Fermi-type Particle Acceleration in Microquasar Jets

VGGRS VII (May 6-8, 2025)

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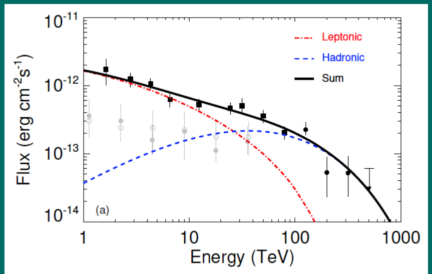
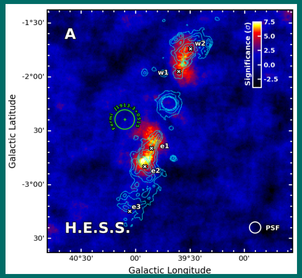
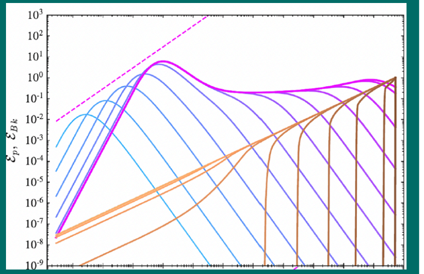
(IPP-Garching & ITP HD)

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

PLASMA ASTRO







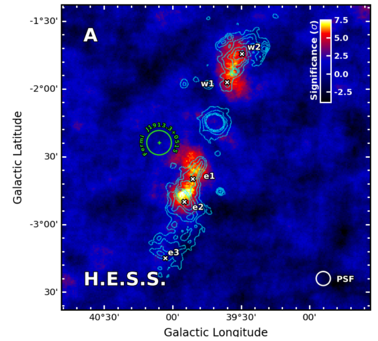
Short Overview

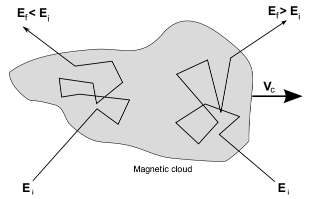
- **MQ Jets @ High Energy Particles** *(intro & context)*

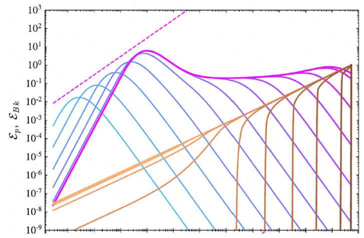
- **On Particle Acceleration in MQs** *(sites & processes)*

- **Fermi-type Particle Acceleration** *(focus on scales beyond binary)*

- ***Characteristics & Expectations*** *(timescales & efficiency)*







Congratulations on the Career & Success of Josep Maria!

Microquasars are X-ray binary stars capable of generating relativistic jets. Galactic microquasars are one of the most recent additions to the field of high energy astrophysics and have attracted increasing interest over the last decade. They are now primary targets for all space-based observatories working in the X-ray and γ-ray domains. The hope is that their study will enable us to understand some of the analogous phenomena observed in distant quasars and active galactic nuclei, which have practically the same scaled-up physics as microquasars. Microquasars are also believed to be

(Paredes & Marti 2003)

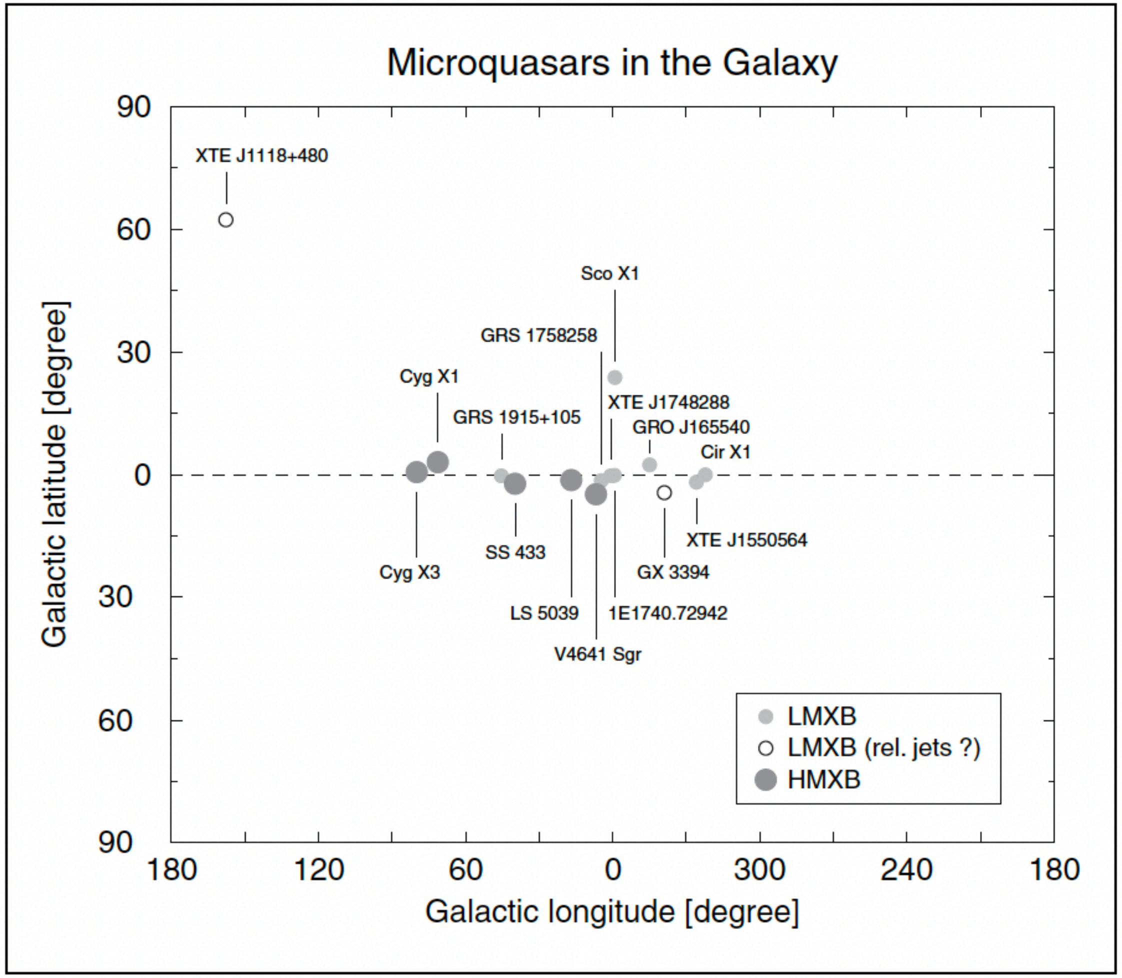


Figure 1. Distribution of known microquasars in galactic coordinates. Filled circles represent those sources where relativistic jets have been imaged, while open circles are used for those where hints of relativistic jets have been seen or are clearly suspected.

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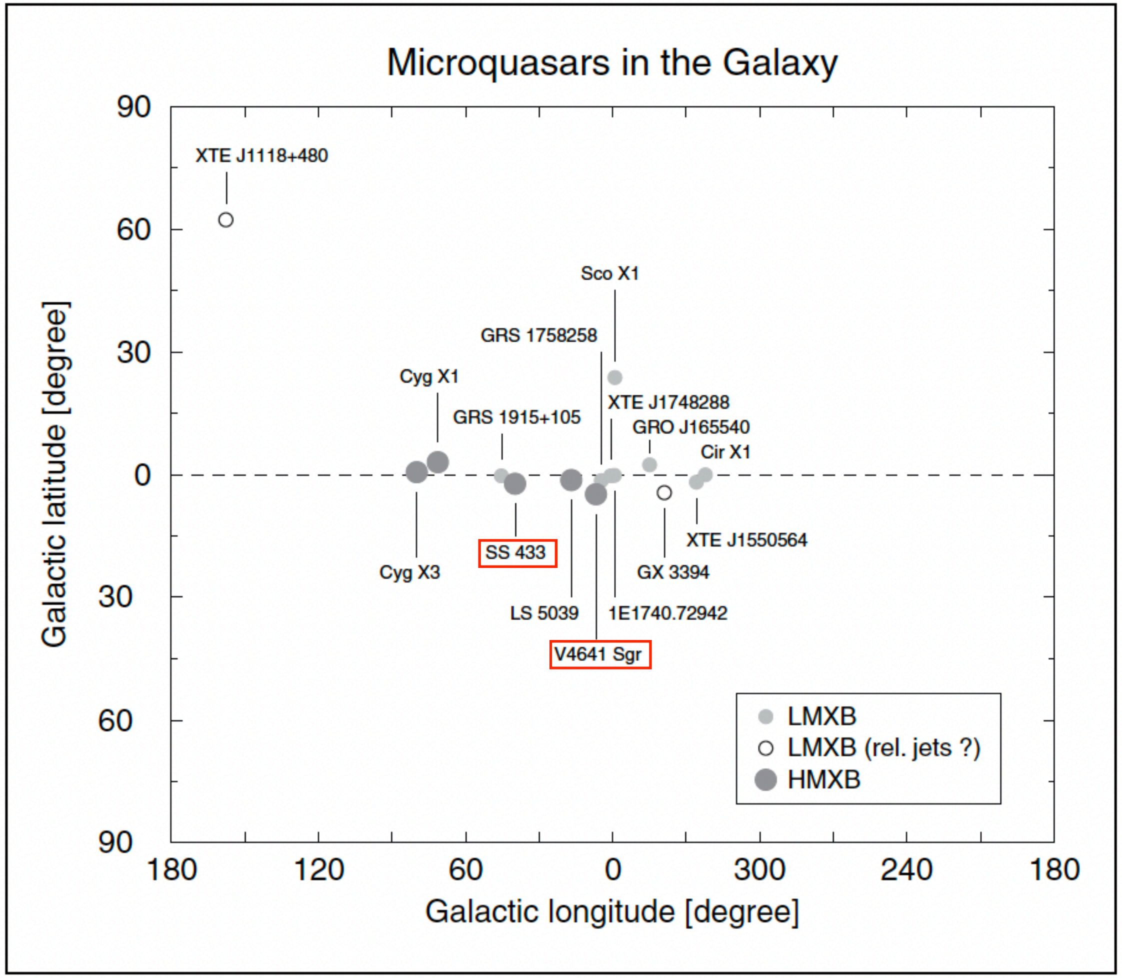

