Particle Acceleration beyond the Synchrotron Burnoff Limit in Gamma-Ray Binary Systems

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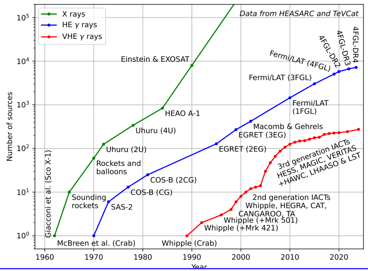
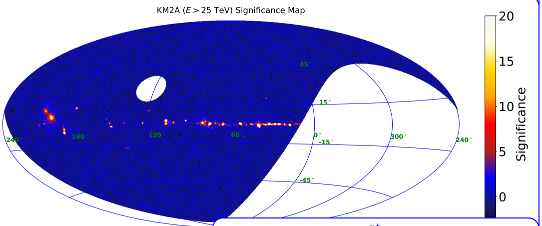
TAUP XICHANG

Introduction

- The 3rd generation of TeV instruments made a revolution in gamma-ray astronomy, and we have (probably) reached the sensitivity level required to probe the Galactic sources of CR
- To reveal the properties of the CR accelerator in a gamma-ray source we need a realistic scenario
- Typically one considers hadronic and/or leptonic contributions to the emission
- Acceleration of UHE electrons has very different implications for CRs compared to the acceleration of protons
- However, often it is hard to discriminate between leptonic and hadronic models
- Many theoretical and phenomenological arguments are used to define the contribution of protons

Kifune Plot





KM2A Sky Map (1st LHAASO catalog)

Protons or Electrons?

spectral features

- synchrotron emission
- Klein-Nishina cutoff
- cooling break

spectral features

- pion bump
- threshold in γp process
- max energy

variability

electrons ?

protons ?

target

γ-ray source

electrons lose energy easily thus in the VHE/UHE regimes acceleration competes with (synchrotron) losses, and the maximum energy is attained when the rate of losses equals the acceleration rate

secondary particles

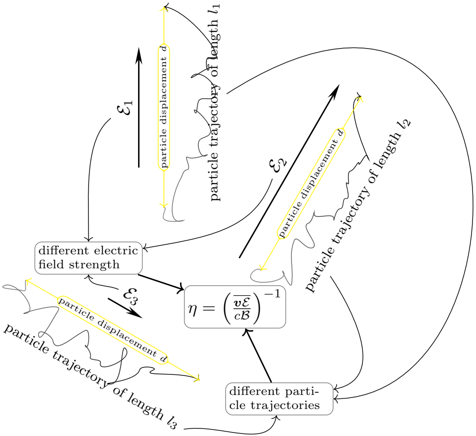
- ν
- $e^{\pm}$

How fast does particle acceleration proceeds?

- Acceleration time: $t_{acc} = E/\dot{E}$
- Magnetic field $\mathcal{B}$ doesn't change particle energy
- Energy gain for a particle: $mc^2\dot{\gamma} = q\vec{v}\vec{\mathcal{E}}$
- Energy gain for ensemble of particles: $\dot{E} = q\overline{\vec{v}\vec{\mathcal{E}}}$
- Acceleration efficiency: $t_{acc} = \eta\frac{E}{q\mathcal{B}c} = \eta\frac{r_{\mathcal{G}}}{c}$ $\eta^{-1} = \frac{q\overline{\vec{v}\vec{\mathcal{E}}}}{E}\frac{E}{q\mathcal{B}c} = \frac{\overline{\vec{v}\vec{\mathcal{E}}}}{\mathcal{B}c}$
- Typically $\mathcal{E} = \frac{v}{c}\mathcal{B} < \mathcal{B}$
- Trajectories are not straight lines: $\overline{\vec{v}\vec{\mathcal{E}}} \ll c\mathcal{E}$

for DSA $\eta = 2\pi\left(\frac{c}{v}\right)^2 = 2\pi\left(\frac{c}{v}\right)\left(\frac{c}{v}\right))$

Acceleration Efficiency



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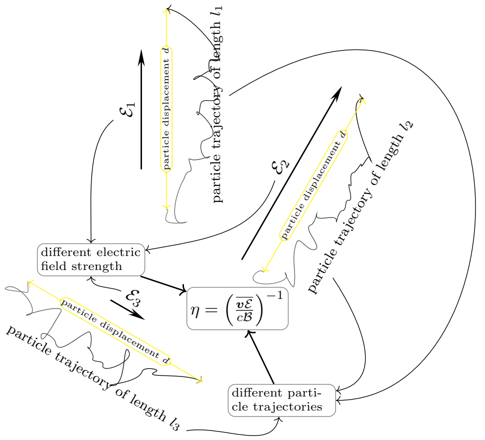
Acceleration Efficiency



