Particle Acceleration at SNR

(old insights on acceleration at non-relativistic shocks)

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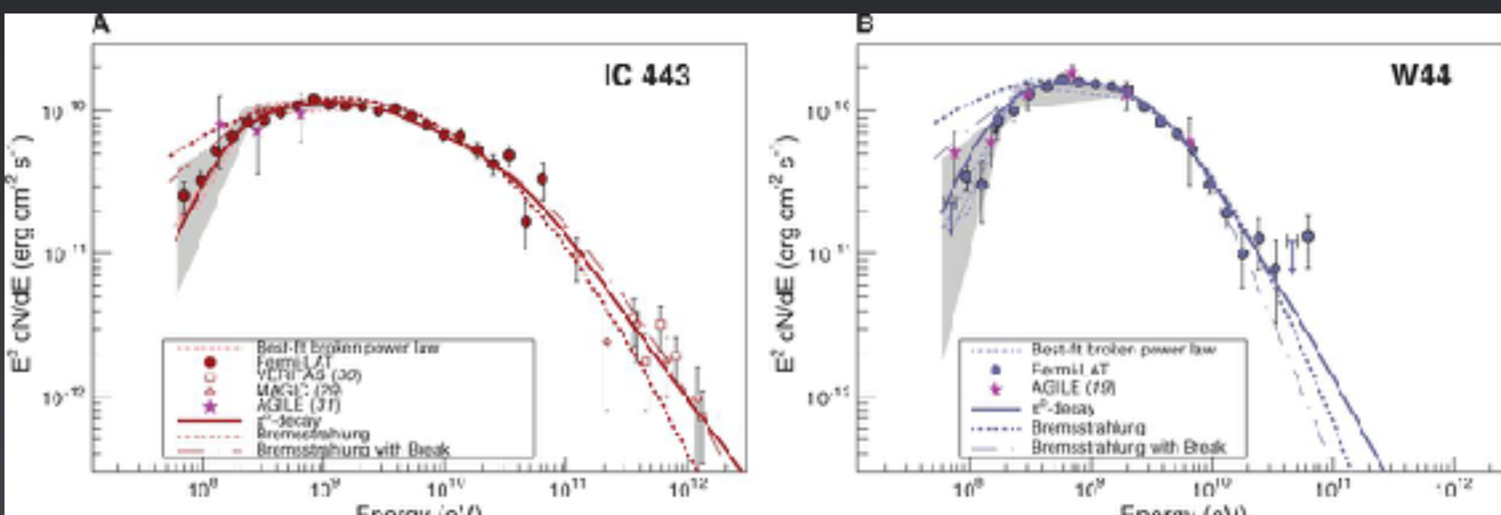
Outline

- SNR as sources of Cosmic Rays
- Has magnetic field amplification solved the PeV problem
- The role of the mean field?
- How well do we understand cosmic ray transport and its implications for CRs in SNR

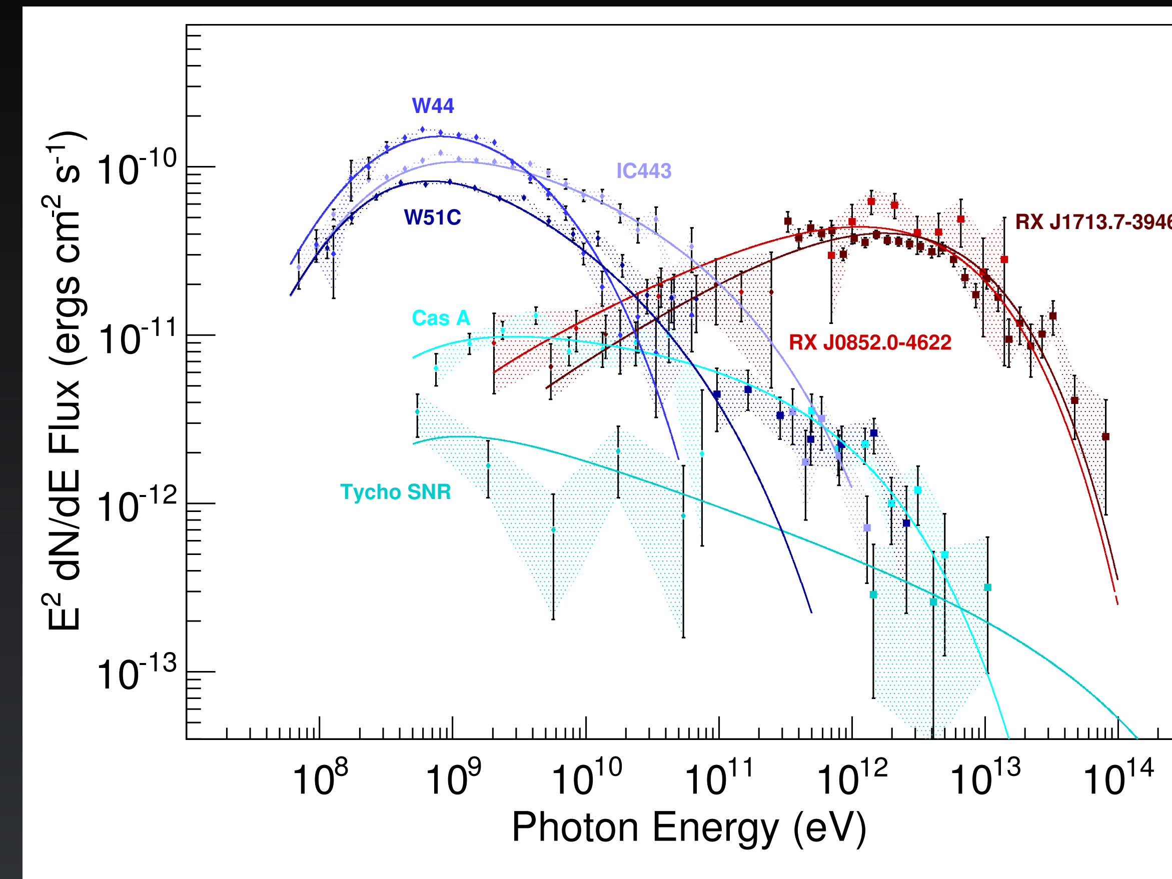
γ-ray observations of ‘CR sources’

Convincing (?) evidence for Pion decay bump

Credit: NASA/DOE/Fermi LAT Collaboration, NOAO/AURA/NSF, JPL-Caltech/UCLA, ROSAT



Ackermann et al 2013



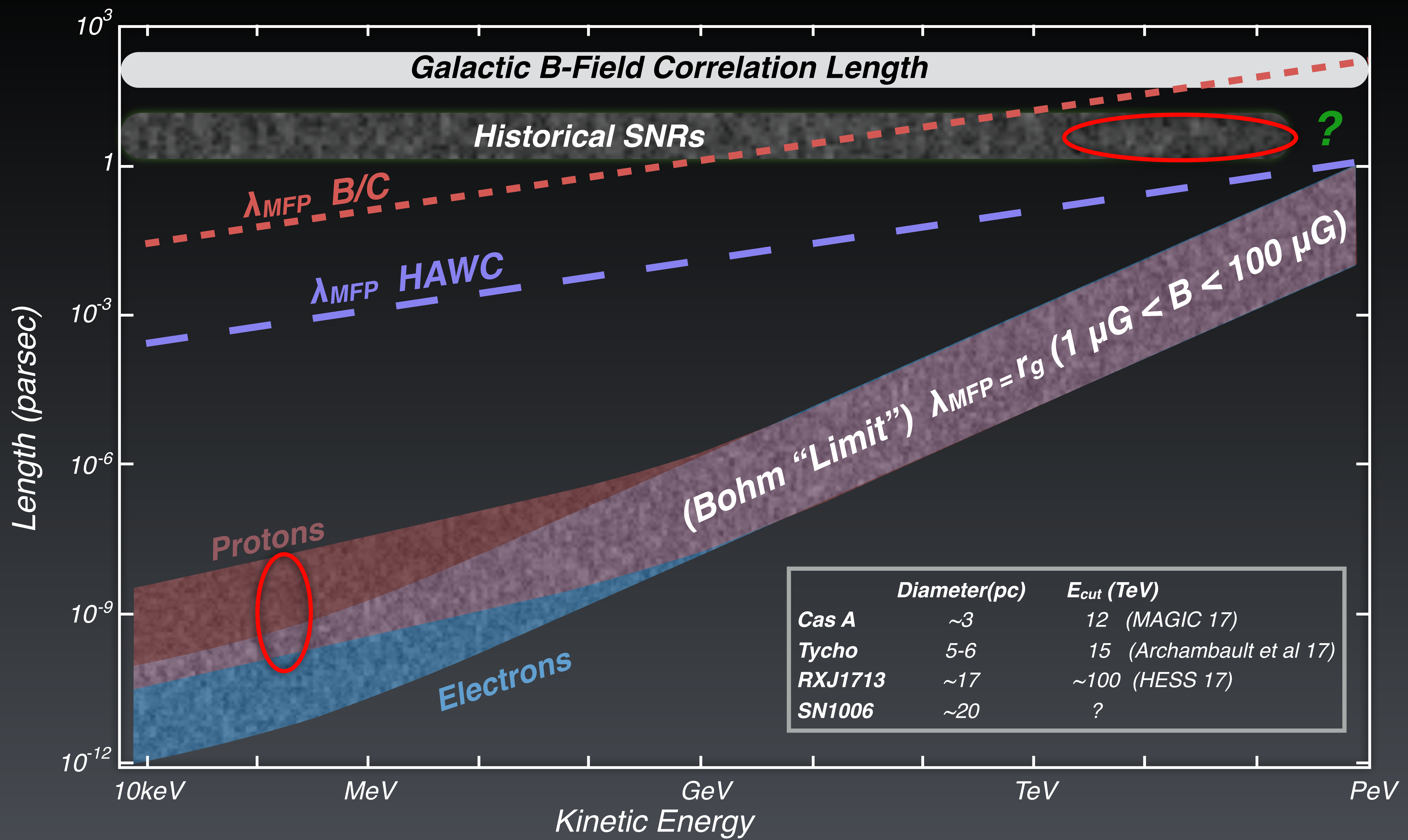
Funk 2015

All cut-offs measured to date in the sub 100 TeV range.

No conclusive evidence of a SNR PeV source yet….

What evidence is there in the theory, to suggest it should be otherwise?

