CRBTSM - the 2nd iteration

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“The Standard Model”

- Galactic CRs are made in SNRs by the DSA mechanism + Bell field amplification.
- Propagation is through diffusion and is well described by the GALPROP code or similar.
- The UHECRs are extra-galactic and come from GRBs or AGNs.

All questionable and far from certain!
Will focus on first two points.

But even within the "standard model" many open questions.

- All SNRs or only some? Reverse shock contributions? Escape from the SNR? Is field amplification dominated by Bell mechanism?
- Is Galactic transport purely diffusive? Role of winds and advection? How realistic is GALPROP ? Stochasticity and local bubble effects?
- Where is the Galactic to extra-galactic transition in the energy spectrum? Heavy or light composition? Photo-dissociation or GZK? TA hot spot?

Motivation for this meeting

- Builds on success of first meeting held in 2014
- Plenty of time for discussion and argument!
- Hopefully find inspiration, as Fermi did, in the majesty of the Dolomites.
- Approach the many questions around the origin(s) of cosmic rays with open but sceptical minds.

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

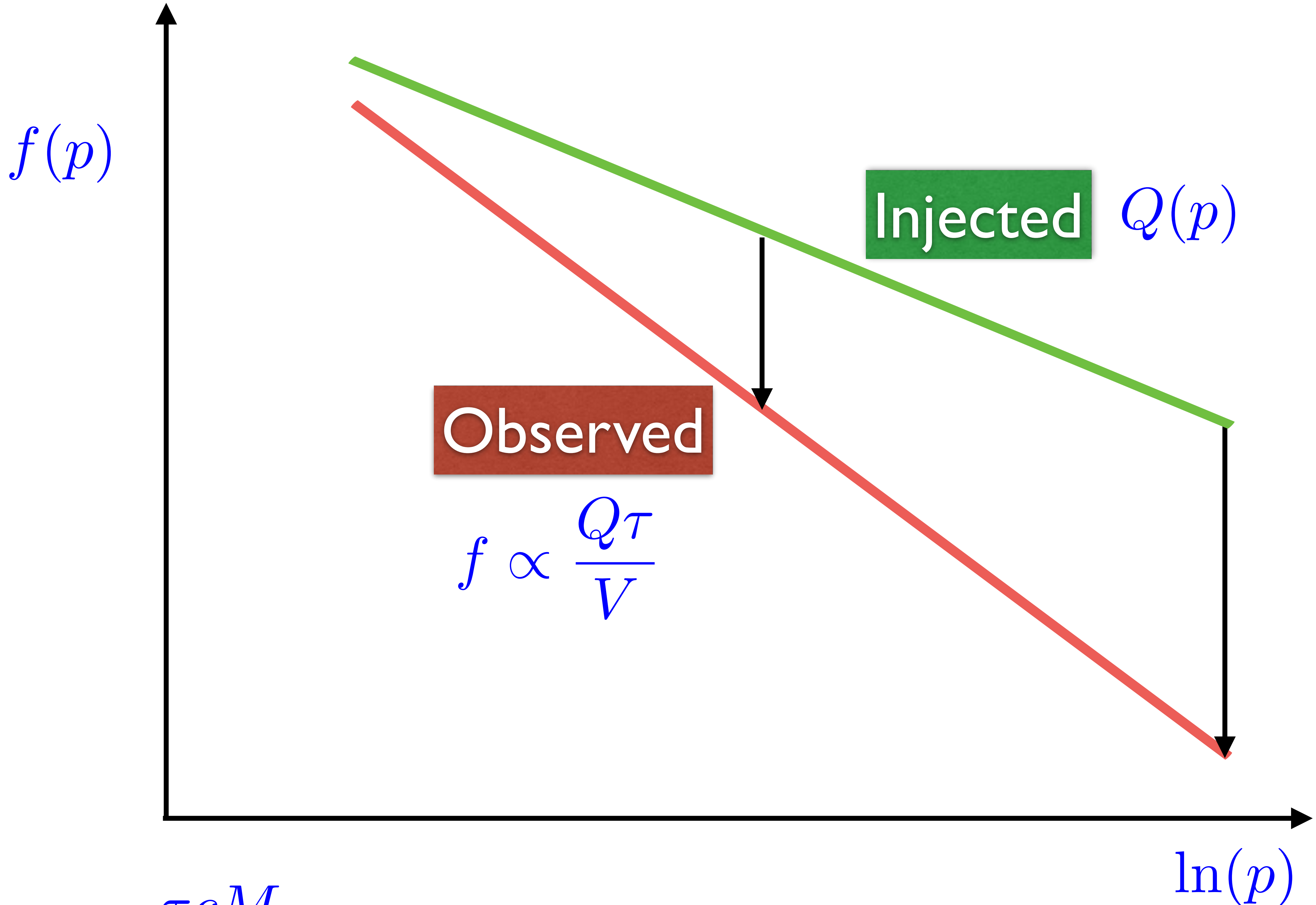
- How much power is required to maintain the observed GCR population? Conventional estimate is about 10^{41} erg/s or 10^{34} W.
  - Ginzburg and Syrovatskii (1964) 0.3×10^{34} W
  - Galprop (Strong et al, 2010) $(0.7 \pm 0.1) \times 10^{34}$ W
  - Drury, Markiewicz and Völk (1989) $< 3 \times 10^{34}$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

Propagation model dependence

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

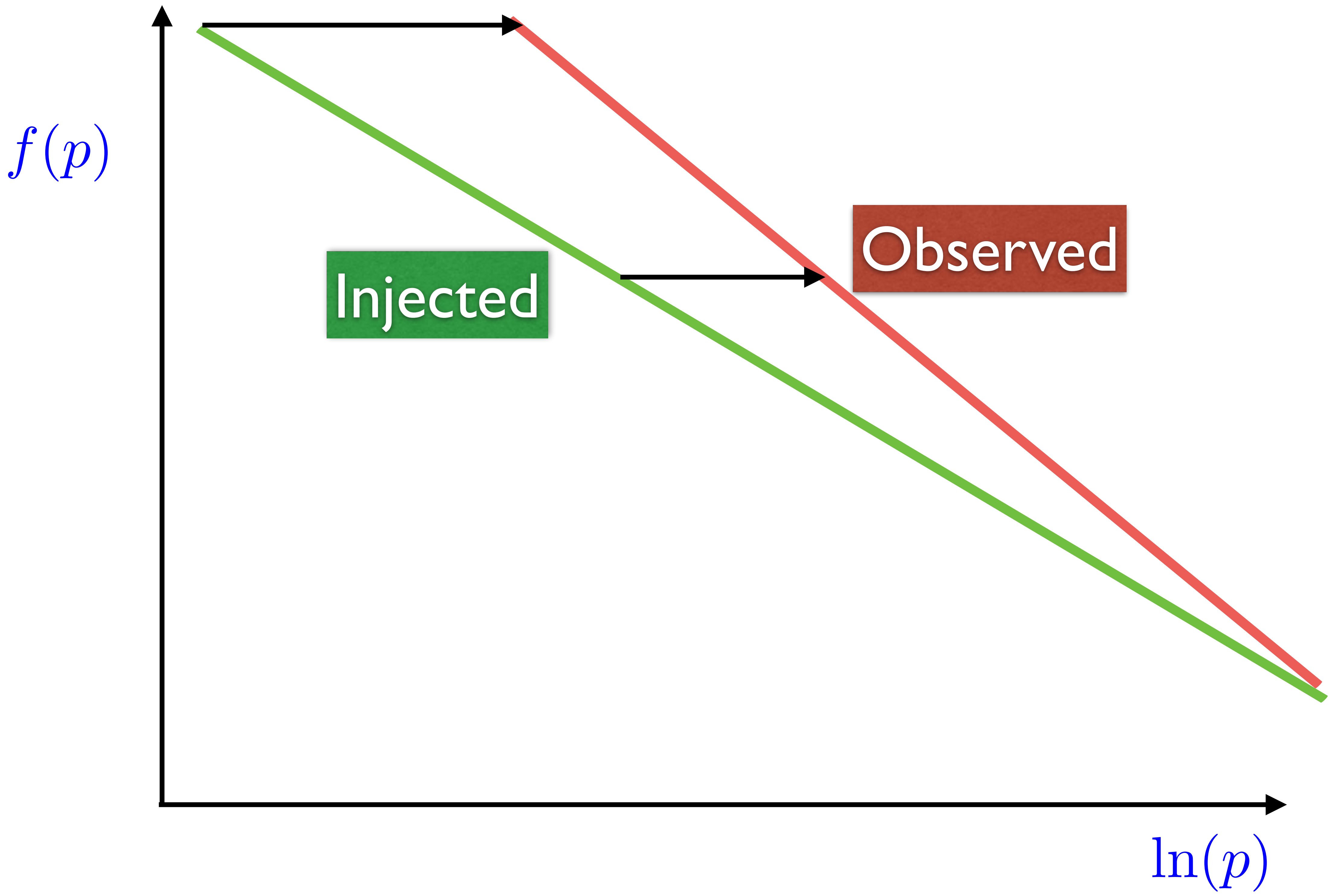
- Spallation secondary to primary ratios clearly show steepening of production spectra in GeV region by about 0.6 in exponent of energy spectrum.
- Can be achieved either by
  - energy dependent escape
  - energy dependent confinement volume
  - boosting of low energy particles by re-acceleration
  -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

