Elliott, Gavrin, Haxton, Ibragimova, & **ER**, *Phys. Rev. C* **108**, 035502
Haxton & ER, *Phys. Lett. B* **861**, 139259

Los Alamos NATIONAL LABORATORY

The gallium neutrino capture cross section:

Solar and laboratory sources

Evan Rule | N3AS Annual Meeting| Aug. 6, 2025

Berkeley UNIVERSITY OF CALIFORNIA

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER

NSF

The Gallium Anomaly

Neutrinos from solar fusion

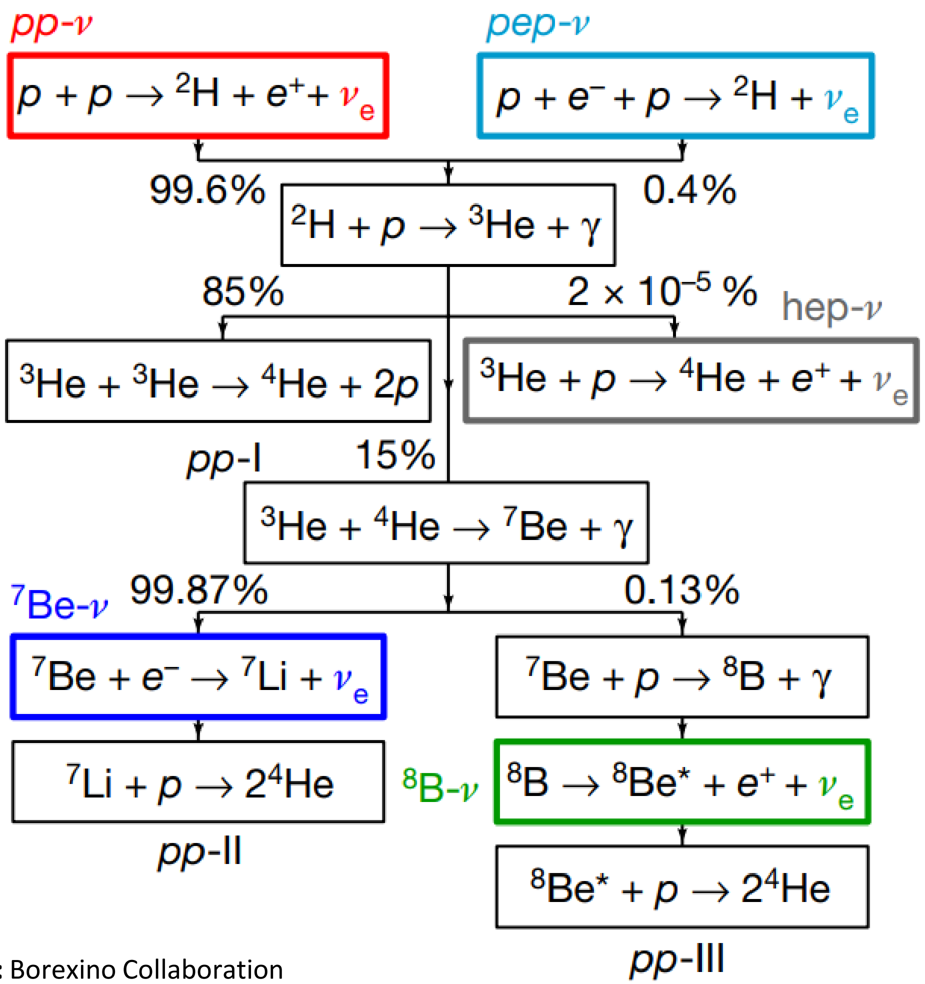


Figure: Borexino Collaboration

The Gallium Anomaly

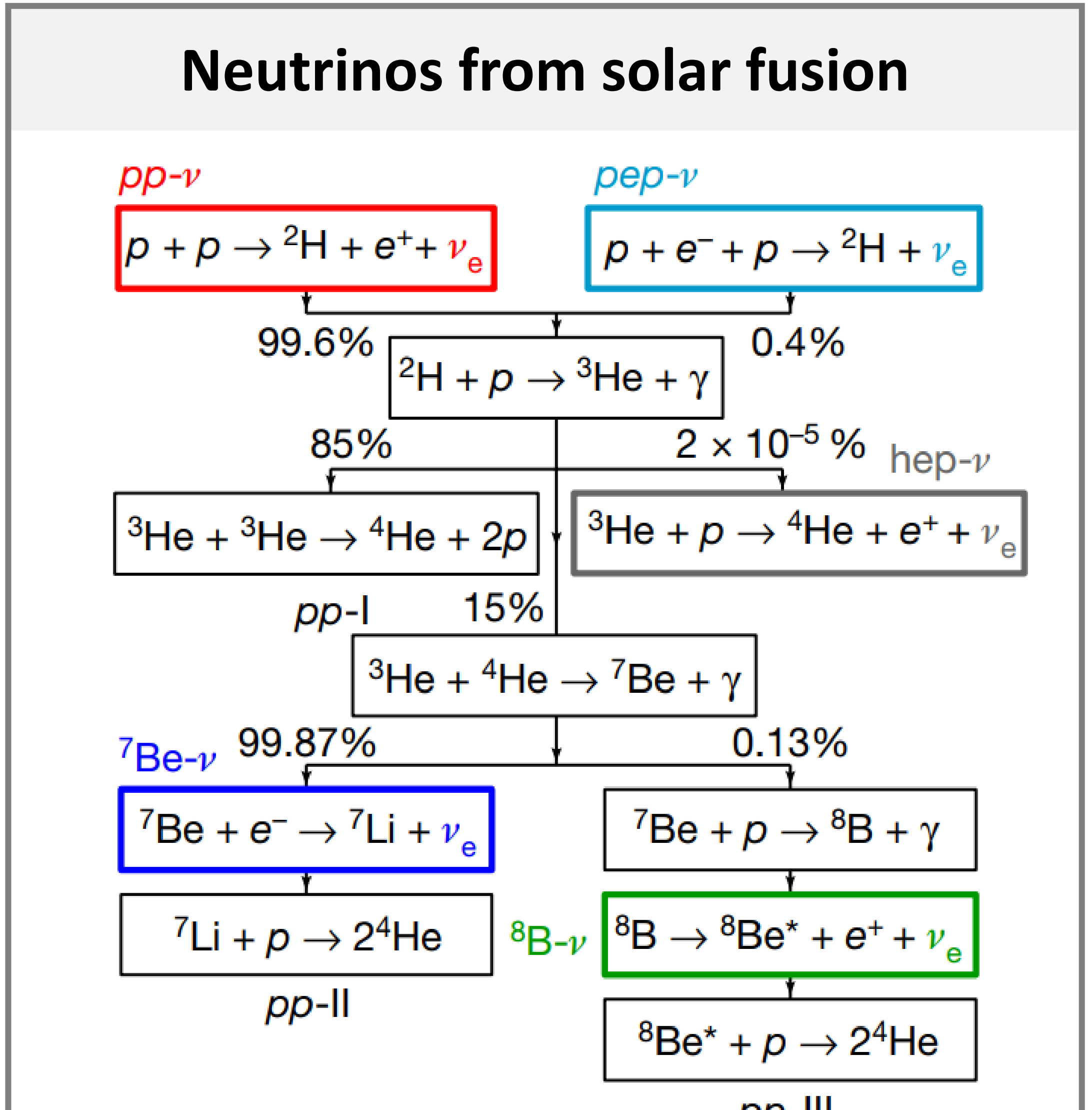
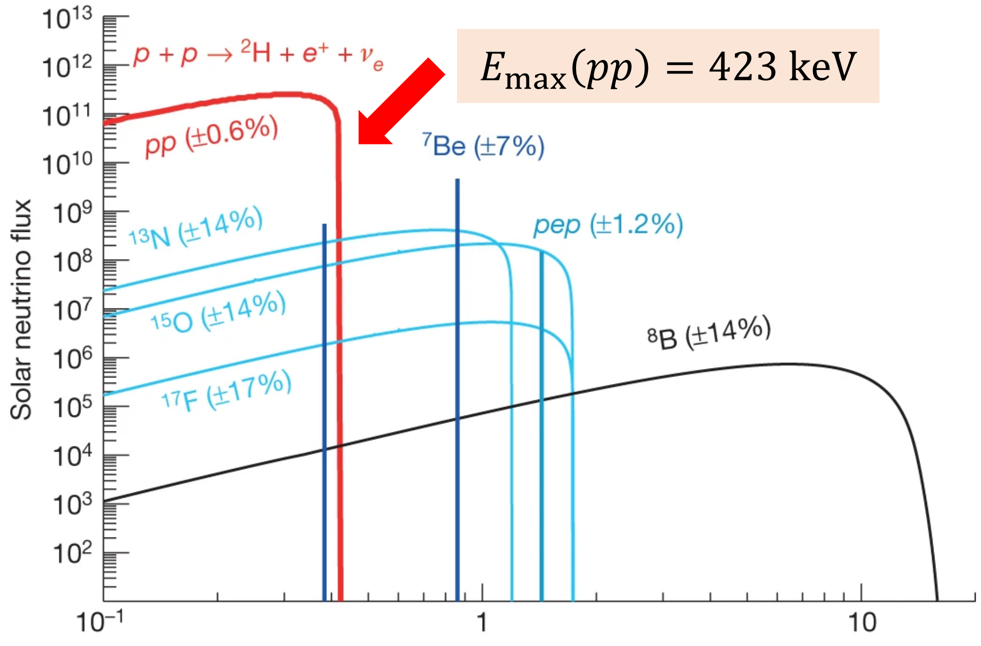


Figure: Borexino Collaboration



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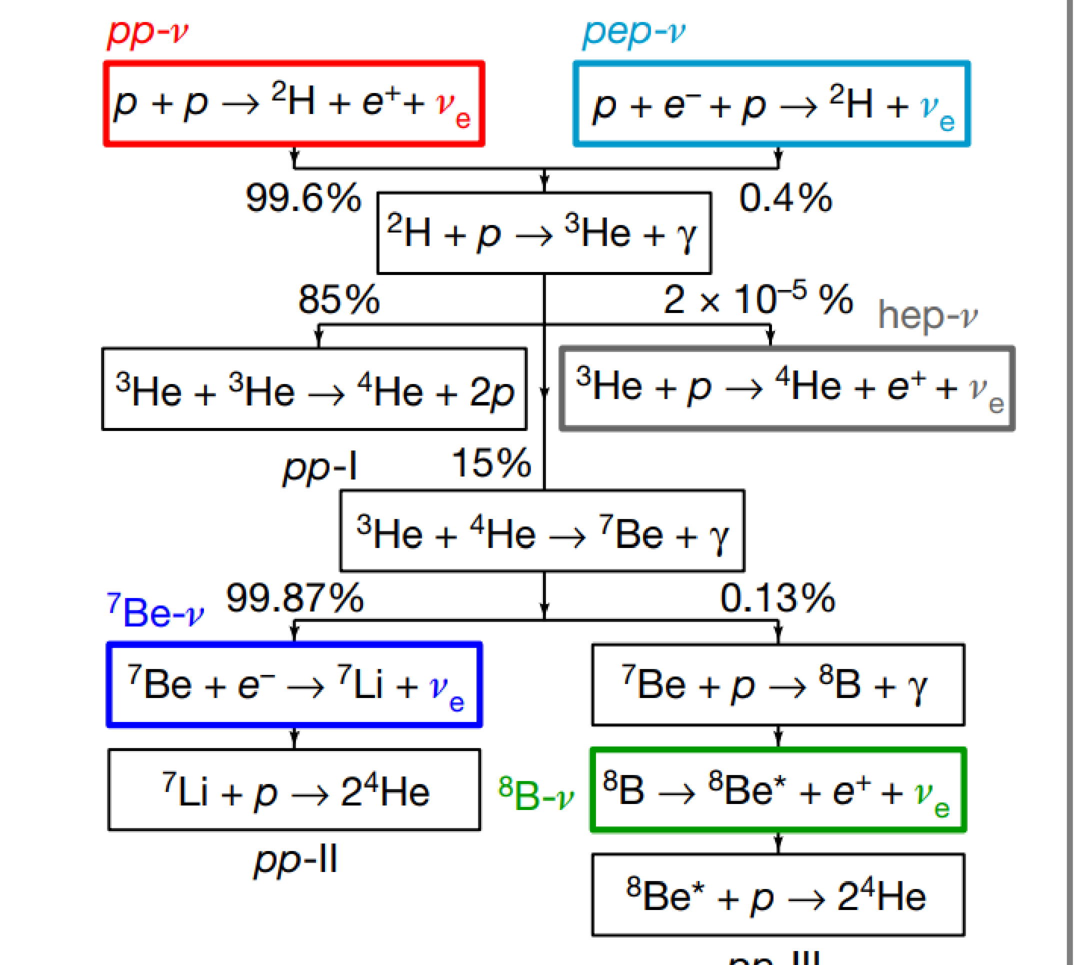


