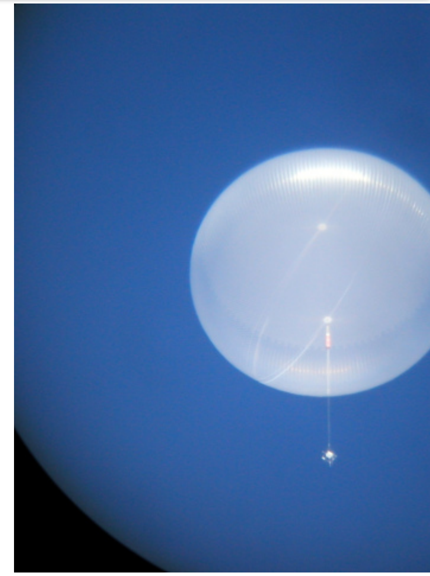
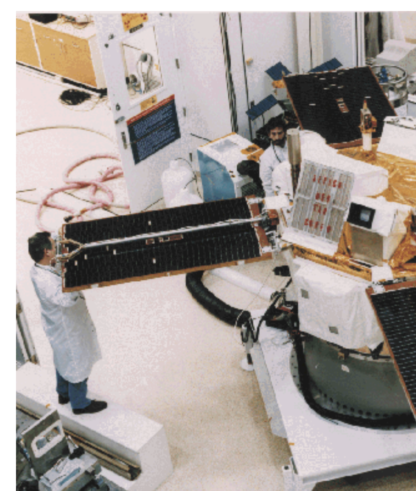
and the measurement of ^{60}Fe



Super-TIGER experiment, balloon borne

- easured elemental abundances for charge (Z) 26 ≤ Z ≤ 40
- eferential acceleration of refractory elements over volatile ements by ~4x ordered by atomic mass (A)
- th refractory and volatiles show a mass dependent hancement with similar slopes
- nsistent with cosmic-ray source material being a mix of ~20% assive Star Material (MSM) and ~80% normal ISM

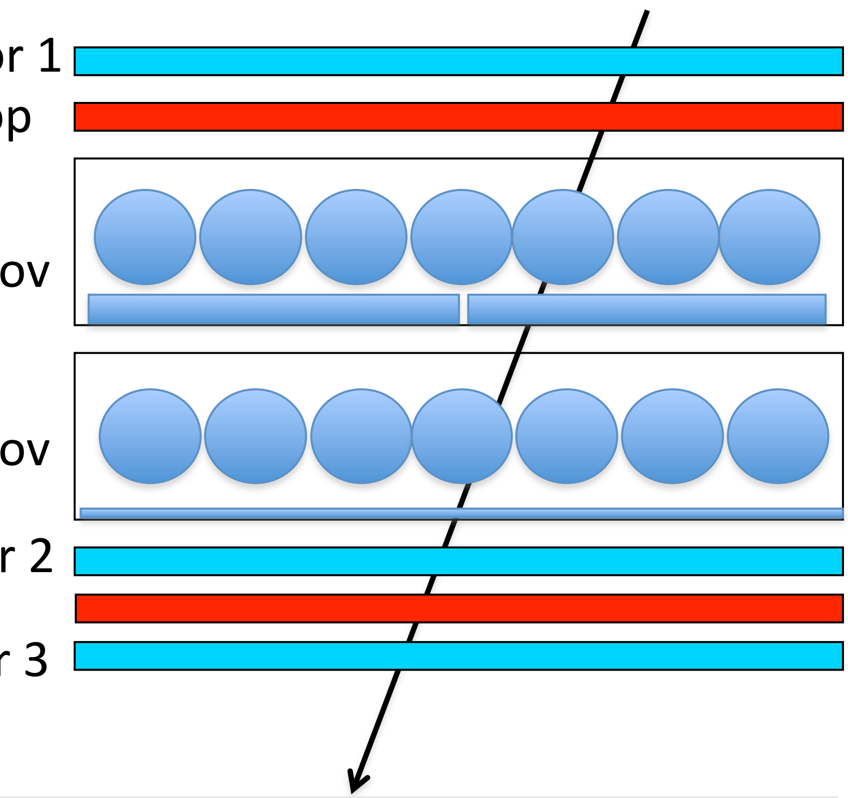
Cosmic Ray Isotope Spectrometer (CRIS) aboard ACE satellite

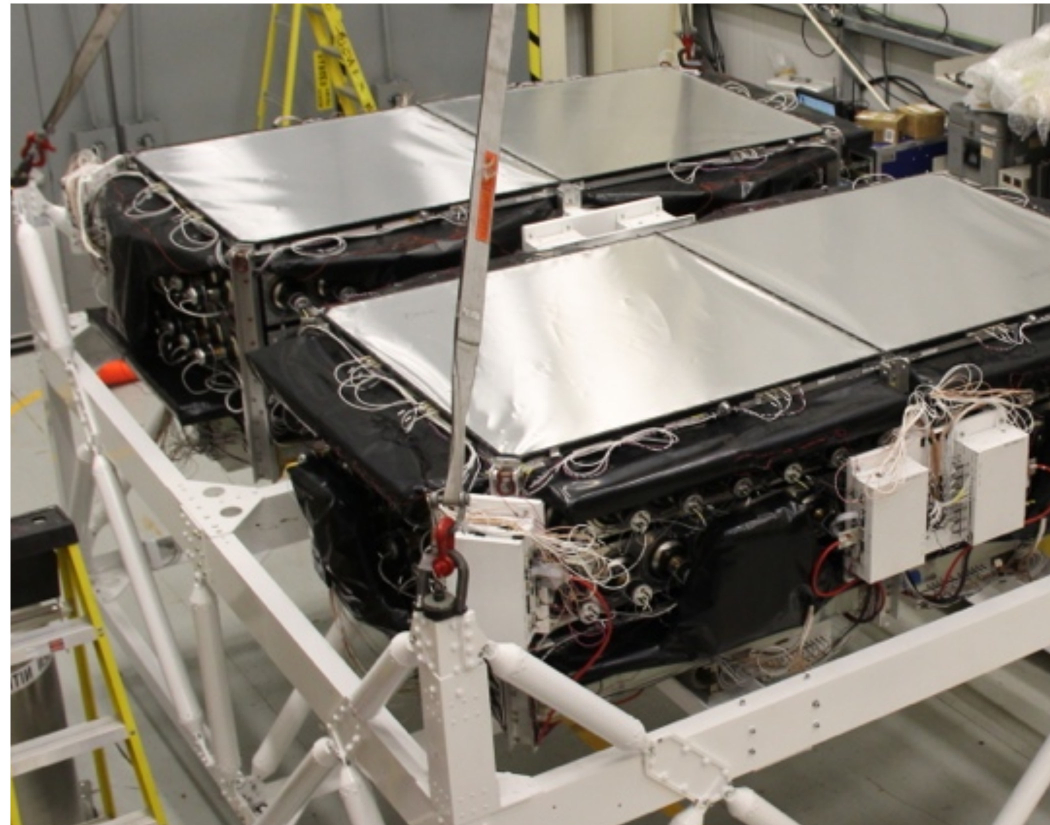


- easured $^{60}Fe/^{56}Fe$ ratio
- nd that the time interval between nucleosynthesis and celeration is < several Myr
- e distance to the source(s) is ≦ 1 kpc
- st conclusive evidence of recent nucleosynthesis in galactic smic rays (GCR)

W.R. BINNS[1], R.P. MURPHY[1], T.J. BRANDT[2], G.A. DE NOLFO[2], T. H
SRAEL[1], A.W. LABRADOR[3], J.T. LINK[2], R.A. MEWALDT[3], J.W. MITC
AUCH[1], K. SAKAI[2], M. SASAKI[2], E.C. STONE[3], C.J. WADDINGTON[5],
J.E. WARD[1], AND M.E. WIEDENBECK[4]

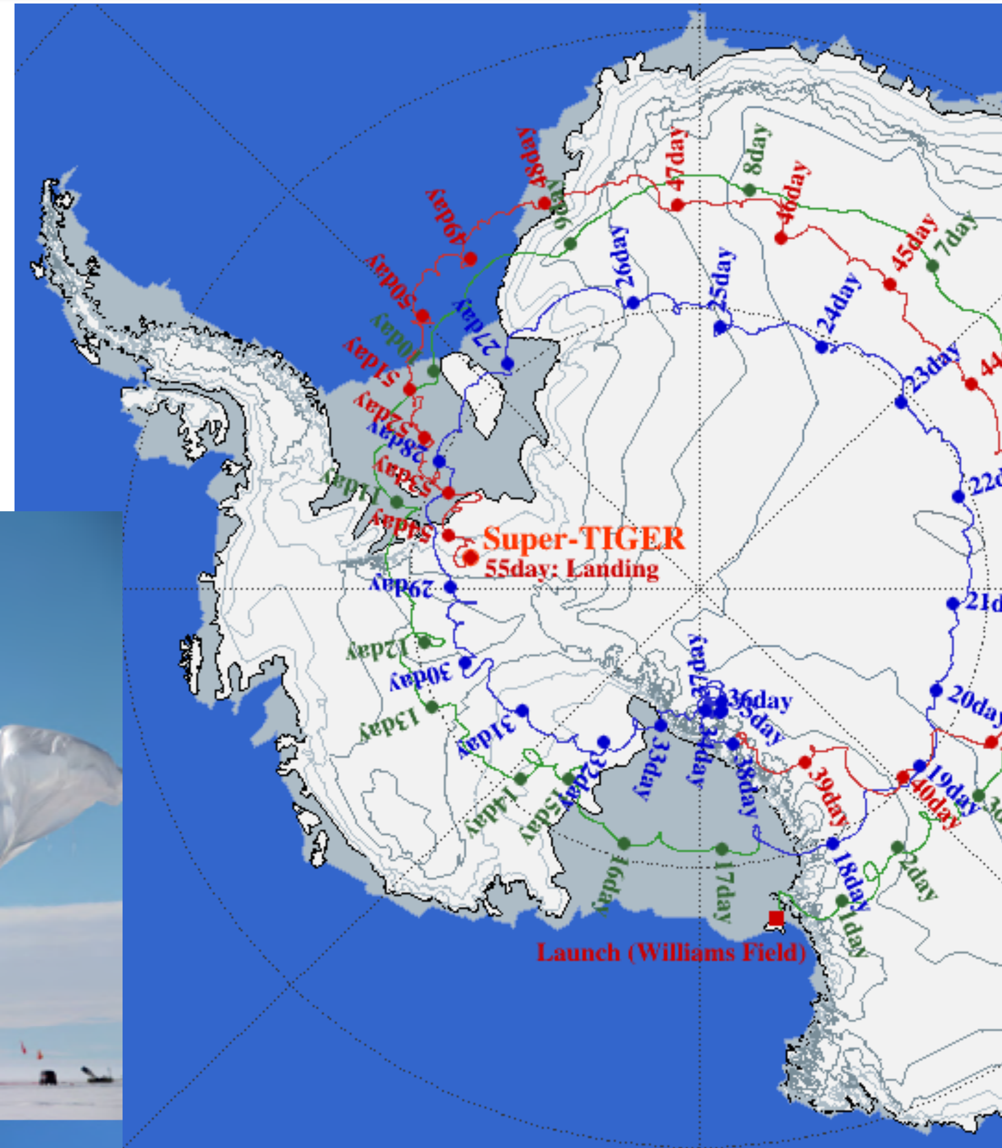
1. Washington University in St. Louis, St. Louis, MO 63130 USA
2. NASA/Goddard Space Flight Center, Greenbelt, MD 2077 USA
3. California Institute of Technology, Pasadena, CA 91125 USA
4. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
5. University of Minnesota, Minneapolis, MN 55455 USA

