# What the Composition of Galactic Cosmic Rays Tells us About the Origin of GCRs

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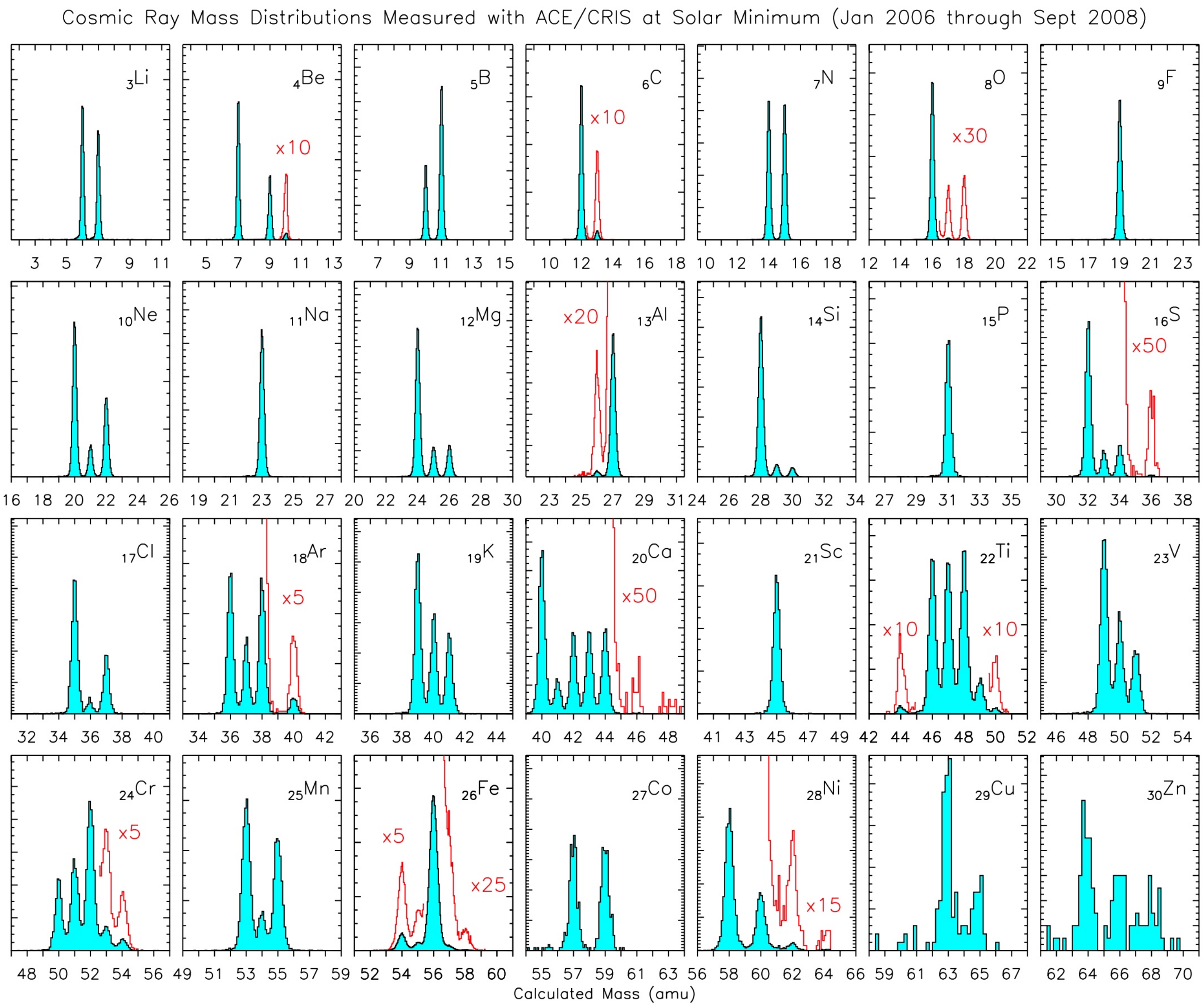
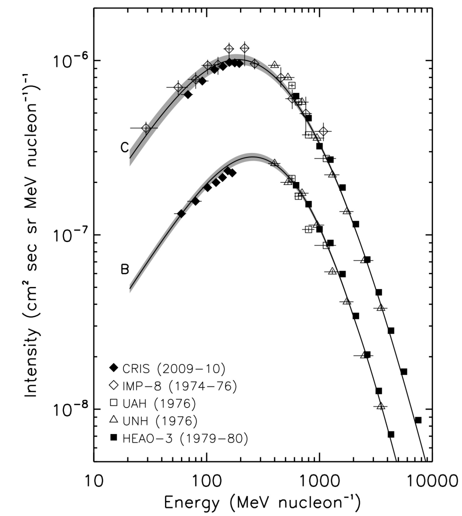
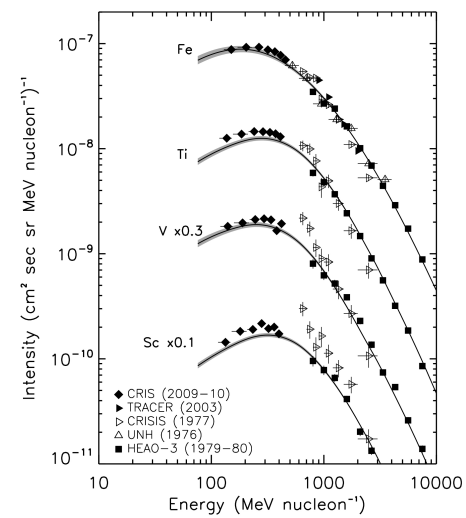
with thanks to the ACE/CRIS and SuperTIGER instrument teams

# Isotopic Composition and Elemental Energy Spectra Have are Now Measured up to Z≃30 in Cosmic Rays below ~1 GeV/nuc



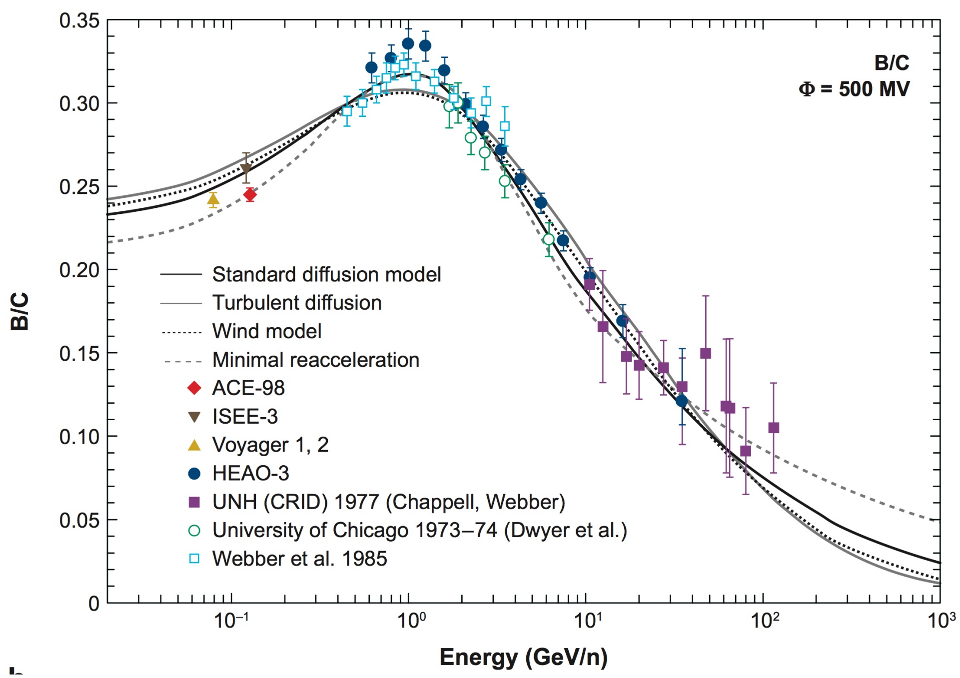

Lave et al., ApJ, 770, 117, 2013

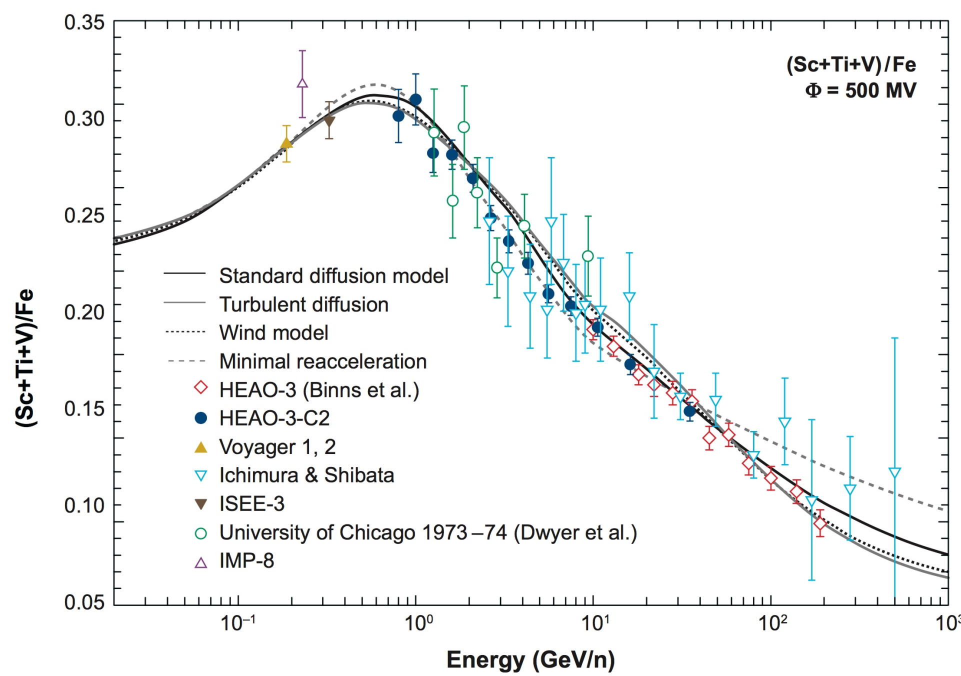
# Categories of Cosmic Ray Elements and Isotopes and the Types of Information They Can Provide

| CATEGORY | SIGNIFICANTLY PRIMARY | DOMINANTLY SECONDARY |
|---|---|---|
| **STABLE** | **H, He, C, O, Fe**<br>fractionation, acceleration<br>**$^{22}$Ne**<br>stellar nucleosynthesis | **B**<br>matter pathlength traversed in the Galaxy<br>**$^{9}$Be**<br>matter pathlength traversed in the Galaxy |
| **RADIOACTIVE**<br>**β- or β+ emitter** | **$^{60}$Fe**<br>time since nucleosynthesis | **$^{10}$Be**<br>time diffusing in the Galaxy |
| **RADIOACTIVE**<br>**pure electron capture** | **$^{59}$Ni**<br>time between nucleo-synthesis and acceleration | **$^{51}$Cr**<br>energy change during transport |

