The Curious Case of the Second 0^+: Resonances in $^{25}Al(p,\gamma)^{26}Si$

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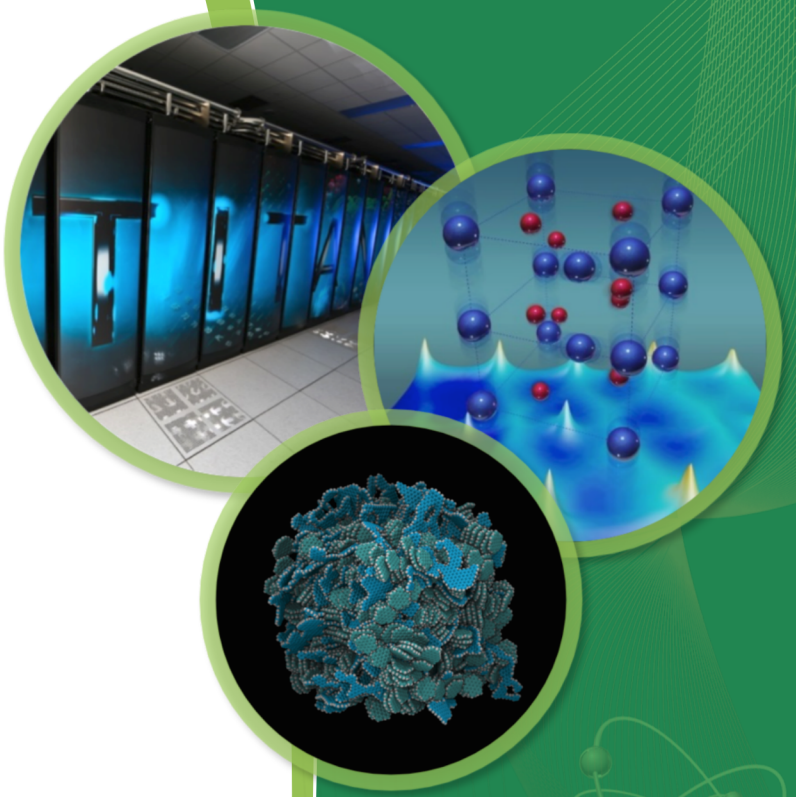
Nuclear Structure 2016



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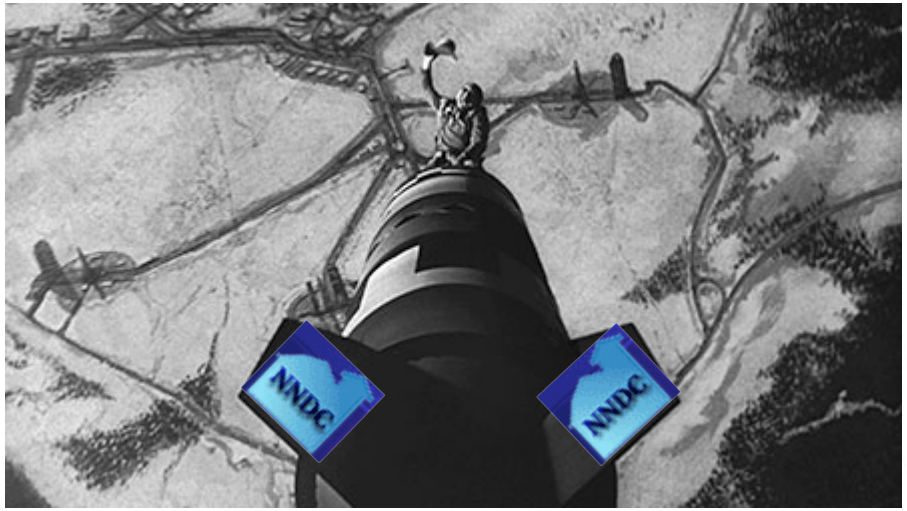
Or,

How I Learned to Stop Worrying and Love Data Evaluation



Resonances in $^{25}Al(p,\gamma)^{26}Si$

- Why resonances in ^{26}Si are of interest
- Literature review
- Reanalysis – why and how
- Adopted values
- Open questions

Why ^{26}Si matters… the *observable* ^{26}Al

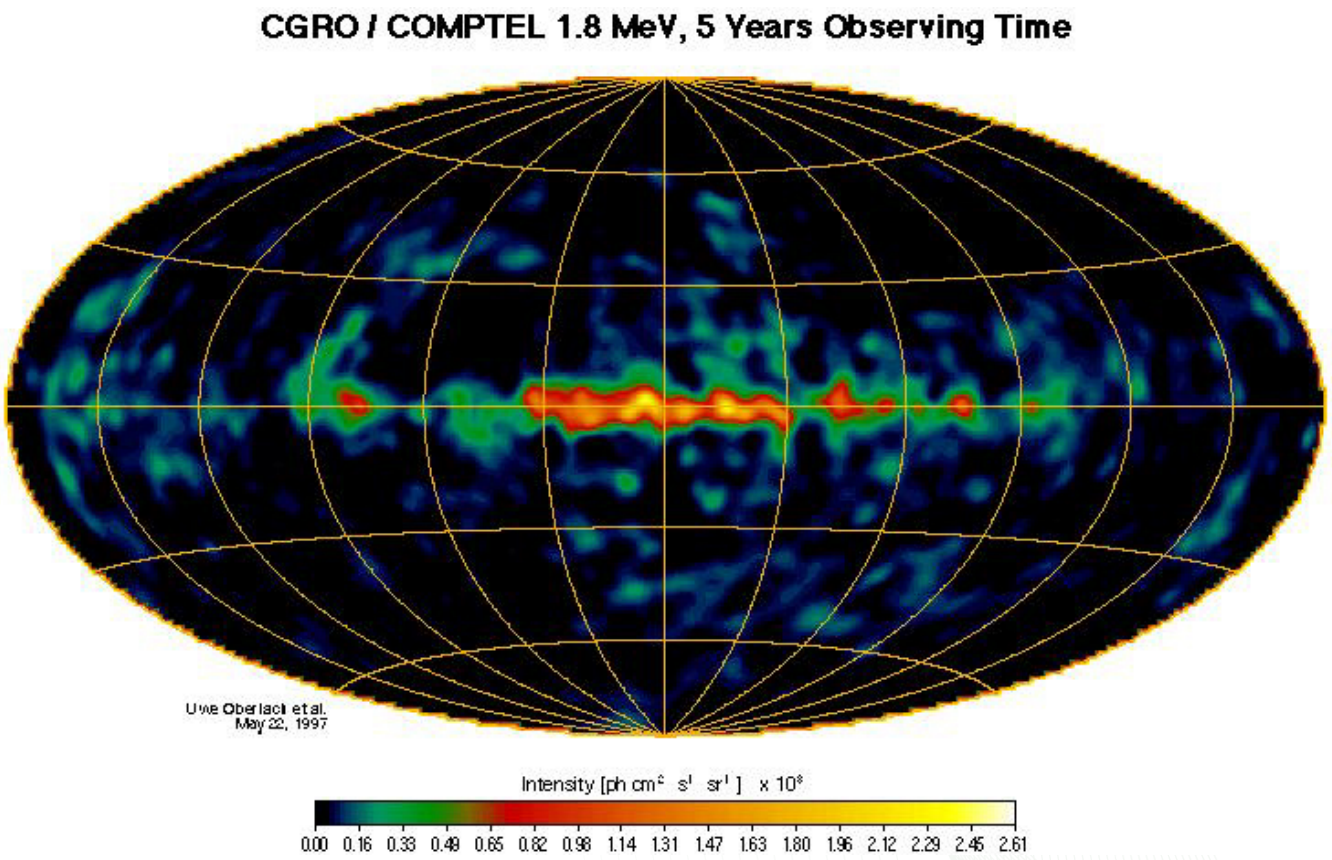
Beginning from the observation of an anomalous ^{26}Mg isotopic ratio in the Allende meteorite, ^{26}Al has been the target of multiple space-based instruments (HEAO, COMPTEL, INTEGRAL) over the past several decades

