The Crab and other Animals

Roger Blandford
Yajie Yuan
Rolf Buehler and Fermi Team
Most of you!

Purdue

Outline

- Observations of compact flares
- Crab Nebula - an introduction
- Crab Nebula – particle acceleration
- Knots, tangles and spheromaks
- Evolution, acceleration and radiation
- Instability and runaway acceleration
- MHD and kinetic simulations
- Summary

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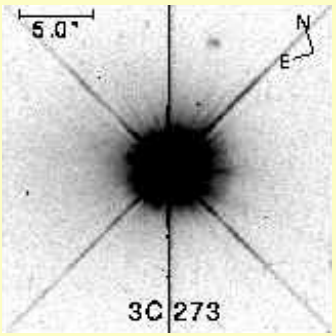
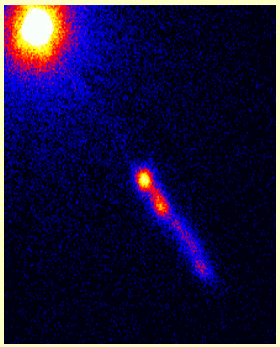
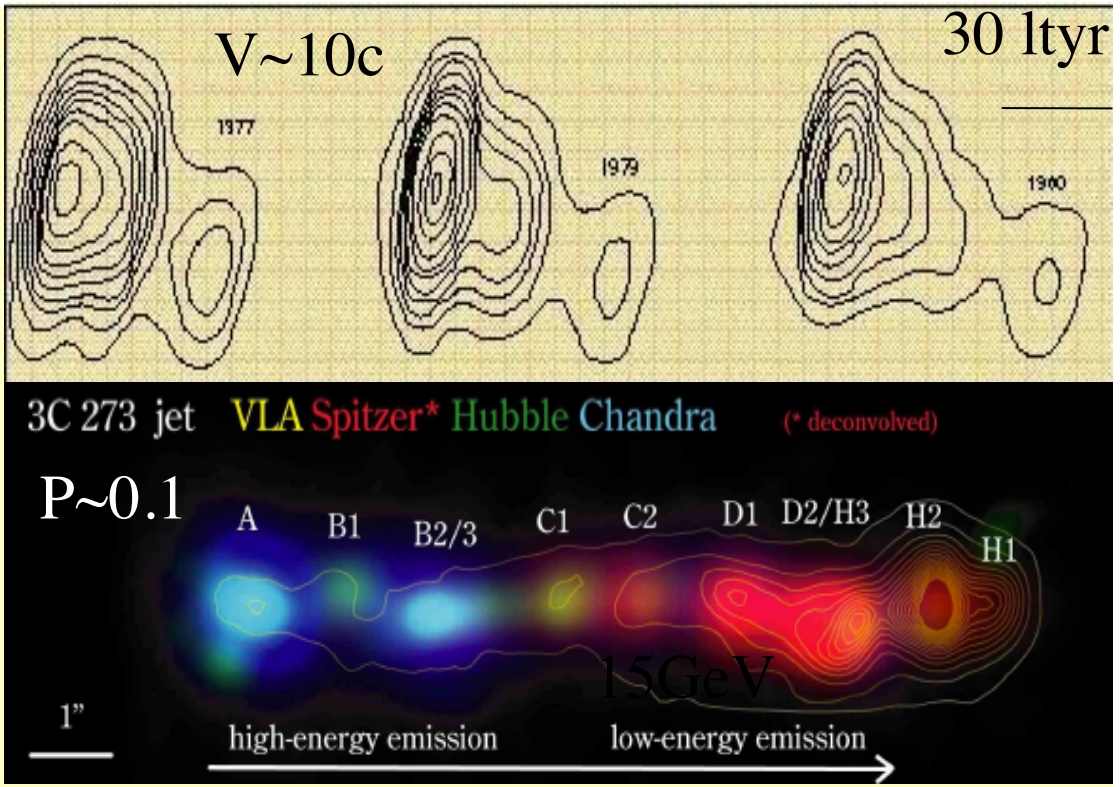
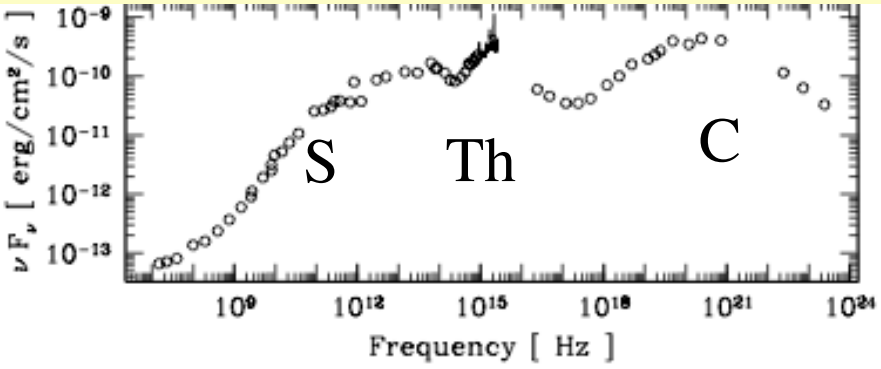