# Secondary-to-Primary Ratios:  Matter Traversed in the ISM

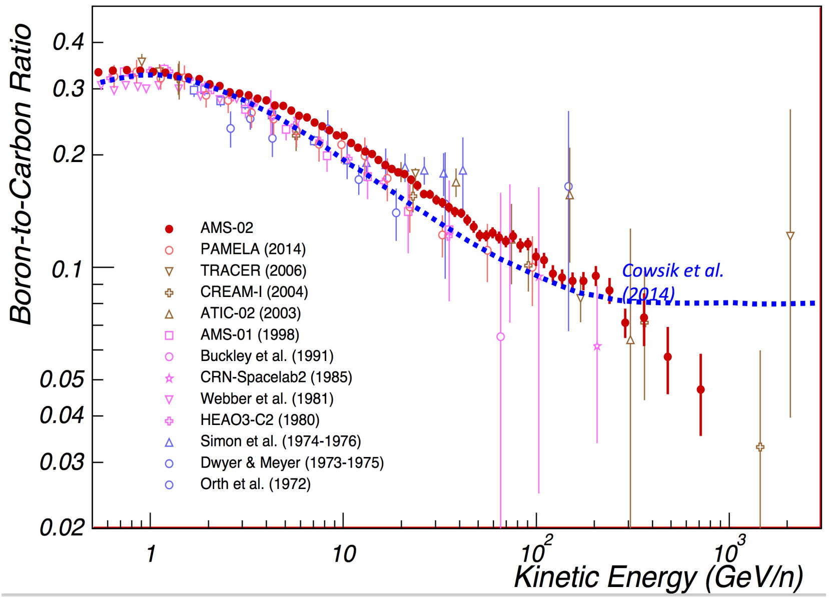
- ratios used to derive the “target thickness” in which primaries must have interacted in order to procude the observed secondaries
- one of the oldest uses of cosmic-ray composition data
- now measured over a wide range of energies
- measured fragmentation cross sections now available for interpreting the ratios
- decreases at high and at low energies contain important clues about the physics of cosmic-ray transport in the Galaxy (weak reacceleration, shrouded sources, galactic wind, etc.)



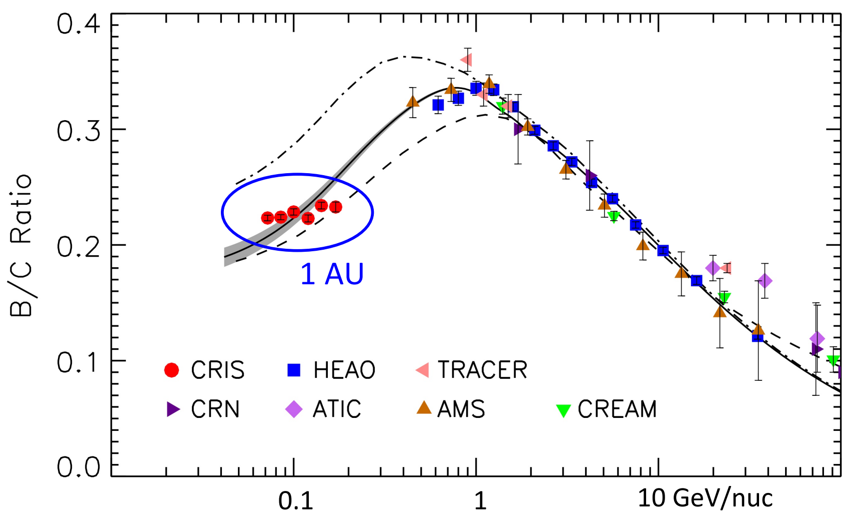




Strong et al., Ann. Rev. Nucl. Part Sci., 57, 285, 2007

# Secondary-to-Primary Ratios (B/C): Matter Traversed in the ISM

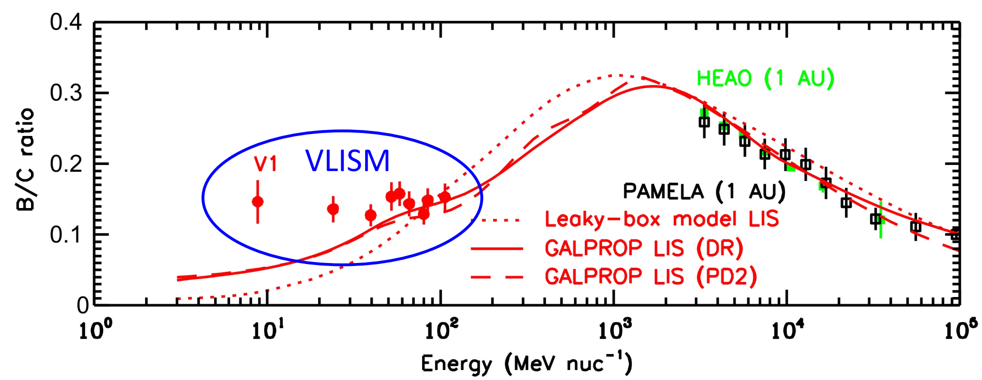



Schael presentation




Lave et al., ApJ, 770, 117, 2013

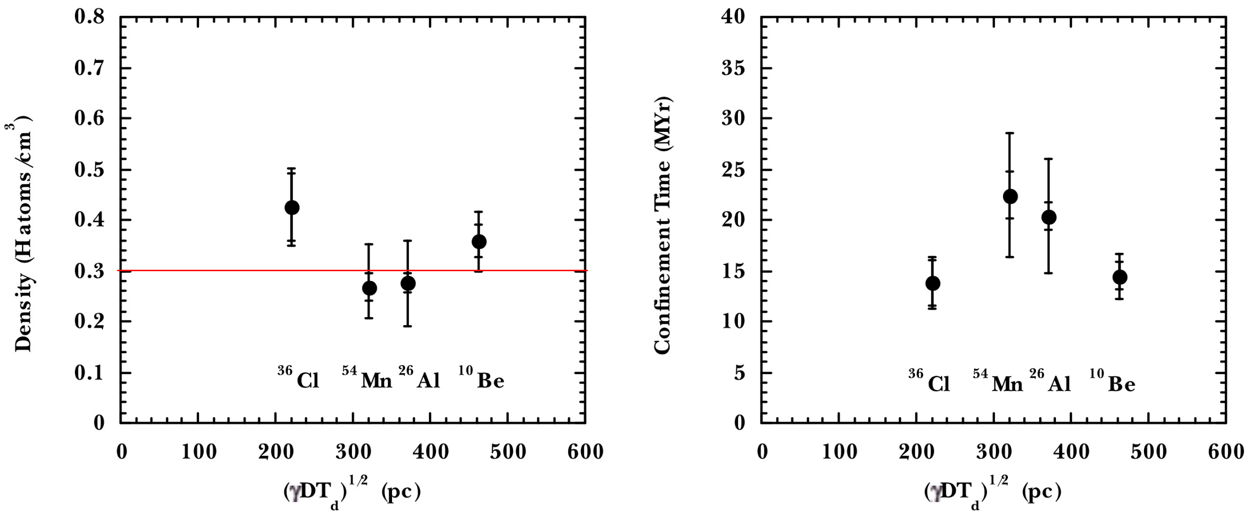
- ratios used to derive the "target thickness" in which primaries must have interacted in order to produce the observed secondaries
- one of the oldest uses of cosmic-ray composition data
- now measured over a wide range of energies
- Voyager 1 measurements now knowledge of B/C down to ~10 MeV/nuc in VLISM
- decreases at high and at low energies contain important clues about the physics of cosmic-ray transport in the Galaxy (weak reacceleration, shrouded sources, galactic wind, etc.)



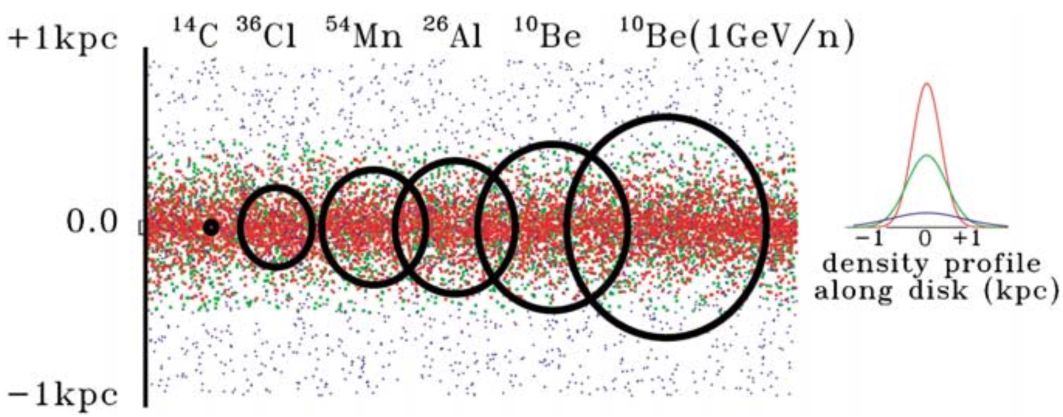

Cummings et al., ApJ, 831, 18, 2013

# Where and for How Long do Secondary Cosmic Rays Propagate in the Galaxy?

ACE/CRIS data




Mewaldt et al., Space Sci. Rev., 99, 27, 2001




radii of circles drawn equal to the distance that each radionuclide can diffuse in it mean life time

