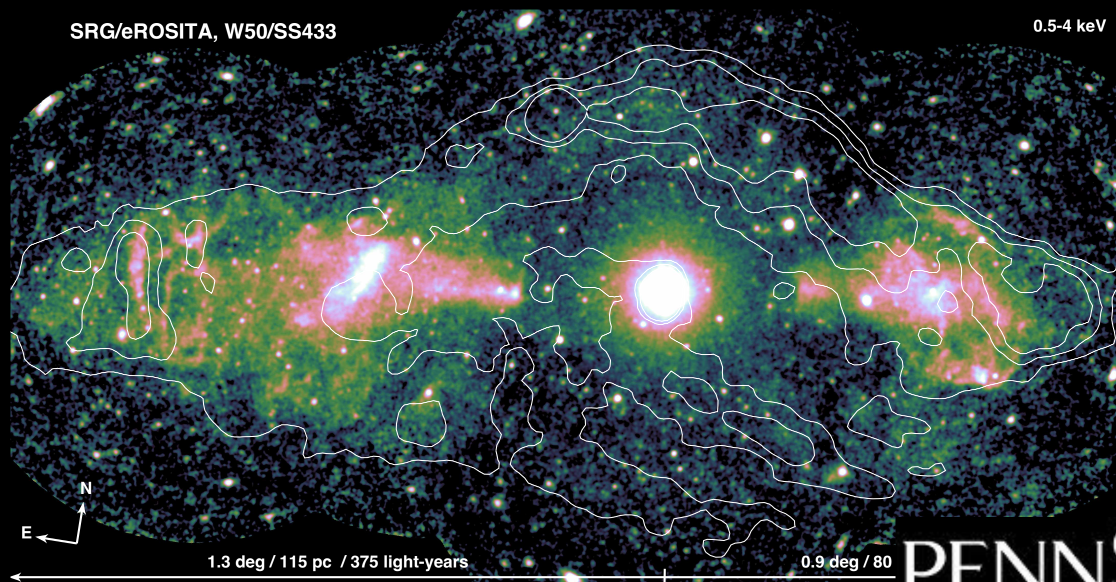
Diffuse Galactic Emission and Galactic Super-PeVatrons



PENNSTATE

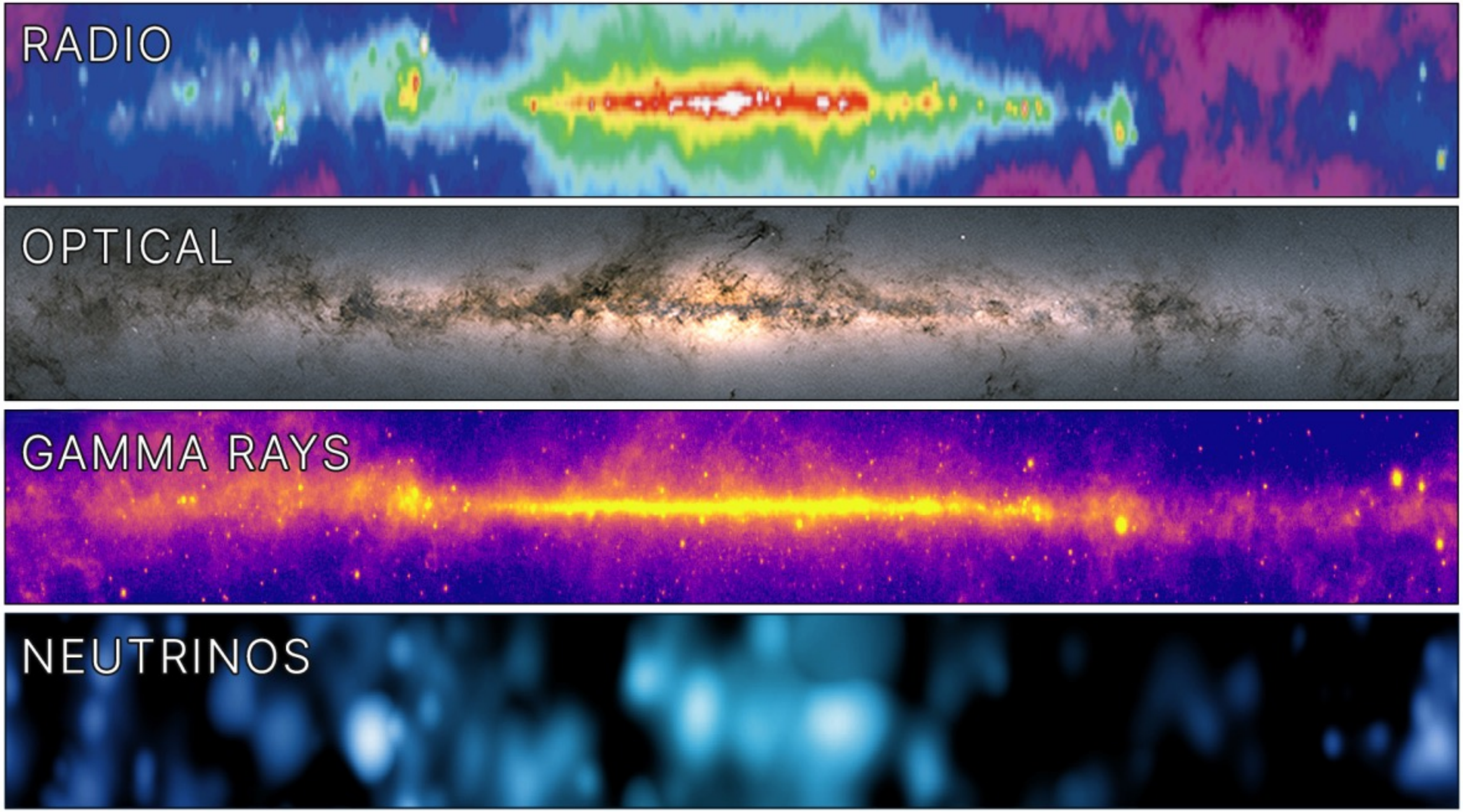
1855

Kohta Murase
(Penn State)

PEPS Workshop 2025

2023: Evidence of Neutrinos from the Milky Way

IceCube 23 Science



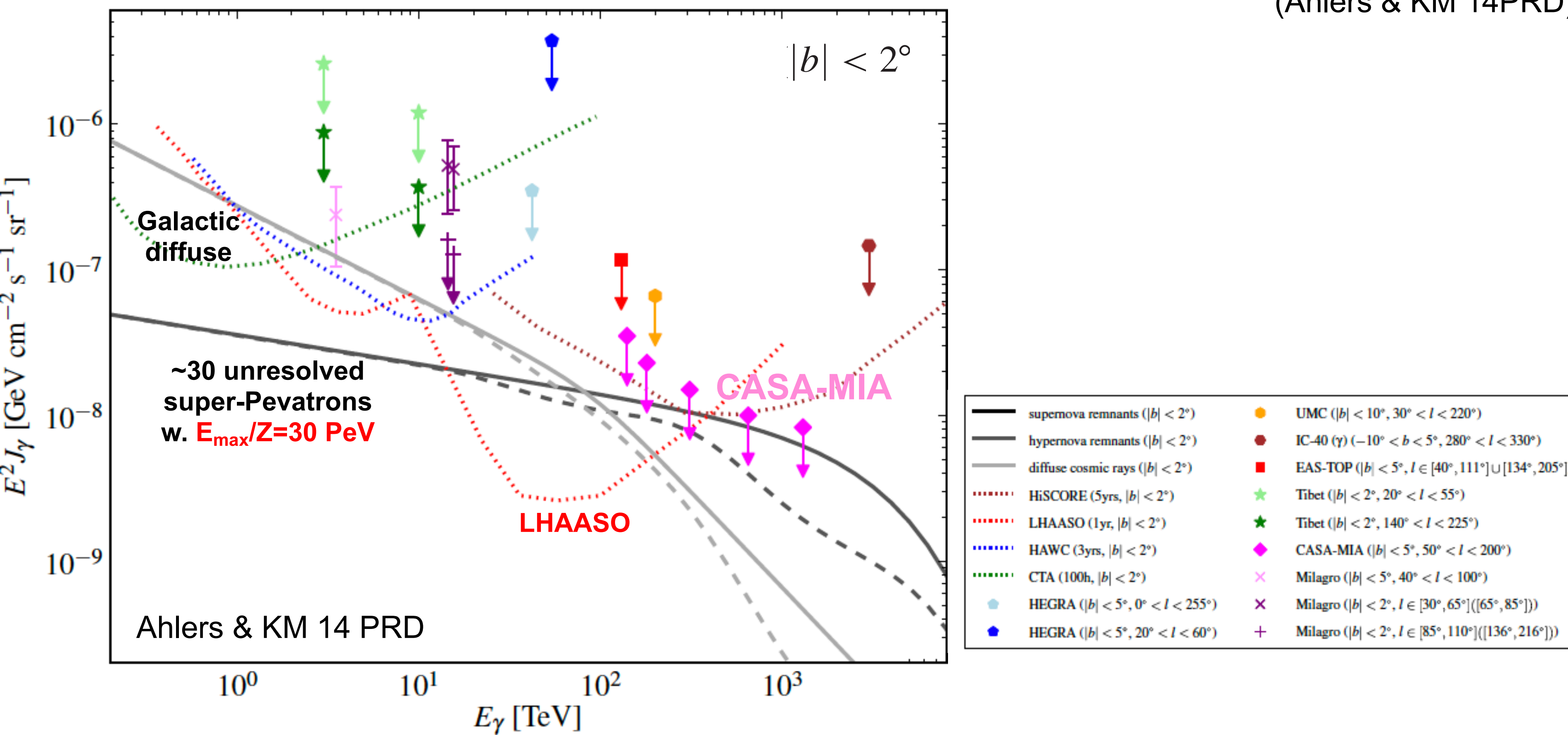
Neutrino emission from the Milky Way (~10% of total) has been observed w. 4.5σ

Galactic Multimessenger Connection: A Decade Ago

$p + p \rightarrow N\pi + X \quad \pi^0 : \pi^{\pm} \sim 1:2 \quad \rightarrow \mathbf{E_\gamma^2}\, \Phi_\gamma : \mathbf{E_\nu^2}\, \Phi_\nu \sim 2:3$

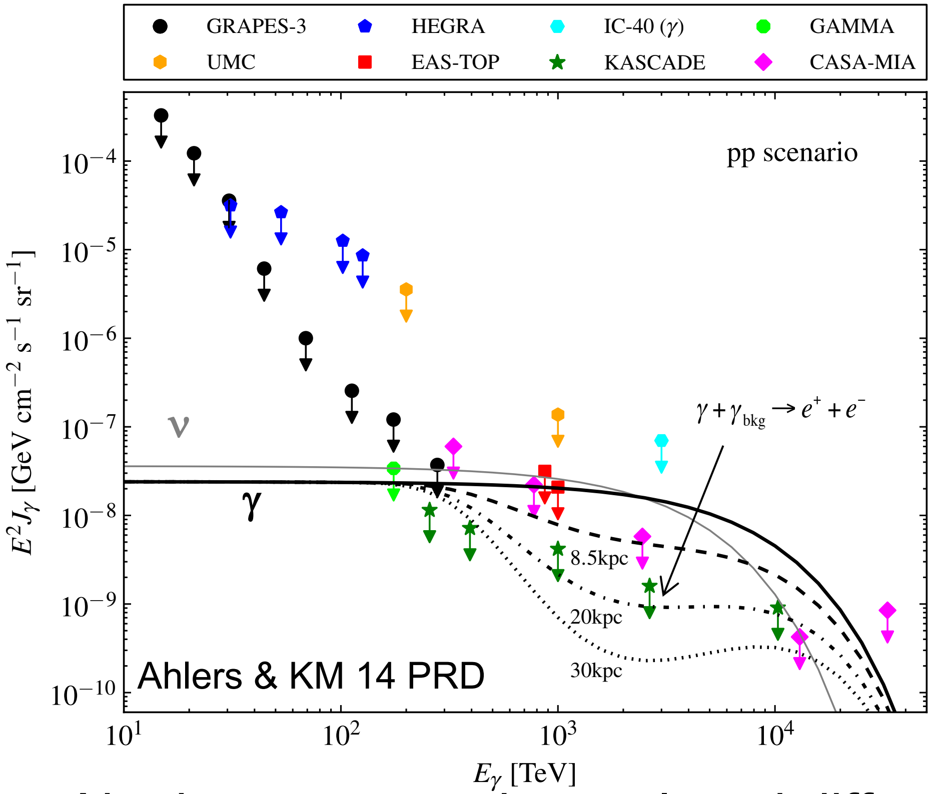
- Most γ rays from Galactic sources reach Earth
- Neither γ rays nor νs were NOT observed in the sub-PeV range a decade ago
- We already learned that Galactic contribution to IceCube νs is subdominant

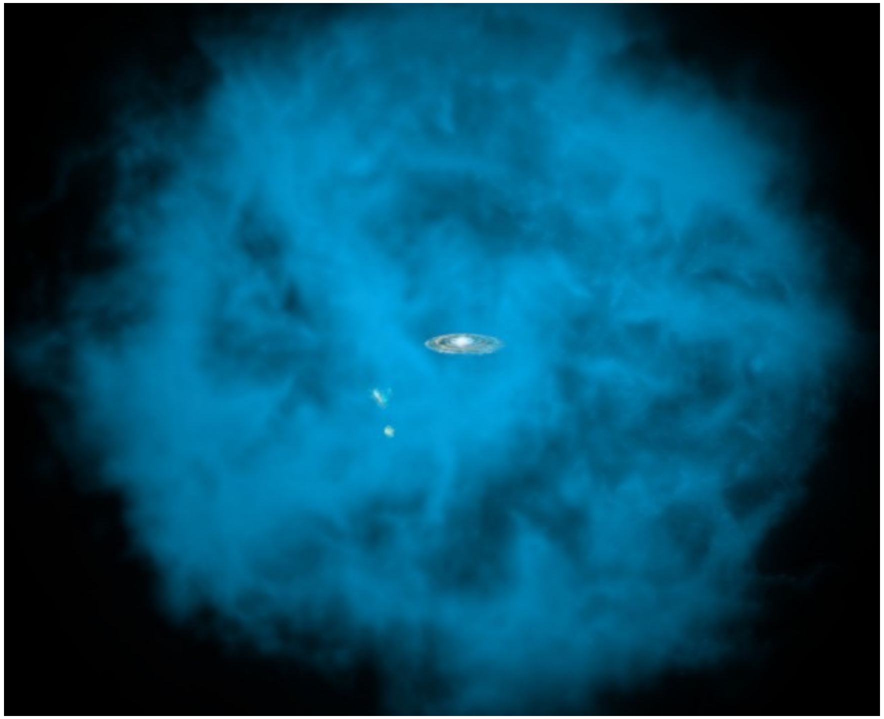
(Ahlers & KM 14PRD)



Galactic Multimessenger Connection: Halo Case

Quasi-isotropic limits (Galactic halo CR model)

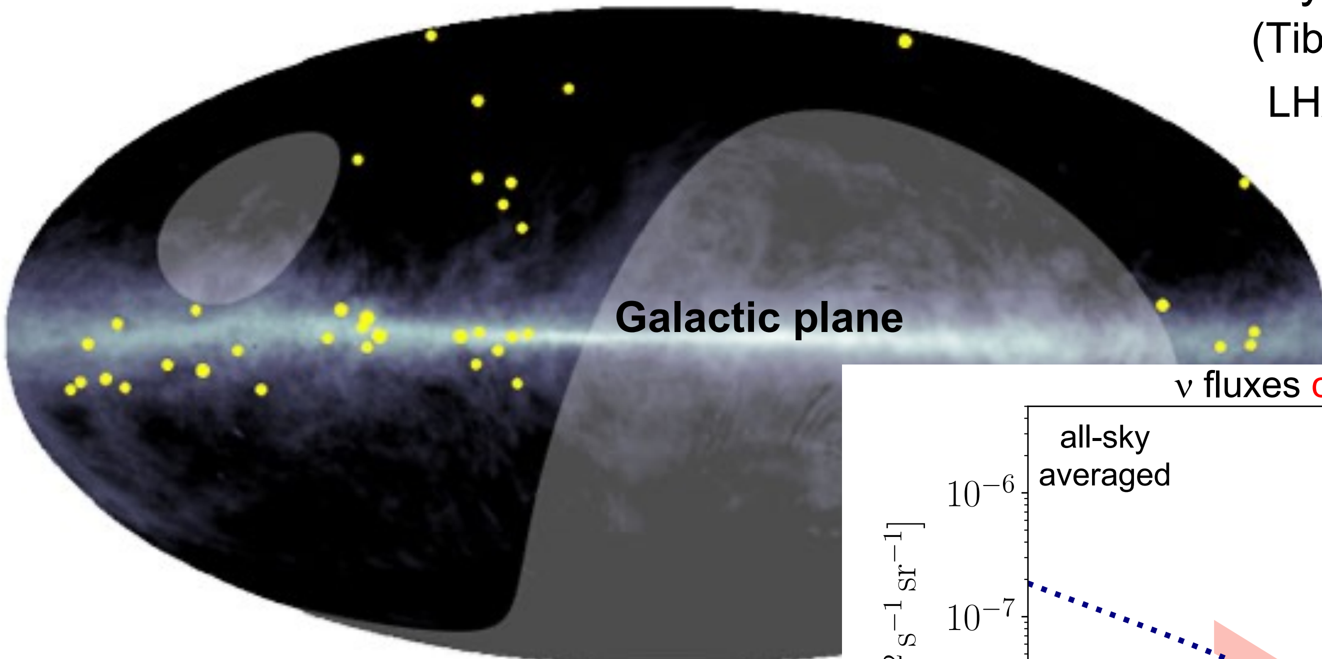




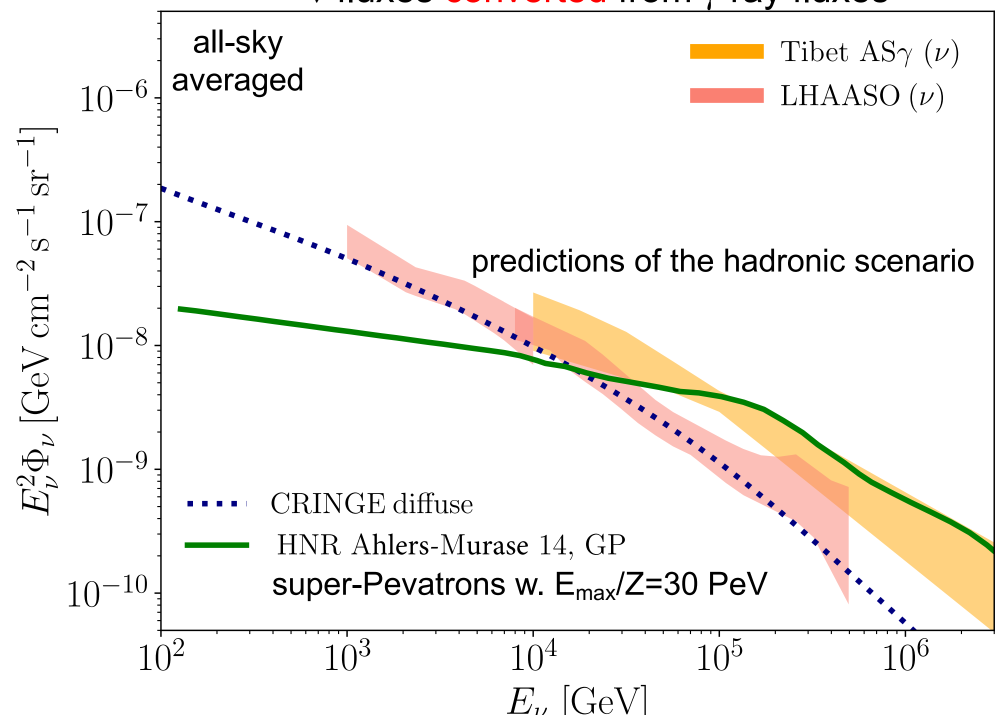
- Air-shower arrays have placed diffuse γ-ray limits at TeV-PeV
  Fermi γ-ray data imply $s_\nu < 2.0$ → extragalactic origins
  (KM Ahlers & Lacki 13 PRDR, KM, Guetta & Ahlers 16 PRL)
- Improved limits with PEPS?
  (related analyses: heavy dark matter searches)

Galactic Diffuse Sub-PeV Gamma Rays Are Seen

Discovery of sub-PeV γ rays in 2021
(Tibet ASγ Collaboration 21 PRL
LHAASO Collaboration 23 PRL)