It seems impossible to reach $\eta \to 1$ under realistic conditions

Synchrotron Burn-Off Limit

- Acceleration Time:

$$t_{acc} = \eta \frac{r_{\mathcal{G}}}{c} = 0.1\eta E_{TeV} B_G^{-1}\,s$$

- Synchrotron Cooling Time

$$t_{syn} \approx 400 E_{TeV}^{-1} \mathcal{B}_G^{-2}\,s$$

- Maximum Energy

$$E_{max} \approx \frac{60\,TeV}{\sqrt{\mathcal{B}_G \eta}}$$

- Cutoff in the Synchrotron Spectrum

$$\hbar\omega \approx 1.15\hbar\omega_c \approx \frac{300\,MeV}{\eta}$$

Synchrotron Burn-Off Limit

Shock acceleration: $\boldsymbol{\eta} = 2\boldsymbol{\pi} \left(\frac{c}{v}\right)^2$

- Acceleration Time:

$$t_{\rm acc} = \eta \frac{r_{\mathcal{G}}}{c} = 0.1\eta E_{\rm TeV} B_{\rm G}^{-1}\,{\rm s}$$

- Synchrotron Cooling Time

$$t_{\rm syn} \approx 400 E_{\rm TeV}^{-1} \mathcal{B}_{\rm G}^{-2}\,{\rm s}$$

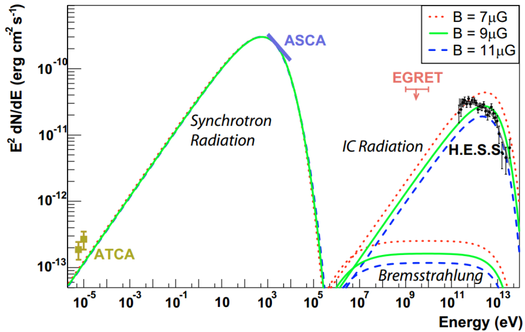
- Maximum Energy

60 TeV

$\hbar\omega_{\rm br} \sim 1\,{\rm keV}$, i.e. $\eta \sim 10^5$ $(v \sim 10^3\,{\rm km\,s^{-1}})$

- Cutoff in the Synchrotron Spectrum

$$\hbar\omega \approx 1.15\hbar\omega_{\rm c} \approx \frac{300\,{\rm MeV}}{\eta}$$



H.E.S.S. detection of RX J1713.7 (Aharonian+2006)

Synchrotron Burn-Off Limit

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- Maximum Ener

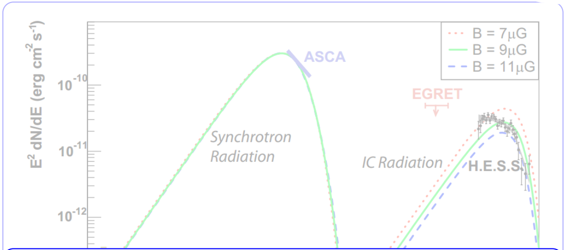
Relativistic shock: $\eta \to 10(?)$

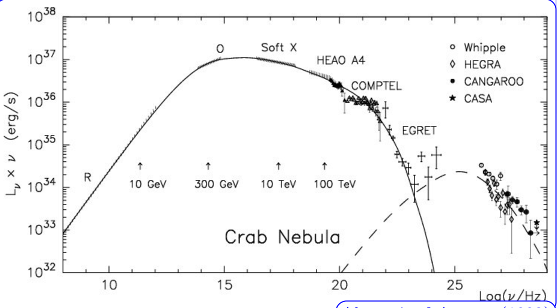
$$E_{max} \approx \frac{60\ TeV}{\sqrt{\mathcal{B}_G \eta}}$$

- Cutoff in the Synchrotron Spectrum

$$\hbar\omega \approx 1.15\hbar\omega_c \approx \frac{300\ MeV}{\eta}$$

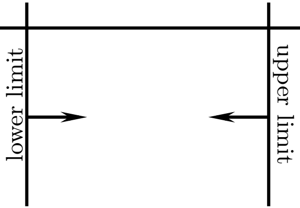
$\hbar\omega_{br} \sim 10^{21-22}$ Hz, i.e. $\eta \sim 10$ ($v \to c$?)