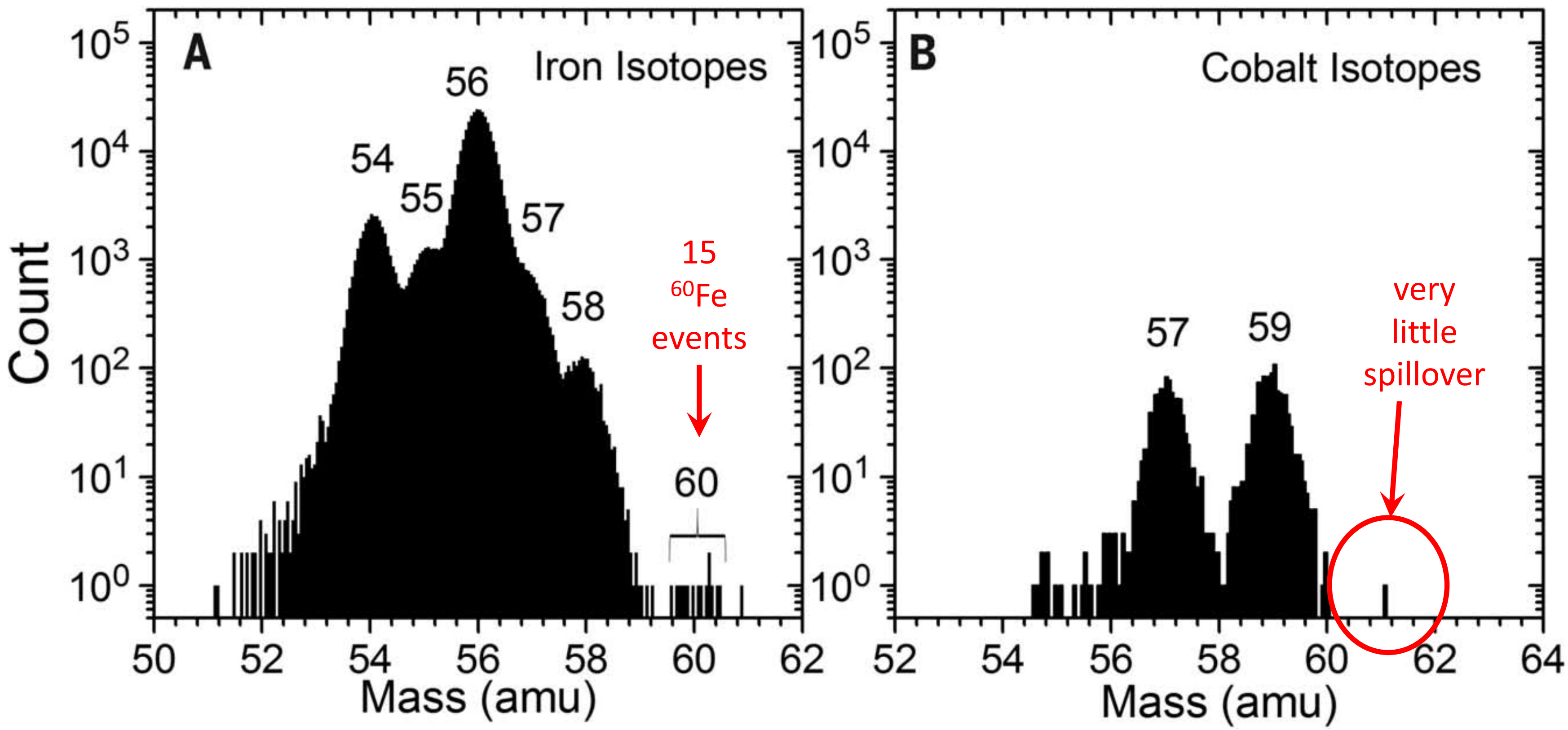
- Reconciling the amount of matter traversed (from B/C) with the time scale inferred from the decay of radioactive secondries requires interstellar densities ~0.3 H atoms/cm$^3$, less than the "typical" IS desity estimate ~1/cm$^3$.
- Conclude that GCRs spend a significant fraction of their time in the galactic halo.
- Cosmic-ray $^{14}$C ($T_{1/2}$=5730 yr) would sample only the galactic disk, but data are not yet sufficiently background-free to allow this short-lived nuclide to be measured.

# First Observation of a Primary Cosmic-ray Radionuclide ($^{60}Fe$)

- $^{60}Fe$ is synthesized in supernovae
- there is no significant source of secondary $^{60}Fe$
- clock is started at the time of stellar nucleosynthesis and not stopped until detection

Fe isotopes:
54, 56, 57, 58: stable
55: $e^-$ capture decay only
60: $\beta^-$ decay (half-life: 2.6 Myr)

Co isotopes:
57: $e^-$ capture decay only
59: stable (and product of $^{59}Ni$ decay)



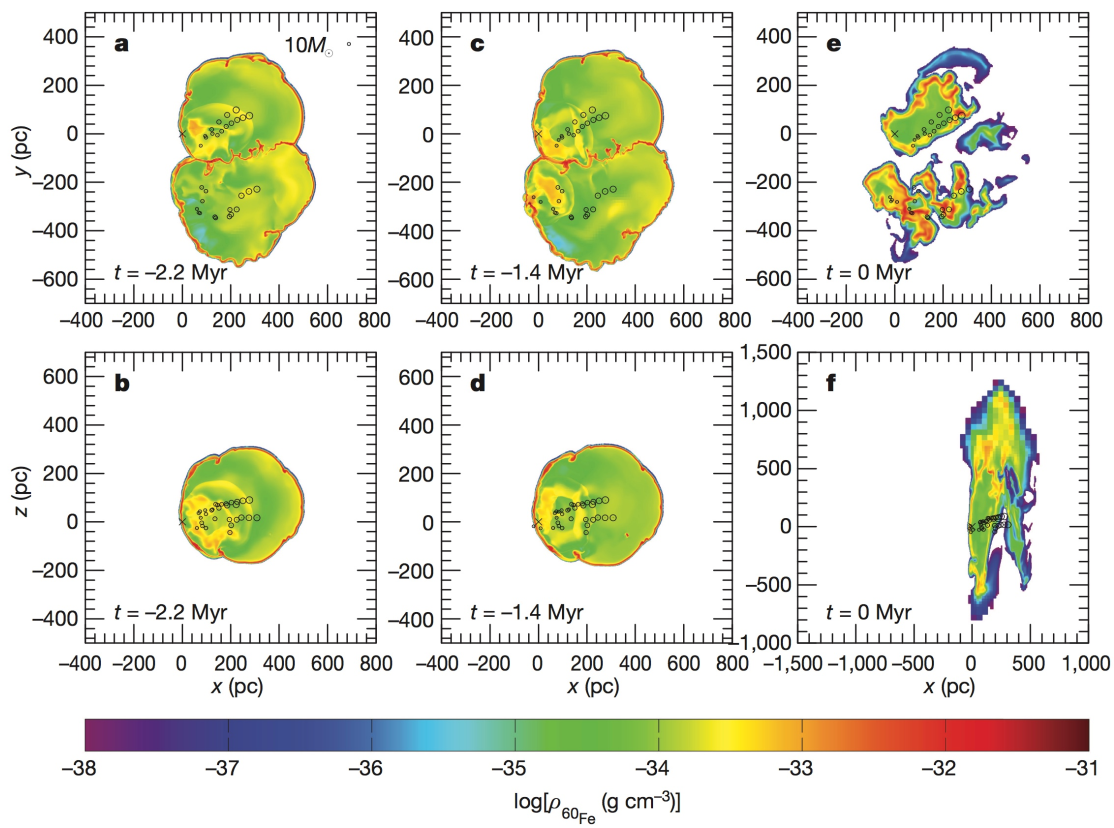

Binns et al., Science, 352, 677, 2016

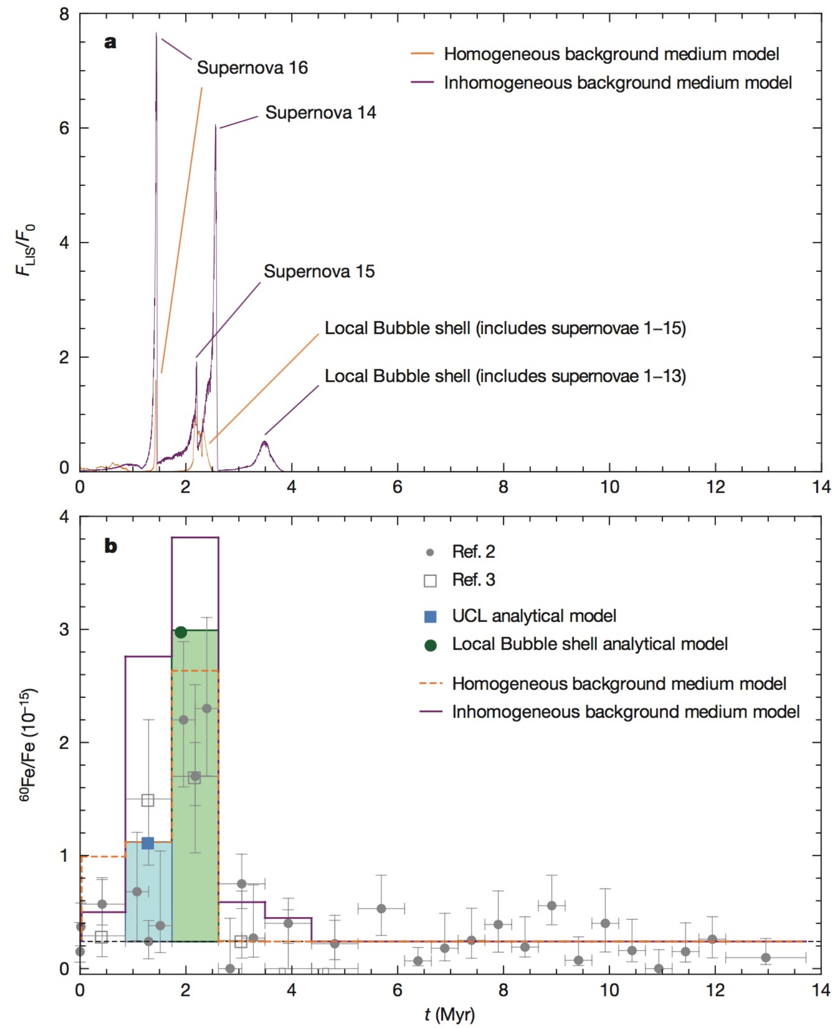
## Significance of Surviving $^{60}$Fe

- the $^{60}$Fe primary clock is sensitive to the time between when this nuclide was synthesized in a supernova explosion and when it is observed
- the fundamental conclusions that can be drawn from the observation of live $^{60}$Fe in the cosmic rays are:
    1) the nucleosynthesis event did not occur significantly longer ago than the 2.6 Myr half-life of $^{60}$Fe
    2) the nucleosynthesis event did not occur significantly farther away than cosmic rays can diffuse on this time scale, ~500 - 1000 pc
- possible associations have been noted between the supernova that produced the GCR $^{60}$Fe and events responsible for $^{60}$Fe that has been found in samples from the ocean floor and from the lunar regolith indicating a nearby supernova ~2 Myr ago (reviewed by Fry et al., ApJ, 2016)
- the derivation of the synthesized abundance of $^{60}$Fe also depends on the the propagation history of cosmic rays between their sources and Earth—several people have pointed out that our initial estimate of the $^{60}$Fe/$^{56}$Fe ratio in the synthesized material using a simple leaky-box model significantly underestimates the source ratio as compared to a more realistic model in which the synthesis occurs in the galactic disk but cosmic rays diffuse throughout a larger halo

