Survey of our Local Environment, and Implications for Local Cosmic Rays

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(With Thanks to Priscilla Frisch, Bob Binns and Marty Israel)

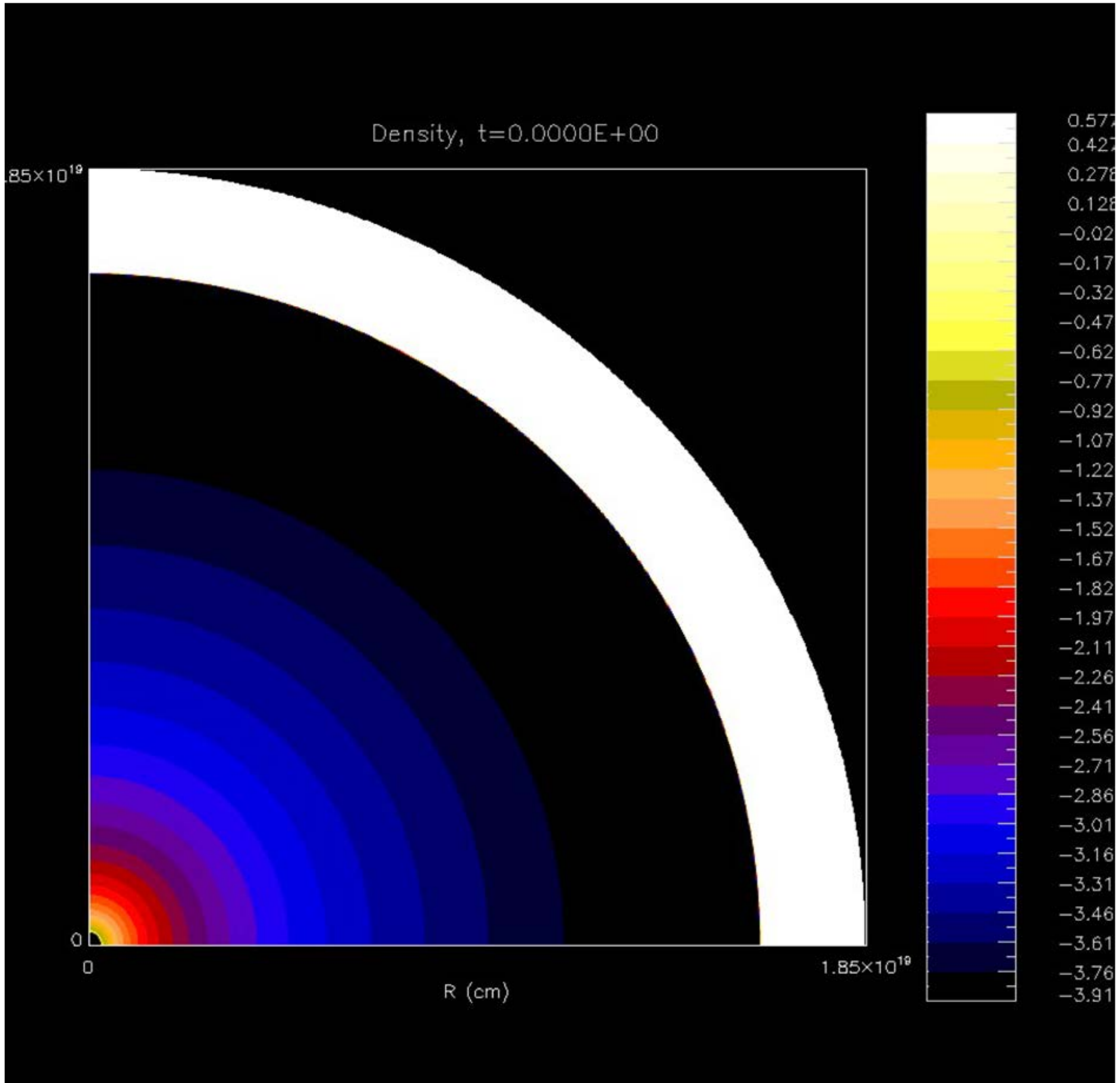
Based partly on work presented in " Effect of Supernovae on the Local Interstellar material", Frisch & Dwarkadas, arXiv:1801.06223

What is a Bubble, and how is it formed?
Formation of W-R Bubble

O-RSG-WR

DENSITY – log scale
(see also Dwarkadas & Rosenberg 2013).

Note: Interior density low throughout, density of shell ~10^4-10^5 times larger.

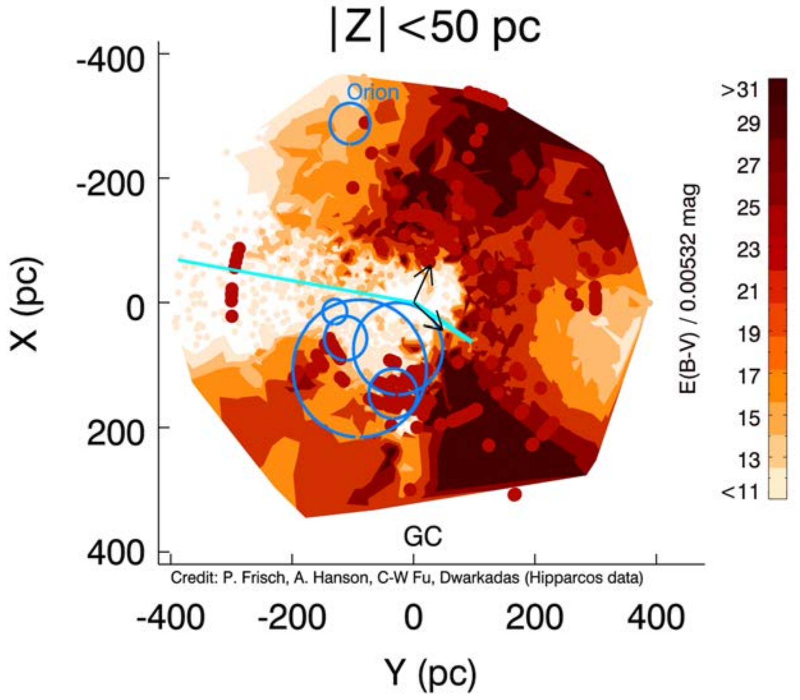


Simulation of wind bubble formed around 40 solar mass star throughout its evolution.

Calculated using the ionization-gasdynamics code AVATAR (Dwarkadas & Rosenberg 2013).

The Local Bubble

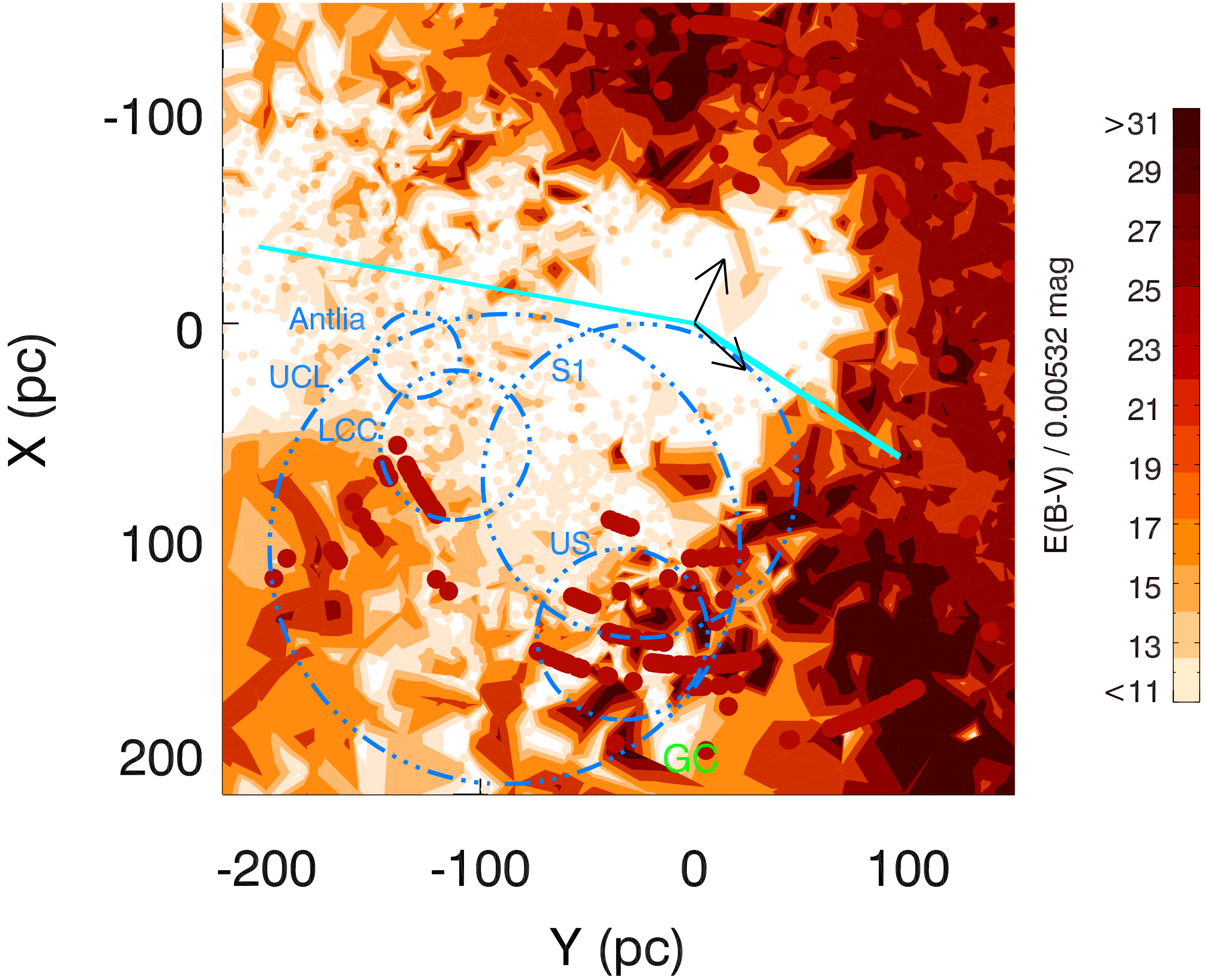
- Feature now known as the "Local Bubble" was originally defined by deficit of starlight reddening by interstellar dust for stars within about 70 pc. Hipparcos catalog provides high-precision astrometric and photometric data that are used to map out the distribution of local interstellar dust (right).
- The deficit of 'local bubble' interstellar dust (and gas) extends beyond 50 pc from the galactic plane.



