Origin(s) of Cosmic Rays

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Three-fold origin of cosmic rays

- Where does the energy come from to power the acceleration process?
- Where does the matter come from that gets accelerated?
- Where and how does the acceleration occur?

Three different questions which have sometimes been confused!

Following the energy

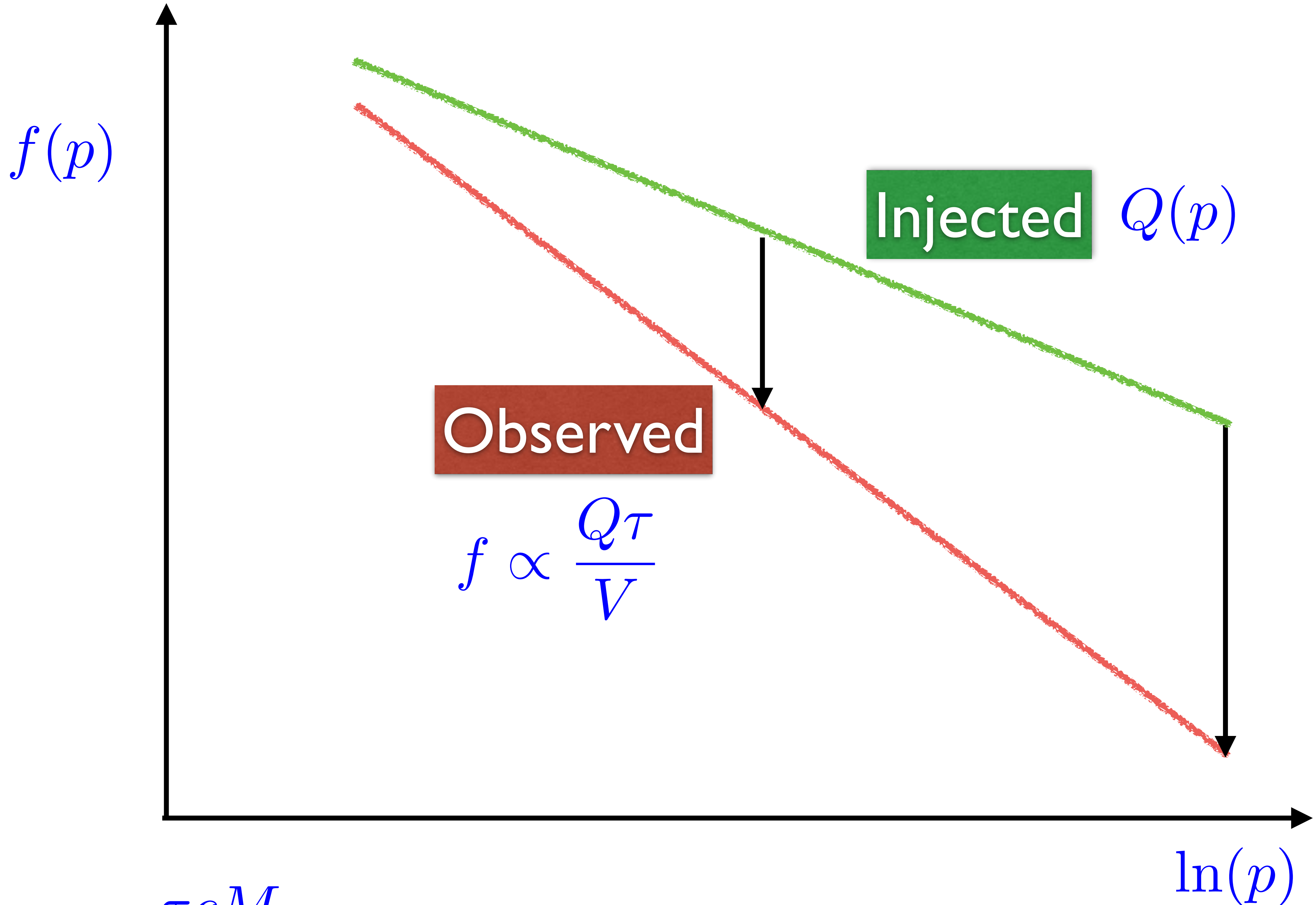
- How much power is required to maintain the observed GCR population? Conventional estimate is about 10^{41} erg/s or 10^{34} W.
  - Ginzburg and Syrovatskii (1964) $0.3 \times 10^{34}\,\mathrm{W}$
  - Galprop (Strong et al, 2010) $(0.7 \pm 0.1) \times 10^{34}\,\mathrm{W}$
  - Drury, Markiewicz and Völk (1989) $< 3 \times 10^{34}\,\mathrm{W}$

Propagation model dependence

- Energy density and escape time for mildly relativistic CRs is well constrained.
- Two problems:
  - How hard is the true injection spectrum at high energies? High estimate of DMV results from assuming hard injection spectrum $\propto E^{-2}$
  - How much energy is contributed by second order Fermi at low energies if using re-acceleration model for propagation?