Either

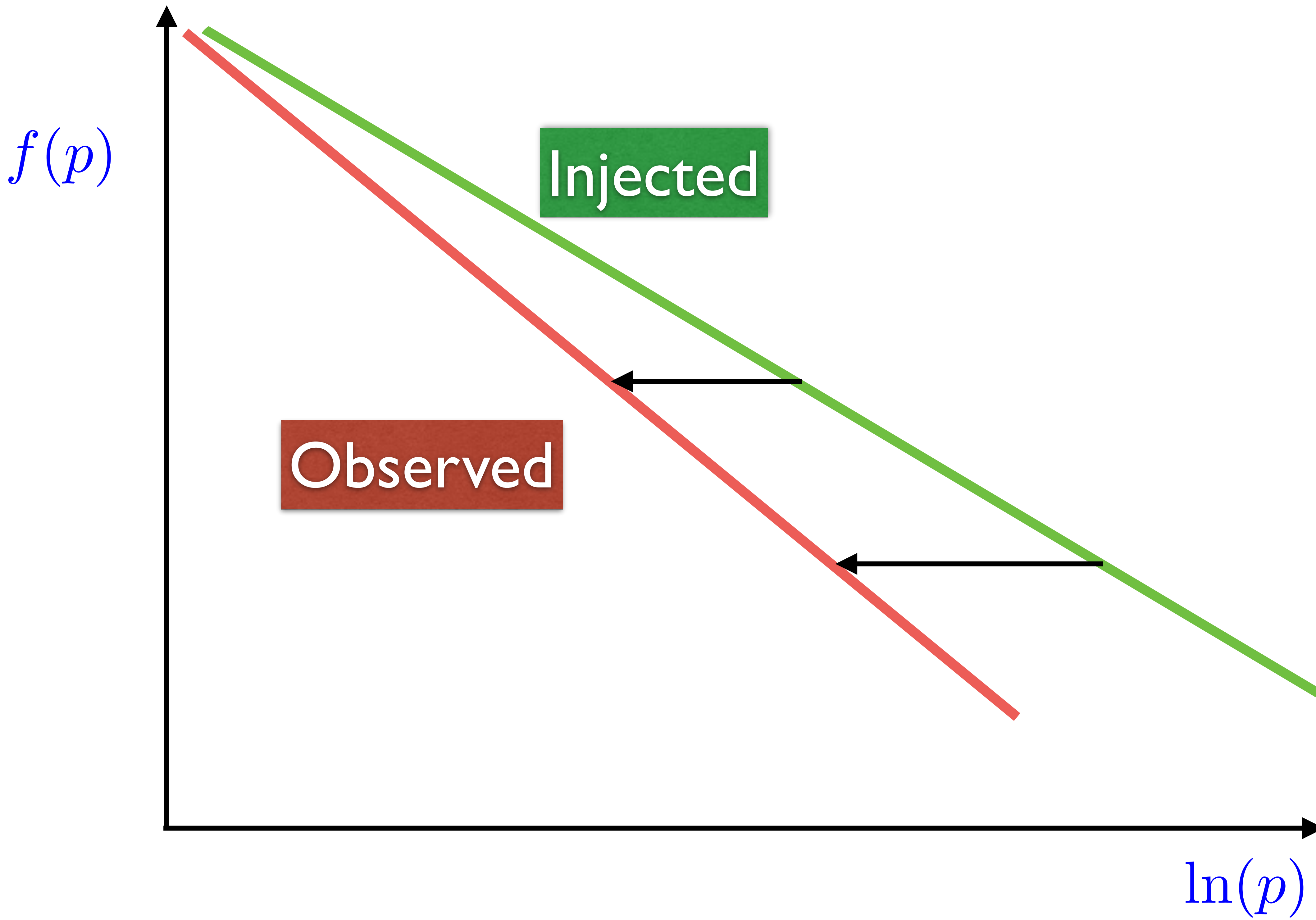


$\frac{\tau c M_{\rm ISM}}{V}$ = "grammage" and is fixed at a few GeV by observations

Or



Or



- Perhaps not so odd that we now see deviations in the observed spectra from simple power-laws - the 200GeV break for example in the proton spectrum.

- Whatever the original injection spectrum, it has certainly been modified and probably by more than one process.

- The wonder is rather that it remains so close to a power-law from a few GeV to a PeV or so.

- Now that we have Voyager data need to face up to low energy spectrum also!

Energetics of re-acceleration

- Basically just second-order Fermi on ISM turbulence - must occur at some level.
- Hard to estimate previously because of lack of knowledge of GCR spectra at low energies as well as relevant ISM turbulence.
- Situation has changed with availability of Voyager in situ measurements outside the heliopause - in particular the LIS spectrum of low-energy protons.

Drury and Strong 2016

arXiv:1608.04227

- Builds on Thornbury and Drury (2014) and Drury and Strong (2015 ICRC paper).
- Numerically integrates the diffusive re-acceleration power using the Vos and Potgeiter (2015) parametrisation of the LIS proton spectrum
- Check against Galprop calculations

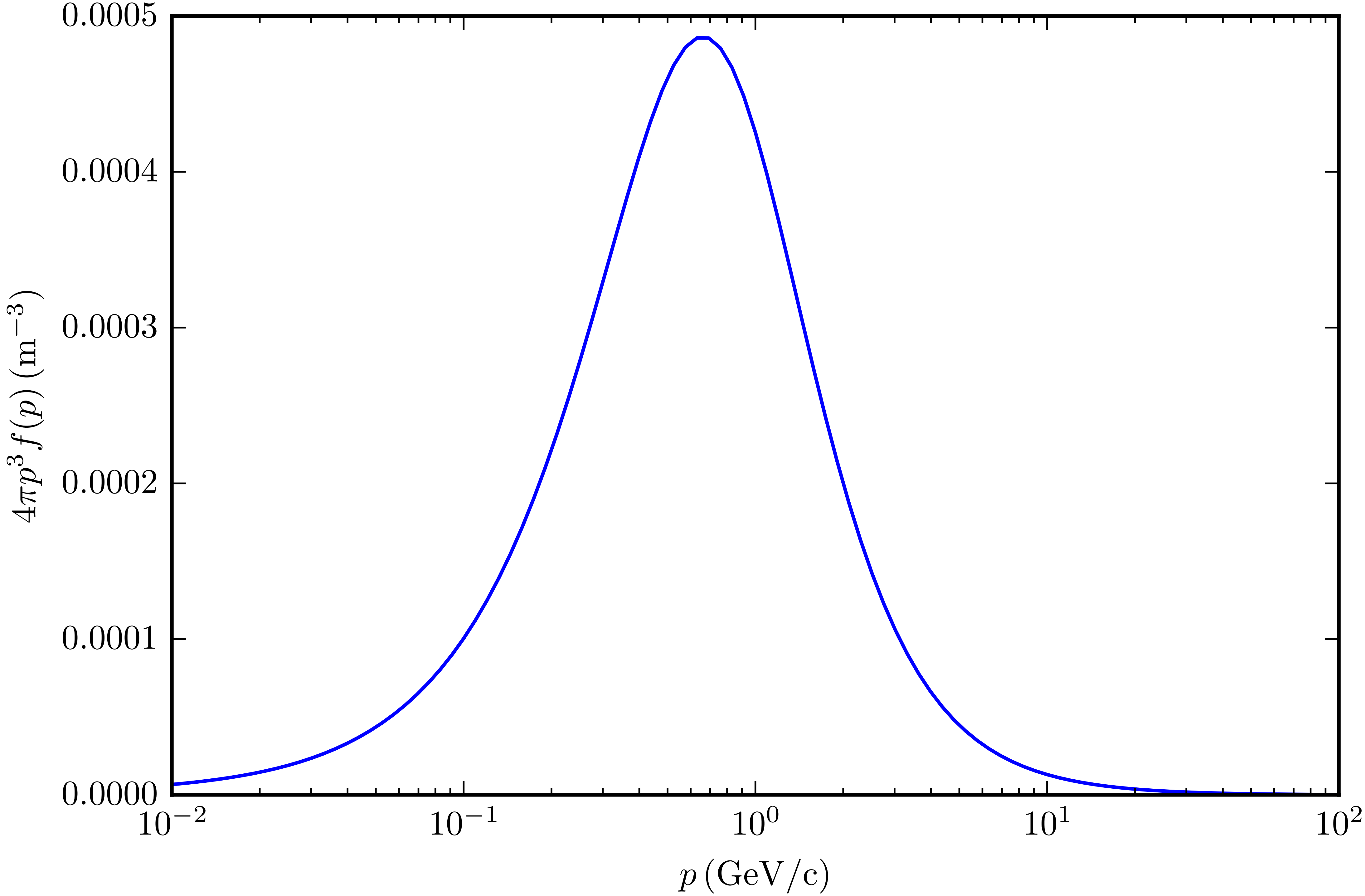
The diffusive re-acceleration power density is

$$P_R = \frac{4}{3\delta(4-\delta^2)} \frac{V_A^2}{D_0} mc^2 \int 4\pi p^2 f \left(\frac{p}{mc}\right)^{1-\delta} dp$$

