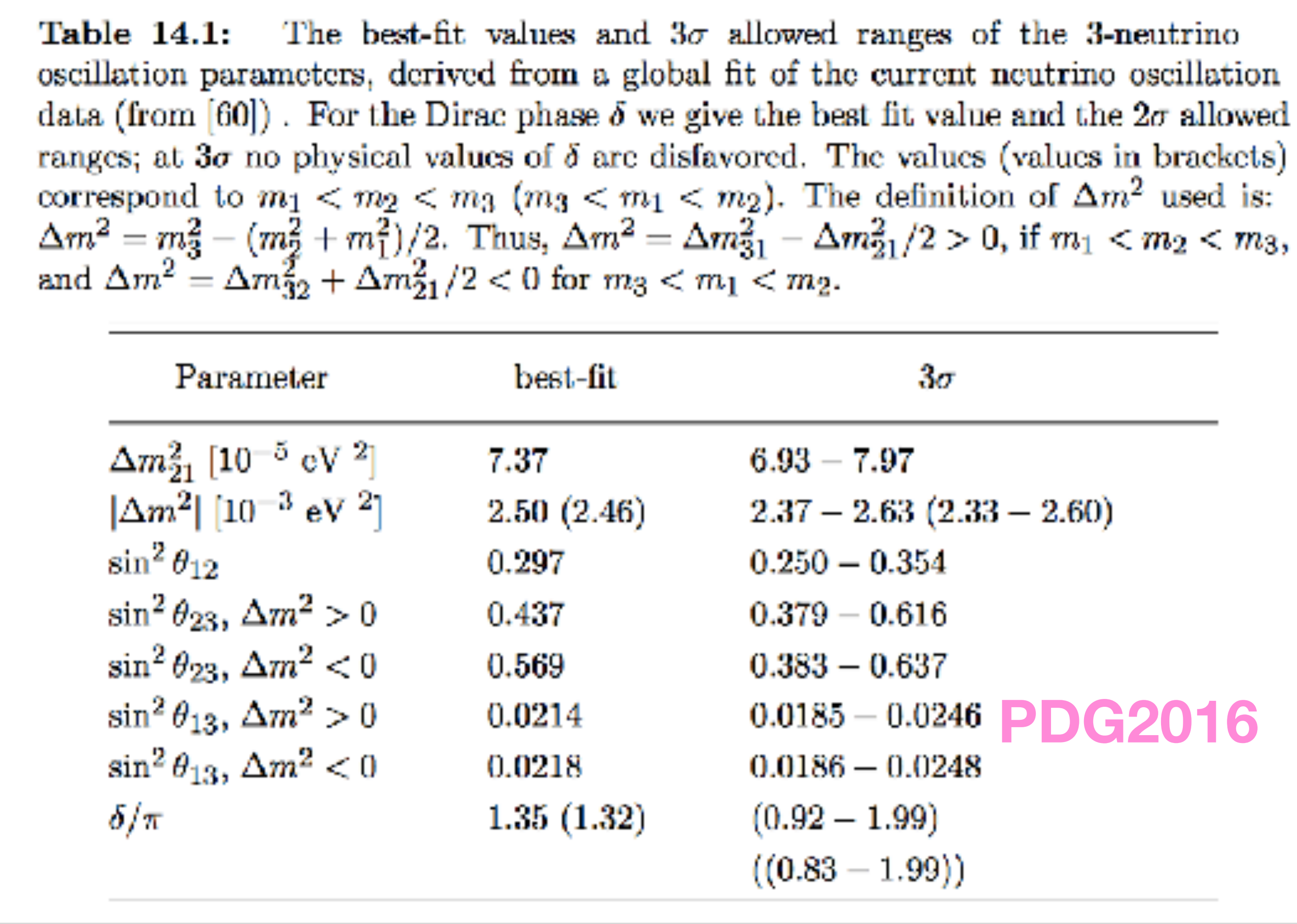


Table 14.1: The best-fit values and 3σ allowed ranges of the **3-neutrino** oscillation parameters, derived from a global fit of the current neutrino oscillation data (from [60]) . For the Dirac phase δ we give the best fit value and the 2σ allowed ranges; at 3σ no physical values of δ are disfavored. The values (values in brackets) correspond to $m_1 < m_2 < m_3$ ($m_3 < m_1 < m_2$). The definition of Δm^2 used is: $\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 = \Delta m_{31}^2 - \Delta m_{21}^2/2 > 0$, if $m_1 < m_2 < m_3$, and $\Delta m^2 = \Delta m_{32}^2 + \Delta m_{21}^2/2 < 0$ for $m_3 < m_1 < m_2$.

Parameter	best-fit	3σ
Δm_{21}^2 $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

PDG2016

Nobel prize 2015

The experiments with solar, atmospheric, reactor and accelerator neutrinos have provided compelling evidences for oscillations of neutrinos caused by nonzero neutrino masses and neutrino mixing

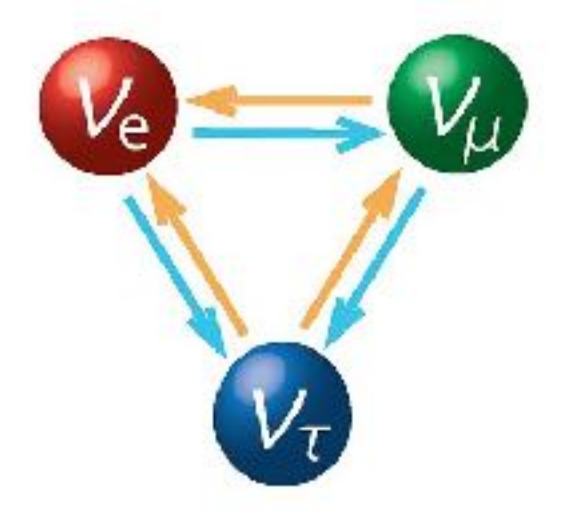
Hints for sterile neutrinos,

beyond the 3 neutrino framework

- Gallium Anomaly, Deficit in the expected rate of calibration sources experiments.
- GALLEX, Phys. Lett. B 342, 440 (1995).
- SAGE, Phys. Rev. C 80, 015807.

$R^{Ga} = 0.86 \pm 0.05$

- We will follow the analysis in: M. A. Acero, C. Giunti and M. Laveder, Phys. Rev. D 78, 073009 (2008).
- Reactor Anomaly G. Mention et al. Phys. Rev. D 83, 073006 (2011) 6% antineutrino deficit.
- Miniboone/LSND data.
- New short-baseline reactor neutrino flux measurements are needed.

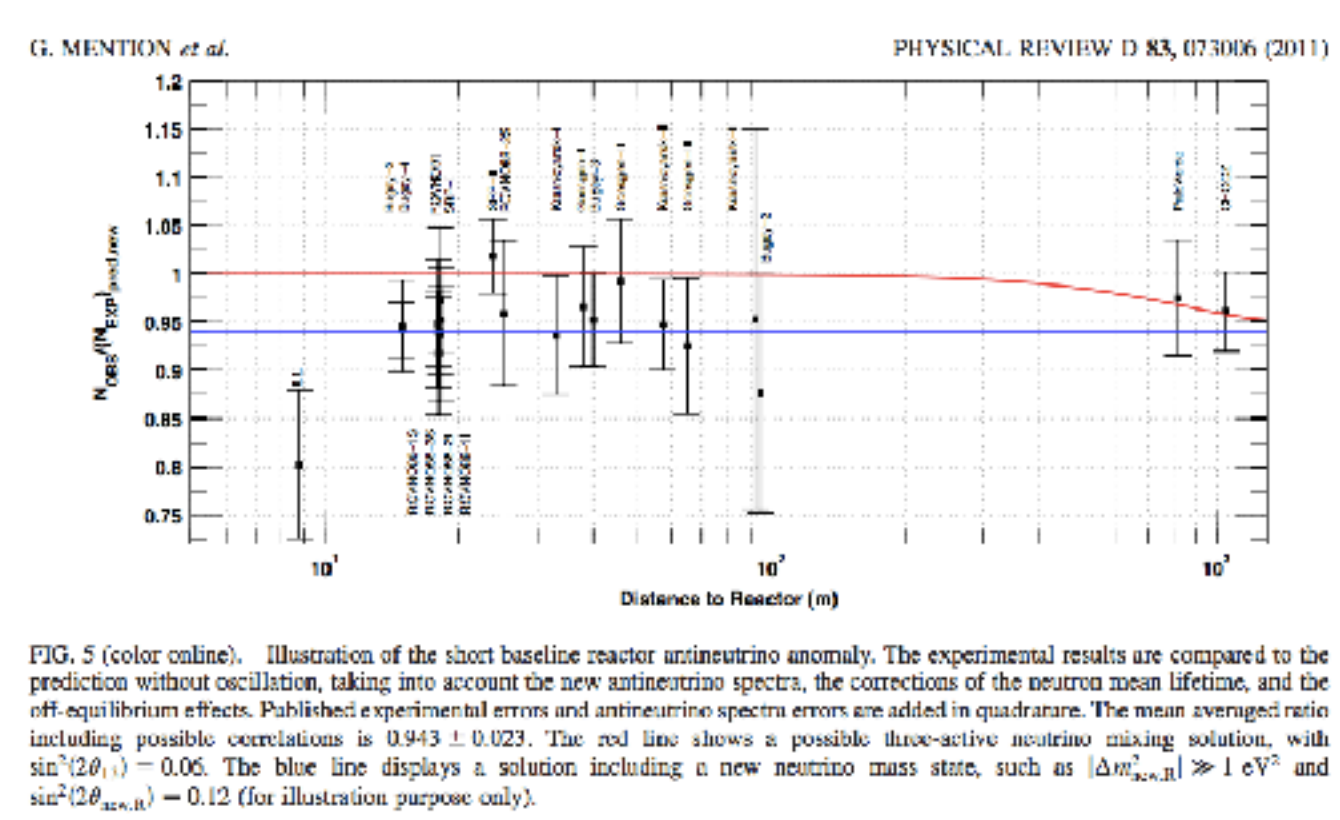


$$P^{\mathrm{SBL}}_{\bar{\nu}_e \to \bar{\nu}_e} = \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right),$$

