Gamma-ray emission from Crab pulsar and Nebula: paradigm shifts?

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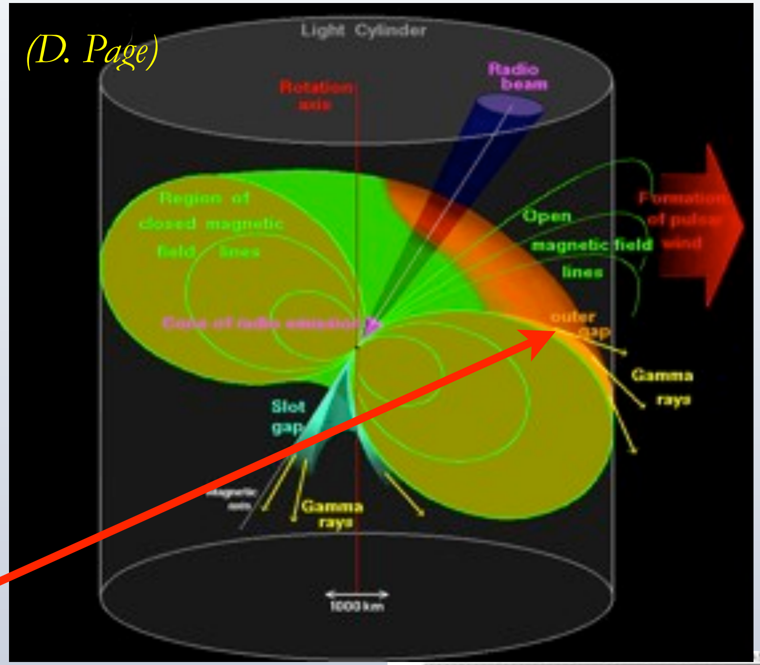
I. Gamma-ray emission from pulsars

Gamma-rays: Outer/slot gaps: messy physics, good fits geometrical

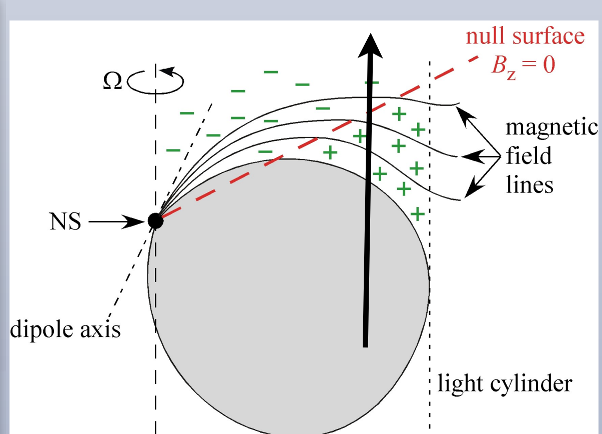
Chen & Rudernman 86

- vacuum dipole (Romani +)
- force-free models (Spitkovsky)
- caustics: dipole + sweep-back + magnetospheric currents + abberation + time of flight

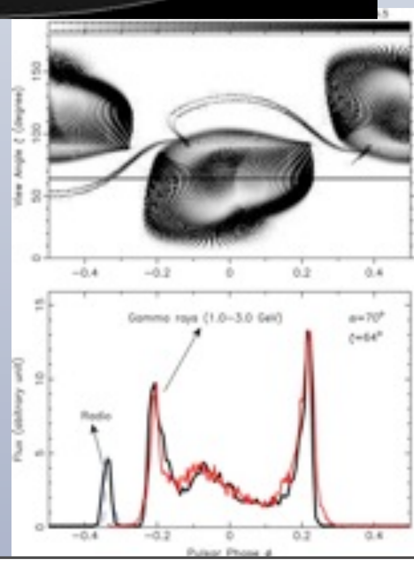


production of gamma-rays (Chen & Ruderman 1986)

- Rotation induces charge density in the magnetosphere
- E|| accelerates particles which emit

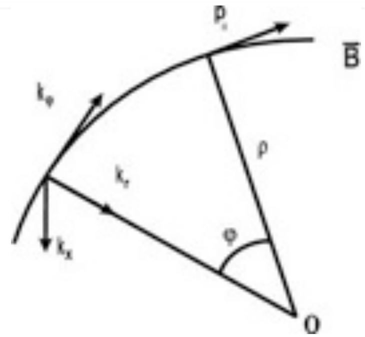


outer gap



Emit what?

- Curvature emission (Chen & Ruderman 1986)

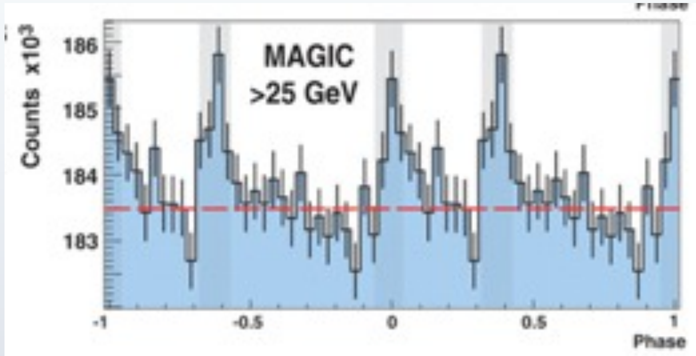


$$\epsilon_{ph} = \frac{\hbar \gamma^3 c}{R_C}$$

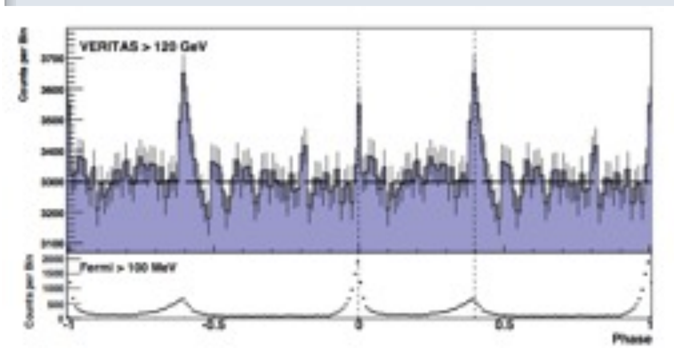
- Hard to solve the full electrodynamic picture: **there is no kinetic model of pulsar magnetosphere**
- $E_{||}$ accelerates particles, produce pairs and currents, pairs screen $E_{||}$, currents distort B-field, changing $E_{||}$, non-local radiative transfer.
- Typically $E_{||}$ ~ 10^{-2}-10^{-1} B
- Maximal $\gamma \geq 10^7$ for primary beam is needed for Crab
- **Clear prediction: above the break the spectrum must be exponentially suppressed**

Crab at VHE

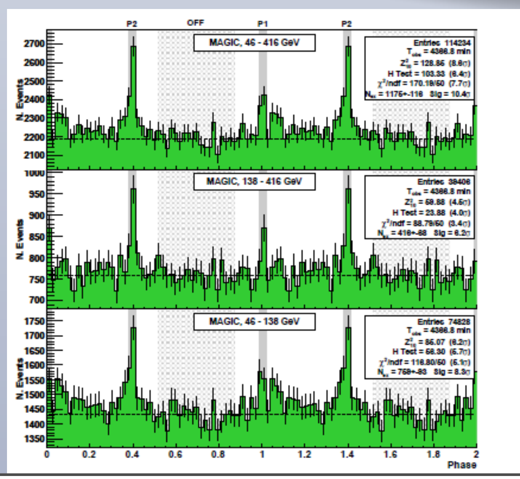
- MAGIC sees Crab at 25 GeV
- Not enough by factor ~ few

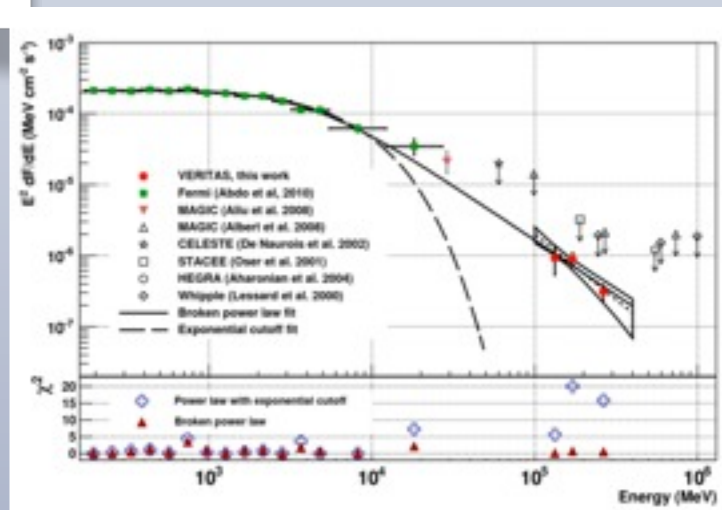


- VERITAS sees Crab at > 150 GeV!
- Cut-off is non-exponential(!): Power-law
- IP is brighter than MP



MAGIC:
Crab at 500GeV





Curvature emission near light cylinder is excluded

Lyutikov + 2012

- Astrophysical E-fields < B-field
- Equate acceleration by $E_{\|} = \eta\,(r/R_{LC})\,B$ to curvature losses in $R_C = \xi R_{LC}$

Maximum possible energy break due to curvature emission

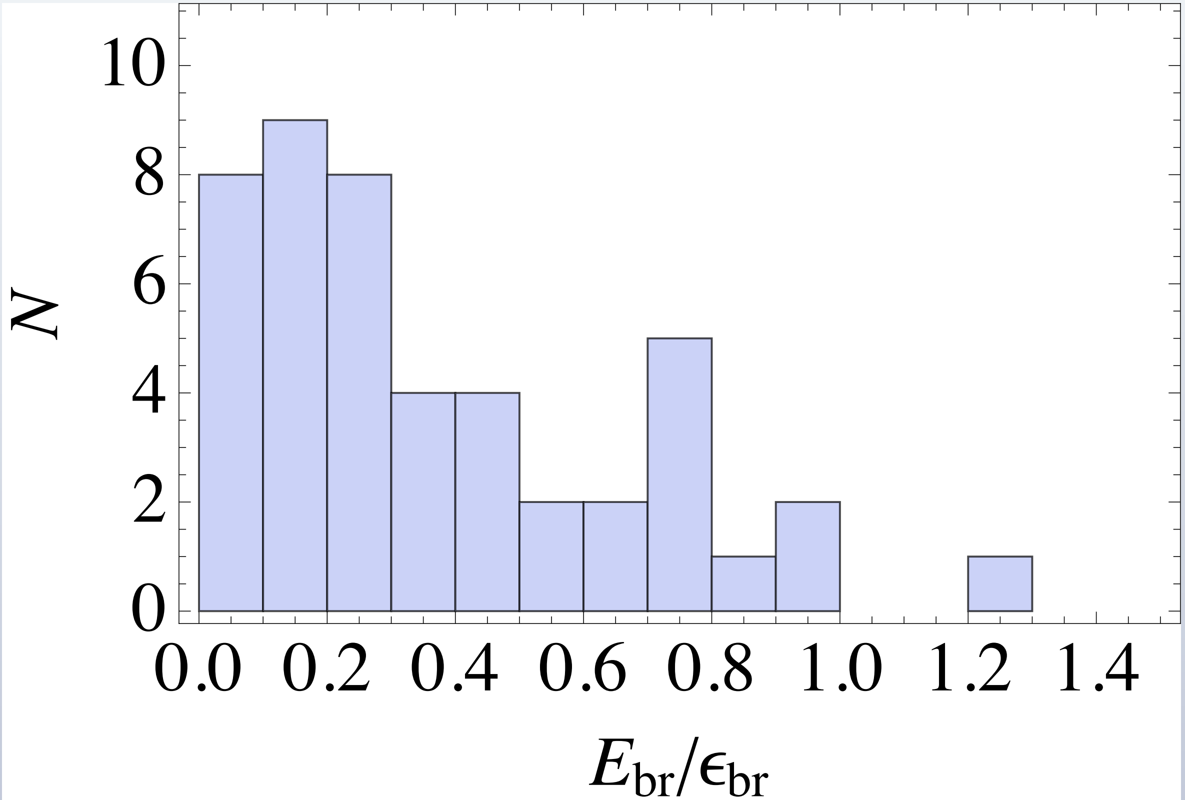
$$\epsilon_{br} = (3\pi)^{7/4} \frac{\hbar}{(ce)^{3/4}} \eta^{3/4} \sqrt{\xi}\, \frac{B_{NS}^{3/4} R_{NS}^{9/4}}{P^{7/4}} \left(\frac{r_{em}}{R_{LC}} \right)^{-1}$$

