Pulsars: Problems and Prospects

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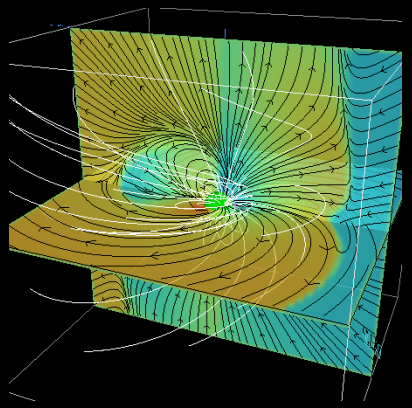
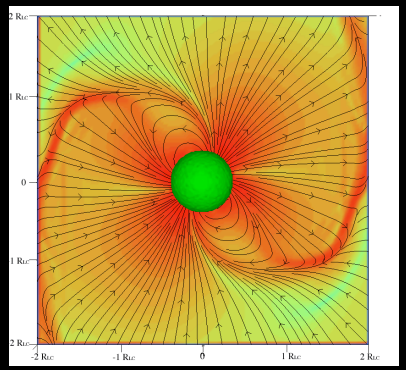
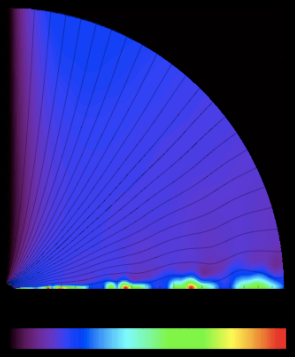
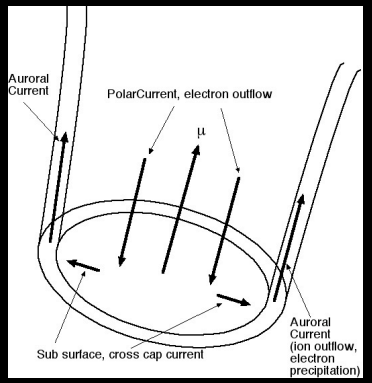


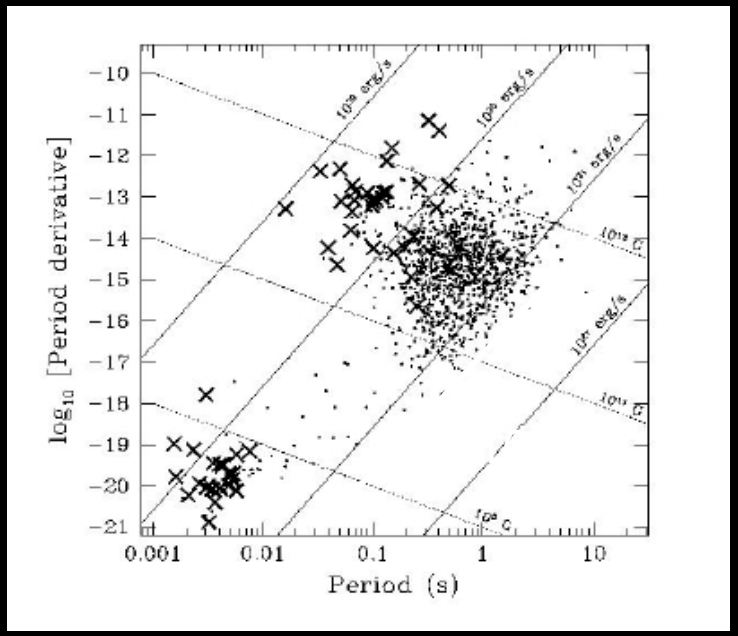






Collaborators: D. Alsop, E. Amato, D. Backer, P. Chang, **N. Bucciantini**, B. Gaensler, Y. Gallant, V. Kaspi, A.B. Langdon, C. Max, **E. Quataert**, **A. Spitkovsky**, M. Tavani, A. Timokhin

Follow the Energy: Spindown



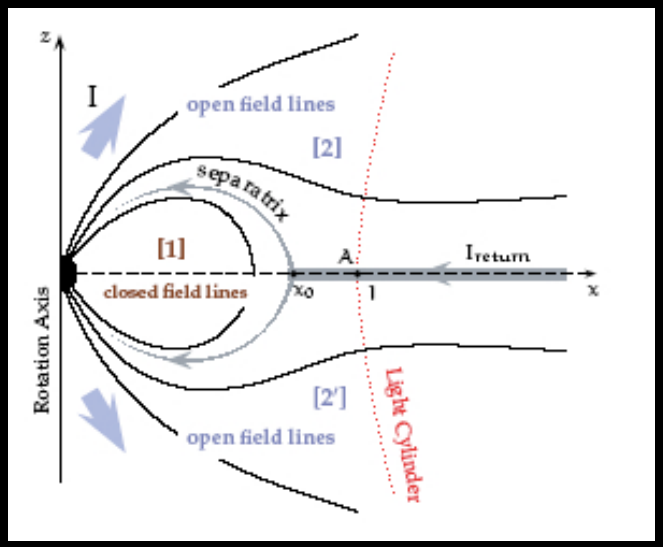
Force Free Magnetosphere -
Spin down by EM torques
Magnetic energy dominant, non-vacuum, enough plasma for $E \cdot B = 0$

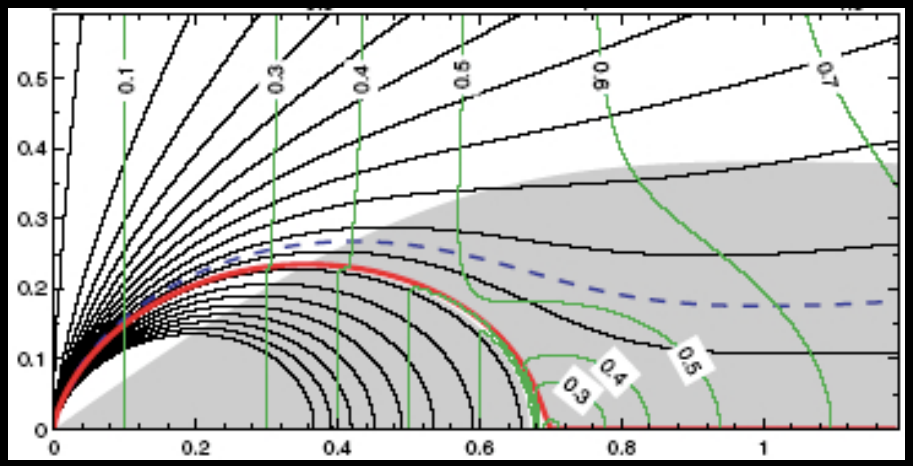
Contopoulos et al (99APJ), Gruzinov (05PRL), Timokhin (06MN, 02-15): FF, aligned rotator, steady state: $R_Y \leq R_L$

Komissarov 06MN rel MHD, McKinney 06 ApJ FF: aligned rotator, evolutionary

Bucciantini et al 06MN, rel MHD, pressure driven flow, aligned rotator, evolutionary: $R_Y \rightarrow R_L$

Spitkovsky 06ApJ: FF, evolutionary, aligned & 3D oblique: $R_Y \rightarrow R_L$ (also kalpotharakos+09)





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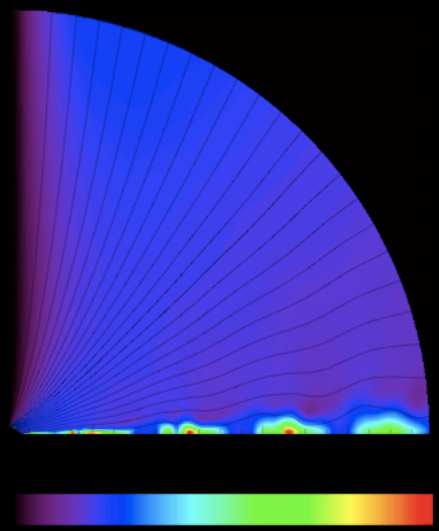
$$R_Y \leq R_L$$

$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 3 + 2\frac{\partial \ln\left(1+\frac{R_L}{R_Y}\right)}{\partial \ln \Omega}$$

$R_Y/R_L < 1$ increases torque because of more open field lines and larger Poynting flux for same R_L

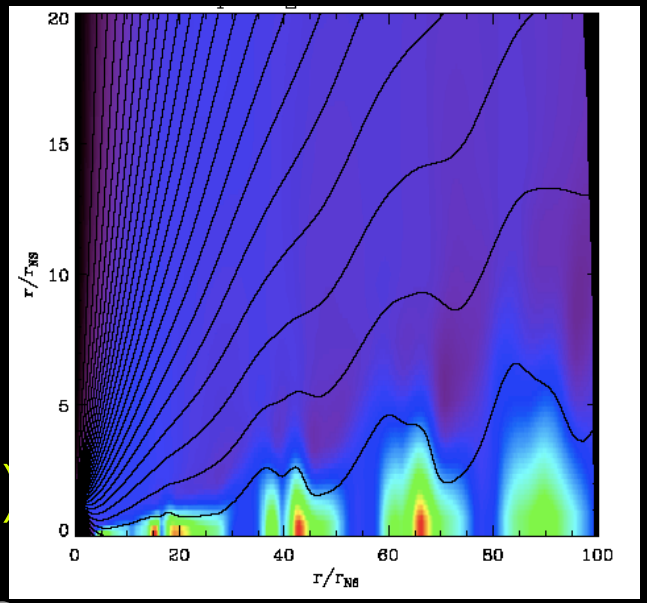
IF R_Y/R_L decreases with decreasing W, n<3; average R_Y/R_L must decrease on spindown timescale, since 2 < n < 3



