Particle Acceleration in Various Environments

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2016

Old predictions, not so old observations.

Predictions:

Non-linear theory of diffusive shock acceleration: kinetic approach that accounts for feedback of the cosmic rays on the flow . (DE 79, 1984, Ellison & DE 1985, Malkov,….Blasi 2001) [use good-enough scheme]

It predicts a differential energy spectrum of $E^{-2}dE$

[or for **NR** particles**, a phase space distribution going as….p^{-5} [NOT p^{-4} as in linear theory for strong shock] just above the injection threshold.**

And approximately this value almost everywhere – by at most ½ order of magnitude over 12 orders of magnitude in energy for a range of compression ratios.

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In order to get this steepening, compression ratio of sub-shock must be reduced to 2.5 – ε, where ε depends on exact definition of sub-shock.

Ellison and Eichler, 1985

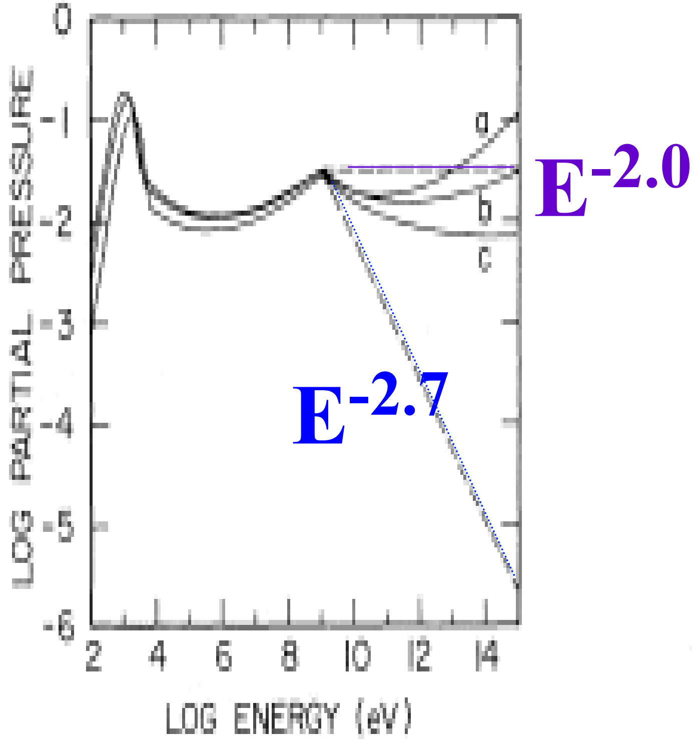


FIG. 1. Post-shock partial pressure, $p_2(E)$, vs energy, E. An energy cutoff = 10^{15} eV has been used. Each label represents a family of curves with a particular u_1/u_{GeV}. The dashed lines indicate the inferred CR source (horizontal) and observed spectra [note that for fully relativistic energies, the partial pressure is proportional to $E^2N(p)$].

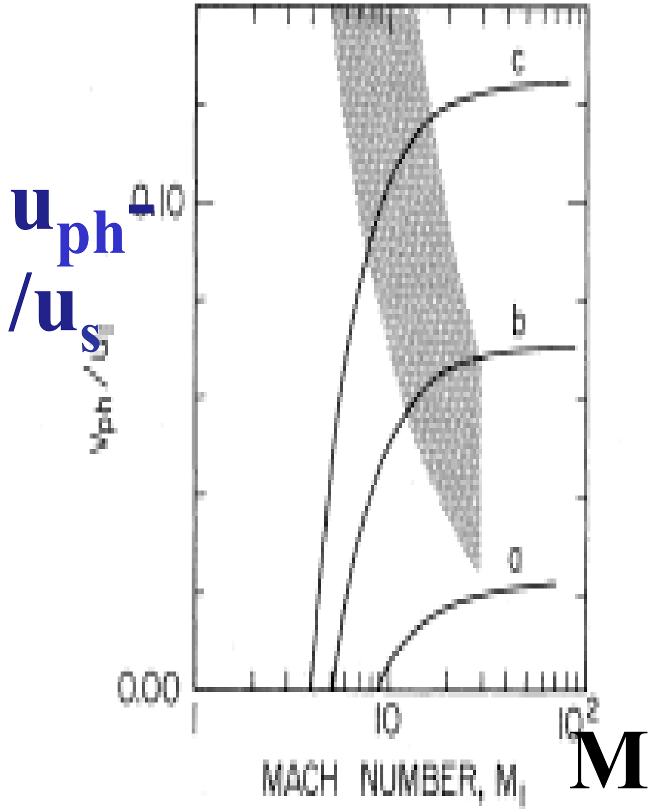


FIG. 2. Phase velocity vs acoustic Mach number. Labels are the same as in Fig. 1. The stippled area shows expected values for SNR's in the HISM if we assume a sound velocity of 100 km s^{-1}, a maximum shock velocity of 3000 km s^{-1}, and $70 < v_A < 200$ km s^{-1}. Most of the volume swept out by the SNR is during the later stages, corresponding to the upper part of the stippled area.

Note that phase velocity of waves, u_{ph}, can be greater than the Alfven velocity when the waves are growing rapidly (Eichler, Ellison, and Fiorito, 1991), so if M_A=100, u_{ph}/u_s can be >>0.01.

Also note that you don't just subtract u_{ph} from u_s, the calculation also includes creation of wave energy and heating of gas by both wave damping and compression. So Mach number is well below M_ by the time fluid element arrives at shock.

This spectrum is insensitive to compression ratio, which is fortunate, since the compression ratio is expected to be different from 4.

Small phase velocities dynamically significant

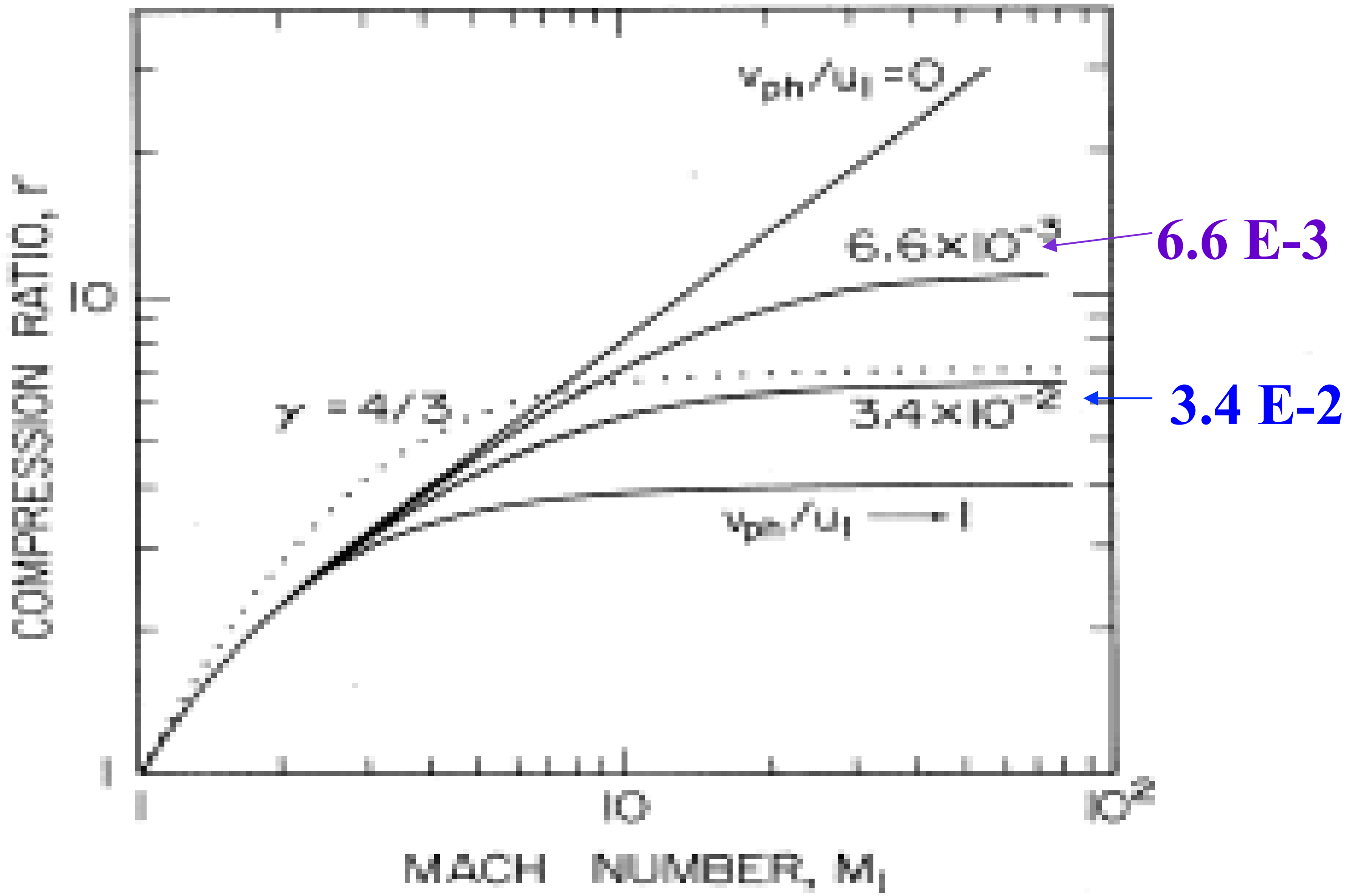
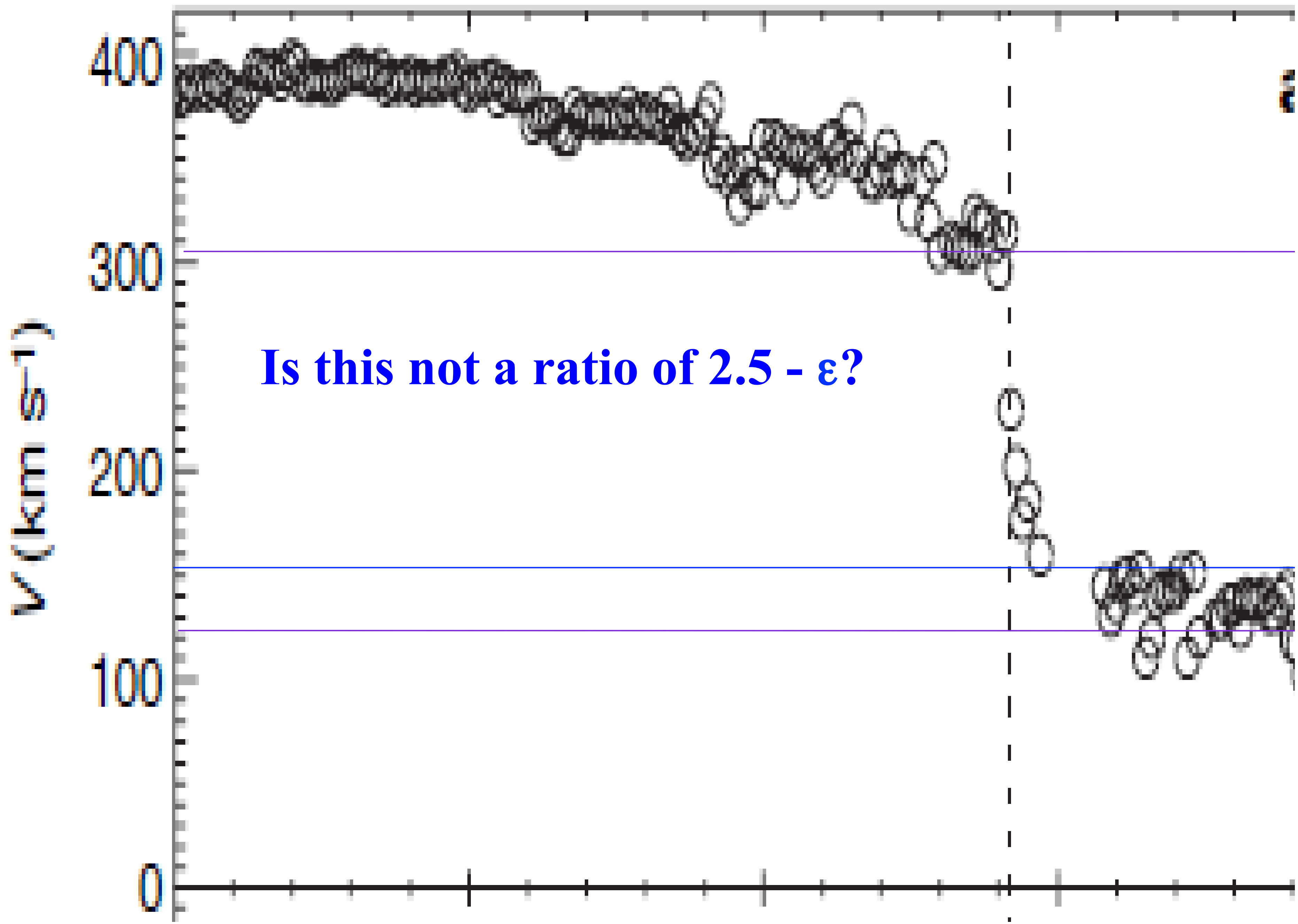


FIG. 3. Compression ratio r vs acoustic Mach number M_1. The dotted line is the classical compression ratio for a relativistic equation of state ($\gamma = \frac{4}{3}$). The curve $v_A/u_1 \to 1$ is just the classical result for $\gamma = \frac{5}{3}$, because no cosmic rays are produced in this limit.

