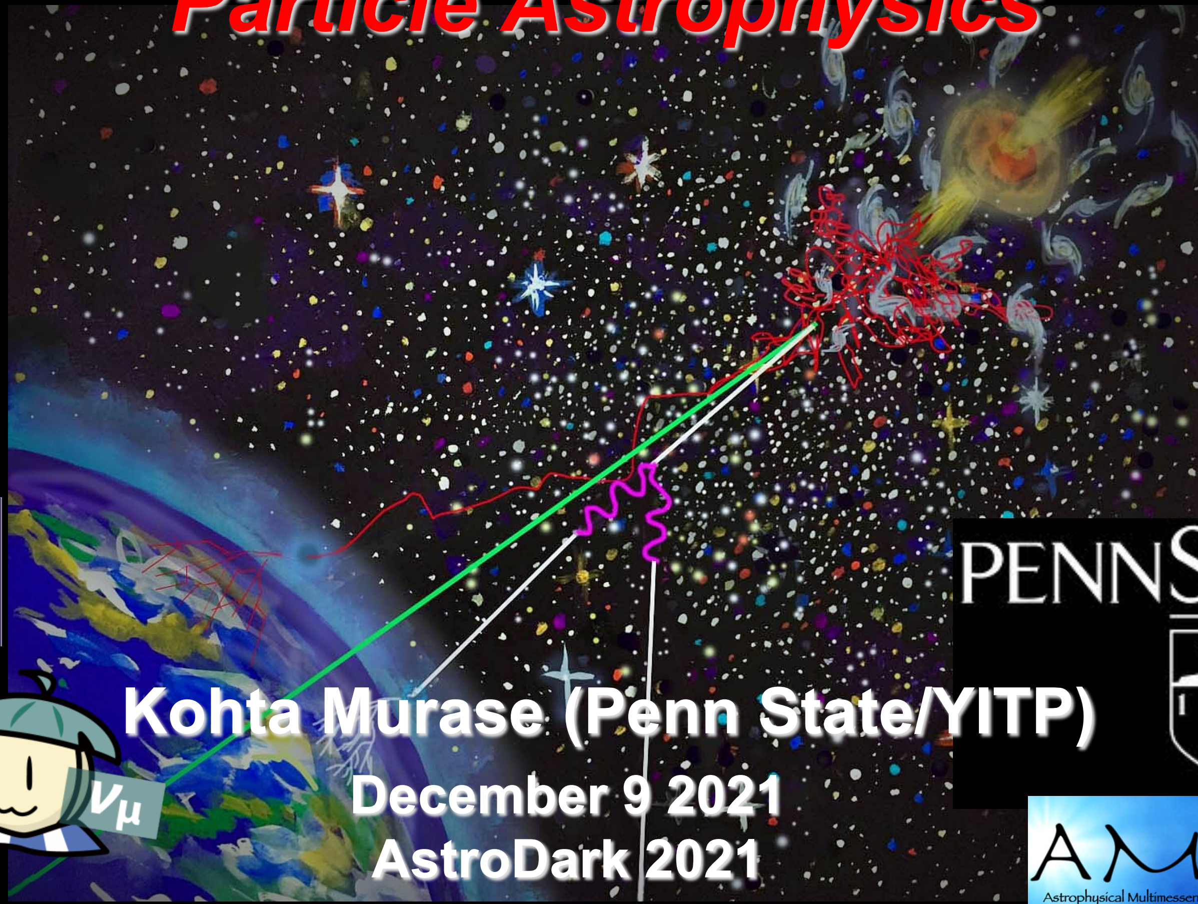
High-Energy Multimessenger Particle Astrophysics

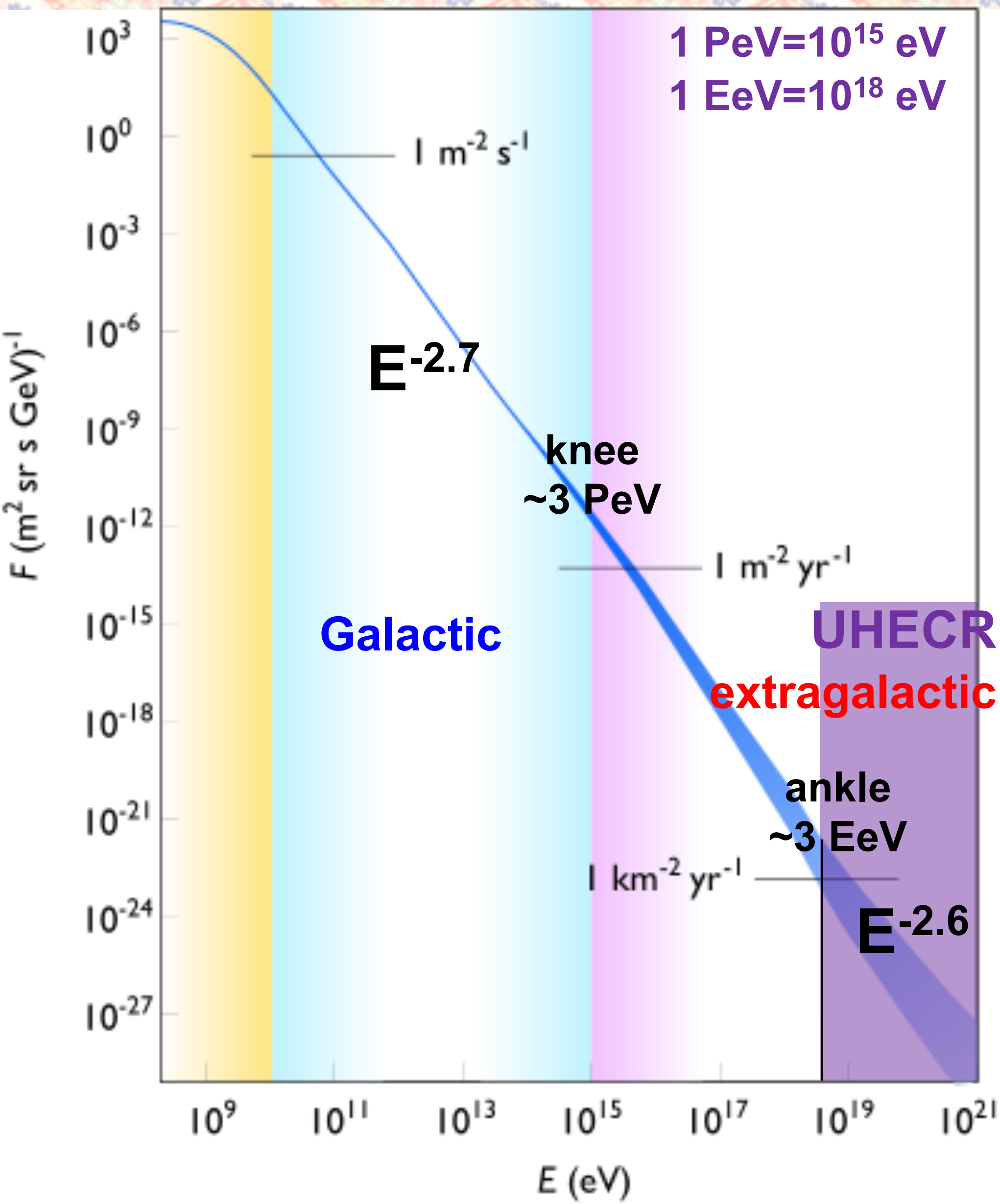


Kohta Murase (Penn State/YITP)

