Constraints on Galactic Cosmic-Ray Origins from Elemental and Isotopic Composition Measurements

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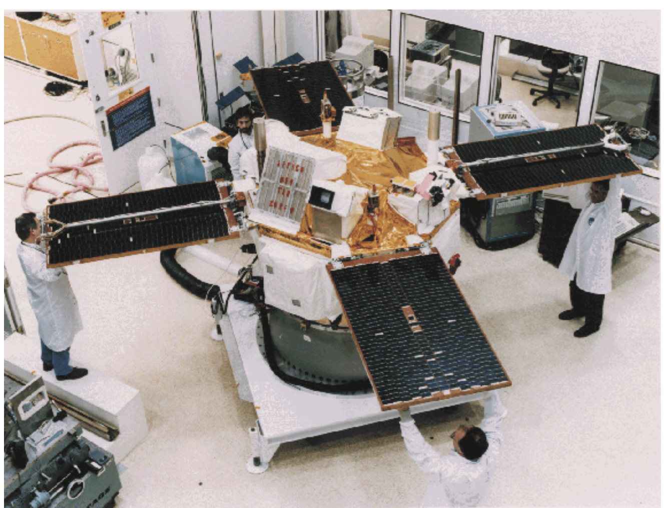
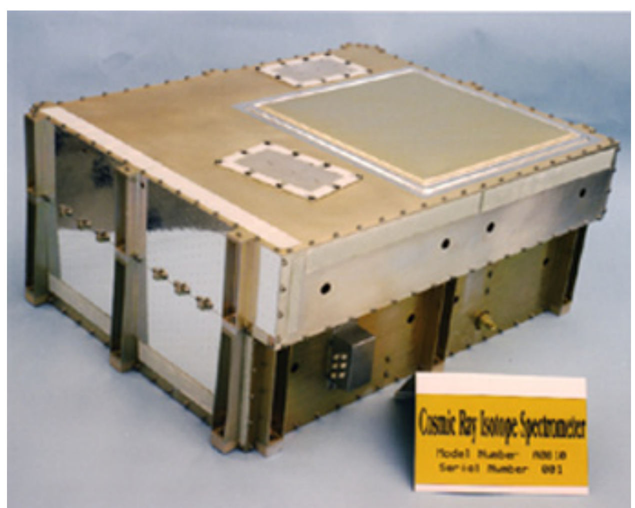
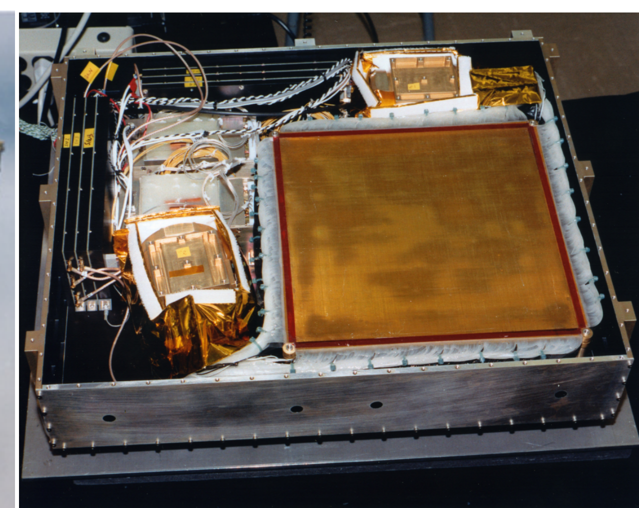
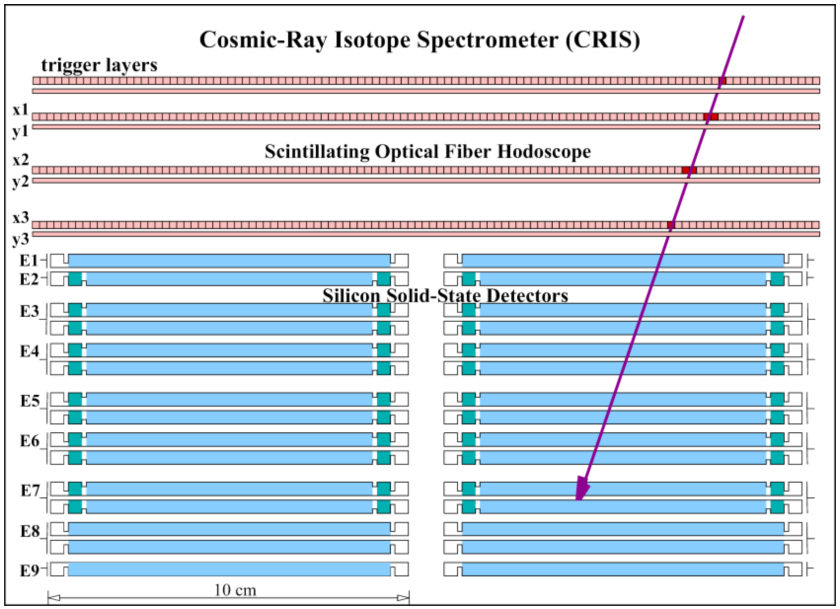
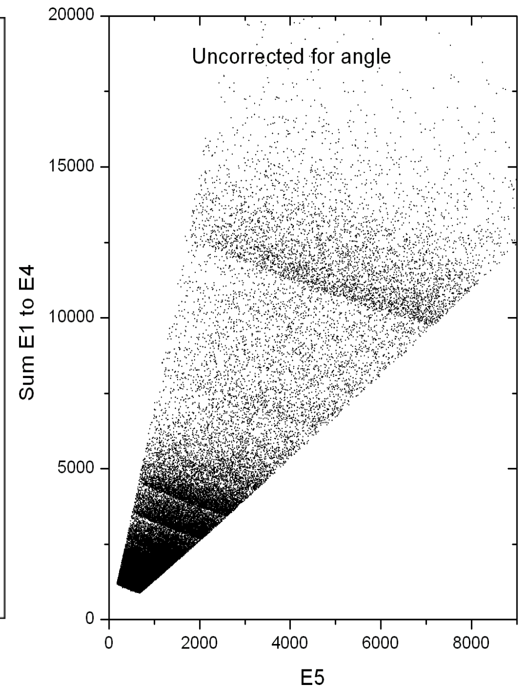