Figure: Borexino Collaboration

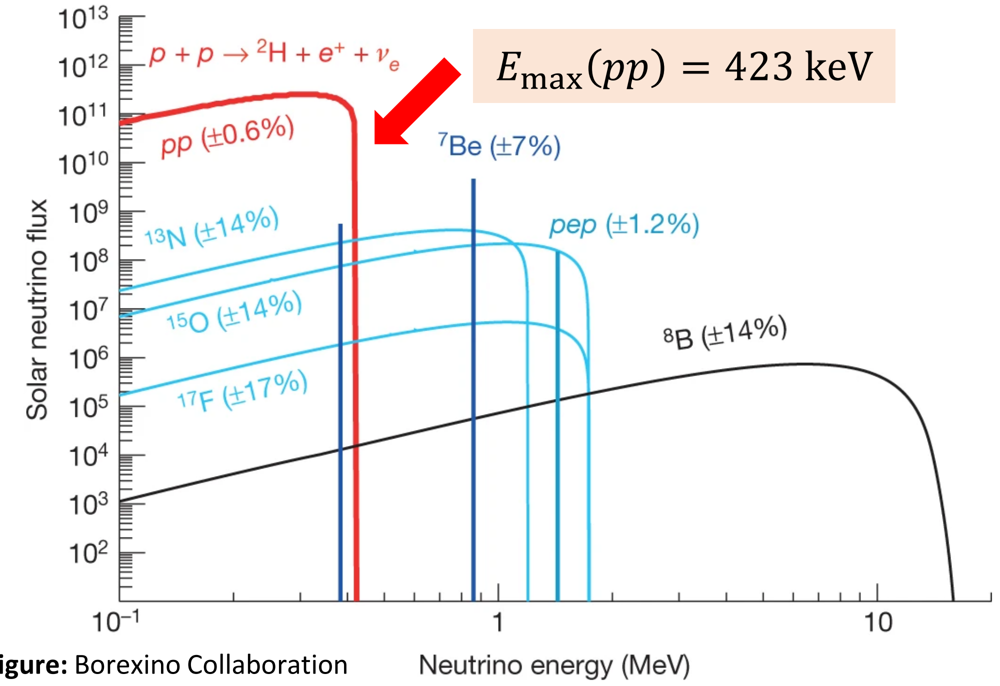
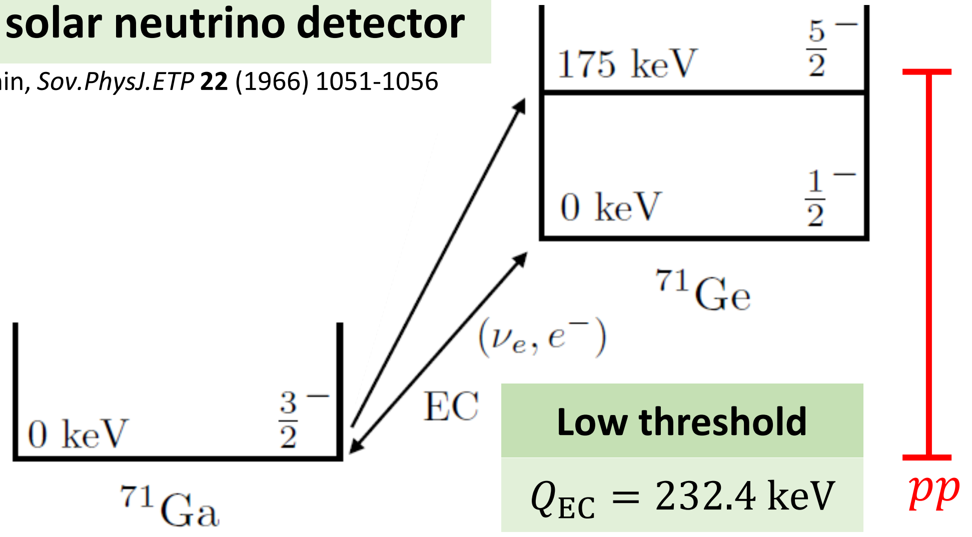
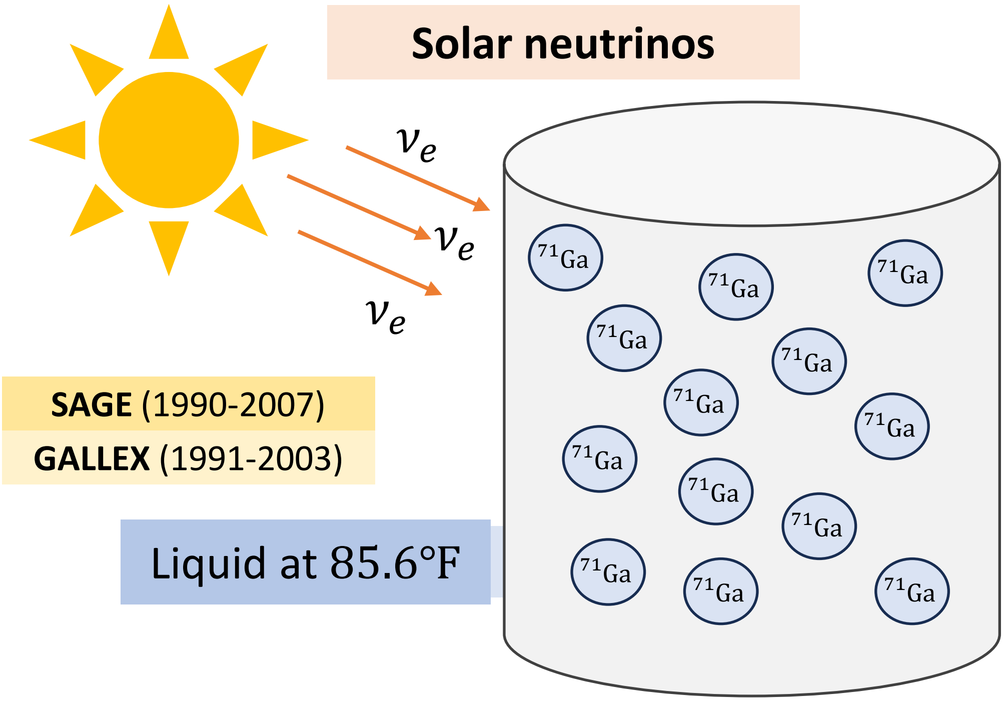


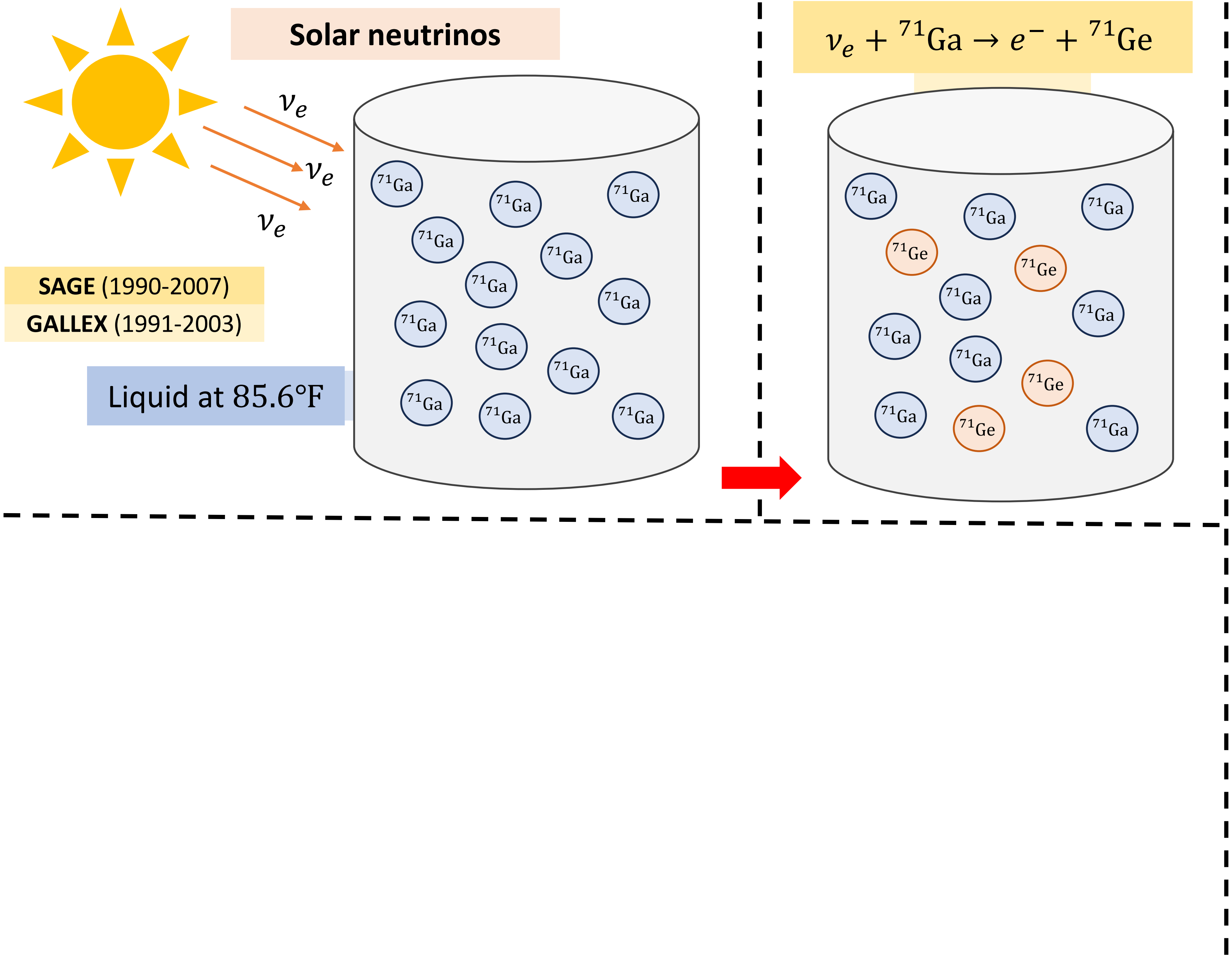
Figure: Borexino Collaboration

^{71}Ga as solar neutrino detector

V.A. Kuzmin, *Sov.PhysJ.ETP* **22** (1966) 1051-1056




Solar neutrinos
ν_e
ν_e
ν_e
SAGE (1990-2007)
GALLEX (1991-2003)
Liquid at 85.6°F
^{71}Ga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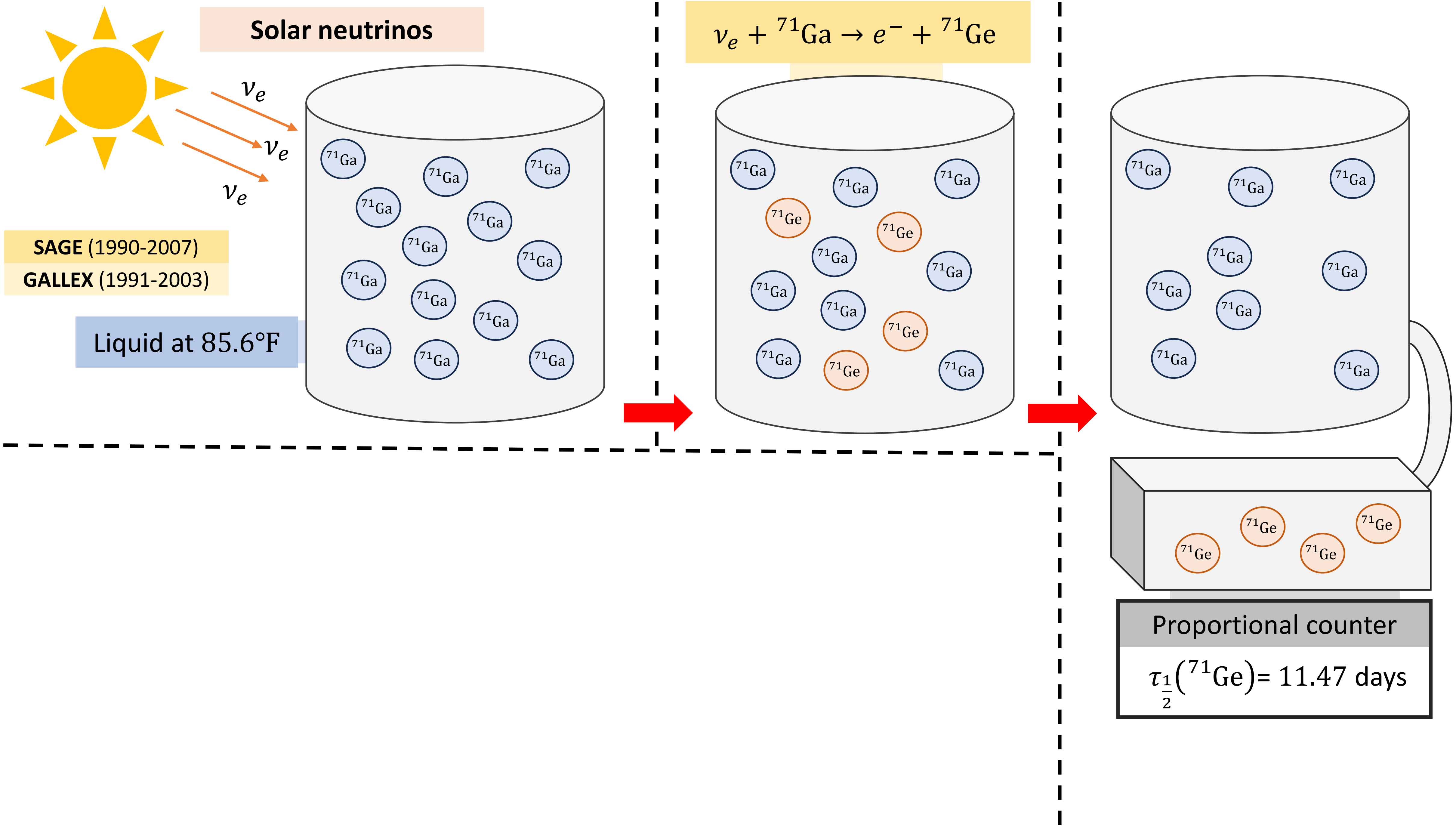
^{71}Ga
$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$
^{71}Ga
^{71}Ge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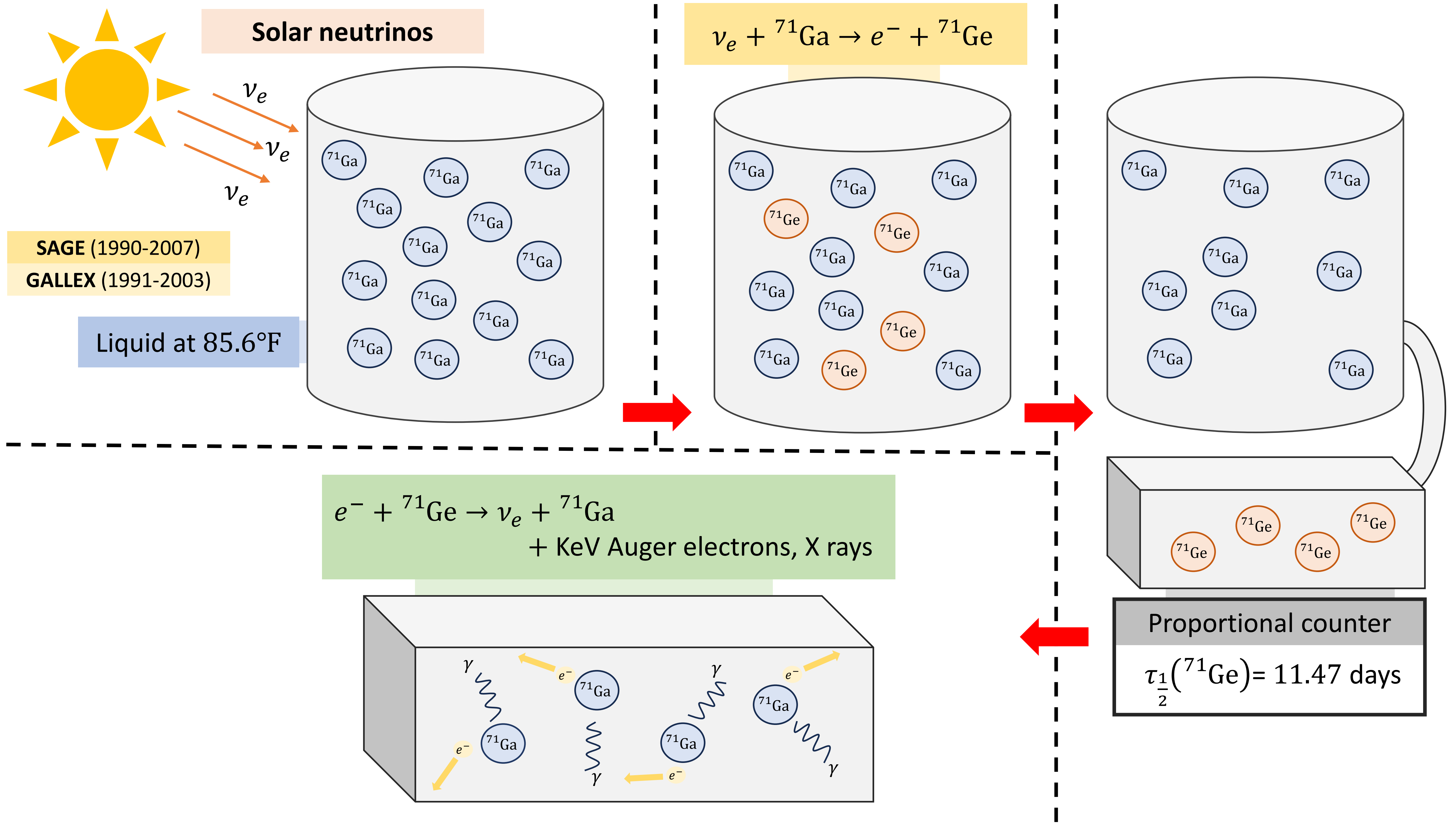
$\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$
^{71}Ge
Proportional counter
$\tau_{\frac{1}{2}}\left({}^{71}\text{Ge}\right)$= 11.47 days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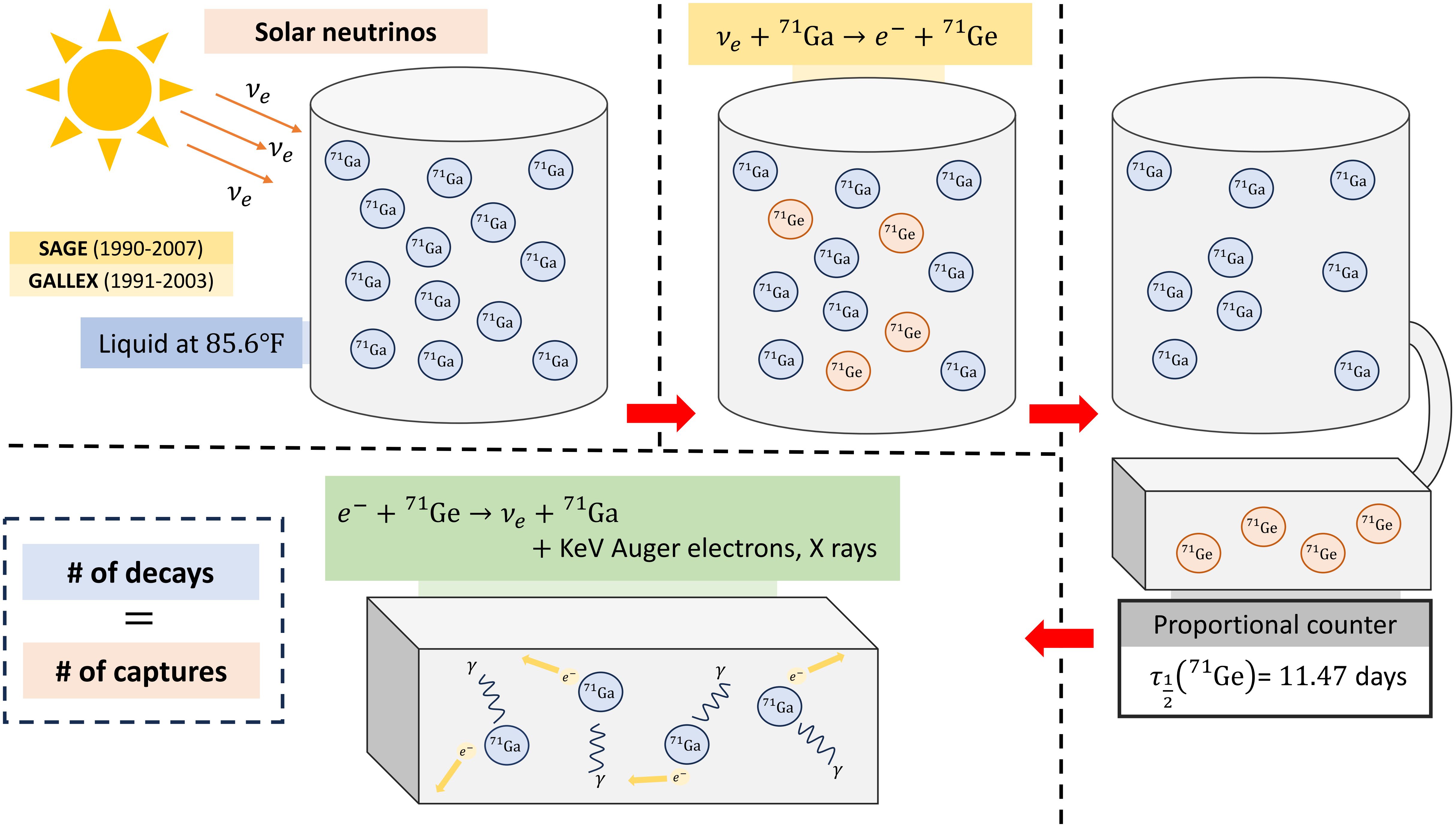
$e^- + {}^{71}\mathrm{Ge} \rightarrow \nu_e + {}^{71}\mathrm{Ga}$
+ KeV Auger electrons, X rays
e^-
γ


