Towards Resolving the Gallium Anomaly

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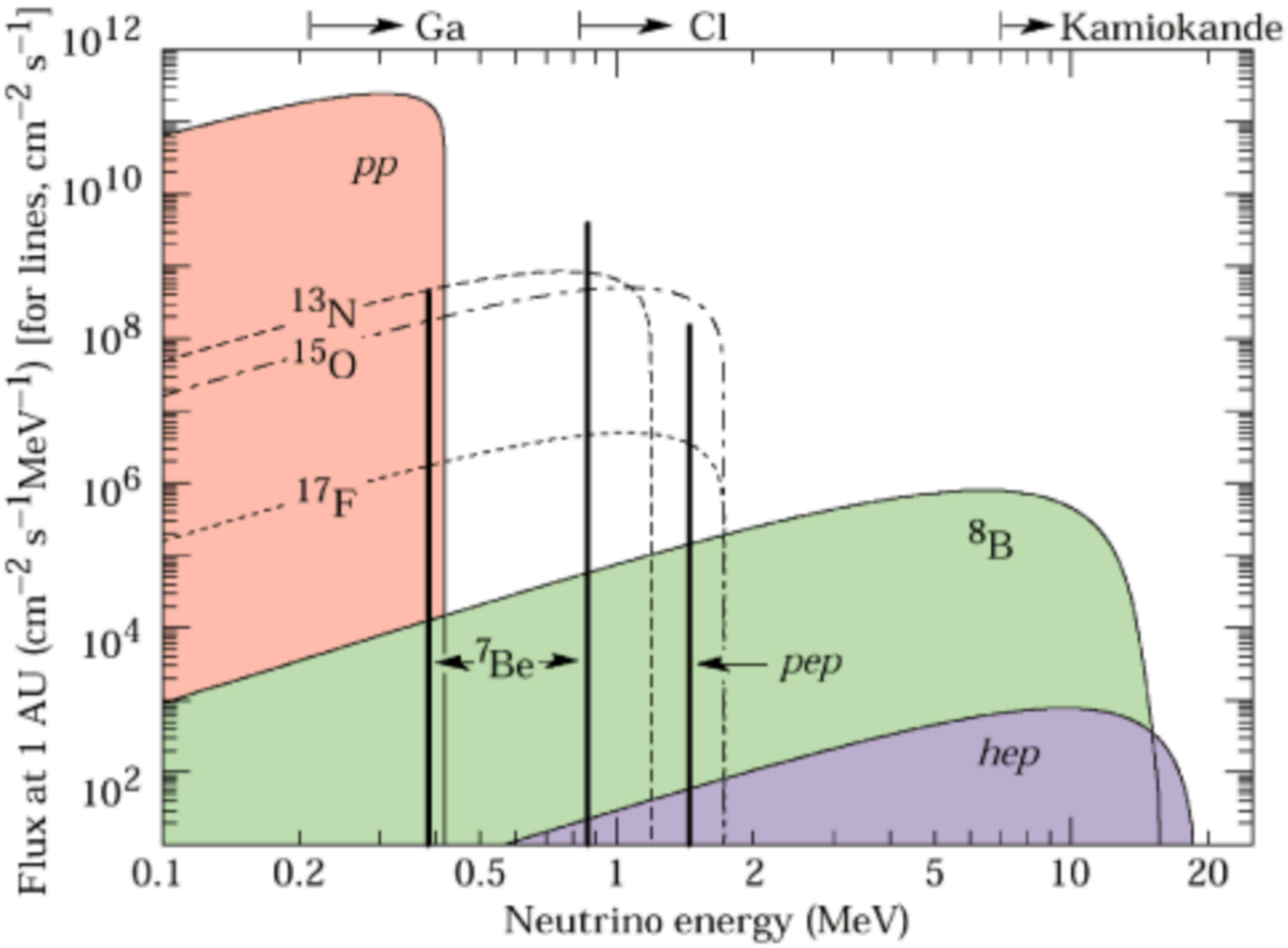
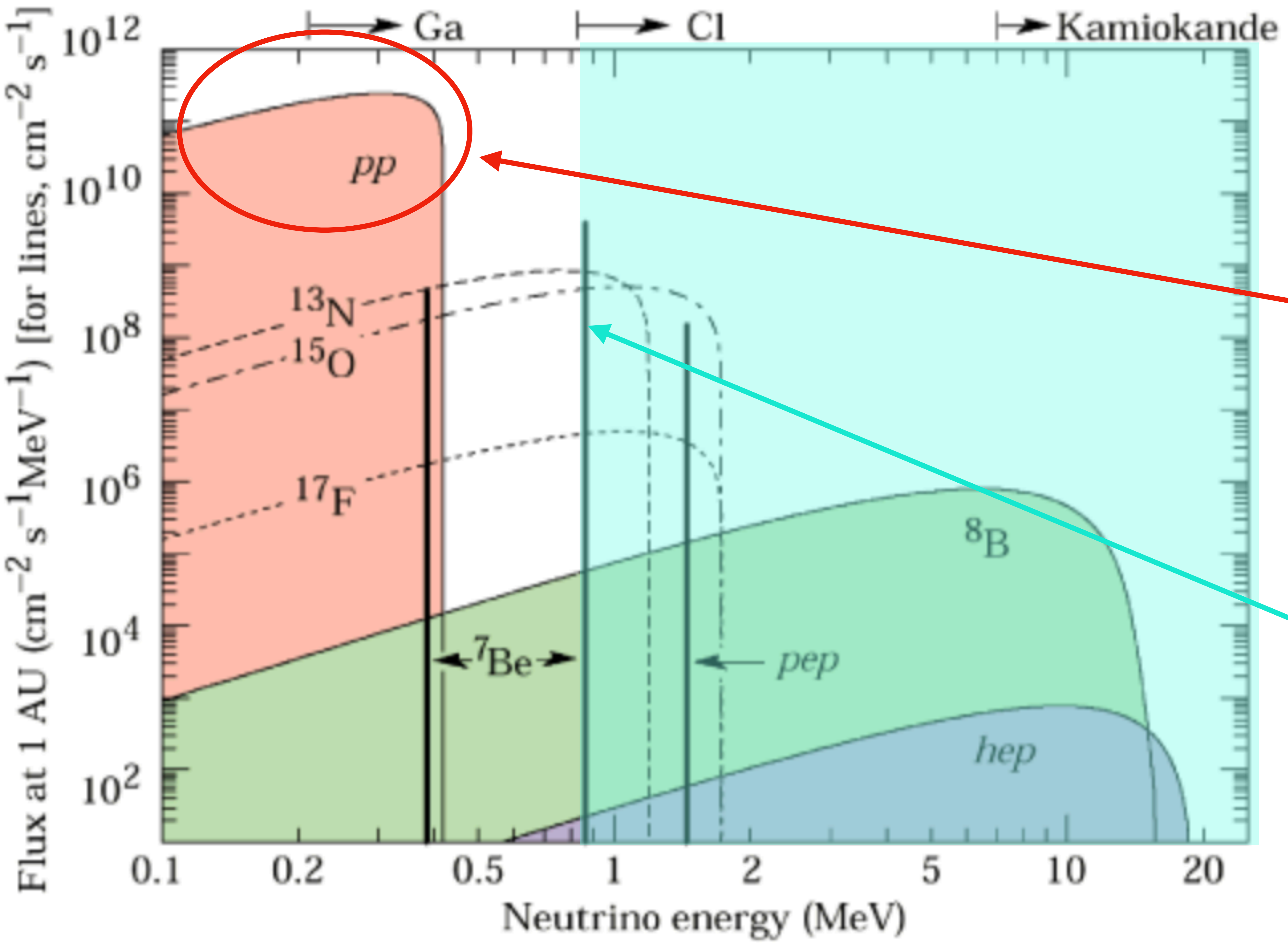
Solar neutrinos



Want to detect all components of the solar neutrino flux to probe our understanding of neutrino physics and solar processes

Solar neutrinos



Want to detect all components of the solar neutrino flux

91% of solar neutrino flux are low energy pp flux from primary pp fusion

Reach of Ray Davis' solar neutrino experiment using Cl

$$\nu_e + ^{37}\mathrm{Cl} \rightarrow ^{37}\mathrm{Ar}^{+} + e^{-}$$

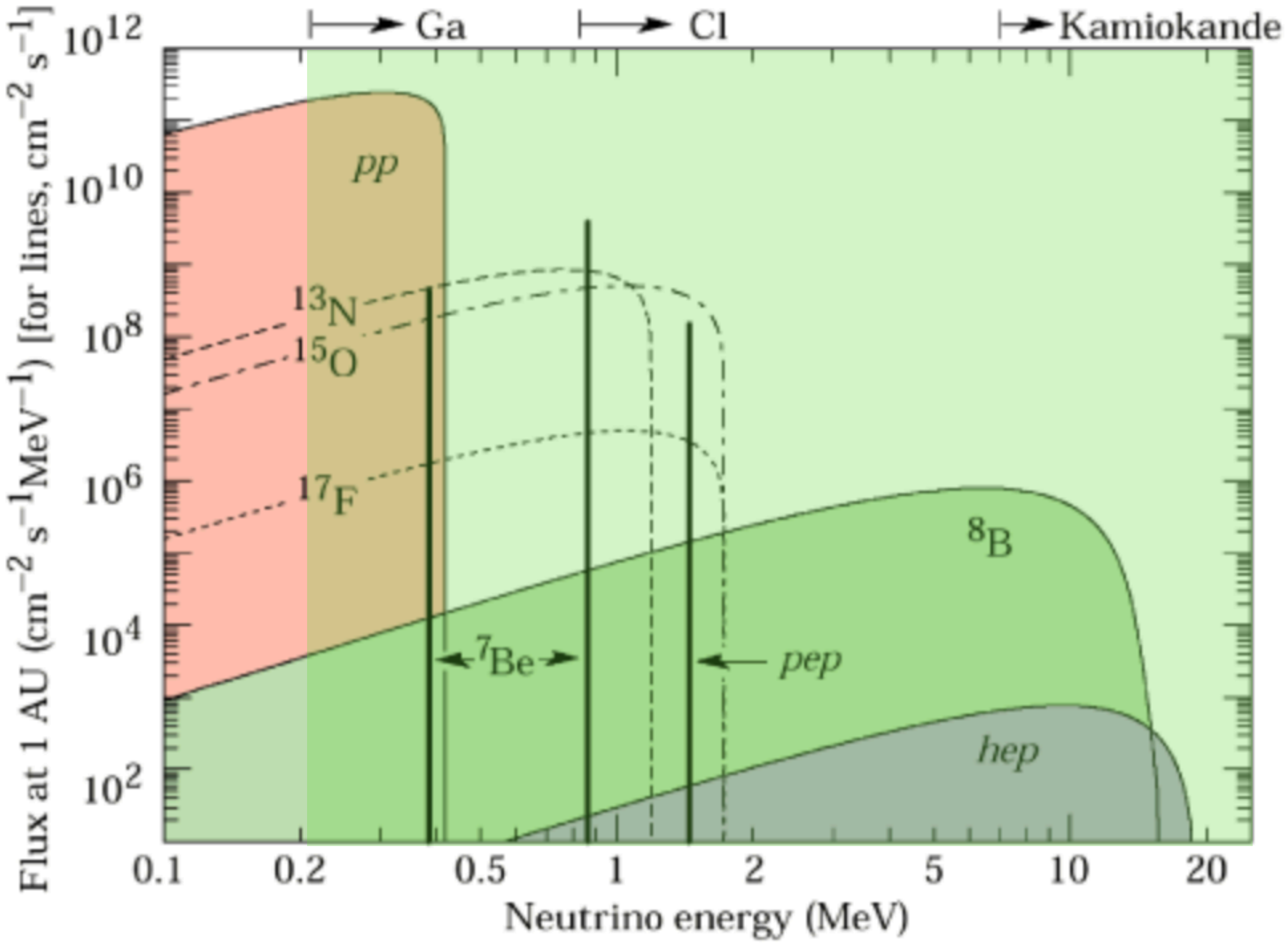
with reaction threshold of 0.8 MeV

Solar neutrinos

Need another experiment with lower threshold to detect pp neutrinos

Use $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$
with reaction threshold of 233 keV!