December 9 2021

AstroDark 2021

Cosmic-Ray Origin – A Century Old Puzzle



cosmic rays = protons, nuclei, electrons…

$$\frac{dN_{\rm CR}}{dE} \propto E^{-s_{\rm CR}}$$

- How is the spectrum formed?
 (ex. Galactic-extragalactic transition)

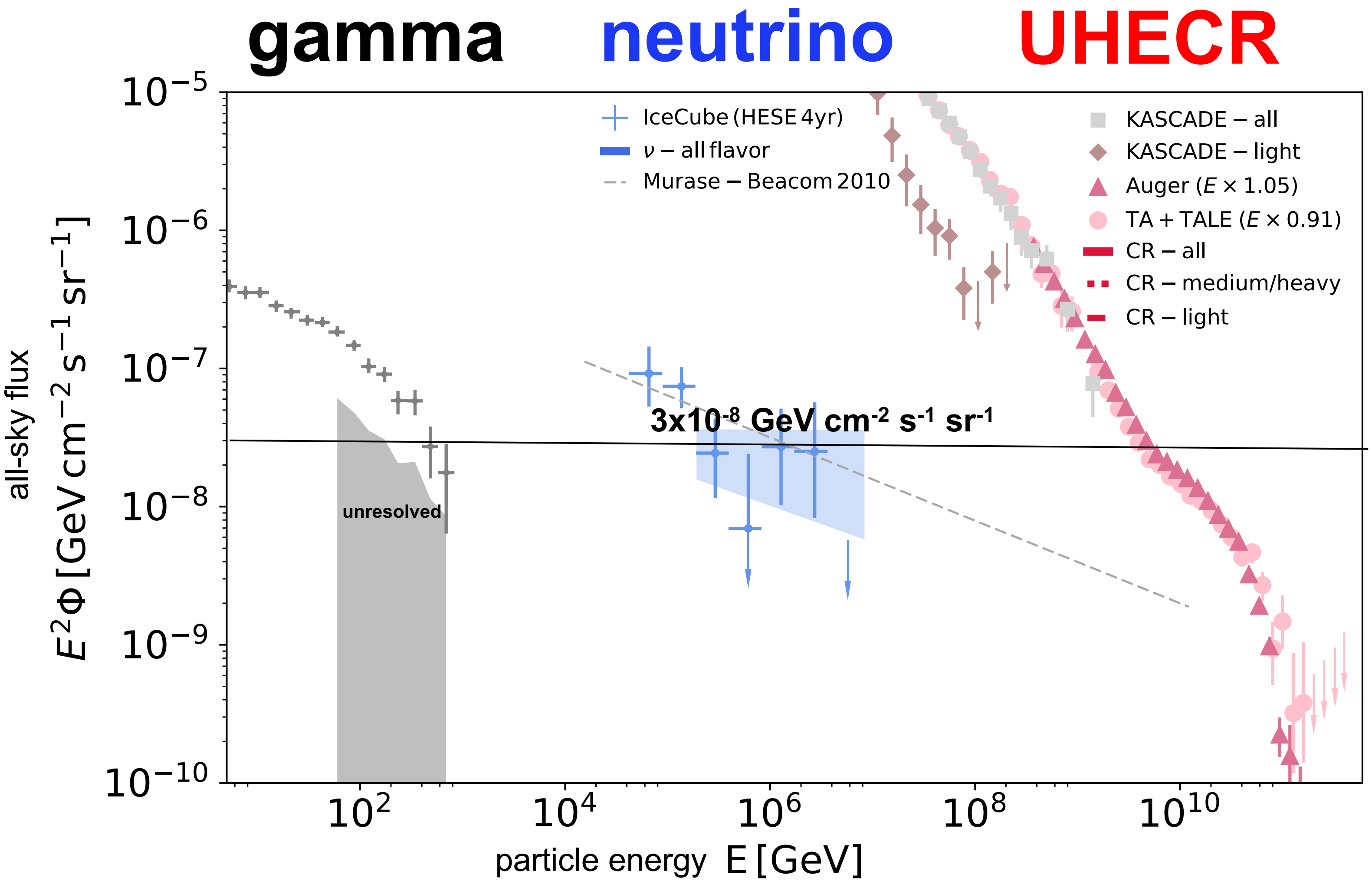
- How are CRs accelerated?
 (ex. Fermi mechanism: s_{CR}~2)

- How do CRs propagate?
 (diffusion, rectilinear, or?)

