Stochastic & Shear Particle Acceleration in astrophysical outflows

and its possible relevance for LS 5039

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Workshop on Variable Galactic Gamma-Ray Sources III

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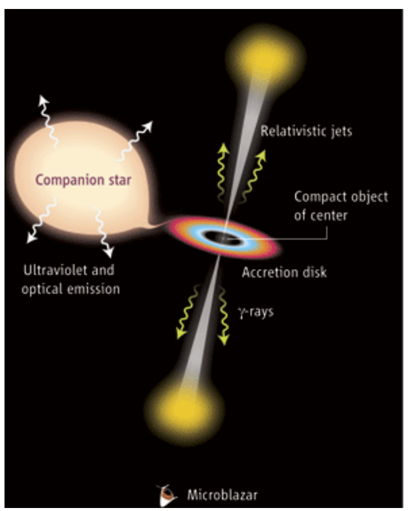

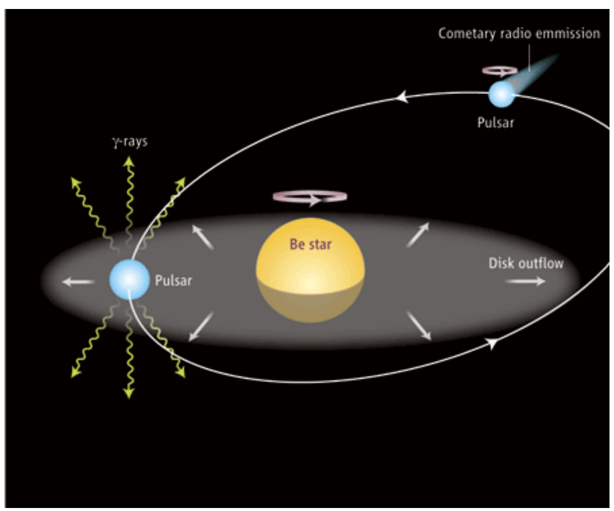

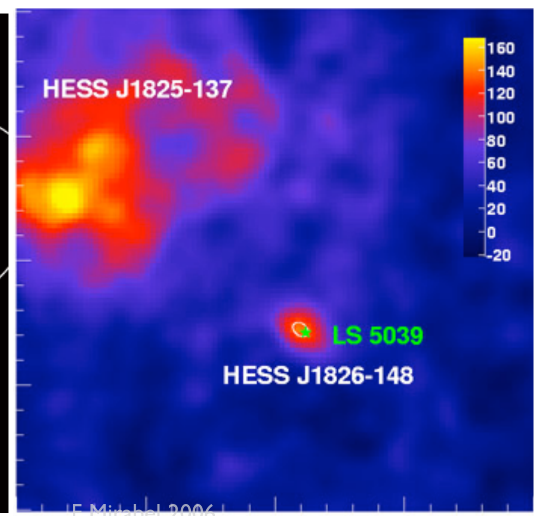

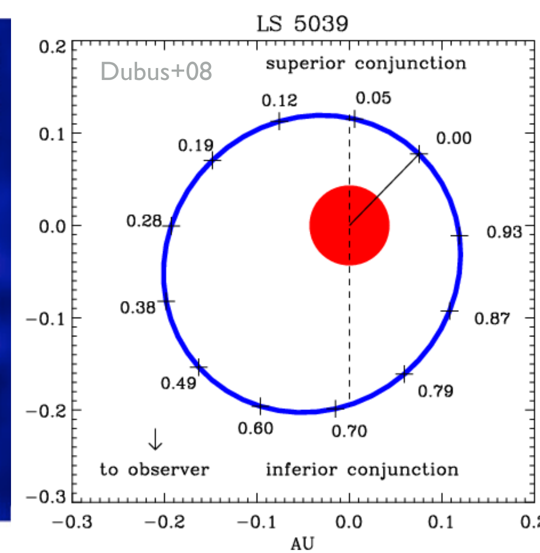

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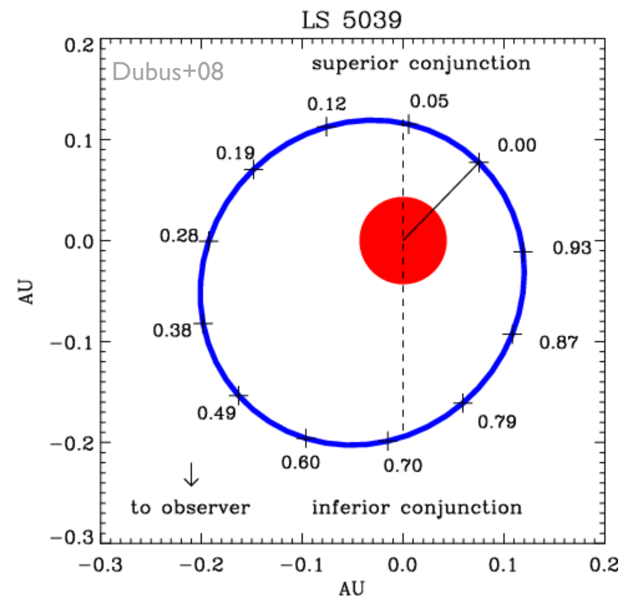
Outline

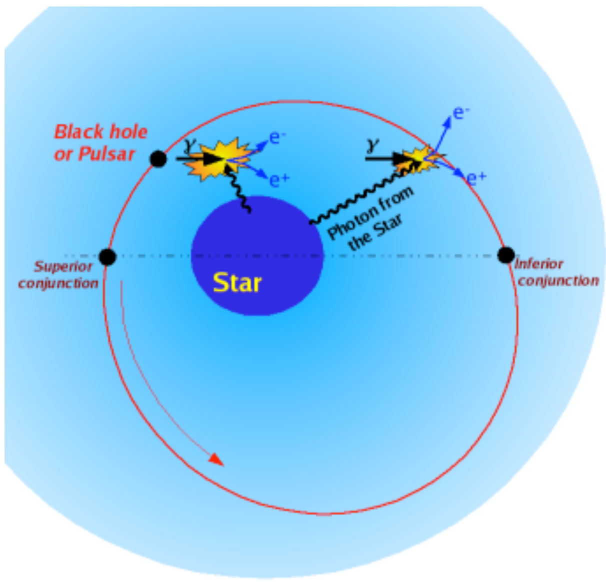
_Efficient particle acceleration in gamma-ray binaries