Bucciantini et al 06

"Average" with respect to plasmoid emission, torque fluctuations

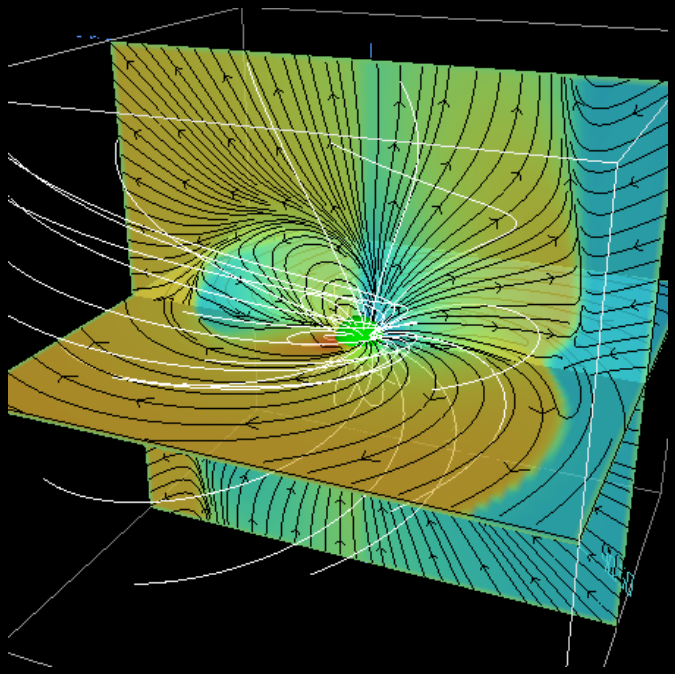
($\delta T/T$ ~ 10-30% ~ obs)

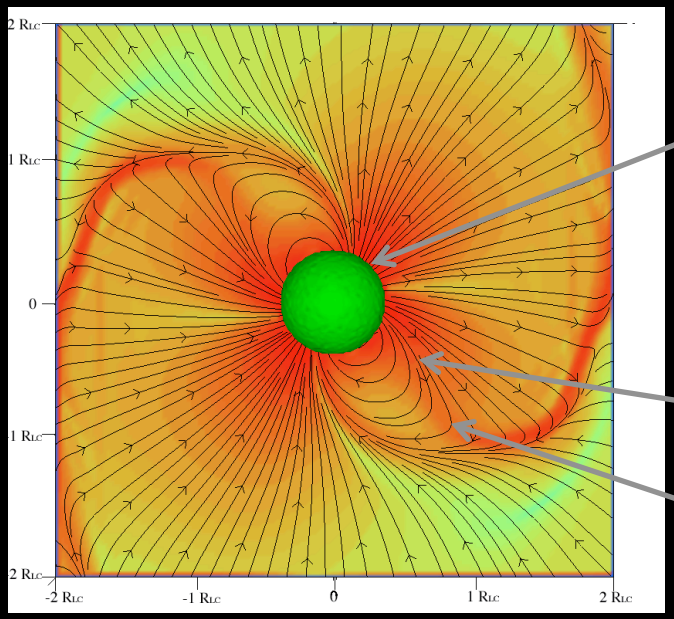


Spindown biases fluctuations toward increasingly open flux??

Aligned Rotator IS like the oblique object (spindown)

Spitkovsky's (2006) oblique force free rotator (ApJL)





Field Lines (with real open flux)

Total Current

$$\dot{E}_R = -I\Omega\dot{\Omega} = k\frac{\mu^2\Omega^4}{c^3}(1+\sin^2 i),\ k = 1\pm 0.1$$

$$i = \angle(\mu, \Omega)$$

Gaps = local zones of charge density < GJ, Parallel E ≠ 0

Acceleration along B ➔ beamed photons, rotation ➔ lighthouse

Force Free model has no gaps, no parallel accelerator

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Implications for Emission:

- Polar cap/flux tube size and shape - noncircular shape, center from displaced magnetic axis - polarization - no need to invoke non-dipole B?
- Electric current magnitude and sign - return currents both spatially distributed and (mostly) in thin sheet - if dissipation regions ("gaps") have parallel potential drops small compared to total magnetospheric voltage,

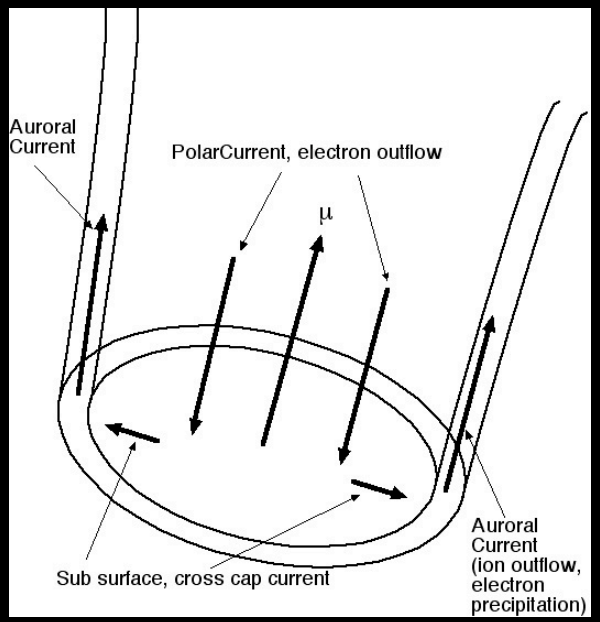
$$\Phi = \sqrt{\frac{\dot{E}_R}{c}} = 4 \times 10^{16}\, Volts \left(\frac{\dot{E}_R}{10^{38.7}\, erg/s} \right)^{1/2} \propto L_{radio},\ L_\gamma (large\ \Phi)$$

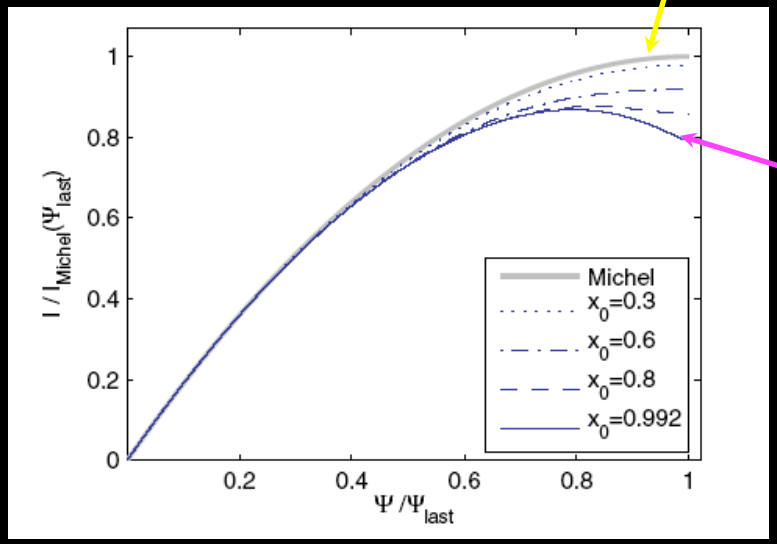
electric current in and outside gaps is known, averaged on magnetosphere transit time (~P/π) - electric currents of gaps/emission sites must fit into magnetospheric circuit - or force free magnetospheric model is wrong - but energy all in field, hard to be non-FF

- Location of return current layer determined - realistic site/physics for outer magnetosphere beaming models of high energy emission)

Known Current - Huge Effect on $E_{\parallel}$?

Aligned rotator for clarity





Polar current contained within distance from magnetic axis, j ≠ const

Cartoon - all models have charge $\varpi = \left(\frac{\psi}{\pi B_{pole}}\right)^{1/2}$, $\psi =$ Magnetic flux density = GJ, polar current density = constant

$\Rightarrow$ "small" $E_{\parallel}$ ($\sim 10^8$ V/m); same true for outer gaps (geometry different, electrodynamics ~ same)

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Effect of Current on $E_{\parallel}$ (continued)

Existing models (RS, FAS, SAF, MT): starvation $E_{\parallel}$ extracts a beam -

Beam Charge Density almost equals GJ: current = constant - small $E_{\parallel}$ - ~10^{8} V/m, DF ~ 10^{12} - 10^{13} V

local electrostatic tail wags the magnetospheric dog!

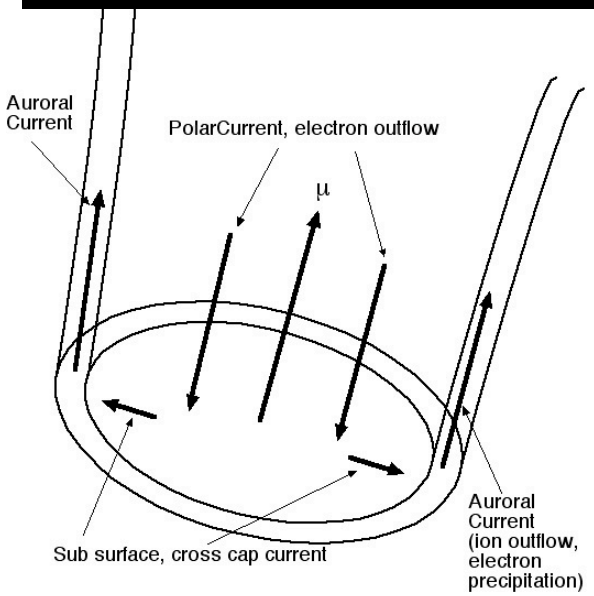
Same issue for outer gaps on open field lines: starvation gap models (steady or unsteady) produce magnetospheric charge density, not current density, but all energy in current!

phenomenological models of data all based on such anti-energetics ideas

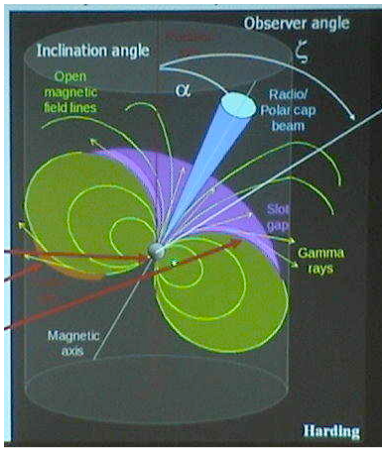
Prospect: Beam & Other Models With Force Free Magnetospheric Structure