For Crab, assuming E=B

$\approx$ 150 GeV

- Detection of Crab above 150 GeV (with non-exponential cut-off) exclude curvature emission as the main emission mechanism (Lyutikov et al. 2011)

Other pulsars: maximal curvature energy at light cylinder



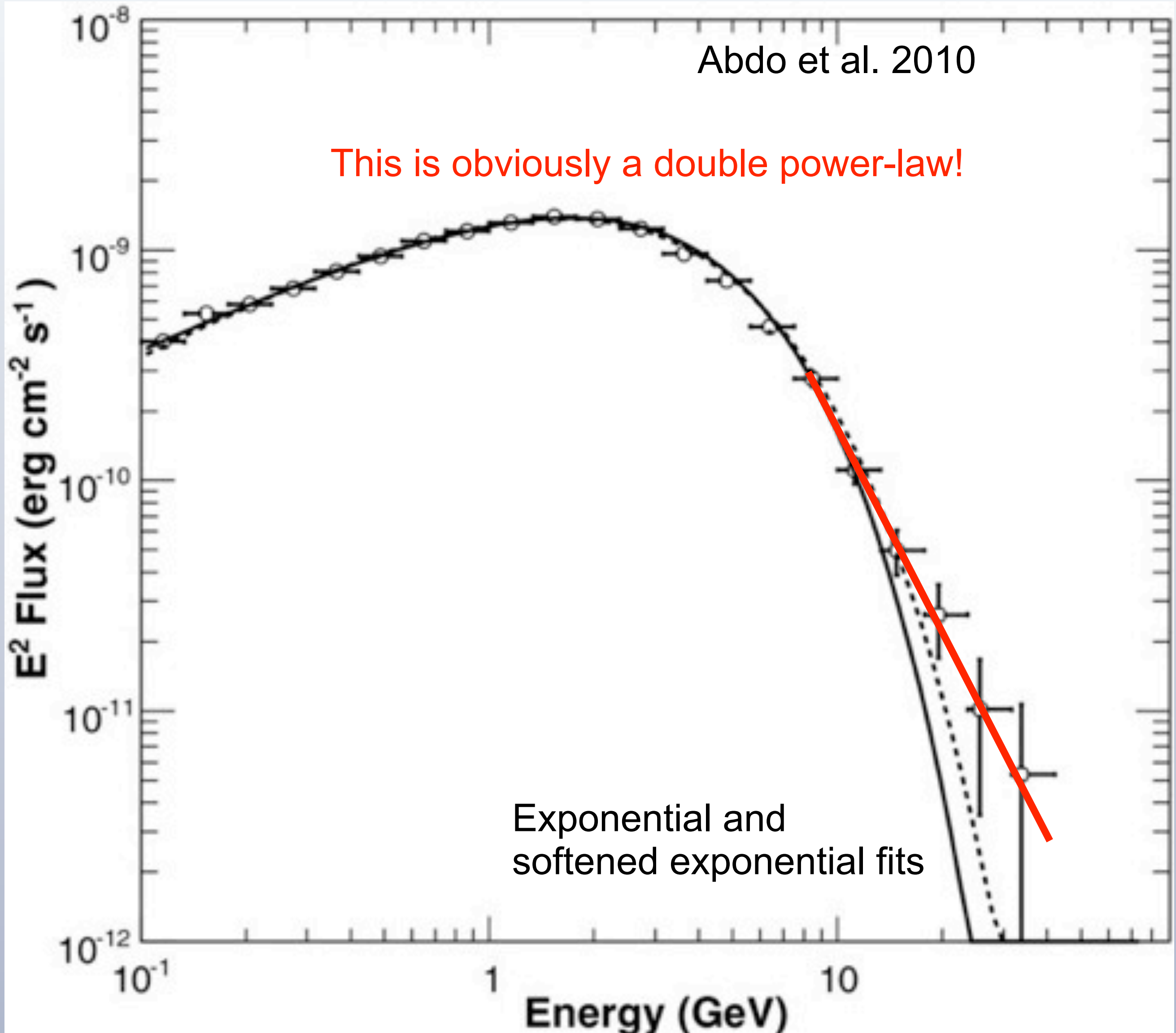
- Ratio of the observed break energies E_{br} for 46 pulsars to the maximum predicted for curvature radiation ε_{br}
- For Crab E_{br}/ε_{br} ~ 0.05 seemed OK, but not OK -> Lower limits

Implications of Crab detection by VERITAS:

- **Spectral break in Crab is not due to curvature emission of the maximal energy of particles**
- **Alternative possibility: IC scattering**
- **Break due to the details of particle distribution and scattering cross-section (in the KN regime)**

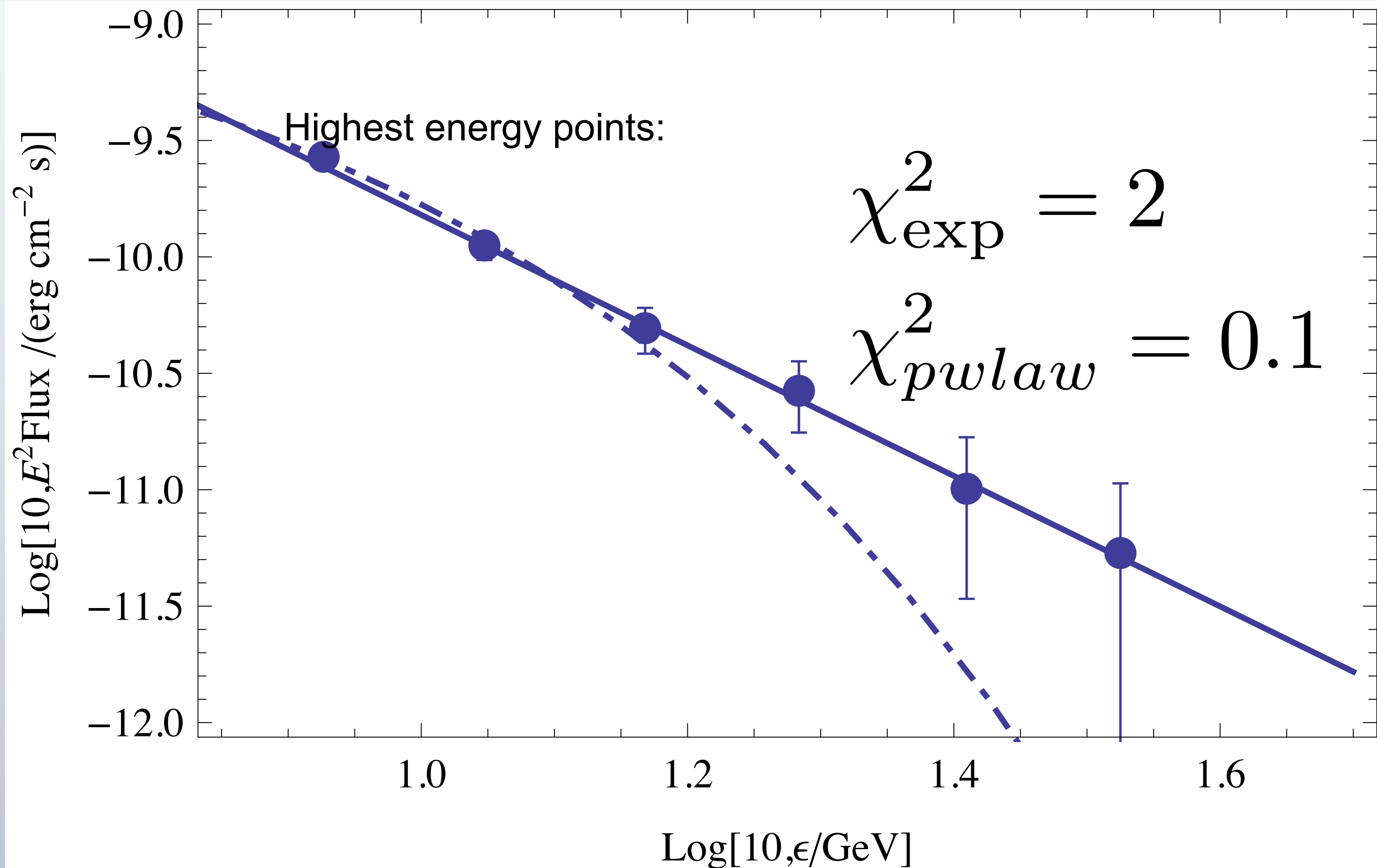
- Is Crab special (e.g. high level of soft photons)?
- What about other pulsars?
  - Vela
  - Geminga

Fermi spectrum of Geminga



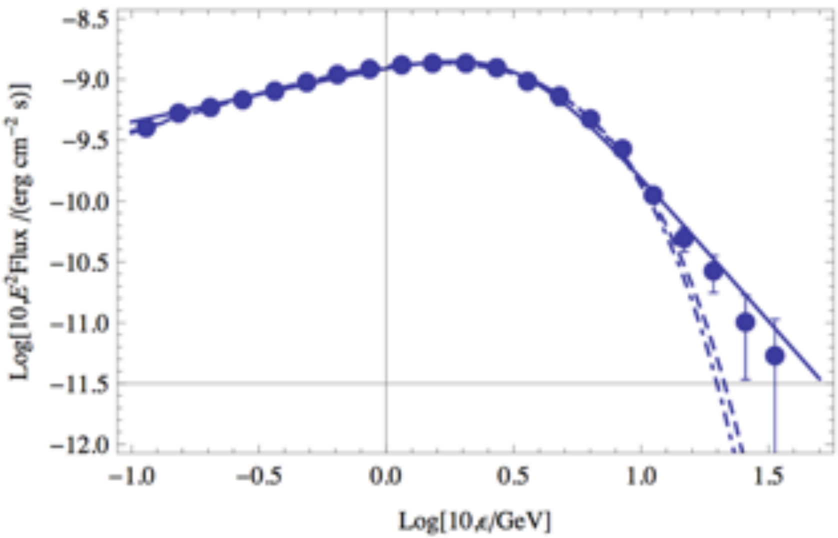
Geminga: fits

Lyutikov 2012

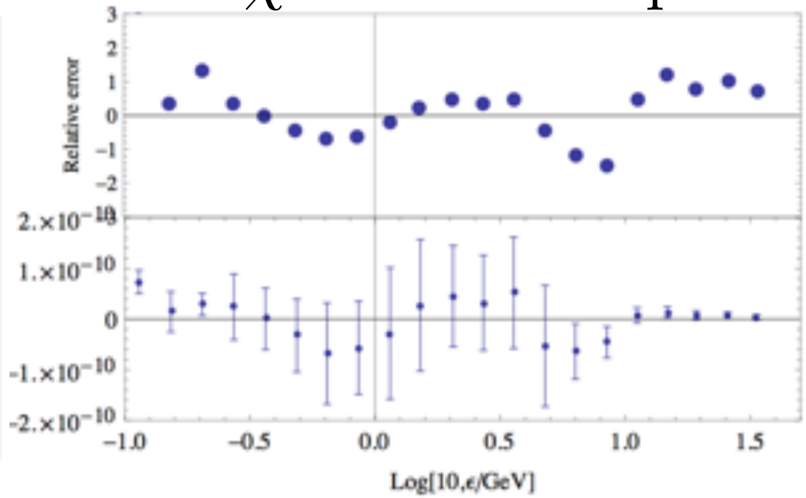


- The highest energy data points actually have the **smallest** error bars.
- Too broad energy bins?
- Geminga is not intrinsically bright - “garden variety”