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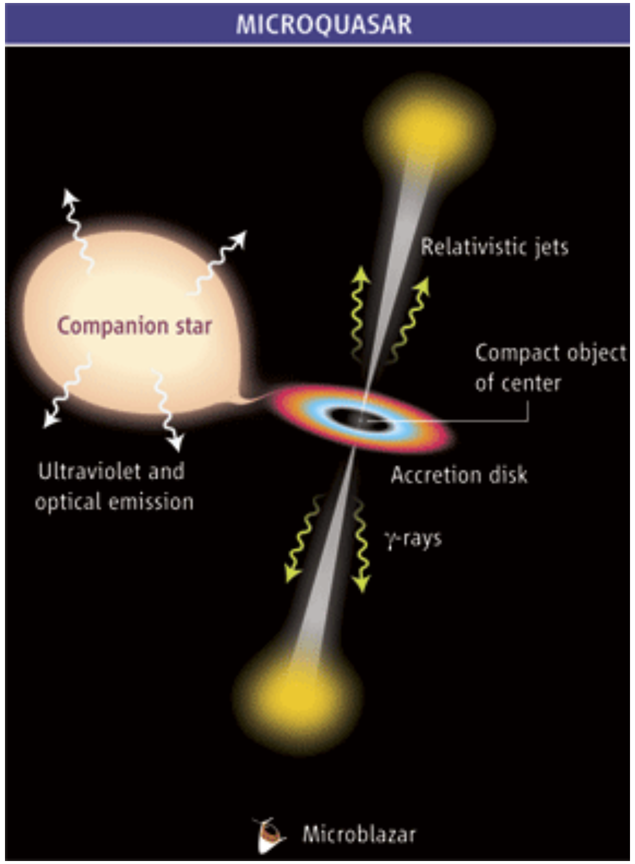

Mirabel 2006

Gamma-Ray-Emitting Accreting X-ray Binaries

Source	BH Mass (M_{sun})	Companion Type	Companion Mass (M_{sun})	Orbital Period (d)	Distance (kpc)	Jet Speed (c)	GeV	VHE >0.1 TeV	UHE >100 TeV
Cygnus X-1	21	O9.7 Iab	~40	5.6	2.2	~0.6-0.9	yes (flaring)	-	yes (>25 TeV)
Cygnus X-3	~7(?)	Wolf-Rayet	12	0.2	9	~0.8	yes (flaring)	-	?
SS 433	~12	A-type supergiant	~20	13	5.5	0.26	?	yes	yes
V4641 Sgr	6	B star	~3	2.8	6	9.5 (superlum.)	-	yes	yes
MAXI 1820+070	7	K-giant	0.5	0.3	3	~0.97	-	-	yes
GRS 1915+105	~10	K-giant	0.5	33.5	9.4	~0.8	yes (persistent)	-	yes

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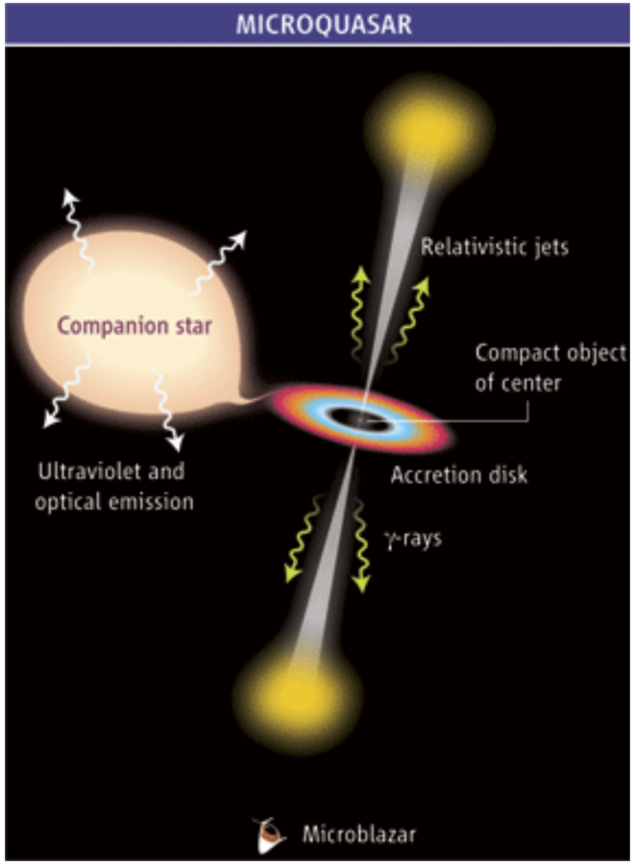

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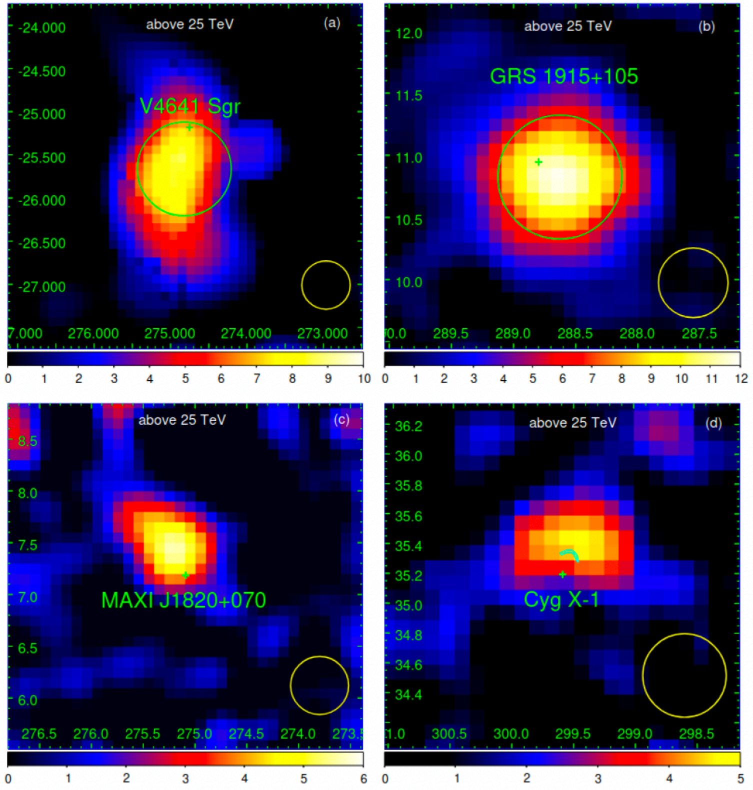
mildly relativistic (modulo SS 433)

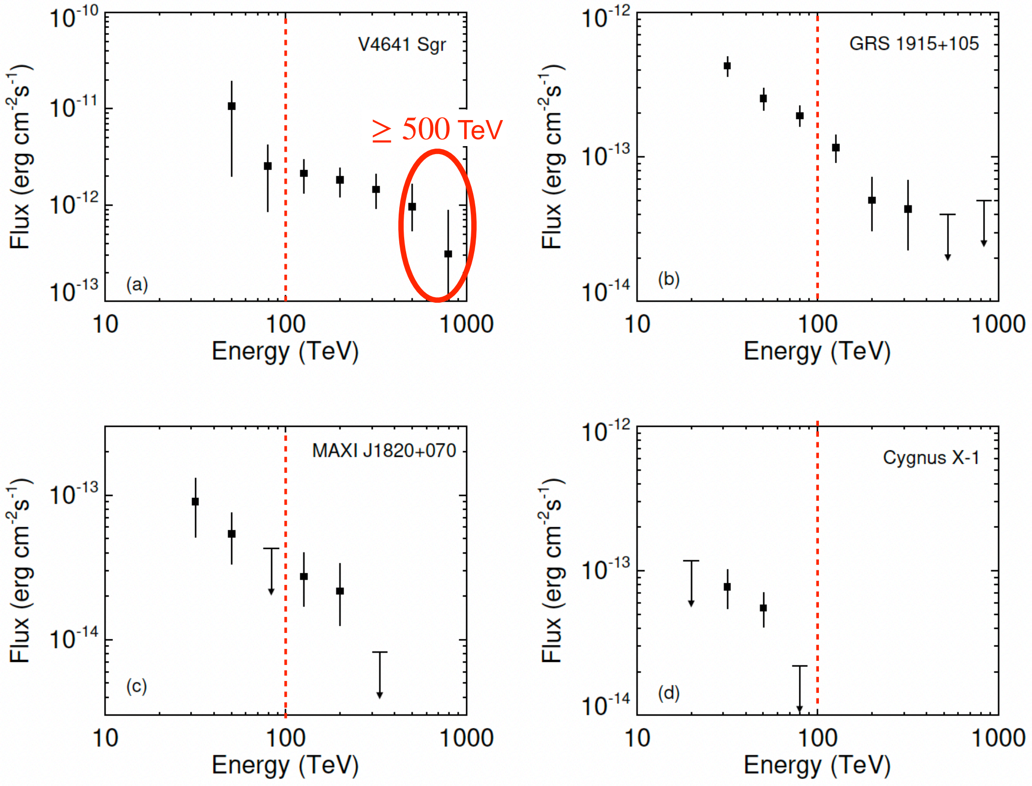
Context (II)

cf. talks by Lalenthra, Sabrina, Jian & Samar

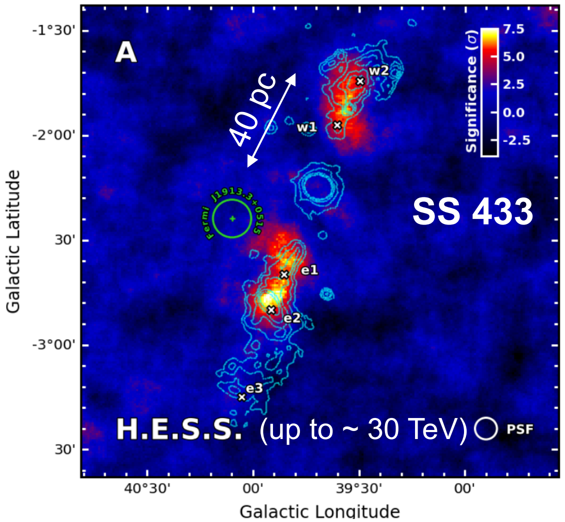
- **MQs as PeV particle accelerators** (caveat: IC, boosting?)
- **U/VHE far away from binary system** *(HAWC, HESS, LHAASO)*