Solar neutrinos
ν_e
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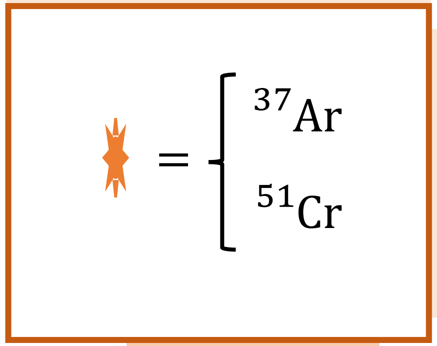
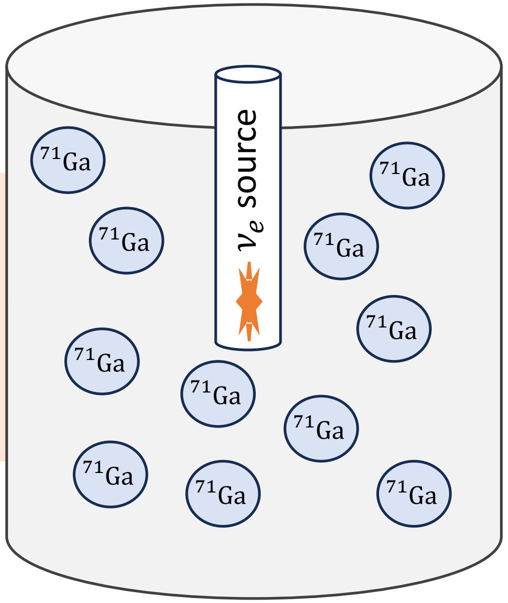
$e^- + {}^{71}\mathrm{Ge} \rightarrow \nu_e + {}^{71}\mathrm{Ga}$
+ KeV Auger electrons, X rays
γ
e^-
# of decays
=
# of captures