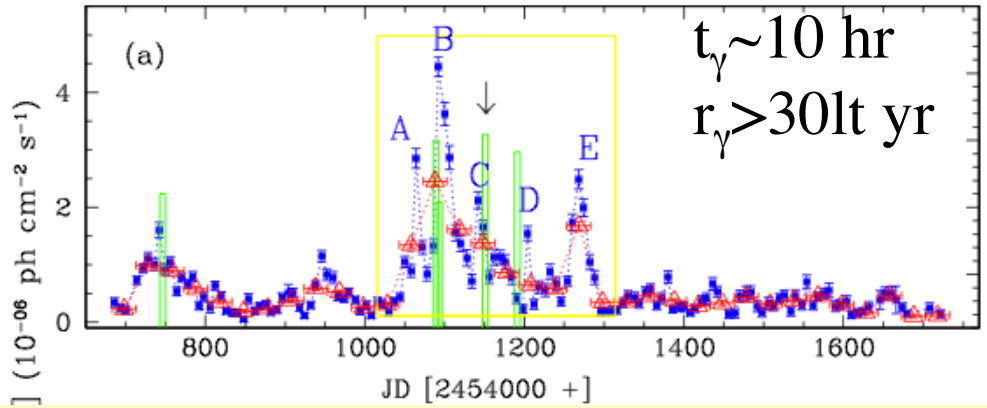




$L_Q \sim 10\, L_{gal} \sim 3 \times 10^{12} L_{sun}$

$M_{BH} \sim 10^9\, M_{sun} \sim 1.5$ lt hr



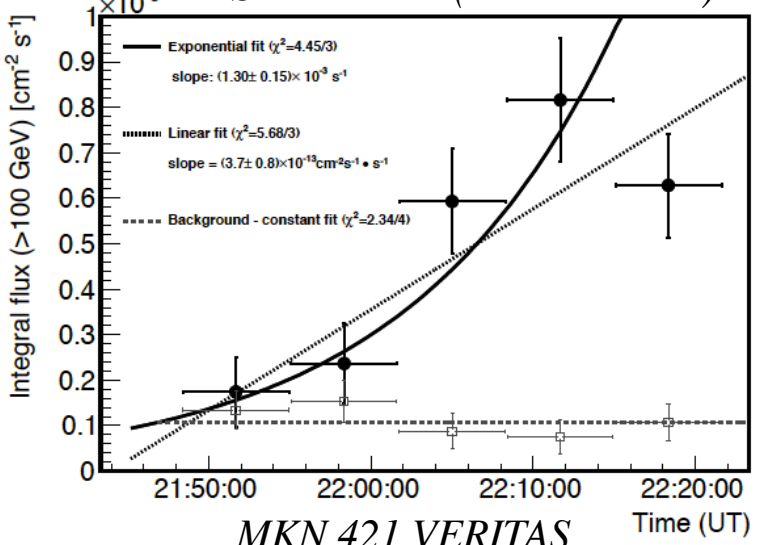


25 kpc

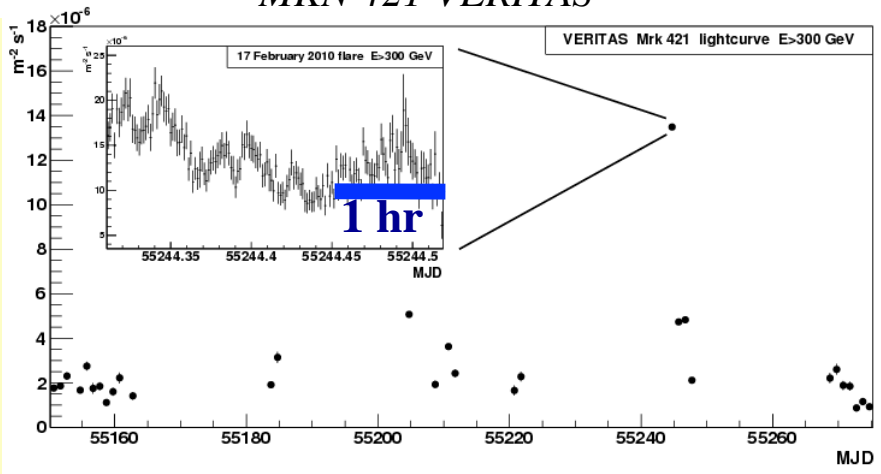
TeV variation

- M87
  - 1 day
- PKS 1222+21
  - 10 min
- MKN 501
  - 5 min?
- PKS 2155-304
  - 2 min?
- MKN 421
  - Radio –TeV hr - min? 20 X

PKS 1222+21 (Aleksik et al)



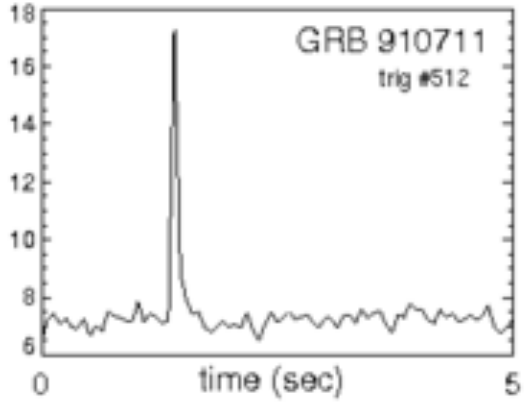
MKN 421 VERITAS

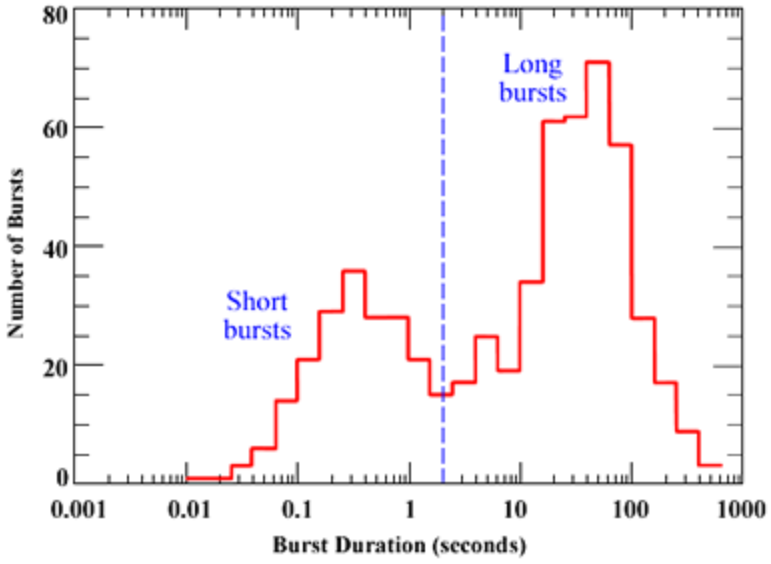


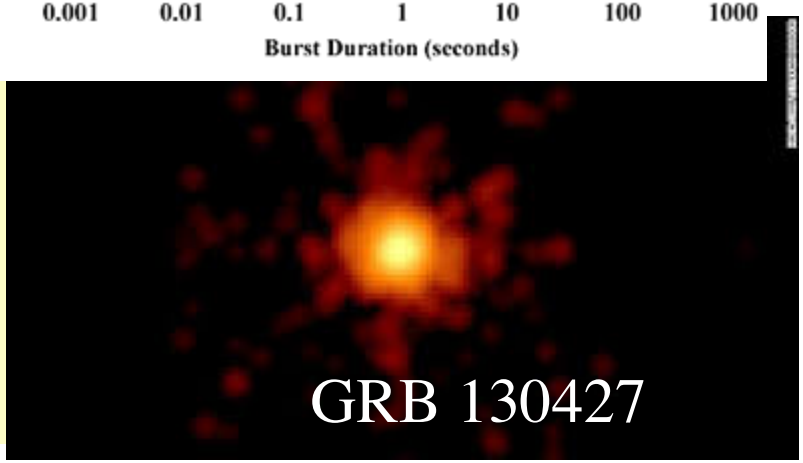
$E_{rad} >> P(ct_{var})^3$

Gamma Ray Bursts

- Long burst core collapse SN
  - Jets with γ ~1000?
  - Rapid variability; high efficiency
- Short bursts NS-NS??
  - Hard spectrum
  - Small SFR/no SN
  - Delayed X-ray emission
  - Fermi-GBM statistics
  - Tidal capture events?
  - Gravitational radiation
  - Neutrinos



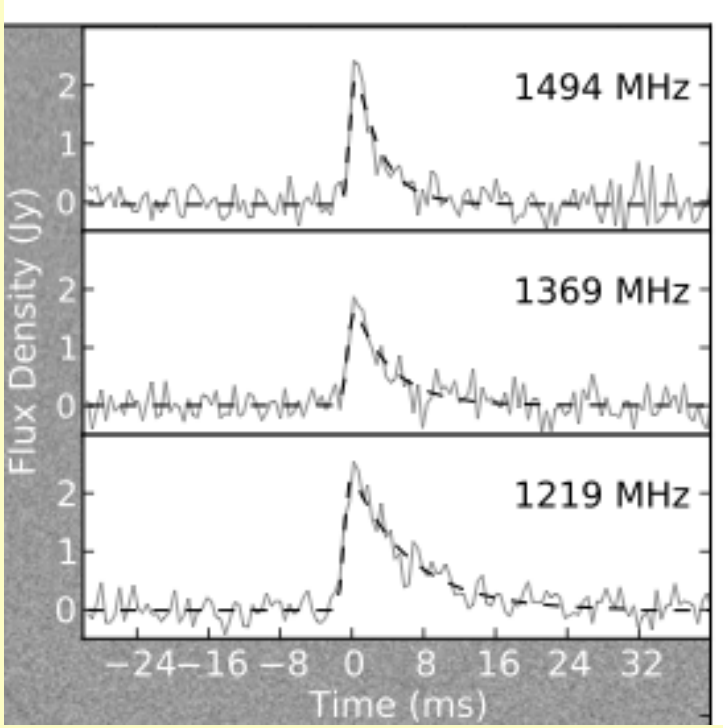




Fast Radio Bursts

- New population of apparently high redshift radio transients
- Identifications unknown but dispersion and scattering consistent with cosmological origin
- ~ 10^{39} erg radio emission in ms
- ~ one every five minutes
- Many possible sources: WD-WD, NS-NS, NS-BH mergers, magnetar explosions…

