Nucleosynthesis around ^{60}Fe via indirect neutron-capture reaction studies

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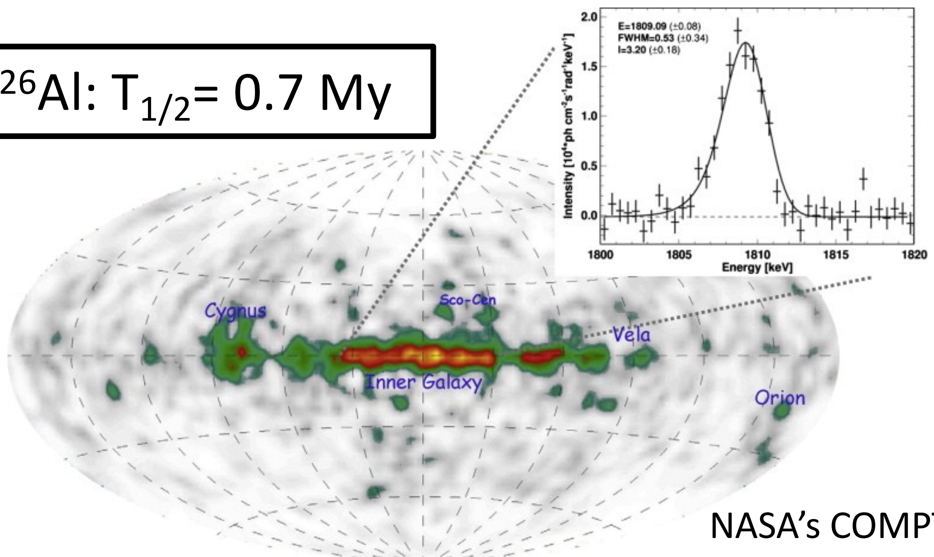
FRIB NSCL NSF

Nucleosynthesis in Massive Stars

- Massive stars are a major source of chemical elements through explosions and stellar winds
- Long lived radioisotopes provide unique signatures of active nucleosynthesis

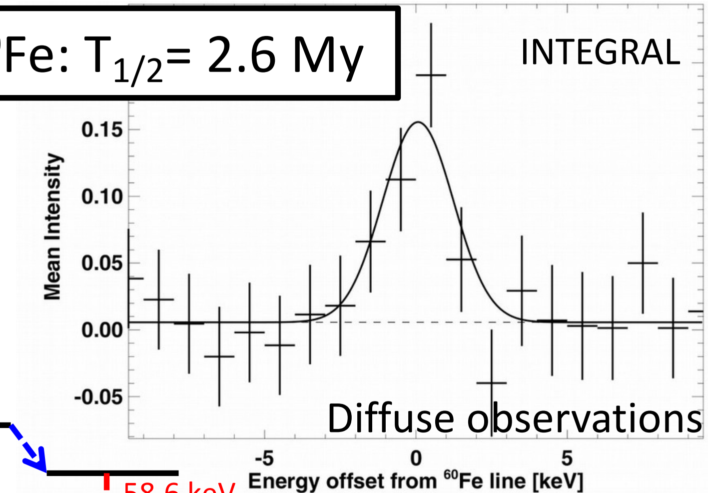
^{26}Al: $T_{1/2}$= 0.7 My

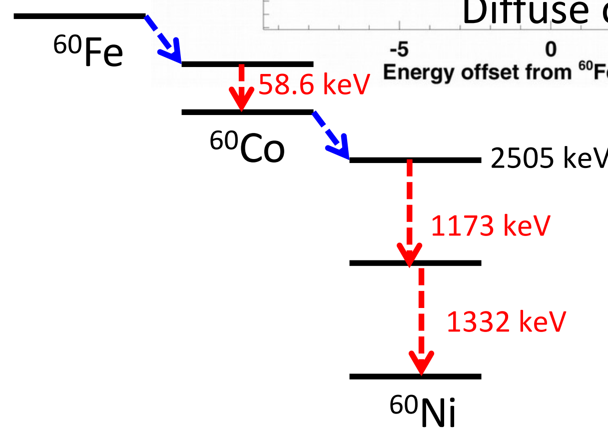


Diehl et al., New Astronomy Reviews 2008

NASA's COMPTEL (1991-2000)

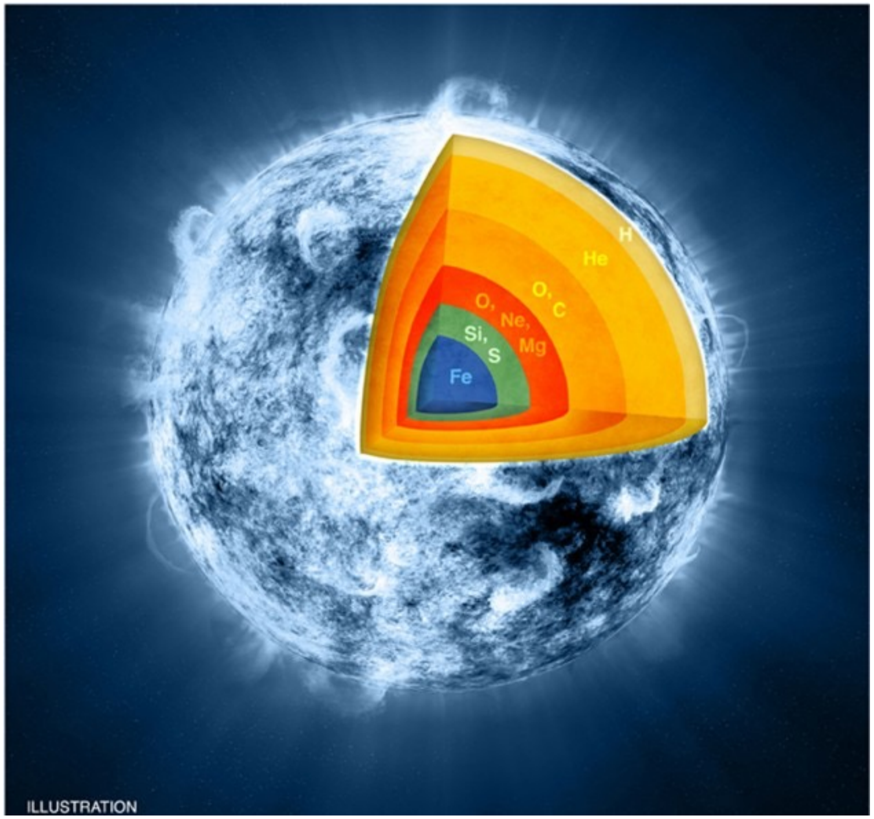
^{60}Fe: $T_{1/2}$= 2.6 My





^{60}Fe/^{26}Al ratio

- The ^{60}Fe/^{26}Al ratio is useful for:
  - probing nucleosynthesis in massive stars
  - Stellar mixing
  - Stellar winds
  - Rotation
  - Explodability
  - Neutron star and black hole mass distributions
  - Solar system origins (possible pollution by nearby SN).
- Both isotopes produced in inner layers of the massive star + ^{26}Al in outer layers.
- Source distance, location and number cancel out