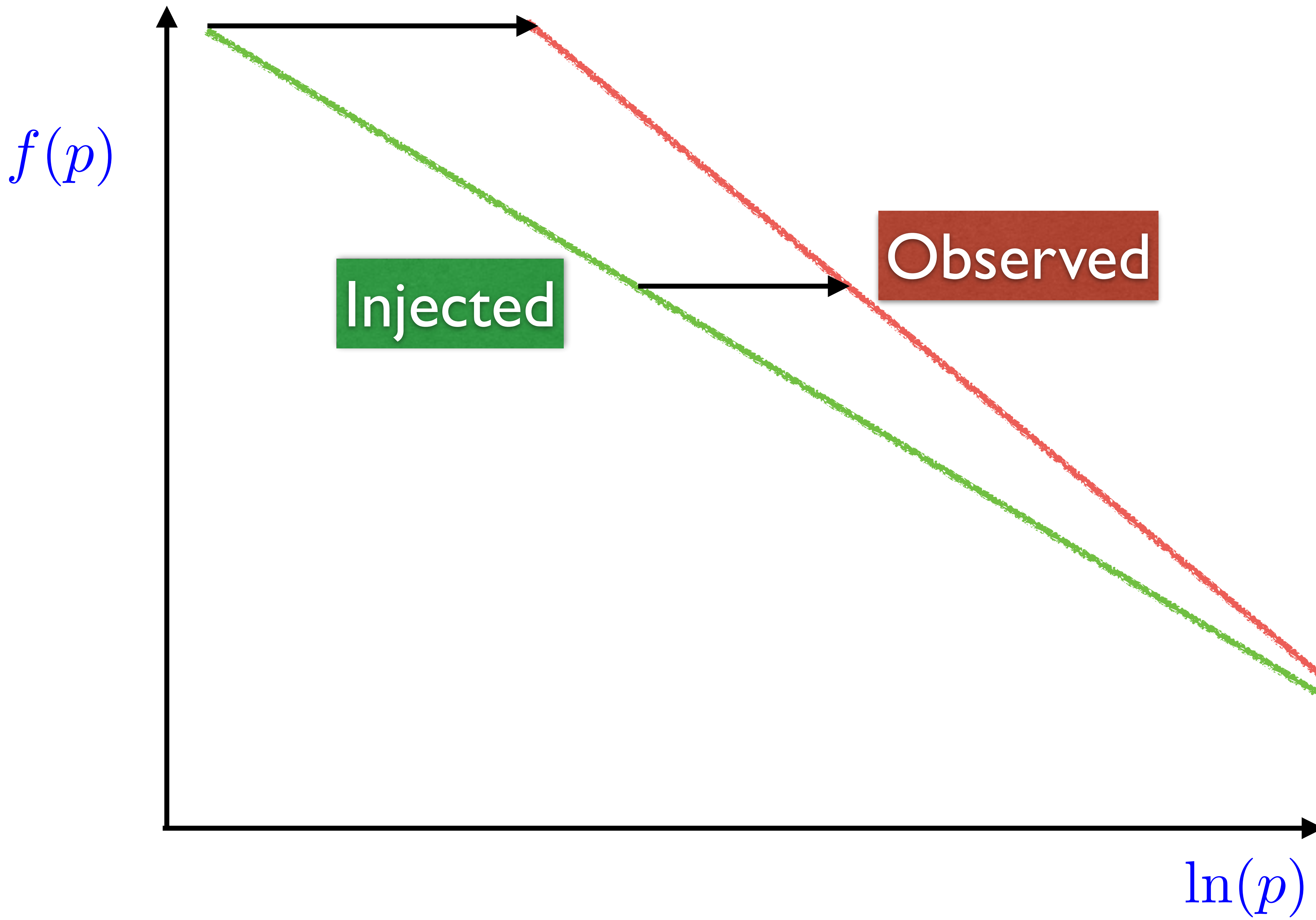
- Spallation secondary to primary ratios clearly show steepening of production spectra in GeV region by about 0.6 in exponent of energy spectrum.
- Can be achieved either by
  - energy dependent escape
  - energy dependent confinement volume
- or by boosting of low energy particles by re-acceleration
- or by a combination of all three processes!

Either



$\frac{\tau c M_{\rm ISM}}{V}$ = "grammage" and is fixed at a few GeV by observations

Or



Energetics of re-acceleration

- Basically just second-order Fermi on ISM turbulence - must occur at some level.
- Hard to estimate because of lack of knowledge of GCR spectra at low energies as well as relevant ISM turbulence.
- Could be very significant though, especially at low energies! Should be calculated in e.g. Galprop.

Thornbury and Drury (2014) show

$$P_R = \int_0^\infty 4\pi p^2 f \, \frac{1}{p^2} \frac{\partial}{\partial p} \left(\frac{p^4 V_A^2 v}{9 D_{xx}} \right) \, dp$$
$$= \int_0^\infty 4\pi p^2 f \left(\frac{V_A^2 p v}{9 D_{xx}} \right) \left[4 + \frac{\partial \ln(v/D_{xx})}{\partial \ln p} \right] \, dp.$$

or writing $\quad D_{xx} = v^2 \tau / 3$

$$P_R = \int_0^\infty 4\pi p^2 f \left(\frac{V_A^2 p v}{3 v^2 \tau} \right) \left[4 + \frac{\partial \ln(v/D_{xx})}{\partial \ln p} \right] \, dp$$

Can be interpreted as mean momentum gain per scattering

$$\frac{\Delta p}{p} = \frac{4}{3}\frac{V_A^2}{v^2}\left[1 + \frac{1}{4}\frac{\partial \ln(v/D_{xx})}{\partial \ln p}\right].$$

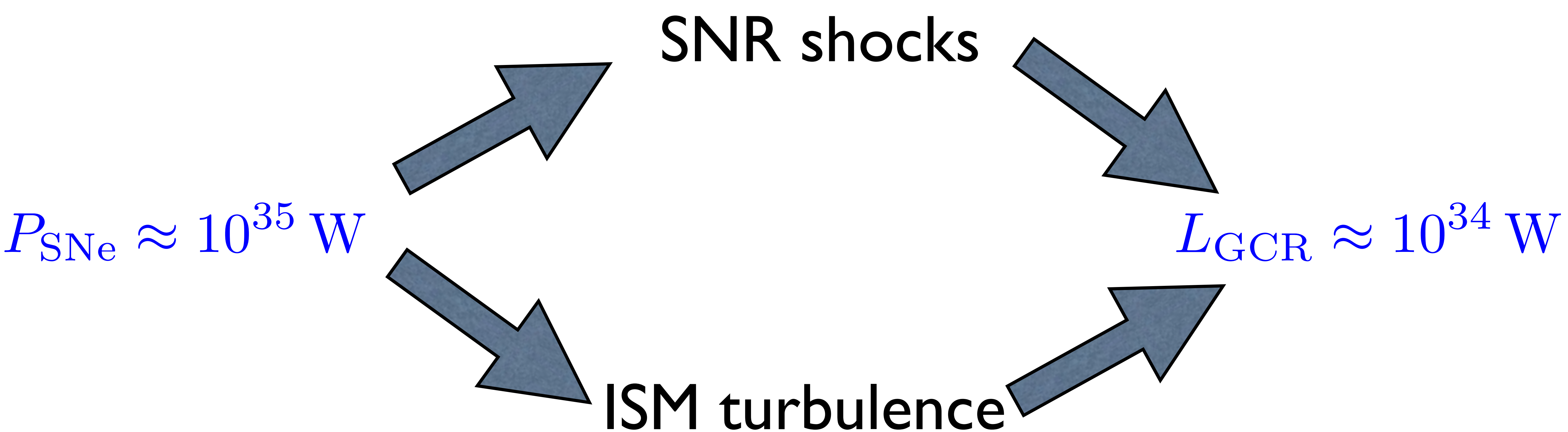
Note importance for mildy sub-relativistic particles! Like ionisation losses, scales as

$$v^{-2}$$

Summary of energetics

- Can safely assume $0.3 \times 10^{34}\,\mathrm{W} < L_{\mathrm{GCR}} < 3 \times 10^{34}\,\mathrm{W}$
- As is well known $P_{\mathrm{SNe}} \approx 10^{35}\,\mathrm{W}$
- No other plausible source of enough energy although pulsar winds and OB winds may contribute at 10% level.
- Solar wind definitely accelerates GCR by pushing them out of the heliosphere, but total power in solar wind is only $3 \times 10^{20}\,\mathrm{W}$ so even for all M stars in Galaxy only get $3 \times 10^{31}\,\mathrm{W}$

- So only plausible source of bulk of energy is SNe
- Adiabatic losses imply not in explosion itself
- So mediated through shocks and/or turbulence driven by SNRs.