The cumulative extinction of interstellar dust is shown over spatial scales of ~ 400 pc

So why is it Local Bubble?

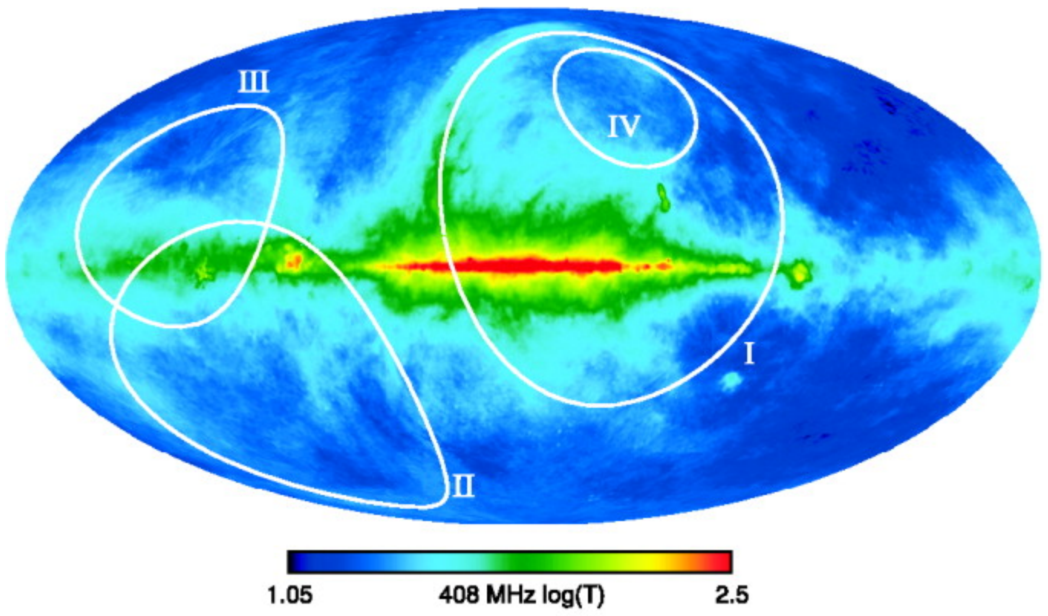
- Presence of hot gas with temperatures ~ 10^6 K
- The discovery of the soft X-ray background (SXRB) motivated measurements of the X-ray spectra at low energies, < 0.25 keV, where a flat X-ray spectrum was found that limited the amount of possible interstellar absorption of the X-ray photons
- The resulting "displacement model" required the X-rays to be produced inside a cavity in the neutral gas.
- Hot gas in a low density cavity $\Rightarrow$ Bubble
- Some suggestions that SNe needed to produce hot gas. Multiple SNe can create a network of tunnels and cavities such as Local Bubble.
- However, others (R. Shelton et al.) have suggested that charge exchange between solar wind and neutral interstellar atoms can mostly, or even fully, explain the hot gas, no local stellar source needed.

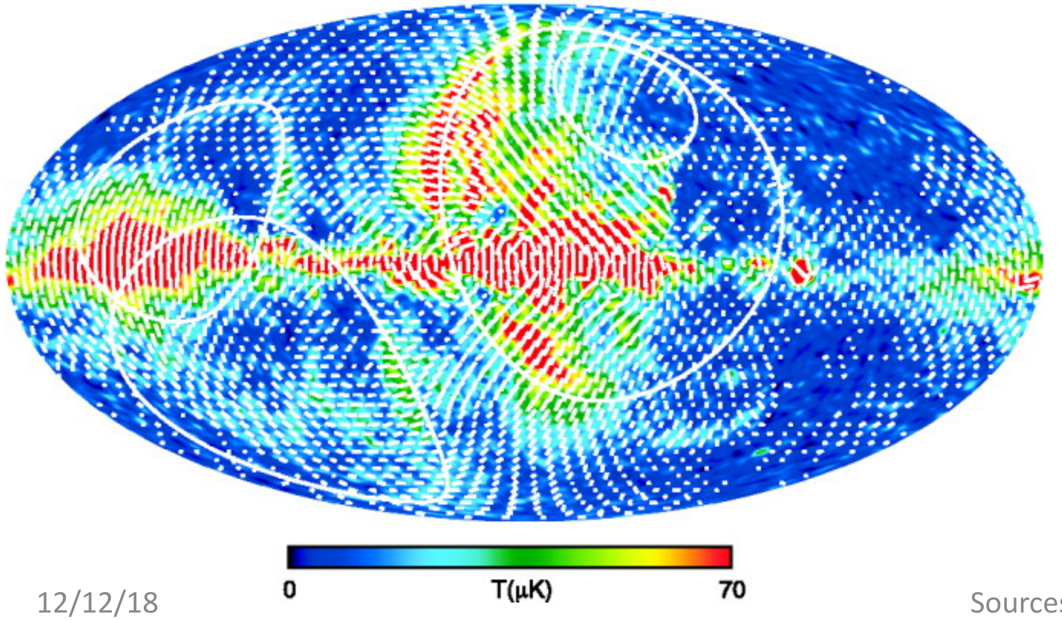


The circles show the three superbubble shells in Sco OB2, (Upper Centauraus Lupus, lower Centaurus Crux, Upper Scorpius) the Antlia SN remnant, the Ori-Eri superbubble, and the S1 shell.

Recent work (Pecaut & Mamjek, 2016) suggests that the three shells in Sco-Cen were not coeval, but instead represent a multitude of smaller star formation episodes.

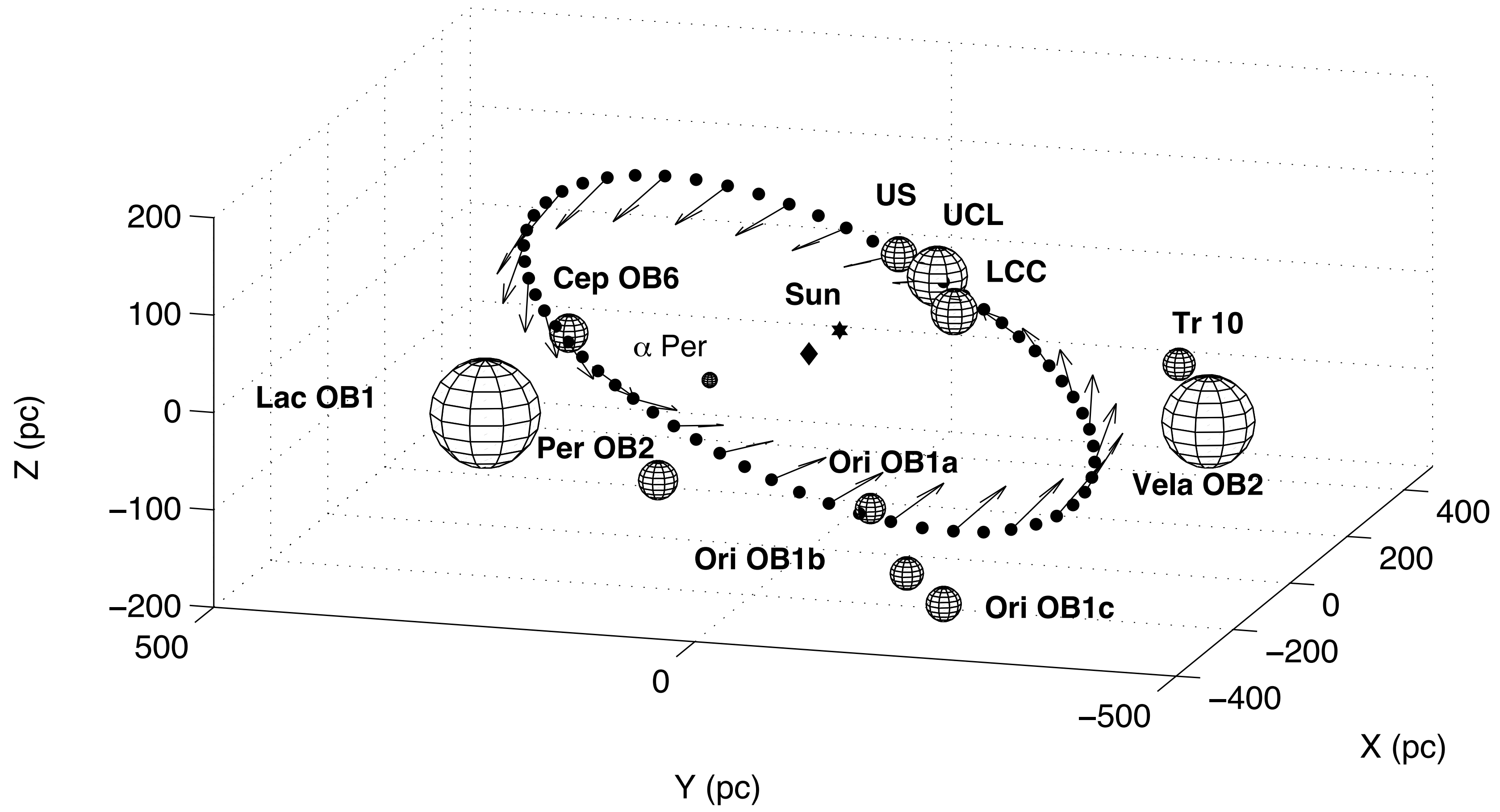
Galactic Loops





Top: Haslam 408 MHz map is shown with circles indicating loops from Berkhuijsen et al. (1971). These ridges of enhanced Galactic radio emission are seen across the sky at low radio frequencies. The North Polar Spur ("Loop I") and the Cetus arc ("Loop II") are examples of these features, which have been described as the remnants of individual supernovae, or of correlated supernovae outbursts that produce blowouts, or as helical patterns that follow the local magnetic fields projecting out of the plane. Four such loops can be seen in the Haslam 408 MHz radio map and the *WMAP* map. Note that the color stretch is logarithmic in temperature. *Bottom*: *WMAP* K-band polarization map with the same loops superimposed. Note that the highly polarized southern feature is close to the North Polar Spur circle and may be related to the same physical structure. Note also that the polarization direction is perpendicular to the main ridge arc of the North Polar Spur, indicating a tangential magnetic field. This is also seen in the southern feature. Whether or not they are physically related remains unclear.

