5th Korean Astrophysics Workshop

Shock Waves, Turbulence and Particle Acceleration

From the perspective of a common, or garden, astrophysicist

Common, or garden, sparrow

Malcolm Longair

Congratulations

To all the speakers on their excellent presentations. Science and presentations of the very highest international quality.

I will concentrate on the topics which I personally find of the greatest interest and concern for the broader issues of astrophysics as a whole.

The Task of the Summariser

Common, or garden, sparrow

The experts

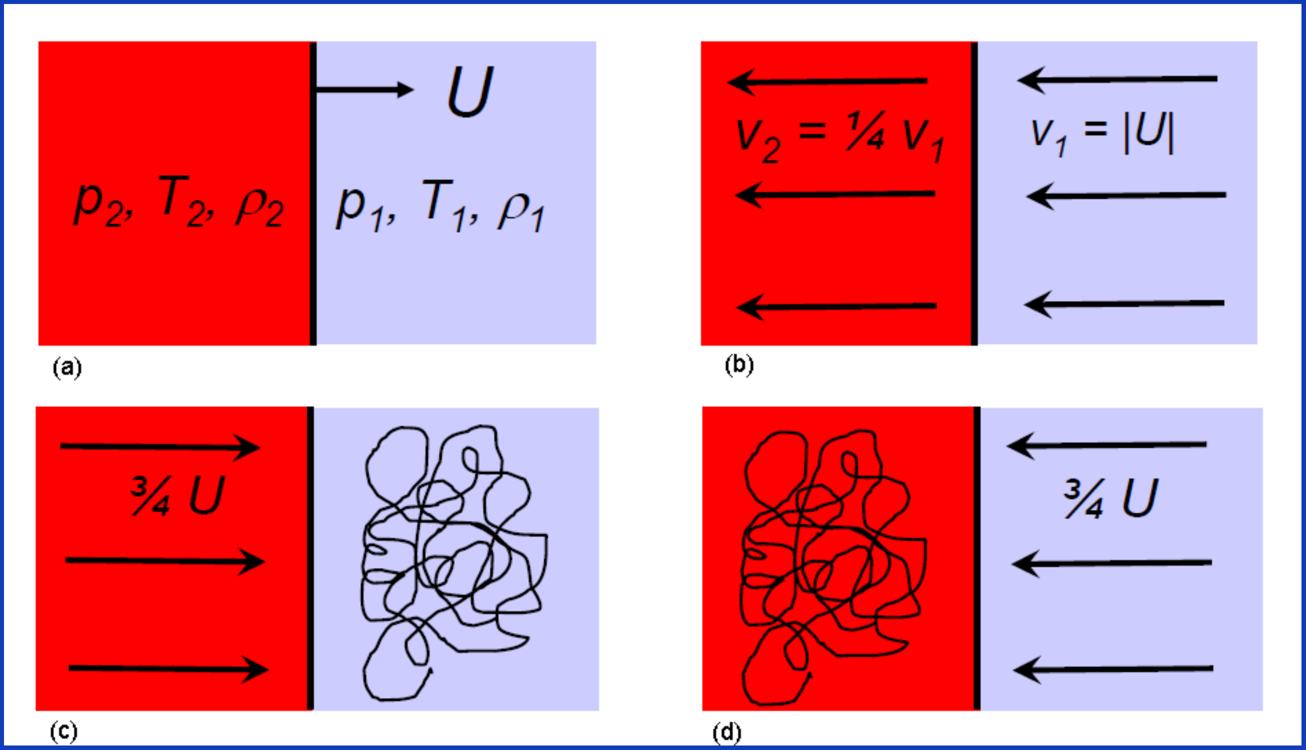
Why do astrophysicists find shock acceleration so appealing?

- It works effectively wherever there are strong shock waves and there are lots of these in astrophysical systems
- It produces naturally a power-law energy distribution of particle energies
- It accelerates the particles where they are needed – it avoids the adiabatic loss problem by tapping the kinetic energy of the flows

Why do astrophysicists find shock acceleration so appealing?

- The formation of the power-law in the simplest model non-relativistic strong shock case has an almost ‘thermodynamic’ character. The acceleration and escape probabilities are fixed by the properties of strong shocks.

The ‘Thermodynamic’ Approach



In my version of the Tony Bell’s approach, the symmetry of the process and the key role of scattering are emphasised and gives $N(E) \propto E^{-2}$.

The Universal Mechanism?

Cosmic rays observed at Earth:

N(E): power-law spectrum "universal" acceleration mechanism working on a wide range of scales.

Generally steeper than E^{-2}.

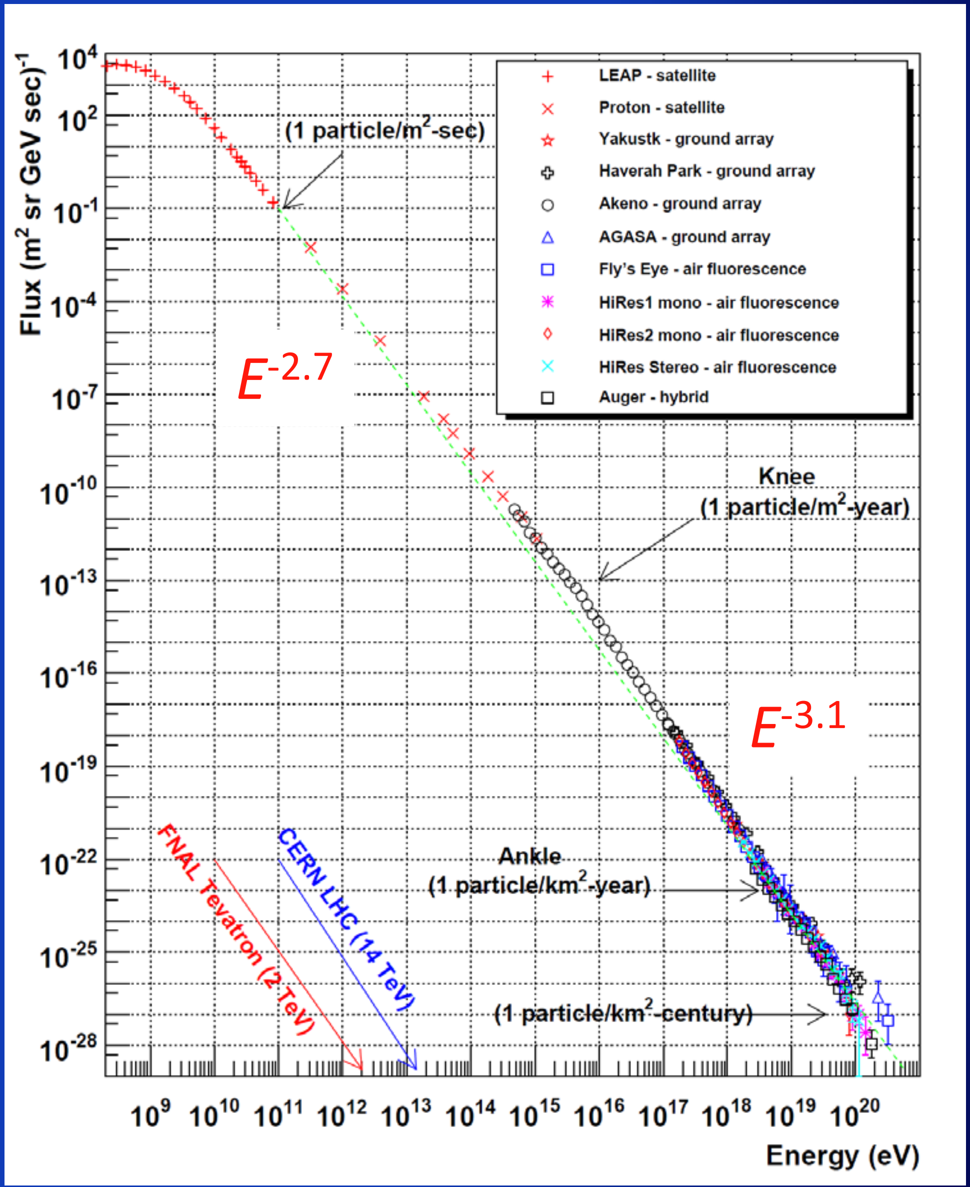
→DSA in the test particle limit predicts a universal power-law

