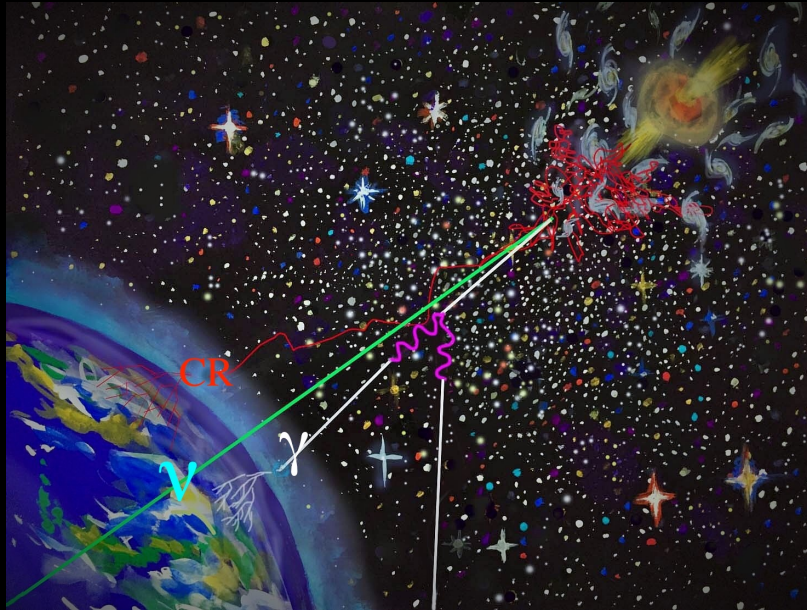


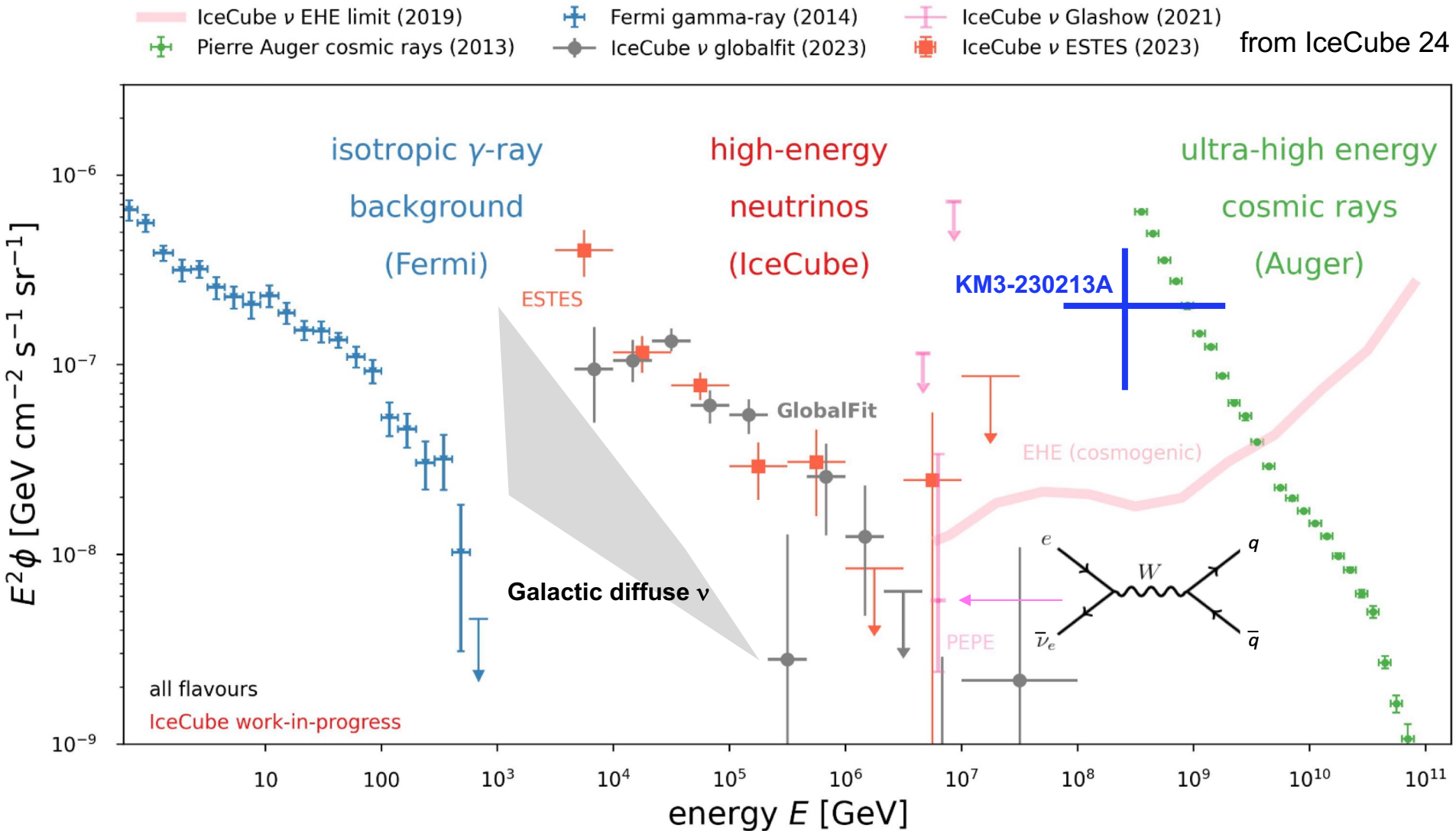
Multimessenger Implications for Extragalactic Sources of Cosmic Rays



PENNSTATE Kohta Murase (Penn State/YITP)



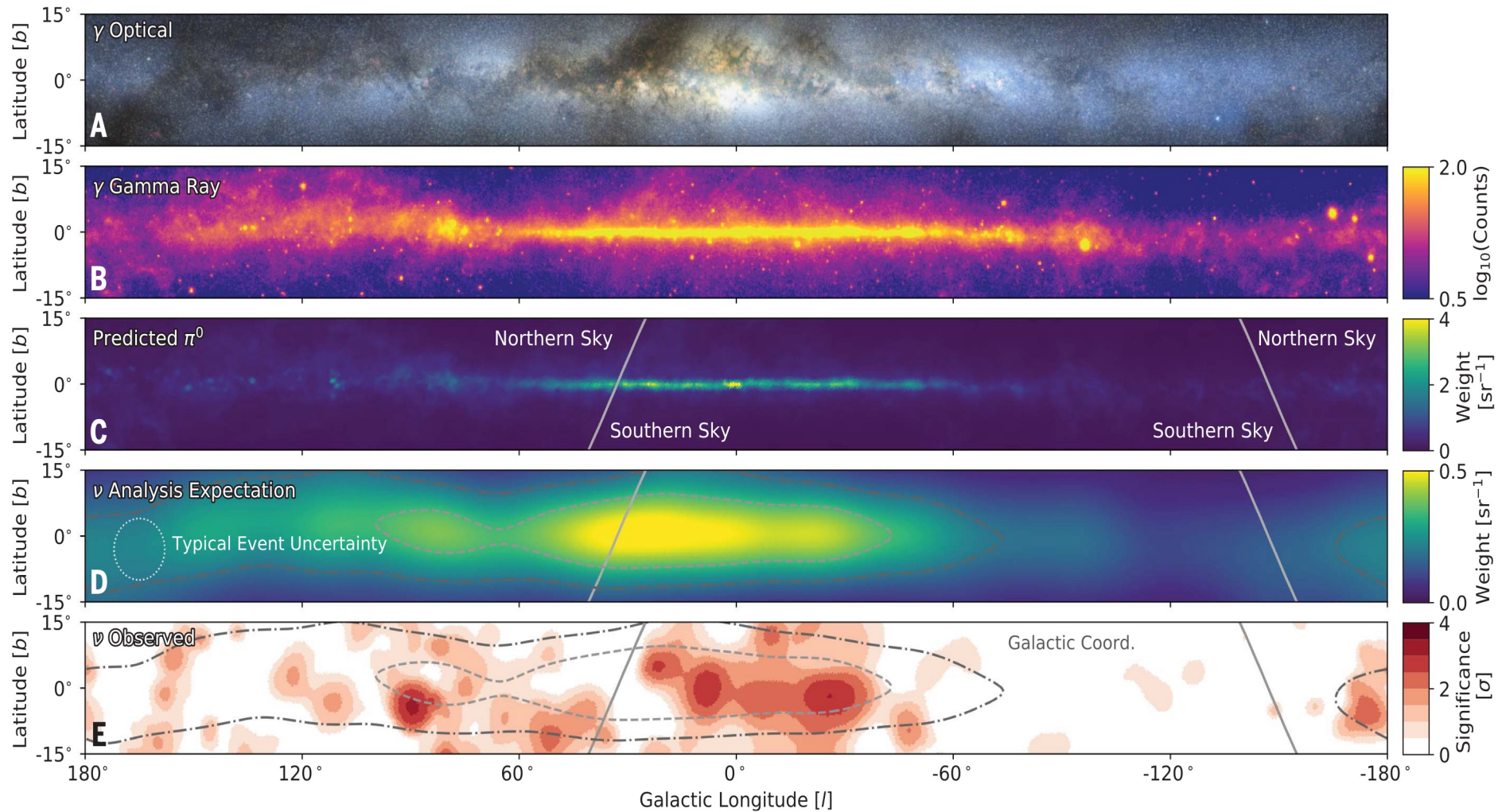
All-Sky Multimessenger Flux & Spectrum



Disclaimer: my talk itself is “diffuse”

Evidence Discovery for Galactic Diffuse Neutrinos

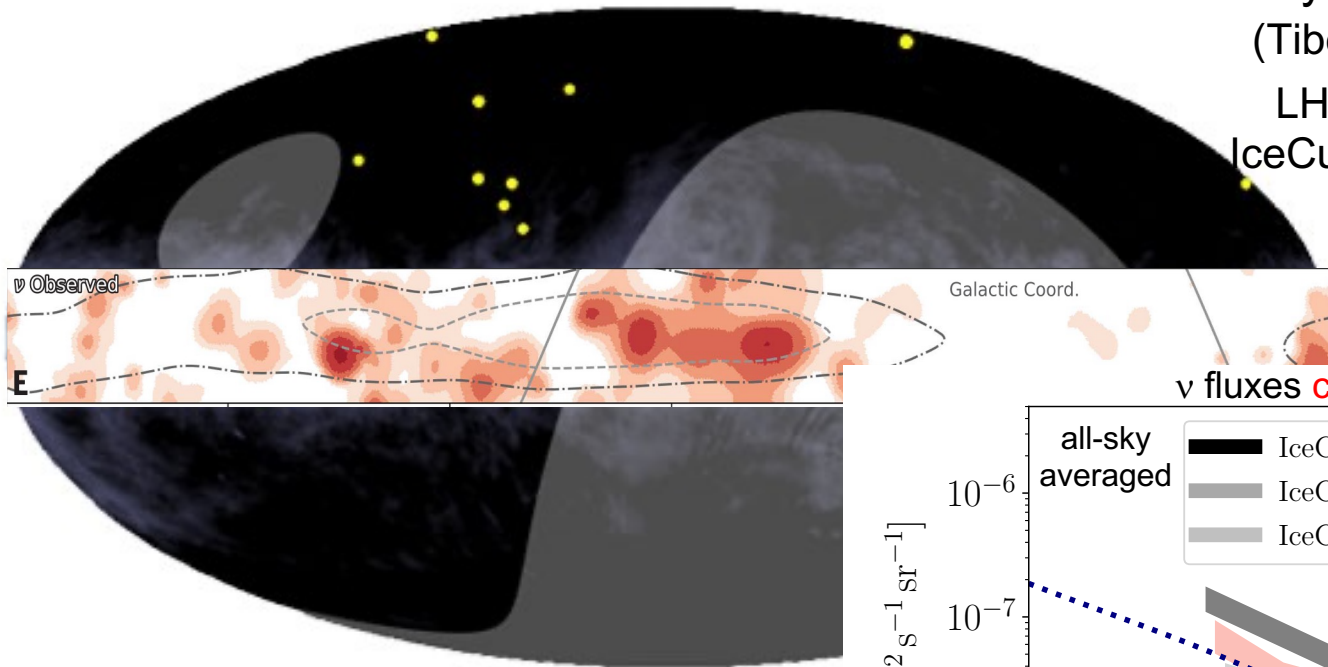
IceCube 23 Science



Now ν emission from the Milky Way (**$\sim 10\%$ of total) has been observed w. $>5\sigma$**

Galactic Multimessenger Connection is Now Seen

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

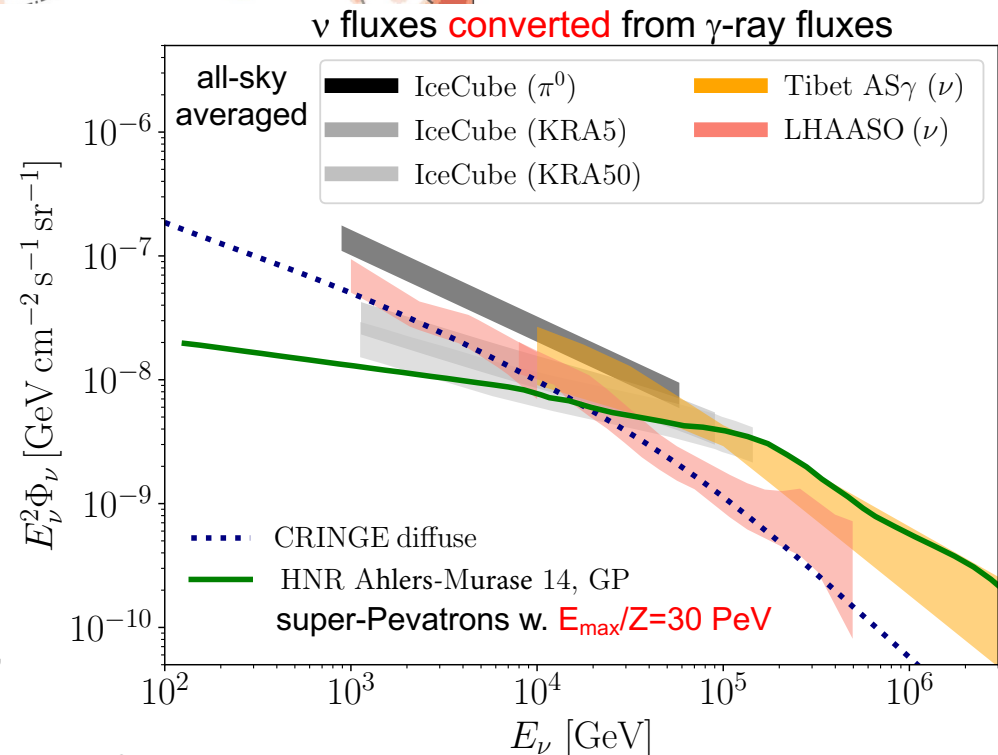


Supporting hadronic (pp) origin

Open questions

- Truly diffuse vs **unresolved sources?**
- Super-PeVatron accelerators?

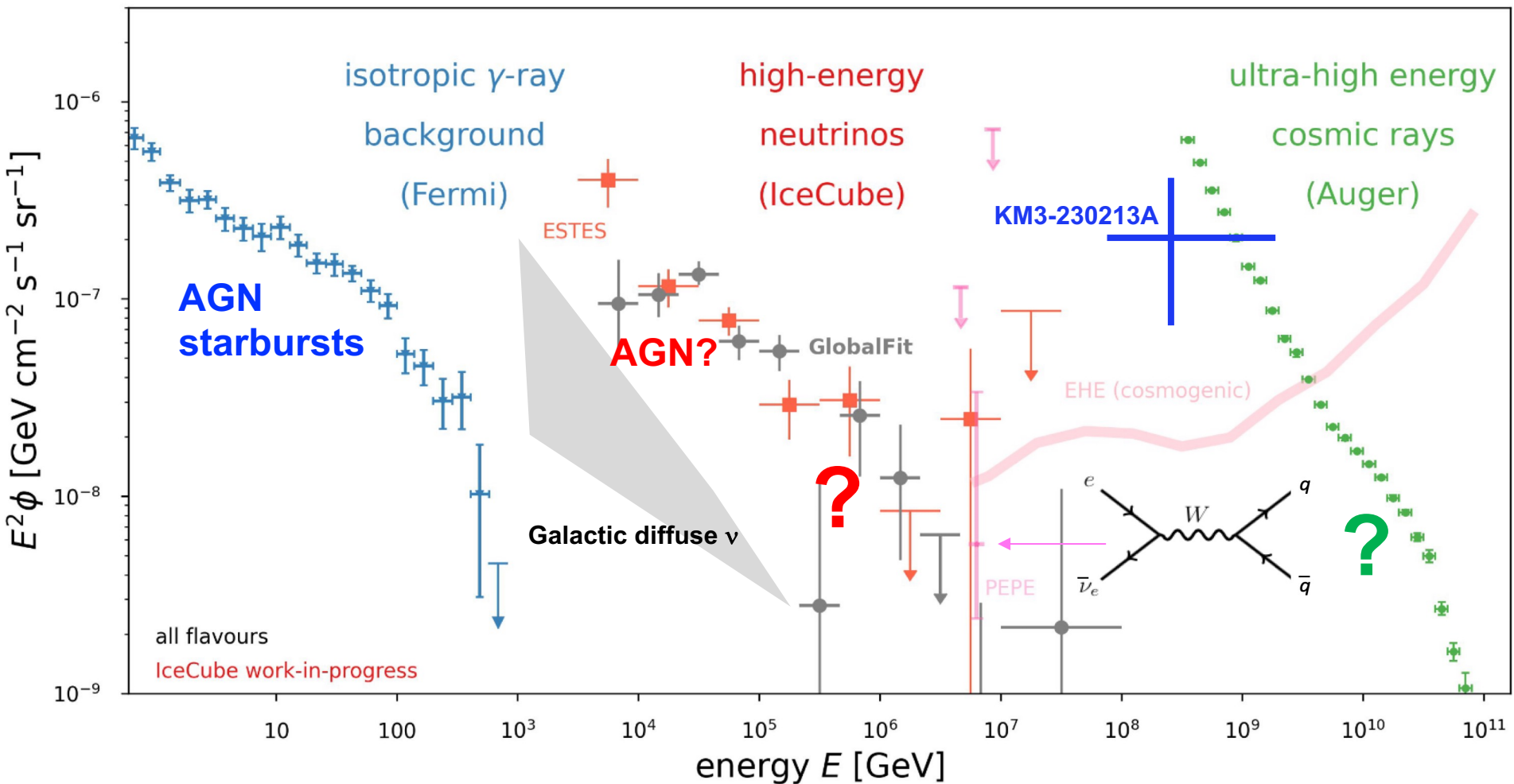
(Schwefer+ 23, Vecchiotti+ 23, Shao+ 23, Ambrosone+ 24, Yan+ 24, Kato+ 24, 25, Lipari & Vernetto 25, Kaci+ 25, Espinosa Castro, KM+ 26, Moghadam+ 26, Roberts+ 26 etc.)



Fang & KM 21 ApJ, 23 ApJL

All-Sky Multimessenger Flux & Spectrum

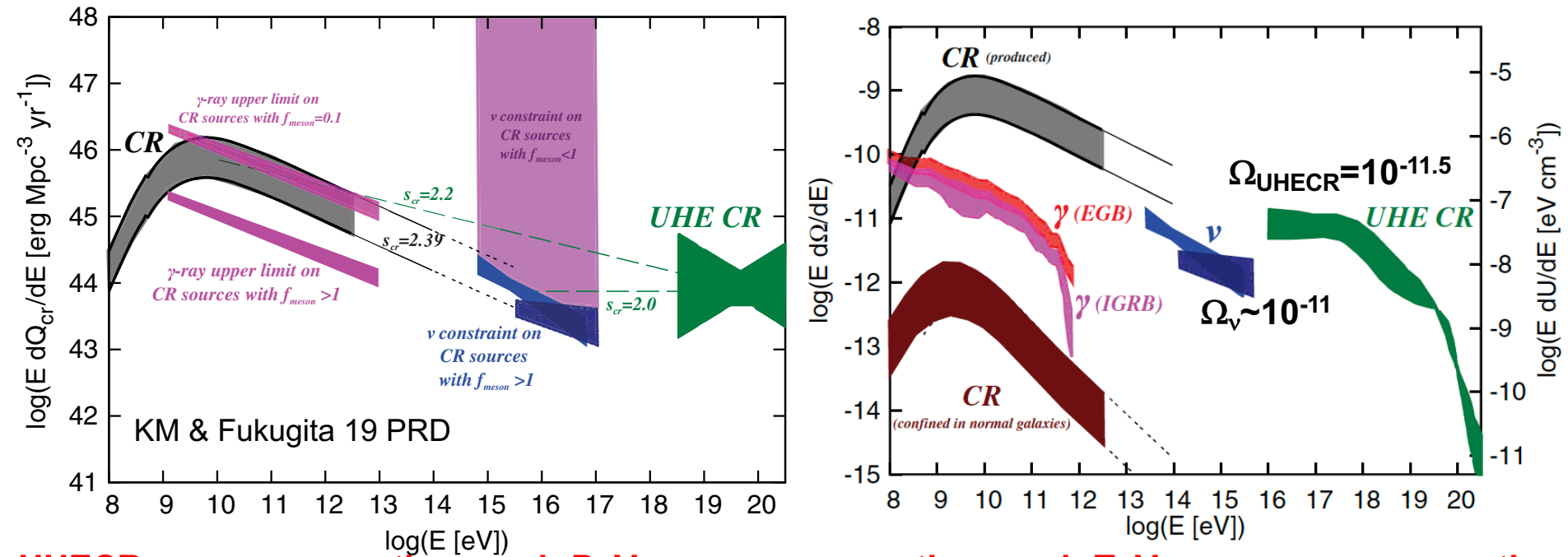
IceCube ν EHE limit (2019) Fermi gamma-ray (2014) IceCube ν Glashow (2021)
 Pierre Auger cosmic rays (2013) IceCube ν globalfit (2023) IceCube ν ESTES (2023) from IceCube 24



Energy Budgets of High-Energy Cosmic Particles

$$E^2 \Phi \approx \frac{ct_H}{4\pi} \varepsilon Q_\varepsilon \xi_z g(E) \propto (\text{Q: energy generation rate density})$$

propagation



UHECR energy generation $\sim$ sub-PeV ν energy generation $\sim$ sub-TeV γ -ray energy generation

	ccSN (CR)	HN (CR)	DNS (CR)	GRB (γ)	LL GRB (γ)	TDE (γ)
$Q [\text{erg Mpc}^{-3} \text{ yr}^{-1}]$	$10^{46.6}$	$10^{45.5}$	$10^{44.5}$	$10^{43.6}$	$10^{43.5}$	$10^{43.5}$
$\rho [\text{Mpc}^{-3} \text{ yr}^{-1}]$	10^{-4}	$10^{-5.5}$	$10^{-5.8}$	10^{-9}	$10^{-6.5}$	$10^{-10.5}$
	SBG (γ)	AGN (X)	BL Lac (γ)	FSRQ (γ)	RG (γ)	Accr/Mger (CR)
$Q [\text{erg Mpc}^{-3} \text{ yr}^{-1}]$	$10^{44.5}$	$10^{46.3}$	$10^{45.4}$	$10^{44.3}$	$10^{44.6}$	$10^{46.5}$
$n [\text{Mpc}^{-3}]$	10^{-4}	$10^{-4} - 10^{-3}$	$10^{-7} - 10^{-6.5}$	$10^{-9} - 10^{-8}$	$10^{-5} - 10^{-4}$	$10^{-6} - 10^{-5}$

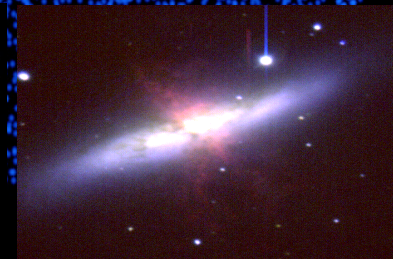
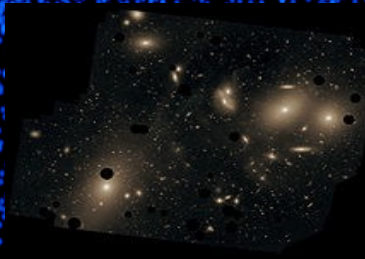
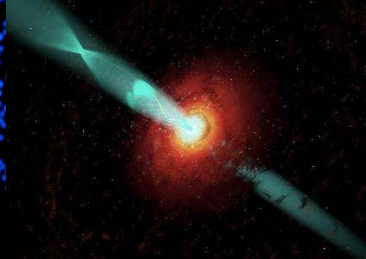
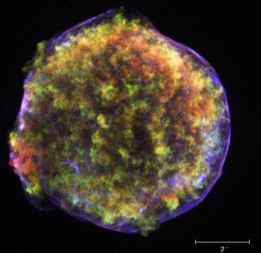
High-Energy Gamma-Ray Sky

