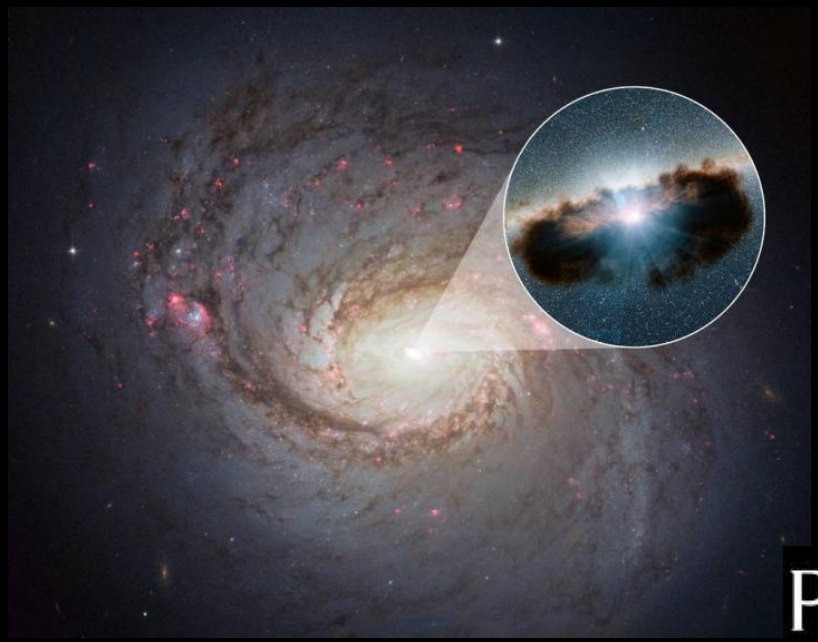
Multimessenger View of High-Energy Cosmic Neutrino Sources

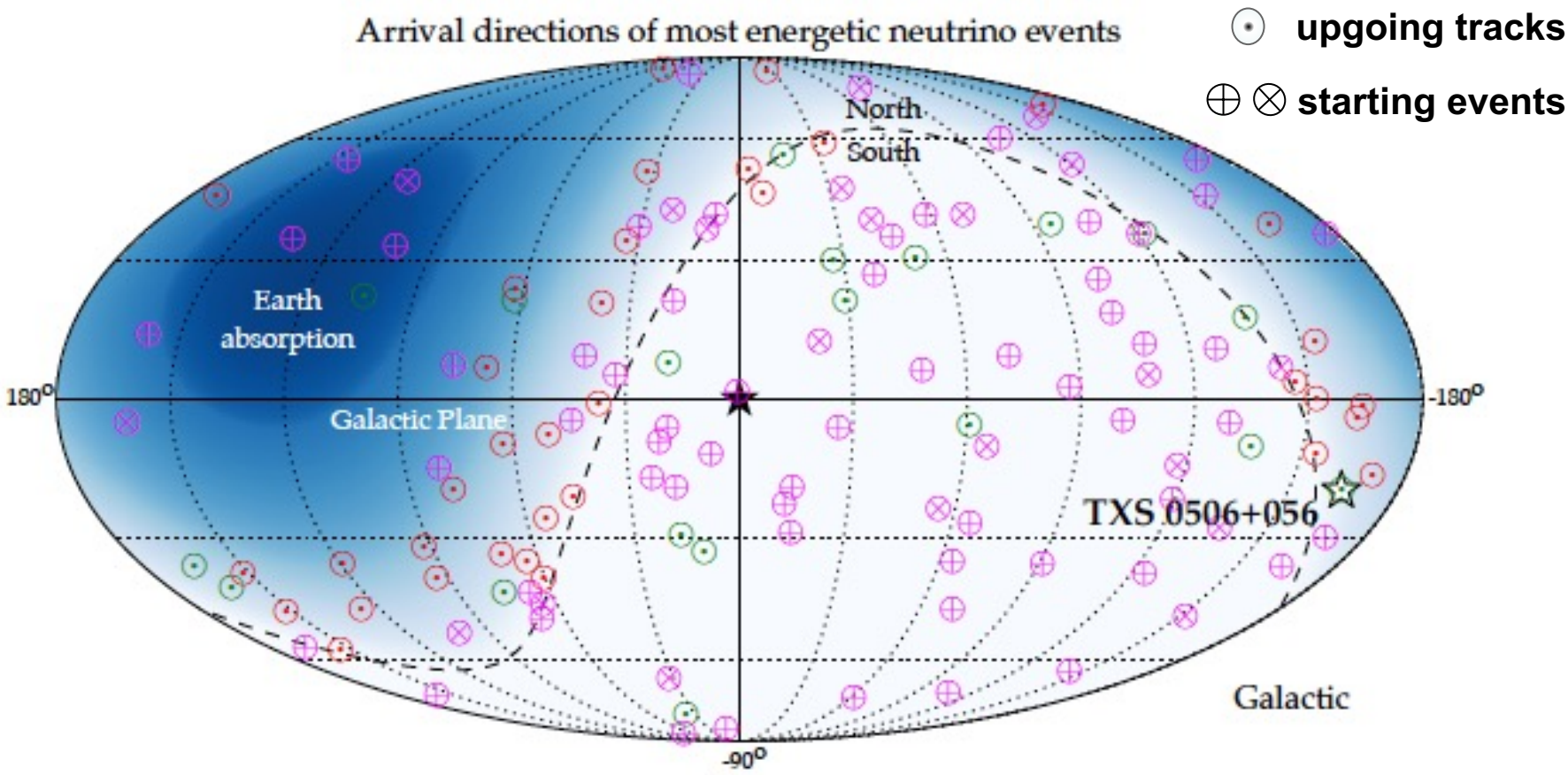


Kohta Murase (Penn State)