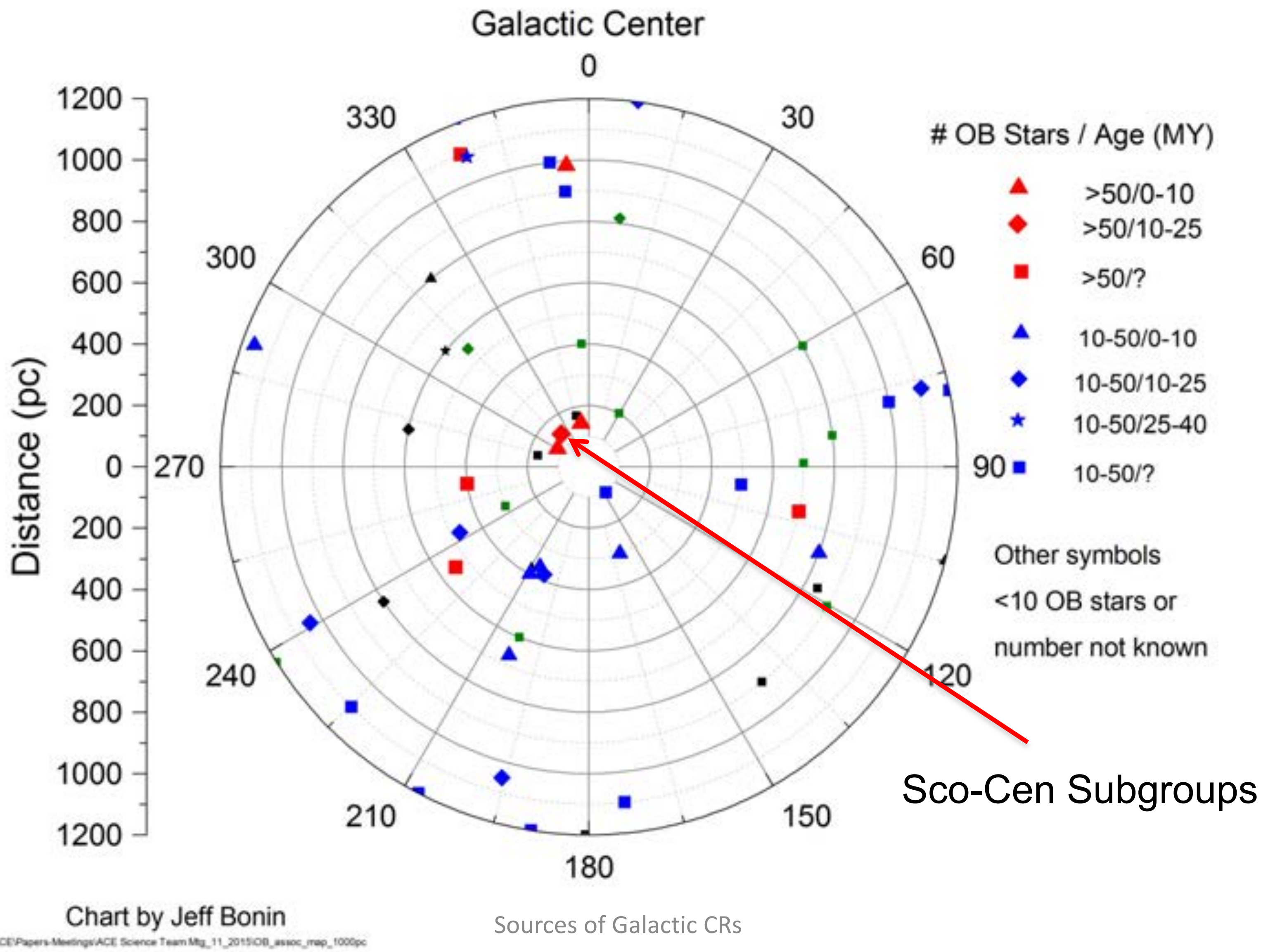
Gould’s Belt



Nearby clusters of O–B2.5 massive stars that are progenitors of core-collapse Type II and Type Ib/c supernovae form a thin planar ring-like structure around the Sun known as “Gould’s Belt”. Gould’s Belt is part of a large-scale warp in the distribution of young stars in the galactic plane.

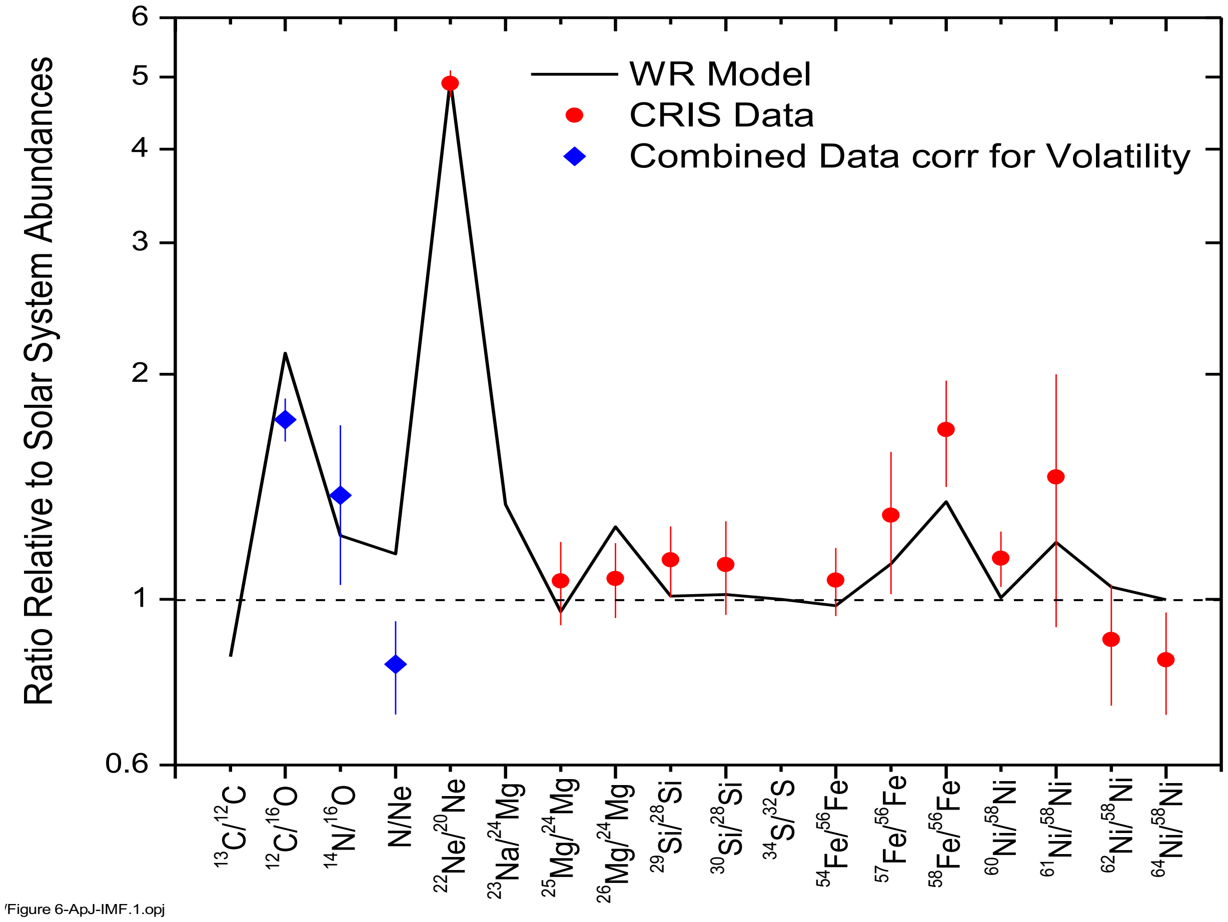
The traditional configuration of Gould’s Belt as an inclined plane defined partly by the Sco OB2 and Orion OB1 associations is shown in the figure (from Grenier 2004). Gould’s belt is tilted by an angle of $\sim 17.2^\circ$ with respect to the galactic plane,