Scale Problems



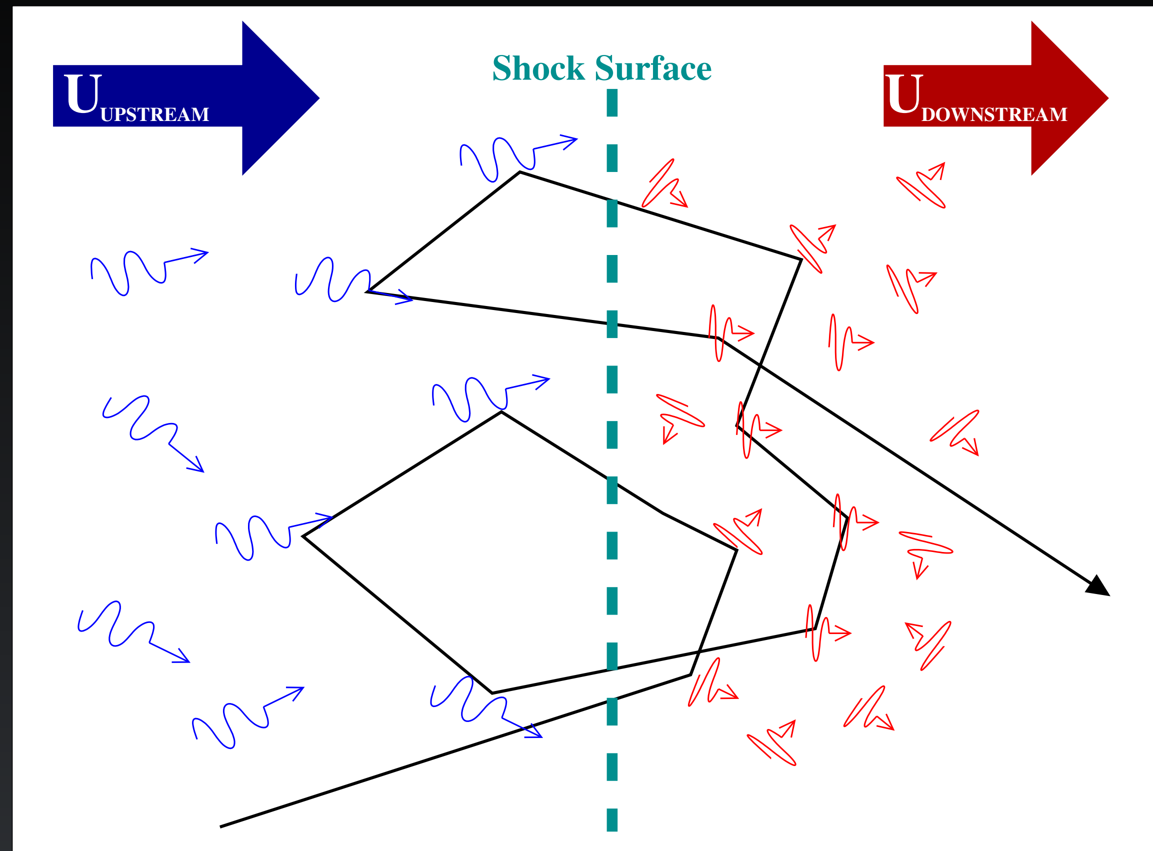
Abeysekara et al. 2017

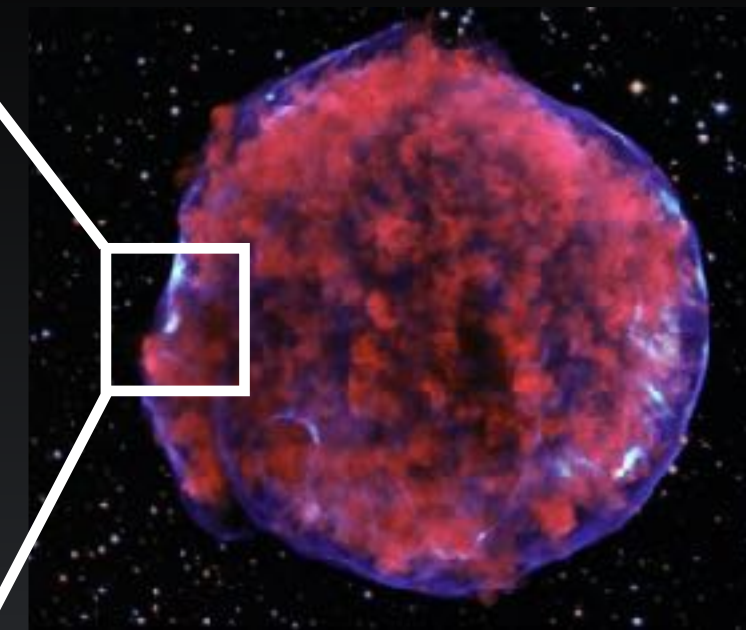
Beck, Beck, Beck et al. 2016

High Mach shocks are efficient accelerators

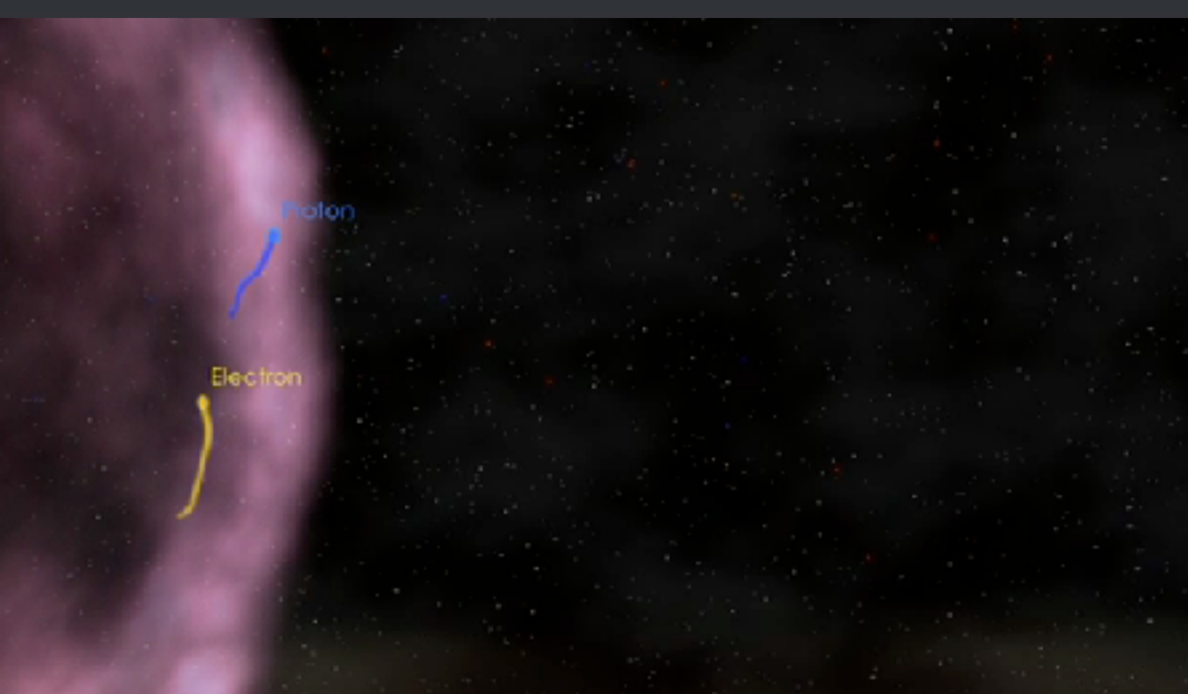
Particles accelerate by repeatedly crossing shock surface.

Now routinely investigated with "first principles" simulations





Krymskii 77, Axford et al. 77, Bell 78, Blandford & Ostriker 78



Credit : NASA's Goddard Space Flight Center

Diffusive Shock Acceleration is a multi-scale plasma physics problem. 2 principal requirements:

1. *Lift particles out of the thermal pool (determined by shock microphysics)*
2. *Regular scattering to maintain isotropy (determined by plasma instabilities)*
3. *Scattering at ALL wavelengths $k\, r_g \sim 1$*

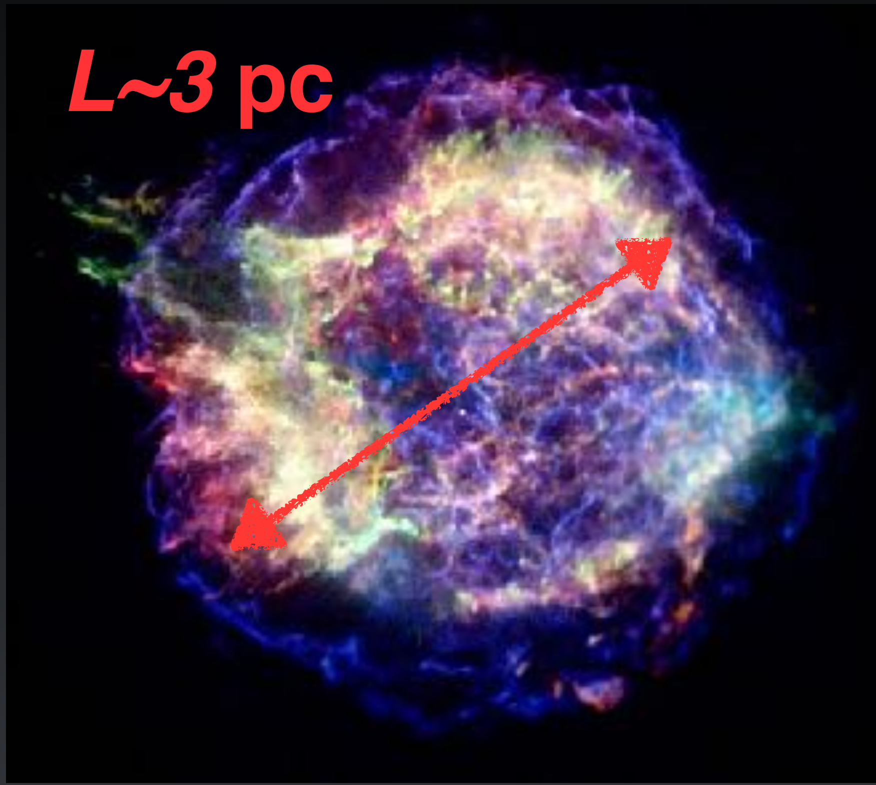
SNR as Pevatrons (i)

The Hillas limit for maximum particle energy is (Hillas 84)

$$\varepsilon_{\max} = q \int_{t_0}^{t} \boldsymbol{E} \cdot d\boldsymbol{r} \approx quBL$$

$$\varepsilon_{\max} < 75Z \left(\frac{u_{\rm sh}}{5,000 \text{ km/s}} \right) \left(\frac{B}{5\mu\text{G}} \right) \left(\frac{L}{\text{pc}} \right) \text{ TeV}$$

or simply $$r_{\rm g,max} < \frac{u_{\rm sh}}{c} L$$



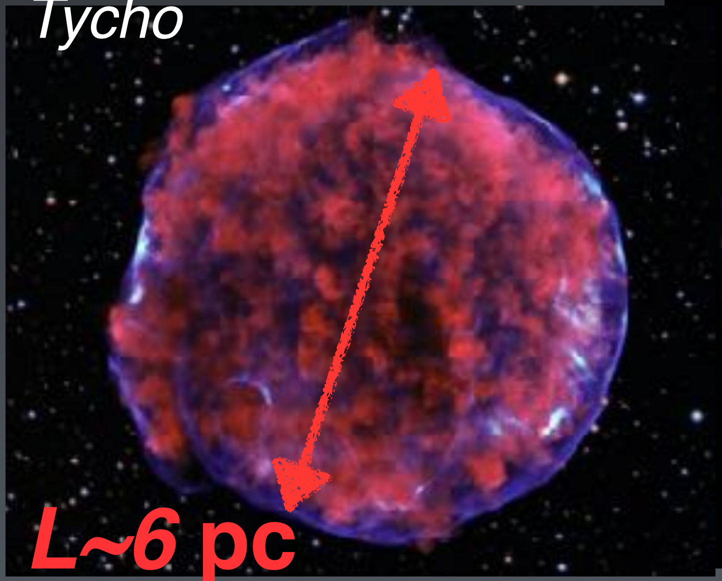
Most nearby young supernova have similar properties:
$n \sim 1$ cm^{-3}, $u_{sh} \sim 5{,}000$ km/s,
L~ a few pc.

