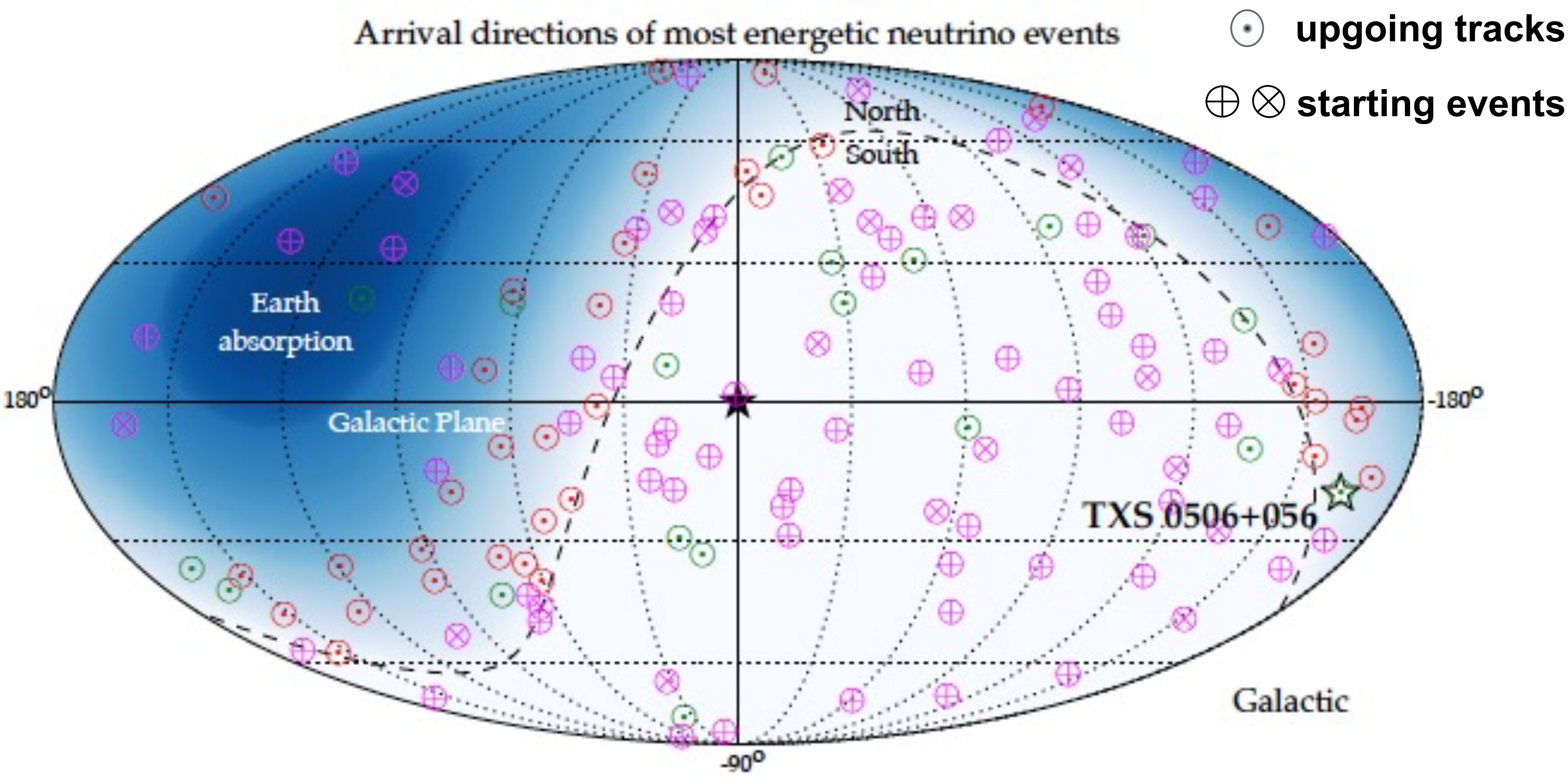
High-Energy Neutrinos from Supermassive Black Holes

Kohta Murase (PSU/YITP)

November 15 2023

CDY Workshop

High-Energy Neutrino Sky

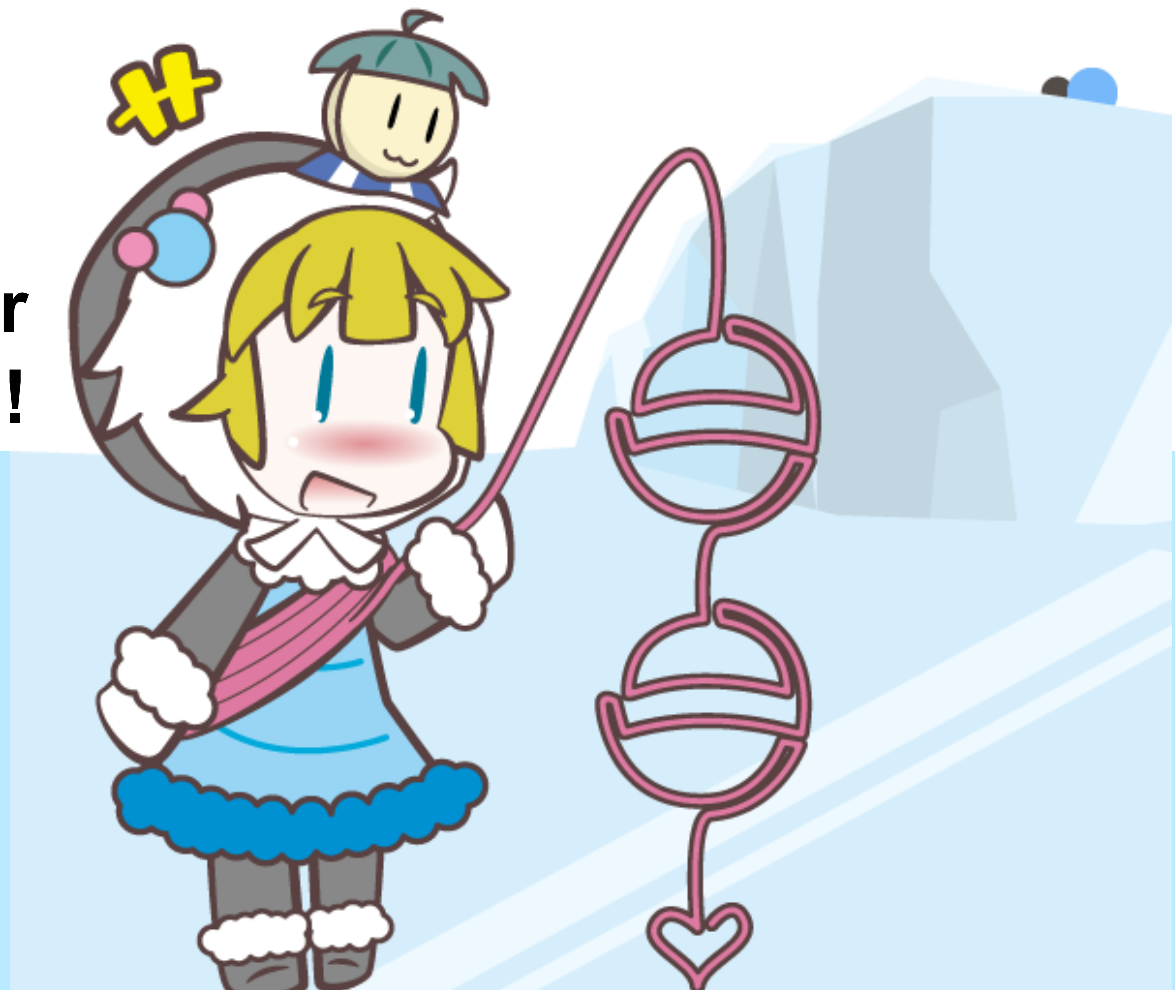


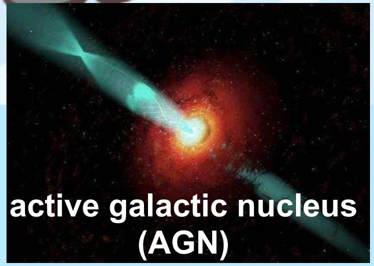
consistent w. isotropic distribution/extragalactic origins

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

Where do neutrinos mainly come from?

monster fishing!!





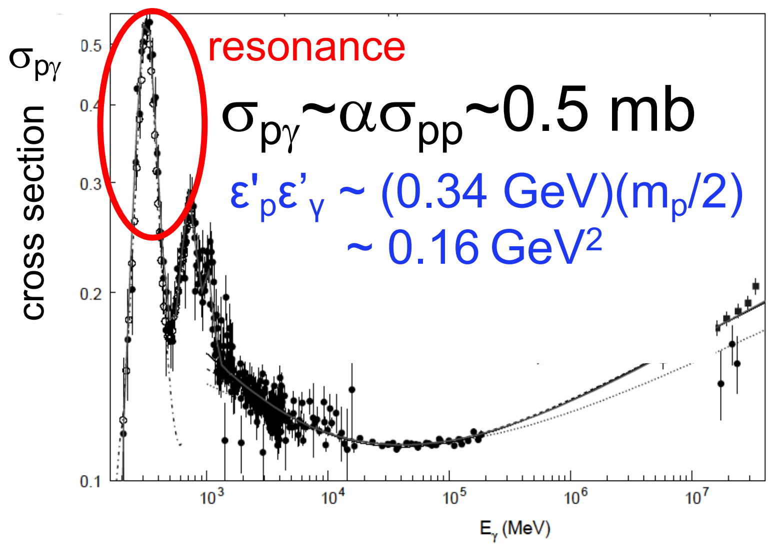
High-Energy Neutrino Production Processes

Cosmic-ray Accelerators

Active galaxy

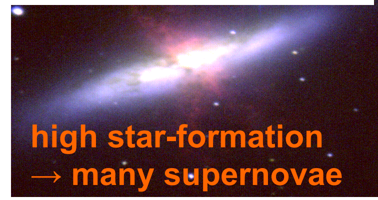
γ-ray burst

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



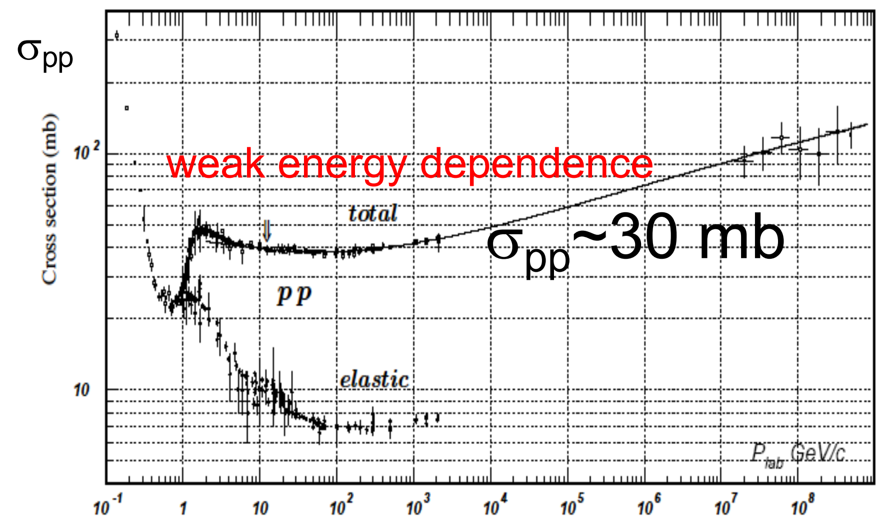
Cosmic-ray Reservoirs

Starburst galaxy

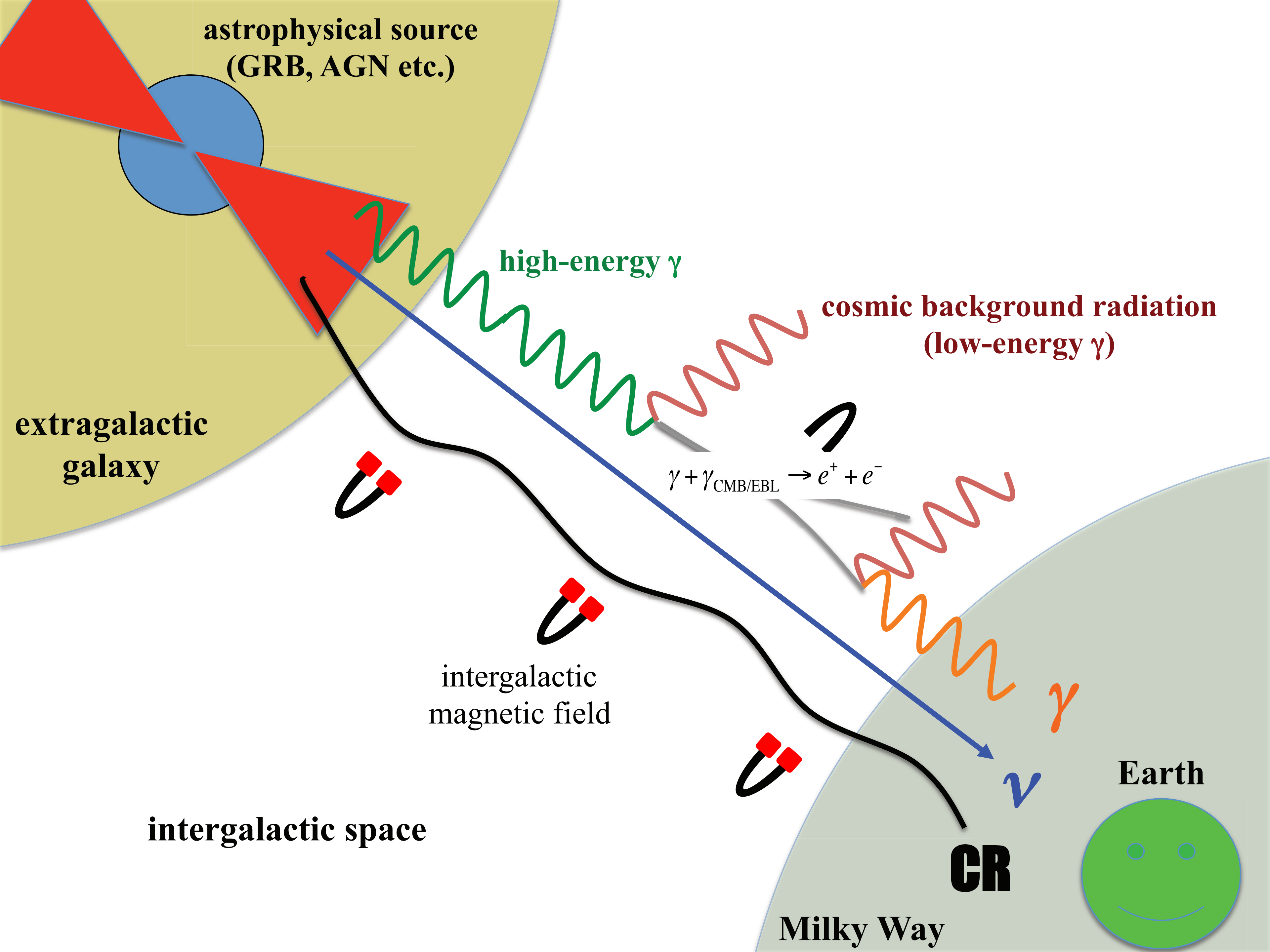


Galaxy cluster

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

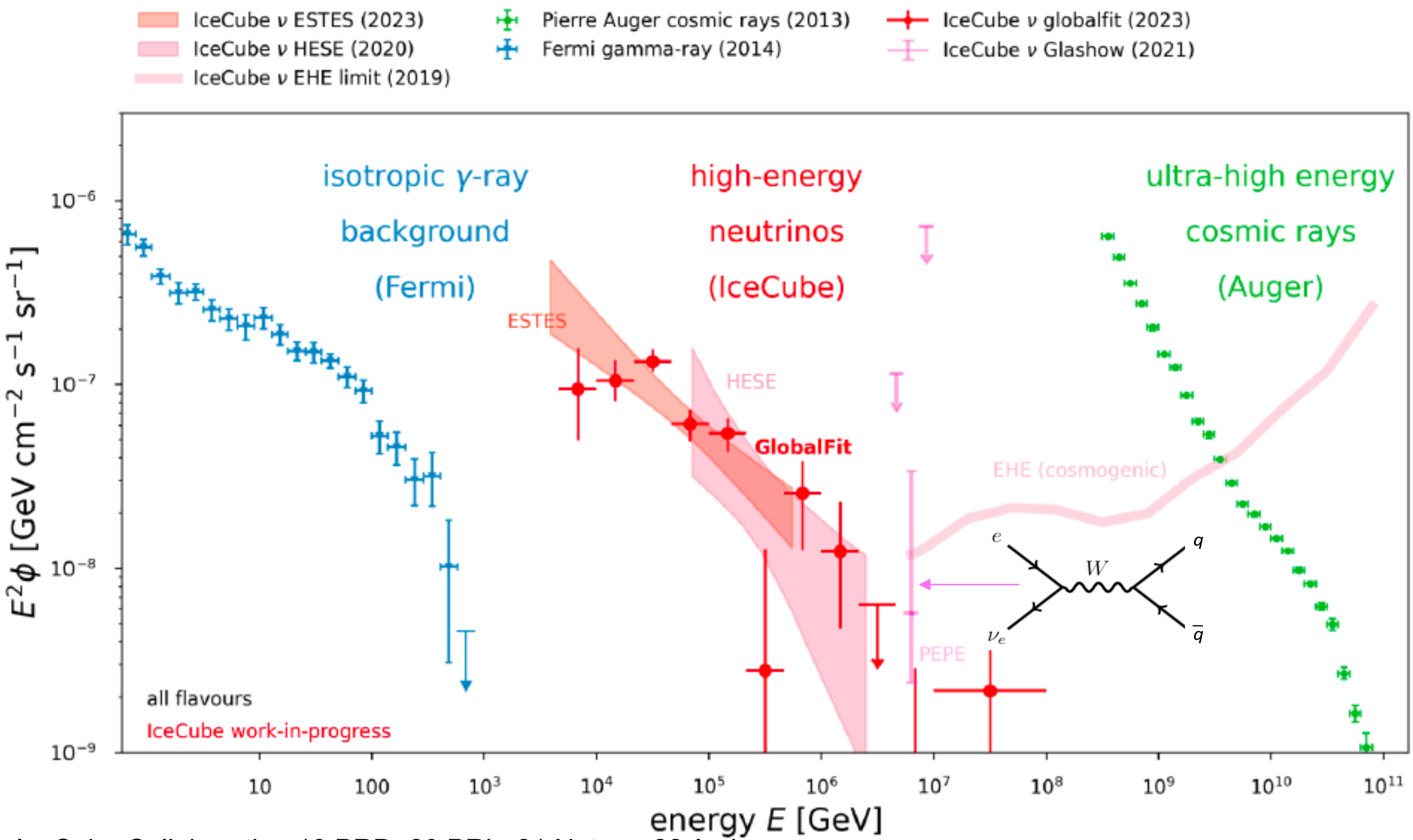


$$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e \ (\text{or } \bar{\nu}_e) + e^{\pm}$$