OB associations in our neighborhood



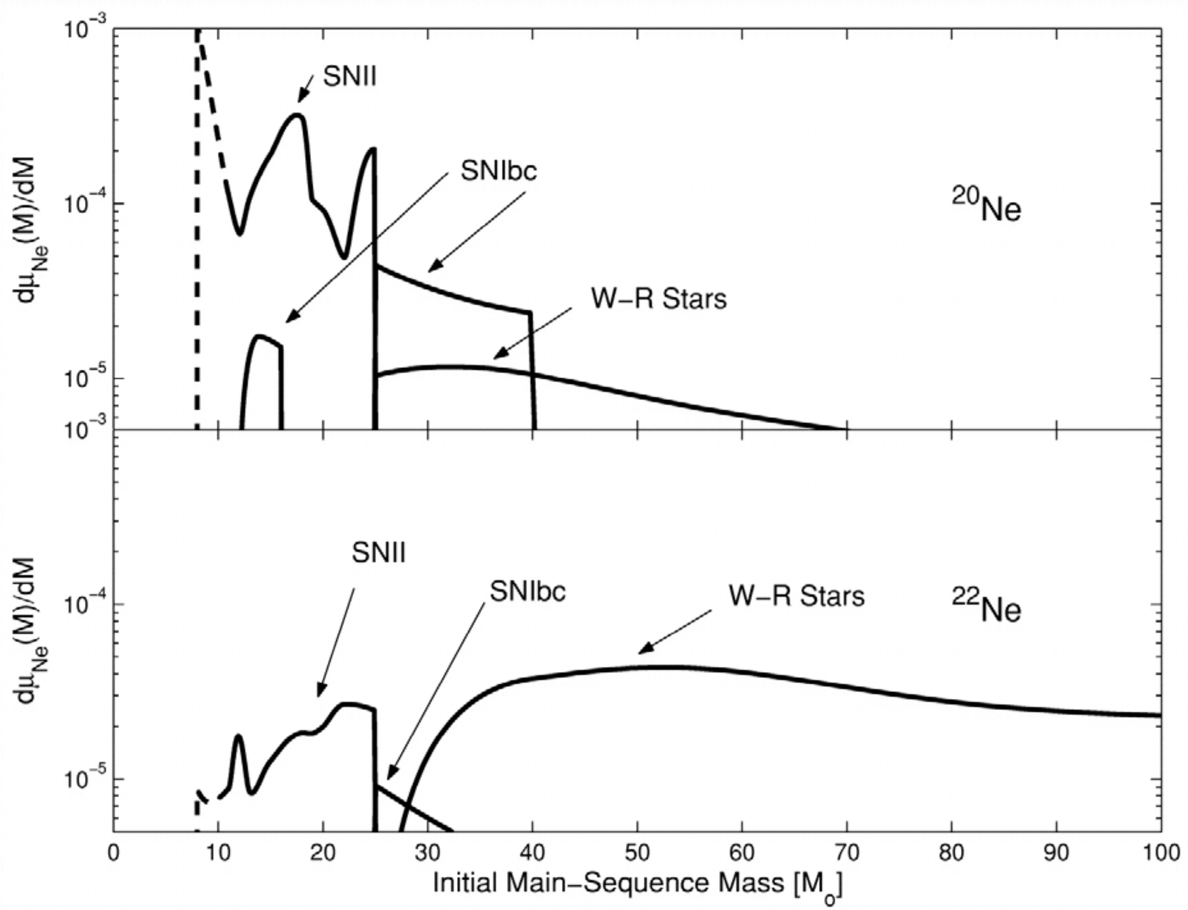
So why is all this important for Local Cosmic Rays?

$^{22}Ne/^{20}Ne$



Main source of high $^{22}Ne/^{20}Ne$ is Wolf-Rayet stars. To get such a high ratio, we must be accelerating the material in W-R star winds – therefore must be due to massive stars.

$^{22}Ne/^{20}Ne$

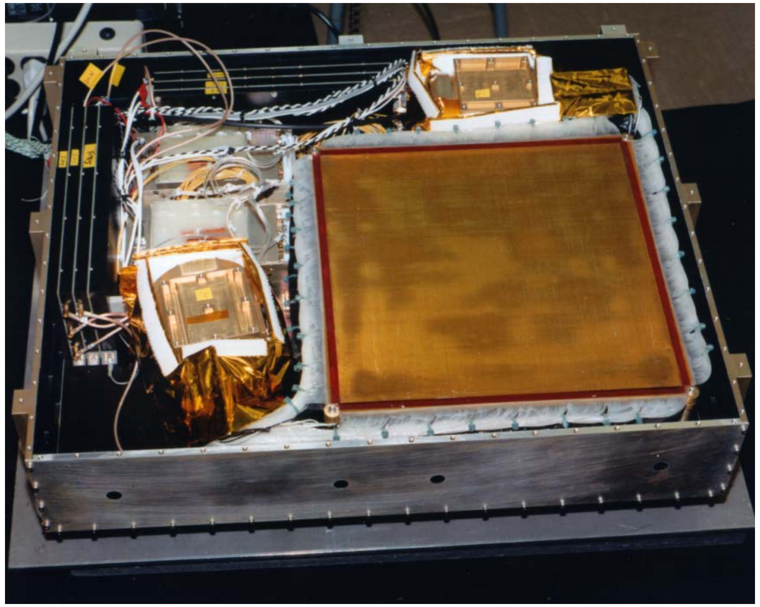


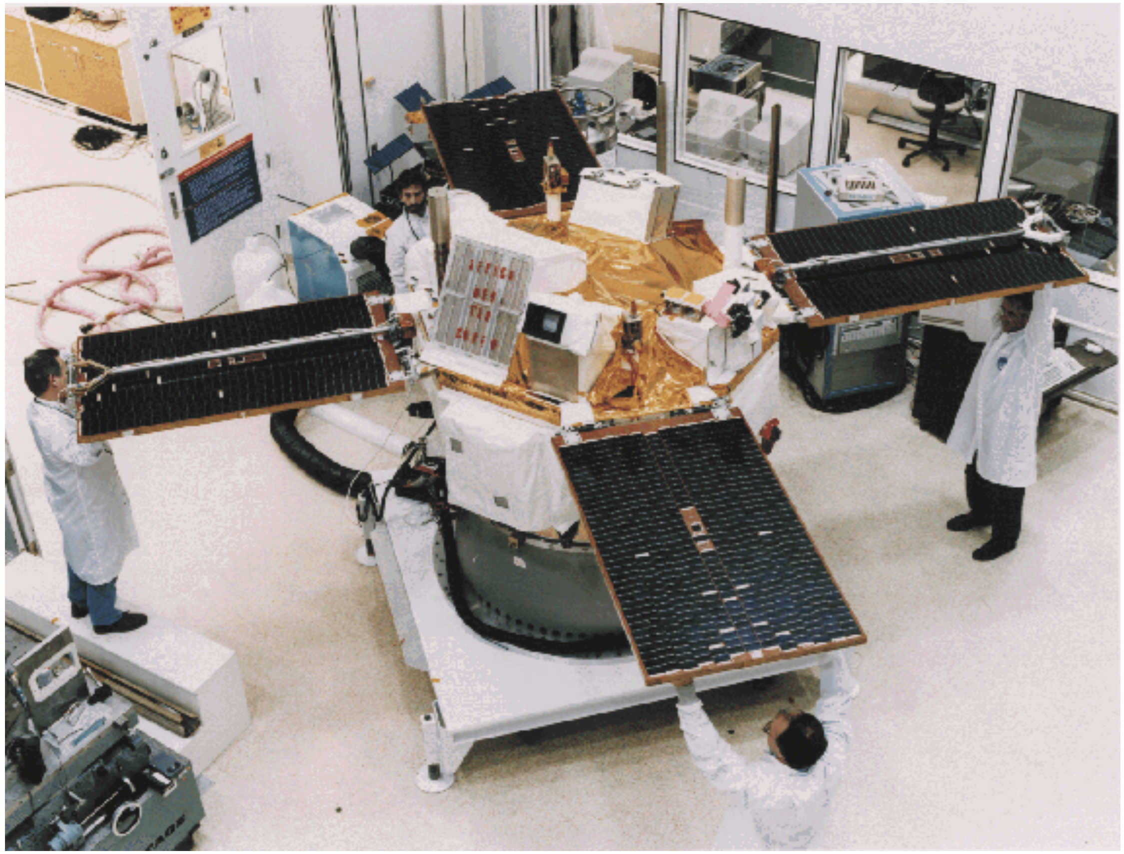
Higdon & Lingenfelter 2003

Main source of ^{22}Ne is W-R stars above about 25 solar masses

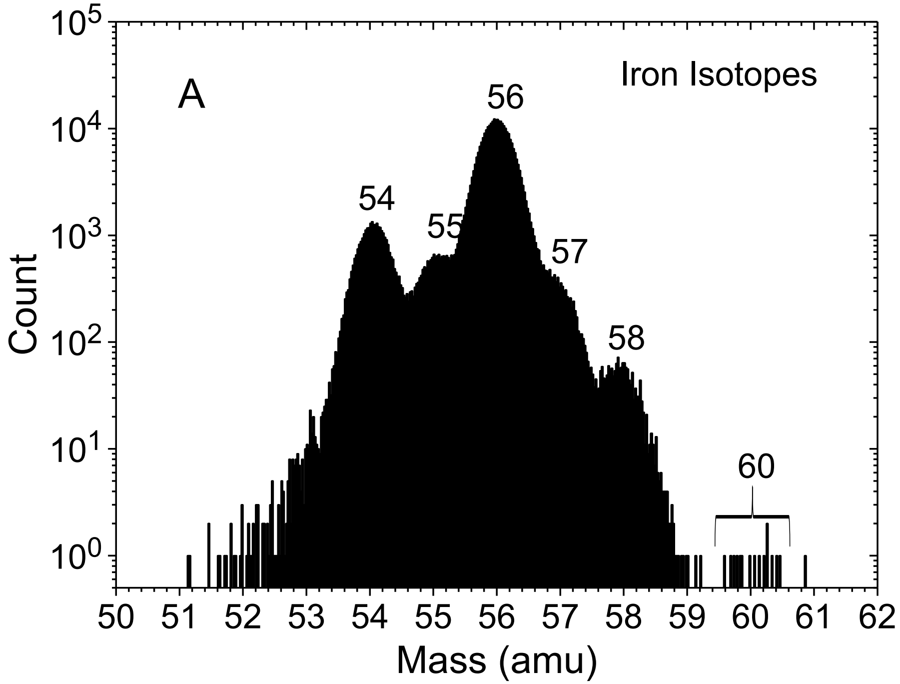
The Cosmic Ray Isotope Spectrometer (CRIS) on ACE