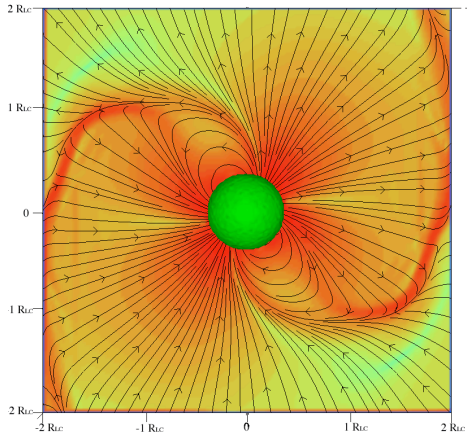
Magnetosphere sets time average j_{pc} to be the Force Free current: close to monopole

$$\langle -en_{beam} \rangle - (-en_{GJ}) = \frac{j_{GJ}}{c}\left(1 - \frac{\Psi}{\Psi_{cap}}\right) - \frac{j_{GJ}}{c} = +\frac{|j_{GJ}|}{c}\frac{\varpi^2}{\varpi_{cap}^2} \rightarrow \frac{|j_{GJ}|}{c}, \varpi \rightarrow \varpi_c$$



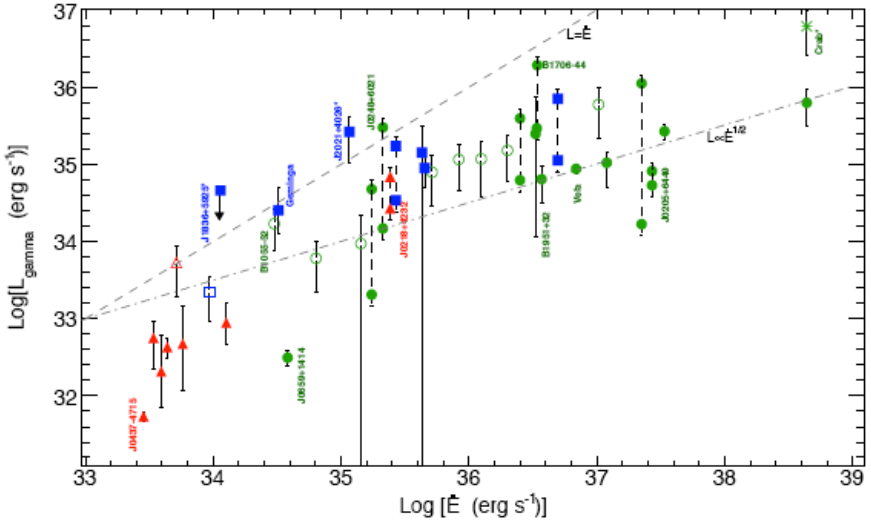
Like a vacuum gap, but $E_{\parallel}$ = 0 at crust surface





Probe Structure with Gamma Rays – fold geometry with accelerator

Gamma Ray Efficiency



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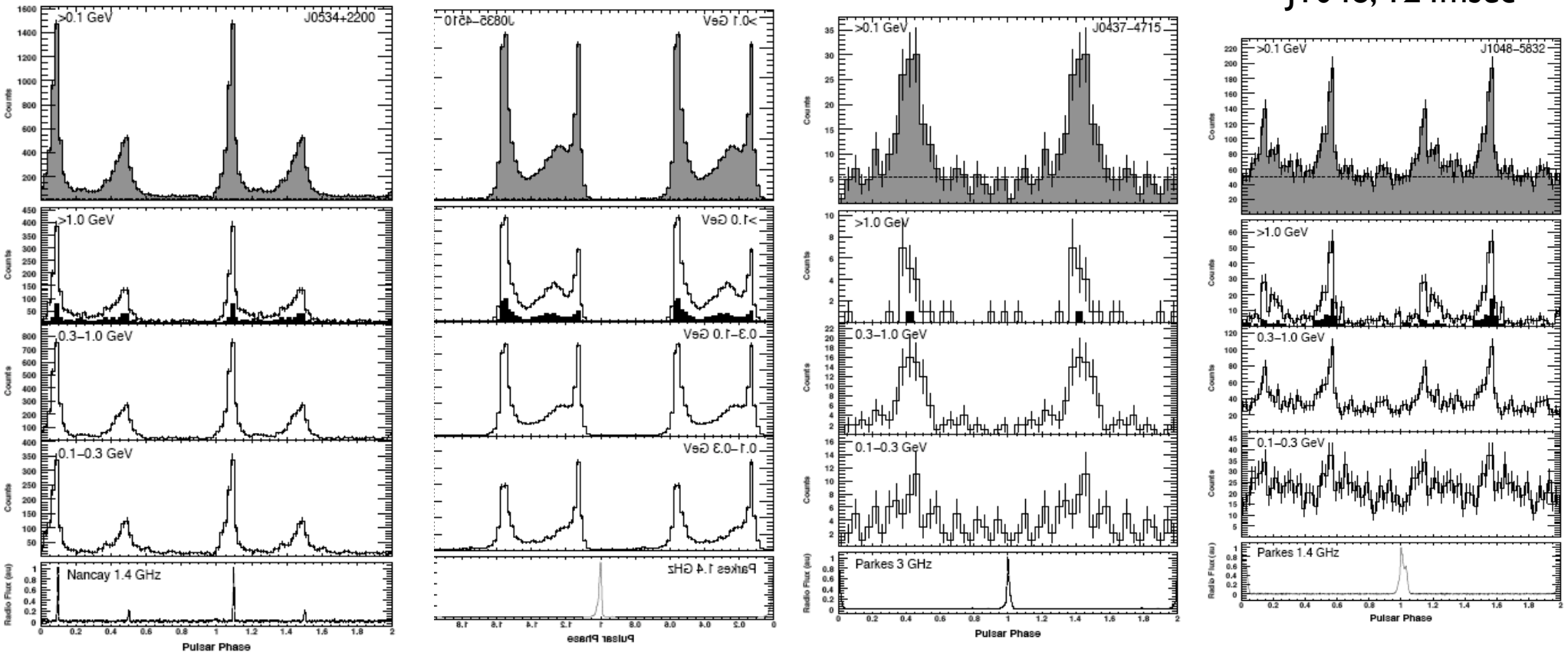
Crab, P=33msec

Vela, P=89msec

J0437, 5.76msec

J1048, 124msec



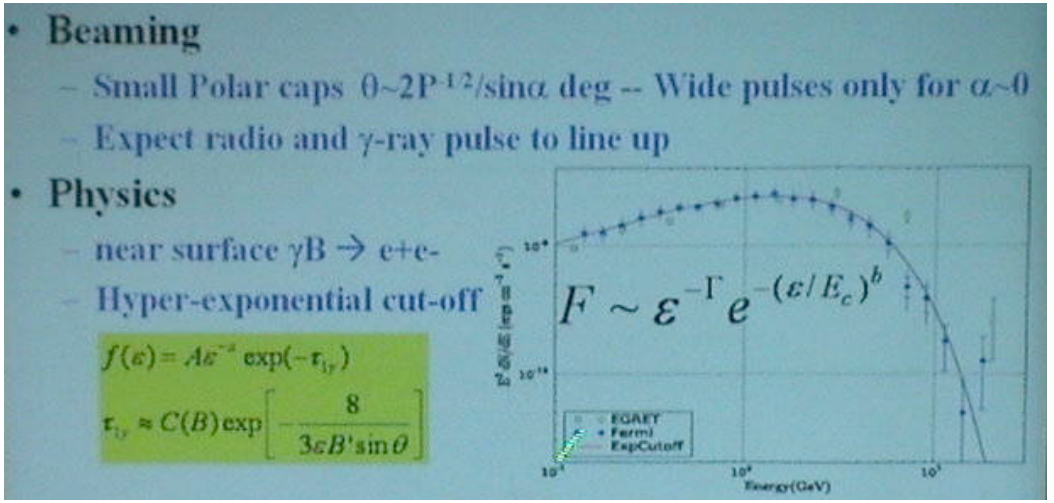
A Few Gamma Pulsars (46 seen by FERMI-LAT)

Most are double peaked, wide separation in rotation phase

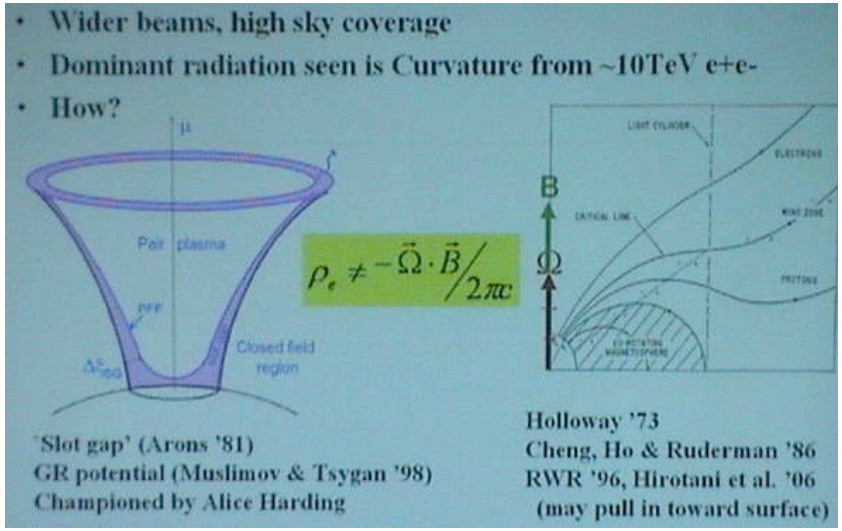
Gamma Ray Tests of Existing Gap Models

Gamma Rays Not from Polar Cap

Super exponential cutoff rejected:
b > 1 rejected at 16 σ



Beamed γ from high altitude more promising – tradition has $E_{\parallel}$ from starvation, quasi-vacuum "gaps"



Slot gap fragile to mild magnetic anomalies, gravitational bending of photon orbits causes pairs to fill gap; Outer gap has physics inconsistent with FF magnetosphere

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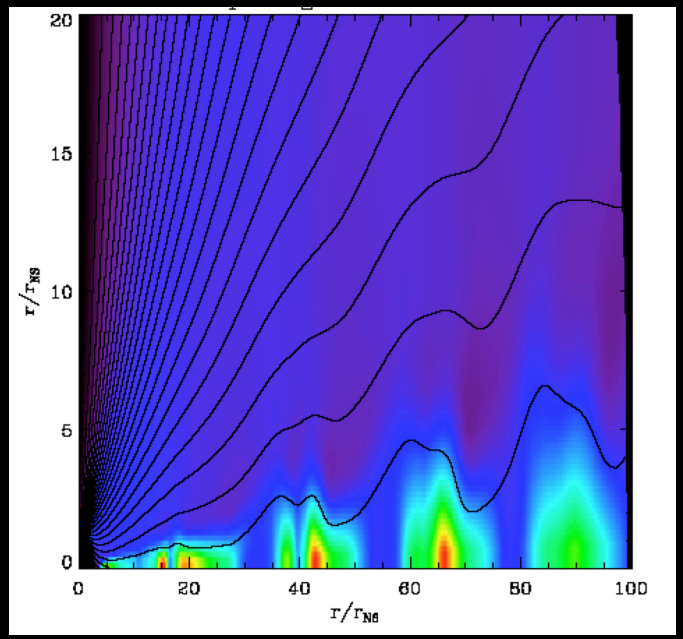
Prospect: Time Dependent Reconnection/Return j