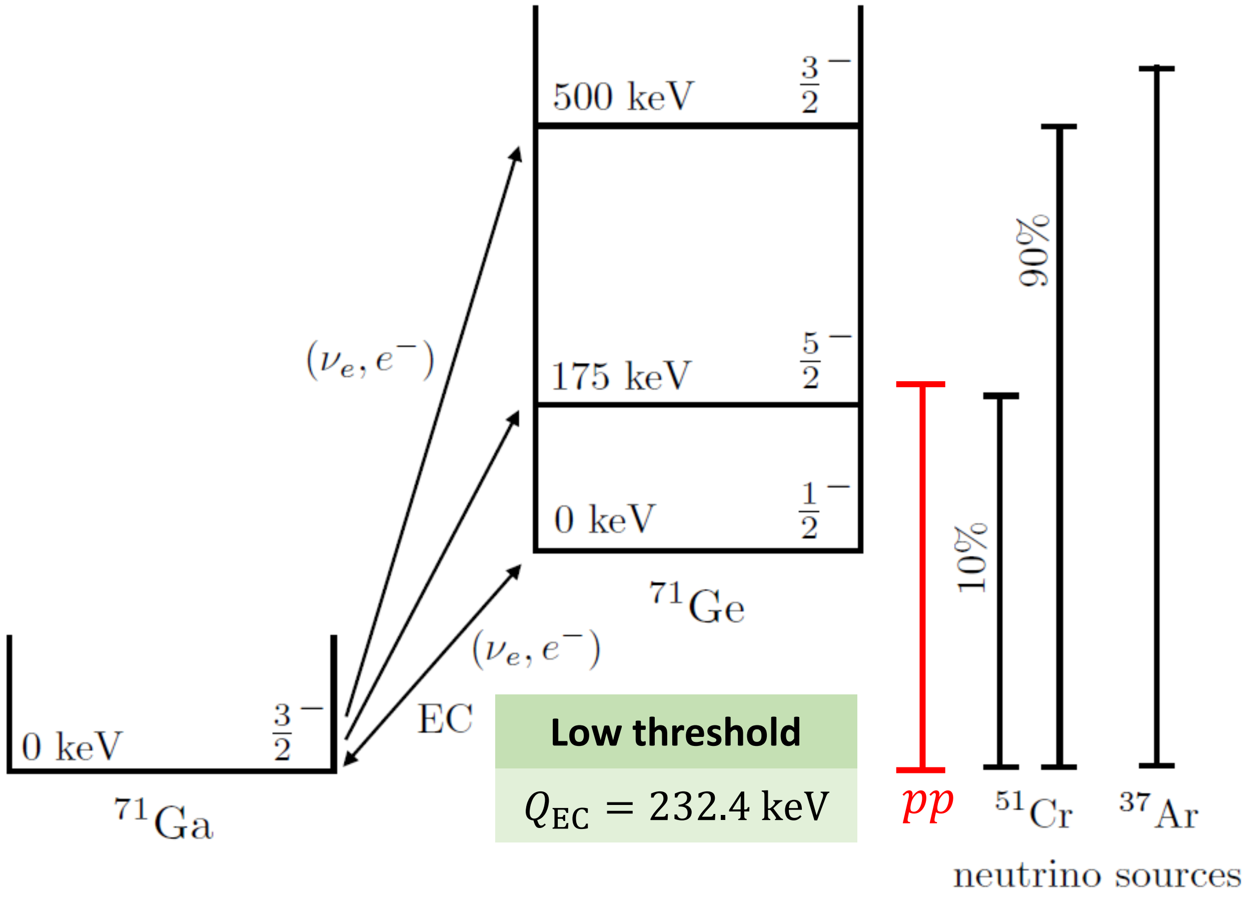
Calibration experiments

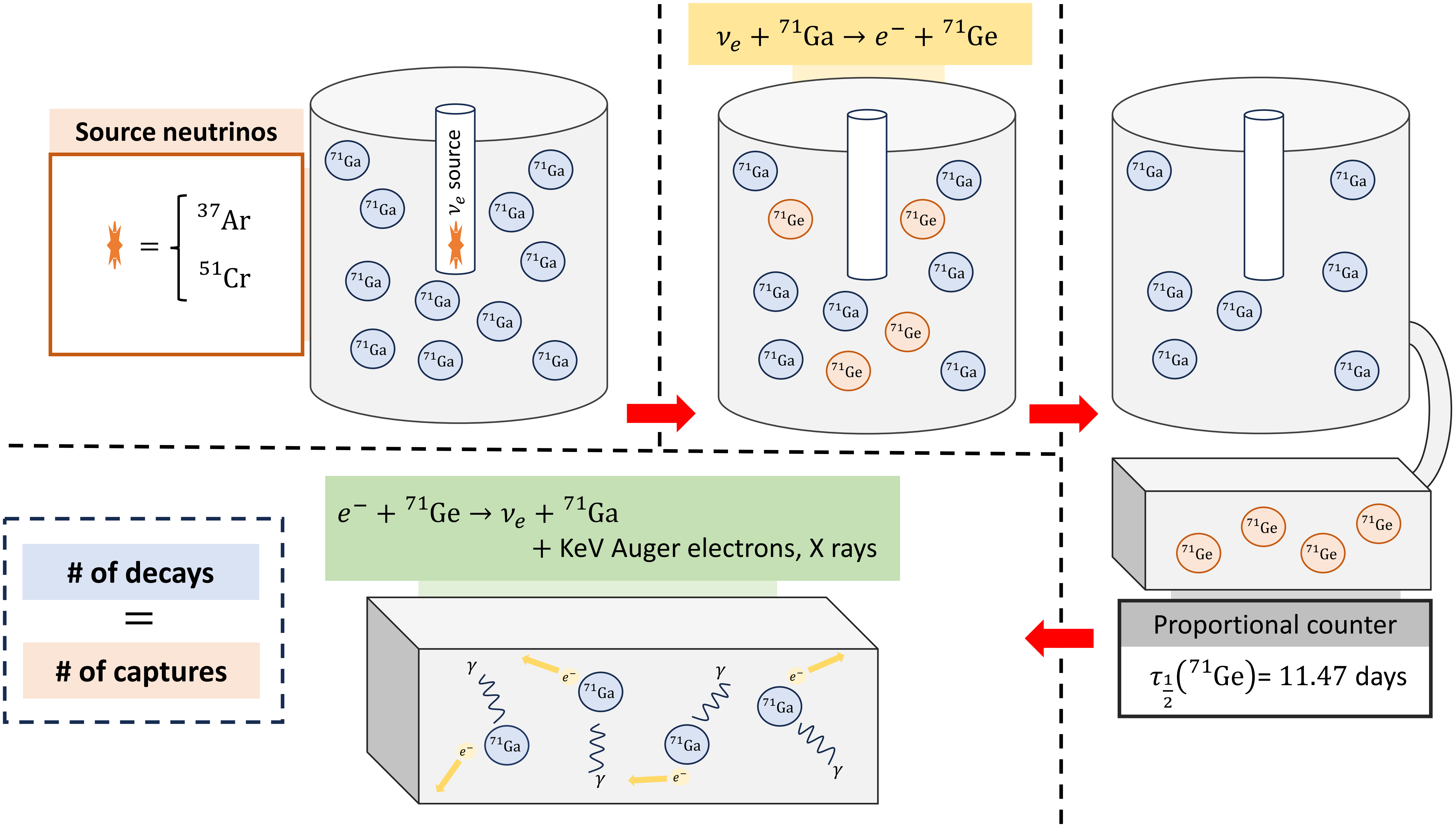
Source neutrinos



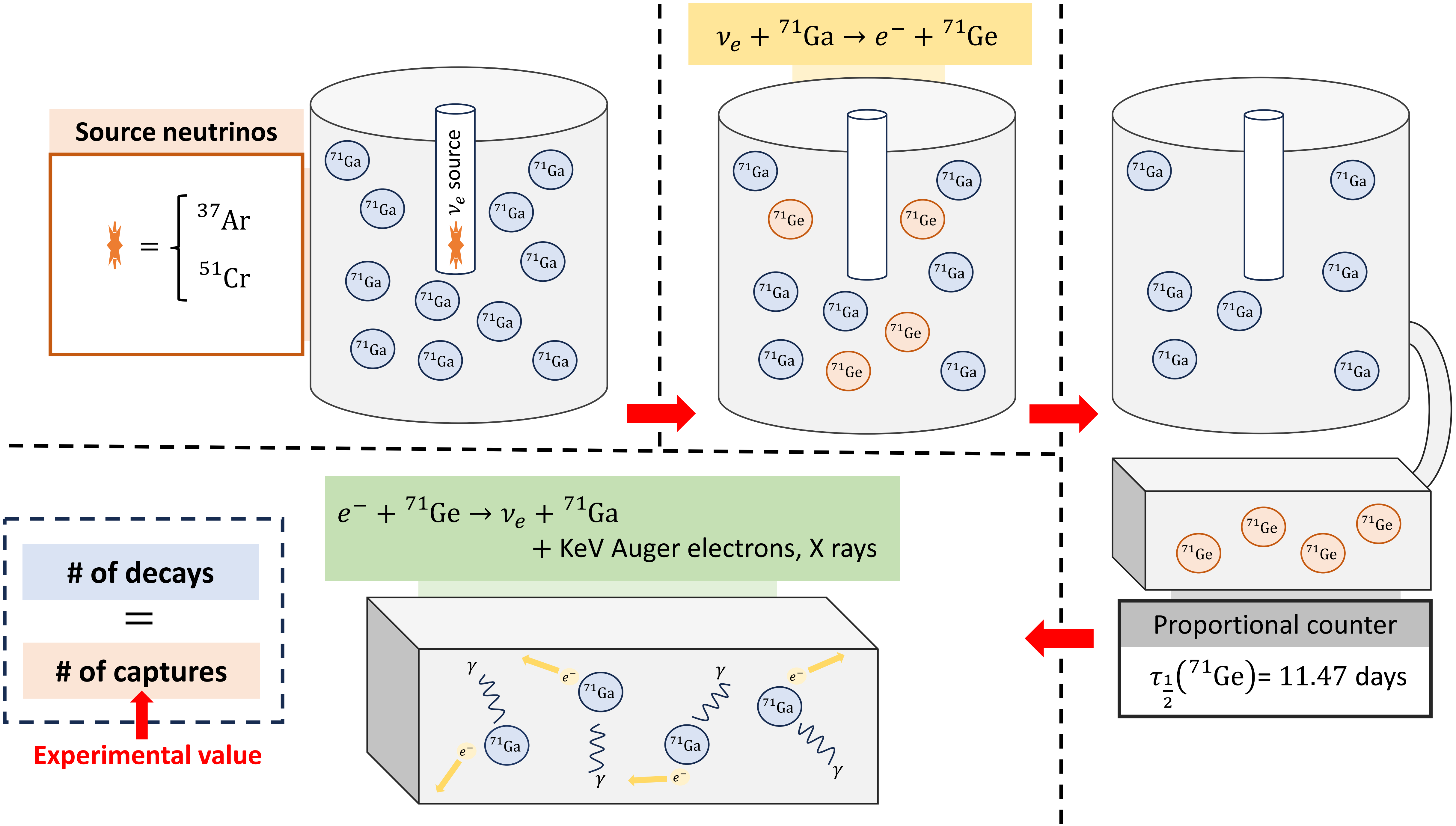


Similar neutrino energies to solar *pp* neutrinos





Source neutrinos
$= \begin{cases} {}^{37}\mathrm{Ar} \\ {}^{51}\mathrm{Cr} \end{cases}$
ν_e source
${}^{71}\mathrm{Ga}$
$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$
${}^{71}\mathrm{Ge}$
Proportional counter
$\tau_{\frac{1}{2}}({}^{71}\mathrm{Ge})$= 11.47 days
$e^- + {}^{71}\mathrm{Ge} \rightarrow \nu_e + {}^{71}\mathrm{Ga}$
+ KeV Auger electrons, X rays
γ
e^-
# of decays
=
# of captures


Source neutrinos
= { ^{37}Ar, ^{51}Cr
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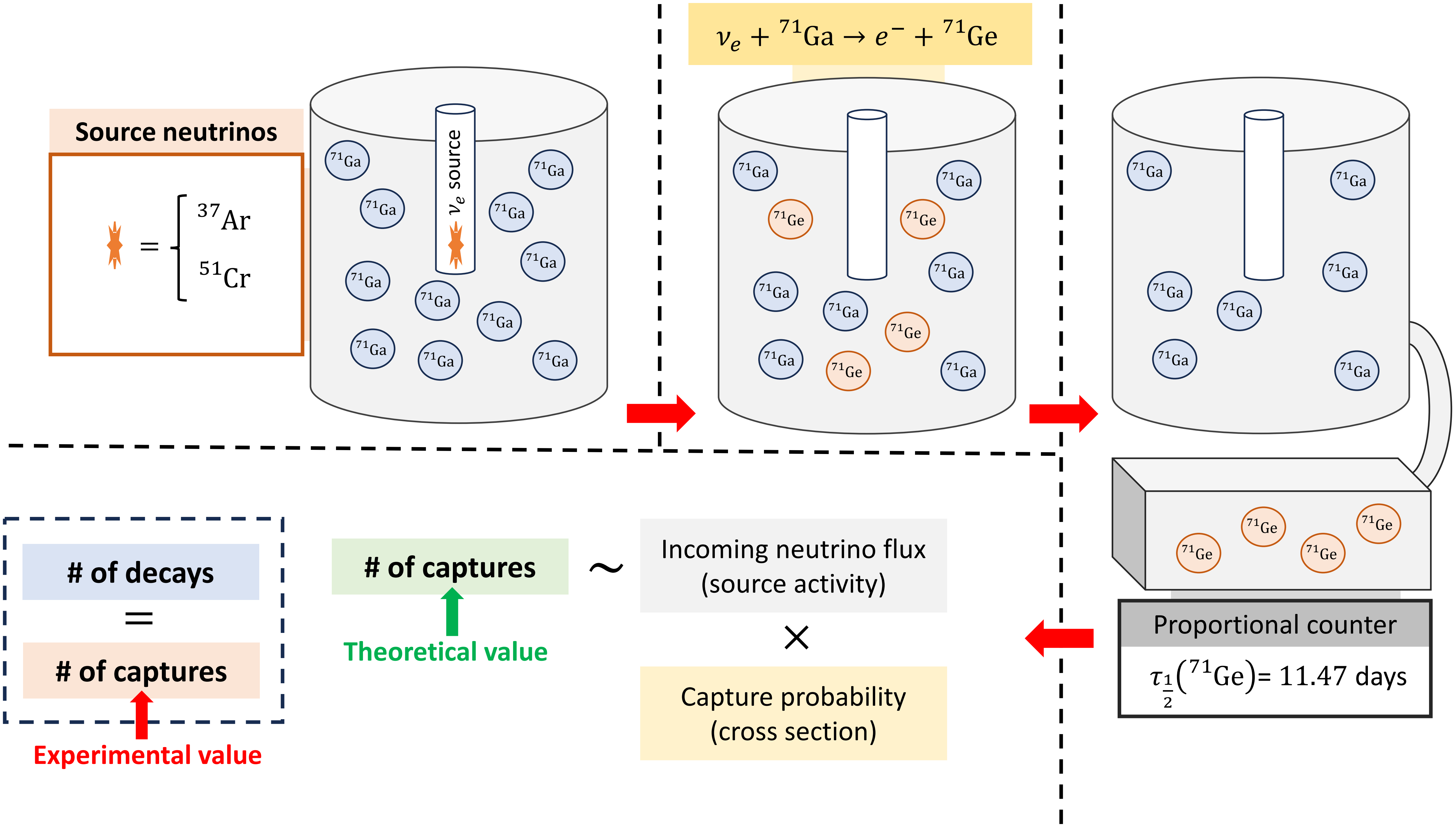
+ KeV Auger electrons, X rays
γ
e^-
# of decays
=
# of captures
Experimental value



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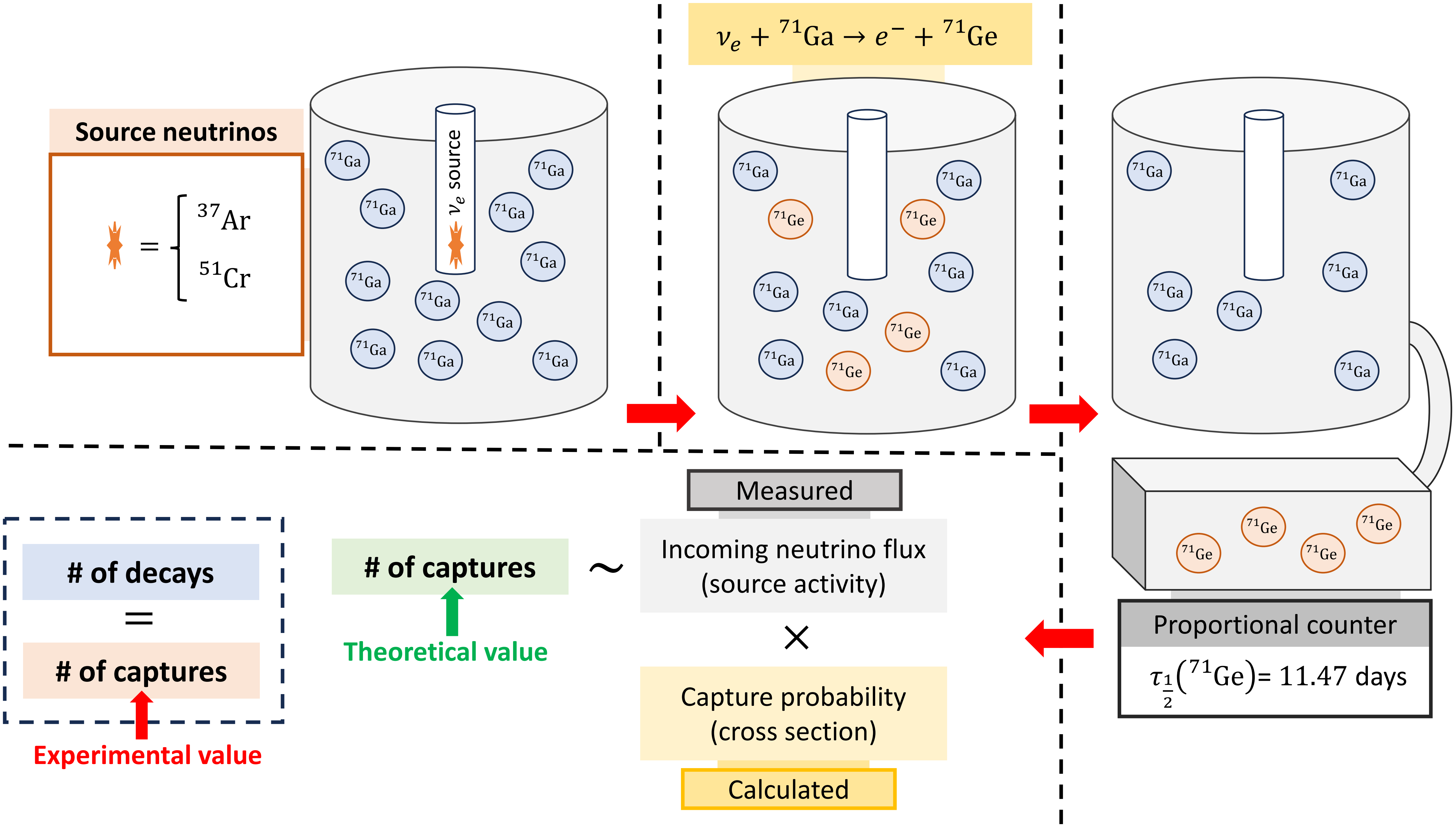
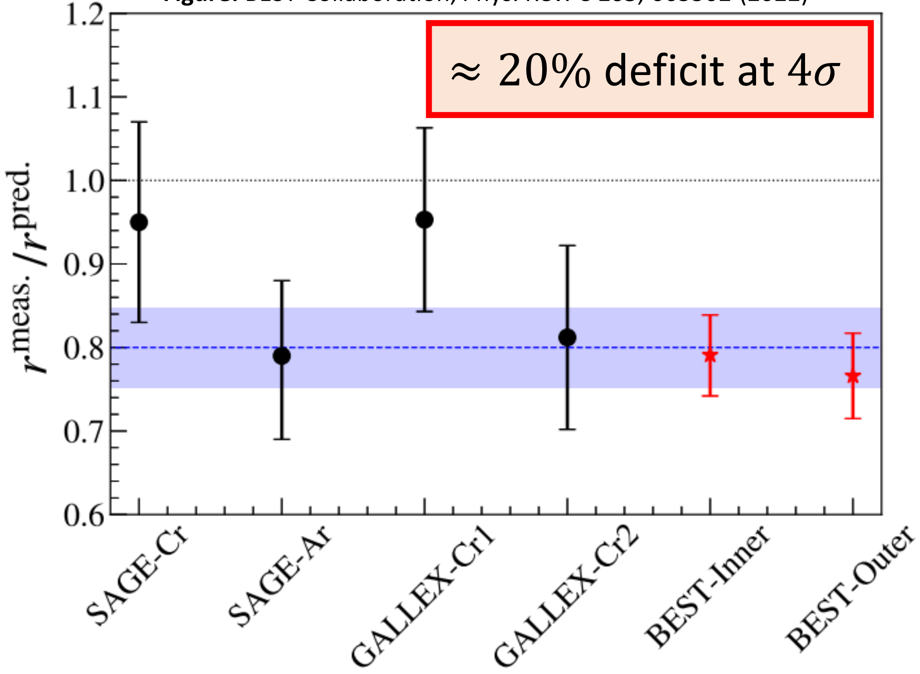
# of decays
=
# of captures
Experimental value
# of captures
Theoretical value
~
Incoming neutrino flux
(source activity)
×
Capture probability
(cross section)



$\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$
Source neutrinos
$= \begin{cases} {}^{37}\text{Ar} \\ {}^{51}\text{Cr} \end{cases}$
ν_e source
^{71}Ga
^{71}Ge
Measured
Incoming neutrino flux (source activity)
×
Capture probability (cross section)
Calculated
# of decays
=
# of captures
Experimental value
# of captures
Theoretical value
~
Proportional counter
$\tau_{\frac{1}{2}}({}^{71}\text{Ge})$= 11.47 days

