PARTICLE-IN-CELL SIMULATIONS OF PULSAR WINDS

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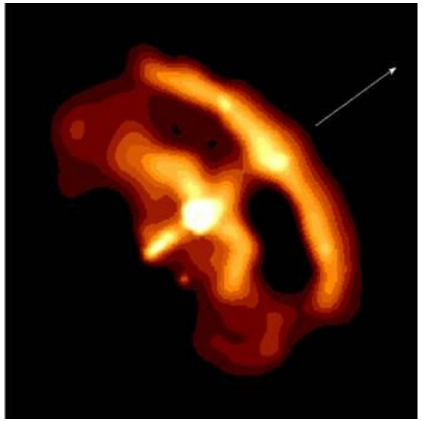
1. "Magnetically striped" relativistic outflow
2. Self-consistent wave: **formation** & stability
3. Energy transport: EM $\rightarrow$ KE
4. Hα and X-ray bow shocks

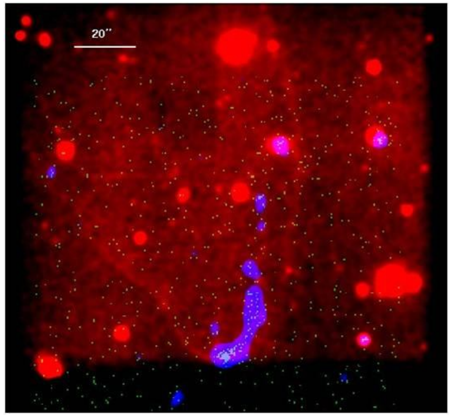
BOX CALORIMETRY

PLERION

BOW SHOCK

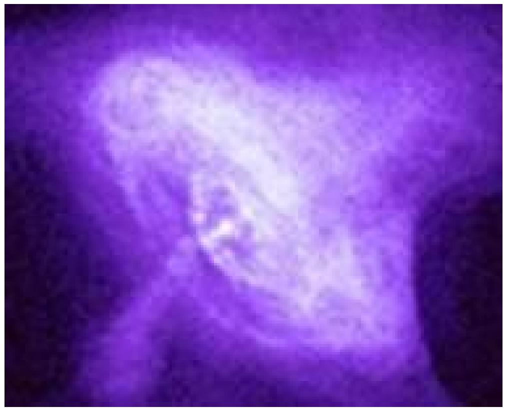
Vela

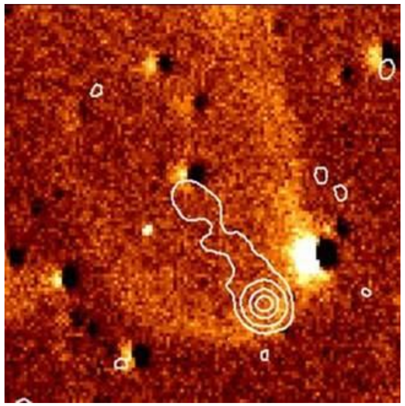




J2124

Crab



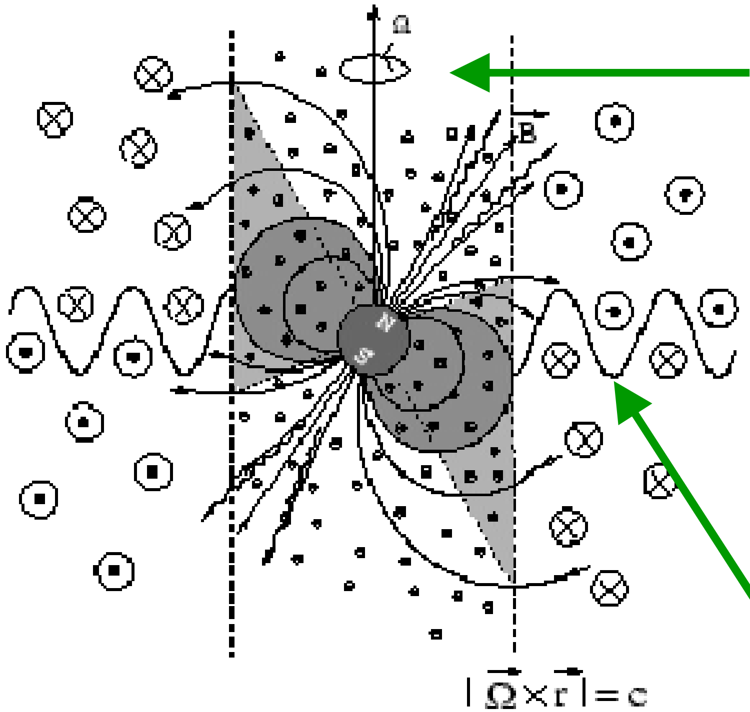


Black Widow

WAVE-LIKE WIND

$J_{\mathrm{disp}} \propto E \propto r^{-1}$

$J_{\mathrm{cond}} \propto n \propto r^{-2}$



circular pol'n
("helix")

linear pol'n
("stripes")

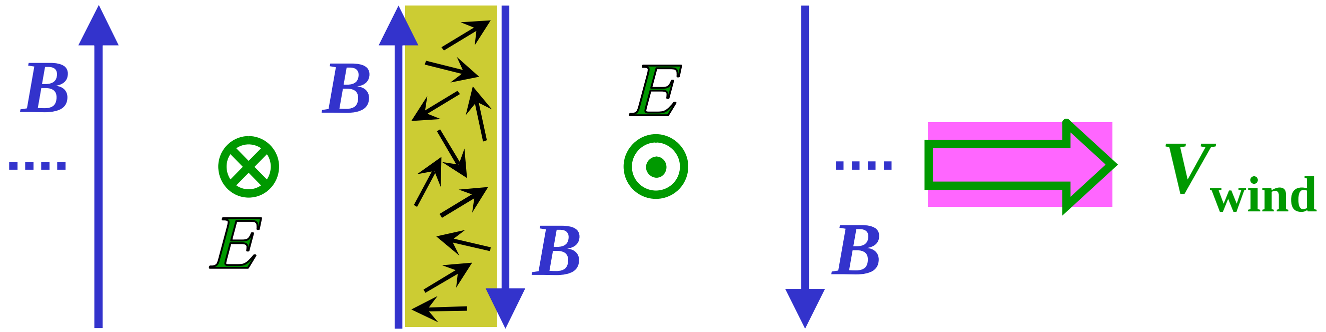
current sheet

$J_{\mathrm{disp}} > J_{\mathrm{cond}}$
for $r > 10^5 r_{\mathrm{LC}}$

Global plasma wave oscillating at Ω_*

I. ENTROPY WAVE

- Alternating magnetic stripes separated by **neutral sheets** (Coroniti 90; Lyubarsky & Kirk 01)
- MHD → "frozen in" → $V_{phase} = V_{wind}$



Reconnection stabilized by **streaming**

- Time dilation ($dN_{\pm}/dt < 10^{40}\ s^{-1}$)
- B field annihilated at shock (Lyubarsky 03)

