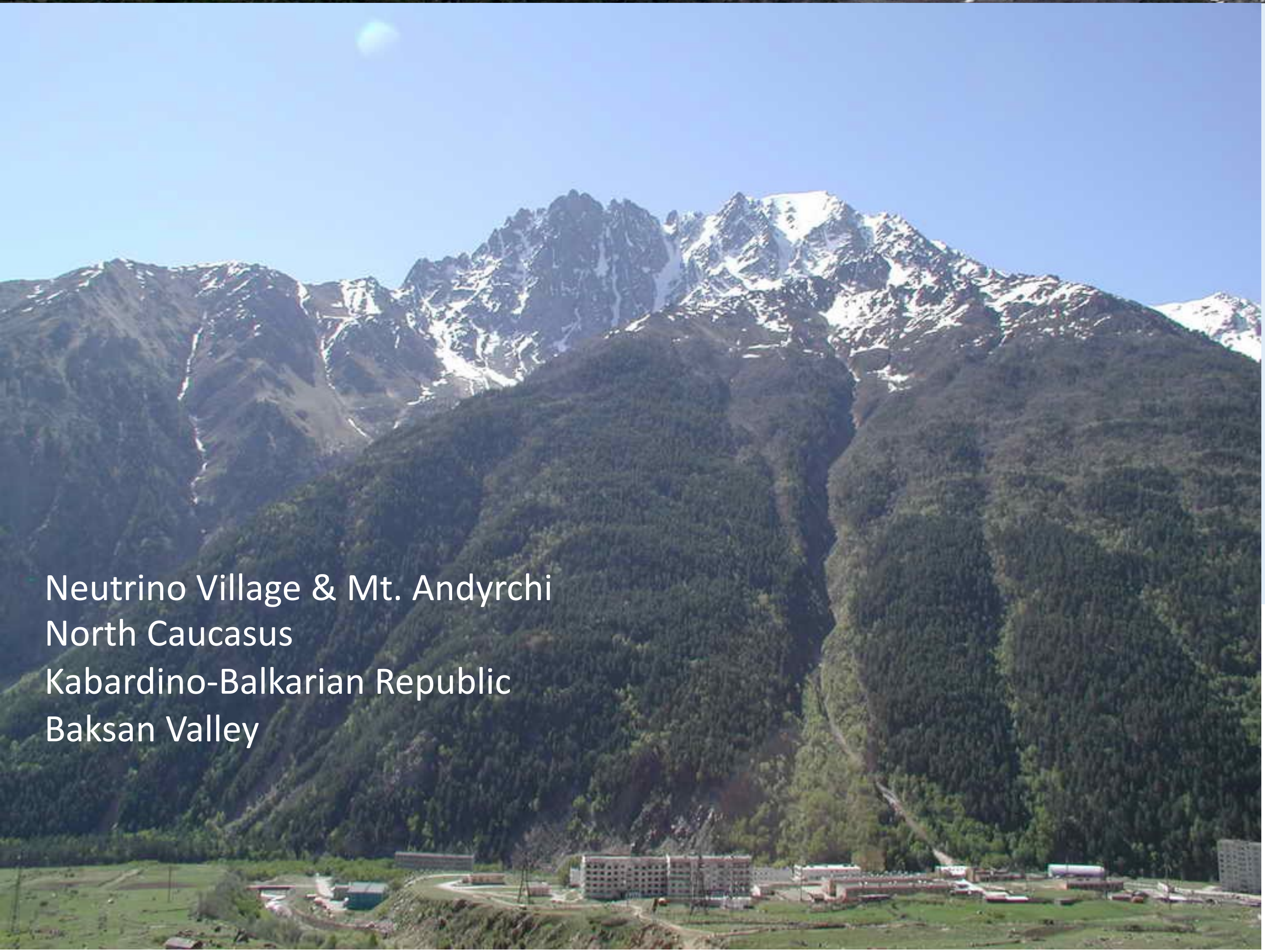
The hunt for sterile neutrinos – the BEST experiment – and other recent short-baseline results



Ralph Massarczyk

Los Alamos

National Laboratory

LA-UR-21-30292

A bit of history of gallium based neutrino searches

- Search for solar neutrinos using neutrino capture in Gallium

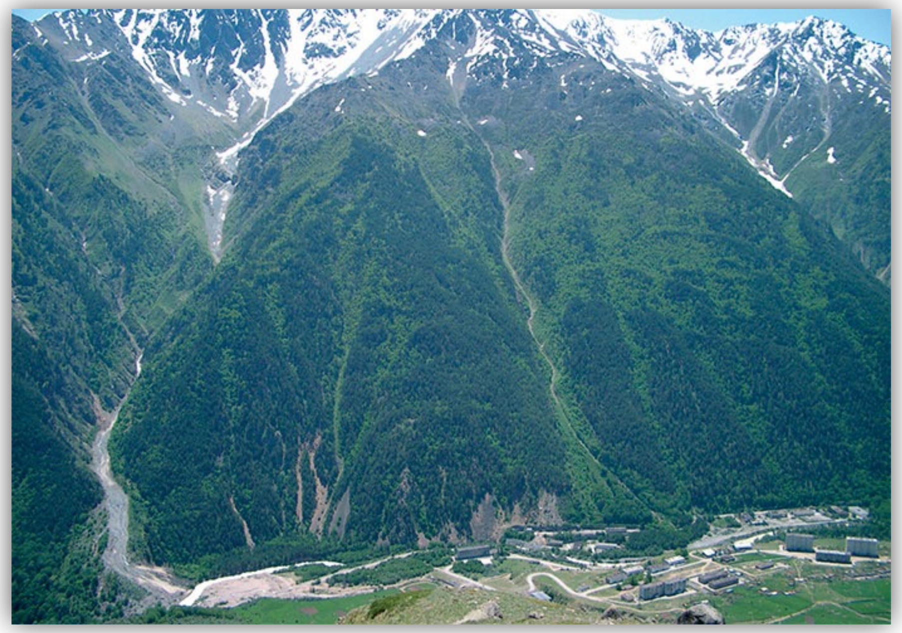
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

- Russian(**S**owjet)-**A**merican-**G**allium **E**xperiment started in the 80s at Baksan – SAGE

- The **Gall**ium **Ex**periment started data taking in ‘91 at Gran Sasso (GALLEX, later GNO)

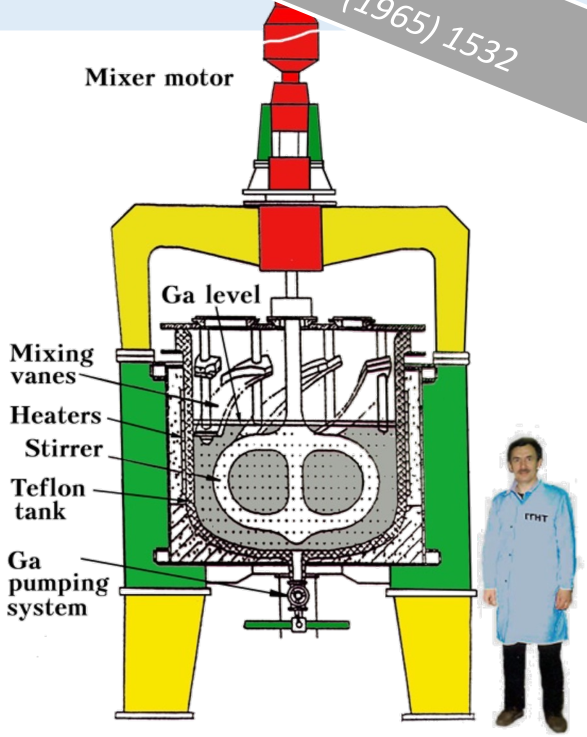
The Gallium Solar Neutrino Experiments

V. A. Kuzmin
Zh. Eksp. Teor. Fiz. 49 (1965) 1532



Deep Underground

Large Mass (~30 - 50t of liquid Ga)

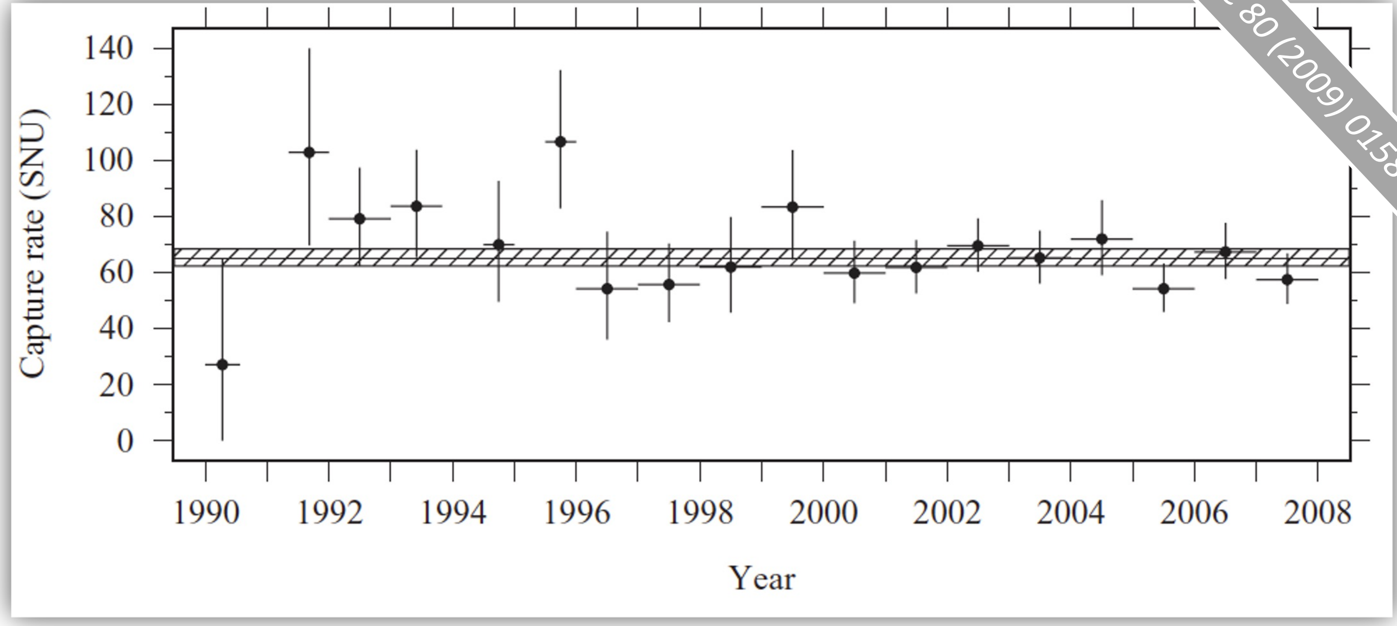


Radiochemical extraction

SAGE and GALLEX Results for Solar Neutrinos

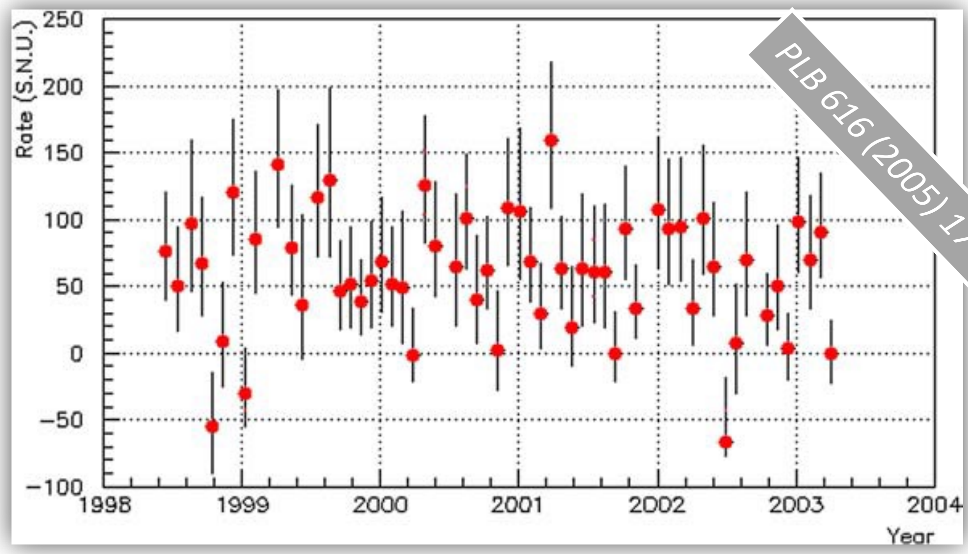
- SAGE/GALLEX/GNO: 66.1 ± 3.1 SNU
- Evidence for the p-p chain reactions for solar neutrino production in the Sun.

SAGE: 1990 – 2007



PRC 80 (2009) 015807

GALLEX/GNO: 1991 - 2003



PLB 616 (2005) 174

1 SNU = 1 interaction/s in a target that contains 10^{36} atoms of the neutrino absorbing isotope

Ga-Solar Neutrino Experiments

Neutrino flux		FLUX in SNU
Bahcall	Total neutrino flux prediction	132 (20)
	Electron neutrino flux (56-60%)	74 (11)
SAGE	2009 publication	65 (6)
GALLEX	2010 publication	67 (7)

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pp chain		FLUX in 10^{10} cm^{-2} s^{-1}
Bahcall and Solar SM		5.98-6.03
BOREXINO	2018 Nature, direct measurement	6.1 (10)
SAGE	2009 publication, total flux and P_{ee}	6.0 (11)

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Agreement of solar flux and other direct measurements

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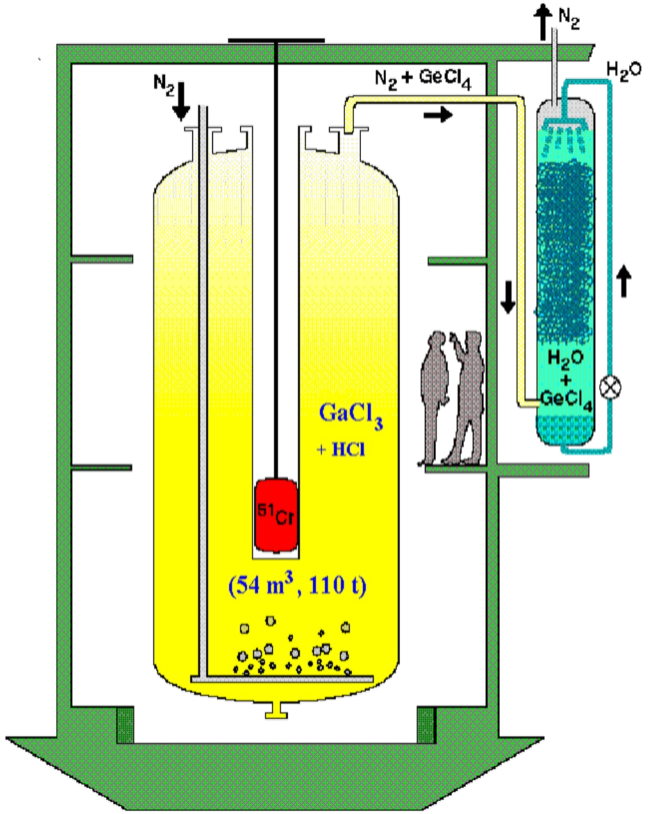
From solar neutrinos to neutrinos from sources

- Measurements of radioactive sources to confirm sensitivity
- ^{51}Cr and ^{37}Ar sources
- Compare the expected rate with the measured rate
- Requires cross section and ν_e flux



An unexpected result - The Ga Anomaly

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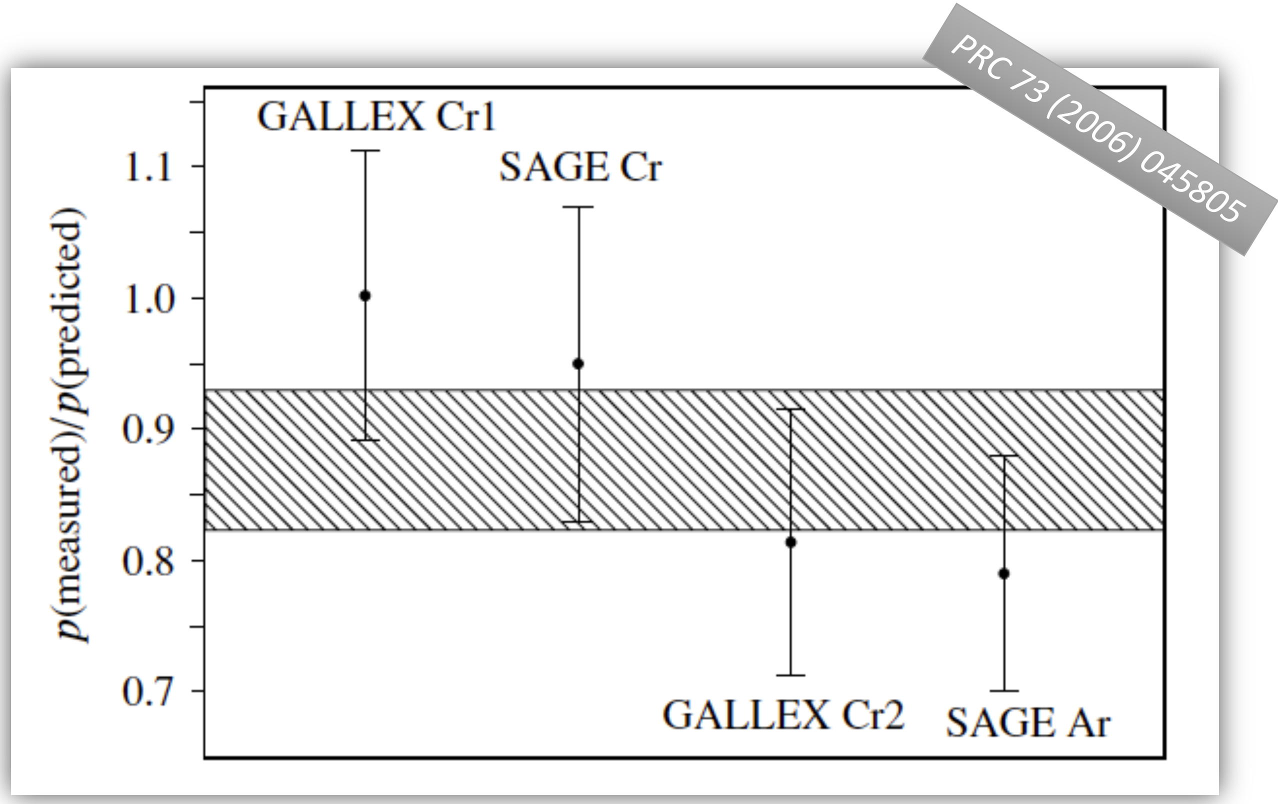
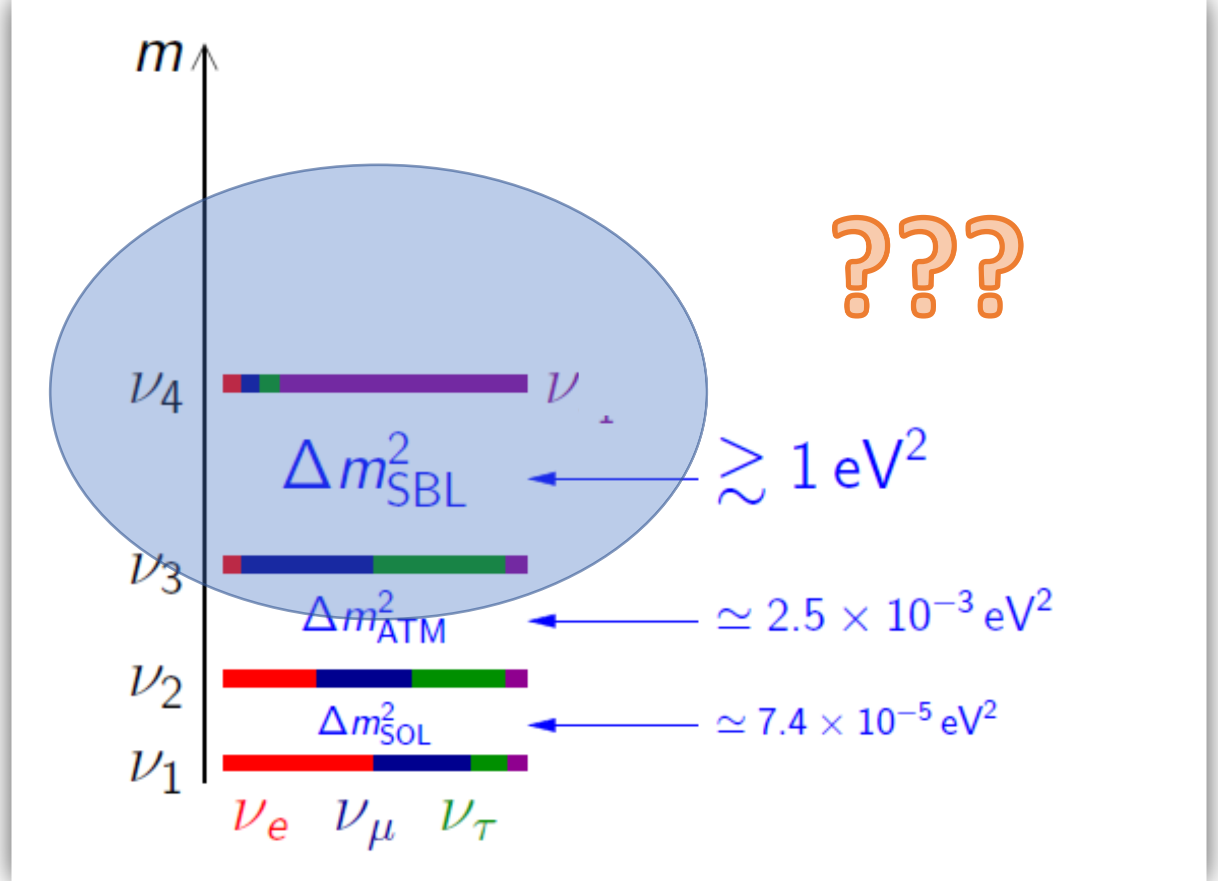


Measured rates of $^{71}Ga(\nu_e,e)^{71}Ge$ are lower than that predicted from the known inputs

The Ga Anomaly

Measured rates of $^{71}Ga(\nu_e,e)^{71}Ge$ are lower than that predicted from the known

Is this disappearance
due to oscillation into sterile neutrinos ?



Evidence for sterile neutrinos (ν_s) ?

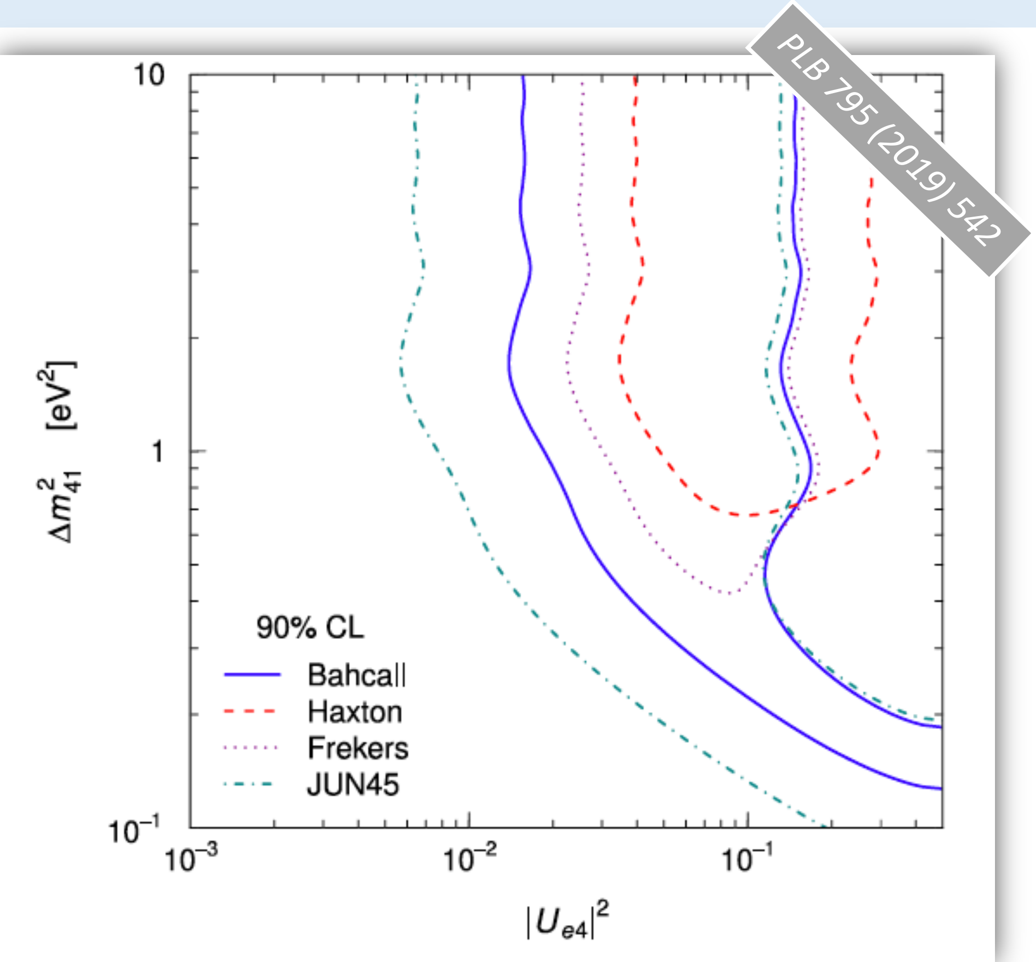
The decreased rate of ν_e detection has been interpreted with the hypothesis that the ν_e are oscillating into undetected ν_s.

$$P_{ee}(E_\nu, r) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]r[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$

E_ν ~ 1 MeV, L ~ 1 m.

<u>Best fits tend toward high Δm² and sin²2q.</u>

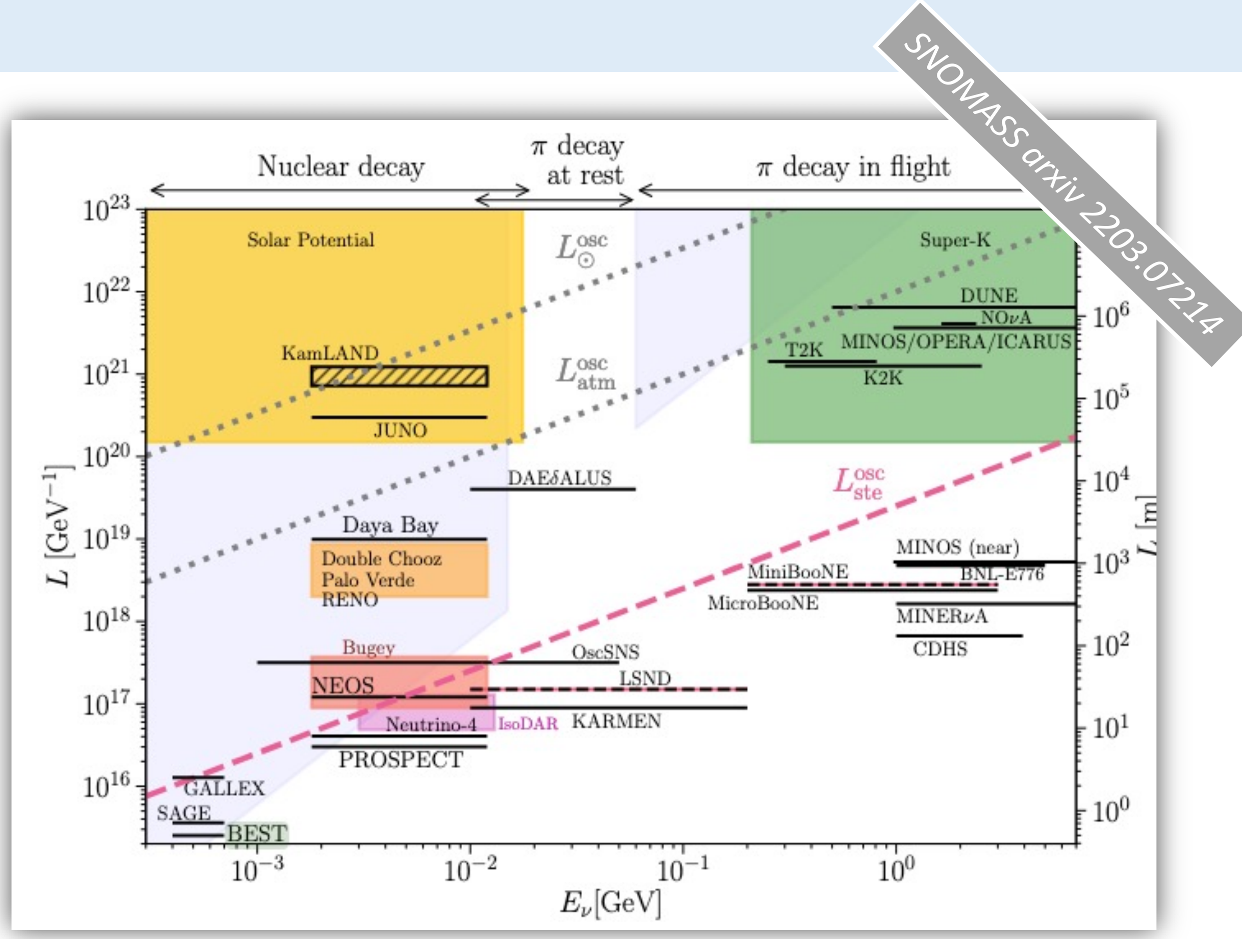
Some references
PRD 78 (2008) 073009, PLB 795 (2019) 542, arXiv:2001.10064, PRD 86 (2012) 113014, NP B168 Proc. Supp. (2007) 344, PRD 97 (2018) 073001, NP B235 Proc. Supp. (2013) 214, J. Phys. G: Nucl. Part. Phys. 43 (2016) 033001



A (light) sterile neutrino ?