The direct observation of ^{26}Al decay, via its characteristic 1.809 MeV gamma ray, is particularly important – and useful – because of the properties of this radioactive isotope:

→ its lifetime (~700,000 years) is long enough to outlast the length of an astrophysical explosion, but much shorter than the age of typical stars or the galaxy (so it's recent)

→ it can be tracked as it moves through the interstellar medium

→ since the flux is reasonably constant, it must be actively produced in the universe in order for us to observe it

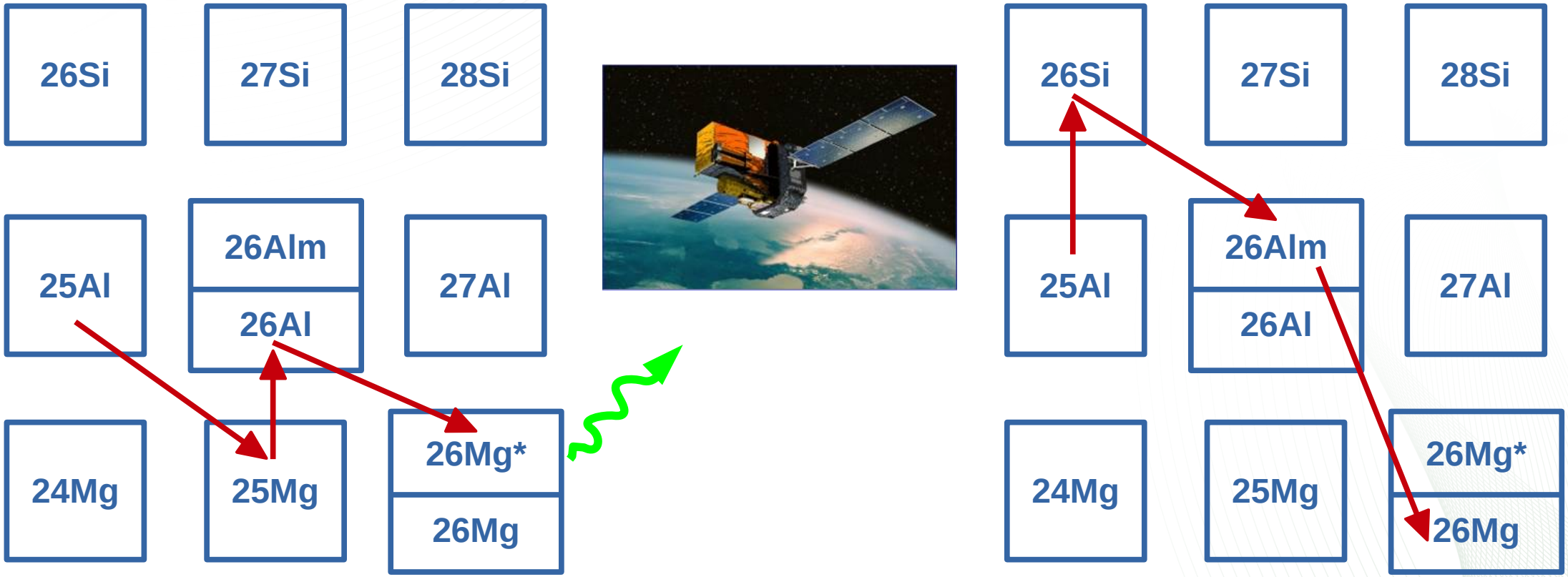


So now the important question: how is the observable ^{26}Al produced?

Production of ^{26}Al

→ Only the ground state produces the 1.809 MeV γ-ray; isomer does not

→ ^{25}Al(p,γ)^{26}Si capture reaction in bypass sequence considered one of three main uncertainties in novae nucleosynthesis



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Current state of knowledge

Resonance: →	A			B			C			D			E		
Measurement: ↓	E_x	J^π	E_r	E_x	J^π	E_r	E_x	J^π	E_r	E_x	J^π	E_r	E_x	J^π	E_r
Compilation [35]	5517.8 ± 0.4[a]	4^+	4[b]	5677.0 ± 1.7	1^+	163.2[b]	5892 ± 4		378.2[b]	5913.8 ± 2.0	3^+	400[b]	5945.9 ± 4.0	0^+	432.1[b]
^{28}Si(p,t) [13]	5562 ± 28												5960 ± 22		
^{24}Mg(^{3}He,n) [14]										5910 ± 30[c]	0^++(4^+)				
^{28}Si(p,t) [15]	5515 ± 5	(4^+)								5916 ± 2	0^+[d]				
^{29}Si(^{3}He,^{6}He) [16]	5526 ± 8	4^+		5678 ± 8									5945 ± 8	3^+	
^{26}P decay [17]										5929 ± 5		412 ± 2			
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^{25}Al(d,n) [26][e]												360 ± 70			(360 ± 70)
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^{27}Si(p,d) [30]	5511 ± 10			5659 ± 22											
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[d] In a later publication [21], additional data plus a new DWBA analysis led to an assignment for this level of 3^+.

[e] Ref. [26] reported a proton decay Q value of 0.36(7) MeV for the first $\ell = 0$ level about the proton threshold, consistent with either Resonance D or E. They assign 3^+ to Resonance D based on the interpretation from Ref. [18].

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Current state of knowledge

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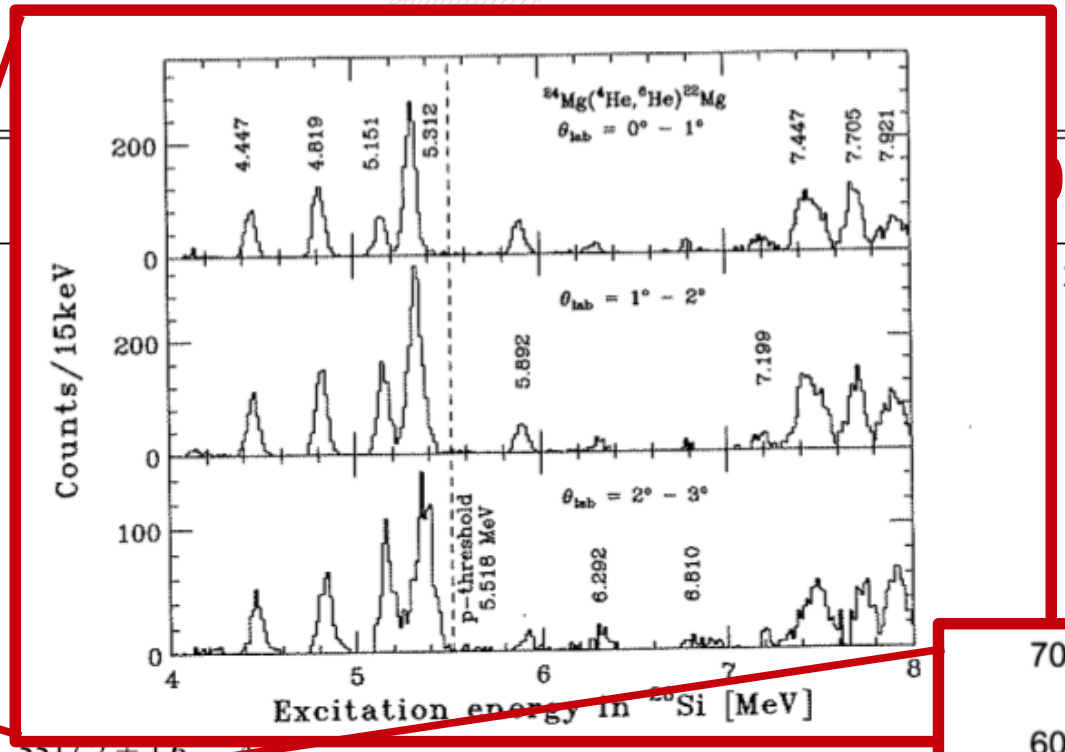
Current