$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2).$$

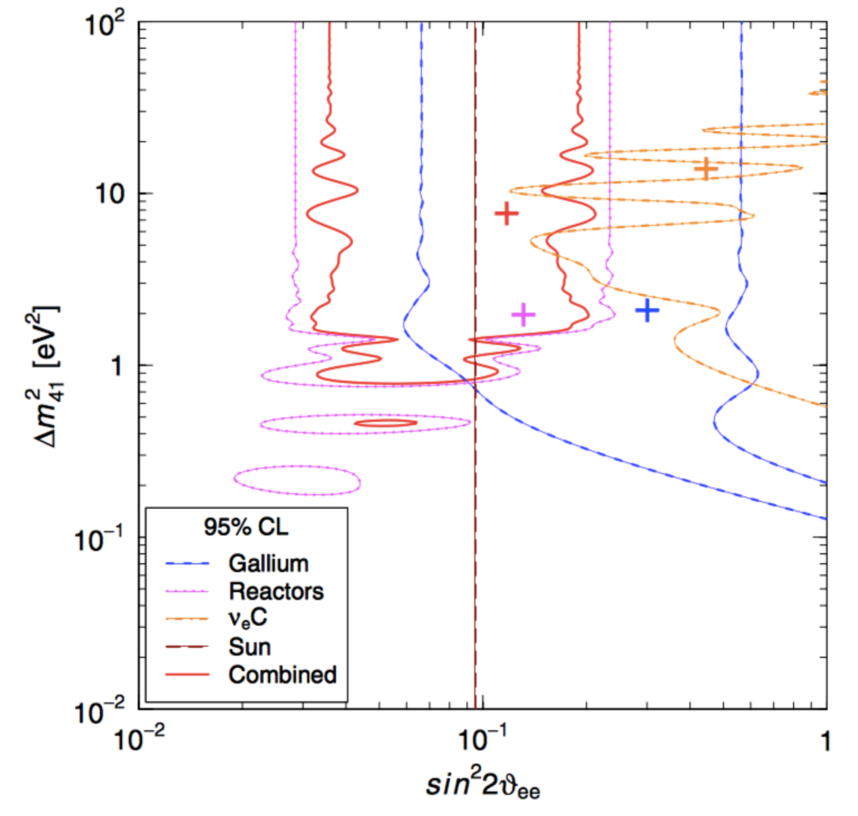
The reactor anomaly

- ~ 6% more neutrinos predicted than are observed by flux measurements.
- Errors in the models based on old measurements or in the nuclear databases used to model the fission processes, OR new physics, such as oscillation to a sterile neutrino.



G. MENTION *et al.* PHYSICAL REVIEW D 83, 073006 (2011)

FIG. 5 (color online). Illustration of the short baseline reactor antineutrino anomaly. The experimental results are compared to the prediction without oscillation, taking into account the new antineutrino spectra, the corrections of the neutron mean lifetime, and the off-equilibrium effects. Published experimental errors and antineutrino spectra errors are added in quadrature. The mean averaged ratio including possible correlations is 0.943 ± 0.023. The red line shows a possible three-active neutrino mixing solution, with $\sin^2(2\theta_{13}) = 0.06$. The blue line displays a solution including a new neutrino mass state, such as $|\Delta m^2_{\rm new,R}| \gg 1\ {\rm eV}^2$ and $\sin^2(2\theta_{\rm new,R}) = 0.12$ (for illustration purpose only).



Giunti & Lavender
PHYSICAL REVIEW D 84, 093006 (2011)

Worldwide hunt for sterile neutrinos@reactors

IBD

$$\bar{\nu}_e + p \rightarrow e^+ + n,$$

- NEOS (24m) Y. J. Ko et al., Phys. Rev. Lett. 118, no. 12, 121802 (2017)

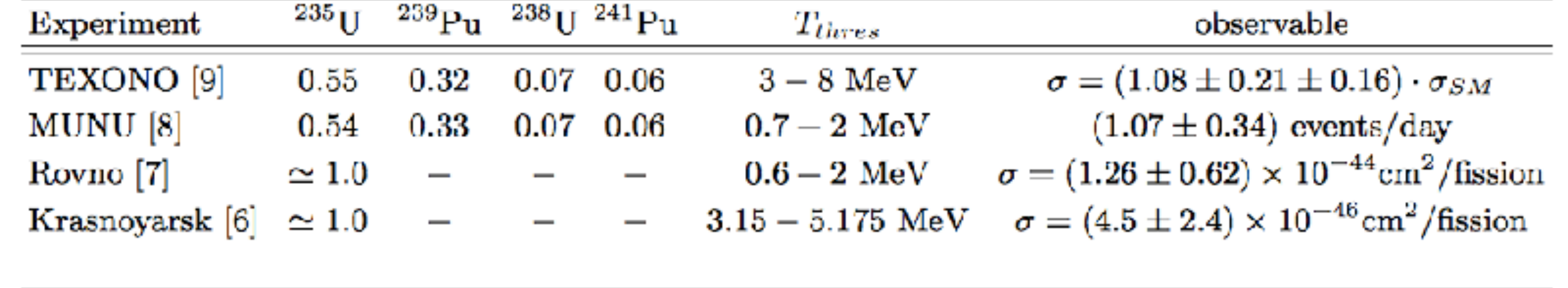
- PROSPECT (7-12m)

- SoLid (6m, 10m)

- STEREO (10m)

- DANNS (11m) I. Alekseev et al., JINST 11 (2016) no.11, P11011. Talk by Dr. Alexander STAROSTIN.

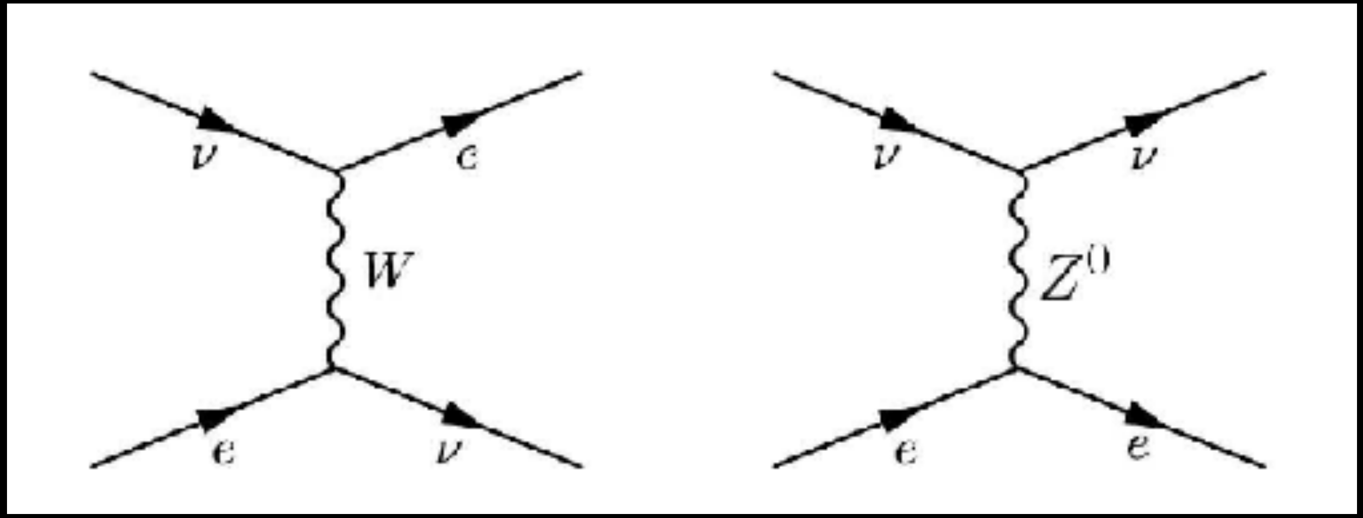
Reactor neutrino-electron scattering experiments



Experiment	^{235}U	^{239}Pu	^{238}U	^{241}Pu	T_{thres}	observable
TEXONO [9]	0.55	0.32	0.07	0.06	3 – 8 MeV	$\sigma = (1.08 \pm 0.21 \pm 0.16) \cdot \sigma_{SM}$
MUNU [8]	0.54	0.33	0.07	0.06	0.7 – 2 MeV	(1.07 ± 0.34) events/day
Rovno [7]	$\simeq 1.0$	–	–	–	0.6 – 2 MeV	$\sigma = (1.26 \pm 0.62) \times 10^{-44} \text{cm}^2/\text{fission}$
Krasnoyarsk [6]	$\simeq 1.0$	–	–	–	3.15 – 5.175 MeV	$\sigma = (4.5 \pm 2.4) \times 10^{-46} \text{cm}^2/\text{fission}$

- Krasnoyarsk Coll., JETP Lett. 55 (1992) 206 [Pisma Zh. Eksp. Teor. Fiz. 55 (1992) 212].
- Rovno, Coll. JETP Lett. 57 (1993)
  768 [Pisma Zh. Eksp. Teor. Fiz. 57 (1993) 755].
- MUNU Coll. Nucl. Instrum. Meth. A 396, 115 (1997).
- M. Deniz et al. [TEXONO Collaboration], Phys. Rev. D 81, 072001 (2010)