- Extension of the Standard model
- Can be useful for a number of problems depending on the **mass**

TeV or higher	Seesaw mechanism
Several hundred GeV or more	Leptogenesis, baryon asymmetry
keV	Dark matter
eV	**Oscillation anomalies**



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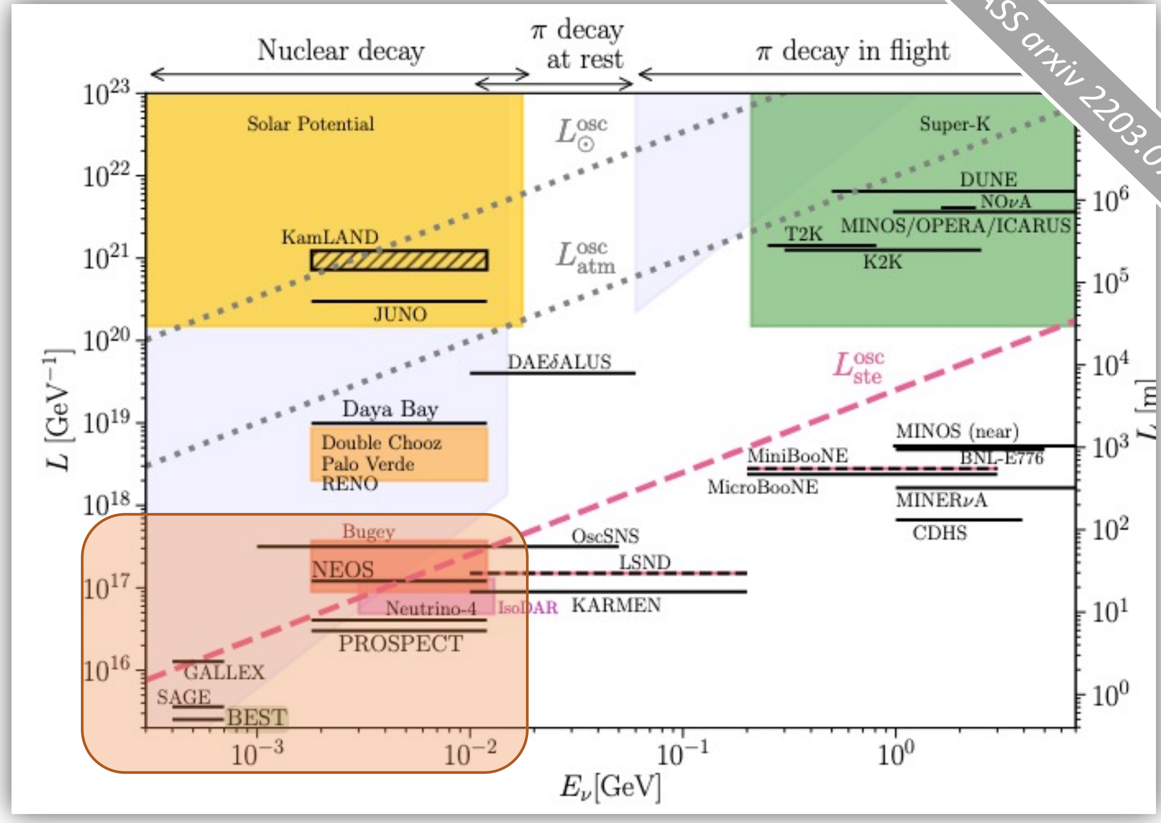
SNOMASS arxiv 2203.07214



BNO INR RAS

Baksan Experiment on Sterile Transitions **(BEST)**

Phys. Rev. Lett. 128, 232501 (2022)
Phys. Rev. C 105, 065502 (2022)

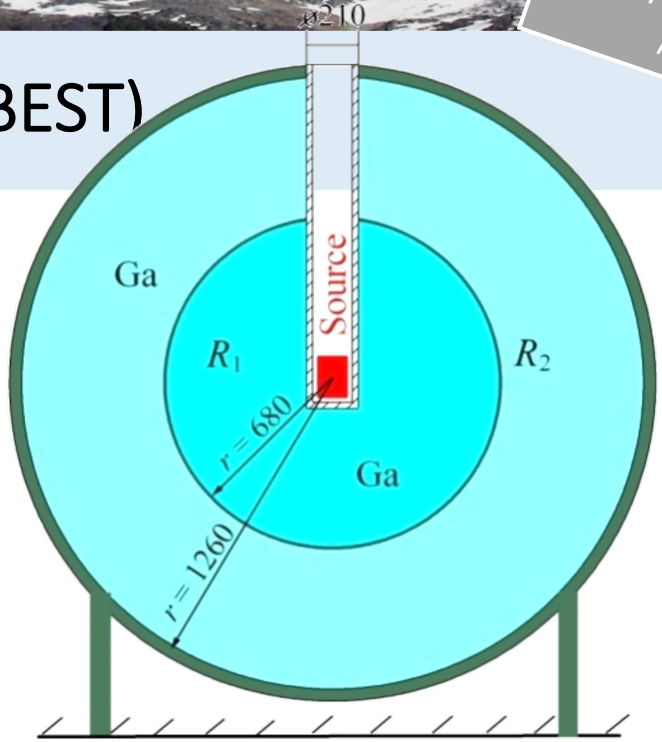
- Neutrinos produced at center of Ga by ^{51}Cr decay:

$$^{51}Cr + e^- \rightarrow {}^{51}V + \nu_e$$

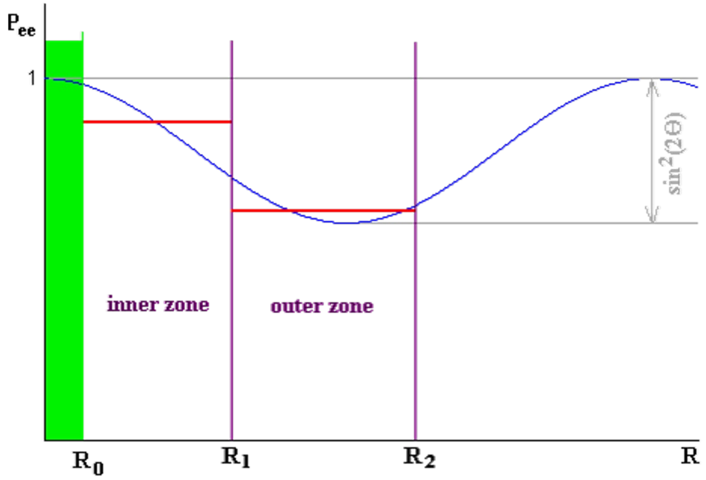
- Monochromatic spectrum of a compact source
- Precisely known intensity of the source (3.4 MCi ~ 10^{17} Bq)
- A search for electron neutrino disappearance via charged-current (CC) reaction only:

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

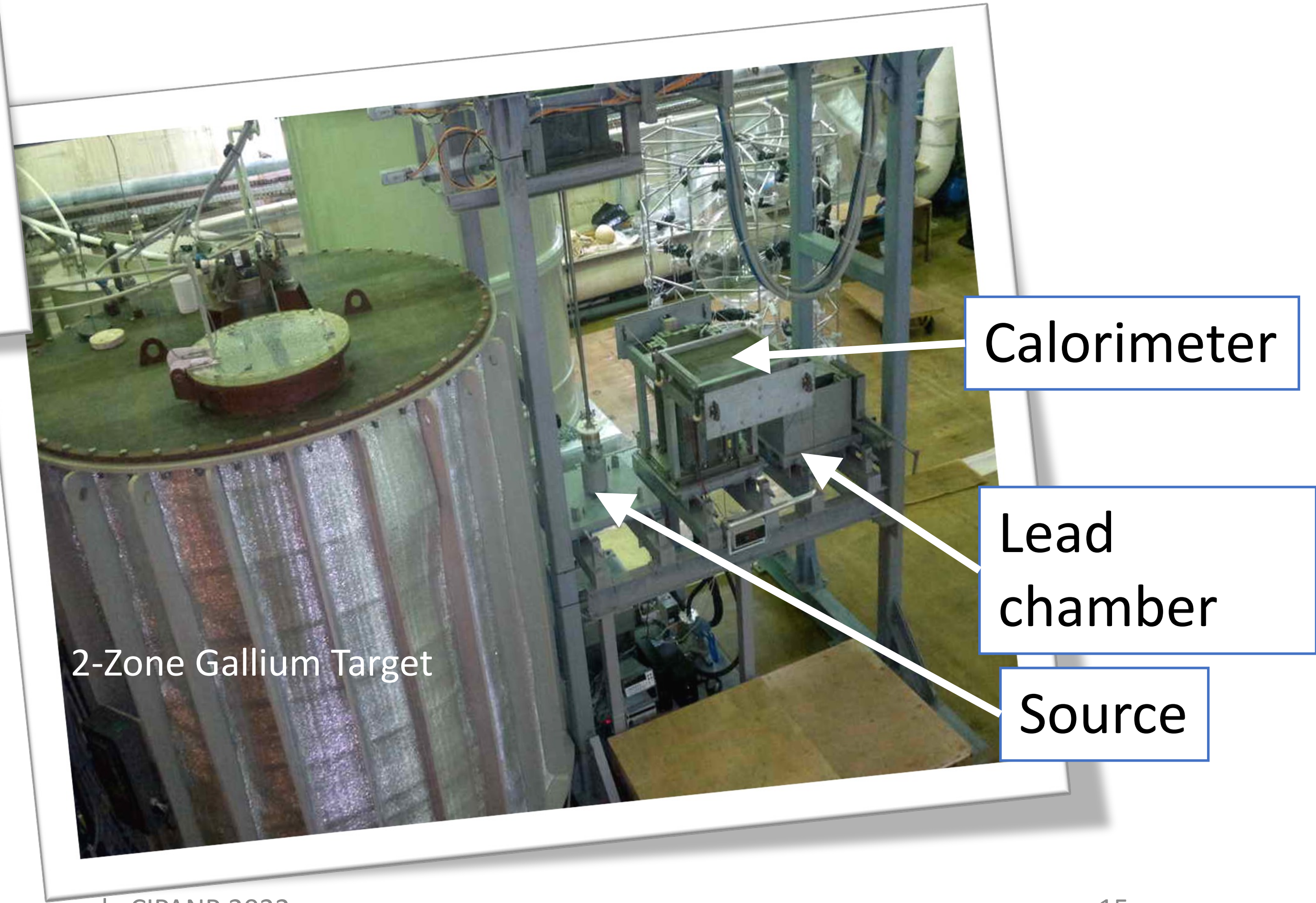
- Two independent zones allowing studies on the dependence of the rate on the distance to the source.
- Very Short Baseline
- Very well-known experimental procedures
- Simple interpretation of results

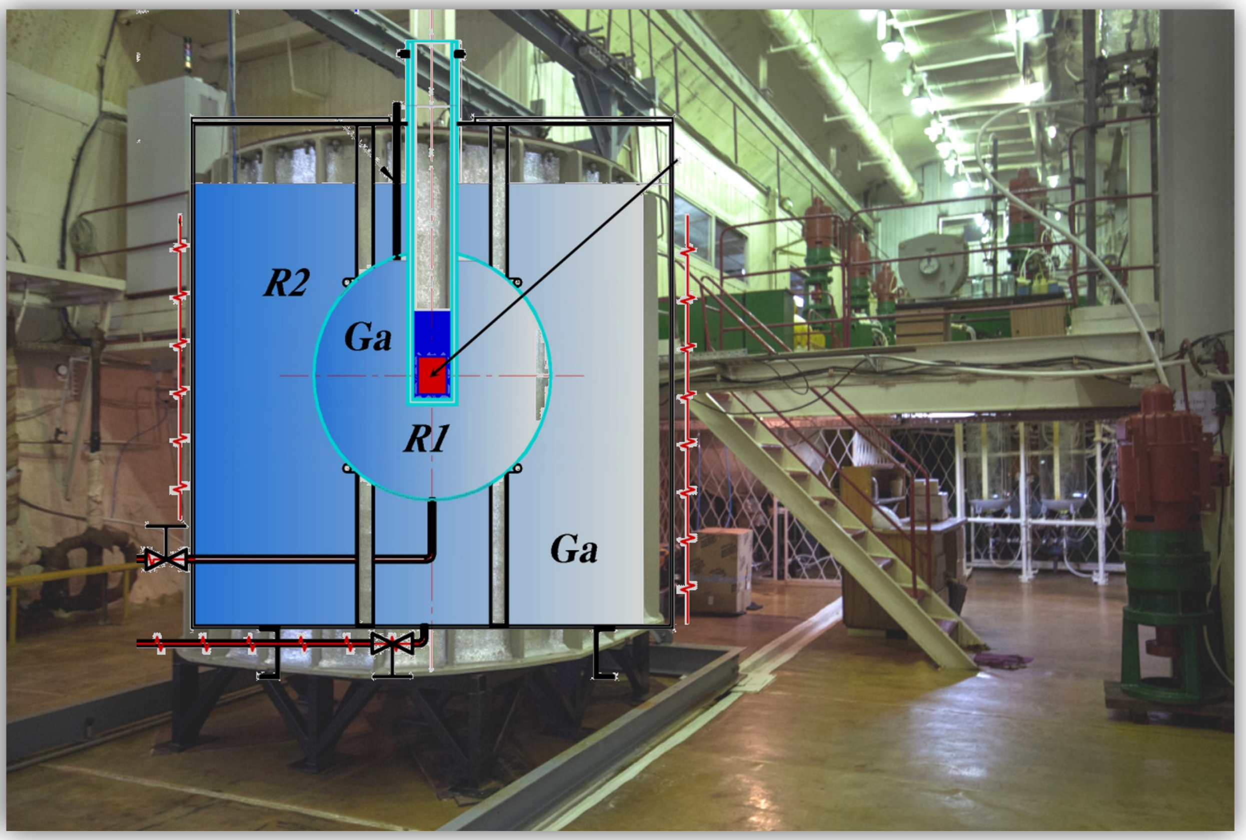


Schematic drawing of the BEST neutrino source experiment.



Construction started in 2011




R2
Ga
R1
Ga

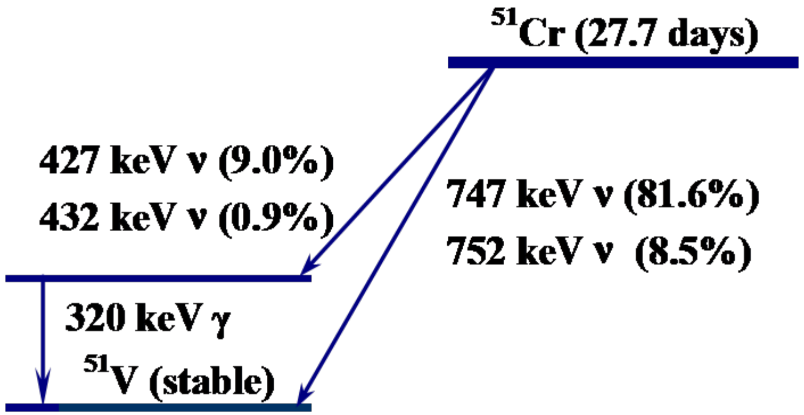
Neutrino Source

JINST 16 (2021) P04012

- Irradiated for ~100 days with thermal neutrons in the SM-3 reactor to produce ^{51}Cr neutrino source

- Thermal neutron flux density – 5×10^{15} n/(cm^2 s)

- Activity at 14:02 on July 5, 2019
  A = 3.414 ± 0.008 MCi

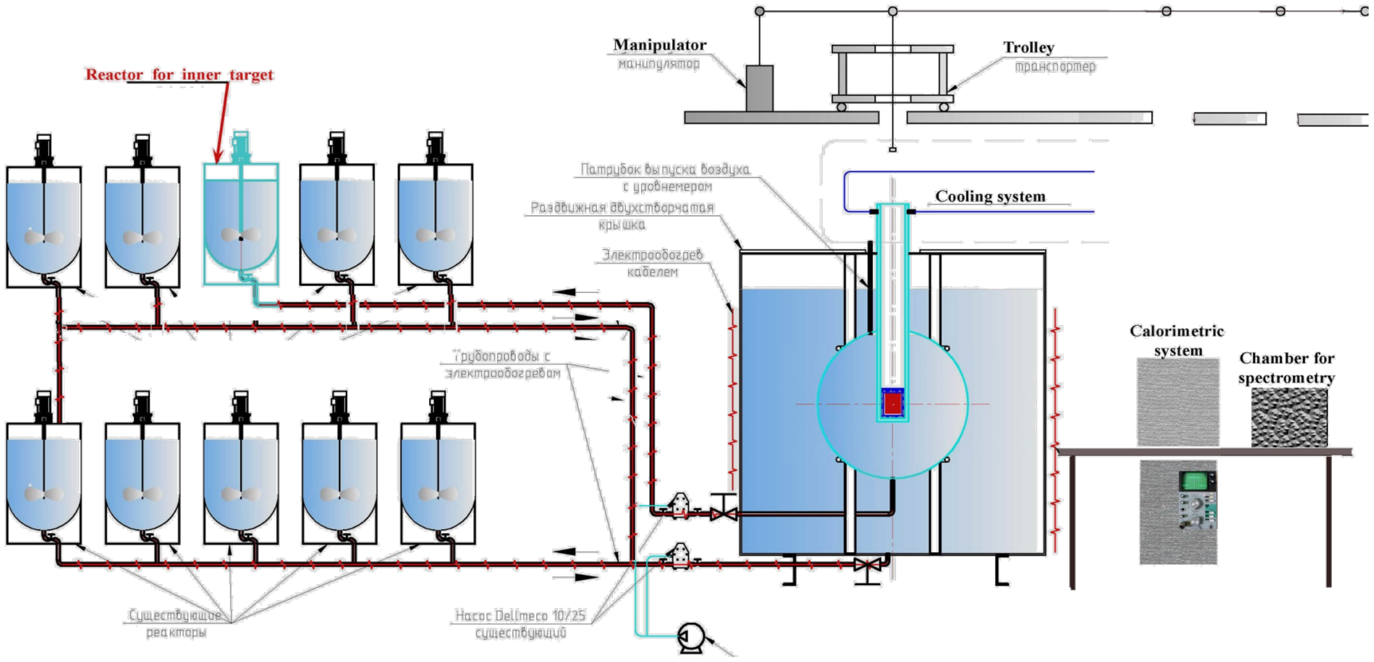


Simple and very well-understood neutrino spectrum

4 kg 97%-enriched ^{50}Cr,
26 chromium disks
h = 4 mm, ∅ 84 and 88 mm.

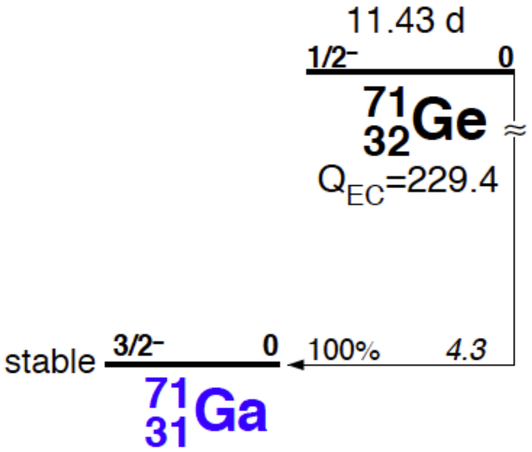
Installation and Operation

1. Expose gallium targets to the source (10 days)
2. Pump Ga into chemical reactors and extraction
3. Count the extracted Ge-gas in proportional counters (up to 100 days)
4. Measure source activity
5. Repeat 10 x



^{71}Ge Decay

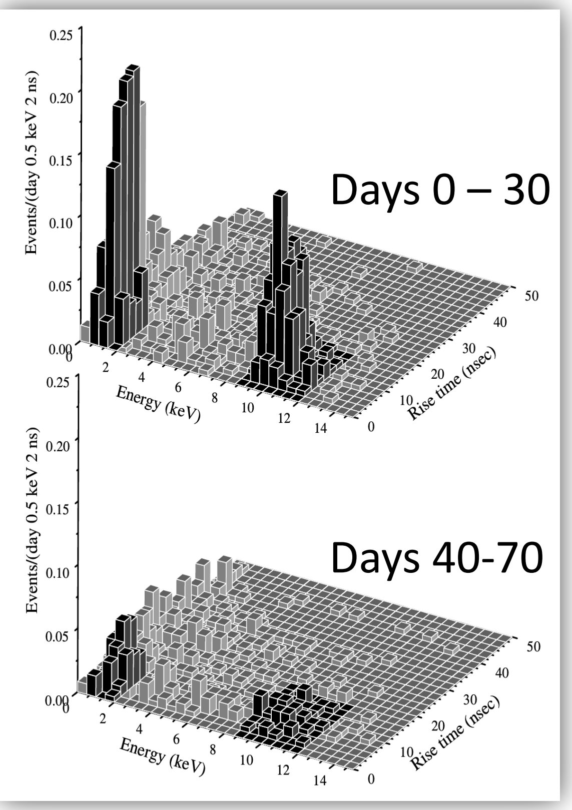
- Extracted GeH_4(Xe) placed in proportional counters
- Half-life of 11.4 d, ground state transition
- K, L, M-shell Capture
- Detection of Auger-electron and x-ray

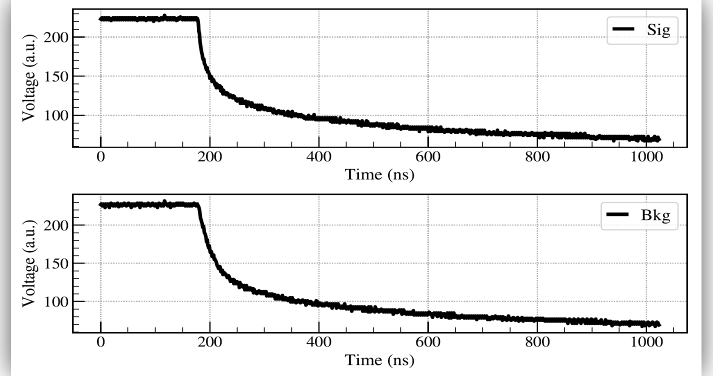


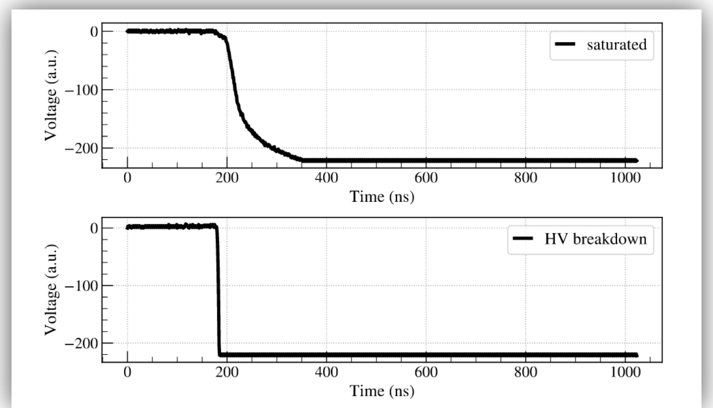
^{71}Ge Candidate Event Selection

Phys. Rev. C 105, 065502 (2022)

- Energy Selection
- Time tagging
- Anti-coincidence with NaI system (1/3 of events removed)
- Pulse shape analysis
  - Alpha-induced events
  - High-voltage breakdowns
  - Rise-Time analysis to suppress Compton background



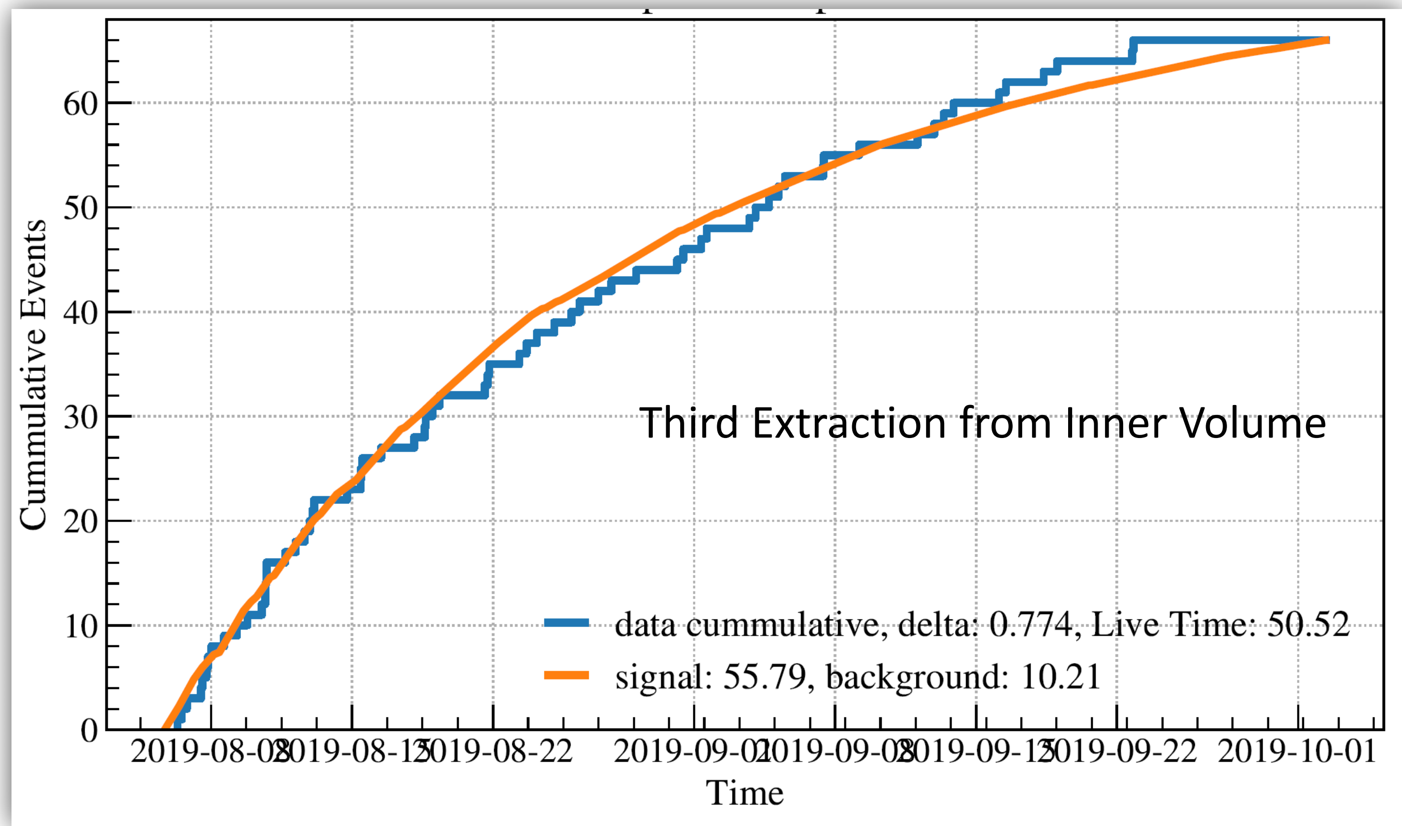




Likelihood Fit for each extraction sample

<u>Maximum likelihood fit to the ***t*** and ***E***</u>

- p: ^{71}Ge production rate, 11.4-d half-life
- b: background rate, constant in time
- ϵ: overall efficiency
- $w_p(E)$ /$w_b(E)$: energy weight factors
- Δ: probability an event will during counting
- τ : total counting time