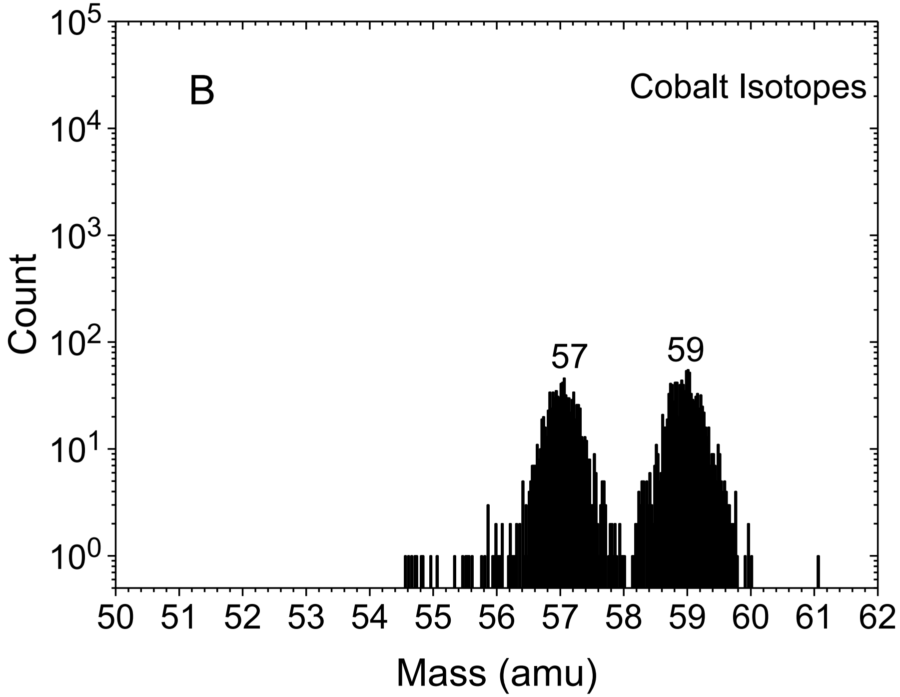
- Launched in August, 1997
- Still collecting excellent quality data





ACE-CRIS Iron & Cobalt Isotope Distributions





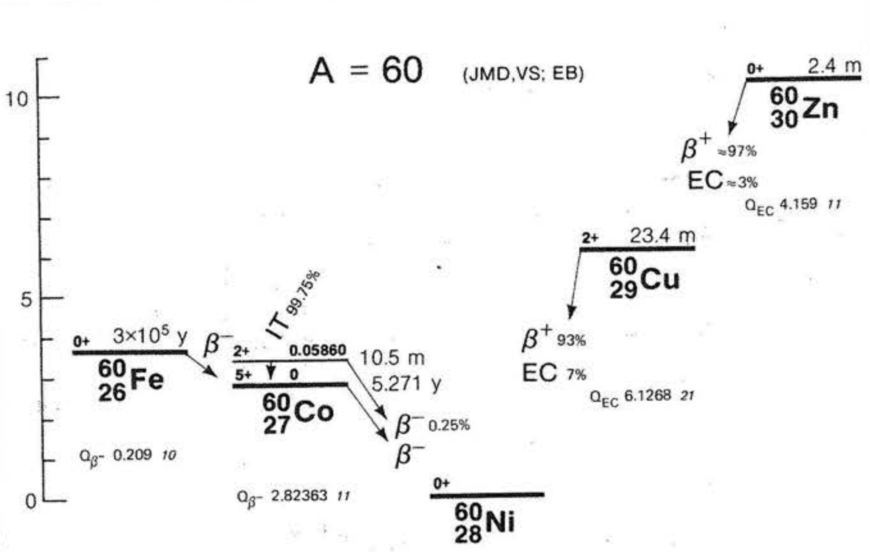
- With 16.8 years of data, CRIS detects 15 ^{60}Fe and 2.95 x 10^5 ^{56}Fe.
- 15 ^{60}Fe events have mean mass estimate of A=60.04 and a standard deviation from mean of 0.28 ± 0.05 amu, consistent with 0.245 ± 0.001 amu for ^{56}Fe.
- The ^{60}Fe observed are almost all primary, not products of interstellar fragmentation
- First observation of a primary cosmic-ray clock
- Strongest argument that this is not a tail of the ^{58}Fe peak can be seen by looking at upper edge of ^{59}Co distribution. Only 1 event near ^{61}Co, but for ^{60}Fe have 15.

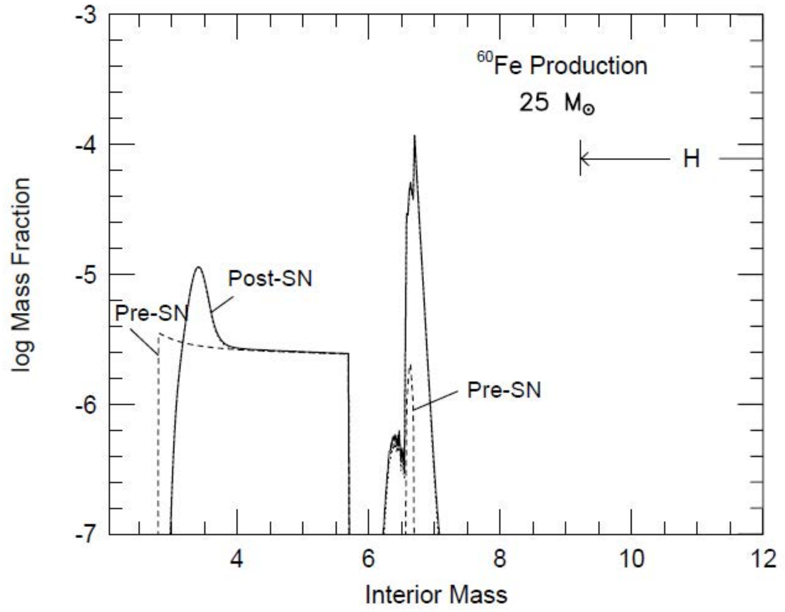
Production & Other Observations of ^{60}Fe

- ^{60}Fe is radioactive and is synthesized primarily in core-collapse SNe by neutron capture
  - β^- decay, 2.62 Myr half-life
  - Emits γ-rays at 1.173 and 1.332 MeV
  - Almost all the ^{60}Fe is in SN ejecta.

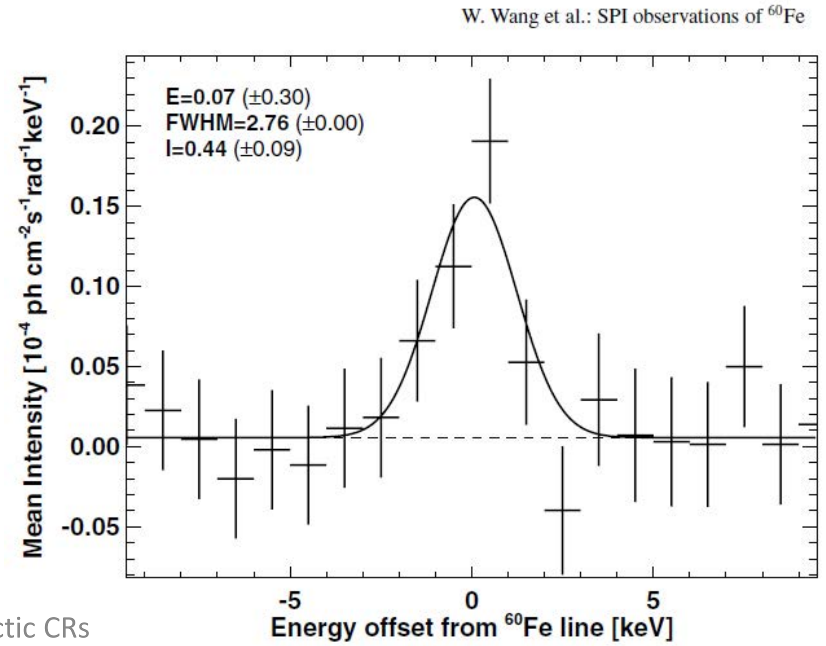
  SNe are the ONLY producers of ^{60}Fe.

- Observed in diffuse emission of γ-rays by INTEGRAL (Wang et al.; Diehl 2013) and RHESSI (Smith 2004)





Timmes et al., *ApJ*, 449, 204, 1995

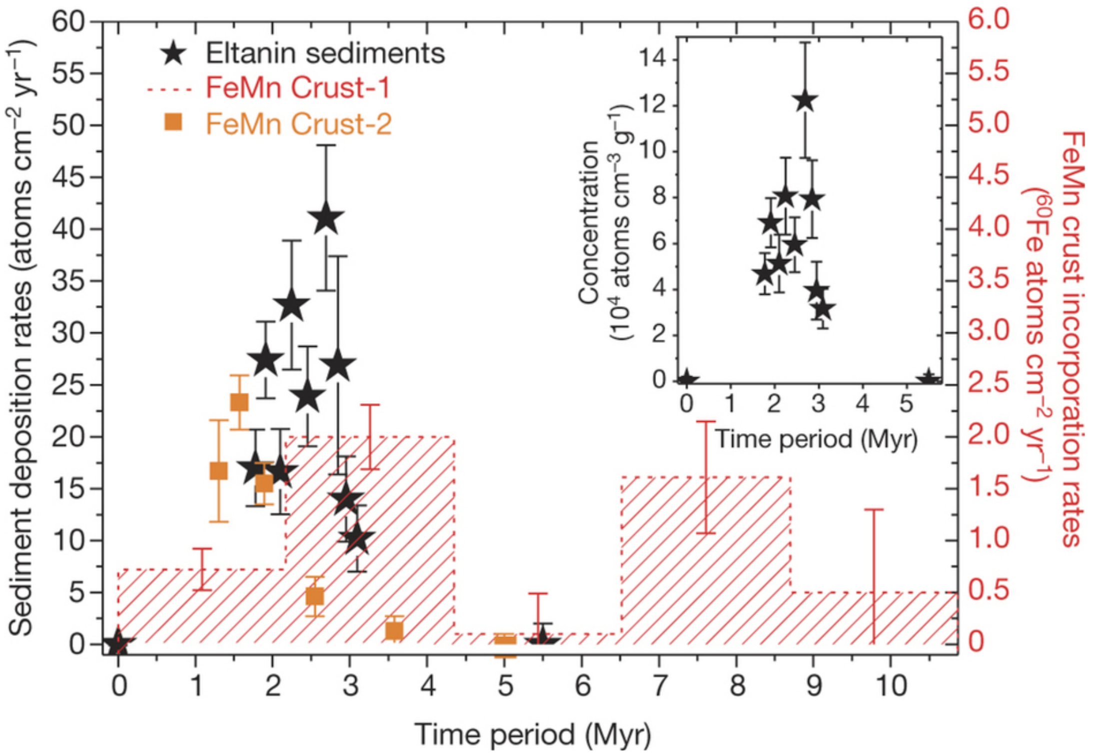


$^{60}Fe/^{56}Fe$ ratio at Earth (top of detector)