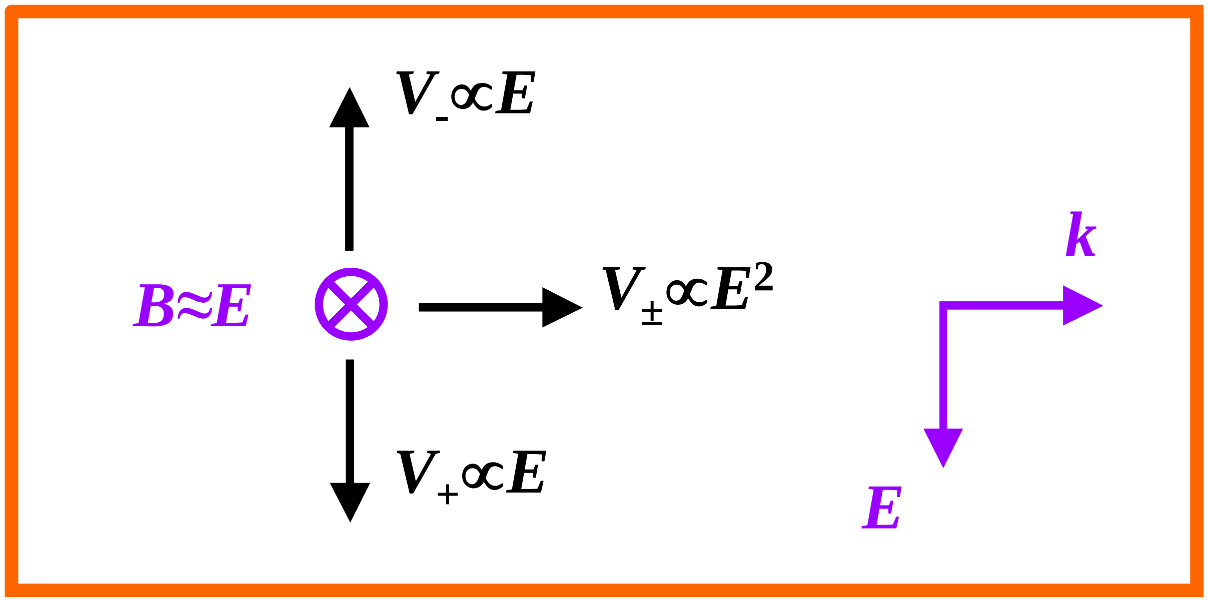
II. EM WAVE

- Sub or superluminal: $V_{\mathbf{phase}} \neq V_{\mathbf{wind}}$
- (Slightly) nonzero electric field in bulk frame
- Propagates in **overdense** plasma: $\omega < \omega_p$
  (Akhiezer & Polovin 56; Kennel et al. 76)

- Transverse-longitudinal

Parametric decays stabilized by **streaming**

- Time dilation: $V_{\mathbf{phase}} \approx c \approx V_{\mathbf{wind}}$ (cf. Asseo et al. 80)
- Radiation losses $\propto (d/dt)^4 = (1 - V_{\mathrm{wind}}/V_{\mathrm{phase}})^4 \approx 0$



V-∝E
B≈E
V±∝E²
V+∝E
k
E

FORMATION

Self-consistent wave ↔ many proper cycles

- Particle-in-cell (PIC) simulations (2.5D)
- **Continuous antenna**
- Circular & linear polarization
- Nonlinear: $eE/mc\omega >> 1$

- Launch with **pre-streaming** relativistic $e^{\pm}$
- 30–200 λ in box with noise < 10%

What happens "in the long run"?

ANTENNAE: A CRITIQUE

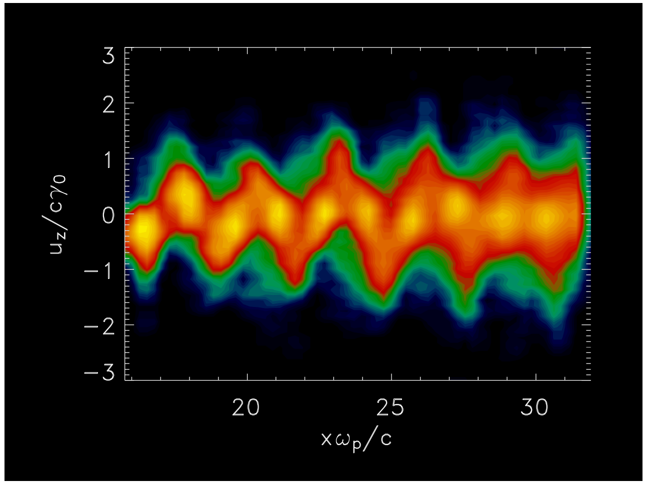
ENTROPY WAVE

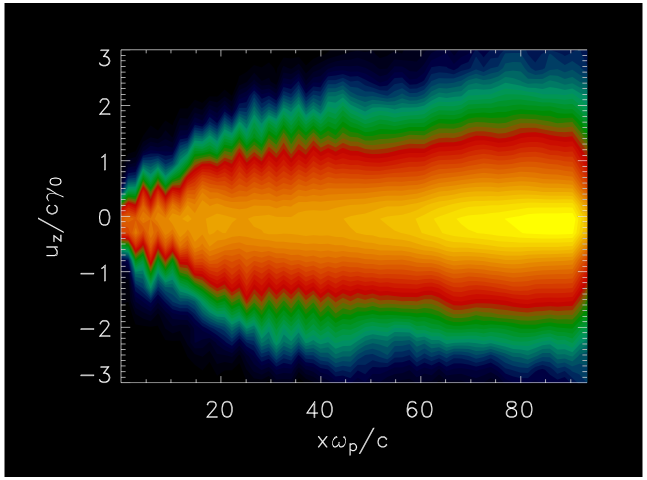
- Usually preloaded, i.e. no antenna (Lyubarsky 03)
- Zero proper cycles → self-consistent wave?
- **Oblique** rotator = tilted split monopole (Bogovalov 99)
  … BUT $e^{\pm}$ flux has $\partial/\partial t \neq 0 \neq \partial/\partial\varphi$ at launch
- **Force-free** simulations (Spitkovsky 06)
  … BUT artificial resistivity wherever $\boldsymbol{E}\cdot\boldsymbol{B} \neq 0$

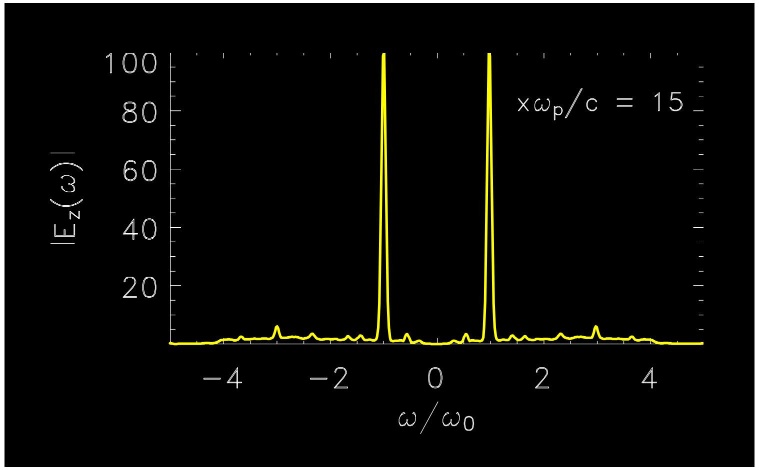
EM WAVE

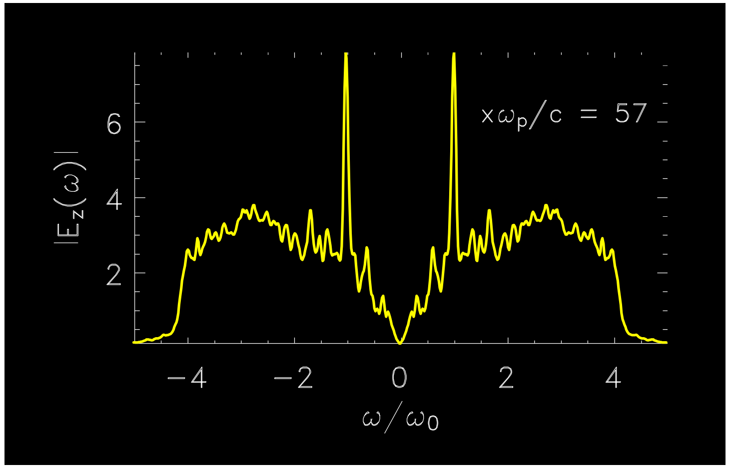
- "Any" antenna & constant (or oscillatory) $e^{\pm}$ flux
  … NOT tuned exactly to entropy wave

