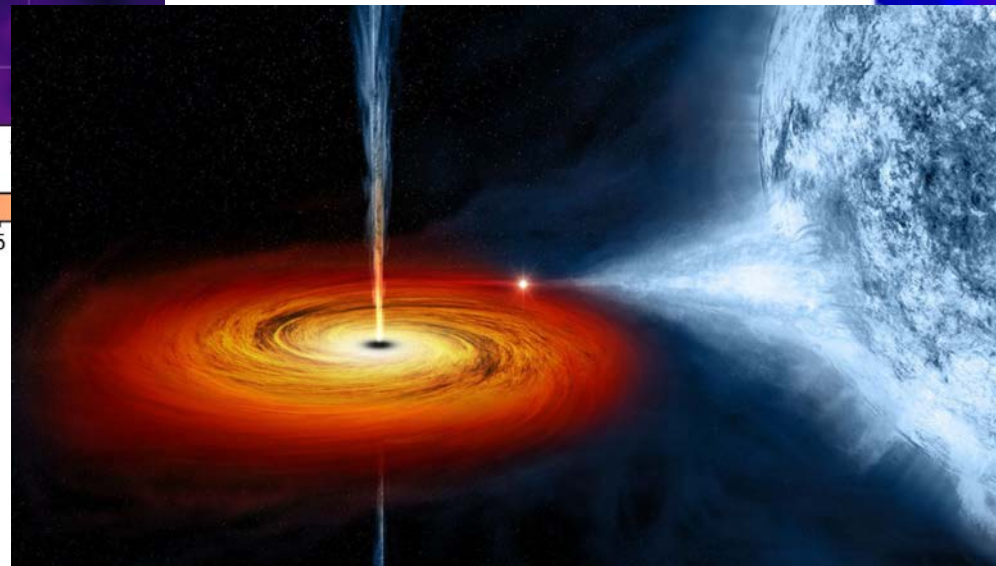
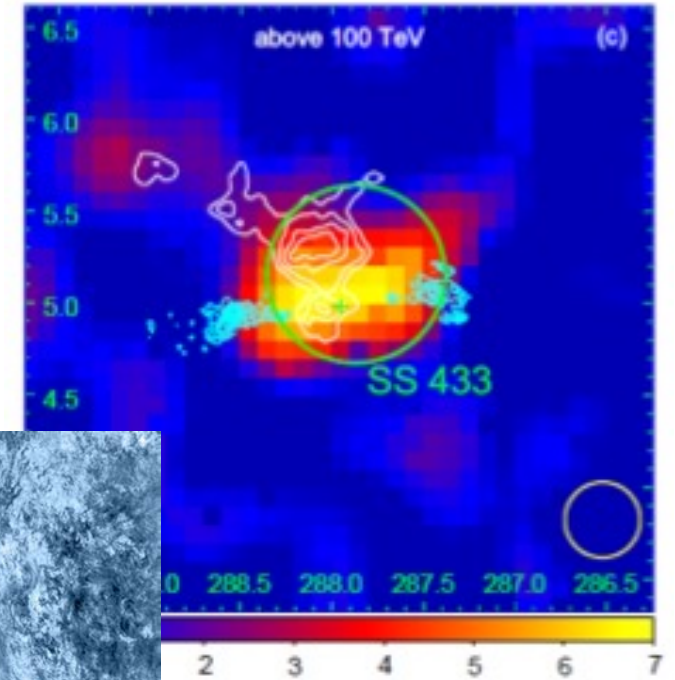
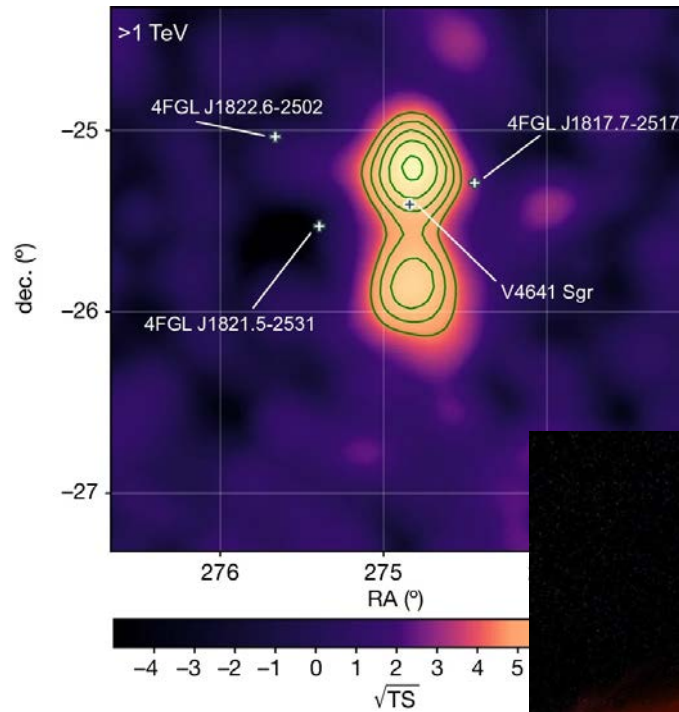


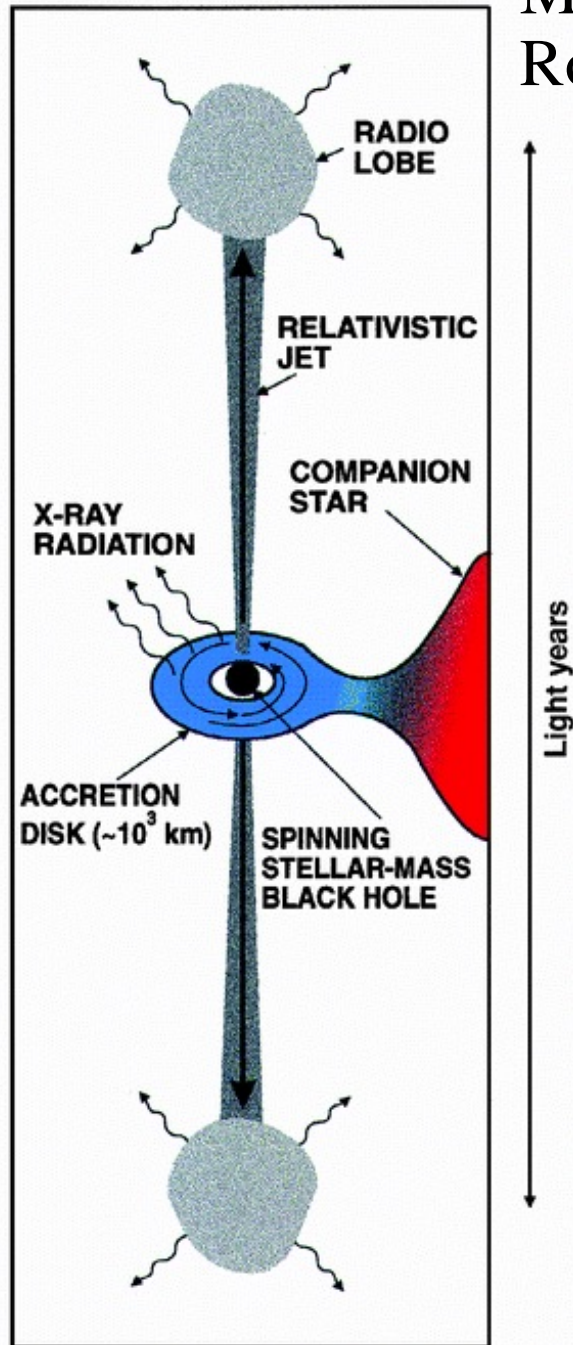
Elucidating physical processes in microquasars with multimessenger observations

Susumu Inoue
(Chiba U.)