Reactor neutrino-electron scattering experiments

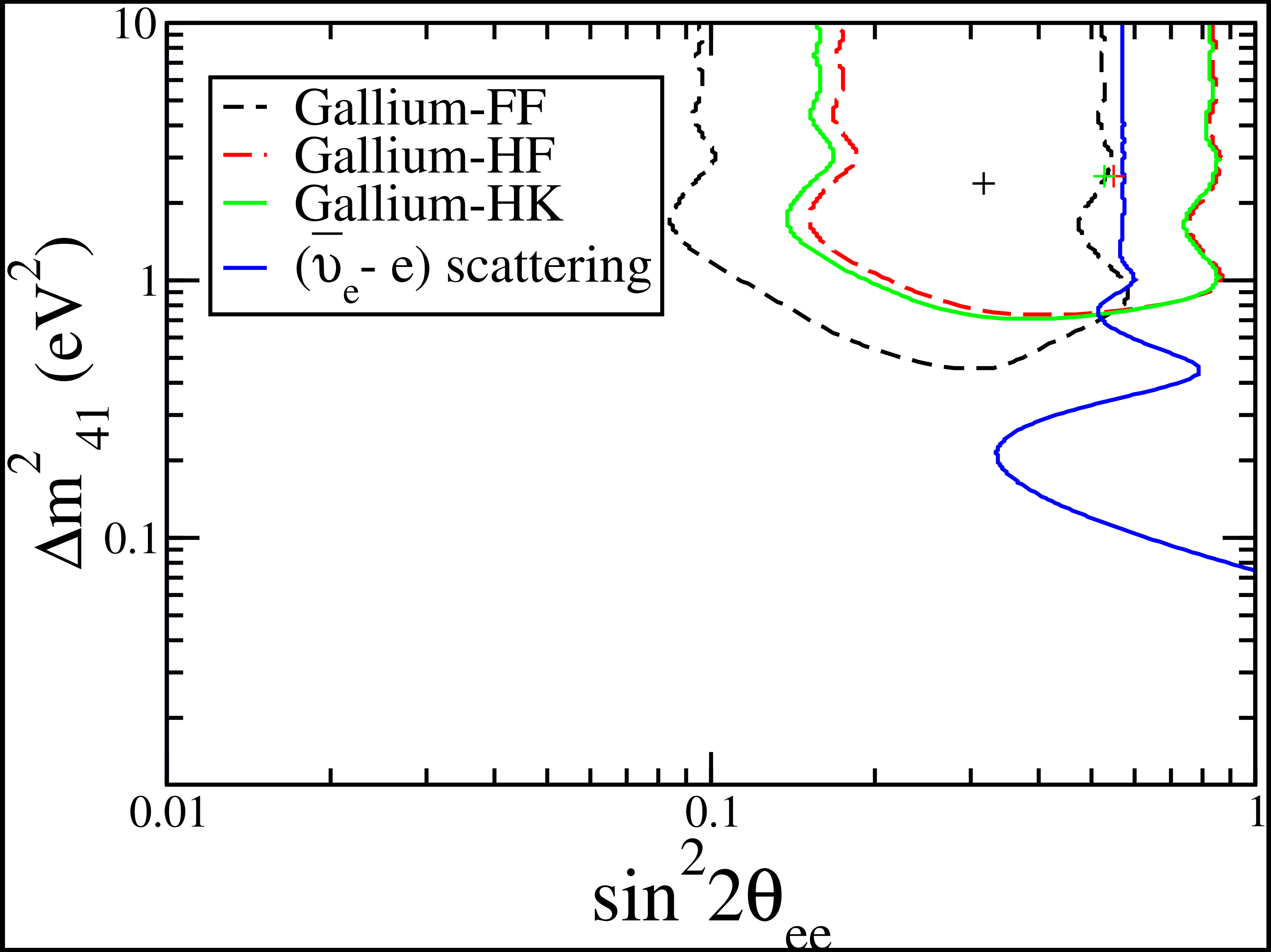


$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_R^2 + g_L^2(1-\frac{T}{E_\nu})^2 - g_L g_R m_e \frac{T}{E_\nu^2}\right],$$

$$g_L = 1/2 + \sin^2\theta_{\rm W}, \quad g_R = \sin^2\theta_{\rm W}$$

$$N_i = n_e \Delta t \int\int_{T_i}^{T_{i+1}}\int \lambda(E_\nu) P^{\rm SBL}_{\nu_\alpha\to\nu_\alpha}\frac{d\sigma}{dT}R(T,T')dT'dTdE.$$

Gallium and Reactor nu-e scattering data



90% C.L. allowed regions Gallium anomaly (Based on *C. Giunti et. al. Phys. Rev. D 86, 113014 (2012)*) and the exclusion from antineutrino-electron scattering data (Blue line).

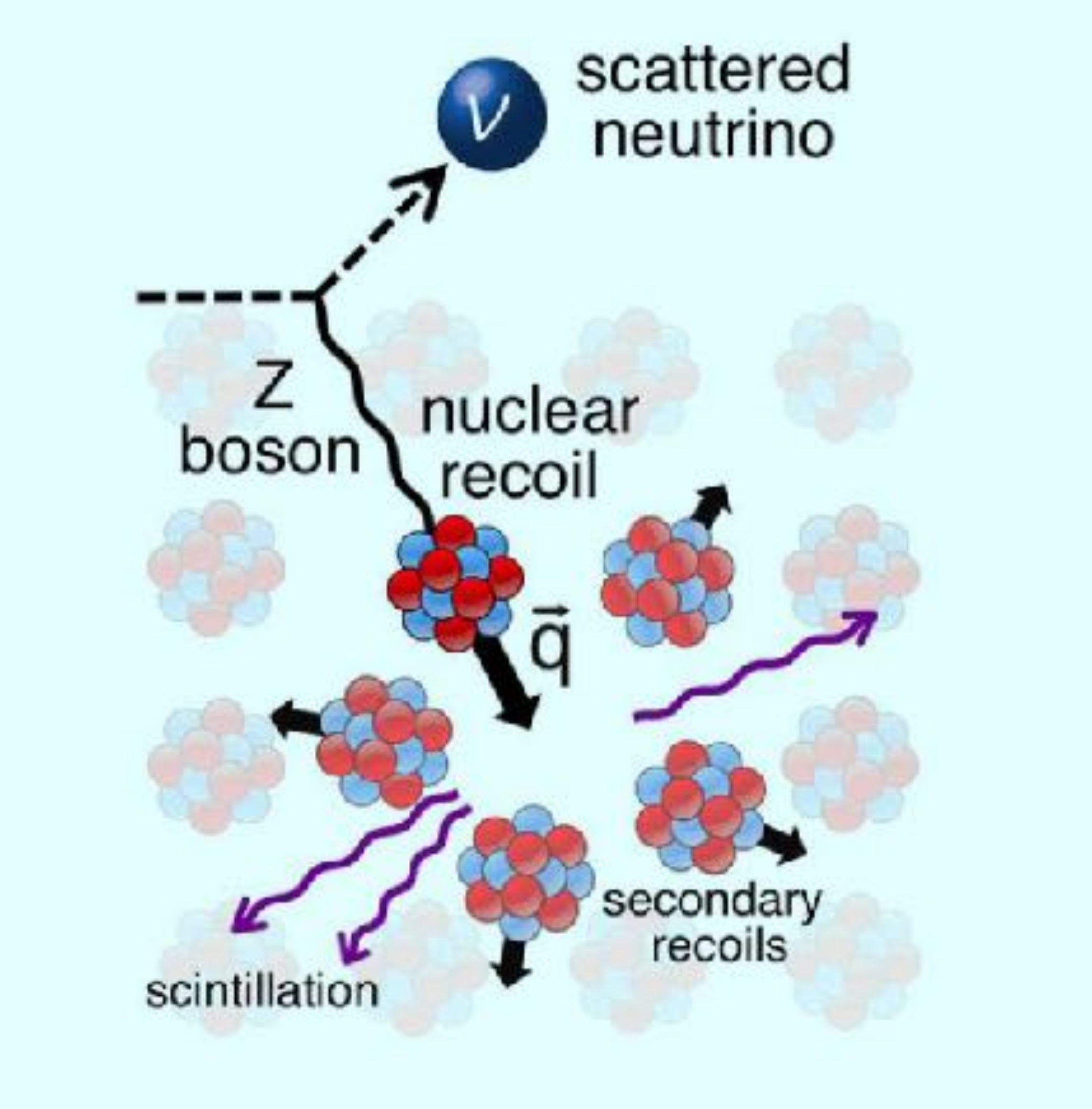
Future nu-e scattering results are expected from GEMMA (Adv.High Energy Phys. 2012, 350150 (2012). Talk by Dr. Alexander STAROSTIN.

Coherent Elastic Neutrino Nucleus Scattering (CNNS)

- Cleanly predicted in the SM. Phys. Rev. D 9, 1389 (1974).
  ”In 1974, Fermilab physicist Daniel Freedman predicted a novel way for neutrinos to interact with matter"

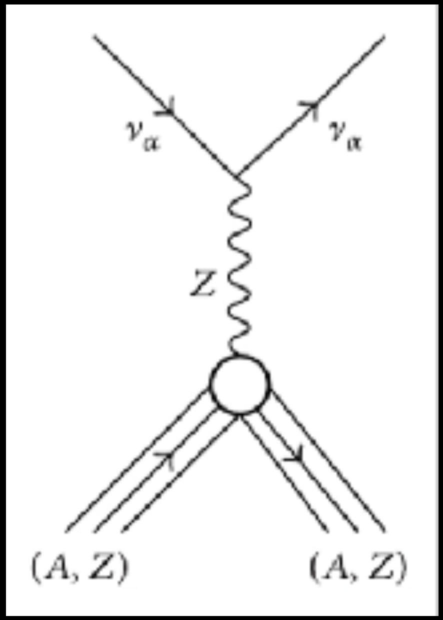
- Recently discovered by the COHERENT Collaboration. 6.7 sigma, using a low-background, 14.6 kg CsI[Na] scintillator. This afternoon plenary talk by Alexey KONOVALOV.

- Irreducible background for WIMP-DM searches.



Coherent elastic neutrino-nucleus scattering. Image credit: COHERENT Collaboration.