Other contributions not ruled out and indeed in some cases quite plausible!

- Pulsars - especially for electrons and positrons!
- OB associations, stellar winds.
- Galactic centre?? Needs variability?
- Differential rotation of Galaxy and magnetic instabilities?

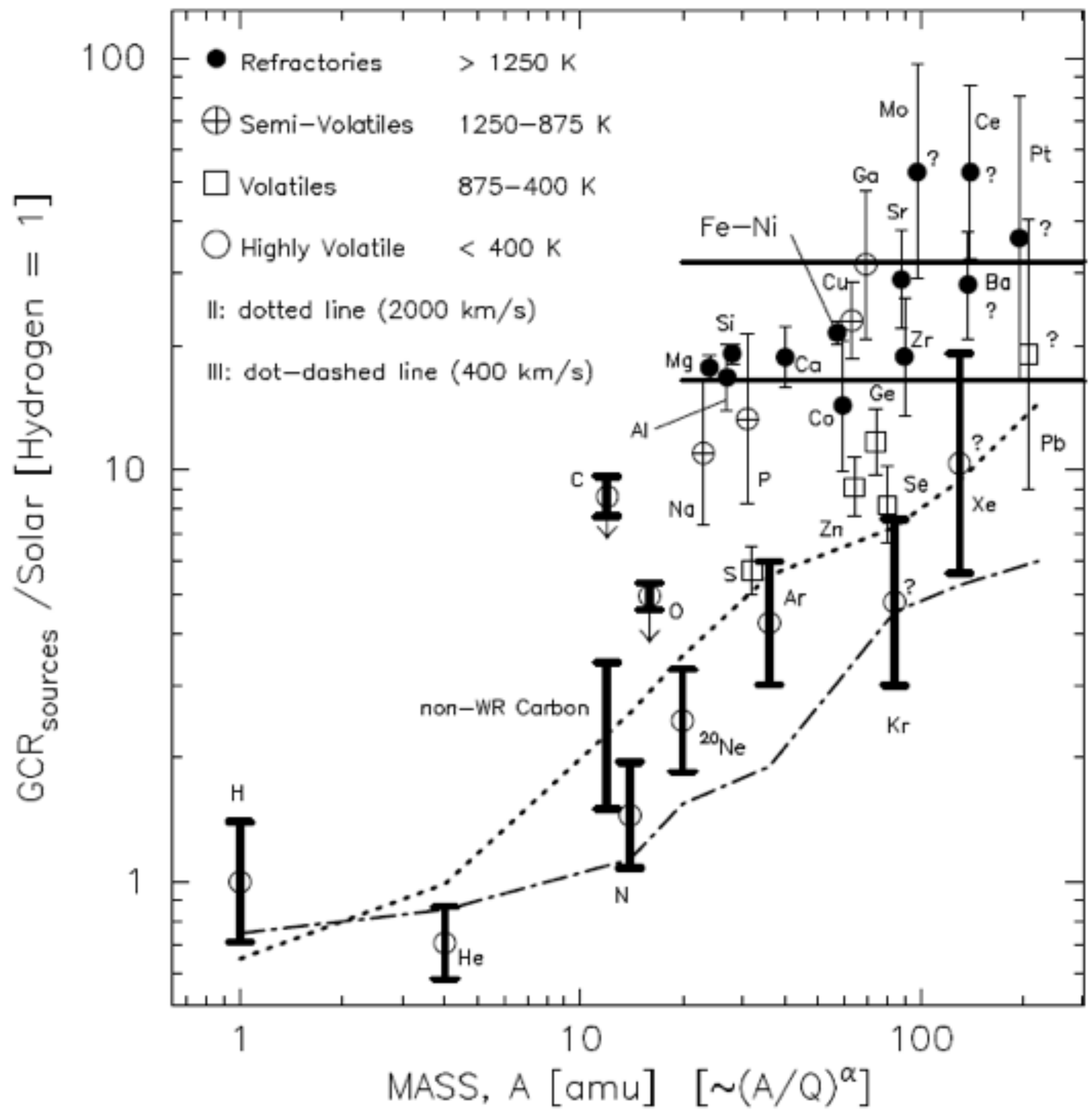
Following the matter

- Use chemical and isotopic composition to try and identify the source(s) of the accelerated material.
  - General chemical abundances.
  - Ultra-heavy r-process nuclei.
  - Ne22 isotopic anomaly.
- Important constraint on models of origin (not ground up Iron, or pure protons for example!).