ν fluxes converted from γ-ray fluxes



Fang & KM 21 ApJ, 23 ApJL

Galactic Diffuse Sub-PeV Gamma Rays Are Seen

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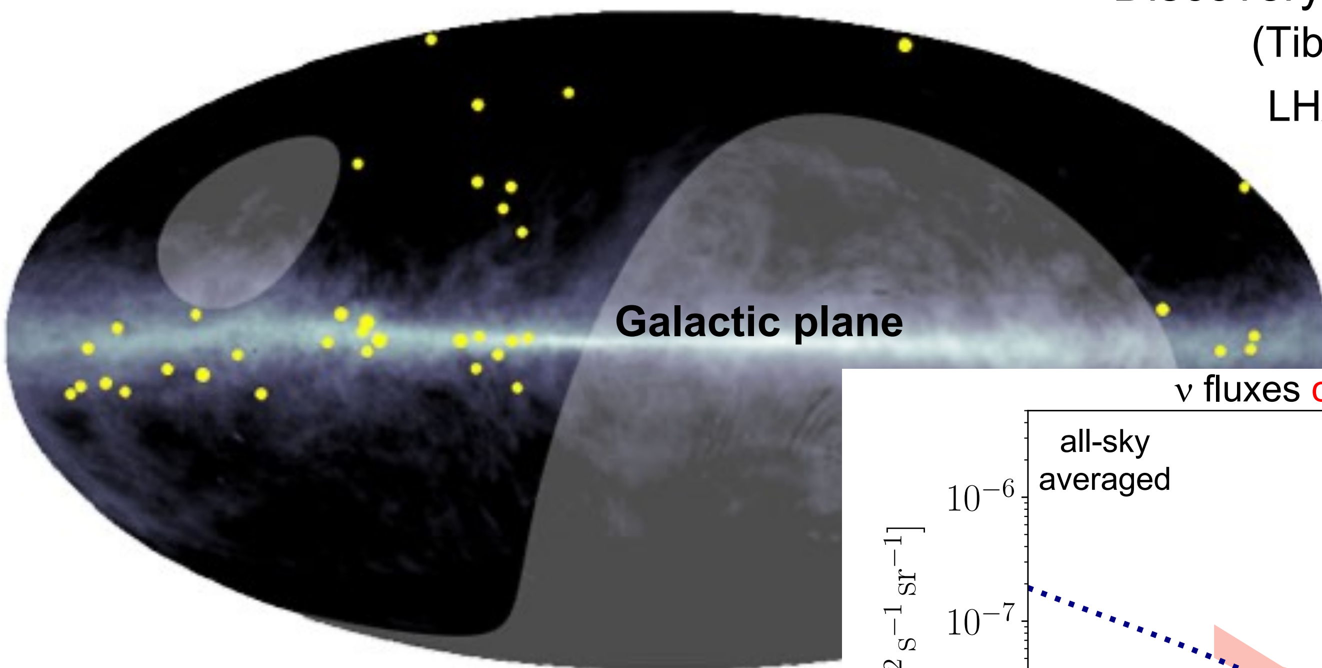
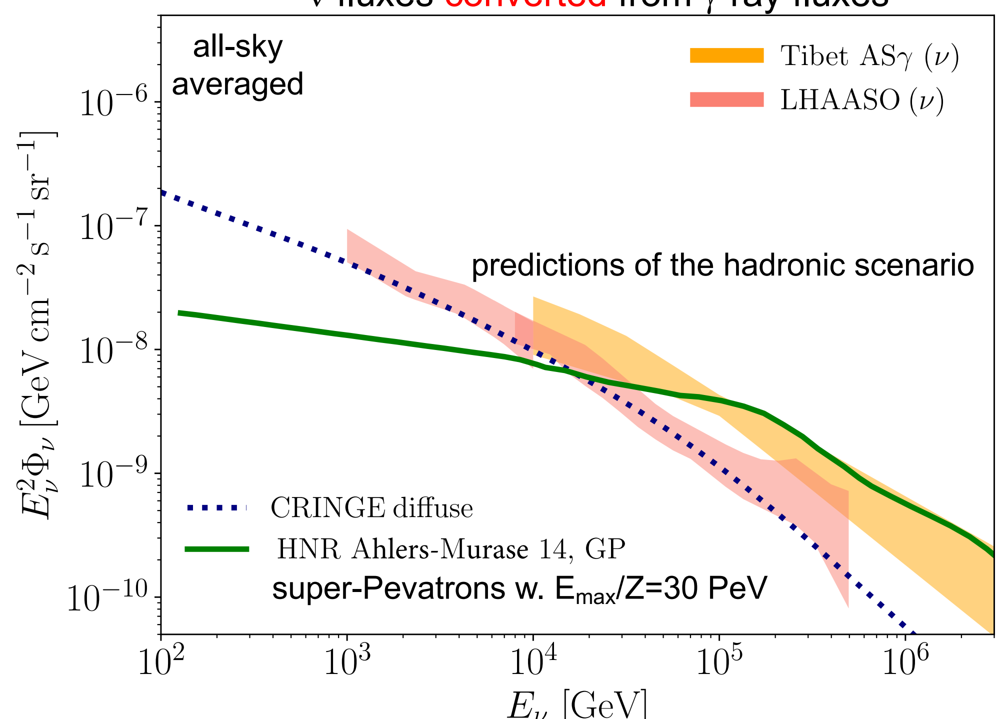


ν fluxes converted from γ-ray fluxes

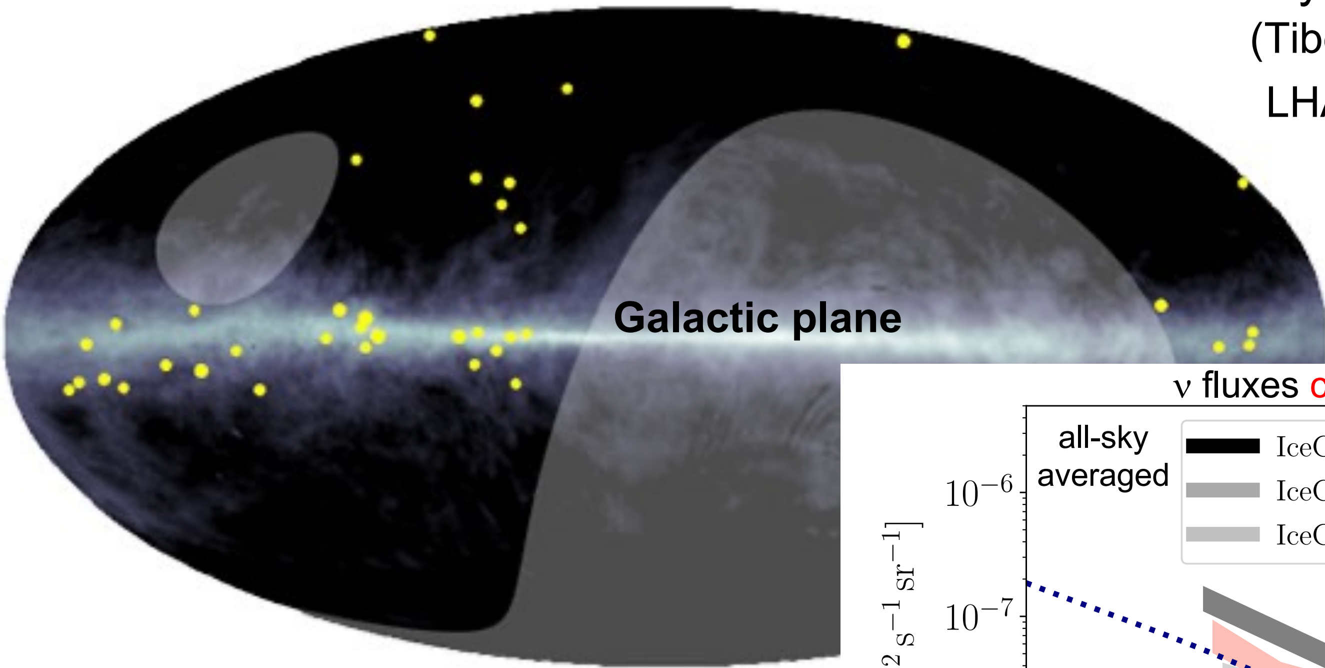


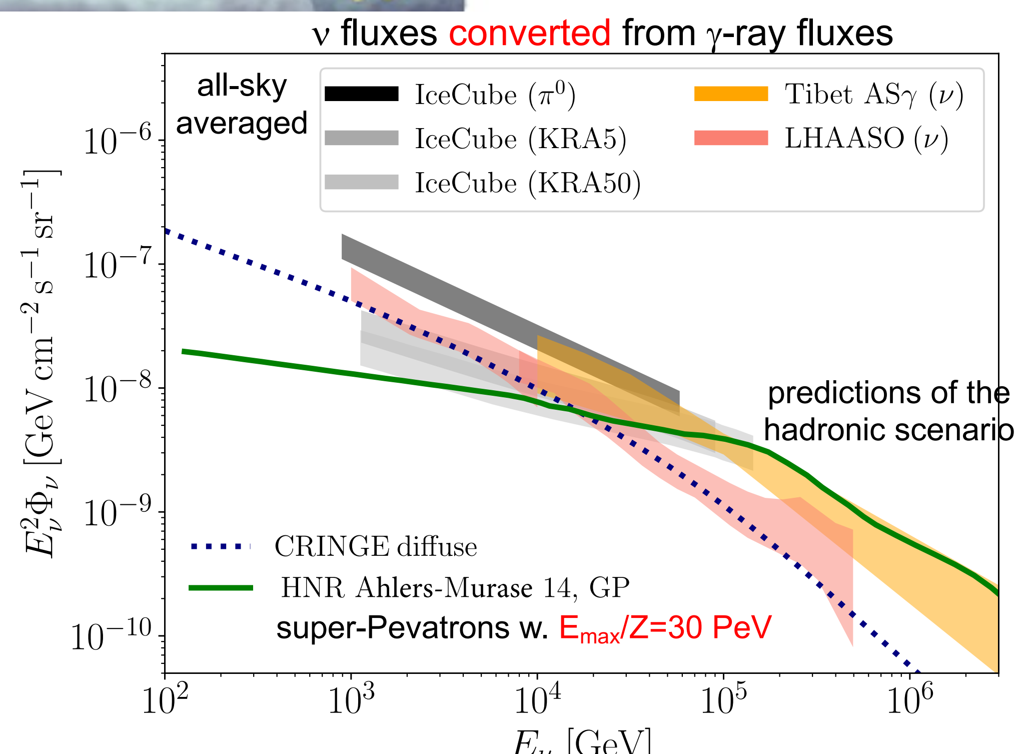
Fang & KM 21 ApJ, 23 ApJL

$$E_\nu^2 F_\nu^\Omega \approx \frac{3}{2}(E_\gamma^2 F_\gamma^\Omega)|_{E_\gamma=2E_\nu} \times \frac{\int ds \int \cos b\, db \int dl\, n_s(s,\, b,\, l)}{\int ds \int \cos b db \int dl\, n_s P_{\gamma,\mathrm{surv}}(E_\gamma = 2E_\nu,\, s,\, b,\, l)}$$

Galactic Multimessenger Connection: Current

Discovery of sub-PeV γ rays in 2021
(Tibet ASγ Collaboration 21 PRL
LHAASO Collaboration 23 PRL)



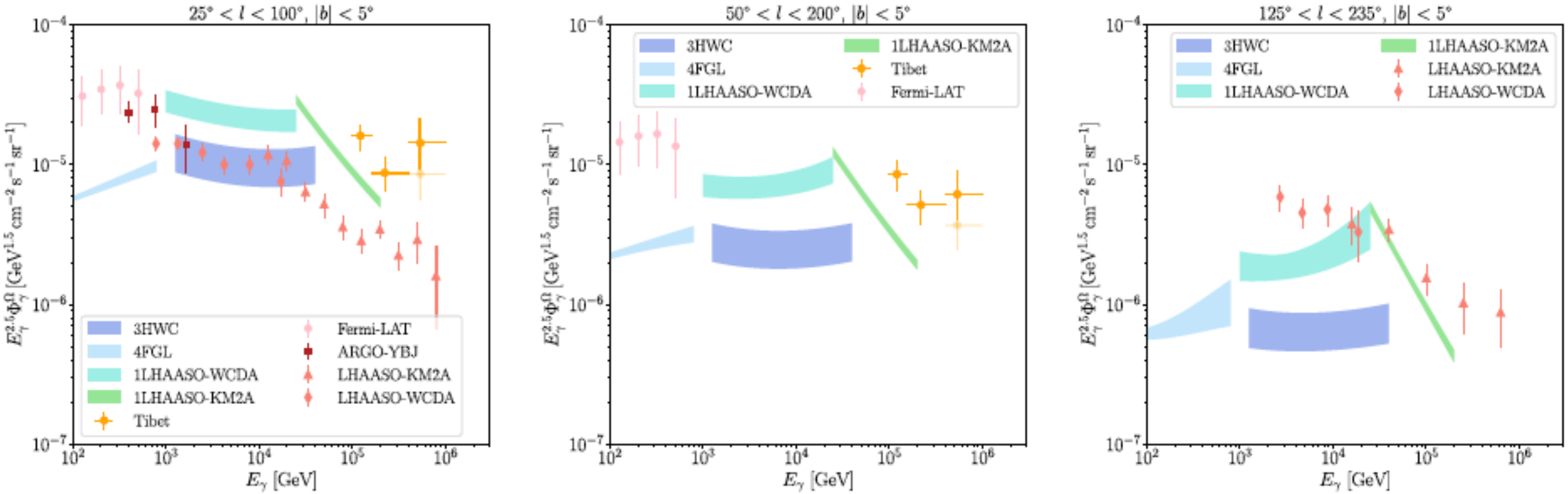


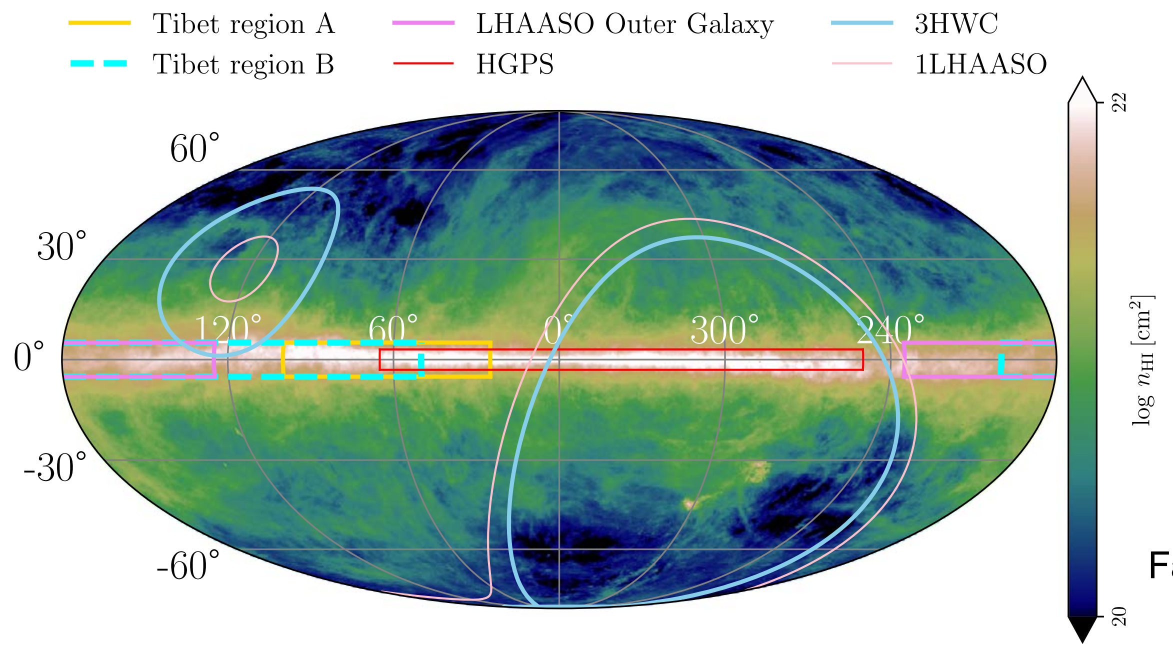
Fang & KM 21 ApJ, 23 ApJL

- Supporting hadronic (pp) origin

- Truly diffuse vs unresolved? (extended)

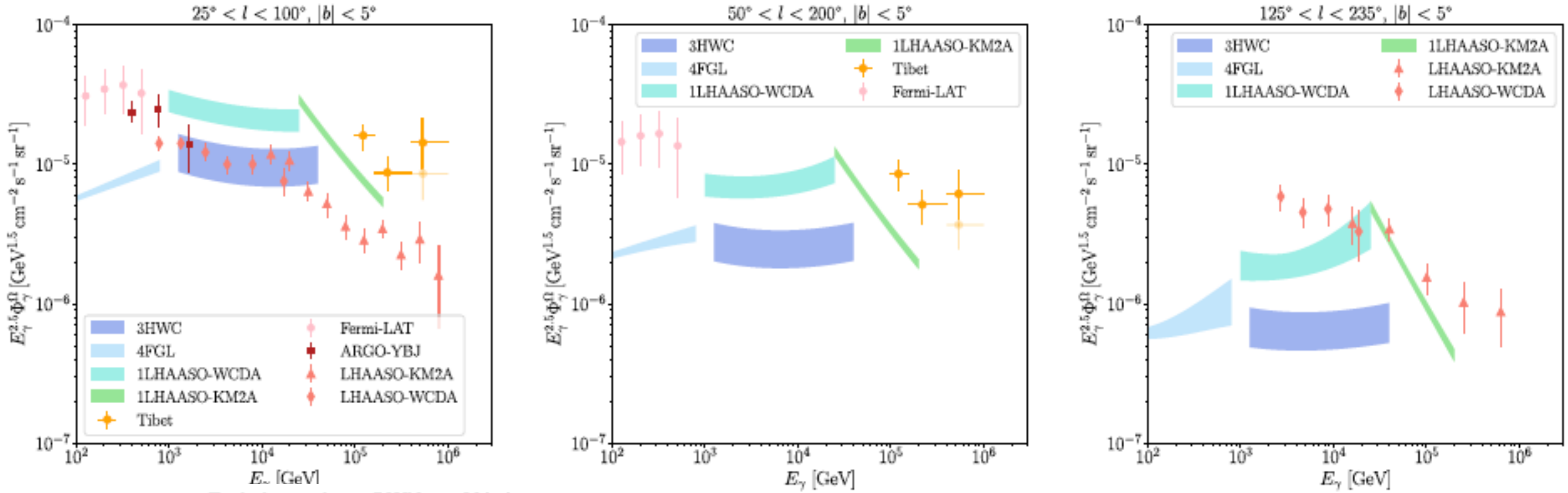
Importance of Improved Measurements

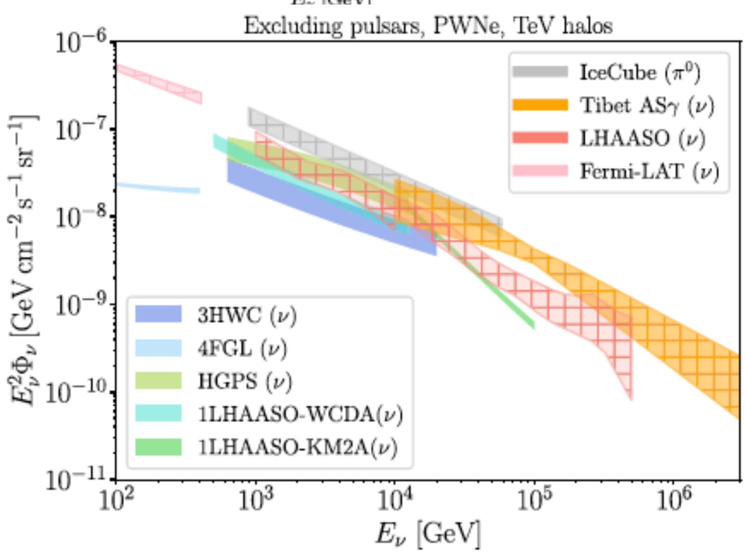


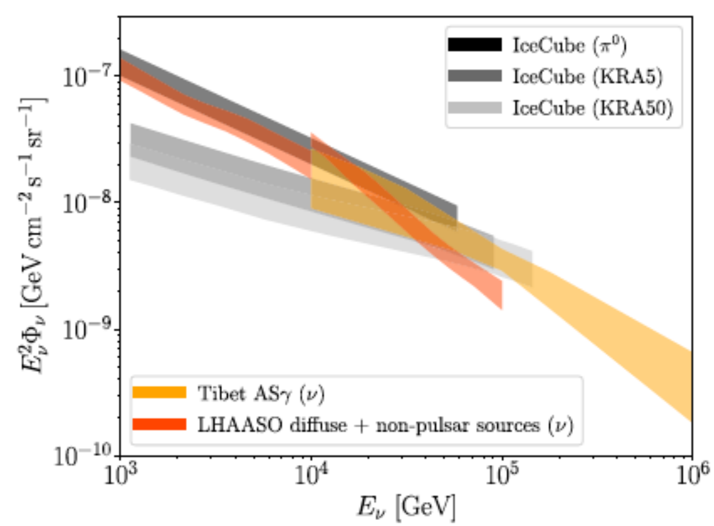


Fang & KM 23 ApJL

Importance of Improved Measurements





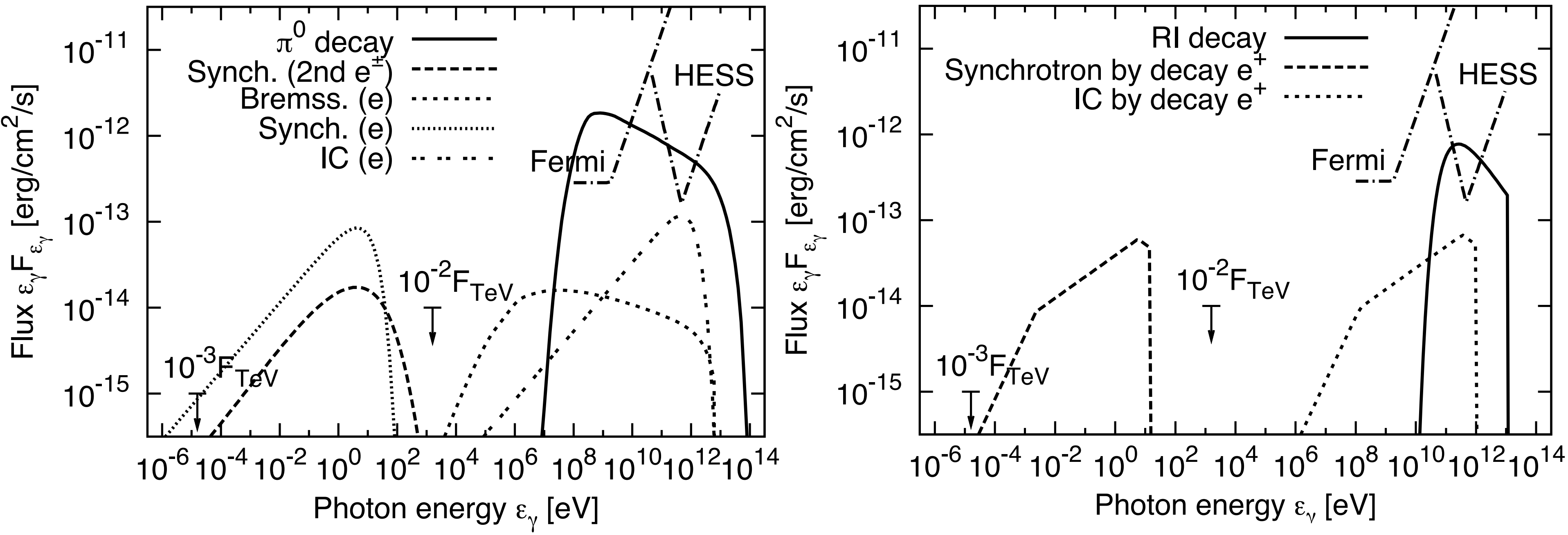


Fang & KM 23 ApJL

Sources may significantly contribute to the Tibet data in the inner region (see also Kato+ 24 ApJL). Unresolved sources at >100 TeV? “Resolved” sources could also contribute to the IceCube data.

