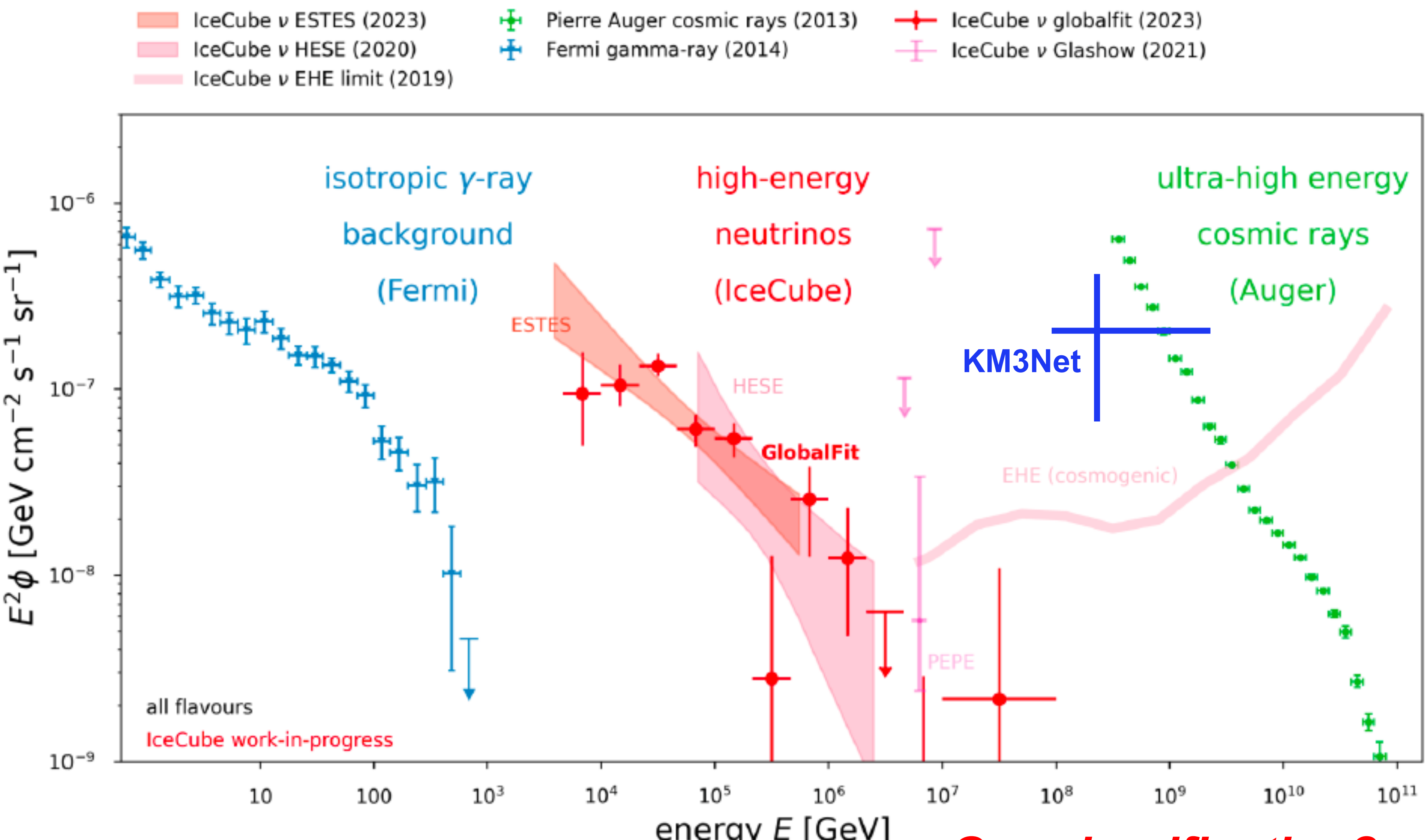
Multimessenger Perspectives on High-energy Cosmic Neutrinos

Kohta Murase
(Penn State)

CIPANP 2025 @ Madison

All-Sky Multimessenger Flux & Spectrum



IceCube Collaboration 18 PRD, 20 PRL, 21 Nature, 22 ApJ

Grand-unification?

High-Energy Neutrinos: Science Questions

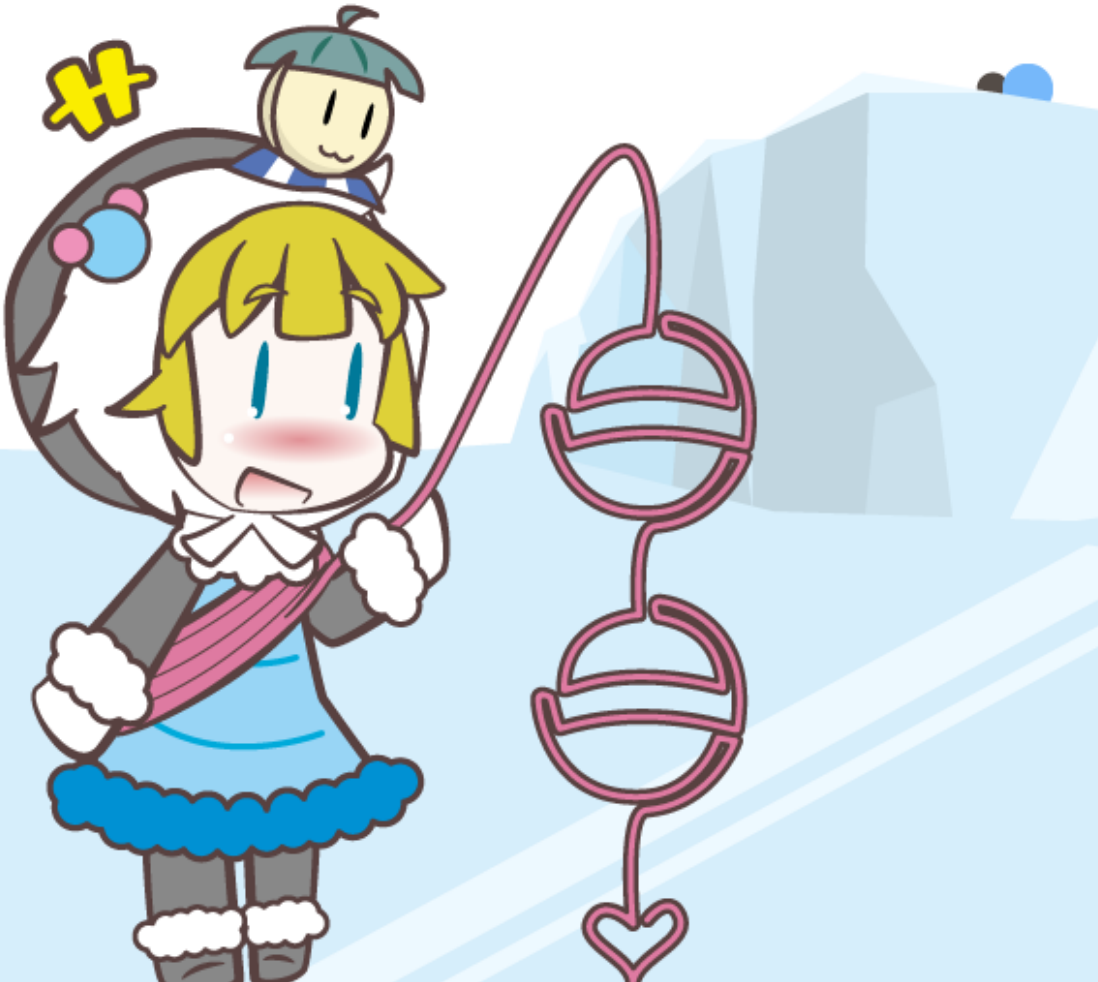
- Origin of high-energy cosmic neutrinos
- Neutrino production mechanism: pp or pγ?
- Connection to γ rays and/or UHECRs?
- Origin of UHECRs (extragalactic CR accelerators)
- Origin of Pevatrons (Galactic CR accelerators)

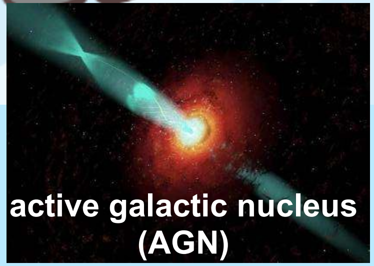
- CR acceleration mechanisms
- Physics in dense environments and high-z sources

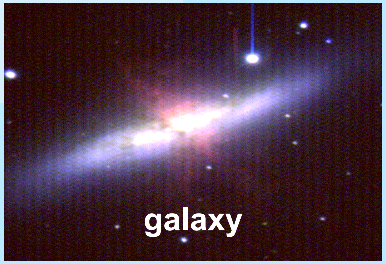
- Neutrino physics
- Physics beyond the Standard Model

Where do neutrinos come from?

monster fishing!!

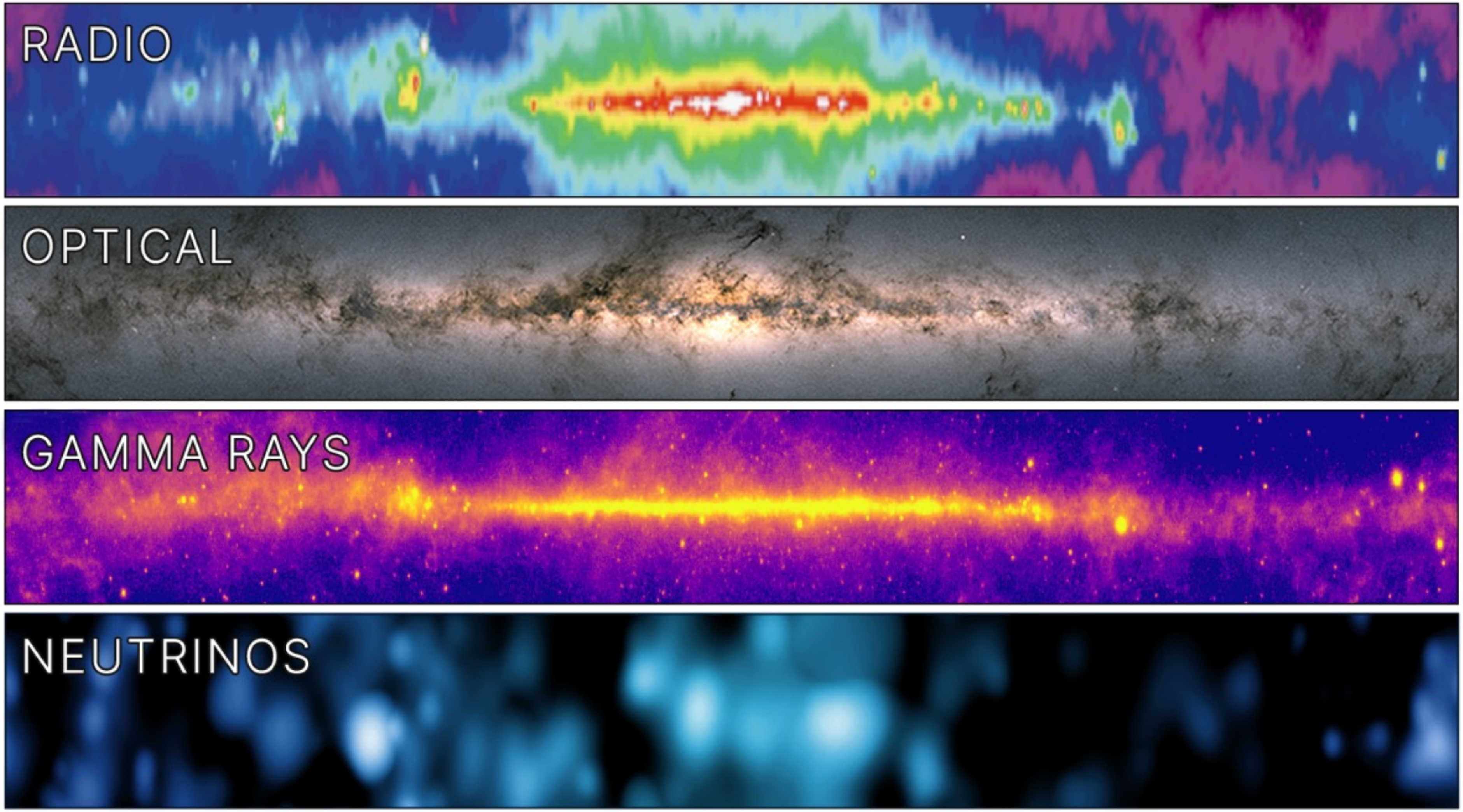






2023: Evidence of Neutrinos from the Milky Way

IceCube 23 Science

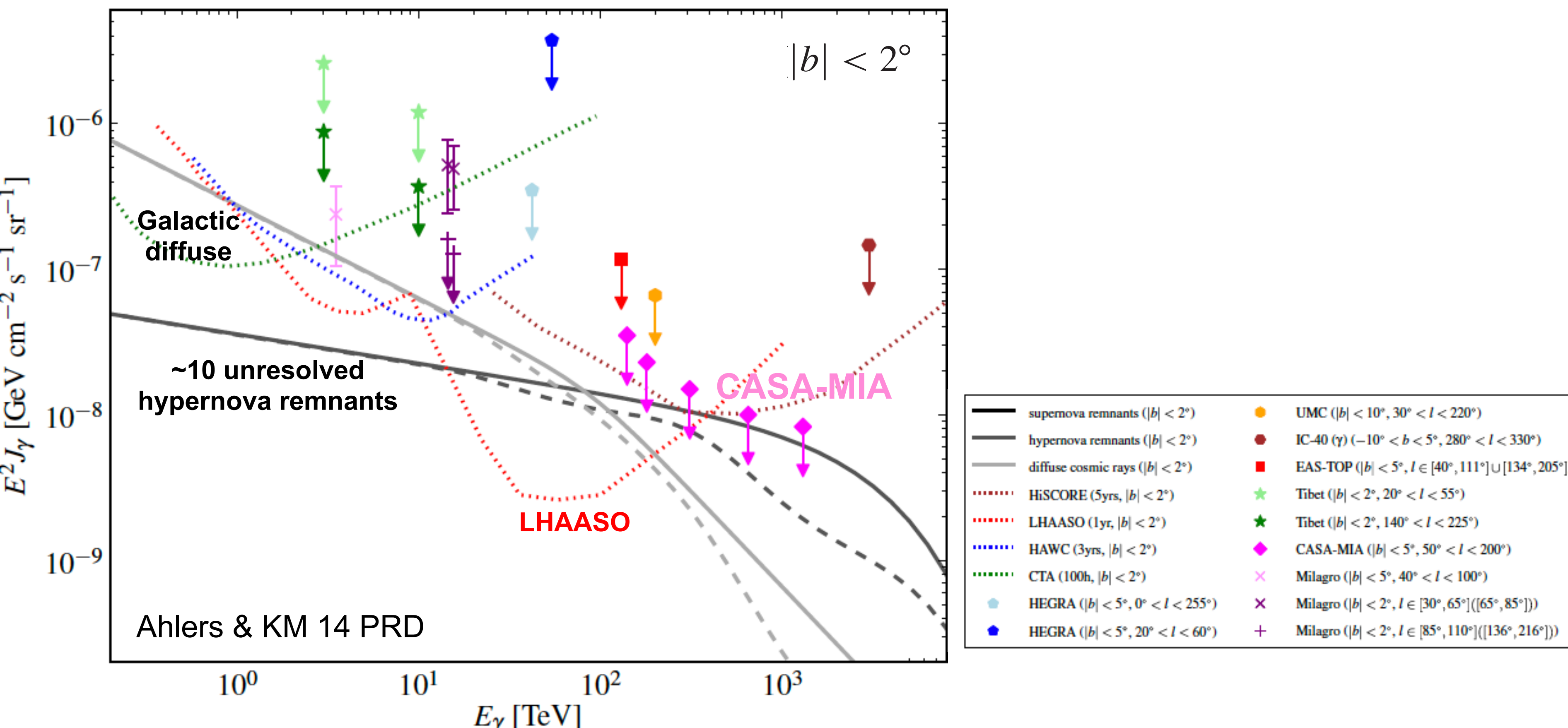


Neutrino emission from the Milky Way (~10% of total) has been observed w. 4.5σ

Importance of Multimessenger Connection – Milky Way Case

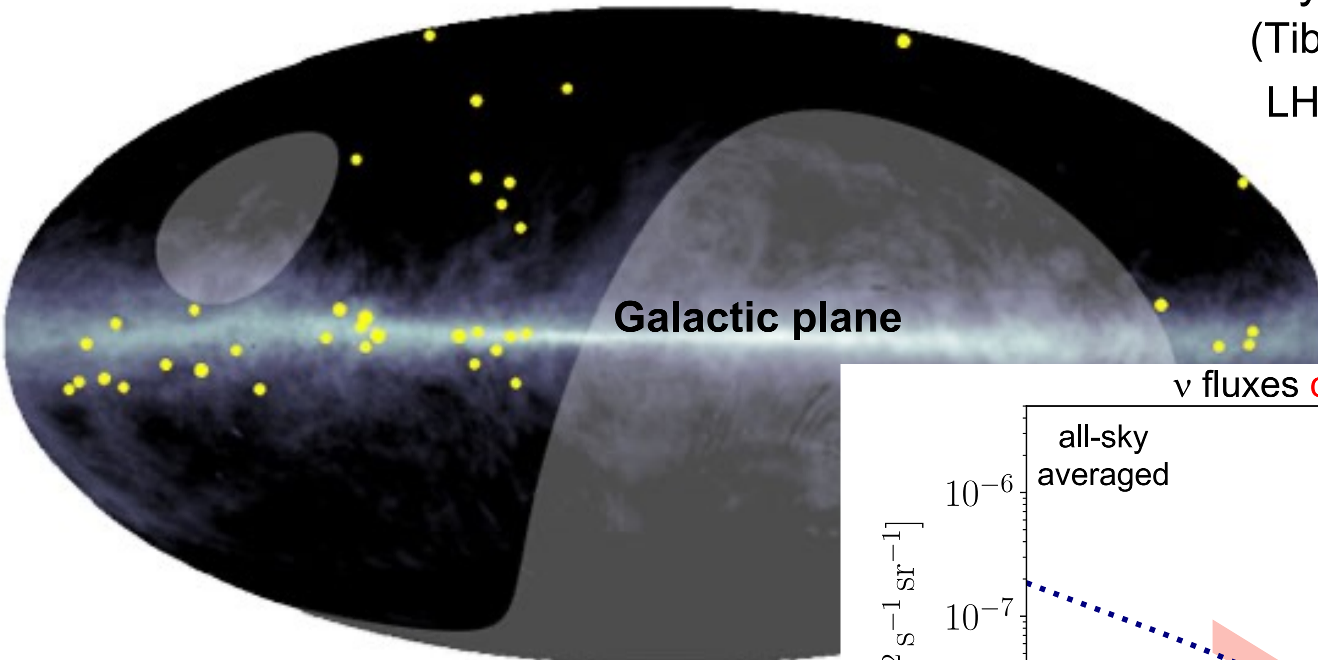
A decade ago, neither γ rays NOR νs were observed in the sub-PeV range.
(Note that most γ rays from Galactic sources reach Earth.)
But we already learned that Galactic contribution to IceCube νs is subdominant.

