Sources: acceleration and composition

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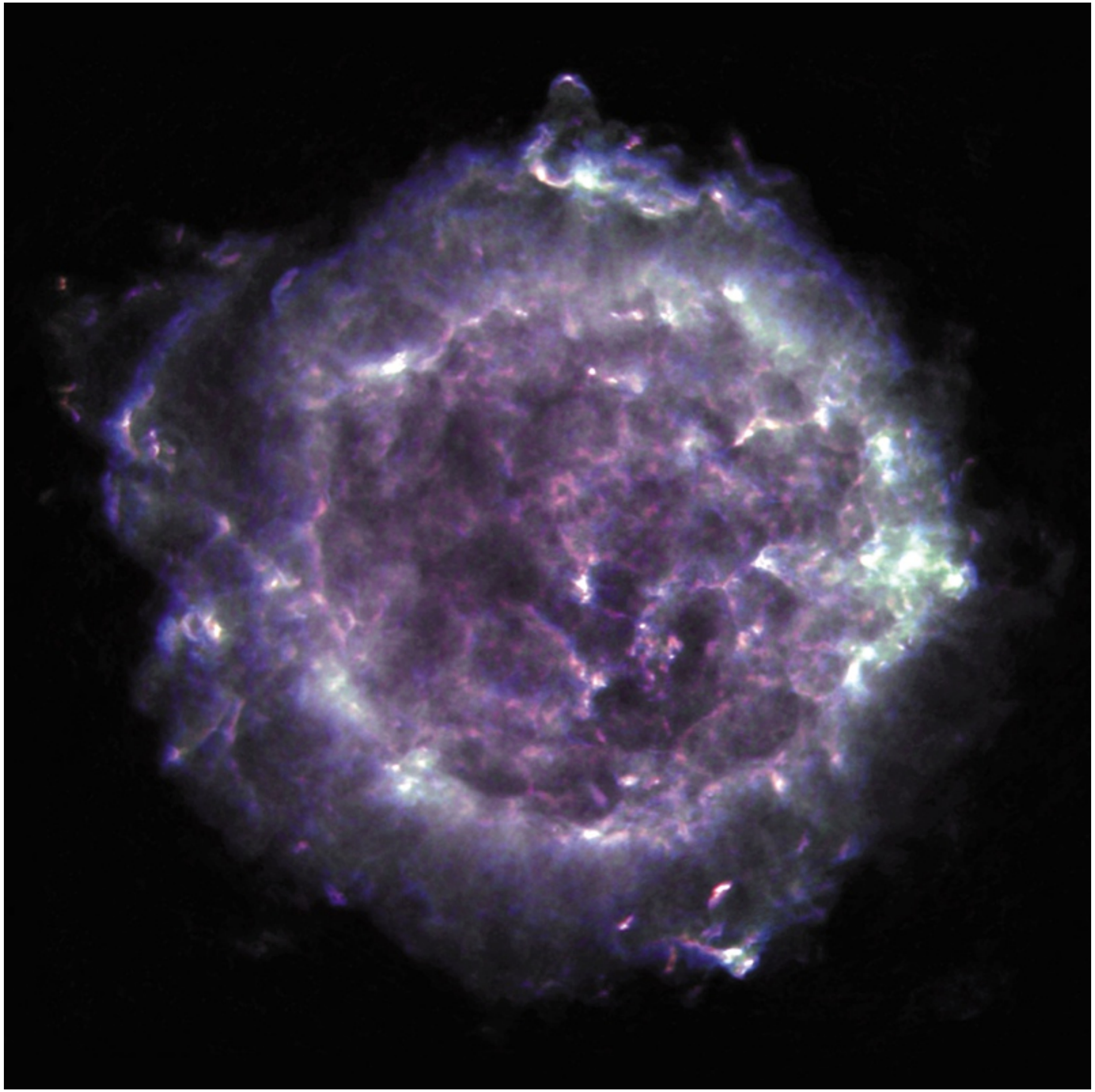
Hope to survey...

- Current status of shock acceleration theory from an astrophysical (mainly cosmic-ray origin) perspective...
- What we think we know about composition...
- Observational evidence in support of the standard picture.

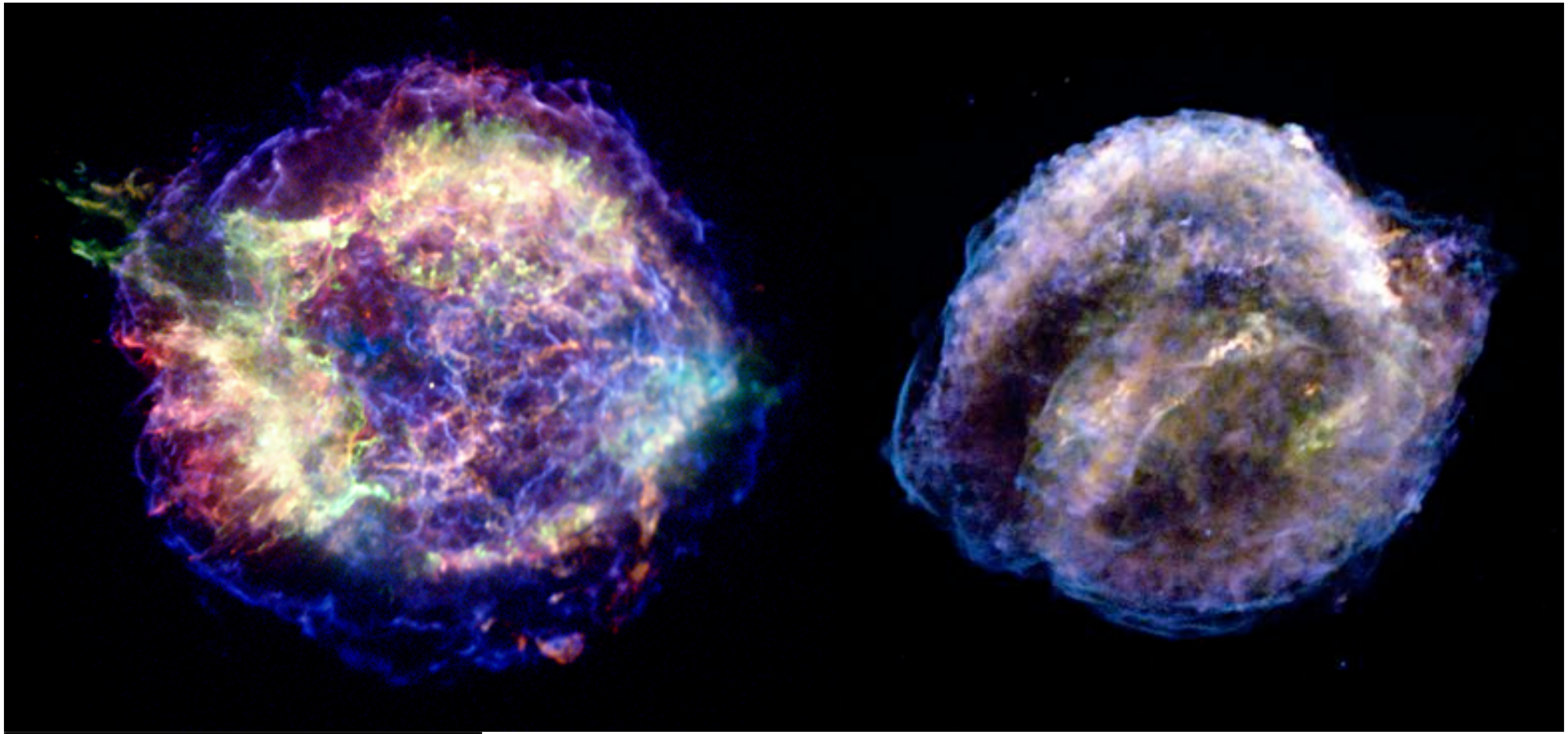
‘Standard model’ for GCRs

- Power estimates (not perhaps as certain as we think) point to SNe as main energy source;
- Adiabatic losses imply SNRs, not SNe;
- Radio synchrotron and non-thermal X-ray emission point to electron acceleration;
- TeV gamma-ray emission suggests proton acceleration also;
- Plausible theory in Diffusive Shock Acceleration at strong outer shock.