Figure: BEST Collaboration, Phys. Rev. C **105**, 065502 (2022)



# of decays

=

# of captures

Experimental value

# of captures ∼ Incoming neutrino flux (source activity) × Capture probability (cross section)

Theoretical value

Measured

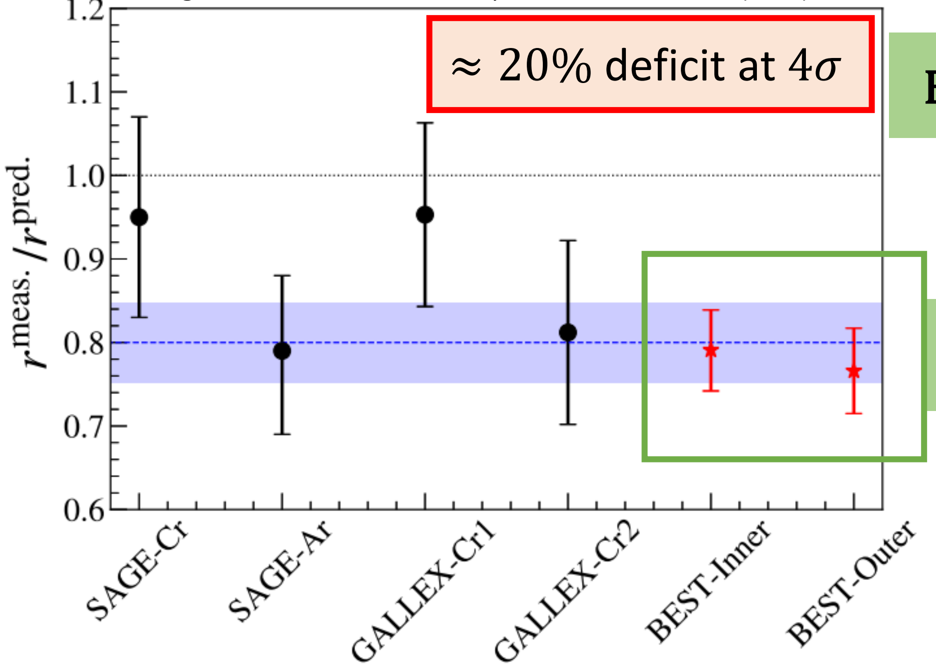
Incoming neutrino flux
(source activity)

×

Capture probability
(cross section)

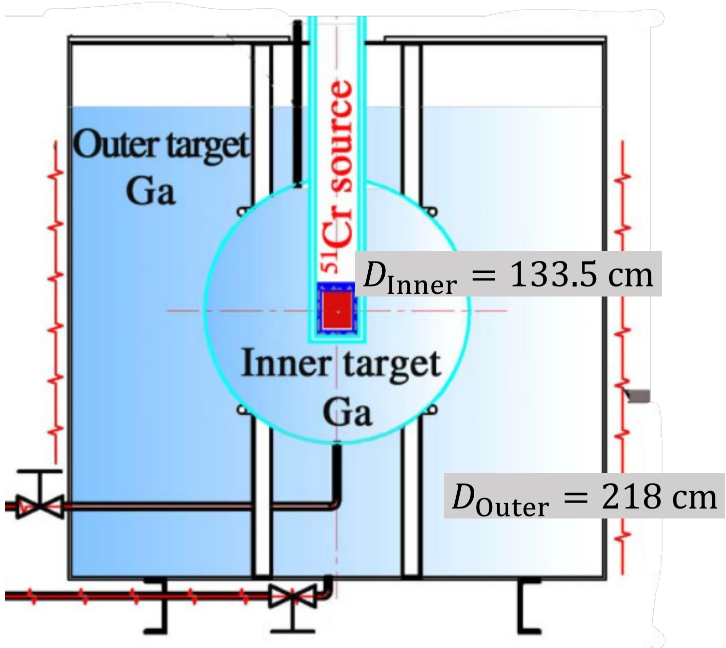
Calculated

Figure: BEST Collaboration, Phys. Rev. C **105**, 065502 (2022)



Baksan Experiment on Sterile Transitions

- 3.4 MCr ^{51}Cr neutrino source
- ≈ 47 tons of liquid gallium
- Inner and outer volumes to probe oscillation length



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

# of decays

=

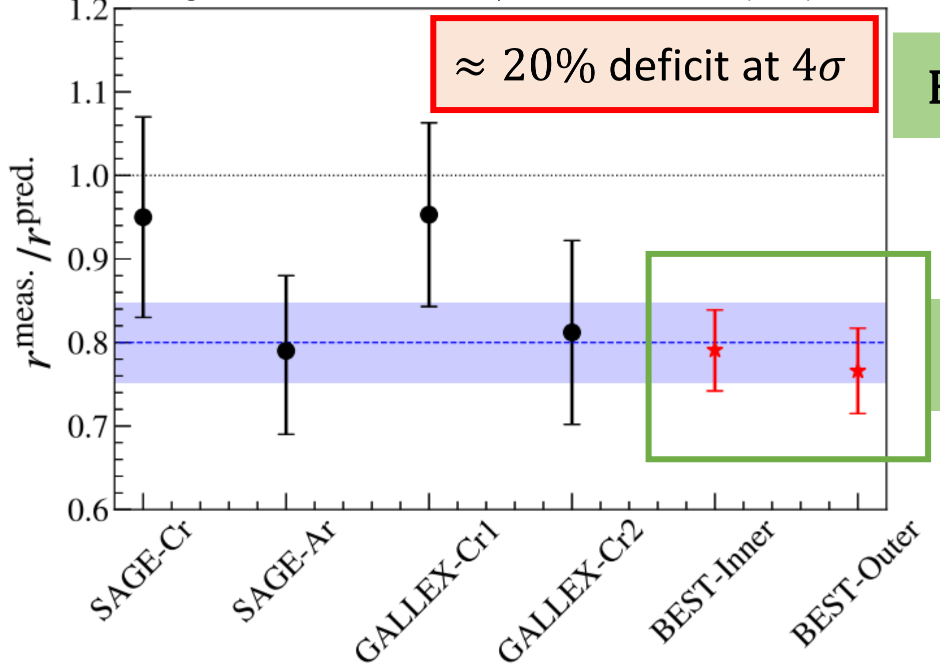
# of captures

Experimental value

# of captures ~ Measured: Incoming neutrino flux (source activity) × Capture probability (cross section): Calculated

Theoretical value

Figure: BEST Collaboration, Phys. Rev. C **105**, 065502 (2022)



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≈ 47 tons of liquid gallium

Inner and outer volumes to probe oscillation length

# of decays

=

# of captures

Experimental value

# of captures ~ Incoming neutrino flux (source activity) × Capture probability (cross section)

Theoretical value

Measured

Calculated

Cross section computed by Bahcall in Phys. Rev. C **56**, 3391 (1997)

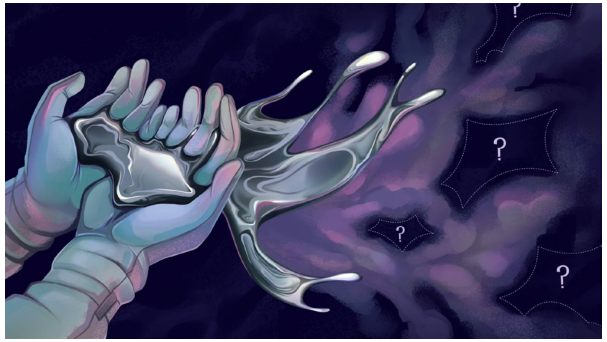
Editors' Suggestion

Elliott, Gavrin, Haxton, Ibragimova, & **ER**, Phys. Rev. C **108**, 035502

Most precise determination of ^{71}**Ga neutrino capture** cross sections for ^{51}**Cr** and ^{37}**Ar** sources

New effects: weak magnetism, radiative corrections

Image: Nico Roper/*Quanta Magazine*



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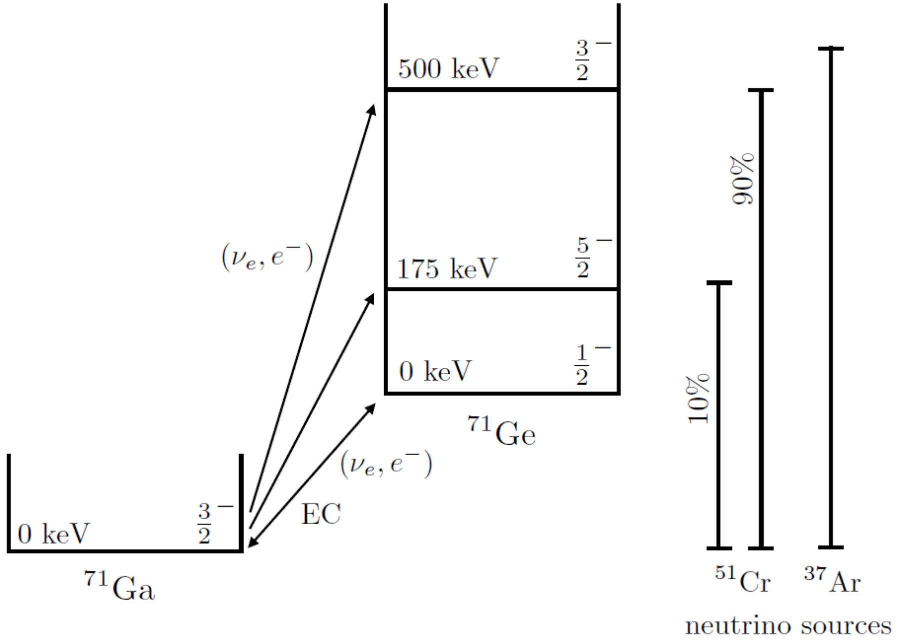
What Could Explain the Gallium Anomaly?

Ground-state contributions **extracted** from **Inverse electron-capture** reaction

$$\tau_{\frac{1}{2}}\left({}^{71}\mathrm{Ge}\right) = 11.465 \pm 0.008 \text{ days}$$

$$\sigma_{\mathrm{g.s.}}\left({}^{51}\mathrm{Cr}\right) = (5.39 \pm 0.08) \times 10^{-45}\ \mathrm{cm}^2$$



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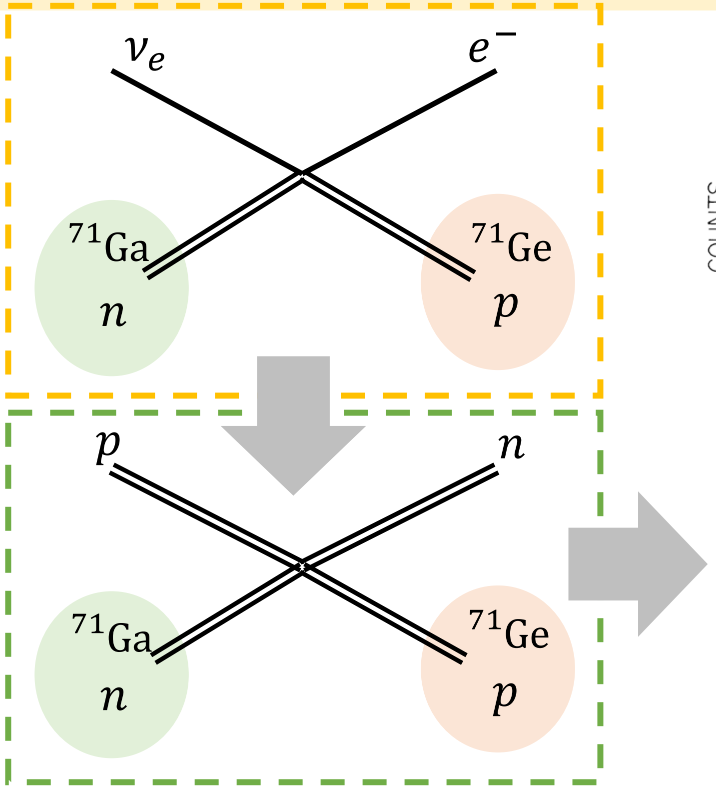
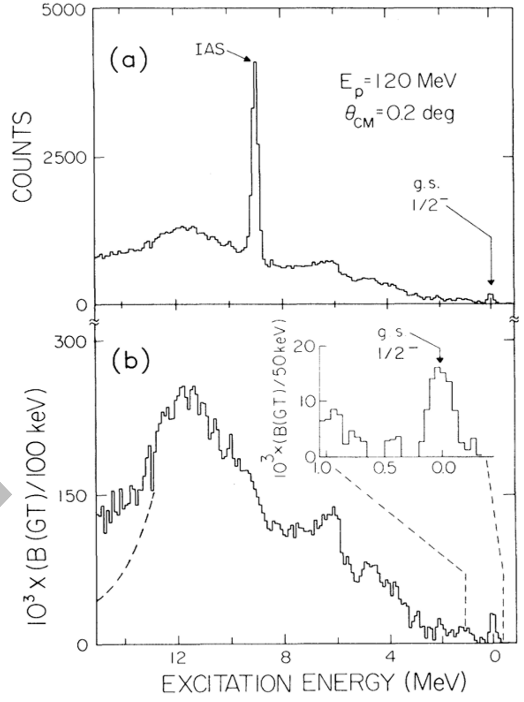
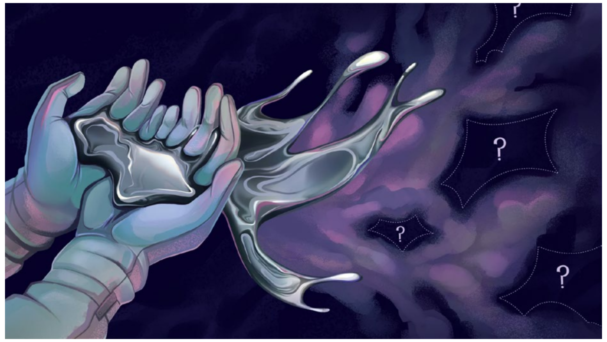


Krofcheck et al., Phys. Rev. Lett. **55**, 1051 (1985)