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

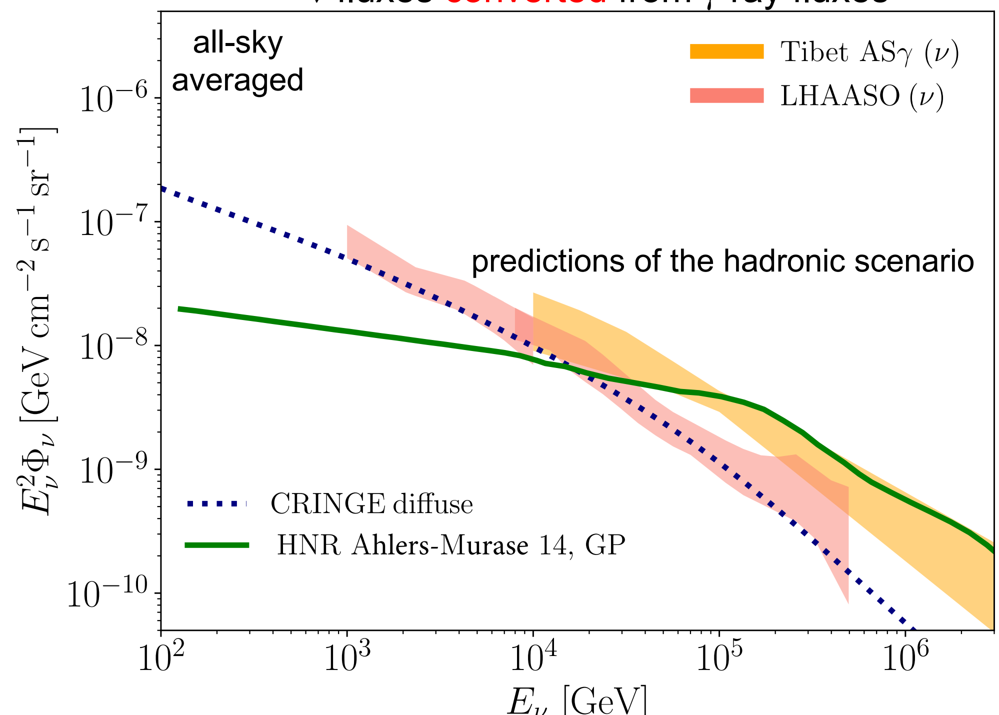


Galactic Diffuse Sub-PeV Gamma Rays Are NOW Measured

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



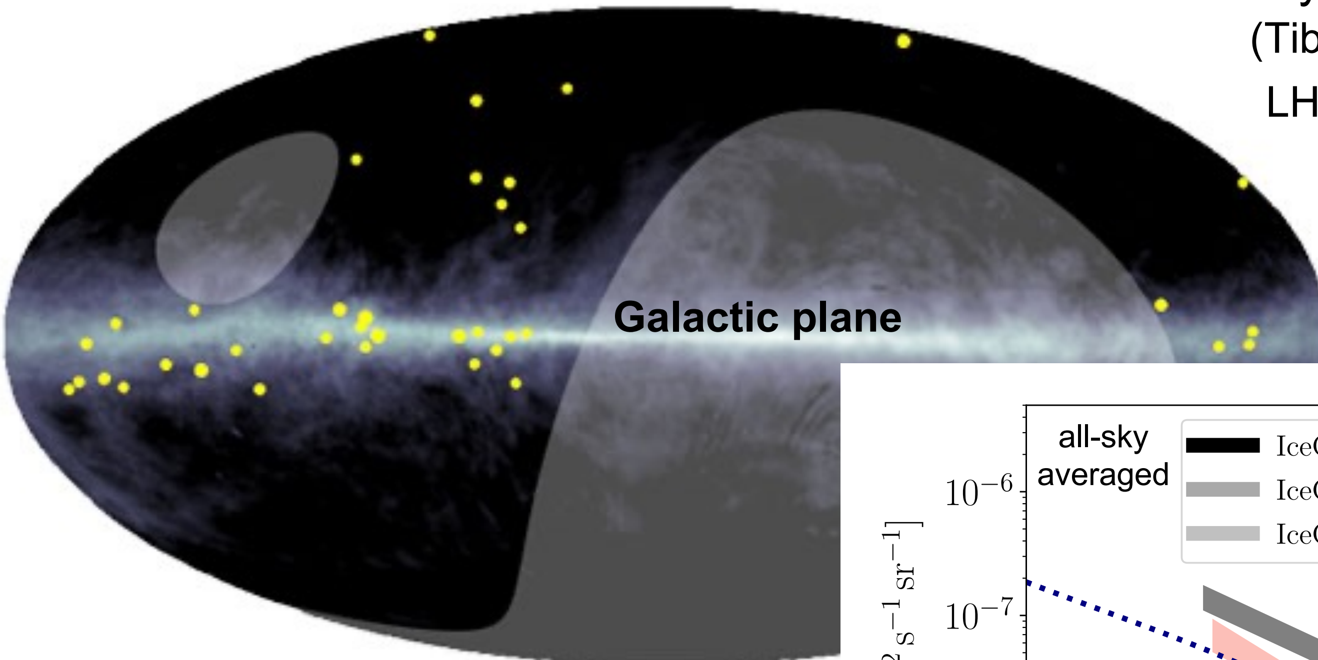
ν fluxes converted from γ-ray fluxes

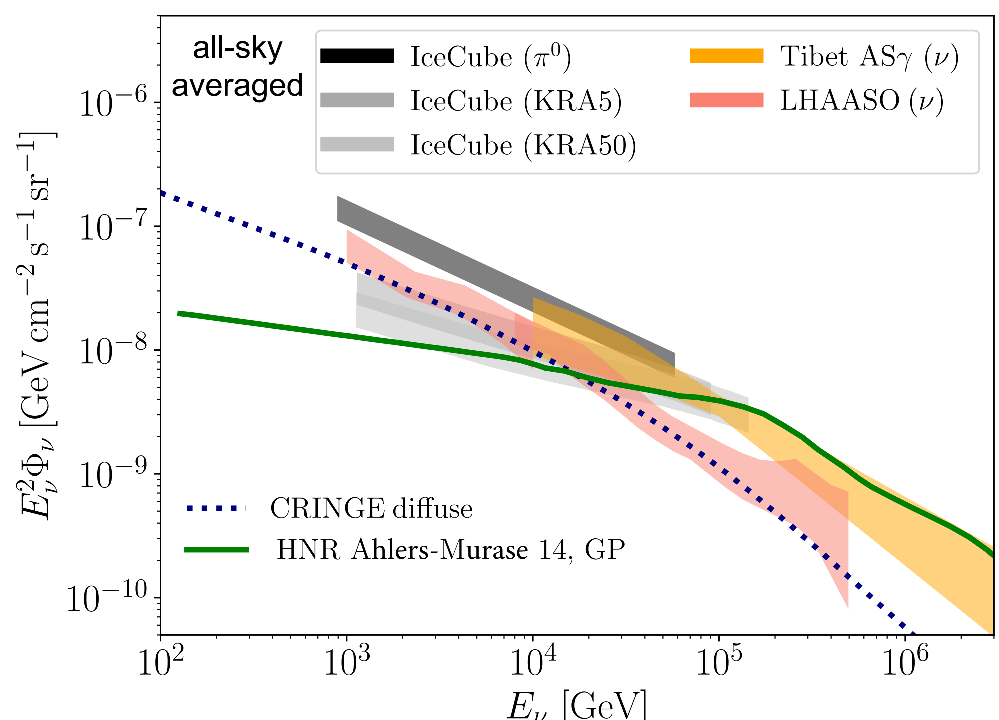


Fang & KM 21 ApJ, 23 ApJL

Galactic Multimessenger Connection: Current

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



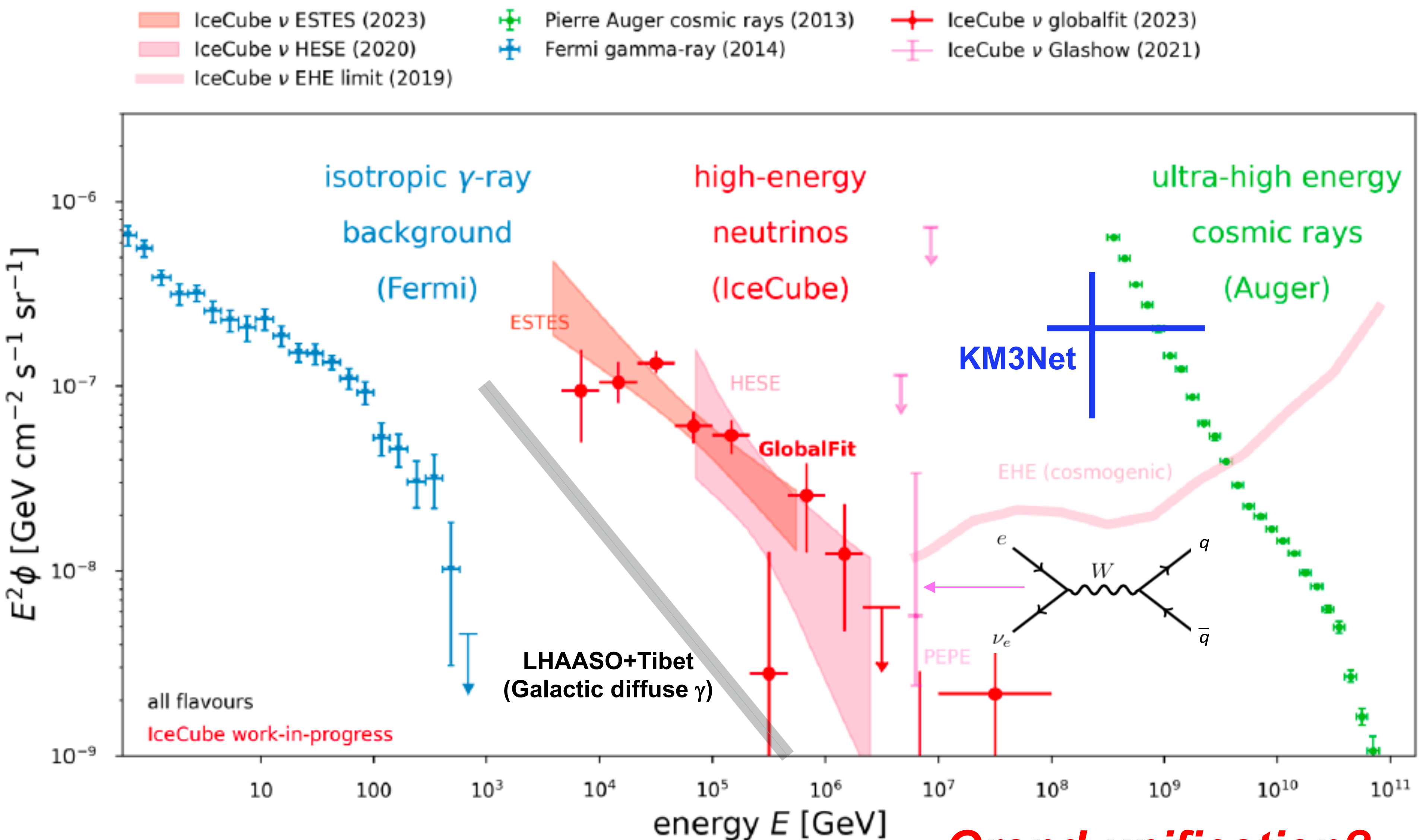


Fang & KM 21 ApJ, 23 ApJL

- Supporting hadronic (pp) origin
- Truly diffuse emission
vs
Unresolved (extended) sources

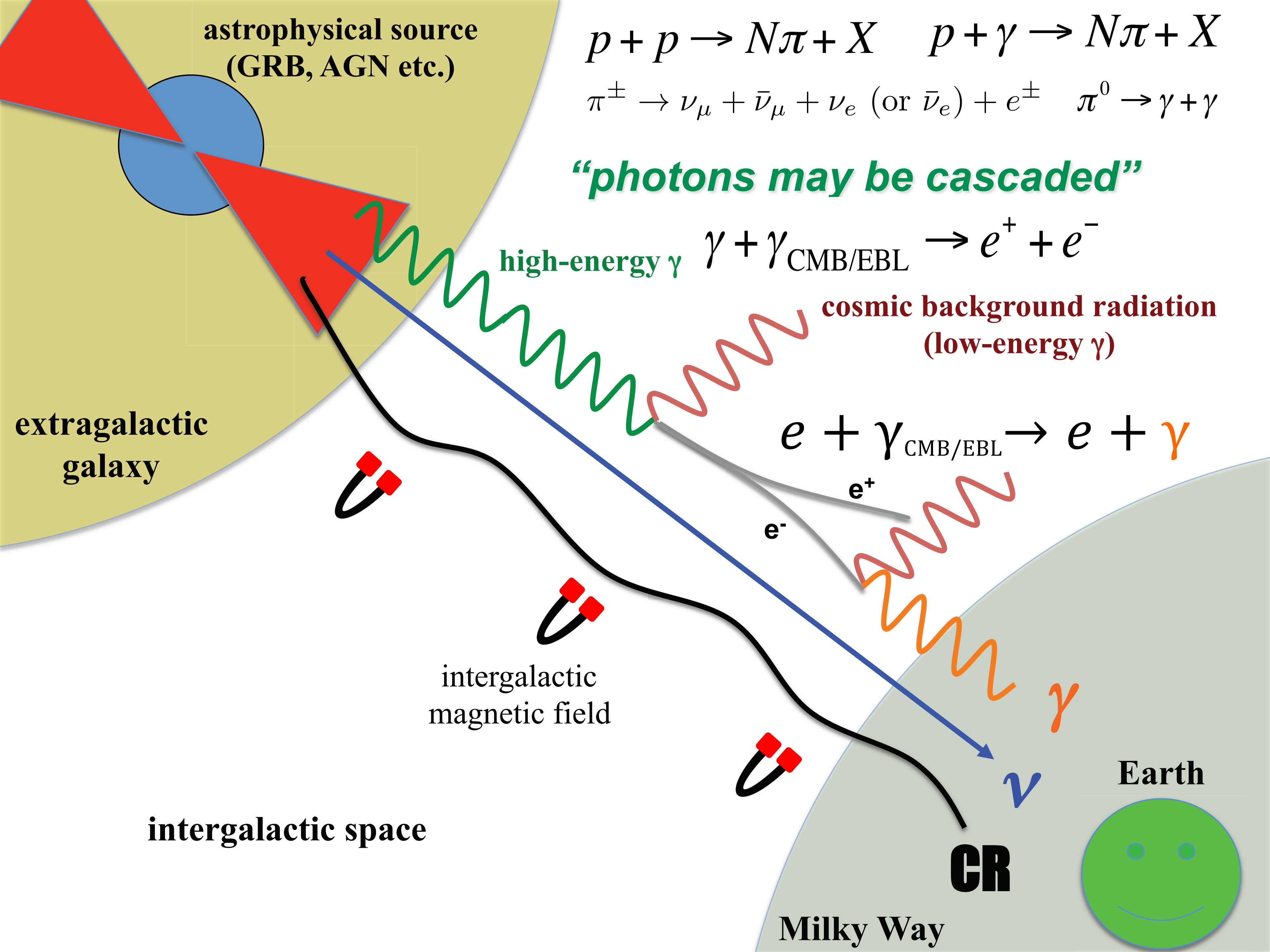
→ SWGO, KM3Net, Gen2 etc.
relevance of templates