Observations:

The Solar Winds Termination Shock (Richardson et al 2008)



"Common" spectrum (Gloeckler and Fisk 2006……2014)

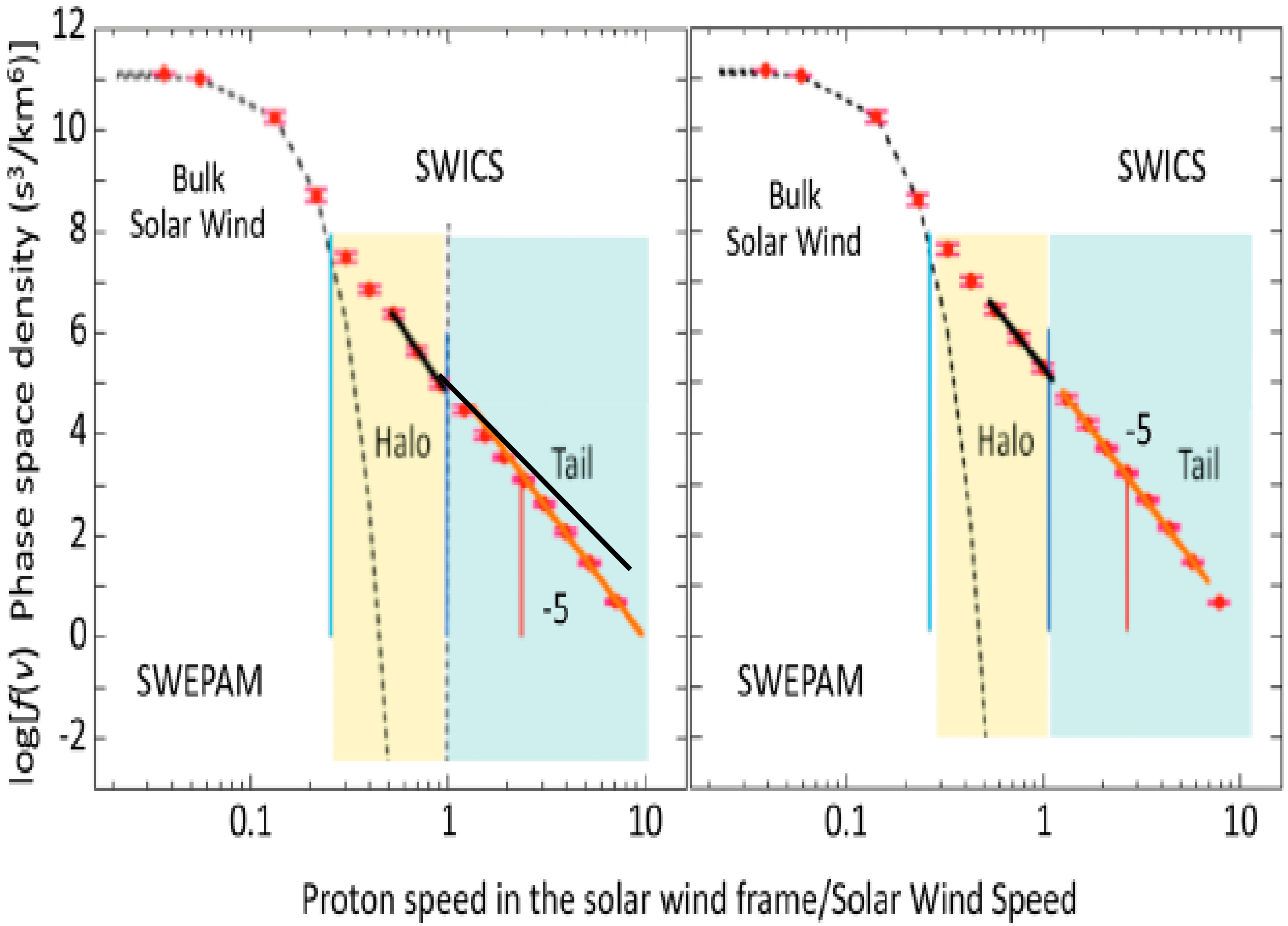


Figure 3. One-hour averaged solar wind frame velocity distribution functions showing the proton bulk solar wind, the halo, and the tail segments during hour 11 of 12 August 2001, (left) during which the strong (compression ratio of 3.85 ± 0.15) shock passed ACE and (right) during the hour of peak tail density that was observed 1 h downstream of the shock.

Preferential acceleration of Heavy Ions

(Hainebach and Eichler, 1981, Ellison Jones and Eichler, 1981)

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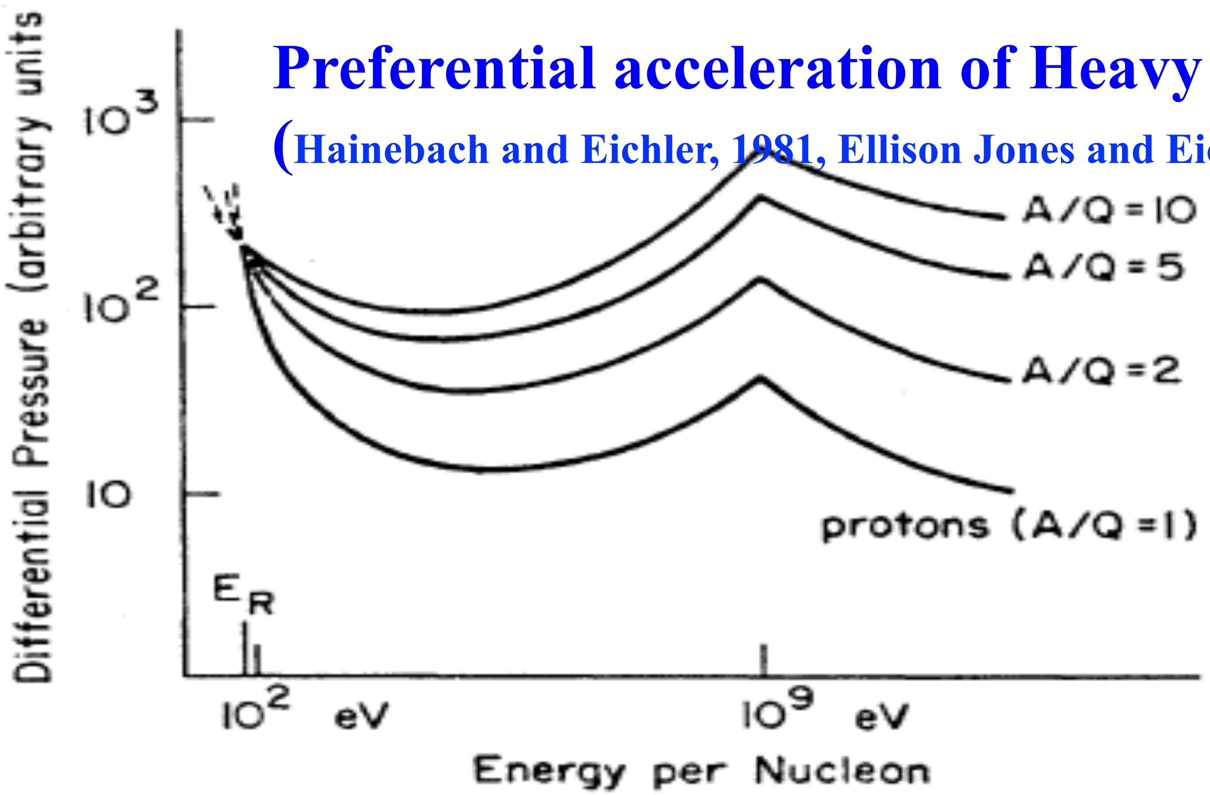
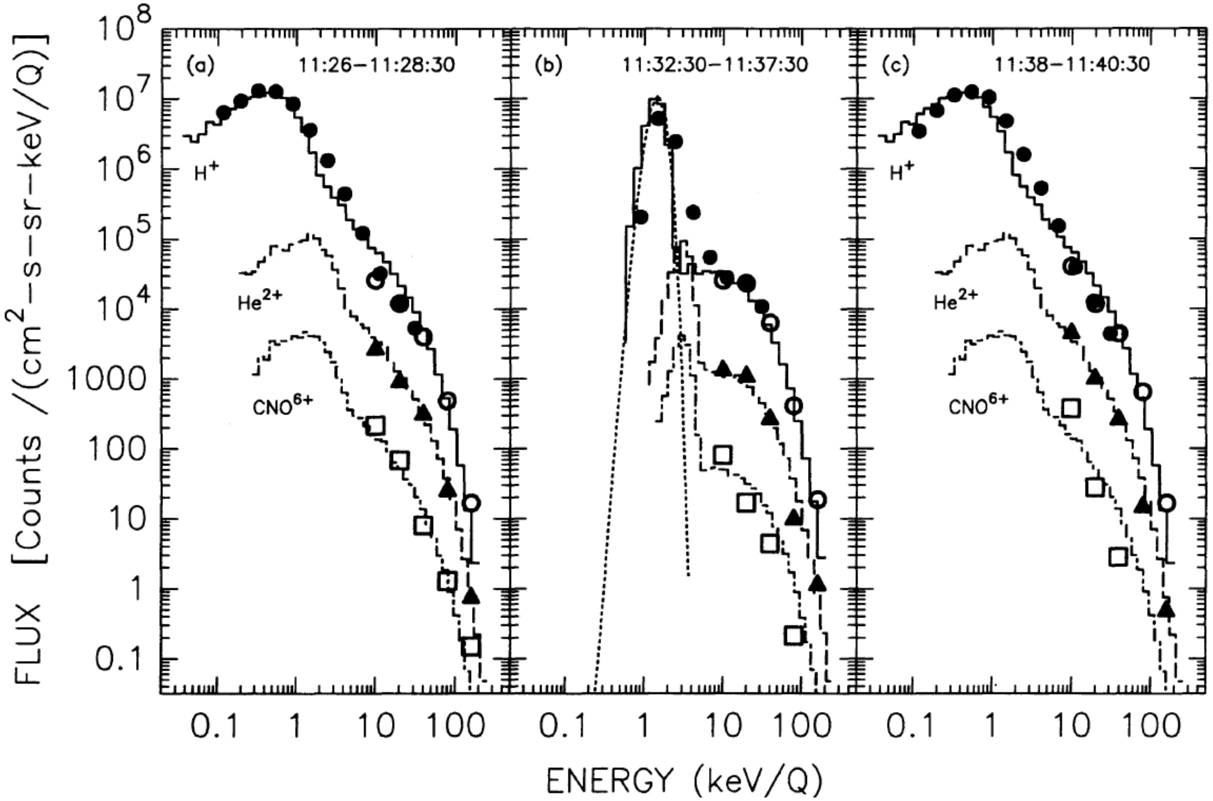


FIG. 1. Ion spectra, as determined by Eqs. (4)–(6), and the approximations in the text, are displayed for the mass-to-charge ratios (A/Q) of 1 (protons), 2, 5, and 10. The overall compression ratio $u(-\infty)/u(+\infty)$ is chosen to be 4. The minimum energy E_K at which the particles are injected by viscous heating is chosen to be 65 eV, corresponding to a shock velocity of roughly 700 km s^{-1}. The actual functions plotted are $(p^2/3m)F_i$ below $m_p c^2$ and $(pc/3)F_i$ above $m_p c^2$. The spectra are normalized so that they all intersect at E_K.

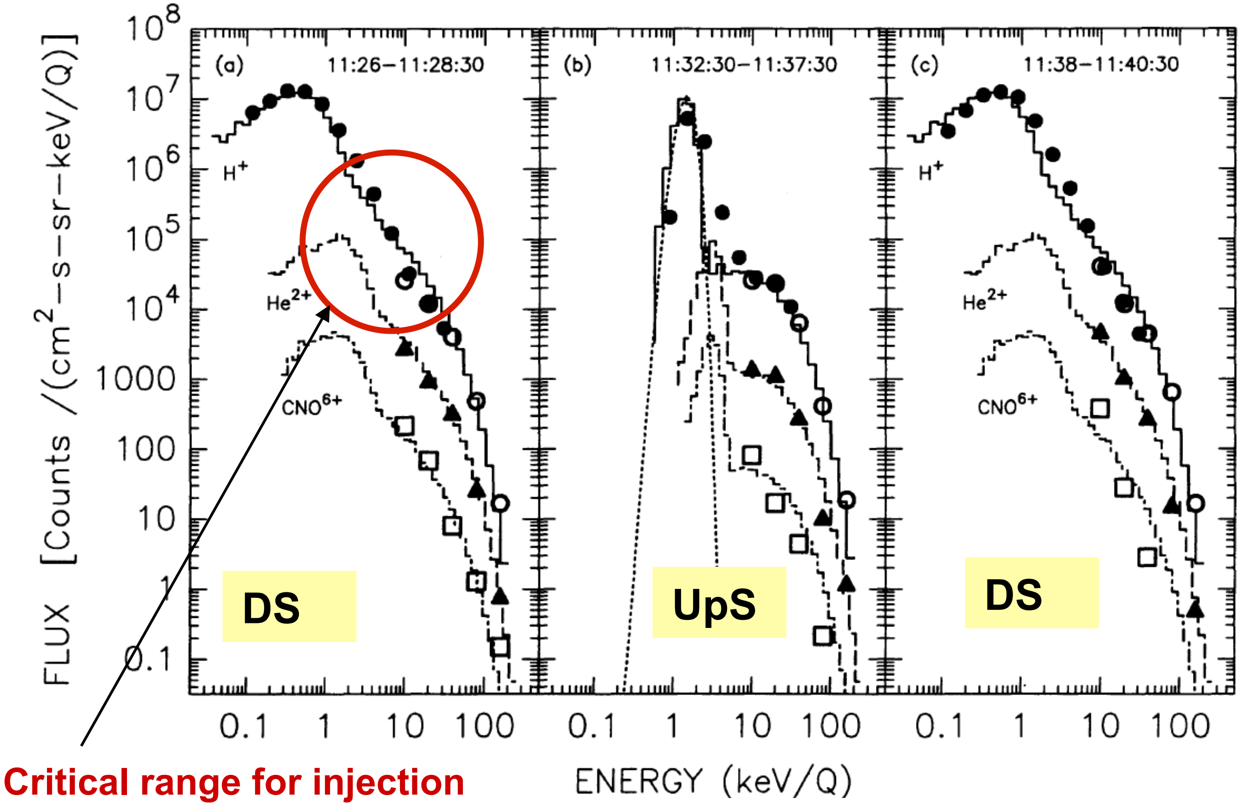
Earth's Q-parallel Bow Shock (Ellison, Mobius, and Paschmann 1990)



All particles, including thermal ones, are computed with MC simulation, modeling magnetic scattering as BGK

Quasi-parallel Earth Bow Shock: **Modeling & observations suggests nonlinear effects are important**

Ellison, Mobius & Paschmann 90



AMPTE observations of diffuse ions at Q-parallel Earth bow shock

H+, He2+, & CNO6+

Observed during time when solar wind magnetic field was nearly radial.

