# The Origin of Cosmic Rays, 50 years on.

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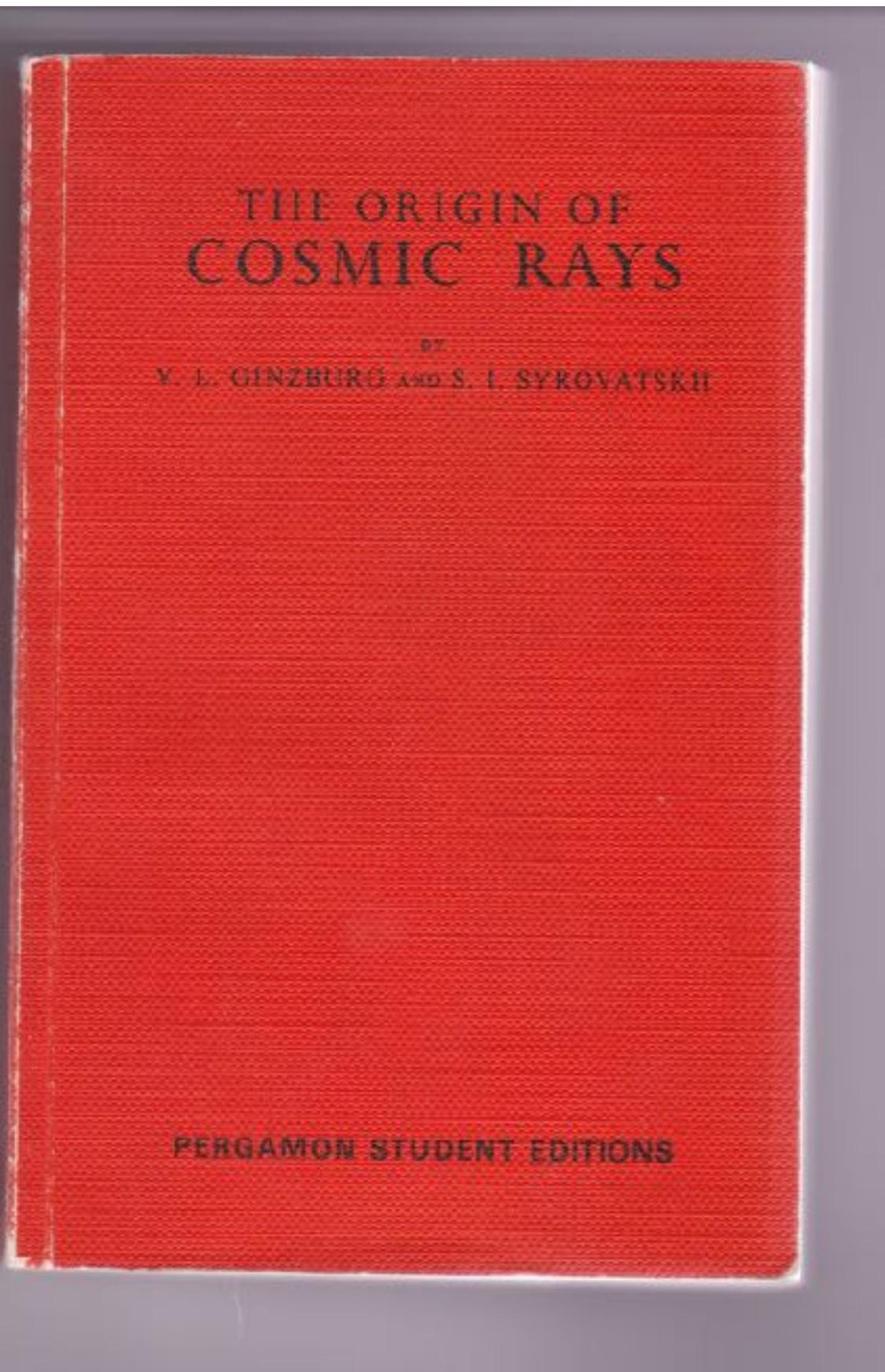
THE ORIGIN OF COSMIC RAYS

BY

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Authorised translation incorporating additional chapter and revisions supplied by the authors in 1964

PERGAMON PRESS

OXFORD · LONDON · EDINBURGH · NEW YORK · PARIS · FRANKFURT

1964

A genuinely "seminal" book. Marked the change of cosmic ray physics from the poor relative of particle physics to a branch of modern astrophysics.

2

INTERNATIONAL ASTRONOMICAL UNION

SYMPOSIUM No. 94

ORIGIN OF COSMIC RAYS

Edited by G. SETTI, G. SPADA, and A. W. WOLFENDALE
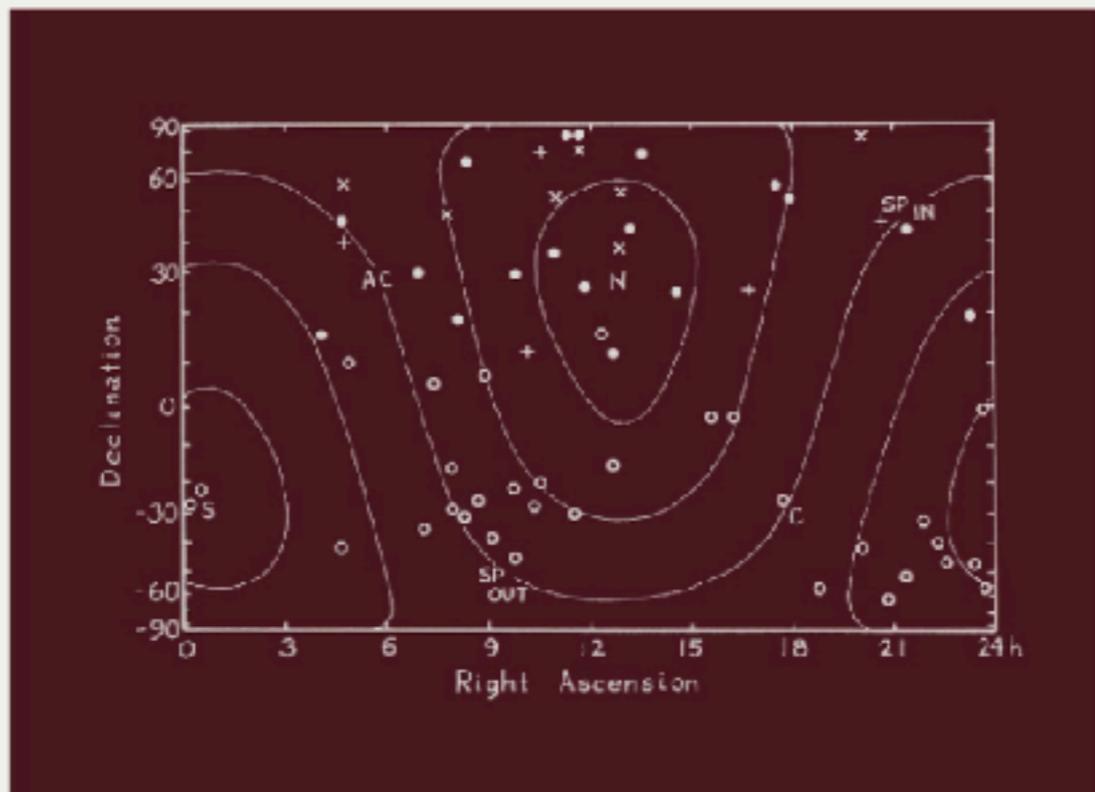
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D. REIDEL PUBLISHING COMPANY / DORDRECHT : HOLLAND

BOSTON : U.S.A. / LONDON : ENGLAND

TABLE OF CONTENTS

My first meeting with Ginzburg, Bologna, 1980.

But where is the physics?

3

Conclusion of Ginzburg's introductory remarks in 1980.

The above enumeration is, of course, rather conditional and incomplete (suffice it to mention also X-ray astronomy, the study of high-energy particles and photons from the Sun and from the magnetospheres of the Earth, Jupiter and other planets, etc.). What has been said is already enough, however, to realize the scale of work to be done. When in all the branches mentioned sufficient data are accumulated (a period of 20-30 years is probably enough and at the same time not too much) high-energy astrophysics will play a still more outstanding role in astronomy than it does today. Besides there is no doubt that some unexpected things are to be encountered, and this is one of the attractive features of Science. One can only envy those men who will see the astronomy of the XXIst century in all its richness.

The 20-30 years are now past and indeed high-energy astrophysics does now play an outstanding role in astronomy, unexpected things have been discovered, and we have a much richer astronomy (and not just for men!).

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 - but not in GS64.

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.

- GS64 $\qquad\qquad\qquad\qquad\qquad\quad 0.3 \times 10^{34}\,\mathrm{W}$

- Galprop (Strong et al, 2010) $\quad (0.7 \pm 0.1) \times 10^{34}\,\mathrm{W}$

- Drury, Markiewicz and Völk (1989) $\; < 3 \times 10^{34}\,\mathrm{W}$

Basic Power Estimate

- Energy density and "grammage" for mildly relativistic CRs are both well constrained.

- Gives a more or less model independent estimate of the cosmic ray power needed to maintain a steady state cosmic ray population in the Galaxy within a simple diffusion or leaky box type propagation model.

$$g = \frac{\tau c M}{V} \qquad\qquad L_{\mathrm{CR}} = \frac{\mathcal{E}_{\mathrm{CR}} V}{\tau}$$

$$L_{\rm CR} \approx \mathcal{E}_{\rm CR} \frac{cM}{g}$$

$$\mathcal{E}_{\rm CR} \approx 0.3\,{\rm eV\,cm^{-3}}$$

$$M \approx 5 \times 10^9 {\rm M_\odot}$$

$$g \approx 5\,{\rm g\,cm^{-2}}$$

$$\implies L_{\rm CR} \approx 3 \times 10^{40}\,{\rm erg\,s^{-1}} = 3 \times 10^{33} {\rm W}$$

NB does not depend on 10Be age etc.