Aharonian&Atoyan (1998)

Constraints on Magnetic Field



- Hillas Criterion

$$E < \sqrt{\frac{\beta\sigma e^2 L}{c}}$$

$$\mathcal{B} > 3\beta E_{\rm PeV}\left(\frac{R}{10^{12}\,{\rm cm}}\right)^{-1}\,{\rm G}$$

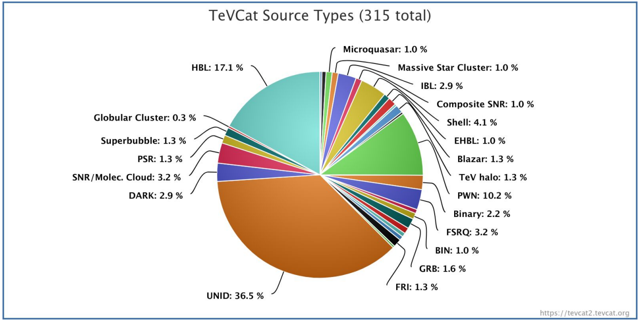
- Variability
  e.g., via the source size or (fast) cooling time

- Synchrotron Losses

$$\mathcal{B} < 3\eta^{-1}E_{\rm PeV}^{-2}\,\mu{\rm G}$$

- Spectral properties
  e.g., via slow synchrotron cooling

These basic estimates suggest that the acceleration of PeV electrons is impossible in compact sources ($R \sim$ AU).
Are there any compact VHE sources?
$\Rightarrow$ PRS, gamma-ray binary systems



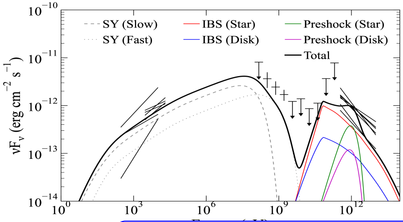
Binary Systems@VHE γ rays

System	Star	Star*	P	VHE	HE	X-ray
PSR B1259-63/LS2883	psr	O/Be	1237d	periodic	variable	periodic
LS 5039	psr(?)	O	3.9d	periodic	periodic	periodic
LS I +61+303	psr(?)	Be	27d	variable	periodic	variable
HESS J0632+057	?	Be	320d	variable	steady(?)	variable
HESS J1832-093	?	Be(?)	86d(?)	variable(?)	periodic(?)	periodic
1FGL J1018.6-5856	?	O	17d	variable	periodic	variable
PSR J2032+4127	psr	Be	50yr	variable	variable	variable
LMC P3	?	O	10d	periodic	periodic	variable
Cyg X-1	bh	O	5.6d	flare	flare	—
Cyg X-3	bh(?)	WR	4.8h	(?)	flare	—
SS433	bh	A	13d	steady	steady(?)	steady
V4641 Sgr	bh	B	2.8d	steady(?)	—	flare
MAXI J1820+070	bh	KG	0.7d	steady(?)	—	flare
GRS 1915+105	bh	RG	33.5d	steady(?)	steady(?)	flare
η Car	BG	O	5.5yr	variable(?)	variable	variable
RS Oph	WD	RG	1.2yr	flare	flare	flare

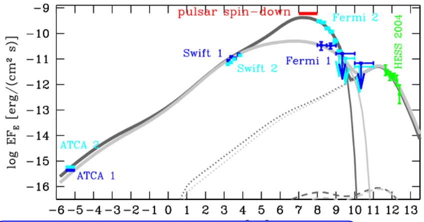
Binary Systems@VHE γ rays

System	Star	Star*	P	VHE	HE	X-ray
Gamma-Ray Binaries						
PSR B1259-63/LS2883	psr	O/Be	1237d	periodic	variable	periodic
LS 5039	psr(?)	O	3.9d	periodic	periodic	periodic
LS I +61+303	psr(?)	Be	27d	variable	periodic	variable
HESS J0632+057	?	Be	320d	variable	steady(?)	variable
HESS J1832-093	?	Be(?)	86d(?)	variable(?)	periodic(?)	periodic
1FGL J1018.6-5856	?	O	17d	variable	periodic	variable
PSR J2032+4127	psr	Be	50yr	variable	variable	variable
LMC P3	?	O	10d	periodic	periodic	variable
MicroQuasars						
Cyg X-1	bh	O	5.6d	flare	flare	—
Cyg X-3	bh(?)	WR	4.8h	(?)	flare	—
SS433	bh	A	13d	steady	steady(?)	steady
V4641 Sgr	bh	B	2.8d	steady(?)	—	flare
MAXI J1820+070	bh	KG	0.7d	steady(?)	—	flare
GRS 1915+105	bh	RG	33.5d	steady(?)	steady(?)	flare
Gamma-Ray Emitting BS						
η Car	BG	O	5.5yr	variable(?)	variable	variable
RS Oph	WD	RG	1.2yr	flare	flare	flare