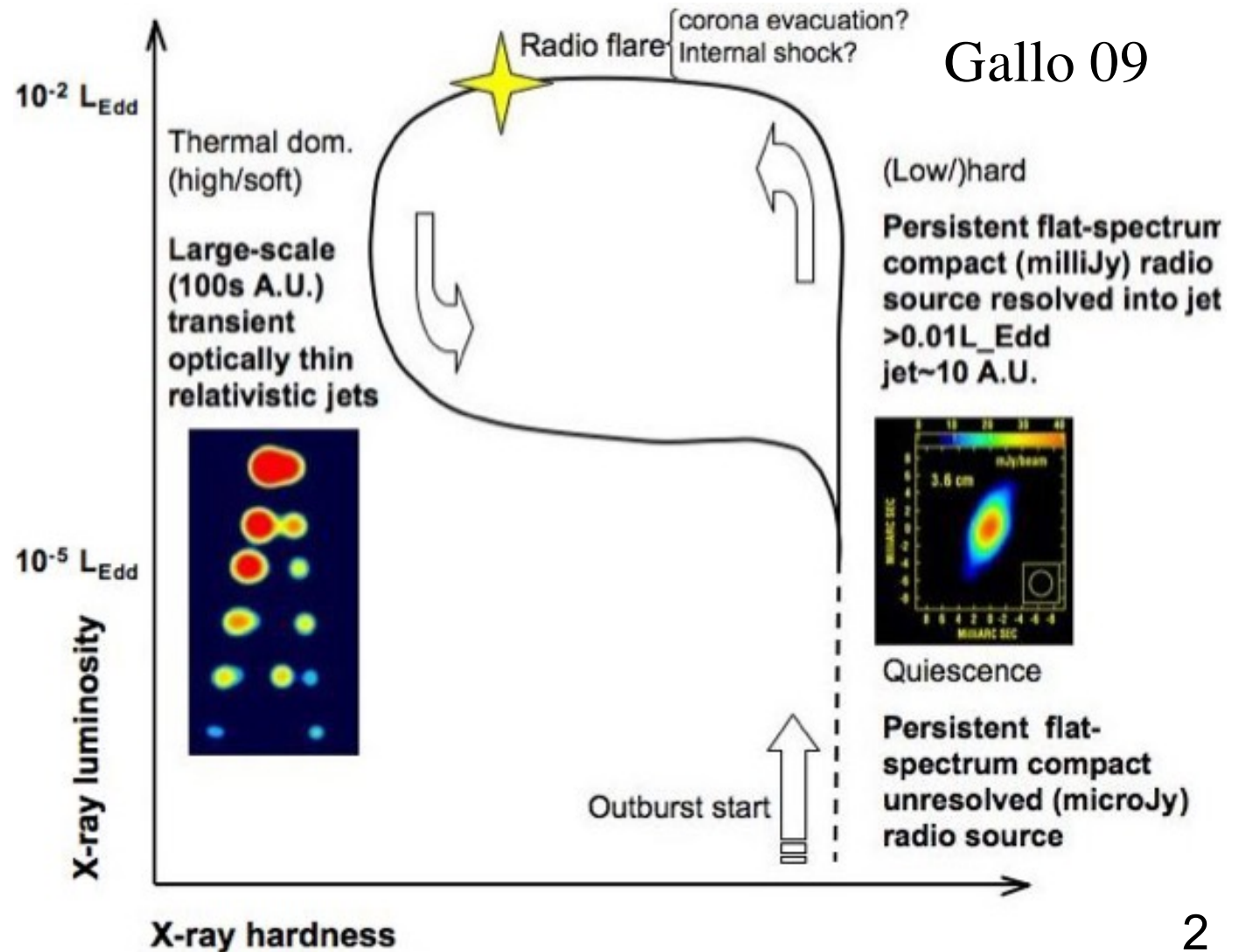
microquasars

MICROQUASAR



Mirabel & Rodriguez 98

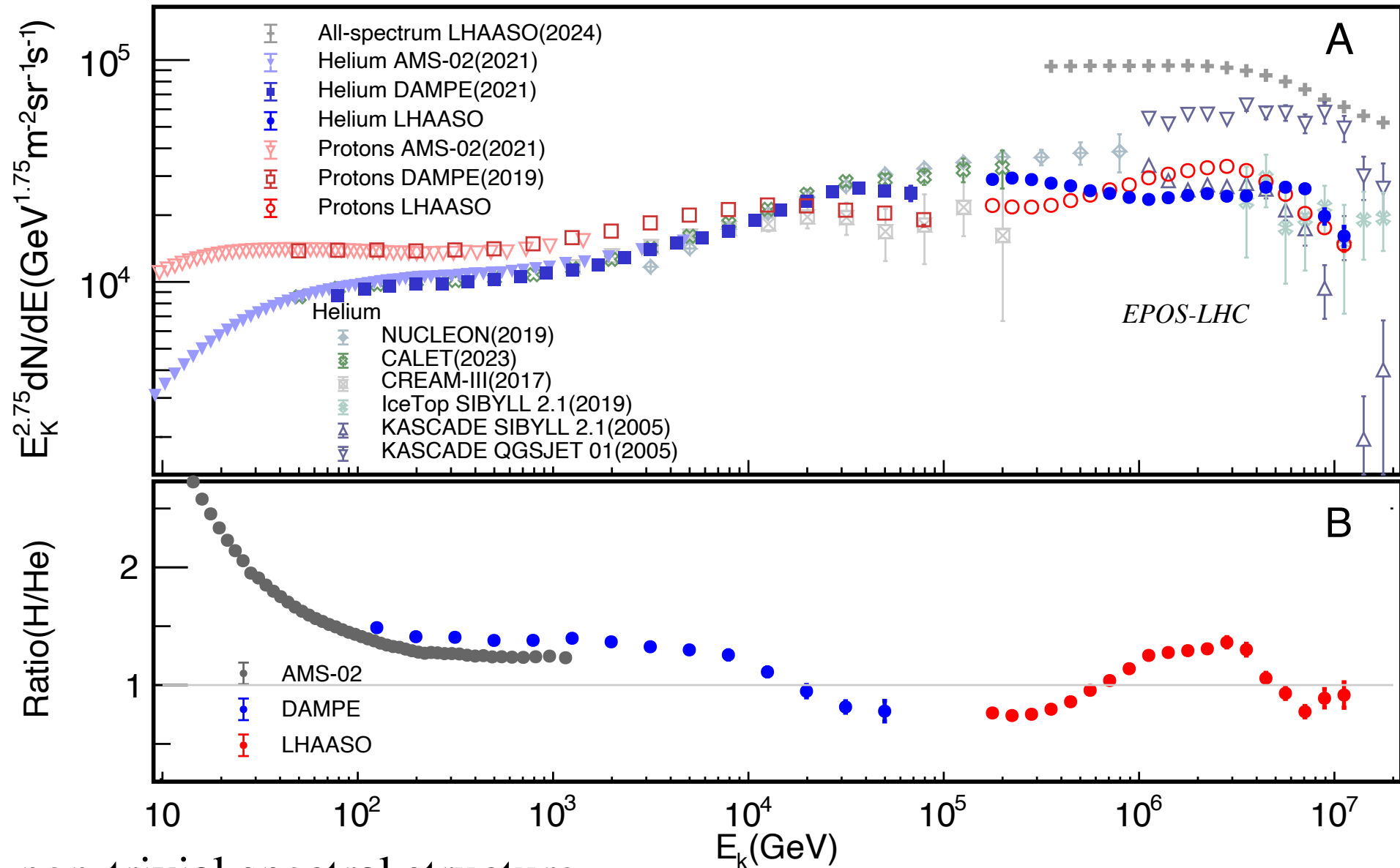
probe of jet-disk connection:
timescales much faster than AGN,
allow study of state transitions
(but challenging to get good
observational coverage)



Gallo 09

cosmic ray spectra up to PeV range

LHAASO Col.
2511.05013



non-trivial spectral structure

different trends of p/He at low E vs high E

single source population strongly disfavored

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.	H 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	H 6.2 ± 0.7^{34}	J1819-2541	8.1	2.67 ± 0.27	40 – 1000	0.36°	3.9
GRS 1915+105	L 9.4 ± 0.6^{35}	J1914+1049	6.1	3.07 ± 0.15	25 – 400	0.33°	0.17
MAXI J1820+070	L 2.96 ± 0.33^{36}	J1821+0726	5.9	3.19 ± 0.29	25 – 400	< 0.28°	0.13
Cygnus X-1	H 2.2 ± 0.2^{37}	J1957+3517	4.0	4.07 ± 0.35	25 – 100	< 0.22°	< 0.01
XTE J1859+226	L 4.2 ± 0.5^{38}	–	1.9	–	–	–	< 0.03
GS 2000+251	L 2.7 ± 0.7^{39}	–	1.7	–	–	–	< 0.04
CI Cam	H $4.1^{+0.340}_{-0.2}$	–	1.4	–	–	–	< 0.03
GRO J0422+32	L 2.49 ± 0.3^{41}	–	0.8	–	–	–	< 0.01
V404 Cygni	L 2.39 ± 0.14^{42}	–	0.5	–	–	–	< 0.02
XTE J1118+480	L 1.7 ± 0.1^{43}	–	0	–	–	–	< 0.01
V616 Mon	L 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⁻²s⁻¹

^c the combined detection significance for the two point-like sources is 12.9σ .