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

$f(p)$

Injected $Q(p)$

Observed

$$f \propto \frac{Q\tau}{V}$$

$\ln(p)$
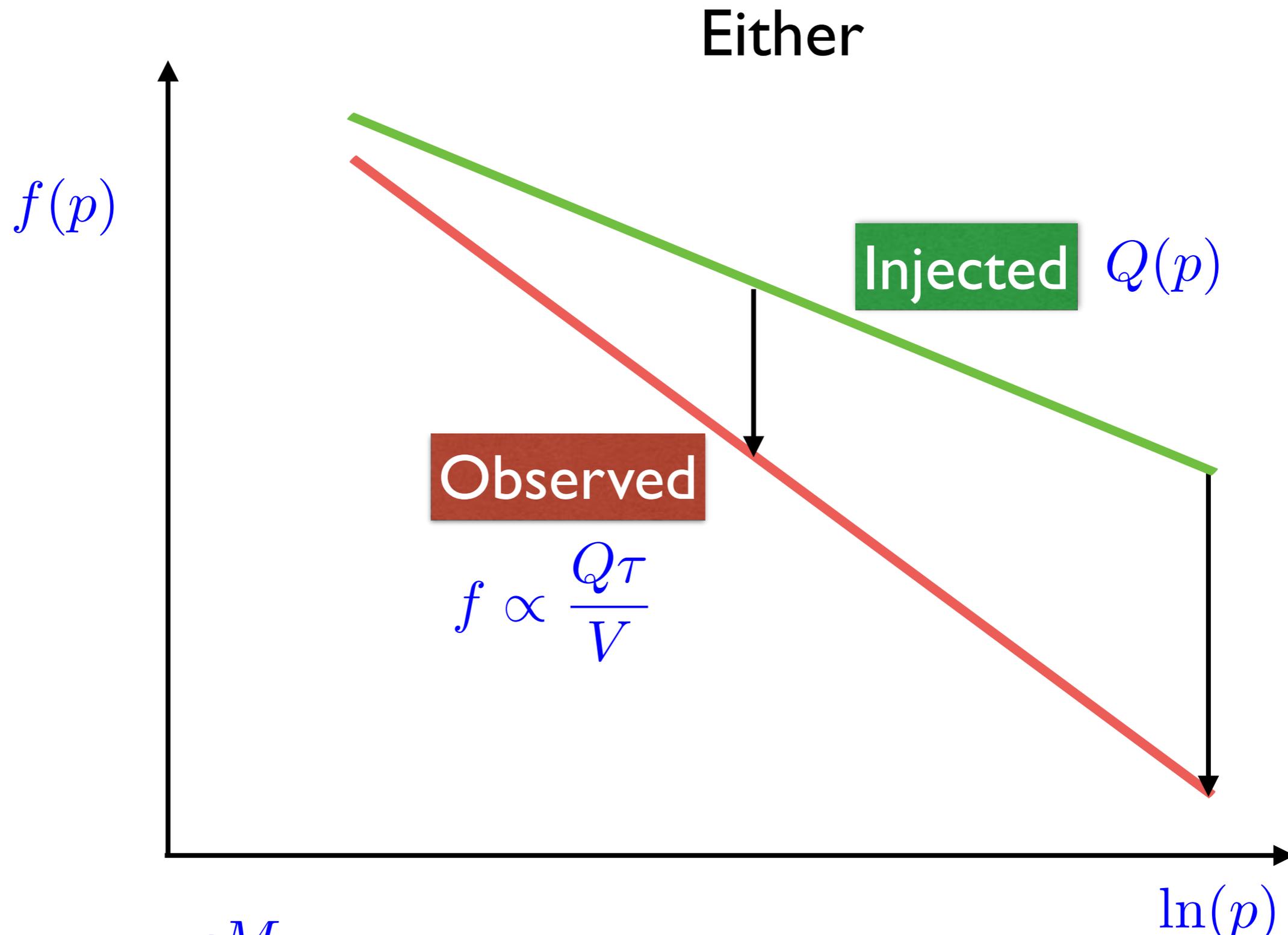
$$\frac{\tau c M_{\mathrm{ISM}}}{V} = \text{"grammage" and is fixed}$$
at a few GeV by observations

Or

$f(p)$

Injected

Observed

$\ln(p)$
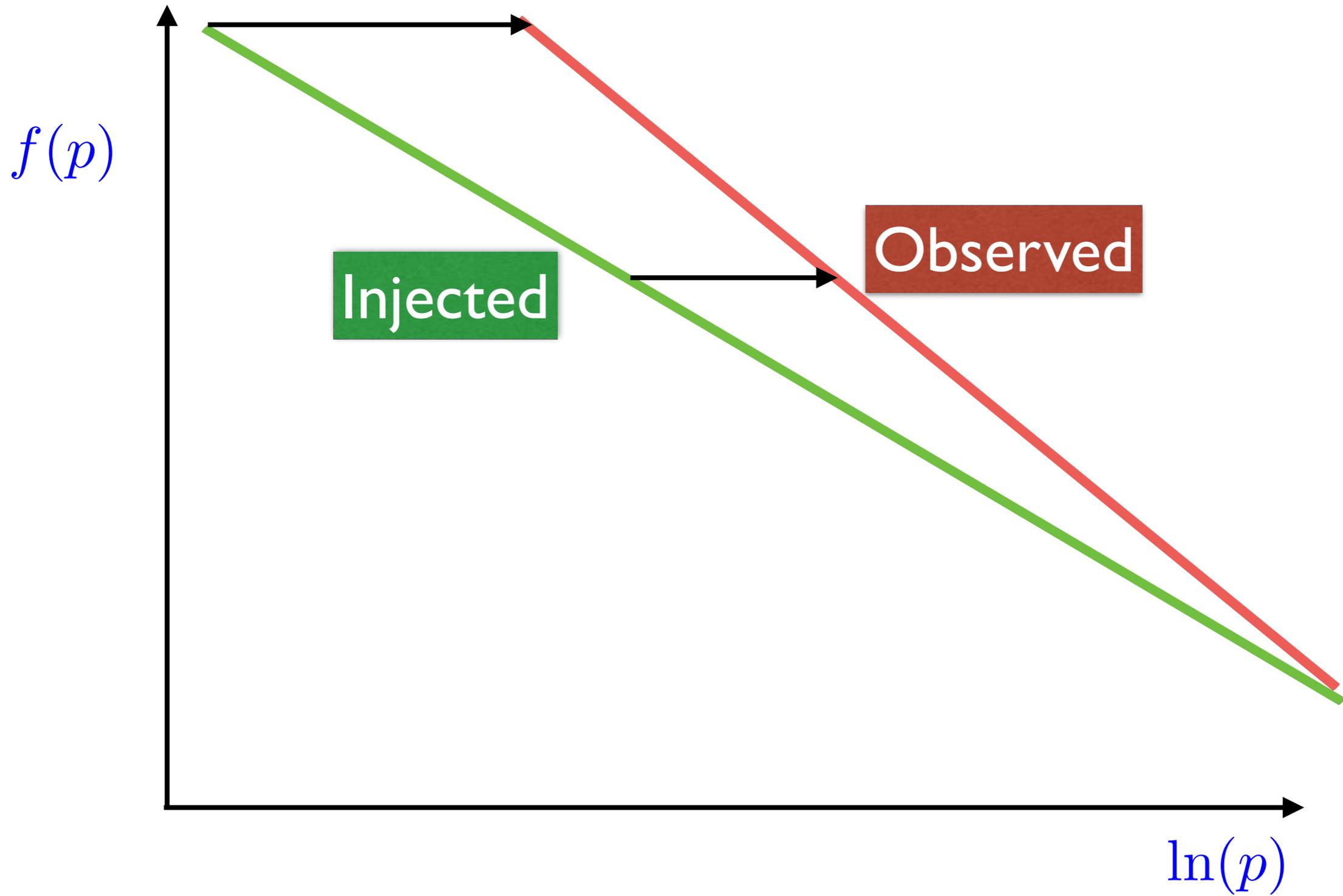
Or
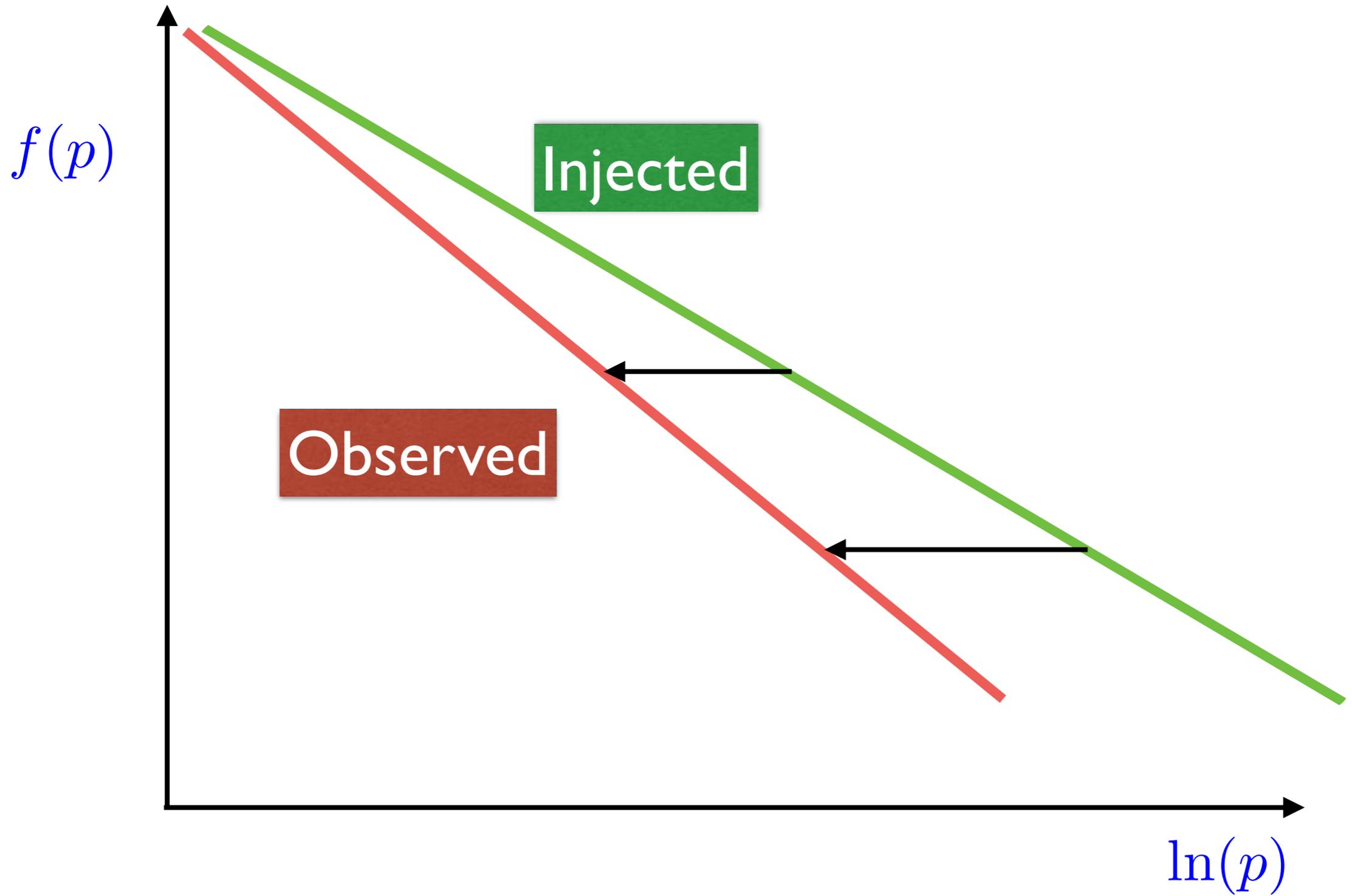
- Perhaps not so odd that we now see deviations in the observed spectra from simple power-laws - the 200GeV breaks for example in the proton and helium spectra (Pamela and AMS02).