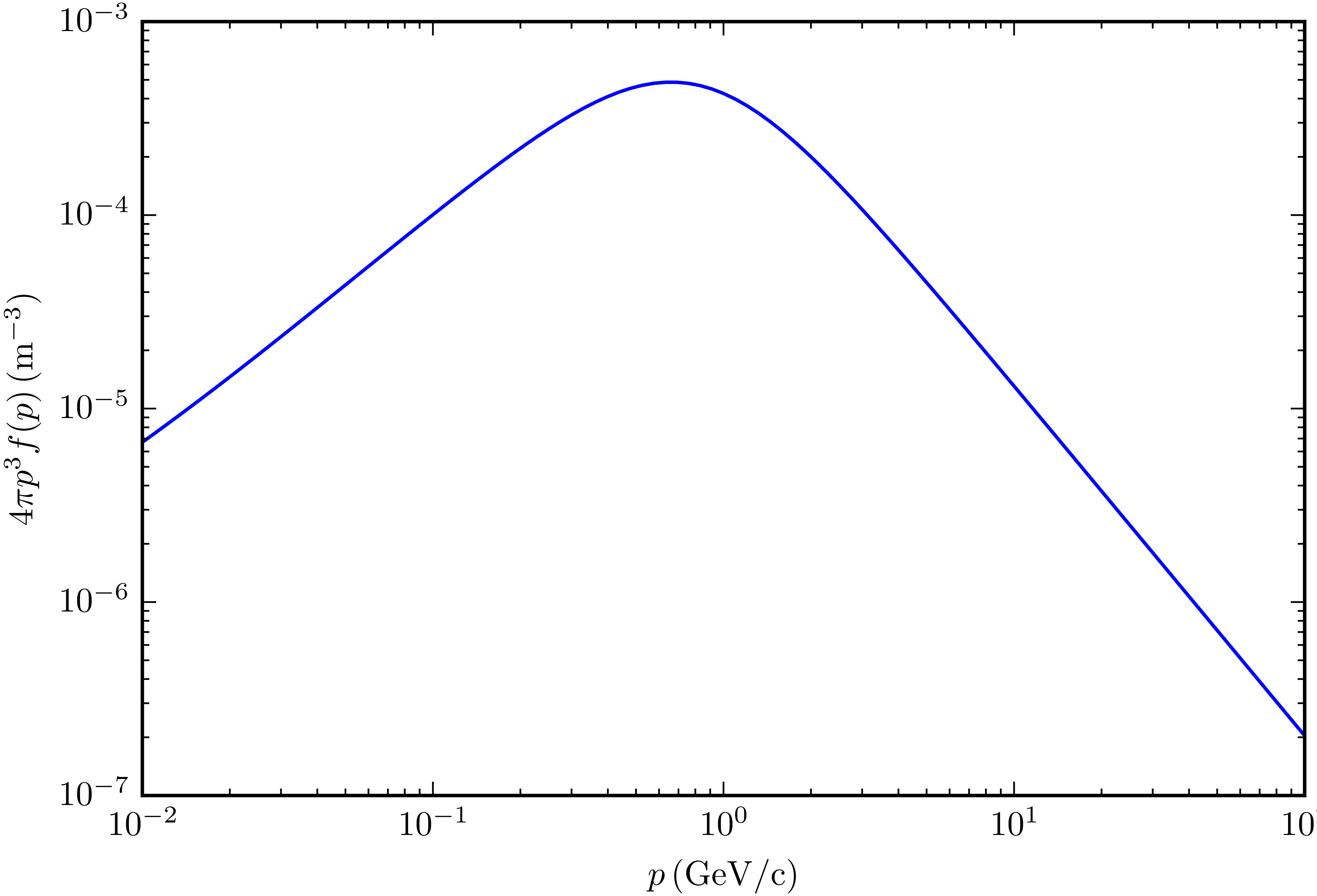
if the spatial diffusion has the standard form

$$D_{xx} = D_0 \left(\frac{v}{c}\right) \left(\frac{p}{mc}\right)^{\delta}$$

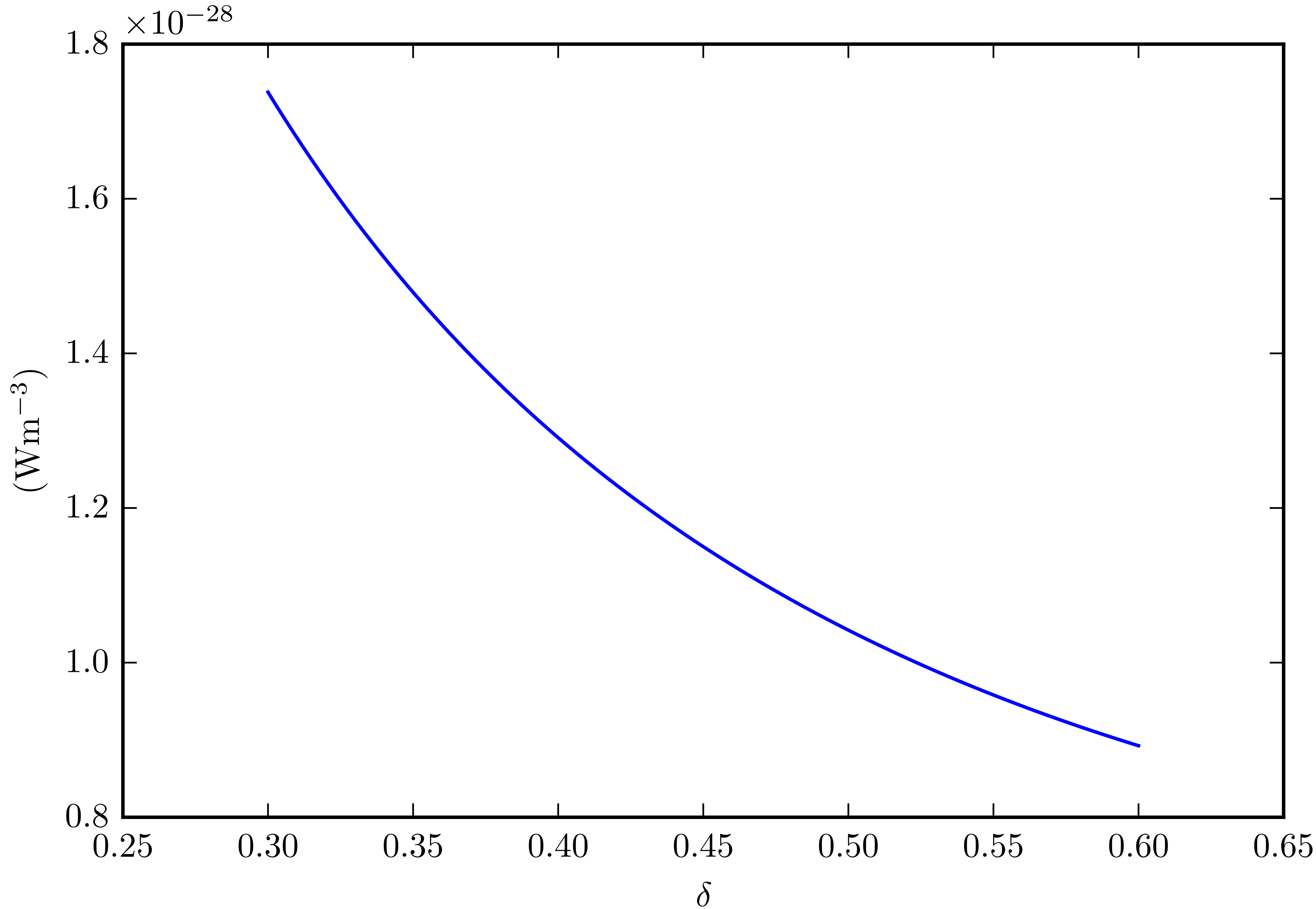
and the Alfvén speed is V_A



The local interstellar proton number spectrum from Vos and Potgieter (2015)



The same, but as a more conventional log-log plot



Diffusive re-acceleration power density

$$P_R \approx 1.3 \pm 0.4 \times 10^{-28}\,\mathrm{W\,m^{-3}} = 1.3 \pm 0.4 \times 10^{-27}\,\mathrm{erg\,cm^{-3}}$$

If we approximate the Galaxy (or rather the confinement volume where diffusive reacceleration occurs) as a cylinder of radius 10 kpc and height 4kpc, then it has a volume of

$$4 \times 10^{61}\,\mathrm{m}^3$$

and thus the total diffusive re-acceleration power integrated over the Galaxy is of order

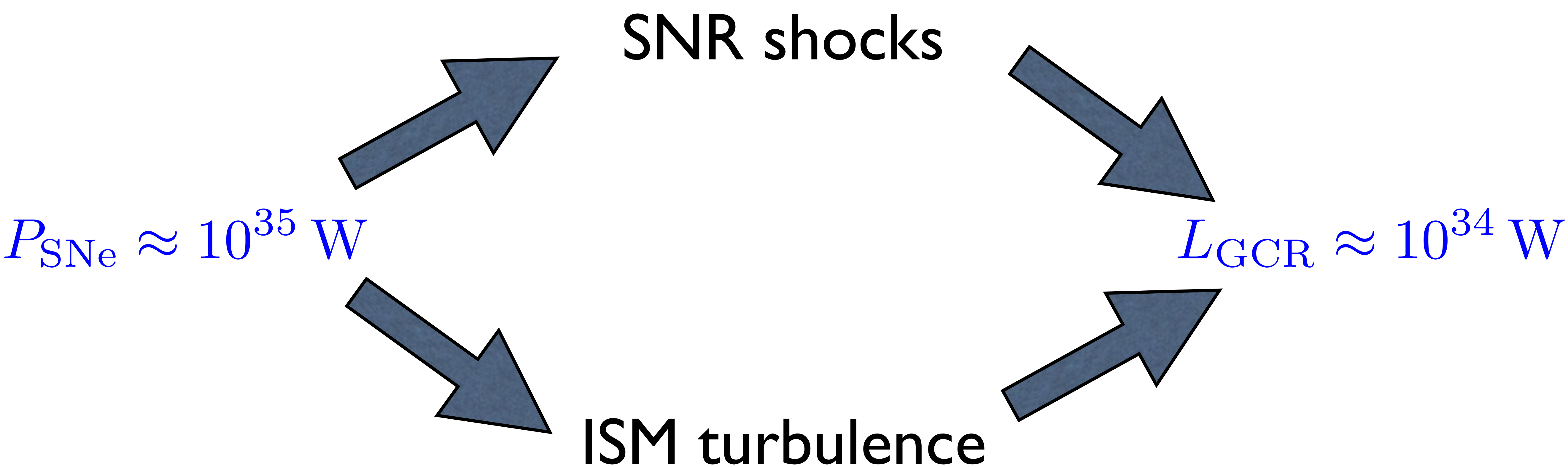
$$5 \times 10^{33}\,\mathrm{W}$$

or as much as half the nominal CR luminosity!