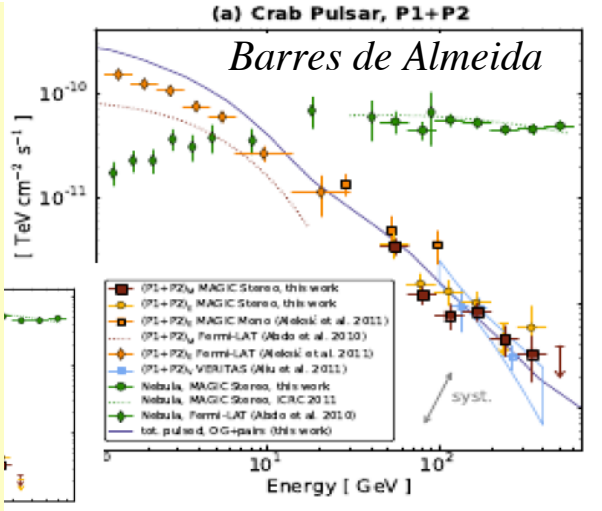
(Lorimer et al 2007, Thornton et al 2013)

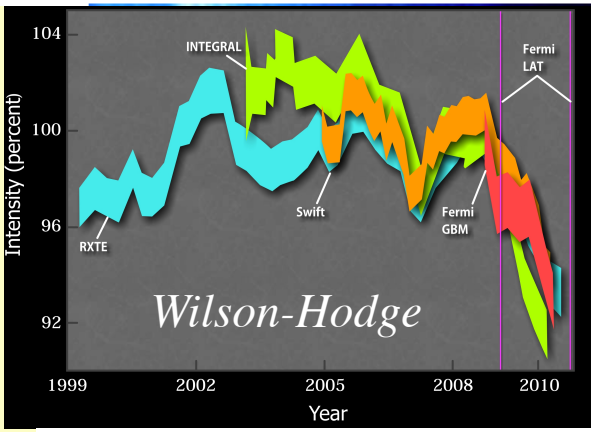


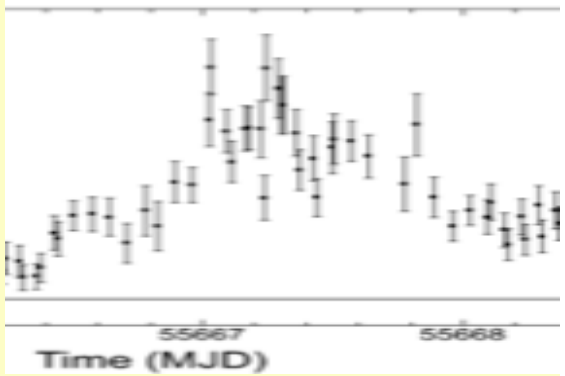
Crab Pulsar and Nebula

Three Surprises

- Crab pulsing at 400 GeV
  - Curvature radiation to ~GeV only
  - Mind the gap
- Secular decline in Crab flux
  - 30 yr timescale in 1000yr source
  - Unit!
- ~400MeV Crab flares
  - 1-10hr variation in 10 lt yr nebula
  - Extreme particle acceleration