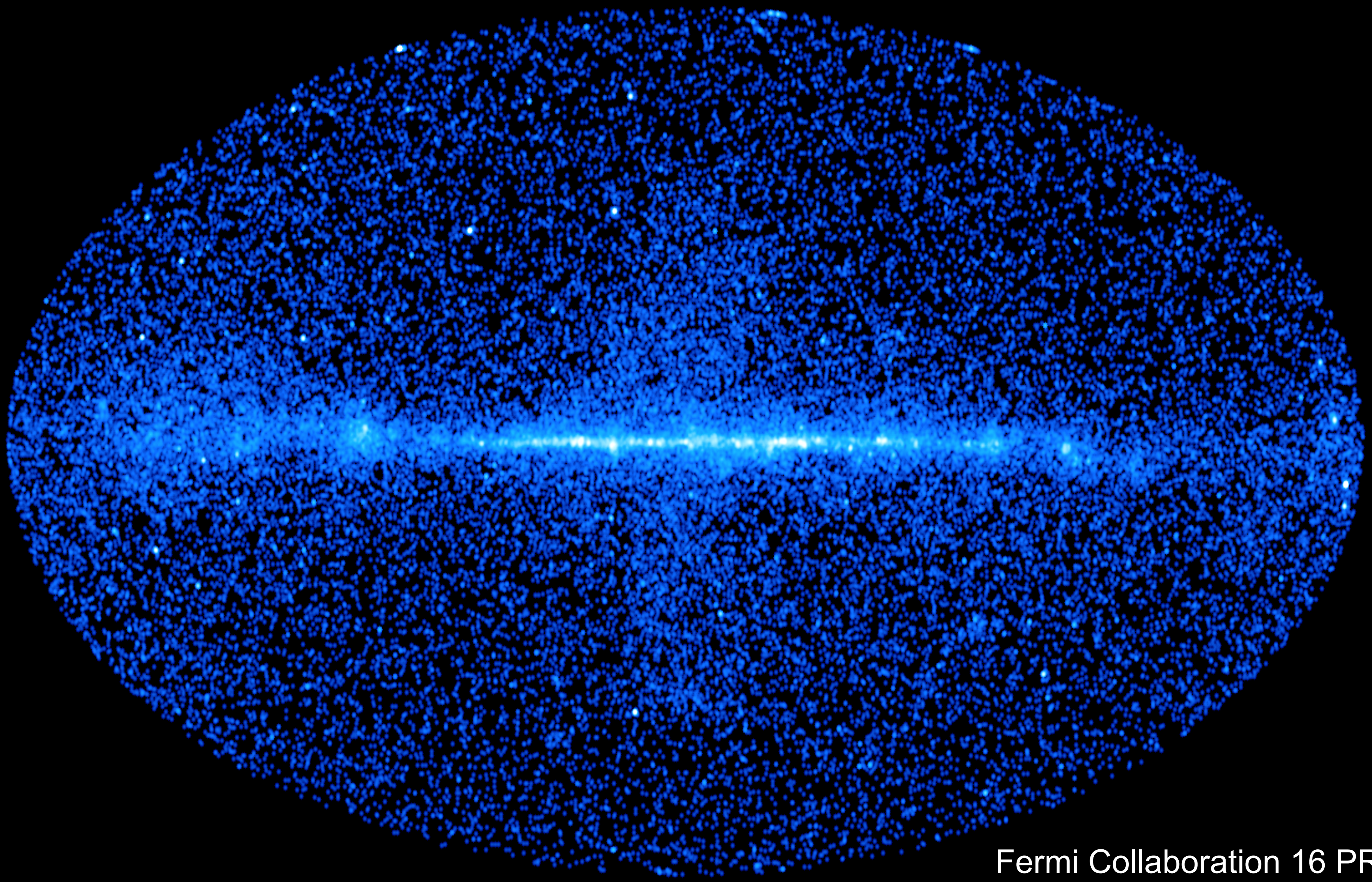
astrophysical source
(GRB, AGN etc.)
high-energy γ
cosmic background radiation
(low-energy γ)
extragalactic
galaxy
$\gamma + \gamma_{CMB/EBL} \rightarrow e^{+} + e^{-}$
intergalactic
magnetic field
γ
ν
Earth
intergalactic space
CR
Milky Way

Updated All-Sky Neutrino Flux & Spectrum



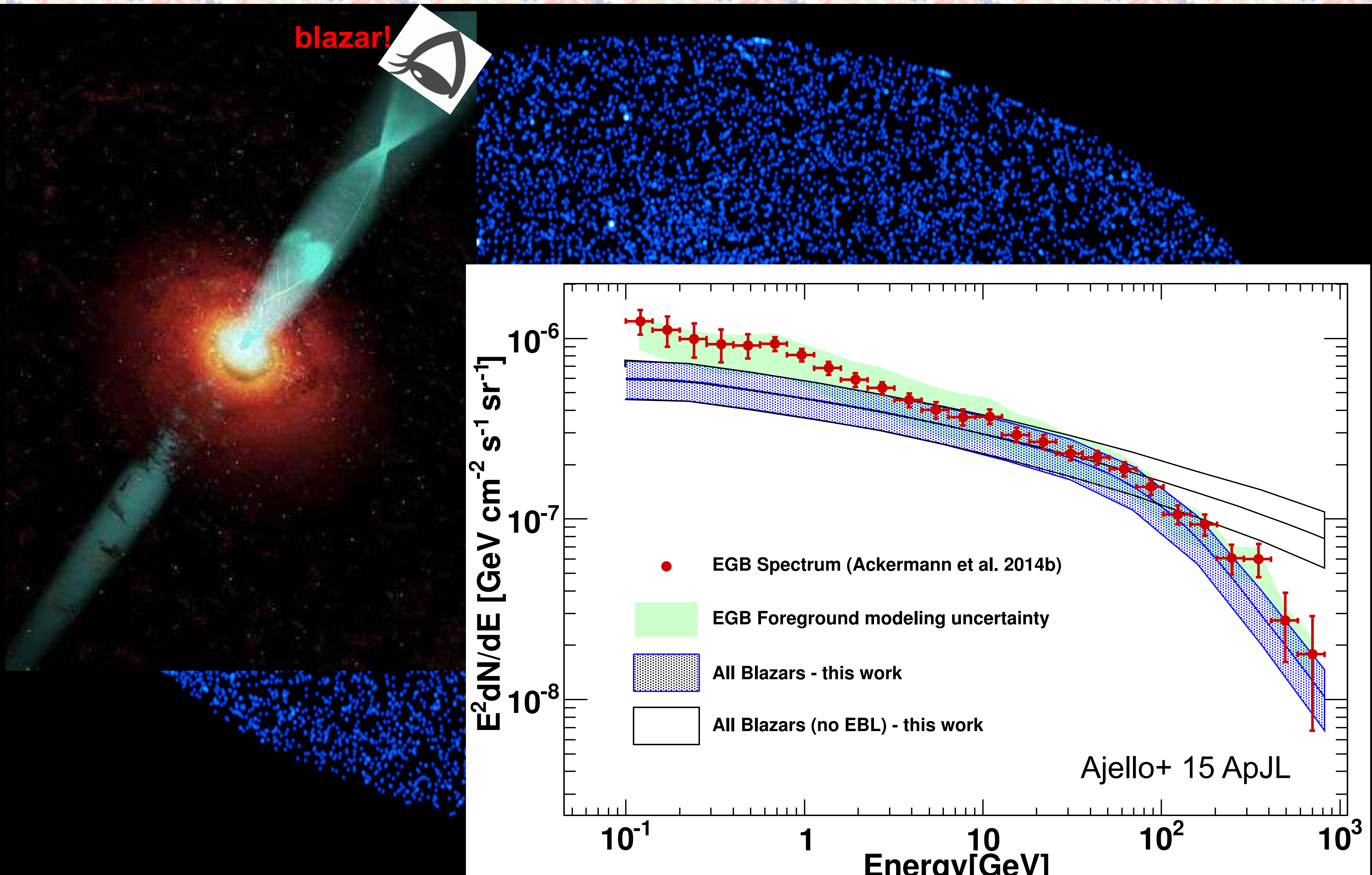
IceCube Collaboration 18 PRD, 20 PRL, 21 Nature, 22 ApJ

Extragalactic Gamma-Ray Sky: Dominated by Jetted AGN



Fermi Collaboration 16 PRL

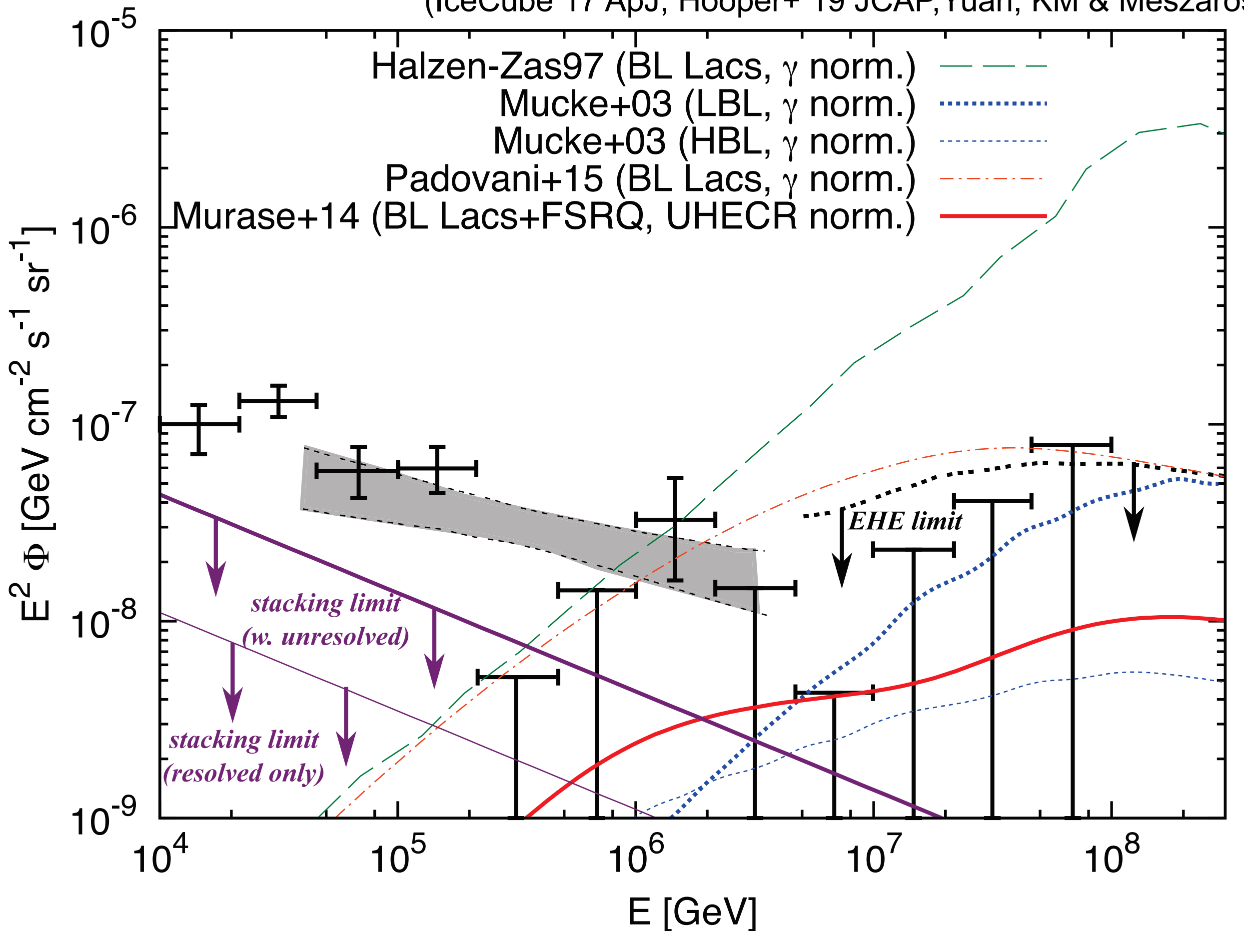
Extragalactic Gamma-Ray Sky: Dominated by Jetted AGN



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)

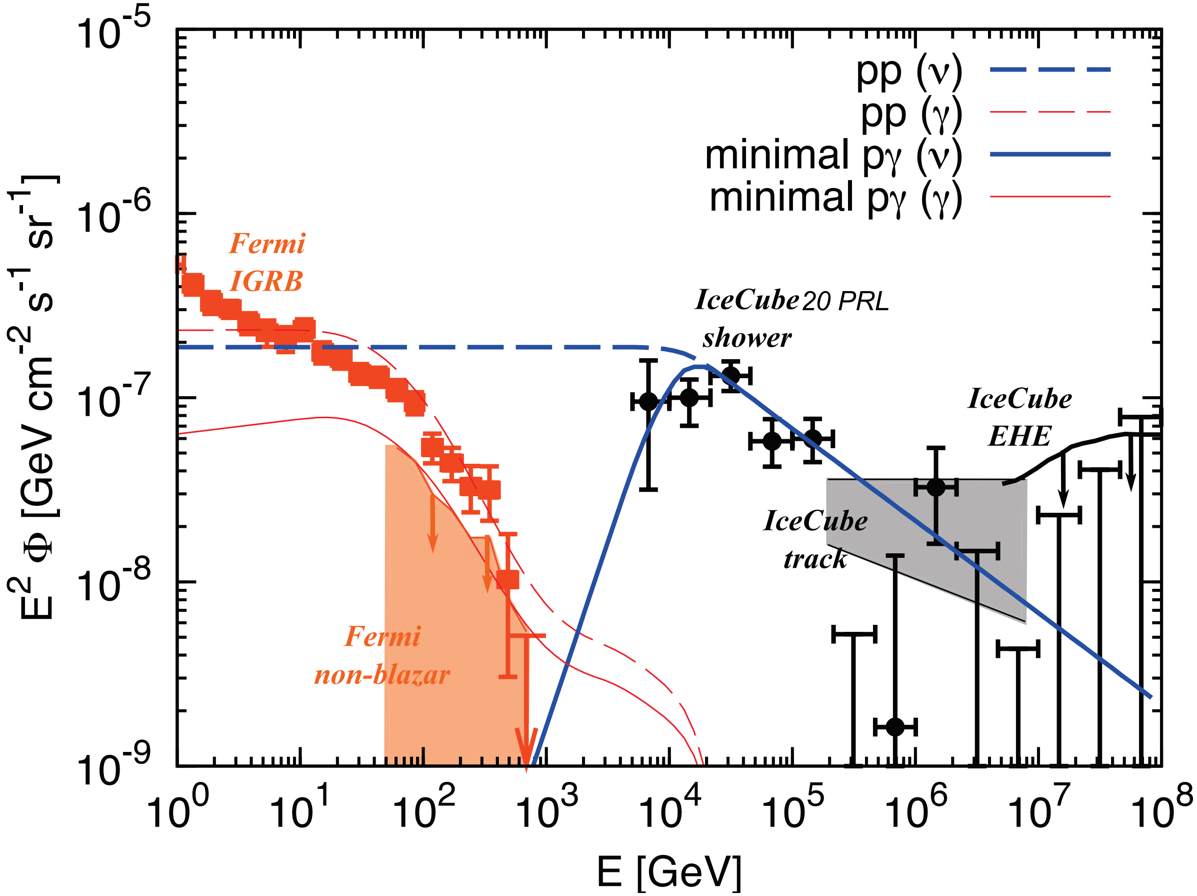


Blazars are subdominant in all parameter space (most likely <~ 30%)

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

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)

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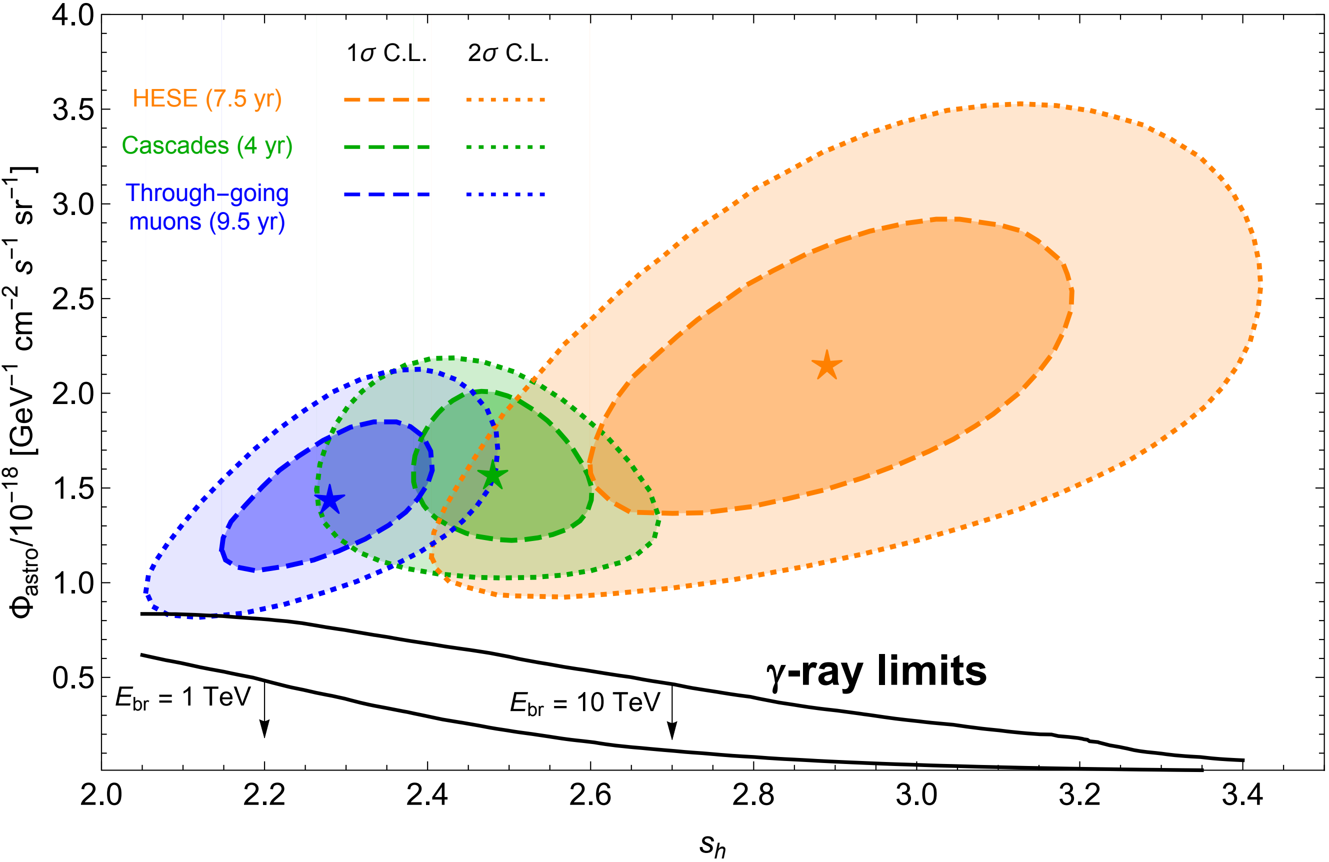
- 10-100 TeV shower data: large fluxes of ~10^{-7} GeV cm^{-2} s^{-1} sr^{-1}