Geminga: broad band fits



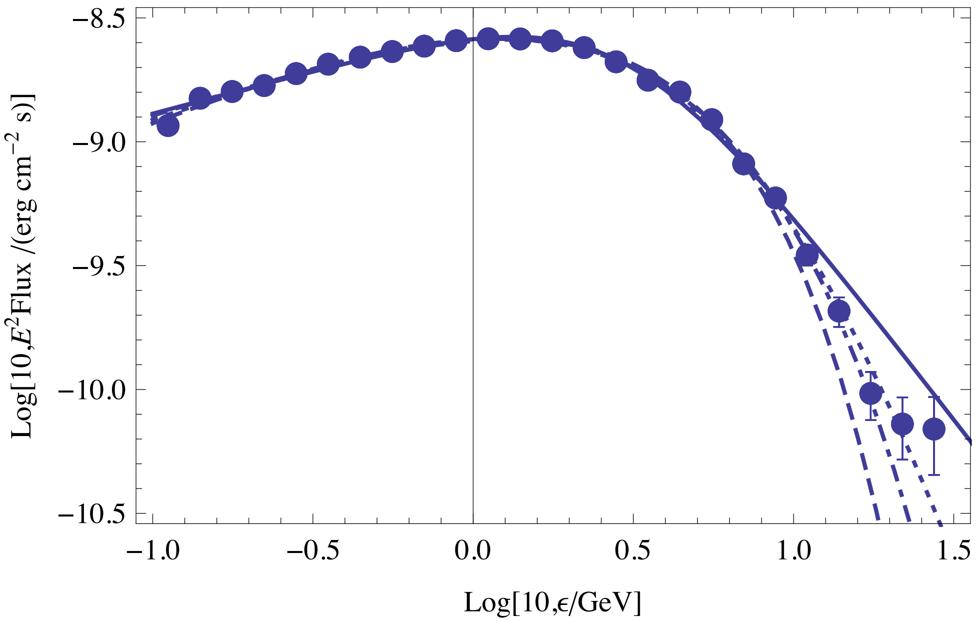
errors χ^2 for double pwlaw



model	Fit function	α	β	ϵ_{br}	reduced, unweighted χ^2	b	dof
a	$\left(\left(\frac{\epsilon}{\epsilon_{br}}\right)^{\alpha}+\left(\frac{\epsilon}{\epsilon_{br}}\right)^{-\beta}\right)^{-1}$	2.38	0.45	3.32	1.26	–	17
b	$\epsilon^{\beta}e^{-\frac{\epsilon}{\epsilon_{br}}}$	–	.70	2.35	1.13	–	18
c	$\epsilon^{\beta}e^{-\left(\frac{\epsilon}{\epsilon_{br}}\right)^{b}}$	–	0.75	1.98	0.83	0.91	17

- The errors are not random
- **Most of the chi^2 is accumulated near the break energy due to the ARBITRARY parametrization of the spectral roll-off**
- Similar results for phase-resolved spectra

Vela



- Double power-law fits are as good as exp.

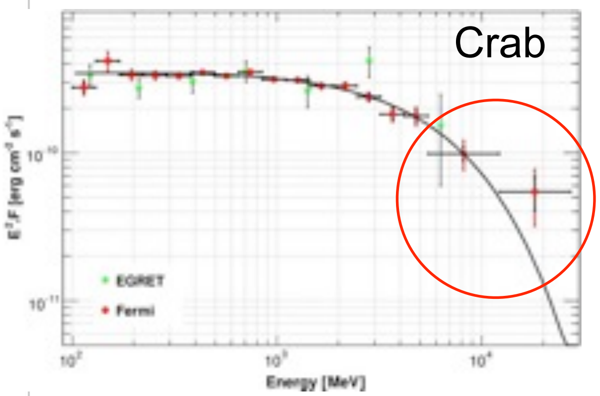
- Various parametrizations of roll-offs reduce chi^2

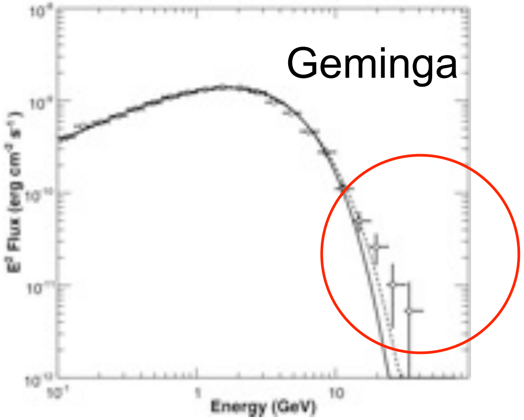
model	Fit function	α	β	ϵ_{br}	reduced χ^2	b	dof
a	$\left(\left(\frac{\epsilon}{\epsilon_{br}}\right)^{\alpha}+\left(\frac{\epsilon}{\epsilon_{br}}\right)^{-\beta}\right)^{-1}$	1.68	0.34	2.91	2.2	–	21
b	$\left(\left(\frac{\epsilon}{\epsilon_{br}}\right)+\left(\frac{\epsilon}{\epsilon_{br}}\right)^{-\beta}\right)^{-\alpha}$	4.11	0.11	8.8	1.3	–	21
c	$\epsilon^{\beta}e^{-\frac{\epsilon}{\epsilon_{br}}}$	–	.42	3.1	2.0	–	22
d	$\epsilon^{\beta}e^{-\left(\frac{\epsilon}{\epsilon_{br}}\right)^{b}}$	–	0.59	1.58	1.4	0.73	21

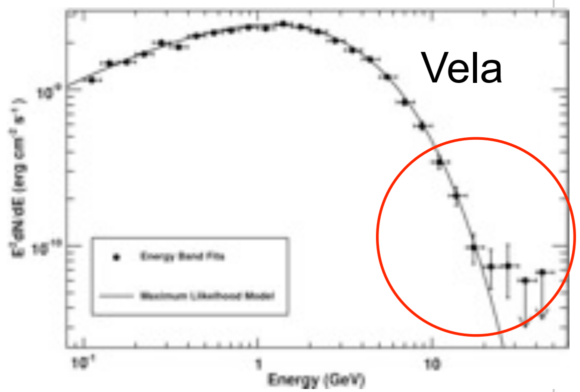
Of the three brightest pulsars, two are inconsistent with exp cut-off, third is consistent with double power law

More hints: spectra

- Most young pulsars and some MSPs have hard excess with respect to models

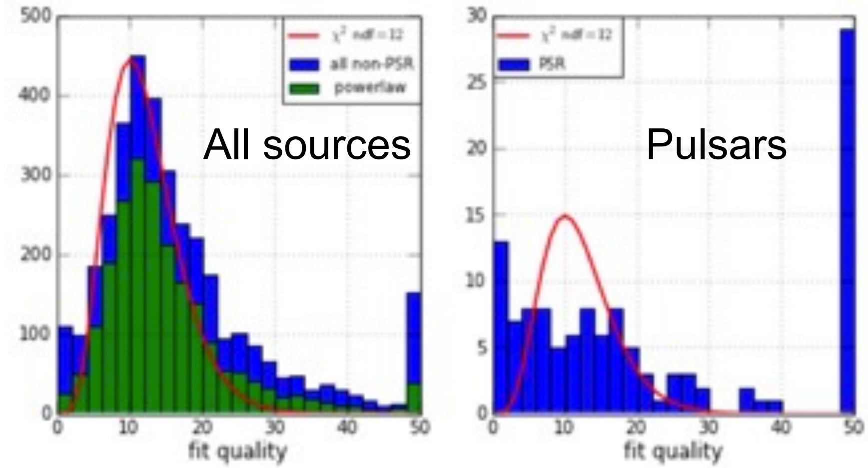






[Paul Ray]
Maxim Lyutikov and Alice Harding shake on a bet over whether the gamma-ray spectrum of the Vela Pulsar is power-law rather than exponentially cutoff above 10 GeV. — at [Aspen Center for Physics].