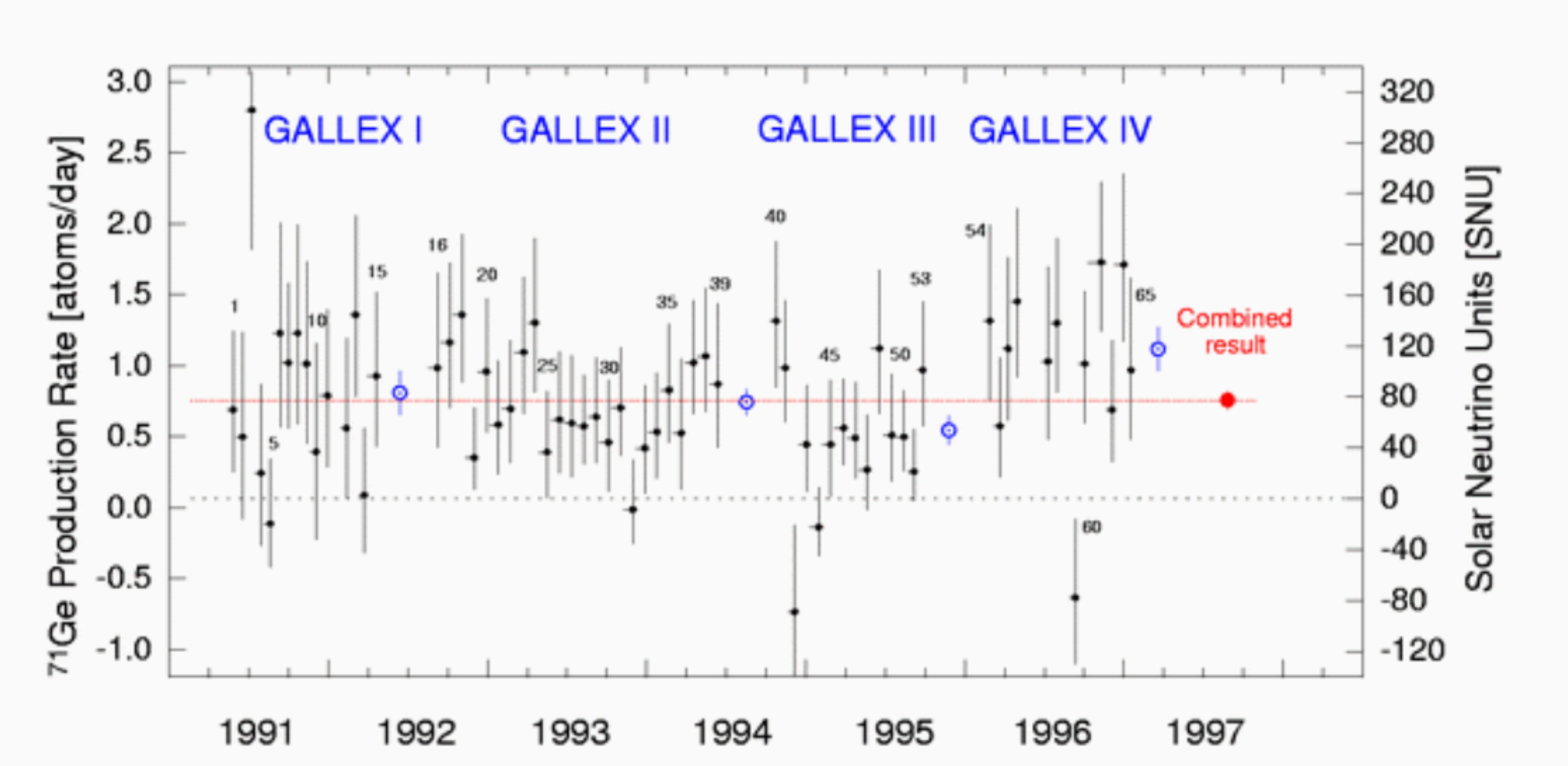
"Gallium experiments"



Solar neutrinos

First detection of pp solar neutrinos with GALLEX, SAGE in 1992

[GALLEX, SAGE '92 '92]



Solar neutrinos

First detection of pp solar neutrinos with GALLEX, SAGE in 1992

[GALLEX, SAGE '92 '92]

Confirmation of solar model and neutrino flavor transition in Sun

Only fraction of electron neutrinos produced in the Sun arrive as electron neutrinos at Earth!

Gallium experiments

Calibration of GALLEX, SAGE experiments with radioactive sources ^{51}Cr

Place source inside of detector, measure number of emitted neutrinos, compare to theory prediction

Gallium experiments

Calibration of GALLEX, SAGE experiments with radioactive sources ^{51}Cr

Place source inside of detector, measure number of emitted neutrinos, compare to theory prediction

Ratio of measured to predicted rate

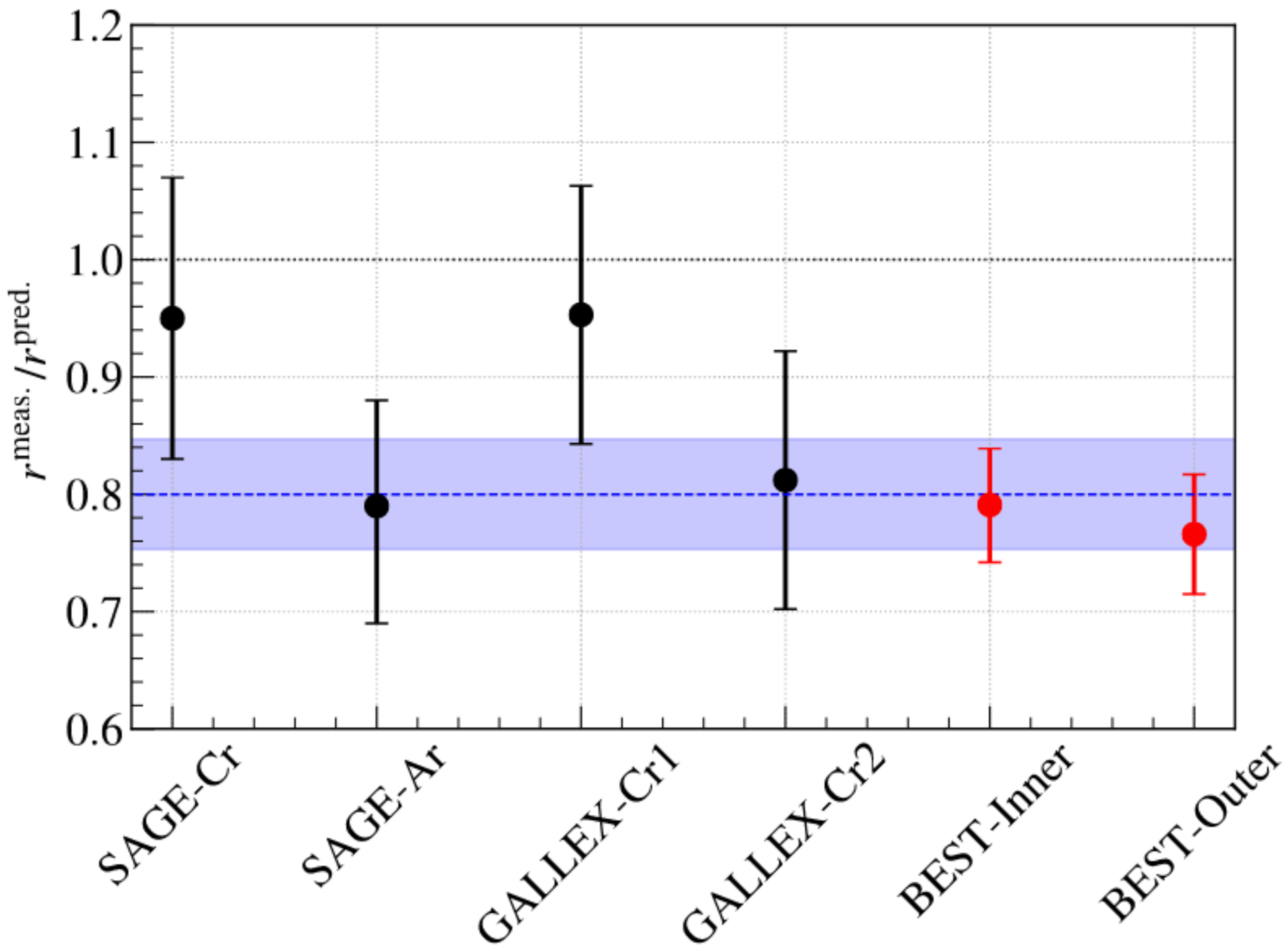
SAGE: 0.95 ± 0.12
GALLEX-Cr1: 0.953 ± 0.11
GALLEX-Cr2: 0.812 ± 0.11

Found deficit of detected neutrinos compared to theory prediction!

Gallium experiments

Calibration of GALLEX, SAGE experiments with radioactive sources ^{51}Cr

Found deficit of detected neutrinos compared to theory prediction!



Deficit confirmed by BEST

Combined significance ~5σ

[BEST 2201.07364]

Gallium anomaly

Significant deficit of neutrinos from
radioactive sources in Gallium experiments

Is the theory prediction wrong, problems with measurement?

Did we find new Physics?