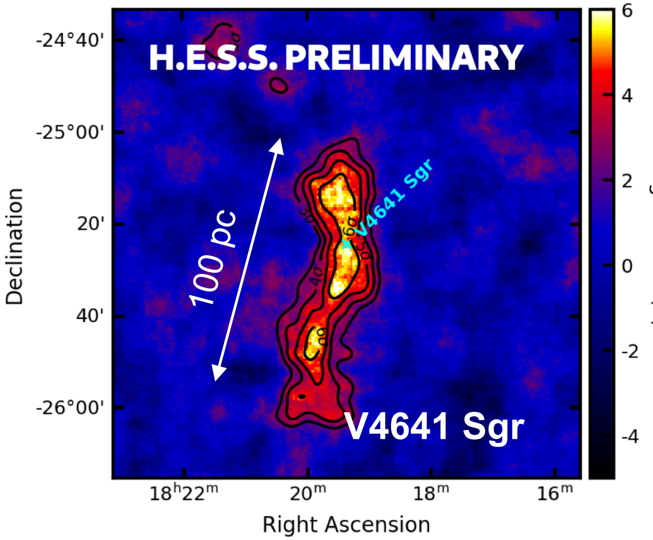


green circle = 68% containment radii
yellow circle = 68% containment PSF
green cross = MQ-BH position



LHAASO+2024





HESS+2024 & Gamma24

Context (III)

Gamma-ray production mechanisms in MQ jets (modulo activity states, radio/X-ray outbursts):

- **Leptonic: IC - SSC or EC** *(e.g., with companion or interstellar radiation fields)*
  (e.g., Atoyan & Aharonian 1999; Paredes+ 2000; Georganopoulos+ 2002; Bordas+2009…)
  - $h\nu \sim \gamma_e m_e c^2$ (KN) $\Rightarrow$ if $\epsilon_\gamma := h\nu \gtrsim 100$ TeV $\Rightarrow$ $\gamma_e \gtrsim 10^8$ [neglecting boosting]

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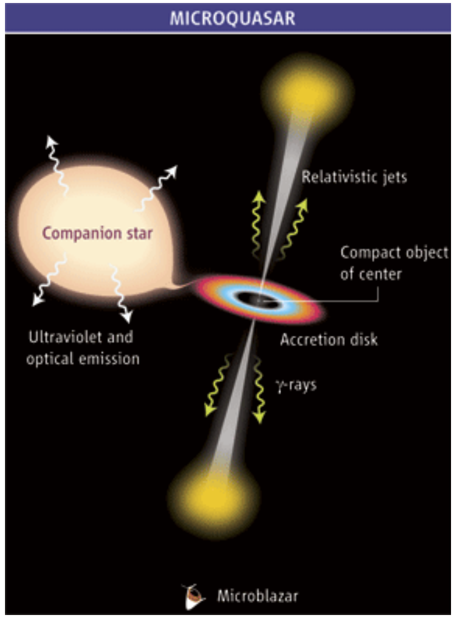

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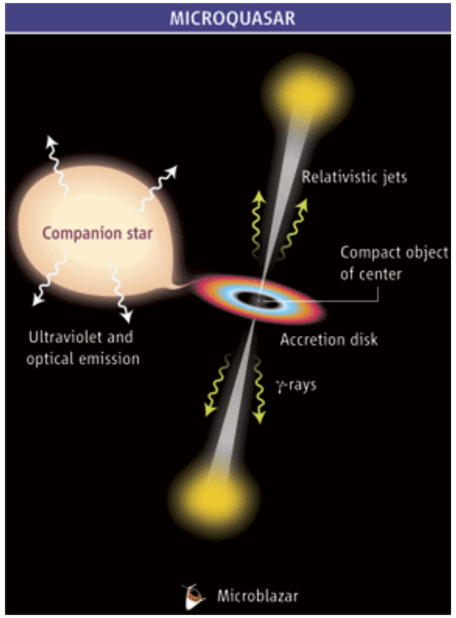
  - **MQs contribution to Galactic CR (knee)?**



$$E_{\rm Hillas} \simeq quBR \simeq 8\,Z\left(\frac{B}{20\ \mu{\rm G}}\right)\left(\frac{u_s}{0.26c}\right)\left(\frac{R}{1.6\ {\rm pc}}\right){\rm PeV} \quad [\text{SS 433}]$$

(compatible with $B_{\rm H} \sim 10^9 \dot{m}^{1/2} M_1^{-1/2}$ G)

$$\Rightarrow L_B = 2\pi R^2 u_B u_j \ \Rightarrow\ L_B \sim 10^{37}\left(\frac{0.2}{\beta_s}\right)\left(\frac{E/Z}{5\ {\rm PeV}}\right)^2 {\rm erg/s}$$

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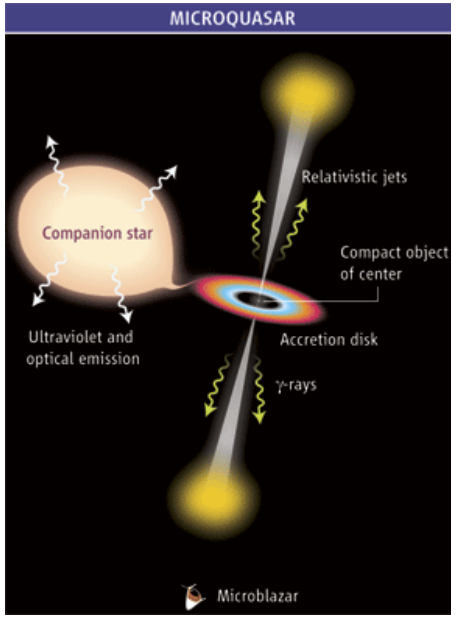
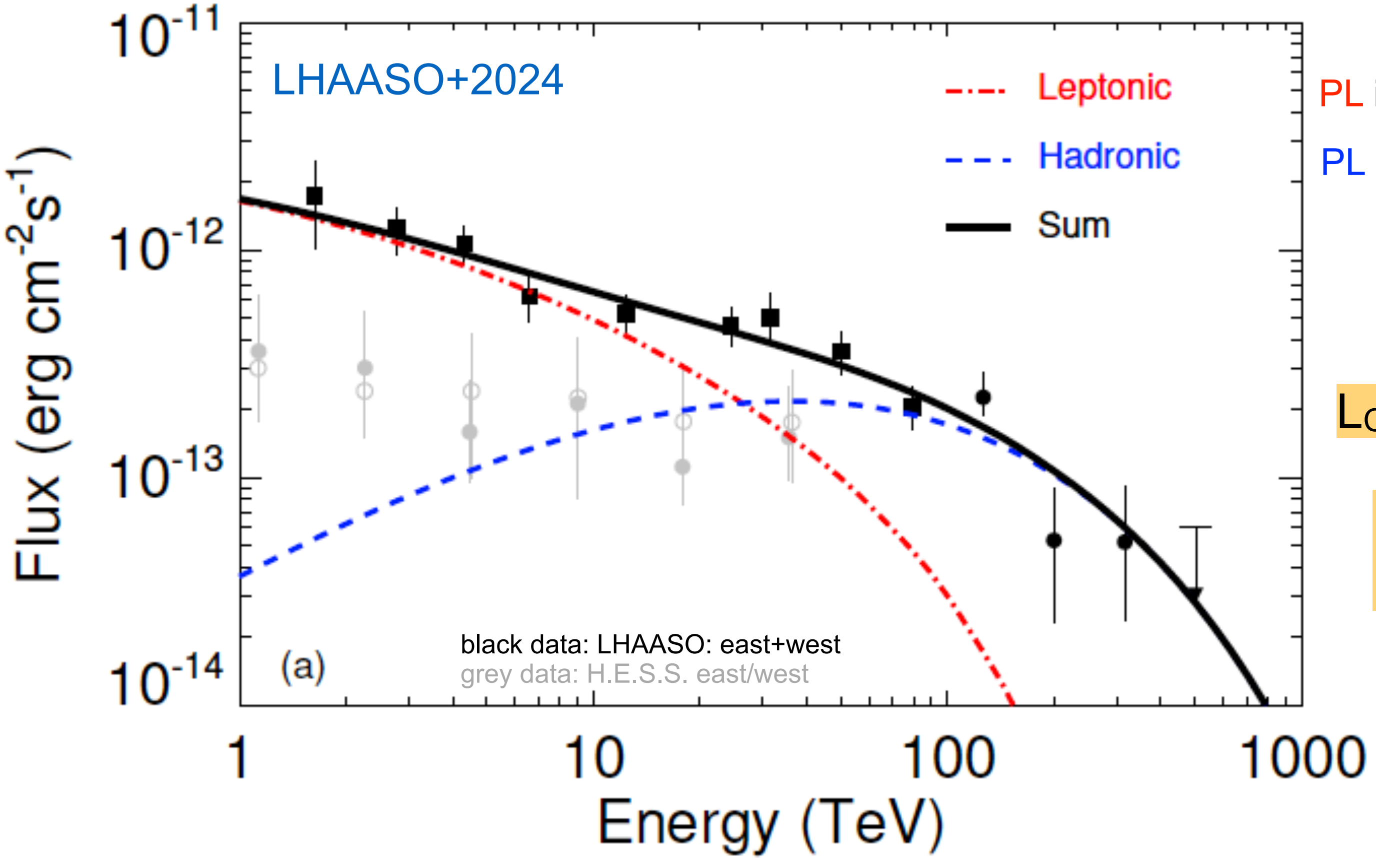


Context (IV)

- **Example: Lepto-hadronic interpretation of SS 433**
  - ➡ leptonic EC (“H.E.S.S.”/shock) + hadronic pp with cloud @ tens of pc (independent component?)