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												D 3+			E 0+?	
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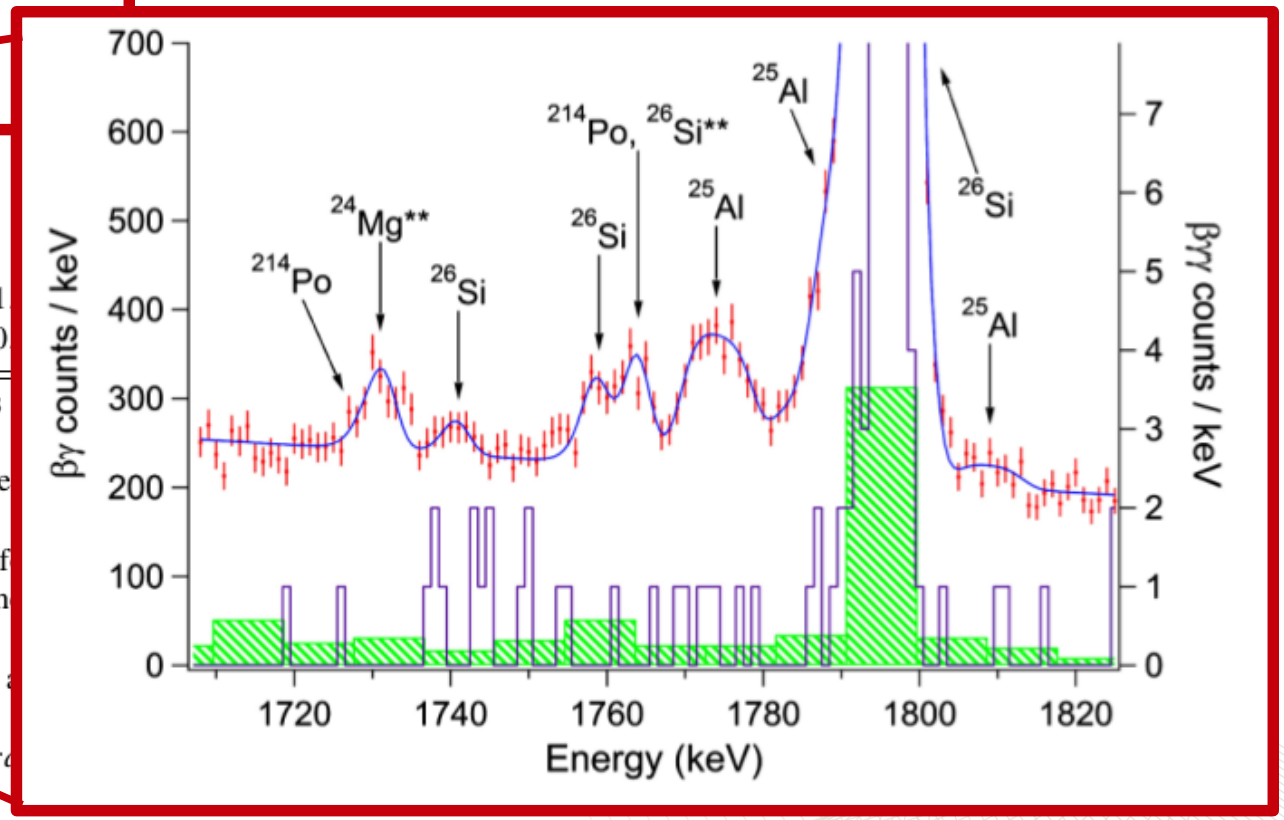


Why data evaluation matters

→ High-resolution gamma spectroscopy data in 2007 (reanalyze earlier data with better-known levels for calibration)

→ High-resolution mass measurement in 2009 (reanalyze earlier data with better-known Q-value)

→ Propagation through the literature of incorrect values (reanalyze earlier data for more meaningful comparisons)

→ Potential issues are brought to light: why are there two 0^+ states when only one is expected?

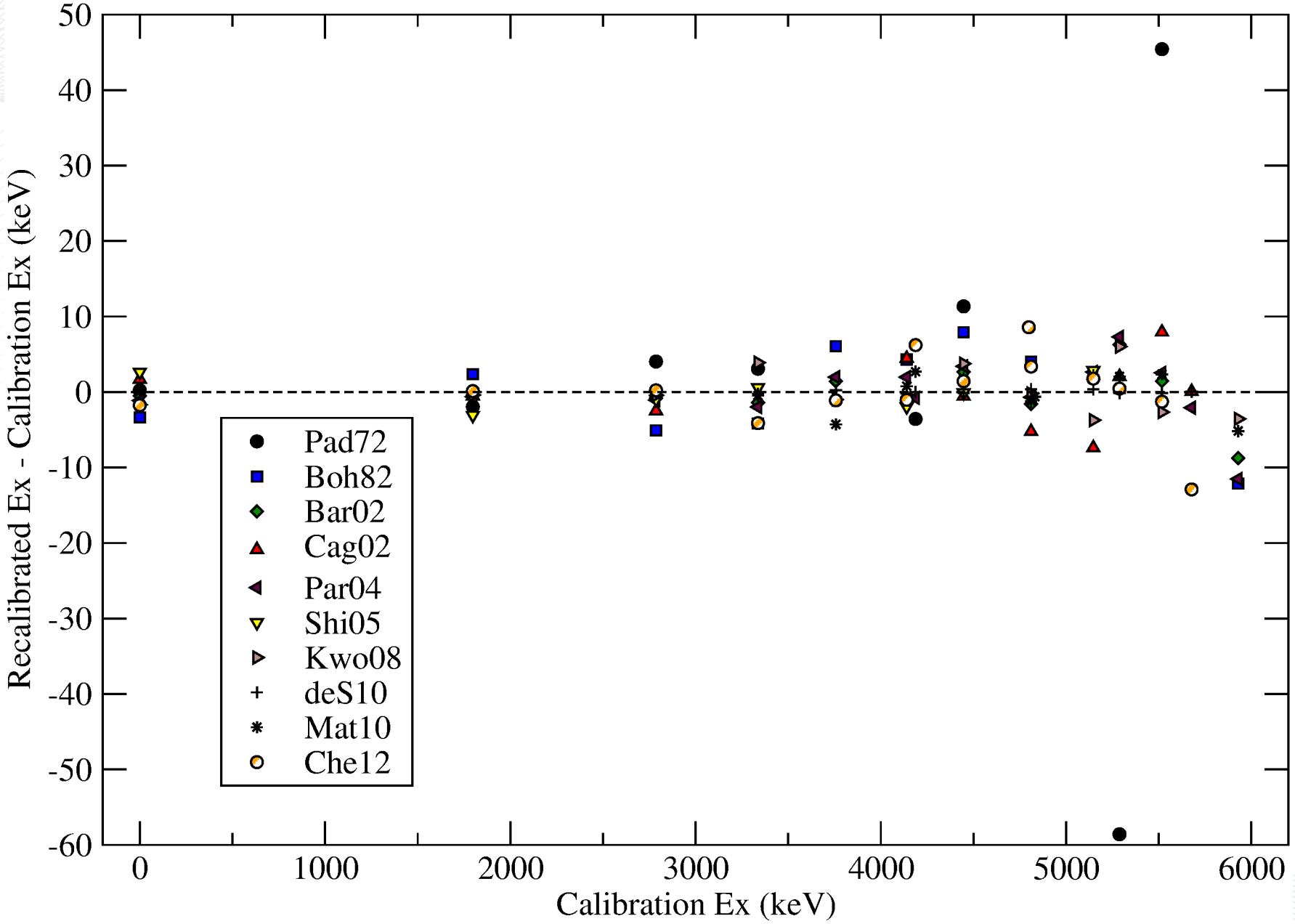
There's a lot of data out there, but it hasn't been compared/combined in a rigorous way
(last time it was done for this reaction was by Chris Wrede in 2009...
six years and over a dozen publications ago!)

