# Elemental Source Composition Measurements and the Origin of Galactic Cosmic Rays

***W.R. Binns, M.H. Israel***

*Washington University in St. Louis, MO, USA*

***M.E. Wiedenbeck***

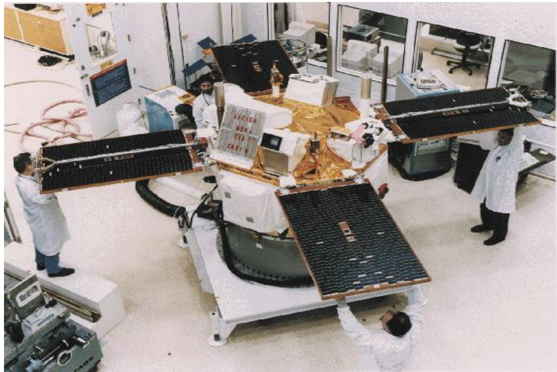
*Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA, USA*

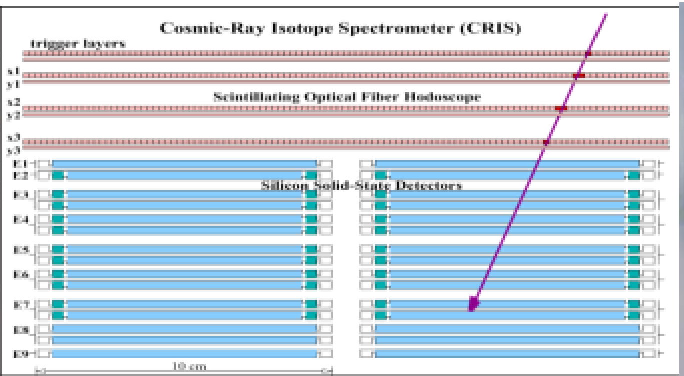
***A.C. Cummings, R.A. Leske, R.A. Mewaldt, E.C. Stone***

