High-Energy Multimesssenger Emission from Supermassive Black Holes

Kohta Murase (PSU/IAS/YITP)

January 31 2023

N3AS Seminar

PENNSTATE

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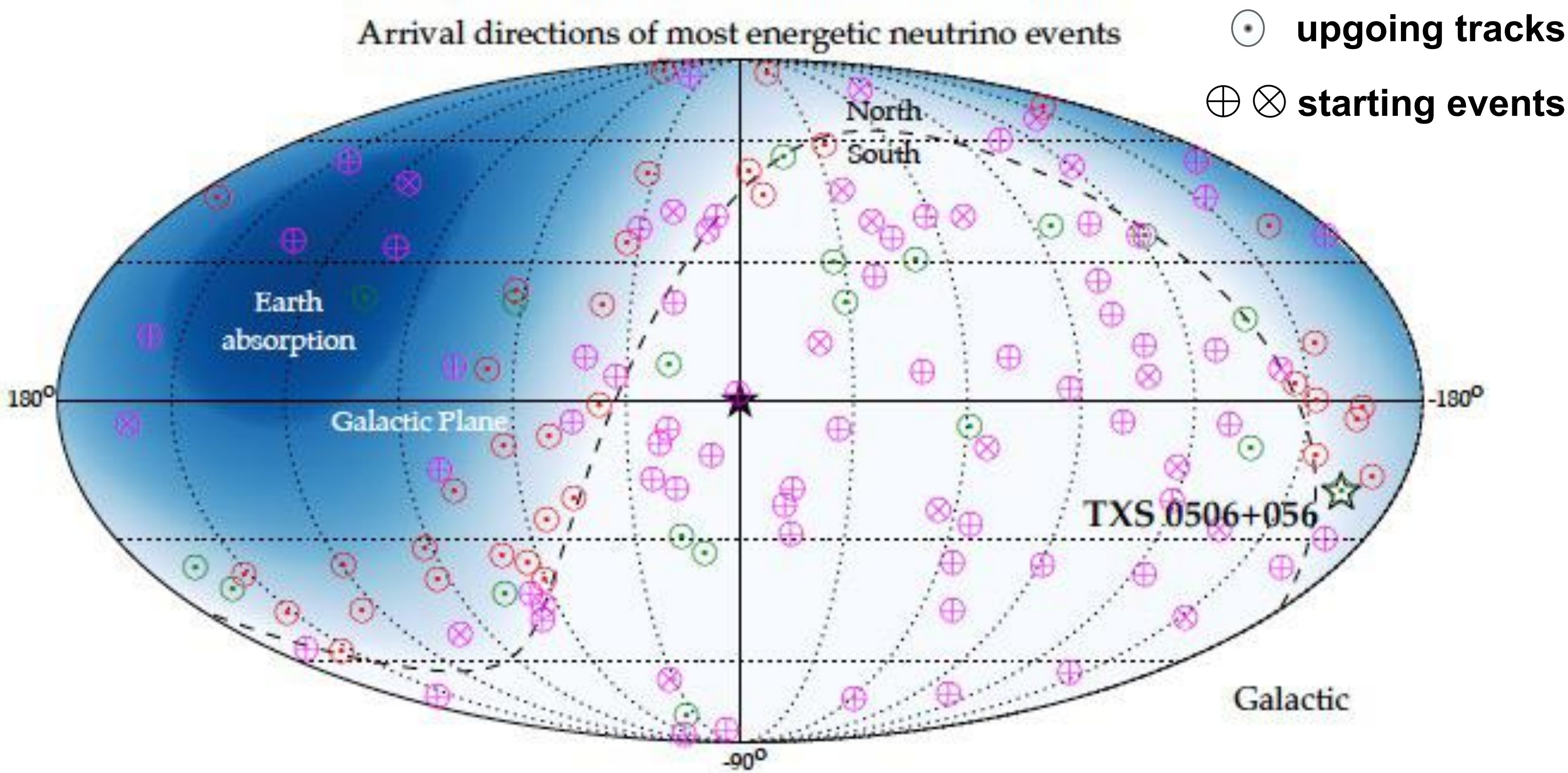
IAS INSTITUTE FOR ADVANCED STUDY

NSF

ν_μ

High-Energy Neutrino Sky



consistent w. isotropic distribution/extragalactic origins

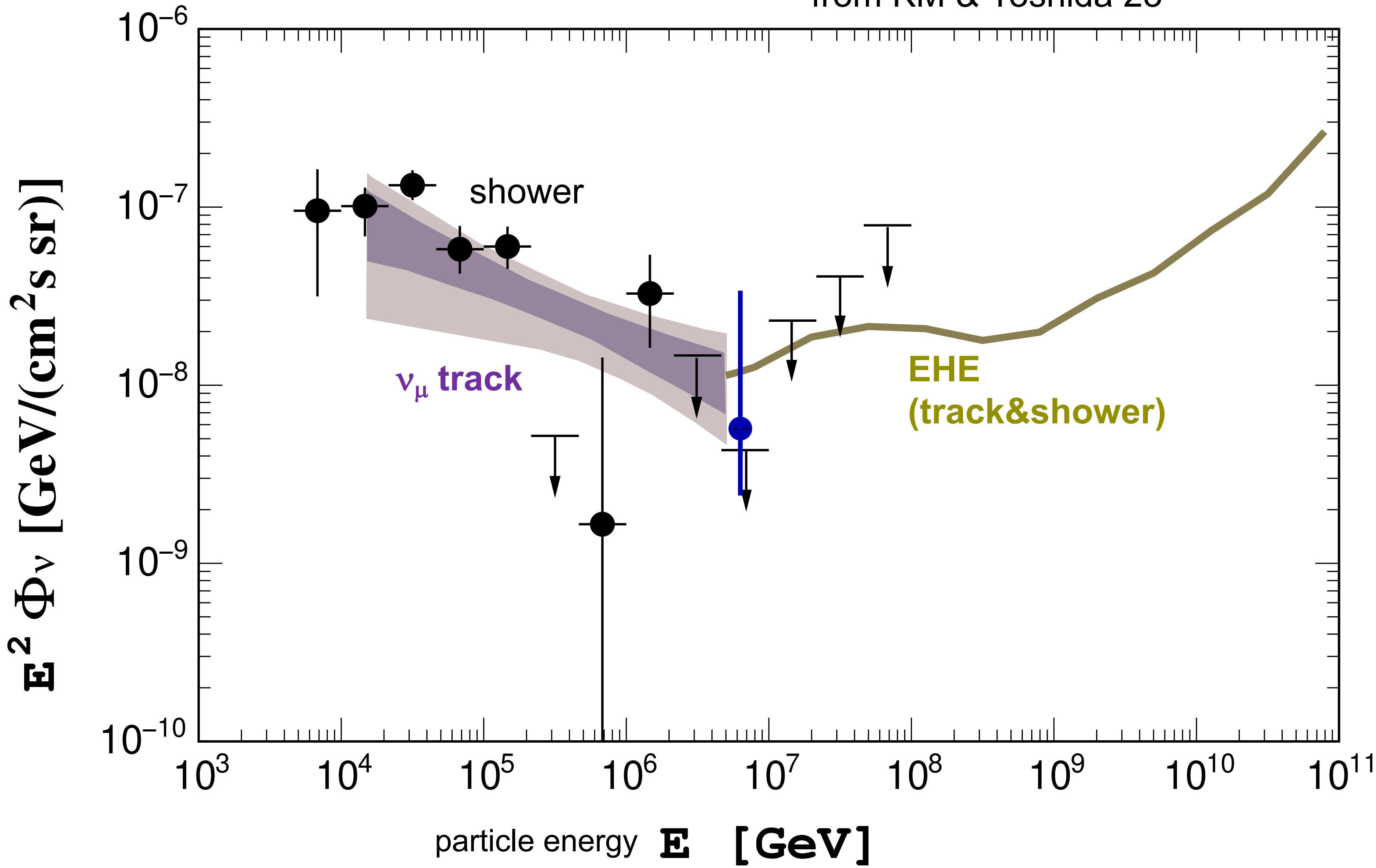
All-Sky Neutrino Flux & Spectrum

all-sky ν flux at E_ν ~200 TeV

$E_\nu^2\Phi_\nu$ ~ 3×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

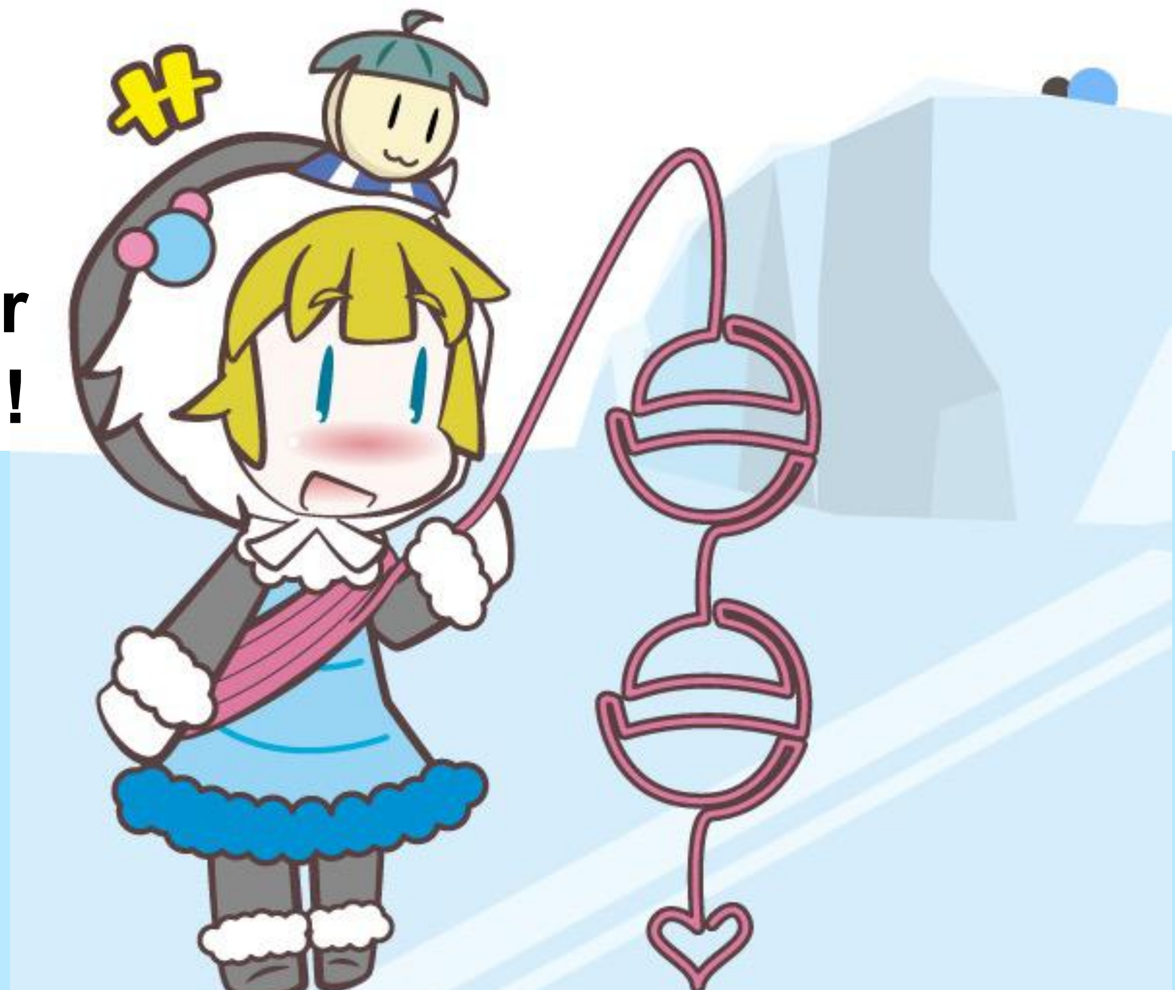
IceCube Collaboration @ Neutrino 2020
IceCube Collaboration 20 PRL

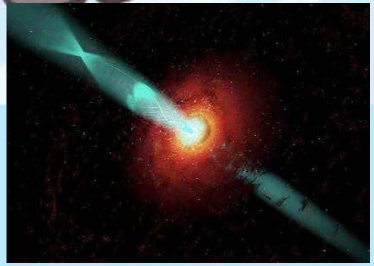
from KM & Yoshida 23

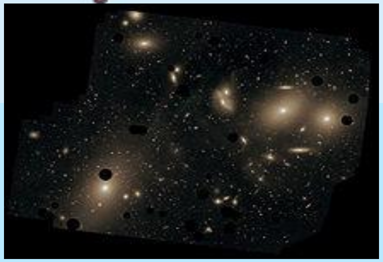


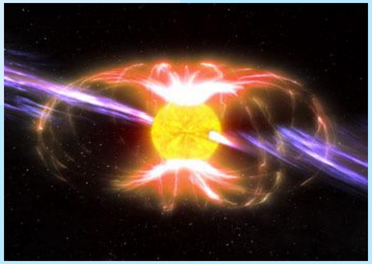
Where Do Neutrinos Come from?

monster fishing!!









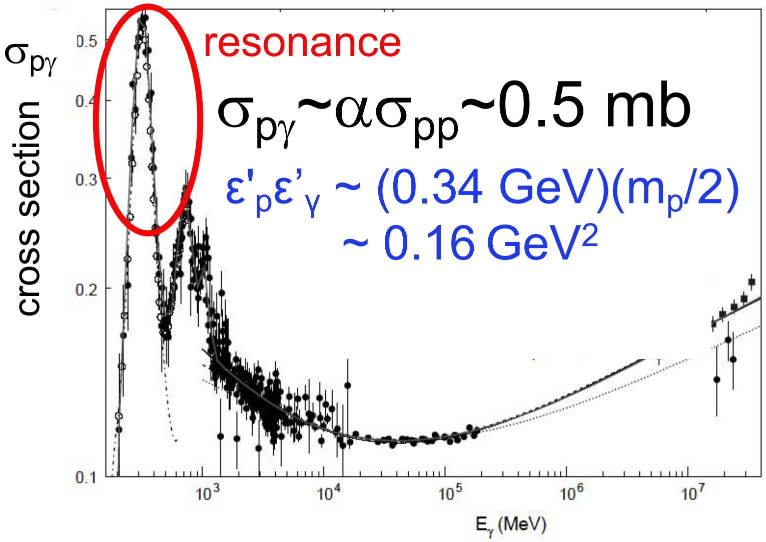
High-Energy Neutrino Production Processes