Also worth noting: ENSDF folks can only work with what you give them… evaluators have a tough job already, so let's not make it tougher by leaving out information they might need

The reanalysis...

→ For transfer data, the excitation energies were recalibrated using a "known" set comprised of the Seweryniak 2007, Bennett 2013, and Doherty 2015 data

→ For decay data, resonance energies were recalibrated using a "known" value derived from the updated, high-precision mass measurements of Eronen 2009 and Kwiatkowski 2010

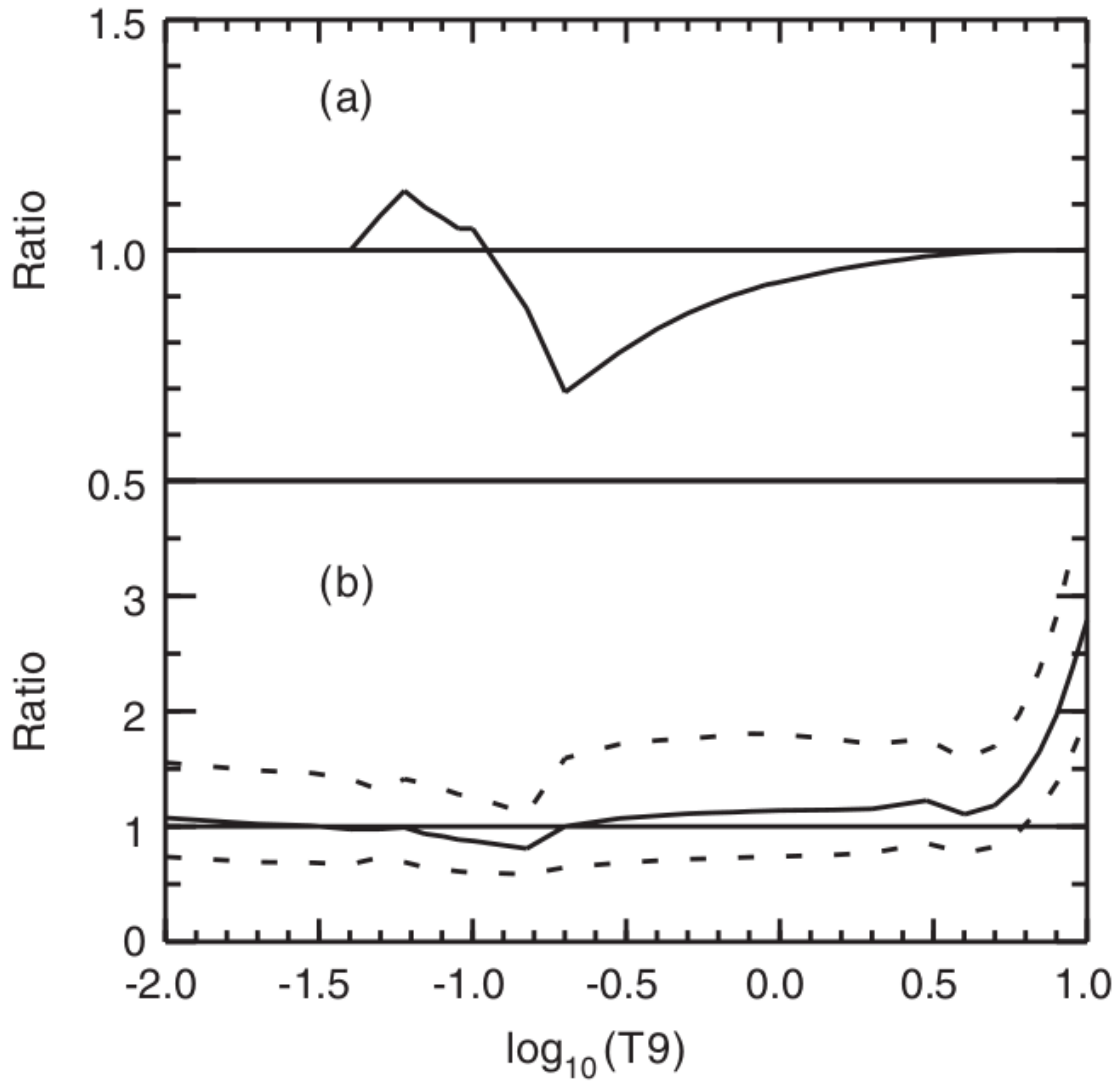


The reanalysis...

Changes in resonance energy can have huge effect (exponential)

→ For example, W.A. Richter calculation: a 6 keV change in the 3^+ resonance energy results in a 30% change in the reaction rate

→ Many of the data in the reanalysis had larger shifts than this (and larger uncertainties!)



W.A. Richter, PRC84, 059802 (2011)

FIG. 1. (a) The new rate (B) divided by the old rate (A) of Ref. [2]. (b) The new rate (B) divided by the rate given in the 2010 evaluation (Table B.37 of Ref. [4]); the solid line is for the median rate and the dashed lines are for the low and high rates.

Adopted values

→ Weighted averages give Ex, combined with better Q value gives Er
→ Bulk of evidence gives spin assignment

Resonance:	A	B	C	D	E
E_x (keV)	5517.3 ± 0.8	5675.2 ± 1.4	5890.0 ± 0.8	5927.6 ± 1.0	5949.7 ± 5.3
J^π	4_4^+	1_1^+	(0_4^+)	3_3^+	$(4_5^+, 0_4^+)$
E_r (keV)	3.5 ± 0.9	161.4 ± 1.5	376.2 ± 1.0	413.8 ± 1.1	435.9 ± 5.3
Refs. included	[15,16,18,22,24,27–30,32,33]	[16,18,22,27,32,33,43]	[20,27,32,33]	[6,14,15,17,18,24,28,29]	[16,18,28]

ENSDF values:	5517.8 +/- 0.4	5677.0 +/- 1.7	5892 +/- 4	5913.8 +/- 2.0	5945.9 +/- 4.0
Difference:	~0.5 keV	~2 keV	~2 keV	~14 keV	~4 keV

Missing pieces

Which 0^+ is the real 0^+? Or are both real?

→ expect a single 0^+ level and two 4^+ levels…

→ seem to have two 0^+ levels and one 4^+ level

→ is mixing from a higher shell involved?