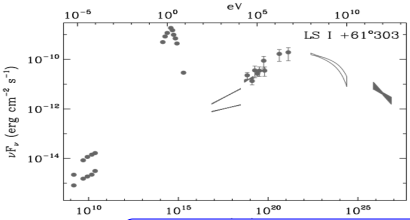
Gamma-Ray Binary Systems



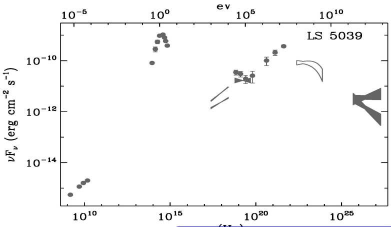
SED of HESS J0632+057 (Kim+2022)



SED of PSR B1259-63/LS2883 (Abdo+2011)

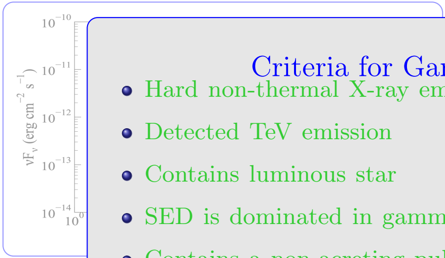


SED of LS I +61+303 (Dubus+2013)



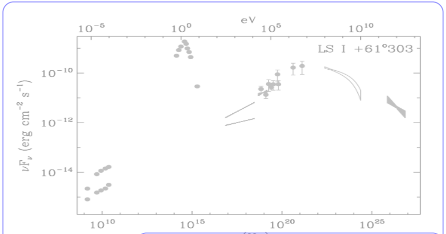
SED of LS 5039 (Abdo+2009)

Gamma-Ray Binary Systems



Criteria for Gamma-Ray Binary:

- Hard non-thermal X-ray emission
- Detected TeV emission
- Contains luminous star
- SED is dominated in gamma-rays
- Contains a non-acreting pulsar



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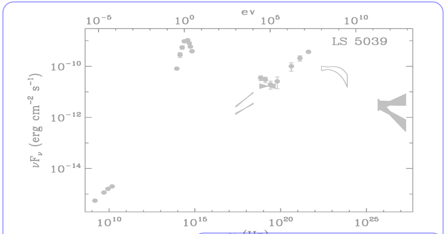

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Gamma-Ray Binary Systems

Criteria for Gamma-Ray Binary:

- Hard non-thermal X-ray emission
- Detected TeV emission
- Contains luminous star
- SED is dominated in gamma-rays

System	X-ray	VHE	Star	SED	PSR
PSR B1259-63/LS2883	✔	✔	✔	✔	✔
LS 5039	✔	✔	✔	✔	✔?
LS I +61+303	✔	✔	✔	✔	✔?
HESS J0632+057	✔	✔	✔	✔	✘
1FGL J1018.6-5856	✔	✔	✔	✔	✘
HESS J1832-093	✔	✔	✔	✔	✘
PSR J2032+4127	✔	✔	✔	✔	✔
LMC P3	✔	✔	✔	✔	✘

Note that ✔ means YES; ✘ means we don't know

Criteria for Gamma-Ray Binary:

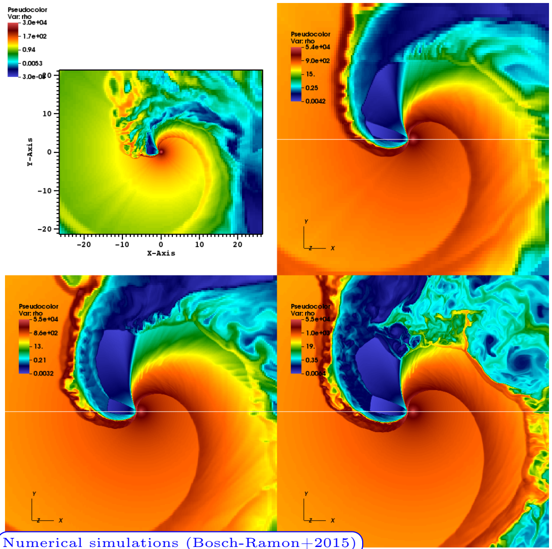
- Hard non-thermal X-ray emission
- Detected TeV emission
- Contains luminous star
- SED is dominated in gamma-rays

System	X-ray	VHE	Star	SED	PSR
PSR B1259-63/LS2883	✔	✔	✔	✔	All contain PSR? (or Magnetar!)
LS 5039	✔	✔	✔	✔	
LS I +61+303	✔	✔	✔	✔	
HESS J0632+057	✔	✔	✔	✔	
1FGL J1018.6-5856	✔	✔	✔	✔	
HESS J1832-093	✔	✔	✔	✔	
PSR J2032+4127	✔	✔	✔	✔	
LMC P3	✔	✔	✔	✔	