Cosmic-ray Accelerators

Active galaxy

γ-ray burst

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

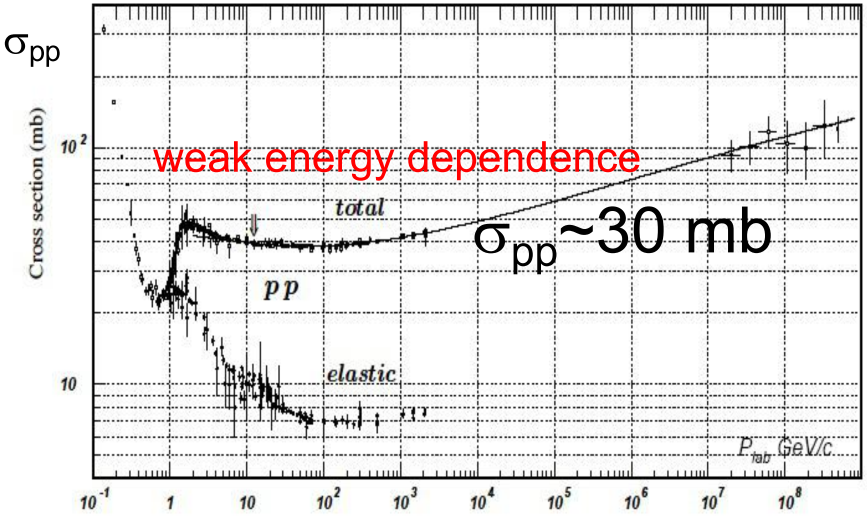


Cosmic-ray Reservoirs

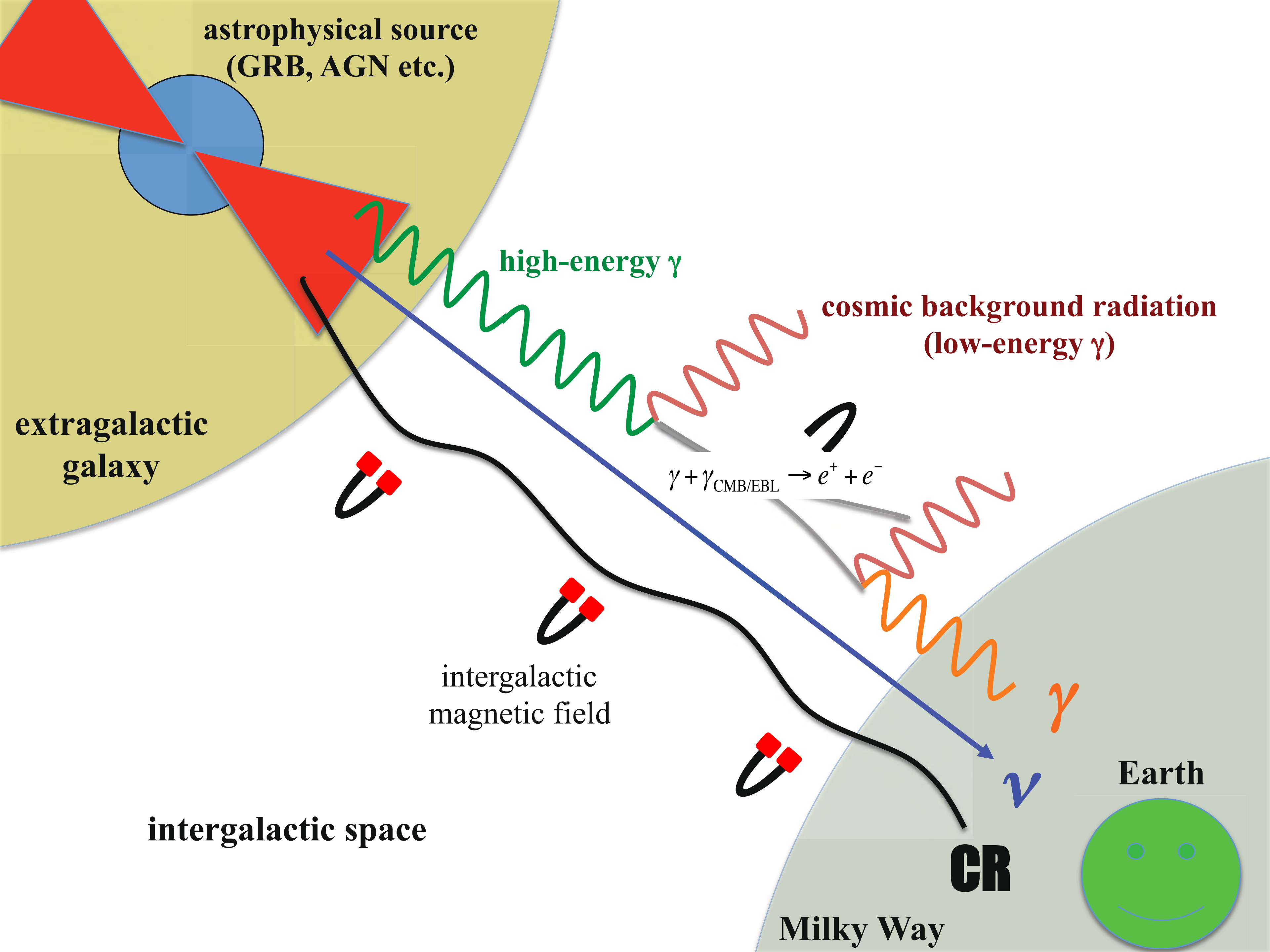
Starburst galaxy

Galaxy cluster

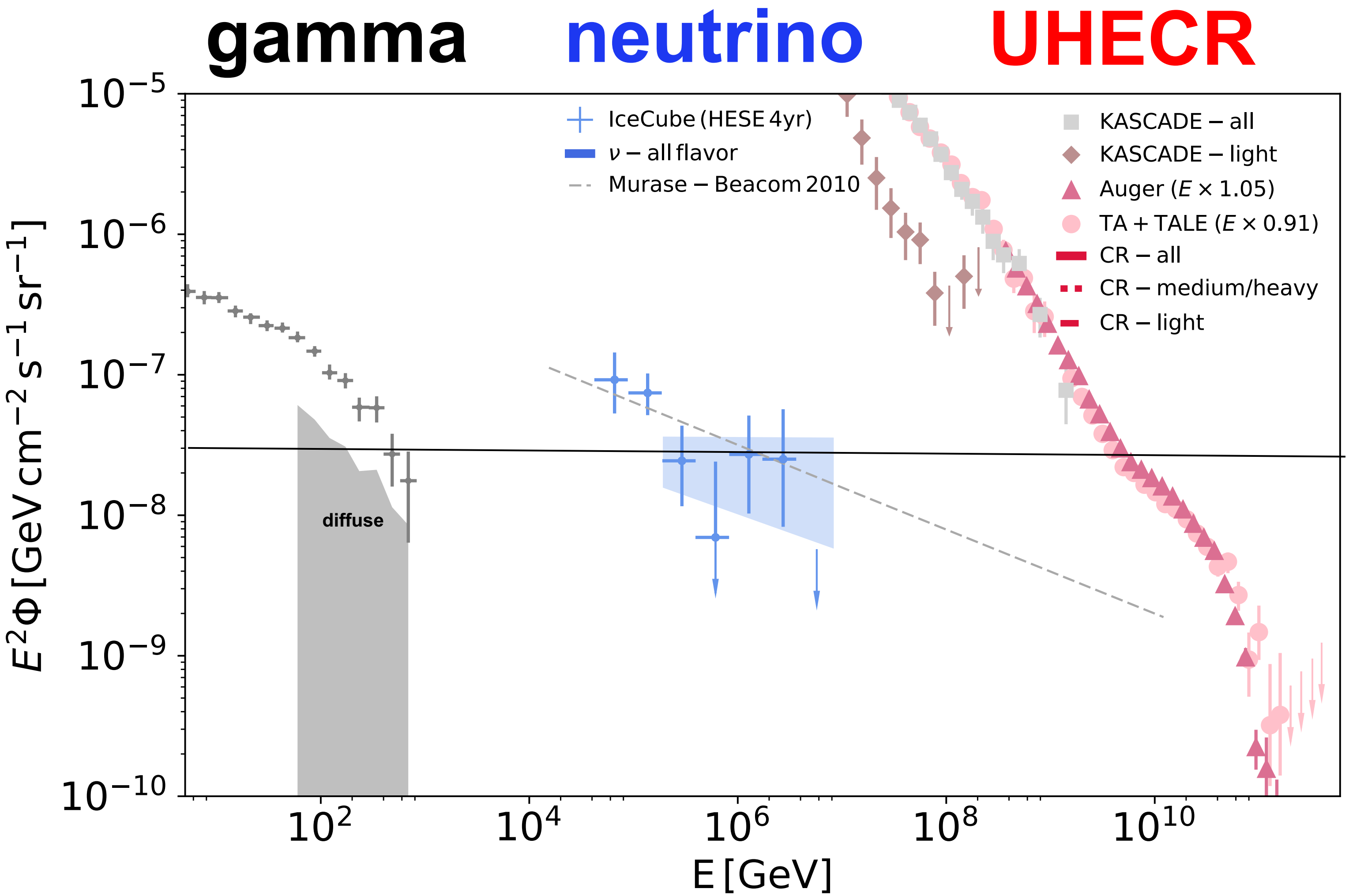
$$p+p \rightarrow N\pi + X$$



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


astrophysical source
(GRB, AGN etc.)
high-energy γ
cosmic background radiation
(low-energy γ)
extragalactic
galaxy
$\gamma + \gamma_{CMB/EBL} \rightarrow e^+ + e^-$
intergalactic
magnetic field
γ
ν
Earth
intergalactic space
CR
Milky Way

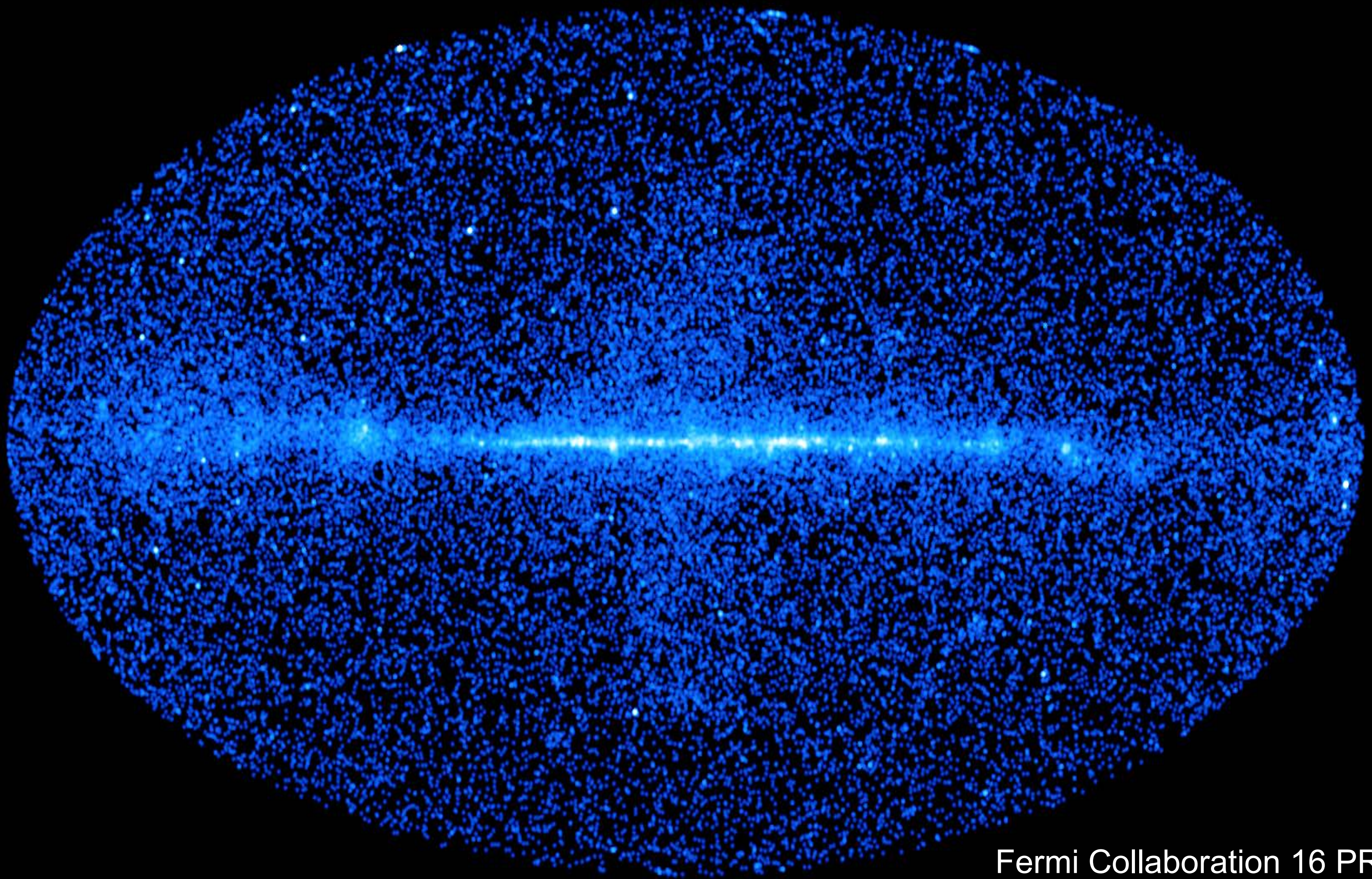
Multi-Messenger Astro-Particle "Backgrounds"



Energy generation rate densities of 3 messengers are all comparable

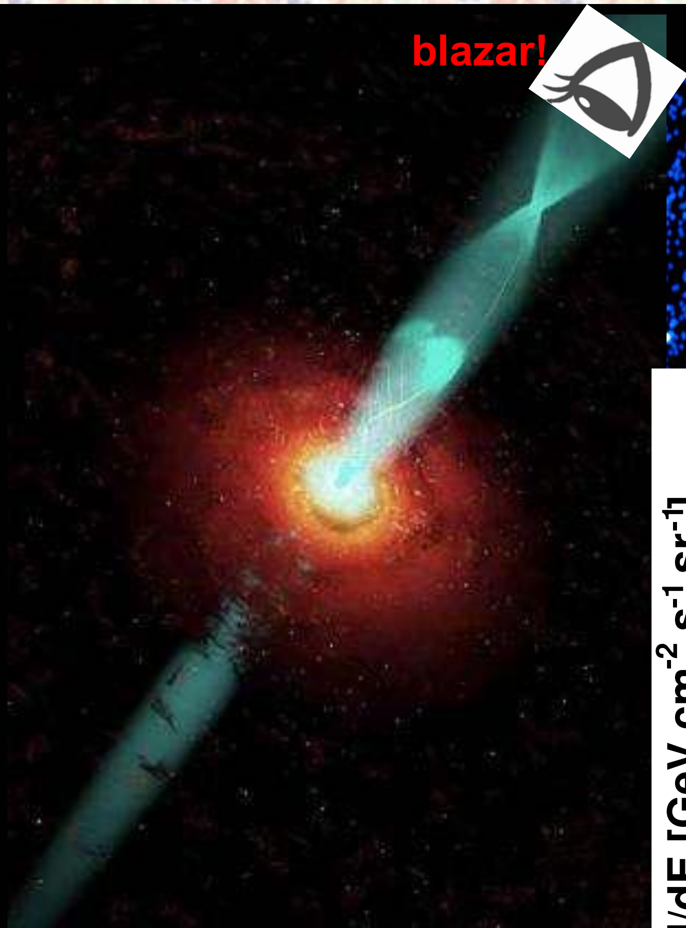
(e.g., KM & Fukugita 19 PRD)

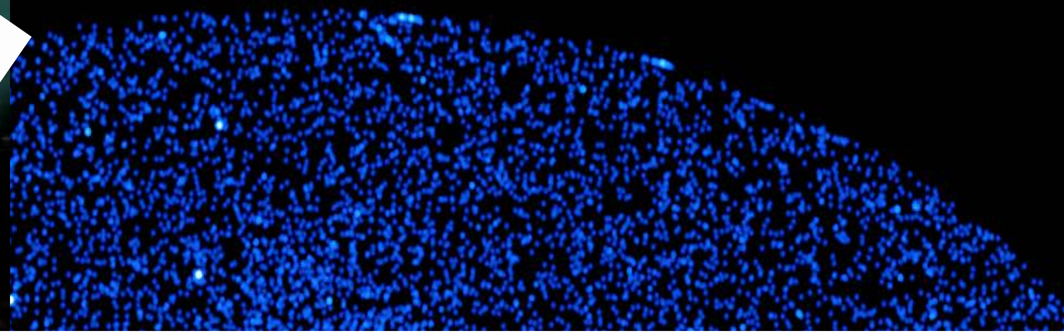
Extragalactic Gamma-Ray Sky: Dominated by Jetted AGN