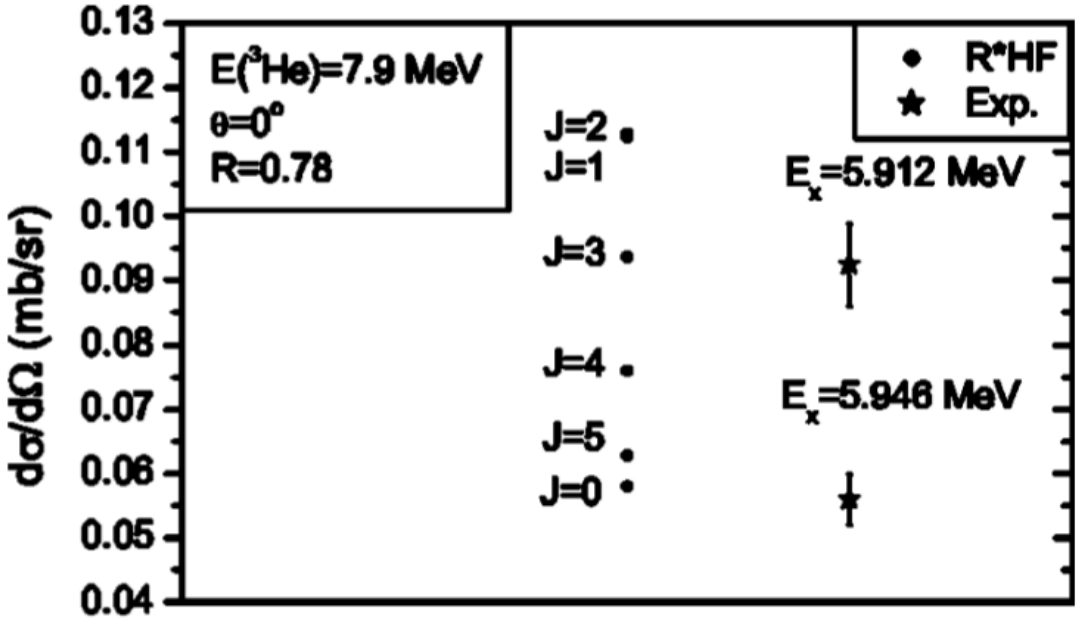
Need more data on partial widths/resonance strengths of these resonances

→ no partial widths or resonance strengths exist for four out of five resonances

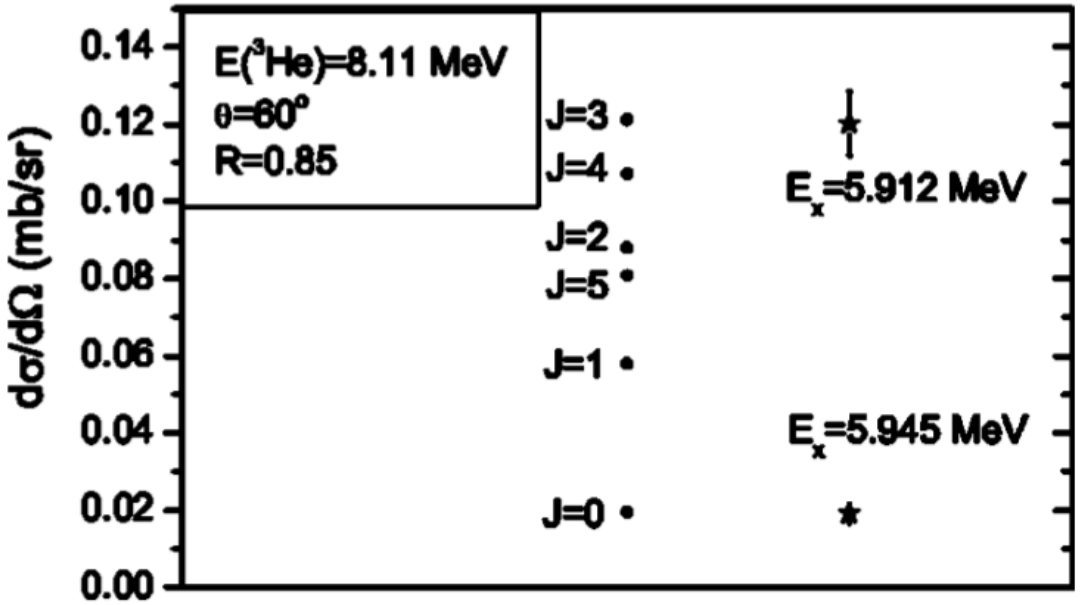
→ calculated strengths exist, but using conflicting information

Need to lower uncertainties on direct capture component of reaction rate as well

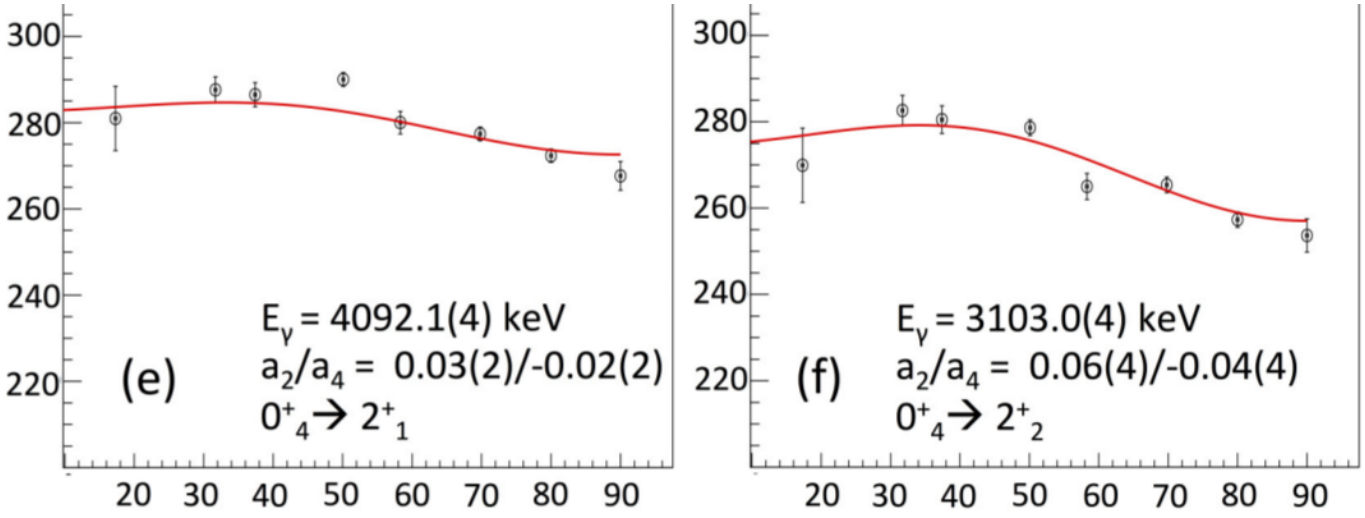
Assignment of 0^+ to Resonances C&E



Parpottas et al PRC70, 065805 (2004)



Doherty et al PRC92, 035808 (2015)



→ Both measurements were $^{24}Mg(^3He,n)$… so why such a discrepancy?