Note that ✔ means YES; ✘ means we don't know

Gamma-Ray Binary Systems

- Ha
- De
- Co
- SE



Numerical simulations (Bosch-Ramon+2015)

Systen	PSR
PSR B	✔
LS 50	✔?
LS I +	✔?
HESS	✘
1FGL	✘
HESS	✘
PSR J	✔
LMC P	✘

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Gamma-Ray Binary Systems

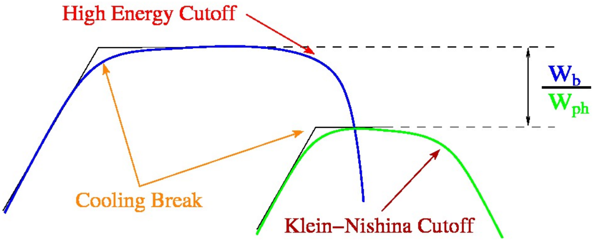
Criteria for Gamma-Ray Binary:

- Hard non-thermal X-ray emission
- Detected TeV emission
- Contains luminous star
- SED is dominated in gamma-rays

System	X-ray	VHE	Star	SED	PSR
PSR B1259-63/LS2883	Why is that important?	✔	✔	✔	✔
LS 5039		✔	✔	✔	✔?
LS I +61+303		✔	✔	✔	✔?
HESS J0632+057		✔	✔	✔	✘
1FGL J1018.6-5856		✔	✔	✔	✘
HESS J1832-093		✔	✔	✔	✘
PSR J2032+4127		✔	✔	✔	✔
LMC P3		✔	✔	✔	✘

Note that ✔ means YES; ✘ means we don't know

Energy Distribution of Electrons in Binary Systems



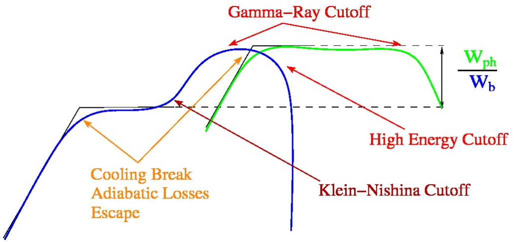
Steady electron distribution:

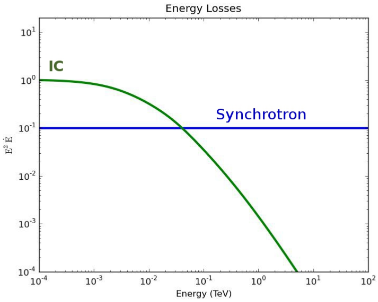
$$\frac{dN_e}{dE} = \frac{1}{\dot{E}} \int_E^\infty dE' \, Q(E)$$

$$\dot{E} = \dot{E}_{syn} + \dot{E}_{ic} + \dot{E}_{ad}$$

$$\dot{E}_{syn/ad/thomson} \propto E^{-\alpha}$$

Hard X-ray spectrum (most likely) implies a leptonic source with the dominant IC cooling on a hot photon field

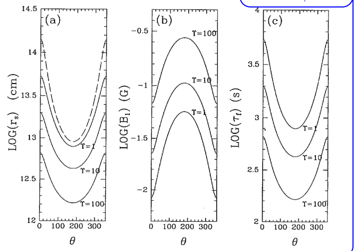




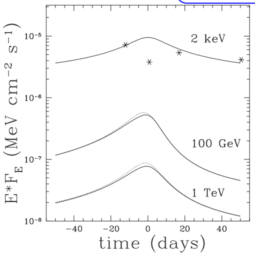
GRBs as "compactified" PWN

- Compactified PWN in binary systems is a quite old concept (e.g., Tavani+1994)
- One-zone model that accounts for the relevant parameters was suggested for PSR B1259-63/LS2883 (Kirk+1999)
- In compact systems gamma-gamma attenuation plays a critical role (Moskalenko+1994, Dubus+2006)
- One-zone modeling points toward very efficient acceleration in binary systems (e.g., Khangulyan+2008,Takahashi+2009)
- Hydrodynamic process in binary systems appear very different from whose in isolated PWNe (Bogovalov+2008)
- Hybrid radiation-hydrodynamic model can reproduce essential features of the spectra and light curve in LS 5039, but require very efficient acceleration and complex injection spectrum (e.g., Dubus+2015)

Tavani+1994



Kirk+1999



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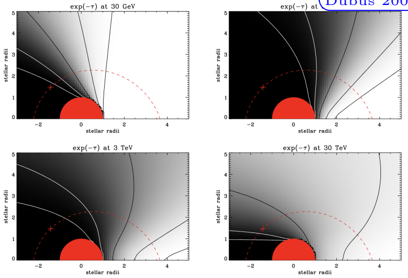
Dubus 2006