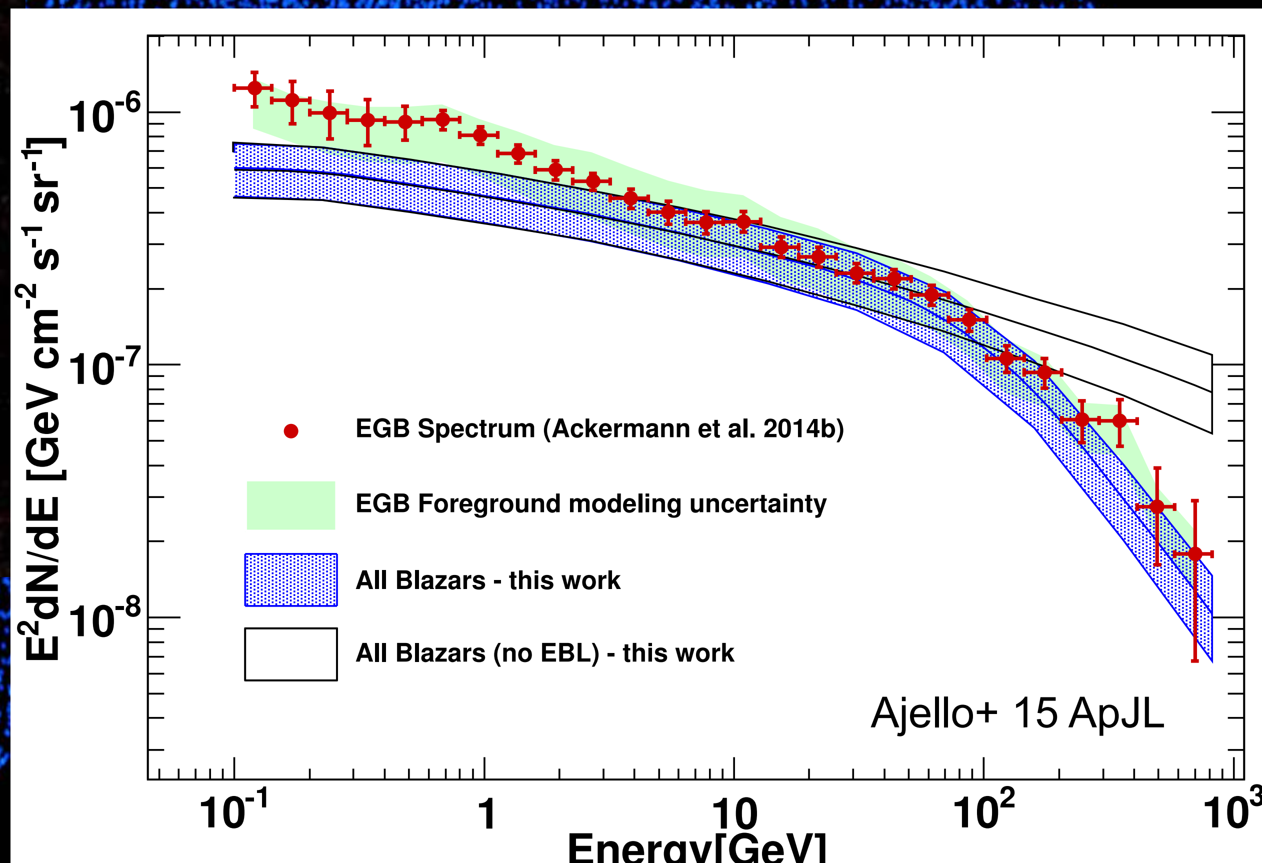


Fermi Collaboration 16 PRL

Extragalactic Gamma-Ray Sky: Dominated by Jetted AGN



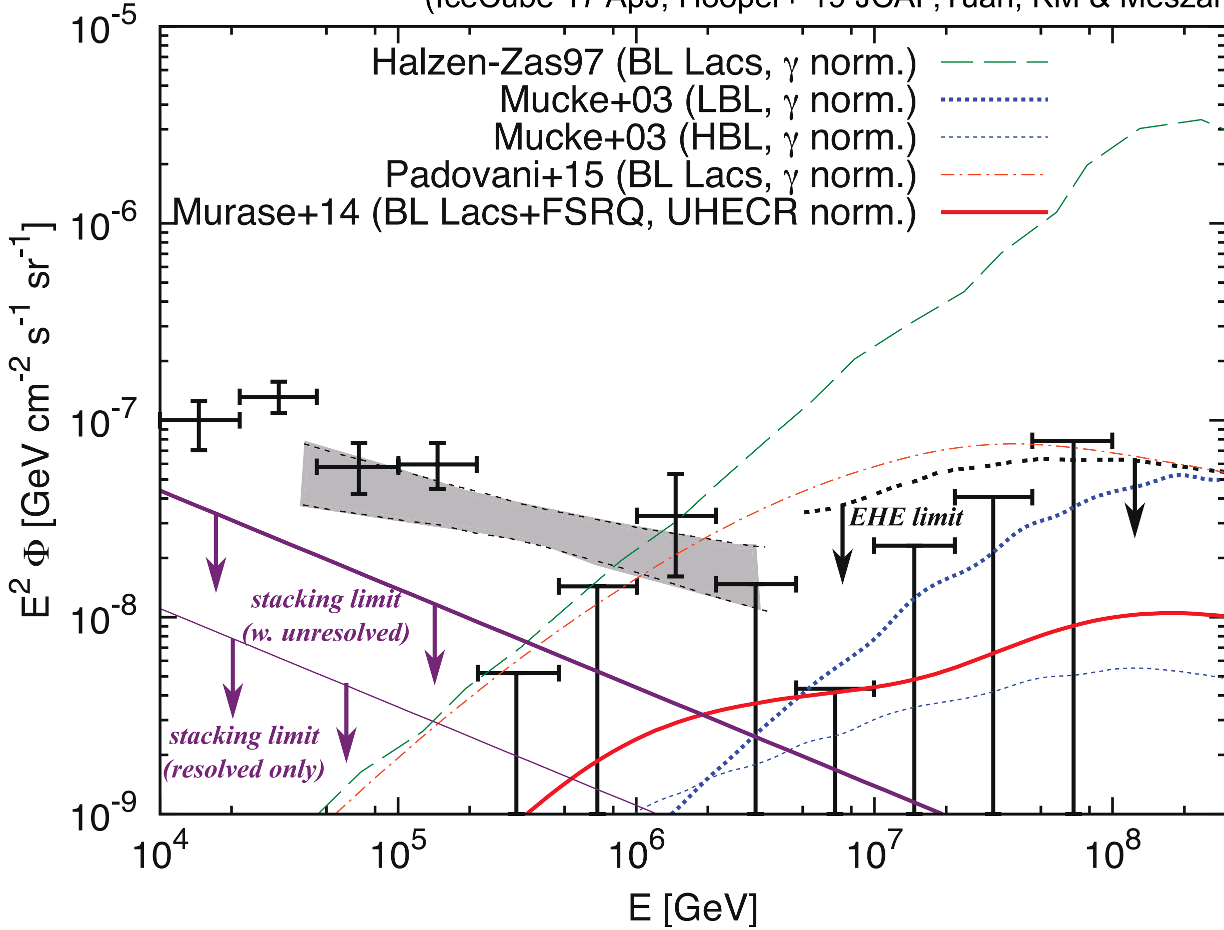




Can Blazars be the Origin of IceCube Neutrinos?

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

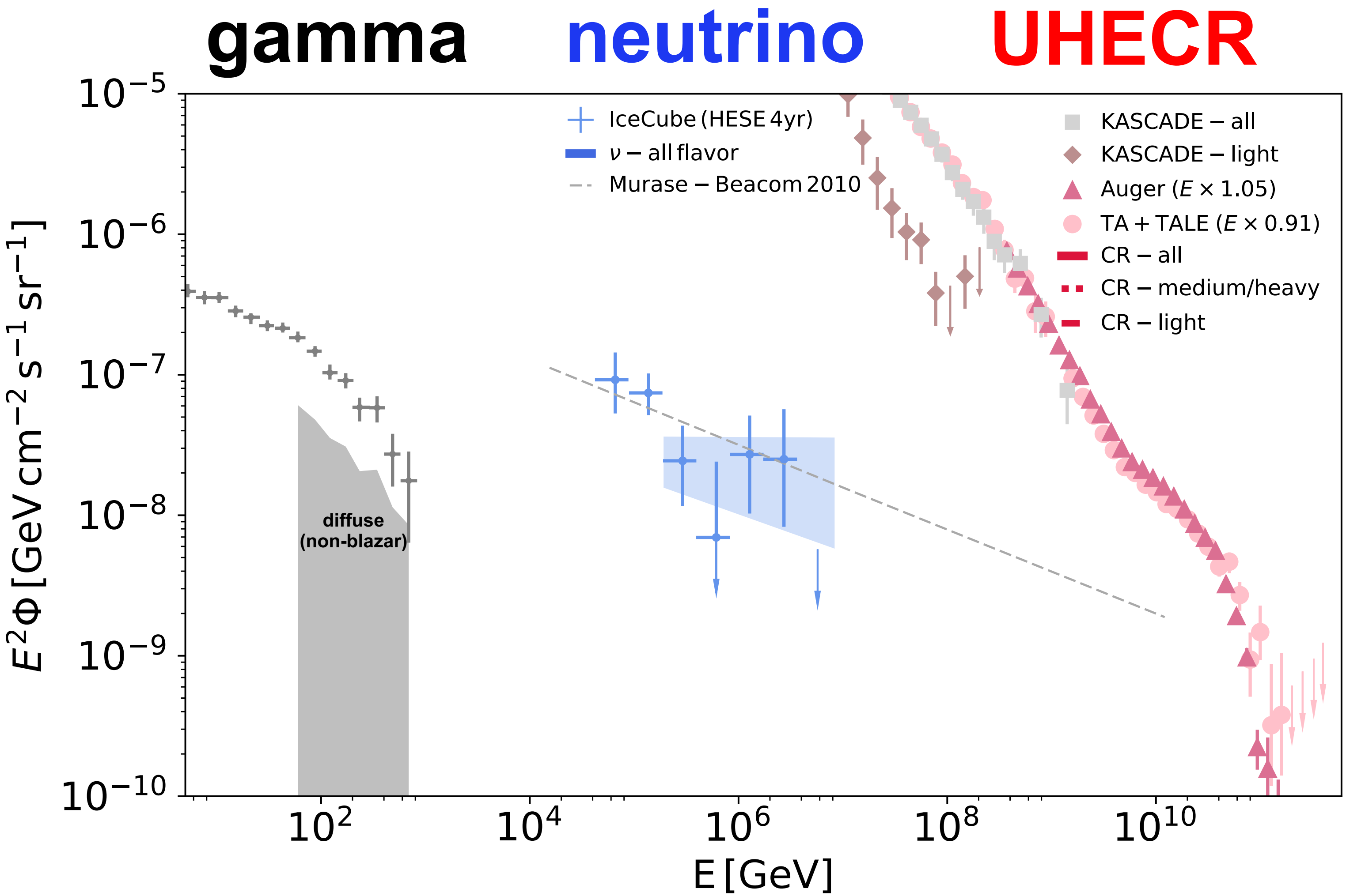
(IceCube 17 ApJ, Hooper+ 19 JCAP,Yuan, KM & Meszaros 20 ApJ, Zou+ 21)



Blazars are subdominant in all parameter space (most likely <~ 30%)

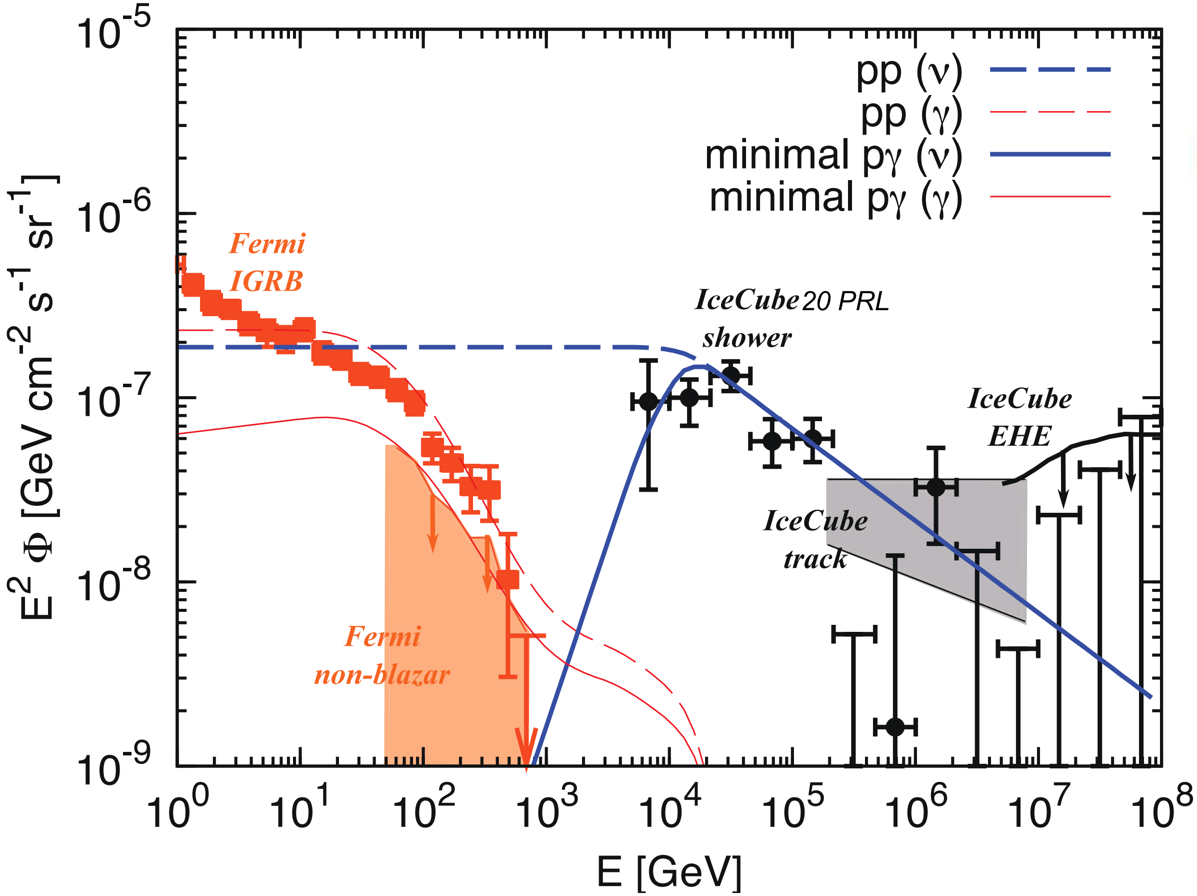
Similar conclusion from neutrino anisotropy limits (KM & Waxman 16 PRD)

Multi-Messenger Astro-Particle "Backgrounds"



Multi-Messenger Implications of 10 TeV ν All-Sky Flux

- 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

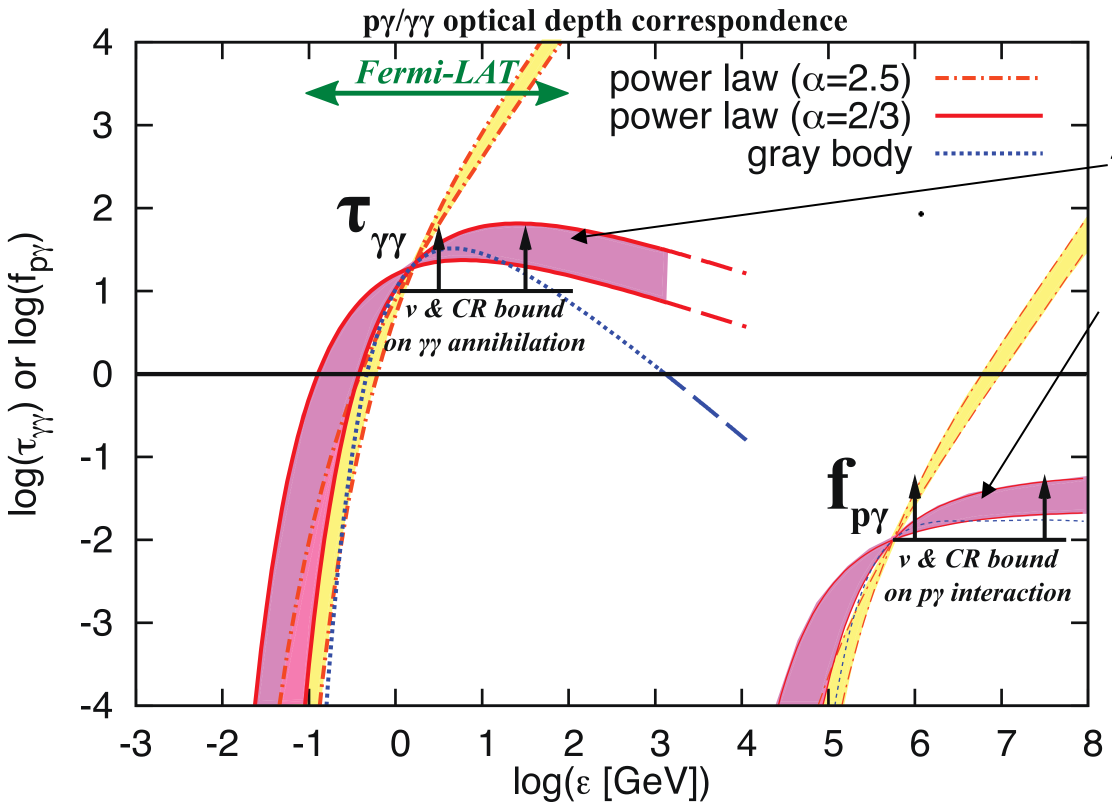
Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent
→ Requiring hidden (i.e., γ-ray opaque) cosmic-ray accelerators
(Galactic components are not sufficient: see also Ahlers & KM 14 PRD, Fang & KM 21 ApJ)

Opacity Argument

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

$\gamma\gamma \to e^+e^-$ **optical depth** $$\tau_{\gamma\gamma} \approx \frac{\sigma^{\rm eff}_{\gamma\gamma}}{\sigma^{\rm eff}_{p\gamma}} f_{p\gamma} \sim 1000 f_{p\gamma} \gtrsim 10$$

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



$$\gamma + \gamma \to e^+ + e^-$$

$$\parallel$$

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

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

KM, Guetta & Ahlers 16 PRL

Solutions to "Excessive" All-Sky Neutrino Flux?