- Observe 15 ^{60}Fe nuclei and 2.95×10^5 ^{56}Fe nuclei. Estimate that
  - ~1 of these ^{60}Fe is the result of interstellar fragmentation of heavier nuclei, probably from ^{62}Ni or ^{64}Ni
  - ~1 $\pm$ ~1 could be background (possibly from interactions in the CRIS instrument above the Si stack).
- So the measured ratio is
- $\underline{^{60}Fe/^{56}Fe} = (13 \pm 1 \pm 3.9)/2.95 \times 10^5 = \underline{(4.4 \pm 1.7) \times 10^{-5}}$
- (The first $\pm$ is uncertainty of the background and the second $\pm$ is $\sqrt{15}$.)
- **Correcting for interactions in the instrument and differing energy ranges yields $\underline{^{60}Fe/^{56}Fe = (4.6 \pm 1.7) \times 10^{-5}}$ at top of Detector.**
- Since the ^{60}Fe half-life is 2.6 Myr, this implies that
  - CR acceleration occurs within several Myr of nucleosynthesis
  - Source material has a recently synthesized component

Observations of ^{60}Fe

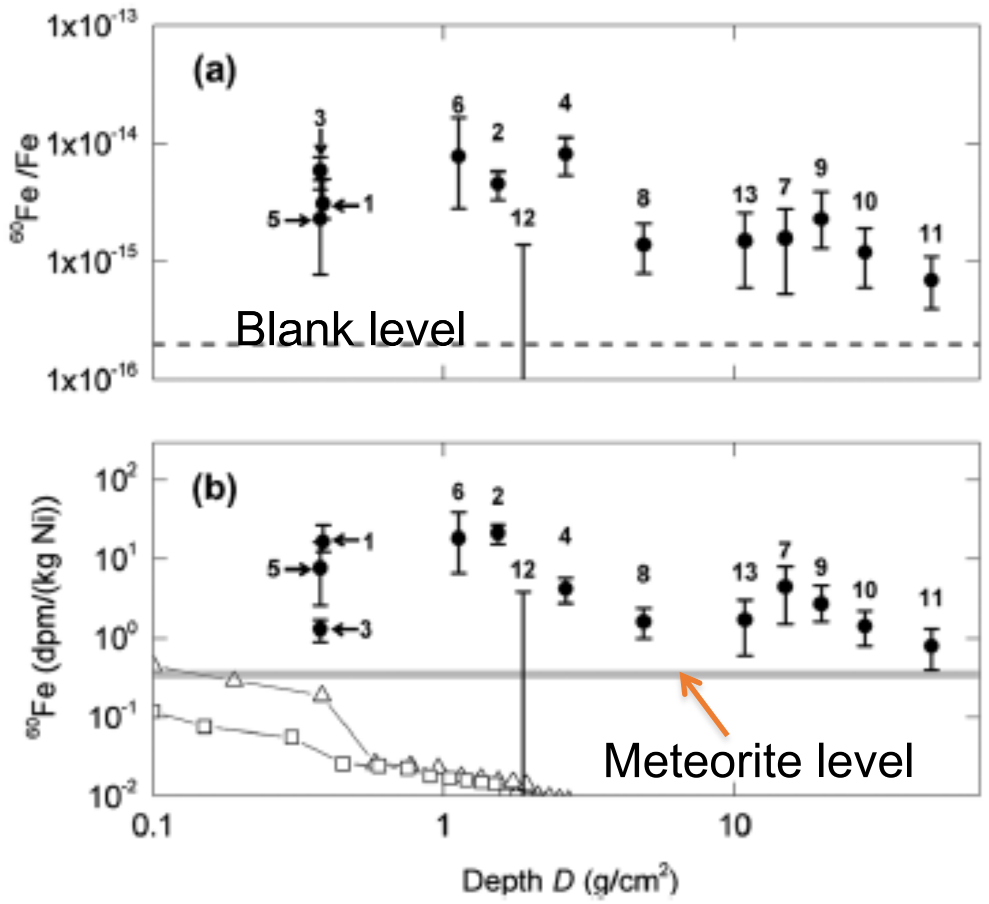
- Wallner et al. (2016) Nature, **532**, 69; accelerator mass spectroscopy
  - 120 deep sea samples from ferro-manganese deposits in all major oceans all contain ^{60}Fe at levels of $^{60}Fe/Fe$=few x 10^{-15}
  - ^{60}Fe Interstellar influxes onto earth via dust grains found for time periods 1.5-3.2 Myr and 6.5-8.7 Myr ago
  - Argue that burst of supernovae in Sun's vicinity delivered the nuclei to Earth



  - Also see Breitschwerdt et al. Nature (2016) **532**, 73
    - Model the Sco-Cen association which generated the local bubble
  - Earlier papers Knie et al., PRL 93, 171103, 2004 & Fitoussi et al. PRL 101, 121101, 2008

Observations of ^{60}Fe on the Moon

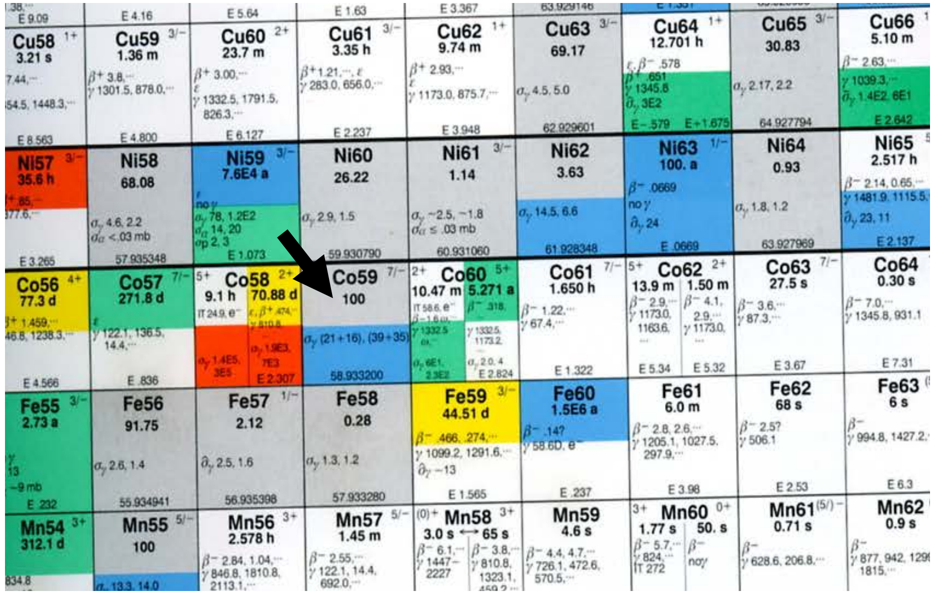
- Lunar Cores— Fimiani et al. analyzed lunar cores. Found relatively high concentrations of ^{60}Fe suggesting the arrival of SN debris on the moon 1.7-2.6 Myr ago. (PRL 116, 151104, 2016)



Distance Estimate to Source

- Mean distance to the sources contributing to cosmic rays at Earth using a diffusive propagation model.
  - CRs originate in a volume surrounding the Sun with radius $L=(D\gamma\tau)^{0.5}$, where D is the diffusion coefficient, γ is the Lorentz factor, and τ is the effective cosmic ray lifetime.
  - Assuming $D=3.5\times10^{28}$ cm^2/s, and γ' s & τ' s for ^{56}Fe and ^{60}Fe, we obtain
    - L_{56} = 790 pc
    - L_{60} = 620 pc
  - Sources are nearby

Minimum Time between nucleosynthesis and acceleration--^{59}Ni

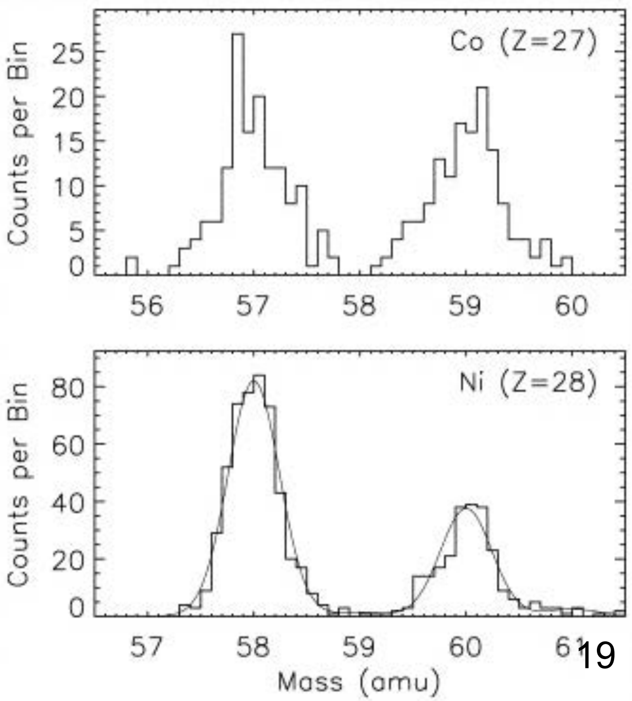


- How long after nucleosynthesis are GCR nuclei accelerated? Does a SN shock accelerate nuclei synthesized in that SN?
    - ^{59}Ni decays only by k-capture.

      $^{59}\mathrm{Ni} + e^{-} \rightarrow {}^{59}\mathrm{Co} + \nu$
    - 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 material is not accelerated in the same supernova that synthesizes it!

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



However, Neronov and Meynet (2016): recent predictions of ^{59}Ni yield result in low ^{59}Ni relative to decay product ^{59}Co, consistent with upper bound of ^{59} Ni in cosmic rays. Removes necessity of decay of ^{59}Ni time interval between explosion and acceleration.

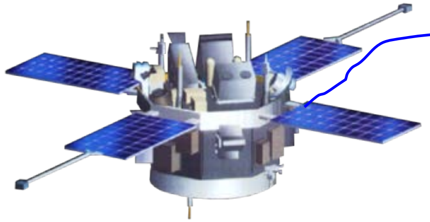
A simplified picture of the chain of events producing cosmic rays detected at Earth (Binns et al.)