Cas-A imaged in radio with the VLA



- Sharpness of radio rims indicate that local diffusion of GeV electrons near shock front is much lower than general ISM diffusion coefficient; *(Achterberg, Blandford and Reynolds, 1994, A&A 281, 220)*
- Consistent with strong particle driven turbulence at shock (Bohm scaling?);
- Relatively new observations (Chandra) - sharp rims in non-thermal X-rays also!
- Not only small spatial scales, also rapid time variations. *(Uchiyama et al, 2007, Nature 449, 576)*



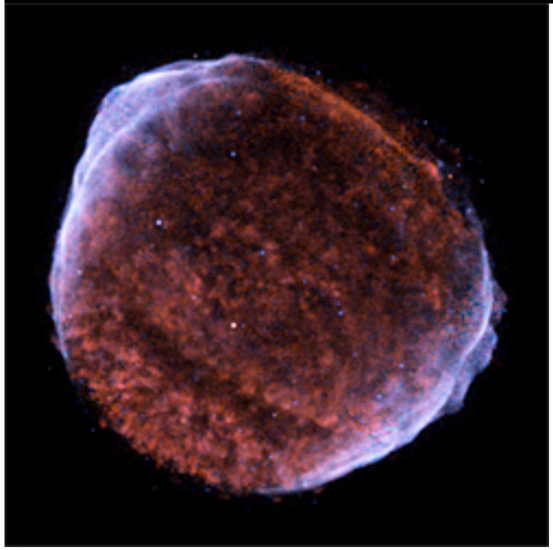


Image mosaic courtesy of Jacco Vink

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

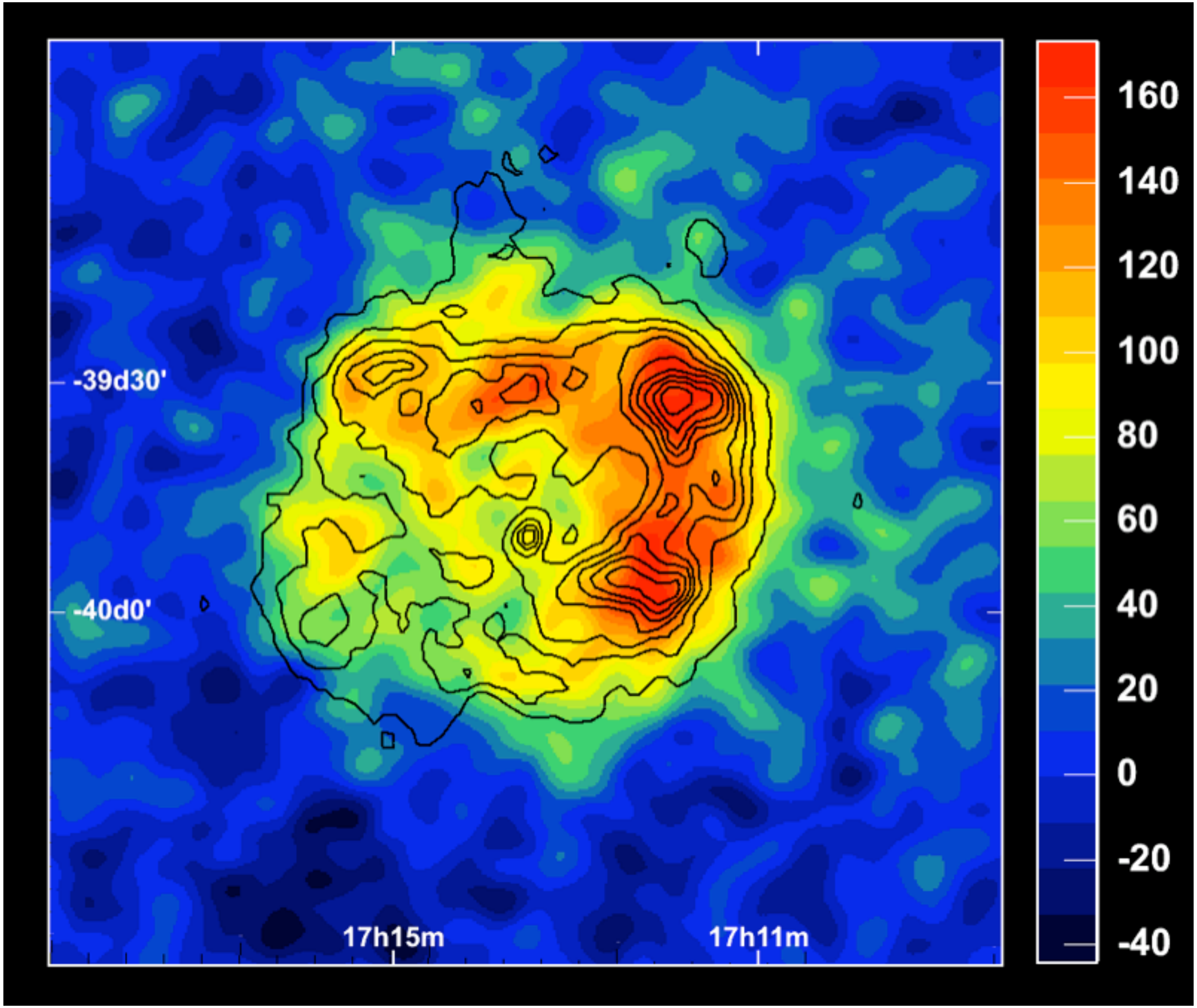
- Other new development is detection of several shell-type SNRs in TeV gamma-rays
- Predicted by theory - accelerated protons plus ambient swept-up ISM as a target must produce gamma-rays through

