Pulsar Winds

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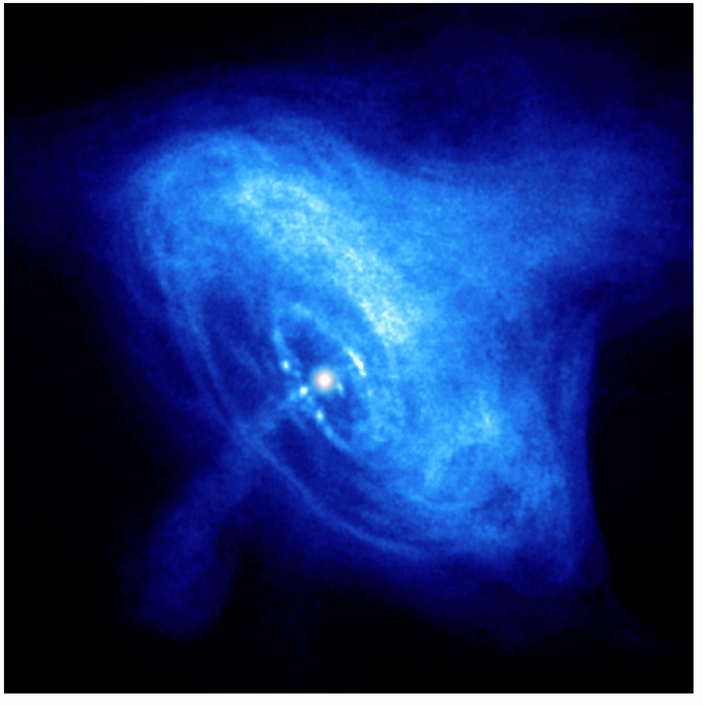
About 50 years after...



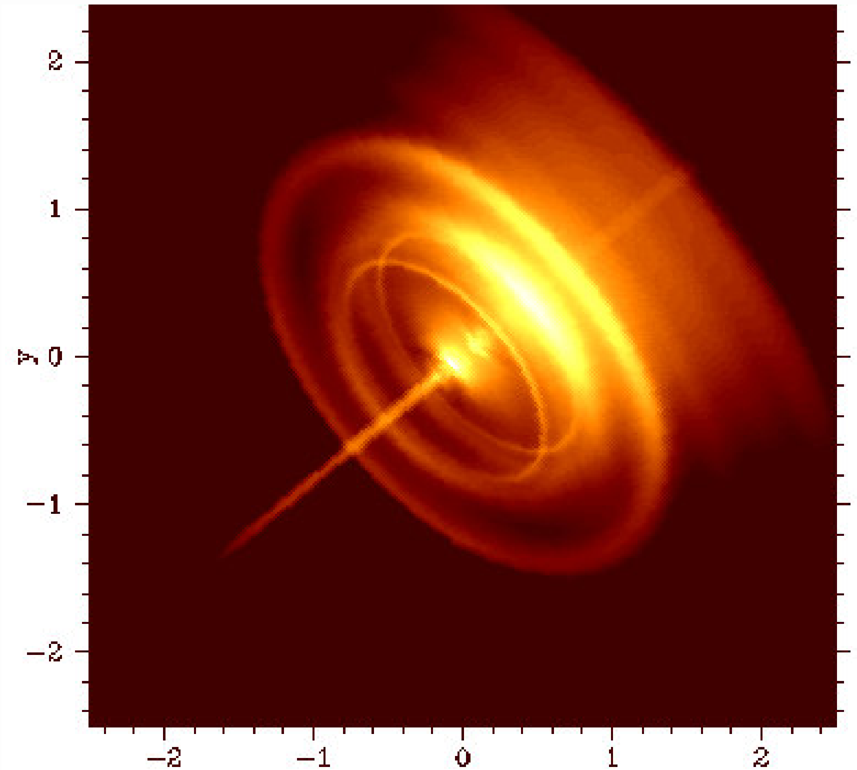
The Crab Nebula
Central star is source of particles and magnetic field (Piddington 1957) and waves (Rees & Gunn 1974).

- Few particles: magnetic dipole radiation? Damping $\Rightarrow$ propagation only for $\omega_{\rm pe} < \Omega$. For Crab: $r > 10^8 r_{\rm L}$ (e.g., Melatos & Melrose 1996)
- Many particles, MHD wind $+$ shock

Topics

- The wind–nebula connection
  - MHD simulation
- Acceleration of the wind
  - Dissipation in shocks/current sheets
- Observation of the wind
  - Optical pulse shapes and polarisation
  - TeV emission — binary system PSR B1259 $-$63
- Acceleration of particles
  - Two mechanisms?

Wind–Nebula Connection



2D relativistic MHD
by at least three groups

Komissarov & Lyubarsky 2003;

Khangoulian & Bogovalov 2003;

Del Zanna et al 2004

Key ingredients:

- relativistic, anisotropic wind (power$\propto \sin^2\theta$)
- low magnetisation σ (at least near equator)

Implications for the wind

- Radial flow, toroidal magnetic field
- Jet formed downstream of termination shock
- Low value of $\langle\sigma\rangle \sim 0.03$
- No constraints on μ parameter ($= L/\dot{M}c^2$) from the dynamics
- Problems with the inner ring (knots, front/back brightness ratio) — may reflect kinetic effects, such as proposed for the wisps

  (Gallant & Arons 1994; Spitkovsky & Arons 2000)

Axisymmetric winds

Exact solution for force-free, split monopole (Michel 1973): no collimation, $B_\phi \propto \sin\theta / r$ (no closed field lines)

Super-(magneto)sonic flow: $\Gamma \rightarrow$ constant (Bogovalov 1997)

$$\begin{aligned} \sigma &= \frac{B^2/8\pi}{\Gamma n m c^2} \\ &= \text{constant} \end{aligned}$$

the σ problem

Possible solutions to the σ problem

Accelerate the wind:

- Collimation? Not for monopole-like flows (e.g., Bogovalov & Tsinganos 1999) but in principle possible (Vlahakis 2004)
- Dissipation? Oblique rotator (Coroniti 1990) and damping of wave component — how fast?

Problem not really a problem:

- σ still high after the shock (Begelman 1998)? Difficult to recover nice pictures. . .
- the (striped) field dissipates in the termination shock (Lyubarsky 2003) Transition must remain thin

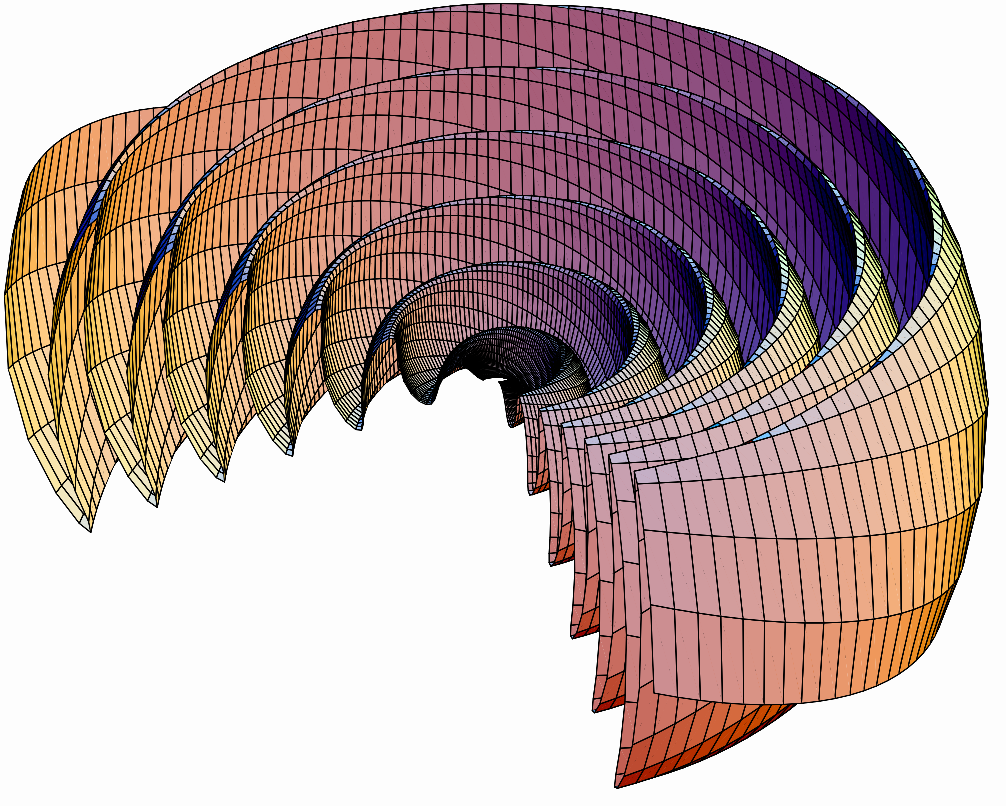
Acceleration of the wind

Dissipation forced by charge starvation ($B \propto 1/r$, $n \propto 1/r^2$)