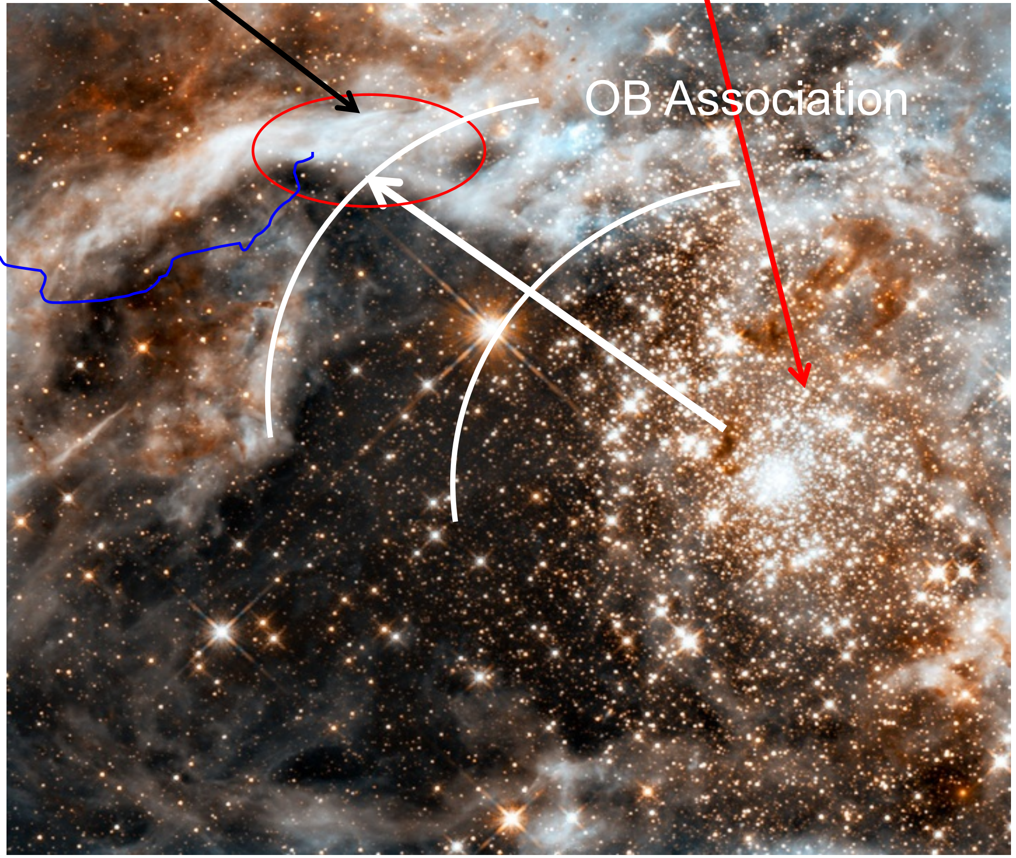
Acceleration of normal ISM from residual ISM in superbubble and the superbubble wall (x 5 dilution of massive star material)

Massive star material (ejecta plus stellar wind) accelerated by core-collapse SN shock in OB association

Detection by ACE

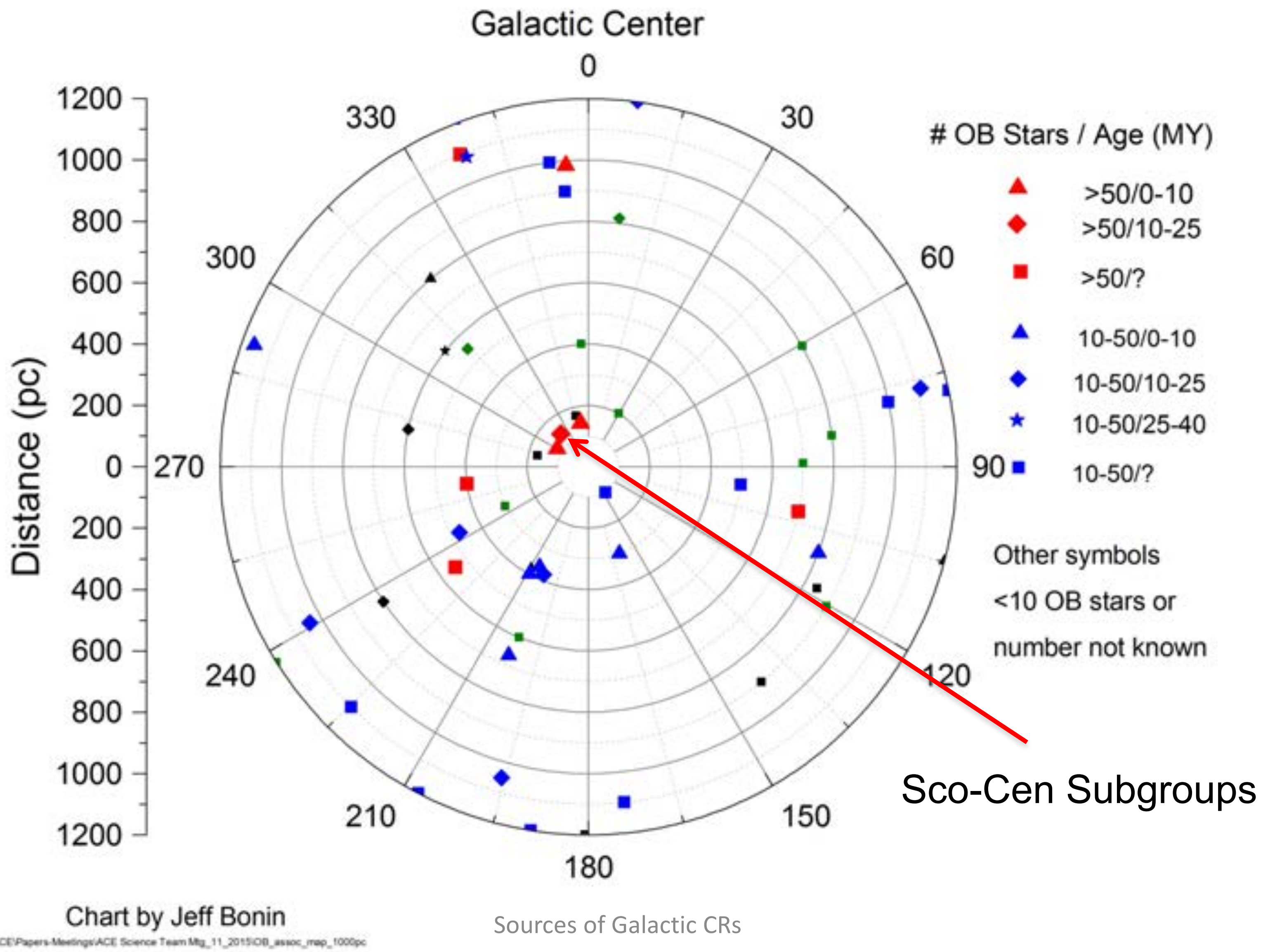
Propagation To ACE





- Interaction losses
- Leakage from the galaxy
- Radioactive decay
- Energy loss and
- reacceleration