PL index s_e = 2.4, $E_{e,max}$ = 200 TeV

PL index s_p = 1.8, $E_{p,max}$ = 1 PeV

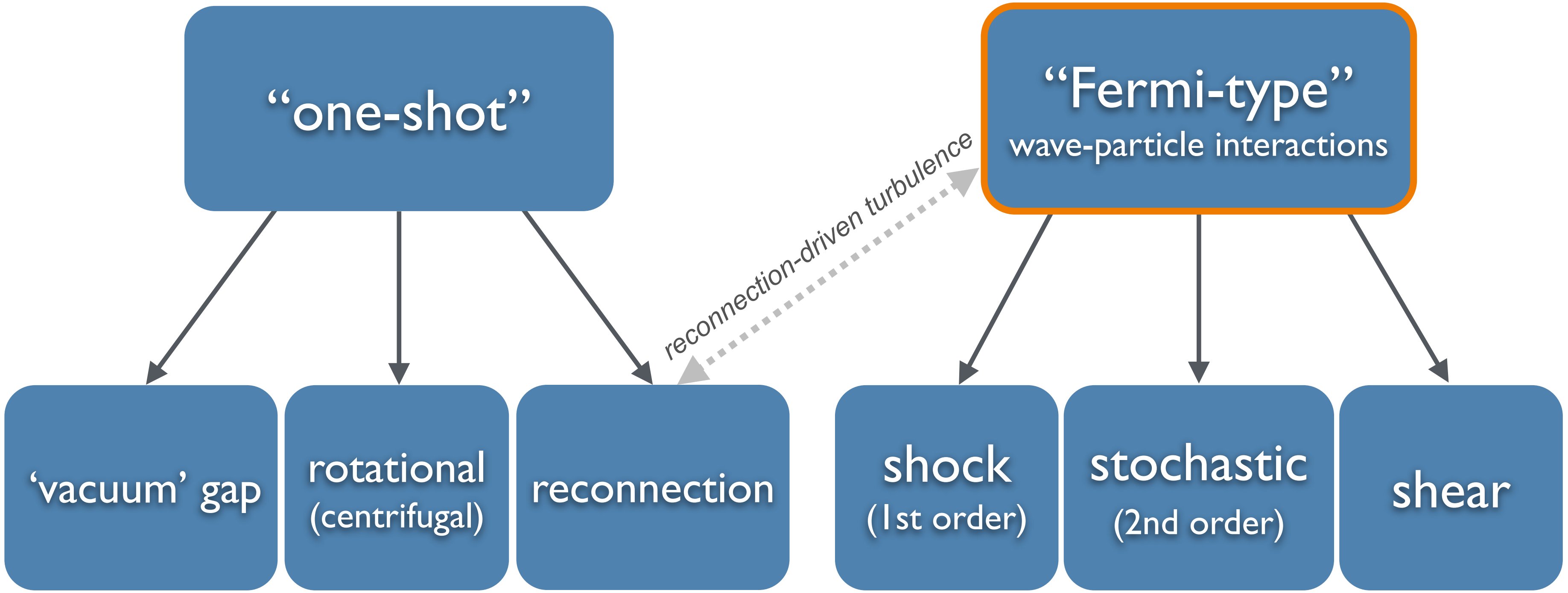
$L_{CR} \sim 10^{38}$ erg/s @ PeV energy

⇒ MQ population (10x) contributing to CR knee (?!)

On Particle Acceleration in MQs

(sites & processes)

Possible Acceleration Processes & Sites *(not exhaustive)*



‘vacuum’ gap	rotational (centrifugal)	reconnection	shock (1st order)	stochastic (2nd order)	shear
BH vicinity	*BH vicinity*	*Accretion & Inner Jet*	*Jet & Termination*	*Corona, Jet & Lobes*	*Jet & Wind*
$\Phi \sim 10^{16} \dot{m}^{1/2} M_1^{1/2} (h/r_g)^{\nu}$ V	$\gamma_p \lesssim 10^5 \, (B_{r_L}/10^6 \, \mathrm{G})^{2/3}$	$\gamma_{p,max} \sim \sigma_p$			
pair density? gap size?	topology? feedback?	efficiency (σ, B_g)? spectral shape?	efficiency (σ)? localized?	efficiency? spectral shape?	efficiency? energetic seeds?

(e.g., FR+ 2007; Bosch-Ramon & FR 2011; FR 2011, 2019)

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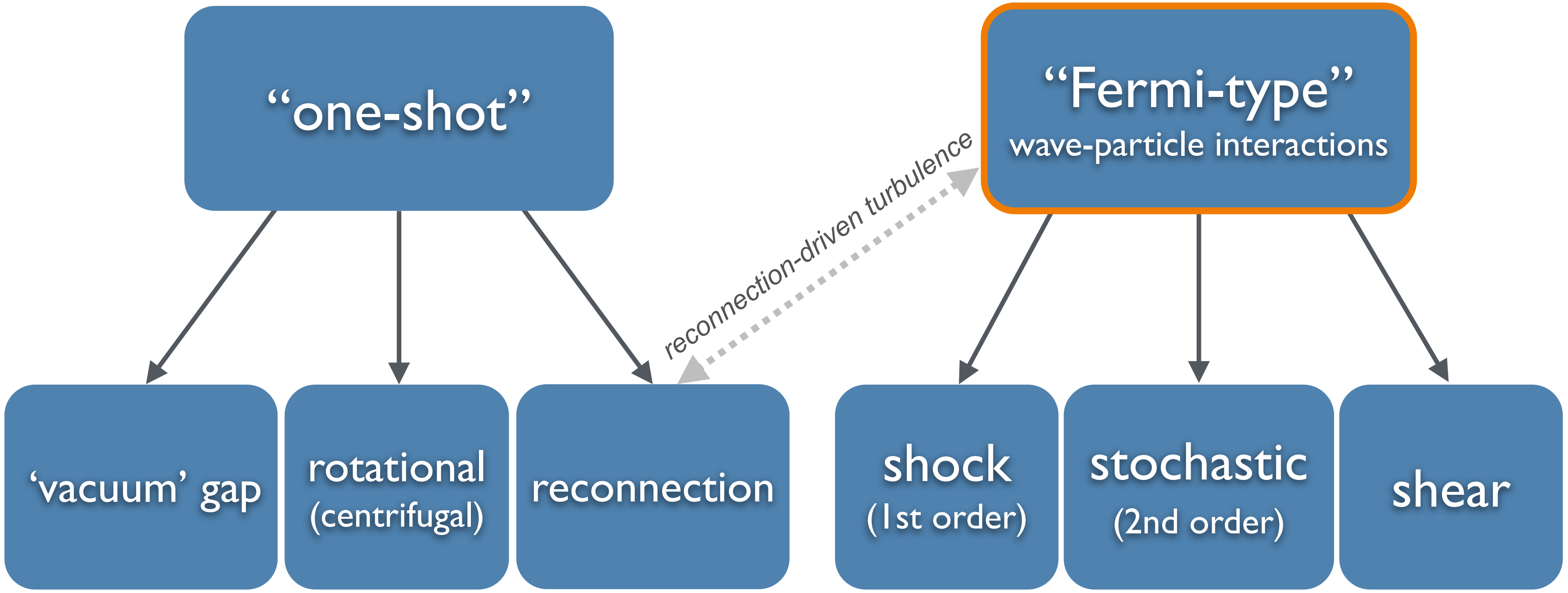

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Jet & Termination — efficiency (σ)? localized?

Corona, Jet & Lobes — efficiency? spectral shape?

Jet & Wind — efficiency? energetic seeds?

may approach max. efficiency $\eta \sim \mathrm{O}(1)$

$t_{\rm acc} \rightarrow r_{\rm gyro}/c$

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Fermi-type Particle Acceleration

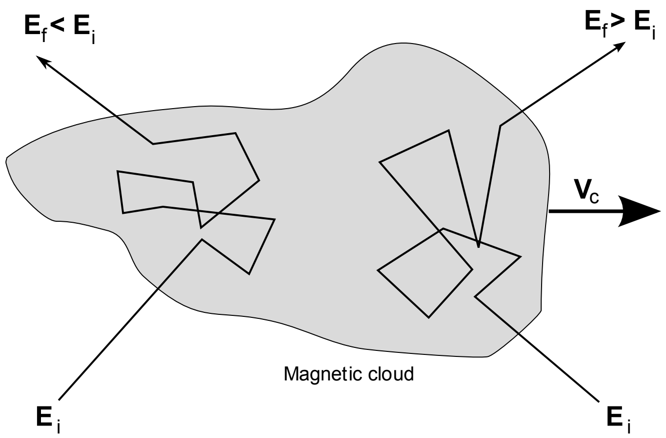
Kinematic effect resulting from scattering off magnetic inhomogeneities ('clouds')

E. Fermi, Phys. Rev. 75, 578 [1949]

➡ energy gain as results of multiple scatterings (stochastic process)

_Ingredients: in frame of scattering centre

- momentum magnitude conserved
- particle direction randomised



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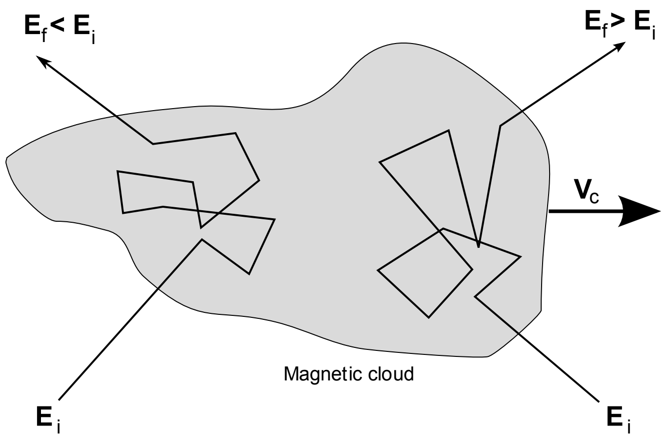

_Characteristic energy change per scattering (for non-relativistic V_c):

$$\Delta E = E_f - E_i = 2\left(E_i V_c^2/c^2 - \vec{p_i} \cdot \vec{V_c}\right)$$