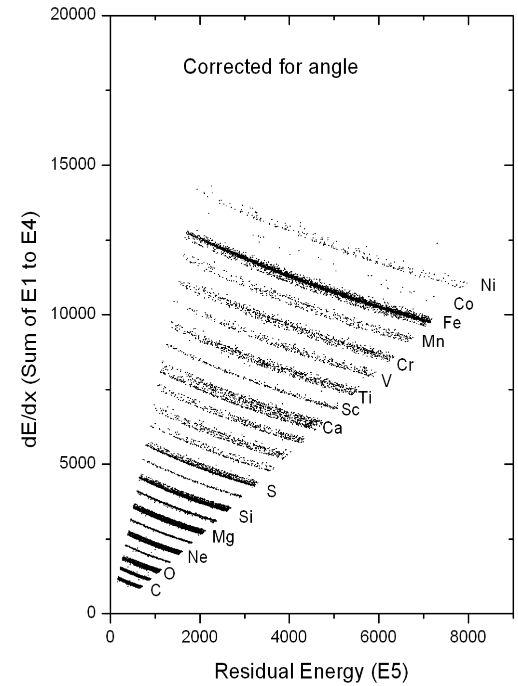




CRIS Instrument

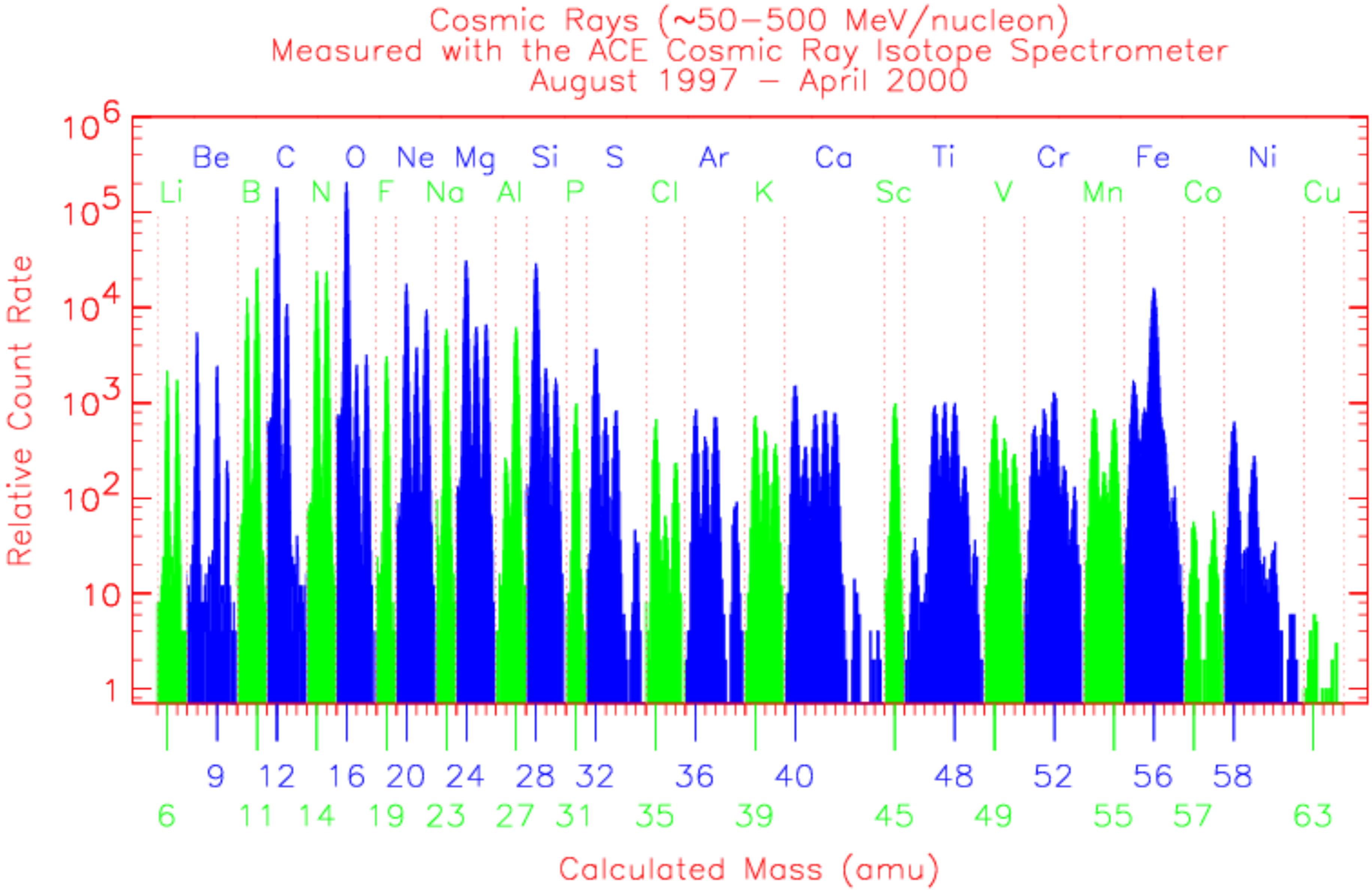






- Large geometrical factor of CRIS (~50 x previous instruments)
- Excellent mass resolution enables precise identification of element and isotope abundances.

CRIS GCR Isotopic Measurements



What do we know about the origin of GCR?

How long after nucleosynthesis are GCR nuclei accelerated?

Does a SN accelerate nuclei synthesized in that SN?

^{59}Ni decays only by K-capture.

$$^{59}Ni + e^- \rightarrow {}^{59}Co + \nu$$

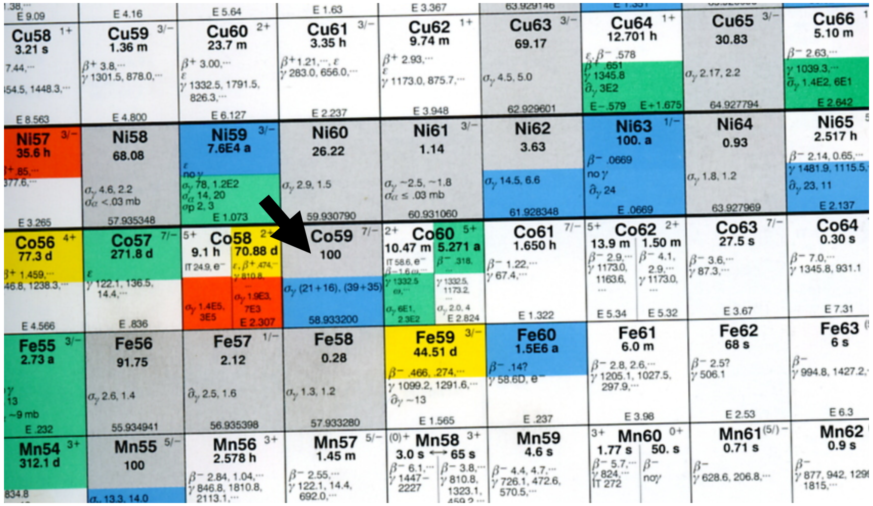
Half-life in the laboratory is 76,000 years.

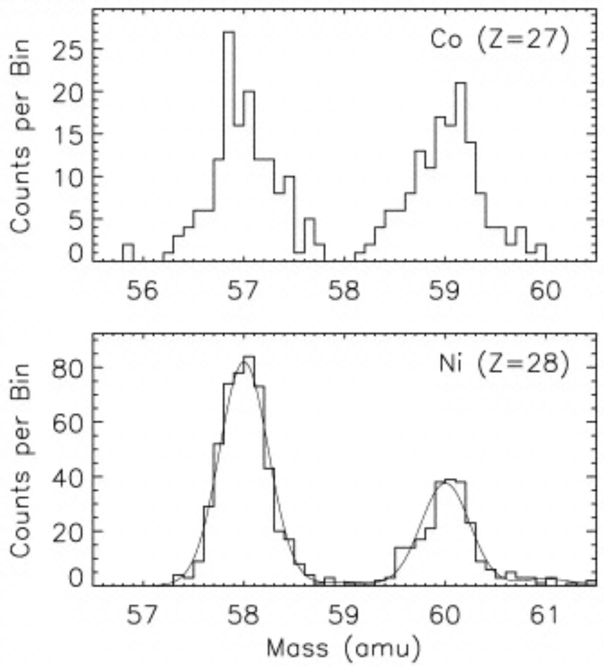
At cosmic-ray energies it is stripped of electrons and so is stable.

If GCR are accelerated by the same SN in which the nuclei are synthesized, expect to see ^{59}Ni in the GCR.

GCR acceleration occurs >~100,000 years after synthesis. So GCR source is ambient interstellar matter, not freshly synthesized.

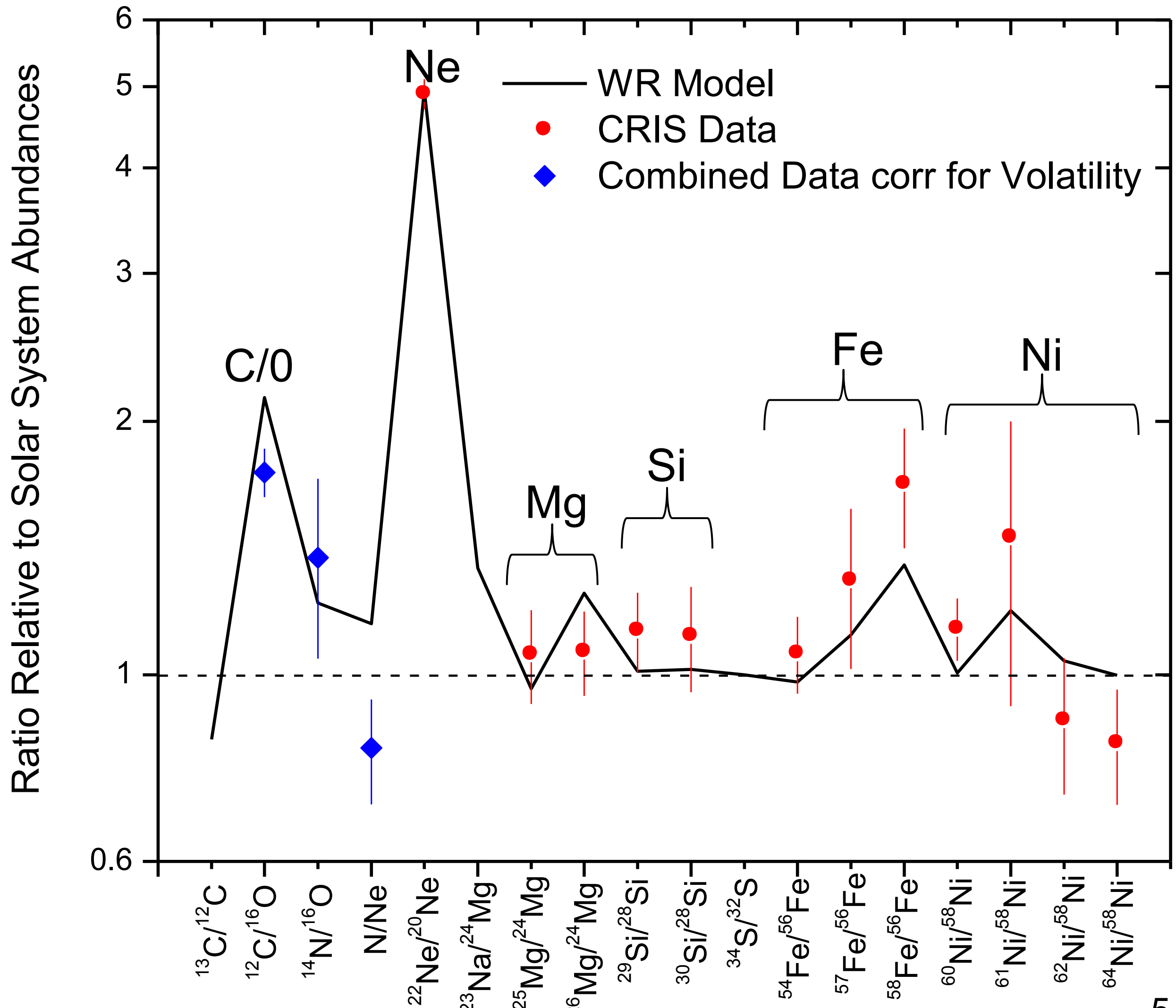
Wiedenbeck, et al., *ApJL*, **523**, L51 (1999)