*California Institute of Technology, Pasadena, CA, USA*

***E.R. Christian, G.A. de Nolfo, T.T. von Rosenvinge***

*NASA Goddard Space Flight Center, Greenbelt, MD, USA*

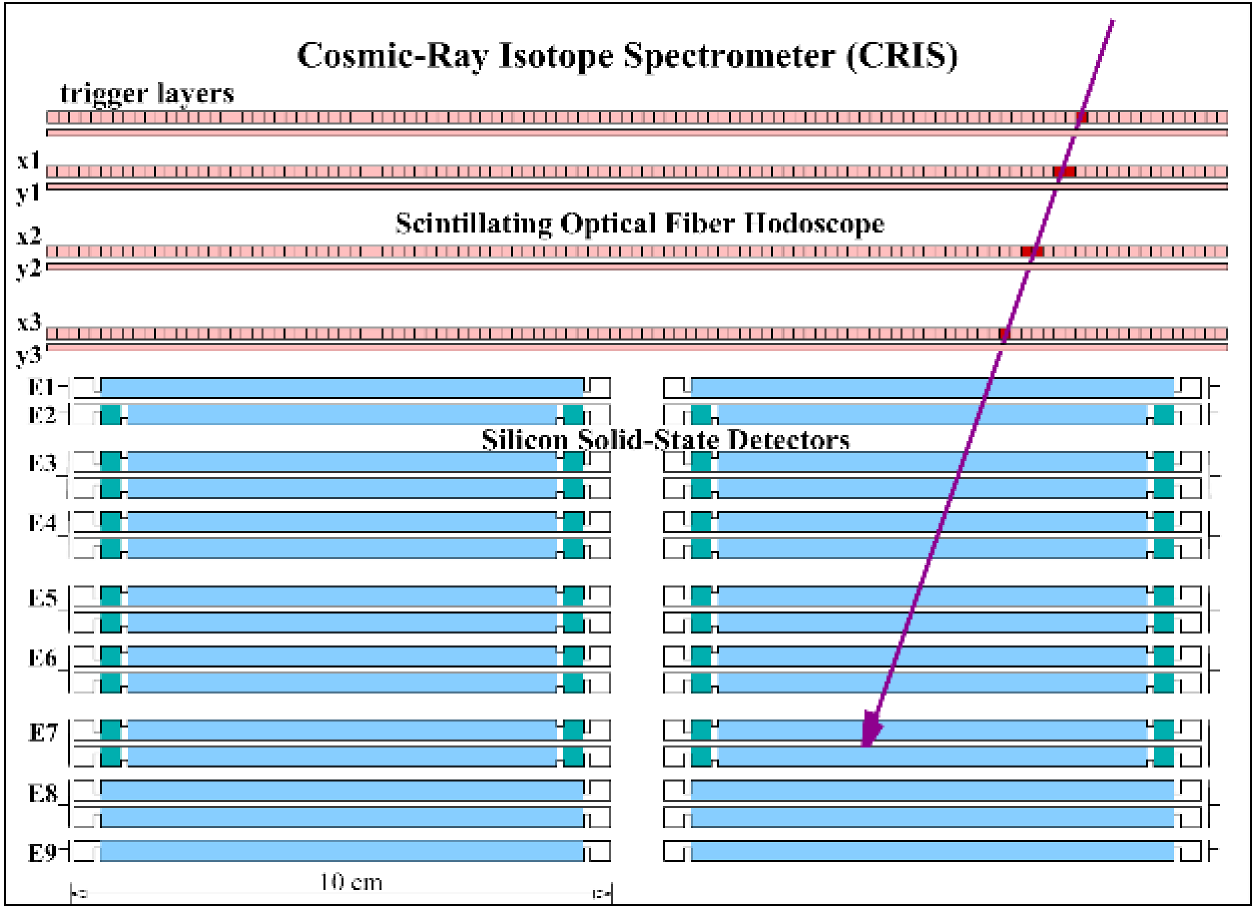




# CRIS Detector System on the ACE Spacecraft

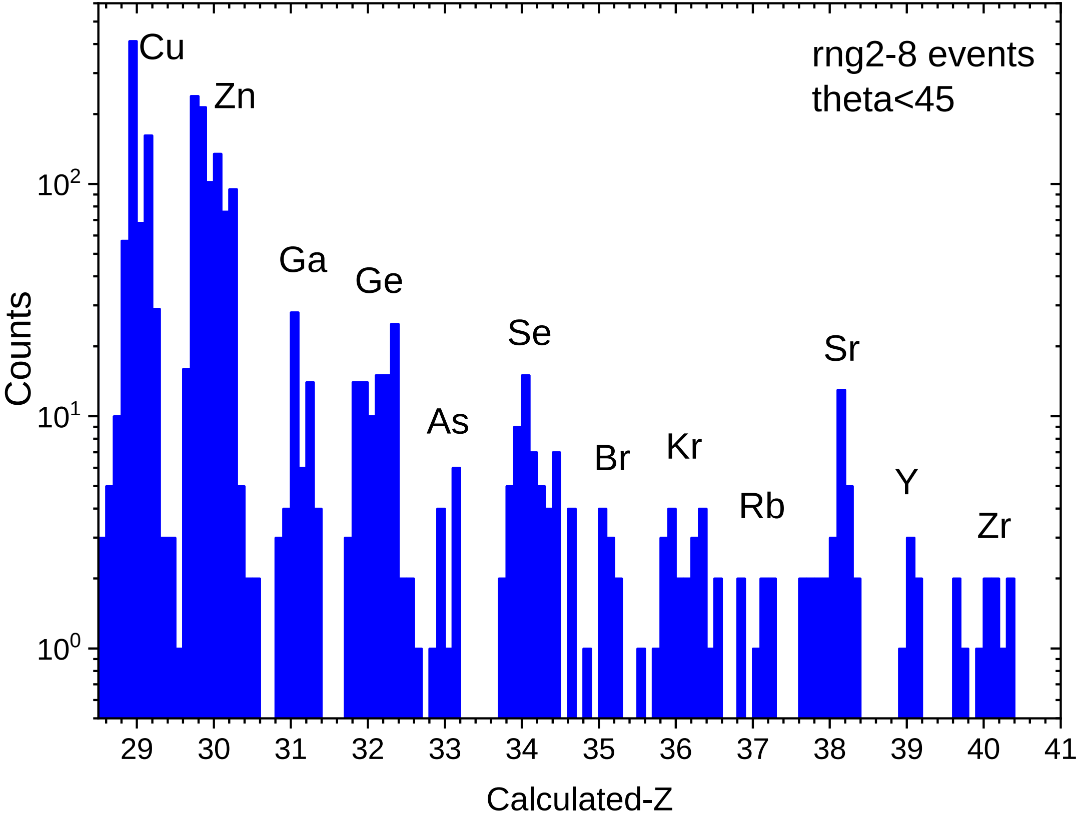
- Designed to measure nuclei between $_{4}$Be and $_{28}$Ni that stop in the Si detector stack.
- Geometrical factor ~250 cm$^2$ sr
- Life-time ≥ 2 years, hopefully 5 years.

- Abundance in cosmic rays of $_{30}$Zn is ~10$^{-4}$ of $_{26}$Fe and of heavier elements ~10$^{-5}$ of $_{26}$Fe.
- UH measurements with CRIS made possible by long life of ACE & CRIS – still returning good data after >21 years.