- 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!

- Diffusive propagation must involve diffusion in momentum as well as in space if scattering magnetic fields are non-stationary.

- For historical reasons within propagation theory this tends to be called diffusive re-acceleration.

- Not to be confused with re-acceleration by weak shock waves (although related).

Energetics of diffusive 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

- 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
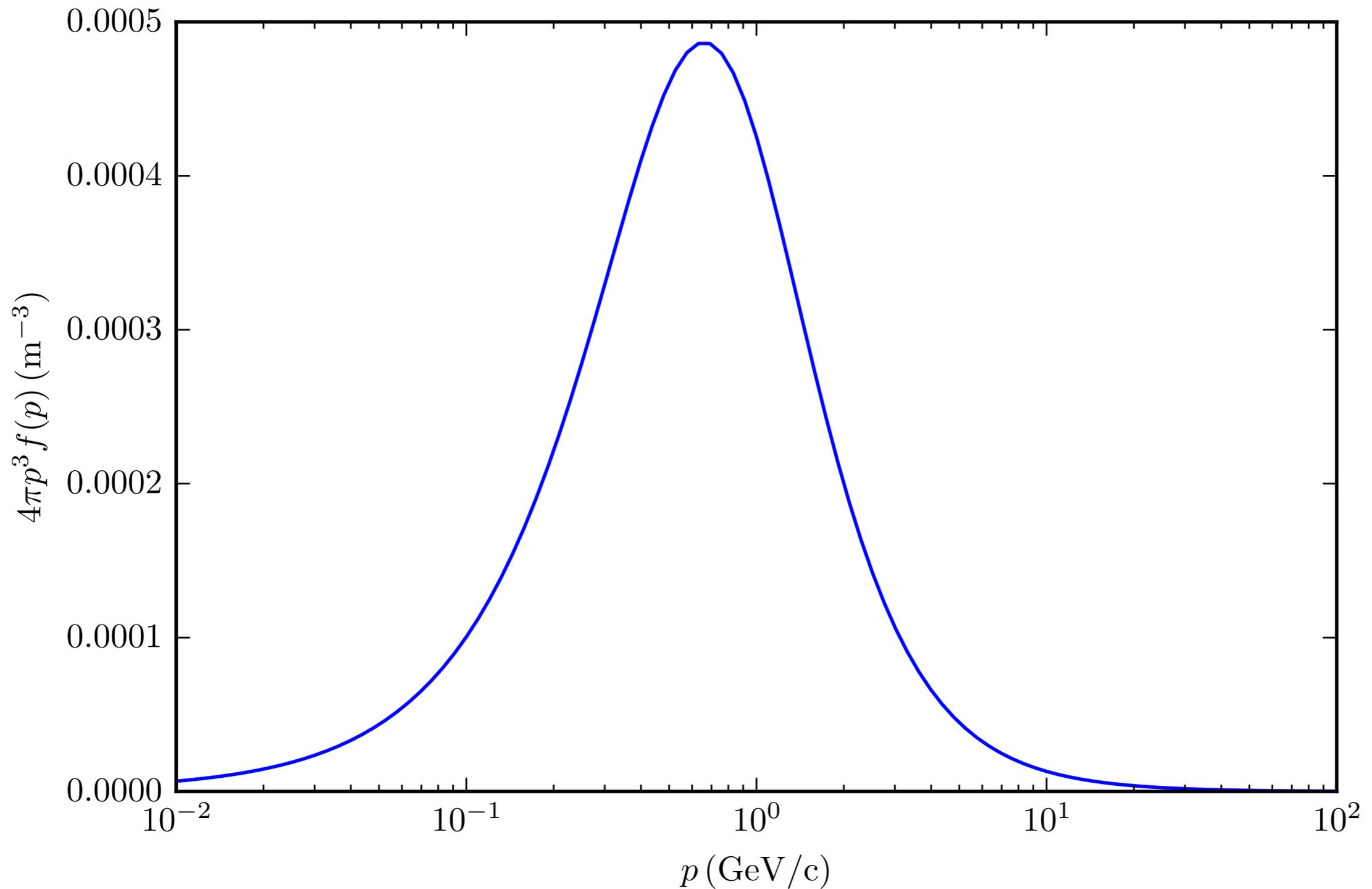
The local interstellar proton number spectrum from Vos and Potgieter (2015)
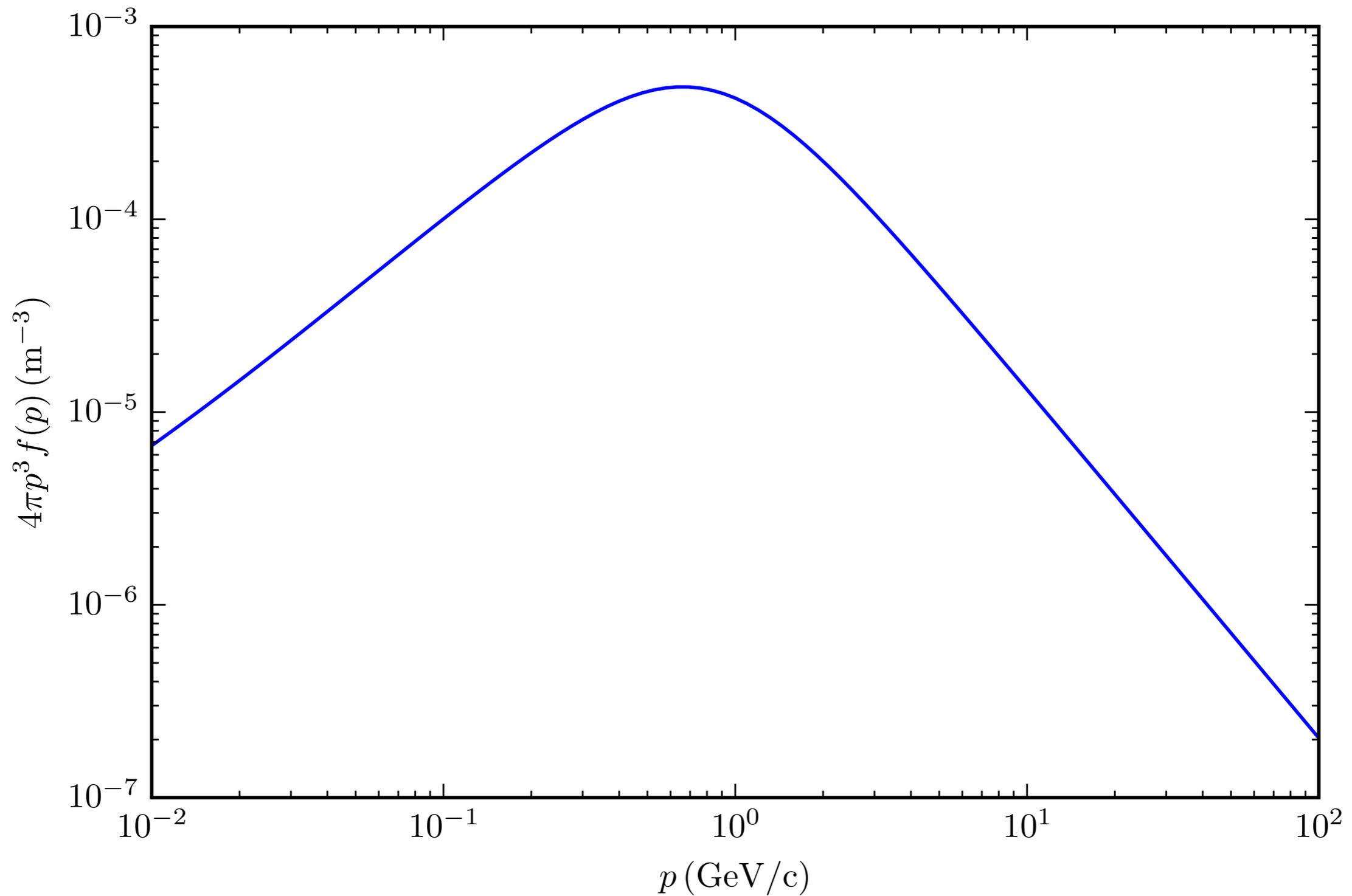
The same, but as a more conventional log-log plot
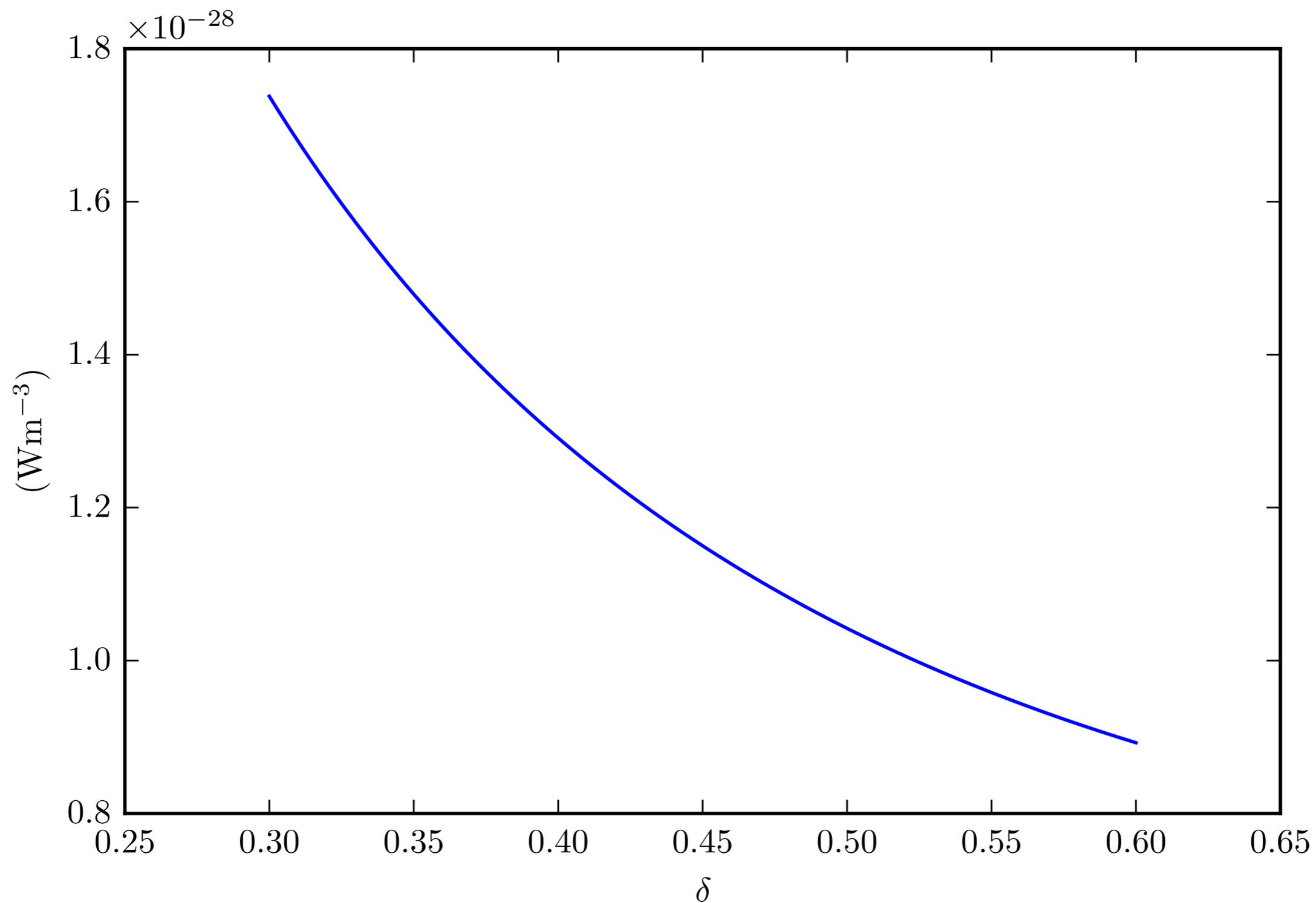
Diffusive re-acceleration power density