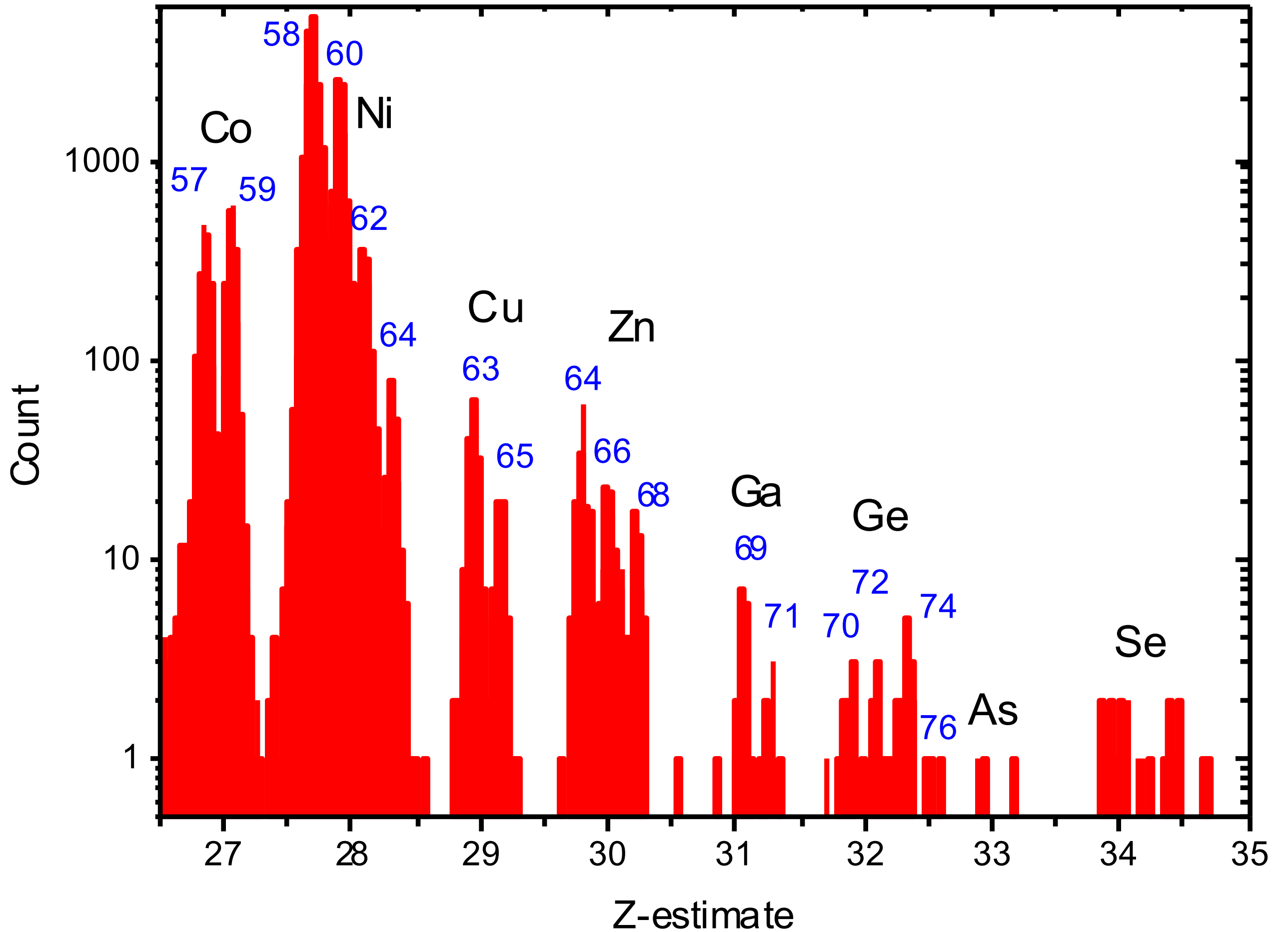
ACE-CRIS isotope ratios for Z≤28

- Based on ACE-CRIS data, Higdon and Lingenfelter (ApJ 590, 822, 2003) showed that the GCR $^{22}Ne/^{20}Ne$ ratio was consistent with a CR source made of a mixture of ~80% SS composition and 20% ejecta from massive stars.
- ➔Superbubble/ OB association origin of GCRs
- Subsequently, Binns, et al (2005) ApJ 634, 351 showed that the GCR abundances of a range of isotope and element ratios for Z≤28 nuclei are also consistent with this same mixture.



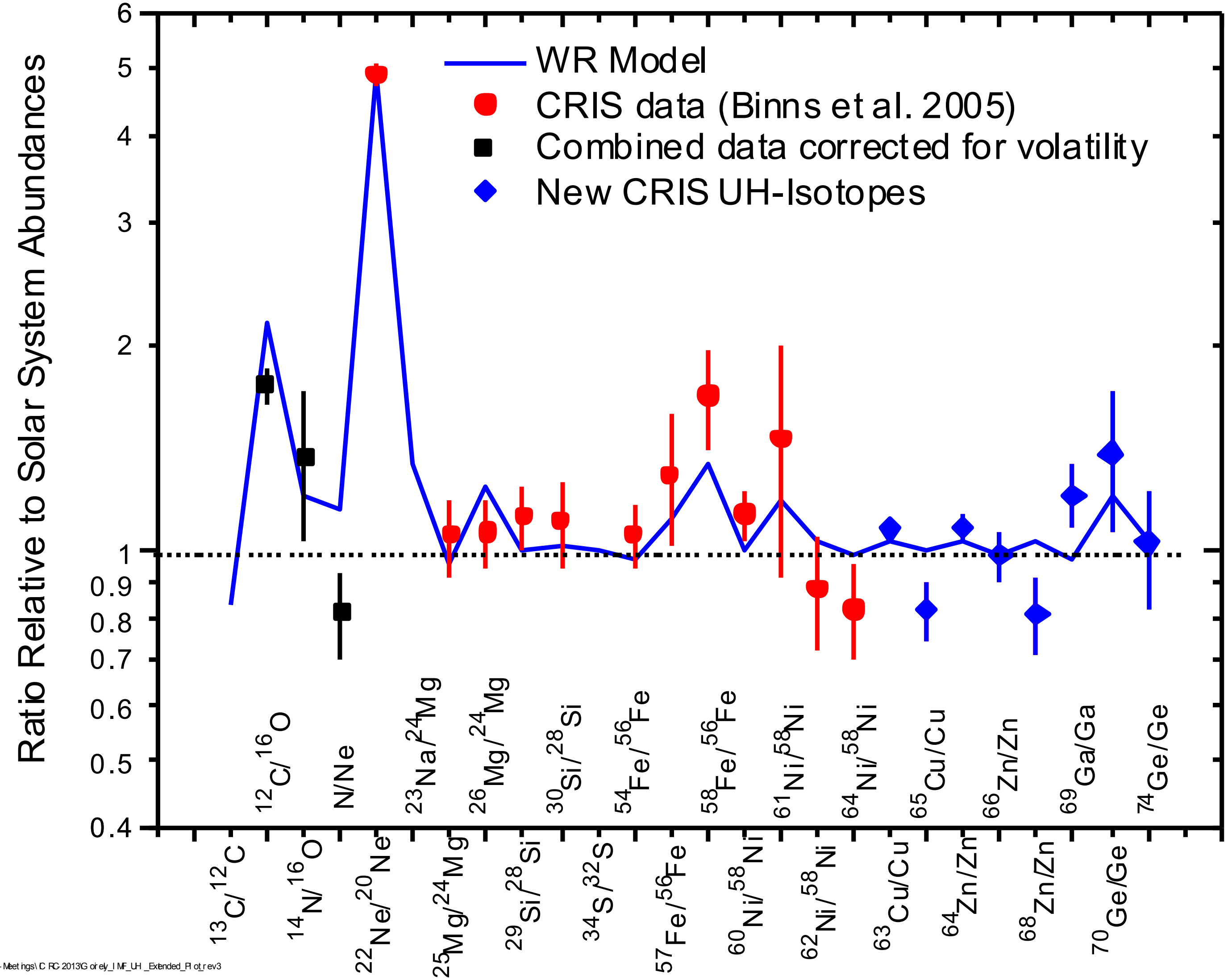
'Figure 6-ApJ-IMF.1.opj

Isotopes for Z>26 nuclei measured by ACE-CRIS



- ACE-CRIS has provided the first, and only existing measurements of isotopic abundances of $_{29}$Cu, $_{30}$Zn, $_{31}$Ga, & $_{32}$Ge.
- We see well resolved isotope peaks from $_{27}$Co through $_{32}$Ge with sufficient statistics for a meaningful measurement.

