The Gallium Anomaly and the BEST Experiment

Steve Elliott
LANL

Baksan Experiment on Sterile Transitions (BEST)

Spokesperson – Vladimir Gavrin

We thank the former Federal Agency for Scientific Organizations (FANO till 2019) of Russian Federation, Ministry of Science and Higher Education of Russian Federation, State Corporation ROSATOM, and the Office of Nuclear Physics of the US Department of Energy for their support.

V.V. Barinov,[1] B.T. Cleveland,[2] S.N. Danshin,[1] H. Ejiri,[3] S.R. Elliott,[4] D. Frekers,[5] V.N. Gavrin,[1, a] V.V. Gorbachev,[1] D.S. Gorbunov,[1] W.C. Haxton,[6, 7] T.V. Ibragimova,[1] I. Kim,[4] Yu.P. Kozlova,[1] L.V. Kravchuk,[1] V.V. Kuzminov,[1] B.K. Lubsandorzhiev,[1] Yu.M. Malyshkin,[1] R. Massarczyk,[4] V.A. Matveev,[8] I.N. Mirmov,[1] J.S. Nico,[9] A.L. Petelin,[10] R.G.H. Robertson,[11] D. Sinclair,[12] A.A. Shikhin,[1] V.A. Tarasov,[10] G.V. Trubnikov,[8] E.P. Veretenkin,[1] J.F. Wilkerson,[13, 14] and A.I. Zvir[10]

[1] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia*
[2] *SNOLAB, Sudbury, ON P3Y 1N2, Canada*
[3] *Research Center for Nuclear Physics, Osaka University, Osaka, Japan*
[4] *Los Alamos National Laboratory, Los Alamos, NM, USA*
[5] *Institut für Kernphysik, Westfälische Wilhelms-Universität Munster, D-48149 Munster, Germany*
[6] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[7] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[8] *Joint Institute for Nuclear Research (JINR) Joliot-Curie 6, 141980, Dubna, Moscow Region, Russia*
[9] *National Institute of Standards and Technology, 100 Bureau Dr, Gaithersburg, MD 20899, USA*
[10] *JSC 'State Scientific Center Research Institute of Atomic Reactors', Dimitrovgrad, 433510, Russia*
[11] *Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA 98195, USA*
[12] *Carleton University 1125 Colonel By Drive Ottawa, K1S 5B6, Canada*
[13] *Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599, USA*
[14] *Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA*

Outline

The Gallium Anomaly: The measurements of the charged-current capture rate of neutrinos on ^{71}Ga from strong radioactive sources have yielded results below those expected, based on the known strength of the principal transition supplemented by theory.

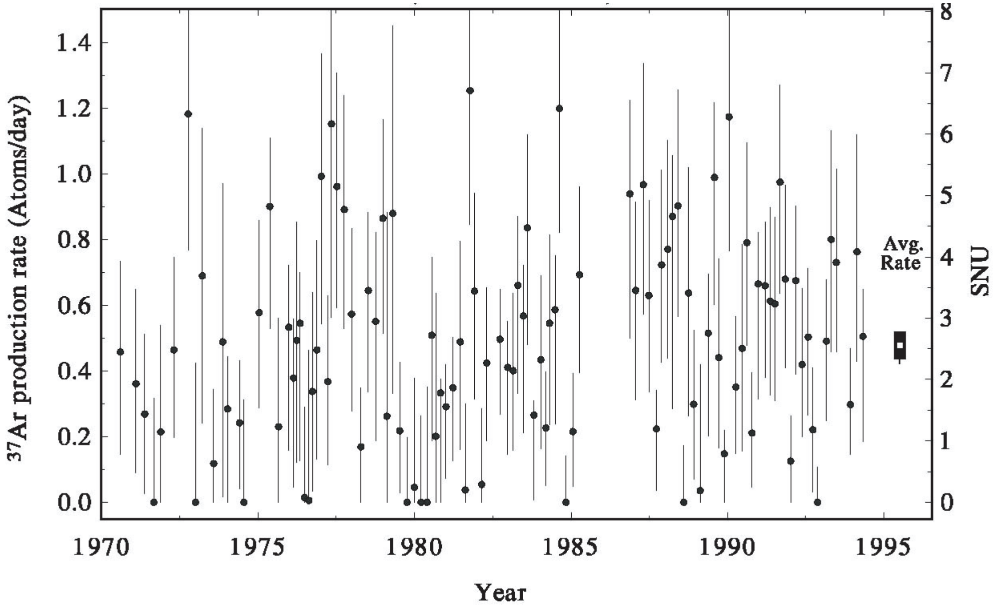
- SAGE History and the Gallium Anomaly
- BEST Description and Results
- Systematic Concerns
- Possible Future Measurements

<u>Key References</u>
BEST Coll. PRL 128 (2021) 232501
BEST Coll. PRC 105 (2021) 015031
Cross section PRC 108 (2023) 035502
PPNP 134 (2024)104082

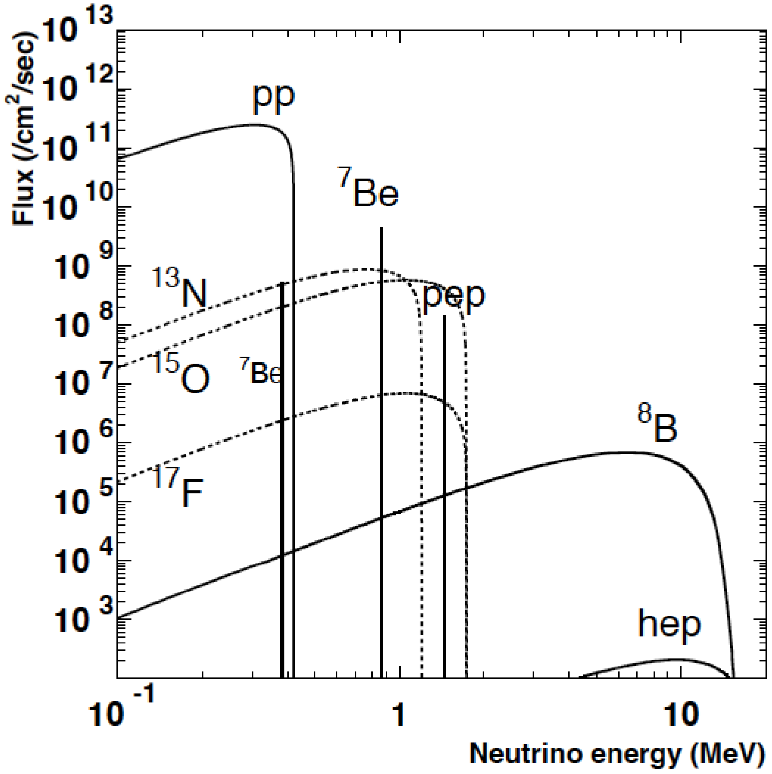
SAGE was an Early Solar Neutrino Experiment

- 1970's – 1990's: Absolute solar neutrino flux measurements disagreed with an absolute flux calculation. The detected neutrinos were high energy and many concerns were raised about the comparison. The *Solar Neutrino Problem*.

The Ray Davis experiment saw x3 less than predicted.



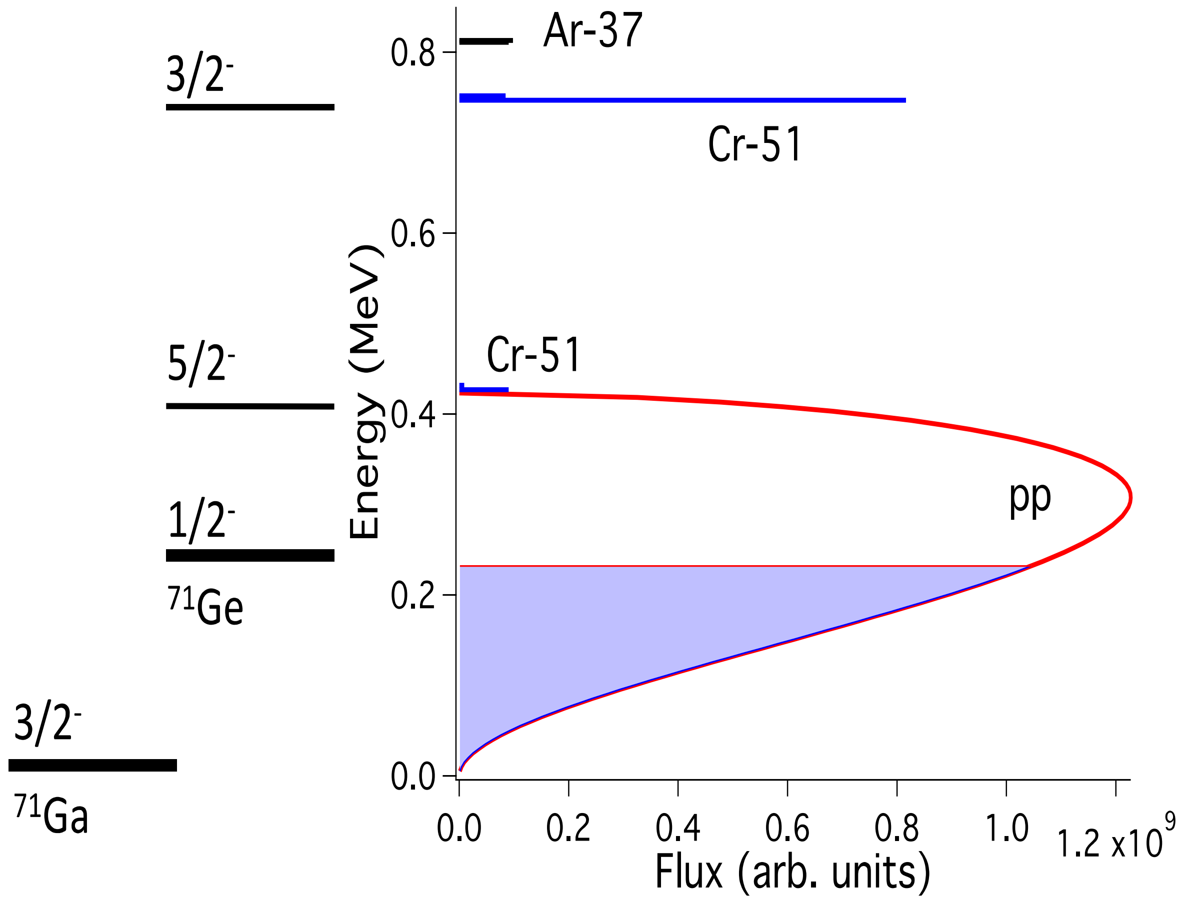
Astrophys J 505 (1998) 505



Astrophys J 555 (2001) 990

SAGE and GALLEX Measured the pp Flux

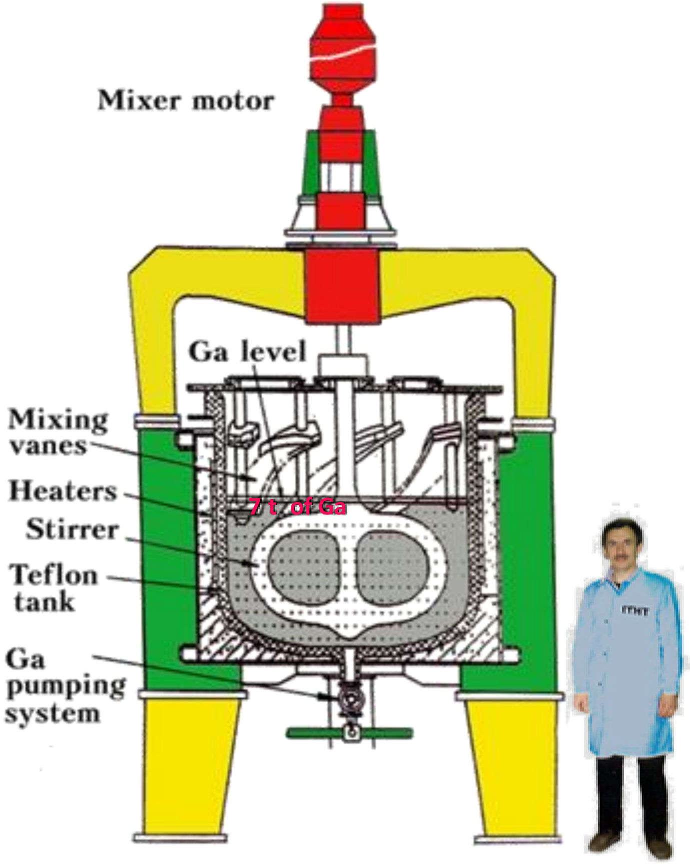
- Mid 1980's, two collaborations formed to measure the low-energy neutrinos from proton-proton fusion within the Sun using Ga as a target. A well-predicted flux from the known solar luminosity.
  - The Soviet-American Gallium Experiment (SAGE).
  - The Gallium Experiment (GALLEX).
- Early 1990s, the Soviet Union separated into various states and the collaboration became the Russian-American Gallium Experiment. The new acronym seemed unfortunate and we stuck with SAGE.



Only sensitive to ν_e.

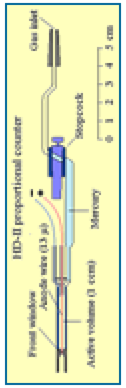
Used Gallium in a radiochemical Experiment (Kuzmin Eksp. Teor. Fiz. 49 (1965) 1532)

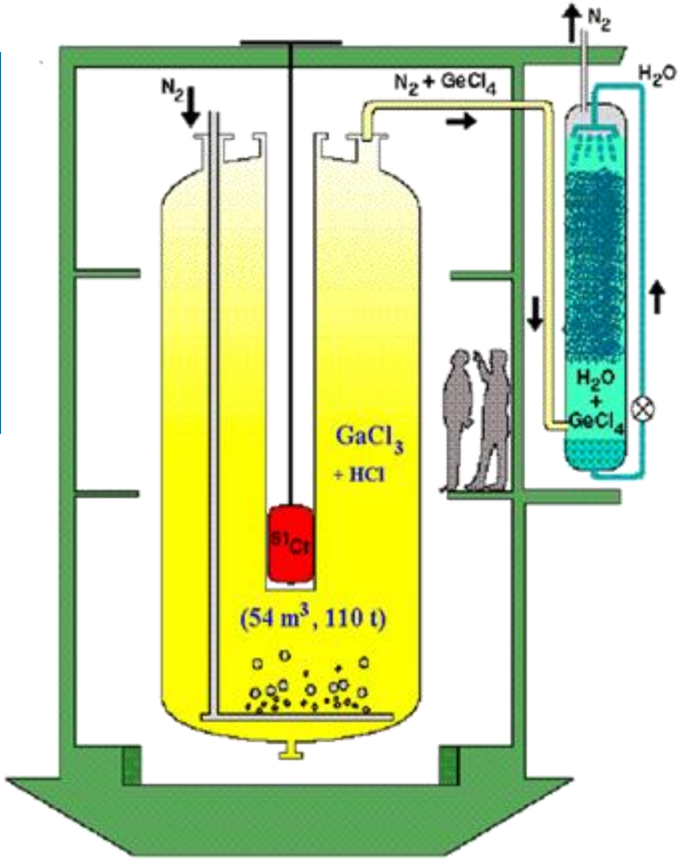
SAGE 50 t of Ga



GALLEX/GNO 30.3 t of Ga

Both experiments were based on radio-chemical extraction technology of a few ^{71}Ge atoms from tons of a Ga target and on technology of counting of ^{71}Ge decays in small proportional counters (~0.5 cm^3).