Towards Resolving the Gallium Anomaly

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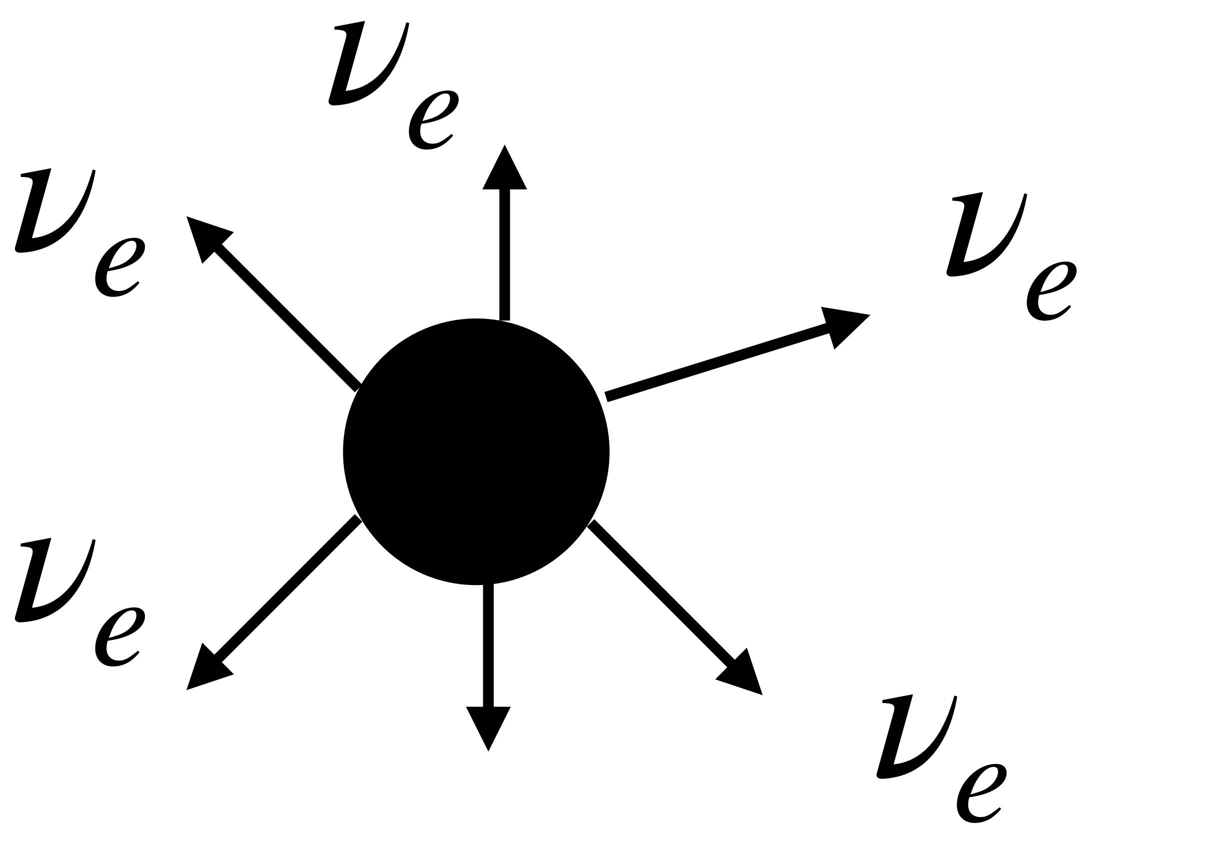
(Dated: June 2, 2023)

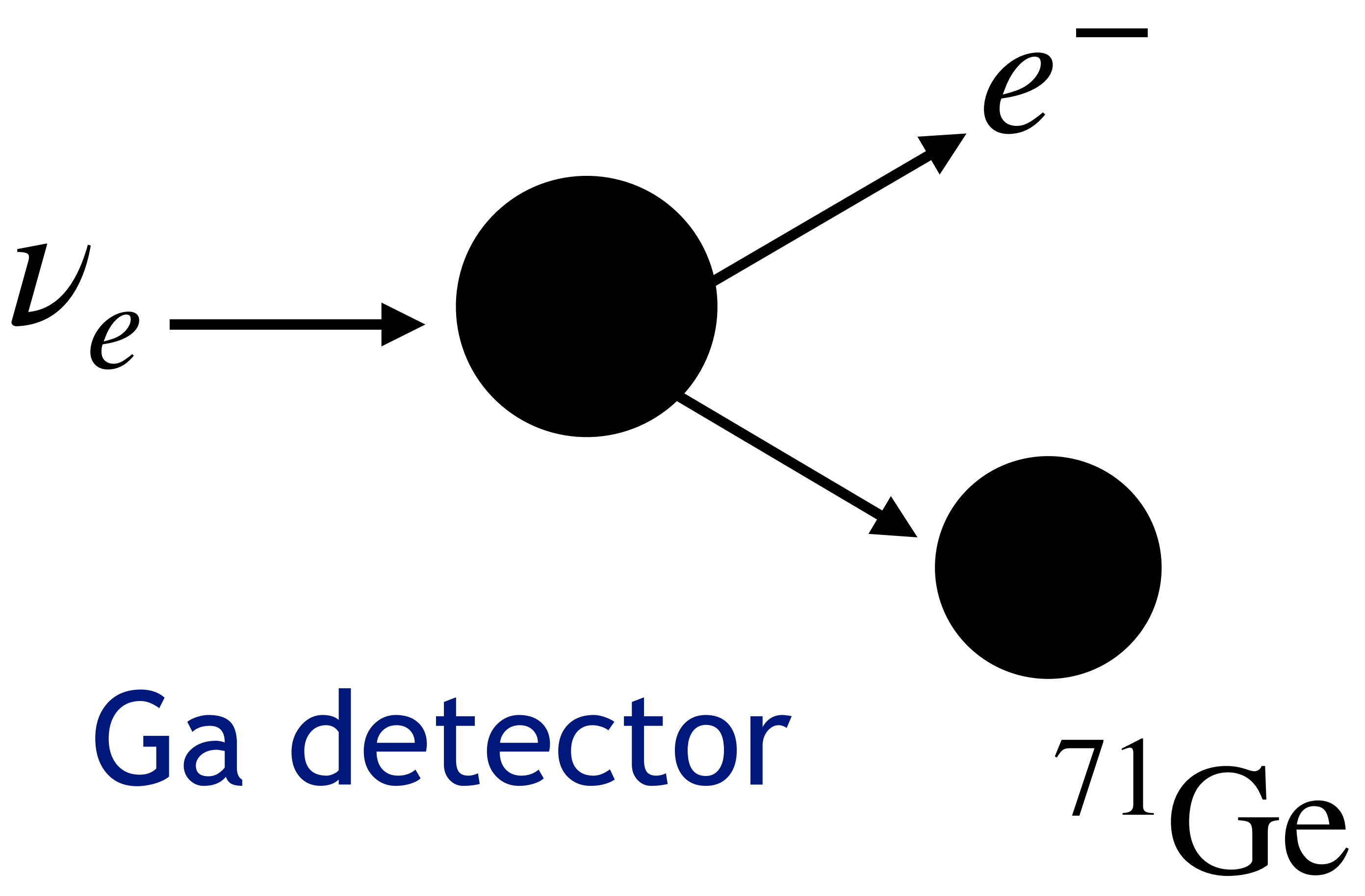
[Brdar, Gehrlein, Kopp 2303.05528]

Gallium experiments

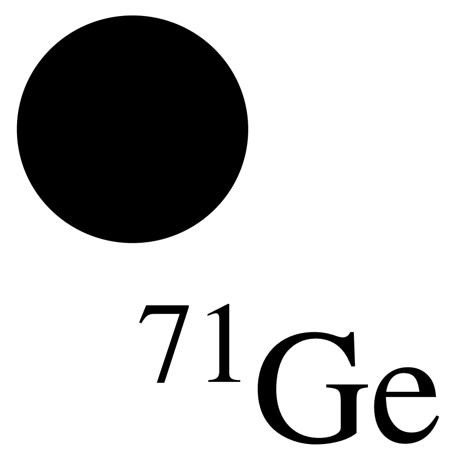
How do these experiments work?



Cr source



Ga detector



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

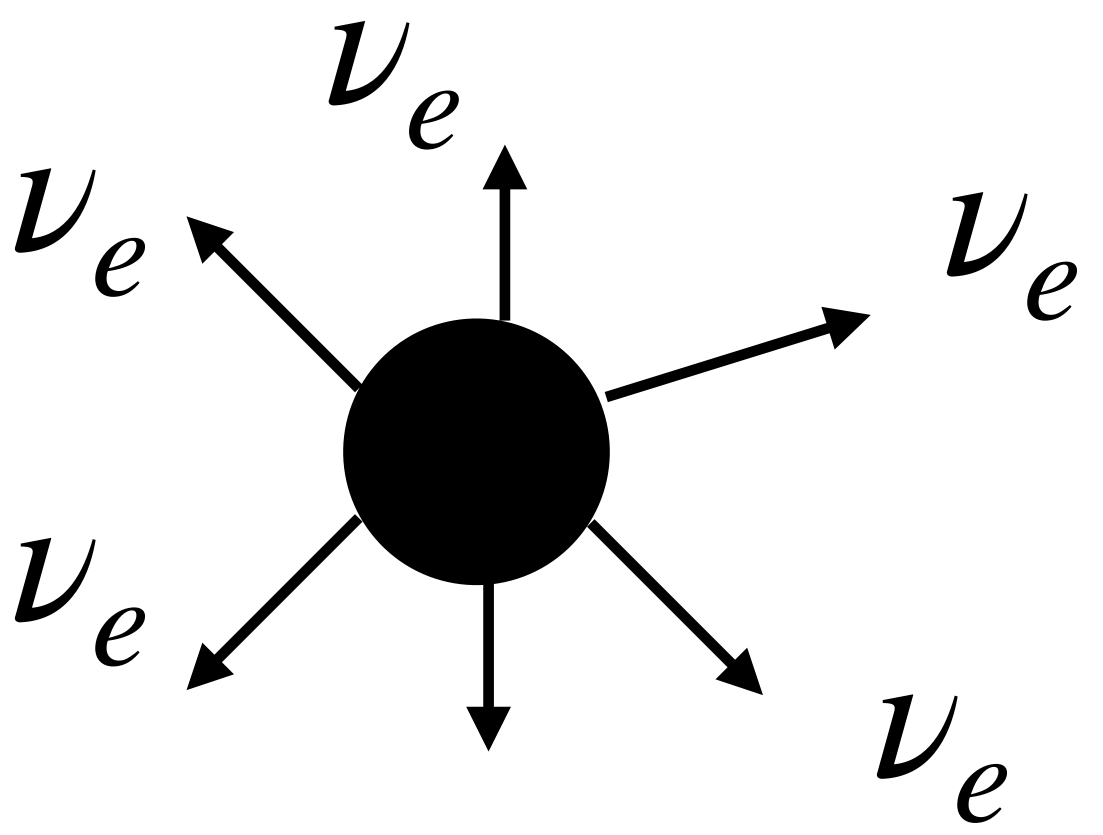
$\nu_e + ^{71}\mathrm{Ga} \rightarrow ^{71}\mathrm{Ge} + \mathrm{e}^-$

Ge extraction

Gallium experiments

How do these experiments work?