Entropy wave or FMS wave (small wavelength approx. $r \gg r_{\rm L}$)

Lyubarsky & Kirk 2001;

Lyubarsky 2003;



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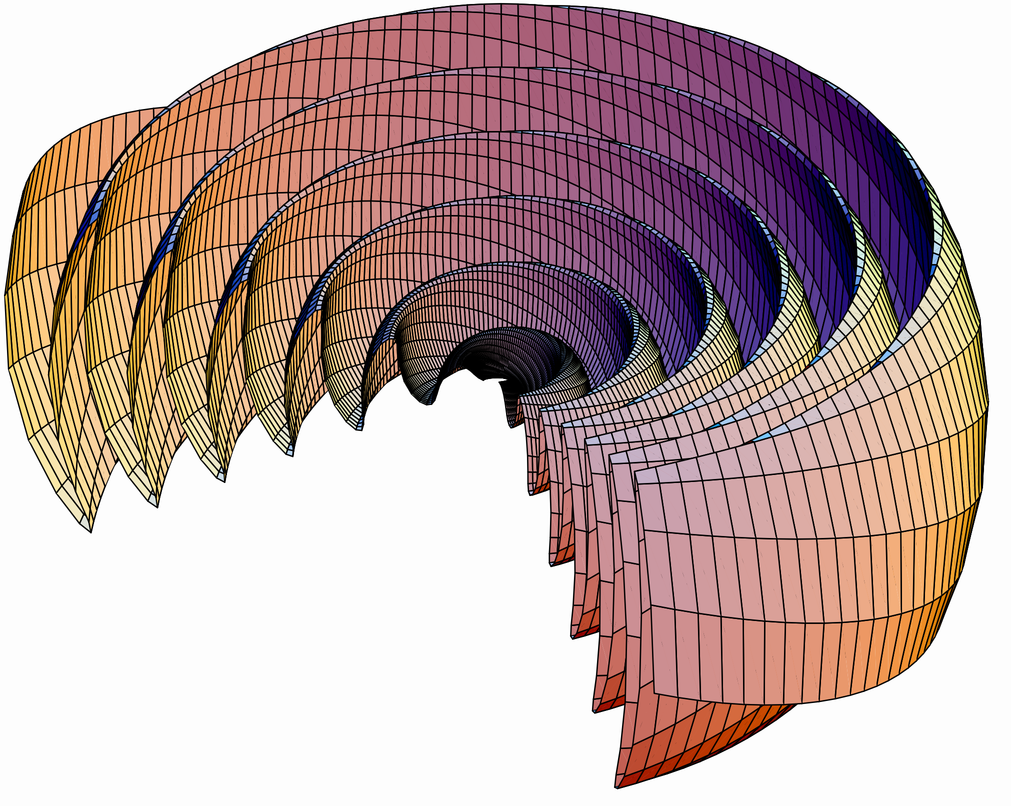
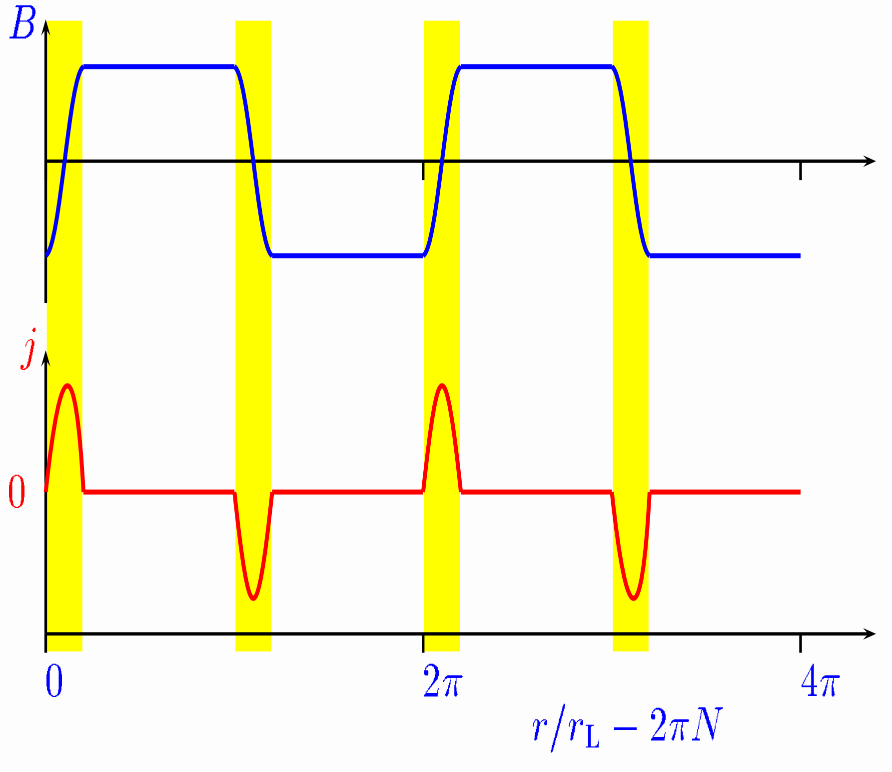
Dissipation $\Rightarrow$ accel. for $\Gamma > \sqrt{\sigma}$



Current sheets



Magnetic pressure balanced by hot plasma in sheet.
Key question:
What controls the dissipation rate?

Modelling the dissipation

Short wavelength approximation (Kirk & Skjæraasen 2003)

Slow dissipation	*Tearing-mode*	*Fast*
Coroniti (1980); Michel (1994); Lyubarsky & Kirk (2001)	Lyubarsky (1996)	Drenkhahn & Spruit (2002)
$\Gamma \propto r^{1/2}$	$\Gamma \propto r^{5/12}$	$\Gamma \propto r^{1/3}$
$\frac{r_{\max}}{r_{\rm L}} = \hat{L}^{1/2}$	$\frac{r_{\max}}{r_{\rm L}} = \mu^{4/5}\hat{L}^{3/10}$	$\frac{r_{\max}}{r_{\rm L}} = \mu^{4/5}\hat{L}^{3/10}$

$\hat{L} = L(\pi^2 e^2/m^2 c^5)$, ($= 1.5 \times 10^{22}$ for Crab)

No consistent conversion mechanism for $\mu > 10\hat{L}^{1/4}$

Observation of the wind?

- Gamma-rays from unshocked wind
  - Targets from companion star: swamped by emission from shocked wind (Ball & Kirk 2000)
  - Targets from neutron star surface: acceleration not permitted for $r < 5r_{\rm L}$ in the Crab

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- Optical pulses from unshocked wind if $r_{\rm emission} < \Gamma^2 r_{\rm L}$ (Pétri)
- TeV emission from shocked wind in PSR B1259 $-$63
  - Hadronic emission (Kawachi et al 2004)
  - Inverse Compton model

Unique pulsar/Be star binary

X-rays from interacting winds Tavani & Arons (1997)

Be star wind:

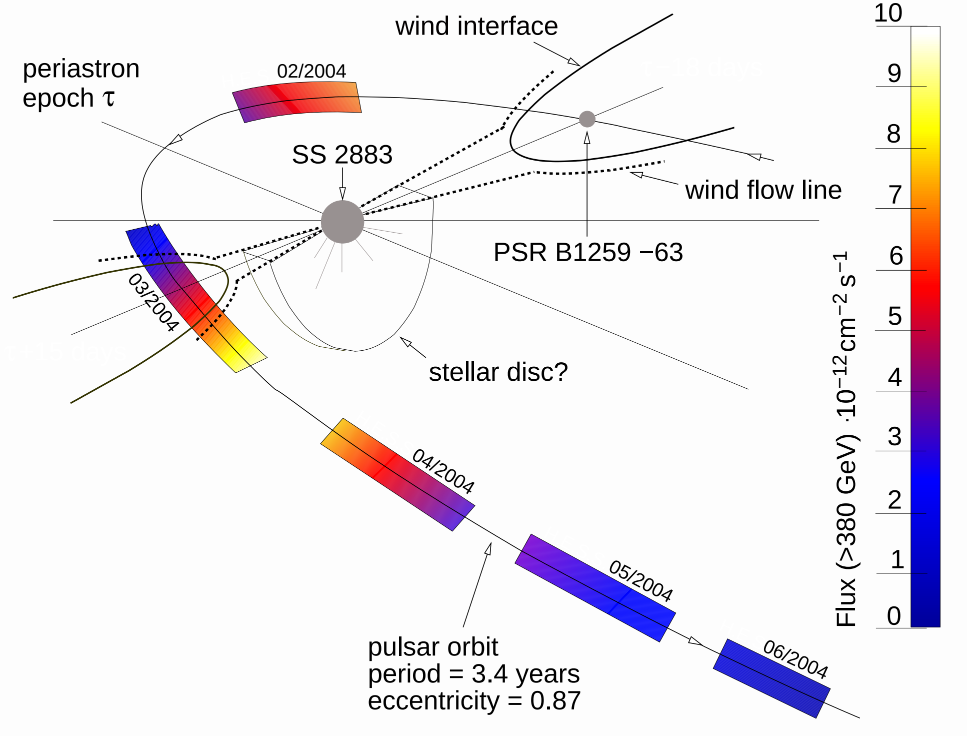
$\dot{M} \sim 10^{-8}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$