Summary of energetics

- Can safely assume $0.3 \times 10^{34}\,\mathrm{W} < L_{\mathrm{GCR}} < 3 \times 10^{34}\,\mathrm{W}$
- Perhaps as much as half of this may come from reacceleration!
- As is well known $P_{\mathrm{SNe}} \approx 10^{35}\,\mathrm{W}$
- Apart from GC 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 most plausible source of bulk of energy is SNe
- Adiabatic losses imply not in explosion itself
- Mediated through shocks and/or turbulence driven by SNRs in the ISM.



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?

Aside on positrons

- Very interesting recent paper by Paolo Lipari on arXiv:1608.02018 points out that the anti-proton and anti-electron data are compatible with a pure secondary production model, but only if the confinement time is shorter than generally assumed and the electron spectrum is intrinsically softer than the proton spectrum.
- Further work definitely required!

The Galactic Centre

- Eddington luminosity of GC supermassive black hole is

$$1.26 \times 10^{31} \left(\frac{M}{M_\odot} \right) \mathrm{W} \approx 5 \times 10^{37} \, \mathrm{W}$$

- Clearly extremely sub-luminous at the moment, but evidence of time variability.
- Could easily make a significant contribution.
- Recent evidence from H.E.S.S. is very exciting in this regard - first Galactic Pevatron detected!

arXiv:1603.07730

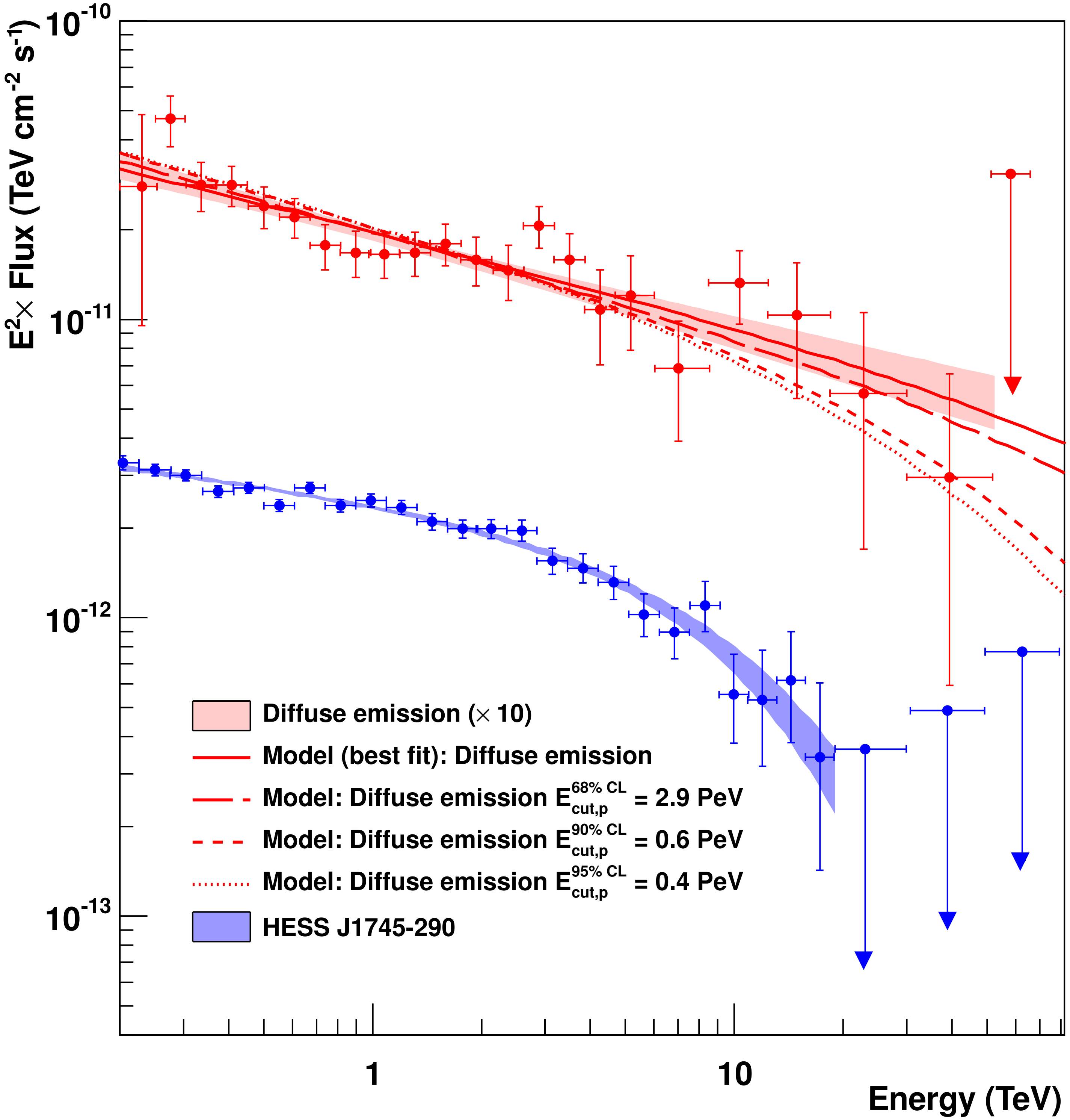


Figure 3: **VHE γ-ray spectra of the diffuse emission and HESS J1745-290.** The Y axis shows fluxes multiplied by a factor E^2, where E is the energy on the X axis, in units of TeVcm^{-2}s^{-1}. The vertical and horizontal error bars show the 1σ statistical error and bin size, respectively. Arrows represent 2σ flux upper limits. The 1σ confidence bands of the best-fit spectra of the diffuse and HESS J1745-290 are shown in red and blue shaded areas, respectively. Spectral parameters are given in Methods. The red lines show the numerical computations assuming that γ-rays result from the decay of neutral pions produced by proton-proton interactions. The fluxes of the diffuse emission spectrum and models are multiplied by 10.

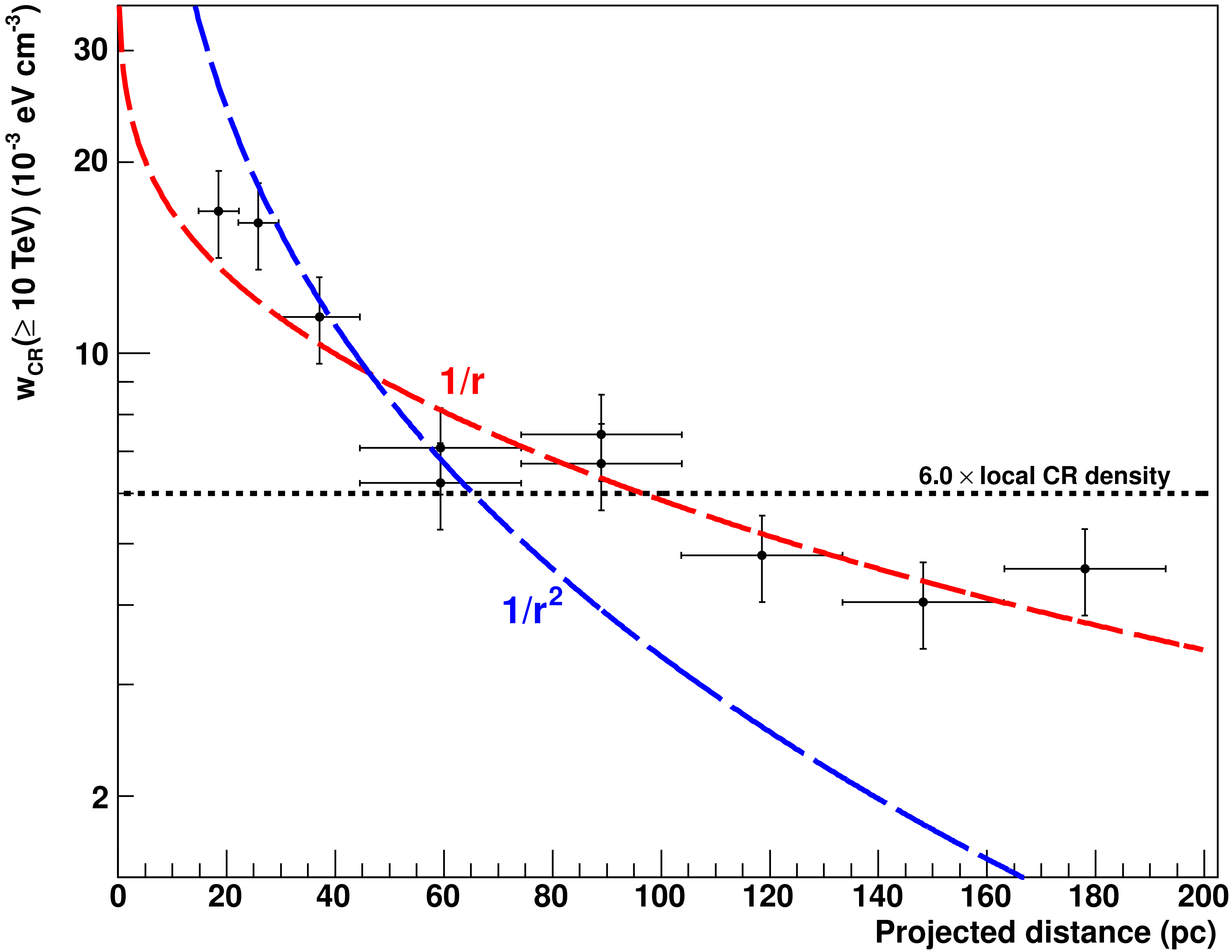


Figure 2: **Spatial distribution of the CR density versus projected distance from Sgr A*.** The vertical and horizontal error bars show the 1σ statistical plus systematical errors and the bin size, respectively. A fit to the data of a $1/r$ (red line, $\chi^2/\mathrm{d.o.f.}$ = 11.8/9), $1/r^2$ (blue line, $\chi^2/\mathrm{d.o.f.}$ = 73.2/9) and an homogeneous (black line, $\chi^2/\mathrm{d.o.f.}$ = 61.2/9) CR density radial profiles integrated along the line of sight are shown. The best fit of a $1/r^\alpha$ profile to the data is found for $\alpha = 1.10 \pm 0.12$ (1σ).The $1/r$ radial profile is clearly preferred by the H.E.S.S. data.