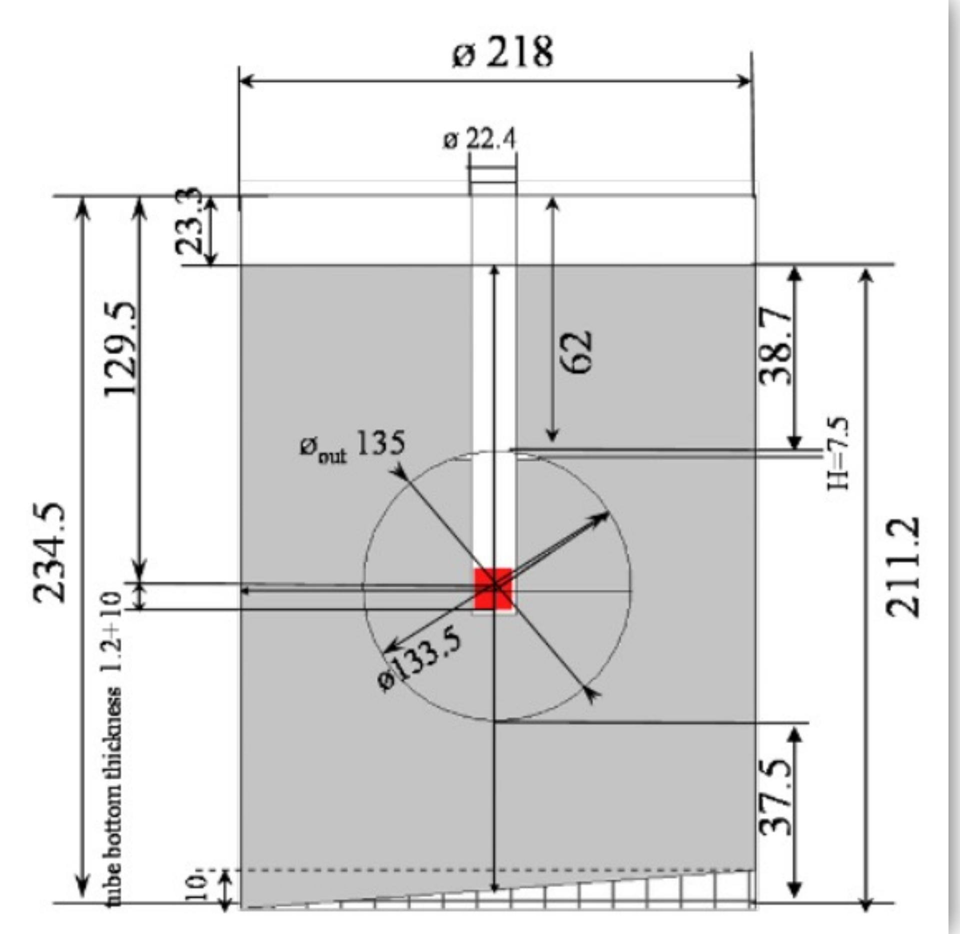
Predicted Production Rates

Production rates are predicted from cross section

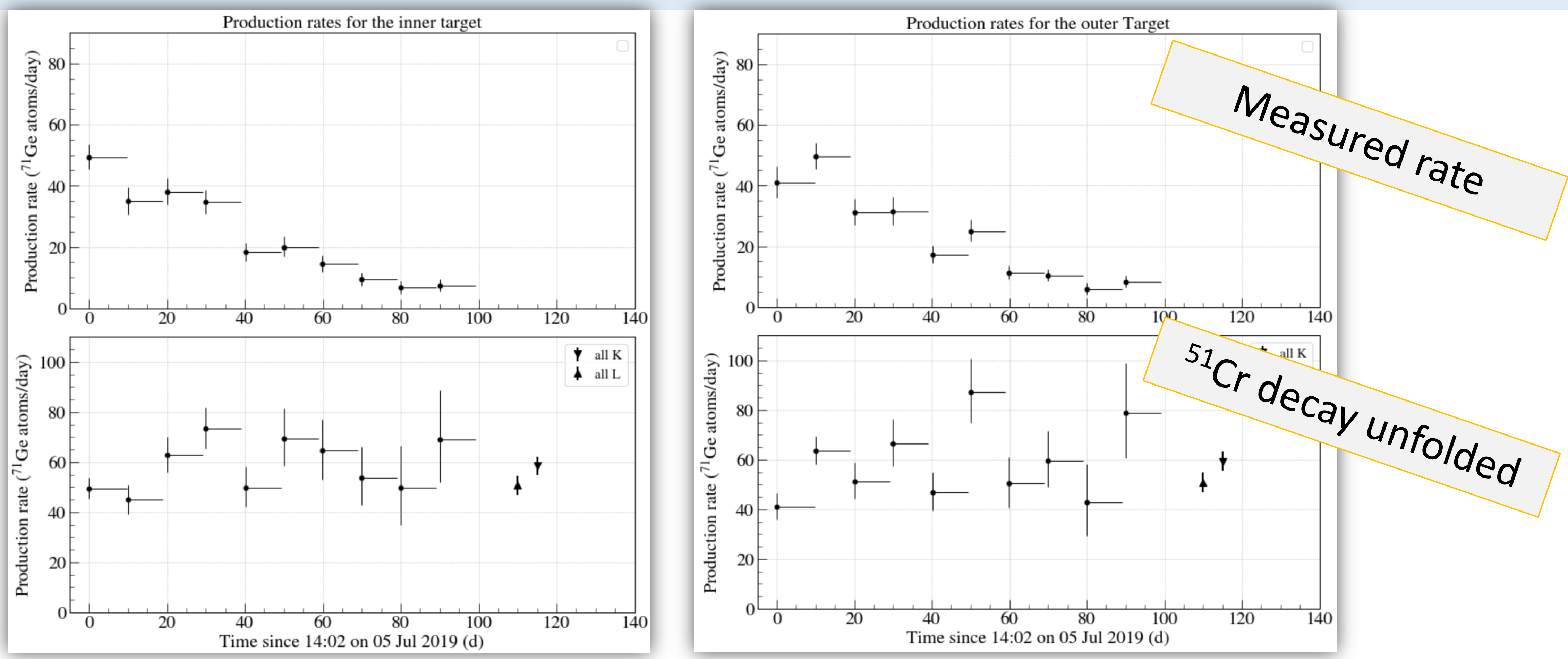
$$P_{ee}(E_\nu, r) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2] r[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$

$$R_j = \frac{n\sigma A}{4\pi}\int_{V_j}\frac{P_{ee}(r)}{r^2}d\vec{x} \approx V_0\frac{1}{N}\sum_{i=1}^{N}\frac{P_{ee}(r)}{r^2}\Theta_j(\vec{x}_i)$$

	Value	Uncertainty Magnitude	Uncertainty %
Atomic density $D = \rho N_0 f_1/M$			
Ga density ρ (g Ga/cm^3)	6.095	0.002	0.033
Avogadro's number N_0 (10^{23} atoms Ga/mol)	6.0221	0.0	0.0
Ga molecular weight M (g Ga/mol)	69.72307	0.00013	0.0002
Atomic density D (10^{22} atoms ^{71}Ga/cm^3)	2.1001	0.0008	0.037
Source activity at reference time A, MCi	3.414	0.008	0.23
Cross section σ (10^{45} cm^2/ (^{71}Ga atom ^{51}Cr decay)], Bahcall	5.81	+0.21,-0.16	+3.6,-2.8
Path length in Ga $< L_{in} >$ (cm)	52.03	0.18	0.3
Path length in Ga $< L_{out} >$ (cm)	54.41	0.18	0.3
Predicted production rate (^{71}Ge atoms/d), R_{In}	69.41	+2.5,-2.0	+3.6,-2.8
Predicted production rate (^{71}Ge atoms/d), R_{Out}	72.59	+2.6,-2.1	+3.6,-2.8



Counting Results



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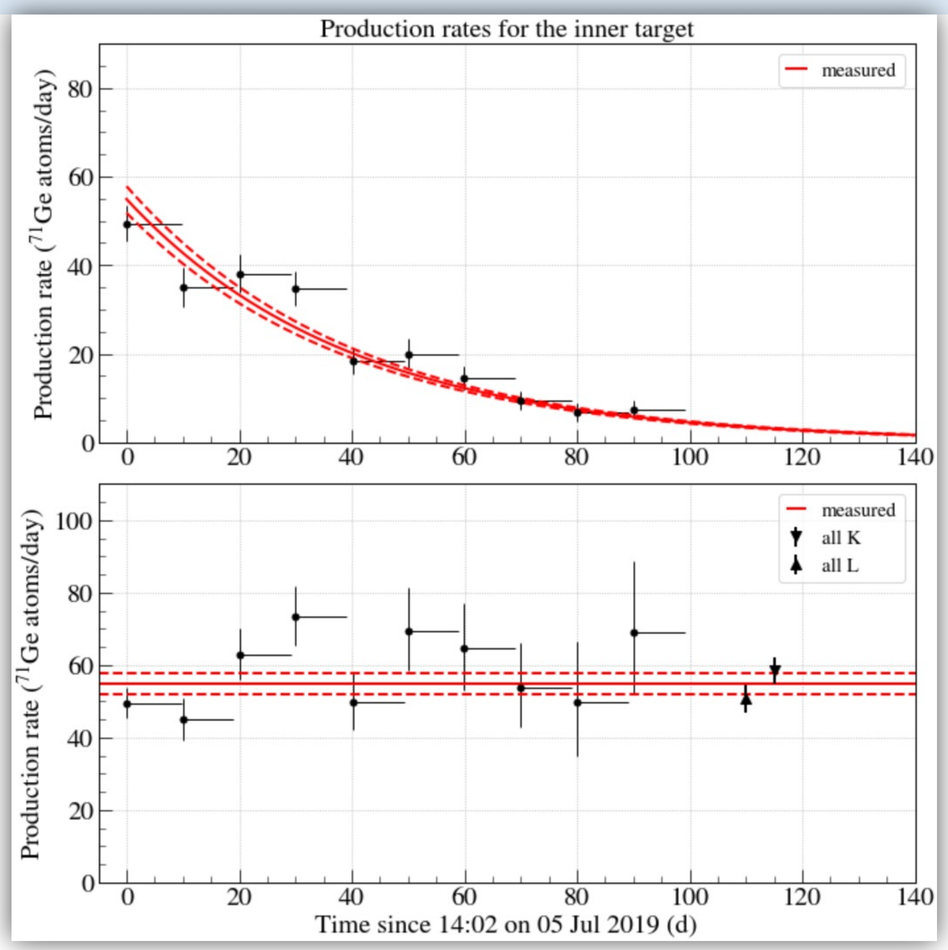
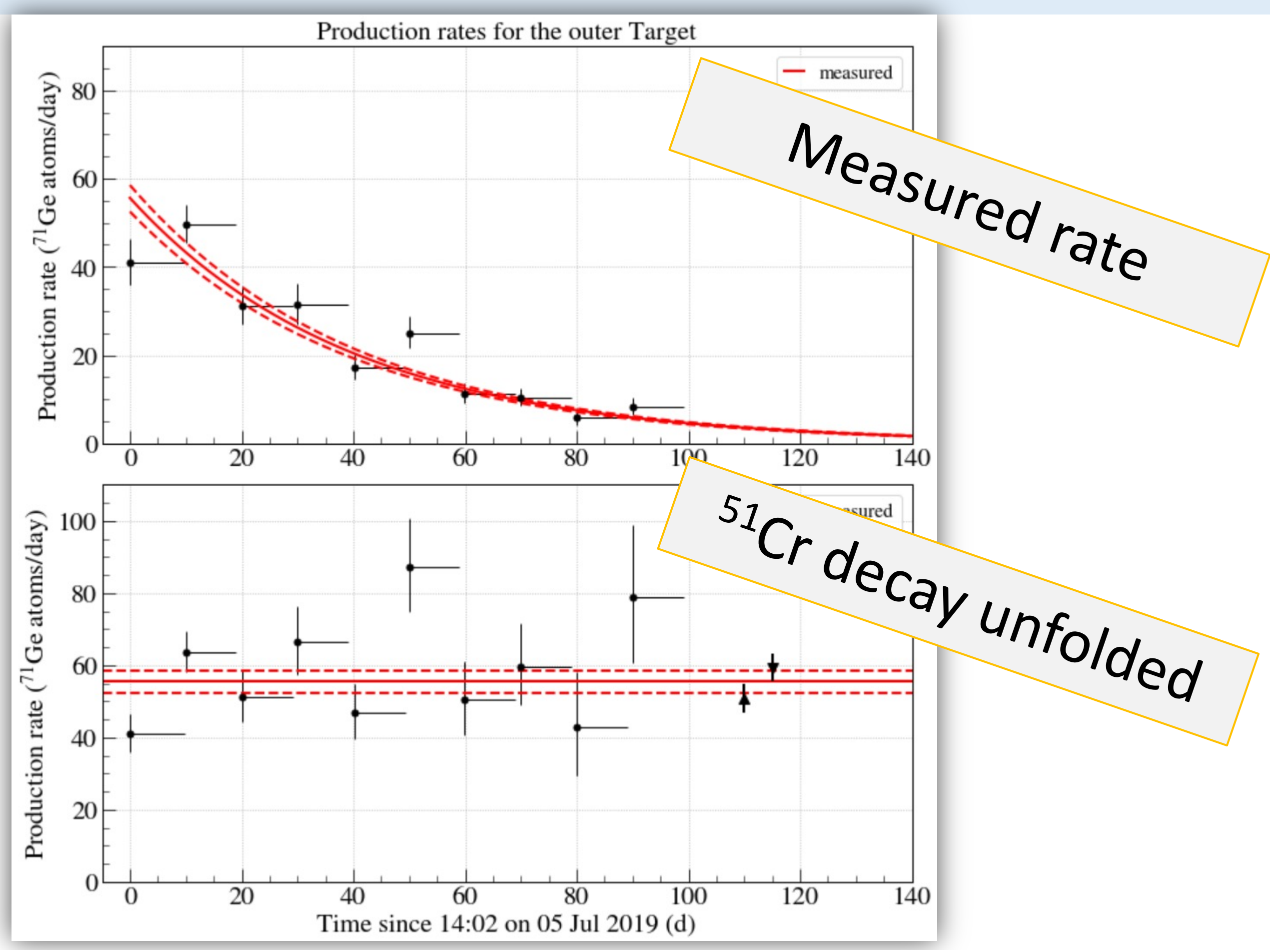
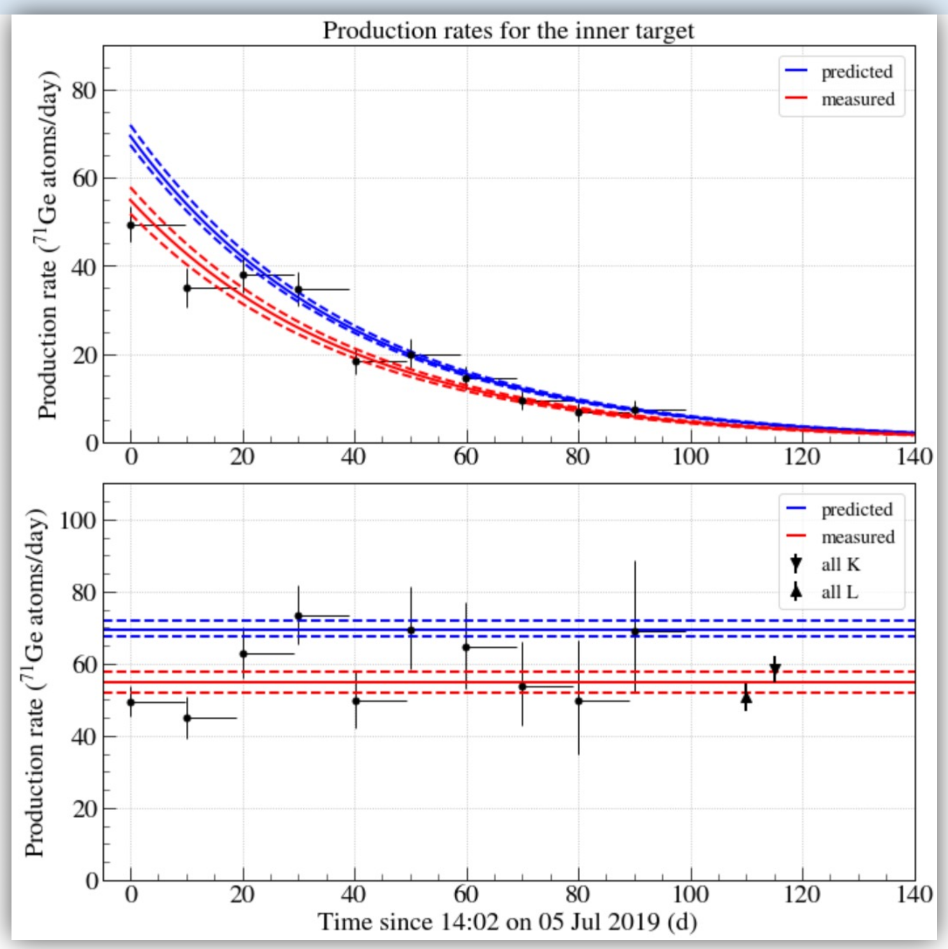
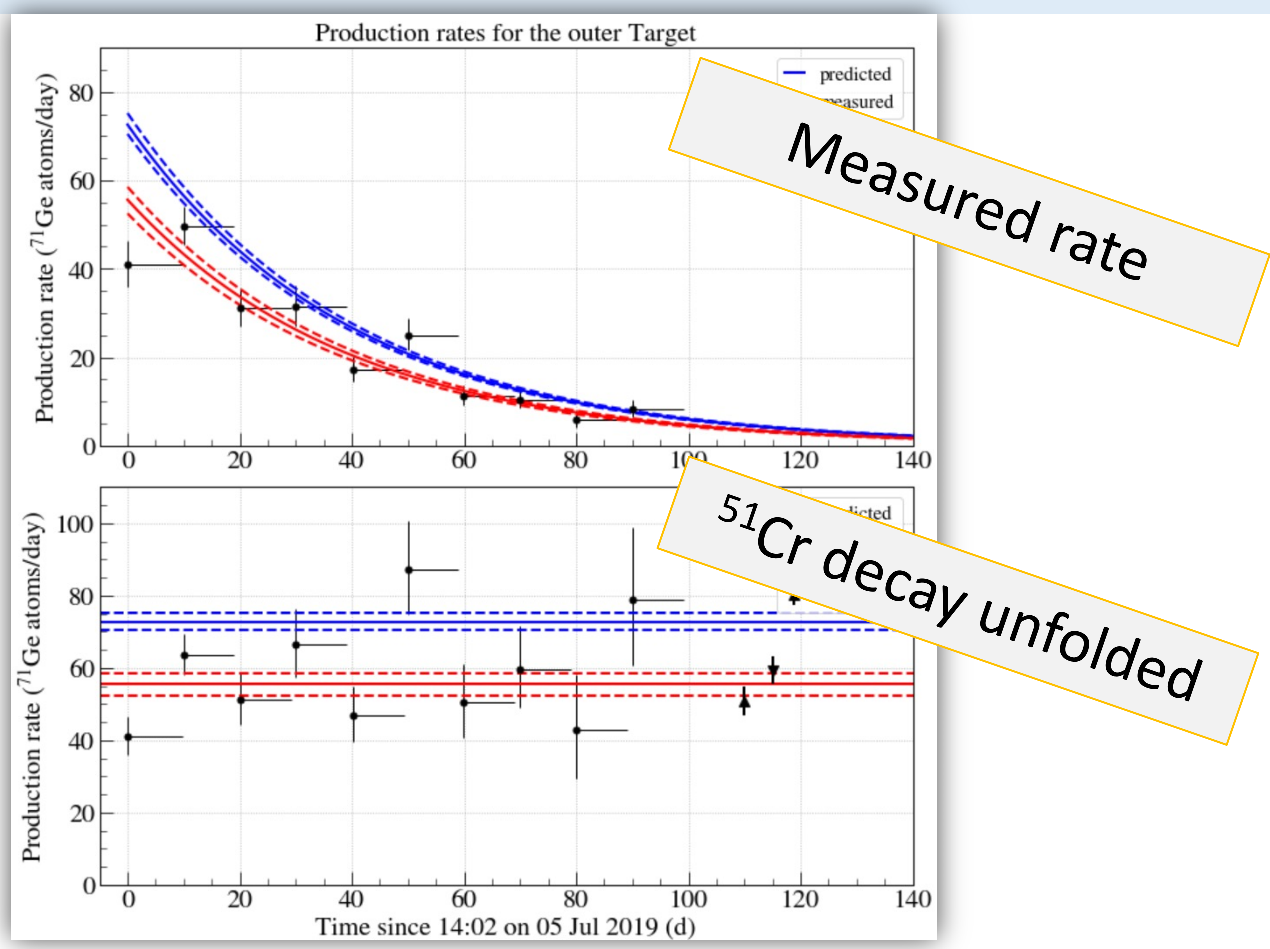


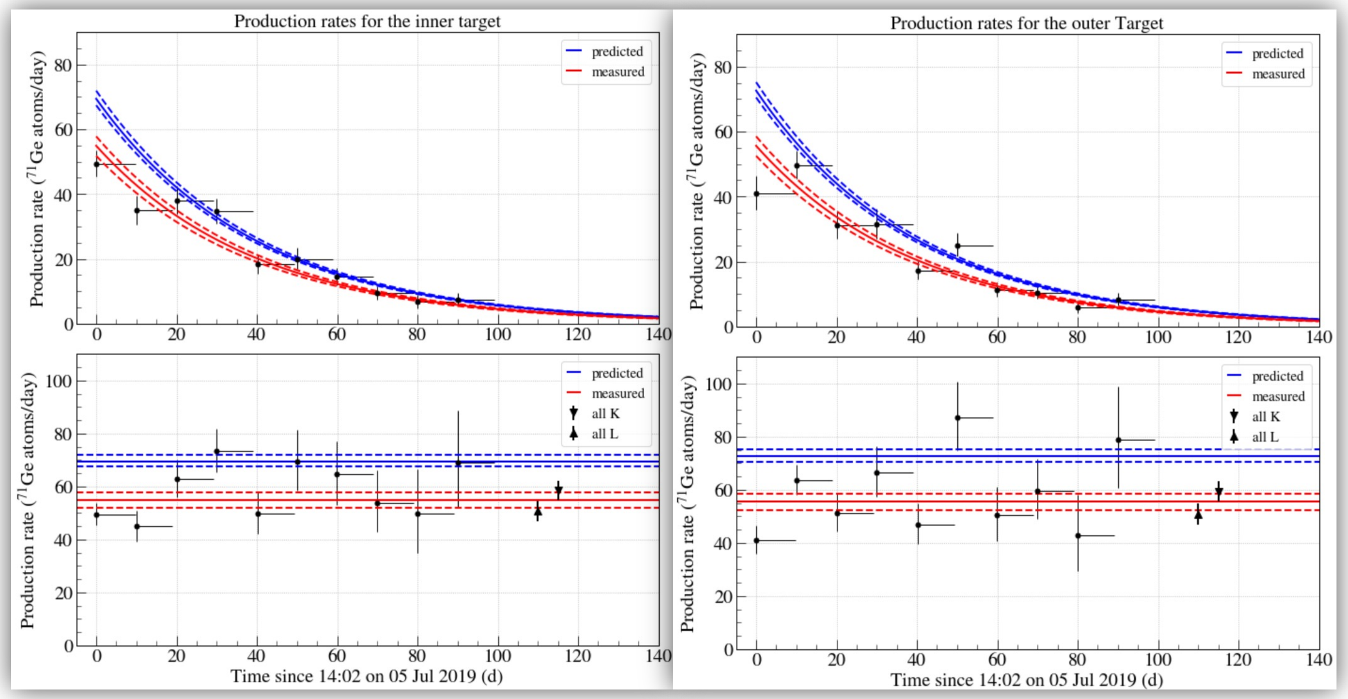


Counting Results vs. Predicted Rates





Predicted vs. Measured Production Rates



	INNER Volume	OUTER Volume
Predicted	$69.4^{+2.5}_{-2.0}$	$72.6^{+2.6}_{-2.1}$
Measured	54.9 ± 2.9	55.6 ± 3.1
Ratio	0.79 ± 0.05	0.77 ± 0.05

4.2σ and 4.8σ less than the unity

Note: $$\frac{0.77 \pm 0.05}{0.79 \pm 0.05} = 0.97 \pm 0.07$$

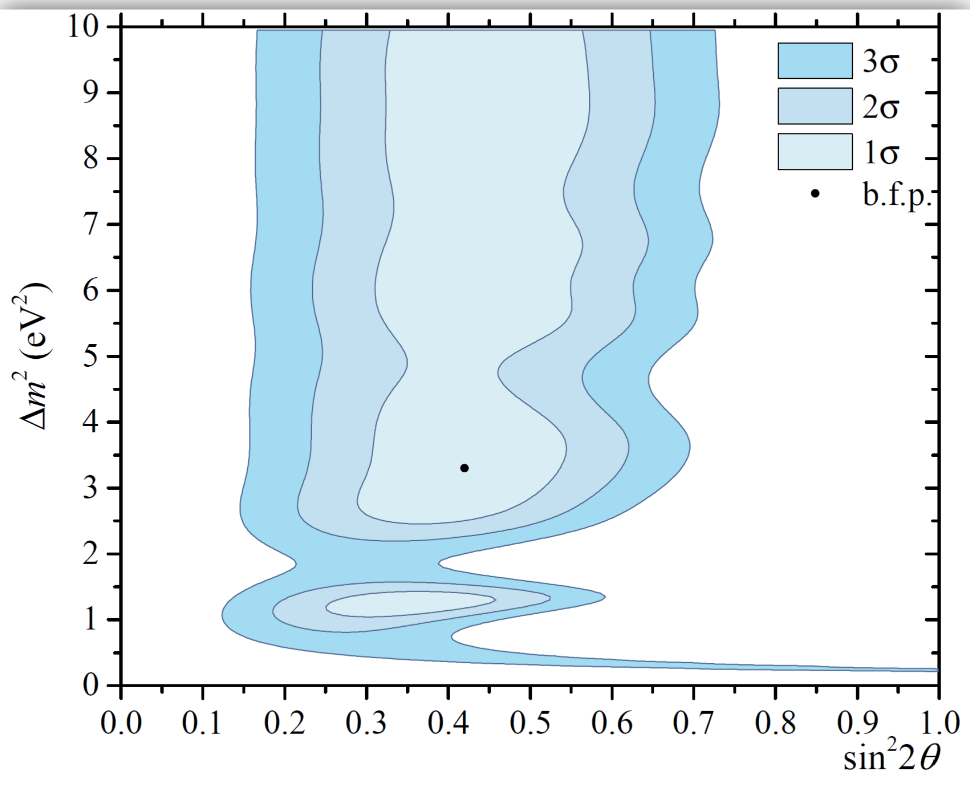
Similar deficits observed in both zones

Oscillation Interpretation

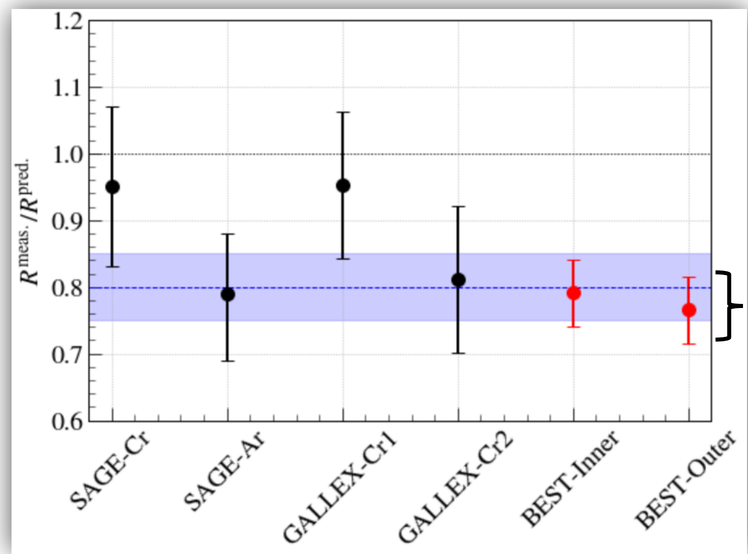
Exclusion curves are calculated by a global minimization of χ^2:

$$\chi^2(\Delta m^2, \sin^2 2\theta) = \left(\boldsymbol{R}^{\mathbf{meas.}} - \boldsymbol{R}^{\mathbf{calc.}}\right)^{\mathrm{T}} \mathbf{V}^{-1} \left(\boldsymbol{R}^{\mathbf{meas.}} - \boldsymbol{R}^{\mathbf{calc.}}\right)$$