Capanema, Esmaili & KM 20
Capanema, Esmaili & Serpico 21

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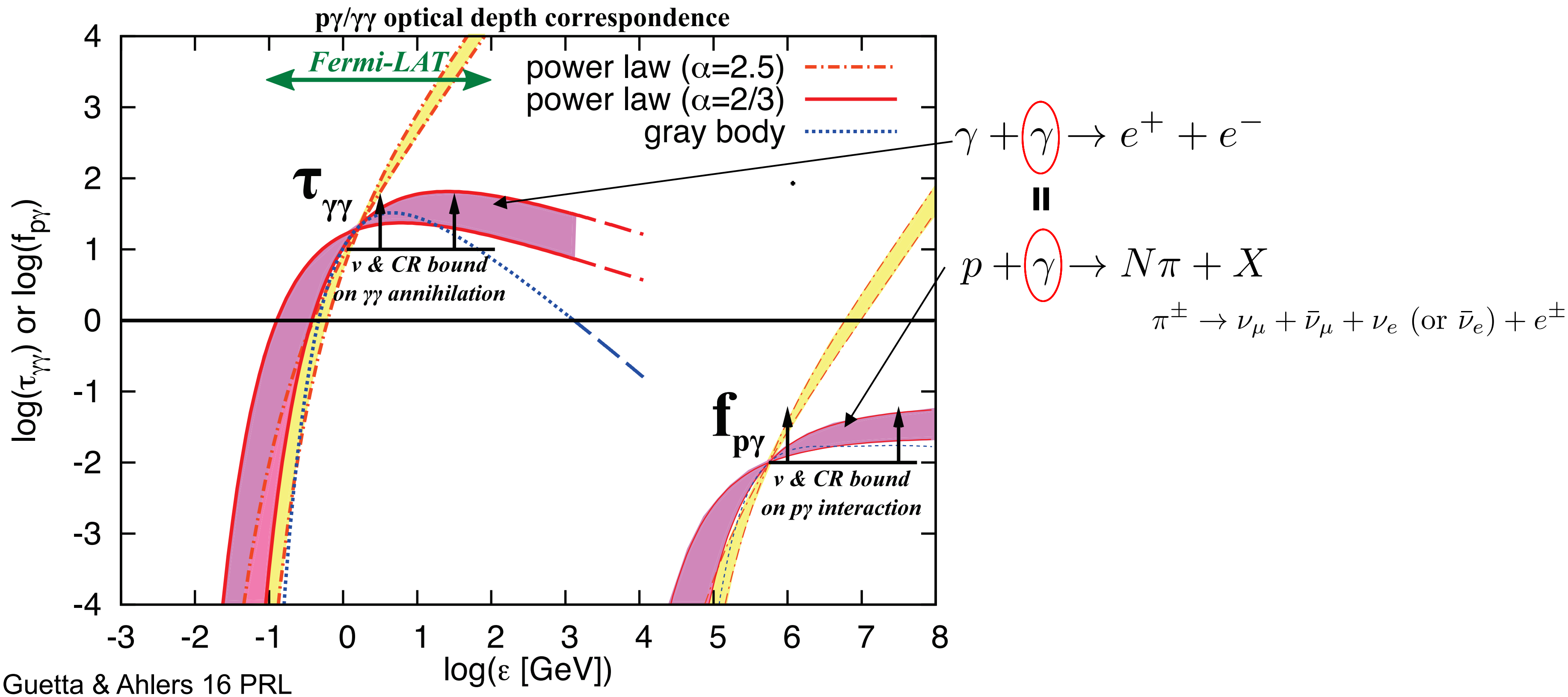
Opacity Argument

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

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



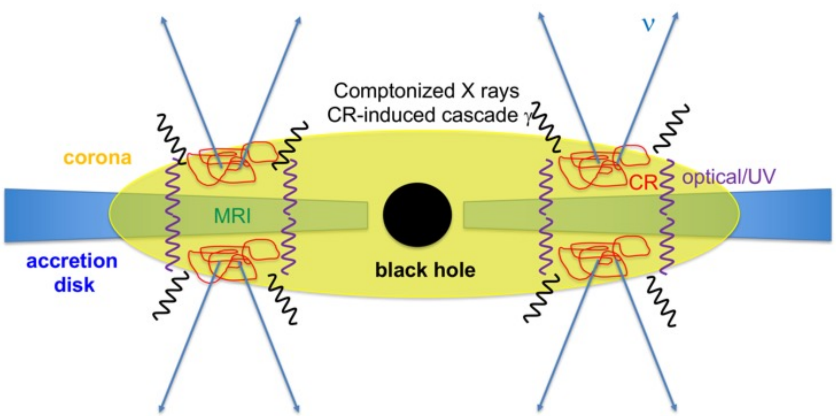
KM, Guetta & Ahlers 16 PRL

Prediction of Hidden Neutrino Sources

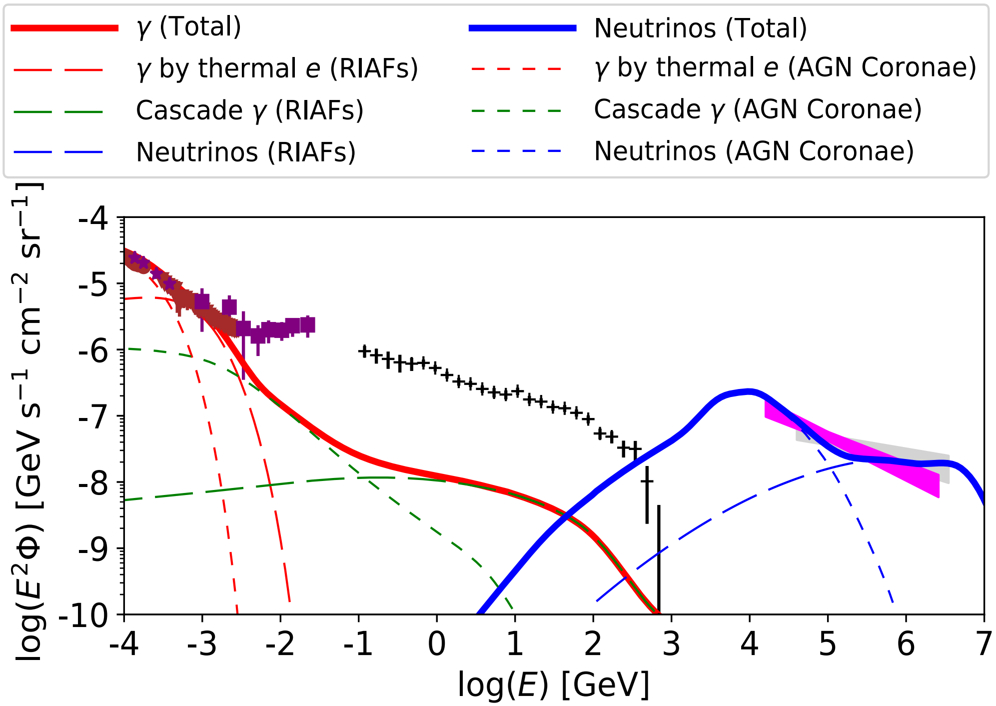
Hidden (i.e., γ-ray opaque) ν sources are actually "natural" in pγ scenarios

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

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

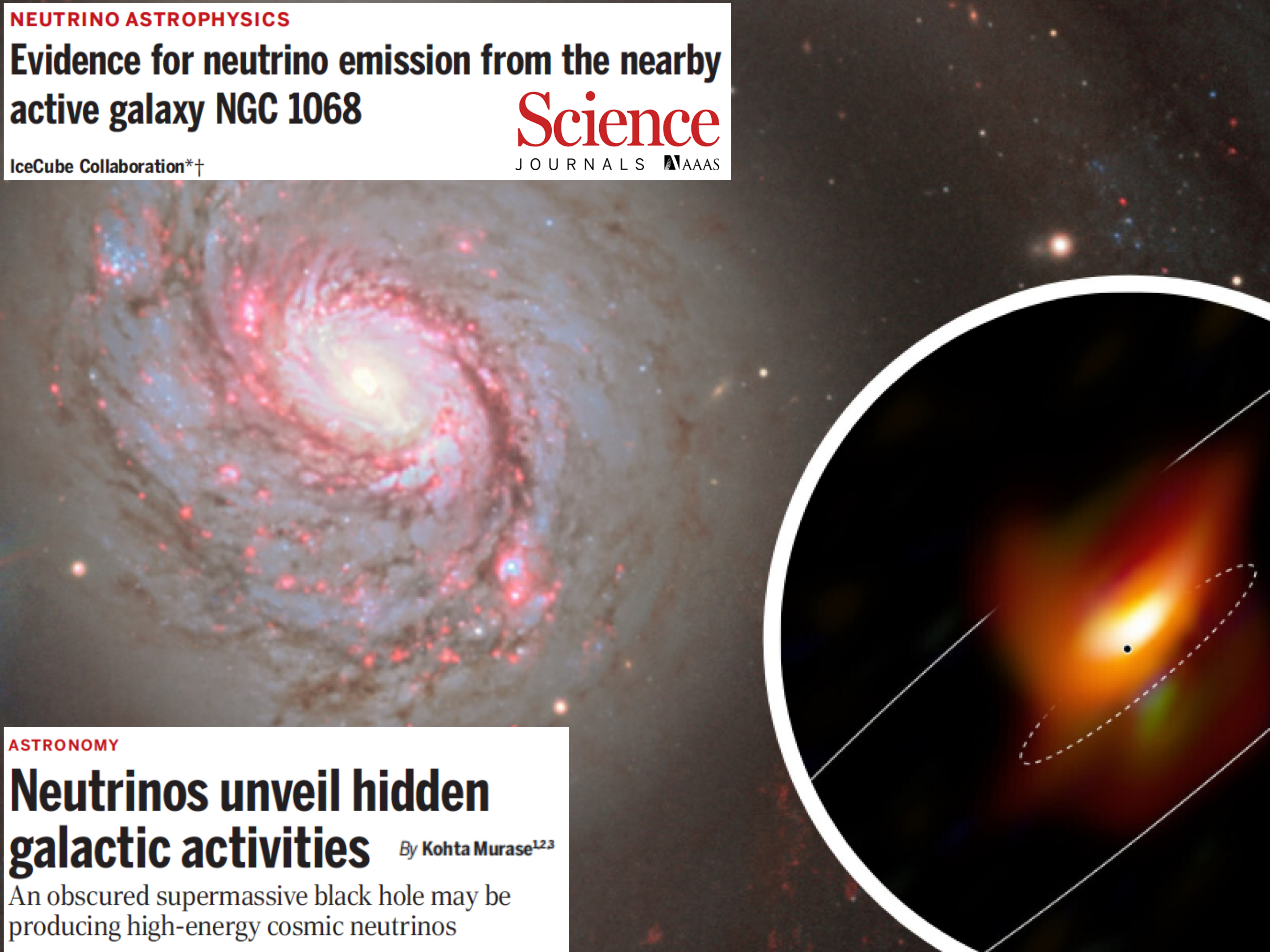


accretion disk + "corona"
opt/UV=multi-temperature blackbody
X-ray=Compton by thermal electrons



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

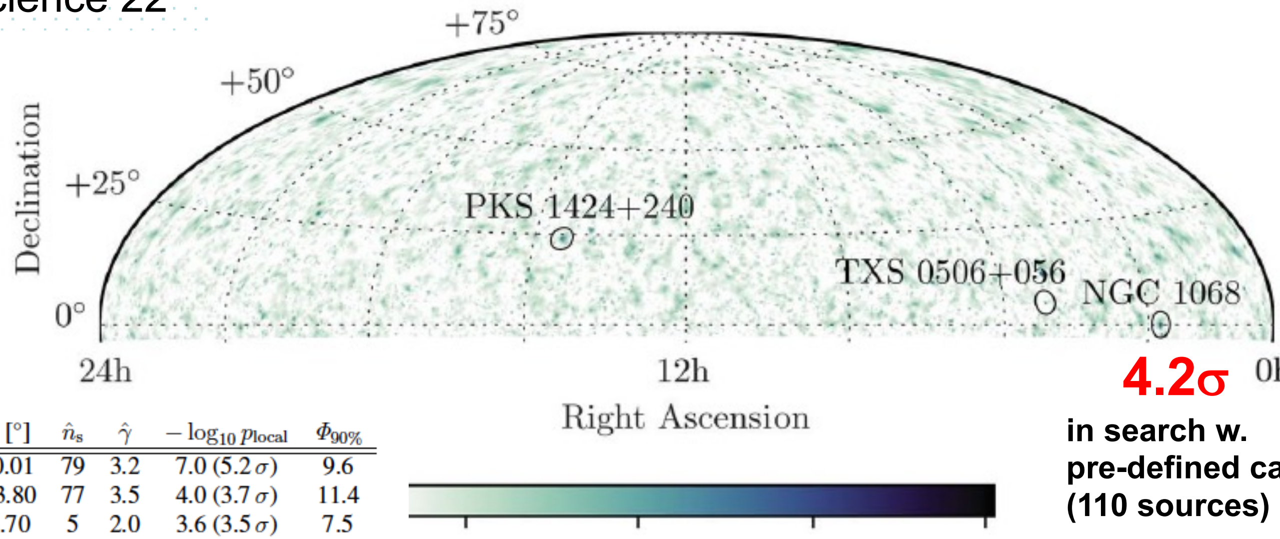
Neutrinos unveil hidden galactic activities

By Kohta Murase[1,2,3]