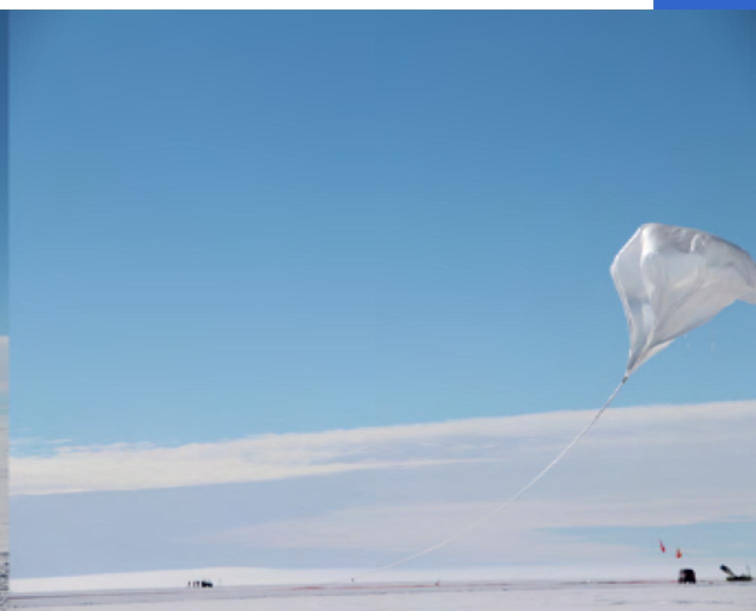


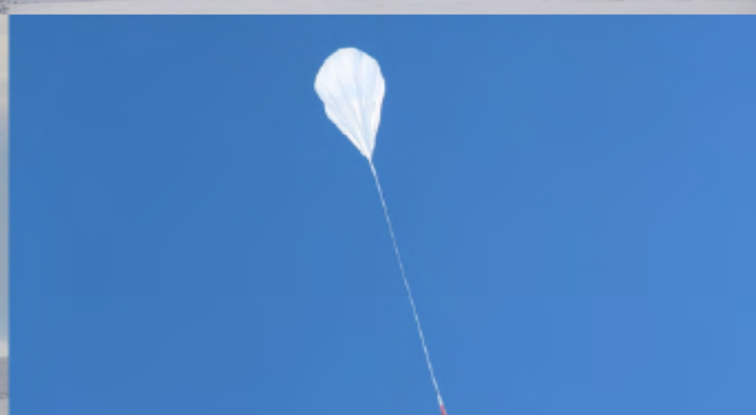


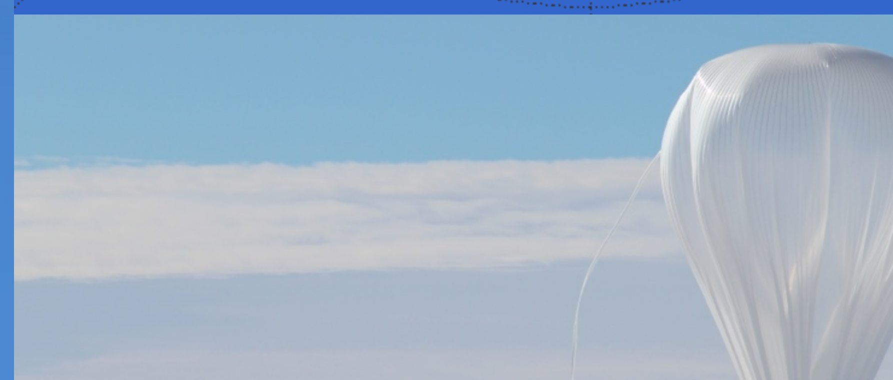
- 7 detectors
- cintillation counters
- cintillating Fiber Hodoscopes
- herenkov Detectors
  - Aerogel, n =1.043 or 1.025 (2.5 or 3.3 GeV/nucleon)
  - Acrylic, n = 1.49 (0.3 GeV/nucleon)
- arly identical modules
- e area 2.9 m^2sr, 7.2 times that of

- nber 8, 2012-February 1,
- y flight--(NASA Heavy-Lift
ific Balloon Record!)
- ted 4.7 x 10^6 iron events