Hypernova Remnants as Unidentified Sources

Ioka & Meszaros 10 ApJ



- pp interactions from cosmic-ray ions (w. molecular clouds?) IC by beta-decay of cosmic-ray ion produced in the past
- Abundance: N_{HNR}~30 vs N_{SNR} ~ 1000
- Source extension: ~1 deg (3 kpc/d)

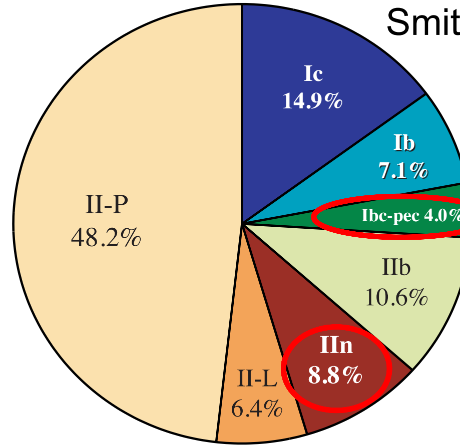
Hypernovae/Interacting SNe as (Super-)Pevatrons

$$E_{\max} \sim 200 \text{ TeV } Z \left(\frac{\tilde{\epsilon}_p}{0.03}\right)\left(\frac{n}{1 \text{ cm}^{-3}}\right)^{1/2}\left(\frac{V_s}{10^4 \text{ km s}^{-1}}\right)^2\left(\frac{R}{1 \text{ pc}}\right)$$

(ex. Bell 04, Zirakashvili & Ptuskin 08, Shure & Bell 13)

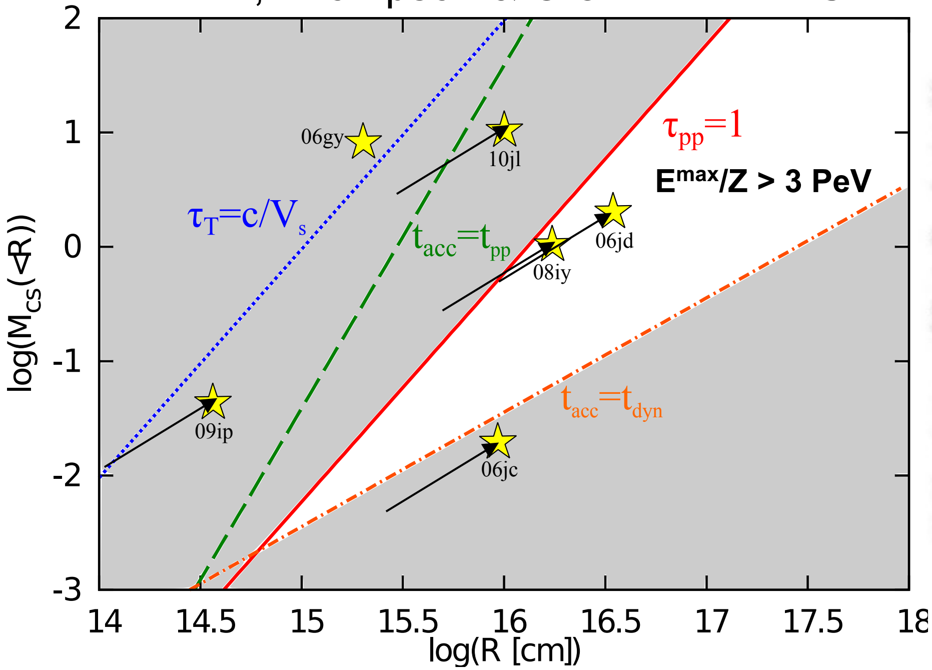
- Typical SNRs would not be PeVatrons (ex. Cas A)…
- Maximum energies will be higher than typical SNRs for explosions w. faster velocities and/or denser CSM → $E_{\max}$ ~ 2 Z PeV or higher for hypernovae

Smith+ 11 MNRAS

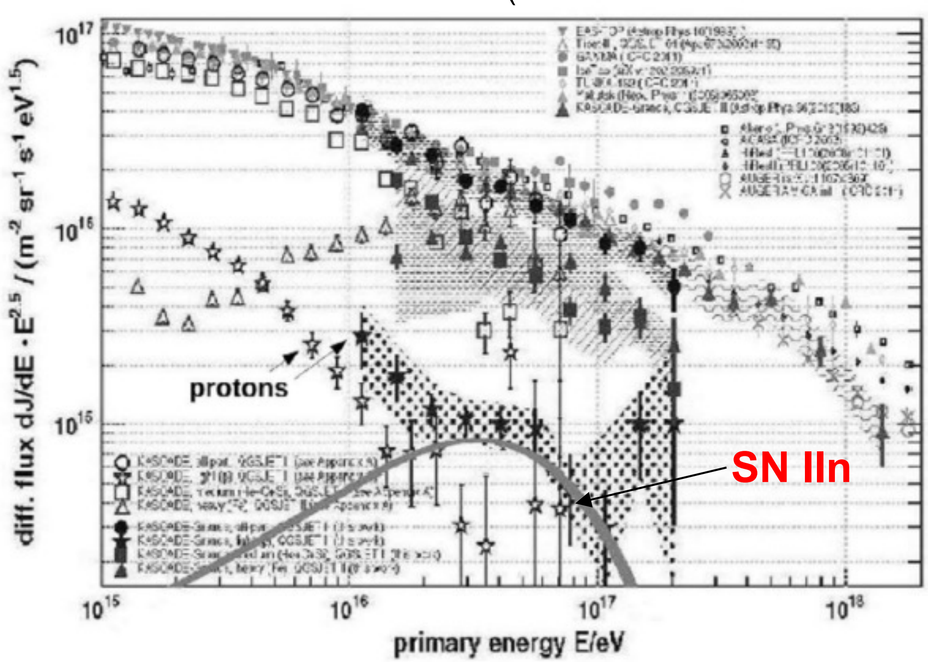


Core-Collapse SN Fractions

KM, Thompson & Ofek 14 MNRAS

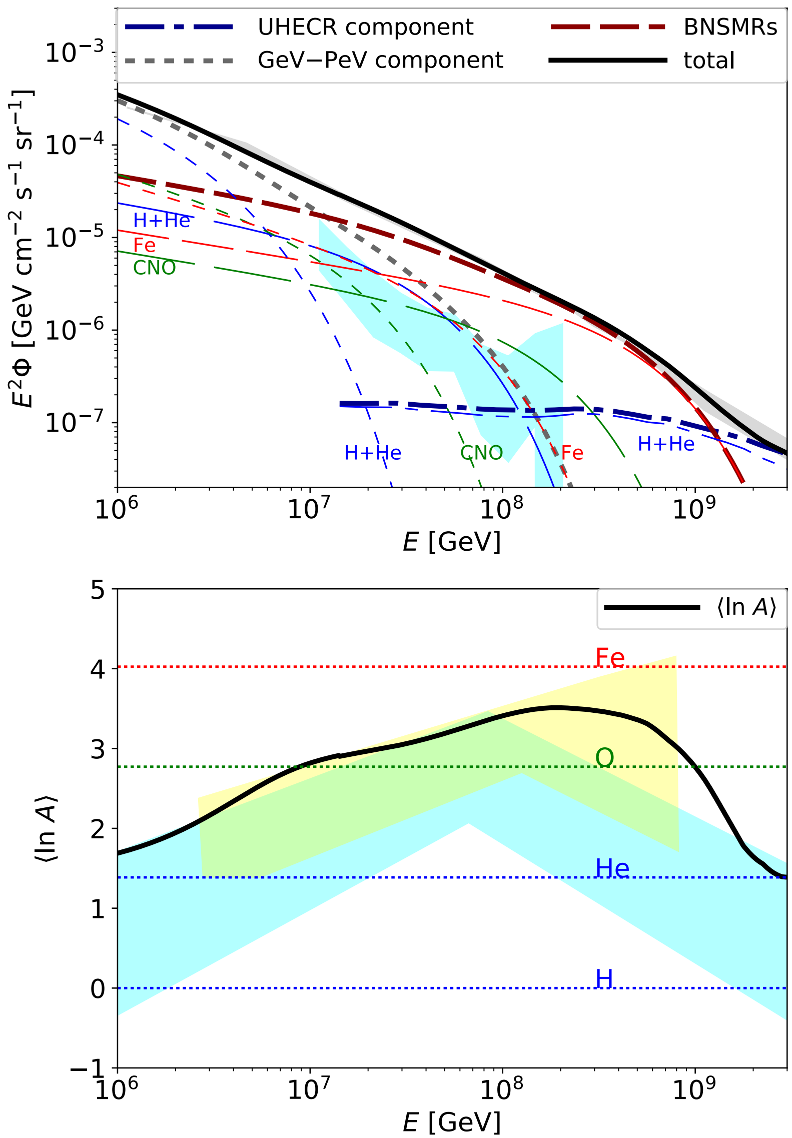


Zirakashvili & Ptuskin 16 APh (see also Sveshnikova 03 A&A)



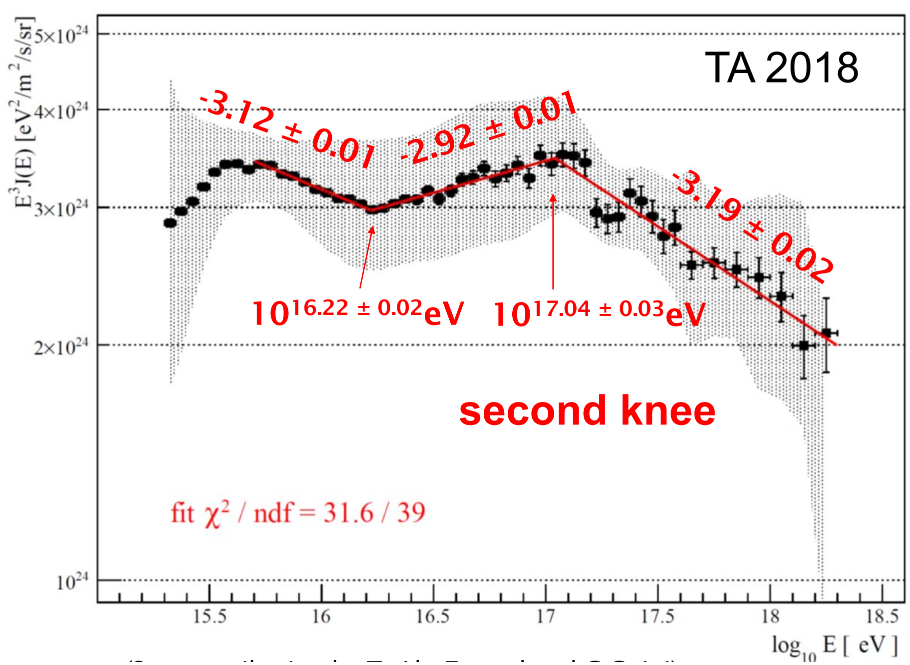
Neutron Merger Remnants as (Super-)Pevatrons

Kimura, KM & Meszaros 18 ApJ

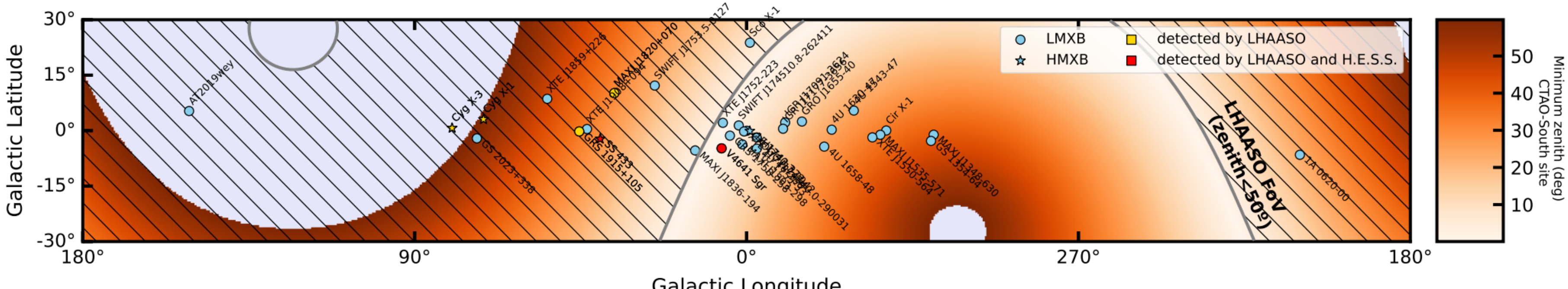


- Merger ejecta
  M_{ej}~0.03-0.05 M_{sun} w. V~0.2-0.3c
- Apply the same scaling from SNRs
  → E_{NS}^{max}/Z ~ 3-30 PeV
  (for E_{SNR}^{max}/Z ~ 0.3-3 PeV)
- With a merger rate of ~ 10^{-4} yr^{-1} gal^{-1} they should contribute to Galactic CRs

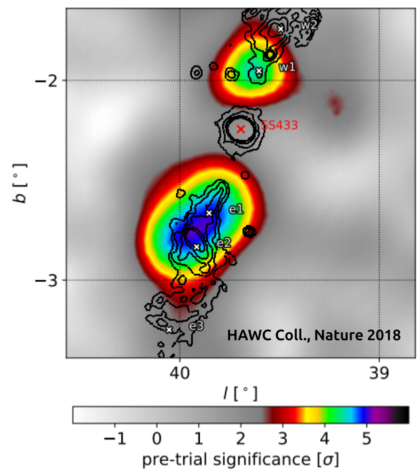
(see Takami+ 13, Rodrigues+ 18 for an extragalactic model)



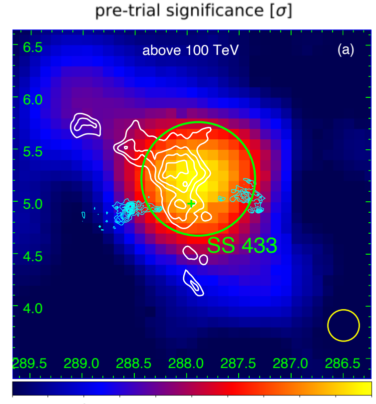
Microquasars as VHE Gamma-Ray Sources

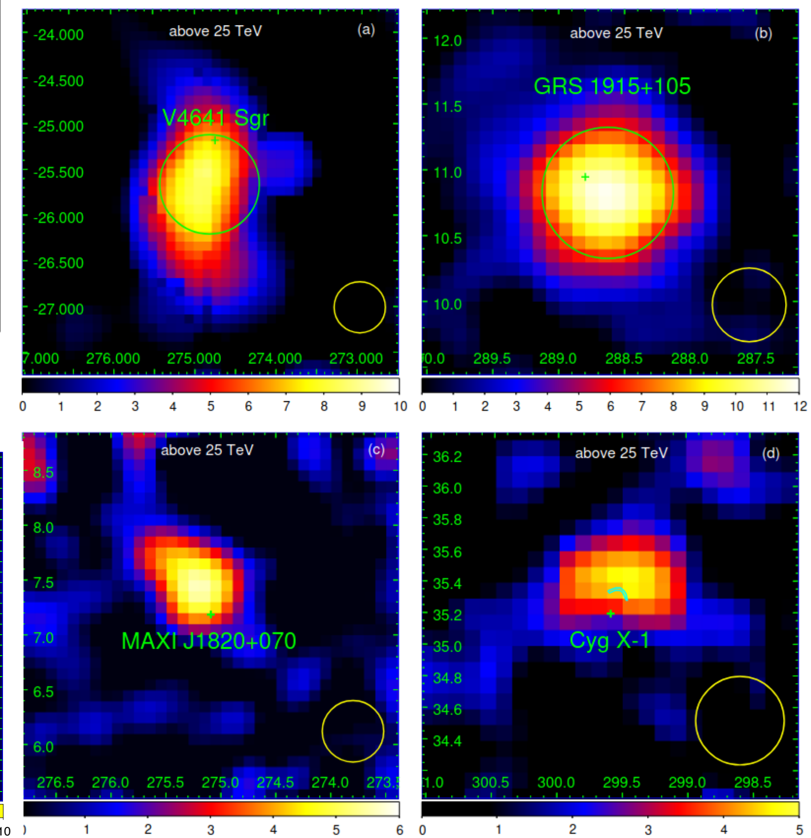


- Detection of SS 433 by HAWC in 2018
- HAWC: SS 433 & V4641 Sgr
- LHAASO: SS 433, V4641 Sgr, G1915+105, Cyg X-1, MAXI J1820+070
- Detected out to 800 TeV
- Persistent
- Extended SS 433, V4641 Sgr, G1915+105