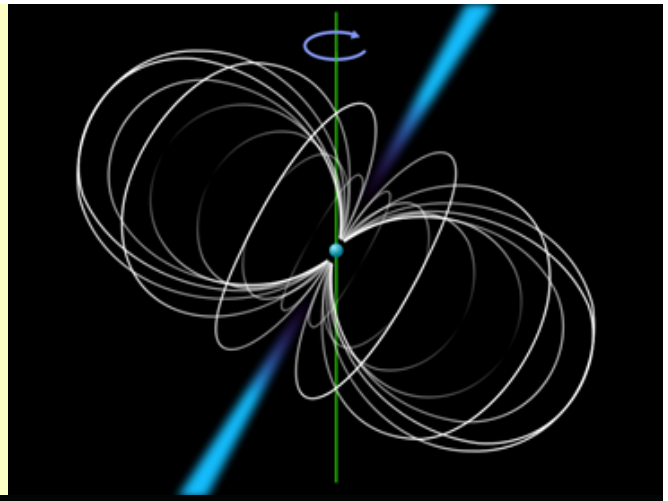


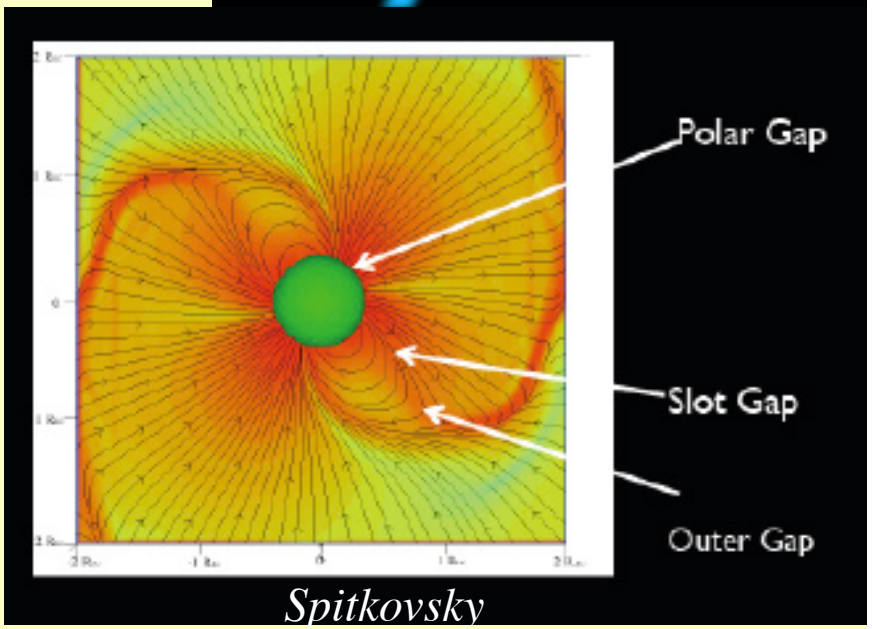




Crab Pulsar

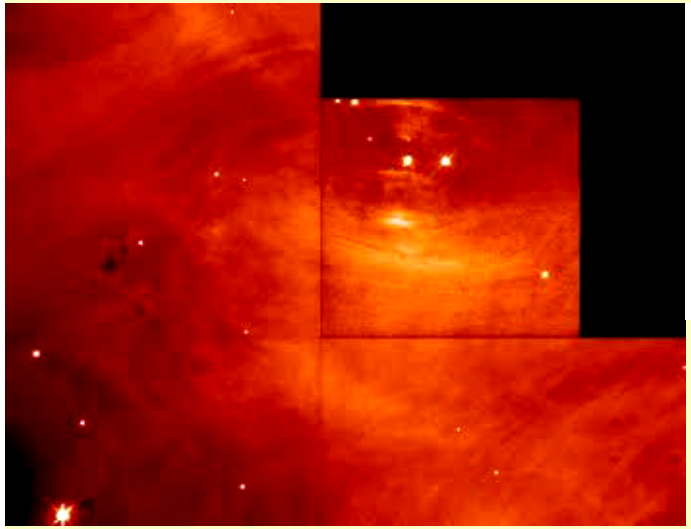
- Discovered in 1968
  - Turning point in history of astronomy
  - Predicted by Pacini
- 1.4 M_{sun}, 12km neutron star
  - 30 Hz spin frequency
  - Light cylinder $R_L = c/\Omega \sim 100\ R_{NS}$
  - 100MHz – 400 GeV pulsation
  - Steady slow down
  - 200 MT surface field; 70° inclination?
  - ~ 50PV; 300TA; 2×10^{31}W ~ $-I\Omega\Omega'$
- Implications of 400GeV pulses
  - Inverse Compton scattering *(Lyutikov)*
  - Dissipation R_L? *(Aharonian)*

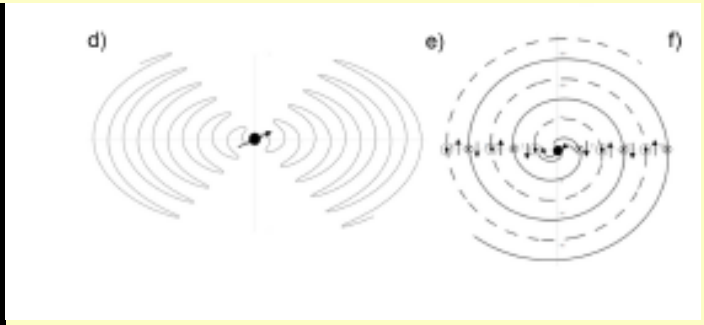




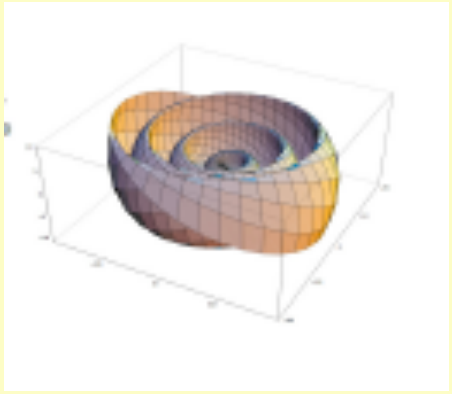
Spitkovsky

Restless Crab Nebula



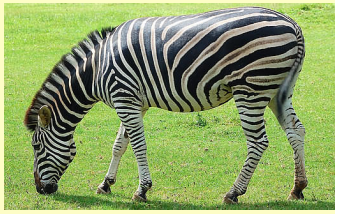


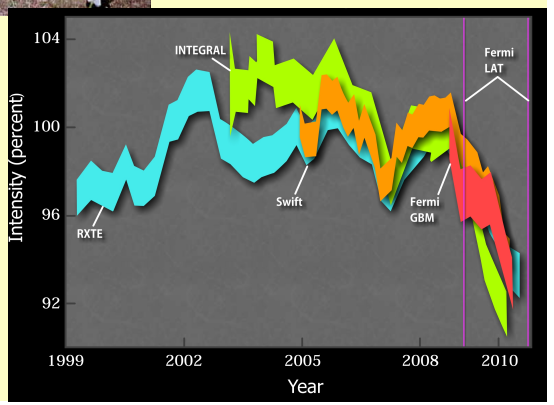
Spitkovsky



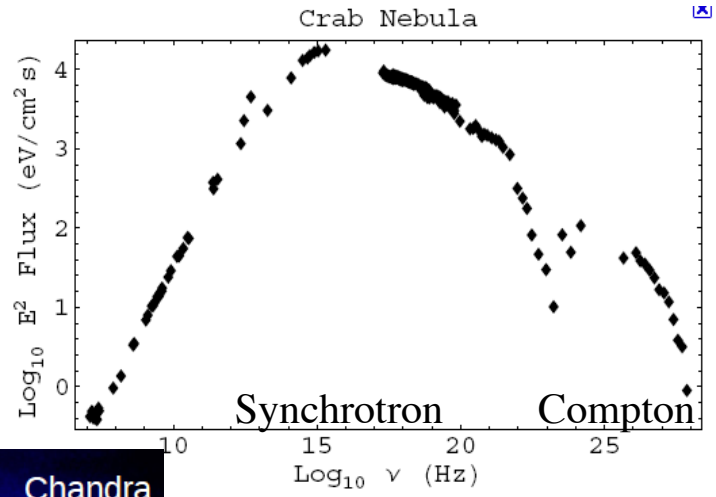
Arons, Komissarov

- What is the nature of the outflow?
  - EM, e^+/e^-, p, Fe
  - What is $\sigma=B^2/\mu_0 n\gamma mc^2$?
- Where do currents close?
  - Wind is current not voltage source
  - Current is AC **and** DC
  - Stripes and toroidal
- Are currents "industrious" or "prodigal"?
  - J x B or -E.j

