Particle acceleration at relativistic shocks

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Topics

- Observational status: GRB
- Basic theory
- Current issues
  - Shock structure
  - Particle transport
- Observational status: Crab Nebula

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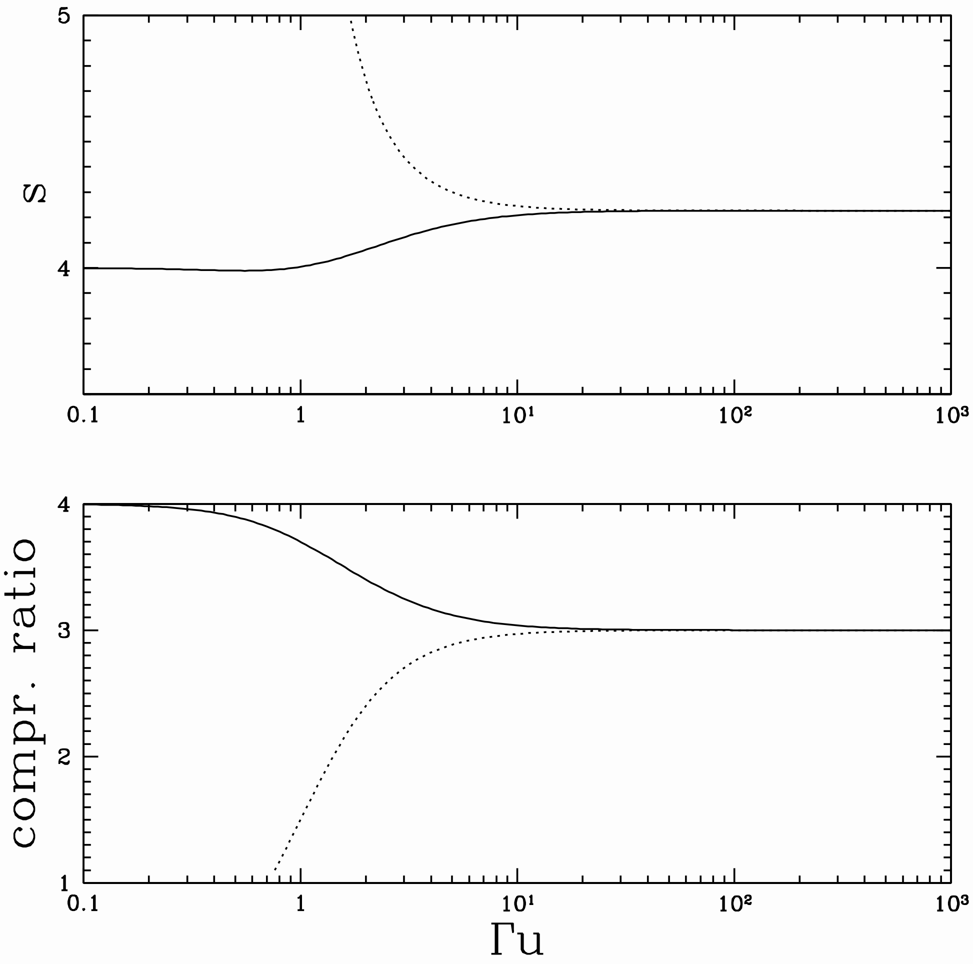
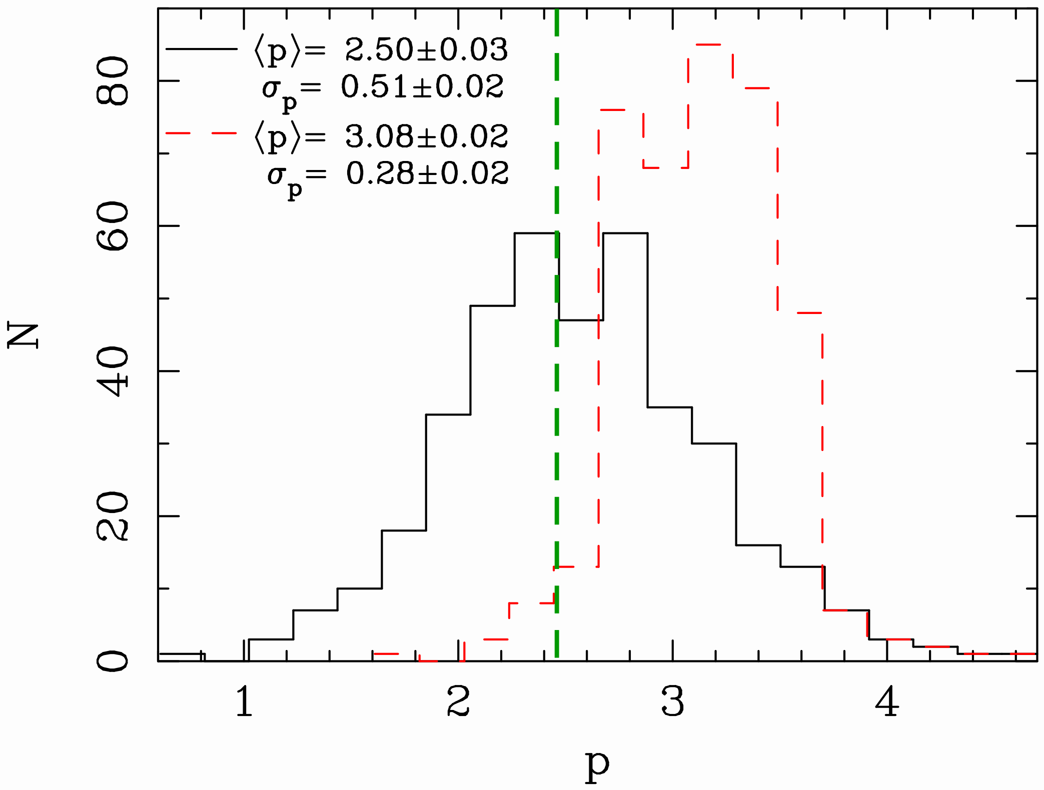
- 1st order Fermi: “universal” power-law index