Fermi γ -ray satellite

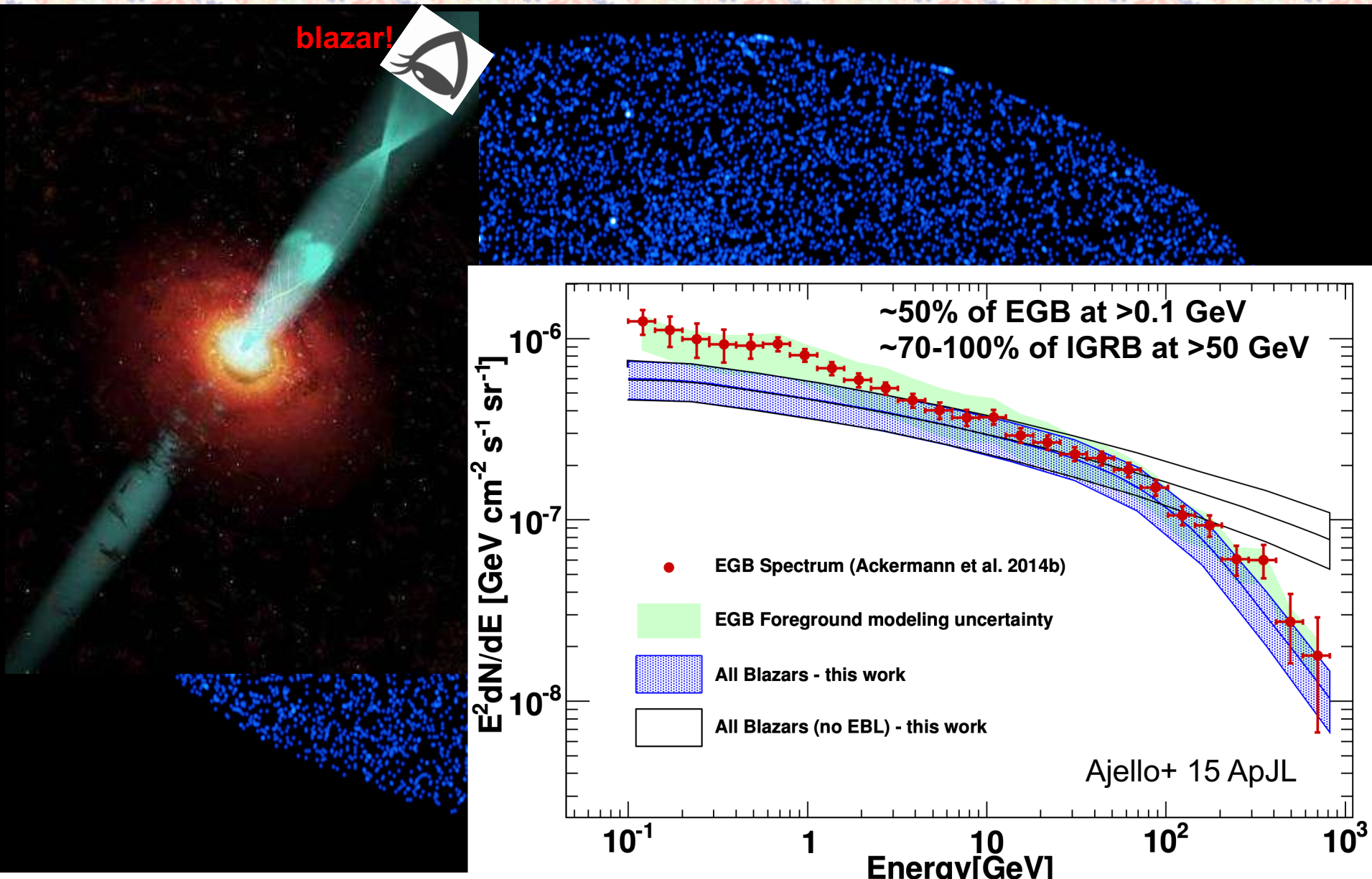


~5000 sources (4FGL)
>3000 AGN

Galactic plane
Galactic sources
extragalactic sources

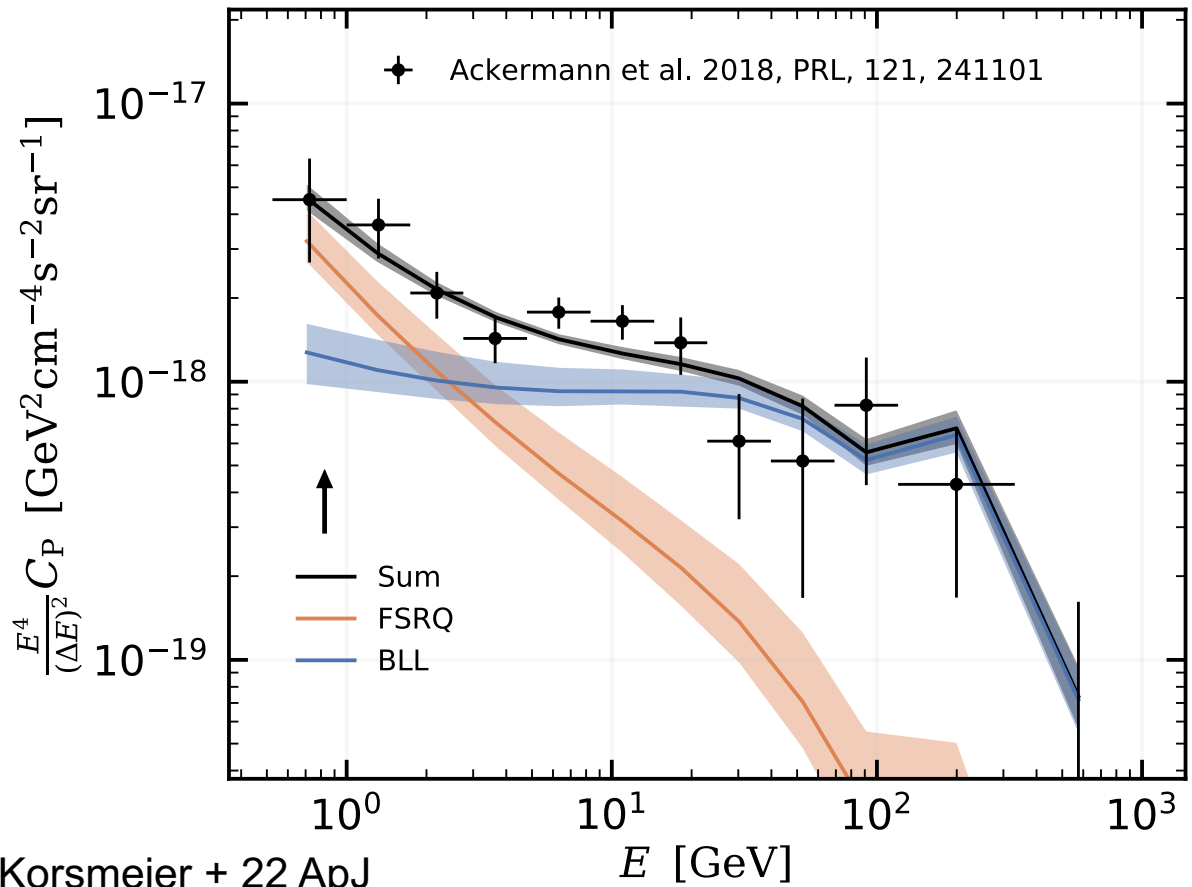


Extragalactic γ -Ray Sky: Dominated by On-Axis Jetted AGN

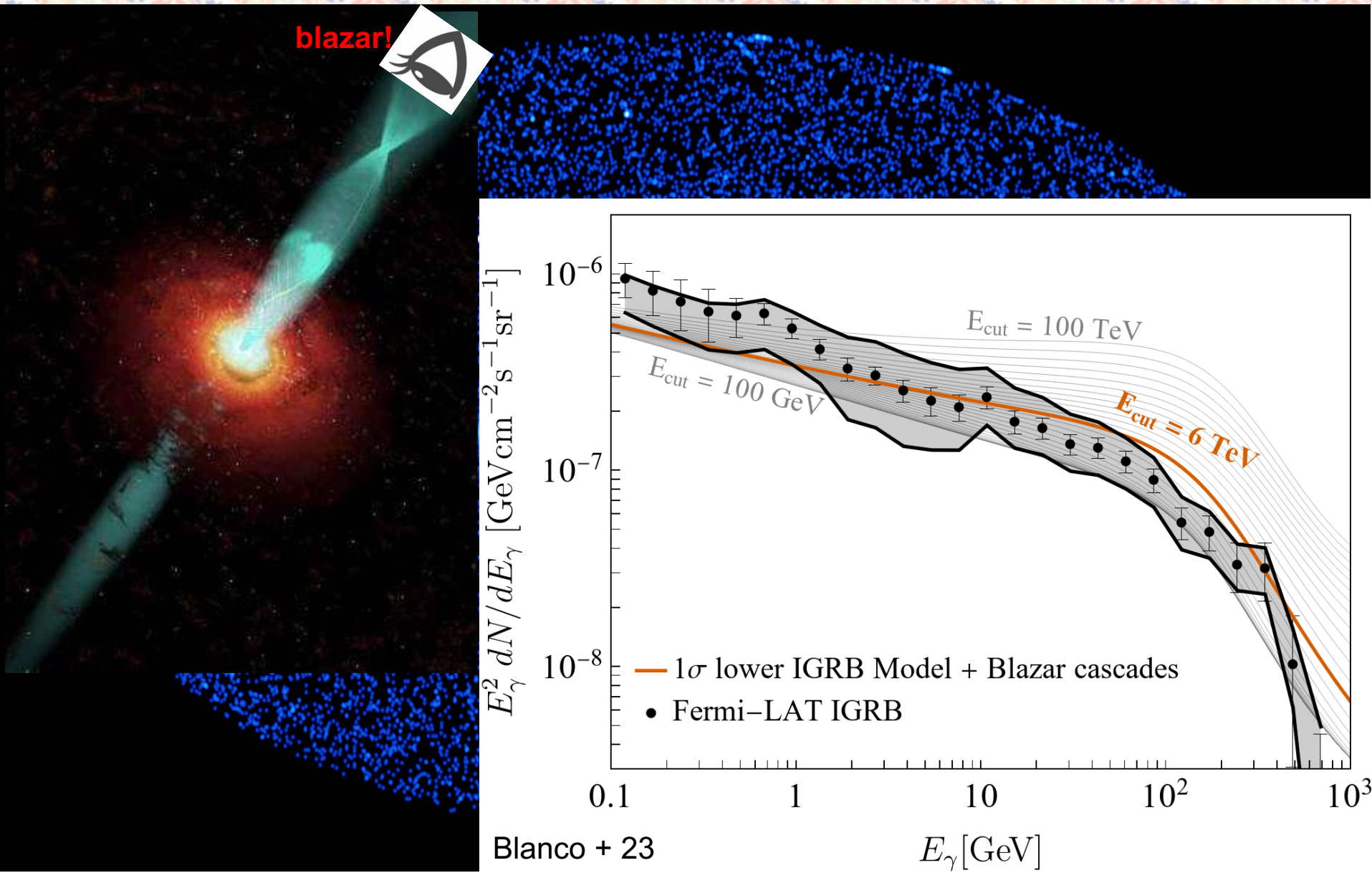


Extragalactic γ -Ray Sky: Dominated by On-Axis Jetted AGN

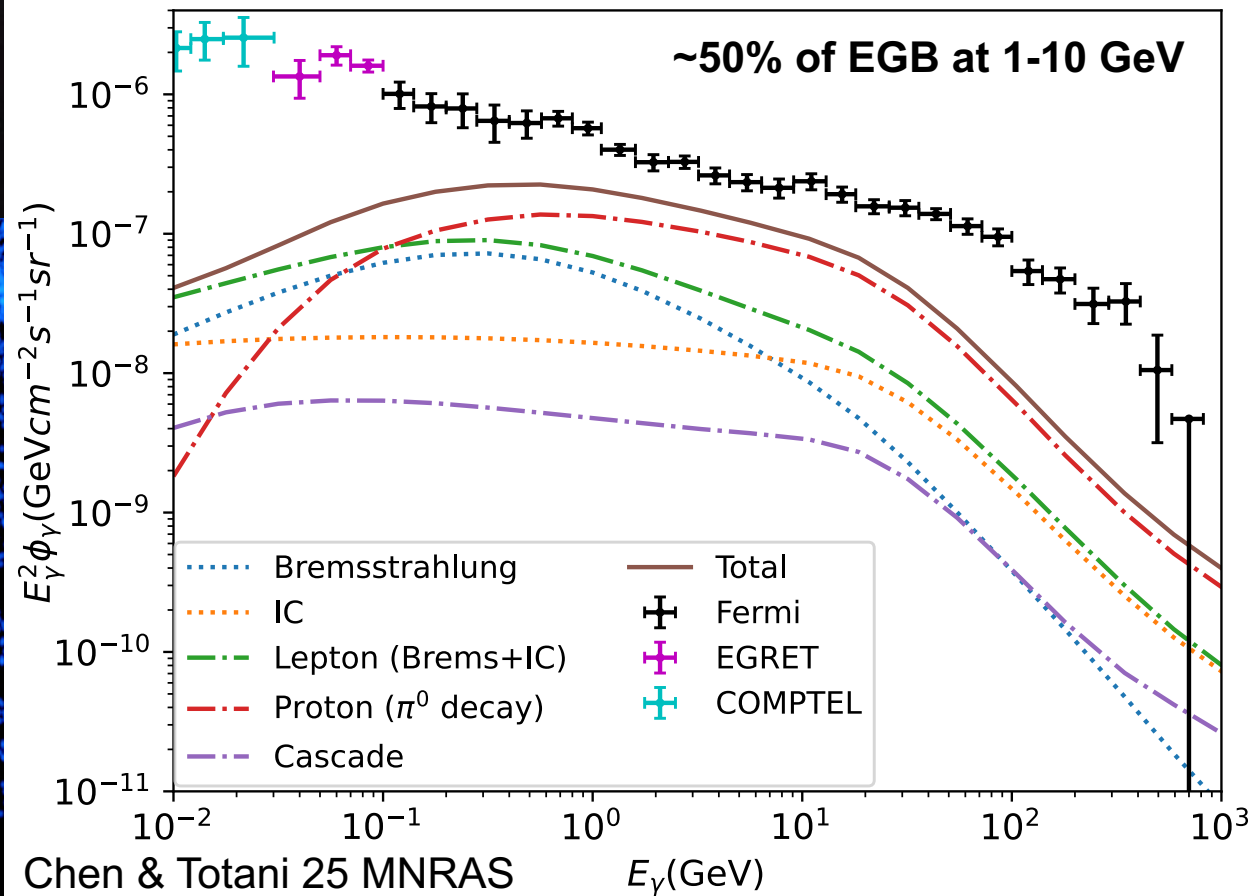
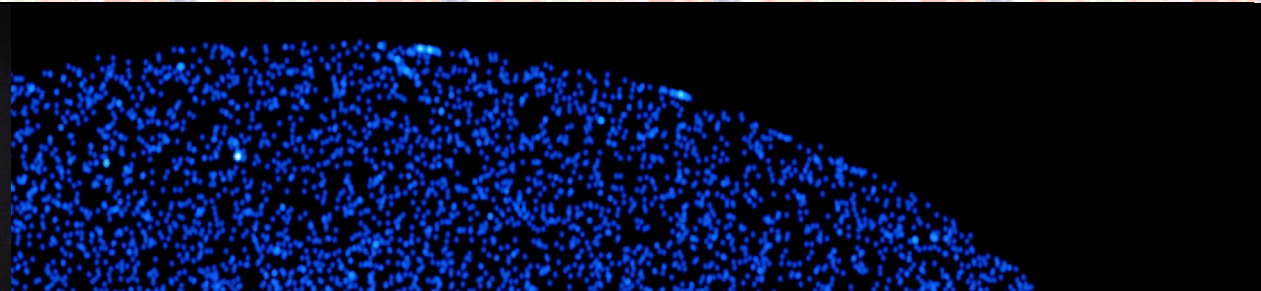
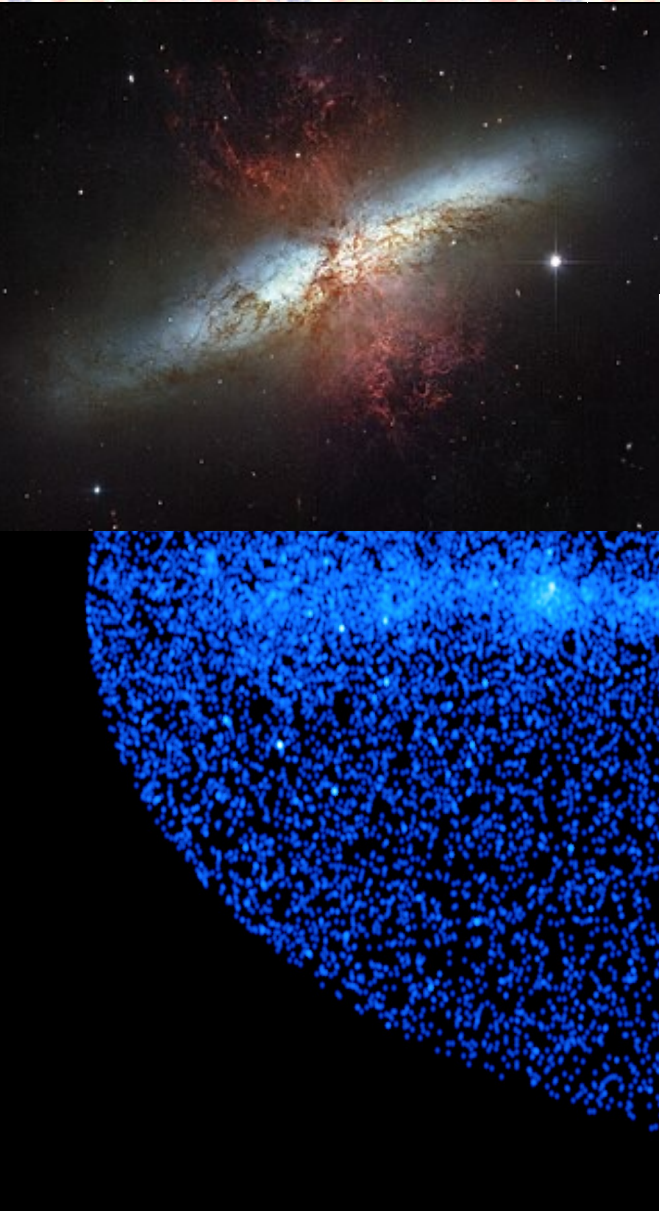
blazar!



Extragalactic γ -Ray Sky: Dominated by On-Axis Jetted AGN



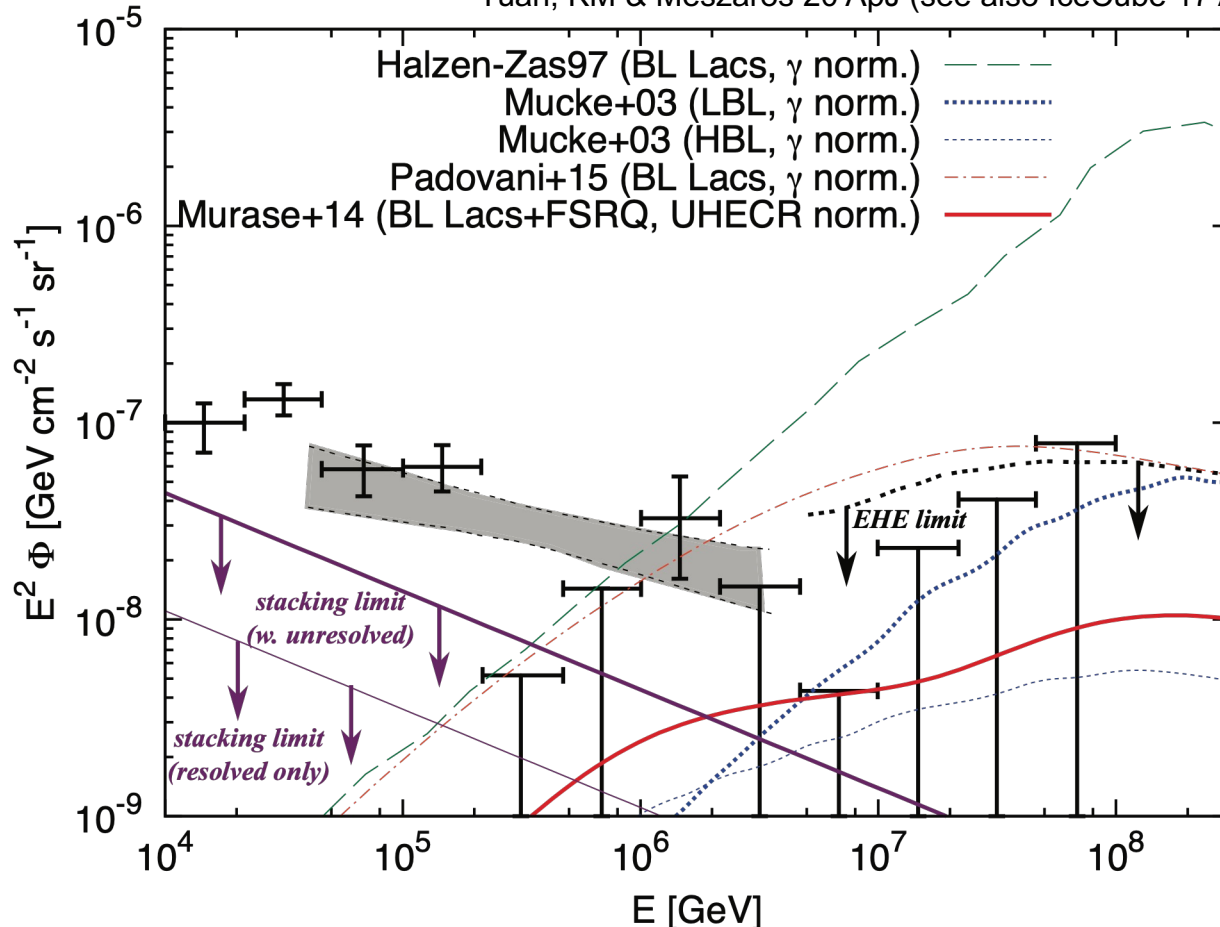
Extragalactic γ -Ray Sky: Star-Forming Galaxies at GeV



Extragalactic ν Sky: NOT Dominated by On-Axis Jetted AGN

γ -ray bright blazars are largely resolved -> **stacking analyses are powerful**

Yuan, KM & Meszaros 20 ApJ (see also IceCube 17 ApJ, Hooper+ 19 JCAP)

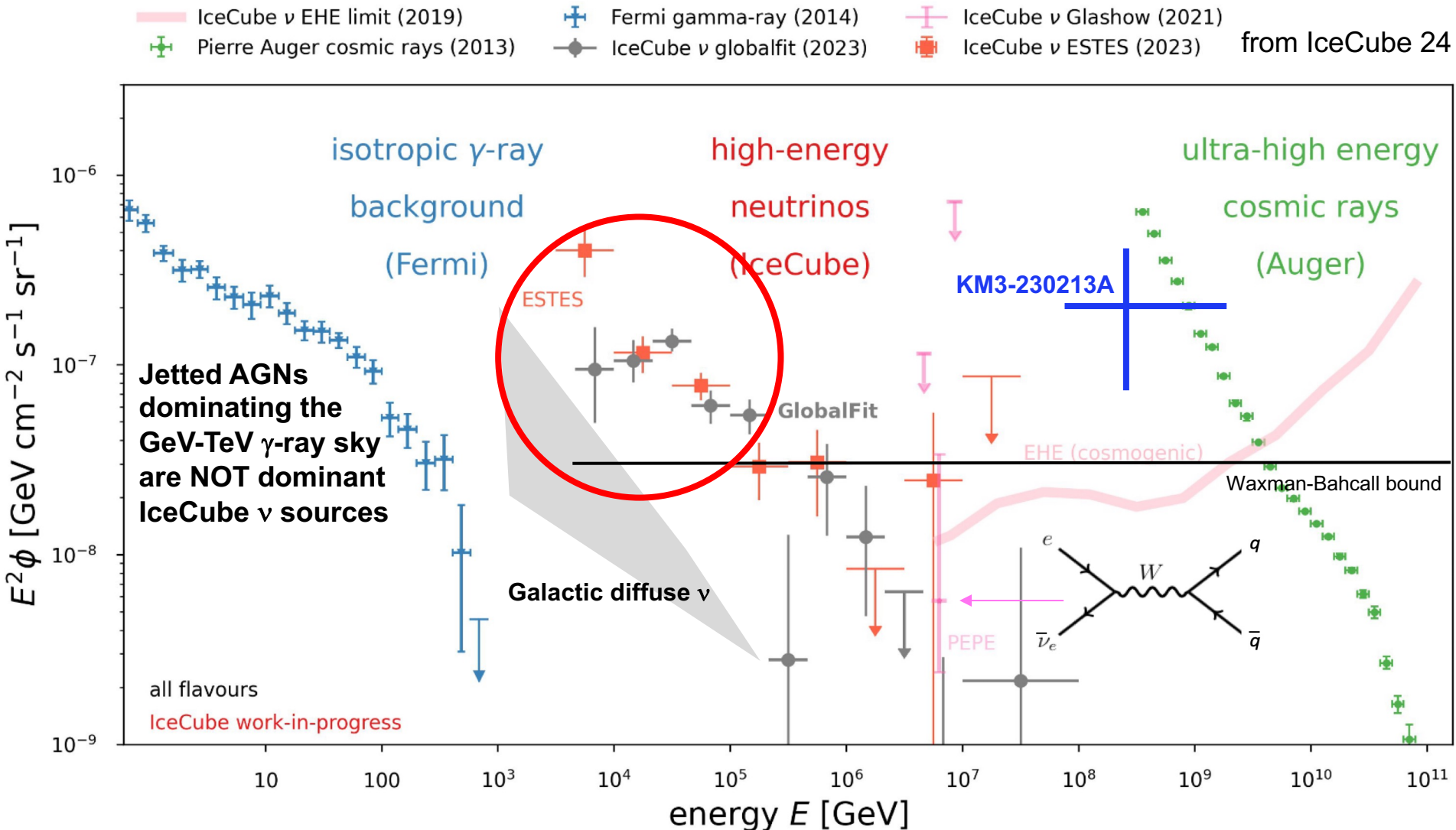


Blazars are subdominant in all parameter space (**most likely $< \sim 30\%$**)

Similar conclusion from neutrino anisotropy (multiplet) limits (KM & Waxman 16 PRD)

Predicted neutrino spectra are harder than the observed one

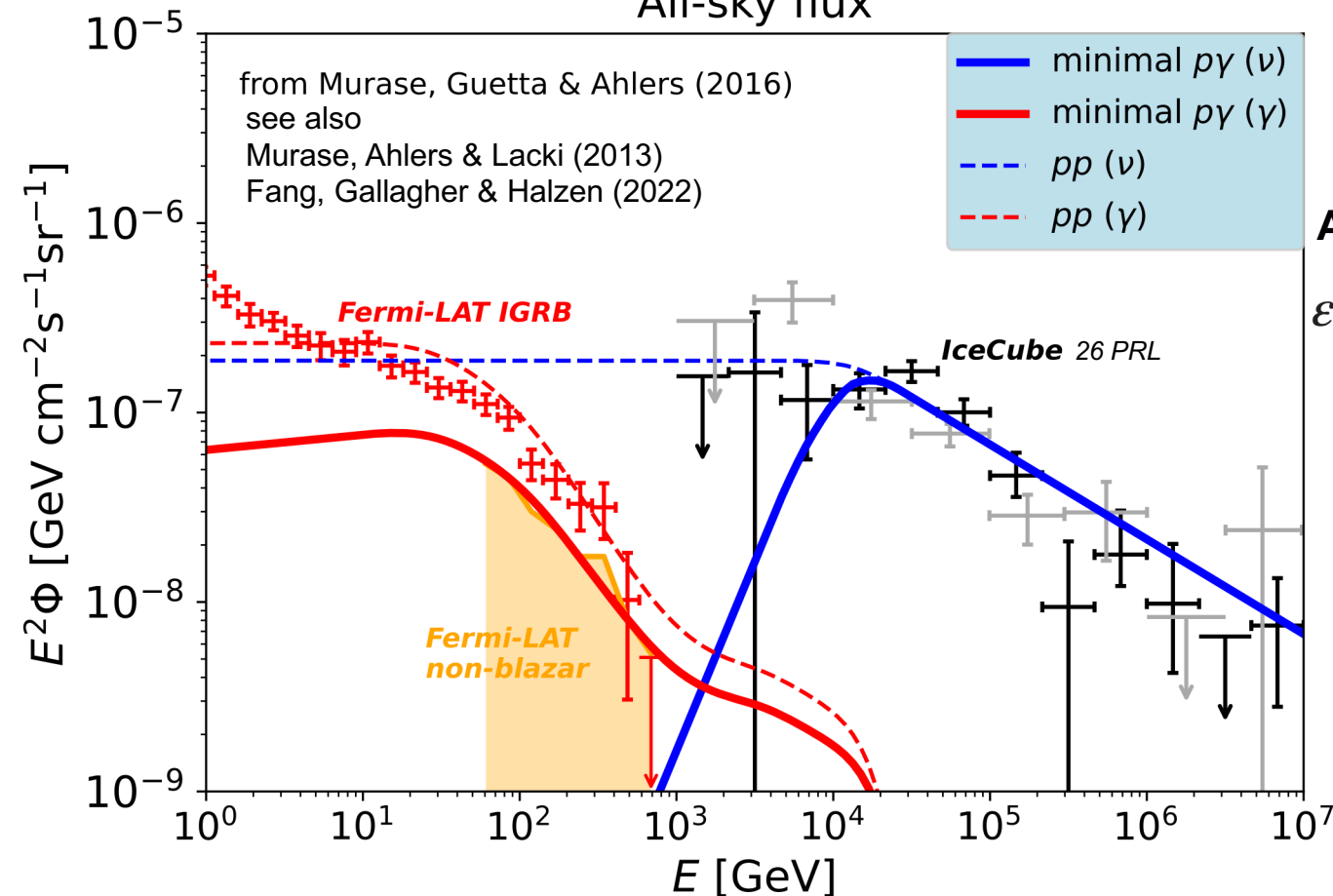
All-Sky Multimessenger Flux & Spectrum



- 10-100 TeV ν flux is **larger than** the benchmark ν flux from UHECR sources
- 10-100 TeV ν flux mainly originates from sources **other than** jetted AGNs (blazars)

Extragalactic Multimessenger Connection

10-100 TeV ν IceCube data: large fluxes of $\sim 10^{-7}$ GeV cm $^{-2}$ s $^{-1}$ sr $^{-1}$
All-sky flux



At sources

$$\varepsilon_\gamma Q_{\varepsilon_\gamma} \approx \frac{4}{3K} (\varepsilon_\nu Q_{\varepsilon_\nu})|_{\varepsilon_\nu = \varepsilon_\gamma/2}$$

$$K = \pi^\pm / \pi^0$$

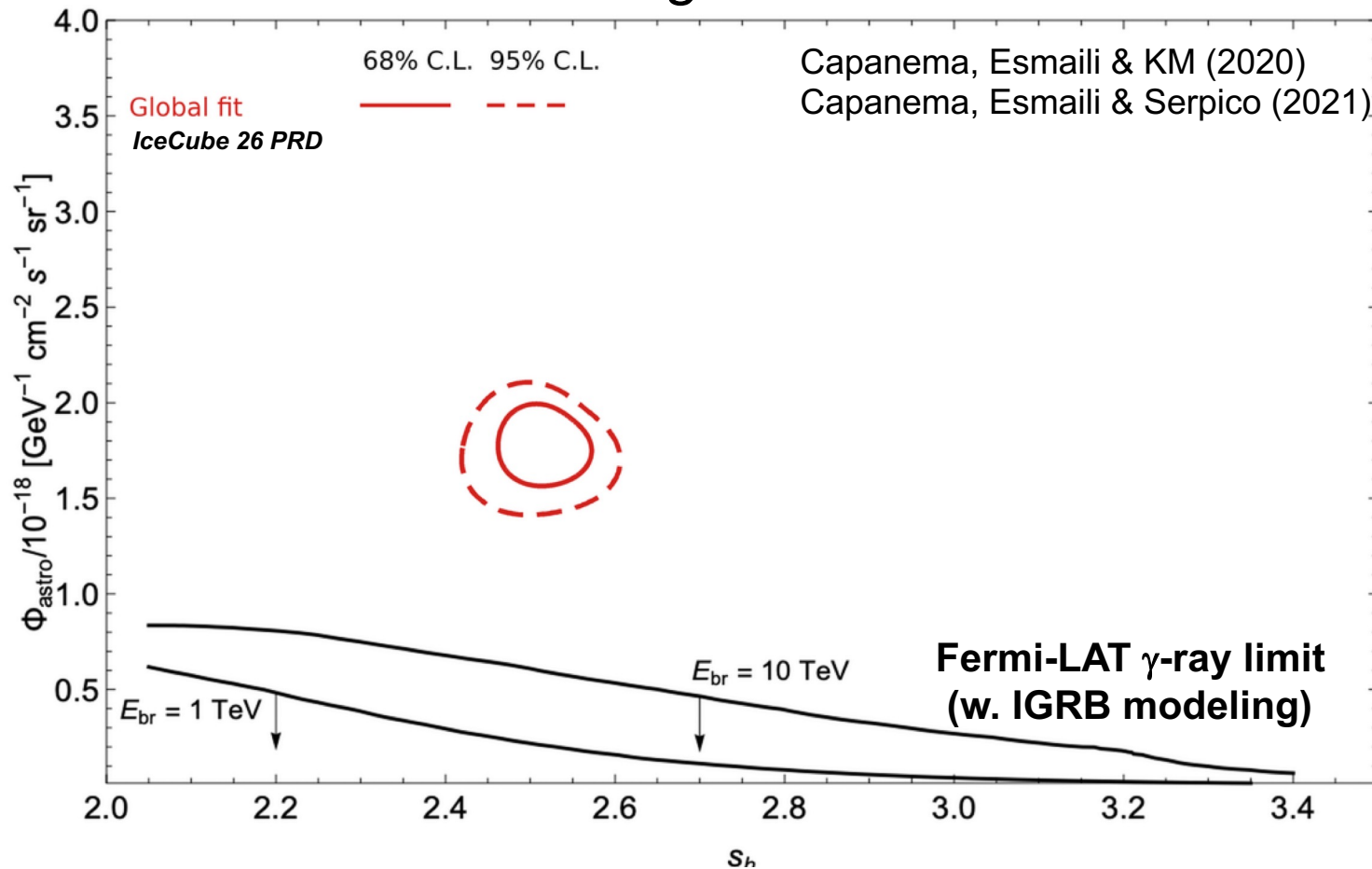
$$pp: K \sim 2$$

$$p\gamma: K \sim 1$$

pp scenarios (e.g., star-forming galaxies) are excluded **if γ -ray transparent**
tension w. γ -ray data ($> \sim 3\sigma$) even for the minimal $p\gamma$ scenario **if γ -ray transparent**
→ majority of ~ 30 TeV ν s: **hidden (i.e., γ -ray opaque)** cosmic-ray accelerators

Extragalactic Multimessenger Connection

10-100 TeV ν IceCube data: large fluxes of $\sim 10^{-7}$ GeV cm $^{-2}$ s $^{-1}$ sr $^{-1}$

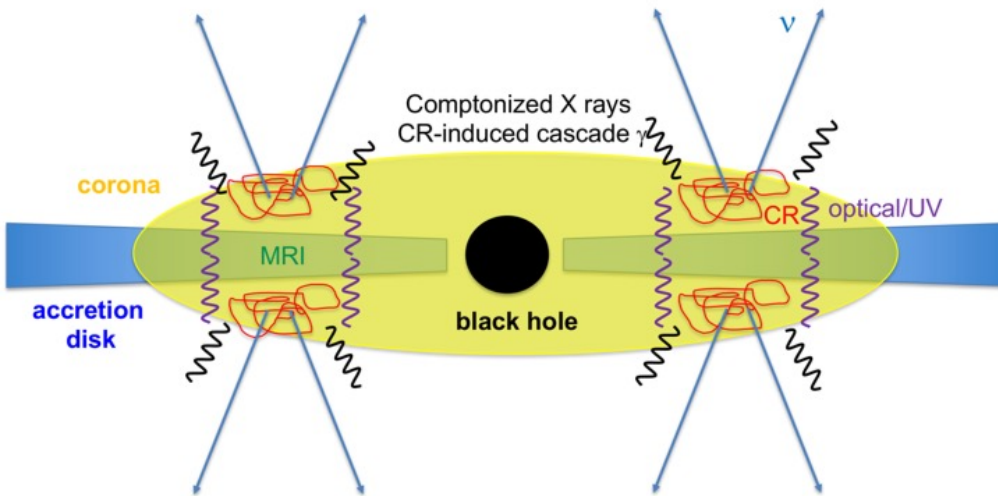


pp scenarios (e.g., star-forming galaxies) are excluded **if γ -ray transparent** tension w. γ -ray data ($>\sim 3\sigma$) even for the minimal $p\gamma$ scenario **if γ -ray transparent** $\rightarrow$ majority of ~ 30 TeV ν s: **hidden (i.e., γ -ray opaque)** cosmic-ray accelerators

Prediction of Hidden Neutrino Sources

Hidden (i.e., γ -ray opaque) ν sources are actually “natural” in $p\gamma$ scenarios

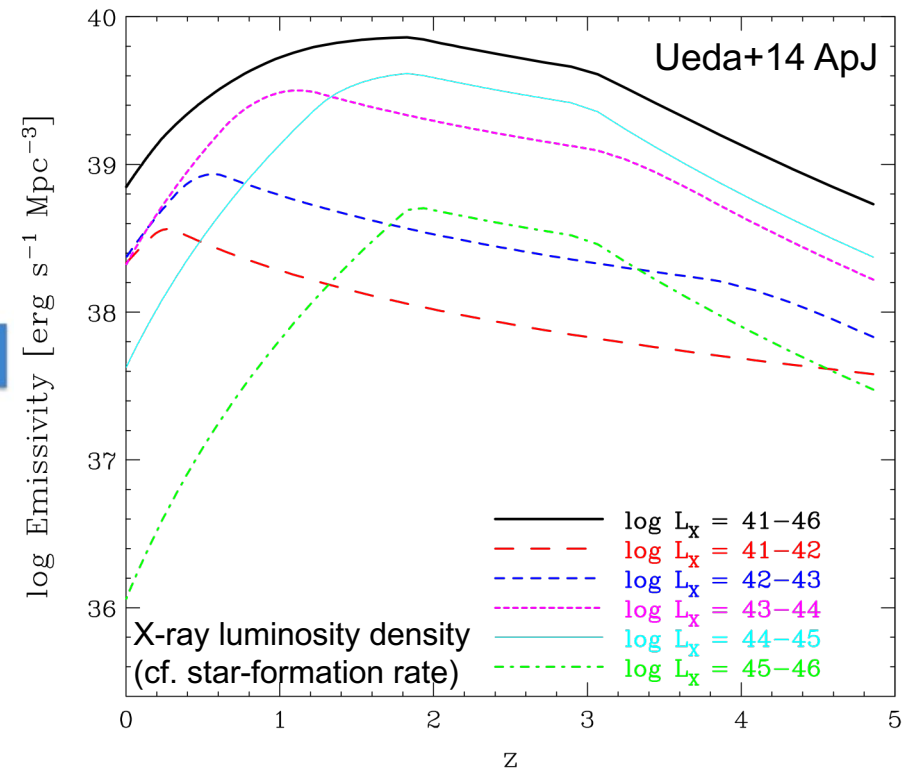
$$\text{optical depth } \tau_{\gamma\gamma} \approx \frac{\sigma_{\gamma\gamma}^{\text{eff}}}{\sigma_{p\gamma}^{\text{eff}}} f_{p\gamma} \sim 1000 f_{p\gamma} \gtrsim 10$$



disk-corona

**opt/UV=multi-temperature blackbody
from disks**

**X-ray=Comptonization by hot electrons
in coronae ($kT_e \sim 10\text{-}100$ keV)**



The X-ray background originates from jet-quiet AGNs (coronae)

Prediction of Hidden Neutrino Sources

all-sky ν intensity of extragalactic ν sources (cf. DSNB)

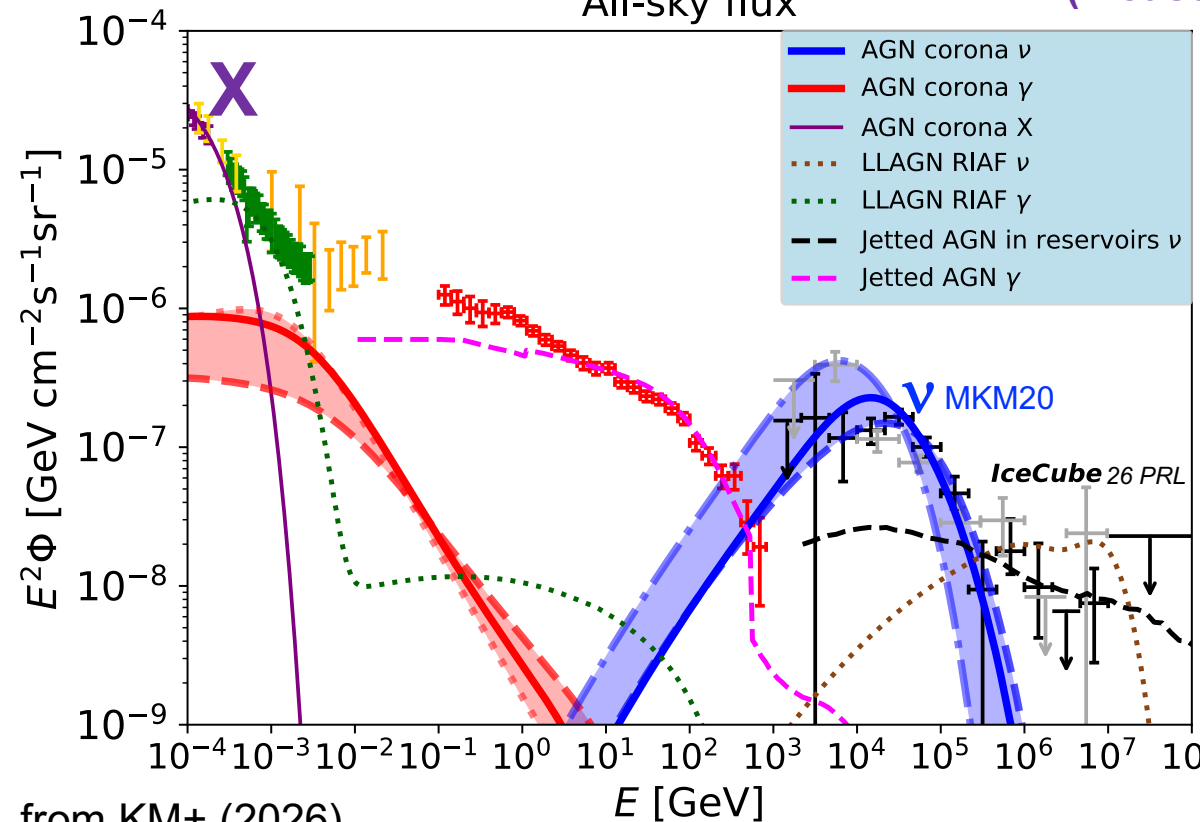
$$\Phi_\nu = \underbrace{\frac{c}{4\pi H_0} \int_{z_{\min}}^{z_{\max}} dz \frac{1}{\sqrt{(1+z)^3 \Omega_m + \Omega_\Lambda}}}_{\text{cosmology}} \underbrace{\int dL_X \frac{d\rho_{\text{AGN}}}{dL_X}(L_X, z, \bar{\lambda})}_{\text{X-ray data (measured)}} \underbrace{\int d\lambda \frac{d\Pi}{d\lambda} \frac{L_{\varepsilon_\nu}(L_X, \lambda)}{\varepsilon_\nu}}_{\text{theory } (\lambda: \text{model parameters})}$$

cosmology

X-ray data
(measured)

theory
(λ : model parameters)

All-sky flux



KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.
(see also Padovani et al. 24 A&A)

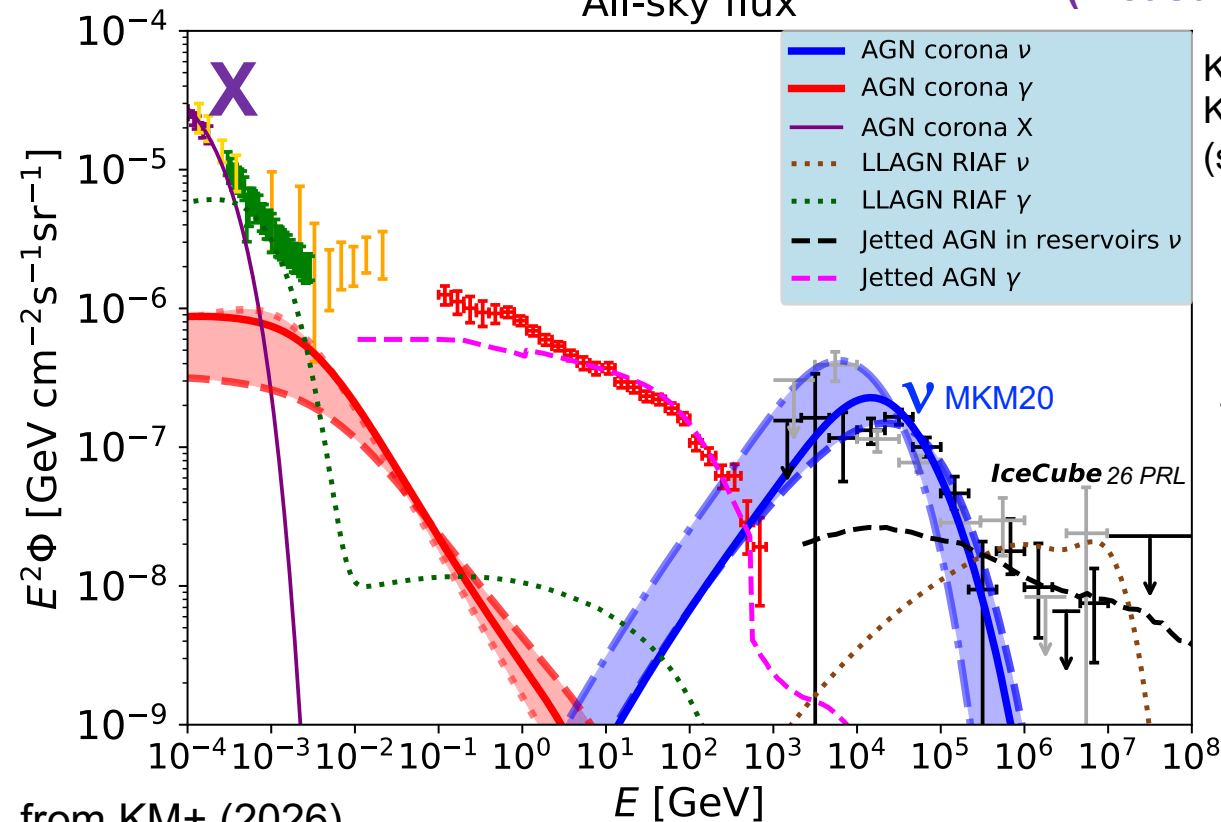
- **Simultaneous** explanation for the all-sky ν and X-ray fluxes
- **Predicting a spectral curvature** consistent w. a ~ 10 -30 TeV break in the ν data (IceCube PRL 26)
- Power-law neutrino spectrum caused by the superposition of spectra with different peaks