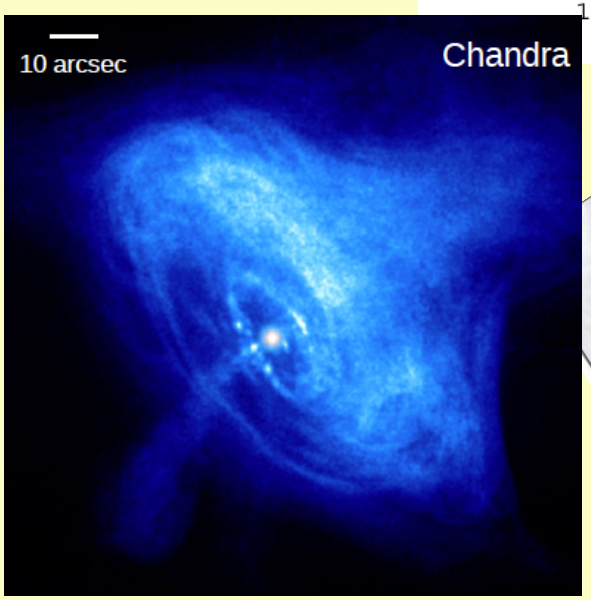


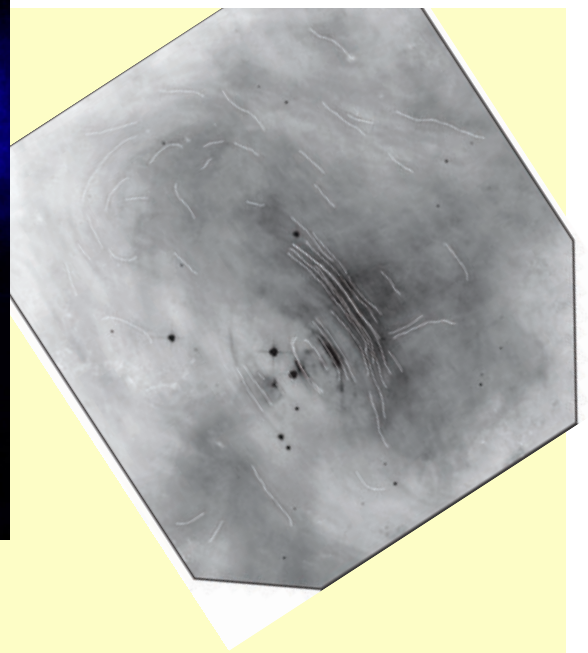


Modeling the Nebula

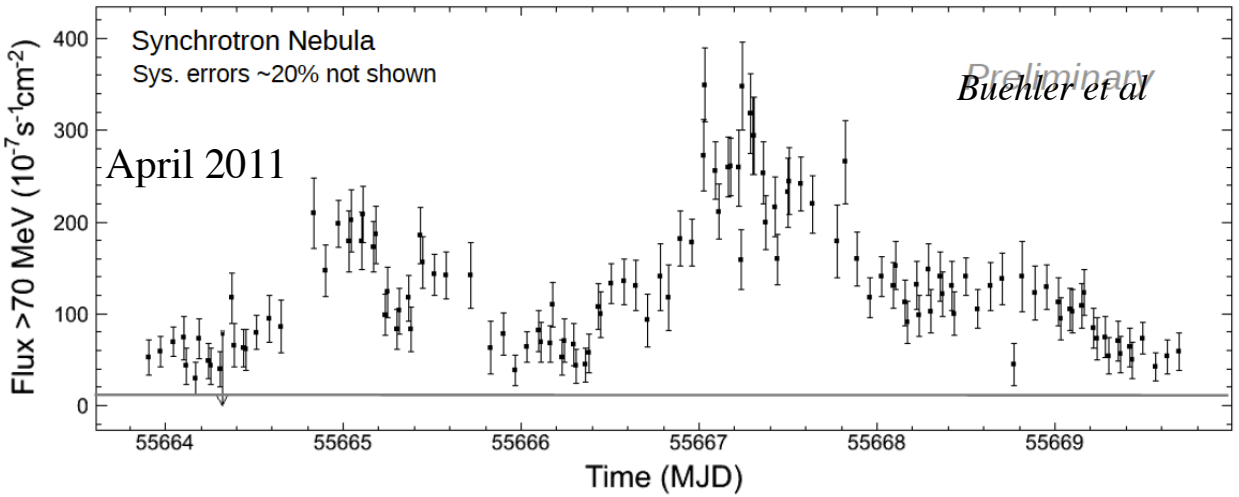


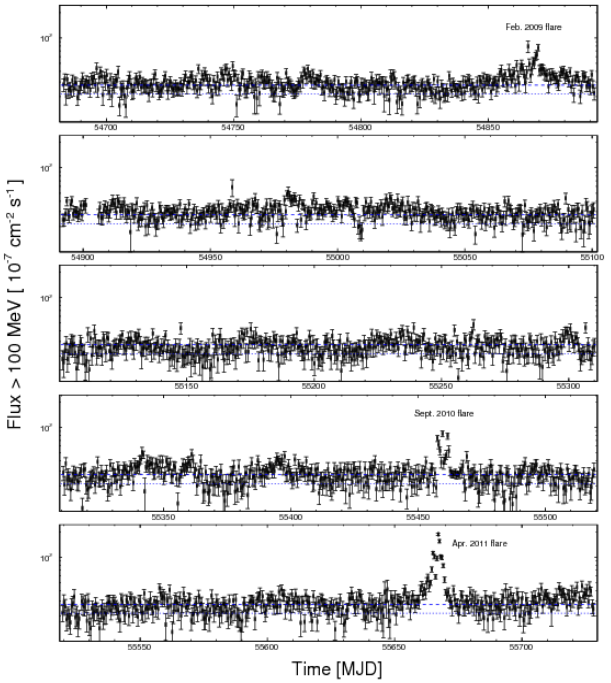
- **Spectral fitting**
  - **Synchrotron:Compton =>B<Beq**
    - Inhomogeneous
- **Flux supply**
  - **No dissipation**
    - $\sigma < 0.001$, $\gamma \sim 10^6$
  - **Dissipation**
    - $\sigma < 100$
    - Axis
      - Jet
      - Kink instability *(Begelman, Lyubarsky Komissarov)*
    - Equator
      - Torus
      - CurrentSheet *(Arons)*



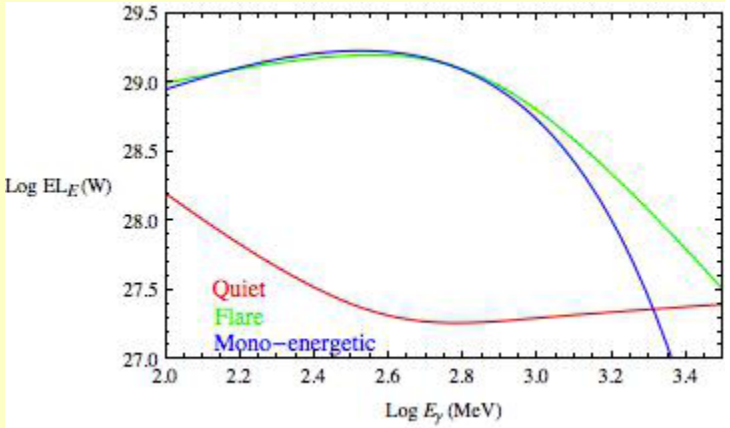


Flaring behavior





- **1-10hr timescale depending on definition**
  - **Are these flares or end of power spectrum?**
- **Only seen at 0.1-1 GeV energy** *Weisskopf , Max, Bietenholtz…*
  - **No associated ROX variation yet**
- **Peak power~0.01 L_{neb}**
  - **Need >0.1 sterad if from wind**
- **Flare energy ~ U_{neb} x10^4 ltd^3**
  - **Need overpressured region or beaming**



Turbulence Spectrum

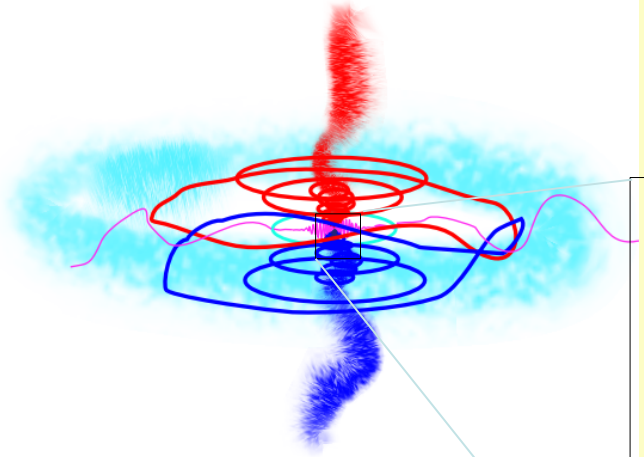
- Top Down
  - Large loops from wind ->small loops
    - cf fluid turbulence
  - Flares are "intermittency"
- Bottom Up
  - Tangled field from wind
    - Variable radial velocity
  - Reconnect, rearrange
    - Unknot, untangle?
- How do we dissipate the flux?