A/Q enhancement predicted by NL DSA matches obs.

Upstream & downstream spectra fully consistent with nonlinear shock acceleration

Observe injection & acceleration of thermal solar wind ions at Quasi-parallel bow shock

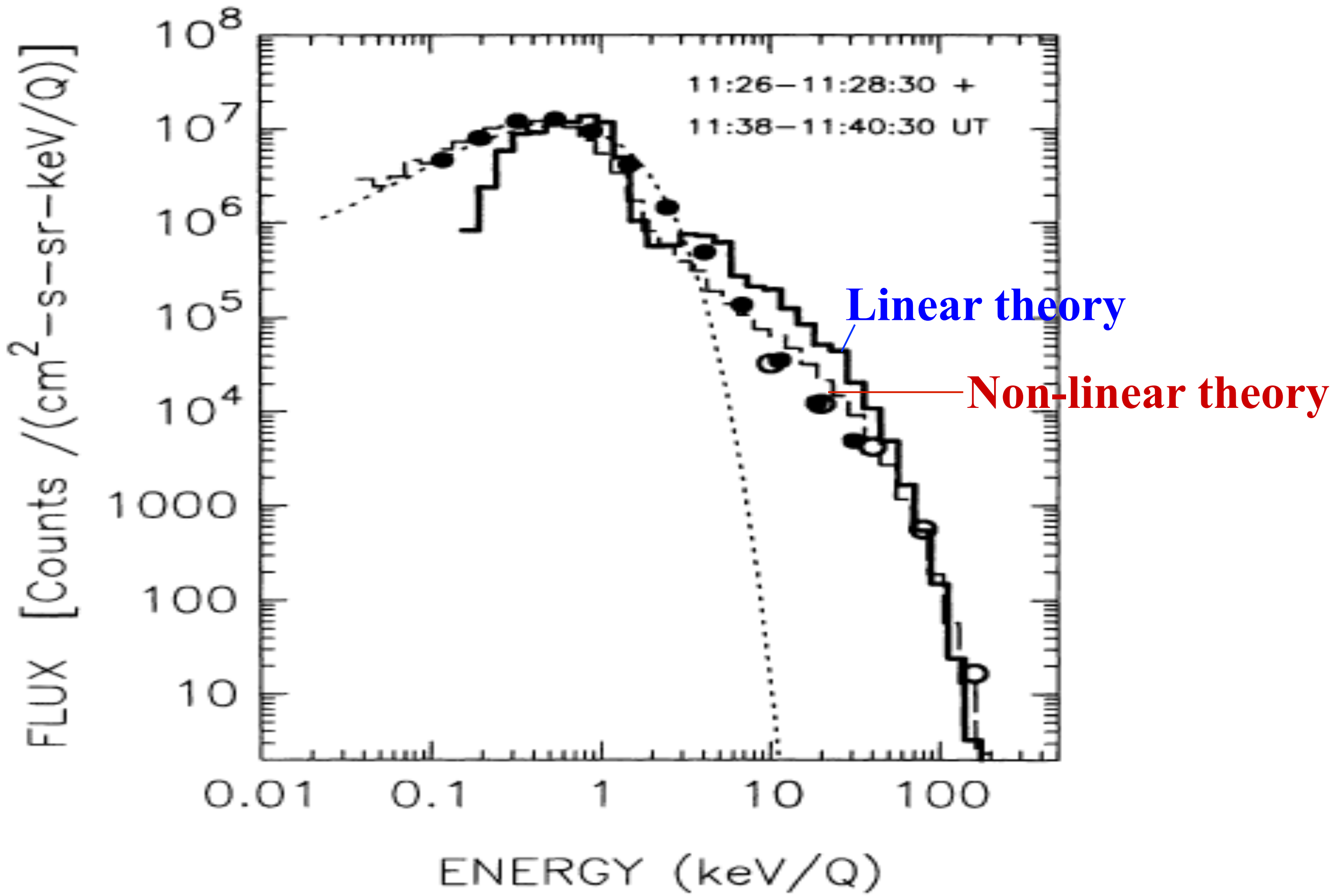
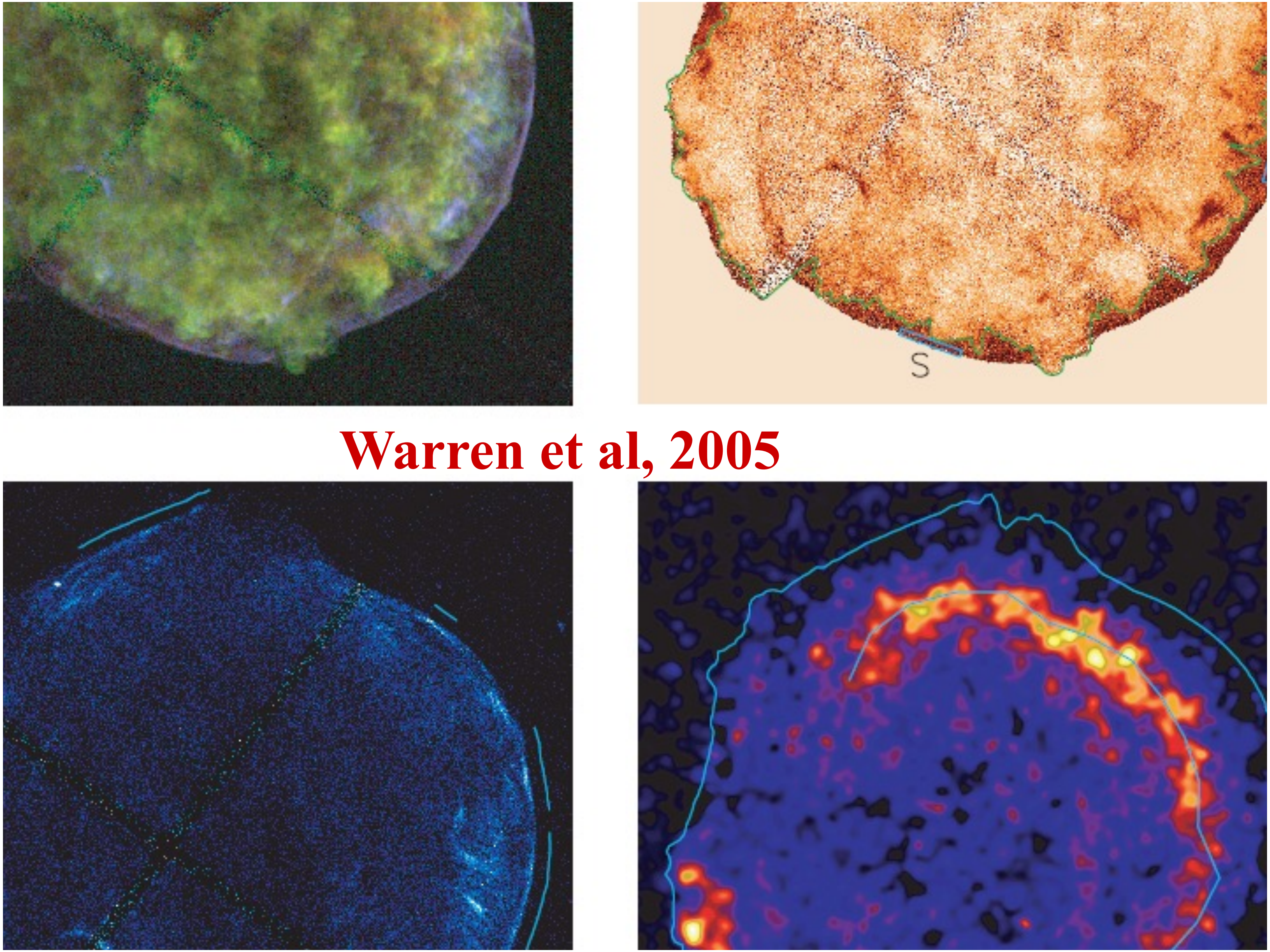
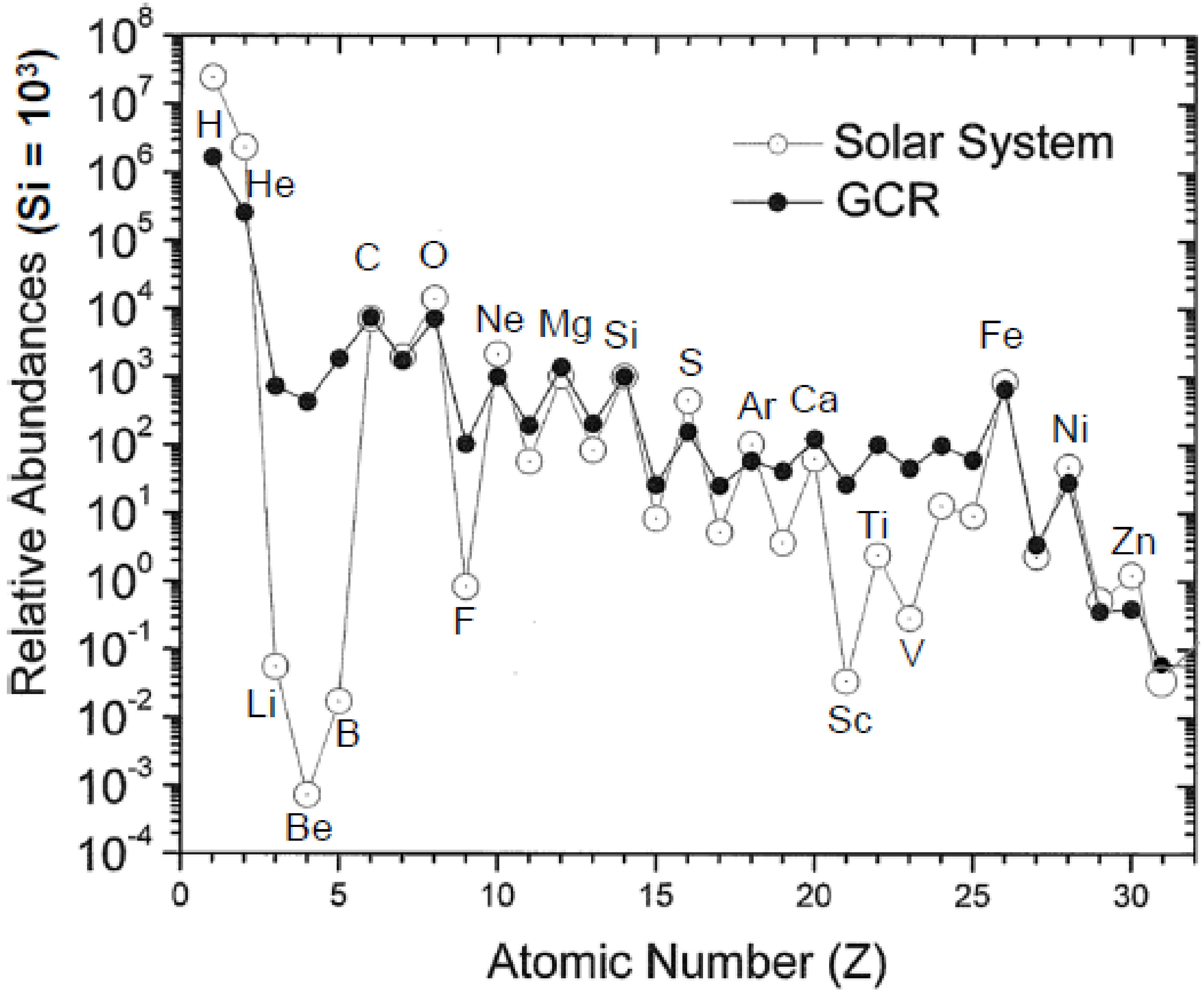