…

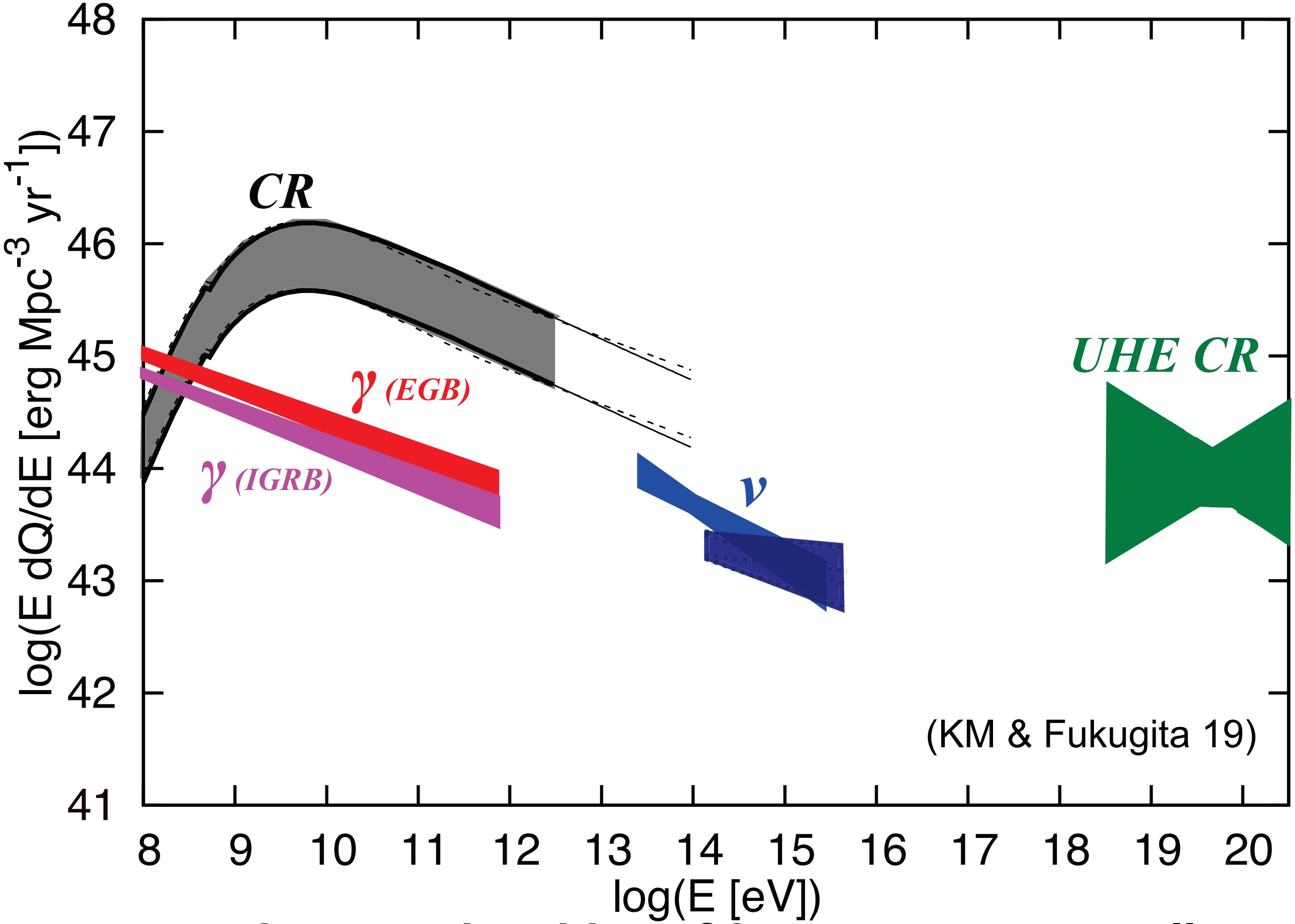
“What is the origin?”

High-Energy Multi-Messenger Astro-Particle Origin?



$$E^2\Phi \approx \frac{ct_H}{4\pi}\left[E\frac{dQ}{dE}\right]\xi_z \times (\text{suppression due to energy losses})$$

Unification or Conspiracy?



Energy generation rate densities of 3 messengers are all comparable

crucial to understand the non-thermal Universe and underlying source physics

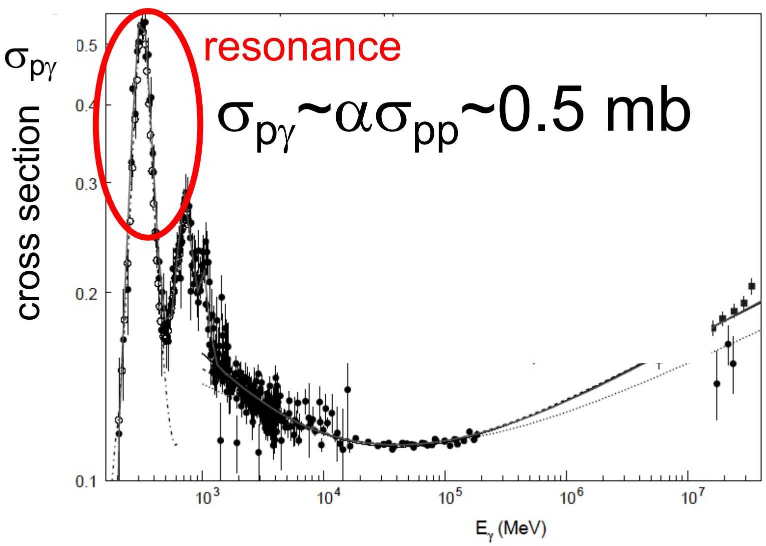
High-Energy Neutrino Production

Cosmic-ray Accelerators

Active galaxy

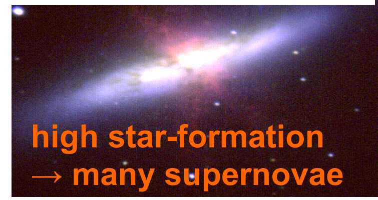
γ-ray burst

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



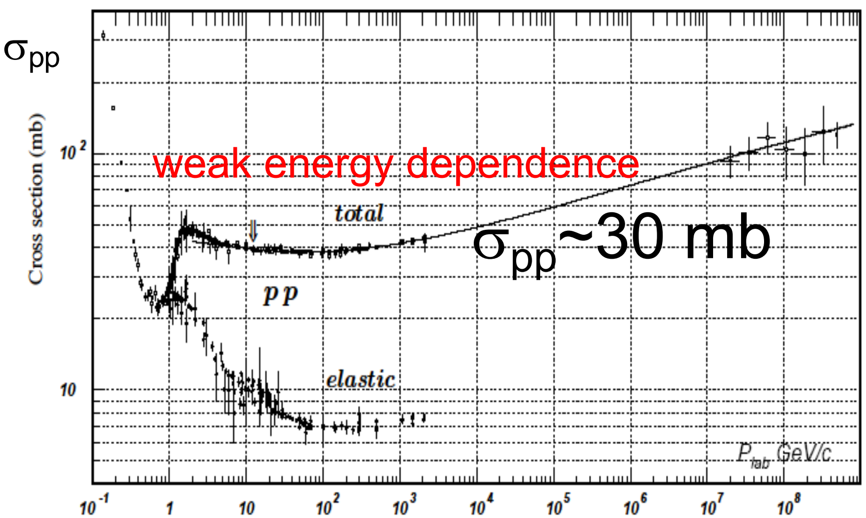
Cosmic-ray Reservoirs

Starburst galaxy



Galaxy cluster

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



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

Fate of High-Energy Gamma Rays

$$\pi^0 \to \gamma + \gamma$$

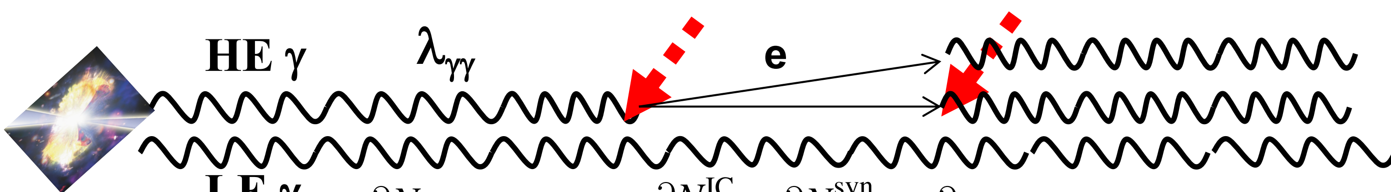
$p + \gamma \to N\pi + X$ $\quad \pi^0 : \pi^{\pm} \sim 1:1 \to$ **$E_\gamma^2 \Phi_\gamma : E_\nu^2 \Phi_\nu$** $\sim 4:3$