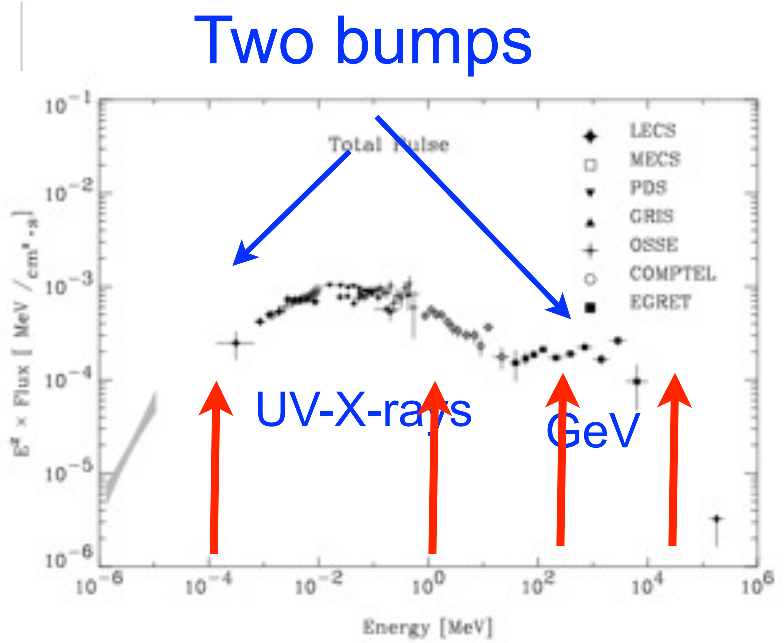
Fermi fit quality

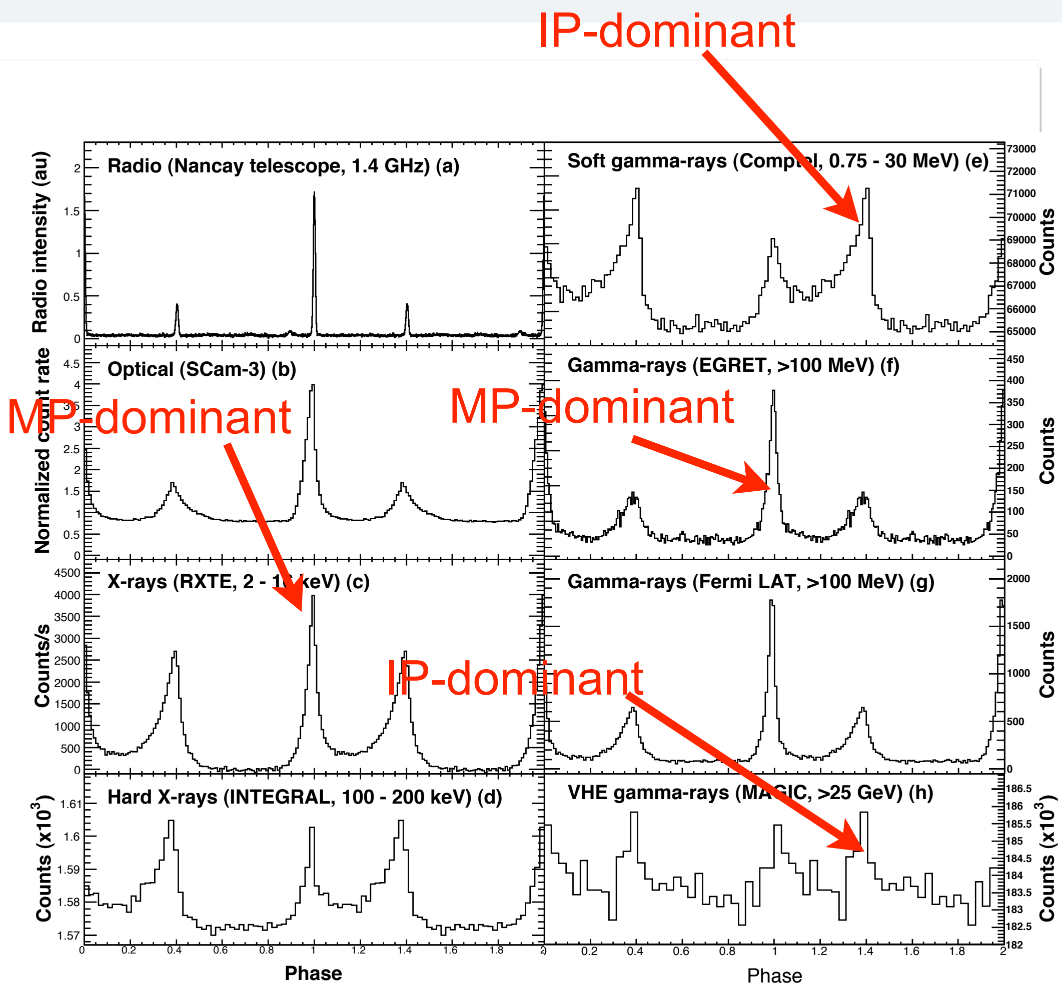


T. Burnett, priv. comm.

Wednesday, May 29, 2013

More hints: Crab spectrum & profiles





-MP/IP pattern is repeated in the two spectral bumps

-Consistent with IC model

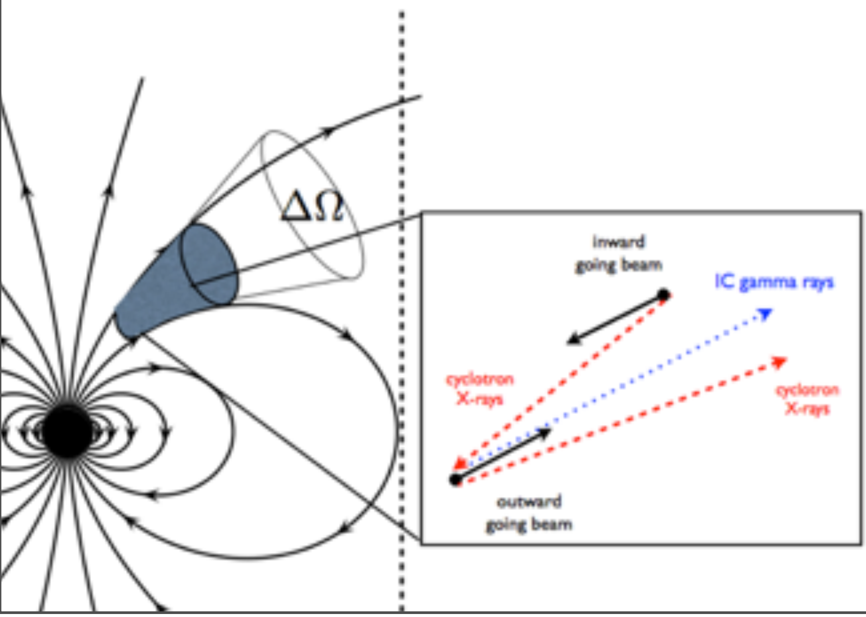
Detection of Geminga or Vela by VERITAS/HESS would be a killer for the curvature model

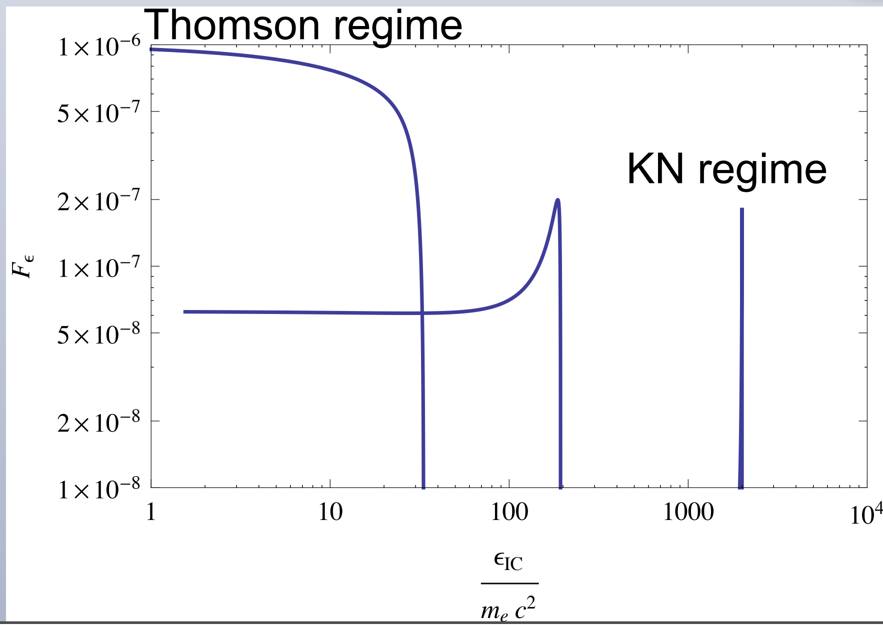
IC model

Lyutikov 2013

- `Off-the shelf'' SSC models not applicable
  - Random B-field of a given value
  - Isotropic particle distribution
  - single value for bulk motion
- Regular B-field, changing sharply
- Strong radiative damping: non-isotropic distribution
- Continuous v_{II}

- Do not model acceleration - infer distribution from observations
- 1D model: Two counter-streaming components:
- optical-X-ray: boosted cyclotron
- gamma rays: IC scattering of the inward cyclotron photons by the outward going particles
- Deep in KN regime: **IC bump is a direct measure of f(p$_{II}$)**

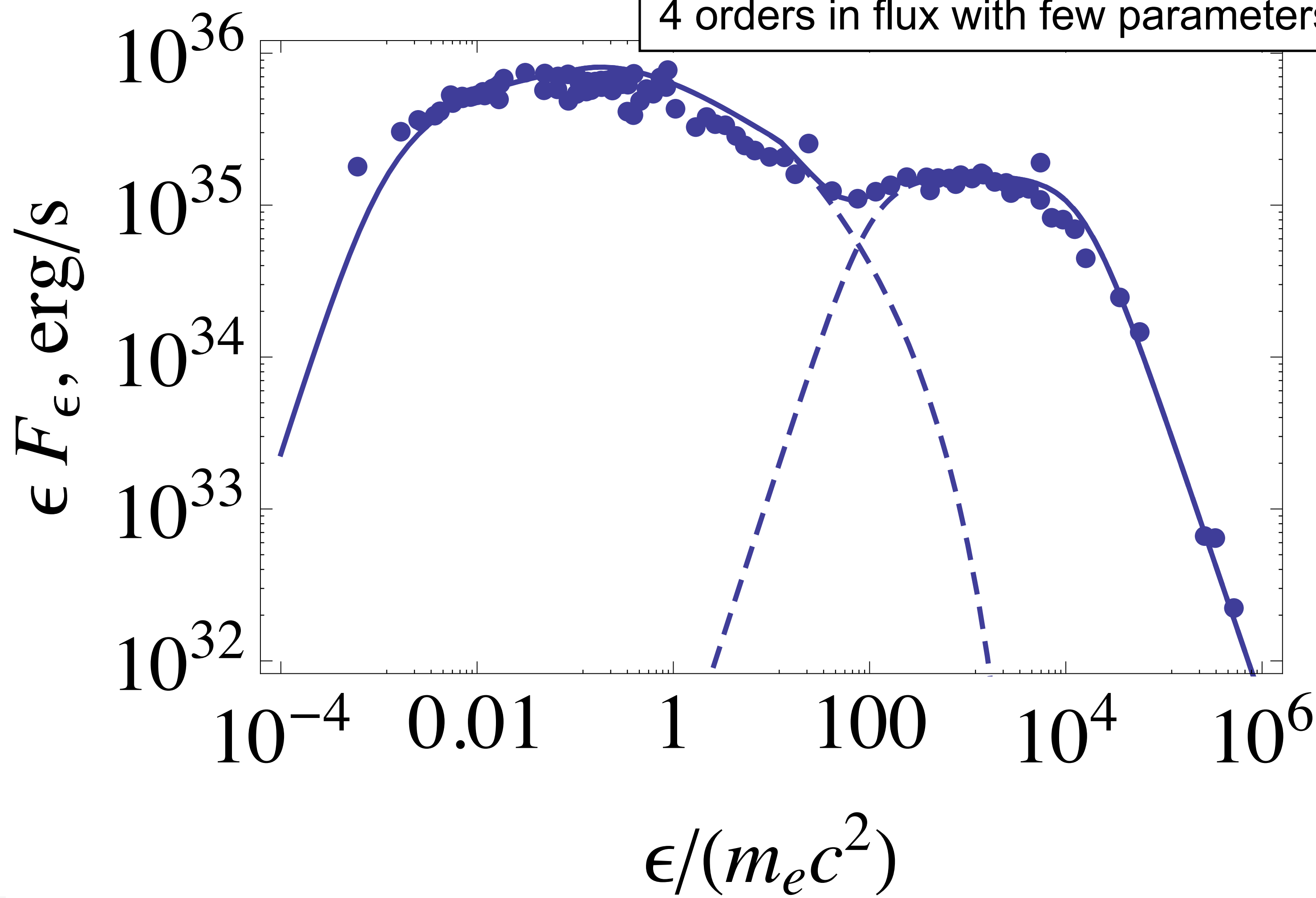




Data fit: 10 orders in energy

Data: Kuiper +, 2001, Fermi, VERITAS

Highly constrained fit, ten orders in energy, 4 orders in flux with few parameters