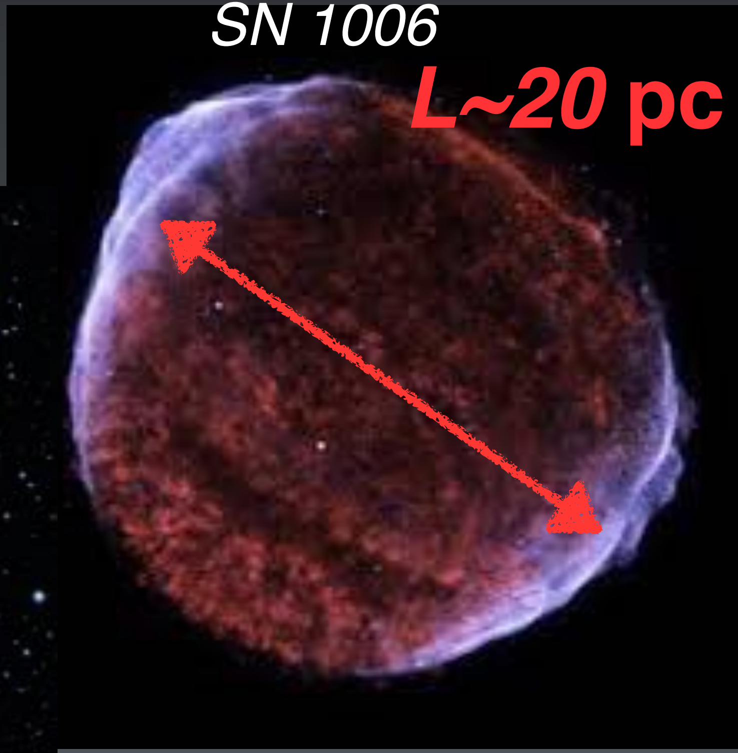
Display non-thermal x-ray rims/hotspots an indication of $B >> B_{ISM}$

If $B=B_{ISM}$, max energy ~ 10-100 TeV

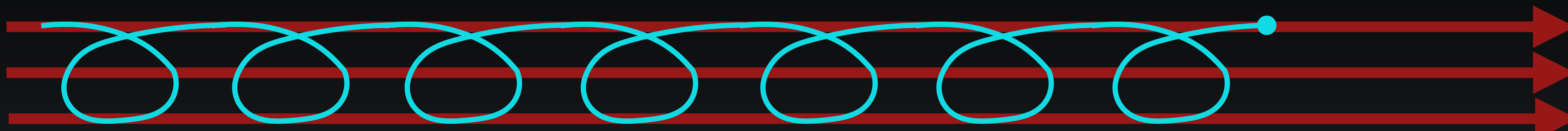
If $B=100B_{ISM}$, max energy -> knee ***??***

Magnetic field scale matters: BR et al 08



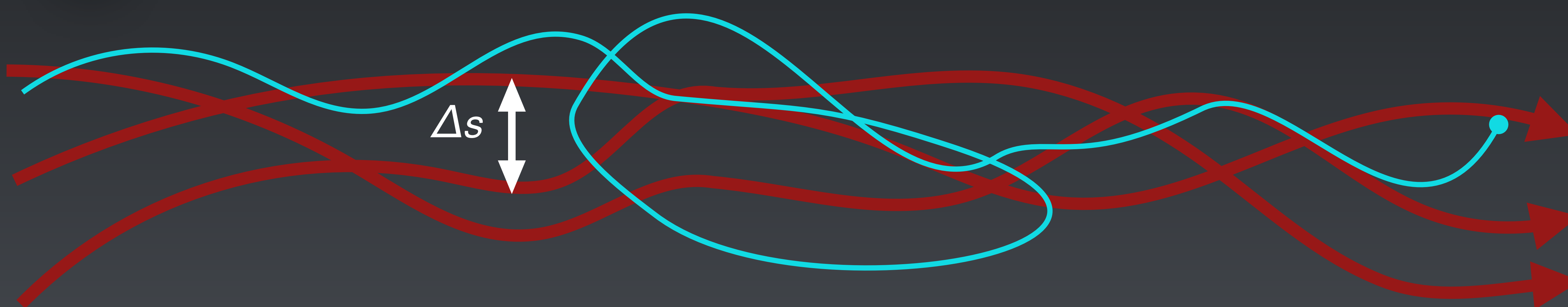


SNR as Pevatrons (ii)



$$\rho\ d^2\boldsymbol{s}/dt^2 \sim -\frac{1}{c}\boldsymbol{j}_{\rm cr} \times \boldsymbol{B} \qquad \Rightarrow \Delta s \sim \frac{j_{\rm cr}B}{\rho c}t^2$$

Bohm diffusion requires $\Delta s \sim r_g$



Energy flux $$\frac{Tj_{\rm cr}}{e} = \eta\rho u_{\rm sh}^3$$

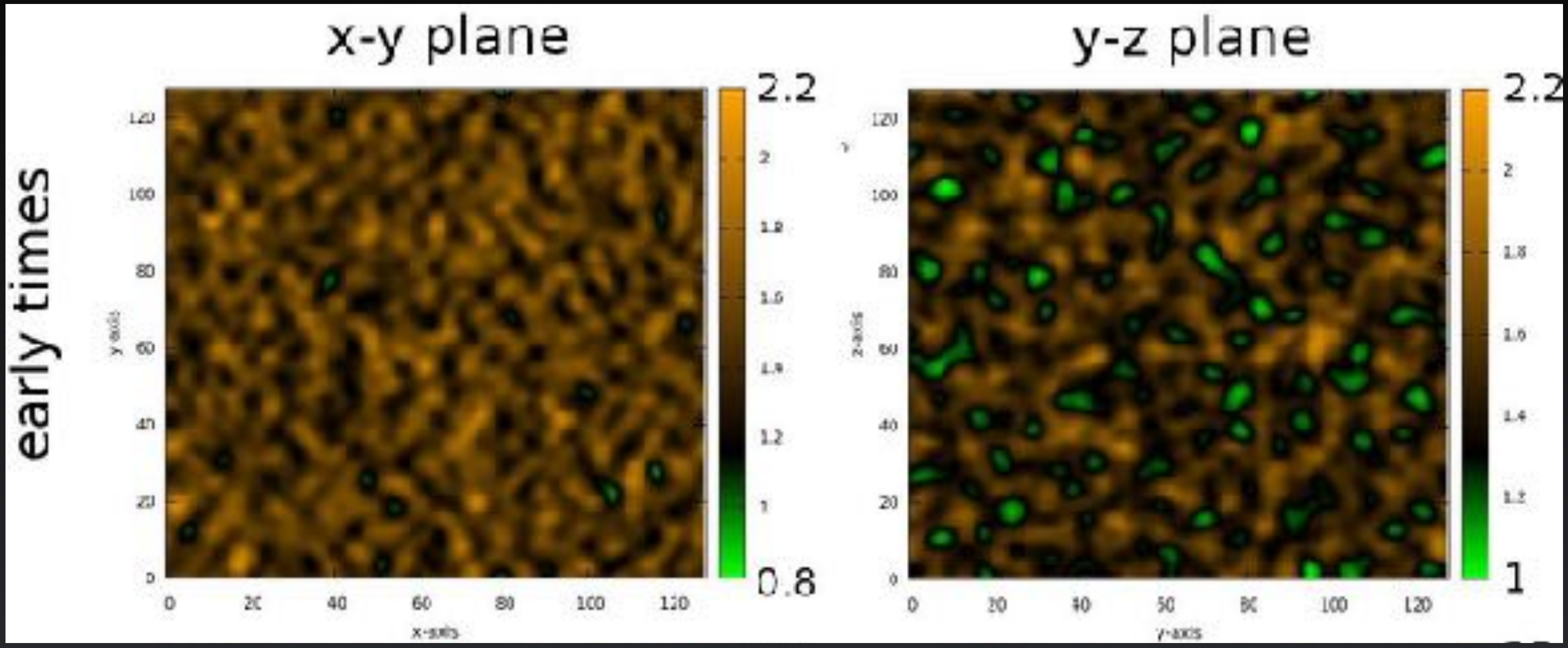
$$\Rightarrow r_{\rm g,max} = \left(\eta\frac{u_{\rm sh}}{c}\right)^{1/2} u_{\rm sh}t$$

Consistent with Hillas/Lagage Cesarksy ($\eta \sim u_{sh}/c$). Doesn't solve PeV problem!!!

Non-resonant field amplification (Bell 04)

Slices of |B| from 3D Hybrid MHD-CR simulation of CR driven magnetic field amplification from BR & Bell (2013).

Fields grow considerably faster on shorter length scales.



Simulations typically show rapid transfer to longer length-scales in non-linear phase.

CRs solved kinetically using an arbitrary order spherical harmonic expansion of the Vlasov-Fokker-Planck equation, including an external gradient term to mimic presence of shock (shock normal along x-axis).

Initial gyro-radius = 2L, mean free path=20L, at end of simulation, MFP~ L/10

SNR as Pevatrons (iii)

In order to get any gain in maximum energy from NR field amplification, one needs on the order of 5-10 growth times.