The ^{60}Fe/^{26}Al puzzle

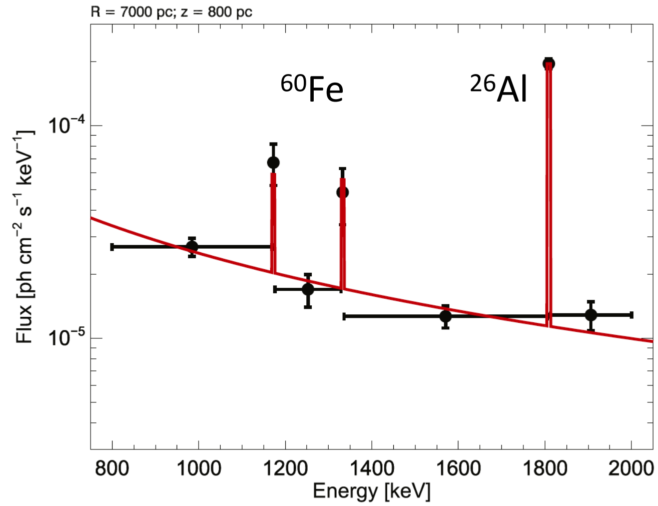
- With more than 15 years of INTEGRAL/SPI observations:

  ^{60}Fe/^{26}Al flux ratio ratio= 0.184 $\pm$ 0.042

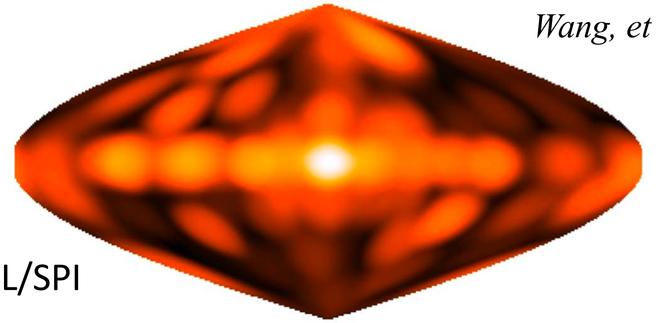
  Wang, et al. ApJ 2020

- Theoretical predictions: consistently higher by factor of 3-10 *Woosley-Heger, Phys. Rep. 2007*
  Limongi-Chieffi, ApJ 2006
  Diehl et al. 2021

- Discrepancy attributed to uncertain nuclear physics.