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

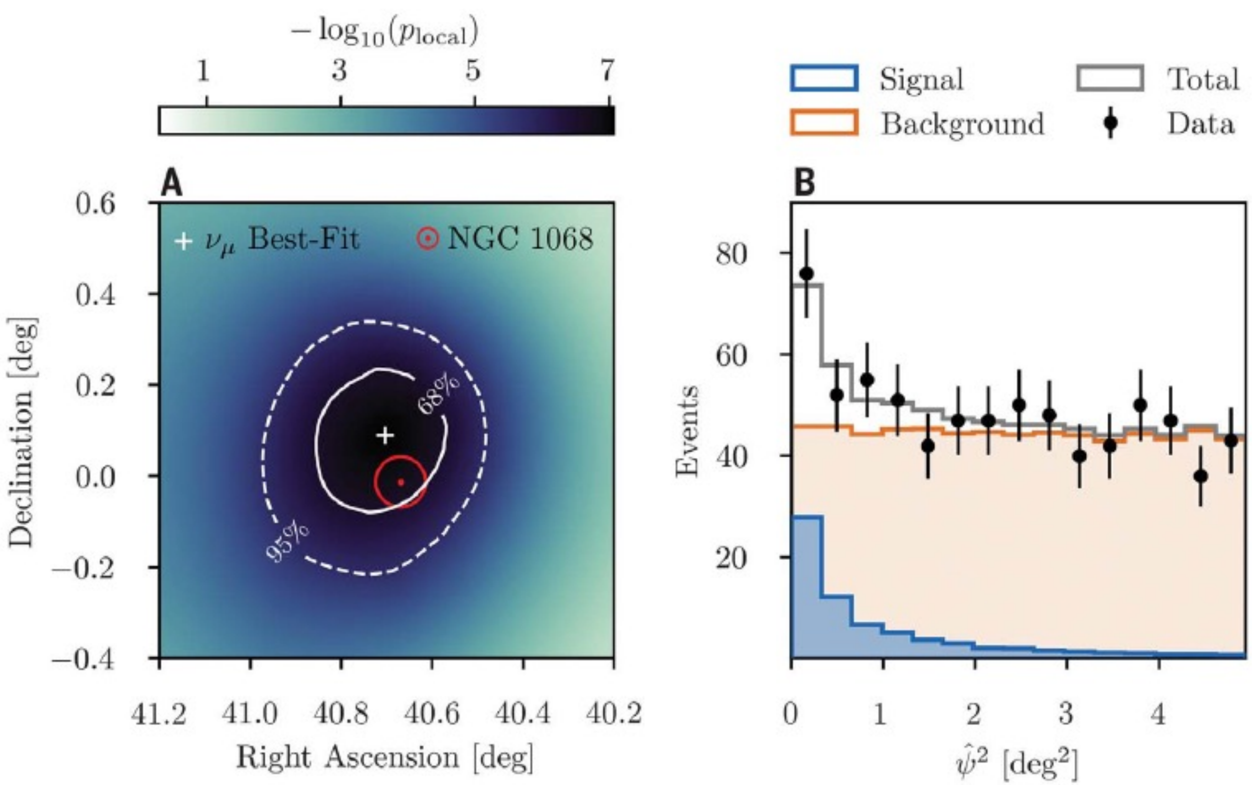
IceCube Collaboration+ Science 22

2011-2020
10 year track data



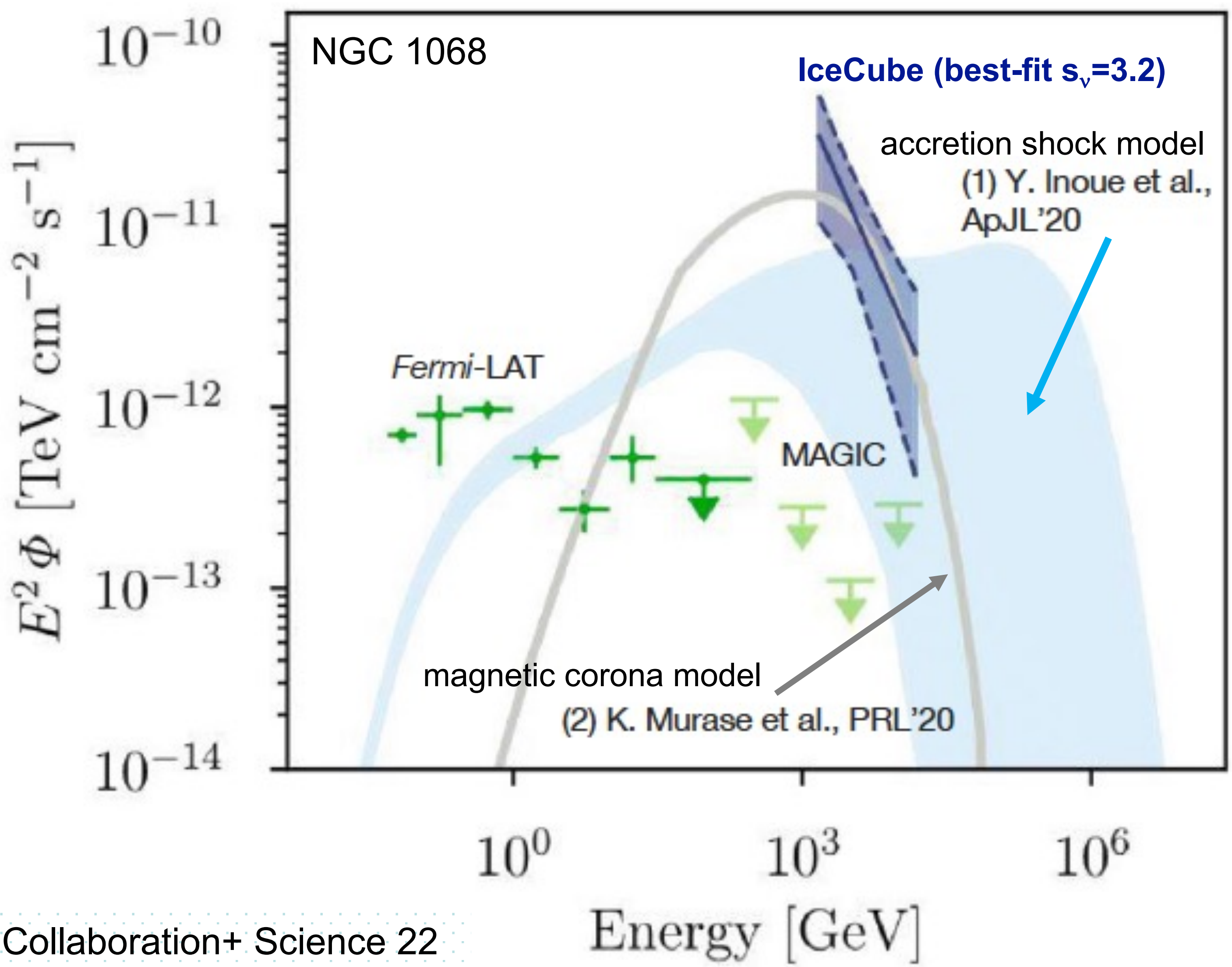
4.2σ
in search w. pre-defined catalog (110 sources)

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$\Phi_{90\%}$
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



~80 excess events

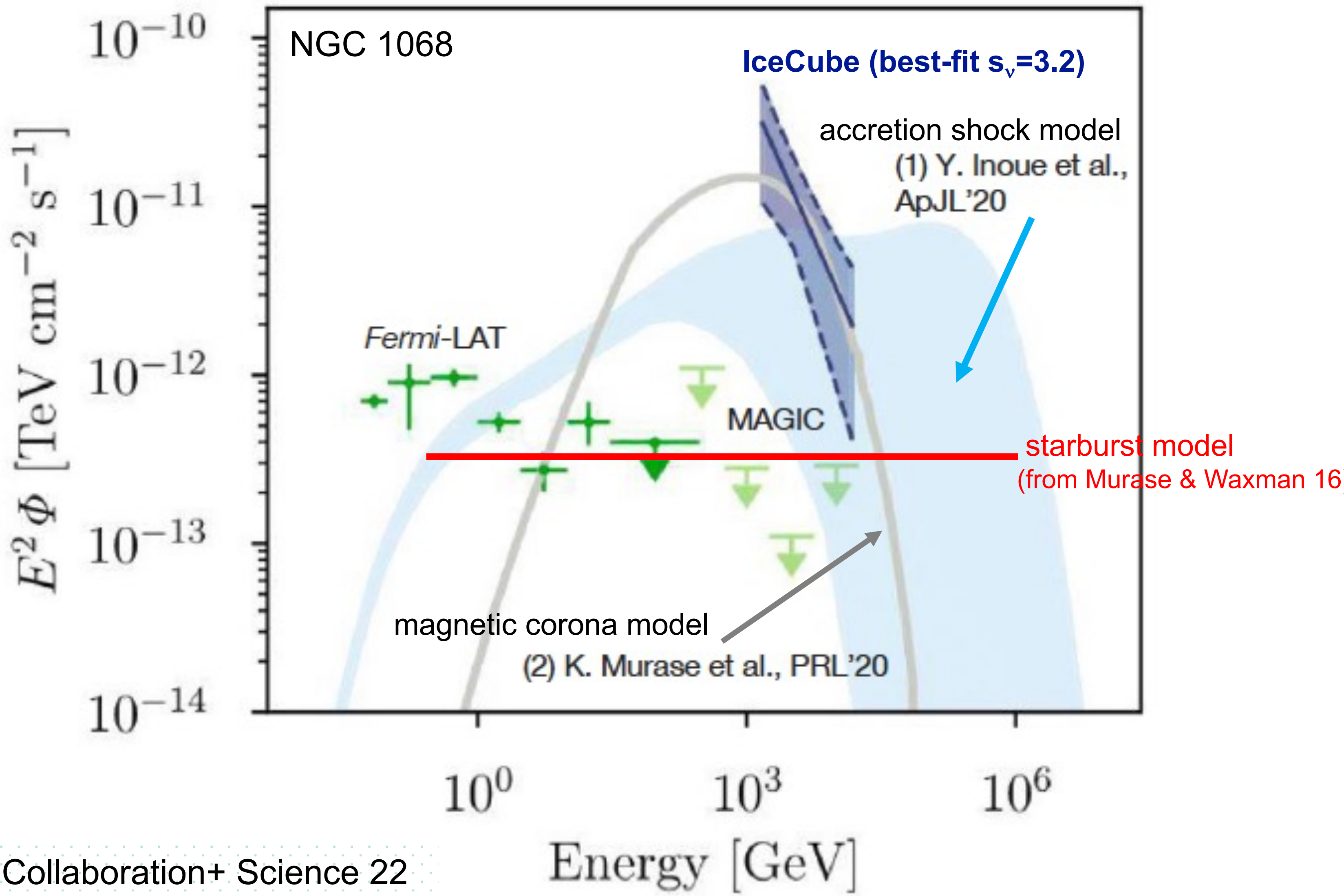
Obscured AGN as a Hidden Neutrino Source



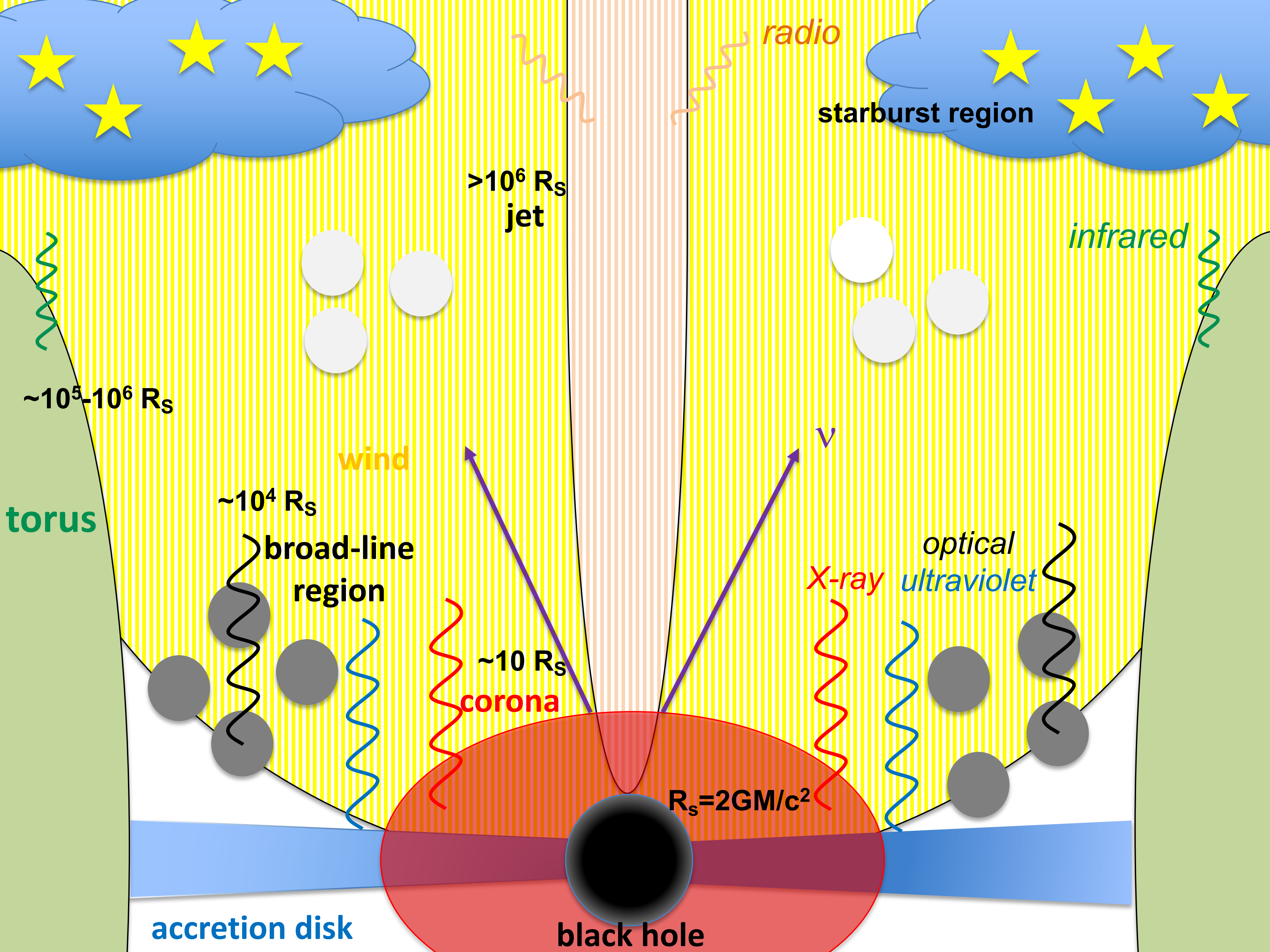
IceCube Collaboration+ Science 22

Obscured AGN as a Hidden Neutrino Source

L_ν~3x10^{42} erg/s << L_{bol} ~ 10^{45} erg/s < L_{Edd} ~ 3x10^{45} erg/s: reasonable energetics



IceCube Collaboration+ Science 22


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

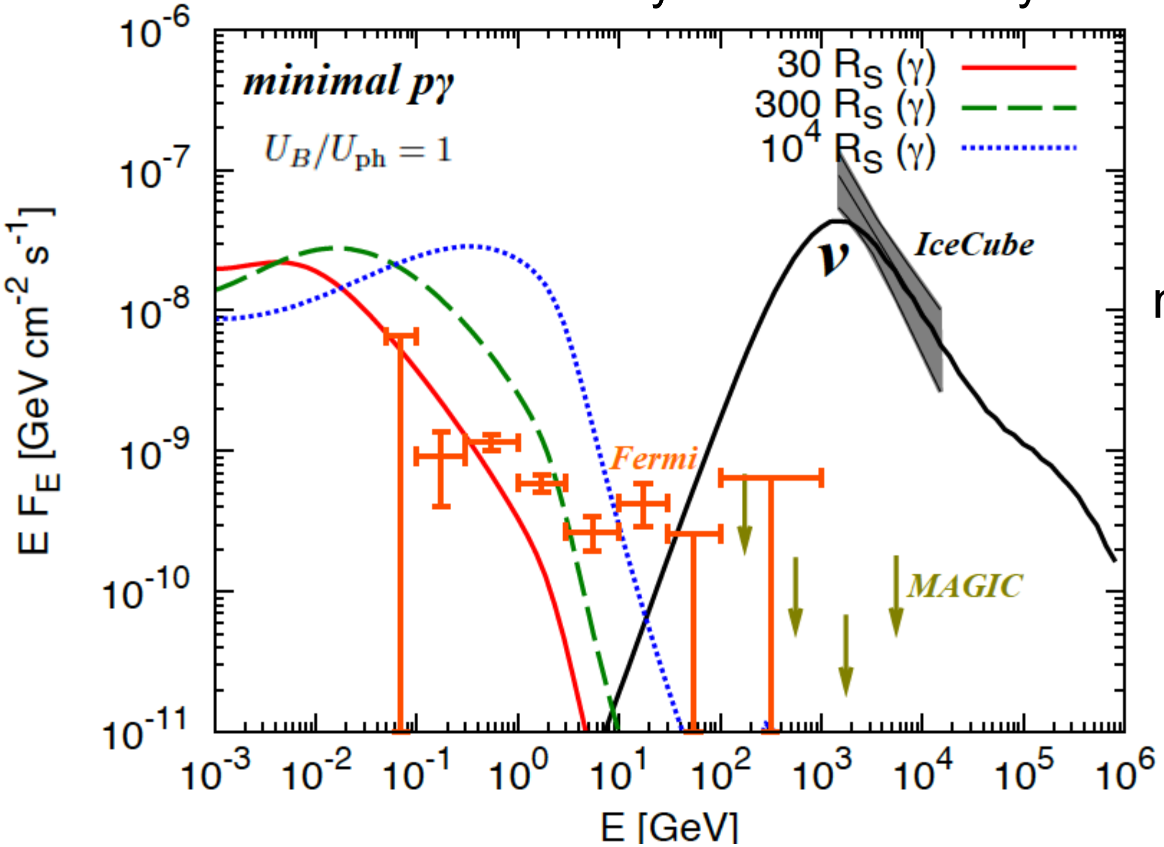
Where Do Neutrinos Come from?

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

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

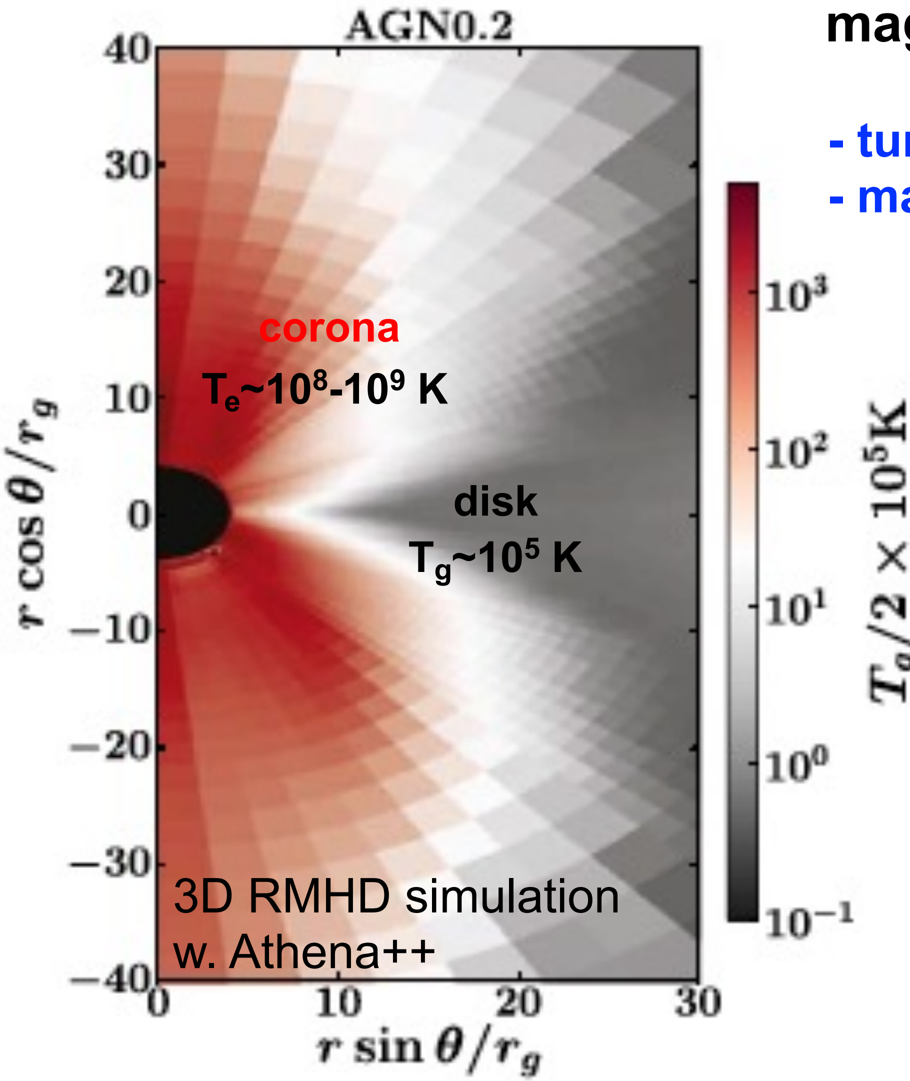


model-independent constraint
w. electromagnetic cascade
R < (30-100) R_S

KM 22 ApJL

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

Particle Acceleration Sites?