December 11

Texas Symposium in Shanghai

High-Energy Neutrino Sky

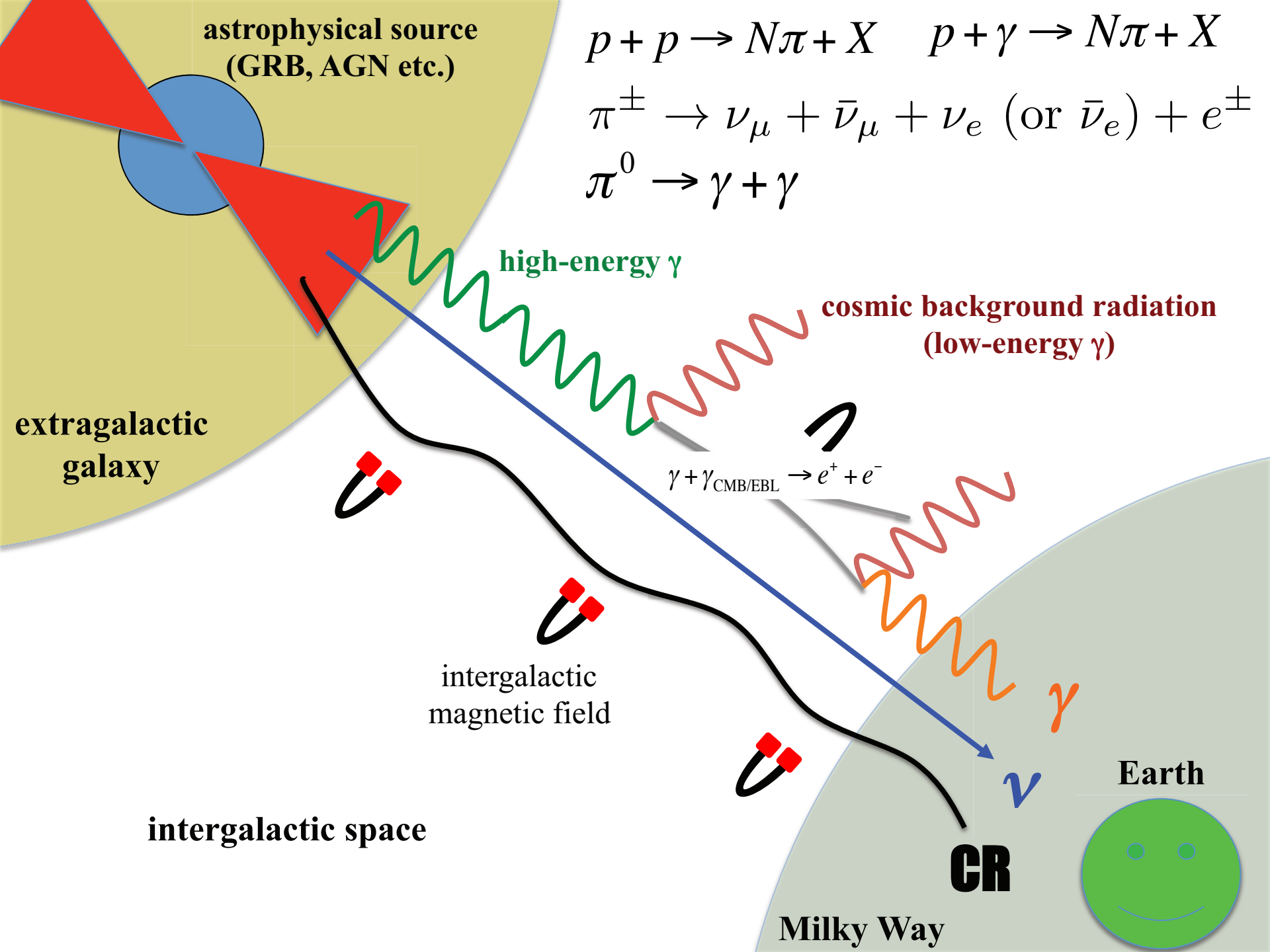


consistent w. isotropic distribution/extragalactic origins

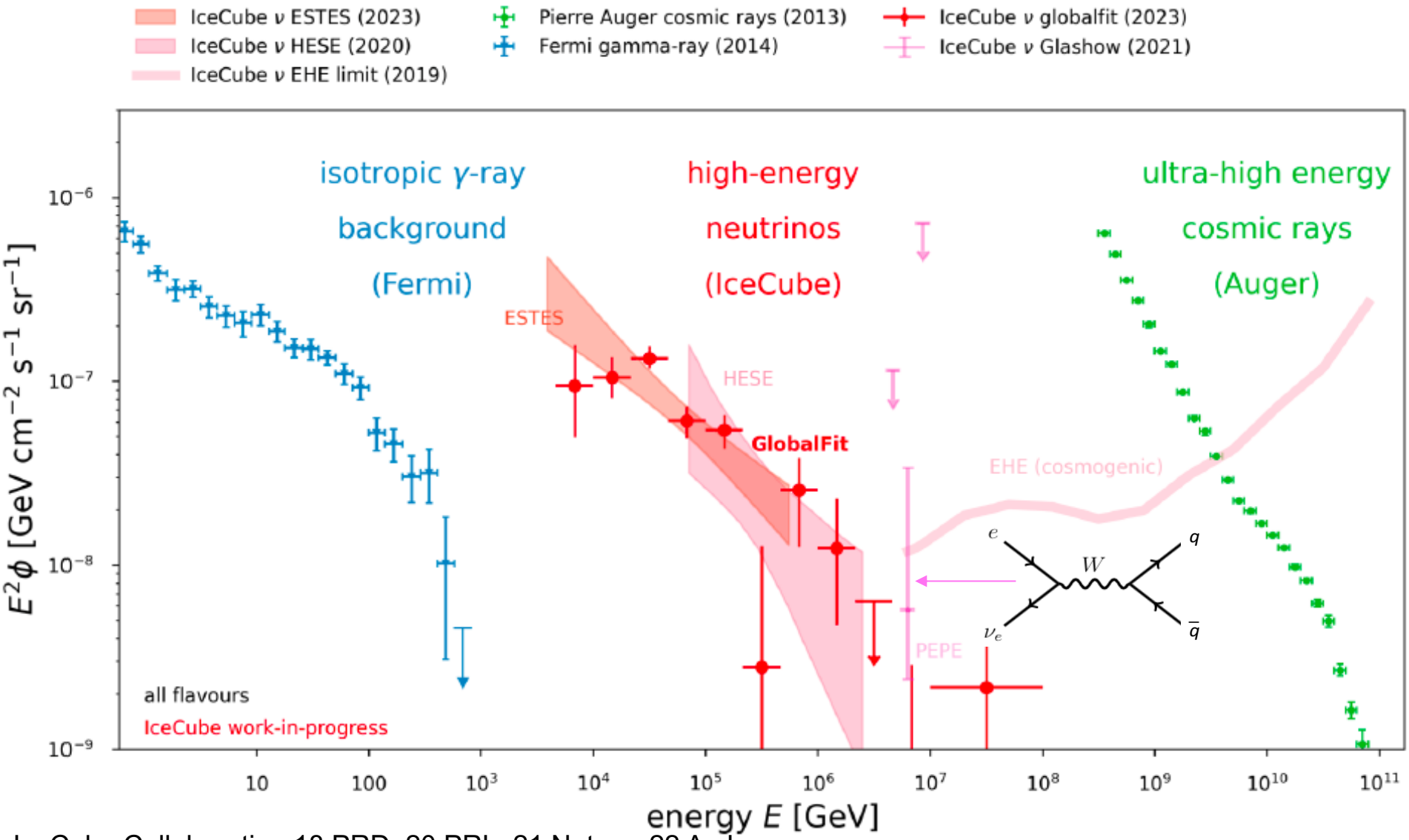
#Galactic contribution: ~10% (IceCube 23 Science)

Where do neutrinos mainly come from?

monster fishing!!


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

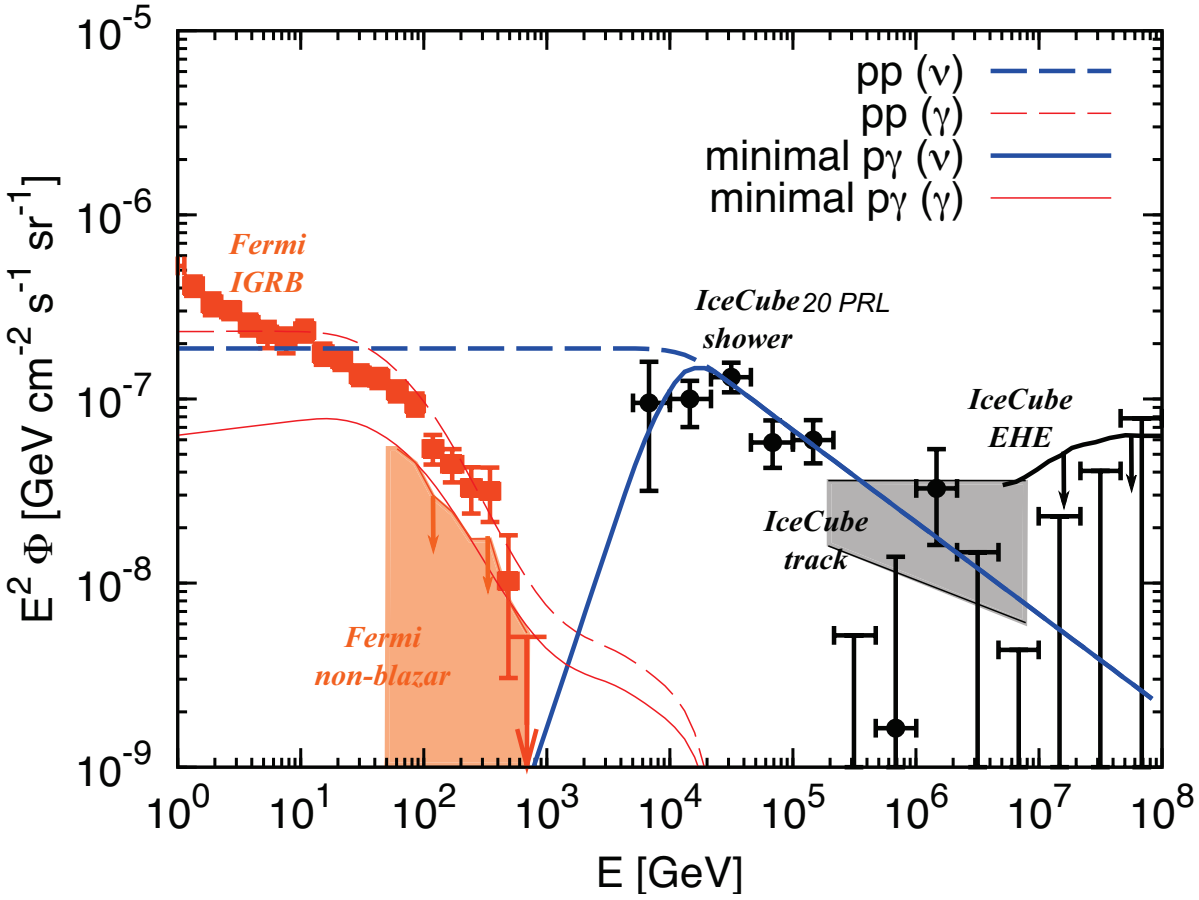
Updated All-Sky Neutrino Flux & Spectrum



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

General Implications of All-Sky ν and ν Fluxes

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



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

K=1 (pγ), K=2 (pp)

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

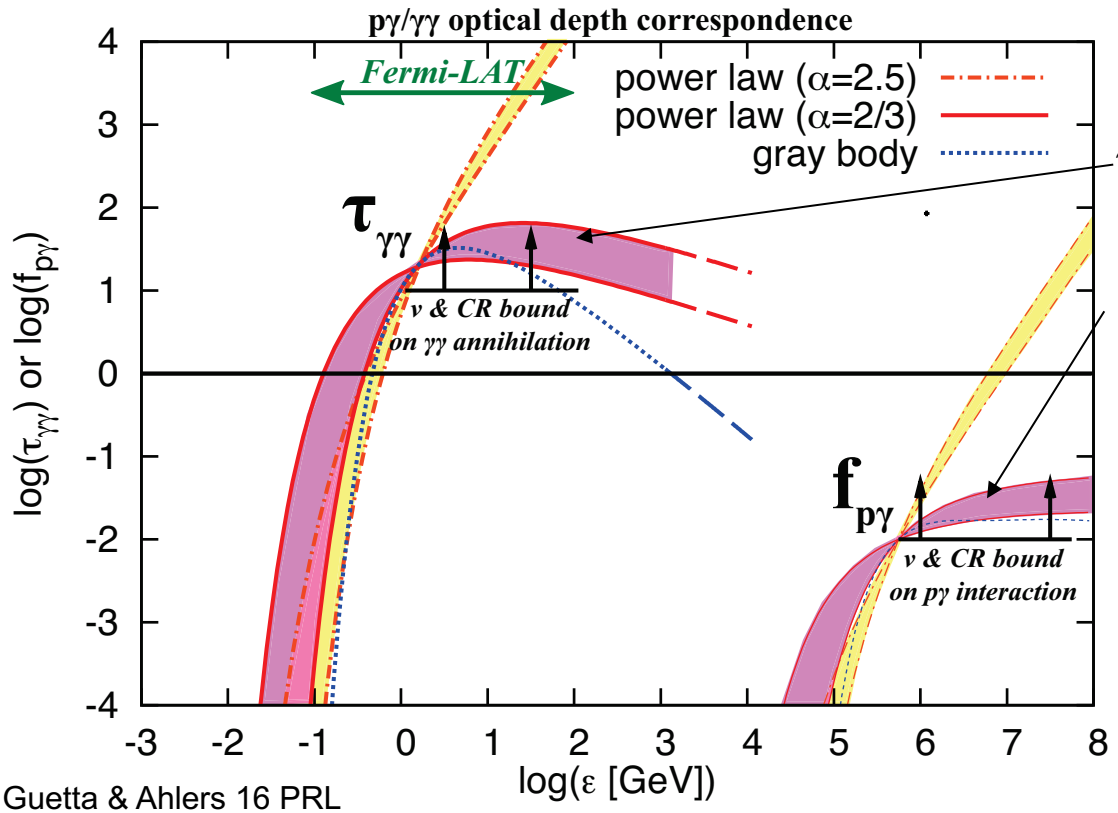
(ν data above 100 TeV can still be explained by γ-ray transparent sources)