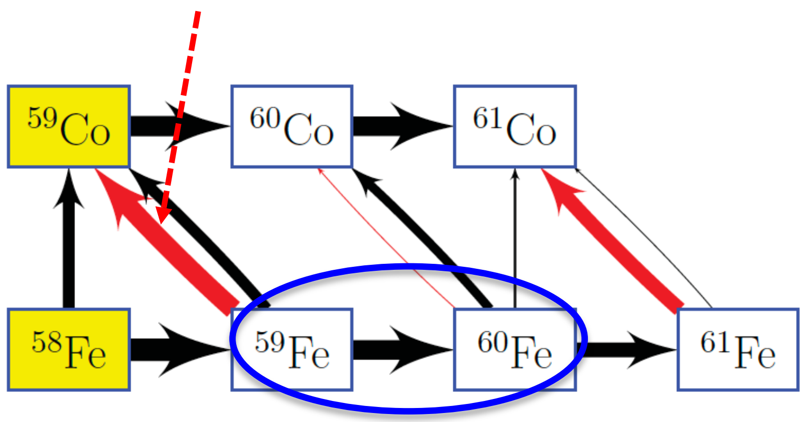
Wang, et al. ApJ 2020



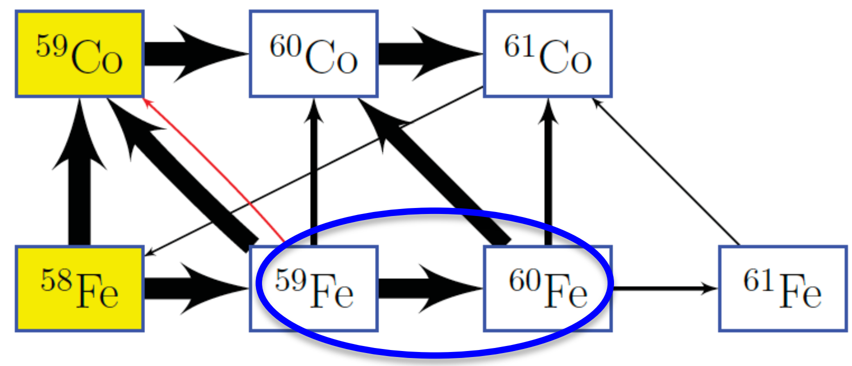
15 years of INTEGRAL/SPI

Reaction paths around ^{60}Fe

Gao et al. PRL 2021



C/Ne Shell burning



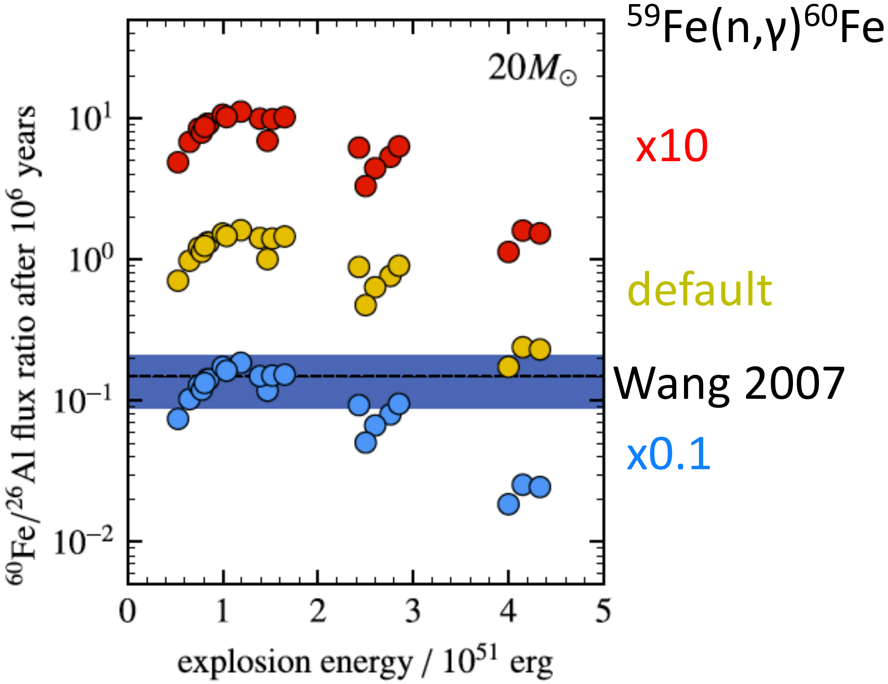
C/Ne explosive Shell burning

β decay

reaction

Neutron Sources:
^{22}Ne(α,n)^{25}Mg and ^{12}C(^{12}C,n)^{23}Mg

Sensitivity of $^{60}Fe/^{26}Al$ to $^{59}Fe(n,\gamma)^{60}Fe$



- $^{60}Fe/^{26}Al$ flux ratio ratio: almost linear dependence with the $^{59}Fe(n,\gamma)^{60}Fe$ reaction rate.
- Models with lower reaction rate or very high explosion energy can match the observed value.
- Direct measurement of $^{59}Fe(n,\gamma)^{60}Fe$ reaction is challenging (^{59}Fe $T_{1/2}$ = 44 days)

Similar results for 15 and 25 solar masses

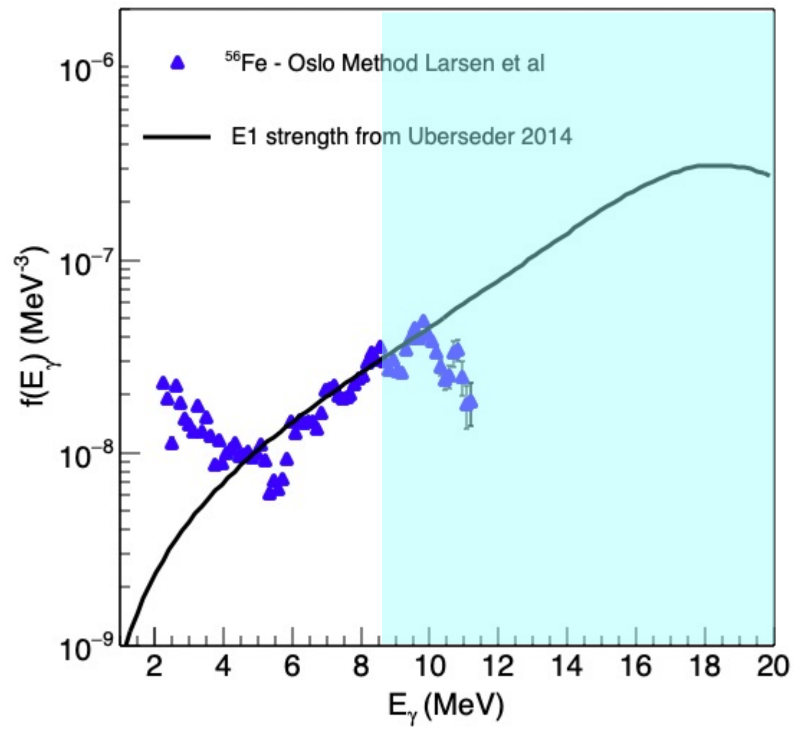
Jones, et al. MNRAS 2019

Previous measurements

Indirect approaches:

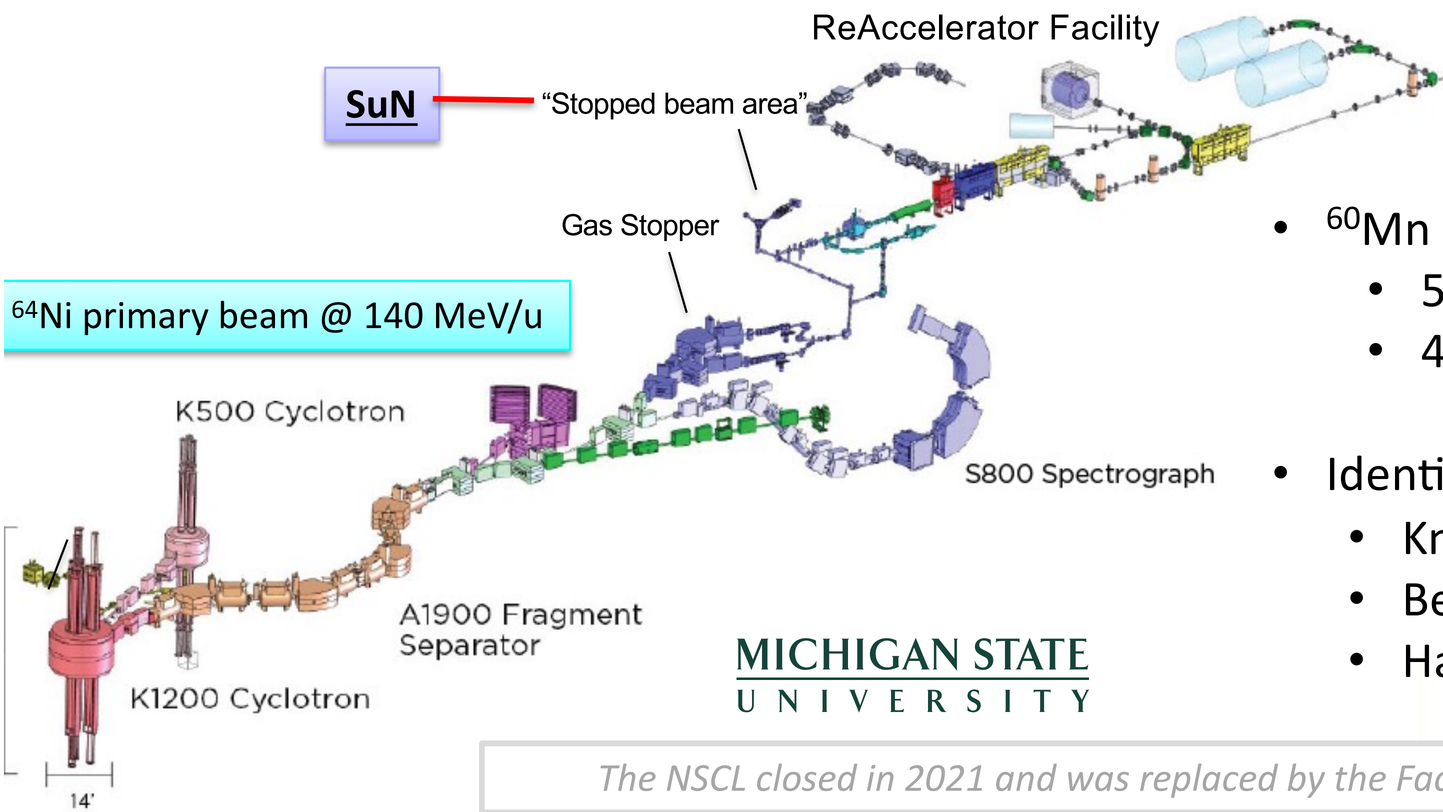
- Constrain Nuclear Level Density (NLD) and γ-ray strength function (γSF)
  - Coulomb dissociation measurement at GSI (Uberseder et al, PRL 2014) - γSF
- Surrogate ratio method (Yan et al, ApJ 2021)