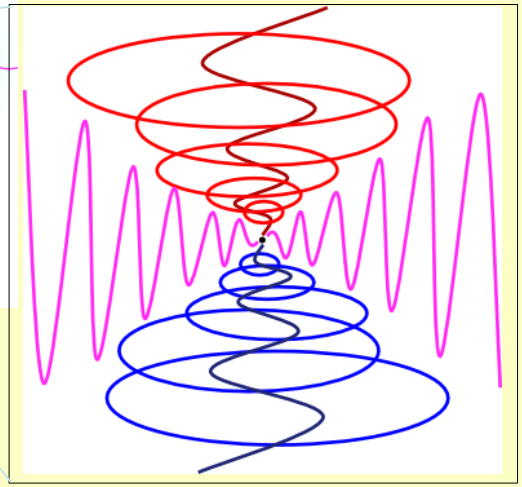
Crab Pulsar and Nebula

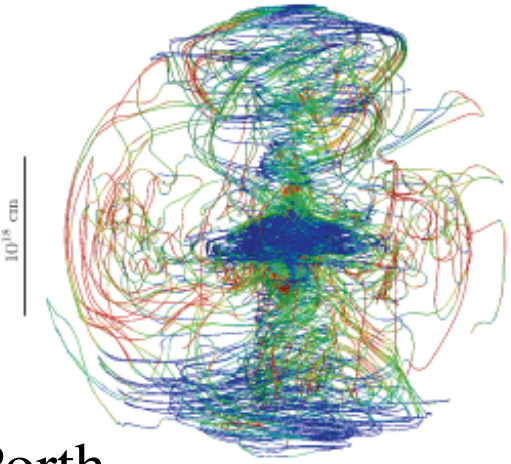
- **Pulsar:** ~50 PV, ~300TA ~2×10^{31}W
- **Nebula:** $L_{10eV} \sim 10^{31}$W, ~10^{42}J, ~1000yr
- **Synch:** B~100nT, E_{10eV}~1TeV, t_{cool}~10 yr
- **UV-X:** $N_E \sim E^{-3.4}$; $S_E \sim E^{-2.4}$
- **R-IR:** $N_E \sim S_E \sim E^{-1.6}$
- **γ-ray:** $10^{27} \rightarrow 10^{29}$ W
- **Flare:** E_{300MeV}~3PeV; r_L~ lt day ϕ_{cool}~0.2

σ? β?

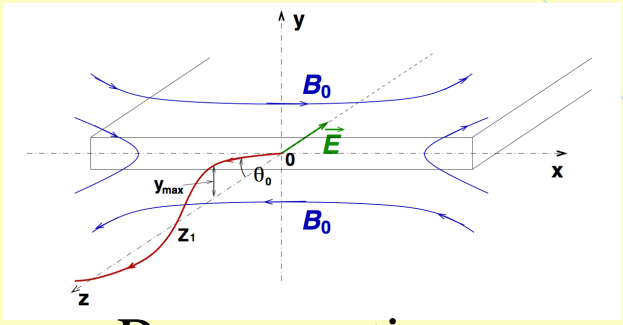
Magnetic Flux Removal?



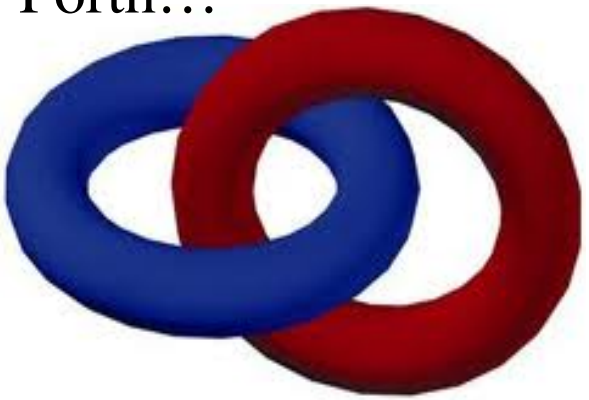




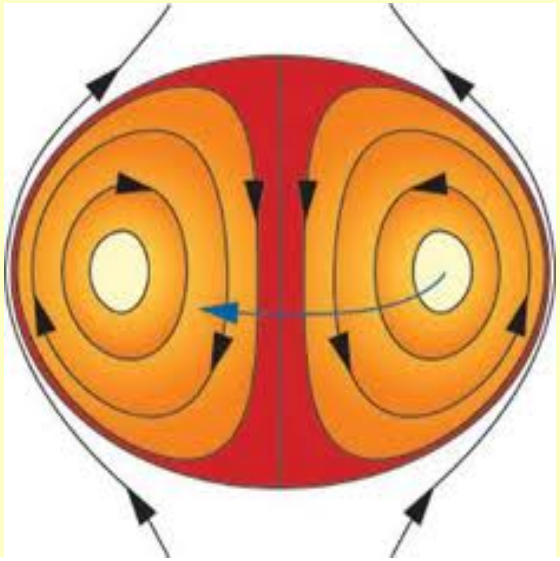
Porth…



Reconnection



Spheromak



$$K \equiv \int \mathbf{A}\cdot\mathbf{B}\, dV = 2\phi\psi$$

Steady reconnection of braided loops of magnetic flux at all latitude create complex network of linked islands/knots…

Woltjer/Taylor
Overpressured
Persistent

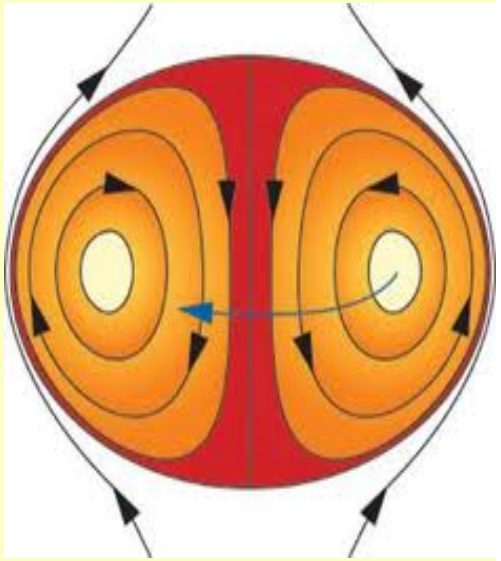
Knots and Tangles

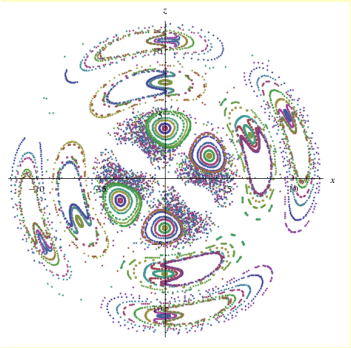
- Knot (eg trefoil)
  - Describable by polynomials
    - Tait, Alexander, Jones…: $t+t^3-t^4$
  - Require reconnection to create and destroy
    - Slow

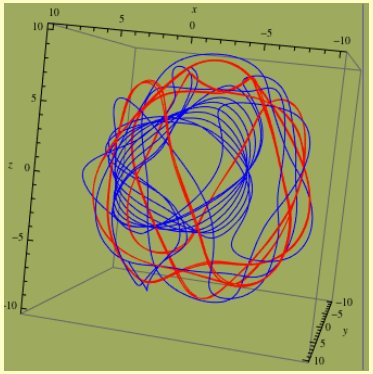
- Tangle/tonk/unknot (eg slip knot)
  - Can become unstable and transition to lower energy configuration at speed of light
  - Create E > c B? and runaway electron acceleration throughout extended volume
  - Magnetic energy -> γ-rays
  - Followed by implosion, chain reaction?

