‘Crab Flare’-Like Phenomena in other PWNe

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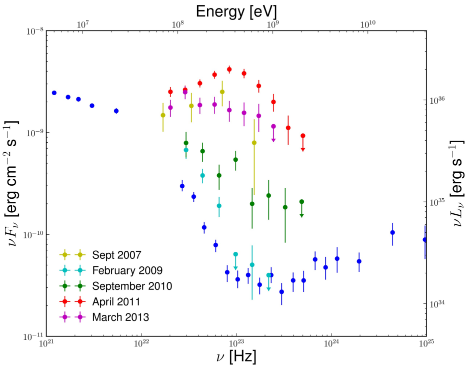
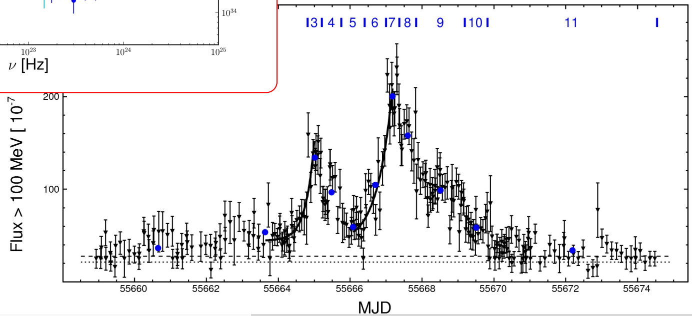
Crab Flares *(talk by Edoardo Striani for a review)*

Bühler+2012

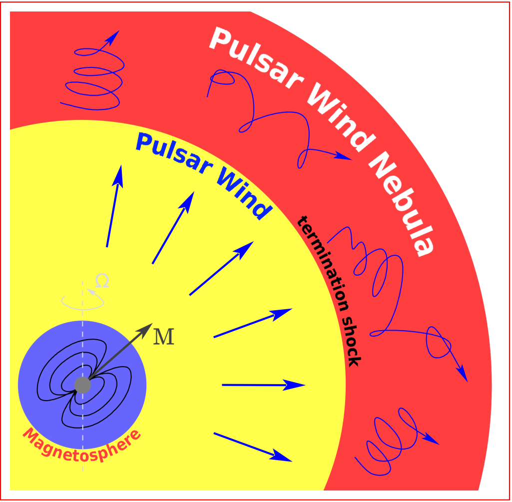


$E_{\rm br} > 300\,{\rm MeV}$

Variability time: $t_{\rm var} \sim 12\,{\rm h}$



MHD View



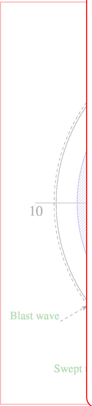
Basic Equations

$$\frac{d}{dr}(nur^2) = 0$$
$$\frac{d}{dr}\left(\frac{urB}{\gamma}\right) = 0$$
$$\frac{d}{dr}(ur^2 ne) + P\frac{d}{dr}(r^2 u) = 0$$
$$\frac{d}{dr}\left[nur^2\left(\gamma\mu + \frac{B^2}{4\pi n\gamma}\right)\right] = 0$$

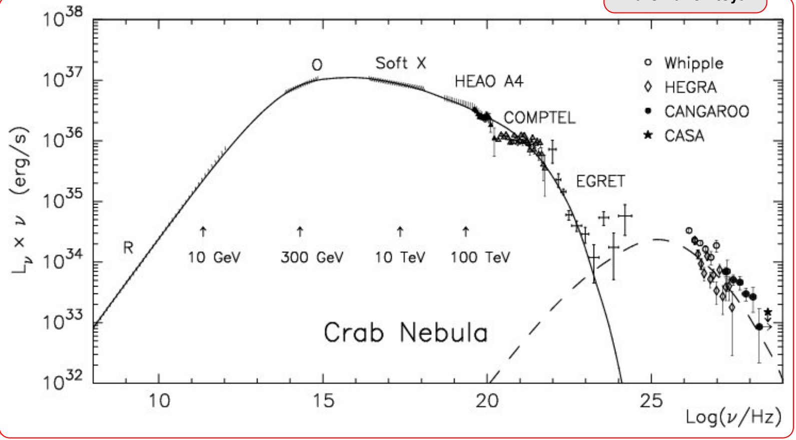
Wind as Boundary Condition:

$$L_{\rm wind} = \dot{N}_{\rm e} m_{\rm e} c^2 \Gamma + 4\pi R_{\rm sh}^2 \frac{cB_{\rm wind}^2}{4\pi} + \dot{N}_{\rm i} m_{\rm i} c^2 \Gamma$$

MHD View



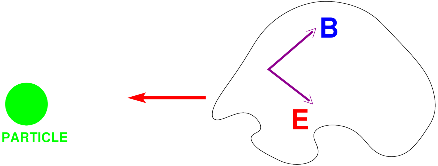
Aharonian&Atoyan



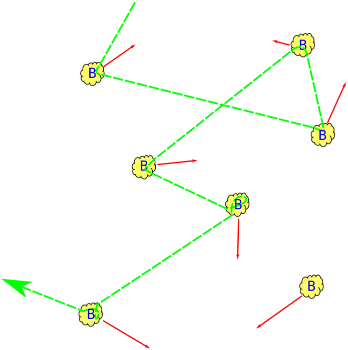
A VERY successful model for SED....