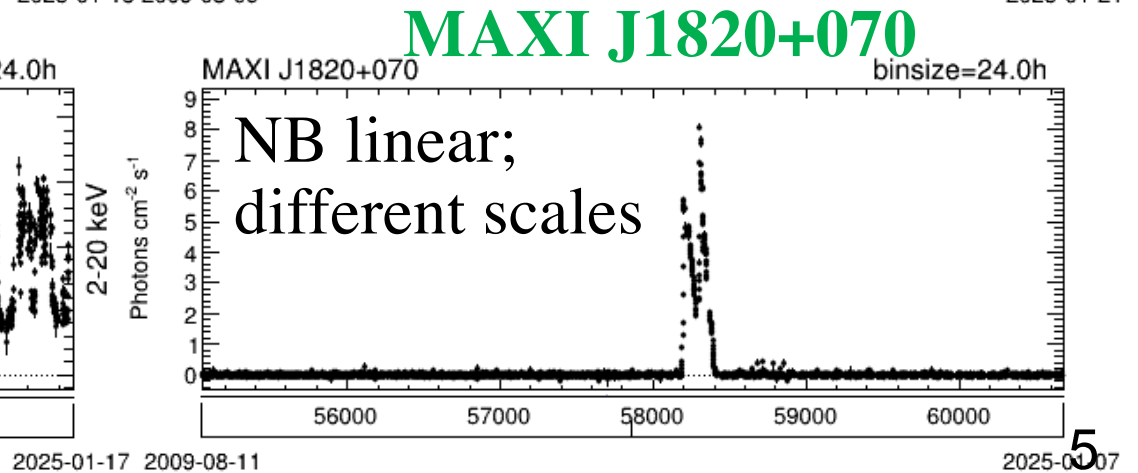
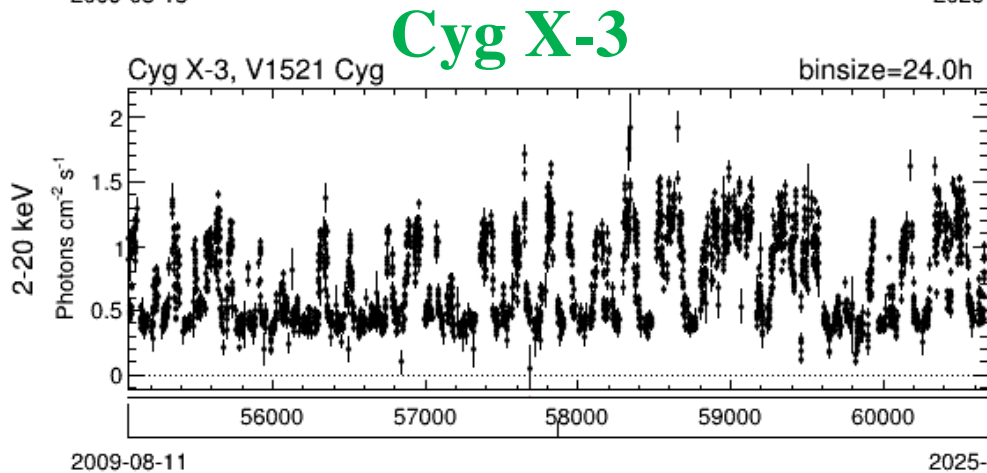
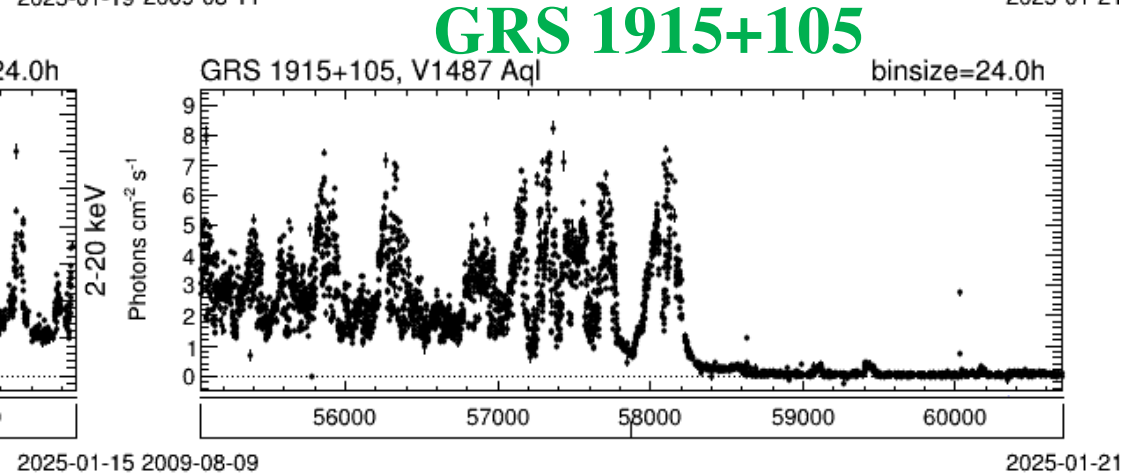
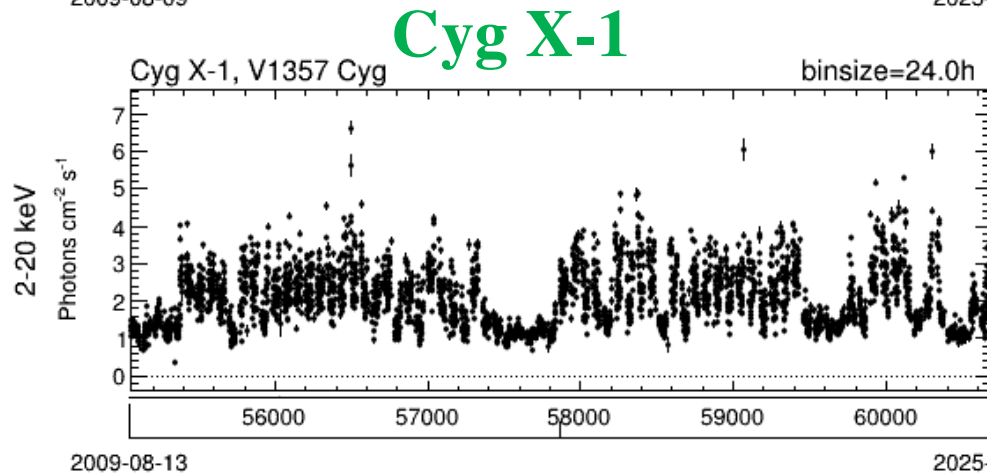
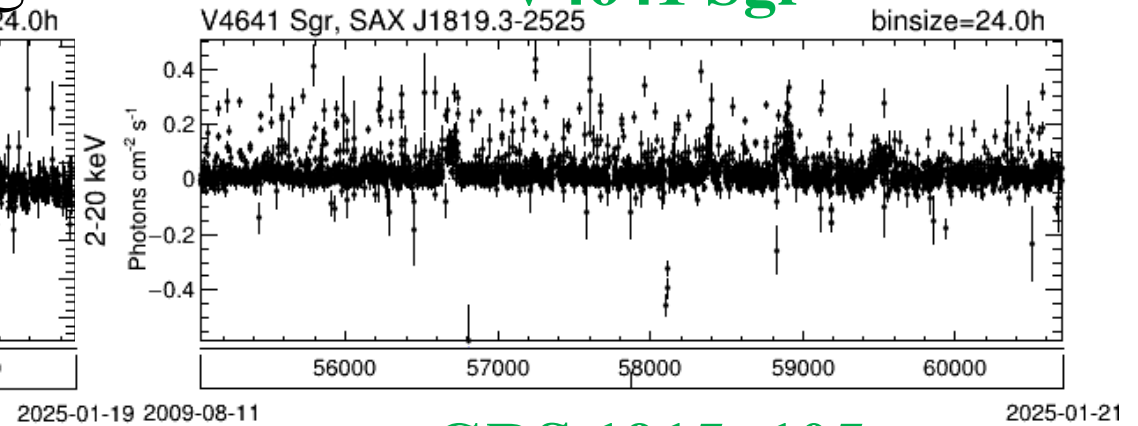
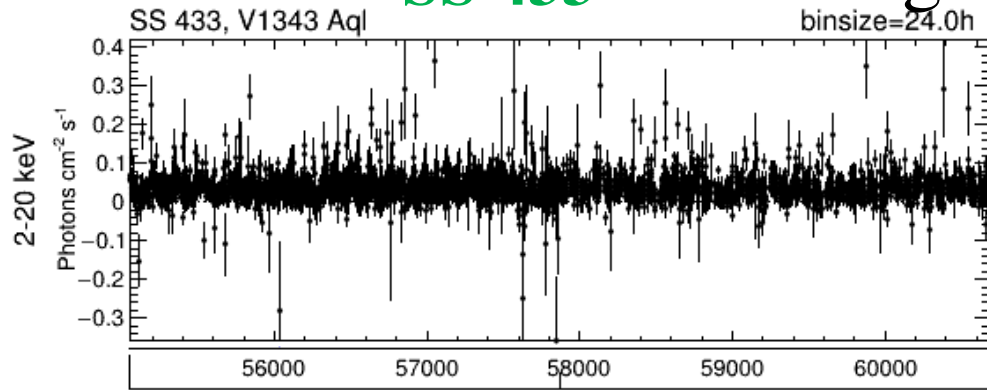
Table 1: LHAASO’s measurement of Galactic BH-jet systems in the field of view.
+ Cyg X-3 H (detection open secret, some info in arXiv source file)

diverse types (HM/LMXB, persistent/transient): condition for PeV unclear

Iwakiri-san: “Looks randomly selected, makes no sense...”

microquasar zoo @PeV vs X-ray (central object)

SS 433 MAXI light curves 2009-V4641 Sgr



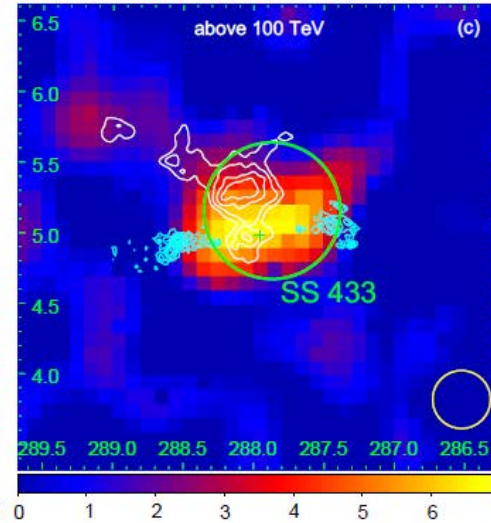
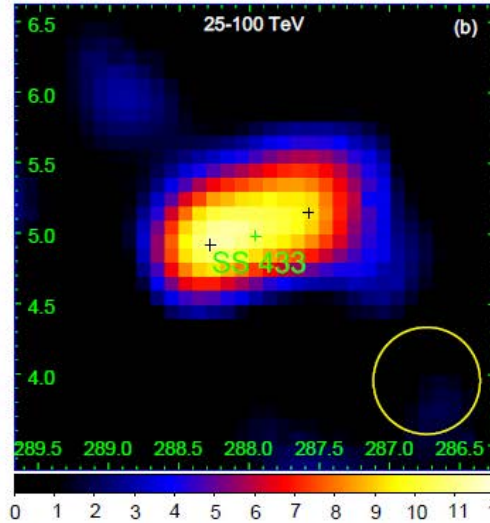
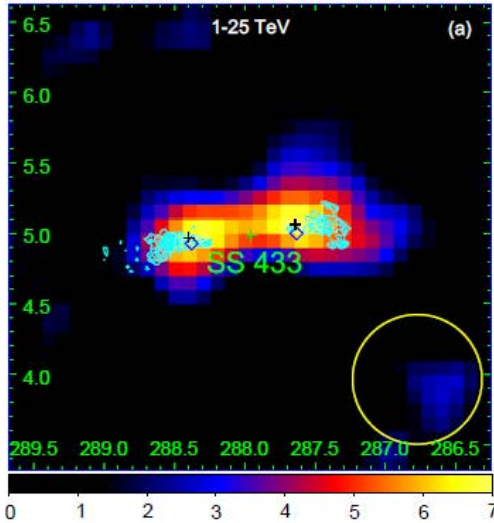
NB linear;
different scales