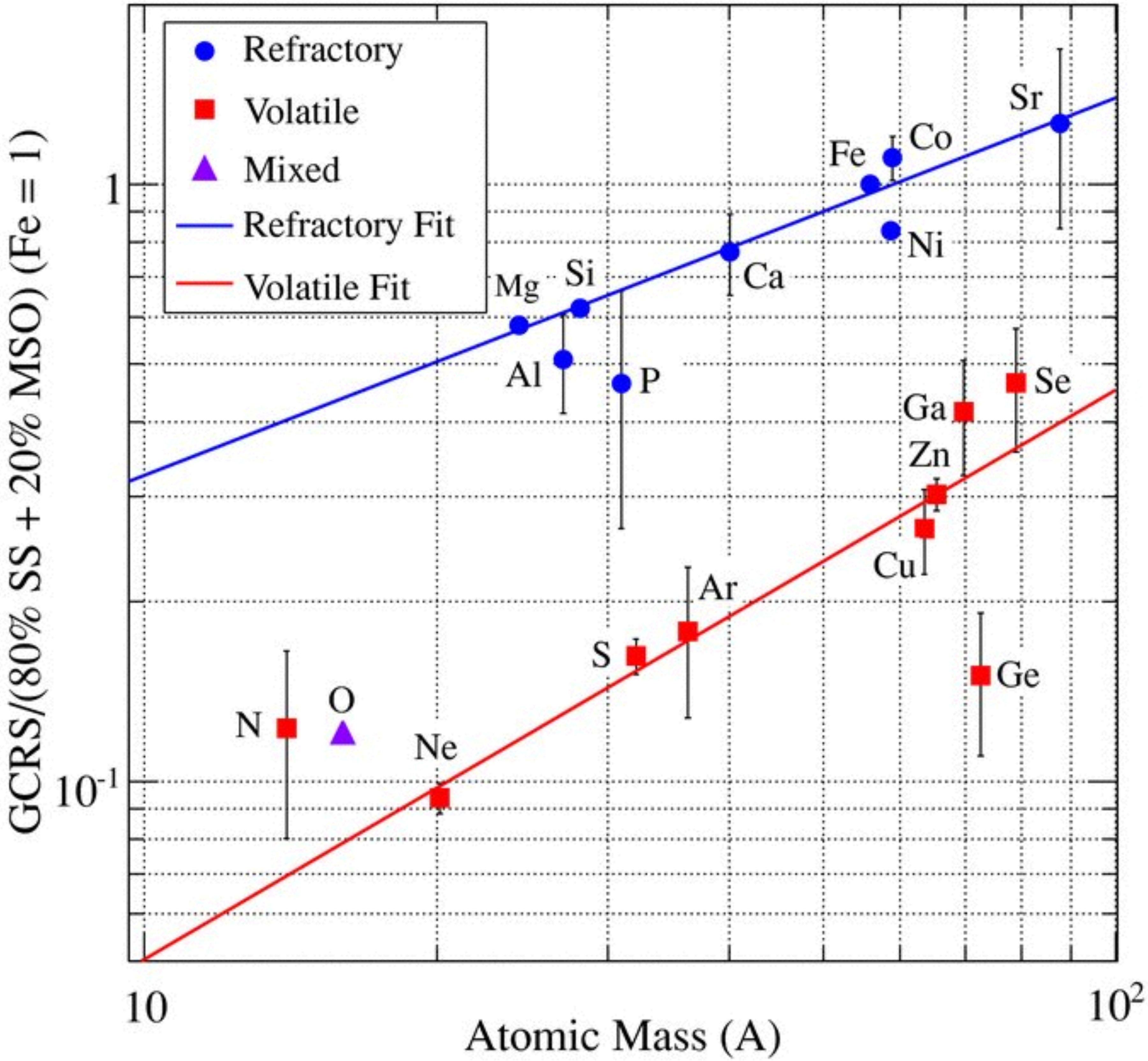
Chemical abundances in the GCRs

- Need to correct for spallation effects during propagation.
- To first order all charge-resolved and de-propagated spectra appear identical as functions of rigidity (may be some slight deviations from this?).
- Composition shows the normal pattern of nucleosynthesis - Fe and CNO peaks, all elements (including actinides) confirmed.
- Definite over-abundance of heavy elements relative to H and He.

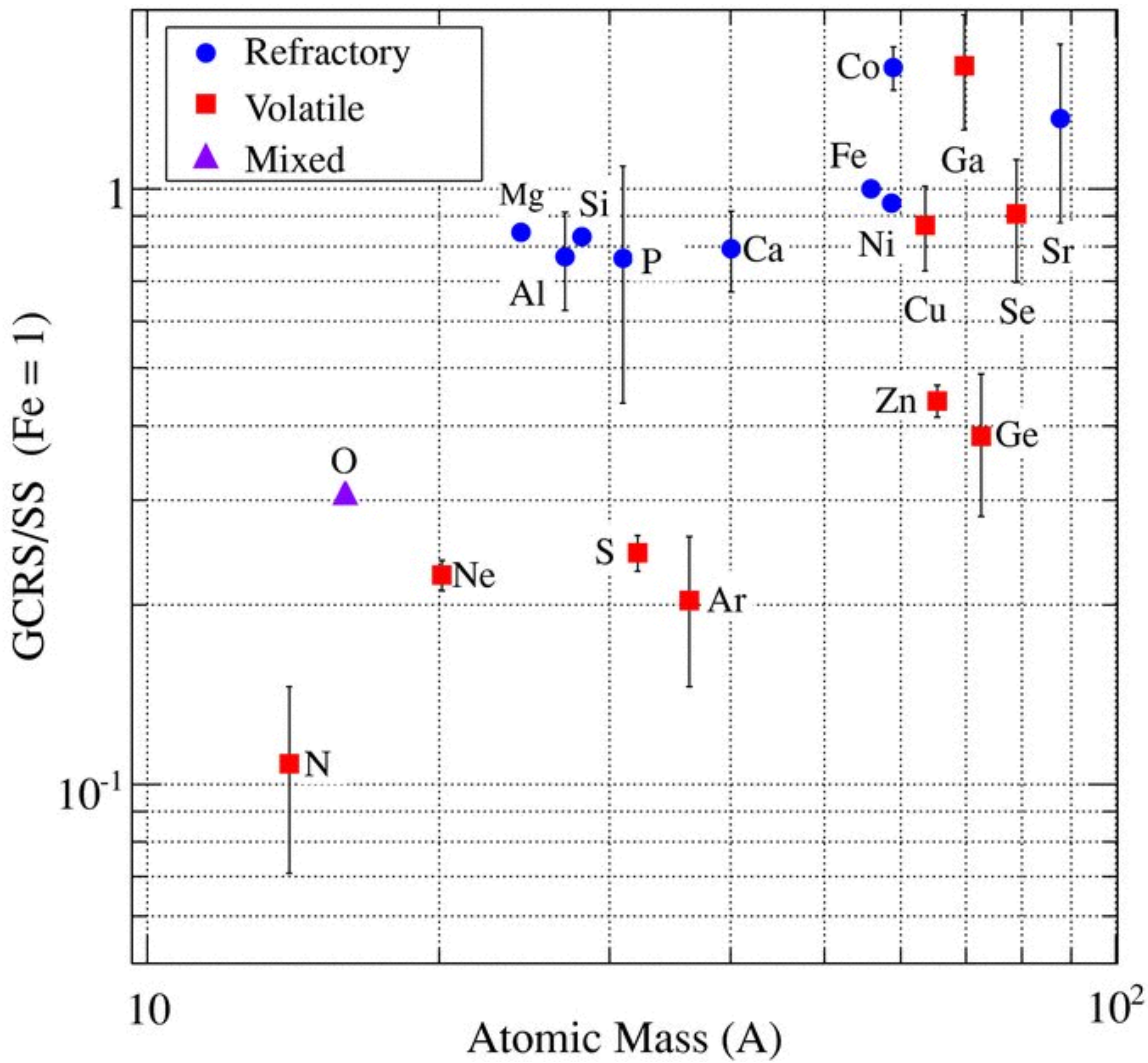
- Chemical abundances can not be fit with a one-parameter model. Need at least two parameters one of which is correlated with chemistry or outer electronic structure of un-stripped atom.
- Telling us something about injection process at low energies - must favour heavy species and refractory elements.
- FIP, volatility, dust chemistry etc…..