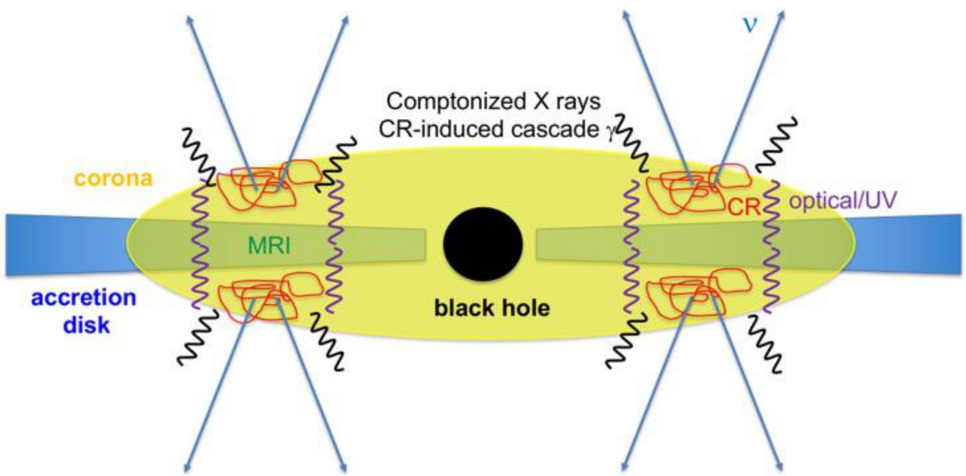
Hidden (i.e., γ-ray opaque) ν sources are actually natural in $p\gamma$ scenarios

(KM, Guetta & Ahlers 16 PRL)

$\gamma\gamma \rightarrow e^+e^-$ optical depth $\tau_{\gamma\gamma} \approx \frac{\sigma_{\gamma\gamma}^{\rm eff}}{\sigma_{p\gamma}^{\rm eff}} f_{p\gamma} \sim 1000 f_{p\gamma} \gtrsim 10$

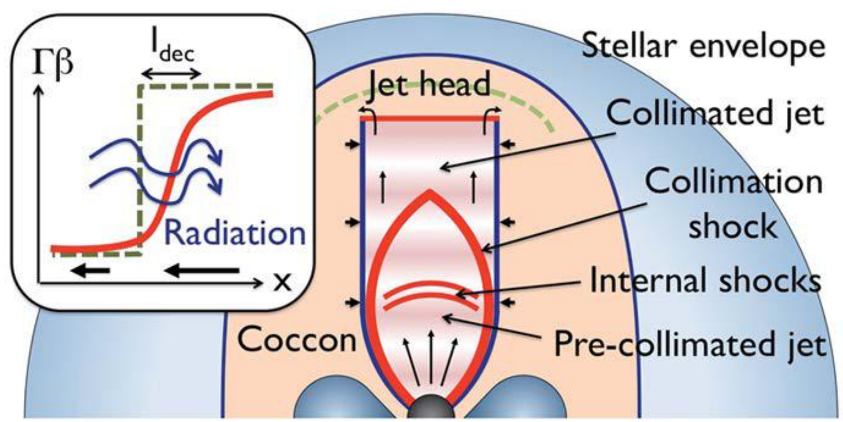
implying that >TeV-PeV γ rays are cascaded down to GeV or lower energies

vicinity of black holes



(from KM, Kimura & Meszaros 20 PRL)

choked jets in supernovae



(from KM & Ioka 13 PRL)

But do such hidden ν sources exist??

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

A supermassive black hole, obscured by cosmic dust, powers the nearby active galaxy NGC 1068. Neutrinos, which rarely interact with matter, could provide information on the galaxy's active core. We searched for neutrino emission from astrophysical objects using data recorded with the IceCube neutrino detector between 2011 and 2020. The positions of 110 known gamma-ray sources were individually searched for neutrino detections above atmospheric and cosmic backgrounds. We found that NGC 1068 has an excess of 79^{+22}_{-20} neutrinos at tera–electron volt energies, with a global significance of 4.2σ, which we interpret as associated with the active galaxy. The flux of high-energy neutrinos that we measured from NGC 1068 is more than an order of magnitude higher than the upper limit on emissions of tera–electron volt gamma rays from this source.

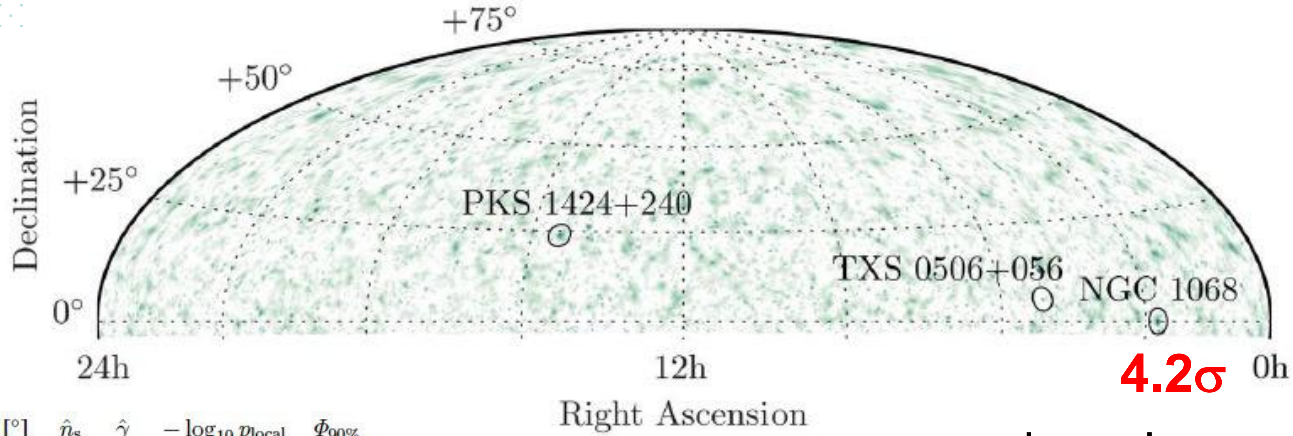
ASTRONOMY

Neutrinos unveil hidden galactic activities

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

By Kohta Murase[1,2,3]

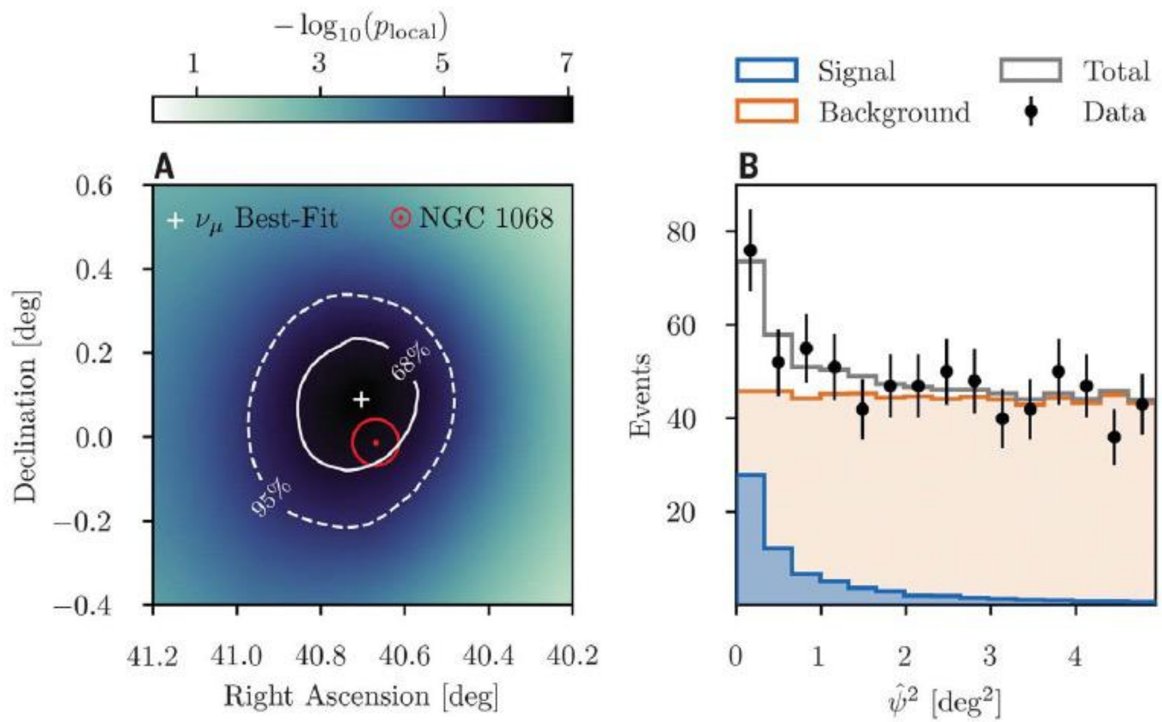
IceCube Collaboration+ 22



4.2σ

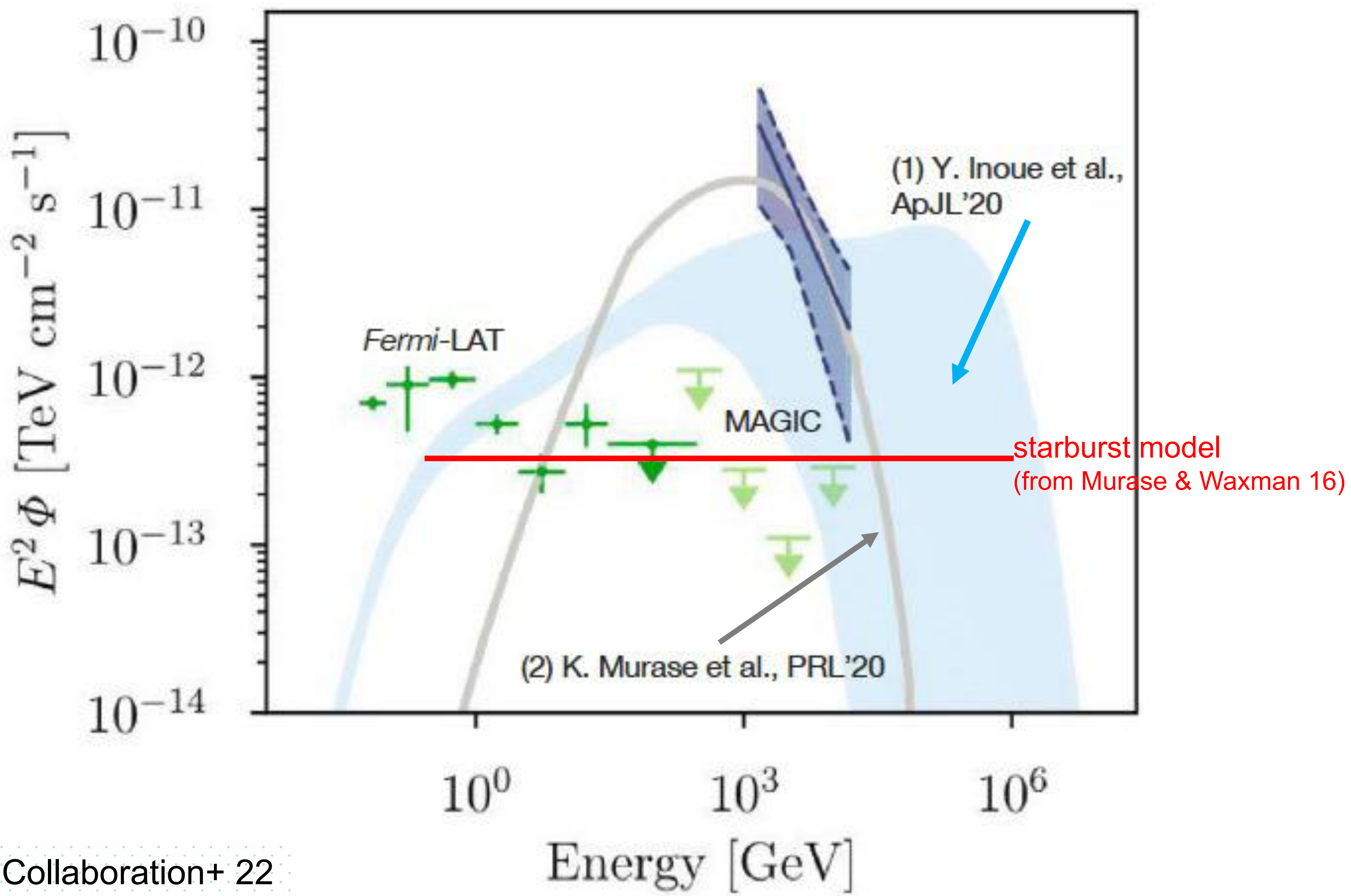
in search w. pre-defined catalog

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\rm local}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5



~79 excess events

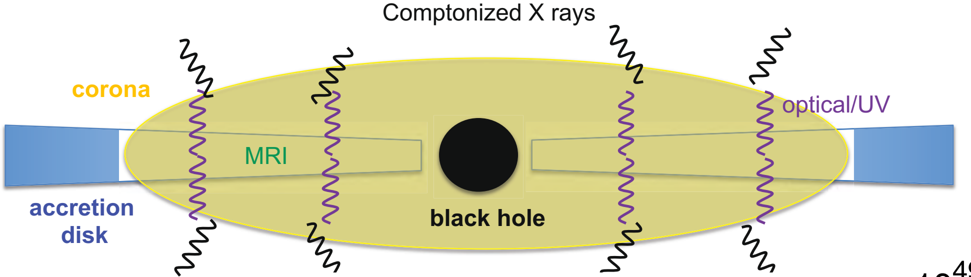
NGC 1068 as a Hidden Neutrino Source



IceCube Collaboration+ 22

Vicinity of Supermassive Black Holes

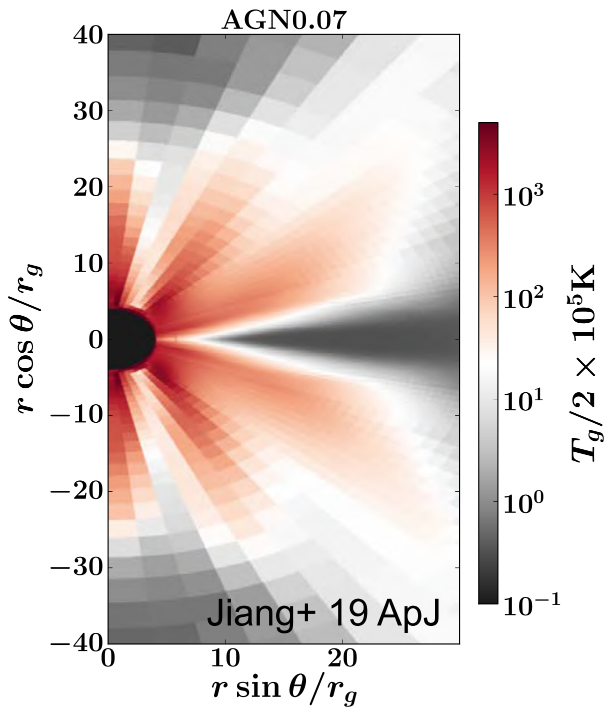
cores of active galactic nuclei (mainly jet-quiet AGNs)