$p + p \to N\pi + X$ $\quad \pi^0 : \pi^{\pm} \sim 1:2 \to$ **$E_\gamma^2 \Phi_\gamma : E_\nu^2 \Phi_\nu$** $\sim 2:3$

comparable

Moreover, accelerated electrons make γ rays by synchrotron & Compton processes

cosmic photon bkg. cosmic photon bkg.



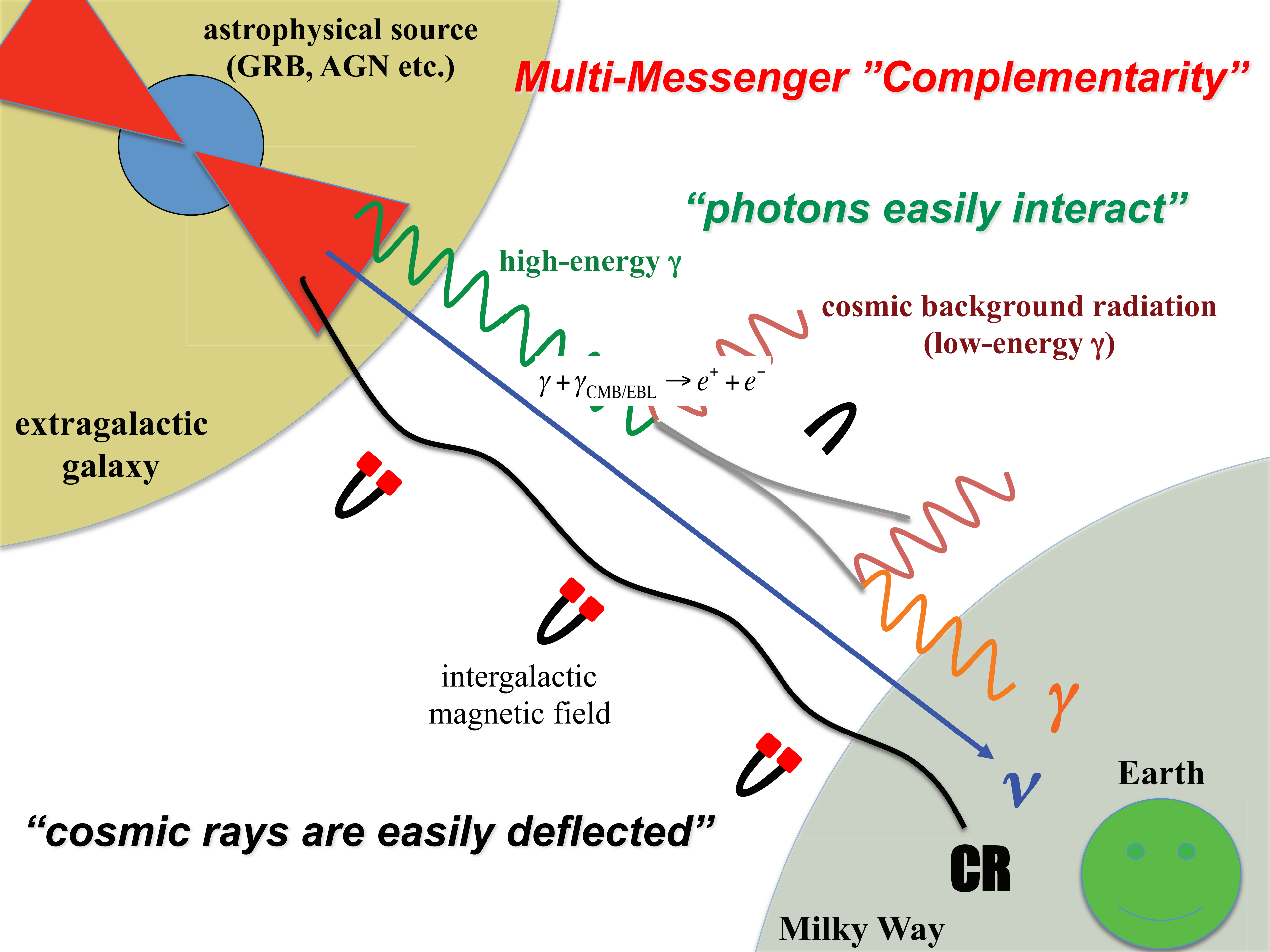
Fermi satellite

airshower detectors

$$\frac{\partial N_\gamma}{\partial x} = -N_\gamma R_{\gamma\gamma} + \frac{\partial N_\gamma^{\rm IC}}{\partial x} + \frac{\partial N_\gamma^{\rm syn}}{\partial x} - \frac{\partial}{\partial E}[P_{\rm ad} N_\gamma] + Q_\gamma^{\rm inj},$$

$$\frac{\partial N_e}{\partial x} = \frac{\partial N_e^{\gamma\gamma}}{\partial x} - N_e R_{\rm IC} + \frac{\partial N_e^{\rm IC}}{\partial x} - \frac{\partial}{\partial E}[(P_{\rm syn} + P_{\rm ad}) N_e] + Q_e^{\rm inj},$$