microquasar zoo @PeV

LHAASO Col. 2410.08988

SS 433 H

Cyg X-3 H



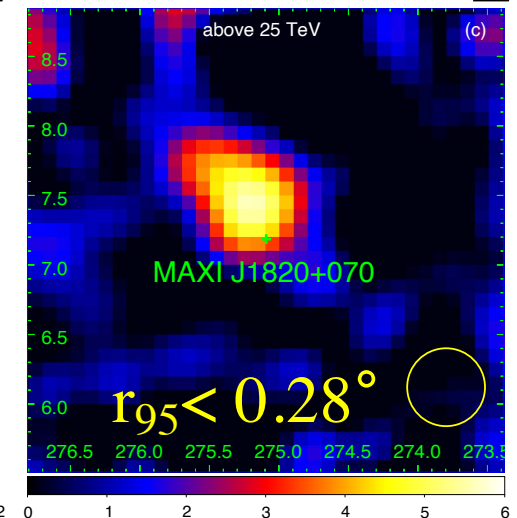
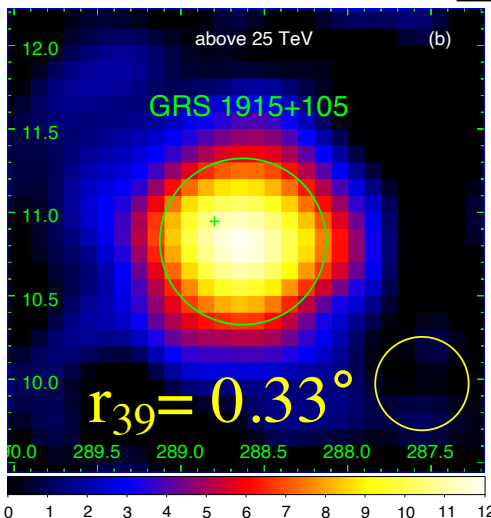
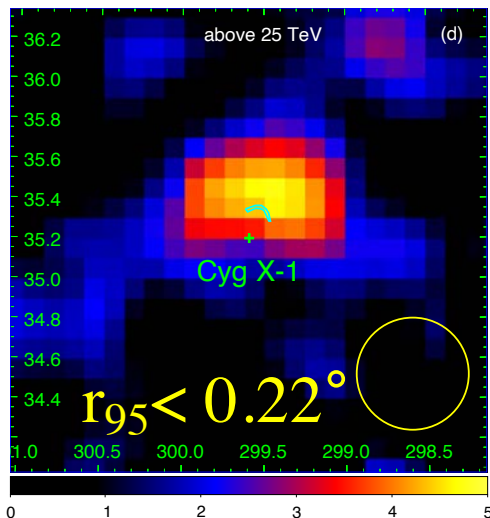
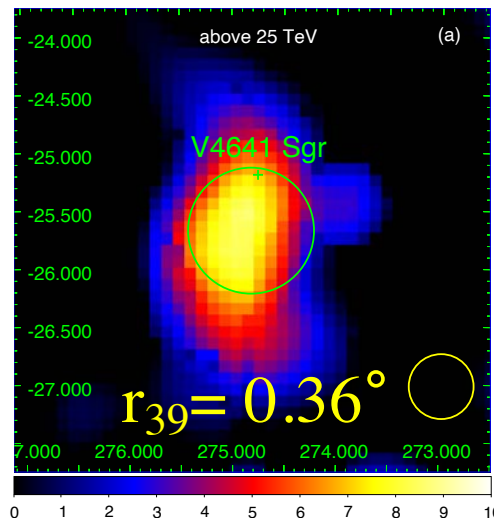
variable ->
likely partly
~<AU?
LHAASO Col.
in prep.

V4641 Sgr H(I?)

