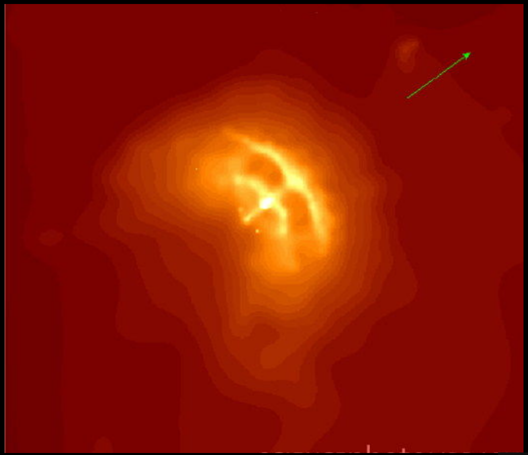
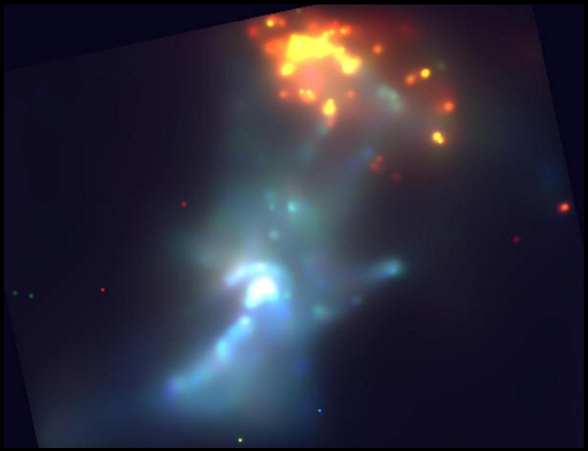
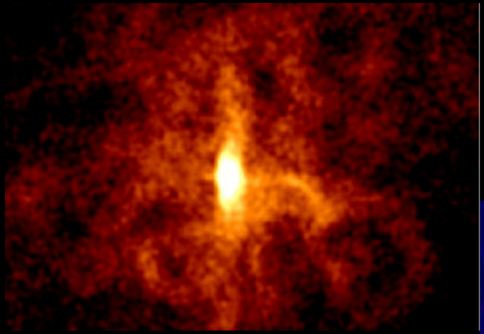
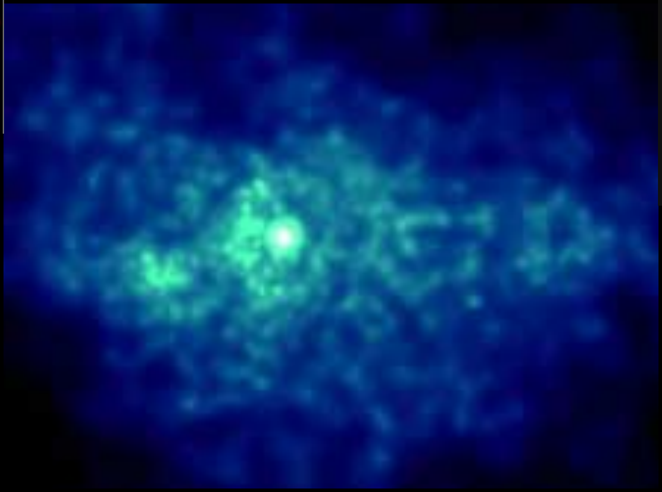
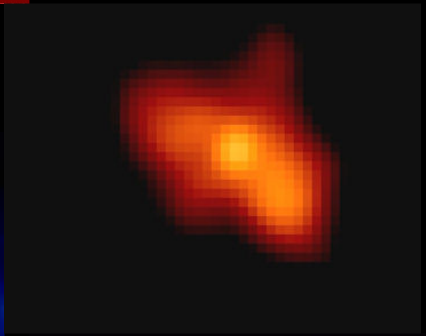
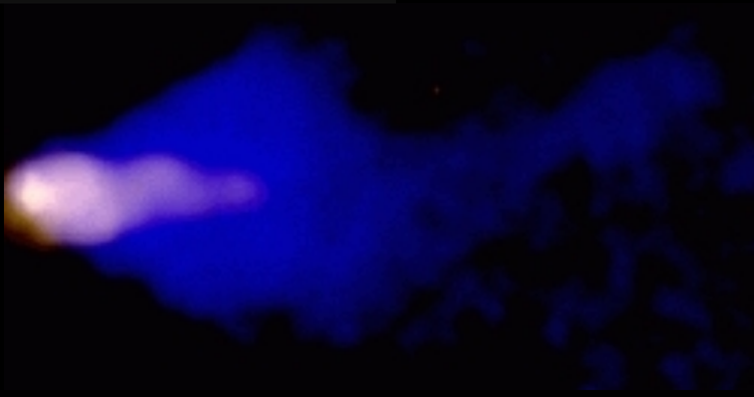
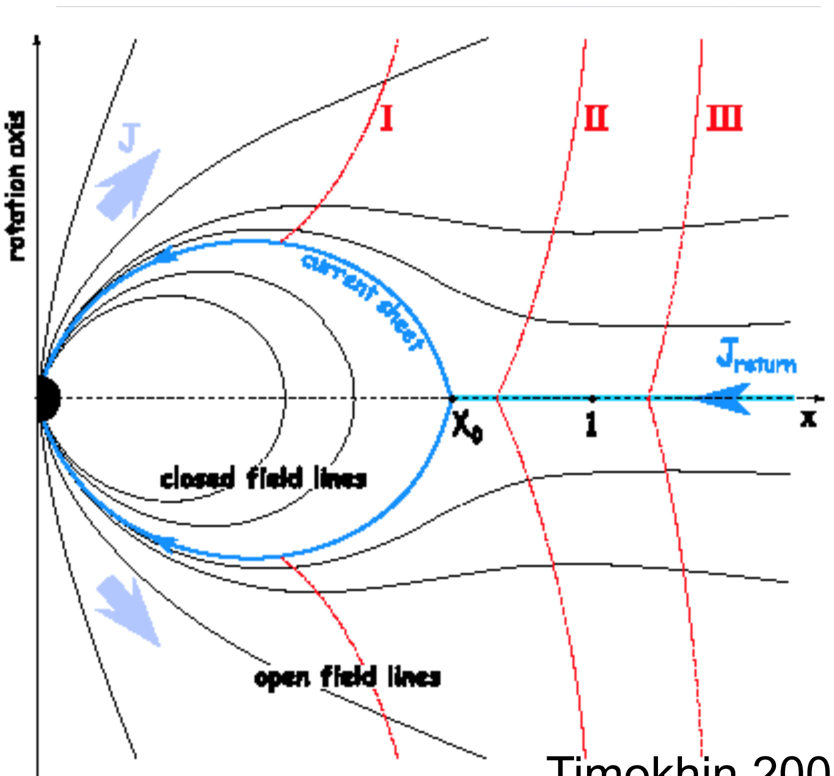
Crab Flares and Magnetic Reconnection in Pulsar Wind Nebulae