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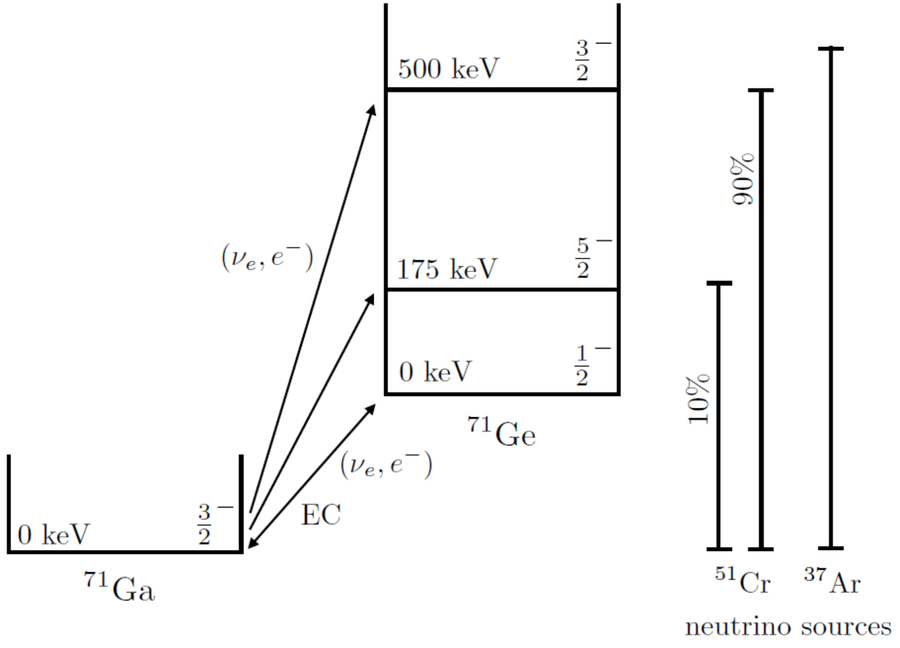

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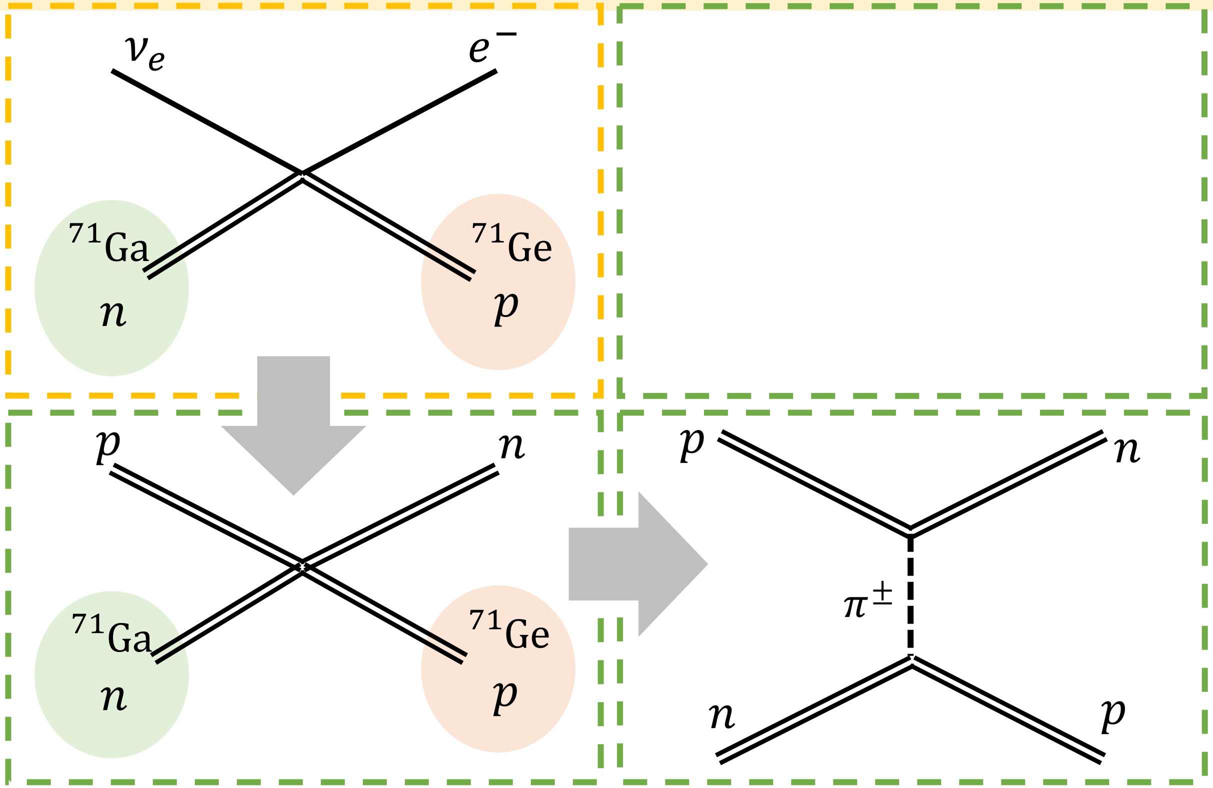

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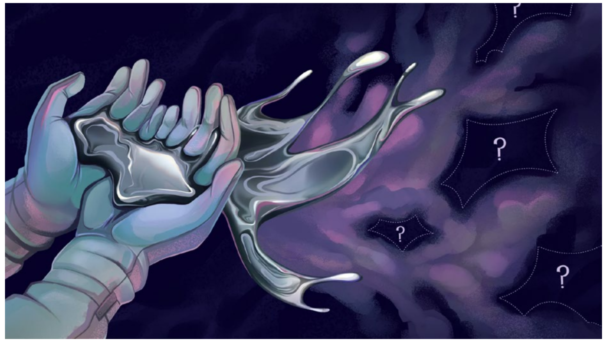

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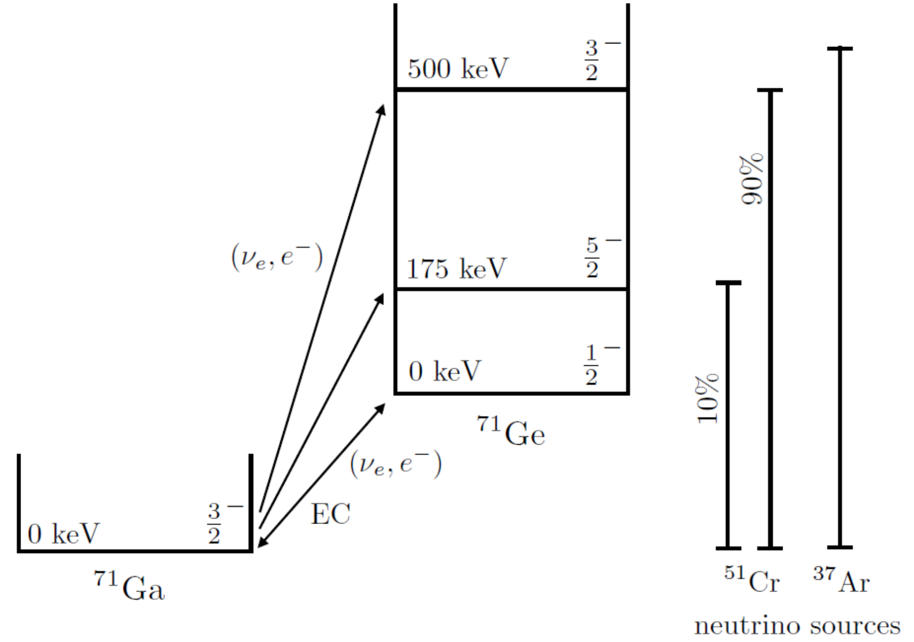

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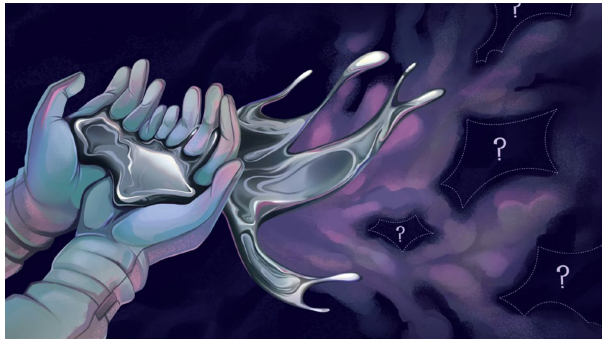

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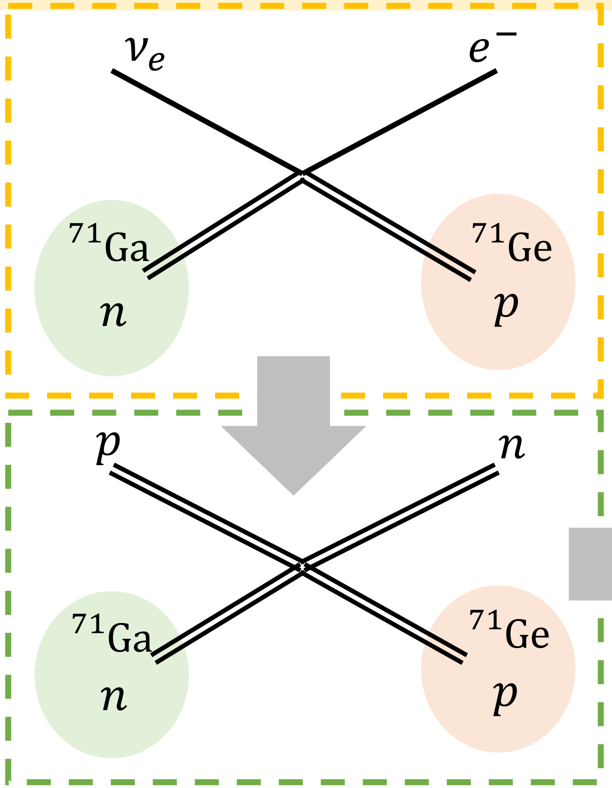
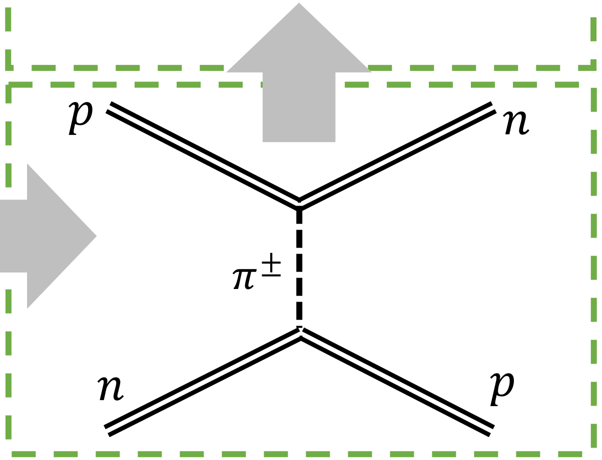
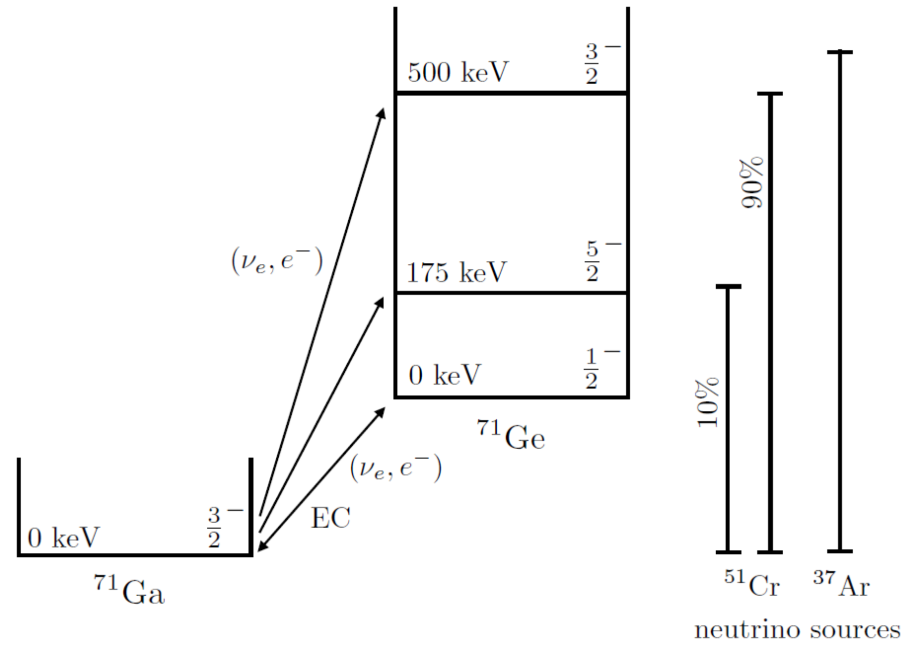


Effective operator	
GT	$\vec{\sigma}\tau_+$
	$+$
Tensor	$\delta\sqrt{8\pi}[Y_2(\hat{r}) \otimes \vec{\sigma}]_1 \tau_+$





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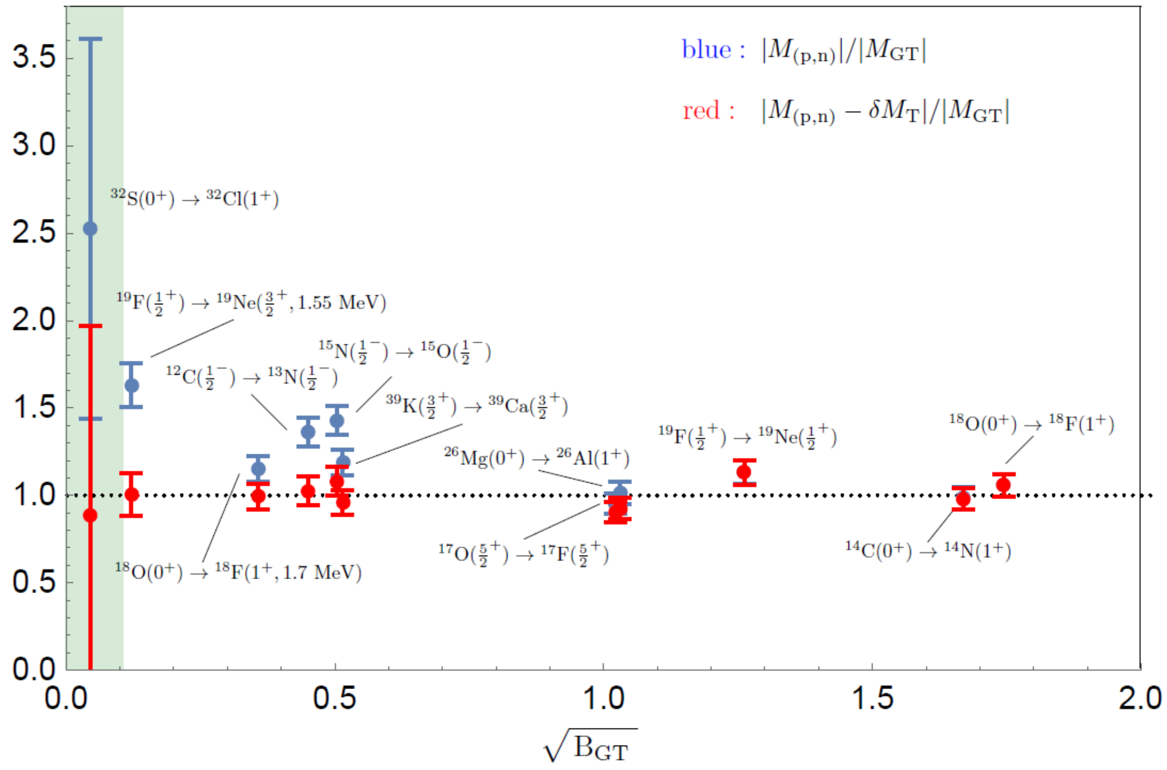