>TeV-PeV γ rays are cascaded to GeV-TeV γ rays



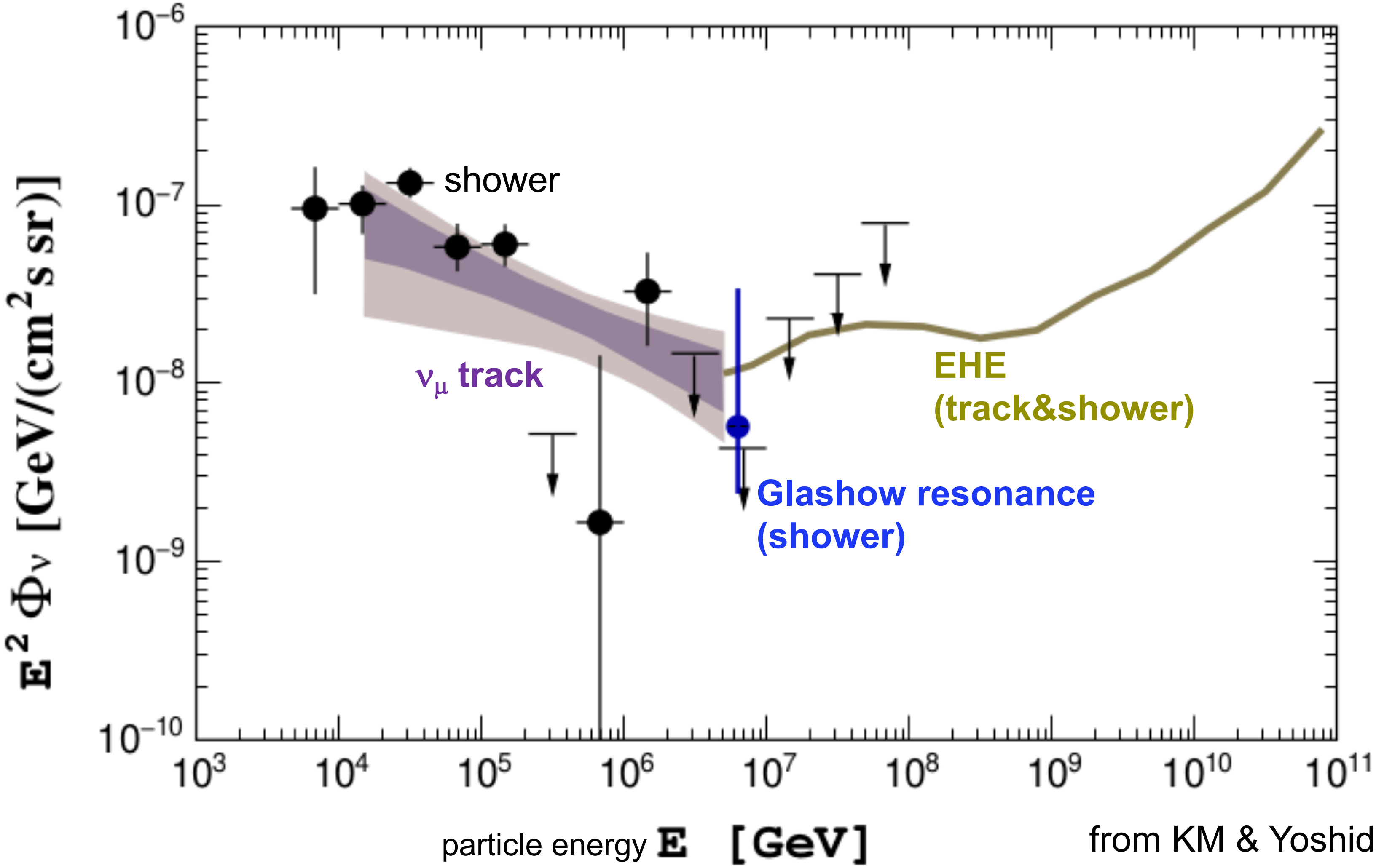
astrophysical source
(GRB, AGN etc.)
Multi-Messenger "Complementarity"
"photons easily interact"
high-energy γ
cosmic background radiation
(low-energy γ)
$\gamma + \gamma_{CMB/EBL} \rightarrow e^{+} + e^{-}$
extragalactic
galaxy
intergalactic
magnetic field
γ
ν
Earth
"cosmic rays are easily deflected"
CR
Milky Way

All-Sky Neutrino Flux & Spectrum

all-sky ν flux at E_ν ~200 TeV

$E_\nu^2\Phi_\nu$ ~ **3x10^{-8} GeV cm^{-2} s^{-1} sr^{-1}**

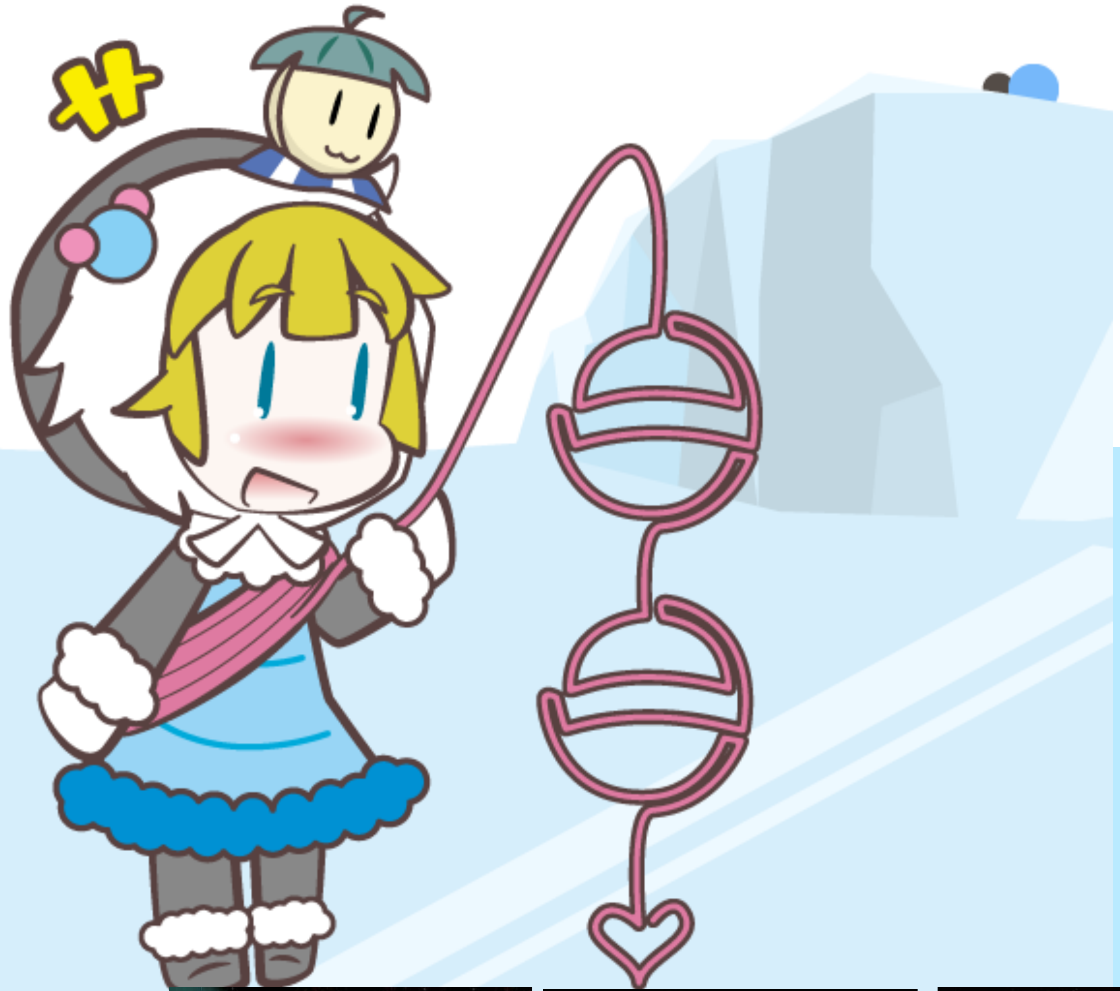
IceCube Collaboration 20 PRL
IceCube Collaboration 21 Nature
IceCube Collaboration 22