$$p + A \rightarrow .... + \pi^0 \rightarrow 2\gamma$$

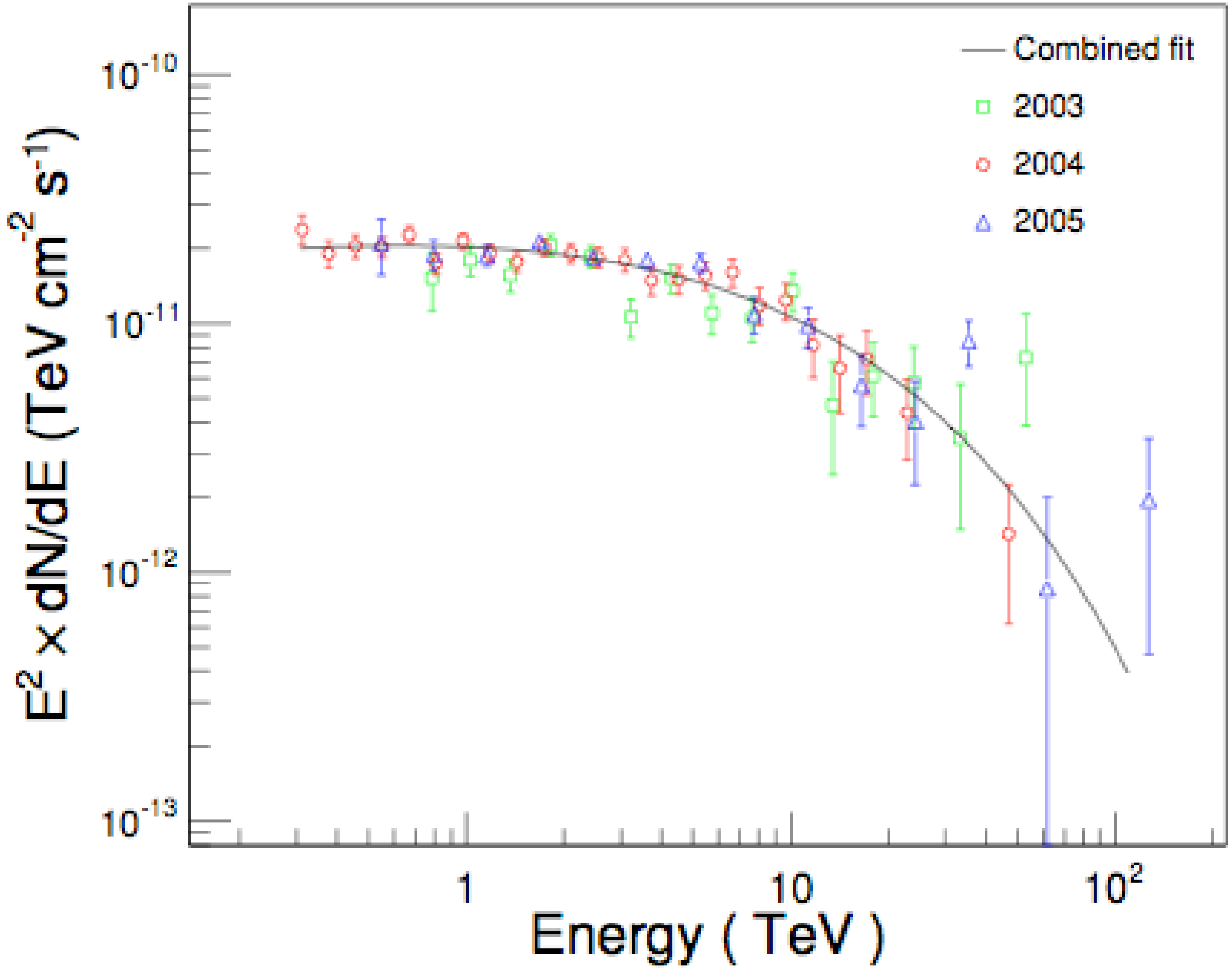
- But also IC channel

$$e + \gamma \rightarrow e + \gamma$$

Iconic H.E.S.S. image of RXJ1713-3945

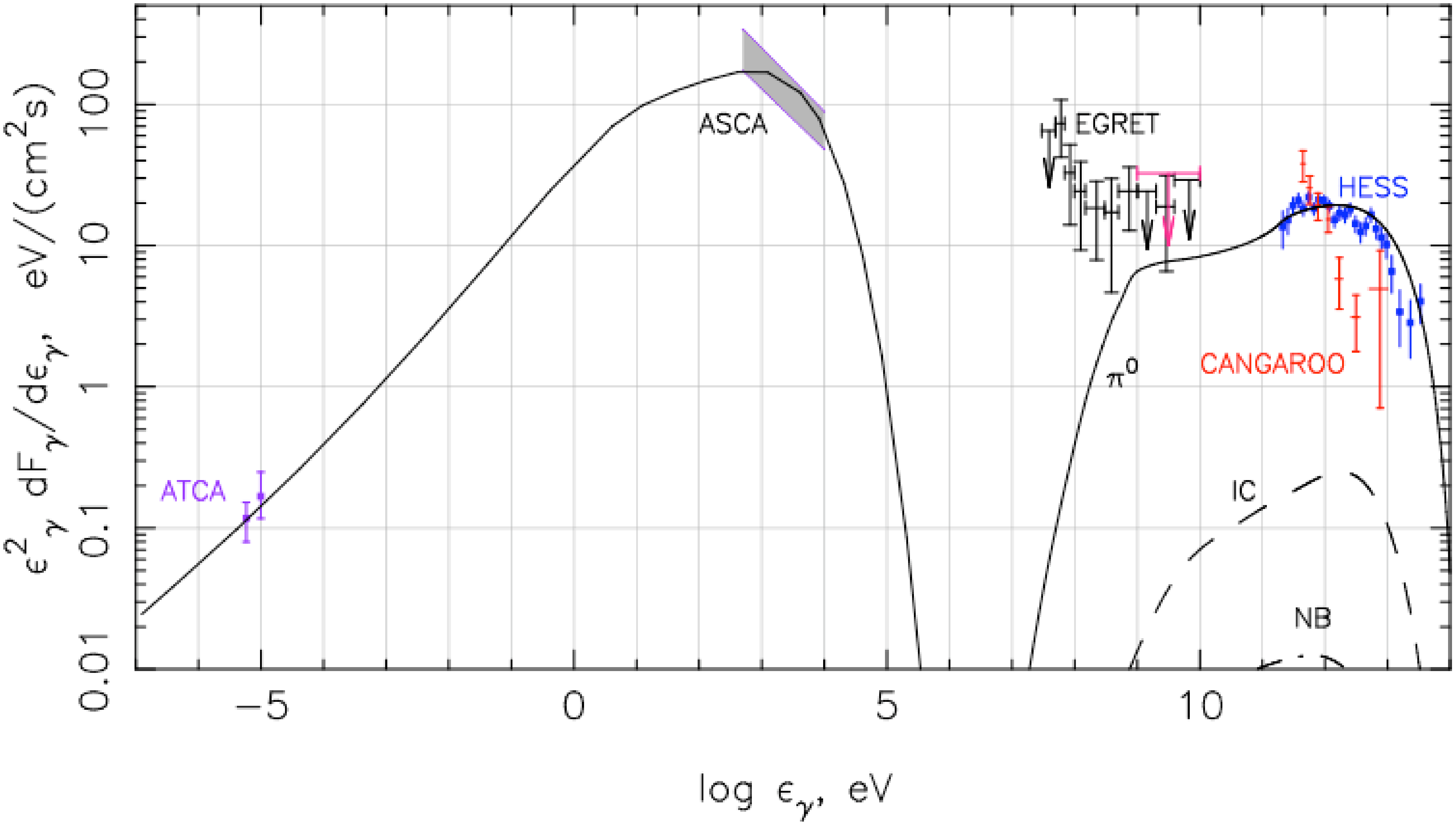


Cover of Nature, vol 432 (2004)



Energy spectrum of RX J1713-3946 showing hard spectrum with high-energy cut-off, astro-ph/0611813

Model fit by Berezhko and Voelk, arXiv0707.4647



Annecy, 25 May 2009

Conclusion-I

- Some supernova remnant shocks accelerate particles, certainly electrons and probably protons, to at least 100 TeV.
- Strong evidence that they do so efficiently, and that fields are highly “turbulent”.
- Growing evidence for significant magnetic field amplification by factors of O(100).

But a few caveats...

- 100 TeV is an order of magnitude below the "knee" in the CR spectrum at about 3PeV.
- Relative importance of electrons and protons is hotly debated.
- Need better observations and greater coverage of the full SED (Fermi, Astro-H, etc).
- SNRs with strong particle acceleration may be quite "cold"?

And not just SNRs...

- Any strong shock in the ISM should be a source of cosmic rays if this picture is correct.
- Mainly SNR shocks, but also superbubbles, colliding stellar winds, high-velocity clouds etc....
- There are other acceleration processes that may also contribute (magnetic reconnection, pulsars etc).