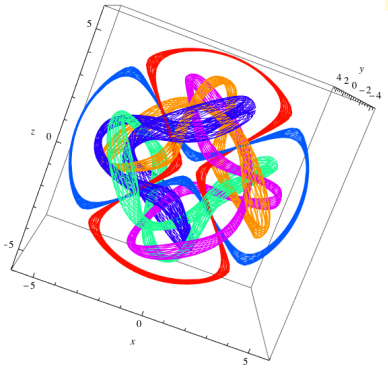
Force-Free Equilibria

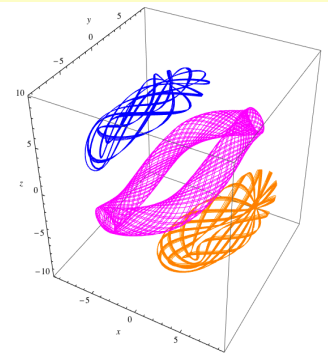
- Family of spheromak solutions
  - n, l, m, s!
- Magnetic ropes –field confined to nested surfaces
- Chaotic field
- Is this robust in the presence of turbulence?

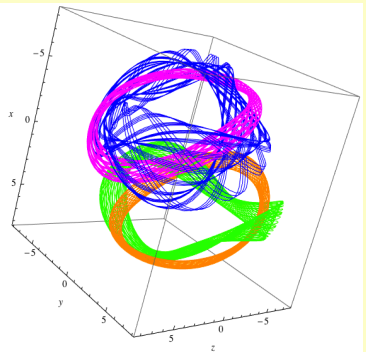


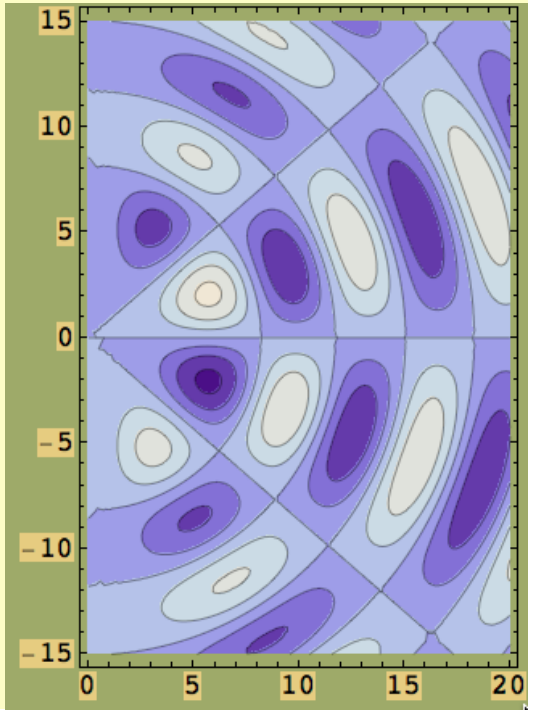




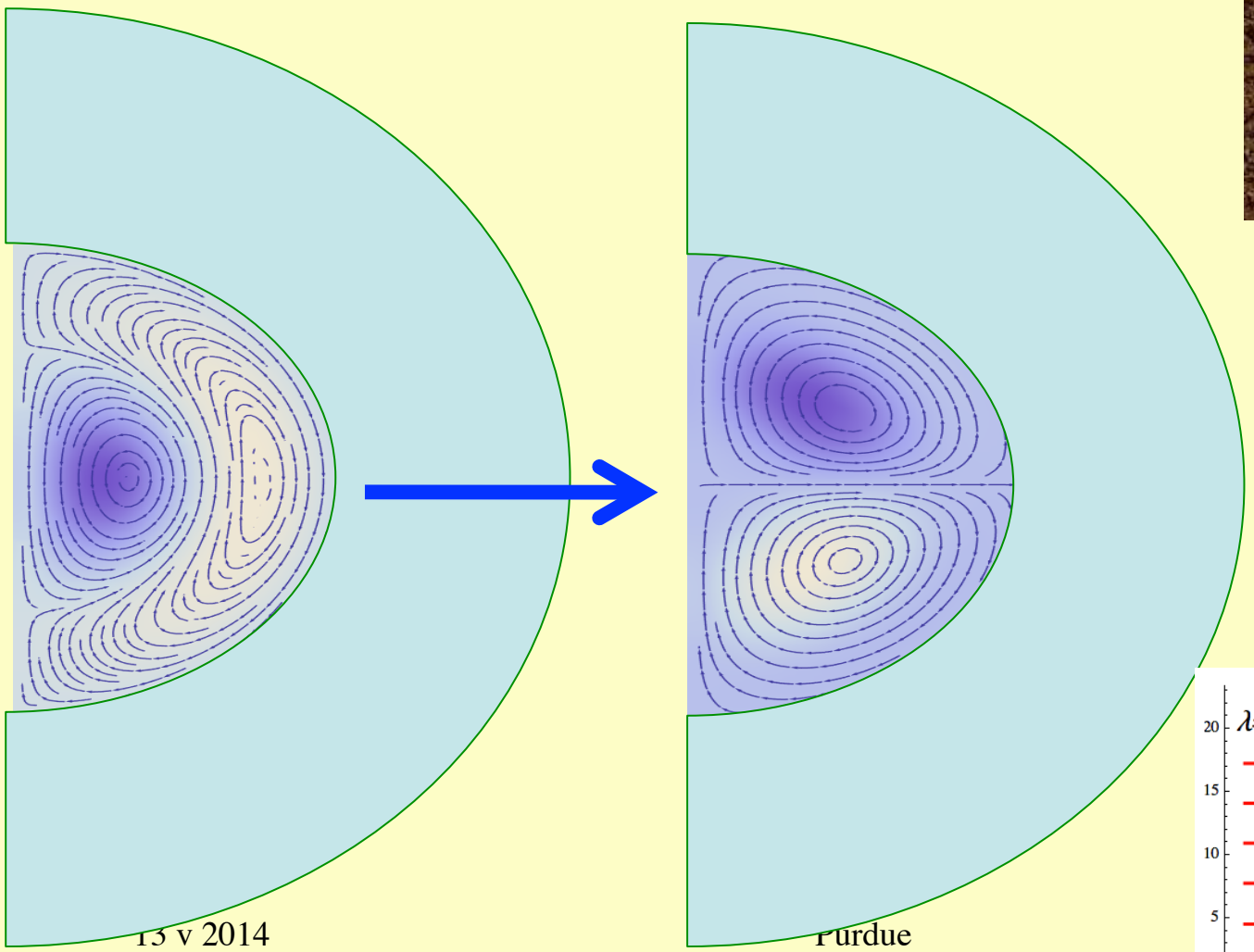


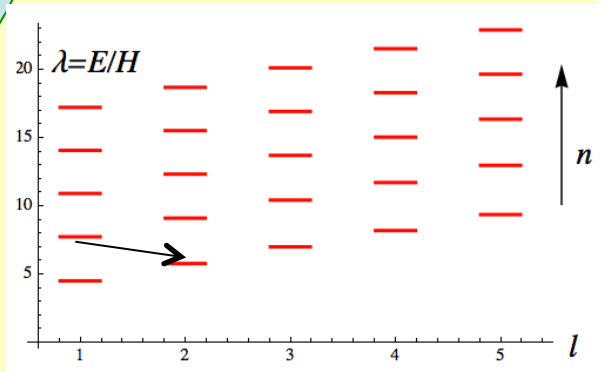






Permitted Transition





Aside on MHD

- Most discussions assume isotropic pressure
  - $P \sim n^{\gamma}$; γ =4/3, 5/3, for ER, NR
  - Appropriate when collisional
- Nebula plasma is strongly collisionless
  - Pressure anisotropic. $P_{||}$, P_{+} when $r_L \ll L$