Particle Acceleration in the MHD Regime

- If particle collides head-on it gains energy
- If collision occurs with velocities parallel it loses energy
- $\nu = v_{\rm rel}\sigma n_1 n_2$, so particle gains energy with higher rate



Does it always proceeds in MHD regime?



Enrico Fermi's wandering magnetic clouds as CR accelerators

Synchrotron Test for MHD Regime

MHD regime implies that

$$\mathcal{E} = B/\eta \qquad \eta > 1$$

Acceleration Time: $E/e\mathcal{E}$

$$t_{\rm acc} = \eta\frac{r_{\rm g}}{c} = 0.1\eta E_{\rm TeV} B_{\rm G}^{-1}{\rm s}$$

Synchrotron Cooling Time

$$t_{\rm syn} \approx 400 E_{\rm TeV}^{-1} B_{\rm G}^{-2}{\rm s}$$

Synchrotron Self Cutoff (e.g., Derishev+2003)

$$\epsilon = 1.15\hbar\omega_{\rm c} \approx 300\eta^{-1}{\rm MeV}$$

Synchrotron Test for MHD Regime

MHD regime implies that

Shock acceleration: $\eta = 2\pi \left(\frac{c}{v_{sh}}\right)^2$

Acceleration Time: $E/e\mathcal{E}$

$$t_{acc} = \eta \frac{r_g}{c} = 0.1 \eta E_{TeV} B_G^{-1} s$$

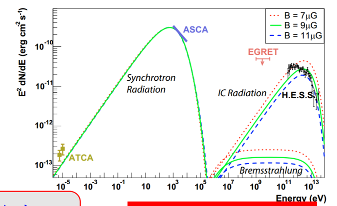
$E_{br} \sim 1\,keV$, i.e. $\eta \sim 10^5$ ($v_{sh} \sim 10^3\,km/s$)

$$t_{syn} \approx 400 E_{TeV}^{-1} B_G^{-2} s$$

Synchrotron Self Cutoff (e.g., Derishev+2003)

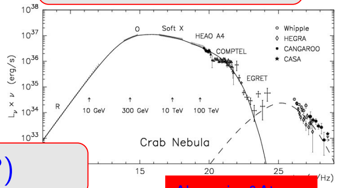
$$\epsilon = 1.15 \hbar\omega_c \approx 300\eta^{-1} MeV$$

$E_{br} \sim 10^{21-22} Hz$, i.e. $\eta \sim 2\pi$ ($v_{sh} \to c$?)



RX J1713.7 Aharonian+

PWN: $\eta \to 1(?)$



Aharonian&Atoyan

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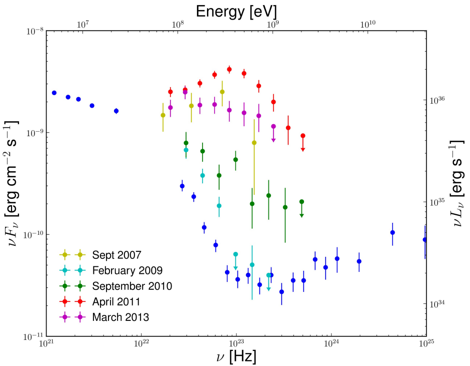

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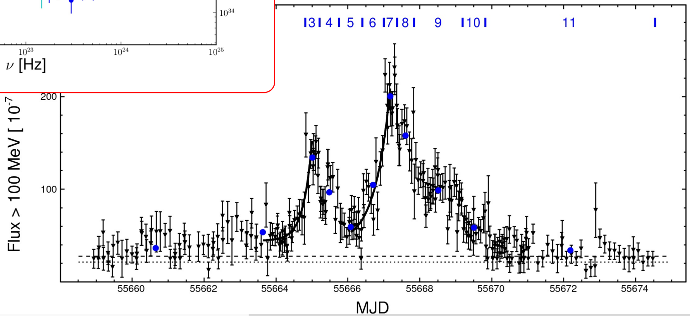