Laboratory Photo showing extraction reactors

Global intensity of muon
$(3.03 \pm 0.19) \times 10^{-9}$ /(cm^{2}s)
Fast neutron flux (>3MeV)
$(6.28 \pm 2.20) \times 10^{-8}$ /(cm^{2}s)

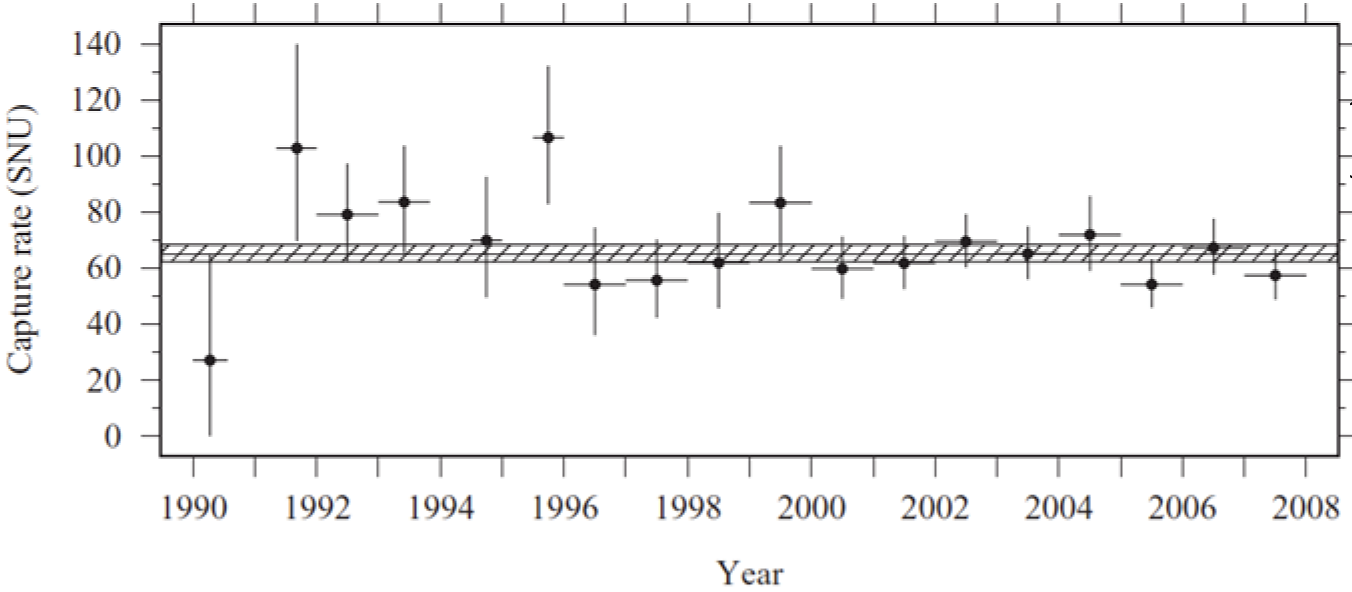
SAGE/GALLEX Saw Fewer Solar ν than Expected

SAGE/GALLEX/GNO: 66.1 ± 3.1 SNU (PRC 80 (2009) 015807)

Direct evidence for the p-p chain reactions for solar neutrino production in the Sun.

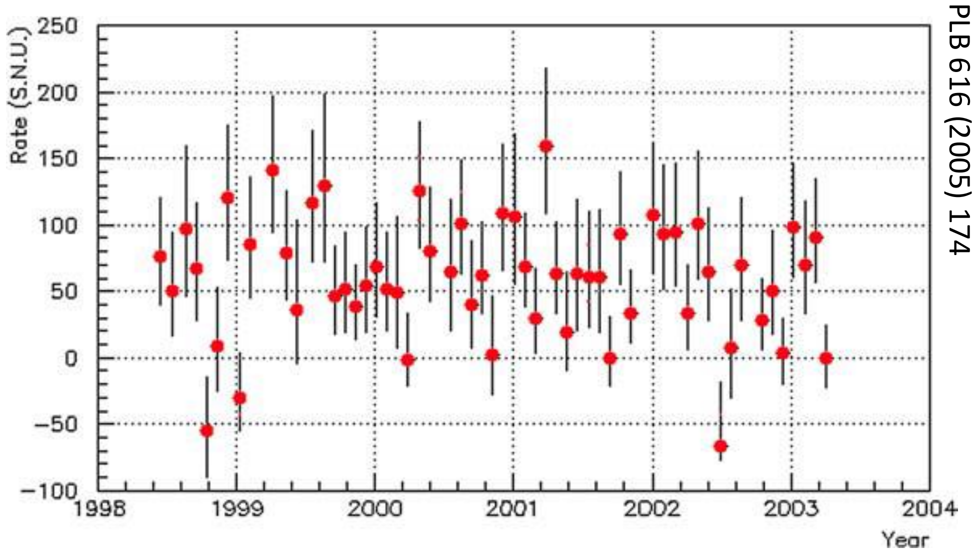
But the rate was again low compared to expectation (132 SNU).

SAGE: 1990 – 2007



PRC 80 (2009) 015807

GALLEX/GNO: 1991 - 2003



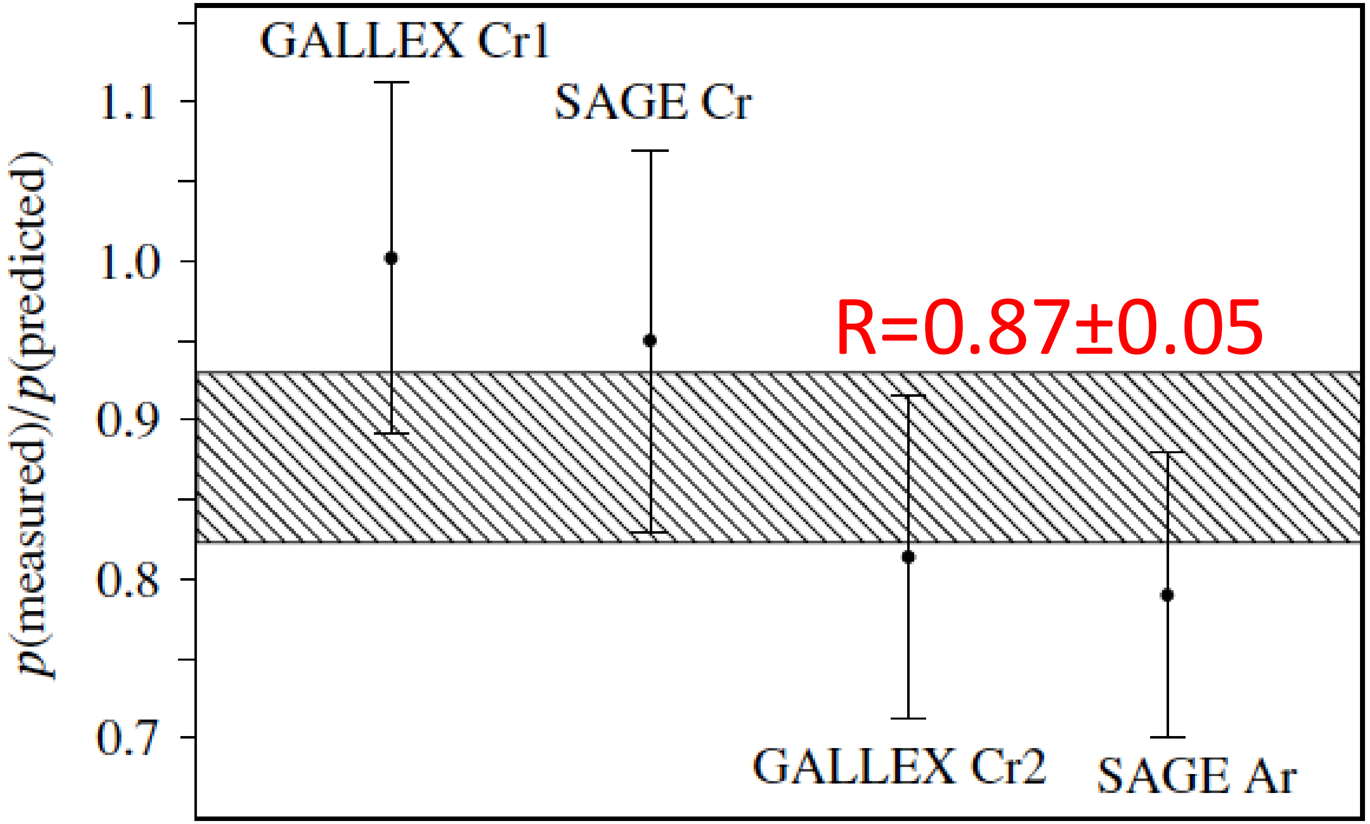
PLB 616 (2005) 174

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

Source Tests of the Ga Results Found Deficit

The importance of the solar ν deficit led to systematic studies, including irradiation with a known ν source.

- The measured rates of $^{71}Ga(\nu_e,e)^{71}Ge$ were lower than that predicted from the known cross section and ν_e flux.
- The statistical precision was not compelling but it drew attention.
- The ν_e sources were the electron-capture isotopes, ^{51}Cr or ^{37}Ar.



PRC 73 (2006) 045805, PRC 80 (2009) 015807

Solar and Atmospheric Neutrinos Show Oscillations

- The results of several experiments, looking at solar ν's and ν's produced in the Earth's atmosphere, demonstrated that the 3 neutrino weak eigenstates are not the mass eigenstates giving rise to phase evolution during propagation; oscillations. Results later confirmed by laboratory neutrino sources.
- Hence an electron neutrino produced by solar fusion will oscillate to a different neutrino flavor (muon or tau) resulting in a probability that it will not be observed in an Earth-based detector only sensitive to electron neutrinos.

$$P_{ee}(E_\nu, L) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\pi L}{L_{\mathrm{osc}}}\right) \quad \text{with} \quad \frac{\pi}{[L_{\mathrm{osc}}/\mathrm{m}]} = 1.27 \, \frac{[\Delta m^2/\mathrm{eV}^2]}{[E_\nu/\mathrm{MeV}]}$$

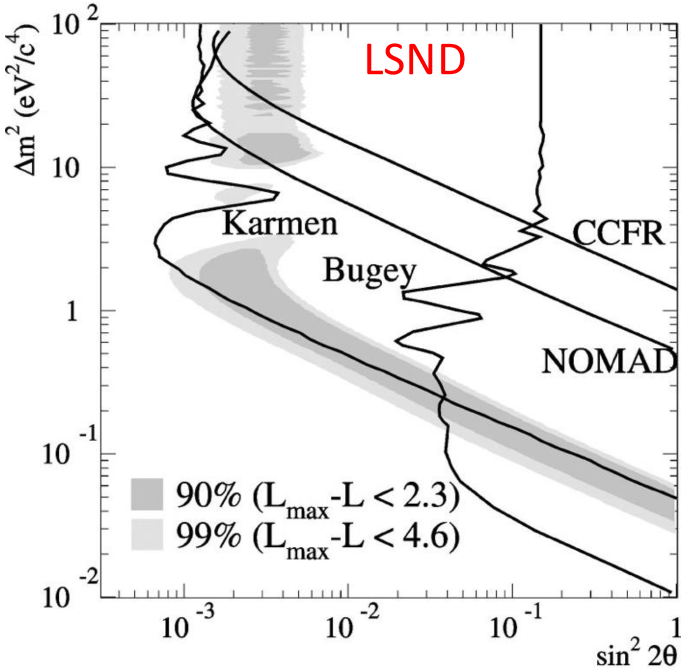
For oscillations to occur, the masses must be different. $\Delta m^2 = m_2^2 - m_1^2$. For the 3 known neutrinos, this requires 2, and only 2, Δm^2.

Evidence for Sterile ν Arose in Mid 90s

- 1995 LSND began a series of claims for the observation of oscillations with a large Δm^2.
- 1998-2009 SAGE and GALLEX completed source measurements with anomalous results.

Many considered this anomaly was further evidence of oscillations.

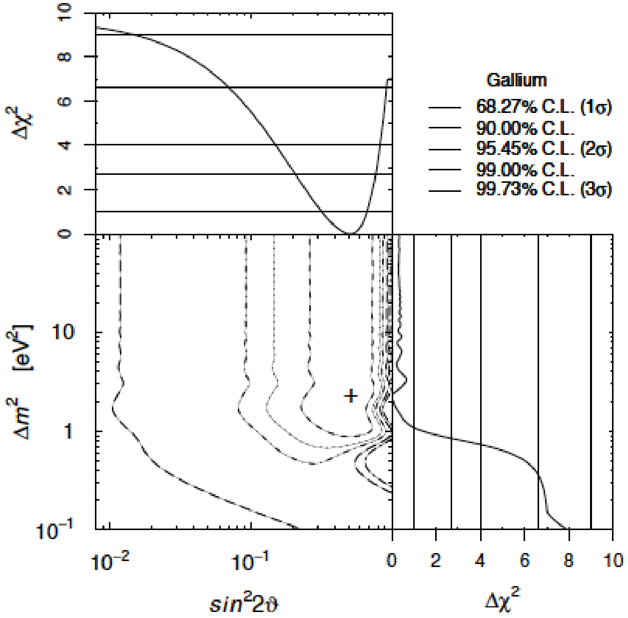
LSND



PRD 64 (2001) 112007

The large Δm^2 would require a third mass difference, and hence a 4th neutrino.

Gallium



PRC 83 (2011) 065504

Choose a Hypothesis to Falsify in New Experiment

- Standard model extensions to explain the sterile neutrino evidence are ubiquitous.
  - 6x6 neutrino matrix with all its mixing angles, masses and phases; CPT violation; non-standard neutrino interactions; neutrino decay; Lorentz violation; extra dimensions; energy dependent mixing parameters; dark photons; neutrinos coupled to fuzzy dark matter or dark energy; bulk neutrinos.
  - Surely more ideas will come.
- Difficult to design an experiment to verify or falsify such a hypothesis.
  - There is always a caveat to any null experiment.
- Better to design an experiment to test the hypothesis that the Ga anomaly is real.
  - Although BEST was designed with some oscillation sensitivity,
  - it was, in particular, a high-sensitivity test to falsify the premise that the Ga anomaly is real.