Opacity Argument

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

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

implying that >TeV-PeV γ rays are cascaded down to GeV or lower energies



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

II

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

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

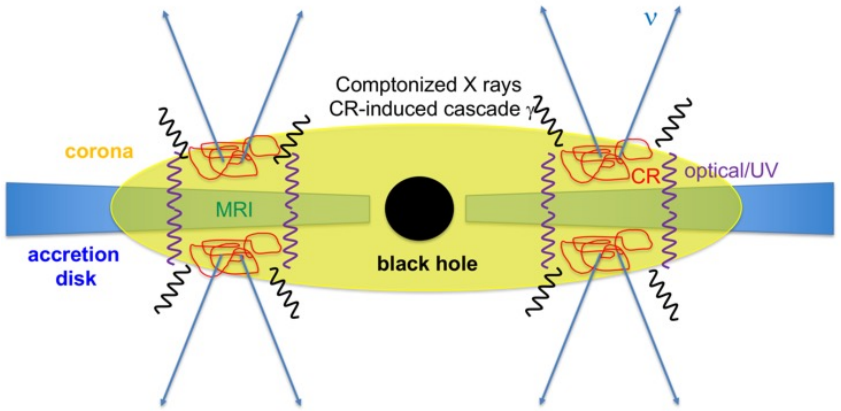
KM, Guetta & Ahlers 16 PRL

Prediction of Hidden Neutrino Sources

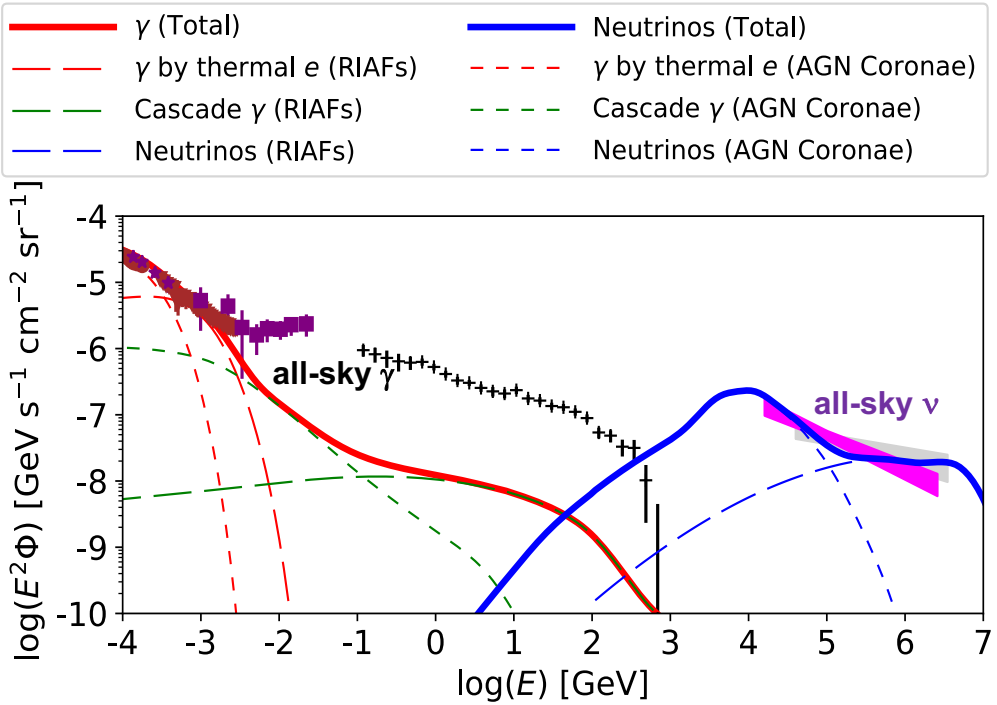
Hidden (i.e., γ-ray opaque) ν sources are actually "natural" in $p\gamma$ scenarios

$\gamma\gamma \to e^+e^-$ 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 ν & X-ray/MeV γ-ray fluxes can be explained by jet-quiet AGN

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

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

Science
JOURNALS AAAS

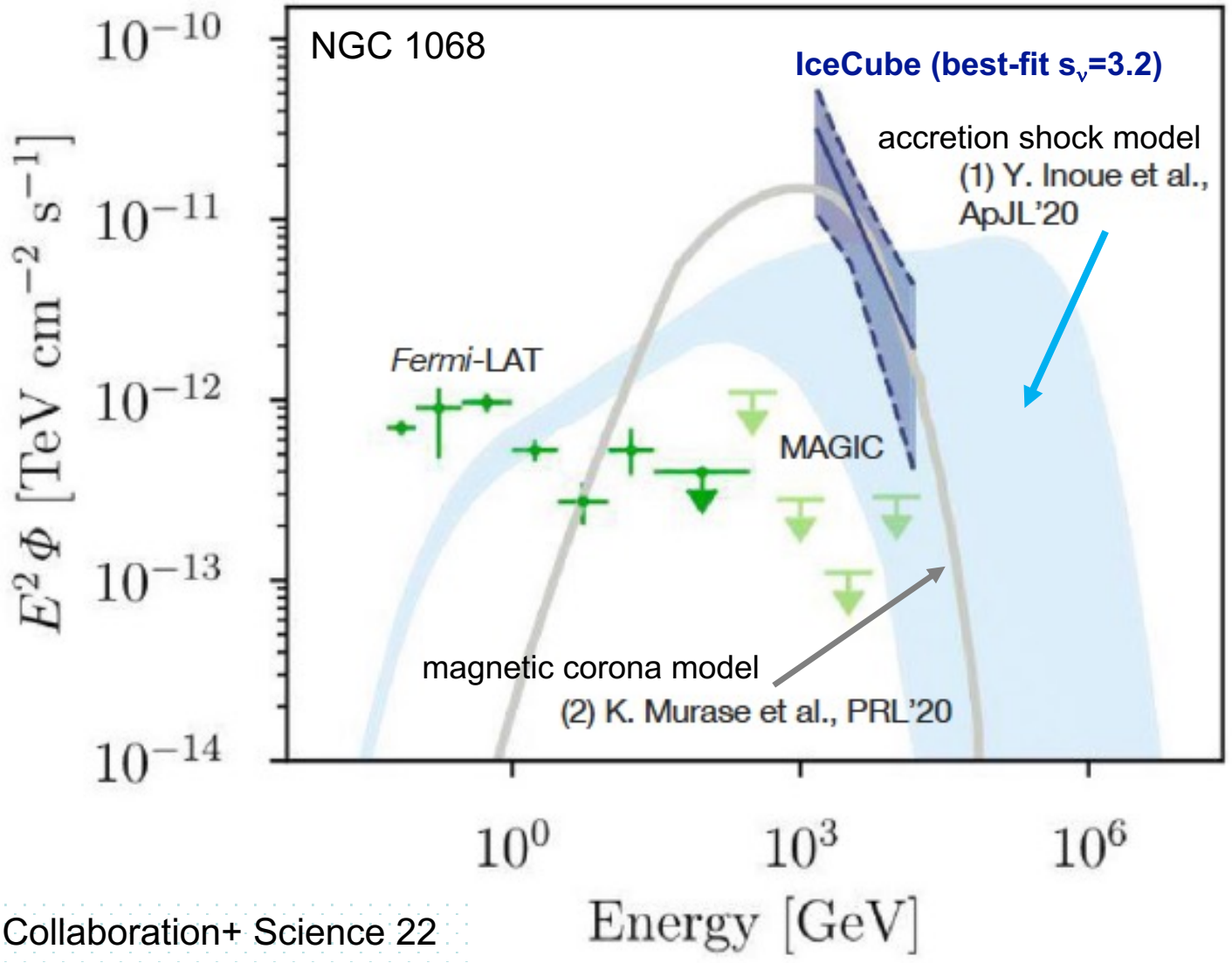
ASTRONOMY

Neutrinos unveil hidden galactic activities

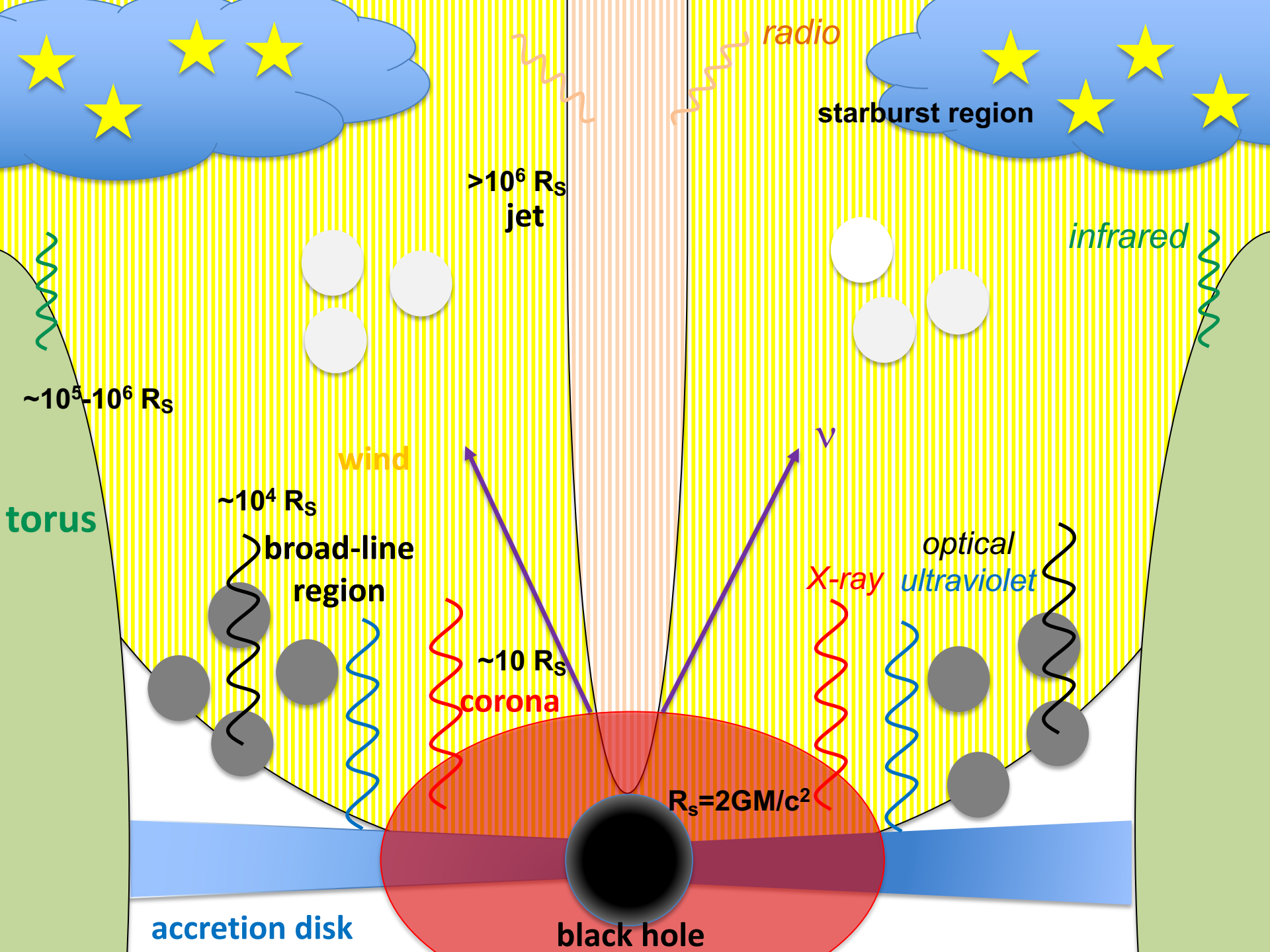
By Kohta Murase[1,2,3]