$\boldsymbol{R}^{\mathbf{meas.}}$: vector of measured rates
$\boldsymbol{R}^{\mathbf{calc.}}$: vector of calculated rates with $R_i^{\mathrm{calc.}}(\Delta m^2, \sin^2 2\theta)$
$\mathbf{V}$: covariance matrix



Combined analysis with other Ga source experiments

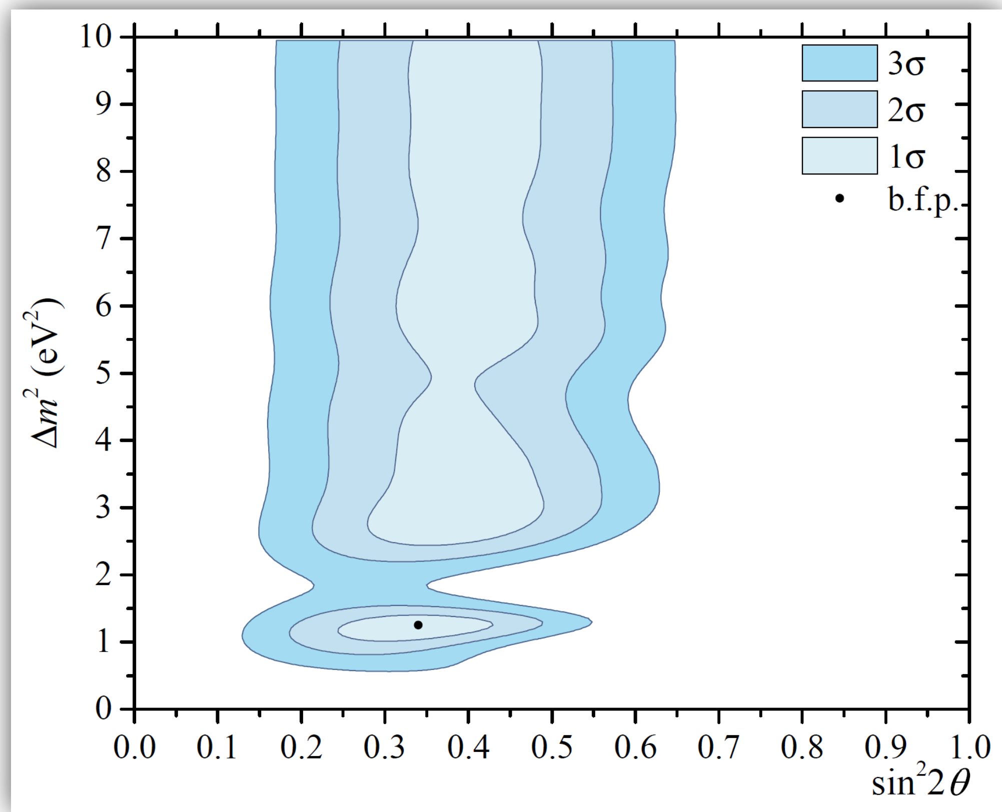


Combined result:

$$R_0 = 0.80 \pm 0.05$$

Experiment	Measured/Predicted	Ref.
SAGE-Cr	0.95 ± 0.12	PRC **59**, 2246 (1999)
SAGE-Ar	$0.79^{+0.09}_{-0.10}$	PRC **73**, 045805 (2006)
GALLEX-Cr1	0.95 ± 0.11	PLB **420**, 114 (1998)
GALLEX-Cr1	0.81 ± 0.11	PLB **420**, 114 (1998)
BEST-Inner	0.79 ± 0.05	
BEST-Outer	0.77 ± 0.05	

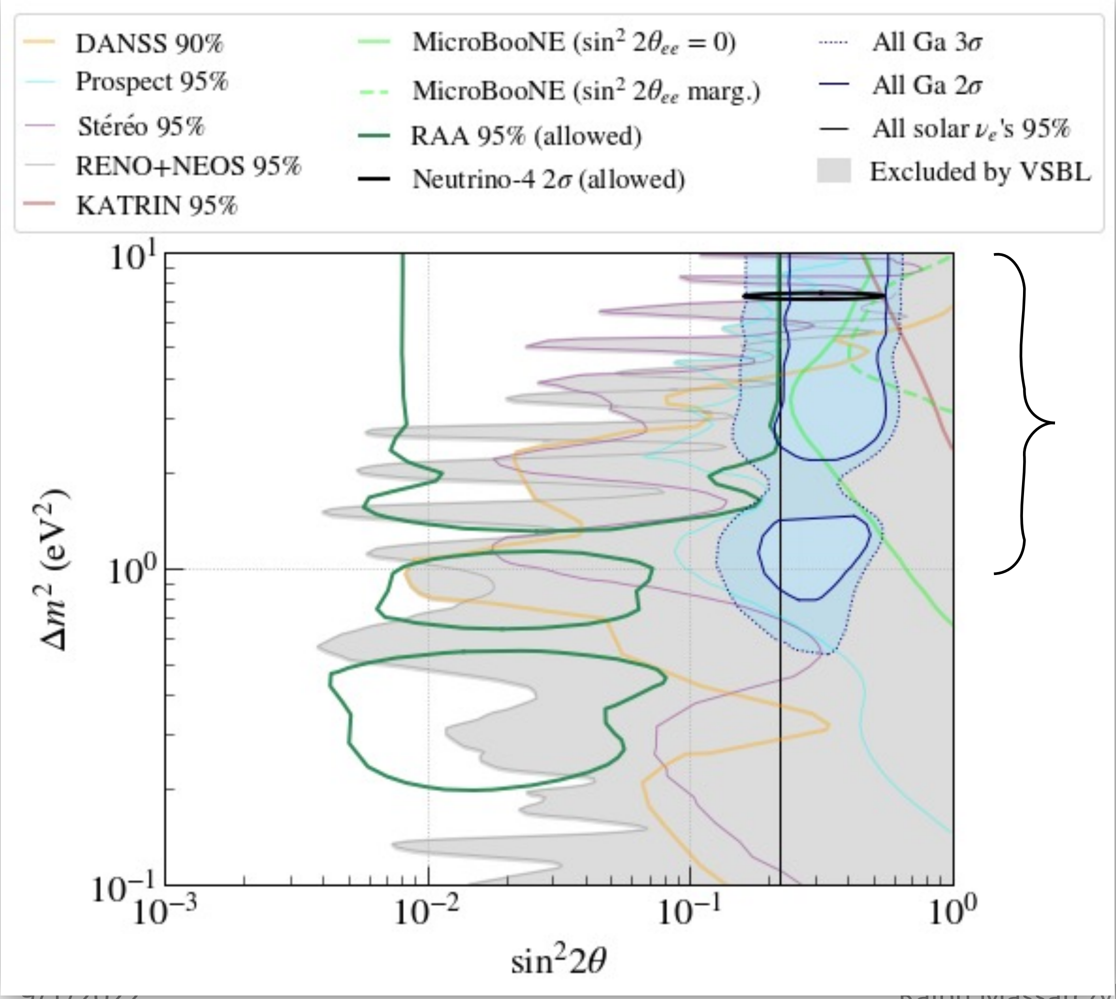
Phys. Rev. Lett. 128, 232501 (2022)



Best combined Ga-data point

$$\Delta m^2 = 1.25 \text{ eV}^2, \sin^2 2\theta = 0.34$$

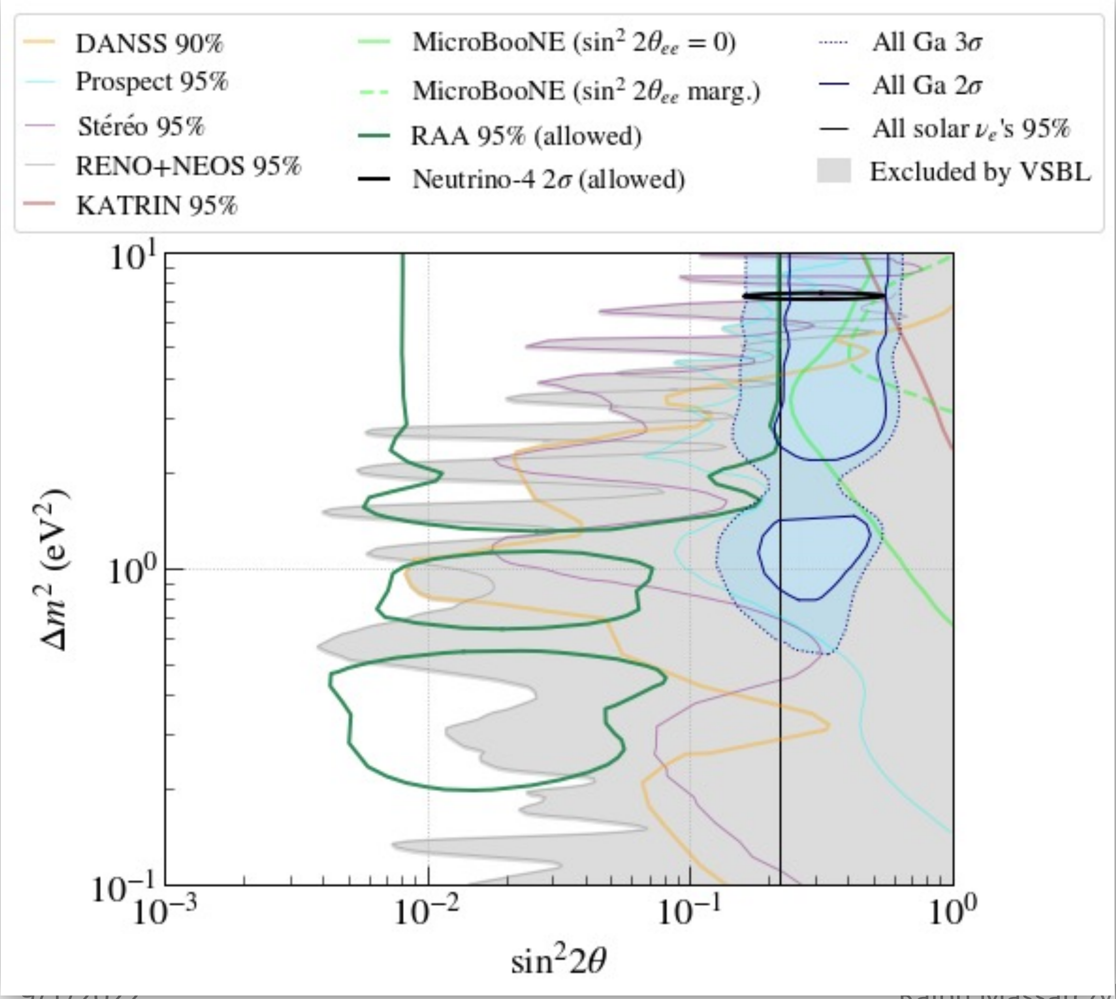
Comparison to Other Oscillation Results



$$P_{ee}(E_\nu, r) = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2[\mathrm{eV}^2] r[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$

Short base line searches
(tens of meter or less)

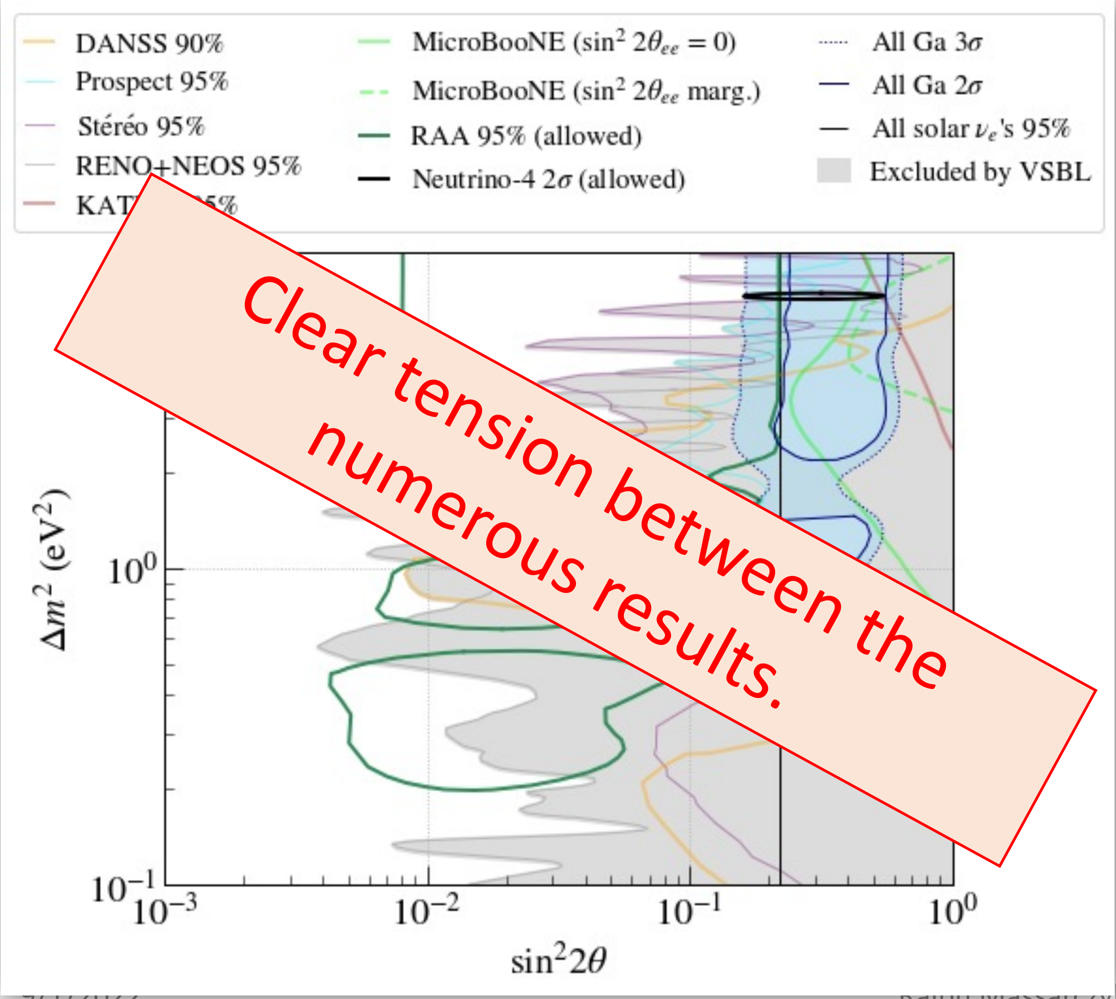
Comparison to Other Oscillation Results



DANSS: *Int. J. Mod. Phys. A 35, 2044015 (2020)*
Prospect: *PRD 103,032001 (2021)*
Stereo: *PRD 102, 052002 (2020)*
RENO: *PRL 125, 191801 (2020)*
RENO+NEOS: *PRD 105, L111101 (2022)*
KATRIN: *PRL 126, 091803 (2021)*
MicroBooNE: *PRL 128, 241802 (2022)*
RAA: *PRD 83, 073006 (2011)*
Neutrino-4: *PRD 104, 032003 (2021)*
Model indep. solar: *PLB 816, 136214 (2021)*

Numerous new experimental, phenomenological, and theoretical results over the last 2-3 years

Comparison to Other Oscillation Results



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Numerous new experimental, phenomenological, and theoretical results over the last 2-3 years

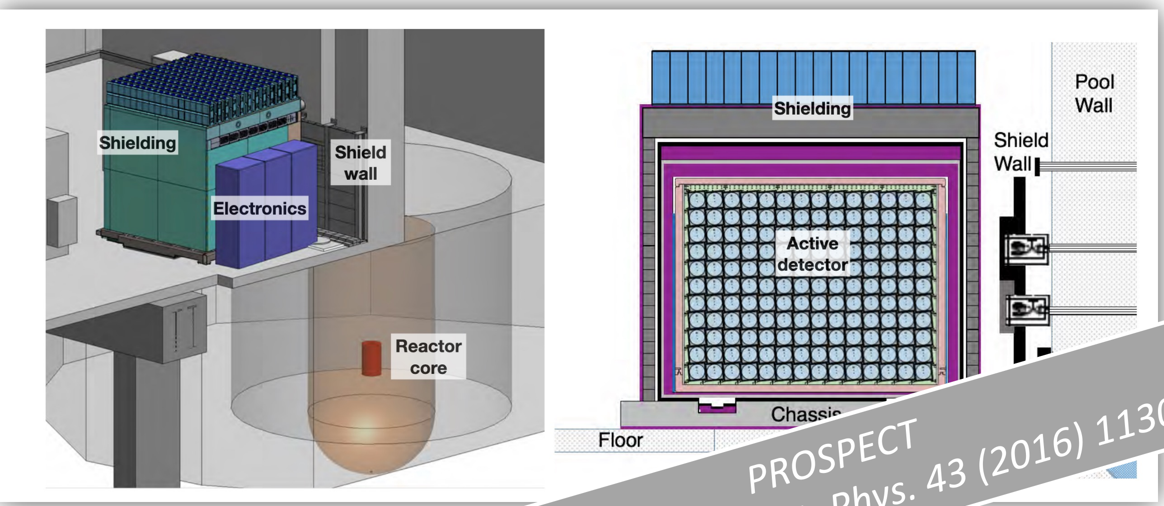
Recent short base line neutrino results

- **Reactor based**
  - o Design restrictions due to available space
  - o Backgrounds due to ambient neutron flux or cosmogenic
  - o Energy and source distribution

  ✓ High (constant) neutrino flux

  ✓ Segmented detectors or movable (relative measurements)
- **Other efforts**
  - µBooNE
  - KATRIN

$$P_{ee}(E_\nu, r) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2] r[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$

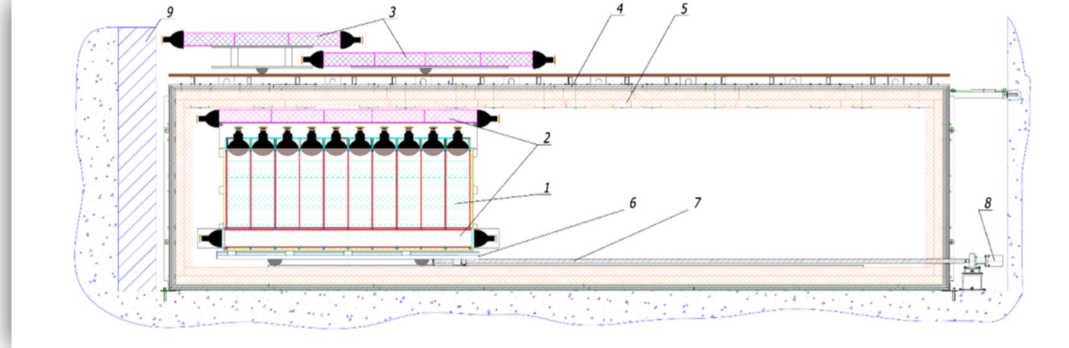


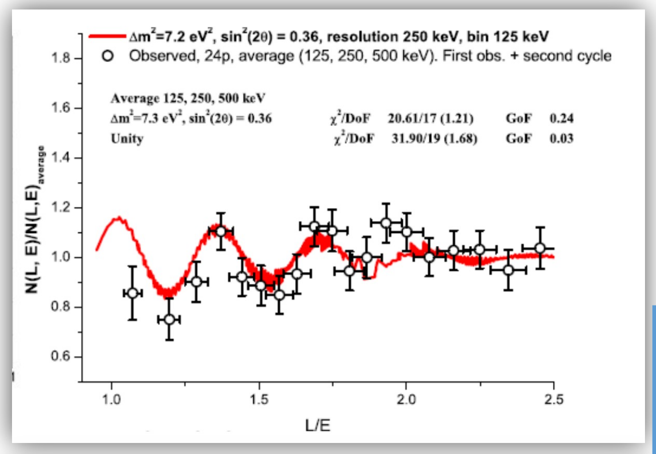
PROSPECT
J. Phys. G: Nucl. Part. Phys. 43 (2016) 113001

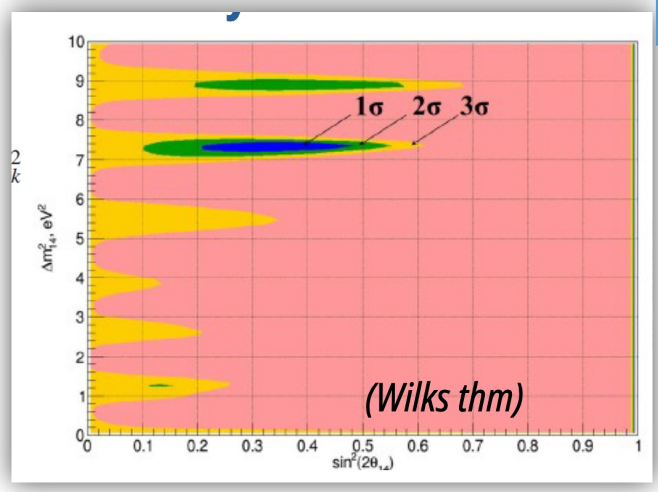
Neutrino-4

PRD 104 (2021) 032003

- Located at the SM-3 reactor at Dimitrovgrad (also used for BEST source production)
- Liquid scintillator + Gd based
- Moveable detector, 6.4 - 11.4 m
- Observation of L/E dependence relative to a base-line averaged spectrum
- Data taking with upgraded detector planned 2023-24







Best fit point in agreement with Gallium experiments

RENO and NEOS

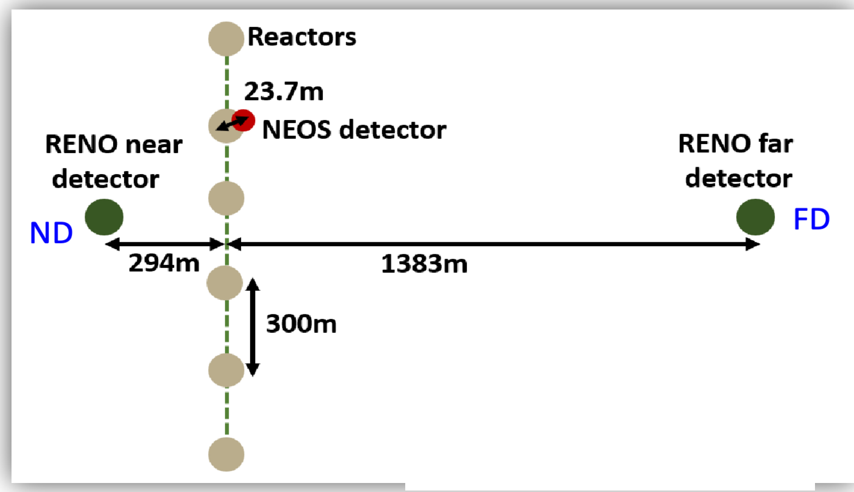
RENO: PRL 125, 191801 (2020)
RENO+NEOS: PRD 105, L111101 (2022)

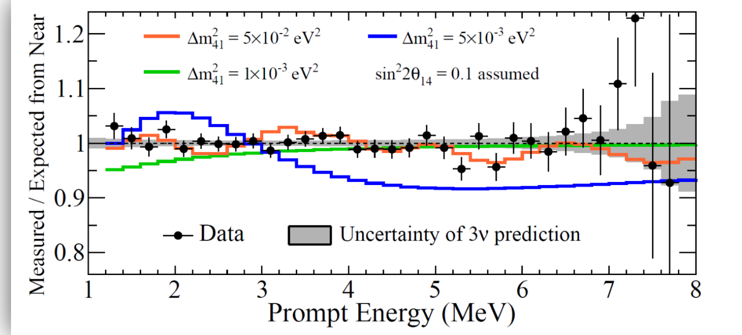
RENO

- At YongGwang
- Liquid Scintillator + Gd
- 2200 days of data

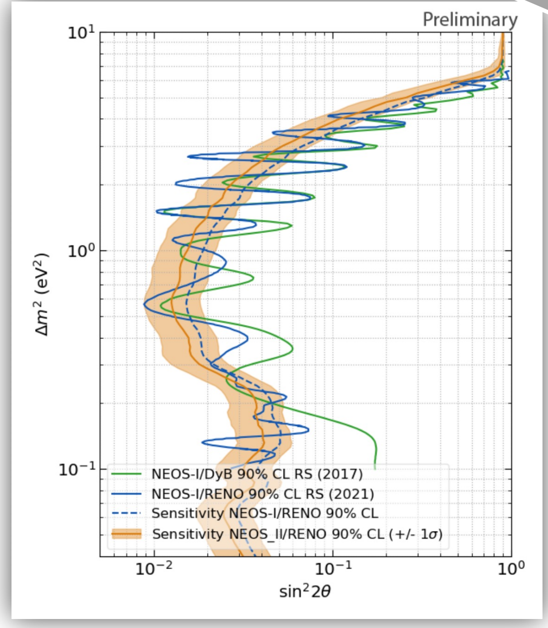
NEOS

- At Daya Bay
- Liquid Scintillator + Gd
- Updates from NEOS-II expected to be published soon





Joint analysis is making use of a different lengths



From Neutrino-22 talk

Previous Best fit in allowed region agrees with Ga-experiment

Prospect, Stereo and DANSS

- Strong rejection of Gallium and Neutrino-4 results
- At the edge or exclusion of old NEOS+RENO results

Prospect (HFIR, 6.7 – 9.2 m)

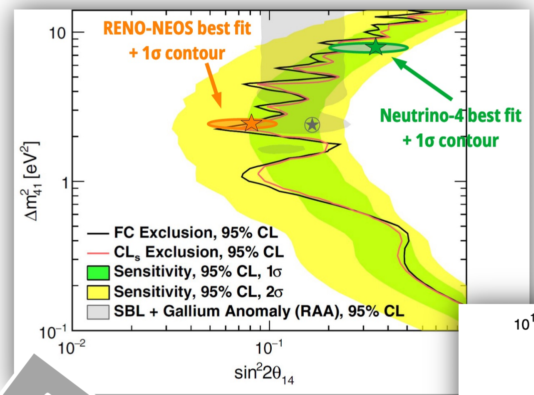
- Located at HFIR, Oak Ridge
- Liquid scintillator + Li based
- Highly segmented detector
- Updates in analysis and upgrade to Prospect II