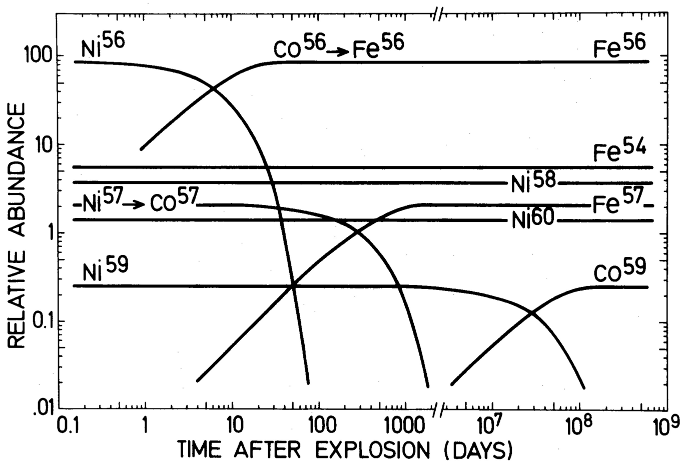
# Where Could the $^{60}$Fe Have Originated?

- $^{60}$Fe detected in ocean sediments has been successfully modeled as coming from supernova that that occurred in the local bubble ~100 pc from the Sun ~2.3 Myr ago
- these parameters are consistent with the requirement that cosmic-ray $^{60}$Fe have come from a supernova <1 kpc away that exploded within the last few Myr




Breitschwerdt et al., Nature, 532, 73, 2016



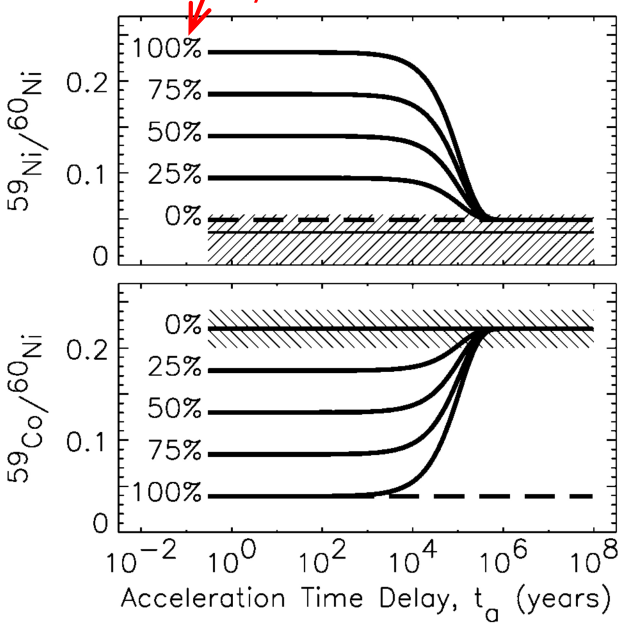

Soutoul & Cassé, ApJ (1978)

# Primary Nuclides that Can Decay Only by Orbital Electron Capture

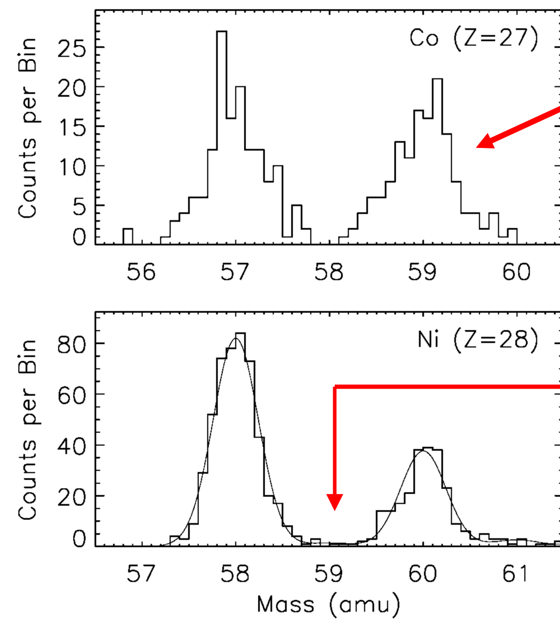
$$^{59}\mathrm{Ni} + e^{-} \Rightarrow {}^{59}\mathrm{Co}$$

traversal of IS matter at cosmic-ray energies strips off orbital electrons and prevents further decays of $^{59}$Ni

fraction of mass-59 material synthesized as $^{59}$Ni




Wiedenbeck et al., ApJL (1999)




$^{59}$Co, the daughter product of $^{59}$Ni decay, is present

$^{59}$Ni missing in arriving cosmic rays

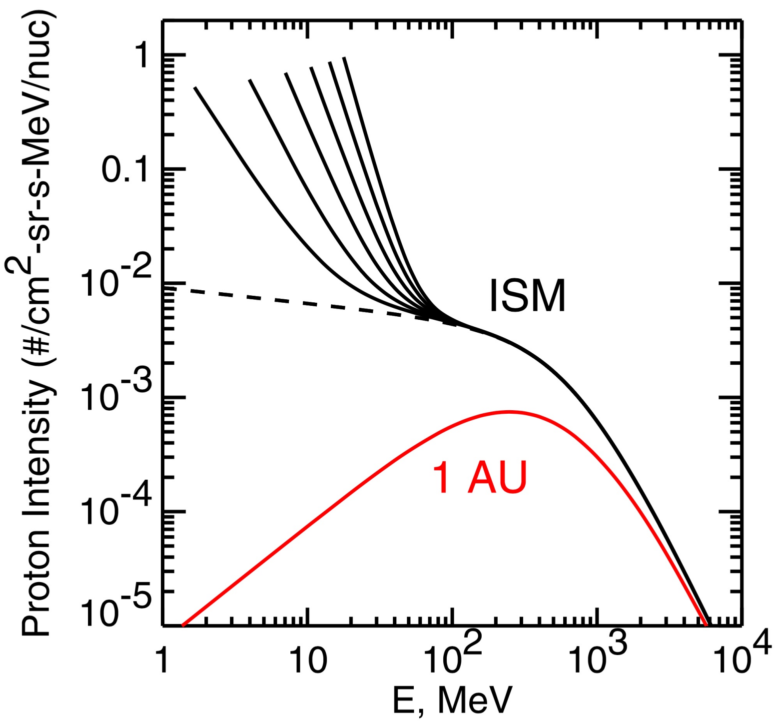
- CRIS measurements of Ni isotopes did not show evidence of $^{59}$Ni
- increased statistics since 1999 have not changed that situation

# Interpretation of the Lack of $^{59}$Ni in the Cosmic Rays

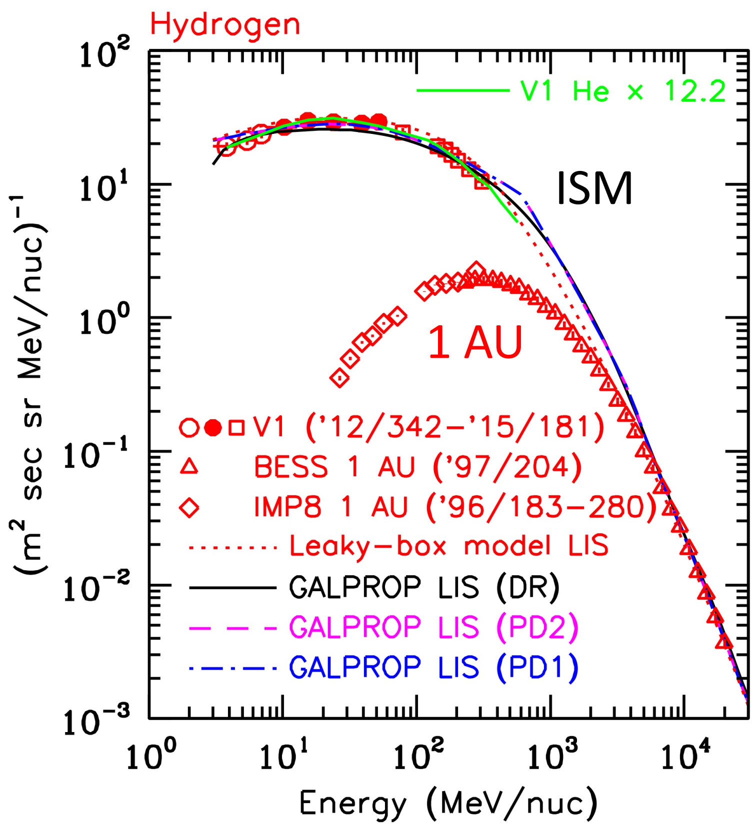
- two possibilities:
  a. $^{59}$Ni was present in supernova ejecta but it spent significantly longer than the half-life (76,000 yr) in the interstellar medium with electrons attached before being accelerated
  b. the nucleosynthesis yield of $^{59}$Ni was so low that the cosmic-ray measurements are not sensitive to the time between nucleosynthesis and acceleration
- the early CRIS result (Wiedenbeck et al., ApJL, 1999) was interpreted as evidence for $>10^5$ yr time delay between nucleosynthesis and acceleration ("possibility a"), based on nucleosynthesis yield calculations current at that time (Woosley & Weaver, ApJS, 1995)
- recently, Neronov & Meynet (A&A 2016) pointed out that the more-recent supernova nucleosynthesis calculations of Chieffi & Limongi (ApJ, 2013) found much lower yields of $^{59}$Ni, supporting "possibility b"
- the question of whether the lack of $^{59}$Ni is attributable to a long time delay between nucleosynthesis and acceleration remains open
- resolving this question is important—a long time delay excludes the possibility that a supernova's nucleosynthesis products could be accelerated by a shock driven by the same supernova
- the resolution depends on conclusively establishing how much $^{59}$Ni is synthesized and ejected by supernovae