All-Sky Multimessenger Flux & Spectrum



IceCube Collaboration 18 PRD, 20 PRL, 21 Nature, 22 ApJ

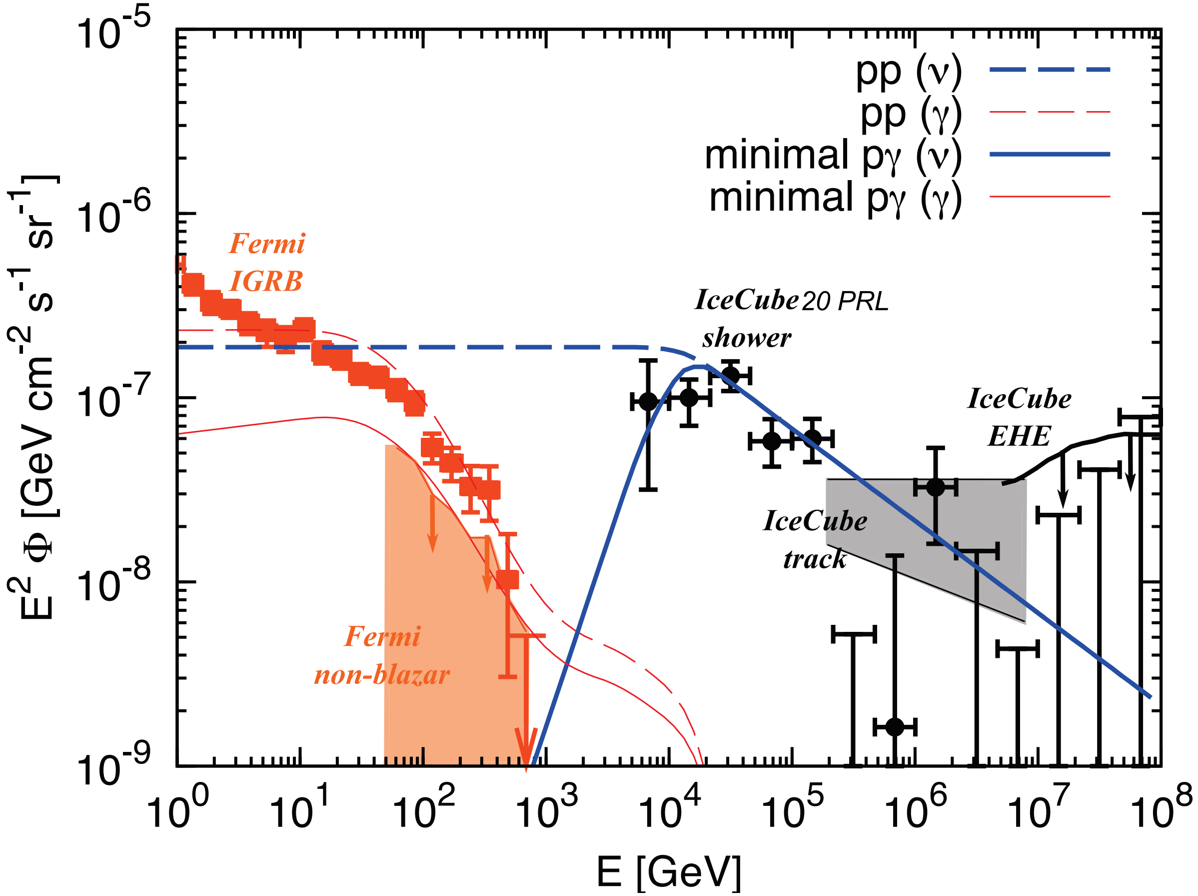
Grand-unification?



astrophysical source
(GRB, AGN etc.)
$p + p \rightarrow N\pi + X$
$p + \gamma \rightarrow N\pi + X$
$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_e$ (or $\bar{\nu}_e$) $+ e^{\pm}$
$\pi^0 \rightarrow \gamma + \gamma$
"photons may be cascaded"
high-energy γ
$\gamma + \gamma_{CMB/EBL} \rightarrow e^+ + e^-$
cosmic background radiation
(low-energy γ)
$e + \gamma_{CMB/EBL} \rightarrow e + \gamma$
e^+
e^-
extragalactic
galaxy
intergalactic
magnetic field
γ
ν
Earth
intergalactic space
CR
Milky Way

Extragalactic Multimessenger Connection: Current

- 10-100 TeV shower data: large fluxes of ~10^{-7} GeV cm^{-2} s^{-1} sr^{-1}



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

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

$$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e\ (\mathrm{or}\ \bar{\nu}_e) + e^{\pm}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

KM, Guetta & Ahlers 16 PRL

see also

KM, Ahlers & Lacki 13 PRDR

Capanema, Esmaili & KM 20 PRD

Capanema, Esmaili & Serpico 21 JCAP

Fang, Gallagher & Halzen 22 ApJL

Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent

→ Requiring hidden (i.e., γ-ray opaque) cosmic-ray accelerators

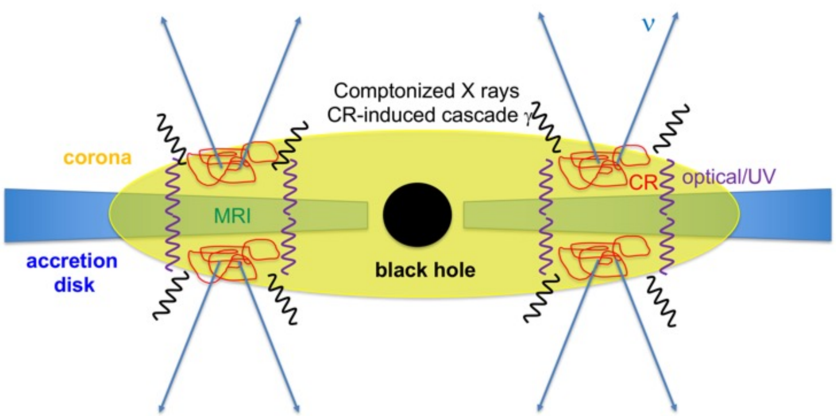
(ν data above 100 TeV can still be explained by γ-ray transparent sources)

Prediction of Hidden Neutrino Sources

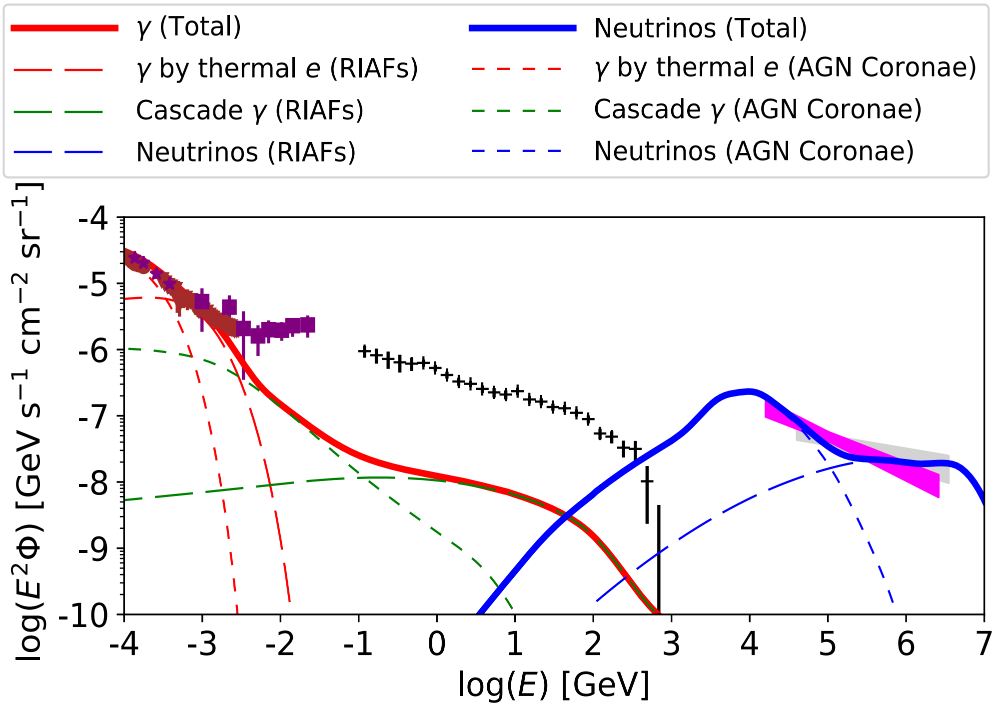
Hidden (i.e., γ-ray opaque) ν sources are actually "natural" in pγ scenarios

γγ→e⁺e⁻ optical depth $\tau_{\gamma\gamma} \approx \frac{\sigma^{\rm eff}_{\gamma\gamma}}{\sigma^{\rm eff}_{p\gamma}} f_{p\gamma} \sim 1000 f_{p\gamma} \gtrsim 10$

KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.



accretion disk + "corona"
opt/UV=multi-temperature blackbody
X-ray=Compton by thermal electrons



All-sky 10-100 TeV *neutrino flux can be explained by AGN*

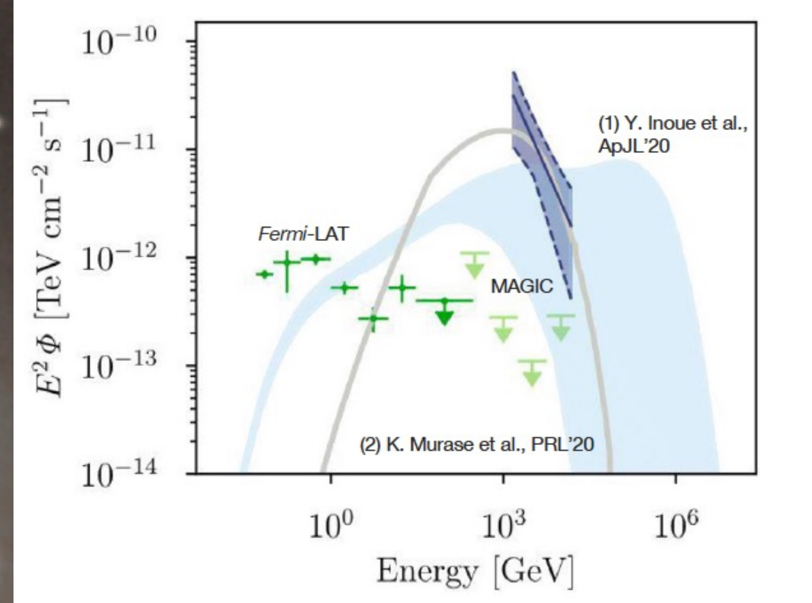
But do such hidden ν source (candidates) exist??

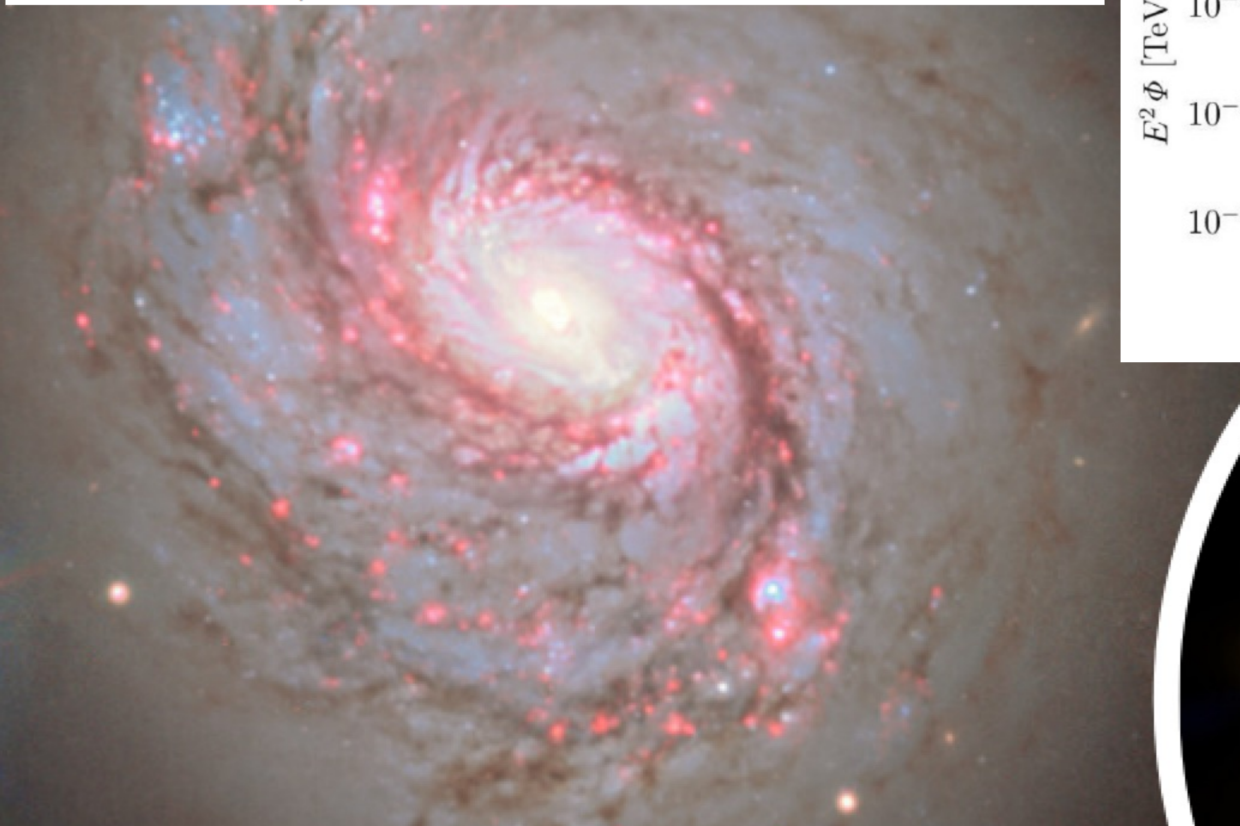
NEUTRINO ASTROPHYSICS

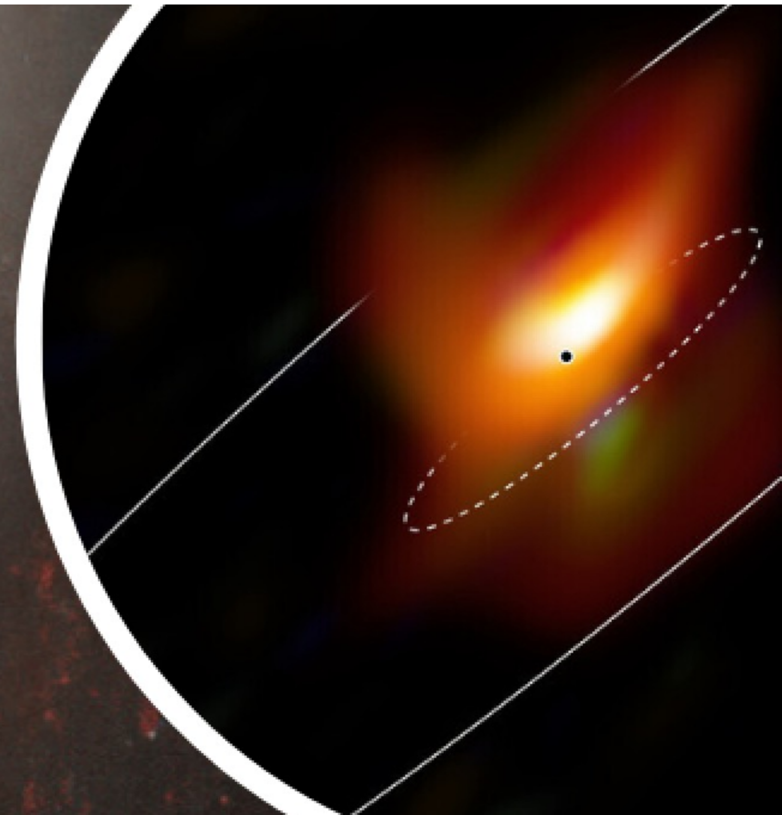
Evidence for neutrino emission from the nearby active galaxy NGC 1068

Science JOURNALS AAAS

IceCube Collaboration*†





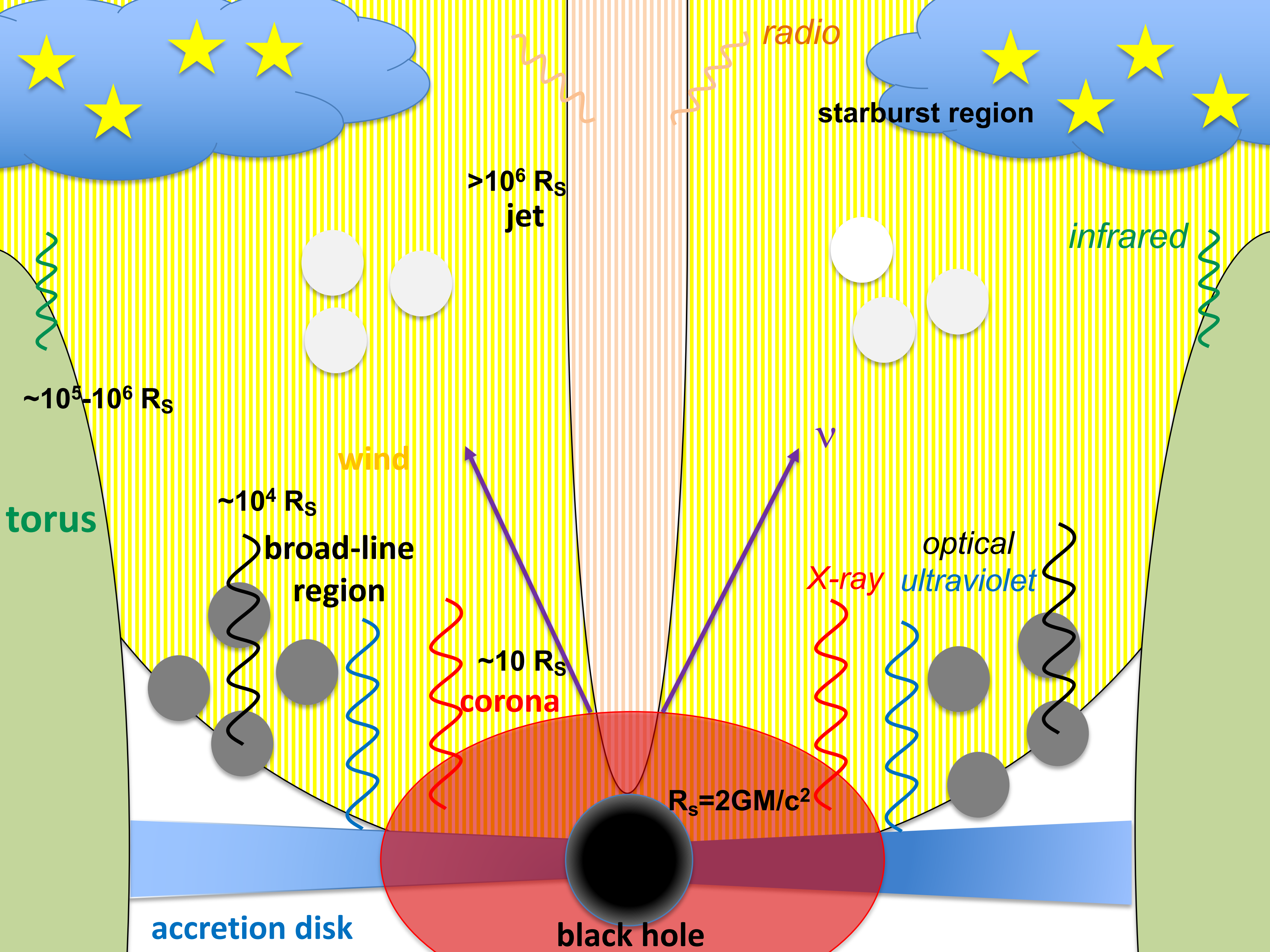


ASTRONOMY

Neutrinos unveil hidden galactic activities

By Kohta Murase[1,2,3]

