

Hadronic Signatures of Black Hole Jets



PENNSTATE



**Kohta Murase
(Penn State)**

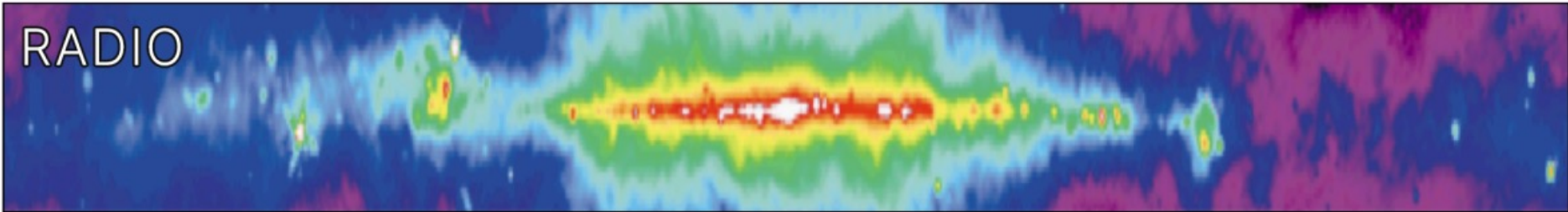


CDHY Pevatron Workshop 2025

2023: Evidence of Neutrinos from the Milky Way

IceCube 23 Science

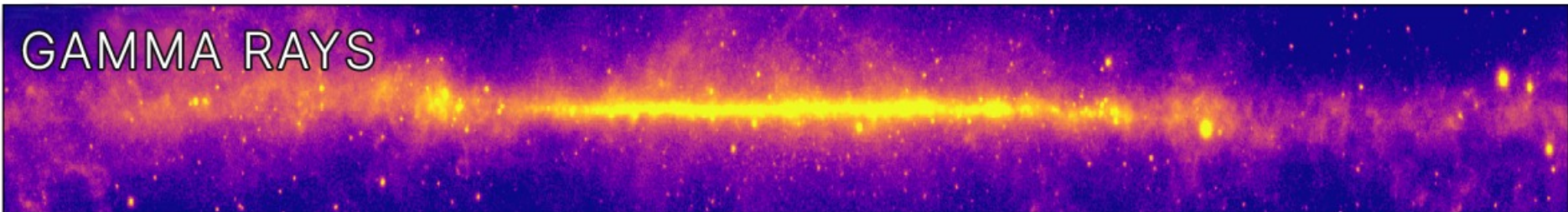
RADIO



OPTICAL



GAMMA RAYS



NEUTRINOS



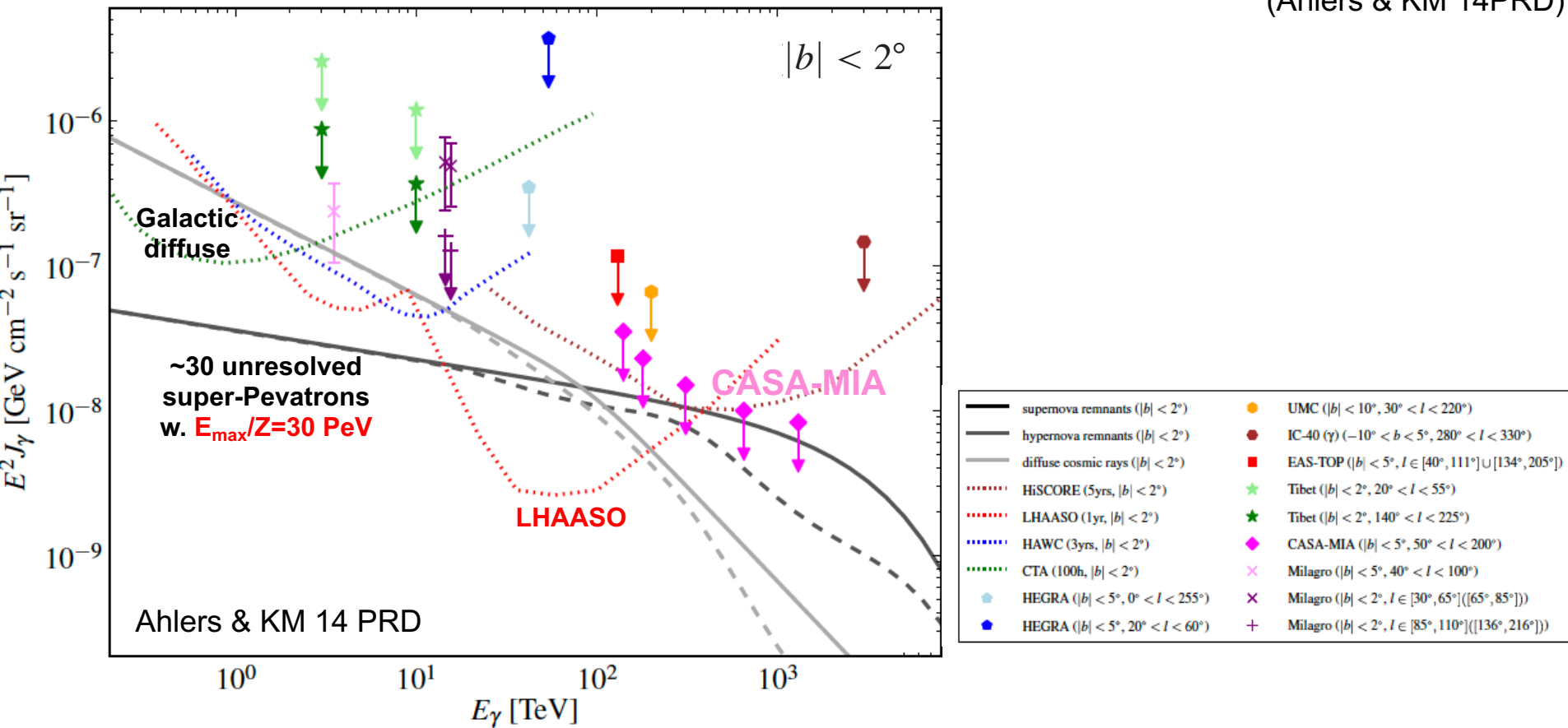
Neutrino emission from the Milky Way (**~10% of total**) has been observed w. 4.5σ

Galactic Multimessenger Connection: A Decade Ago

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

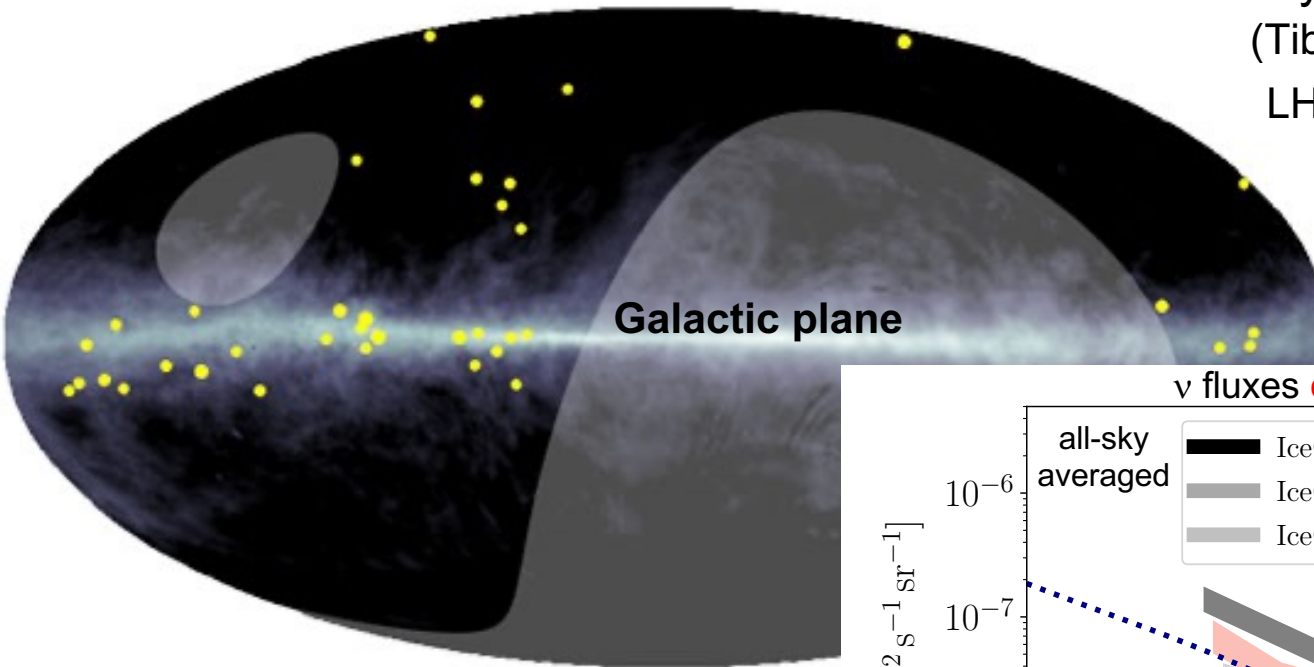
- Most γ rays from Galactic sources reach Earth
- Neither γ rays nor ν s were NOT observed in the sub-PeV range a decade ago
- We already learned that Galactic contribution to IceCube ν s is **subdominant**

(Ahlers & KM 14PRD)



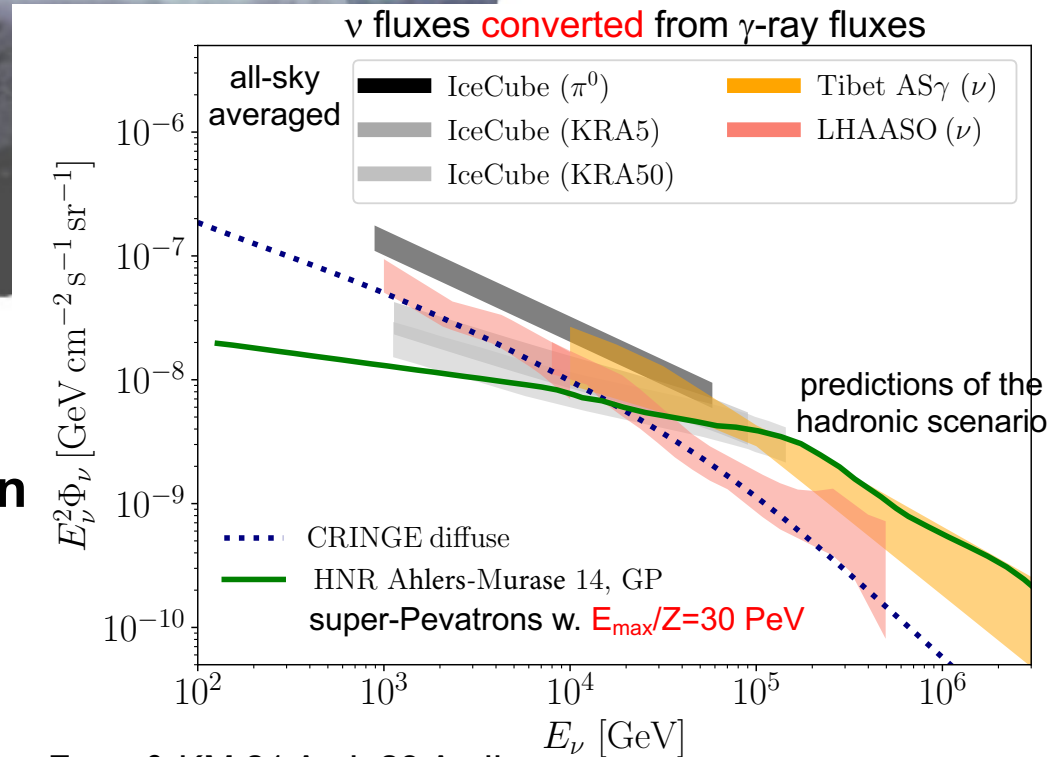
Galactic Multimessenger Connection: Current

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



- Supporting hadronic (pp) origin
- Truly diffuse vs unresolved? (extended)

See Ke Fang's talk

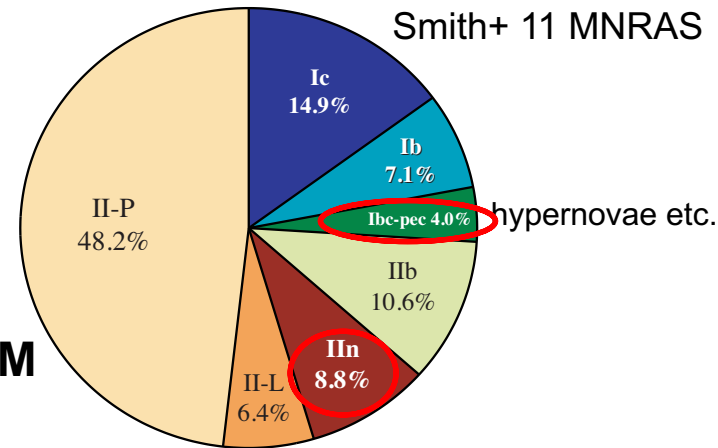


Fang & KM 21 ApJ, 23 ApJL

Hypernovae/Interacting SNe as (Super-)Pevatrons

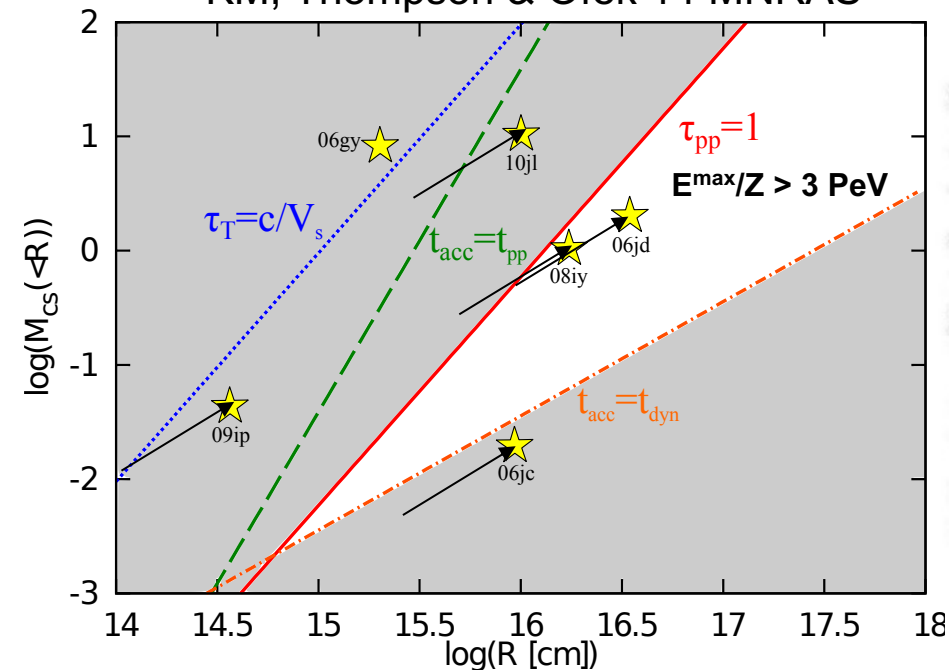
$$E_{\max} \sim 200 \text{ TeV } Z \left(\frac{\tilde{\epsilon}_p}{0.03} \right) \left(\frac{n}{1 \text{ cm}^{-3}} \right)^{1/2} \left(\frac{V_s}{10^4 \text{ km s}^{-1}} \right)^2 \left(\frac{R}{1 \text{ pc}} \right)$$

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

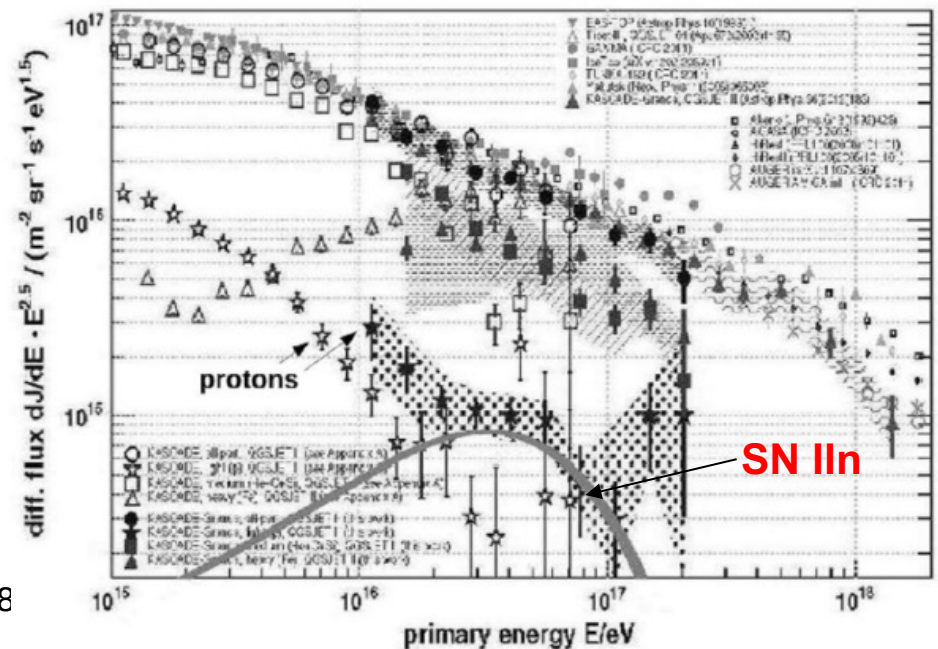


maximum energies will be higher than typical SNRs for explosions w. faster velocities and/or denser CSM