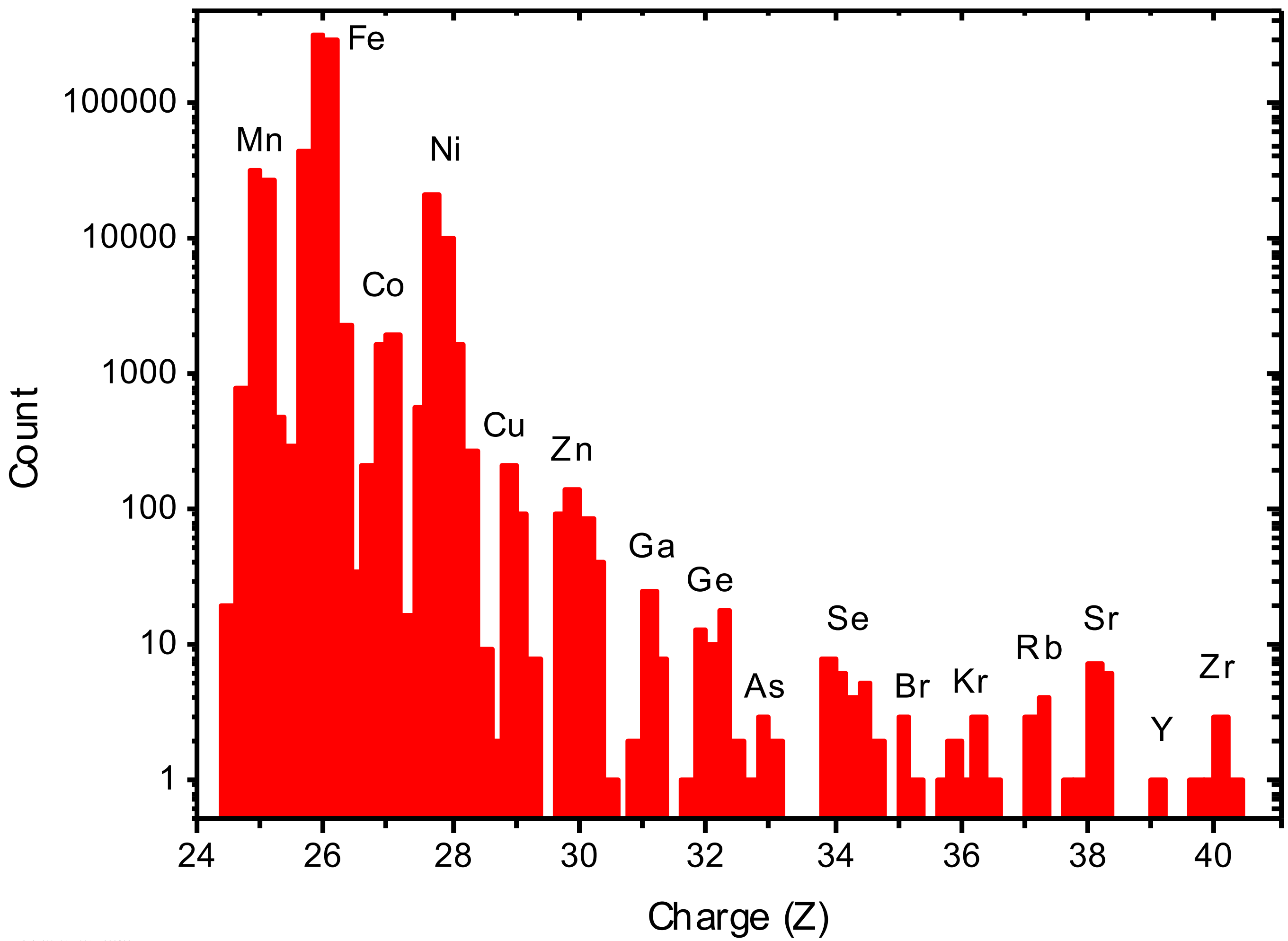
Ultra-heavy isotopes in context of previous lower-Z data



- Note that the new isotopic ratio error bars (blue diamonds) are statistical only. Systematic errors have not yet been included.

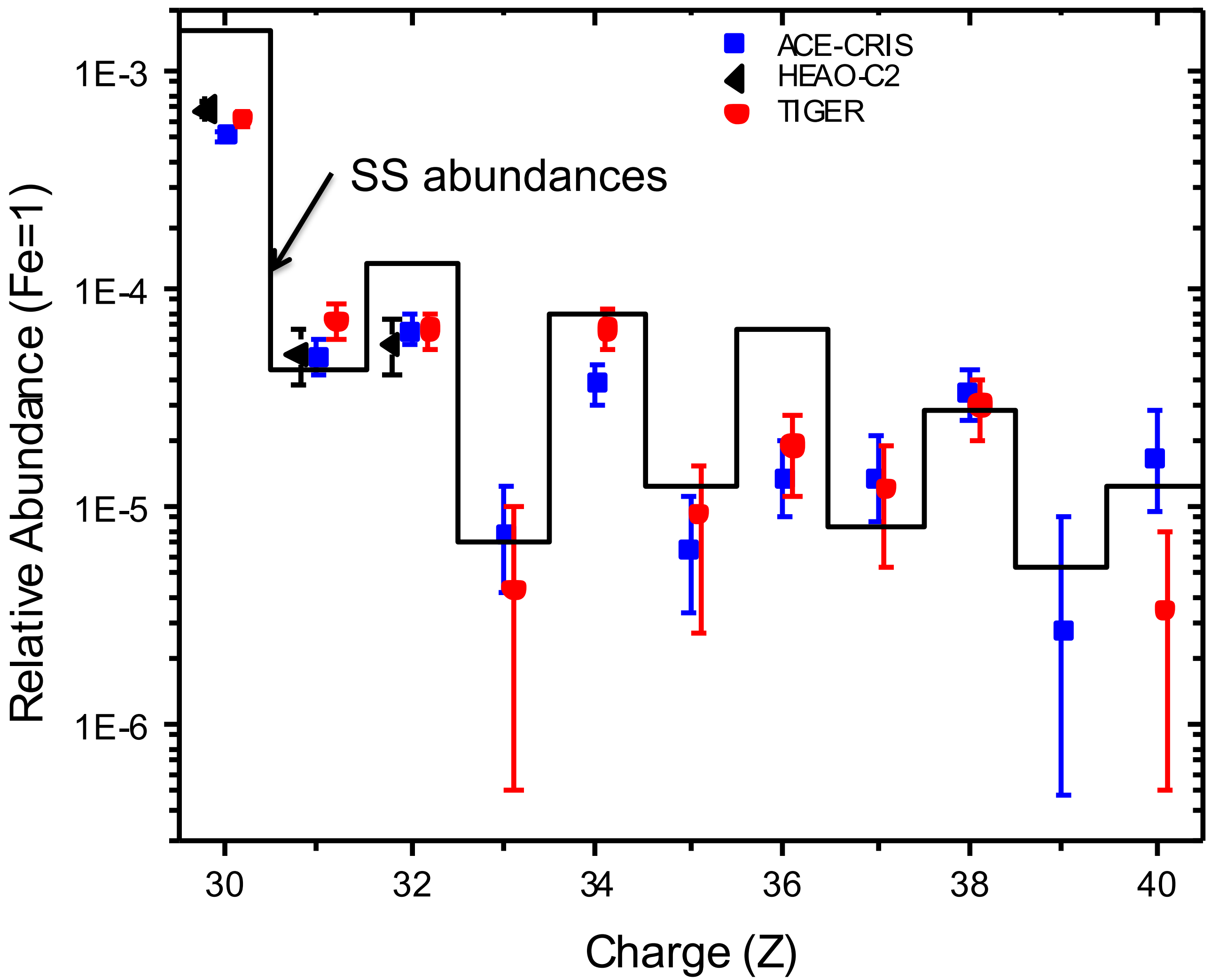
New data (blue diamonds) are consistent with model, but also with solar system abundances.
➔CR source must be able to produce isotope ratios that are "equivalent to" that obtained by mixing ~20% of MSO with ~80% of normal ISM.

