Particle acceleration in Poynting-flux dominated outflows

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Relativistic bulk motion

Object	*Evidence*	*Lorentz factor*	*Radiation mechanism*
Radio Galaxies	direct	10	synchrotron
Micro-Quasars	direct	3	synchrotron
γ-ray Bursts	indirect	250	synchrotron/IC
γ-ray Blazars	indirect	50	synchrotron/IC
Pulsar Winds	theory	10^5	synchrotron

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Highest energy: relativistic flows with maximal B

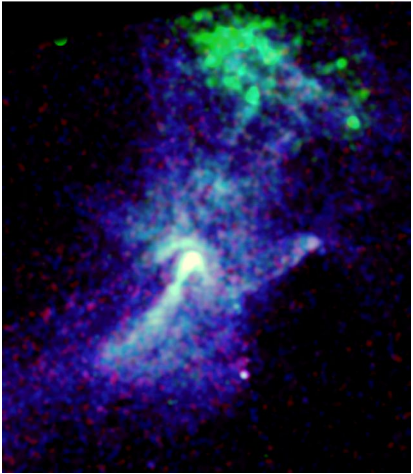
$\Rightarrow$ Low density, *Poynting-flux dominated*

Pulsar Wind Nebulae

> 2000 pulsars, $\sim$ 50 with observed nebulae

Crucial advance:

high resolution images



PSR 1509

Chandra, false colour

(Image: NASA)

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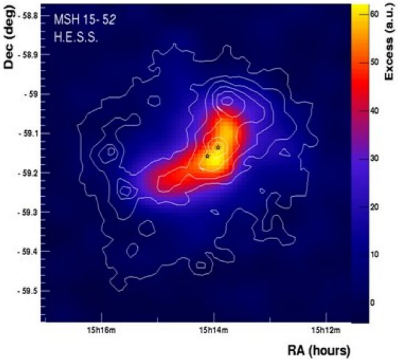
H.E.S.S., TeV gamma-rays

White contours: ROSAT

(0.6–2.1 keV)



$\sim$ 40 PWN are TeV gamma-ray sources (H.E.S.S. A&A '18)

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Crab

optical: red (Hubble ST)

X-ray: blue (Chandra)

(Image: NASA/CXC//SAO)

Outline

- Acceleration in vacuum waves
- Low density “force-free” approximation for steady flows — the *unipolar inductor*
- Mix waves and low density flows — striped winds and *reconnection*
- Lower the density still further — *inductive acceleration*
- Optional extras:
  - application to γ-ray flares from the Crab
  - the importance of proton loading

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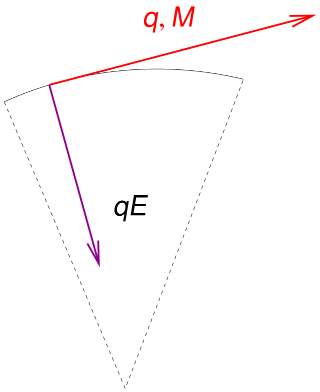
- Staelin & Reifenstein '68: Discovery of the Crab Pulsar.

Plane waves

- Circular polarization
- E and B rotate at angular speed ω, with constant magnitudes and $\vec{E} \perp \vec{B}$.
- If particle moves in a circle, with $\vec{v}$ always parallel to $\vec{B}$:

$$\begin{aligned} \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} &= q\vec{E} \\ \Rightarrow |q|\, E/p &= \omega \\ \Rightarrow \gamma &= \sqrt{1 + a^2} \end{aligned}$$



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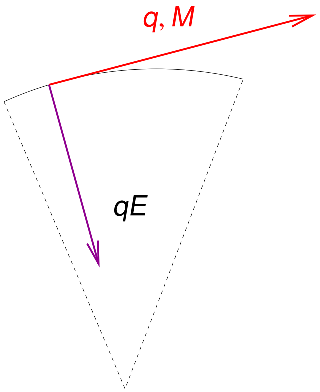