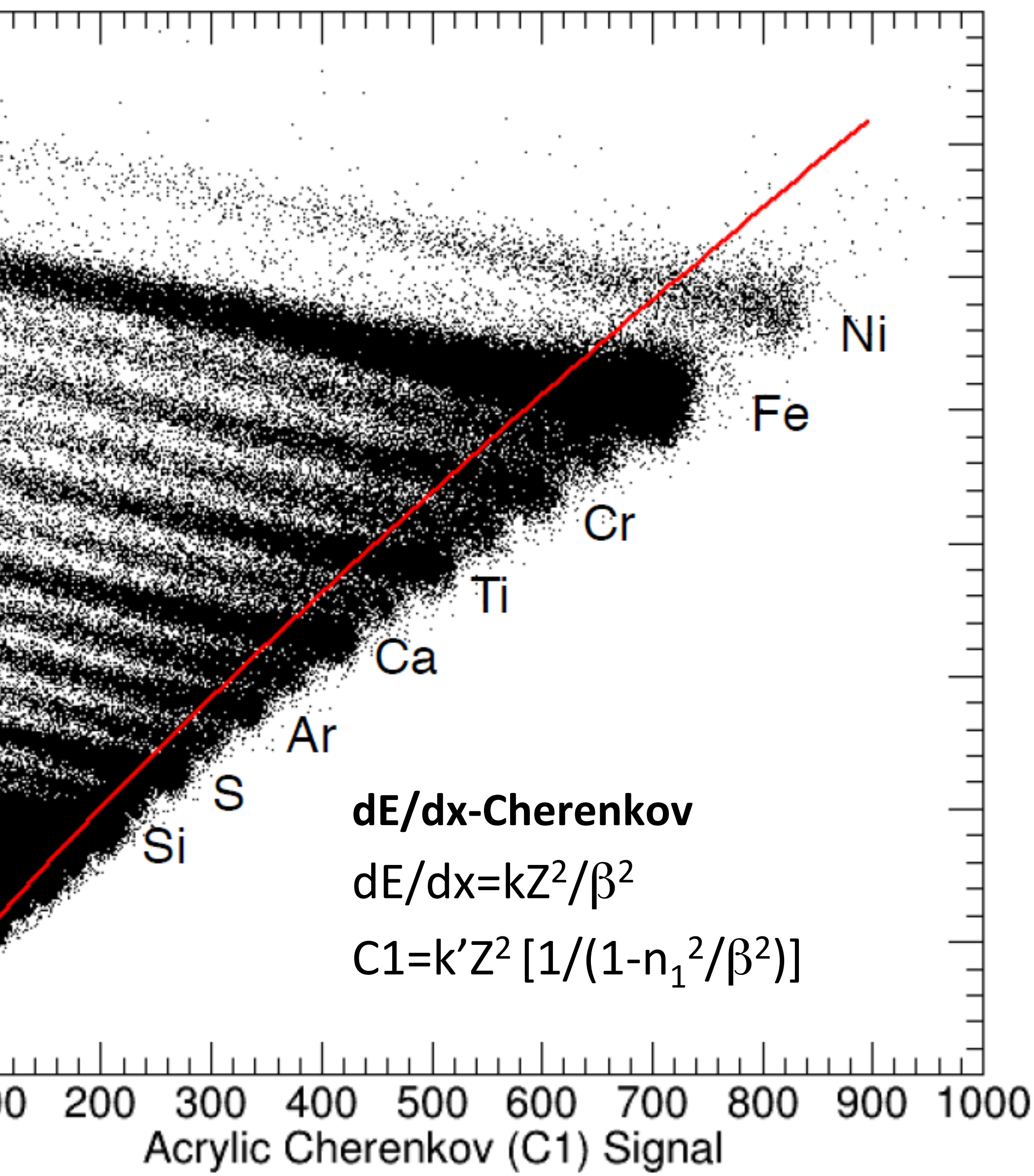




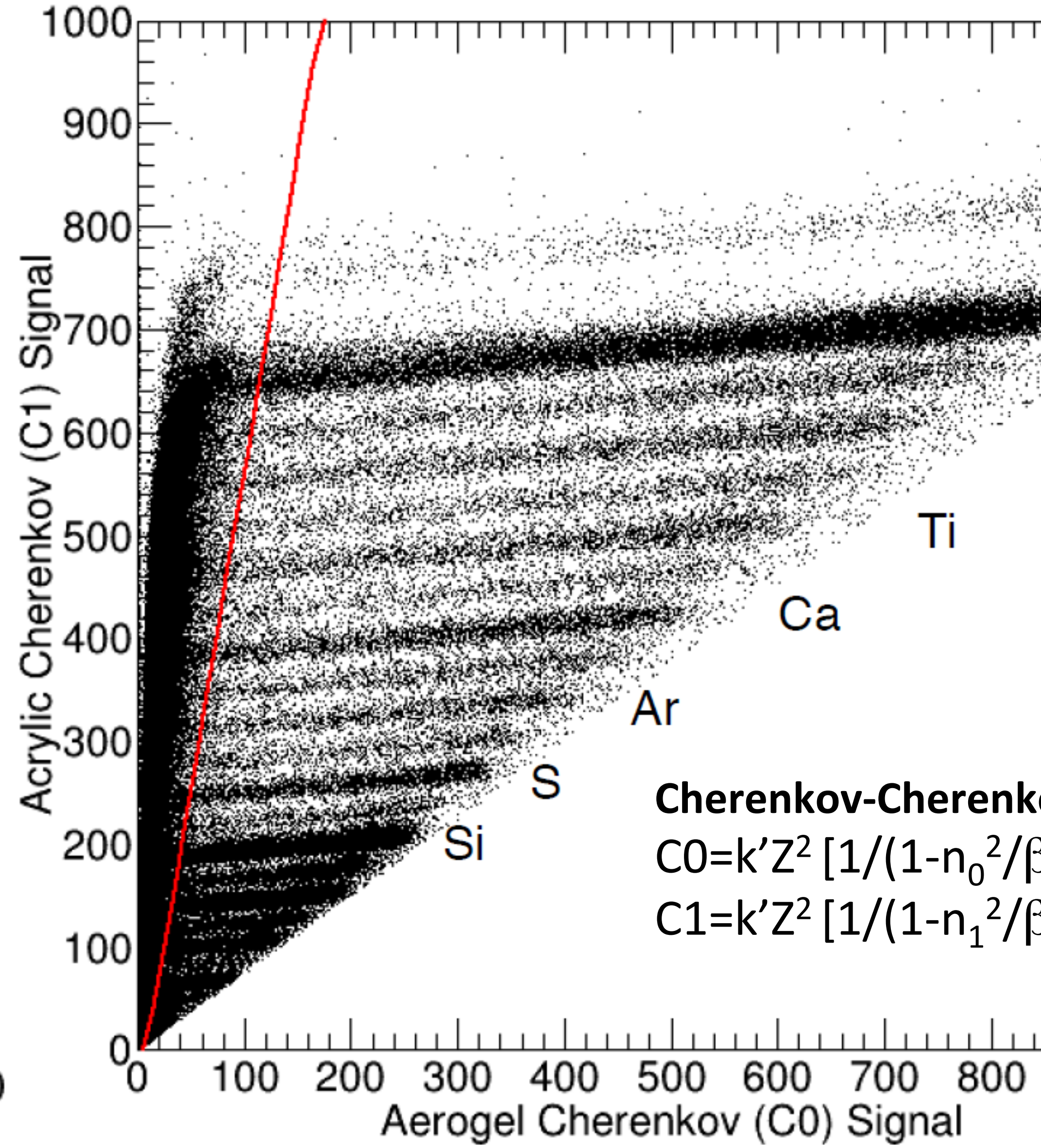




rgies: Scintillator vs Acrylic C



High Energies: Acrylic C vs Aerog

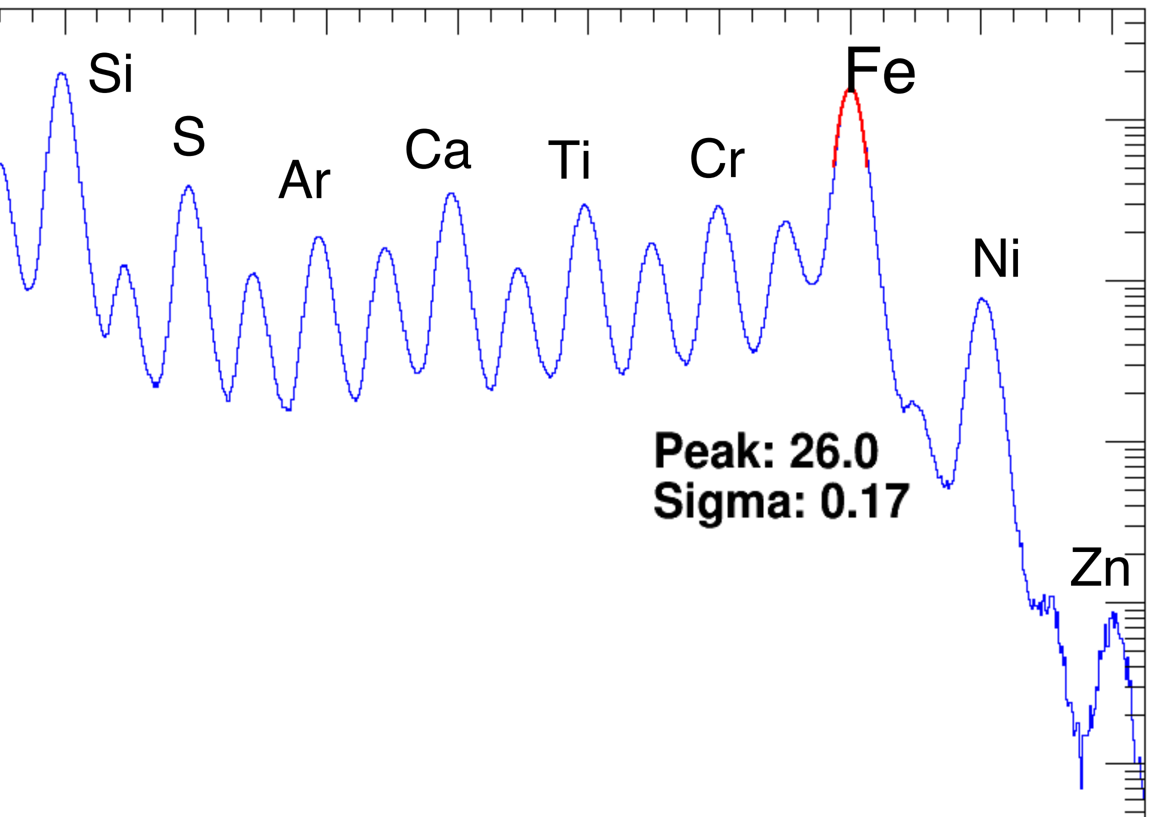


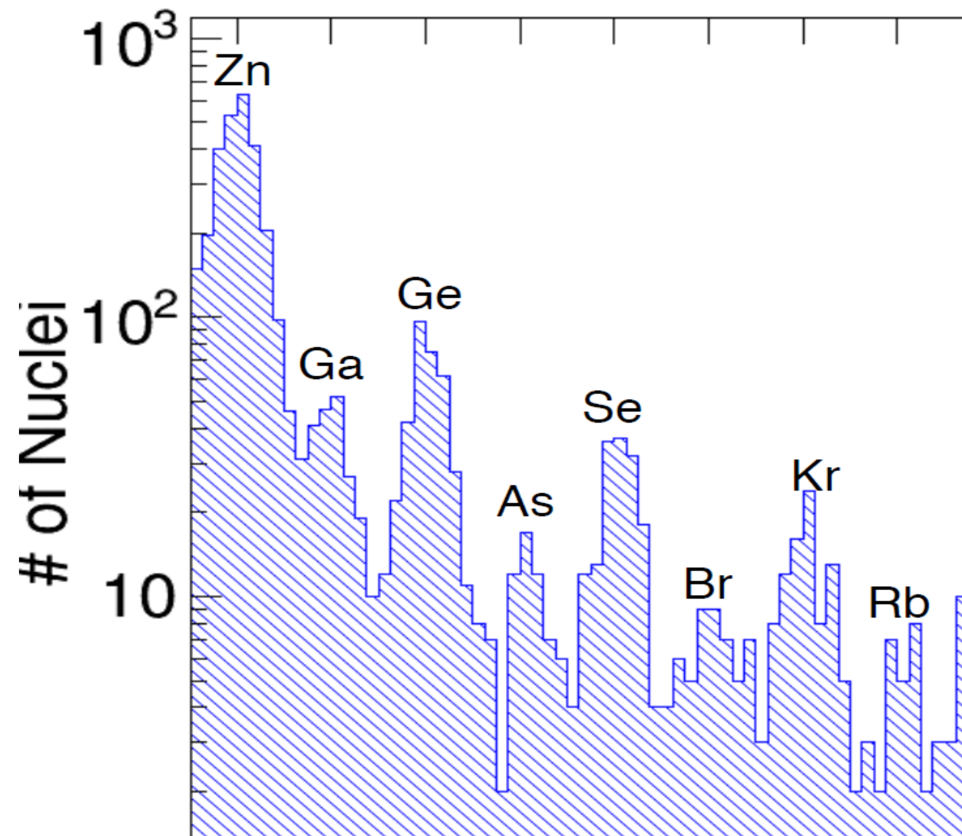
800 MeV/nuc at top of atmosphere

t high statistics measurement of abundances of all elements with Z≤40

st nuclei are in the energy range 0.8-10 GeV/nuc

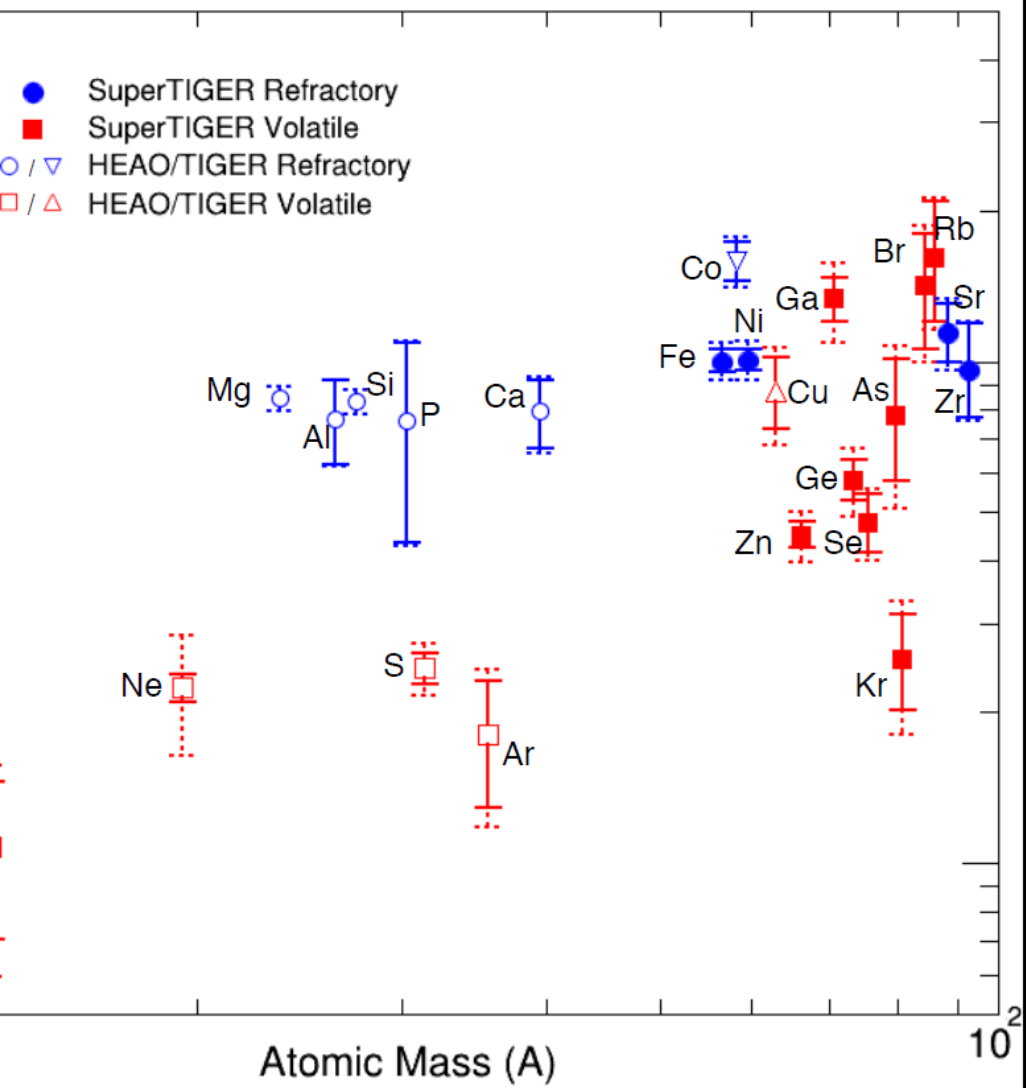
nplementary to ACE measurement taken in space, but with large nbers of events for ST