CeNNS



Cross section

$$\left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\text{SM}} = \frac{G_F^2 M}{2\pi}\left[1 - \frac{MT}{E_\nu^2} + \left(1 - \frac{T}{E_\nu}\right)^2\right]\left\{\left[(Zg_V^p + Ng_V^n)F(q^2))\right]^2\right\}$$

$$g_V^p = \rho_{\nu N}^{NC}\left(\frac{1}{2} - 2\hat{\kappa}_{\nu N}\hat{s}_Z^2\right) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR}$$

$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}$$

The maximum recoil energy is related with the neutrino energy and the nucleus mass through :

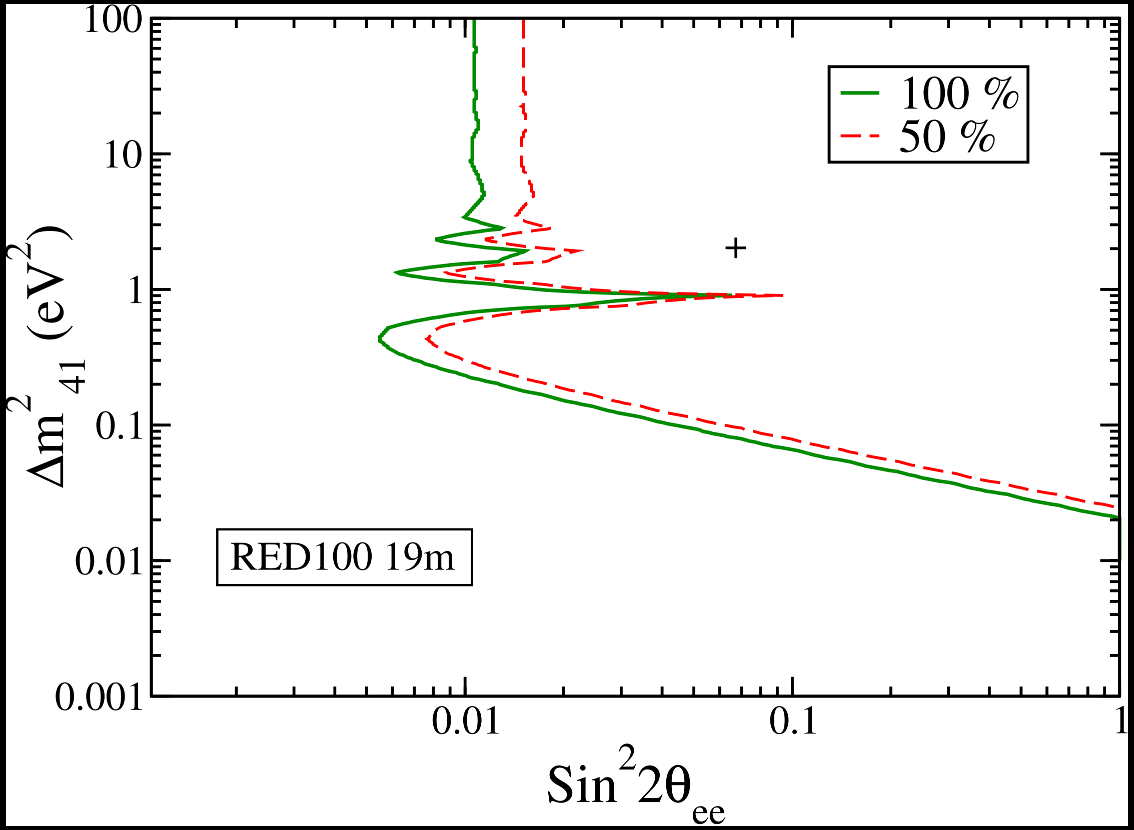
$$T_{\max}(E_\nu) = 2E_\nu^2/(M + 2E_\nu)$$

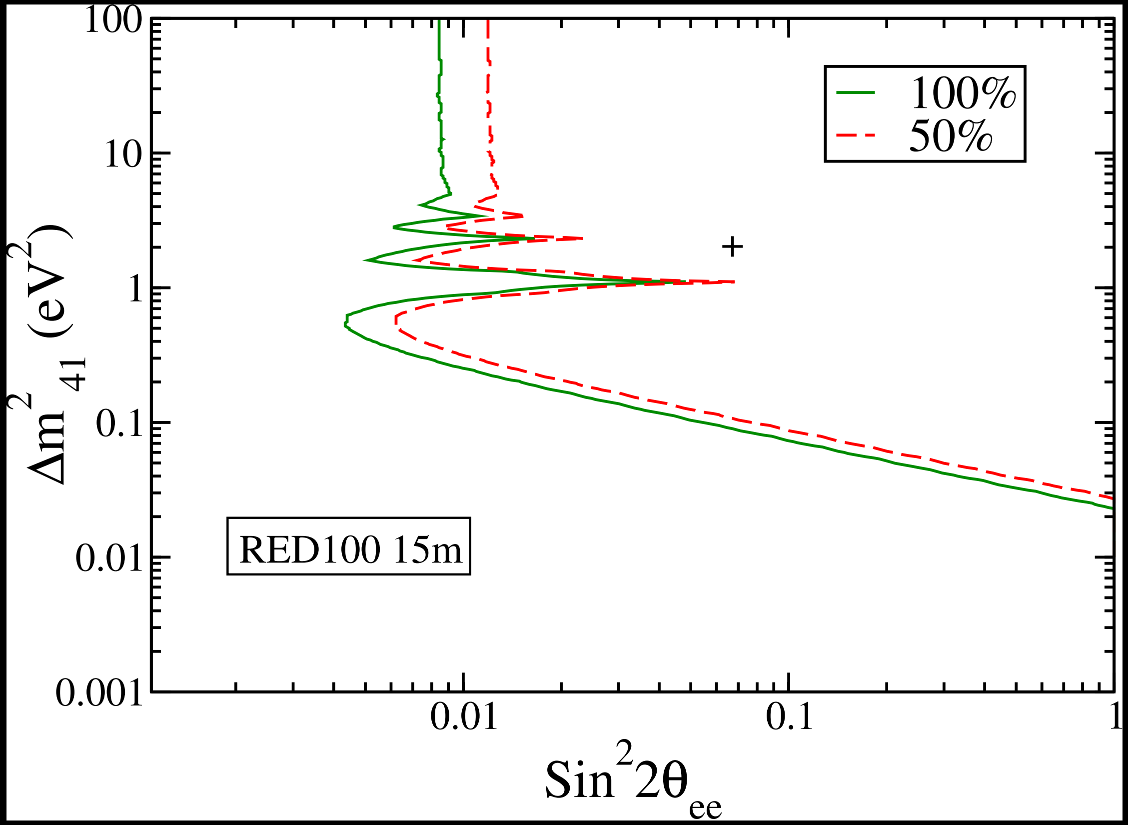
CENNS experiments

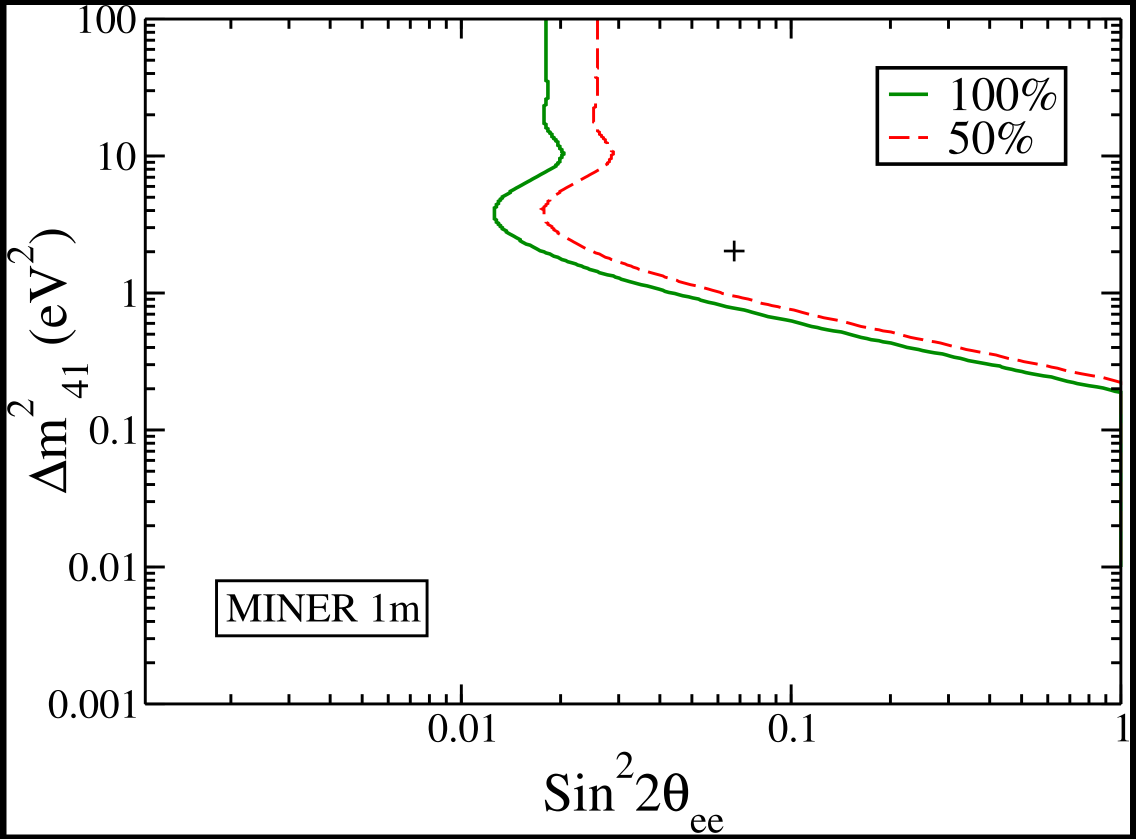
	^{235}U	^{239}Pu	^{238}U	^{241}Pu	T_{thres}	Baseline	Det. Tec.
TEXONO(1kg)	0.55	0.32	0.07	0.06	100 eV	28 m	Ge
RED100	0.54	0.33	0.07	0.06	500 eV	19 m	Liq. Xe
MINER	1.0	–	–	–	10 eV	1-3 m	$^{72}Ge:^{28}Si$ (2:1)
CONNIE	$\simeq 1.0$	–	–	–	50 eV	30 m	CCD