ACE-CRIS Elemental Abundances for Z≥25 nuclei



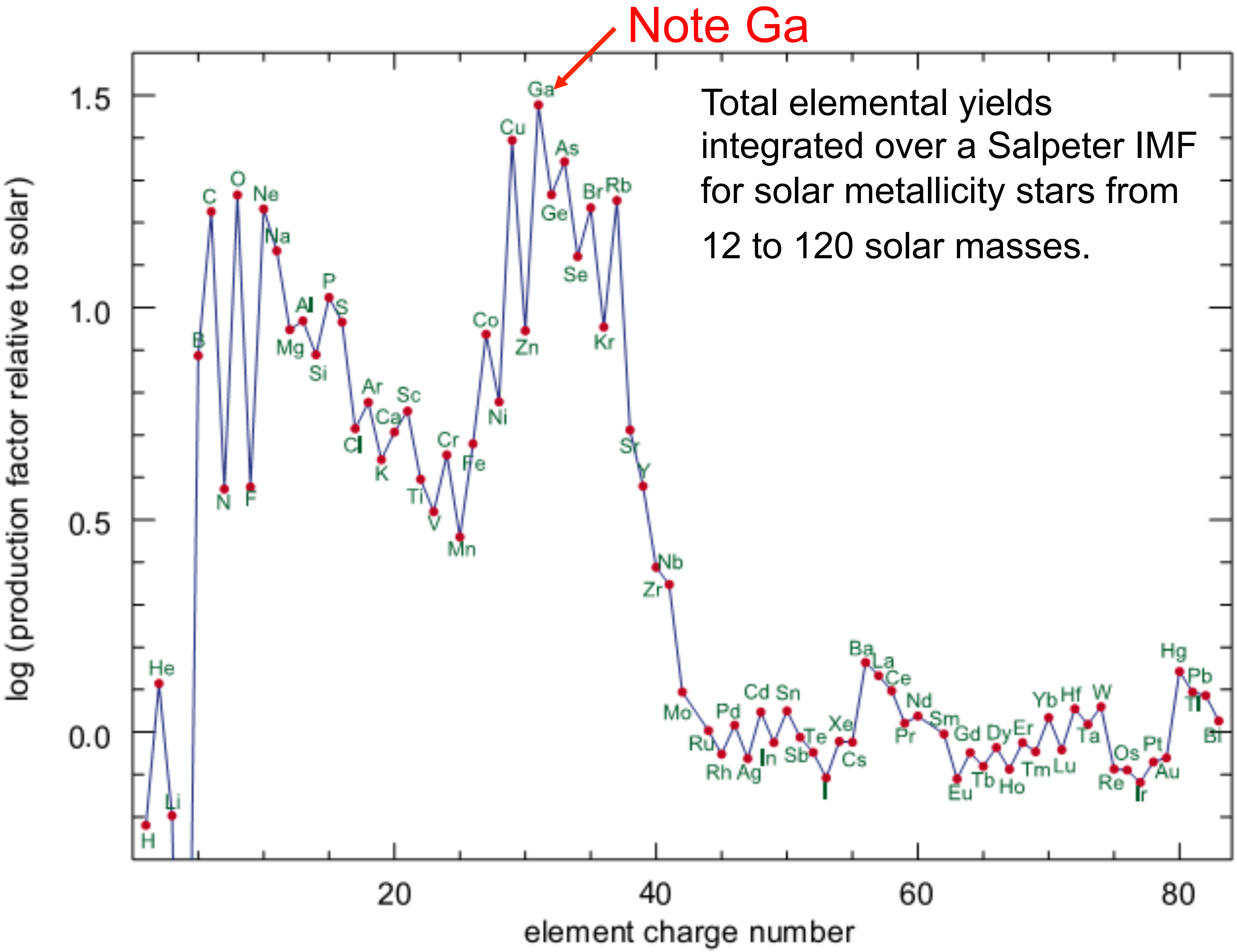
- Excellent resolution in charge for UH nuclei
- Limited statistics at the highest Z