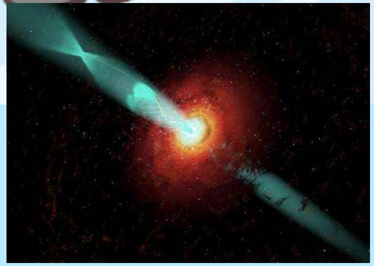


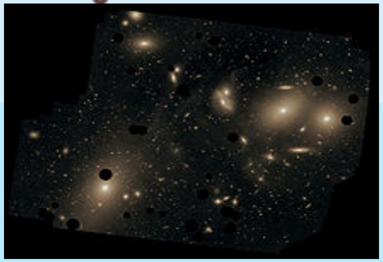
from KM & Yoshida 22

Where do neutrinos mainly come from?

monster fishing!!



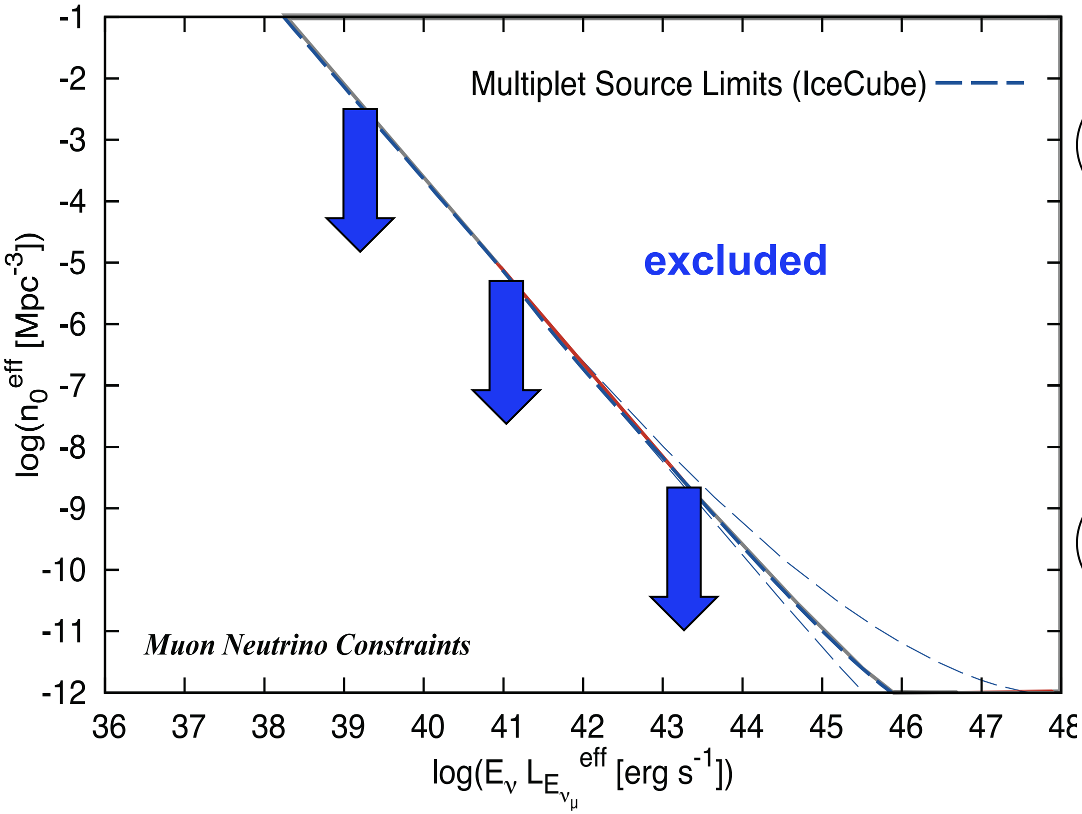


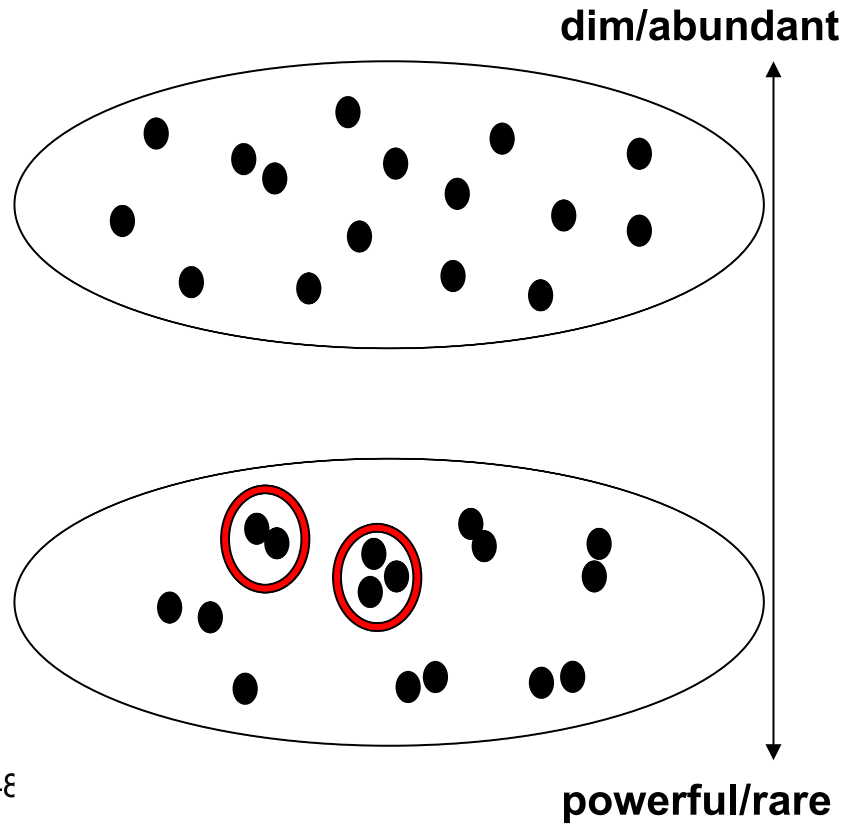


What Can We Learn from Neutrinos?