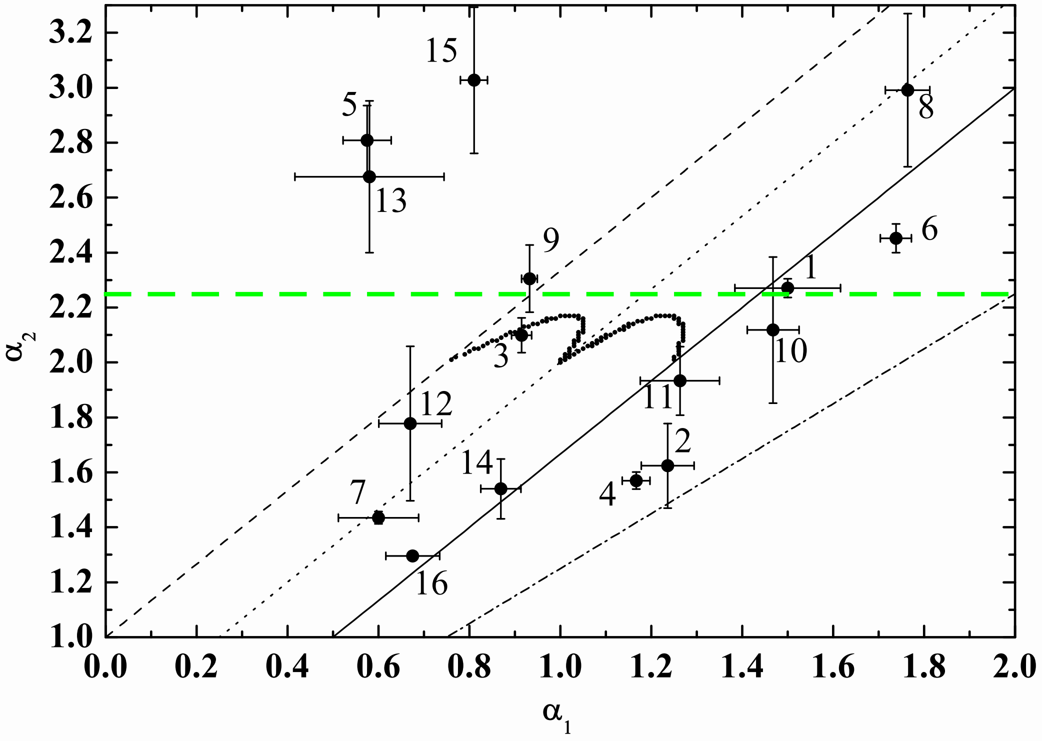
Observational status: GRB

- 1st order Fermi: “universal” power-law index
- BATSE bursts Shen, Kumar & Robinson (2005)