KM, Thompson & Ofek 14 MNRAS

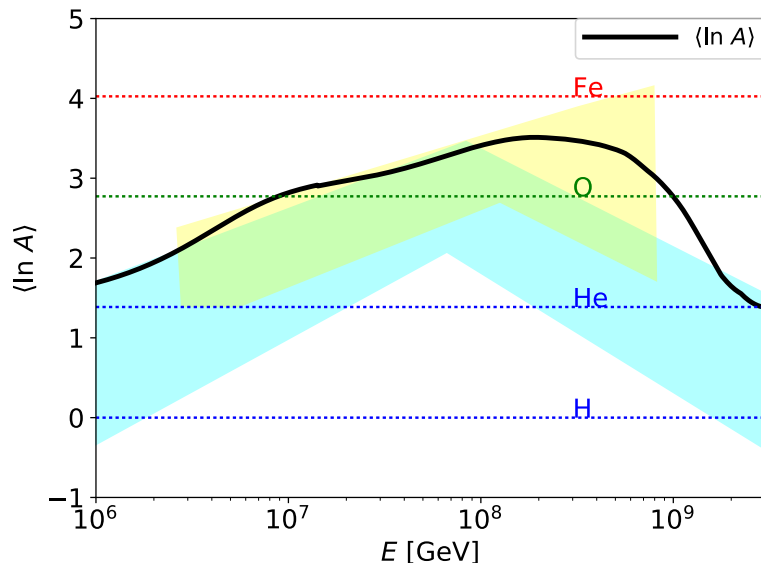
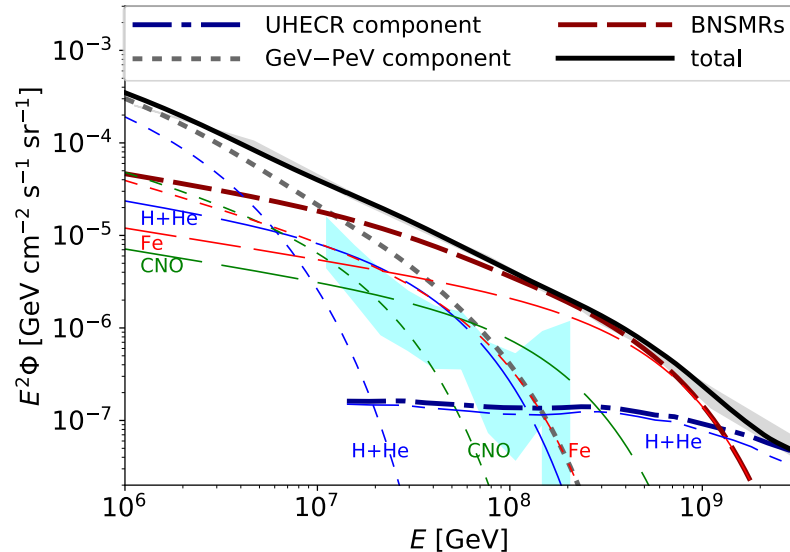


Zirakashvili & Ptuskin 16 APh (see also Sveshnikova 03 A&A)

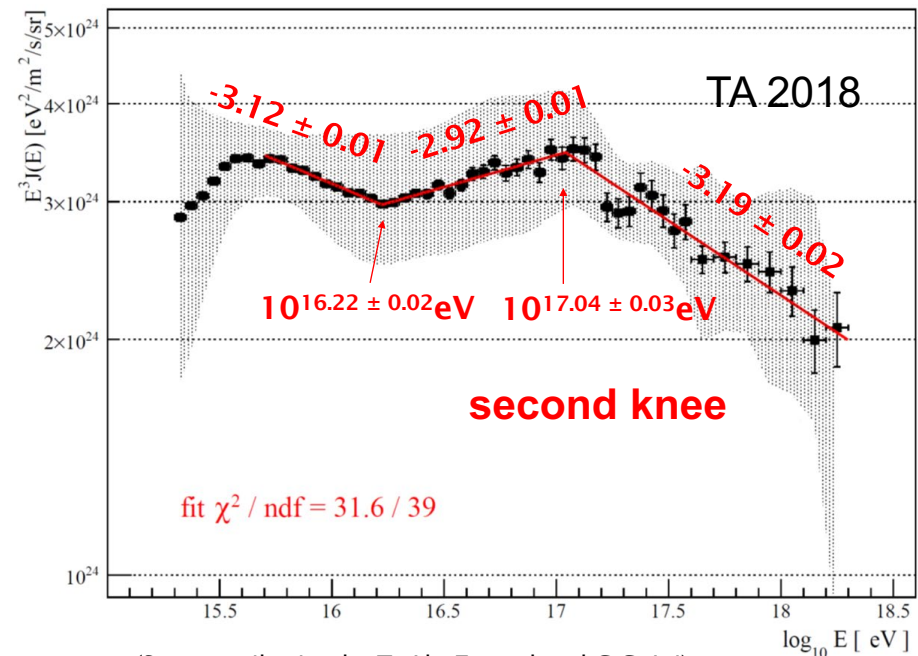


Neutron Merger Remnants as (Super-)Pevatrons

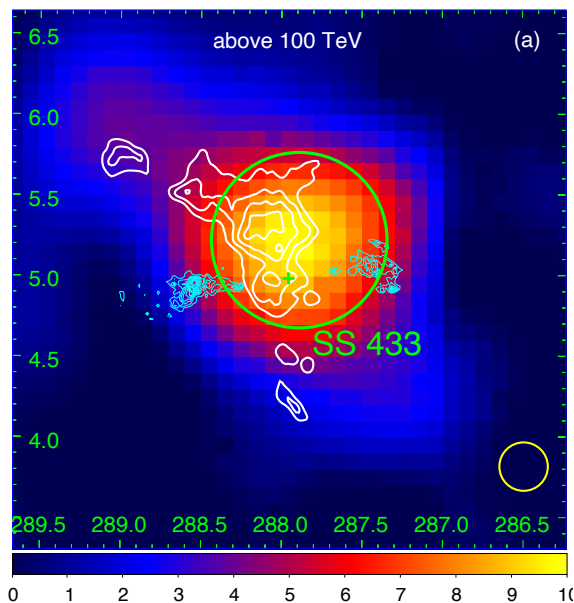
Kimura, KM & Meszaros 18 ApJ



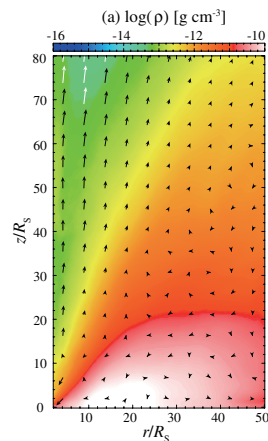
- Merger ejecta
 $M_{\text{ej}} \sim 0.03\text{--}0.05 M_{\text{sun}}$ w. $V \sim 0.2\text{--}0.3c$
- Apply the same scaling from SNRs
 $\rightarrow E_{\text{NS}}^{\text{max}}/Z \sim 3\text{--}30 \text{ PeV}$
 (for $E_{\text{SNR}}^{\text{max}}/Z \sim 0.3\text{--}3 \text{ PeV}$)
- With a merger rate of $\sim 10^{-4} \text{ yr}^{-1} \text{ gal}^{-1}$
 they should contribute to Galactic CRs
 (see Takami+ 13, Rodrigues+ 18 for an extragalactic model)



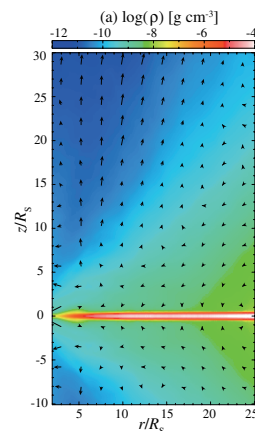
Microquasars as Super-Pevatrons



Hot Accretion Flow (RIAF)



Standard accretion disk



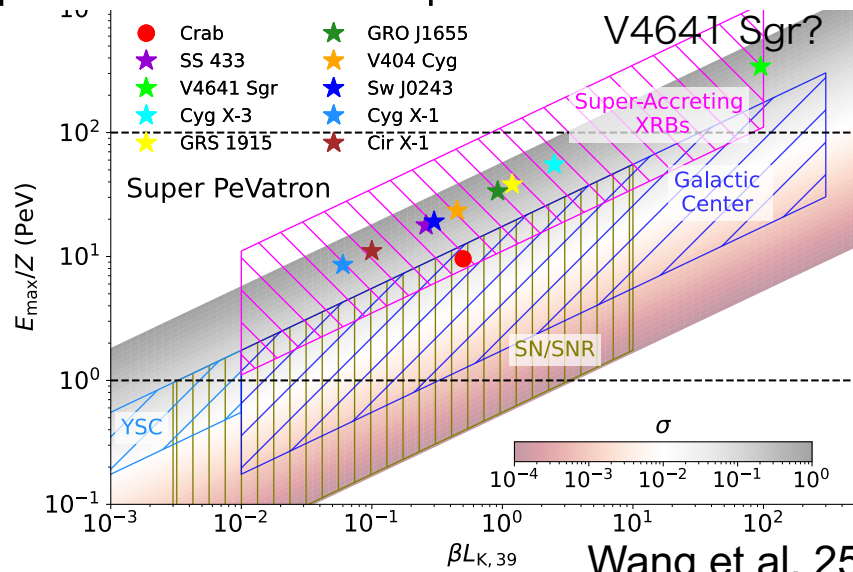
Slim disk + Jets

$L \sim 0.01 L_{\text{Edd}}$

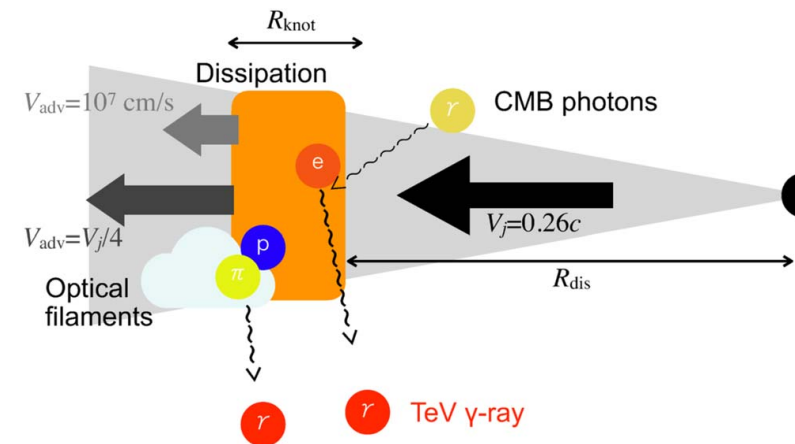
$L \sim L_{\text{Edd}}$

$L = \eta \dot{M} c^2$

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

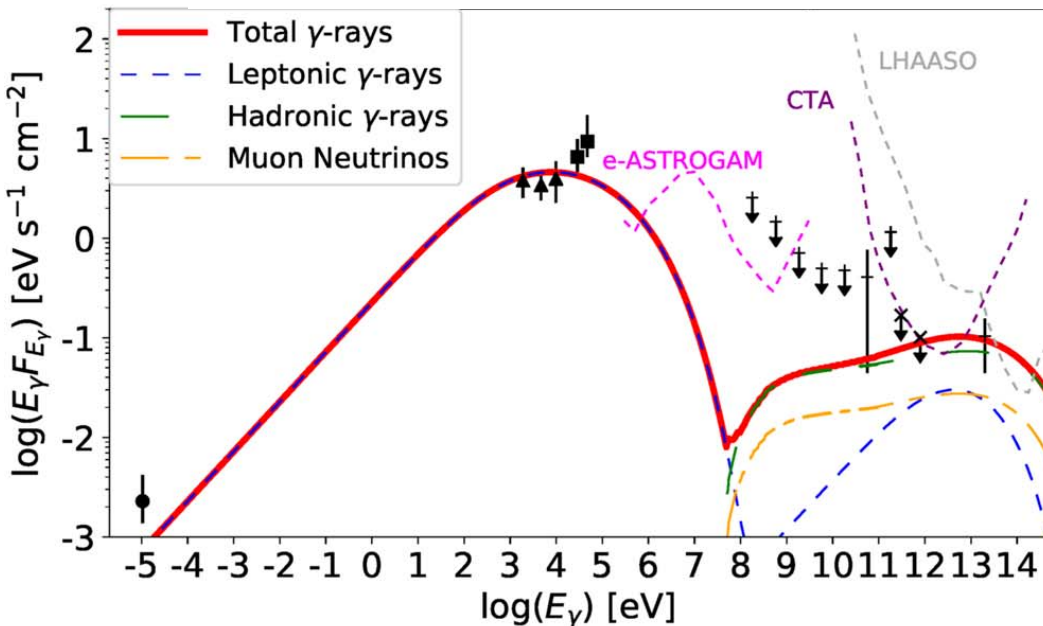


Hadronic Gamma-Ray Signatures?

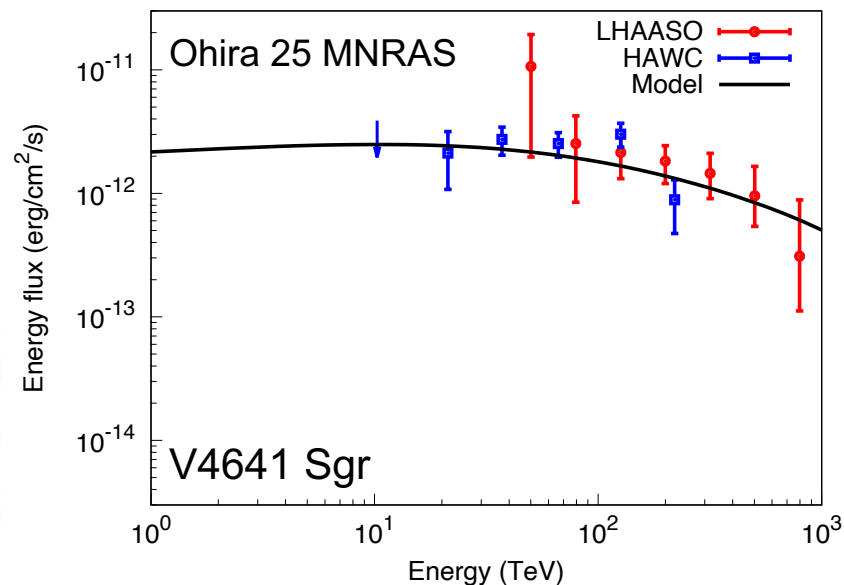


Kimura, KM & Meszaros 20 ApJ

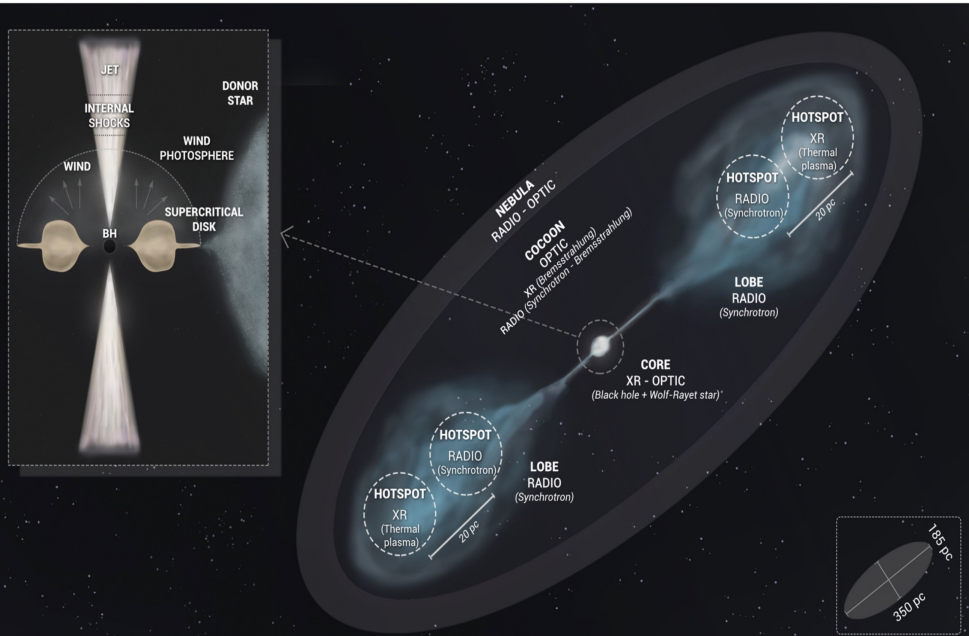
leptohadronic scenario for SS 433



- VHE γ -ray detections from microquasars (HAWC, LHAASO, HESS)
- Theoretically expected (Aharonian & Atoyan 96)
- Leptonic dominance at 1-10 TeV (HAWC Collaboration 18, HESS Collaboration 24)
- Hadronic contribution is possible especially at higher energies
- ν detection: more than 2 decades even w. IceCube-Gen2 (SS 433)



Common Acceleration Mechanisms between Microquasars and AGNs?