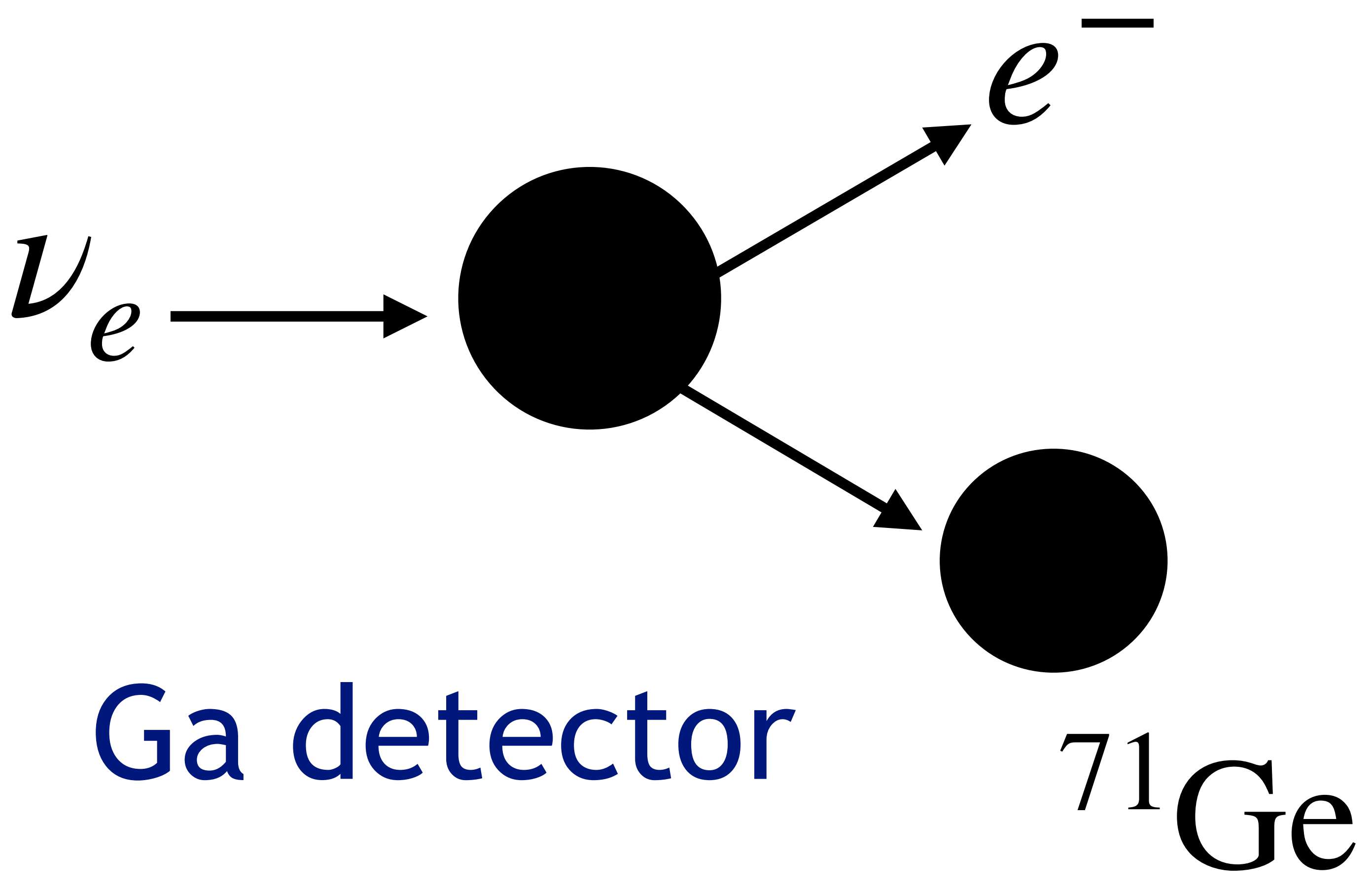
Cr Source activity?



Cr source

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

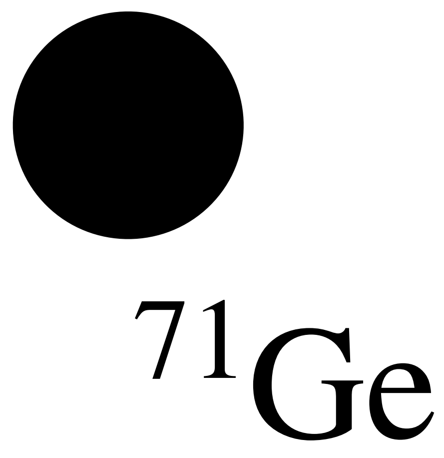
neutrino detection cross section of neutrinos on Ga?



Ga detector

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

Ge extraction efficiency?



Ge extraction

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Source: Chromium-51 branching ratios

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

Cr source intensity measured calorimetrically
almost all the heat production comes from the de-excitation gamma rays from first excited state of $^{51}\mathrm{V}$

Only ~ 10% of all $^{51}\mathrm{Cr}$ decays populate the first excited state of $^{51}\mathrm{V}$

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

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

Cr source intensity measured calorimetrically
almost all the heat production comes from the de-excitation gamma rays from first excited state of $^{51}\mathrm{V}$

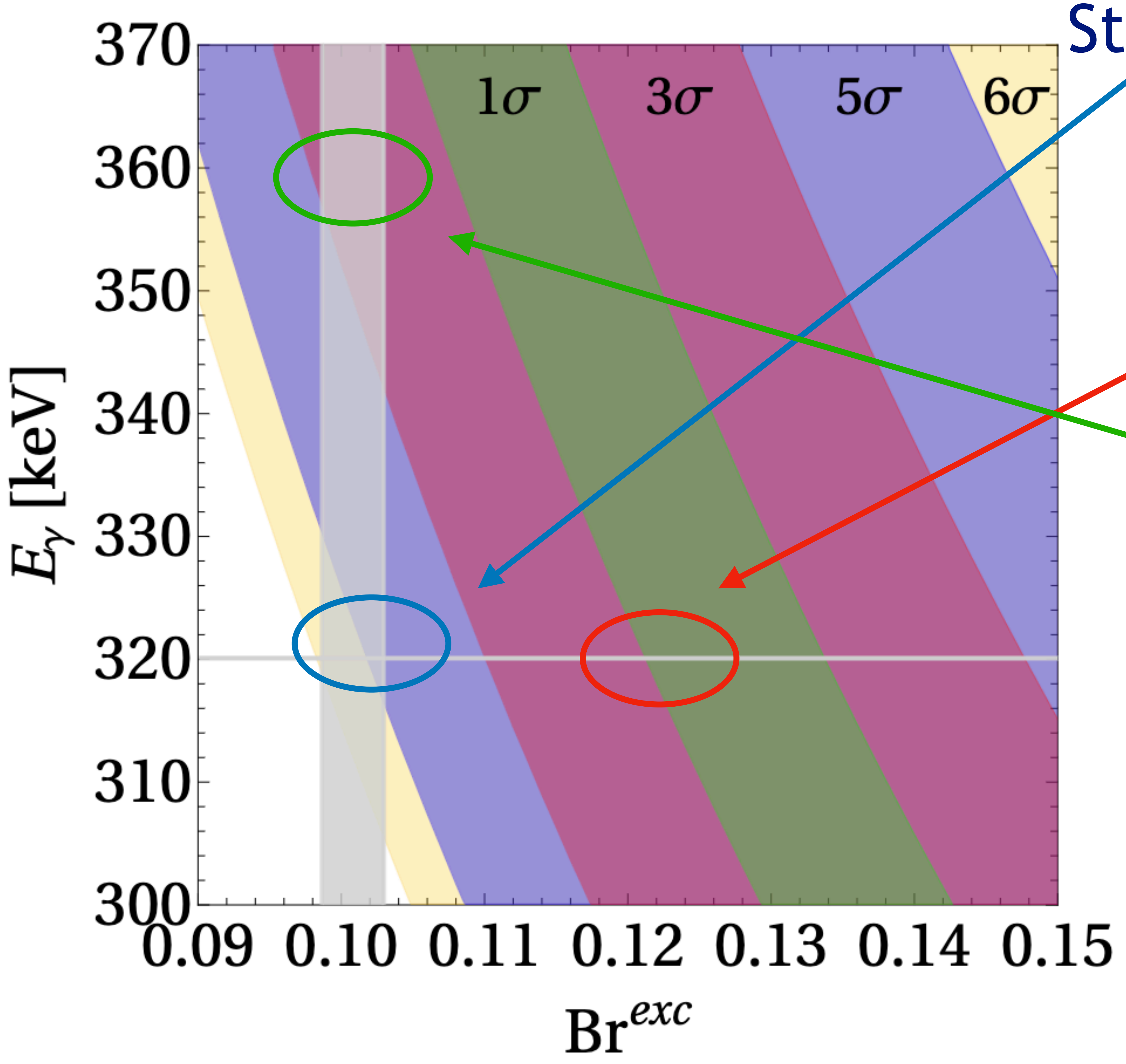
Only ~ 10% of all $^{51}\mathrm{Cr}$ decays populate the first excited state of $^{51}\mathrm{V}$

Can the anomaly be resolved if the BR into excited state of $^{51}\mathrm{V}$ is increased?
Energy of de-excitation gamma rays is larger than expected?

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Source: Chromium-51 branching ratios



Standard assumption

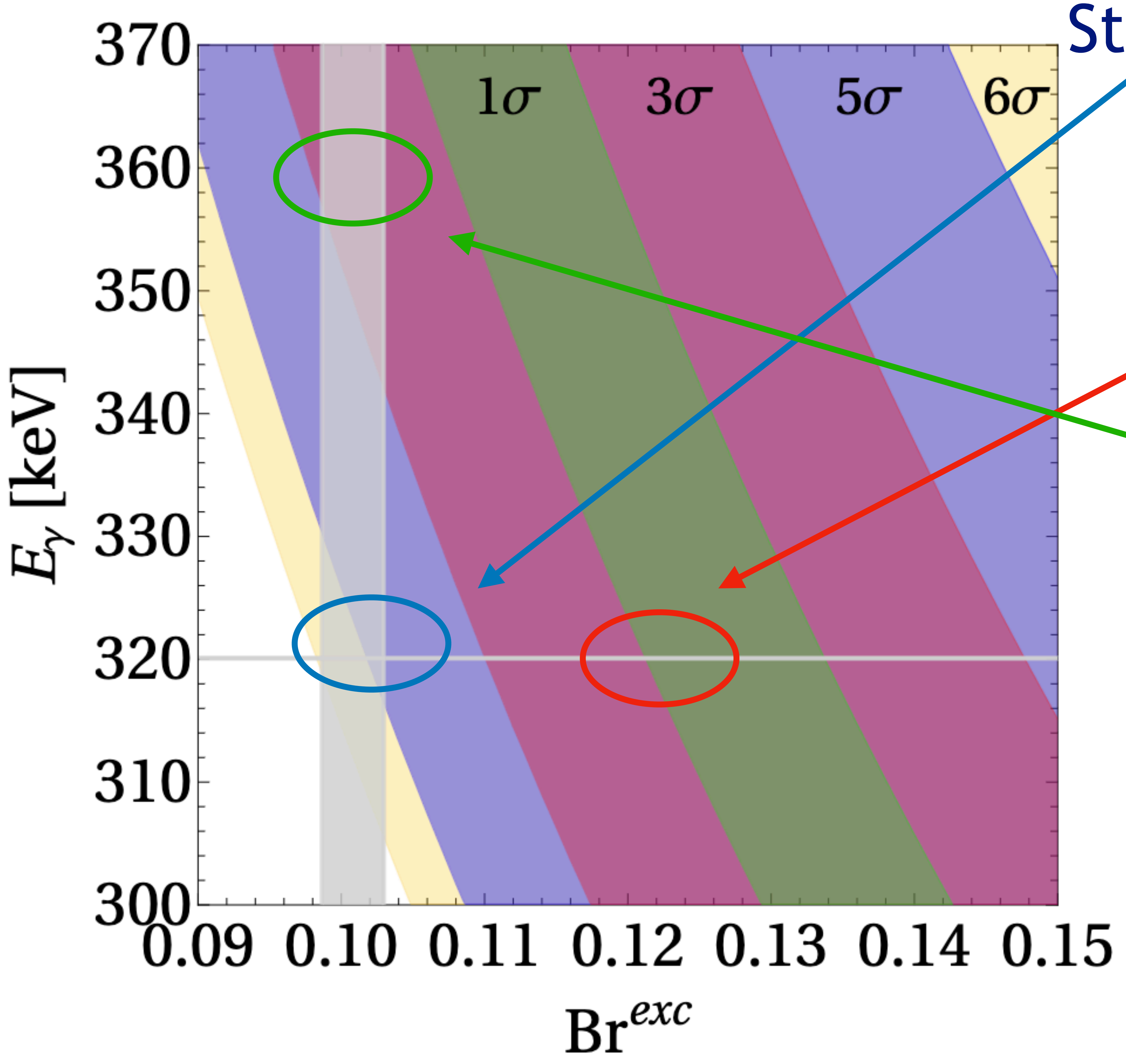
Increase BR into excited state of ^{51}V by 2%
→ anomaly resolved

increasing E_γ while keeping
$BR_{exc} \simeq 10\%$

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Source: Chromium-51 branching ratios



Standard assumption

Increase BR into excited state of $^{51}\mathrm{V}$ by 2%

→ anomaly resolved

increasing E_γ while keeping

$\mathrm{BR}_{\mathrm{exc}}$ ≃10%

new heat source impacts other radioactive decays

Why did we miss it so far?