- Here we performed an experiment using the β-Oslo method
- Extracted the low-energy part of the the γSF and



Uberseder, et al. PRL (2014)
Larsen, et al, PRL (2013)
Spyrou et al. PRL (2014)

National Superconducting Cyclotron Lab

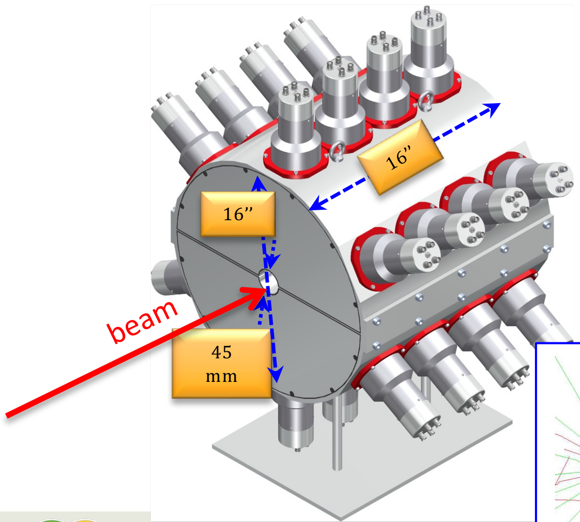


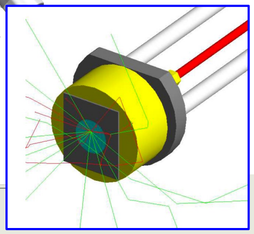
- ^{60}Mn beam:
  - 59(1)% g.s. 1^+
  - 41(1)% isomer 4^+
- Identification based on:
  - Known γ-ray intensities
  - Beta-feeding intensity
  - Half-lives (0.28 s 1^+ , 1.77s 4^+)

The NSCL closed in 2021 and was replaced by the Facility for Rare Isotope Beams (FRIB)

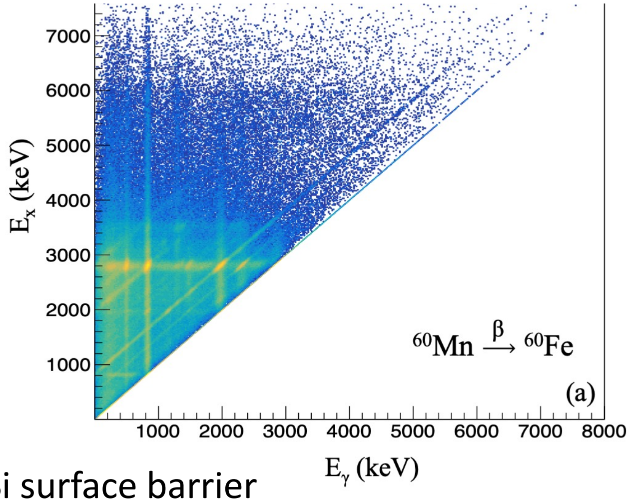
SuN detector

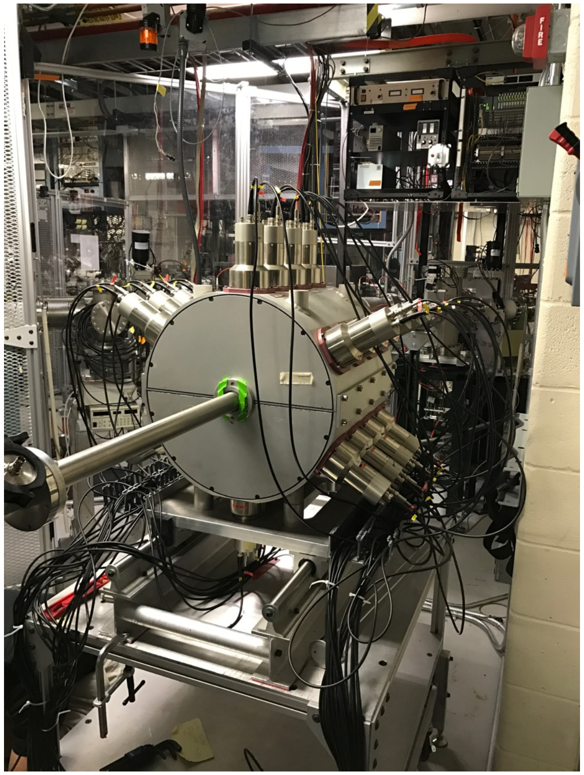
- Large size - high efficiency γ-calorimeter 16x16''
- Summing of all γ-rays gives the excitation energy
- Segmented detector: information about individual γ-rays
- SuN detector + Si
- Apply β-Oslo method to extract NLD and γSF.