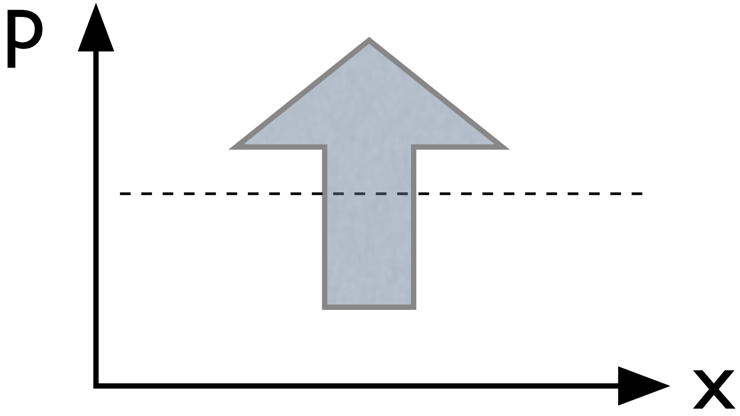
Diffusive Shock Acceleration

- Belongs to the general class of Fermi acceleration processes - energy comes from differential motion in magnetised plasma.
- Very efficient because collisionless plasma shocks are highly compressive and have strongly disordered magnetic fields (thus distributions close to isotropy, transport is diffusive).

Useful to think in terms of the acceleration flux,

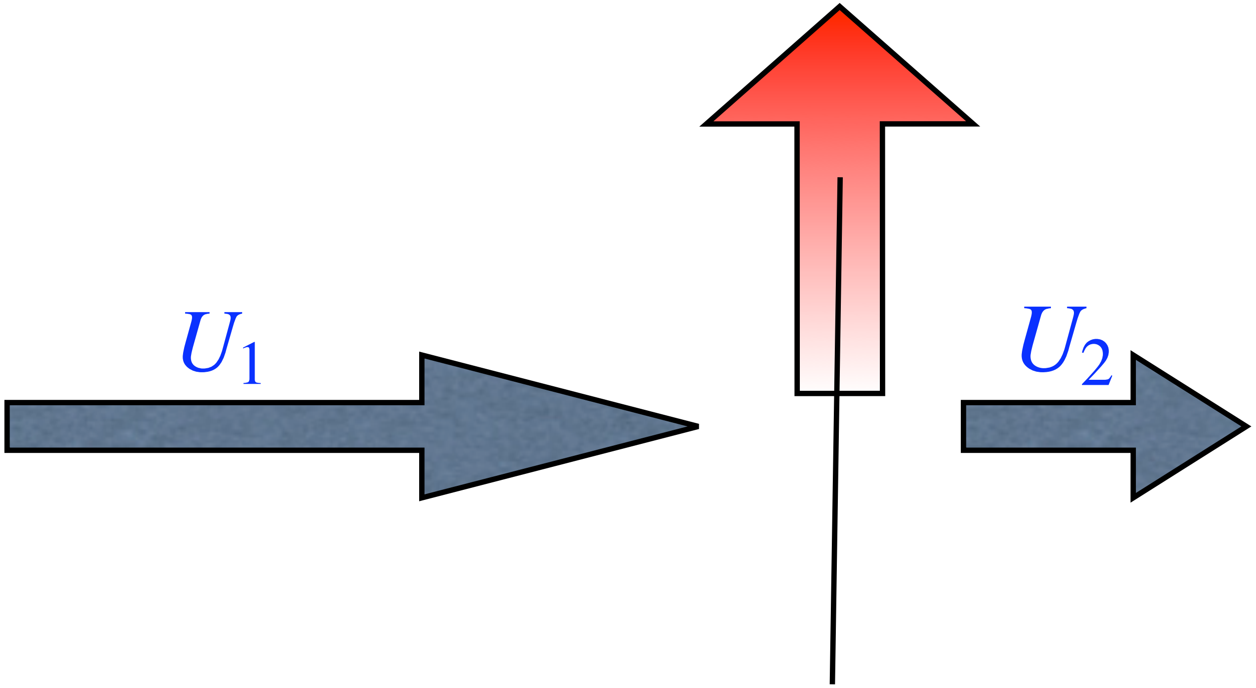
$$\Phi(p) = \int \frac{4\pi p^3}{3} f(p)(-\nabla \cdot \vec{U})\, d^3x$$

Rate at which particles are being accelerated through a given momentum (or energy) level.



If compression occurs only at the shock, then

$$\Phi(p) = \frac{4\pi p^3}{3} f_0(p)\,(U_1 - U_2)$$

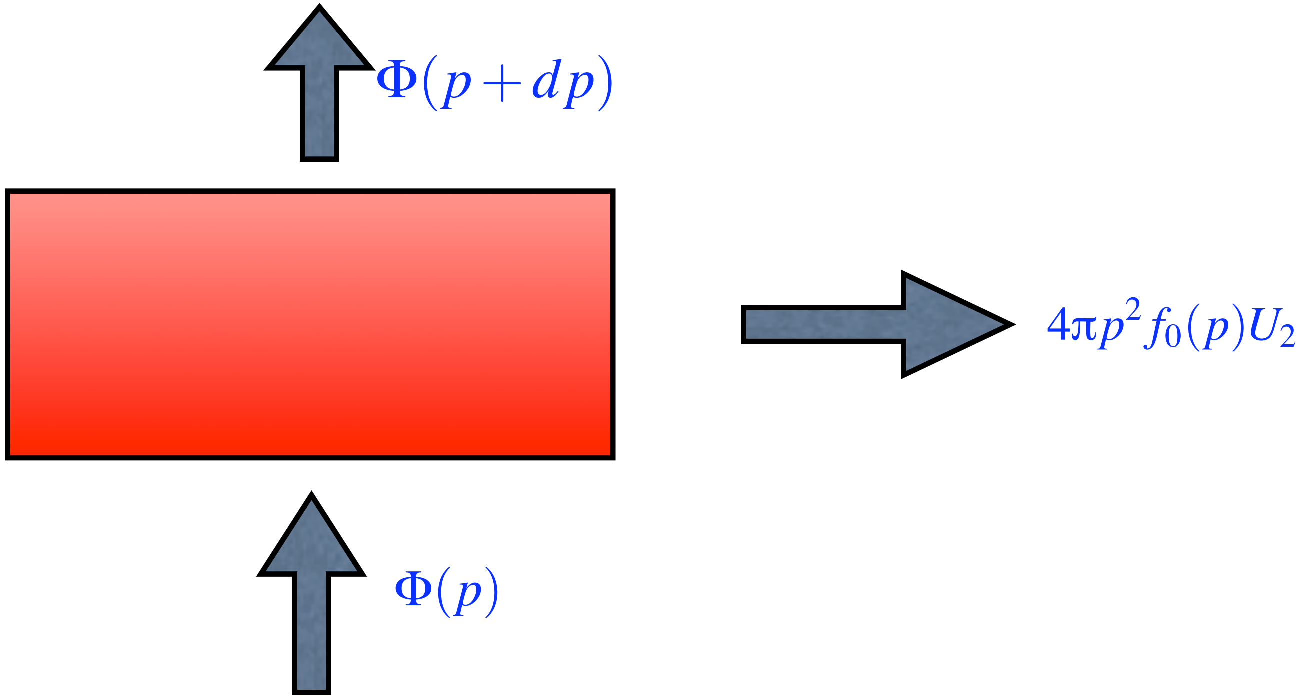


(basically just
Liouville's theorem)

and is localised at the shock.