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Details of the fit

- 4 parameters (R_{em}, gamma, $v_{gyration}$, multiplicity), 4 measurables (energies and fluxes of two bumps).
- Kinematics: cyclotron peak at ~ 100 keV, IC peak at ~ GeV:
- L_X, L_{gamma}:

$$\frac{R_{em}}{R_{NS}} \sim 15$$

$$\gamma \sim 2000$$

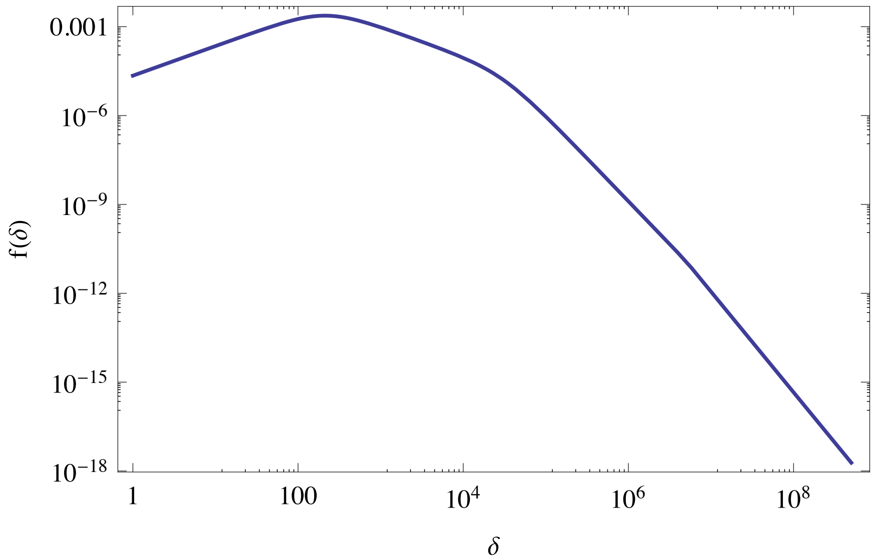
$$\lambda = \frac{8\pi}{b_{NS}} \tilde{\epsilon}_s^2 \frac{\lambda_C}{r_E} \frac{1}{\eta_\Omega} \frac{L_{IC}}{L_X} \left(\ln \left(\frac{\tilde{\epsilon}_{max}}{\tilde{\epsilon}_{min}} \right) \right)^{-1} \approx 10^5$$

$$\beta_0 = \frac{2\sqrt{r_E}\lambda_C \sqrt{\ln \frac{\tilde{\epsilon}_{max}}{\tilde{\epsilon}_{min}}}}{\sqrt{\pi m_e c^3 \Delta\Omega \tilde{\epsilon}^2 L_{IC}^{1/2}}} \approx 4 \times 10^{-5} \Delta\Omega_{-2}^{1/2}$$

cyclotron emission

Measured distribution function **f($p_{\parallel}$)**

- Deep in KN regime: **IC component traces particle distribution**



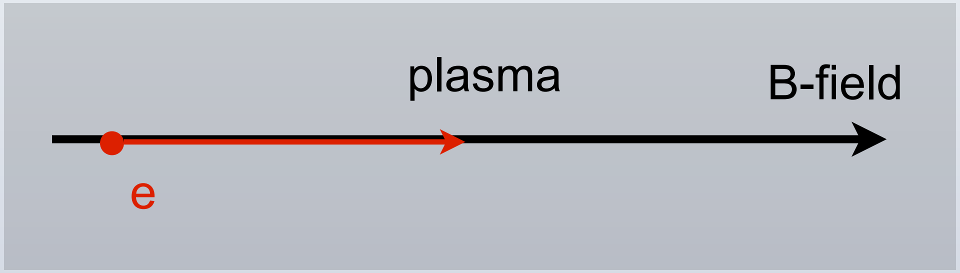
$$f(\delta) \propto \begin{cases} \delta^m, & m \approx 1, \text{ for } \delta_0 < \delta < \delta_1 \\ \delta^n, & n \approx -1, \text{ for } \delta_1 < \delta < \delta_2 \\ \delta^l, & l \approx -3, \text{ for } \delta_2 < \delta < \delta_3 \\ \exp^{-\delta/\delta_3}, & \text{for } \delta_3 < \delta \end{cases}$$

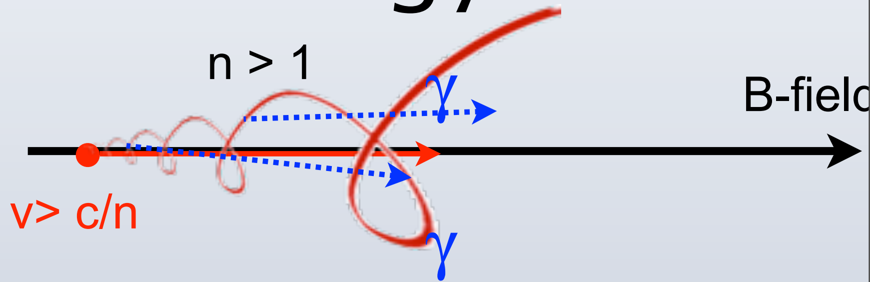
$$\delta_0 \approx 10,\ \delta_1 \approx 10^4,\ \delta_2 \approx 10^6,\ \delta_3 \geq 10^8$$

- plus counter-streaming. **Typical gamma ~ 10^3** (very reasonable)
- **multiplicity: 10^6 -10^7**- highish, but still reasonable, consistent with average ~10^6 need for the nebula
- $\beta_0 \propto (r - R_{NS})^3$ - came from spectral fit. Why gyration?

In progress!

Relating all pulsar non-thermal emission, from radio to VHE gamma rays, 18 orders in energy



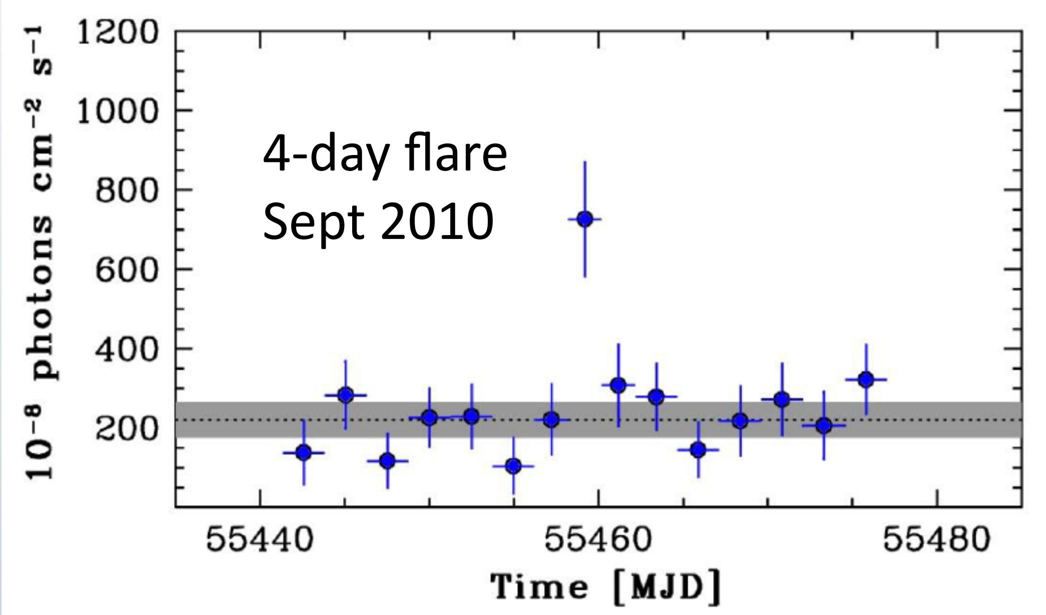


- gyration is excited at anomalous cyclotron resonance (Kazbegi + 91, Lyutikov + 98)
- Relativistic plasma streaming along B-field excites EM waves at the anomalous cyclotron resonance $\omega - k_{\|} v_{\|} = \ominus \omega_B/\gamma$
- Particle goes **up** in Landau levels **and** emits a photon (of negative energy in the center of gyration frame) $\beta_0 \propto (r - R_{NS})^3$
- Alignment of radio and gamma (?).
- **Radio and gamma are intrinsically related!**

Implications:

- Spectral breaks are not due to curvature emission of the maximal energy particles
- Alternative possibility: IC scattering, break due to the details of particle distribution and scattering cross-section (in the KN regime)
- typical gamma ~ 10^3 - very reasonable
- high multiplicity, ~ 10^6 -10^7, but Crab nebula needs 10^6 on average.
- Pair production in the outer gaps
- $\beta_0 \propto (r - R_{NS})^3$ - follows from the theory of radio emission: radio and VHE gamma are related! (18 orders)
- Critique: where are soft photons in non-Crab pulsars? - IC scattering in KN is highly energy dependent, favors UV

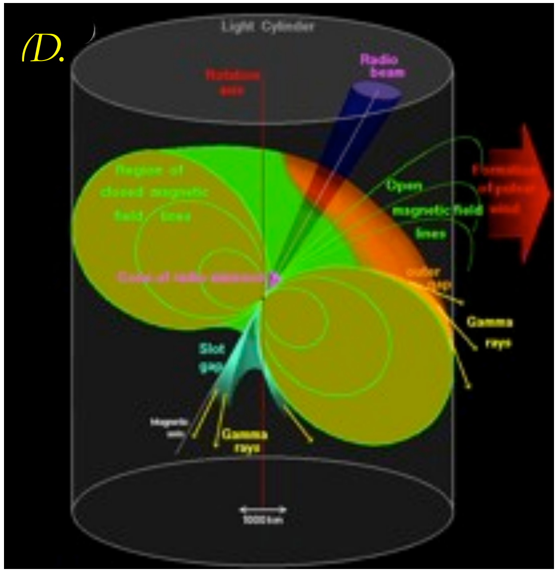
II. Crab nebula flares: evidence for reconnection

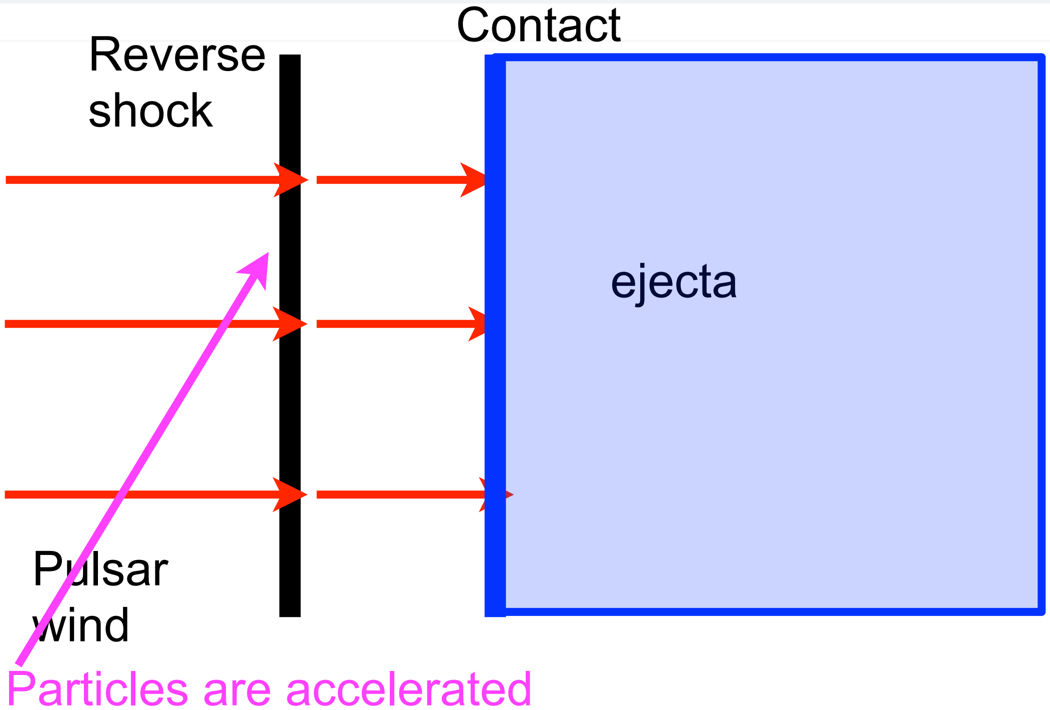


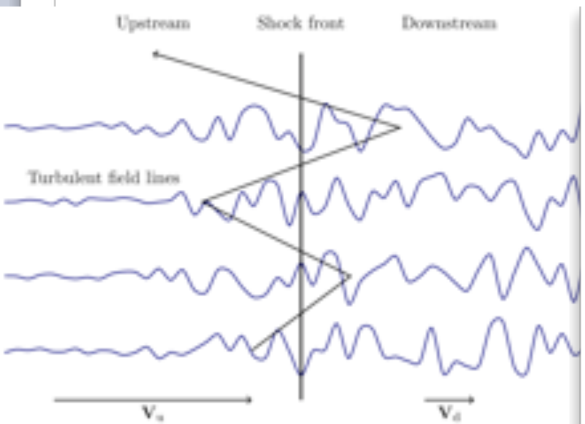
Tavani et al. 2011

- ~ few days increase in 100 MeV-1GeV flux, factor of few-tens
- about once per year
- Nothing at other energies or the pulsar
- Time scales << dynamical time for inner rings (months) ->
  Localized intermittent events - what events?