- The case of LS 5039 (efficiency constraints)
- Gamma-ray emission from different sites



_Potential *acceleration mechanisms & emission sites*

- Source phenomenology
- Shear particle acceleration (recap)
- Stochastic acceleration and Expanding flows



LS 5039 @VHE and X-rays

Periodically modulated TeV emission at P_{orb}=3.9 d :

- produced inside or very close to system
- due to γγ-absorption and anisotropic IC

VHE spectrum extends well beyond 10 TeV: (Aharonian+ 06)

- stellar radiation peaks ~10 eV (T~4 x10^4 K)
- IC scattering (KN!) needs >10 TeV electrons

X-ray (Suzaku 2007) observations: (Takahashi+ 09)

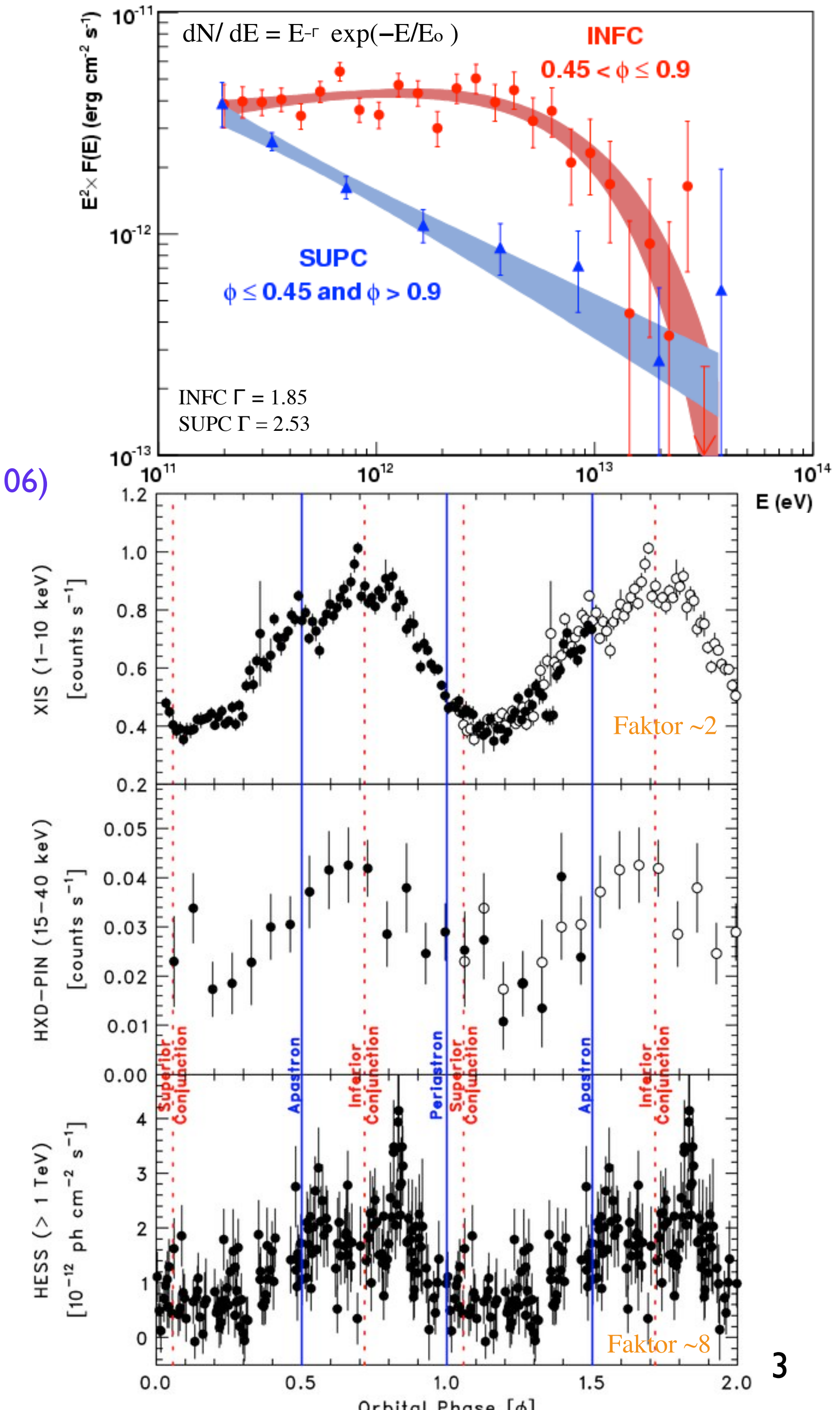
- hard power law up to ~70 keV

  $\Rightarrow n_e(\gamma) = n_0\, \gamma^{-s}$, $s \approx 2$

  (in Gauss-type fields up to $\gamma \sim 10^{6\text{-}7}$)

- periodic modulation at orbital period

  ⇒ origin?



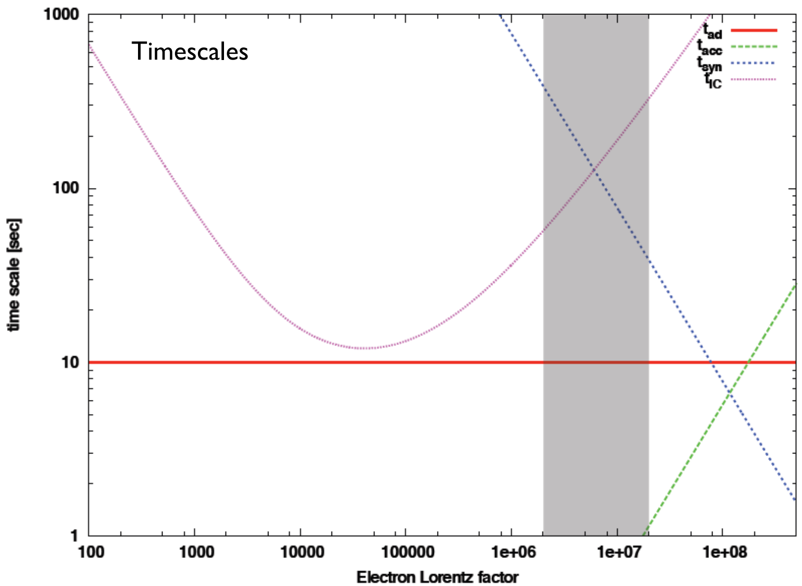
Evidence for extreme particle acceleration in LS 5039 ?