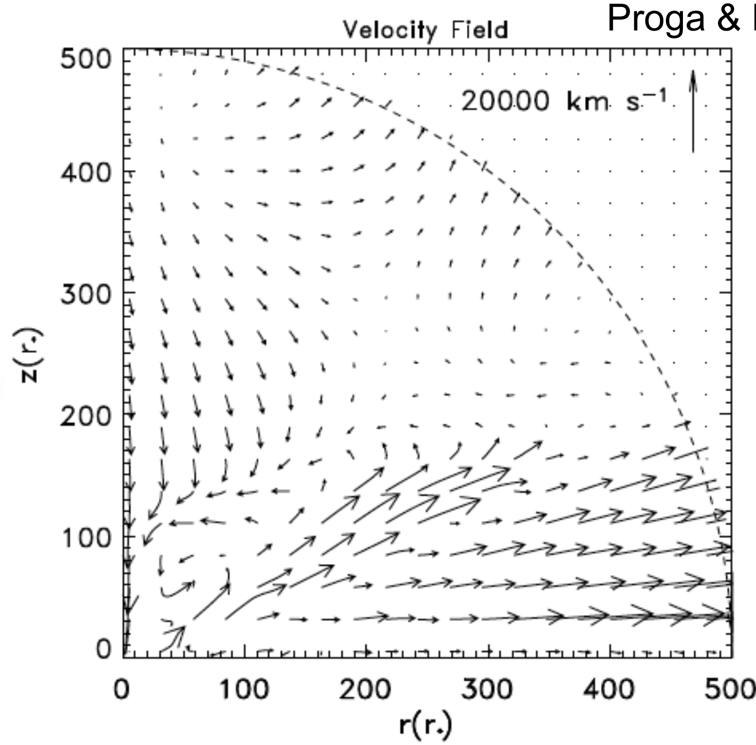
Jiang, Blaes, Stone & Davis 19
see also Miller & Stone 00, Liska+ 22

magnetically-powered corona

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

- **turbulence/shear**
- **magnetic reconnection**

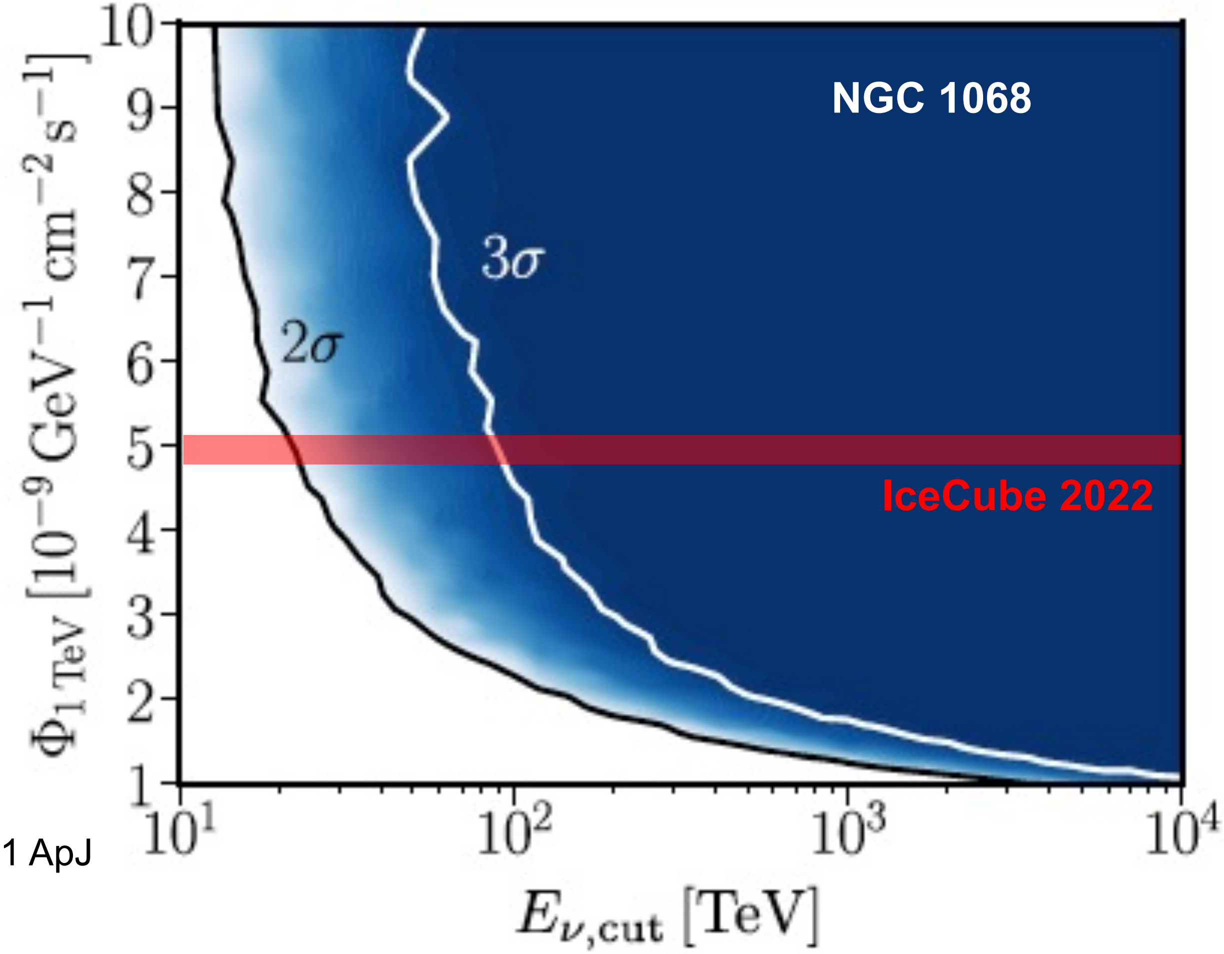
Proga & Kallman 04



failed disk wind/accretion shock

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

Neutrinos Can Constrain Cosmic-Ray Spectra

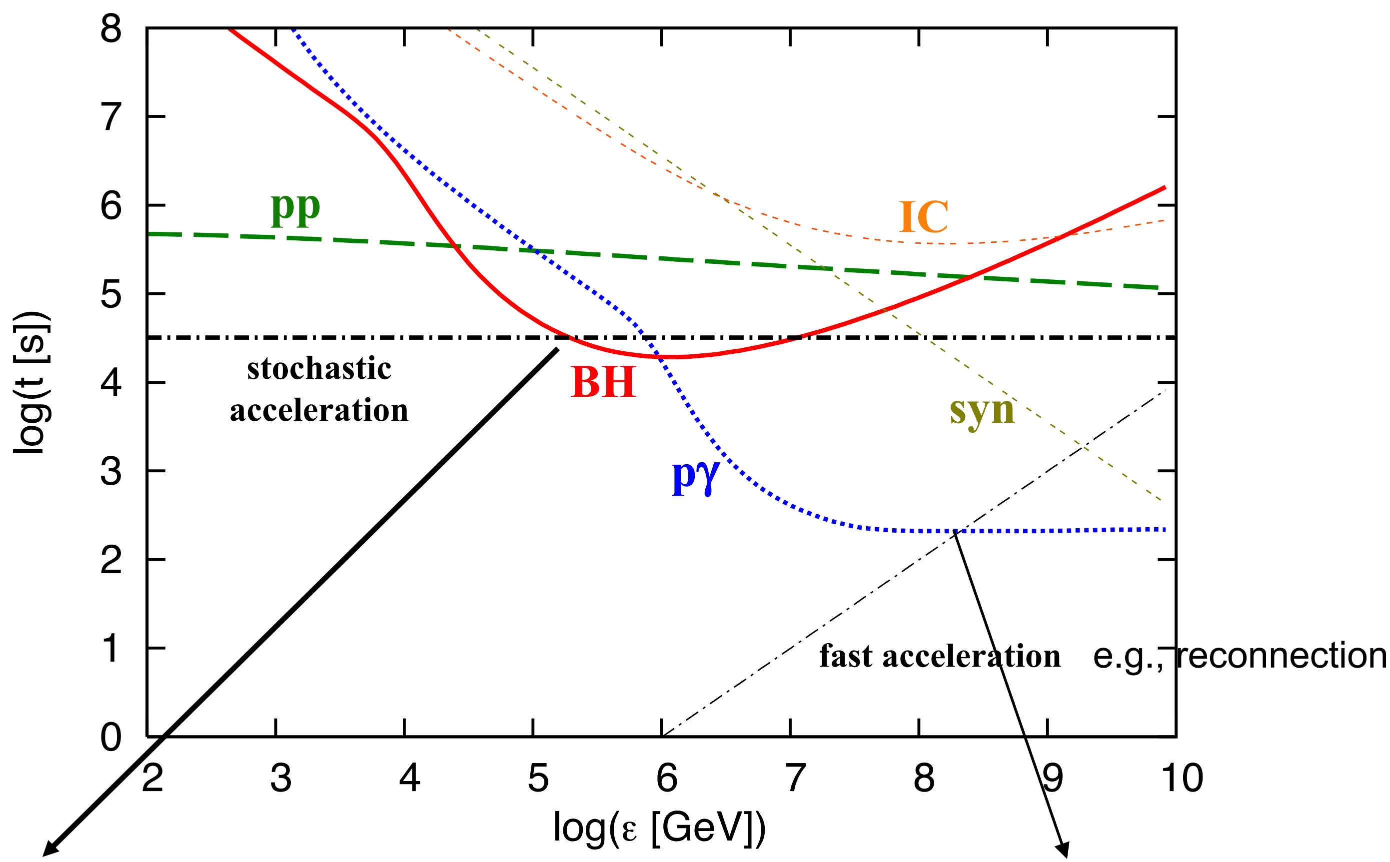


Kheirandish, KM & Kimura 21 ApJ

- $E^{-3.2}$ spectrum cannot be extended to GeV energies (see also KM 22 ApJL)
- **ε_ν^{max} < 20-30 TeV (ε_p^{max} < 100 TeV)** for E^{-2} spectrum
  # not necessarily power laws to fit the IceCube data

Particle Acceleration: Fast or Slow?

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



cooling break & pile-up

ε_p^{max} ~ **100 TeV**

$\rightarrow \varepsilon_\nu^{max}$ ~ **20 TeV**

KM, Kimura & Meszaros 20

1. hard w. a cutoff at ε_p^{max} ~ 100 TeV

Kheirandish, KM & Kimura 21

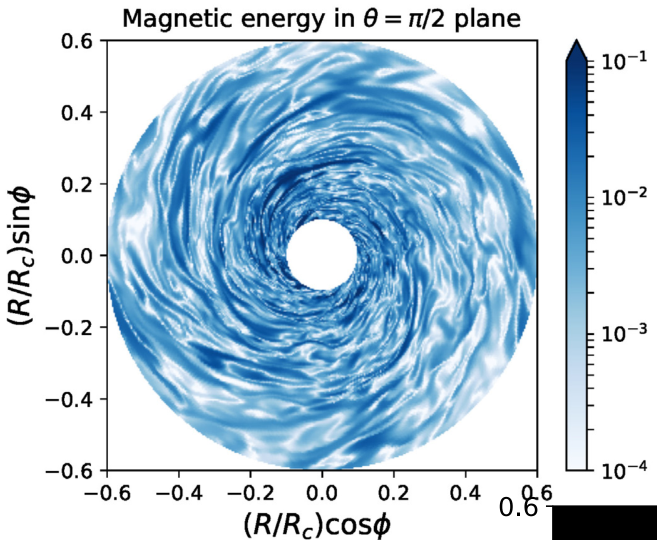
2. intrinsically broken power law

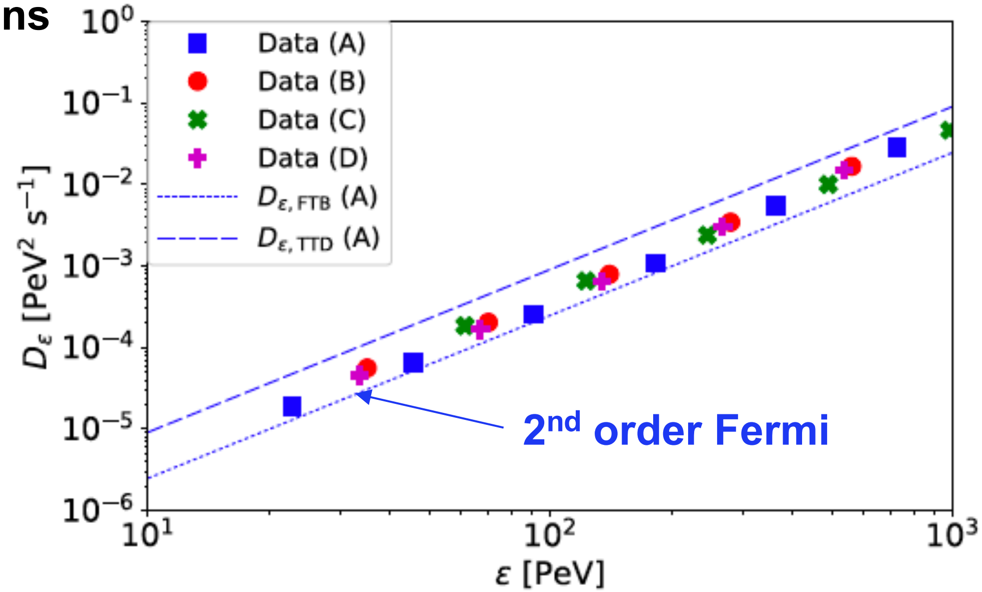
Fiorillo + 23

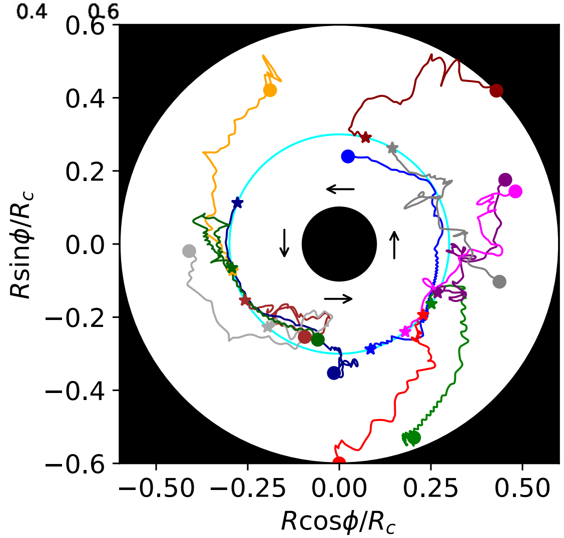
Particle Acceleration in Turbulence is Seen in Simulations

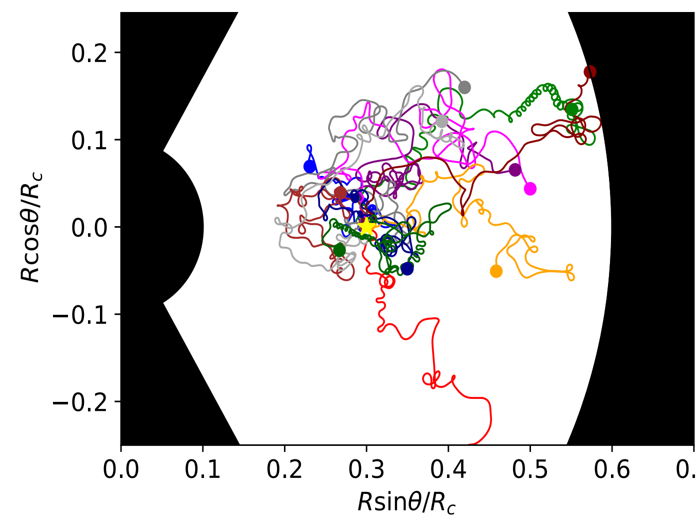
stochastic acc. in 3D global MHD simulations

test particle sim. w. Athena++









Kimura, Tomida & KM 19
see also
Nattila & Beloborodov 21
Sun & Bai 21

effects to be considered: cooling, intermittency, escape, feedback…

Particle Acceleration in Turbulence is Seen in Simulations

stochastic acc. in 3D global MHD simulations

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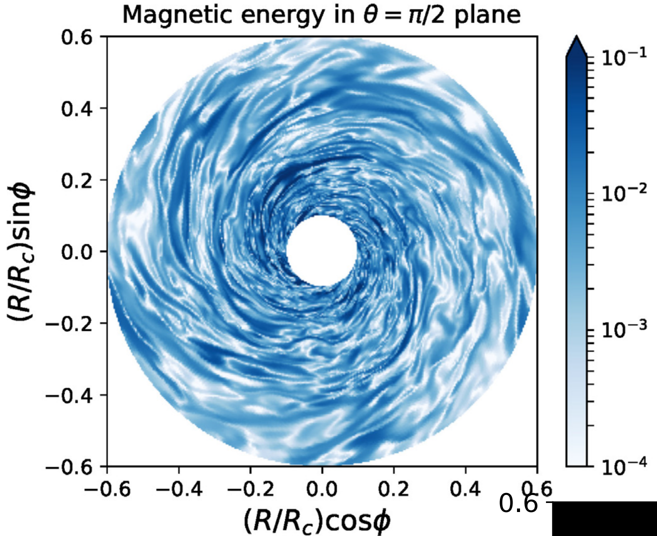