From Ellison, Drury and Meyer (1997) ApJ 487 197



Rauch et al, 2009 ApJ 697, 2083 COSMIC RAY ORIGIN IN OB ASSOCIATIONS AND PREFERENTIAL ACCELERATION OF REFRACTORY ELEMENTS: EVIDENCE FROM ABUNDANCES OF ELEMENTS 26Fe THROUGH 34Se

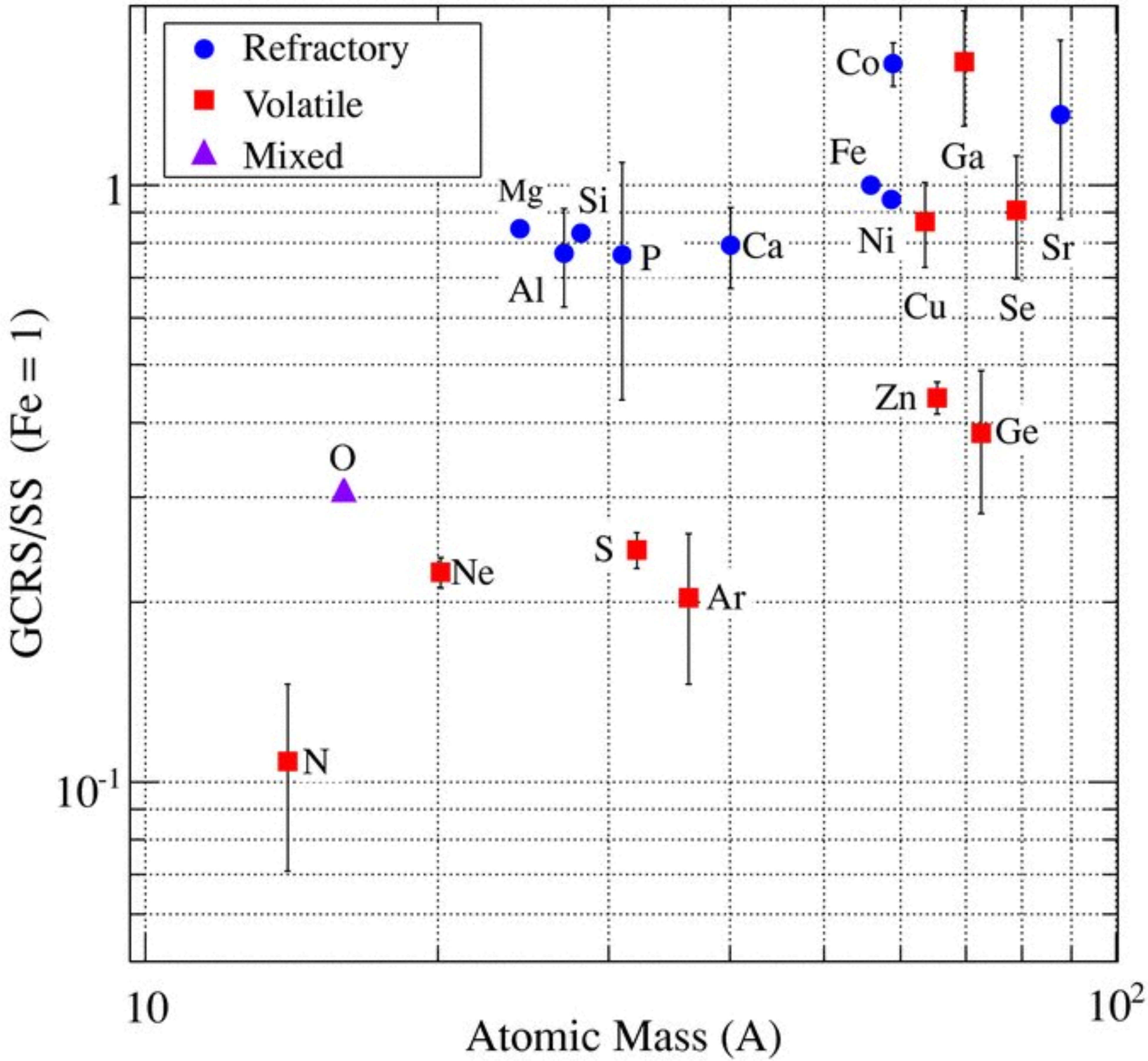


Refractory
Volatile
Mixed
GCRS/SS (Fe = 1)
Atomic Mass (A)
1
10^{-1}
10
10^2
Co
Ga
Fe
Mg
Si
P
Ca
Al
Ni
Cu
Se
Sr
Zn
Ge
O
Ne
S
Ar
N

Injection must be highly selective!

- Simple energy argument.
  - Even for a strong SNR shock going at 1% of the speed of light, the KE per proton is only 10^{-4} of the rest mass energy.
  - Thus can only accelerate one proton in ten thousand to relativistic energies!
- A fortiori for ISM turbulence.

- So given that injection must be highly selective, sensitivity to mass, charge and even chemistry is not too surprising.
- In shock acceleration theory actually expect high rigidity species to be preferentially injected.
- Plausible (?) model for preferential injection of particles sputtered from dust grains presented by Ellison, Drury and Meyer.
- Strongest evidence is perhaps oxygen abundance.