Acceleration efficiency $t_{acc} := \eta\, r_g / c$ for origin of TeV: (Khangulyan+ 08)

- min. variability ~1 hr gives lower limit on B
- from $t_{acc} \leq \min(t_{IC,KN}, t_{syn})$: $\eta < 100$ ($z < 5\, R_{orb}$) and $\eta < 10$ ($z \ll R_{orb}$)

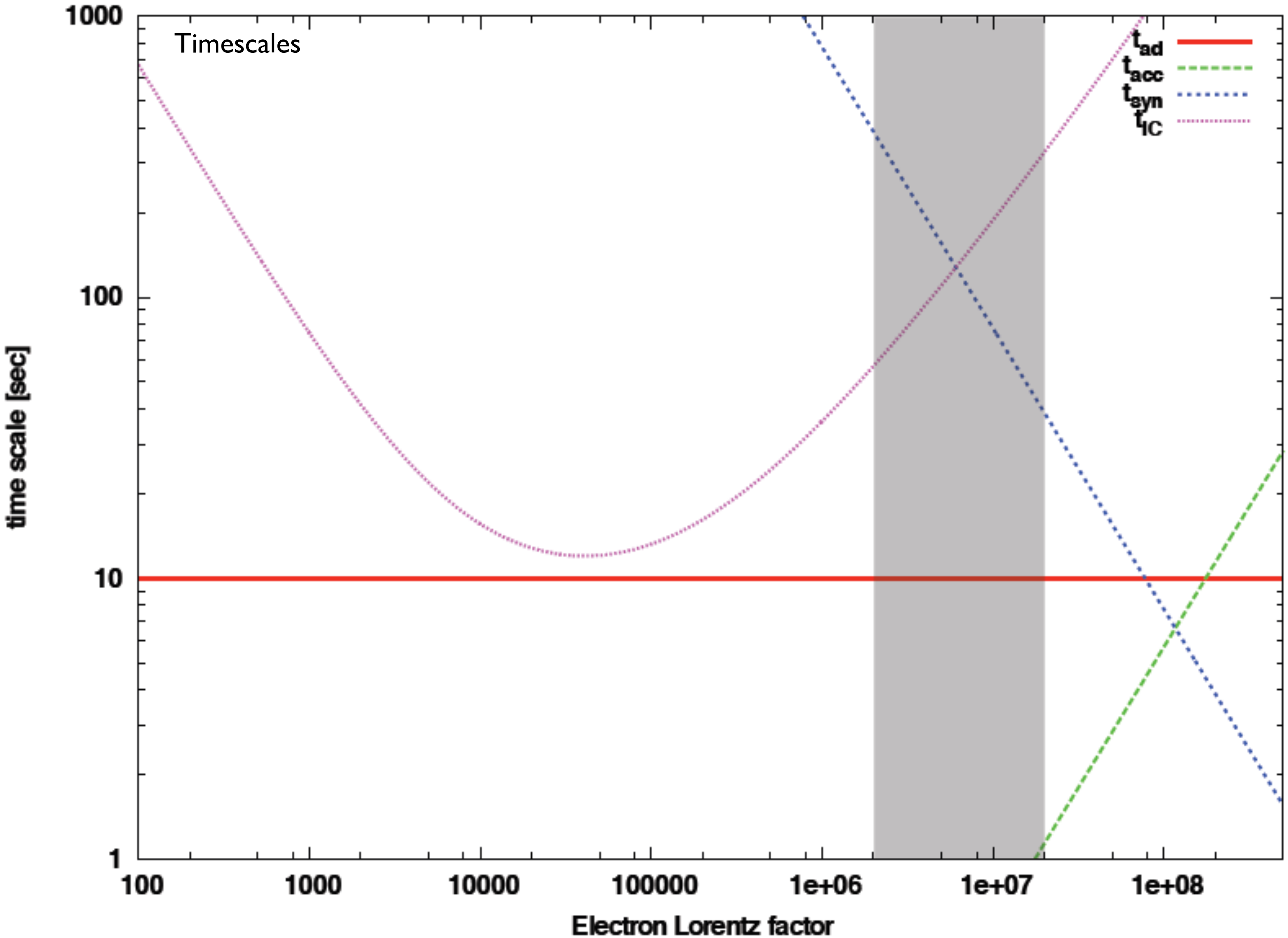
Origin of X-ray "periodicity" ? (Takahashi+ 09)

- if due to dominant *adiabatic cooling* **$\eta \leq 3$**
- *similar for m.f. modulation (equipartition stellar field), synchrotron HE (~100 MeV)* (Chernyakova+ 14)



Parameters:
$\eta = 1$
$R = 10^{11}$ cm
$u = c/3$
$B = 1$ G
$d = 2 \times 10^{12}$ cm
$L_{star} = 7 \times 10^{38}$ erg/s

Evidence for extreme particle acceleration in LS 5039 ?



~R/u

~ 1/B

~ 1/γB^2

~ d^2

Parameters:

η = 1

R = 10^{11} cm

u = c/3

B = 1 G

d = 2 x 10^{12} cm

L_{star}=7 x 10^{38} erg/s

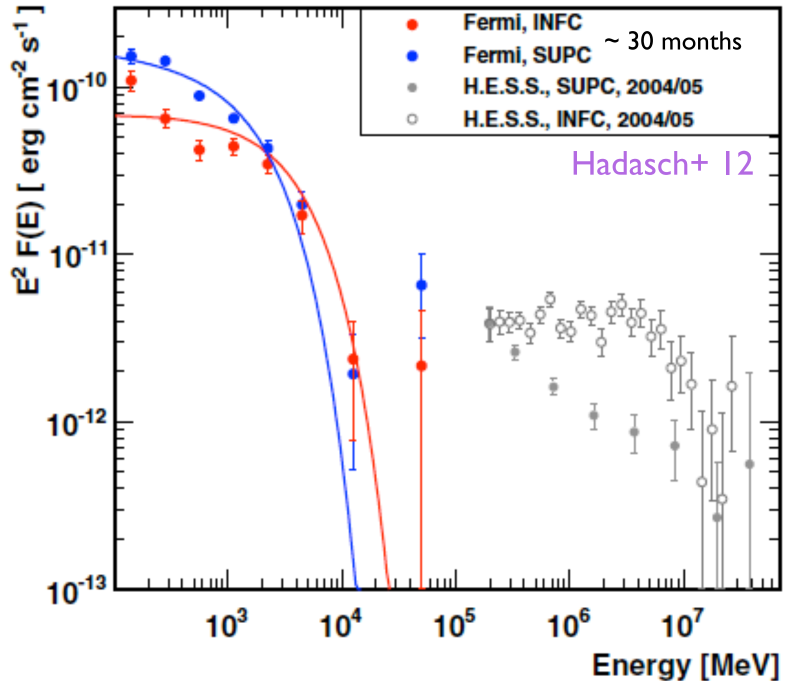
LS 5039 @ Fermi-LAT energies

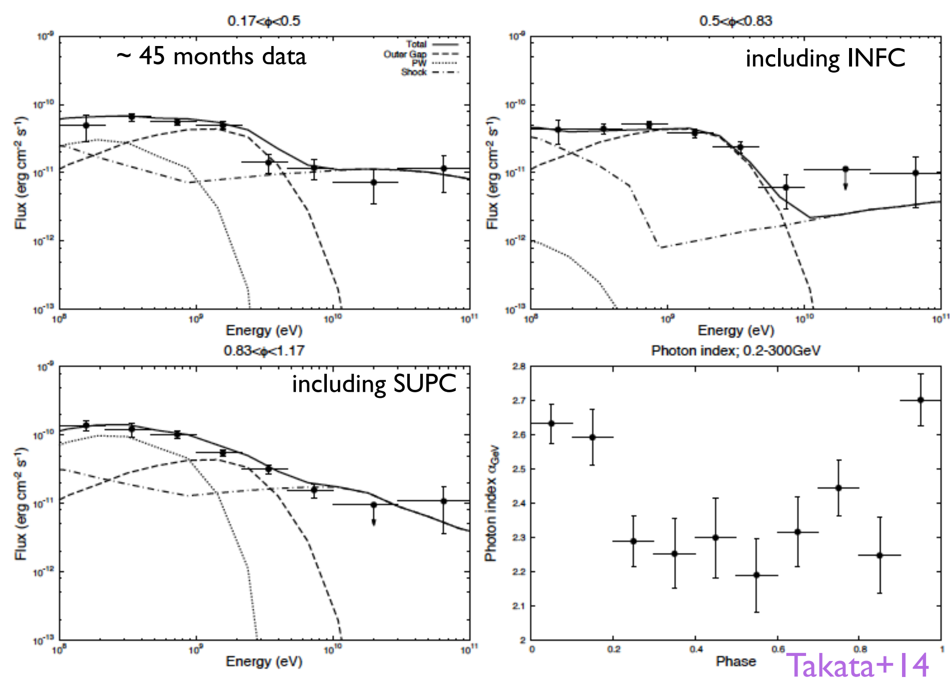
HE emission *beyond* 10 GeV:

- *phase-averaged* spectrum (>100 MeV) fits power law (photon index≈2) with exponential cut-off E_c ≈ (2-4) GeV

- LC modulated with orbital period, but shifted to TeV/X-rays ("anti-phase"), trend for shift increase with HE energy? (Chernyakova+14)

- *phase-resolved spectrum:*
  - *excluding* SUPC: cut-off at E_c ≈2 GeV and spectra similar,
  - *including* SUPC: enhancement at 0.1-0.3 GeV and softer spectrum





LS 5039 @ gamma-ray energies

- *Two-component HE emission*? Different locations?

  (one for <1GeV at SUPC, plus one for entire orbit?)

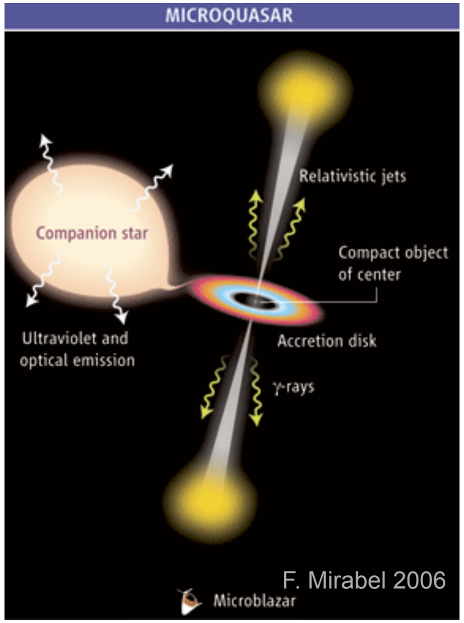
- HE & VHE gamma-rays from different locations dominating?
  - magnetospheric HE (~1-10 GeV)?
    - but modulation & no pulsation?
  - unshocked pulsar wind (IC, ~0.5 GeV)?
  - termination shock/wind stand-off (GeV-VHE)

  +.......

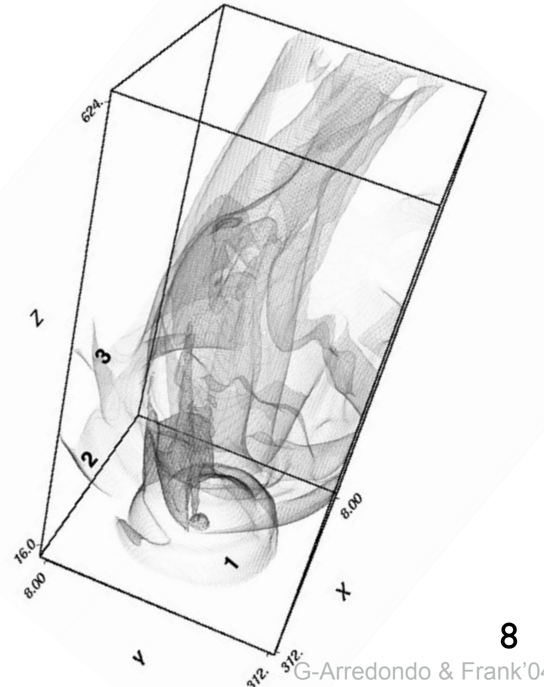
On the nature of LS 5039

Microquasar-Scenario?