Cyg X-1 H

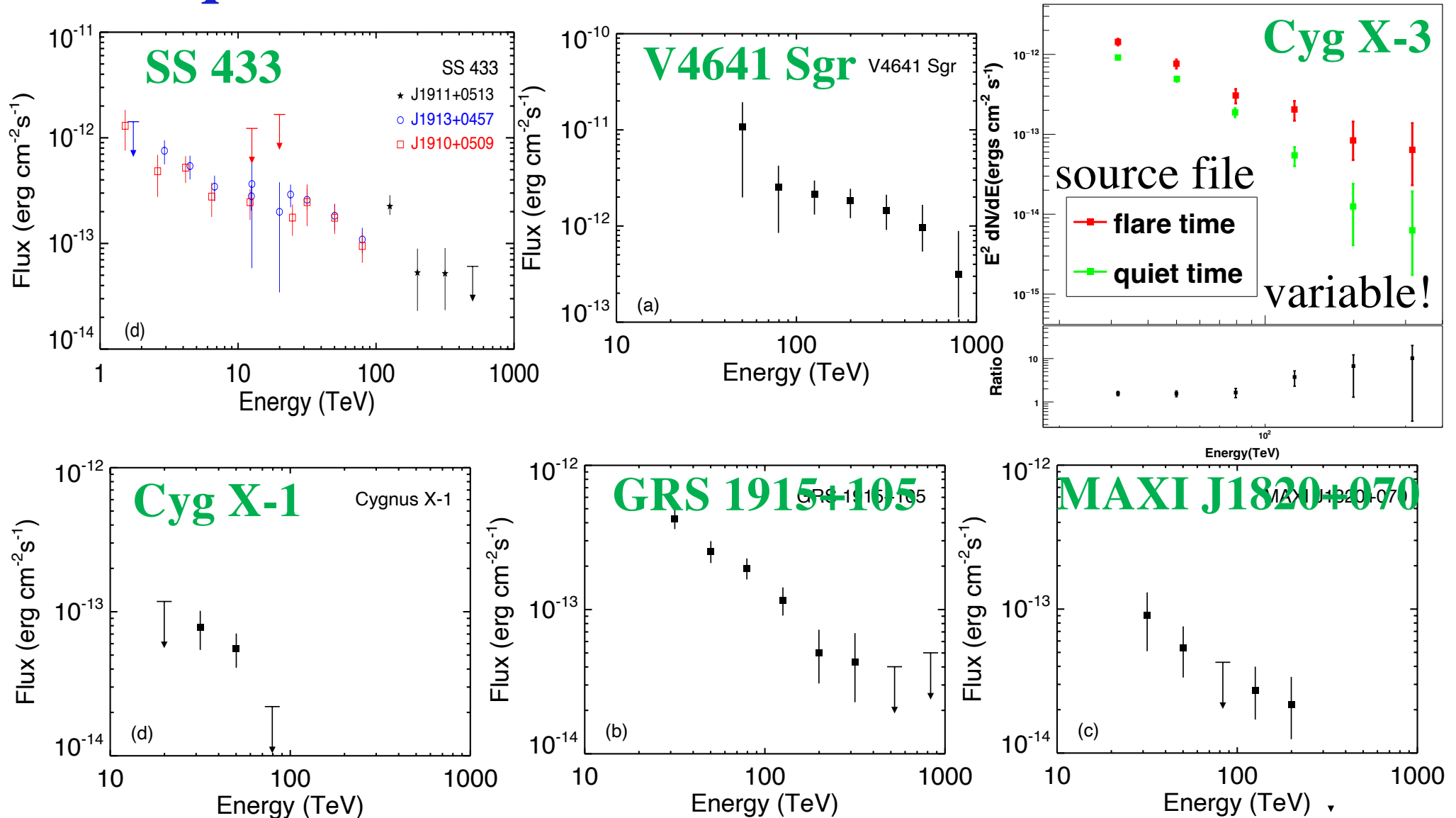
GRS 1915+105_L

MAXI J1820+070_L



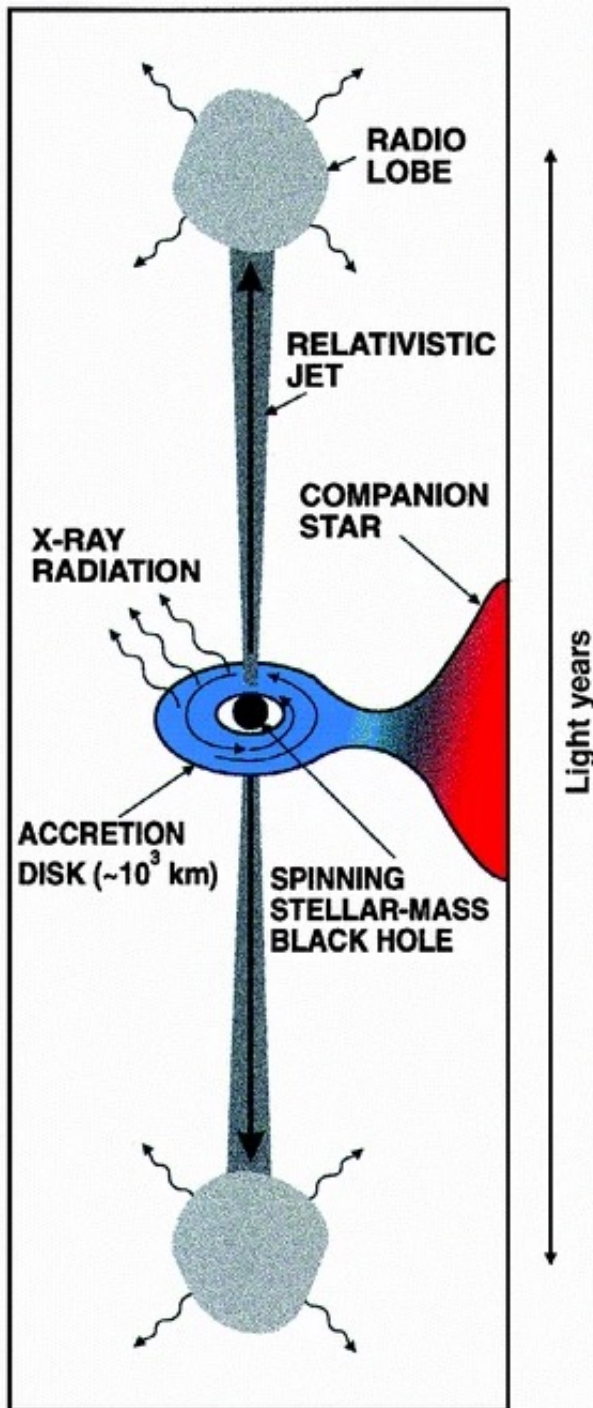
many spatially extended ~100 pc (correlation with other bands unclear)
some consistent with point source (but limited statistics)
diverse particle acceleration and/or emission sites? -> IACT followup 6

microquasar zoo @PeV LHAASO Col. 2410.08988



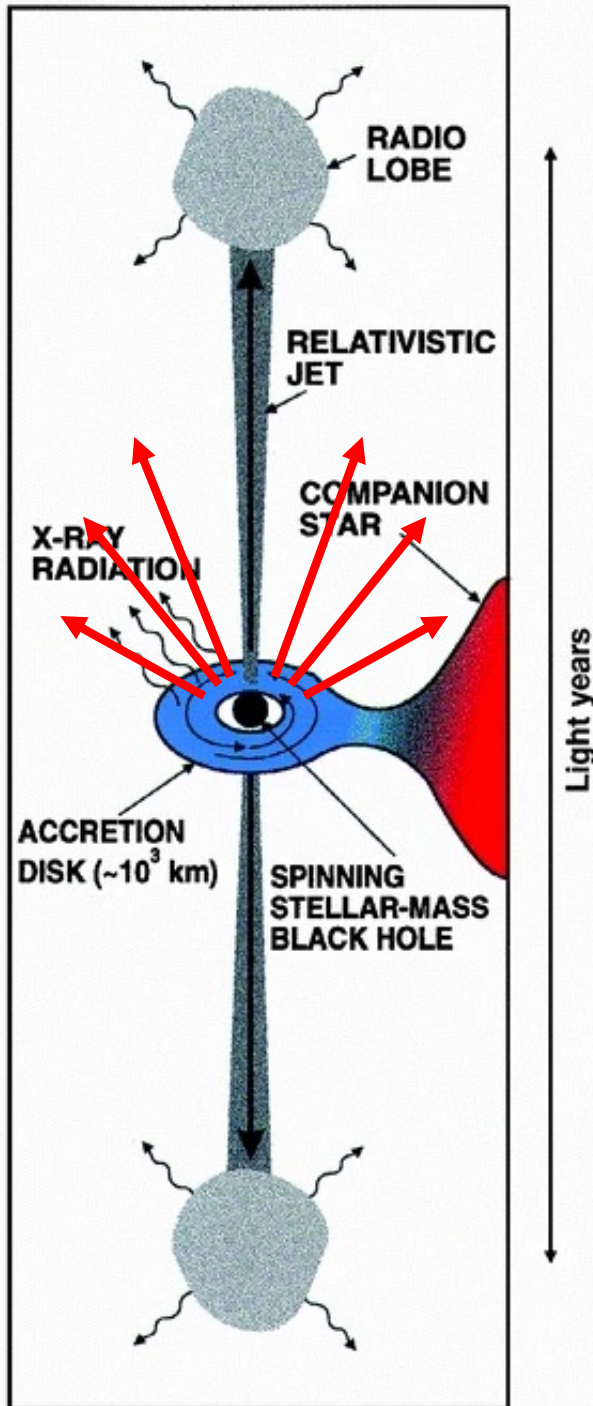
no clear evidence for spectral cutoffs (so far)
 no time variability (so far)... except Cyg X-3!
 ν fluxes not high unless gamma rays significantly absorbed

microquasars: potential particle acceleration sites



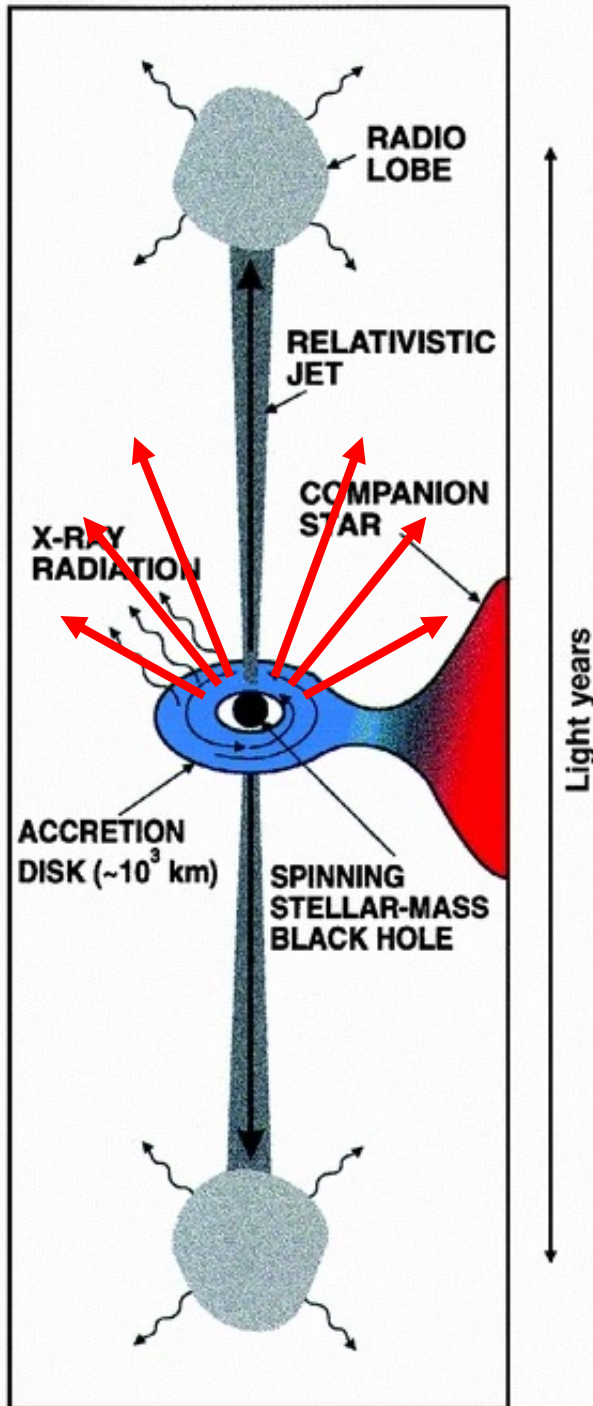
- disk corona
- jet internal shocks
- jet termination shocks
- jet + stellar wind (HMXB)