$p_1 \simeq \frac{E_1}{c}$

➡ *energy gain for head-on* $(\vec{p}_i \cdot \vec{V}_c < 0)$,
loss for following collision $(\vec{p}_i \cdot \vec{V}_c > 0)$

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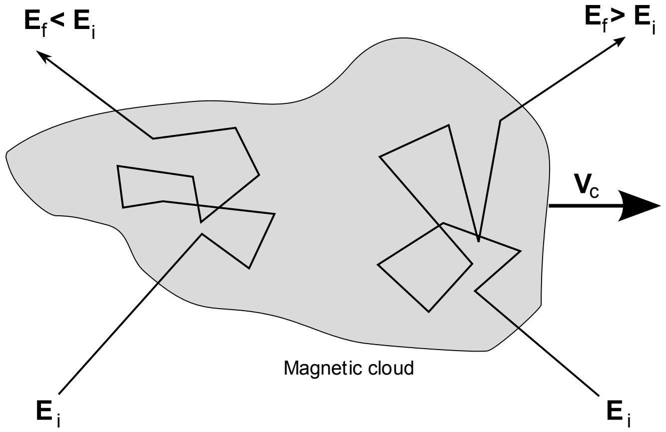

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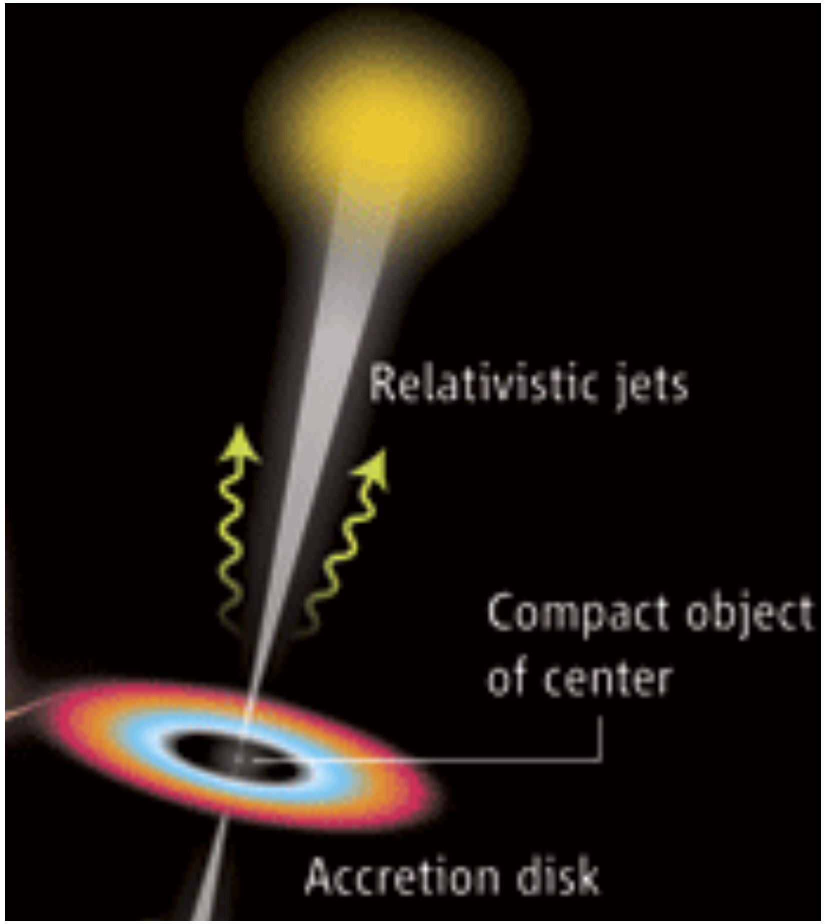
I. **stochastic:** average gain 2nd order: $\langle \Delta E \rangle \propto (v_A/c)^2 E$

II. **shock:** spatial diffusion, head-on, 1st order: $\langle \Delta E \rangle \propto (v_s/c) E$

III. **stochastic-shear:** drawing on 'systematic' velocity:

$\langle \Delta E \rangle \propto (\Delta u_{sh}/c)^2 E$ with $\Delta u_{sh} \sim (\partial u/\partial x)\,\lambda$

Fermi-type Particle Acceleration in “mildly relativistic” MQ Jets



For favourable conditions, Fermi-type particle acceleration known to produce power-laws: $n(p) \propto p^{-\alpha}$

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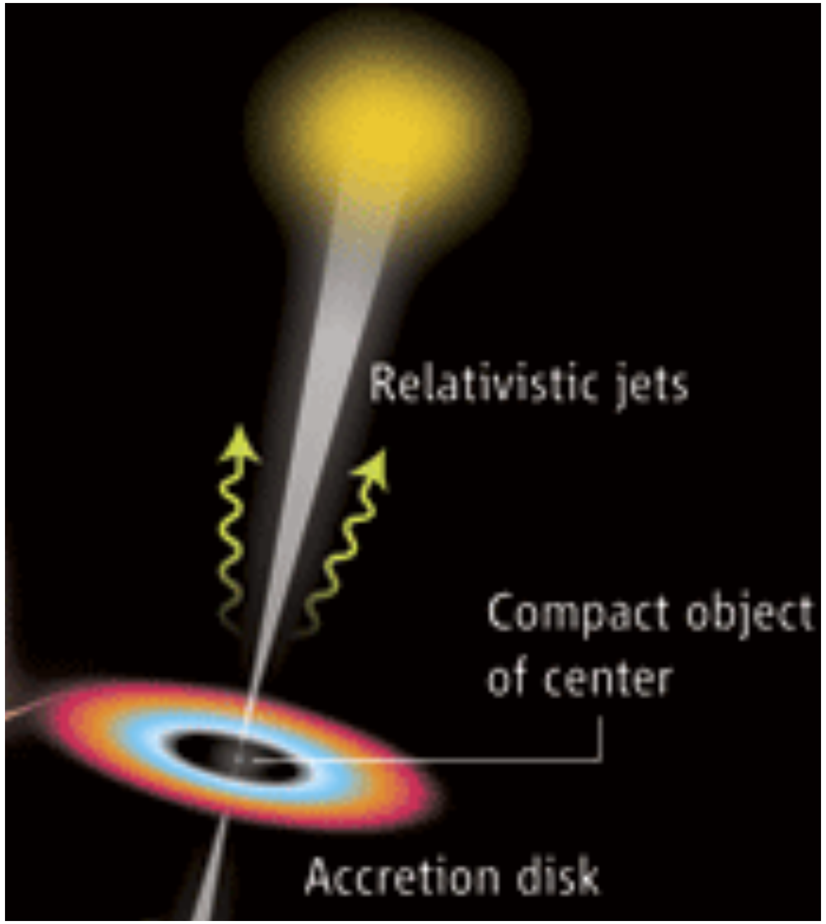

For favourable conditions, Fermi-type particle acceleration known to produce power-laws: $n(p) \propto p^{-\alpha}$

- *shock - power-law index:* $\alpha \simeq 2$

- *“shear” - power-law index depends on flow speeds*
  - ➡ $\alpha \to 1$ for highly relativistic flows
  - ➡ $\alpha \gg 1$ for sub-relativistic flows

  (FR & Duffy 2019, 2022)

- *“classical Fermi-2” - can be as hard as* $n(p) \sim p^{-1}$
  - ➡ energy content $\epsilon_p \propto p^2 n(p)$ growing
  - ➡ *expect non-linear feedback to set-in:* $\alpha \to 2$

  (Lemoine, Murase & FR 2024)

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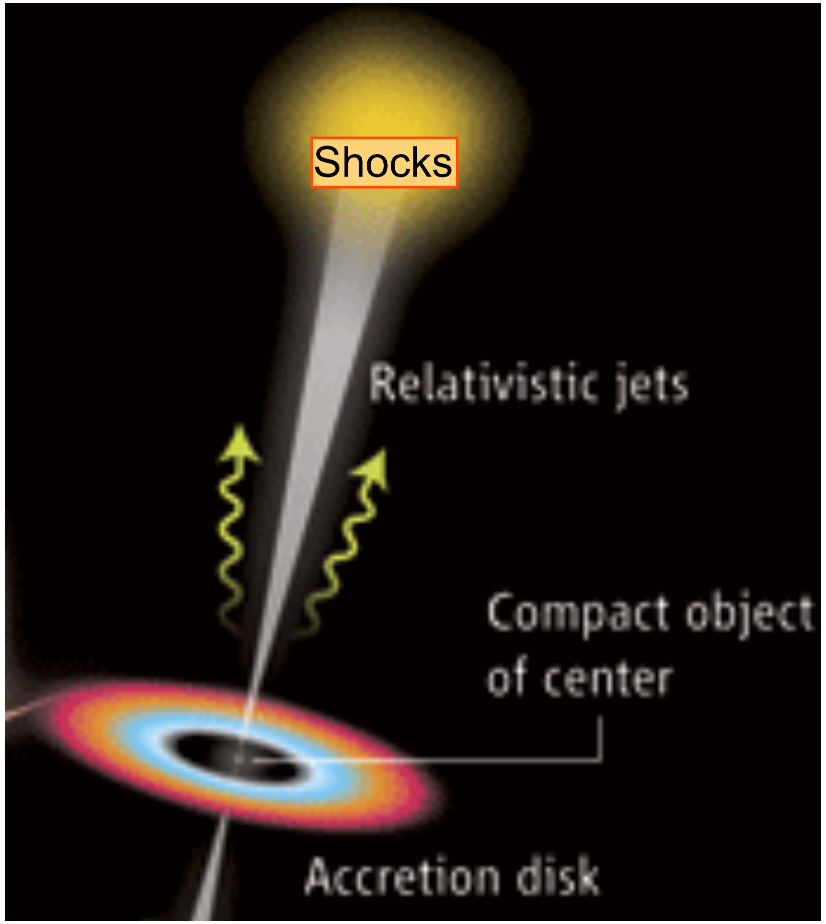