Prediction of Hidden Neutrino Sources

all-sky ν intensity of extragalactic ν sources (cf. DSNB)

$$\Phi_\nu = \underbrace{\frac{c}{4\pi H_0} \int_{z_{\min}}^{z_{\max}} dz \frac{1}{\sqrt{(1+z)^3 \Omega_m + \Omega_\Lambda}}}_{\text{cosmology}} \underbrace{\int dL_X \frac{d\rho_{\text{AGN}}}{dL_X}(L_X, z, \bar{\lambda})}_{\text{X-ray data (measured)}} \underbrace{\int d\lambda \frac{d\Pi}{d\lambda} \frac{L_{\varepsilon_\nu}(L_X, \lambda)}{\varepsilon_\nu}}_{\text{theory } (\lambda: \text{model parameters})}$$

All-sky flux



KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.
(see also Padovani et al. 24 A&A)

In general, for know population

$$\varepsilon_p^b \gtrsim 20 \text{ GeV} \left[\left(\frac{E_\nu^2 \Phi_\nu|_{100 \text{ TeV}}}{10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}} \right) \left(\frac{3}{\xi_z} \right) \times \left(\frac{1+K}{2K} \right) \left(\frac{1+f_{\text{BH}}+f_{\text{mes}}}{f_{\text{mes}}} \right) \times \left(\frac{Q_{\text{CR}}}{3 \times 10^{46} \text{ erg Mpc}^{-3} \text{ yr}^{-1}} \right) \right]^{20/11}$$

Prediction of Hidden Neutrino Sources

all-sky ν intensity of extragalactic ν sources (cf. DSNB)

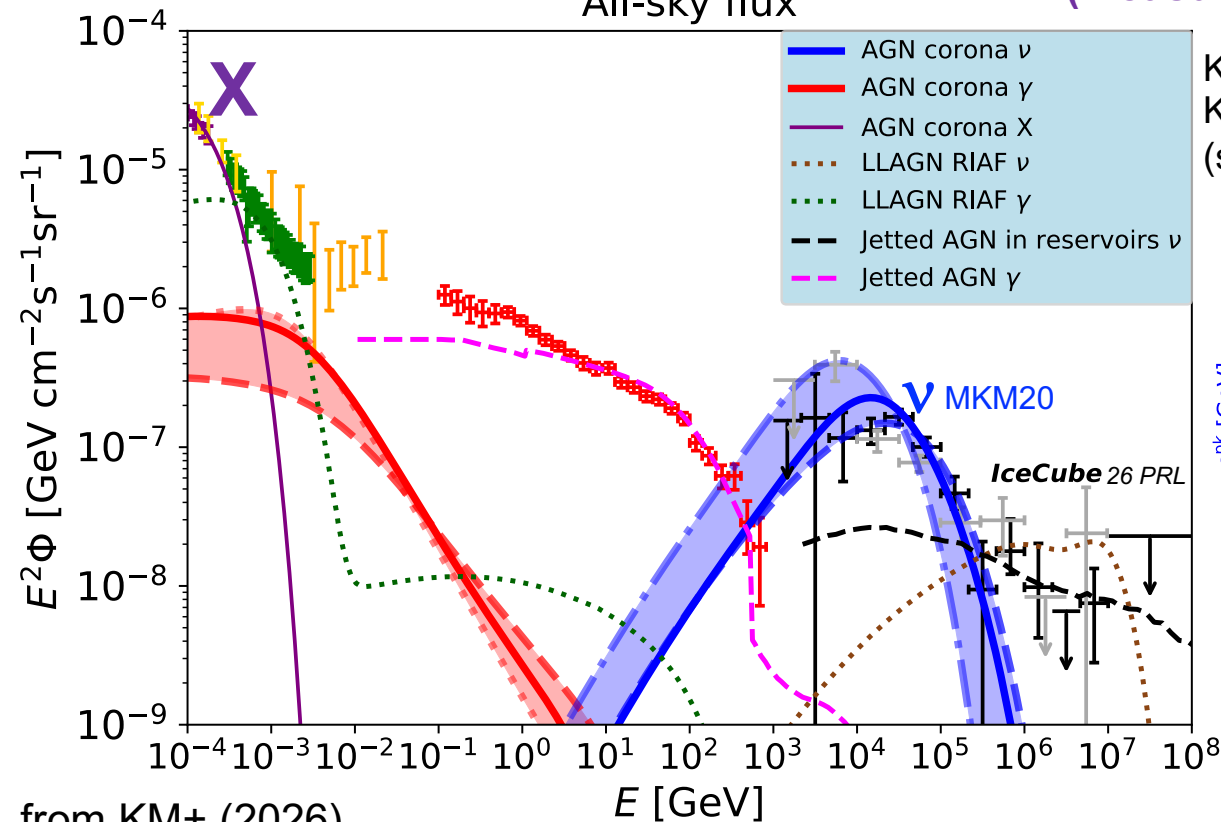
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cosmology

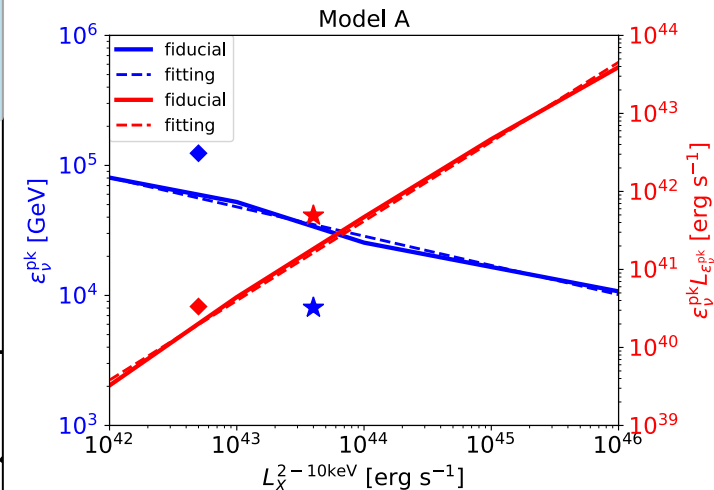
X-ray data
(measured)

theory
(λ : model parameters)

All-sky flux



KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.
(see also Padovani et al. 24 A&A)



- $\text{p}\gamma$ efficiency ($\uparrow$ at high E)
- Hard cosmic-ray spectrum
- Bethe-Heitler cooling

Prediction of Hidden Neutrino Sources

all-sky ν intensity of extragalactic ν sources (cf. DSNB)

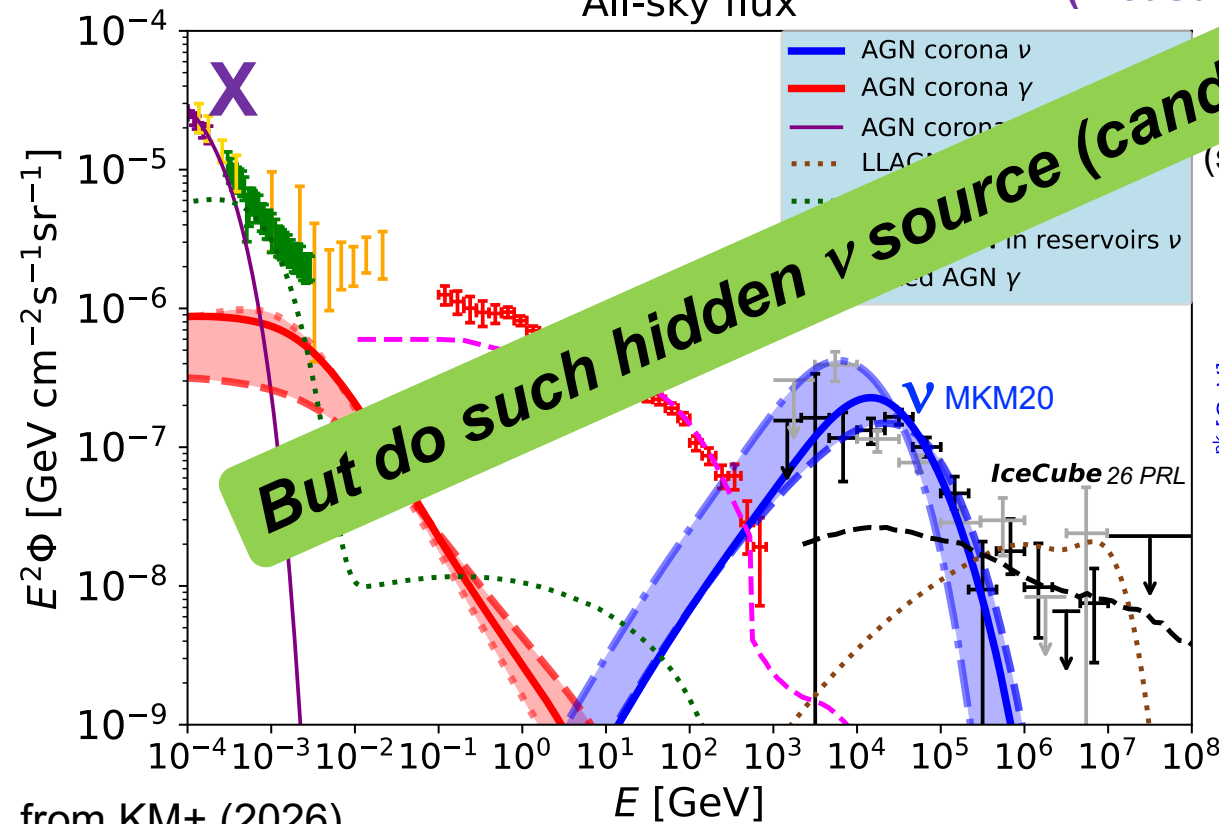
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cosmology

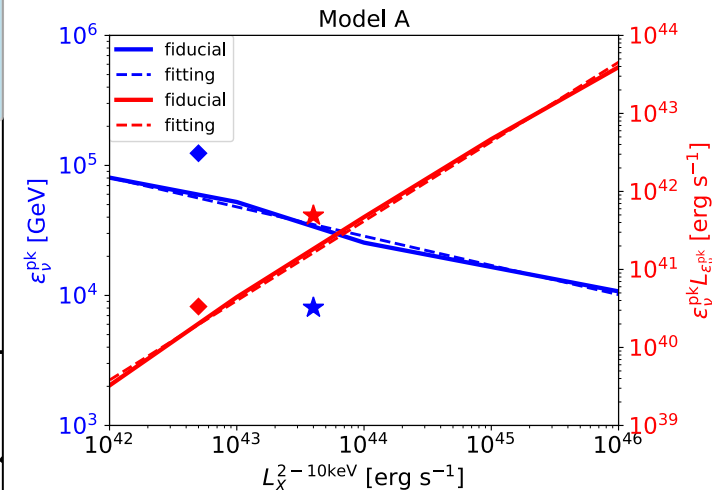
All-sky flux

X-ray data
(measured)

theory
(model parameters)



(see also Padovani et al. 24 A&A)



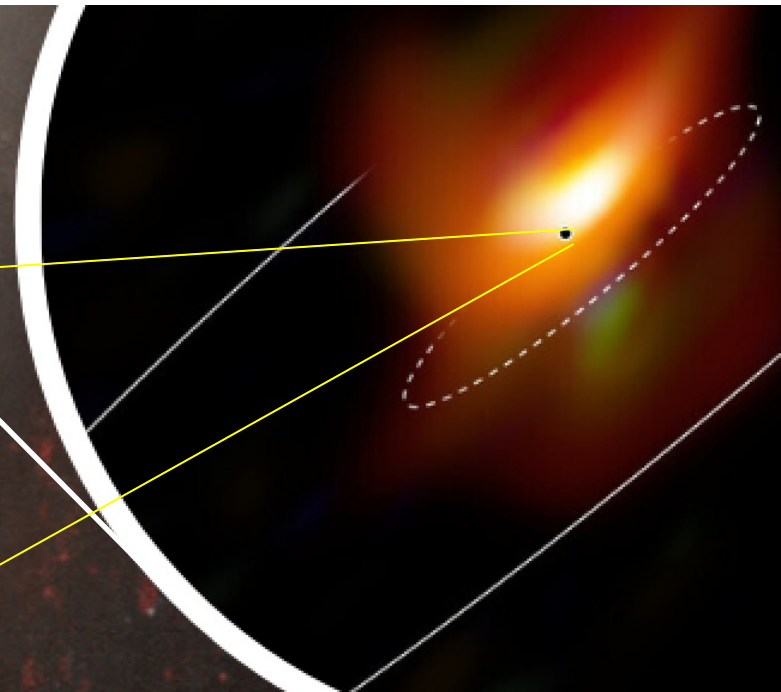
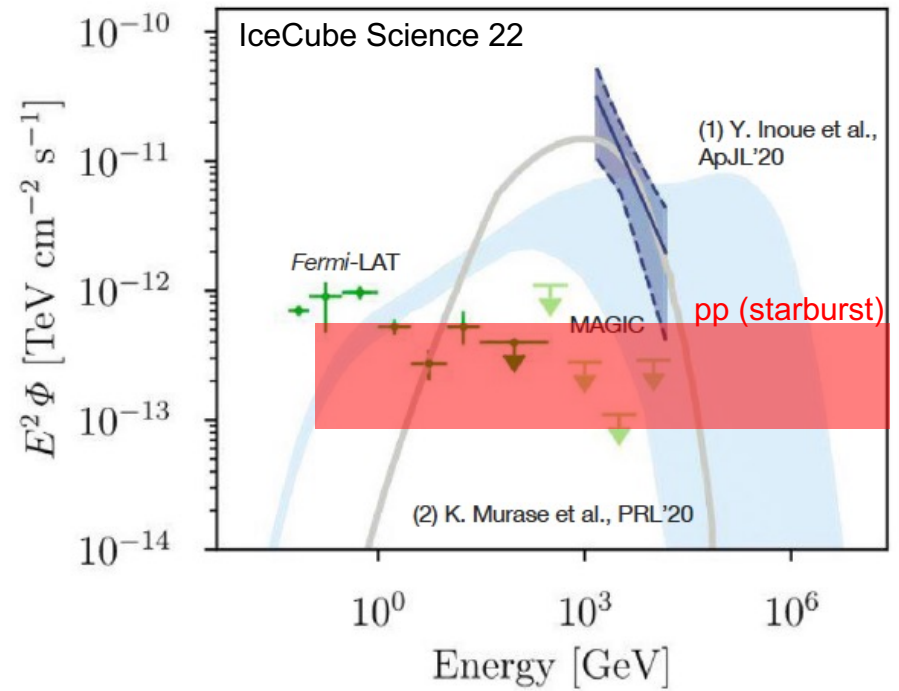
- py efficiency ($\uparrow$ at high E)
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NGC 1068

one of the powerful AGNs in the local universe

distance: ~ 10 Mpc

$L_v \sim 10^{42}$ erg/s $\ll L_{\text{corona}} \sim 8 \times 10^{43}$ erg/s
 $\ll L_{\text{bol}} \sim L_{\text{Edd}} \sim 10^{45}$ erg/s

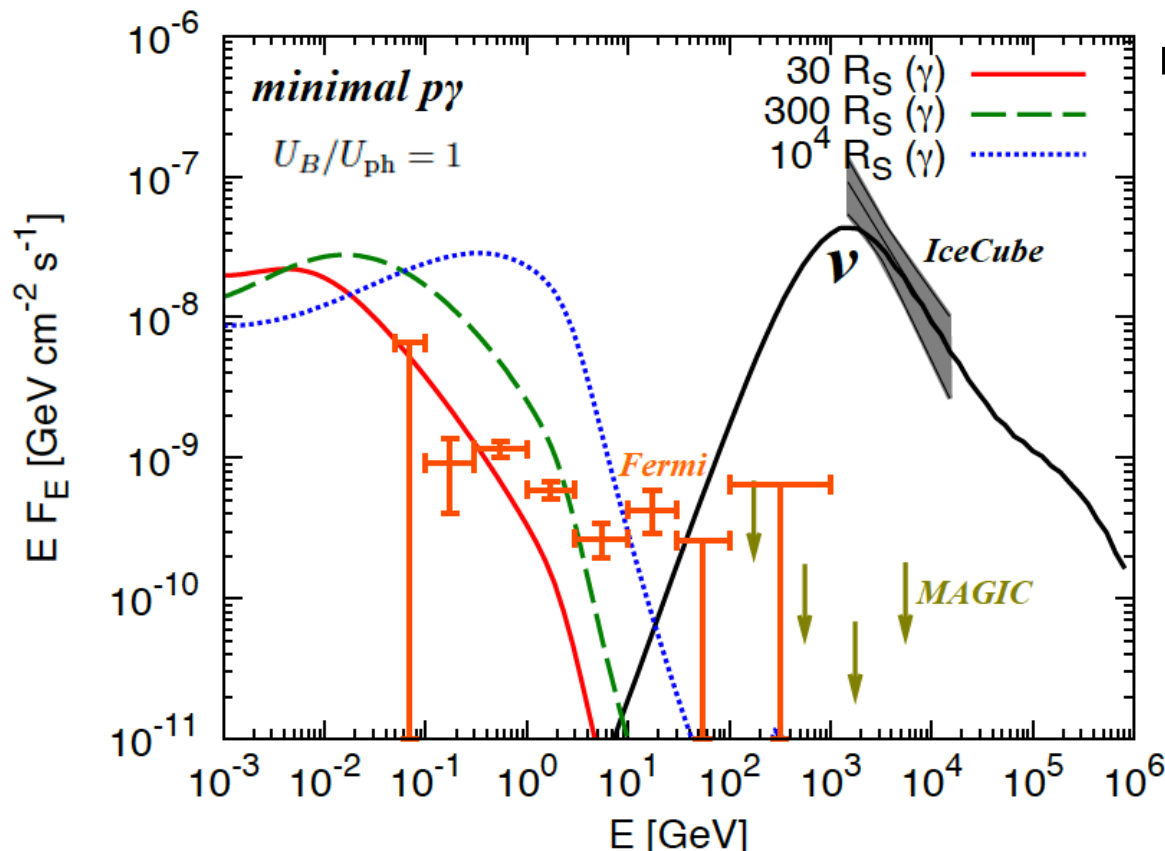


Where Do Neutrinos Come from?

$$\gamma + \gamma \rightarrow e^+ + e^-$$

for 0.1-300 GeV γ rays

$$\tau_{\gamma\gamma} \sim \left(\frac{1}{4\pi} \right) \left(\frac{\sigma_{\gamma\gamma}}{R} \right) \left(\frac{L_X}{m_e c^3} \right) \left(\frac{\varepsilon_\gamma}{m_e c^2} \right) \gtrsim 10$$



model-independent constraint
 considering **elemag cascade**

$$R < (15-30) R_S$$

KM 22 ApJL

see also

Das, Zhang & KM 24 ApJ

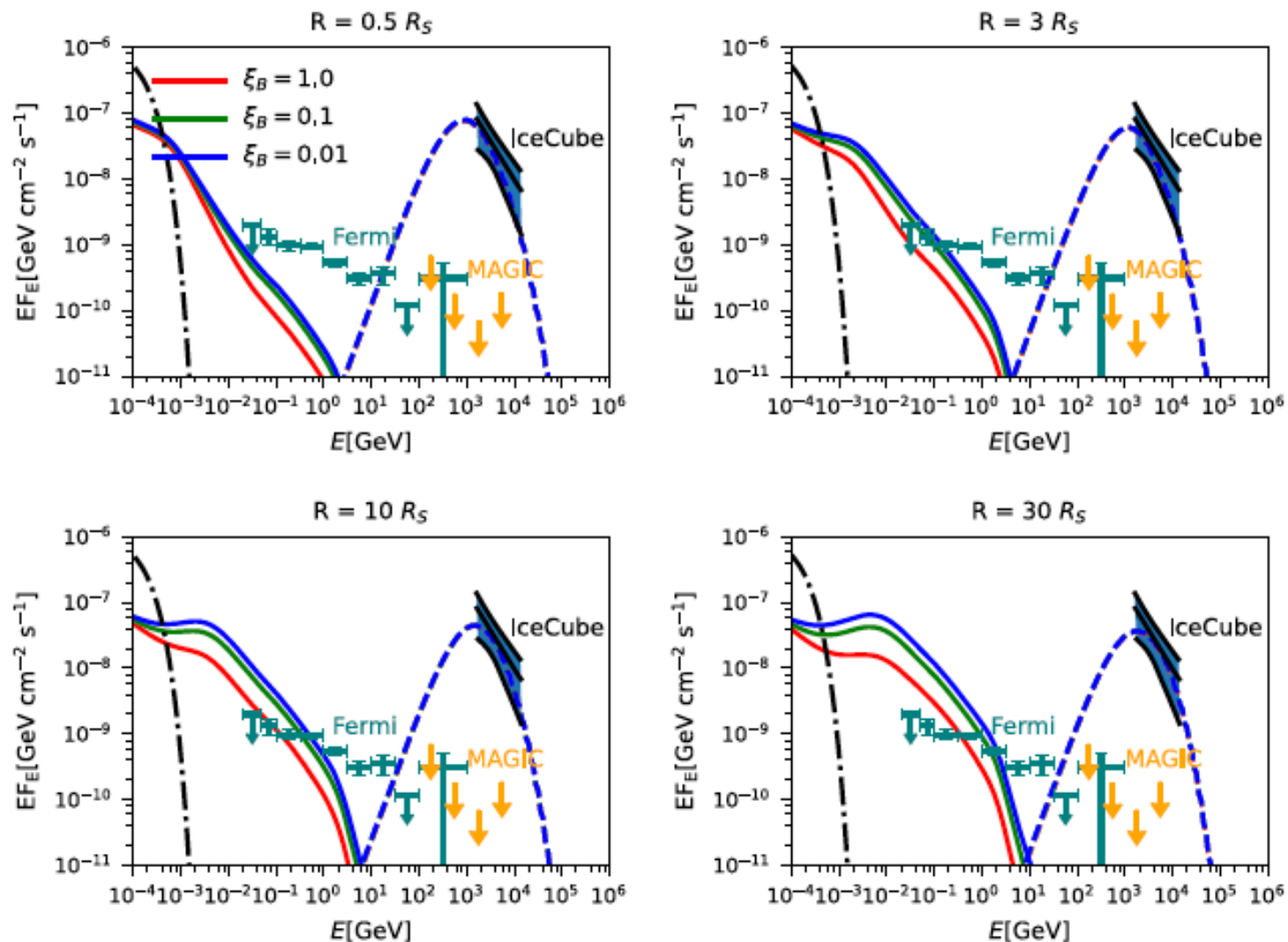
Blanco, Hooper, Linden & Pinetti 25 PRD

compatible w. p_γ calorimetry ($f_{p_\gamma} > 1$) condition: **$R < 30-100 R_S$**

Massive black hole: sub-PeV proton accelerator & ideal beam dump

Updated Fermi Analysis & Impacts of Magnetic Fields

Das, Zhang & KM 24, Das, KM & Zhang 26 (see also Ajello, KM & McDaniel 23 ApJL for updated Fermi analysis)



magnetization $\xi_B = U_B/U_{\text{ph}}$ (cf. corona model: $\xi_B \sim 1$, shock model: $\xi_B \lesssim 0.01$)

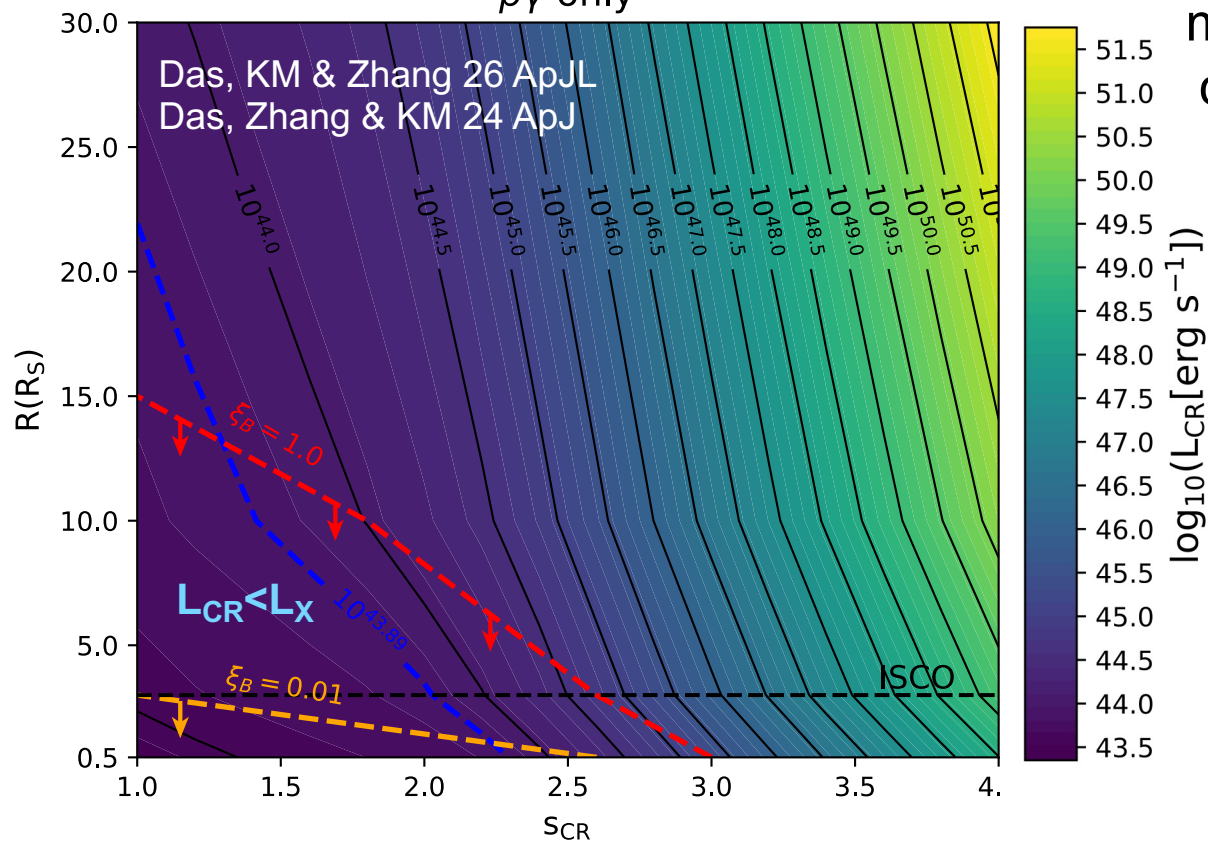
What Can We Learn from NGC 1068?

$$\gamma + \gamma \rightarrow e^+ + e^-$$

for 0.1-300 GeV γ rays

$$\tau_{\gamma\gamma} \sim \left(\frac{1}{4\pi} \right) \left(\frac{\sigma_{\gamma\gamma}}{R} \right) \left(\frac{L_X}{m_e c^3} \right) \left(\frac{\varepsilon_\gamma}{m_e c^2} \right) \gtrsim 10$$

$p\gamma$ only



model-independent constraint
considering **elemag cascade**

$$R < (15-30) R_S$$

- CR spectrum: **hard**
 $S_{CR} < \sim 2$
- Emission region is likely to be **strongly magnetized**
 $\xi_B = U_B/U_{ph} > \sim 0.01$
 $\beta = P_{th}/P_B < \sim 10$

$$4 \text{ kG} \lesssim B \lesssim 50 \text{ kG} \mathcal{R}_1^{-5/6} \zeta_e^{-1/6}$$

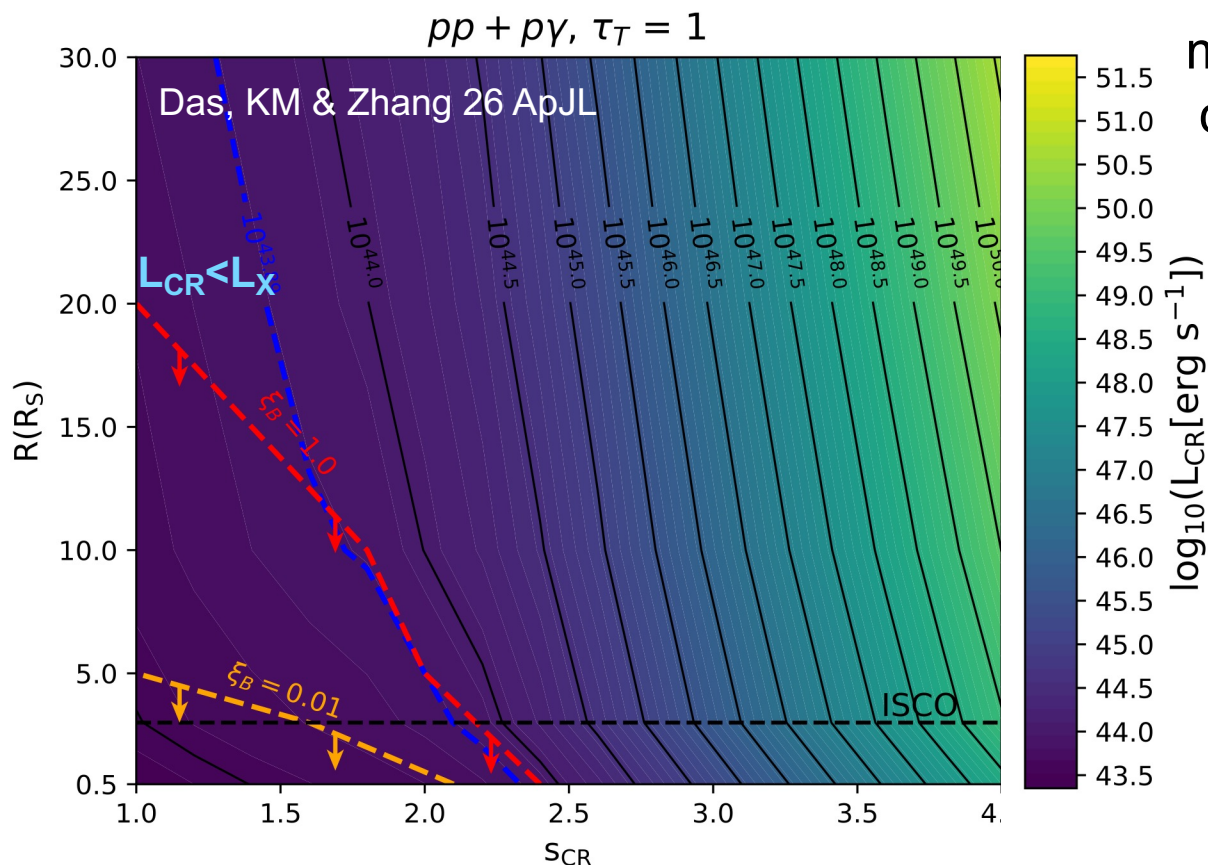
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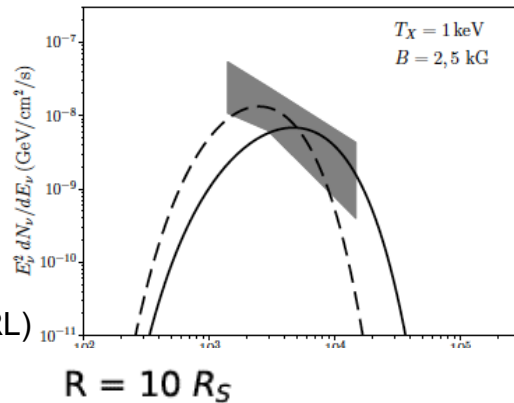
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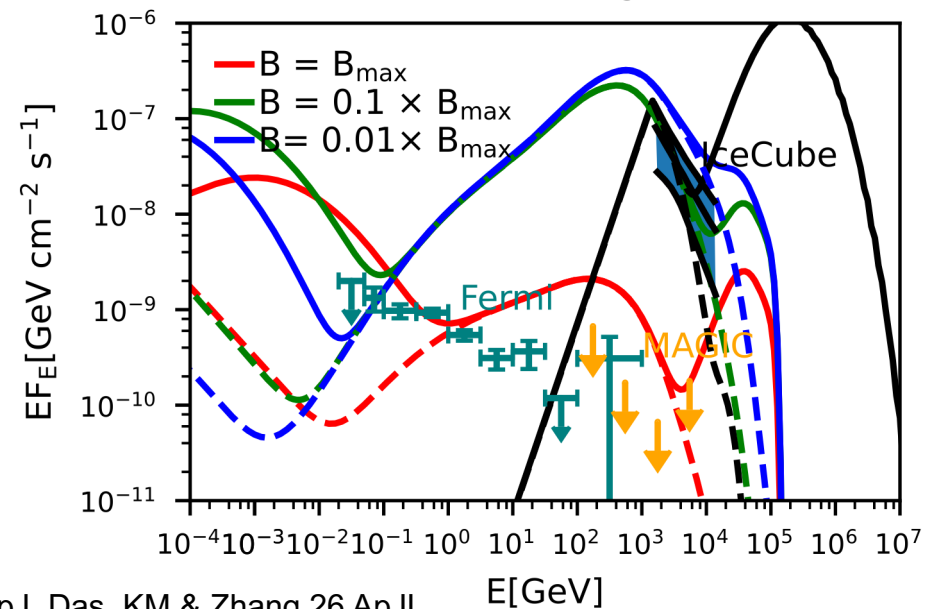
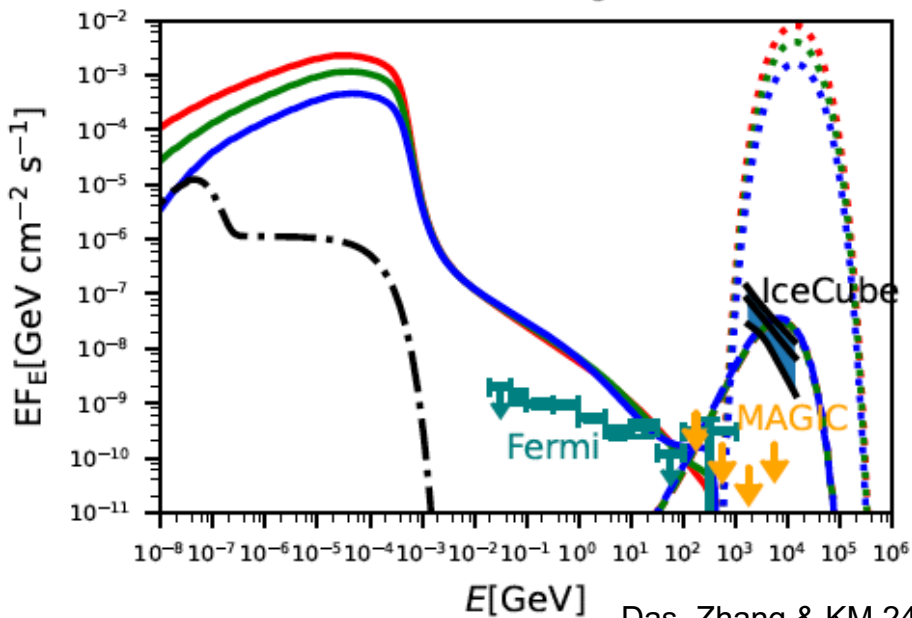
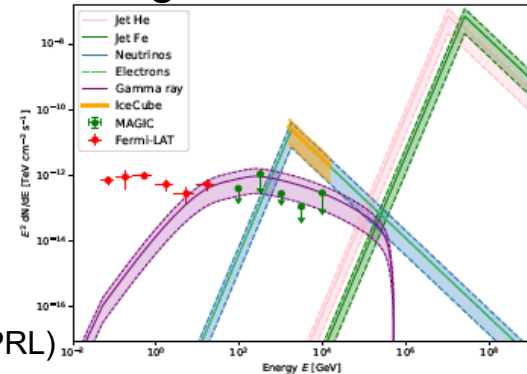
Neutrino Production Mechanisms: pp & $p\gamma$