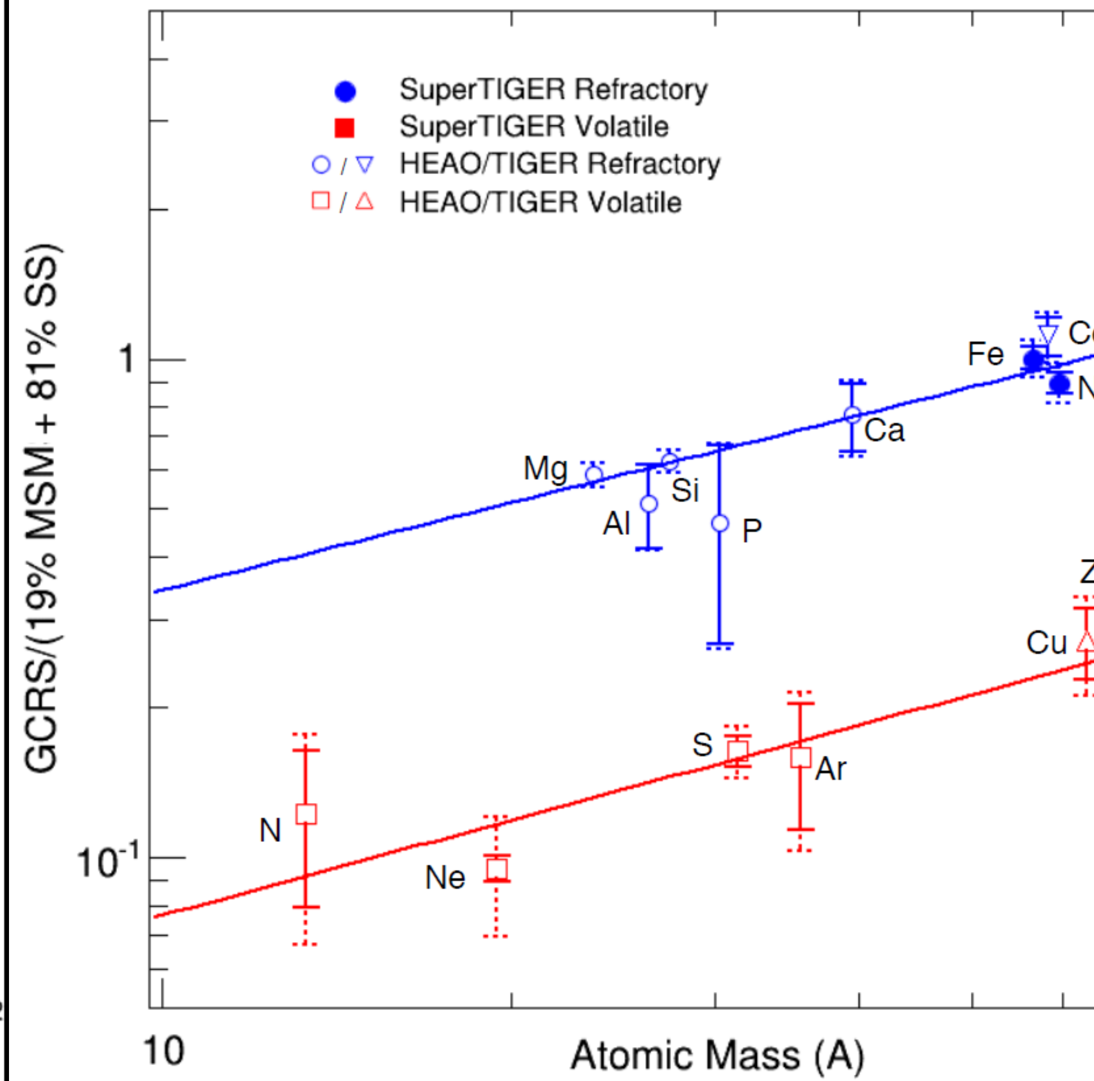


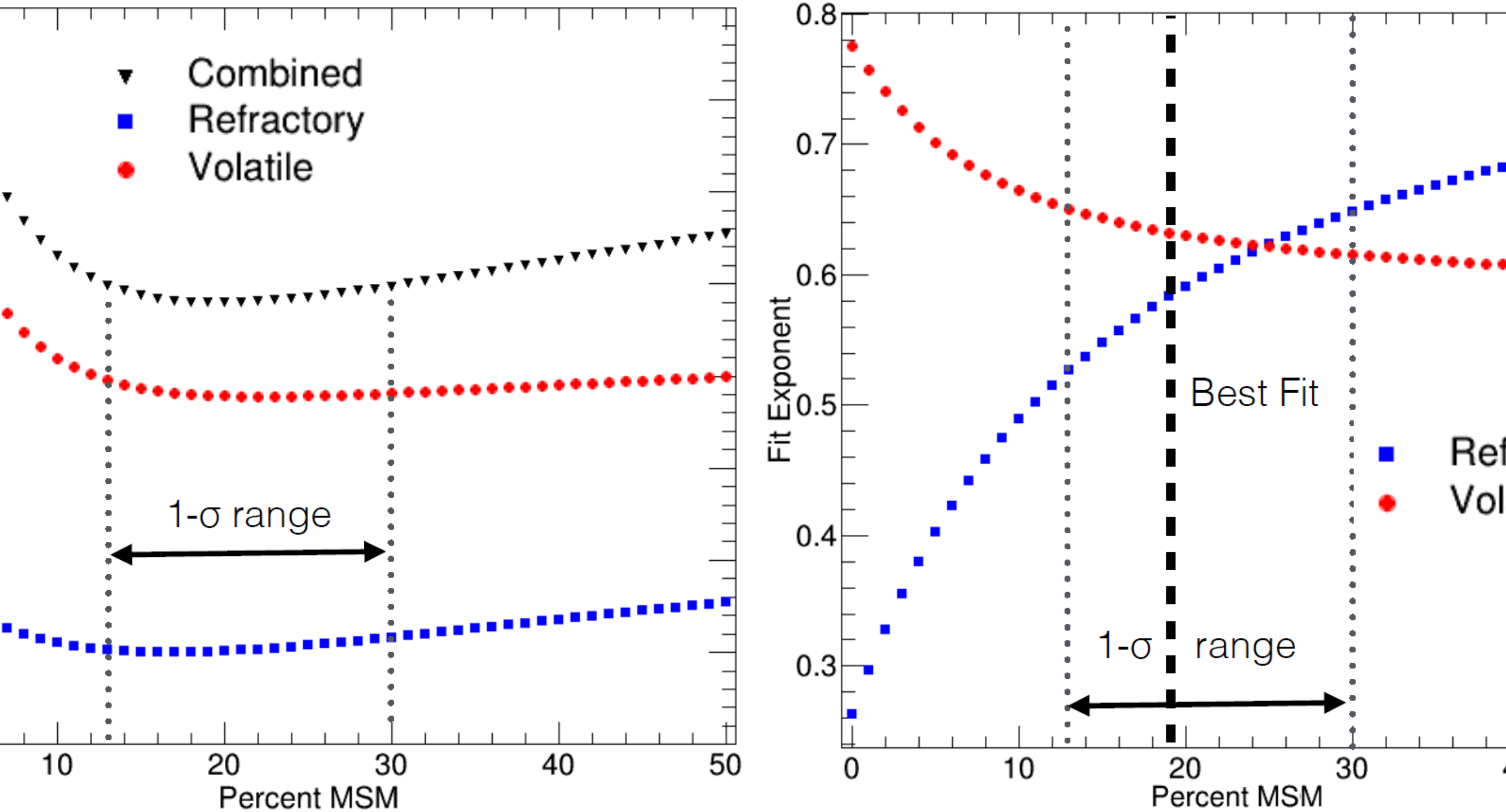
GCRS/ Massive Star Material (MSM) Mix

GCRS/SS



GCRS/MSM m





est fit = 19^{+11}_{-6} % MSM

Summary

esults support a model of cosmic ray origin in whic
e source material consists of a mixture of 19^{+11}_{-6} %
SM with ~81% of normal ISM

referential acceleration of refractories over volatile
x4

oth refractories and volatiles show a mass depend
nhancement with similar slopes of C1 ~ 0.6 ± 0.1

$$(y = C_0 A^{C1})$$

atural place for this is in OB associations

isotope in galactic cosmic rays

W.R. Binns, M.H. Israel, K.A. Lave

Washington University

M.E. Wiedenbeck

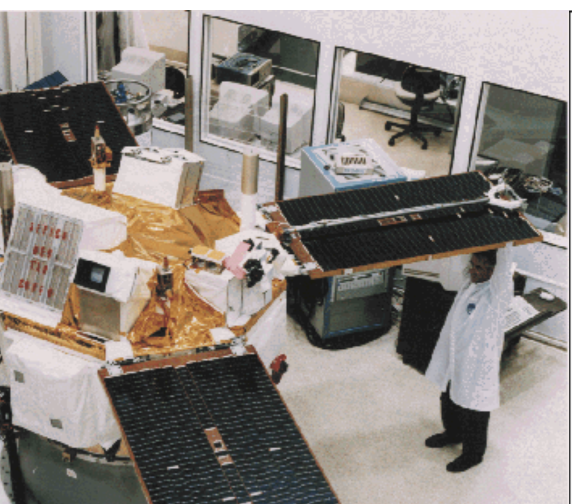
JPL/Caltech

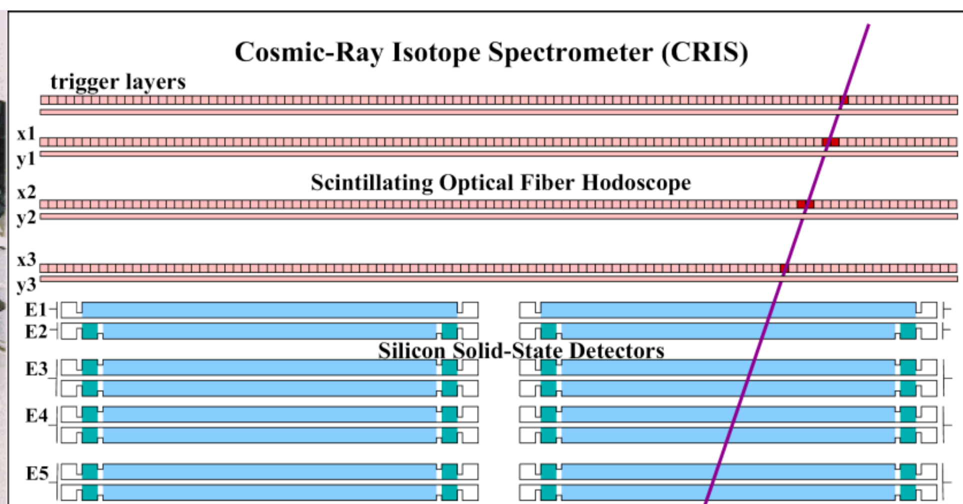
A.C. Cummings, R.A. Leske, R.A. Mewaldt, E.C. Stone

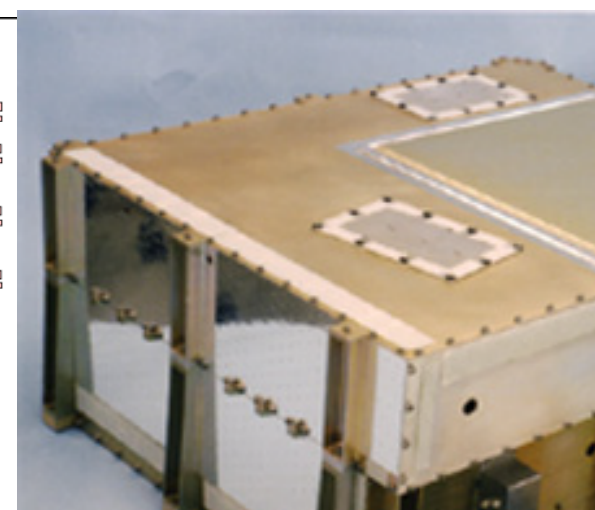
Caltech

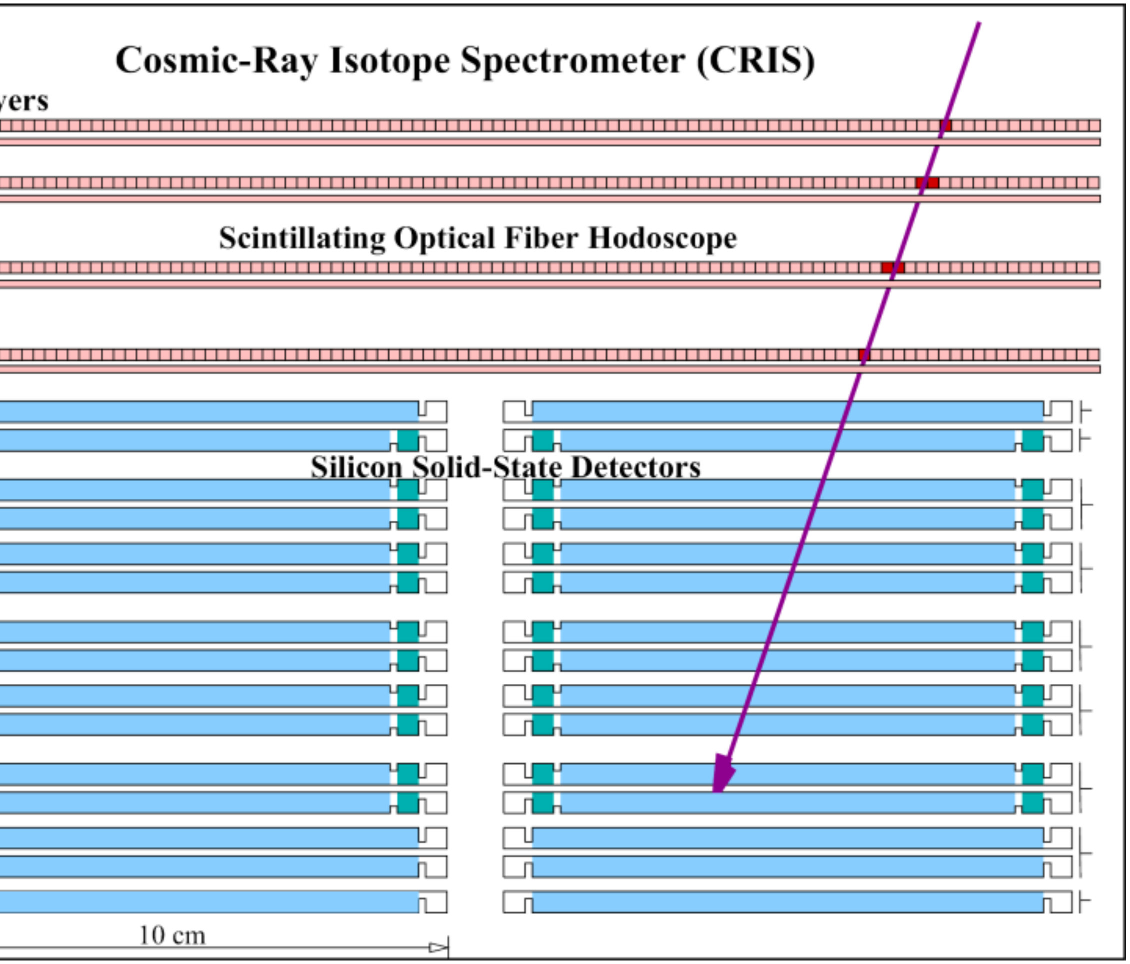
E.R. Christian, G.A. de Nolfo, T.T. von Rosenvinge