# Cosmic Ray Intensity in the Very Local Interstellar Medium (VLISM)

- solar modulation prevents cosmic rays below a few 100 MeV/nuc from penetrating to the inner heliosphere
- spectra measured near Earth would allow high intensities below 100 MeV/nuc in the VLISM
- direct measurements by Voyager 1 now rule out such extreme low-energy increases
- provides constraints on contribution of GCRs to heating and ionizing the ISM (see Cummings et al. 2016)

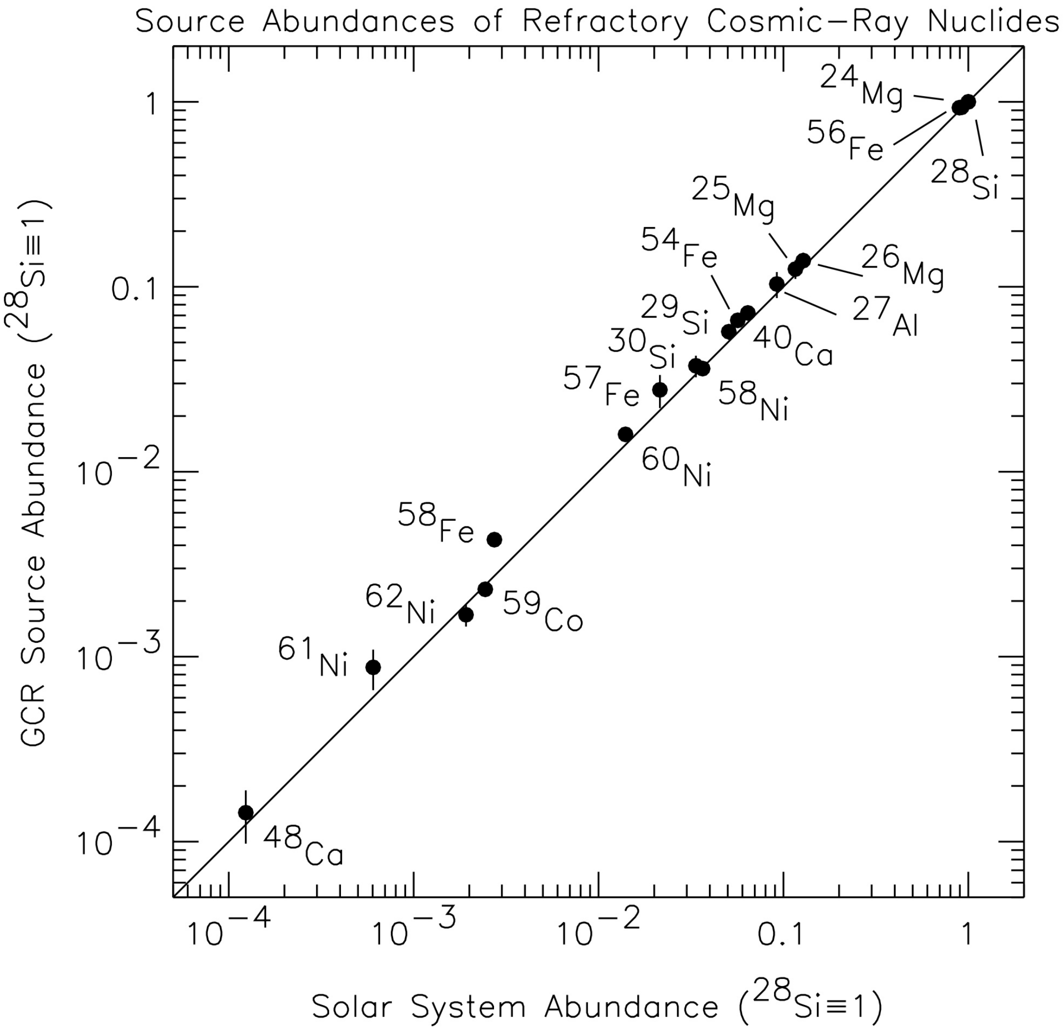



Wiedenbeck, SSR 176, 35, 2013




Cummings et al., ApJ 831,18, 2016

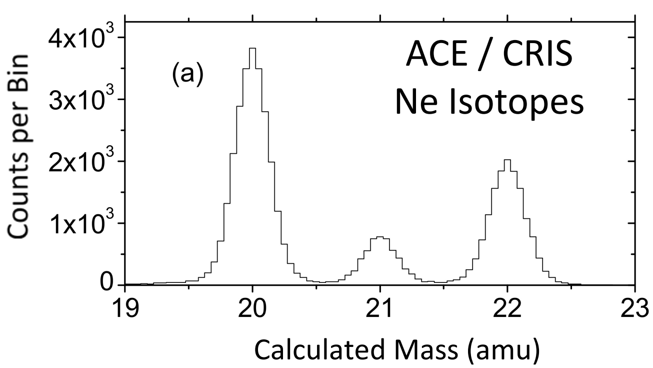
# Source Composition of Refractory Cosmic-Ray Nuclides

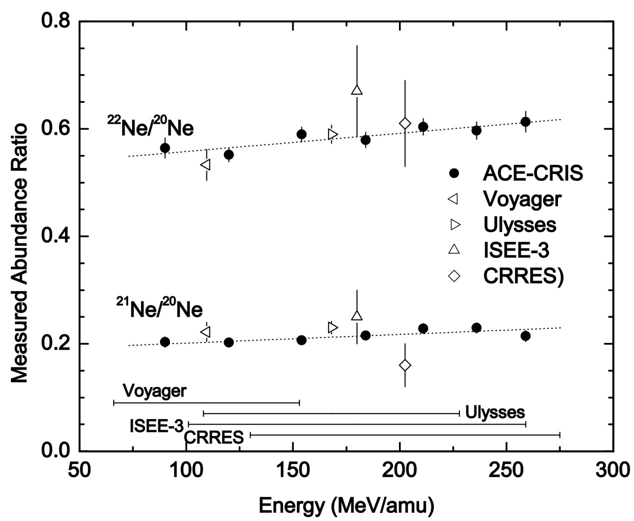



- within a factor ≲2, all refractory nuclides that have been studied with ACE/CRIS have been found to have solar-like relative abundances
- no signature of a particular type of supernova source found—GCR source looks like a mix of many contributions, just like most ISM material

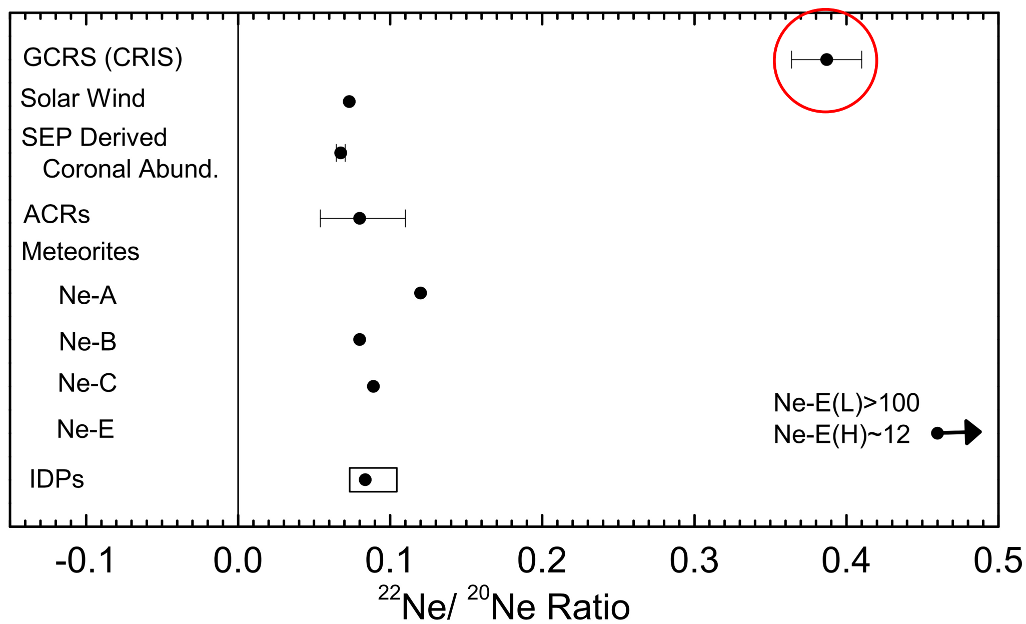

Wiedenbeck et al., Proc. 28th ICRC (Tsukuba), 4, 1899, 2003
see also Wiedenbeck et al., Space Sci. Rev., 99, 15, 2001