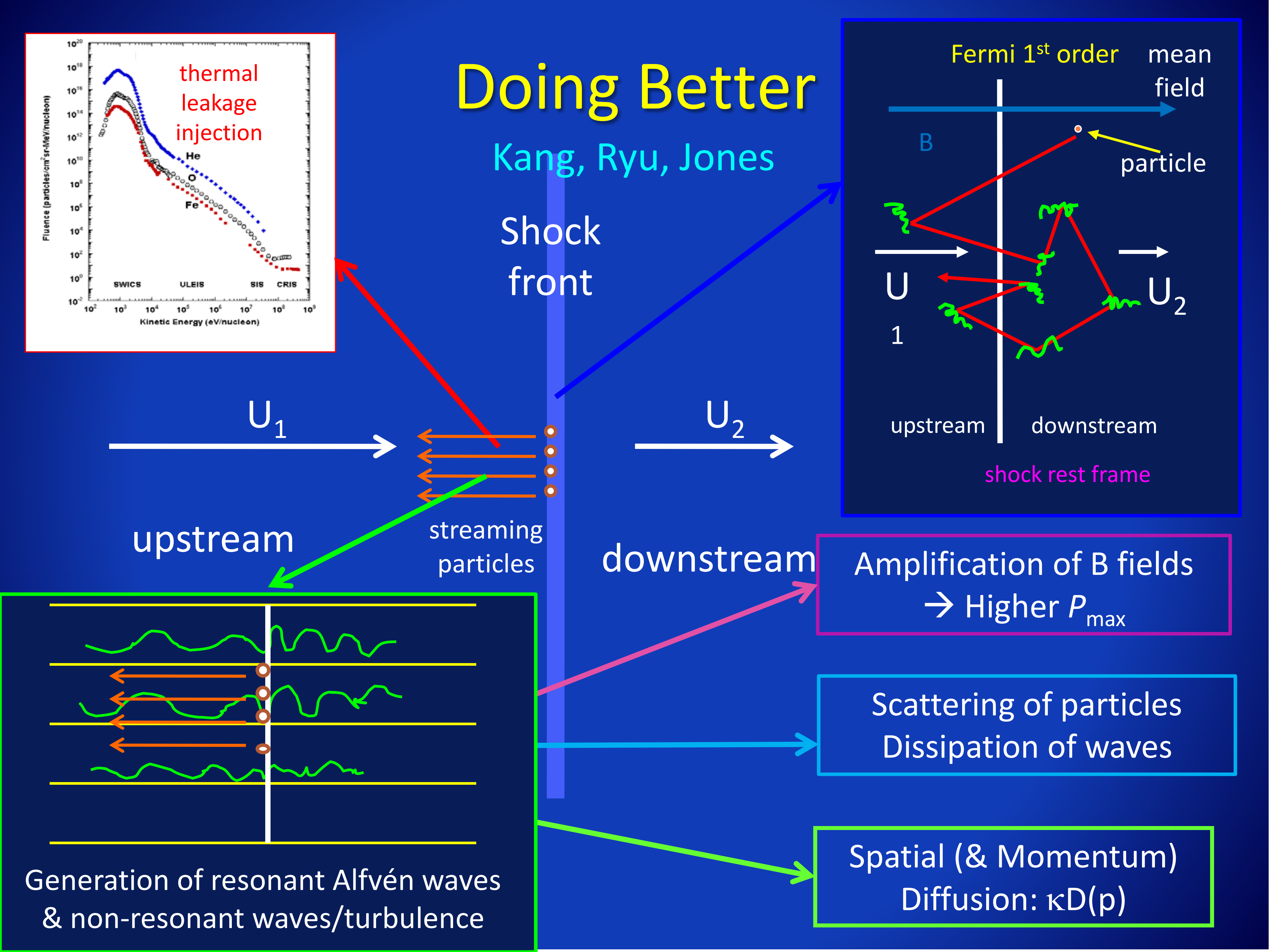
$$f(p) \sim p^{-q}$$

$$N(E) \sim E^{-q+2}$$

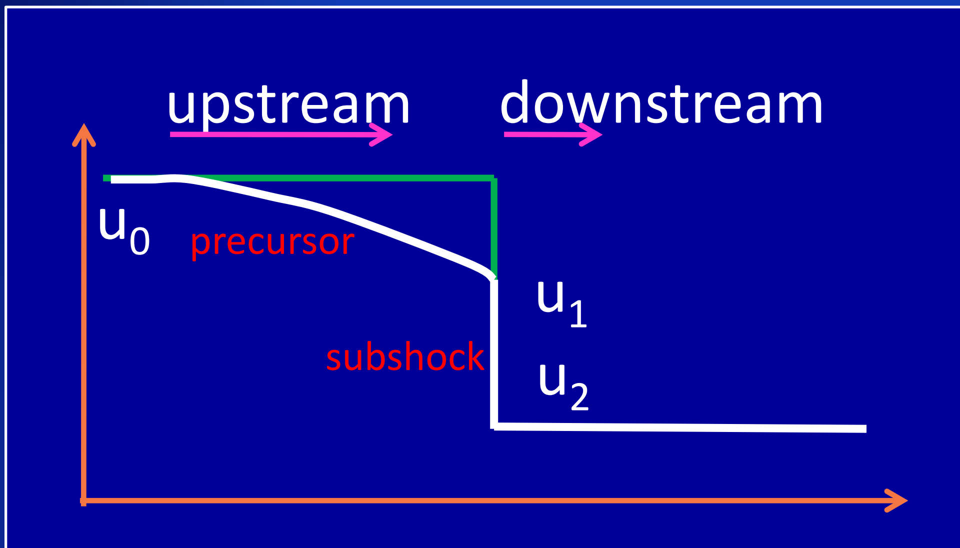
$$q = 3r/(r-1)$$

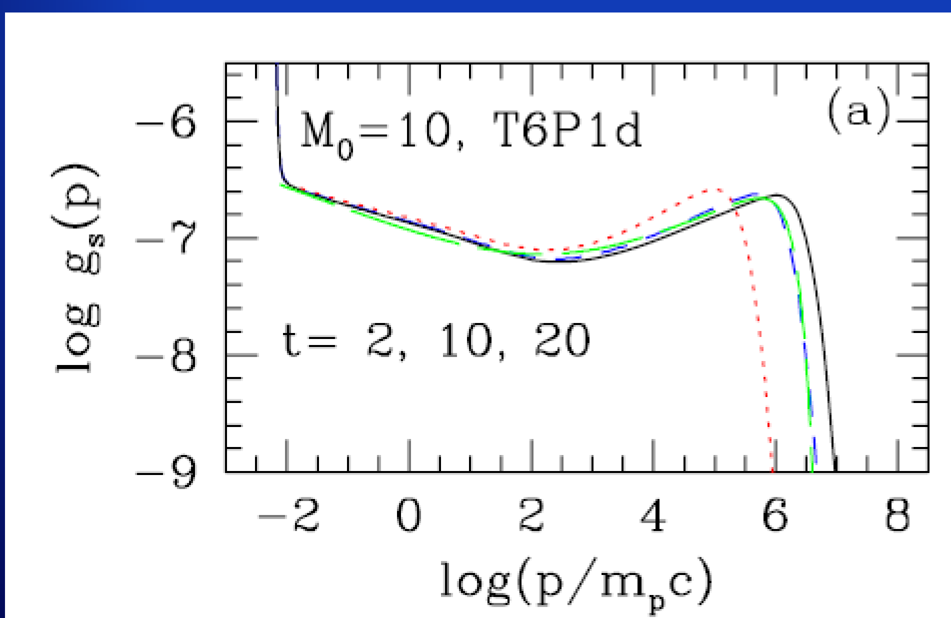
$$r = \rho_2/\rho_1 = u_1/u_2$$




Doing Better
Kang, Ryu, Jones
thermal
leakage
injection
He
O
Fe
SWICS
ULEIS
SIS
CRIS
Kinetic Energy (eV/nucleon)
Fluence (particles/cm² sr-MeV/nucleon)
Fermi 1st order
mean field
B
particle
U1
U2
upstream
downstream
shock rest frame
Shock front
U1
U2
streaming particles
upstream
downstream
Amplification of B fields
→ Higher Pmax
Scattering of particles
Dissipation of waves
Spatial (& Momentum)
Diffusion: κD(p)
Generation of resonant Alfvén waves
& non-resonant waves/turbulence

The “standard model?”

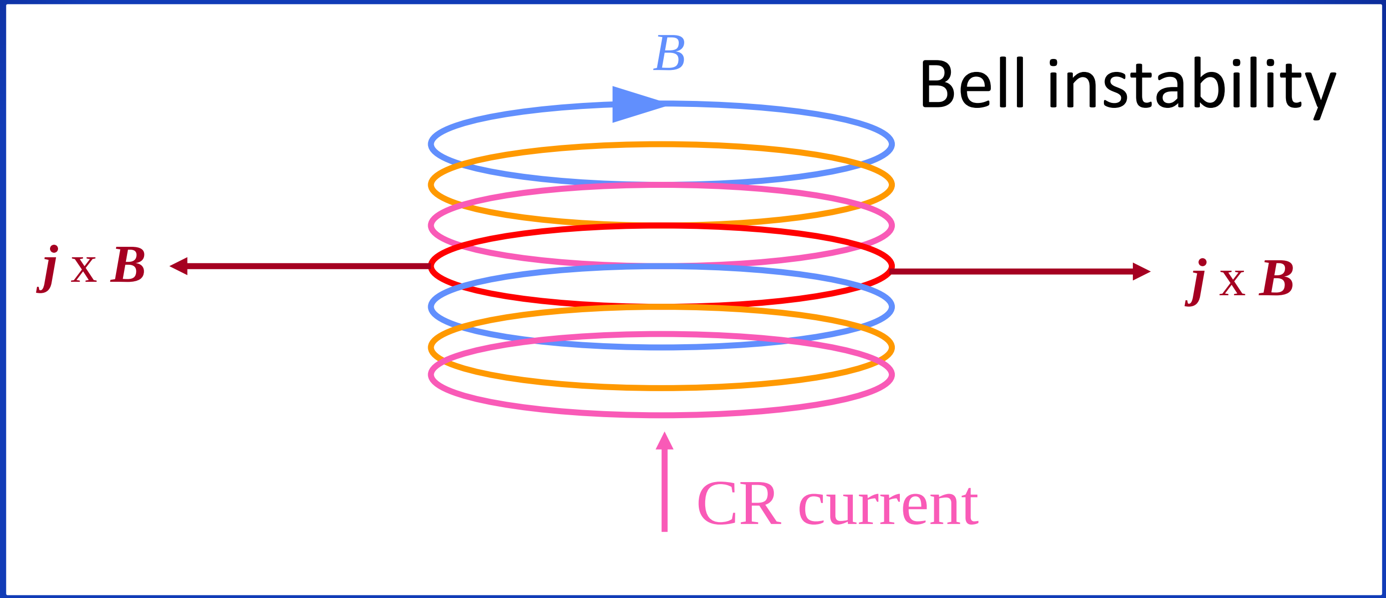




Incorporating the influence of the precursor on the acceleration process helps matter. They showed that there is a self-similar solution with attractive features.

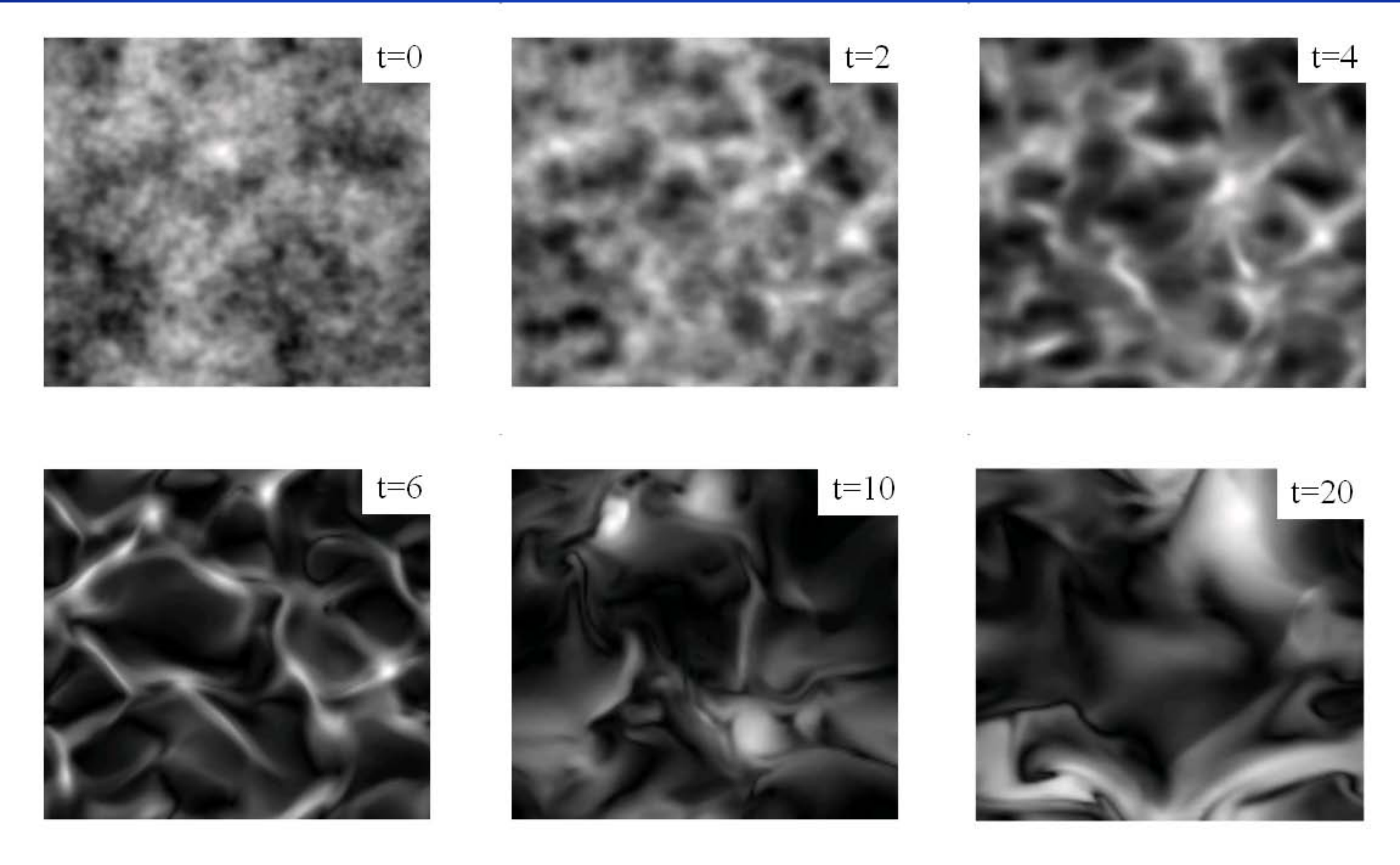
- Steepening of spectrum
- Cut-off at high energies

Accelerating Particles to the 'Knee'



One of the really exciting developments since KAW4 has been the realisation of the various instabilities which can enhance the strength of the magnetic field by a very significant factor and X-ray observations which show that these strong fields are realised in the shocks in supernova shells.

Accelerating Particles to the 'Knee'



The formation of cavities and walls in $|B|$ & ρ

But many other possible ways of enhancing the magnetic field (Reville)

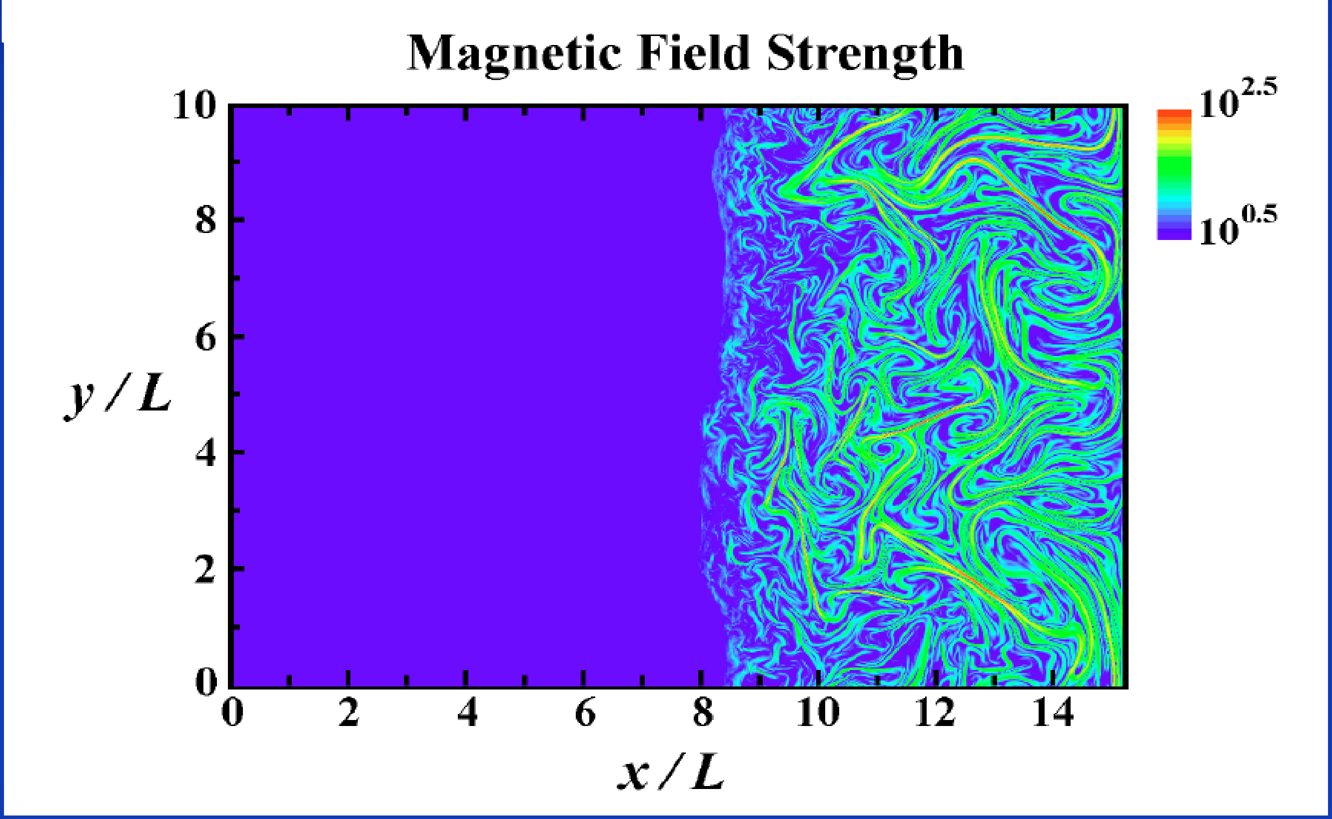
Inside a cosmic ray precursor, several instabilities can operate