→ Another $(^3He,n)$ measurement (deSereville) saw Resonance C but not Resonance E

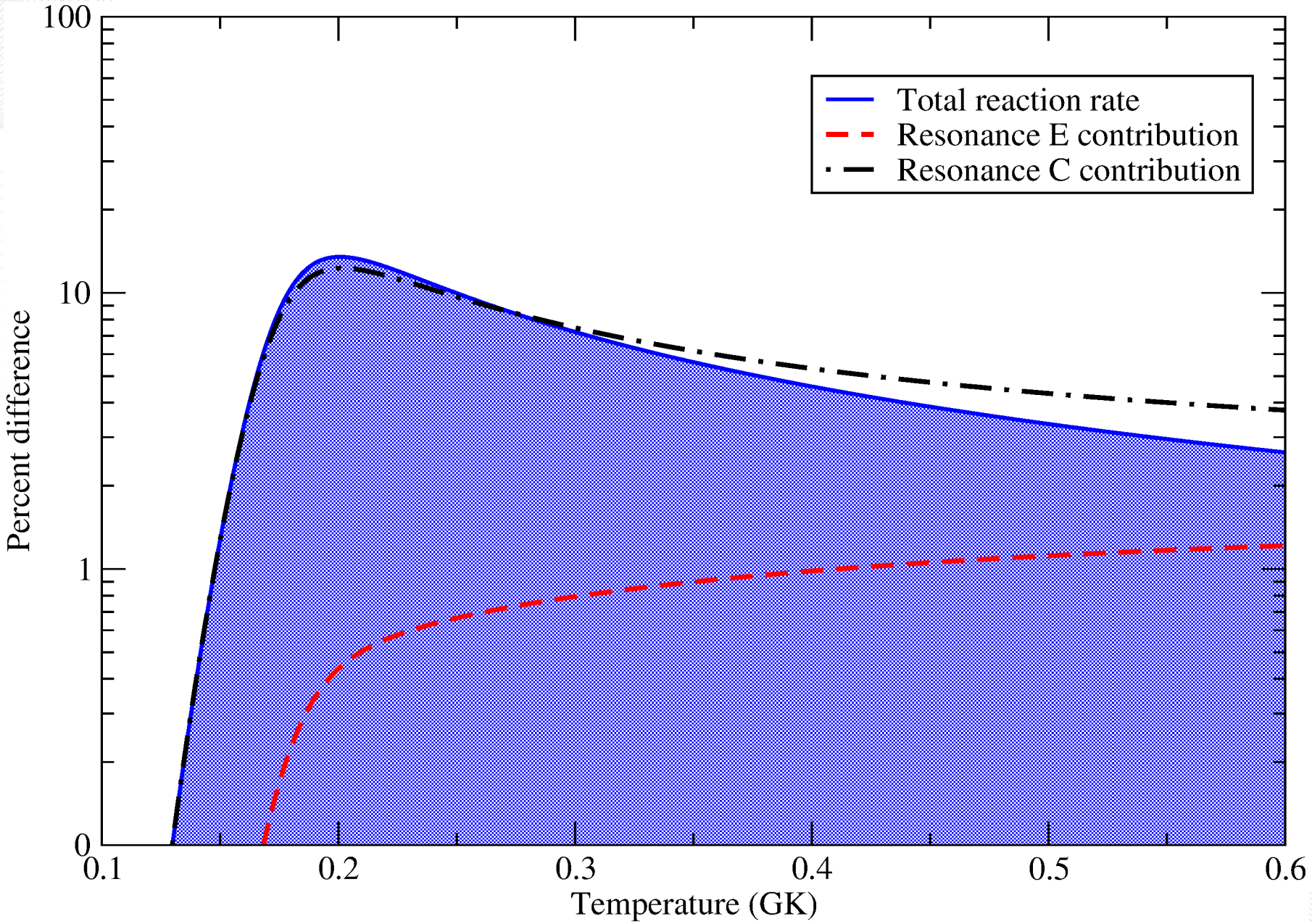
→ Ultimately, there appears to be more evidence for Resonance C being the 0^+

The 0^+ issue

Expect the fourth 0^+ in this region… so which is it?

→ if the 5890 keV (C) level is the 0^+ and 5950 keV (E) is 4^+, reaction rate at lower temps (~0.2 GK) differs by 14% from the currently adopted rates in the literature

→ differences in the reaction rate ultimately cause differences in the calculated cosmic ^{26}Al production



What next?

Try harder to get this (and similar) information out there!

→ cf. "High-precision mass measurements of ^{25}Al and ^{30}P at JYFLTRAP," L. Canete et al, EPJ A 52 pp 124 (2016):

> "The spin for the next excited state at 5946 keV is unclear. It has been claimed to be a 0^+ [52] as well as 3^+ [49]. The shell-model calculations [62] suggest it to be 0^+..."

Some good news: the information is getting around (2016 ENSDF evaluation includes the updated level energies! see M.S. Basunia and A.M. Hurst, Nuclear Data Sheets 134, pp 1)

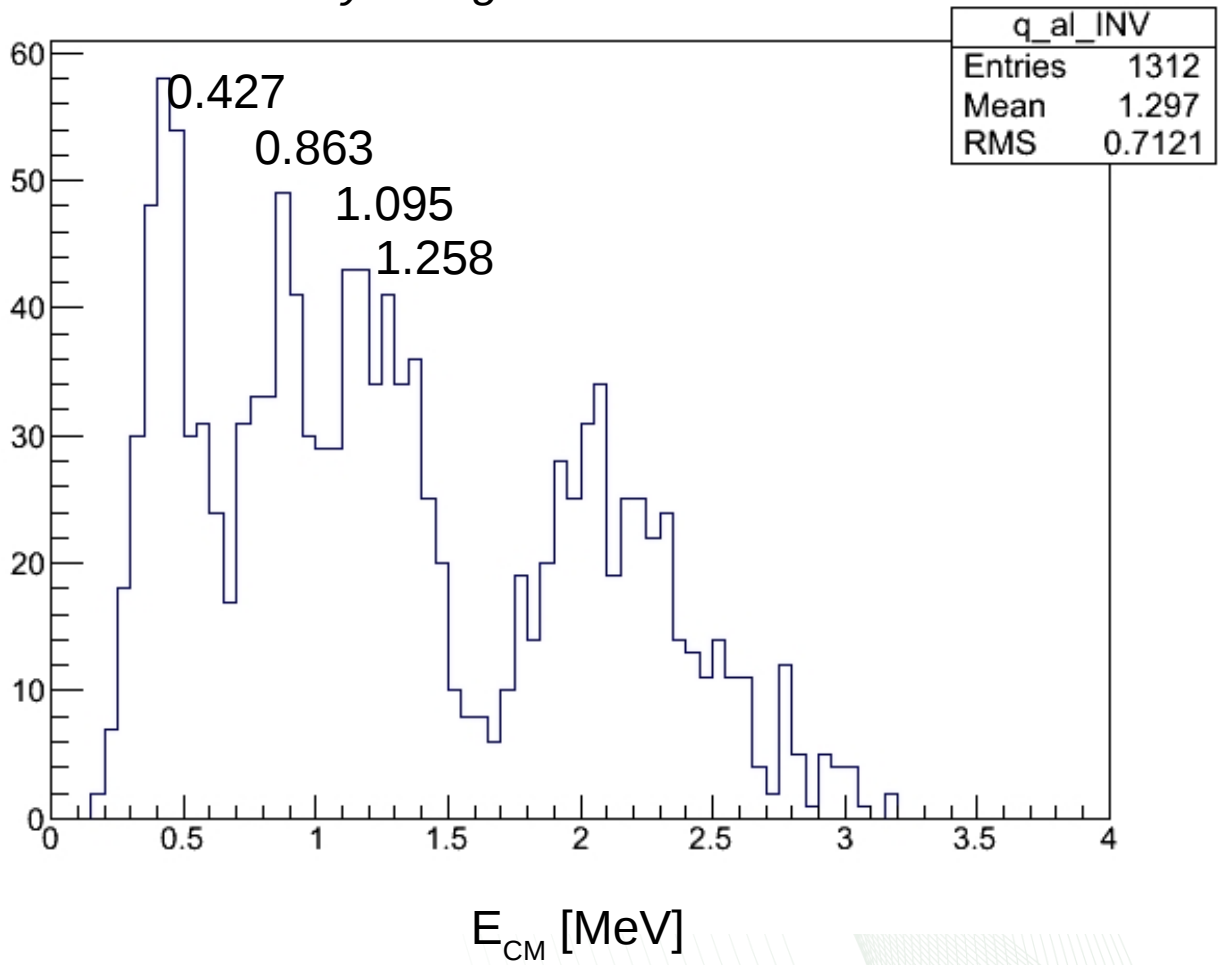
Further studies of ^{26}Si would benefit from single-nucleon transfer (populates low *l* states, reaction mechanism better understood, etc):