microquasars: potential particle acceleration sites



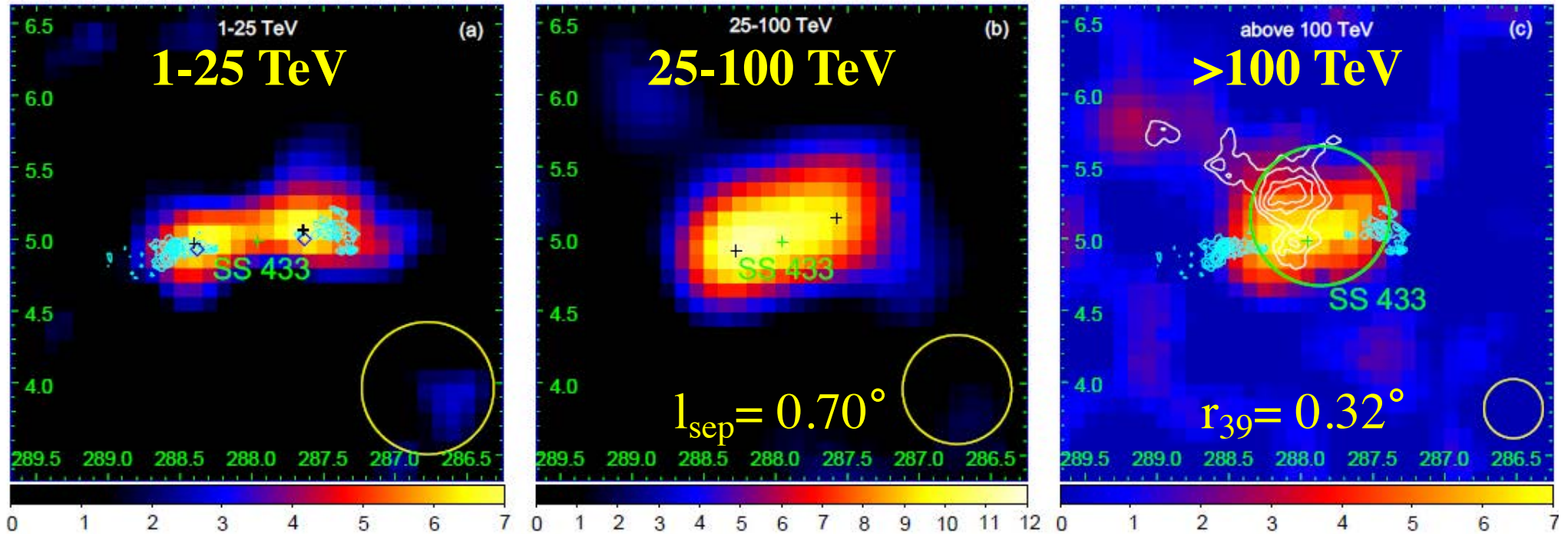
- disk corona
- jet internal shocks
- jet termination shocks
- jet + stellar wind (HMXB)
- disk wind internal shocks
- disk wind termination shocks
- disk wind + stellar wind (HXMB)
- disk wind + companion star

microquasars: potential particle acceleration sites



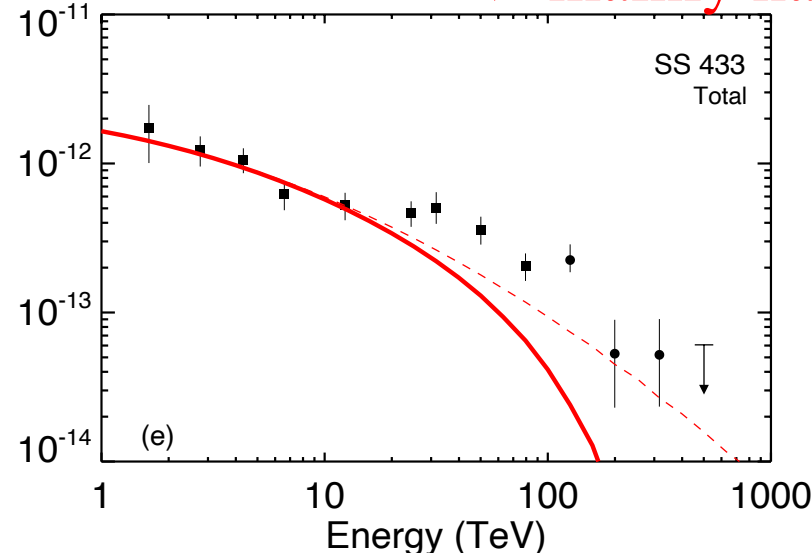
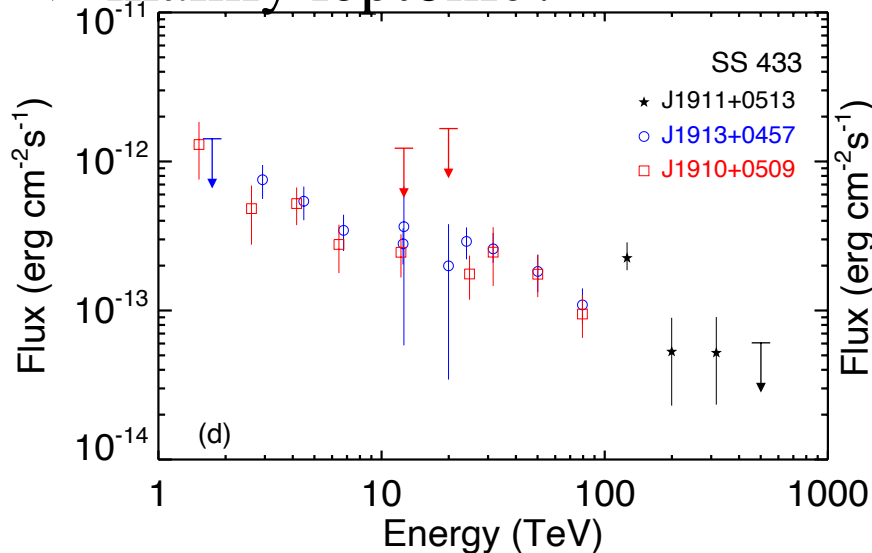
- disk corona
- jet internal shocks
- jet termination shocks
- jet + stellar wind (HMXB)
- disk wind internal shocks
- disk wind termination shocks
- disk wind + stellar wind (HXMB)
- disk wind + companion star

NB: absence of high ν absorption features
= absence of ultra fast winds? e.g. GX 13+1
 $\neq$ absence of clumpy ultra fast winds!
c.f. as in AGN PDS 456 XRISM Col. 25a,b



more correlated with X-ray jet
-> mainly leptonic?

more correlated with HI?
-> mainly hadronic?



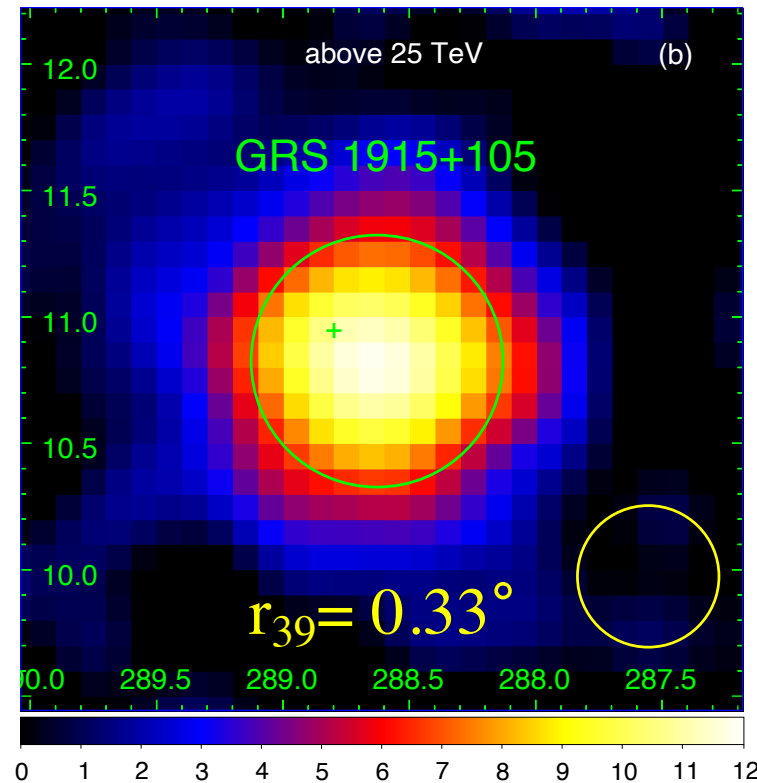
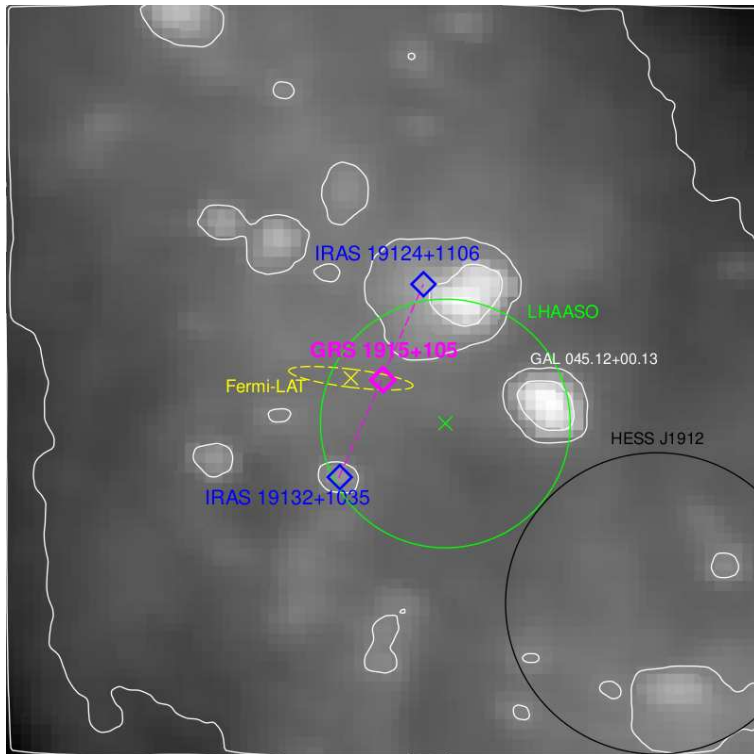
possible
evidence
of enhanced
confinement

12.9 σ (total), up to ~ 300 TeV

nature of acceleration site? 9

GRS 1915+105

LHAASO Col. 2410.08988



LHAASO: $r > \sim 50$ pc, consistent with ~ 80 pc separation of radio IR sources
 $\sim$ potential jet termination regions (bow shock structure Motta+ 25)