- Streaming instability (Bell 1978)
- Drury instability (Drury 1984)
- Firehose instability (Quest & Shapiro 1996)
- Non-resonant instability (Lucek & Bell 2000, Bell 2004)
- Small-scale dynamo (Beresnyak et al 2009)

Instabilities can also operate downstream

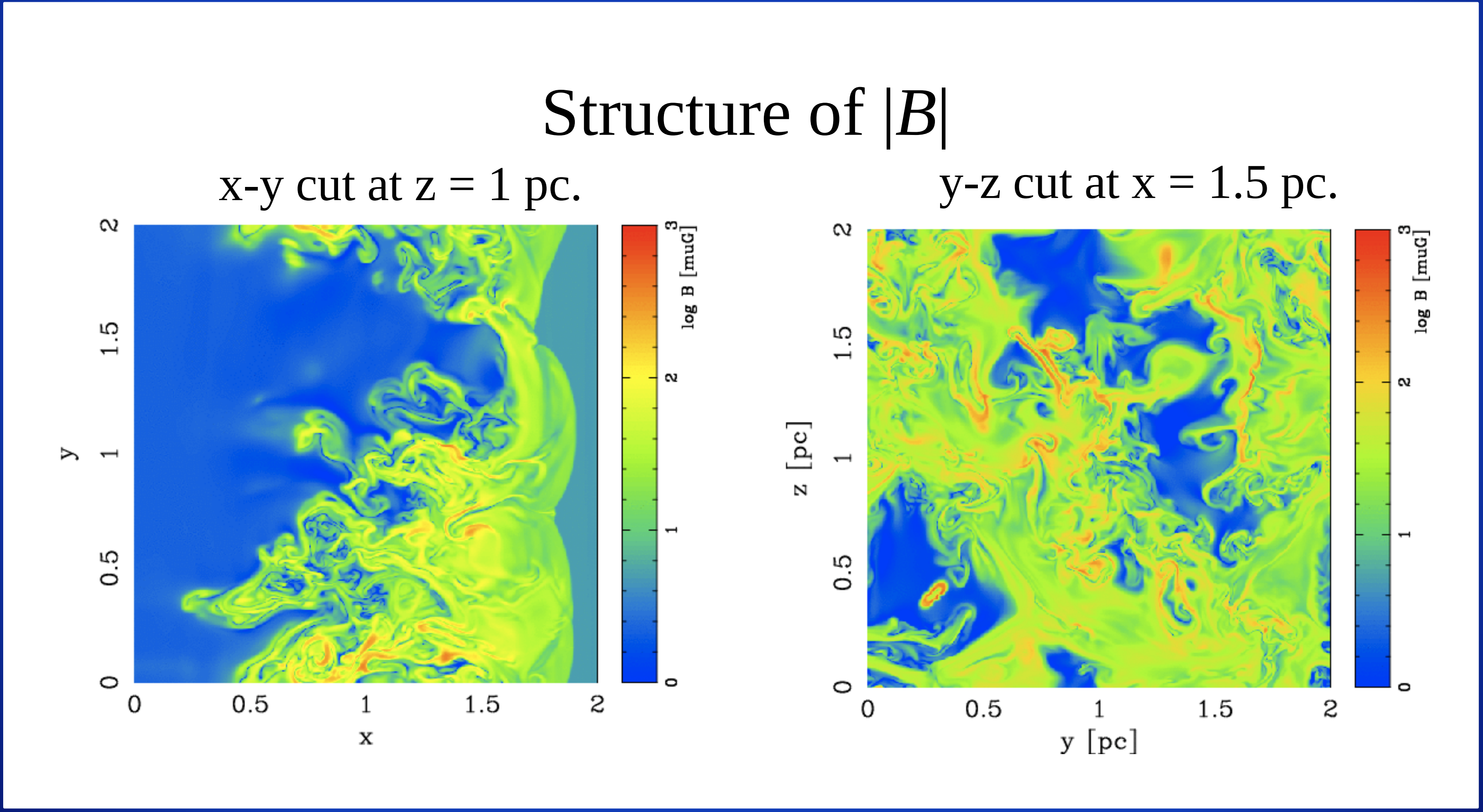
- Nonlinear Richtmeyer-Meshkov instability (Giacalone & Jokipii 2007)
- Charge exchange current driven instability (Ohira et al. 2009)

Magnetic field Amplification



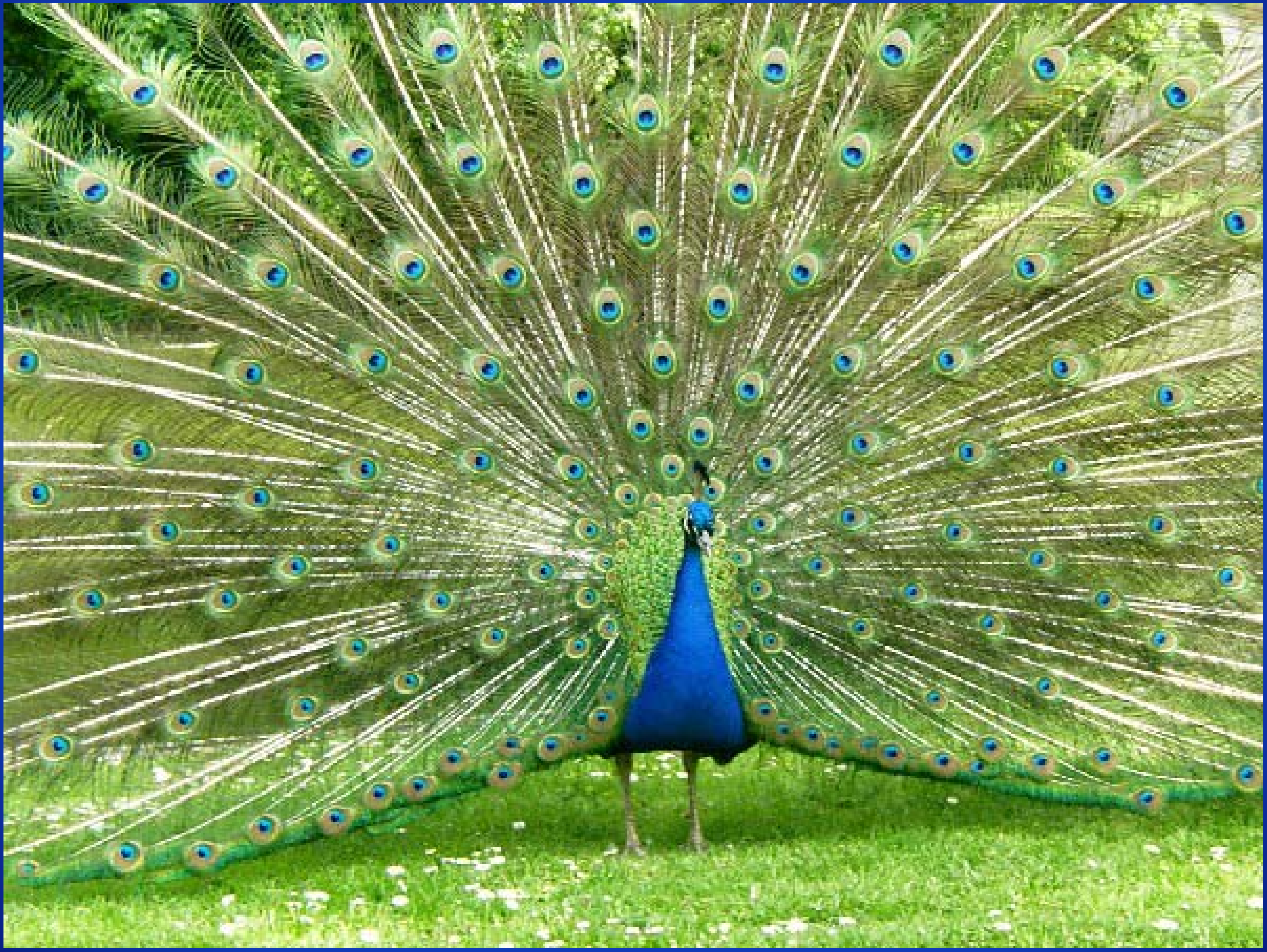
Giacalone & Jokipii simulations of magnetic field amplification including the effect of density turbulence on a strong shock.

3D simulation of turbulent amplification of magnetic field



Inoue

The Plasma Physics and Turbulence



The Plasma Physics

→ A Bit More Depth ....

– where Does this lead us? → {multi-population system with feed back loops

Gas + C.R.'s

[shock, incl. CR's]

[Diffn – Conv. Eqn.]

Waves

[N_{AW} kinetics]

[N_{AC} kinetics]

[Mean field equations

– modulational instability feed back

– CR – AW feedback for confinement

→ CR – shock feedback

– Drury process

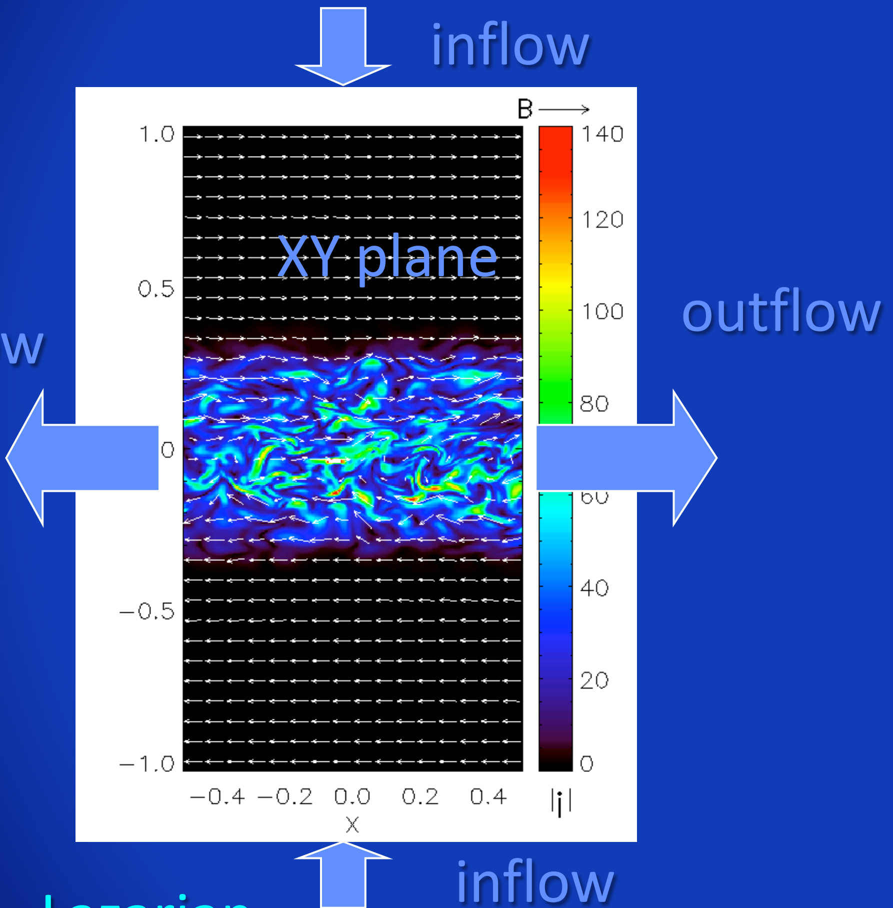
– Acoustic effect on confinement.