Nonsignificant ν event clustering constrains source population

Silvestri & Barwick 10, KM, Beacom & Takami 12





What Can We Learn from Neutrinos?

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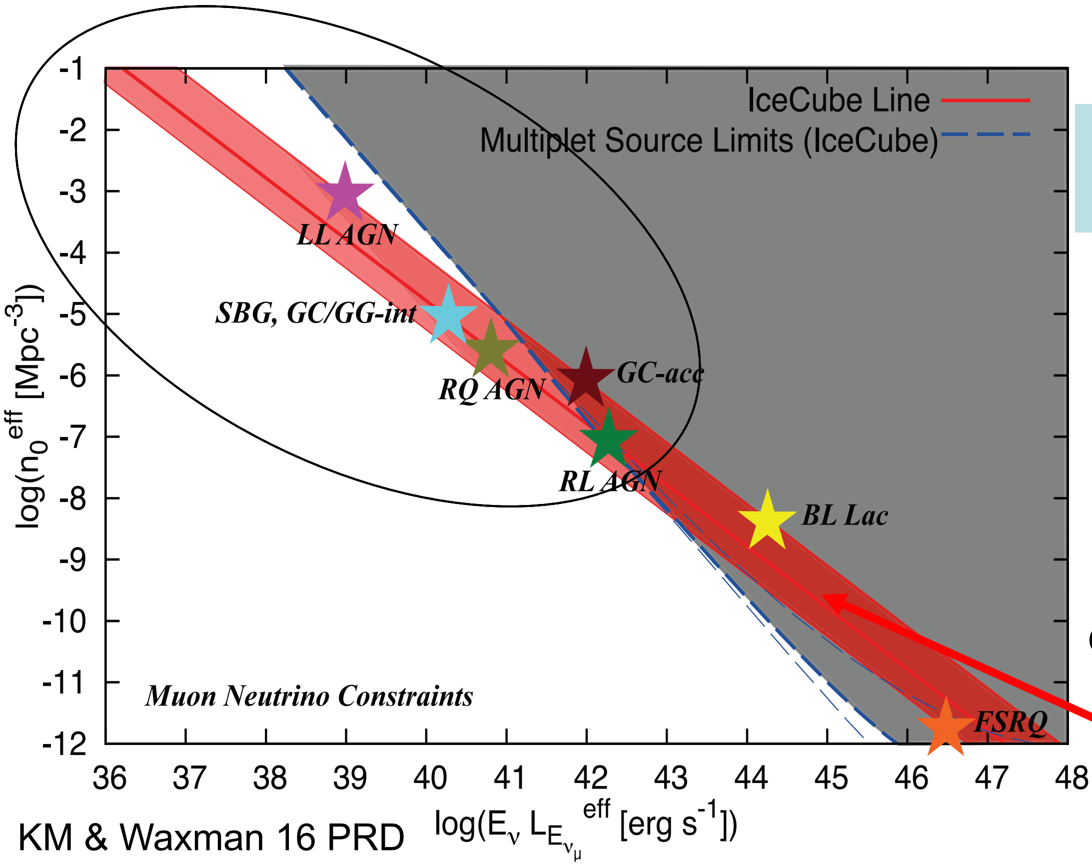


KM & Waxman 16 PRD

all-sky flux = line of sight integral over the Hubble size

$$E_\nu^2 \Phi_\nu = \frac{c}{4\pi} \int \frac{dz}{(1+z)^2 H(z)} [n_s \varepsilon_\nu L_{\varepsilon_\nu}] \propto \frac{d_H}{4\pi} n_0 L_\nu$$

