# Particle acceleration in the context of Gamma-ray Binaries

**Frank M. Rieger**

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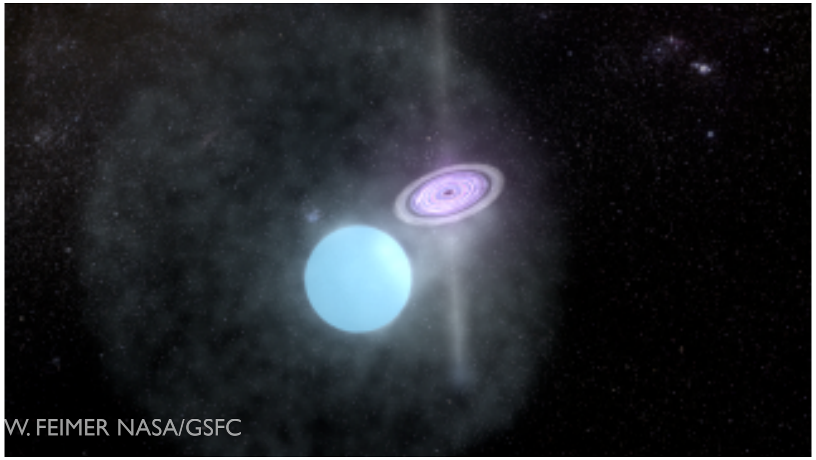
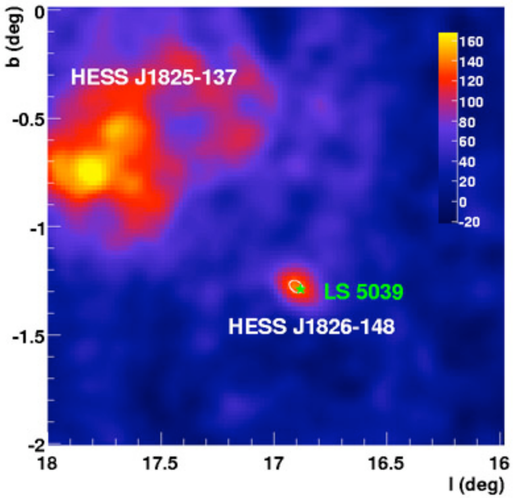
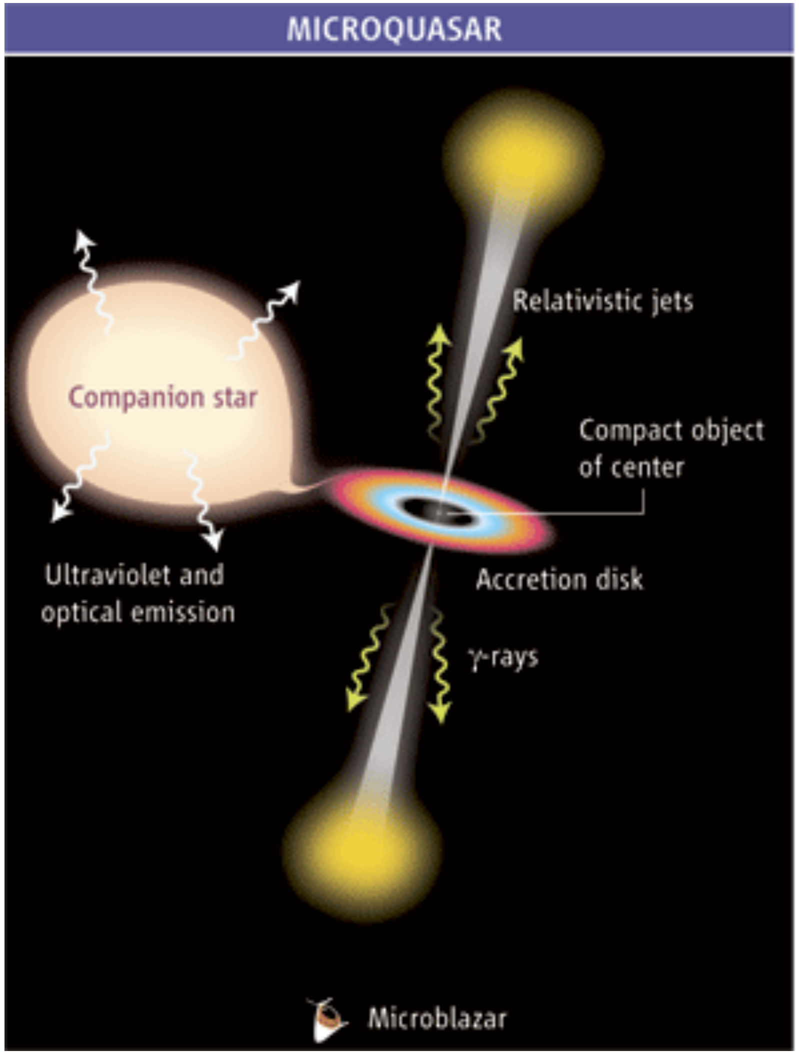
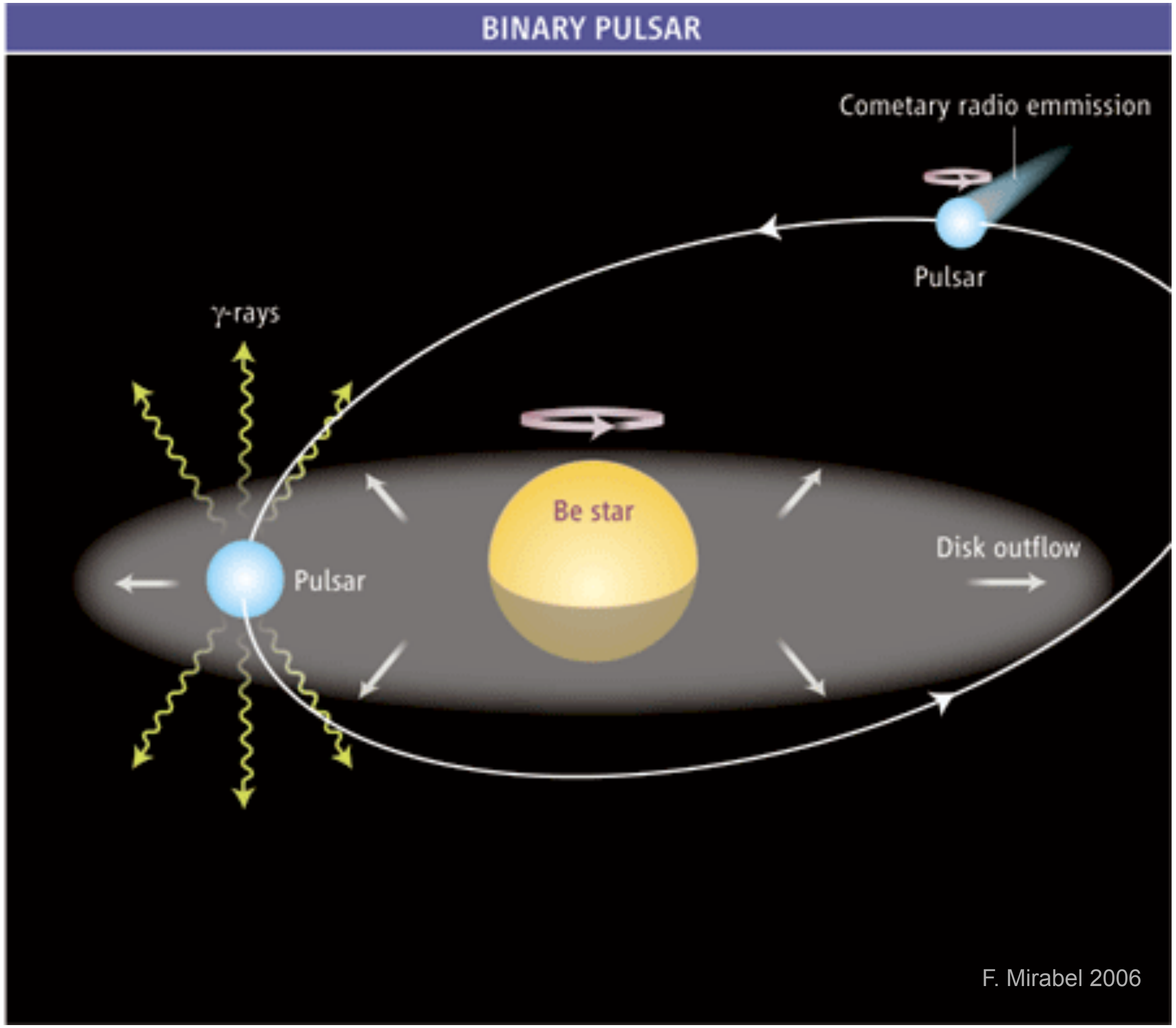