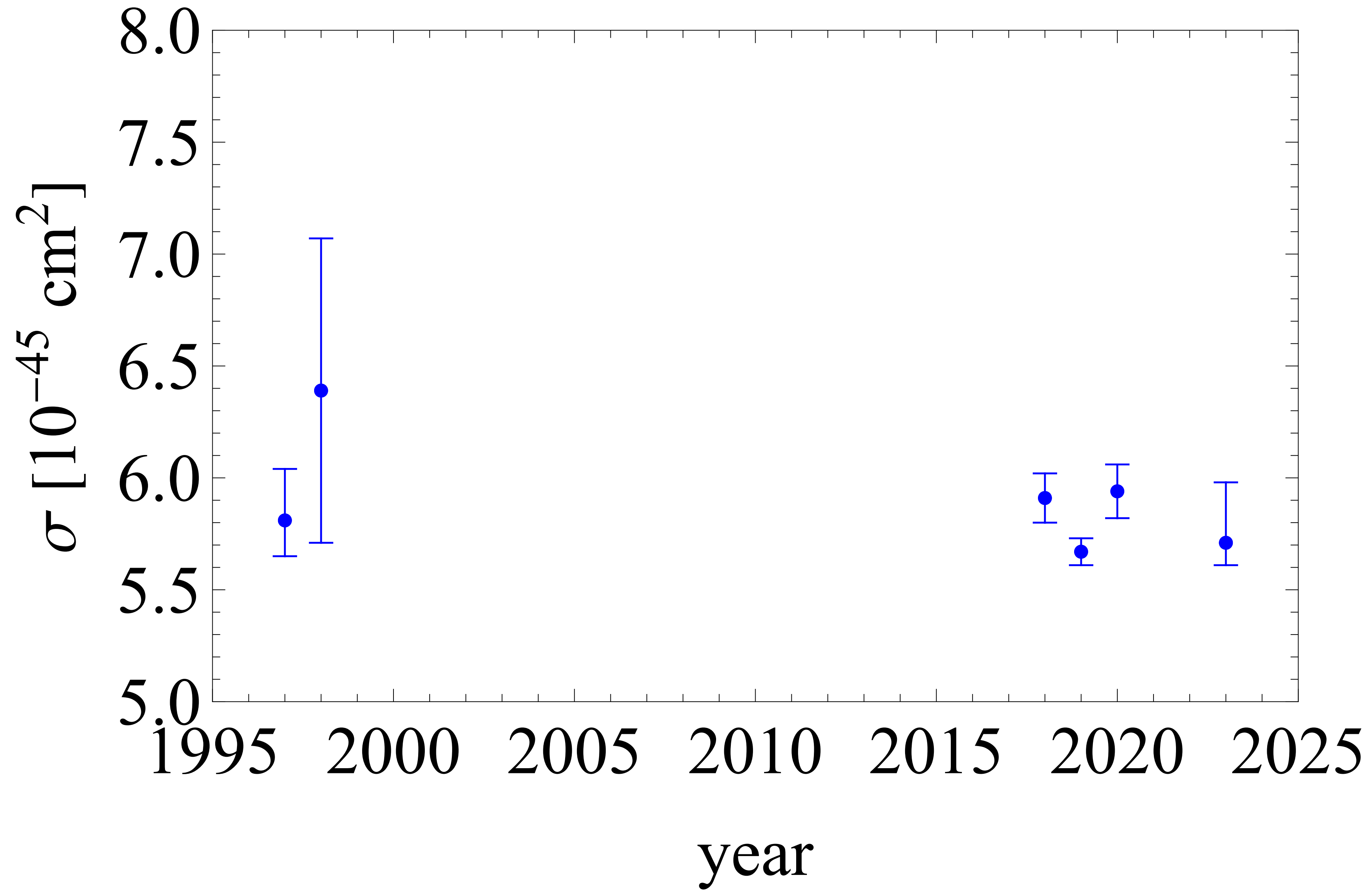
Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Detection: The cross section for neutrino capture on Gallium-71

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

Theoretical cross section calculation $\sigma(\nu_e + {}^{71}\mathrm{Ga})$ reevaluated recently



[Elliott, Gavrin, Haxton, Ibragimova, Rule 2303.13623]

[Elliott, Gavrin, Haxton 2306.03299]

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Detection: The cross section for neutrino capture on Gallium-71

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

Cross section calculation $\sigma(\nu_e + {}^{71}\mathrm{Ga})$ has two contributions:

- transitions to the ground state of ${}^{71}\mathrm{Ge}$ (for which the nuclear matrix element is the same as for the well-studied inverse process, electron capture decay of ${}^{71}\mathrm{Ge}$)
- transitions to excited states of ${}^{71}\mathrm{Ge}$ (can only be calculated theoretically, with sizeable uncertainties)

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Detection: Germanium-71 Decay Rate

Measurement from 1985

$$T_{1/2}(^{71}\text{Ge}) = 11.43 \pm 0.03 \text{ days}$$

[Hampel, Remsberg '85]

Recently measured again:
same best fit, smaller uncertainty

[Collar, Yoon 2307.05353]

fully explain anomaly: $T_{1/2}(^{71}\text{Ge}) >$ larger by at least 2 days (67σ),
reduction of significance to below 3σ: increase of $T_{1/2}(^{71}\text{Ge})$ by about one day (33σ)

[see also Giunti, Li, Ternes, Xin 2212.09722]

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Detection: Germanium-71 Decay to New Excited States of Gallium-71?

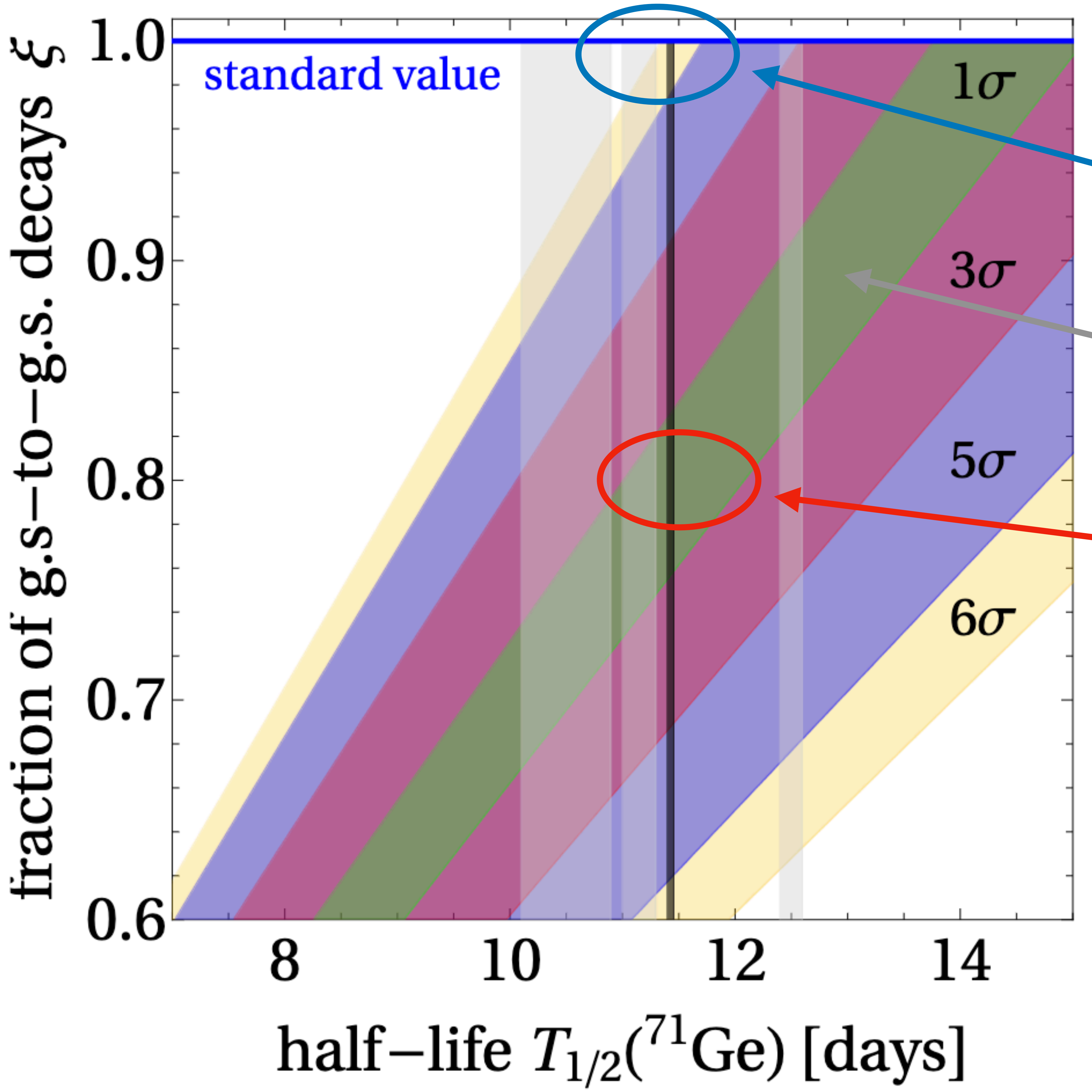
Assumption: decay of $^{71}\mathrm{Ge}$ via electron capture goes to the ground state of the daughter nucleus $^{71}\mathrm{Ga}$
(lowest-lying known excited state of $^{71}\mathrm{Ga}$ has an energy above the Q-value of $^{71}\mathrm{Ge}$ decay)

Additional, yet undiscovered, low-lying excited state of $^{71}\mathrm{Ga}$?

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Detection: Germanium-71 Decay to New Excited States of Gallium-71?



ξ: the fraction of $^{71}\mathrm{Ge}$ decays that go to the ground state of $^{71}\mathrm{Ga}$

$\xi = 1$: standard assumption

Different measurements of half-life

If~ 20% fraction of $^{71}\mathrm{Ge}$ goes into a new state → Nuclear matrix element for ground state-to-ground state transitions overestimated → anomaly resolved

How could we have miss the existence of such an excited state?