$v_{\rm wind} \sim 10^3\,\mathrm{km\,s}^{-1}$

Pulsar wind:

$L_{\rm s.d.} \approx 8 \times 10^{35}\,\mathrm{erg\,s}^{-1}$

Momentum balance:

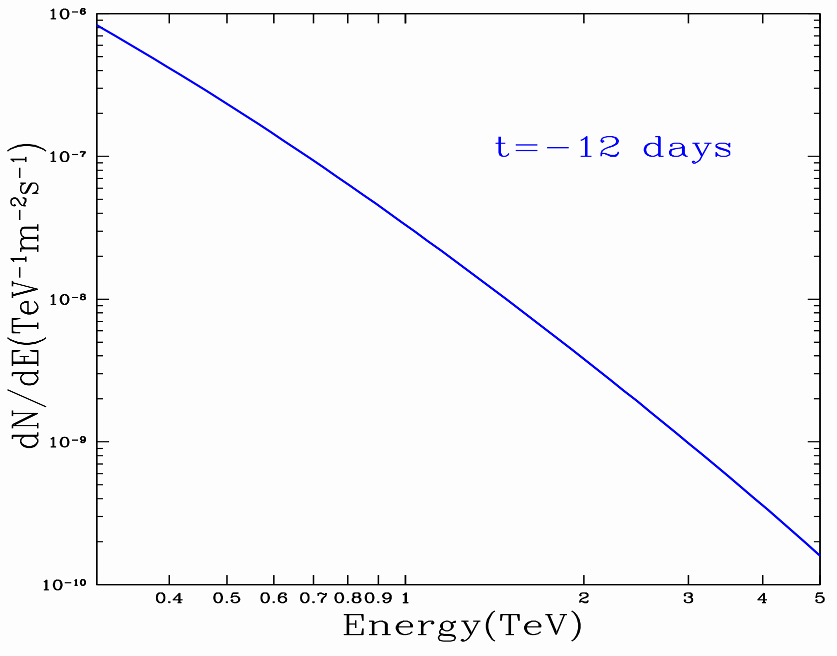


$$\frac{r_{\rm Be}}{r_{\rm p}} = \sqrt{\frac{L_{\rm s.d.}}{\dot{M} v_{\rm wind} c}} \sim 0.7$$

Based on cartoon by O. de Jager

But $L_{\rm s.d.} \gg L_{\rm Be\ wind}$

PSR B1259 −63: predicted spectrum



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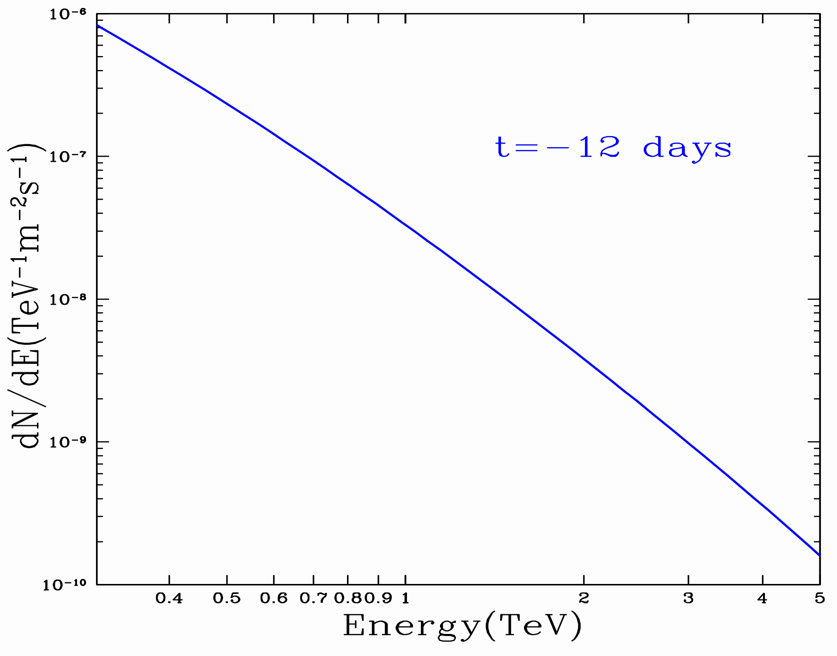

- B from P, $\dot{P}$ and
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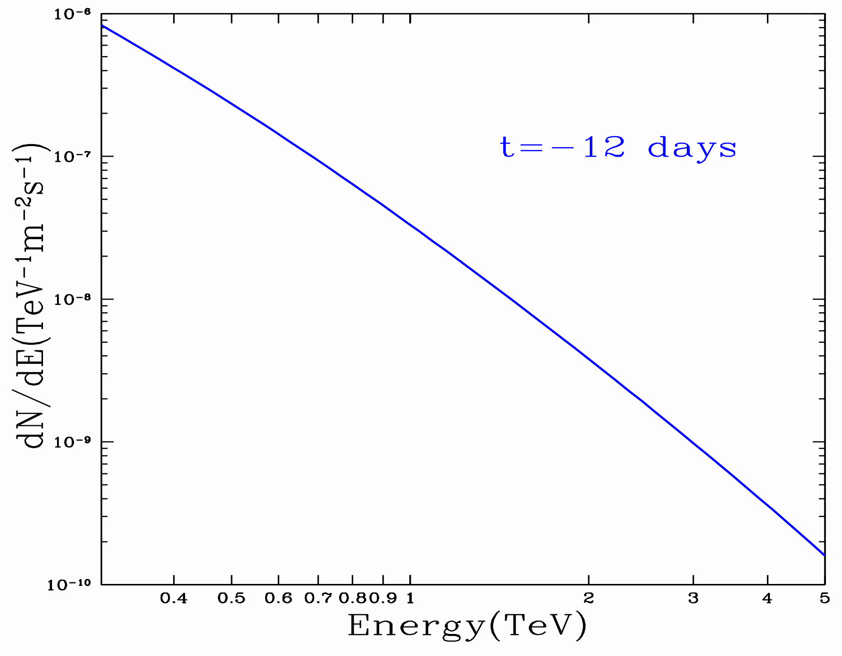

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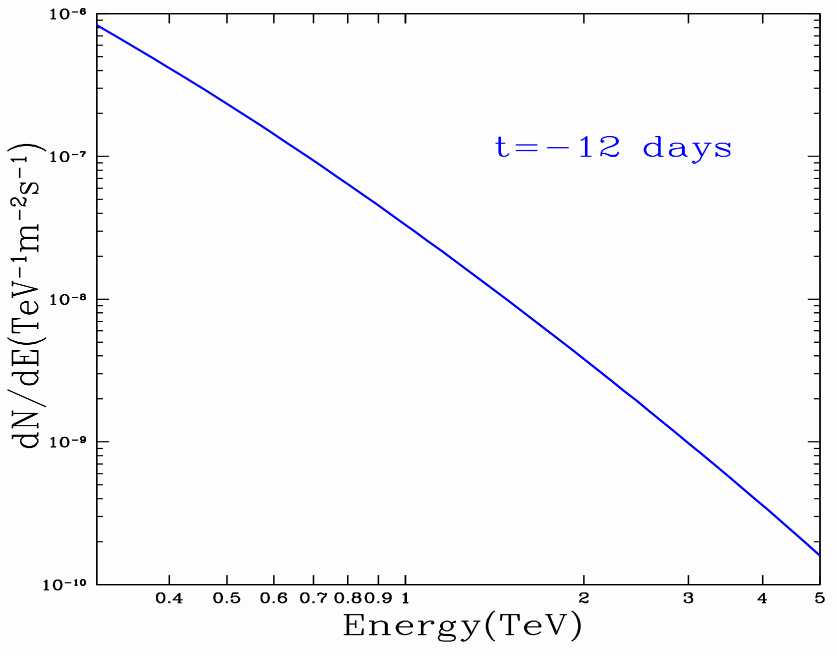