**Max Planck Institut für Kernphysik**
Heidelberg, Germany

# GAMMA-RAYS FROM BINARIES




AGNs, GRBs

Pulsars, PWN

# Outline

★_Motivation:  On extreme particle acceleration in LS 5039  (requirements)

- Requirements (Efficiency, spectral index)

★_On possible particle *acceleration sites* in binary systems

- “Termination” shock (PW-SW)
- Relativistic (re-accelerated post-shock) PW flow
- Striped pulsar wind
- Mildly relativistic jet (μQ)

★ _On possible non-thermal, particle *acceleration mechanisms*

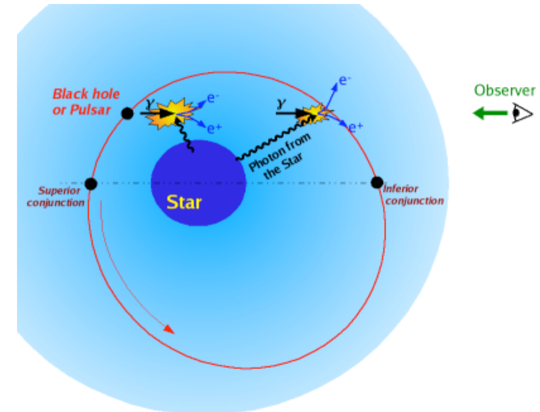
- Fermi-type particle acceleration
- Reconnection

★ _What to expect for Gamma-Ray Binaries?