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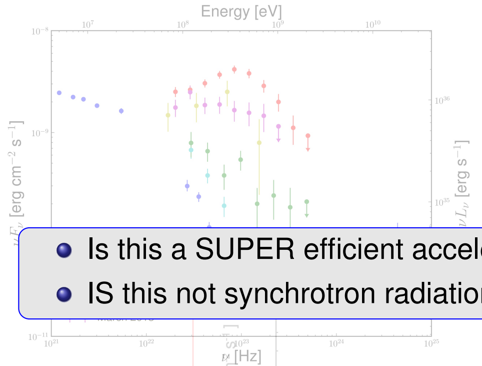
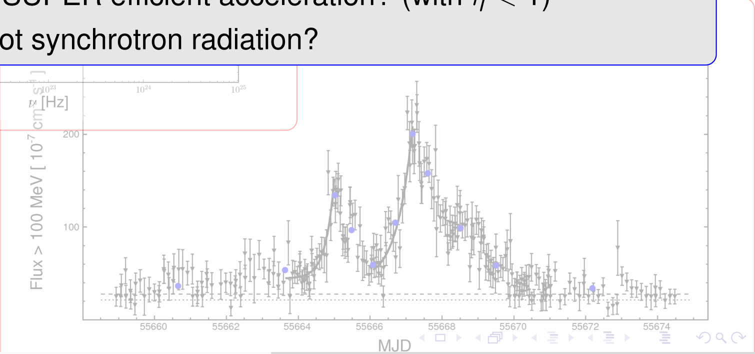
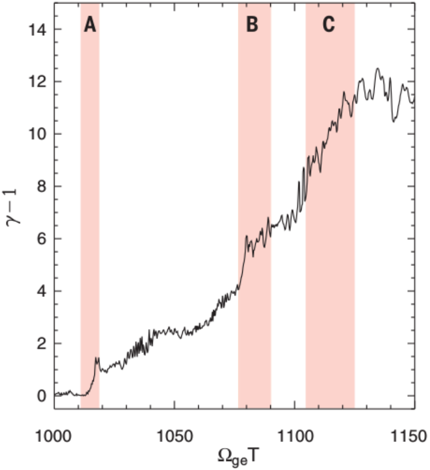


$E_{br} > 300\,\mathrm{MeV}$

Variability time: $t_{var} \sim 12\,\mathrm{h}$

- Is this a SUPER efficient acceleration? (with $\eta < 1$)
- IS this not synchrotron radiation?





Matsumoto+ 2015

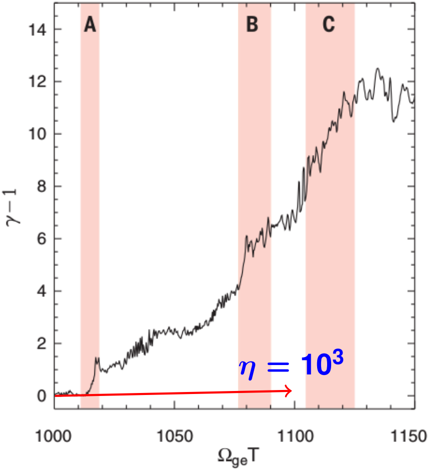
Gyro freq. is $\Omega_{ge} = \frac{eB}{mc}$, so

$$\Omega_{ge} T = \gamma T / t_{acc}$$

$$\frac{d\gamma}{d(\Omega_{ge} T)} = \eta^{-1}$$

Different acceleration regimes

- DSA ($v = 0.1c$)$\rightarrow \eta = 10^3$
- Crab Nebula $\rightarrow \eta = 10$
- Can it be even more efficient? $\eta \rightarrow 1$



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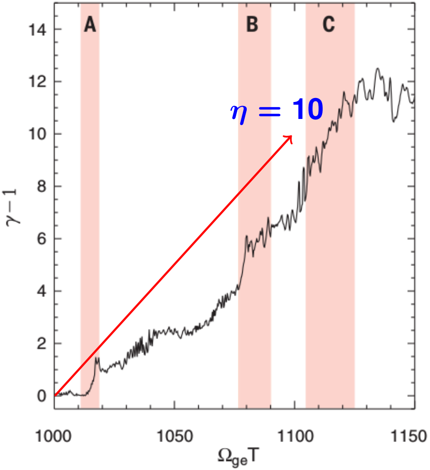
Non-MHD Particle Acceleration in Astrophysics: Reconnection



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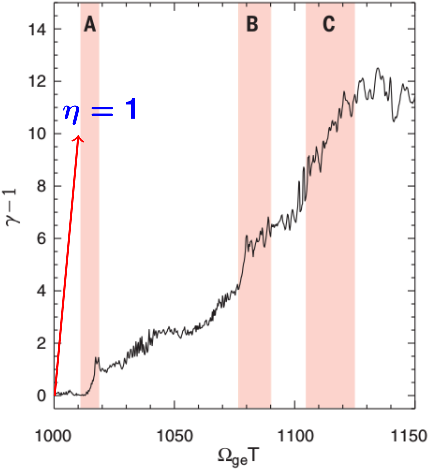

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Different acceleration regimes

- DSA ($v = 0.1c$)$\to$ $\eta = 10^3$
- Crab Nebula $\to$ $\eta = 10$
- Can it be even more efficient? $\eta \to 1$