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

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 comes from reacceleration if standard Galprop fitting used!

- 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.

SNR shocks

ISM turbulence

$P_{\mathrm{SNe}} \approx 10^{35}\,\mathrm{W}$

$L_{\mathrm{GCR}} \approx 10^{34}\,\mathrm{W}$
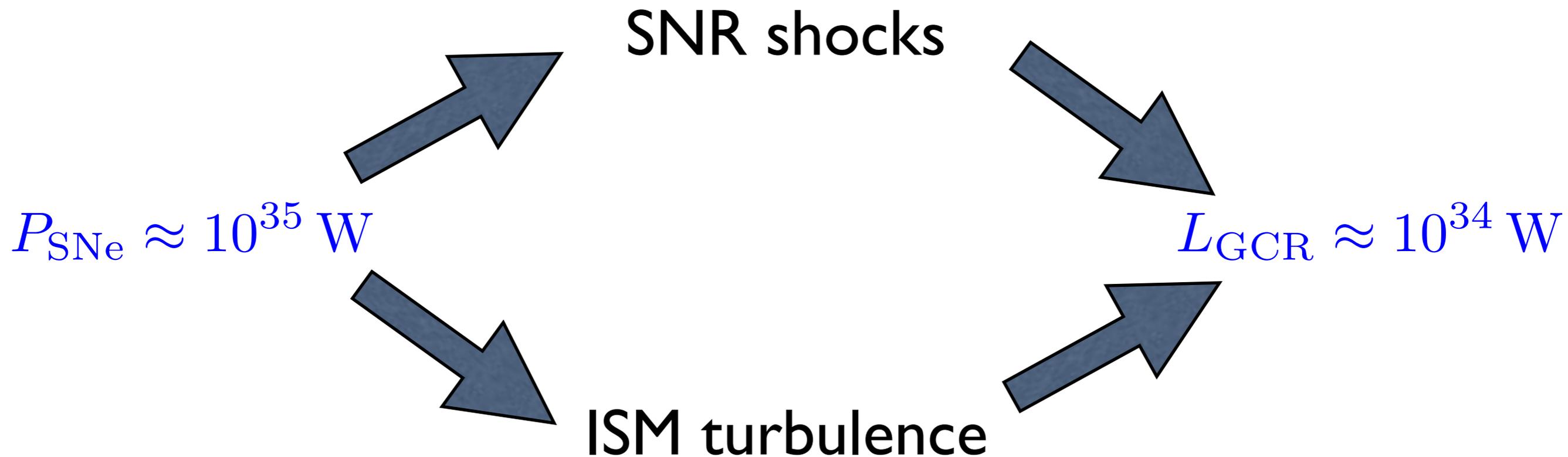
Other contributions not ruled out and indeed in some cases quite plausible!

- Pulsars - especially for electrons and positrons!

- OB associations, stellar winds.

- Galactic centre?? Needs variability? Mentioned as a possibility in GS64.

- Differential rotation of Galaxy and magnetic instabilities/reconnection?

The Galactic Centre

- Eddington luminosity of GC supermassive black hole is

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

- 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
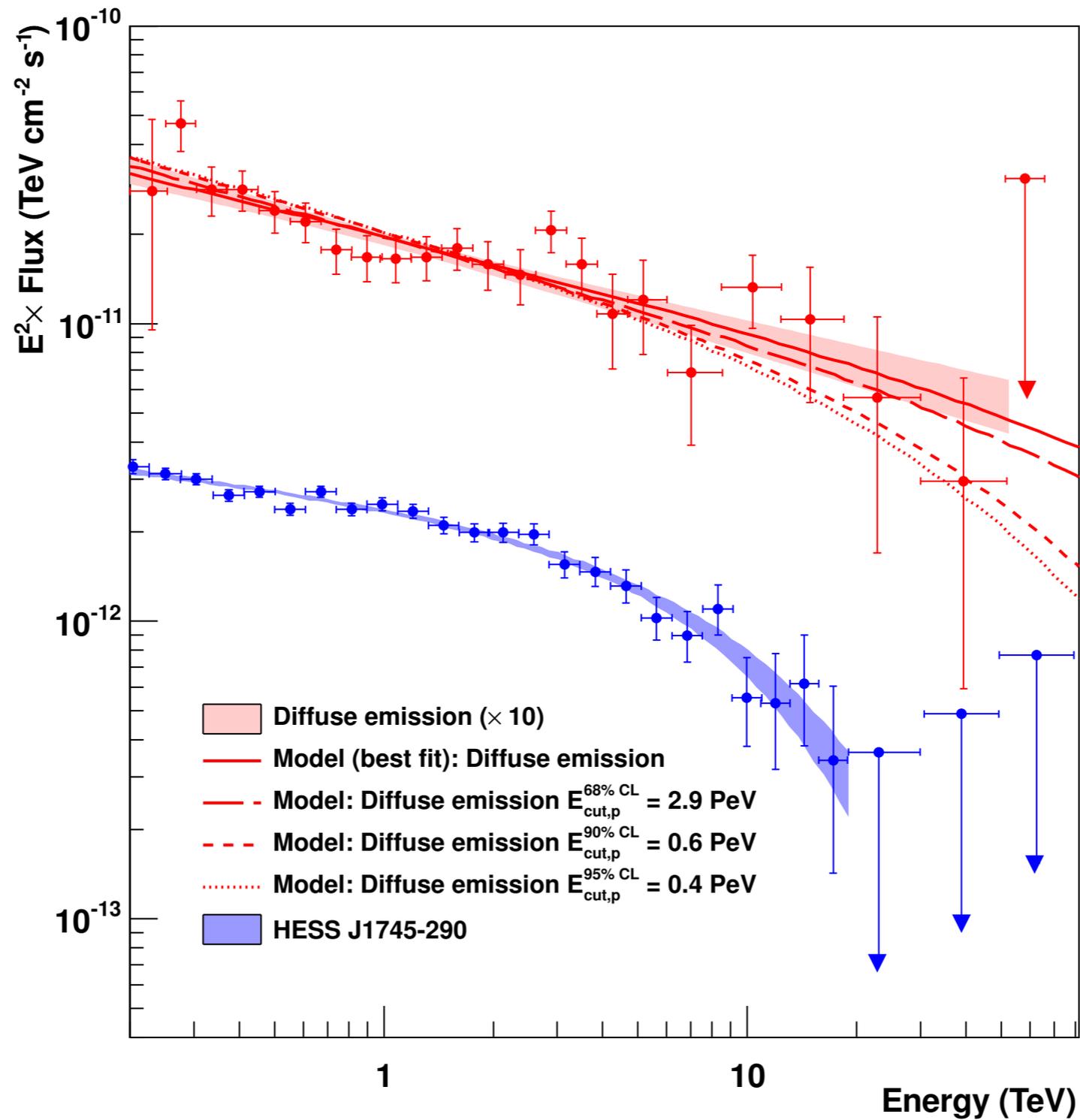
Figure 3: **VHE γ-ray spectra of the diffuse emission and HESS J1745-290.** The Y axis shows fluxes multiplied by a factor E^2, where E is the energy on the X axis, in units of $TeV cm^{-2}s^{-1}$. The vertical and horizontal error bars show the 1σ statistical error and bin size, respectively. Arrows 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.