Alice K. Harding (NASA/GSFC) and the *Fermi* LAT collaboration

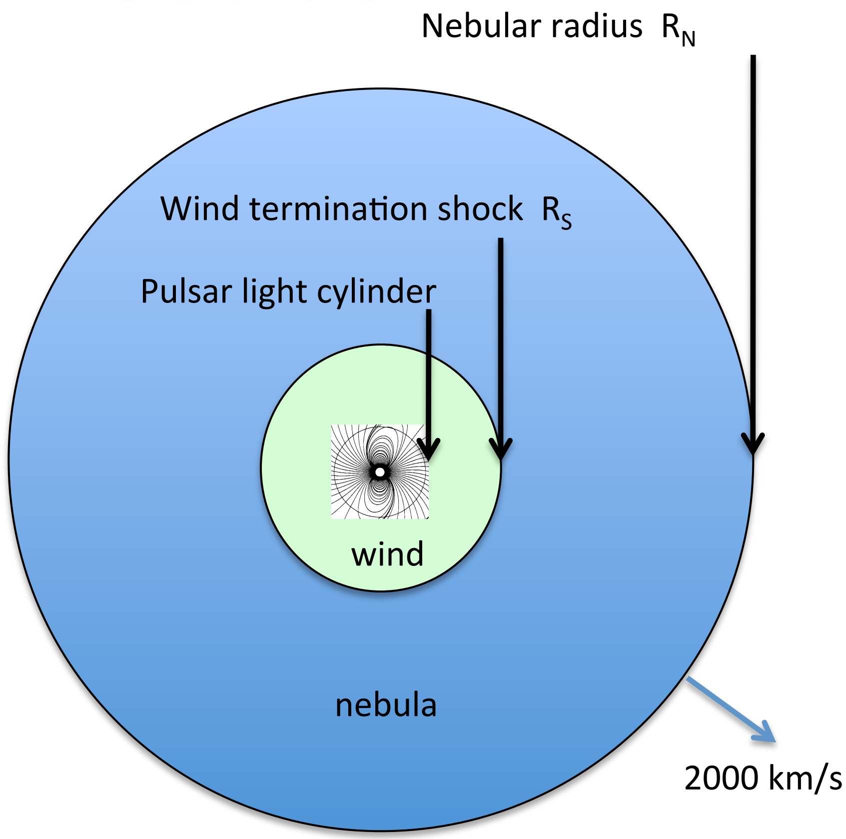
Pulsar Wind Nebulae

Pulsar Wind Nebulae



Timokhin 2007



- Remnant from 1054 AD supernova at 2 kpc

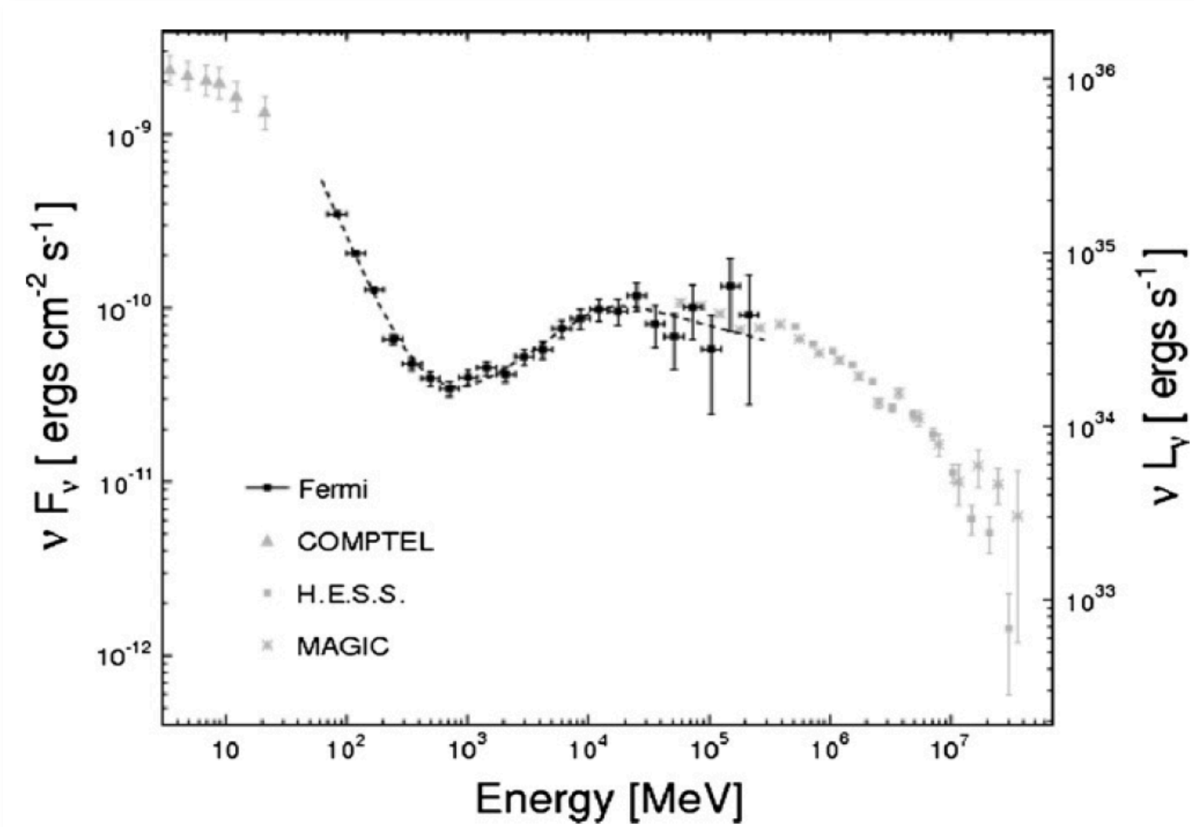
- Standard reference in X-rays and VHE gamma rays

Termination shock radius

$$\frac{\dot{E}_{sd}}{4\pi c R_S^2} \approx \frac{\dot{E}_{sd}\tau}{\frac{4}{3}\pi R_N^3} \Rightarrow R_S \approx 3\times 10^{17}\,cm$$

Rees & Gunn (1974)

Crab nebula spectrum

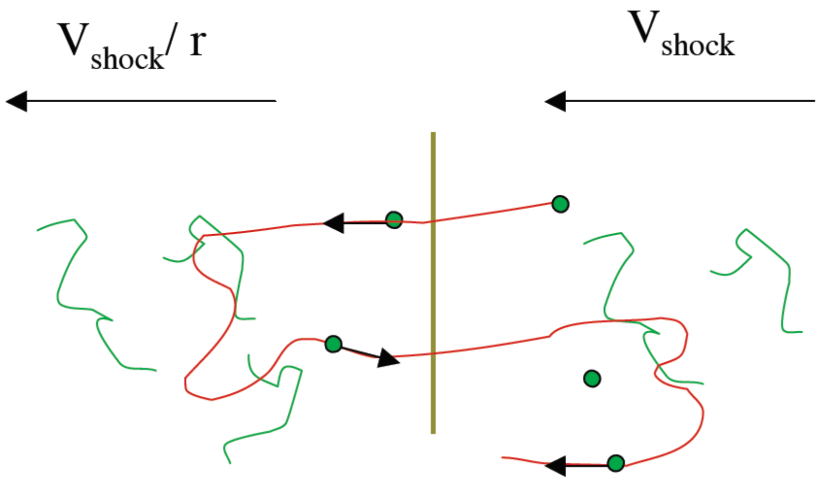


- Well described by synchrotron self-Compton model (Gould 1965)
- Cutoff in high-energy synchrotron component (~ 100 MeV) requires electrons with ~ 2 x 10^{15} eV (DeJager & Harding 1992) – synchrotron loss timescale ~ weeks
- Voltage across open field lines ~ 3 x 10^{16} eV
- Nebula could be variable ~ 1-100 MeV (DeJager et al. 1996, Munch et al. 1995)

Traditional acceleration models

- Diffusive acceleration (1st order Fermi) at termination shock
  (Fermi 1949, Blandford & Ostriker 1978, Eichler 1979)
  - Problem: Crab TS is relativistic and has B nearly perpendicular to flow

  → *superluminal*



- Resonant absorption of ion-cyclotron waves (Hoshino, Arons, Gallant & Langdon 1992)
  - Problem: requires most of spin-down energy in ions upstream of shock

Limitations of traditional models

- No diffusive acceleration at superluminal shocks – not enough turbulence to scatter particles upstream (Sironi & Spitkovsky 2009)
- "Sigma problem" – need wind to be particle-dominated upstream: low σ (Kennel & Coroniti 1984)

$$\sigma = \frac{U_B}{U_p}$$

but wind has high σ near pulsar. How and where does energy get transferred from fields to particles??

- Maximum SR energy from acceleration (E < B) limited by synchrotron losses

(Guilbert et al. 1983, deJager et al. 1996):

$$\dot{\gamma}_{syn}(\gamma_{\max}) = \dot{\gamma}_{acc}(\gamma_{\max})$$

$$\gamma_{\max} \propto B^{-1/2}$$

$$E_{syn}^{\max} = \frac{3}{2}\gamma^2 B \approx \frac{9}{4}\frac{mc^2}{\alpha} \cong 160\,MeV$$

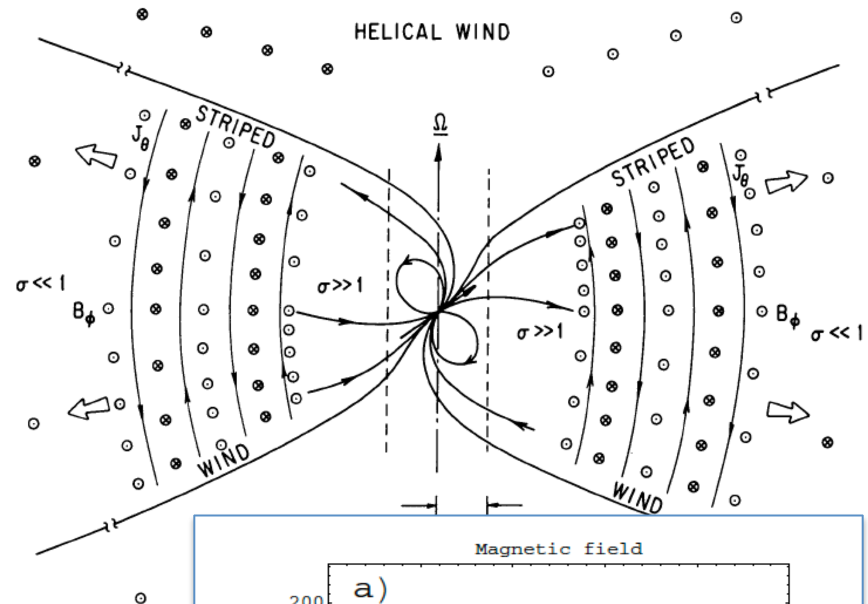
Reconnection in PWNe

- Reconnection in striped wind (Coroniti 1990)?

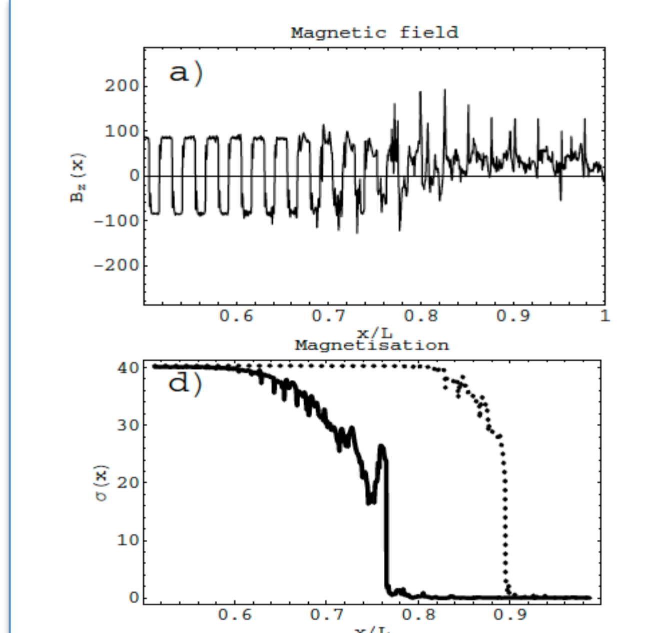
  Could solve several problems at once:
  1. transfer energy to particles
  2. enable acceleration at TS
  3. E > B in reconnection layer

  ⟶ can exceed E_{syn}^{max} limit

  (Uzdenzky et al. 2011)