- Multimessenger connection **must be considered**
- Exotic models are excluded if relevant processes are consistently included
- Also unlikely by the energetics requirement: $L_{\text{CR}} < L_{\text{bol}} \sim L_{\text{Edd}} \sim 10^{45} \text{ erg/s}$

Neutrinos
from $\gamma\gamma \rightarrow \mu^+\mu^-$
(Hooper & Plant 23 PRL)



Neutrons from
photodisintegration
(Yasuda, Inoue & Kusenko 25 PRL)

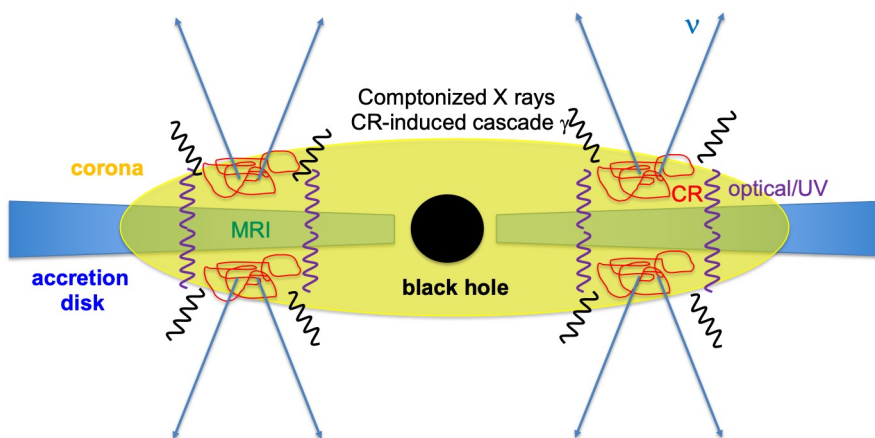


Neutrino Production Models

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

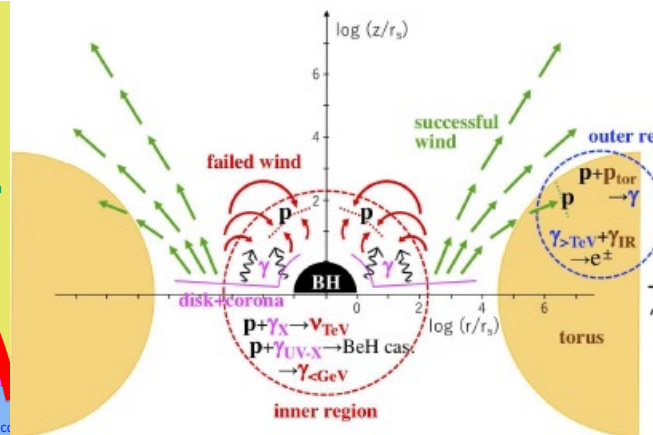
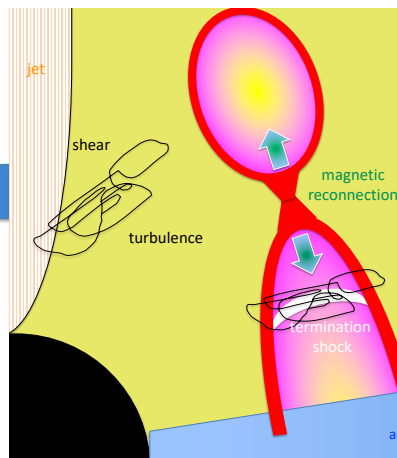
$$p + p \rightarrow N\pi + X$$

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

$$\beta = P_g / P_B < 0.1-10 \rightarrow B \gtrsim 10^2 \text{ G}$$

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

shocks

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

$$\beta = P_g / P_B \gtrsim 10-100$$

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

Magnetically Powered Turbulent Corona Model

- Astrophysical data (NGC 1068):

luminosity ($L_X \sim 3 \times 10^{43}$ erg/s), mass ($M_{BH} \sim 6 \times 10^6 M_{sun}$), optical depth ($\tau_T \sim 0.4$)

- Coronal parameters (data & magnetohydrodynamics):

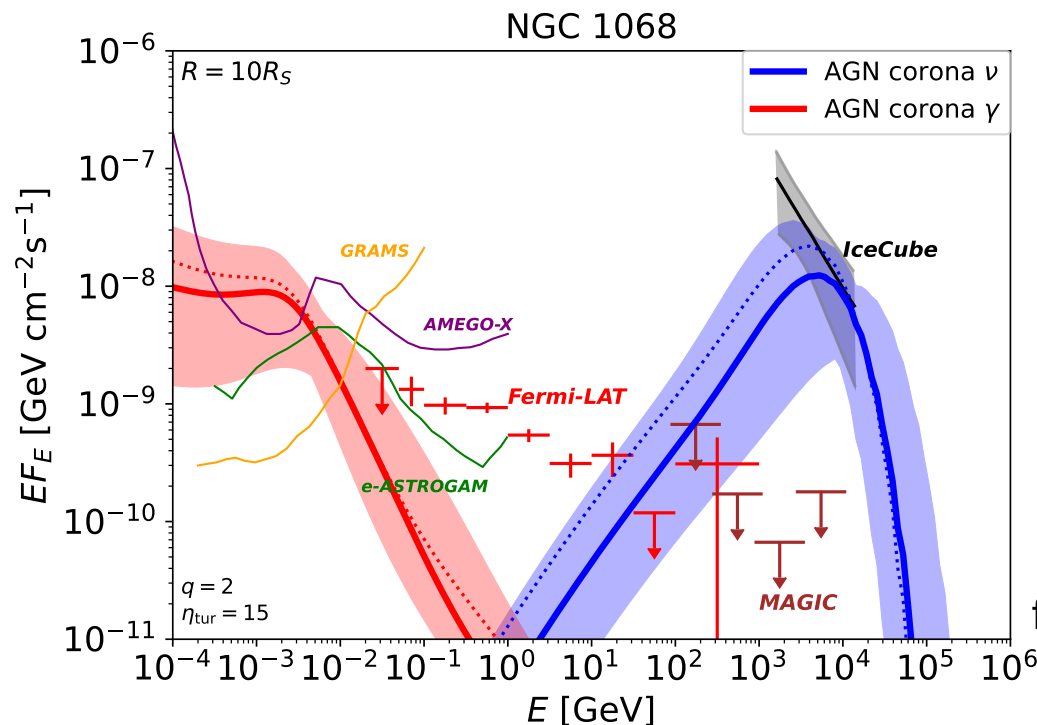
emission region size (R/R_S), magnetic fields, viscosity

- CR parameters (particle acceleration):

Injection efficiency (P_{CR}/P_{th}), acceleration efficiency (η_{tur}), spectral index (q)

Lemoine's talk on Tue

(KM+ 20, see also Kheirandish, KM+ 21, Eichman+ 22, Fiorillo+ 24, Lemoine & Rieger 25, Wang+ 26, Yang+ 26...)



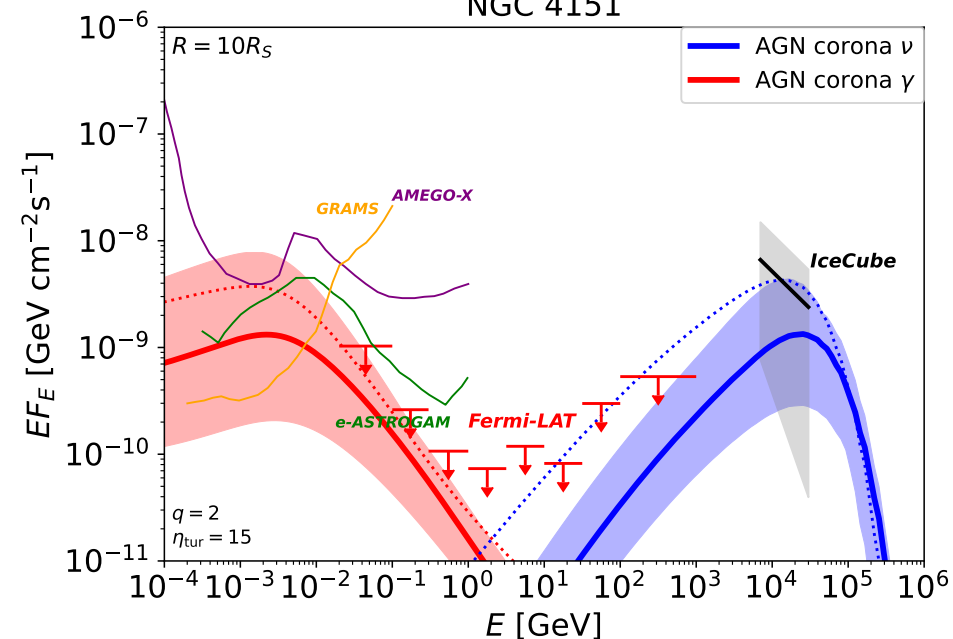
from KM+ (2026)

Corona Model: Predictions and Hints

- Theory prediction: ν luminosity $\sim$ intrinsic X-ray luminosity (KM+ 20 PRL, 24 ApJL)
brightest for IceCube: **NGC 1068, NGC 4151**
brightest in the southern sky: **Circinus, NGC 4945**
- IceCube ν evidences/hints: (IceCube Collaboration 22, 25a, 25b, 26a, 26b, Neronov+ 24 PRL)
NGC 1068 ($\sim 4\sigma$), **NGC 4151** ($\sim 3\sigma$),
14 AGNs in the south incl. **Circinus** ($\sim 3\sigma$)
consistent w. the theoretical picture

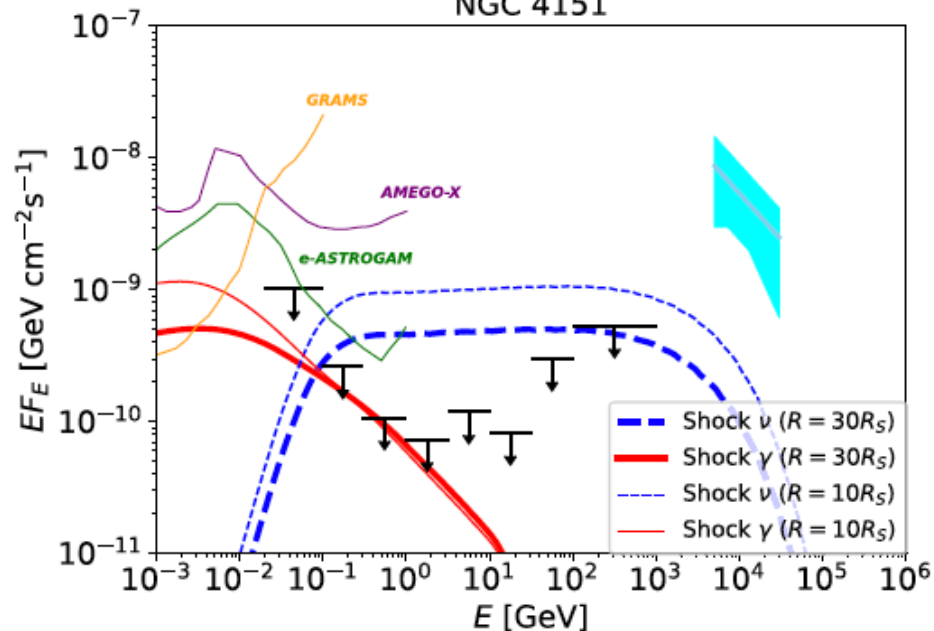
stochastic acceleration

NGC 4151



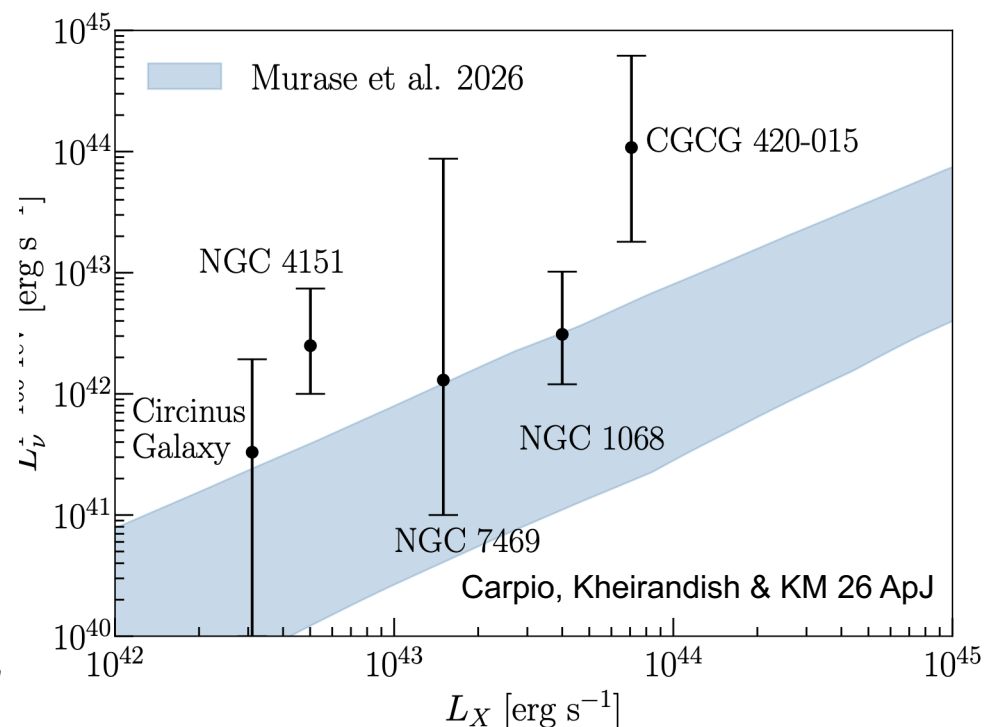
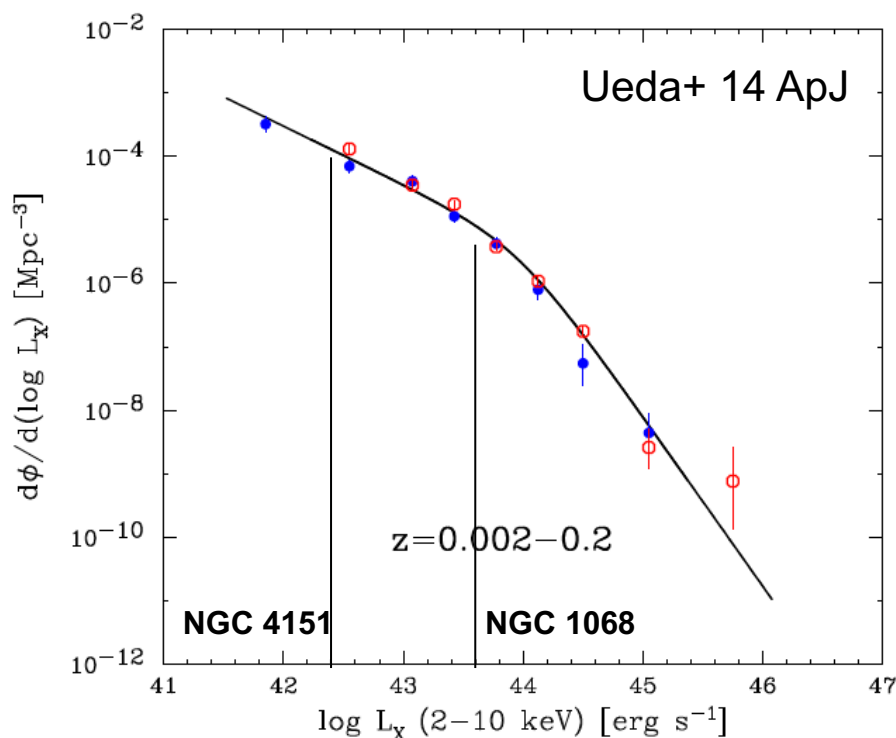
fast acceleration (E^2 injection)

NGC 4151

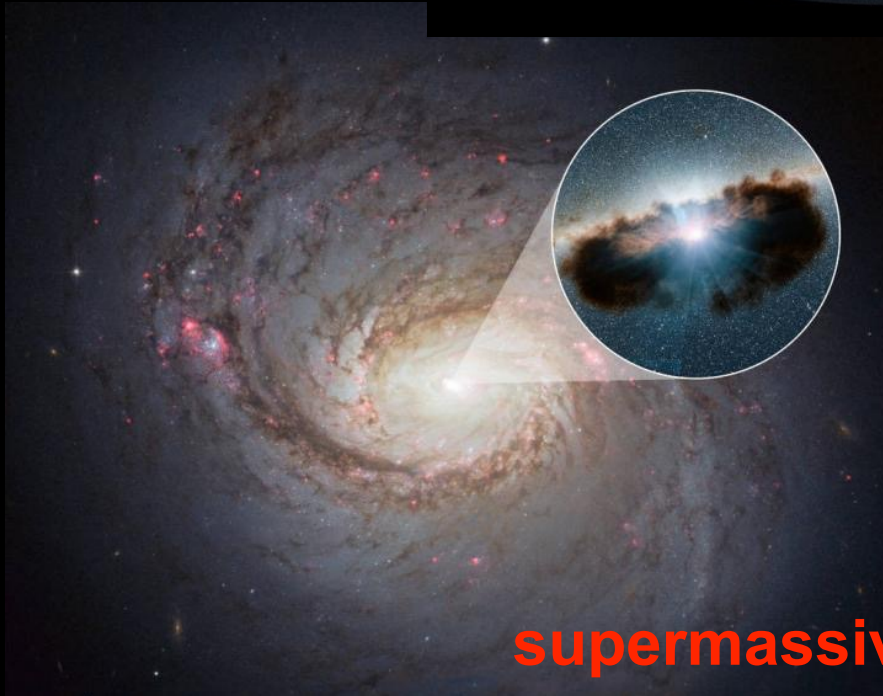
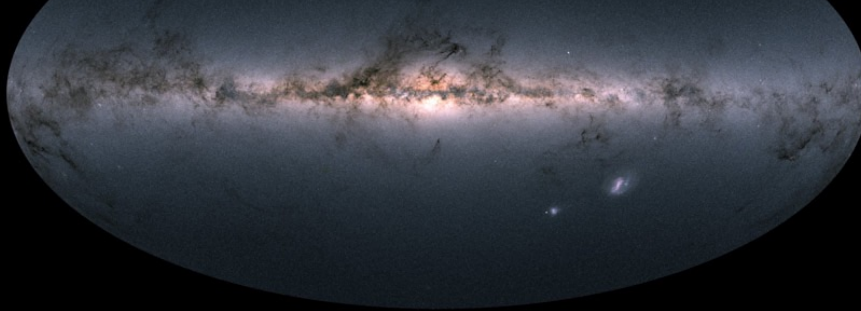


Consistency between NGC 1068 and All-Sky Neutrino Flux?

- All-sky ν flux has been explained by the magnetically powered corona model
- NGC 1068 can be consistently explained by the same model (KM+ 20 PRL, 26 PRD)
- Differential ν flux at 10 TeV: $\sim 10^{-8}$ GeV cm $^{-2}$ s $^{-1}$ $\rightarrow$ $EL_E \sim 10^{41}$ erg/s
- NGC 1068-like AGNs are **rare**: $n \sim 10^{-5}$ Mpc $^{-3}$ $\rightarrow$ $EQ_E \sim 3 \times 10^{43}$ erg Mpc $^{-3}$ yr $^{-1}$
- NGC 1068-like AGN contribution: $E^2 \Phi_\nu < \sim 7 \times 10^{-8}$ GeV cm $^{-2}$ s $^{-1}$ sr $^{-1}$
- In reality, neutrino spectra depend on X-ray luminosities etc. (dispersion)



Galaxy
subdominant ν sources (Milky Way)



supermassive black holes

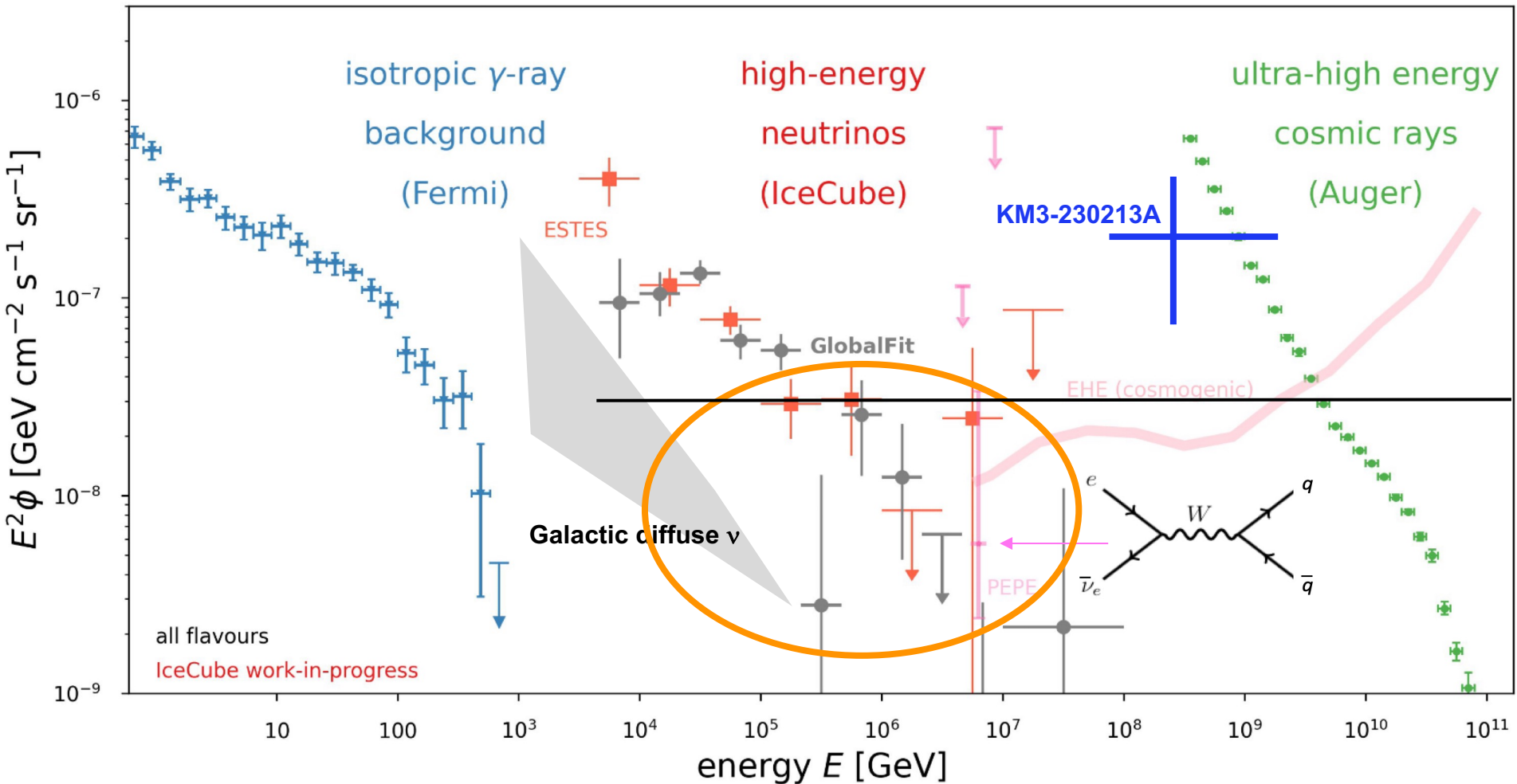
Jet-quiet AGN
hidden ν sources
(NGC 1068...)



Jet-loud AGN
>100 TeV ν sources?
(TXS 0506+056?)

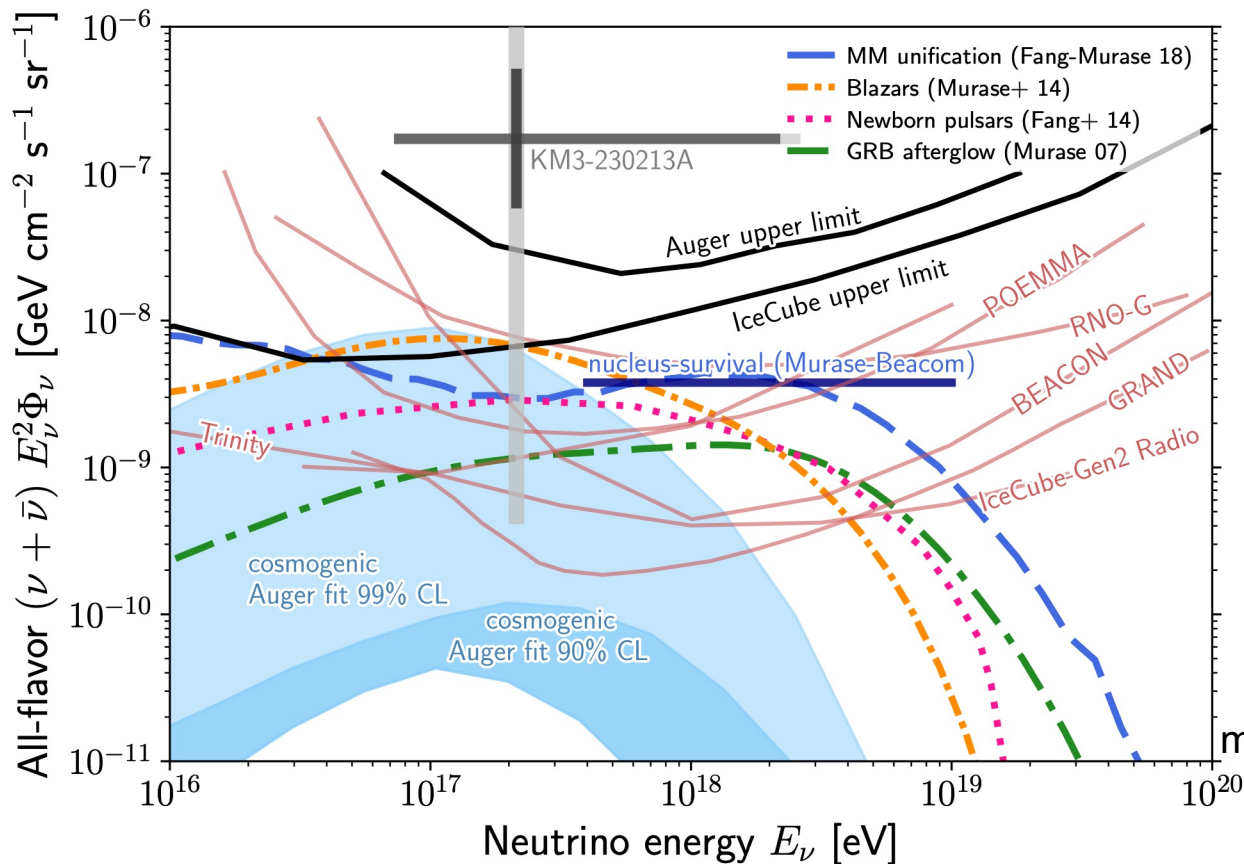
All-Sky Multimessenger Flux & Spectrum

IceCube ν EHE limit (2019) Fermi gamma-ray (2014) IceCube ν Glashow (2021)
Pierre Auger cosmic rays (2013) IceCube ν globalfit (2023) IceCube ν ESTES (2023) from IceCube 24



Hunting Ultrahigh-Energy Neutrinos

UHECR w. $E/Z > 10^{18.5}$ eV requires **UHE ν w. $E_\nu > \sim 100$ PeV**



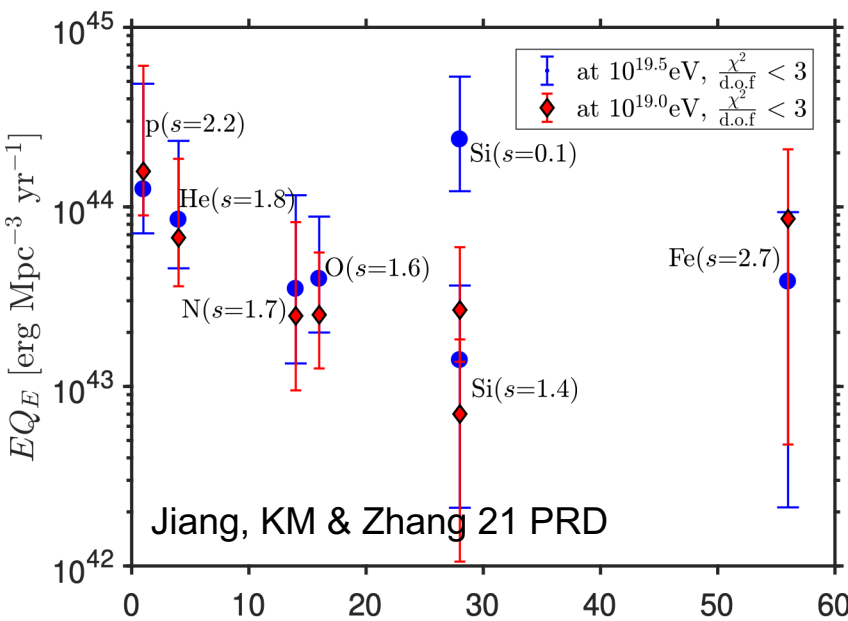
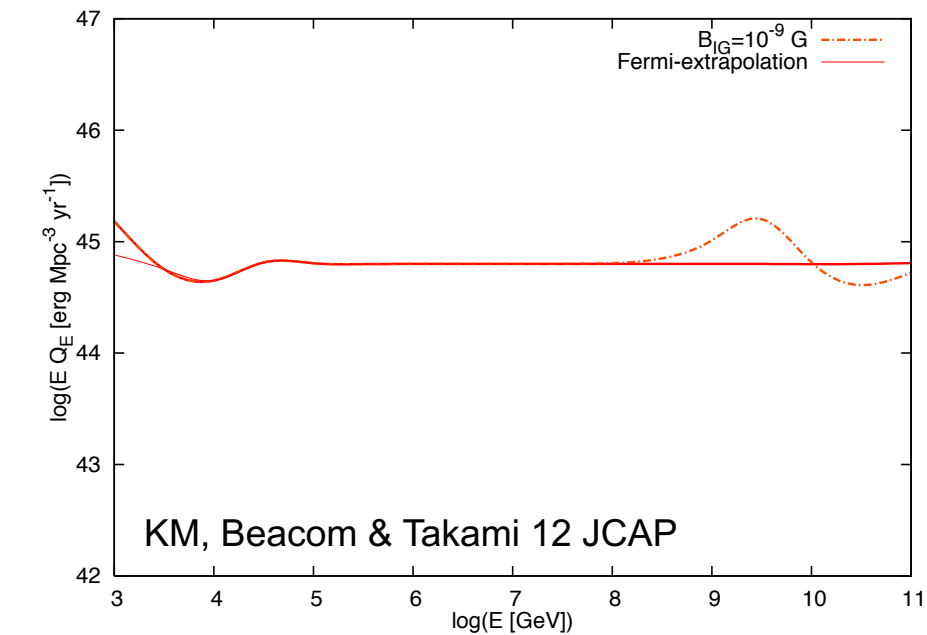
IceCube 25, Li+ 25, Yuan & Lu 25
KM3Net 25, 26, Yuan+ 25
Mukhopadhyay & Kimura 26
KM3Net 26, Yu & Zhang 26...

modified from Kotera+ KM 26 JCAP

- Auger data: UHECRs are largely “nuclei”
nucleus survival (semi-transparency) $\rightarrow E^2\Phi_\nu < \sim 3 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
- Existing models consistent w. KM3Net+IceCube: $E^2\Phi_\nu < \sim 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

Energy Budgets of High-Energy Cosmic Particles

$$E^2\Phi \approx \frac{ct_H}{4\pi}\varepsilon Q_\varepsilon \overset{\text{propagation}}{\xi_z} g(E) \propto (\mathbf{Q}: \text{energy generation rate density})$$



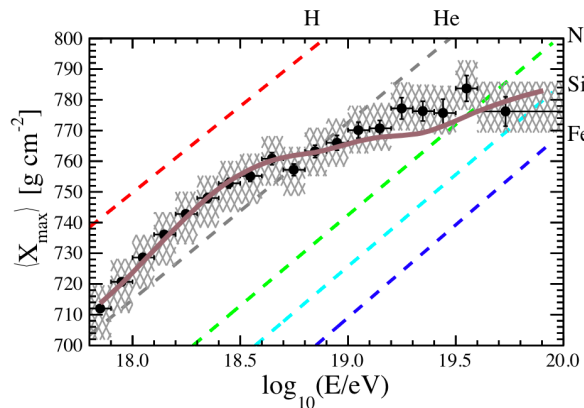
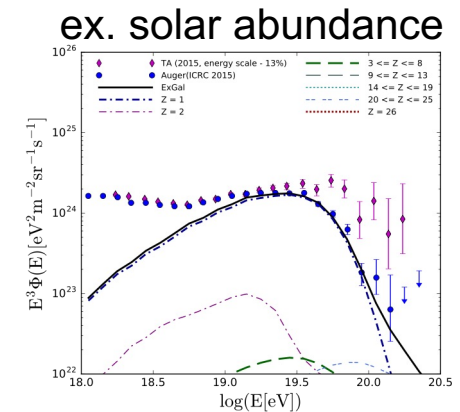
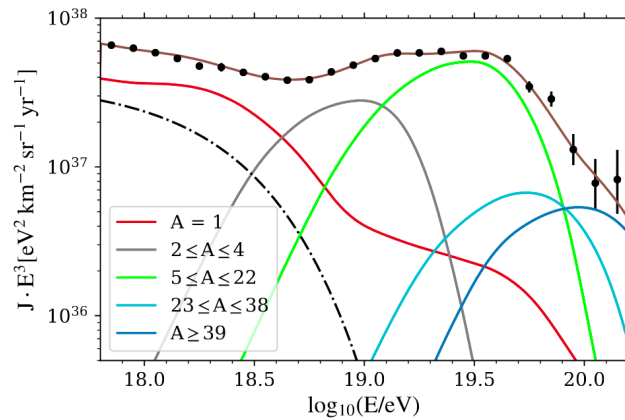
$$Q_\gamma = L_\gamma n_s \lesssim 6 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} (3/\xi_z)$$

$$\approx (0.2-2) \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \text{ at } 10^{19.5} \text{ eV}$$