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

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

$$E_{\max}/Z > 3 \text{ PeV} \rightarrow \xi < \sim 10 \text{ (for } B \sim 30 \mu\text{G)}$$

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

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

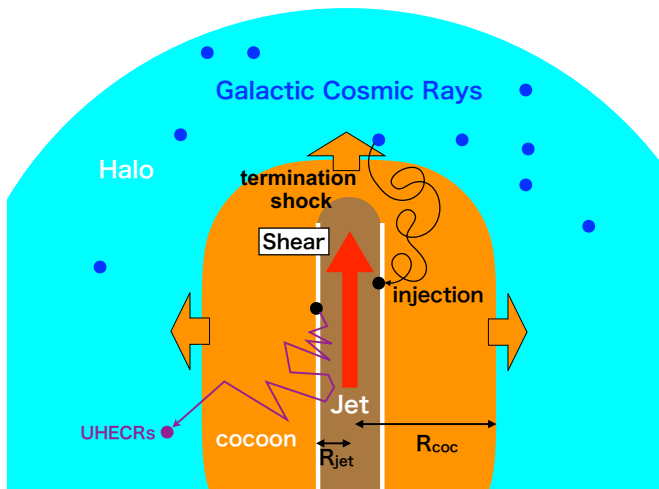
→ internal shocks/termination shock: may not be promising for UHECRs

Alternative acceleration mechanisms?

Particle Acceleration by Large-Scale Jets

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

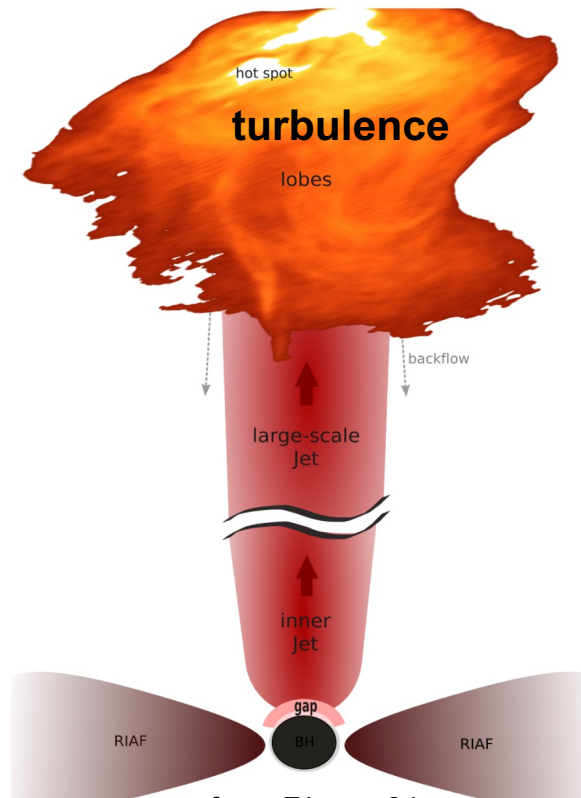
(Caprioli 15, Kimura, KM & Zhang 18)



from Kimura, KM & Zhang 18

Turbulent shear acceleration in backflows

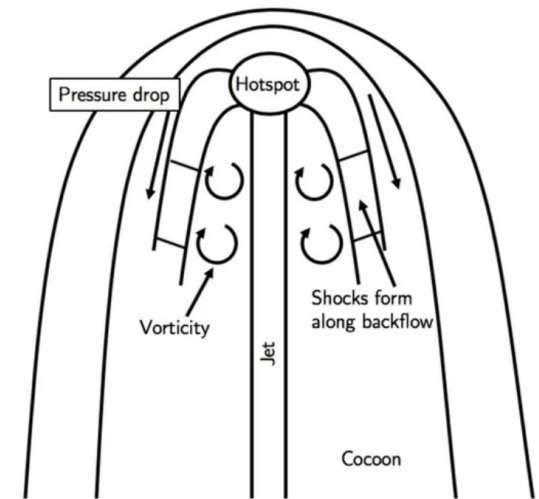
(Hardcastle 10, Ohira 13)



from Rieger 21

DSA acceleration in backflows in cocoons

(Matthews+ 18, 19)



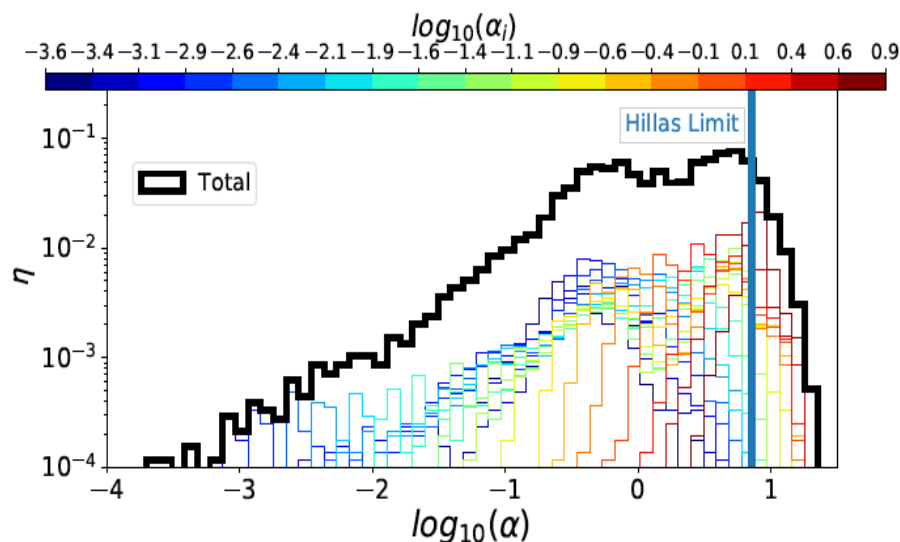
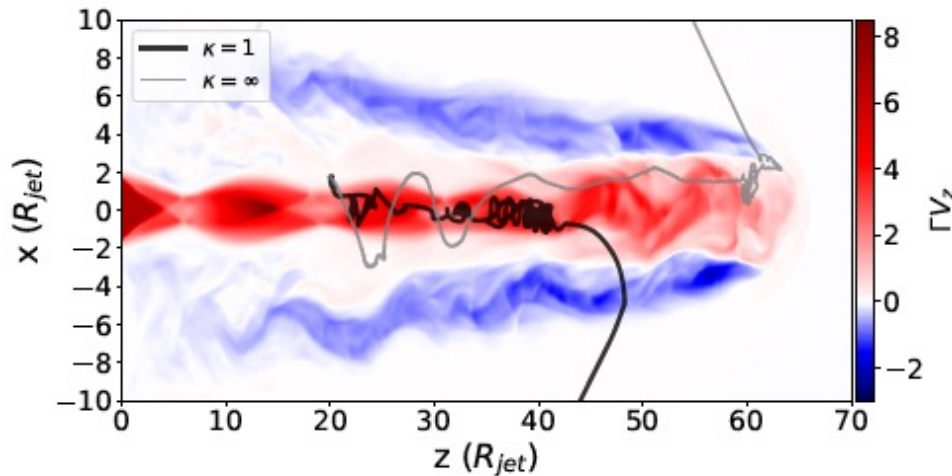
from Matthews+ 19

“Reacceleration” of galactic CRs by AGN jets

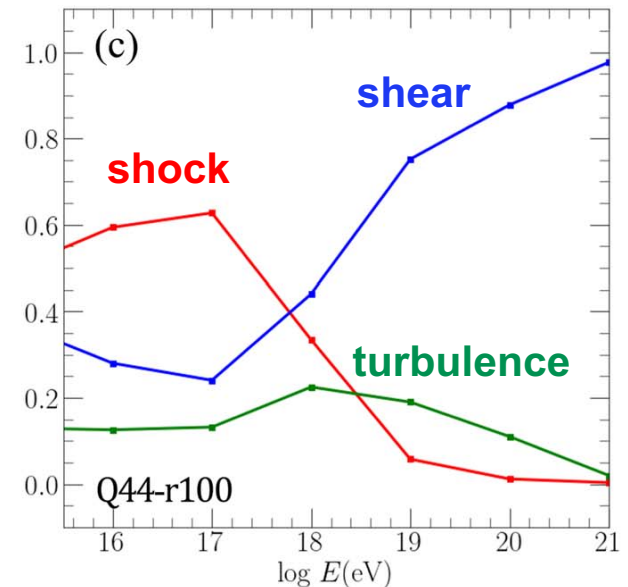
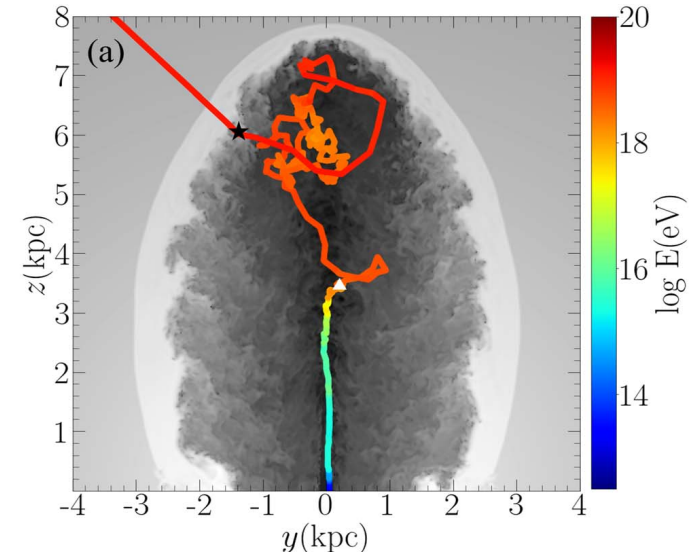
Test Particle Simulations of Particle Acceleration

MHD simulations

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

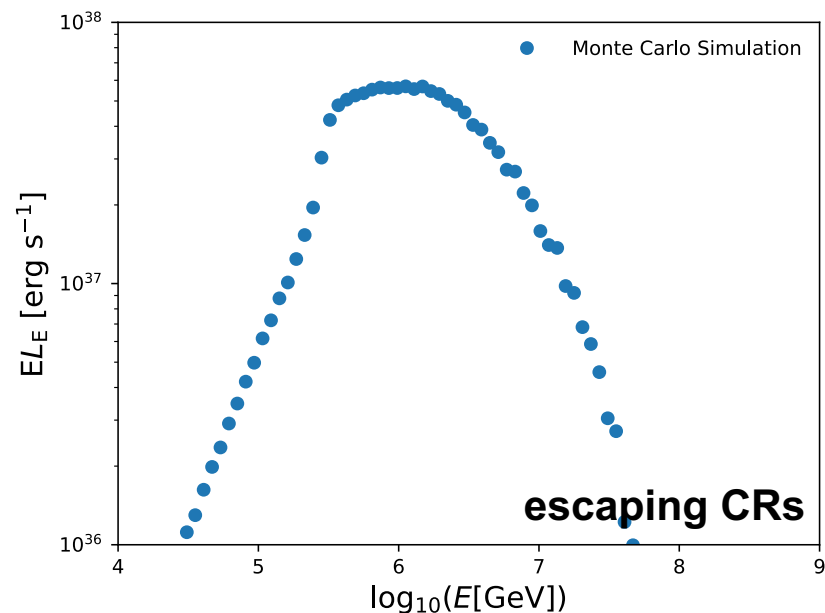


HD simulations (Seo, Ryu & Kang 24 ApJ)



Shear Acceleration Model for Microquasars

Zhang, Kimura & KM 2506.20193

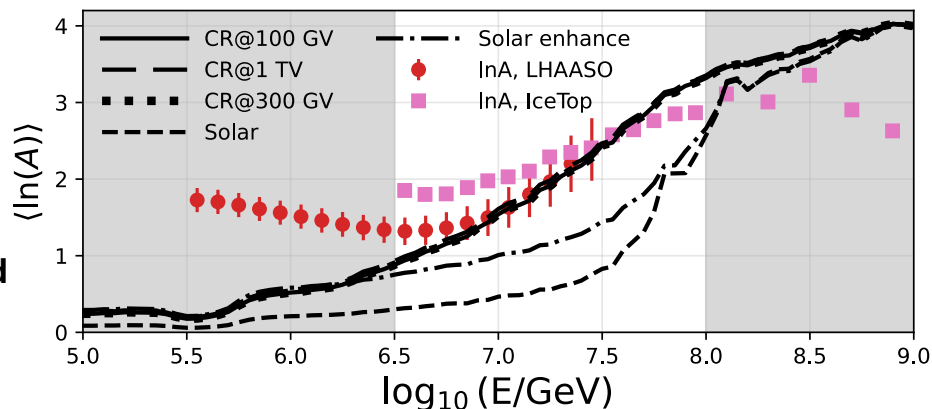
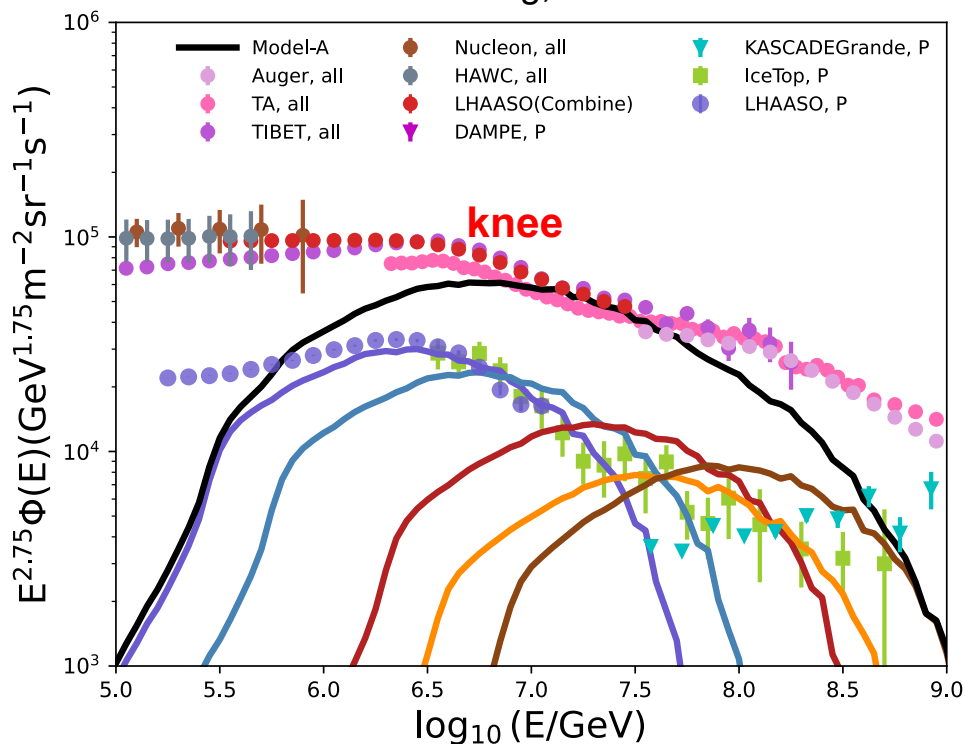


- Injection: Galactic CRs at $\sim$ TeV
- $B_{\text{coc}} \sim 10\text{-}30 \mu\text{G}$ w. $r_{\text{coc}} = 60 \text{ pc}$ (Kolmogorov assumed)
- $B_{\text{jet}} \sim 50\text{-}100 \mu\text{G}$ w. $r_{\text{jet}} = 3\text{-}4 \text{ pc}$

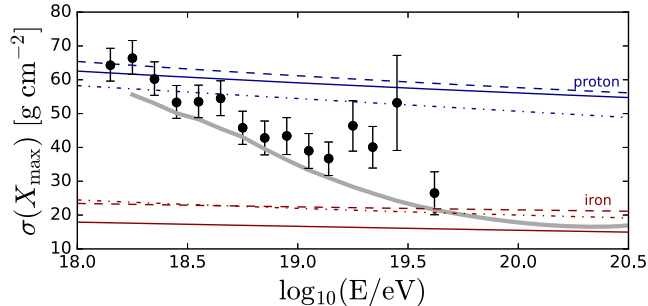
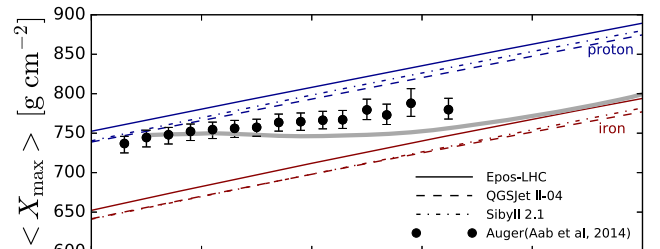
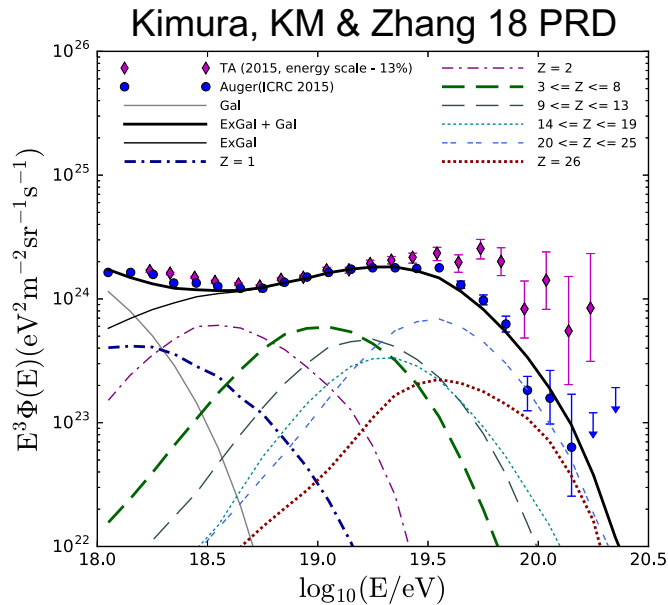
$$E_{\text{max}} = \zeta e B_{\text{coc}} l_{\text{coh}}^{1/2} r_{\text{jet}}^{1/2} \Gamma_{\text{jet}} \beta_{\text{jet}} \sim 4 \text{ PeV}$$

$$L_{\text{CR}} \approx E_{\text{max}} \dot{N}_{\text{CR}} \sim 10^{38} \text{ erg/s} \ll L_{\text{Edd}}$$