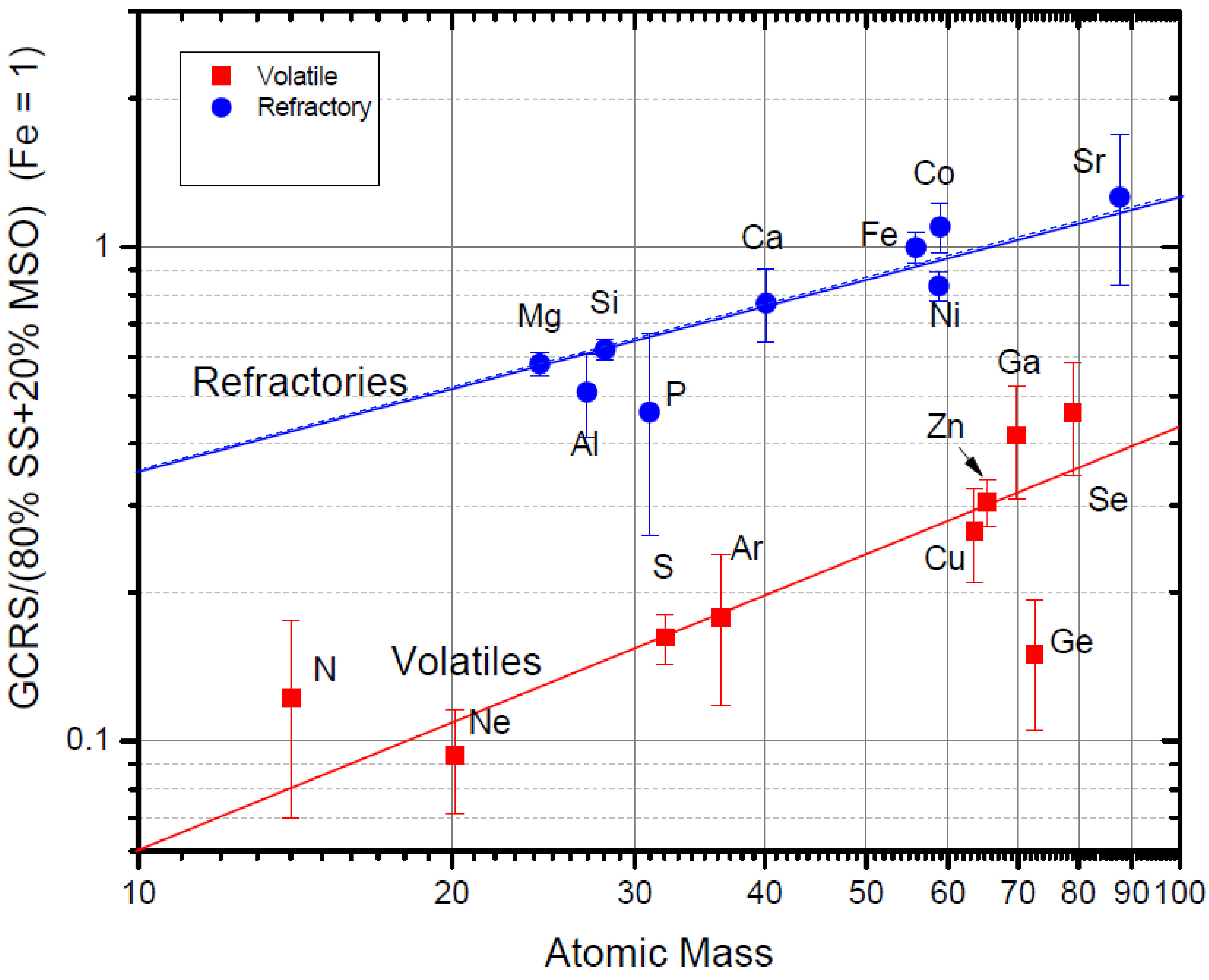
FIG. 13.—Downstream spectra (*points plus dashed line*) compared to a thermal distribution (*dotted line*). The thermal distribution has a temperature of 6×10^6 K, a density of 5.7 cm^{-3}, and a velocity of 115 km s^{-1}. Also shown is the Monte Carlo simulation result for a discontinuous shock transition (dotted line in Fig. 9). The heavy solid line shows the best fit obtainable for the given solar wind conditions when no upstream slowing of the solar wind is assumed.



Warren et al, 2005


Relative Abundances (Si = 10³)
Atomic Number (Z)
Solar System
GCR
H
He
Li
Be
B
C
O
F
Ne
Mg
Si
S
Ar
Ca
Sc
Ti
V
Fe
Ni
Zn

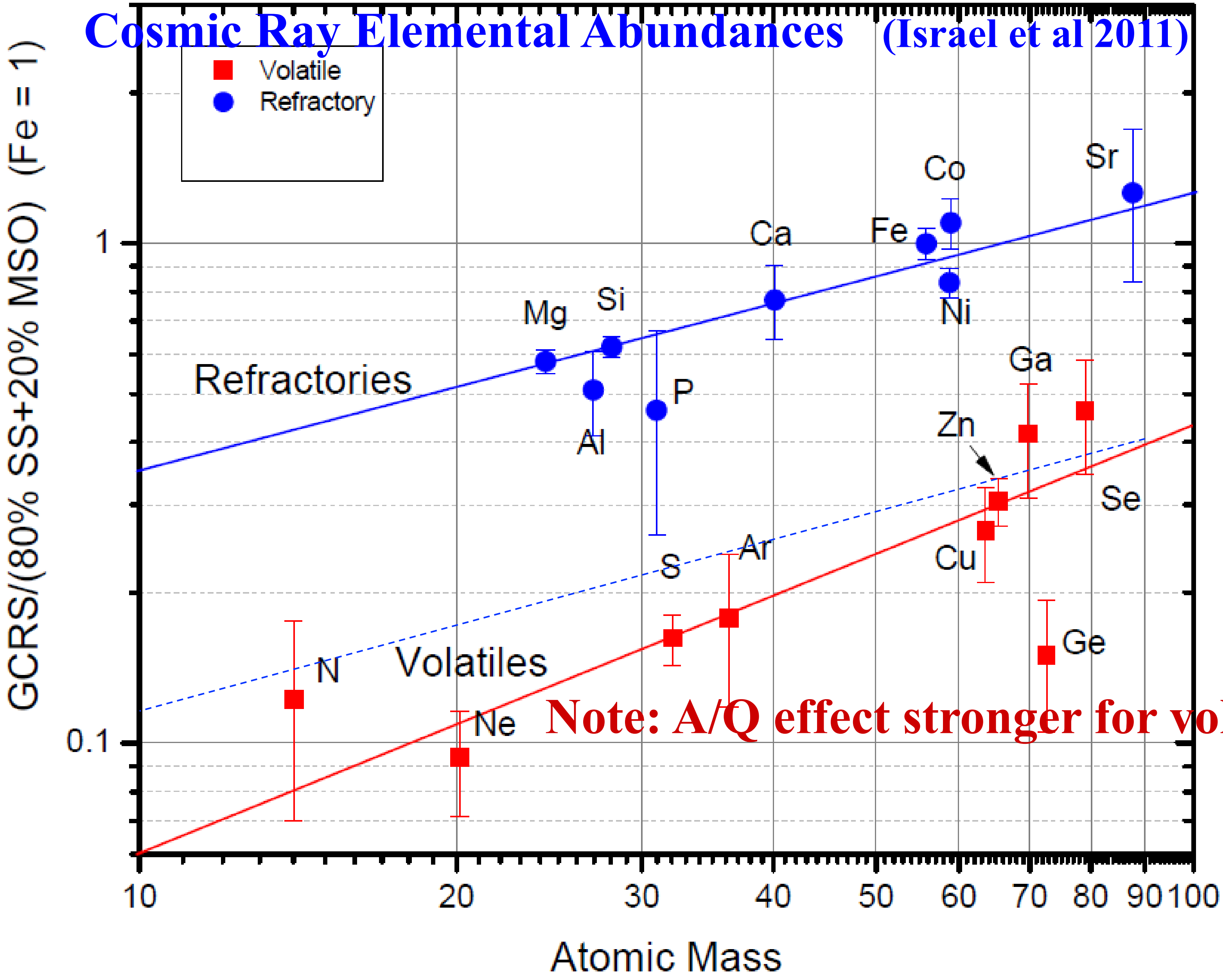
Cosmic Ray Elemental Abundances (Israel et al 2011)



Now compare GCR source abundances with a mixture of 80% SS (Lodders) and 20% Massive Star Outflow including SN ejecta (Woosley & Heger).

Observed CR

Cosmic Ray Elemental Abundances (Israel et al 2011)



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For Z>26, data from TIGER Rauch et al. *ApJ* **697**, 2083 (2009)
For Z<26, data from HEAO-C2 Englemann et al. *A&A* **233**, 96 (1990)

Observed (E>0.8 GeV at top of atr

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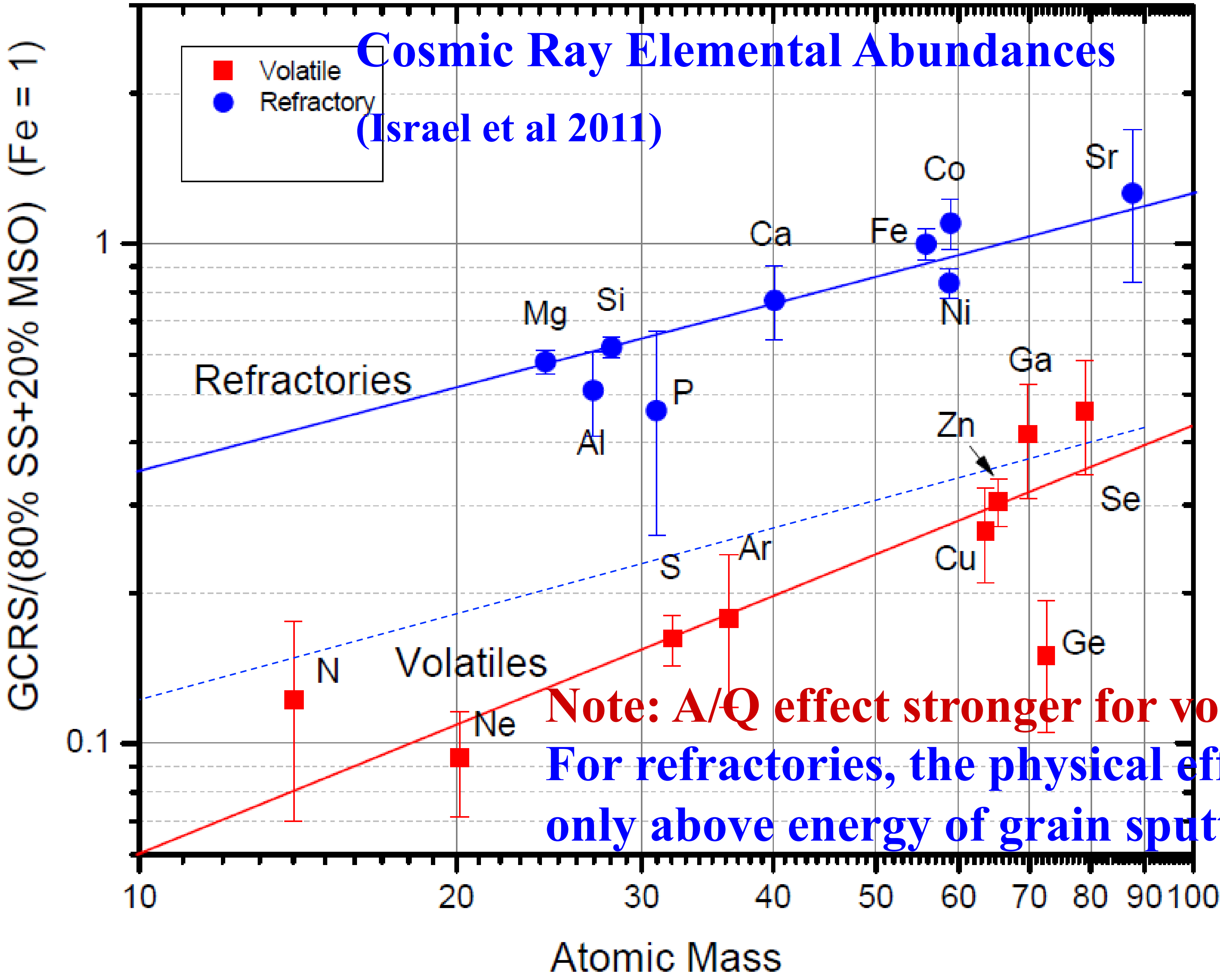

Note: A/Q effect stronger for volatiles!

For refractories, the physical effect operat
only above energy of grain sputtering.

Now compa
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abundance
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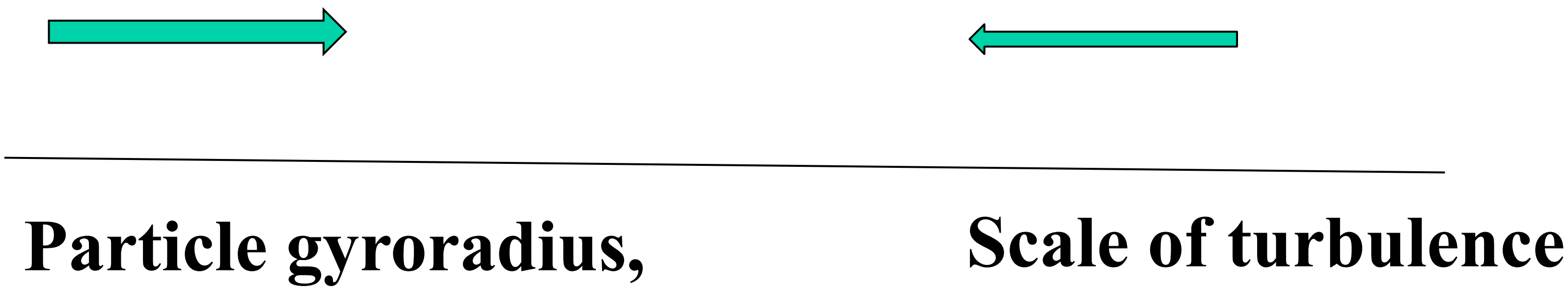
How important is second order acceleration?
Is there any situation where the acceleration is primarily 2nd order?