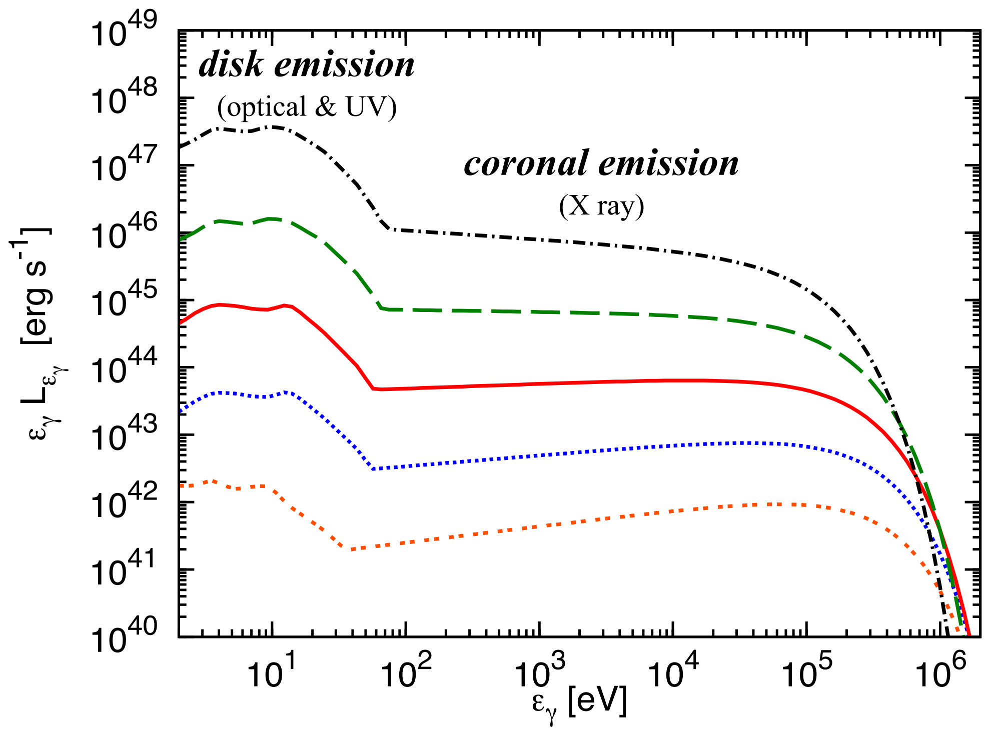


disk-corona system

opt/UV=multi-temp. blackbody

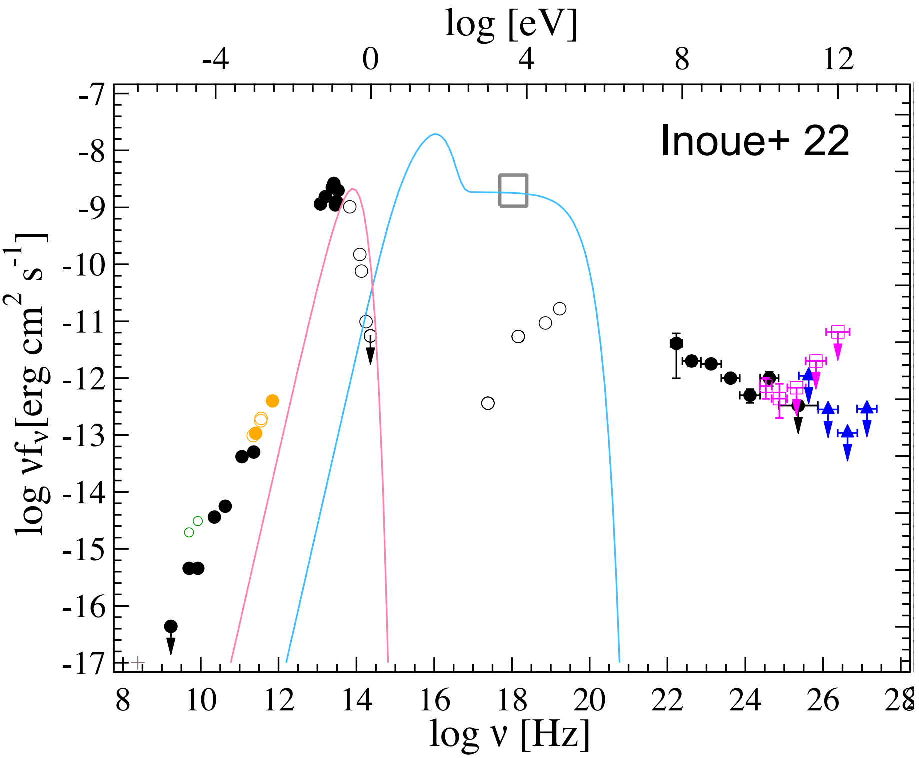
X-ray=Compton by thermal e

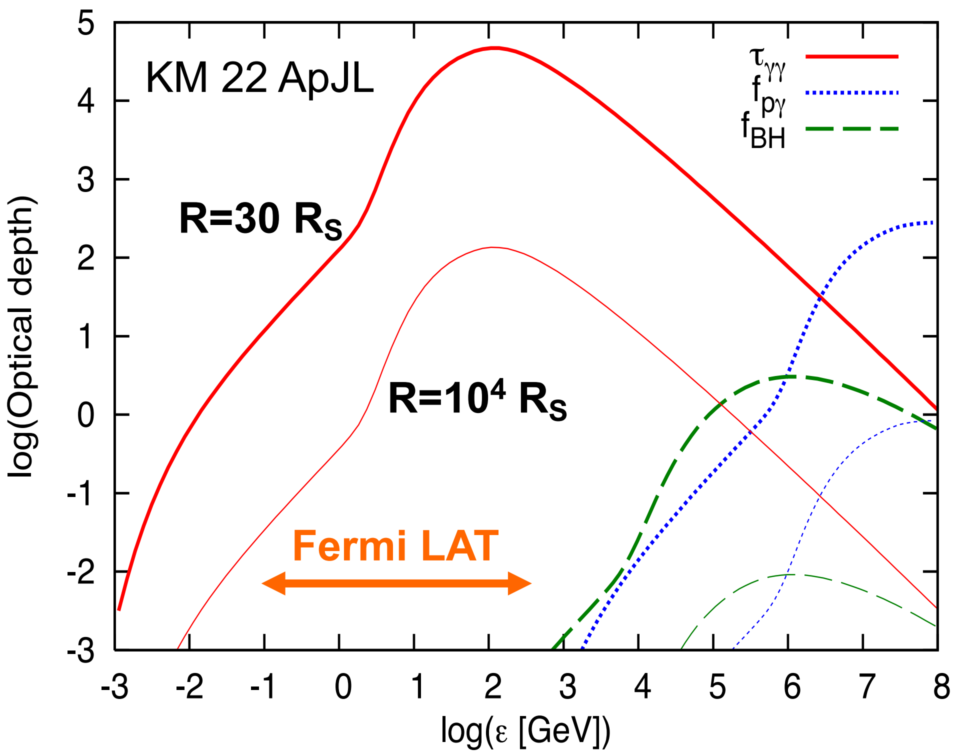




photomeson optical depths: both f_{pp} & $f_{p\gamma} > 1$ ("calorimetric")

Implications of Opaueness





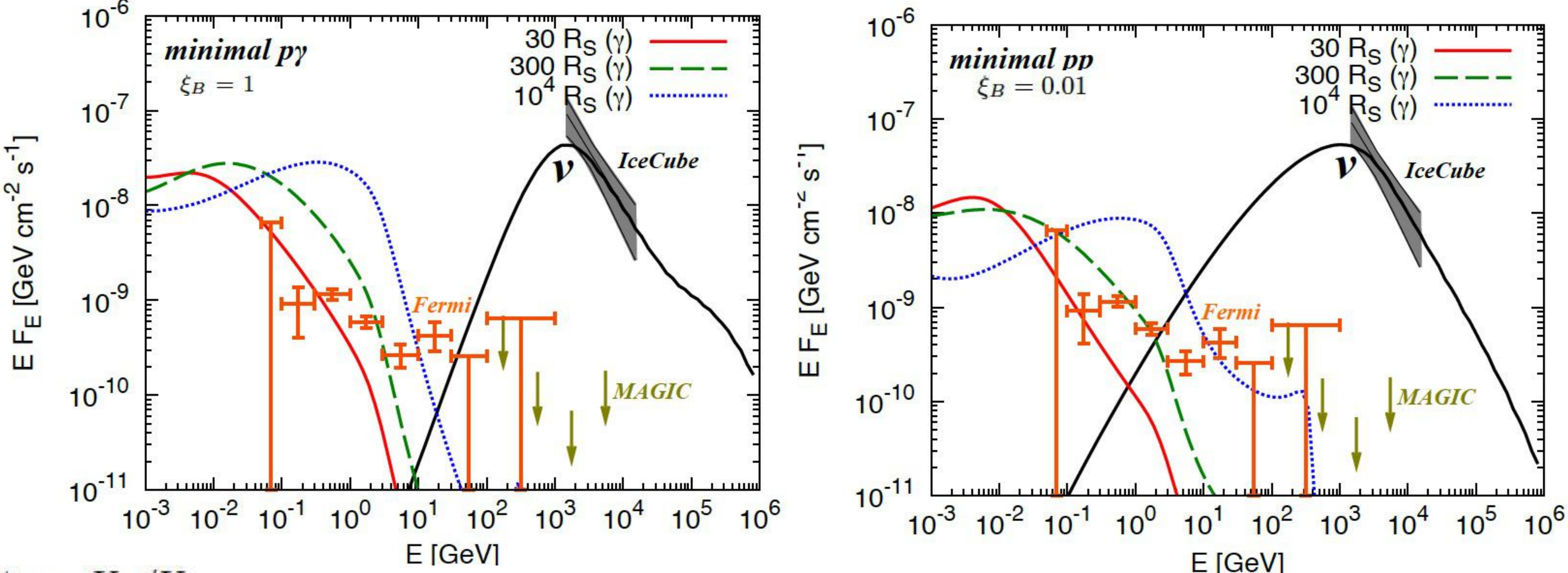
- NuSTAR: N_H~10^{25} cm^{-2} → L_X=7x10^{43} erg/s (Marinucci+ 16 MNRAS)
- Bolometric luminosity: ~10^{45} erg/s
- GeV gamma-rays can escape at >10^4 R_S ~ R_{BLR}

$\tau_{\gamma\gamma} \gtrsim 10$ for 0.1-300 GeV γ rays → **R < 30-100 R_S**

Where do Neutrinos Come from?

Q. neutrino emission radius?

KM 22 ApJL



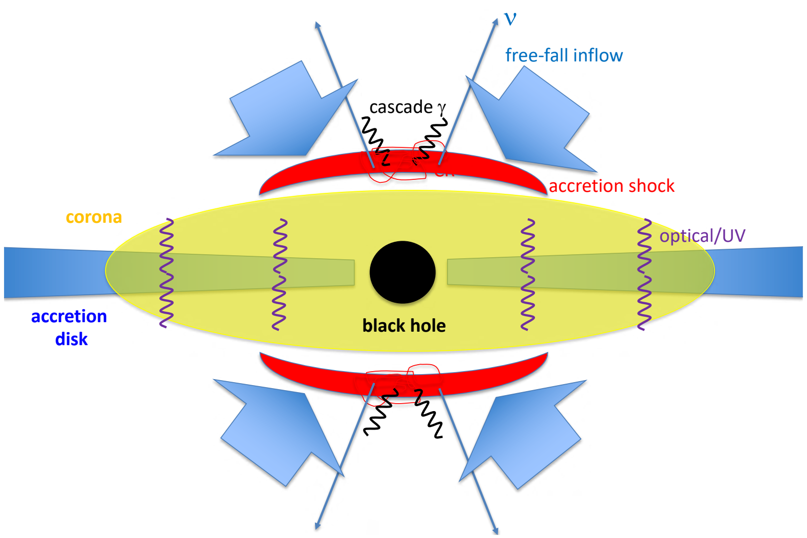
$\xi_B \equiv U_B/U_\gamma$

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

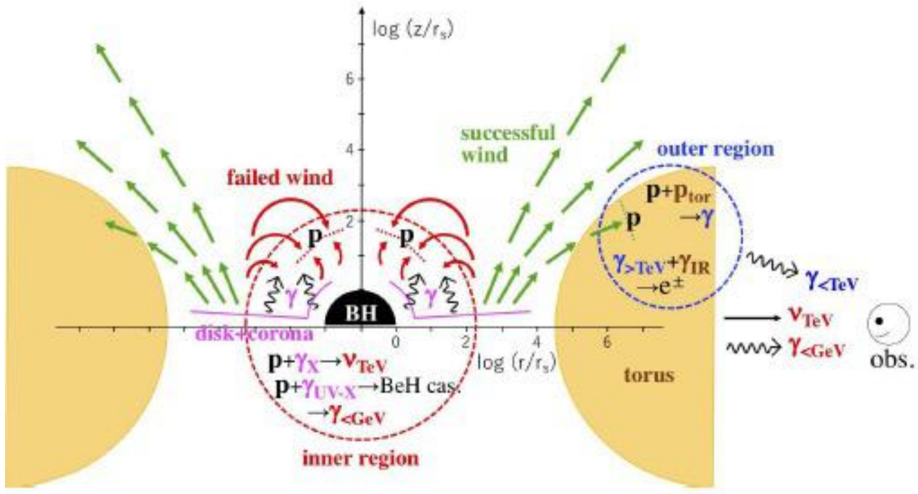
Neutrino emission most likely comes from the SMBH vicinity (ex. coronal regions, base of outflows)

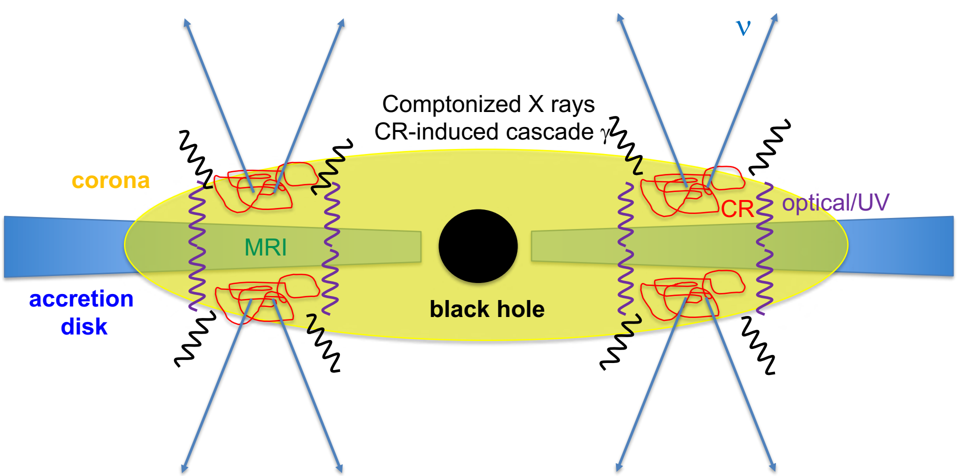
AGN Models

Accretion shock model
(ex. Stecker+ 91, Y. Inoue+ 20 ApJ)



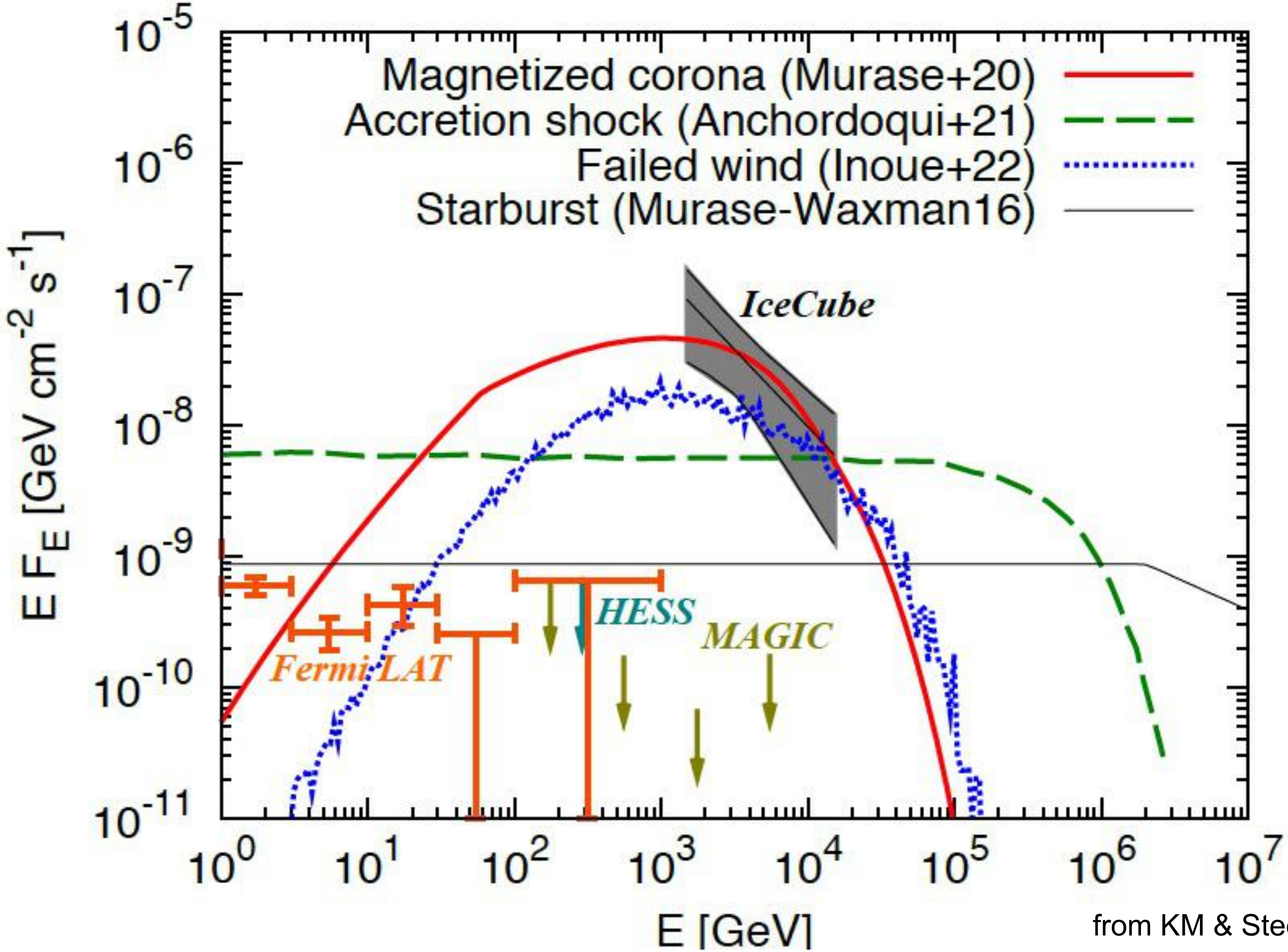
Failed-wind model
(S. Inoue, Cerruti, KM+ 22)





Magnetically-powered corona model
(KM+ 20 PRL, Eichmann+ 22)

AGN Models

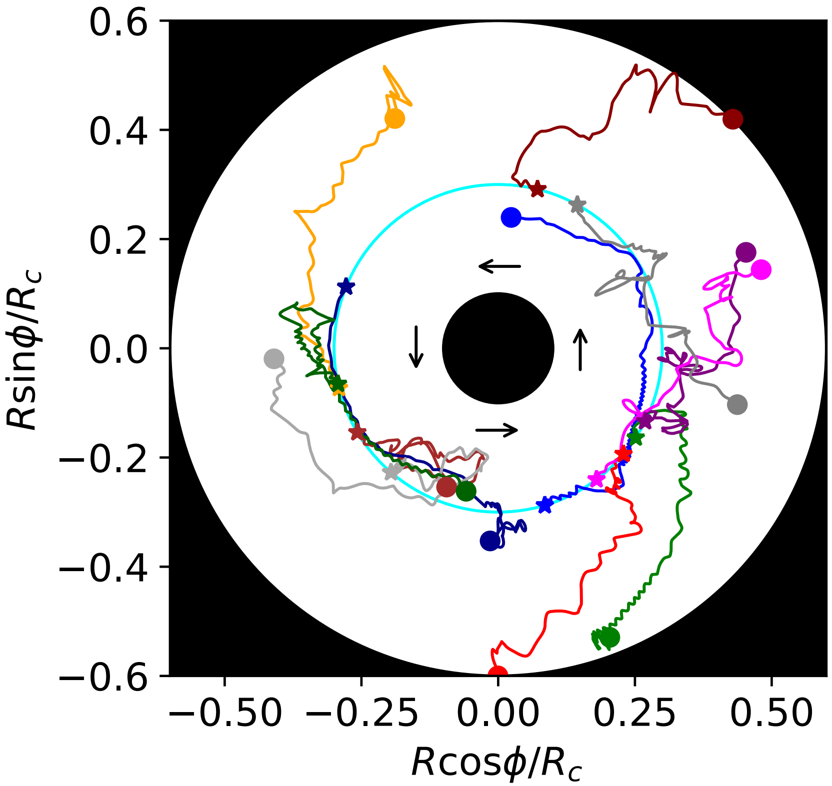


from KM & Stecker 22

Particle Acceleration in Coronae?