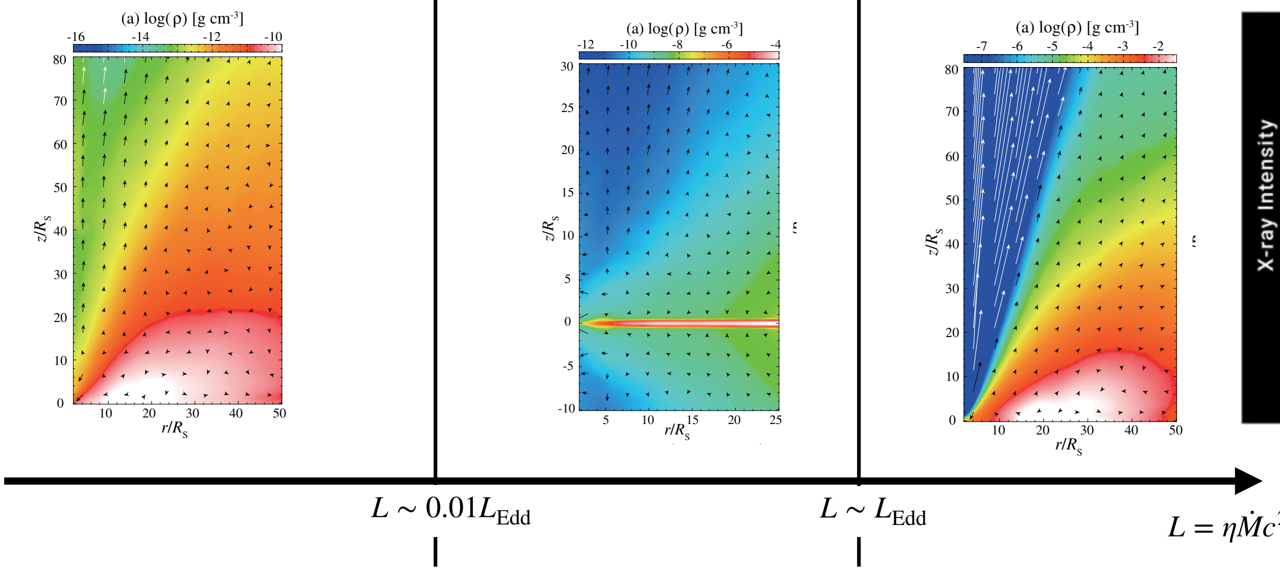
LHAASO Collaboration 24

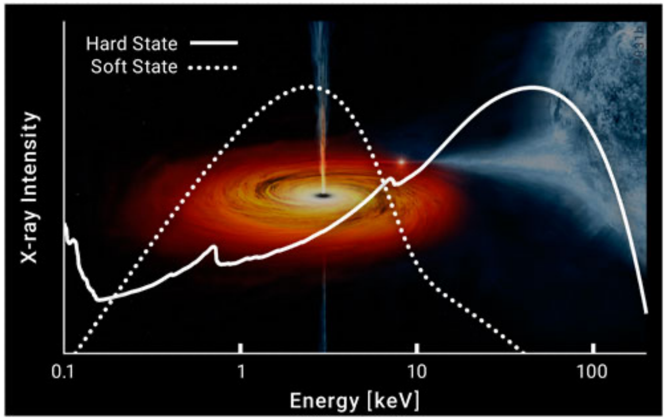




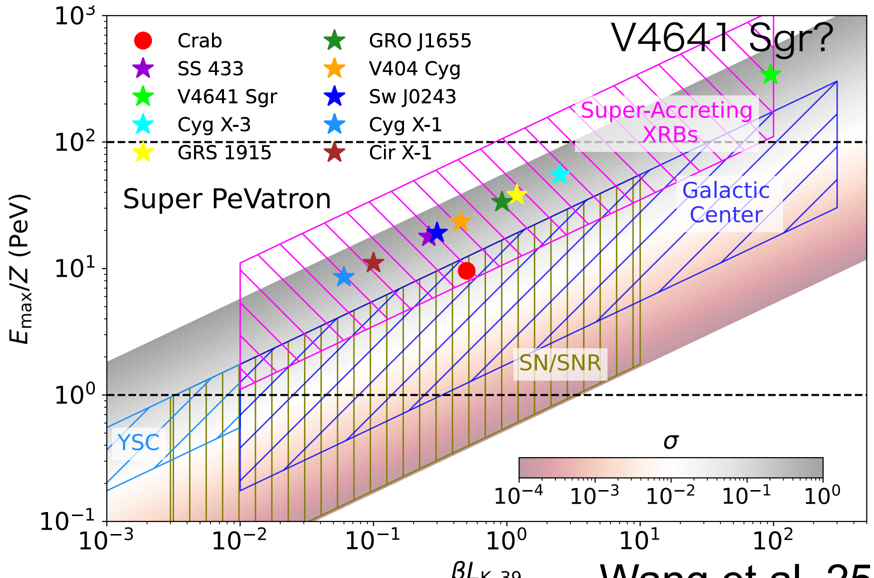
Microquasars as Super-Pevatrons

Hot Accretion Flow (RIAF) | Standard accretion disk | Slim disk + Jets



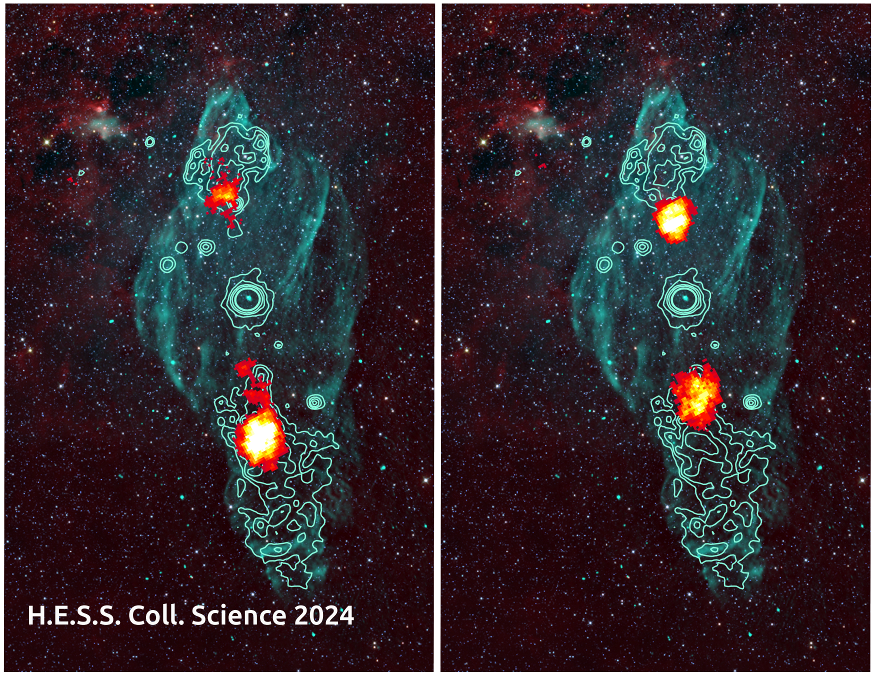


- Jetted X-ray binaries
- Some of them are super-Eddington → powerful jets & outflows
- Hillas condition allows super-Pevatrons
- CR luminosity required for the knee $L_{CR} \sim 10^{38}$ erg/s ~ (0.001-1)L_{Edd} for a few to ~10 sources

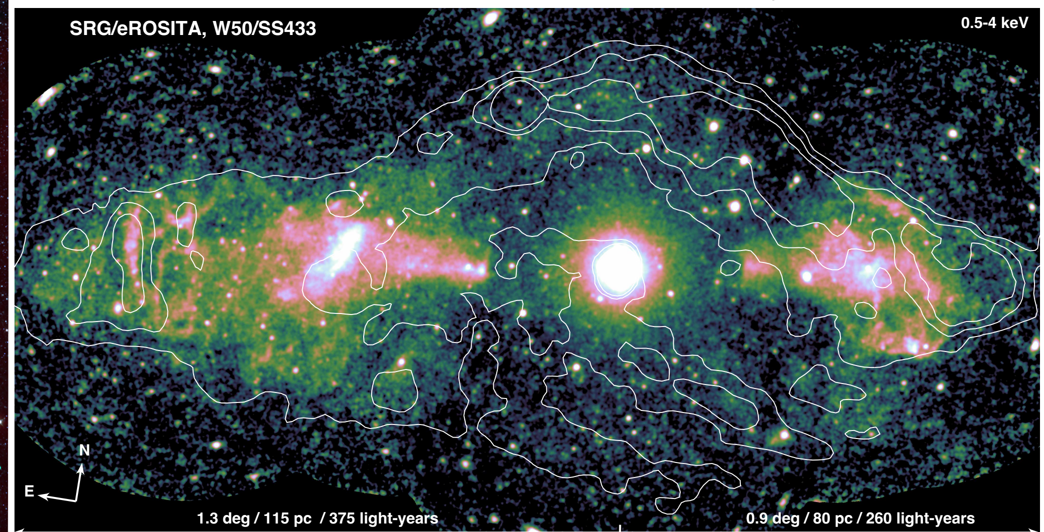


Wang et al. 25

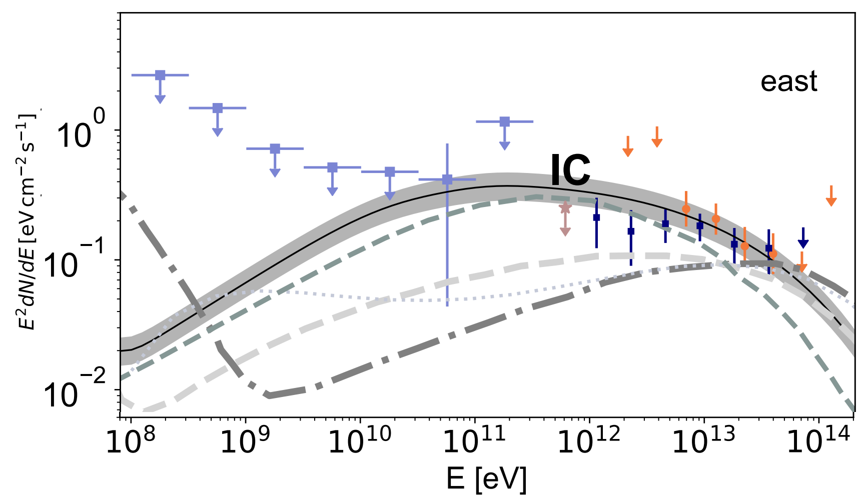
SS 433



Sunyaev et al. 25

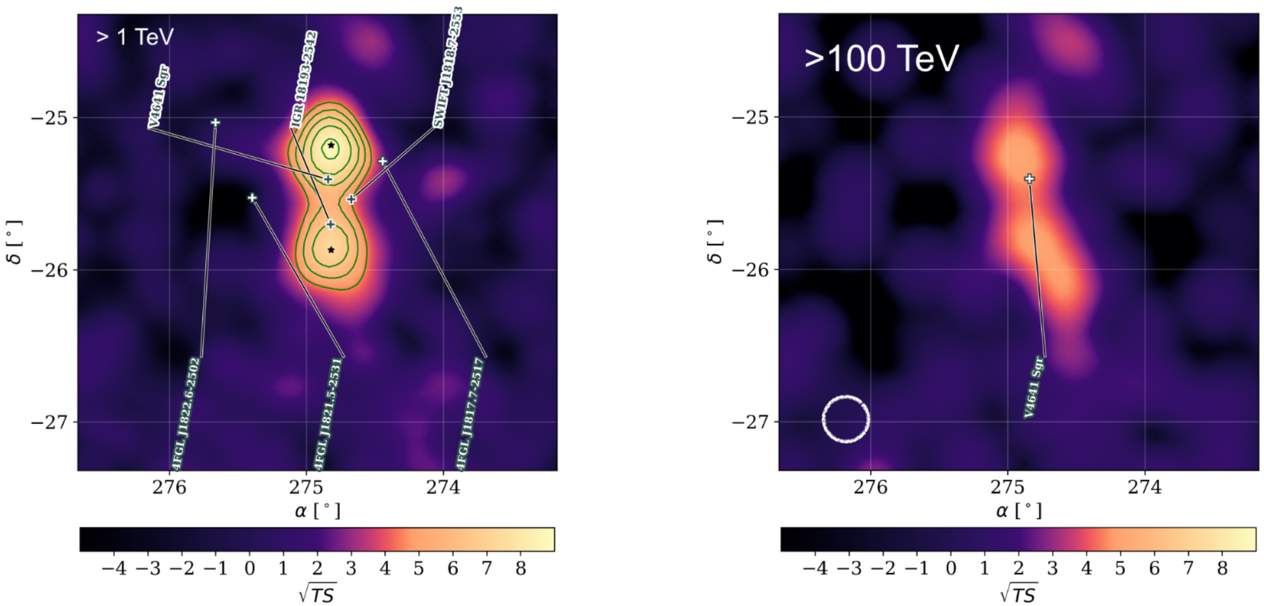


HAWC Collaboration 24



- γ-ray morphology ~ X-ray morphology → leptonic origin
- Shock acceleration of electrons
- Coincident w. gas distribution above 100 TeV (hadronic?)

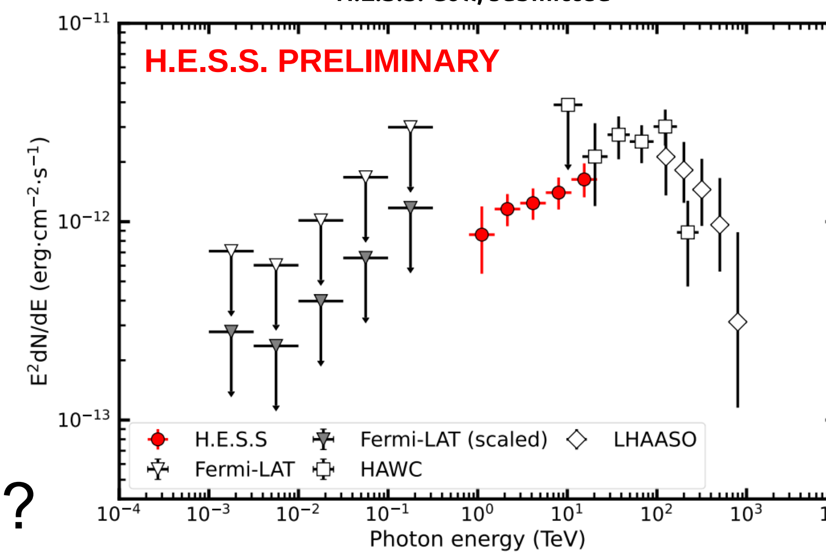
V4641 Sgr



HAWC Collaboration 24 Nature

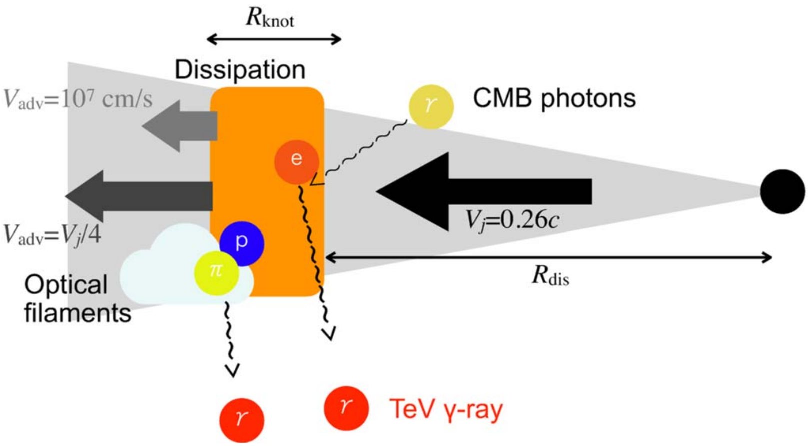
from Oliviera-Nieto @ CDHY

H.E.S.S. Coll, submitted



- Hard spectrum peaking at ~100 TeV
- Brightest microquasar
- Elongated w. ~100 pc
- Target gas not seen
- Hadronic w. hard indices?
- Leptonic w. weak magnetic fields?

Hadronic Gamma-Ray Signatures?

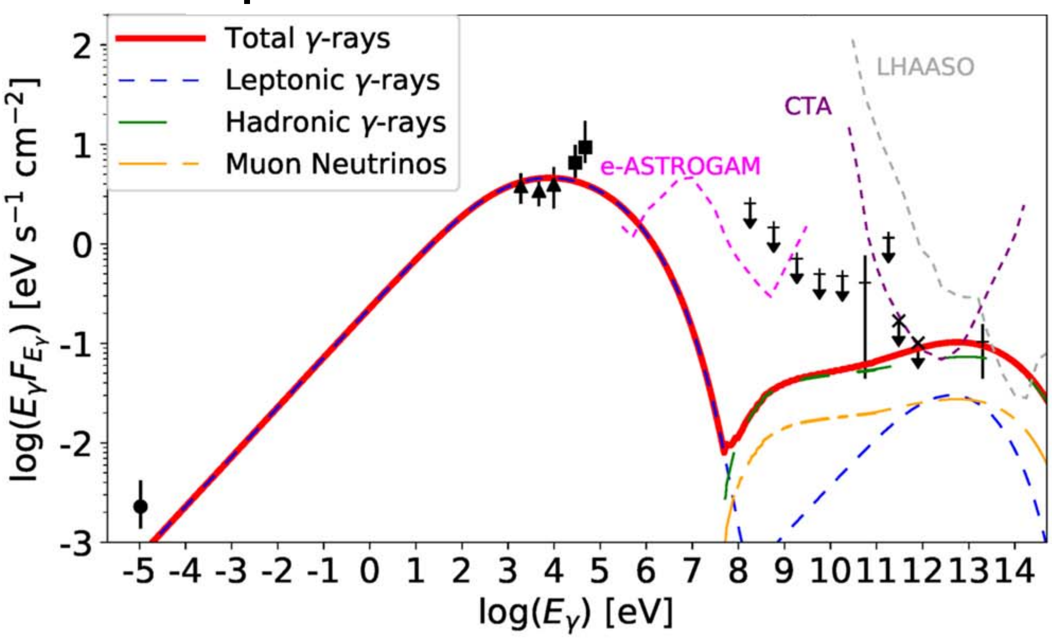


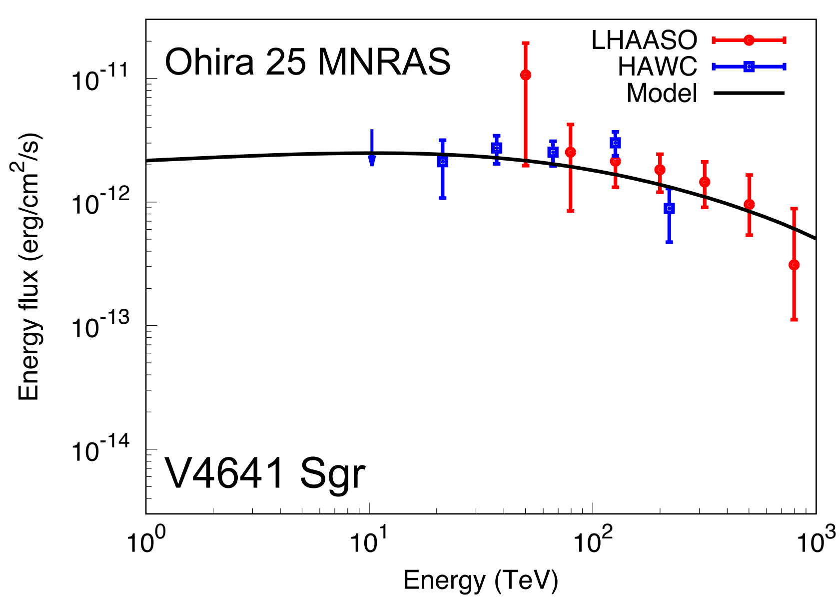
- SS 433: likely more leptonic at 1-10 TeV
  (HAWC Collaboration 18, HESS Collaboration 24)

- Hadronic contribution is still possible especially at higher energies
- ν detection: more than 2 decades even w. IceCube-Gen2 (SS 433)

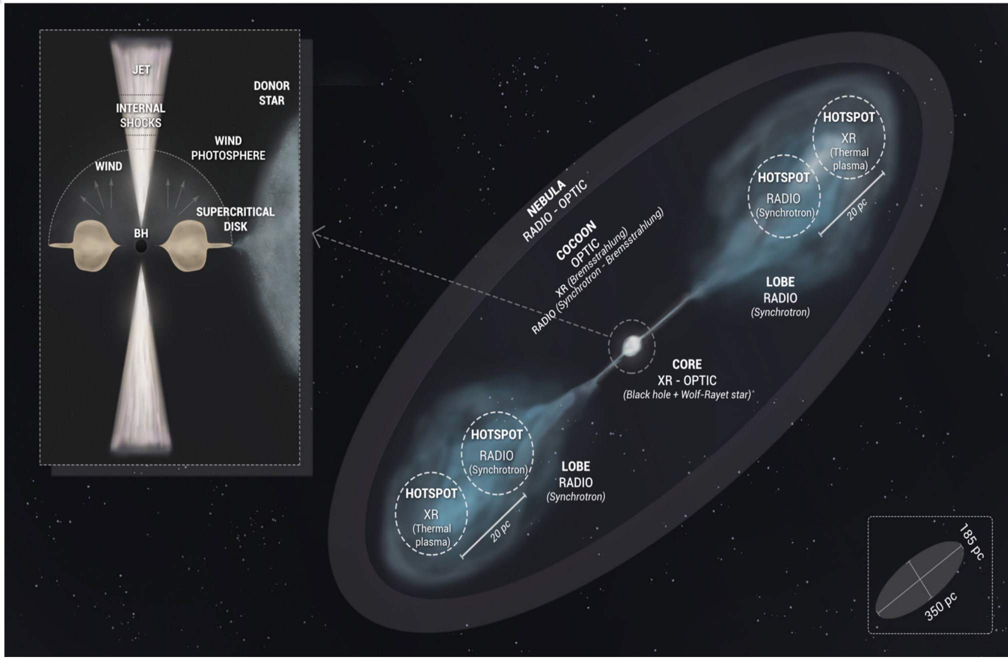
Kimura, KM & Meszaros 20 ApJ

leptohadronic scenario for SS 433





Common Acceleration Mechanisms between Microquasars and AGNs?