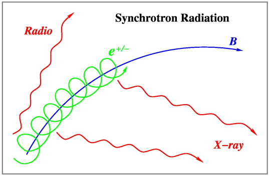
Synchrotron Radiation

- Single Particle Spectrum:

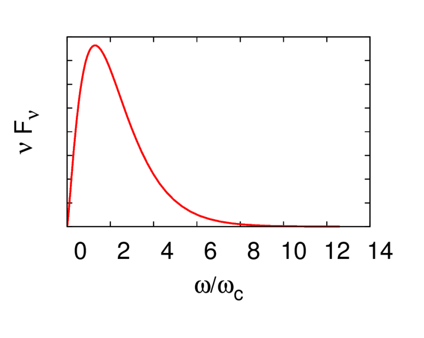
$$\frac{\mathrm{d}I_{\mathrm{syn}}}{\mathrm{d}\omega} = \frac{\sqrt{3}}{2\pi}\frac{e^3 B}{mc^2} F\left(\frac{\omega}{\omega_{\mathrm{c}}}\right)$$

where $\omega_{\mathrm{c}} = \frac{3eB\gamma^2}{2mc}$ and $F(x) = x \int\limits_x^\infty K_{5/3}(x')\mathrm{d}x'$

- Energy Losses: $\dot{E}_{\mathrm{syn}} = -\frac{4}{3} U_{\mathrm{B}} c\gamma^2$



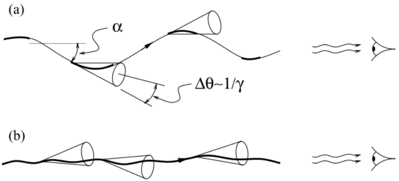
Synchrotron radiation is a precisely described radiation process. This concerns however only the case of homogeneous magnetic field...



Radiation in Turbulent Fields

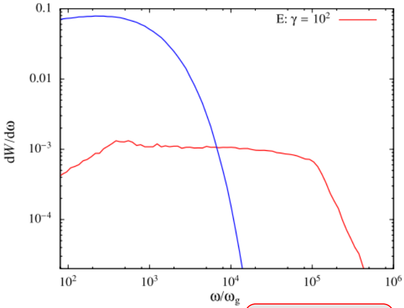
- Study of emission in turbulent media has a long history (e.g., Gatmantsev1973, Tsytovich&Kaplan1973, Chiuderi&Veltri1974)
- There are two basic approaches: perturbation theory and full description of trajectories (via kinetic equation or numerically)

credit Medvedev2000



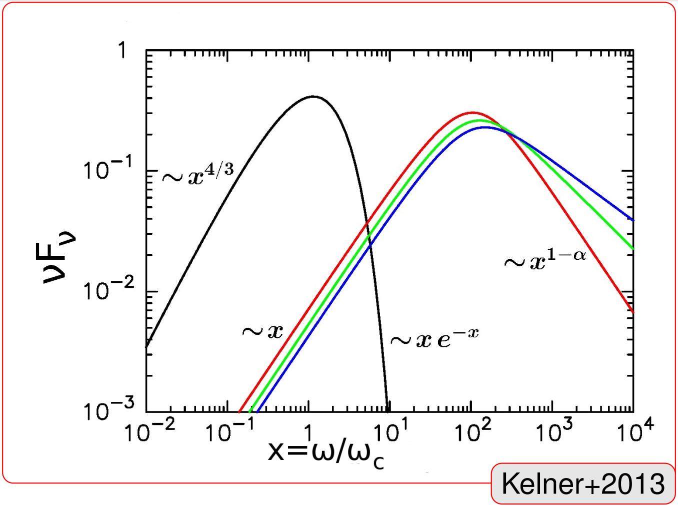
$$\frac{dW}{d\omega} = \frac{e^2\omega}{2\pi c^3}\int_{\omega/2\gamma^2}^{\infty}\frac{|w_{\omega'}|^2}{\omega'^2}\left(1-\frac{\omega}{\omega'\gamma^2}+\frac{\omega^2}{2\omega'^2\gamma^4}\right)d\omega'$$

$$\frac{\partial W}{\partial t} + \mathbf{v}\frac{\partial W}{\partial \mathbf{r}} - (\mathbf{\Omega}\,\mathcal{O})W + e\mathbf{E}\frac{\partial W}{\partial \mathbf{p}} = \int_0^\infty \mathrm{d}\tau\left\{\left(\frac{ec}{\mathcal{E}}\right)^2 \mathcal{O}_\alpha T_{\alpha\beta}(\Delta\mathbf{r}(\tau),\tau)\,\mathcal{O}_\beta + e^2\frac{\partial}{\partial p_\alpha}K_{\alpha\beta}(\Delta\mathbf{r}(\tau),\tau)\frac{\partial}{\partial p_\beta} - \frac{e^2c}{\mathcal{E}}\left(\mathcal{O}_\beta S_{\alpha\beta}\frac{\partial}{\partial p_\alpha} + \frac{\partial}{\partial p_\alpha}S_{\alpha\beta}\mathcal{O}_\beta\right)\right\} W(\mathbf{r}-\Delta\mathbf{r}(\tau),\mathbf{p}-\Delta\mathbf{p}(\tau),t-\tau)\,.$$