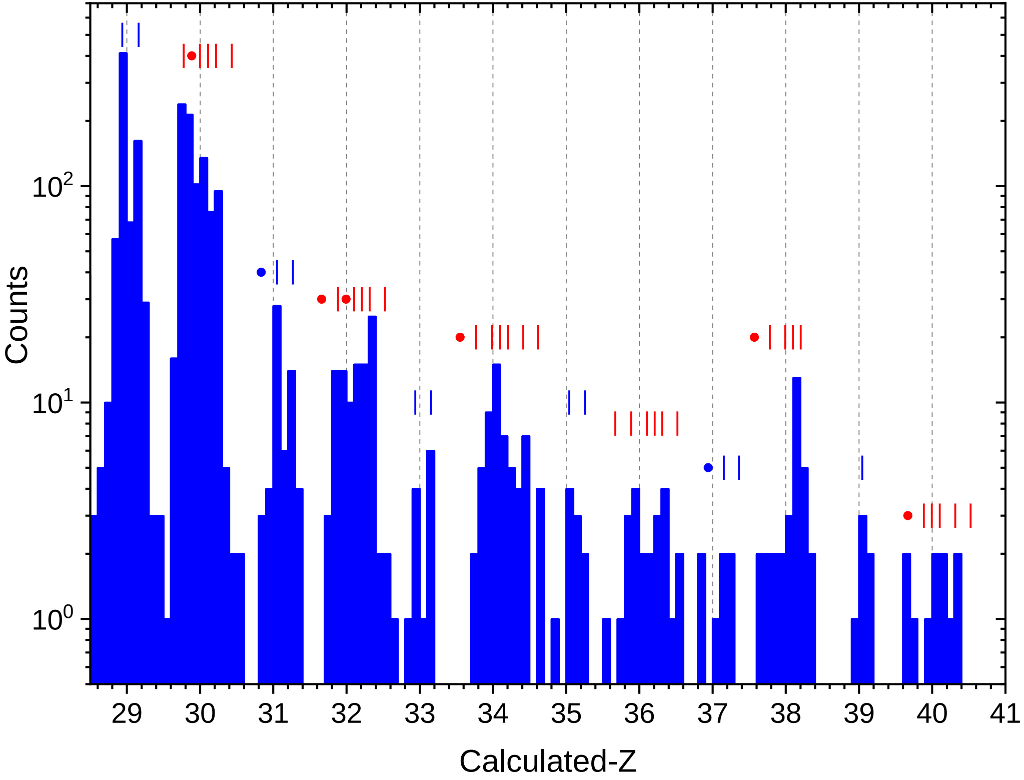
# ACE-CRIS Measurement of UH Elemental Abundances

- Data taken over time interval from Dec. 4, 1997 through Feb. 18, 2019
- A total of 7406 days of actual data
- Excellent resolution in charge for UH nuclei
- Data set corresponds to 1.5 x $10^6$ Fe nuclei



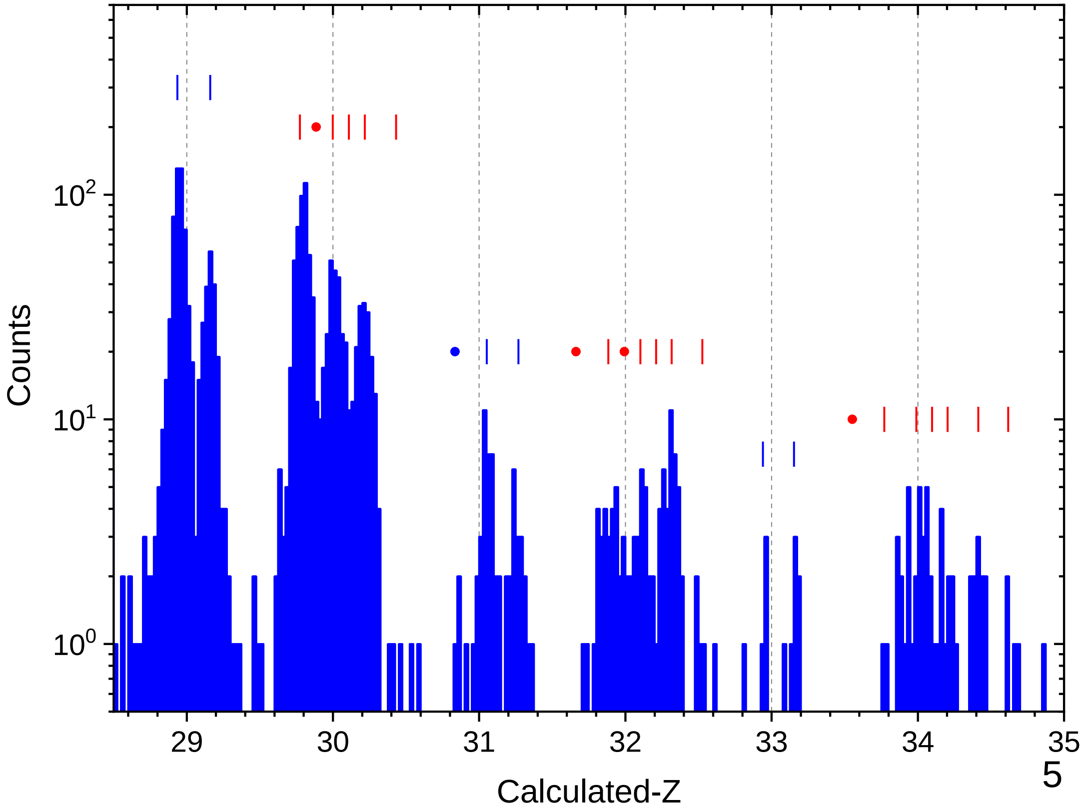
# ACE-CRIS Measurement of UH Elemental Abundances