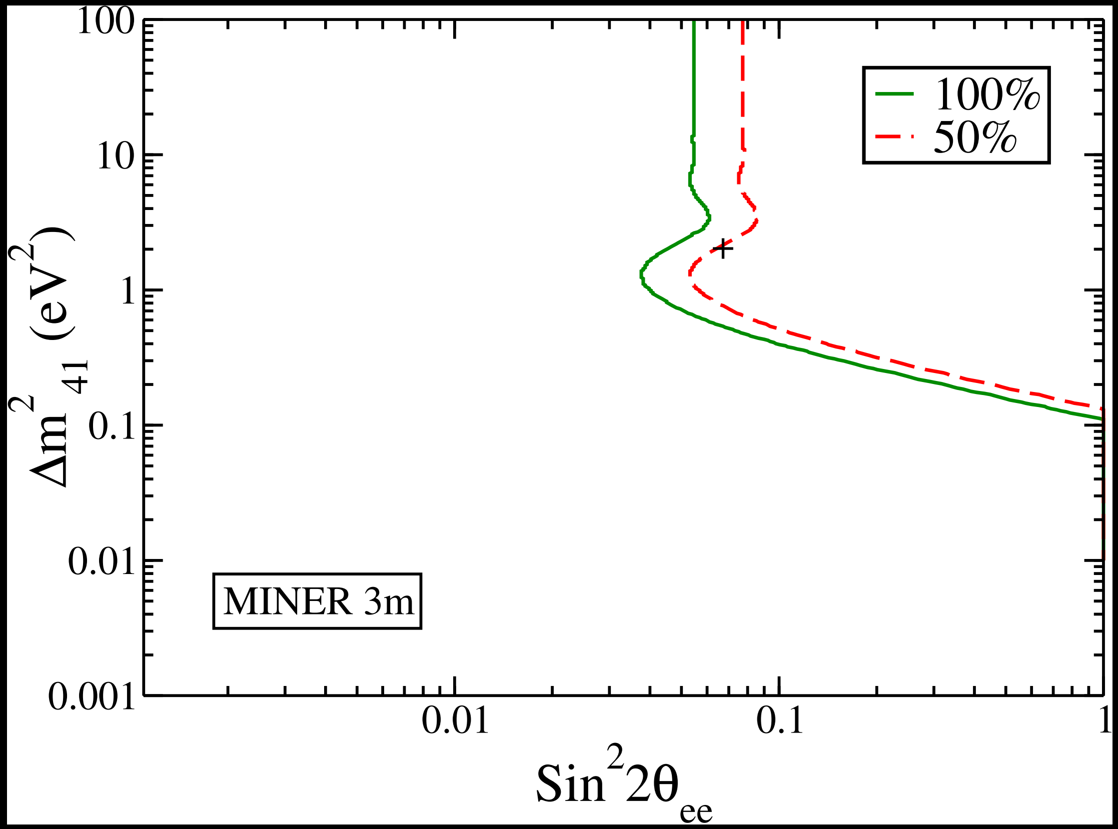
- We consider 4 cases of CeNNS experimental proposals.
- The case of sterile neutrinos was also looked at in: T. S. Kosmas, D. K. Papoulias, M. Tortola and J. W. F. Valle, Phys. Rev. D 96, 063013 (2017). Bhaskar Dutta et al. Phys. Rev. D 94, 093002 (2016)
- SM tests. i.e. B. C. Canas, E. A. G., O. G. Miranda, M. Tortola and J. W. F. Valle, Phys. Lett. B 761, 450 (2016).E. AG, O. Miranda, M. Tortola, and J. W. F. Valle, Phys.Rev. D85, 073006 (2012), 1112.3633.
- BSM, non standard neutrino interactions, neutrino electromagnetic properties, etc.. i. e. Barranco, O. G. Miranda and T. I. Rashba, JHEP 0512, 021 (2005),J. Barranco, A. Bolanos, E. A. G., O. G. Miranda and T. I. Rashba, Int. J. Mod. Phys. A 27, 1250147 (2012), Kosmas Adv. in HEP 2015(2015):763648.