An obscured supermassive black hole may be producing high-energy cosmic neutrinos



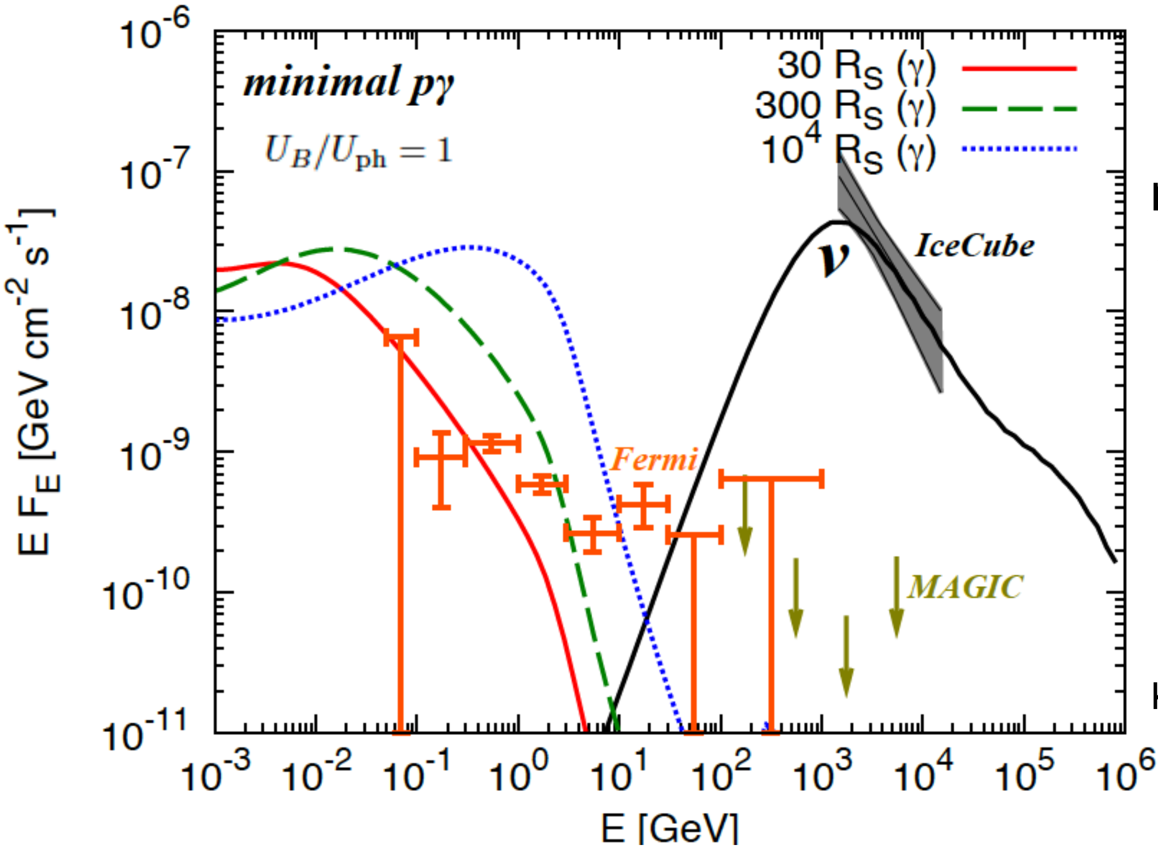
radio
starburst region
>10^6 R_S
jet
infrared
~10^5-10^6 R_S
ν
wind
~10^4 R_S
torus
broad-line
region
optical
X-ray
ultraviolet
~10 R_S
corona
R_S=2GM/c^2
accretion disk
black hole

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 < (10-30) R_S

(BSM applications (e.g., Herrera & KM 24) → constraints on $\sigma_{DM\text{-}p}$ at sub-GeV)

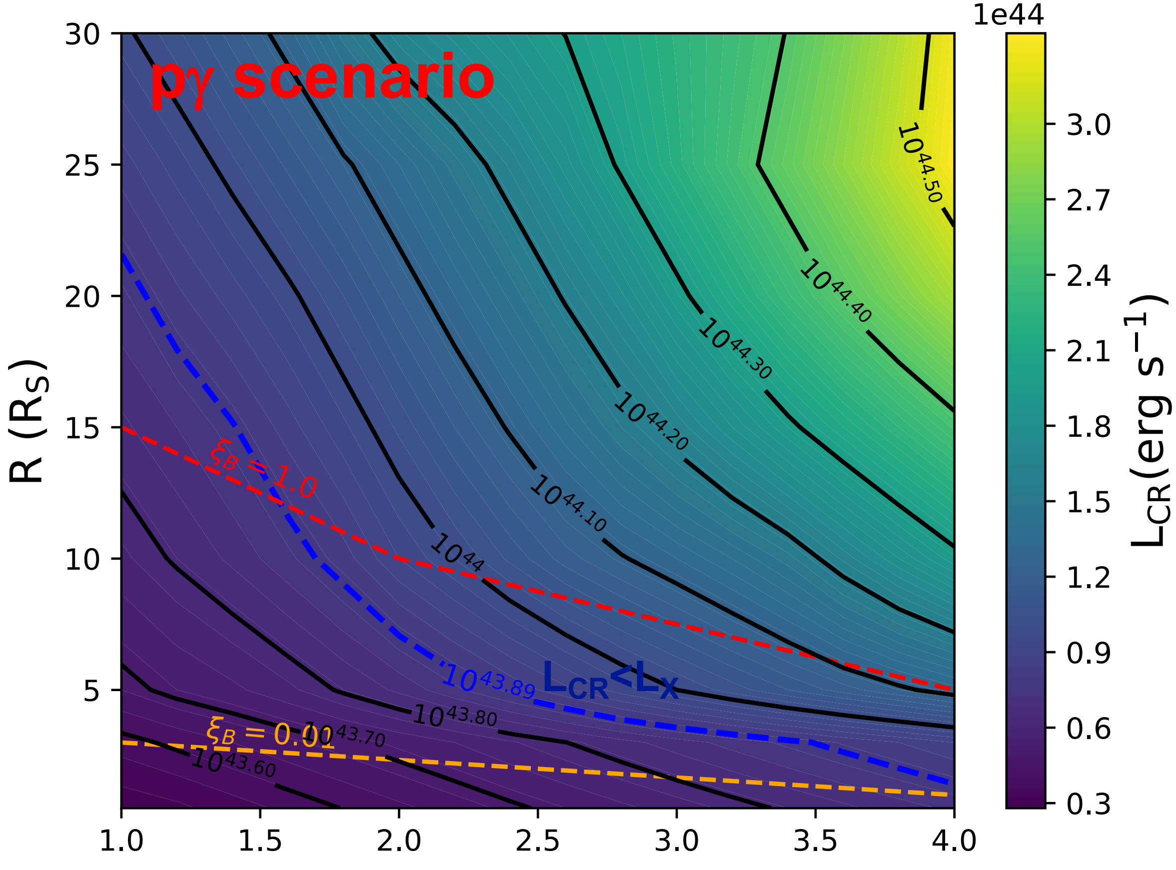
KM 22 ApJL, Das, Zhang & KM 24 ApJ

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

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

Updated Multimessenger Implications for ν Production Sites and Coronae

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



Das, Zhang & KM 24 ApJ

γ-ray constraint

$\xi_B = U_B/U_{ph}$ >~0.1
synchrotron cascade
→ **R <~ (5-15) R_S**

$\xi_B = U_B/U_{ph}$ <~0.1
inverse-Compton cascade
→ **R < R_{ISCO} unlikely**

CR energetics constraint

$L_{CR} < L_X$
→ **R <~ (1-20) R_S**

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

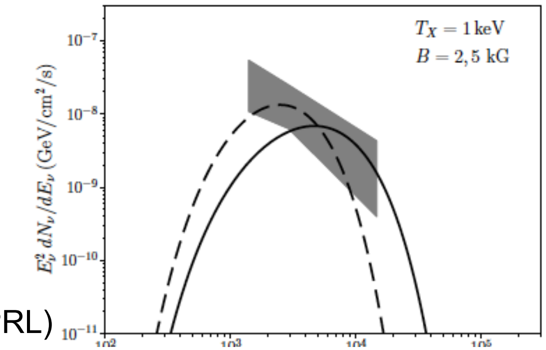
$$\beta = \frac{8\pi n_p k_B T_p}{B^2} \approx \frac{\tau_T G M_{\rm BH} m_p}{\sqrt{3}\zeta_e \sigma_T R^2 U_\gamma}\xi_B^{-1} \approx \left(\frac{\tau_T}{\sqrt{3}\zeta_e \lambda_{\rm Edd}}\right)\xi_B^{-1}$$

τ_T~0.1-1 for X-ray corona, λ_{Edd}~0.5
ξ_B >~ 0.1 leads to **β <~ 1**

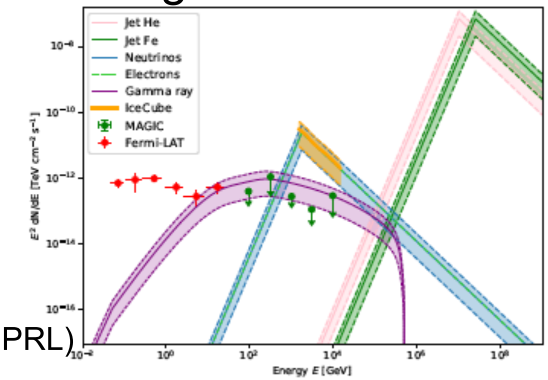
Multimessenger Implications for Neutrino Production Mechanisms

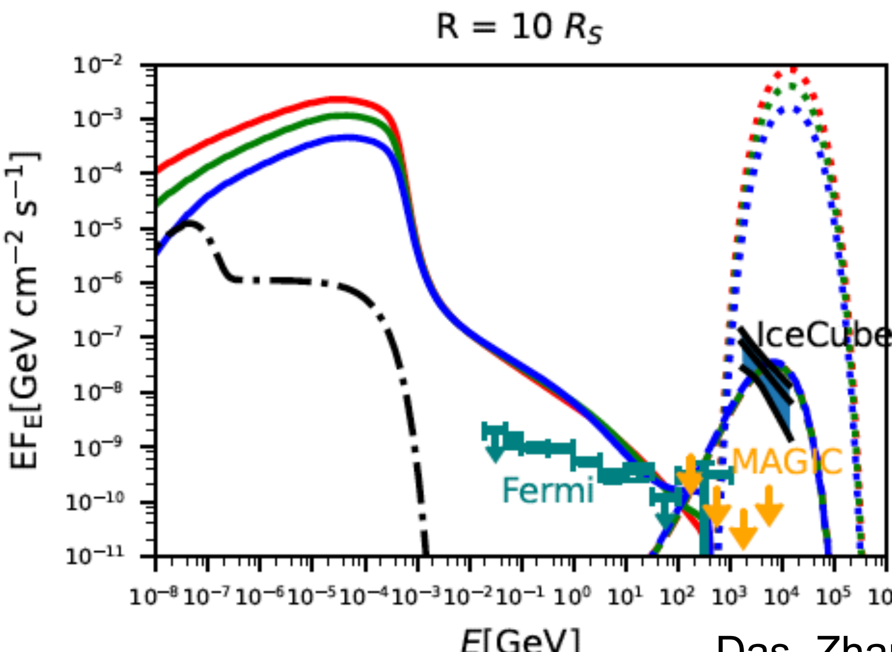
- Multimessenger connection is robust and must be considered
- Exotic models are excluded if relevant processes are consistently included
- Also unlikely by the energetics requirement: $L_{CR} < L_{bol} \sim L_{Edd} \sim 10^{45}$ erg/s

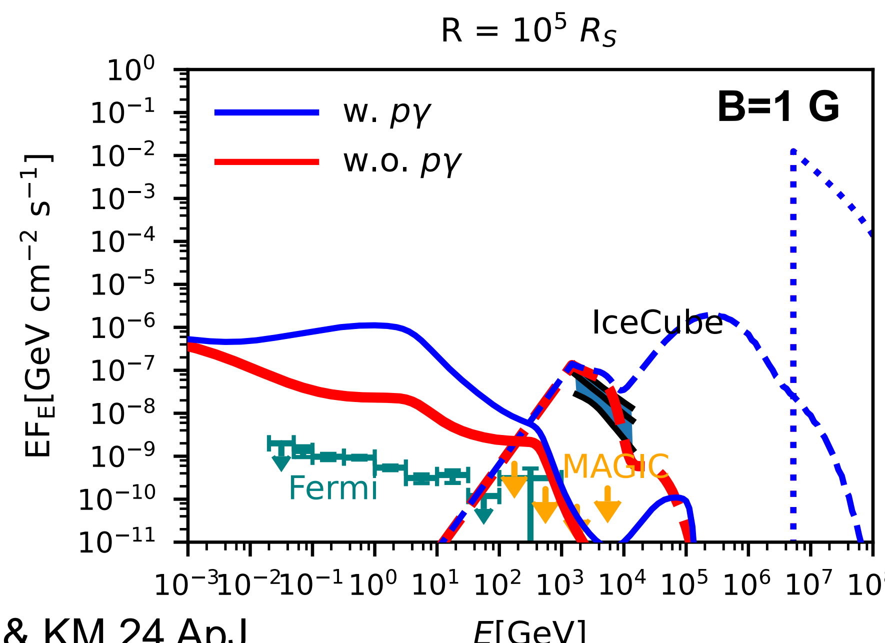
Neutrinos from $\gamma\gamma \rightarrow \mu^+\mu^-$
(Hooper & Plant 23 PRL)



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







Das, Zhang & KM 24 ApJ

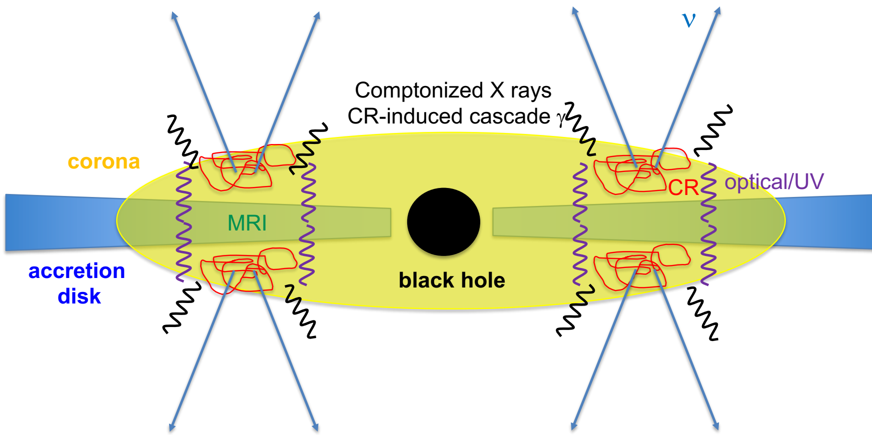
Neutrino Production Models

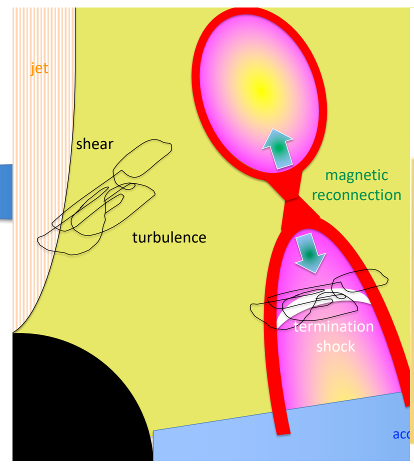
$$p+\gamma \rightarrow N\pi + X$$

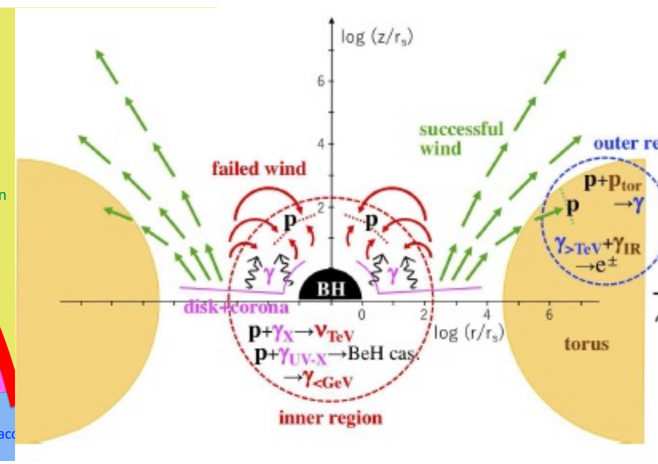
$$p+p \rightarrow N\pi + X$$

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

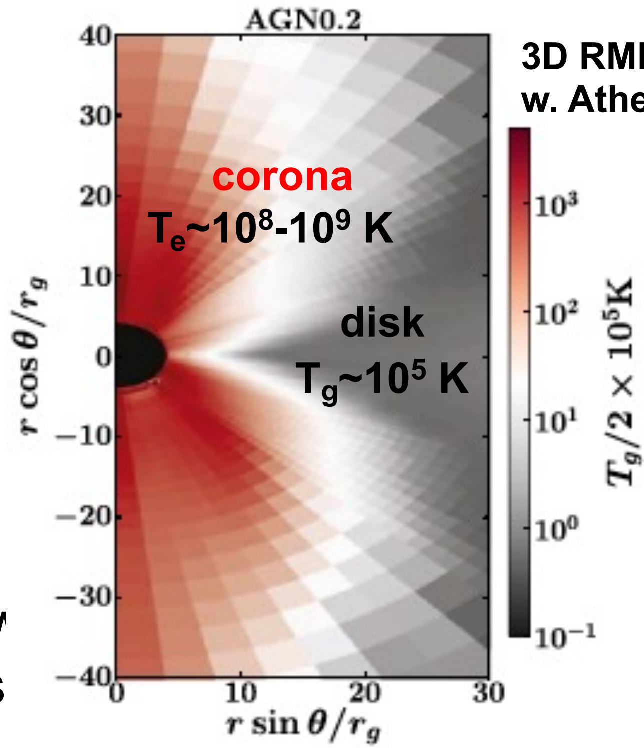
$\beta=P_g/P_B$ < 0.1-1 → B > 10^3 G
L_{CR} <~ L_X <~ L_B (turbulent)