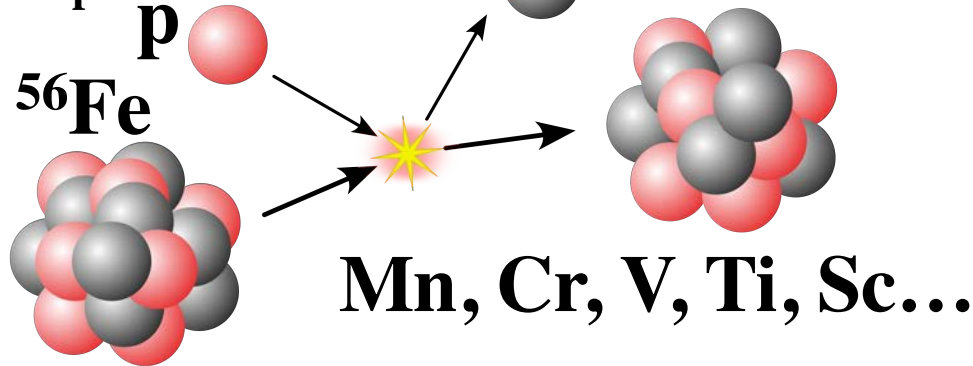
LAT: $r \sim < 10$ pc, consistent with point source; BH at edge of error region
no variability

spallation by hot thermal protons near BH

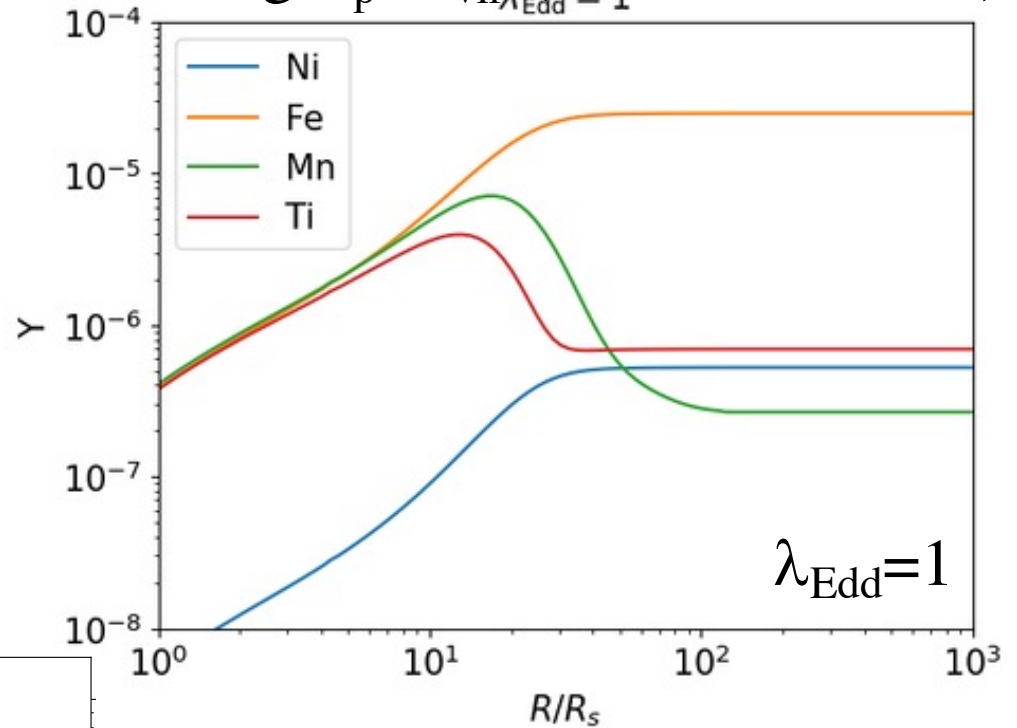
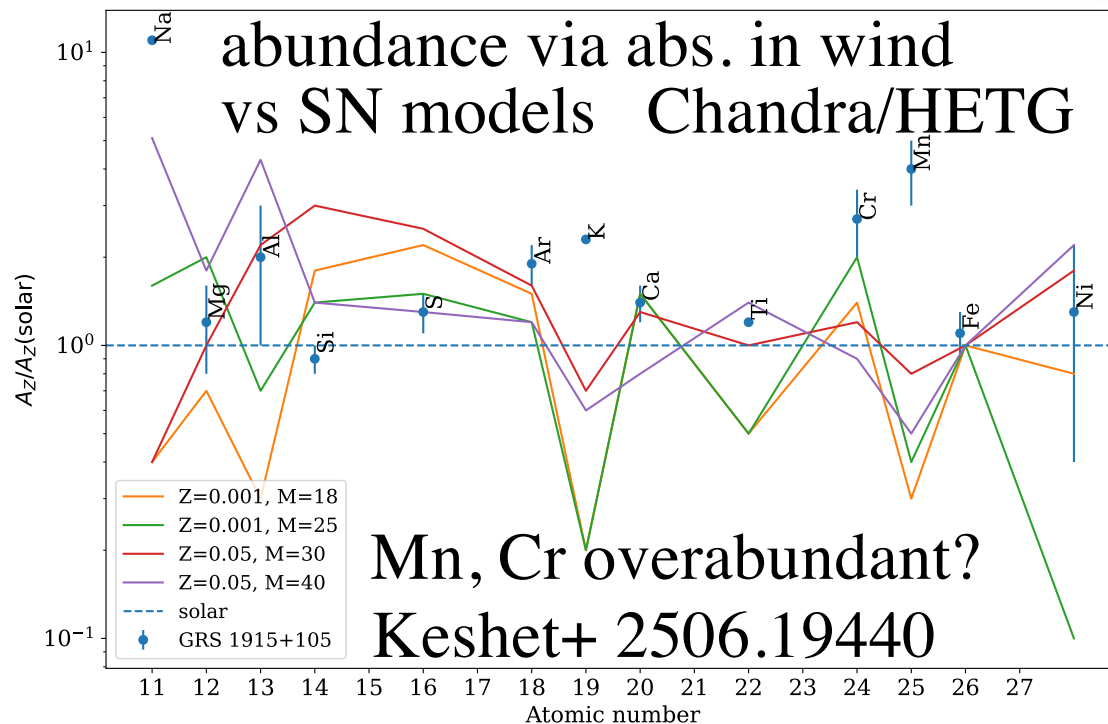
Ekanger, SI, Kimura+, in prep.

assuming $T_p \sim T_{\text{vir}}$ (corona or shock)

$E_k > \sim 10 \text{ MeV}$
($v_p > 0.15c$)

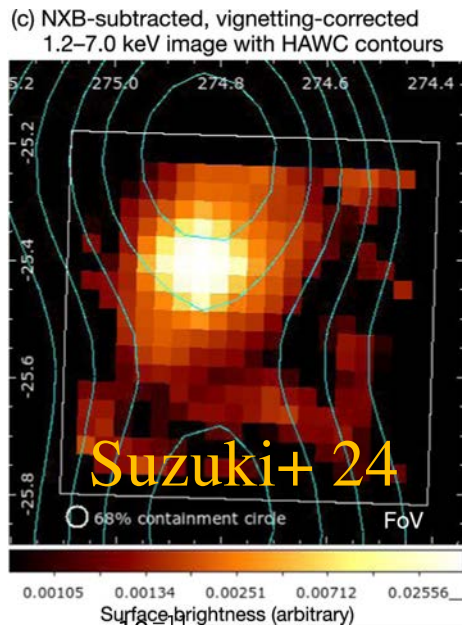
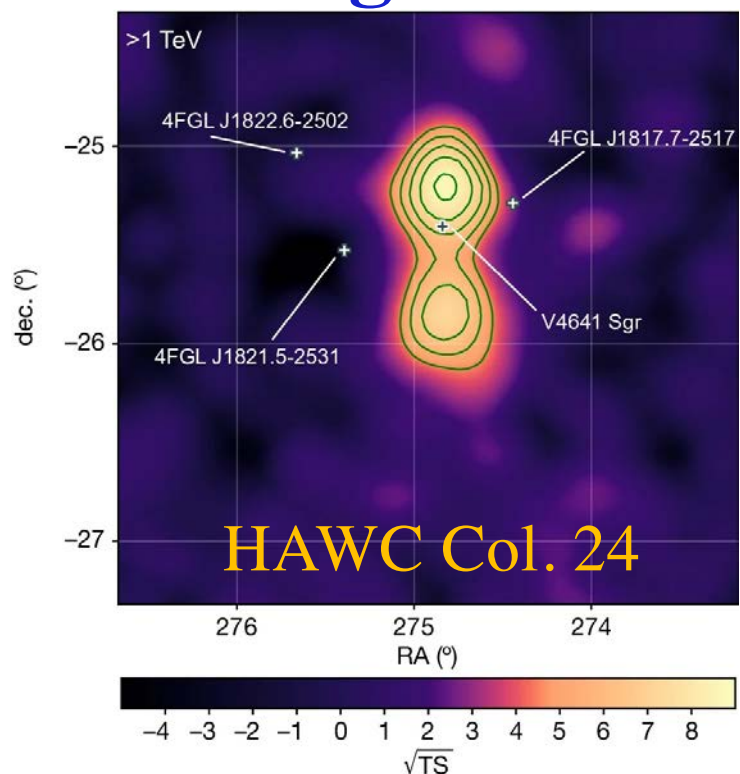