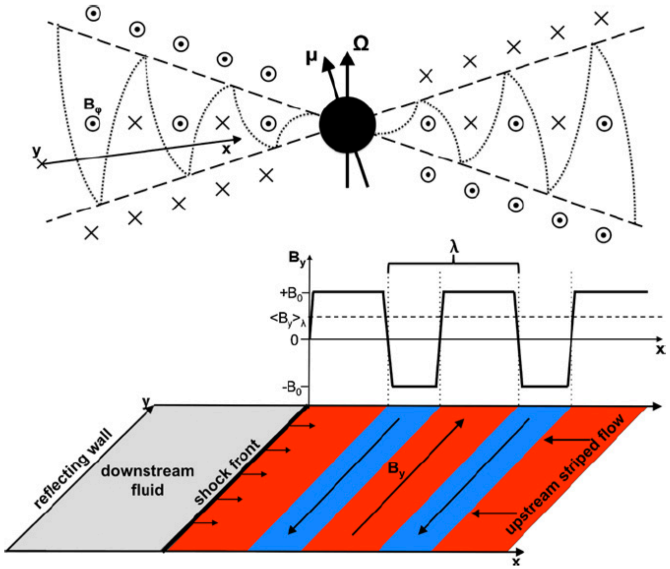
- But reconnection is not fast enough
  - wind Γ increases (Lyubarski & Kirk 2001)
- But compression of stripes near shock will drive faster reconnection –
  "shock-driven reconnection"
  (Lyubarski 2003, Lyubarski & Petri 2007)
- But 1D simulations do not give non-thermal accelerated particles
  2D simulations – maybe … (Lyubarsky & Liverts 2008)