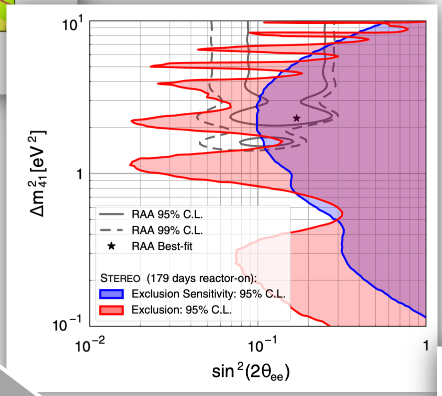
Stereo (ILL, Grenoble, 9.4 -11.2m)

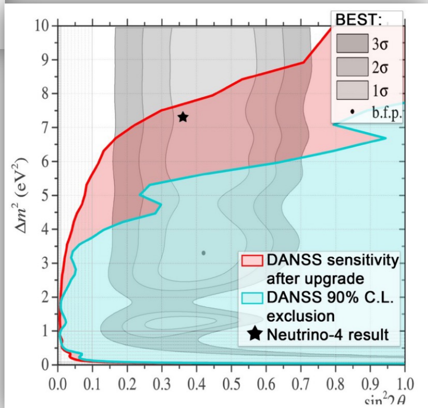
- Liquid scintillator + Gd based
- Segmented detector

DANSS (Kalininskaya Power Plant, 10-12m)

- Movable
- Plastic scintillator + Gd







DANSS: Int. J. Mod. Phys. A 35, 2044015 (2020)
Prospect: PRD 103,032001 (2021)
Stereo: PRD 102, 052002 (2020)

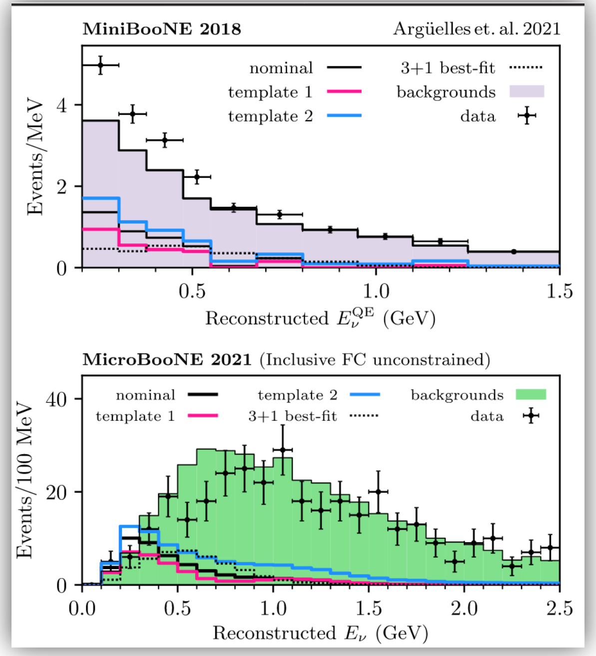
PRL 128, 241802 (2022)

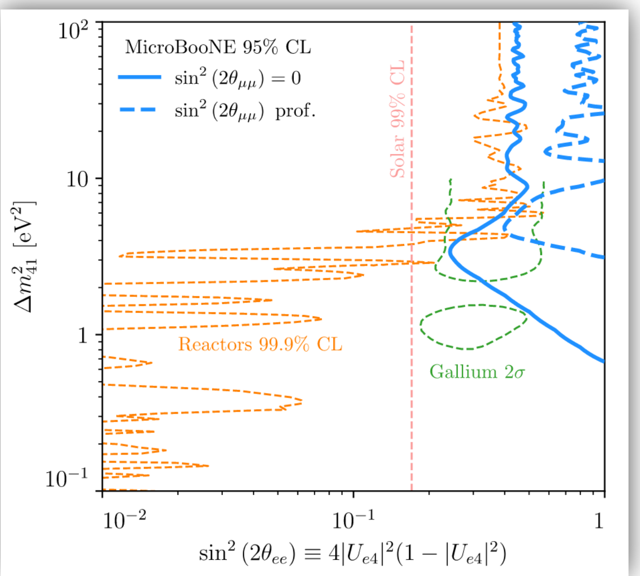
µBooNE

Best fit point in agreement with Gallium experiments

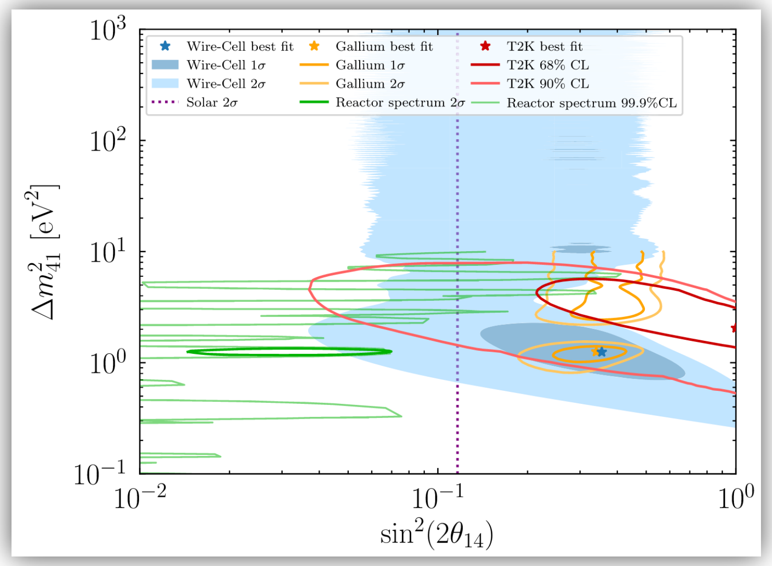
- Combined analysis of MiniBooNE and µBooNE data to evaluate background contributions (new analysis coming)
- Not short baseline (470m), but high distance/energy
- Liquid Argon TPC at Fermilab's Neutrino beamline
- Sterile neutrinos are one possible explanation discussed

$$P_{ee}(E_\nu, r) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]r[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$





Analysis by P. Denton
PRL 129, 061801 (2022)



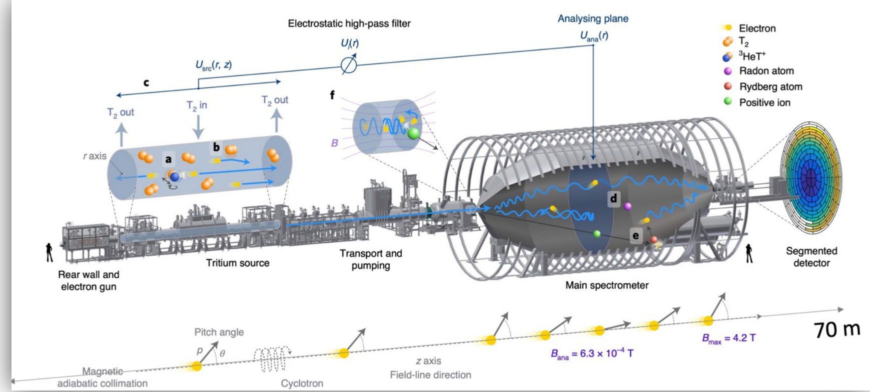
KATRIN

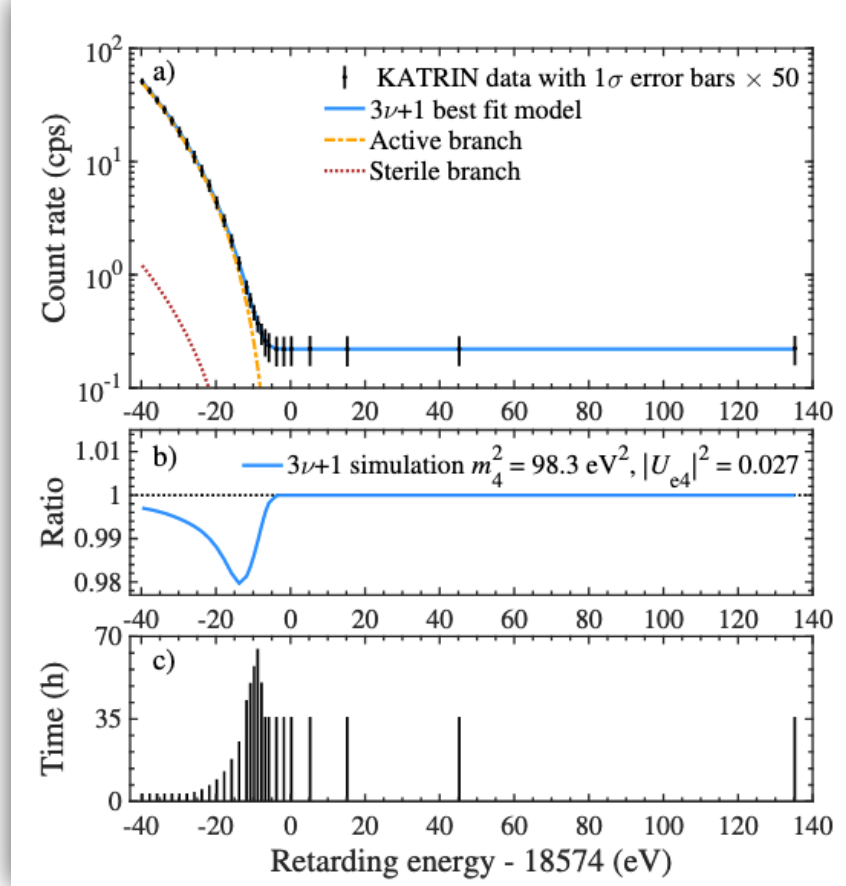
PRL 126, 091803 (2021)

- Neutrino mass experiment
- Sterile neutrino would create a shape distortion close to the endpoint

$$\frac{d\Gamma}{dE} = \left(1 - |U_{e4}|^2\right)\underbrace{\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$

- Future run will complement reactor searches
- Searches for keV sterile neutrinos will follow





KATRIN

PRL 126, 091803 (2021)

Results exclude high Δm^2 phase space, current data does not exclude Gallium best fit point

- Neutrino mass experiment
- Sterile neutrino would create a shape distortion close to the endpoint

$$\frac{d\Gamma}{dE} = \underbrace{\left(1-|U_{e4}|^2\right)\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2\frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$

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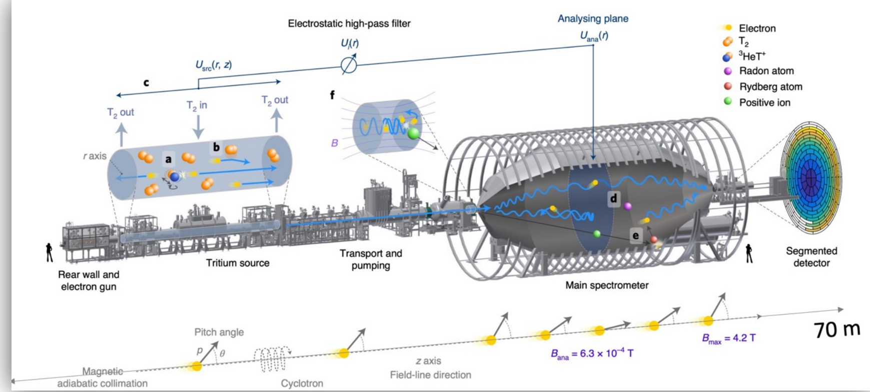
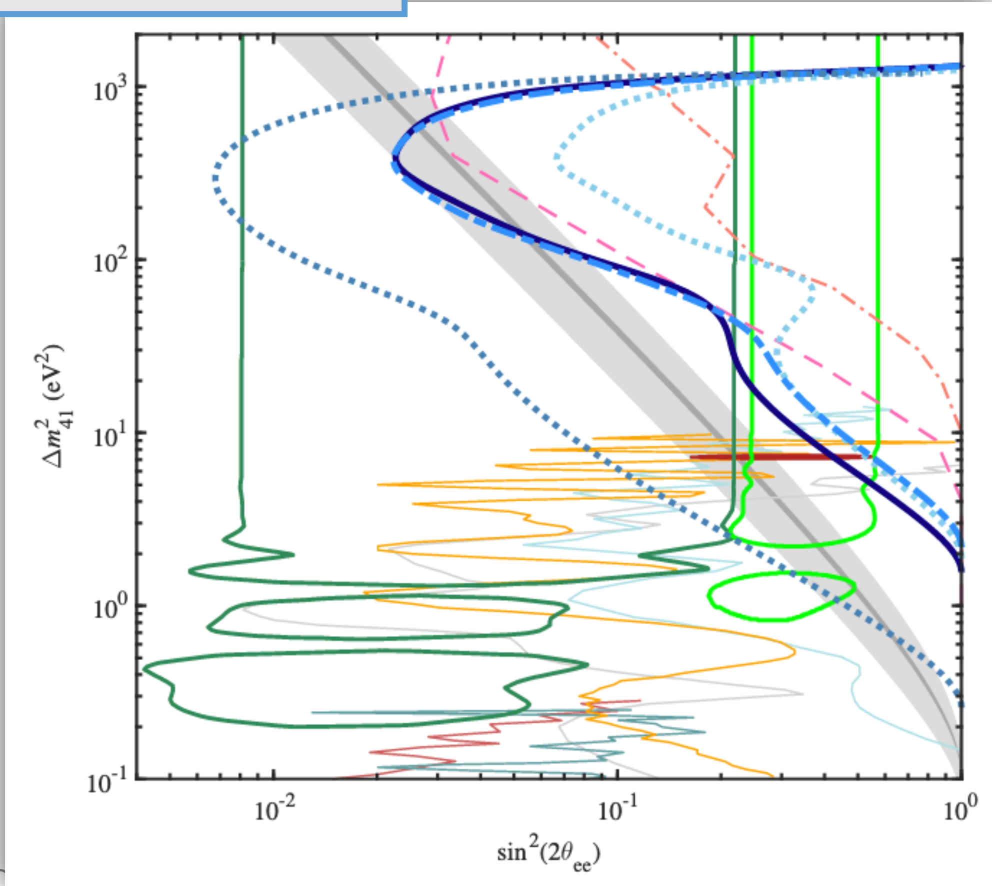
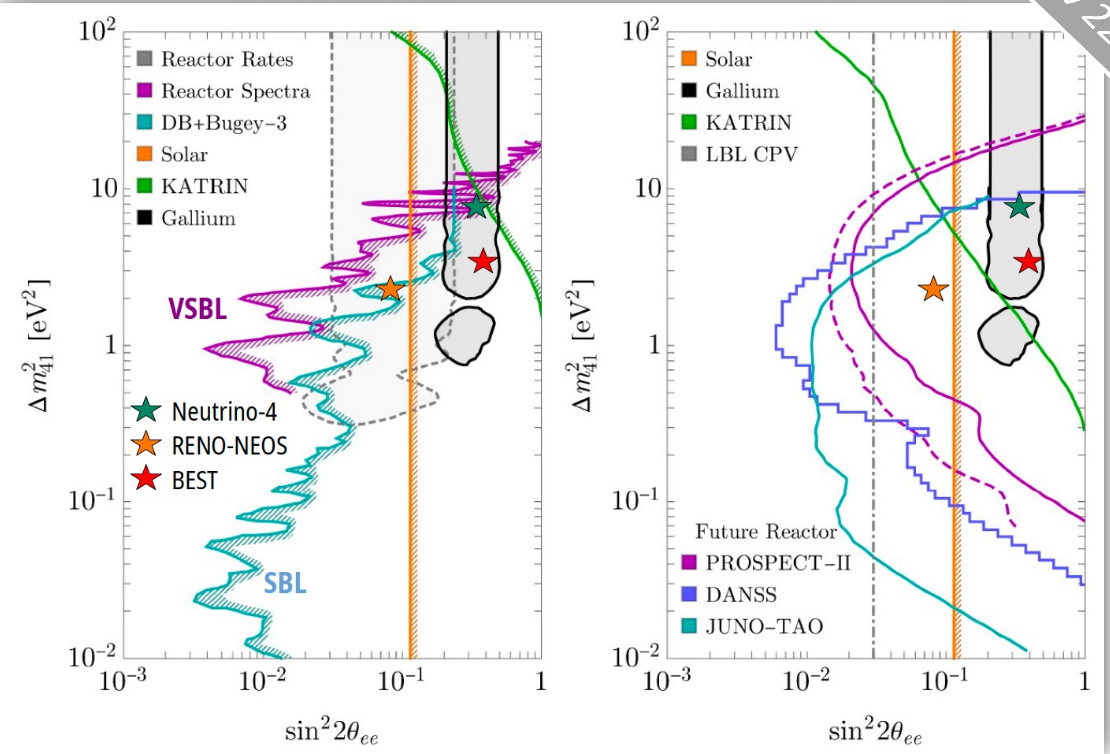




So what's next – A general overview

snowmass arxiv 2203.07214

- More data coming in and on-goings analysis by various groups
- New experiments, e.g. SoLid, SBND …
- Detector upgrades ongoing or planned
  - Larger detector
  - Improved Signal to background arrangement
- KATRIN and μBooNE + miniBooNE complementary efforts



So what's next – A better BEST ?

Phys. Rev. Lett. 128, 232501 (2022)
Phys. Rev. C 105, 065502 (2022)

Because the rate in the two volumes is equally depressed, a number of potential explanations beyond oscillations have been considered. No clear alternative has been identified.

Experimental features that have been studied without finding a cause for the anomaly

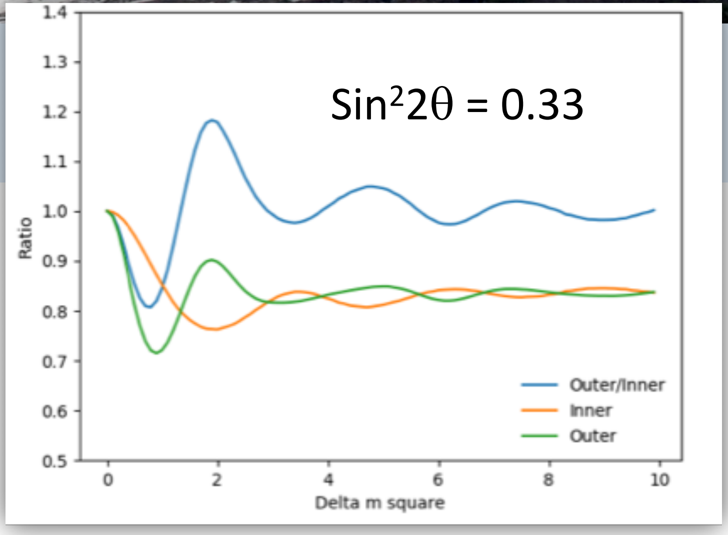
- Cross Section
- Source Strength
- Extraction Efficiencies
- Counting Efficiencies
- Average Path Length

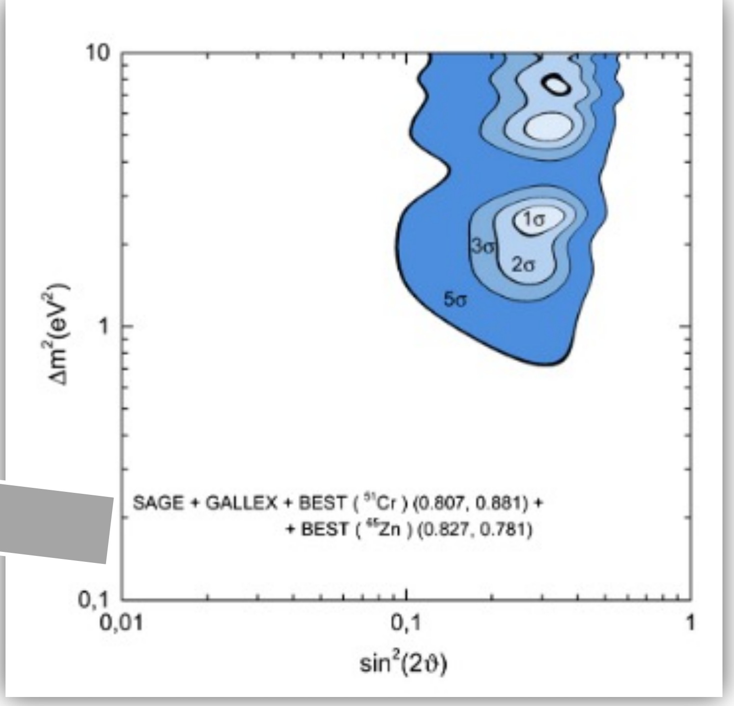
		Uncertainty	
	Value	Magnitude	%
Atomic density $D = \rho N_0 f_1 / M$			
Ga density ρ (g Ga/cm^3)	6.095	0.002	0.033
Avogadro's number N_0 (10^{23} atoms Ga/mol)	6.0221	0.0	0.0
Ga molecular weight M (g Ga/mol)	69.72307	0.00013	0.0002
Atomic density D (10^{22} atoms ^{71}Ga/cm^3)	2.1001	0.0008	0.037
Source activity at reference time A, MCi	3.414	0.008	0.23
Cross section σ (10^{45} cm^2/ (^{71}Ga atom ^{51}Cr decay)], Bahcall	5.81	+0.21,-0.16	+3.6,-2.8
Path length in Ga $< L_{in} >$ (cm)	52.03	0.18	0.3
Path length in Ga $< L_{out} >$ (cm)	54.41	0.18	0.3
Predicted production rate (^{71}Ge atoms/d), R_{In}	69.41	+2.5,-2.0	+3.6,-2.8
Predicted production rate (^{71}Ge atoms/d), R_{Out}	72.59	+2.6,-2.1	+3.6,-2.8

So what's next – A better BEST ?

Because the rate in the two volumes is equally depressed, a number of potential explanations beyond oscillations have been considered. No clear alternative has been identified.

- **Shorter Radius**
  - Smaller inner volume → smaller source needs R&D.
  - Half the volume, need 8x the source strength for same rate
- **Higher energy source**
  - ^{65}Zn source → 1.35 MeV vs. 0.75 MeV
  - Almost twice the cross section.
  - 6-7 kg of enriched ^{64}Zn to produce 0.5 MCi.
  - About 9x longer half life (244 d)

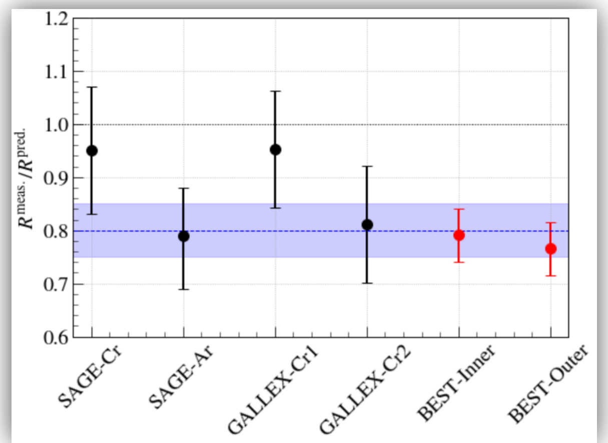




PRD 97 (2018) 073001

Summary:

- BEST observed a reduced rate in both measurement volumes, <u>but no distance dependence</u>
- **<u>The Ga Anomaly is reaffirmed</u>**
- Results are consistent with, but no proof of, oscillations



Summary:

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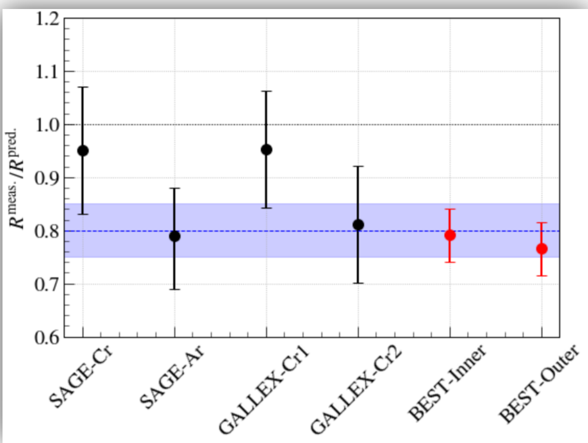
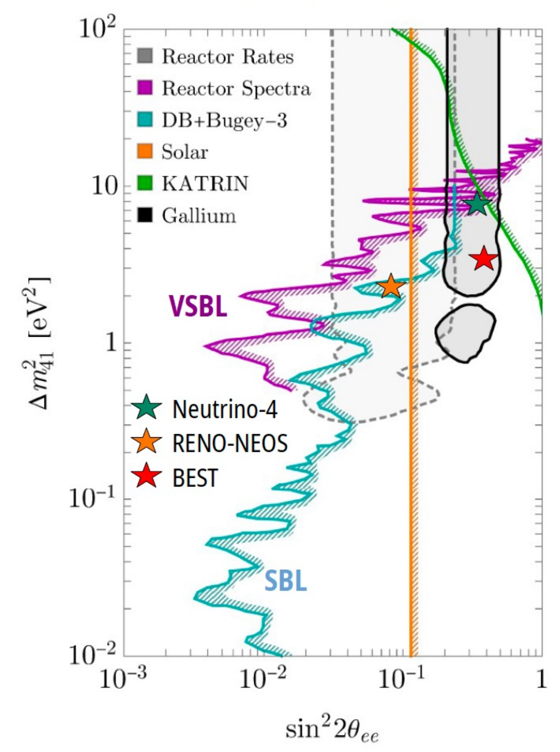
- Results are consistent with, but no proof of, oscillations
- Some experimental results from µBooNE or Neutrino-4 also hint to the existence of non-standard model neutrinos
- A number of reactor based searches and KATRIN partially exclude the same parameter space

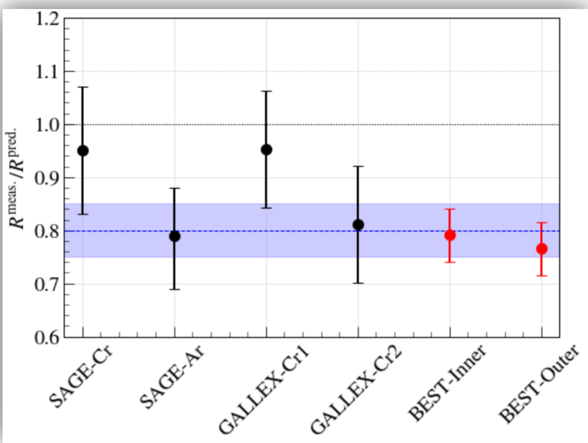


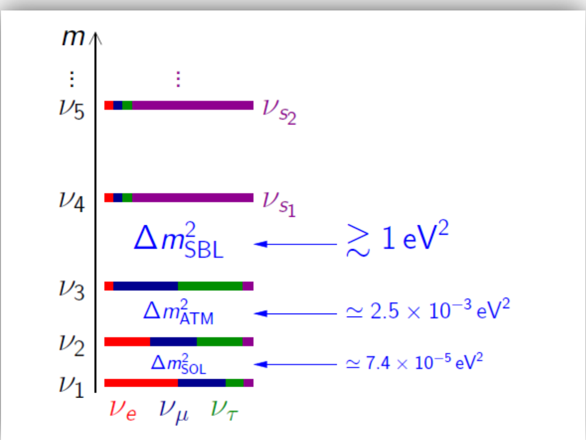


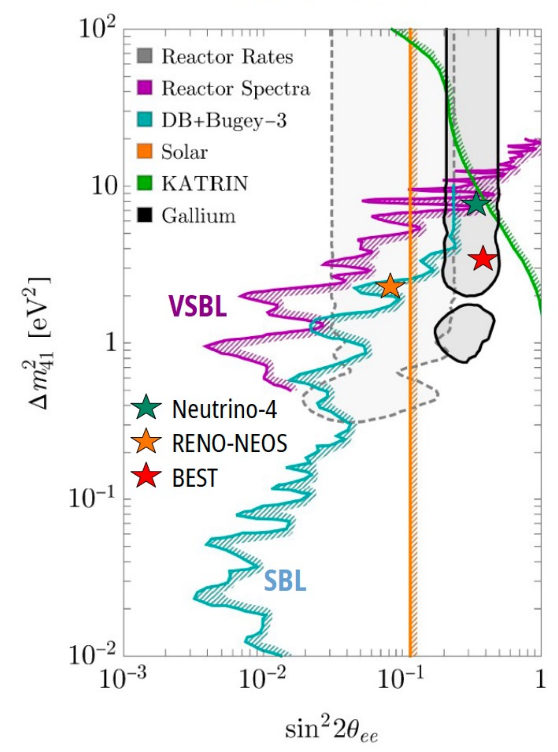
Summary:

Join us as a PostDoc to work on neutrinos:
IRC112442 @ jobs.lanl.gov

- BEST observed a reduced rate in both measurement volumes, but no distance dependence
- **The Ga Anomaly is reaffirmed**
- Results are consistent with, but no proof of, oscillations
- Some experimental results from µBooNE or Neutrino-4 also hint to the existence of non-standard model neutrinos
- A number of reactor based searches and KATRIN partially exclude the same parameter space
- This could be first steps into a whole ”dark (?)” sector
- Interesting times lay in front of us







Backups

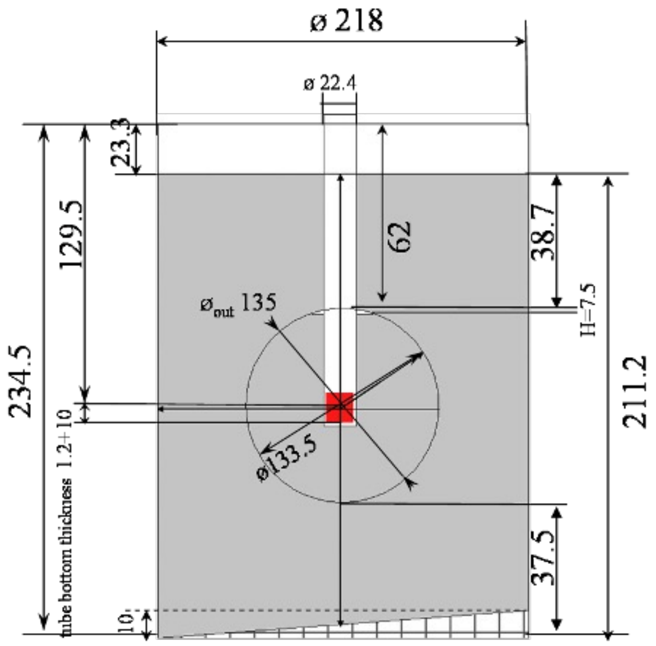
Backups

BEST Schedule

- Construction began 2011
- Source Arrived: July 5, 2019
- Exposures: July 5 – Oct. 13, 2019
- Counting: July 16, 2019 – Mar. 20, 2020
- Counter Calibration: Mar. 2020 – Jan. 2021
- Results and technical draft posted:

Sept. 2021 and Feb 2022

arXiv:2109.11482 and arXiv:2201.07364



SAGE and GALLEX Neutrino Source Experiments

Neutrino sources

^{51}Cr: 747 keV (81.6%), 427 keV (9.0%), 752 keV (8.5%), 432 keV (0.9%)

^{37}Ar: 811 keV (90.2%), 813 keV (9.8%)

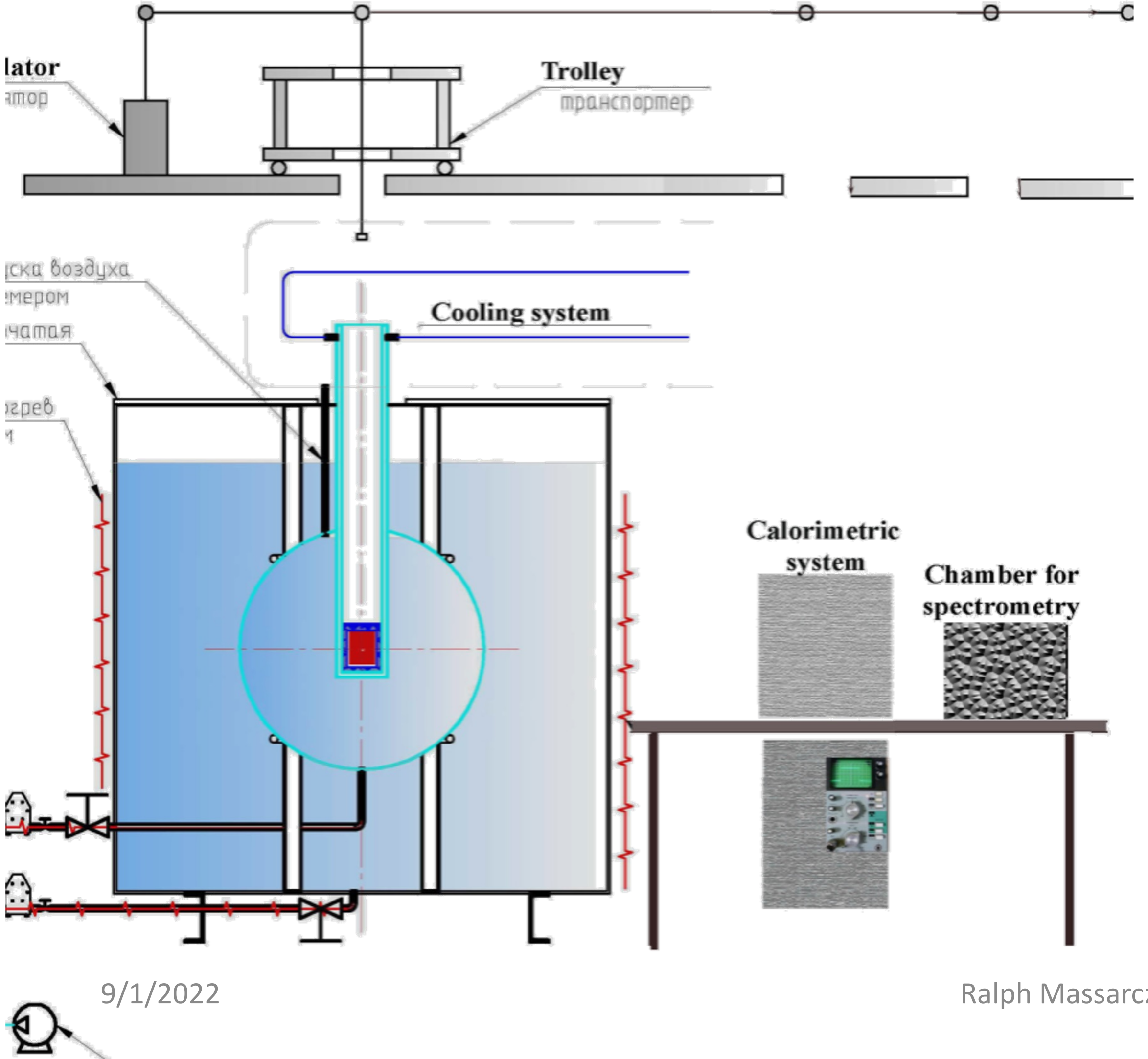
GALLEX:		SAGE:		BEST	
1994 –1995	$A(\mathrm{Cr}_1) = 1.714 \pm 0.036$ MCi	1994 –1995	$A(\mathrm{Cr}) = 0.517 \pm 0.006$ MCi	2019 – 2020	$A(\mathrm{Cr}) = 3.414 \pm 0.008$ MCi
1995 –1996	$A(\mathrm{Cr}_2) = 1.868 \pm 0.073$ MCi	2004	$A(\mathrm{Ar}) = 0.409 \pm 0.002$ MCi		

Results:

GALLEX:		SAGE:		BEST	
PLB 342 (1995)	$R_1(\mathrm{Cr}) = 0.953 \pm 0.11$	PRC 59 (1999)	$R_3(\mathrm{Cr}) = 0.95 \pm 0.12$	submitted	*this talk*
PLB 420 (1998)	$R_2(\mathrm{Cr}) = 0.812 \pm 0.10$	PRC 73 (2006)	$R_4(\mathrm{Ar}) = 0.791 \pm 0.084$		

R – ratio of the measured production rate to that expected from the cross section (PRC 56 (1997) 3391) (no uncertainty on cross section included)

Source Activity Measurements



1) Move the source into a lead container
2) Measure γ spectrum at 21.65 m with a Ge detector *(1h)*
3) Move the source into the calorimeter
4) Measure the heat emitted by the source *(20-21 h)*

Extraction Efficiency of ^{71}Ge and Ge Carrier

Efficiency is measured by adding a known amount of (stable) Ge and measuring the mass of extracted Ge *(Int. J. Mass Spec. 392 (2015) 41)*

Amount of added Ge carriers:

- 2.4 µmol ^{72}Ge (92%)
- 2.4 µmol ^{76}Ge (95%)

Mean extraction efficiency from Ga: 98%

Mean overall efficiency (including GeH_4 synthesis): 96%

Q-Value Measurements

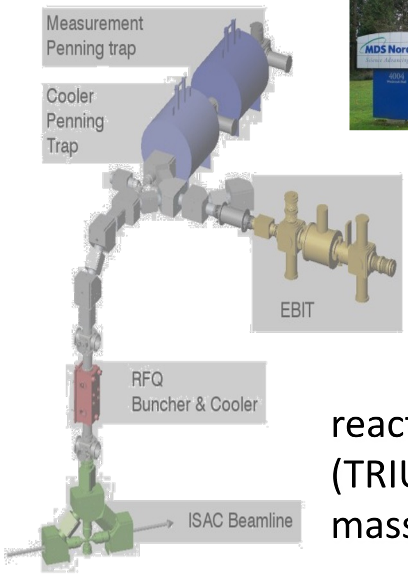
$$\sigma(^{51}Cr) = \sigma_0(^{51}Cr)\left[1 + 0.67\frac{B_1(GT)}{B_0(GT)} + 0.22\frac{B_2(GT)}{B_0(GT)}\right]$$

$$\downarrow$$

$$\sigma_0(^{51}Cr) = F(atom)\frac{1}{ft}$$

$$\downarrow$$

$$ft \; \infty \; Q_{EC}^2 \cdot t$$



The TITAN Beamline

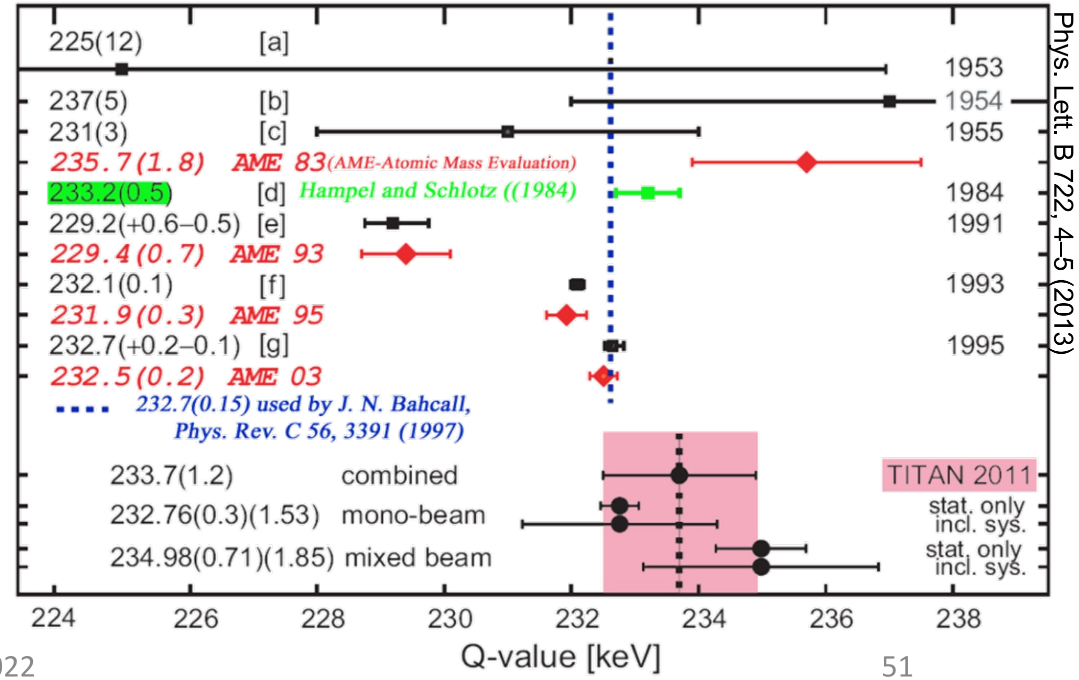
Penning trap Q-value determination of the $^{71}Ga(\nu,e^-)^{71}Ge$ reaction.

First direct Q-value measurement of the $^{71}Ga(\nu,e^-)^{71}Ge$ reaction was carried out in a Penning trap using the TITAN (TRIUMF's Ion Trap for Atomic and Nuclear science) mass-measurement facility at ISAC/TRIUMF.

Q-value obtained from combined results of the two independent mass-measurement methods is 233.7±1.2 keV, which is in agreement with the previously accepted Q-value for the ν cross-section calculations.

The TITAN result excludes an incorrect Q-value as a cause for the gallium anomaly observed in the GALLEX and SAGE calibration runs.

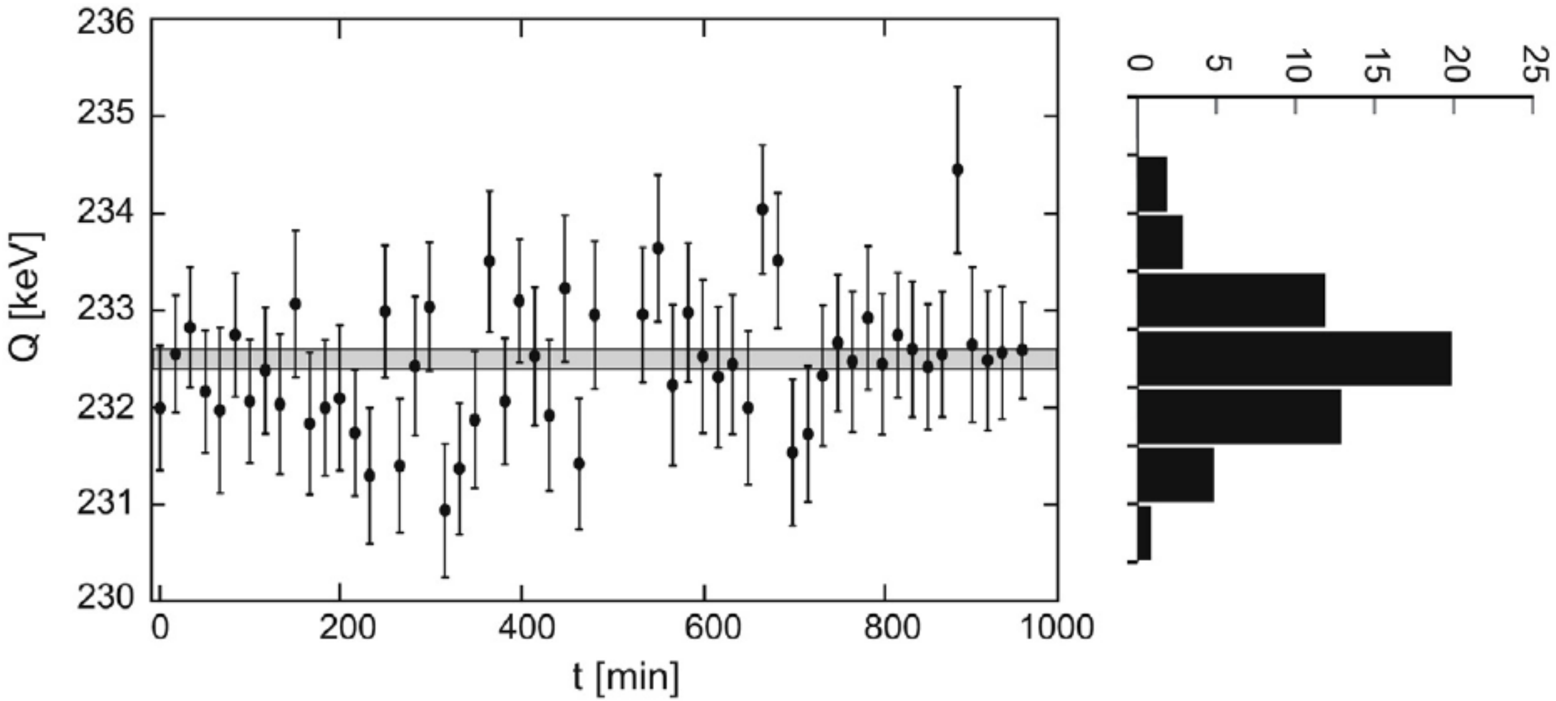
Comparison of previous Q-value measurements



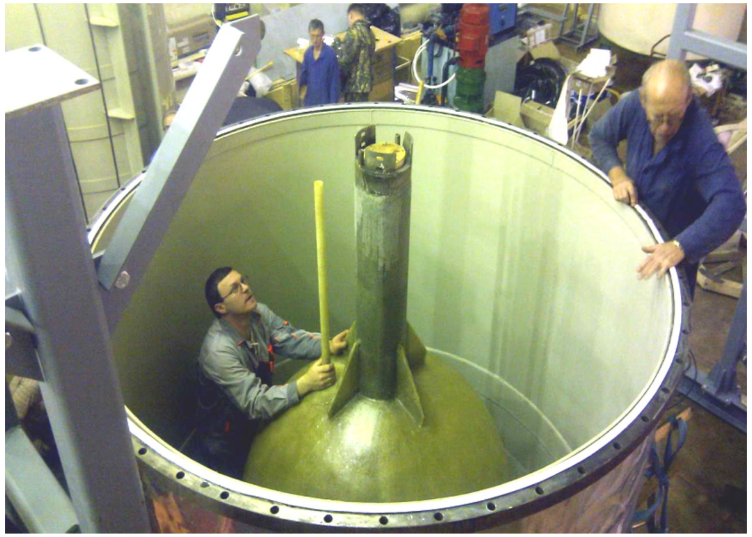
Most Recent Q-Value measurement (Int. J. Mass Spec. 406 (2016) 1)

Result 232.443 ± 0.093
±0.04%

Claims uncontrolled systematic uncertainties were present in TITAN measurements.



Work on creation of the two-zone reactor for the BEST Ga target



In August-September 2015, two solar measurements were carried out from the BEST gallium target. Extractions and counting of ^{71}Ge atoms were performed independantly for each zone.

The result of the analysis of these measurements is $\mathbf{66.4^{+28.1}_{-24.3}}$ SNU, agrees with the result of the period of measurements 1990 to 2014, **64.6** $\pm$ **2.4** SNU (with statistical uncertainty only).

Pulse Shape Analysis

- The rise time cut values were measured for each counter used in the experiment.
  - A trace of active $^{71}GeH_4$ was added to each counter to determine its T_N.
  - Counters filled with typical gas mixture. Efficiency accounts for pressure and GeH_4 fraction.
  - 96% acceptance window for each detector was determined (limit on T_N).

Counter Filling					T_N	
Extraction name	Counter name	Pressure (mmHg)	GeH4 fraction (%)	Syst. Slot	K-peak	L-peak
Inner-1	YCT92	630	8.8	3.5	17.6	13.0
Inner-2	YCT2	640	9.5	3.2	16.6	10.1
Inner-3	YCN43	650	9.3	Z.3	13.2	10.0
Inner-4	YCT97	640	9.2	3.7	17.3	11.4
Inner-5	YCN46	650	9.5	Z.8	15.2	11.3
Inner-6	YCN42	640	9.8	3.8	13.2	9.1
Inner-7	YCT92	640	9.3	3.5	17.6	13.0
Inner-8	YCT2	645	9.5	3.2	16.6	10.1
Inner-9	YCN43	640	9.1	Z.3	13.2	10.0
Inner-10	YCT97	650	9.1	3.7	17.3	11.4

Counter Filling					T_N	
Extraction name	Counter name	Pressure (mmHg)	GeH4 fraction (%)	Syst. Slot	K-peak	L-peak
Outer-1	YCN113	635	9.5	3.4	13.6	9.1
Outer-2	YCT3	635	9.5	3.1	16.4	10.3
Outer-3	YCNA9	640	10.5	Z.4	18.8	13.2
Outer-4	YCT9	635	9.6	3.6	14.9	9.1
Outer-5	YCN41	635	10.0	Z.1	13.4	10.3
Outer-6	YCT4	630	9.0	3.3	13.2	10.2
Outer-7	YCN113	630	10.3	3.4	13.6	9.1
Outer-8	YCT3	640	9.5	3.1	16.4	10.3
Outer-9	YCNA9	635	9.9	Z.4	18.8	13.2
Outer-10	YCT9	645	9.5	3.6	14.9	9.1

Exposure and Extraction

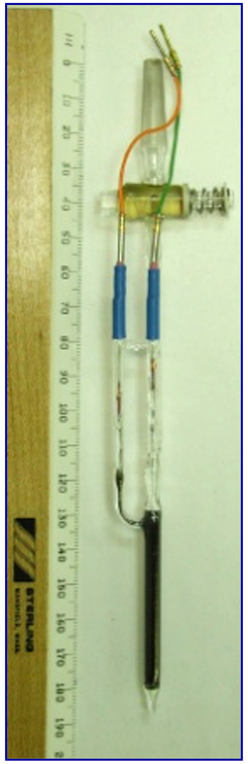
Source exposure				Extraction from cylindrical target		Massa Ga (tons)	Extraction efficiency		Extraction from spherical target		Massa Ga (tons)	Extraction efficiency	
Begin		End											
Dayyear	Mo Da Hr Mn	Dayyear	Mo Da Hr Mn	Name	Date (2019)		from Ga	into GeH4	Name	Date (2019)		from Ga	into GeH4
186.585	07.05 14:02	196.376	07.15 09:02	Cr1	15 Jul 13:59	40.09	0.97	0.91	Cr11	15 Jul 16:01	7.4	0.98	0.93
197.362	07.16 08:41	206.372	07.25 08:56	Cr2	25 Jul 13:51	40.09	0.97	0.92	Cr21	25 Jul 16:32	7.4	0.97	0.92
207.282	07.26 06:47	216.374	08.04 08:59	Cr3	04 Aug 12:47	40.09	0.98	0.97	Cr31	04 Aug 16:37	7.4	0.97	0.92
217.286	08.05 06:52	226.371	08.14 08:54	Cr4	14 Aug 12:51	40.09	0.98	0.94	Cr41	14 Aug 15:35	7.4	0.97	0.92
227.258	08.15 06:12	236.458	08.24 11:00	Cr5	24 Aug 14:35	40.09	1.00	0.97	Cr51	24 Aug 17:17	7.4	0.99	0.96
237.342	08.25 08:13	246.37	09.03 08:51	Cr6	03 Sep 12:35	40.09	1.00	0.98	Cr61	03 Sep 15:18	7.4	1.00	1.00
247.243	09.04 05:50	256.368	09.13 08:50	Cr7	13 Sep 12:29	40.09	1.00	1.00	Cr71	13 Sep 15:11	7.4	1.00	1.00
257.241	09.14 05:47	266.37	09.23 08:52	Cr8	23 Sep 12:32	40.09	1.00	1.00	Cr81	23 Sep 15:17	7.4	1.00	1.00
267.240	09.24 05:46	276.369	10.03 08:51	Cr9	03 Oct 12:27	40.09	0.95	0.88	Cr91	03 Oct 15:00	7.4	0.97	0.92
277.200	10.04 04:49	286.367	10.13 08:48	Cr10	13 Oct 12:26	40.09	0.99	0.95	Cr101	13 Oct 14:59	7.4	0.99	0.94

Source exposure of the two concentric zones

- 10 exposures
- Mean exposure time: 9.18 d
- Masses: 7.4 t (inner) / 40.09 t (outer)

Chemical extraction of ^{71}Ge

- Efficiency is measured by adding a known amount of (inactive) Ge and measuring the mass of extracted Ge
- Amount of added Ge carriers:
  - 2.4 µmol ^{72}Ge (92%); 2.4 µmol ^{76}Ge (95%)
- Mean extraction efficiency from Ga: 98%
- Mean overall efficiency (incl. GeH_4 synthesis): 96%



The extracted Ge activity is measured using proportional counters

Gas Synthesis Procedure (PRC 60 (1999) 055801)

- NaOH is added to concentrated aqueous solution to adjust pH.
- Air is swept out with a He flow.
- Low tritium $NaBH_4$ dissolved in H_20 is added.
- Mixture is heated.
- The Ge is reduced by $NaBH_4$ to make GeH_4.
- He sweeps the GeH_4 onto a chromatography column at -196^oC.
- When reaction complete, column is warmed and GeH_4 is eluted and captured.
- A measured quantity of old low-background Xe is added to make gas mixture.

Systematic Uncertainties

Parameter	Value	Uncertainty
Ga Density ρ (g/cm^3)	6.095	$\pm$0.002
Avogadro's Number N_A (10^{23} atoms Ga/mol)	6.0221	negiligible
Ga molecular weight M (g Ga/mol)	69.72307	$\pm$0.00013
^{71}Ga isotopic abundance f (%)	39.8921	$\pm$0.0062
Atomic Den. $n = \rho N_A f/M$ (10^{22} atoms ^{71}Ga/cm^3)	2.1001	$\pm$0.0008
Source Activity at Ref. Time A (MCi)	3.414	$\pm$0.008
Average Path Length Inner Vol. L_{in} (cm)	52.03	$\pm$0.18
Average Path Length Outer Vol. L_{out} (cm)	54.41	$\pm$0.18
Cross section σ (10^{-45} cm^2)	5.81	+0.21, -0.16

Origin of uncertainty	Uncertainty (%)
Chemical extraction efficiency	
Efficiency of extraction from Ga metal	±1.0
Efficiency of synthesized into GeH_4	±1.3
Carrier carryover	-
Mass of gallium	-
Chemical extraction subtotal	±1.6
Counting efficiency	
Calculated efficiency	
Volume efficiency	-1.3, +1.5
Peak efficiency	±1.1
Simulations to adjust for counter filling, Monte Carlo interpolation	±0.6
Calibration statistics	
Centroid	±0.1
Resolution	±0.3
Rise time cut	-
Gain variations	+0.4
Counting efficiency subtotal	-1.5 +1.7
Residual radon after time cuts	-0.05
Solar neutrino background	±0.20
^{71}Ge carryover	±0.04
Subtotal	±0.22
Energy weihting in analysis	±0.15
Total systematic uncertainty	**-2.5 +2.6**

^{51}Cr Energy Release per Decay (J. Phys.: Conf. Ser. 798 (2017) 012140)

Table 1. The total energy release with Cr-51 decay.