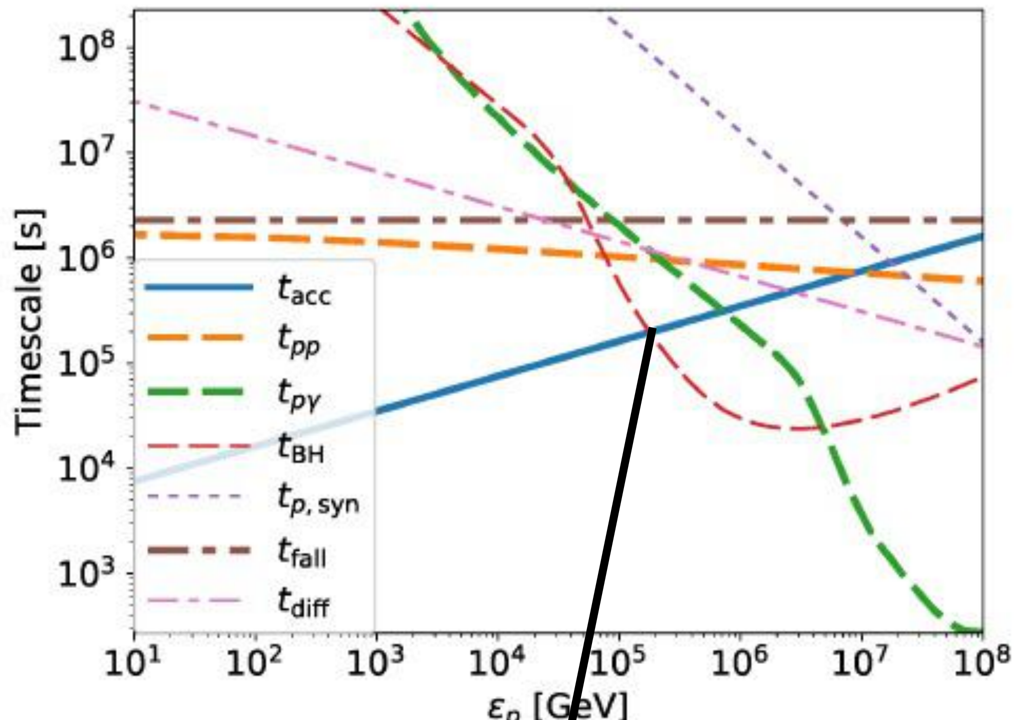
Magnetorotational Instability (MRI) -> turbulence & reconnection

Kimura, Tomida & KM 19 MNRAS
Sun & Bai 21 MNRAS



stochastic acc. in global MHD simulations w. Athena++

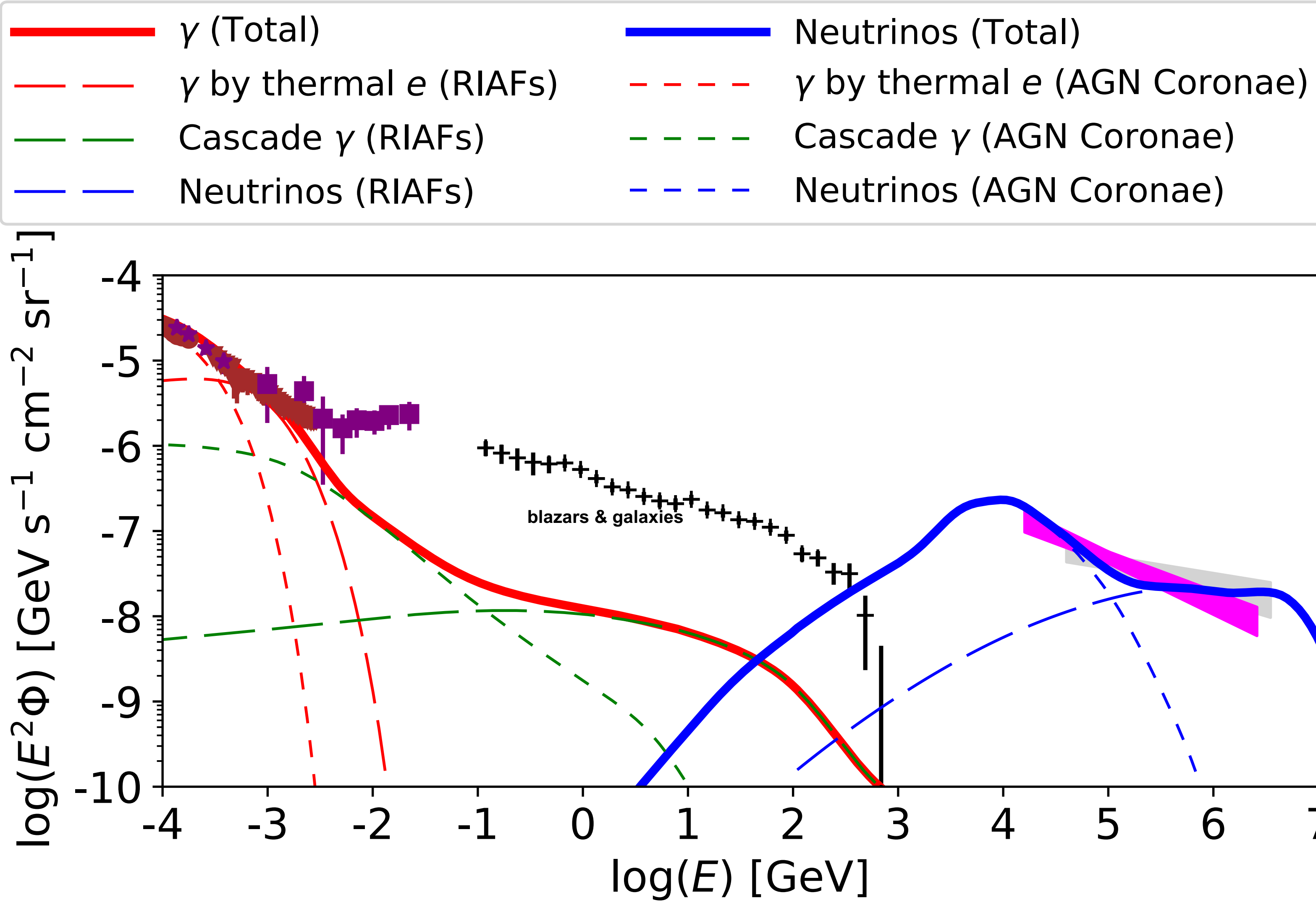
KM, Kimura & Meszaros 20 PRL



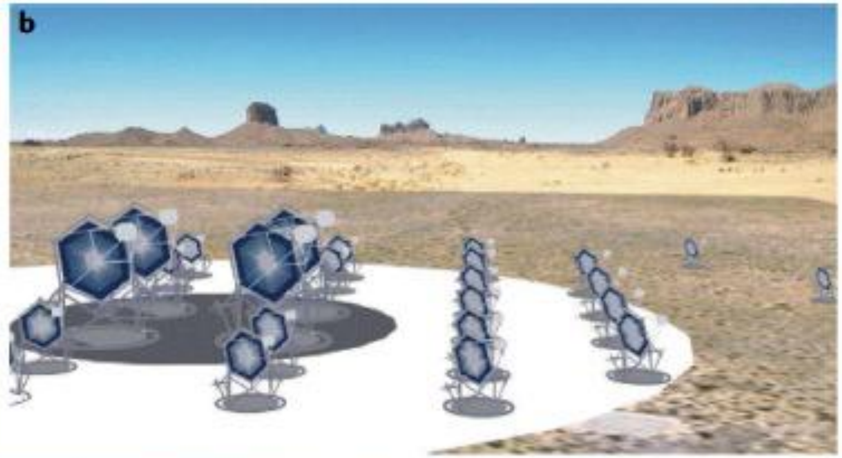
ε_p^{max} ~ 100 TeV (ε_ν^{max} ~ 20 TeV)

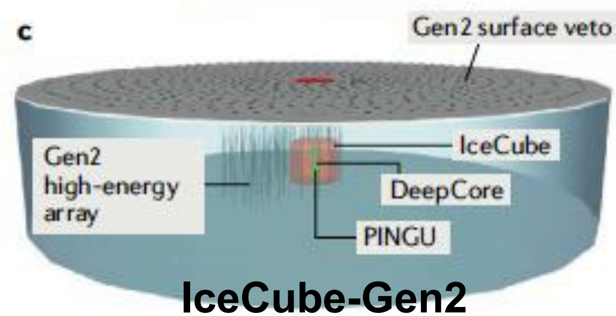
AGN Manifesting in the Multi-Messenger Sky?

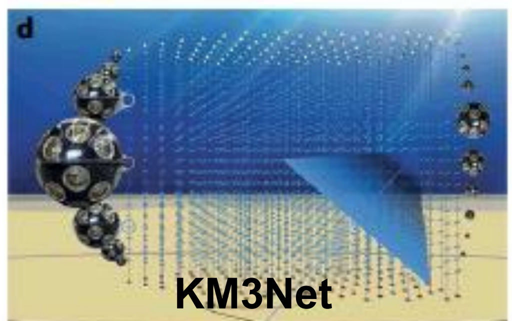
KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.

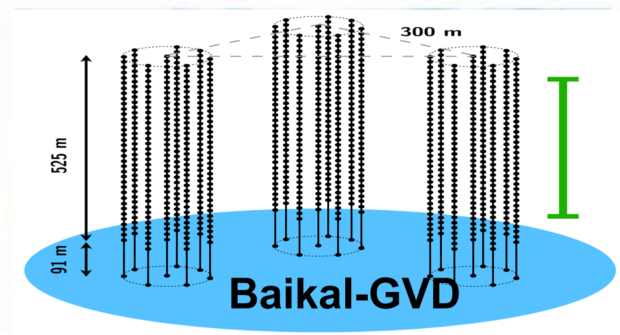


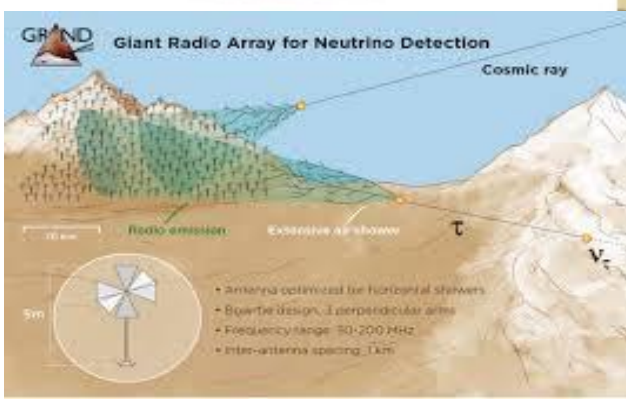
Testability











More multi-messenger data in the next decade will enable us to test the proposed models

X-ray Brightest AGN in 2-10 keV (Swift)

Kheirandish, KM & Kimura 21 ApJ

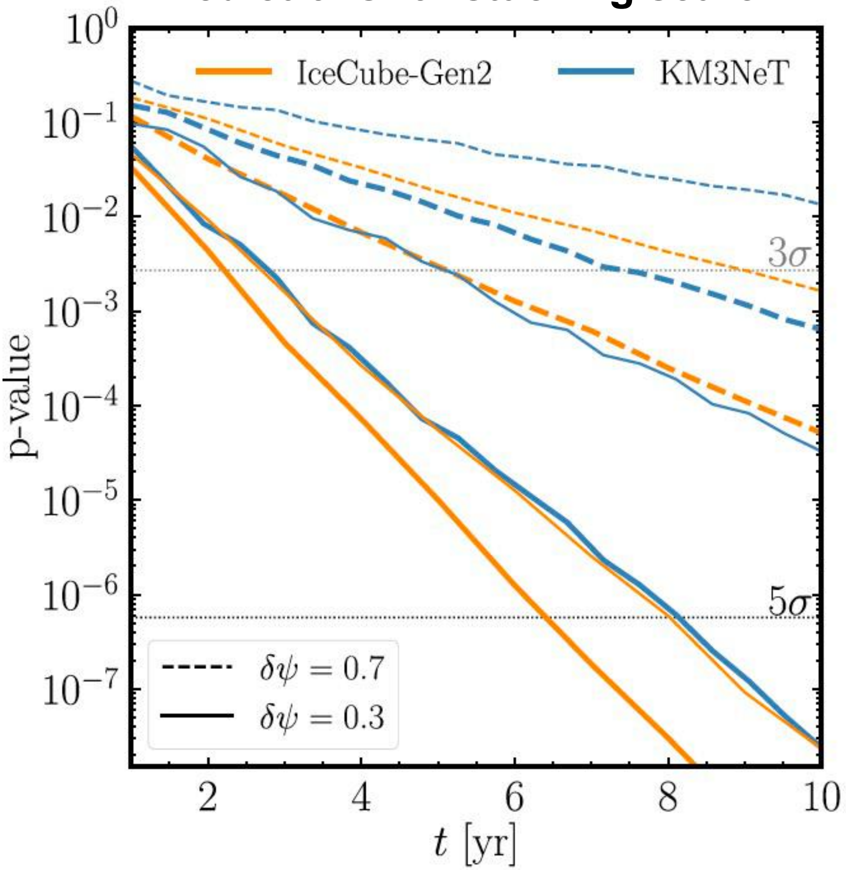
Top 10 sources for IceCube	Top 10 sources for KM3Net
1. NGC 1068	1. *Cen A
2. *NGC 1275	2. Circinus Galaxy
3. CGCG 164-019	3. ESO 138-1
4. UGC 11910	4. NGC 7582
5. *Cen A	5. NGC 1068
6. Circinus Galaxy	6. NGC 4945
7. NGC 7582	7. NGC 424
8. ESO 138-1	8. UGC 11910
9. NGC 424	9. CGCG 164-019
10.NGC 4945	10. *NGC 1275