shocks

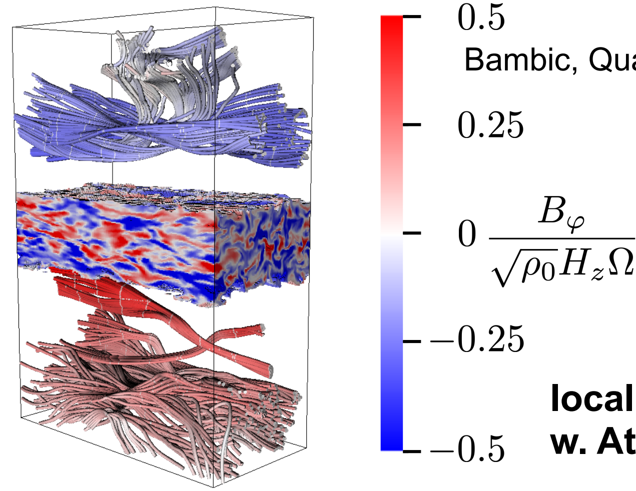
submm → B~10-100 G
$\beta=P_g/P_B$ >~ 100
L_B, L_{CR} <~ L_X

Strongly Magnetized, Collisionless, Turbulent Coronae

Jiang, Blaes, Stone & Davis 19 ApJ see also Liska+ 22 ApJ



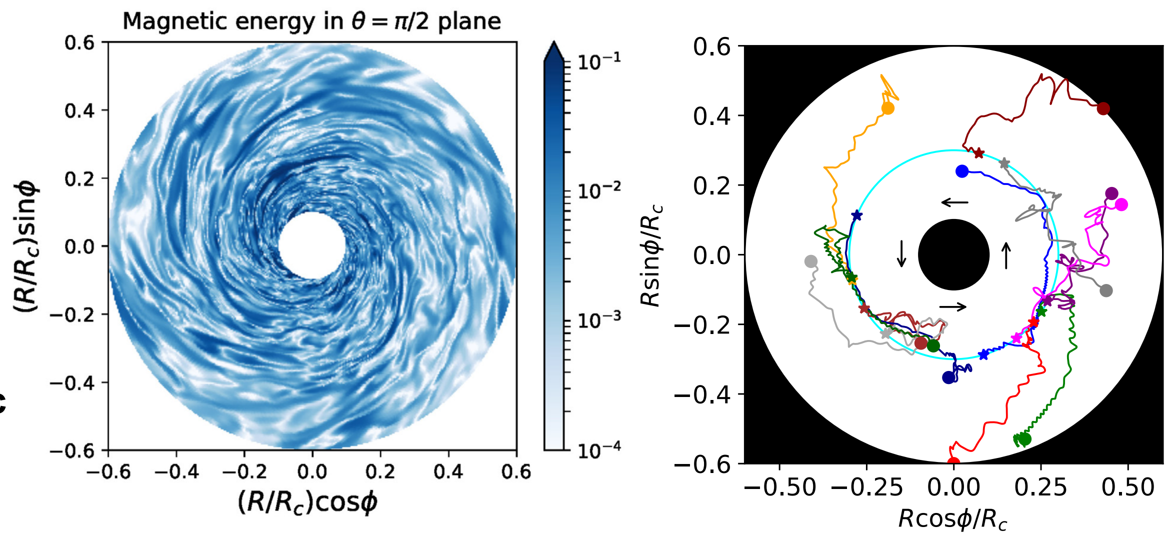
3D RMHD simulation w. Athena++



Bambic, Quataert & Kunz 23 MNRAS

local MHD simulation w. Athena++

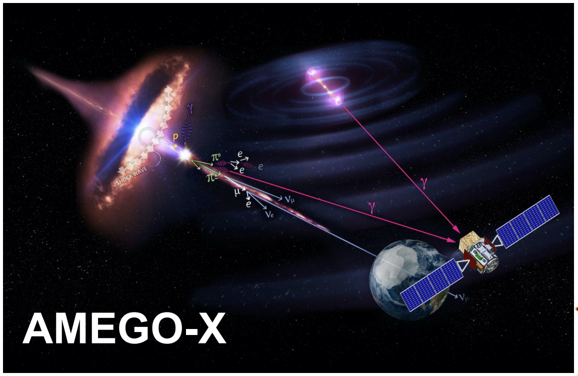
Kimura, Tomida & KM 19 MNRAS (see also Sun & Bai 21 MNRAS)



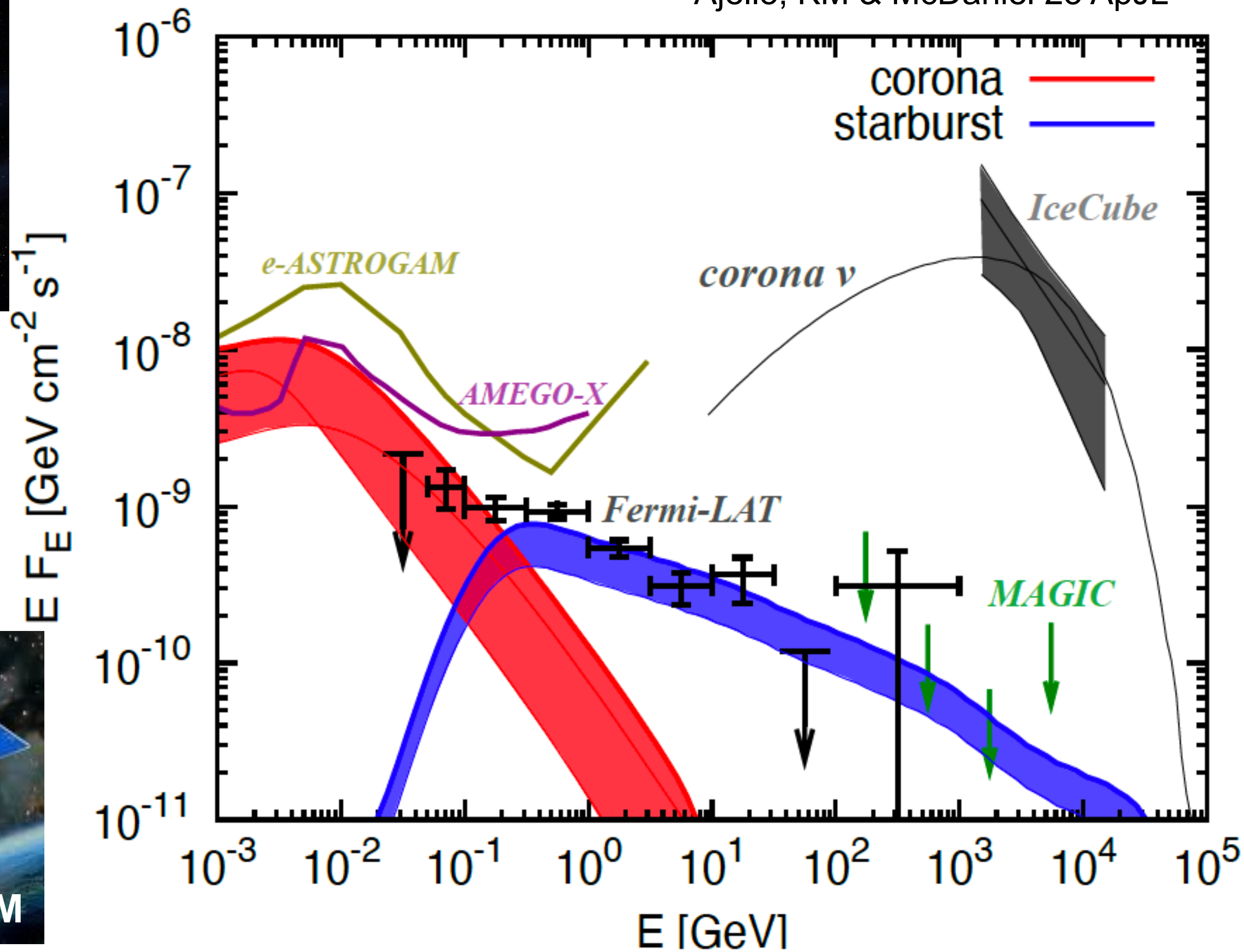
Test-particle simulations of stochastic acceleration based on 3D global MHD

High-energy neutrinos now meet the frontier of astroplasma physics

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



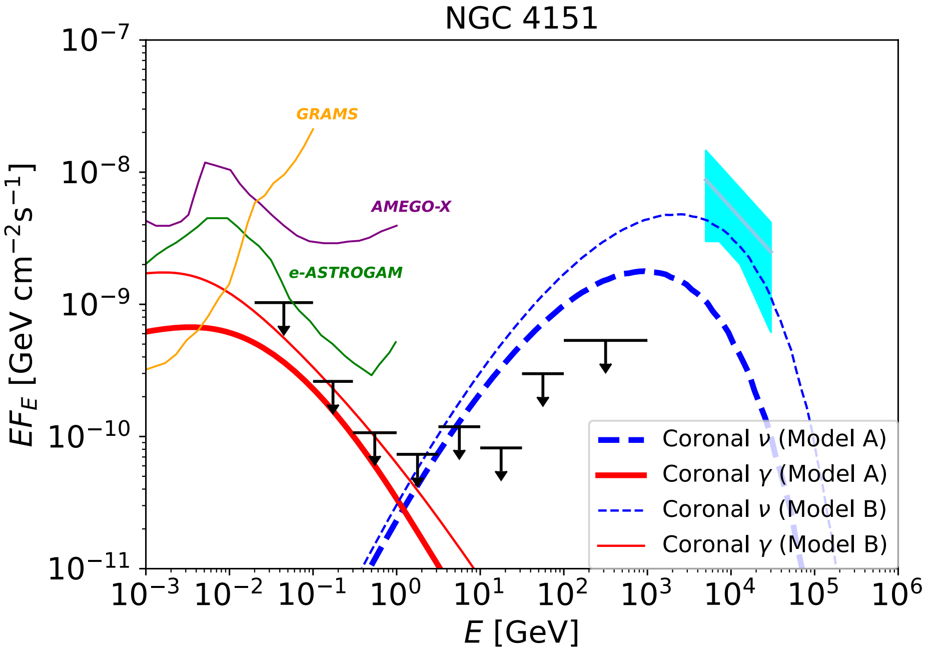
Ajello, KM & McDaniel 23 ApJL

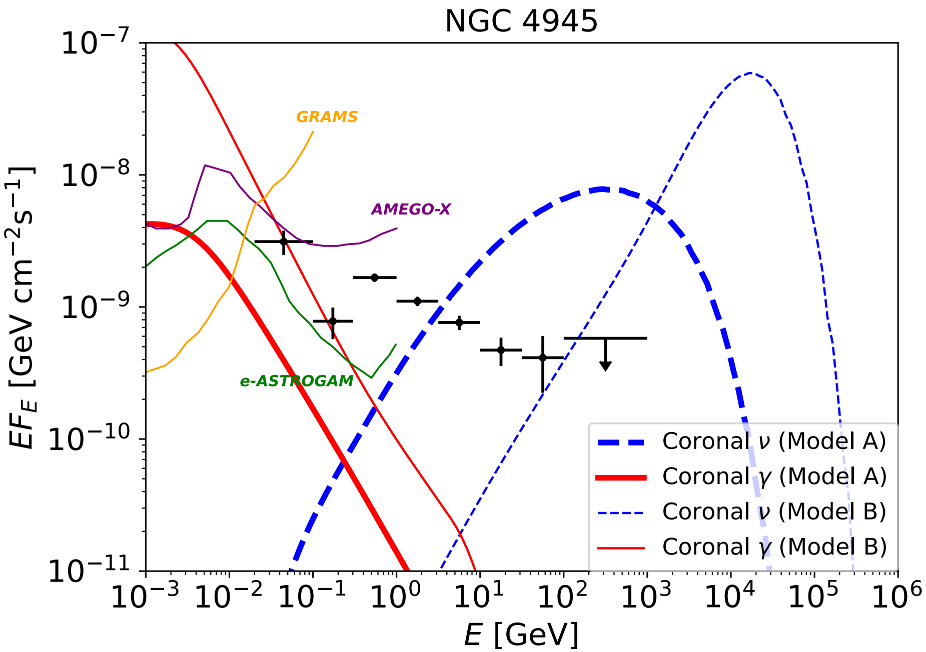


- Corona model prediction: cascade γ rays should appear in the MeV range
- Fermi γ-ray observation: sub-GeV "excess" over the starburst component

Other AGNs?

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



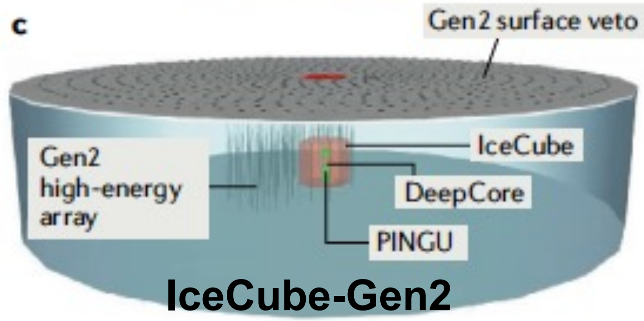


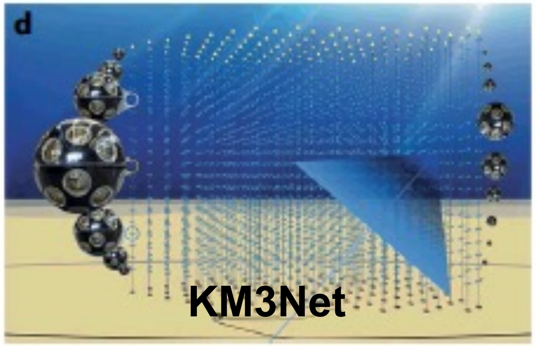
Model A: same as NGC 1068
Model B: P_{CR}/P_{vir}=8%

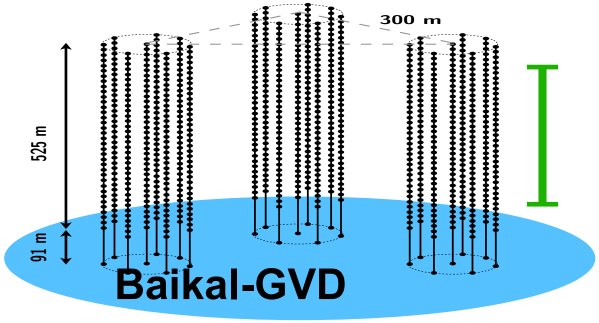
KM, Karwin, Kimura, Ajello & Buson 24 ApJL

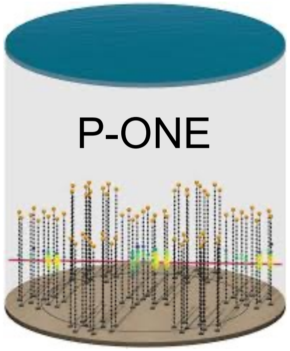
Bright Future (w. Some Patience)