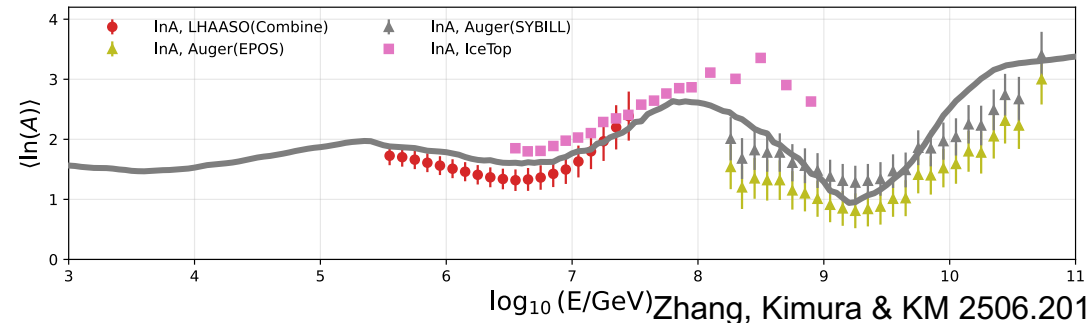
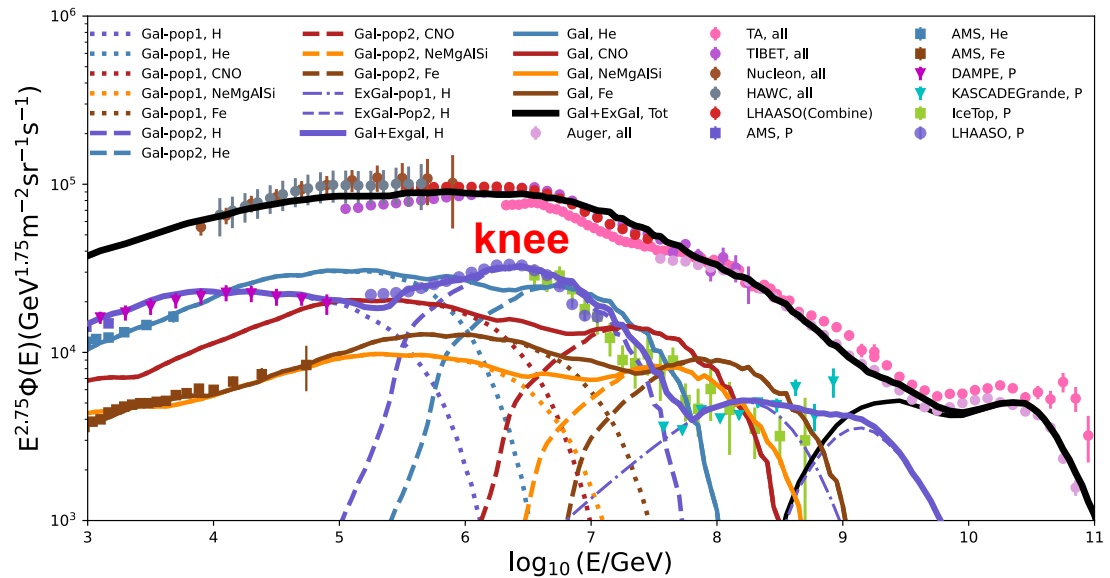
$$Q_{\text{cr,tot}} \sim 1.3 \times 10^{42} \text{ erg kpc}^{-3} \text{ yr}^{-1}$$



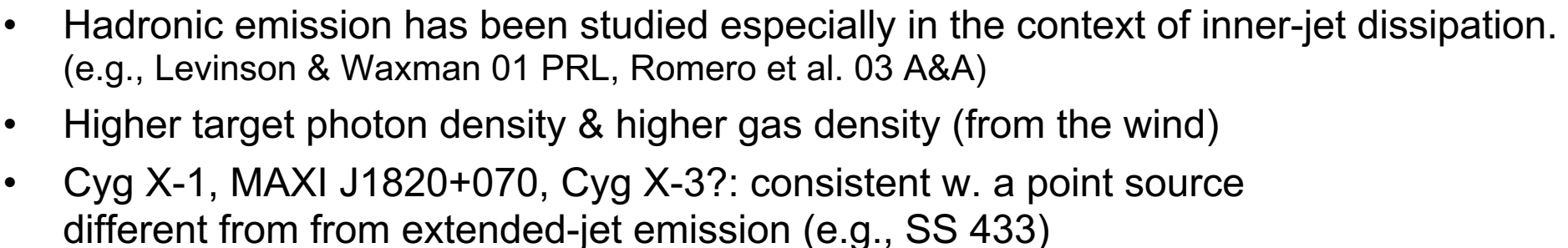
Shear Acceleration Model vs Cosmic-Ray Data



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



compact jet models

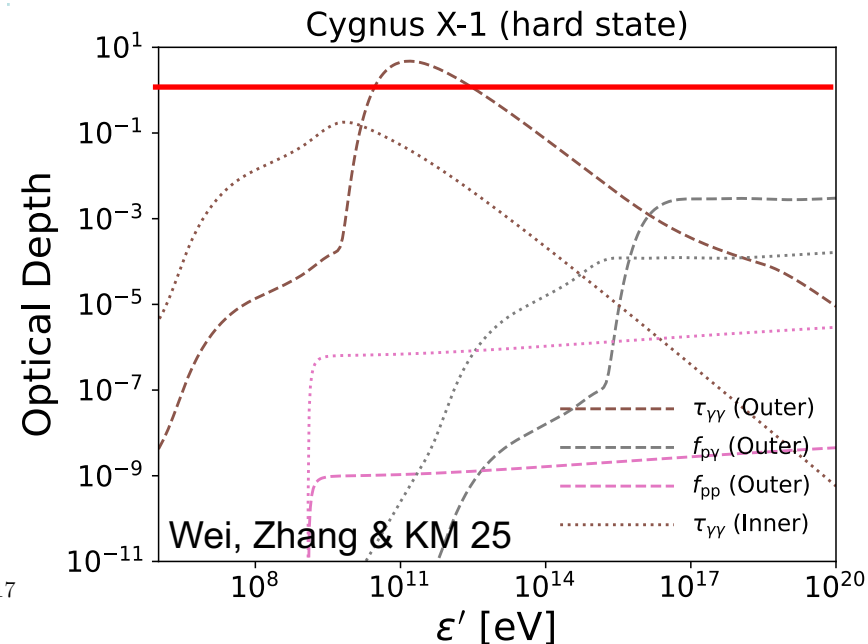
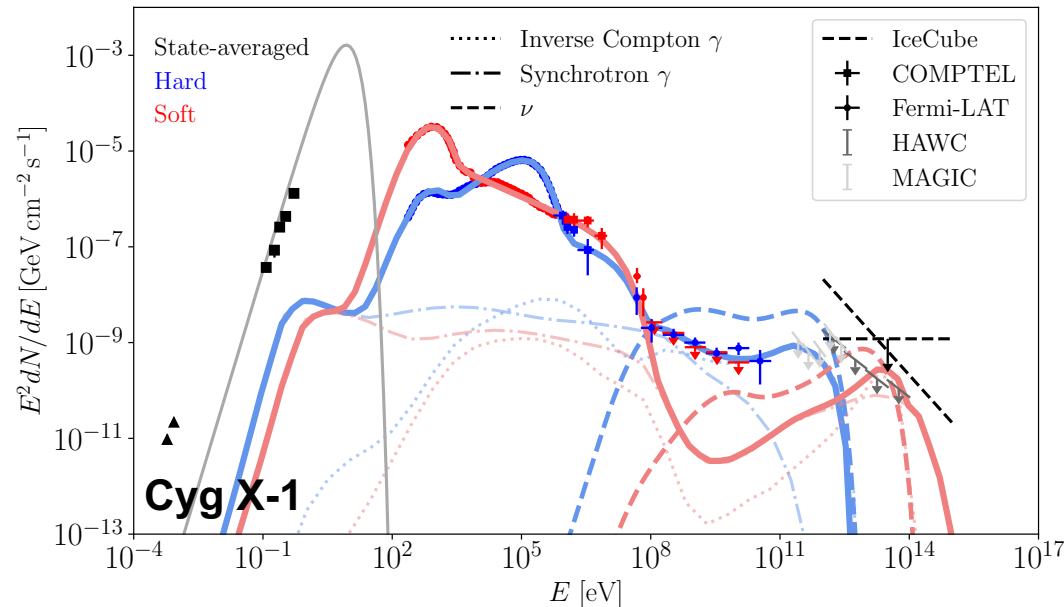


Hadronic Emission from Compact Regions?

Such compact emissions are also of interest in the context of AGN

1. Coronae of X-ray binaries?

Corona (Fang+ 24 ApJL)

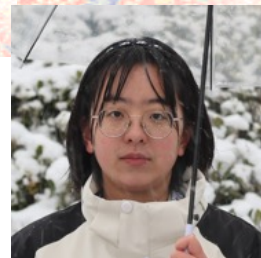


2. Isolated black holes or low-luminosity AGN (Sgr A*)

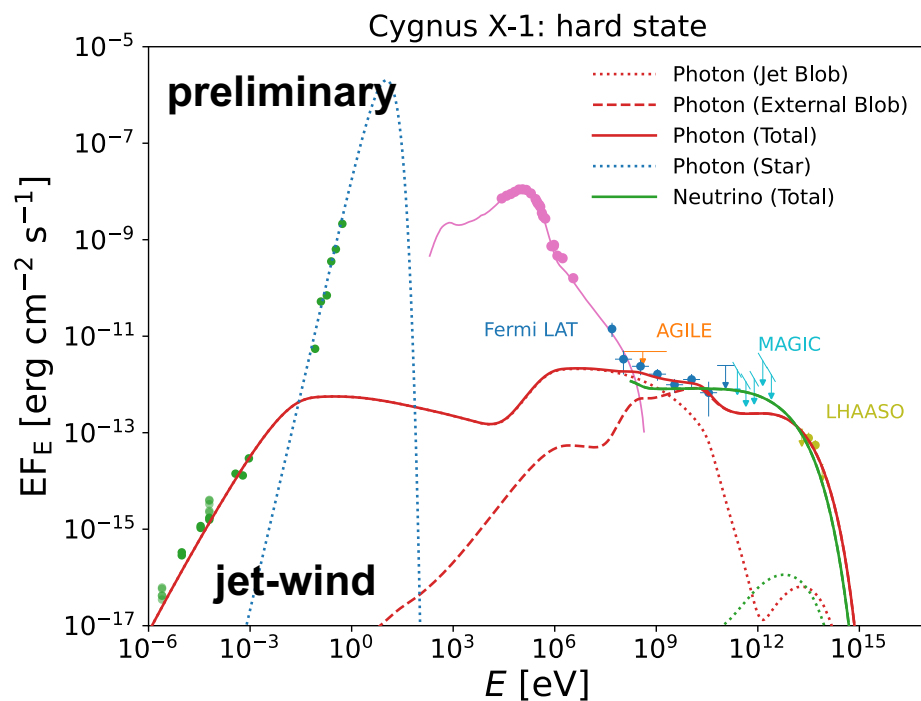
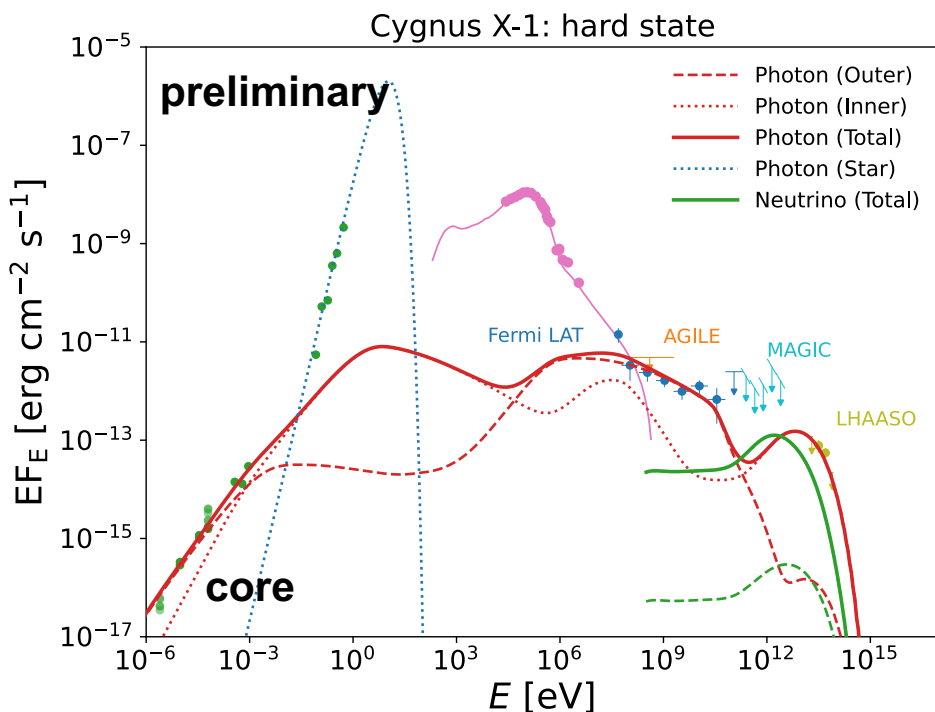
a. Jets and RIAFs in isolated black holes (Ioka+KM 17 MNRAS, Kimura+ 21)

b. CRs from Sgr A* may interact w. the CMZ (Fujita, Kimura & KM 15 PRD)

Applications to Cygnus X-1



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

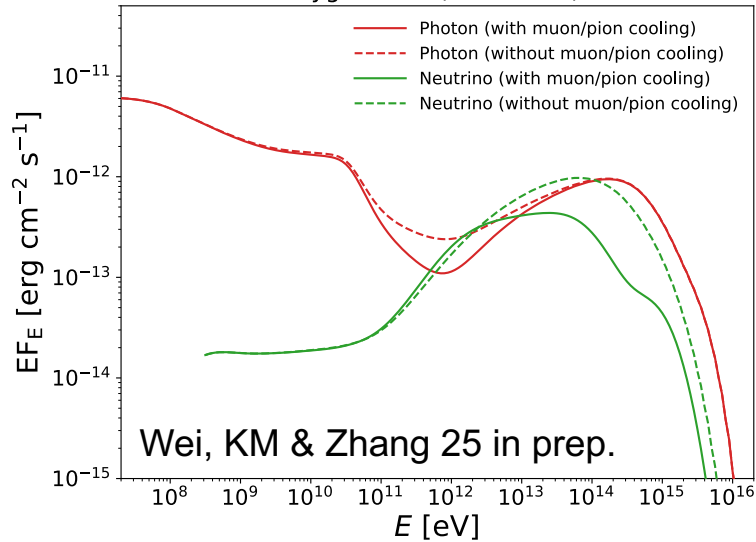


Wei, KM & Zhang 25 in prep.