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Calibration of the radiochemical Germanium extraction efficiency

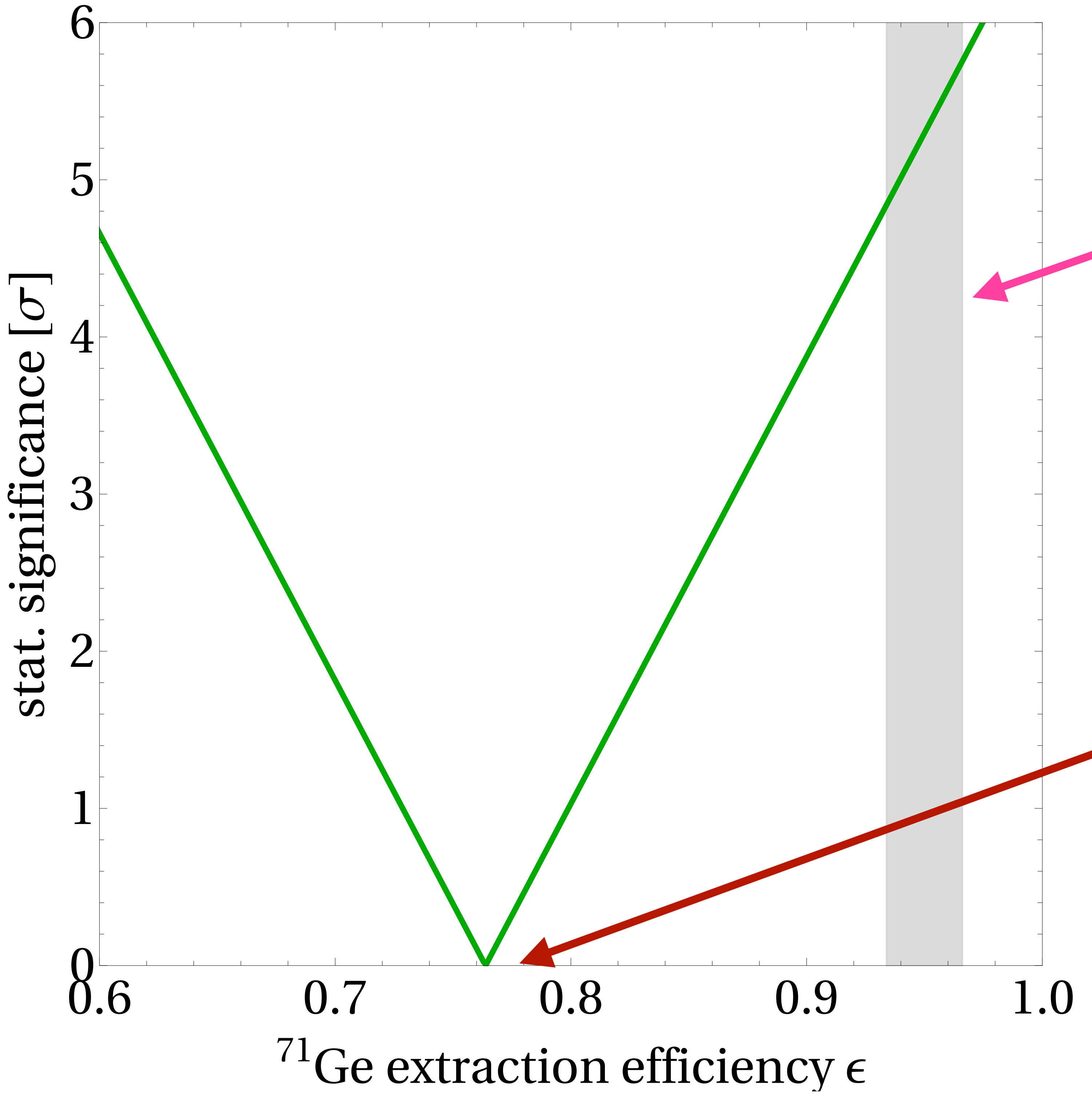
Challenge:
extracting O(100) ^{71}Ge nuclei from more than 47 tons of liquid gallium

- Calibration of extraction efficiency with stable Ge
- Solar results of experiments agree with other measurements (with 10% uncertainty)

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Calibration of the radiochemical Germanium extraction efficiency



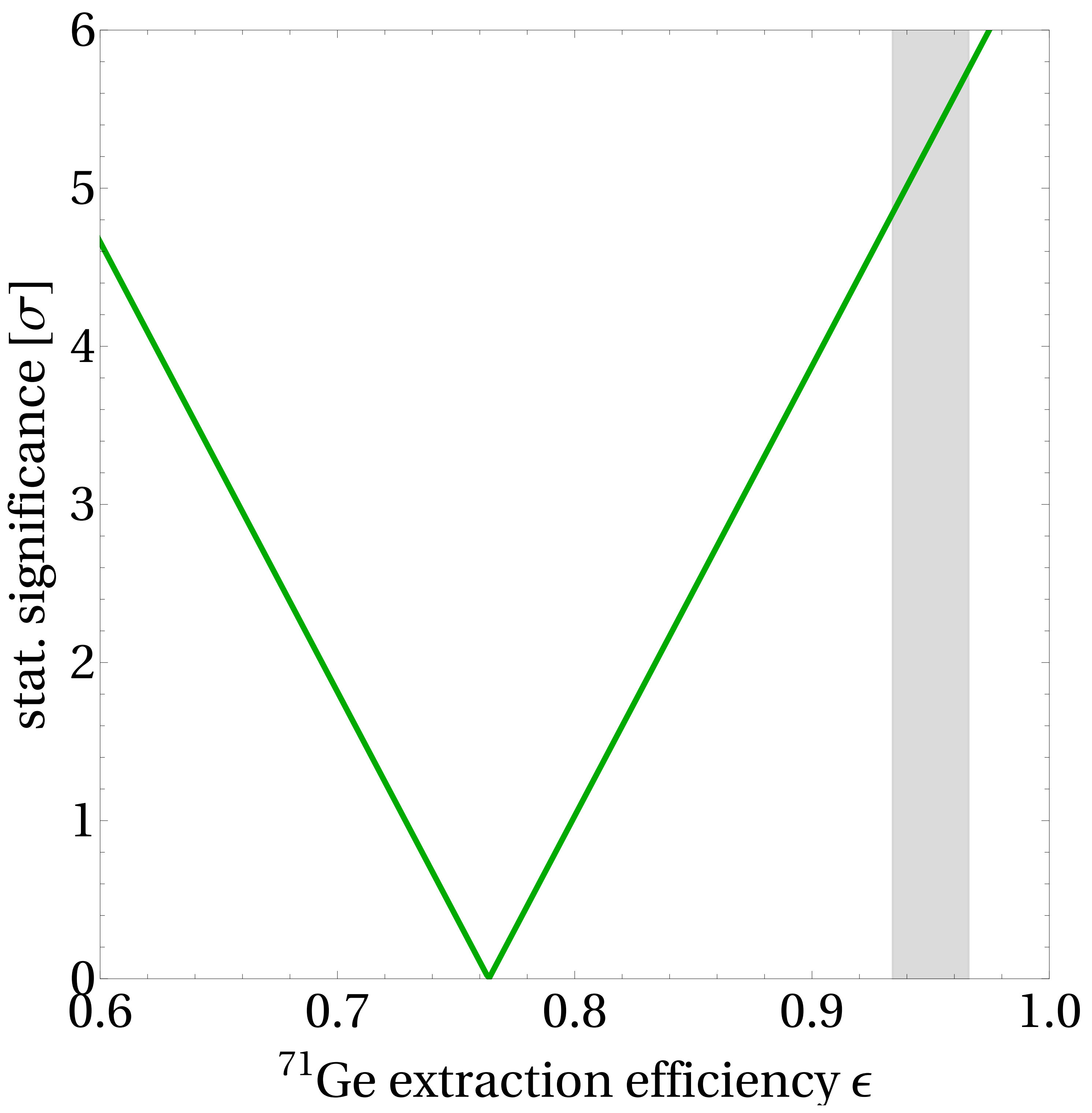
Efficiency from calibration: 95%

Reduction of extraction efficiency to 75% resolves anomaly

Gallium anomaly: SM

[Brdar, Gehrlein, Kopp 2303.05528]

Calibration of the radiochemical Germanium extraction efficiency



Efficiency from calibration: 95%

Reduction of extraction efficiency to 75% resolves anomaly

→ existence of an unidentified route for (stable) germanium to enter the detector: amount of extra germanium needed corresponds to ~ 10^{17} atoms

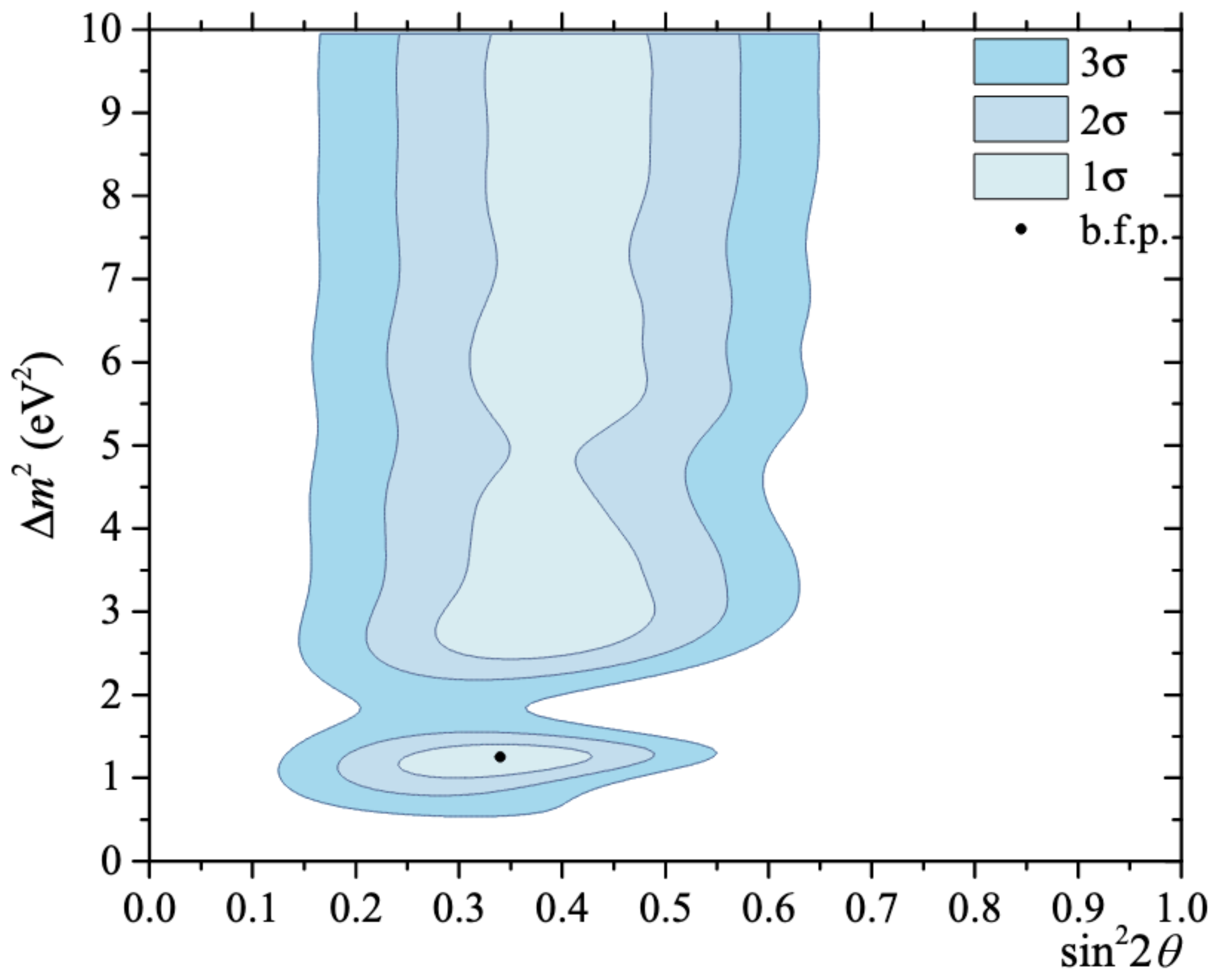
Gallium anomaly: BSM

[BEST 2303.05528]