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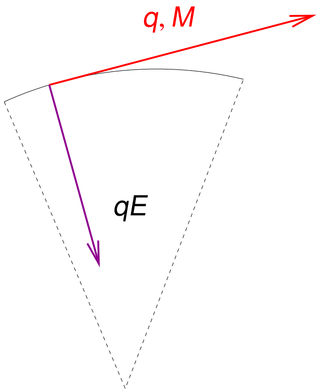

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Radius $= c/\omega = \lambda/2\pi$

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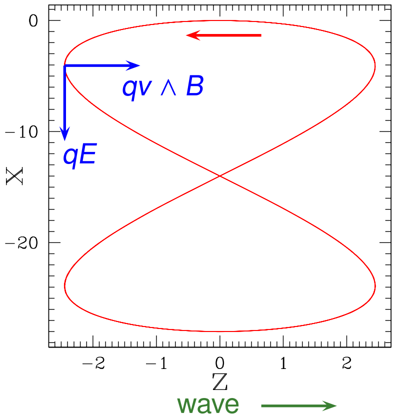

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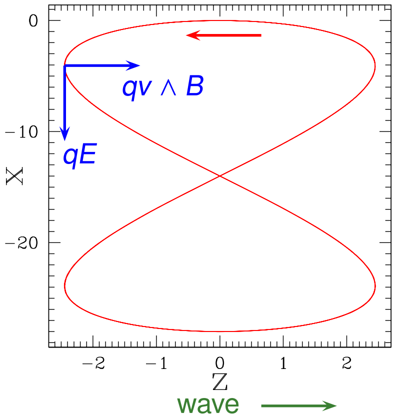

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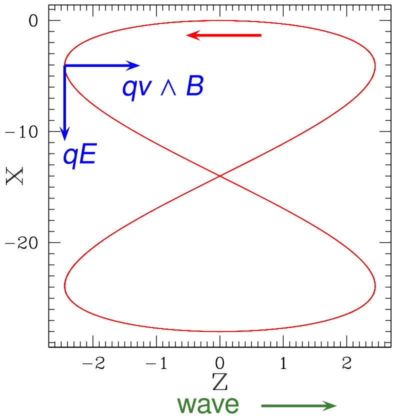

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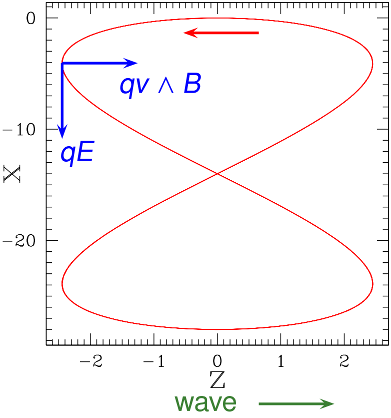

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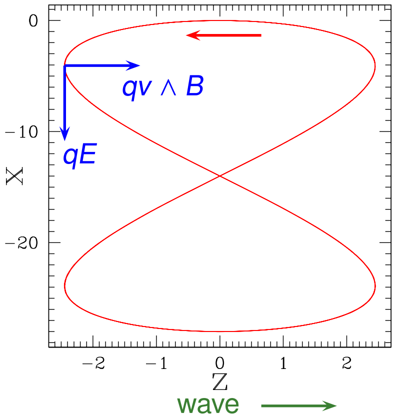

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Note: $a_{\rm Le} = \left[4\pi \left(dL/d\Omega\right) e^2/m^2 c^5\right]^{1/2} = 3.4 \times 10^{10} \left(4\pi L_{38}/\Omega\right)^{1/2}$.

Vacuum waves — summary

- Hillas' limit not reached.
- Energy depends sensitively on launch phase.
- Negligible DC component of magnetic flux ($\propto 1/r^3$)

MHD outflows

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- Solutions can imply unphysical charge carriers

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Supersonic, radial MHD flows have $\gamma =$ constant.