- $L_{\text{Edd}} \sim 3 \times 10^{39}$ erg/s, $\varepsilon_p \sim 0.03$, $\varepsilon_e \sim 10^{-5}$, $\varepsilon_B \sim 10^{-3} - 10^{-1}$
- Either pp or $p\gamma$: sub-TeV dip $\rightarrow$ indication of core scenario

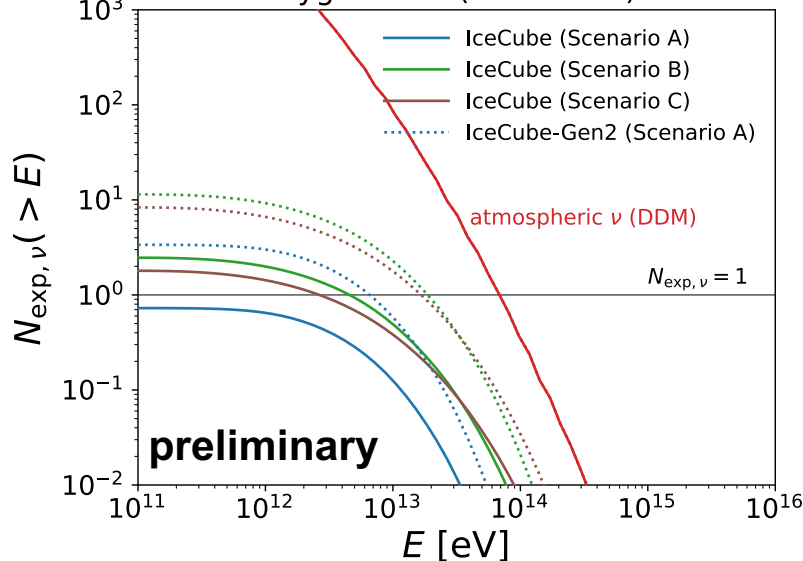
Neutrinos

Cygnus X-1 (hard state)

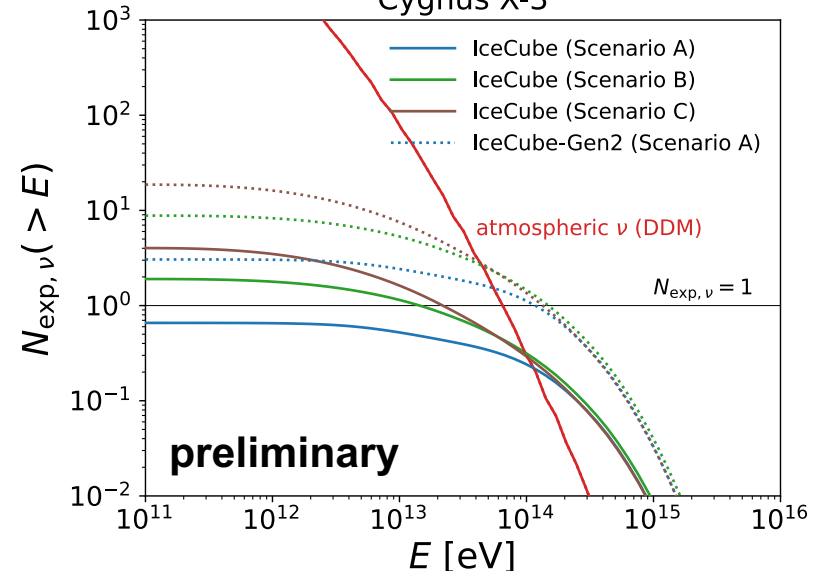


- Potentially more neutrinos than gamma rays if hidden
- Significant pion/muon cooling (which are often ignored) can reduce both neutrino and secondary synchrotron fluxes
- (Not surprisingly) neutrino detection is challenging as in ~ 10 -100 pc jet models

Cygnus X-1 (hard state)



Cygnus X-3



Summary

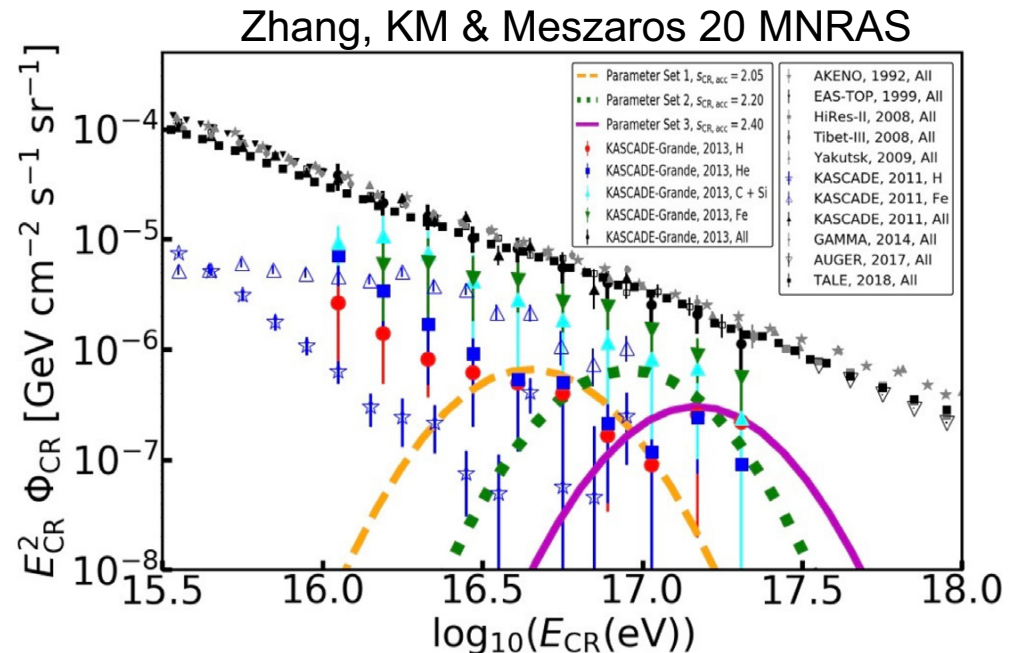
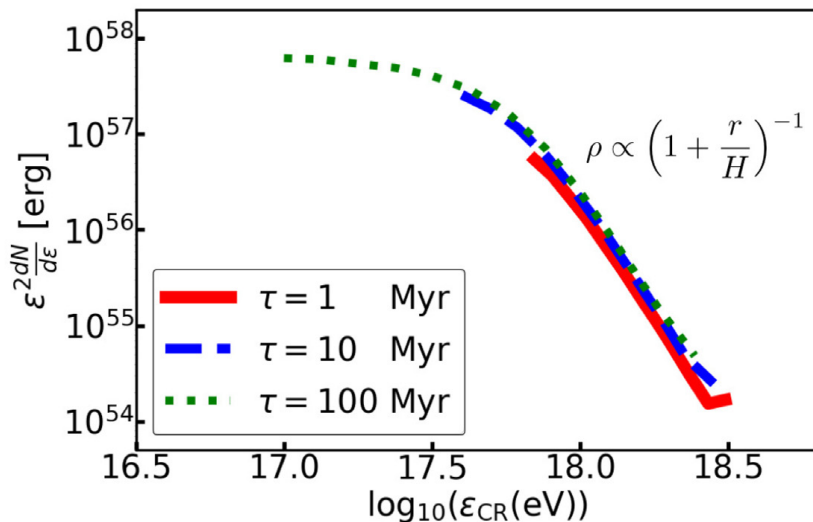
- Galactic diffuse: **multimessenger connection** now observed
supporting the hadronic origin whether the origin is truly diffuse or not
contribution of super-Pevatrons may be dominant above 100 TeV
- Microquasars as emerging super-Pevatrons
potential contributor to cosmic rays around the knee
shear acceleration (jet-cocoon boundary behind the termination shock)
common explanation for the highest-energy cosmic rays? (cf. AGN)
- Compact 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?

Milky Way Galactic Winds as Super-Pevatrons?

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

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

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

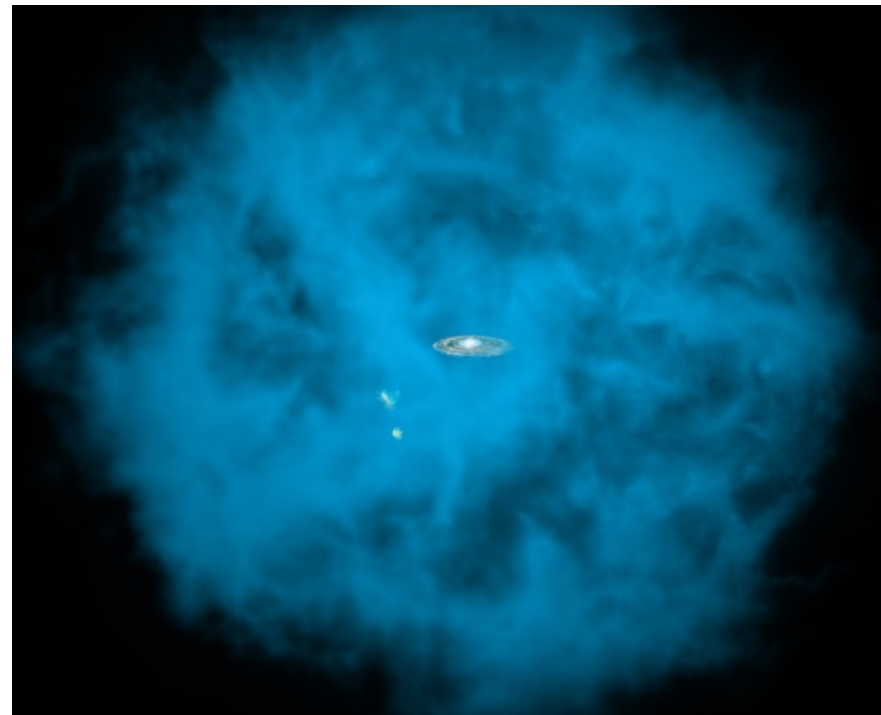
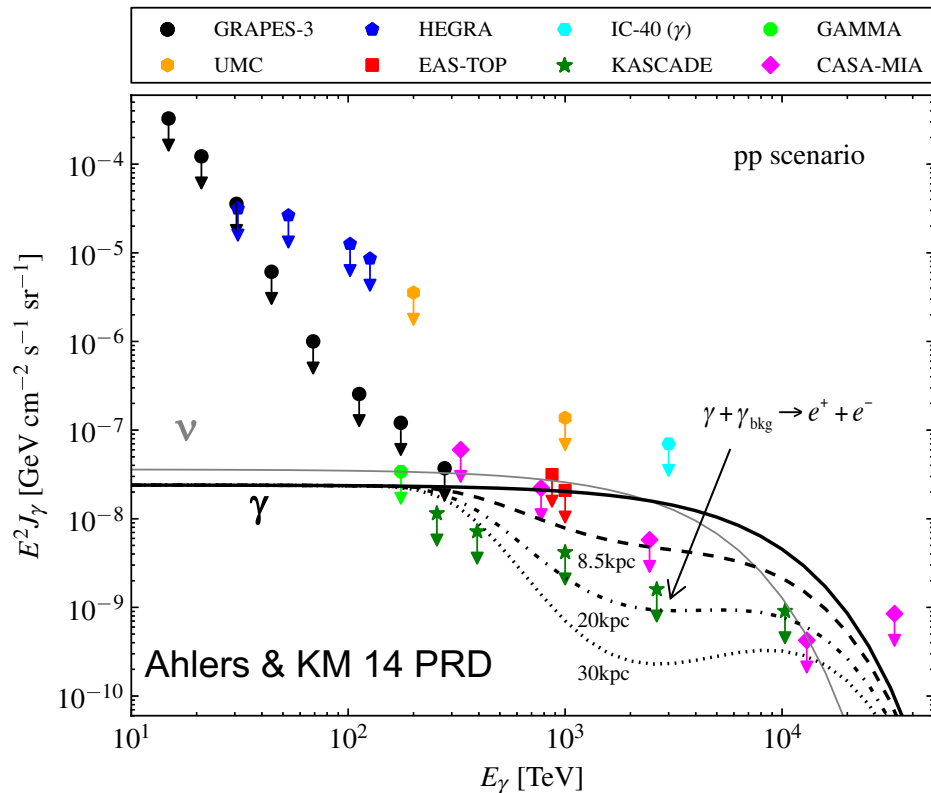


Possibly $\sim 10^{20}$ eV by scaling up Milky-Way-like galaxies???

(ex. Anchordoqui 18, KM & Fukugita 19, Peretti+ 21)

Galactic Halo Contribution?

Isotropic limits (Galactic halo CR model)



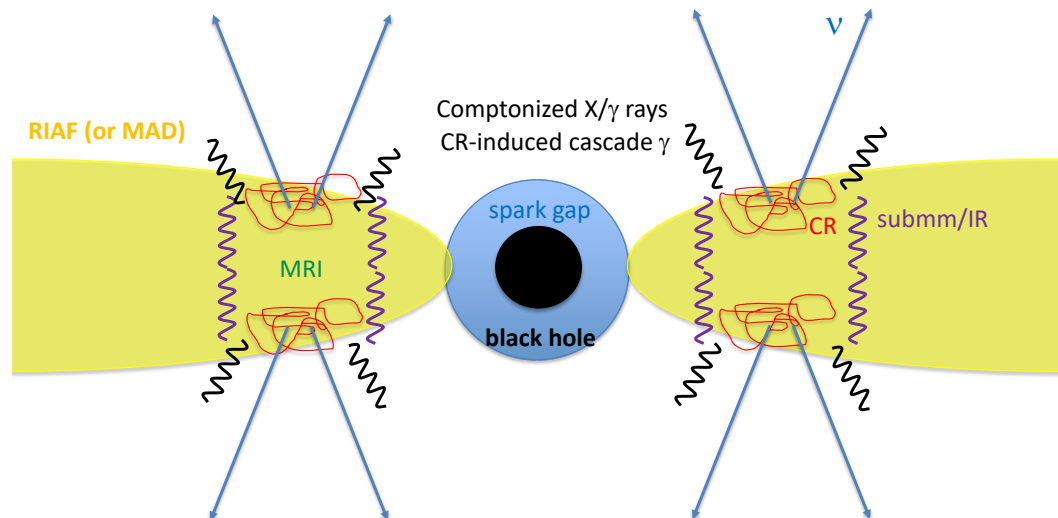
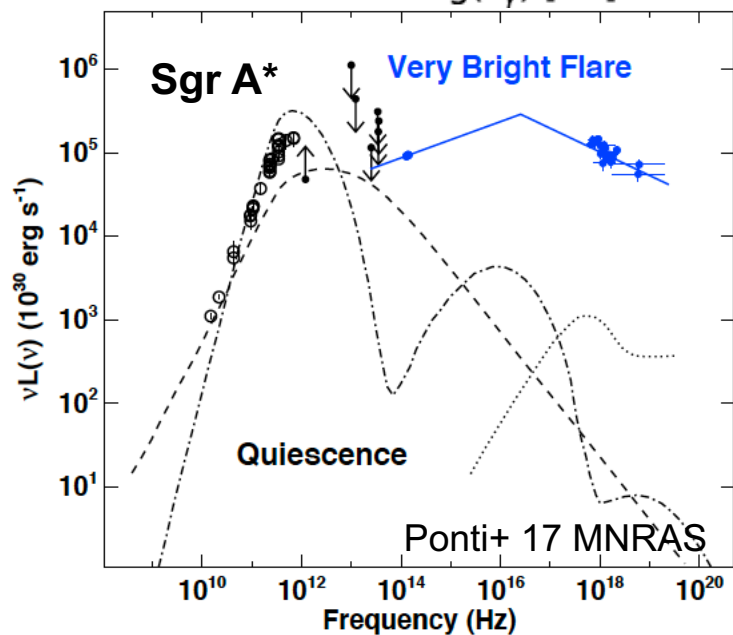
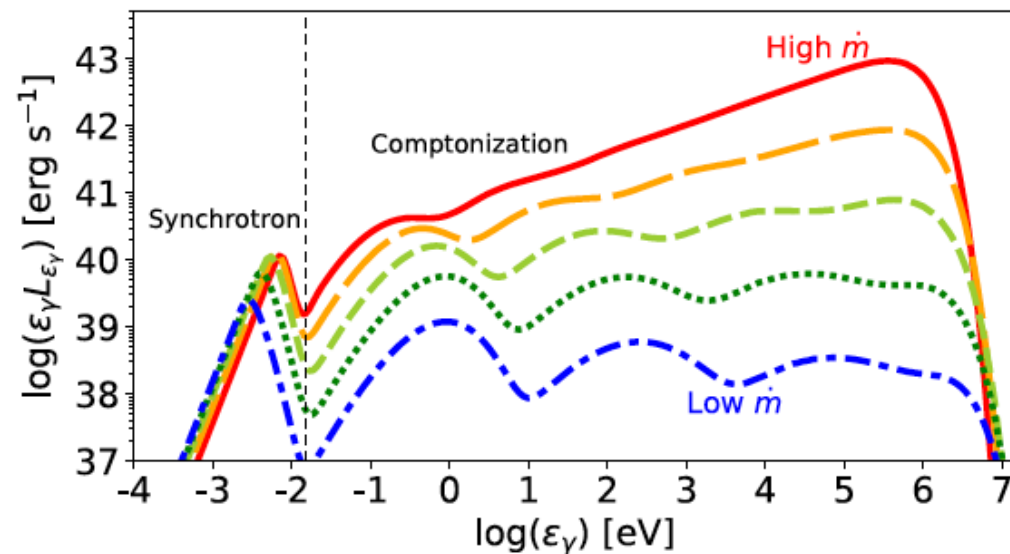
- Airshower arrays have placed diffuse γ -ray limits at TeV-PeV
Fermi γ -ray data imply $s_v < 2.0 \rightarrow$ support extragalactic scenarios
(KM Ahlers & Lacki 13 PRDR, KM, Guetta & Ahlers 16 PRL)
- Template analyses are also feasible (depending on CR distribution)
(spatial information needed)

Radiative Inefficient Accretion Flows

Kimura, KM & Toma 15 ApJ

Kimura, KM & Meszaros 21 Nature Comm.