Si surface barrier



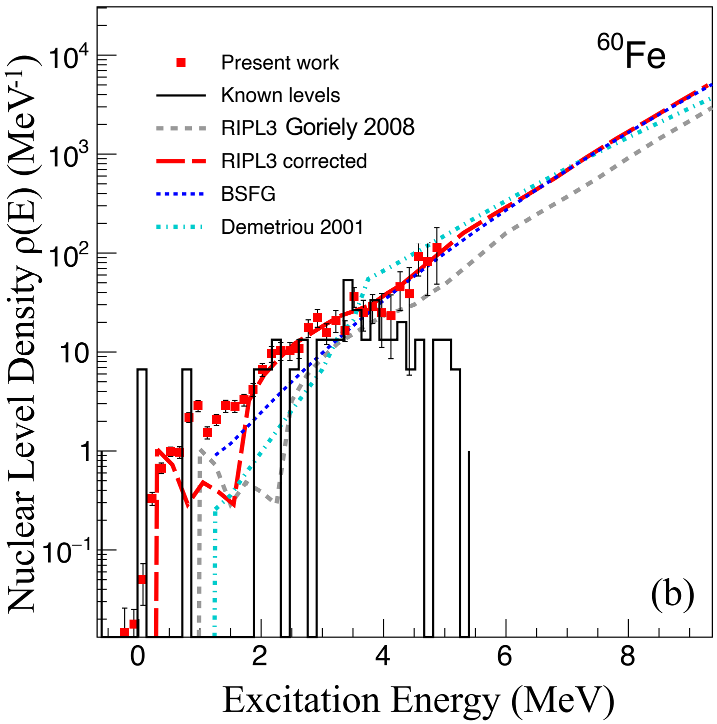


Simon., et al., Nucl. Instr. Meth A (2013)

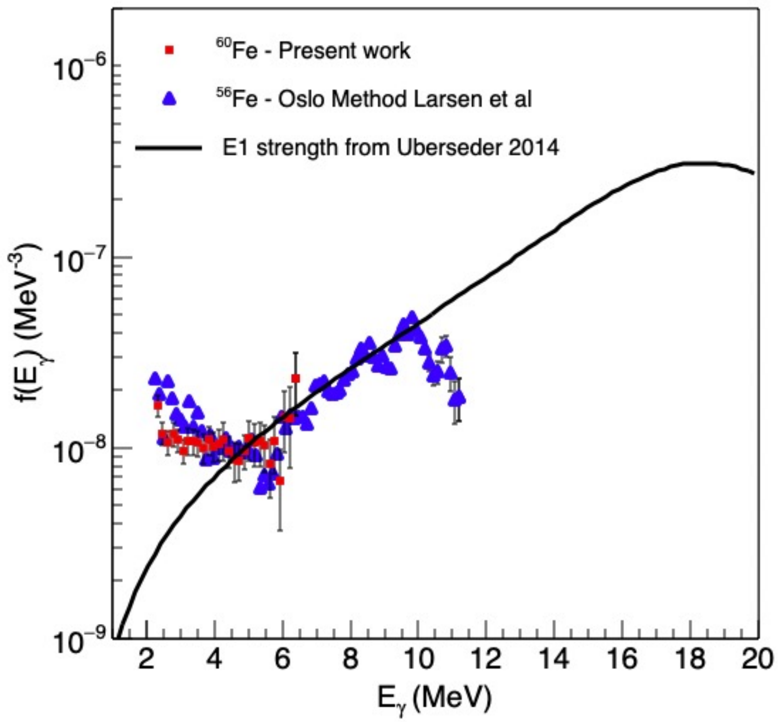
Results

AS et al. Nature Com. Accepted (2024)

Nuclear Level Density



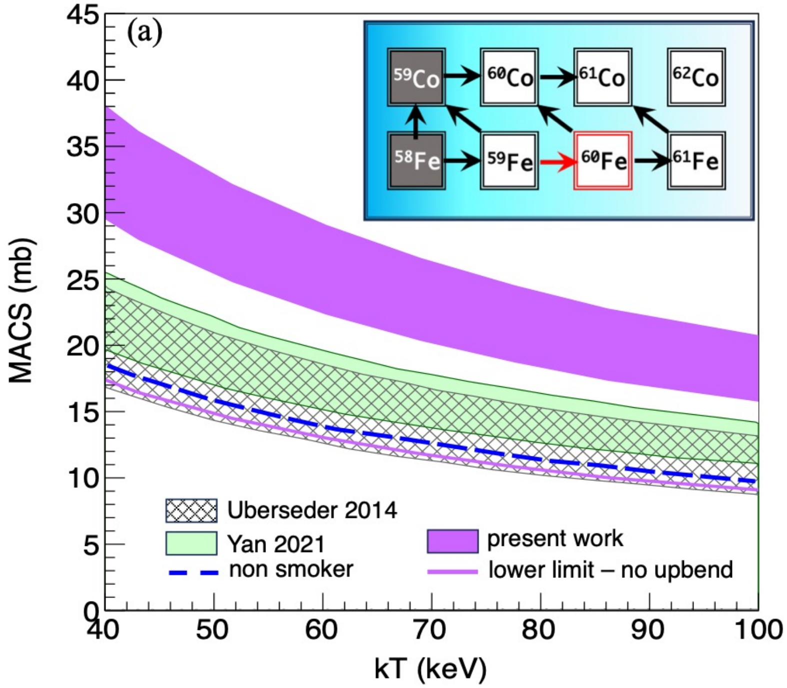
γ-ray Strength Function

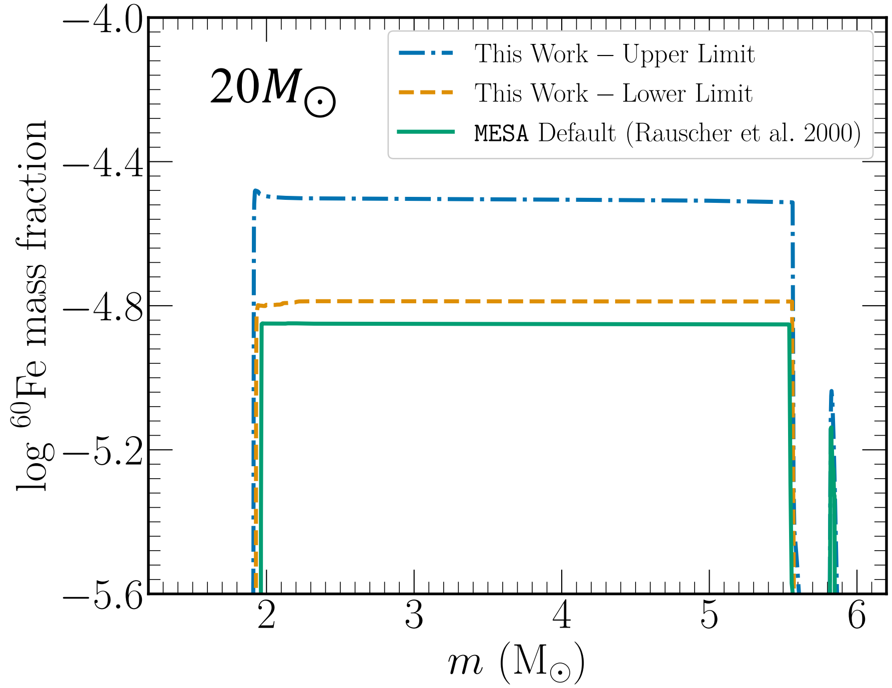


Uberseder, et al. PRL (2014)
Larsen, et al, PRL (2013)