Source Measurement Overview

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

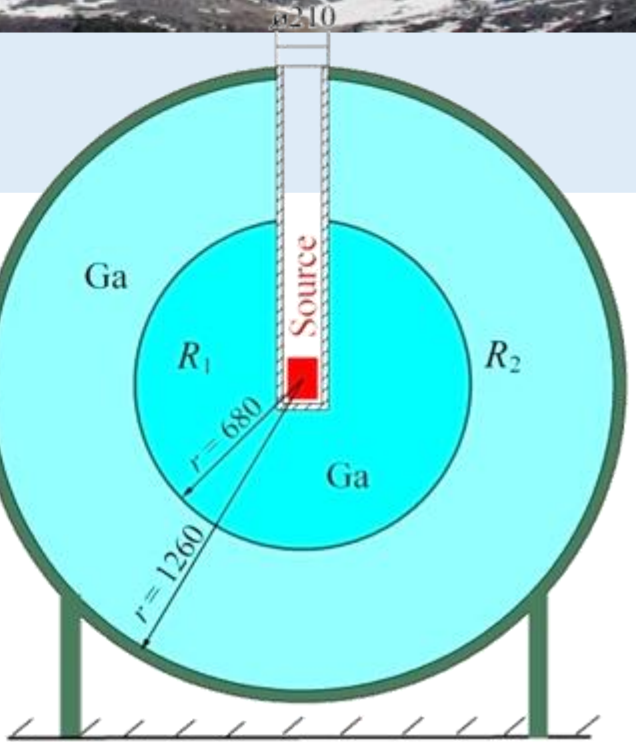
$$^{51}Cr + e^- \rightarrow {}^{51}V + \nu_e$$

- This is a well-understood monochromatic spectrum of a compact source. The source intensity is well measured.
- These neutrinos are detected via a charged-current (CC) reaction on Ga surrounding the source:

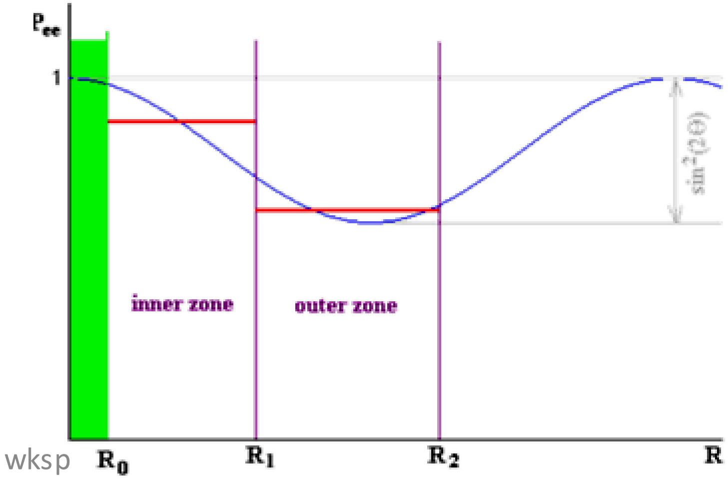
$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

- ^{71}Ge is radioactive and can be counted when it decays.
- Almost zero ν background. Mainly from the Sun.

  The source, 3.4 MCi, greatly exceeds the solar rate.
- Well established experimental procedures for extraction and counting of the ^{71}Ge developed in SAGE solar measurements.

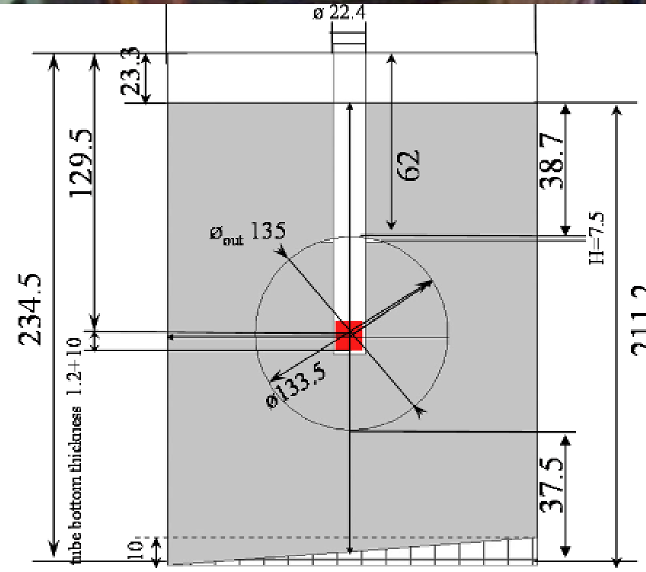


Schematic drawing of the BEST neutrino source experiment.

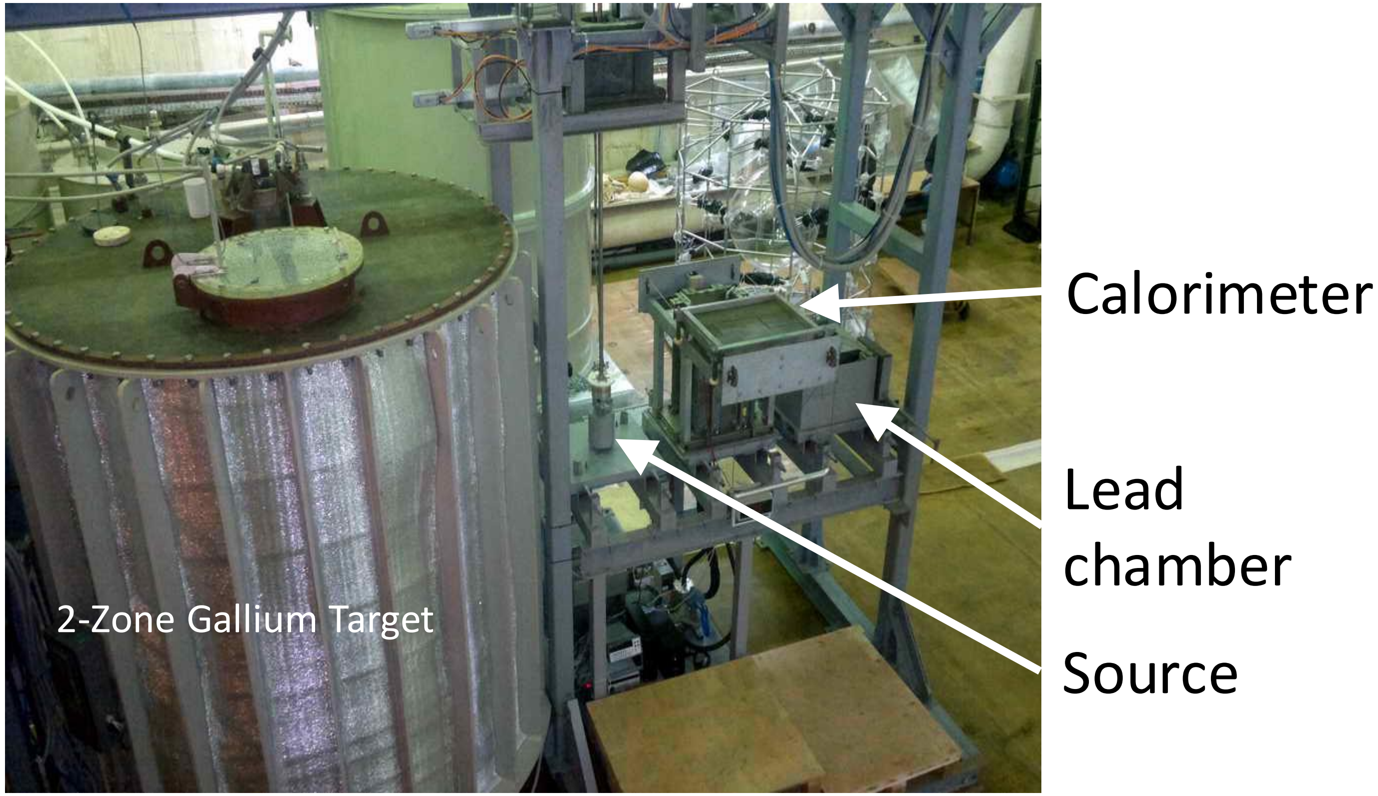


BEST Schedule

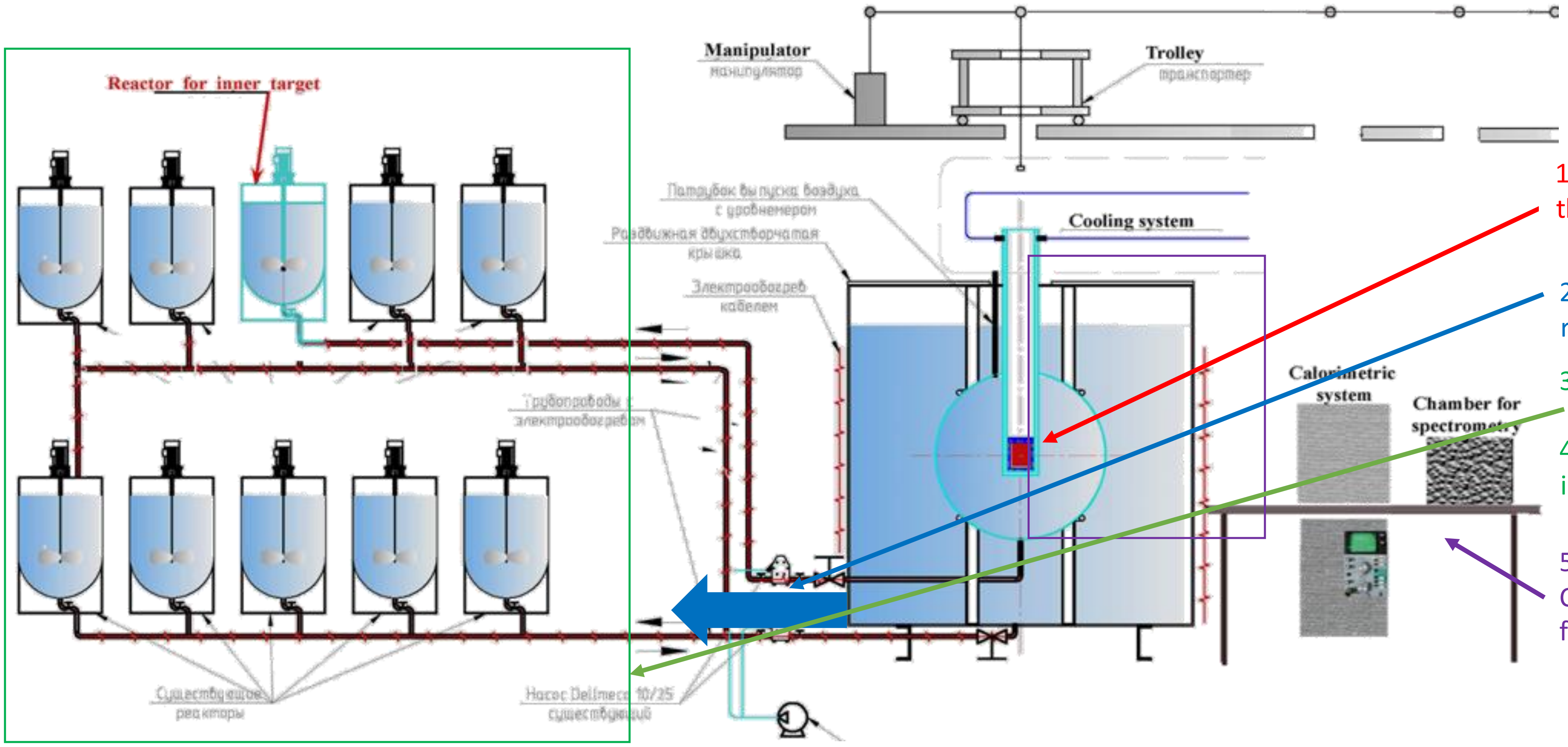
Construction began 2011
Source Arrived: July 5, 2019
Exposures: July 5 – Oct. 13, 2019
Counting: July 16, 2019 – Mar. 20, 2020
Counter Calibration: Mar. 2020 – Jan. 2021
PRL draft posted: Sept. 2021