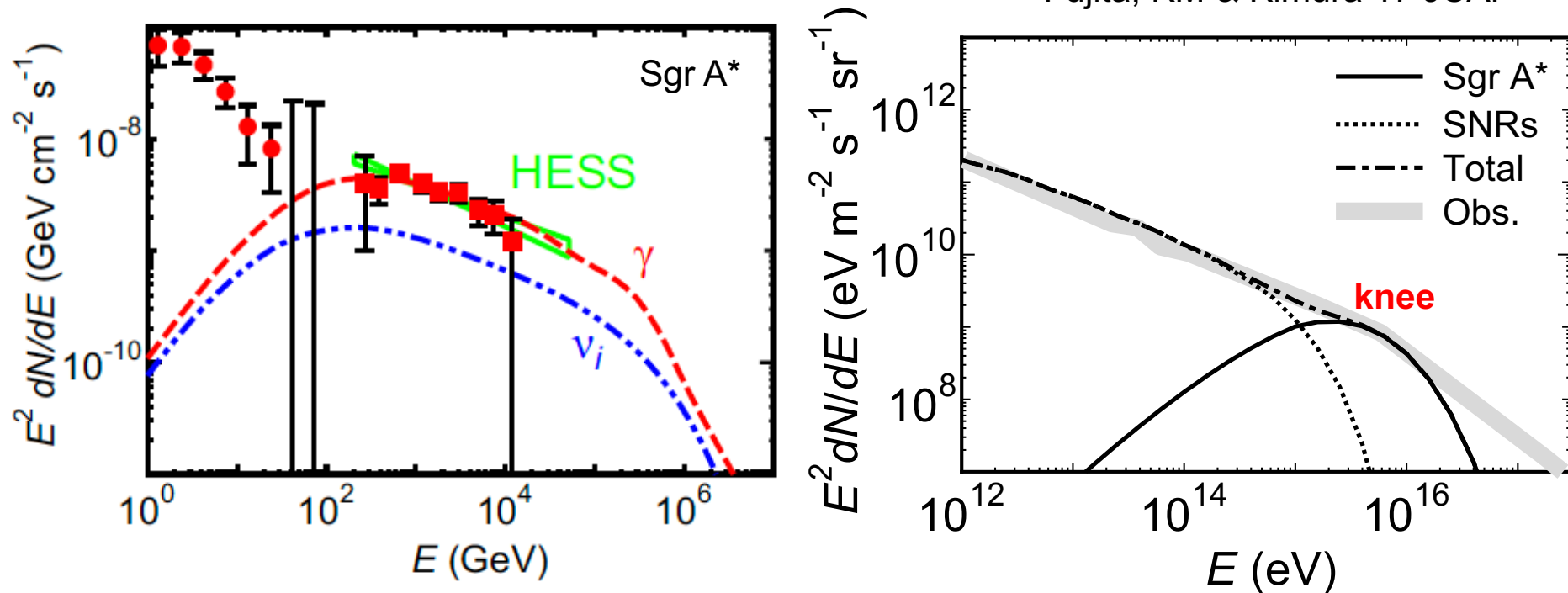
- RIAF for $\dot{m} < 0.03$
- Hot plasma
- Electrons are mostly thermal (collisional for electrons, collisionless for protons)



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

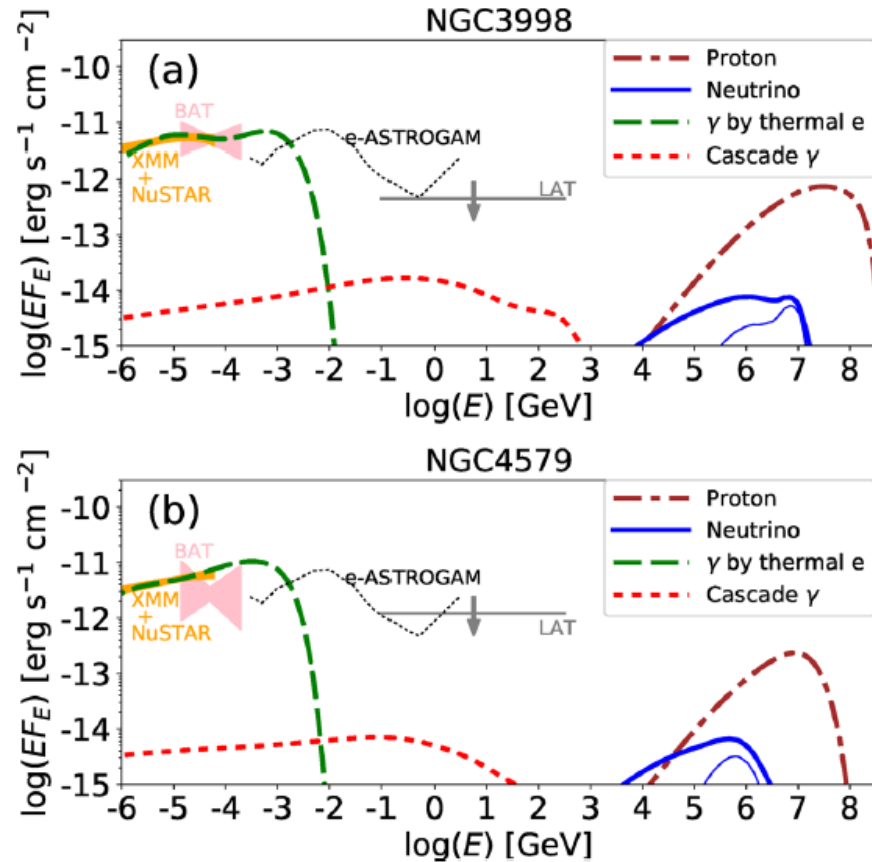
Fujita, Kimura & KM 15 PRD
Fujita, KM & Kimura 17 JCAP



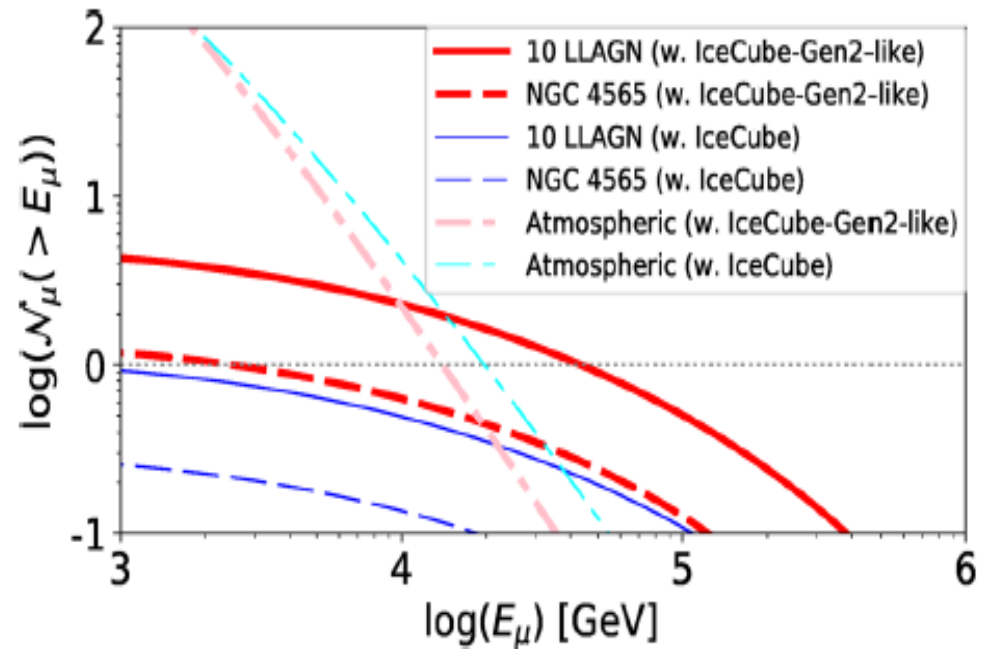
- CRs escaping from RIAFs interact with the CMZ.
- Effective pp optical depth: $f_{pp} \sim 0.1$ ($t_{\text{diff}}/0.1 \text{ Myr}$)

Detectability of Nearby Low-Luminosity AGN

Kimura, KM & Meszaros 21 Nature Comm.



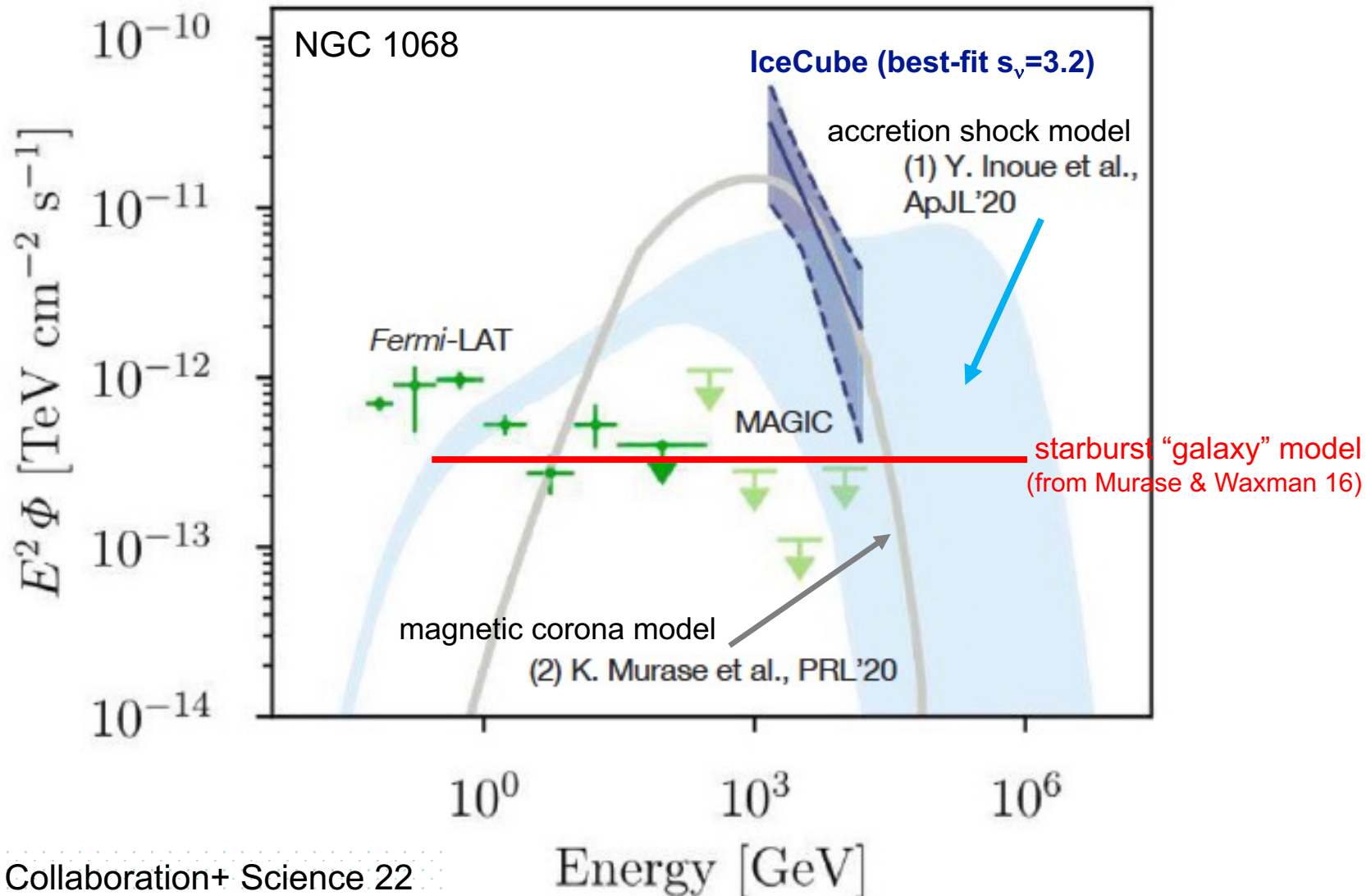
Predictions for stacking search

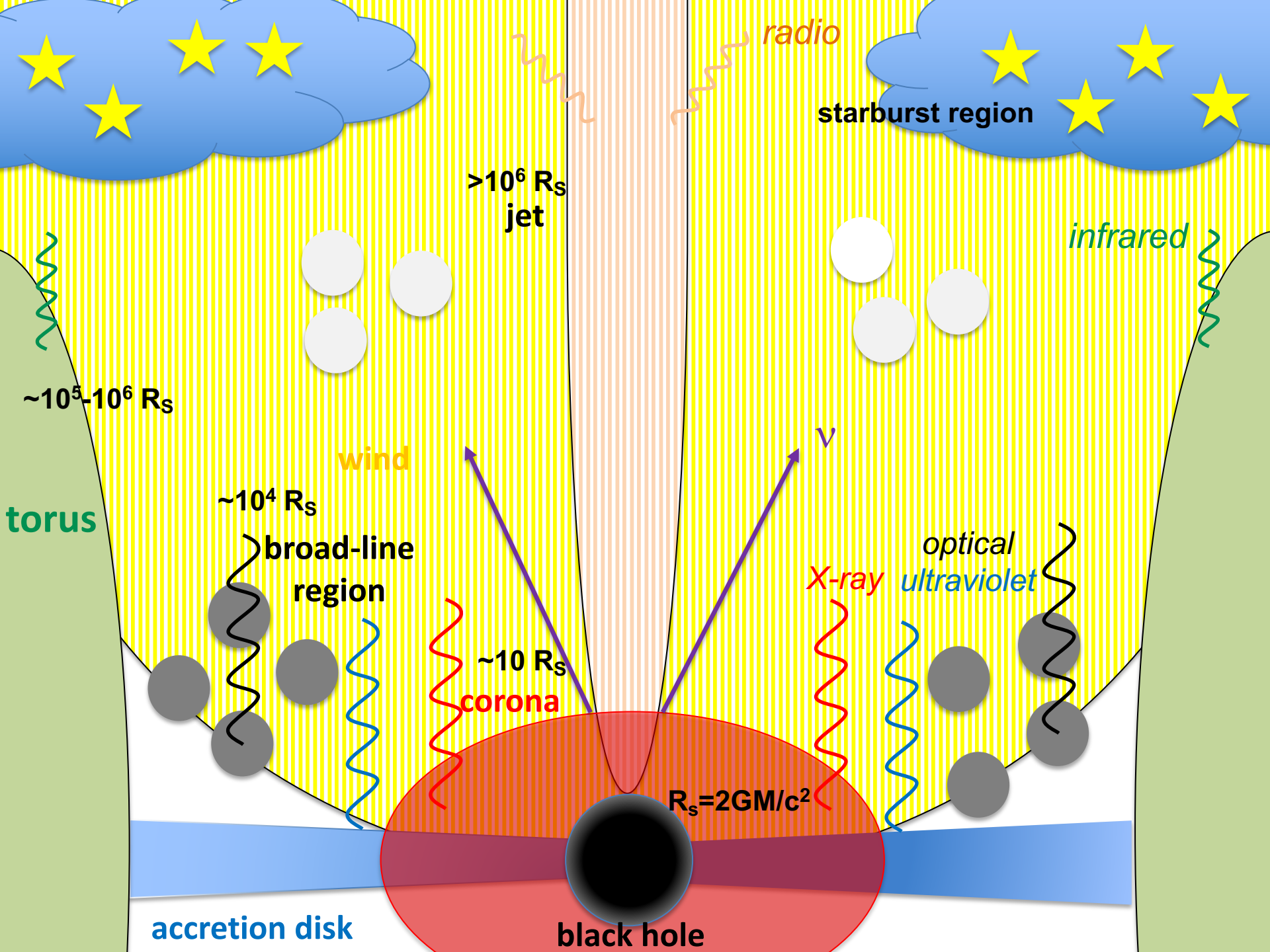


- Detection of MeV γ due to thermal electrons is promising (CR-induced cascade γ rays are difficult to observe)
- Nearby LL AGN can be seen by IceCube-Gen2/KM3Net

Obscured AGN as a Hidden Neutrino Source

$L_\nu \sim 3 \times 10^{42} \text{ erg/s} \ll L_{\text{bol}} \sim 10^{45} \text{ erg/s} < L_{\text{Edd}} \sim 3 \times 10^{45} \text{ erg/s}$: reasonable energetics