PIC SIMULATIONS





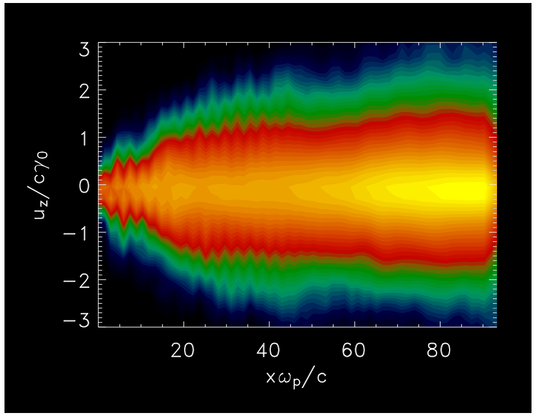




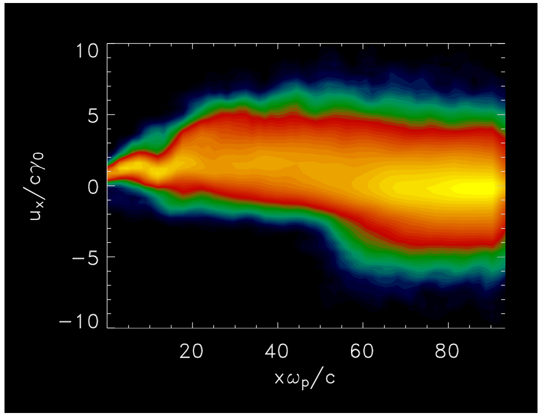
WAVE “SURVIVES” SHOCK

(Skjaeraasen et al. 05)

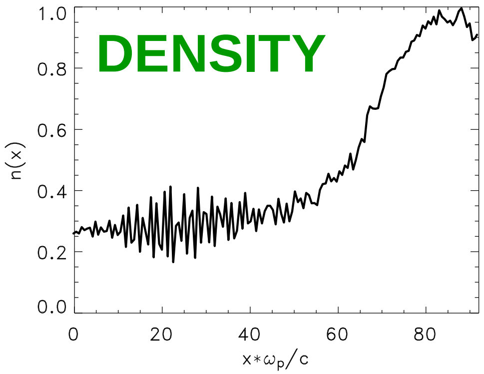
TRANS

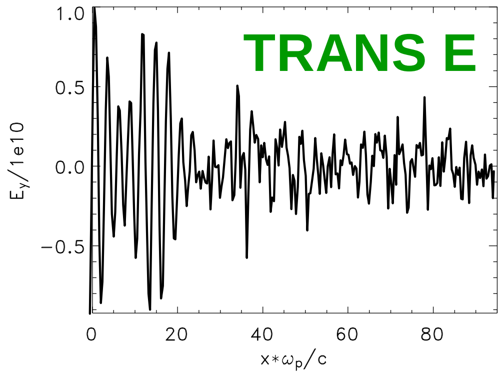


WEIBEL
HEATING



LONG





Crab:
10^{-3} pc
≈ 0.1"

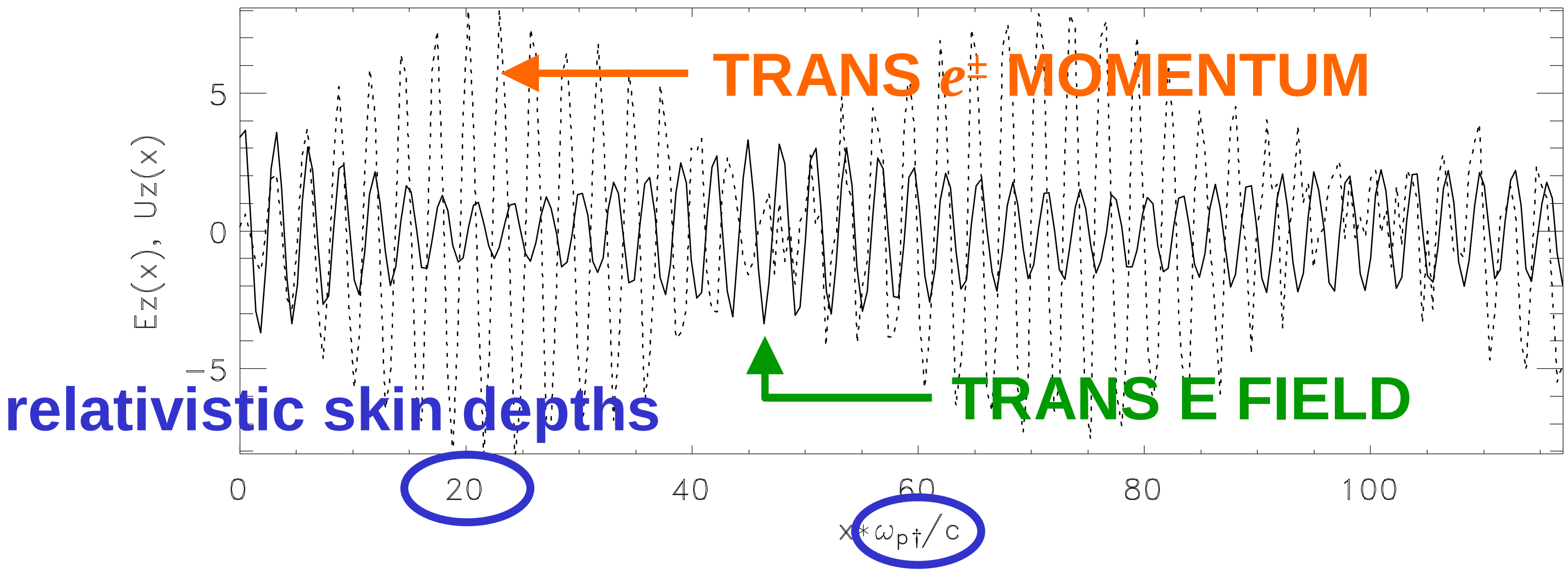
Wave **survives** ~ 10^2 skin depths beyond shock

KEY PIC RESULTS

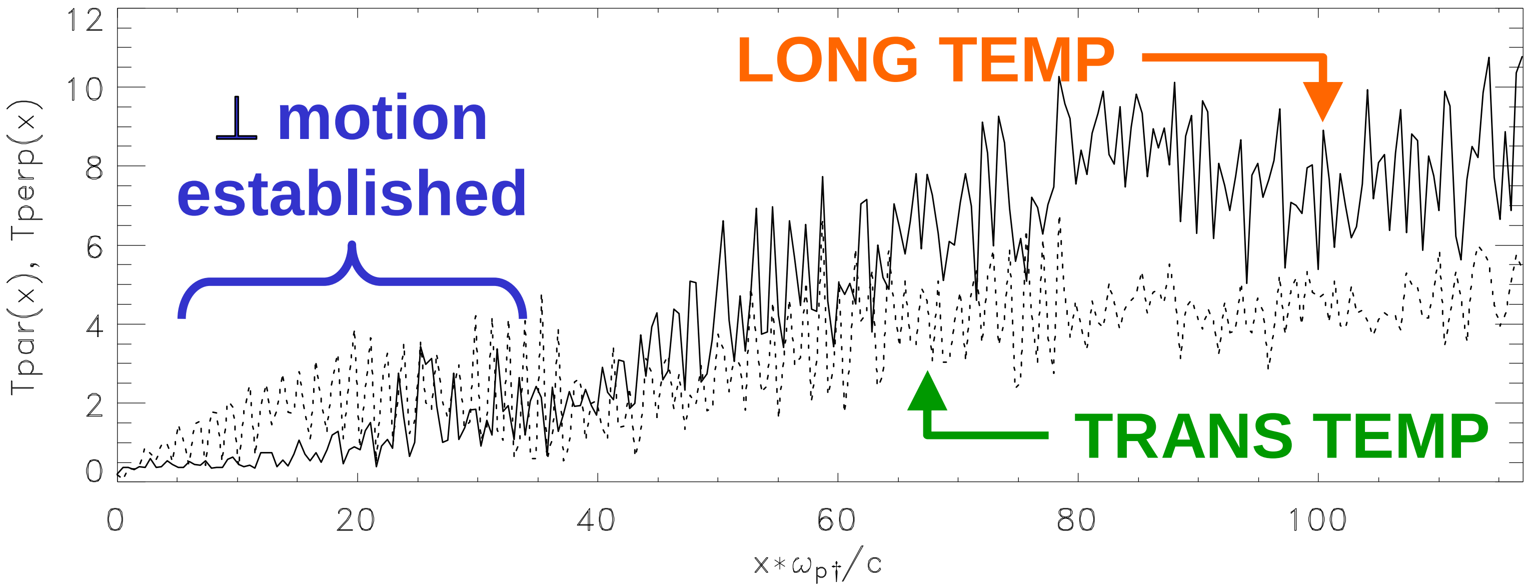
- Self-consistent, **phase-coherent** EM wave if:
  $\rightarrow$ ***strong antenna*** (**PSR**) decelerates flow (V_{wind}) by transverse acceleration
  $\rightarrow$ ***dense plasma*** (**GRB**) boosts J_{cond} & V_{phase}
- **"Stationary" wave** after $10^2 - 10^3$ **skin depths**
- **EM** > or < **KE** asymptotically