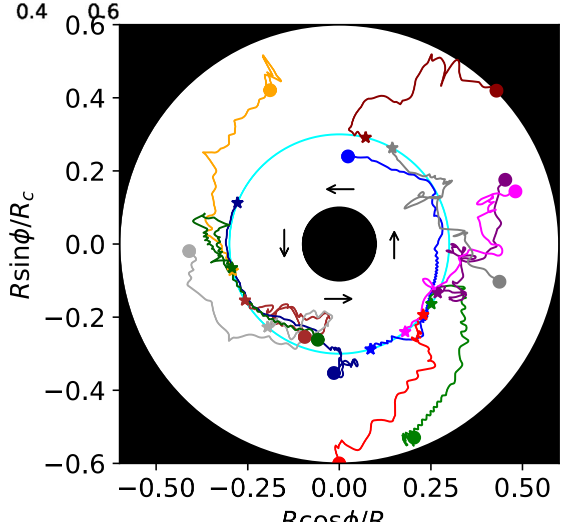

Kimura, Tomida & KM 19
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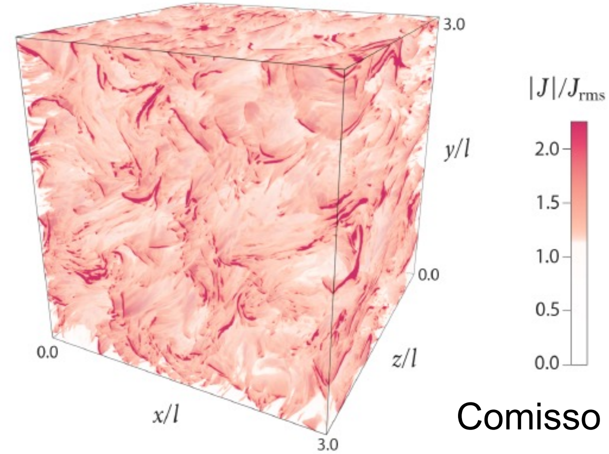
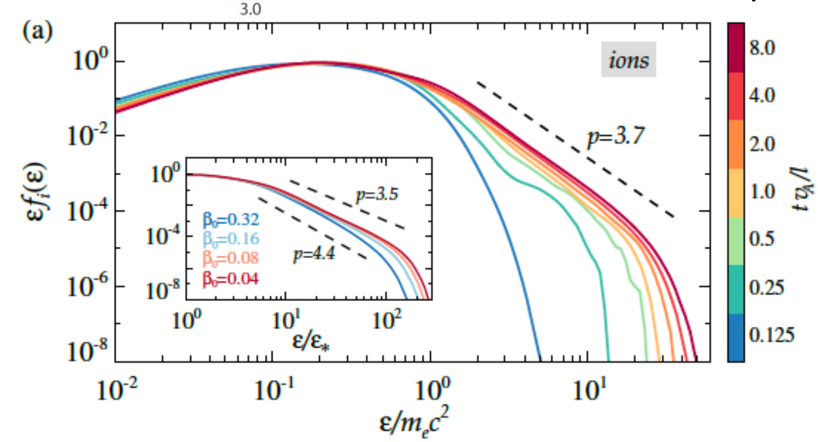
stochastic acc. in 3D PIC simulations



Comisso & Sironi 22 ApJ

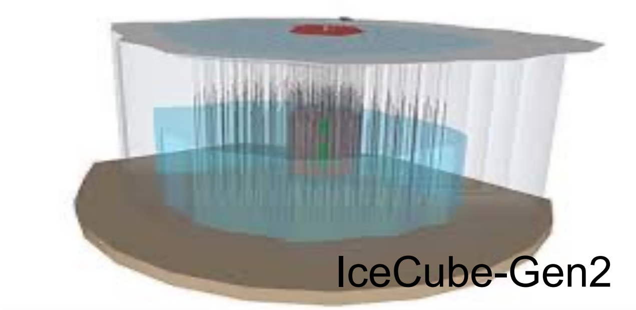


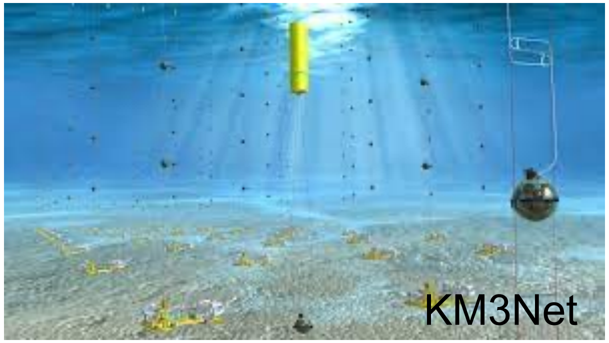
magnetic reconnections are very promising for injections (e.g., Mbraek+ 23)

Bulk may be turbulent acceleration. But how much is the volume filling factor of regions with σ>100?

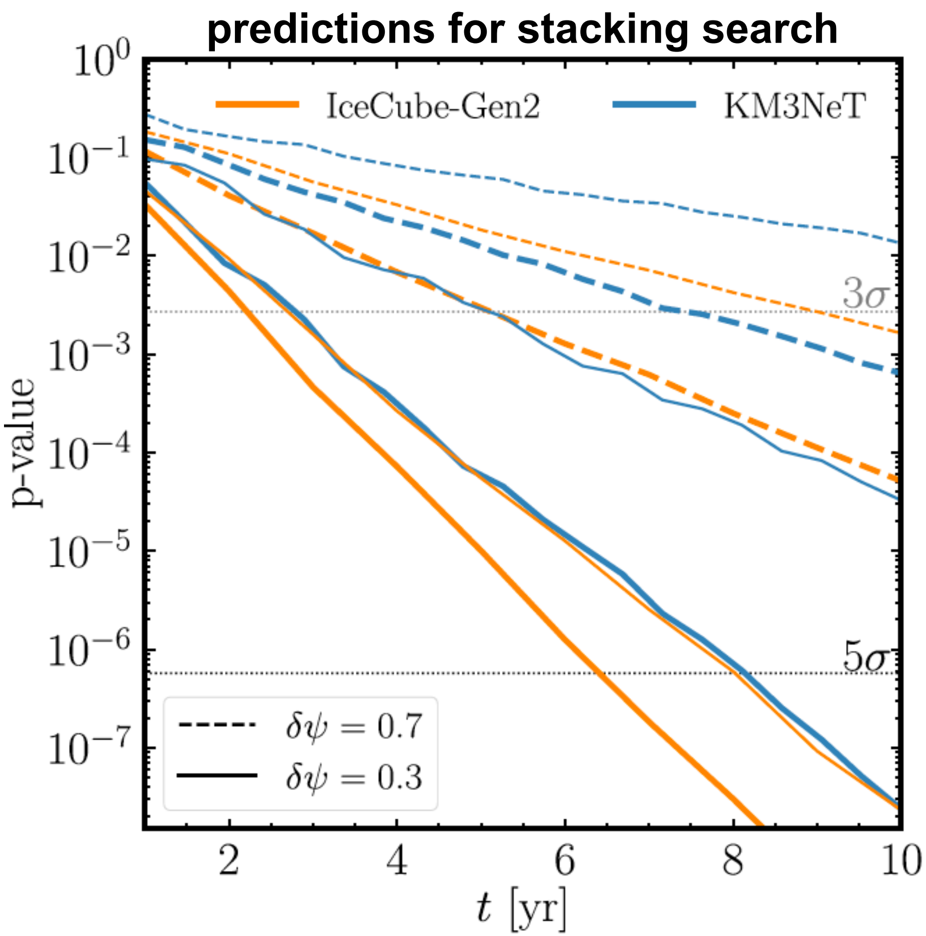
More Hints & More Tests (Neutrinos)

- 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)



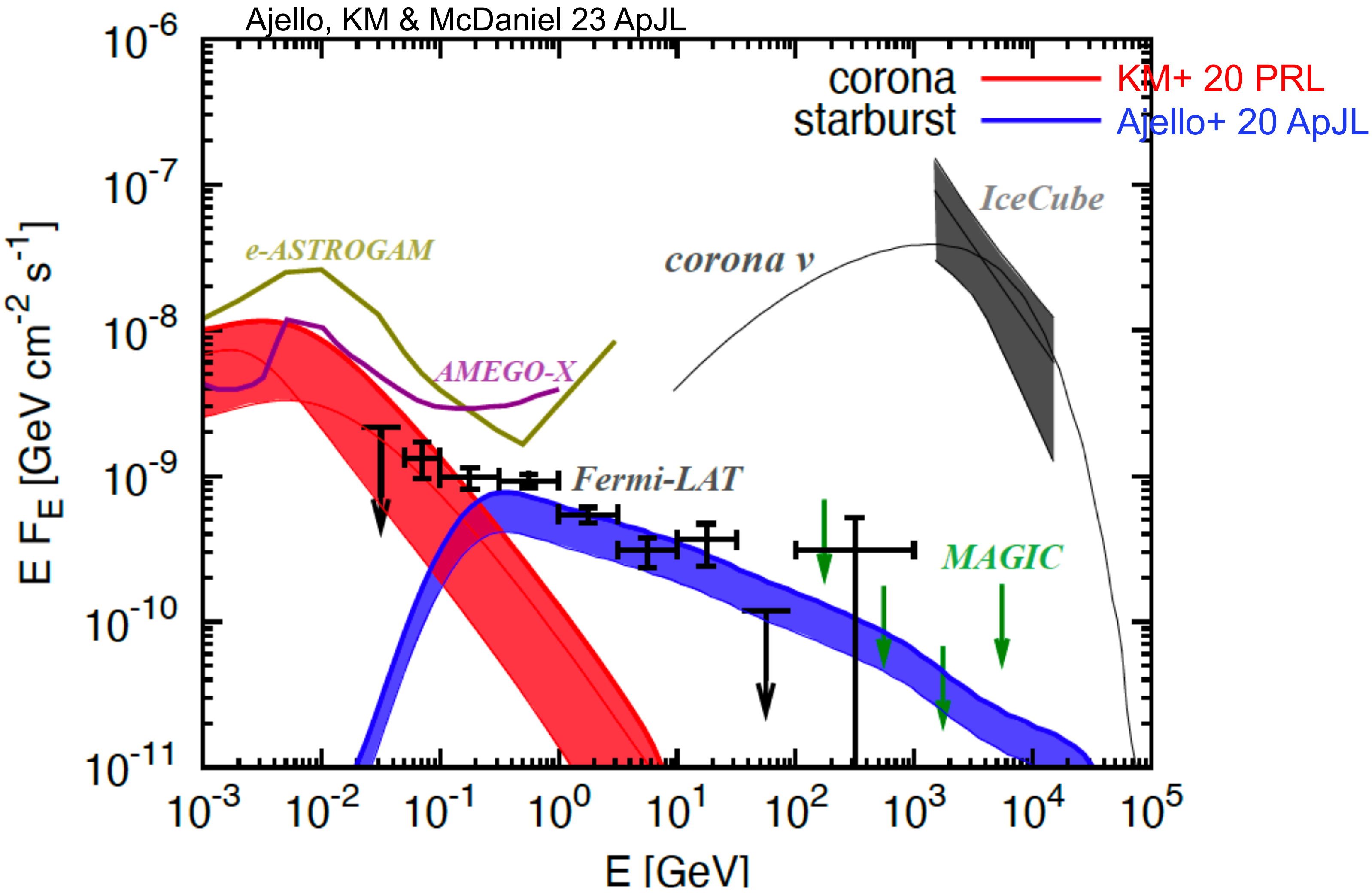


KM, Kimura & Meszaros 20 PRL
Kheirandish, KM & Kimura 21 ApJ



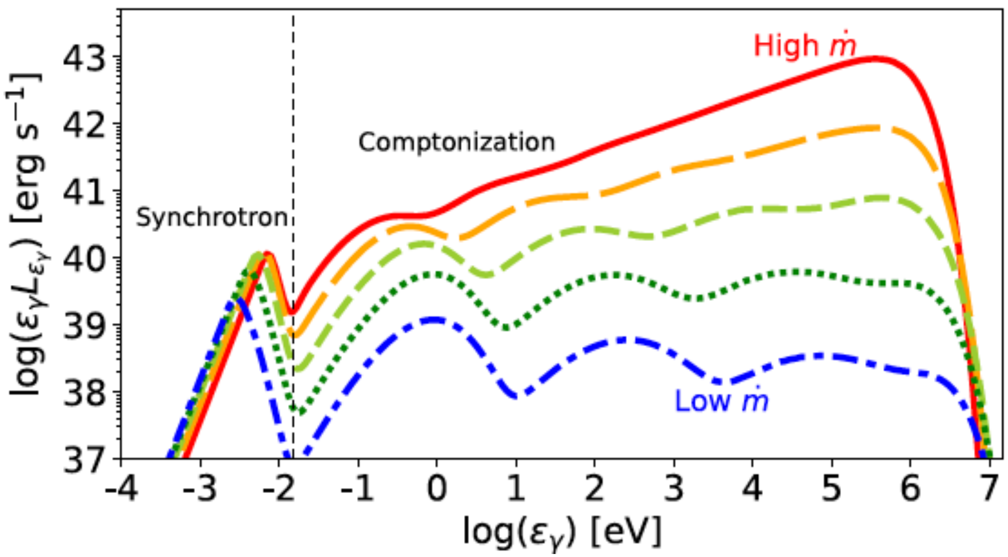
testable w. near-future data or by next-generation neutrino detectors

Gamma Rays Are Not Gone: MeV γ-ray Tests



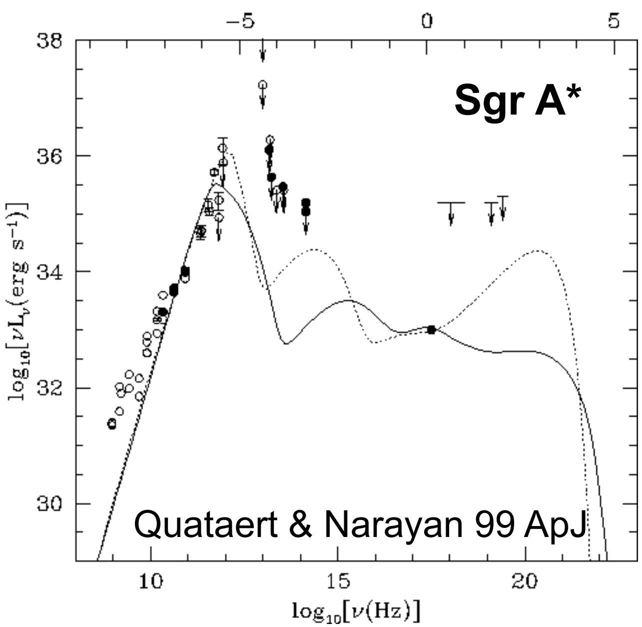
- Prediction: CR-induced cascade γ rays should appear in the MeV range
- We found a sub-GeV “excess” over the $\pi^0 \rightarrow 2\gamma$ (starburst) component

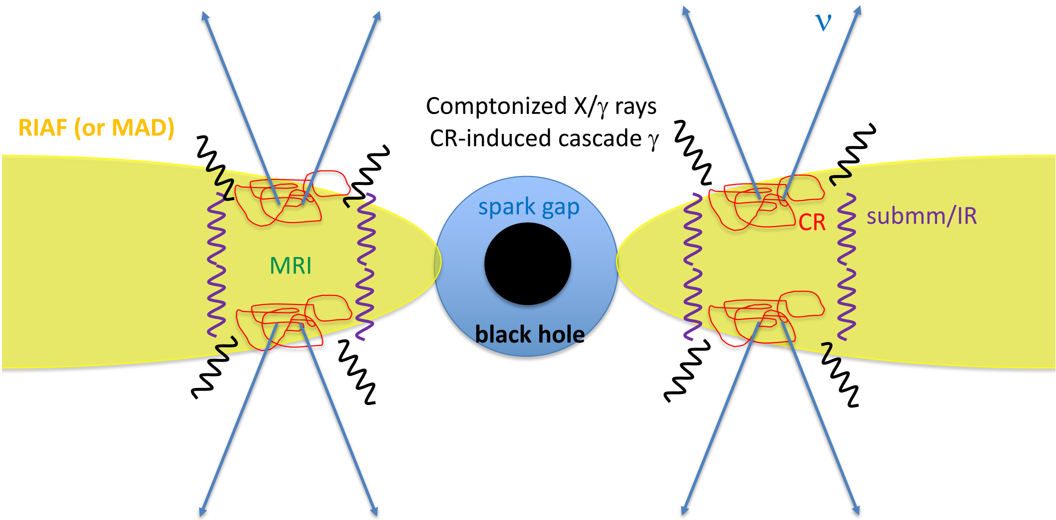
Applications to Low-Luminosity AGNs



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

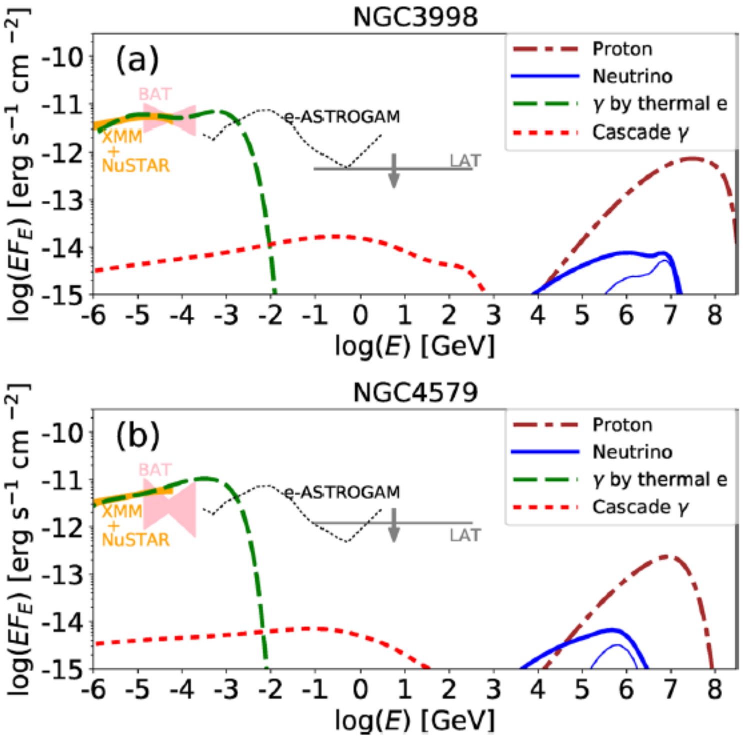
- RIAF/MAD for mdot<0.03
- Electrons are mostly thermal (collisional for electrons but collisionless for protons)