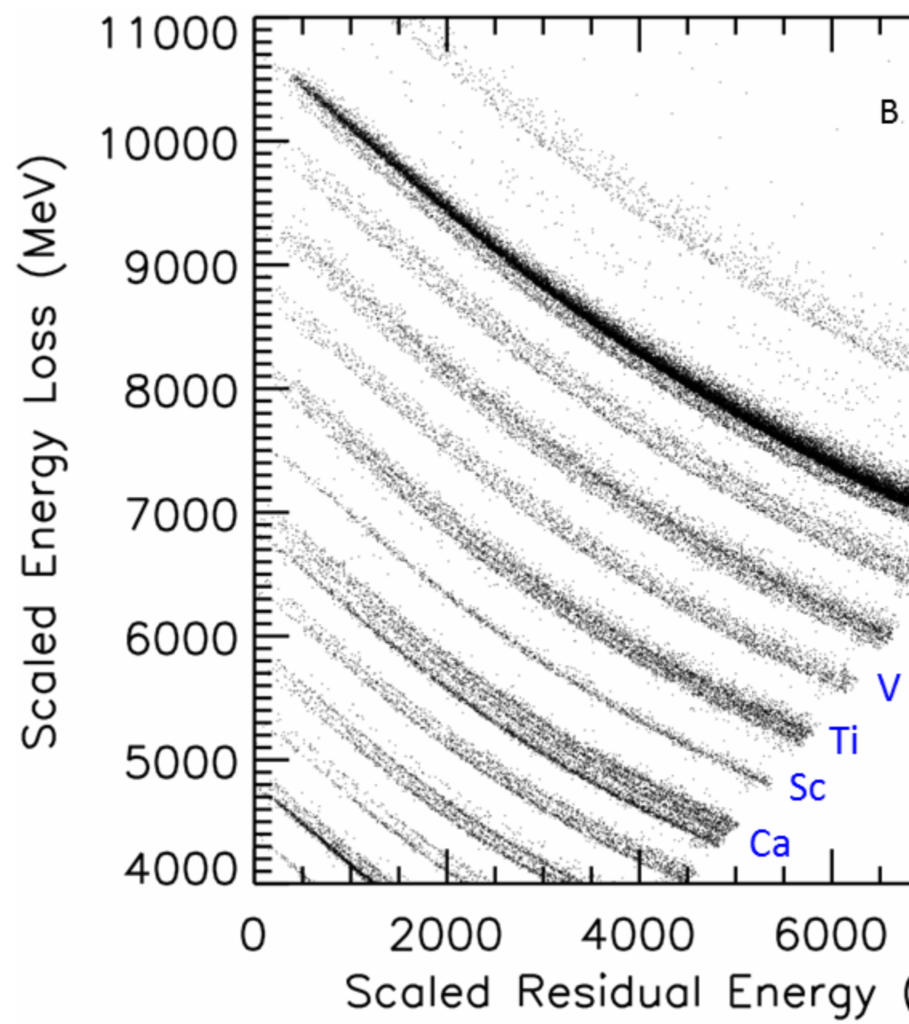
Goddard Space Flight Center











- CRIS uses multiple dE/dx vs. total energy method for charge and mass identification
- Energy range for the analysis presented here is ~240-470 MeV/n

$$dE/dx = kZ^2/\beta^2$$

$$E_{KE} = 0.5\, m\beta^2$$

a-rays--INTEGRAL (Wang, et al., 2007; nl 2013) and RHESSI (Smith, 2004)

se galactic emission, not point source, due e ^{60}Fe lifetime being longer than ejection scales (~1 Myr).

able origin is SNe.

ea manganese crust--analysis of core-s--Wallner et al. (2016) Nature.

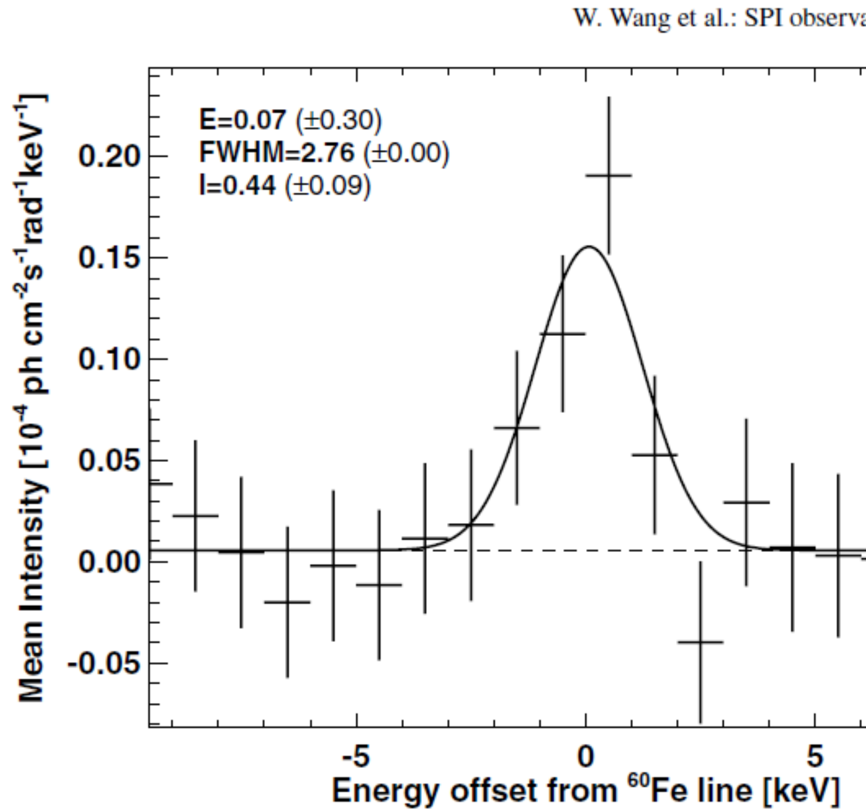
peak deposited 1.5-3.2 Myr ago

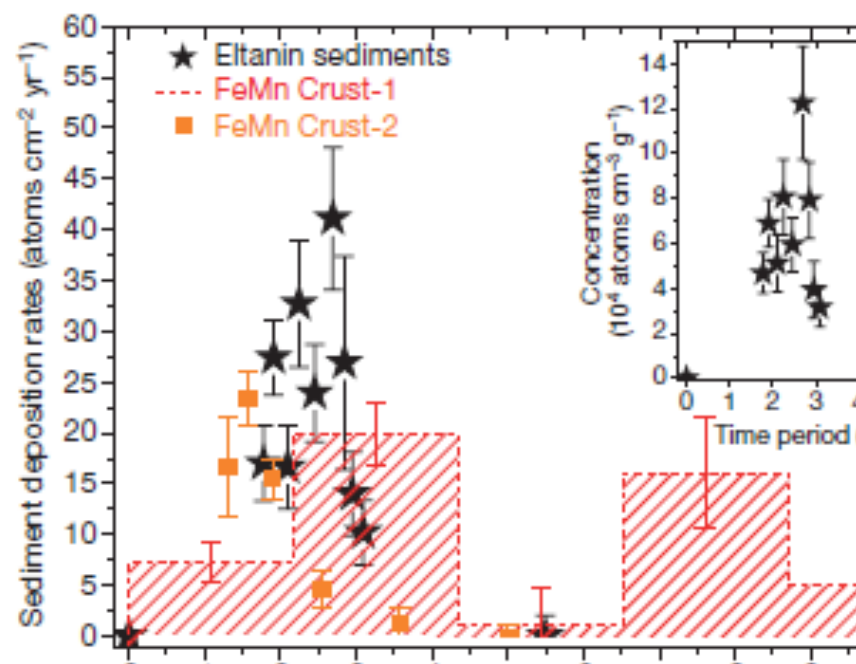
istent with deposition of ejecta from SNe 2.3 Myr ago at distances ~100 pc schwerdt et al. (2016) Nature

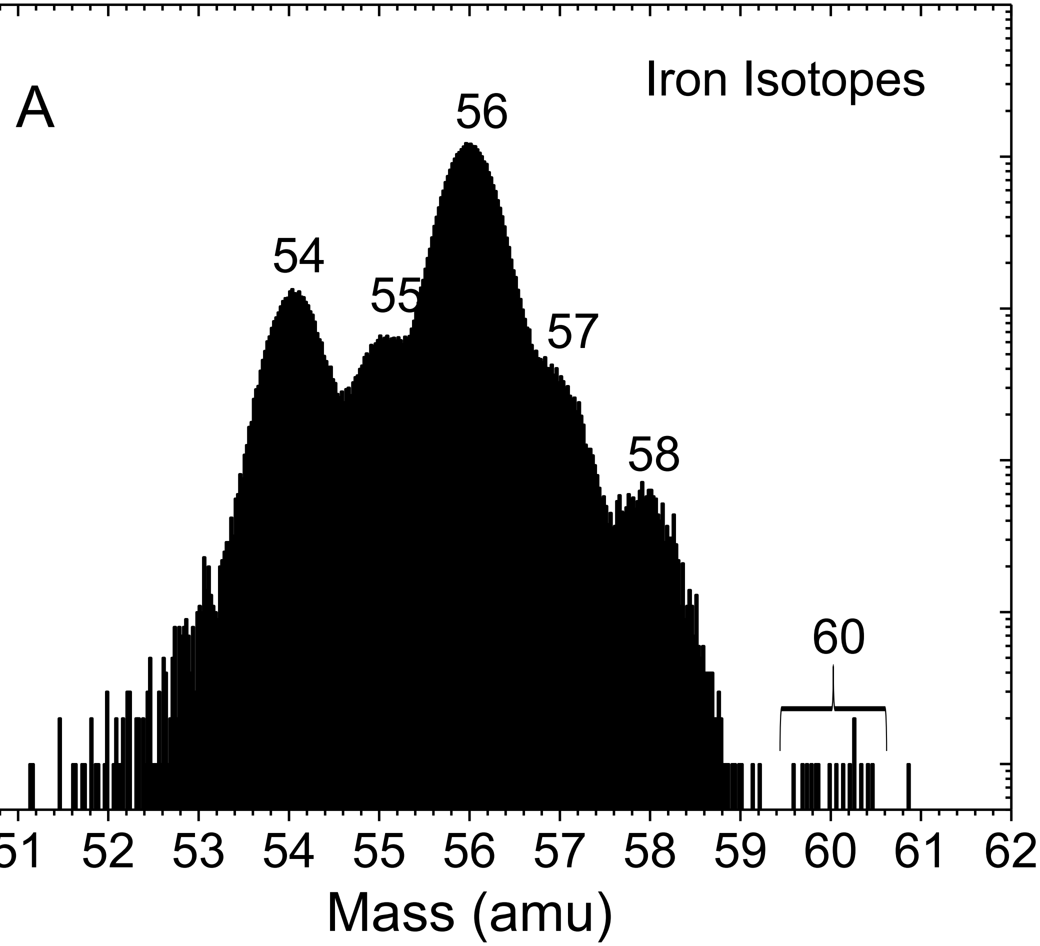
g earlier data, Fry et al. (2015) ApJ ated 15-120pc for ^{60}Fe producing SNe: atible with production by CC or EC SNe

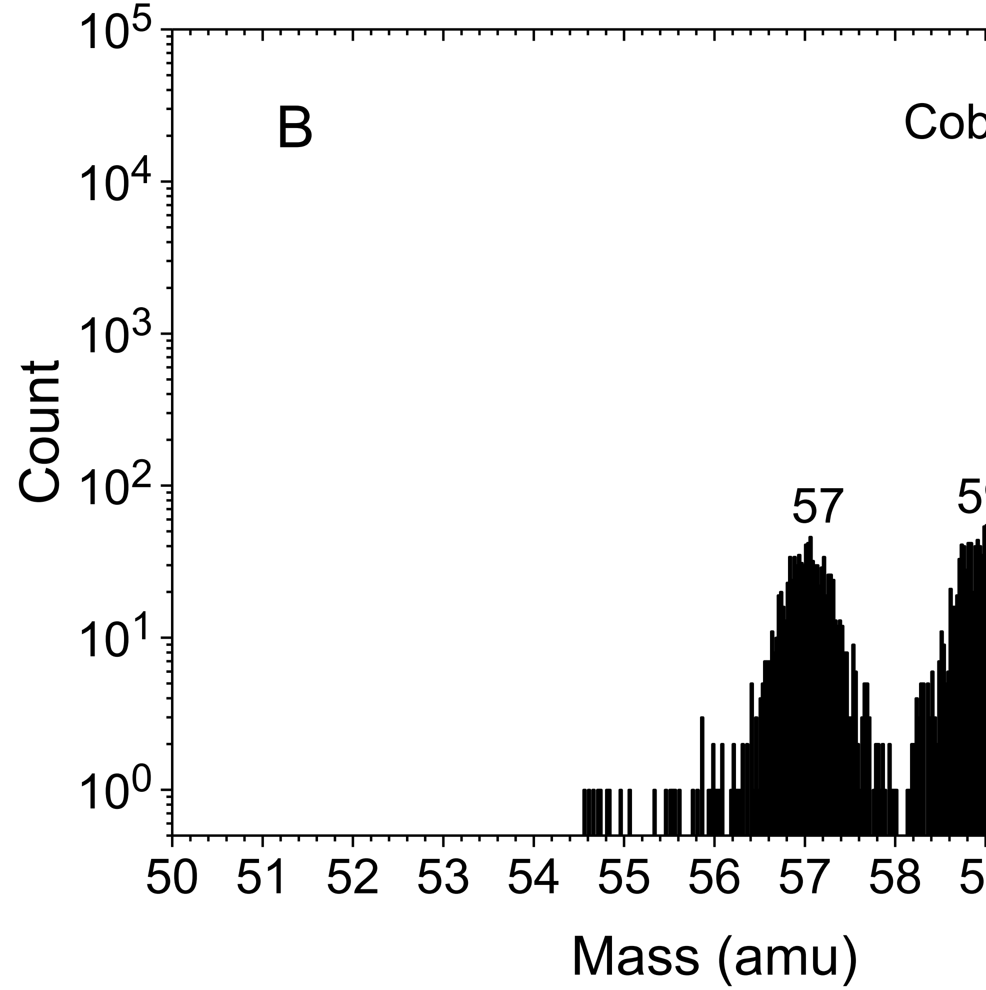
tofossils in Pacific Drill Cores

vig et al., PNAS 2016









^{0}Fe events have mean mass estimate of A=60.04 and a standard ation from mean of 0.28 ± 0.05 amu, consistent with 0.245 ± 0.001 ı for ^{56}Fe.