Observational status: GRB

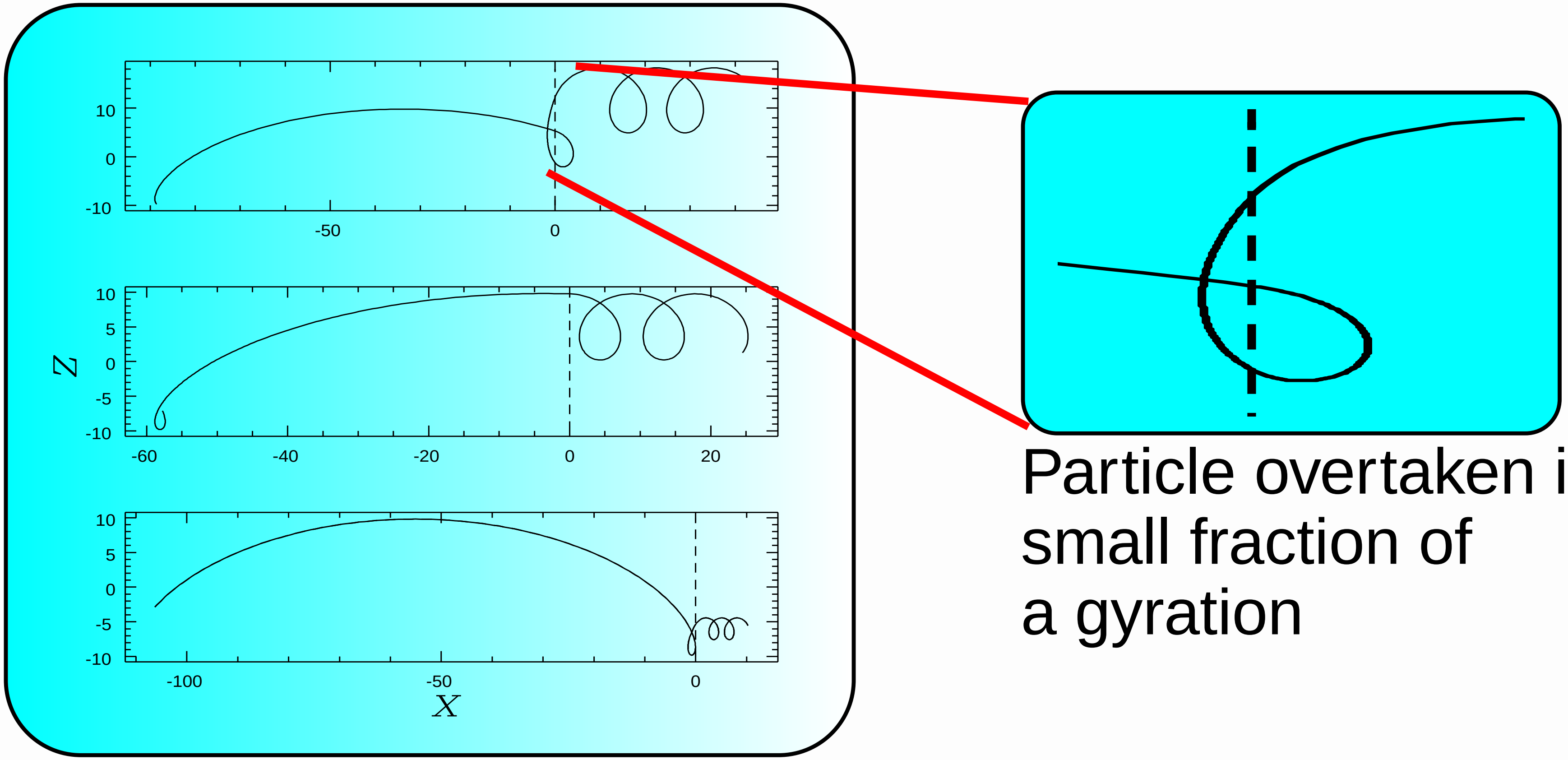
- 1st order Fermi: “universal” power-law index
- BATSE bursts Shen, Kumar & Robinson (2005)
- Optical afterglow measurements Zeh, Klose & Kann (2006)