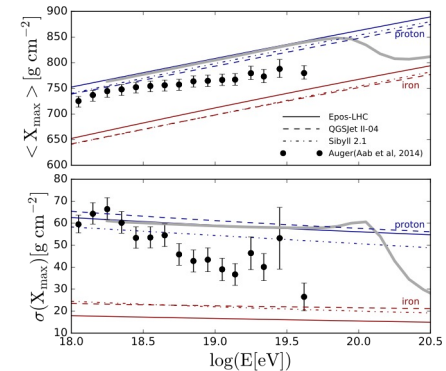
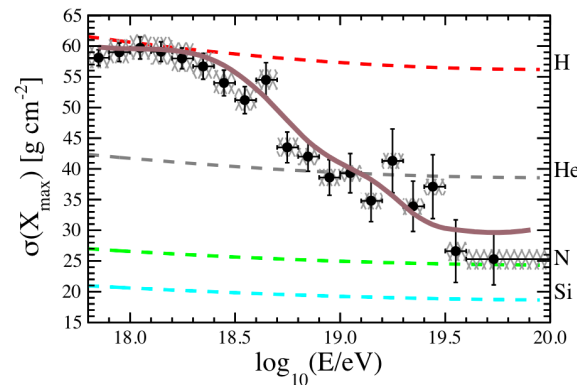
	ccSN (CR)	HN (CR)	DNS (CR)	GRB (γ)	LL GRB (γ)	TDE (γ)
$Q [\text{erg Mpc}^{-3} \text{ yr}^{-1}]$	$10^{46.6}$	$10^{45.5}$	$10^{44.5}$	$10^{43.6}$	$10^{43.5}$	$10^{43.5}$
$\rho [\text{Mpc}^{-3} \text{ yr}^{-1}]$	10^{-4}	$10^{-5.5}$	$10^{-5.8}$	10^{-9}	$10^{-6.5}$	$10^{-10.5}$
	SBG (γ)	AGN (X)	BL Lac (γ)	FSRQ (γ)	RG (γ)	Accr/Mger (CR)
$Q [\text{erg Mpc}^{-3} \text{ yr}^{-1}]$	$10^{44.5}$	$10^{46.3}$	$10^{45.4}$	$10^{44.3}$	$10^{44.6}$	$10^{46.5}$
$n [\text{Mpc}^{-3}]$	10^{-4}	$10^{-4} - 10^{-3}$	$10^{-7} - 10^{-6.5}$	$10^{-9} - 10^{-8}$	$10^{-5} - 10^{-4}$	$10^{-6} - 10^{-5}$

UHECR Challenges Are Heavy, Hard, and Survival

- Intrinsic abundance
 $f_H=0, f_{He}=0.245$
 $f_N=0.681, f_{Si}=0.05,$
 $f_{Fe}=0.025$



Auger 24 JCAP

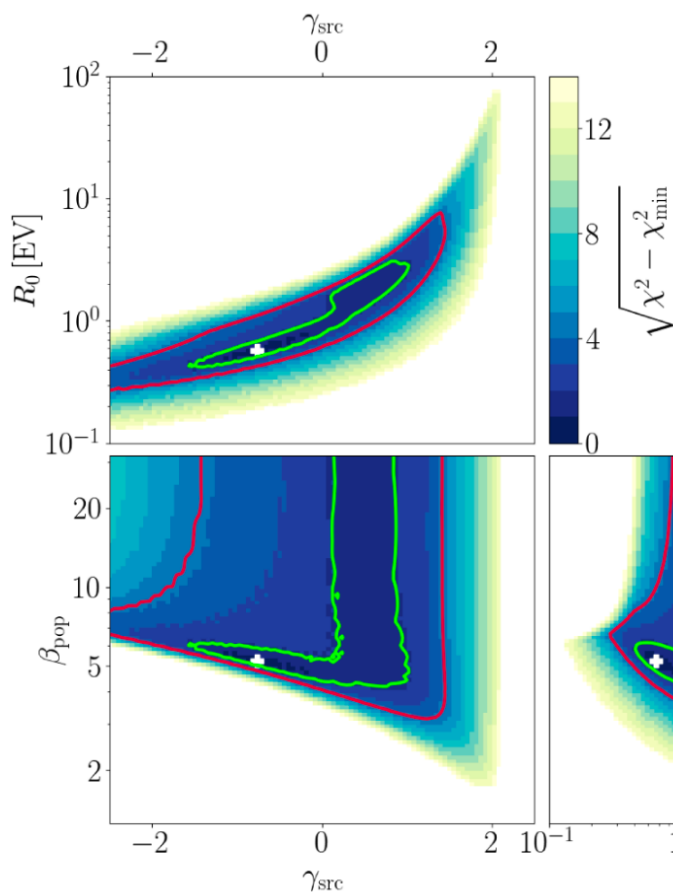


Zhang, KM+17 PRD

- Nucleus-**survival** dilemma
powerful sources but disintegration & ν production should be inefficient
- Heavy**-rich composition
intrinsic abundance/injection vs “reacceleration”
- Hard** “escape” spectrum ($\neq$ acceleration spectrum)

(KM & Beacom 10 PRD)

UHECR Challenges Are Rigid



luminosity-dependent maximum energy

$$R_{\text{max}} \sim R_0 \beta^{1/2} \left(\frac{L}{L_0} \right)^{1/2}$$

→ power-law distribution of rigidity
(in the limit of no energy losses)

$$p(R_{\text{max}}) \propto R_{\text{max}}^{-\beta_{\text{pop}}}$$

**Small dispersion in R_{max}
only a factor of 2-3**

Ehlert, Oikonomou & Unger 23 PRD

- Contributions of a very few number of nearby sources?
- Saturation by energy losses?
- R_{max} controlled by total energy rather than radiation luminosity?
(Note that R_{max} does not have to depend on the radiation luminosity function.)

Your Favorite Cosmic Monsters?

Luminosity requirement

$$L_B \equiv \epsilon_B L \gtrsim 2 \times 10^{45} \frac{\Gamma^2 E_{20}^2}{Z^2 \beta} \text{ erg s}^{-1} \quad \text{Transients (large L) or Nuclei (large Z)?}$$

Starburst galaxies



(ex. Jokipii & Morfill 85,
Anchordoqui+ 01, Bertone+ 02)

Active galactic nuclei



(ex. Ginzburg & Syrovatskii 64,
Takahara 90, Rachen & Biermann 93,
Murase+ 12)

Galaxy clusters



(ex. Norman+ 95, Kang+ 96,
Inoue+ 07, Murase+ 08)

Collapsars long GRBs/TRSNe



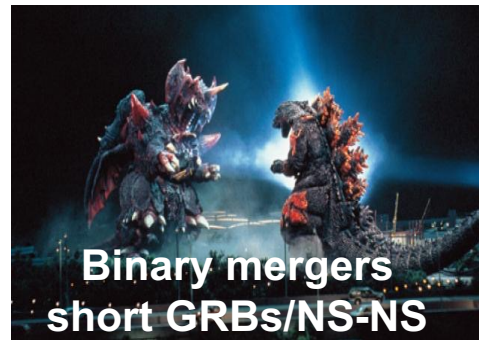
(ex. Waxman & Bahcall 95, 01,
Vietri 95, Murase+ 06, Wang+ 07,
Murase+08, Chakraborty+ 09)

Newborn pulsars/ magnetars



(ex. Blasi+ 01, Arons 03,
Murase+ 09)

Binary mergers short GRBs/NS-NS



(ex. Takami+ 13,
Murase & Fukugita 19,
Rodrigues+ 19, Farrar 24)

Tidal disruption events



(ex. Farrar & Gruzinov 09,
Farrar & Piran 14,
Zhang, Murase+ 17)

Particle Acceleration in AGN

Black hole vicinity

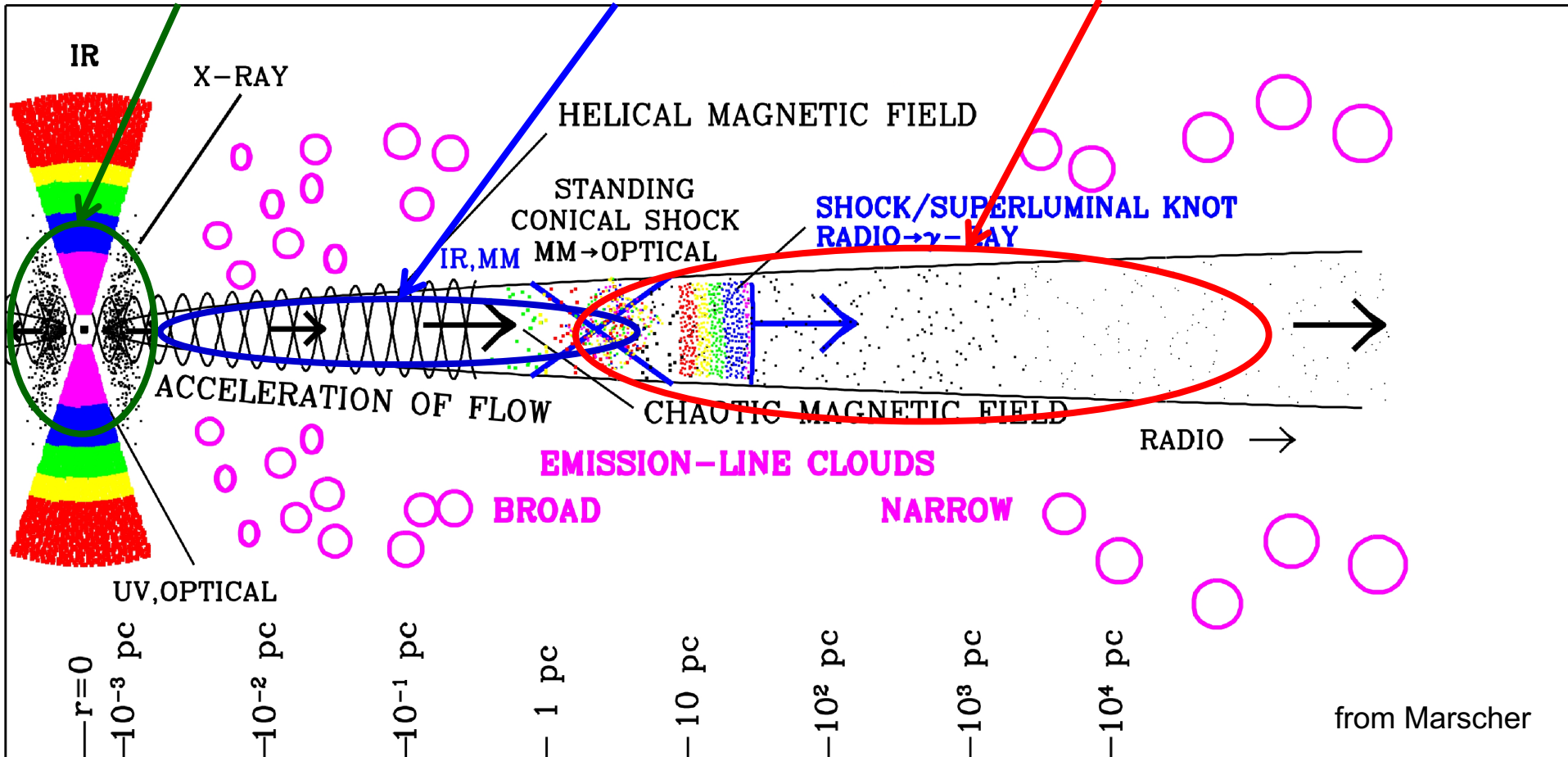
$r \sim 1-100 R_s$,
 $B \sim 10-10^4 \text{ G}$, $\Gamma \sim 1$

Inner jet (blazar zone)

$r \sim 10^{16}-10^{18} \text{ cm}$,
 $B \sim 0.1-100 \text{ G}$, $\Gamma \sim 10$

Large-scale jet, hot spot, cocoon

$r \sim 10^{20}-10^{21} \text{ cm}$,
 $B \sim 1 \mu\text{G} - 1 \text{ mG}$, $\Gamma \sim 1$

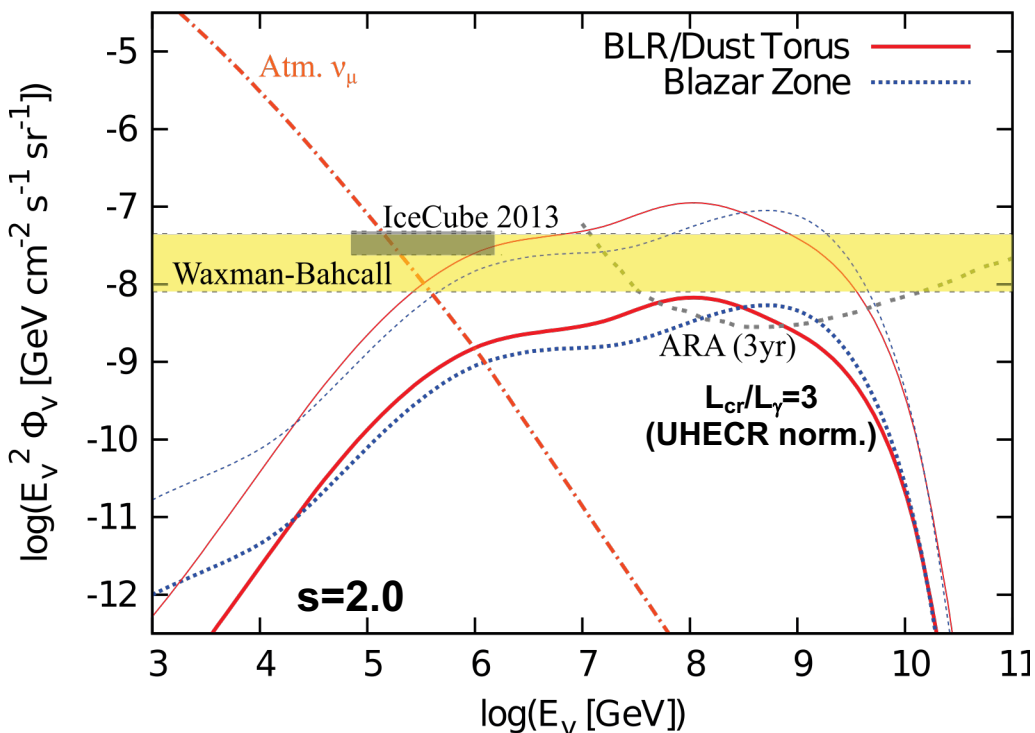


from Marscher

Hillas condition: $E_{\max} \sim ZeBr\Gamma \sim 3 \times 10^{19} \text{ eV } Z (\Gamma/10) (B/0.1 \text{ G}) (r/10^{17} \text{ cm})$

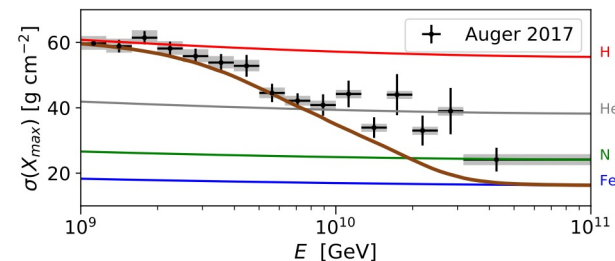
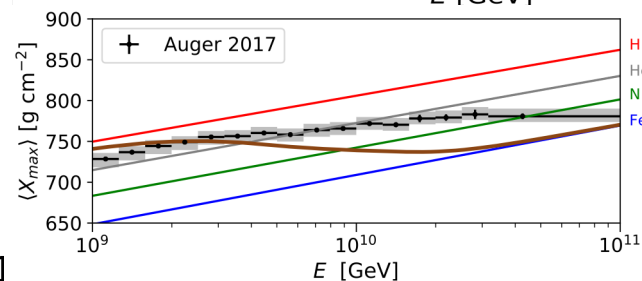
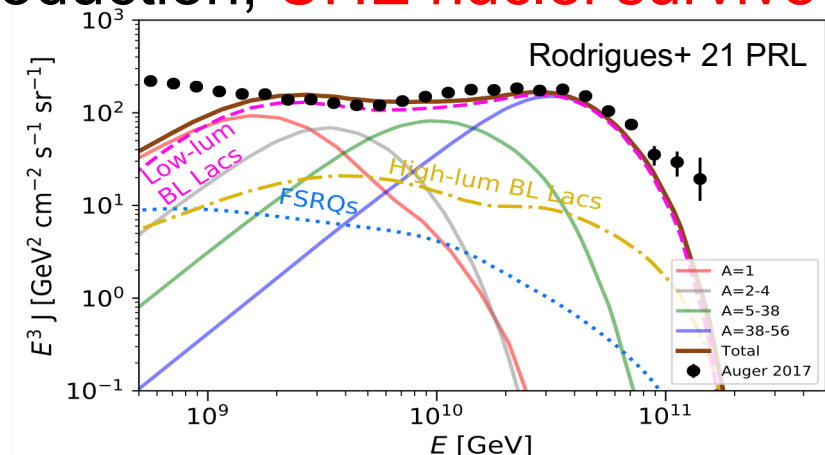
Blazars as UHECR Sources?

- FSRQs: **efficient ν production**, UHECRs largely destroyed
- BL Lac objects: less efficient ν production, **UHE nuclei survive**



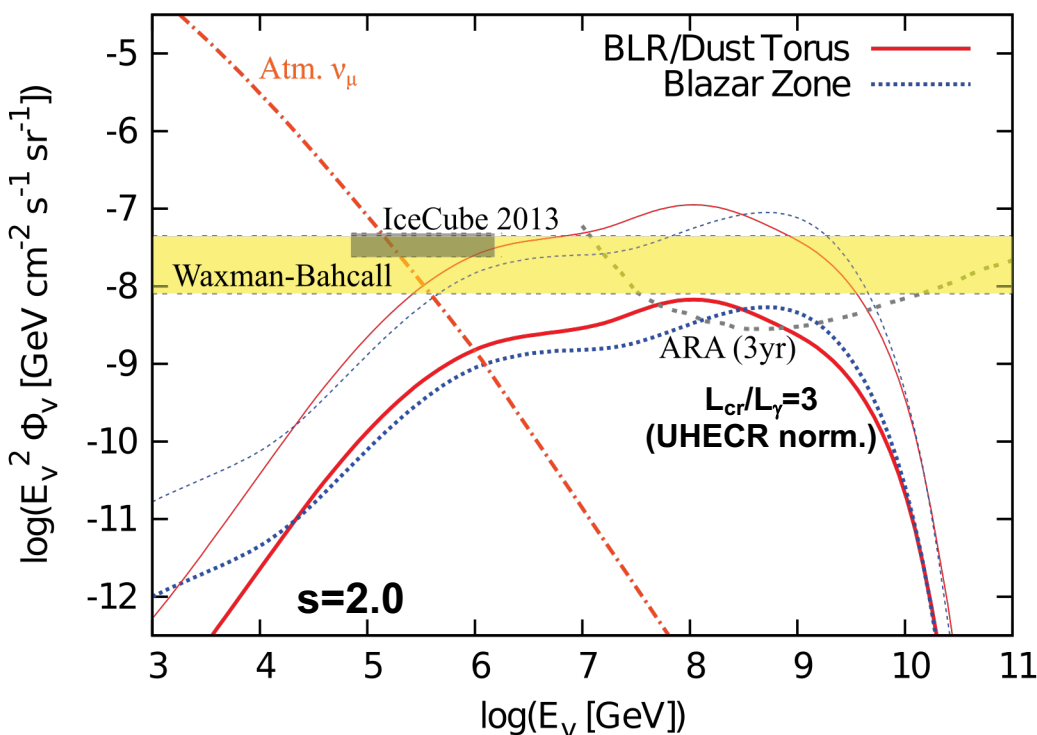
KM, Inoue & Dermer 14 PRD

- UHECR-blazar model $\rightarrow$ predicting EeV ν
- IceCube & Auger started to constrain the relevant parameter space

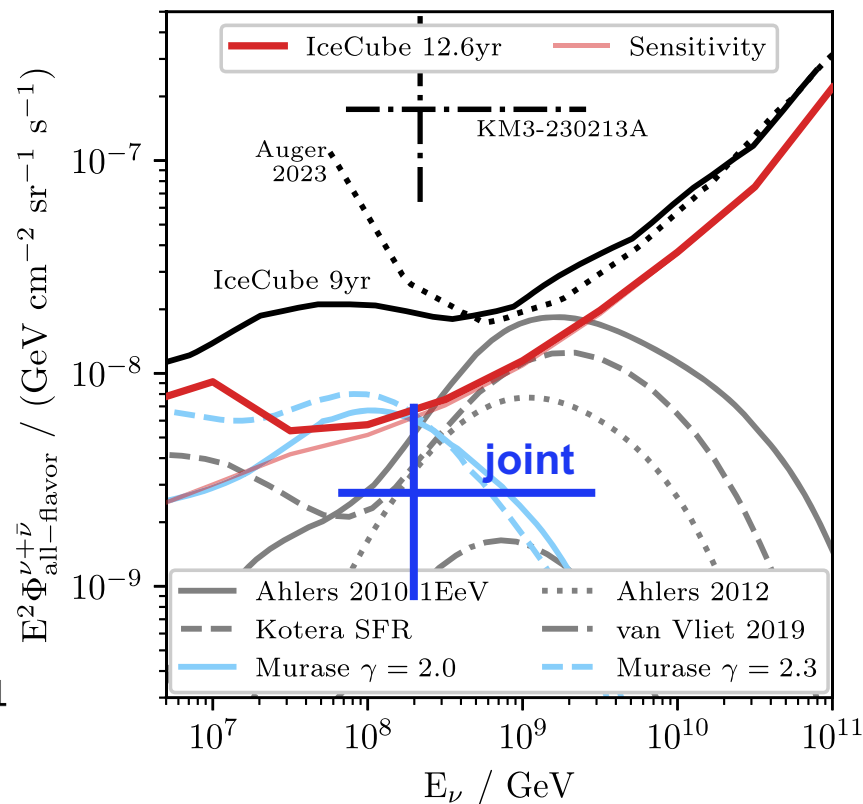


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KM, Inoue & Dermer 14 PRD



IceCube Collaboration 25 PRL

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Black hole vicinity

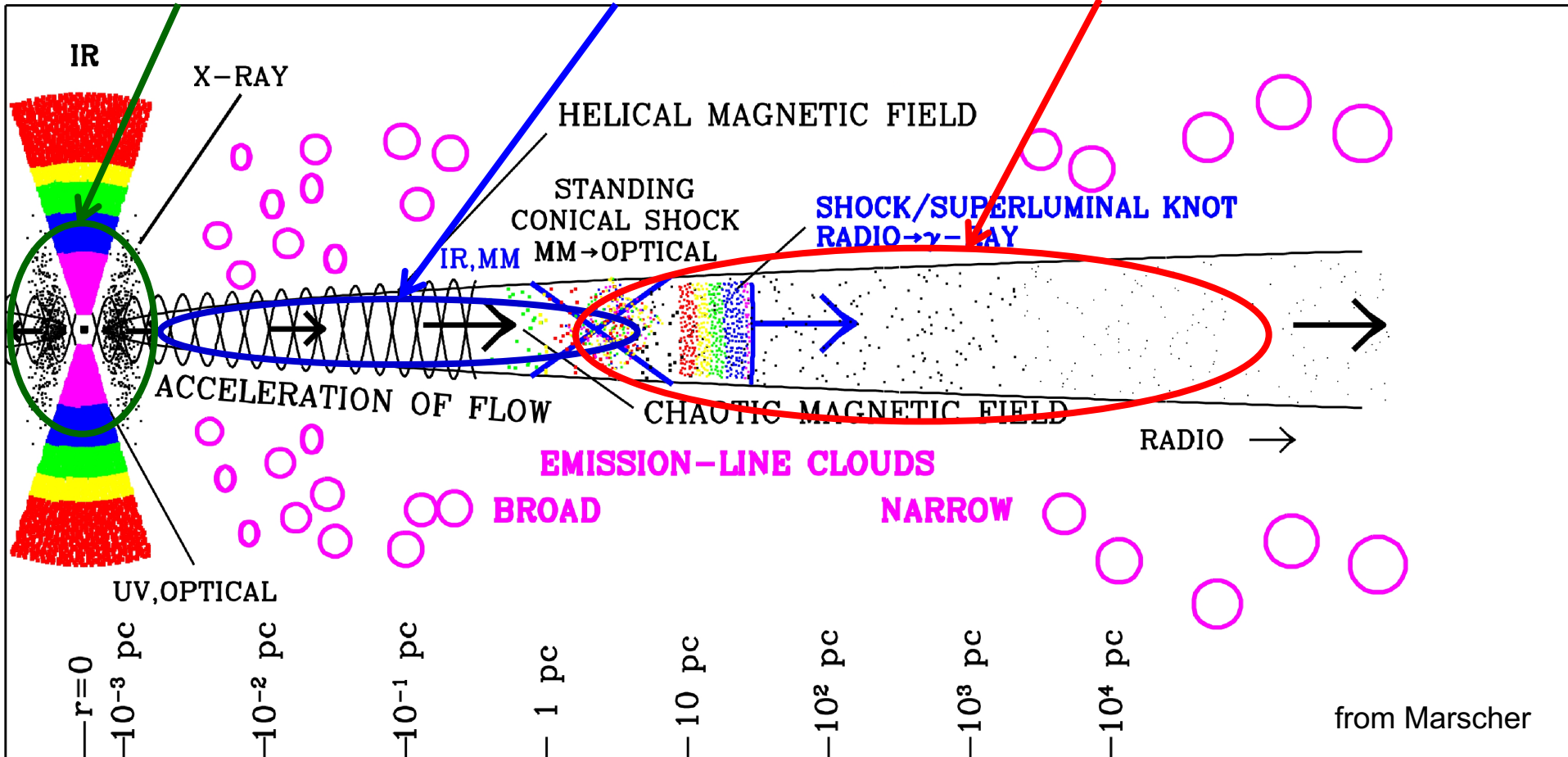
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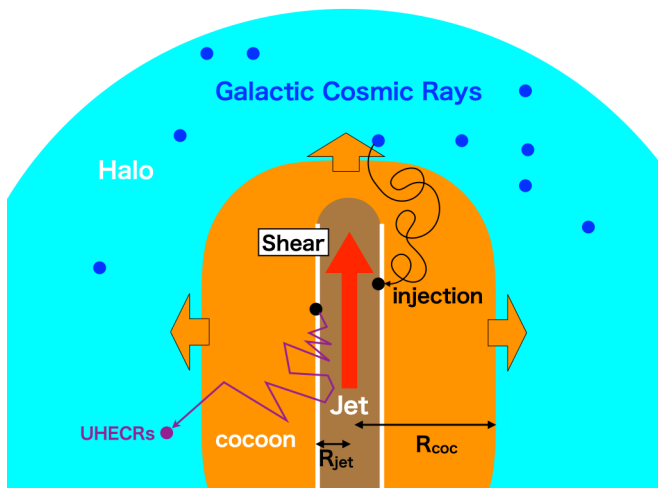
from Marscher

Hillas condition: $E_{\max} \sim ZeBr\Gamma \sim 3 \times 10^{19} \text{ eV } Z (\Gamma/10) (B/0.1 \text{ G}) (r/10^{17} \text{ cm})$

Reacceleration by Large-Scale Jets

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

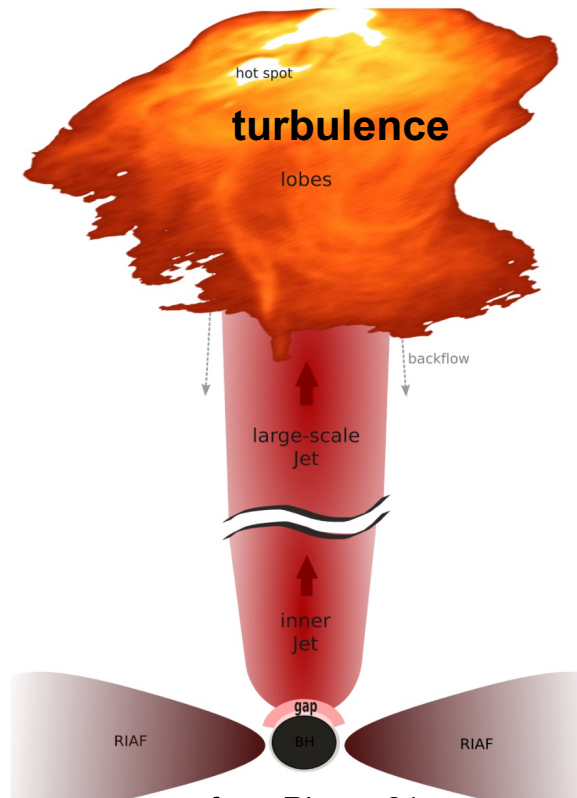
(Caprioli 15, Kimura, KM & Zhang 18)



from Kimura, KM & Zhang 18

Turbulent shear acceleration in backflows

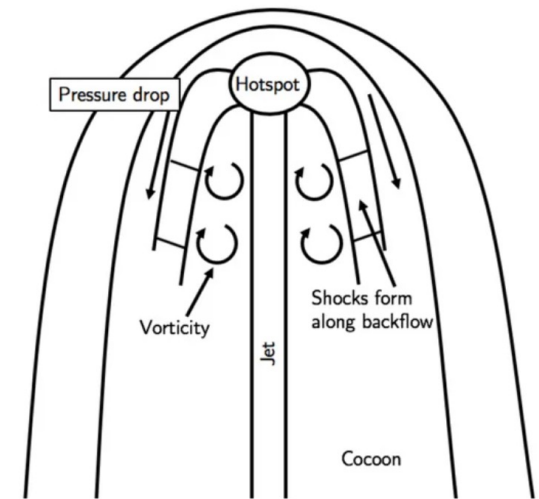
(Hardcastle 10, Ohira 13)



from Rieger 21

DSA acceleration in backflows in cocoons

(Matthews+ 18, 19)



from Matthews+ 19

Super-solar abundance of nuclei in AGN?

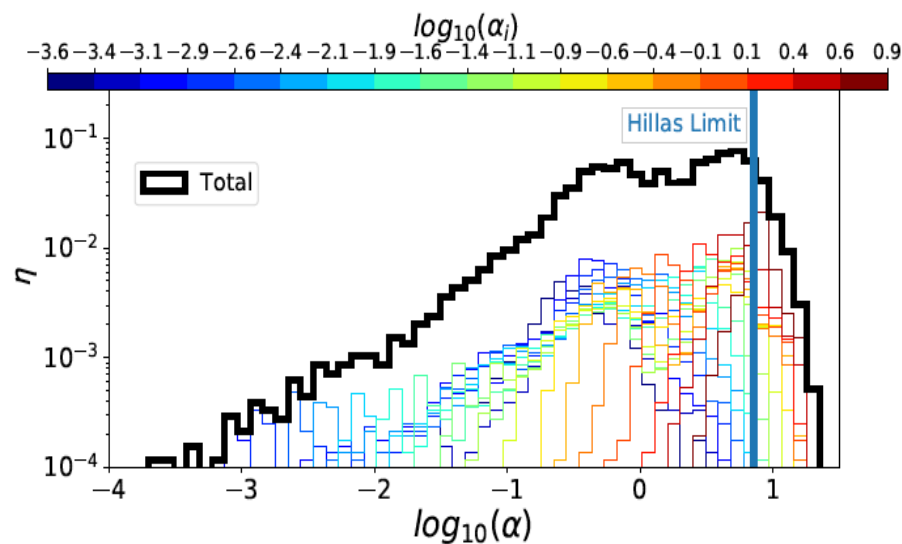
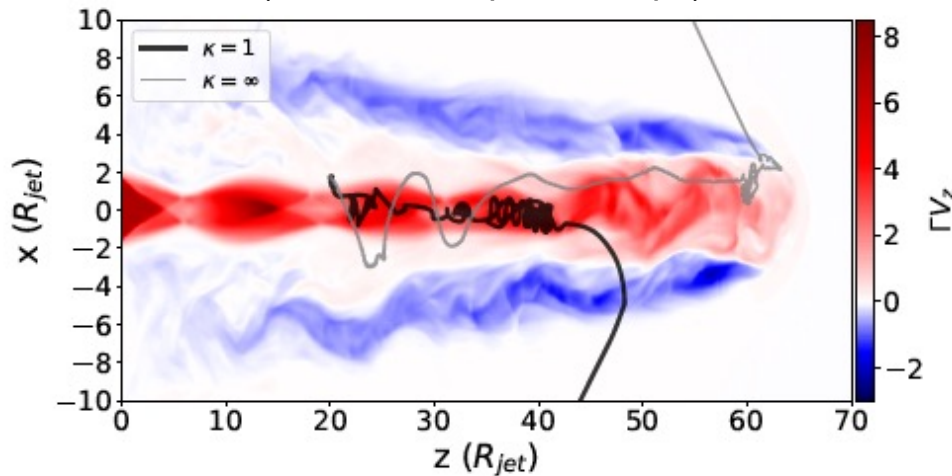
→ “Reacceleration” of galactic CRs by AGN jets (not free!)