Construction started in 2011

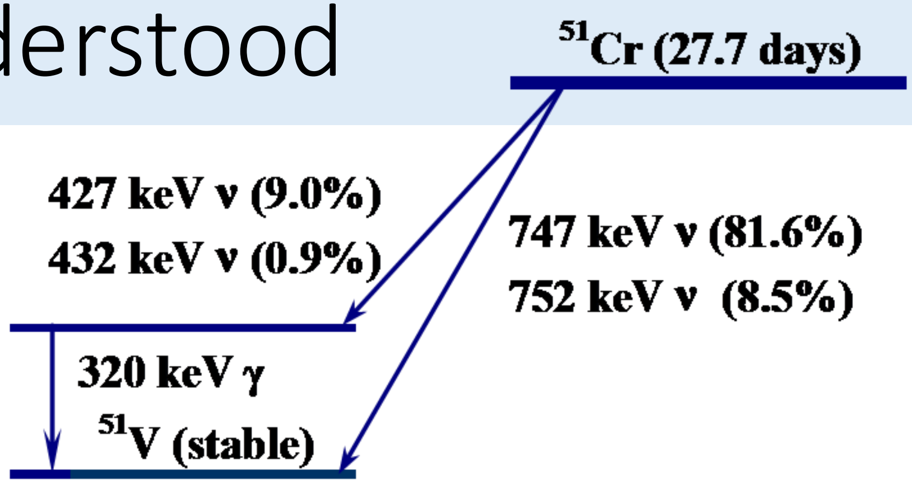


The Operation of BEST

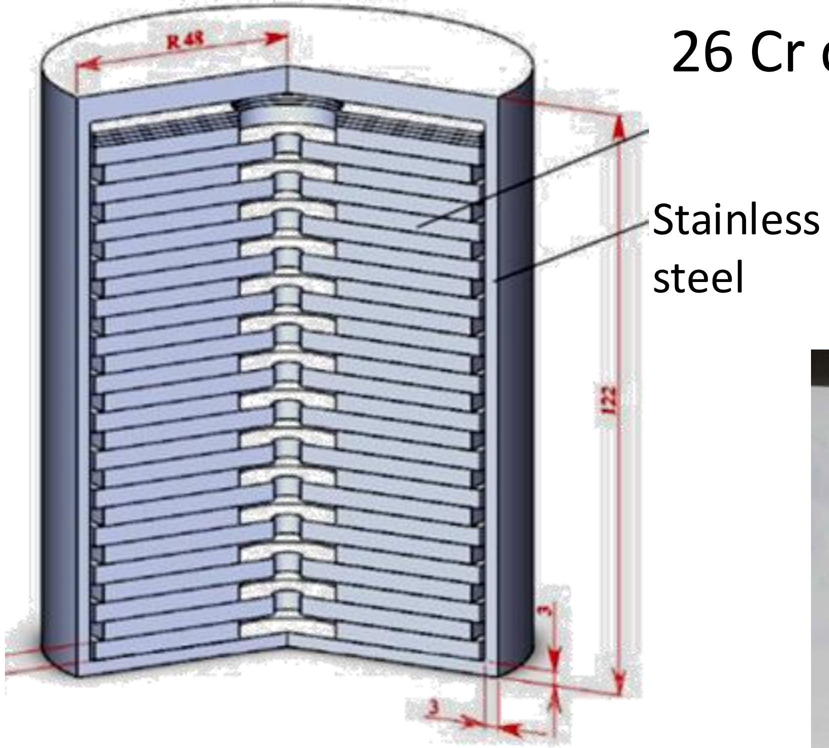


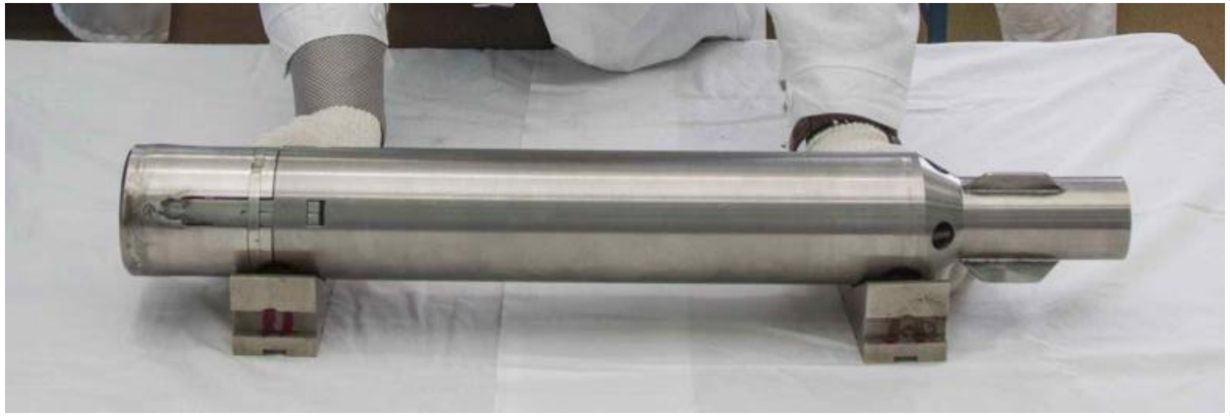
1. Expose gallium targets to the source
   $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
2. Pump Ga to the chemical reactors
3. ^{71}Ge chemical extraction
4. ^{71}Ge decay measurement in proportional counters
5. Semiconductor & Calorimetric measurement for source activity

The Neutrino Spectrum is Well-Understood



26 Cr disks

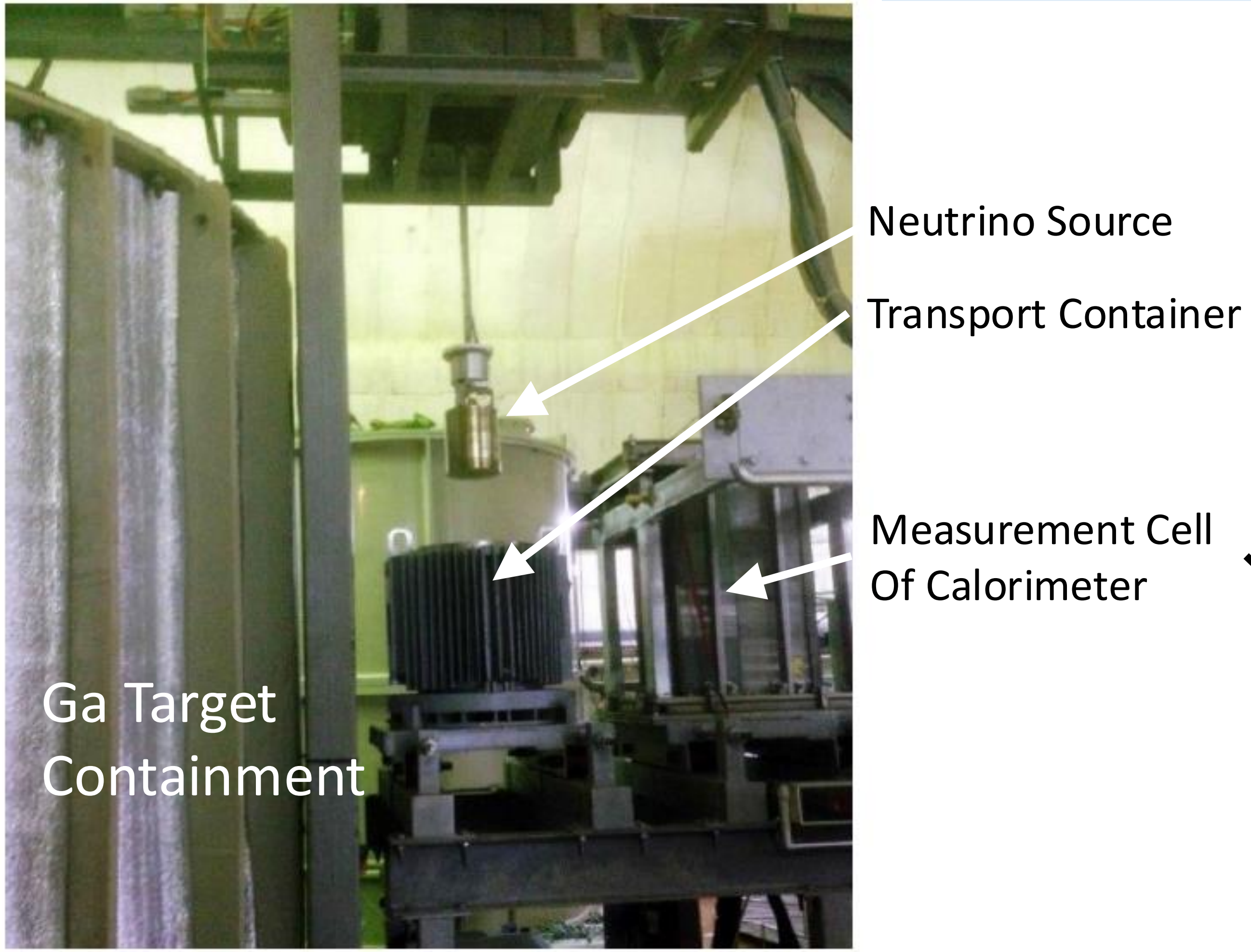




4 kg 97%-enriched ^{50}Cr,
h = 4 mm, ∅ 84 and 88 mm.

Irradiated for ~100 days with thermal neutrons (RIAR, Dmitrovgrad)
Thermal neutron flux density – 5×10^{15} n/(cm^2 s)

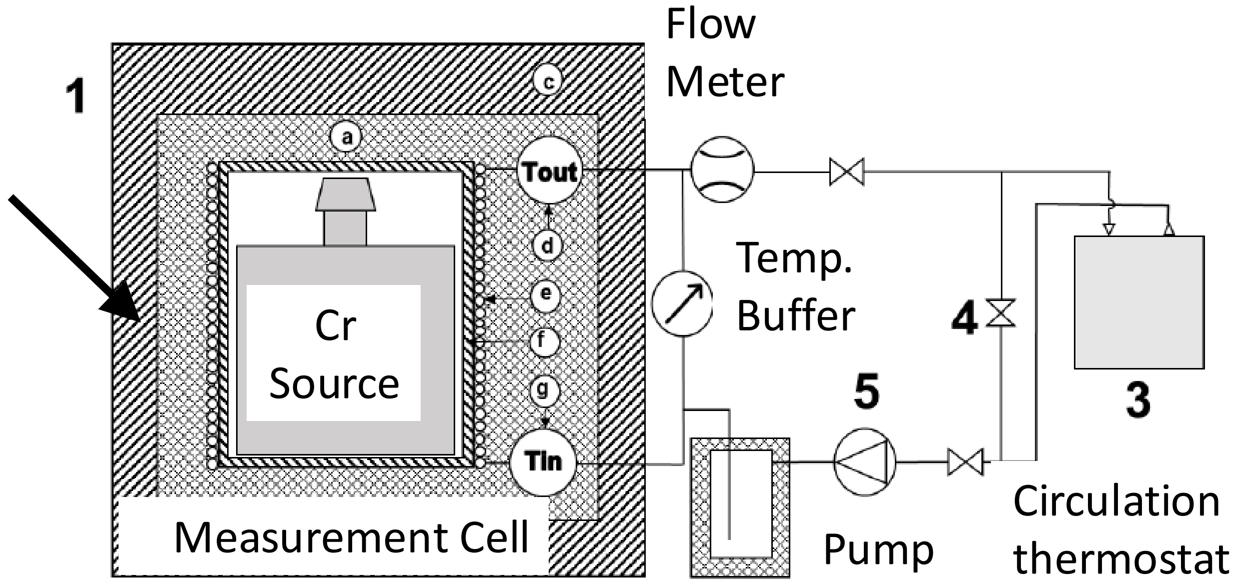
^{51}Cr Source Activity Was 3.4 MCi (JINST 16 (2021) P04012)



Activity at 14:02 on July 5, 2019

A = 3.414 ± 0.008 MCi

Energy/decay = 36.750 ± 0.84 keV



BEST Extraction Procedure (PRC 60 (1999) 055801)

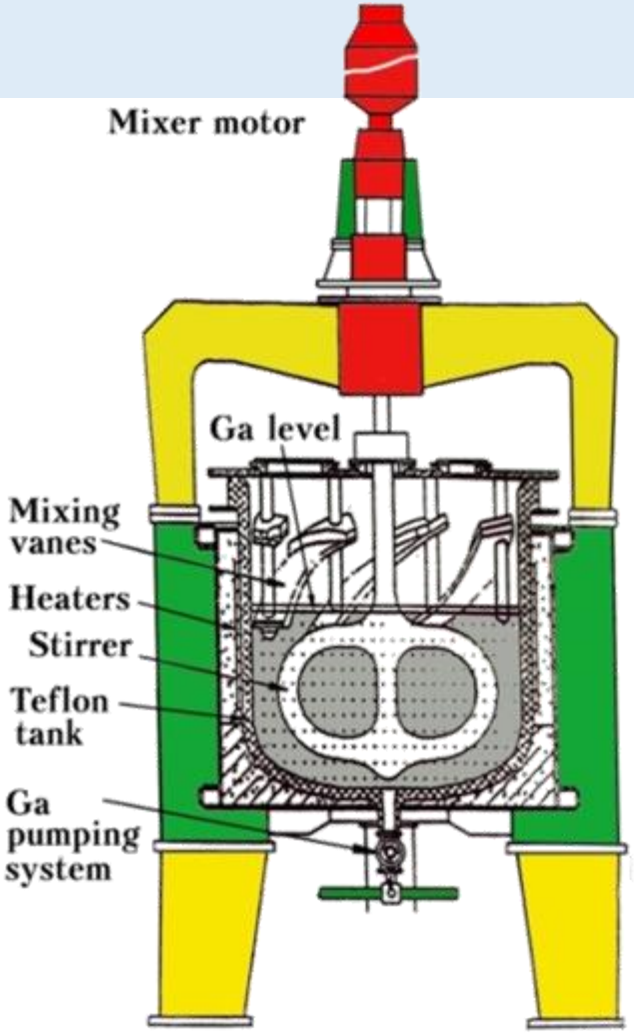
^{71}Ge extraction (30 hours in *total*) :

1) Add Ge carrier to Ga at start of exposure.
2) Pump Ga from each zone to chemical reactors: inner zone → 1 reactor, outer zone → 6 reactors.

2) The Ge is extracted through an oxidation reaction.

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)*



Extraction Efficiency of ^{71}Ge Measured with Ge Carrier

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

Amount of added Ge carriers (about 175 μg):

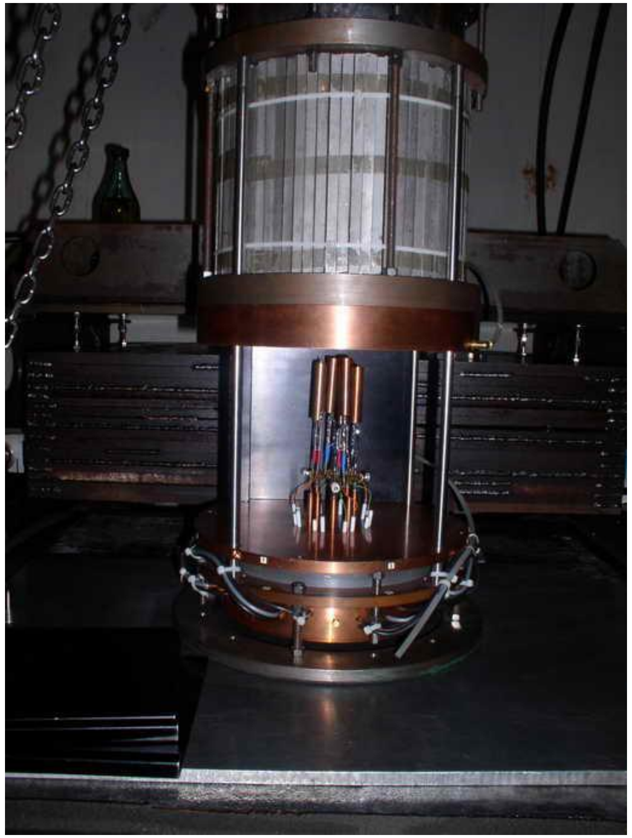
- 2.4 μmol ^{72}Ge (92% isotopic enrichment)
- 2.4 μmol ^{76}Ge (95%)

Mean extraction efficiency from Ga: 98%

Mean overall efficiency (including GeH_4 synthesis): 96%

Fill proportional counter with a Xe-GeH_4 mix

Data Acquisition has Operated for Decades



- Two 8-channel systems
- Xe-GeH_4 gas
- PC contained within NaI well
- PC pulses digitized at 1GHz, 100 MHz bandwidth, 8 bit
- Risetime = 3.5 ns
- 0.37<E<15 keV

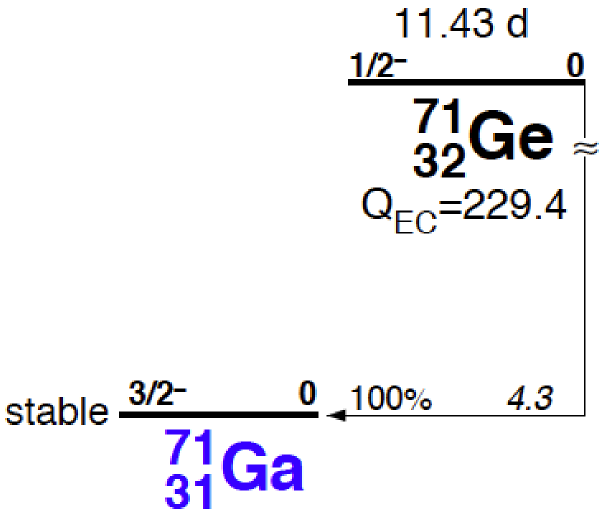
^{71}Ge Decay is Observed

Auger decays produce point-like ionization in gas. In contrast β's or Compton recoils might deposit a similar amount of energy, but over an extended path.