Basic theory

Field orientation: $B_{\|} = B'_{\|}$, $B_{\perp} = \Gamma_{\rm shock} B'_{\perp}$.

Large $\Gamma \Rightarrow$ perpendicular shock.



Particle overtaken in small fraction of a gyration

Shock-drift vs. 1st order Fermi

No scattering:

- *no stochastic acceleration*
- upper limit on energy gain
- no characteristic spectrum

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With scattering:

- cyclic energy gain $+$ escape probability
- energy gain limited only by loss processes
- characteristic power-law spectrum for nonthermal particles ($E \gg \Gamma m_{\rm e} c^2$, in $e^{\pm}$ plasma, $E \gg \Gamma m_{\rm p} c^2$ in e-p plasma)

Current issues

Is first-order Fermi a valid paradigm?
Two main questions:

1. Can (a significant number of) particles escape thermalization at a relativistic shock transition?
2. If so, how can their transport be modelled?

Methods of attack:

1. P.I.C. simulation
2. Monte-Carlo, integration of trajectories, analytic description.

Shock structure

≥ 5 groups perform large scale 3D relativistic P.I.C. simulations (e.g., Jaroschek et al., Spitkovsky & Arons, Frederiksen et al., Nishikawa et al., Medvedev et al)
— good for study of thermalization process
— steady-state shock structure not yet understood
However, “easier” for $e^{\pm}$ plasma :

- At low magnetization, Weibel-produced fields overwhelm ordered component $\Rightarrow$ 1st order Fermi possible, but not (yet?) seen
- At high magnetization, field fluctuations small — stochastic transport across B suppressed $\Rightarrow$ 1st order Fermi unlikely: shock drift? surfatron?

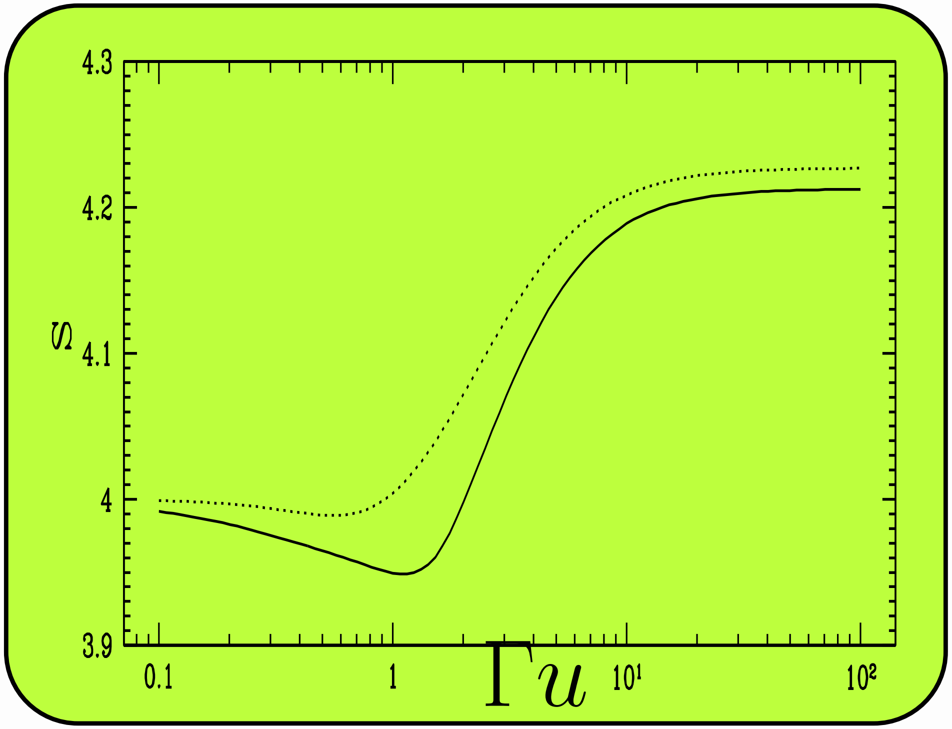
Particle transport

Three different approaches:

- analytic description of (anisotropic) diffusion in angle (Kirk & Schneider, Heavens & Drury, Achterberg et al, Kirk et al)

Anisotropic scattering

Effect of anisotropic scattering



$$D_{\mu\mu} \propto \frac{1-\mu^2}{\sqrt{\mu^2+\left(\lambda_\parallel/\lambda_\perp\right)^2}}$$

For large Γ_{shock}
and $\lambda_\parallel/\lambda_\perp = 1/10$

$$\Delta s \approx 0.02$$

Particle transport

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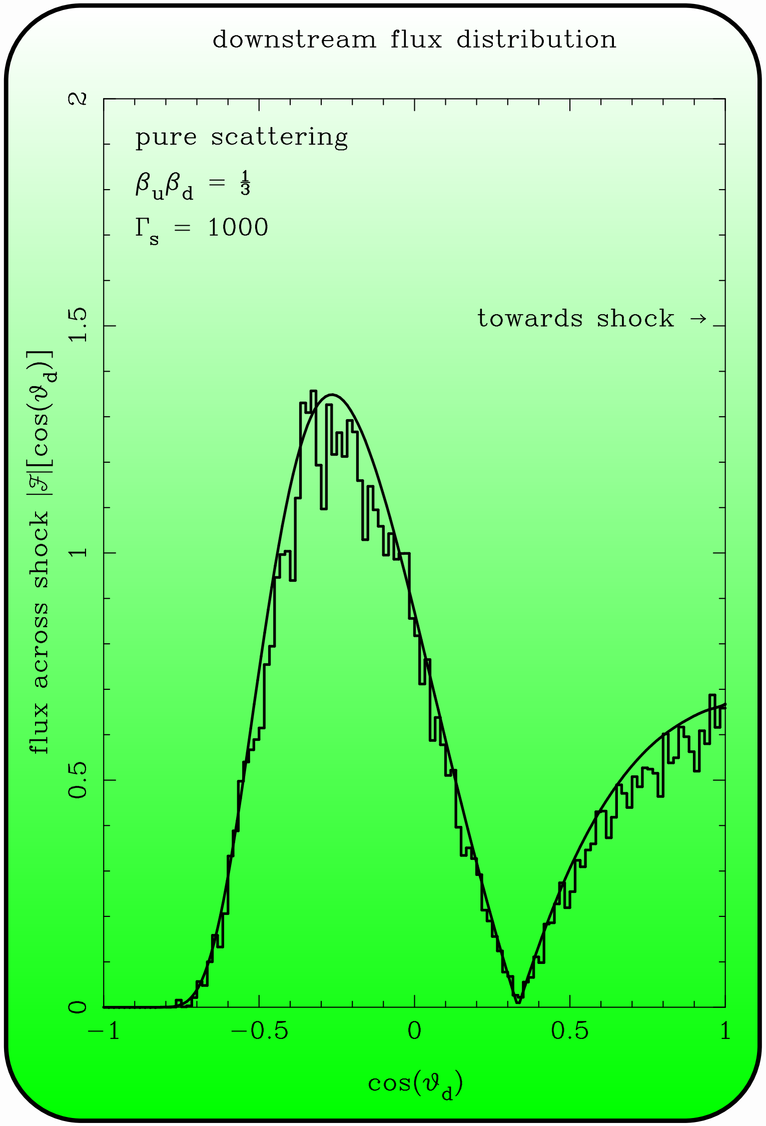
- analytic description of (anisotropic) diffusion in angle (Kirk & Schneider, Heavens & Drury, Achterberg et al, Kirk et al)
- Monte-Carlo simulation of diffusion in angle (e.g., Baring, Ellison & Double, Meli & Quenby, Achterberg et al, Virtanen,. . .)