ngest argument that this is not a tail of the ^{58}Fe peak can be seen by ing at upper edge of ^{59}Co distribution.

y 1 event near ^{61}Co, but for ^{60}Fe have 15.

e observe 15 ^{60}Fe nuclei and 2.95x10^{5} ^{56}Fe nuclei. W
timate that

~1 of these ^{60}Fe is the result of interstellar fragmentation of heavier nu
probably ^{62}Ni or ^{64}Ni

~1 ± ~1 could be background (possibly from interactions in the CRIS
instrument above the Si stack).

o our measured ratio is

Fe/^{56}Fe = (13 ± 1 ± 3.9)/2.95x10^{5} = (4.4 ± 1.7) x 10^{-5}

e first ± is uncertainty of the background and the second ± is √15.)

orrecting for interactions in the instrument and differin
ergy ranges yields ^{60}Fe/^{56}Fe = (4.6 ± 1.7) x 10^{-5} at to
etector.

nce the ^{60}Fe halflife is 2.6 Myr, this implies

CR acceleration occurs within several Myr of nucleosynthesis

a more quantitative upper limit on the time between
eosynthesis and acceleration we need:

/^{56}Fe at the cosmic ray accelerator compared with the ra
the nucleosynthesis process that produced them.

get from the ratio at Earth to the ratio at the accelerator, w
a "leaky box" model of propagation in the galaxy, with
meters derived from CRIS observations of beta-decay
ndaries

Be, ^{26}Al, ^{36}Cl, ^{54}Mn (Yanasak et al., ApJ 563, 768 (2001))

our of these are fit by a simple leaky box model with

$$\tau_{esc} = 15.0 \pm 1.6 \text{ Myr}$$

$$n_H = 0.34 \pm 0.04 \ /\text{cm}^3$$

is simple leaky-box, steady-state model, ignoring energy loss and ene
endence, we use our measured ratio at Earth N_{60}/N_{56}= (4.6 ± 1.7) x 10
in the ratio at the accelerator $R_A=Q_{60}/Q_{56}$

$$\frac{\delta N_i}{\delta t} = 0 = -\frac{N_i}{\tau_{esc}} - \frac{N_i}{\gamma\tau_{i\ decay}} - \frac{N_i}{\tau_{i\ interact}} + Q_i; \text{ where } \frac{N_i}{\tau_{i\ interact}} = \sigma_i n_H v_i N_i$$

Rewriting this, we get

$$Q_i = \frac{N_i}{\tau_{esc}} + \frac{N_i}{\gamma\tau_{i\ decay}} + \frac{N_i}{\tau_{i\ interact}}$$

riting this equation for ^{60}Fe and ^{56}Fe, and taking the ratio, we obtain

$$= \frac{Q_{60}}{Q_{56}} = \frac{N_{60}}{N_{56}} \frac{\{\frac{1}{\tau_{esc}} + \frac{1}{\tau^{60}{}_{int}} + \frac{1}{\tau^{60}{}_{decay}}\}}{\{\frac{1}{\tau_{esc}} + \frac{1}{\tau^{56}{}_{int}}\}}$$

N_i =GCR # density of species
τ_{esc}= escape time from the galaxy
$\tau_{i\ decay}$ = decay time for radioactive n
$\tau_{i\ interact}$= mean time between interact
γ = Lorentz factor for time dilati

So, with τ_{esc} =15.0 Myr, τ^{56}_{int}=4.45 Myr, τ^{60}_{int} =4.27 Myr, τ^{60}_{decay} = 5.90 Myr (the mean life at rest, 3.75 Myr, multiplied by average Lorentz factor γ= 1.56)

We obtain the ratio at the acceleration source

$R_A = Q_{60}/Q_{56} = (7.5 \pm 2.9) \times 10^{-5}$

/e then assume that the source material is actually a mix of 80% normal ISM and 20% massive star material (see previous ork on SuperTIGER & ACE), so the ratio ejected by the massive ars is

$R_{MS} = 5R_A = (3.75 \pm 1.5) \times 10^{-4}$

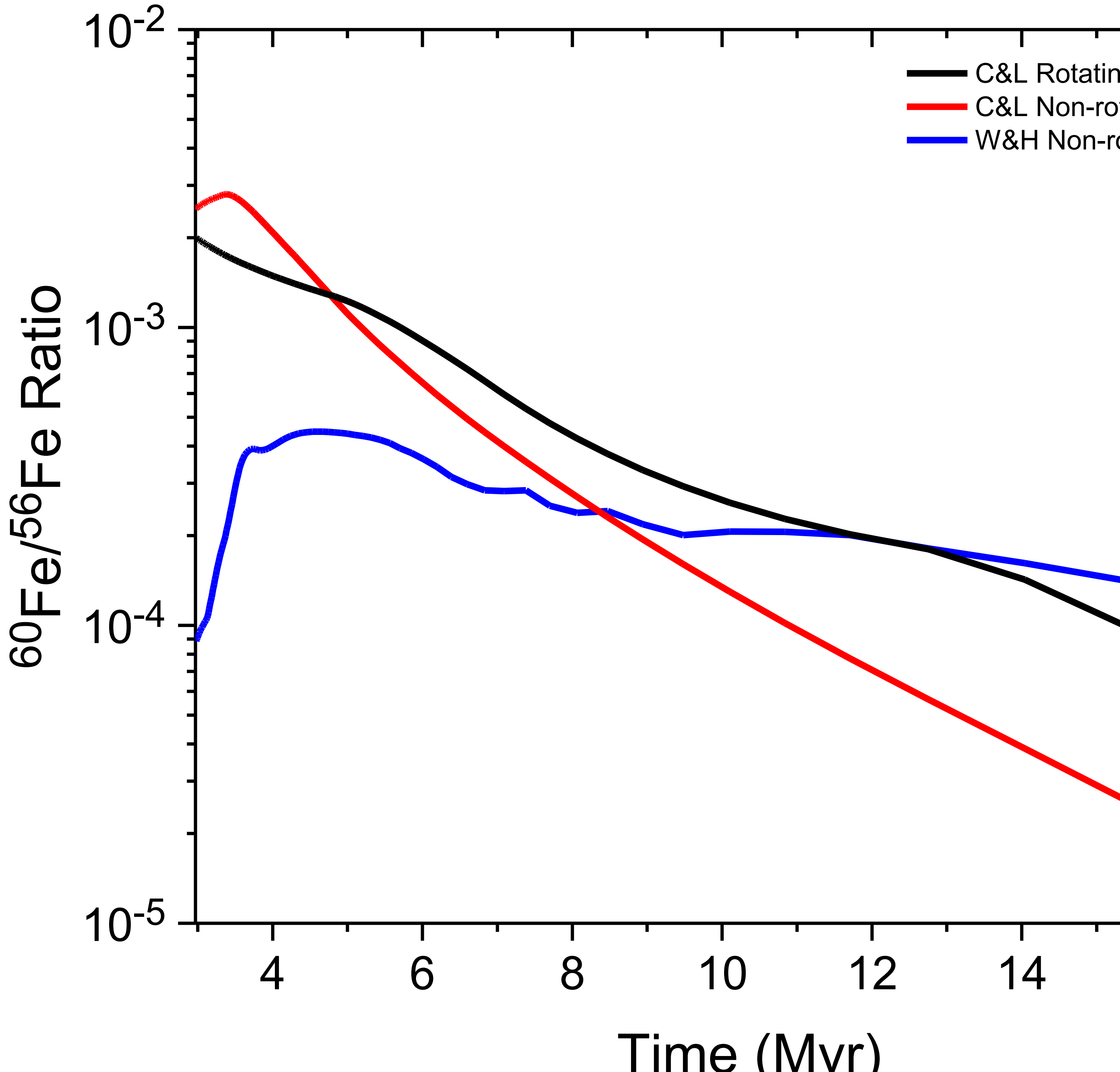
e & Limongi (2013)
oosley & Heger
yields used.

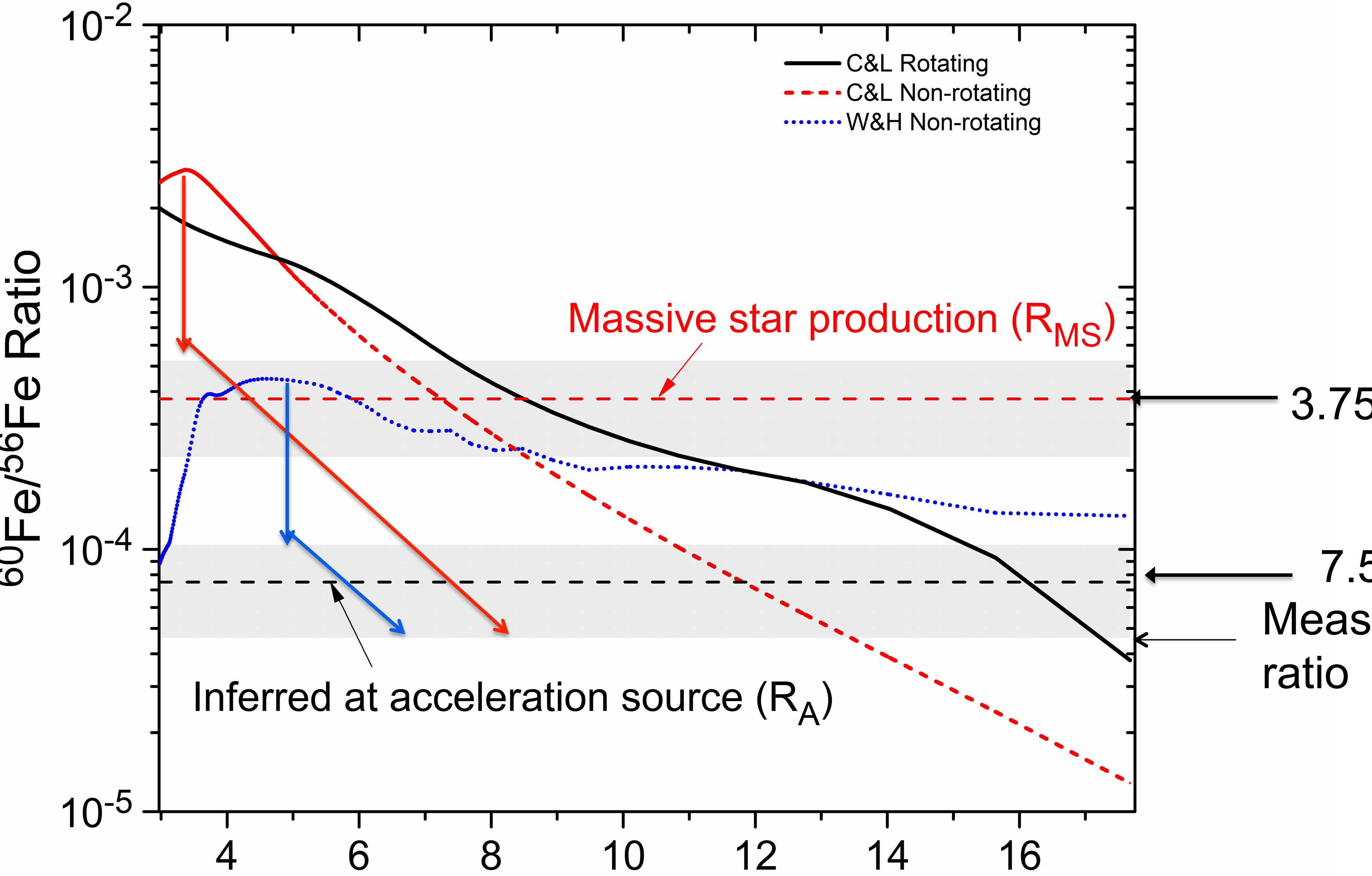
interpolation
en calculated masses

ime increments of
yr for ^{60}Fe and ^{56}Fe
on into superbubble.

aterial previously
d was decayed
ing to its exponential
e of 3.78 Myr, and
to the newly injected
al.

are clearly
ntial differences in
culations.