Leads to a pulse shape analysis technique to remove them. BEST fits the pulse waveform.

ADP (Cl expt.): Astrophys. J. 496 (1998) 505
Pulse fit: NIM A290 (1990) 158

- Half-life of 11.43 d, ground state transition
- K Capture (88% of all decays)
  - 41.5% Auger e- 10.367 keV
  - 41.2% Auger e- 1.2 keV & x ray 9.2 keV
  - 5.3% Auger e- 0.12 keV & x ray 10.26 keV
- L and M capture give almost entirely Auger e-
  - L gives 1.2 keV Auger, M gives 0.12 keV Auger
- The proportional counter observes Auger e- with high efficiency
  - The X ray efficiency is much less
  - As a result, the number of K/L peak counts are about equal

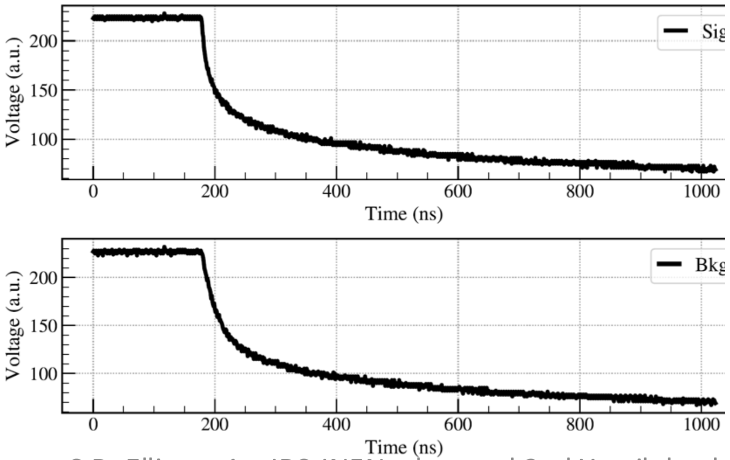


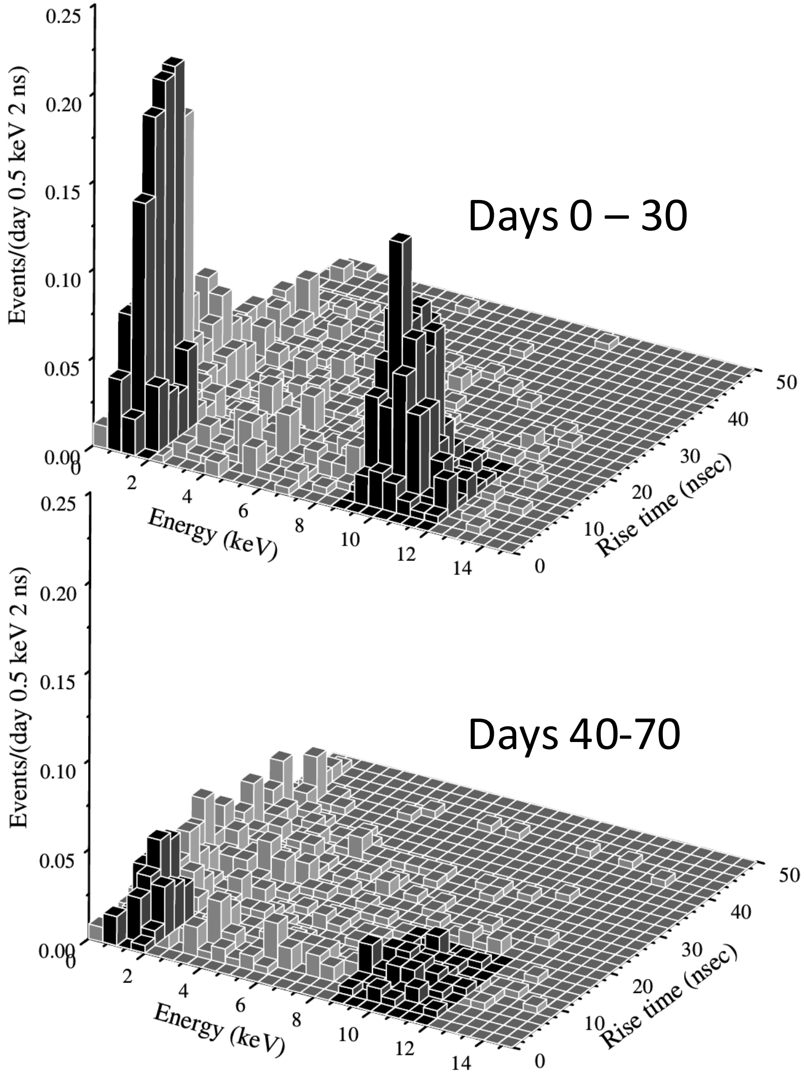
^{71}Ge Candidate Event Selection

- Energy calibration
- Time tagging
  - Periods of expected high background
    - Reject 2.6-hour periods after shield opening for Rn
  - Anti-coincidence with NaI system
  - Pulse shape analysis
    - Alpha-induced events
    - High-voltage breakdowns
    - Compton scattering
    - Beta-induced backgrounds

~1.5 evts /day

Risetime (RT) of the pulses





Likelihood Fit to Candidate Events

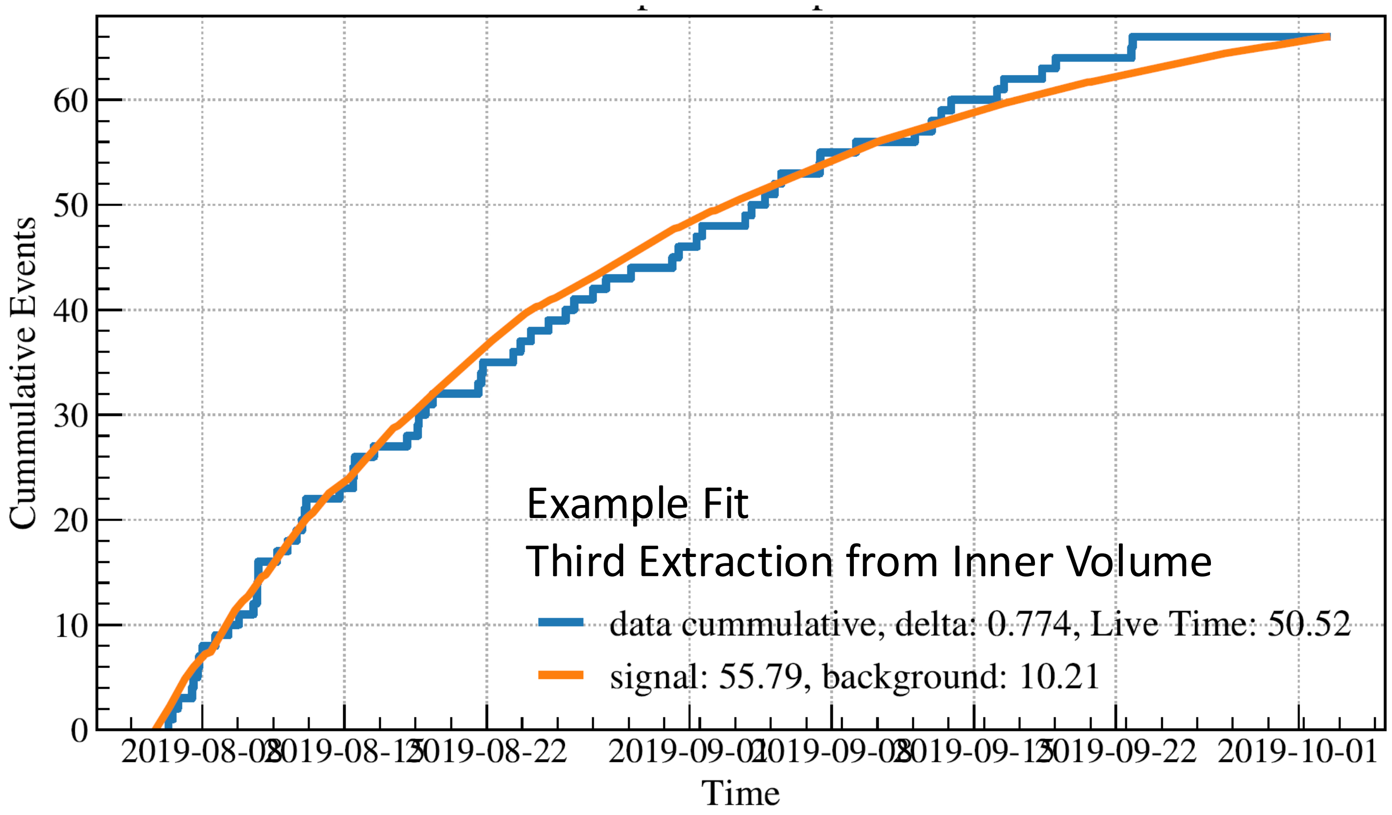
- Maximum likelihood fit to the *t* and *E* dependence of each candidate event

$$\mathcal{L} = e^{-p\epsilon\Delta/\lambda - b\tau} \prod_{i}^{l} \left[\frac{w_p(E_i)}{w_b(E_i)} p\epsilon e^{-\lambda t_i} + b\right]$$

(PRC 60, 055801 (1999))

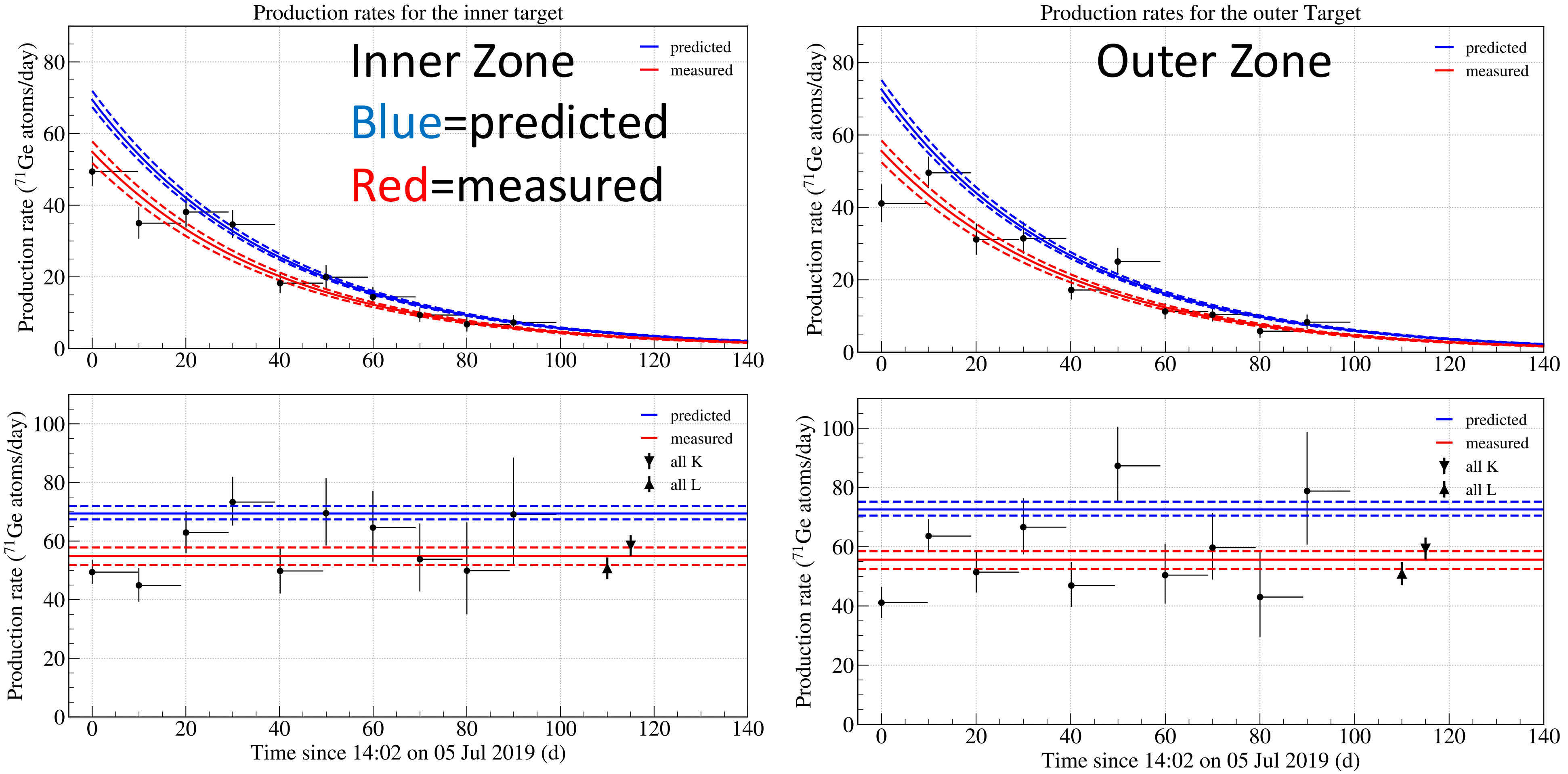
p: ^{71}Ge production rate, 11.4-d half-life
b: background rate, constant in time
ϵ: overall efficiency
$w_p(E)$ /$w_b(E)$: energy weight factors
Δ: probability an event will during counting
τ : total counting time

* Weight factors are determined by examining the energy spectra for each counter



Counting Results: Ten 10-day exposures of each zone

Perform Exposures until Cr has decayed away.