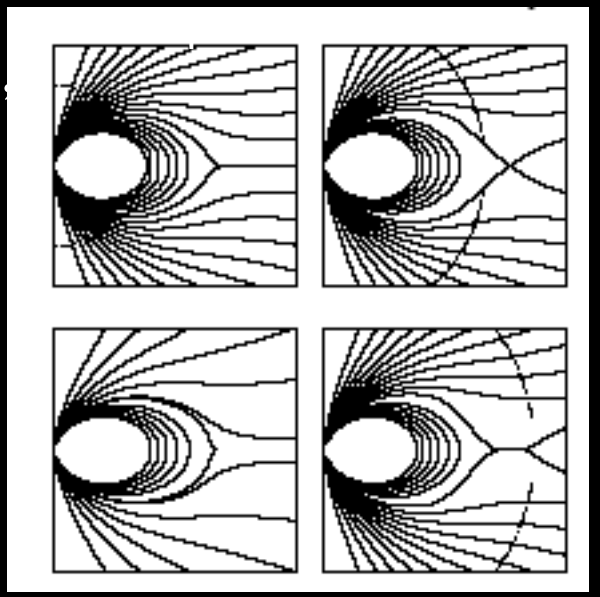


Sporadic X-Point, Plasmoid formation *occurs continuously*

Pairs all come from pole, on open field lines

Sporadic reconnection moves plasma across separatrix

non-corotation, time variable E at all times



- Plasma, j flow to star in thin separatrix layer - dynamics in Kinetic Alfven waves, boundary layer $E_{\|}$ - replaces outer gap
- Space charge in boundary current alters polar acceleration(!) enhances pair creation (?)
- Kinetic Alfven wave $E_{\|}$ extracts ion return current
- Torque fluctuations, limit cycles built in (drifting subpulses)

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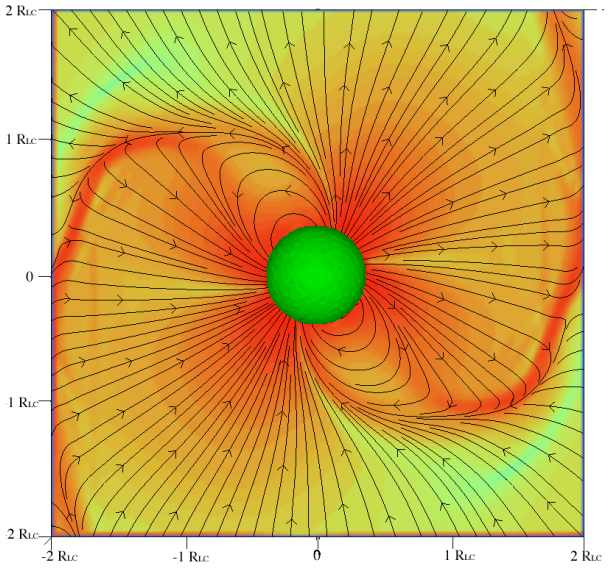
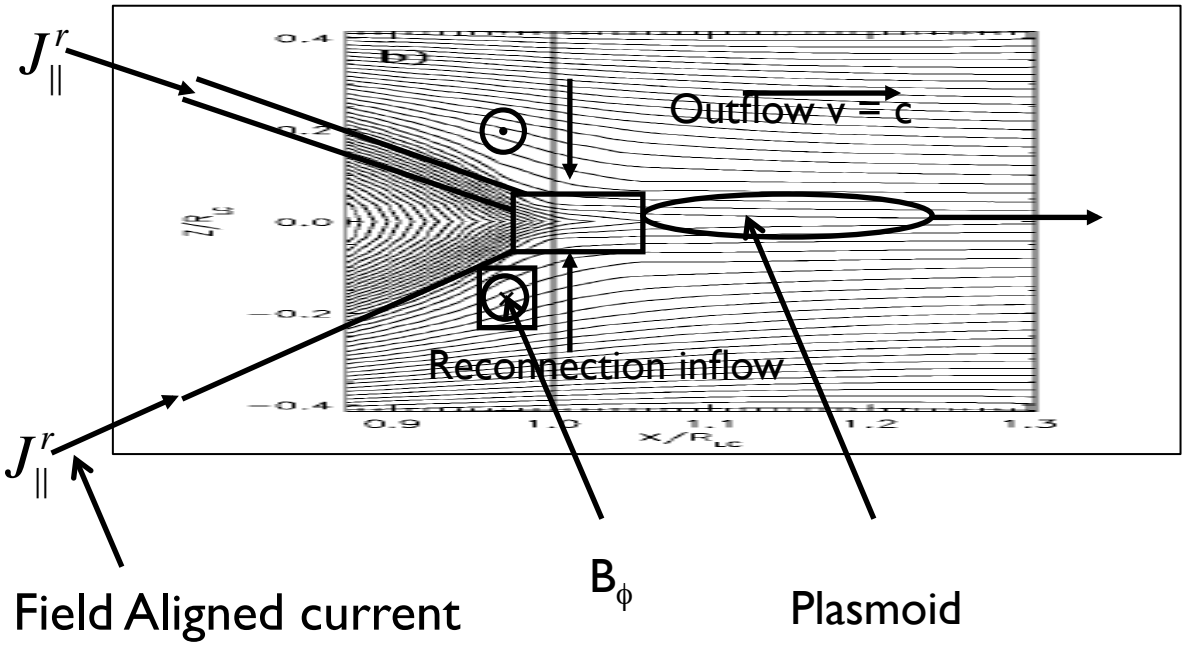
- Beamed γ-, X-rays from boundary layer? Hollow cone radio?

Acceleration in Current Sheets – New Work (in progress), with A.S.





Current Sheet = "Kinetic Alfven Wave", thickness ~ c/ω_p

$E = E_{perp} + v \times B + E_{parallel}$

$$E_{||} = \frac{4\pi}{\omega_p^2}\frac{DJ_{||}}{Dt}$$

Vacuum gap (starvation) not in picture, particle inertia good enough to provide "resistance" in large inductance circuit, voltage $\longrightarrow \Phi$

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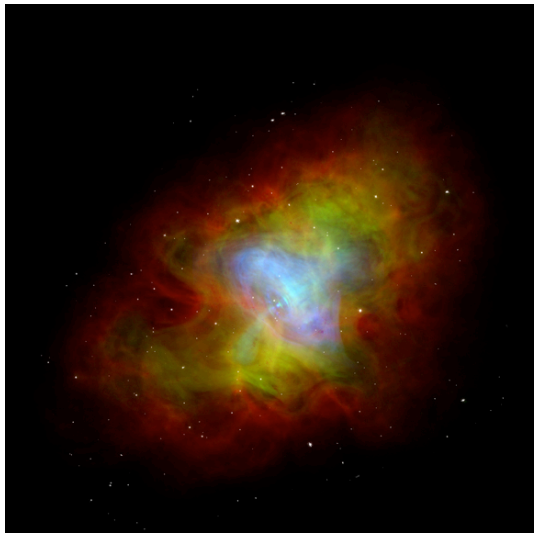
Follow the Mass Loss: From Whence all the Pairs?

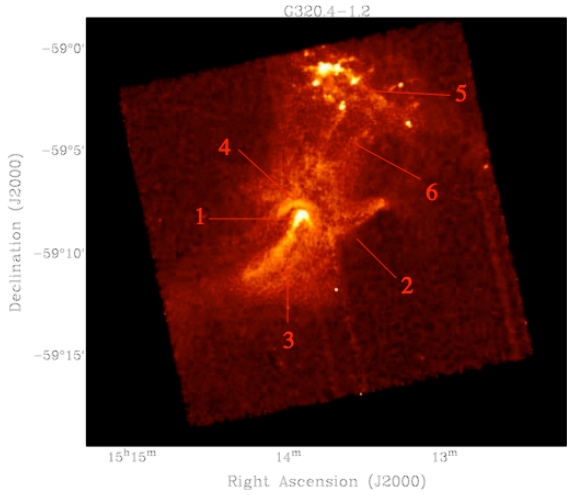
Pulsar Wind Nebulae: Nebular Synchrotron requires particle injection $\dot{N}_{\pm}$ >> Goldreich-Julian current $\dot{N}_{GJ} = c\Phi/e$

PAIR PROBLEM

X-Rays:current injection rate (compact, strong B nebulae - Crab, G54,…)
measured rates ~ existing (starvation) gap rates $\kappa_{\pm} = \dot{N}_{\pm}/\dot{N}_{GJ} \leq 10^4$ pairs/GJ

Radio measures injection rate averaged over nebular histories. rate > 10^6





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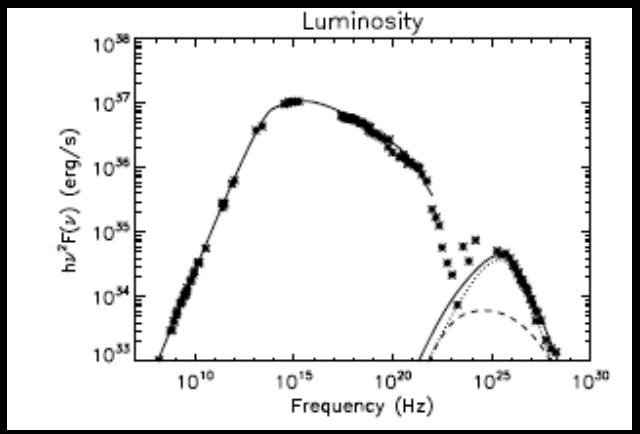
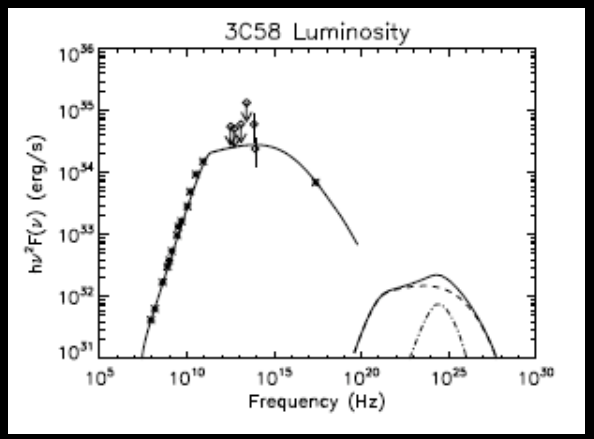
Low $\sigma = B^2/8\pi m_{\pm} c^2 n_{\pm} \Gamma_w$ at termination $\rightarrow$ $\Gamma_w = e\Phi/2m_{\pm}c^2\kappa_{\pm}$