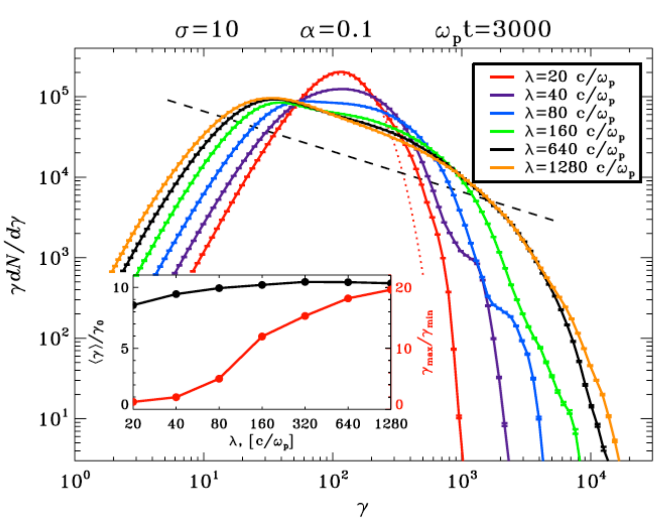


Lyubarski & Petri 2007

Shock-driven reconnection

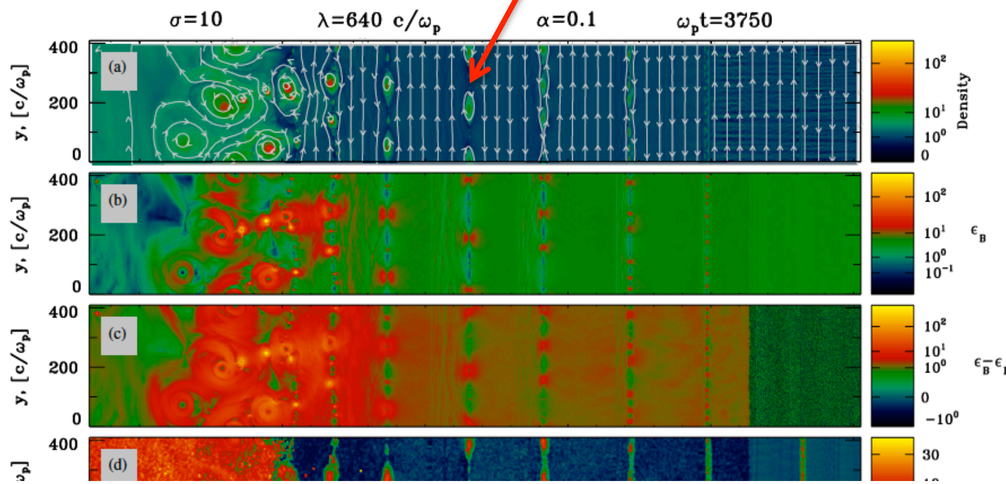
Sironi & Spitkovsky 2011





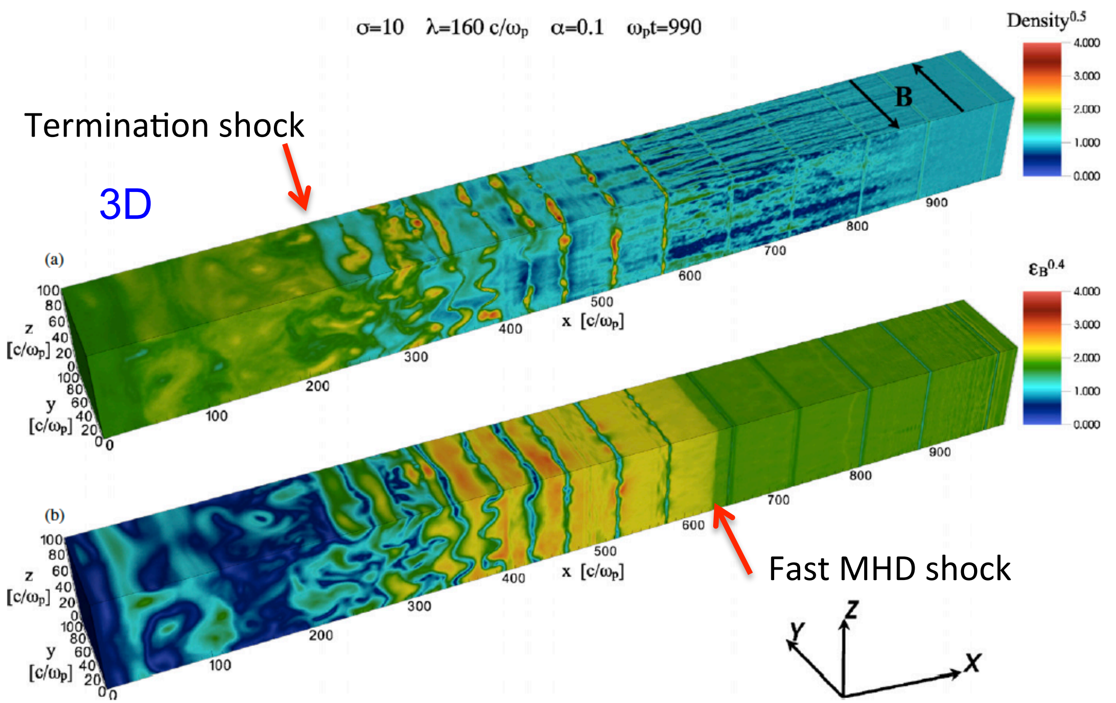
2D

Particles accelerated at X-points where E > B



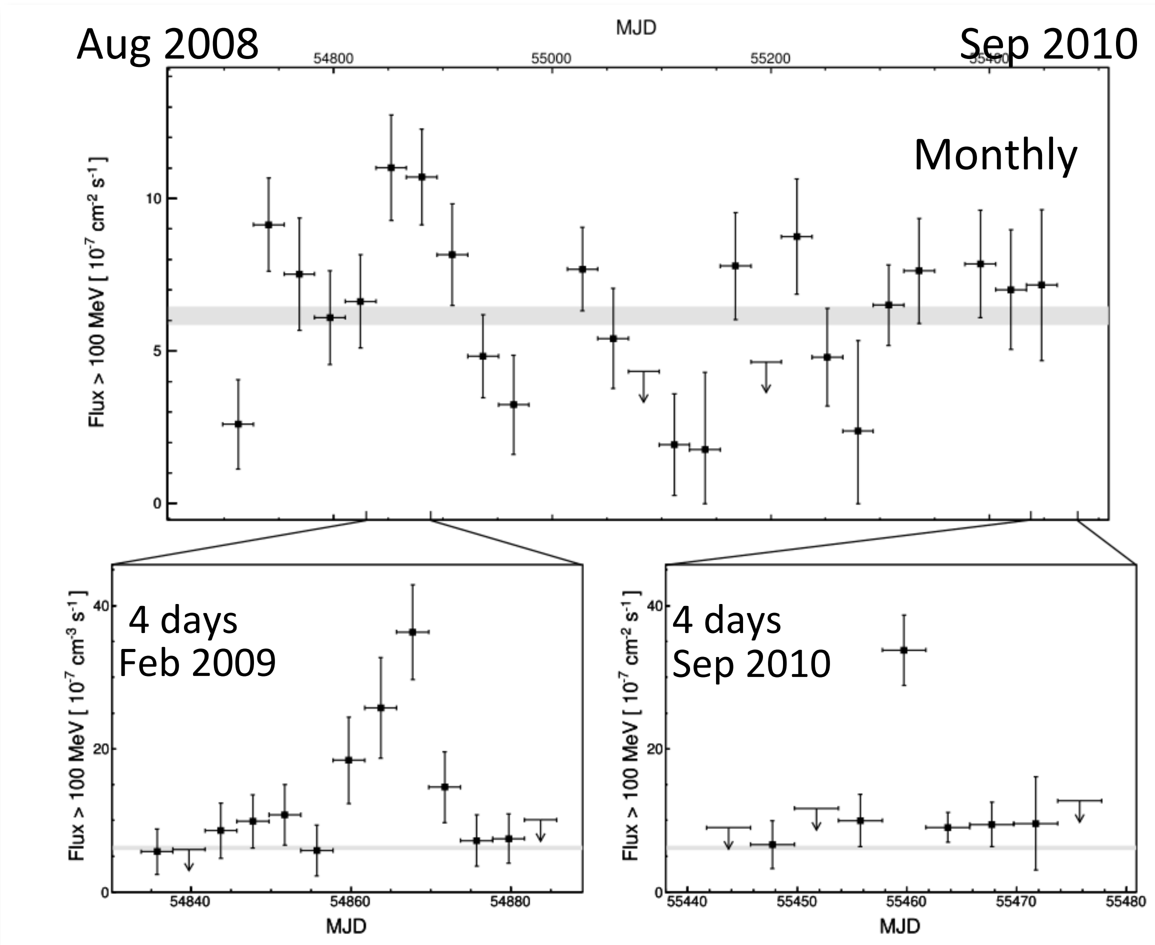
Termination shock

3D



Fast MHD shock

High Energy Crab Flares observed with Fermi LAT



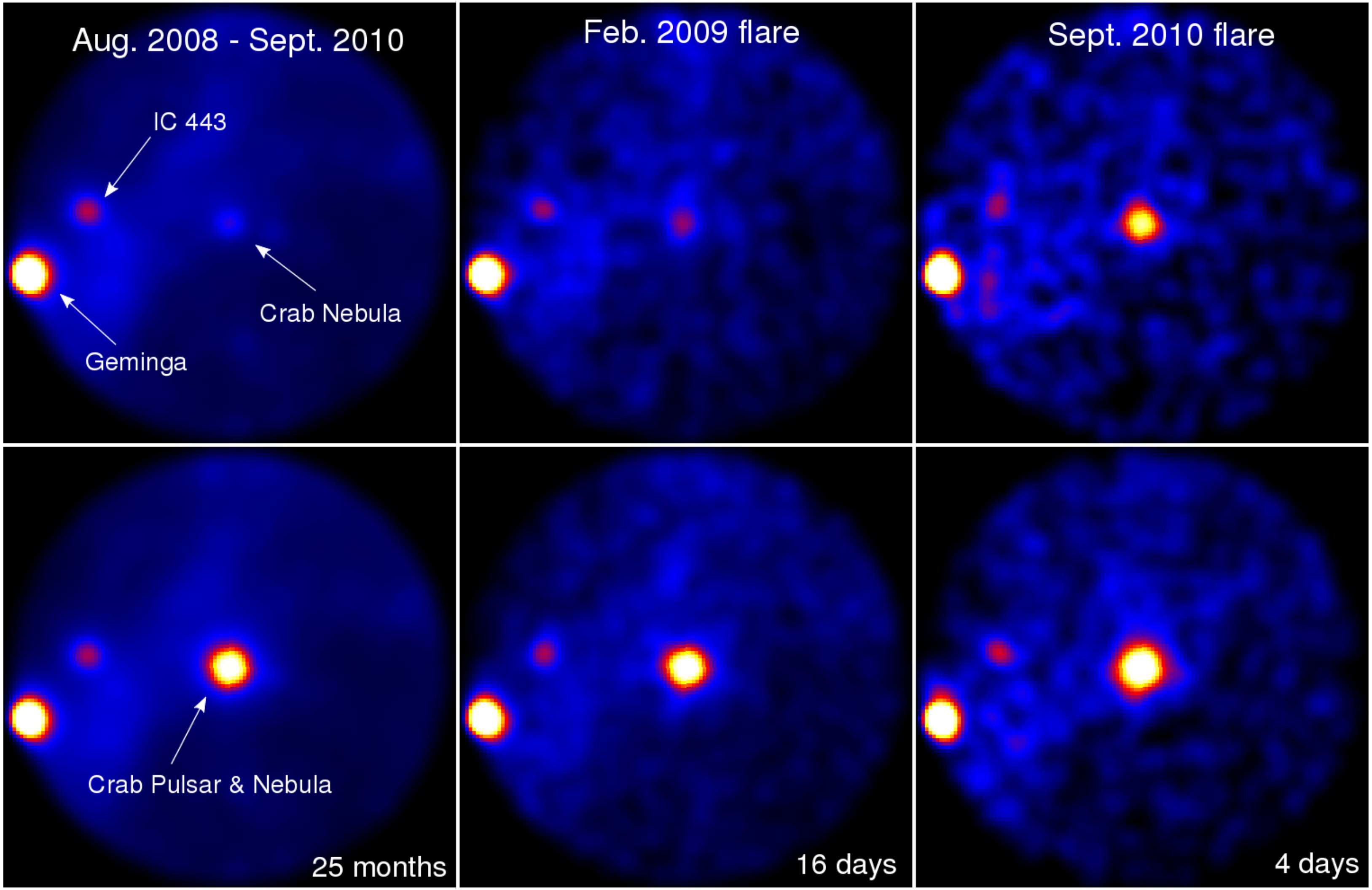
- Monthly variations
- Two flares
  - Flux increase by factor ~4 during ~16 days (26 Jan to 11 Feb, 2009)
  - Flux increase by factor ~6 during ~4 days (18 to 22 Sep 2010)
- Variation on several day timescales only seen in synchrotron component (< 100 MeV)

Nebula flux: off-pulse phase only
Abdo et al. 2011, Science, 331, 739

Not from the pulsar!

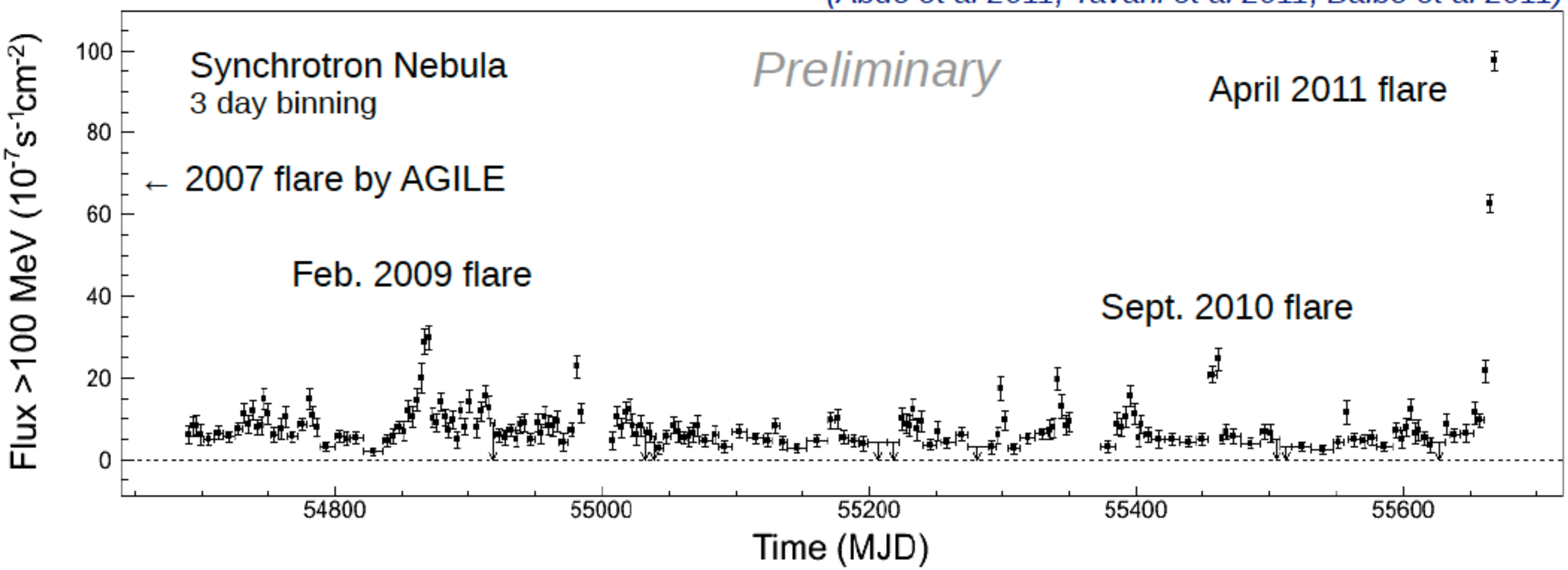
Top row shows off-pulse phases only.

Before flares



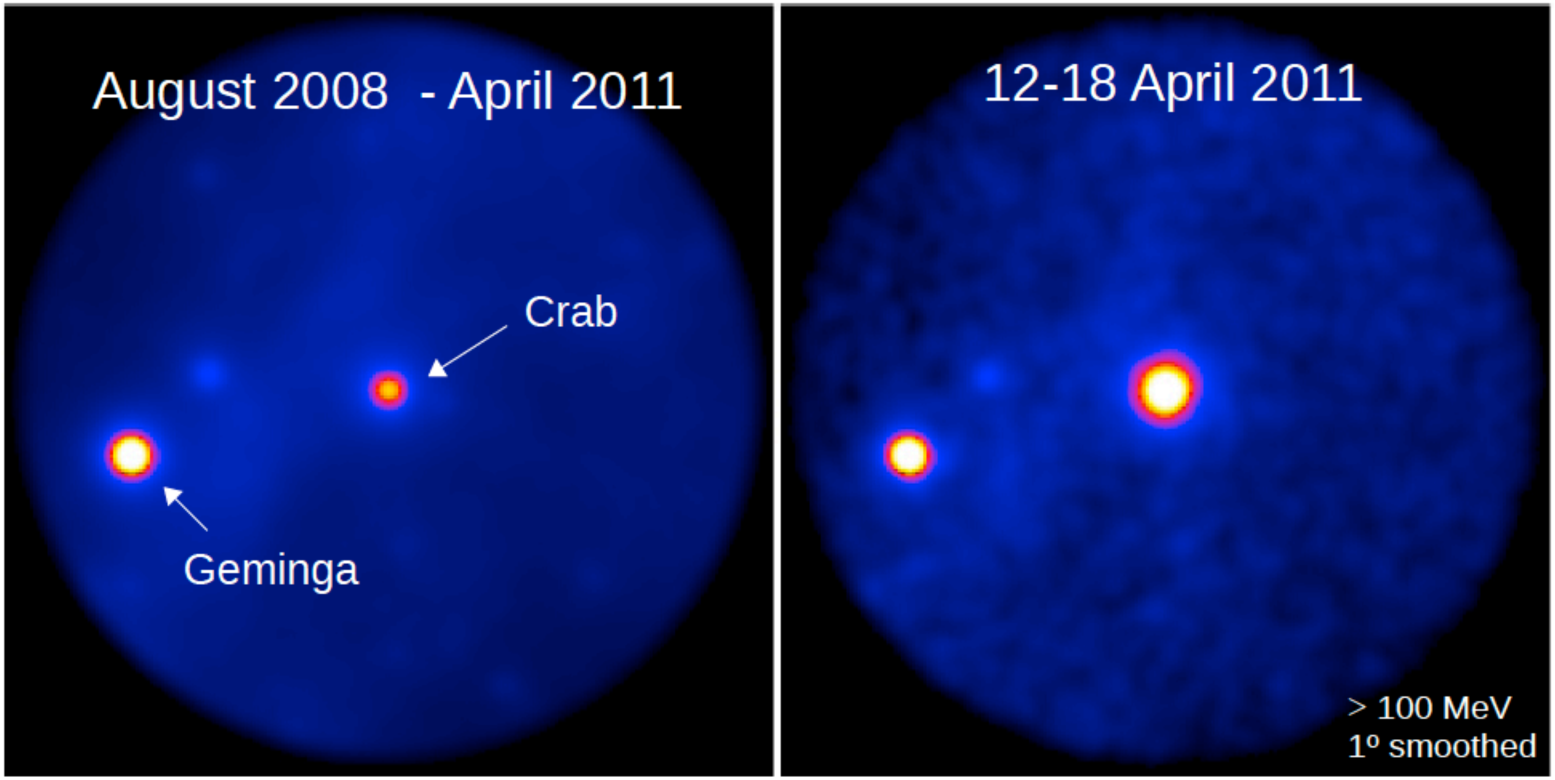
Fermi LAT light curve of synchrotron nebula

(Abdo et al 2011, Tavani et al 2011, Balbo et al 2011)



Average flux ~6 10^{-7} ph/cm²/s above 100 MeV, whith three flares as extremes of persistent variability. Flux increase by ~5 during 2009 and 2010 flares.