MACRO

- Still need $V_{\mathrm{phase}} \sim c \sim V_{\mathrm{wind}}$ to suppress parametric instabilities & radiation losses
- BUT antenna-driven wave less "fragile" than hypothetical infinite wave (cf. Asseo et al. 80)



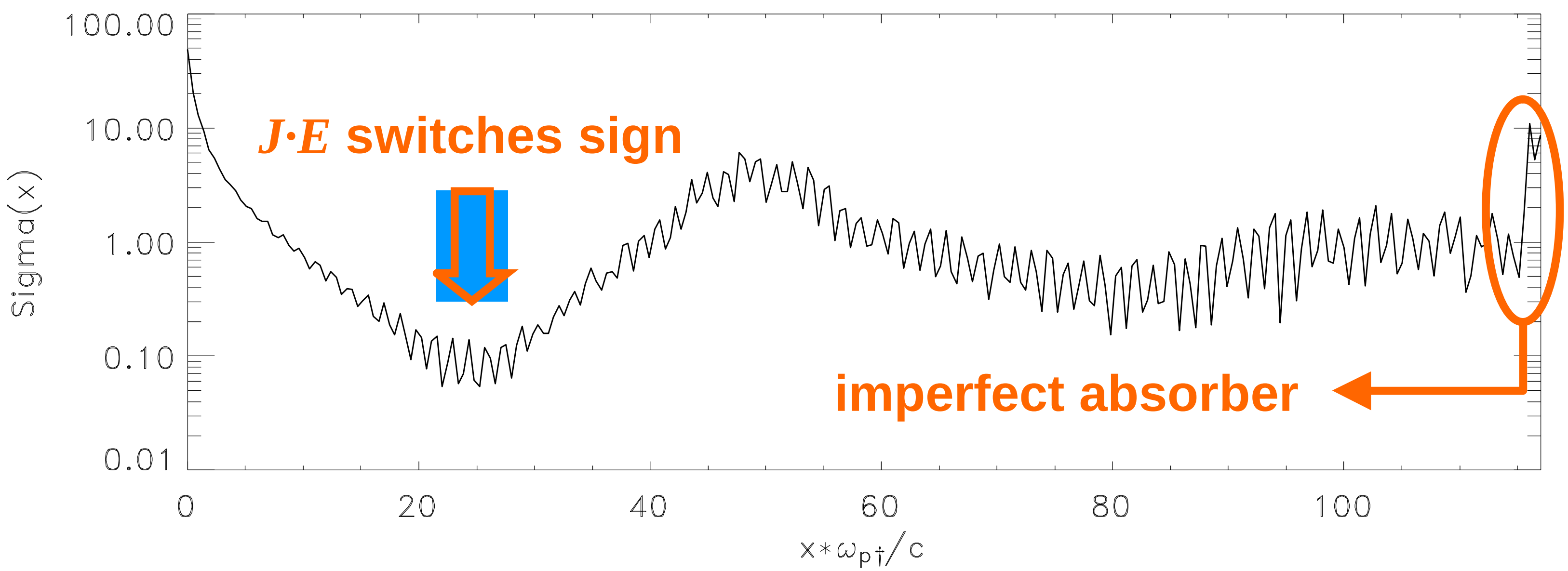
- ***J·E* ≠ 0** at injection (cf. infinite wave)
  → field ↓ as it accelerates $e^{\pm}$ transversely
- ***J·E*** switches sign at $x \approx 20$
  → energy transfer reverses
- Field-momentum **relative phase** $= 0 \rightarrow \pi/2$
  → **semi-stationary** wave after **~ 100 c/ω_p**



- Initially: **transverse heating** as $e^{\pm}$ and fields tend towards stationary relative phase
- **Streaming slows** as $T_{\perp}$ rises and $(\boldsymbol{V}\times\boldsymbol{B})_x < 0$

- Later: $\boldsymbol{J}\cdot\boldsymbol{E}$ switches sign, **longitudinal heating** by weak electrostatic field

σ = EM flux : KE flux



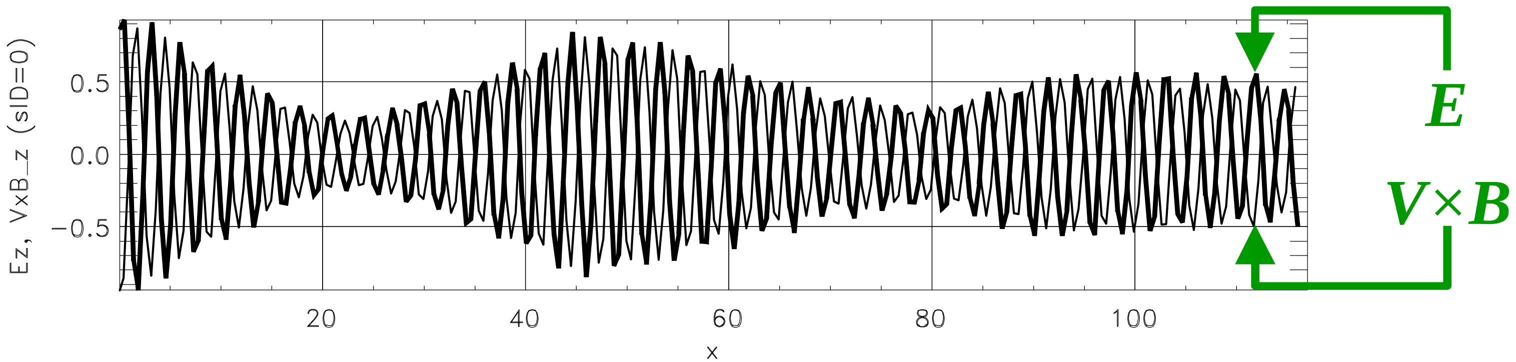
- Can easily form **high-σ** or **low-σ** flows
- Start with $\sigma_0 = 80$, end up with $\sigma_\infty \approx 1$

  $\sigma_0 = 10^3$ $\sigma_\infty \approx 10$
- EM & KE **independent** only if **circular** pol'n

IS ANY OF THIS MHD?

- Pulsar magnetosphere emits dense plasma
- Shorts out rest-frame electric field $\boldsymbol{E}'$

- Superluminal EM wave “must have” $\boldsymbol{E}' \neq \mathbf{0}$
- True… BUT tiny $\boldsymbol{E}'$ if streaming!

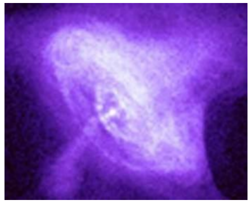


$\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B} \approx \mathbf{0} \rightarrow$ **nearly MHD!**