Impact on ^{59}Fe(n,γ)^{60}Fe and ^{60}Fe production

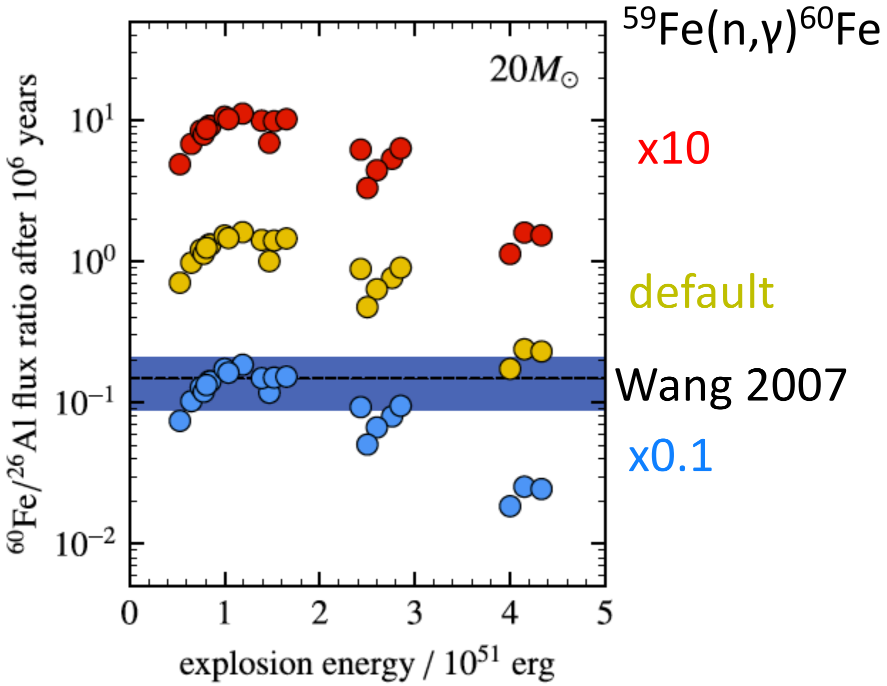
AS et al. Nature Com. Accepted (2024)





Stellar evolution calculations using MESA by Carl Fields

What does this mean?

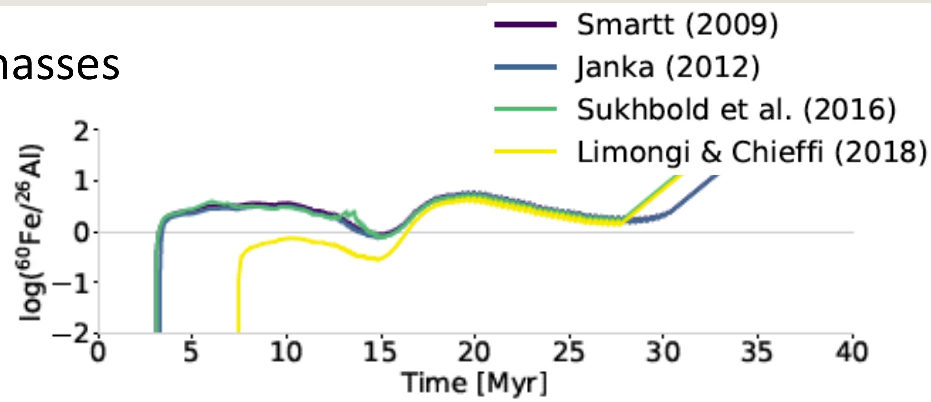


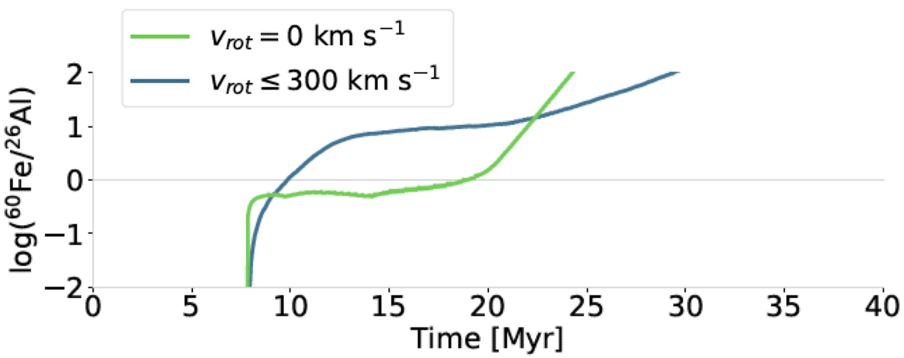
- New results ≈factor of 2 higher cross section
- Higher production of ^{60}Fe
- Higher ^{60}Fe/^{26}Al ratio
- Puzzle not solved… made worse
- But… now we know that the solution does not come from nuclear physics
- Where could it come from?

Jones, et al. MNRAS 2019

Effect of Explodability and Rotation

- Limongi & Chieffi 2018: No SN above 25 solar masses
- Reduced $^{60}Fe/^{26}Al$ ratio
- Connected to neutron star/black hole mass distributions





- Stellar rotation produces a lot more ^{60}Fe
- Reason: more neutrons
- Rotation seems to increase the $^{60}Fe/^{26}Al$ ratio

Pleintinger M. M. M., 2020, PhD thesis, Technische Universität München

Diehl, et al. 2021

Summary

- ^{60}Fe and ^{26}Al detections can help us understand massive star evolution, explosion and nucleosynthesis
- $^{60}Fe/^{26}Al$ ratio sensitive probe – models overestimate it
- $^{59}Fe(n,\gamma)\,^{60}Fe$ affects the production of ^{60}Fe
- New measurement shows a higher reaction cross section, hence more ^{60}Fe
- $^{60}Fe/^{26}Al$ ratio discrepancy even worse
- Pointing to stellar properties as a solution to the puzzle - Explodability? Rotation? Other?