GRS 1915+105



abundance confirmed via emi.
with XRISM
Miller+ 2510.25089

V4641 Sgr: “micro Fermi bubble” pevatron



leptonic γ favored from SED

- $B < 3 \mu\text{G}$
- electron transport over 40 pc without energy loss?

electron accel. to $> 0.8 \text{ TeV}$

$\rightarrow$ proton accel. to $> 0.8 \text{ TeV}$

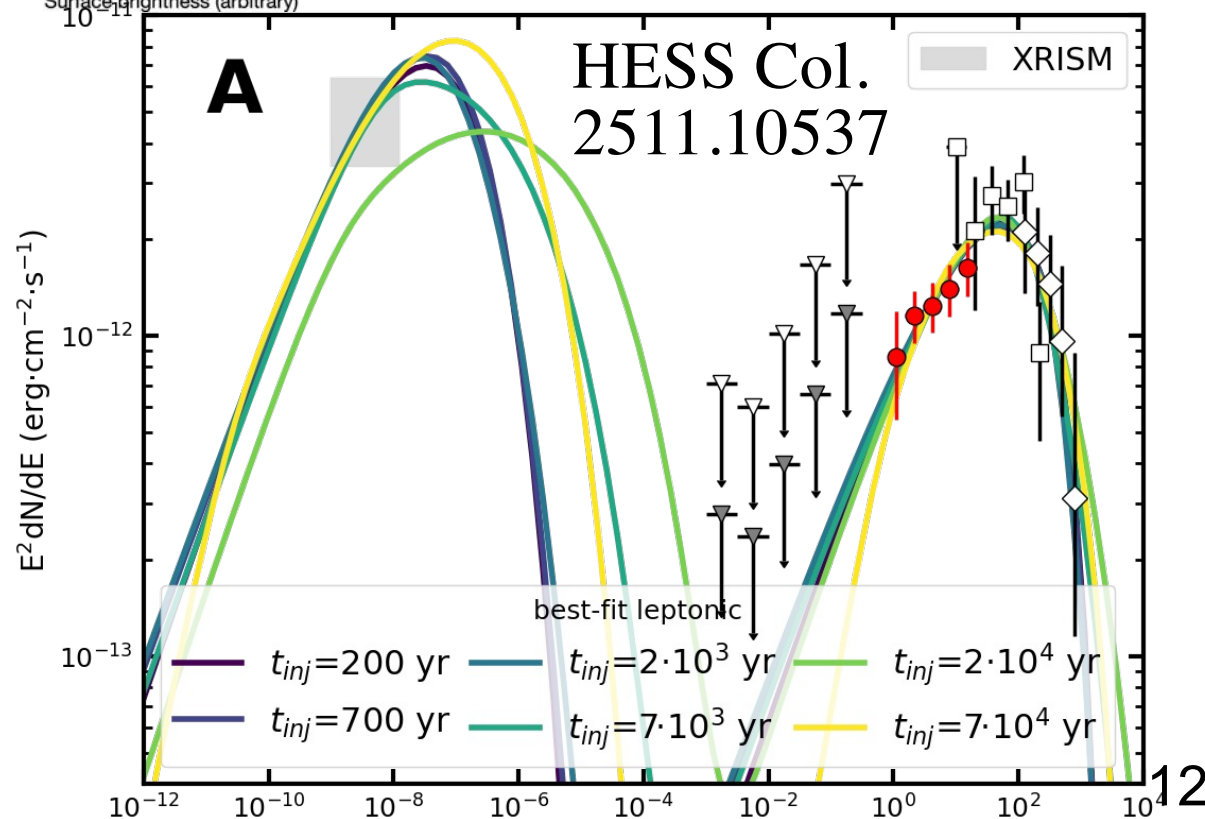
8.8σ , up to $\sim 200 \text{ TeV}$

extended $> \sim 80 \text{ pc}$

no obvious counterparts in GeV, X-ray, radio

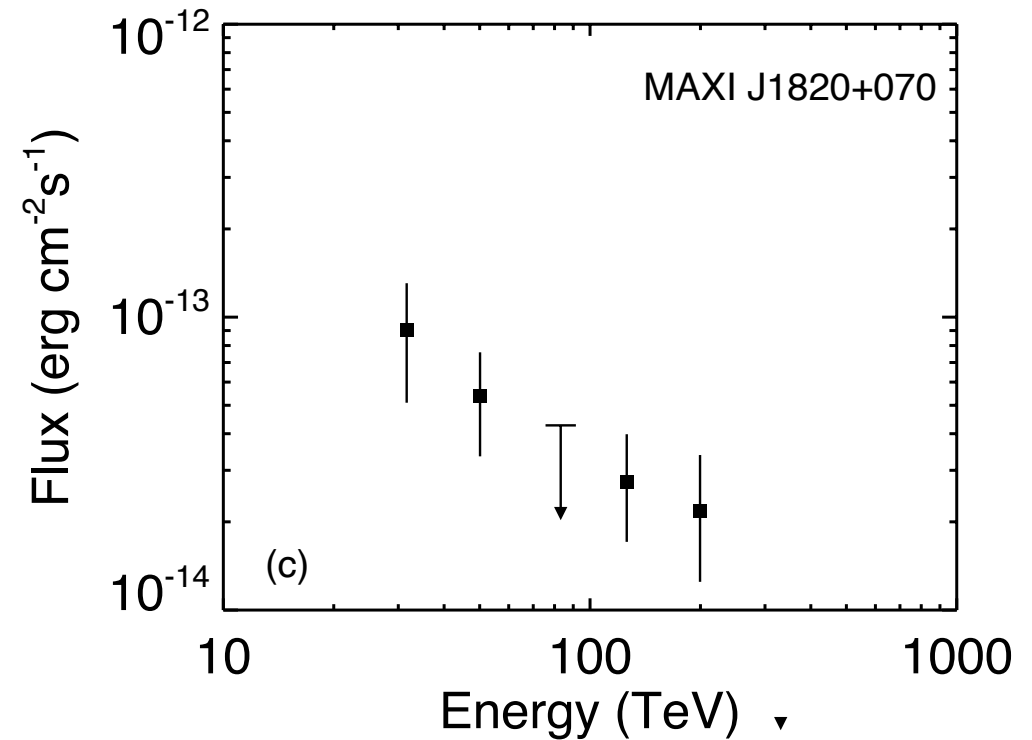
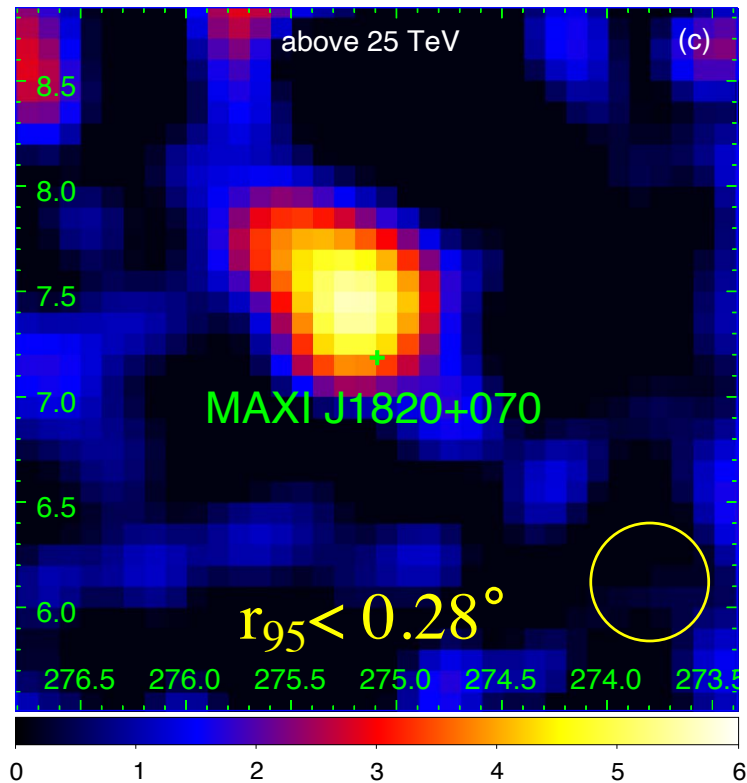
$\sim 500\text{--}600 \text{ pc}$ off Gal. Plane

$n_{\text{gas}} < 0.2 \text{ cm}^{-3}$



MAXI J1820+020: LHAASO

LHAASO Col. 2410.08988



5.9 σ , up to ~ 200 TeV

$r \sim < 15$ pc (consistent with point source) $\leftrightarrow$ SS 433, V4641 Sgr

offset in direction of sub-pc radio jet?

X-ray outburst from BH only around 2018

$\rightarrow$ $\sim$ yr timescale variability?

$\rightarrow$ some unidentified sources likely as yet unrecognized microquasars 13

summary: γ rays from microquasars and prospects

significant, surprising, mysterious, diverse results

- CR origin: strongest evidence yet for PeV hadron accelerator
SS 433 morphology >100 TeV TBC
possible first evidence for enhanced confinement of
hadrons near identified sources
viability as sources still open question
- unidentified TeV-PeV sources: some likely microquasar
(MAXI J1820 would be unID 8 years ago)
- mystery bubble: ~ 100 pc TeV-PeV structure without
obvious radio, X-ray, GeV counterparts (V4641 Sgr)
- mystery zoo: diverse types of microquasars
-> diversity of sites (large/small scales), processes?
- stay tuned for interesting CTA results in the near future!