→ (d,n) proton transfer (J. Baker et al)
→ proton scattering
→ direct proton capture (A. Chen et al)

Example: ^{25}Al(d,n) @ FSU

- ^{25}Al beam production with RESOLUT
- Measure decay+daughter coincidences in ^{25}Al(d,n)^{26}Si* → ^{25}Al+p
- Observe complex res.-spectrum
  0.427(50) MeV 3^+
  0.863(50) MeV $2^+/4^+$
  1.095(50) MeV ?
  1.258(40) MeV 3^-
- Compare cross sections to ^{25}Mg(d,p)^{26}Mg "mirror" reaction
- The "main" astrophysical 3^+ resonance is identified at 0.427(50) MeV ← Consistent with Resonance D (closer to reanalysis value than original literature value)

courtesy of Ingo Wiedenhoever



Take-home:

→ **Structure matters to astrophysics**

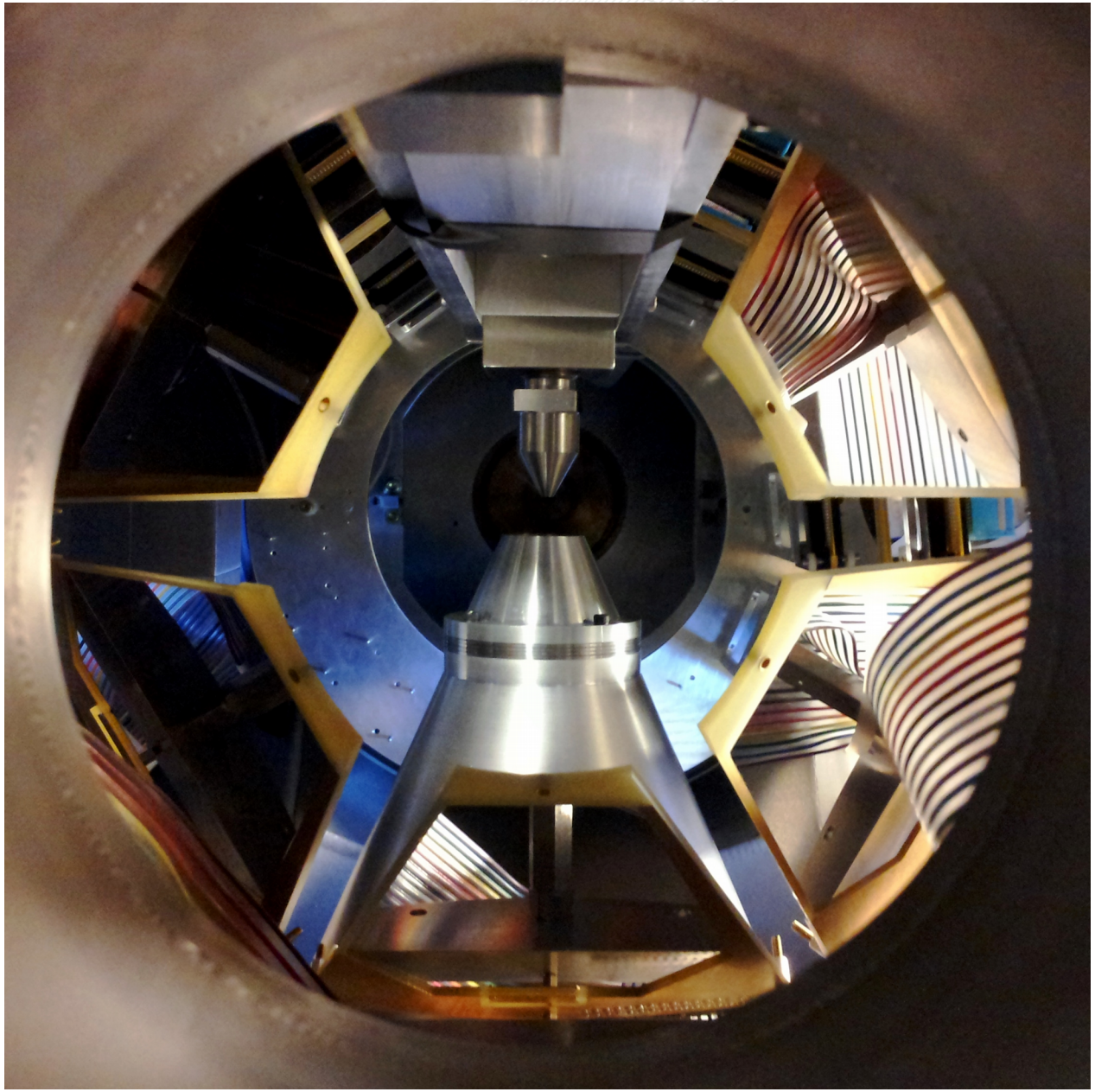
→ **Careful evaluation matters to everyone**

Thanks

Aaron Hurst
Chris Wrede
Alan Chen
Ingo Wiedenhoever
Michael Smith

Extras

A word on how we can improve:



For either the direct proton capture or single-nucleon transfer, a beam of ^{25}Al is required – probably low intensity

Measurement depends on a dense hydrogen/deuterium target

Utilize the advantages of a gas jet target!

→ dense (10^{18}-10^{19} #/cm^2)
→ pure (fed from cylinder, recirc.)
→ uniform
→ localized (4-5mm diam)

See Paul Thompson (UTK) poster
...and your conference badge!

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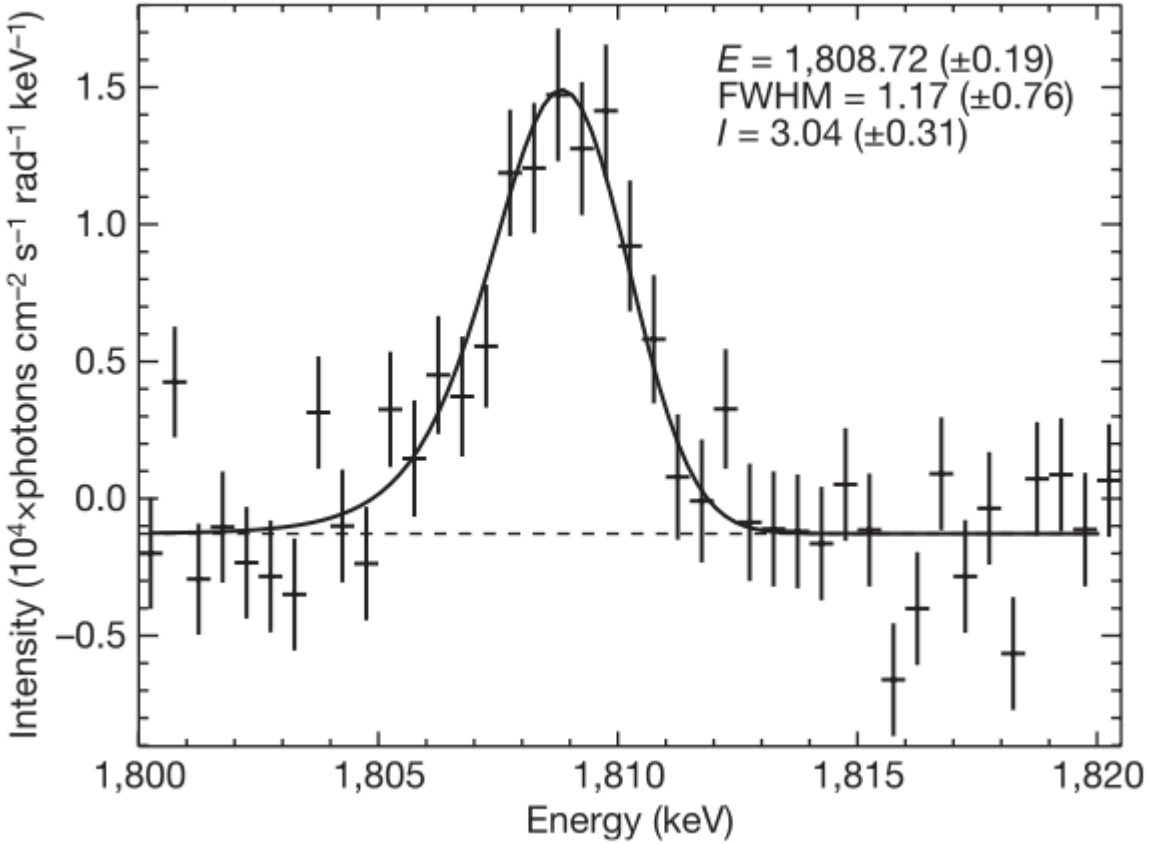