- BH-jet, accretion-powered scenario
- Multiple emission sites possible (Perucho & Bosch-Ramon'12)
    - magnetospheric (IC-GeV)
    - jet (internal shocks…)
    - jet-wind interaction…
- expect mildly relativistic jet speeds v_j~0.5-0.7 c



- 1st order Fermi (parallel shock) not efficient enough (?)
    - $t_{acc} \approx 20\ \kappa/u_s^2 \geq 6\ t_L\ (c/u_s)^2 > 10\ t_L$
    - *escape:* quasi-perpendicular shocks? (Jokipii 1987)
    - kinetic theory: $\kappa_{||} = \lambda c/3$, $\kappa_{\perp} = \kappa_{||}/(1+\lambda^2/r_g^2)$
    - but: already using Bohm limit $\lambda \to r_g$



G-Arredondo & Frank'04

Particle acceleration and emission in LS 5039

Expect potential contributions from multiple zones:

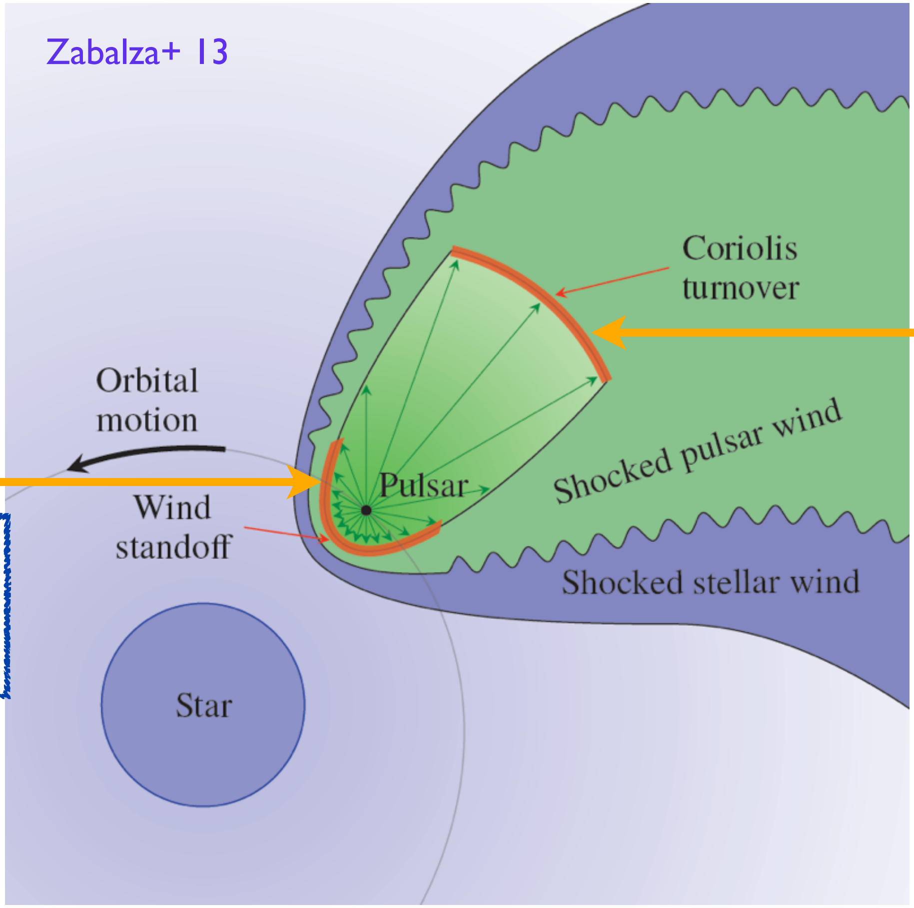
(cf. Bosch-Ramon & FR 12)

- pulsar magnetosphere
- pulsar wind (IC)
- “termination” shock(s)
- (re-accelerated?) shocked pulsar wind
- .....

GeV ?

deep inside r~R_{orb}/10
strong IC losses &
pair production

η~2000



Shock @ balance between PW and Coriolis-induced (orbit-tangent) SW ram pressures
Bosch-Ramon & Barkov 11

TeV ?

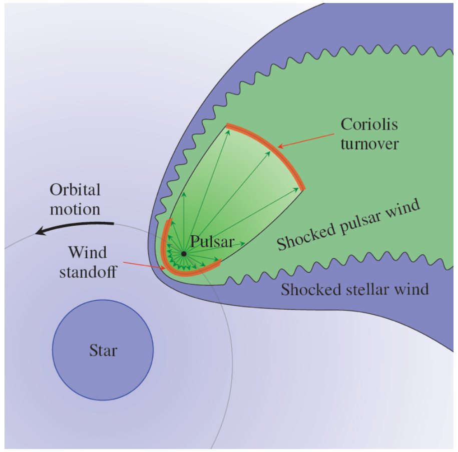
r~ few R_{orb}
reduced IC losses &
pair absorption

η~10-20
KN-IC limited, B~0.3 G

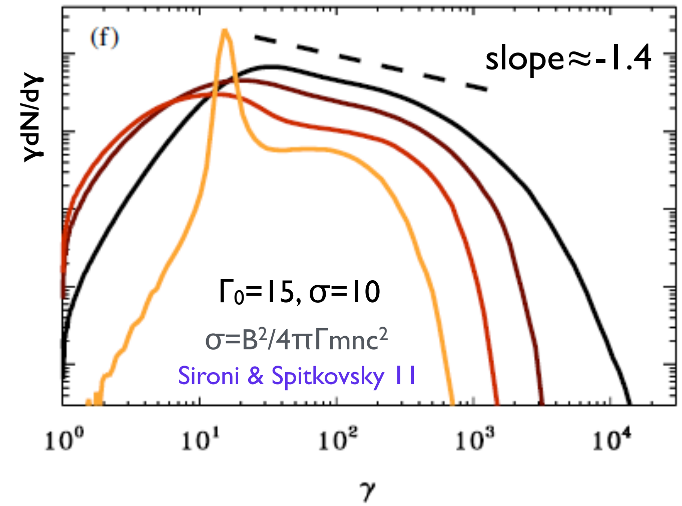
X-rays in ~10 G (Takata+14) ?