Need for efficient acceleration: example of SS 433 (Kimura, KM & Meszaros 20 ApJ)

$\gamma_e^X < \gamma_e^{max} \rightarrow \xi$ <~ 30-100

$E_{max}/Z > 3$ PeV $\rightarrow \xi$ <~ 10 (for B ~ 30 μG)

$$t_{acc} \approx \frac{20\xi E_i}{3ceB\beta_j^2}$$

AGN: blazars & hot spots: ξ >~ 10^4 (ex. Inoue & Takahara 96, Araudo et al. 16, Zhang et al. 18)

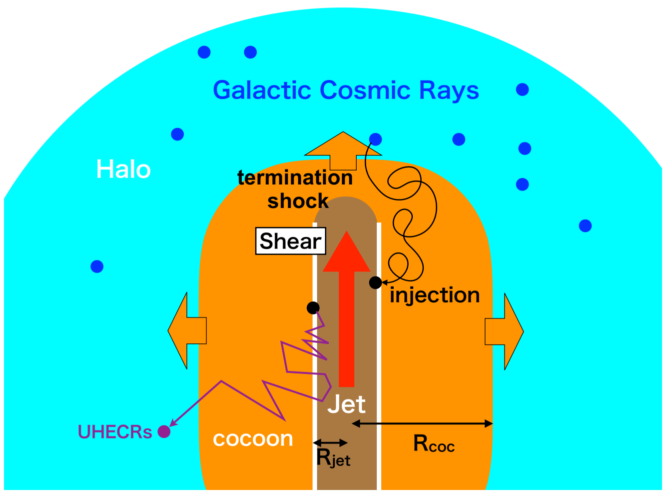
$\rightarrow$ internal shocks/termination shock: may not be promising for UHECRs

Alternative acceleration mechanisms?

Particle Acceleration by Large-Scale Jets

(Discrete) one-shot/shear acceleration at the jet-cocoon boundary

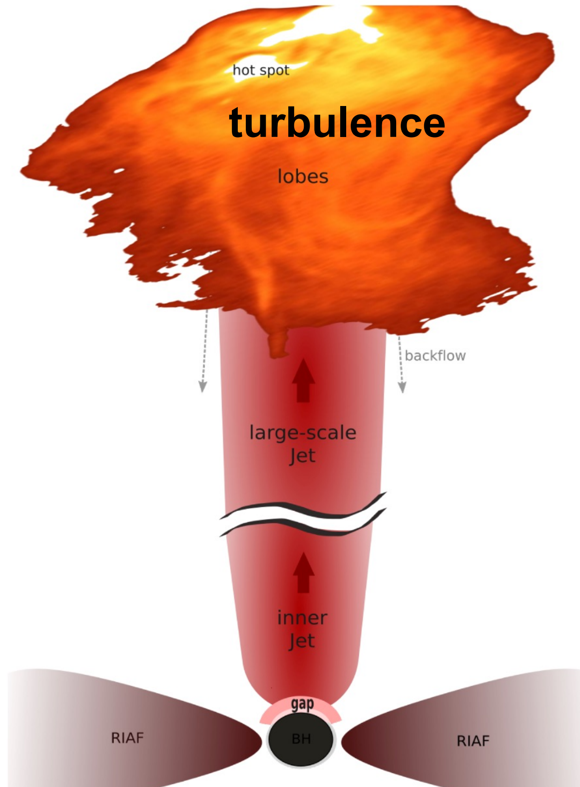
(Caprioli 15, Kimura, KM & Zhang 18)



from Kimura, KM & Zhang 18

Turbulent shear acceleration in backflows

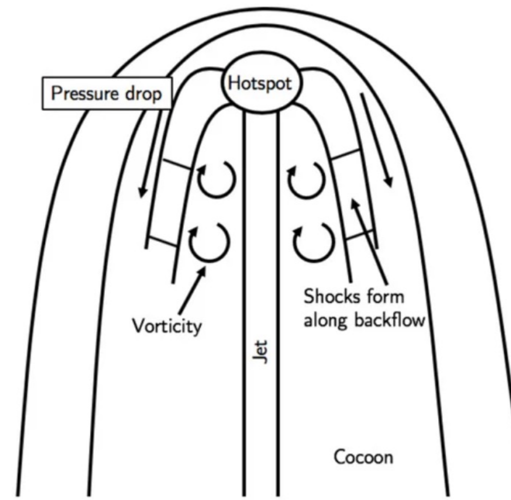
(Hardcastle 10, Ohira 13)



from Rieger 21

DSA acceleration in backflows in cocoons

(Matthews+ 18, 19)



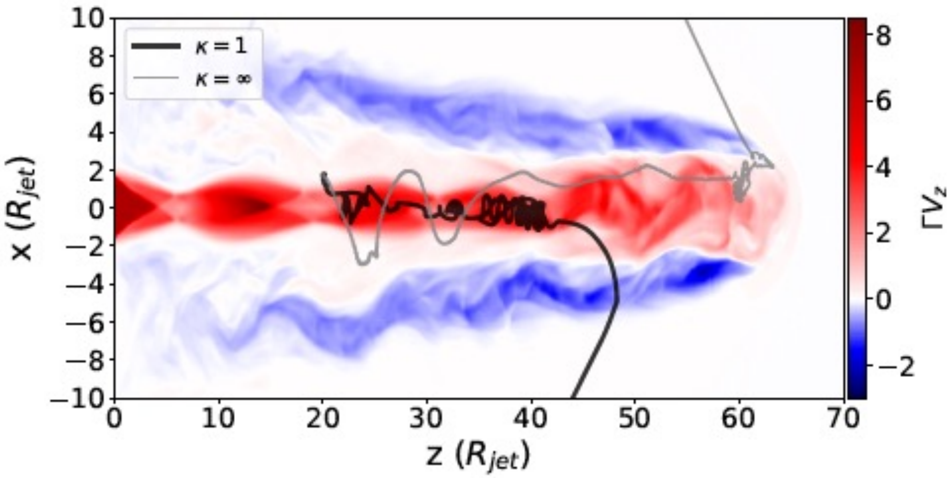
from Matthews+ 19

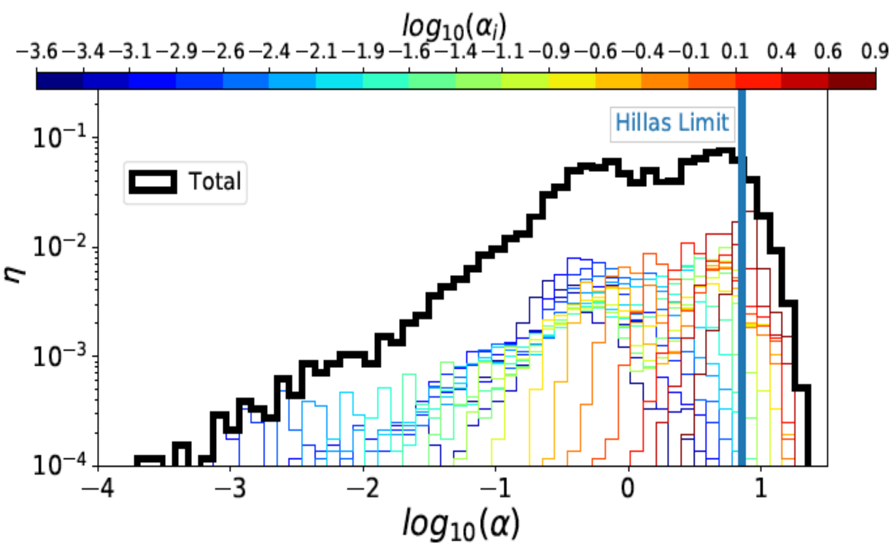
"Reacceleration" of galactic CRs by AGN jets

Test Particle Simulations of Particle Acceleration

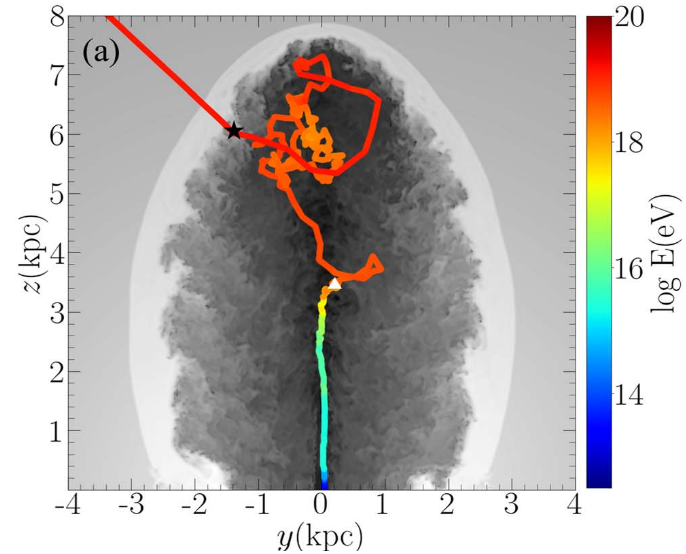
MHD simulations

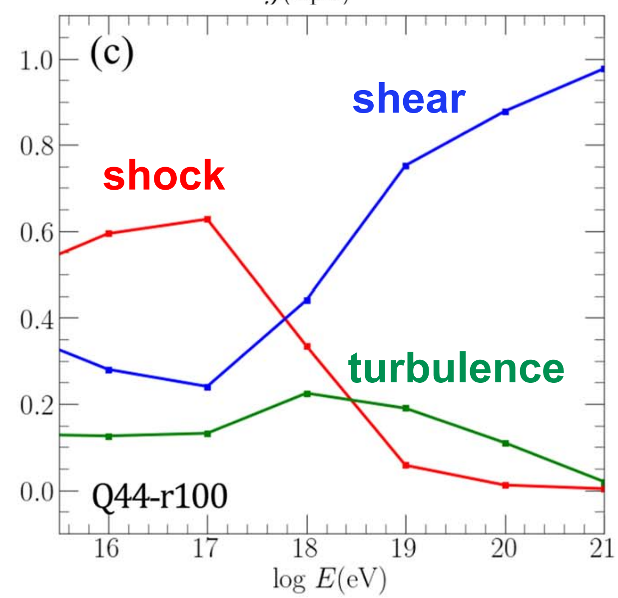
(Mbarek & Caprioli 21 ApJ
see also Mbarek, Caprioli & KM 23 ApJ, 25 PRD)





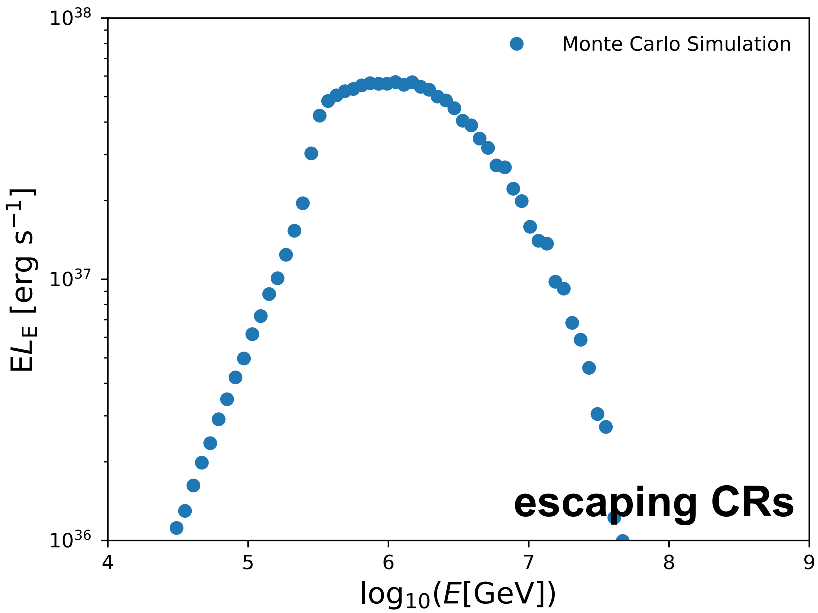
HD simulations (Seo, Ryu & Kang 24 ApJ)

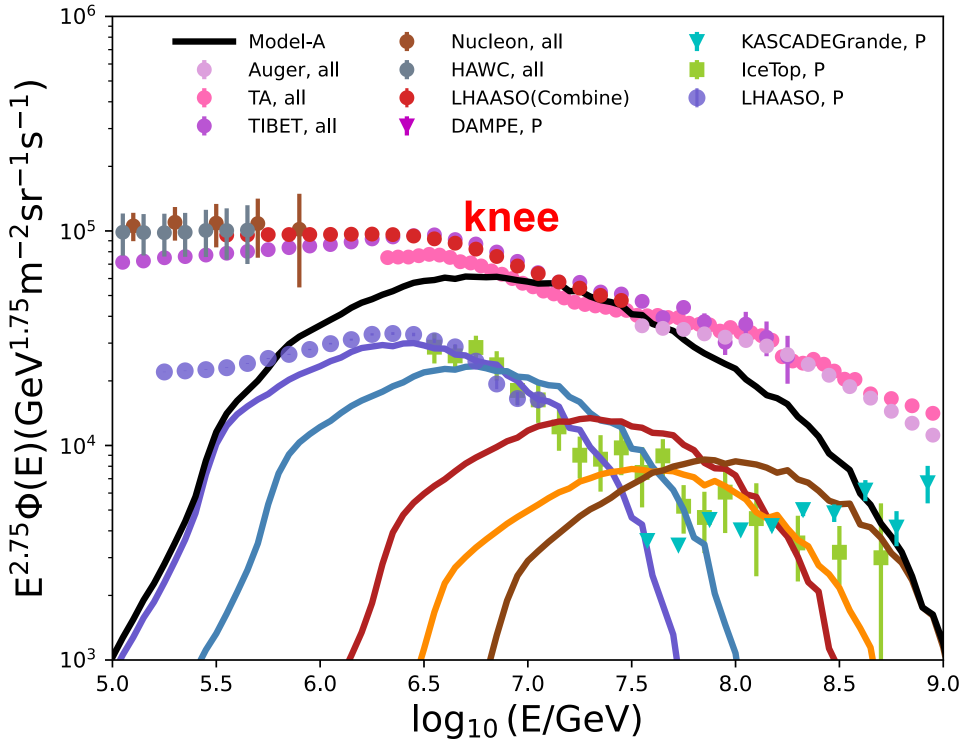


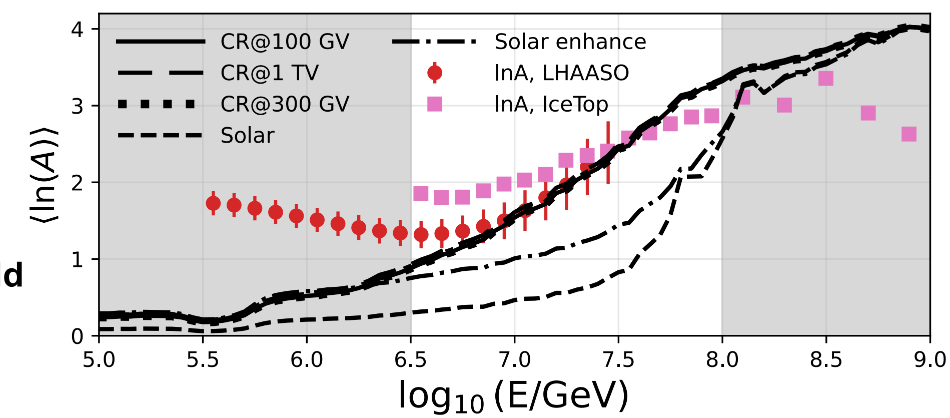


Shear Acceleration Model for Microquasars

Zhang, Kimura & KM 2506.20193







- Injection: Galactic CRs at ~TeV
- B_{coc}~10-30 μG w. r_{coc}=60 pc (Kolmogorov assumed)
- B_{jet} ~ 50-100 μG w. r_{jet}=3-4 pc

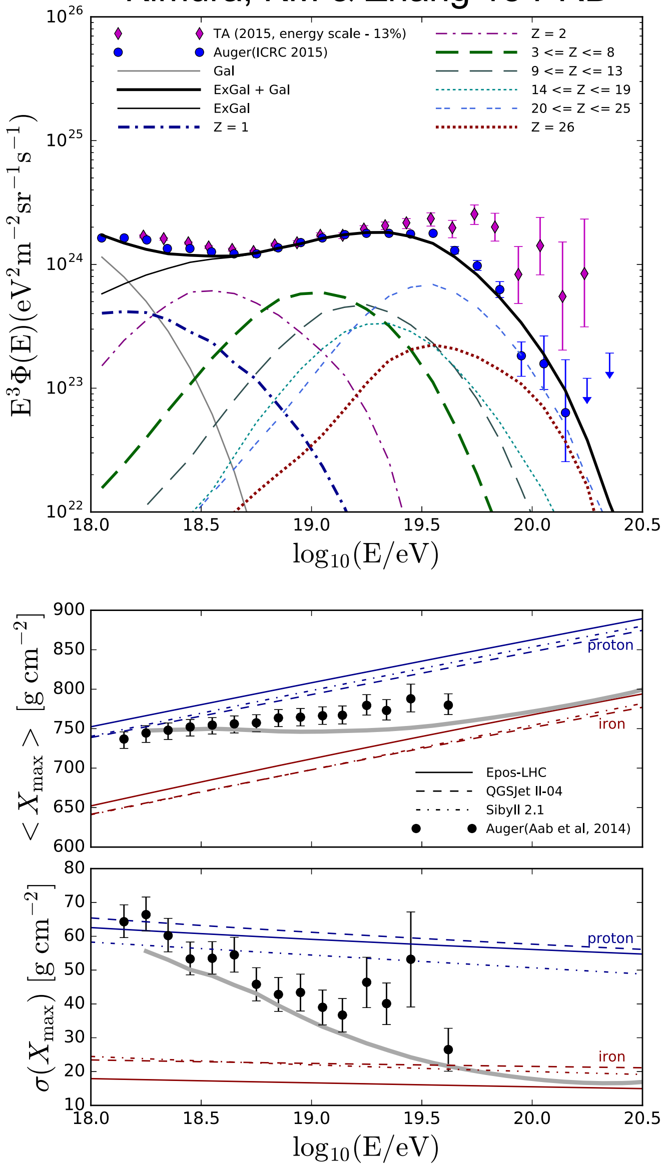
$E_{\max} = \zeta e B_{\rm coc} l_{\rm coh}^{1/2} r_{\rm jet}^{1/2} \Gamma_{\rm jet}\beta_{\rm jet}$ **~ 4 PeV**

$L_{\rm CR} \approx E_{\max}\dot{N}_{\rm CR}$ **~ 10^{38} erg/s << L_{Edd}**

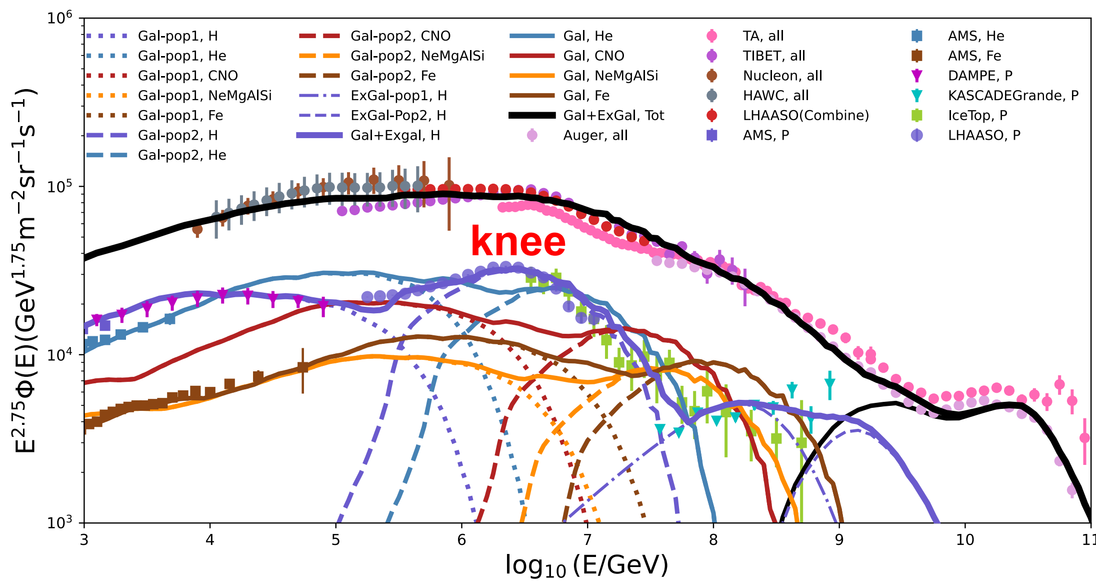
$Q_{\rm cr,tot} \sim 1.3\times10^{42}\ {\rm erg\ kpc^{-3}\ yr^{-1}}$