# On extreme particle acceleration in LS 5039

## _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 (HESS+ 06)

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

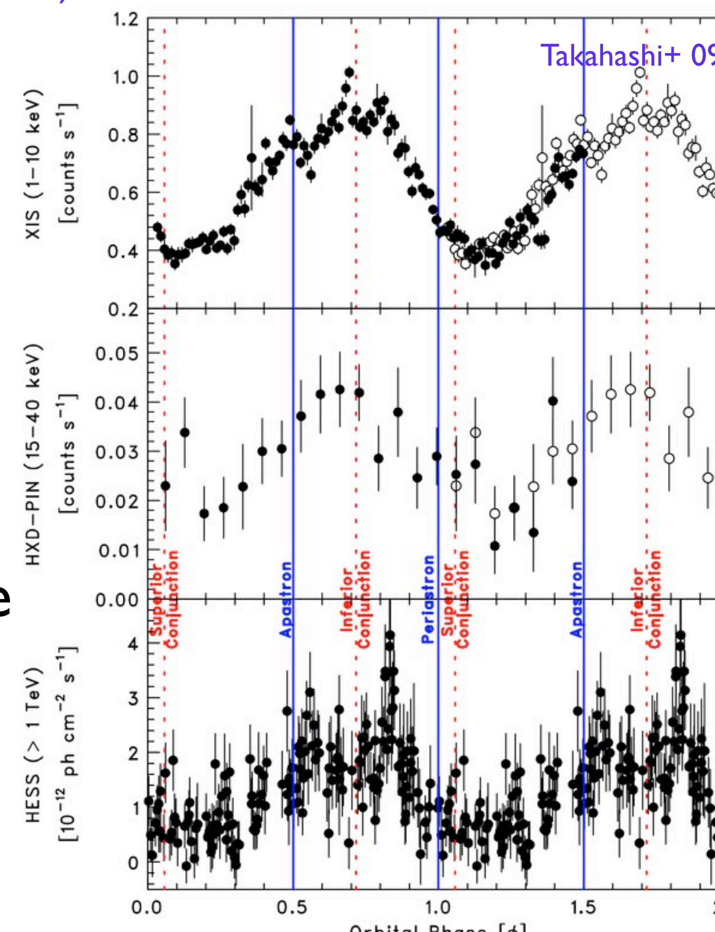
## _Acceleration efficiency $t_{acc}$ := η $r_g$ /c

- min. variability ~1 hr gives lower limit on B
- from $t_{acc} \lesssim \min(t_{IC,KN}, t_{syn})$: (Khangulyan+ 08)

  η < 100 (z<5 $R_{orb}$), and η < 10 if deep inside

## _Recent Suzaku observations (Takahashi+ 09)

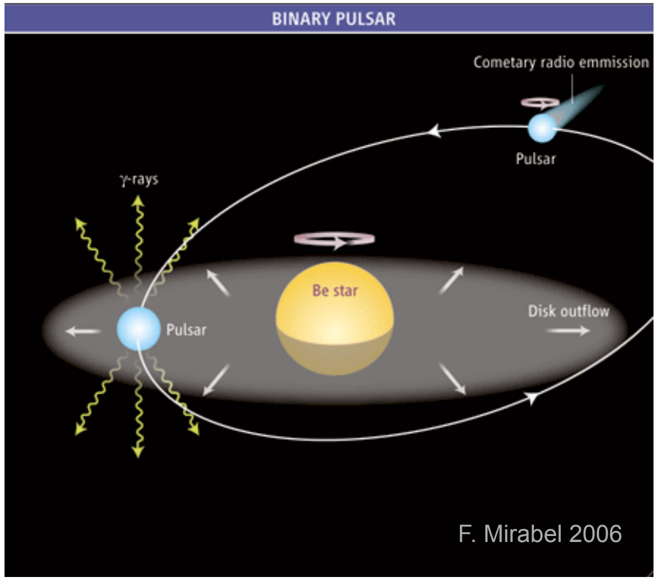
- X-ray power law ⇒ $n_e(\gamma) = n_0\, \gamma^{-s}$, s≈2
- "periodic": if due to adiabatic cooling η ≤ 3



# On possible particle acceleration sites in binary systems

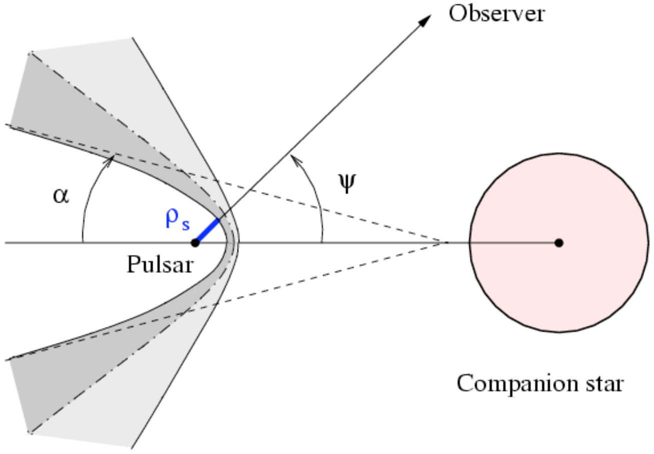
## (1) "Termination" shock: (Dubus 06; [K&C 84])

- standoff distance given by pressure balance
- located deep in system: $R_t \sim R_{orb}/10 \sim 10^{11}$ cm
- in contrast to isolated pulsars: $R_t \sim 10^3\, r_L$
- ordered, relativistic flow of particles and fields is randomized *(1st order Fermi?)*




*Pulsar wind:* (cf. Kirk+ 09)

- expected to be highly relativistic with $\Gamma >> 1$
  - launched as Poynting flux dominated wind
  - $\sigma = B^2/(4\pi\, n\, m_e c^2\, \Gamma) >> 1$
  - asymptotic radial flow speed $\Gamma \sim \sigma^{1/2} > 100$
  - $\sigma$-problem: want to have $\sigma << 1$ at shock
- how to achieve efficient conversion?