# $^{22}$Ne/$^{20}$Ne – the Only GCR Source Isotope Ratio Thus Far Found to Differ Significantly from Solar




Binns et al., ApJ, 634, 351, 2005

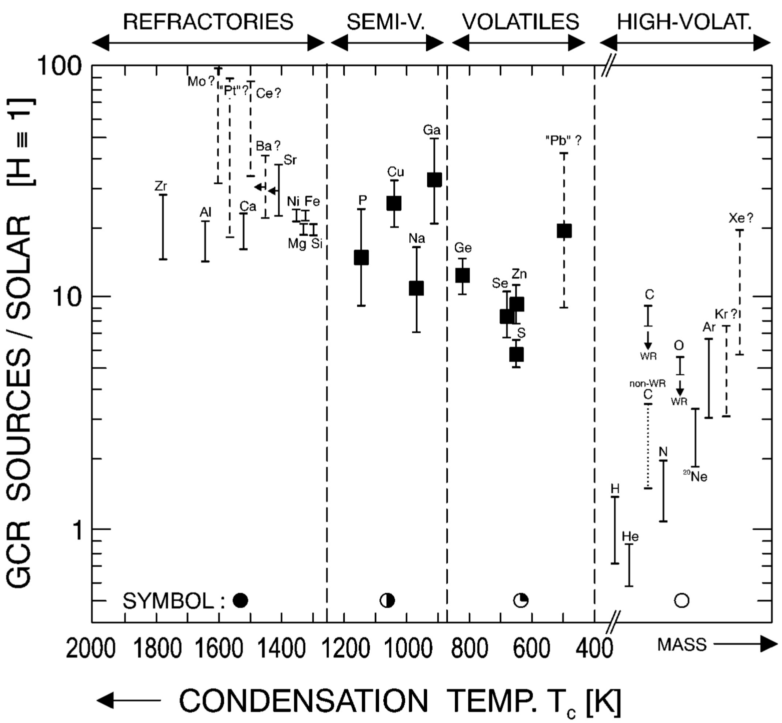


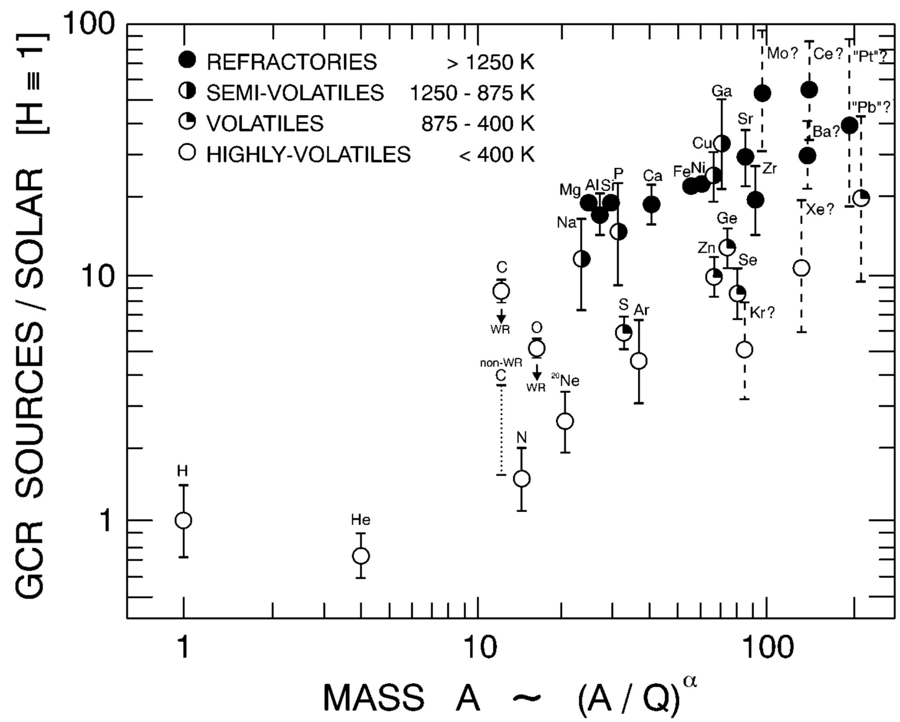

Cassé & Paul (1982) noted that Wolf-Rayet stars are a likely source for the cosmic-ray $^{22}$Ne bacause:

- they have high mass-loss rates via fast stellar winds
- those winds have blown away the hydrogen shell leaving a surface rich in He-burning products
- He burning produces large enhancements of $^{22}$Ne because when H is burned to He by the CNO process, residual heavy elements get burned to $^{14}$N, which then captures alpha particles and produces $^{22}$Ne

# Fractionation Based on Volatility and Mass

- ratios of GCR source abundances relative to solar values are a factor ~4 greater for refractory (low FIP) elements than for volatiles (high FIP)
- Ellison, Drury & Meyer (1997) proposed that patter is due to acceleration of refractory grains by IS shocks followed by sputtering of suprathermal ions from fast grains in collisions with IS gas
- process results in suprathermal ions that can be efficiently accelerated by subsequent shocks

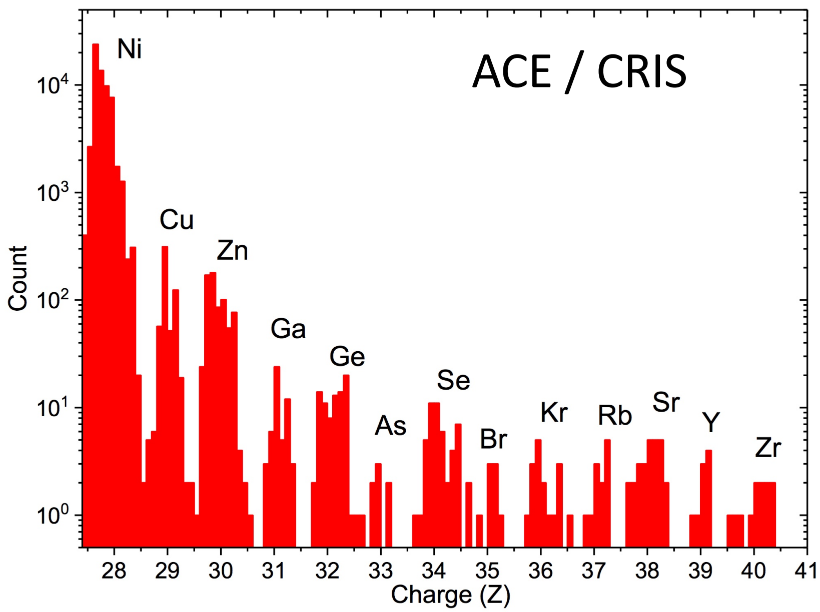


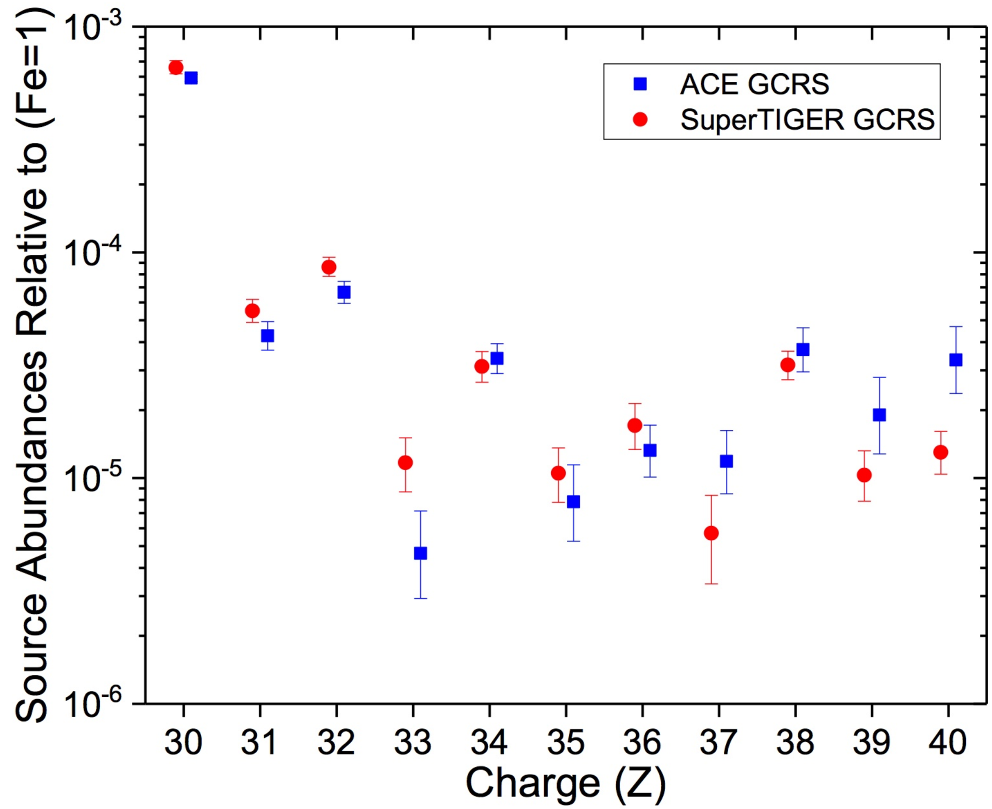

Meyer, Drury & Ellison, ApJ, 487, 182 1007

# Relative Abundances of Ultraheavy Elements

- elemental composition has now been extended up through $_{40}$Zr by the TIGER and SuperTIGER balloon experiments (Rauch et al. 2009; Murphy et al. 2016) and by the ACE/CRIS satellite experiment

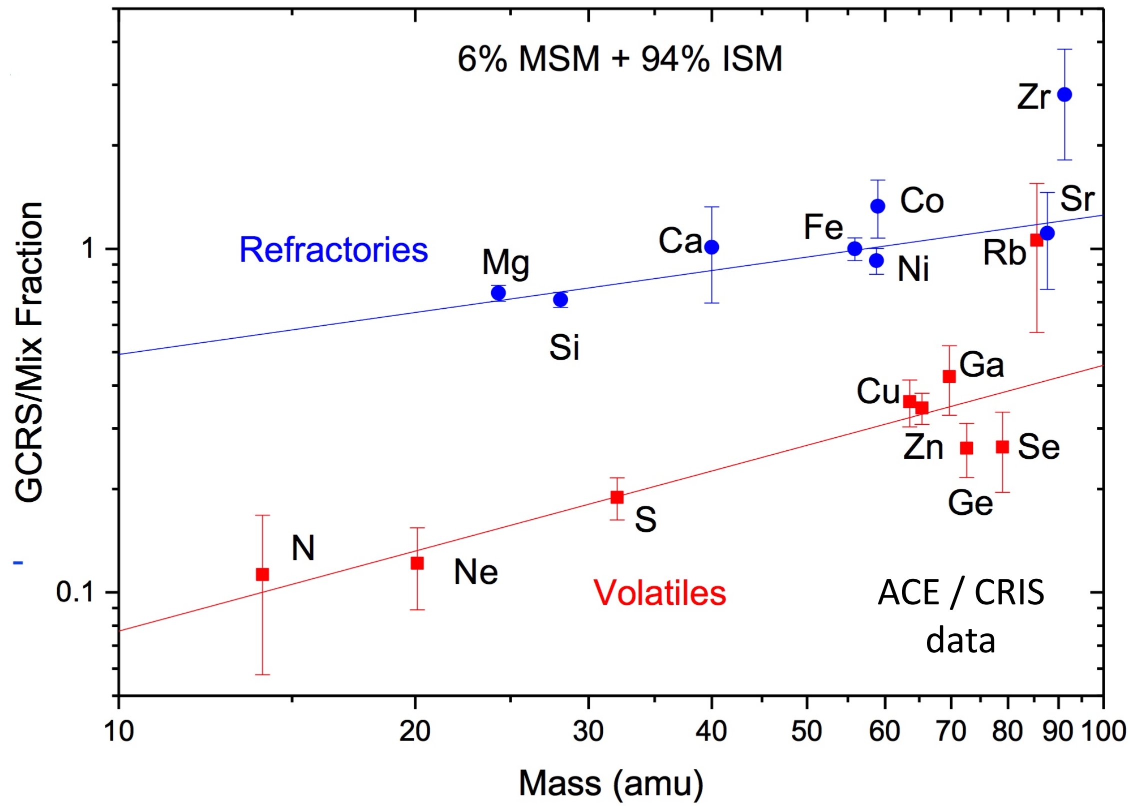



Binns et al., Proc. 35th ICRC (Busan), paper CRD070 (presented by R. Mewaldt); see also Wiedenbeck ACE/CRIS Highlight Paper