This leads to yet another expression for maximum energy, although now ***independent of B***

$$\varepsilon_{\max} = 10^{13}\frac{P_{\rm cr}}{\rho u_{\rm sh}^2}\frac{\sqrt{n}\ u_8^3\ t_{100}}{\ln(p_{\max}/mc)}{\rm eV}$$

This is in effect a confinement limit (Bell, Schure, BR, Giacinti 13 , See also Zirakashvilli & Ptuskin 08, BR, Kirk, Duffy 09)

For typical historical SNR conditions, this limits the maximum energy to be on the order of ε_{max}~100 TeV

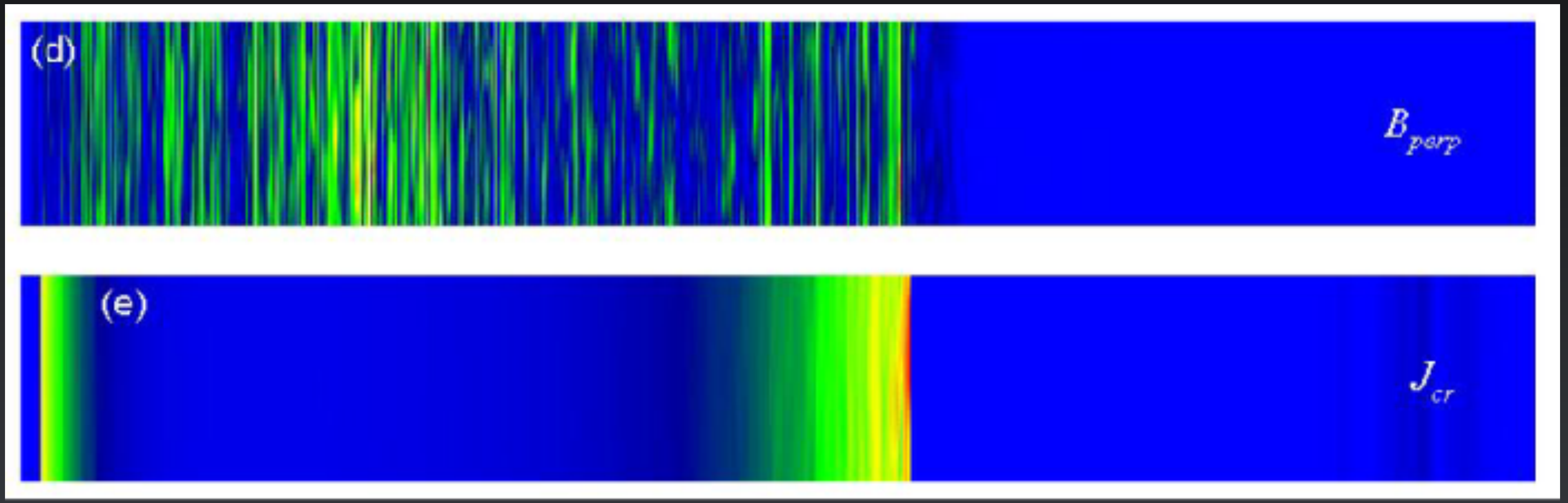
(Consistent with all the previous estimates!!)

Conclusions well supported by hybrid MHD-VFP simulations.

Maximum energy in NR scenario

$$\varepsilon_{\max} = 10^{13}\,\frac{P_{\rm cr}}{\rho u_{\rm sh}^2}\,\frac{\sqrt{n}\;u_8^3\;t_{100}}{\ln(p_{\max}/mc)}\,\mathrm{eV}$$

Key assumptions of this model are supported by 2D & 3D MHD-CR simulations (Bell, Schure, BR & Giacinti 2013)



To get any benefits from rapid NR growth, one should look earlier in SNR evolution when $u_8 >> 1$

Ambient conditions (v_A, magnetic field geometry, scaling r^{-1} or r^{-2} ?, etc.) will be dependent on SN progenitor.
(See Volk & Biermann '88, Takamoto & Kirk '15, Zirakashvilli & Ptuskin '18)

Potentially no Galactic SNR Pevatrons currently according to these conclusions!!
However, current concepts of escape may need to be revised.

CRs as probes of Shock Conditions

Theory predicts a power-law that :

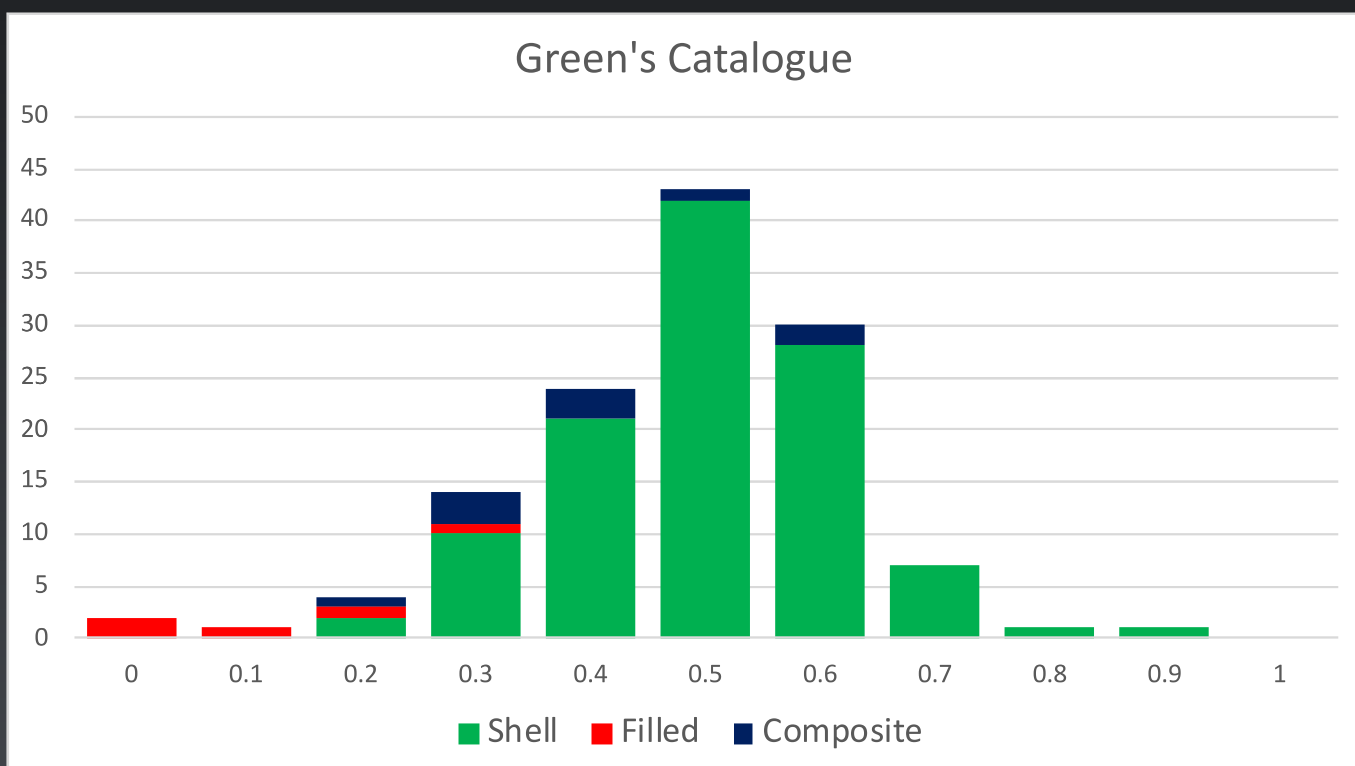
- *depends on a single variable*
- *is not inconsistent with CR spectrum*
- *Likewise with radio*

$$f \propto p^{-s} \Rightarrow S_\nu \propto \nu^{-(s-3)/2}$$

$$\frac{\partial \ln f}{\partial \ln p} = -\frac{3r}{r-1}$$

Where $r = u_1/u_2$

(r —> 4 for strong shocks)

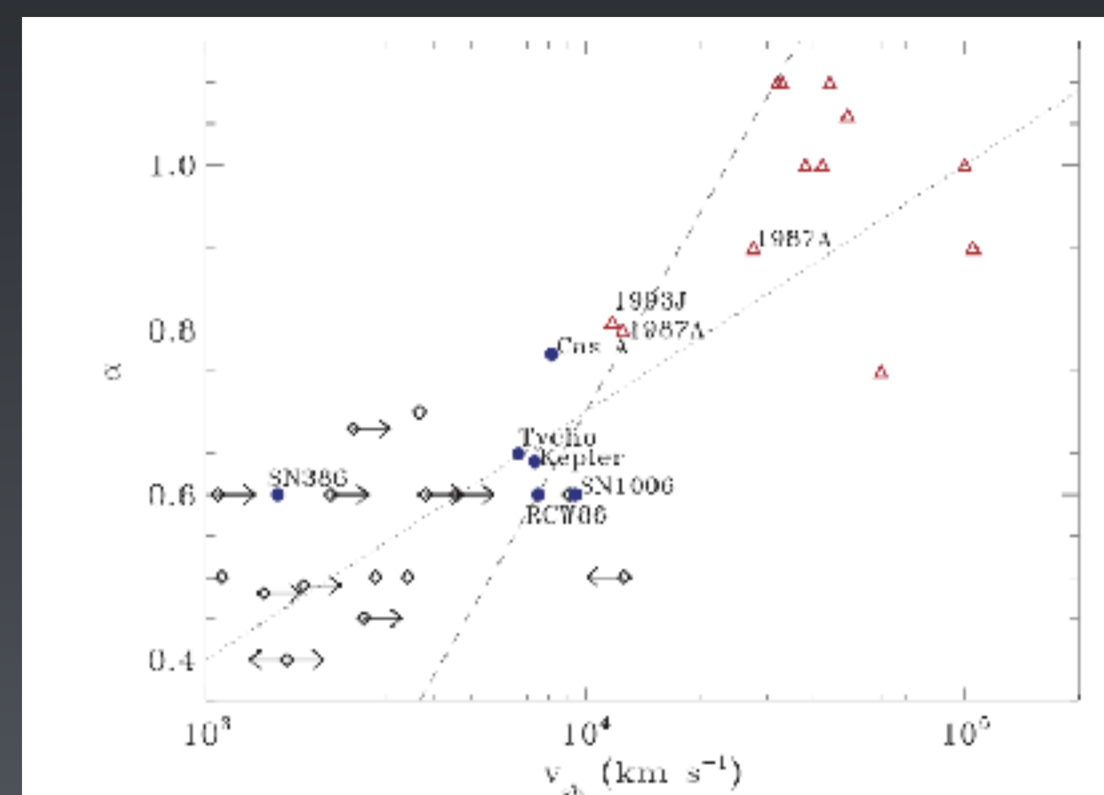


Histogram of Galactic SNR peaks at 0.5 (equivalent to p-4 spectrum)

Can all others be accounted for simply through change in compression ratio alone?