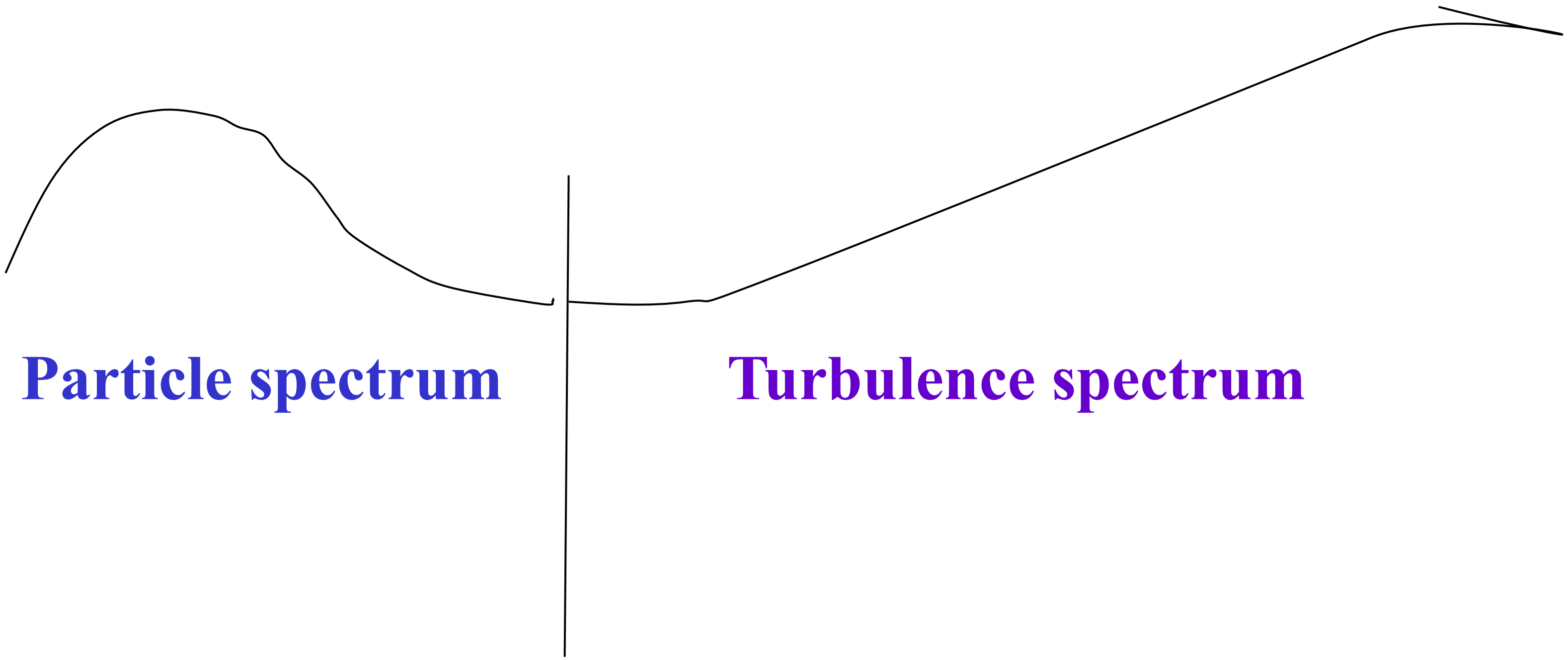
Impulsive Solar Flares

Observed to be extremely rich in He3. Enhancement relative to He4 can be dramatic…2 to 3 orders of magnitude.

On the other hand, not so efficient in overall energetic particle yield.

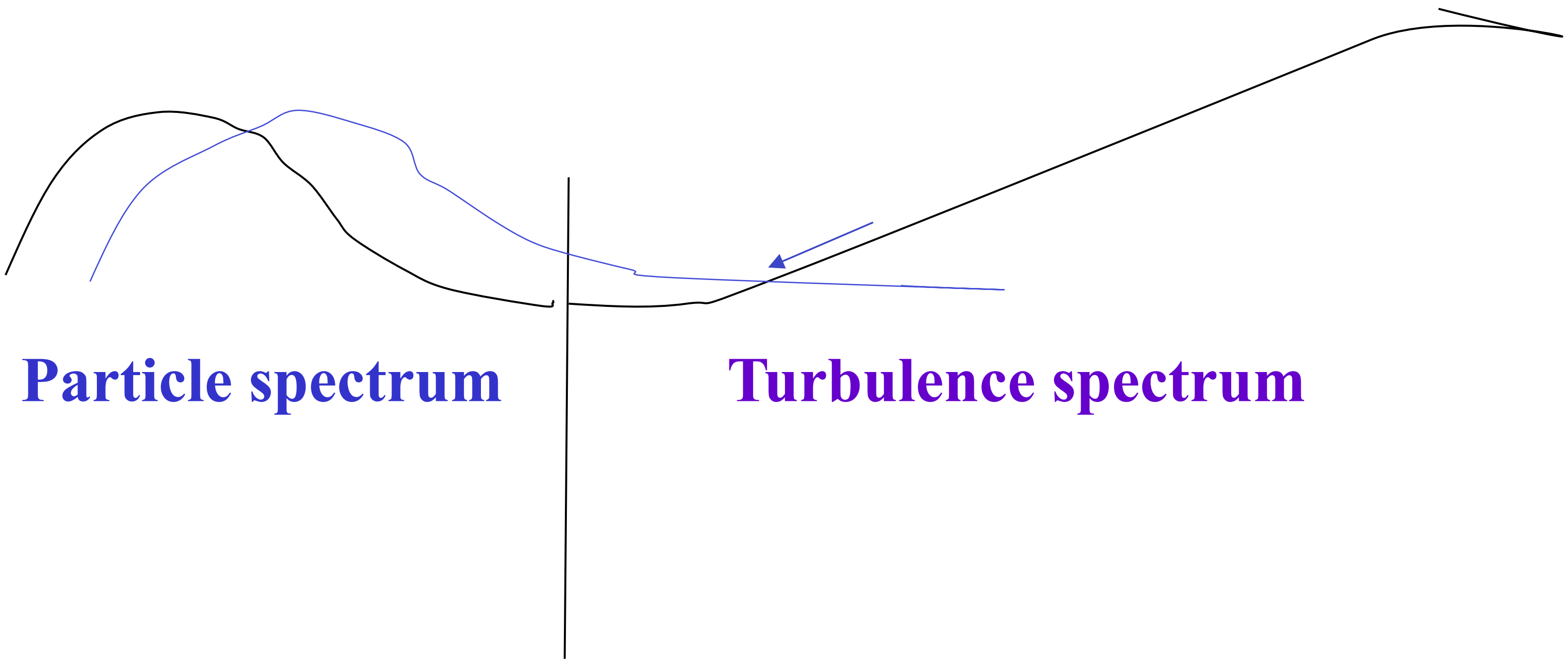
Cyclotron damping of Alfven wave turbulence (Eichler 1979) hypothesized to have ***highly*** plutocratic injection mechanism, as turbulence cascades from larger spatial scales, where it is resonantly damped by energetic particles, to smaller scales, where it is damped by less energetic particles.





Resonant energy transfer from waves to particles

Huge enhancement of heavy elements predicted



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In small, **impulsive, solar energetic particle (SEP)** events, that is precisely what has been observed to occur.

Mason et al 2004

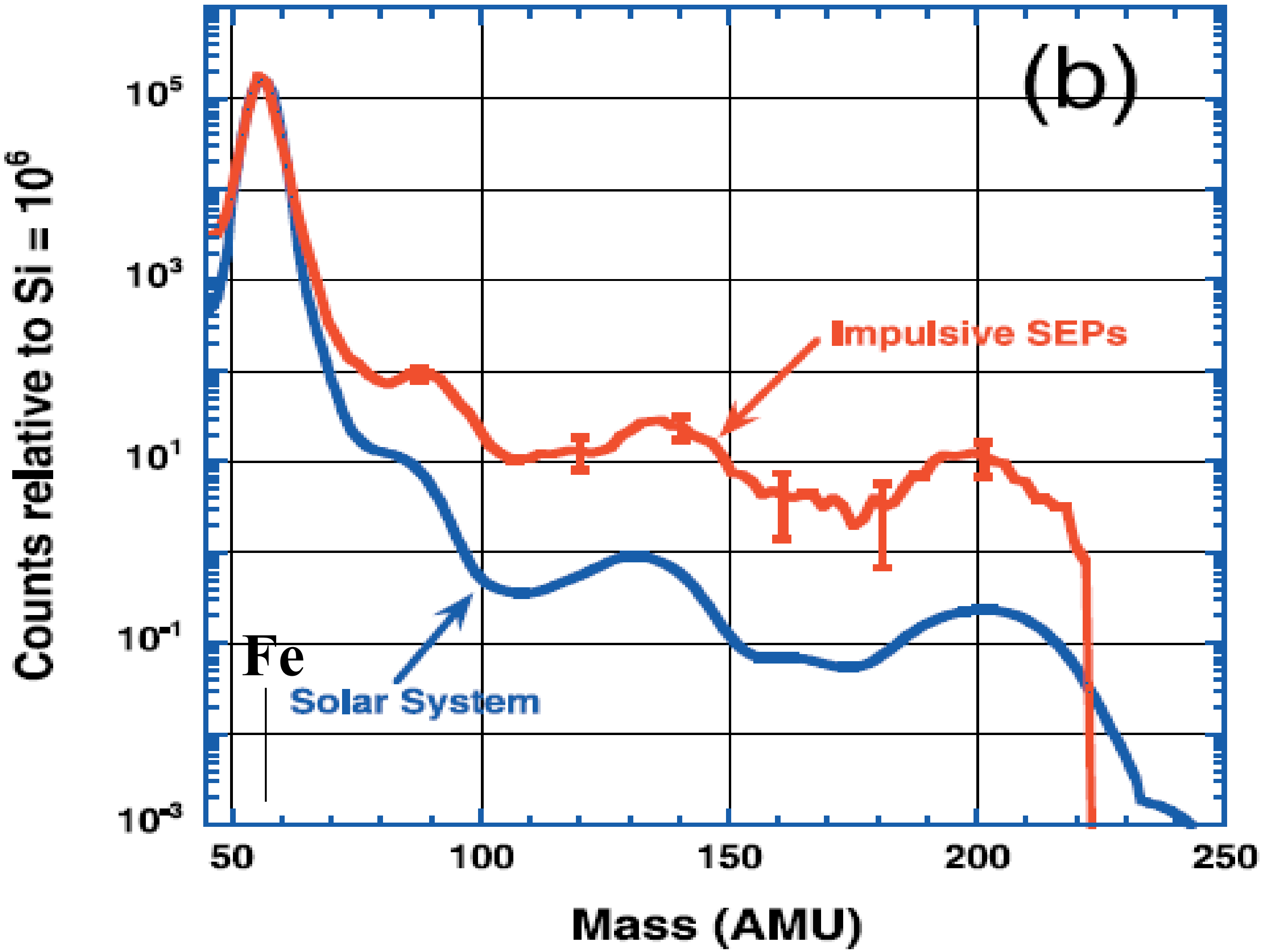

FIG. 6.—(*a*) Mass histogram of Fe peak and heavy nuclei during all periods in which UH nuclei were observed. (*b*) *Red curve*: Five-bin–smoothed data from (*a*) showing typical statistical uncertainties. *Blue curve*: Solar system abundances smoothed by mass resolution function of ULEIS (see text).

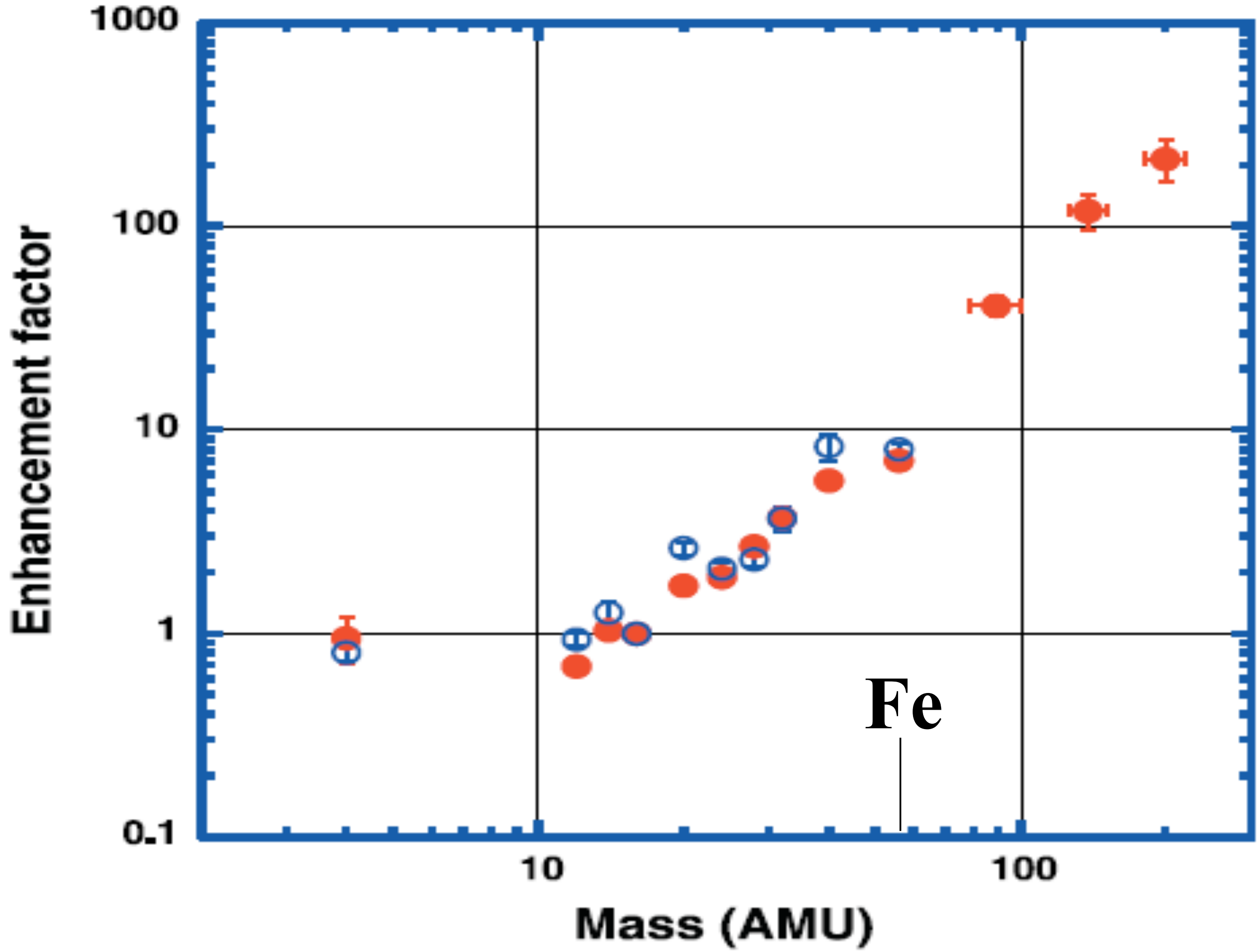

FIG. 7.—*Filled red circles*: Enhancement factor for ^{3}He-rich heavy-ion abundances, compared with gradual SEP ions and solar system abundances. *Blue circles*: Values from Reames (1995).

But total energy in SEP energetic particles very small compared to energy in flare? Acceleration very inefficient.