# Fractionation Pattern

- refractory elements are enhanced in GCRS relative to volatiles, which is believed to be due to efficient acceleration of dust grains (Ellison et al., ApJ, 1997)
- Rauch et al. (2008) noted that fractionation is well organized as a function of mass, but only if it is assumed that the source material contains a small admixture of freshly synthesized and ejected "massive star material" (MSM) ⇒ taken as evidence for cosmic-ray acceleration in massive-star associations




Binns et al., Proc. 35th ICRC (Busan), paper CRD070
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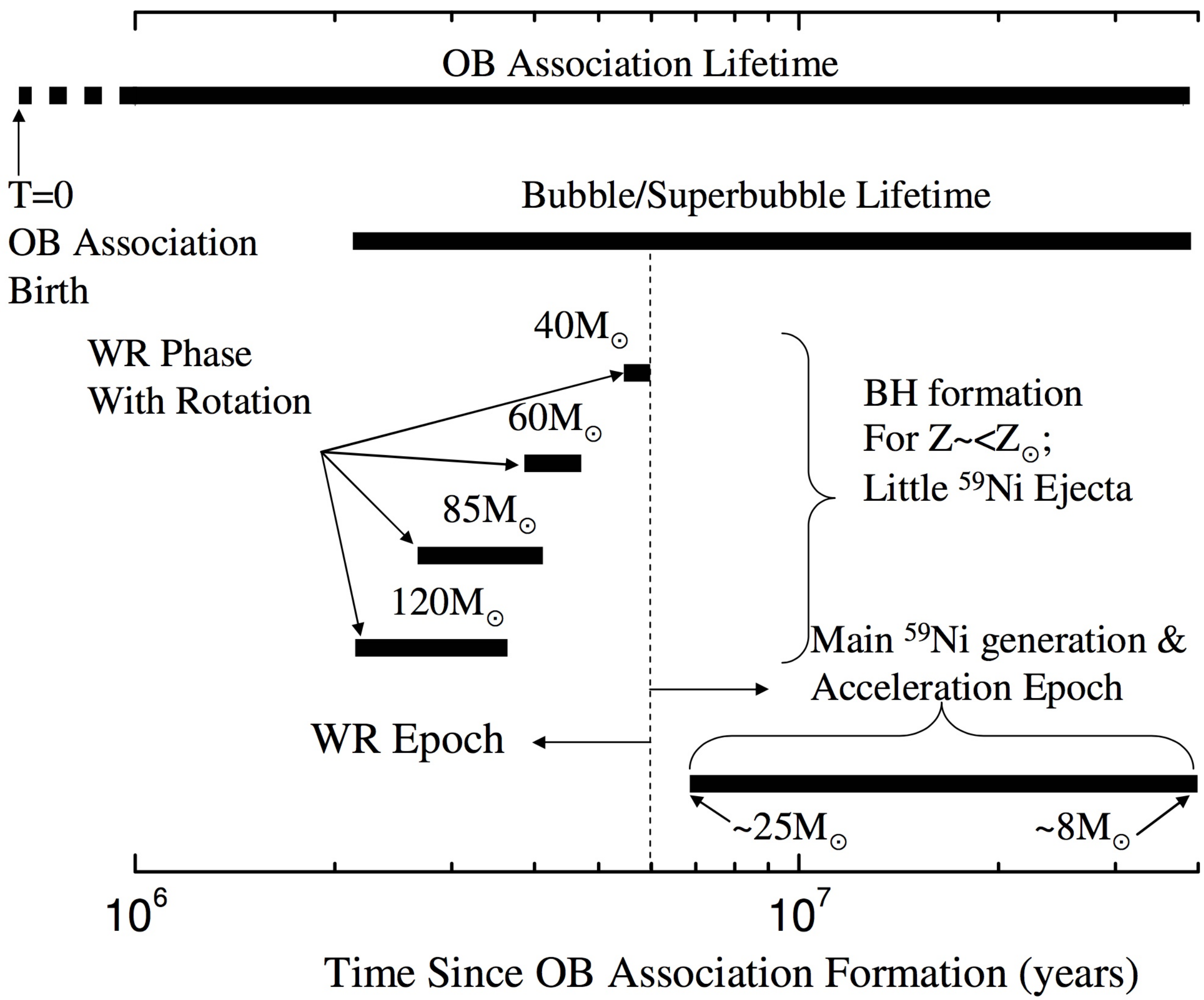
ACE/CRIS Highlight Paper

# A Possible Scenario for Cosmic-Ray Acceleration in a Superbubble

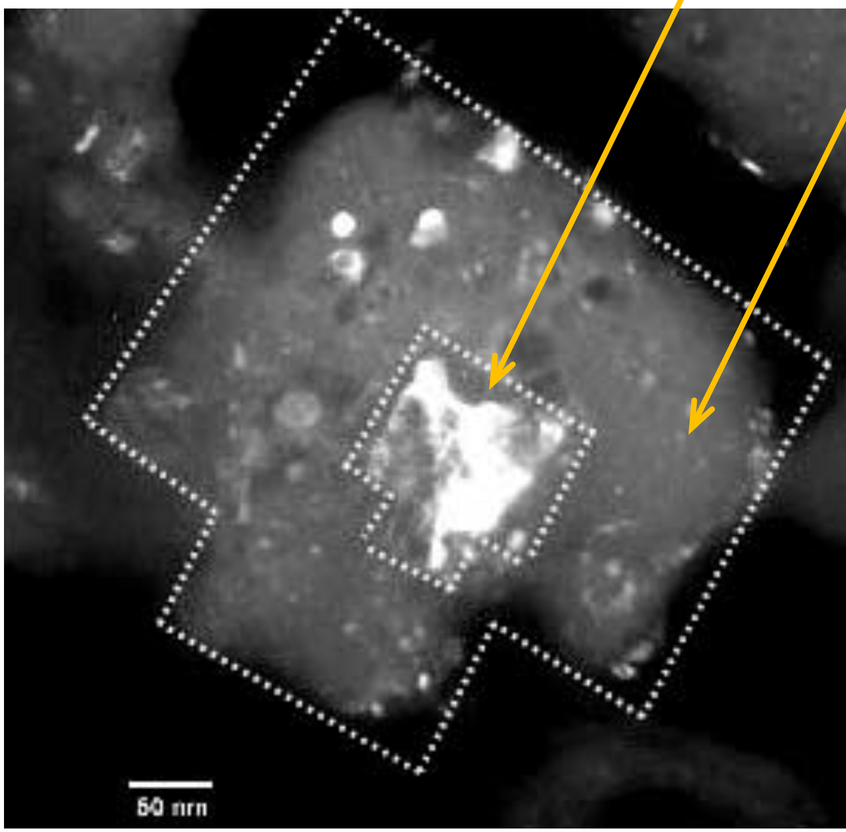



Binns et al., Space Sci. Rev., 130, 439, 2007

# Possible Additional Evidence for Acceleration of Interstellar Dust

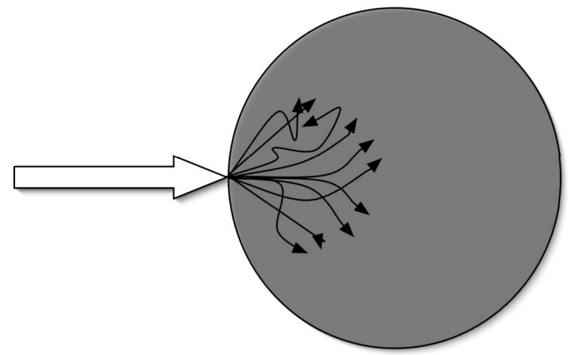
some interplanetary dust particles contain submicron size glass particles with embedded metal and sulfides (GEMS):

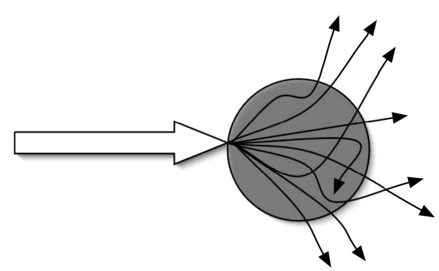
- crystalline center
- surrounded by glassy envelope




Westphal & Bradley, ApJ, 617, 1131, 2004

- structure interpreted as due to exposure to ionizing radiation
- Westphal & Bradley suggested grains are accelerated in IS shocks, similar to high-rigidity ions
- passage through IS gas results in heavy bombardment with low-energy protons
- irradiation can sometimes knock out suprathermal ions from the grain allowing them to be accelerated more efficiently by subsequent shocks