27
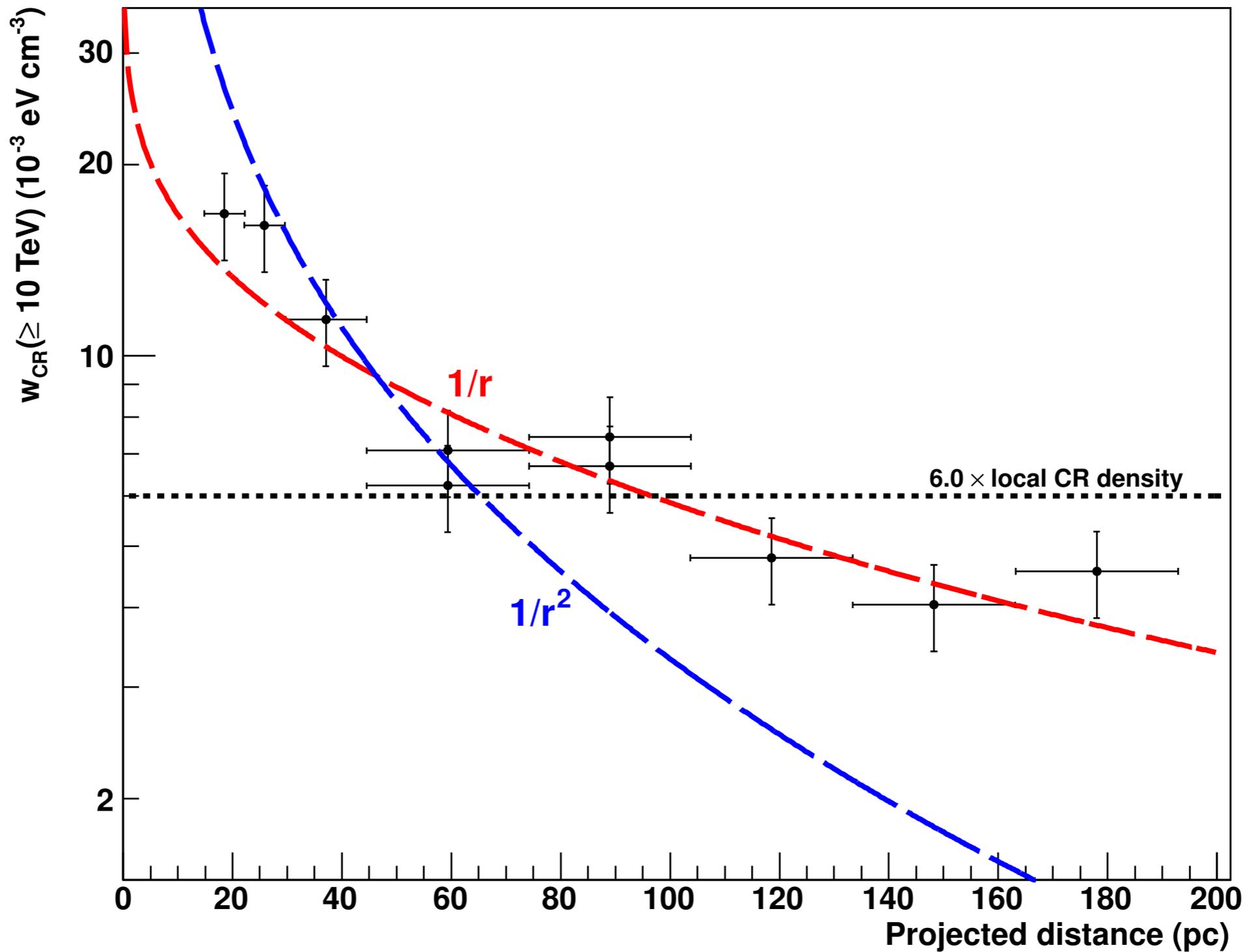
Figure 2: **Spatial distribution of the CR density versus projected distance from Sgr A*.** The vertical and horizontal error bars show the 1σ statistical plus systematical errors and the bin size, respectively. A fit to the data of a $1/r$ (red line, $\chi^2/\text{d.o.f.} = 11.8/9$), $1/r^2$ (blue line, $\chi^2/\text{d.o.f.} = 73.2/9$) and an homogeneous (black line, $\chi^2/\text{d.o.f.} = 61.2/9$) 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 if stronger in past?

Fermi bubbles also seem to require 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!).

rays in interstellar space. It can be said with certainty that any theory of the origin of cosmic rays cannot expect serious success unless it rests on a detailed analysis of the observed composition of primary cosmic radiation.

GS64 page 7

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 deviations from this in high resolution data (hydrogen definitely softer than helium).

- 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.
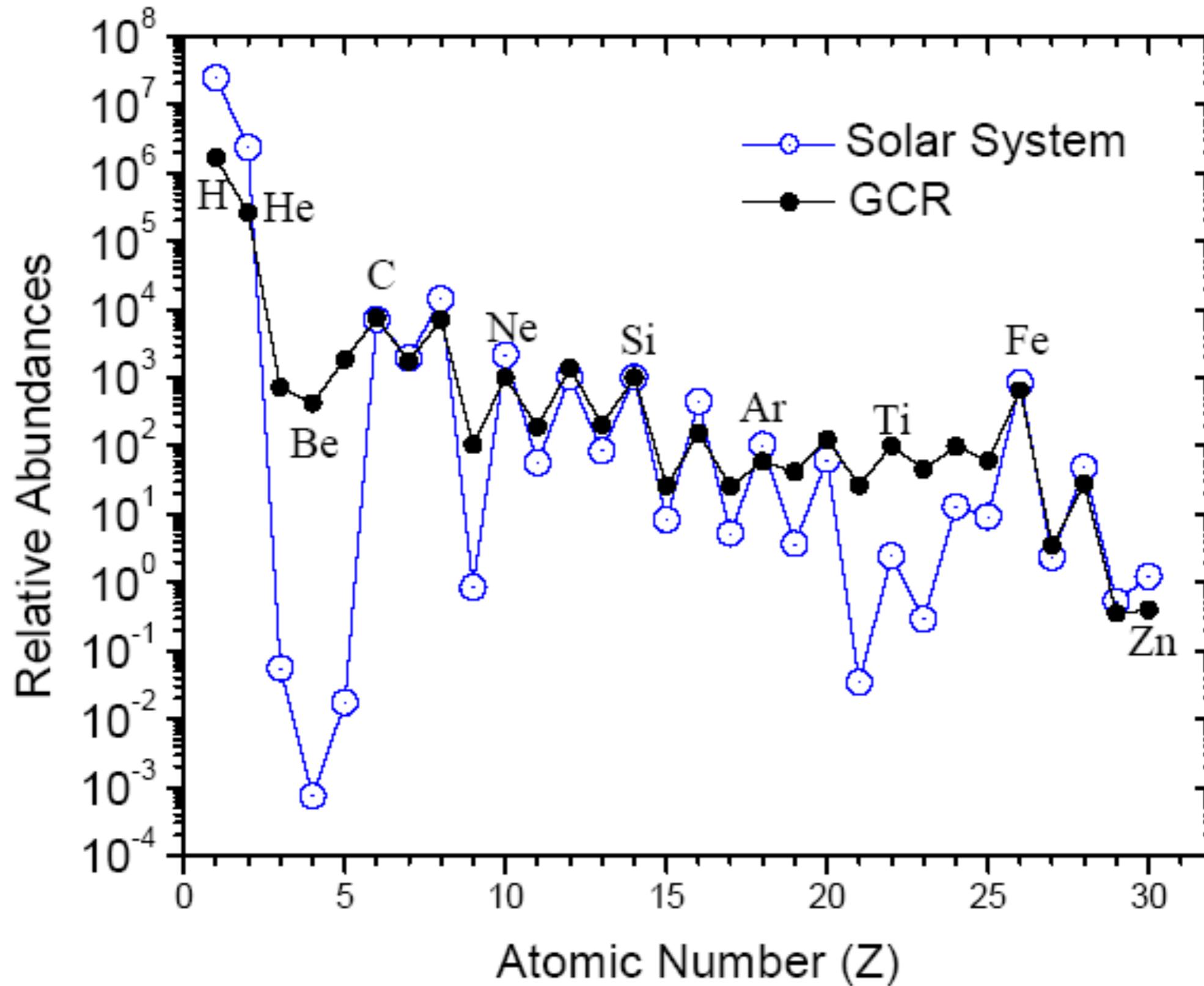
- Need much the same nucleosynthetic mix as in solar system material - not all r-process for example. No one class of SNe.