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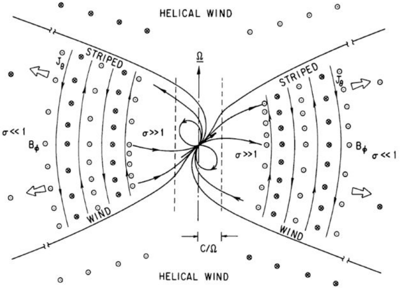
- Con's:
  - Trajectories complicated — unclear what fraction (if any) of injected particles achieve the maximum energy
  - Test-particle treatment: no backreaction on the flow

The striped wind



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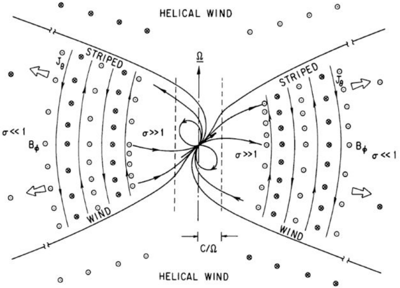

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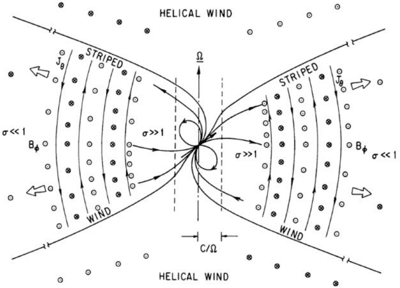

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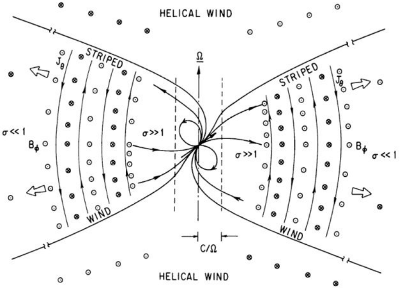

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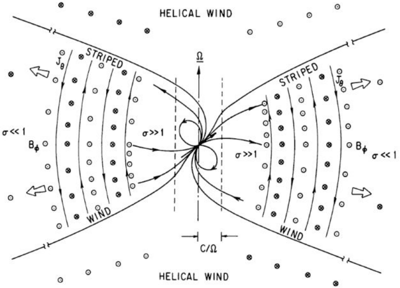
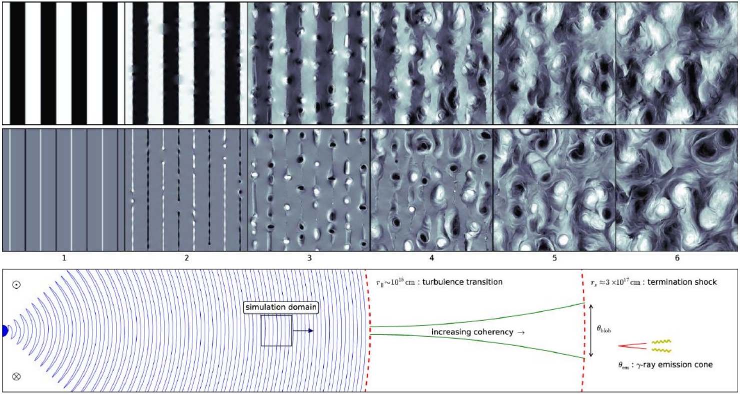


Reconnection in stripes:

- $\Rightarrow$ slow, bulk acceleration
- Fails at $r \approx \kappa_{\rm L}^2 r_{\rm L} < r_{\rm TS}$

Local PIC simulations



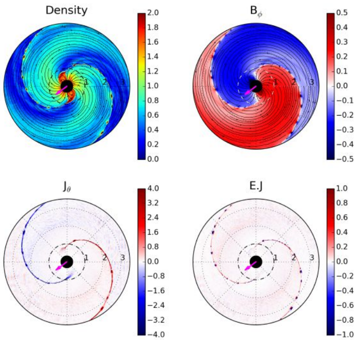
Zrake '16

- Stripes unstable, fully turbulent at TS
- . . . but bulk acceleration not taken into account.