Now write down particle conservation law for balance between rate of advection away from shock region and acceleration

$$\frac{\partial \Phi}{\partial p} = -4\pi p^2 f_0(p) U_2$$



Particles interacting with the shock fill a “box” extending one diffusion length upstream and downstream of the shock,

$$L = \left(\frac{\kappa_1}{U_1} + \frac{\kappa_2}{U_2}\right)$$

so time dependent particle conservation is

$$\frac{\partial}{\partial t}\left(4\pi p^2 f_0(p) L\right) + \frac{\partial \Phi}{\partial p} = -4\pi p^2 f_0(p) U_2$$

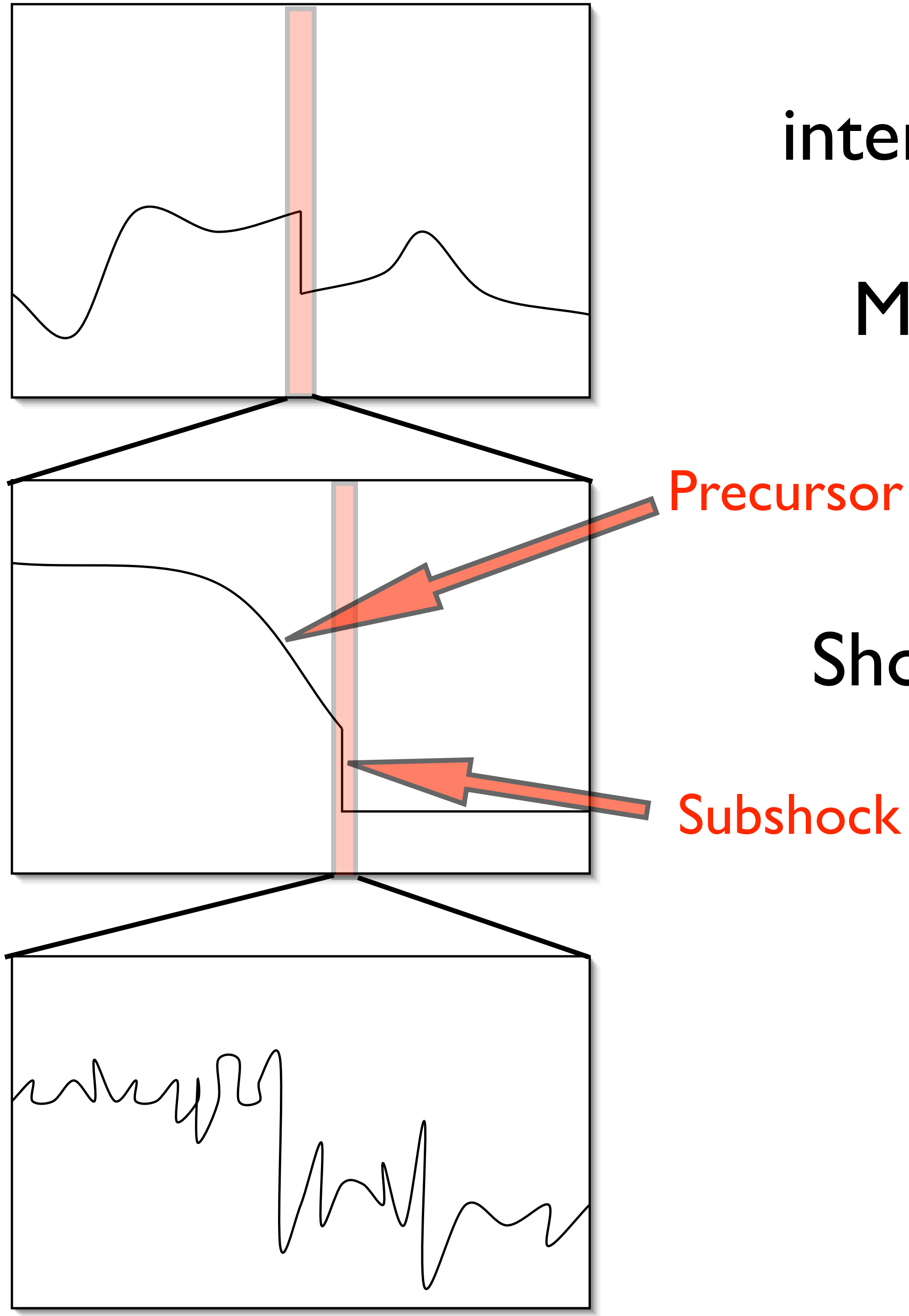
- Standard results of test particle “linear” theory of DSA follow immediately from this simple box model:
  - steady-state spectrum is power-law

$$f(p) \propto p^{-3U_1/(U_1-U_2)}$$

  - acceleration time-scale is

$$t_{\mathrm{acc}} = \frac{3L}{U_1 - U_2}$$

- DSA is a mesoscopic theory operating on intermediate length and time scales. Can distinguish two extreme scales..
    - Outer scale of macroscopic system and maximum energies
    - Inner scale of injection processes and kinetic effects
- DSA theory bridges the gap between these two regimes.



Outer scale,
interaction of SN ejecta and environment,
Magnetohydrodynamics
shock formation

Intermediate scales
Shock acceleration theory
shock structure

Inner scale
Plasma physics
Injection!

- Note that in the heliosphere scales are usually not very well separated!

- Two main issues in non-linear DSA are:
  - To understand the precursor structure;
  - To understand the injection process (in SNRs need to throttle back the injection to about $\approx 10^{-4}$).

Semi-analytic approach to steady mesoscopic structure

Can (hopefully) assume steady planar structure with fixed mass and momentum fluxes.

$$\begin{aligned} \rho U &= A \\ AU + P_G + P_C &= B \end{aligned}$$

and we still have the steady balance between acceleration and loss downstream...

$$\frac{\partial \Phi}{\partial p} = -4\pi p^2 f_0(p) U_2$$

.. but the problem is that the acceleration flux now depends on the upstream velocity profile ***and*** the particle distribution.

However, if one makes an *Ansatz*

$$f_0(p) \rightarrow f(x,p)$$

the particle conservation equation and the momentum balance equations, become two coupled equations (in general integro-differential) for the two unknown functions.

$$U(x), \quad f_0(p)$$

An obvious *Ansatz* would be to assume a distribution similar to that familiar from the test-particle theory,

$$f(x,p) = f_0(p)\exp\int\frac{U(x)\,dx}{\kappa(x,p)}$$

This is actually close to Malkov's *Ansatz* who, however, uses

$$f(x,p) = f_0(p)\exp\int\left(-\frac{1}{3}\frac{\partial\ln f_0}{\partial\ln p}\right)\frac{U(x)\,dx}{\kappa(x,p)}$$

which is better for strongly modified shocks.

Motivation comes from exact solution for uniformly distributed compression, *ie* linear velocity field. Easy to check that

$$f = p^{-7/2} \exp\left(\frac{-\alpha x^2}{2\kappa}\right)$$

identically satisfies

$$\frac{\partial f}{\partial t} + U\frac{\partial f}{\partial x} - \frac{1}{3}\frac{\partial U}{\partial x}p\frac{\partial f}{\partial p} = \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right)$$

for $U(x) = -x, \qquad \kappa \propto p, \qquad \alpha = \frac{7}{6}$

$$
\begin{aligned}
f(x,p) &= p^{-7/2} \exp\left(\frac{-\alpha x^2}{2\kappa}\right) \\
&= f_0(p) \int \left(-\frac{1}{3}\frac{\partial \ln f_o}{\partial \ln p}\right) \frac{U(x)\,dx}{\kappa}
\end{aligned}
$$

So the additional factor introduced by Malkov in the exponential can be thought of as compensating for the fact that the acceleration is distributed over the whole precursor and is not just concentrated at one point.