Bell, Schure, BR '11 took a sample where estimates of shock velocity could be made, highlighting a trend:

Faster shocks — Steeper spectra



Galactic (◇) Historic (●) Extragalictic (△)

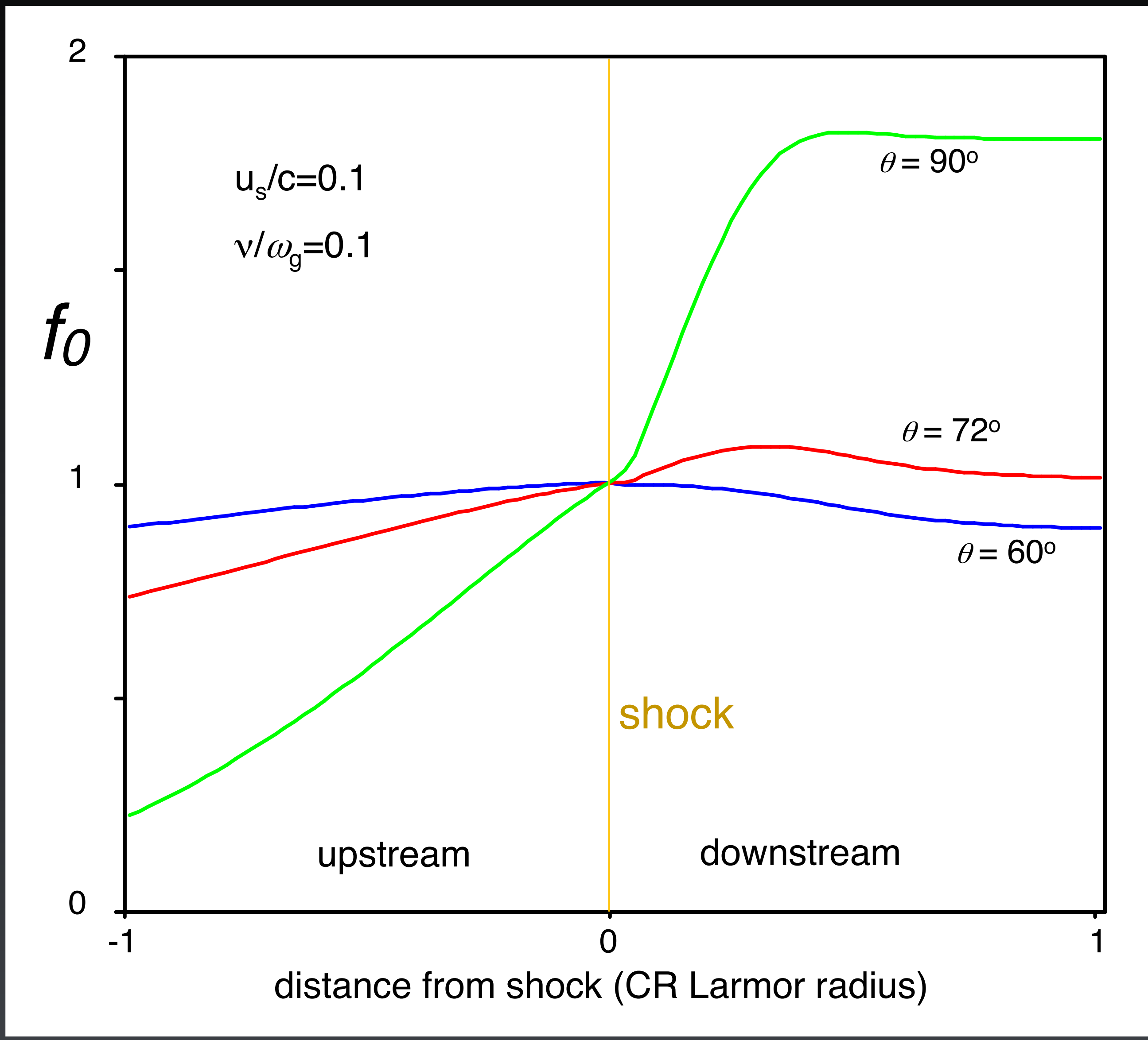
Effect of obliquity on spectrum shape

Situation complicated at oblique shocks, since drifts/anisotropies in the plane of the shock affect downstream solution (diffusion approximation breaks down in vicinity of shock).

Can lead to corrections at least of order ~u/c

$$\frac{\partial \ln f_0}{\partial \ln p} = -\left(3 + \frac{f_\infty}{f_0}\right)$$

1D shock, test-particle VFP simulations (Bell, Schure, BR ’11)



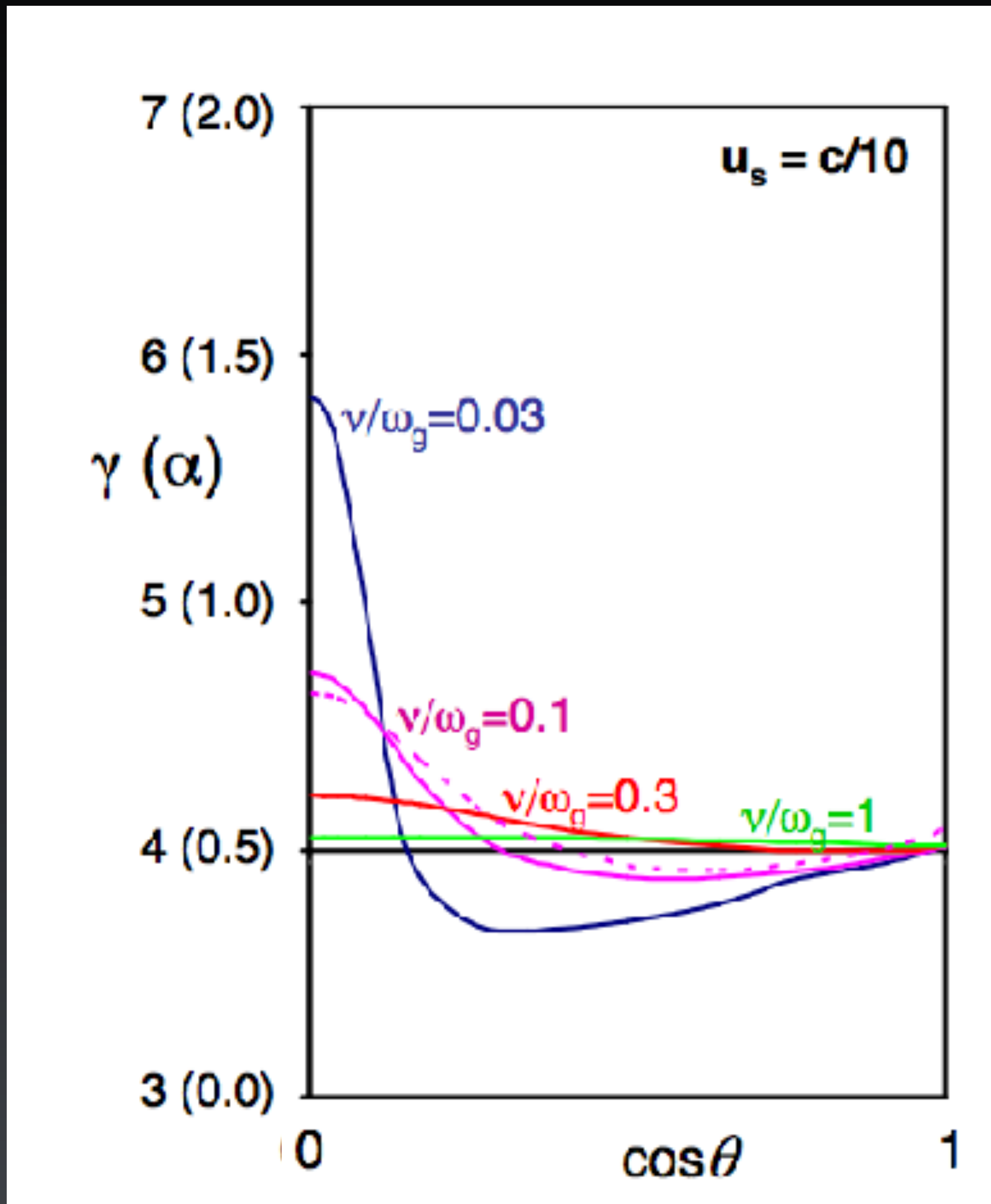
free parameters:

- *scattering rate* ν
- *shock velocity* u_s
- *magnetic field orientation* θ

Larger obliquity ⇒ larger anisotropy ⇒

more harmonics required for convergence

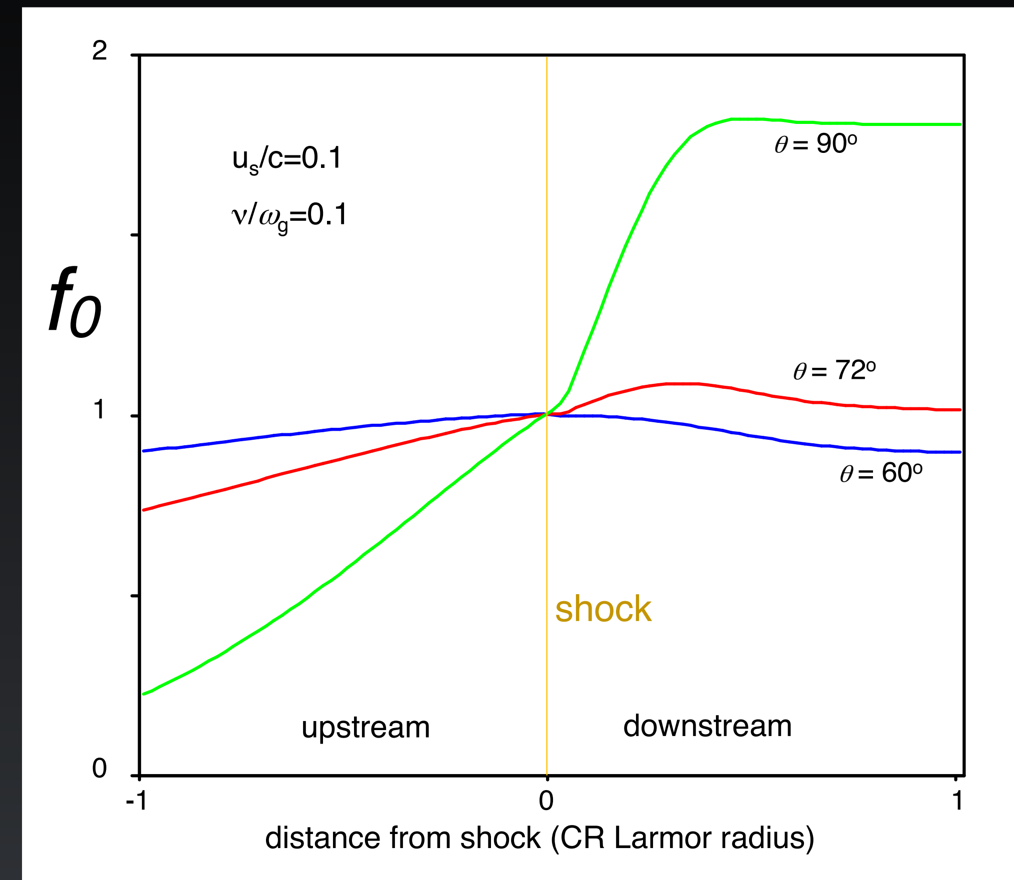
Effect of obliquity on spectrum



spectral index $\gamma = -\dfrac{\partial \ln f_0}{\partial \ln p}$ vs shock obliquity