- Suggestive of steady spherical diffusion from central source with uniform diffusion coefficient.

$$\kappa \nabla f \propto r^{-2} \implies f \propto r^{-1}$$

- Not ballistic escape, nor advection by an outflow, which would both imply steeper radial gradients.

Corresponding power (in PeV particles) is

$$L_{\mathrm{GC}} \approx 4 \times 10^{30} \left(\frac{D}{10^{30}\,\mathrm{cm^2 s^{-1}}} \right) \mathrm{W}$$

Not all that much, but could just about supply Galaxy with PeV particles?

Fermi bubbles also strongly suggest powerful non-thermal activity in the Galactic centre region.

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.
  - Live Fe60 detected.
- 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 with slight deviations from this in high resolution data (especially harder helium spectra).
- 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.

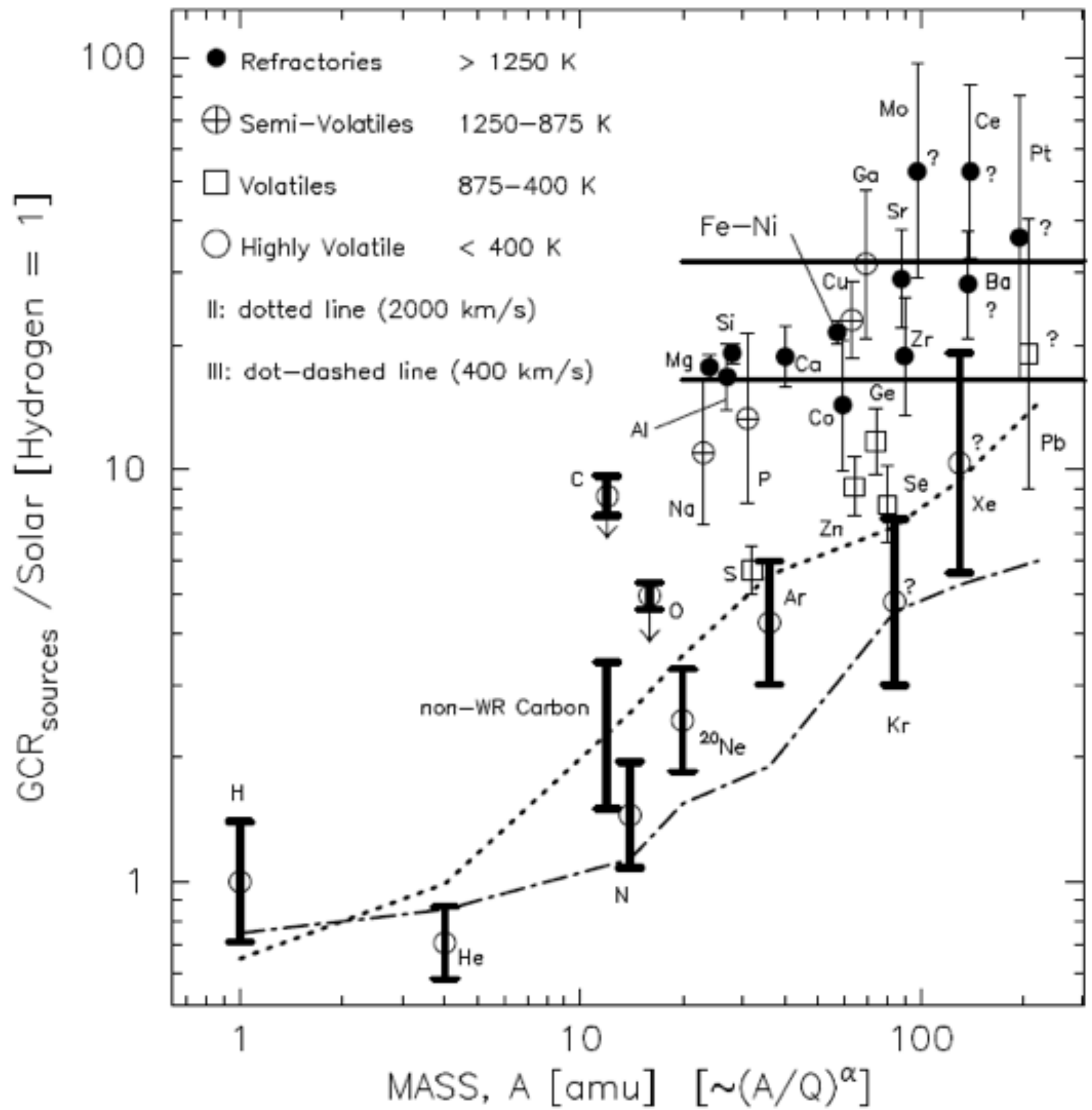
- Need roughly the same nucleosynthetic mix as in general ISM - not all r-process for example. No one class of SNe.

- 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.

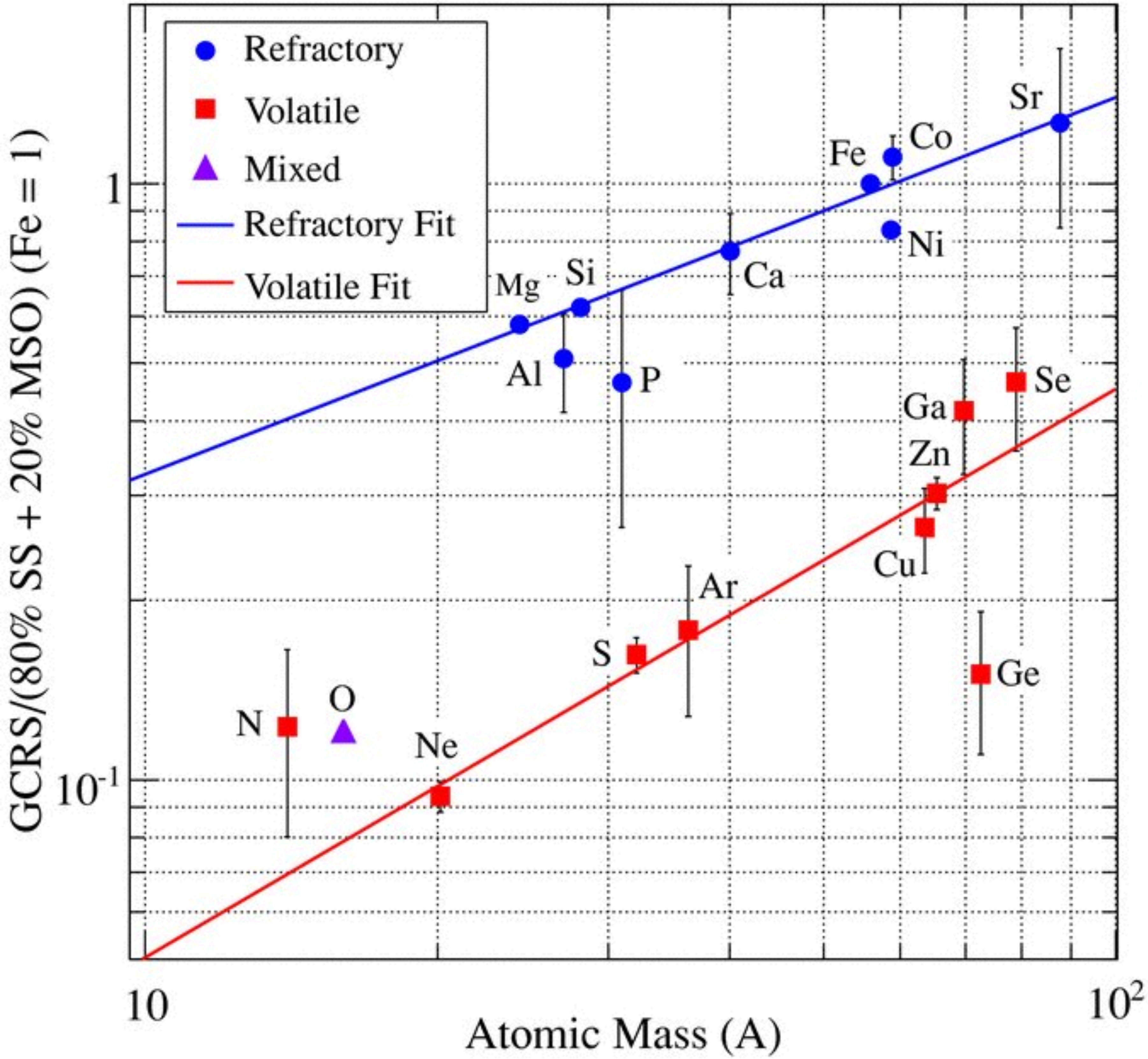
- Telling us something about injection process at low energies - must favour heavy species and refractory elements.