Cerutti+ 08

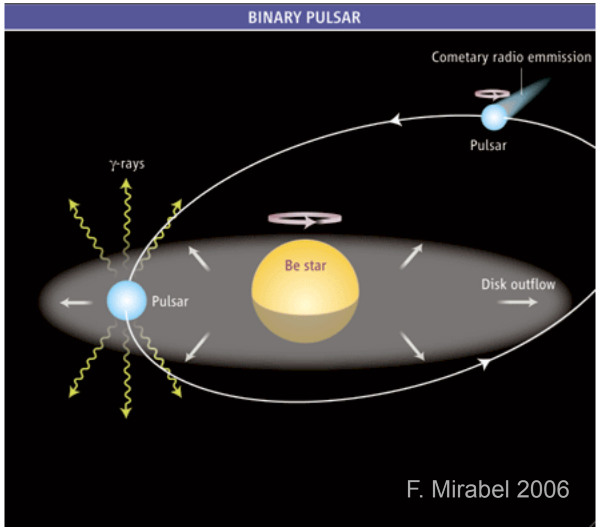
# On possible particle acceleration sites in binary systems

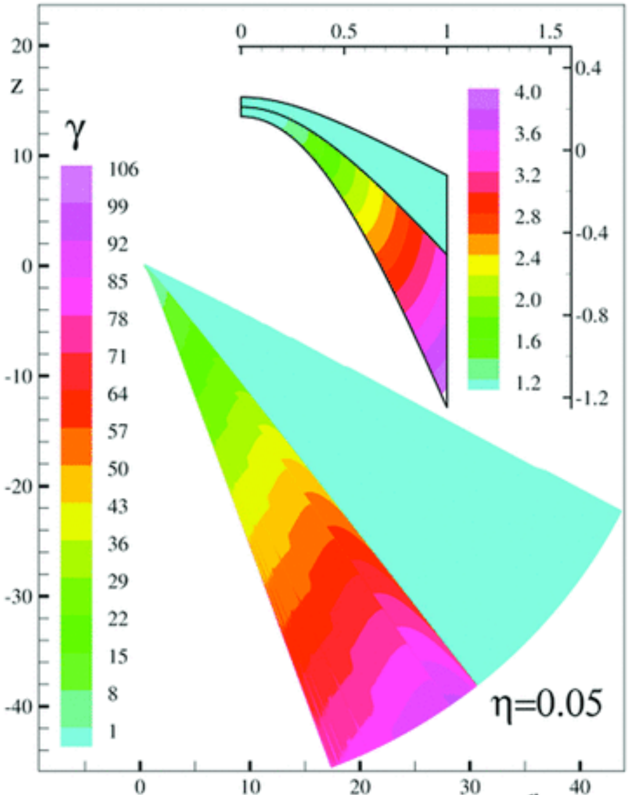
## (2) Relativistic post-shock flow:

Interaction of relativistic pulsar wind ($\Gamma \sim 10^6$) with non-relativistic stellar wind (Bogovalov+ 08)

- Hydro-limit (no m.f.; cold, isotropic winds)
- post-shock flow gets accelerated to $\Gamma \sim 100$
  - adiabatically (transfer thermal heat to bulk motion)
- confined to rather narrow region
- significant flow velocity gradients possible

  *(shear acceleration?)*



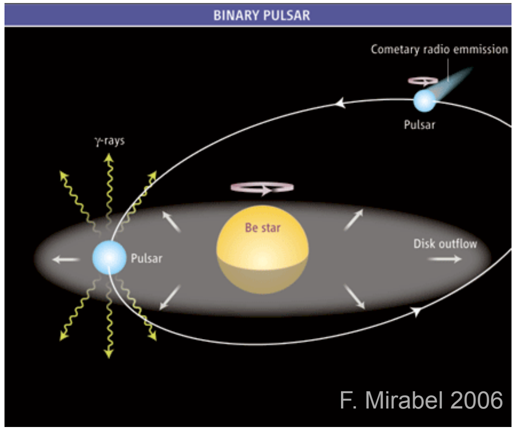

Bogovalov+ 08

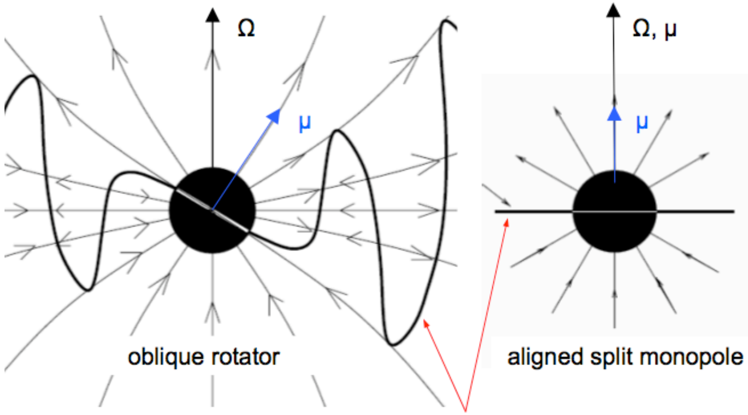
# On possible particle acceleration sites in binary systems