Blasi introduces a further factor to interpolate between these and recommends the following modified version of Malkov's *Ansatz*

$$f(x,p) = f_0(p) \exp \int \left(-\frac{1}{3} \frac{\partial \ln f_0}{\partial \ln p} \right) \left(1 - \frac{1}{r_{\mathrm{tot}}} \right) \frac{U(x)\, dx}{\kappa(x,p)}$$

Note that all of these are approximations and not exact solutions despite the impressions sometimes given. The good news is that they all give very similar answers....

Consensus view...

- Spectra are generically curved, softer at low energies, hardening in the relativistic region before cutting off.
- Hardening at high energies at most changes spectral index from 4 to 3.5, so not too extreme.
- Subshock is reduced to point where injection matches capacity of shock to accelerate; suggests minimum subshock compression ratio of about 2.5 and typically of order 3, even in strong shocks.

But...

- All approaches assume steady structure on the mesoscopic scale.
- In fact exist many possible instabilities.
- However can hope that theory still applies in mean sense - basic physics is very robust.
- Also not all bad news - offers exciting prospect of amplified B fields and thereby reaching higher energies.

- Bell's non-resonant instability
  - Energetic cosmic rays penetrate upstream ignoring small-scale field structure - unmagnetised on these scales.
  - Return current of low-energy particles is forced through magnetised plasma
  - Field lines coil up and attraction of parallel currents amplifies disturbance.

- MHD is theory of strongly magnetised plasmas.
- Usually rewrite Lorentz force on plasma to eliminate currents using induction law.
- Need to modify this for case considered.

$$\begin{aligned}
\nabla \wedge B &= j_{CR} + j_{th} \\
j_{th} &= \nabla \wedge B - j_{CR} \\
F &= j_{th} \wedge B \\
&= (\nabla \wedge B) \wedge B - j_{CR} \wedge B
\end{aligned}$$

- If CR are strongly scattered then the additional force term can be shown to reduce to an additional cosmic ray pressure,

$$\langle j_{CR} \wedge B \rangle \approx \nabla P_{CR}$$

- But on length scales where the CR are not scattered can drive a current-driven instability

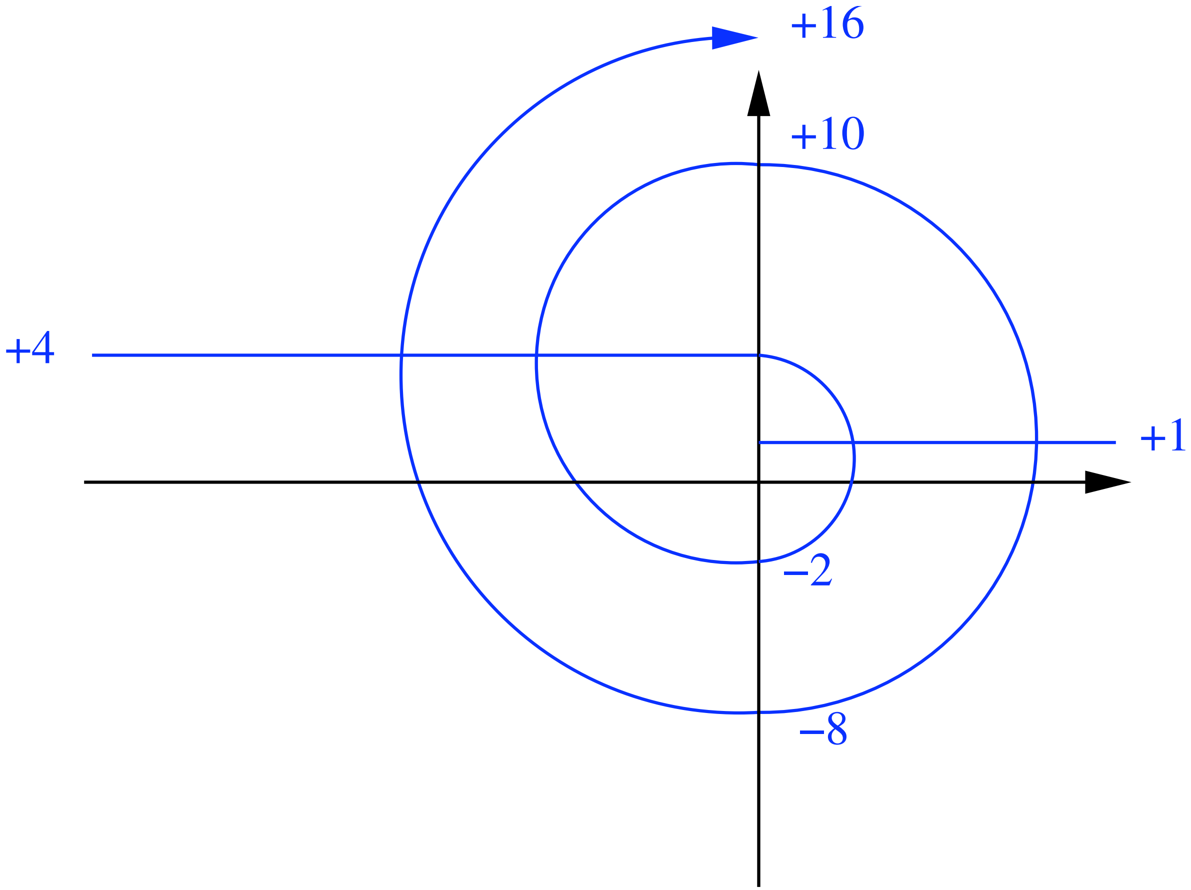
Figure 4: The paths of four magnetic field lines in (x,y,z) at $t = 6$.

(from Bell 2005)

Composition

- Injection
- Chemical composition of ions
- Electron to proton ratio

Where do the particles come from? The so-called "injection problem" - not really a problem (at least for ions)...