Predicted Production Rate well Known

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

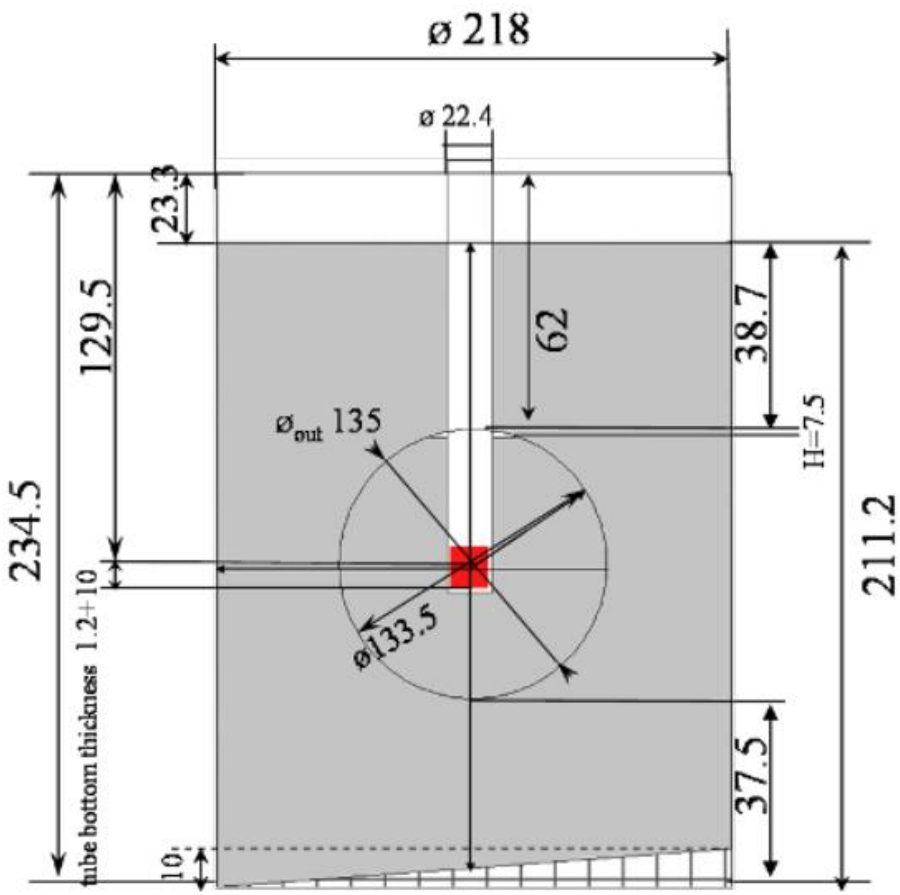
${}^{71}\mathrm{Ge} + e^- \rightarrow {}^{71}\mathrm{Ga} + \nu_e$

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	%
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



Predicted vs. Measured Production Rates (BEST PRC, old σ)

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	$55.6^{+2.6}_{-2.7}$

	IN	OUT
Predicted	$69.41^{+2.5}_{-2.0}$	$72.59^{+2.6}_{-2.1}$
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

Result can be Interpreted as Oscillation

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

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

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

For the Ga source experiments, the cross section uncertainties are the only significant contribution to the correlated uncertainty.

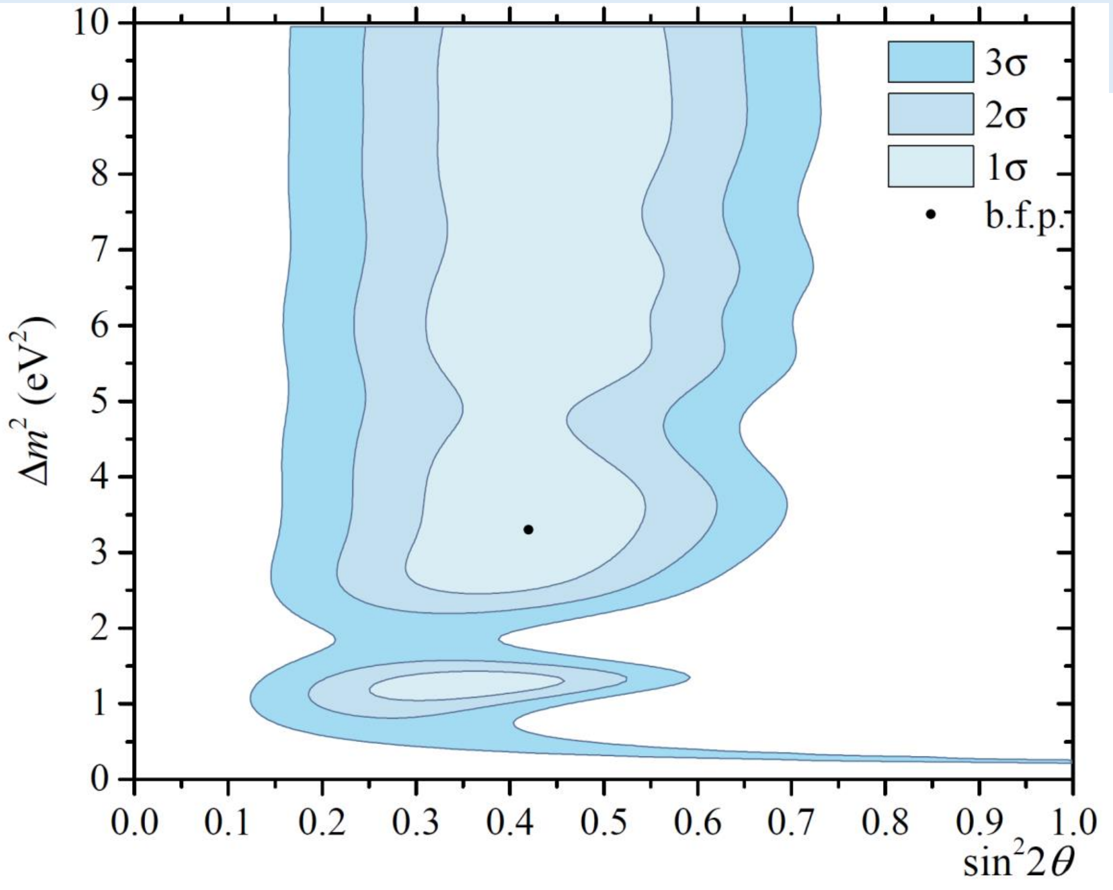
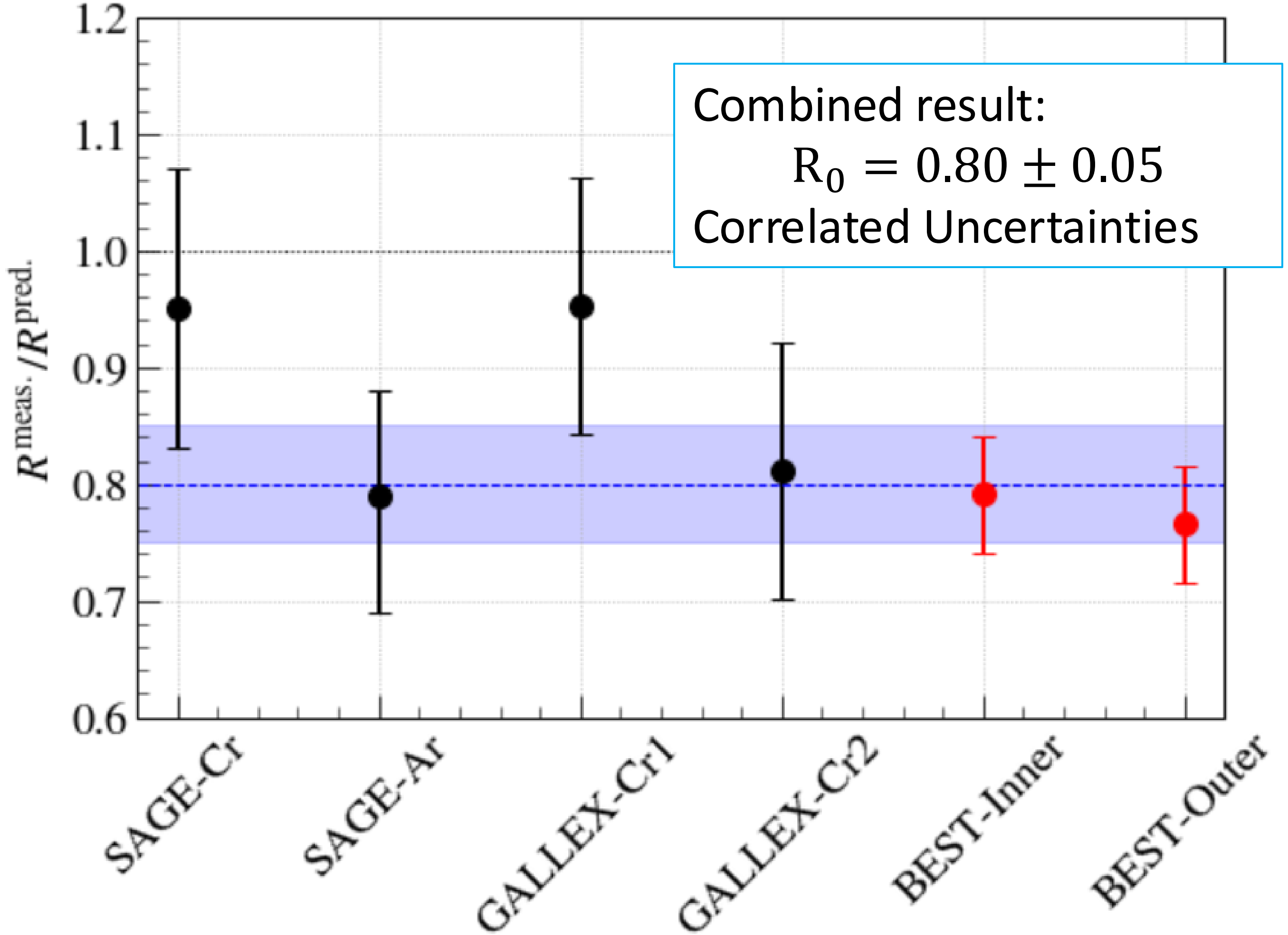


FIG. 7. Allowed regions for two BEST results. The best-fit point is $\sin^2 2\theta$=0.42, Δm^2 = 3.3 eV^2 and is indicated by a point.

Combined Analysis with Other Ga Source Experiments



Combined result:

$R_0 = 0.80 \pm 0.05$

Correlated Uncertainties

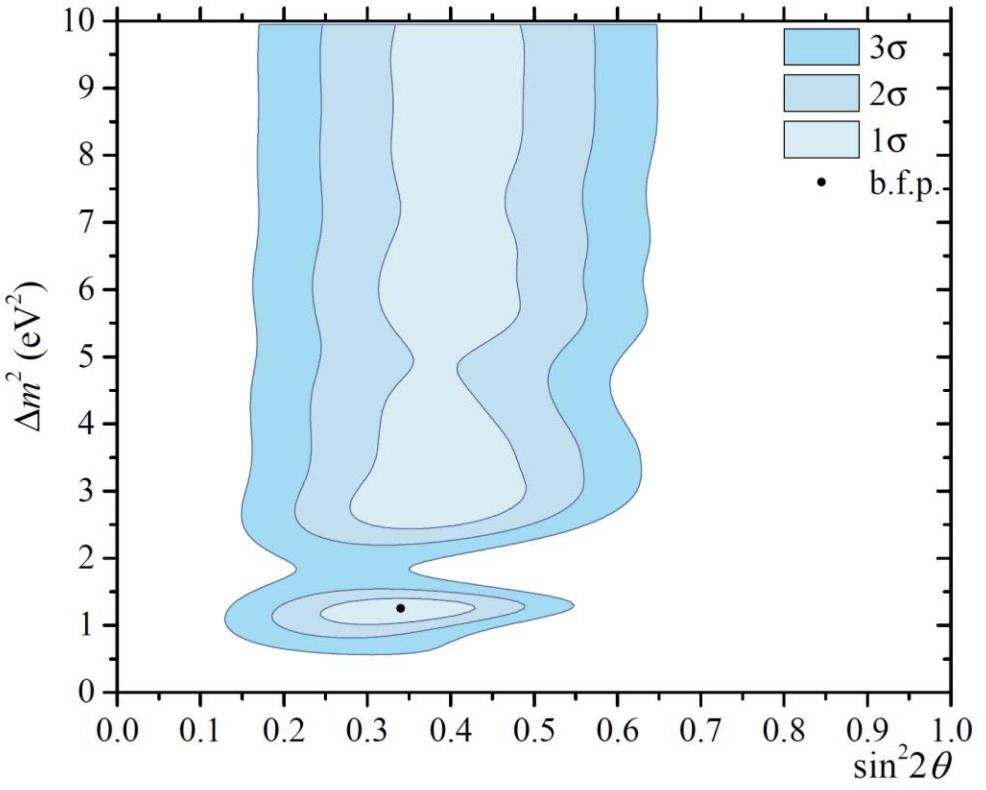
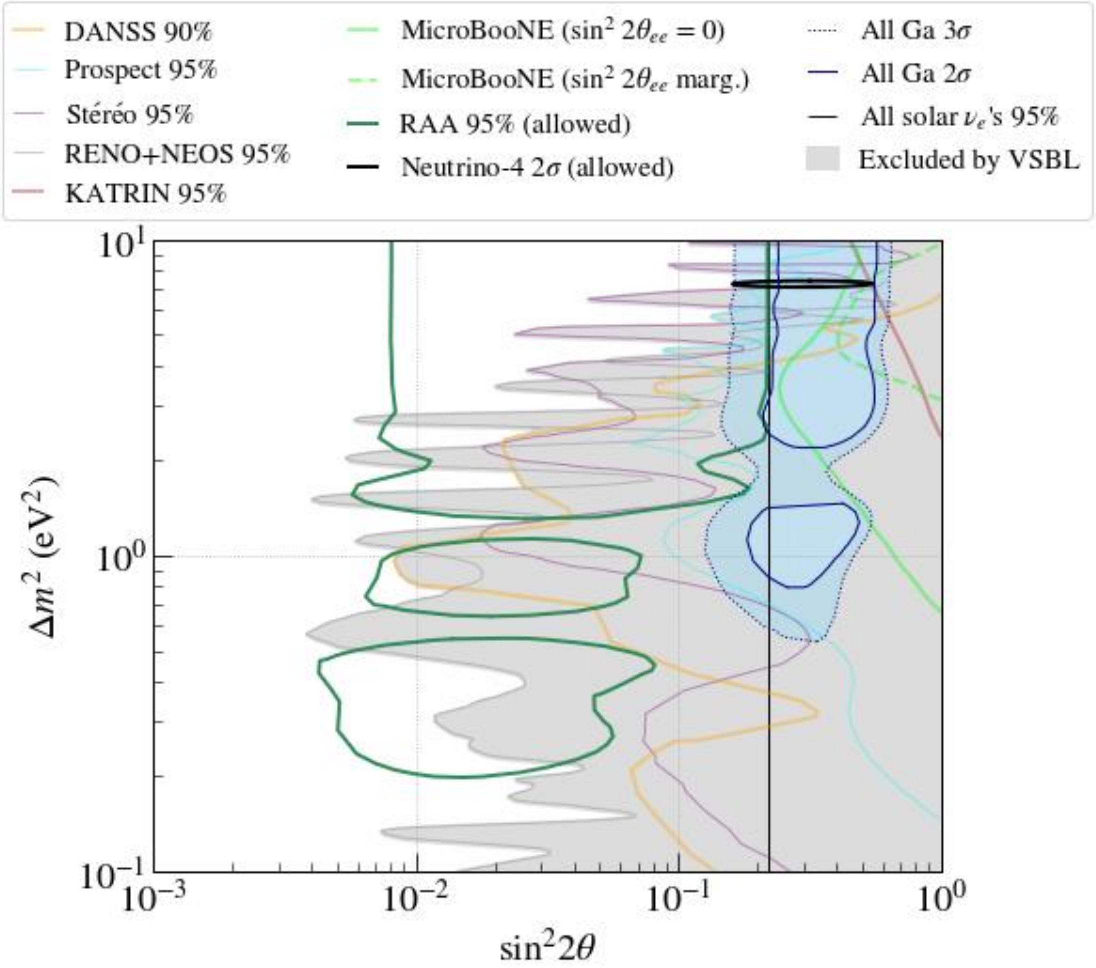


FIG. 8. Allowed regions for two GALLEX, two SAGE and two BEST results. The best-fit point is $\sin^2 2\theta$=0.33, Δm^2 = 1.25 eV^2 and is indicated by a point.