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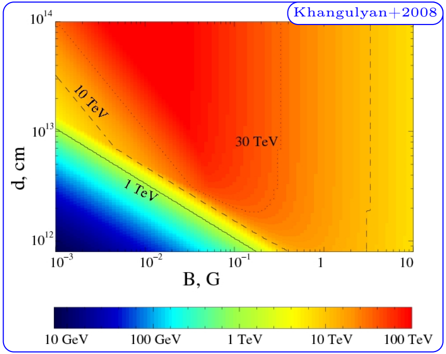
Khangulyan+2008



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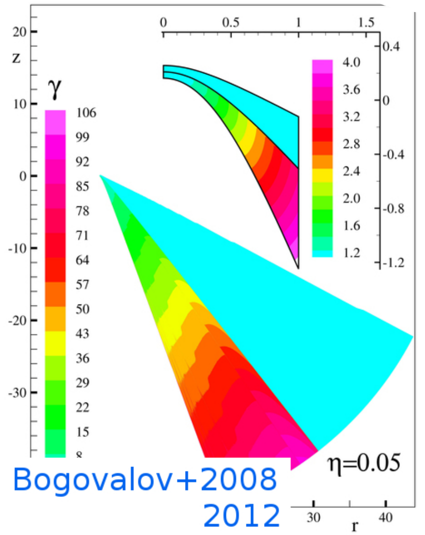

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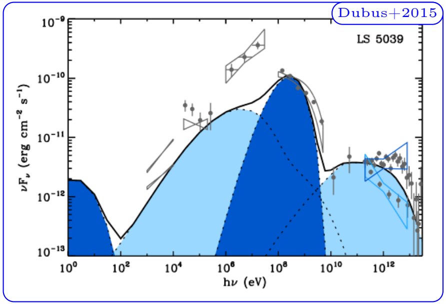
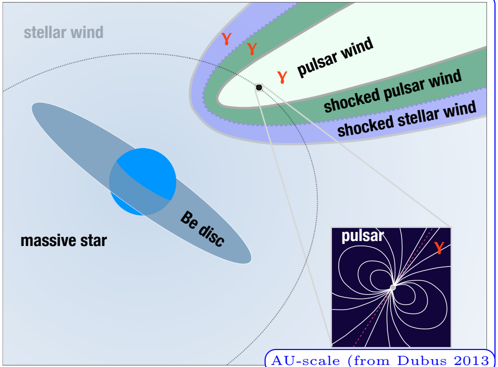


Acceleration vs Losses

$$E_{max} \sim \sqrt{\beta\sigma}\sqrt{\frac{e^2 L}{c}}$$

“Hillas upper limit” doesn’t depend on the size!

PC-scale



AU-scale (from Dubus 2013)

Acceleration vs Losses

$$E_{\rm max} \sim \sqrt{\beta\sigma}\sqrt{\frac{e^2 L}{c}}$$

"Hillas upper limit" doesn't depend on the size!

The maximum drop of electric potential is, however, only one of the conditions required for acceleration to this limit. Other constraints include

- Source age:
$$t_{\rm acc} < t_{\rm age}$$
- Confinement:
$$t_{\rm acc} < t_{\rm esc}$$
- Cooling:
$$t_{\rm acc} < t_{\rm cool}$$

None of these is a necessary condition – one still needs an acceleration process that can operate with efficiency η.

$$\mathcal{B}R \propto \sqrt{L}$$

- Source age: $t_{\rm age} = R/\beta c$
$$E_{\rm max} < \frac{e\mathcal{B}R}{\eta_{\rm acc}}\frac{ct_{\rm age}}{R} = \frac{e\mathcal{B}R}{\eta_{\rm acc}\beta}$$
- Conf. 1: $t_{\rm esc} = R/\beta c$
$$E_{\rm max} < \frac{e\mathcal{B}R}{\eta_{\rm acc}\beta}$$
- Conf. 2: $t_{\rm esc} = R^2/6\eta_{\rm D}D_{\rm B}$, where $D_{\rm B} = r_{\mathcal{G}}c/3$
$$E_{\rm max} < \frac{e\mathcal{B}R}{\sqrt{2\eta_{\rm acc}\eta_{\rm D}}}$$
- Radiative cooling: $t_{\rm cool} \propto E^{-\delta}R^2$
$$E_{\rm max}^{1+\delta} < \frac{e\mathcal{B}R}{\eta_{\rm acc}}\frac{ct_0}{R_0}\frac{R}{R_0}$$

Constraint from cooling become more important on "smaller scales"