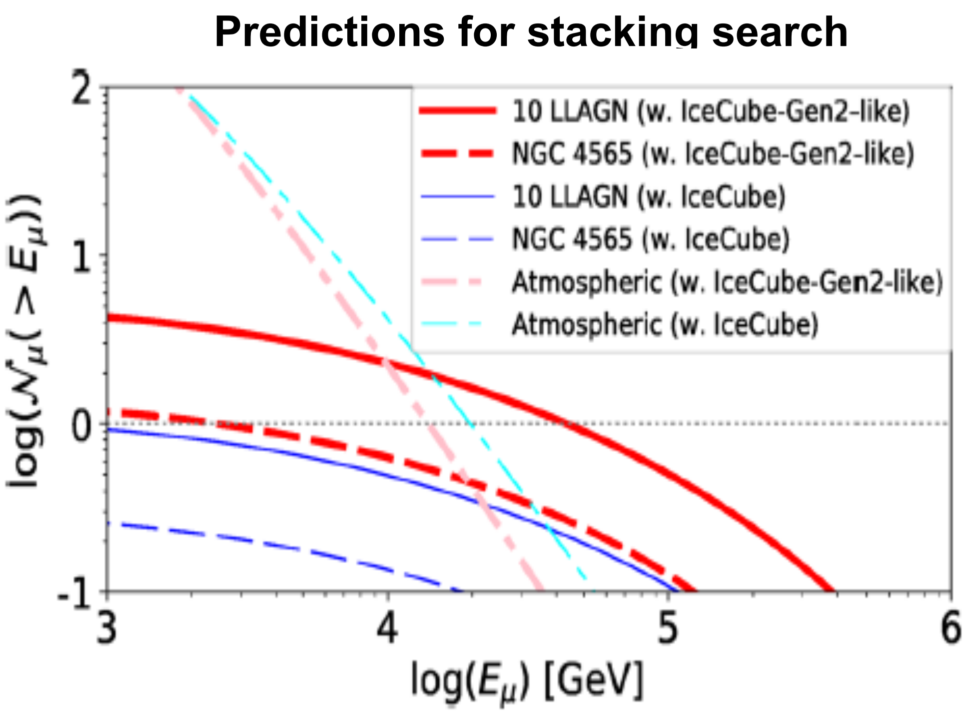




Detectability of Nearby Low-Luminosity AGN

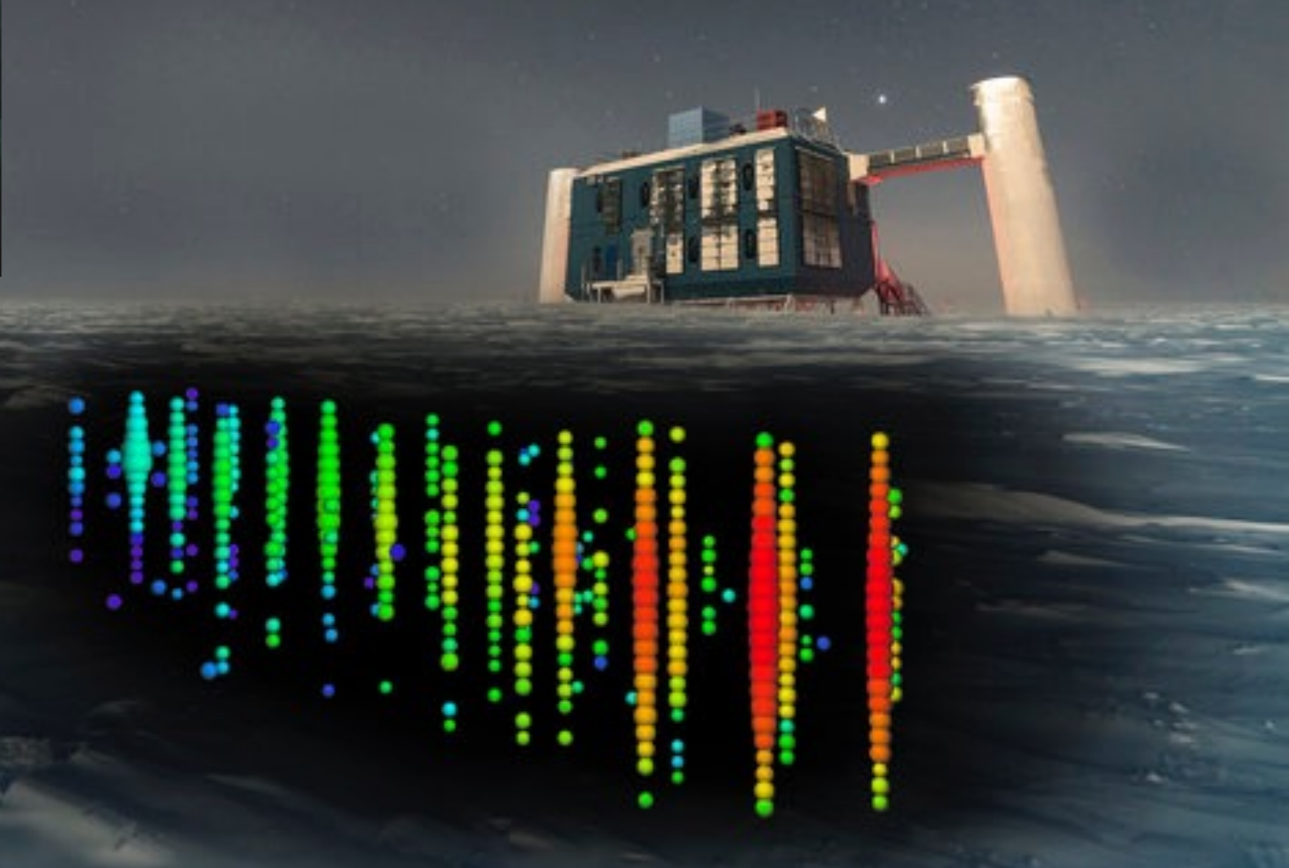
Kimura, KM & Meszaros 21 Nature Comm.





- 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

High-Energy Multimessenger Transients

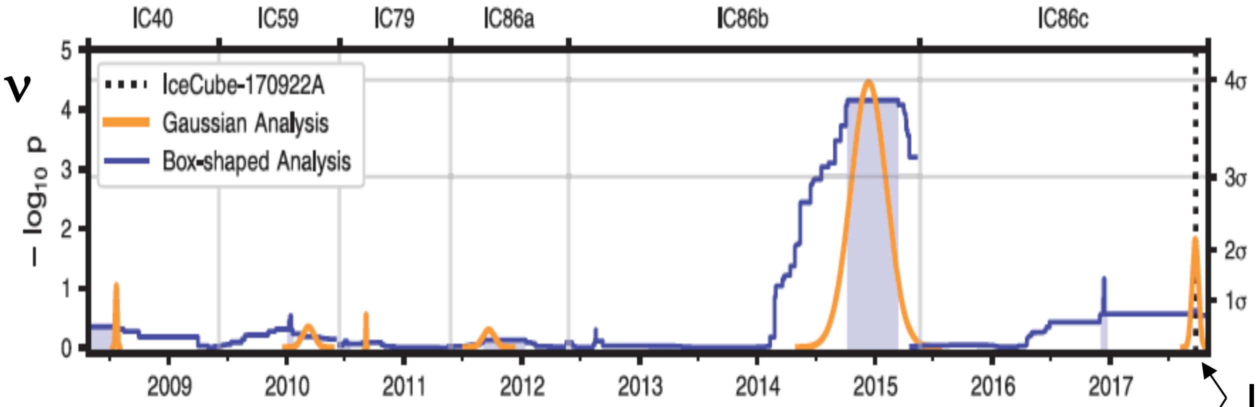


Flares from Supermassive Black Hole Jets?

IceCube 18 Science

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

ν



TXS 0506+056

"jetted AGN"

IceCube-170922A (E_ν~0.2-1 PeV)

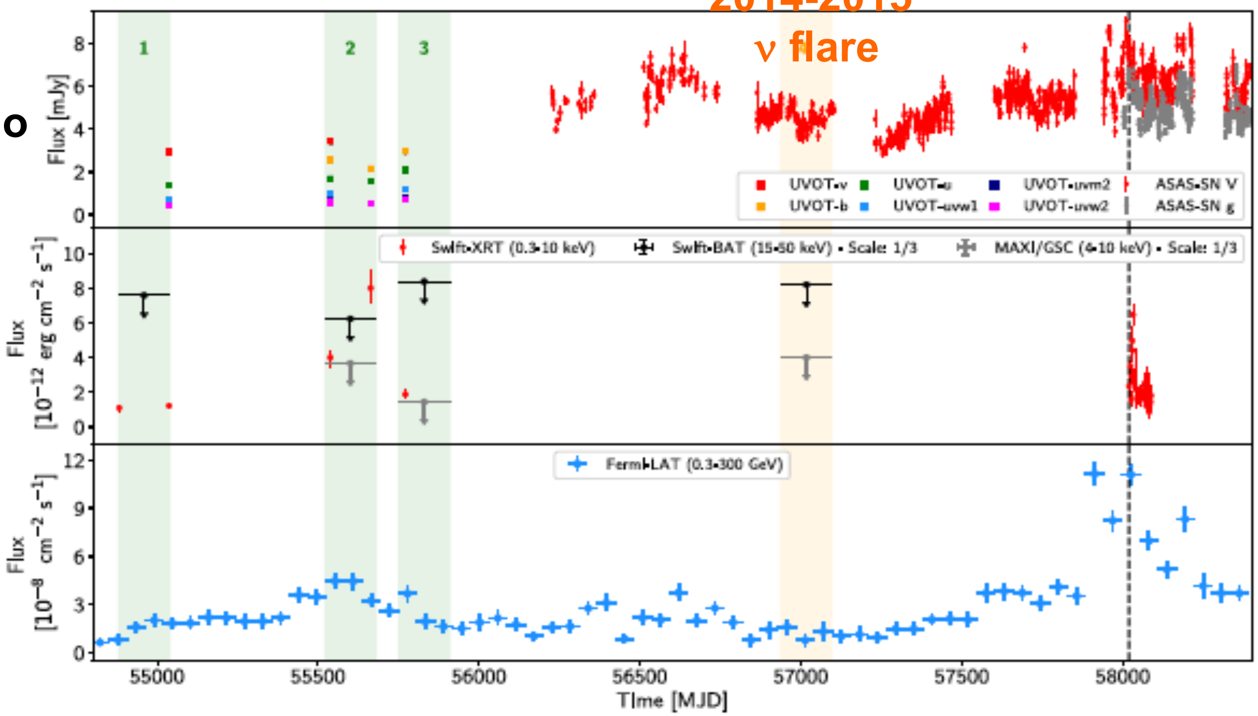
2014-2015

ν flare

radio

X

γ



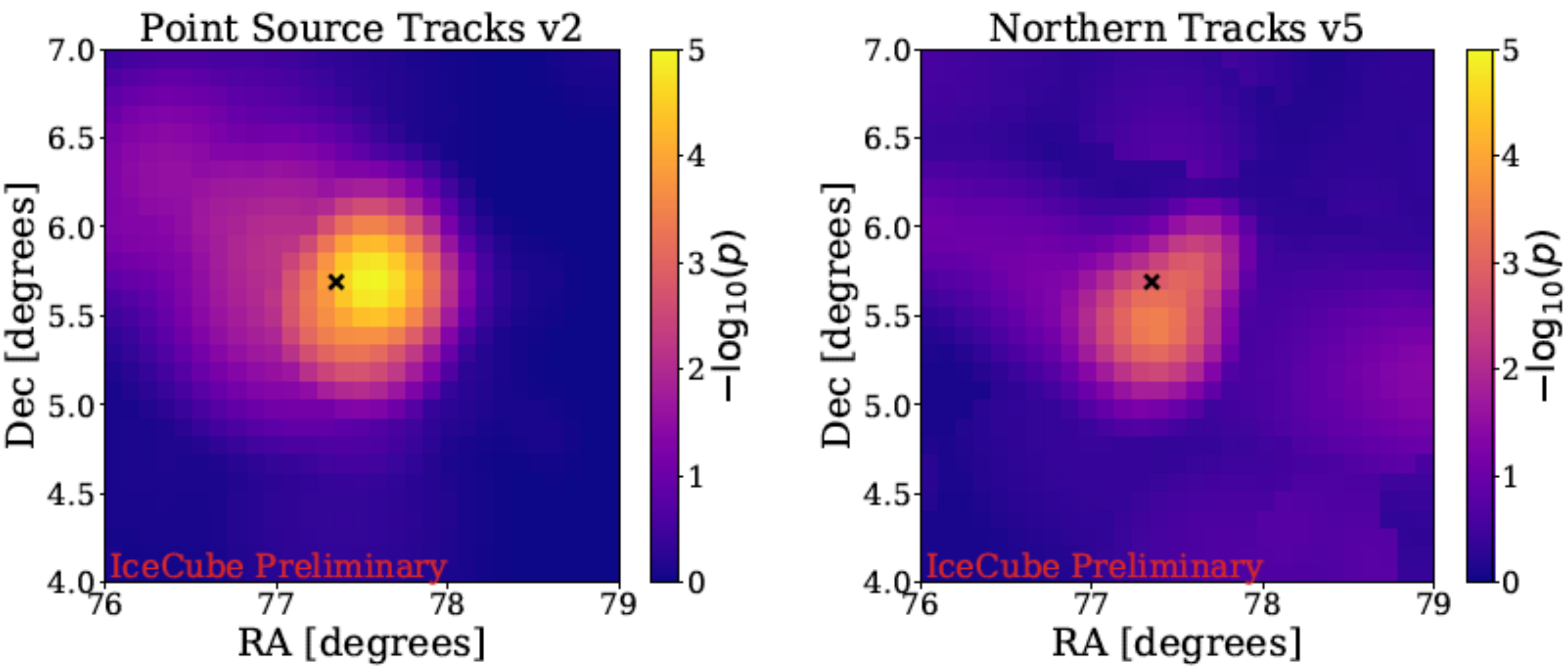
2017 multimessenger flare

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

Petropoulou, KM+ 20 ApJ

Updated in Analysis on 2014-2015 Neutrino Flare

IceCube 23 ICRC

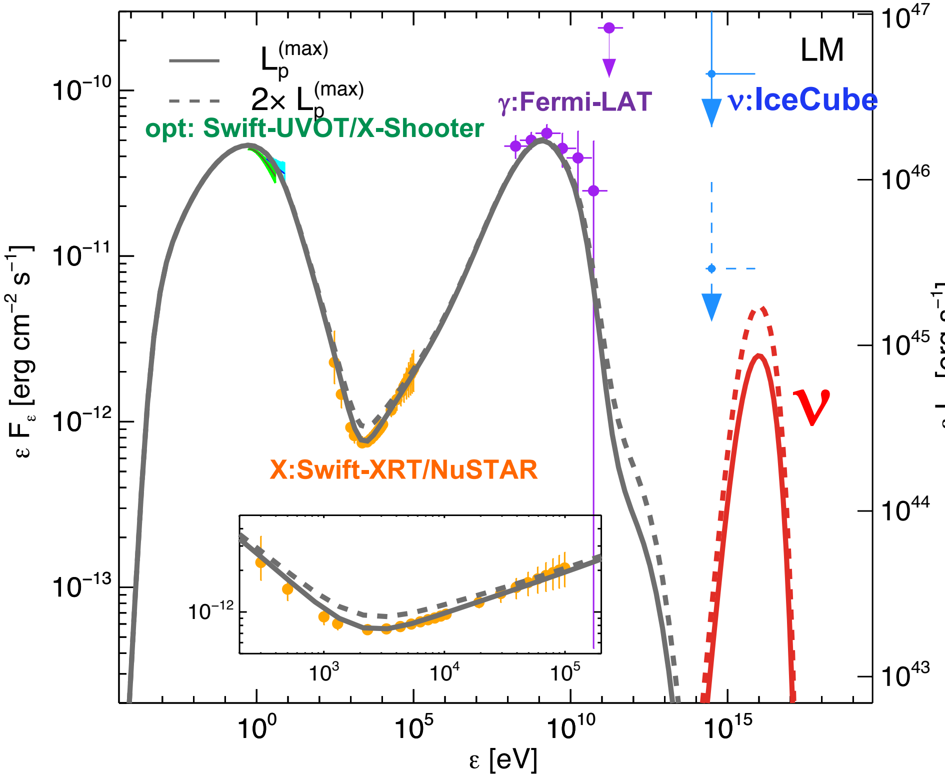


Sample	p (pre-trial)	Best-Fit Flux ($\times 10^{-15}$ TeV^{-1} cm^{-2} s^{-1})	γ	T_{start} (MJD)	T_{stop} (MJD)
Point Source Tracks v2	7e-5	1.6	2.2	56937.81	57096.22
Northern Tracks v5	1e-3	0.76	2.2	56927.86	57091.33

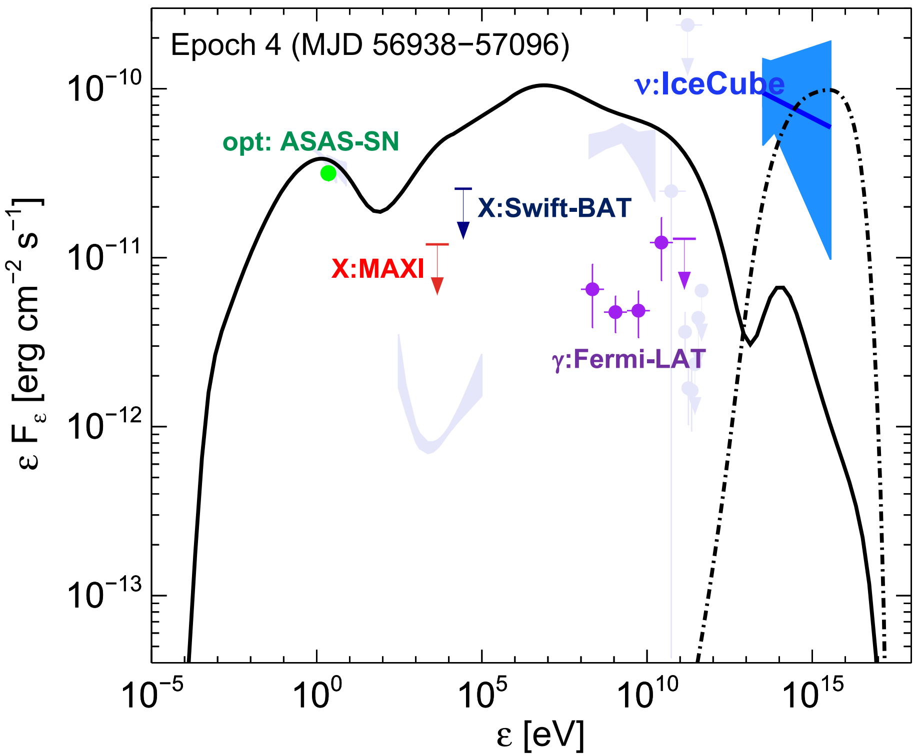
"Power" of Multimessenger Approaches

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

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



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



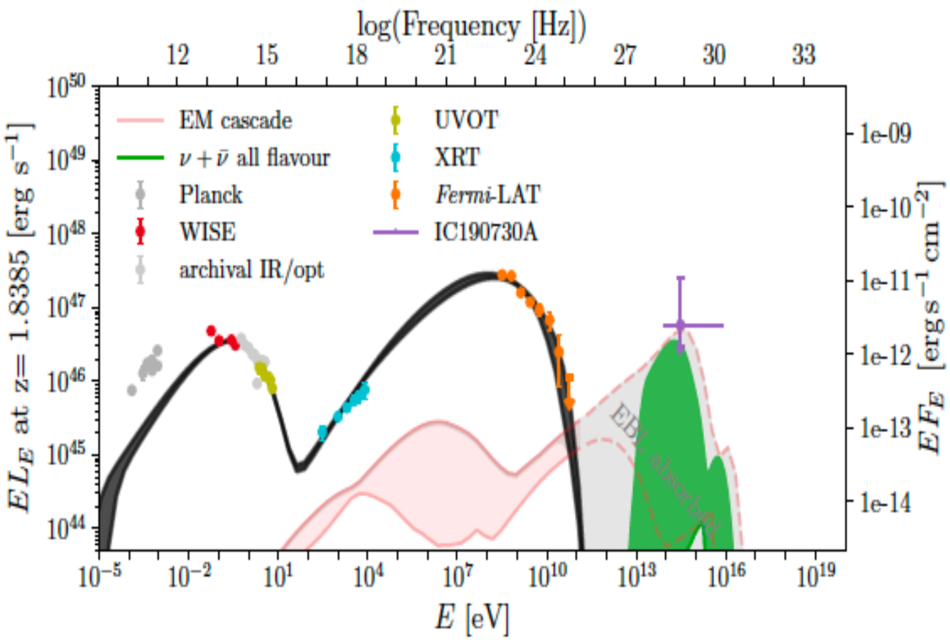
$F_{\nu theory} \sim F_{EMtheory} < F_{EMobs} < F_{\nu obs}$