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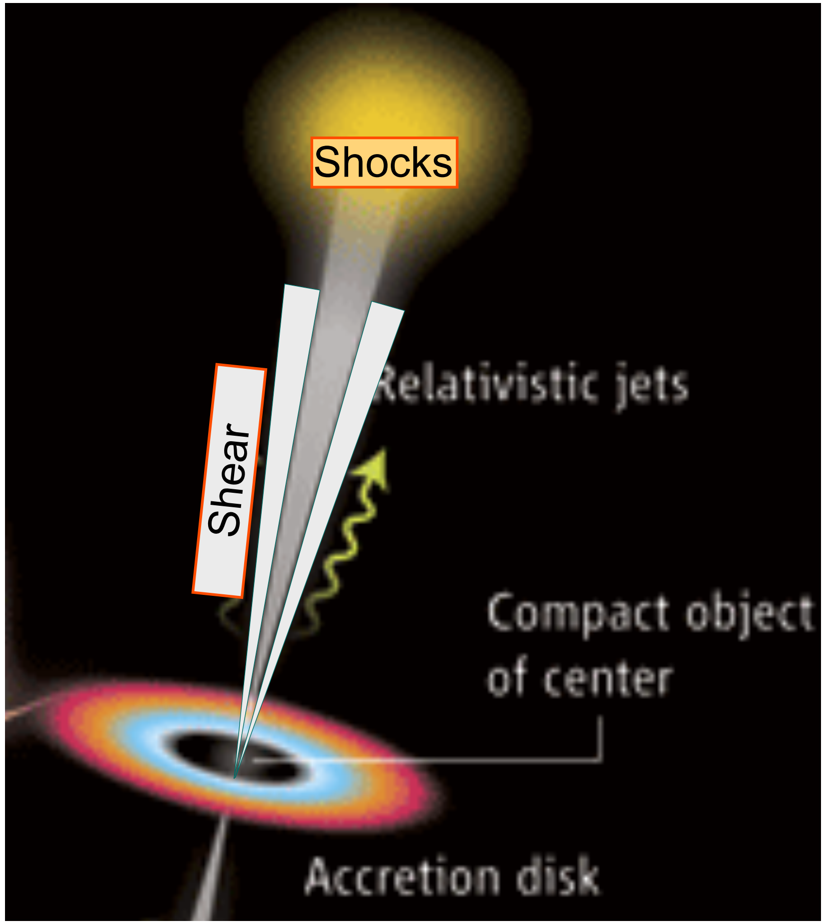

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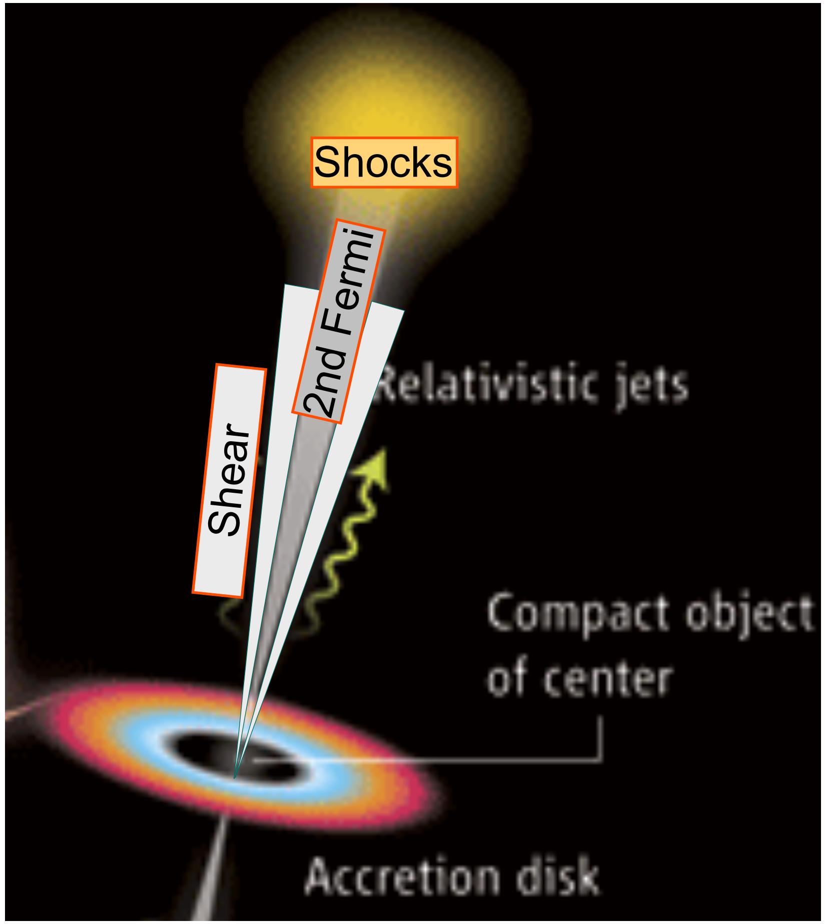

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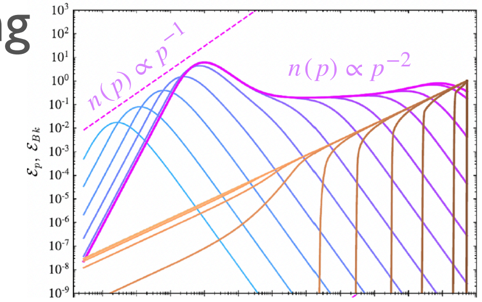
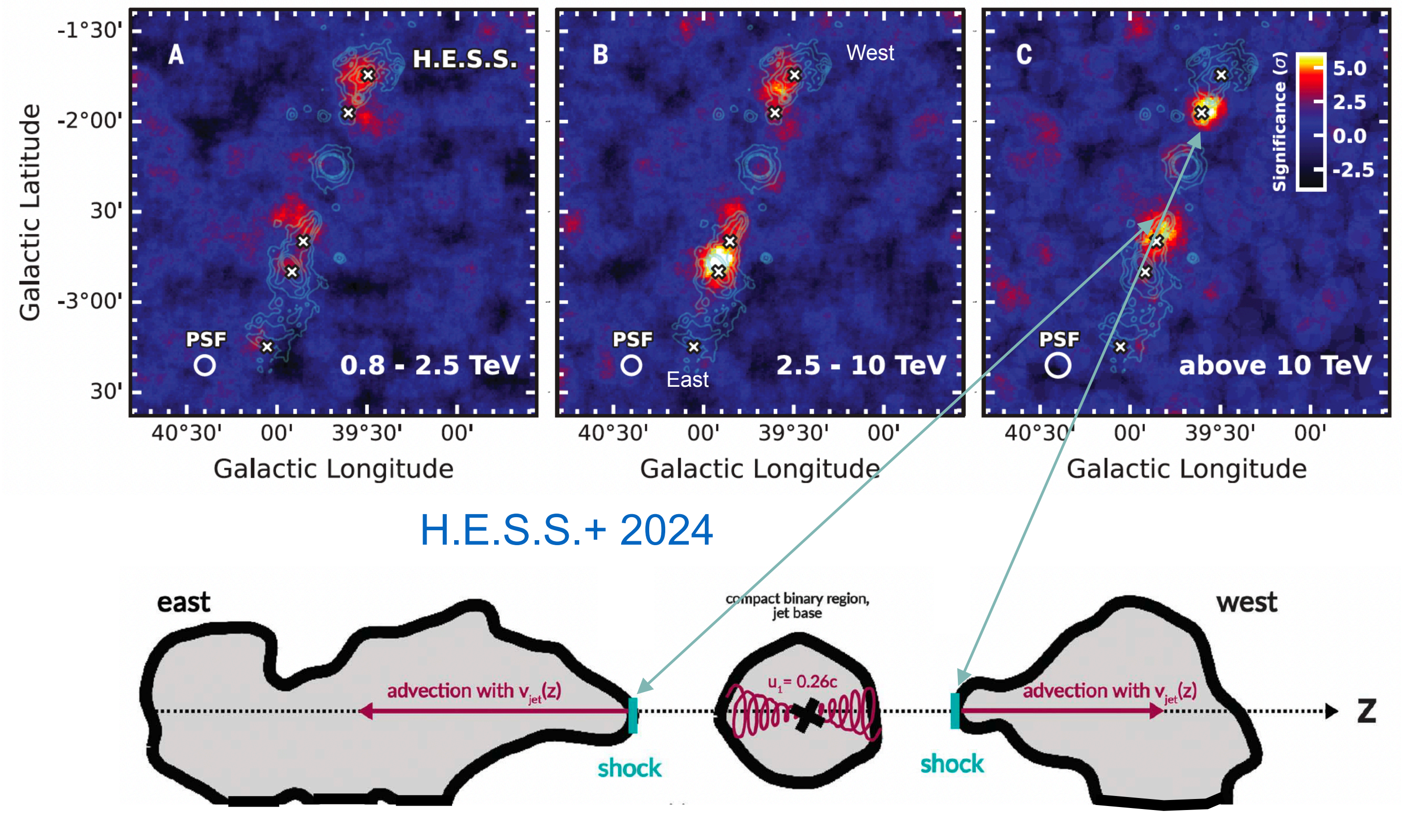


Example: 1st order Fermi (DSA) shock acceleration in SS 433

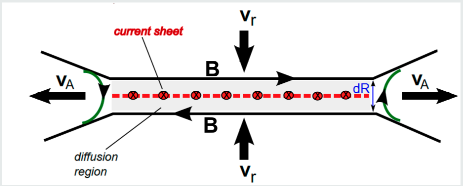
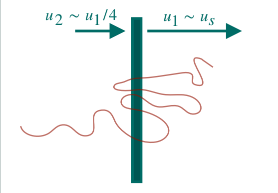
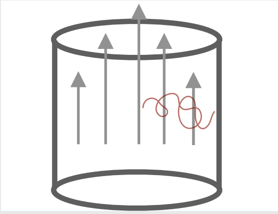
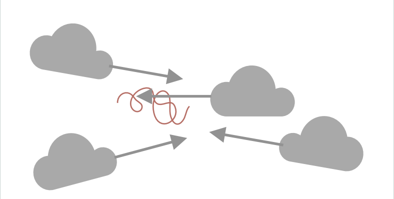
Re-brightening @ Standing Shock in pc-scale Outflow