Reville&Kirk2010

Synchrotron v.s. Jitter Emission Spectra



- low energy part
  $x^{4/3} \to x$
- maximum
  $\omega_c \to \frac{mc^2\omega_c}{eB\lambda}$
- high energy part
  $xe^{-x} \to x^{1-\alpha}$,
  where $\Psi \propto q^{-2-\alpha}$ for $q \gg 1$

Synchrotron v.s. Jitter Emission Spectra

- Photon formation length
  $$\lambda_{\rm ph} = \frac{mc^2}{eB}$$
- Shortest wavelength due to Landau damping
  $$\lambda_{\rm min} = \sqrt{\frac{\bar\epsilon}{4\pi e^2 n}}$$
- Shift of the emission peak is determined by their ratio:
  $$\frac{\lambda_{\rm ph}}{\lambda_{\rm min}} = \frac{mc^2}{\bar\epsilon}\sqrt{\frac{\bar\epsilon n 4\pi}{B^2}} = \frac{1}{\Gamma\sigma_n} \ll 1$$

I.e., jitter regime hardly can be activated in PWNe, thus one needs either Doppler boosting, or extreme acceleration to explain Crab Flares. But an interesting question if these phenomena also occurs in other PWNe

$x=\omega/\omega_c$

Kelner+2013

- low energy part
  $x^{4/3} \rightarrow x$
- maximum
  $\omega_c \rightarrow \frac{mc^2\omega_c}{eB\lambda}$
- high energy part
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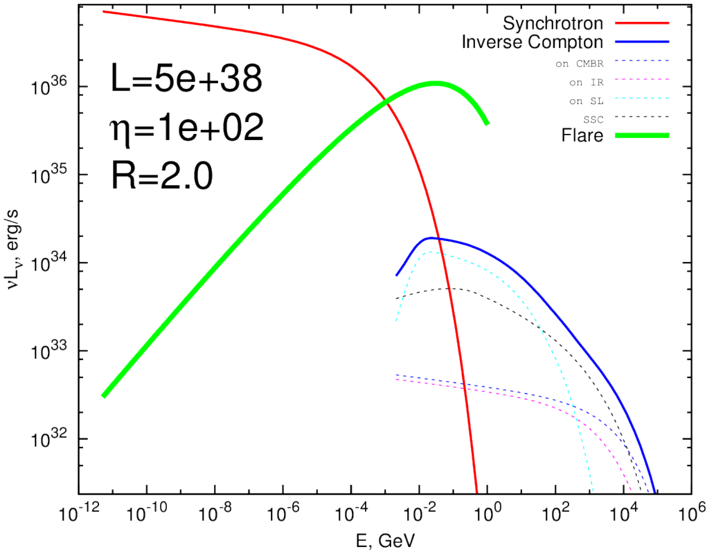
Is Crab a unique flaring PWN?

- Spindown luminosity of the Crab pulsar, $\sim 4 \times 10^{38}\mathrm{erg/s}$, is one of the highest of the known to date, but...
- This is not the highest...
- This is not the brightest pulsar $L_{\mathrm{sd}}/(4\pi D^2)$...
- Can we see similar phenomena from other PWNe?
- HOW SHOULD THIS PHENOMENA MANIFEST IT-SELF IN OTHER PWN?

Possible Flares in other PWNe



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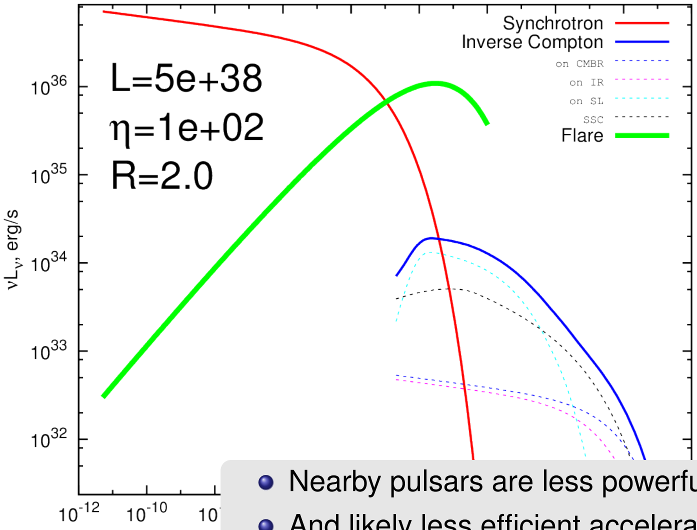
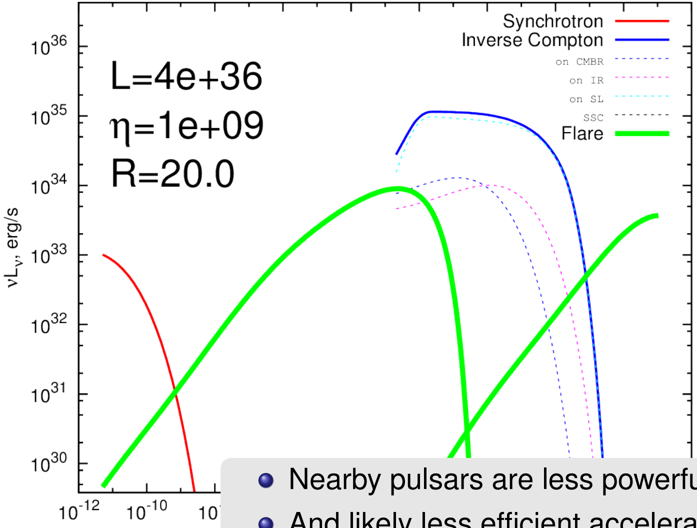