- Width of element distributions is primarily dependent upon the number of stable isotopes for each element.
- Red and blue lines show the calculated position of each stable isotope for an element.
- Red and blue circles show the calculated position of isotopes that can only decay by electron-capture and thus are stable when fully stripped.
- (Red lines and circles for even-Z elements, blue for odd-Z elements).



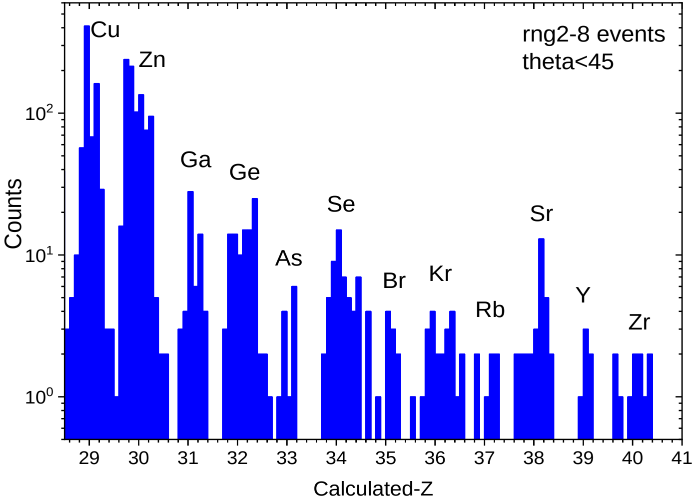
# ACE-CRIS Measurements of UH Isotopic Abundances

- Same data set as previous page, but with finer binning
- Clear isotope resolution through $_{32}$Ge and beyond
- Isotope analysis is still in progress.

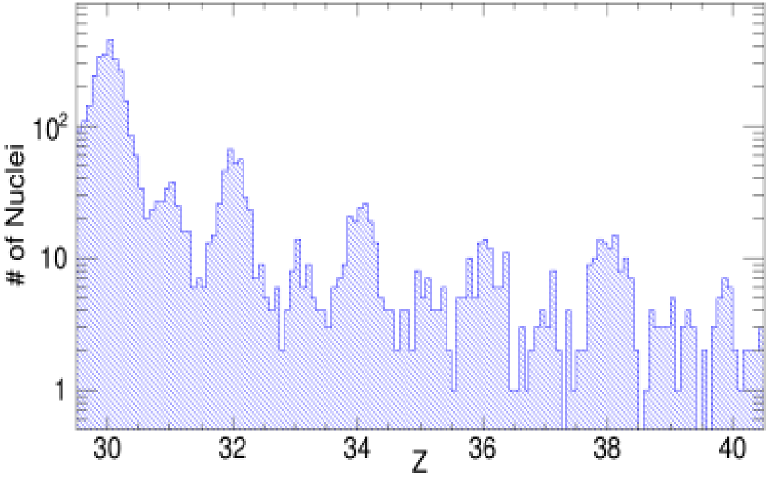


# ACE-CRIS & SuperTIGER UH data compared

ACE-CRIS data from ~21 years



ST data from 55-day flight Dec. 2012 – Jan. 2013,
Murphy et al. (2016) ApJ, 831:148