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

Obscured AGN as a Hidden Neutrino Source



IceCube Collaboration+ Science 22


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

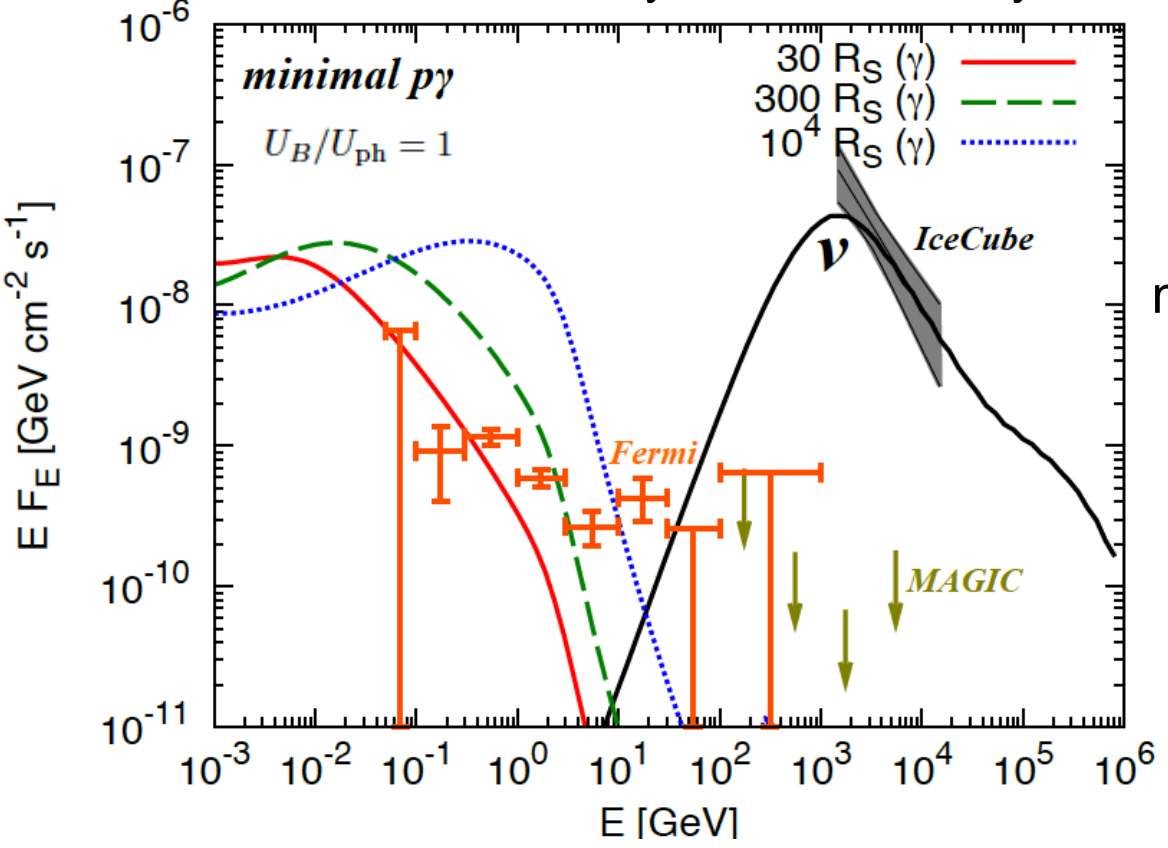
Where Do Neutrinos Come from?

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

for 0.1-300 GeV γ rays

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

NuSTAR: $N_H \sim 10^{25}$ cm^{-2} → $L_X \sim 3\times10^{43}$ erg/s @ 10 Mpc (Marinucci+ 16 MNRAS)
bolometric luminosity ~ disk luminosity: ~10^{45} erg/s

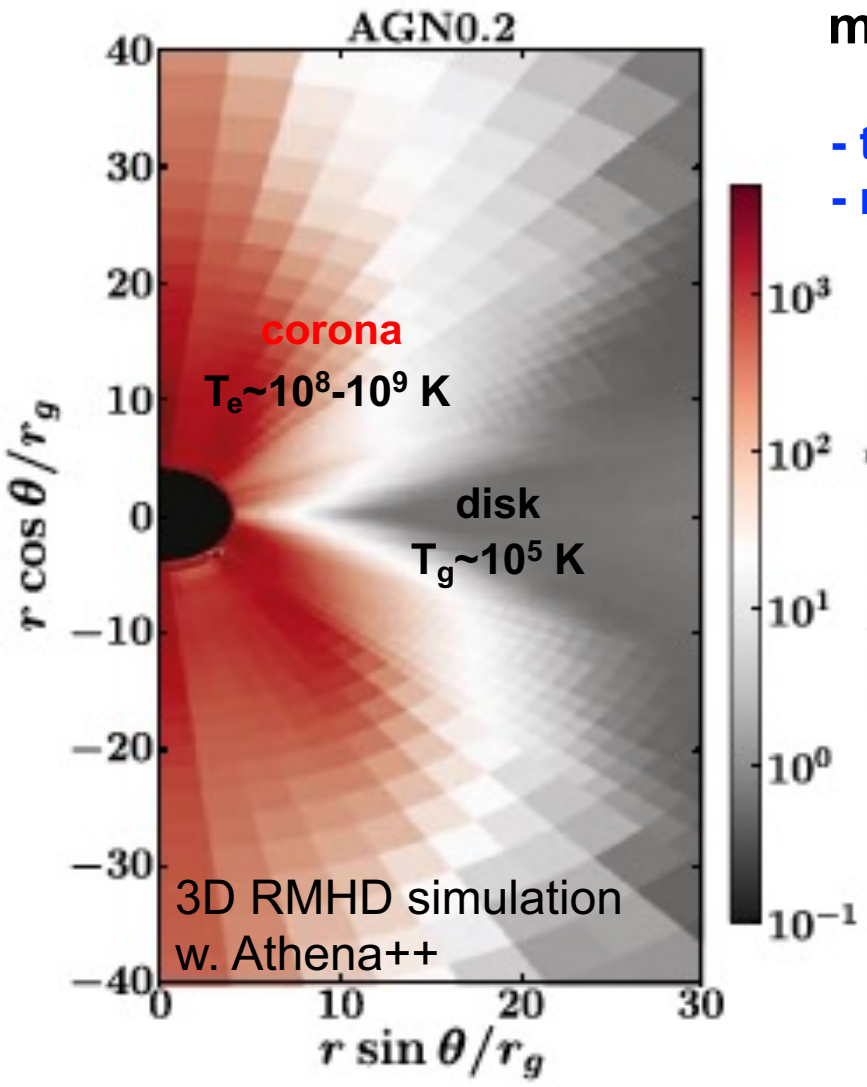


model-independent constraint
w. electromagnetic cascade
R < (30-100) R_S

KM 22 ApJL

compatible w. proton calorimetry condition (pγ optical depth $f_{p\gamma}$>~1)

Particle Acceleration Site?



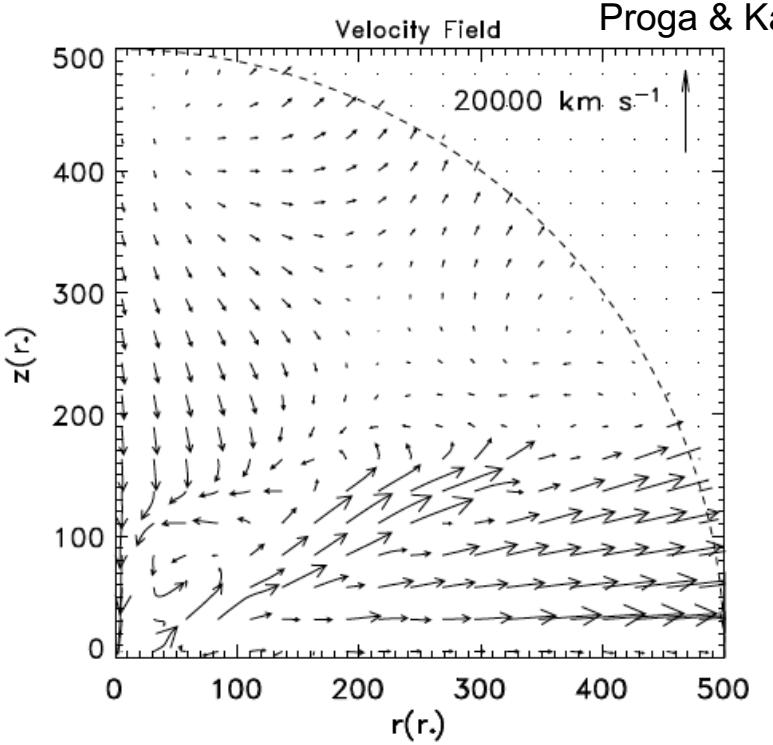
Jiang, Blaes, Stone & Davis 19
see also Miller & Stone 00, Liska+ 22

magnetically-powered corona

(KM+ 20, Kheirandish, KM & Kimura 21)