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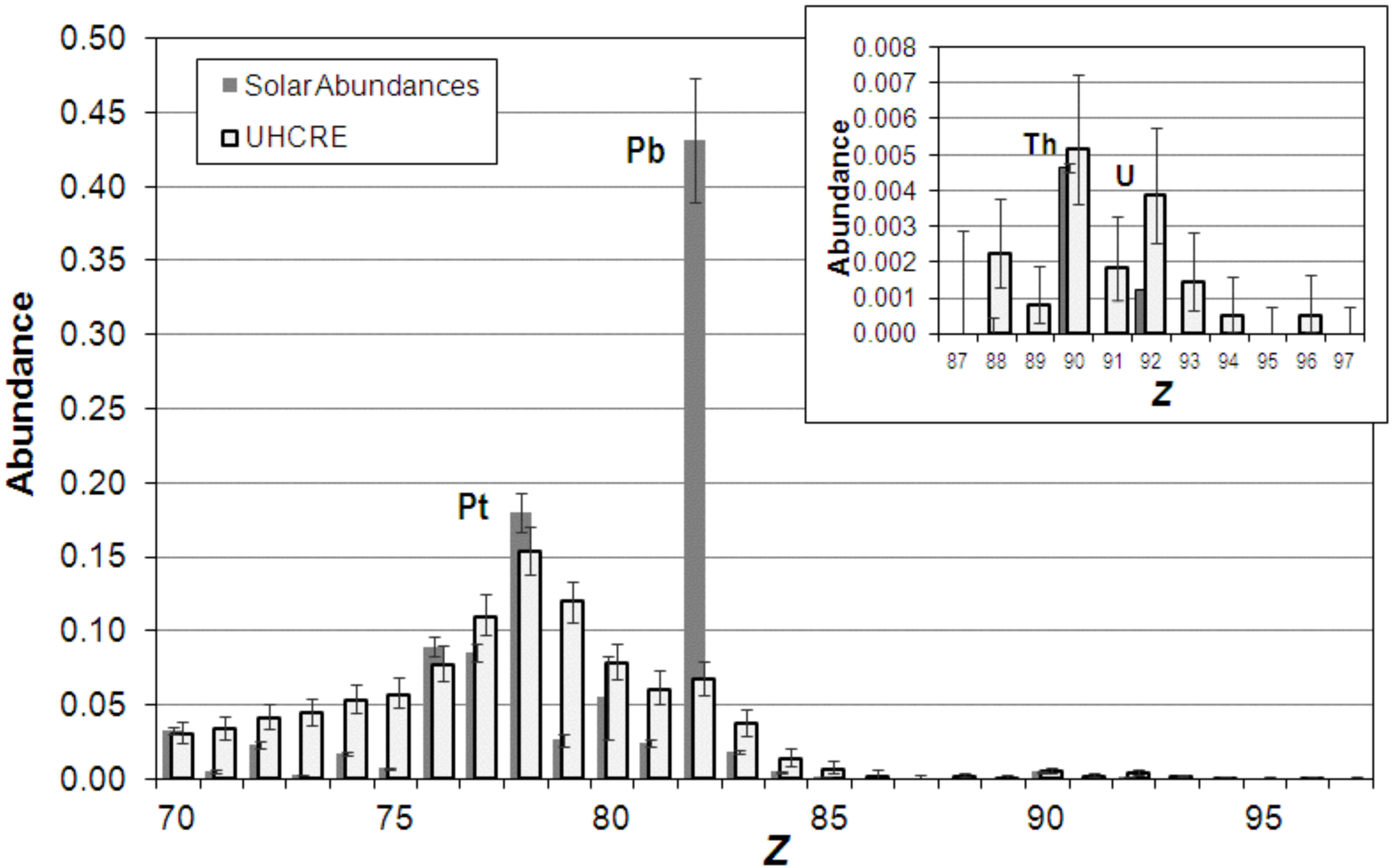
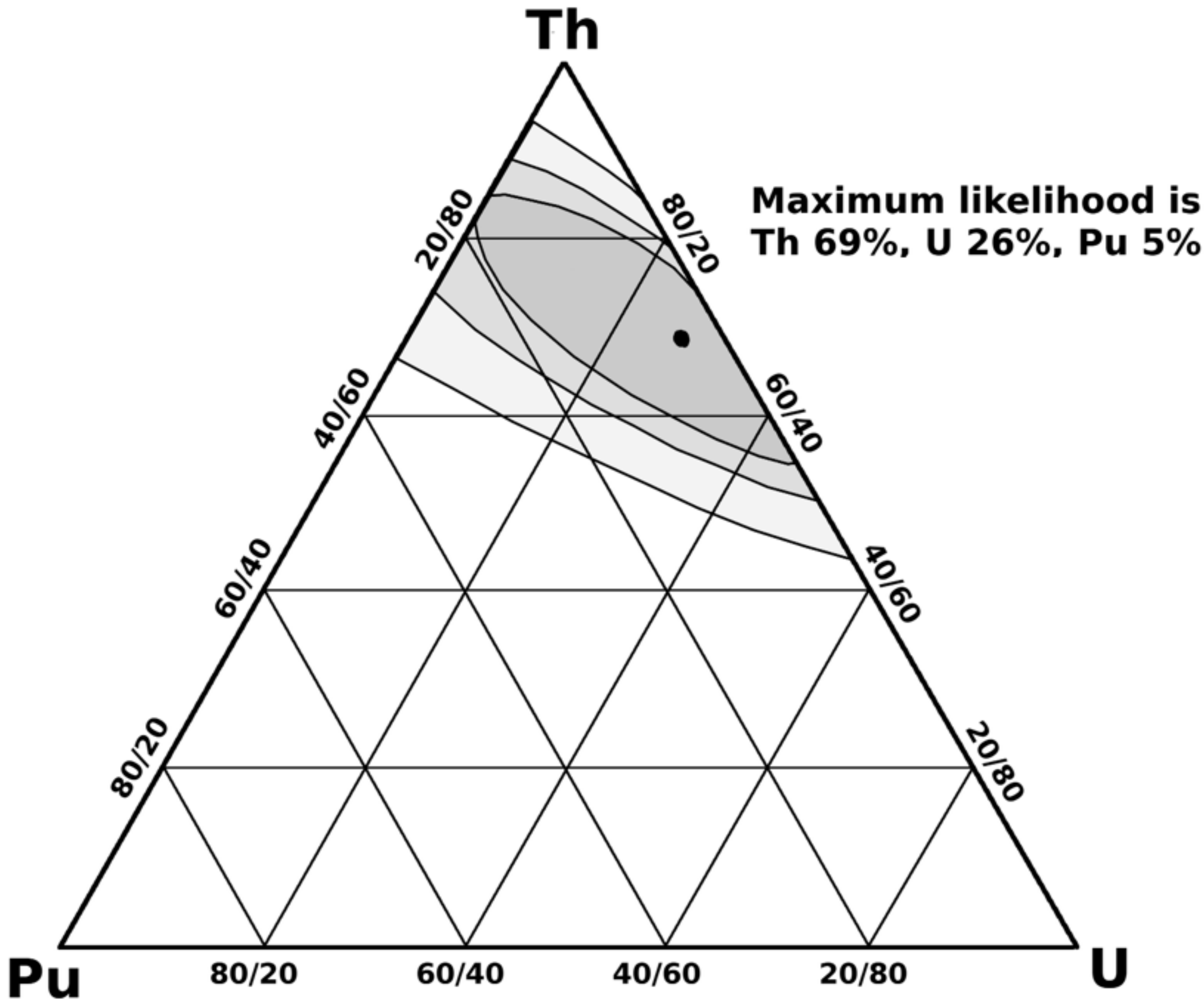
Ga
Ge
Se
Sr

Ultra-heavies and r-process enhancements.

- Confused picture.
- Lead is clearly under-abundant relative to Pt (volatility or nucleosynthesis?).
- Definite evidence of actinides, but no obvious over-abundance.
- Best data come from UCHRE on LDEF (Donnelly et al, 2012, Ap.J. 747:40) which had an exposure of 170 m^2 sr yr, but poor charge resolution.
- Saw 35 good actinide events including one possible trans-uranic Curium nucleus.



Solar Abundances
UHCRE
Pb
Pt
Abundance
Z
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
70
75
80
85
90
95
Th
U
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
87
88
89
90
91
92
93
94
95
96
97


Th
Pu
U
Maximum likelihood is
Th 69%, U 26%, Pu 5%
20/80
40/60
60/40
80/20
80/20
60/40
40/60
20/80
80/20
60/40
40/60
20/80

Summary of composition

- Source is a well-mixed sample of relatively “normal” matter - contributions from all types of SNe and major nucleosynthetic routes required in similar proportions to general Galactic ISM.
- Hints for a “dusty” source with preferential injection of elements expected in grains.
- Hints that source contains a mixture of old and relatively new material.
- Ne22 hints at contamination of source by WR winds.