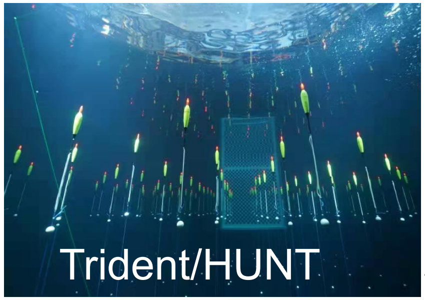
AMEGO-X

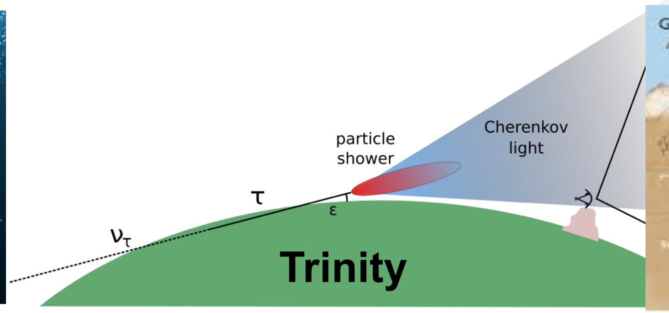


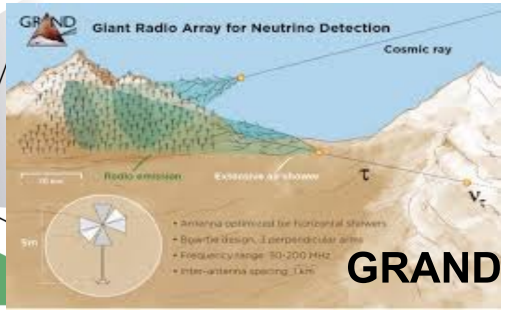


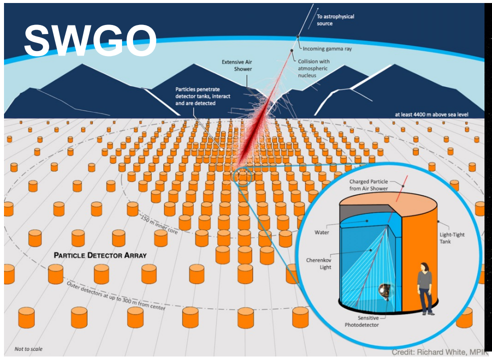












More multimessenger data in the next decade will enable us to test the proposed models

Summary

Success of multimessenger approaches to high-energy ν sources

Multimessenger quests for the origin of high-energy cosmic neutrinos

- Galactic: multimessenger connection is now observed
  supporting the hadronic origin of the Galactic diffuse γ-ray flux
  → interplay w. further TeV-PeV γ-ray observations

- Extragalactic: multimessenger connection requires γ-ray hidden ν sources
  AGN (jet-quiet): promising as primary sources of the all-sky neutrino flux
  Prediction: NGC 1068 is the brightest and NGC 4151 is the
  NGC 1068: evidence of a hidden ν source **(need more statistics)**
  νs should be produced within 10-30 Schwarzschild radii
  → "unique" probe of non-thermal phenomena powered by black holes
  (theoretical studies w. state-of-art simulations)
  testable w. planned MeV γ-ray and ν detectors

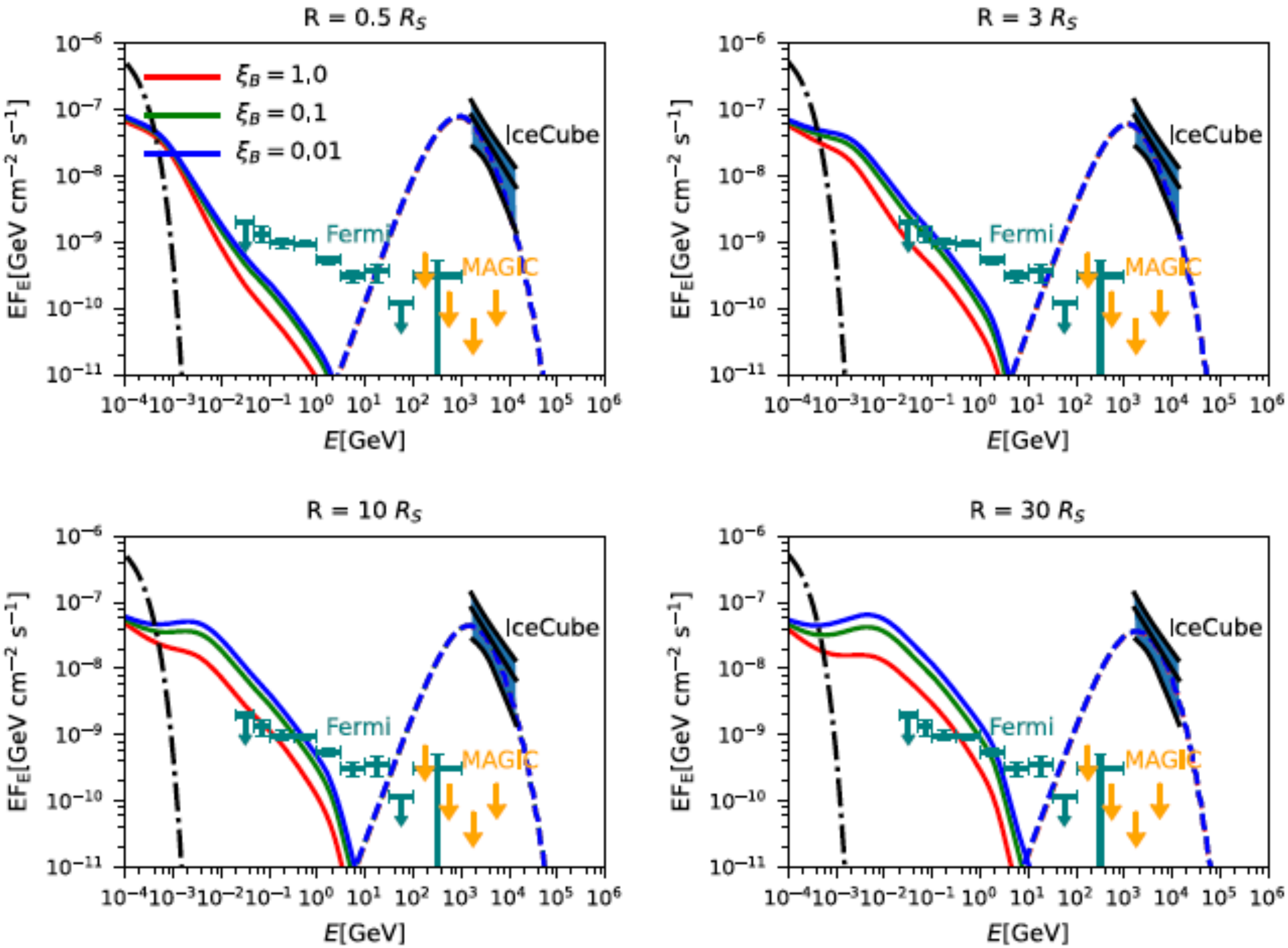
High-energy multimessenger transients

- Strategic multimessenger searches in the Einstein Probe and Vera Rubin era

Thank you very much!

Updated Fermi Analysis & Impacts of Magnetic Fields

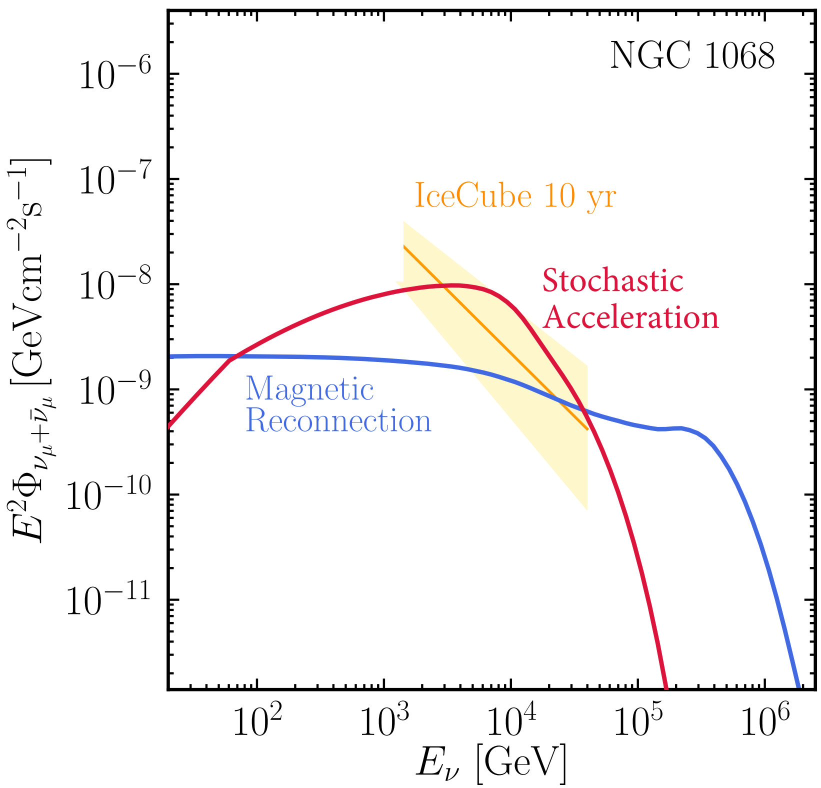
Das, Zhang & KM 24 ApJ (see Ajello, KM & McDaniel 23 ApJL for updated Fermi-LAT analysis)

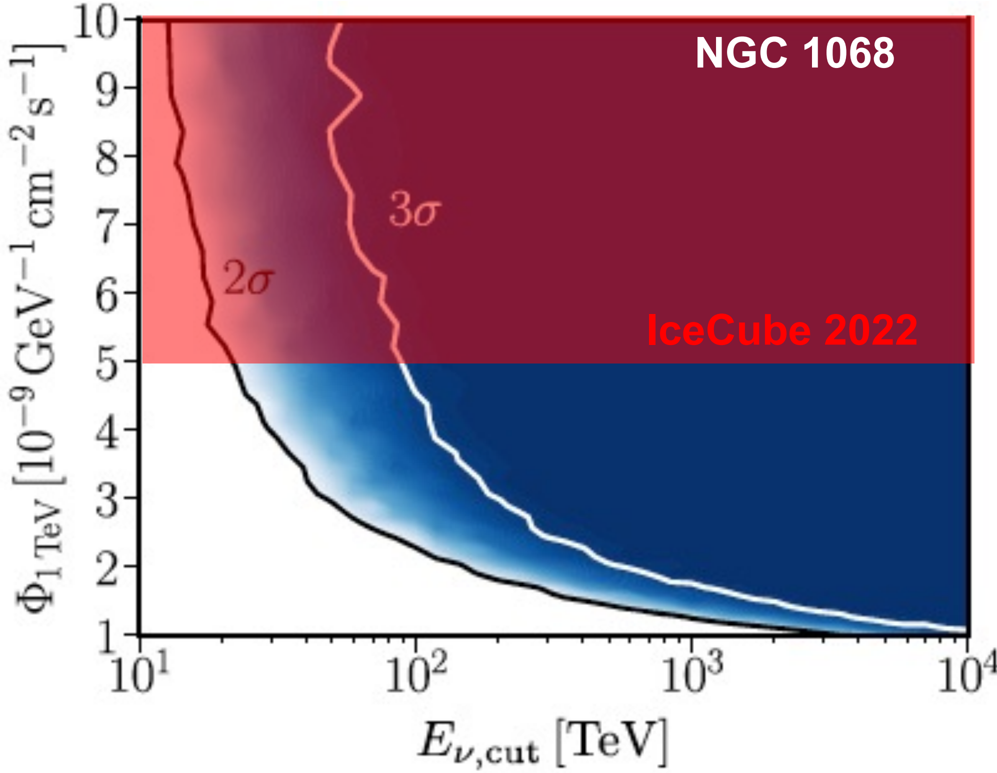


magnetization $\xi_B = U_B/U_{ph}$ (cf. corona model: $\xi_B \sim 1$, shock model: ξ_B <~ 0.01)

Neutrinos Can Probe Particle Acceleration in Coronae

Kheirandish, KM & Kimura 21 ApJ



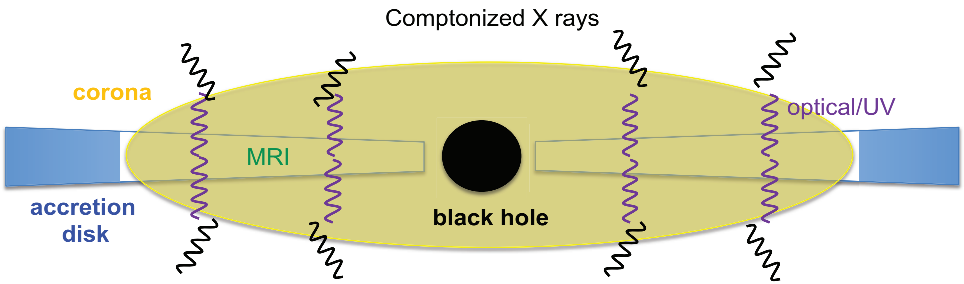


Constraints on E_{cut} for E^{-2} spectrum

ε_ν^{max} < 20-30 TeV (ε_p^{max} < 1-1.5 PeV)

(Bohm diffusion is excluded for the accretion shock model)

Coronal Regions: Births and Deaths of Cosmic Rays

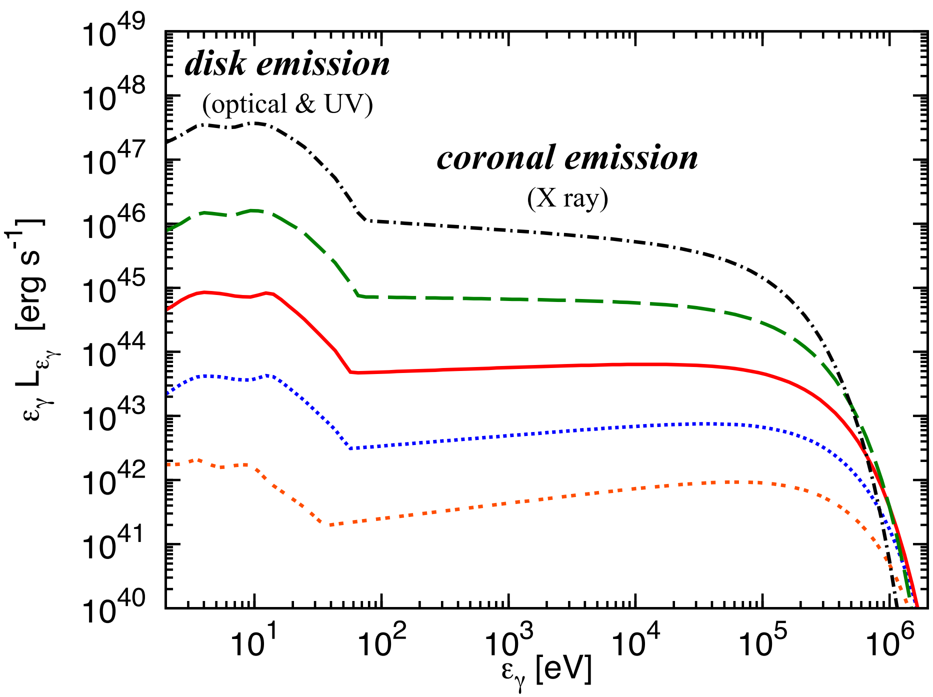


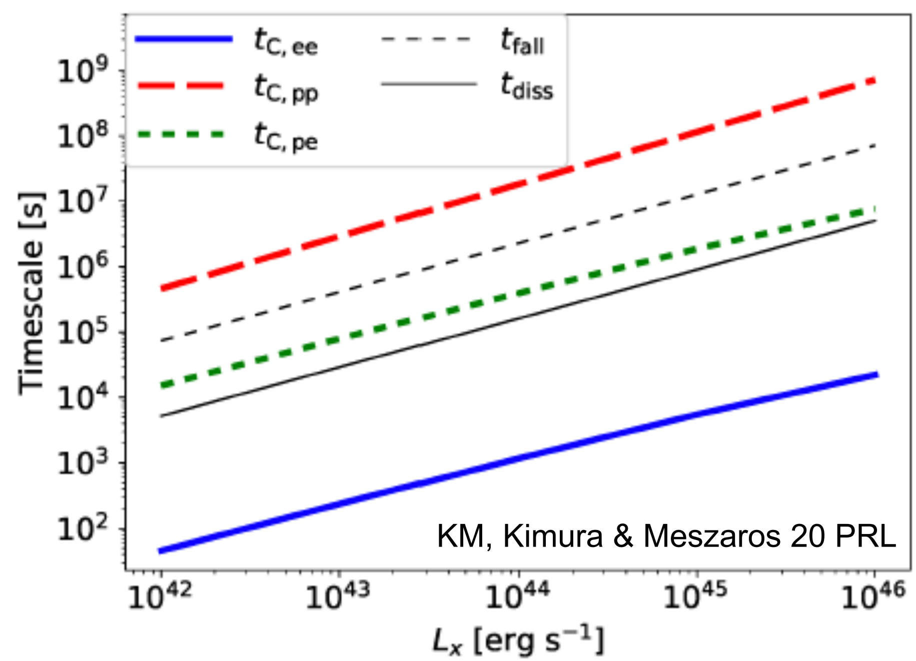
$T_p \sim T_{vir} \sim 10^{11}$-$10^{12}$ K @ R~10 R_S

$\beta = P_g/P_B$ < 0.1-1 (σ_p >~ 0.01)