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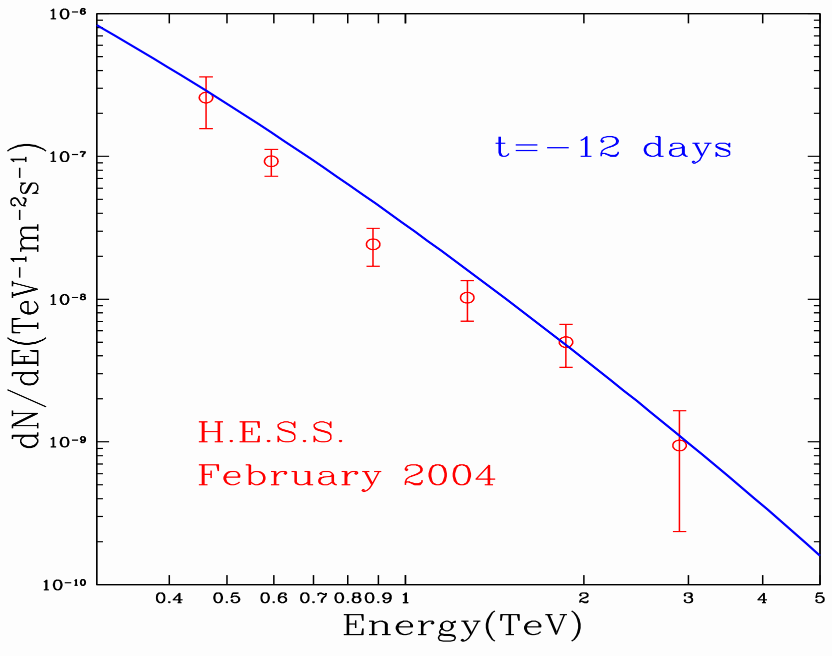

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Observations with H.E.S.S. telescopes

Schlenker et al (2005), Aharonian et al astro-ph/0506280

TeV photon index

$$\frac{\mathrm{d}\ln N}{\mathrm{d}\ln \epsilon} \approx -2.7$$

Electron injection rate

$$\frac{\mathrm{d}\ln Q}{\mathrm{d}\ln \gamma} = -q$$

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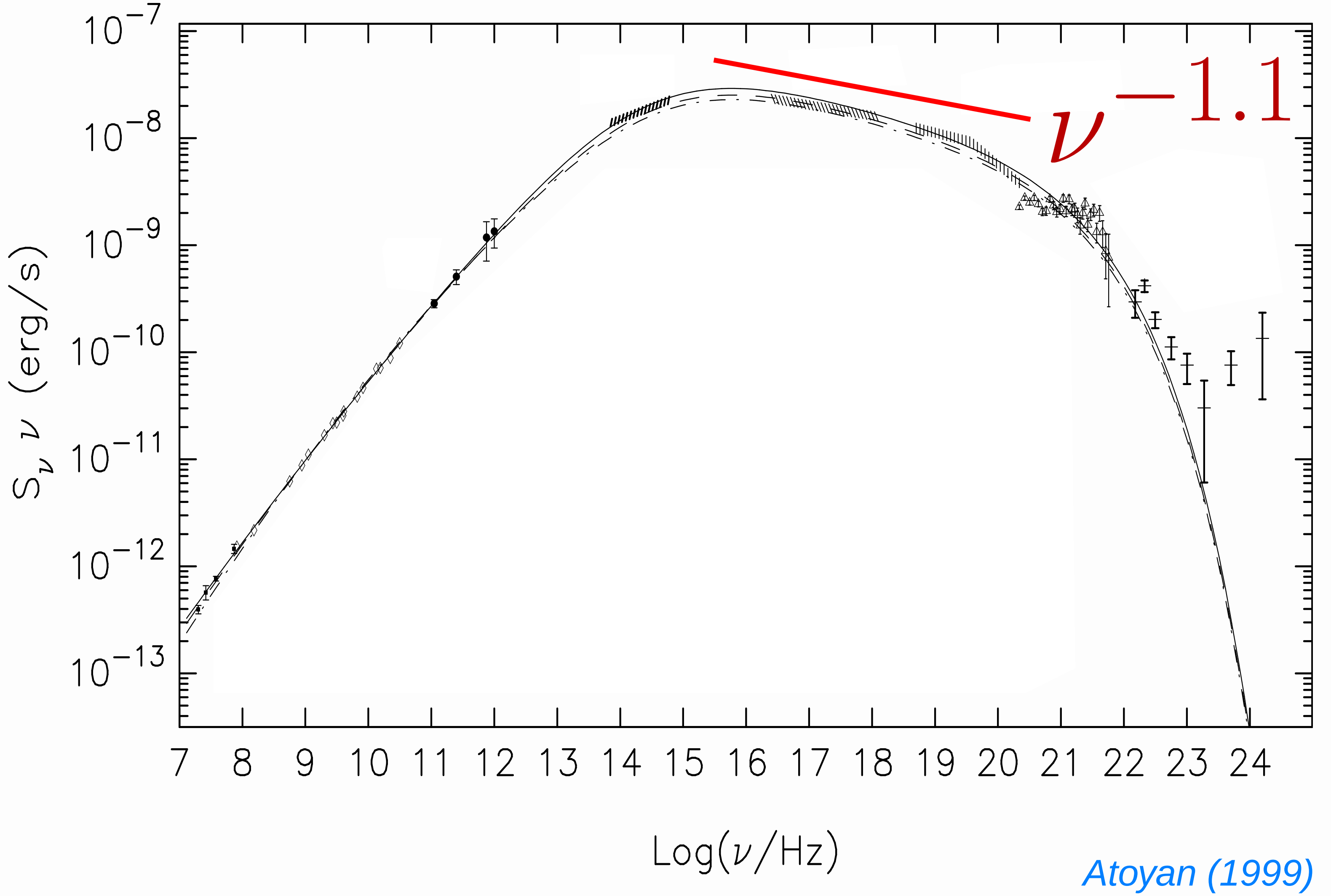
Connect with acceleration theory?

Crab Nebula



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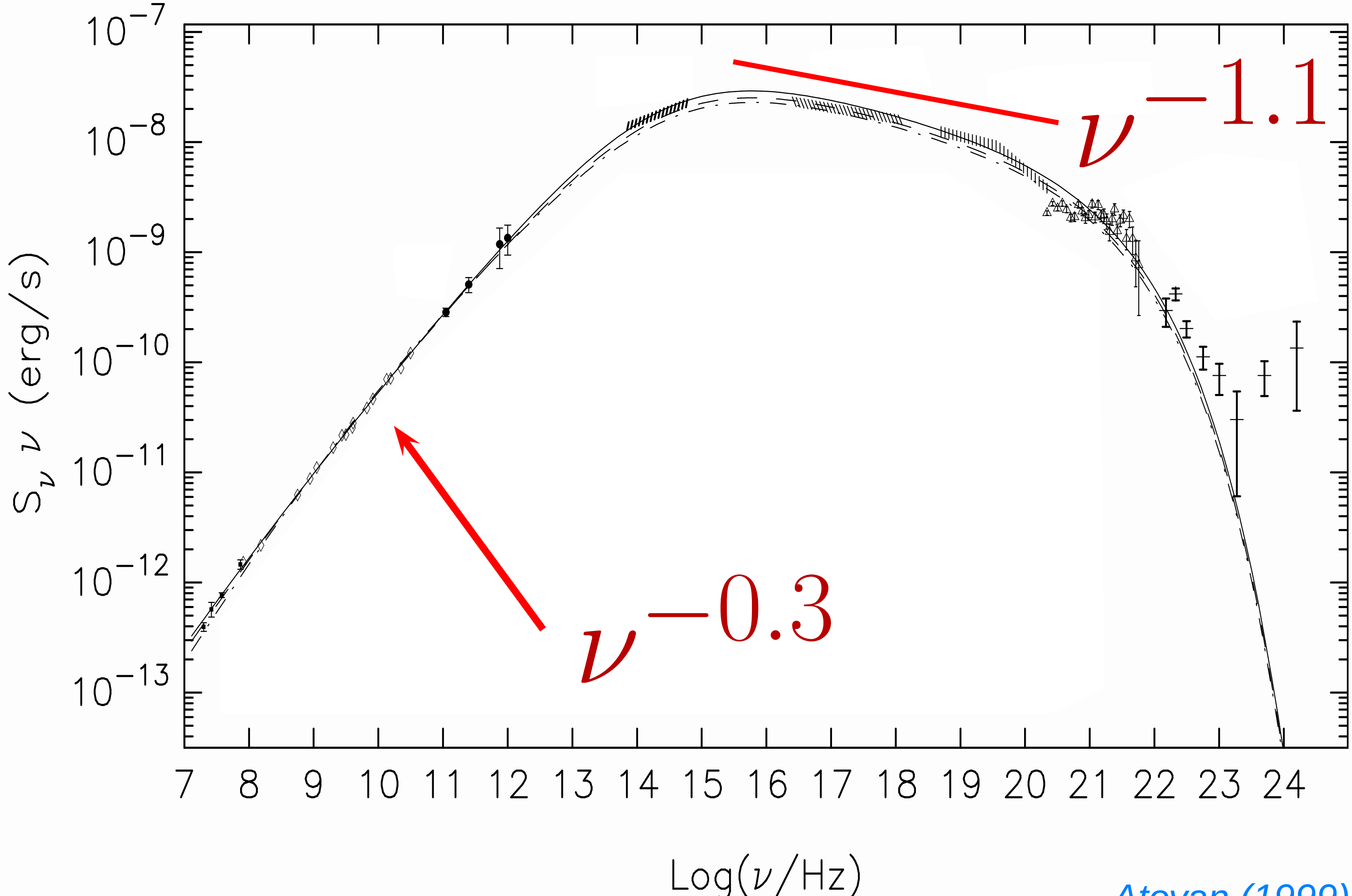