Where and how?

- Probably powered by SNe explosions.
- Accelerates well-mixed Galactic material with mild contamination from recent nucleosynthesis and WR winds, but also lots of old matter.
- Strongly suggests SNRs, either isolated or in super bubbles, as the acceleration site.
- DSA as plausible primary process with possibility of some second order Fermi at low energies.

Diffusive Shock Acceleration

- First peer-reviewed publication by G. F. Krymsky in 1977, Akad. Nauk. SSSR Doklady, 234, 1306.
- Axford et al 1977, ICRC "paper" in Plovdiv proceedings.
- A. Bell 1978, MNRAS 182, 147 (derived from PhD thesis, so work probably done 1976/77).
- R. Blandford and J. Ostriker, 1978, ApJ 221, L29.

- Variant of Fermi acceleration operating at strong collision-less plasma shocks. Has many advantages for being a theory of CR origin.
  - No need for separate injection process.
  - Naturally produces power-law spectra with exponents close to what we need.
  - High efficiency appears quite natural.
  - Relies only on rather simple basic physics.

But not without problems:

- Maximum energy is far too low unless diffusion is driven to Bohm limit - and even then hard to get to the “knee” in SNRs (Ginzburg, Lagage and Cesarsky, Hillas).
- Accelerated particles are left behind the shock (ie inside a SNR) - need a theory of escape also.
- Nonlinear reaction effects complicate picture.

Possible partial solution

- Magnetic field amplification ahead of the shock by reaction of accelerated particles (Bell et al).
  - Can increase maximum energy (scales as $BR\dot{R}$)
  - Leads to enhanced escape at high energies if B becomes a decreasing function of time.
- Note that "source" for Galprop and friends is basically time integrated escape over life of remnant - not instantaneous post-shock spectrum.

- NB field must be amplified:
    - Ahead of the shock, ie upstream. No use just amplifying the post-shock field (which is easy). Have to use CRs themselves.
    - On sufficiently large scales to interact with highest energy particles - problem for Bell's current driven process which works on scales much smaller than gyro-radius of driving particles (cf Beresnyak and Li, 2014 ApJ 788:107)
- Leads me to favour bulk CR pressure driven modes (as in Drury and Falle) as primary mechanism for field amplification (Downes and Drury, 2012, 2014)

- Not just enough to find a shock with a sufficiently amplified magnetic field, there must also be enough power in the shock to produce, assuming some reasonable efficiency, the particle luminosity required.

- This may in fact be the explanation for the turn-down at the "knee" - the very fast shocks capable of accelerating to beyond the "knee" may not have enough total power. Maximum power is only reached at "sweep-up" when the shock has interacted with an ambient mass roughly equal to the ejecta mass.

Possible consequences

- Pevatron phase could be very short early phase in life of a SNR.
- SNRs entering the Sedov phase would then be surrounded by a halo of escaping high-energy particles.
- Low energy (GeV) CRs on the other hand remain trapped inside the SNR until the end of its evolution.
- Compositional variation with energy?

Some historical notes

Long history of suspected SNR/CR links

- Baade and Zwicky 1934 - remarkably prescient!
- Ginzburg and Syrovatskii 1963 - radio synchrotron emission and energy budget arguments.
  - Definitely GeV electrons in SNRs
  - GCR nuclear luminosity of Galaxy could be supplied by few % of SNe mechanical power.
- DAV 1994 - possible test with gamma-rays from shell-type SNRs

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington, and California Institute of Technology, Pasadena

Communicated March 19, 1934

D. Conclusions.—From the data available on super-novae we conclude

(1) Mass may be *annihilated* in bulk. By this we mean that an assembly of atoms whose total mass is M may lose in the form of electromagnetic radiation and kinetic energy an amount of energy E_T which probably cannot be accounted for by the liberation of known nuclear packing fractions. Several interpretations of this result are possible and will be published in another place.

(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

Our two conclusions are essentially independent of each other and should perhaps be judged separately, each on its respective merits.

Astron. Astrophys. 287, 959–971 (1994)