EM → KE CONVERSION

σ = EM flux : KE flux

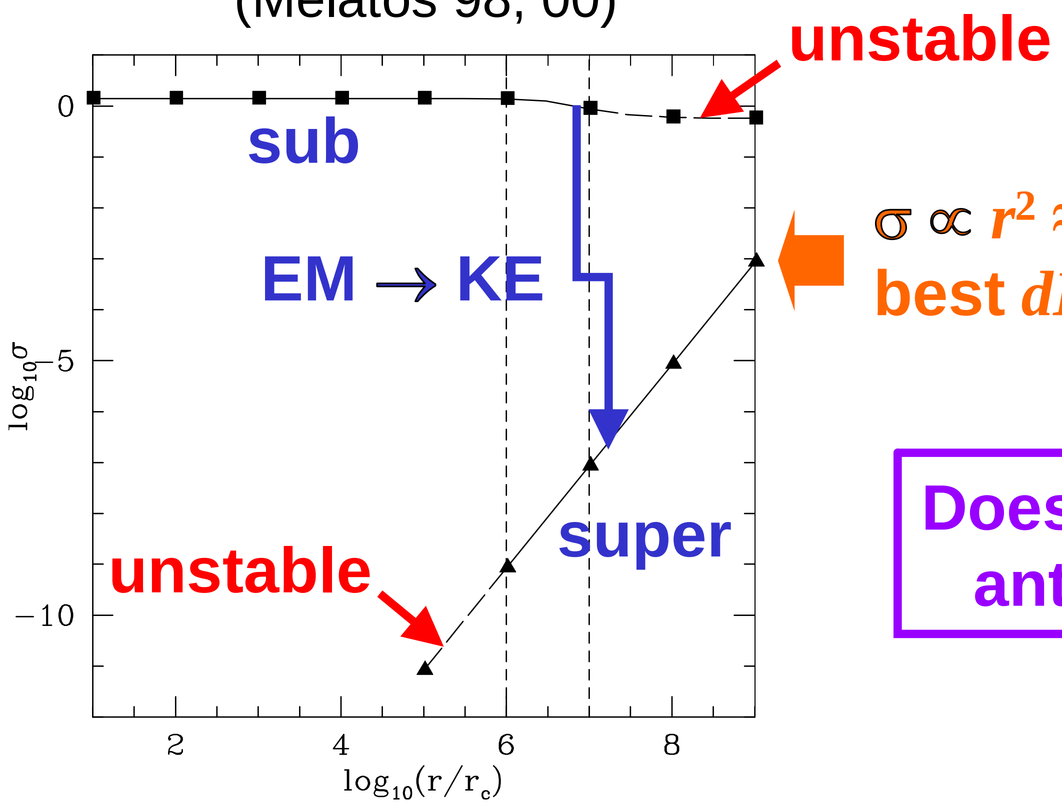
- **Shock:** $\sigma \approx 10^{-3}$ so MHD flow can decelerate from shock ($c/3$) to edge of PWN ($1500\ \mathrm{km\ s^{-1}}$)
- **Pulsar:** $\sigma \approx 10^{6}$ ($e^{\pm}$ cascades)



CRAB

- Force-free **linear accelerator** (Contopoulos et al. 02)
- **Reconnection** in striped wind (Lyubarsky & Kirk 01)
- **Annihilation** in shock (Lyubarsky & Petri 07)
- **Wave conversion** via instability (Melatos & Melrose 96)

(Melatos 98, 00)



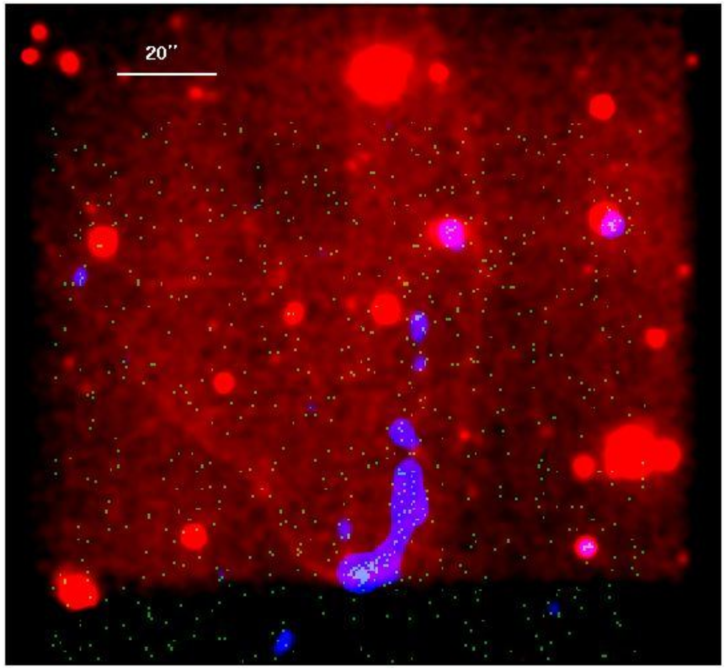
$\sigma \propto r^2 \approx 10^{-3}$ for best dN/dt & Γ

Does idea apply to antenna wave?

- Small **radial** magnetic field (e.g. spiral, or self)
- High-σ, subluminal → low-σ, superluminal wave: parametrically unstable at $\approx 10^7\ \lambda$ (Melatos 98)
- **How?** Why so **“silent”?**

Hα BOW SHOCKS

PSR J2124–3358



(Gaensler et al. 02;
Chatterjee et al. 07)

- **Energy flux** v. **latitude**
- **EM** wave

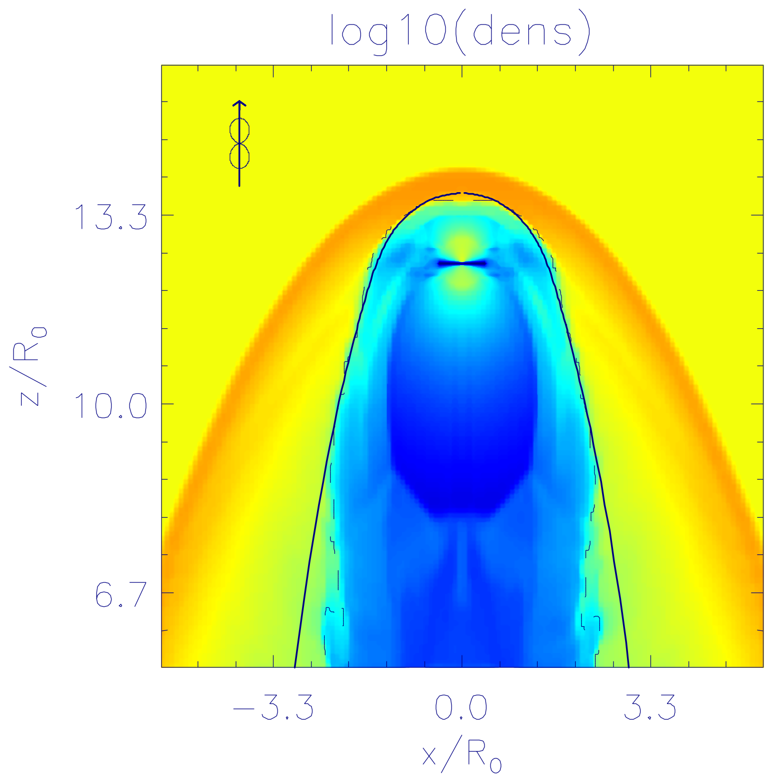
  (“vacuum dipole”)

  $\propto 1 + \cos^2\theta$
- **Entropy** wave

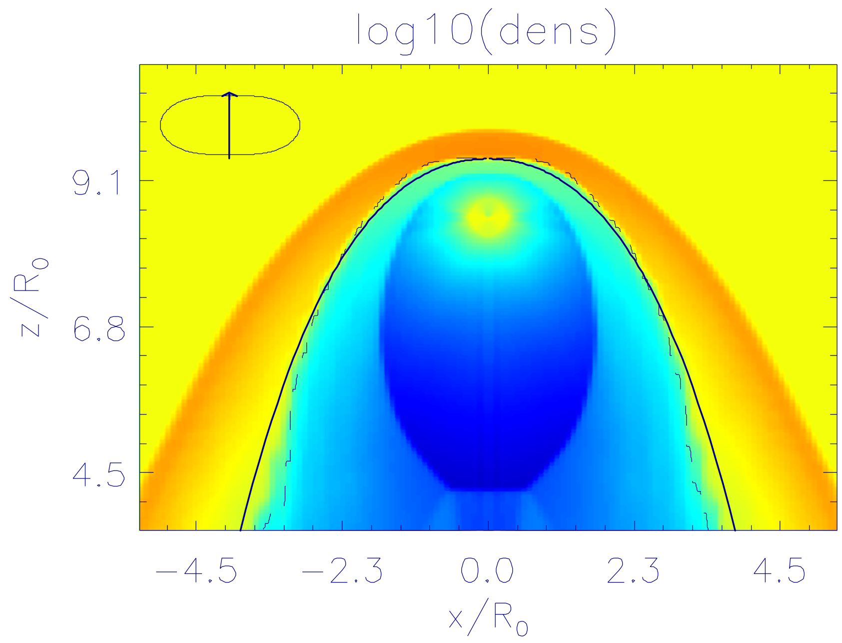
  (split monopole)

  $\propto \sigma^{-1} + \sin^2\theta$

Bow shock shape?