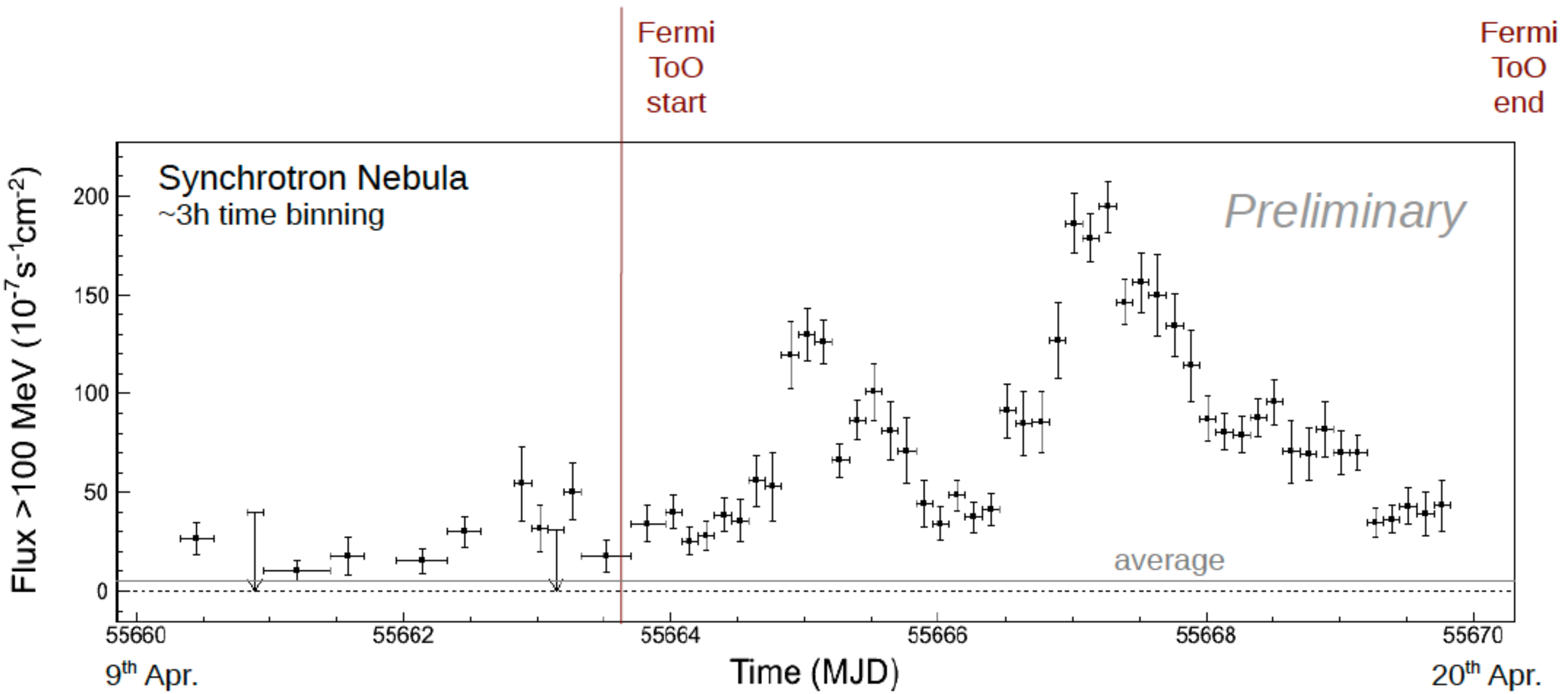
Before and during the April 2011 flare



During the flare, the Crab was the brightest source in the gamma-ray sky

Credit: Rolf Buehler and Fermi LAT

2011 flare in 3 hour binning



Synchrotron nebula increased by factor ~30 during very good Fermi and Chandra coverage