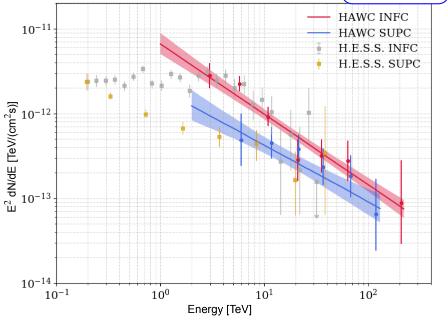
Constraints on Particle acceleration in LS 5039

- Electron gyroradius:
  $r_{\mathcal{G}} = 3 \times 10^{12} E_{PeV} \mathcal{B}_G^{-1} cm$
- Synchrotron cooling time:
  $t_{syn} = 0.4 E_{PeV}^{-1} \mathcal{B}_G^{-2} s$
- Acceleration time:
  $t_{acc} = 10^2 \eta E_{PeV} \mathcal{B}_G^{-1}$
- Acceleration of electrons:
  $\eta \mathcal{B}_G \lesssim 4 \times 10^{-3} E_{PeV}^{-2}$
- Confinement of electrons:
  $\mathcal{B}_G > E_{PeV}$ (note $a \sim 2 \cdot 10^{12}$cm)
- Thus one obtains

$$\eta E_{PeV}^3 < 4 \times 10^{-3}$$

i.e. one gets $\eta \sim 1$ for $E_{PeV} \approx 0.2$

HAWC 2025



Is it hard to get such an efficient acceleration?

- For DSA the typical estimate is $\eta = 2\pi(c/v)^2 \gg 10$
- One can get quite efficient acceleration in some numerical experiments, $\eta \sim 10$, but still $\eta \sim 1$ seems unrealistic

Ingredients in the scenario

- Ultrarelativistic wind
- Relativistic shock
- Intense photon field

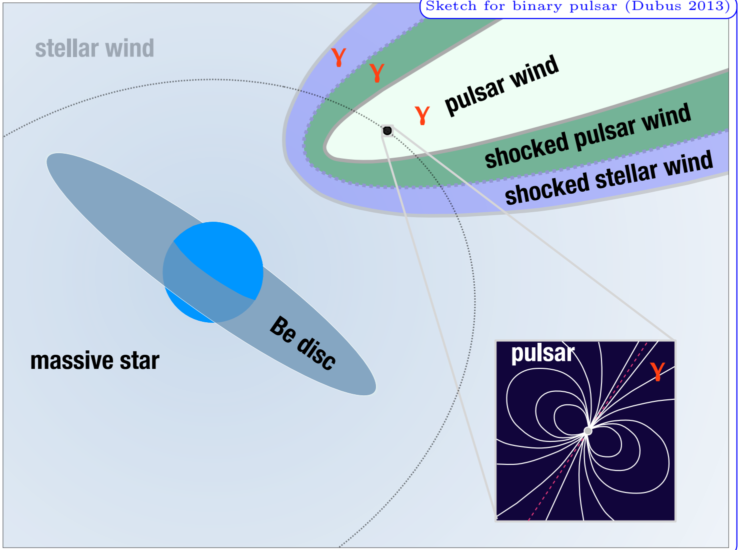
☞ Relativistic shock means acceleration of relativistic particles

☞ Intense photon field implies $\gamma\gamma$ attenuation

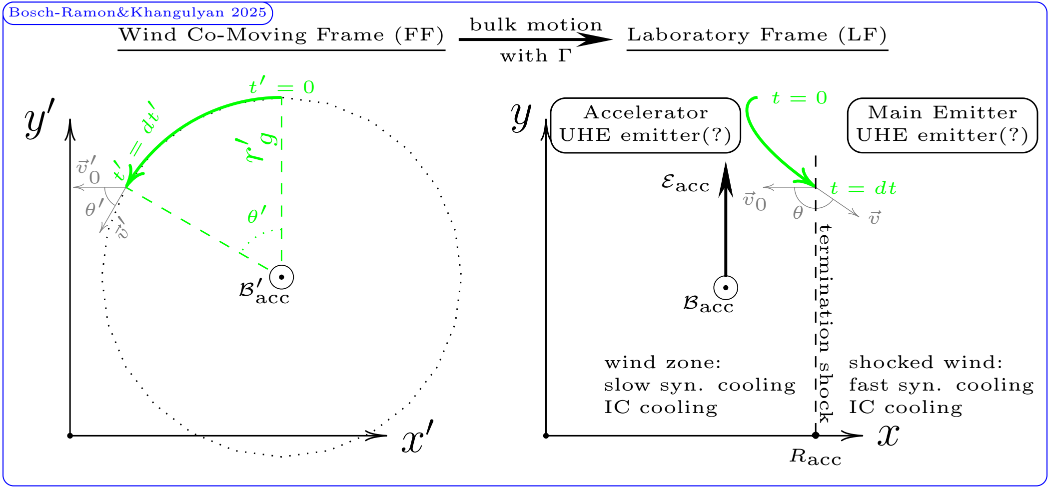
☞ $\gamma\gamma$ attenuation leads to injection of secondaries all over the source

What happens to secondaries created in the pulsar wind zone?