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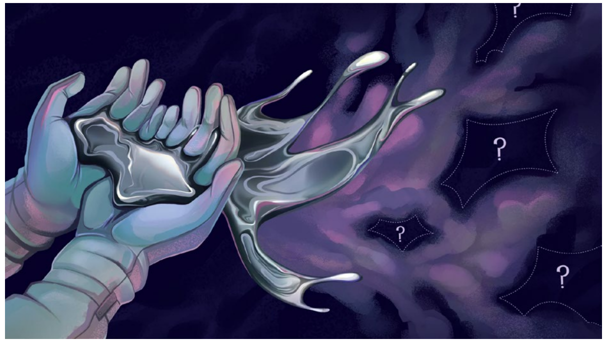

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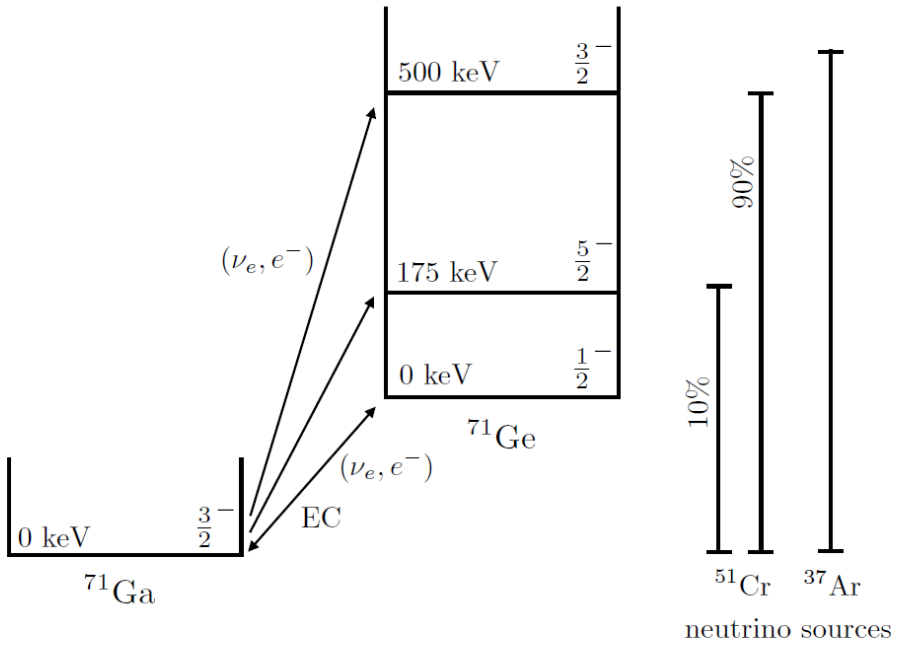

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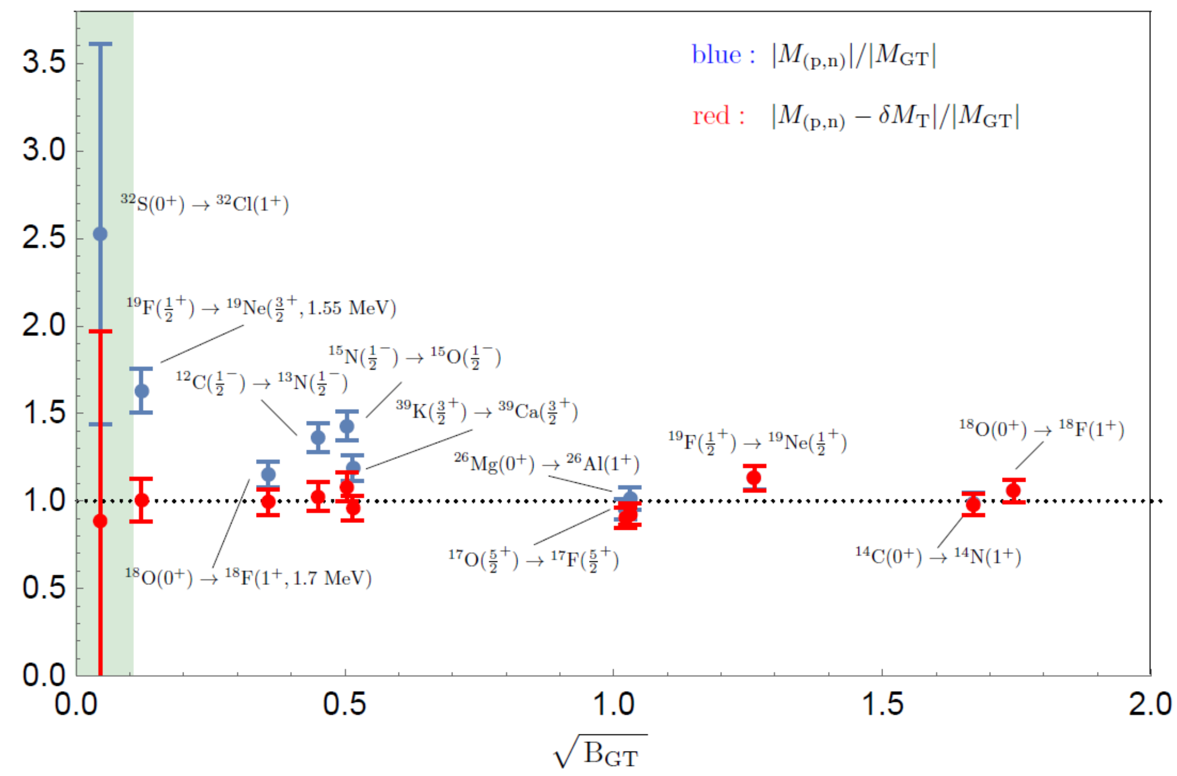

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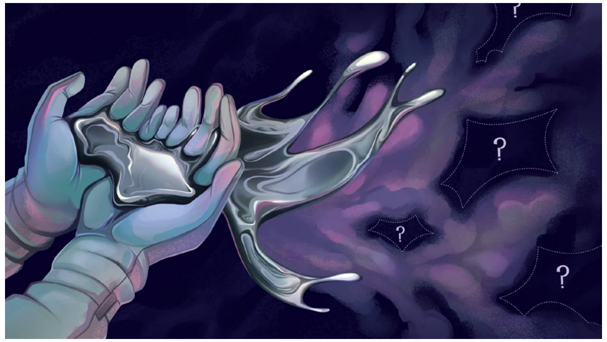

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What Could Explain the Gallium Anomaly?

Result

$\sigma(^{51}\mathrm{Cr})$ **2.4% smaller** than Bahcall's cross section

Bahcall's cross section:

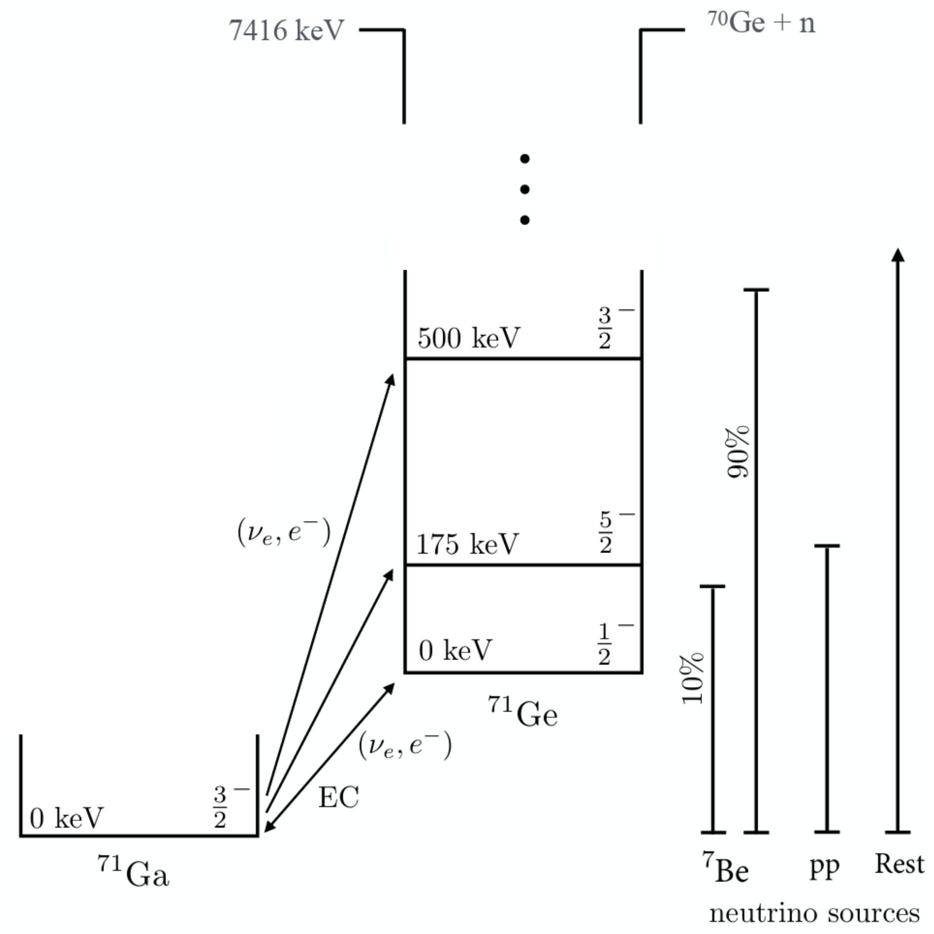
$$R = \begin{cases} 0.79 \pm 0.05, & \text{Inner Volume} \\ 0.77 \pm 0.05, & \text{Outer Volume} \end{cases}$$

Our cross section:

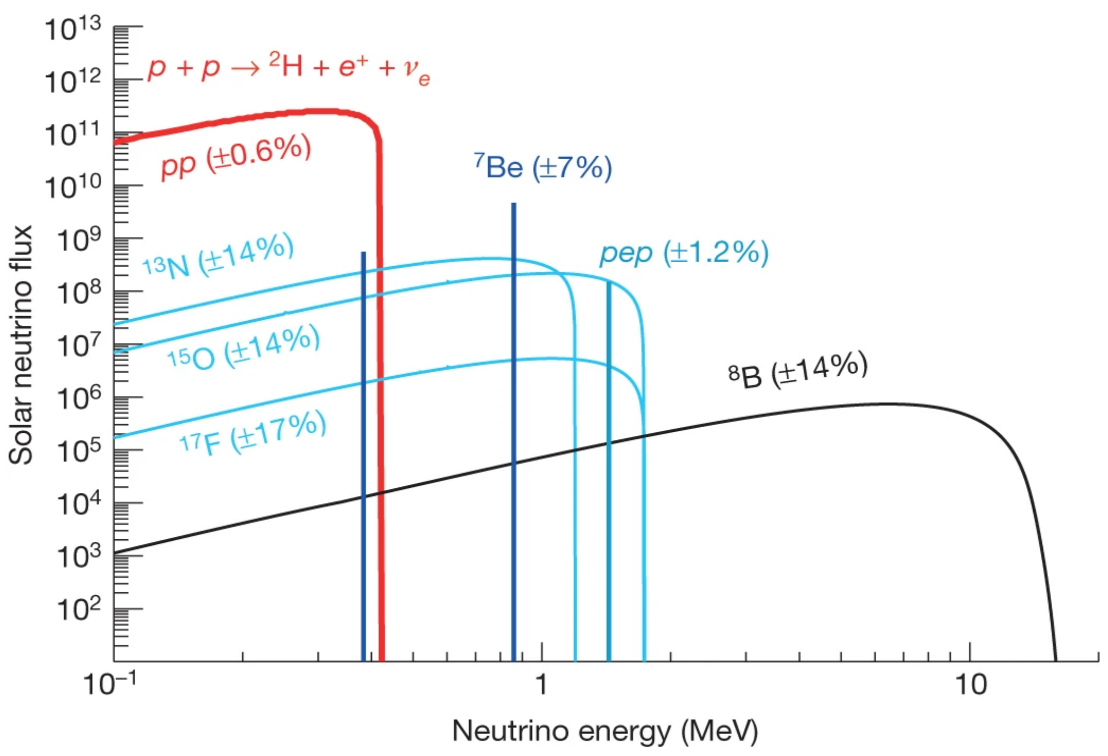
$$R = \begin{cases} 0.81 \pm 0.05, & \text{Inner Volume} \\ 0.78 \pm 0.05, & \text{Outer Volume} \end{cases}$$

How do these improved calculations apply to capture of solar neutrinos?