Current models of pulsar wind: relativistic shock





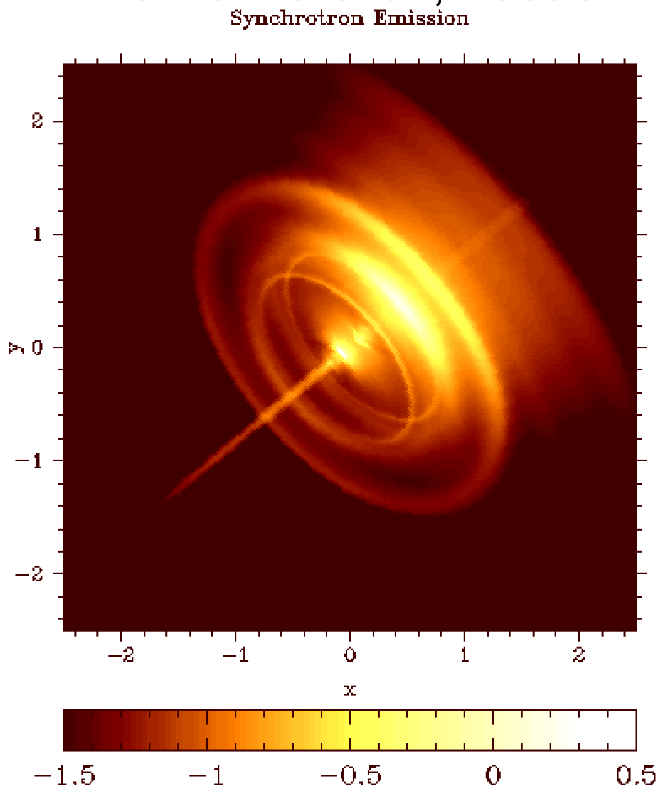


- How much energy is carried by particles, and how much by B-field? $\sigma = \frac{B^2}{4\pi\gamma\rho c^2}$
- Models of pulsar magnetospheres: sigma >>1
- Models of the nebular: sigma <<1
- Small sigma: strong shocks, acceleration by Fermi
- **Acceleration is slow,on time-scale >> gyration**

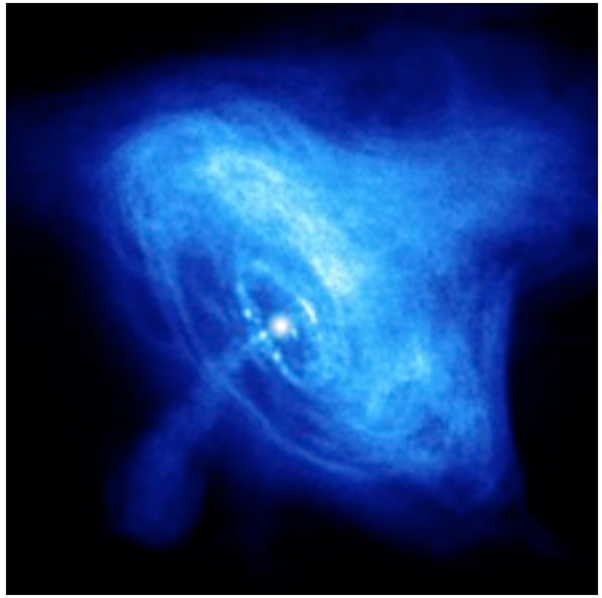
We have a problem...

PWN morphology is well reproduced with low magnetized wind

Komissaov & Lyubarski,
Del Zanna et al., Bucciantini



Chandra image of Crab

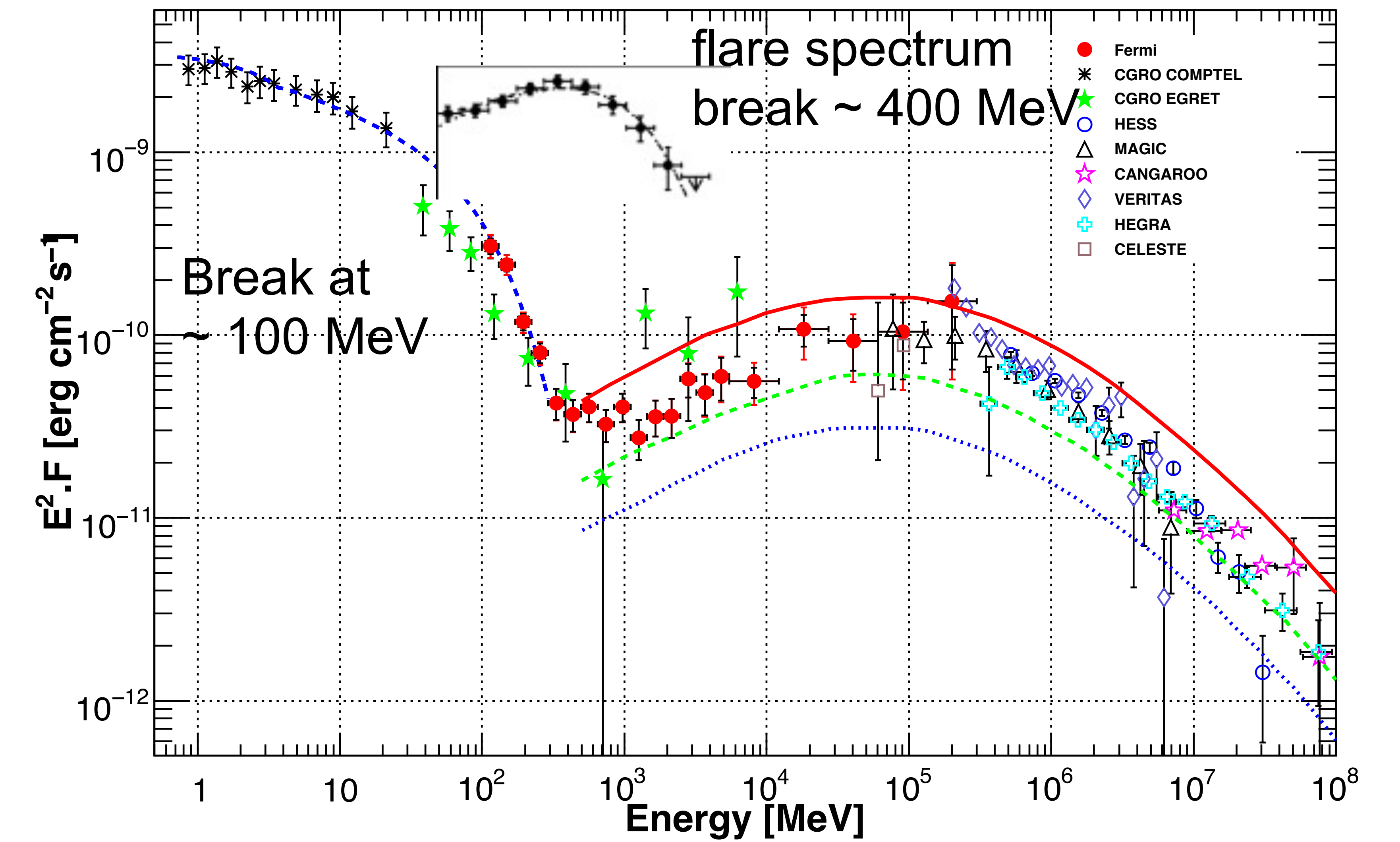


Need low magnetized wind, sigma ~ 0.001

$$\sigma = \frac{B^2}{4\pi\gamma\rho c^2}$$

But: spectrum of Crab nebula

Tavani et al. 2010
Beuhler et al., 2011



Upper limit to synchrotron frequency

Accelerating E-field < B-field

$$eEc = \eta eBc = \frac{4e^4}{9m^2c^3}B^2\gamma^2$$

$$E_p = \frac{27}{16\pi}\eta\frac{mhc^3}{e^2} = 236\,\eta\,\mathrm{MeV}.$$

Lyutikov '10,
Komissarov & Lyutikov '11
de Jager '98 (for shocks)

- Same as Fermi acceleration on inverse gyroscale (requires very efficient scattering, stochastic acceleration: eta << 1)
- **Typically eta < 10^{-2} for stochastic shock acceleration: this excludes stochastic acceleration schemes even for "normal" PWN emission**

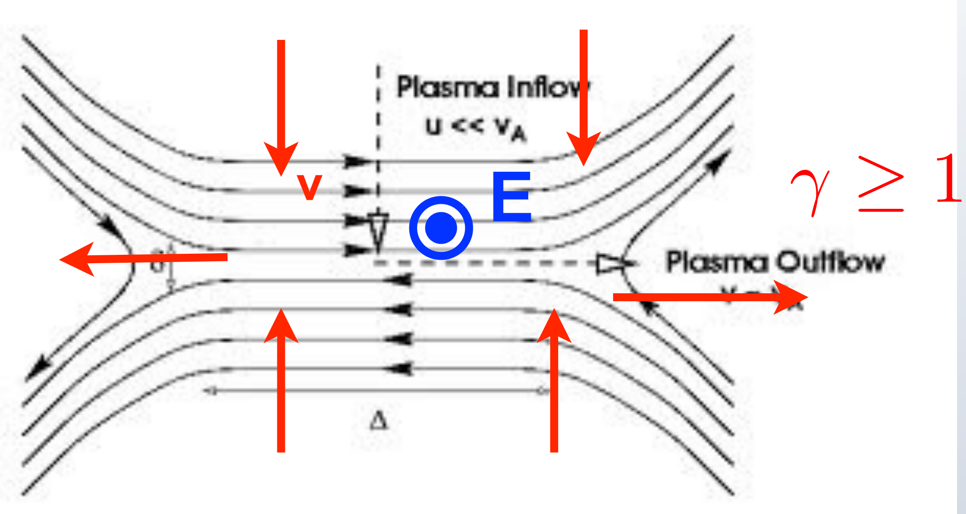
Contradiction: low magnetized pulsar wind can reproduce Nebula morphology, but not the spectrum

Particle acceleration?...

- Highly magnetized, sigma >> 1, shocks are weak, not likely to be efficient accelerators.
- All the energy in the B-field: accelerate particles directly via **reconnection.**

Paradigm change (?): some (most?) particles are accelerated by magnetic reconnection (and not shocks)

Reconnection: efficient, non-stationary



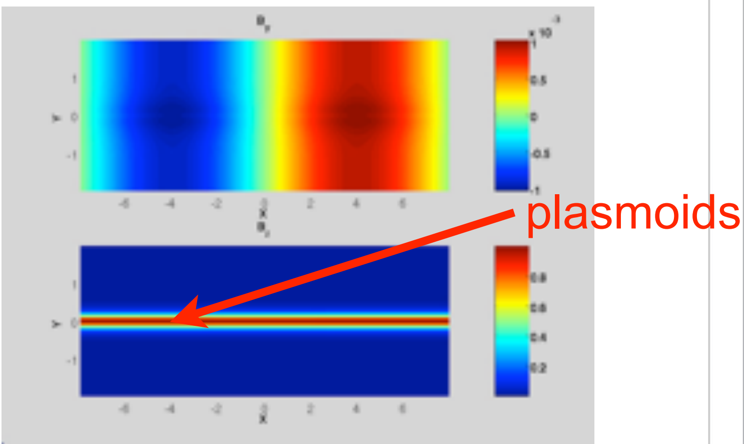
Reconnection in sigma >> 1 plasma: outflow can be relativistic (Lyutikov & Uzdensky 2002, others)

New plasma physics regime: sigma >> 1 plasma.