- VHE emission up to ~ 30 TeV
- leptonic EC modelling with $B = 20\mu$G, v_s = 0.26c, injection power L_e~10^{38} erg/s
- electron PL spectral index = 2 as expected for strong shocks
- energy-dependent morphology compatible with advection speed $v_s/4$ (= downstream of shock)
- max. electron energy (iff Bohm) $t_{\mathrm{acc}} \simeq 8\kappa/v_s^2 = t_{\mathrm{syn,e}} \Rightarrow \gamma_{\mathrm{e,max}} \sim 4 \times 10^9$ (2 PeV)



H.E.S.S.+ 2024

Possible Acceleration Processes *(characteristics)*

Cartoon	**TYPE**	**Applicability constraint**	**Power-Law expectation** $n(p) \propto p^{-\alpha}$	**Others**
	**Reconnection**	highly magnetised $\sigma \gg 1$	function of σ may reach $\alpha \sim 1$	*Guide field? max. Lorentz factor and particle slope are connected*
	**Shock**	weakly magnetised $\sigma \ll 1$	quasi-universal $\alpha \simeq 2$	*localized; e^- injection problem? Maxwellian contribution?*
	**Shear**	intermediately magnetised $\sigma \lesssim 0.3$	function of flow speed	*extended emission; energetic seed injection needed*
	**Stochastic (2nd order)**	sufficiently magnetised $\sigma \gtrsim 10^{-2}$	dependent on escape, may be as hard as $\alpha \simeq 1$	*extended emission; turbulence characteristics? feedback*

$\sigma := B^2/(4\pi\rho c^2)$

Fermi-type Particle Acceleration in mildly-relativistic MQ jets

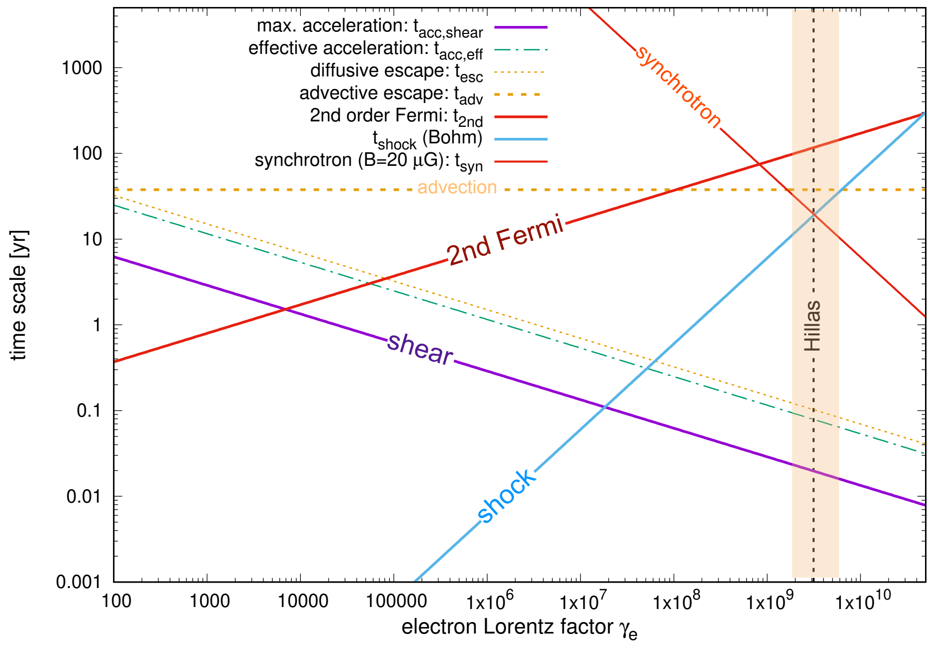
Illustration: SS 433-type, pc-scale parameters

(i.e., $B = 20\mu$G; R = 1 pc; v_s = 0.2c; but allowing for higher jet speeds $\Gamma_j \leq 2$)

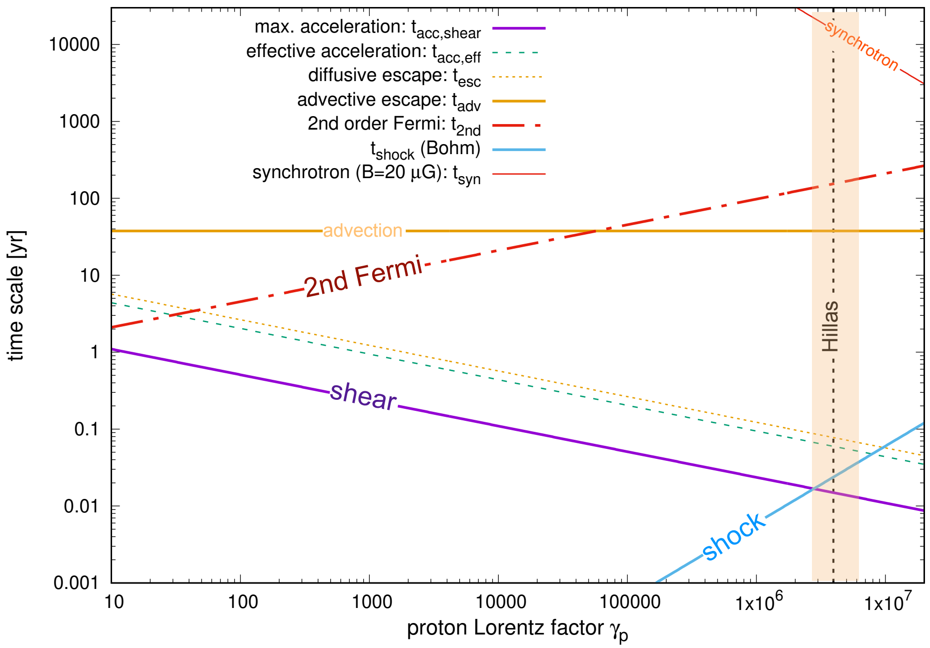
➡ electrons/protons: Hillas-constrained ⇒ may reach PeV energies (shock, shear)

➡ 2nd Fermi providing seed injection into shear…

electrons (cf. FR & Duffy 2025)



protons



$\beta_A = c/10$; $d \sim 10$ pc; $l_{coh} \sim \Delta r \sim r/10$

Kolmogorov-type mean free path for stochastic ($\lambda \propto l_{coh}^{2/3}\gamma^{1/3}$)

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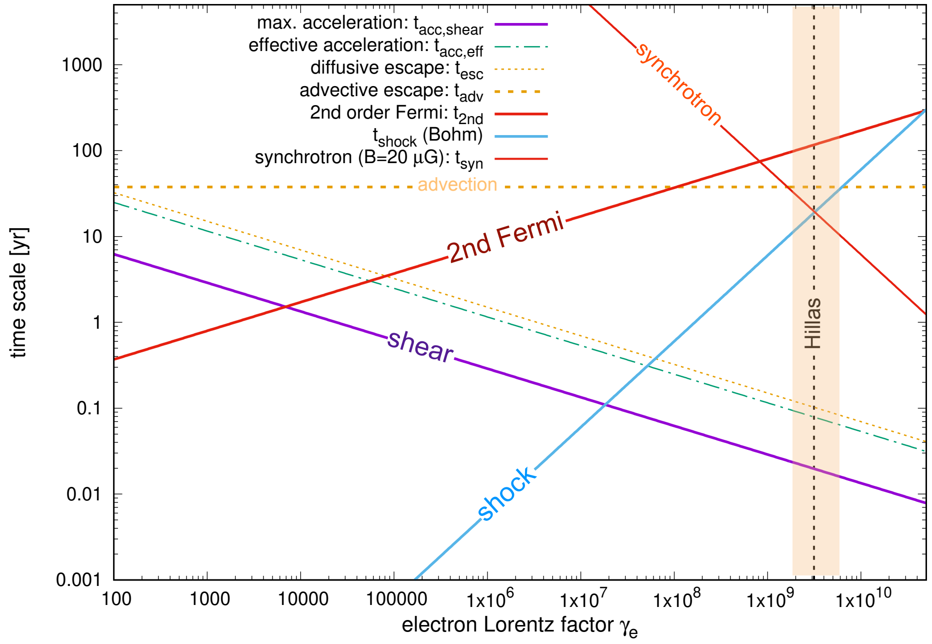

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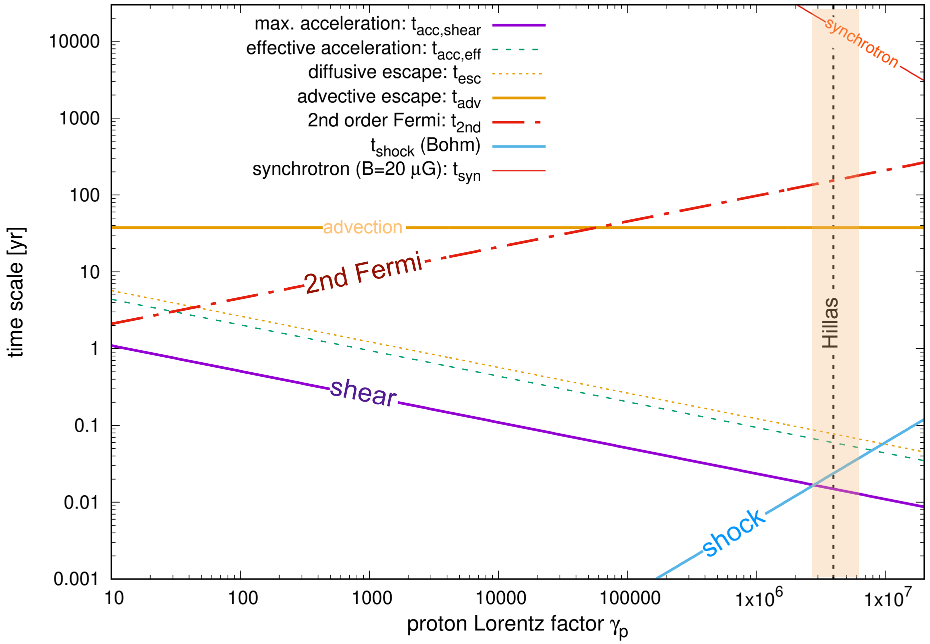

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in non-relativistic jets, only shocks appear sufficiently effective (cf. diffusive escape)

Conclusion & Outlook

MQs are (potential) PeV particle accelerators

⇒ evidenced by gamma-ray emission beyond 100 TeV energies

⇒ MQs as possible contributors to CR flux around knee

- **see (jet-related) gamma-ray emission originating far away from binary**

⇒ need to 'fully' characterise emission (hadronic?!)