Sterile neutrino mixing with electron neutrino

Electron neutrino oscillate into sterile neutrinos
Survival probability:

$$P_{ee} = 1 - \sin^2(2\theta)\sin^2(\Delta m^2 L/(4E))$$



Gallium anomaly: BSM

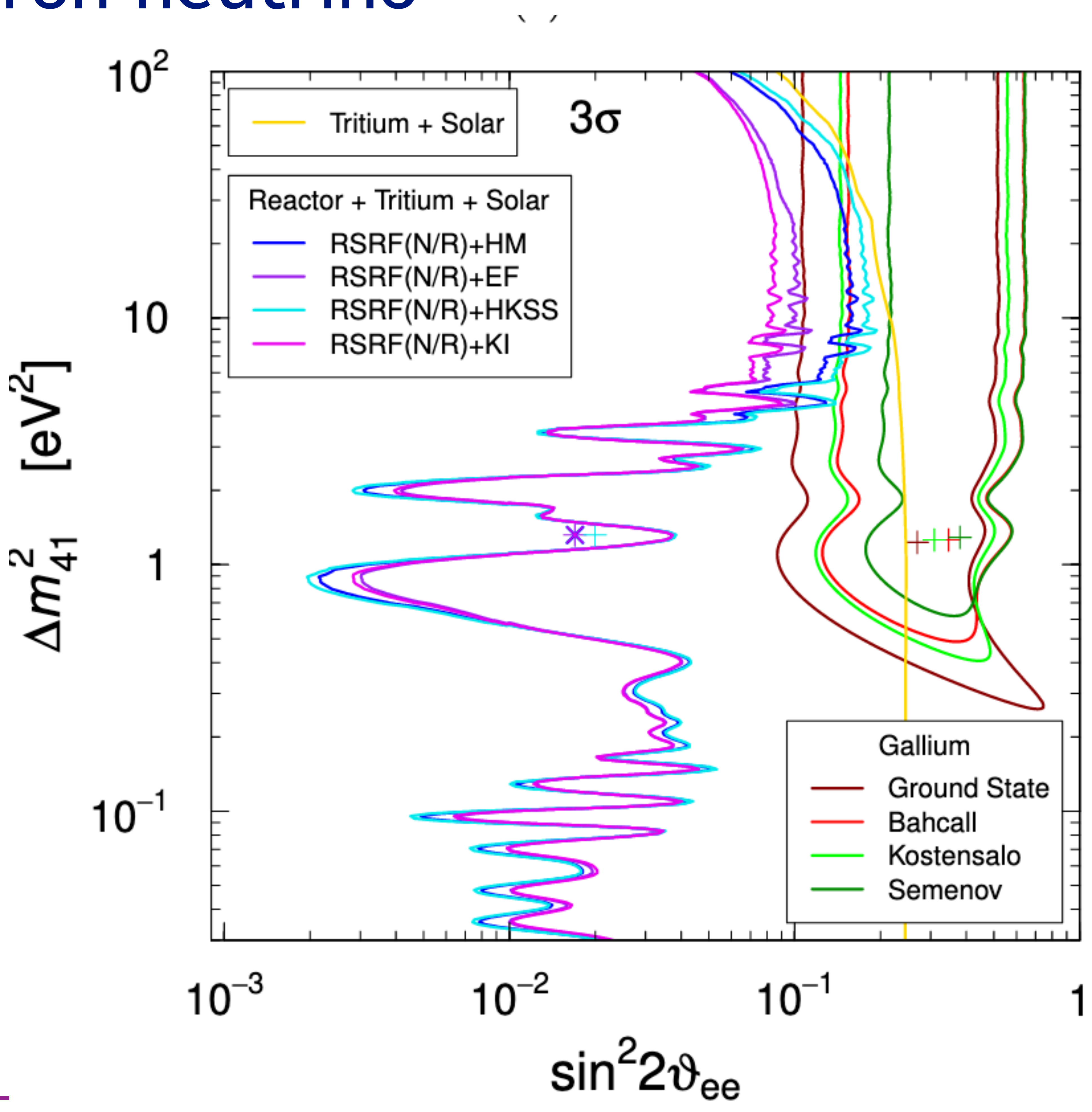
[Giunti, Li, Ternes, Tyagi, Xin 2209.00916]

Sterile neutrino mixing with electron neutrino

Comparison to global neutrino data
(no anomalies observed!)

- Reactor experiments
- Beta decay experiments
- Solar neutrino experiments
- Cosmology

Preferred region from Gallium experiments
ruled out



Gallium anomaly: BSM

[Brdar, Gehrlein, Kopp 2303.05528]

To avoid constraints from other experiments:

- Neutrinos at Gallium experiments have narrow energy range:

- Neutrinos travel very short baseline:

Gallium anomaly: BSM

[Brdar, Gehrlein, Kopp 2303.05528]

To avoid constraints from other experiments:

- Neutrinos at Gallium experiments have narrow energy range:

Sterile neutrino mixing stimulated by narrow MSW or parametric resonance at Cr energy

- Neutrinos travel very short baseline:

Very short lived sterile neutrino decays outside of Gallium experiments into active neutrinos to regenerate flux

But regenerated neutrinos have lower energy → alleviates tension, doesn't solve it

Gallium anomaly: BSM

[Brdar, Gehrlein, Kopp 2303.05528]

Invoke narrow resonance of active-sterile mixing just a Cr energy above the cutoff of the solar pp neutrino flux & below the energy of solar $^7\mathrm{Be}$ neutrinos, sub-MeV neutrinos cannot be detected with inverse beta decay

Sterile neutrino mixing stimulated by MSW resonance

Mixing angle enhanced for

$$V = \frac{\Delta m^2}{2E_\nu^{\text{res}}} \cos 2\theta_{e4}^{\text{vac}}$$

Gallium anomaly: BSM

[Brdar, Gehrlein, Kopp 2303.05528]

Sterile neutrino mixing stimulated by MSW resonance

Active-sterile mixing angle in matter enhanced for

$$V = \frac{\Delta m^2}{2E_\nu^{\text{res}}} \cos 2\theta_{e4}^{\text{vac}}$$

Potential generated by SM weak interaction too small

→ introduce new interaction with ultralight DM vector ϕ^μ

$$\mathscr{L} \supset g_s \phi^\mu \overline{\nu}_s \gamma_\mu \nu_s$$

Gallium anomaly: BSM

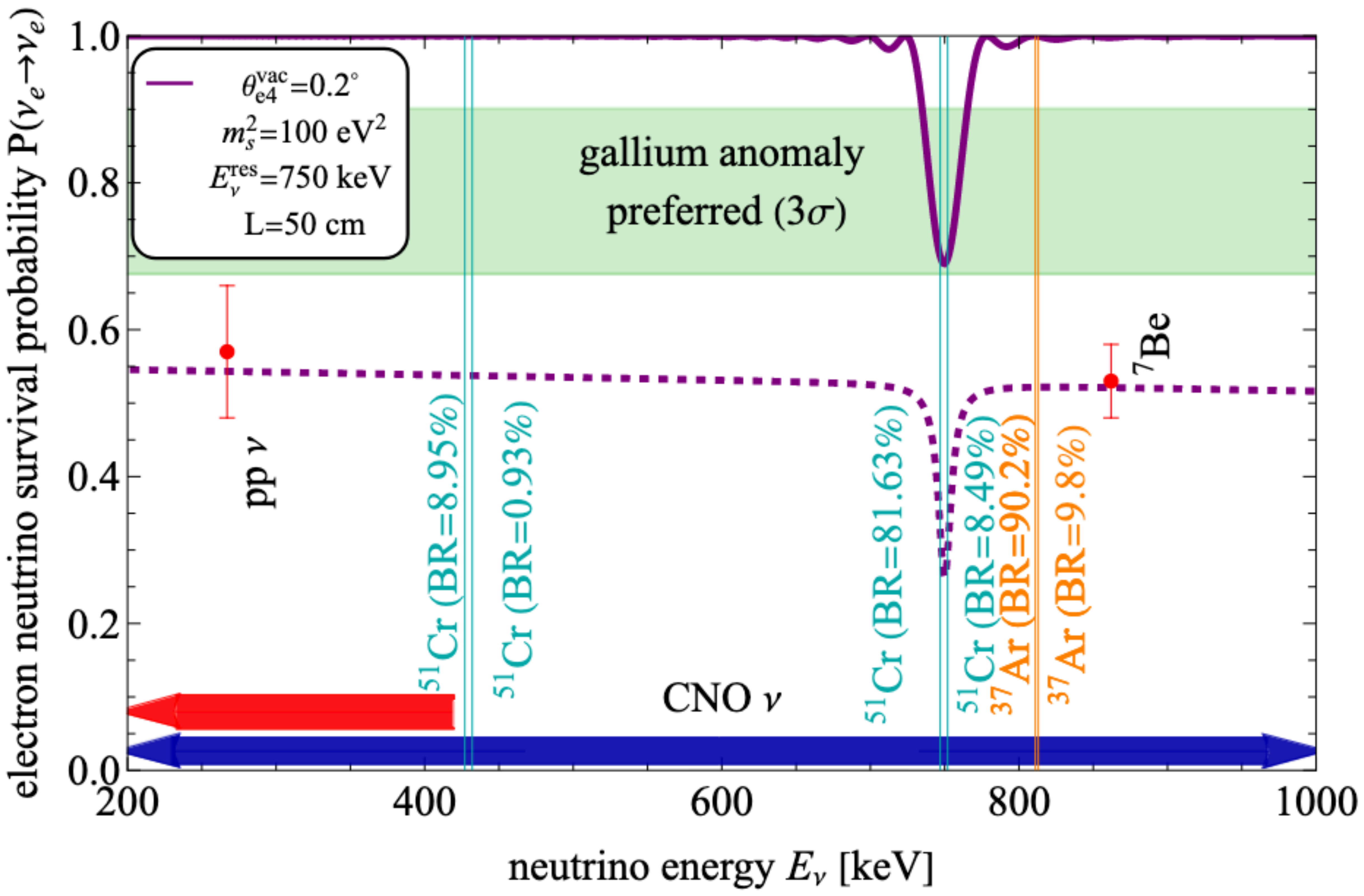
[Brdar, Gehrlein, Kopp 2303.05528]

Sterile neutrino mixing stimulated by MSW resonance

Active-sterile mixing angle in matter enhanced for

$$V = \frac{\Delta m^2}{2E_\nu^{\text{res}}} \cos 2\theta_{e4}^{\text{vac}}$$

Terrestrial constraints on DM-neutrino couplings significantly alleviated as DM couples to sterile in this model



$$V = 6.7 \times 10^{-5}\ \text{eV},\ g_s/m_\phi = 0.311\ \text{eV}^{-1}$$

Gallium anomaly: BSM

[Brdar, Gehrlein, Kopp 2303.05528]