^{26}Al was first radioisotope directly observed in space, by high-precision, satellite-based instruments

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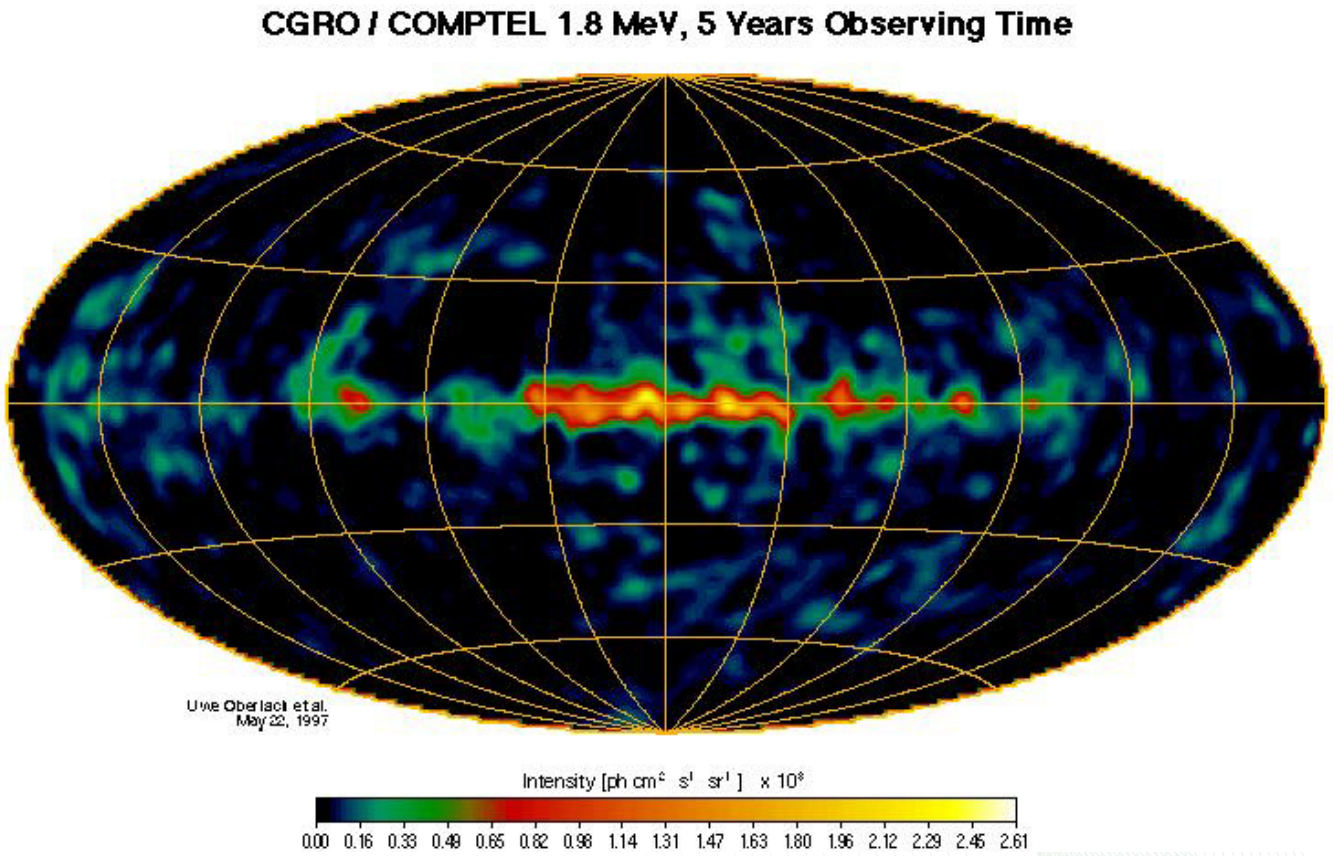

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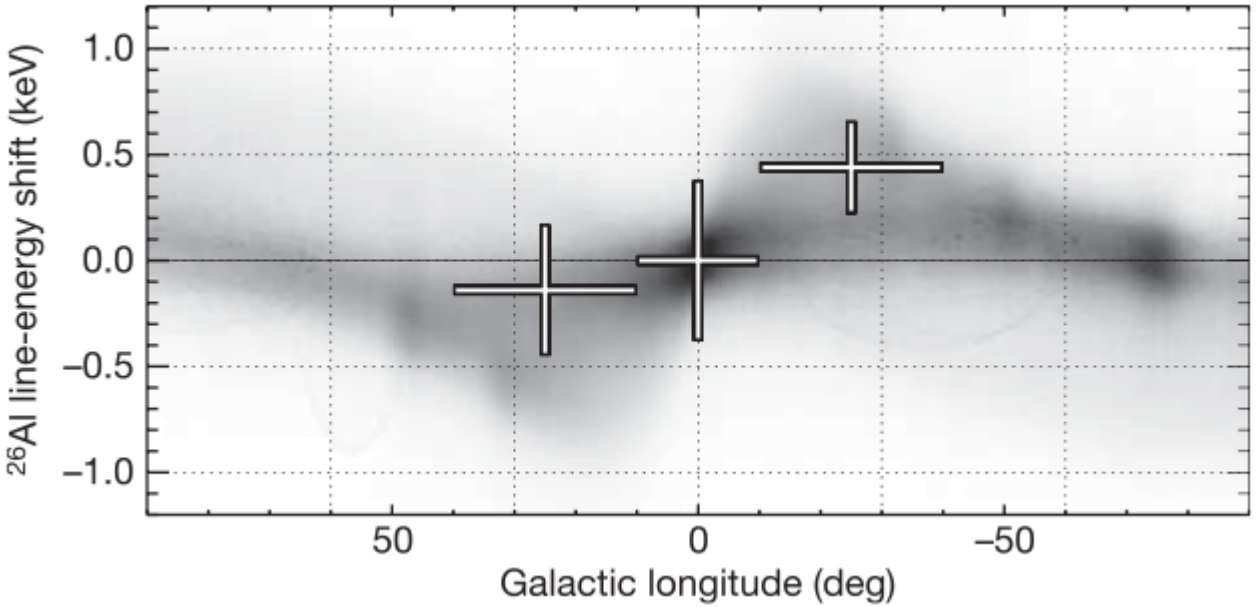
4) INTEGRAL shows that the sources are near massive stars, and that the ^{26}Al co-rotates with the galactic plane...



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5) The direct observation of ^{26}Al decay is particularly important – and useful – because of the properties of this radioactive isotope:

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