→ **B > 10^3 G**

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





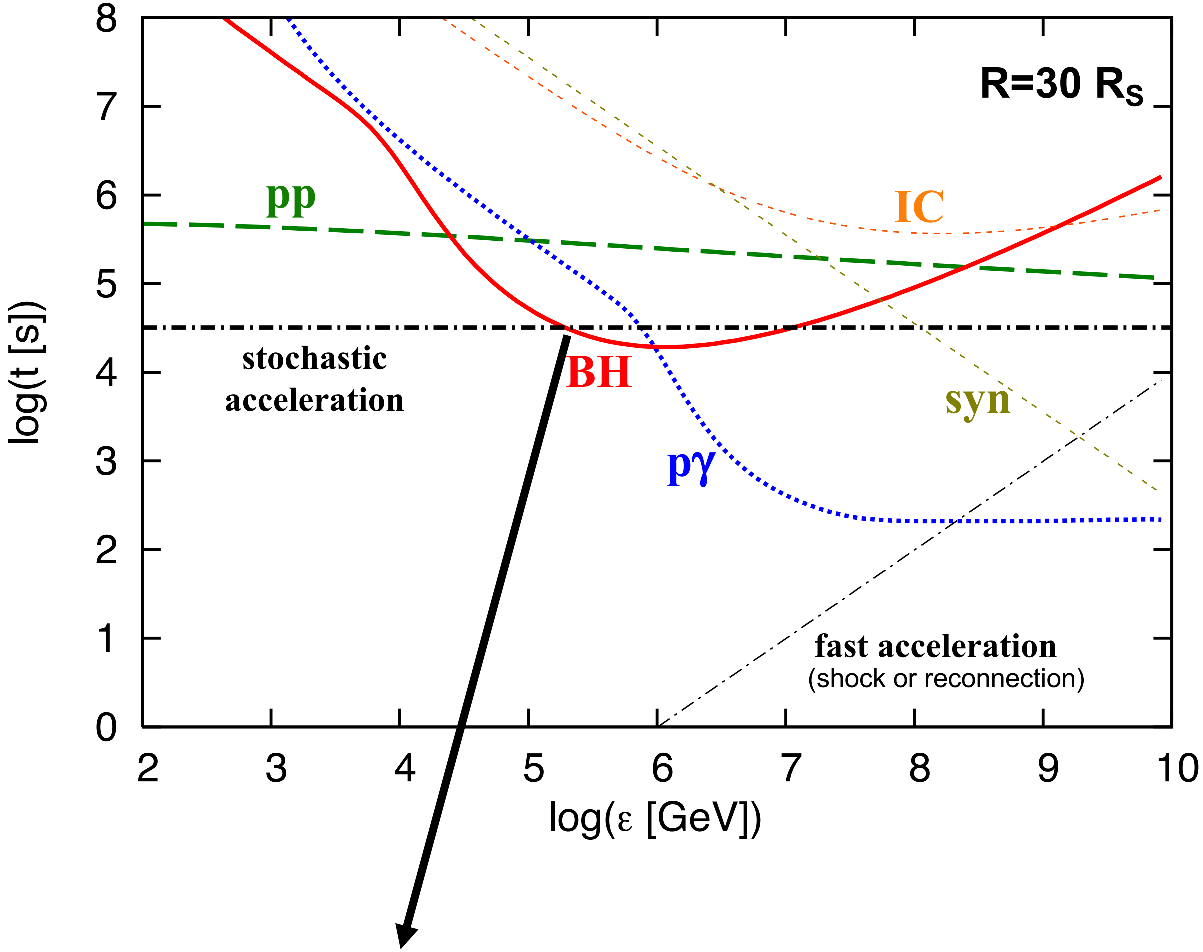
effective optical depth: both **f_{pp} & $f_{p\gamma}$ > 1**
("nearly calorimetric")

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

Particle Acceleration: Fast or Slow?

$p\gamma \rightarrow pe^+e^-$ (Bethe-Heitler process) is important for protons producing 1-10 TeV νs

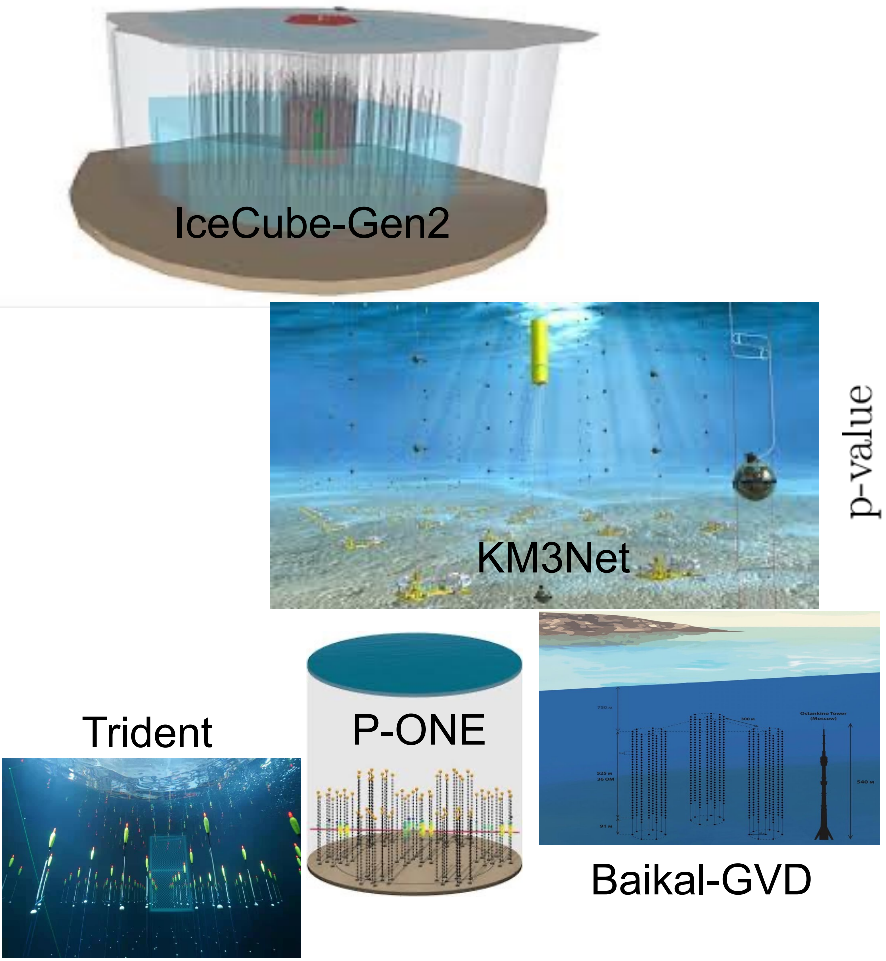
(KM, Kimura & Meszaros 20 PRL)

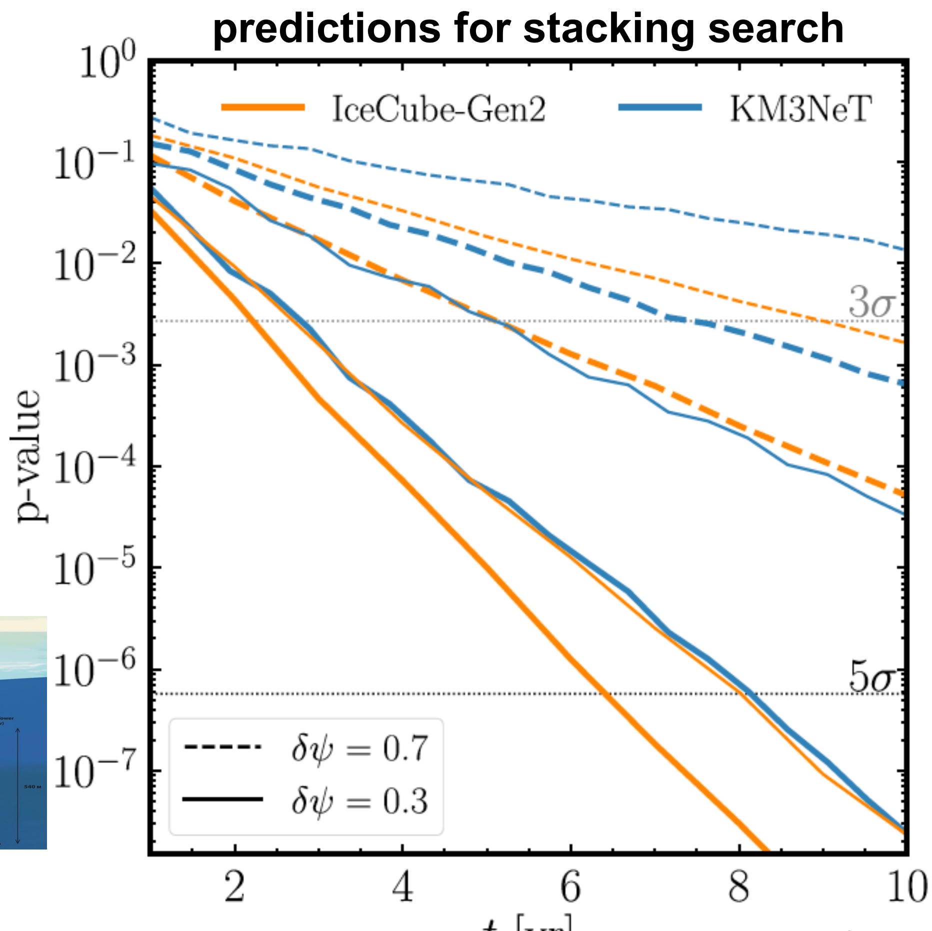


ε_p^{max} **~ 100 TeV** → ε_ν^{max} **~ 2 TeV** (consistent w. IceCube)

Further Tests with Neutrinos

- 2.6σ with 8 yr upgoing ν_μ events and IR-selected AGN (IceCube 22 PRD)
- Good news for KM3Net/Baikal-GVD/P-ONE: many bright AGN in south

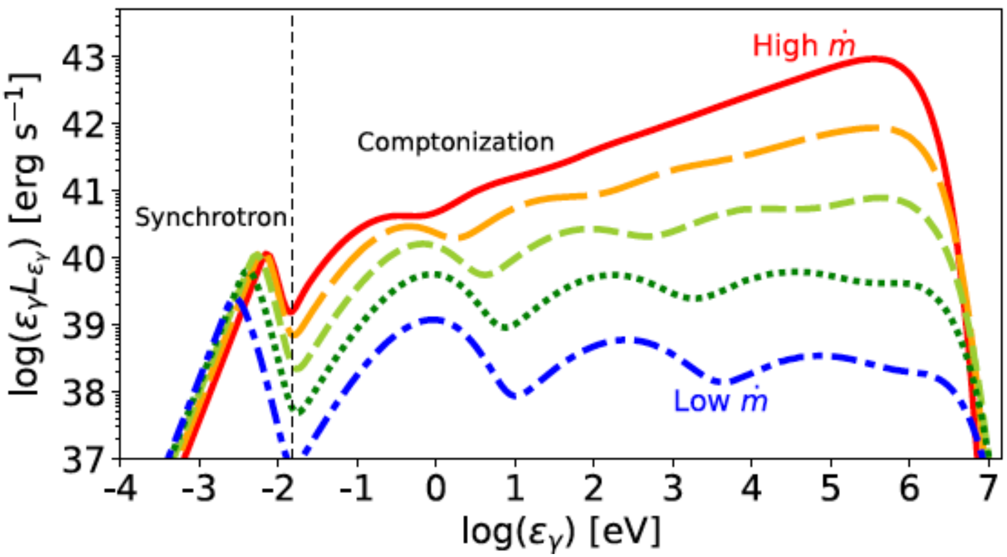




Kheirandish, KM & Kimura 21 ApJ

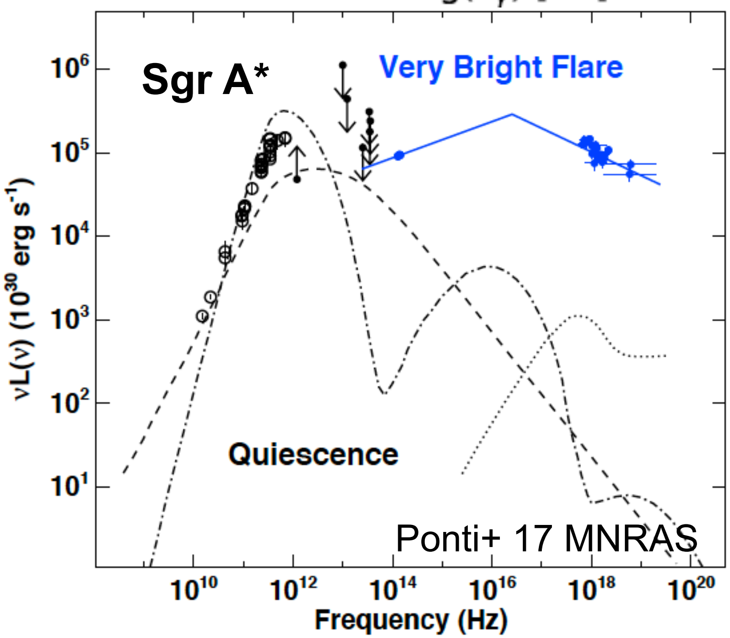
testable w. near-future data or by next-generation neutrino detectors

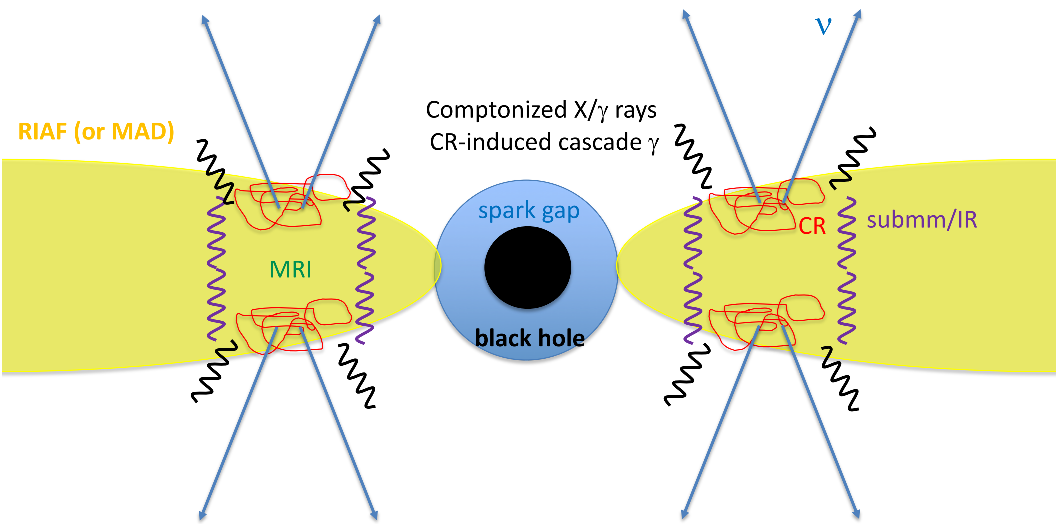
Radiative Inefficient Accretion Flows



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

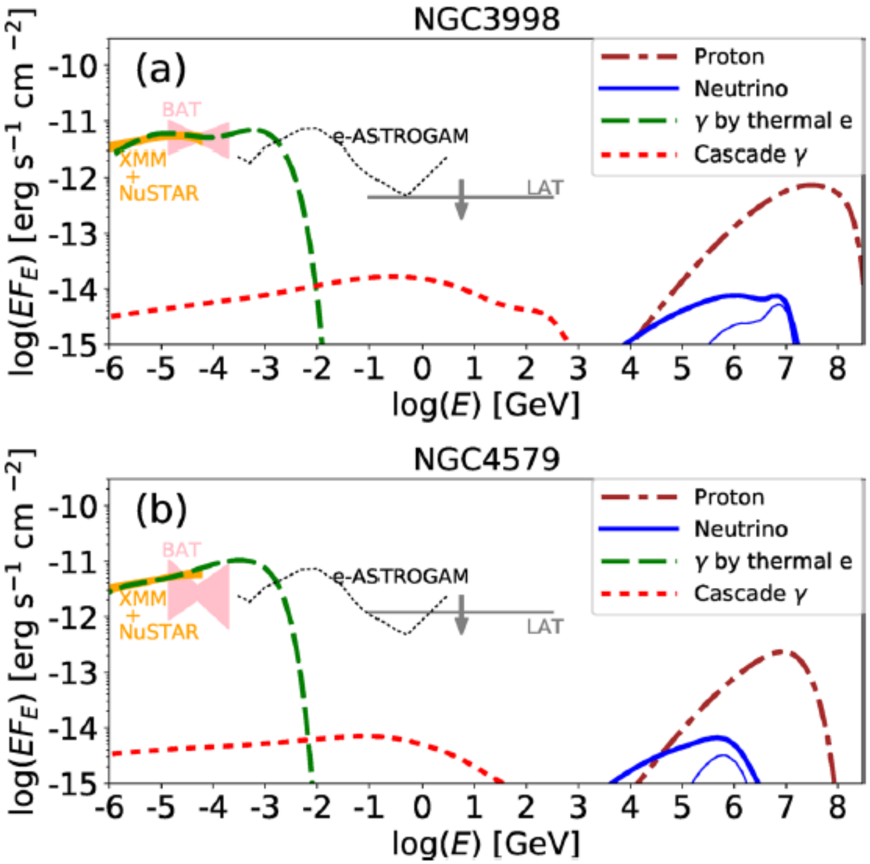
- RIAF for mdot<0.03
- Hot plasma
- Electrons are mostly thermal (collisional for electrons collisionless for protons)

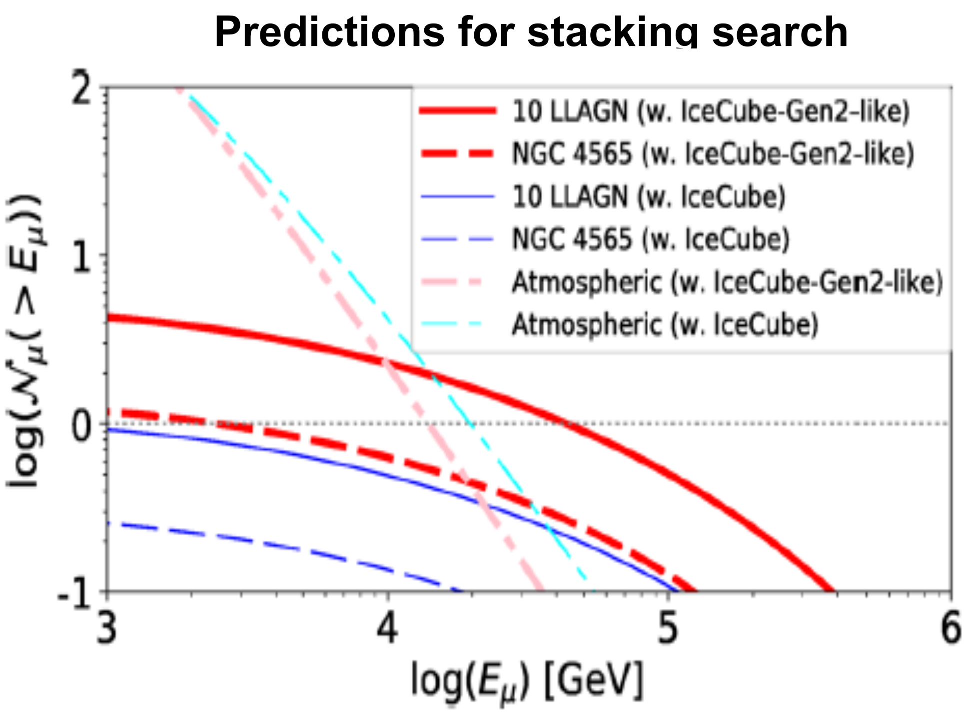




Detectability of Nearby Low-Luminosity AGN

Kimura, KM & Meszaros 21 Nature Comm.