(cosθ = 1 ⇒ parallel shock)

Bell, Schure & BR, 11
BR in prep



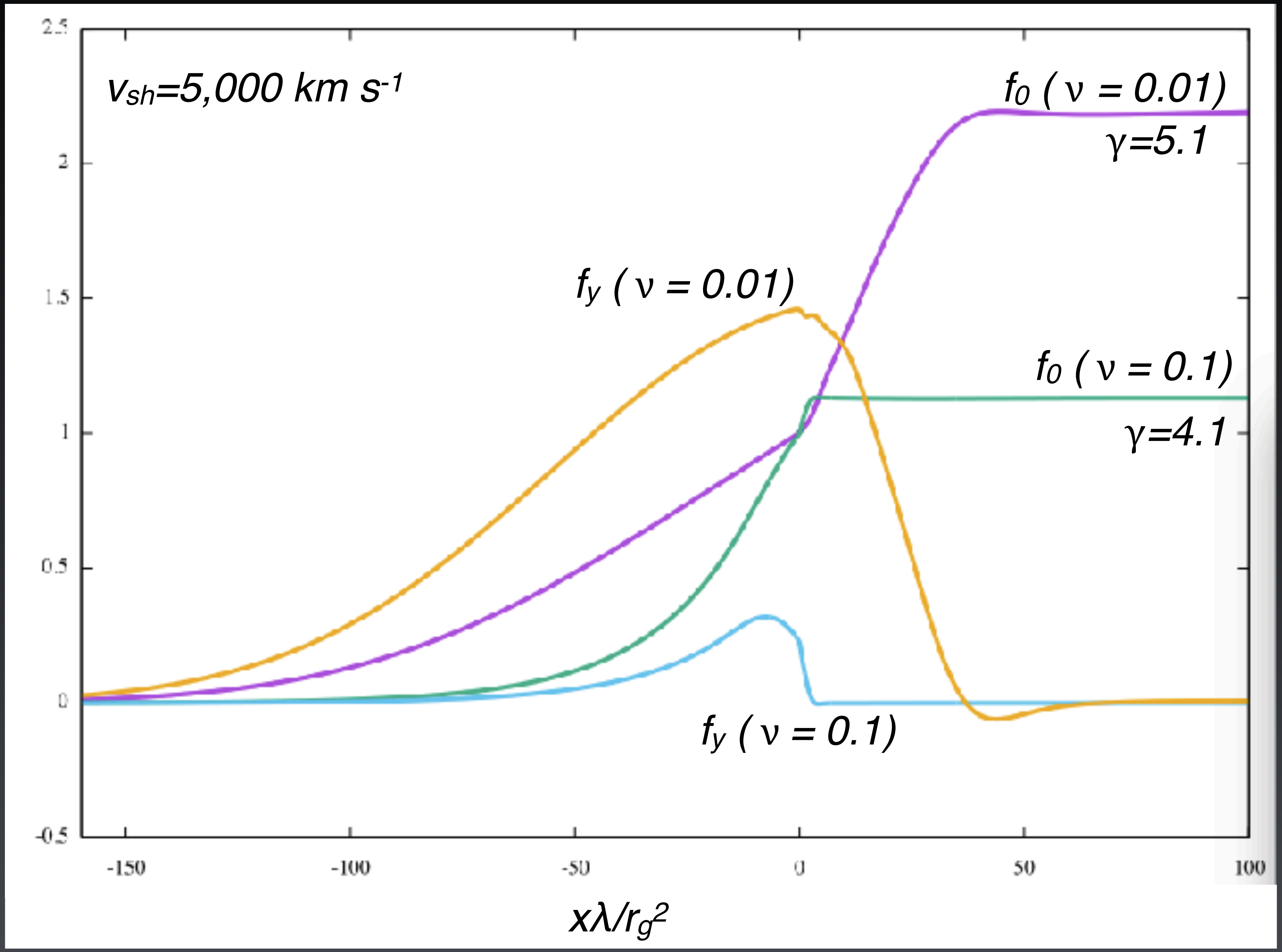
f ~ p^{-4} spectrum recovered for quasi parallel shocks

Quasi-perp shocks can be significantly steeper
(For example shocks in wind of rotating progenitor)

Intermediate obliquities can be flatter (enhanced acceleration due to SDA)

Why do we never see these flat spectra in young SNR?

Perp shocks with weak scattering



Note, for perpendicular shocks, precursor is steep, current are strong!!

Theory on self generated fields (self-consistent scattering) less clear for such scenarios

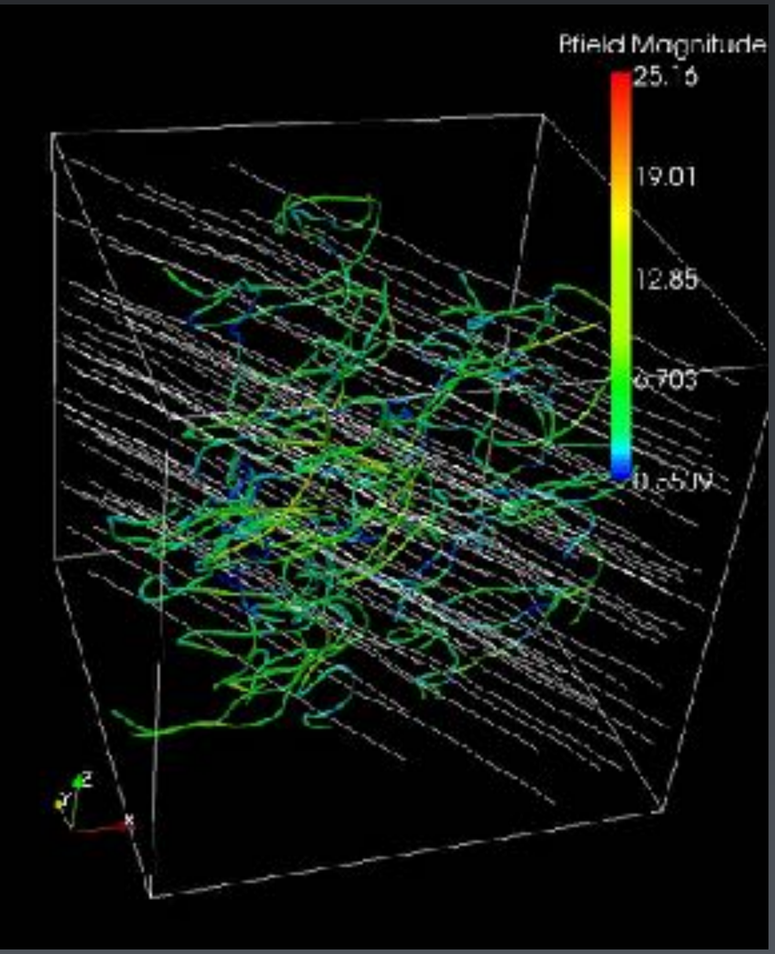
Self-generated fields at Oblique shocks

For misaligned fields and particle gradients, magnetised particles produce currents due to scattering:

$$\boldsymbol{j}_{\rm cr} = e \int \left[D_\perp \boldsymbol{\nabla} + (D_\parallel - D_\perp)\mathbf{b}(\mathbf{b}\cdot\boldsymbol{\nabla}) - D_\wedge\ \mathbf{b}\times\boldsymbol{\nabla} \right] f\ d^3p$$

$$D_\parallel = \frac{1}{3}\lambda v, \quad D_\perp = \frac{D_\parallel}{1+(\lambda/r_g)^2}, \quad D_\wedge = \frac{\lambda}{r_g} D_\perp \quad \mathbf{b} = \cos\theta_N \hat{\boldsymbol{x}} + \sin\theta_N \hat{\boldsymbol{z}}$$

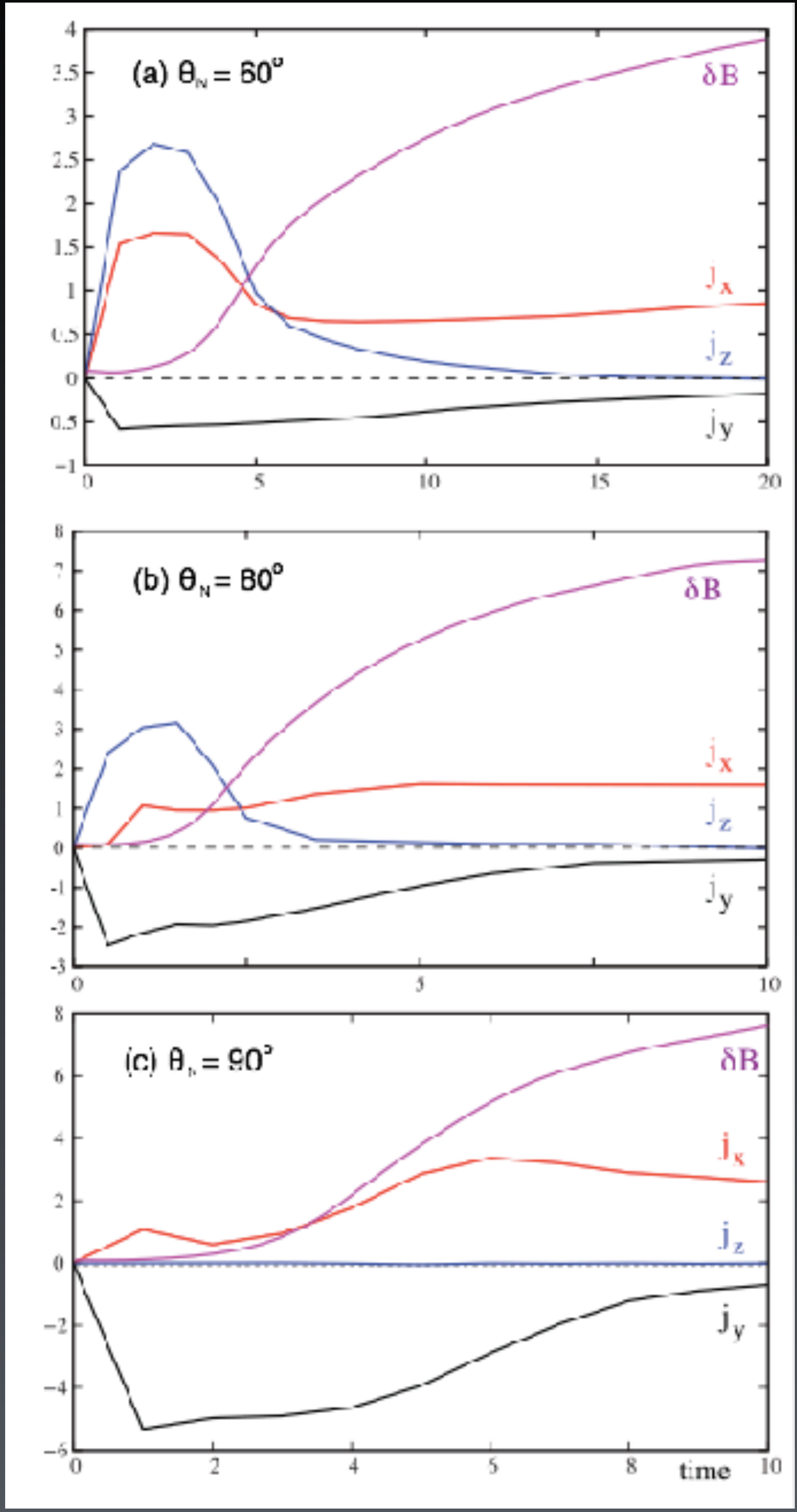
3D hybrid simulations with periodic BCs, and external driving
BR & Bell 2013