## (3) "Striped pulsar wind" shock

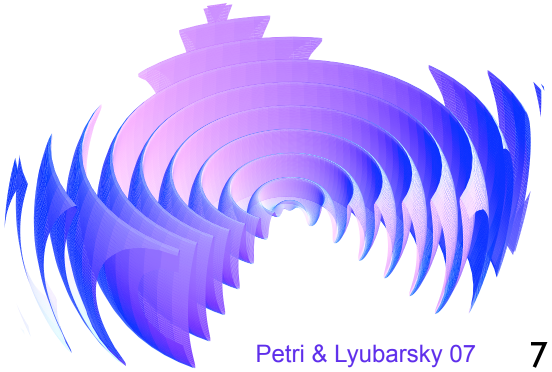
Current pattern induced by an oblique rotator separating stripes of different polarity

- small wavelength $2\pi\, r_L \ll R_t$
- cannot continue to $r \rightarrow \infty$ as carriers in sheet $n \sim 1/r^2$, while surface current $j_s = \int j dx \sim B_\theta \sim 1/r$
- presumably magnetic field reconnects
- dissipation rate probably too slow (Kirk & Skjaeraasen 03)
- $\sigma$ still high at termination shock
- *Reconnection* at termination shock (Petri & Lyubarsky 07)



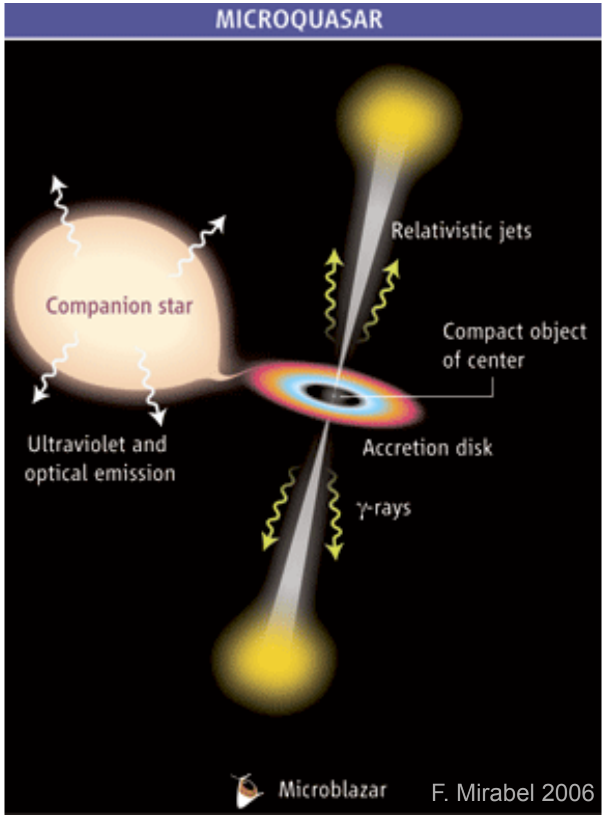
e.g., Michel 71; Coroniti 90; Bogovalov 99; Contopoulos 06

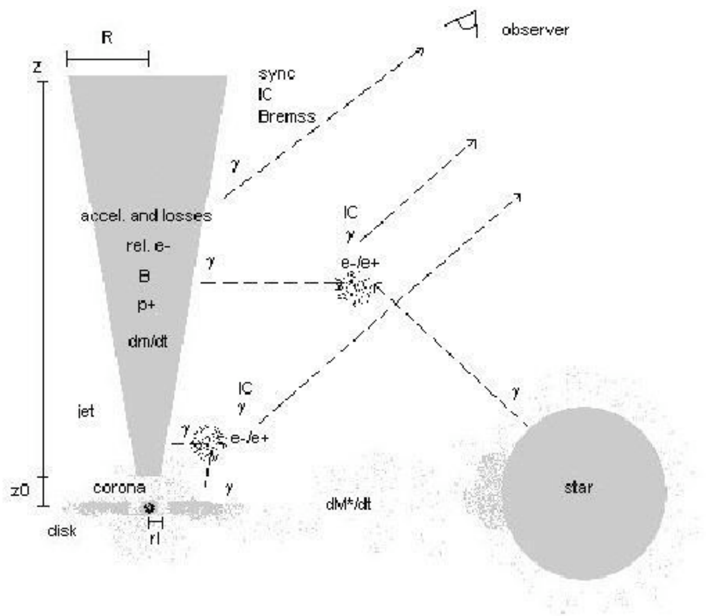

Petri & Lyubarsky 07

## (4) Mildly relativistic jet (µQuasar)

BH-jet, accretion-powered scenario

- collimated outflow with θ ~ several degree
- mildly relativistic speeds expected $v_j$~0.5-0.7 c
- emission could emerge from different scales
- *Fermi-type particle acceleration*




e.g., Paredes+ 06, Bosch-Ramon+ 06

# On non-thermal particle acceleration mechanisms (basics)

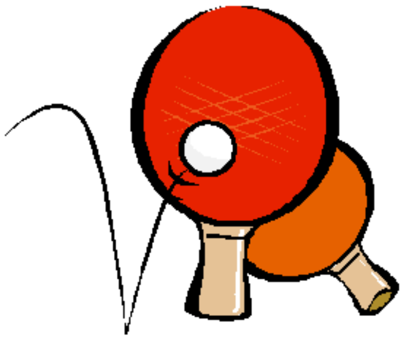
## (I) Fermi-type "stochastic" particle acceleration

based on Fermi's original concept: (Phys. Rev. 75, 578 [1949])