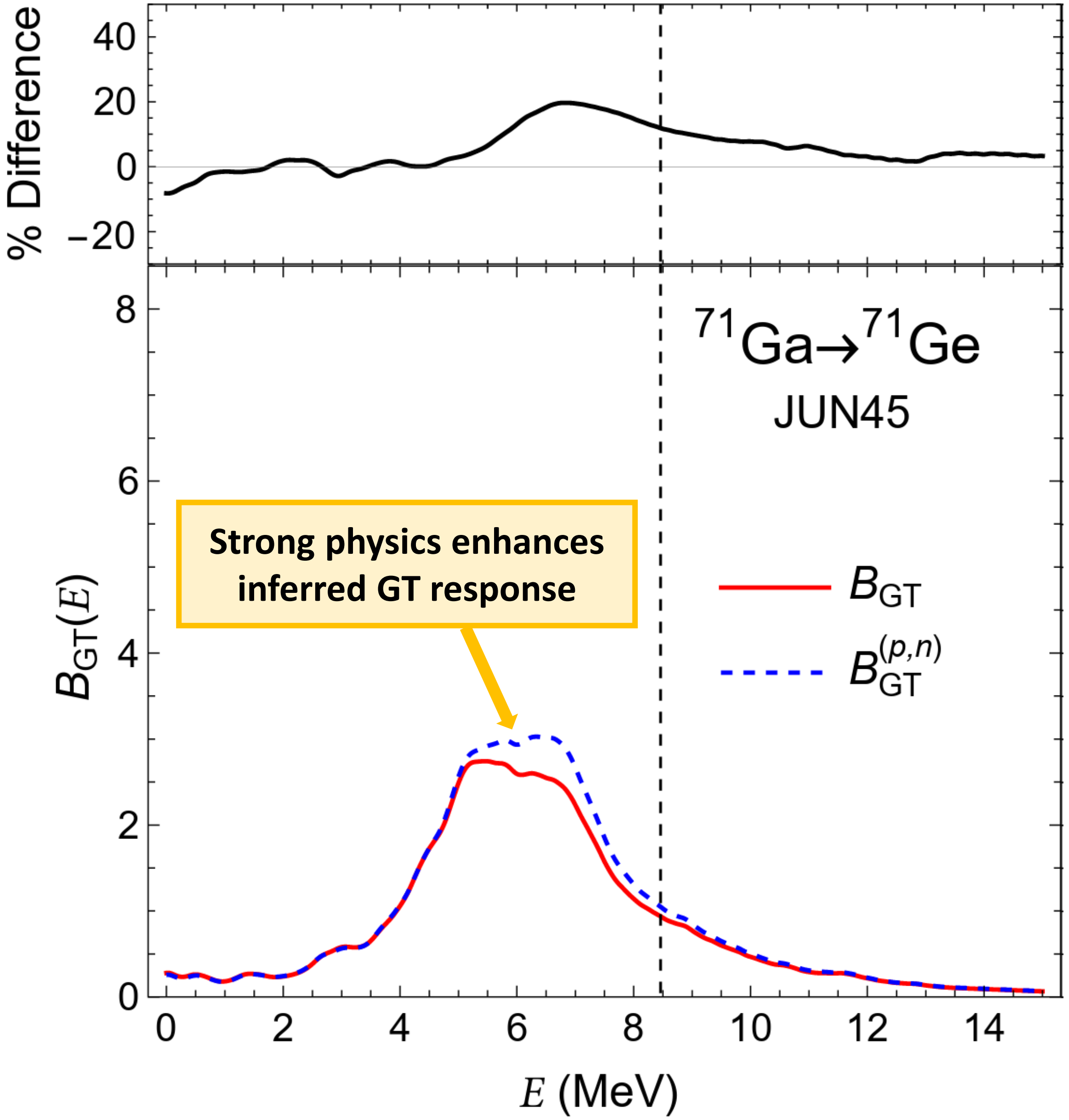
Branch to ^{71}Ge up to 8.46 MeV



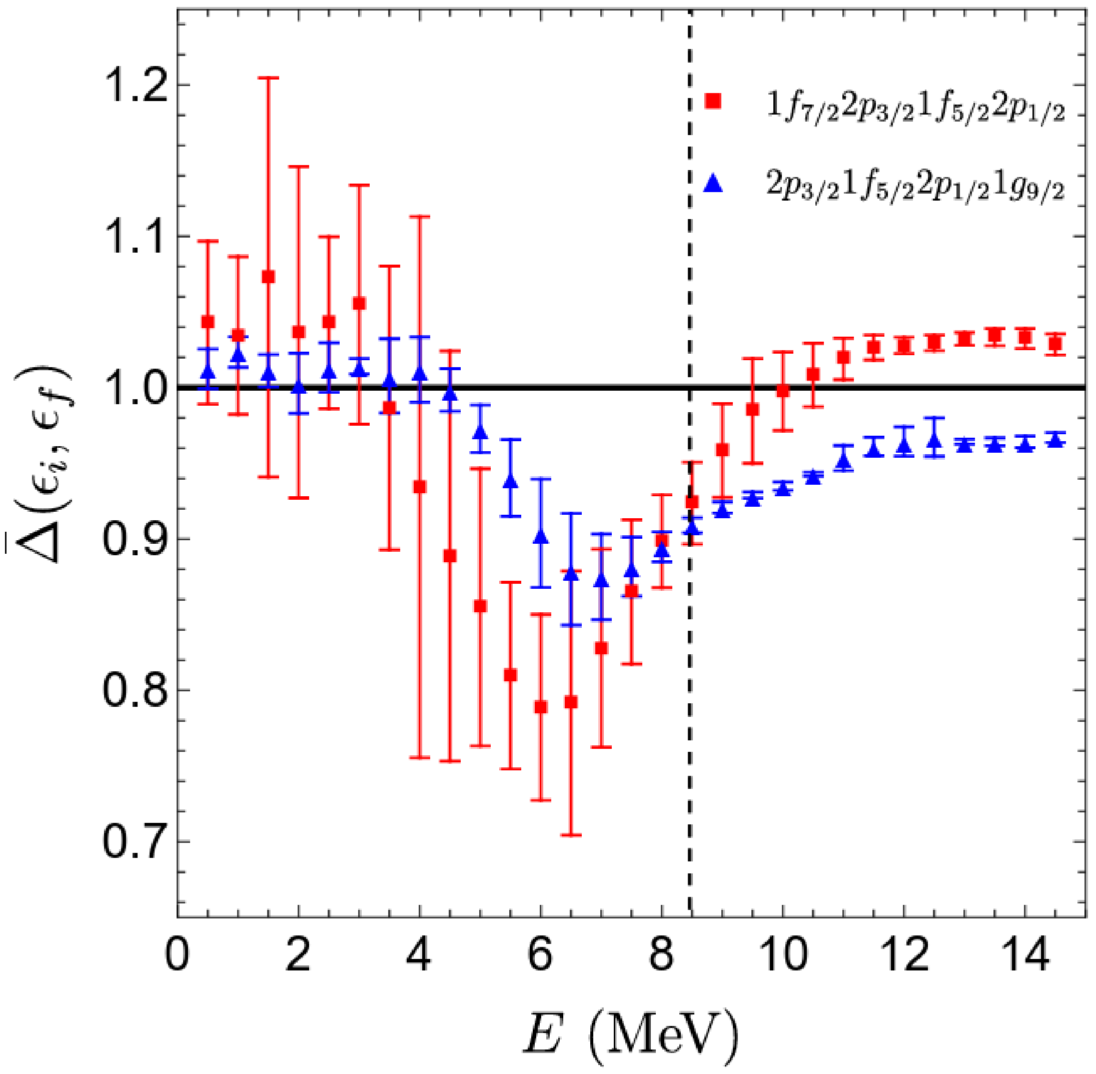
Solar neutrinos can **excite many states** of ^{71}Ge
- Up to and beyond neutron separation threshold



Shell-model response functions



Correction factor



Reduced uncertainties

	Cross sections		Expected capture rates (different solar models)		
ν Source	$\langle\sigma\rangle_{\mathrm{HR}}$ (10^{-45} cm^2)	$\langle\sigma\rangle_{\mathrm{Bahcall97}}$ (10^{-45} cm^2)	$\langle\sigma\phi\rangle_{\mathrm{HR,GS98}}$ (SNU)	$\langle\sigma\phi\rangle_{\mathrm{HR,AAG21}}$ (SNU)	$\langle\sigma\phi\rangle_{\mathrm{HR,MB22p}}$ (SNU)
pp	$1.158^{+0.009}_{-0.009}$	$1.172^{+0.027}_{-0.027}$	$69.0^{+0.7}_{-0.7}$	$69.5^{+0.7}_{-0.7}$	$68.9^{+0.7}_{-0.7}$
pep	$20.4^{+1.0}_{-0.5}$	$20.4^{+3.5}_{-1.4}$	$2.92^{+0.15}_{-0.08}$	$2.96^{+0.15}_{-0.08}$	$2.90^{+0.15}_{-0.08}$
^{7}Be	$7.05^{+0.35}_{-0.09}$	$7.17^{+0.50}_{-0.22}$	$34.2^{+3.0}_{-2.6}$	$31.9^{+2.8}_{-2.4}$	$34.4^{+3.3}_{-2.8}$
^{8}B	$2.57^{+0.30}_{-0.25} \times 10^3$	$2.40^{+0.77}_{-0.36} \times 10^3$	$12.9^{+2.3}_{-2.3}$	$11.1^{+1.9}_{-1.9}$	$13.0^{+2.5}_{-2.5}$
hep	$7.84^{+0.9}_{-0.9} \times 10^3$	$7.14^{+2.3}_{-1.1} \times 10^3$	$0.062^{+0.021}_{-0.021}$	$0.064^{+0.021}_{-0.021}$	$0.062^{+0.020}_{-0.020}$
^{13}N	$5.94^{+0.28}_{-0.07}$	$6.04^{+0.36}_{-0.18}$	$1.66^{+0.28}_{-0.27}$	$1.32^{+0.18}_{-0.17}$	$1.84^{+0.29}_{-0.28}$
^{15}O	$11.2^{+0.5}_{-0.2}$	$11.4^{+1.4}_{-0.6}$	$2.32^{+0.43}_{-0.42}$	$1.77^{+0.29}_{-0.28}$	$2.58^{+0.48}_{-0.47}$
^{17}F	$11.2^{+0.5}_{-0.2}$	$11.4^{+1.4}_{-0.6}$	$0.060^{+0.012}_{-0.012}$	$0.038^{+0.006}_{-0.006}$	$0.053^{+0.009}_{-0.009}$
Total			$123.2^{+6.9}_{-6.3}$	$118.6^{+6.1}_{-5.5}$	$123.8^{+7.4}_{-6.8}$

	Cross sections		Expected capture rates (different solar models)		
ν Source	$\langle\sigma\rangle_{\mathrm{HR}}$ (10^{-45} cm^2)	$\langle\sigma\rangle_{\mathrm{Bahcall97}}$ (10^{-45} cm^2)	$\langle\sigma\phi\rangle_{\mathrm{HR,GS98}}$ (SNU)	$\langle\sigma\phi\rangle_{\mathrm{HR,AAG21}}$ (SNU)	$\langle\sigma\phi\rangle_{\mathrm{HR,MB22p}}$ (SNU)
g_A precision pp	$1.158^{+0.009}_{-0.009}$	$1.172^{+0.027}_{-0.027}$	$69.0^{+0.7}_{-0.7}$	$69.5^{+0.7}_{-0.7}$	$68.9^{+0.7}_{-0.7}$
pep	$20.4^{+1.0}_{-0.5}$	$20.4^{+3.5}_{-1.4}$	$2.92^{+0.15}_{-0.08}$	$2.96^{+0.15}_{-0.08}$	$2.90^{+0.15}_{-0.08}$
^{7}Be	$7.05^{+0.35}_{-0.09}$	$7.17^{+0.50}_{-0.22}$	$34.2^{+3.0}_{-2.6}$	$31.9^{+2.8}_{-2.4}$	$34.4^{+3.3}_{-2.8}$
^{8}B	$2.57^{+0.30}_{-0.25} \times 10^3$	$2.40^{+0.77}_{-0.36} \times 10^3$	$12.9^{+2.3}_{-2.3}$	$11.1^{+1.9}_{-1.9}$	$13.0^{+2.5}_{-2.5}$
hep	$7.84^{+0.9}_{-0.9} \times 10^3$	$7.14^{+2.3}_{-1.1} \times 10^3$	$0.062^{+0.021}_{-0.021}$	$0.064^{+0.021}_{-0.021}$	$0.062^{+0.020}_{-0.020}$
^{13}N	$5.94^{+0.28}_{-0.07}$	$6.04^{+0.36}_{-0.18}$	$1.66^{+0.28}_{-0.27}$	$1.32^{+0.18}_{-0.17}$	$1.84^{+0.29}_{-0.28}$
^{15}O	$11.2^{+0.5}_{-0.2}$	$11.4^{+1.4}_{-0.6}$	$2.32^{+0.43}_{-0.42}$	$1.77^{+0.29}_{-0.28}$	$2.58^{+0.48}_{-0.47}$
^{17}F	$11.2^{+0.5}_{-0.2}$	$11.4^{+1.4}_{-0.6}$	$0.060^{+0.012}_{-0.012}$	$0.038^{+0.006}_{-0.006}$	$0.053^{+0.009}_{-0.009}$
Total			$123.2^{+6.9}_{-6.3}$	$118.6^{+6.1}_{-5.5}$	$123.8^{+7.4}_{-6.8}$

	Cross sections		Expected capture rates (different solar models)		
ν Source	$\langle\sigma\rangle_{\mathrm{HR}}$ (10^{-45} cm^2)	$\langle\sigma\rangle_{\mathrm{Bahcall97}}$ (10^{-45} cm^2)	$\langle\sigma\phi\rangle_{\mathrm{HR,GS98}}$ (SNU)	$\langle\sigma\phi\rangle_{\mathrm{HR,AAG21}}$ (SNU)	$\langle\sigma\phi\rangle_{\mathrm{HR,MB22p}}$ (SNU)
pp	$1.158^{+0.009}_{-0.009}$	$1.172^{+0.027}_{-0.027}$	$69.0^{+0.7}_{-0.7}$	$69.5^{+0.7}_{-0.7}$	$68.9^{+0.7}_{-0.7}$
pep	$20.4^{+1.0}_{-0.5}$	$20.4^{+3.5}_{-1.4}$	$2.92^{+0.15}_{-0.08}$	$2.96^{+0.15}_{-0.08}$	$2.90^{+0.15}_{-0.08}$
^{7}Be	$7.05^{+0.35}_{-0.09}$	$7.17^{+0.50}_{-0.22}$	$34.2^{+3.0}_{-2.6}$	$31.9^{+2.8}_{-2.4}$	$34.4^{+3.3}_{-2.8}$
^{8}B	$2.57^{+0.30}_{-0.25} \times 10^3$	$2.40^{+0.77}_{-0.36} \times 10^3$	$12.9^{+2.3}_{-2.3}$	$11.1^{+1.9}_{-1.9}$	$13.0^{+2.5}_{-2.5}$
hep	$7.84^{+0.9}_{-0.9} \times 10^3$	$7.14^{+2.3}_{-1.1} \times 10^3$	$0.062^{+0.021}_{-0.021}$	$0.064^{+0.021}_{-0.021}$	$0.062^{+0.020}_{-0.020}$
^{13}N	$5.94^{+0.28}_{-0.07}$	$6.04^{+0.36}_{-0.18}$	$1.66^{+0.28}_{-0.27}$	$1.32^{+0.18}_{-0.17}$	$1.84^{+0.29}_{-0.28}$
^{15}O	$11.2^{+0.5}_{-0.2}$	$11.4^{+1.4}_{-0.6}$	$2.32^{+0.43}_{-0.42}$	$1.77^{+0.29}_{-0.28}$	$2.58^{+0.48}_{-0.47}$
^{17}F	$11.2^{+0.5}_{-0.2}$	$11.4^{+1.4}_{-0.6}$	$0.060^{+0.012}_{-0.012}$	$0.038^{+0.006}_{-0.006}$	$0.053^{+0.009}_{-0.009}$
Total			$123.2^{+6.9}_{-6.3}$	$118.6^{+6.1}_{-5.5}$	$123.8^{+7.4}_{-6.8}$

States above S_n decay to ^{71}Ge

Summary

The Gallium Anomaly	**Collaborators:** Steve Elliott, Wick Haxton, Vladimir Gavrin, Tatiana Ibragimova
20% fewer neutrino captures than **predicted**	
Cross section reanalysis affirms anomaly	

Solar neutrino capture	**Collaborators:** Wick Haxton
Reduced uncertainties by factor of $\mathbf{2-3}$	
Increased cross section for **high-energy neutrinos** by $\approx \mathbf{10\%}$	