[Bottom line: evolve AW, AC populations on [redacted] equal footing with f_{CR}, gas dynamics

→ How?

Diamond, Malkov

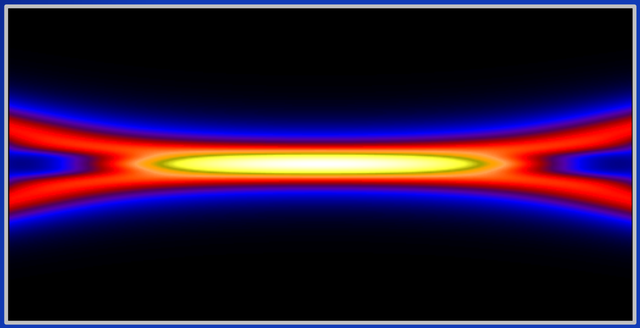
The Turbulence



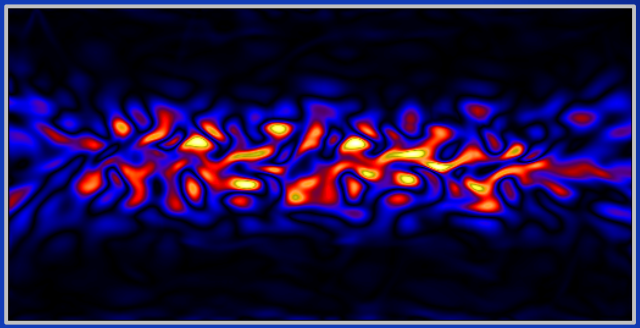
Lazarian

Lazarian has emphasised the importance of incorporating the most recent understanding of turbulent phenomena into all these studies. Jokipii has emphasised the importance of working in three dimensions. These are demanding long-term challenges.

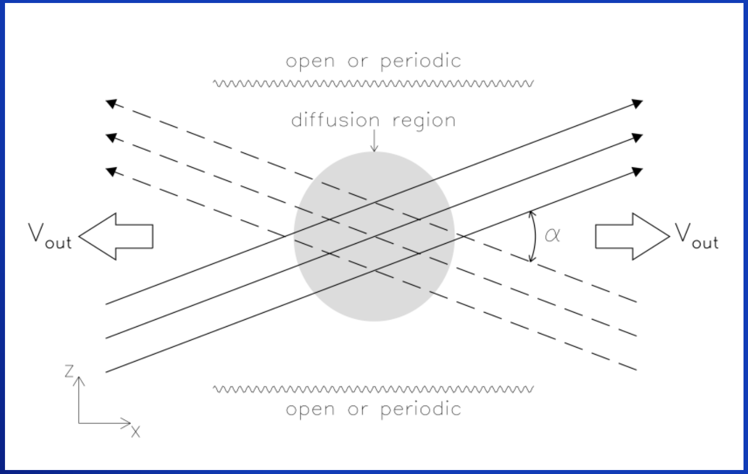
Reconnection in Three Dimensions



Sweet-Parker reconnection

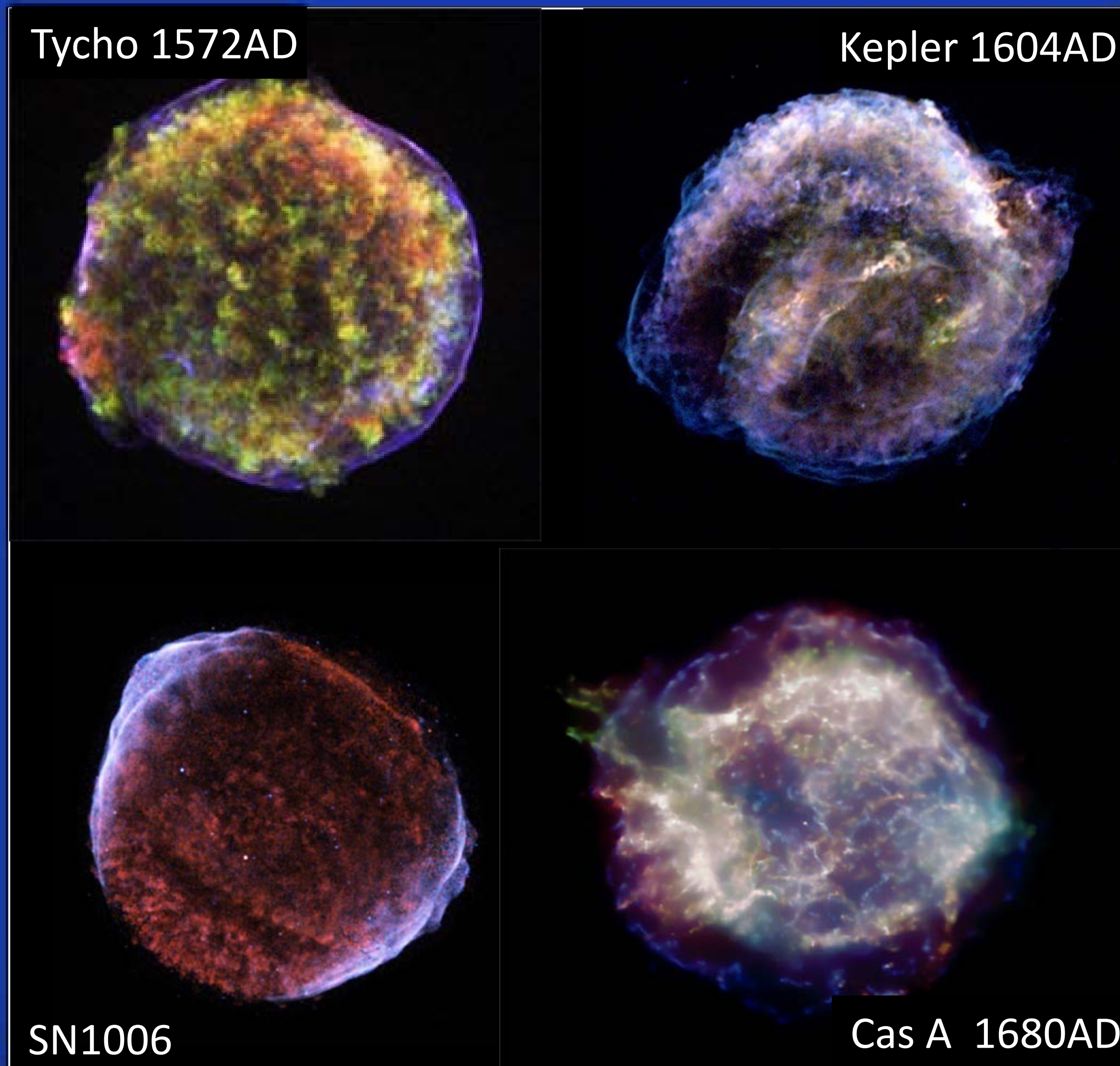


Lazarian-Vishniac reconnection



The essential role of turbulence in three dimensions in speeding up the process of reconnection.

The Shocks observed in X-rays



Vink
Laming
Völk
Reynolds

Chandra observations

The Shocks observed in X-rays and in Hα emissions lines

The narrowness of the X-ray emission and their variability are compelling direct evidence for particle acceleration in strong shocks.

The Hα emission provides a new diagnostic tool for probing the shock and precursor regions. Atomic physics of charge exchange provides direct estimates of the T_e/T_i.

The Shocks observed in X-rays and in Hα emissions lines

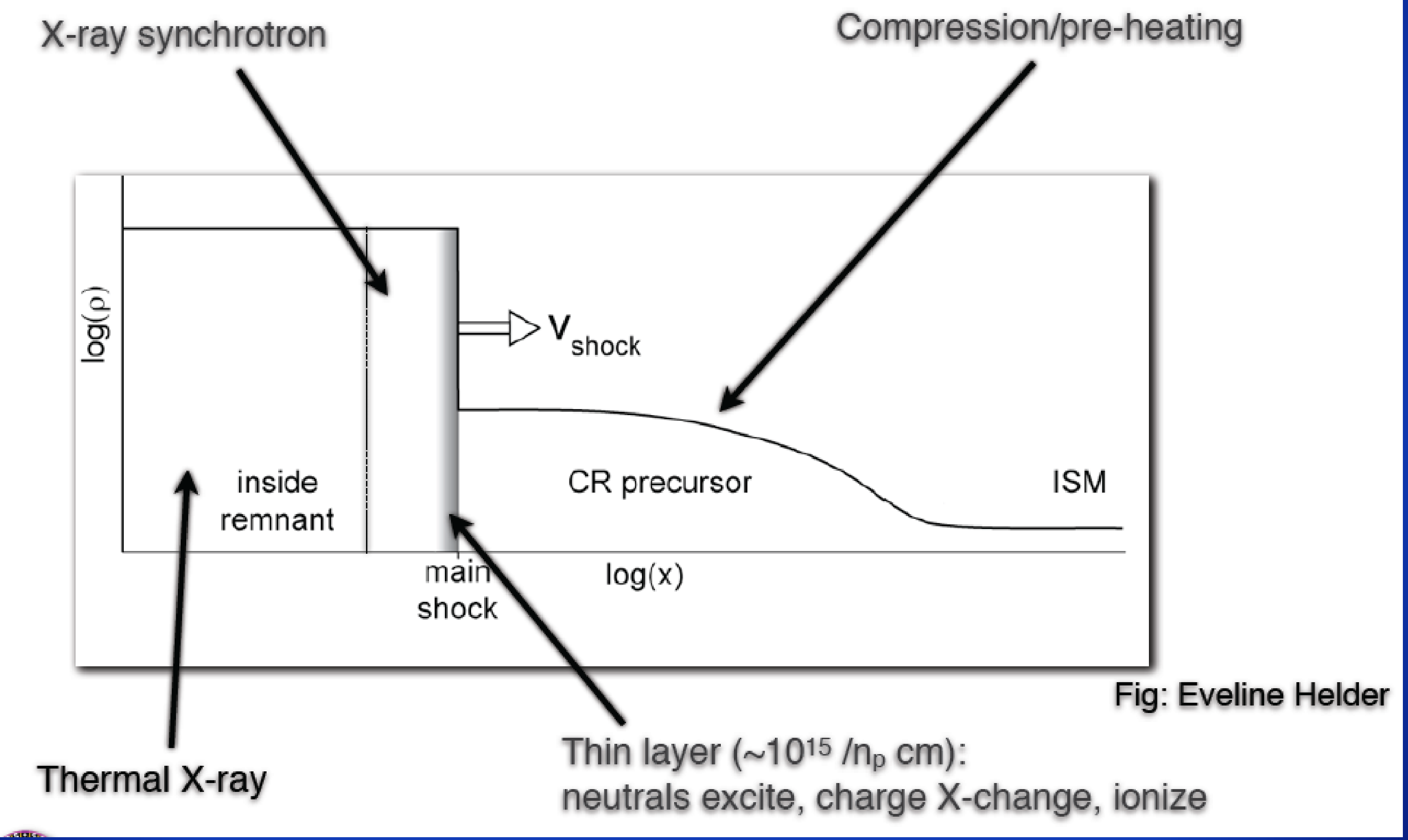
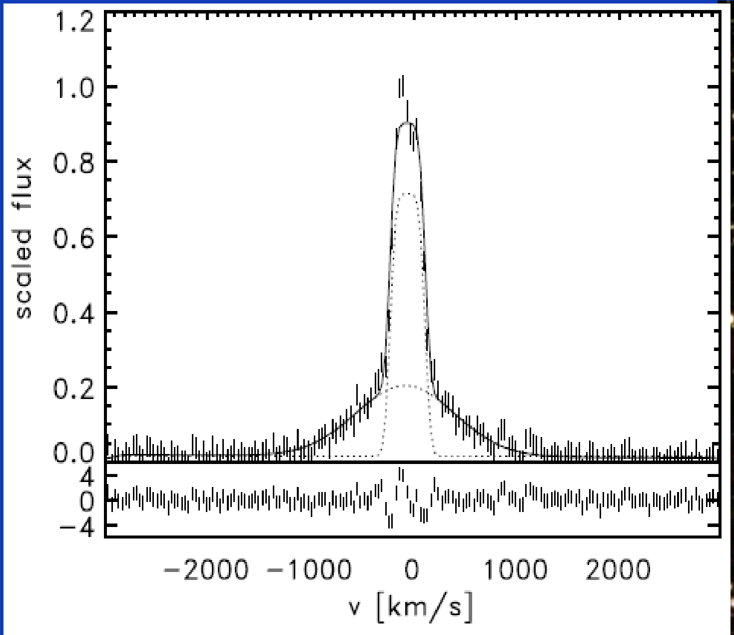