- *kinematic effect:* particle acceleration as result of scattering off randomly moving magnetic inhomogeneities ("magnetic clouds")
- characteristic energy change per scattering:

$$\Delta\epsilon := \epsilon_2 - \epsilon_1 = 2\Gamma^2 \epsilon_1 \left( \frac{u^2}{c^2} - \frac{u}{c} \frac{\vec{p}\vec{u}}{|\vec{p}||\vec{u}|} \right)$$

➡ *energy gain for head-on, loss for following collision*



### (I.I) "*2nd order Fermi*" acceleration:

- scattering off magnetic turbulence (Alfven waves)
- average over all momentum directions:

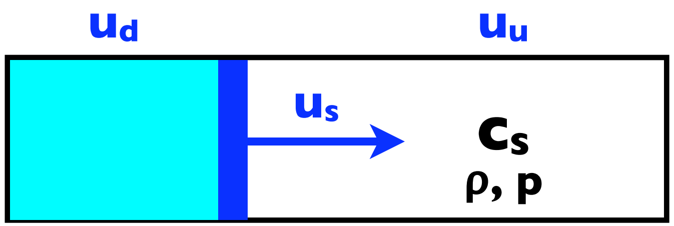
$$\frac{< \Delta\epsilon >}{\epsilon_1} \propto \left( \frac{u_A}{c} \right)^2$$

(−) very small energy gain in low-σ flows

(−) tends to give flat spectra s < 2 (e.g. Virtanen+ 05; R+ 07)

(+) "distributed" mechanism

## (I.2) "*1st order Fermi*" (shock)




- better if only head-on collisions:

$$\Delta\epsilon := \epsilon_2 - \epsilon_1 = 2\Gamma^2\epsilon_1\left(\frac{u^2}{c^2} - \frac{u}{c}\frac{\vec{p}\vec{u}}{|\vec{p}||\vec{u}|}\right)$$

- late '70s: applies to shock propagating through plasma (e.g. Krymsky'77; Bell'78)

➡ *non-relativistic* shocks:

(±) "reasonably" efficient

(+) s fixed by compression ratio:

(s=2 for strong shock)

$$\frac{<\Delta\epsilon>}{\epsilon_1} \propto \left(\frac{u}{c}\right)$$

in shock frame: $u = u_u - u_d > 0$

➡ *relativistic* shocks:

(+) efficient enough $t_{acc} \sim t_L$

(±) "universal" index s≈2.3

(±) generically perpendicular

$$\frac{<\Delta\epsilon>}{\epsilon_1} \sim \Gamma_r^2(1-\cos\theta) \rightarrow O(1)$$

(Gallant & Achterberg'99; Kirk+ 00, Achterberg+ 01)

## (I.3) *Shear* particle acceleration

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

Particle acceleration in the presence of flow velocity gradients:

- E.g., (gradual) shear flow with frozen-in scattering centers:

$$\vec{u} = u_z(x)\ \vec{e}_z$$

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

"2nd order Fermi-type"

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

with characteristic effective velocity:

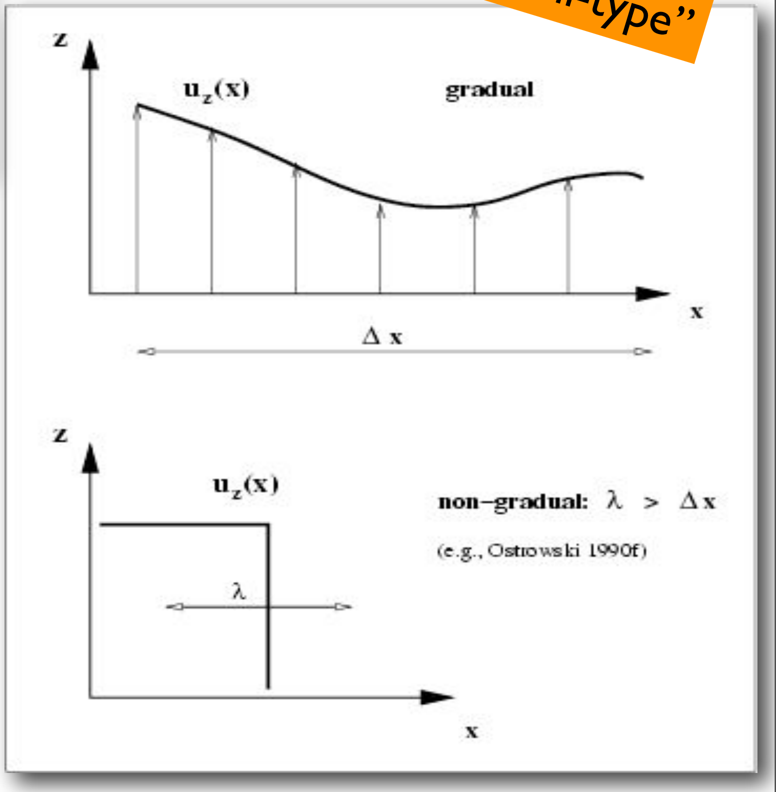
$$u = \left(\frac{\partial u_z}{\partial x}\right)\lambda \qquad \lambda = \text{mean free path}$$