OB associations in our neighborhood

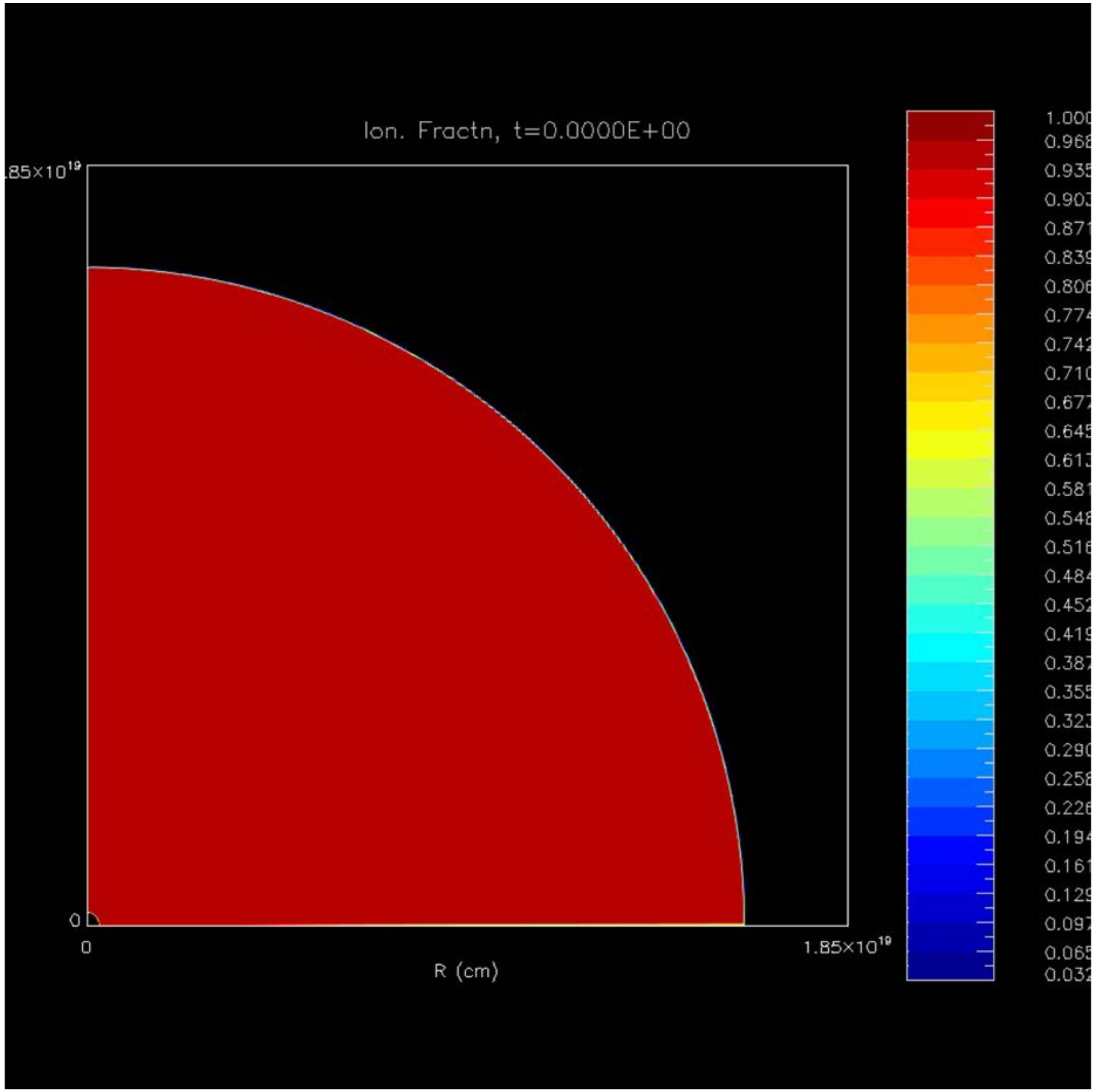


Ionization-Gasdynamics Simulation of Wind-Blown Bubble from W-R Star

IONIZATION FRACTION

Simulation carried out using AVATAR code, including Ionization from the star

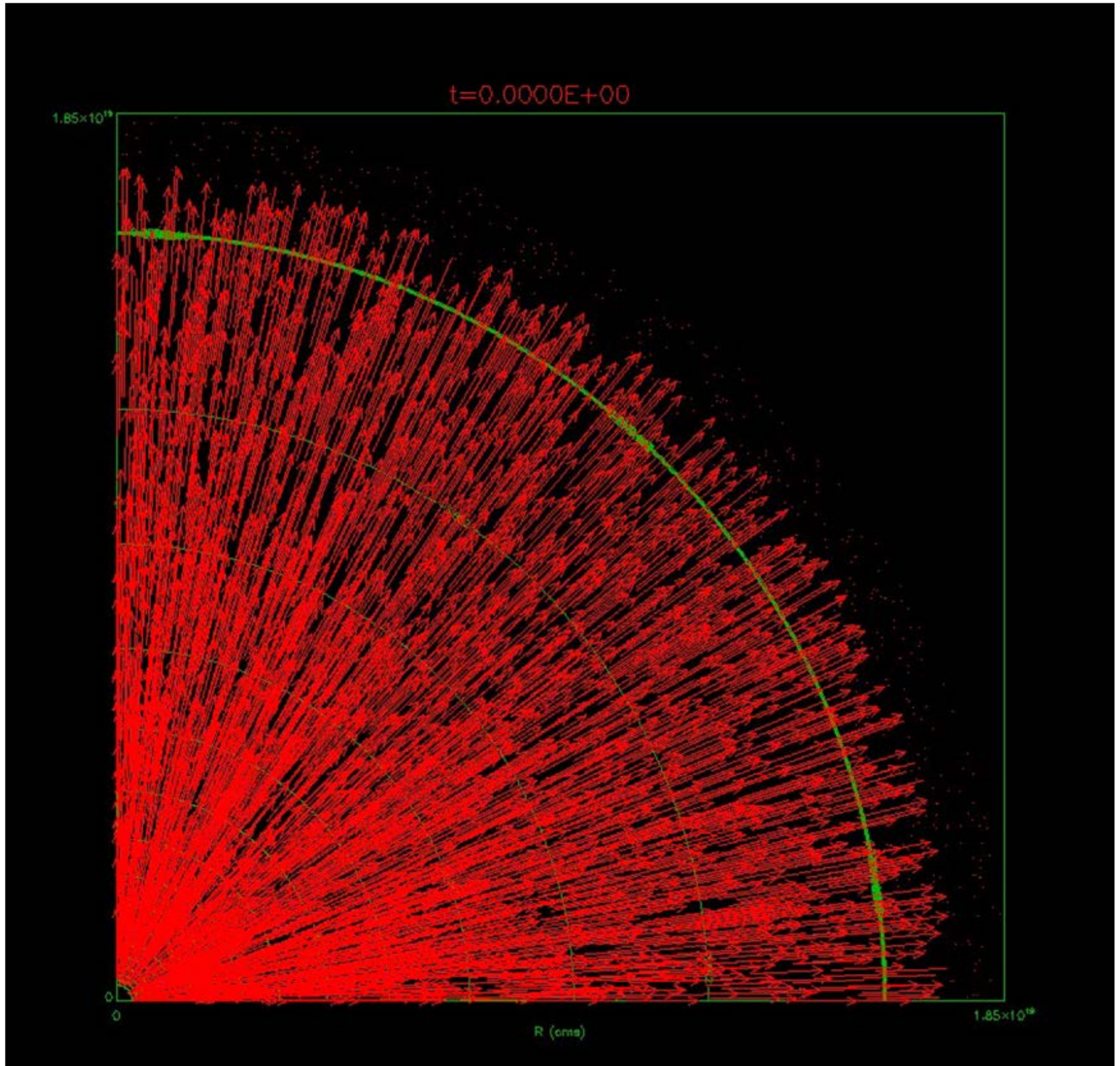
See also Dwarkadas and Rosenberg (2013).



IONIZATION-GASDYNAMICS MODELLING

DENSITY CONTOURS OVER VELOCITY VECTORS

See Dwarkadas & Rosenberg (2013, HEDP).



Conclusions

- Combination of ^{22}Ne and ^{60}Fe results suggests that:
  - Local Cosmic Rays are accelerated by Massive stars and Supernovae
  - Wolf-Rayet stars must be involved
  - The supernova producing the ^{60}Fe could arise from the same W-R star or in the same association.
  - Time required between nucleosynthesis and transport to Earth does not greatly exceed the ^{60}Fe half-life of 2.6 Myr
  - Our distance from the source of this nuclide does not greatly exceed the distance that GCRs can diffuse over this time scale, <~ 1 kpc
  - The CR source is a mix of newly synthesized material with old ISM

➡ These results point to cosmic ray acceleration in a single star or group of massive stars, forming an OB association, which give rise to bubbles and superbubbles.

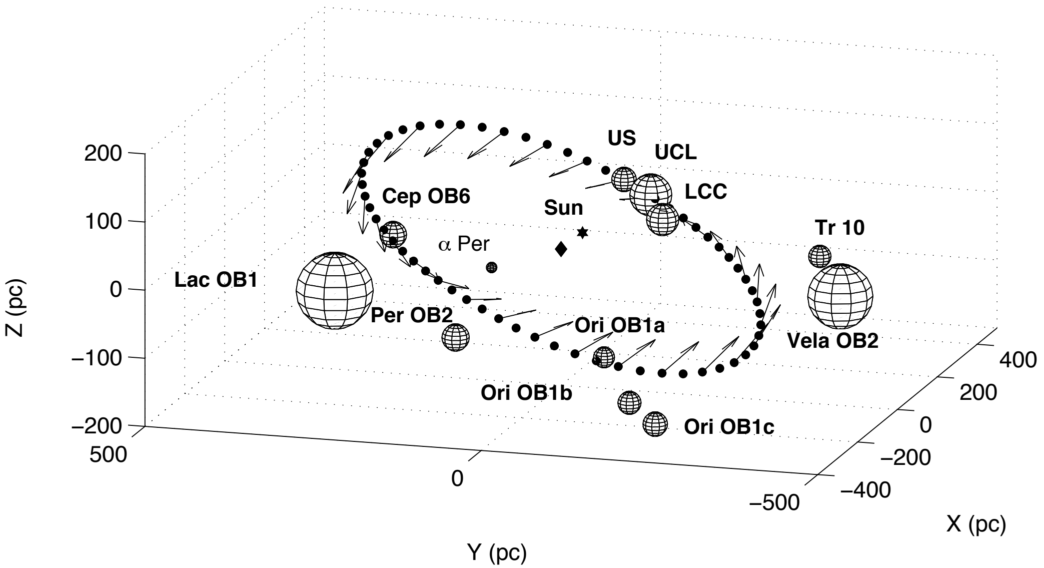
- Bubbles and Superbubbles will be in general partially ionized.
- Large-scale turbulence within bubbles must be taken into account.

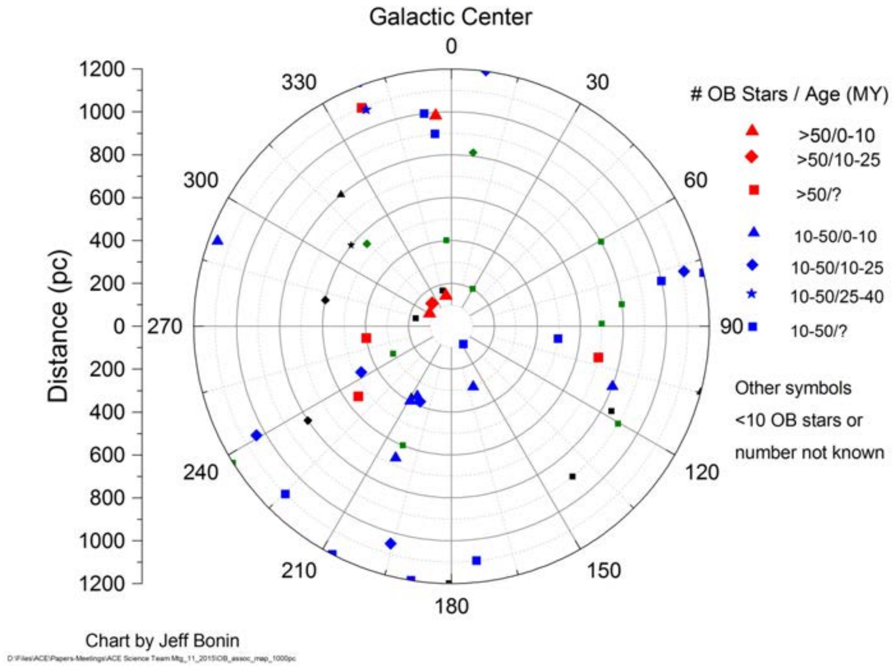
Combining ^{59}Ni results with results on ^{60}Fe we obtain the time between nucleosynthesis and acceleration of :

10^5 yr < τ < several Myr

(not sure if this is still valid in light of recent results)

Conclusions





Questions and Discussion