Collaboration

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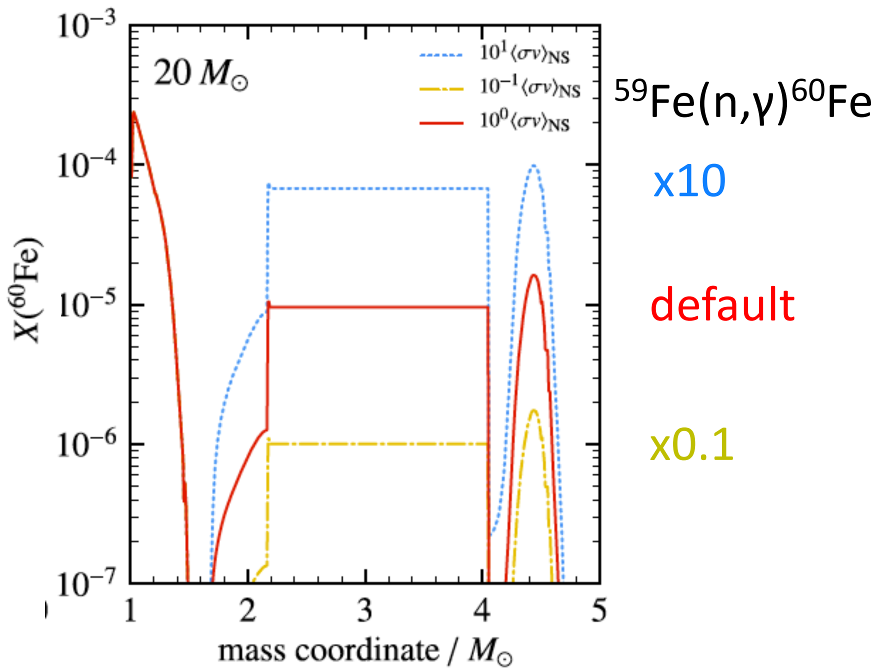
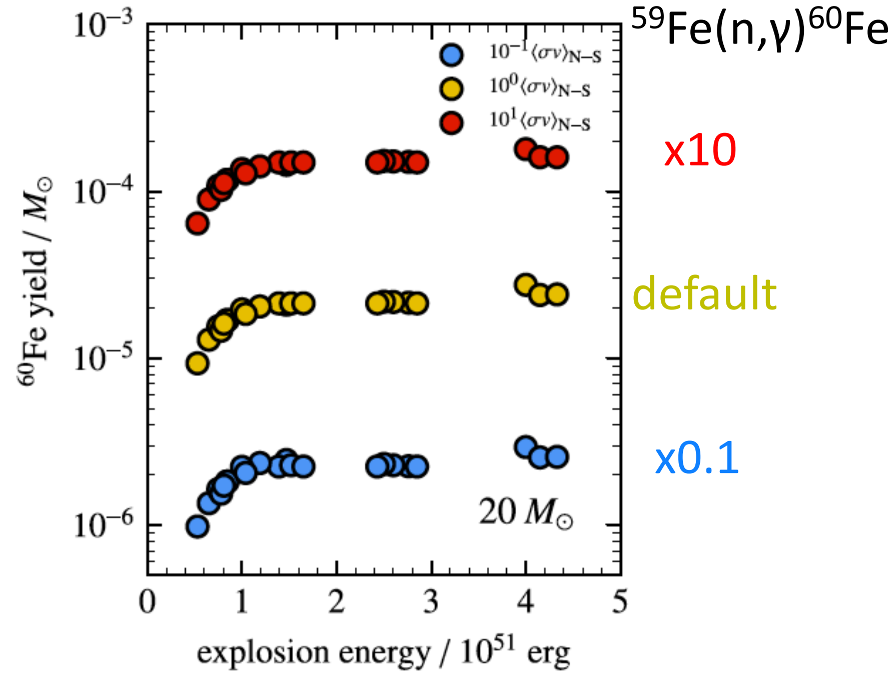
Sensitivity of ^{60}Fe to ^{59}Fe(n,γ)^{60}Fe



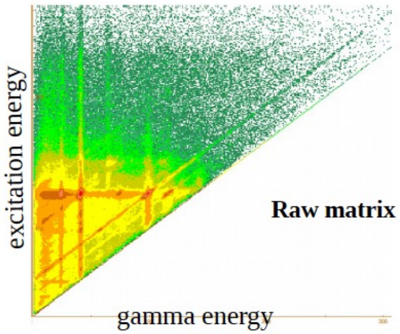


Similar results for 15 and 25 solar masses

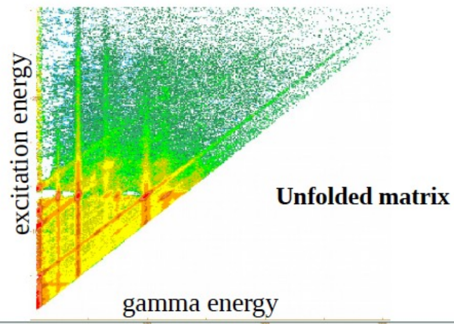
Jones, et al. MNRAS 2019

Oslo analysis

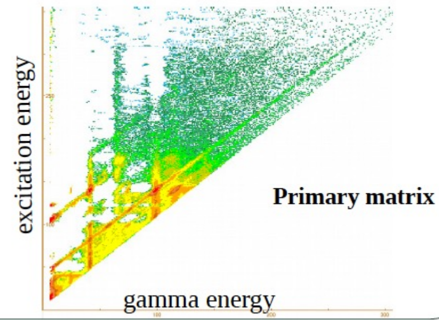
1. Create an excitation vs. γ-energy matrix.