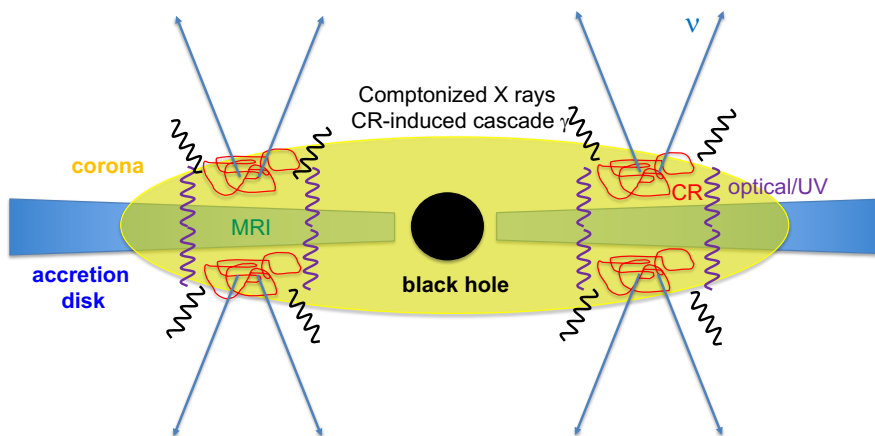


Neutrino Production Models

$$p + \gamma \rightarrow N\pi + X$$

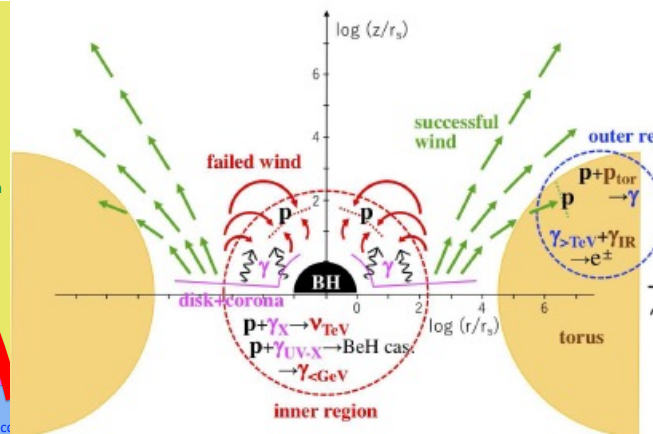
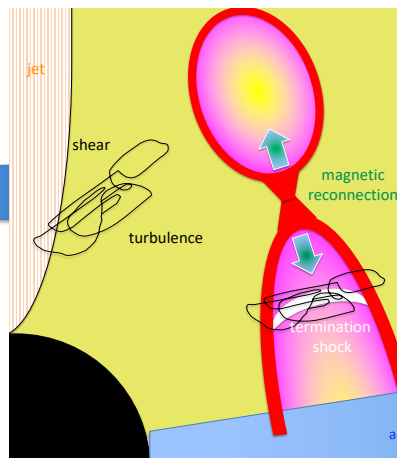
$$p + p \rightarrow N\pi + X$$

magnetically-powered corona or jet base
(KM+ 20, Kheirandish, KM & Kimura 21)



failed-wind or accretion shock
(S. Inoue, Cerruti, KM+ 22, Y. Inoue+ 20)

shear at the base of jets
(KM 22, Lemoine & Rieger 25)



turbulence
magnetic reconnection

$$\beta = P_g / P_B < 0.1-1 \rightarrow B > 10^3 \text{ G}$$

$$L_{CR} \ll L_X \ll L_B \text{ (turbulent)}$$

shocks

submm $\rightarrow B \sim 10-100 \text{ G}$

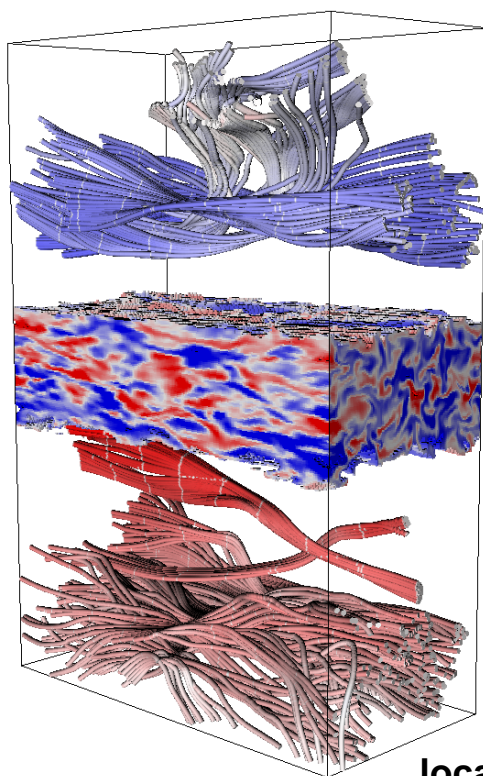
$$\beta = P_g / P_B > \sim 100$$

$$L_B, L_{CR} \ll L_X$$

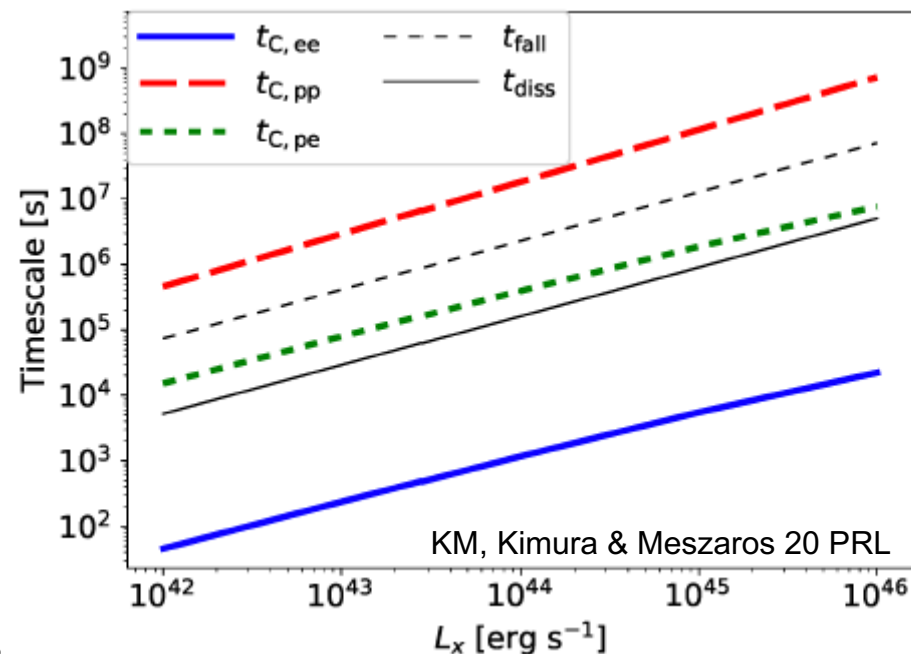
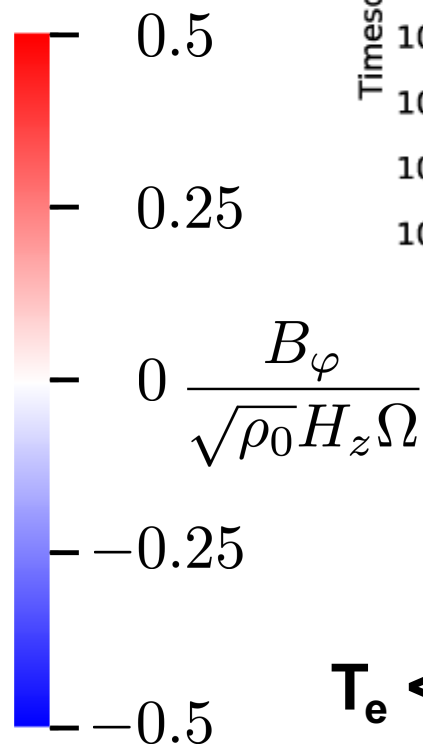
Particle Acceleration in Magnetized, Turbulent Coronae

$$\beta = P_g / P_B < 0.1-1 \quad (\sigma_p \gtrsim 0.01)$$

$$\rightarrow B > 10^3 \text{ G}$$



local MHD simulation
w. Athena++



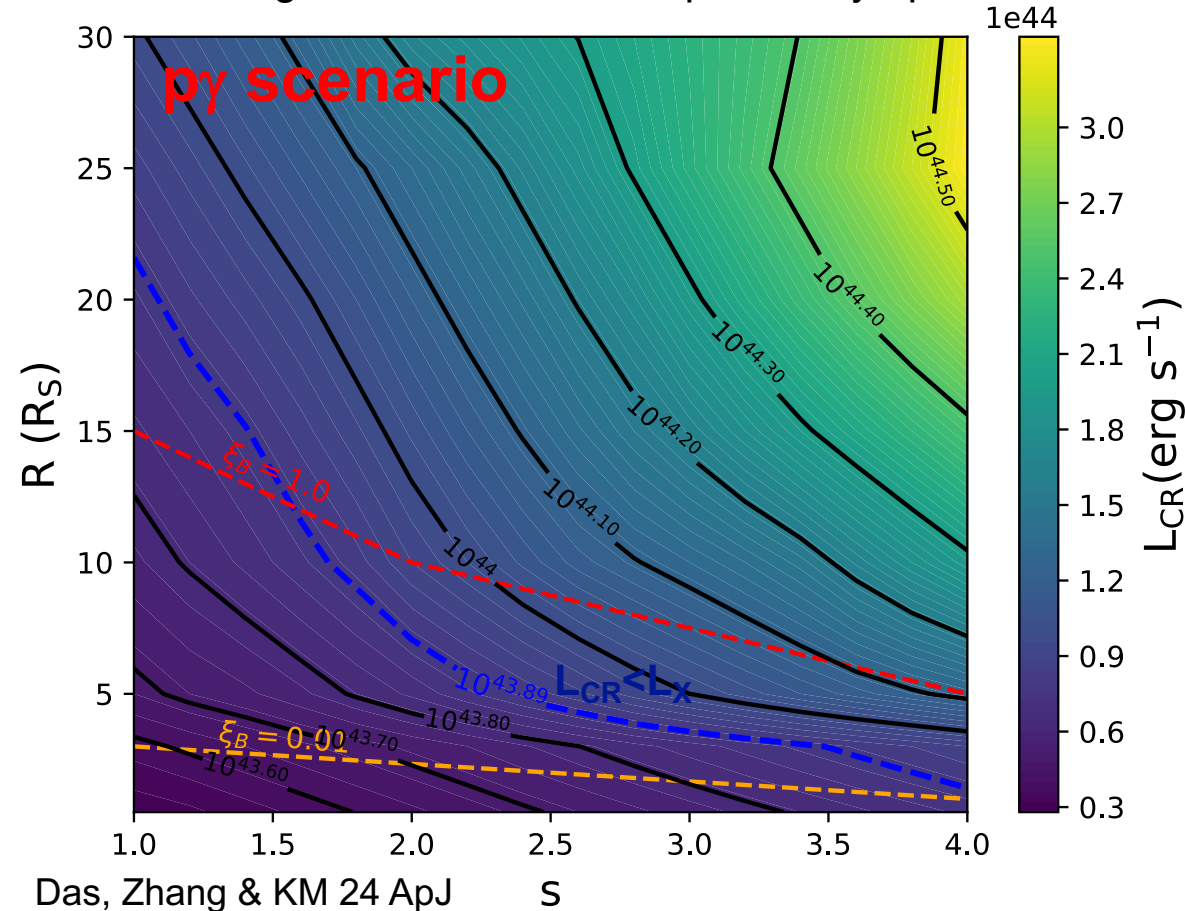
$$T_p \sim T_{\text{vir}} \sim 10^{11}-10^{12} \text{ K @ } R \sim 10 R_S$$

$$T_e \sim 10^8-10^9 \text{ K } (\leftarrow t_{\text{Comp}} \sim t_{\text{heat}})$$

$T_e < T_p$ (two-temperature corona)
collisionless for protons

Multimessenger Implications for Coronae as ν Production Sites

Multimessenger constraints are improved by updated Fermi-LAT analyses (Ajello, KM & McDaniel 23 ApJL)



CR energetics constraint

$L_{\text{CR}} < L_X$
 $\rightarrow R < \sim (1-20) R_s$

γ -ray constraint

$\xi_B = U_B/U_{\text{ph}} > \sim 0.1$
 synchrotron cascade
 $\rightarrow R < \sim (5-15) R_s$

$\xi_B = U_B/U_{\text{ph}} < \sim 0.1$
 inverse-Compton cascade
 $\rightarrow R < R_{\text{isco}}$ unlikely

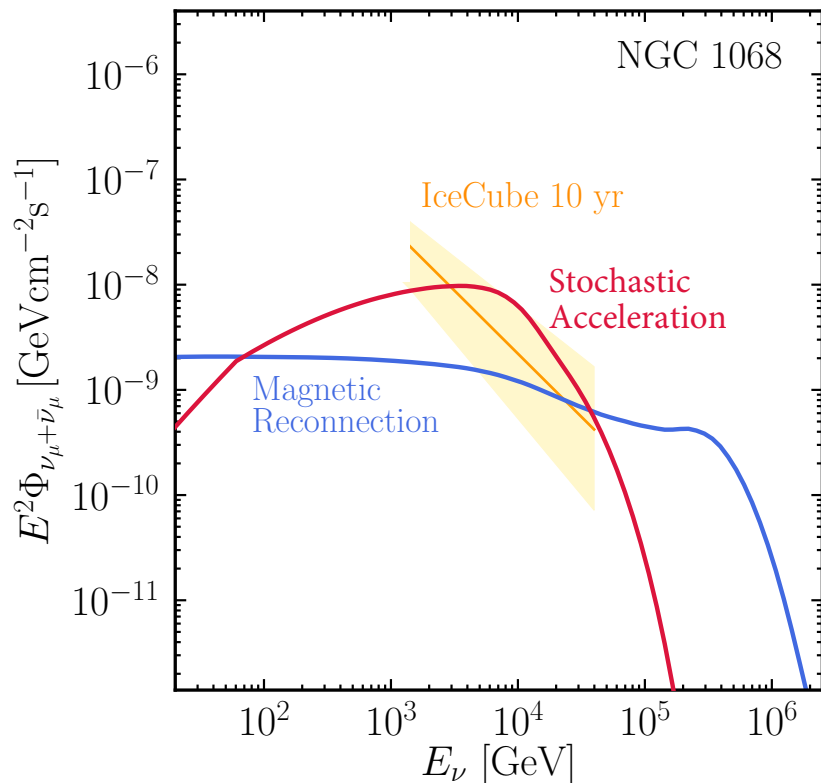
If ν emission comes from X-ray coronae, plasma should be **magnetically dominated**

$$\beta = \frac{8\pi n_p k_B T_p}{B^2} \approx \frac{\tau_T G M_{\text{BH}} m_p}{\sqrt{3} \zeta_e \sigma_T R^2 U_\gamma} \xi_B^{-1} \approx \left(\frac{\tau_T}{\sqrt{3} \zeta_e \lambda_{\text{Edd}}} \right) \xi_B^{-1}$$

$\tau_T \sim 0.1-1$ for X-ray corona, $\lambda_{\text{Edd}} \sim 0.5$
 $\xi_B > \sim 0.1$ leads to **$\beta < \sim 1$**

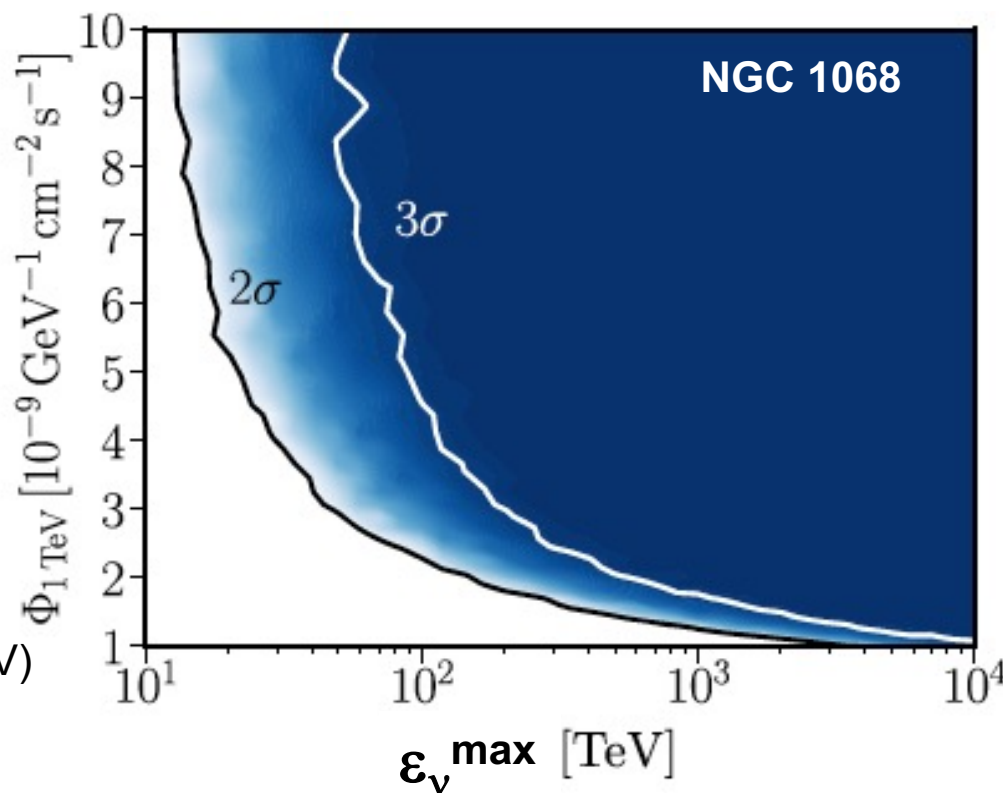
Neutrinos Can Probe Particle Acceleration in Coronae

Kheirandish, KM & Kimura 21 ApJ



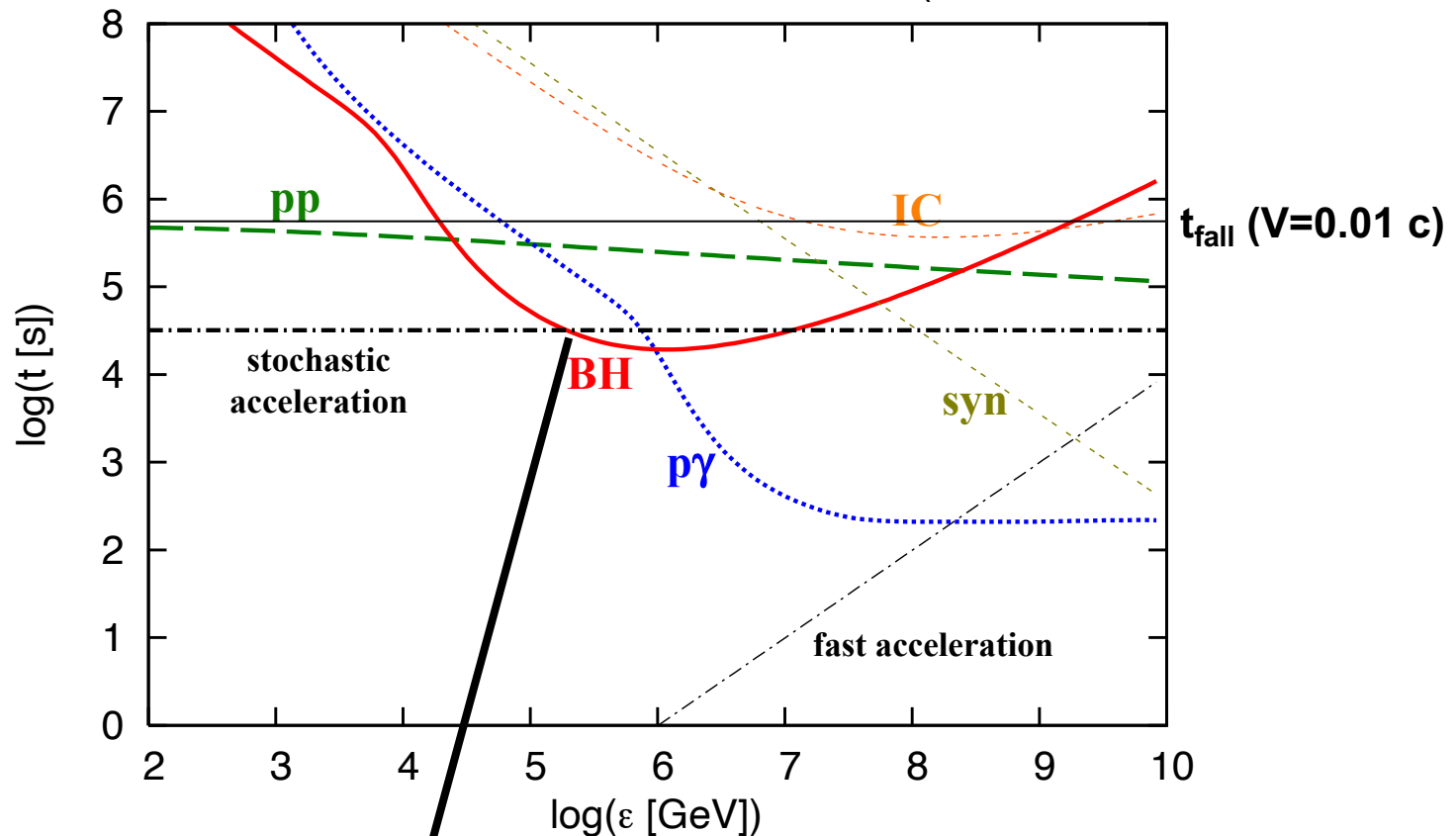
$E_\nu^2 \Phi_{\nu\mu} \sim 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} @ 1 \text{ TeV}$
 constraints for an E_ν^{-2} spectrum
 $\epsilon_\nu^{\text{max}} < 10 \text{ TeV}$ ($\epsilon_p^{\text{max}} < 200 \text{ TeV}$)

(cf. acceleration w. $t_{\text{acc}} = r_L/c \rightarrow \epsilon_p^{\text{max}} \sim 10\text{-}100 \text{ PeV}$)



Particle Acceleration: Fast or Slow?