Exclusion regions (sensitivity study), RED100 and MINER as a case study

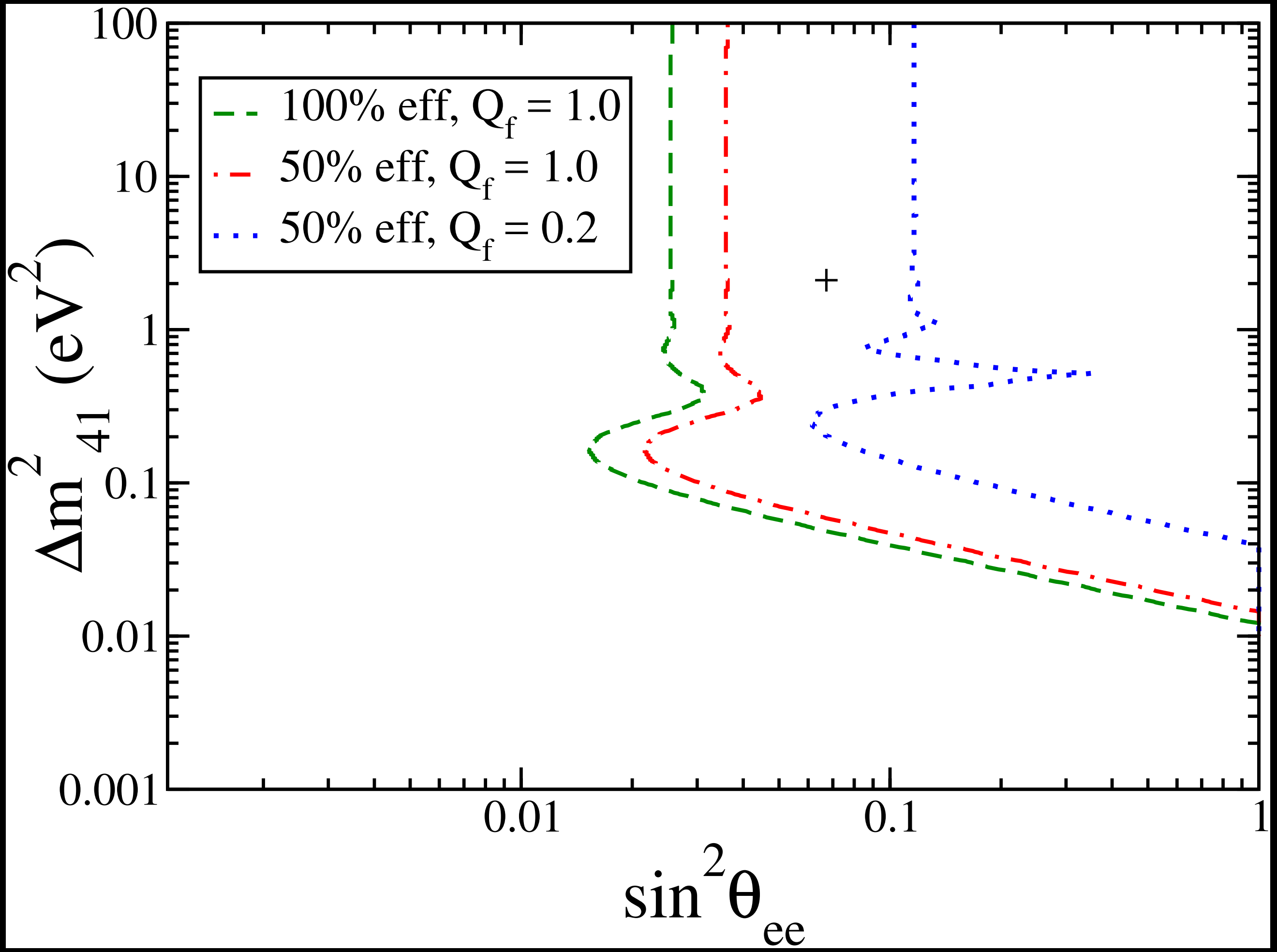








TEXONO-(1kg)@Kuo Sheng reactor
With different quenching factors



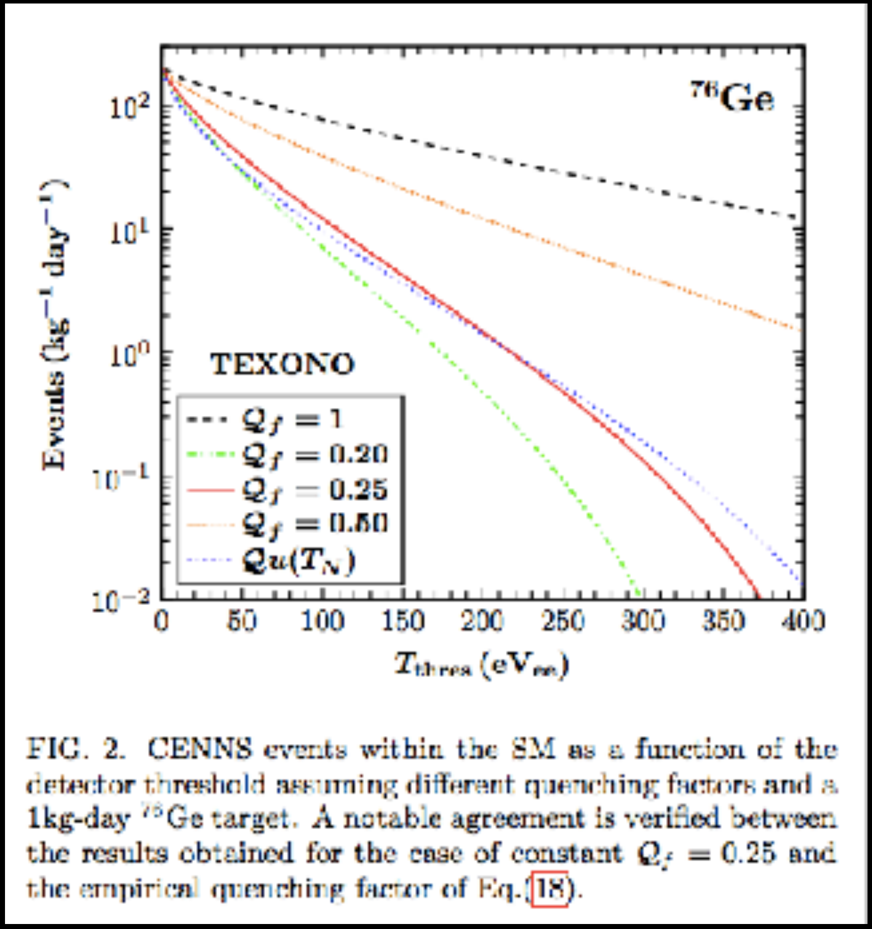
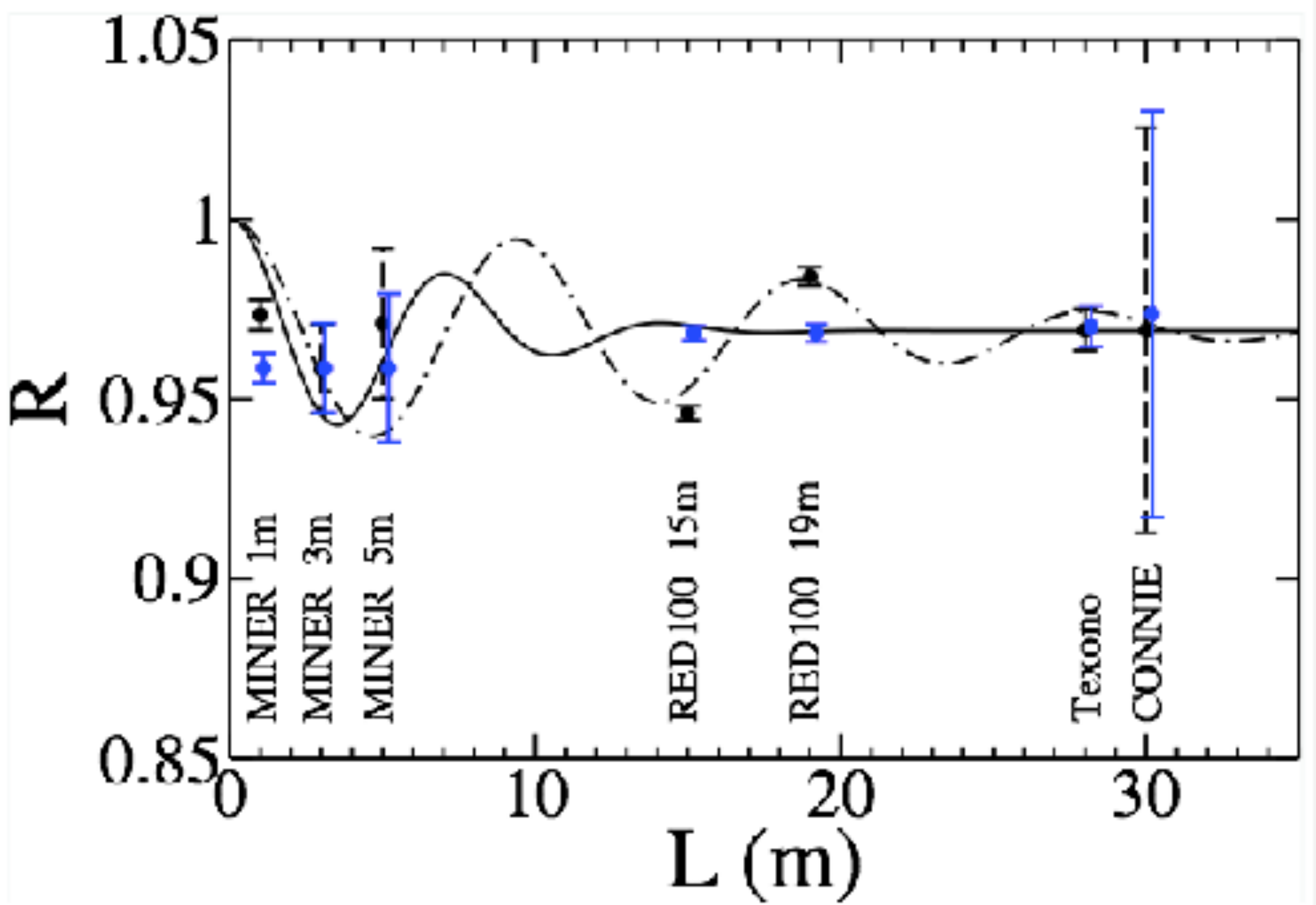


FIG. 2. CENNS events within the SM as a function of the detector threshold assuming different quenching factors and a 1kg-day ^{76}Ge target. A notable agreement is verified between the results obtained for the case of constant $Q_f = 0.25$ and the empirical quenching factor of Eq.(18).

Kosmas et. al Phys.Rev. D96 (2017) 063013

Reactor flux factor in ^{235}U

- Ratios of predicted to expected rates for different proposed CENNS experiments. The black dots show the expected ratio for the case of a sterile neutrino, $\sin^2\theta_{ee} = 0.062$ and $\Delta m^2 = 1.7$ eV.
- The blue dots give the ratio for the case of 5 % decrease in the ^{235}U, C. Giunti, Phys. Lett. B 764, 145 (2017).
- Black line: Average probability, mean energy of 4 MeV. Dotted black (6.5 MeV). 15%ER



Conclusions

- For the first time we considered reactor antineutrino-electron scattering data, using it to impose restrictions on the (3+1) oscillation parameter space.
- Future nu-e scattering measurements are highly desirable, GEMMA for instance.
- short-baseline coherent elastic neutrino-nucleus scattering experiments can probe effects associated to light sterile neutrinos.
- Particularly, the RED100, TEXONO, MINER, (CONNIE) proposals could test the current best fit point of the sterile allowed parameter space.
- Regarding the need of a precise antineutrino flux determination, CENNS is particularly attractive, since the detection technique is different from that of IBD detectors.