Tension with Comparison to Other Oscillation Results



Clear tension between the numerous results.

BEST Best-fit point

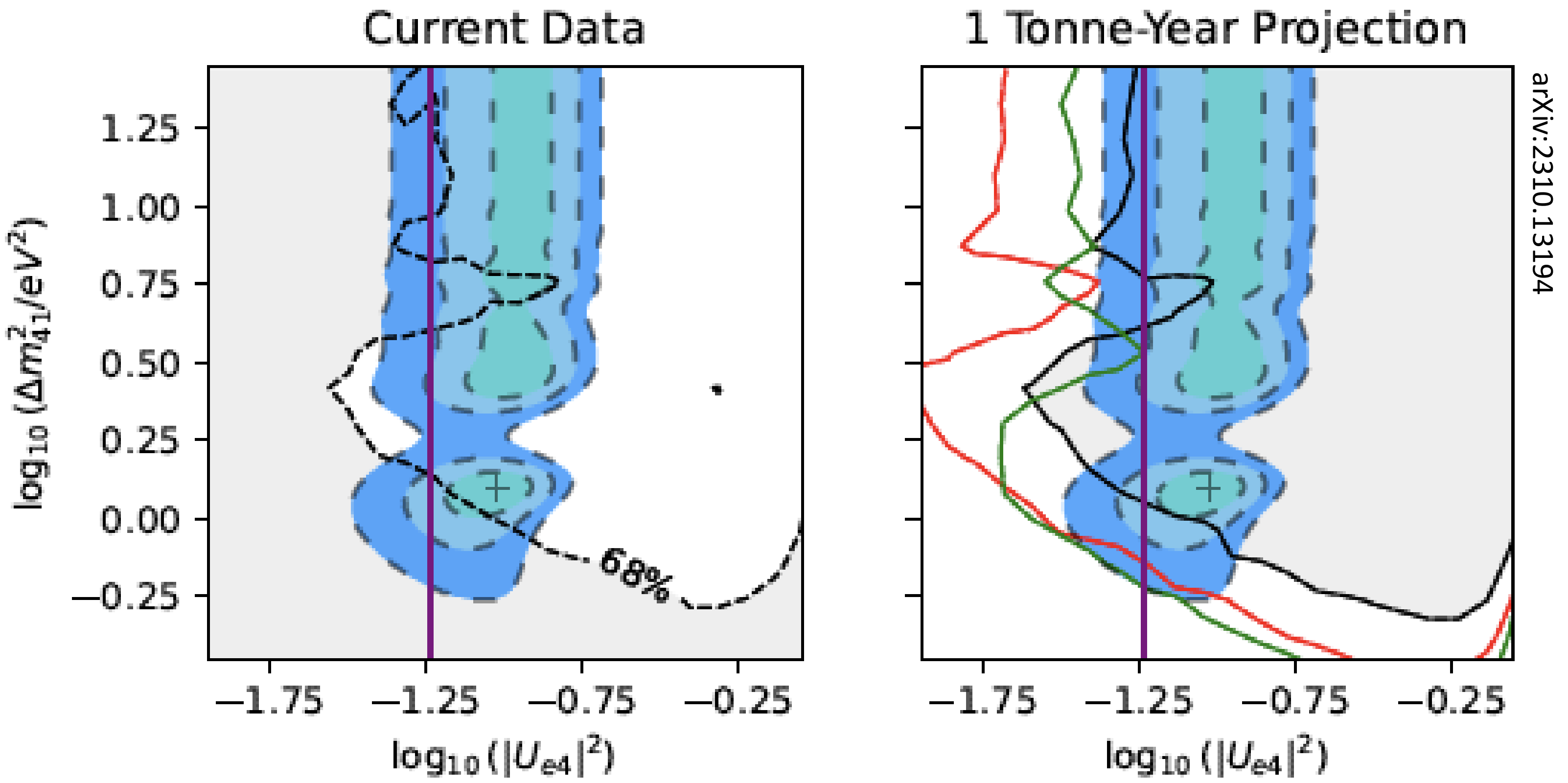
$$\Delta m^2 = 1.25$$

$$\sin^2 2\theta = 0.34$$

DANSS: Int. J. Mod. Phys. A **35**, 2044015 (2020)
Prospect: PRD **103**,032001 (2021)
Stereo: PRD **102**, 052002 (2020)
RENO+NEOS: arXiv:2011.00896 (2020)
KATRIN: PRL **126**, 091803 (2021)
MicroBooNE: arXiv:2111.10359
RAA: PRD **83**, 073006 (2011)
Neutrino-4: JETP Lett. **112**, 199 (2020)
Model indep. solar: PLB **816**, 136214 (2021)

Recent Analysis of Coherent Scattering

- Not very statistically compelling.
- But interesting and more results will come.
- Used CsI results from COHERENT.



Inclusion

Exclusion

Result Consistent with, but not Proof of, Oscillations

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

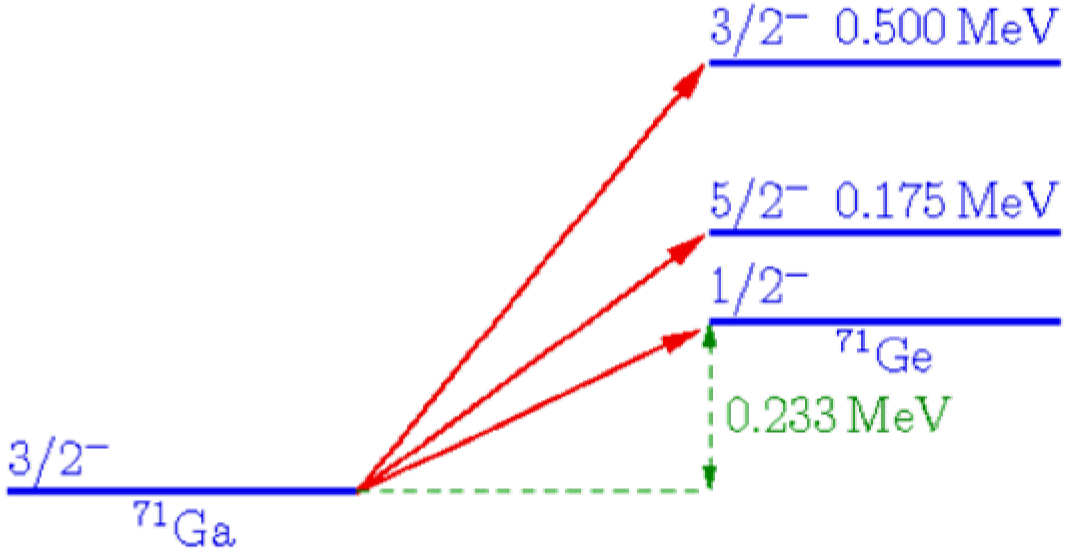
But no dependence on oscillation length was observed. So although the results are consistent with oscillations, there is no ‘smoking gun’ evidence that is not subject to caveats.

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

The Cross Section is Well Known

- 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.
- Recently much better charge exchange measurements have become available. (PLB 706 (2011) 134, PLB 722 (2013) 233, PRC 91 (2015) 034608)
- Bahcall's result is at the average of the two methods with an uncertainty that encompasses both, so BEST used that value. 5.81×10^{-45} cm^2



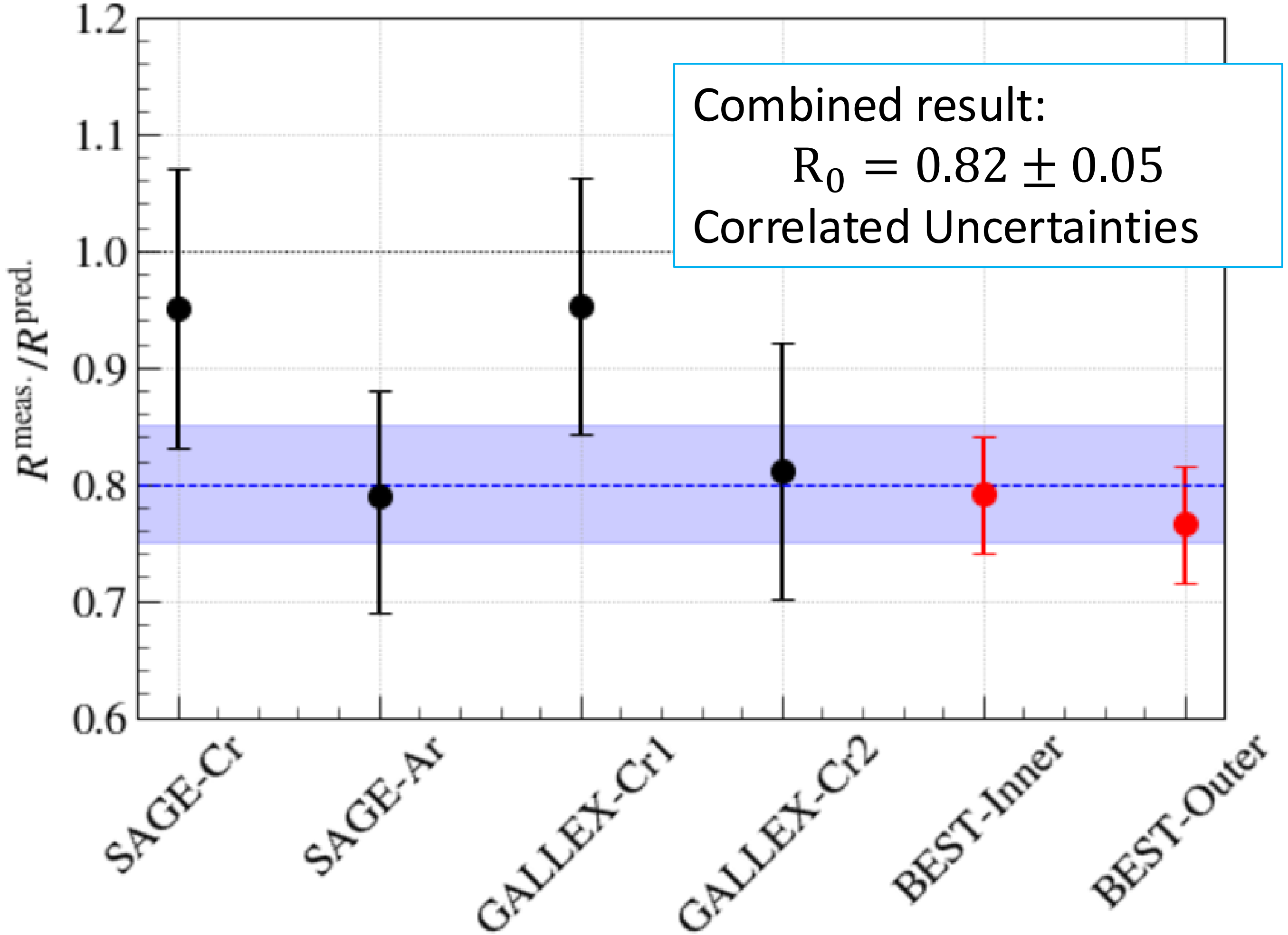
^{51}Cr and ^{37}Ar ν's can only excite first 3 levels in ^{71}Ge.

Haxton and Rule Updated Cross Section (PRC 108 (2023) 035502)

$$\sigma_{\rm gs} = \frac{G_F^2 \cos^2\theta_C}{\pi} p_e E_e \mathcal{F}(Z_f, E_e)\, g_A^2\, \tilde{\mathrm{B}}_{\mathrm{GT}}^{(\nu,e)}(\mathrm{gs})\, \frac{[1+g_{v,b}]_{(\nu,e)}}{[1+g_{v,b}]_{EC}}\, [1+\epsilon_q].$$

- Recent re-examination of the cross section and its uncertainties.
- Considered effects not previously evaluated, weak magnetism, non-universality in radiative corrections. These turned out to be small (~0.5% each).
- Developed shell-model technique to estimate the interference between Gamow-Teller and Tensor contributions to the charge exchange measurements. This is critical when the GT strength is small – like the case of ^{71}Ga.
  - Compared to experimental cases of (p,n) and beta decay amplitudes.
  - Found $(5.69^{+0.28}_{-0.06})$x10^{-46} cm^2 compared to Bahcall $(5.81^{+0.21}_{-0.16})$x10-^{46} cm^2.
  - Agrees to 1σ.

Combined Analysis after Small Update of σ.