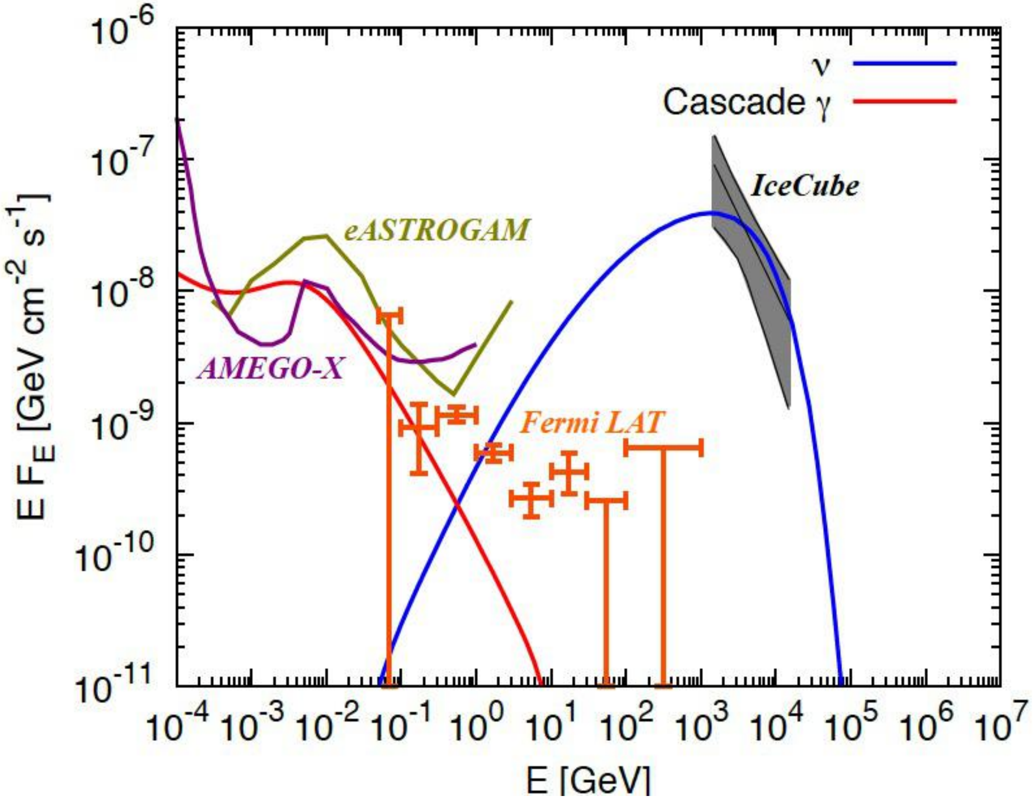
*** may belong to different classes**

Detectability of Nearby Seyfert Galaxies

KM, Kimura & Meszaros 20 PRL, Kheirandish, KM & Kimura 21 ApJ

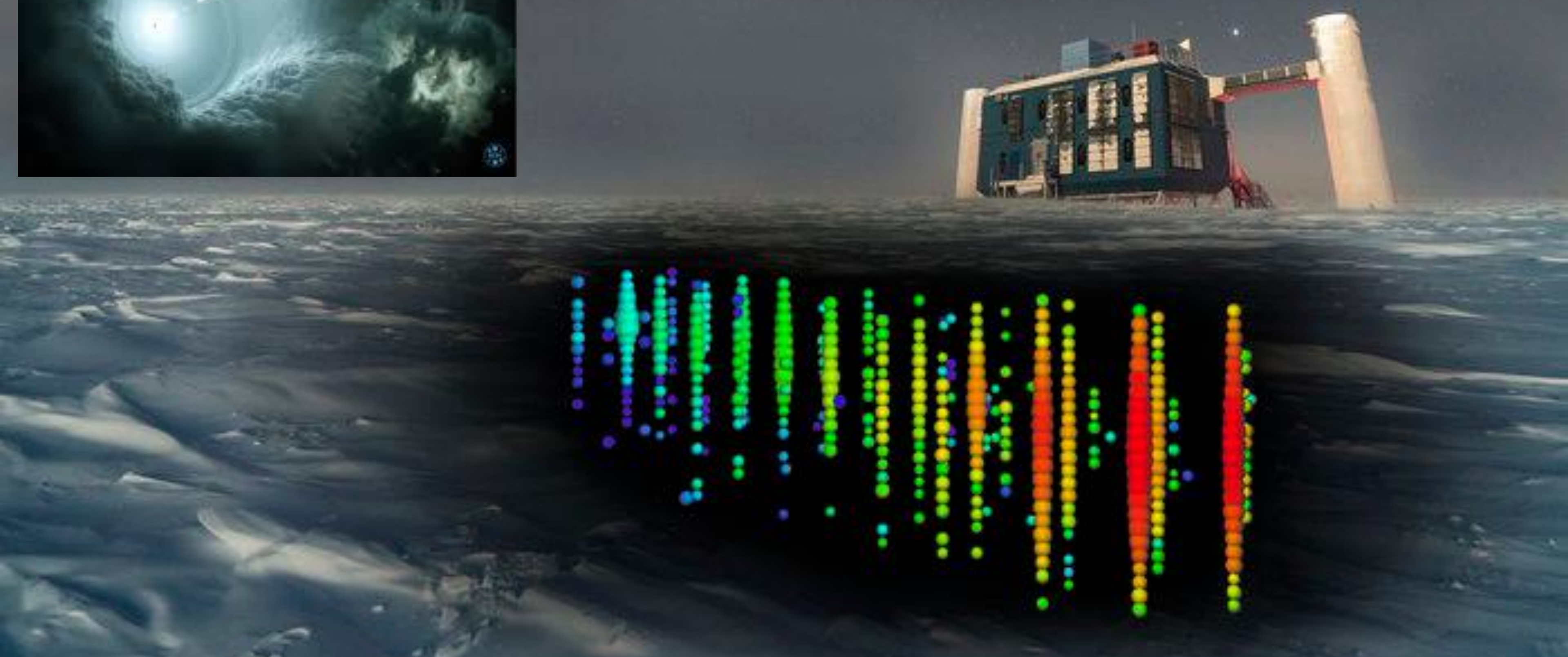
Predictions for stacking search



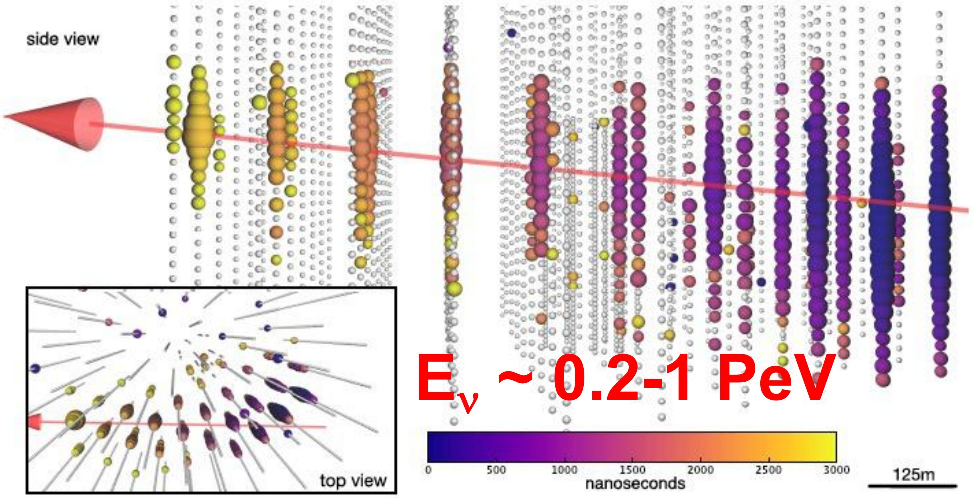


- Testable w. near-future data or by next-generation neutrino detectors given that the angular resolution is <0.3 deg
  #2.6σ with 8 yr upgoing ν_μ events and IR-selected AGN (IceCube 22 PRD)
- CR-induced cascade γ rays are promising in the MeV range

Transients

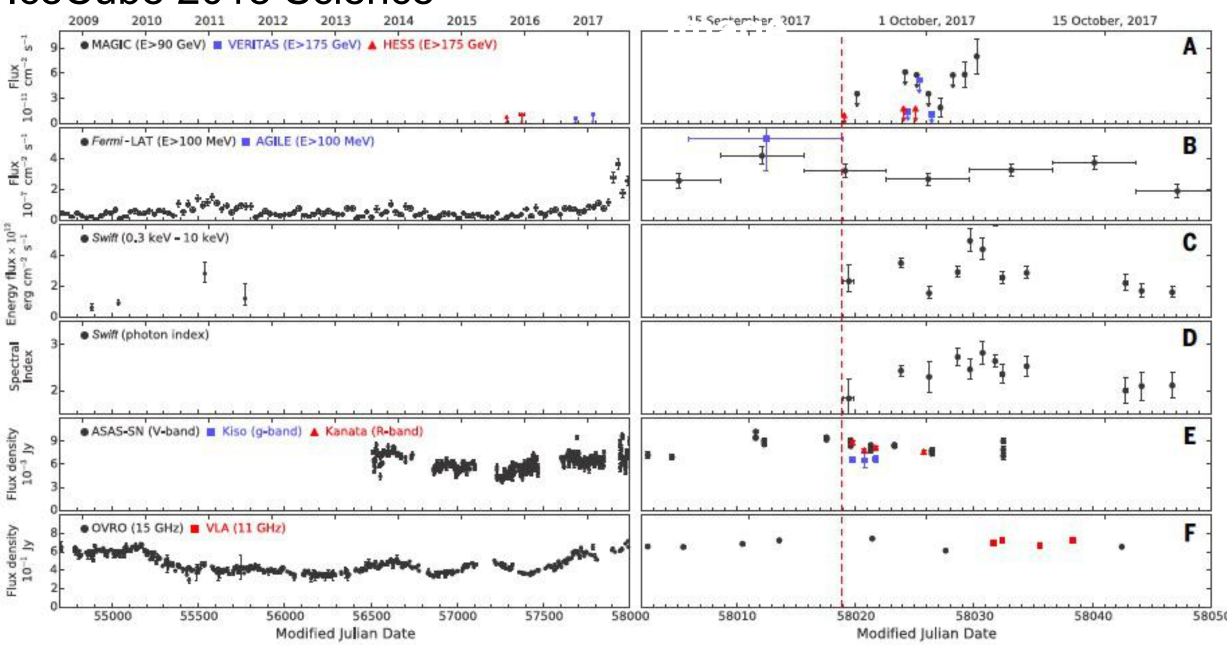


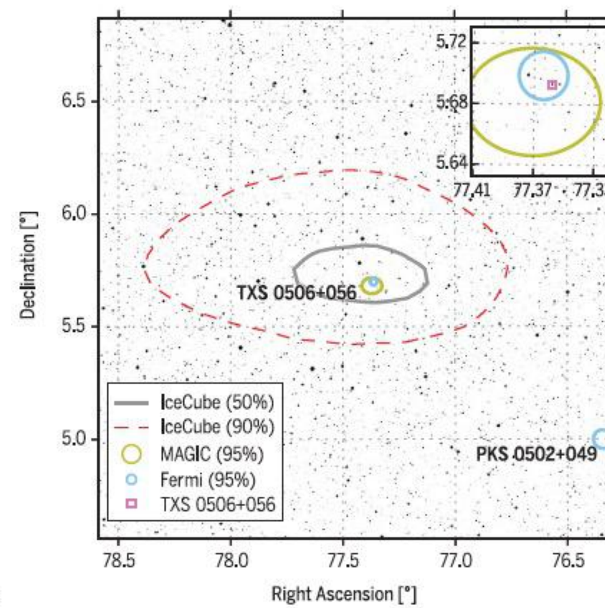
IceCube 170922A & TXS 0506+056



- IceCube EHE alert pipeline
- Automatic alert (via AMON/GCN)
- Kanata observations of blazars
  -> Fermi-LAT (Tanaka et al.)
  ATel #10791 (Sep/28/17)
- Swift (Keivani et al.)
  GCN #21930, ATel #10942
  NuSTAR (Fox et al.) ATel #10861
- **~3σ coincidence**