Fig: Eveline Helder

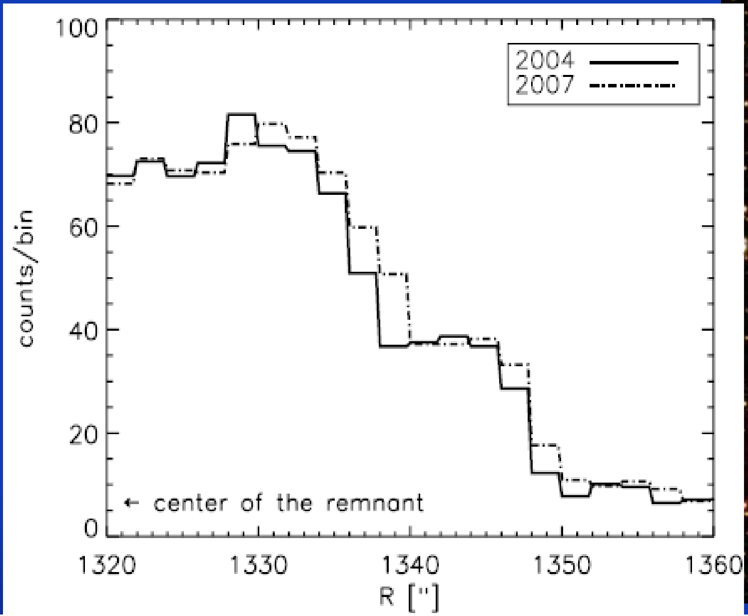
Vink

The Shocks observed in X-rays and in Hα emissions lines

VLT:
Ha line
(broad+narrow)
(optical)



Chandra:
Proper
motion
(X-ray)

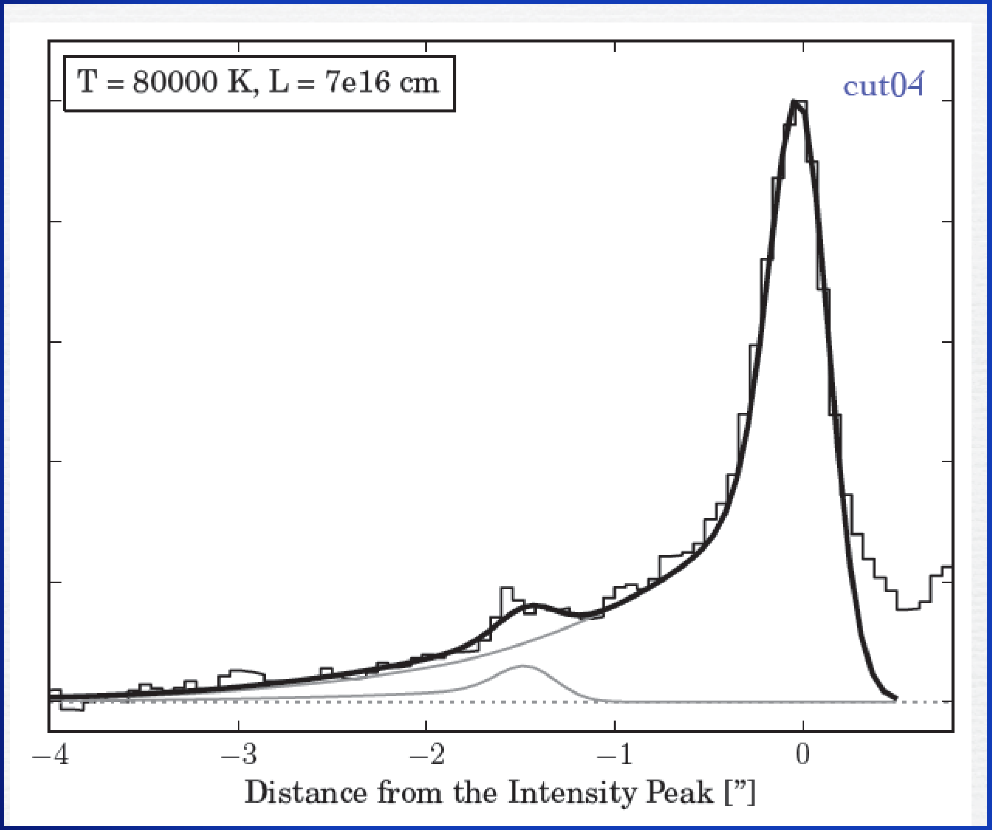


Yamazaki

HST observations of the knot g in Tycho's supernova remnant

Jae-Joon Lee

HST observations of the knot g in Tycho's supernova remnant

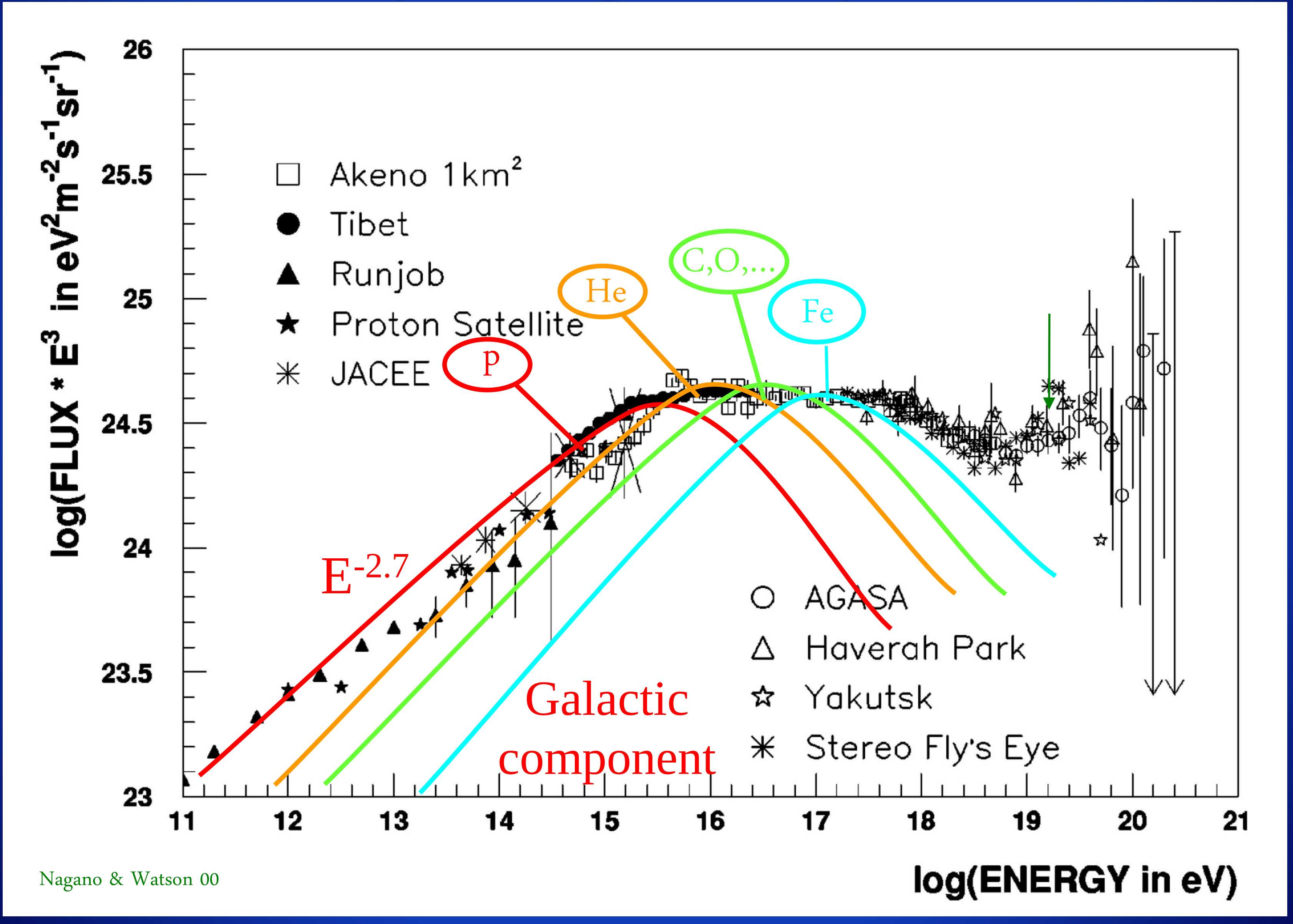


HST image of Tycho reveals a faint extension of the Hα emission to the upstream, which Lee proposes is the emission from the strong shock precursor.

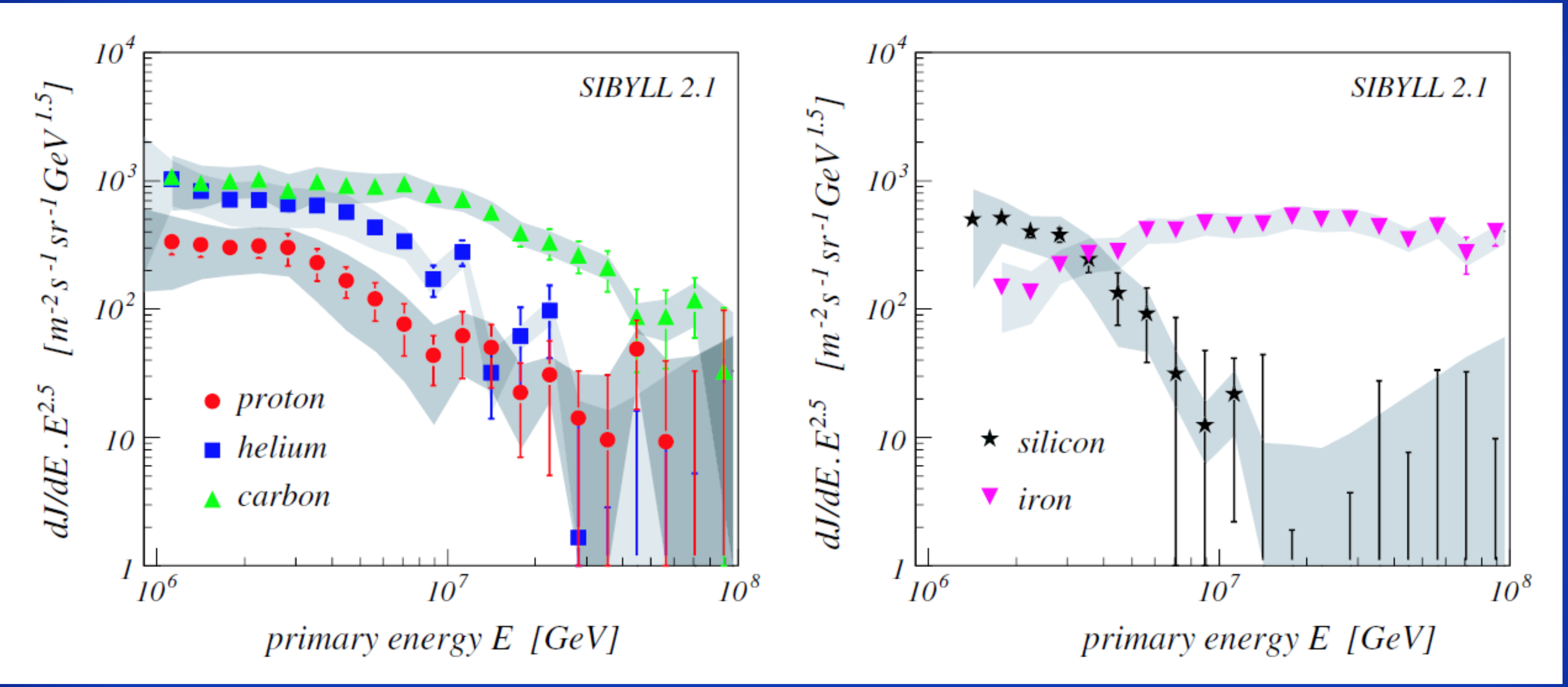
The observed intensity profile is well fitted by his precursor emission model and is used to constrain some of the CR acceleration parameters.