PWN Name	$\kappa_{\pm}$	Γ_w	F_{init}(PV)	Age (yr)
Crab	$> 10^6$	5×10^4	100	955
3C58	$> 10^{5.7}$	3×10^4	15	2100
B1509	$> 10^{5.3}$	1×10^4	121	1570
Kes 75	$> 10^5$	7×10^4	22	650

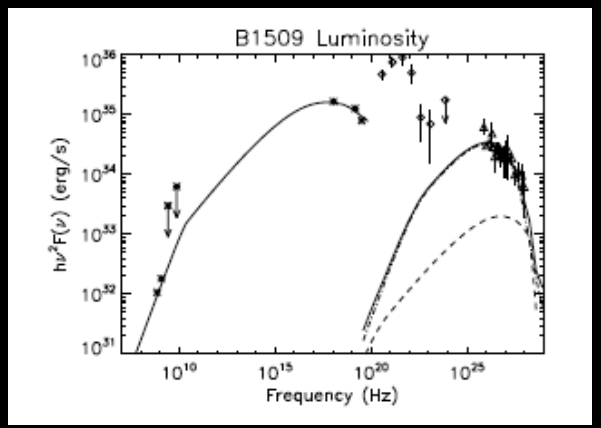
From one zone evolutionary model of observed spectrum <u>including</u> radio (with Bucciantini, Amato) – injection spectrum <u>convex,</u> $\gamma^{-1.5} \longrightarrow \gamma^{-2.3}$



Crab



3C58



PSR B1509/MSH 15-52

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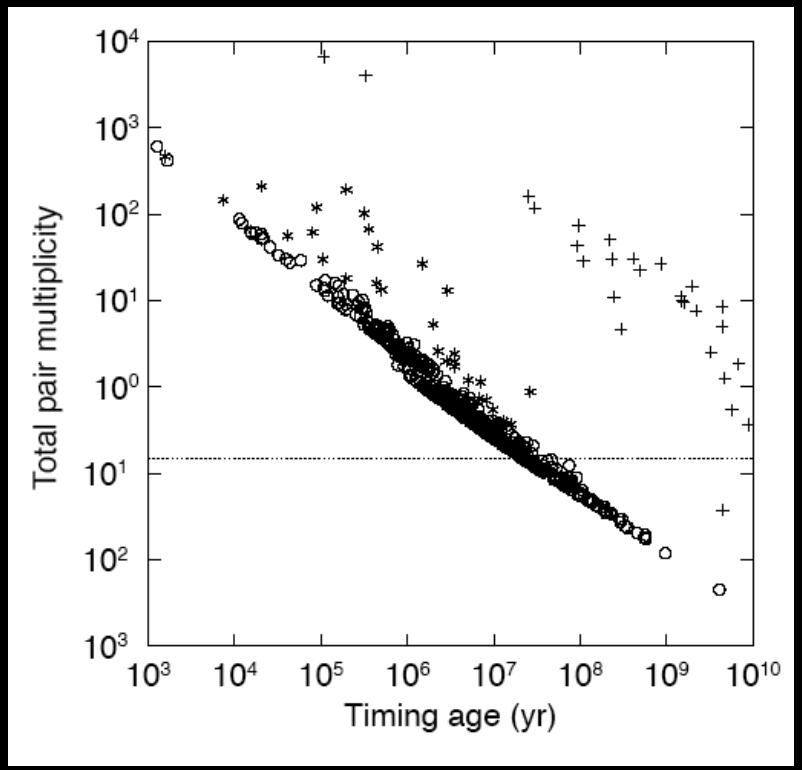
Why so many Pairs (continued)

Pulsar death line ($\Phi = \sqrt{\dot{E}_R / c} \approx 10^{12}$ V) models need dense ($E_{||} = 0$) pairs over all $P, \dot{P}$ space

Starvation electric field polar caps (charge density controls current) do make a few pairs at low voltage (plenty at high Φ), but not dense - shorting out electric field not clear - more pairs needed (or FF-MHD not applicable) - same lesson as from PWNe



Hibschman & JA 01

Many (not all) radio emission ideas need dense (large multiplicity) pairs

All transfer effects need dense pairs - something is missing

(not non-dipole fields!)

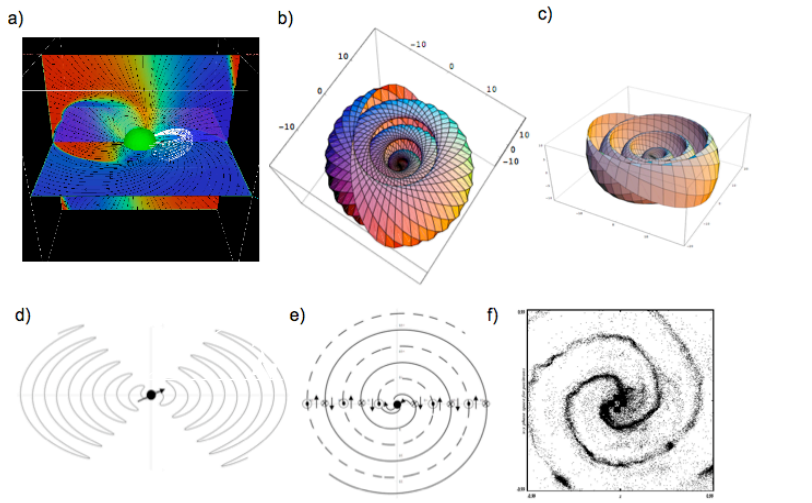
Likely flaw: All models assume density >> GJ in current carrying plasma have zero parallel E - NOT TRUE – aurora

Shorting out $E_{parallel}$ at surface of first pair creation assumed by everyone, good idea (?) in steady flow, Not so in unsteady flow

•Current + pairs becomes time dependent (?), averages to FF (GJ, Alber et al, Levinson, others), electric field averages to small starvation (?) value – PC heating? Large $E_{parallel}$ over greater length: more pairs (?)

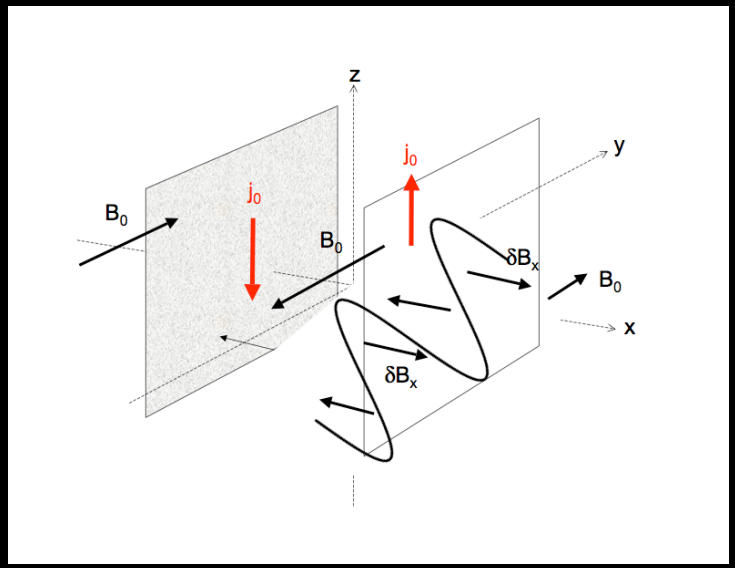
(Timokhin & JA PIC + Monte Carlo hybrid)

Prospect: Wind Structure, dissipation and (?) emission: low σ at TS



Oblique rotator:
striped wind ($-\iota < \lambda < \iota$)
Current sheets blow
out at speed c
Sheets dissipate,
$R_L << r << R_{shock}$

Two Stream (Weibel-like)
Instability of neighboring sheets
Anomalous B diffusion at Bohm rate



Dissipation of Stripes (low σ) at $r << R_{TS}$
Radiation from stripes (pulses?)
Asymptotic wind ⟶ aligned rotator?

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Other current flow instabilities in current layer lead to similar anomalous resistivity & stripe decay (collisionless tearing mode, drift kink instability: "reconnection", although detailed X-point dynamics likely inhibited): Striped component of toroidal field coverted to kinetic energy of flow at r ~ 0.01-0.1 R_{TS} –

REQUIRES LARGE MASS LOADING, $\Gamma_w < 10^{4.5}$

Runaway Beam in Current Sheet: DIFFUSION COEFFICIENT PROPORTIONAL TO p^2,
current carriers become "runaways":
gain energy faster in resistive electric field than scattring causes loss, current becomes a beam, energy/particle -> $e\Phi$ –
large fraction of spindown energy loss carried in current sheet, acts as a linear accelerator (weak synchrotron losses)

Flow upstream of termination shock is low σ, pairs + high energy beam carrying comparable amounts of the kinetic energy flow
Beam composition: electrons ($\Omega \cdot \mu > 0$)
positrons (+ heavy ions drawn up from surface): ($\Omega \cdot \mu < 0$),
proportion depends on reconnection dynamics at Y line, partition uncertain
Beam component has large inertia/particle,
$\gamma \cong q_{beam}\Phi/m_{beam}c^2$ $r_{Larmor} \cong R_{shock}$; $L_{beam} \cong L_{spindown}$ (??)