Measured Element Abundances Compared with SS

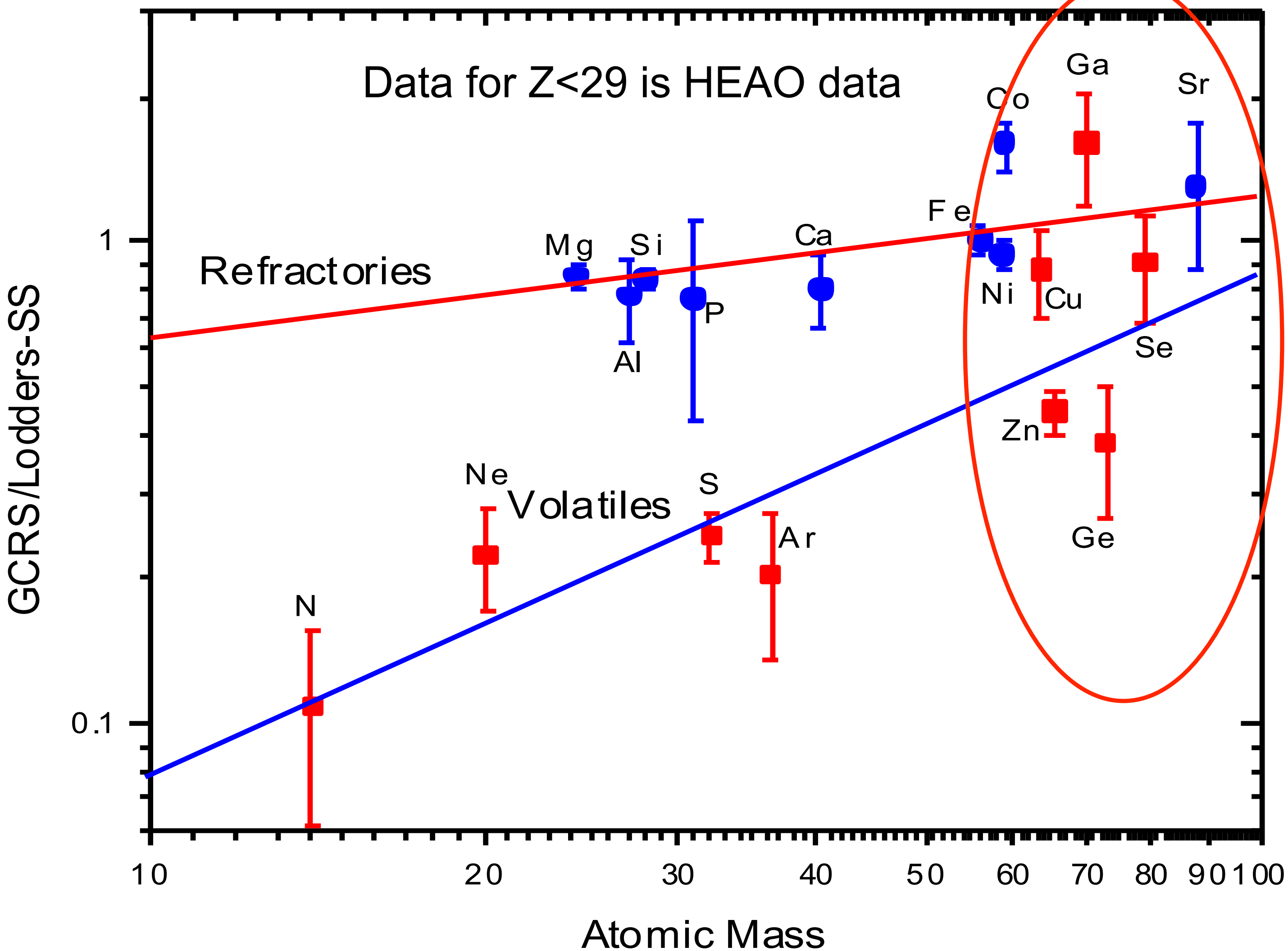


8_2_11-ElementICRCpaper/Abund_rel_Fe_ACE_TIG_HEAO

S.E. Woosley, A. Heger / Physics Reports 442 (2007) 269–283



TIGER+HEAO-C2 data

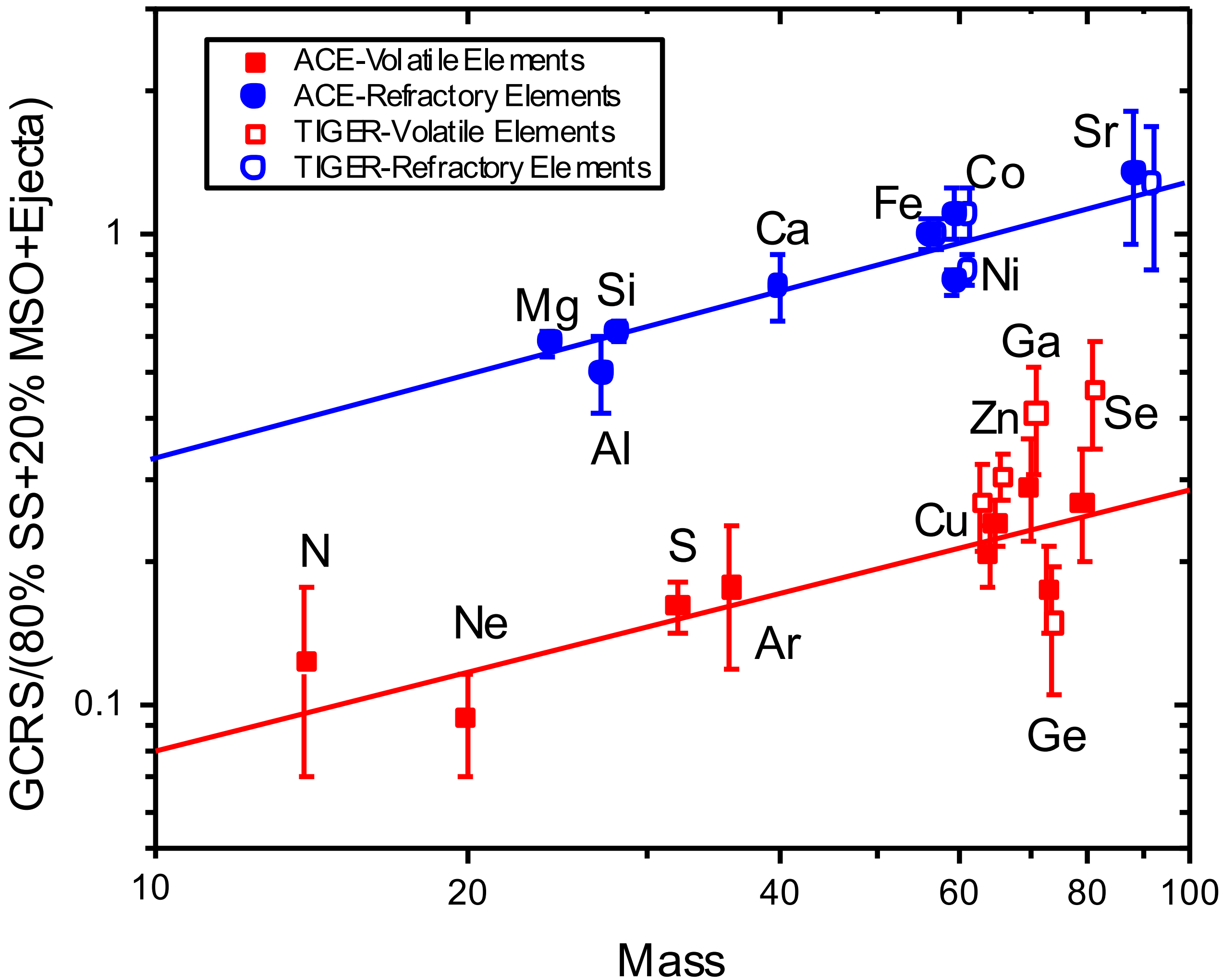


Updated version of plot in Meyer, Drury, & Ellison *Ap.J.* **487** 182 (1997)

Preferential acceleration of elements found in interstellar grains, and mass-dependent acceleration of the volatiles.

There is a lot of scatter here when comparing the cosmic-ray source with solar system abundances.

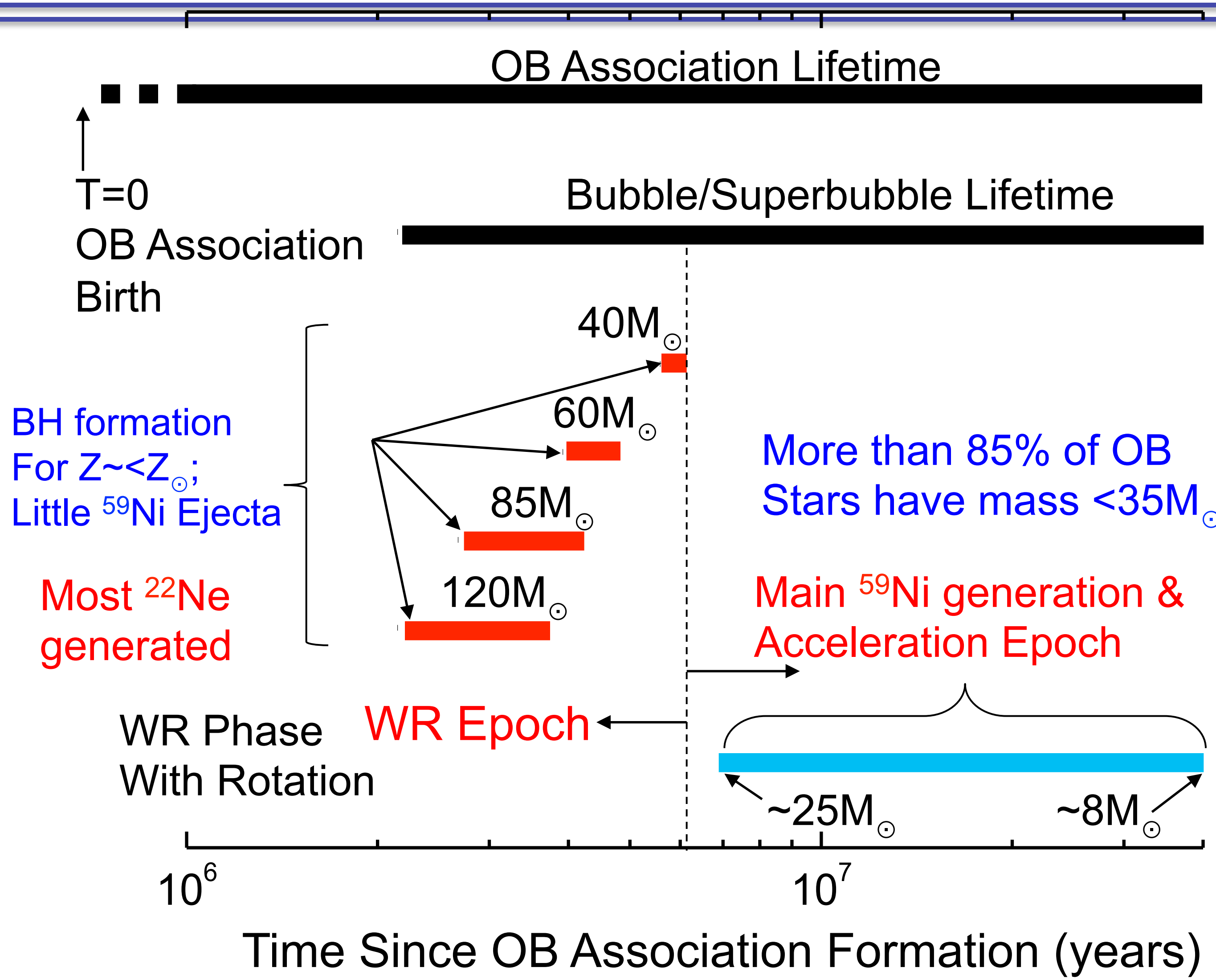
ACE & TIGER data



- Now compare GCR source abundances with a mixture of 80% SS and 20% Massive Star Outflow (WR & precursor) plus SN ejecta (Woosley & Heger, ApJ 2007).
- Ordering and separation of refractories and volatiles is greatly improved.
- Volatile and refractory slopes are similar and show an enhancement of refractories over volatiles of ~4 over the full range of masses

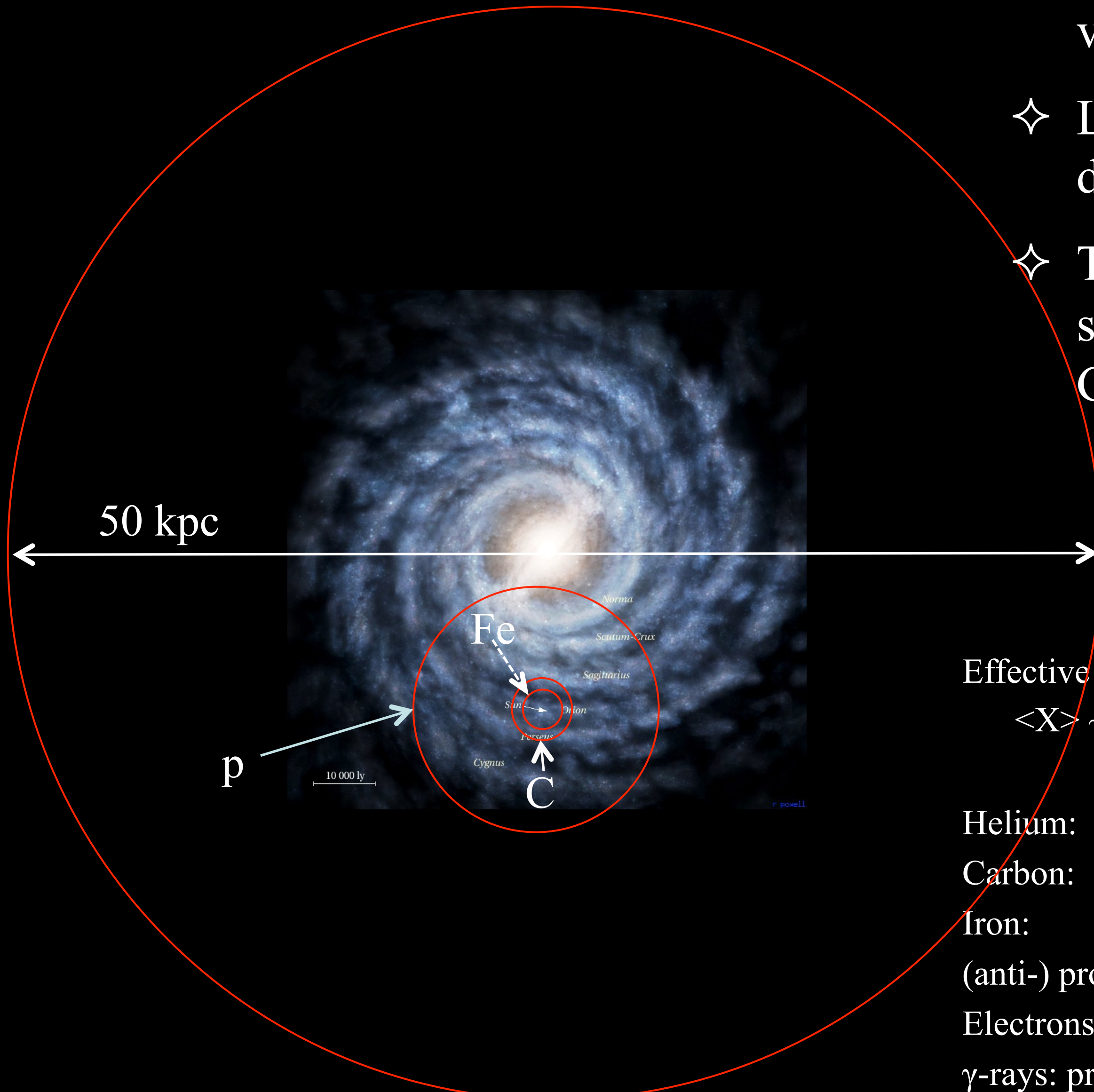
TIGER data--Rauch et al. *ApJ* **697**, 2083 (2009)