Type of energy release	Energy, keV	Contribution to ^{51}Cr decay	Energy release with ^{51}Cr decay, keV
Gamma rays	320.0835 (4)	0.0991 (2)	31.720 (64)
K-capture	5.465	0.8919 (17)	4.874 (9)
L-capture	0.628	0.0927 (14)	0.0582 (9)
M-capture	0.067	0.0154	0.001
inner bremsstrahlung	751 (max)	$3.8\times10^{-4}\times0.902$ (±10%)	0.096 (10)
inner bremsstrahlung	430 (max)	$1.2\times10^{-4}\times0.0983$ (±10%)	0.001
Total			36.750 (84) 0.23%

Energy Calibration

PRC **60**, (1999) 055801

$$\frac{P_K(^{71}\mathrm{Ge})}{P(^{55}\mathrm{Fe})} = \frac{10.367}{5.895}[1-(4.5G+2.78)(V-V_{\mathrm{crit1}})\times 10^{-6}] \ ,$$

$$\frac{R_K(^{71}\mathrm{Ge})}{R(^{55}\mathrm{Fe})} = \sqrt{\frac{5.895}{10.367}}[1+1.5\times 10^{-3}(V-V_{\mathrm{crit2}})] \ ,$$

$$V_{\mathrm{crit1}} = 10.5G+0.6P+588 \quad V_{\mathrm{crit2}} = 6G+P/3+824$$

Counter	^{55}Fe			L-peak						K-peak					
				Position			Resolution			Position			Resolution		
	Pos. (a.u.)	Resol. (%)	En non-linearity factor	Pred. from ^{55}Fe	True	Ratio	Pred. from ^{55}Fe	True	Ratio	Pred. from ^{55}Fe	True	Ratio	Pred. from ^{55}Fe	True	Ratio
sys2z															
YCN43	437.39	18.2	0.982	86.81	87.16	1.00	40.92	40.29	0.98	755.35	725.50	0.96	15.88	12.98	0.82
YCNA9	431.86	19.7	0.938	85.71	86.32	1.01	44.29	42.57	0.96	712.39	728.84	1.02	17.19	16.02	0.93
YCN41	442.80	18.0	0.967	87.88	87.00	0.99	40.40	37.24	0.92	753.01	732.49	0.97	15.68	13.34	0.85
YCN46	448.93	18.5	0.915	89.10	90.61	1.02	41.48	39.62	1.04	722.39	748.55	0.96	16.10	14.16	0.88
Mean sys2z						1.00			0.96			1.00			0.87
std						0.01			0.03			0.04			0.05
sys3															
YCN113	337.36	18.8	0.982	66.96	57.71	0.86	42.09	42.13	1.00	582.61	564.38	0.97	16.34	14.13	0.86
YCT92	334.67	18.9	0.964	66.42	56.72	0.85	42.40	41.88	0.99	567.37	563.97	0.99	16.46	13.90	0.84
YCT3	342.65	19.3	0.932	68.01	58.24	0.86	43.23	40.61	0.94	561.61	576.97	1.03	16.78	14.19	0.85
YCT2	337.00	18.8	0.982	66.89	57.77	0.86	42.24	41.62	0.99	581.98	563.33	0.97	16.40	14.05	0.86
YCT9	334.80	19.1	0.978	66.45	57.97	0.87	42.90	39.42	0.92	575.83	569.62	0.99	16.65	13.89	0.83
YCT97	332.81	18.6	0.932	66.05	57.11	0.86	41.64	38.75	0.93	545.48	559.25	1.03	16.16	13.51	0.84
Mean sys3						0.86			0.96			1.00			0.85
std						0.01			0.03			0.03			0.01

- Bi-weekly calibration with ^{55}Fe source, 5.9 keV.
- Calibration gain and resolution scaled to K/L peaks using an empirical formula adjusting for GeH_4 fraction (G) and pressure (P).
- Peak position & resolution verified by separate ^{71}Ge measurements.

^{51}Cr Source (JINST 16 (2021) P04012)

Neutrino Source

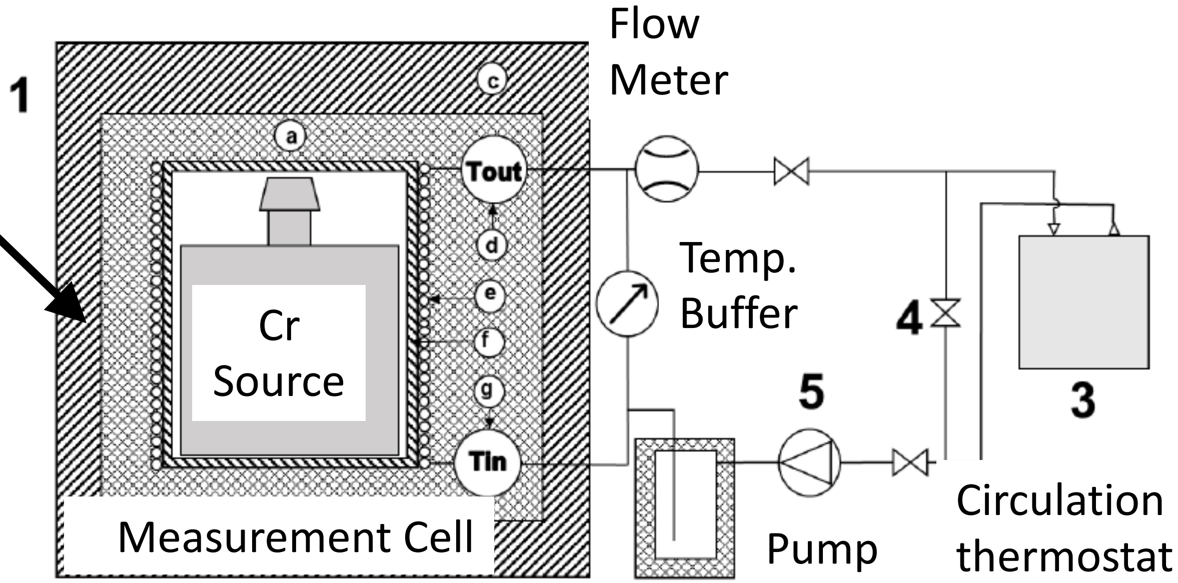
Transport Container

Measurement Cell
Of Calorimeter

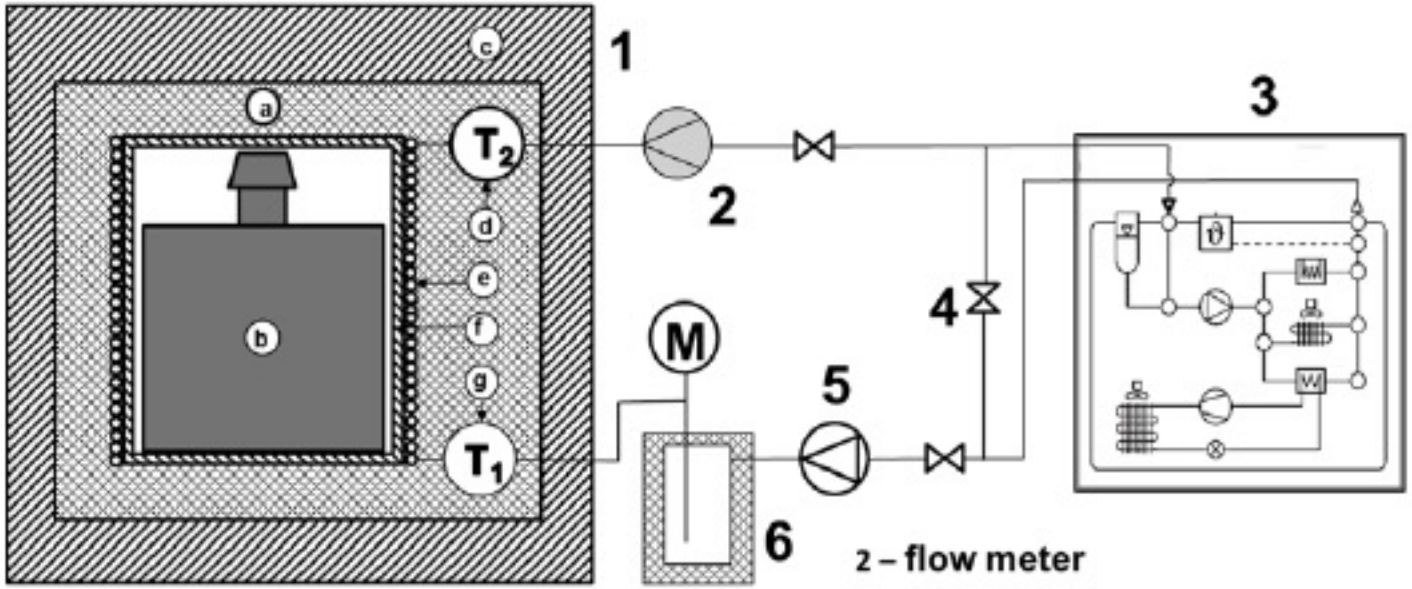
Activity at 14:02 on July 5, 2019

A = 3.414 ± 0.008 MCi

Energy/decay = 36.750 ± 0.84 keV



The Calorimeter

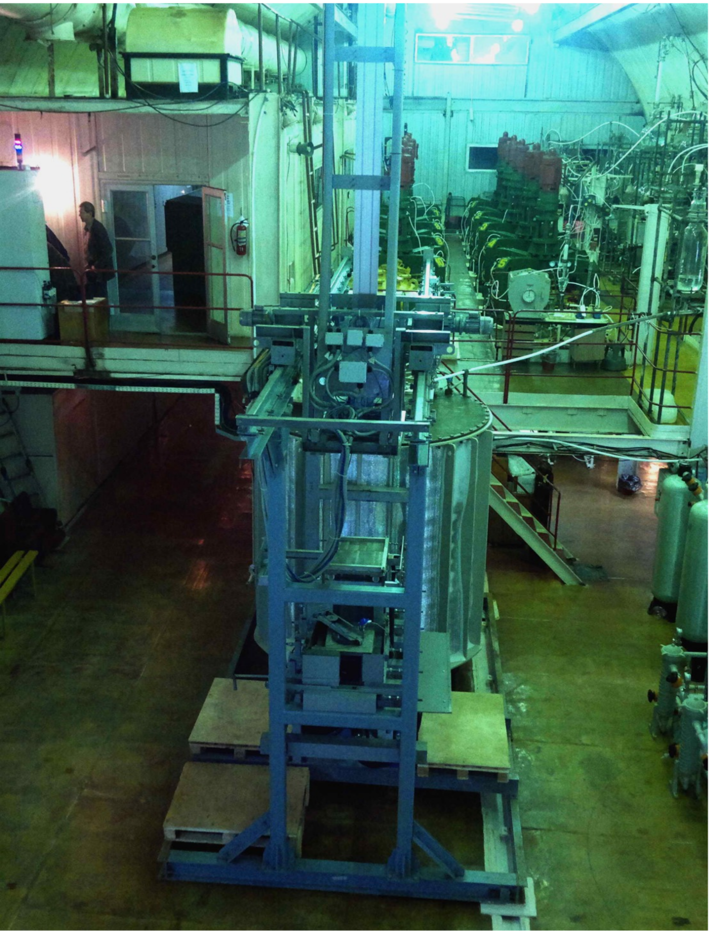


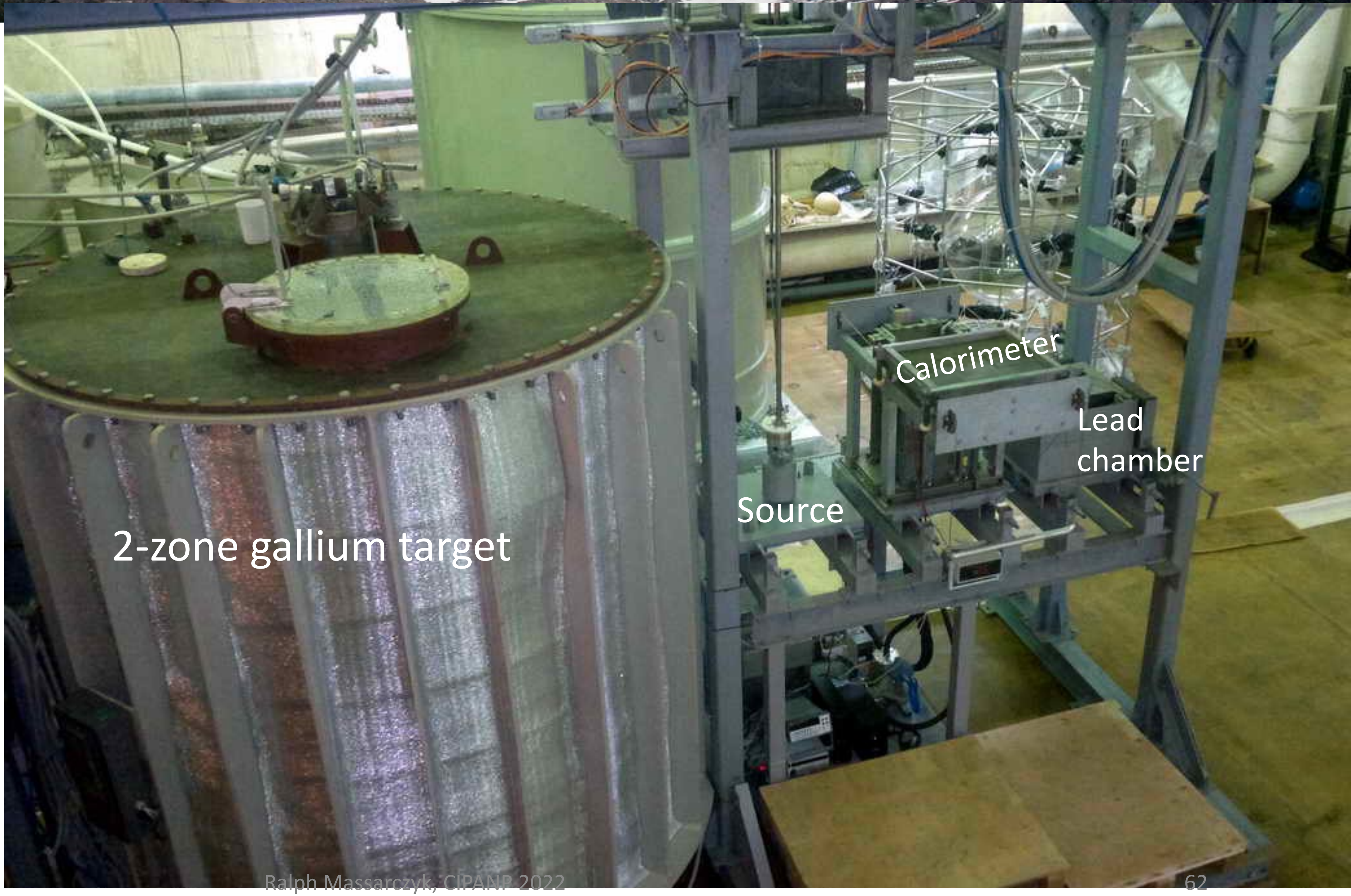
1 – MEASUREMENT CELL
a – thermal insulation
b – neutrino source
c – biological shield
d – output thermistor
e – heat exchanger
f – container
g – input thermistor

2 – flow meter
3 - thermostat
4 - bypass
5 - gear pump
6 – temperature damper
M - manometer

Figure 1. Hydraulic circuit of the mass flow calorimeter.


BNO INR RAS

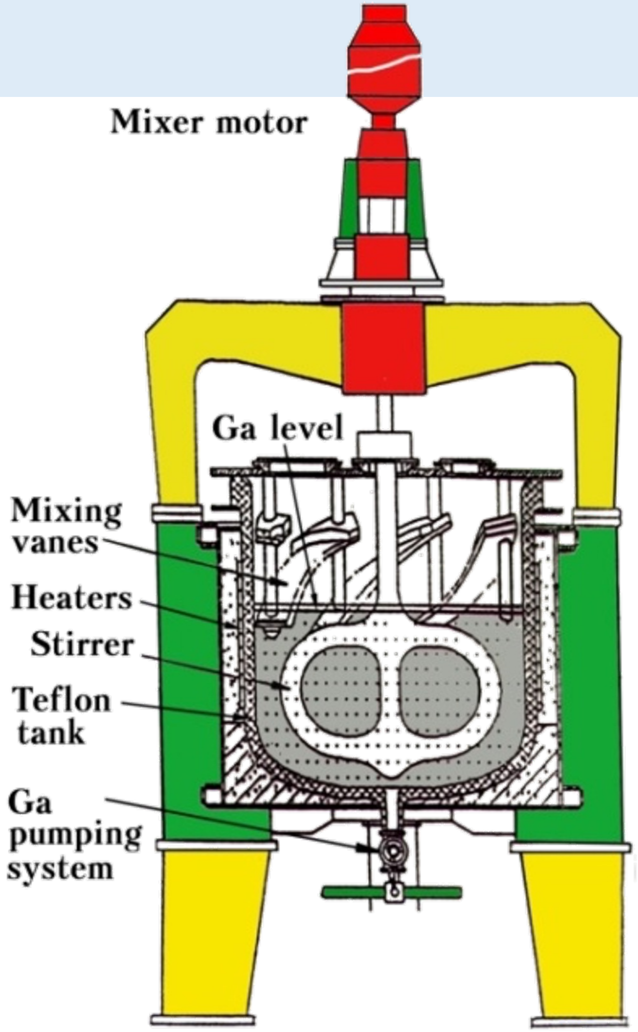



2-zone gallium target
Source
Calorimeter
Lead
chamber

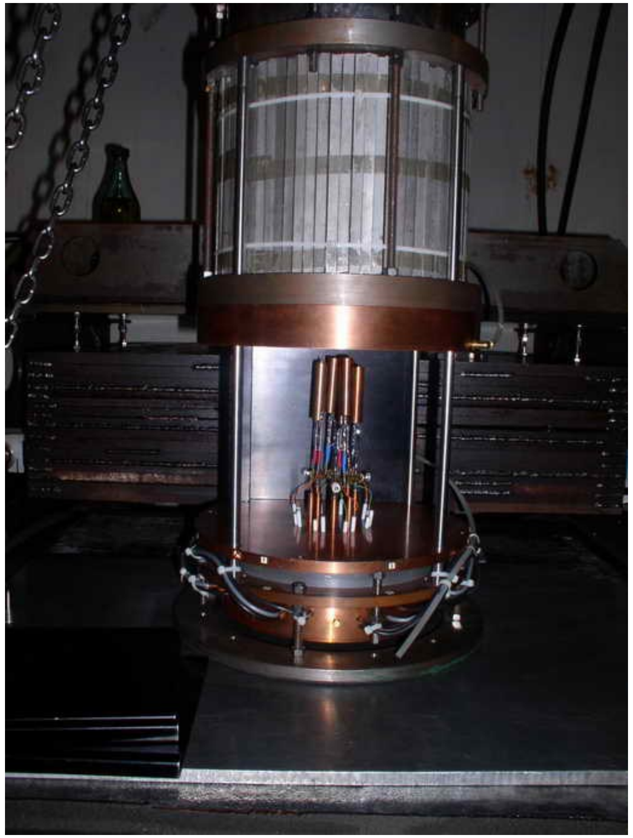
BEST Extraction Procedure (PRC 60 (1999) 055801)

^{71}Ge extraction (30 hours in *total*) :

1) Pump Ga from each zone to chemical reactors: inner zone → 1 reactor, outer zone → 6 reactors; *(4.5 h).*
2) In each reactor the germanium carrier, in the form of $GeCl_4$, is extracted from the metal into aqueous phase by an oxidation reaction.
3) The aqueous solution is concentrated by evaporation. *(16h)*
4) The gas GeH_4 is synthesized, mixed with Xe, and placed into a proportional counter.
5) ^{71}Ge decays are counted. *(60 – 150 days)*

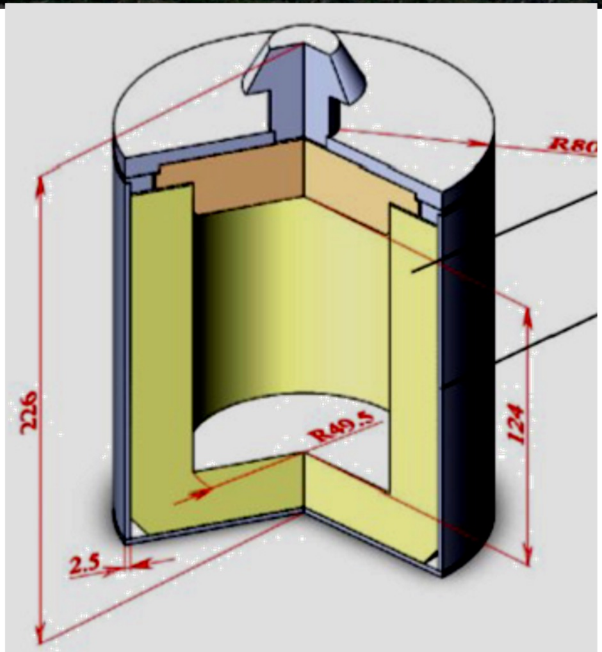


Data Acquisition



- Two 8-channel systems
- Proportional counter (PC) contained within NaI well
- PC pulses digitized at 1GHz, 100 MHz bandwidth, 8 bit
- Risetime = 3.5 ns
- 0.37<E<15 keV

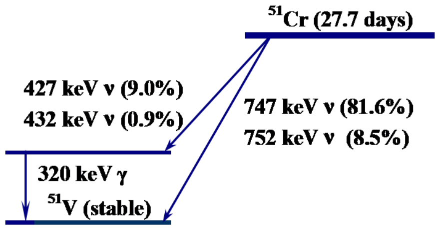
BEST: Neutrino source

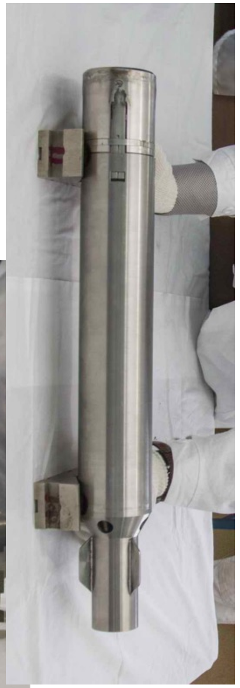


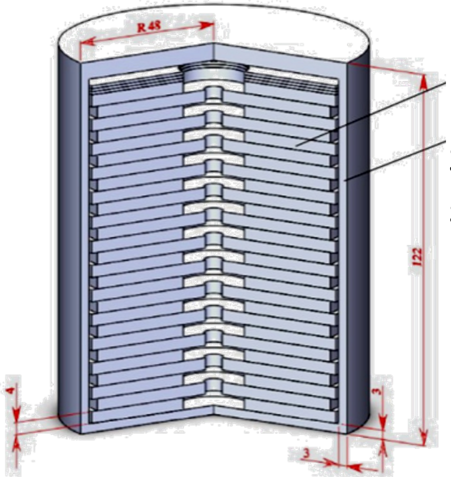
Biological protection , tangsten

Stainless steel

4 kg 97%-enriched ^{50}Cr,
26 Cr metal disks
h = 4 mm, ∅ 84 and 88 mm.







26 chrome metal disks

Stainless steel

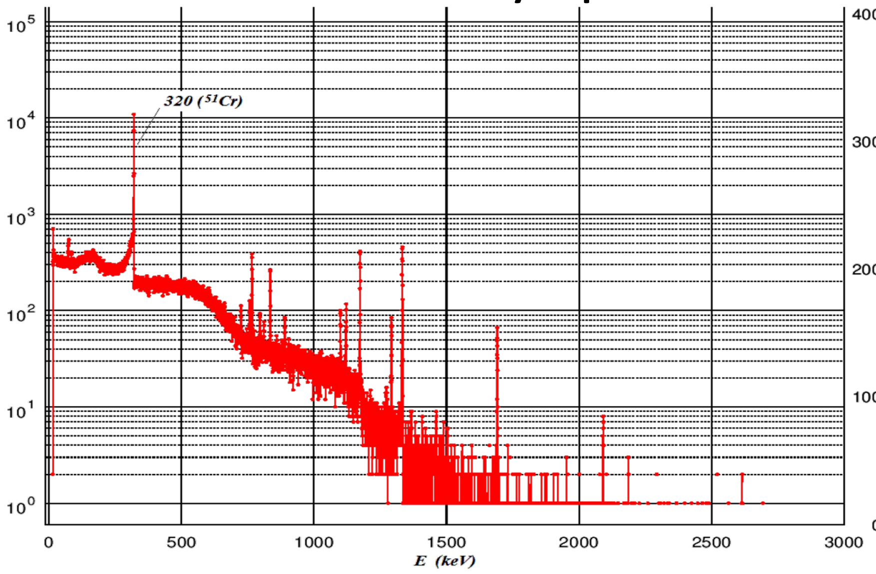
Chromium disks from metallic ^{50}Cr enriched up to 97%.
The enrichment was performed by the JSC “PA “Electrochemical Plant” (Zelenogorsk).
These disks were irradiated for ~100 days with thermal neutrons in the SM-3 reactor (RIAR, Dmitrovgrad). Thermal neutron flux density – 5×10^{15} neutrons /(cm^2 s)

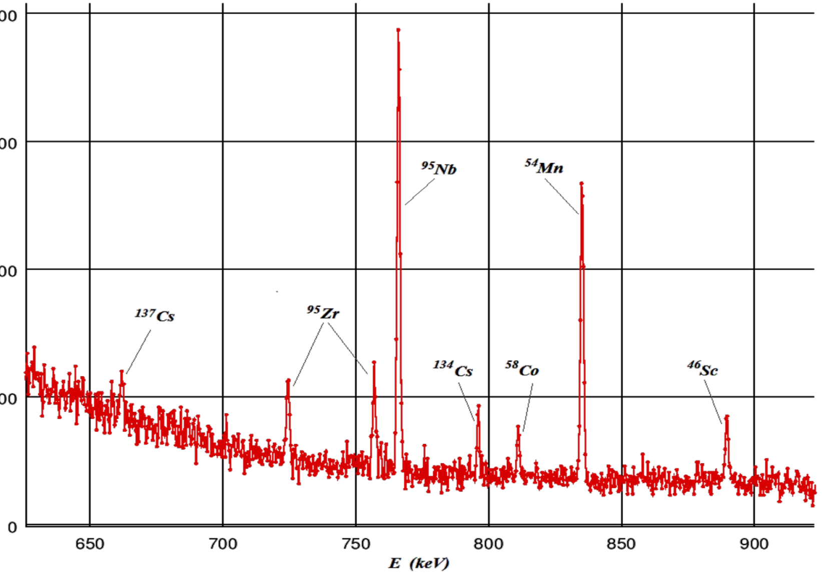
Gamma Ray Spectroscopy of Source

Measured nuclide impurities in the ^{51}Cr source and their contribution to the source activity measurement at the reference time 14:02 on 05.07.2019

	Isotope, $T_{1/2}$	The energy in the line, keV	The output lines, %	Activity on July 5, mCi	W, mW
1	^{137}Cs, 30.05 y	662	85	8.5×(1±0.23)	0.06
2	^{95}Zr, 64 d	724	11.1	60×(1±0.12)	2.1
		757	54.38		
3	^{95}Nb, 35 d	766	99.8	87×(1±0.04)	
4	^{134}Cs, 2.06 y	796	85.5	3.3×(1±0.18)	0.04
5	^{58}Co, 70.85d	811	99.44	6.0×(1±0.27)	0.08
6	^{54}Mn, 312 d	835	100	13×(1±0.05)	0.1
7	^{46}Sc, 83.8 d	889	100	5.2×(1±0.10)	0.07
		1120	100		
8	^{59}Fe, 44.5 d	1099	57	23×(1±0.07)	0.22
		1291	43.2		
9	^{60}Co, 5.27 y	1173	100	6.6×(1±0.03)	0.11
		1332	100		
10	^{124}Sb, 60.2 d	1690	47.5	5.8×(1±0.06)	0.1
		2091	5.5		
11	^{154}Eu (?), 8.6 y	1274	34.9	0.86×(1±0.18)	0.01
		1595	1.8		
Σ					2.9

Source Gamma Ray Spectrum





From 11 spectrometric measurements of gamma radiation of the source,
- the total amount of heat release from impurity radionuclides is 2.9 ± 0.5 mW , which is ~$4\cdot10^{-6}$ of the initial ^{51}Cr source power, and can be neglected; confirmation of a high purity of the material used to produce the ^{51}Cr source

Measured Production Rates

K+L-peak

Extraction	Number of candidate events	Number fit to ^{71}Ge	^{51}Cr source production	Solar ν production	Carryover	^{71}Ge Production decay rate (atoms/day)
Inner-1	180	176.3	175.5	0.8	0.0	$49.4^{+4.0}_{-4.2}$
Inner-2	129	111.5	107.7	0.8	3.1	$44.9^{+5.6}_{-5.9}$
Inner-3	132	117.6	115.3	0.7	1.6	$62.9^{+7.1}_{-7.4}$
Inner-4	93	87.3	85.6	0.6	1.1	$73.3^{+8.0}_{-8.6}$
Inner-5	134	60.2	58.4	0.6	1.2	$49.8^{+7.7}_{-8.2}$
Inner-6	81	48.8	47.7	0.4	0.7	$69.5^{+11.0}_{-12.0}$
Inner-7	91	45.0	43.9	0.5	0.6	$64.6^{+11.6}_{-12.6}$
Inner-8	59	33.6	32.4	0.6	0.6	$53.8^{+11.0}_{-12.2}$
Inner-9	106	23.7	22.7	0.6	0.4	$49.9^{+14.9}_{-16.5}$
Inner-10	88	25.2	24.3	0.6	0.3	$69.1^{+17.3}_{-19.4}$
Comb. K+L	1093	724.0	708.2	6.1	9.7	$54.9^{+2.4}_{-2.5}$

K+L-peak

Extraction	Number of candidate events	Number fit to ^{71}Ge	^{51}Cr source production	Solar ν production	Carryover	^{71}Ge Production decay rate (atoms/day)
Outer-1	181	133.4	129.6	3.7	0.1	$41.1^{+5.2}_{-5.3}$
Outer-2	174	163.8	158.6	3.3	1.9	$63.6^{+5.5}_{-5.7}$
Outer-3	116	92.5	88.2	2.8	1.5	$51.4^{+6.9}_{-7.3}$
Outer-4	98	82.3	78.9	2.5	0.8	$66.6^{+9.2}_{-9.8}$
Outer-5	120	64.0	59.5	3.5	1.0	$46.9^{+7.2}_{-7.9}$
Outer-6	97	62.3	59.3	2.6	0.4	$87.3^{+12.3}_{-13.2}$
Outer-7	69	38.0	34.4	3.2	0.4	$50.4^{+9.6}_{-10.6}$
Outer-8	68	43.4	39.2	3.9	0.4	$59.7^{+10.8}_{-11.7}$
Outer-9	66	20.2	17.0	3.0	0.2	$43.0^{+13.5}_{-15.3}$
Outer-10	81	31.8	28.0	3.6	0.2	$78.8^{+18.1}_{-20.0}$
Comb. K+L	1069	738.8	699.8	32.2	6.8	$55.6^{+2.6}_{-2.7}$

Minor contributions from solar neutrinos and by carry-over events (~2%)

Consistent with, but not Proof of, Oscillations

These results reaffirm the Ga anomaly, with higher statistical precision.