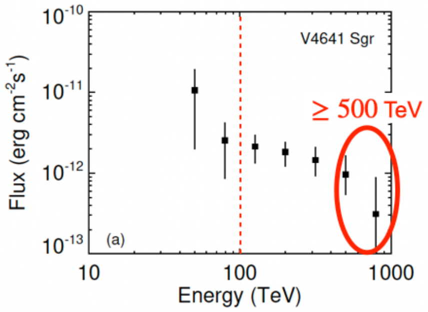
⇒ need to connect to jet physics (mildly relativistic; properties?)

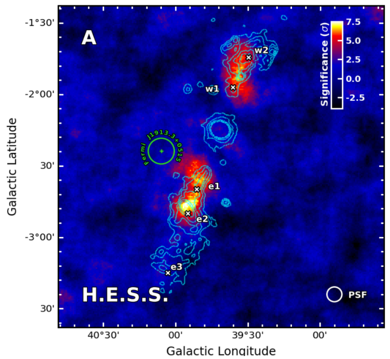
- **Fermi-type particle acceleration as promising conceptual framework**

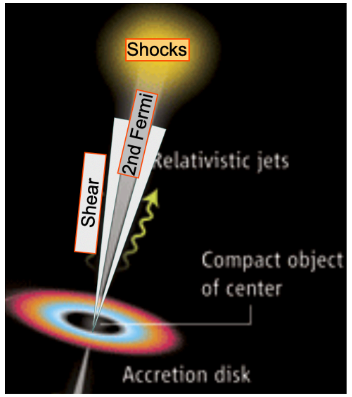
⇒ can reach Hillas-type maximum energies via shock or stochastic-shear (for mildly relativistic jets)

⇒ may in reality see combination of several processes (hybrid acceleration)

- **need further "high-resolution" observations to progress…**







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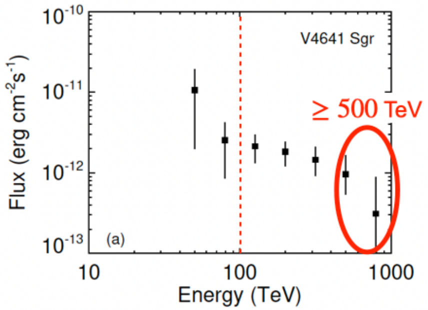
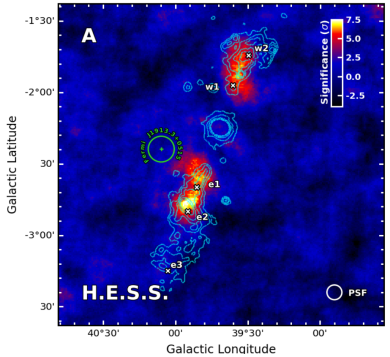
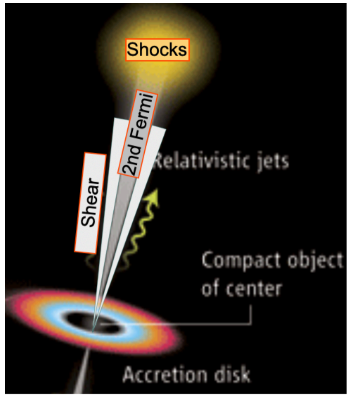






Thank you! Questions =)

BONUS

(A.) Microquasars at UHE energies

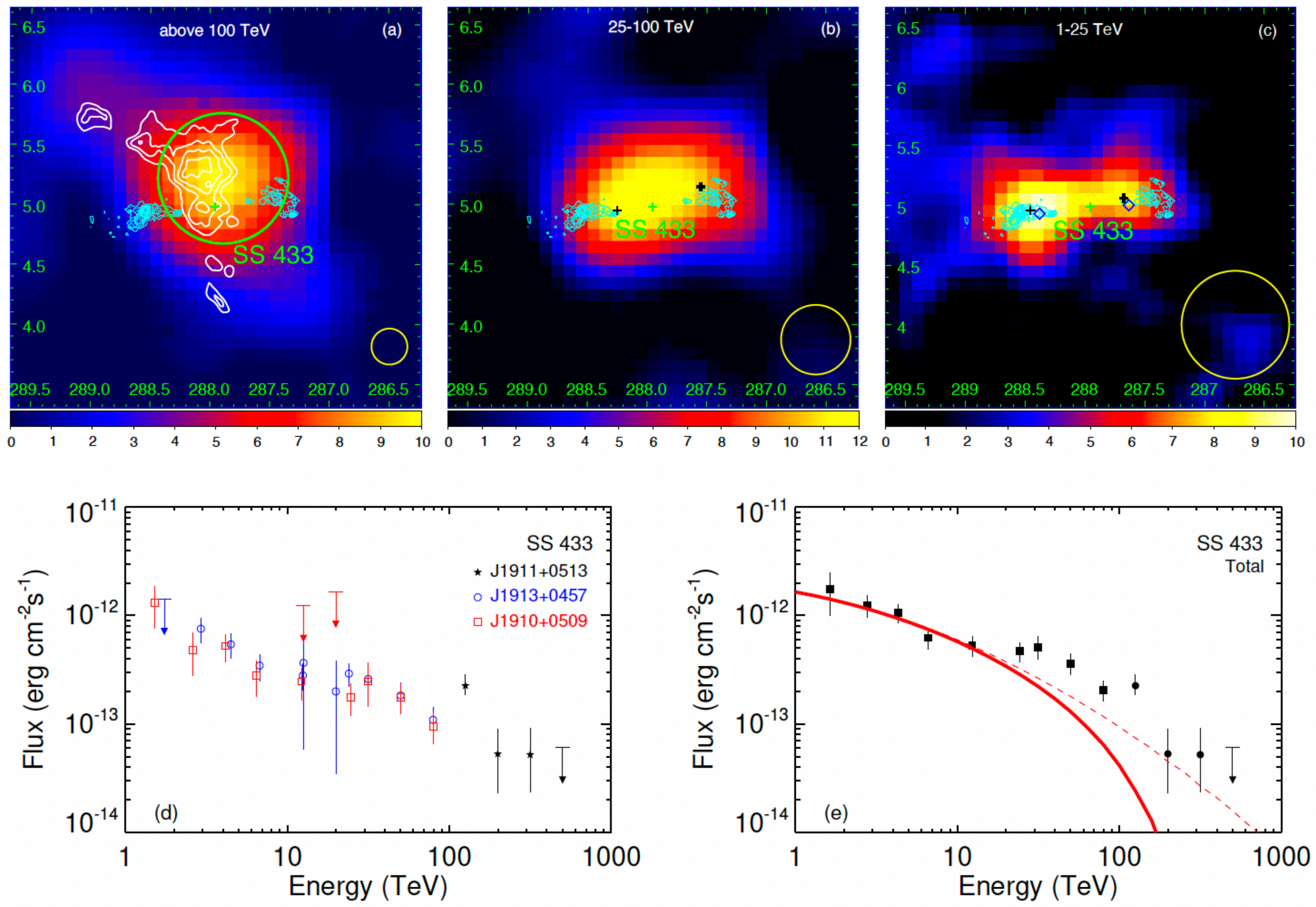
Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon Index	Energy Range (TeV)	Extension[a]	Flux[b] (Crab Unit)
SS 433 E.		J1913+0457	9.7[c]	2.78 ± 0.19	$25 - 100$		0.10
SS 433 W.	4.6 ± 1.3[33]	J1910+0509	8.6[c]	2.92 ± 0.21	$25 - 100$	0.70°	0.082
SS 433 central		J1911+0513	9.8	4.03 ± 0.29	$100 - 400$	0.32°	0.32
V4641 Sgr	6.2 ± 0.7[34]	J1819-2541	8.1	2.67 ± 0.27	$40 - 1000$	0.36°	3.9
GRS 1915+105	9.4 ± 0.6[35]	J1914+1049	6.1	3.07 ± 0.15	$25 - 400$	0.33°	0.17
MAXI J1820+070	2.96 ± 0.33[36]	J1821+0726	5.9	3.19 ± 0.29	$25 - 400$	$< 0.28°$	0.13
Cygnus X-1	2.2 ± 0.2[37]	J1957+3517	4.0	4.07 ± 0.35	$25 - 100$	$< 0.22°$	< 0.01
XTE J1859+226	4.2 ± 0.5[38]	–	1.9	–	–	–	< 0.03
GS 2000+251	2.7 ± 0.7[39]	–	1.7	–	–	–	< 0.04
CI Cam	$4.1^{+0.3}_{-0.2}$[40]	–	1.4	–	–	–	< 0.03
GRO J0422+32	2.49 ± 0.3[41]	–	0.8	–	–	–	< 0.01
V404 Cygni	2.39 ± 0.14[42]	–	0.5	–	–	–	< 0.02
XTE J1118+480	1.7 ± 0.1[43]	–	0	–	–	–	< 0.01
V616 Mon	1.06 ± 0.1[44]	–	0	–	–	–	< 0.01

[a] separation between two point-like sources of SS 433 below 100 TeV; 39% containment radius for SS 433 central, V4641 Sgr and GRS 1915+105; one-tailed 95% confidence upper limit for the source size for MAXI J1820+070 and Cygnus X-1.
[b] at 100 TeV, 1 CrabUnit $\simeq 10^{-12}$ erg cm^{-2}s^{-1}
[c] the combined detection significance for the two point-like sources is 12.9σ.

Table 1: LHAASO's measurement of Galactic BH-jet systems in the field of view.

LHAASO+2024

(A.) SS 433 at UHE energies



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(B.) Complexity in CR spectrum

DAMPE (arXiv:2304.00137)