Global PIC simulations

- Striped wind launched by split monopole

Cerutti & Philippov '17



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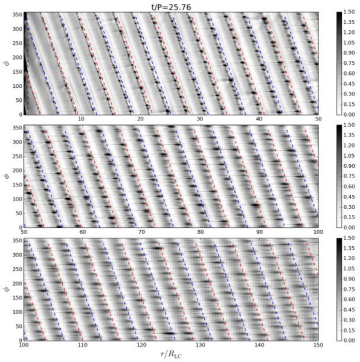

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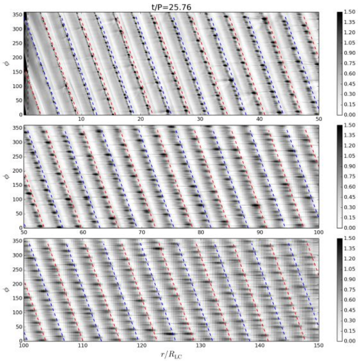
- ...but $a_{\rm L} \sim 100$
- and initial conditions favour dissipation

Cerutti & Philippov '17



Observational constraint

THE ASTROPHYSICAL JOURNAL, 613:L57–L60, 2004 September 20

THE DOUBLE PULSAR SYSTEM J0737−3039: MODULATION OF THE RADIO EMISSION FROM B BY RADIATION FROM A

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"...we conclude that the observed modulation is due to the influence of the 44Hz magnetic dipole radiation on the magnetosphere of B" (located at $r = 1600 r_L$)

Reconnection in the striped wind — summary

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- Hillas' limit not reached: $\gamma_{\mathrm{max}} < a_{\mathrm{L}}^{1/2}$, because the sheet must have time to thermalize.

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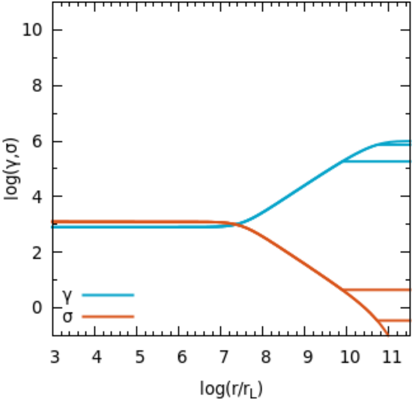

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  3. Coasting, wave fully dissipated

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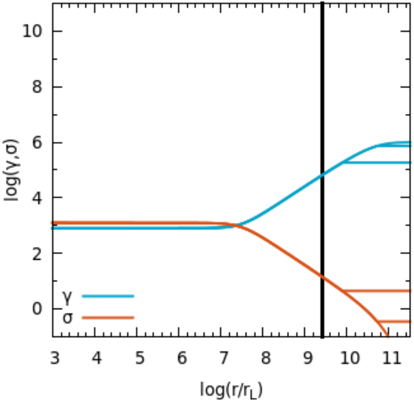

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The Crab Nebula — gamma-ray flares

Three major puzzles:

- Synchrotron emission at 400 MeV
- Variability on timescale of hours
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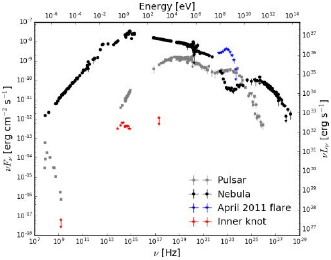

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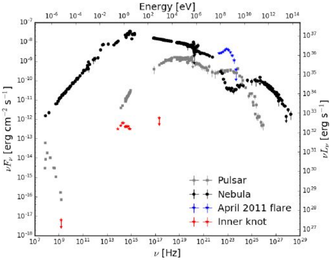

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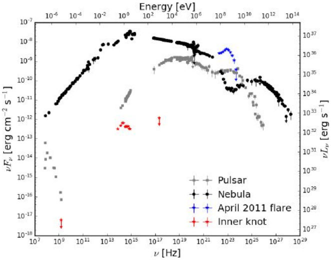

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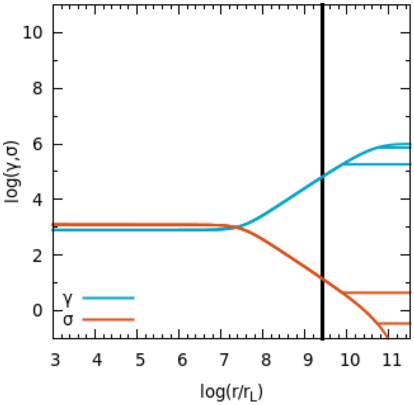
Inductive acceleration JK & Giacinti, PRL '17