- **What are dynamic and dissipative properties of such plasmas? - very different from laboratory and space plasmas.**
- Pulsar winds, AGN & GRB jets and magnetospheres of BHs
- Alfven velocity is highly relativistic
  - E-field is dynamically important
  - charge density is important

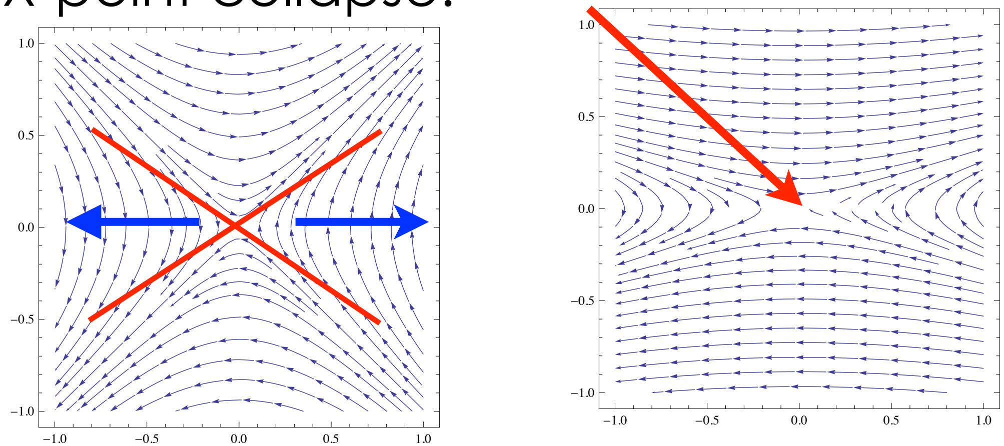
Physical model: collapse of magnetic X-point in force-free plasma

- Current sheet can be unstable to tearing

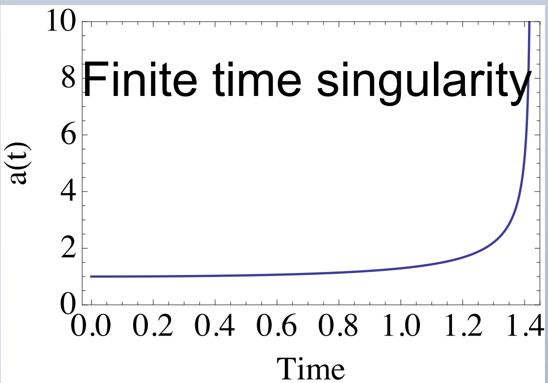


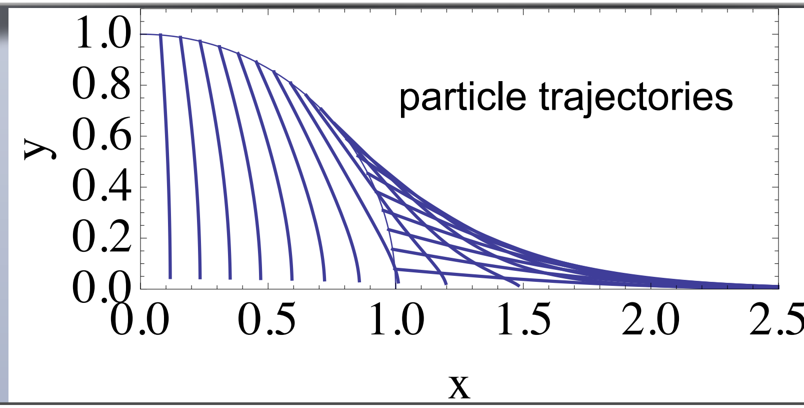
Lyutikov 2003, Komissarov+ 2007

X-point collapse: current sheet formation

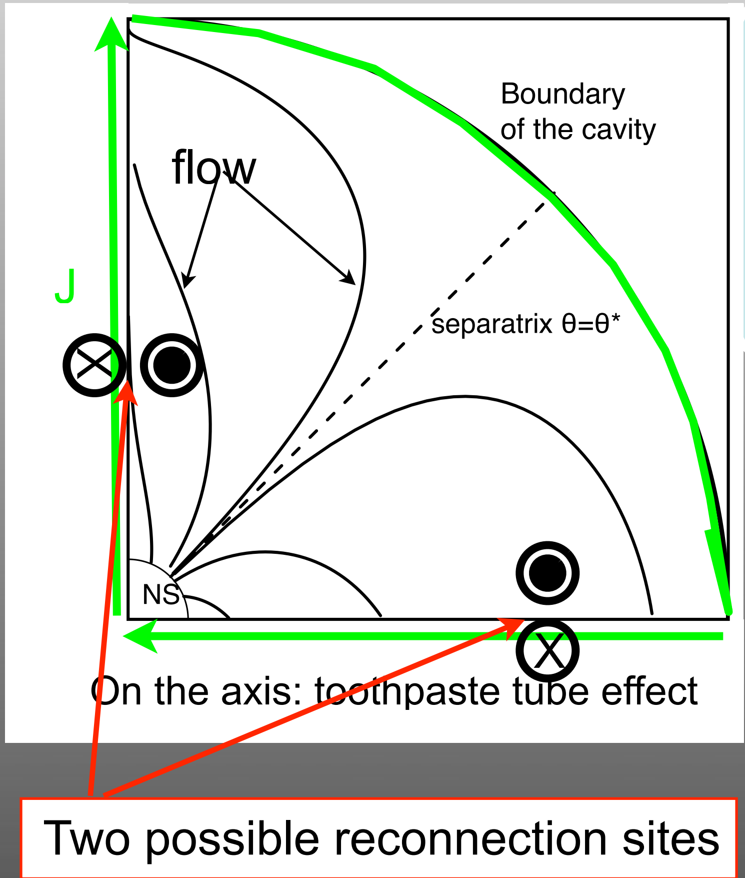


- **explosive** dynamics on Alfven (light) time
- Starting with smooth conditions
- E ~ B_0 (field outside), E>B with resistivity
- Particles drift towards null line





High sigma model of pulsar wind nebulae *(Lyutikov 2010)*



- *Lyutikov (2010): 100 MeV is still too much.*
- *Ideal flow in the bulk, dissipation on boundary*
- "We propose that [...] the excessive magnetic flux is destroyed in a reconnection-like process"

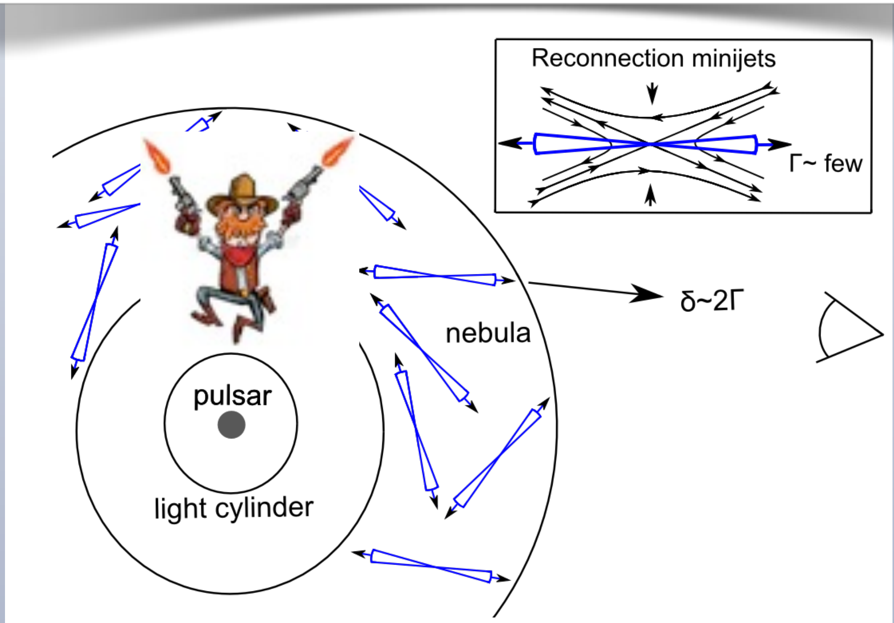
High sigma model of PWNe

- No shocks! (Acceleration in reconnection)
- Relativistic bulk motion of emitting plasma

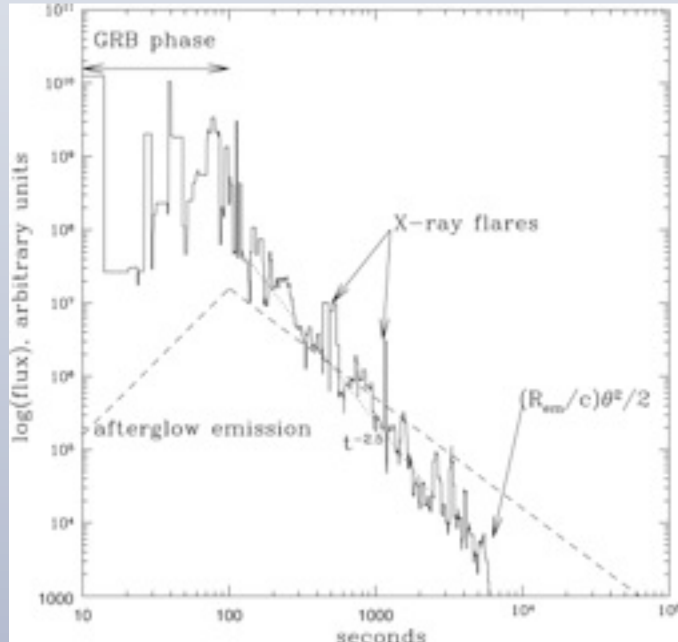
Statistical model: Nebula emission originates in spontaneous relativistic reconnection outflows

Clausen-Brown, Lyutikov 2012

- Relativistic reconnection: Lyutikov & Uzdensky, Lyubarsky, Hoshino
- $E \sim (v_{in}/c)\ B \sim B$
- outflow gamma >> 1
- Can be non-stationary (tearing instability)



GRBs: Prompt emission produced by emitters moving randomly in the bulk frame (Lyutikov 2006).



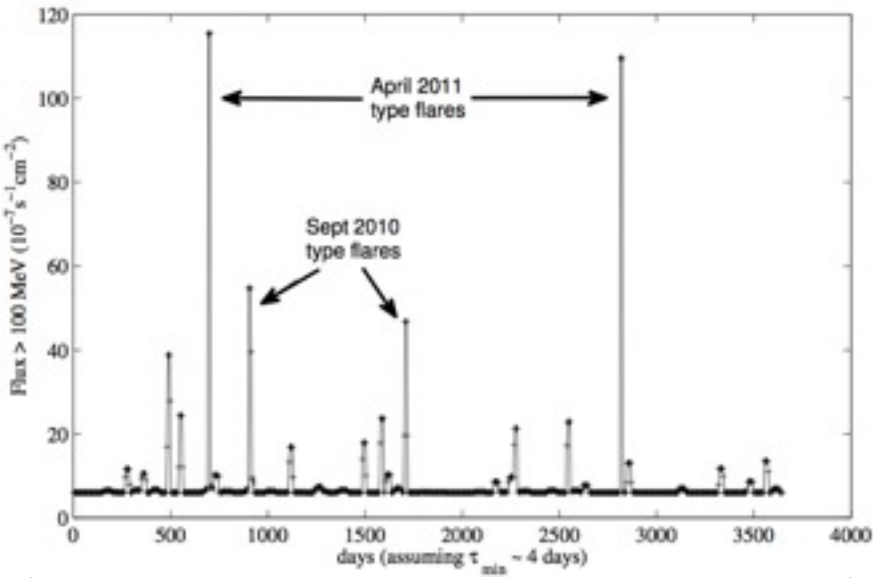
Also can be important for AGNs

Flare statistics: isotropic flares

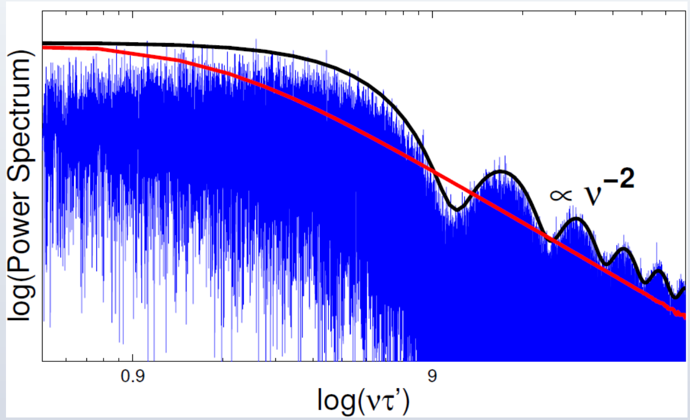
- probability of flare flux

$$\rho(F)dF \propto F^{-\frac{q+1}{q}}dF \approx \frac{1}{F}dF$$

- average flare flux is dominated by bright rare flares.