But no dependence on oscillation length was observed. So although the results are consistent with oscillations, there is no ‘smoking gun’ evidence that is not subject to caveats.

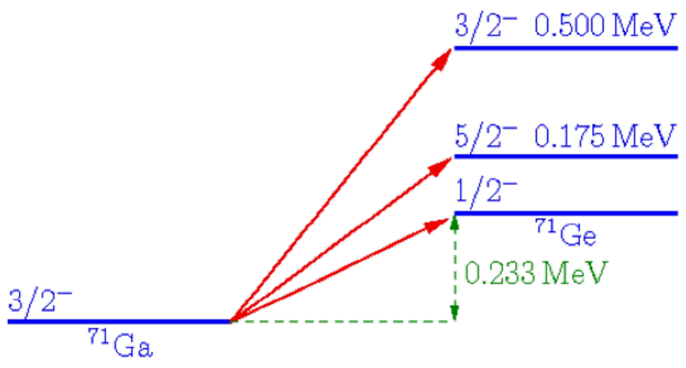
Because the rate in the two volumes is equally depressed, a number of potential explanations beyond oscillations have been considered. No clear alternative has been identified.

- Cross Section
- Source Strength
- Extraction Efficiencies
- Counting Efficiencies
- Average Path Length

$$P_{ee}(E_\nu, r) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2] r[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$

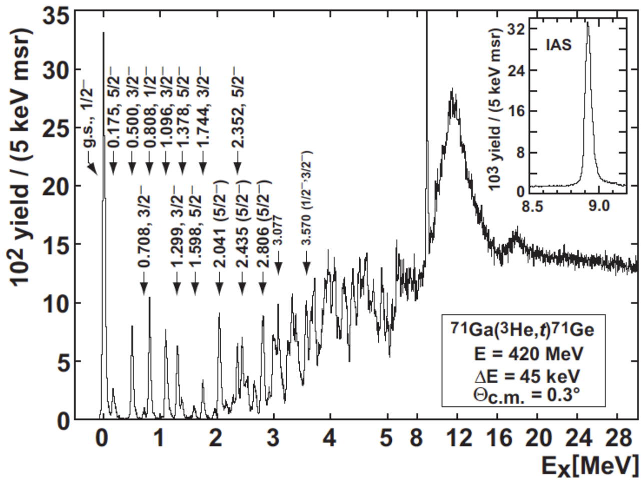
$$R_j = \frac{n\sigma A}{4\pi}\int_{V_j}\frac{P_{ee}(r)}{r^2}d\vec{x} \approx V_0\frac{1}{N}\sum_{i=1}^{N}\frac{P_{ee}(r)}{r^2}\Theta_j(\vec{x}_i)$$

The Cross Section



- Bahcall estimated the ground state cross section by deriving the transition strength from the well-known ^{71}Ge decay rate. (PRC 56 (1997) 3391)
  - The excited states (ES) were estimated from imprecise charge exchange measurements and found to be ~5%.
- Recently much better charge exchange measurements have become available. (PLB 706 (2011) 134, PLB 722 (2013) 233, PRC 91 (2015) 034608)
  - Show that the ES contribution is about 7%.
  - But, the Gamow-Teller and tensor contributions might cancel. (PLB 431 (1998) 110)
- New shell model calculations avoid the GT-tensor concern, but must reproduce other low energy characteristics. (PLB 795 (2019) 542)
  - This agreement is modest and not fully reassuring.
  - New shell model work is desirable.
- Bahcall's result is at the average of the two methods with an uncertainty that encompasses both, so BEST uses that value. 5.81×10^{-45} cm^2

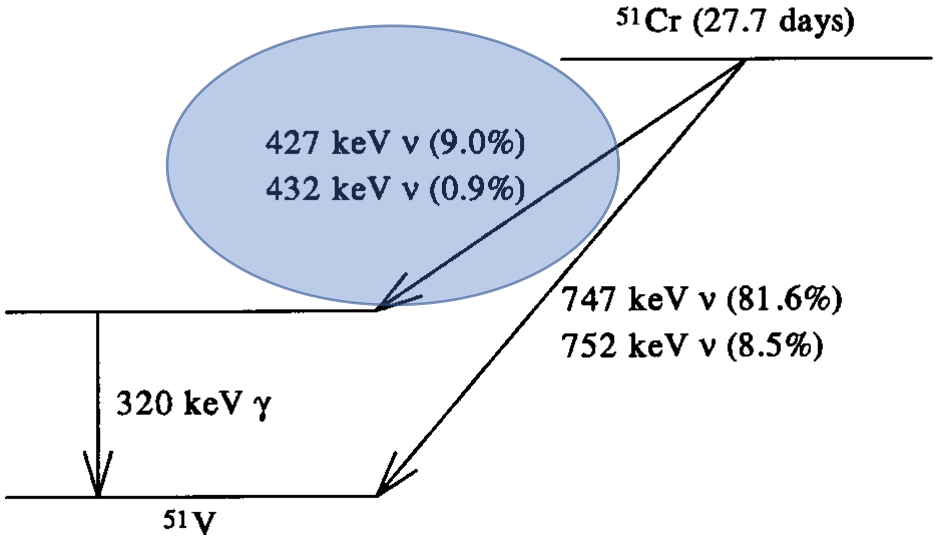
^{51}Cr and ^{37}Ar n's can only excite first 3 levels in ^{71}Ge.



PRC 91 (2015) 034608

Source Strength

- The activity measurement precision is best from calorimetry.
- This technique has been confirmed by other estimates building confidence. (PRC 59 (1999) 2246)
    - Direct counting of 320-keV line with Ge detector.
    - Reactor physics and neutron transport.
- Cr decay scheme.
    - The branching ratio to the 320-keV level is key for interpreting the activity of the source.
    - It is claimed to be known to ~0.1%, too small to explain 20% depression.

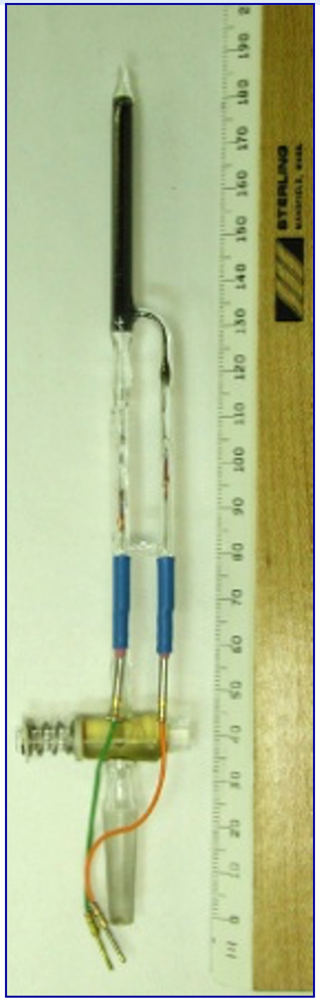


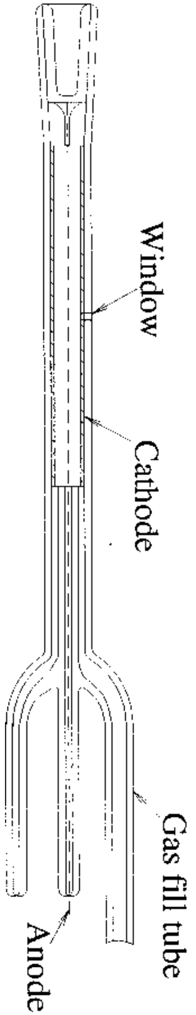
Extraction Efficiencies (PRC 73 (2006) 045805)

- A variety of extraction efficiency tests have been done – all consistent with experimental values. (PRC 60 (1999) 055801)
- ^{70,72}Ga radioactive isotopes produced by neutron activation were used for the carrier. Extraction of the Ge isotopes resulting from their decay was as expected. Tests question that atomic excitations during nuclear processes result in Ge ending up in un-extractable chemical form.
- ^{68}Ge produced cosmogenically when the Ga resided on surface was counted during many initial extractions. The reduction during these extractions followed the expected trend.
- A <u>sample of carrier doped with ^{71}Ge</u> was produced and the measured extraction efficiency was as expected from the stable carrier determination.

Counting Efficiencies (PRC 60 (1999) 055801)

- Counter efficiencies were cross checked several ways.
- Volume efficiency checked with ^{37}Ar loaded counter gas
  - ^{40}Ca(n,α)^{37}Ar
  - Gas activity measured in a large counter (2.5 cm^3) with high efficiency
  - Then used in experiment’s counters to determine efficiency
- L- & K-Peak Efficiencies with ^{69}Ge and ^{71}Ge loaded counter gas
  - ^{69}Ga(p,n)^{69}Ge
  - $^{69}GeH_4$-Xe fill, measure Auger e$^-$ and 1106keV γ ray. The relative rates of γ/e determines efficiency.
  - ^{70}Ge(n,γ)^{71}Ge
  - $^{71}GeH_4$-Xe fill, measure in both large and experimental counters





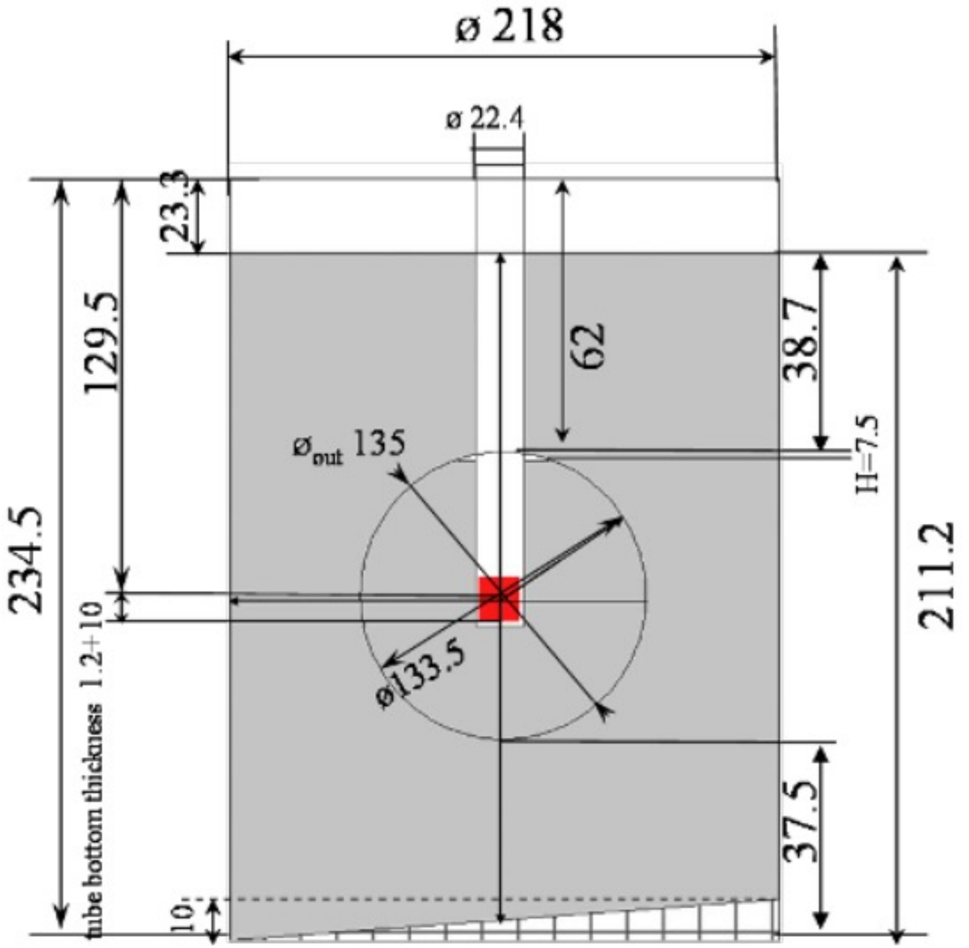
Average Path Length and Geometry

$$R_j = \frac{n\sigma A}{4\pi}\int_{V_j}\frac{P_{ee}(r)}{r^2}d\vec{x} \approx V_0\frac{1}{N}\sum_{i=1}^{N}\frac{P_{ee}(r)}{r^2}\Theta_j(\vec{x}_i)$$

Due to irregular geometry, calculated by Monte Carlo Integration.
Verified by comparing calculated Ga masses to measured.
Uncertainty estimated by varying geometry parameters.
Uncertainty about 0.3%.

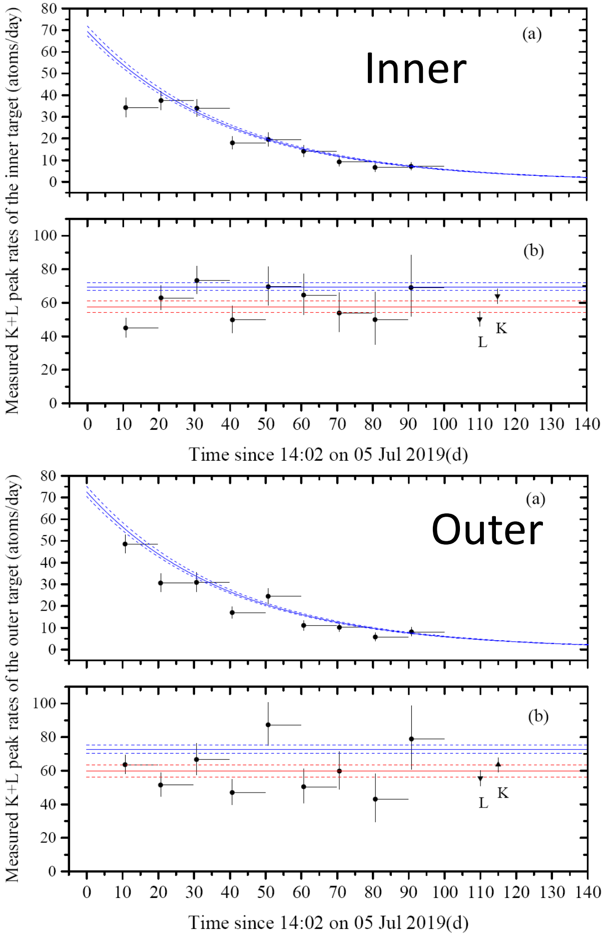
$\langle L_{in}\rangle = 52.03 \pm 0.18$ cm
$\langle L_{out}\rangle = 54.41 \pm 0.18$ cm

These are the average path length of a neutrino through the Ga zone. It is <u>not</u> the oscillation length.



Fit Excluding First Extraction

A fit that excludes the first data point does not change the qualitative conclusion although the statistical significance is decreased.



	IN	OUT
Predicted	$69.41^{+2.5}_{-2.0}$	$72.59^{+2.6}_{-2.1}$
Measured	57.7 ± 3.5	59.8 ± 3.6
Ratio	0.83 ± 0.05	0.82 ± 0.06

2.9σ and 3.2σ less than the unity

Note: $\frac{0.83\pm0.05}{0.82\pm0.06} = 0.99 \pm 0.08$

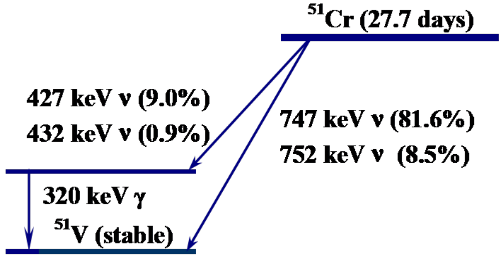
Similar deficits observed in both zones

Source Activity – ^{51}Cr Branching Ratio Uncertainty

The calorimetry heat measurement relies on the branching ratio of the 320-keV Cr emission to normalize to activity.
If the branching value is in error, so would be the source strength. But the BR is claimed to be known to a precision much smaller than our result, 0.1%. Even so, would not explain Ar result.

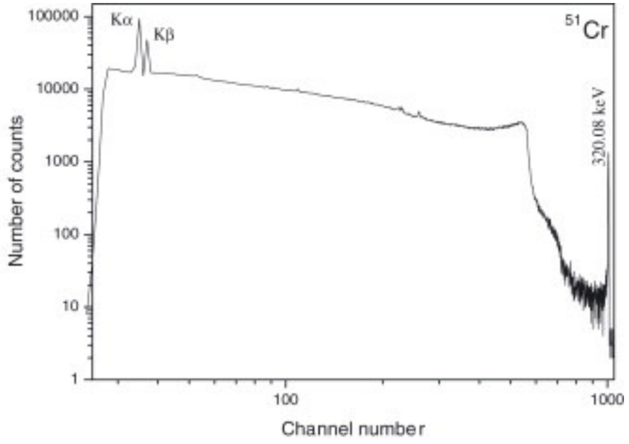
ENDF data

E(decay)	E(level)	Iε†‡	Log *ft*	Comments
(432.37 *21*)	320.0835	9.930 *10*	5.8631 *7*	εK=0.8910; εL=0.09347; εM+=0.01556
(752.45 *21*)	0.0	90.070 *10*	5.3910 *3*	εK=0.8919; εL=0.09268; εM+=0.01541



Specific Results

Ref	branch	method
NIM A 339 (1994) 20	0.0990(8)	NaI – absolute activity ???
NIM A 339 (1994) 20	0.1008(11)	Ge – absolute activity ???
Applied Radiation and Isotopes 68 (2010) 596	0.0987(3)	Beta-gamma coincidence (Ge-based)
Applied Radiation and Isotopes 62 (2005) 63	0.099(1)	Si(Li) with fixed activity



Cross Section – Energy of ^{51}Cr Neutrinos

- Cross section scales approximately as neutrino energy squared.
- Q value is well known: 0.1%. So no more than about 0.2% on cross section
- The energies of the emitted neutrinos are taken from the decay Q value and specific K/L shell energies.
- A full calculation of the final atomic state should be pursued. If the shell is altered during the decay, the energy of that state will not be shared with the neutrino.
- Maybe a keV decrease in neutrino energy…
  - 1 keV out of 750 is about 1.3%, cross section might decrease by maybe 2.5%.
  - Too small to explain difference.
- Would have to do similar calculation for Ar.

Cross Section – Electron Density at the Nucleus

Concern raised by RGH Robertson

- The ground state cross section for ^{71}Ga-> ^{71}Ge is derived from the decay rate of ^{71}Ge.
- The decay rate is proportional to $|M|^2|\psi(0)|^2$, where $\psi(0)$ is the electron density at the nucleus. If the theoretical $\psi(0)$ is estimated high, the cross section would be underestimated.
- The cross section, however, only needs the matrix element $|M|^2$.
- Hence a calculation of $\psi(0)$ is used to convert the decay rate to a cross section.
- Experimental tests of $\psi(0)$ measure the ratio of electron capture to positron decay.
  - For ^{22}Na, measurement is ±1%, but disagrees with theory by 6%. (Appl. Rad. Iso. 134 (2018) 225)
  - But theory is high wrt experiment, so effect seems to be in wrong direction to be an explanation.
  - Need a better experimental test, and hopefully with A near 71 (^{68}Ga?)
  - Will need complementary calculations.

Cross Section – Electron Density at the Nucleus

Concern raised by RGH Robertson

- The ground state cross section for ^{71}Ga-> ^{71}Ge is derived from the decay rate of ^{71}Ge and the electron density at the nucleus

$$\sigma_0 = \frac{1.2429 \times 10^{-47}\ \mathrm{cm}^2}{\Sigma_i q_i^2 g_i^2}$$

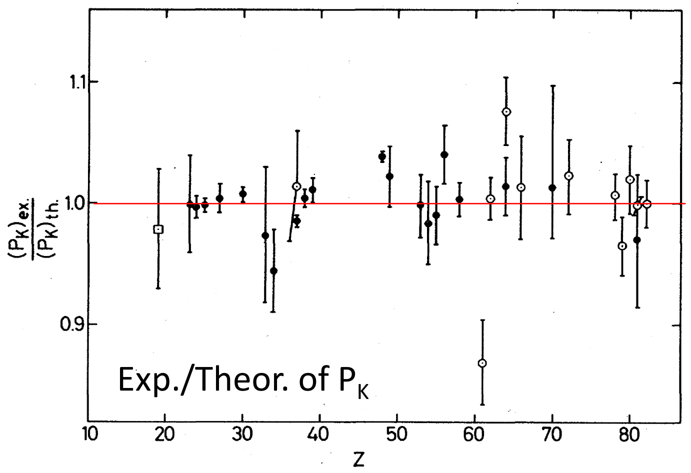
q_i: $E_{threshold}$-$E_{binding,i}$

g_i^2: square of the radial wavefunction

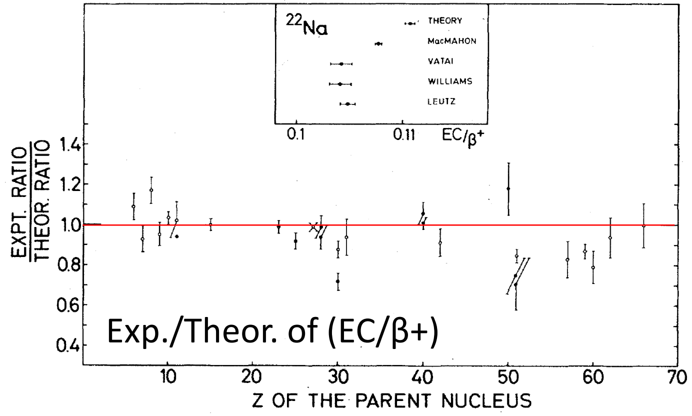
[PRC **56**, 3391 (1997)]

- For this calculation, g_i^2 is only calculated, not measured
- Experimental tests of g_i^2 measure the ratio of electron capture to positron decay (EC/β+)
  - $P_{EC}/P_{\beta+} = (P_K+P_L)/P_{\beta+} = P_K/P_{\beta+}\,(1+P_L/P_K)$
  - $\sigma(P_L/P_K)$~ ±3%, $\sigma(P_K)$~ ±5%
  - $(EC/\beta+)_{theory}$ systematically *higher* than $(EC/\beta+)_{exp.}$ (see figure on the right).
  - For most nuclides, effect is in the opposite direction to the Ga anomaly
  - For ^{22}Na, measurement is ±1%, but disagrees with theory by 5%. (Appl. Rad. Iso. 134 (2018) 225)
  - Need a better experimental test, and hopefully with A near 71 (^{68}Ga?)
  - Will need complementary calculations.

Rev. Mod. Phys. **49**,1 (1977)



Rev. Mod. Phys. **49**,1 (1977)



EC/β+ Ratio Near A=71

Rev. Mod. Phys. **49**,1 (1977)

Nuclide	Z	A	K/β+ Theory	K/β+ Exp.	Ratio (Exp./Theory)	Ref.
Zn	30	65	30.5±0.4	27.7±1.5	0.908	Hammer (1968)
Ga	31	68	1.36±0.03	1.28±0.12	0.941	Ramaswamy (1959)

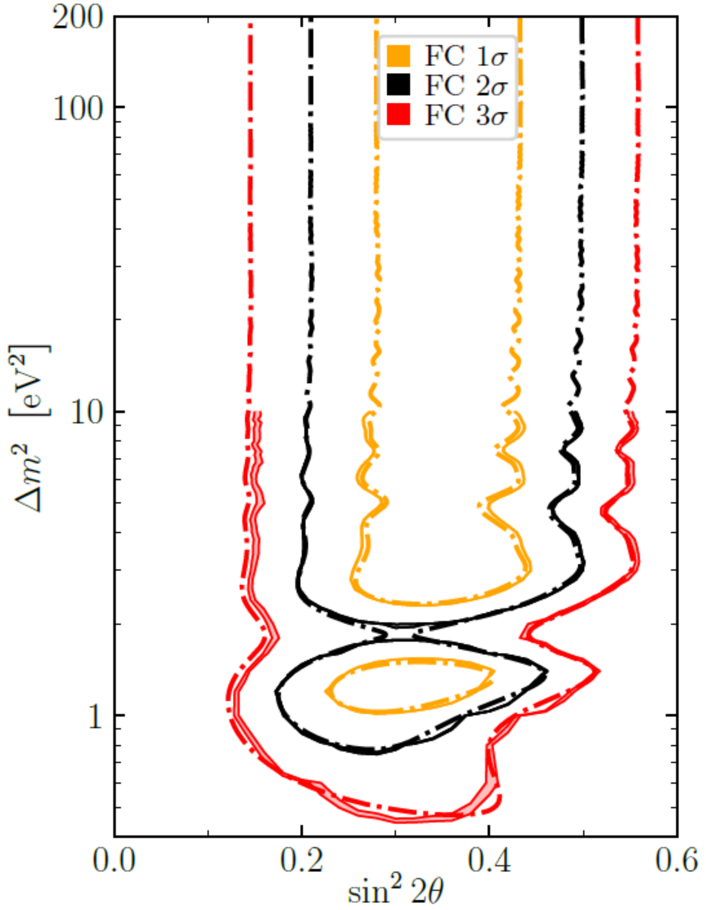
Nuclide	Z	A	EC/β+ Theory	EC/β+ Exp.	Ratio (Exp./Theory)	Ref.
Zn	30	65	34.5±0.04	24.9±1.5	0.722	Sehr (1954)
Na*		22	0.1143±0.001	0.1083±0.009	0.948	Mougeot (2018)

* Included here as it is the most studied nuclide for EC/β+ Ratio

Wilk’s Theorem in Question

- In our analysis for the oscillation parameters, the test statistic is assumed to be χ^2 distributed (Wilk’s theorem)
- However, Wilk’s theorem is in doubt when: EPJ.C **80**, 750 (2020), EPJ.C **81**, 2 (2021)
  - The population of likelihood function occurs near the parameter space edge
    - Physical bound at $\sin^2 2\theta \geq 0$
  - There is a degeneracy in parameter space
    - Δm^2 becomes undefined when $\sin^2 2\theta \rightarrow 0$
    - $\sin^2 2\theta$ becomes unphysical when $\Delta m^2 \rightarrow 0$

  The test statistic *a priori* significantly deviates from a χ^2 distribution
- Neutrino-4 significance reduces 3.2 σ → 2.6 σ when full Monte Carlo calculation is done
- BEST may observe similar effect
  - However, the best fit is further from the borders, so impact might be less
- Other analysis methods may be considered: CLs method, FC method, etc.



Wilk’s (dotted) vs Feldman-Cousins (solid). Analysis by arXiv:2111.12530.