- turbulence/shear
- magnetic reconnection

Proga & Kallman 04

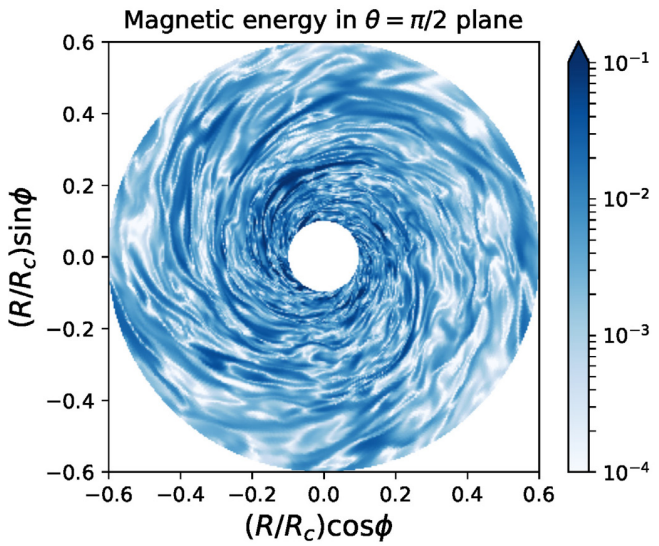


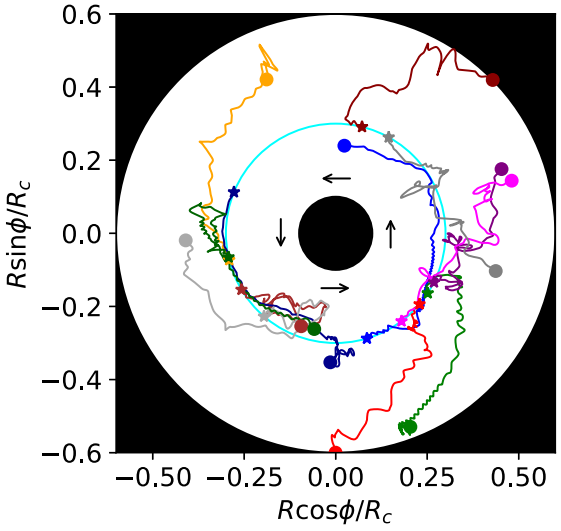
failed disk wind/accretion shock

(S. Inoue, Cerruti, KM+ 23, Y. Inoue+ 20)

Particle Acceleration Mechanism?

Kimura, Tomida & KM 19 MNRAS



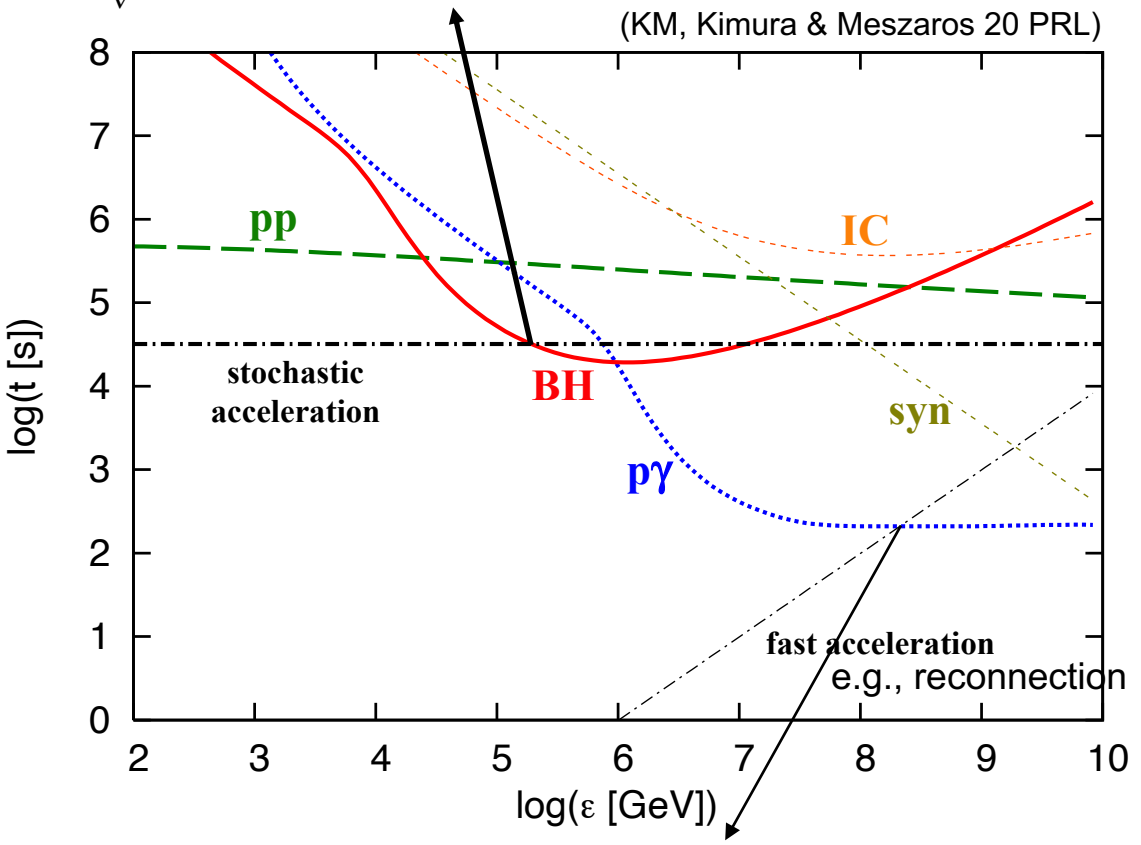


see next Kawashima's talk!

$p\gamma \rightarrow pe^+e^-$ is typically important for 1-10 TeV νs cooling cutoff & pile-up at ε_p^{max} ~ 100 TeV

$\rightarrow \varepsilon_\nu^{max}$ ~ 20 TeV consistent w. ν data

(KM, Kimura & Meszaros 20 PRL)

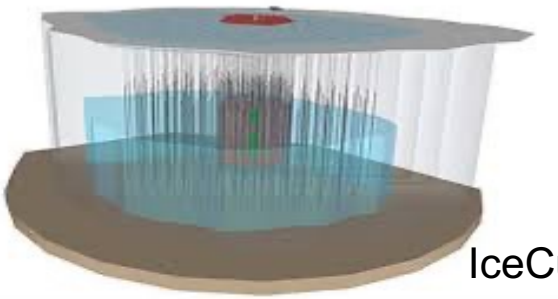


hard spectra cannot be extended to cooling cutoff

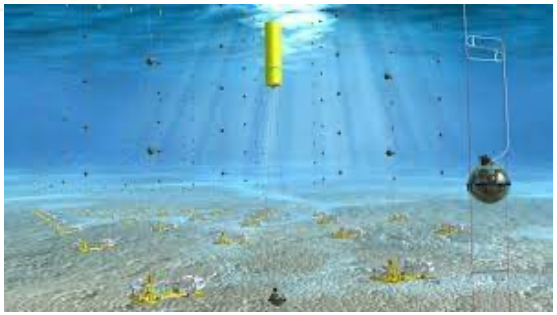
1. intrinsically ε_p^{max} << 10-100 PeV (Kheirandish, KM & Kimura 21 ApJ)
2. intrinsically broken power laws (Fiorillo + 23)

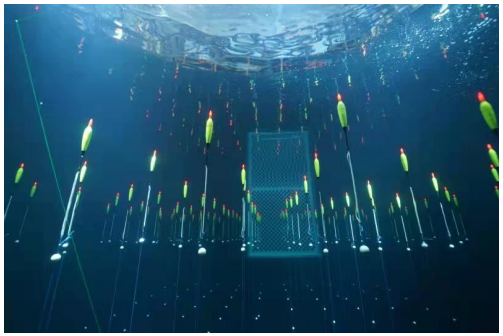
Neutrinos: More Hints & More Tests

- 2.7σ excess of νs from two nearby AGN including NGC 4151 (IceCube 23 ICRC)
- 2.6σ with 8 yr upgoing ν_μ events and IR-selected AGN (IceCube 22 PRD)