Angular distribution

Comparison of MC/analytic angular distributions



Achterberg et al
MNRAS 328, 393 (2001)

Particle transport

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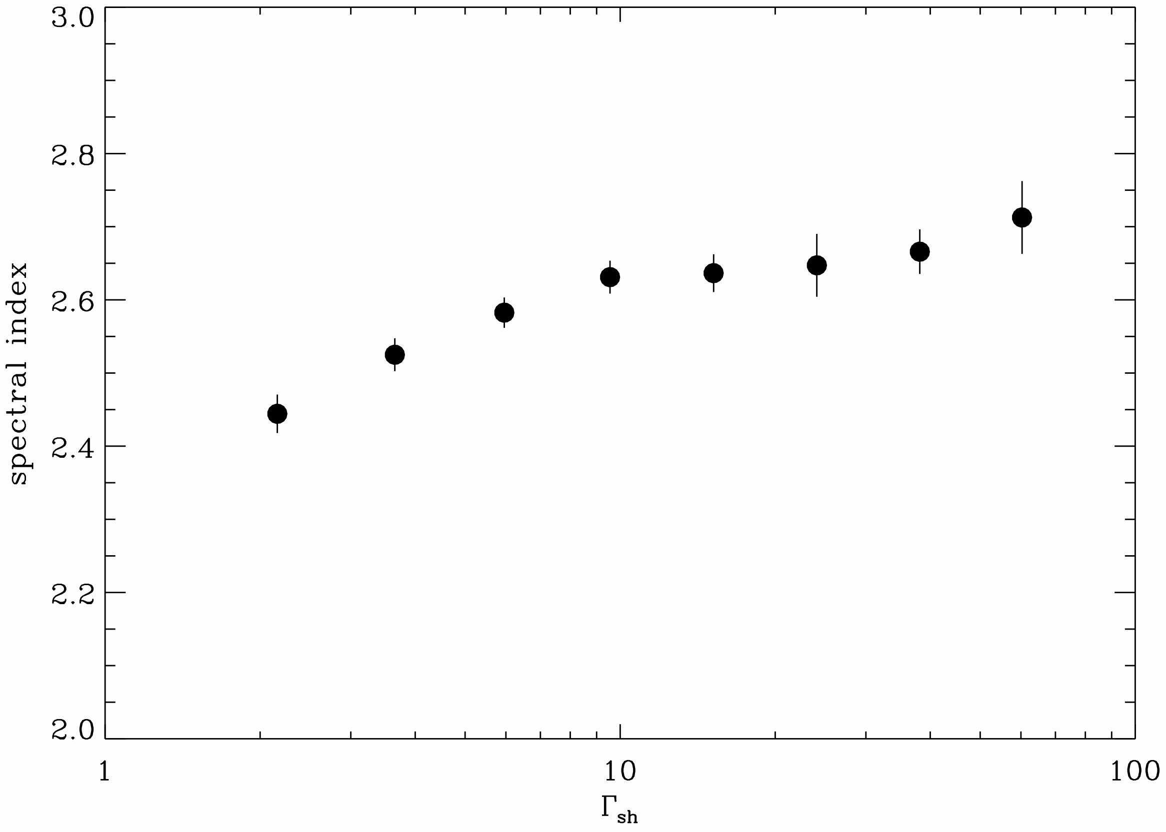
- analytic description of (anisotropic) diffusion in angle (Kirk & Schneider, Heavens & Drury, Achterberg et al, Kirk et al)
- Monte-Carlo simulation of diffusion in angle (e.g., Baring, Ellison & Double, Meli & Quenby, Achterberg et al, Virtanen,. . .)
- computation of trajectories in a realisation of a turbulent field (Ballard & Heavens, Bednarz & Ostrowski, Lemoine & Pelletier, Lemoine & Revenu)

Trajectory integration

Power law index from compressed turbulence
(Lemoine & Revenu 2006)