- FIP, volatility, dust chemistry etc…..

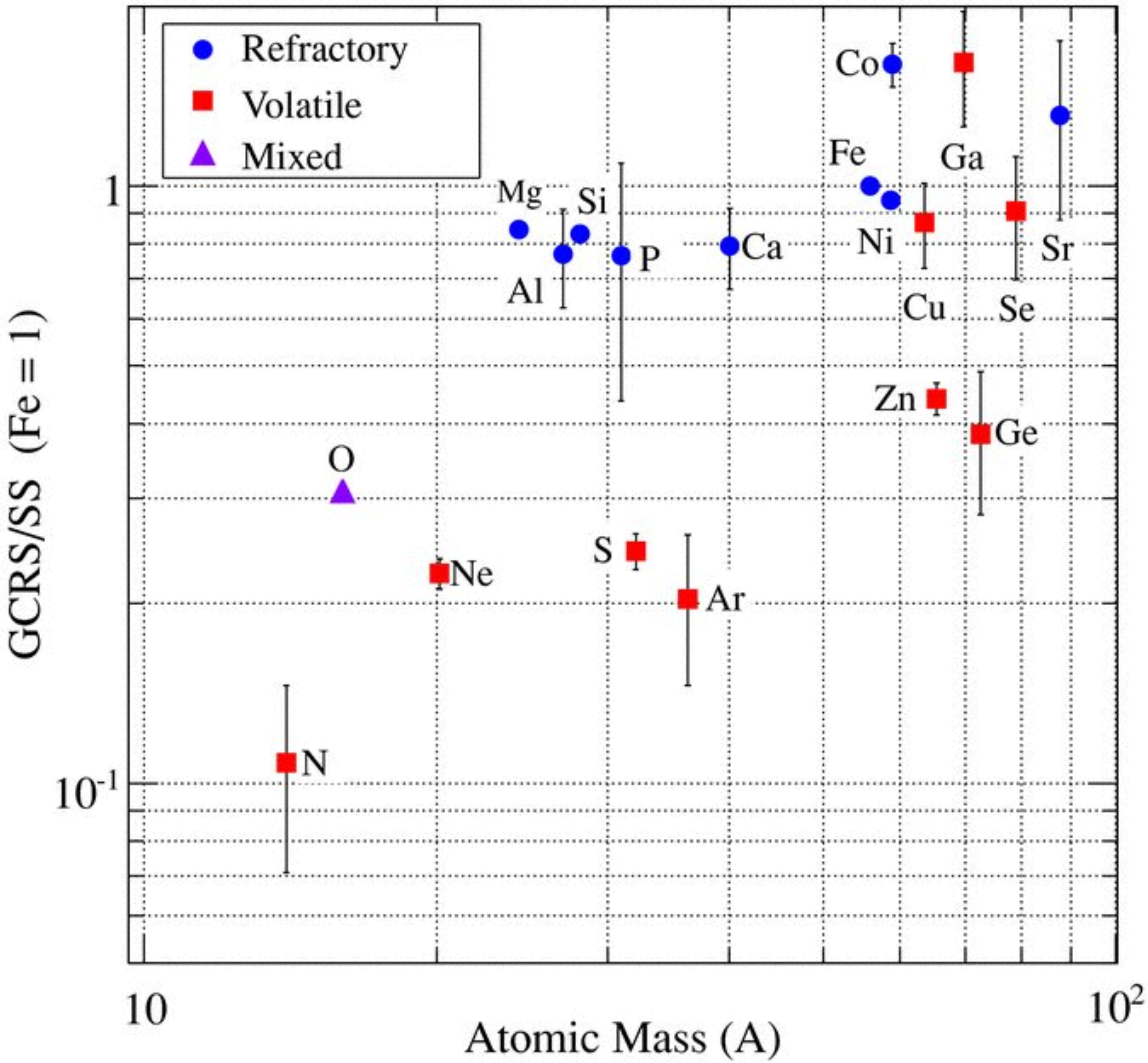
No. 1, 1997 GALACTIC COSMIC RAYS FROM SNRs. II. 199



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



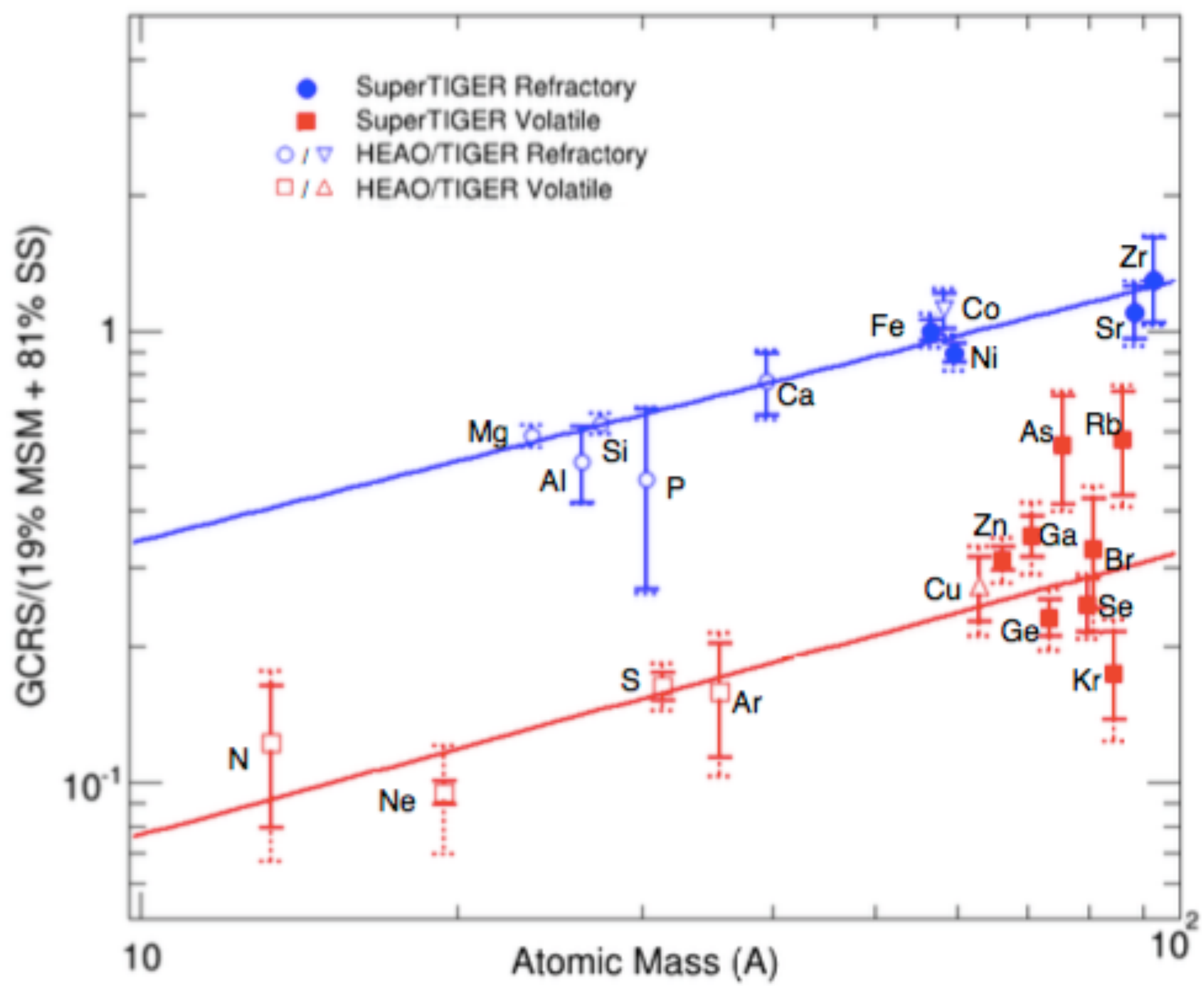
Rauch et al, 2009 ApJ 697, 2083 COSMIC RAY ORIGIN IN OB ASSOCIATIONS AND PREFERENTIAL ACCELERATION OF REFRACTORY ELEMENTS: EVIDENCE FROM ABUNDANCES OF ELEMENTS 26Fe THROUGH 34Se



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

Latest Tiger results (Murphy et al, arXiv:1608.08183)

These results support a model of cosmic-ray origin in which the source material consists of a mixture of 19^{+11}_{-6} \% material from massive stars and ~81\% normal interstellar medium (ISM) material with solar system abundances. The results also show a preferential acceleration of refractory elements (found in interstellar dust grains) by a factor of ~4 over volatile elements (found in interstellar gas) ordered by atomic mass (A). Both the refractory and volatile elements show a mass-dependent enhancement with similar slopes.



Time to acceleration?