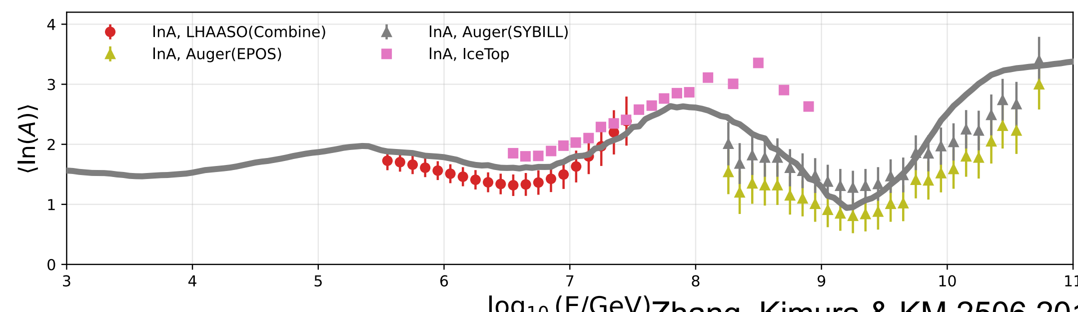
Shear Acceleration Model vs Cosmic-Ray Data

Kimura, KM & Zhang 18 PRD



- Simulated spectra (sub-exponential)
- Galactic and extragalactic highest-energy data may be explained by injection to reacceleration at the same rigidity

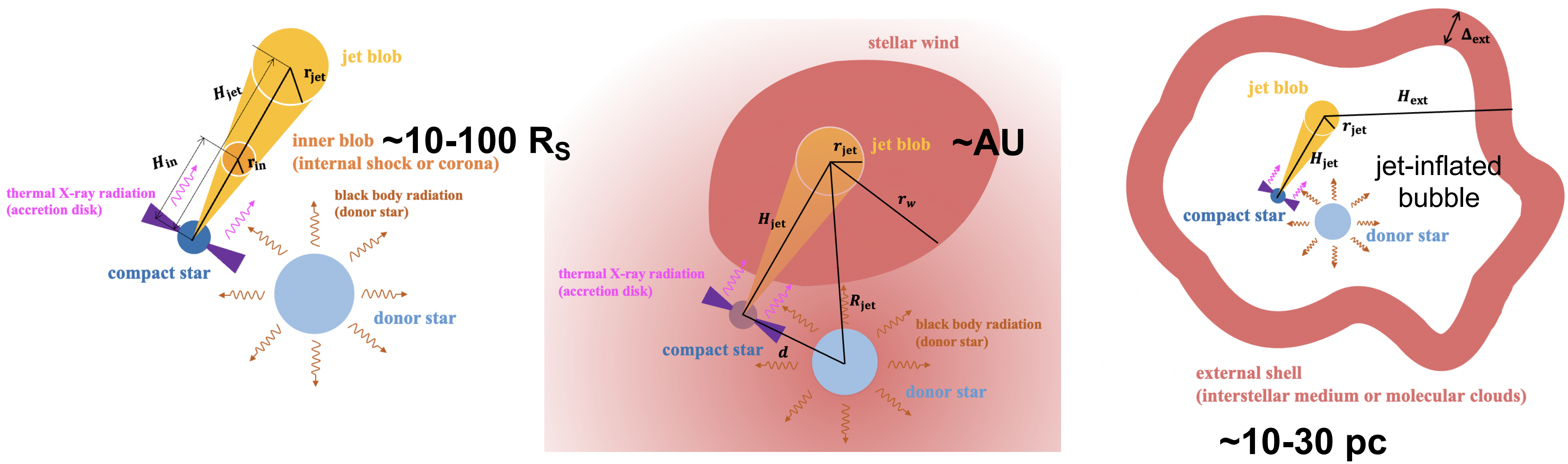




Zhang, Kimura & KM 2506.20193

Hadronic Emission from Microquasars?

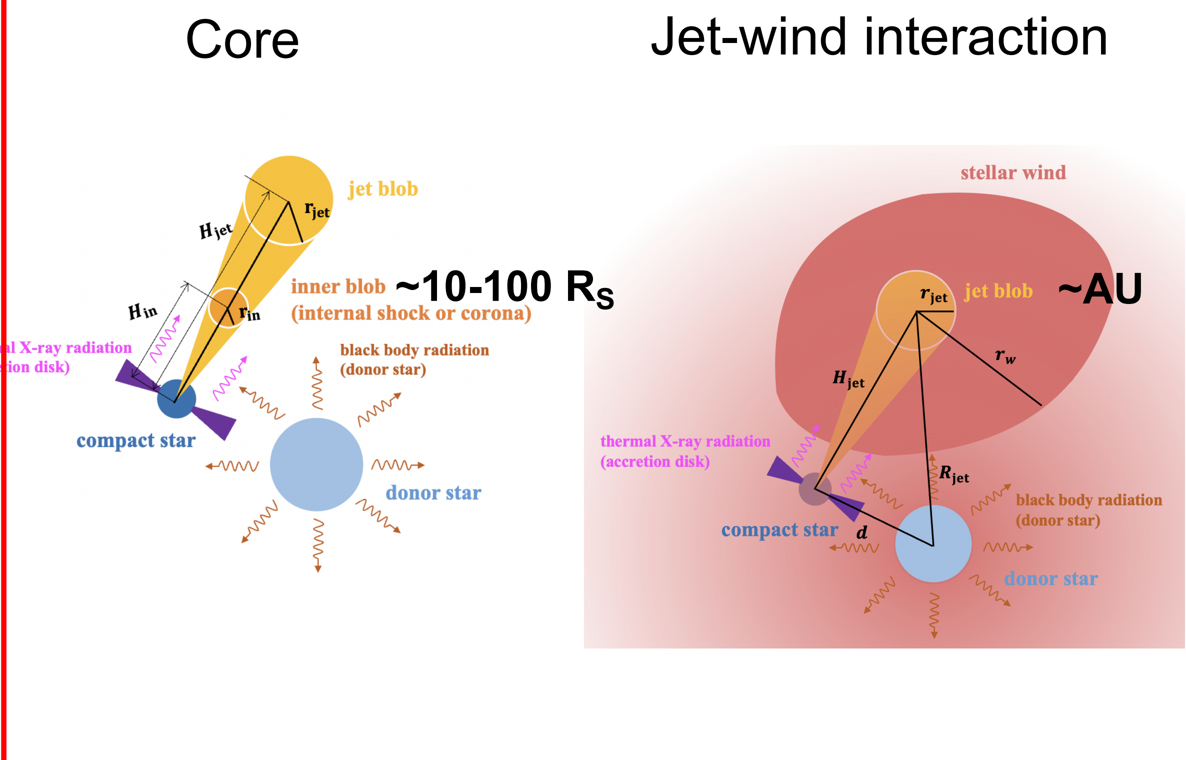
Core | Jet-wind interaction | Cosmic-ray escape

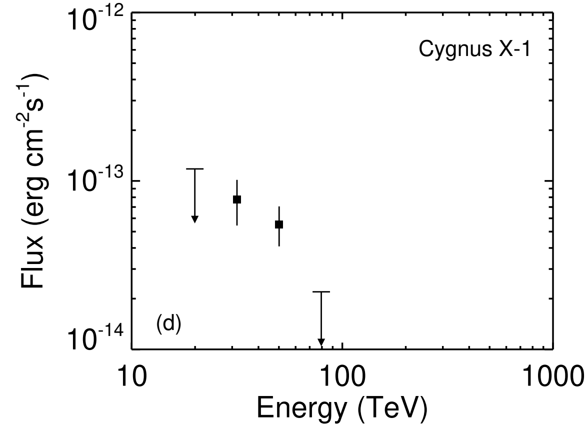


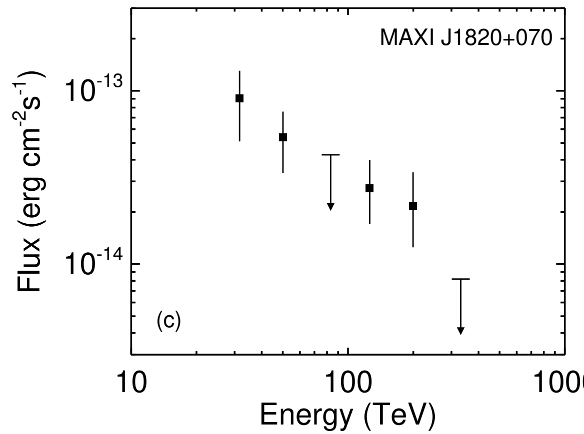
- Hadronic emission has been studied especially in the context of inner-jet dissipation. (e.g., Levinson & Waxman 01 PRL, Romero et al. 03 A&A)
- Higher target photon density & higher gas density (from the wind)
- Cyg X-1, MAXI J1820+070, Cyg X-3?: "consistent" w. a point source could be different from from extended-jet emission (e.g., SS 433)

Hadronic Emission from Compact Regions?

compact jet models







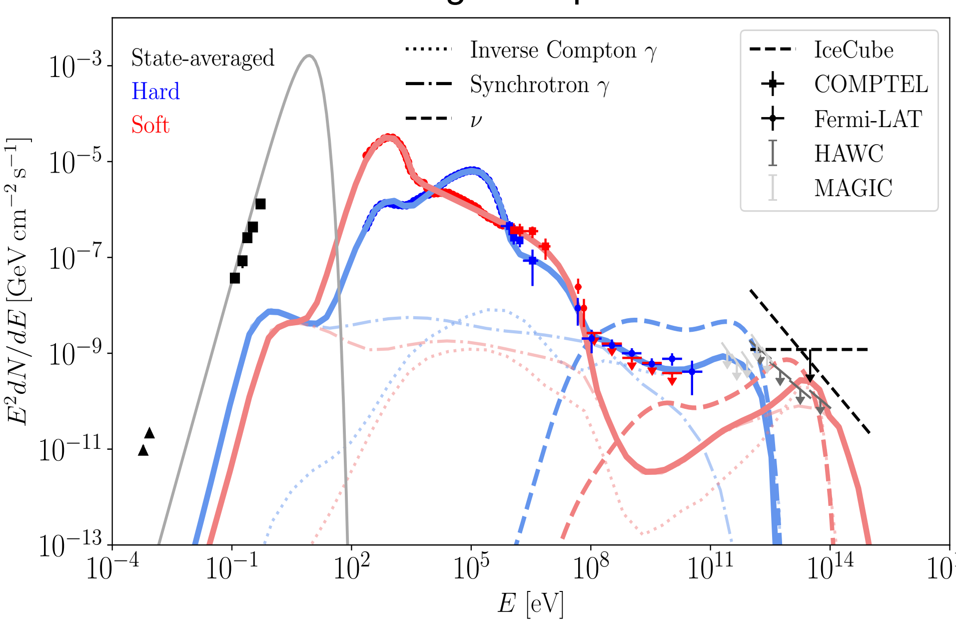
- Hadronic emission has been studied especially in the context of inner-jet dissipation. (e.g., Levinson & Waxman 01 PRL, Romero et al. 03 A&A)
- Higher target photon density & higher gas density (from the wind)
- Cyg X-1, MAXI J1820+070, Cyg X-3?: "consistent" w. a point source could be different from from extended-jet emission (e.g., SS 433)

Hadronic Emission from Compact Regions?

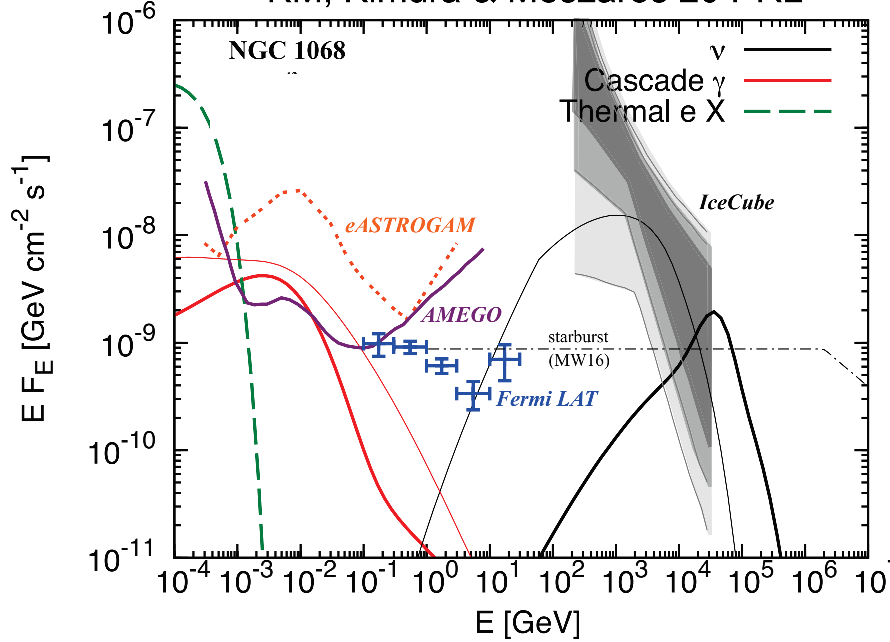
Such compact emissions are also of interest as well in AGN

1. Compact jets
   a. compact gamma-ray and radio-emitting jets (~0.1-10 AU)
   b. outflowing corona (consistent w. IXPE)
2. Black-hole “corona”

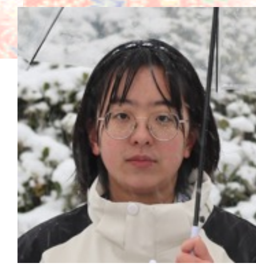
Fang+ 24 ApJL



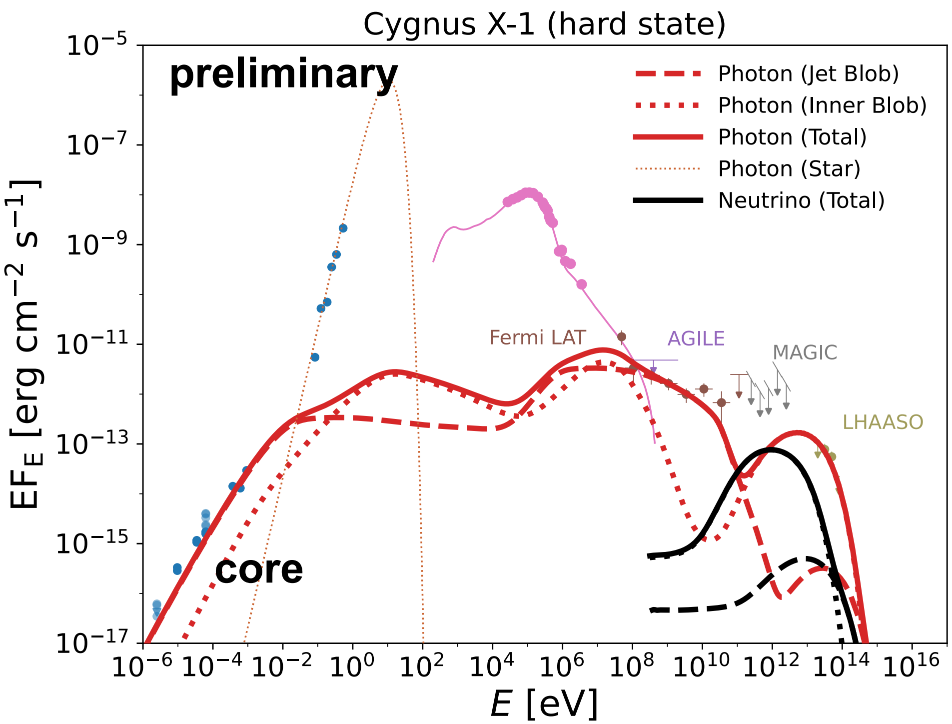
KM, Kimura & Meszaros 20 PRL

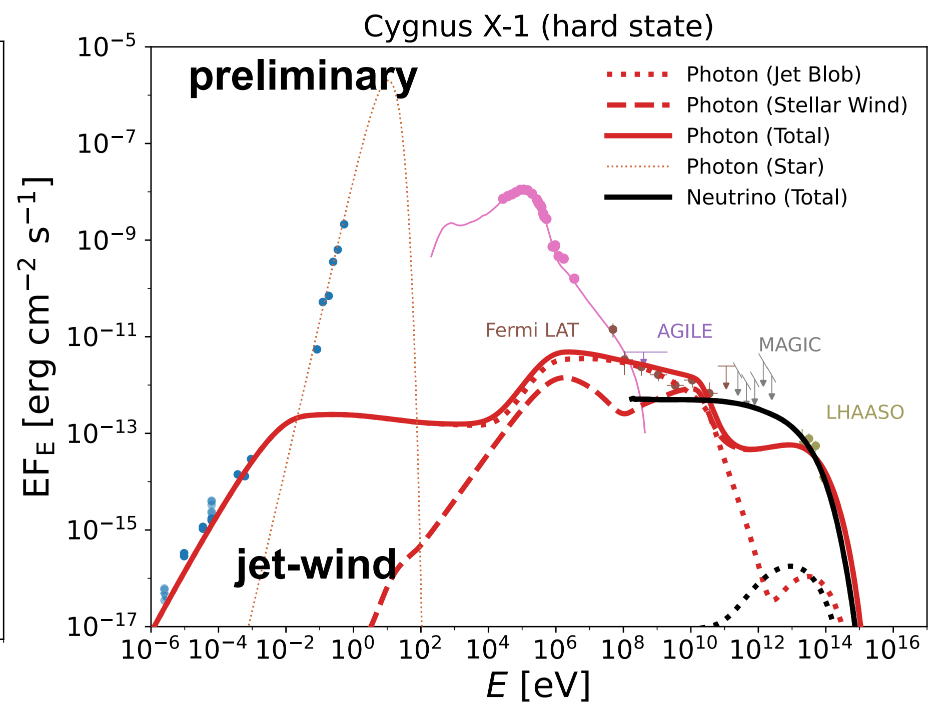


Applications to Cygnus X-1



- Sub-Eddington accretion w. M_{BH}~ 21 M_{sun}, O-type star
- LHAASO: a point source with significance of 4.4σ above 25 TeV



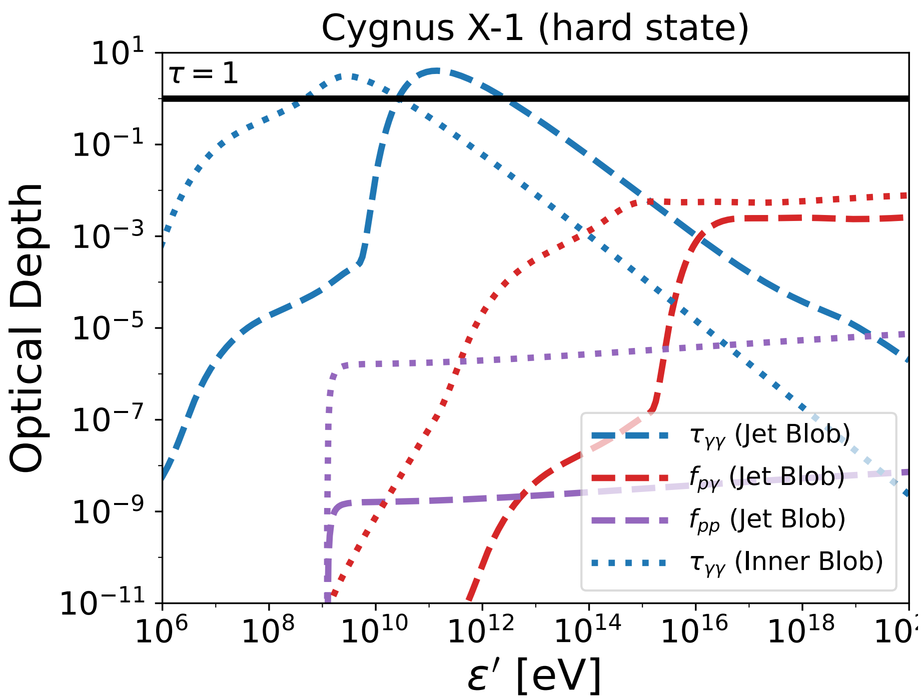


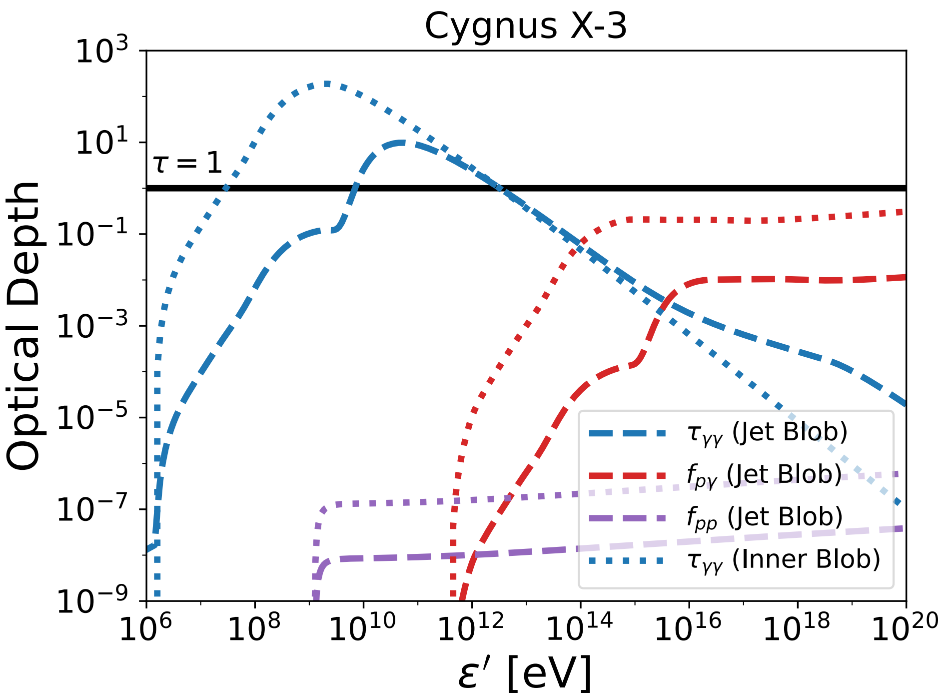
Wei, KM & Zhang 25 in prep.