(±) needs energetic seed particles

$t_{acc} \sim (\varepsilon/\Delta\varepsilon)\ \tau \sim 1/\lambda$

(±) "non-universal" index s=1+α

(+) distributed mechanism



# On non-thermal particle acceleration mechanisms (basics)

## (2) *Reconnection*

(e.g., Zenitani & Hoshino '01; Craig & Litvinenko' 02; Zweibel & Yamada 09)

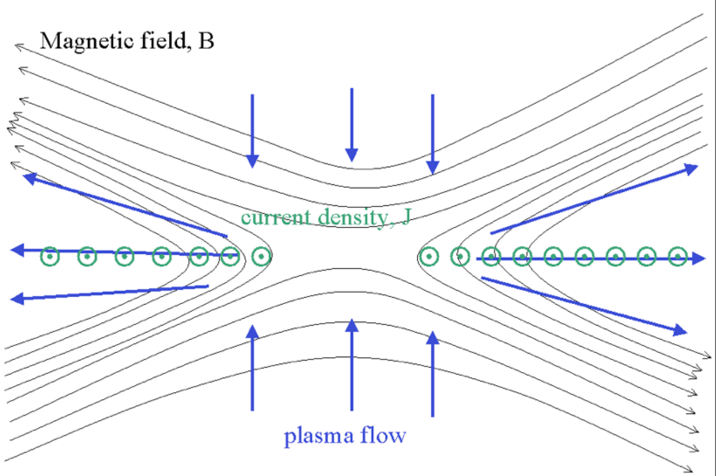
Significant energy release by change of magnetic field topology

- Possible in the presence of large magnetic field gradients
- associated with large current densities ("current sheets"): $4 \pi \mathbf{J} = c\, \nabla \times \mathbf{B}$
- electric field runs || to current density $\mathbf{E} = -\mathbf{v}_i/c \times \mathbf{B} + \mathbf{J}/\sigma$ *(resistive MHD)*
- particle acceleration along electric field no longer inhibited by m.f
  - acceleration rate: $d\varepsilon/dt \approx e\, E\, c$
  - escape rate: $(1/N)\, dN/dt \approx -1/\tau \approx c/r_g = c\, eB/\varepsilon$
  - ➡ particle energy spectrum: $N(\varepsilon) \propto \varepsilon^{-s}$, $\mathbf{s} \approx E/B \approx \mathbf{1}$

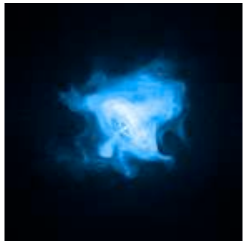
(+) can be fast in relativistic pair plasmas

(±) non-thermal distribution (1d vs 2d+ PIC)

(−) "power-law" index



# What to expect for Gamma-Ray Binaries?



## (I) 1st order Fermi at "termination" shock?

### *(A) ultra-relativistic case $\Gamma_s \sim 10^6$* (low $\sigma$ <<1)

- need high conversion (Poynting→kinetic) for < $R_t \sim 10^3\ r_L$ ($\sigma$-problem!)
- perpendicular field orientation: $B_{||} = B_{||}'$ ; $B_\perp \rightarrow 3\ \Gamma_s\ B_\perp'$ (proper frames)
  - ➡ particles are prevented from diffusing back upstream
  - ➡ no multiple crossings, no 1st order Fermi (shock-drift instead?)
  - ➡ Escape: significant scattering (Weibel-produced at low $\sigma$) with $\delta B/B>1$
    - ➡ no pitch- but large-angle scattering, no "universal" index?

(Pelletier+ 08; Baring' 09)

### *(B) Highly relativistic case $\Gamma << 10^6$* (high $\sigma$ at shock)

- for high $\sigma$, field fluctuations small - cross-field transport suppressed
- 1st order Fermi unlikely, but if it operates
  - ➡ "weak" shock (low compression, downstream relativistic)
  - ➡ inefficient accelerator, deep spectra...

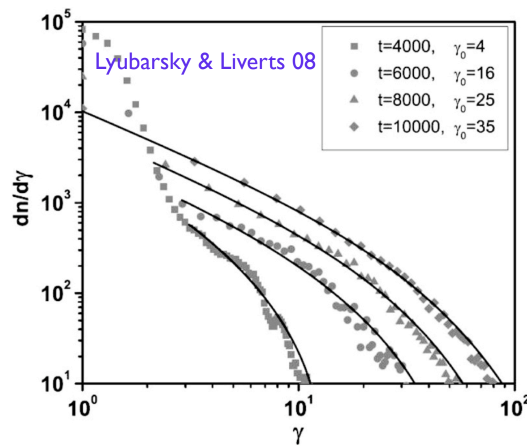
(cf., Kirk & Duffy'99; Kirk'04)

# What to expect for Gamma-Ray Binaries?

## (2) Reconnection in a striped pulsar wind?

(e.g., Petri & Lyubarksy'07)

- possible, if flow stays Poynting-dominated (slow dissipation before)
- termination shock: plasma compression may lead to forced annihilation
  - ➡ relativistic pair plasma: downstream Lamor radius ~ sheet thickness > $2\pi\ r_L$ (full dissipation)
  - ➡ full dissipation requires $R_t/r_L \sim 10^3$ > *multiplicity*, and may not be achieved in LS 5039
  - ➡ downstream flow still relativistic
- can be fast: $t_{acc} \sim t_L$
- *Problem:* (Jaroschek+04, Zenitani & Hoshino'07, but see Lyubarsky & Liverts'08)
  - 1d simulation: no evidence for non-thermal particle distributions
  - 2d+ (no striped wind): power-law over limited (!) energy range
    - **s=1** (acceleration region/X-type neutral line)
    - **s=3** (whole simulation box)