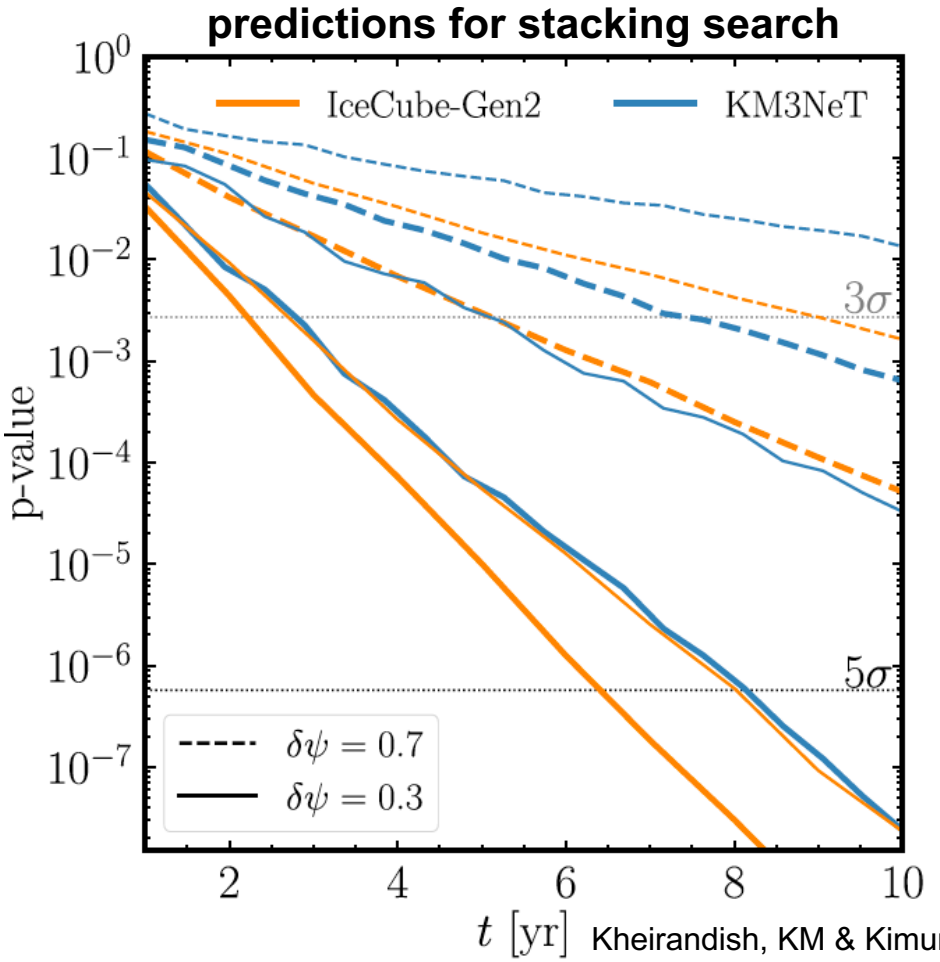


IceCube-Gen2





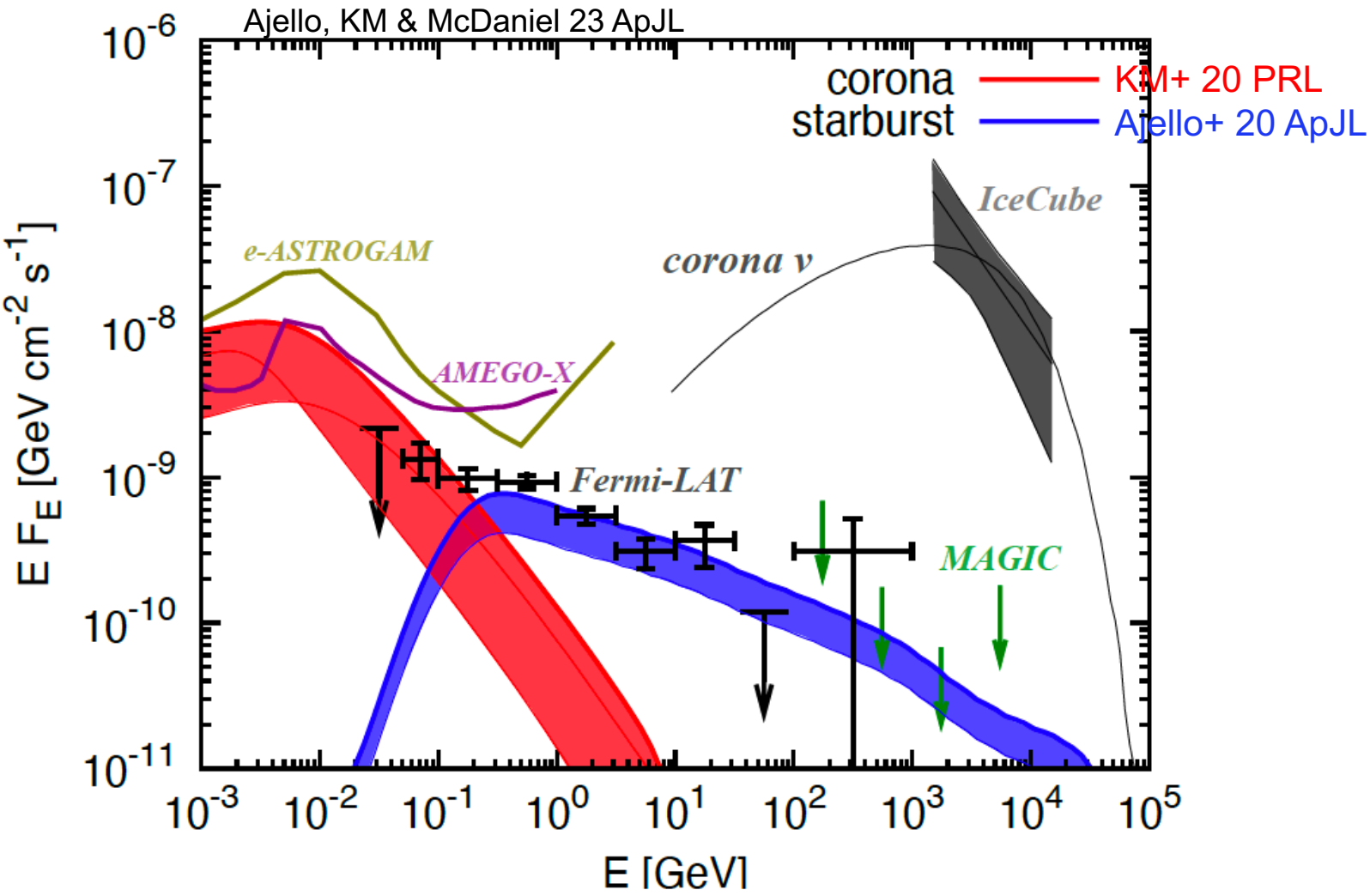
Trident



Kheirandish, KM & Kimura 21 ApJ

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

Gamma Rays Are Not Gone: MeV γ-ray Tests



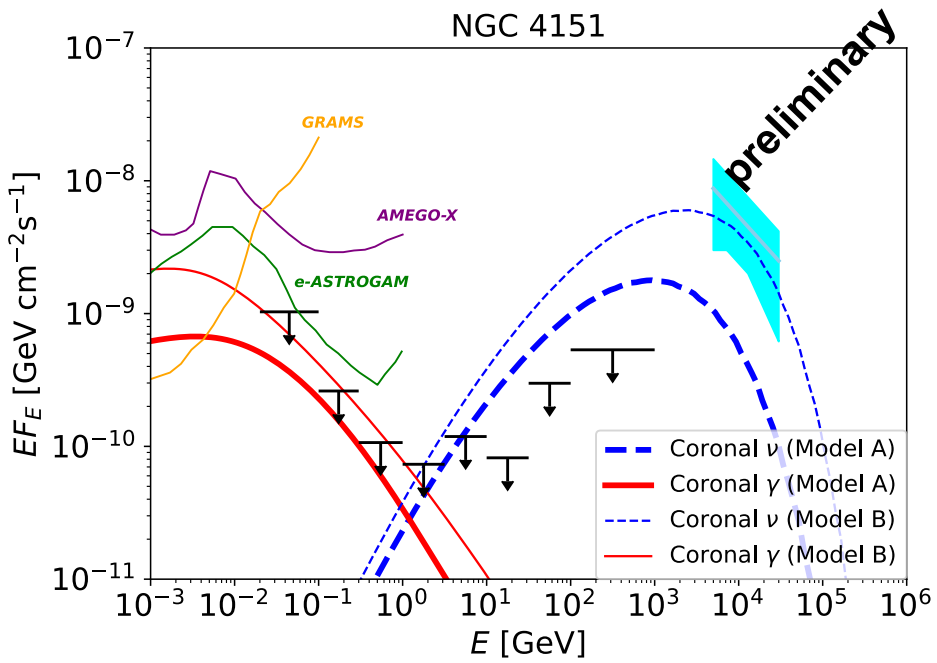
- Prediction: CR-induced cascade γ rays should appear in the MeV range
- We found a sub-GeV "excess" over the $\pi^0 \rightarrow 2\gamma$ (starburst) component

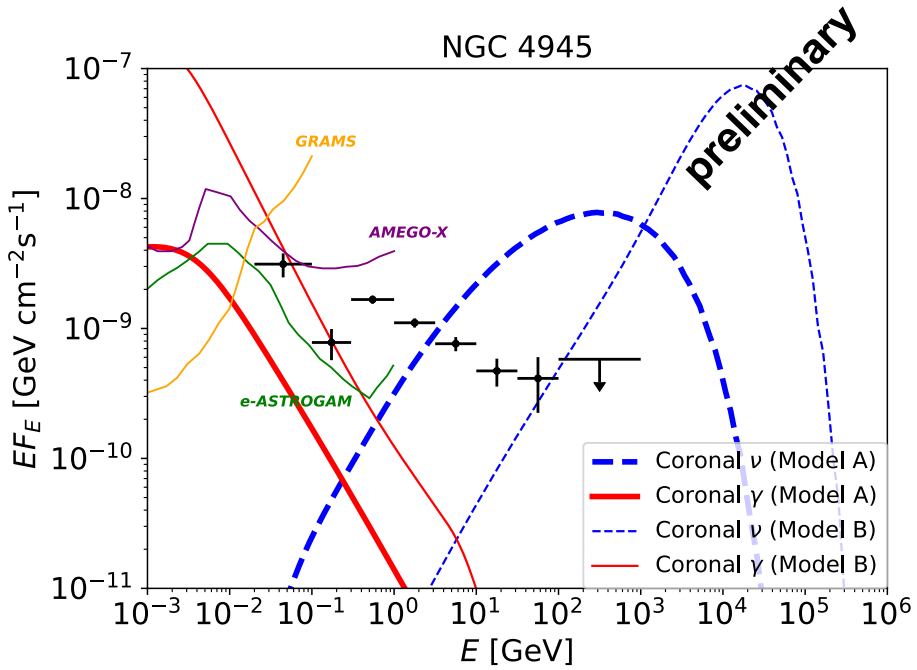
Other AGNs?

Prediction: ν bright AGN ~ intrinsically X-ray bright AGN

- brightest AGN in north: NGC 1068, NGC 4151
- brightest AGN in south: NGC 4945, Circinus, ESO 138-1

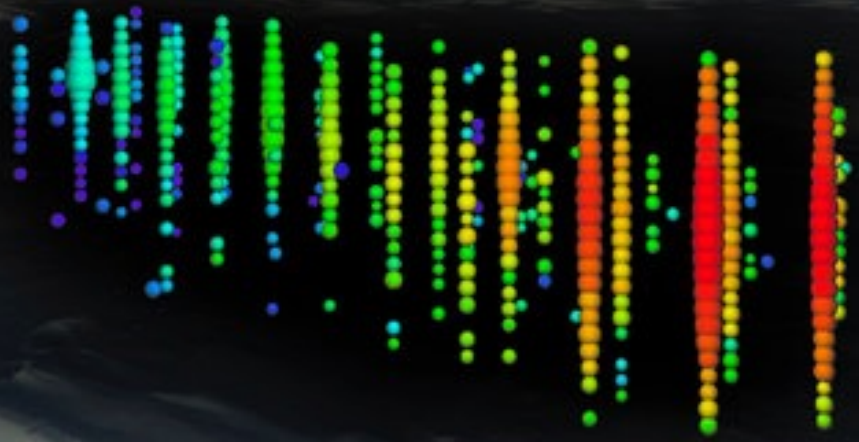
- Magnetically-powered corona model explains:
  NGC 1068: ν & sub-GeV γ, NGC 4151: ν, NGC 4945: sub-GeV γ
- Critical test: multi-TeV ν – MeV γ connection





KM, Karwin, Kimura, Ajello & Buson 23 in prep.