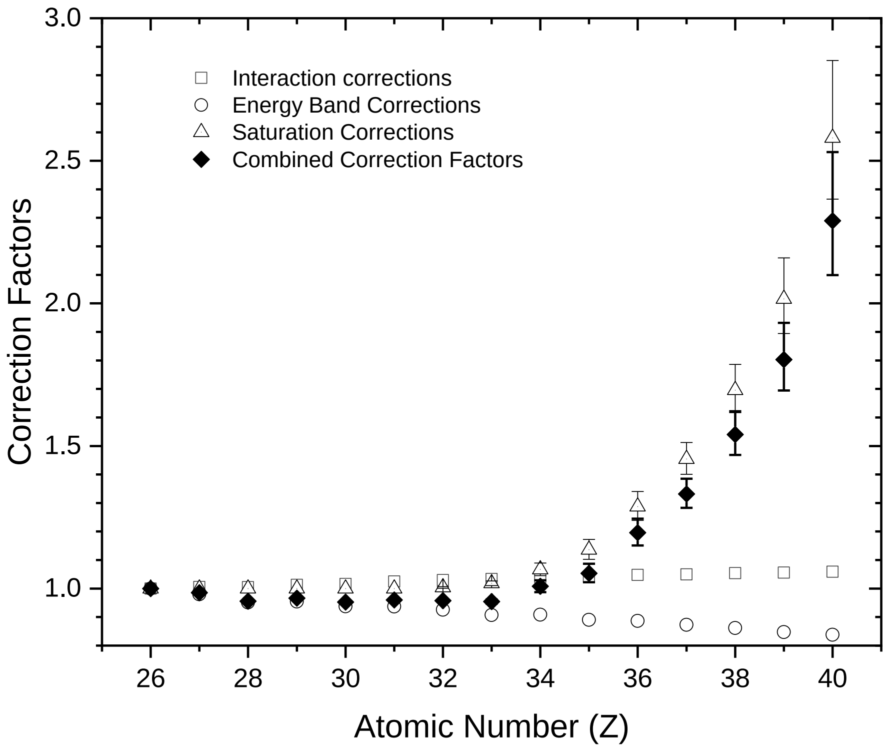
Also see Walsh et al. this session – re-analysis of these ST data extending the charge range to Z=56

- Excellent charge resolution dependent on number of isotopes
- Data set corresponds to 1.5 x $10^6$ Fe nuclei
- Energy range 125-725 MeV/nucleon, depending on Z

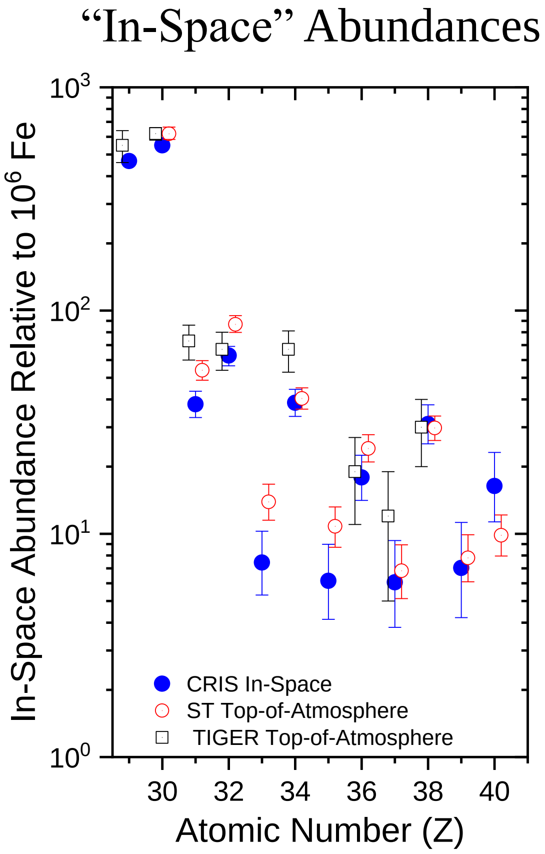
- Charge resolution $\sigma = 0.21$ cu, also excellent
- Data set corresponds to 4.2 x $10^6$ Fe nuclei
- Energy range for most nuclei at top-of-atmosphere is ~0.8-10 GeV/nucleon