Sterile neutrino mixing stimulated by MSW resonance

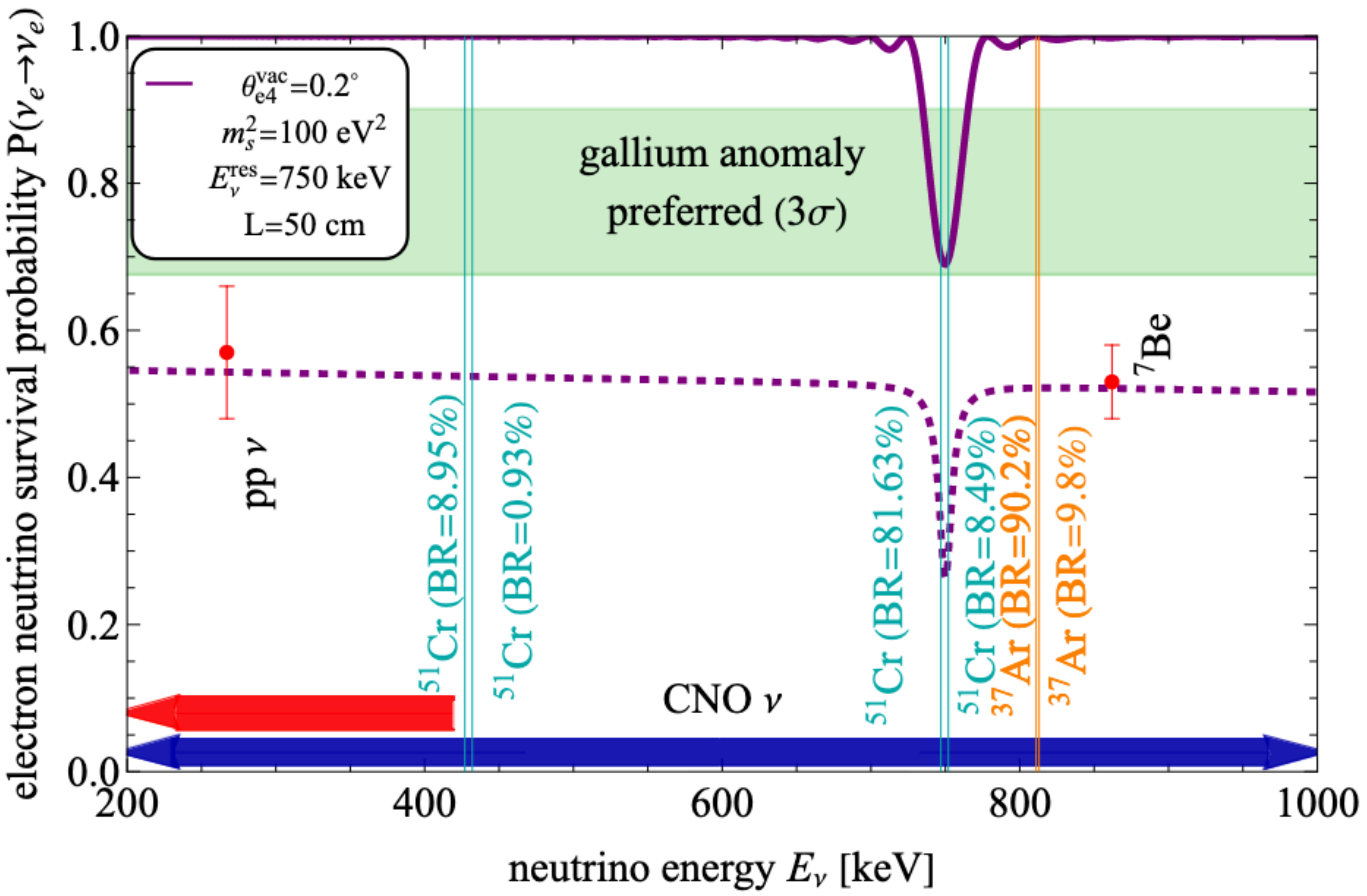
Active-sterile mixing angle in matter enhanced for

$$V = \frac{\Delta m^2}{2E_\nu^{\text{res}}} \cos 2\theta_{e4}^{\text{vac}}$$

Around $z \sim 7000$ adiabatic conversion of active neutrinos into steriles→ $N_{\text{eff}} < N_{\text{eff}}^{\text{SM}}$

Introduce new decay channel

$$\nu_s \to \Phi + \nu_a$$

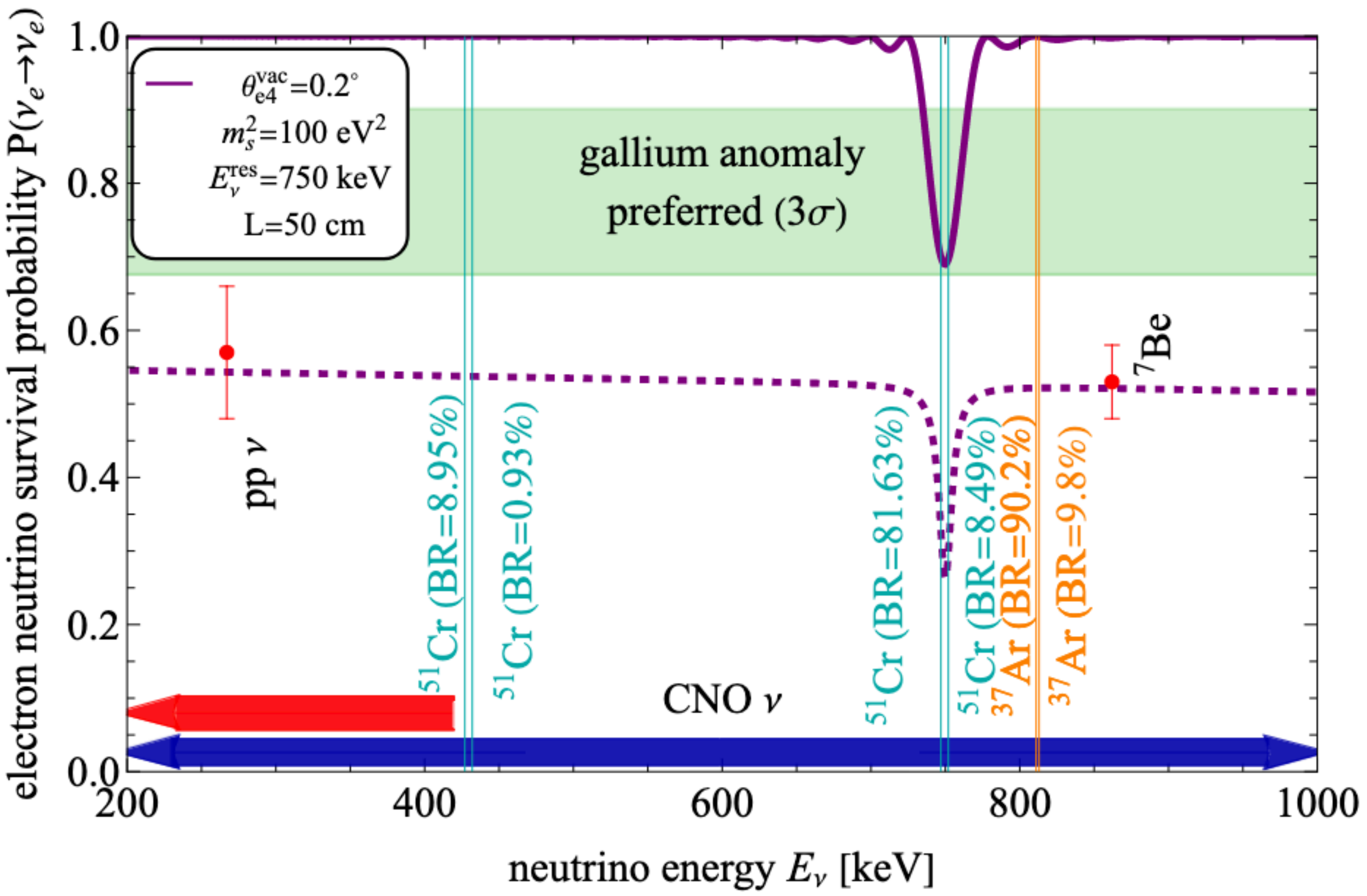


Gallium anomaly: BSM

[Brdar, Gehrlein, Kopp 2303.05528]

Sterile neutrino mixing stimulated by MSW resonance

- Successful explanation of Ga anomaly
- Moderate fine-tuning of MSW resonance energy and Cr energy
- Consistent with terrestrial probes+ small extension for cosmological probes
- Test with CNO neutrinos
- Test with Ga experiments with Zn or Ar source



Gallium anomaly: Conclusions

Summary

- Gallium anomaly significant and unresolved
- Discussed explanations in the SM and beyond
- SM explanation: Ge extraction efficiency biased?
- BSM explanation: resonantly enhanced active-sterile mixing at Cr energy
- Other BSM explanations in literature
- Future tests of solution to anomaly necessary!

Thanks for your attention!

Appendix: Gallium anomaly

[Brdar, Gehrlein, Kopp 2303.05528]

Summary

scenario	comments	our rating
Explanations within the Standard Model		
increased ^{71}Ge half-life (Section 2.1 and Ref. [39])	would lead to smaller matrix element for $\nu + {}^{71}$Ga; but the ^{71}Ge half-life has been measured many times with different methods in [38], all of which yield consistent results. So it is hard to imagine a bias in these measurements.	★★☆☆☆
new ^{71}Ga excited state (Section 2.2)	would imply a bias in the extraction of the $\nu + {}^{71}$Ga matrix element from the measured ^{71}Ge half-life. Some very old experiments claim the existence of such a state, but this has not been confirmed in more recent observations.	★★☆☆☆
increased BR(^{51}Cr $\to$ ^{51}V*) (Section 3)	would cause a bias in translating the heat output of the source to a neutrino production rate. Measurements of BR(^{51}Cr $\to$ ^{51}V*) show some tension, but it is far less than the shift required to explain the gallium anomaly.	★★★☆☆
^{71}Ge extraction efficiency (Section 4)	one of SAGE's calibration runs has revealed a large bias. Could a small, unnoticed, bias have been present in all gallium experiments?	★★★★☆

Appendix: Gallium anomaly

[Brdar, Gehrlein, Kopp 2303.05528]

Summary

scenario	comments	our rating
Explanations beyond the Standard Model		
ν_s coupled to ultralight DM (MSW resonance, Sec. 5.1.1)	several exotic ingredients; somewhat tuned MSW resonance; new ν_4 decay channel required for cosmology.	★★★★☆
ν_s coupled to dark energy (MSW resonance, Sec. 5.1.2)	several exotic ingredients; somewhat tuned MSW resonance; cosmology similar to the previous scenario.	★★★☆☆
ν_s coupled to ultralight DM (param. resonance, Sec. 5.1.3)	several exotic ingredients; somewhat tuned parametric resonance; cosmology requires post-BBN DM production via misalignment.	★★★★☆
decaying ν_s (Section 5.2)	difficult to reconcile with reactor and solar data; regeneration of active neutrinos in ν_s decays alleviates tension, but does not resolve it.	★★☆☆☆
vanilla eV-scale ν_s (Refs. [17, 18])	preferred parameter space is strongly disfavored by solar and reactor data.	★☆☆☆☆

Appendix: Gallium anomaly

[Brdar, Gehrlein, Kopp 2303.05528]

Summary

scenario	comments	our rating
ν_s with CPT violation (Refs. [130])	avoids constraints from reactor experiments, but those from solar neutrinos cannot be alleviated.	
extra dimensions (Refs. [131–133])	neutrinos oscillate into sterile Kaluza–Klein modes that propagate in extra dimensions; in tension with reactor data.	
stochastic neutrino mixing (Ref. [134])	based on a difference between sterile neutrino mixing angles at production and detection (see also [135, 136]); fit worse than for vanilla ν_s.	
decoherence (Refs. [137, 138])	non-standard source of decoherence needed; known experimental energy resolutions constrain wave packet length, making an explanation by wave packet separation alone challenging.	
ν_s coupled to ultralight scalar (Ref. [139])	ultralight scalar coupling to ν_s and to ordinary matter affects sterile neutrino parameters; can not avoid reactor constraints	