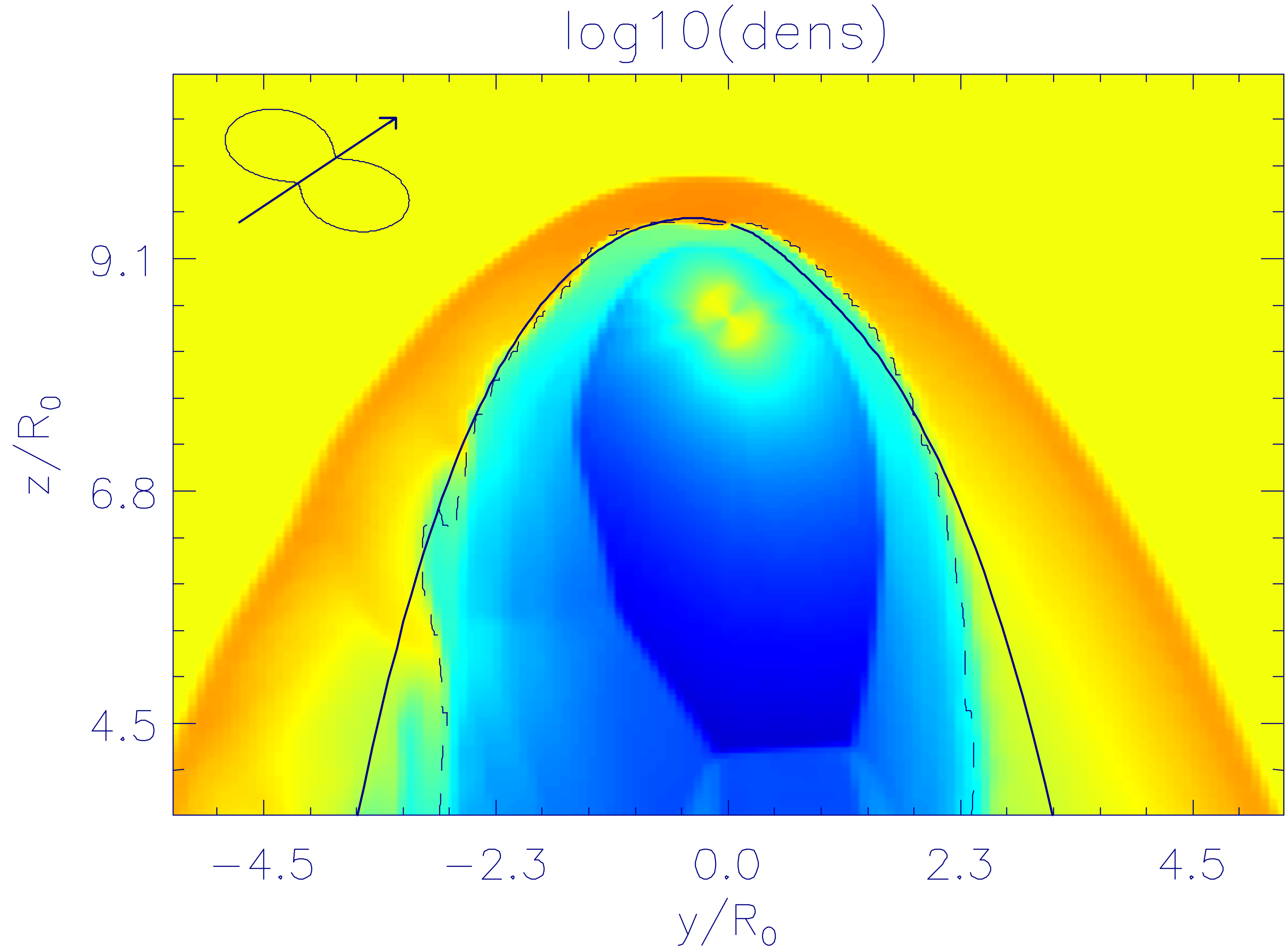


"EM WAVE"



"ENTROPY WAVE"

- Density contours (pure hydro)
- Indistinguishable along most lines of sight



Spin ∠ kick; density wall; Doppler (Vigelius et al. 07)

X-RAYS FROM THE DOUBLE PSR

- Shock intercepts 0.1% of A's spin-down power
- Shock $\sim 10^3\, R_L$ from A
- **Predict high σ**

- If high σ, expect **low L_X**

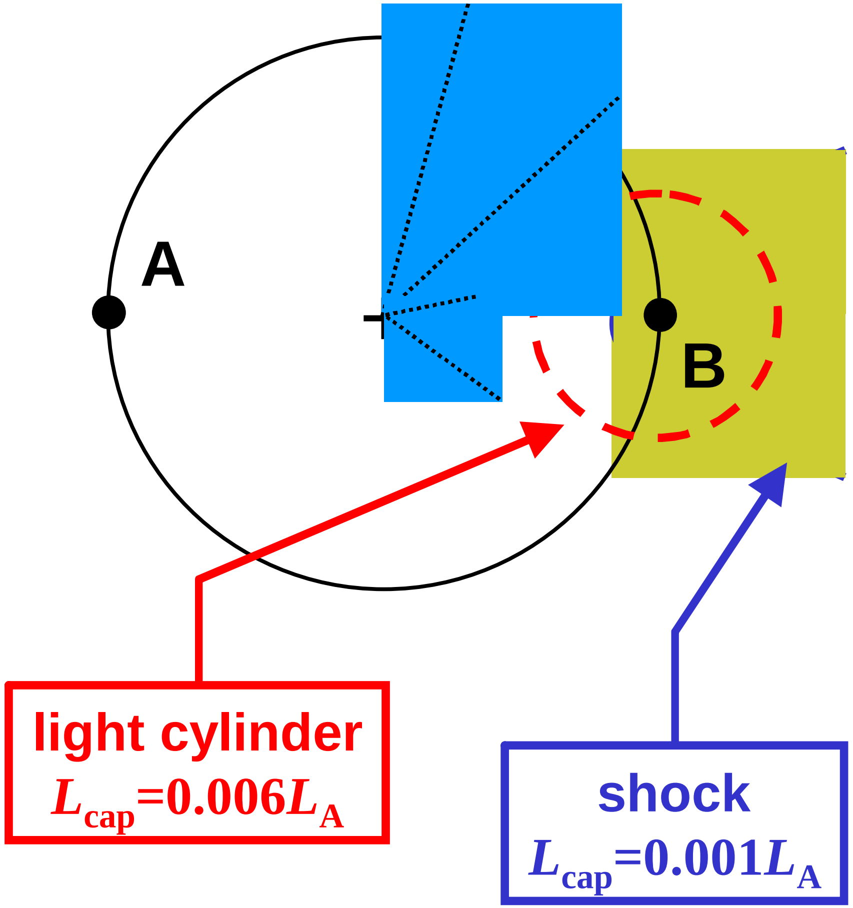
$$L_X \approx L_{\rm cap}/(8\sigma^{1/2})$$