Jae-Joon Lee

Decomposing the Spectrum

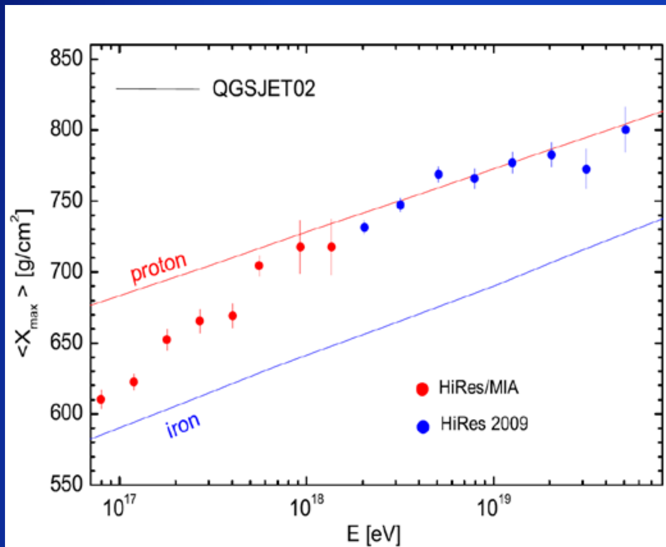


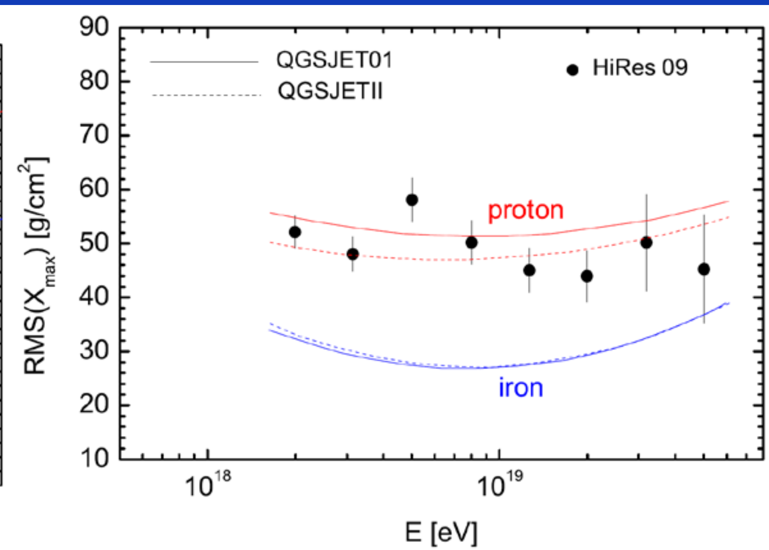
Decomposing the Cosmic Ray Spectrum



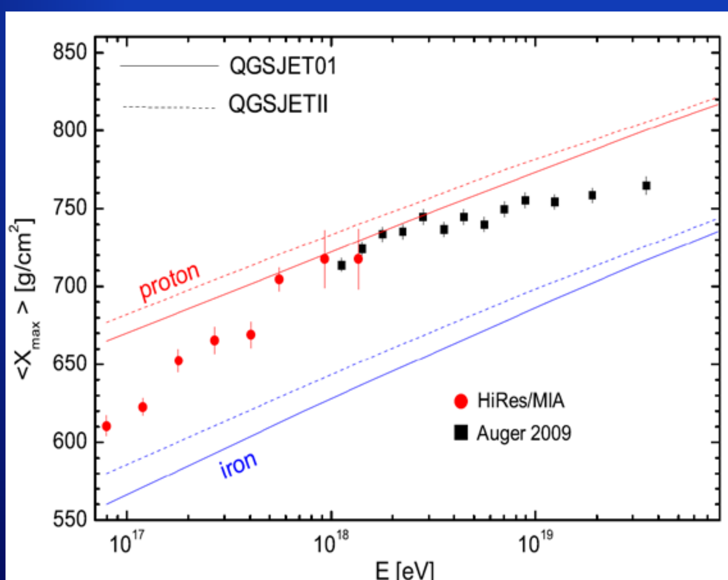
KASCADE results

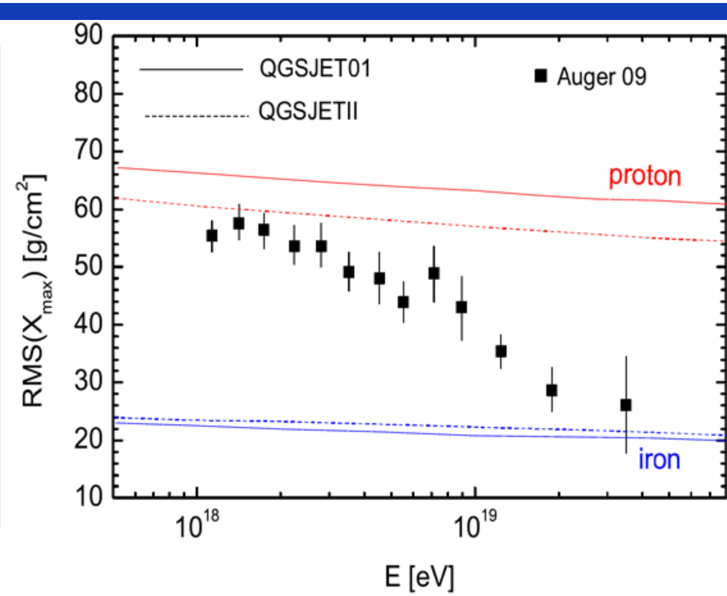
Decomposing the Cosmic Ray Spectrum



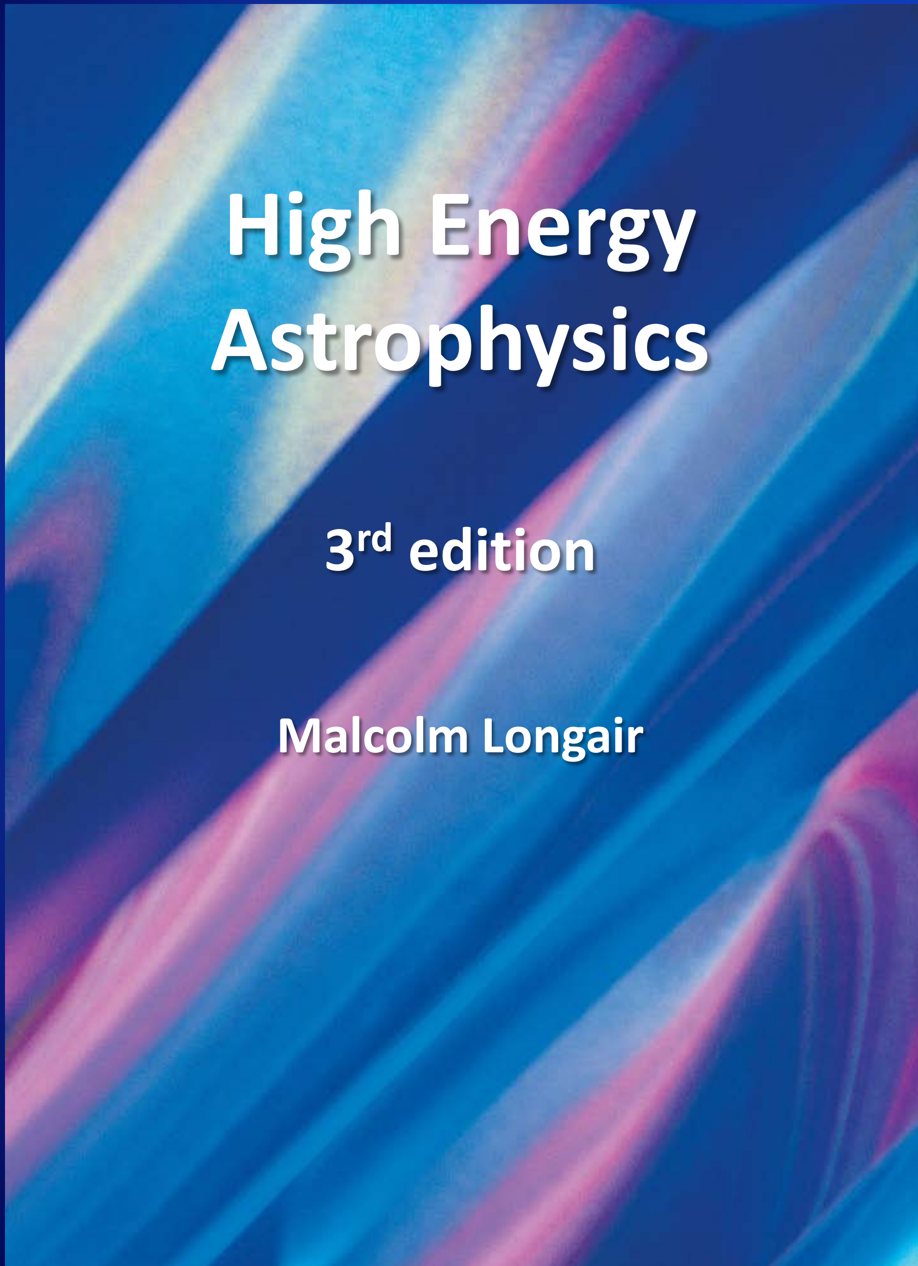


Fly’s Eye





Auger

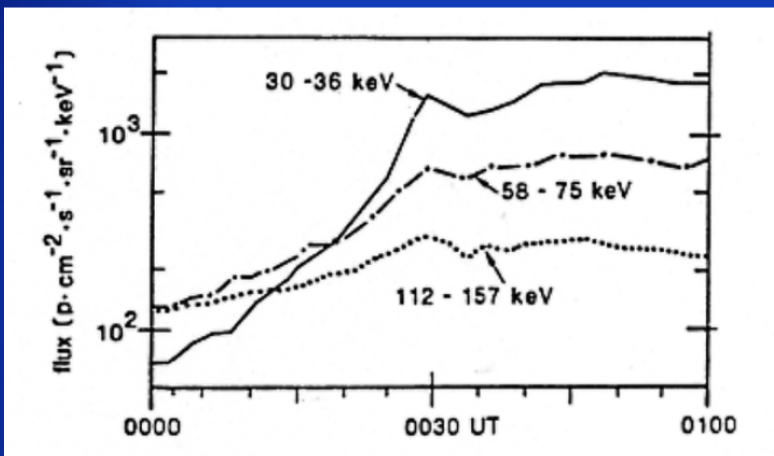


High Energy Astrophysics 3rd Edition

To be submitted to Cambridge University Press

22 December 2009

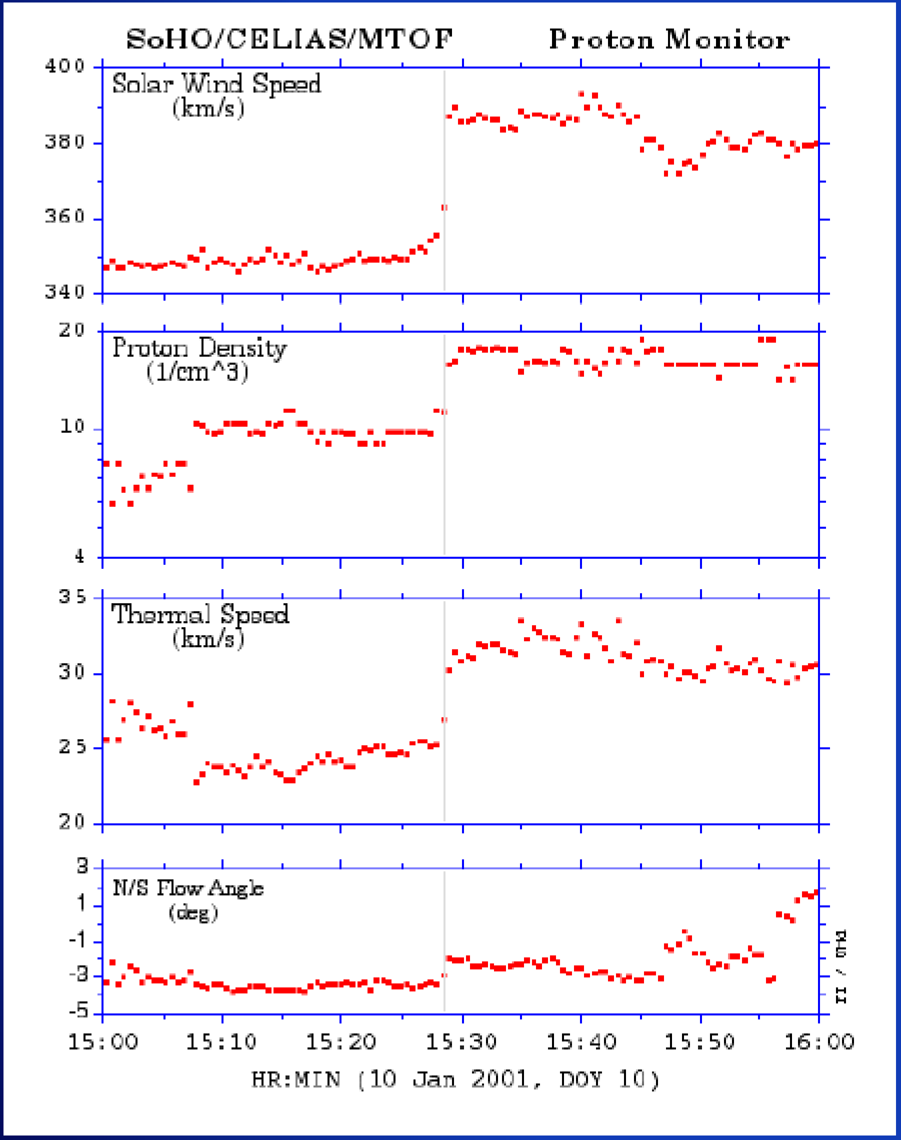
Clues from the Heliosphere



The heliosphere provides an laboratory for testing the theory of diffusive shock acceleration. I was very pleased to include this example of an inter-planetary shock and energetic particle acceleration.