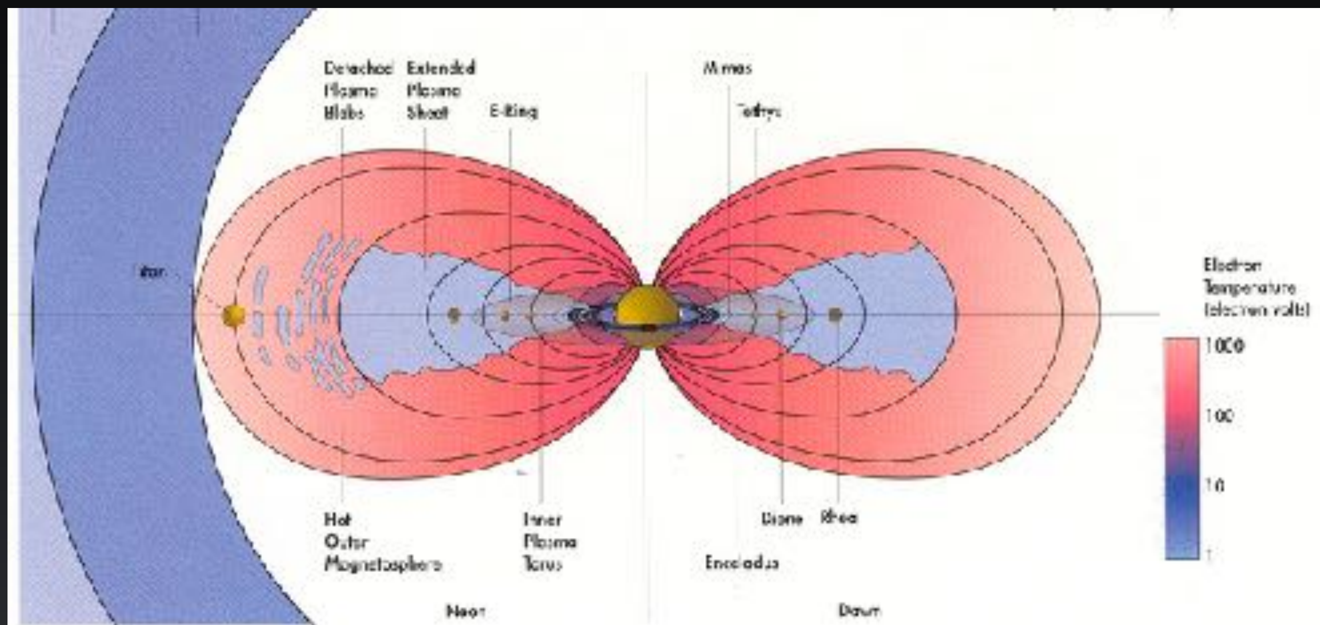
MHD-VFP sims, BR & Bell 13

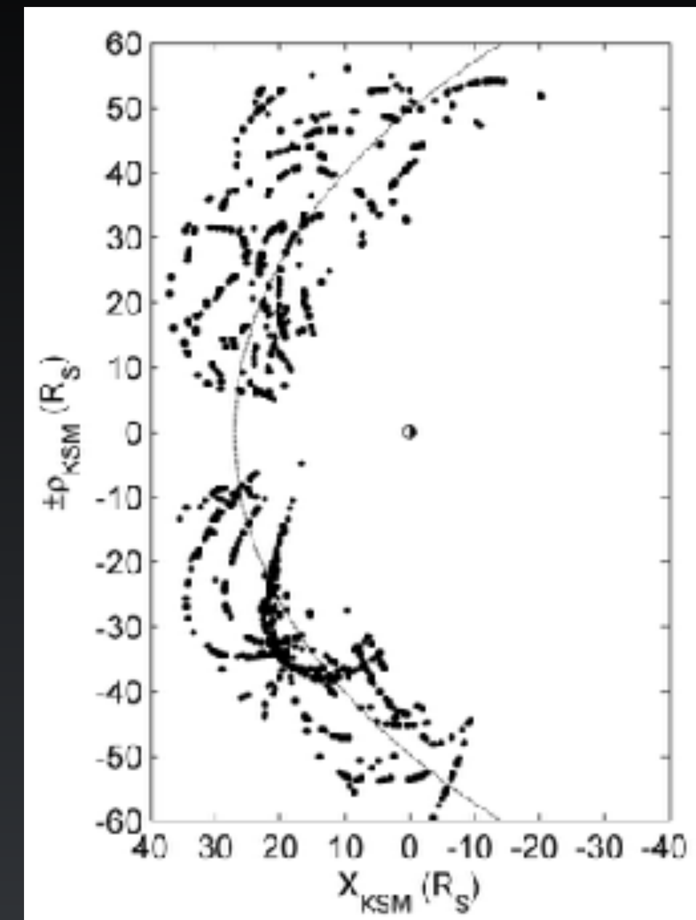
In all cases

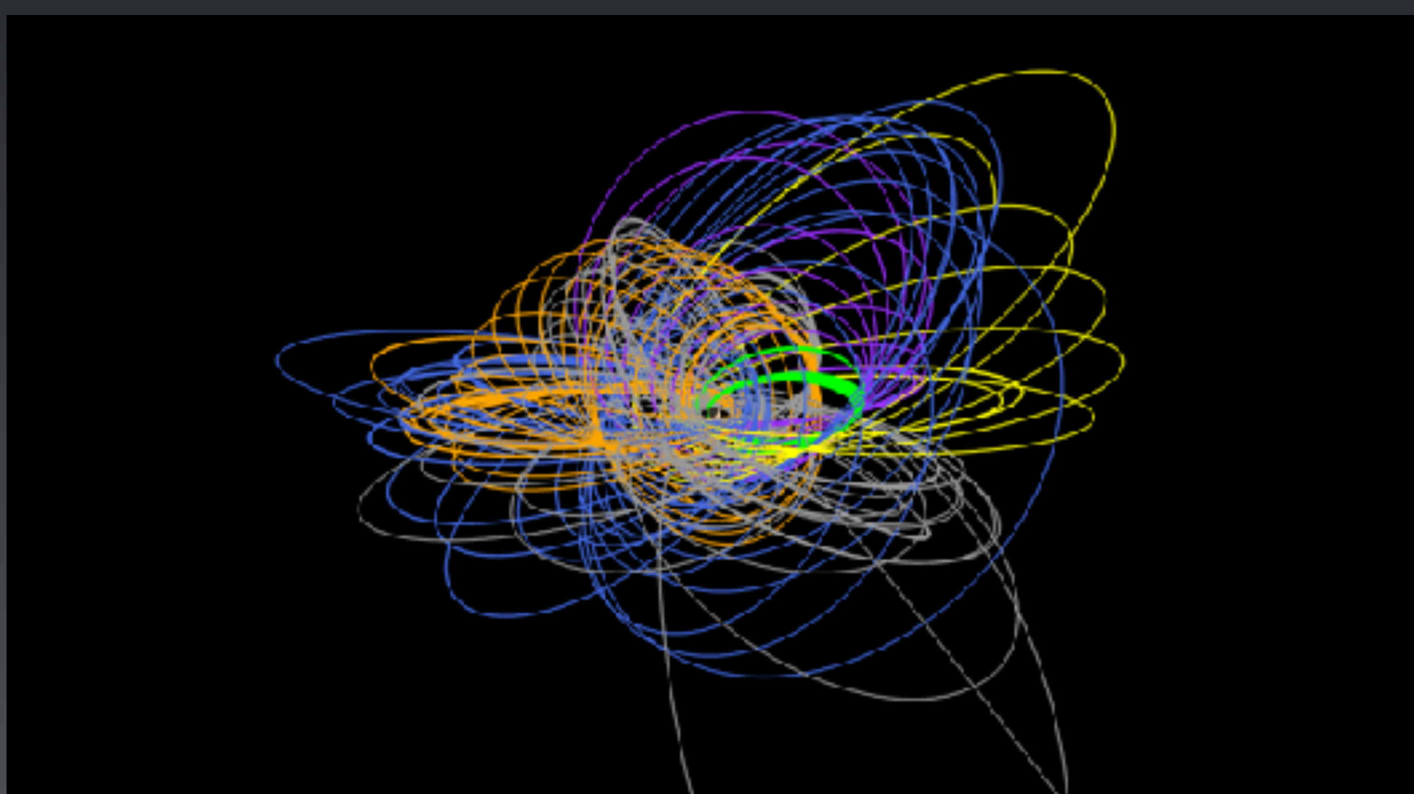
- *anisotropic currents match diffusive predictions at early times*
- *Currents excite MHD instabilities*
- *When fluctuating component exceeds background value, particles behave "unmagnetised"*
- *oblique currents reduce, shock approaches parallel-like configuration* ***for all obliquities*** *(provided acceleration is efficient)*
- *But higher energy particles still see ordered field…….*