Bulk acceleration of the pulsar wind

Inductive acceleration — not complete until $r = a_\mathrm{L} r_\mathrm{L} > r_\mathrm{TS}$

Quiescent Crab parameters:
$a_\mathrm{L} = 7.6 \times 10^{10}$
$\mu = 10^6$, $(\kappa \approx 10^4)$



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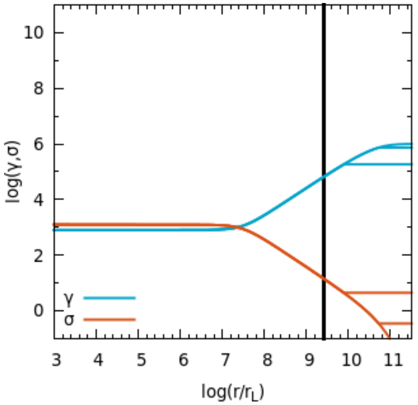

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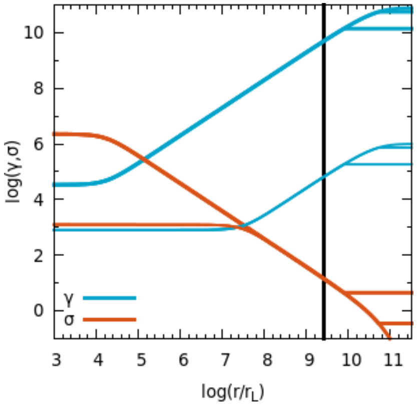

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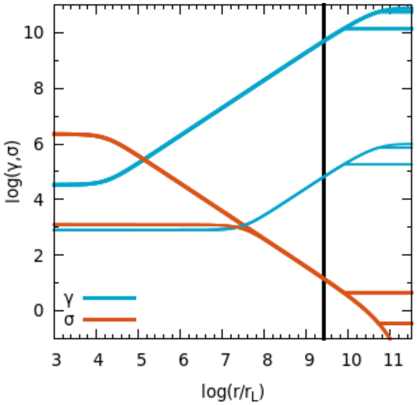
$\Rightarrow$ Injection into the nebula of radially-collimated multi-PeV electron/positron beams



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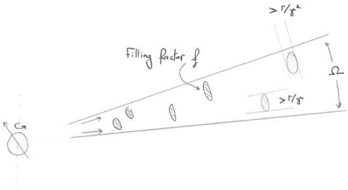

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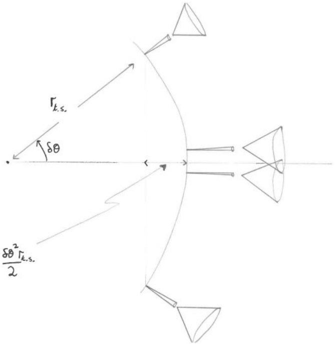

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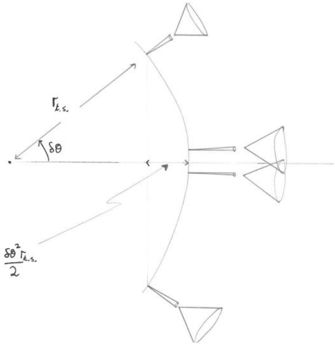

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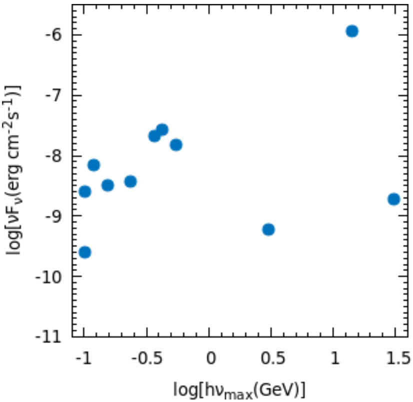

Known pulsars
(Filling factor $f = 1$)