- L_{Edd}~3×10^{39} erg/s, ε_p~0.03, ε_e~10^{-5}, ε_B~10^{-3}-10^{-1}
- Either pp or pγ: sub-TeV dip → indication of core scenario

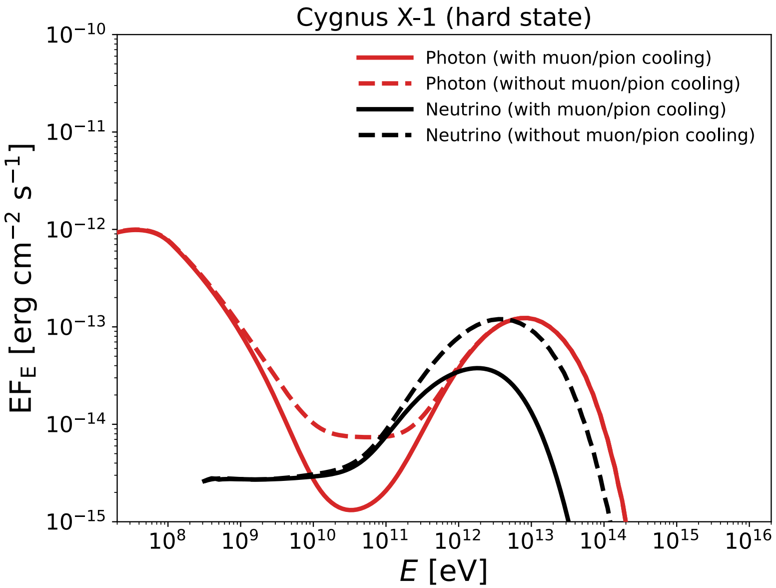
Optical Depths for Core Regions

Wei, Zhang & KM 25 in prep.



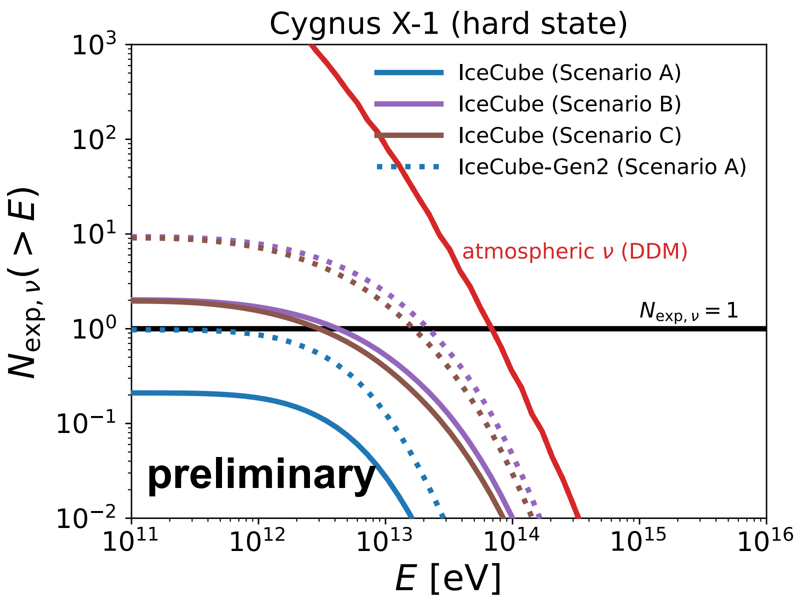


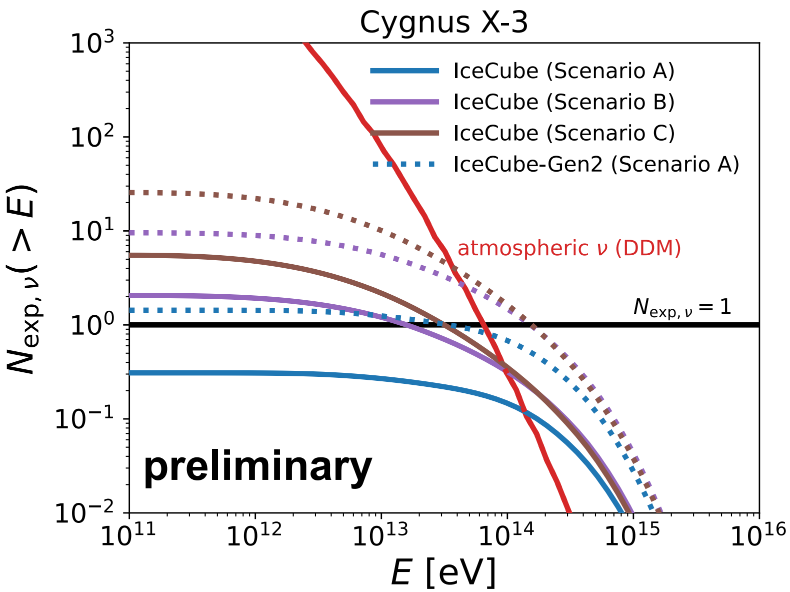
Neutrinos



- Potentially more neutrinos than gamma rays if hidden
- Significant pion/muon cooling (which are often ignored) can reduce both neutrino and secondary synchrotron fluxes
- (Not surprisingly) neutrino detection is challenging as in ~10-100 pc jet models

Wei, KM & Zhang 25 in prep.





Summary

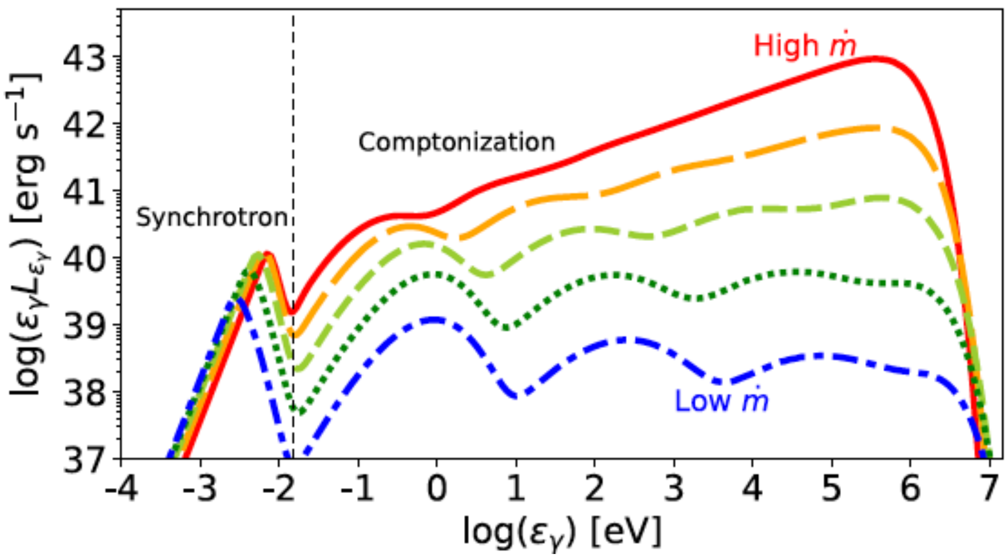
- Galactic diffuse: multimessenger connection now observed
  supporting the hadronic origin whether the origin is truly diffuse or not
  contribution of unresolved super-Pevatrons may be significant above 100 TeV

- Microquasars as emerging super-Pevatrons
  potential contributor to cosmic rays around the knee
  consistent w. leptonic origins but hadronic components may exist
  shear acceleration (jet-cocoon boundary behind the termination shock)
  common explanation for the highest-energy cosmic rays? (cf. AGN)

- Compact "core" regions as partially γ-ray hidden cosmic-ray accelerators
  ~0.1-1 PeV photons may come from either $p\gamma$ or pp process
  gamma-ray attenuation signature at sub-TeV energies?
  neutrino detection is challenging

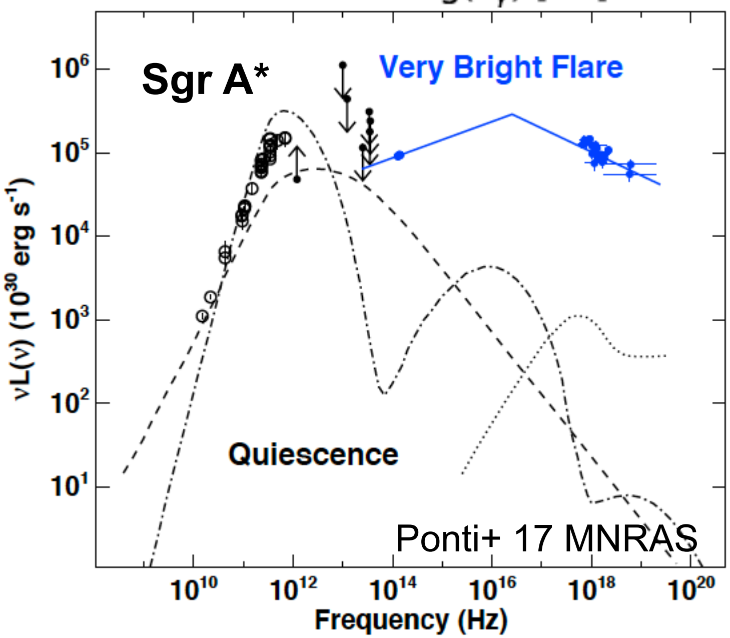
- Connections to isolated black holes and past Sgr A* activities?

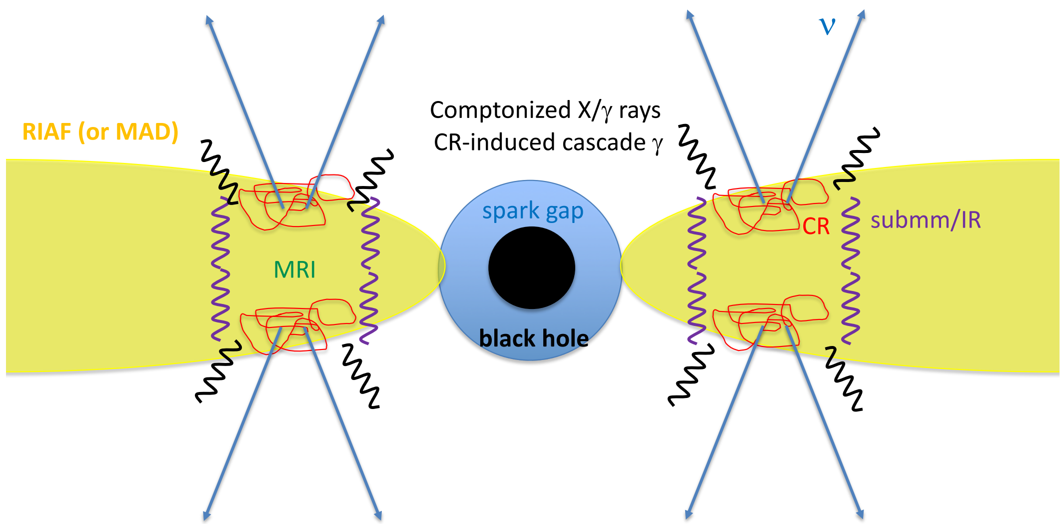
Radiative Inefficient Accretion Flows



Kimura, KM & Toma 15 ApJ
Kimura, KM & Meszaros 21 Nature Comm.

- RIAF for mdot<0.03
- Hot plasma
- Electrons are mostly thermal (collisional for electrons collisionless for protons)

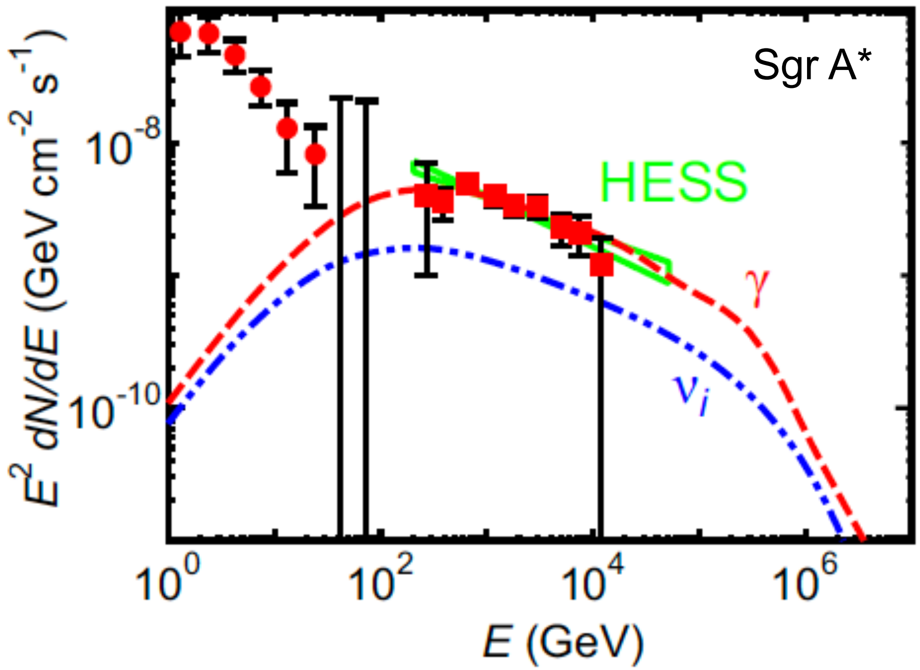


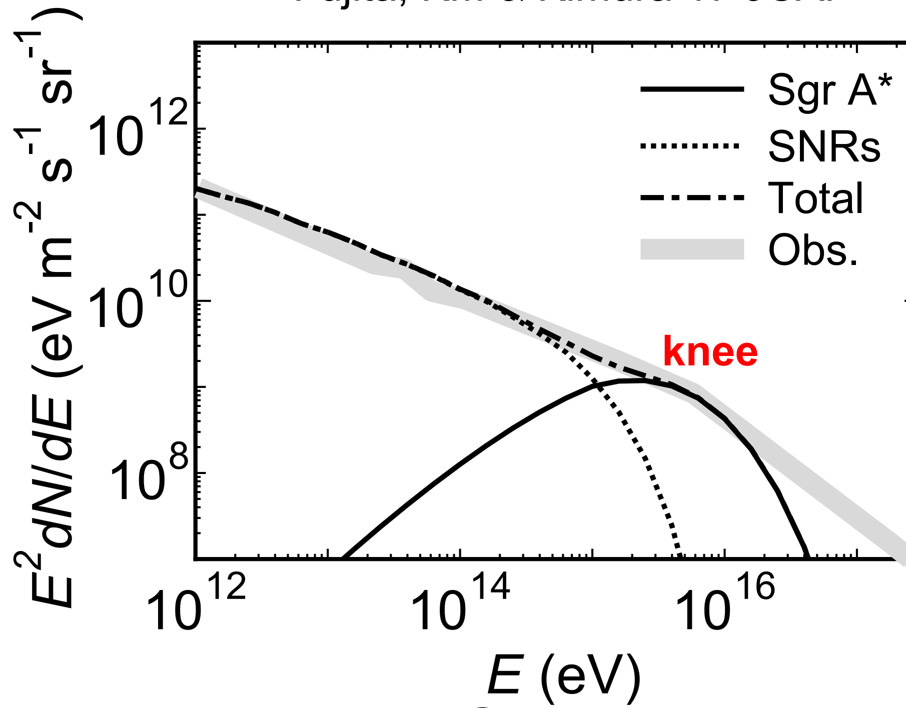


Sgr A* Black Hole as a PeVatron

Sgr A*: black hole w. radiatively inefficient accretion flow (RIAF)
RIAFs may accelerate protons up to PeV energies and beyond

Fujita, Kimura & KM 15 PRD
Fujita, KM & Kimura 17 JCAP

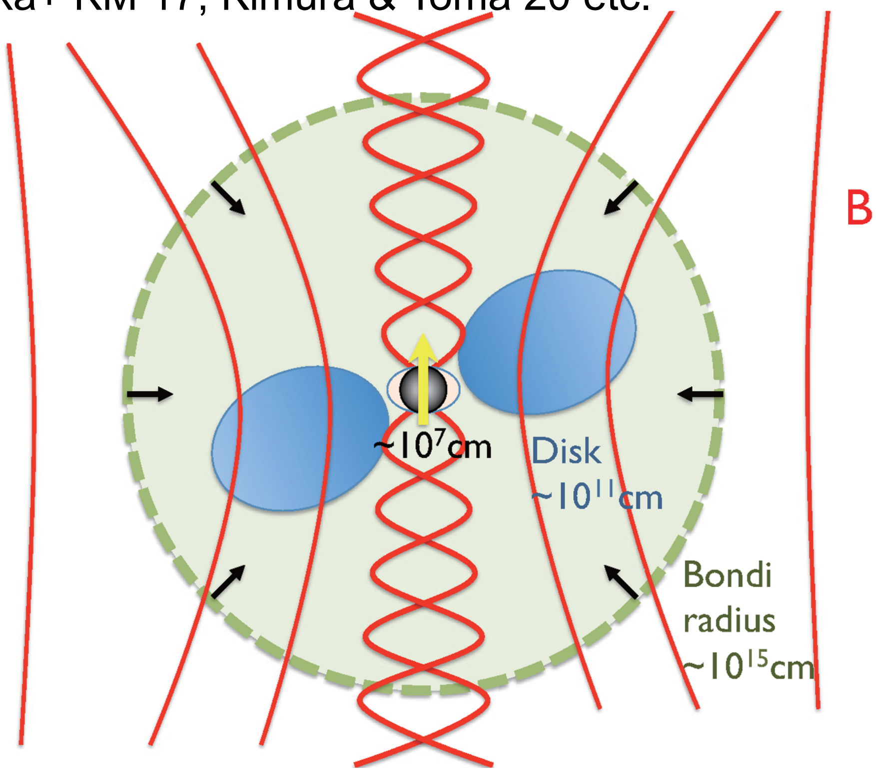


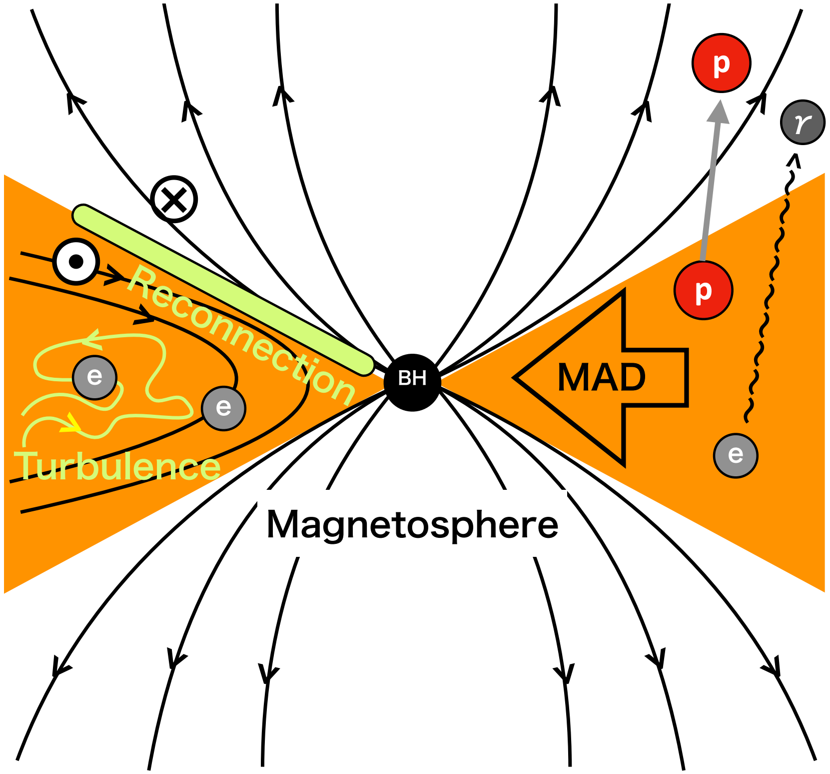


- CRs escaping from RIAFs interact with the CMZ.
- Effective pp optical depth: f_{pp} ~ 0.1 (t_{diff}/0.1 Myr)
- Extragalactic LL AGNs may explain IceCube neutrinos

Isolated Black Holes as PeVatrons?