Then, at KAW4, it was stated that there is little convincing evidence for DSA. As was pointed out, this was one of the few events observed which looked like DSA

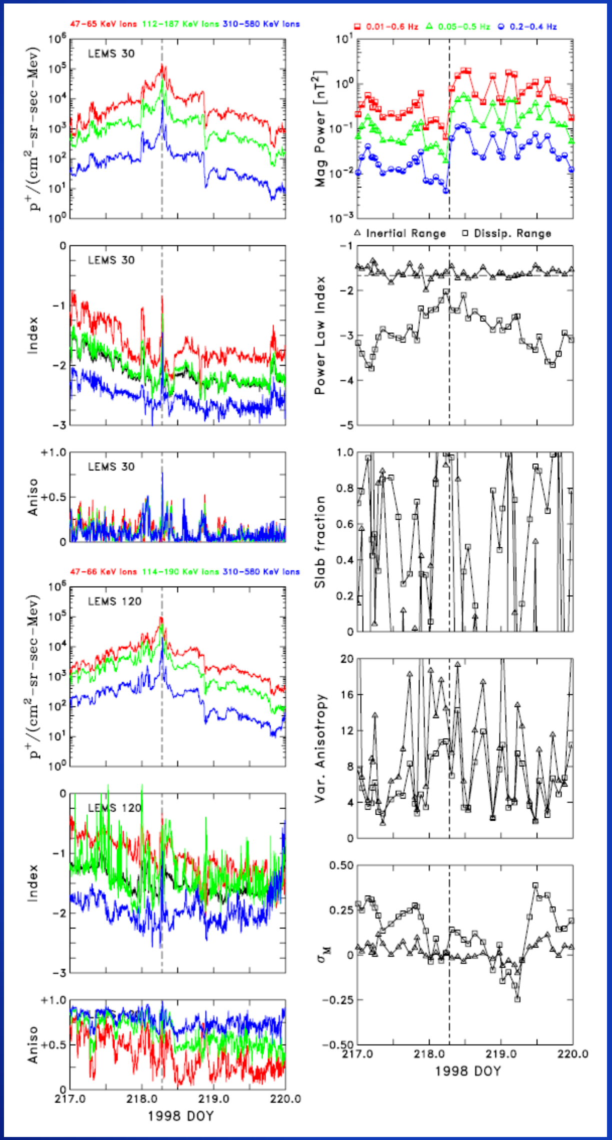
Clues from the Heliosphere



So, removed this evidence from 3rd edition.

But, by 9.30 on Friday, Jokipii convinced me that indeed the mechanism is operating the in the many different types of shock in the heliosphere.

Clues from the Heliosphere



By 10.00 on Friday, Marty Lee had convince me that generally the phenomena are very much more complex that the simple model.

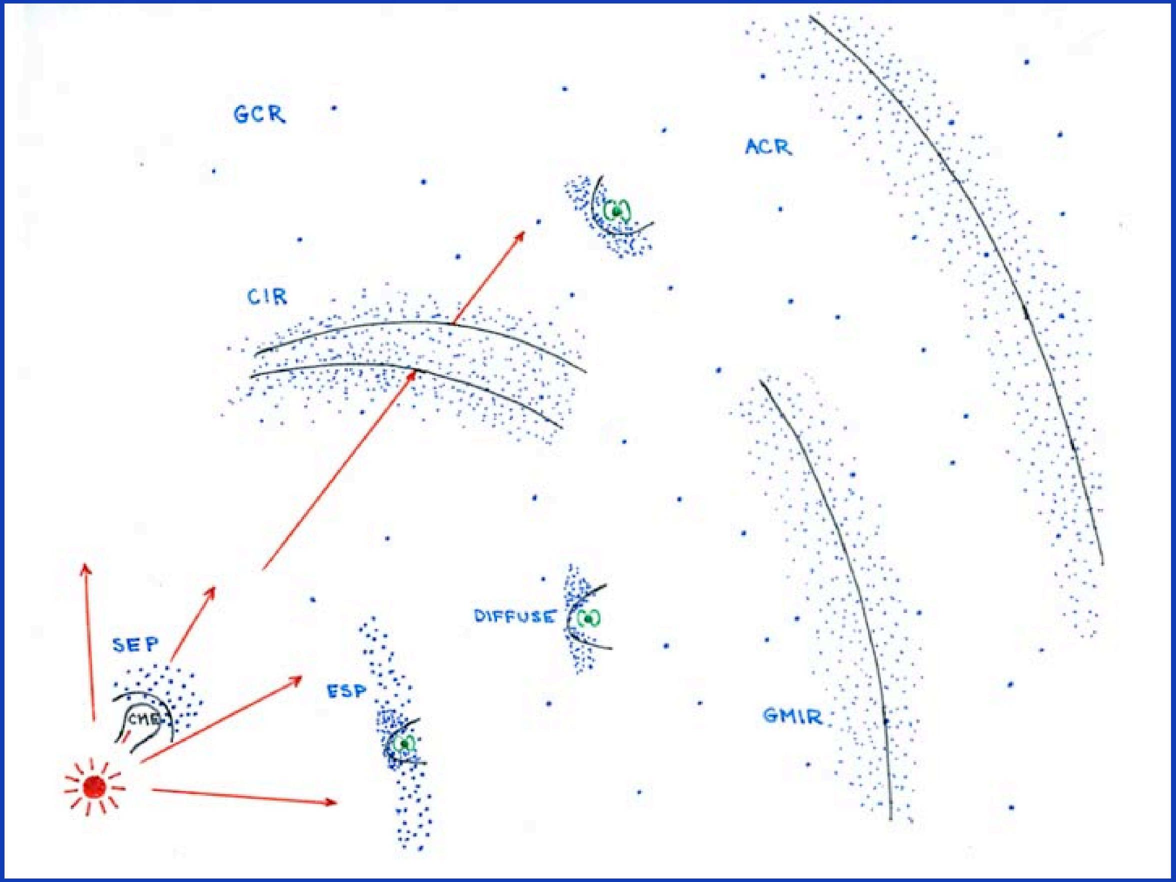
He showed examples where things seemed to go wrong, but almost certainly the models are oversimplified.

Clues from the Heliosphere

Jokipii perspective

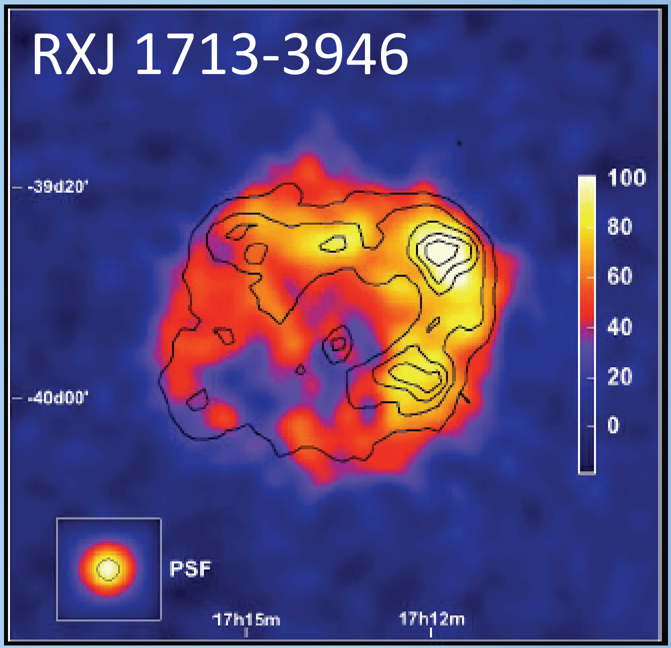
- Collisonless shock waves are observed in the heliosphere from the Sun to the termination shock of the solar wind.
- They produce many different populations of energetic particles.
- Recent analyses suggest that many of the anomalies seen are the result of the shocks interacting with pre-existing, upstream turbulence.

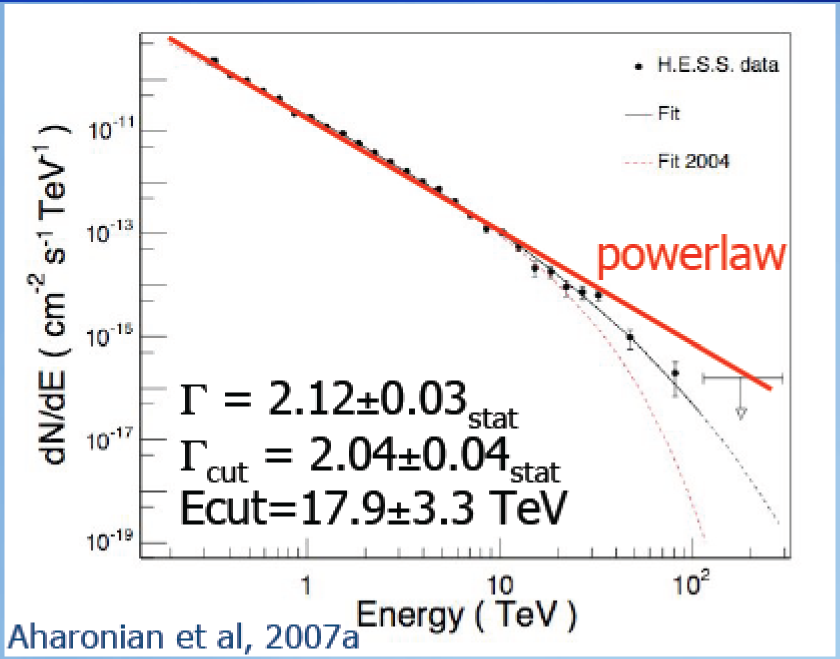
Clues from the Heliosphere

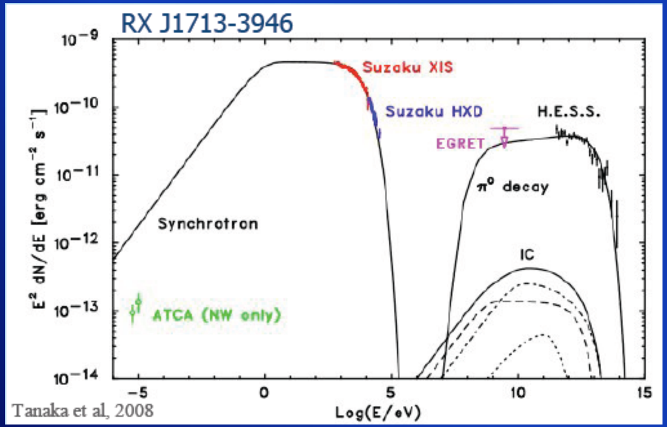


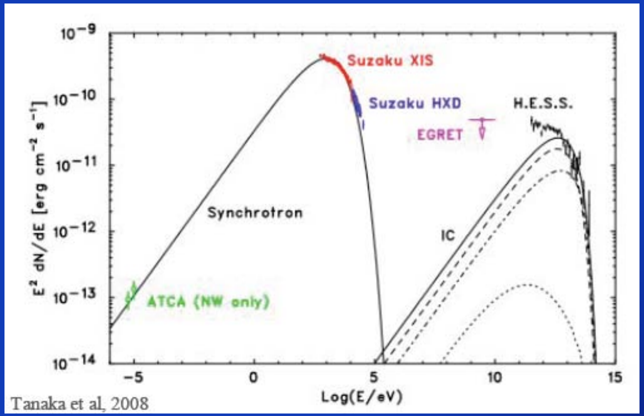
- Too complicated for astrophysicists, but we need to keep a close watch on developments.