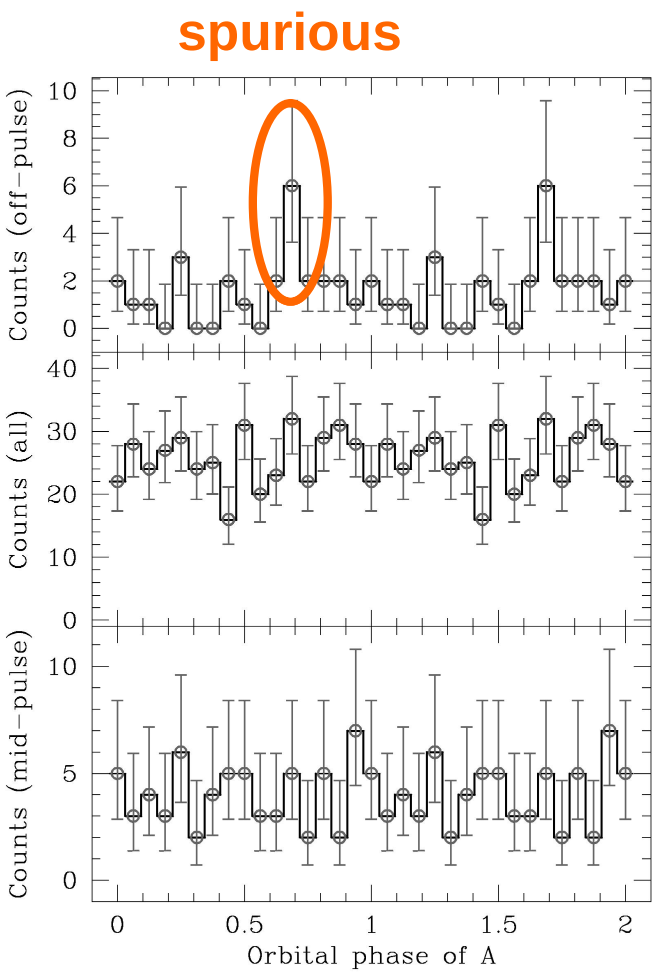
- If low σ, expect high L_X

$$L_X \approx L_{\rm cap}$$

and **orbital** modulation

PSR J0737–3039





(Chatterjee et al. 08)

- A = nonthermal pulses
- B = nothing

- **Zero orbital modulation**
(epoch folding, H statistic)

- Spectra (Chandra, XMM)

$\mathbf{L_{shock} < 0.0002\ L_A \ll L_{cap}}$

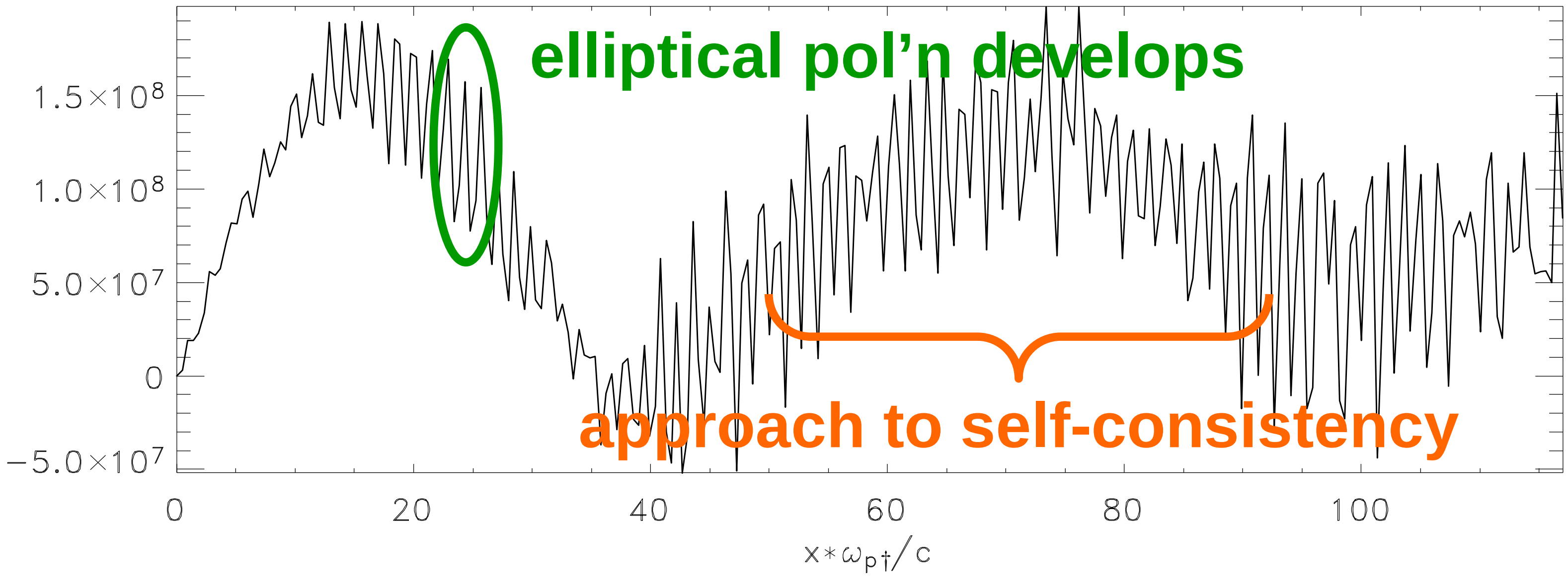
- Consistent with **high** σ
- Cf. magnetic annihilation in shock itself (Lyubarsky 03)

SUMMARY

- **Self-consistent,** antenna-driven EM wave forms after $\sim 10^2$ skin depths (low or high σ)
- Subluminal (EM) $\rightarrow$ superluminal (KE)
- Hα (PWN) & X-ray (double PSR) bow shocks

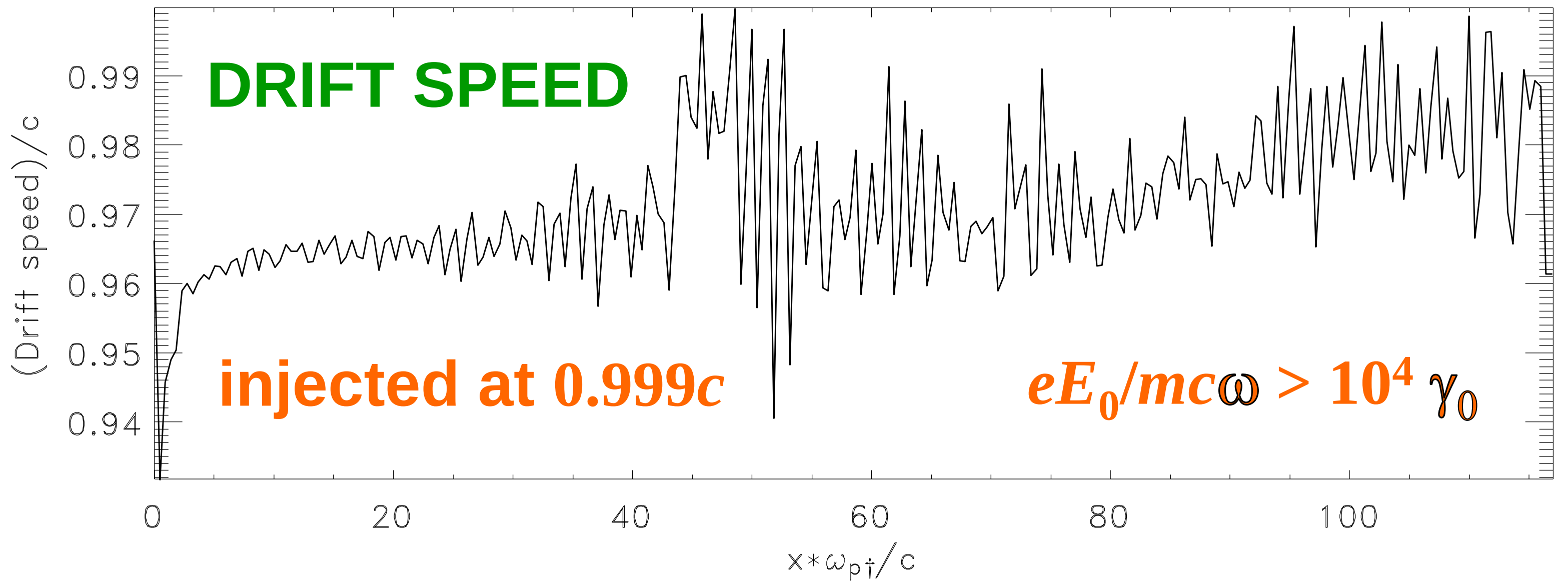
Things to do!