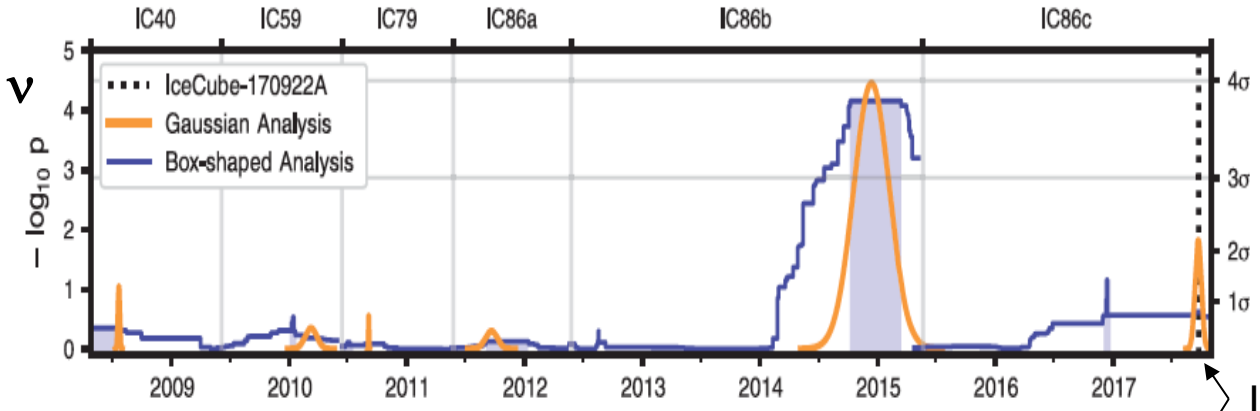
High-Energy Multimessenger Transients



Flares from Supermassive Black Hole Jets?

IceCube 2018 Science

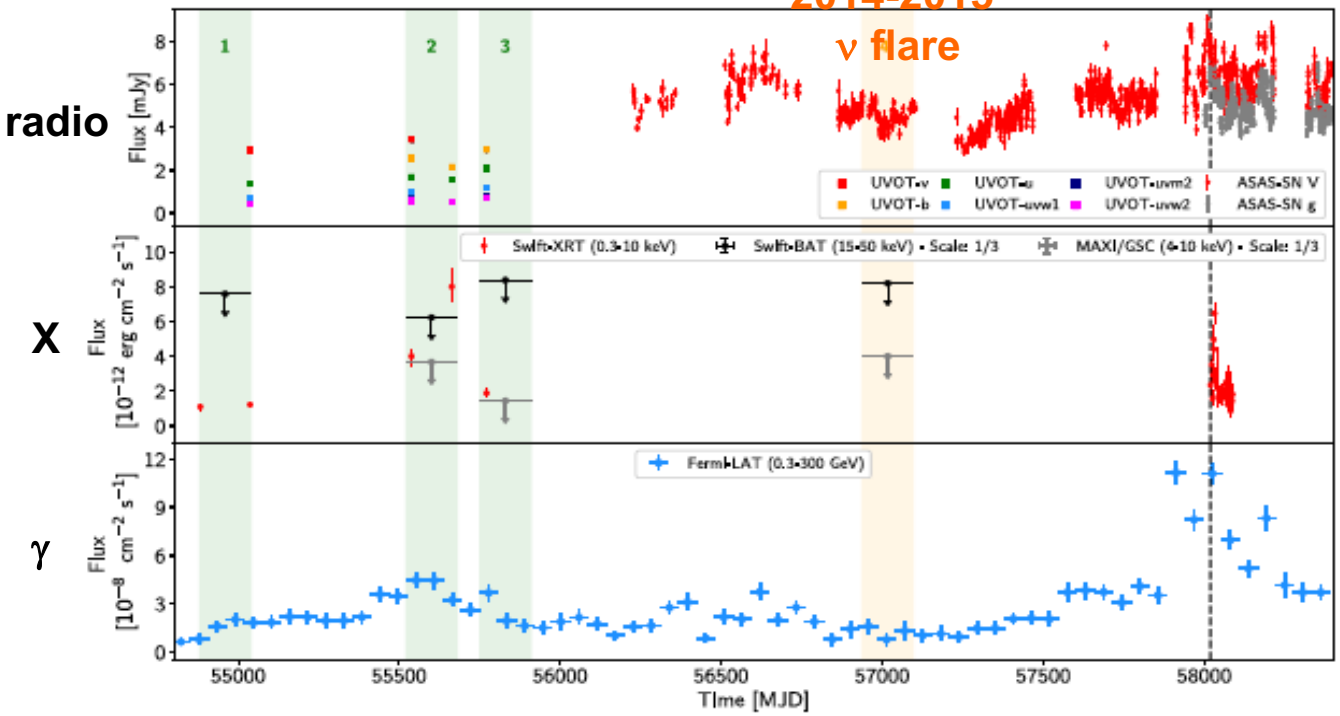
~13 events (~3.5σ): 2014-2015 neutrino orphan flare



TXS 0506+056
"jetted AGN"

IceCube-170922A (E_ν~0.2-1 PeV)

2014-2015 ν flare



2017 multimessenger flare

- IceCube EHE alert pipeline
- Automatic alert (via AMON/GCN)
- γ/X/UV/opt/radio counterparts
- **~3σ coincidence**