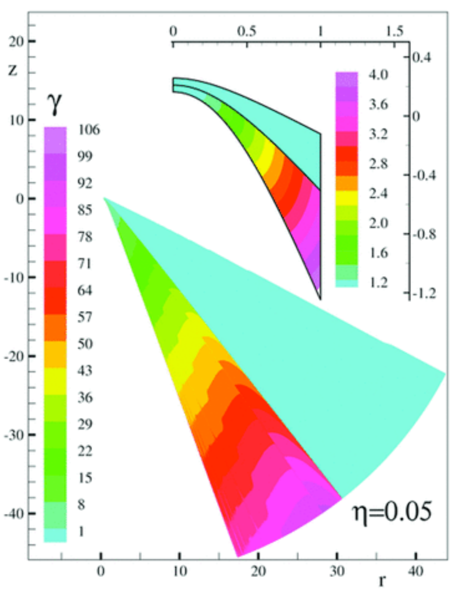

- Note: annihilation of ordered field may make 1st order Fermi possible (requires ~full dissipation)

# What to expect for Gamma-Ray Binaries?

## (3) Stochastic particle acceleration in post-shock flow

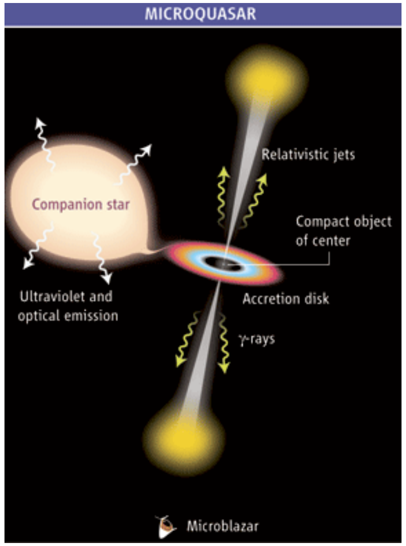
- possible re-acceleration of post-shock flow to $\Gamma \sim 100$ (Bogovalov+ 08)
- *Hydro-limit*: applies to $\sigma << 1$ flows, thus low Alfven speed $v_A/c \approx \sigma^{1/2}$
  - ➡ don't expect efficient 2nd order Fermi

- but large velocity gradients: may have shear acceleration (R & Duffy'05)
  - ➡ requires energetic seed particles
  - ➡ from shock/thermalization etc?
  - ➡ radiative constraints may not apply: $t_{acc} \propto 1/\lambda$
  - ➡ no characteristic index?
  - ➡ need to take relativistic effects into account



# What to expect for Gamma-Ray Binaries?

## (4) Fermi acceleration in mildly relativistic jet?




- 1st order Fermi at internal shocks ($u_s$~ 0.1c):
  - ➡ "non-relativistic", robust spectral index **s≈2**
  - ➡ not efficient enough? $t_{acc} \sim t_L\ (c/u_s)^2$
  - ➡ Escape (I): external shocks $u_s$~0.5 c
  - ➡ Escape (II): shear acceleration:

*Example*: minimum shear acceleration timescale

$t_{acc} \sim 10\ r_g\ (0.5c/u_j)^2$

➡ need high jet speeds

➡ may change spectral index (cf. R+ 07)

# To conclude

_On extreme particle acceleration in Gamma-Ray Binaries (e.g., LS 5039)

- need "more" data - X-ray periodicity in LS 5039?
- need detailed modelling (adiabatic losses, relativistic effects)
- may not simply see only one acceleration mechanism at work
- the classical 1st Fermi @ termination shock picture may not work

# THANK YOU!

# Fermi Acceleration Timescales

(e.g., Drury '83; Kirk '94; Duffy & Blundell '05; R.+ 07)

➡ **1st order Fermi - standard shock** (non-relativistic):

_with shock crossing time $t_c \sim \kappa/(u_s c)$, where $\kappa \sim \lambda c$

$$t_{\rm acc} = \frac{\epsilon}{d\epsilon/dt} \simeq \frac{\epsilon}{\Delta\epsilon}\, t_c \sim \frac{\kappa}{u_s^2} \propto \frac{\lambda}{u_s^2}$$

➡ **2nd order Fermi** (stochastic):

_with scattering time $\tau \sim \lambda/c$

$$t_{\rm acc} = \frac{\epsilon}{d\epsilon/dt} \simeq \frac{\epsilon}{\Delta\epsilon}\, \tau \sim \left(\frac{c}{v_A}\right)^2 \left(\frac{\lambda}{c}\right) \propto \frac{\lambda}{v_A^2}$$

➡ **shear** (gradual, non-relativistic):

$$t_{\rm acc} = \frac{\epsilon}{d\epsilon/dt} \simeq \frac{\epsilon}{\Delta\epsilon}\, \tau \sim \left(\frac{c}{\frac{\partial u_z}{\partial x}\lambda}\right)^2 \left(\frac{\lambda}{c}\right) \propto \frac{1}{\lambda}$$

Significance - (i) scales with synchrotron losses...
- (ii) requires energetic seed particles