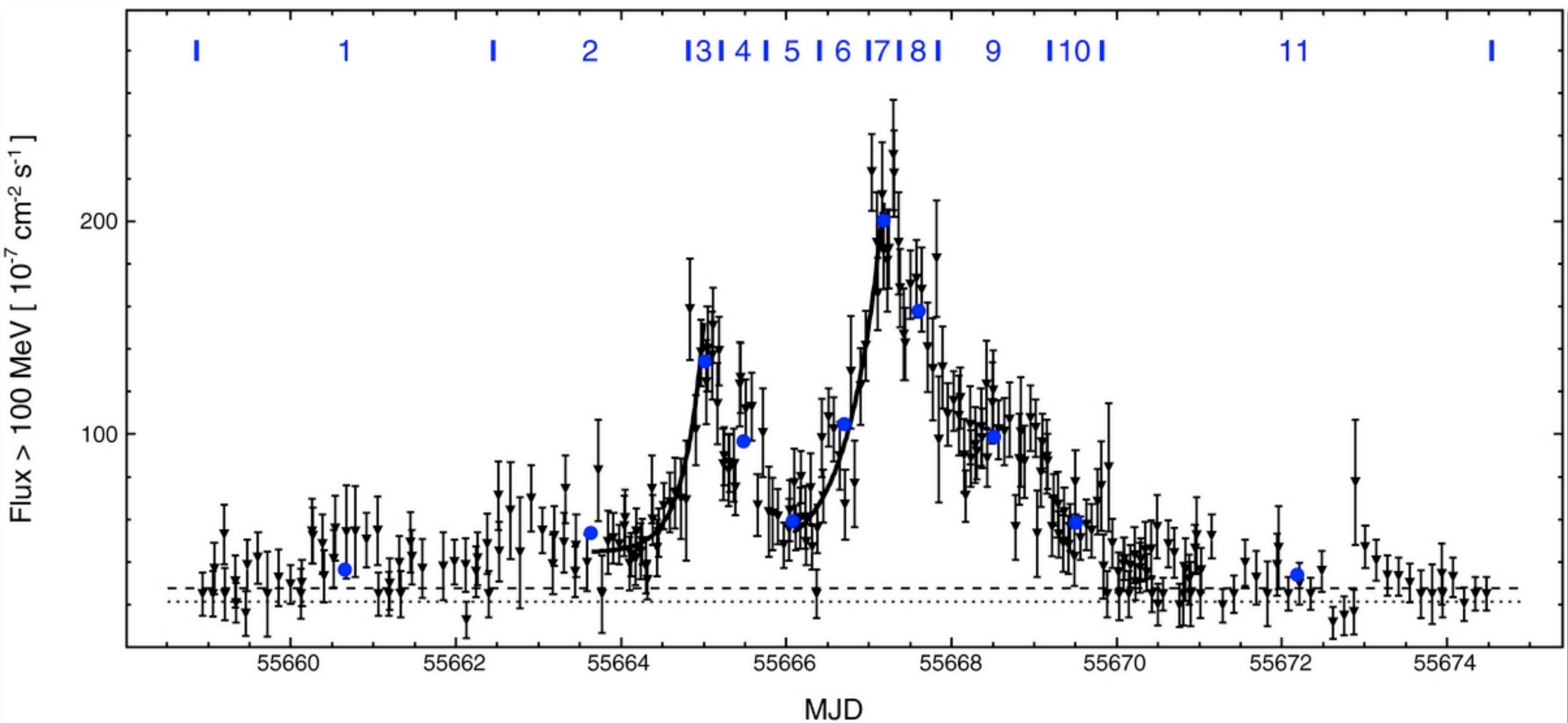
Credit: Rolf Buehler and Fermi LAT

Spectral evolution of the April 2011 flare

Divide the flare into bins of constant flux defined by Bayesian Block analysis

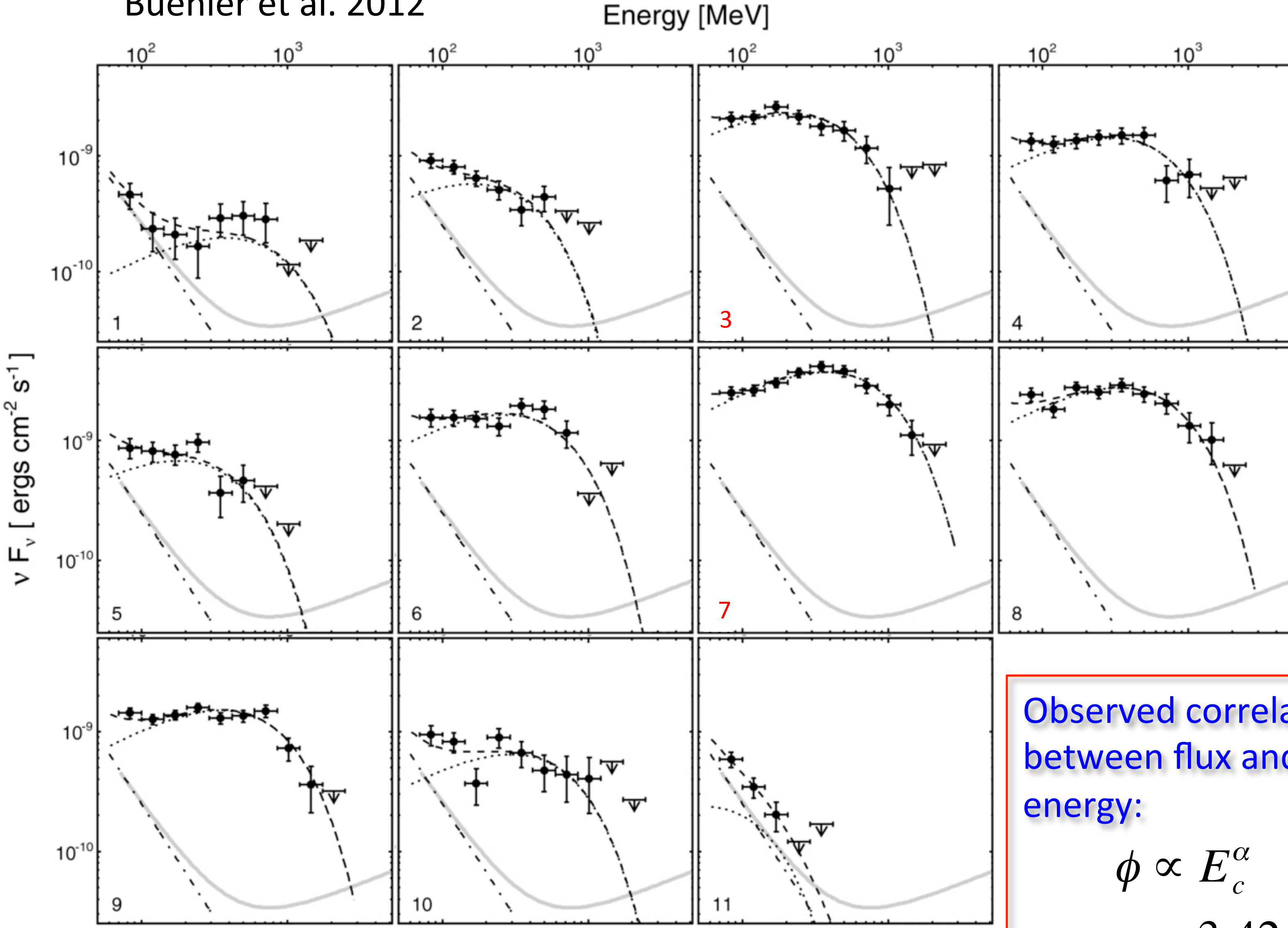
Buehler et al. 2012

Fast variability < 1 hour



Spectrum vs. time in flare

Buehler et al. 2012

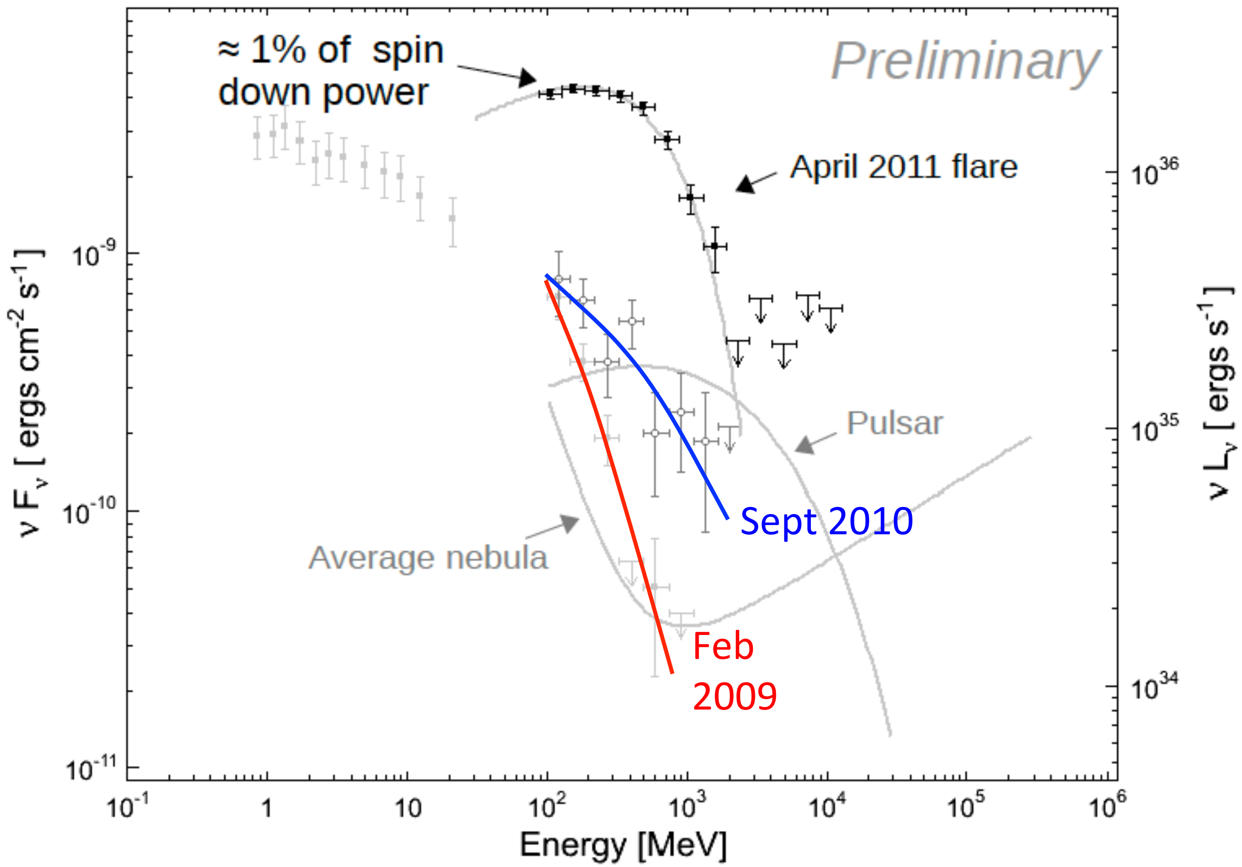


Observed correlation between flux and cutoff energy:

$$\phi \propto E_c^{\alpha}$$

$$\alpha = 3.42 \pm 0.86$$

Spectrum of the nebular flares



New spectral component of power law of index 1.6 and exponential cutoff at 580 MeV (Pulsar like, but no sign of pulsation in flare photons)

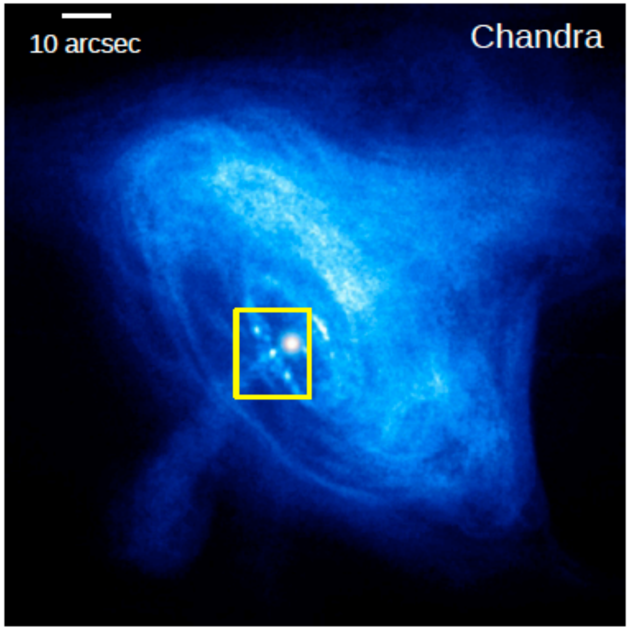
Credit: Rolf Buehler and Fermi LAT

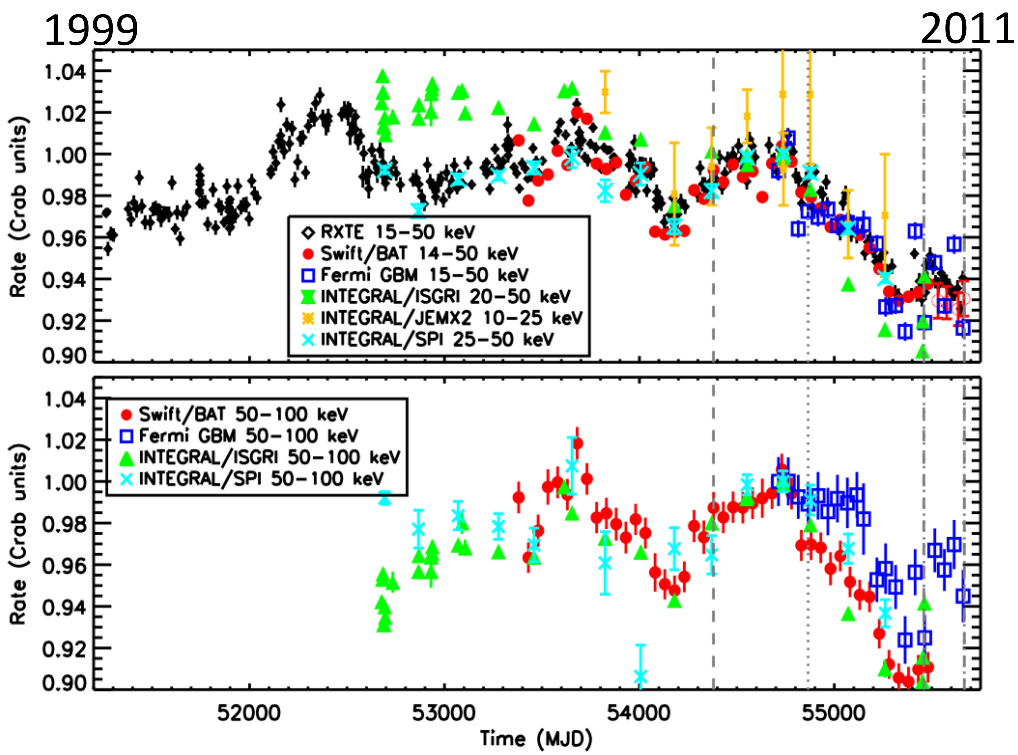
Multiwavelength monitoring

Following Sept 2010 flare, Chandra and HST monitoring program started (Tennant et al. 2011, Caraveo et al. 2010)