Particle transport

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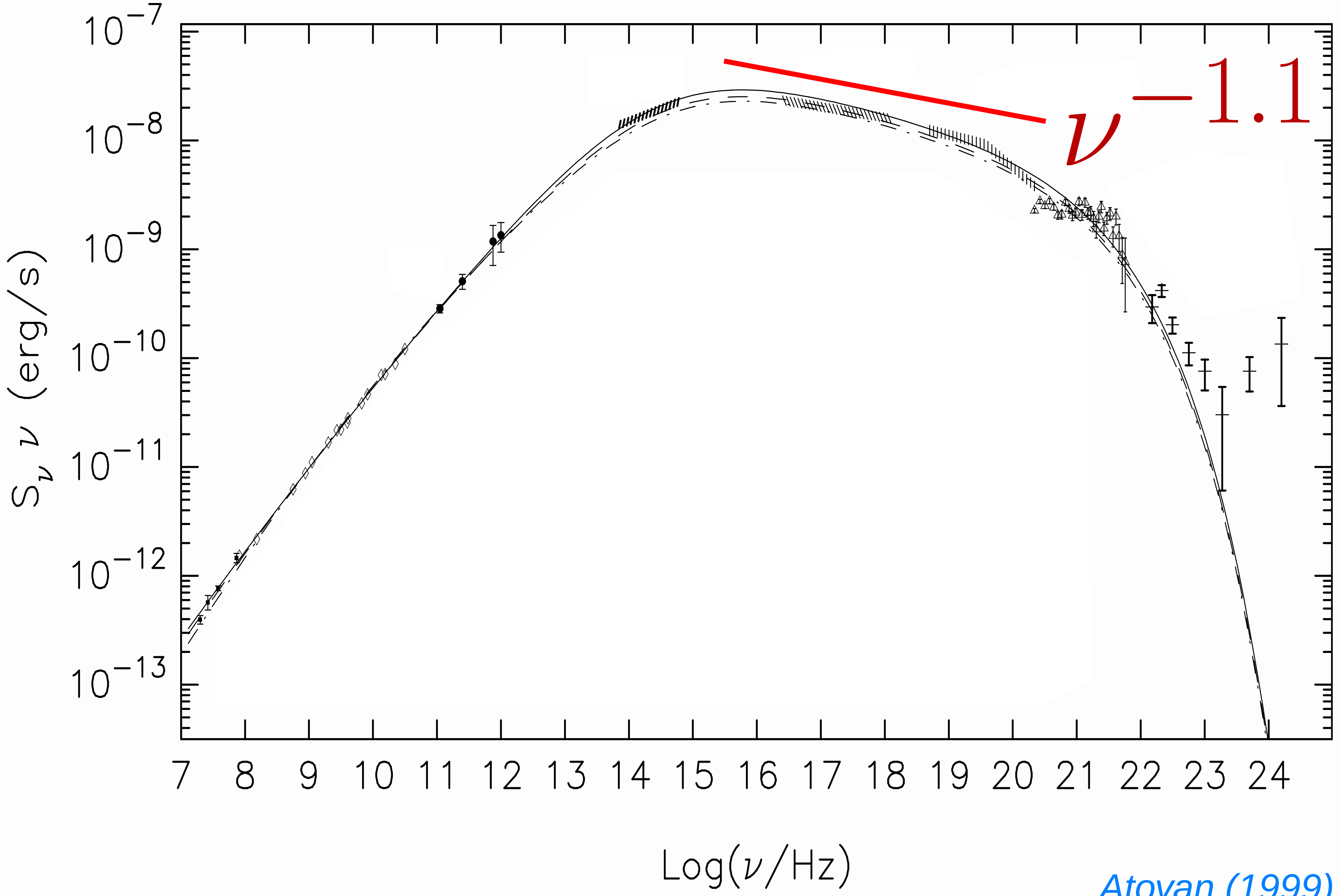
- analytic description of (anisotropic) diffusion in angle
- Monte-Carlo simulation of diffusion in angle
- computation of trajectories in a realisation of a turbulent field

Asymptotic spectrum confirmed
Role of ordered field confirmed
Steepening also by compressed turbulence?