$p\gamma \rightarrow pe^+e^-$ (Bethe-Heitler process) is important for protons producing 1-10 TeV vs
(KM, Kimura & Meszaros 20 PRL)

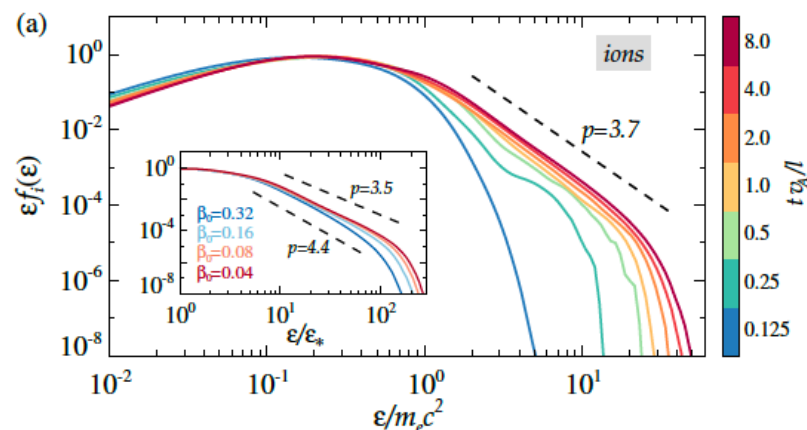
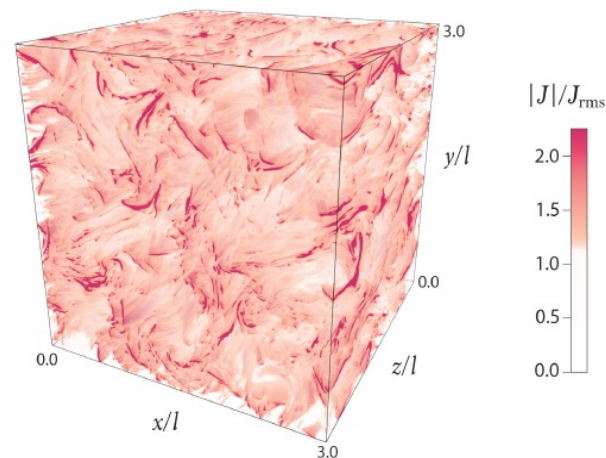
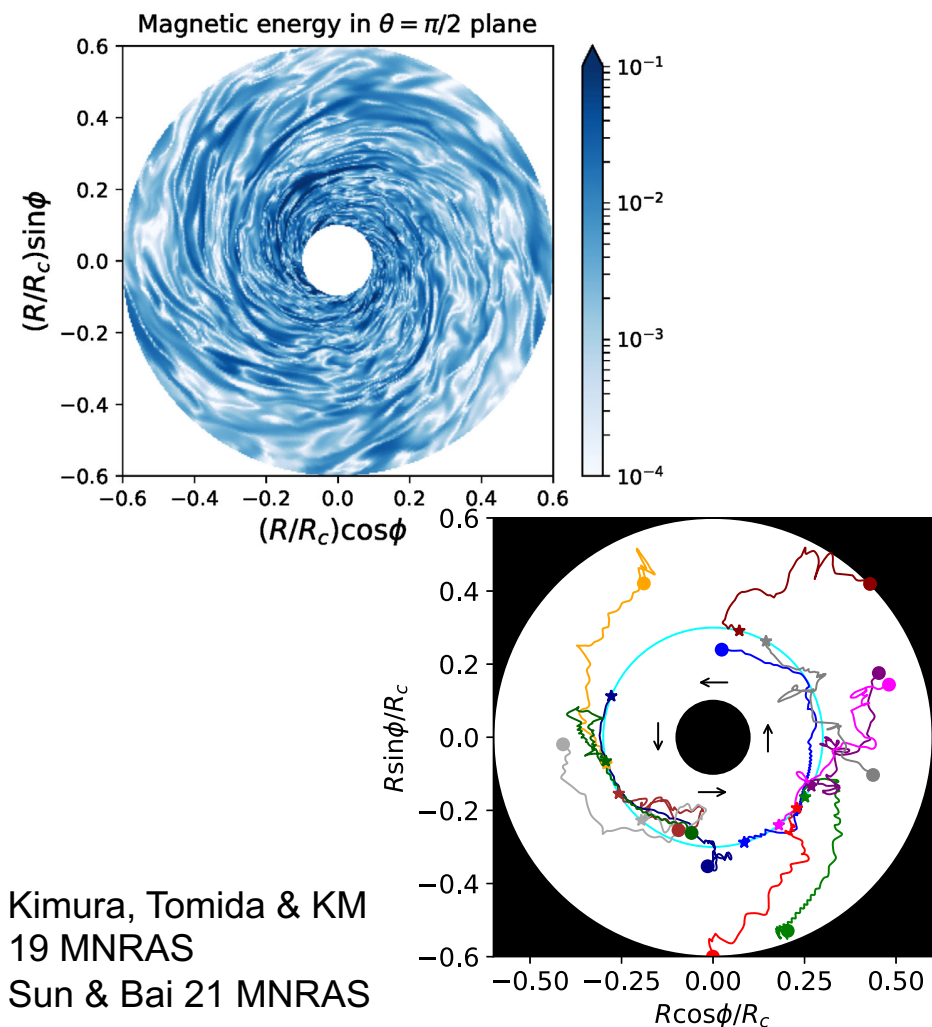


$\epsilon_p^{\text{max}} \sim 100 \text{ TeV} \rightarrow \epsilon_v^{\text{max}} \sim 2 \text{ TeV}$ (consistent w. IceCube)

Particle Acceleration Mechanism in Coronae (Extra)?

stochastic acc. in 3D global MHD simulations

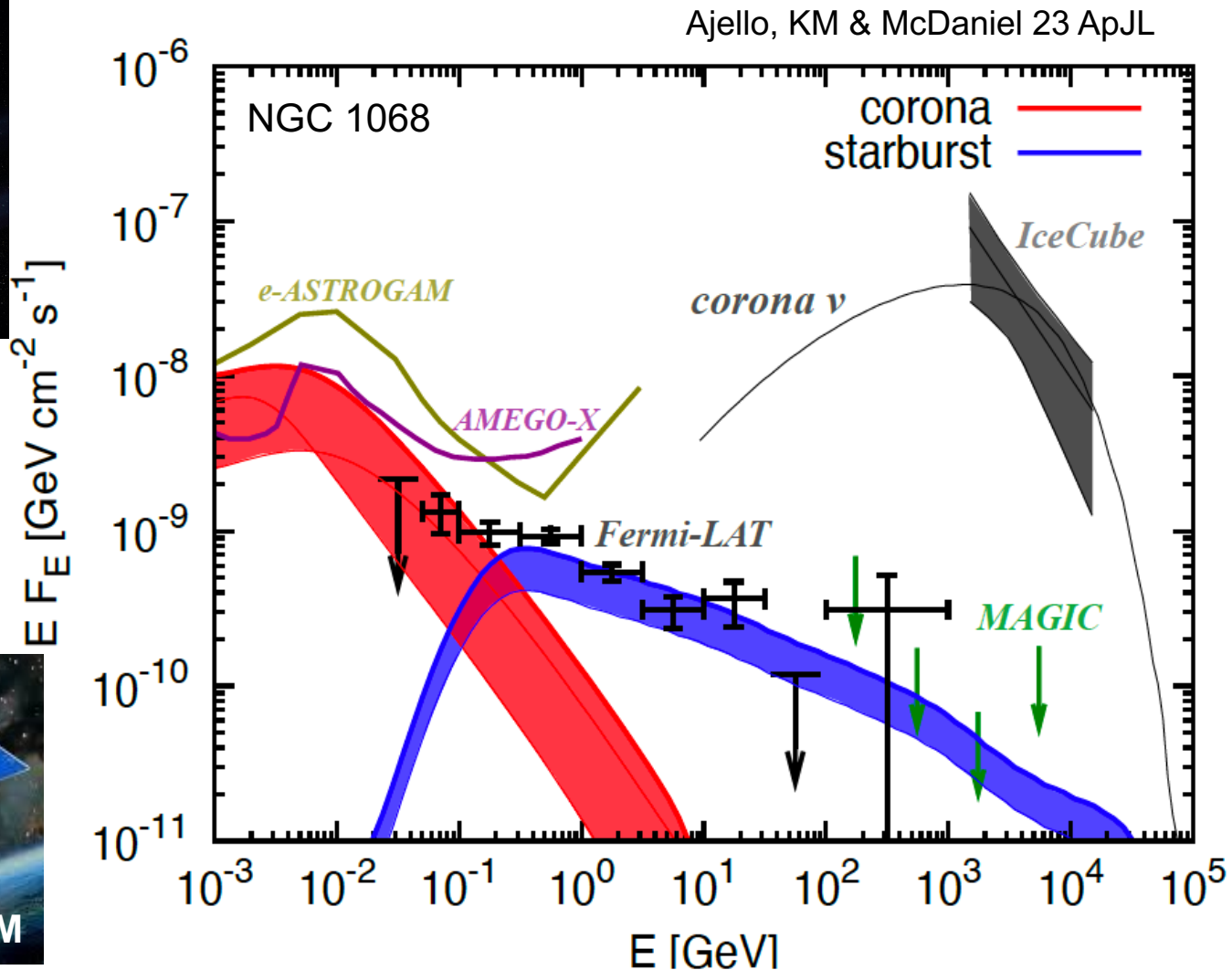
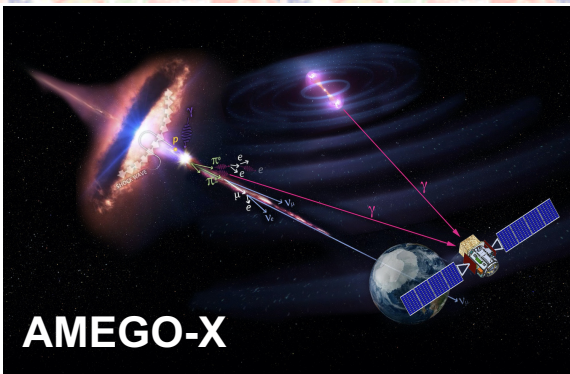
stochastic acc. in 3D PIC simulations



see also Hoshino 15 PRL, Zhdankin+ 17 PRL
Comisso & Sironi 22

High-energy neutrinos now meet the frontier of astrophysics

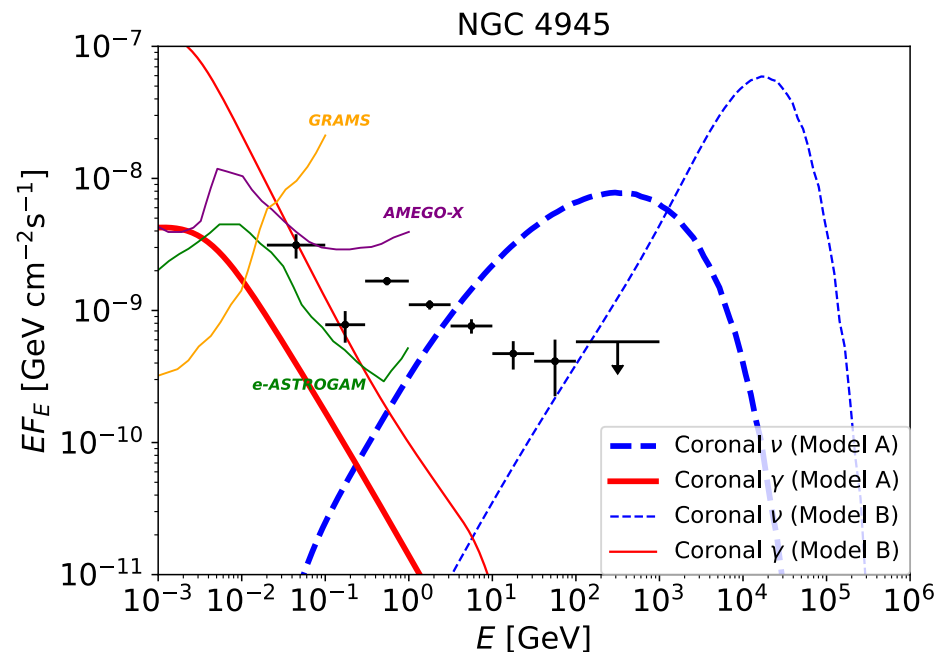
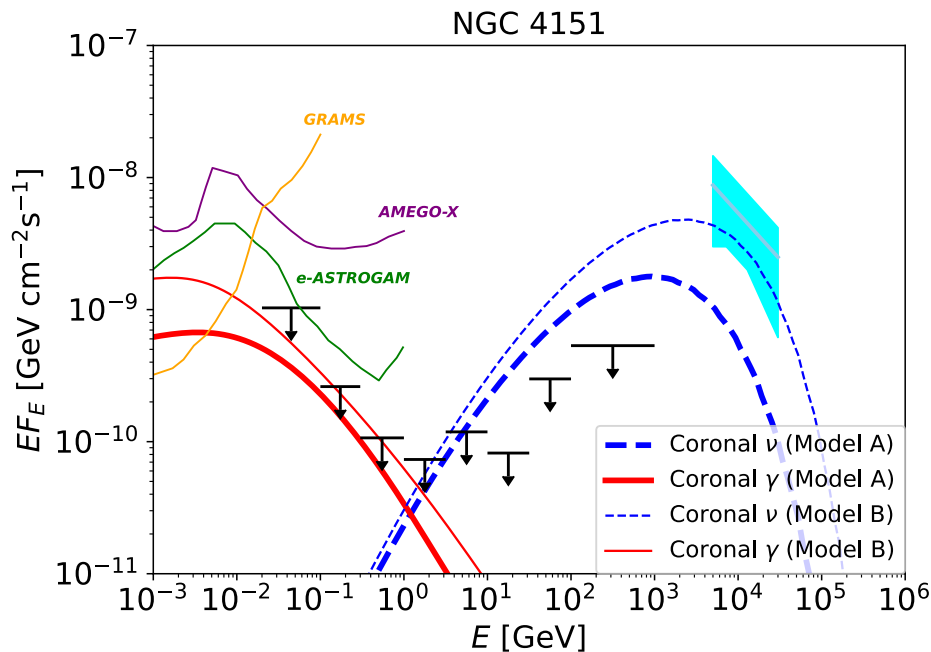
γ Rays Must Not Be Gone: Hints & Future MeV γ -Ray Tests



- Corona model prediction: cascade γ rays should appear in the **MeV** range
- **Fermi γ -ray observation**: sub-GeV “excess” over the starburst component

Other AGNs?

- Corona model prediction: ν luminosity $\sim$ intrinsic X-ray luminosity
 brightest in north: **NGC 1068, NGC 4151** (KM+ 20 PRL, KM+ 24 ApJL)
 brightest in south: **NGC 4945, Circinus**
- IceCube ν TeV excess: (IceCube Collaboration 24a, 24b, 24c)
NGC 1068 ($\sim 4\sigma$), **NGC 4151** ($\sim 3\sigma$), **Circinus** ($\sim 3\sigma$ for AGNs in south)
- Fermi γ -ray sub-GeV excess:
NGC 1068, NGC 4945



Thank you very much!