Also observations during the flares with Swift, RXTE, MAXI

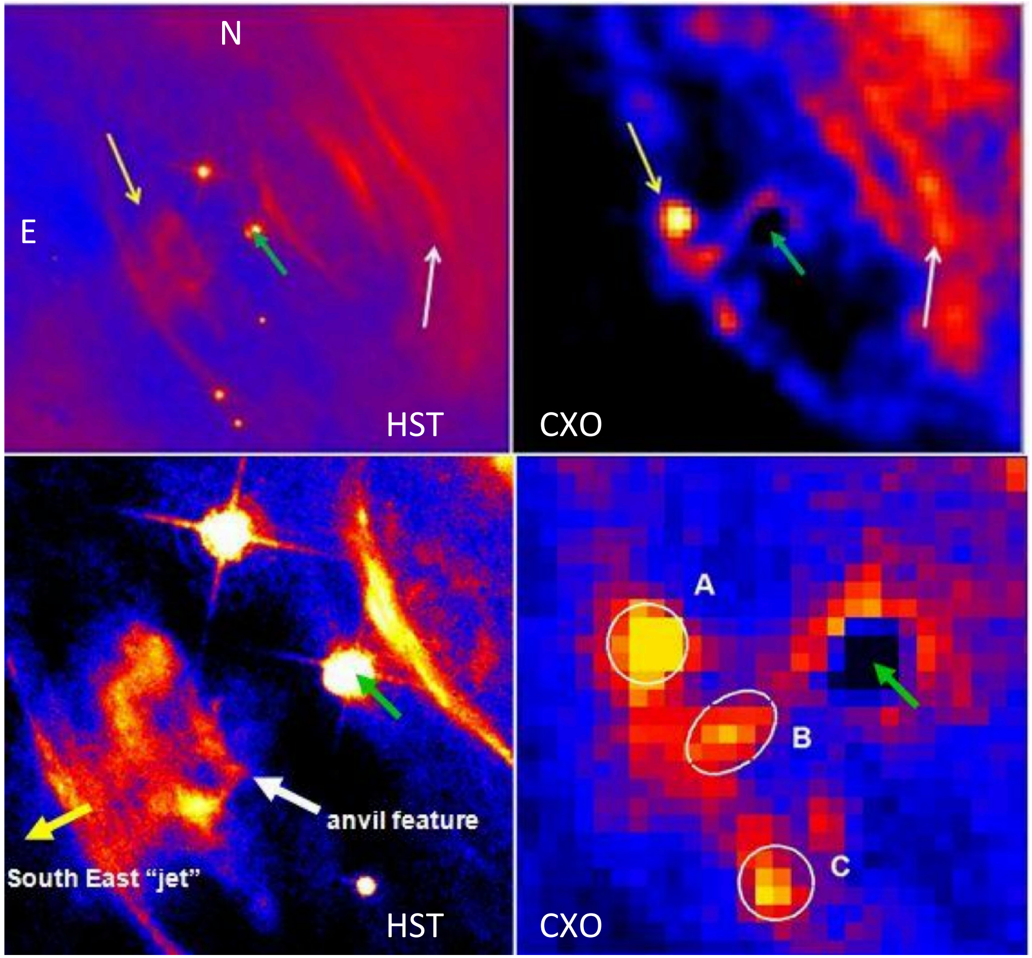
No evidence of flaring in any other wavebands





But continuous variation of nebula flux in X-rays – 7% decline since 2008 (Wilson-Hodge 2011)

Where are the flares occurring?



- HST ACS
  - Oct 2, 2010 (3500-11000 Å)
  - 28”×28”
- Chandra ACIS
  - Sep 28, 2010 (0.5-8 keV)
- 4-day flare implies region <1.5”

What causes the flares?

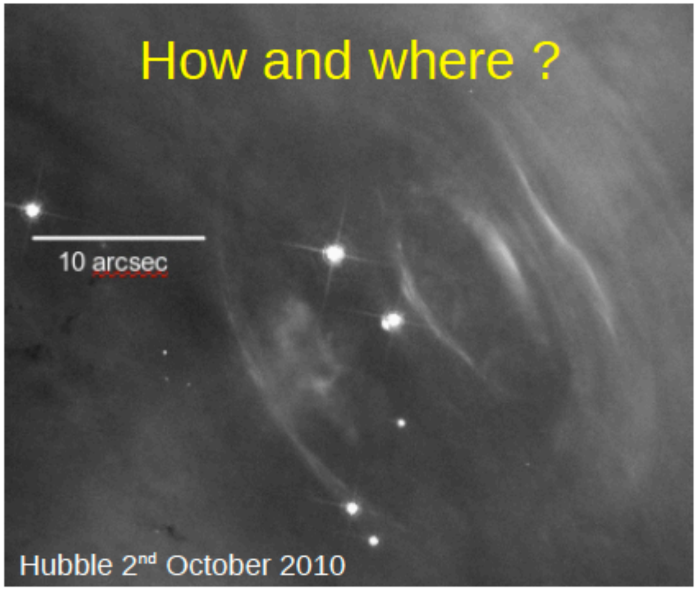
• April flare spectrum (SED) peaks ~ 500 MeV!
(significant synchrotron emission > 1 GeV)
Violates maximum from acceleration (E < B)
limited by synchrotron losses

•Variations on timescales ~ 1 hr Compact emission region < 0.0004 pc ~ 0.04”
Not resolved by Chandra or HST

• No correlated variability detected in any other waveband (Caraveo et al. 2010, Tennant et al. 2011)

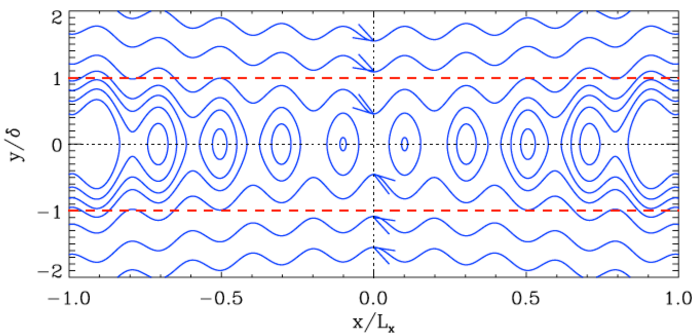
• Relativistic Doppler boosting?
(Lyutikov 2010, Komissarov & Lyutikov 2011)
Requires $\Gamma \sim 3$

• Magnetic reconnection in current layer?
(Kirk 2004, Uzdensky, Cerutti & Begelman 2011)
E > B in thin (< r_L) reconnection layer



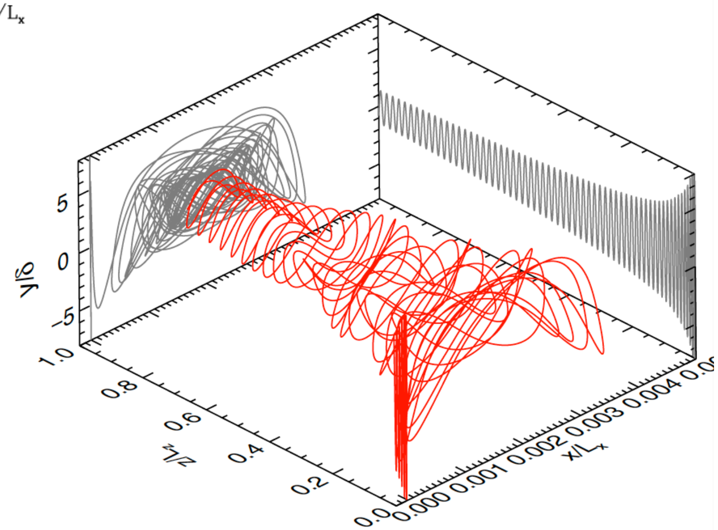
Crab flares: reconnection in pair plasma