Observational status: Crab Nebula



Atoyan (1999)

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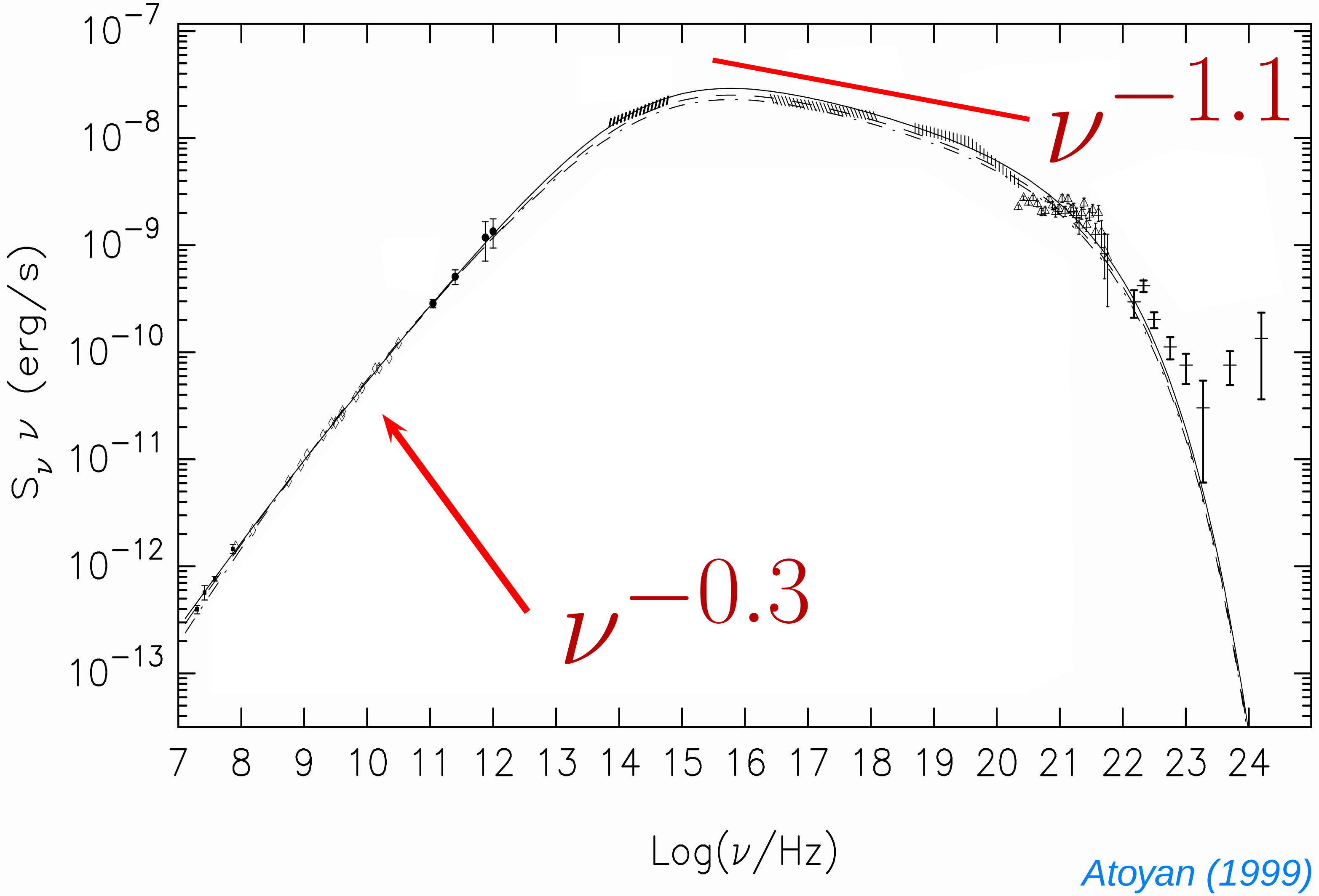

Atoyan (1999)

Conclusions

- Robust prediction of spectral slope ($p = 2.2$–2.3 for strong ultrarelativistic shock)
- High magnetization upstream suppresses stochastic acceleration
- Effect of anisotropic downstream turbulence controversial
- Several well-known effects permit “deviant” spectra: shock deceleration, change of compression ratio by field generation or pair production, contribution of “thermal” electrons to synchrotron spectra