Nuclei can survive photodisintegration

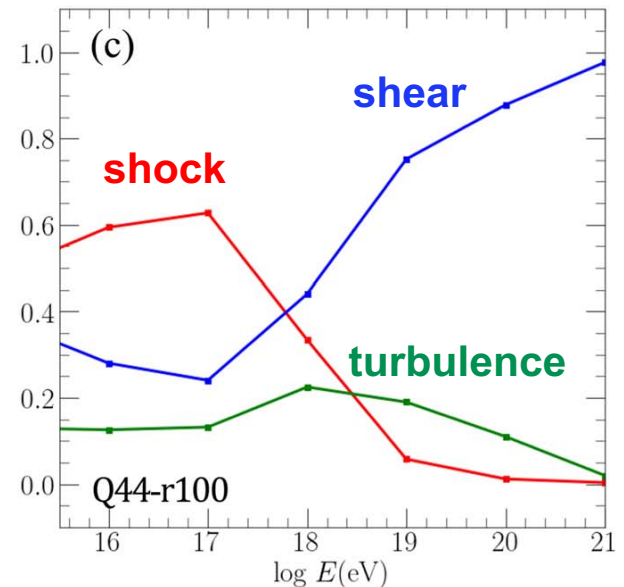
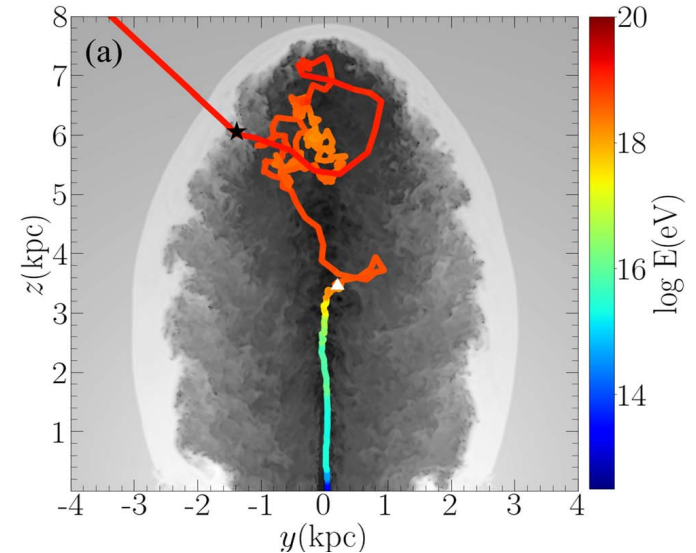
Test Particle Simulations of Particle Acceleration

MHD simulations

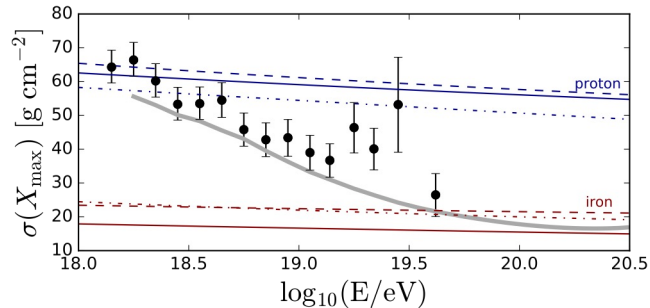
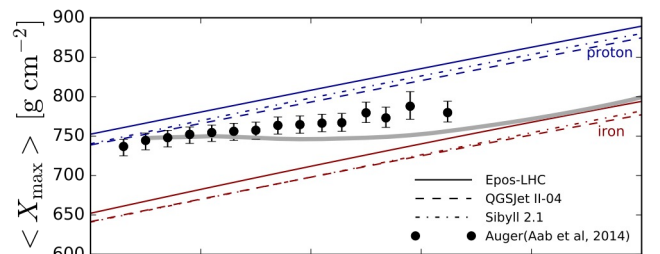
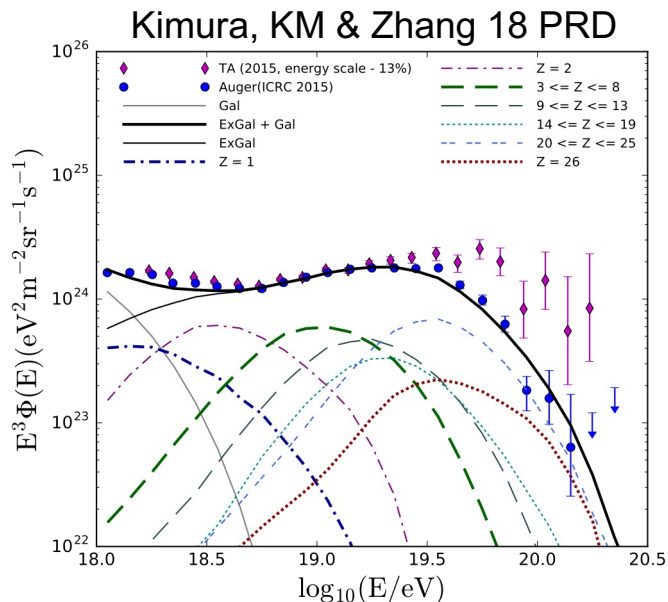
(Mbarek & Caprioli 21 ApJ)



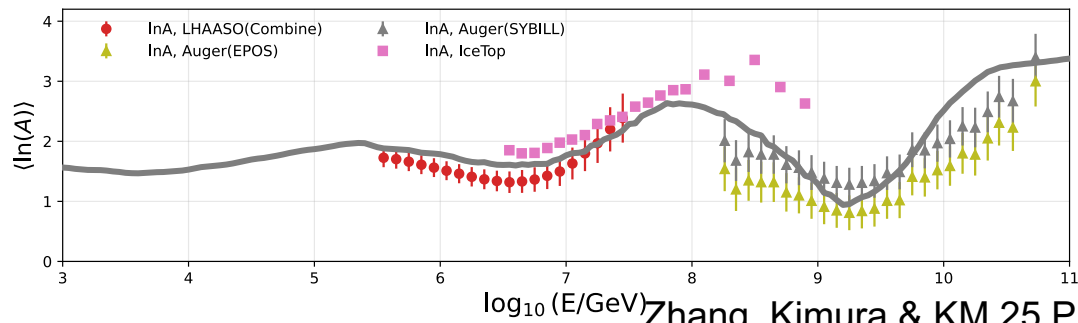
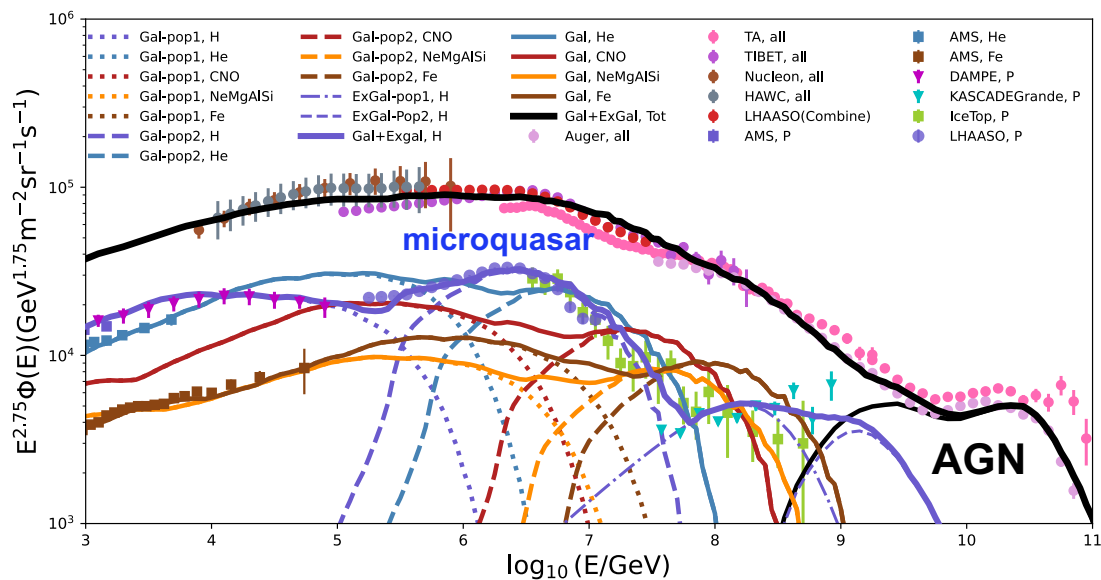
HD simulations (Seo, Ryu & Kang 24 ApJ)



Simulations: Confronted with Cosmic-Ray Data

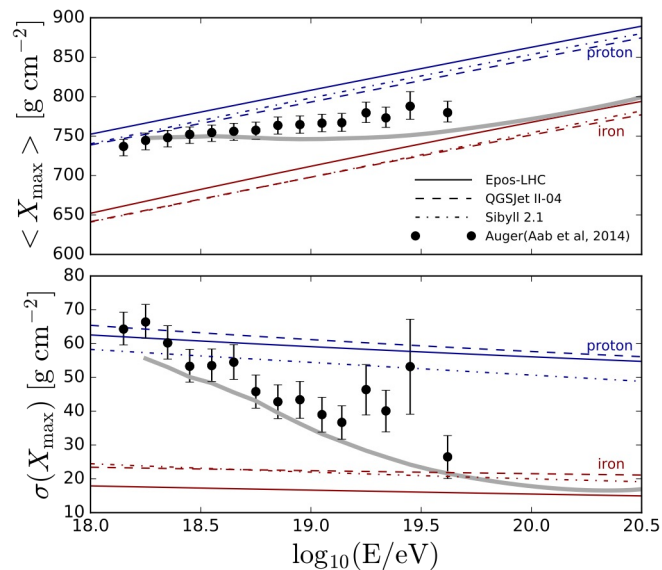
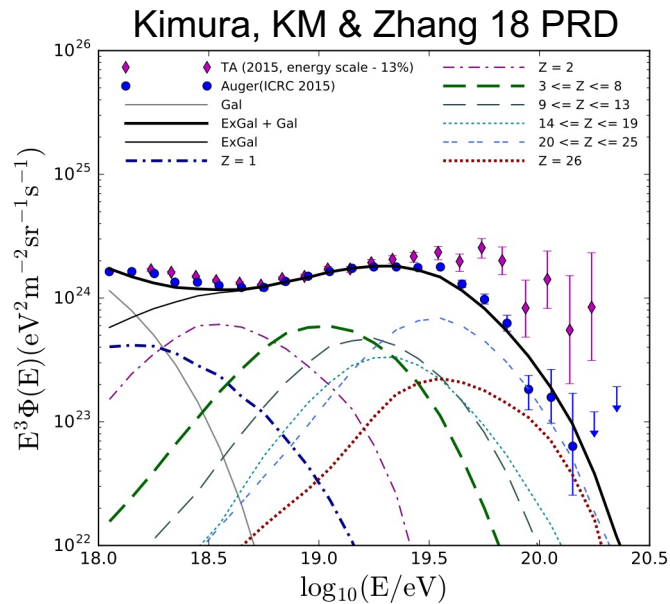


- Simulated (Monte Carlo) spectra
- UHECR data may be explained by injection to reacceleration at the same rigidity
- Unified mechanism for the knee & UHECRs?

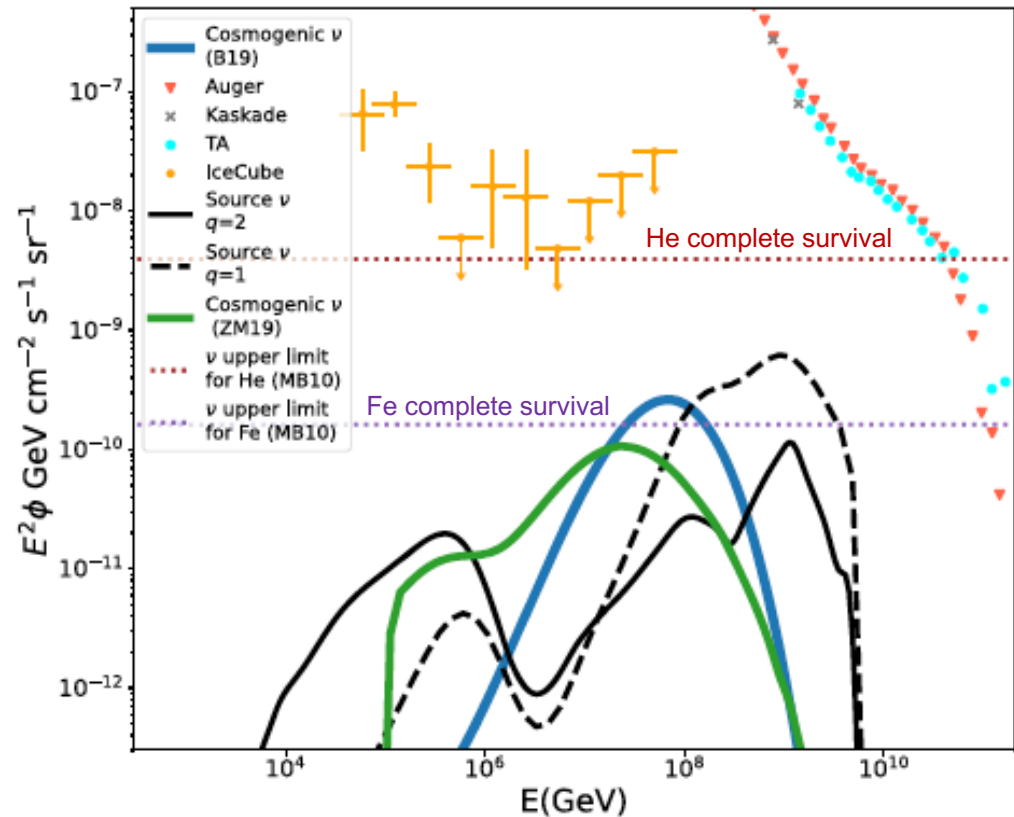


Zhang, Kimura & KM 25 PRD

Simulations: Predictions for All-Sky Neutrino Flux



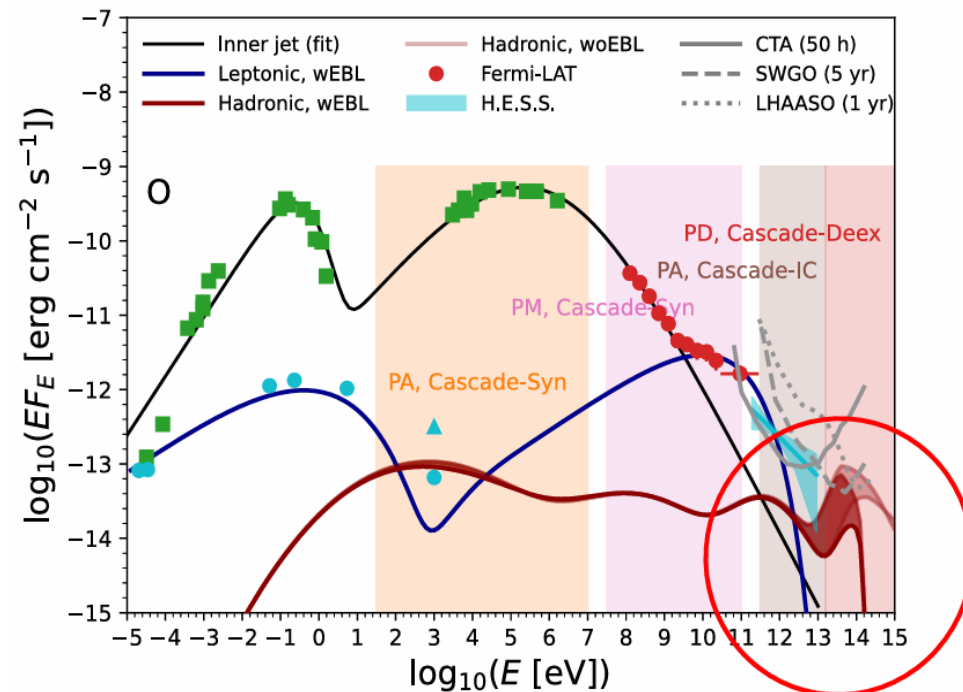
- Simulated (Monte Carlo) spectra
- UHECR data may be explained (for injection at the same rigidity)
- $E_{\nu}^2 \Phi_{\nu} \sim 10^{-10} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (required by nucleus-survival)



Mbarek, Caprioli & KM 23 Apr

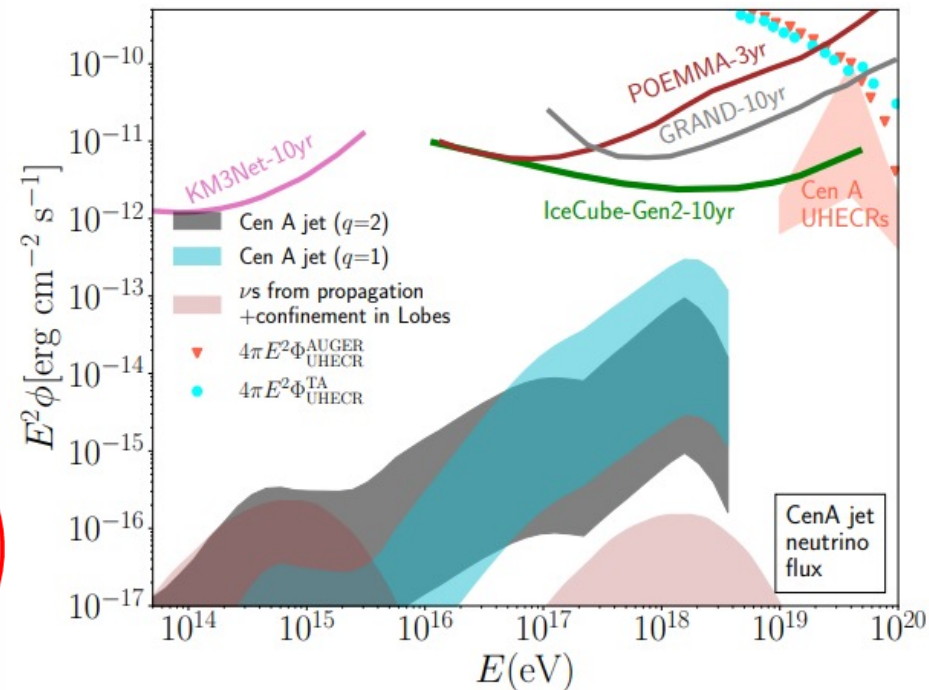
Centaurus A: The Most Promising Target?

Intermediate anisotropy: $\sim 4\sigma$ excess toward the Cen A region (Auger 22 ApJ)
 → What should we do next (toward $>5\sigma$ and after) in the GCOS era?
 → ν and γ signals would be important for gathering more clues.



Zhang & KM 23 MNRAS

Photodisintegration-deexcitation,
 Bethe-Heitler-induced pairs
 → **SWGO & CTA south**



Mbarek, Caprioli & KM 25 PRD

Prediction of espresso-shear acc.
 But nucleus-survival limits the ν flux

cosmic-ray reservoir scenario

**accelerator
(ex. AGN)**

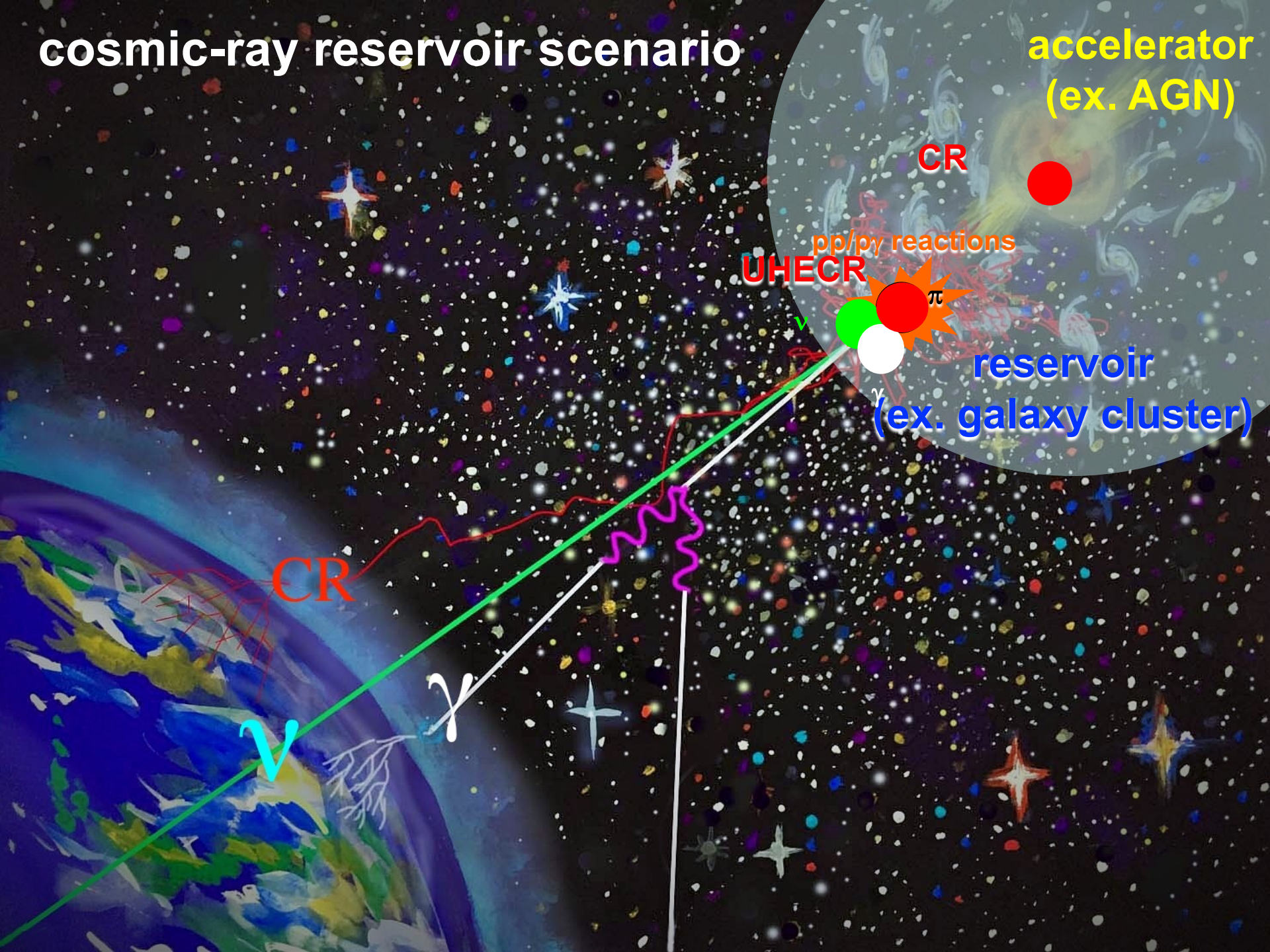
CR

pp/py reactions

UHECR

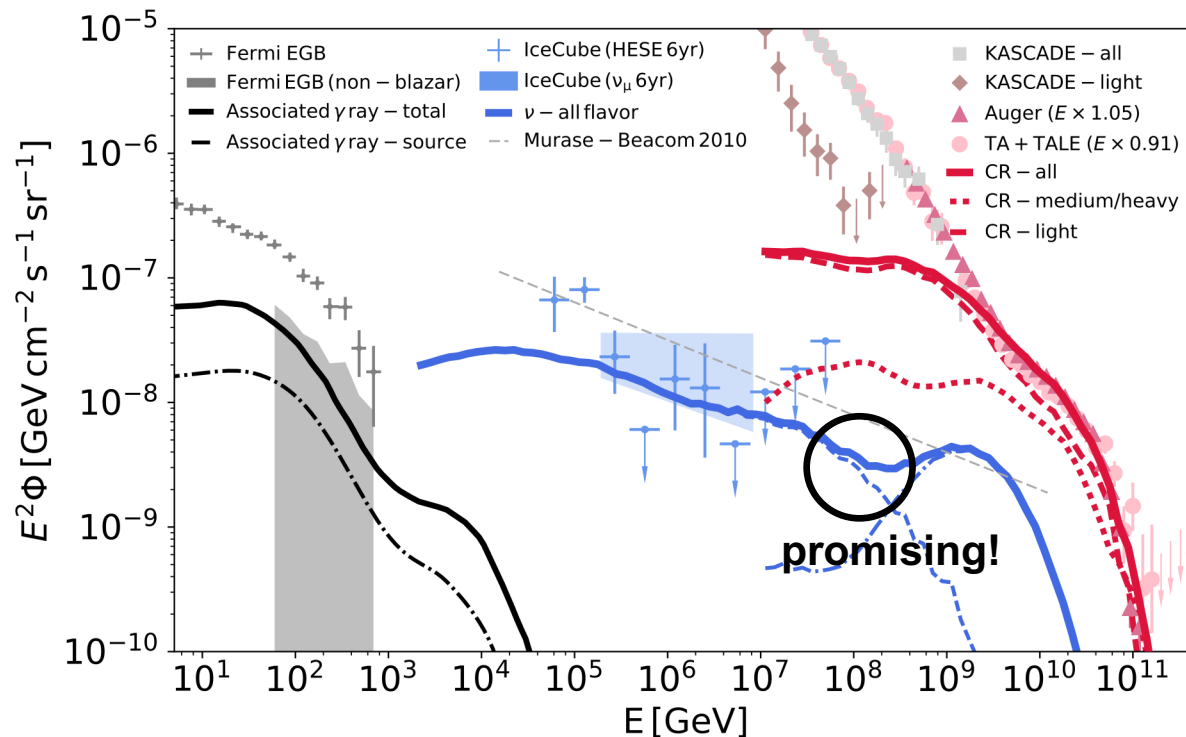
π

reservoir
(galaxy cluster)

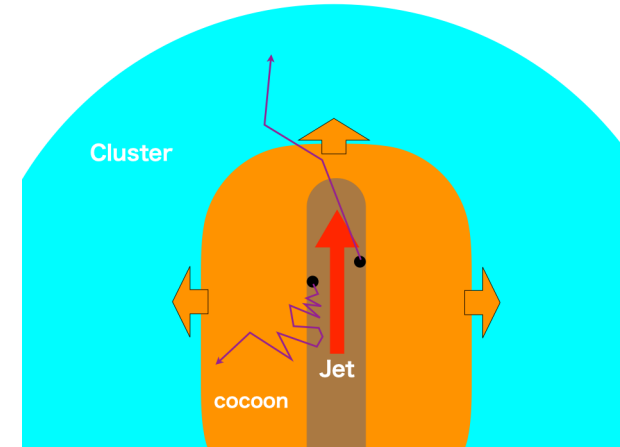


Ex. AGN Embedded in Galaxy Clusters/Groups

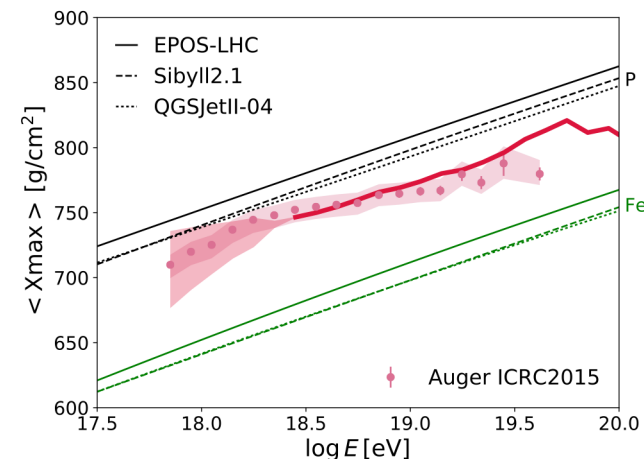
- Jetted AGN as “UHECR” accelerators
- confinement in **cocoons** & **clusters**
- escaping CR nuclei: harder than CR protons
- **smooth transition** from source ν to cosmogenic ν



explaining >0.1 PeV neutrinos, sub-TeV gamma rays, and UHECRs (including **proton ankle at 100 PeV** & **composition**)



Fang & KM 18 Nature Physics
(ex. KM, Inoue & Nagataki 08 ApJL
Kotera, Allard, KM+ 09 ApJ)



Transient UHECR Sources?

$$n(E) \sim \rho_0 \times \tau_d \propto E^{-2} \text{ for burst sources}$$

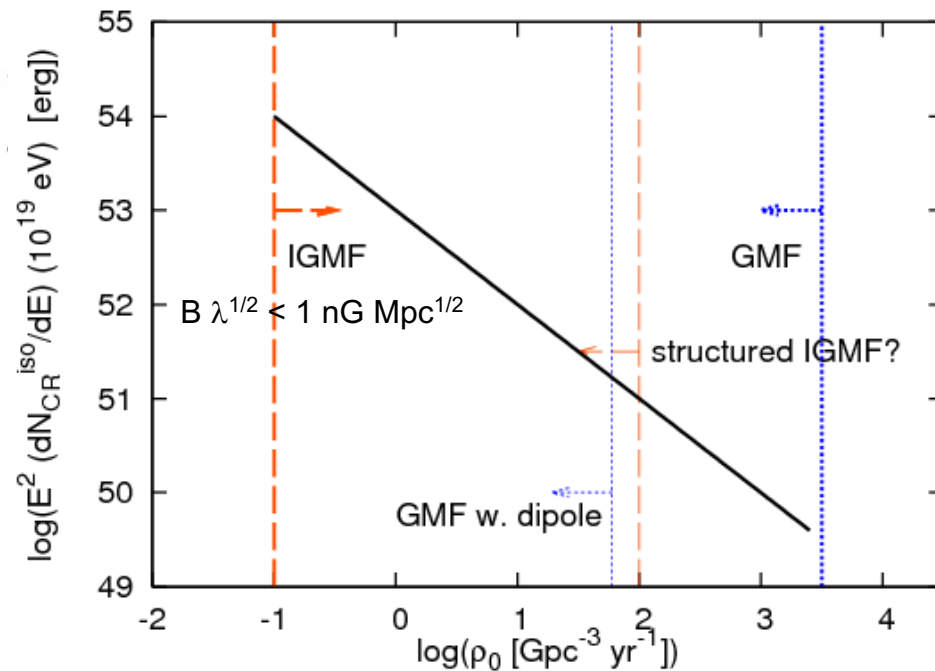
small-scale anisotropy $n_s > 10^{-5} - 10^{-4} \text{ Mpc}^{-3}$

intermediate anisotropy toward the Cen A region

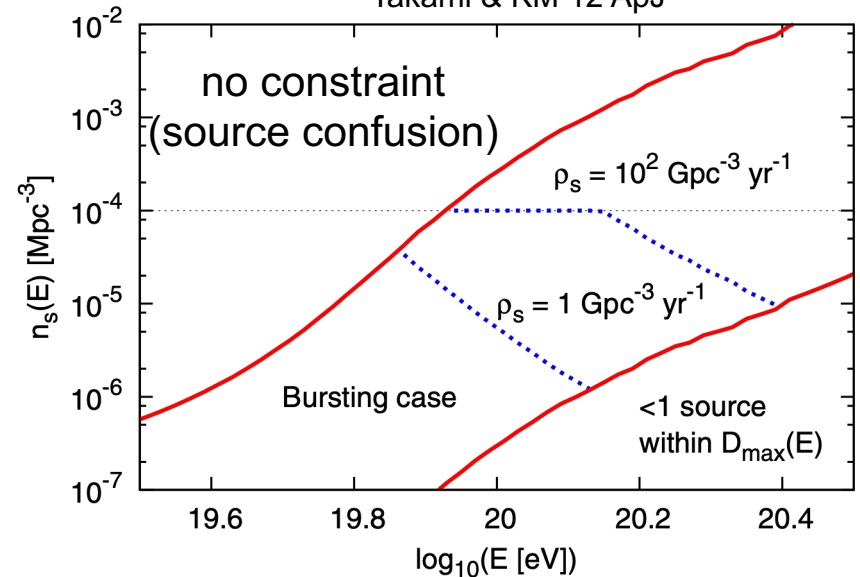
Takami & Sato 09 Aph
Auger 13 JCAP, 23 ICRC
Takami, KM & Dermer 16 ApJ

Auger 22 ApJ

KM & Takami 09 ApJL



Takami & KM 12 ApJ



Burst rate is limited to avoid MW's overshining & too large anisotropy (KM & Takami 09)

Transients: source density can be high & energy dependent

Transient UHECR Sources?

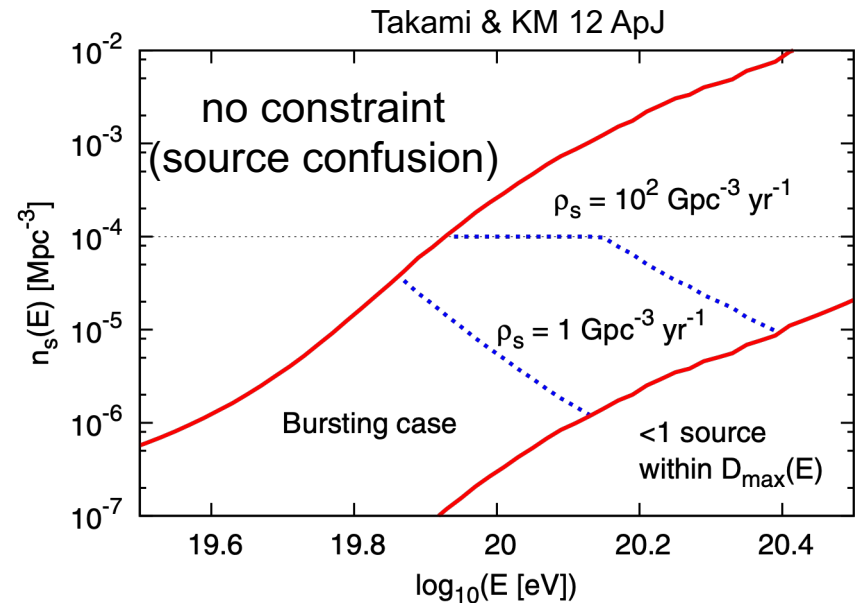
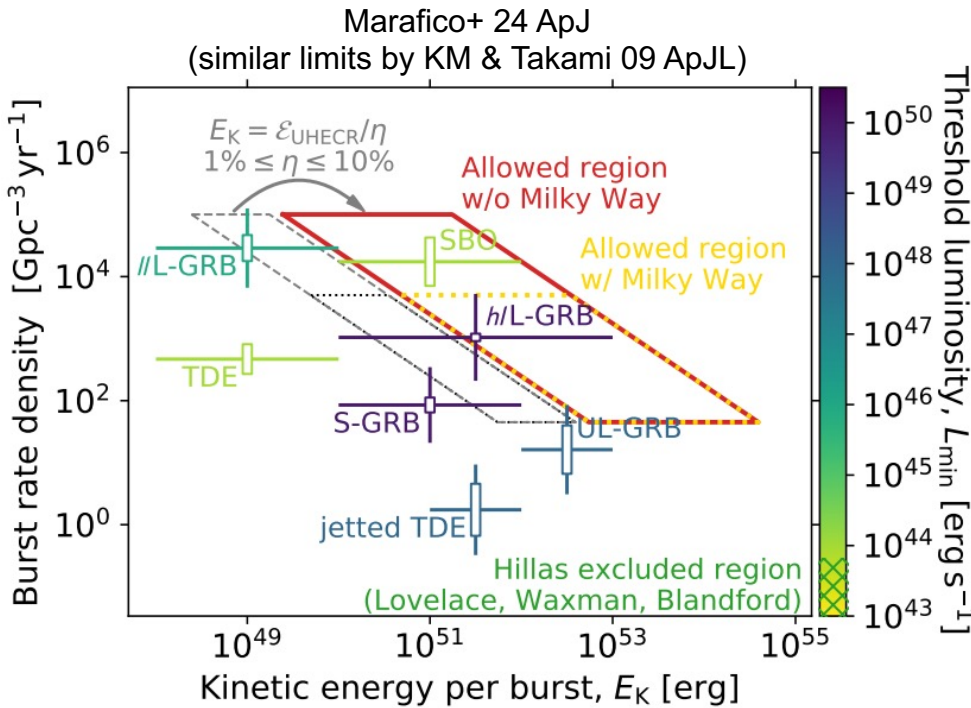
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Takami & Sato 09 Aph
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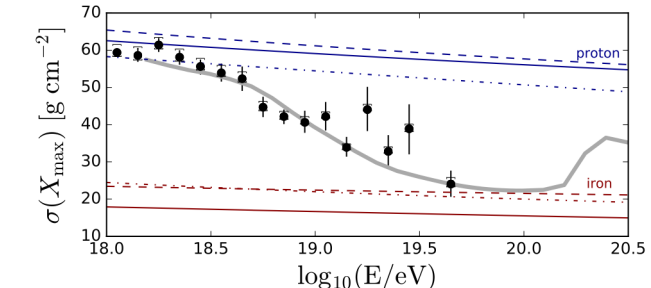
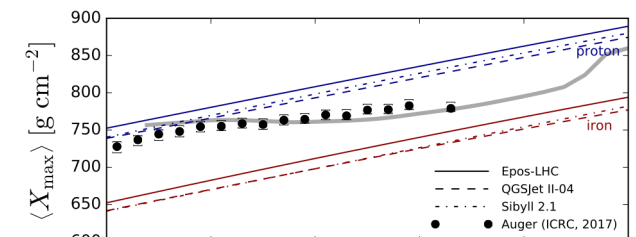
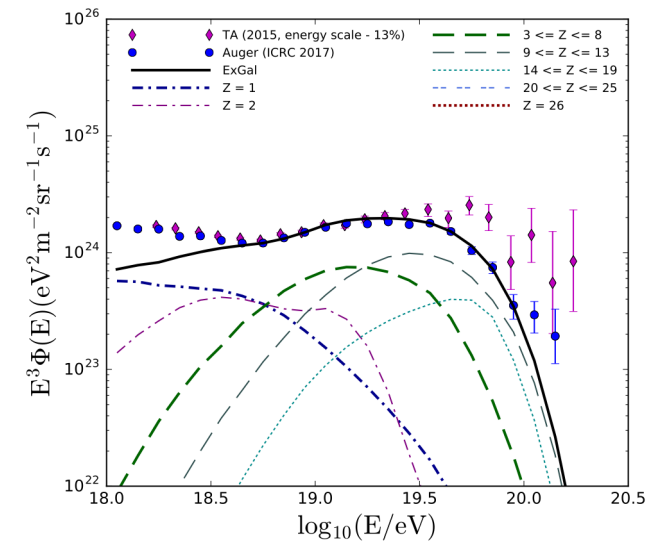
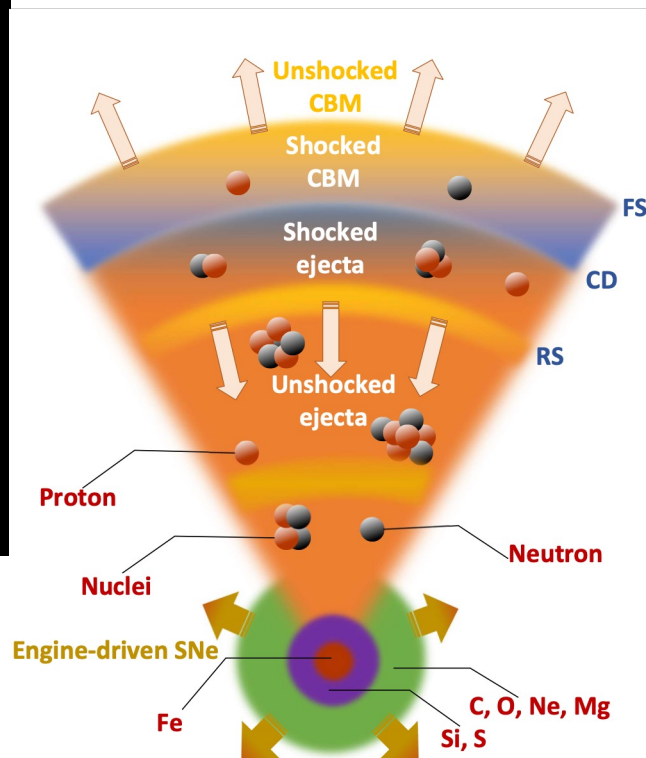
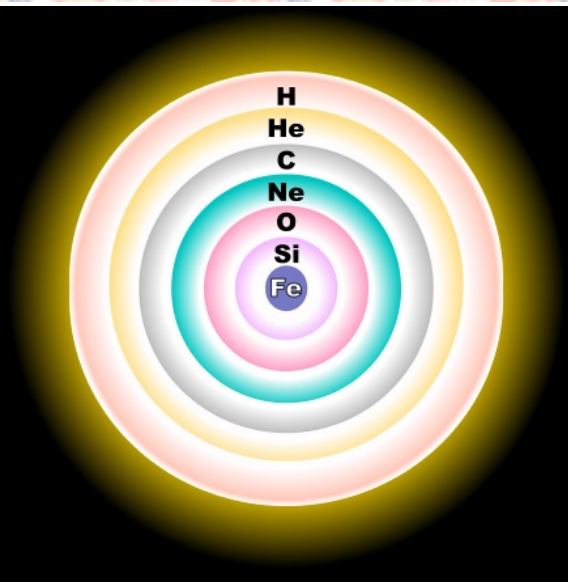
Auger 22 ApJ