- 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…..
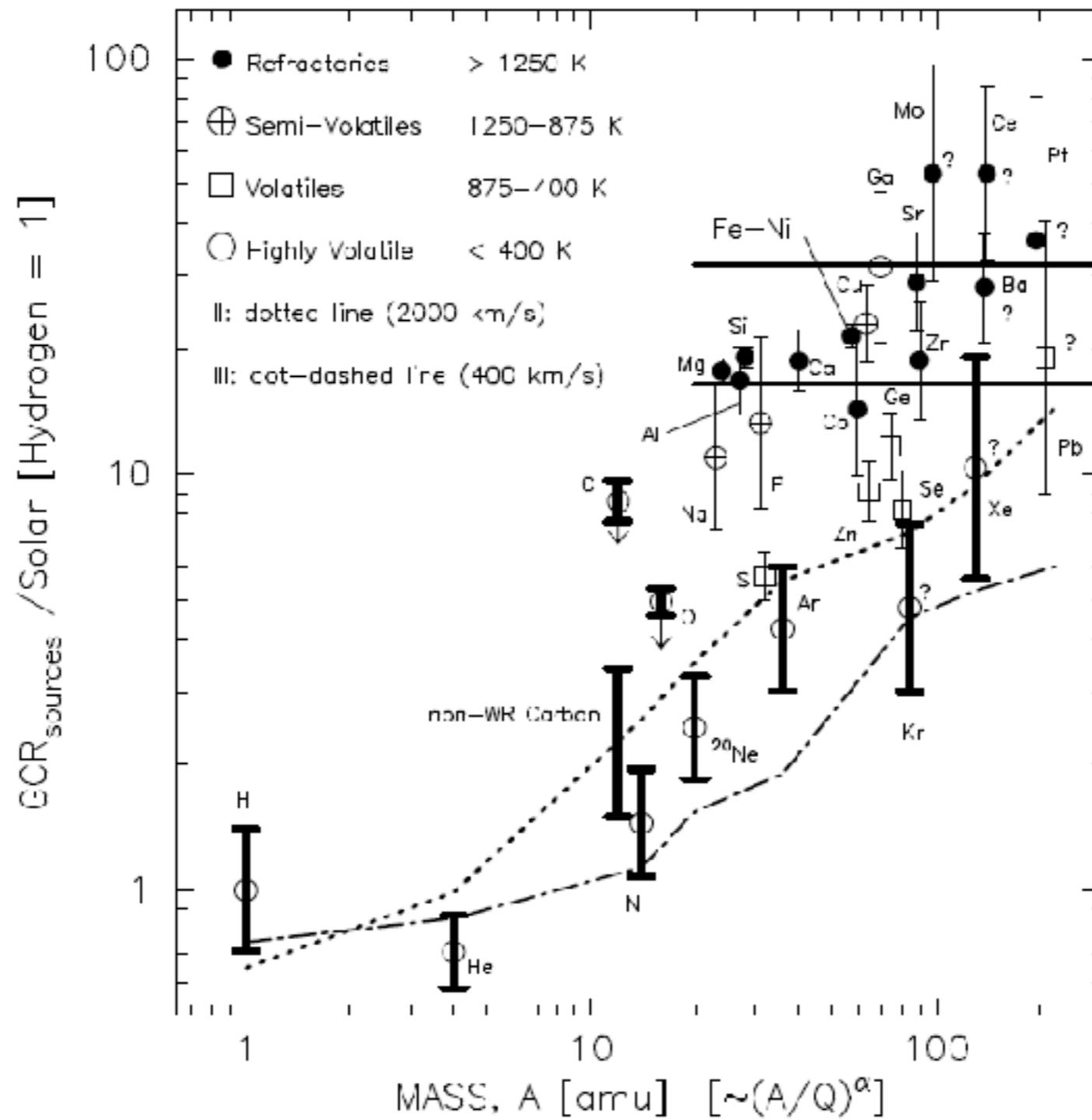
From Ellison, Drury and Meyer (1997) ApJ 487 197
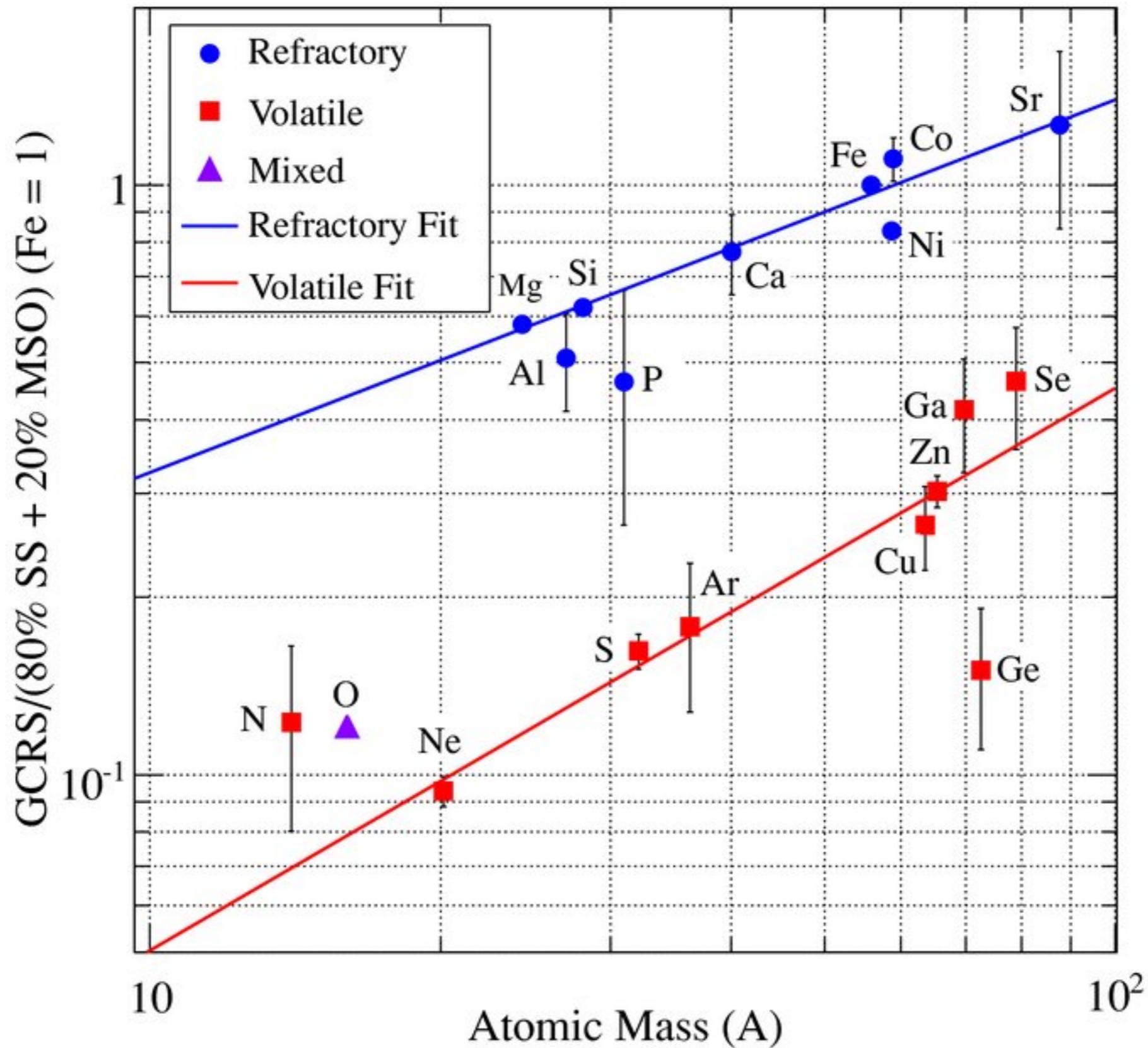
Rauch et al, 2009 ApJ 697, 2083 COSMIC RAY ORIGIN IN OB ASSOCIATIONS AND
PREFERENTIAL ACCELERATION OF REFRACTORY ELEMENTS: EVIDENCE FROM
ABUNDANCES OF ELEMENTS 26Fe THROUGH 34Se