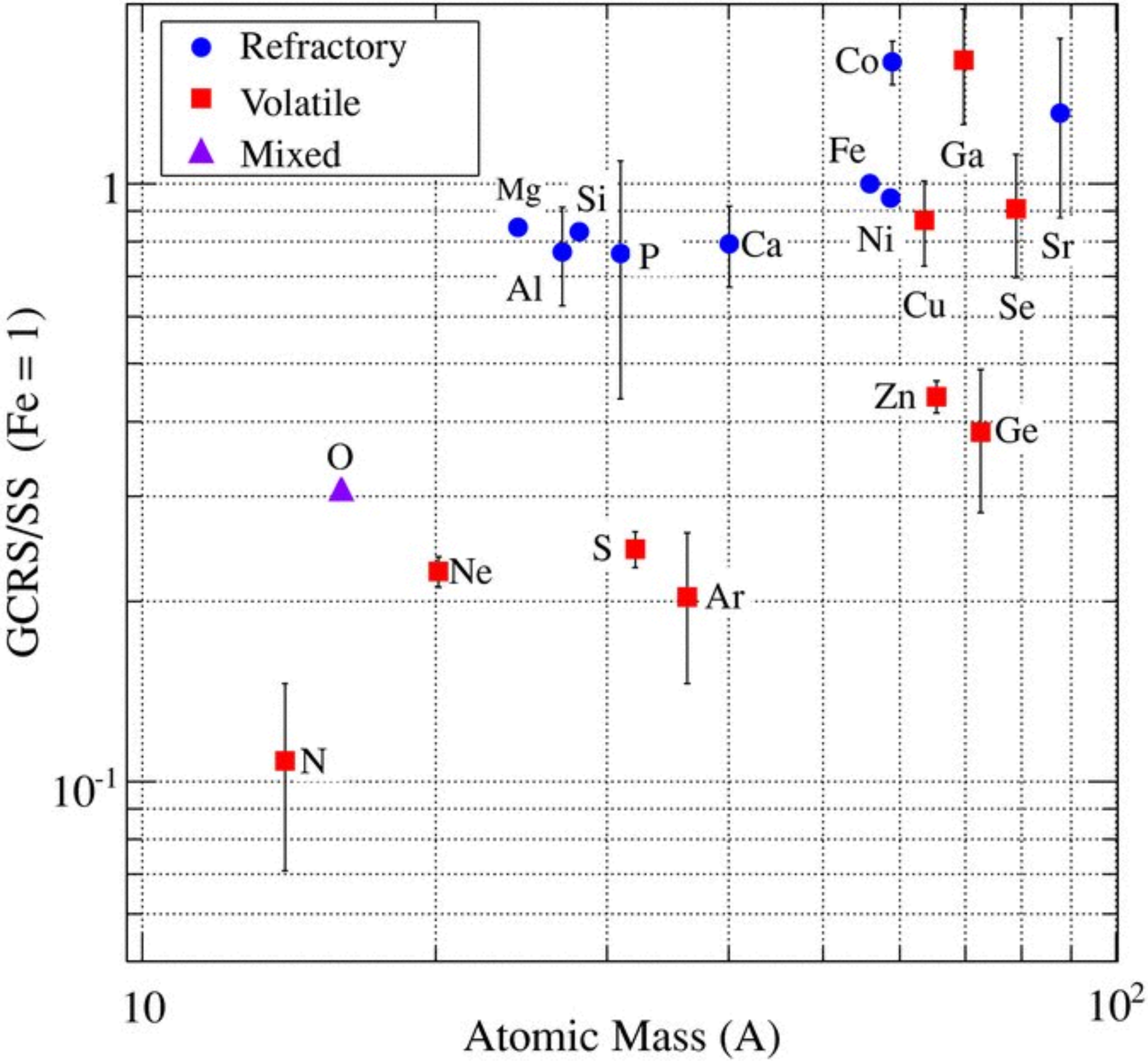
The Cosmic Ray Isotope Spectrometer (CRIS) on the ACE spacecraft has been measuring the isotopic composition of Galactic Cosmic Rays (GCRs) since August 1997. Using selected data from the past seventeen years, we have a set of 2.95 x 10^5 ^{56}Fe nuclei in the energy interval 240 to 470 MeV/nucleon with excellent mass resolution characterized by $\sigma = 0.24$ amu. In this data set we have detected fifteen well resolved ^{60}Fe nuclei. ^{60}Fe is β^- unstable with a half-life of 2.6 million years. The detection of these radioactive nuclei permits us to set an upper limit of a few million years on the time between nucleosynthesis of these nuclei and their acceleration to cosmic-ray energies. A lower limit of 10^5 years was established by the CRIS observation that the electron-capture isotope ^{59}Ni is essentially absent in the GCRs. These two limits bracket the nucleosynthesis-to-acceleration time to a range that is consistent with the emerging evidence that the bulk of GCRs are accelerated in associations of massive stars (OB associations).

M. Israel et al, APS April 2016

Injection must be highly selective!

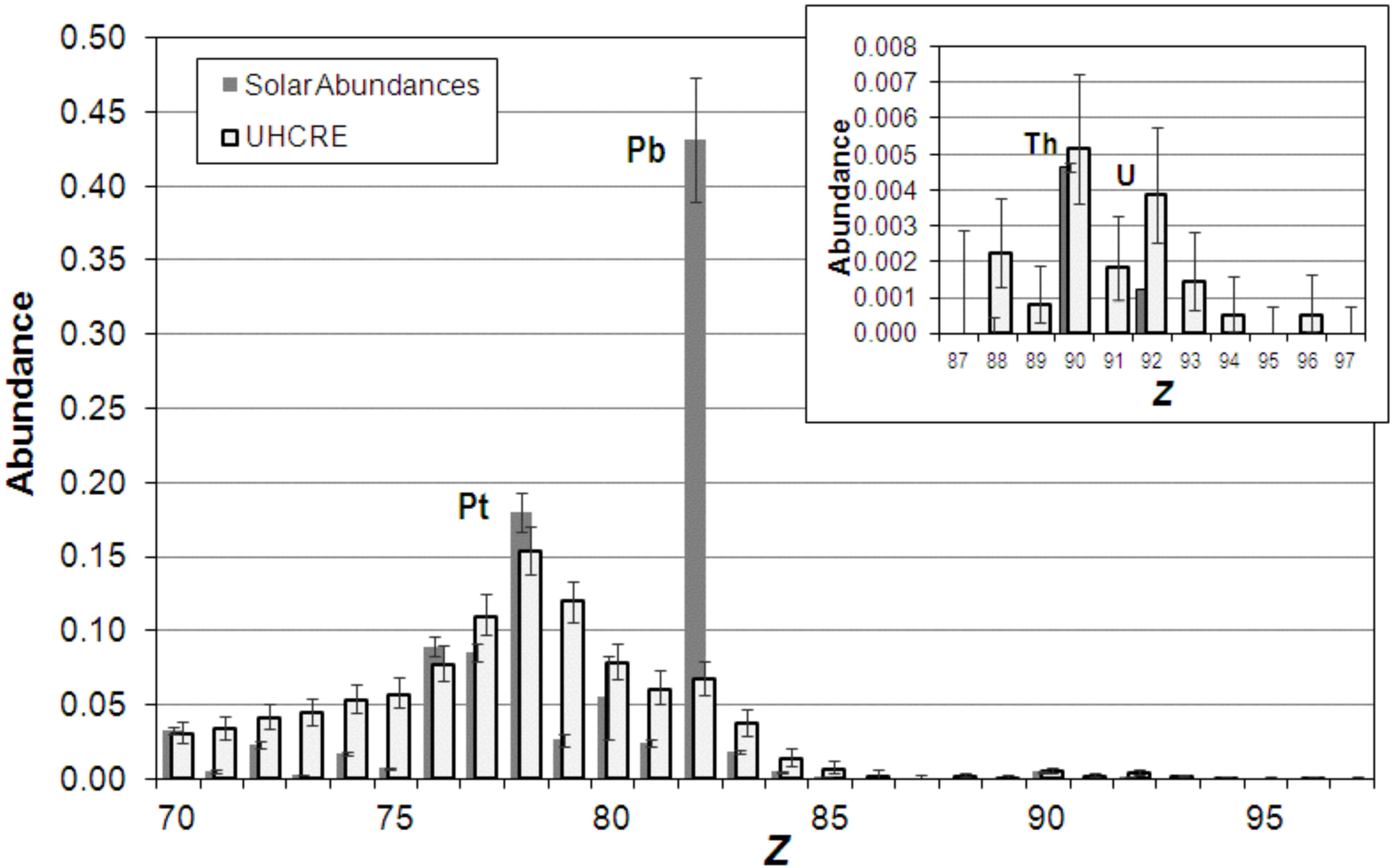
- Simple energy argument.
  - Even for a strong SNR shock going at 1% of the speed of light, the KE per proton is only 10^{-4} of the rest mass energy.
  - Thus can only accelerate one proton in ten thousand to relativistic energies!
- A fortiori for ISM turbulence.

- 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.