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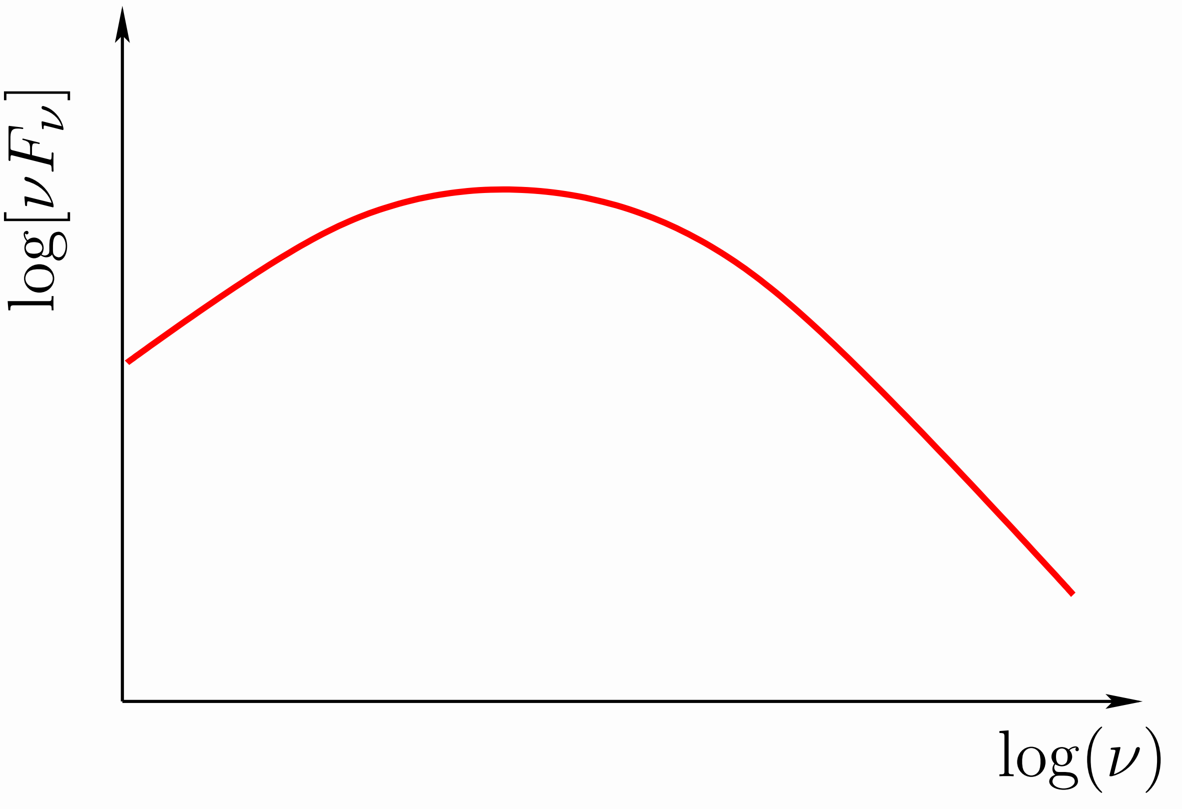
Two mechanisms?



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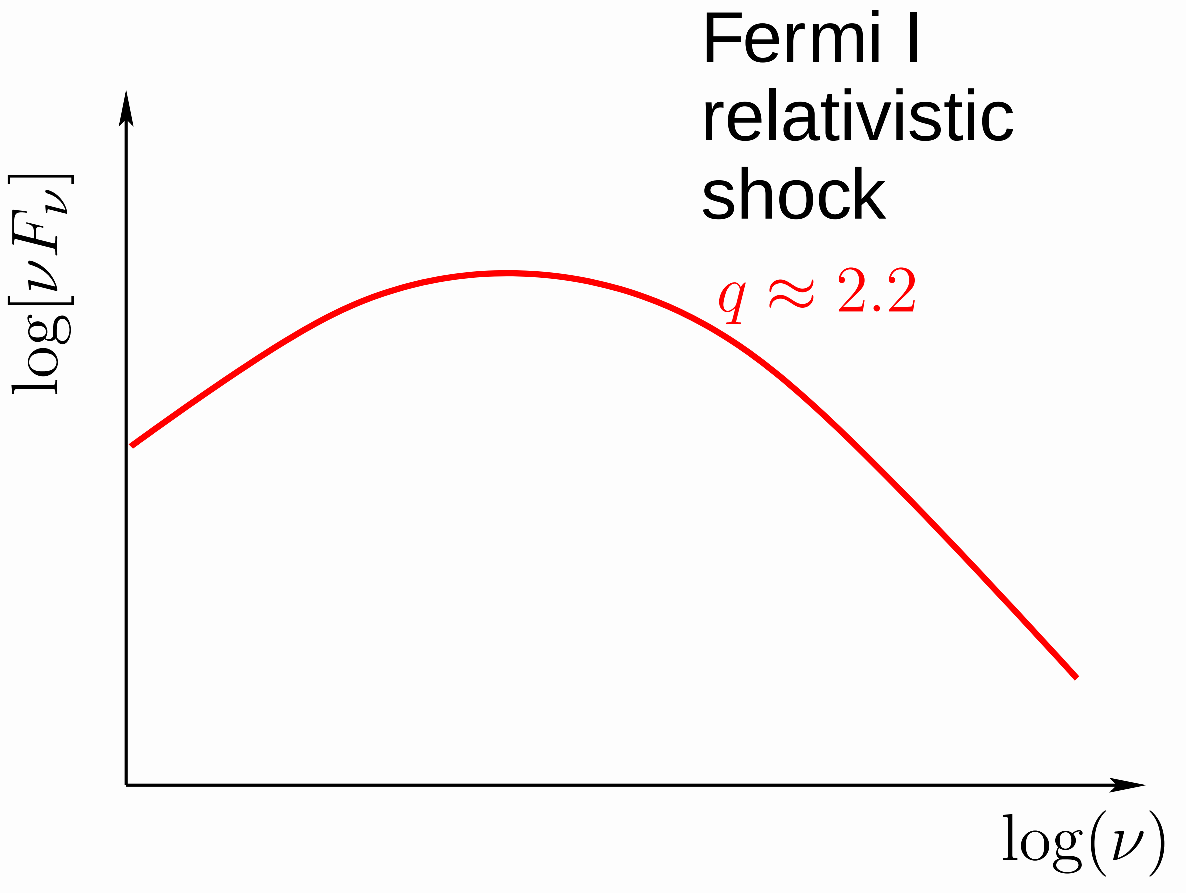