ASTRONOMY
AND
ASTROPHYSICS

The gamma-ray visibility of supernova remnants. A test of cosmic ray origin

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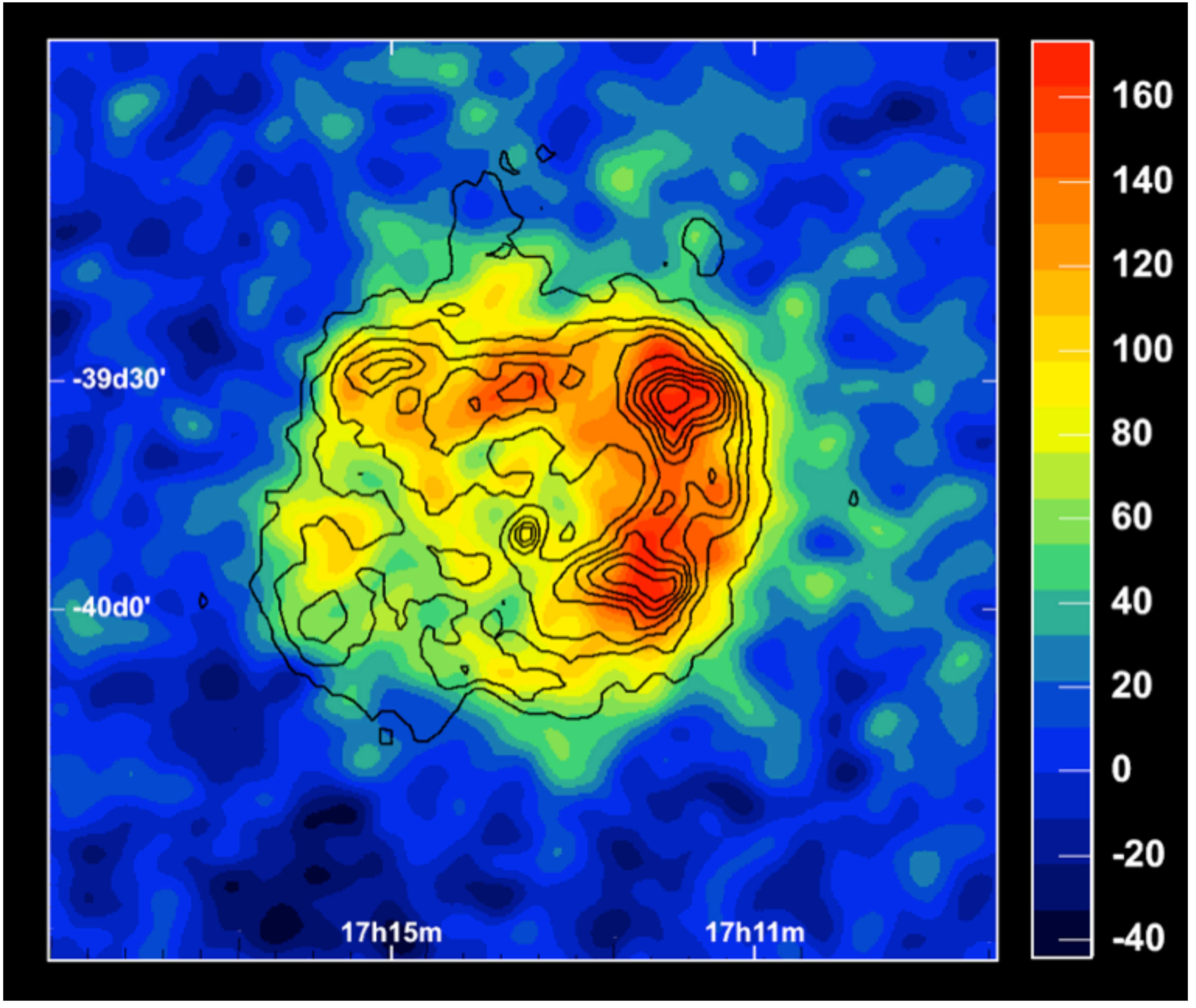
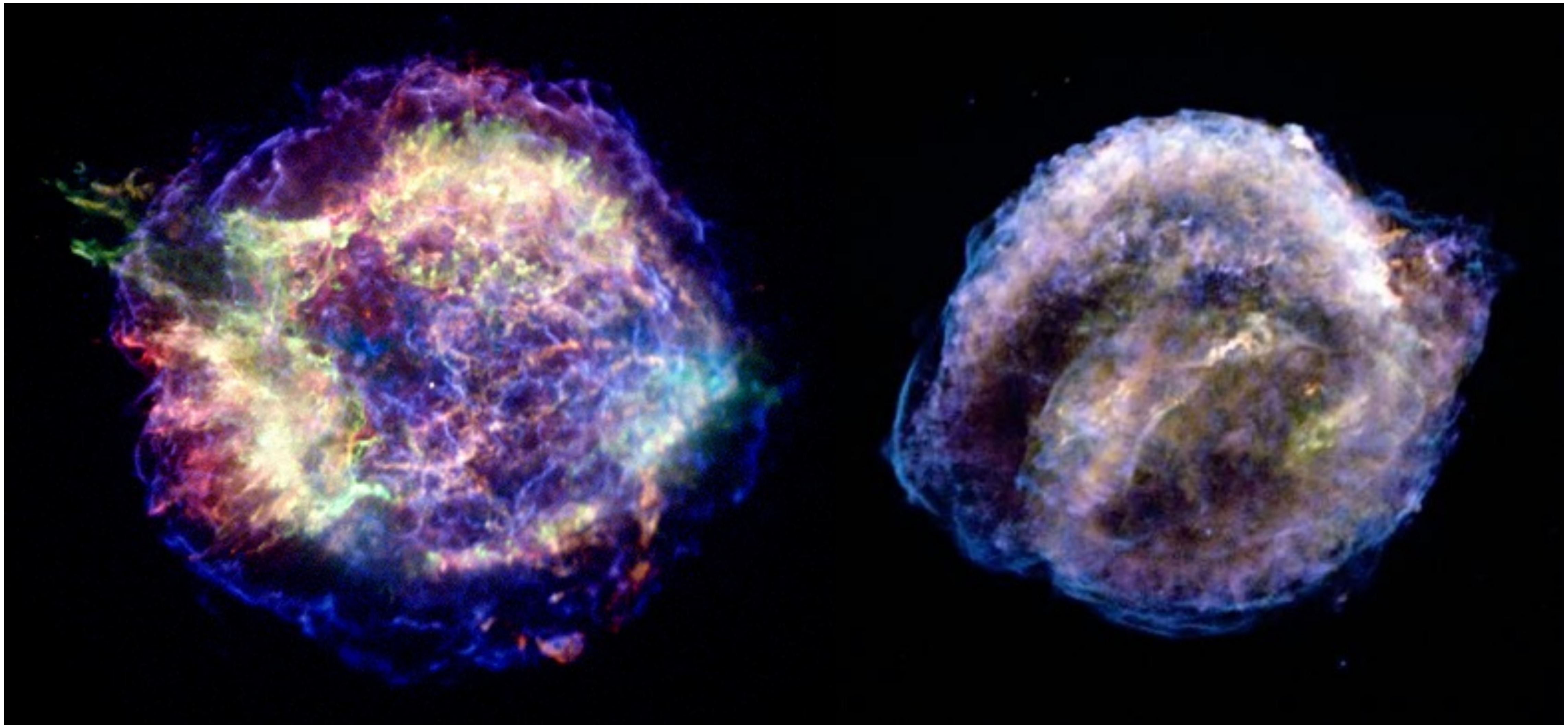
A detailed discussion of instrumental sensitivities and backgrounds shows that detection of SNRs in the $E_\gamma > 100\,\mathrm{MeV}$ band with, for example, the Energetic Gamma Ray Experiment Telescope (EGRET) will be difficult, but should not be impossible. However, and significantly, the prospects look much better in the TeV band accessible to modern imaging atmospheric Cherenkov telescopes. It should be possible to detect SNRs out to distances of several kpc if the region of the ISM into which they are expanding has a high enough density ($n > 0.1\,\mathrm{cm}^{-3}$) so that their γ-ray luminosity is high enough.

Ten years later!





Sharp non-thermal X-ray rims around young SNRs point to TeV electrons and high magnetic fields! Also rapid time variability [Uchiyama et al, Nature (2007) 449 576]

Image mosaic courtesy of Jacco Vink

Recent developments

- Definite proof of acceleration of GeV nuclei in some SNRs through detection of the pion production threshold by both Agile and Fermi (Giuliani, A et al, 2011, ApJ 742 30; M. Ackermann *et al.* 2013 *Science* **339** 807.)
- Fairly convincing arguments that in remnants such as Tycho there is a significant hadronic signal at TeV energies though multi-wavelength models (e.g. Slane et al 2014, ApJ **783** 33.)
- Plausible detection of clouds illuminated by nearby SNRs (W28, IC443 etc).

But challenges remain…

- Where are the Pevatrons? All observed TeV emission from SNRs implies proton spectra turning down well before the knee region.
- What is the true production spectrum - tension remains between acceleration theory (favours hard spectra) and propagation theory (softer spectra).
- Why is the knee where it is and how do we get from the knee to the ankle?
- Direct detection of CR precursors in SNR shocks?