37
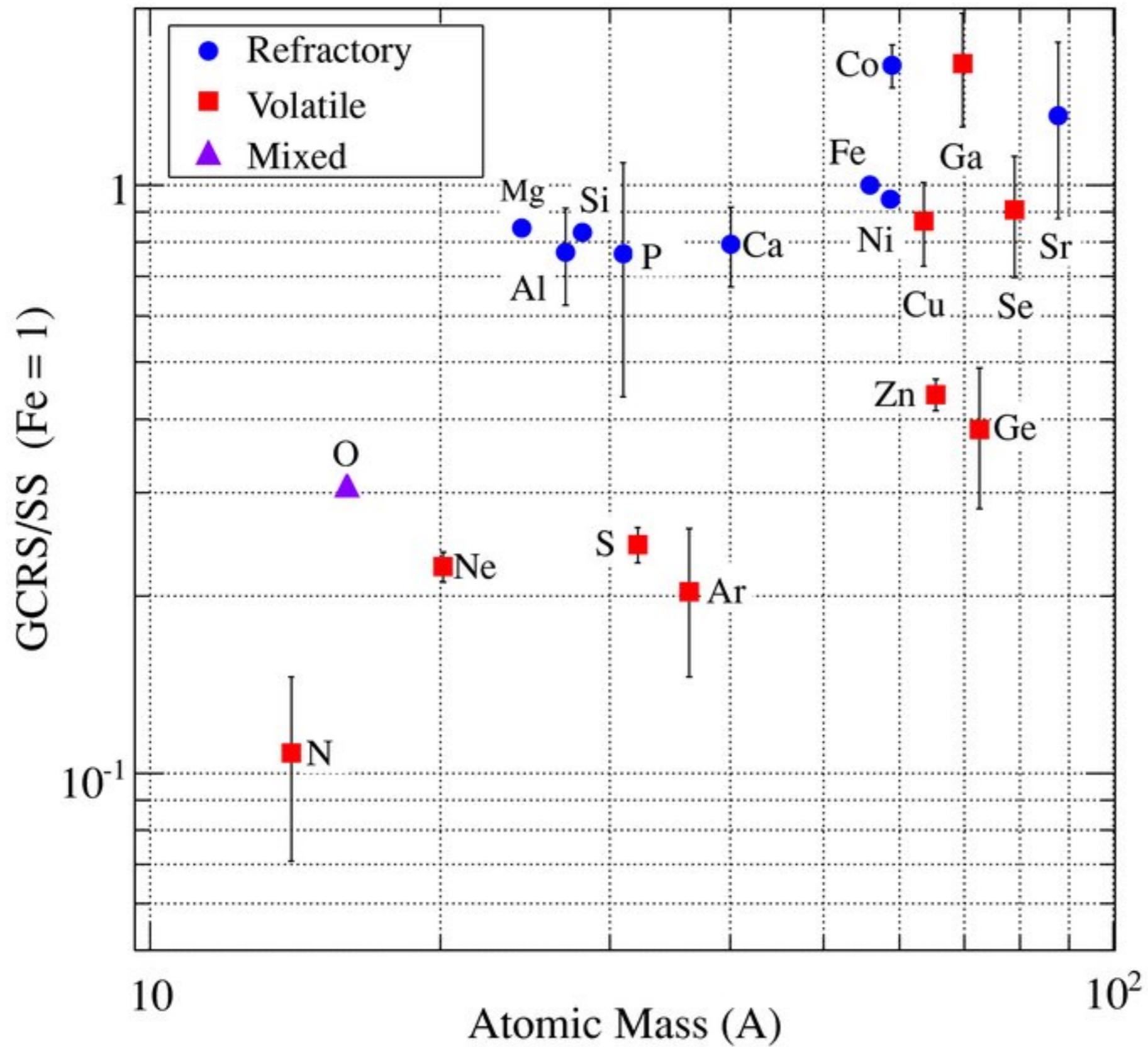
Latest Tiger results (Murphy et al, arXiv:1608.08183)

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.
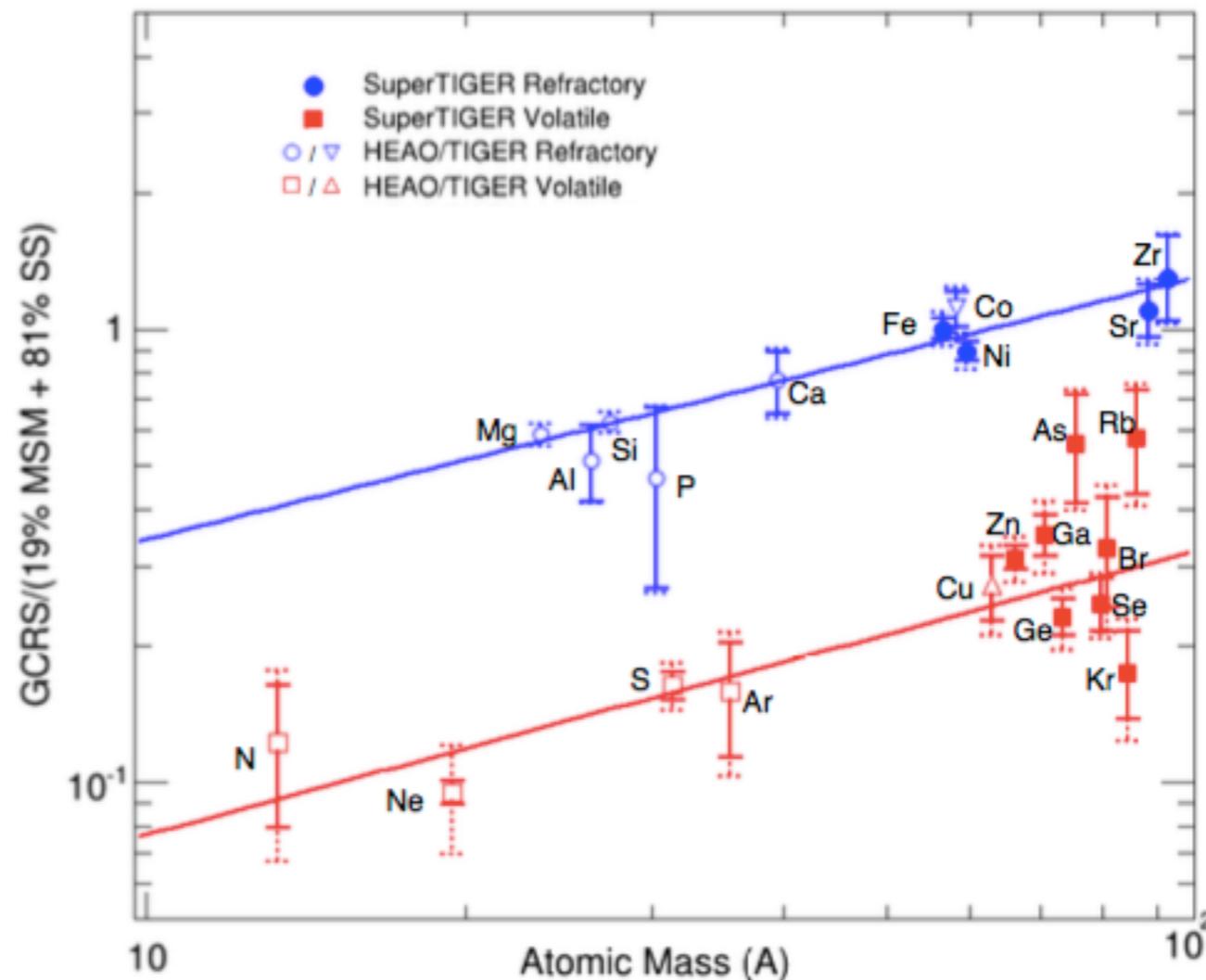
Time to acceleration?

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

See talk by Dieter Breitschwerdt for more on ^{60}Fe

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.

43
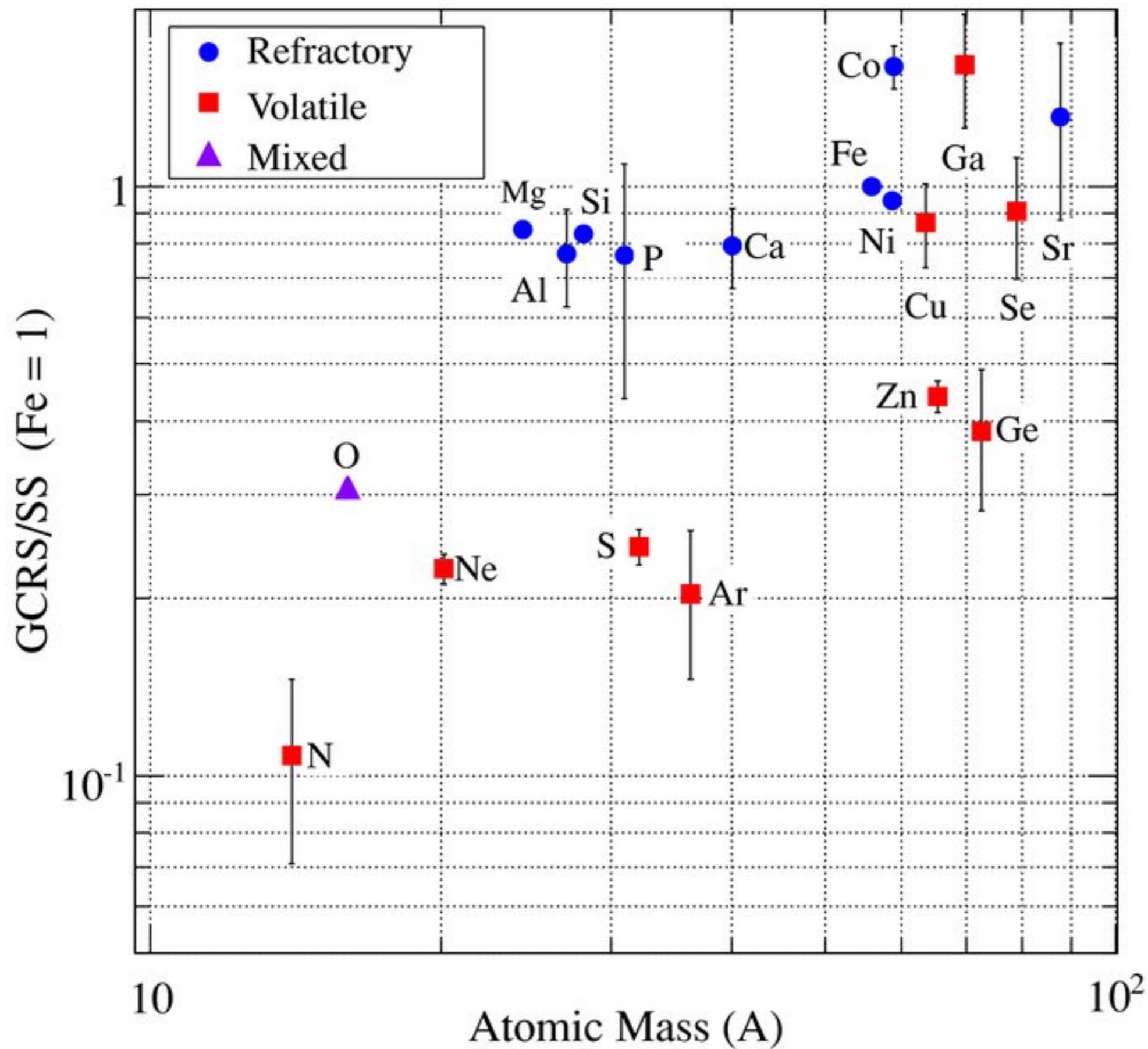
Ultra-heavies and r-process enhancements.