Ioka+ KM 17, Kimura & Toma 20 etc.

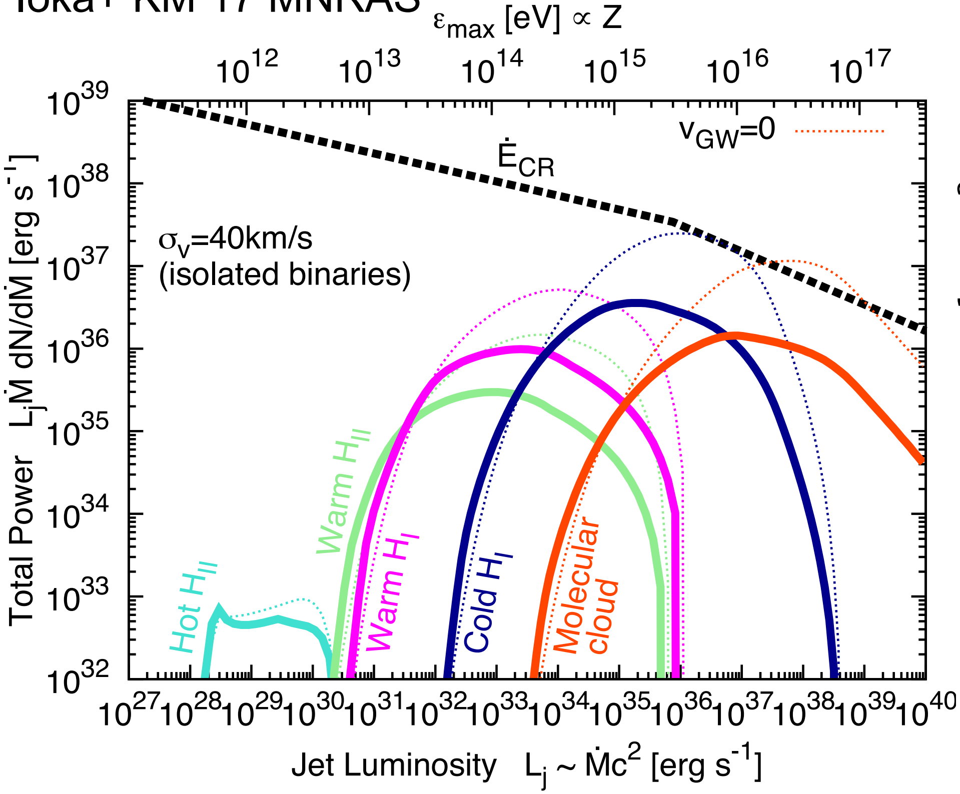




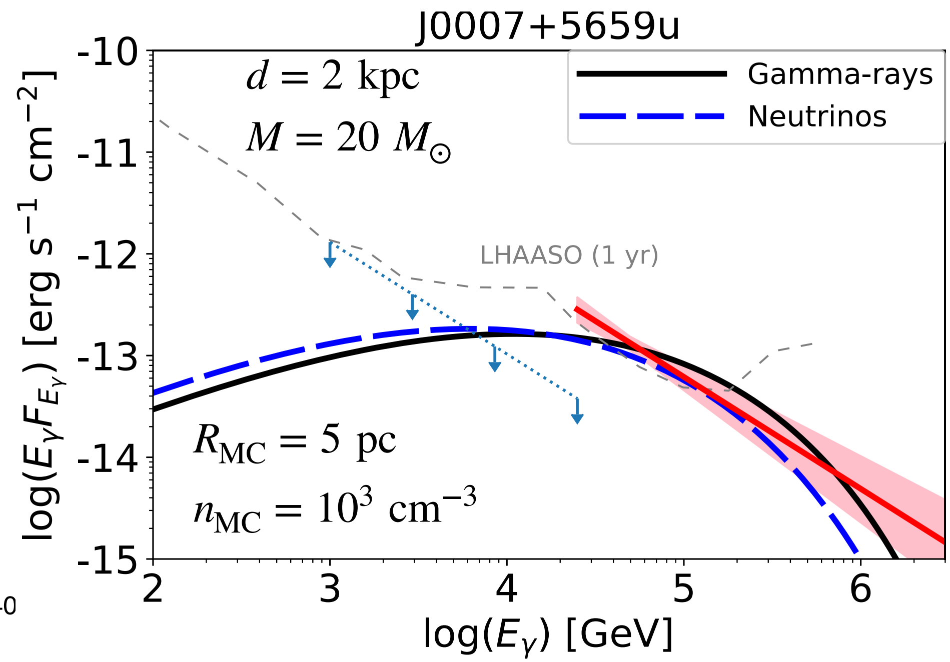
- ~0.1% of stars form black holes → N ~ 10^8
- ISM gas may accrete w. the Bondi-Hoyle-Littleton rate
- BH embedded in molecular clouds: Mdot c^2 ~ 10^{35}-10^{36} erg/s
- CR acceleration may occur in both jets and disks

Isolated Black Holes as PeVatrons?

Ioka+ KM 17 MNRAS



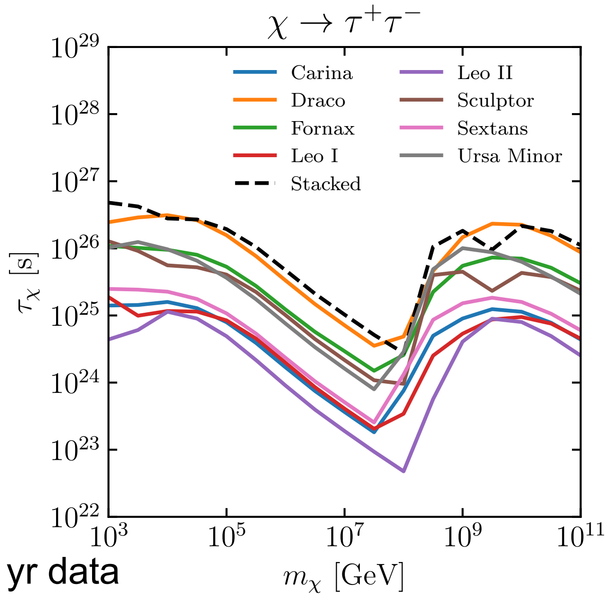
Kimura et al. 25 ApJ

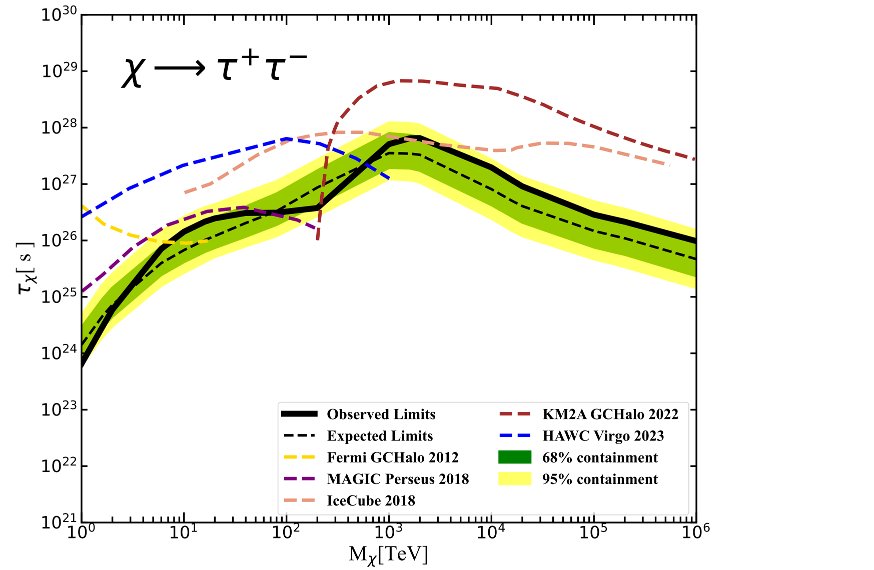


- ~10^5 isolated BHs in molecular clouds
- ~10^5 merged BHs → spinning & jets
- Either BH population can be PeVatrons that could also contribute to the CR spectrum around the knee

Search for Heavy Dark Matter in Dwarf Galaxies

decaying dark matter

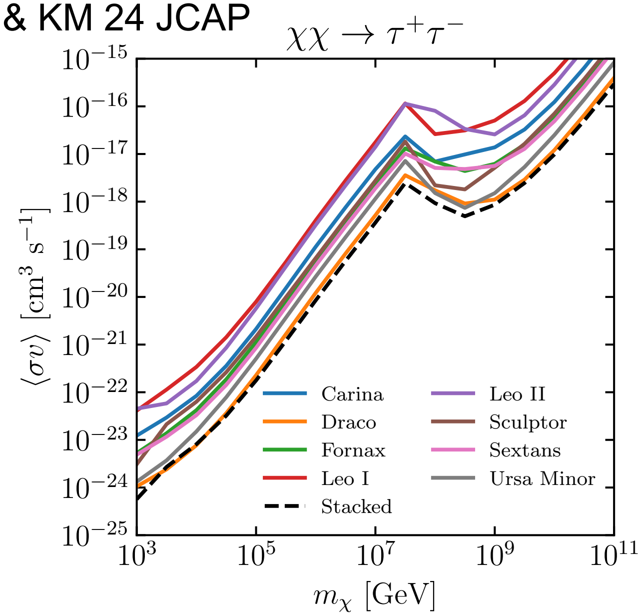


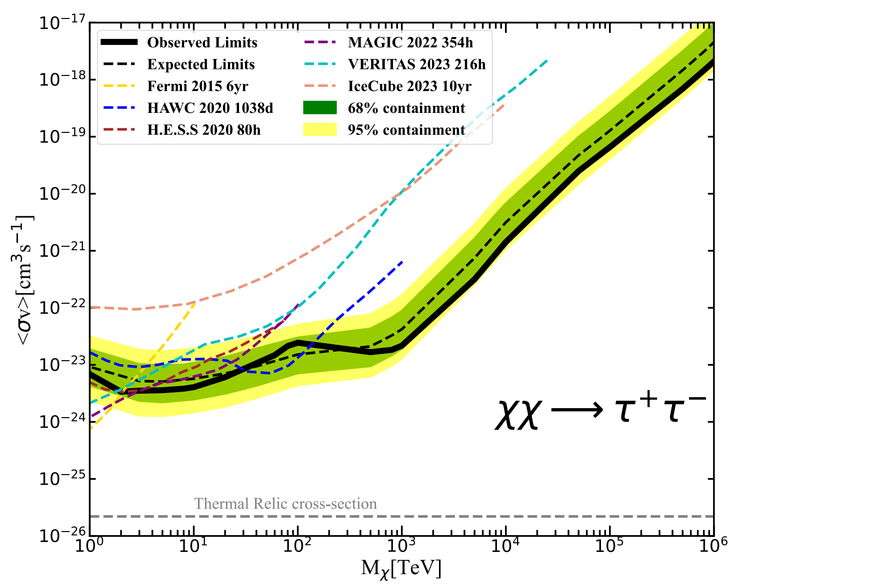


Fermi-LAT 14 yr data
Song, Hiroshima & KM 24 JCAP

LHAASO Collaboration 24 PRL

annihilating dark matter





Search for Heavy Dark Matter in Dwarf Galaxies

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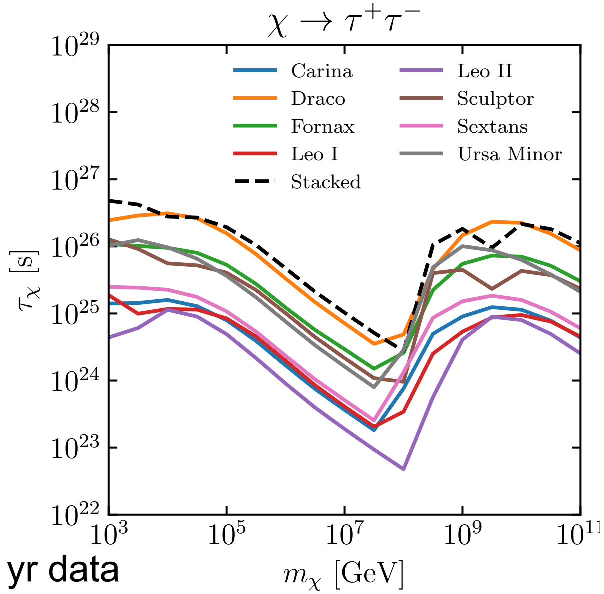
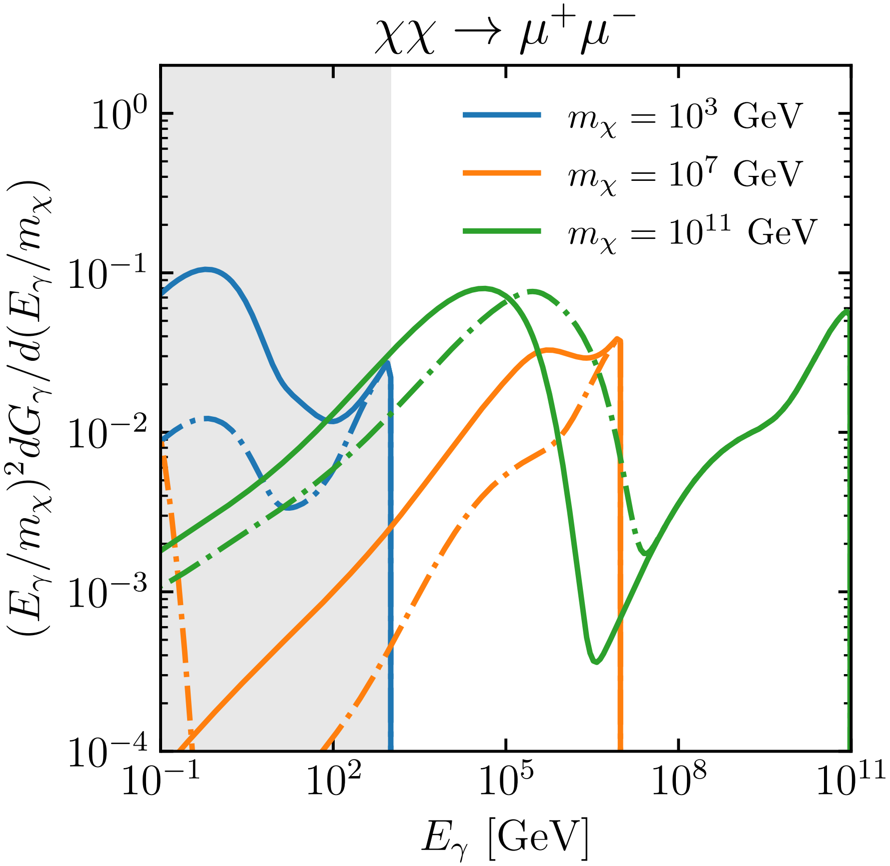
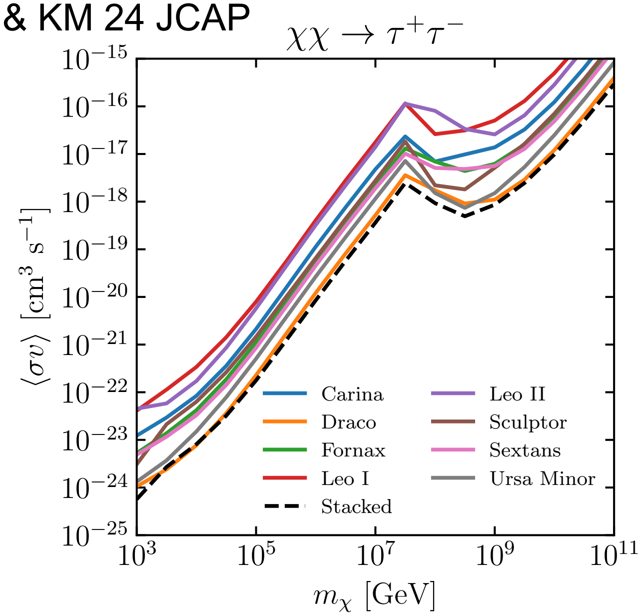


Fermi-LAT 14 yr data
Song, Hiroshima & KM 24 JCAP



annihilating dark matter



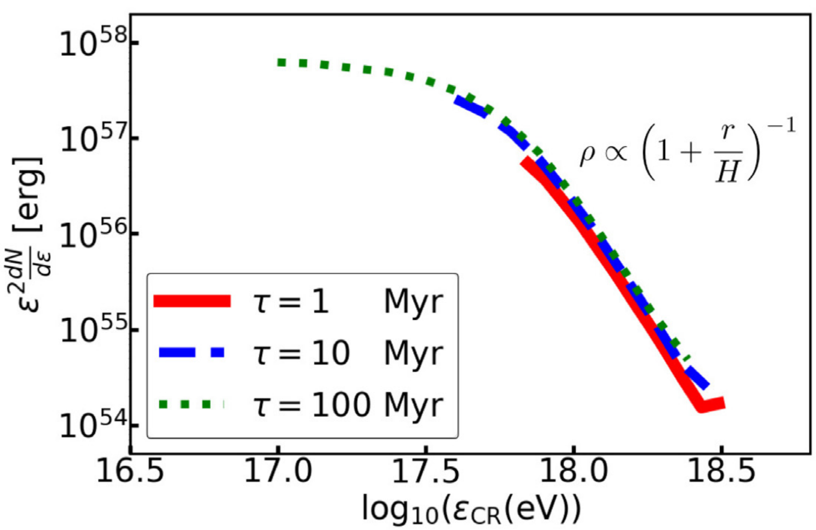
For m_χ>~10^{11} GeV, synchrotron emission may appear in the PeV range

Milky Way Galactic Winds as Super-Pevatrons?

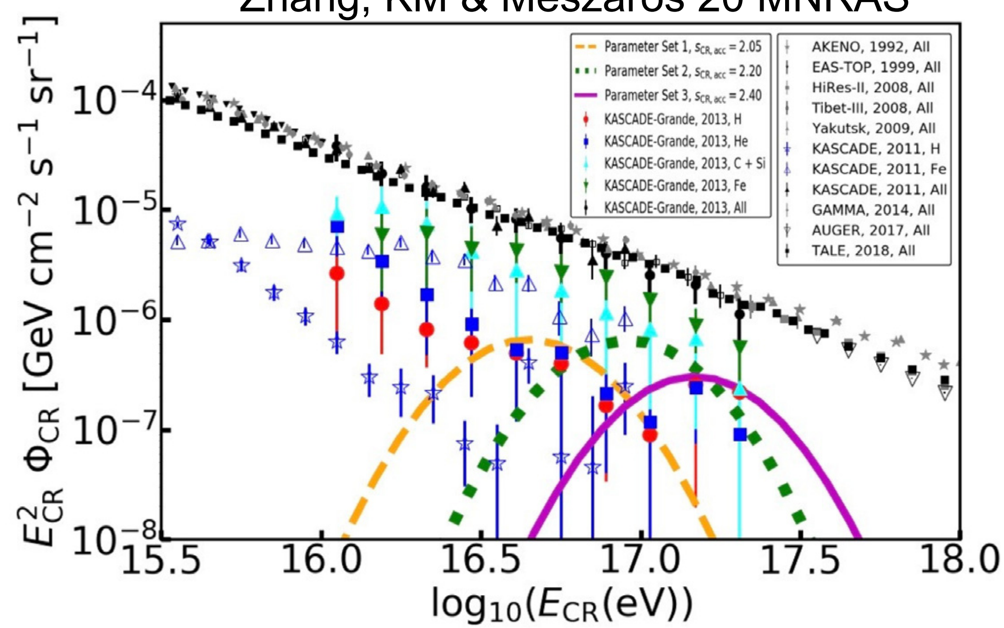
AGN winds $\varepsilon_p^{\max} \approx (3/20)(V_w/c)eB_wR \simeq 21 \text{ PeV } \epsilon_{B,-2}^{1/2} L_{w,44}^{1/2} (V_w/1000 \text{ km s}^{-1})^{1/2}$

starburst-driven winds $$\varepsilon_{\max}(t) \simeq \frac{3}{20} \cdot Z \cdot e \cdot B \cdot R_s \cdot \frac{V_s}{c}$$

$$\simeq 1.6 \times 10^{17}\, Z\, \epsilon_{B,-2}\, (\mathrm{SFR}_4 \cdot E_{ej,51})^{3/5} \rho_{0,-21}^{-1/10}\, t_{\mathrm{Myr}}^{-1/5} \text{ eV}$$



Zhang, KM & Meszaros 20 MNRAS



Possibly ~10^{20} eV by scaling up Milky-Way-like galaxies???
(ex. Anchordoqui 18, KM & Fukugita 19, Peretti+ 21)