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Since 1979 Sridhar and Goldreich (1994) change paradigm of cascading Alfven wave turbulence. Turbulence anisotropic, with most modes having $k_{perpedicular} >> k_{parallel}$. They don't resonate with particles. They just go into heat

On the other hand, spectrum is a very steep function of $k_{parallel}$, so heavy ions accelerated much more effectively than light ones (Eichler, 2014).

Ultrahigh Energy Cosmic Rays

Originally though to be mostly extragalactic protons as highest energies.

AGN worked just fine, and probably still do, even if UHECR are not mostly protons.

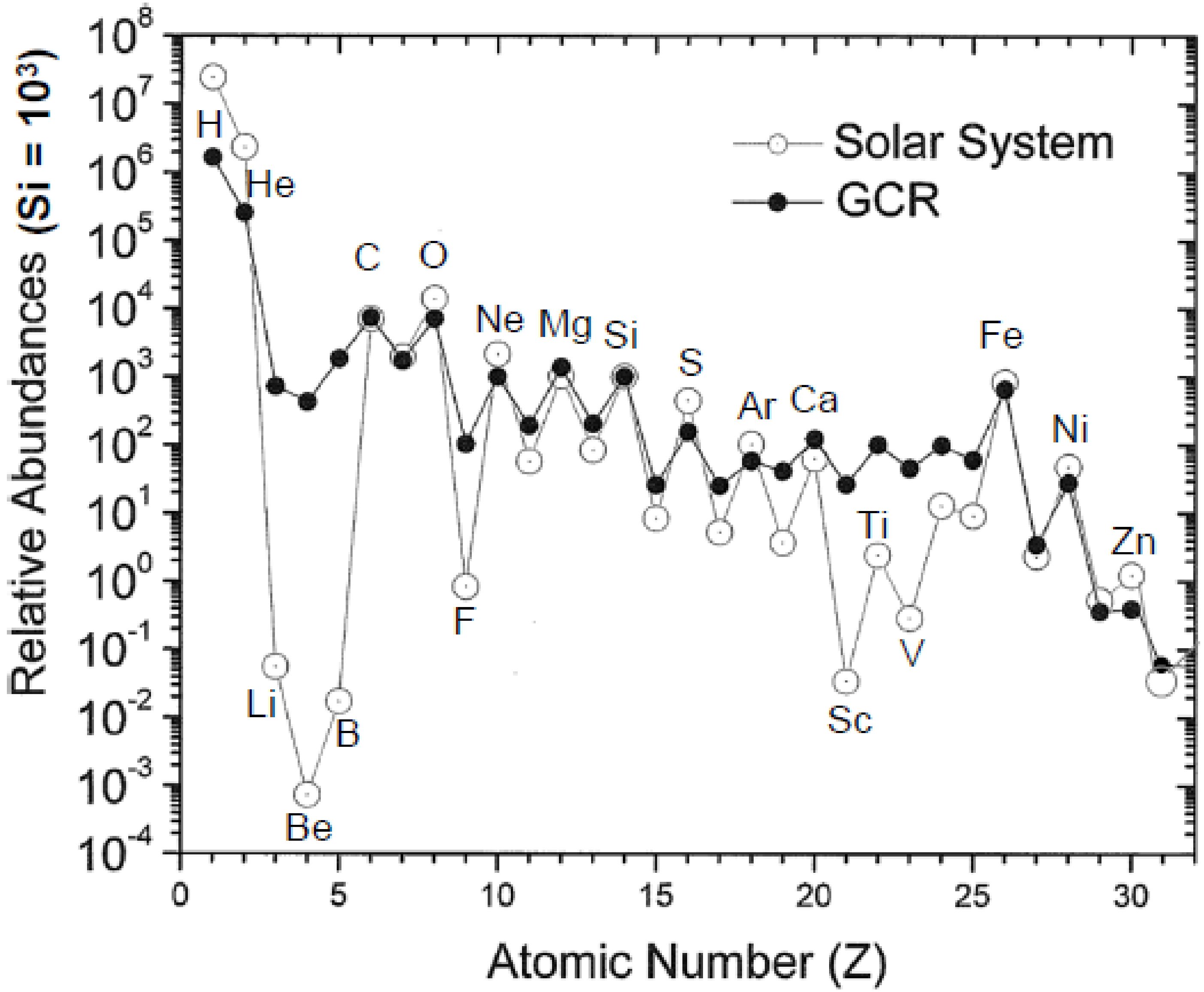
Levinson and Eichler (1993) proposed GRB, but, because GRB (if judged by their prompt emission) don't have enough energy to account for UHECR (not even close), they were suggested for UHECR of *Galactic* origin.

Auger data raises the possibility that highest energy CR are iron-like!

Note: If CR much below the ankle are mostly Galactic protons, *how can you avoid* Galactic iron component? (Mixed composition model, Allard and co-workers)

Do the math: Fe/p well below cutoff is expected to be at least 2×10^{-4} in energy/nucleon, hence, for $N(E) = k\,E^{-p}$, at least $2 \times 10^{-4} \times 56^{-1+p} \sim 1/30$ in total energy.

But high energy cutoff is proportional to energy/ charge, at high γ, iron stripped by CMB photons, so high energy exponential cutoff is 26 X that of protons. So sum everything:



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10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30

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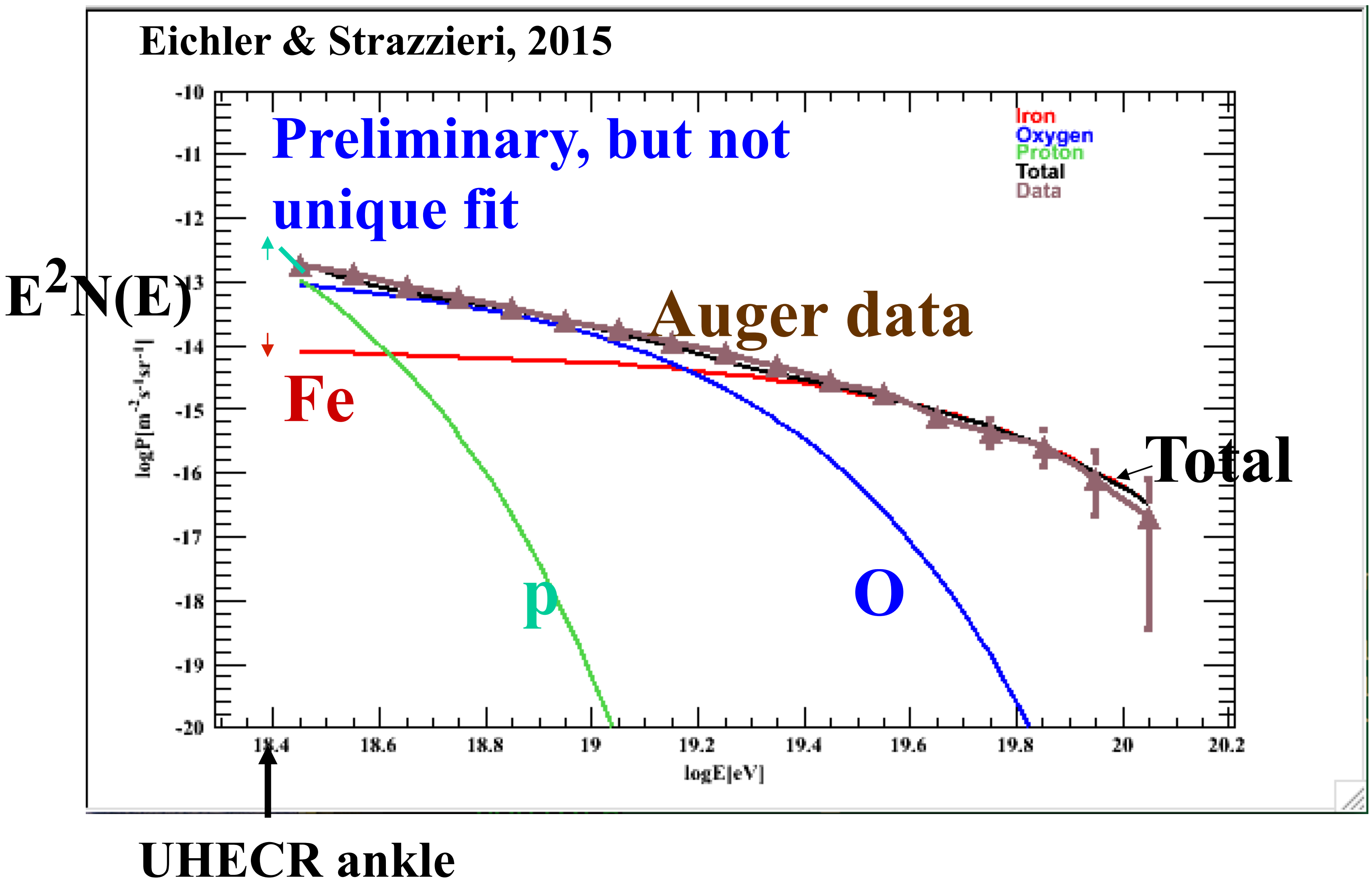
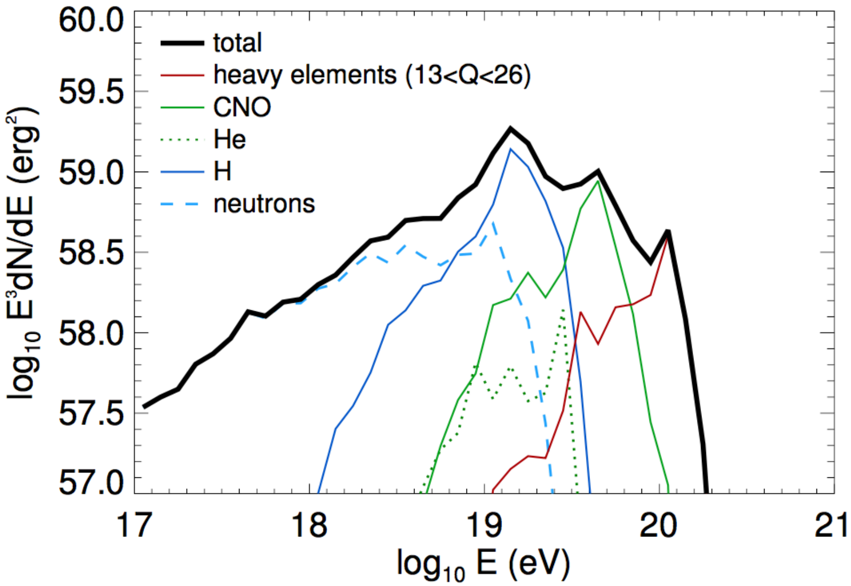
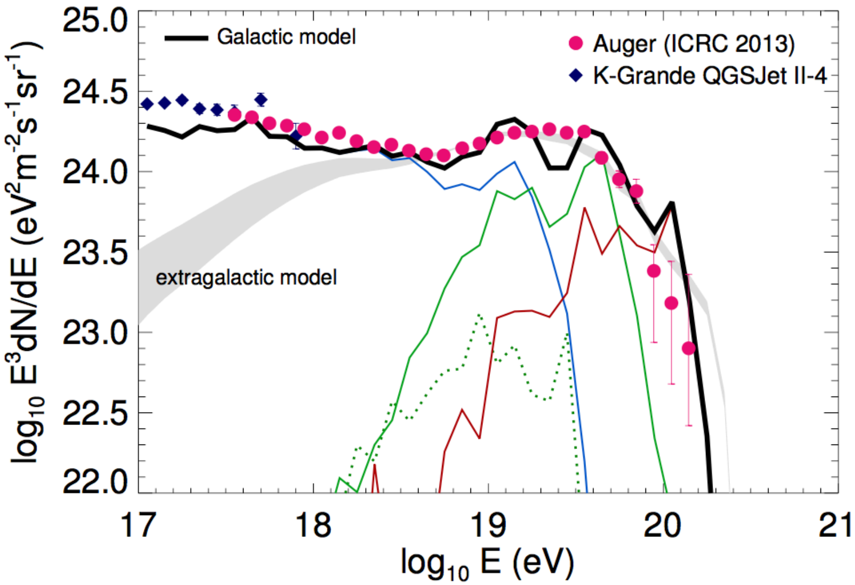

Eichler & Strazzieri, 2015
Preliminary, but not unique fit
Iron
Oxygen
Proton
Total
Data
E²N(E)
logP[m⁻²s⁻¹sr⁻¹]
Auger data
Fe
p
O
Total
logE[eV]
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
20
20.2
UHECR ankle

The "ankle" in a Galactic mixed composition model





spectrum of UHECRs accelerated at GRB internal shocks (including particle escape and energy losses) [Globus et al. 2015 or tomorrow]

require high luminosity GRBs (to have a large neutron tail, and thus a softer proton component)

=> may produce too strong small scale anisotropy; however many Galactic GRBs are expected to contribute at a given time (the exact number depends on the beaming factor)

=> propagated spectrum

escape rate $\propto (E/Q)^{-\alpha}$ with $\alpha \sim 0.9$.

Ankle naturally forms if UHECR from Galactic GRB. It represents the point where escaping neutrons, which have a typical DSA spectrum, meet escaping charged particles, which have a harder spectrum.

Composition at the ankle naturally mostly protons but mixed.

Galactic iron near ~10^{20} eV is hard to avoid unless UHECR below ankle are extragalactic! ....which is getting harder to accommodate due to constraints from diffuse gamma ray background.