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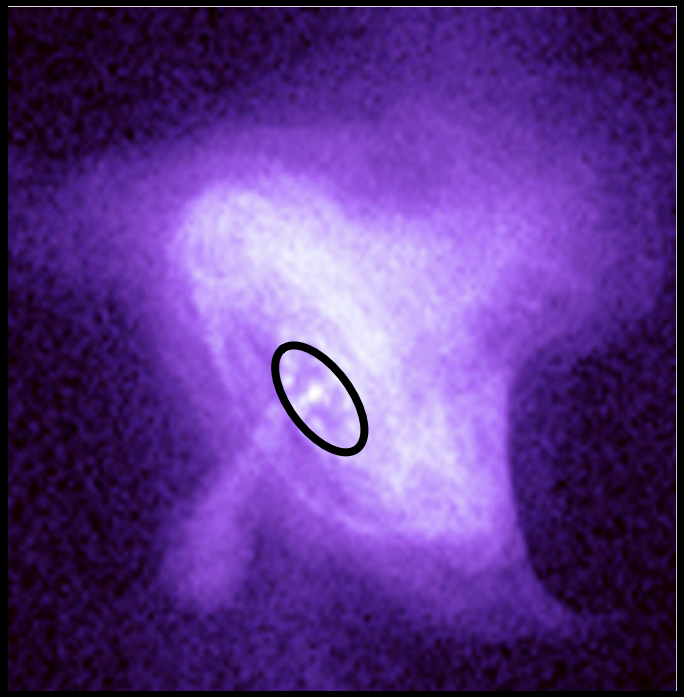
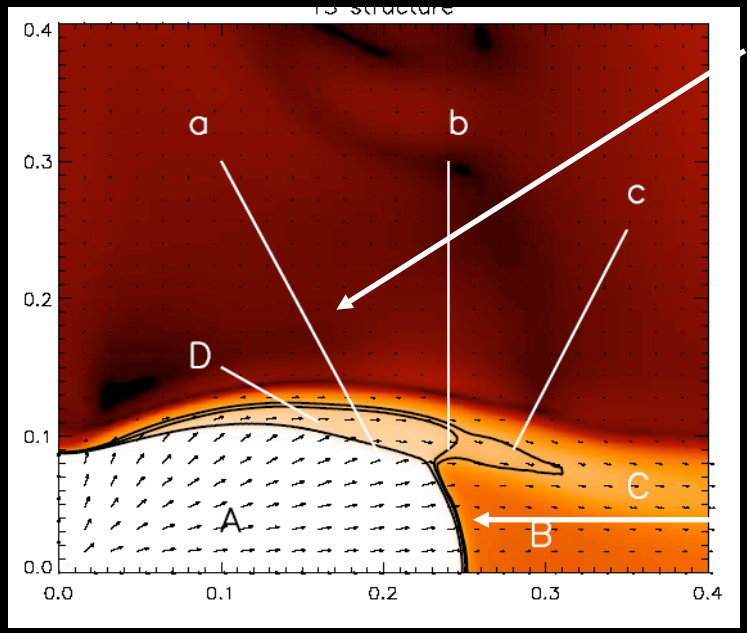
Termination Shock = Magnetic Sandwich



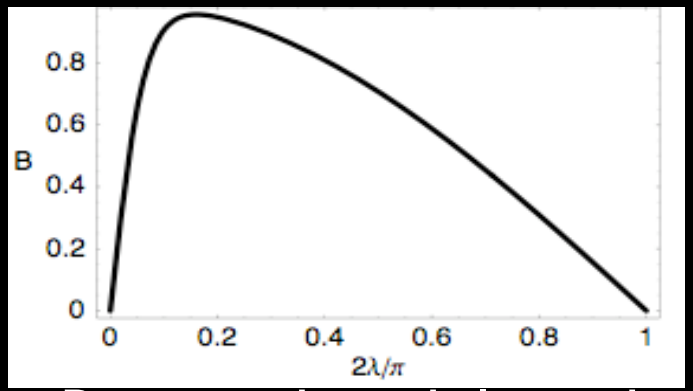
Termination Shock Location



Termination Shock Structure (from del Zanna et al 04)

High density pairs, mildly magnetized shock

Low density pairs, beam, unmagnetized shock



B strength with latitude - Unmagnetized in equator

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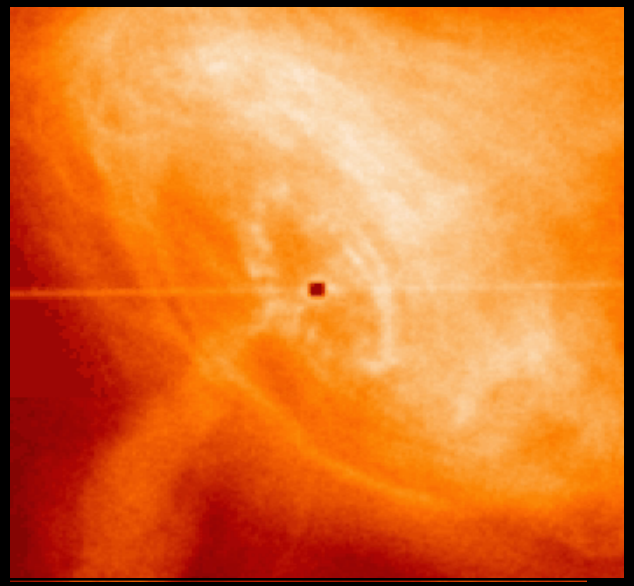
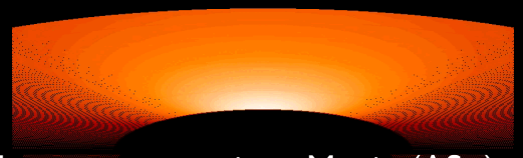
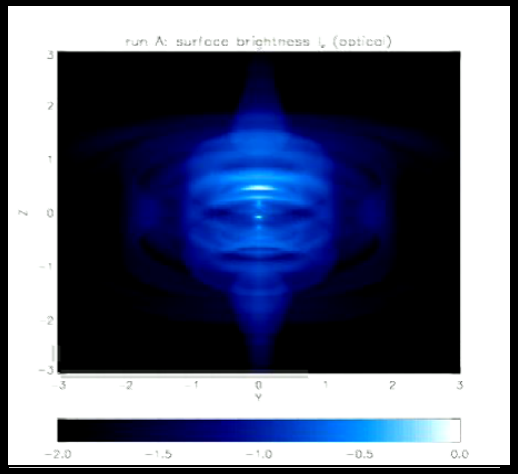


Chandra Movie



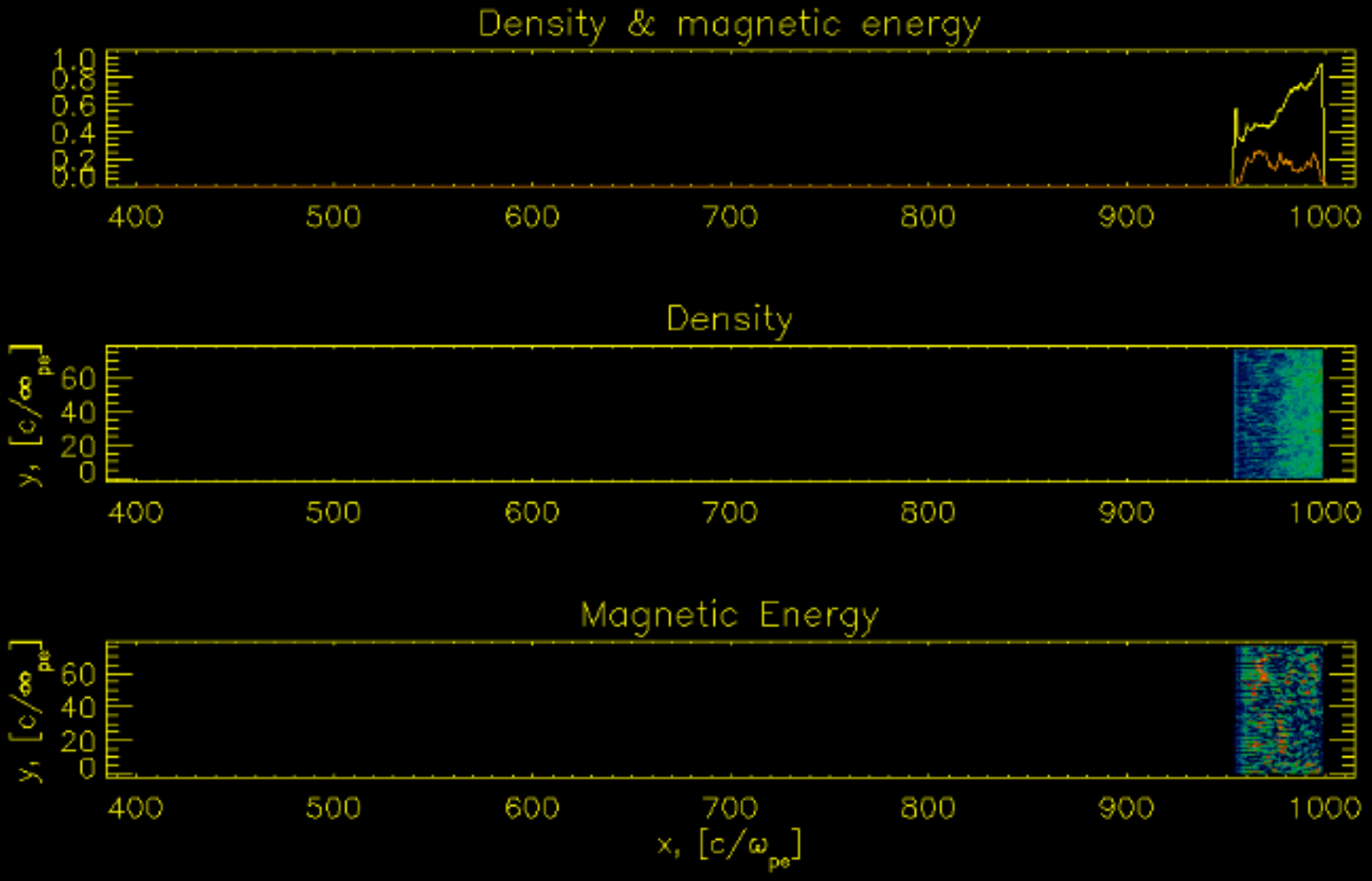
Equatorial beam compressions Movie (AS+)