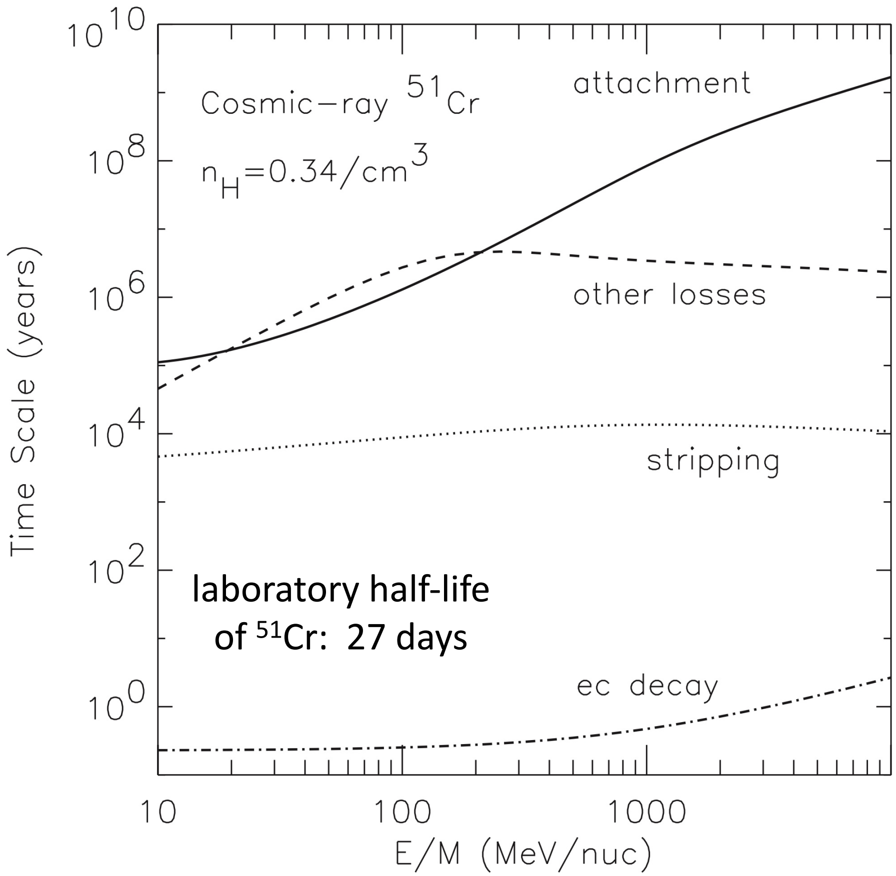




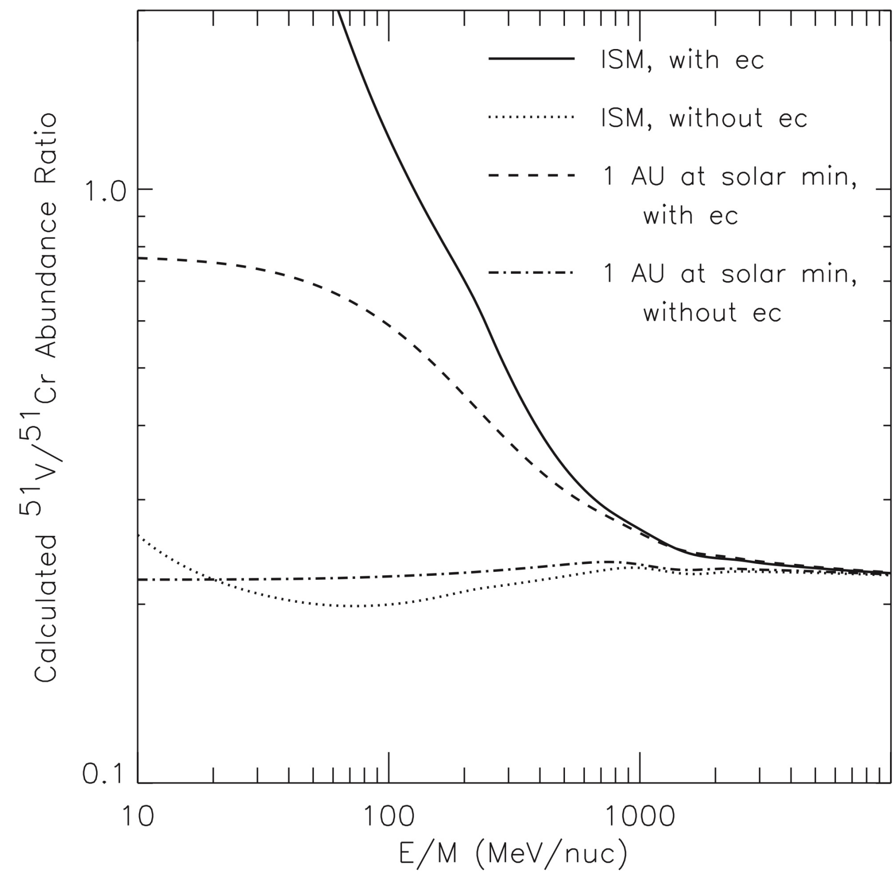
# Electron Capture Secondaries Produced During Propagation

- electron attachment cross sections fall rapidly with increasing energy
- produces a "feature" in the spectra of ec parent and daughter spectra in the ISM
- proposed as diagnostic of various energy-changing processes: adiabatic deceleration during solar modulation, weak reacceleration during propagation

time scales for physical processes during propagation in the ISM

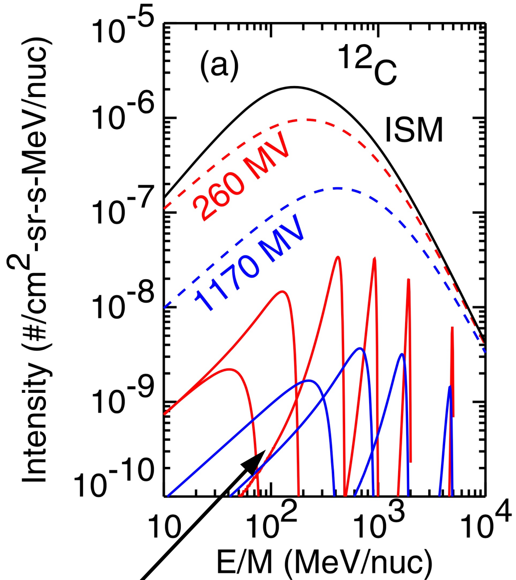



effect of electron capture + ec decay on daughter-parent ratios in ISM and near Earth




Niebur et al., JGR, 108, A10, 8033, 2003

# Energy Loss Due to Solar Modulation Probed Using ec-decay Isotope Measurements

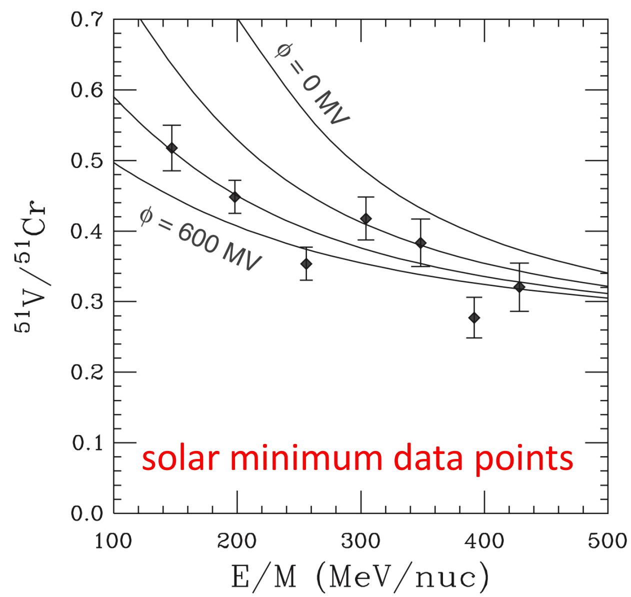


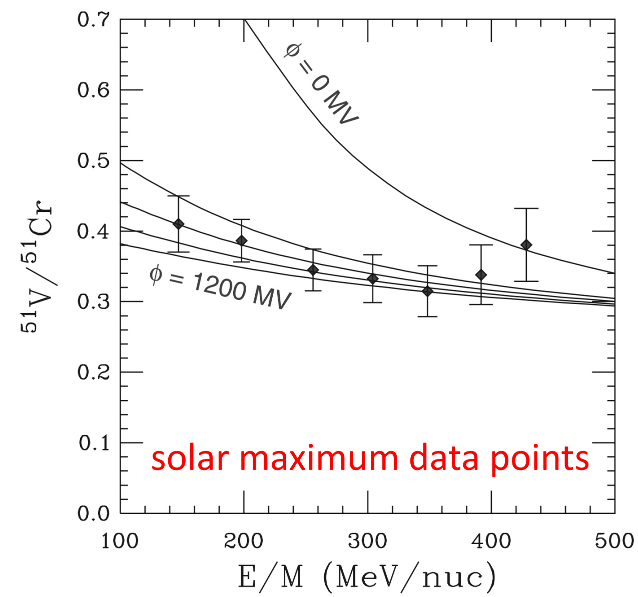

calculated energy distributions at Earth due to mono-energetic distributions in VLISM:
solar min
solar max

Wiedenbeck, SSR 176, 35, 2013

- low-energy increase of ec parent/daughter ratio in the VLISM should appear at lower energy at 1 AU during solar maximum than at solar minimum
- first attempt to observe effect of solar modulation changes on ec parent/daughter ratio $^{51}V/^{51}Cr$ made using isotope measurements from ACE/CRIS

ACE / CRIS data




Niebur et al., JGR, 108, A10, 8033, 2003

# Conclusions

- measurements of elemental and isotopic composition and elemental energy spectra below ~1 GeV/nuc are providing important constraints on the origin of cosmic rays and the cosmic ray environment of the solar system:
  - amount of matter traversed in the Galaxy
  - time to escape and mean density in regions traversed
  - upper limits on the time and distance from the supernova that synthesized $^{60}Fe$
  - the very low-energy part of the cosmic-ray spectrum in the VLISM (and its contributions to ionizing and heating the ISM)
  - fractionation and the possible role played by acceleration of interstellar dust
  - contributions from nucleosynthesis in special environments ($^{22}Ne$)
- a model of cosmic ray origin that appears to be consistent with the observations has nucleosynthesis and acceleration occurring in associations of massive stars:
  - contribute an admixture of "massive start material" that gets accelerated along with old, solar-like interstellar matter
  - drive supernova shocks that are subsequently responsible for the acceleration
- an interesting question to consider: can the low-energy cosmic rays we observe near the solar system have predominantly been accelerated and confined locally?
  - in the local bubble? (density ~0.3 H/cm$^3$ is compatible with radioactive seconaries)
  - what additional tests could answer this question?