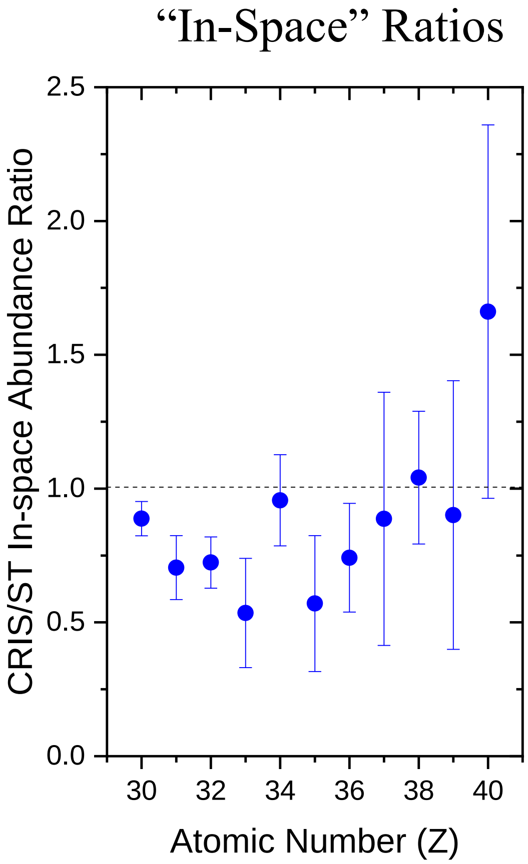
# Correction Factors for CRIS In-Space Abundances

- Need corrections for:
  - Interactions in the instrument
  - Z-dependent width of energy band and cosmic-ray energy spectrum somewhat different in the band for each element.
    - 120 – 570 MeV/nucleon for $_{26}$Fe
    - 150 – 730 MeV/nucleon for $_{40}$Zr
  - PHA saturation
    - PHA saturates for signals from widest angle, lowest energy Z≥~32.
    - The saturation corrections are derived from a Monte Carlo calculation and are large for Z ≥ 38; however, we believe that they are well understood.
    - Uncertainties plotted on saturation corrections are worst case and reflect differences in gains and thicknesses among detectors.



# Compare ACE-CRIS & SuperTIGER "In-Space"

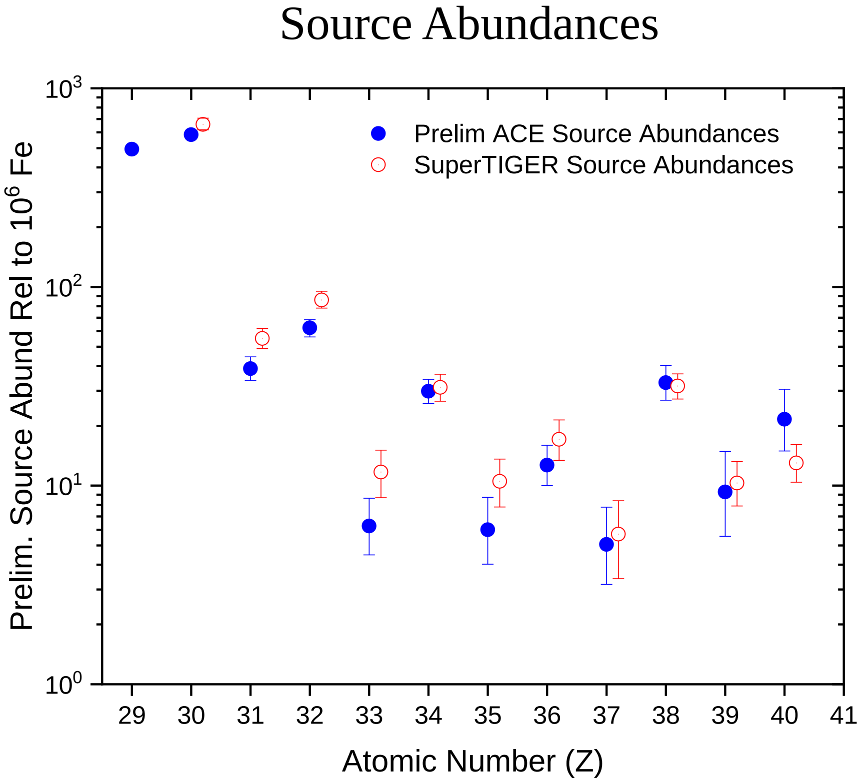




Differences between CRIS & ST:

- CRIS 125-725 MeV/nucleon
  ST ~ 0.8-10 GeV/nucleon
- CRIS 2 full solar cycles
  ST 2 months $\phi \sim 540$ MV
- CRIS in space
  ST extrapolated to Top of Atmos.
- CRIS complete charge separation
  ST good $\sigma$
- ST has ~3x larger statistics