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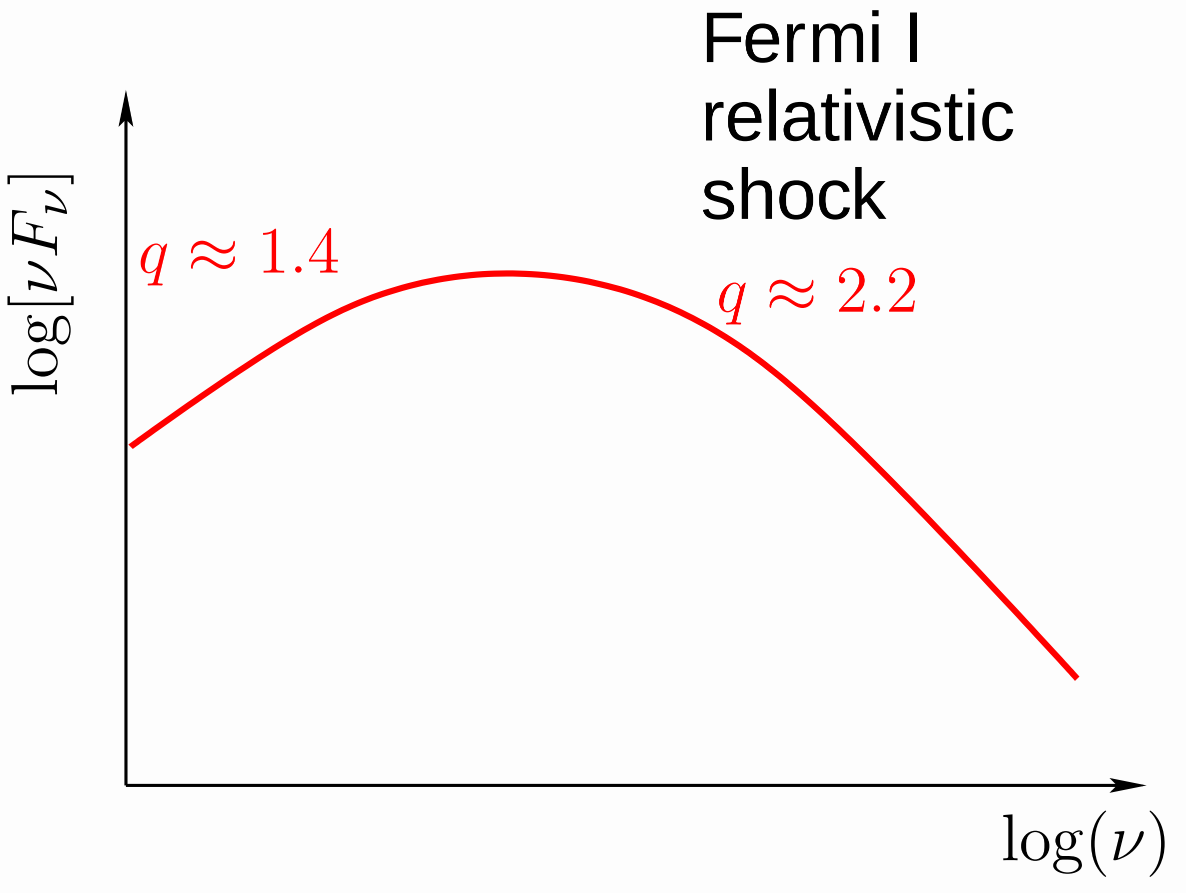

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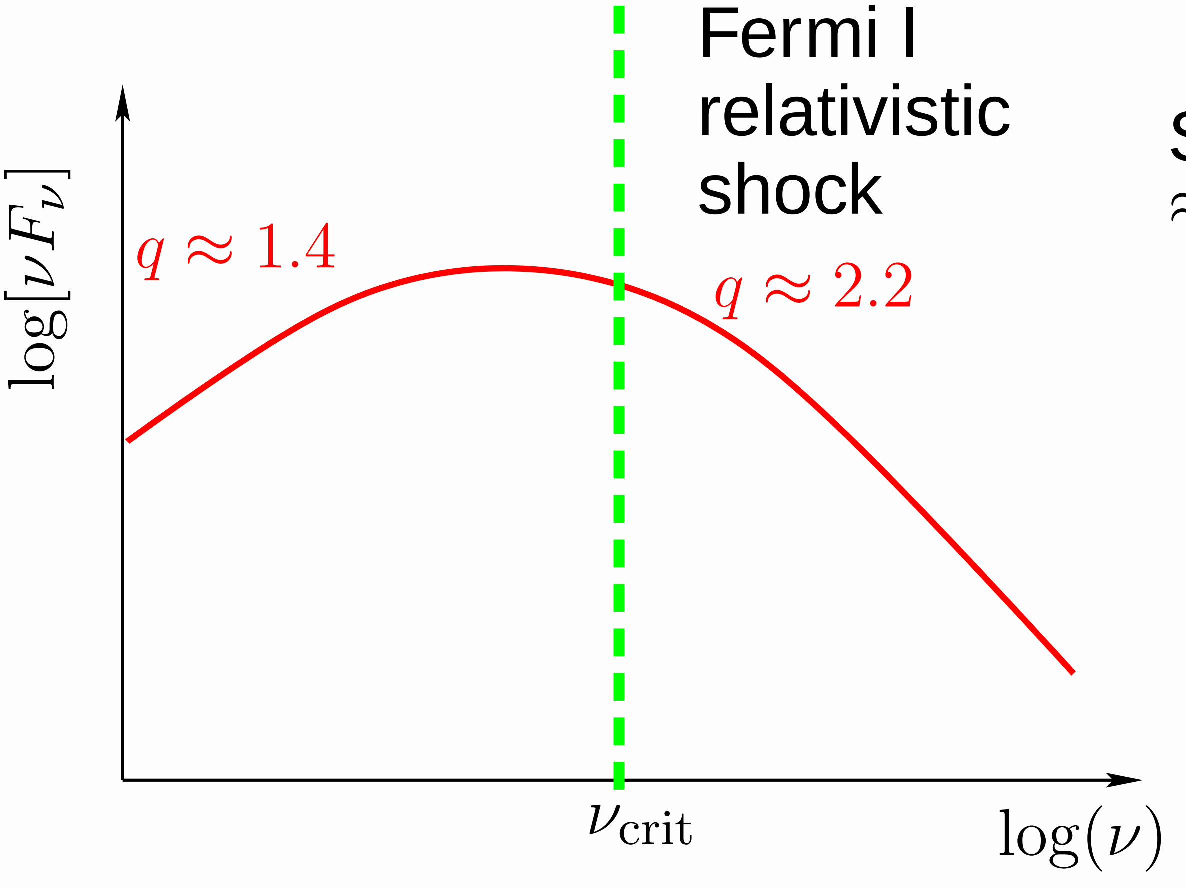

Shock width
≈ gyro radius

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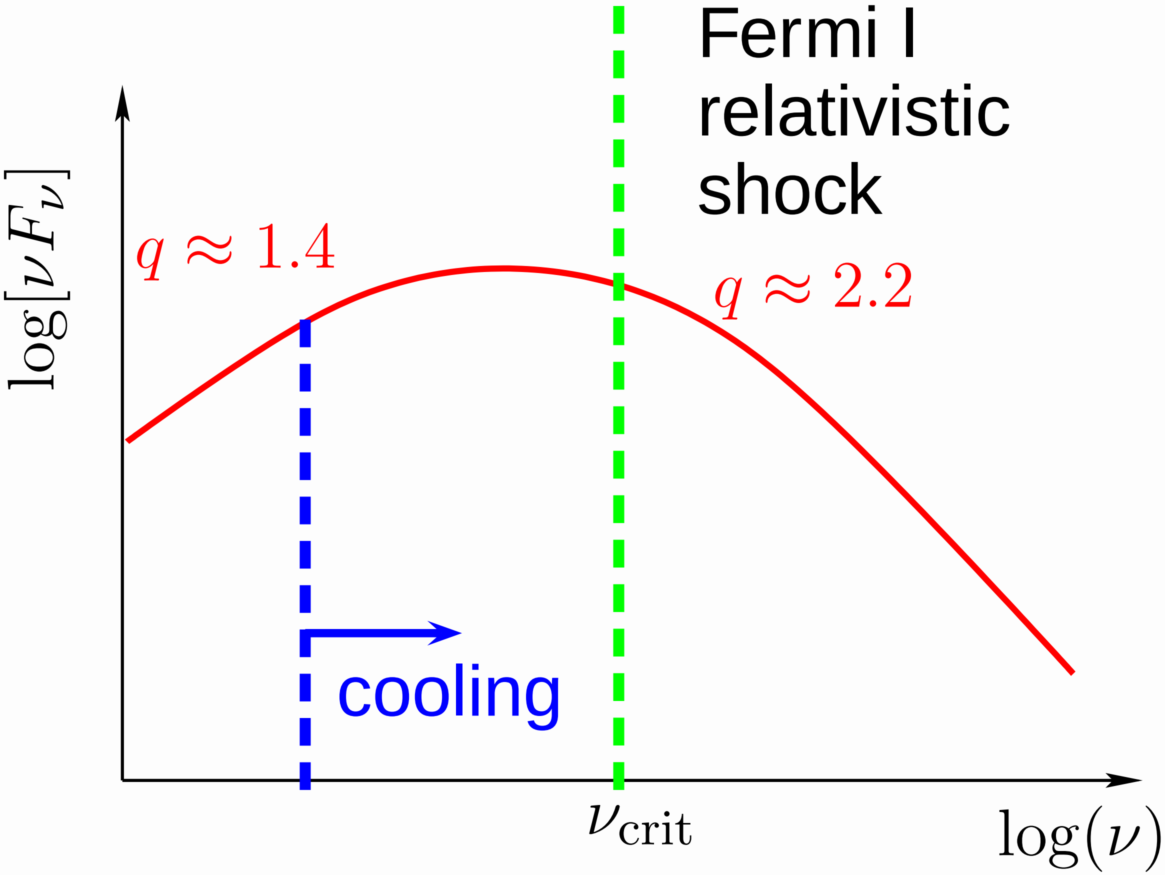