Particle acceleration at PW termination shock (TS)

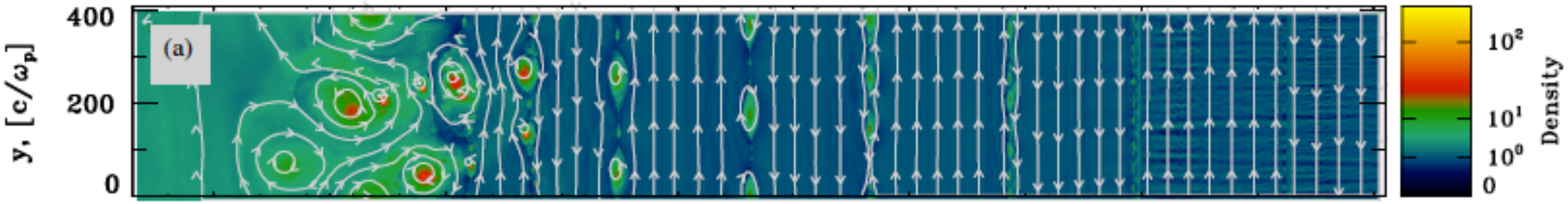
Particle acceleration by **driven** magnetic reconnection:



- at TS, flow gets compressed and m.f annihilates (Lyubarski '03)
- 2D-PIC: *all* magnetic energy given to particles: (Sironi & Spitkovsky '11, '14)
  - power-law particle spectrum (downstream) possible
    from $\gamma_{min} \approx \Gamma_{PW}$ to $\gamma_{max} \approx \Gamma_{PW}\, \sigma^{1/(2-p)}$
  - needs stripe wavelength (measured in post-shock plasma)
    $\lambda / (r_{Larmor}\, \sigma)$ > several tens
    equiv: $4\,\pi\,\kappa\, R_{LC}/R_{TS}$ > several tens (with $n = \kappa\, n_{GJ}$)



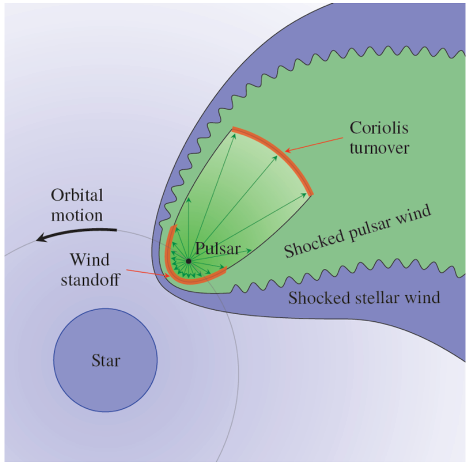
- "Better" for gamma-ray binaries: $R_{TS} \sim 10^3\, R_{LC}$
  $\Gamma_{PW}\, \sigma \sim 10^4$ (Petri & Dubus '11)
  spread: $\gamma_{max}/\gamma_{min} = \sigma^2$
  $\Rightarrow \sigma < 10$ for LS 5039 @ GeV?



$\omega_p = (4\pi e^2 n_{co}/\gamma_0\, m)^{1/2}$ hydro shock magnetic island formation fast MHD shock Sironi & Spitkovsky 11

Efficient stochastic acceleration in post-shock flow ?

CASE I: Post-shock magnetization not too small



- *assume:* full m.f. dissipation at TS does not occur
- Alfven speed $v_A/c \approx \sigma^{1/2} \gtrsim 0.1$
- stochastic 2nd order Fermi $t_{acc} \simeq (c/v_A)^2\, \tau_s$
  can reach $\gamma_{max} \sim 10^7$
- diffusion equation (zero-order approximation):

$$\boxed{\cancel{\frac{\partial f}{\partial t}} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(\cancel{p^4 \beta_s} f\right) + \frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f}{\partial p} - \cancel{\frac{f}{T_{\rm esc}}}}$$

with momentum-space *diffusion coefficient* $D_p = p^2\, (v_A/c)^2 / 3\, \tau_s = D_0\, p^{2-\alpha}$

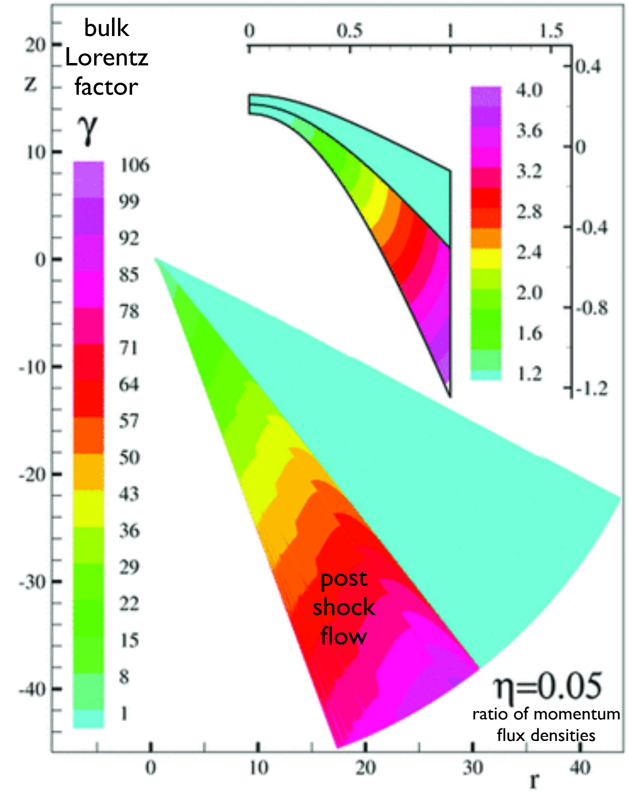
where $\tau_s \propto p^\alpha$ (α=0 *hard-sphere*, α=1/3 *Kolmogorov*, α=1/2 *Kraichnan*, α=1 *Bohm*)

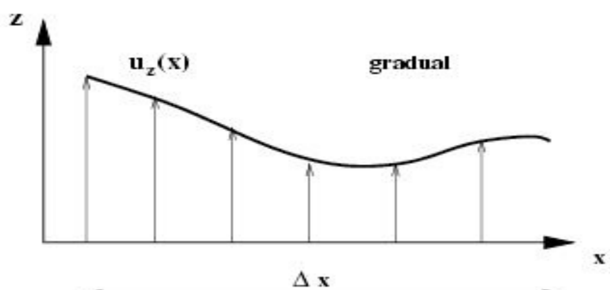
- Solution $f(p) \sim \int dp\, p^{\alpha-4} \exp(-c_1\, p^\alpha / \alpha)$ … (for $\alpha \neq 0$)
- for hard-sphere: $n(p) \sim p^2 f(p) \sim p^{-(1+a)}$ with $a = 1/[3\, t_{ad}\, D_0\,]$, "hard spectrum"
- will need full time, space & momentum study

Efficient shear acceleration in post-shock flow ?