- 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.
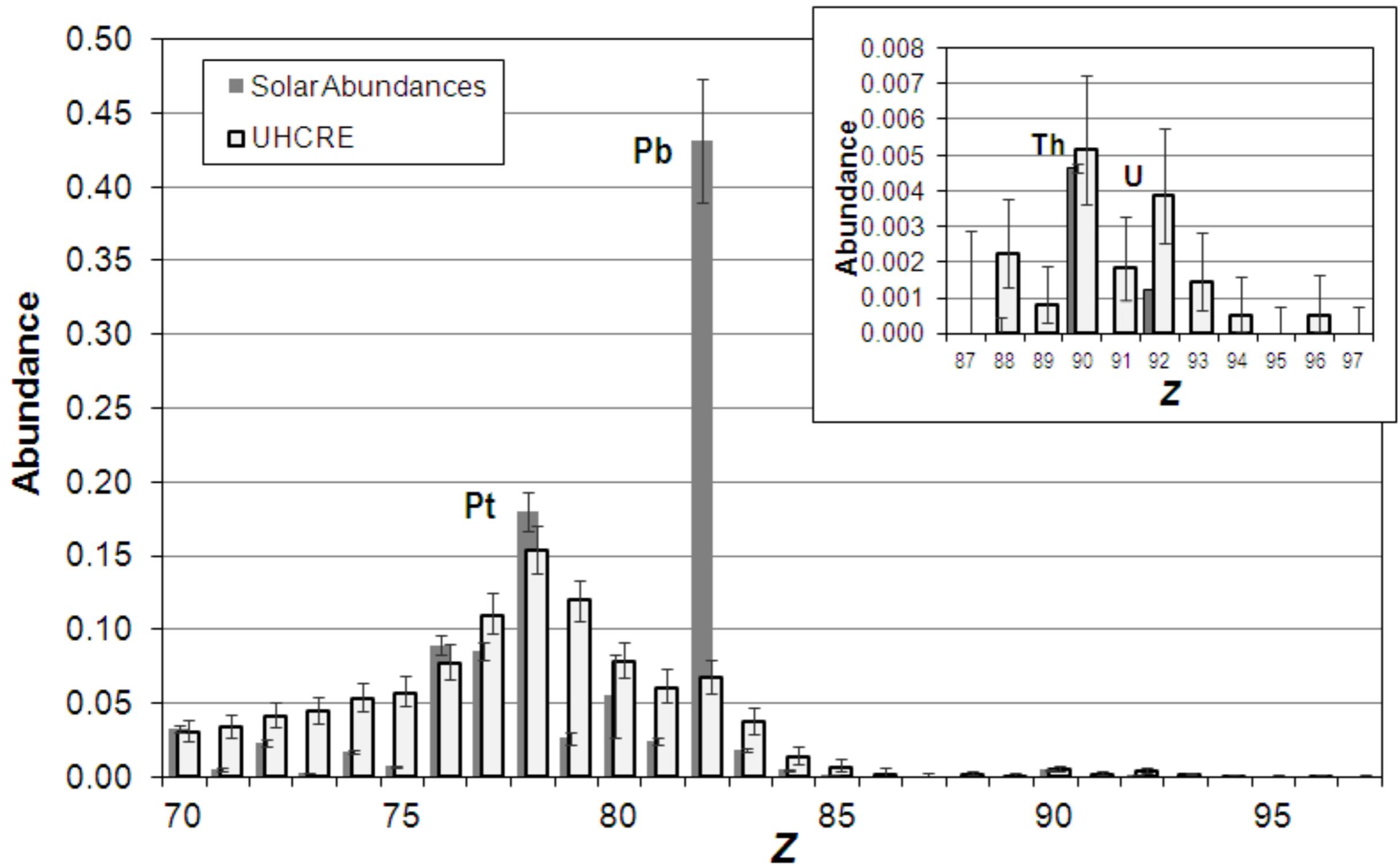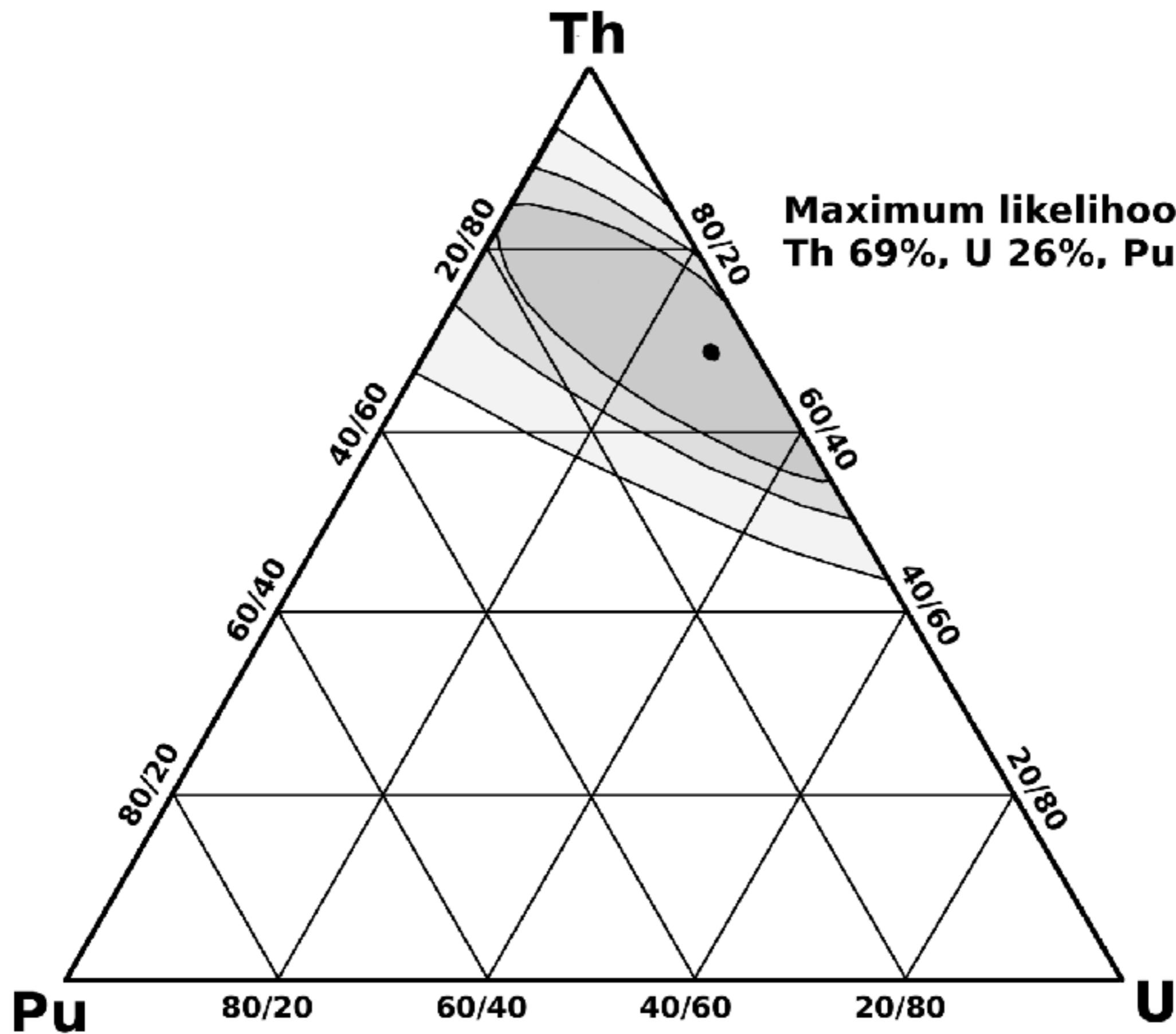
Maximum likelihood is Th 69%, U 26%, Pu 5%

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!).

- 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. but reasonably well understood IF shock structure steady (Eichler, Malkov, Blasi).

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? Now clear that proton spectra are softer than helium - was Grigorov right after all?

Observational tests

- GS64 pointed to radio astronomical observations to trace CR electrons in Galaxy and in SNRs.

- Now have non-thermal X-rays.

- GeV to TeV gamma rays.

- Evidence for acceleration to 100TeV of electrons and probably of protons in some SNRs.

- Not as clear cut as we had hoped! But case is quite convincing.

Remaining problems

- Getting to the "knee" remains a challenge.

- Origin of the particles above the "knee"?

- Why is the anisotropy so low?

- Tension between theory and observation on the production spectrum - how hard?

- Origin of the UHECR - extragalactic sources?

- Dynamical transport models needed - not just diffusion.

Magnetic reconnection remains a real alternative acceleration mechanism!

- Seen in many systems (solar flares, geo-magnetic events, laboratory plasmas).

- Sudden release of magnetic energy seems only plausible mechanism for Crab flares?

- But difficult to model - no simple theory and complicated geometry. PIC codes making progress however (Spitkovsky, Sironi et al).

Summary and conclusions

- Energetics still seem to point to SNRs as ultimate engine for most GCR production below a PeV or so as first stated by GS64.

- Composition points to correlated SNRs and super bubbles.

- Role of turbulent diffusive reacceleration and magnetic reconnection needs to be reconsidered, but DSA still "best bet".

- The Galactic centre Pevatron detection is an exciting new development but significance unclear.

- Propagation models need to be much more dynamic with CR-driven outflows and winds (Fermi bubbles).

- For the most part GS64 got it astonishingly right!