Thank you!
Спасибо

COHERENT Collaboration results

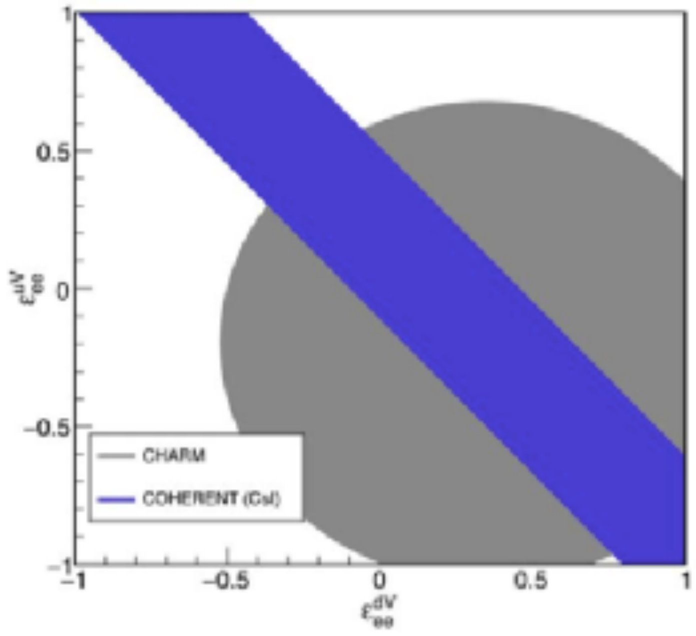
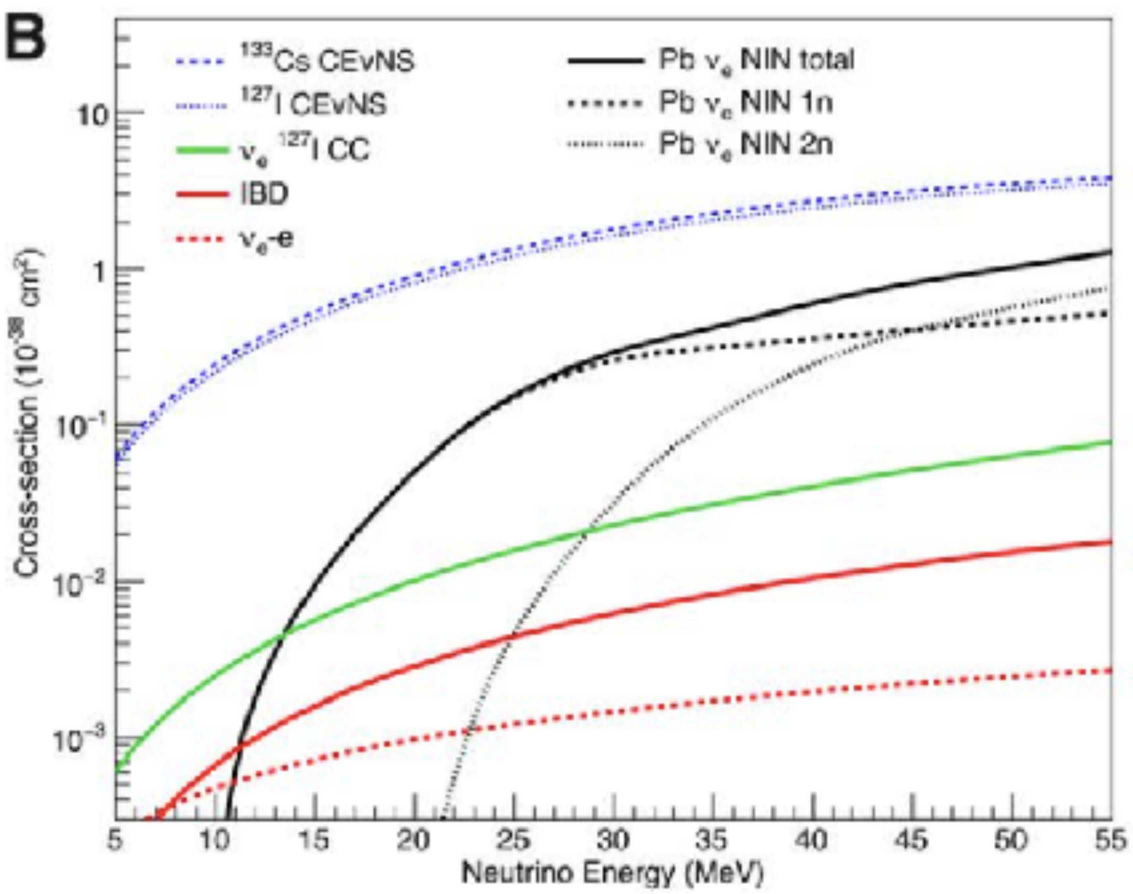
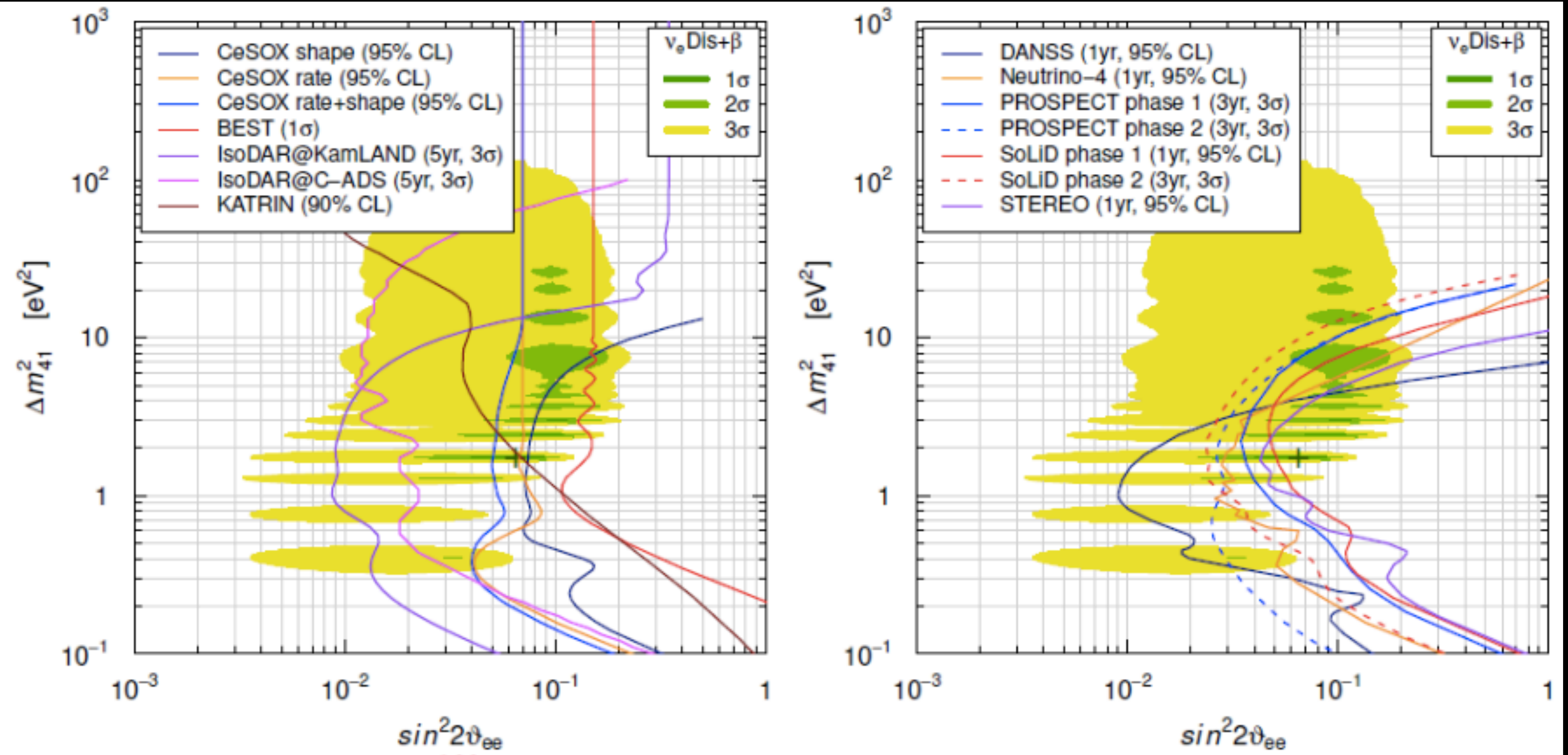


Fig. 4. Constraints on non-standard neutrino-quark interactions. Blue region: values allowed by the present data set at 90 % C.L. ($\chi^2_{min} < 4.6$) in $\varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV}$ space. These quantities parametrize a subset of possible non-standard interactions between neutrinos and quarks, where $\varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV} = 0,0$ corresponds to the Standard Model of weak interactions, and indices denote quark flavor and type of coupling. The gray region shows an existing constraint from the CHARM experiment (*34*).



Carlo Giunti Moriond 2017



CeSOX (Gran Sasso, Italy) $^{144}\mathrm{Ce} \rightarrow \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

BEST (Baksan, Russia) $^{51}\mathrm{Cr} \rightarrow \nu_e$
$L \simeq$ 5-12m [PRD 93 (2016) 073002]

IsoDAR@KamLAND (Kamioka, Japan)
$^{8}\mathrm{Li} \rightarrow \bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

IsoDAR@C-ADS (Guangdong, China)
$^{8}\mathrm{Li} \rightarrow \bar{\nu}_e$ $L \simeq$ 15m [JHEP 1601 (2016) 004]

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

KATRIN (Karlsruhe, Germany) $^{3}\mathrm{H} \rightarrow \bar{\nu}_e$ [Drexlin@NOW2016]

Other experiments restrictions to sterile neutrinos.

$$\begin{aligned}
P_{\overline{\nu}_e\to\overline{\nu}_e} &\approx 1 - 4(1-|U_{e4}|)^2|U_{e4}|^2\sin^2\Delta_{41} \\
&\quad - 4(1-|U_{e3}|^2-|U_{e4}|^2)|U_{e3}|^2\sin^2\Delta_{31} \\
&\approx 1 - \sin^2 2\theta_{14}\sin^2\Delta_{41} - \sin^2 2\theta_{13}\sin^2\Delta_{31}.
\end{aligned}$$

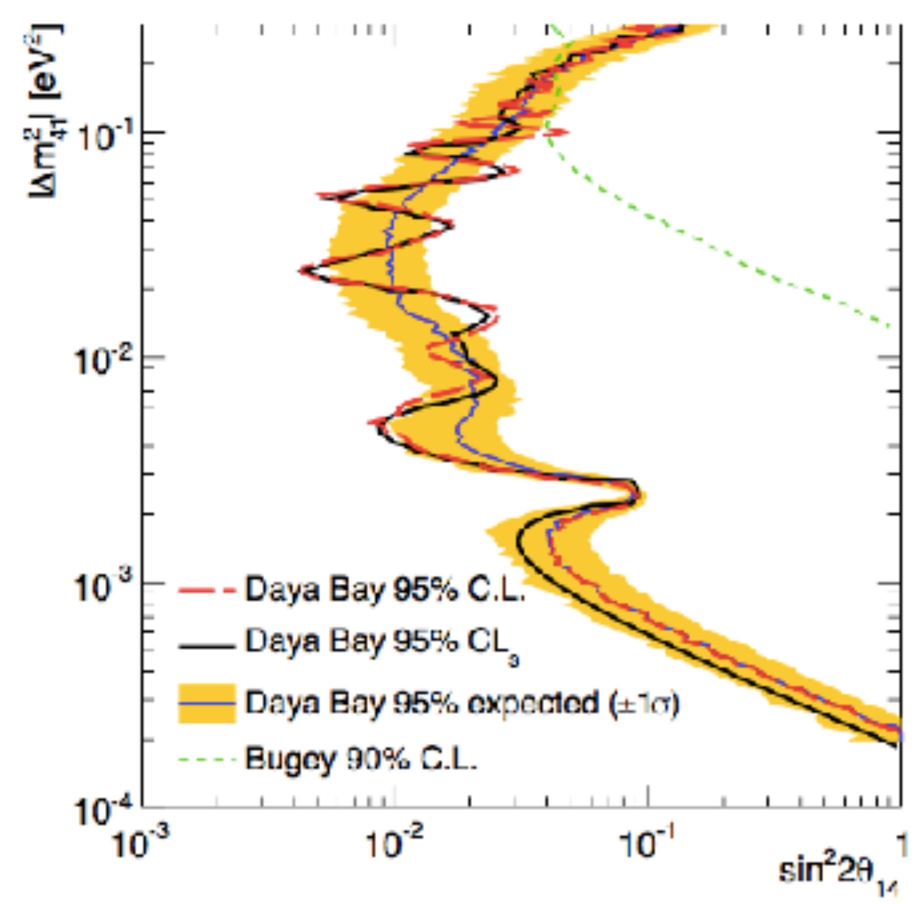


FIG. 3. Exclusion contours in the $(\sin^2 2\theta_{14}, |\Delta m^2_{41}|)$ plane, under the assumption of $\Delta m^2_{32} > 0$ and $\Delta m^2_{41} > 0$. The red long-dashed curve represents the 95% CL exclusion contour with the Feldman-Cousins method [40] from method A. The black solid curve represents the 95% CL$_s$ exclusion contour [41] from method B. The expected 95% CL 1σ band in yellow is centered around the sensitivity curve, shown as a thin blue line. The region of parameter space to the right side of the contours is excluded. For comparison, Bugey's [43] 90% CL limit on $\overline{\nu}_e$ disappearance is also shown as the green dashed curve.