CASE II: Post-shock magnetization small ($\sigma \ll 1$)

- low Alfven speed, no efficient 2nd order Fermi
- Hydro-limit applies: (Bogovalov+ 08 & 12)
  - possible re-acceleration of post-shock flow to $\Gamma \gg 1$
    (adiabatically: thermal heat to bulk motion)
  - large velocity gradients
- shear particle acceleration possible (FR & Duffy '05, '06)
  - 2nd order "Fermi-type"
  - draws on *systematic* velocity component
  - needs energetic seed particles





$$\frac{<\Delta\epsilon>}{\epsilon_1} \propto \left(\frac{u}{c}\right)^2 = \left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2$$

Shear acceleration (recap)

(e.g., Jokipii & Morfill '90; FR. & Duffy '04, '06)

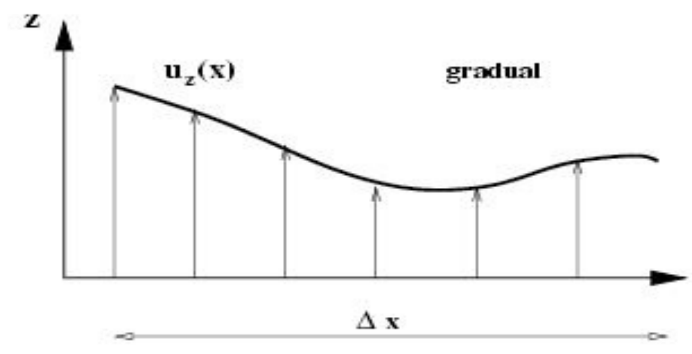
- *Gradual* shear flow with frozen-in scattering centers: $\vec{u} = u_z(x)\ \vec{e}_z$

- like 2nd Fermi, stochastic process with average gain:

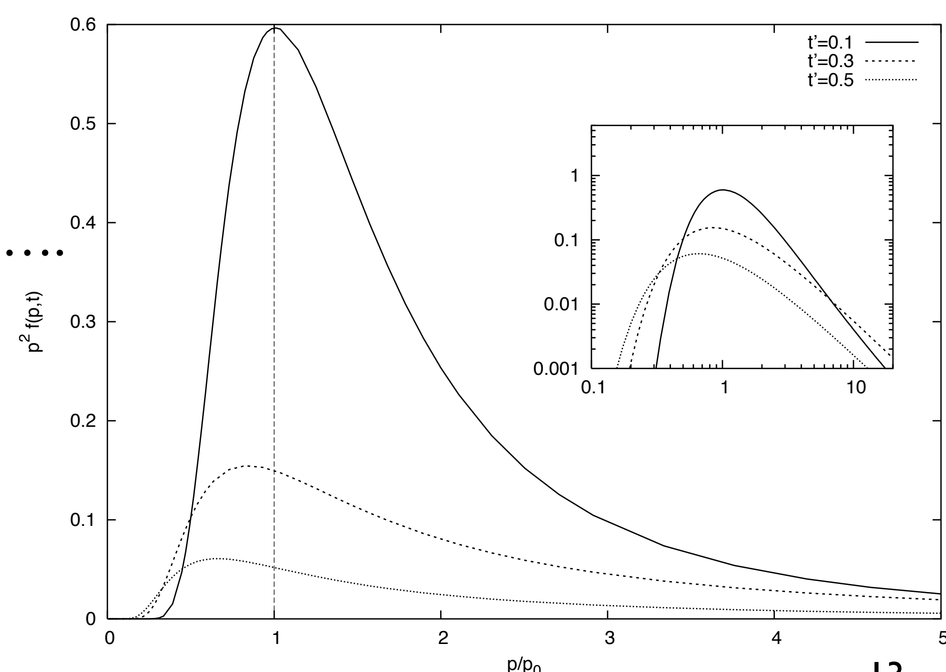
$$\boxed{\frac{< \Delta\epsilon >}{\epsilon_1} \propto \left(\frac{u}{c}\right)^2 = \left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2}$$

with characteristic effective velocity:

$$u = \left(\frac{\partial u_z}{\partial x}\right)\lambda \qquad \lambda = \text{mean free path}$$



- $t_{acc} \approx E / (dE/dt) \sim 1/\lambda$
- seed from acceleration @ TS (GeV), stochastic….
- easier for protons….
- $n(\gamma) \sim \gamma^{-(1+\alpha)}$, with α=1 for $\lambda \sim r_g$ (Bohm)
    - *change of slope?*
- boost to TeV energies? relativistic effects?



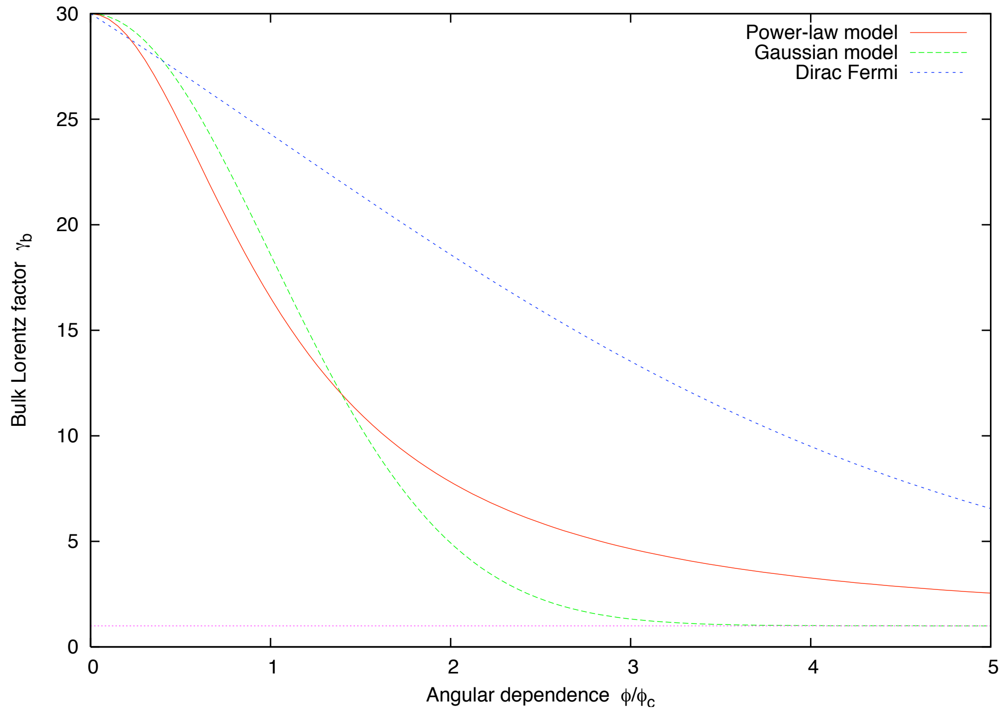
Efficient shear acceleration in post-shock flow ?