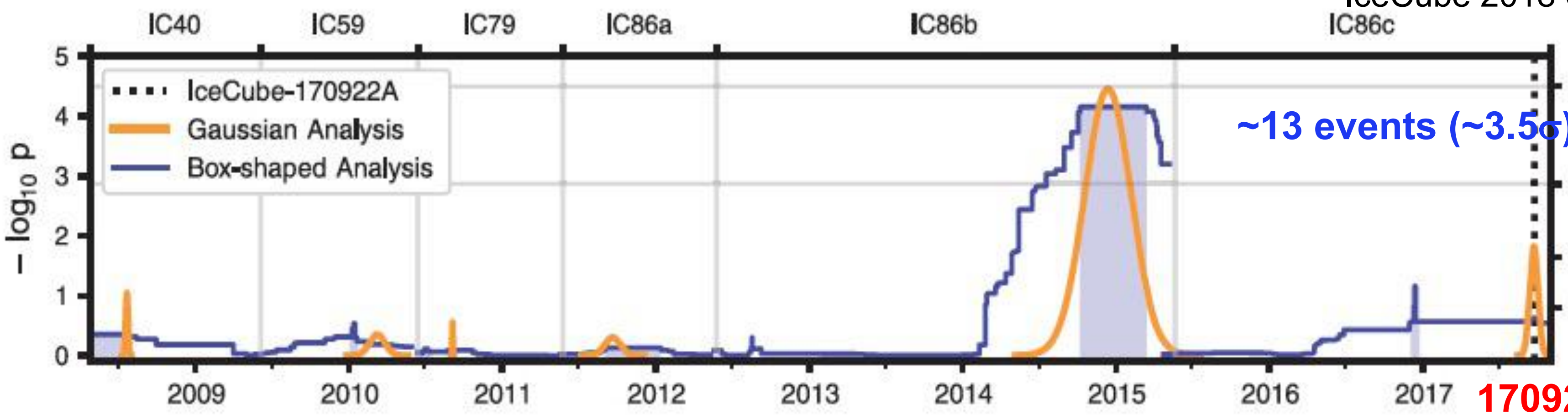
IceCube 2018 Science

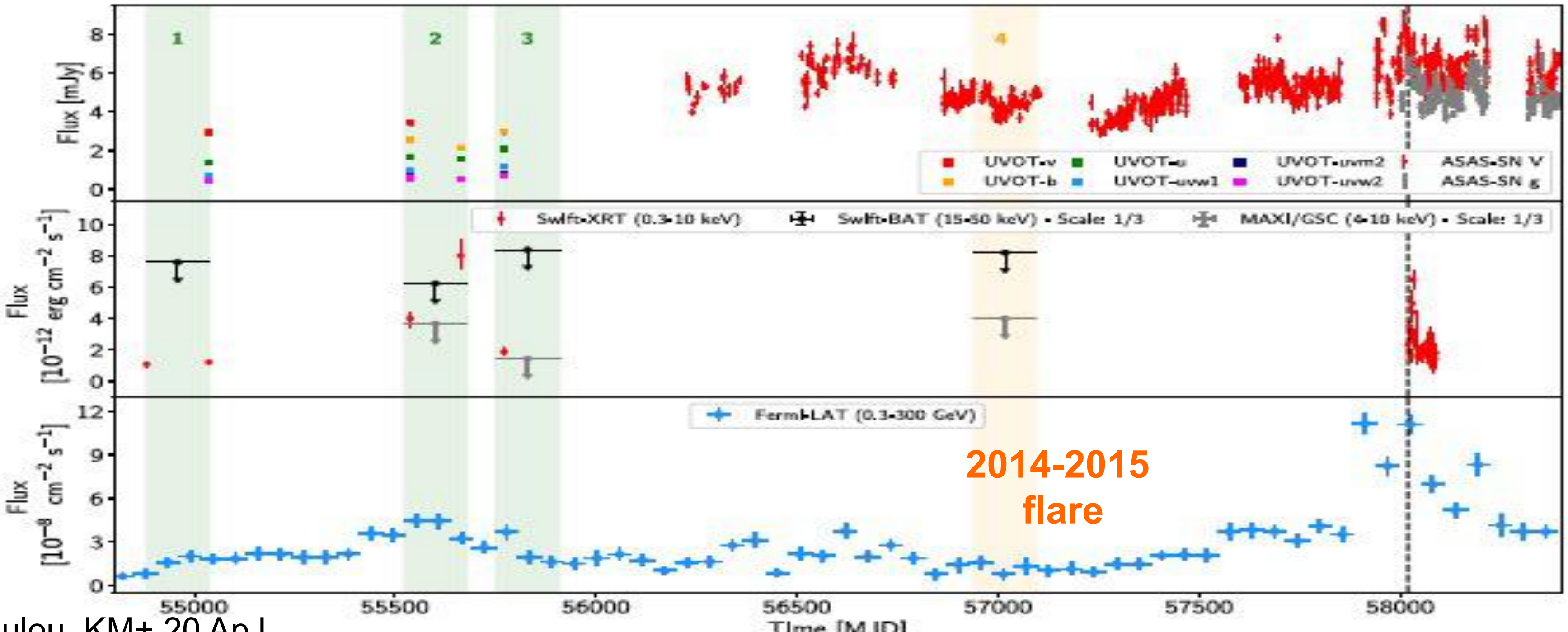




2014-2015 Neutrino Flare

IceCube 2018 Science



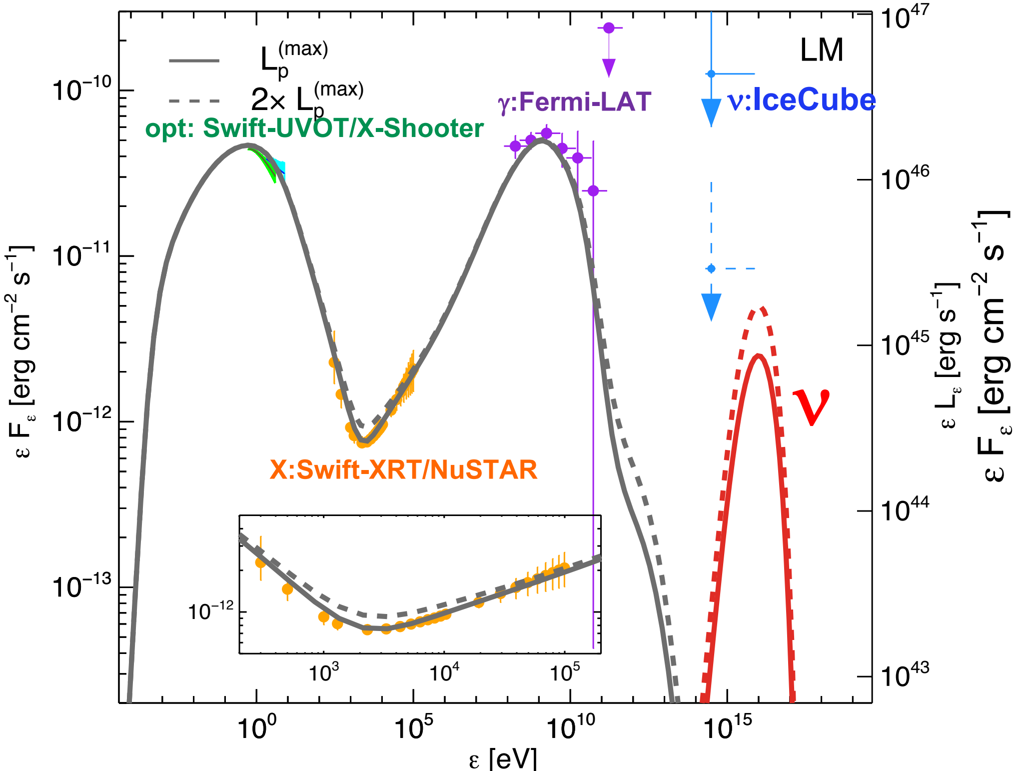


Petropoulou, KM+ 20 ApJ

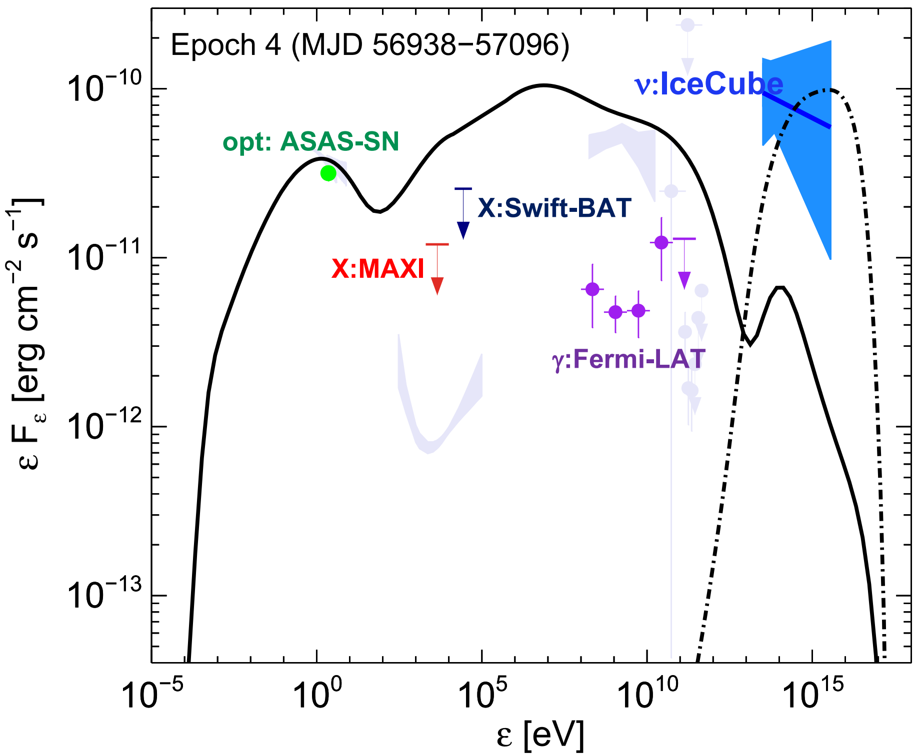
“Power” of Multi-Messenger Approaches

$p\gamma \rightarrow \nu, \gamma + e$ **electromagnetic energy must appear at keV-MeV**

2017 multi-messenger flare
Keivani, KM et al. 18 ApJ



2014-2015 neutrino flare
Petropoulou, KM et al. 20 ApJ



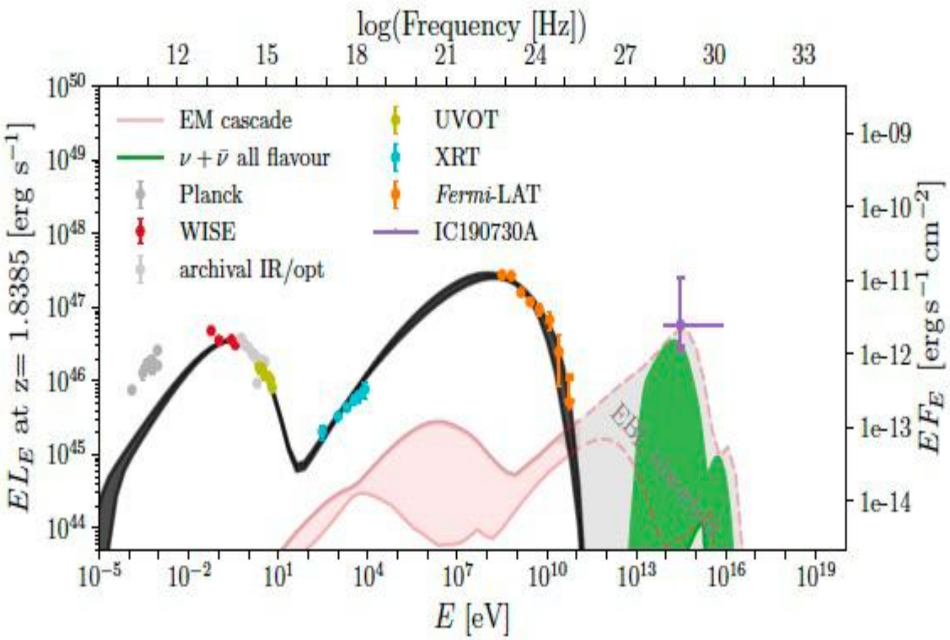
$F_\nu \sim F_{cas} < F_{obs}$

Puzzling: standard single-zone models do NOT give a concordance picture

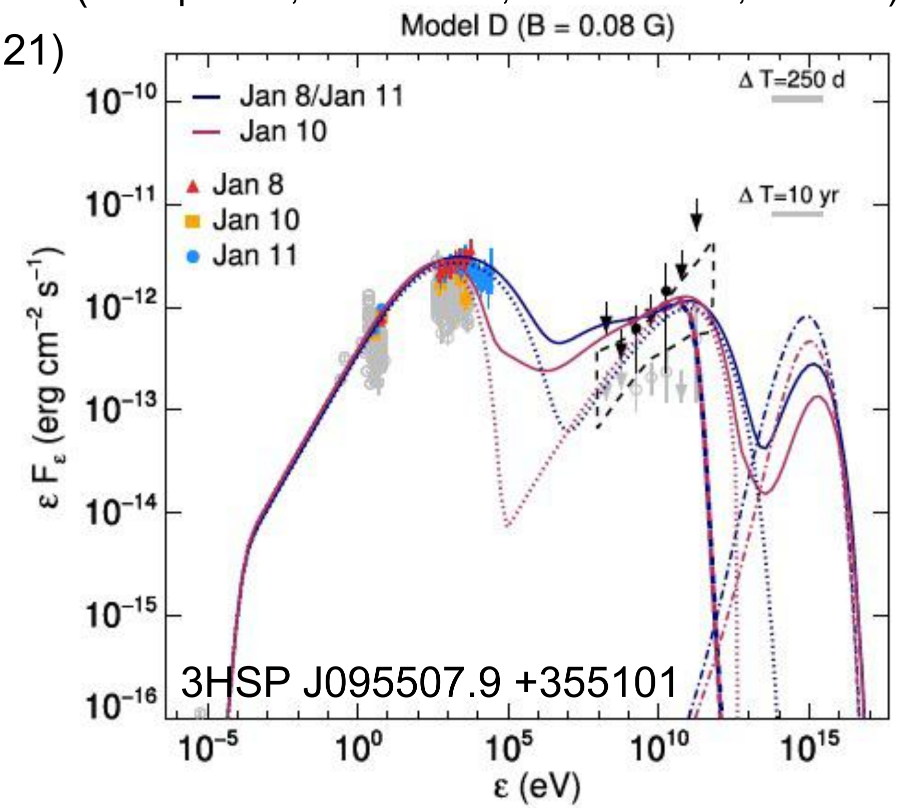
More Coincidences w. Blazars

More follow-up campaigns and/or larger statistics in ν data are necessary
But the situation is still puzzling…

IceCube-190730A (Oikonomou, Petropoulou, KM+ 21)

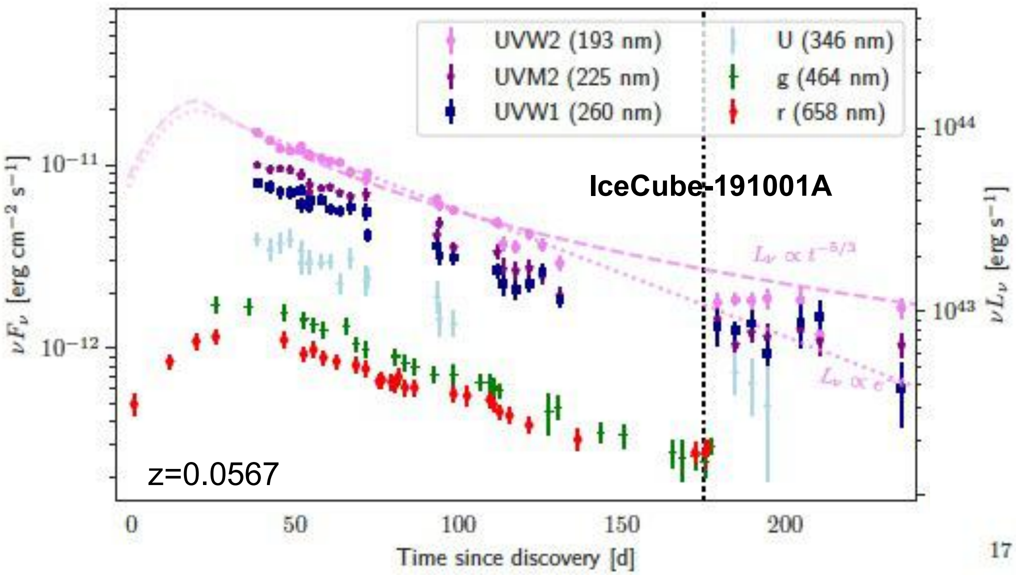


IceCube-200107A
(Petropoulou, Oikonomou, Mastichiadis , KM+ 20)



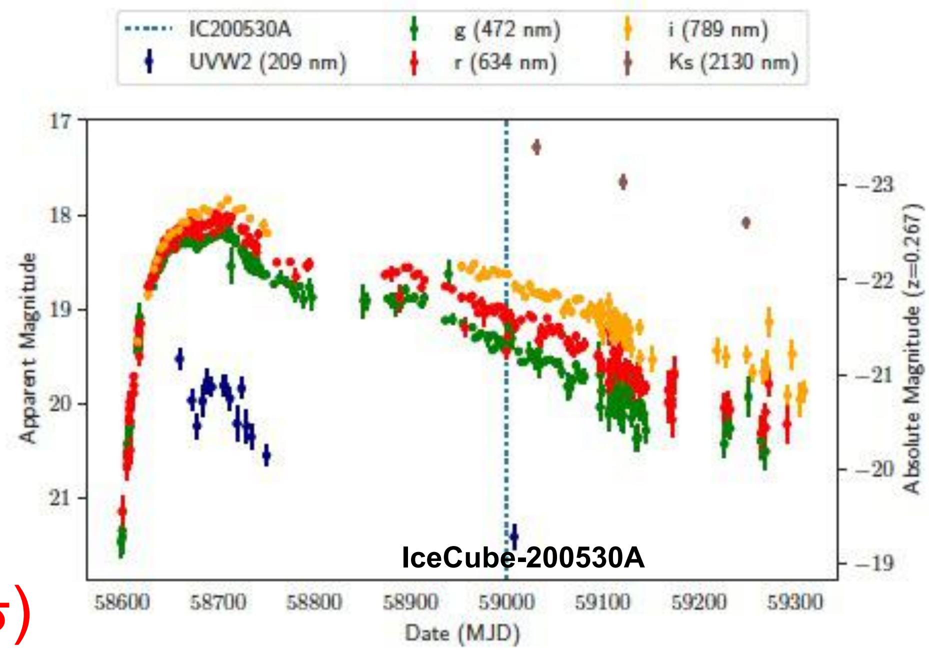
- PKS 1502+106: FSRQ
  promising but no coincidence w. γ-ray flaring, unseen in ν point-source search
- 3HSP J095507.9+355101: extreme BL Lac
  coincidence w. X-ray flaring but the alert rate is at most ~1-3% in 10 years
- PKS 0735+178: coincidence w. X-ray & γ-ray flaring TXS 0506+056-like (Sahakyan+ 22)

Coincidences w. Optical Transients



IceCube-191001A
& AT 2019dsg
(Stein+ 21 Nature Astron.)

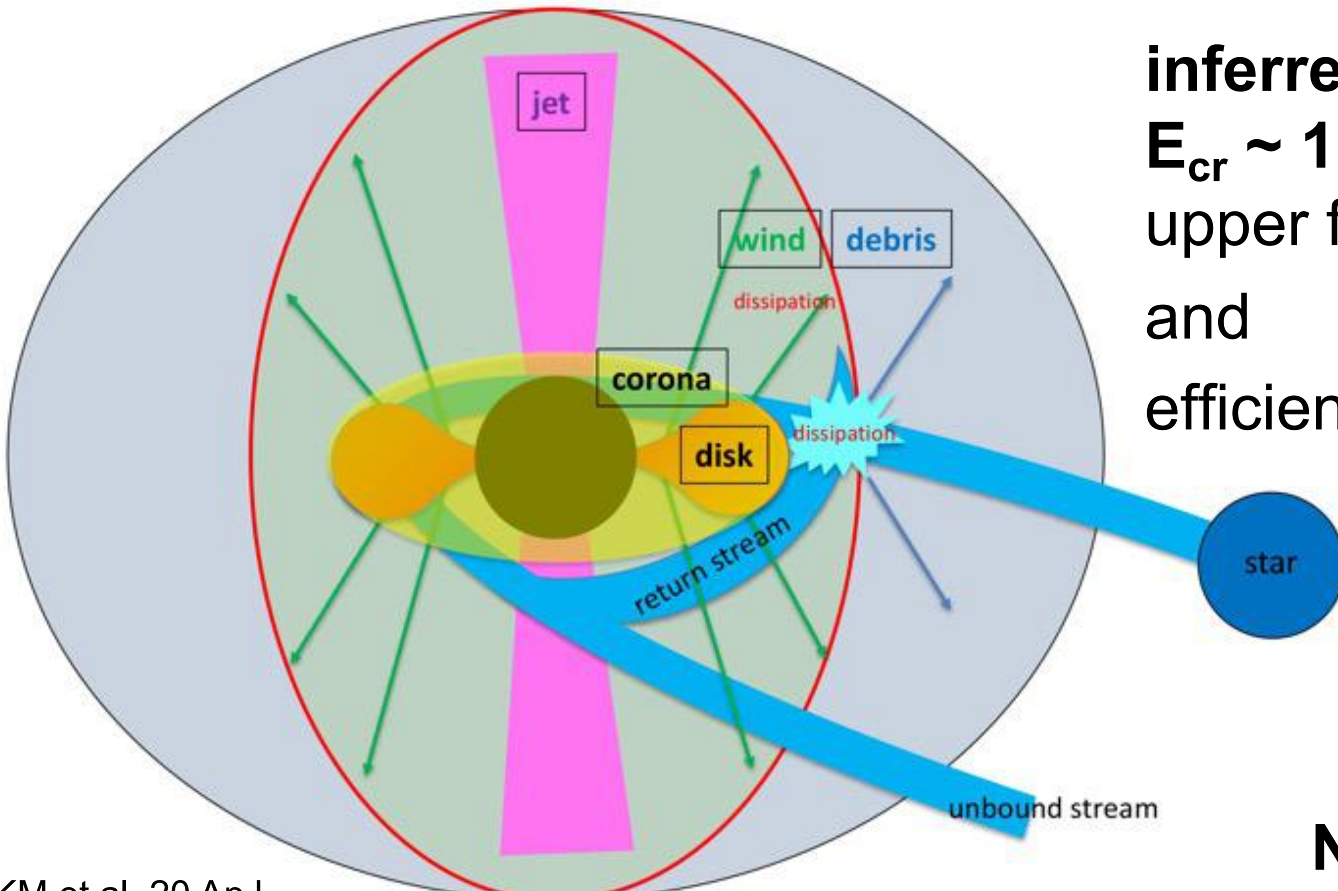
IceCube-200530A
& AT 2019fdr
(Reusch+ KM 21 PRL)



Both are rare optical transients
with strong radio emission (>3.4σ)

Neutrinos from Black Hole "Flares"?

- AT 2019dsg, AT 2019fdr, AT 2019aalc: TDE candidates
- TDE and AGN νs could originate from common mechanisms (disk-corona? jet? wind colliding w. stellar debris?)



KM et al. 20 ApJ

inferred CR energy
$E_{cr} \sim 10^{53\text{-}54}$ erg > E_{EM}
upper fluctuation

and

efficient CR acceleration

Need more data

Summary

- Multi-messenger analyses w. 10 TeV ν data have suggested hidden CR accelerators

- NGC 1068: evidence for a hidden neutrino source
- Emission radius: $R<30\text{-}100\ R_S$
- All-sky νs (even at 10 TeV) can be explained as γ-ray hidden sources
- More in south (KM3Net/Baikal-GVD) IceCube-Gen2, MeV γ–ray tests

- Transients – blazar flares, TDEs
- TXS 0506+056 and other coincidences: no simple picture
- TDE and AGN νs could originate from common mechanisms
- More data are needed

from Murase's talk
@ Neutrino 2014

WANTED

~~Diffuse or A~~ssociated

ν

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