Statistical analisys

neutrino -electron scattering experiments

$$N_i = n_e \Delta t \int \int_{T_i}^{T_{i+1}} \int \lambda(E_\nu) P^{\mathrm{SBL}}_{\nu_\alpha \to \nu_\alpha} \frac{d\sigma}{dT} R(T,T') dT' dT dE.$$

Future coherent elastic neutrino nucleus scattering experiments

$$N^{\mathrm{NS}}_{\mathrm{events}} = t\phi_0 \frac{M_{\mathrm{detector}}}{M} \int_{E_{\nu\mathrm{min}}}^{E_{\nu\mathrm{max}}} \lambda(E_\nu) P^{\mathrm{SBL}}_{\nu_\alpha \to \nu_\alpha} dE_\nu \int_{T_{\mathrm{min}}}^{T_{\mathrm{max}}(E_\nu)} \left(\frac{d\sigma}{dT}\right)^{\mathrm{coh}}_{\mathrm{SM}} dT.$$

$$N^{\mathrm{SM}}_{\mathrm{events}} = t\phi_0 \frac{M_{\mathrm{detector}}}{M} \int_{E_{\nu\mathrm{min}}}^{E_{\nu\mathrm{max}}} \lambda(E_\nu) dE_\nu \int_{T_{\mathrm{min}}}^{T_{\mathrm{max}}(E_\nu)} \left(\frac{d\sigma}{dT}\right)^{\mathrm{coh}}_{\mathrm{SM}} dT,$$

the Gallium data we perform a Max. Likelihood fit, more details in: C. Giunti, et al, Phys. Rev. D 86, 113014 (2012)

NEOS Experiment
Y. J. Ko et al.,
Phys. Rev. Lett. 118, no. 12, 121802 (2017)

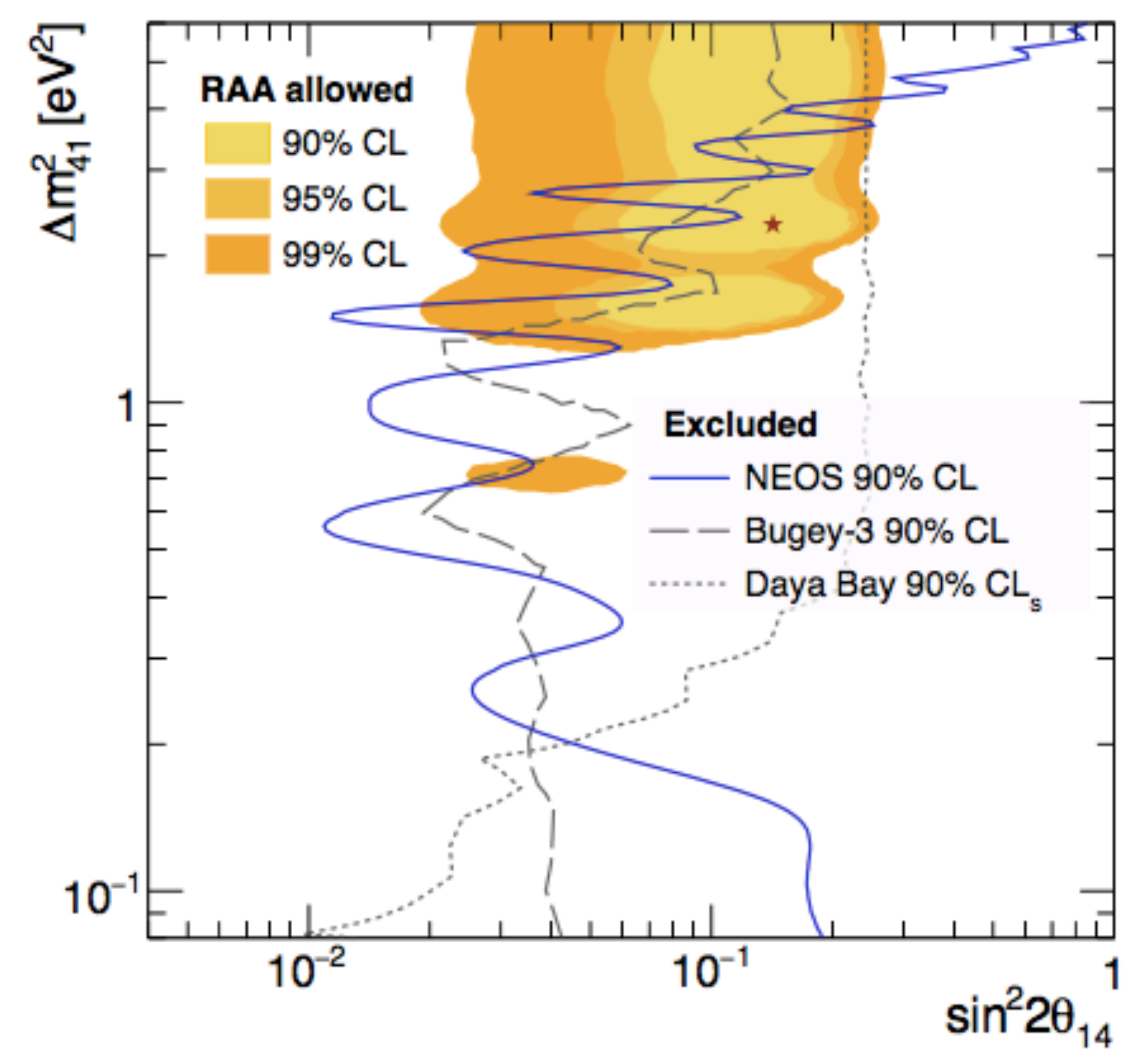
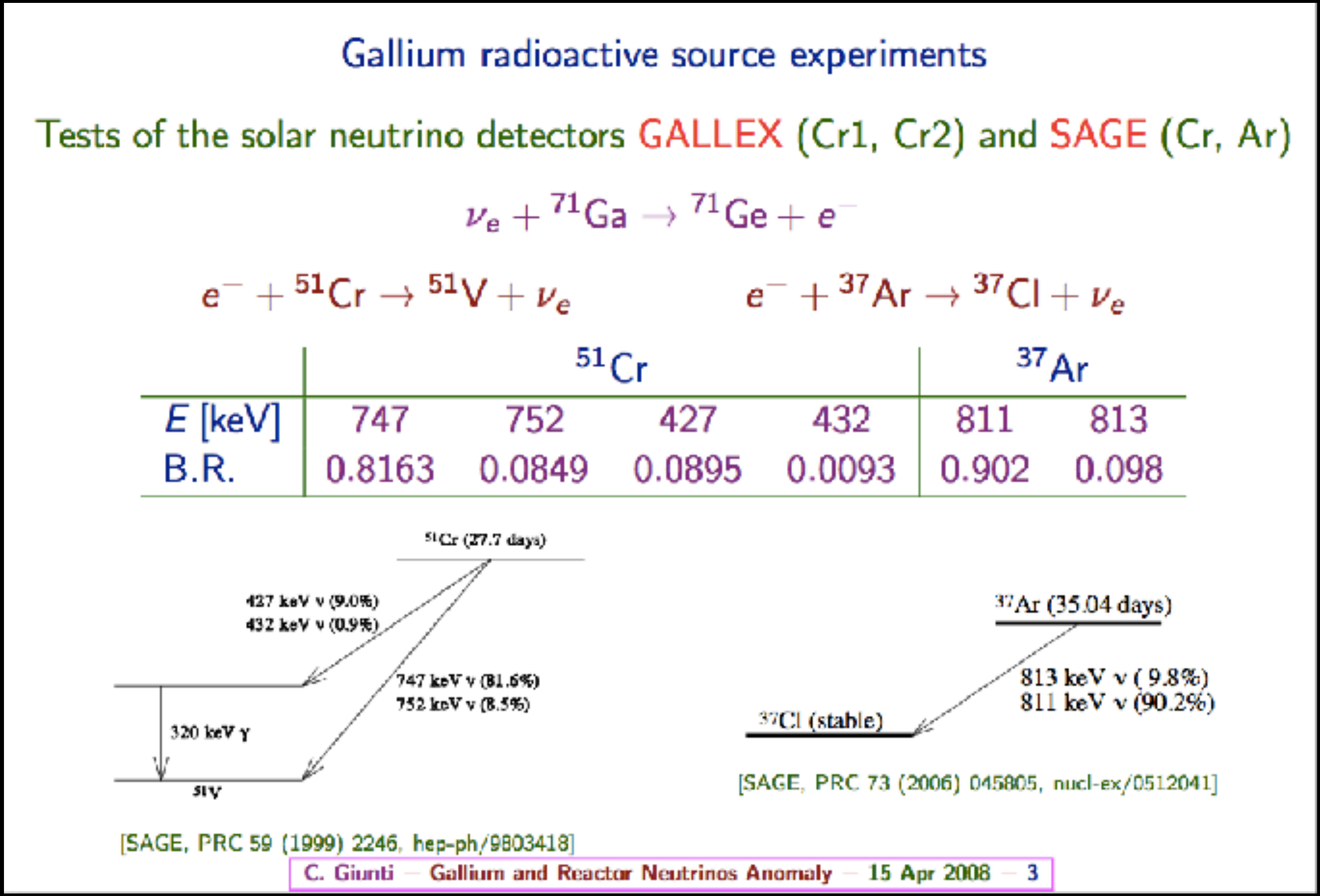


FIG. 4. Exclusion curves for 3+1 neutrino oscillations in the $\sin^2 2\theta_{14} - \Delta m^2_{41}$ parameter space. The solid-blue curve is 90% CL exclusion contours based on the comparison with the Daya Bay spectrum, the dashed-gray curve is the Bugey-3 90% CL result [10]. The dotted curve shows the Daya Bay 90% CL$_s$ result [34]. The shaded area is the allowed region from the reactor antineutrino anomaly fit and the star is its optimum point [12].

Gallium Anomaly

$R_{Ga} = 0.86 \pm 0.05$



Gallium radioactive source experiments

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

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

$$e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e \qquad e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$$

	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098

[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]

[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

C. Giunti — Gallium and Reactor Neutrinos Anomaly — 15 Apr 2008 — 3

GALLEX (1.9m)
SAGE (0.6m)