Uzdensky, Cerutti & Begelman 2011
Cerutti, Uzdensky & Begelman 2011

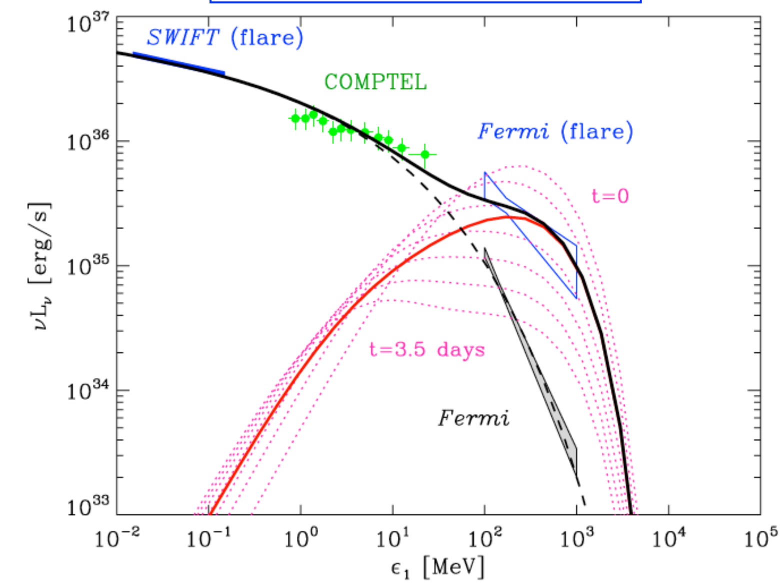


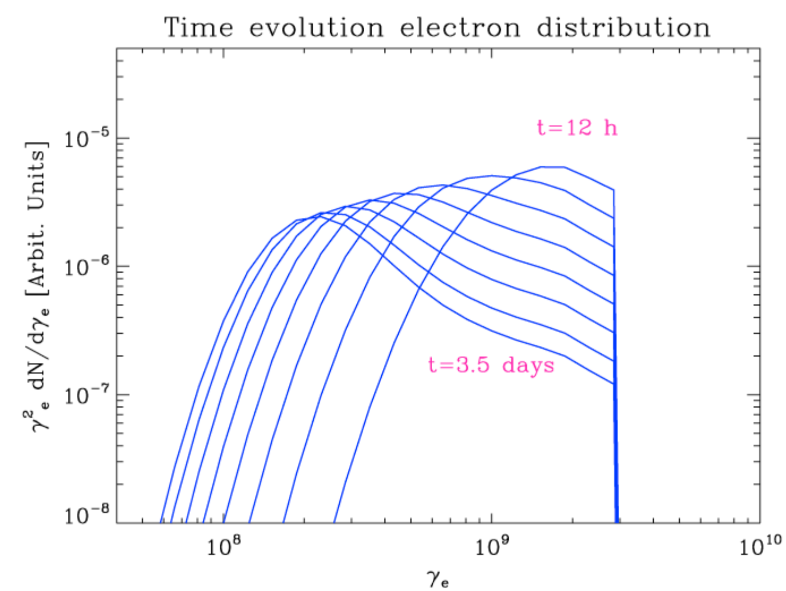
E > B in reconnection layer

Particles are focused toward reconnection layer



Emission toy model

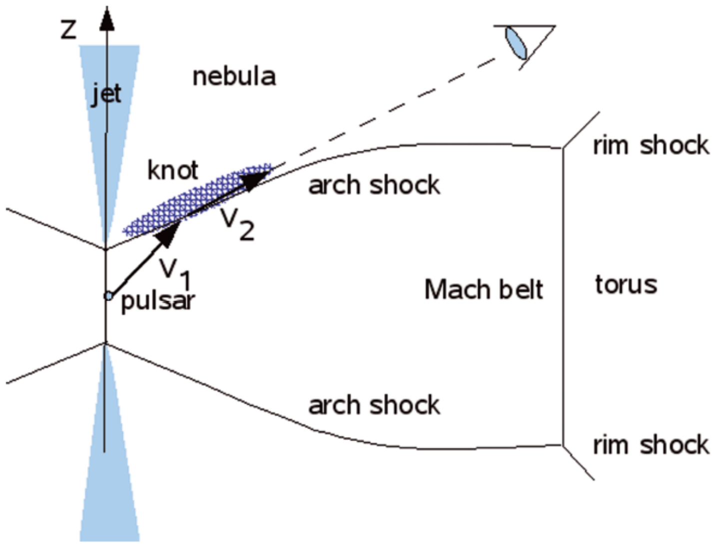


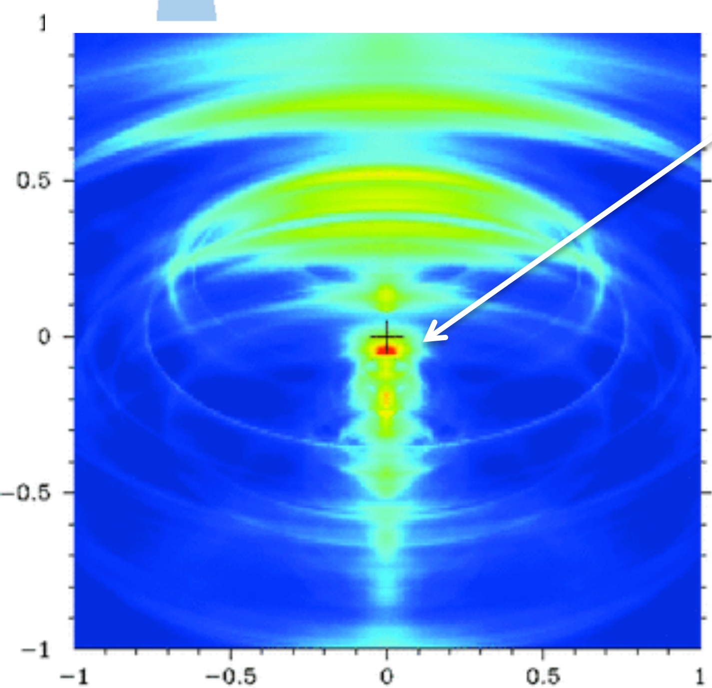


- Radiation above classical limit in RL
- Variability on synchrotron loss timescale of PWN field – B ~ 5 mG
- Flare spectrum from mono-energetic particles with $\gamma \sim 2 \times 10^9$

Crab flares: Doppler boosting

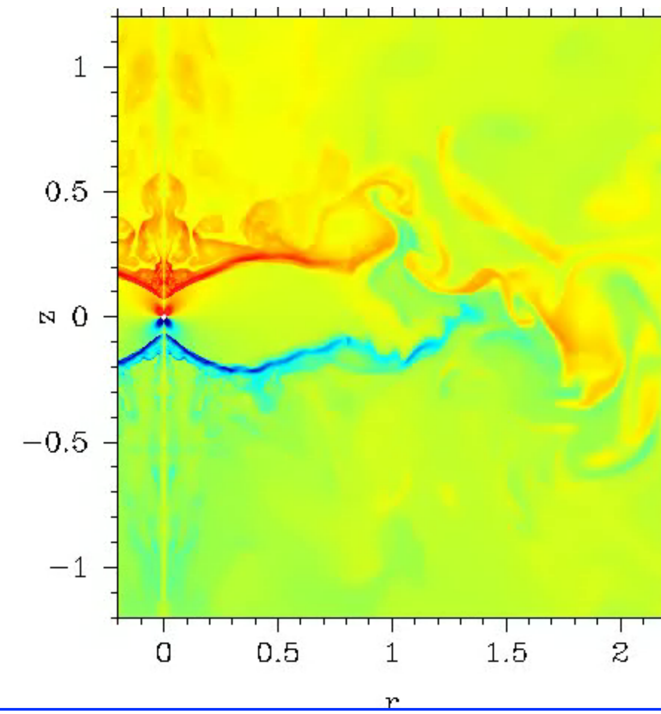
Komissarov & Lyutikov 2011





inner knot
L ~ 6 lt-days

Camus et al. 2009 – relativistic MHD sims



- Flares from variability of Doppler boosting of post-shock flow

$$\varepsilon_\gamma^{obs} = \frac{\varepsilon_\gamma}{D}, \qquad j_\gamma^{obs} = D^{2+\alpha} j_\gamma$$

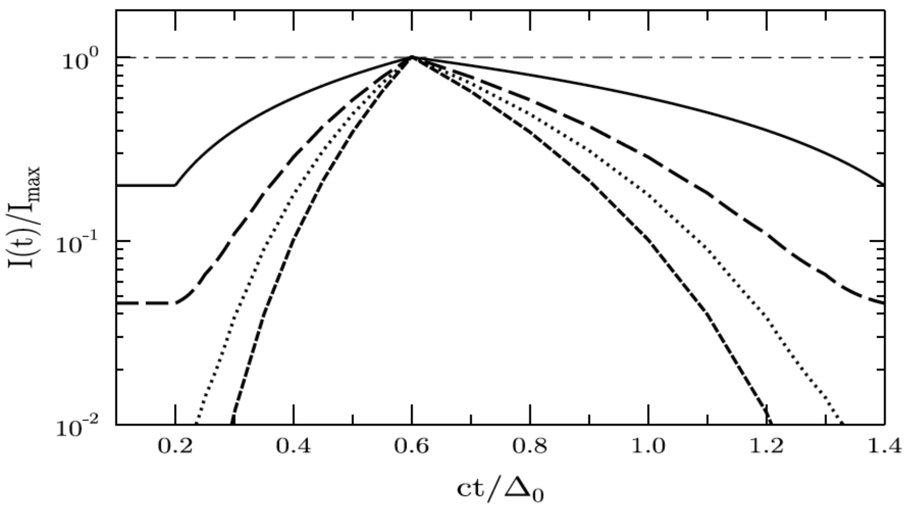
$$D = \gamma(1 - \beta\theta)$$

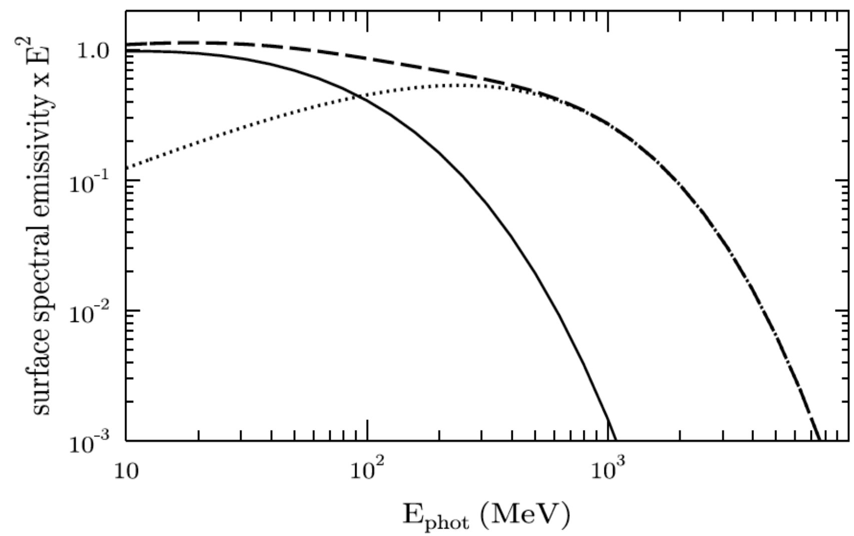
- Possibly from inner knot
- Could explain correlation between flux and cutoff energy (Lyutikov et al. 2011)

Crab flares: fluctuations in magnetic field

Bykov et al. 2012

- Pairs are accelerated by shock-driven reconnection and diffusive 1st order Fermi mechanism at termination shock
- Particles encounter fluctuations in B field downstream of shock
- If scale of field fluctuations is smaller than SR loss length scale, can overcome E_{syn}^{max} limit





- What is the origin of the B field fluctuations?
- Model prediction: no simultaneous variability of IC spectrum above 100 TeV (in contrast to reconnection model where acceleration energy increases – Bednarek & Idec 2011)

Summary & Conclusions

- Magnetic reconnection likely occurring in striped pulsar winds
- Four high energy (>100 MeV) flares observed from the Crab Nebula
  - Acceleration of electrons to >PeV poses difficulties to diffusive shock acceleration
- Doppler boosting or magnetic reconnection?
- Current flare models with acceleration via MR hopeful, but none address timing/rarity or distribution of flares