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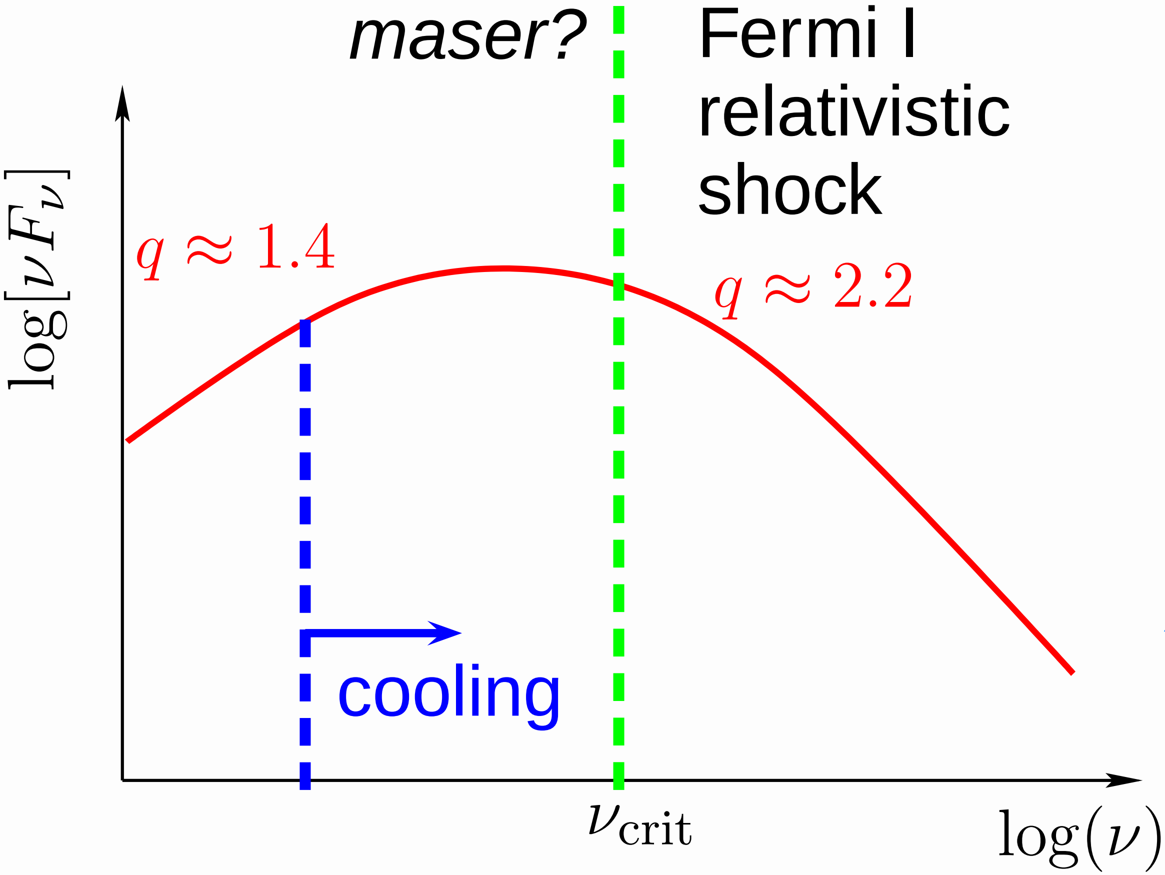

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resonant cyclotron
absorption ($p - e^+$)?

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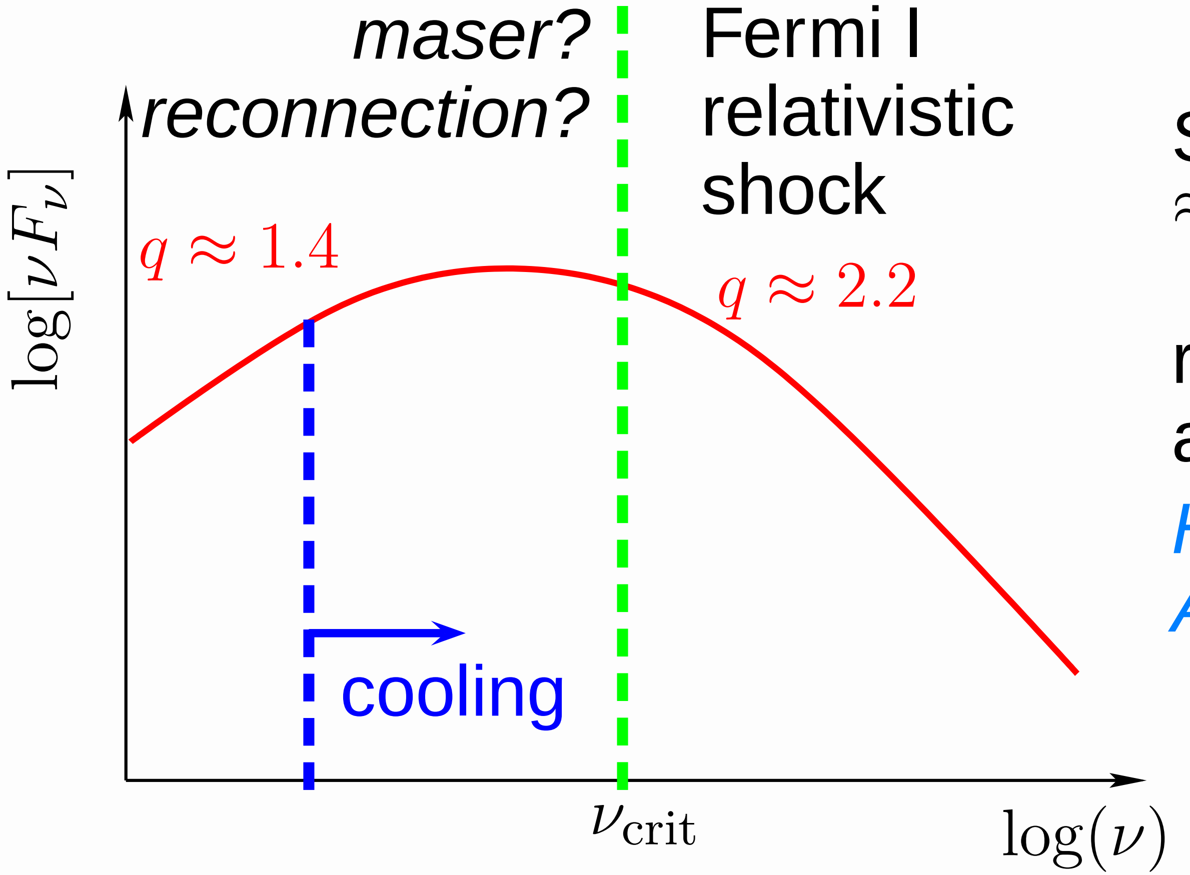