Burst rate is limited to avoid MW's overshining & too large anisotropy (KM & Takami 09)

Transients: source density can be high & energy dependent

Collapsars (Low-Luminosity GRBs/Engine-Driven SNe)



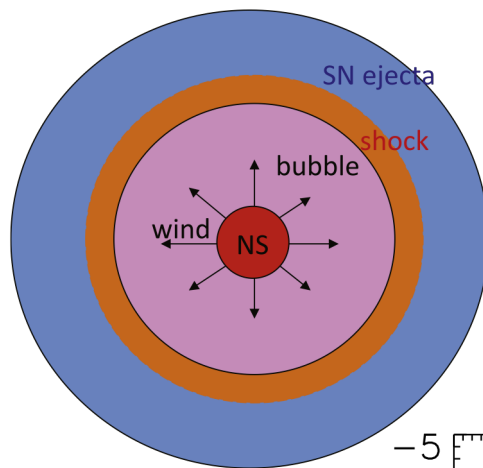
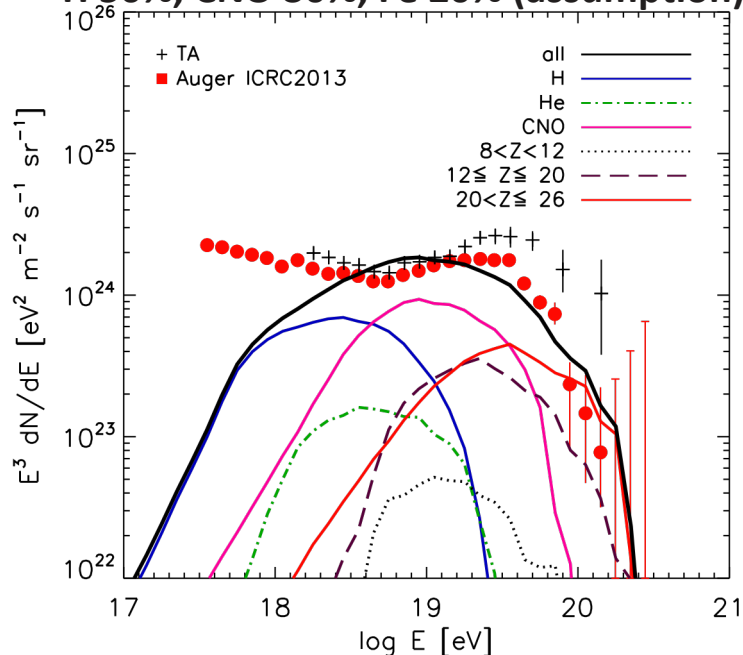
KM+06, Wang+07, KM+ 08
Charkraborty+ 09

1. "Intermediate" and (ultra)heavy mass nuclei:
"prediction" of progenitor models (not free!)
2. Transrelativistic ejecta (shocks/turbulence)
3. Instantaneous escaping spectrum: can be hard
3. Nuclei can survive
4. Correlation w. starburst galaxies

Zhang, KM+ 18 PRD, Zhang & KM 19 PRD

Newborn Pulsars/Magnetars from Collapsars/Mergers

H 50%, CNO 30%, Fe 20% (assumption)



Blasi, Epstein & Olinto 00 ApJ

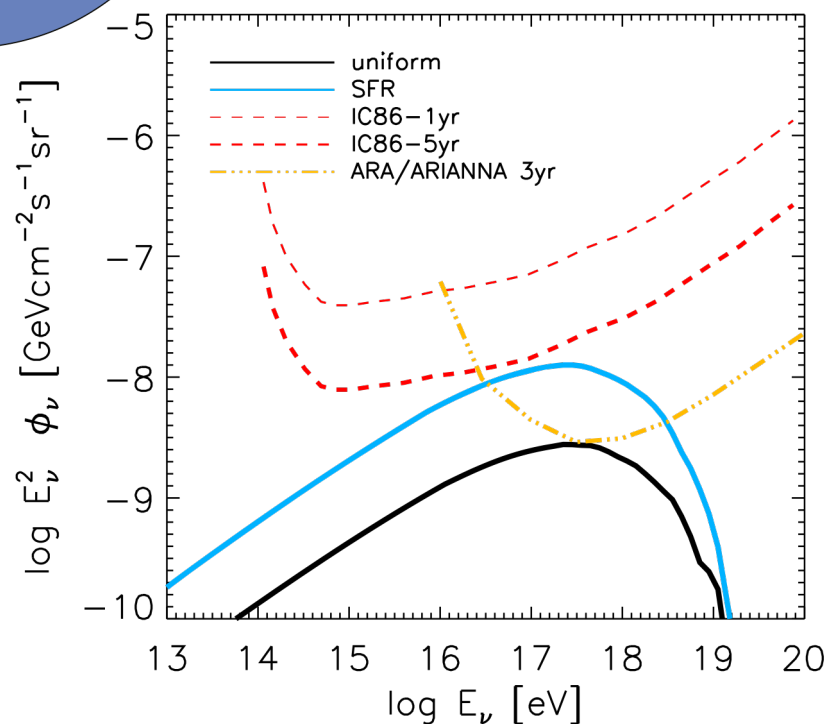
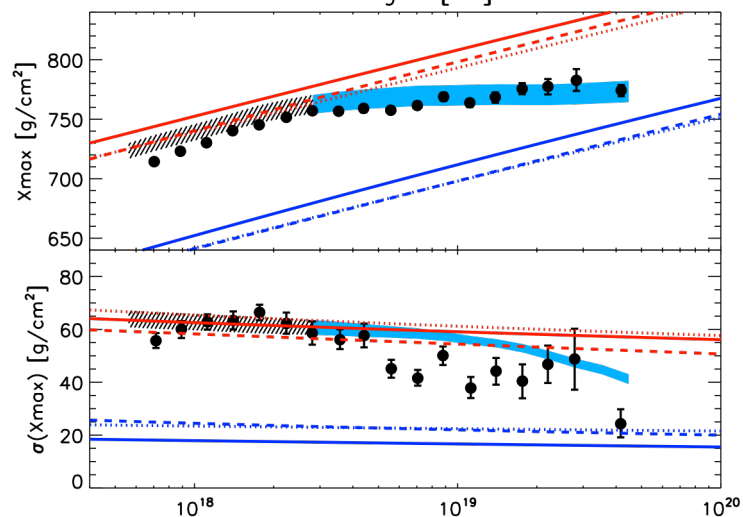
Arons 03 ApJ

KM, Meszaros & Zhang 09 PRD

Fang, Kotera & Olinto 12 ApJ

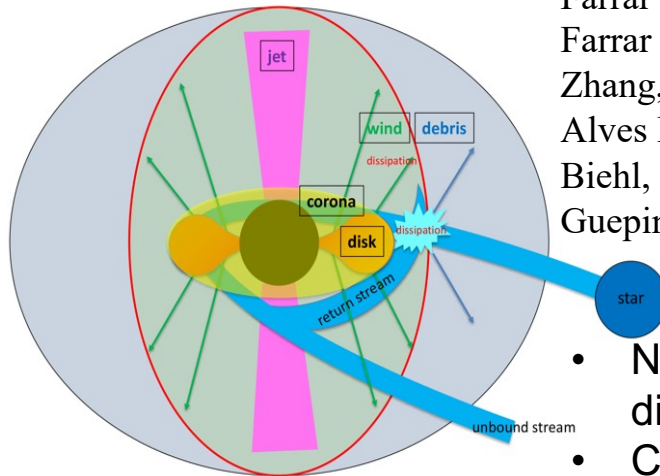
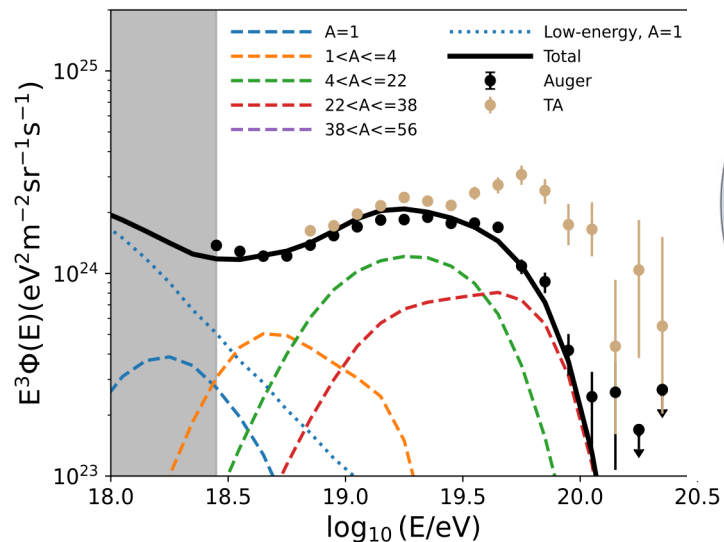
Fang, Kotera, KM & Olinto 14 PRD

- Nuclei can be supplied from the neutron star surface
- Ion acceleration mechanism is uncertain



Tidal Disruption Events

(CO 70%, Si 30%) CO-Si white dwarf



Farrar & Gruzinov 09

Farrar & Piran 14

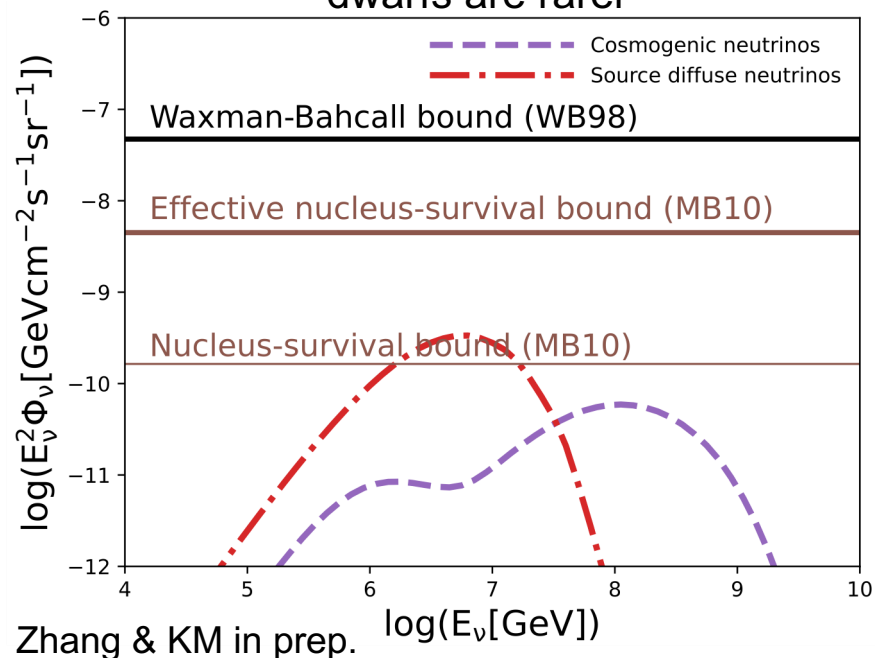
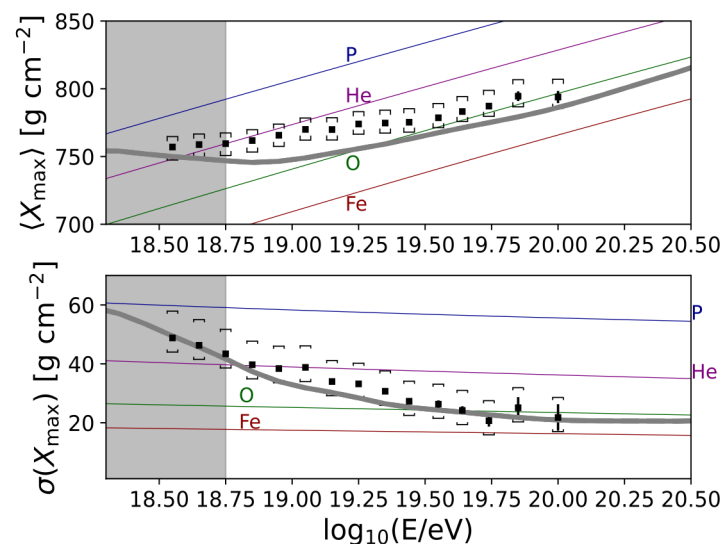
Zhang, KM, Oikonomou & Li 17

Alves Batista & Silk 17

Biehl, Boncioli, Lunardini & Winter 18

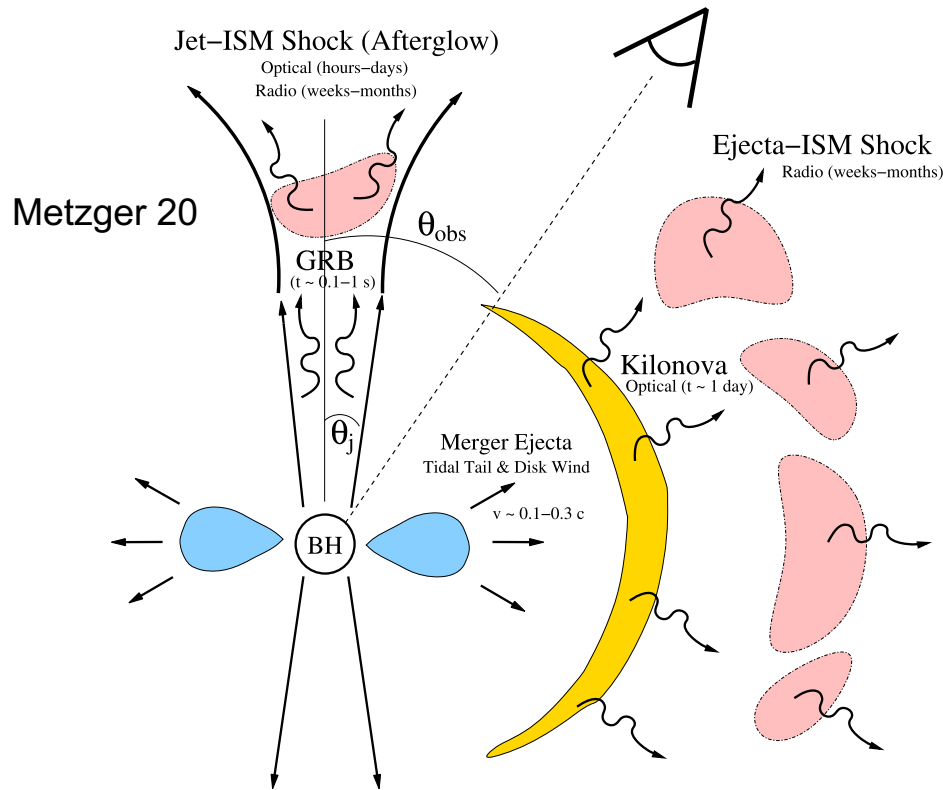
Guepin, Kotera, Barausse, Fang & KM 18

- Nuclei can be supplied for the disruption of white dwarfs
- CO-Si & O-Ne-Mg white dwarfs are rarer



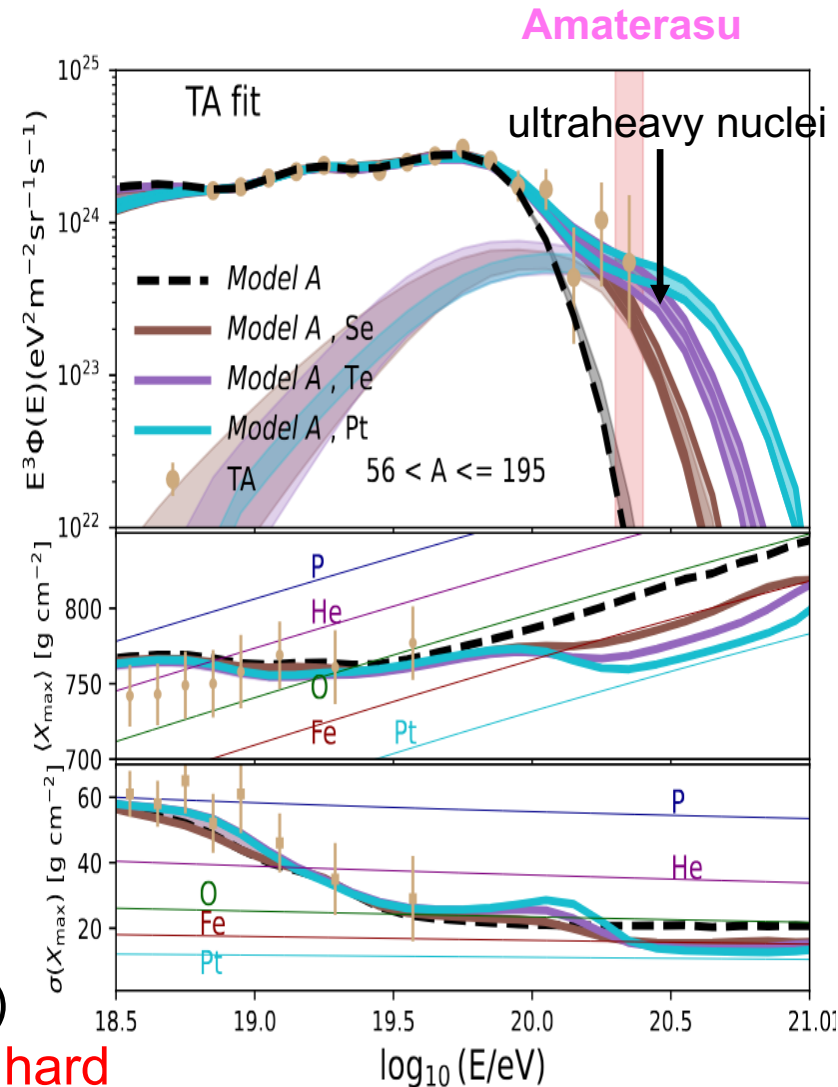
Zhang & KM in prep. $\log(E_v[\text{GeV}])$

Compact Binary Mergers (NS-NS Mergers and Short GRBs)



Takami+ 13, Kimura+ 18, Rodrigues+ 19,
KM & Fukugita 19, Farrar 24, Zhang, KM+ 24

1. “(Ultra)heavy” mass nuclei (r-process)
2. Transrelativistic ejecta (shocks/turbulence)
3. Instantaneous escaping spectrum: can be **hard**
4. Nuclei **can survive**



Zhang, KM+ 26 PRL

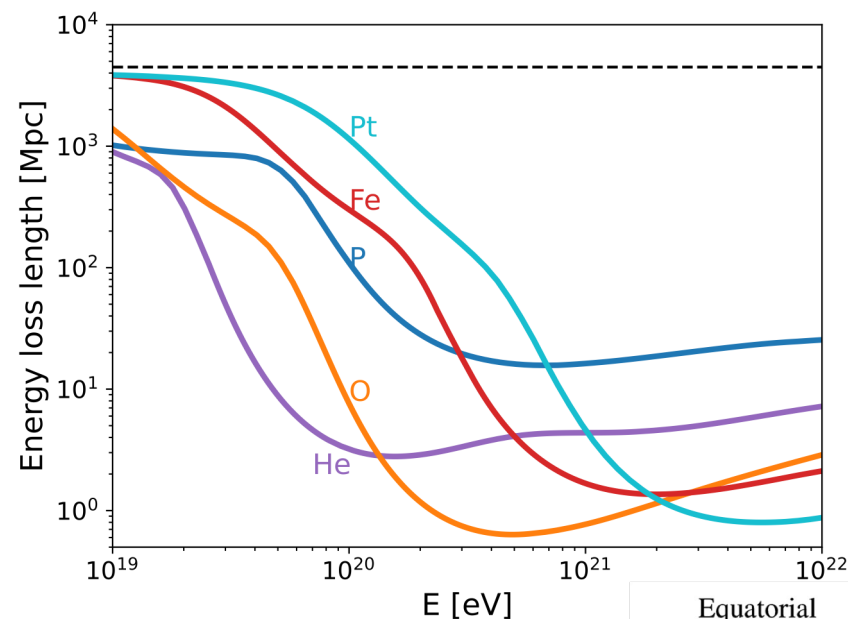
Ultraheavy UHECRs

- UH-UHECRs may come from collapsars as well as binary neutron mergers
- Energy loss lengths of UH-UHECRs are longer than p & Fe at ~0.1-1 ZeV

current constraints on energy budget

$$Q_{\text{UH-UHECR}}^{\text{Auger}} \lesssim (0.1 - 15) \times 10^{42} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

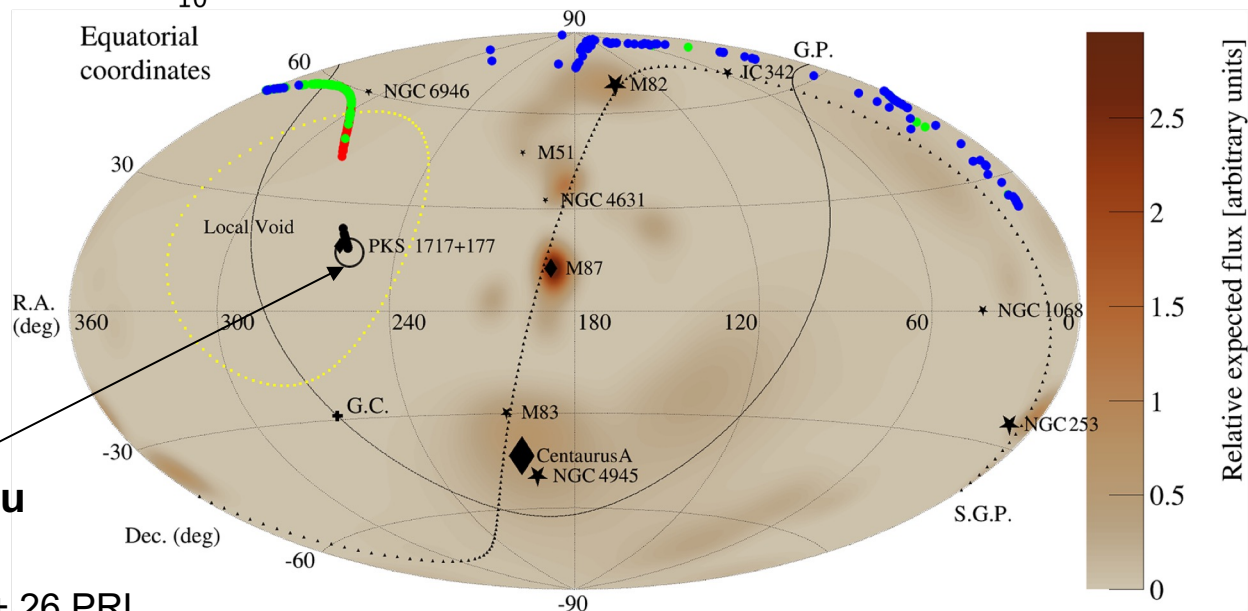
$$Q_{\text{UH-UHECR}}^{\text{TA}} \lesssim (1.4 - 5.6) \times 10^{43} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$



black: Z=1
red: Z=26
green: Z=40
blue: Z=78

Amaterasu

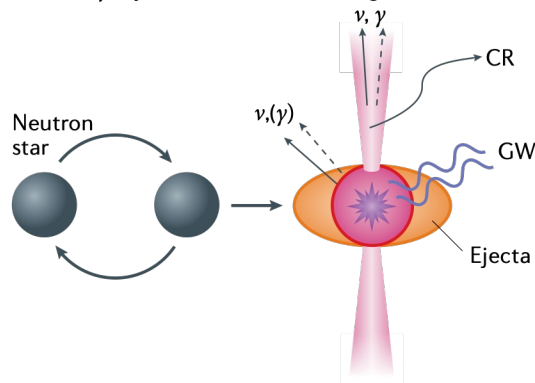
Zhang, KM+ 26 PRL



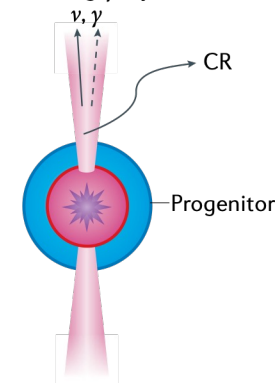
Time-Domain Frontier: Multimessenger/Multienergy ν Transients?

pointing & timing $\rightarrow$ good chance to discover ν sources

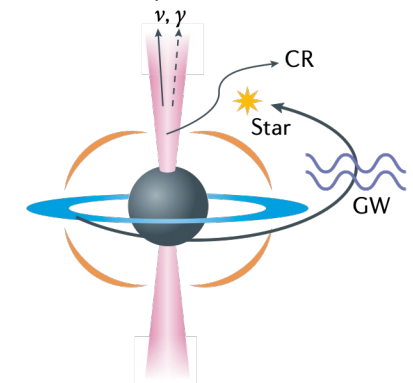
a Short γ -ray burst neutron star merger



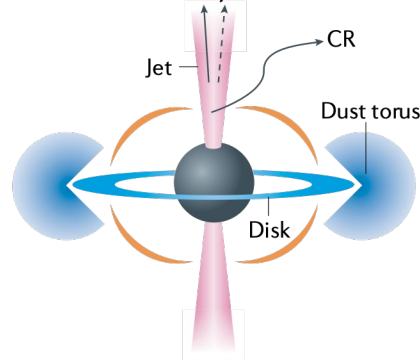
b Long γ -ray burst



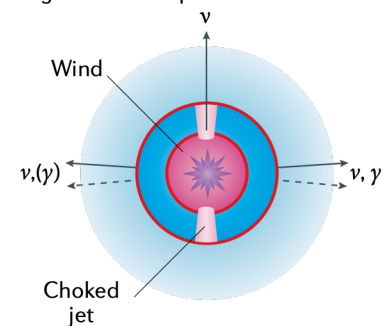
c Tidal disruption event



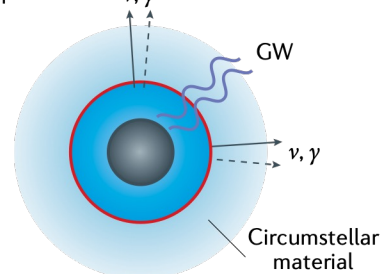
d Blazar flare



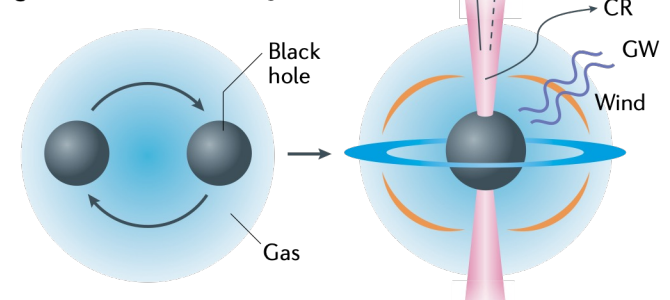
e Engine-driven supernova



f Supernova

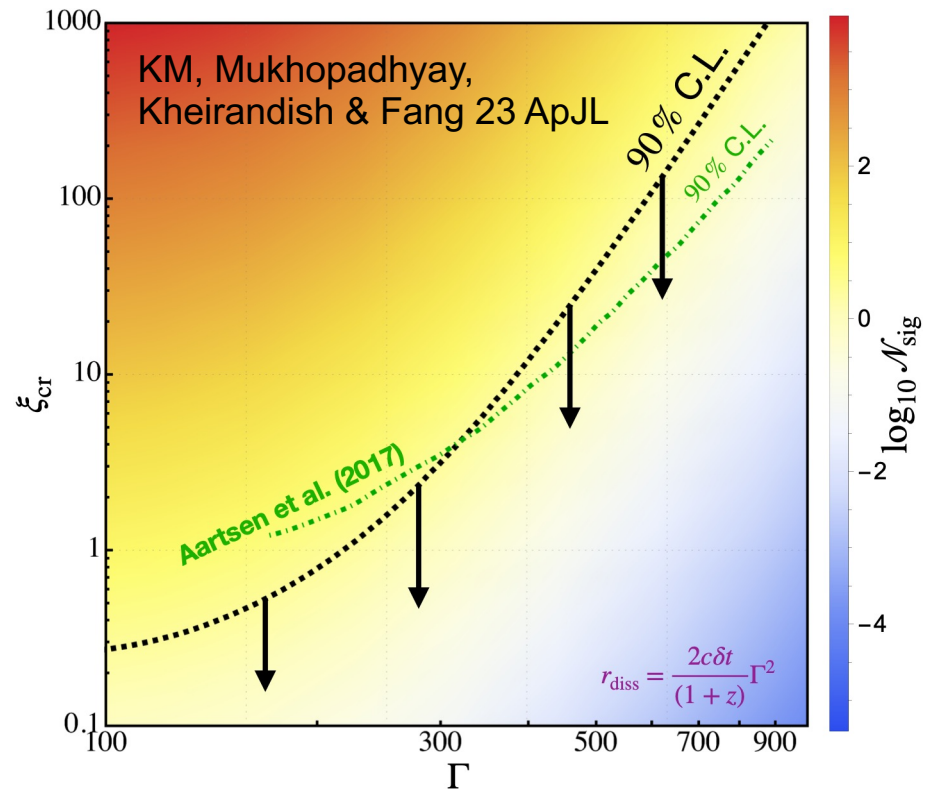
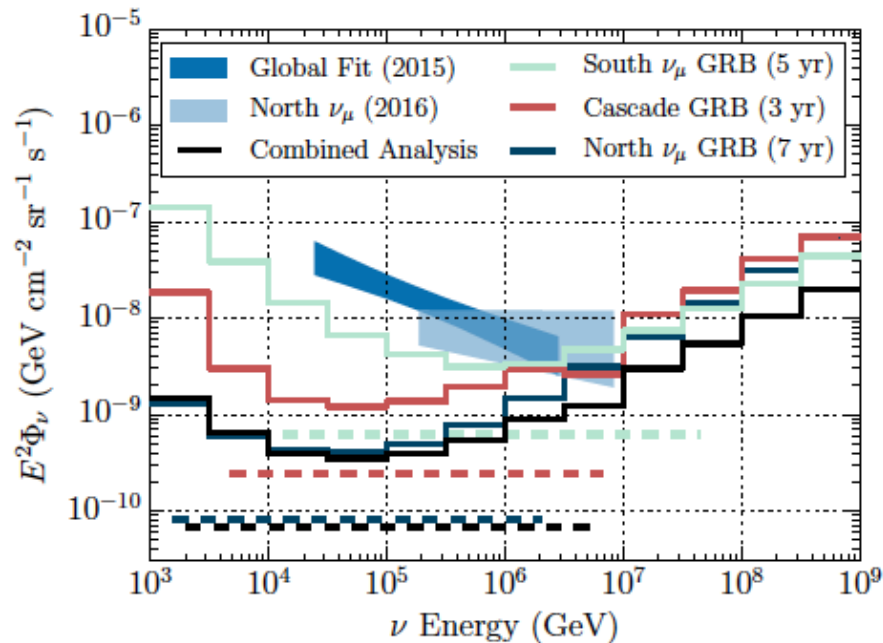


g Double black hole merger



GRB Neutrino Searches

1172 GRB samples



- Classical GRB: $< \sim 1\%$ of the diffuse IceCube flux
- DO NOT overinterpret results:
 - Constraints are much weaker at EeV (ex. ν afterglow models)
 - Constraints are much weaker at GeV-TeV (ex. sub-photospheric models)
 - Constraints are weaker for longer-lasting emission (ex. flares/afterglows)
 - Not applied to other transients (ex. low-luminosity GRBs, choked jets)