C&L Rotating
C&L Non-rotating
W&H Non-rotating
Massive star production (R_MS)
Inferred at acceleration source (R_A)
60Fe/56Fe Ratio
10-2
10-3
10-4
10-5
4
6
8
10
12
14
16
3.75
7.5
Meas
ratio

ake the largest $^{60}Fe/^{56}Fe$ ratio at any time in lifetime of OB assoc be R_{MS}.

ssume that all ^{60}Fe is deposited at that time.

	C&L model	W&H model
s (Massive Star material)	2.8×10^{-3}	4.5×10^{-4}
(Accel. Source)=0.2 x R_{MS}	5.6×10^{-4}	9.0×10^{-5}
wer limit on measurement of o	4.6×10^{-5}	4.6×10^{-5}

times

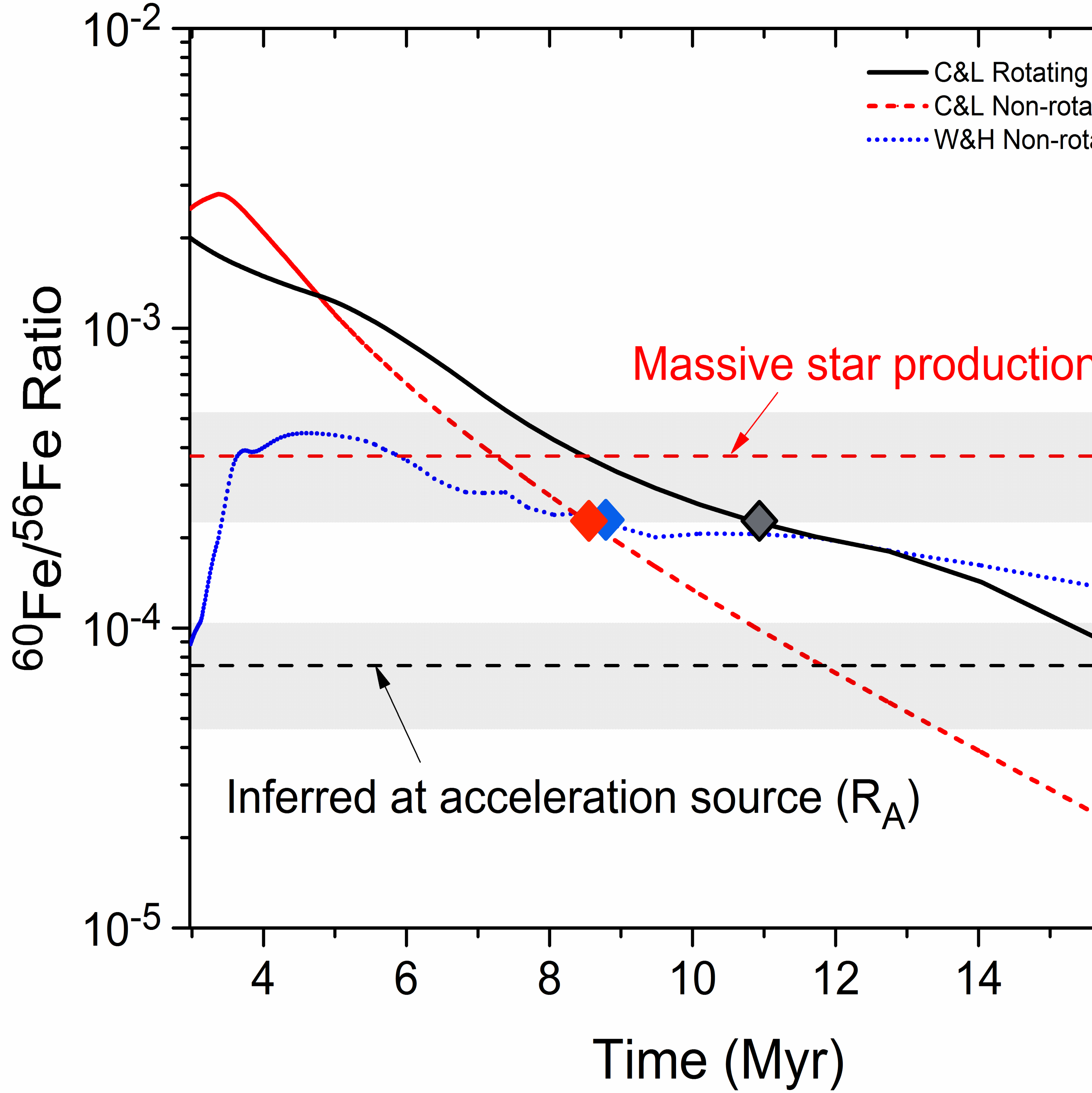
V&H τ =(3.78 Myr) x ln[(9 x 10^{-5})/(4.6 x 10^{-5})]=2.5 Myr

C&L τ =(3.78 Myr) x ln[(5.6 x 10^{-4})/(4.6 x 10^{-5})]=9.4 Myr

arly the calculated upper limit depends strongly on the assumed cleosynthesis model.

acceleration—A different approach

- ...or cross-over points ... three model ... with the lower ... ar for R_{MS}, which is ... 10^{-4}.
- ...overs occur ~5-8 ... er the first core-... e (~3Myr after ... ation formation)
- ...we see that the ... etween ... synthesis and ... ration is of order a ... lion years.



acceleration

evious work (Wiedenbeck et al. 1999) on ^{59}Ni, using cleosythesis yields of Woosley &Weaver (1995) dicated a lower limit on the time between cleosynthesis and acceleration of ~10^5 years.

ombining this with our present results on ^{60}Fe we obta e time between nucleosynthesis and acceleration of ^{5} yr < T < several Myr.

We note that Neronov & Meynet (A&A 2016) show that the lower imit of 10^5 years is no longer required, if you use the Chieffi & Limongi yields for ^{59}Ni & ^{59}Co.

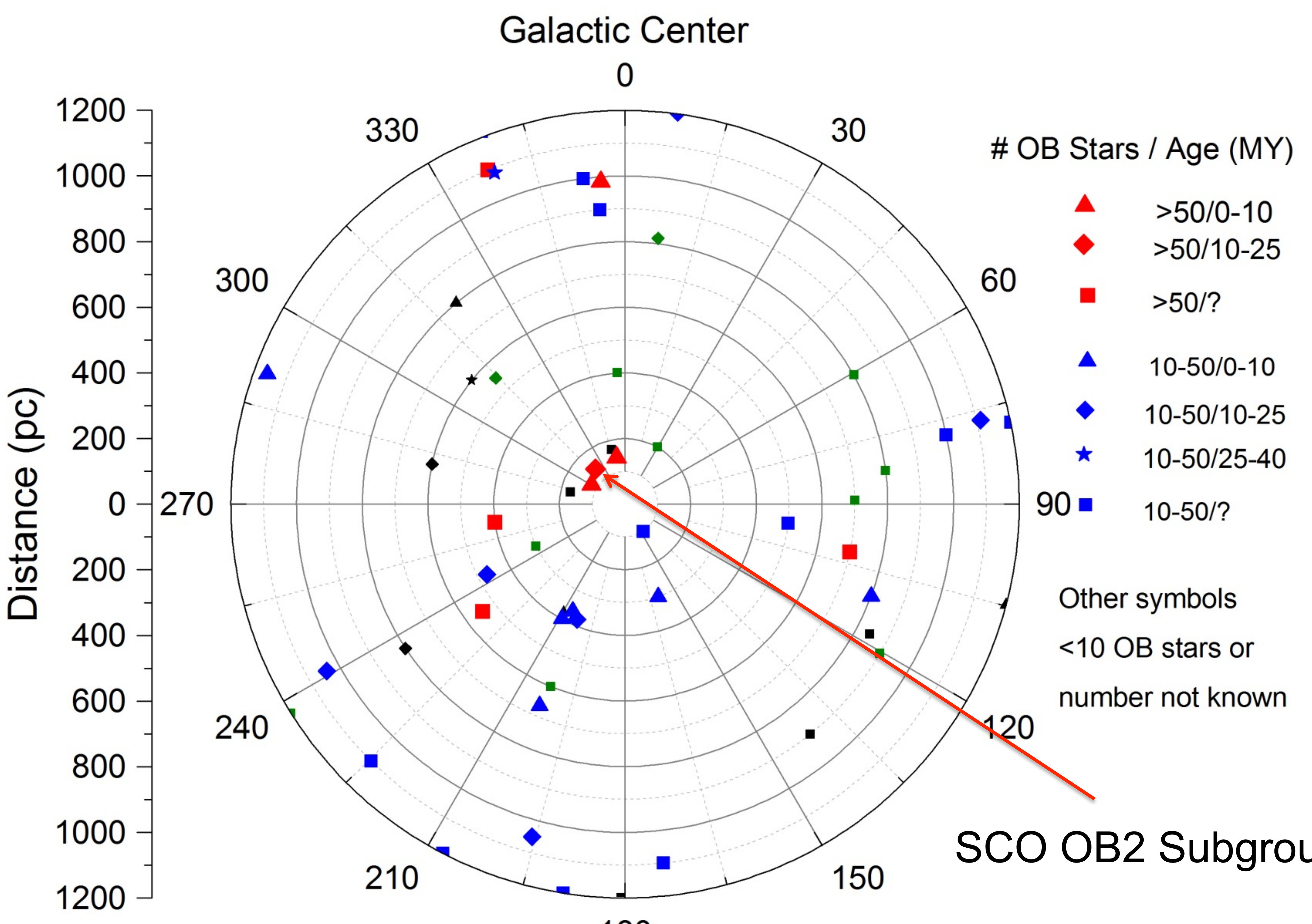
e can also estimate the mean distance to the sources ntributing to cosmic rays at Earth using a diffusive opagation model.

CRs originate in a volume surrounding the Sun with radiu $L=(D\gamma\tau)^{0.5}$,where D is the diffusion coeffiient

Assuming $D=3.5\times10^{28}$ cm^2/s, and γ's & τ's for ^{56}Fe and ^{6} we obtain

- L_{56} = 790 pc
- L_{60} = 620 pc

So the volume sampled by the ^{60}Fe is about half that sampled by the ^{56}Fe.