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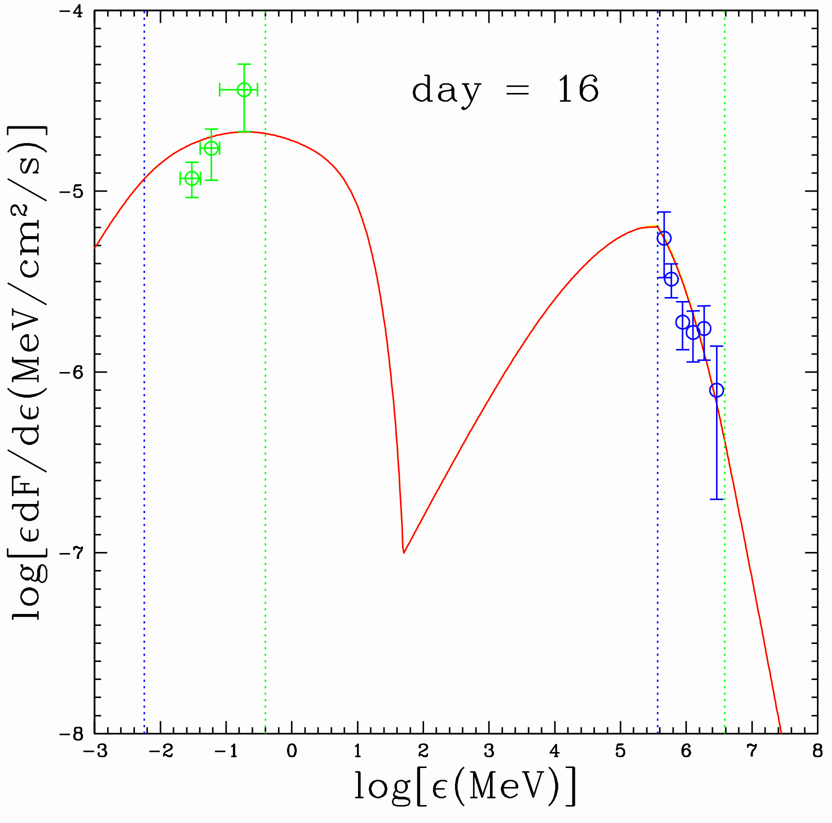
PSR1259-63: modelling



INTEGRAL: Shaw et al 2004

H.E.S.S. 2005

1. Radiative losses at periastron

Crab-type injection

$dn/d\gamma \propto \gamma^{-1.6}$ at $\gamma < \Gamma_{\rm peak}$

- Adiabatic loss timescale $> 15D/c$
- 10% efficiency
- $\Gamma_{\rm wind} \approx 6 \times 10^4$

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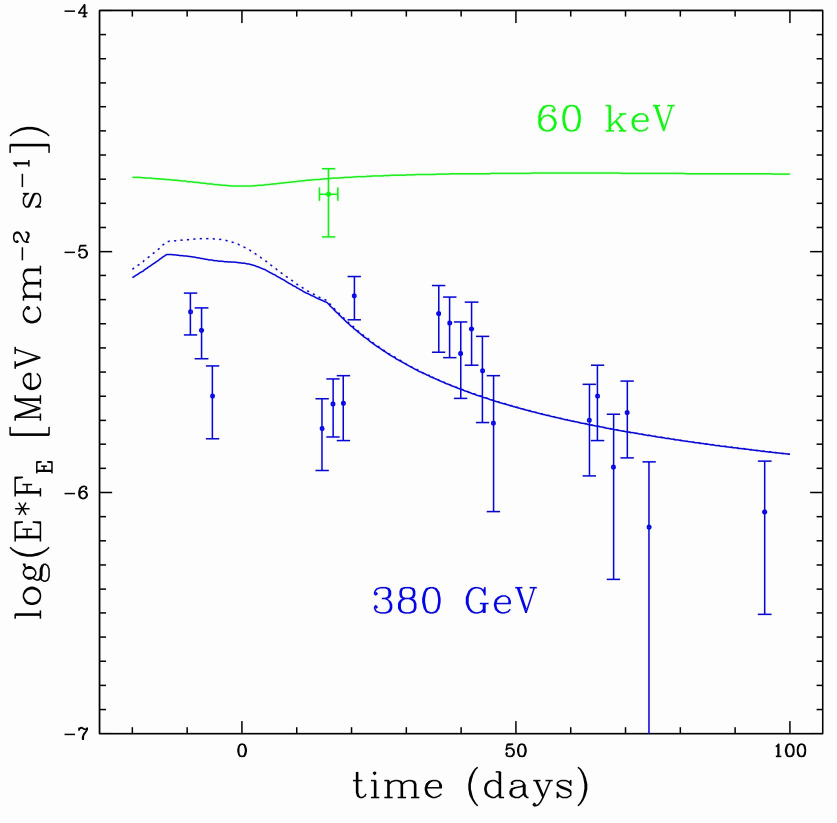

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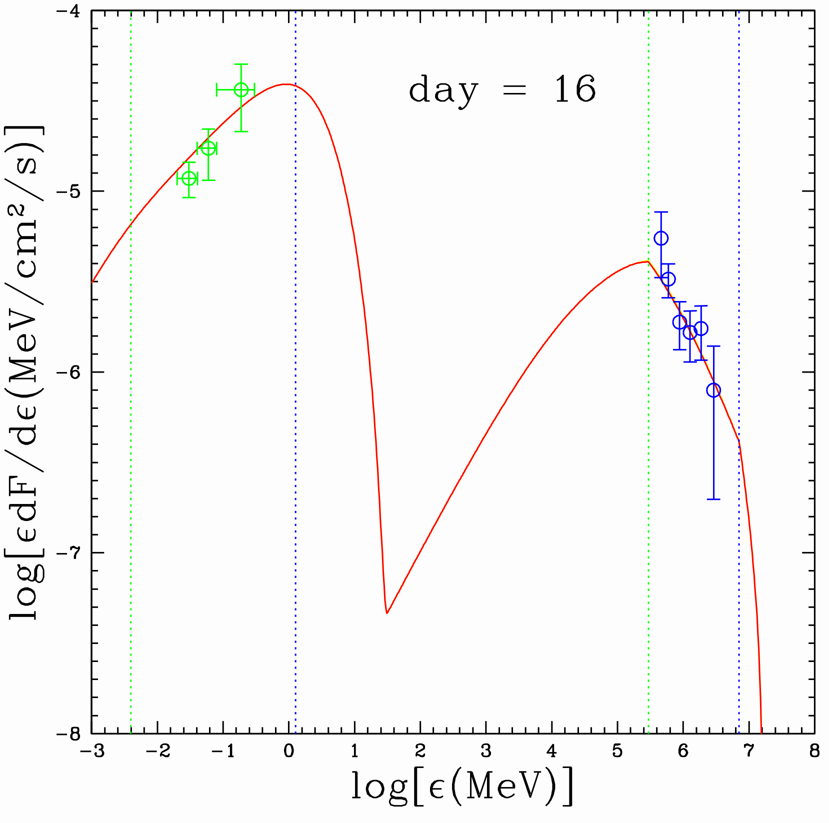

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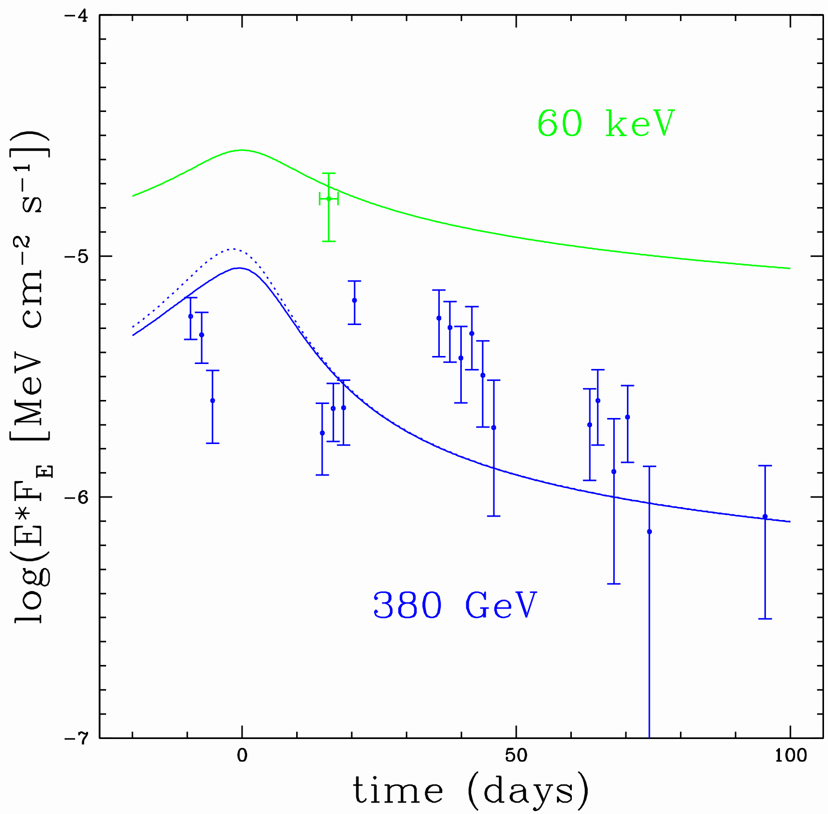

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