Optical, Infrared and X Rays: New ν Transient Searches



Einstein Probe



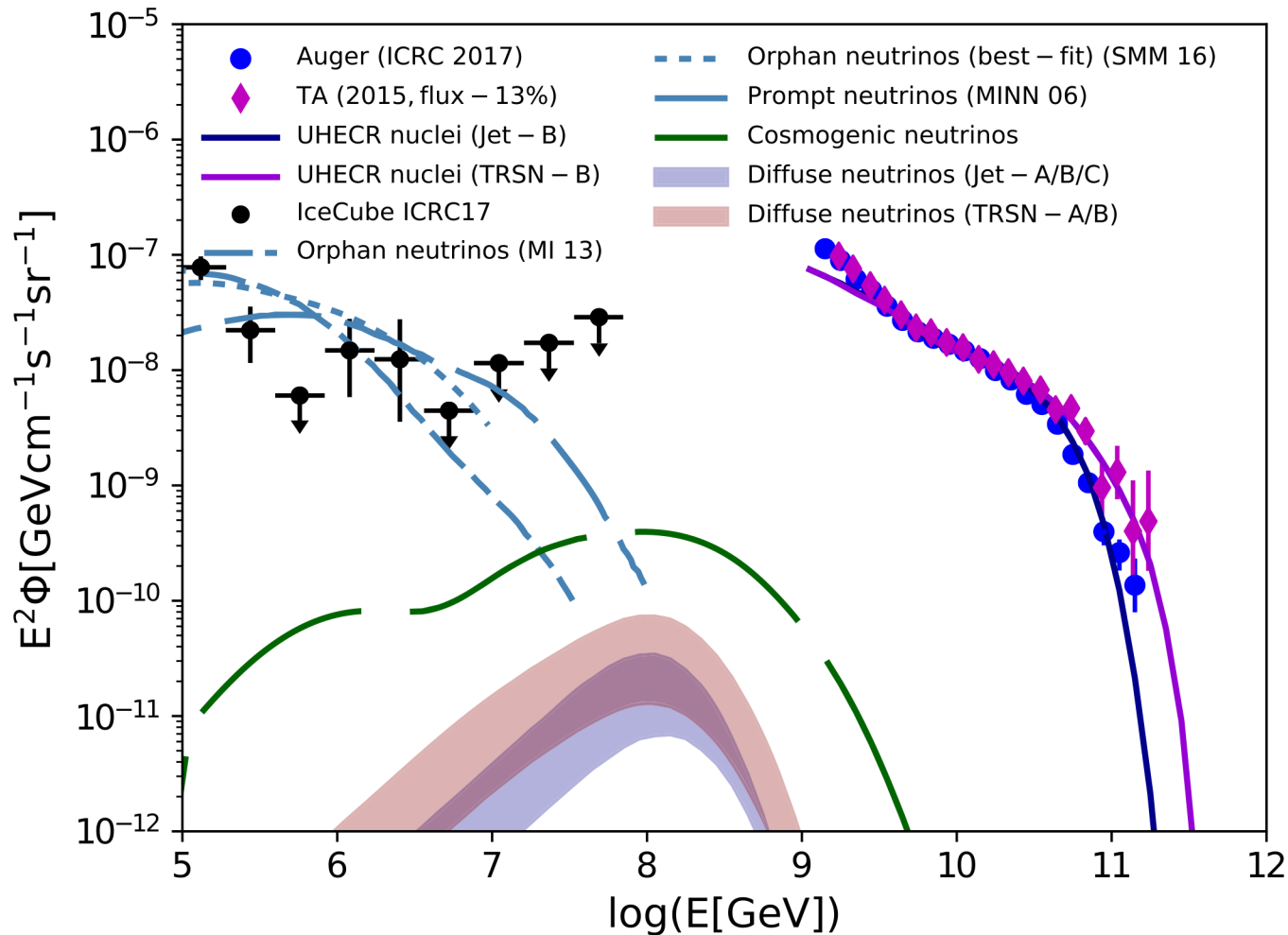
Vera Rubin Telescope

- Supernovae, tidal disruption events, low-luminosity gamma-ray bursts...
(e.g., Stein+ 21 Nature Astronomy, Reusch+ KM 21 PRL)
- Testability of models have been limited by the number of detected transients
- Stacking searches
- **Neutrino multiplet followups**
- **Multimessenger alert followups**
Neutrino singlet followups would need spectroscopic information



Nancy Grace Roman Telescope

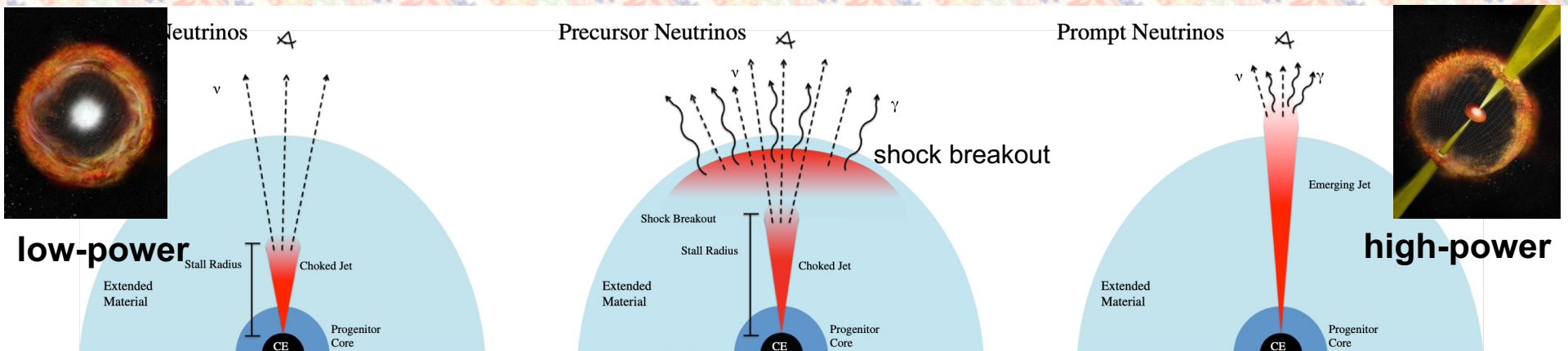
Neutrinos from Engine-Driven Supernovae



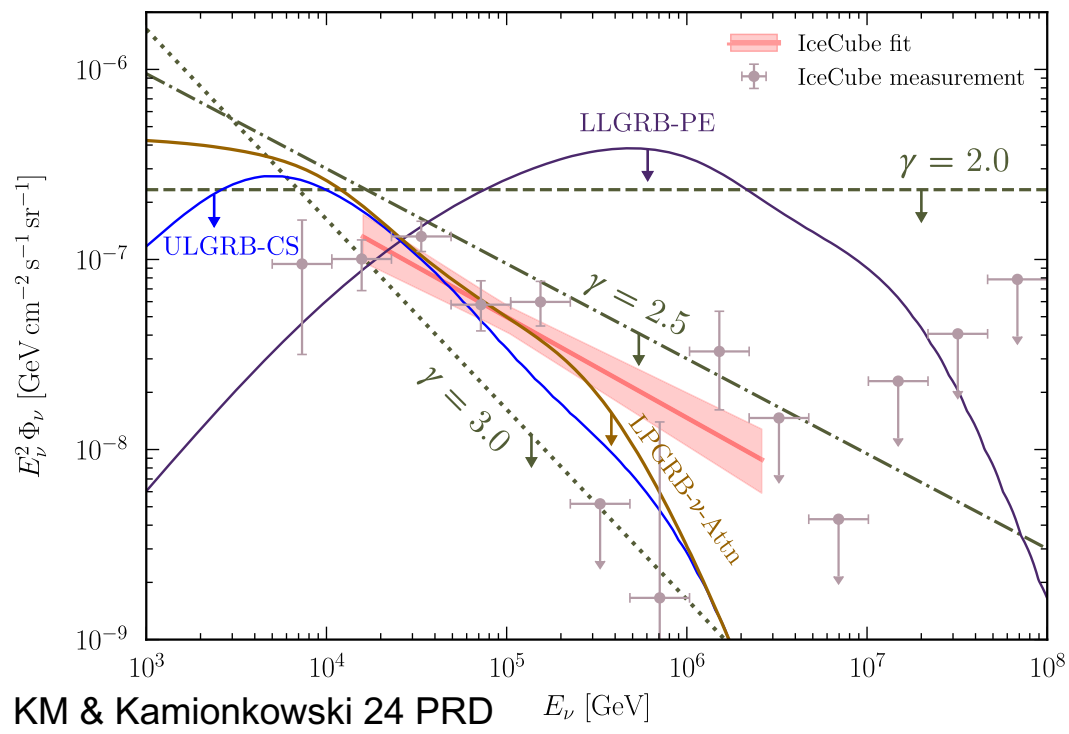
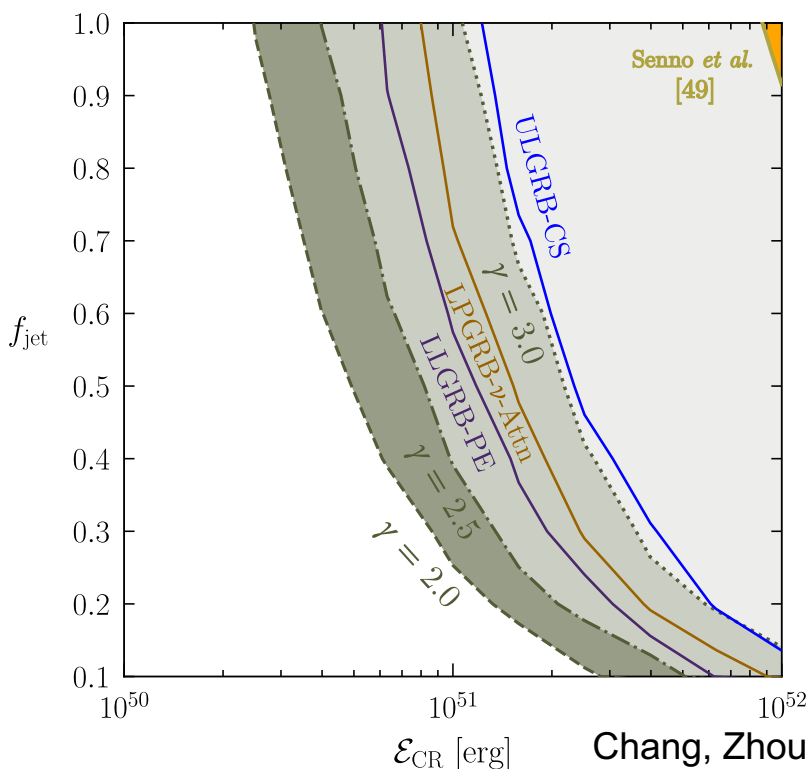
Zhang & KM 19 PRD

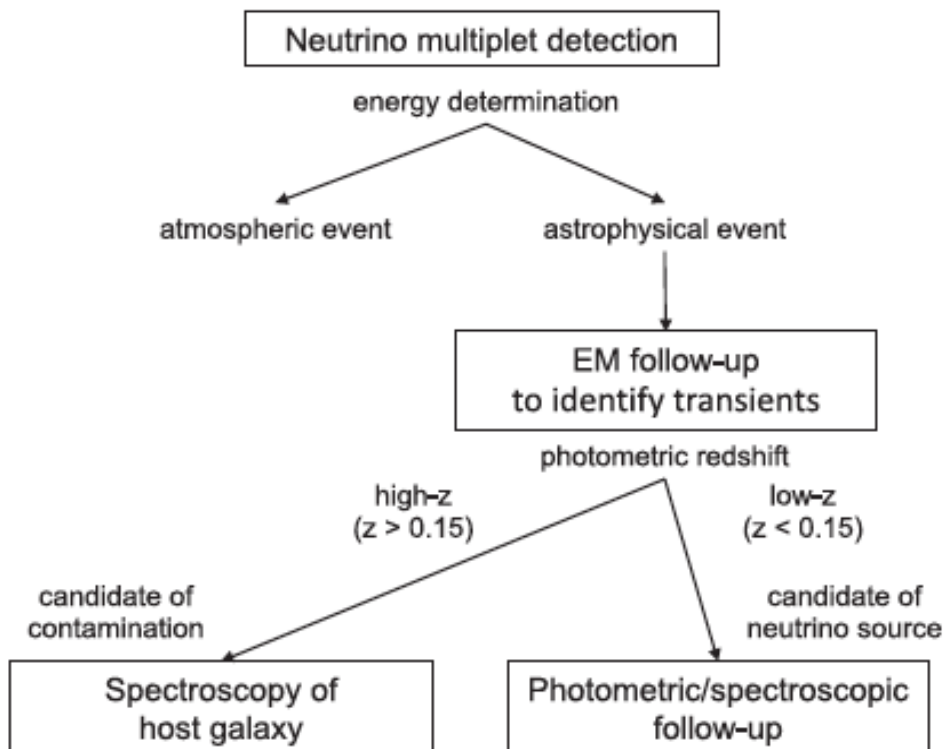
- EeV: cosmogenic neutrinos overwhelm source neutrinos
- TeV-PeV ν s may also be produced (KM+ 06, Senno, KM & Meszaros 16)

Stacking Searches w. Optical Supernovae

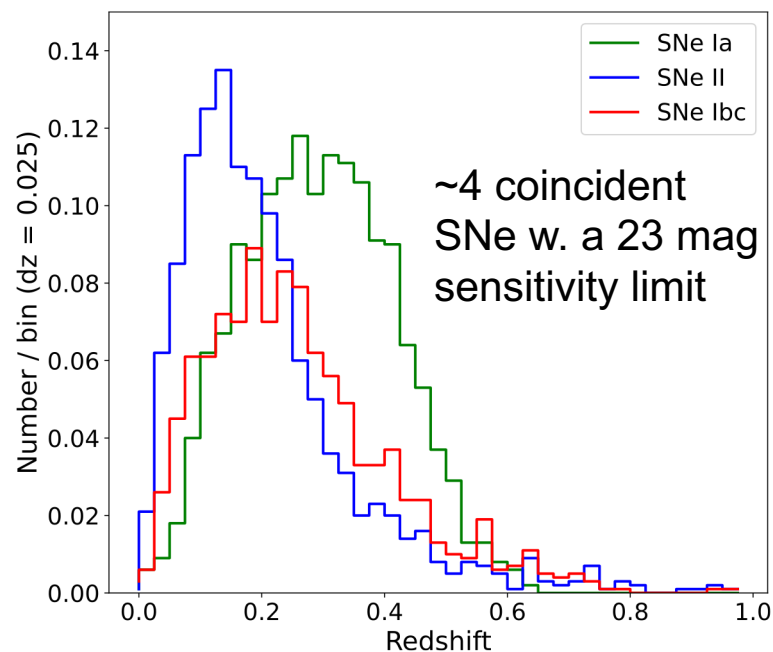
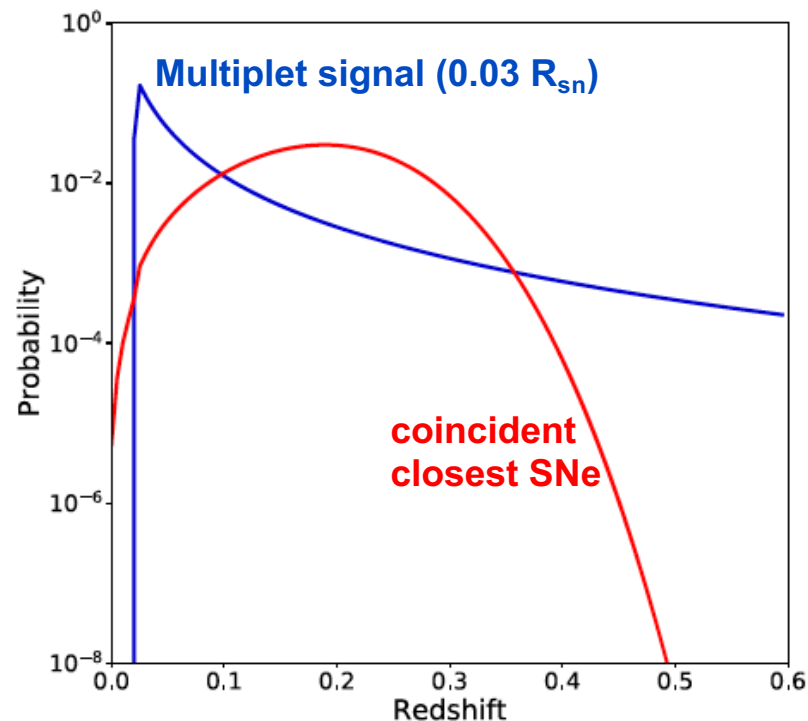


from Senno, KM & Meszaros 16 PRD





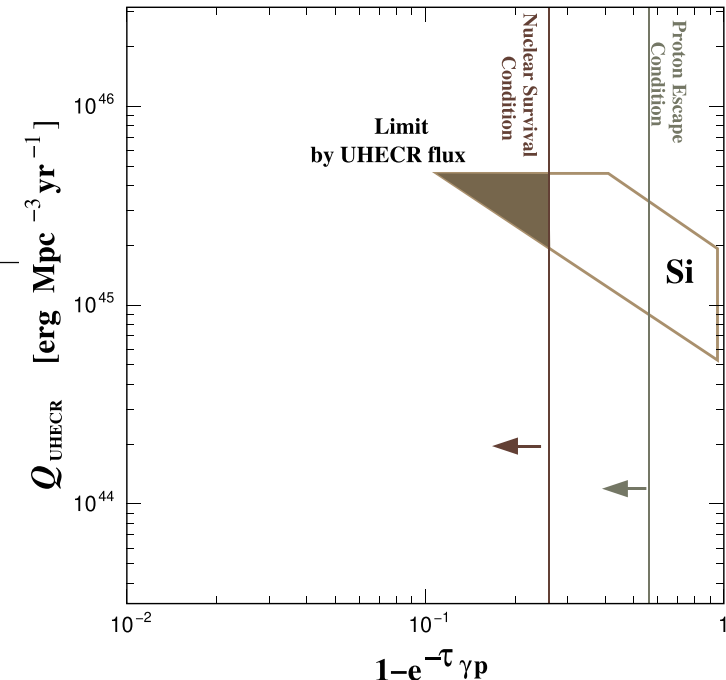
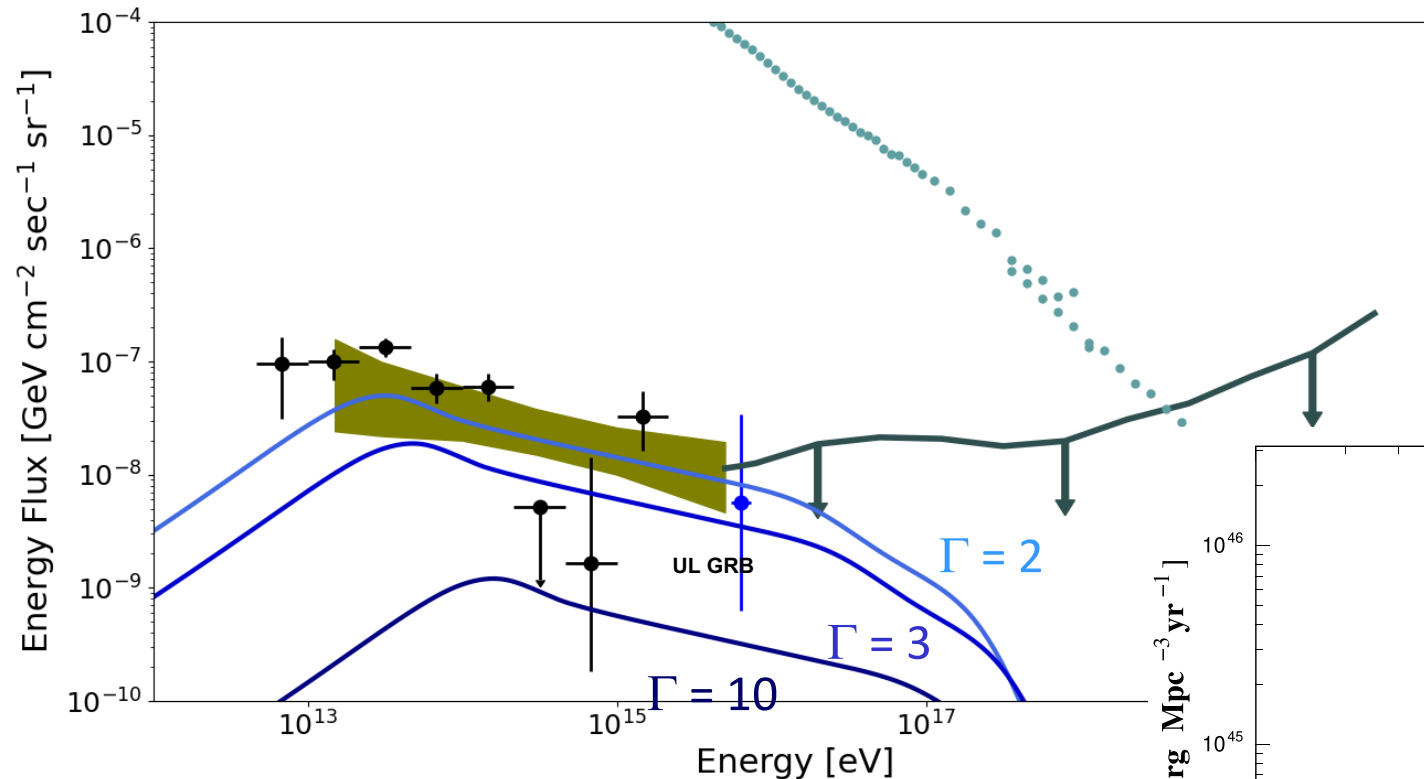
- Need for long-duration multiplet alerts
lower FAR ($< 1/\text{yr}$)
likely to be low redshifts if SN-like
- Discriminating optical transients is a key
- Sensitivity: $\sim (30-3000) \text{ Gpc}^{-3} \text{ yr}^{-1}$
more improved w. KM3Net/IceCube-Gen2



Testing UHECR-PeV ν Unification Scenarios

Yoshida & KM 24 PRD

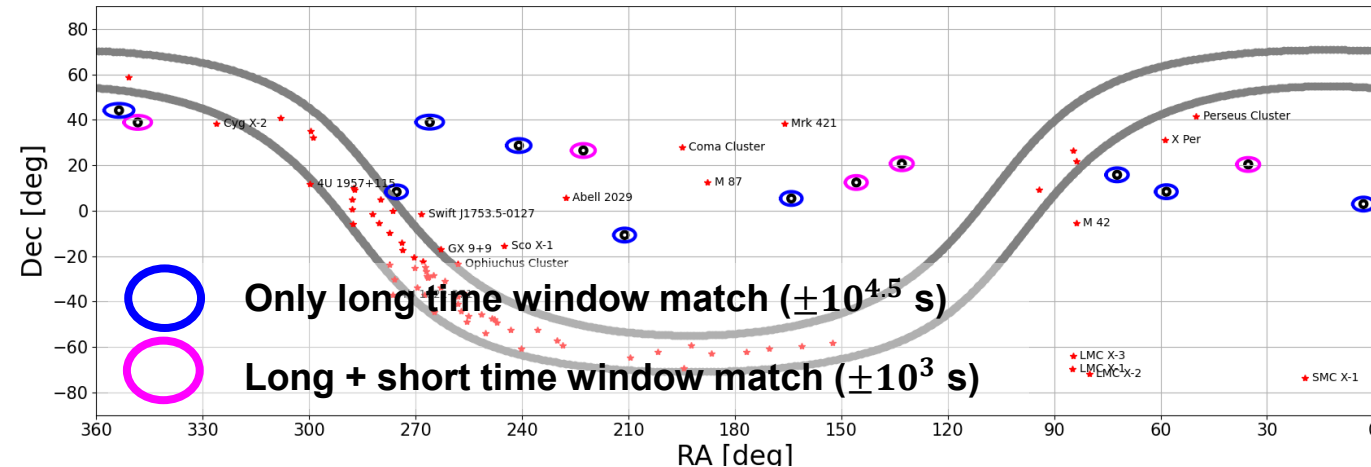
$\xi_{CR}=10$



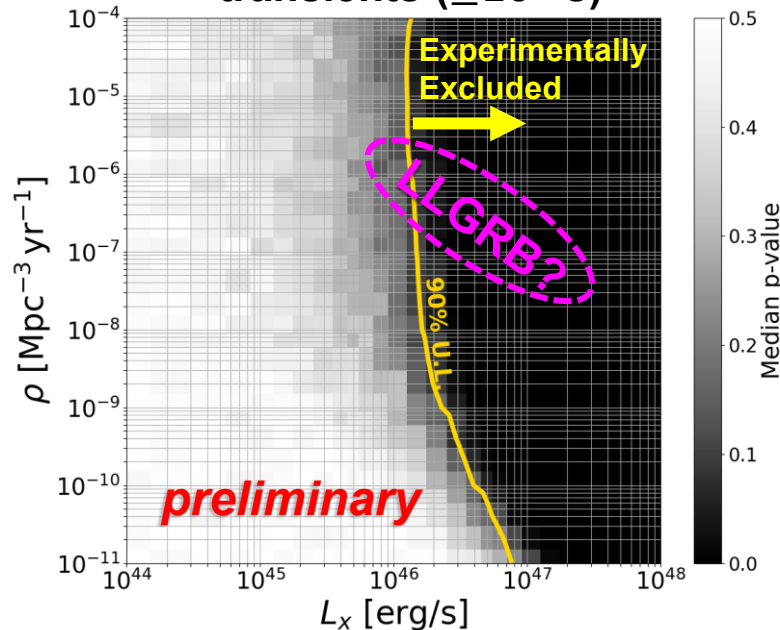
- Common origin of PeV ν s and UHECRs requires narrow parameter space for sources
- Viable models include LLGRBs and TDEs
→ optical & X-ray transient searches

ν -Triggered Follow-Up Searches w. Einstein Probe

slides from
Nobu Shimizu
@ TeVPA 2026



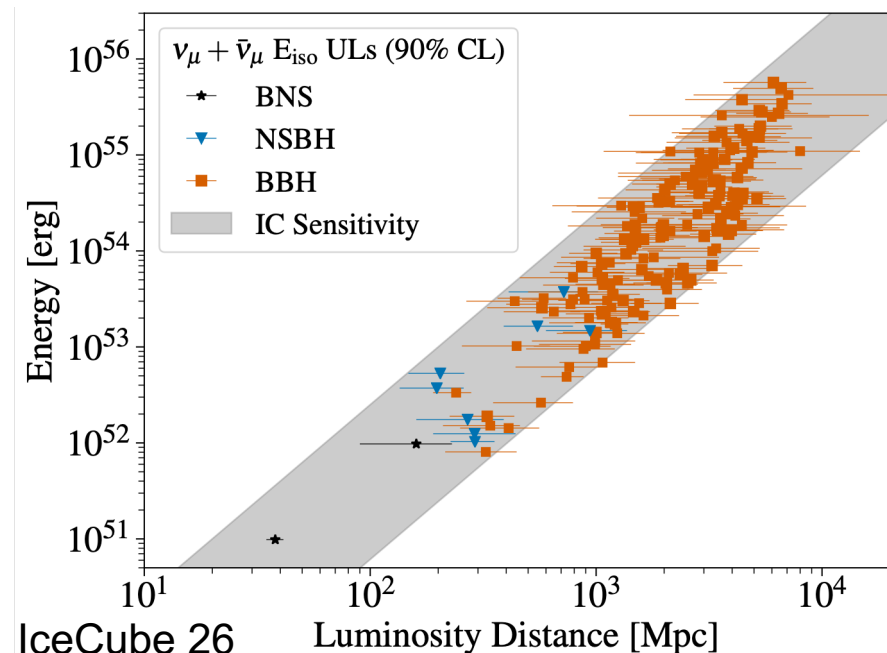
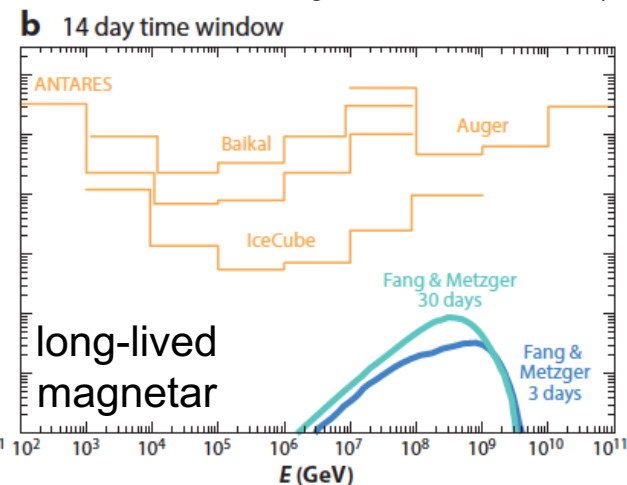
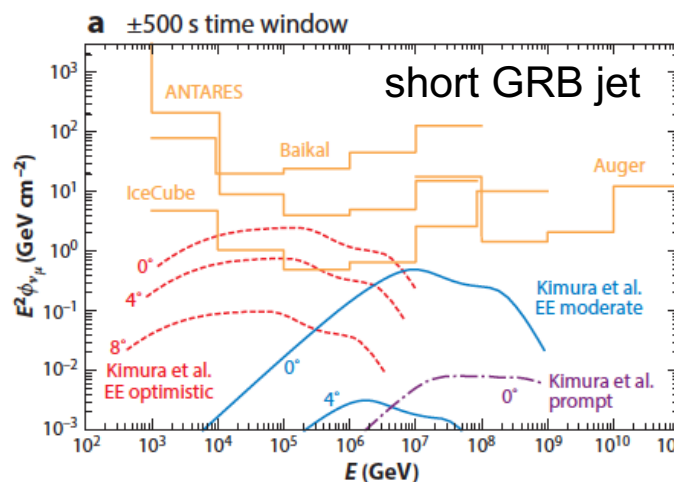
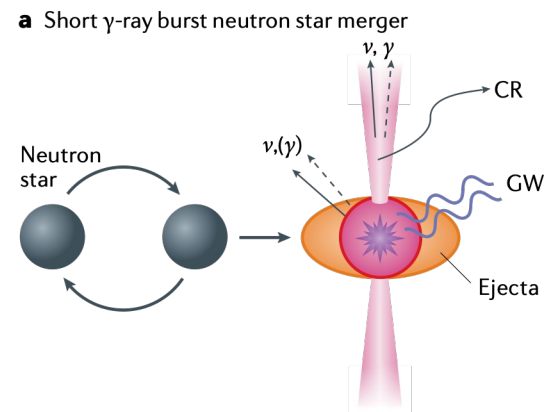
Short time scale
transients ($\pm 10^3$ s)



- Performed follow-up analyses on ~2 years of IceCube alerts w. EP/WXT to search for X-ray transient counterparts:
14 alerts : long time window $\pm 10^{4.5}$ s
5 alerts : short time window $\pm 10^3$ s
- No X-ray counterpart was observed
- Meaningful constraints on LLGRBs and TDEs as origins of high-energy neutrinos

High-Energy Neutrino – Gravitational Wave Transients?

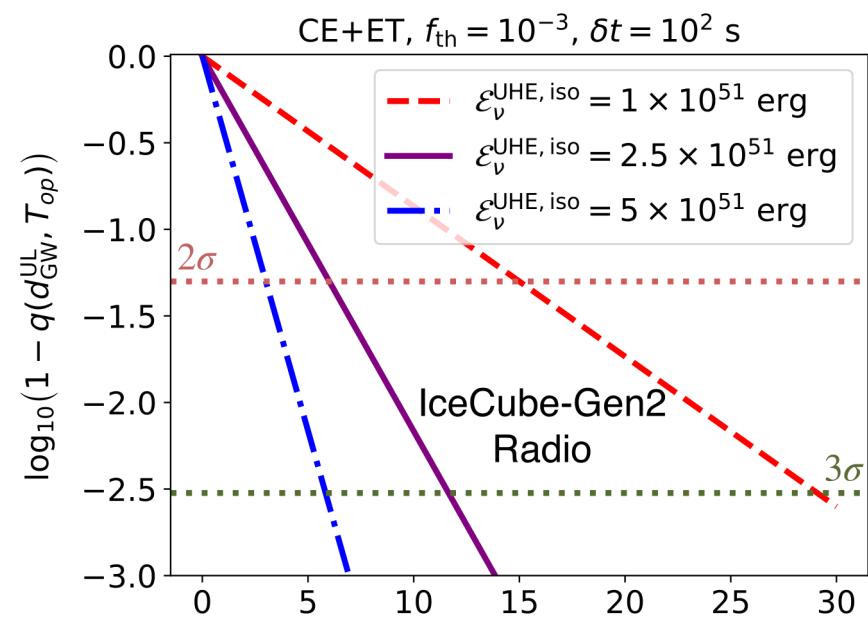
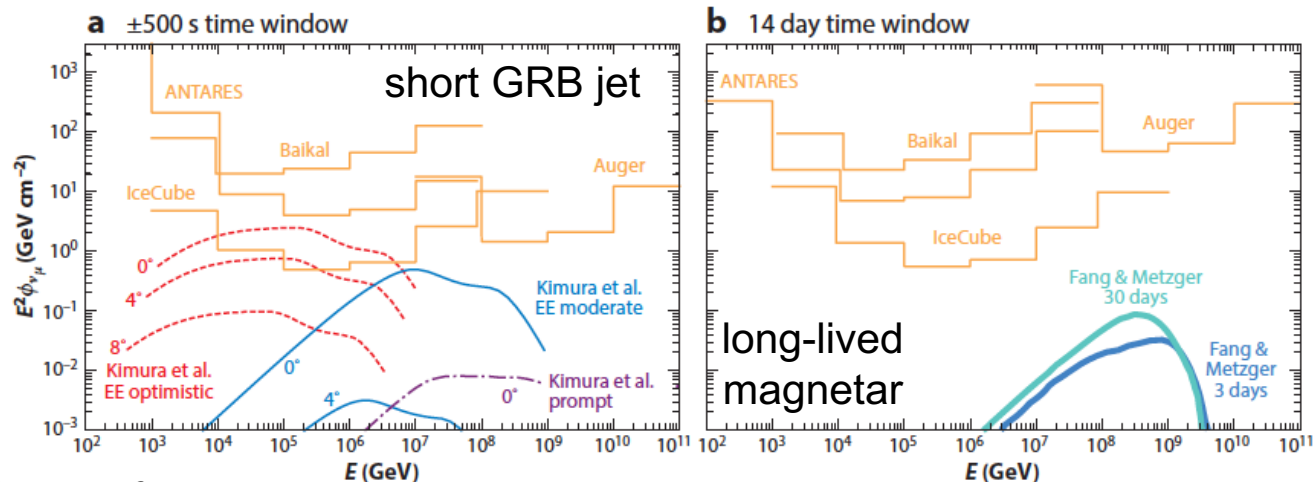
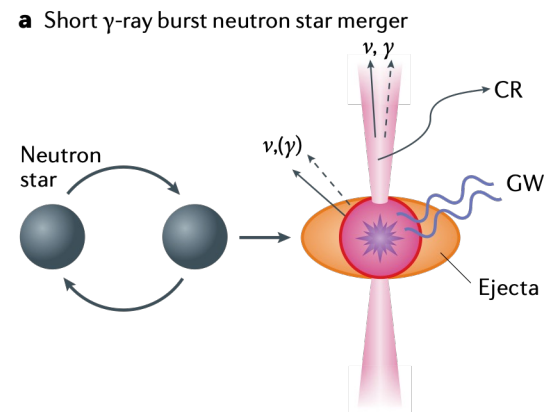
GW170817 (ANTARES-IceCube-Auger-LIGO-VIRGO 17)



- No statistically significant coincident ν emission from significant GW sources (164 BH-BH + 10 NS-BH + 2 NS-NS) during O1-O4a run
- Consistent w. theoretical expectations

High-Energy Neutrino – Gravitational Wave Transients?

GW170817 (ANTARES-IceCube-Auger-LIGO-VIRGO 17)



- No statistically significant coincident ν emission from significant GW sources (164 BH-BH + 10 NS-BH + 2 NS-NS) during O1-O4a run
- Consistent w. theoretical expectations
- Could be detected w. next-generation neutrino and GW detectors

Summary

Extragalactic: multimessenger connection → **hidden ν sources**

- AGN (jet-quiet): promising as dominant sources of the all-sky neutrino flux
predicted spectral curvature is consistent w. recent data
- Associated AGNs: **hidden ν sources**
NGC 1068 → ν s from pp or p γ produced within 10-20 Schwarzschild radii
Unique probe of high-energy phenomena powered by black holes

UHECR theory challenges: **heavy, hard, rigid, & survival**

Supermassive black holes (AGNs)

- UHECR acceleration in sub-pc jets (blazars)
→ EeV neutrinos provide a powerful test (given that nuclei are loaded)
- **Reacceleration in kpc jets (shear/turbulent/shock acceleration)**
→ Naturally heavy-rich abundance with hard escape spectra

Bursts from black holes/neutron stars (transients)

- Natural loading of intermediate/heavy/ultraheavy nuclei
 - **Collapsars: transrelativistic ejecta/jets – intermediate/ultraheavy nuclei**
 - Fast-rotating pulsars/magnetars: winds/jets - heavy nuclei
 - Tidal disruption events – intermediate nuclei for WD disruption
 - Compact binary mergers: transrelativistic ejecta/jets - ultraheavy nuclei