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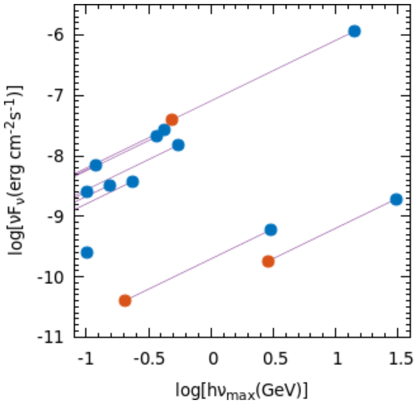

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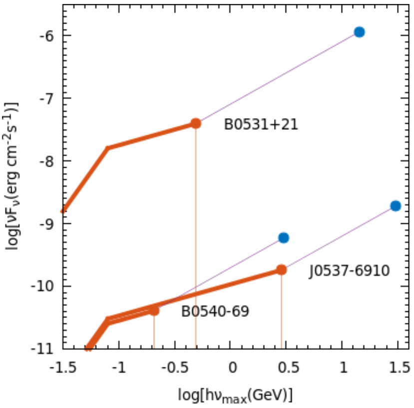

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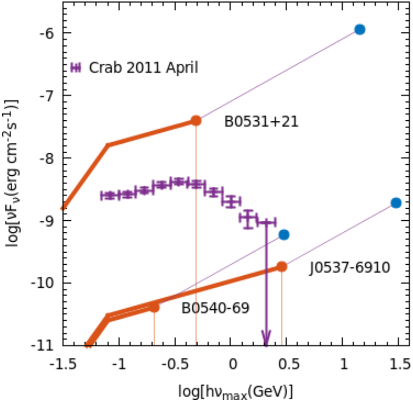

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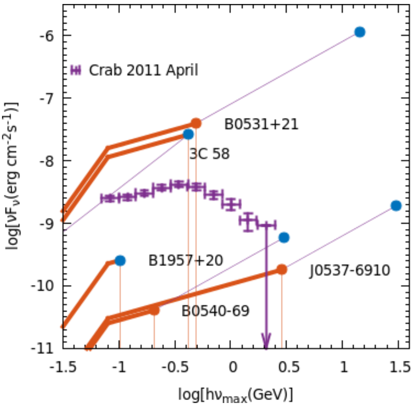

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- Similar flares from J0537−6910, B0540−69, 3C 58, Black Widow. . . ?

Adding some spice. . .

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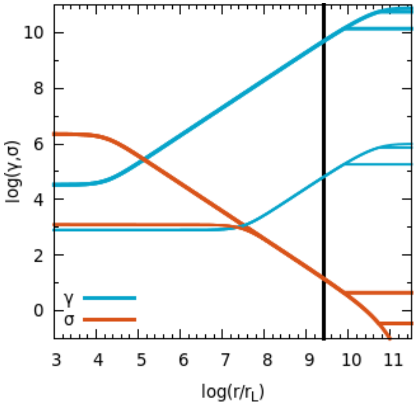

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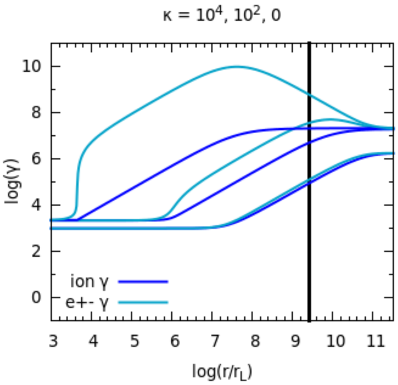

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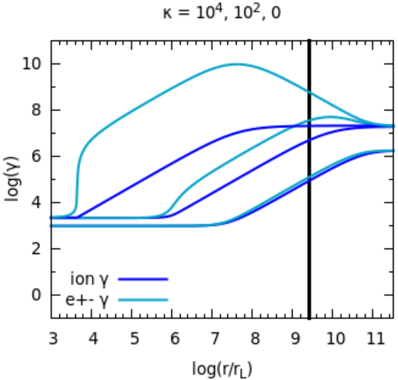

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- Set $\kappa_{\mathrm{L,p}} = 1$
- Lepton dominated: no change (Hillas' limit not reached)
- Proton dominated:
  - Rapid lepton acceleration
  - For $\kappa_{\mathrm{L,e}} = 1$, Hillas' limit reached by protons *and* leptons
  - Heavy particles speed up acceleration