Laboratories in our own Solar-System





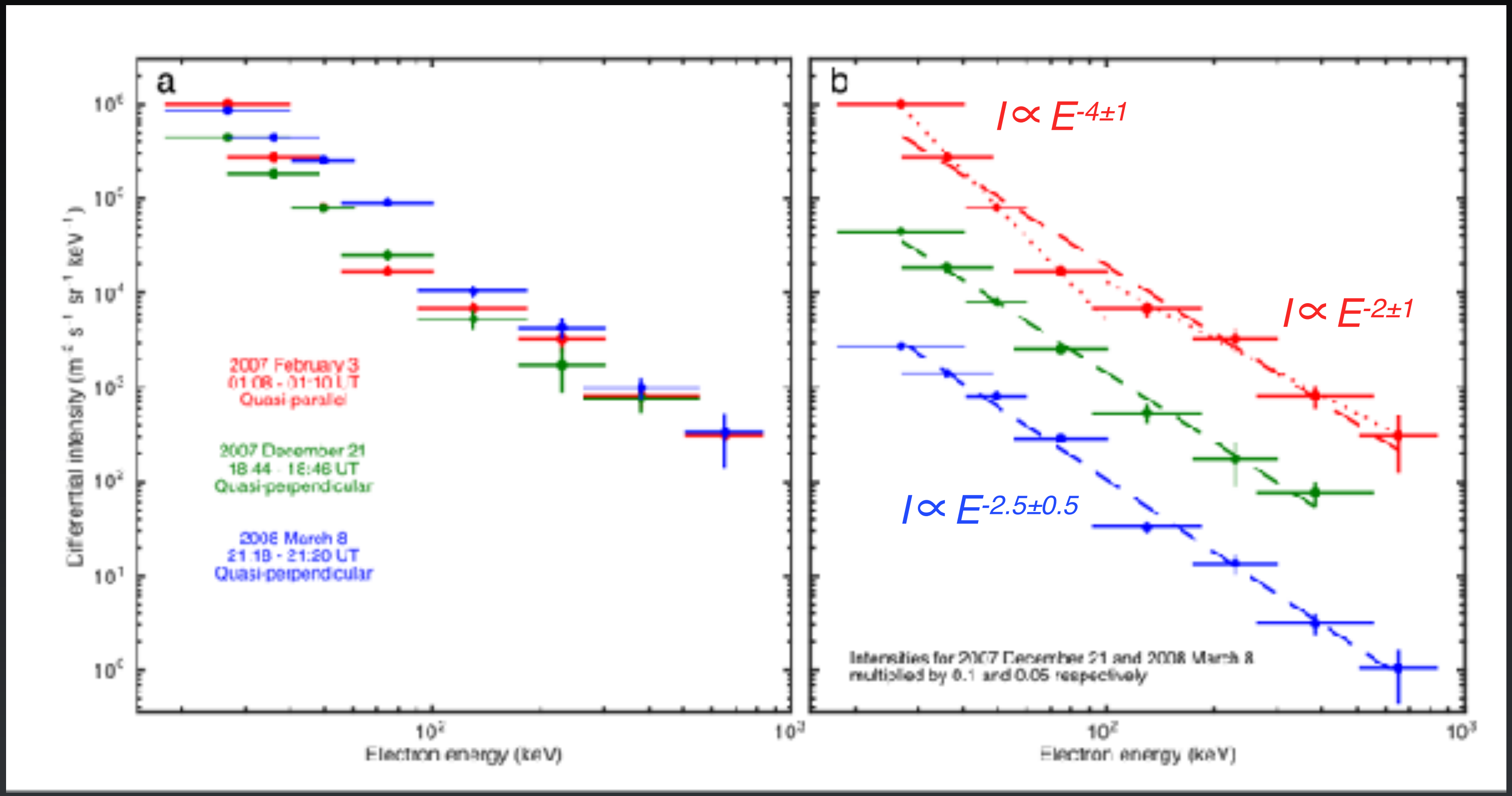


Credit: *NASA/JPL-Caltech*

Cassini has performed numerous crossing of the bow shock of Saturn (Sulaiman et al. 2016)

Due to varying solar wind conditions, in situ measurements of shocks with M_A *as large as 100 have occurred*

Power-laws & spectral breaks



Spectral break only observed in quasi-parallel case.

Note, Alfvén Mach number significantly higher for parallel case (100) vs perpendicular (10-15)

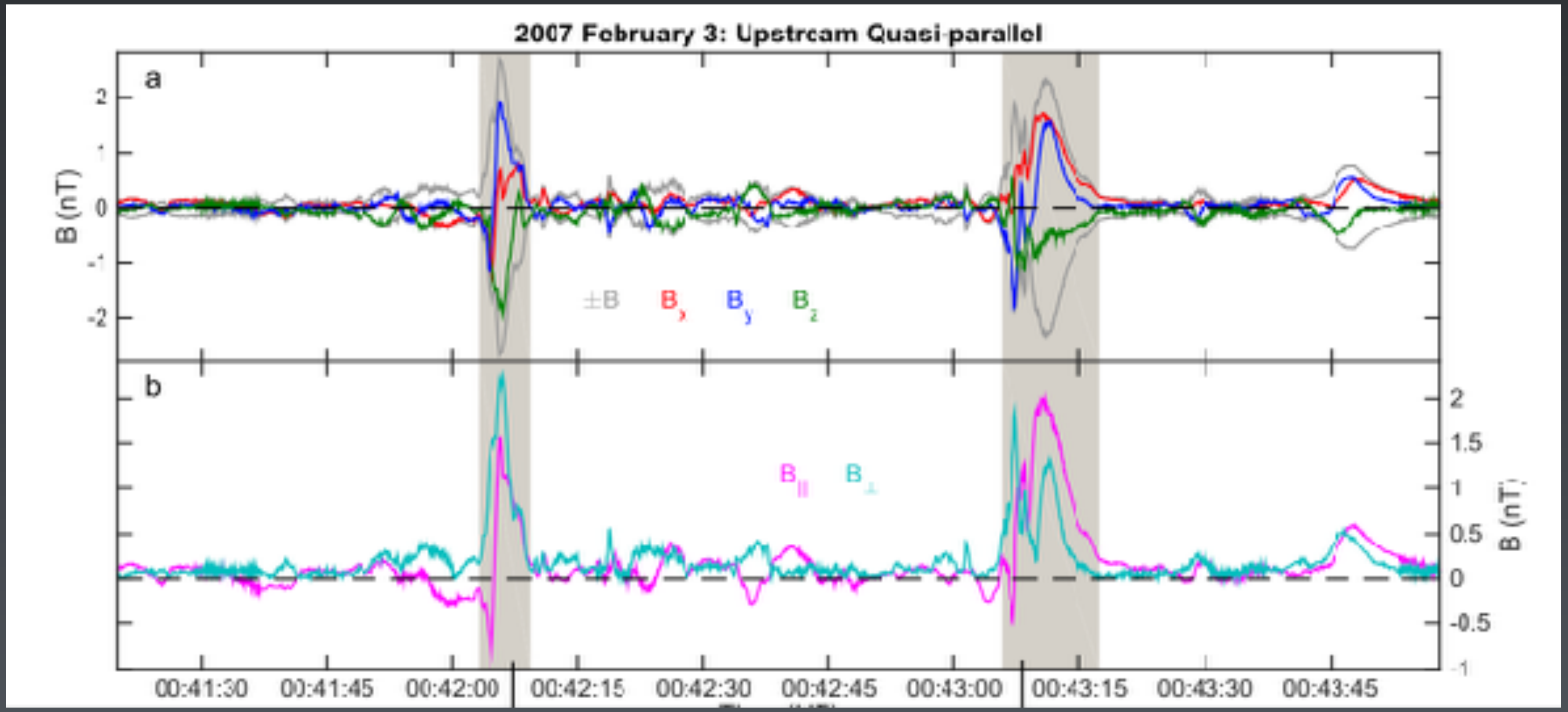
Masters et al 2017

*Spectral break corresponds to energy where gyro radius matches **exactly** the average wavelength of SLAMS**

Lower energy e^-s trapped,

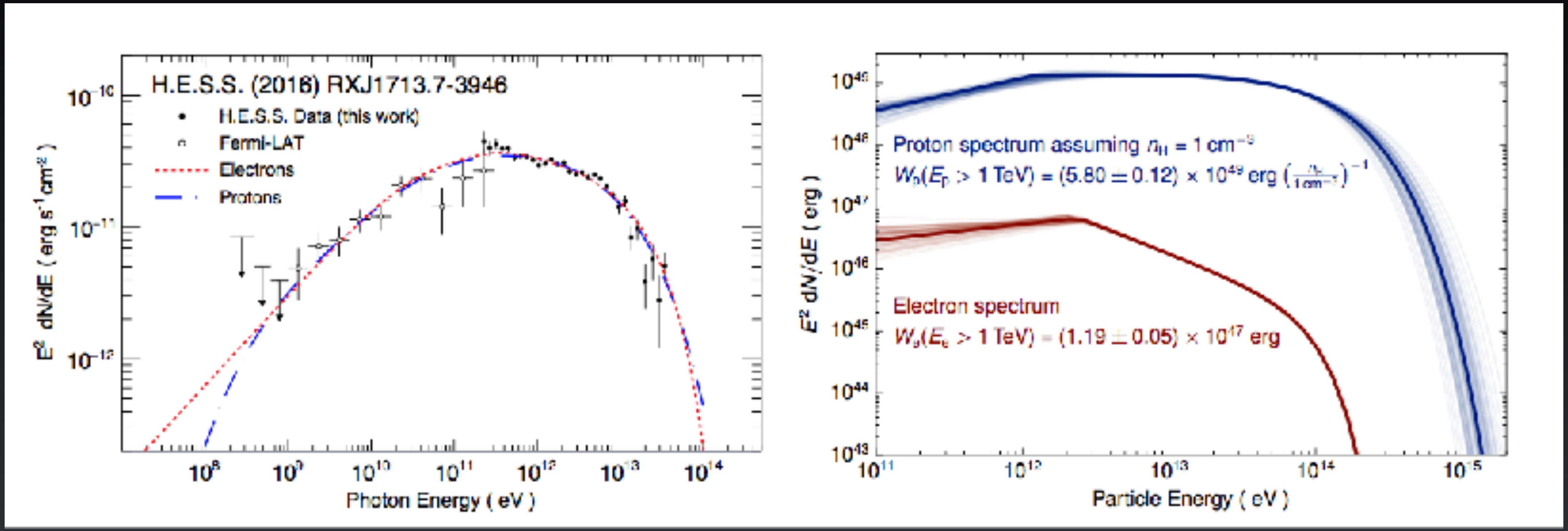
Higher energy e^-s diffusive ?

Can similar transport transitions produce spectral breaks in SNRs?



**Short Large Amplitude Magnetic Structures*

Power-laws & spectral breaks



HESS Collab. 2017

Spectral break at a few TeV?

What does this tell us about plasma physics?

Highlights need for more reliable non-linear CR acceleration theories.

Summary & Conclusions

- All current Galactic SNR past their PeV lifetime?
- Will CTA simply probe relics of previous activity?
- What do steep/flat spectra really tell us?
- What information can we extract from CTA with better statistics?