- Nearby pulsars are less powerful (L)
- And likely less efficient accelerators (η)
- Often more extended (R)

Possible Flares in other PWNe



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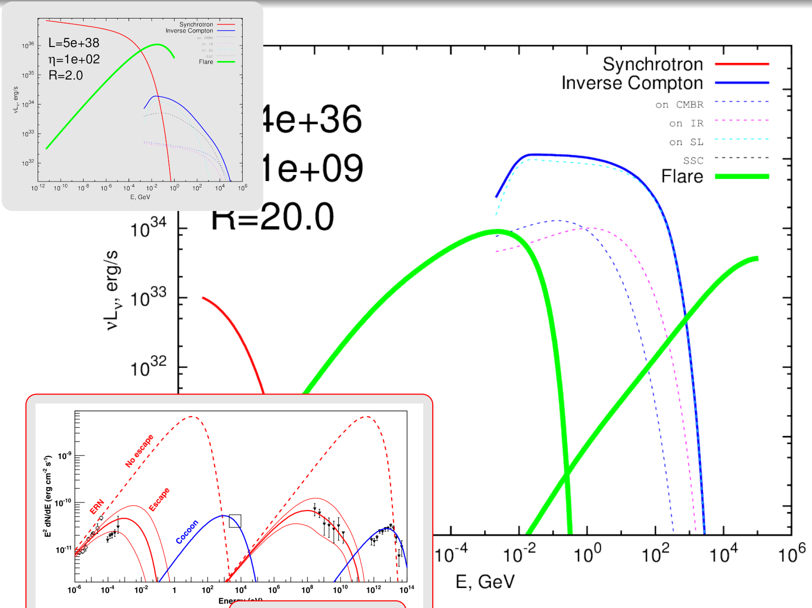
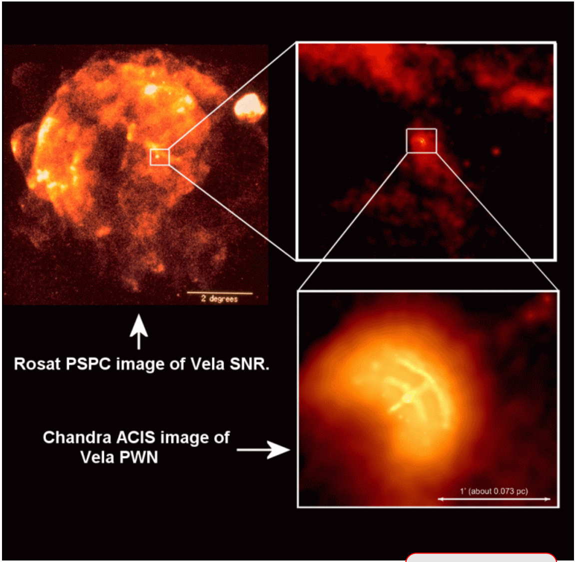
Possible Flares in other PWNe



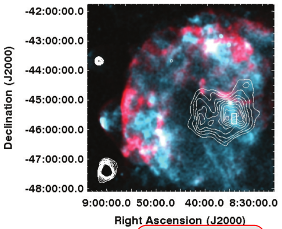
Vela X PWN (Hinton+)

Vela SNR



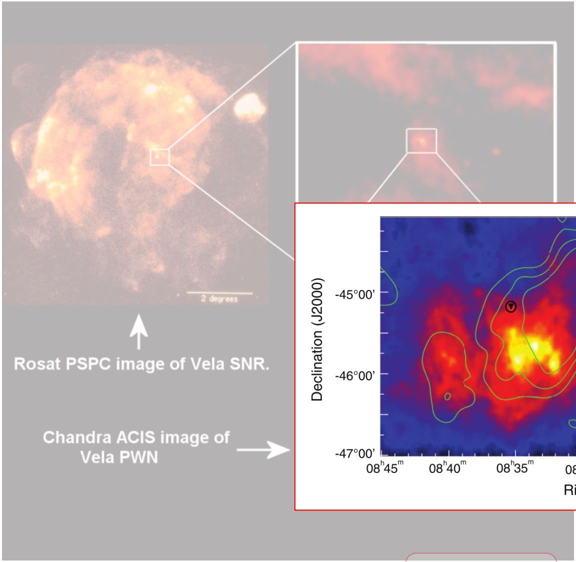
from O. Kargaltsev

- Distance $\sim$ 290 pc
- Size: 8° ($\sim$ 40 pc)
- τ: $\sim$ 11 kyr
- SD: $\sim 7 \times 10^{36}\,\mathrm{erg\,s^{-1}}$