- Ponderomotive "pinching" (Skjaeraasen et al. 08)
- Charge starvation in diverging flow with PIC
- Match antenna to magnetosphere
- Magnetar winds in GRBs (Bucciantini et al. 07)



- $e^{\pm}$ angular momentum w.r.t. instantaneous electric vector (space-independent frame)
- **Constant** if **infinite** plane wave
- Stationary asymptotically

- Phase speed: $\mathbf{1.01}c < E/B < \mathbf{1.3}c$



- **Decelerate** flow by **energising transversely**

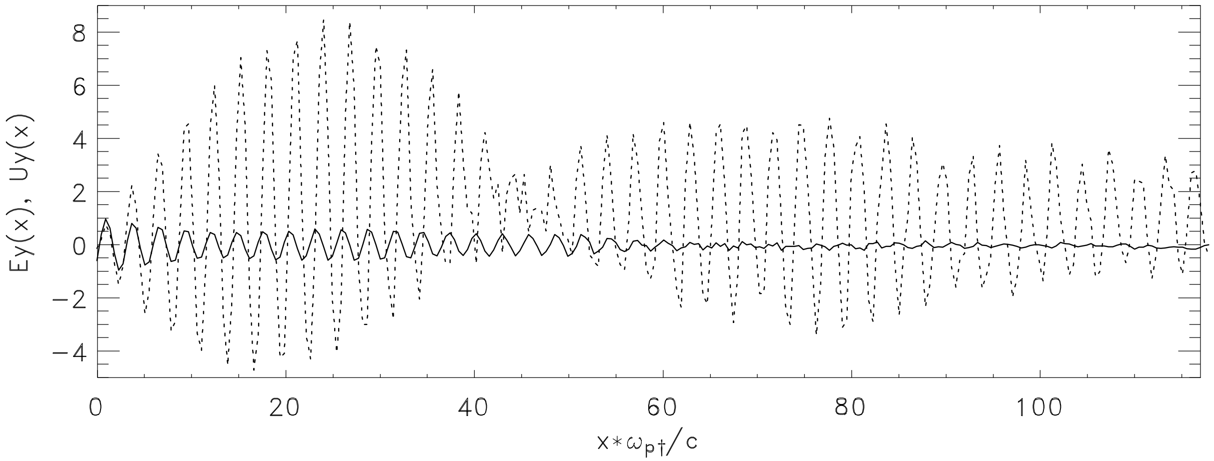
$V \times B$

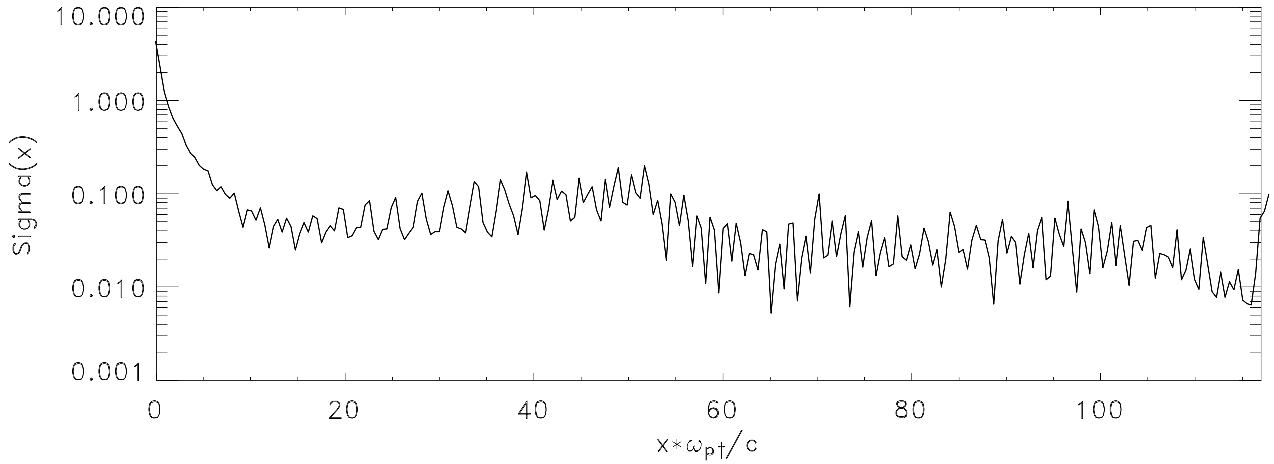
- Drift speed $\approx 0.96c$ for $x < 80$ even as $p_x \uparrow$
- Accelerates to $0.98c$ for $x > 80 \rightarrow$ longitudinal E

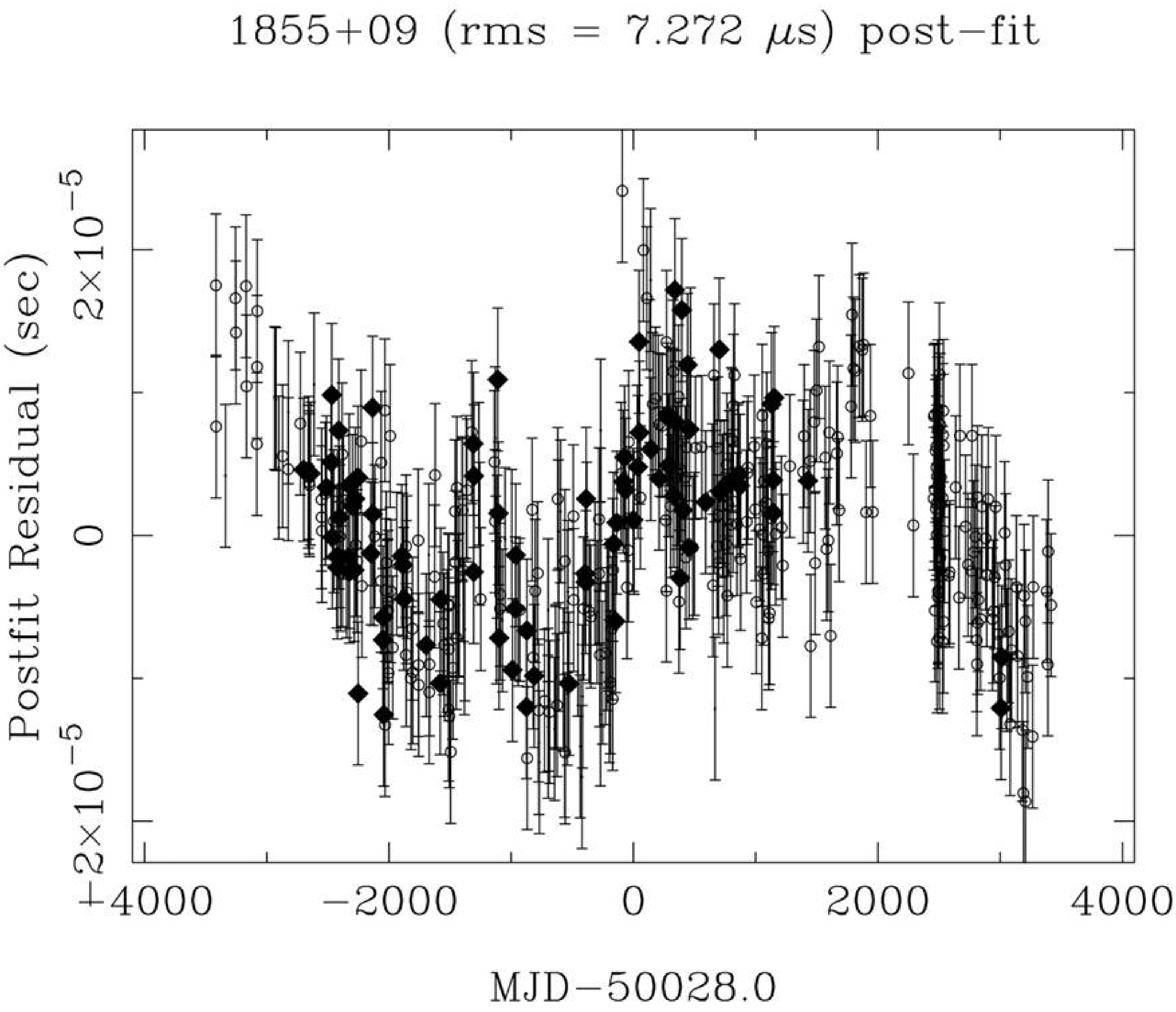
?

- Insensitive to antenna frequency
- Sensitive to antenna amplitude

PONDEROMOTIVE SHAPING






1855+09 (rms = 7.272 μs) post-fit
Postfit Residual (sec)
2×10^−5
0
−2×10^−5
−4000
−2000
0
2000
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