$$\rho \boldsymbol{a} = \rho \boldsymbol{g} - \nabla \cdot P + \rho_e \mathbf{E} + \mathbf{j} \times \mathbf{B}$$

$$\Rightarrow \boldsymbol{j}_{\perp} = \frac{P_{||}\, \boldsymbol{B} \times (\boldsymbol{B} \cdot \nabla)\, \boldsymbol{B}}{B^4} - \left[\nabla \times \left(\frac{P_{\perp}\, \boldsymbol{B}}{B^2}\right)\right]_{\perp} + \frac{P_{\perp}\, \boldsymbol{B} \times \nabla B}{B^3} + \frac{\rho_e\, \boldsymbol{E} \times \boldsymbol{B}}{B^2} + \rho \frac{\boldsymbol{g} \times \boldsymbol{B}}{B^2} + \rho \frac{\boldsymbol{a} \times \boldsymbol{B}}{B^2}$$

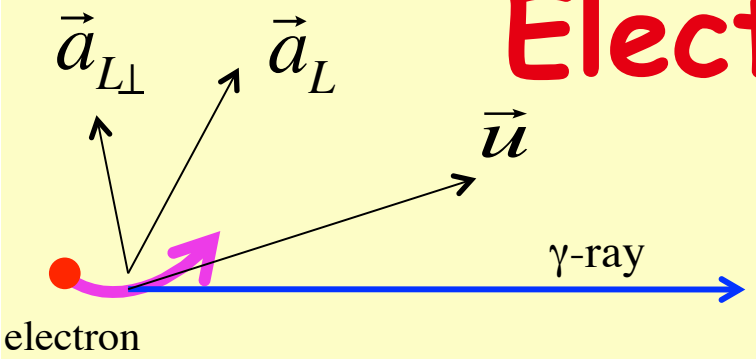
curvature magnetization gradient ExB gravity acceleration

  - $P_{||} \sim n^2 B^{-1}$; $P_{+} \sim n B^{1/2}$ … changes dynamics, stability…
  - When $r_L \sim r$, compose current from orbits (cf stars!)

Particle Acceleration/Dissipation

- Spheromak+resistance
  - U_{mag} -> heated plasma -> radiation
  - Isochoric vs isobaric
  - Implosion?
- Collision frequency
  - Electrostatic waves from counterstreaming pairs
  - Gyroresonant scattering
  - Firehose modes
  - Mirroring
- Low pitch angle particles may runaway
  - dominate dissipation?
  - $E \sim B\,R / t \sim (mc/e)d\gamma/dt \Rightarrow \gamma mc^2 \rightarrow eZ_0 I \sim 3\,B_{-7}\,R_{14}$ PeV

Electrodynamics



- 0.011photons emitted in turning through angle γ^{-1}
- Classical not quantum process

$$\frac{d\vec{u}}{dt} = \vec{a}_L - \frac{2r_e}{3c}\gamma^2 a_{L\perp}^2 \hat{\vec{u}}, \quad \frac{d\vec{x}}{dt} = \hat{\vec{u}}$$

$$\vec{a}_L = \frac{e}{m}\left(\frac{\vec{E}}{c} + \hat{\vec{u}} \times \vec{B}\right)$$

$$a_{L\perp}(\vec{x}, \hat{\vec{u}}) = \frac{e}{m}B_e = \frac{e}{m}\left[B_\perp^2 + \left(\frac{E_\perp}{c}\right)^2 - 2\frac{\vec{E} \times \vec{B}.\hat{\vec{u}}}{c}\right]^{1/2}$$

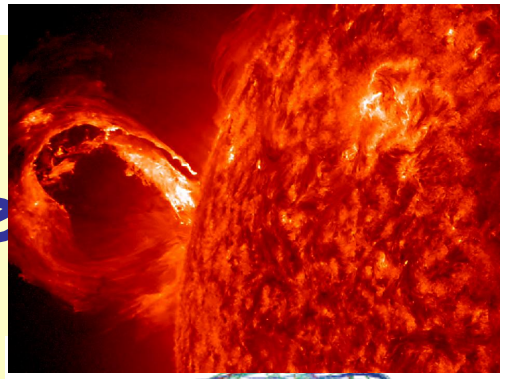
- $\gamma_9^2 B_{e\text{-}7} = 16(E_\gamma/400\text{MeV})$; $r_L = 1.7 \times 10^{13}\ \gamma_9\ B_{e\text{-}7}^{-1}$ m
- Radiation reaction dominates when $E_\gamma > \alpha^{-1} m_e c^2 \sim 70$ MeV; $\lambda < r_e$
- If only uniform magnetic field, electron cools in 12°
- If add electric field, E>5cB to avoid energy loss
- E>cB in all frames.

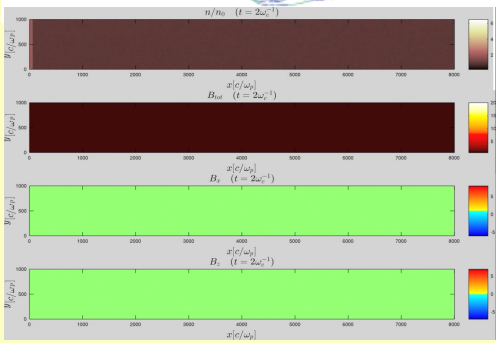
Need 2 PeV electrons in a 100nT field

Jitter radiation? *(Teraki, Takahara)*

Future

- Observations especially of flare
- MHD simulations
- Kinetic/PIC calculations
- Solar/space physics
- HED experiments
  - Z-Pinch
  - LCLS
  - NIF/OMEGA…





Sandia Z-pinch (stable?)
~30 MA, ~30MV, ~100ns!,
4 GK,~300TW X-rays
B~1 kT, r ~ 1mm??

Summary

- Many examples of intense flares from compact sites
- Crab Nebula continues to surprise, instruct, confound…
- Seem to need new, generic volumetric acceleration/ emission scheme for dissipating electromagnetic energy rapidly from compact regions of pair plasma
- Magnetic loops likely to become tangled/knotted
- Ohmic dissipation of knots/islands-> particle acceleration
- Current carried by the accelerated particles
- Runaway acceleration of minority of particles to high energy is possible – electromagnetic implosions
- In extreme cases major dissipation can be radiation-reaction limited – Synchrotron or Compton
- MHD simulations, kinetic calculations, HED experiments…