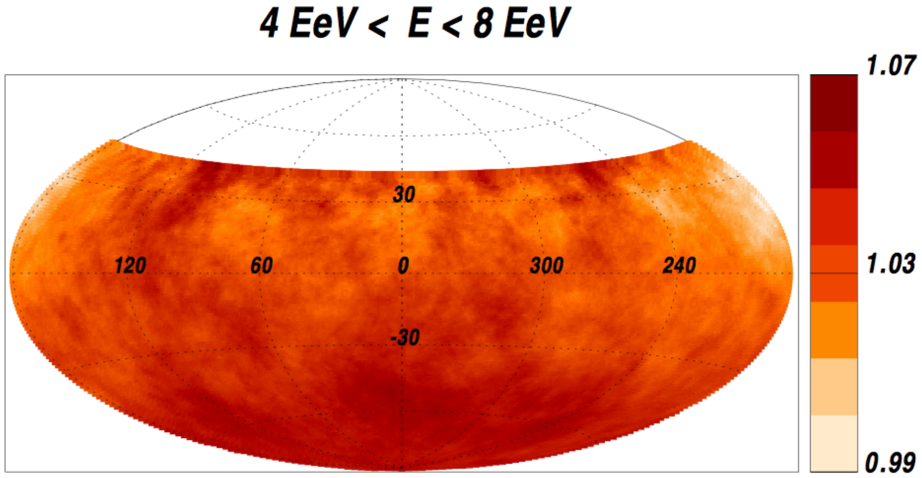
All that is needed is a Galactic source that gets protons to $10^{18.5}$ eV - e.g. GRB (Levinson & DE 1993) and you end up, almost unavoidably, with enough heavies at 10^{20} eV to explain the highest energy UHECR data.

Future generation isotropy, composition experiments could resolve whether UHECR just below and above ankle are Galactic or extragalactic.

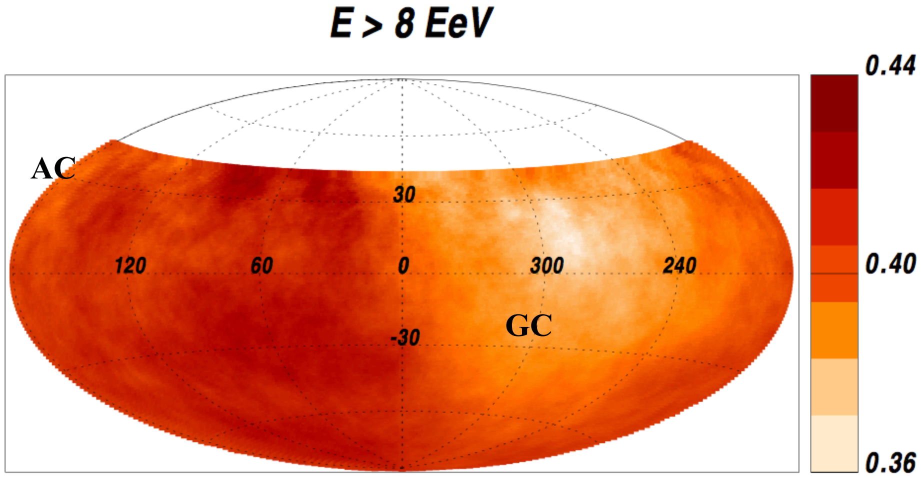
UHECR isotropy: Thought by many (using oversimplified transport models, [e.g. DE and Pohl, 2011) to constrain UHECR origin to be extragalactic. But this doesn't follow (Kumar and Eichler, 2014, Eichler, Globus and Kumar, 2016), not even if UHECR source distribution scales like Galactic star formation, because a) anisotropic diffusion lowers anisotropy b) intermittency can lower anisotropy and c) most importantly, drift causes the outer disk is better connected to the Earth than the inner disk.

Kumar and Eichler (2014) (actually Kumar) predicted anti-center anisotropy, together with N-S anisotropy, at high energy *before* it was discovered (PAO Collaboration, 2015) .

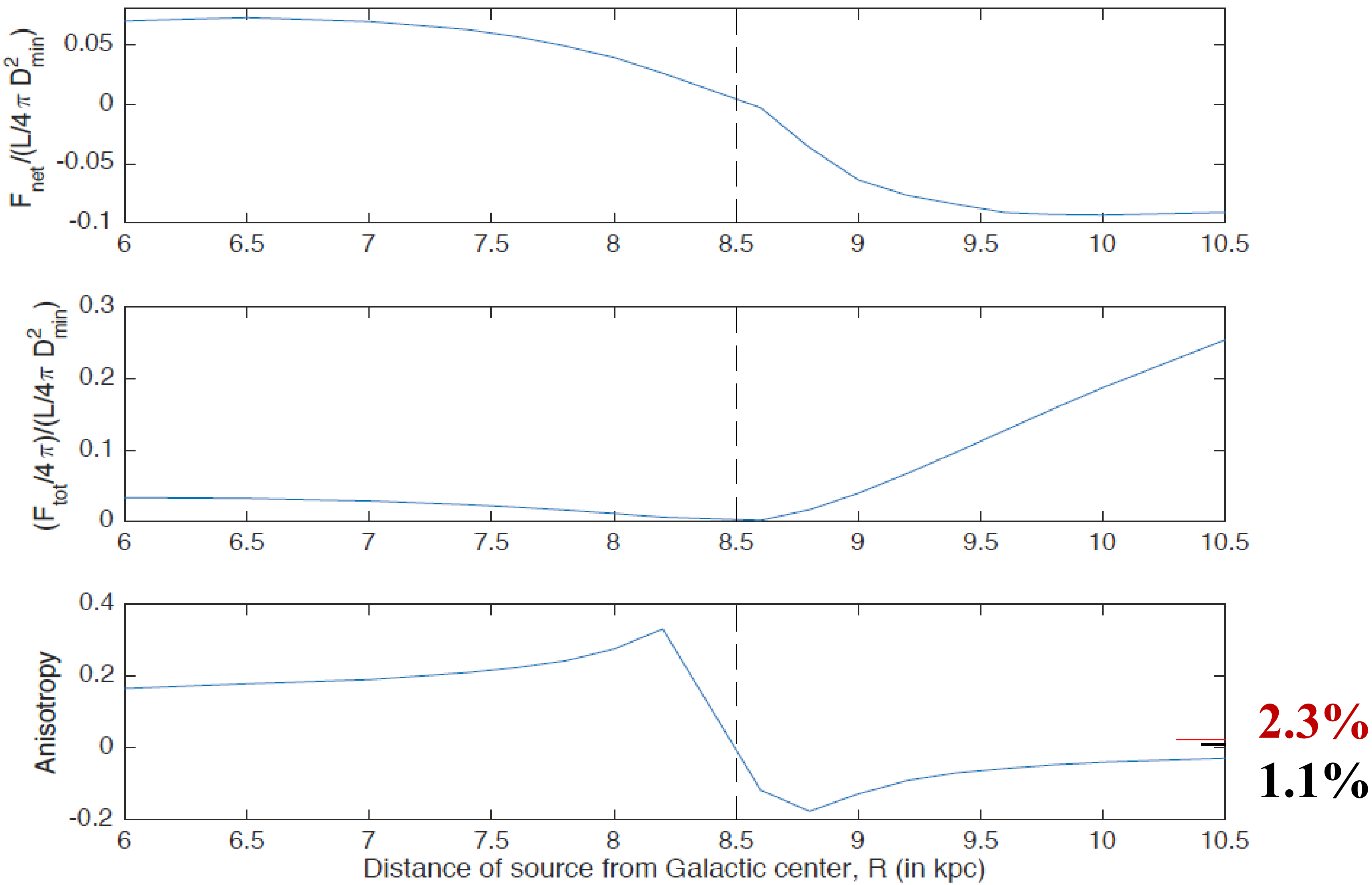
A large scale anisotropy (Auger)



compatible with isotropy to several %

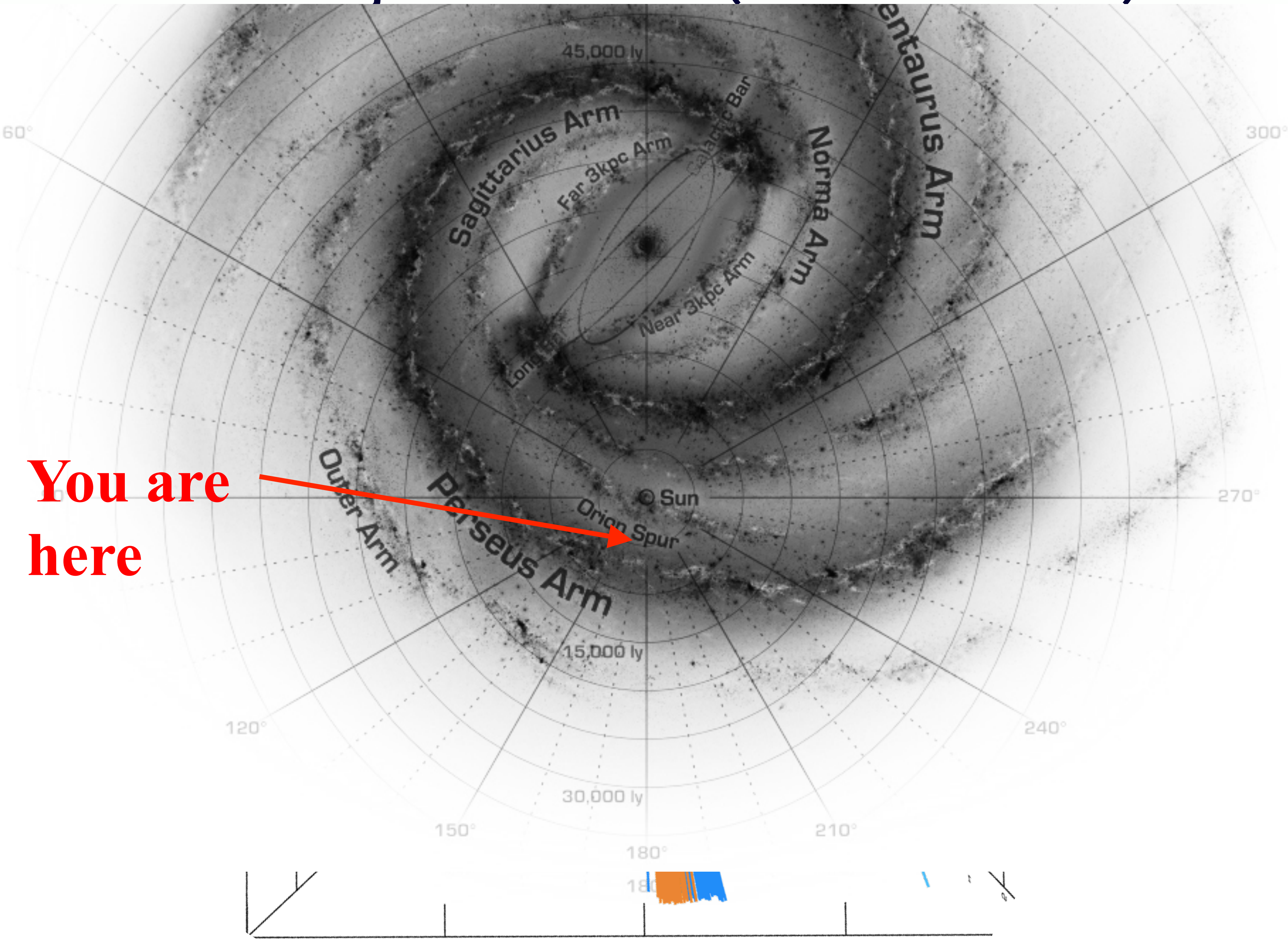


excess in the "direction" of the anticenter (longitude)