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

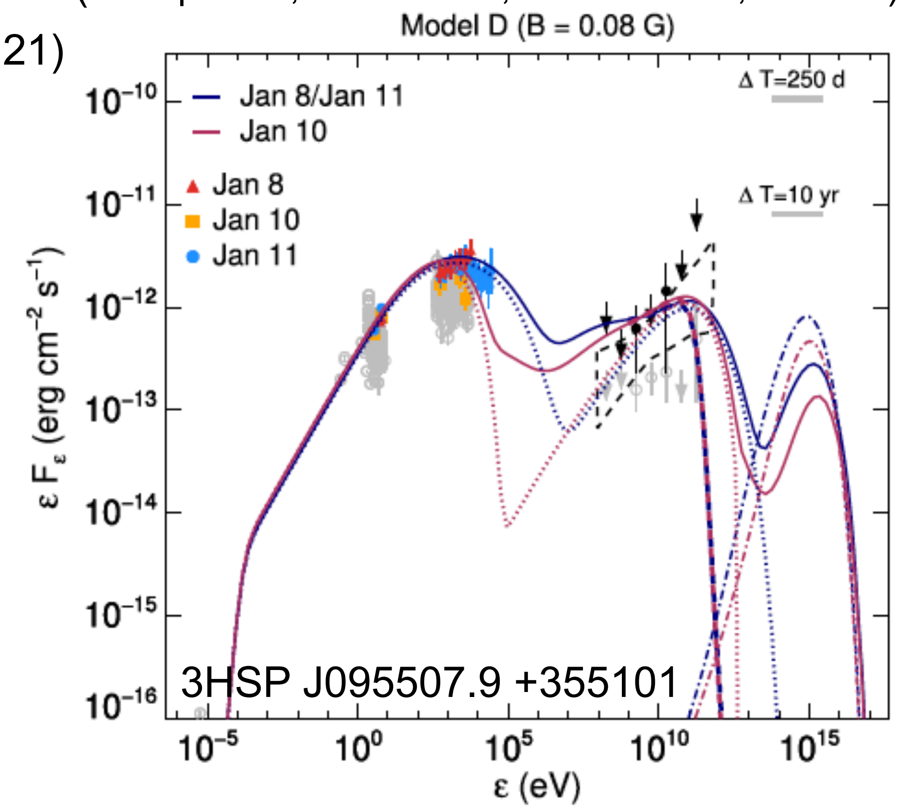
More Coincidences w. Blazars

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: TXS 0506+056-like coincidence w. X-ray & γ-ray flares** (Sahakyan+ 22)

Flares May Still Matter in Neutrinos

pγ scenario: L_ν scales w. L_γ

Yoshida, Petropoulou, KM & Oikonomou 22 ApJ
see also KM, Oikonomou & Petropoulou 18 ApJ

$$L_\nu \propto L_\gamma^{\gamma_{\rm lw}}$$ **($\gamma_{\rm lw}$~1.5-2)**

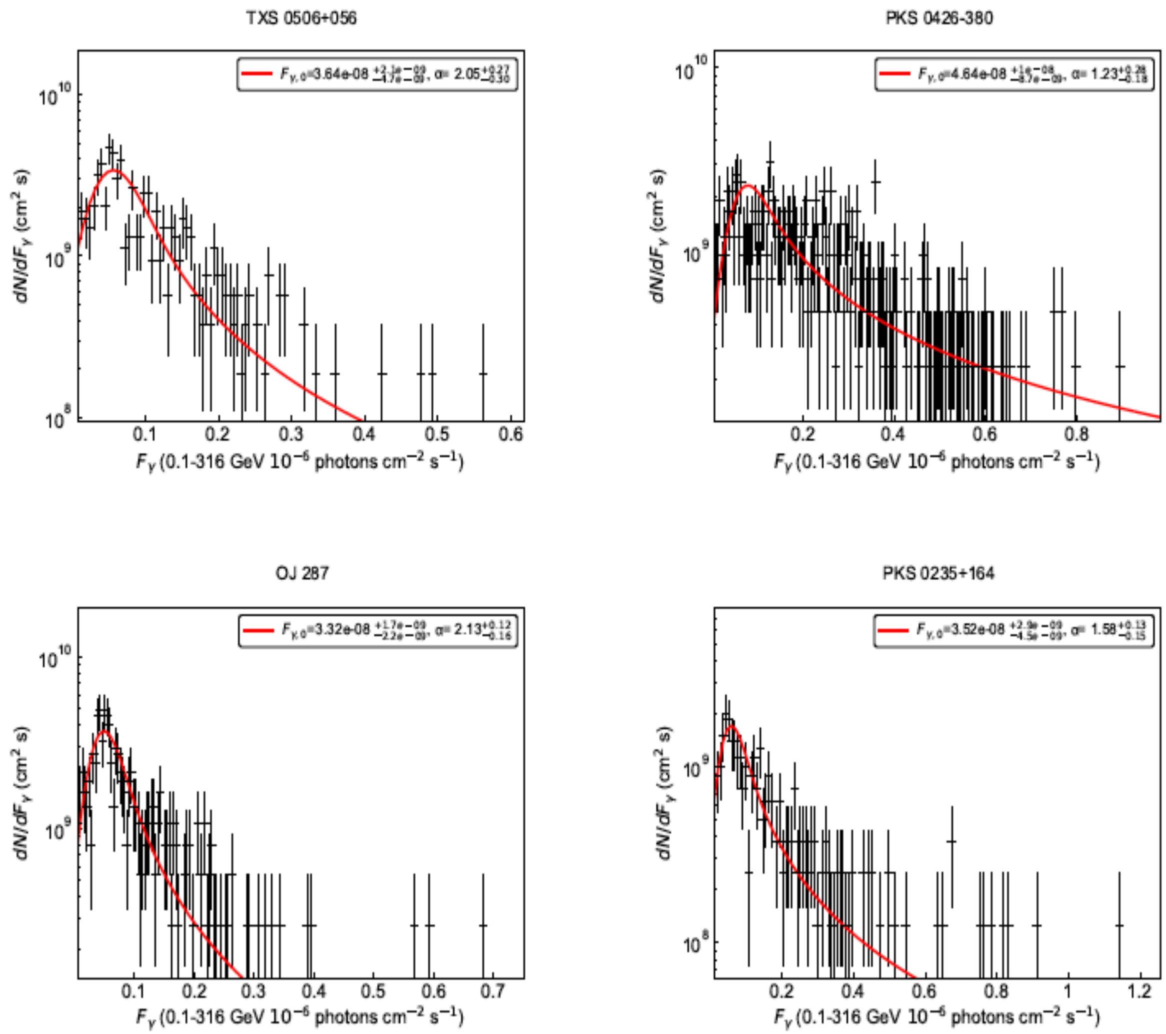
flare distribution

$$\frac{dN_{\rm fl}}{dL_\gamma} \propto L_\gamma^{-\alpha}$$

$$\bar{L}_\nu \propto L_\nu^2 \frac{dN_{\rm fl}}{dL_\nu} \propto L_\nu^{1-\frac{\alpha-1}{\gamma_{\rm lw}}}$$

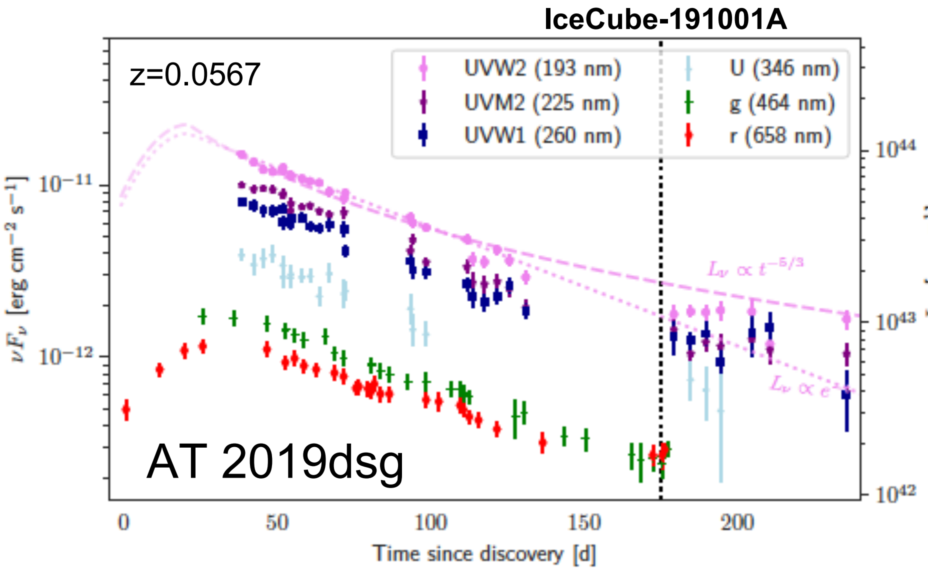
index is often **positive**

neutrino emission may be dominated by flare phases

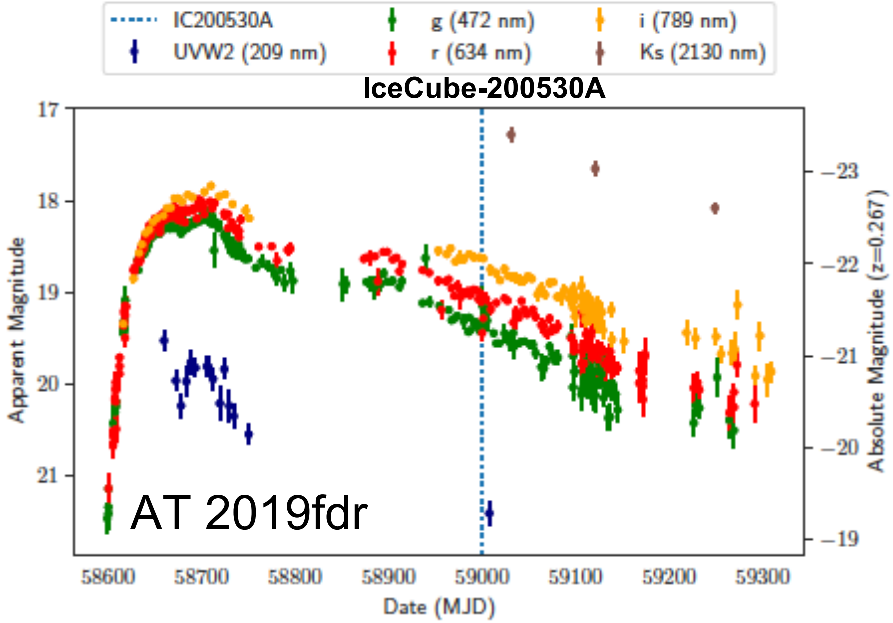


Coincidences w. Long-Duration "Optical" Transients

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



Stein+ 21 Nature Astron.

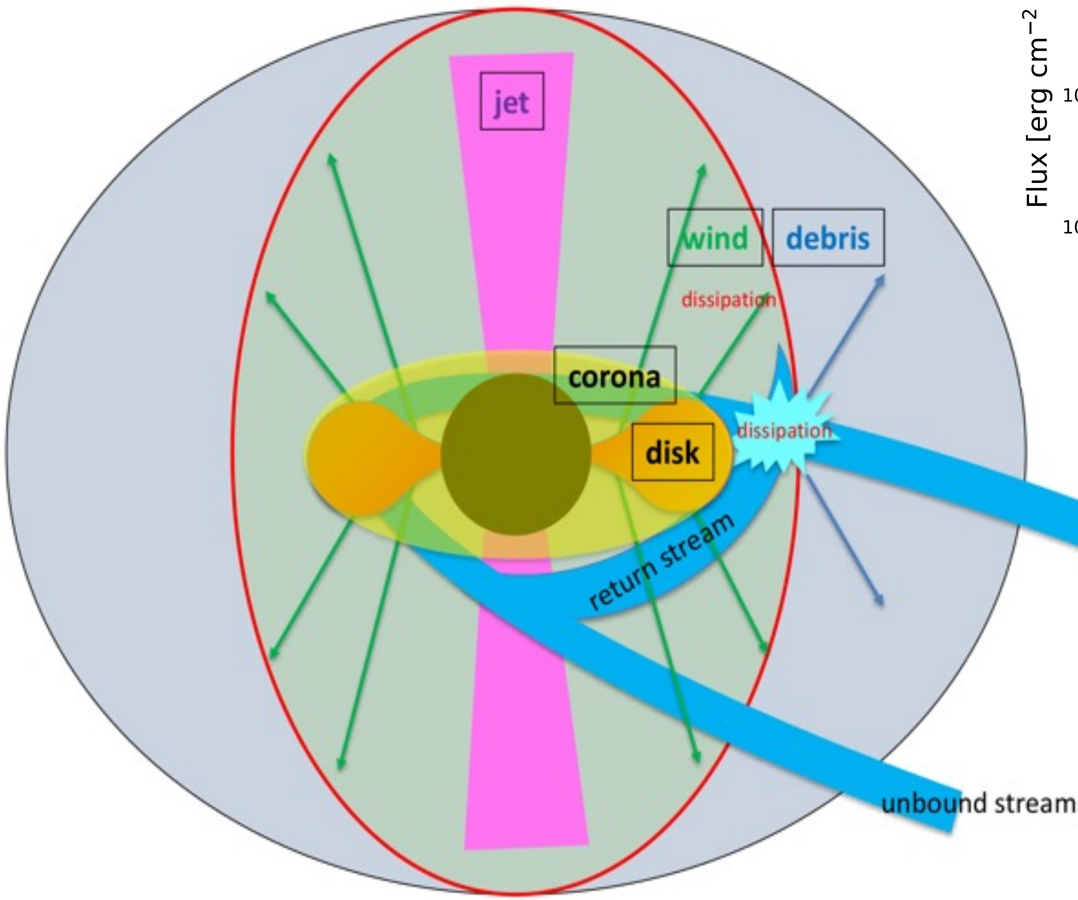


Reusch+ KM 21 PRL

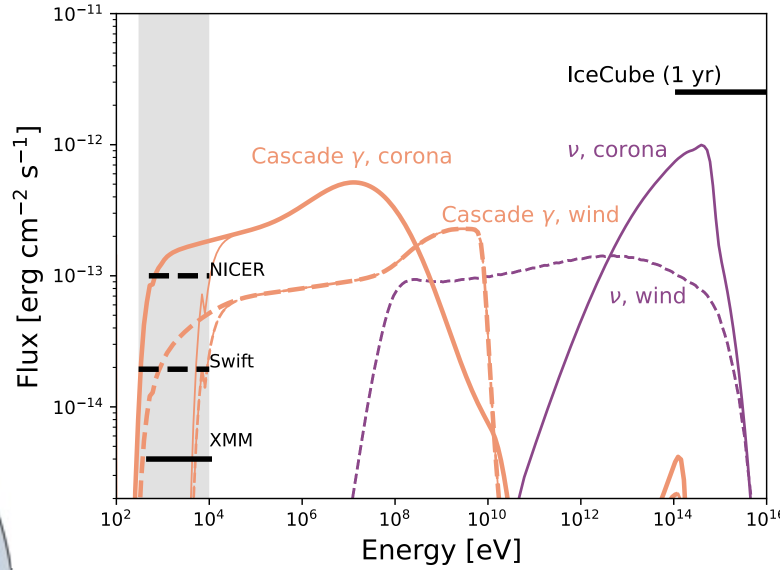
- 5 optical candidates reported (van Velzen+ 23, Jiang+ 23)
- All are rare optical transients w. strong infrared echoes
- Possible neutrino time delays w. ~150-300 day

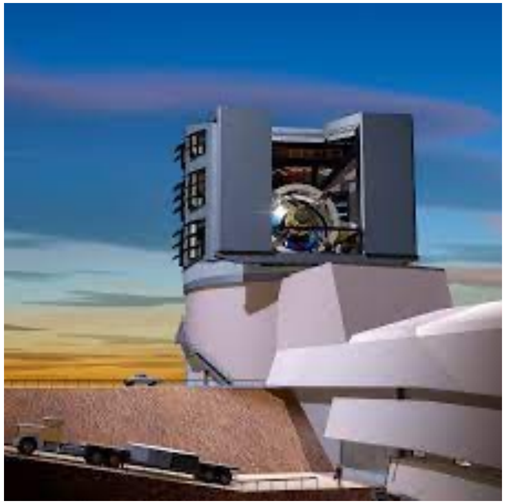
Neutrinos from Tidal Disruption Events?

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



KM, Kimura, Petropoulou & Oikonomou 20 ApJ





Supermassive black holes as hidden particle accelerators
Multimessenger interpretations?

Summary

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

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

- NGC 1068: evidence for a hidden neutrino source
- Emission radius: $R<30\text{-}100\ R_S$ → collisionless coronae?
- Sub-GeV γ-ray excess? (MeV: AMEGO-X, e-ASTROGAM)
  More in south (KM3Net/Baikal-GVD), IceCube-Gen2
- Understanding non-thermal phenomena in coronae

SMBH flares – blazar flares, TDEs

- TXS 0506+056 & other coincidences: no concordance
- Neutrinos could be predominantly during flares
- TDE and AGN νs could originate from common mechanisms
- Need more data: strategic searches, multiplet follow-up etc.