# Compare ACE-CRIS & SuperTIGER at Source

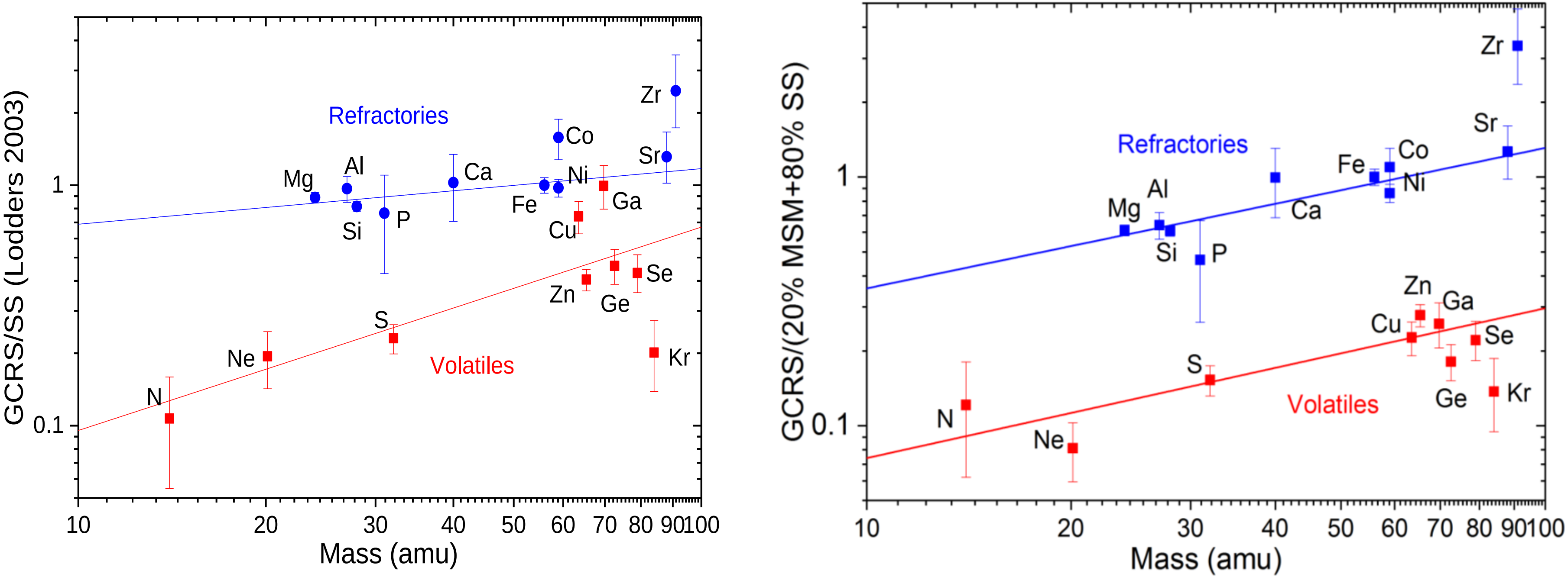


- Note that derivation of Source Abundances from CRIS data is still preliminary.
- ACE-CRIS & SuperTIGER are consistent for $Z \geq 34$.
- Disagreement for $30 \leq Z \leq 33$ possibly due in part to ST contamination of low 30s by non-Gaussian tails from Fe & Ni.
- Reanalysis of ST data by Walsh may eliminate this problem.
- Disagreement possibly due in part to energy difference.

# CRIS GCRS/Solar-System Abundances

GCR Source compared to Normal ISM

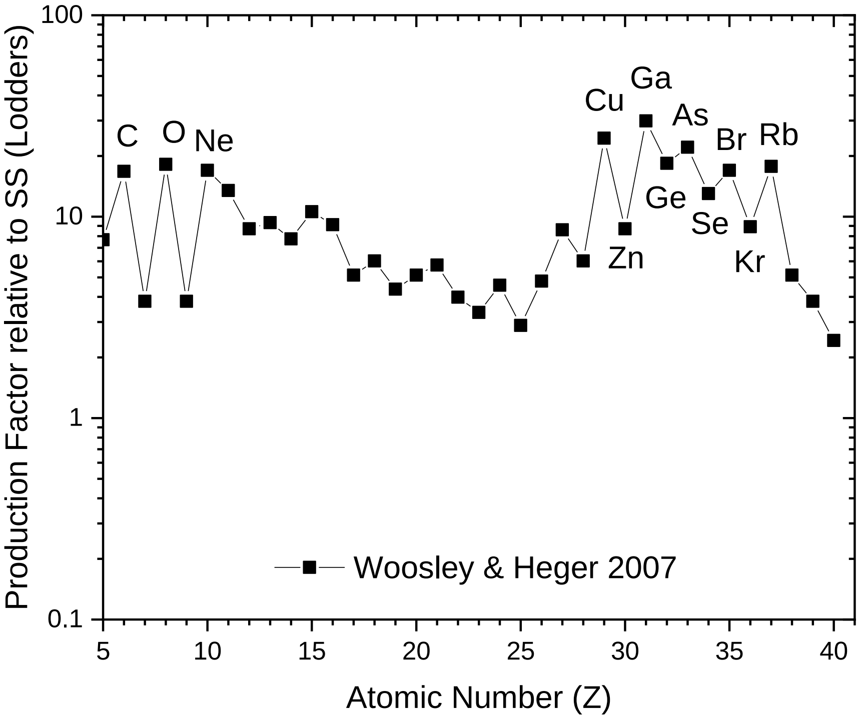
20% MSM + 80% Normal ISM mix



We have previously shown that when one plots the GCRS abundances relative to a mix of massive star material (MSM) and Normal ISM vs. mass instead of relative to Normal ISM only (Solar System material), the refractories and volatile elements separate nicely with similar slopes.