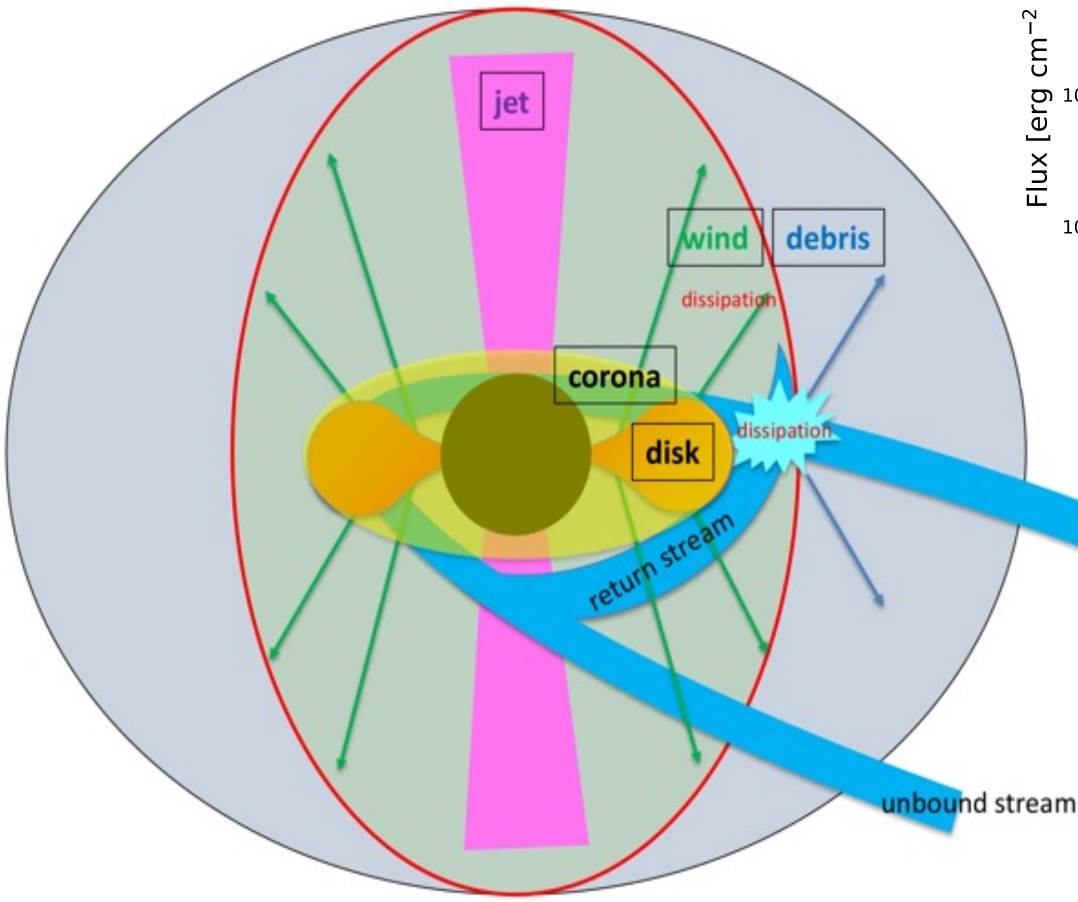




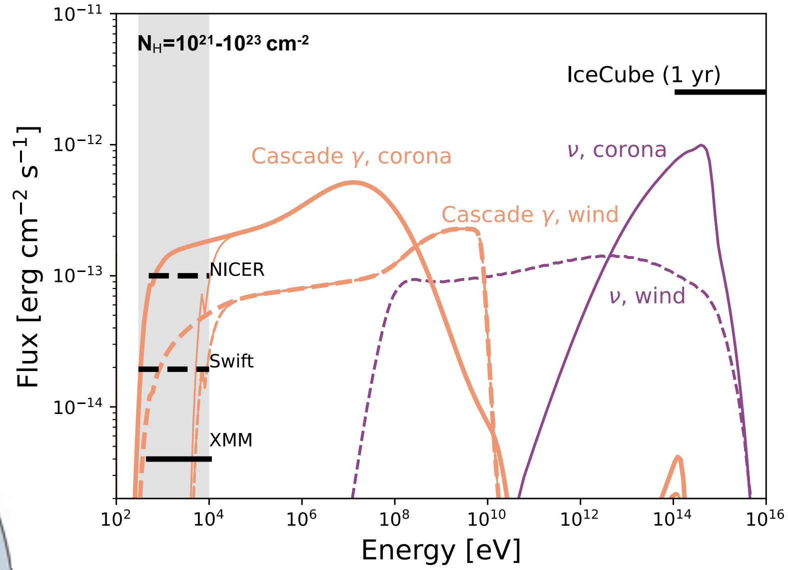
- Detection of MeV γ due to thermal electrons is promising (CR-induced cascade γ rays are difficult to observe)
- Nearby LL AGN can be seen by IceCube-Gen2/KM3Net

TDEs as High-Energy Multimessenger Transients

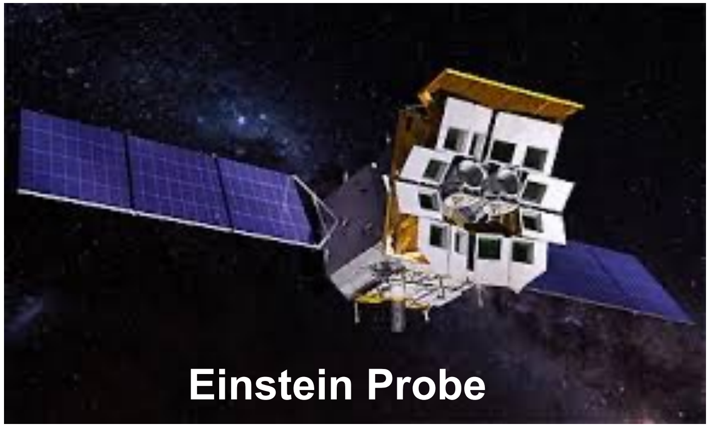
TDE and AGN νs could come from "common" mechanisms (disk-corona, hidden wind, hidden jet)



KM, Kimura, Zhang et al. 20 ApJ

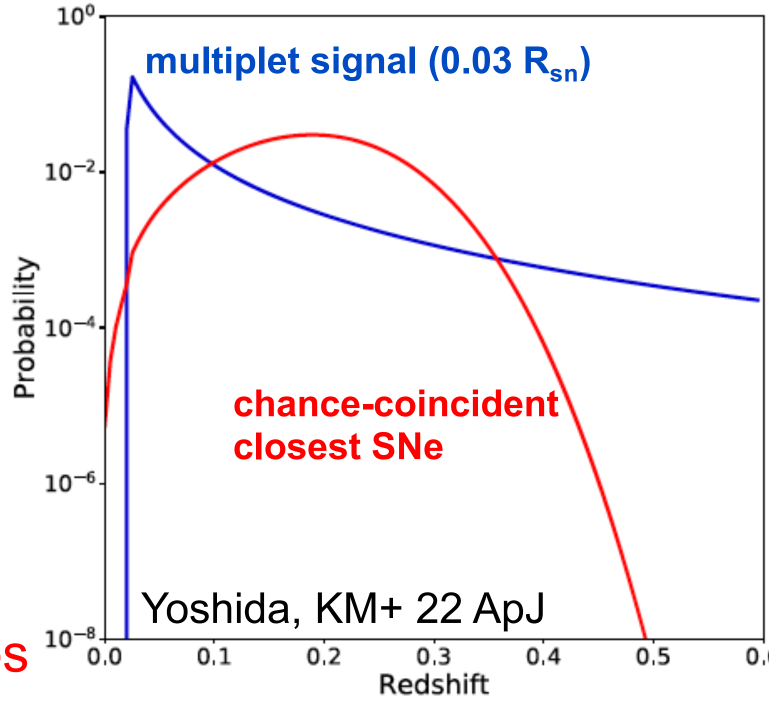


No Patience? Game Changing in ν Transient Searches



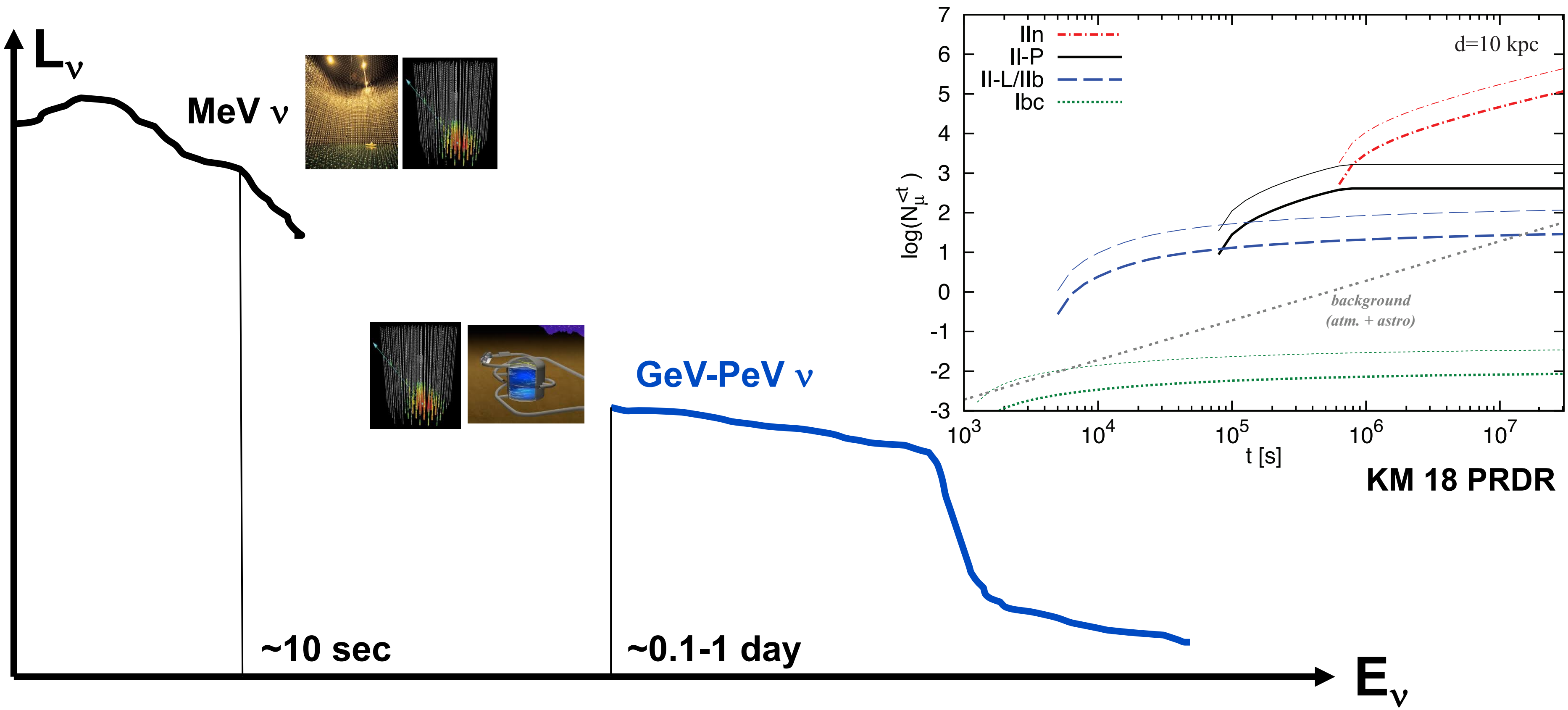
- Supernovae, tidal disruption events, low-luminosity gamma-ray bursts…
  (e.g., Stein+ 21 Nature Astronomy, Reusch+ KM 21 PRL)
- Testability of models have been limited by the number of detected transients

- Neutrino singlet followups would need spectroscopic information
- Neutrino multiplet followups
- Multimessenger alert (e.g., AMON) followups



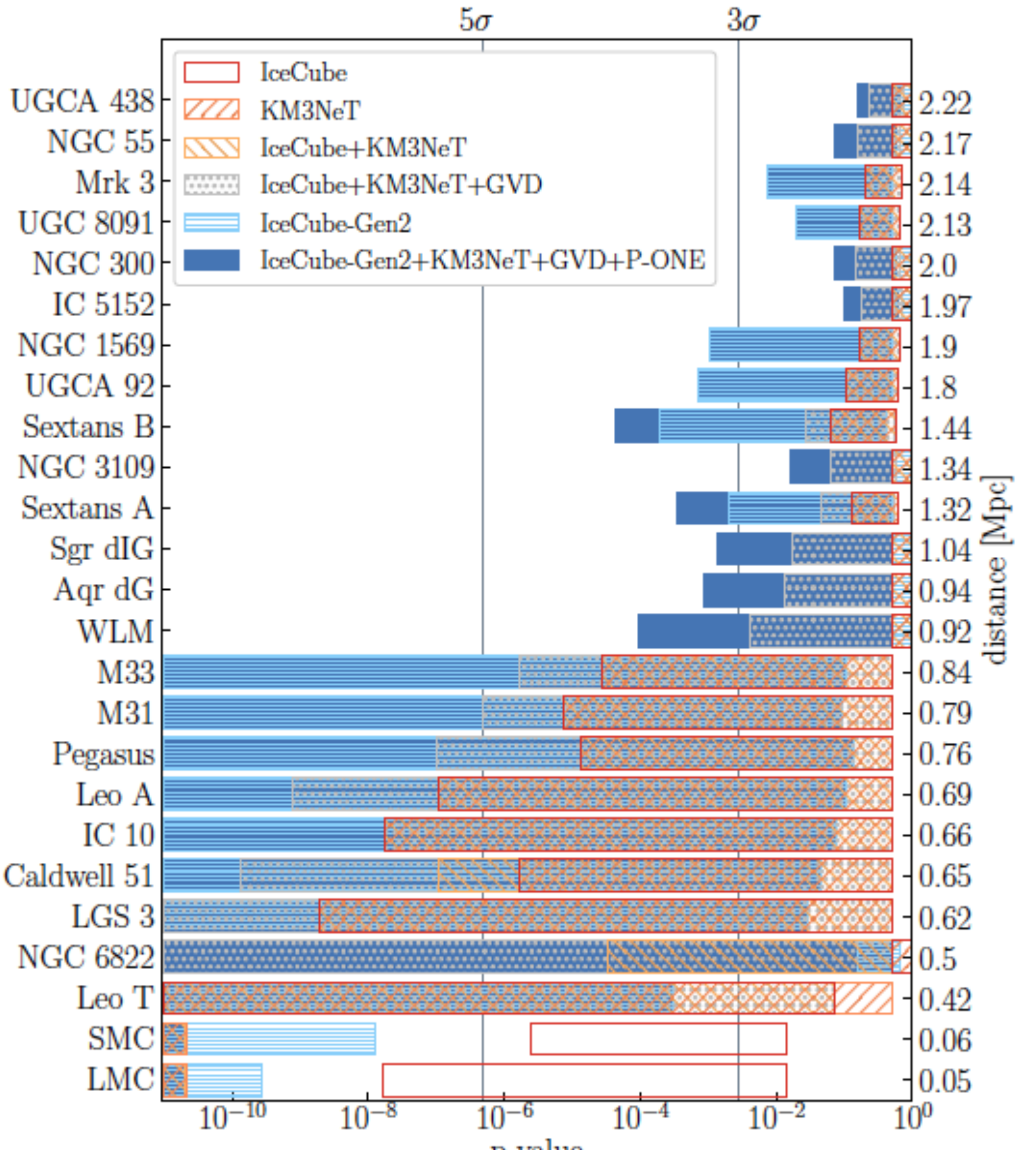
Promising ν Transients: Nearby Supernovae

- Enhanced circumstellar material: ubiquitous for supernova progenitors
- Type II: ~100-1000 events of TeV ν from the next Galactic SN
  ex. Betelgeuse: $\sim 10^3$-3×10^6 events, Eta Carinae: $\sim 10^5$-3×10^6 events
- SNe as "multi-messenger" & "multi-energy" neutrino source
- Real-time monitoring of CR ion acceleration & new physics tests



KM 18 PRDR

Detectability of Minibursts



Kheirandish & KM 23 ApJL

- CCSN rate enhancement in local galaxies (ex. Ando+ 05 PRL)
- Neutrino telescope networks are beneficial for nearby SNe at Mpc
- II-P: detectable up to ~3-4 Mpc
  IIn: detectable up to ~10 Mpc