OB Association History



Cosmic Ray Sampling of Galaxy

- Direct measurements probe a very small volume of the Galaxy
- Light & heavy nuclei probe different propagation volume
- The propagation distances are shown for nuclei for rigidity ~1 GV



Effective propagation distance:

$\langle X \rangle \sim \sqrt{6D\tau} \sim 4.5\times10^{21}\, R^{1/4}\,(A/12)^{-1/3}$ cm

~ 1.5 kpc $R^{1/4}\,(A/12)^{-1/3}$

Helium: ~ 2.1 kpc $R^{1/4}$

Carbon: ~ 1.5 kpc $R^{1/4}$ - 0.36% of the surface area

Iron: ~ 0.9 kpc $R^{1/4}$ - 0.16%

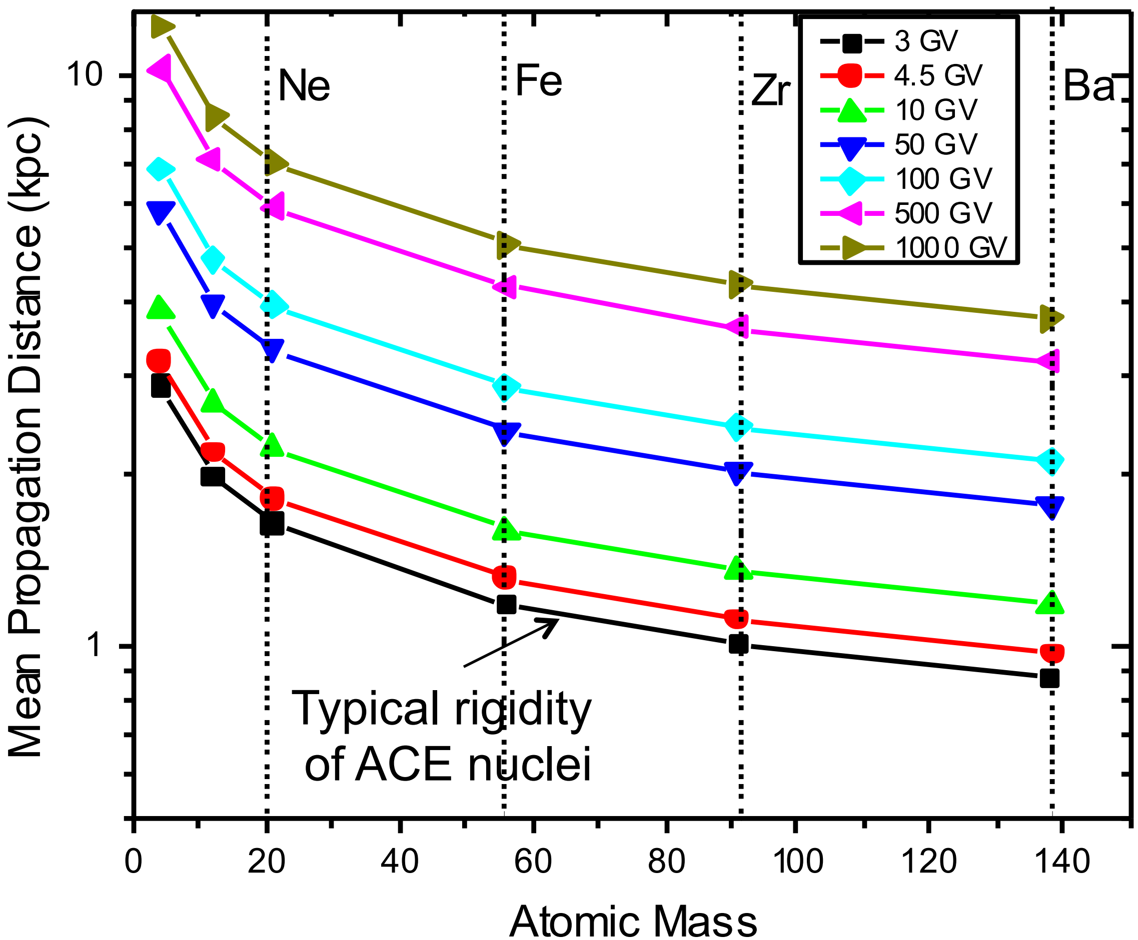
(anti-) protons: ~ 6 kpc $R^{1/4}$ - 5.76%

Electrons ~ 1 kpc $E_{12}^{-1/4}$

γ-rays: probe CR p (pbar) and e± spectra in the whole Galaxy ~50 kpc across

Chart provided by Igor Moskalenko

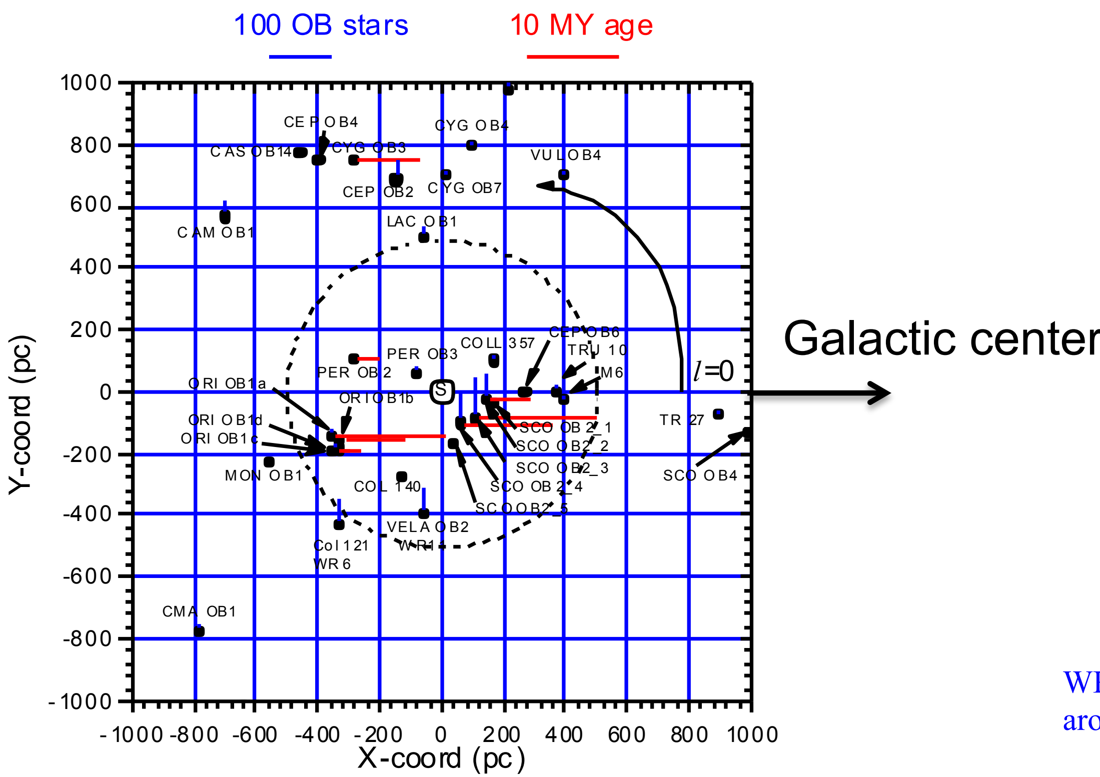
Propagation distance as function of mass and rigidity