Supernova Remnants and γ-ray emission









Acero

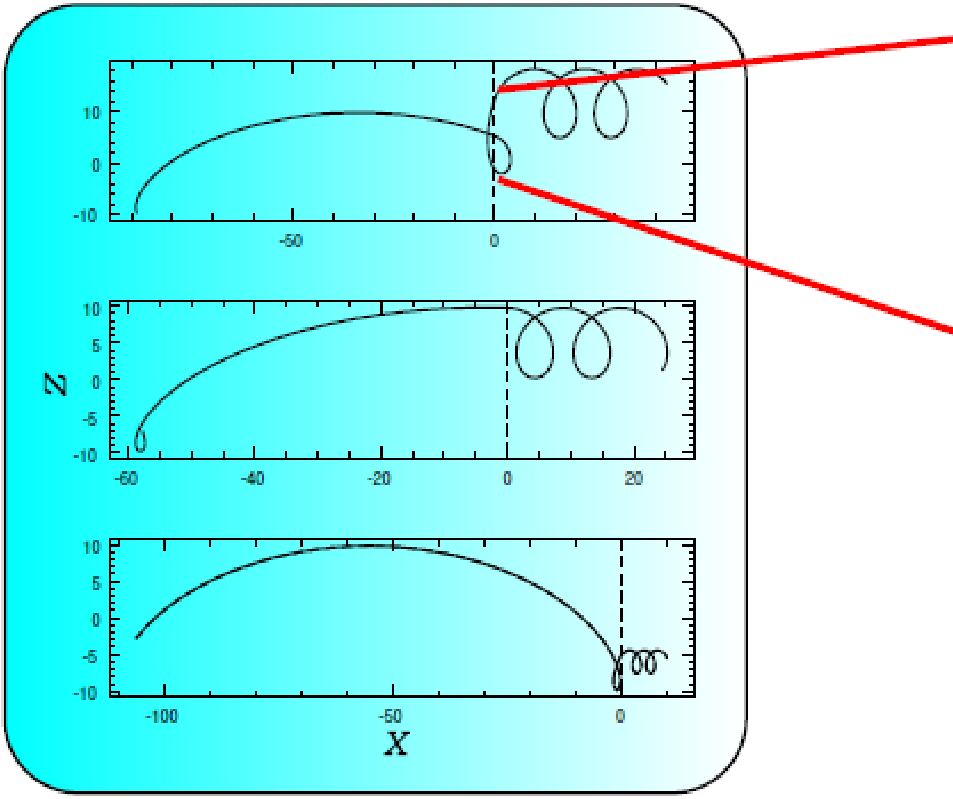
Supernova Remnants and γ-ray emission

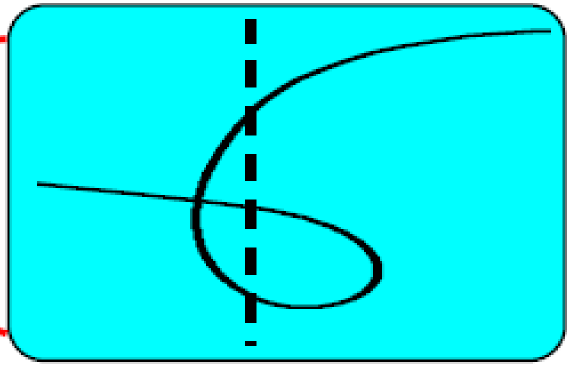
- Note the careful analysis of Völk to account in detail for the observations of two of the best observed g-ray supernova remnants observed by HESS.

- This is an excellent example of the necessary detail needed to apply the shock acceleration paradigm to the wealth of data now available for such sources.

Relativistic Shocks

Average field orientation: $B_{\parallel} = B'_{\parallel}$, $B_{\perp} = \Gamma_{\mathrm{shock}} B'_{\perp}$.





Particle overtaken in small fraction of a gyration

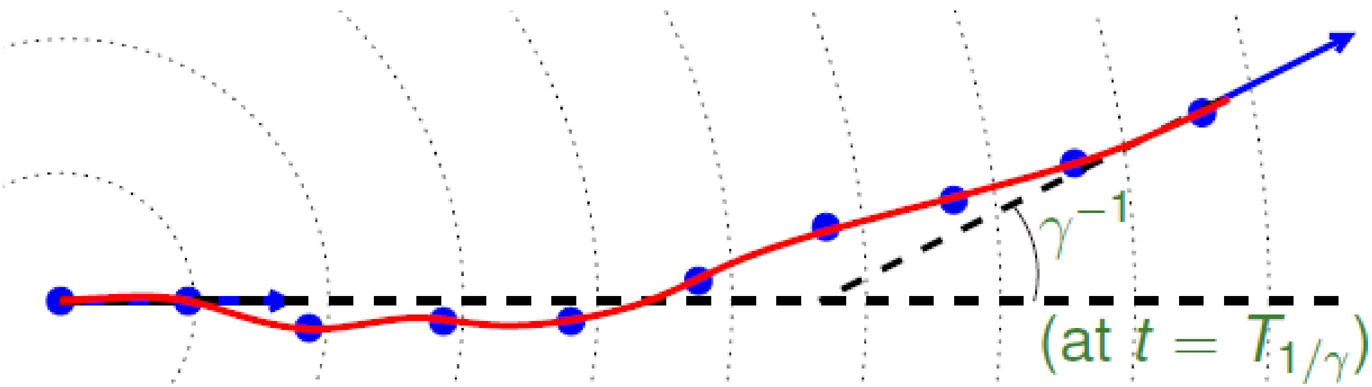
Short-wavelength turbulence needed ($a < \bar{\gamma}$)

Kirk, Marcowith

Jitter and the Formation Time

Magneto-brems., diffuse synchrotron, jitter...

Incoherent (single particle) radiation determined by trajectory

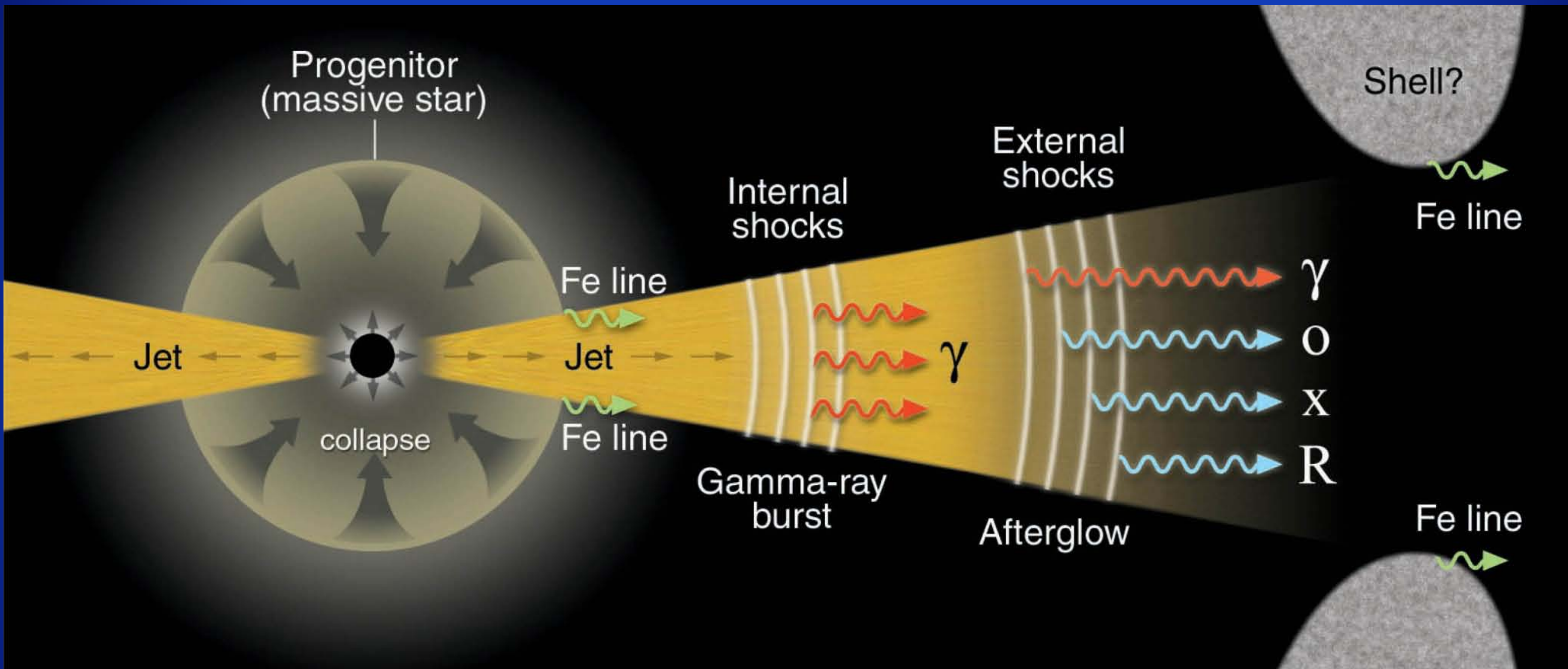


Fundamental concept: formation time T:

- Classically: time for particle to lag $\sim$ 1 wavelength behind wavefront
- QM: time needed to create photon

Formation length can be large: $T = 2\gamma^2 c/\omega$, for $T < T_{1/\gamma}$

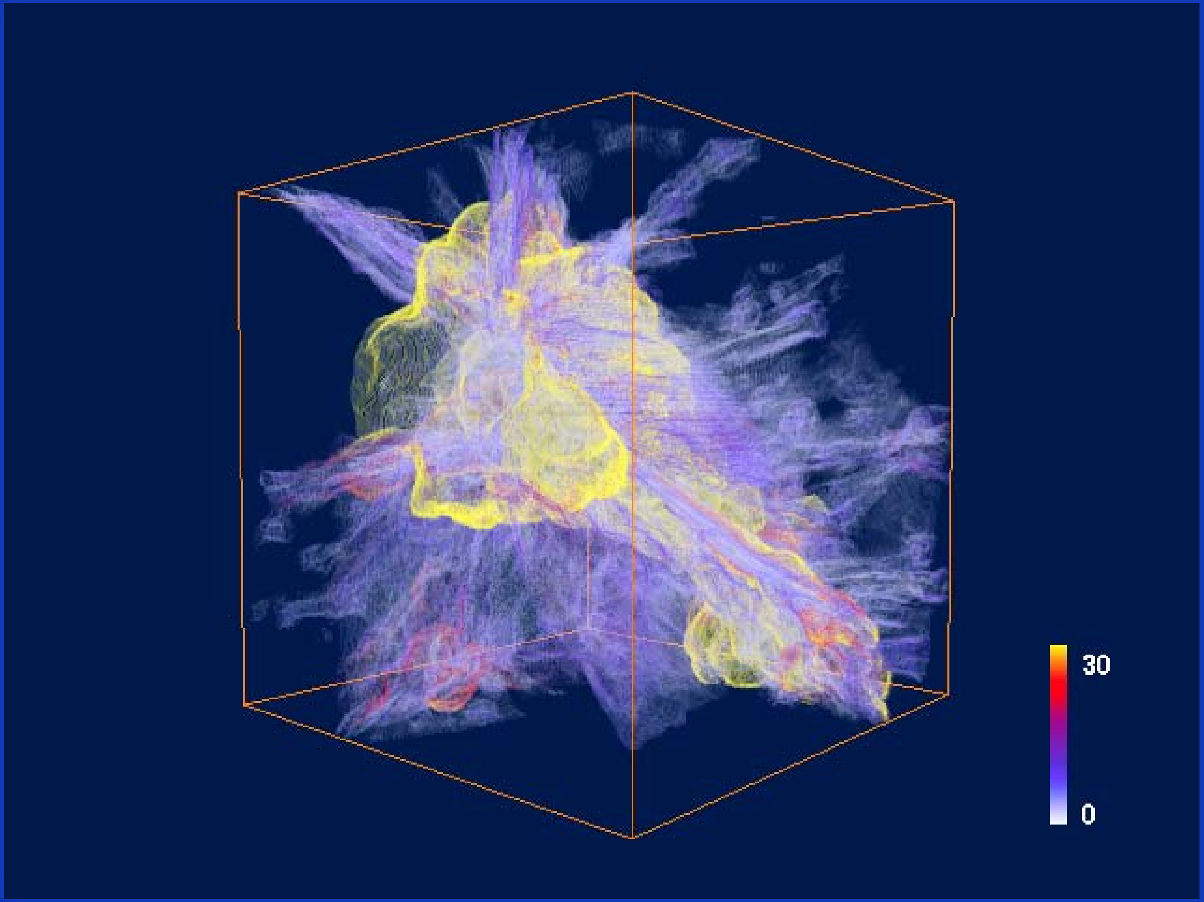
Relativistic Shocks



Nishikawa

These issues must be taken very seriously to understand relativistic jets in g-ray bursts and radio jets.

Distribution of Shock Mach Numbers in Cluster of Galaxies



The Invisible Universe of Shocks

Ryu and Kang

The Origin of Magnetic Fields

- Vishniac analysis needs very careful thought. As I understand what he is saying, the problem of the origin of cosmic magnetic fields in galaxies may not be as severe as is customarily assumed. Weak galactic magnetic fields on smallish scales can be generated by dynamos.

- On the cosmological scale, Ryu finds that intergalactic magnetic fields of interesting field strengths can be generated in his simulations by intergalactic turbulence.

Clusters of Galaxies

These offer many opportunities for studying shocks on the largest scales :

- structure formation,
- coalescing clusters, etc

The diagnostic tools

- Relativistic electrons – synchrotron radiation and its polarisation, inverse Compton
- Pion decay γ-rays
- Magnetic fields

Final Thoughts

- There are many enormous challenges ahead. Building plasma physics and turbulence in much more physical detail.
- Increasing the physical input into massive three-dimensional simulations.
- Exploiting all the present and future facilities
- Building as physical models of the phenomena as possible

Thanks

The very warmest thanks to:

Jung Yeon Cho

Hyesung Kang

Chang-Mo Ryu

Dongsu Ryu

All the helpers, secretaries, colleagues, students who have been so helpful and supportive.