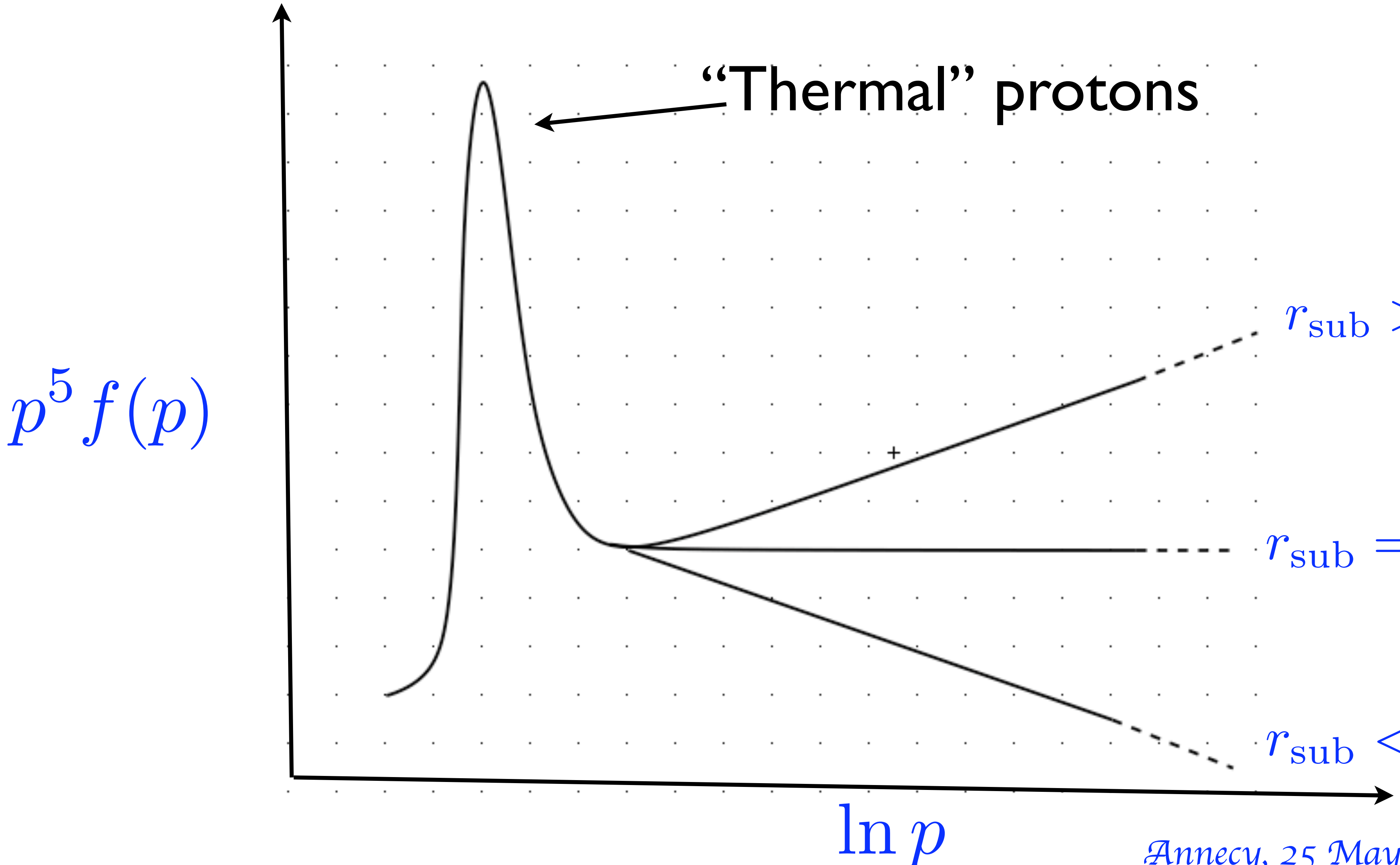
Have back-streaming ions for compression > 2.

Real problem is to throttle back the ion injection. If more than 0.0001 are injected in typical SNR shocks have severe energy problems!

Electron injection is another matter and is NOT well understood - but there are certainly mechanisms that could get electrons to the point where their gyro-radii are comparable to supra-thermal protons at which point conventional shock acceleration can take over.

Note that injection favours high rigidity particles - roughly matches observed chemical composition of the GCR, but a detailed match appears to need a dust contribution.

$$P_C = \int 4\pi p^2 f(p) \frac{pv}{3} p \, d\ln p$$

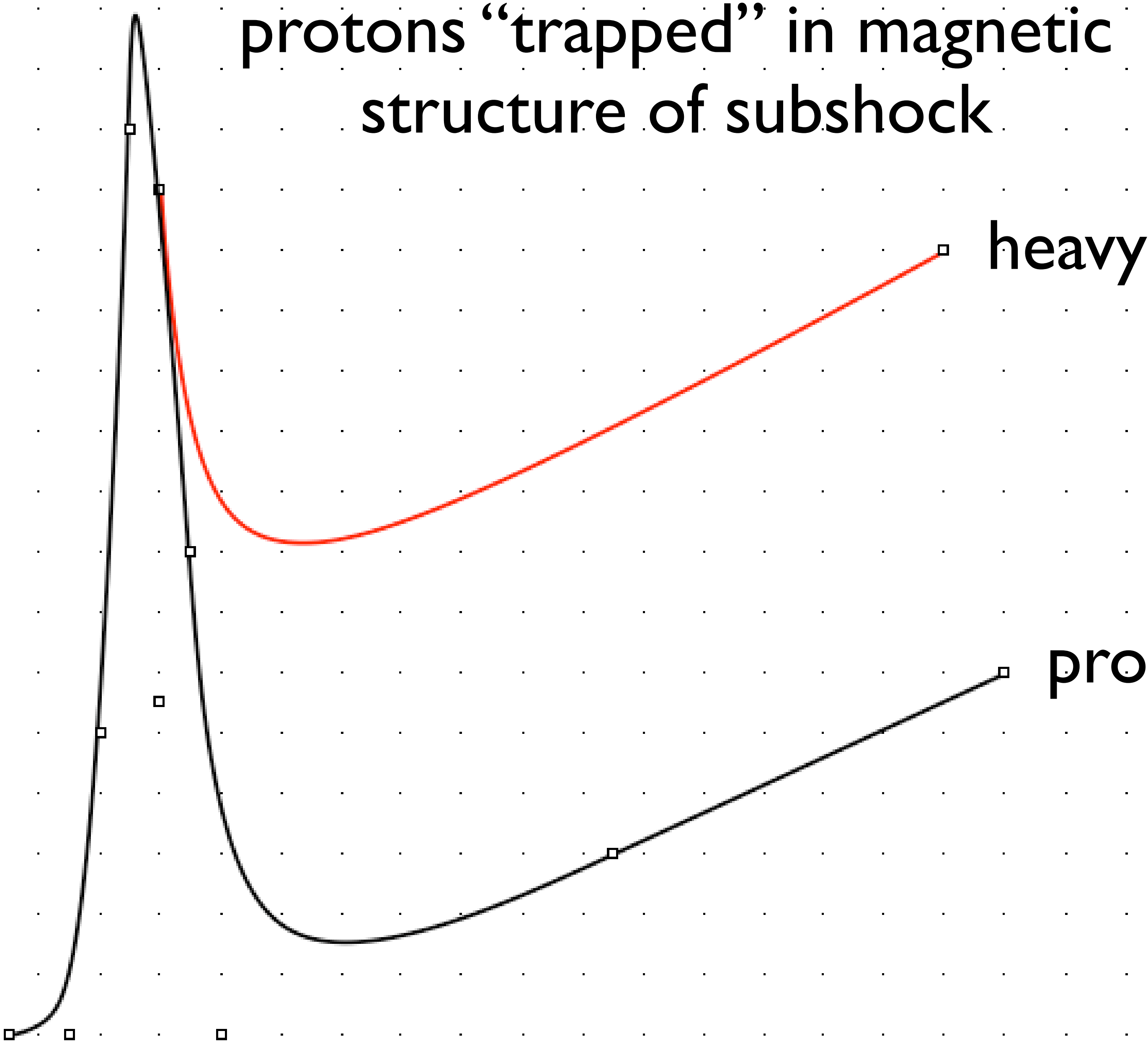


In the non-relativistic part of distribution, above injection energy but well below transition to relativistic regime, a local minimum in the pressure per logarithmic interval (and thus a distinction between non-thermal and thermal populations) requires a sub-shock compression of more than 2.5

$$r_{\rm sub} = 2.5 \implies f(p) \propto p^{-5}$$

But if there is a long "lever arm" between injection and the relativistic regime, the sub-shock compression cannot be much larger than about 3....

Preferential injection of “heavy” ions



protons “trapped” in magnetic structure of subshock

heavy ions

protons

Thus expect chemical composition of accelerated particles to be bulk composition of ISM modulated by a smooth increasing function of initial mass to charge ratio....

Works in general terms, but clearly does not reproduce the detail of the GCR composition (which is rather accurately determined at a few GeV/nucleon from many experiments).

What does seem to work is a dust/gas model.

Most heavy elements (Fe, Si, Al, Ca) in the ISM are in the form of ISM dust particles (mainly silicate minerals).

Small dust grains are electrically charged and behave like extremely heavy ions, so can be slightly accelerated.