LaMassa+2008

Vela SNR



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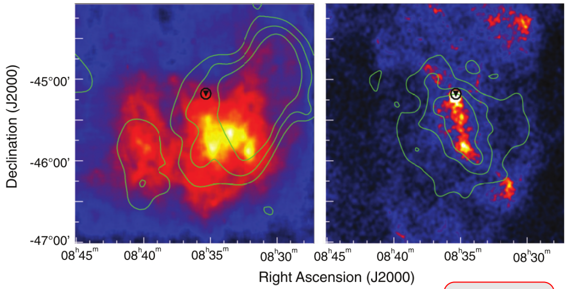
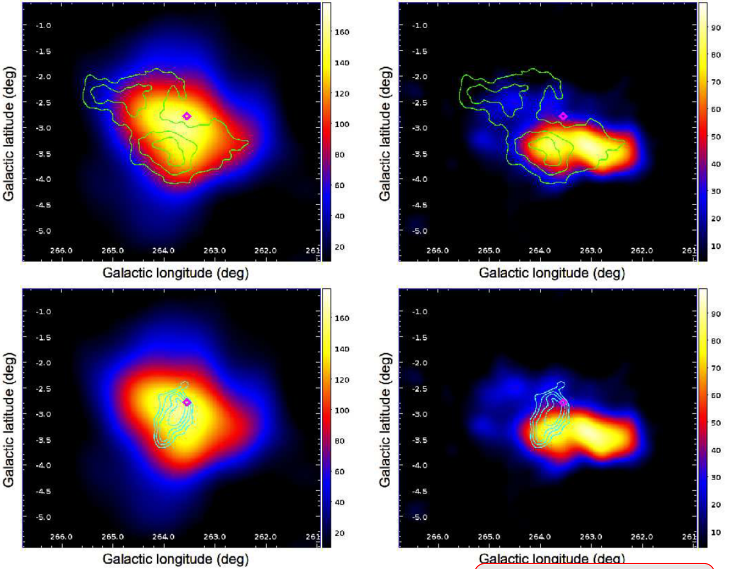


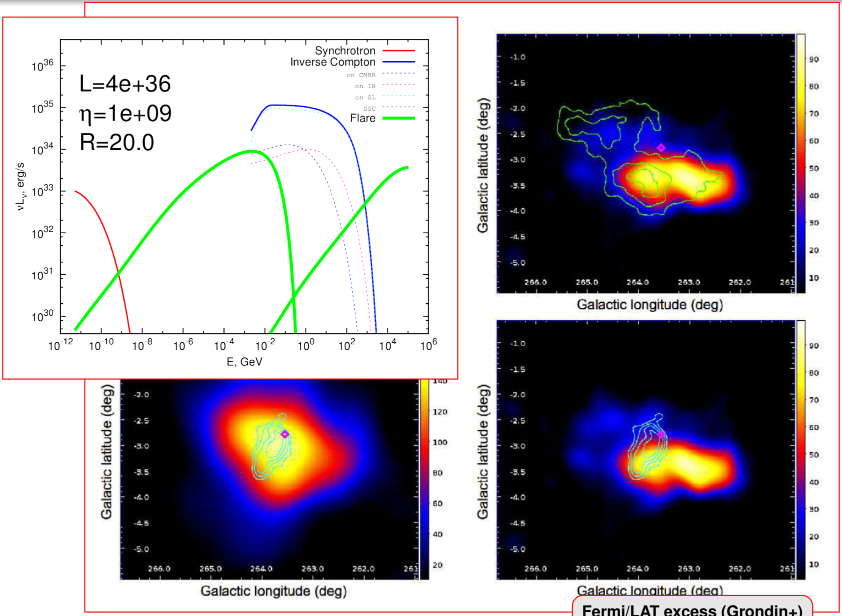
Hinton+2011

Vela X Pulsar Wind Nebula



Fermi/LAT excess (Grondin+)

Vela X Pulsar Wind Nebula



Fermi/LAT excess (Grondin+)

What is the Cocoon?

Inhomogeneous interstellar medium? Possibly, if crushed PWN...