2. Unfold the matrix with a known response function.



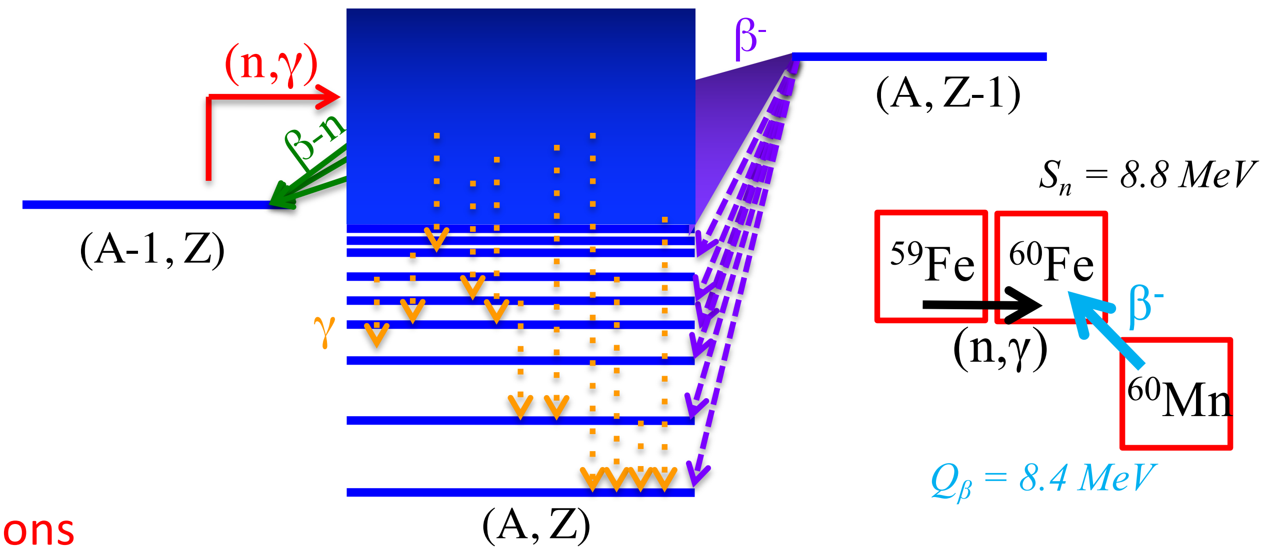
3. Isolate the first emitted γ-rays in the decay cascade.



β-Oslo

- Populate the compound nucleus via β-decay (large Q-value far from stability)
- Spin selectivity – correct for it
- Extract level density and γ-ray strength function

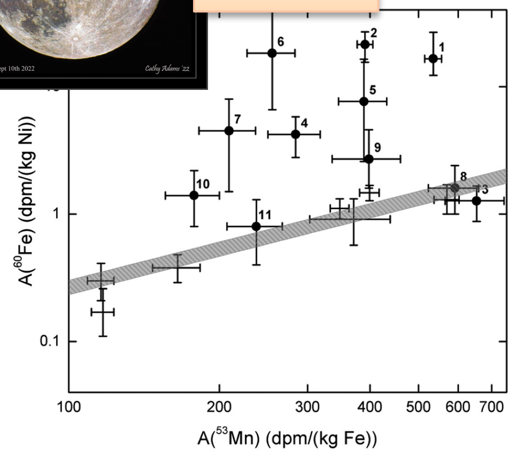
•Advantage: Can reach (n,γ) reactions with beam intensity down to 1 pps.



Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

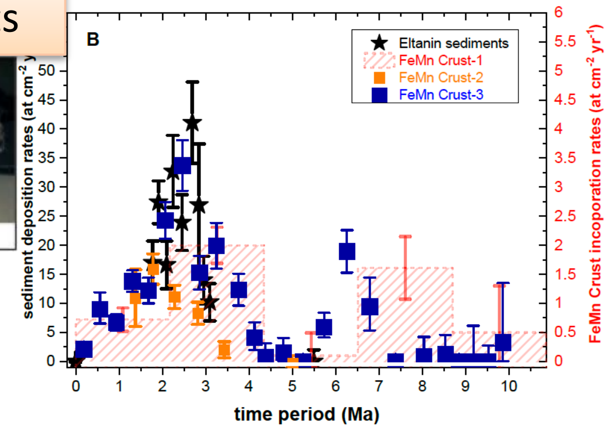
^{60}Fe within the solar system

Moon



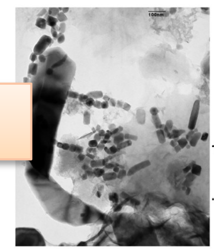
Fimiani, et al. PRL 2016

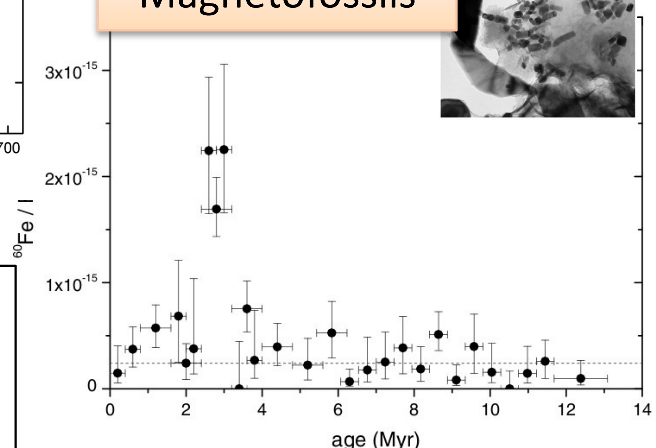
Ocean sediments



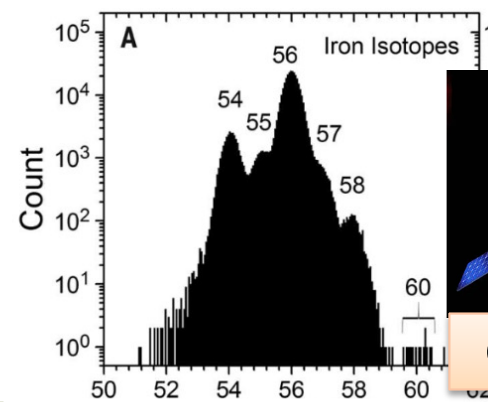
Wallner, et al., Nature 2016

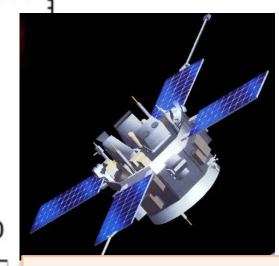
Magnetofossils





Ludwig, et al. PNAS 2016





Cosmic rays

Binns, et al., Science 2016

Interpreting the findings requires knowledge of ^{60}Fe production/ejection