Galactic Center
0
30
60
90
120
150
210
240
270
300
330
Distance (pc)
1200
1000
800
600
400
200
0
OB Stars / Age (MY)
>50/0-10
>50/10-25
>50/?
10-50/0-10
10-50/10-25
10-50/25-40
10-50/?
Other symbols
<10 OB stars or
number not known
SCO OB2 Subgrou

st importantly, we can draw the *model independent* clusion that the detection of ^{60}Fe surviving in GCRs ies

me from nucleosynthesis including acceleration and trans Earth does not greatly exceed the ^{60}Fe half-life of 2.6 My

ur distance from the source of this nuclide does not great ceed the distance that GCRs can diffuse over this time s 1 kpc.

upper limit on the time between nucleosynthesis and celeration is several Myr

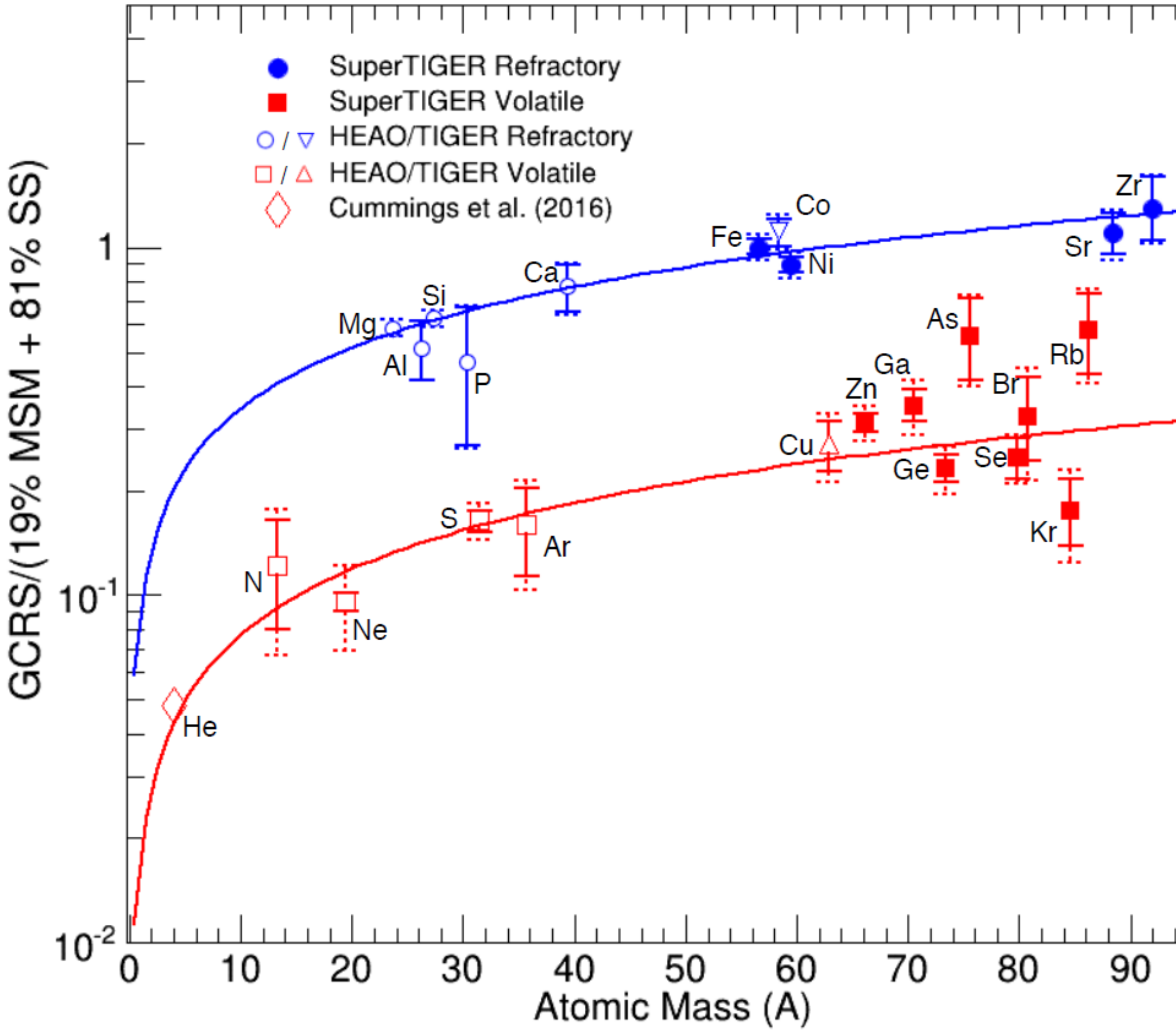
ource material has a newly synthesized component, i.e. is x of new and old ISM

atural place for the origin of the ^{60}Fe that we have

Backups

e that the
um data
nt is not
uded in the

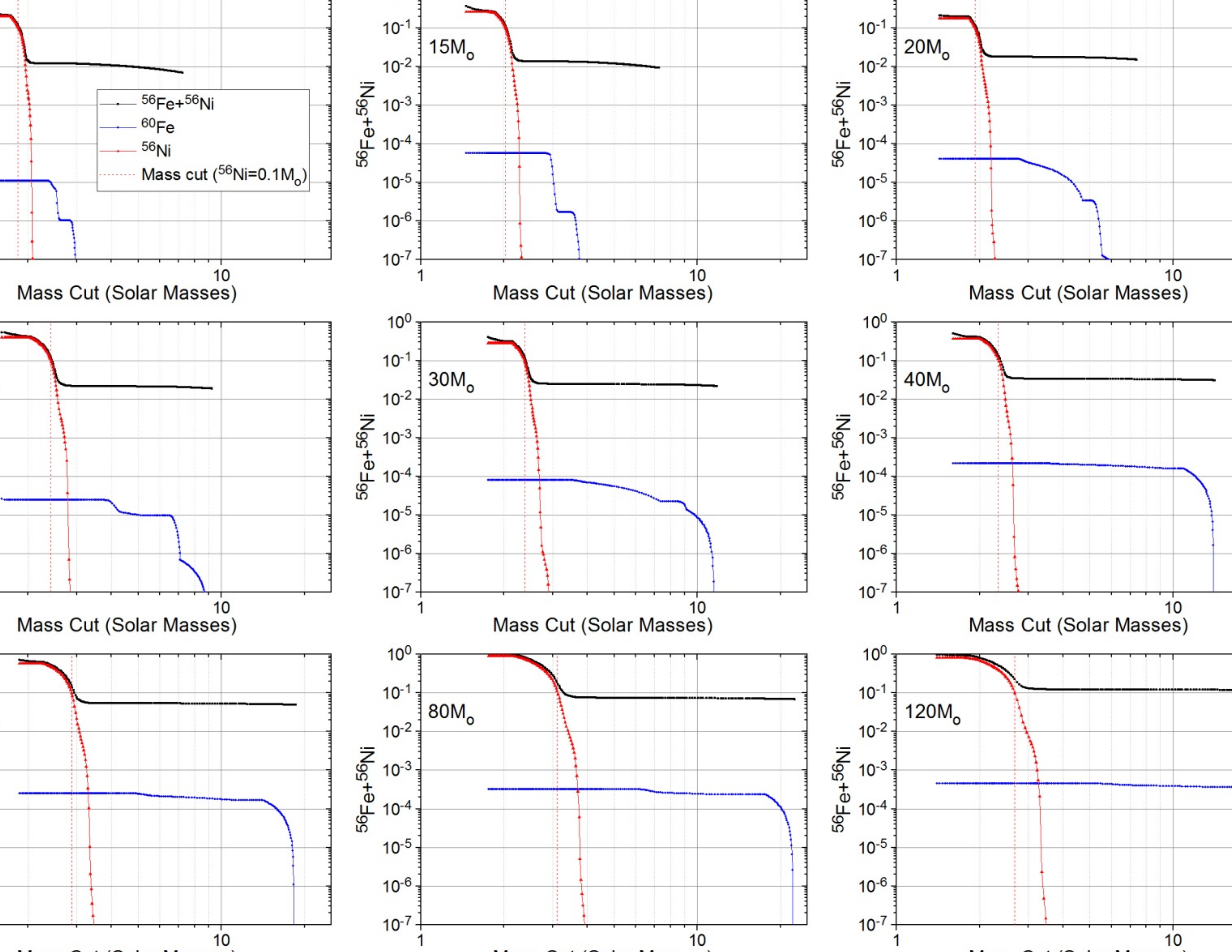
falls right on the
est fit line to the
eavier elements



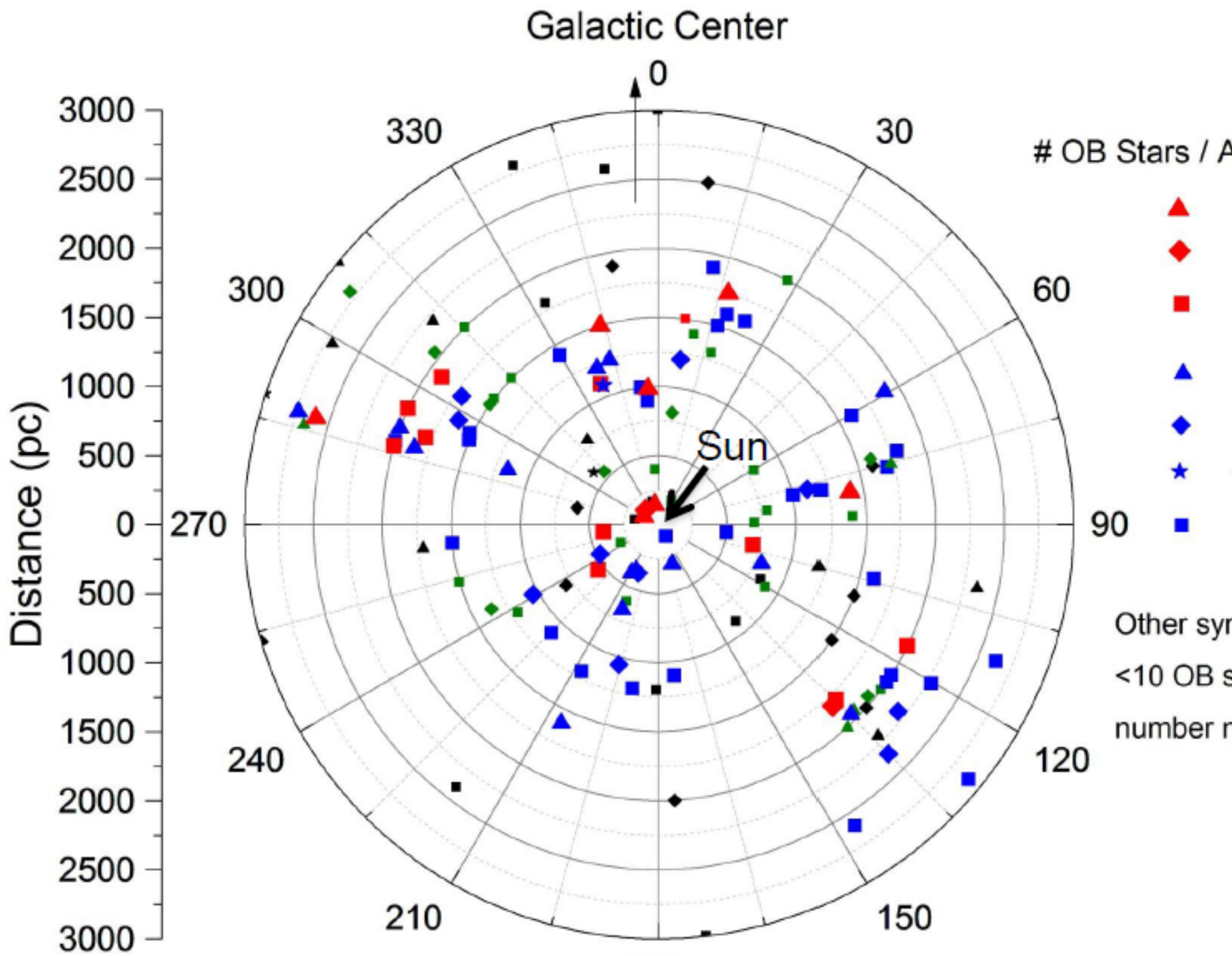
the ^{60}Fe events look different (peculiar?) in any way fr other Fe events?

- eak location is right
- stribution standard deviation (rms) (0.28±0.07amu) is consistent Fe (0.24 amu)
- stributed in time similarly to ^{56}Fe
- heta distributions look similar to nearby isotopes
- stributions in energy look similar to nearby isotopes
- stributions in position on detectors look similar to nearby isotope
- odoscope signals look reasonable compared to nearby isotopes
- estricting angle to <20 degrees reduces ^{60}Fe roughly proportiona

conclude that it is not an artifact, but is really ^{60}Fe.



$^{56}Fe+^{56}Ni$
^{60}Fe
^{56}Ni
Mass cut ($^{56}Ni=0.1M_o$)
15M$_o$
20M$_o$
30M$_o$
40M$_o$
80M$_o$
120M$_o$
$^{56}Fe+^{56}Ni$
Mass Cut (Solar Masses)


Galactic Center
0
330
30
300
60
270
90
240
120
210
150
Distance (pc)
3000
2500
2000
1500
1000
500
0
500
1000
1500
2000
2500
3000
Sun
OB Stars / A
Other sy
<10 OB s
number r