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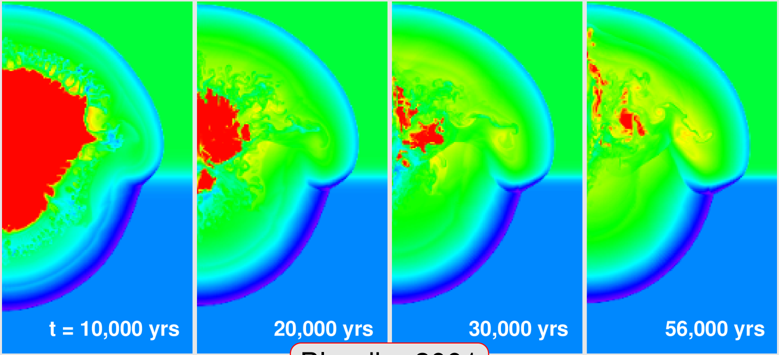
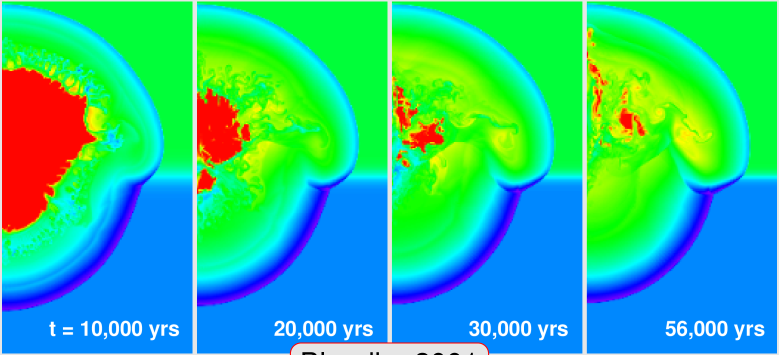


Blondin+2001

What is the Cocoon?

Inhomogeneous interstellar medium? Possibly, if crushed PWN...



Blondin+2001

Cocoon gets disconnected from the PSR$\sim$ **20 kyr**, how relevant is cooling? $t_{\rm syn}\left(E_{\to 60{\rm TeV}}\right) \simeq 2\times 10^3 B_{5\mu G}^{-3/2}\ {\rm yr}$

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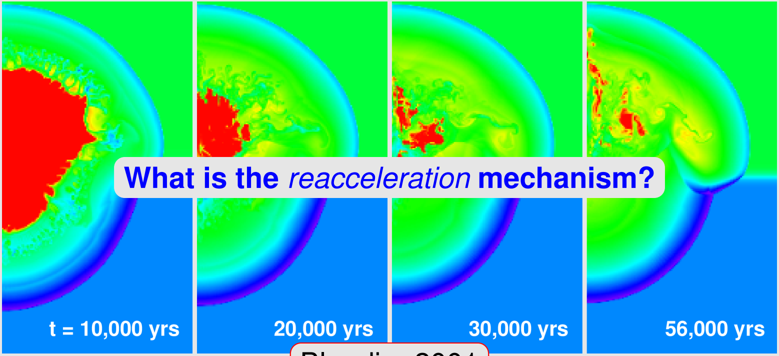

What is the *reacceleration* mechanism?

Blondin+2001

Cocoon gets disconnected from the PSR$\sim$ **20 kyr**, how relevant is cooling? $t_{\rm syn}\left(E_{\to 60{\rm TeV}}\right) \simeq 2\times 10^3 B_{5\mu G}^{-3/2}\ {\rm yr}$

- Is that energetically possible? $w_{\rm b} > w_{\rm e}$
  - Energy density in magnetic field

$$w_{\rm b} = 10^{-12} B_{5\mu G}^2 \,{\rm erg\,cm^{-3}}$$

  - Energy density in relativistic electrons

$$w_{\rm e} = \frac{E_{\rm e}}{V} = \frac{L_{\rm VHE} t_{ic}}{V} \sim 4 \times 10^{-13} {\rm erg\,cm^{-3}}$$

- This is however only necessary condition, not sufficient (what is the time-scale?)
  - Require two fluid/PIC simulation for confirmation
  - Theoretical models are also needed

Crab Flare vs Cocoon in Vela X PWN

Crab Flares

- Energetic: $\sim$ 1% of SD
- Spectral slope: $\Gamma < 1.5$
  not a robust conclusion
- Non-MHD:
  max energy arguments
- Broadband spectrum: unknown
- Morphology: unresolved

Vela X Cocoon

- Energetic: $\sim$ 5% of SD
- Spectral slope: $\Gamma < 1.5$
  measured
- Non-MHD:
  particle re-acceleration(!)
- Broadband spectrum: measured
- Morphology: X-ray and TeV

Conclusion

- Phenomena responsible for the Crab Flares may have rather different manifestation in other PWNe.
- Vela X PWN represents possibly the best extended PWN to search for analogy of Crab Flares
- Gamma-ray observations of the Vela X PWN allowed to determine the distribution of VHE electrons
- VHE (CTA) – X-ray observation allow to recover the spatial and energy distributions of the particles and B-field