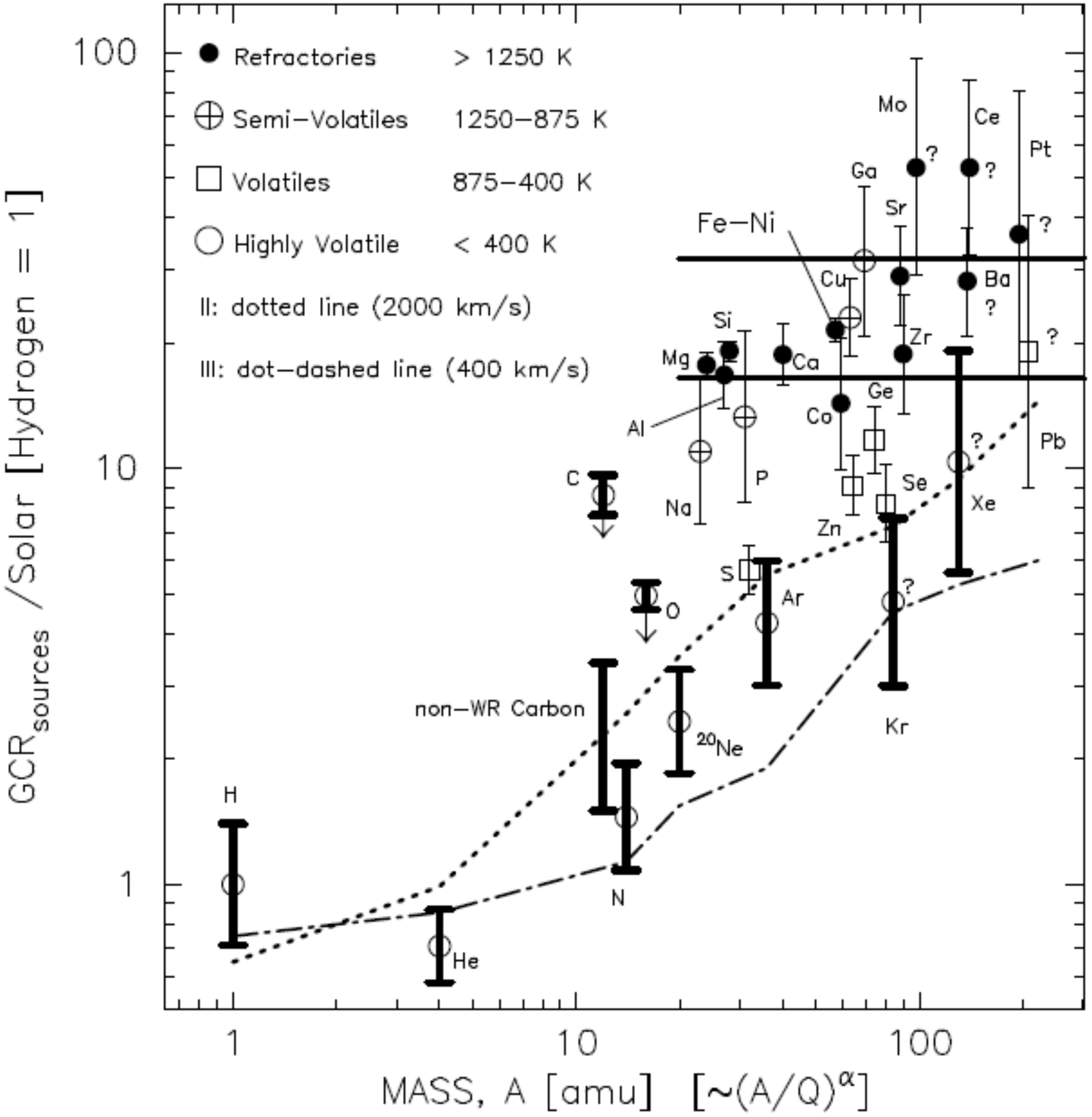
Acceleration is stopped by frictional losses which sputter supra-thermal secondary ions off the surface of the grain.

These secondary ions, if upstream of the shock, are then swept in and accelerated bypassing all the low-energy Q/M filtering

Two separate mechanisms for ion injection

- Gas species injected with smooth Q/M modulation.
- Refractory species injected via grain sputtering with roughly constant efficiency of order 30 time protons.

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



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

Very suggestive that the two elements that are known to be significant components of both the gas phase and the dust phase, Oxygen and Carbon, seem to lie between these two components in the abundance data....

Straightforward shock acceleration theory, applied to a dusty ISM with standard composition, appears to be able to give a good quantitative fit to all the GCR compositional data.

Electrons are still very much “work in progress”

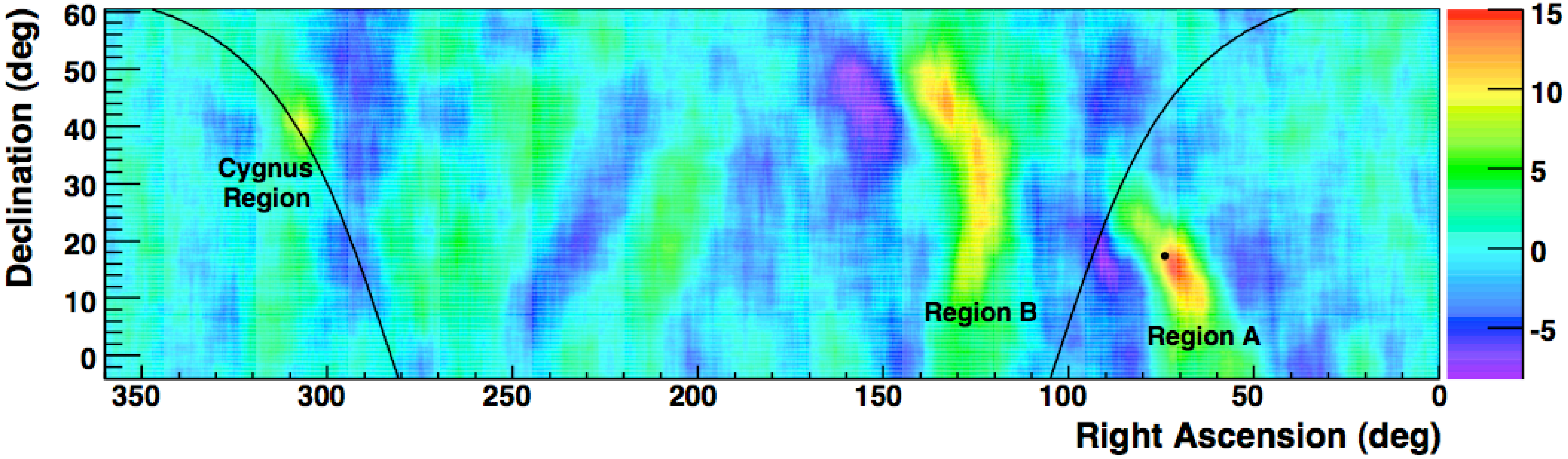
Conclusions

- Shock acceleration from ISM is still very much “standard model” for GCR origin.
- Nonlinear modification understood ***if*** structure is stationary (doubtful).
- Ion composition consistent with dust/gas model (in fact retrodicted).
- Electron injection rate very uncertain, but certainly not zero.
- Magnetic field amplification appears real.

Questions pour les etudiants

- Milagro anisotropy data and hot spots?
- Discrepancy between propagation models and acceleration theory for the source spectra?
- Role of pulsars as electron sources?

A brand new mystery....



Milagro has reported structure, including two localised hot-spots (regions A and B) in the arrival directions of hadronic cosmic rays at 10 TeV!!

arXiv:0801.3827