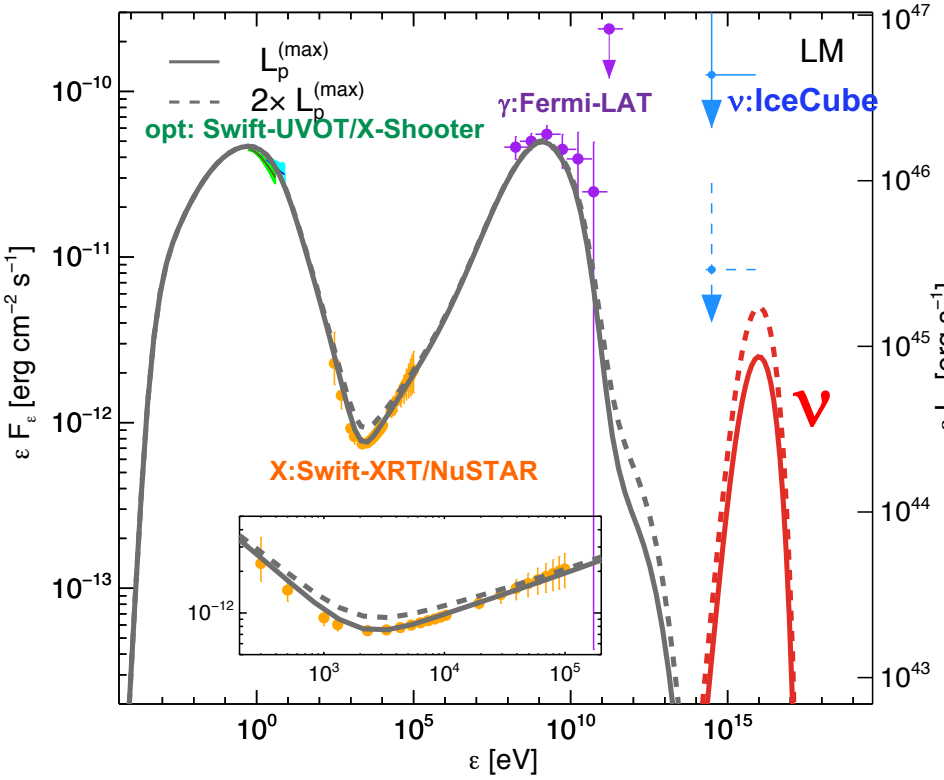
Petropoulou, KM+ 20 ApJ

"Power" of Multimessenger Approaches

Tension: $F_{\nu theory} \sim F_{EMtheory} < F_{EMobs} < F_{\nu obs}$

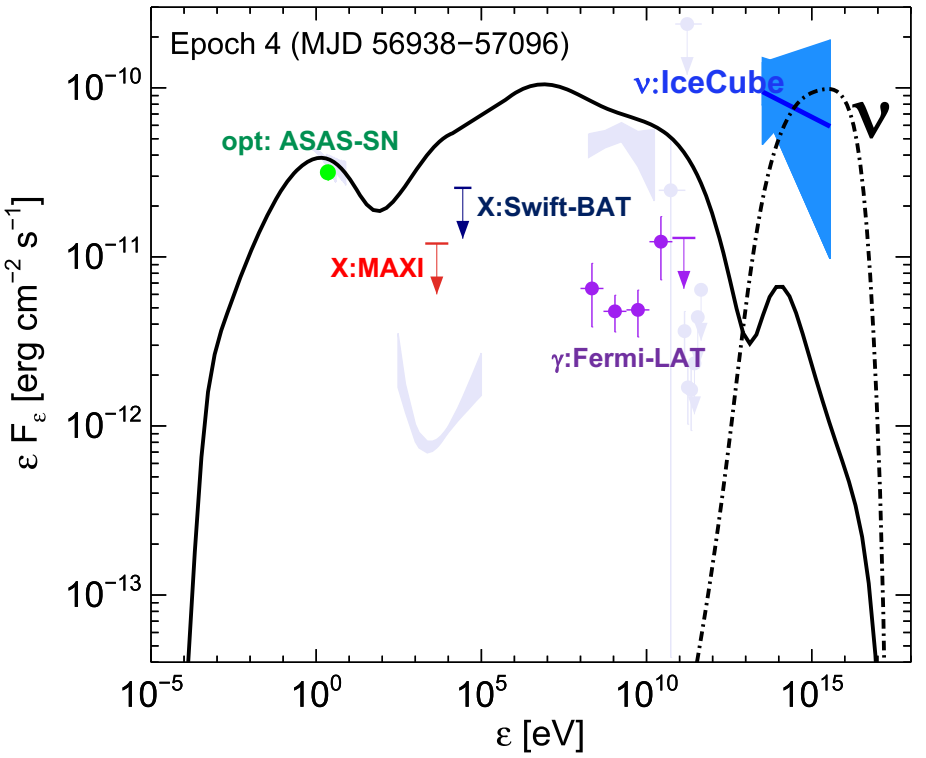
2017 multi-messenger flare

Keivani, KM et al. 18 ApJ



2014-2015 neutrino flare

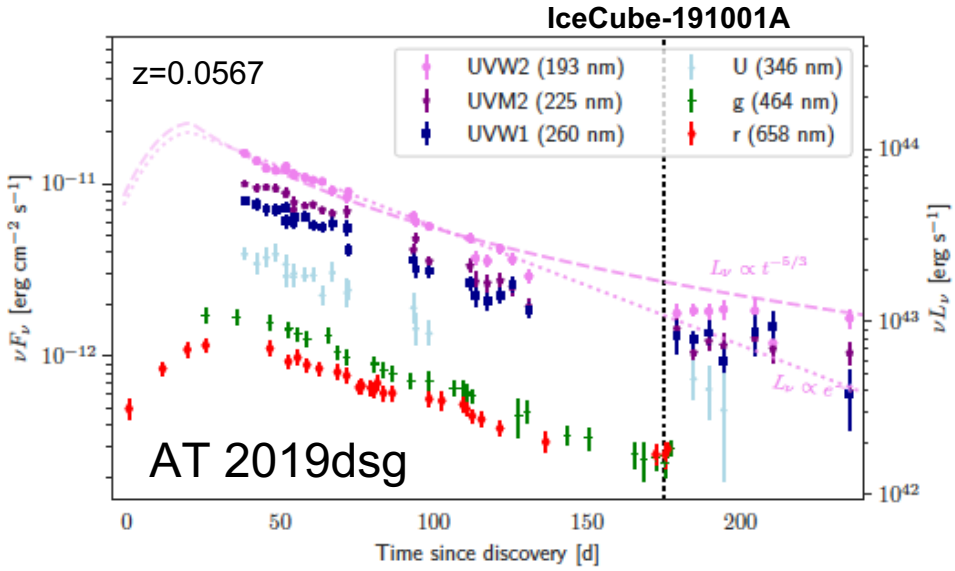
Petropoulou, KM et al. 20 ApJ



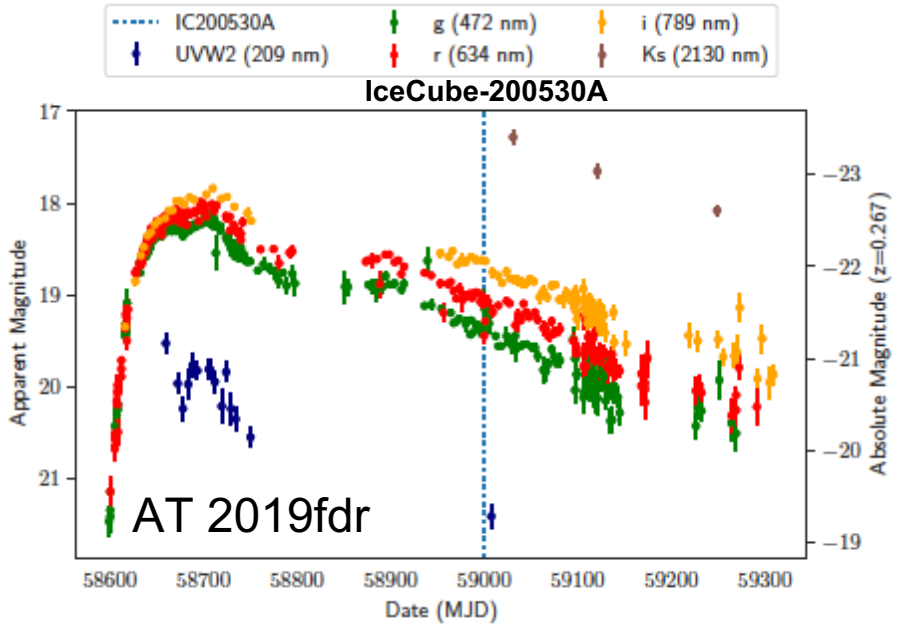
- More coincidences? (ex. PKS 1502+106, 3HSP J095507.9+355101, PKS 0735+178)
- νs may be predominantly produced during flares (KM, Oikonomou & Petropoulou 18 ApJ
  Yoshida, Petropoulou, KM & Oikonomou 23 ApJ)

Coincidences w. Long-Duration "Optical" Transients

Tidal disruption events (TDEs):
flares from supermassive black holes through the disruption of a star



Stein+ 21 Nature Astron.

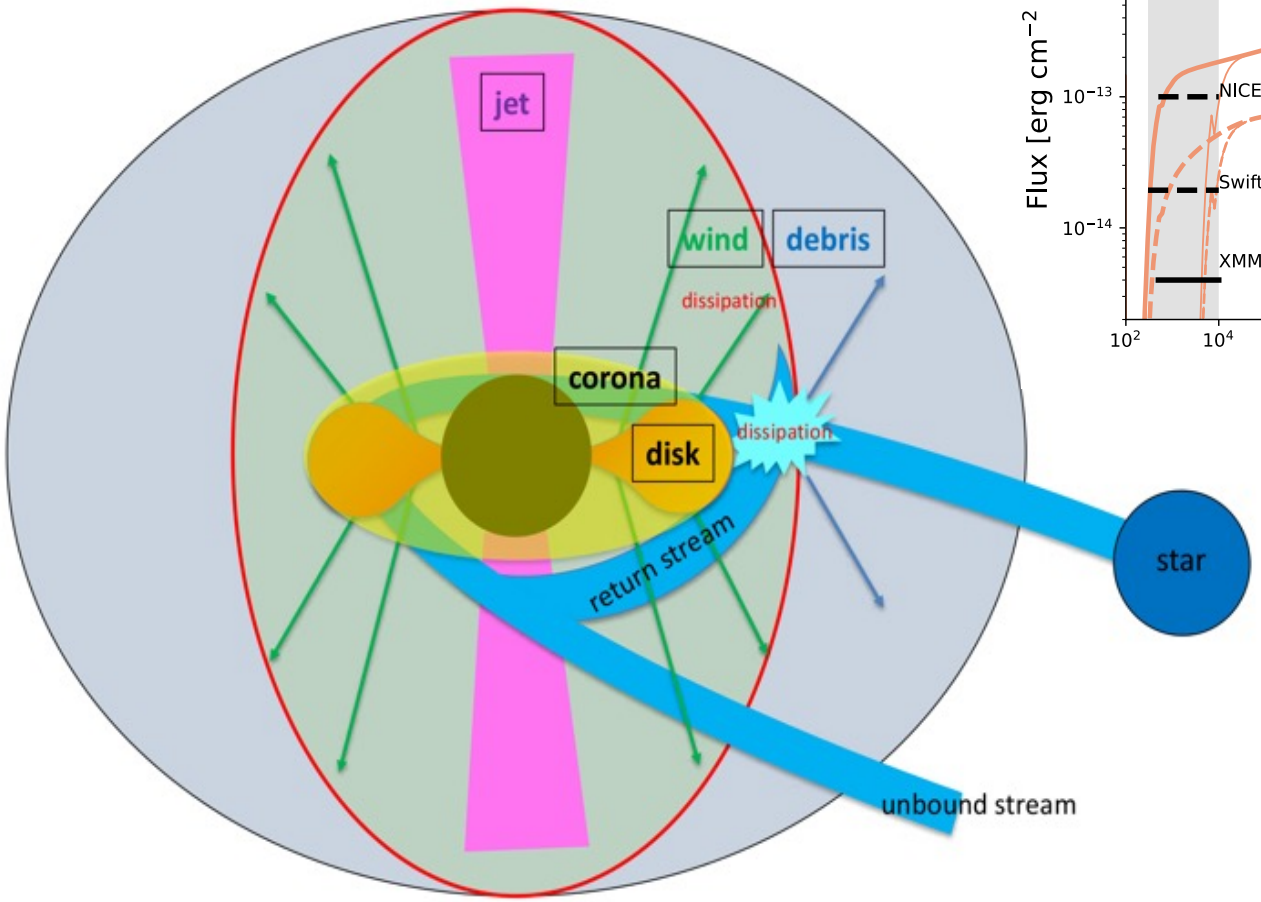


Reusch+ KM 21 PRL

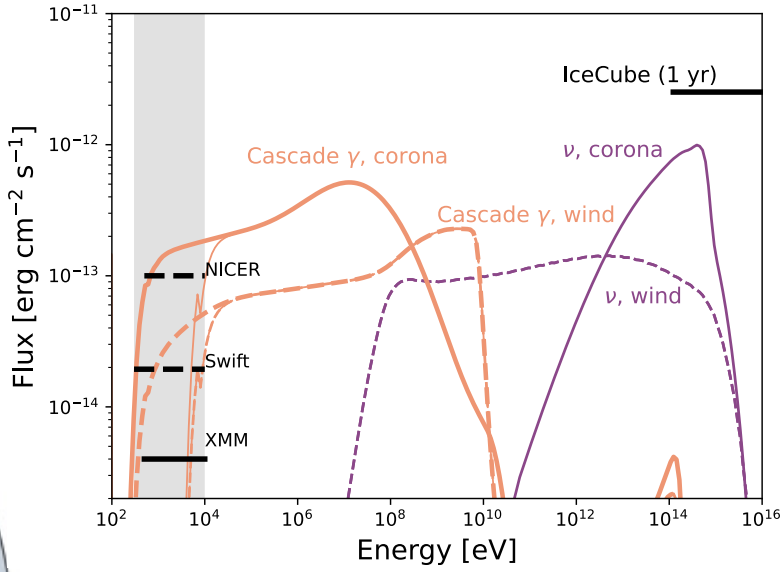
- 5 optical candidates reported (van Velzen+ 23, Jiang+ 23)
- All are rare optical transients w. strong infrared echoes
- Possible neutrino time delays w. ~150-300 day

Neutrinos from Tidal Disruption Events?

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



KM, Kimura, Zhang et al. 20 ApJ



Supermassive black holes as hidden particle accelerators
Multimessenger interpretations?

Summary

- Multi-messenger analyses on all-sky 10 TeV ν and sub-TeV γ requirement of hidden CR accelerators

Jet-quiet AGNs - all-sky νs can be explained

- NGC 1068: evidence for a hidden neutrino source
- Emission radius: $R<30\text{-}100\ R_S \rightarrow$ collisionless coronae?
- Sub-GeV γ-ray excess? (MeV: AMEGO-X, e-ASTROGAM)
  More in south (KM3Net/Baikal-GVD/Trident), IceCube-Gen2
- Theoretical understanding of coronal plasma (PIC, MHD…)

SMBH flares – blazar flares, TDEs

- TXS 0506+056 & other coincidences: no concordance
- But blazar νs may be predominantly produced during flares
- TDE and AGN νs could be produced by similar mechanisms
- Need more data: strategic searches, multiplet follow-up etc.

WANTED

from Murase's talk @ Neutrino 2014

~~Diffuse or~~ Associated

ν

- Source identification may not be easy
  (ex. starbursts: horizon of an average source TXS, TDEs)
- promising cases: "bright transients (GRBs, AGN flares)",
  "rare bright sources (powerful AGN)", "Galactic sources"
- Not guaranteed but rem NGC 1068 e succe Galactic Plane strophysics