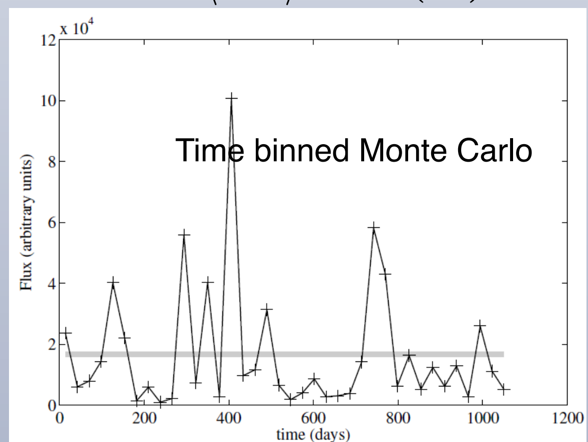


Power-law from shot noise!

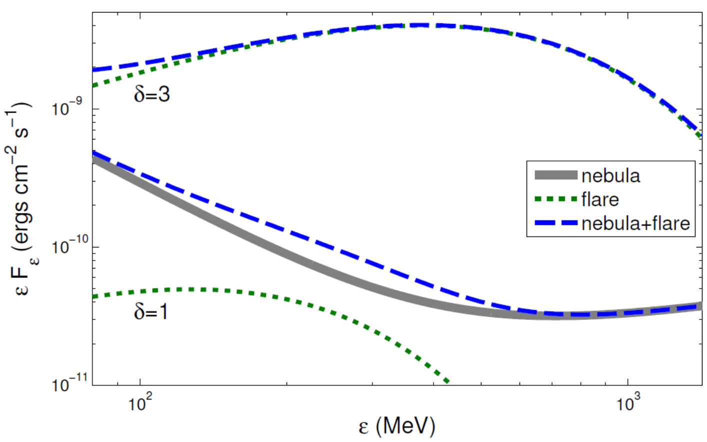


time average → $\langle F(t)\rangle \approx n\tau'(2\Gamma)^{2+\alpha}F'$

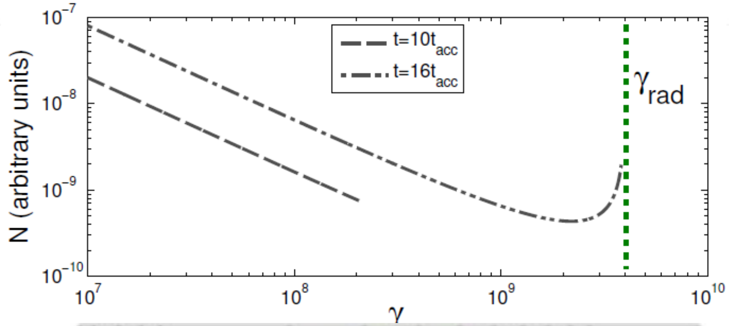
std. dev. → $\frac{\sigma}{\langle F(t)\rangle} \approx \gamma_1 \approx \frac{\Gamma^{3/2}}{(n\tau')^{1/2}}$

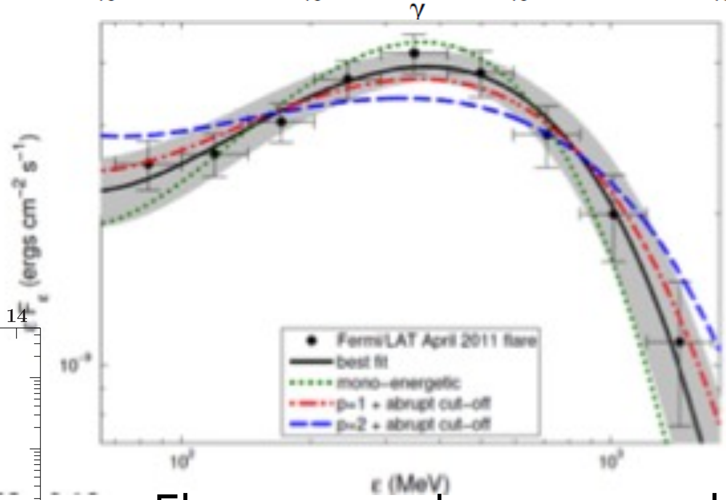


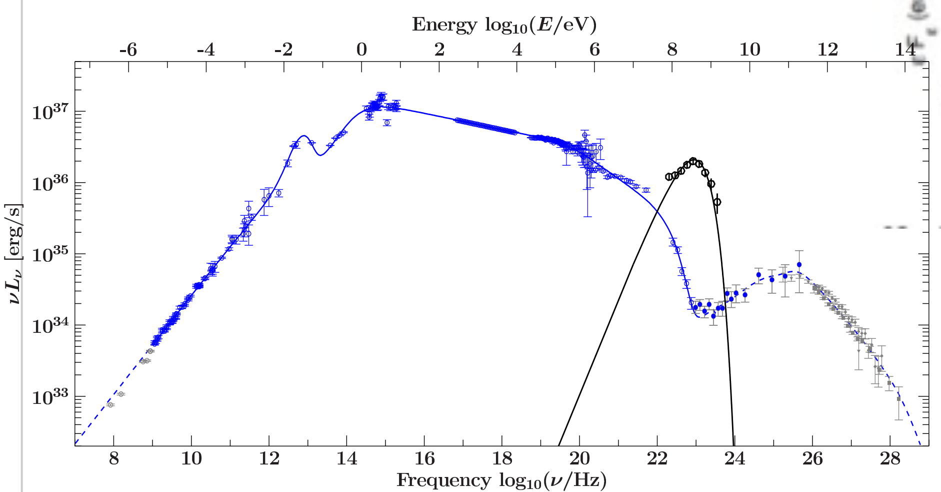
Γ ~ few increases flux and peak energy, **nearly mono-energetic spectrum**



mild boost - huge increase in flux





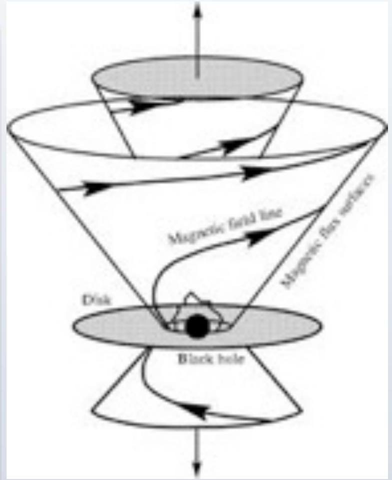


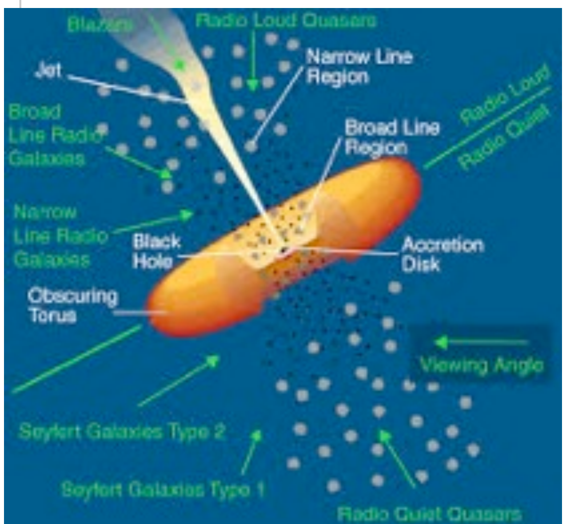
- Flare spectrum: nearly mono-energetic
- Flares are not seen at lower energies

Consistent with observations (Clausen-Brown & Lyutikov 2012)

Relevance to other sources: AGNs, GRBs

- BHs in AGNs and GRBs work similar to pulsar: rotating, magnetized central object produces relativistic magnetized wind
- What is the particle acceleration mechanism in the jets?

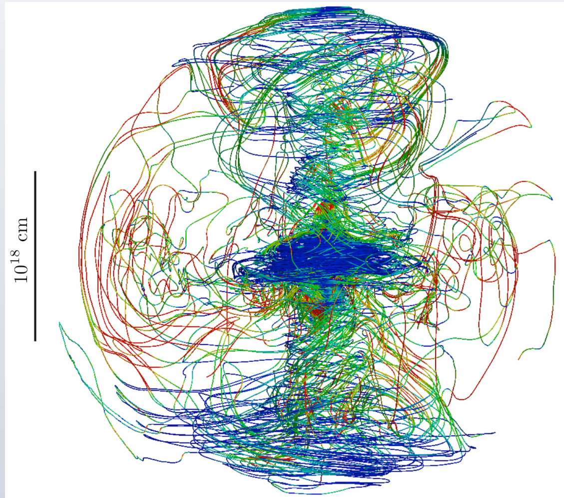


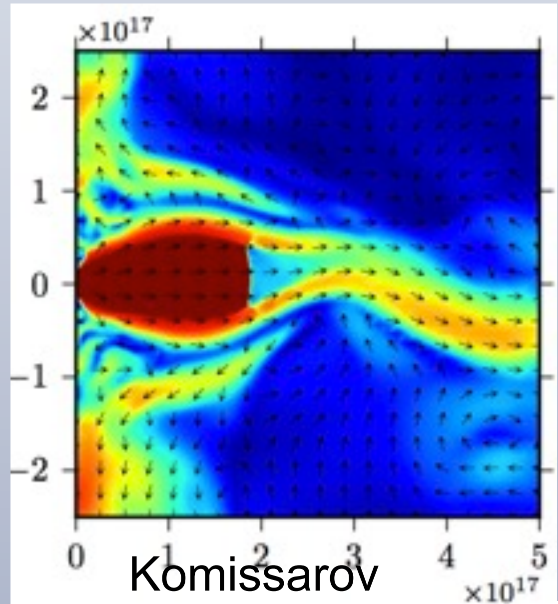


Wednesday, May 29, 2013

What causes flares? - Current-driven instabilities in highly magnetized plasma

- Plasma with B-field is a non-linear anisotropic system, can slowly reach a threshold, then evolve explosively
- Flares are slowly externally-driven, suddenly “self-produced”, not like shocks
  - c.f., Solar flares
- DC-type acceleration in inductive-resistive E-field
- Need acceleration on scale of ~ light day, about 1 degree in polar angle (relativistic motion will help a bit)





Conclusion: paradigm changes (?)

- **Inverse Compton emission may be the dominant high energy emission mechanism in the majority of pulsars**

- **Reconnection is an important, perhaps dominant, mechanism of particle acceleration in PWNe and possibly in other high energy sources.**