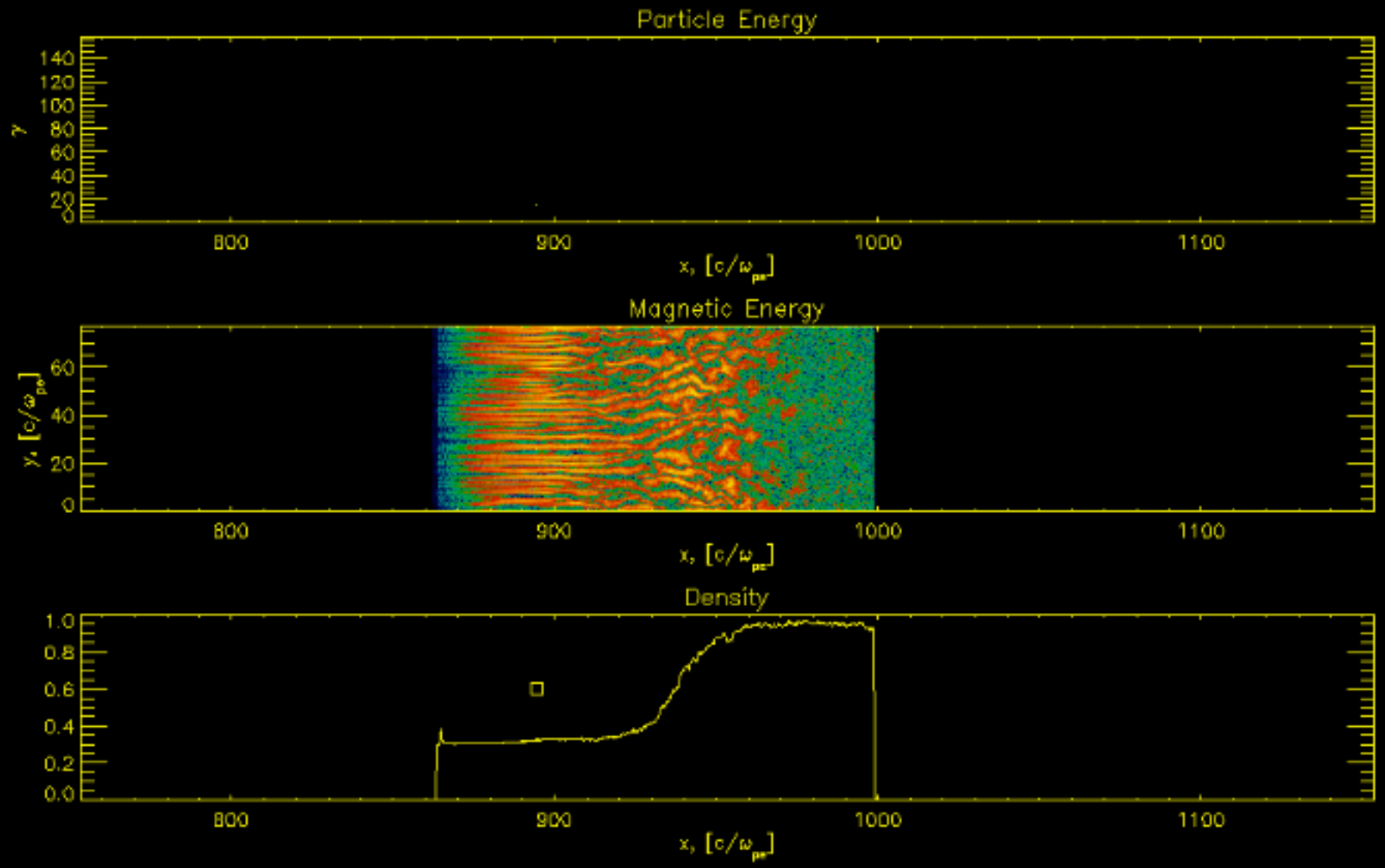
MHD Shear and Vorticity Instability Movie (SK+)

Unmagnetized shock Movie (Spitkovsky 08)
PIC Simulation of Weibel turbulence mediated shock

2.5D relativistic PIC, electrons-positrons, $B_0 = 0$, $\Gamma=15$; 3D (Spitkovsky & JA) similar



Movie - Trace particles that end up in the tail - scattering weakens at large γ, particles lost to tail.



Large simulations (50,000x800 cells, 5000x80c/$\omega_{p\pm}$)- suprathermal particles (Fermi acceleration) well developed

Density, t=8400/ω_p
$B^{1/2}$, t=8400/ω_p

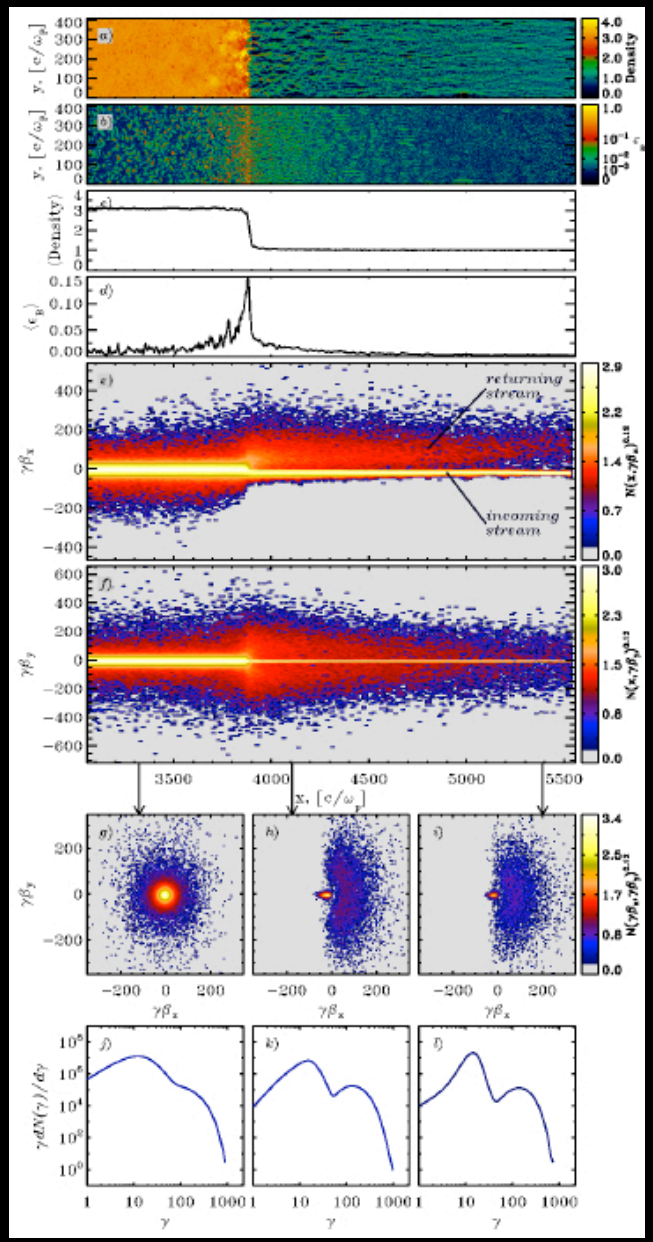
1D density, $B^{1/2}$
t=8400/ω_p

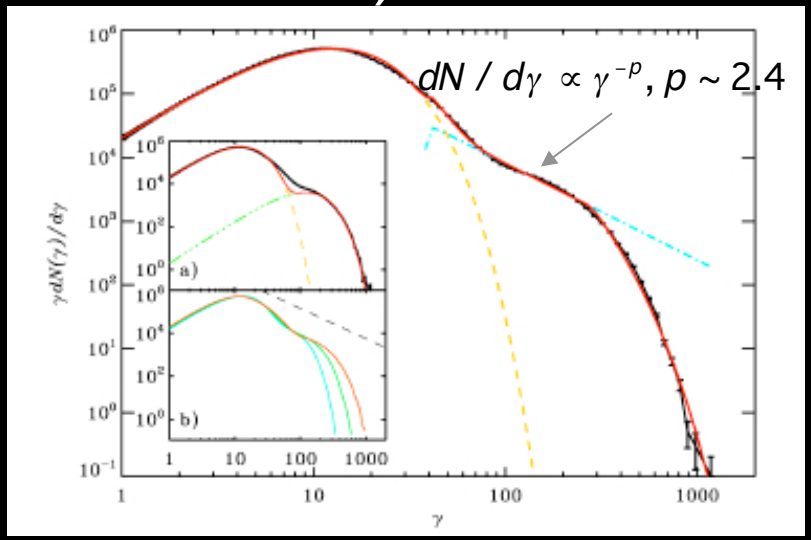
P_{flow}-x

P_{perp}-x

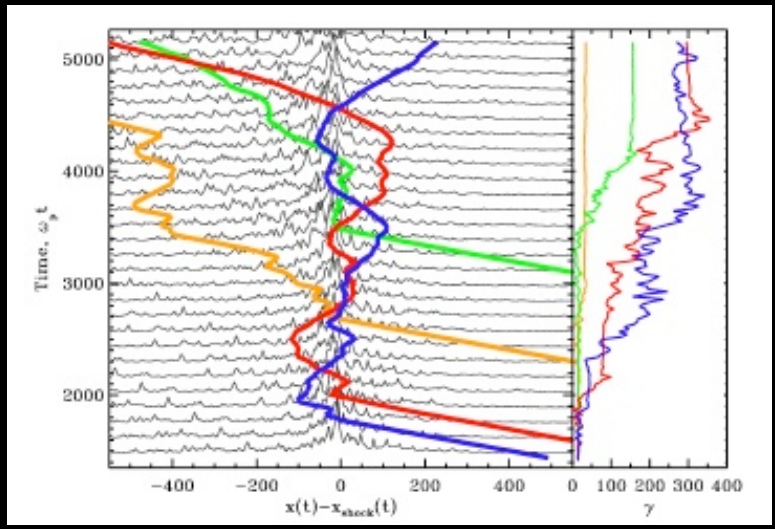
P_{flow}-P_{perp} slices

Particle spectra in slices





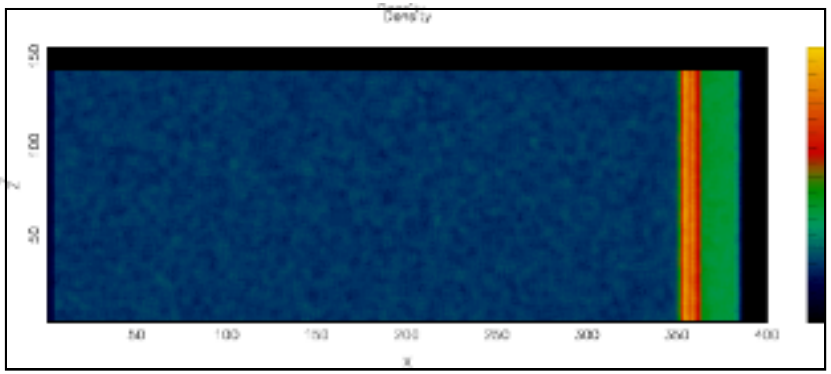
Downstream particle spectra: Maxwellian + exponentially cutoff power law (biMaxwellian, growth of power law component)