Illustration: Shear acceleration in expanding outflows (FR+, in prep)

- Flow profile: $u^\alpha = \gamma_b\,(1,\ v_r(\theta)\,/c\ ,\ 0,\ 0)$ θ = polar angle
- Characteristic acceleration time scale:

$$t_{acc}(r,\theta)' \sim r^2 / [\gamma_b^2\,\lambda] \times 1/[v_r^2 + 0.75\,\gamma_b^2\,(\partial v_r/\partial\theta)^2]$$

- power-law, Gaussian and Fermi-Dirac profile for γ_b :

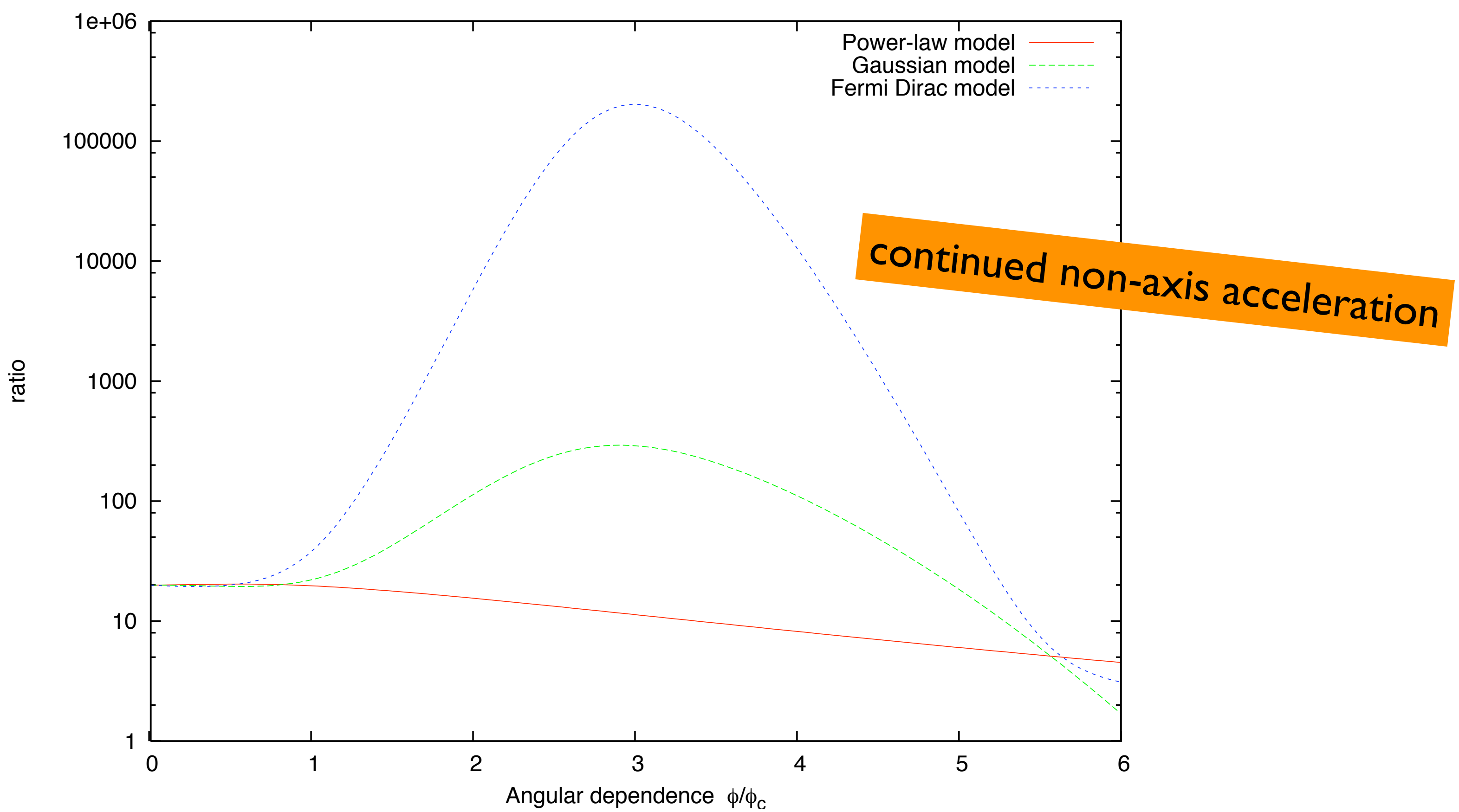


Evolution of γb with polar angle θ for power-law (**b** = 1.8), Gaussian and Fermi-Dirac type (β_c = 0.5) profile, respectively, assuming γ_{b0} = 30.

Efficient shear acceleration in post-shock flow ?

Illustration: Shear acceleration in expanding outflows

- acceleration versus adiabatic losses ($t' \sim r / c\, \gamma_b$)
- need sufficient energetic particles ($\lambda / r > 10^{-6}$)



Ratio of viscous shear gain versus adiabatic losses times (r/λ), illustrated for θ_c =0.05 rad.

To conclude

Extreme particle acceleration in Gamma-Ray Binaries

- evidence for $t_{acc} \sim O(10)\ r_g/c$ for TeV in LS 5039
- PW & SW interaction results in several potential acceleration sites (challenges for BH-jet scenarios)
- Difficulties of traditional shock accelerate picture
- Particle re-acceleration by stochastic & shear processes possible (alternative, two-step)
- need to improve understanding of origin of periodic X-ray emission....

THANK YOU!