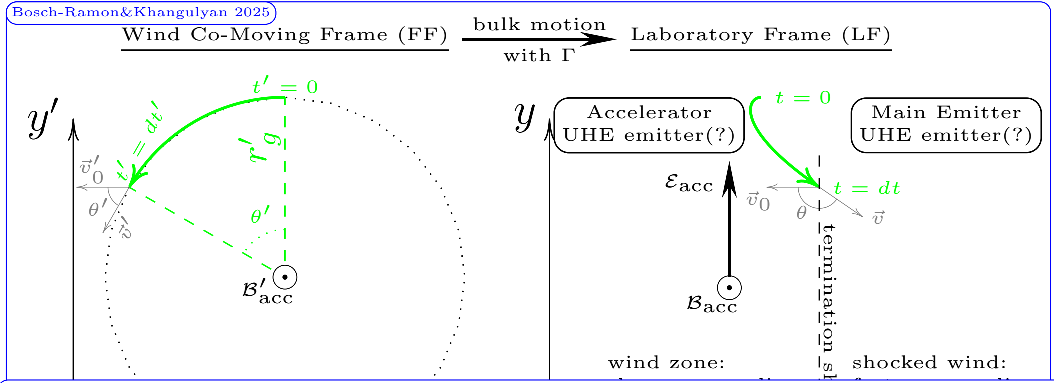
Sketch for binary pulsar (Dubus 2013)



A possible solution?

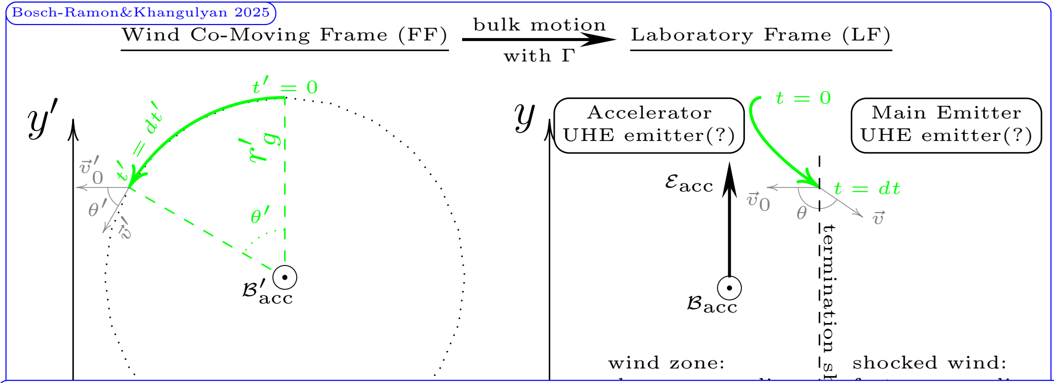


A possible solution?



- 100 GeV gamma rays are attenuated with in the system
- Pairs created in the wind zone, would see a factor of $\Gamma_{\rm wind}$ weaker magnetic field, thus synchrotron losses are suppressed
- If a particle turns by an angle $\theta \sim 1/\Gamma$ in the co-moving frame then its energy is strongly changed in the lab frame

A possible solution?



- This process injects particles with energy such that turn by $\theta \sim 1/\Gamma$ occurs in the lab frame during the time R_{ts}/c
- This corresponds to the maximum energy of accelerated particles of $eR_{ts}B_{wind} \approx \sqrt{\frac{e^2\sigma L}{c}}$
- For $\sigma L \approx 10^{36}\,\mathrm{erg\,s^{-1}}$, this yields ~ 1PeV

Summary

- At present, the pulsar scenario is favored for gamma-ray binary systems
- In systems with pulsars, the gamma-ray emission is most likely produced by very-relativistic electrons upscattering soft photons from the optical companion
- HAWC and LHAASO data point towards the presence of UHE electrons in these systems, which seems to be forbidden by fast synchrotron losses
- Acceleration of UHE electrons in presence of dense photon and strong magnetic field poses an interesting challenge for acceleration theories
- Lose vs acceleration collision can be resolved if one assumes that UHE electrons are accelerated in the pulsar wind zone
- This is a realization of the so-called "converter" acceleration mechanism suggested by E.Derishev, and it may have important implications for interpretation of UHE observations: the synchrotron burn-off limit might be violated in sources containing relativistic outflows (in particular in PWNe)