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

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
Th
U
Abundance
Z
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
70
75
80
85
90
95
0.008
0.007
0.006
0.005
0.004
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0.002
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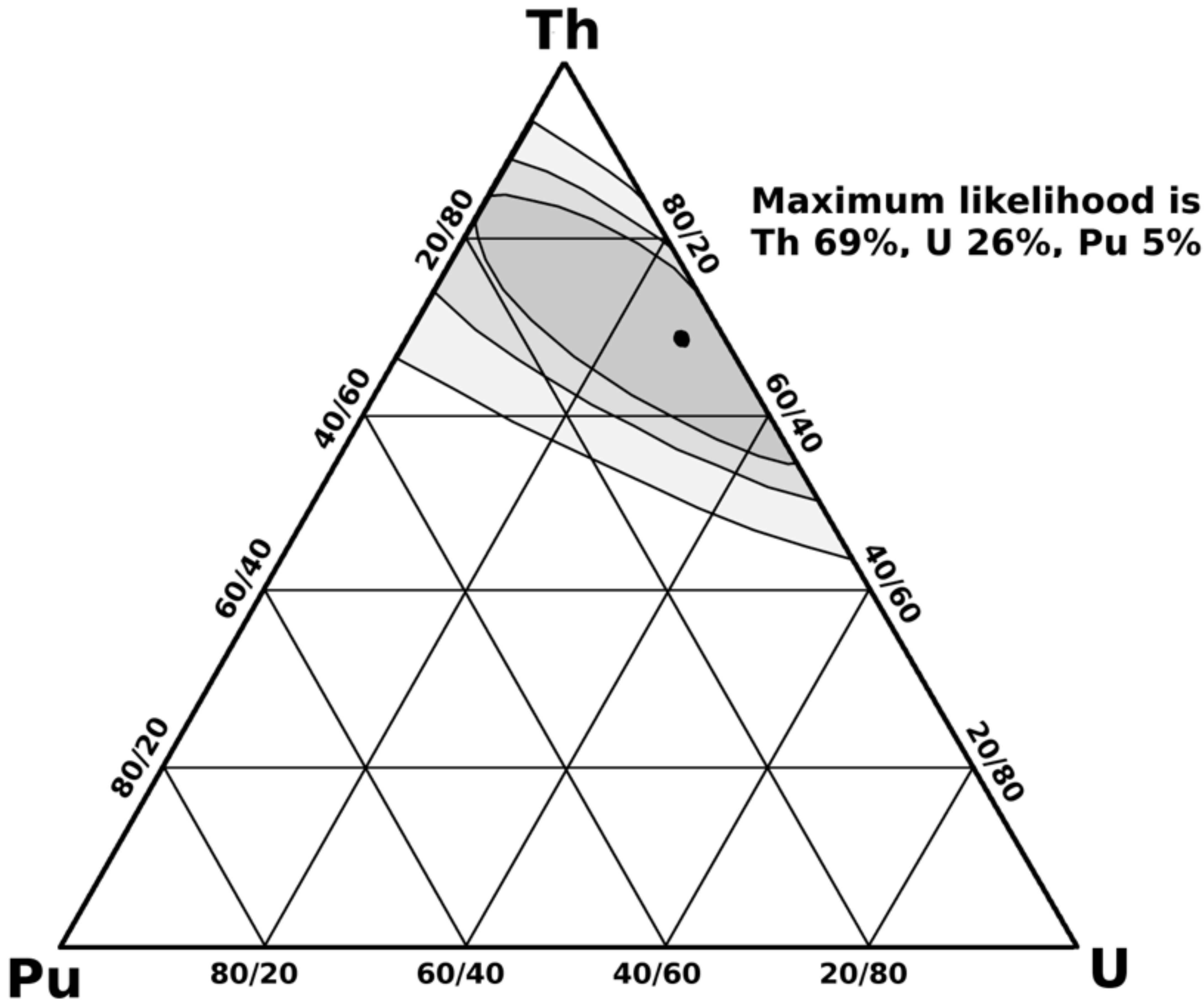
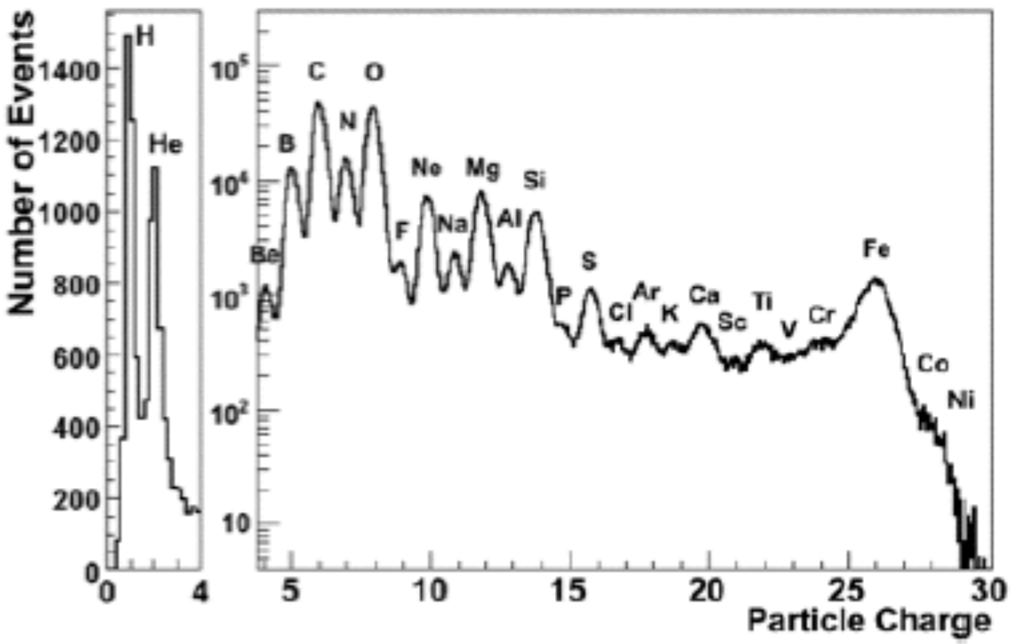
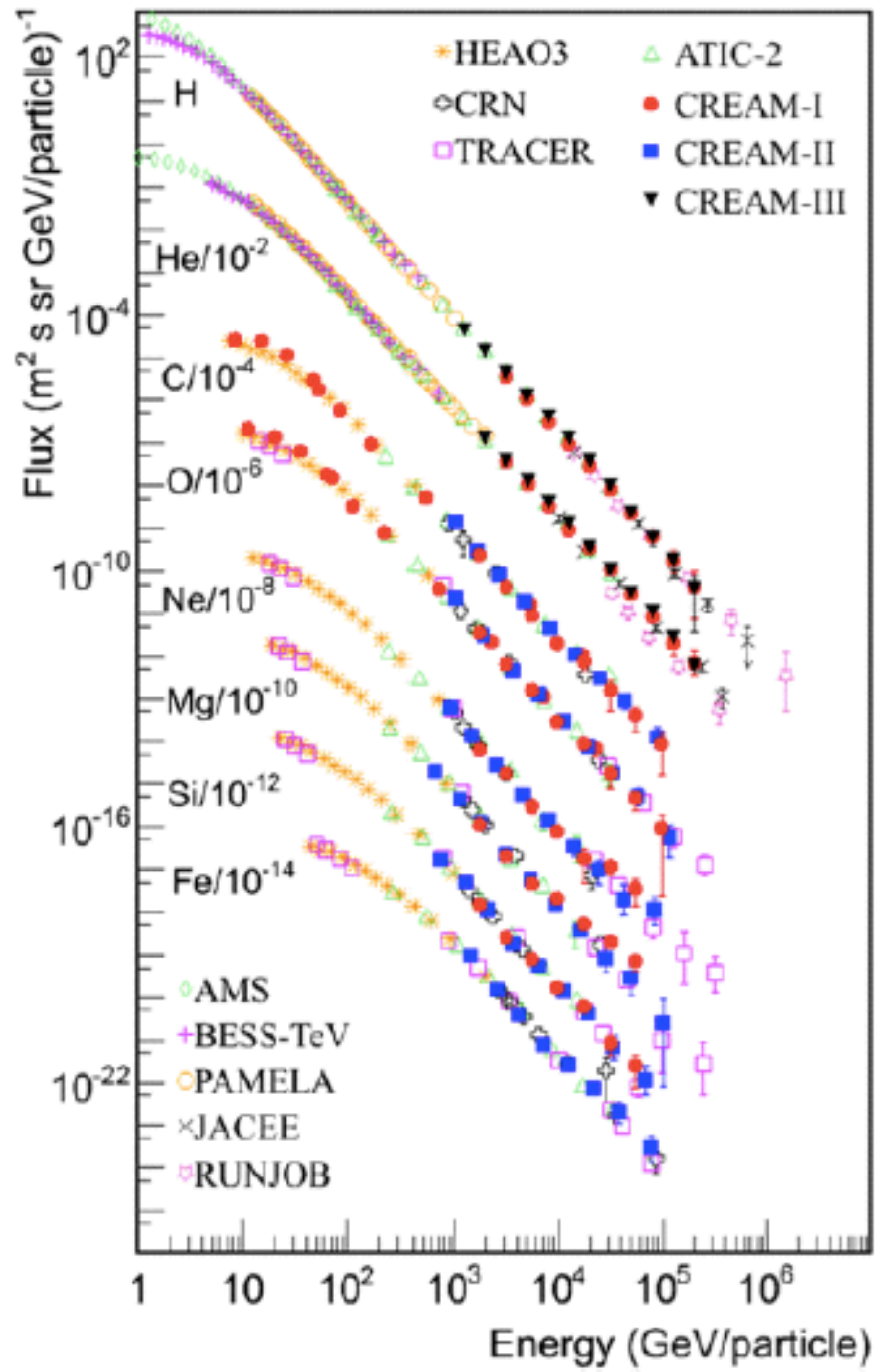

Th
Maximum likelihood is
Th 69%, U 26%, Pu 5%
20/80
40/60
60/40
80/20
80/20
60/40
40/60
20/80
Pu
80/20
60/40
40/60
20/80
U

CREAM: results

- Charge identification:



- Mesure from H to Fe over 3 decades in energy.



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 (confirmed by 60Fe data).
- 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?

Summary and conclusions

- Energetics still seem to point to SNRs as ultimate engine for most CR production.
- Composition points to correlated SNRs and super bubbles.
- Role of turbulent diffusive reacceleration needs to be reconsidered, but DSA still "best bet".
- The Galactic centre Pevatron detection is an exciting new development but significant unclear.
- Propagation models need to be much more dynamic with CR-driven outflows and winds.