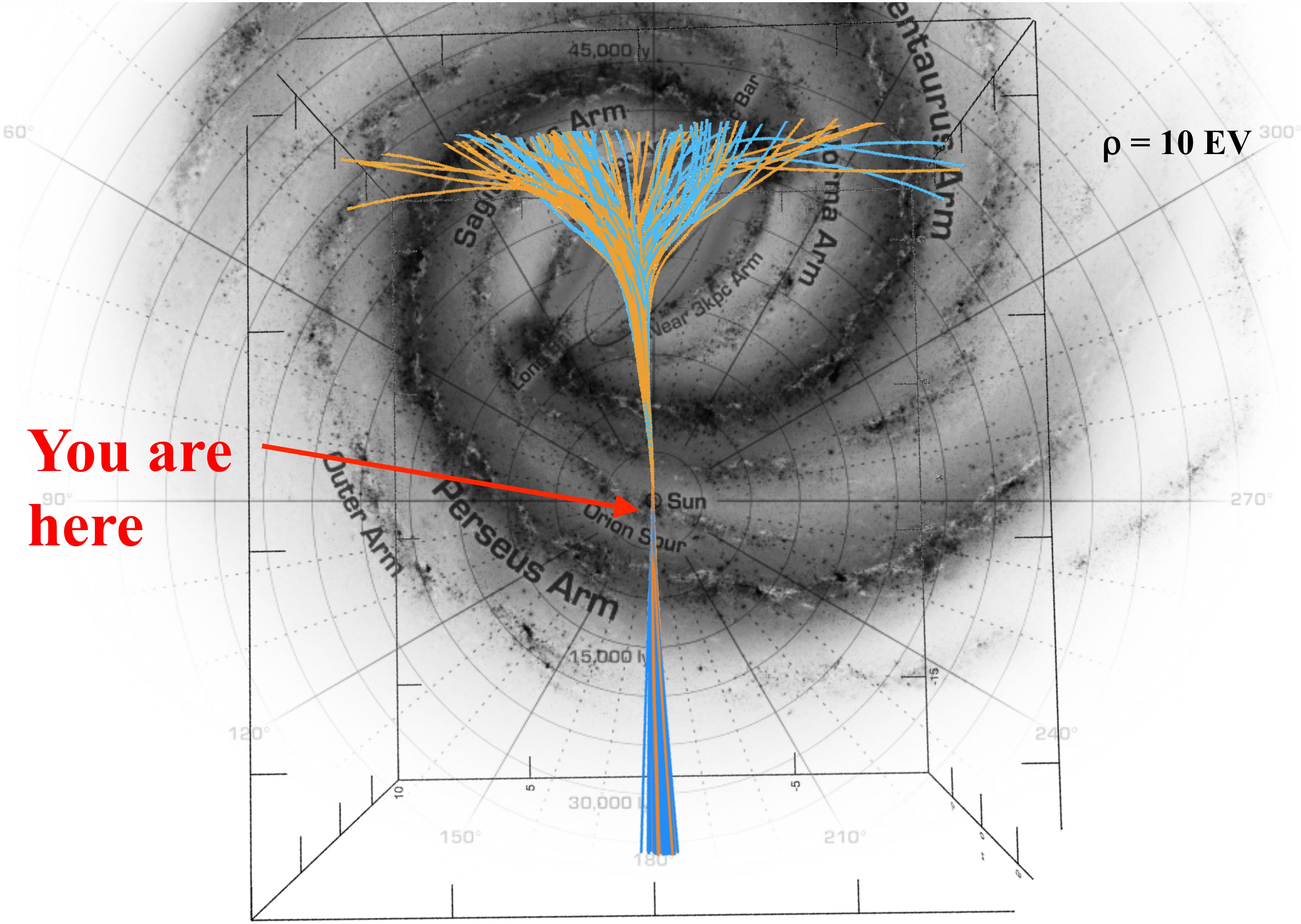


1.1% assuming sources scale as star formation in Galaxy

UHECR trajectories in the (Jahnnsen-Farrar) GMF

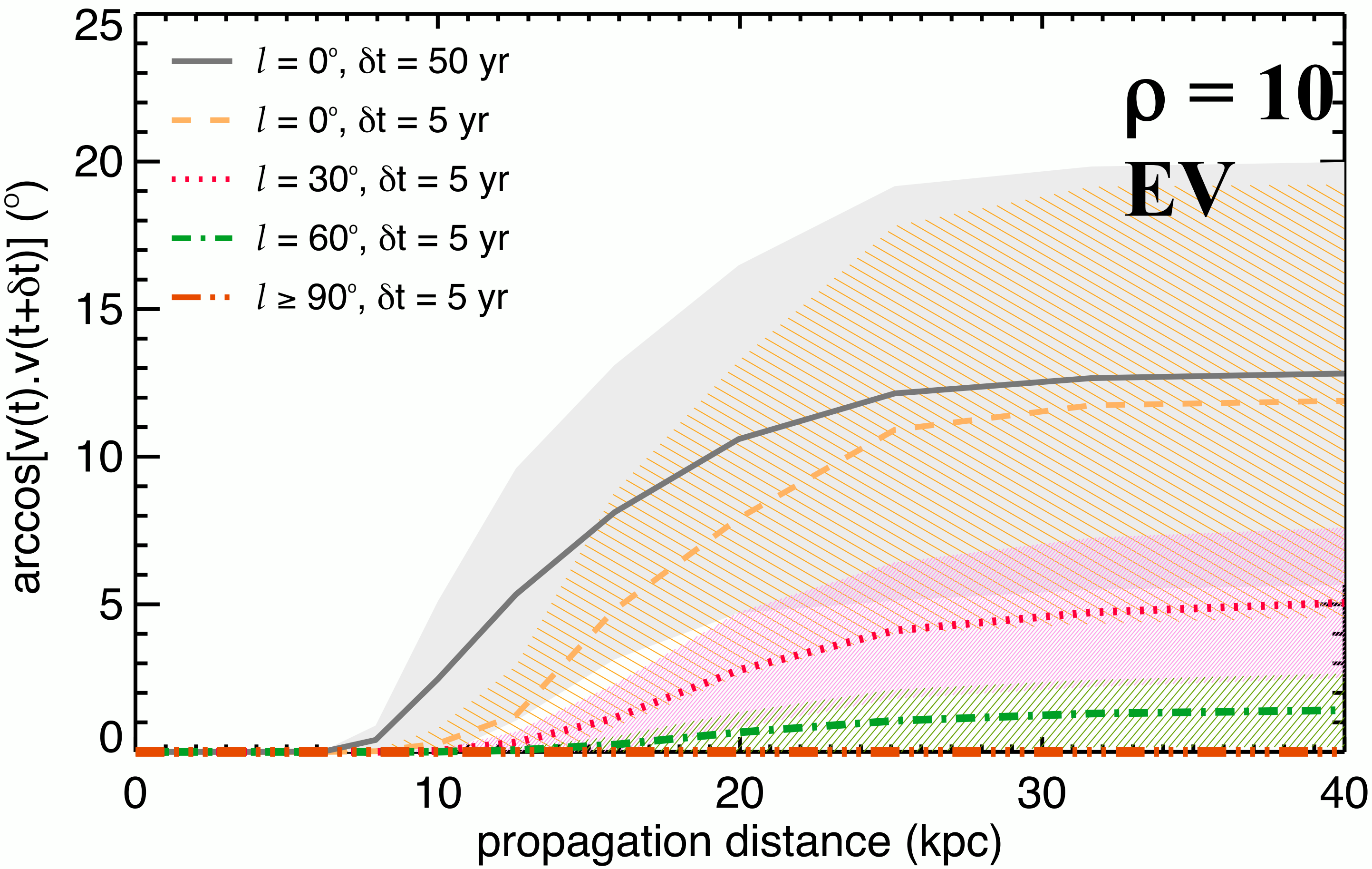


UHECR trajectories in the (Jahnsenn-Farrar GMF



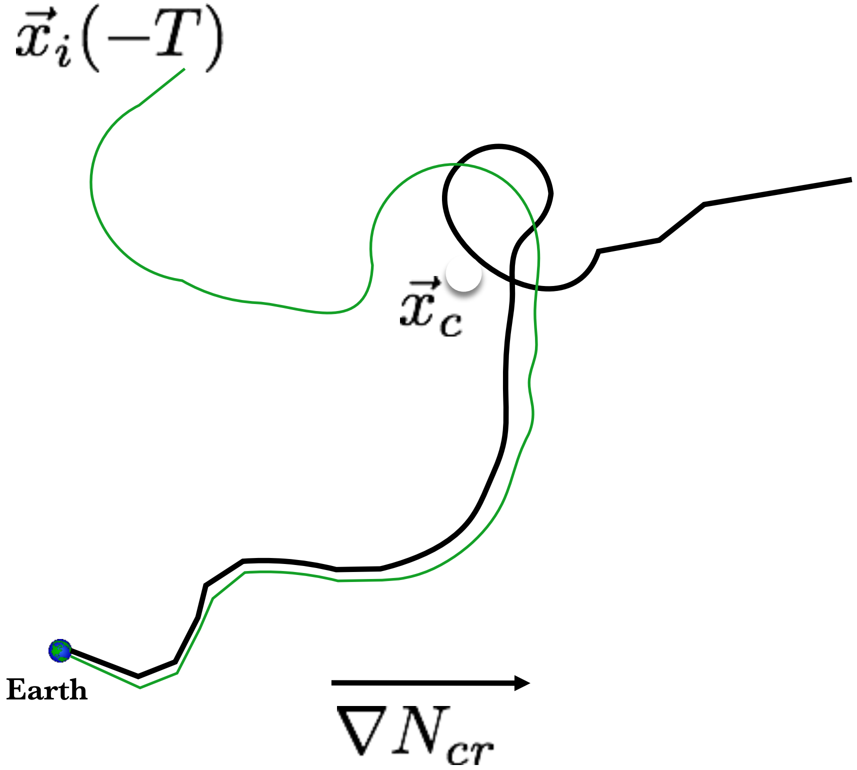
Do small scale anisotropies change within a human lifetime?

Angular decorrelation due to the Earth motion (5 years)



Do small scale anisotropies change within a human lifetime?

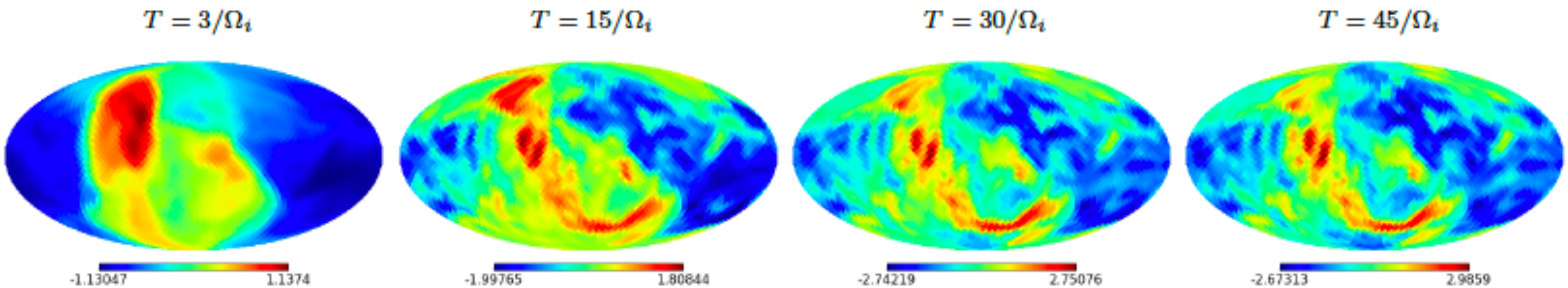
Estimating differential directional CR Flux



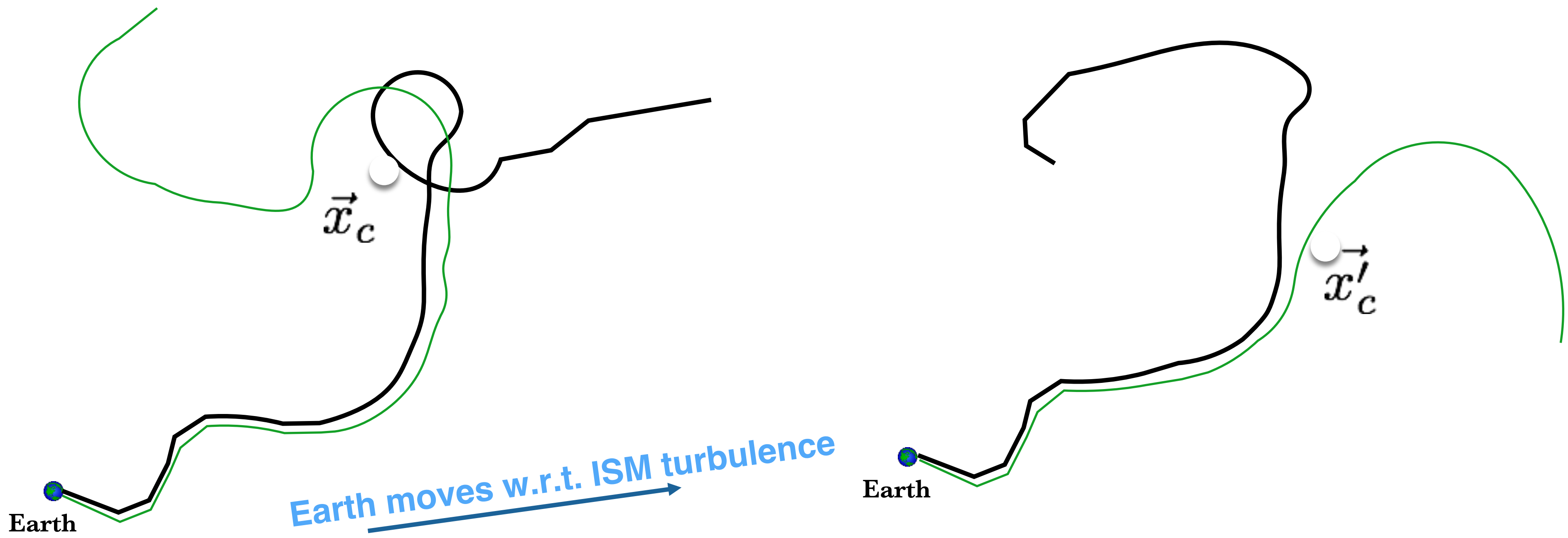
Large number of backtracked trajectories per angular bin to trace the probability distribution

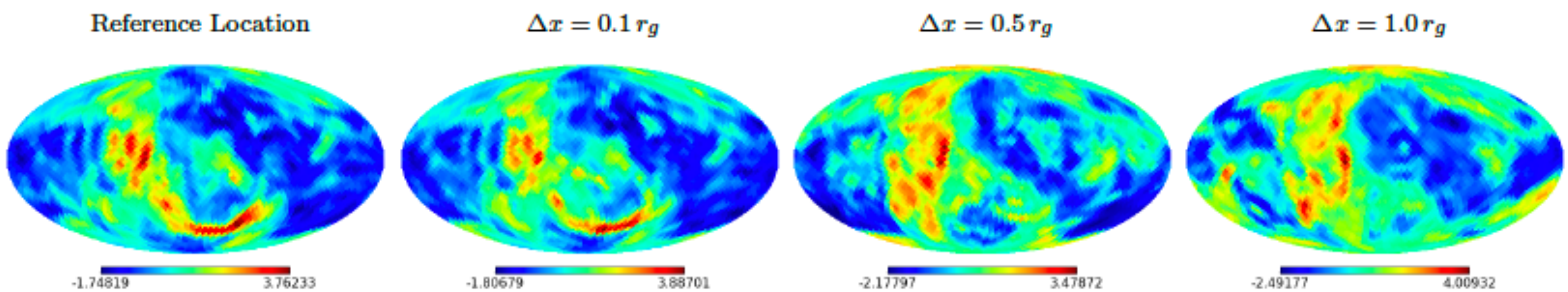
$$\vec{x}_c(-T) = \frac{1}{n}\sum_{i=1}^{n}\vec{x}_i(-T)$$

$$Flux \propto N_{cr}(\vec{x}_c)$$



Variability of CR Flux skymap





Conclusions

Measured compression ratios,[1] in heliosphere and in SNR, particle spectra,[2] composition,[3] all consistent with early non-linear predictions.

1 Bow shock, termination shock, SNR

2 Bow shock, interplanetary shocks,

3 Bow shock, Galactic CR

The hard, honest work that went into matching theory and experiment deserves high recognition.

4)Acceleration mechanisms other than DSA may operate in Nature, e.g. cyclotron damping of turbulent Alfven waves.

5) UHECR may be Galactic