# Woosley & Heger Production Factors

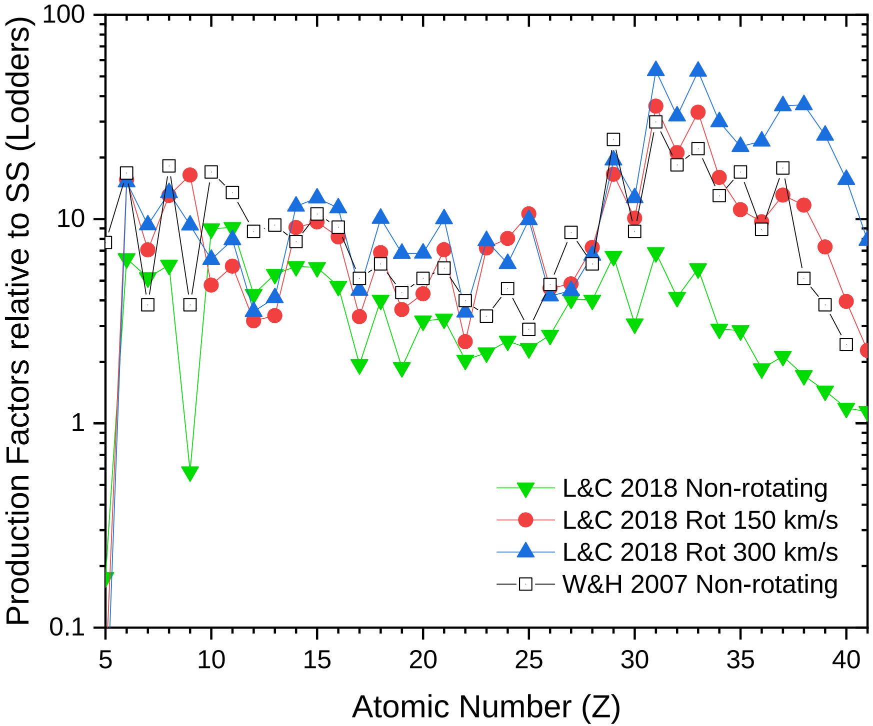
- We have used the Woosley & Heger 2007 production factors for non-rotating stars plotted at right
- The largest production factors are for the nuclei in the low-30’s charge range
- When we add massive star material to normal ISM, these $_{29}$Cu to $_{37}$Rb nuclei are enhanced and the GCRS/(SS+massive star) ratio becomes smaller (since it is added in the denominator), pulling the low-30’s nuclei down



S. E. Woosley & A. Heger (2007) Phys. Rep. 442, 269

# Model Comparisons

- More recently Limongi & Chieffi have calculated production yields in 2018 for both rotating and non-rotating models of massive stars.
- We see at right, L&C 2018 nonrotating has little to no enhanced production factors for the UH elements.
- L&C 2018 rotating 150 km/s has comparable production factors to W&H 2007 non-rotating.
- L&C 2018 rotating 300 km/s has even higher production factors than W&H.



M. Limongi & A. Chieffi, ApJS 237:13, 2018 July

# Conclusions

- ACE-CRIS (preliminary) and SuperTIGER source abundances are similar, but ACE-CRIS abundances appear to be systematically lower for $Z<34$. Disagreement for $30 \leq Z \leq 33$ possibly due in part to ST contamination of low 30s by non-Gaussian tails from Fe & Ni. Reanalysis of ST data by Walsh may eliminate this problem. Possibly also due in part to difference of energy.
- The substantially improved ordering of the GCR abundances, seen in our previous data, when taken relative to a mix instead of pure ISM, argues that the GCRs are accelerated from a mix of massive star material and ISM.
- The $^{22}$Ne/$^{20}$Ne ratio, the $^{60}$Fe/$^{56}$Fe ratio, and the fact that most of the accelerators are in OB associations also argues that a mix of source material is required.
- However the fraction of massive star material mixing with normal ISM is clearly dependent upon the model of stellar production of heavy nuclei used.
- Recent advances in 3D modeling of supernovae promise improved estimates of massive star material, and will lead to improved models of Galactic cosmic ray origin.