- Mean propagation distance calculated from Moskalenko and Strong model is shown at left.
- ACE-CRIS energies for iron nuclei are ~150-600 MeV/nuc at instrument
- Outside the heliosphere, ~0.5-1 GeV/nuc gives a typical rigidity ~3 GV
- Mean propagation distance of ACE-CRIS nuclei is of order 1kpc

OB Association Origin of GCRs

- WR star wind ejecta, enriched in ^{22}Ne and perhaps in ^{58}Fe, mixes within the superbubble with
  - Average ISM (represented by solar-system abundances)
  - Ejecta from core-collapse Sne
  - Higdon & Lingenfelter (2003); Binns et al. (2005)
- Refractory elements--mostly in interstellar grains; volatile elements mostly gas
- SN shocks accelerate mix of material in superbubbles (SB) to cosmic ray energies
  - Grains preferentially accelerated (Ellison et al. 1997)

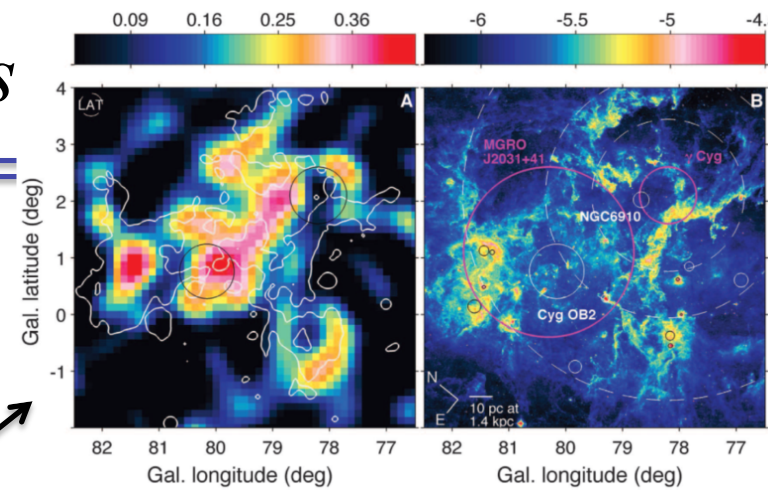


N44 Superbubble in LMC--Credit:Gemini Obs, AURA, NSF

WR (Sharpless 308) ~1.6 kpc distant Diameter of bubble around star ~ 20 pc—Credit: Don Goldman, Roseville, CA USA

Recent γ-ray observations

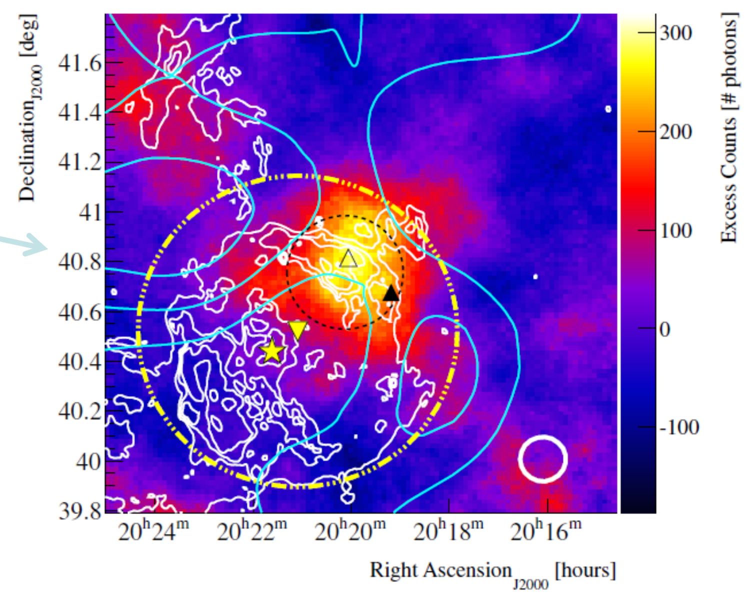
- Recent γ-ray measurements—Fermi-LAT, Veritas, HESS
  - Fermi--γ-rays consistent with π^0 decay observed from SNRs IC443 and W44➔hadrons being accelerated— both are core-collapse SNRs and IC443 is a member of the Gem OB-1 association (Ackermann et al. Science 339 (2013) 807).
  - Fermi--Distributed emission observed (Energy 1-100 GeV) in a "cocoon" along line between Cygnus OB2 to NGC 6910. Morphology of emission region is coincident with edge of Cygnus superbubble (Ackermann et al. Science 334 (2011) 1103).
  - Veritas—Distributed emission (Energy 0.3-10 TeV) observed within radio shell of SNR G78.2+2.1, which is nearby the Fermi "cocoon" (Aliu et al., ApJ 770 (2013) 93).
  - 12 γ-ray SNR sources summarized by Dermer & Powale (A&A 553 (2013) A34), only one of which is believed to result from Type Ia SN.
- Most core-collapse SNe occur in OB associations (~90%; Higdon & Lingenfelter, ApJ 628 (2005) 738).



Distributed γ-ray emission From the Cygnus-X superbubble

8-μm map of same region with circles for γ-Cygni and stellar clusters

The Astrophysical Journal, 770:93 (7pp), 2013 June 20



Veritas γ-ray observation of distributed emission within shell of SNR G78.2+2.1 in Cygnus X

OB association origin?

- N. Prantzos, A&A 538, A80 (2012)
  - Detailed model of OB association/superbubble scenario
  - ^{22}Ne/^{20}Ne ratio depends on age of OB association as expected
  - In his model, he finds that he cannot account for a ^{22}Ne/^{20}Ne ratio as high as what we have measured after mixing with normal ISM.
  - Concludes that GCRs do not come predominately from OB associations
- The maximum in the ratio occurs early in the association lifetime—suggests that we are seeing the ^{22}Ne from young nearby associations

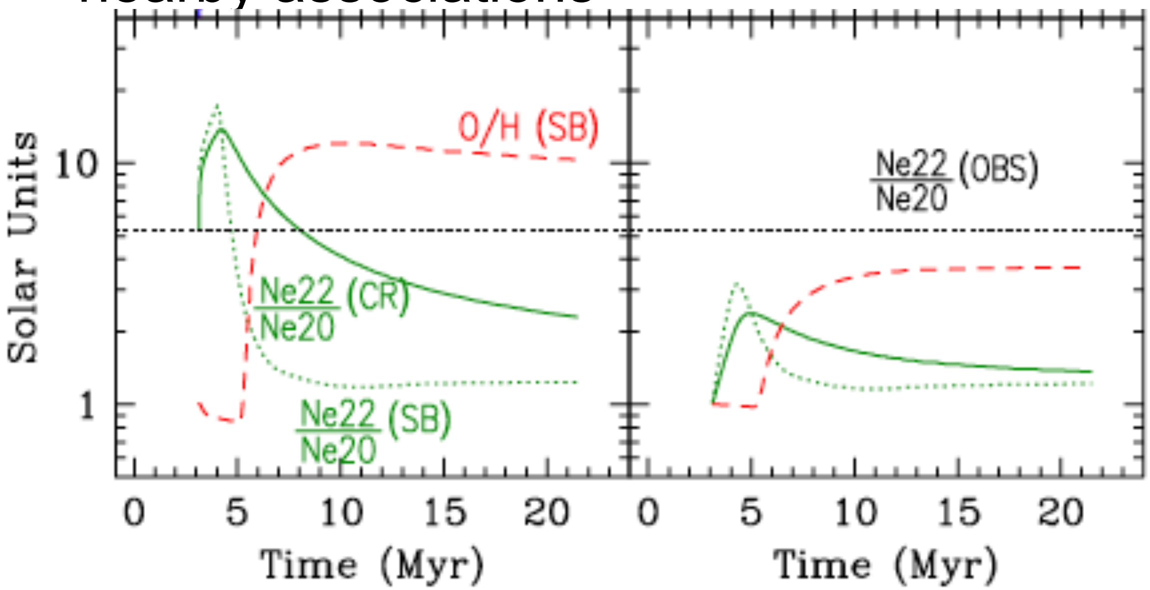


Figure taken from Prantzos paper above

Conclusions

- Several independent observations supporting an OB association-superbubble origin of a substantial fraction of GCRs
  - ACE-CRIS isotope measurements from Neon (Z=10) through Germanium (Z=32)
  - ACE-CRIS and TIGER/HEAO-3 elemental abundances ($6 \leq Z \leq 38$)
  - Fermi observation of distributed γ-ray emission over the Cygnus-X superbubble
  - Fermi observation of γ-ray emission from core-collapse SNR
  - Veritas observation of distributed emission near the Fermi "cocoon"
- OB associations are where most of the accelerators are!
- Strong evidence for the OB-association origin of GCRs