Combined result:

$$R_0 = 0.82 \pm 0.05$$

Correlated Uncertainties

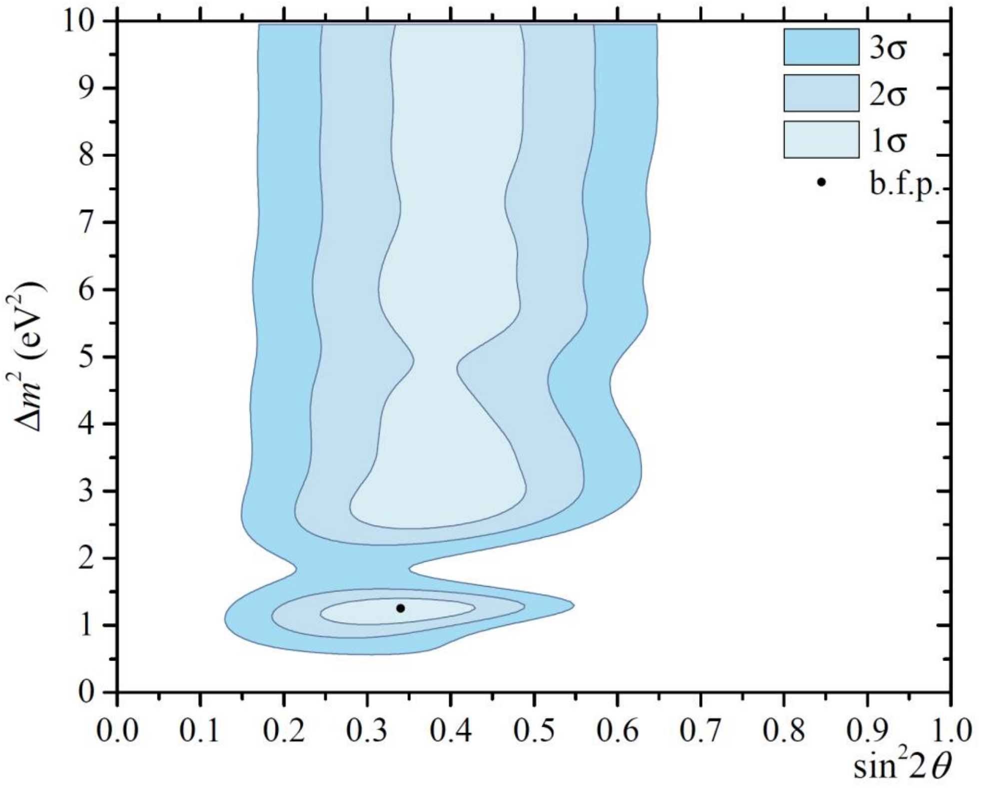


FIG. 8. Allowed regions for two GALLEX, two SAGE and two BEST results. The best-fit point is $\sin^2 2\theta$=0.33, Δm^2 = 1.25 eV^2 and is indicated by a point.

SAGE Extraction Efficiencies are Well Known (PRC 73 (2006) 045805)

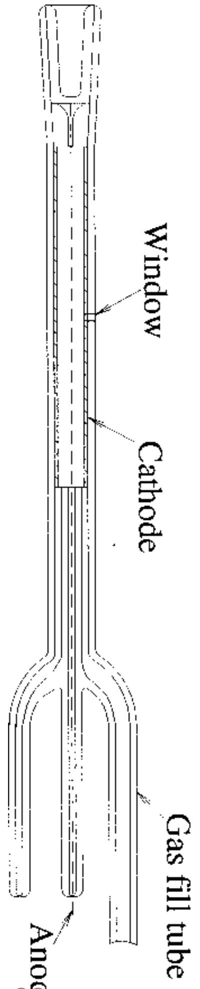
- A variety of extraction efficiency tests have been done – all consistent with experimental values. (PRC 60 (1999) 055801)
- $^{70,72}Ga$ radioactive isotopes produced by neutron activation were included with the carrier. Extraction of the Ge isotopes resulting from their decay was as expected. Tests 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 sample of carrier doped with ^{71}Ge was produced and the measured extraction efficiency was as expected from the stable carrier determination.

GALLEX Also did Extraction Efficiency Tests (Phys. Lett. B436 (1998) 158)

- GALLEX also did a variety of extraction efficiency tests – all consistent with experimental values.
- A known amount of ^{71}As was added to the Ga. The ^{71}As (2.72 d) decays to ^{71}Ge, which is then extracted and counted. The extraction was 100±1% validating the procedures.
- Rules out 'hot atom' effects.

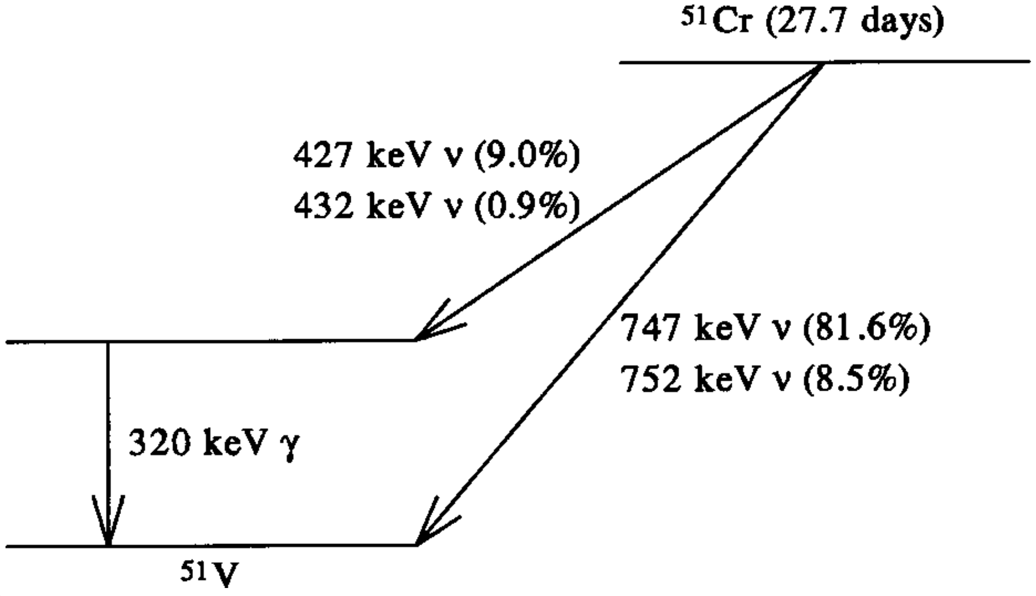
Counting Efficiencies are Well Determined (PRC 60 (1999) 055801)

- Counter efficiencies were cross checked several ways.
- Volume efficiency checked with ^{37}Ar loaded counter gas
- L- & K-Peak Efficiencies with ^{69}Ge and ^{71}Ge loaded counter gas.



Source Strength is Well Measured

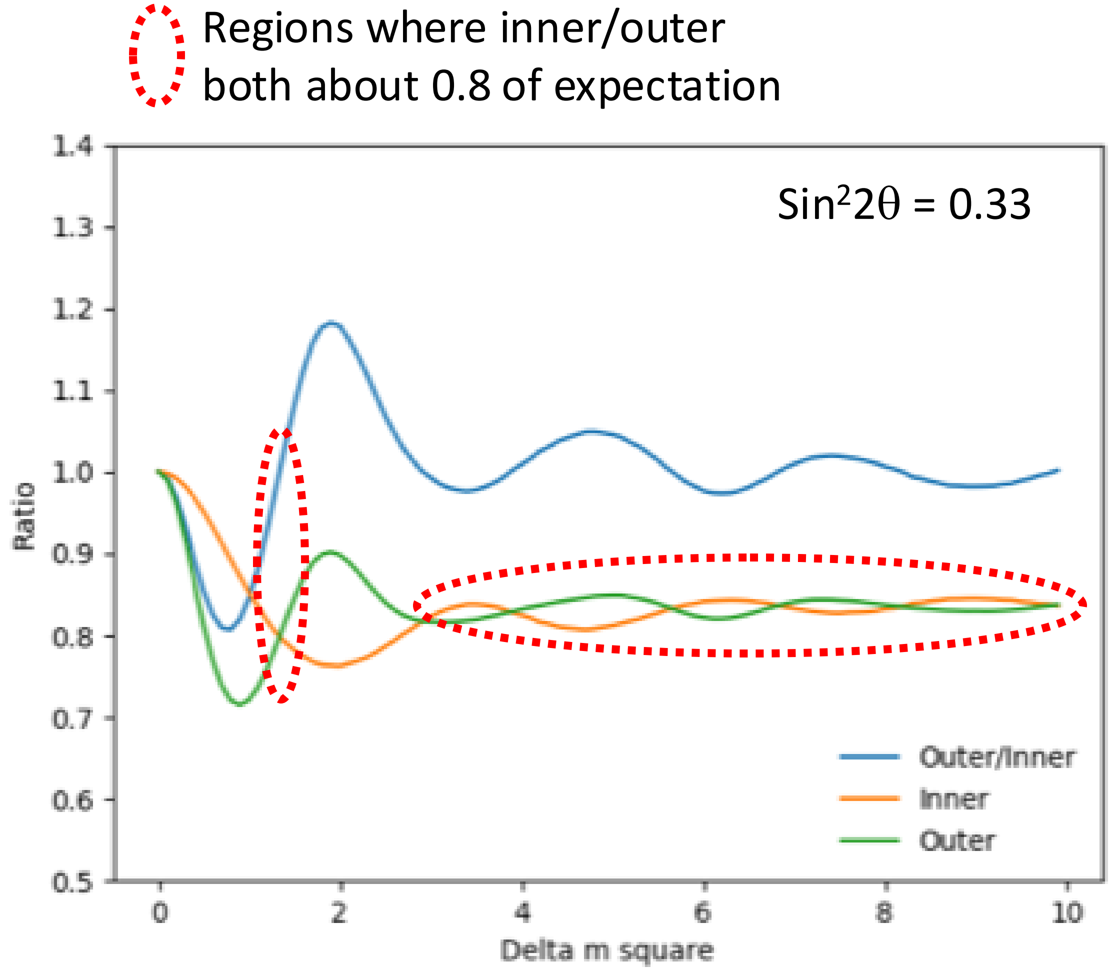
- The activity measurement precision is best from calorimetry.
- This technique has been confirmed by other estimates building confidence. (PRC 59 (1999) 2246)
  - Direct counting of 320-keV line with Ge detector.
  - Reactor physics and neutron transport.
- Cr decay scheme.
  - The branching ratio to 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.



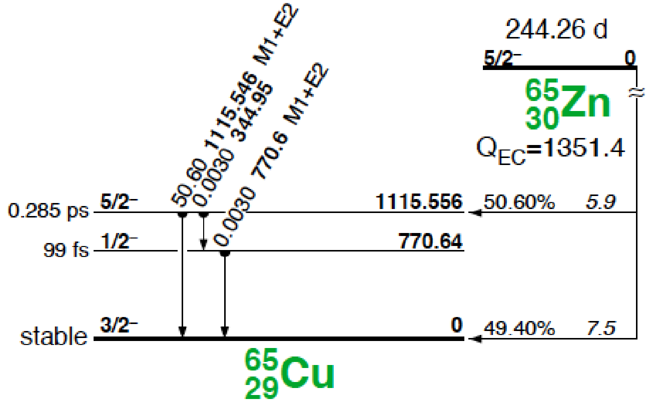
Higher Energy Source Could Probe Shorter L_{OSC}

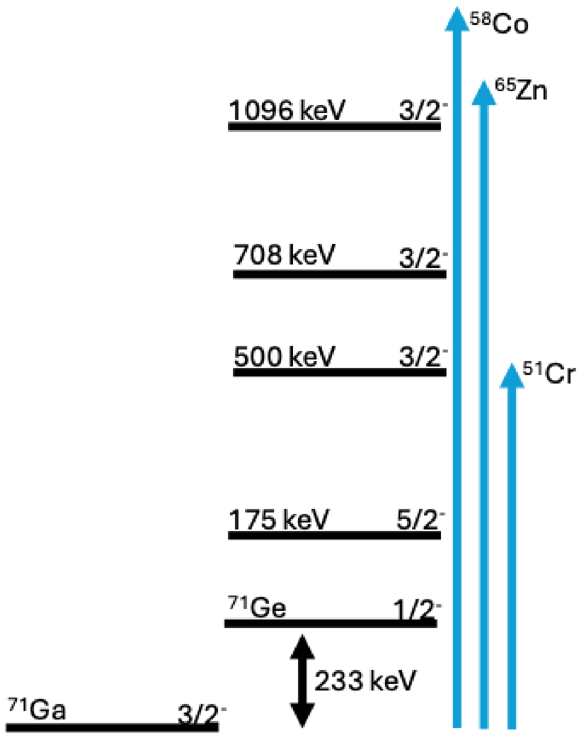
If oscillations, the oscillation length is short (large Δm^2). BEST has poor Δm^2 resolution for values greater than ~2 eV^2.

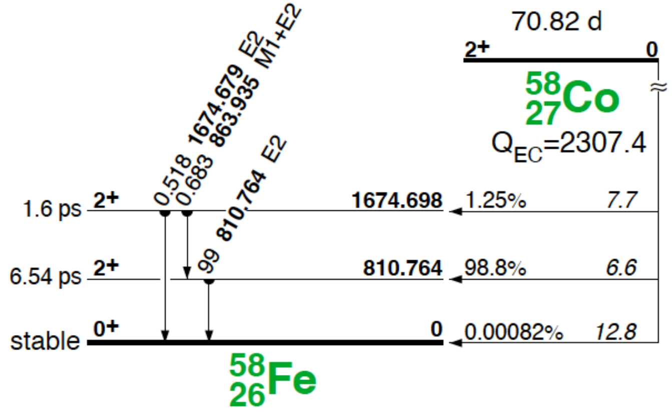
- Smaller inner volume probably not feasible.
  - Half the volume, need 8x the source strength.
- ^{65}Zn Source (PRD 97 (2018) 073001)
  - Higher energy source (1.35 MeV vs. 0.75 MeV).
  - Almost twice the cross section.
    - But adds excited states.
  - About 9x longer half life (244 d), many more events.



Co and Zn Provide Higher Energies, Longer Lifetimes







ν energies: 1351 keV (47.8%, small β⁺ branch)
The ν at 235.8 keV produces negligible ^{71}Ge
Irradiate for 295 d 32 kg ^{64}Zn, 94% enriched
Results in ~330 kCi
The 1115-keV γ will require shielding
(arXiv:1807.02977; PRD 97 (2018) 073001)

ν energies: 1497 keV (98.8%)
With a rare branch at 633 keV (1.2%)
Irradiate for 70 d ^{58}Ni(n,p)^{58}Co
Results in ~400 kCi
Small amount of ^{60}Co produced
These and the ^{58}Co γs require a thick shield

But more excited states contribute to cross section.

Summary: see arXiv:2109.11482

- BEST measured the ^{71}Ge production in Ga from neutrinos emitted by ^{51}Cr at two distances.
- The ratio of the measured-to-predicted rates in both the inner and outer zones are depressed by about 20% from unity. The ratio-of-ratios is ~1.
- The Ga Anomaly is reaffirmed.
- No dependence on oscillation length was observed.