Labeled particles gaining energy

J. Arons: HEPROII 2009

Magnetized Transverse Pair Shock (higher latitude):
Pairs, unidirectional B, 3D, colliding shells, σ = 0.1



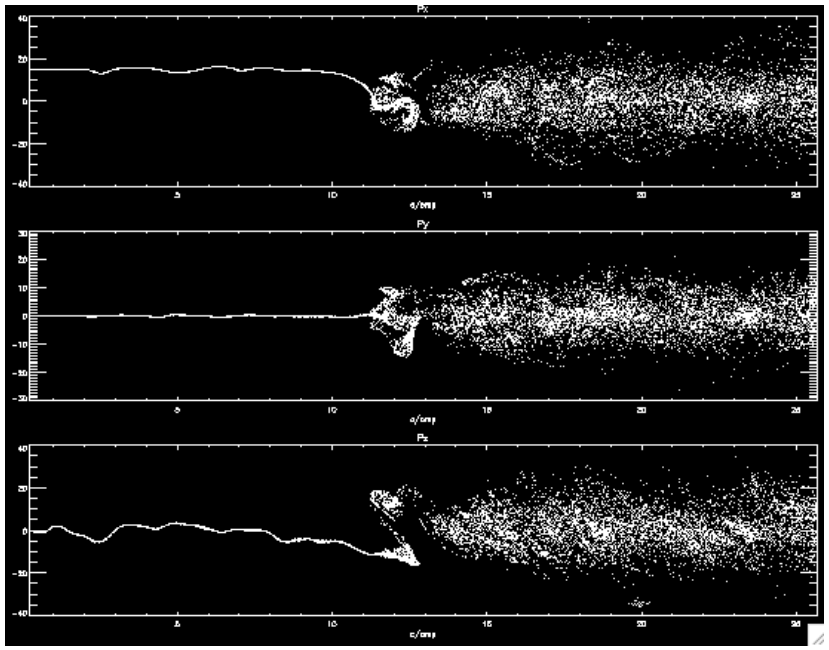
Density in B-v plane Movie

3D Phase space

P_x-x
$<v_x$

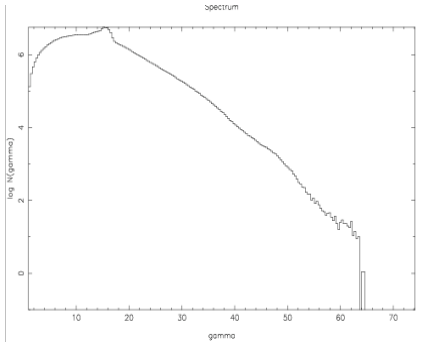
P_y-x
B_0

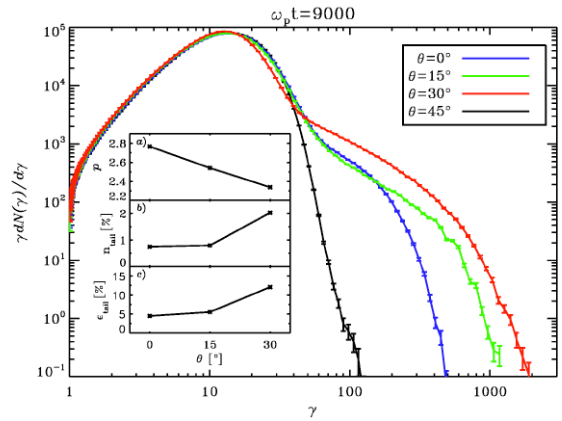
P_z-x
E_0



Complete Thermalization – rapid relativistic synchrotron emission and self-absorption (synch thermalization ~ BH disks, but collective) - true for all superluminal Θ_{BN}

Log f(E)



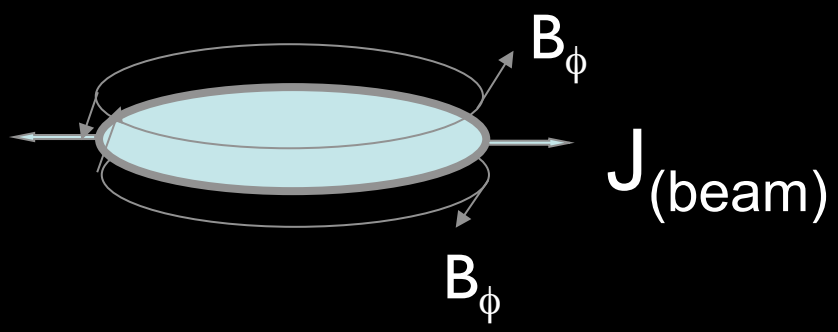


Sironi & Spitkovsky 09

Turbulence too weak, wrong kind (not scattering) to support DSA in $\langle\sigma\rangle > 0.01$ flow, = latitude aveage in MHD nebula models

Pulsar Wind Toroidal Field entirely across flow; composition = pairs. Does shock acceleration fail for best studied/most easily studied relativitic outflow?

Perhaps/Perhaps not – conclusion applies only if upstream B not structured – high mass loaded, low Γ_w wind has sandwich geometry



Clue: MHD nebular models require unusually weak field in equator, plasma + beam flow in equatorial current sheet allows formation of $\sigma < 10^{-3}$ shock, Fermi acceleration possible in equatorial outflow: feeds torus, if accel to PeV

(needs turbulence not demonstrated in $\sigma < 10^{-3}$ PIC), spectrum OK for optical, X-ray, gamma ray from nebulae

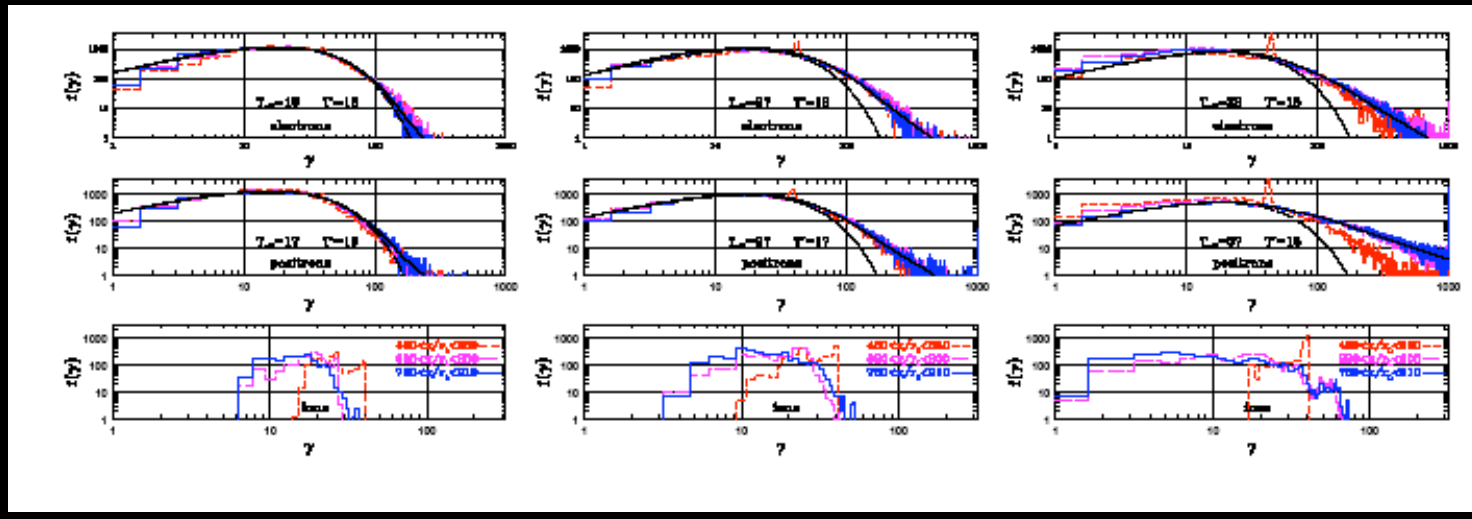
Flat spectrum radio emitters accelerated by cyclotron resonance in higher σ zones at higher latitude?

Amato & JA 1D PIC – hasn't yet been done in 2D and 3D

electrons

positrons

beam= "protons"



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Conclusions: Pulsar Problems and Prospects

- Force Free Currents - Charge Neutrality conflicts with j
  - New Polar Accelerator Models - short time variability?
- Closed/Open Magnetosphere - Reconnection?
  - Cross field transport in closed zone
  - Plasma transfer from open to boundary layer, closed field - n < 3?
  - Return current formation and plasma $E_{||}$ - kinetic Alfven waves
  - Torque noise, subpulse phase variations
  - Boundary layer acceleration, HE photon emission
  - Enhanced Polar Pair Creation (?)
- Wind Current Sheet Dissipation
  - High $\sigma \longrightarrow$ low σ? Anomalous resistive decay of stripes in mass loaded, low(er) $\Gamma_w \sim 10^4$; Current in equatorial current sheet = runaway beam
- PWNe termination shocks – Magnetic Sandwich Geometry
  - unmagnetized in equator ("sandwich filling"): Fermi acceleration (O,X,γ)
  - cyclotron acceleration at higher latitude: flat radio spectrum?