$E_\nu^2 \Phi_\nu \sim 3\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

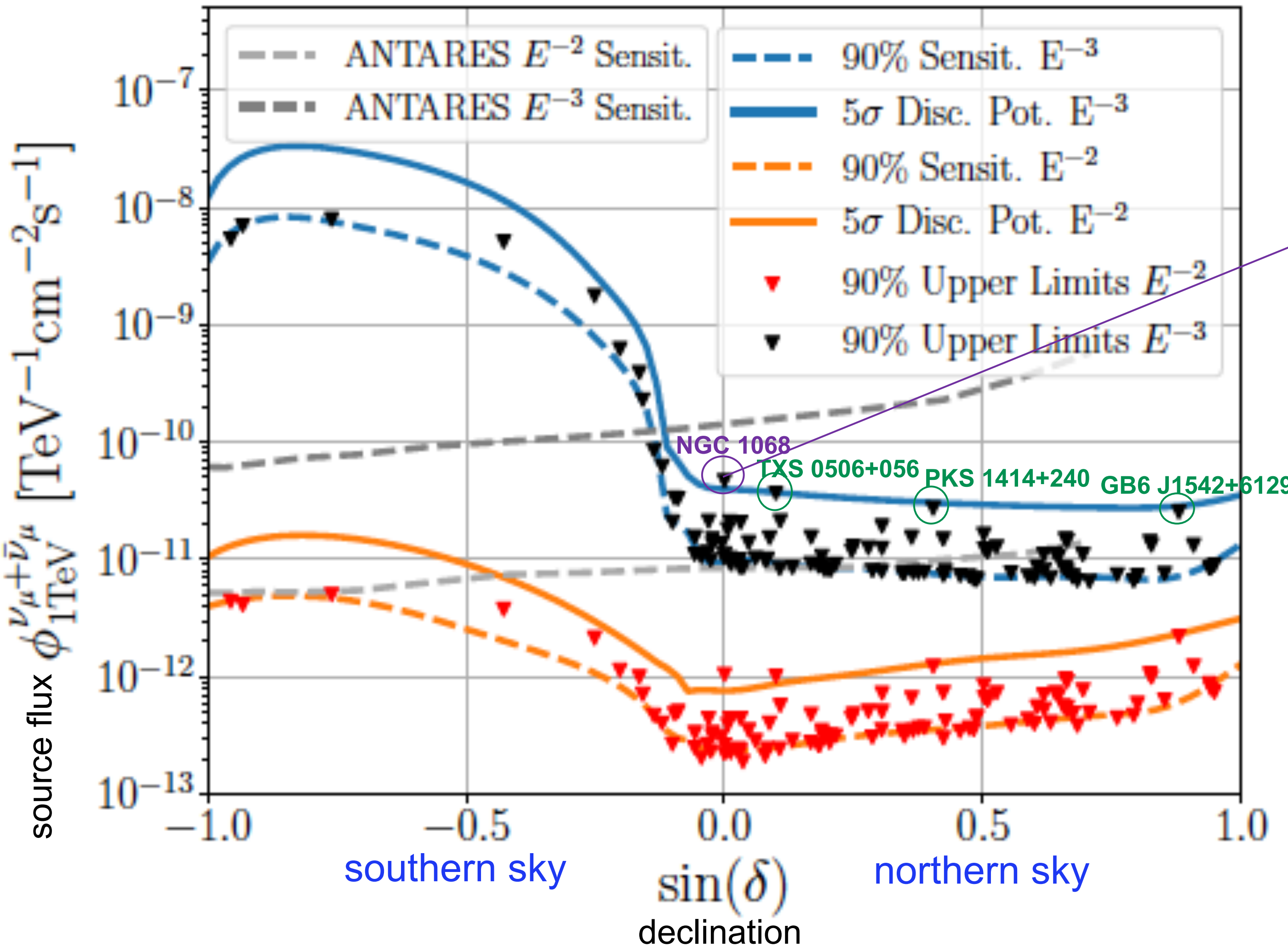
energy generation rate density

$n_0 L_\nu \sim 3\times10^{43}$ erg Mpc^{-3} yr^{-1}

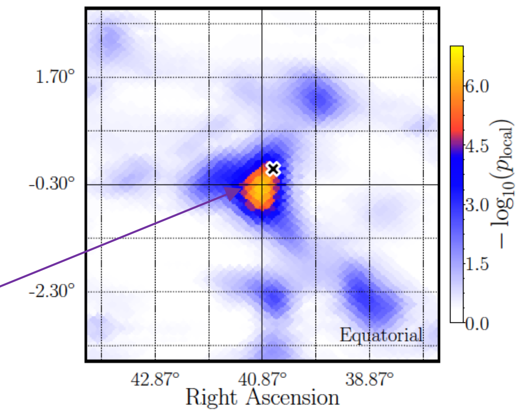
Rare source classes (e.g., blazars) are likely to be “subdominant”

IceCube Source Searches

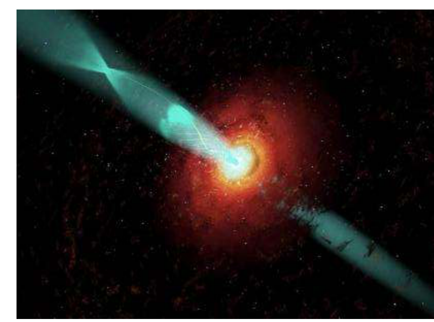
IceCube Collaboration 20 PRL



AGN/starburst galaxy

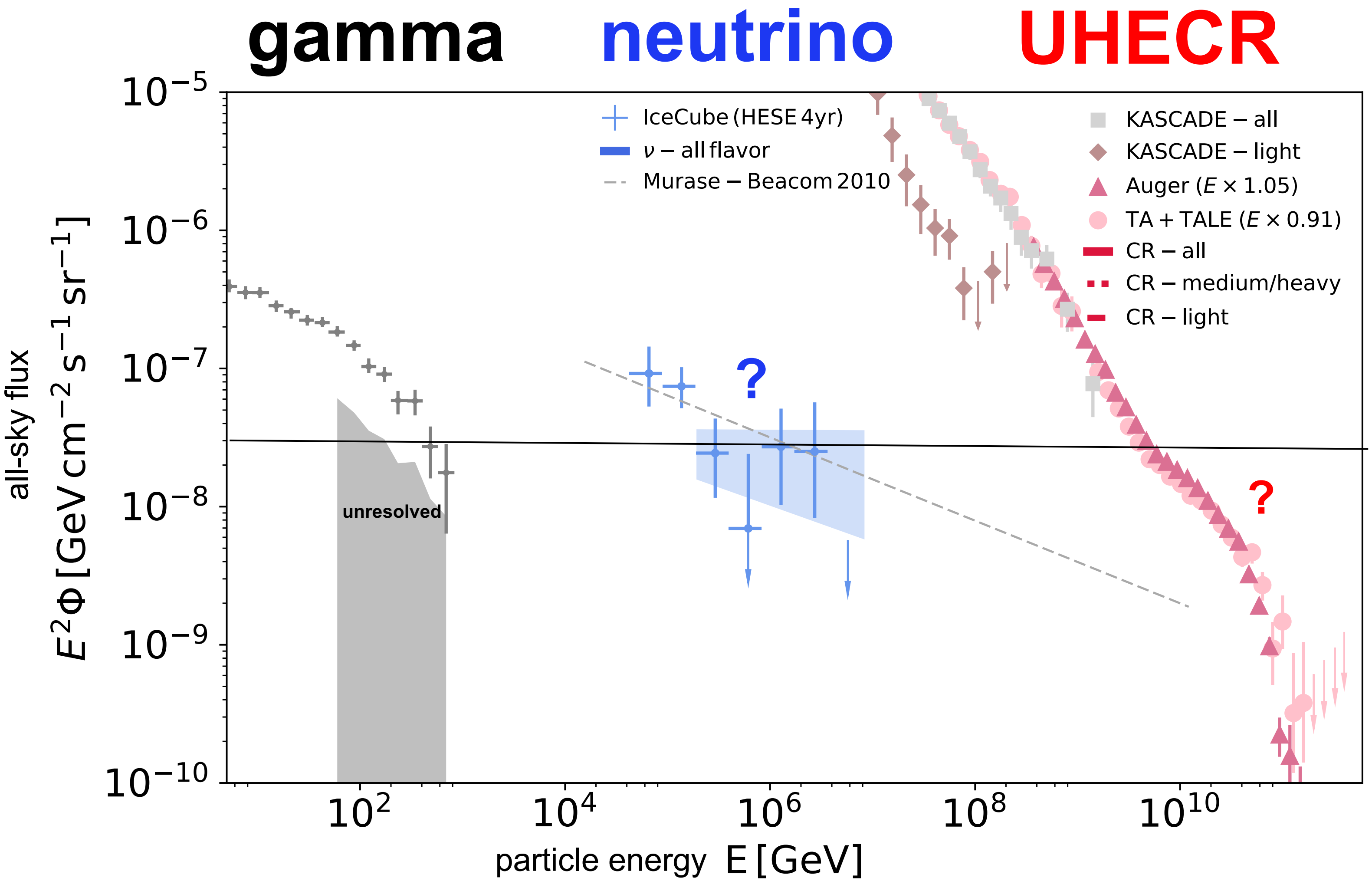


Jetted AGN

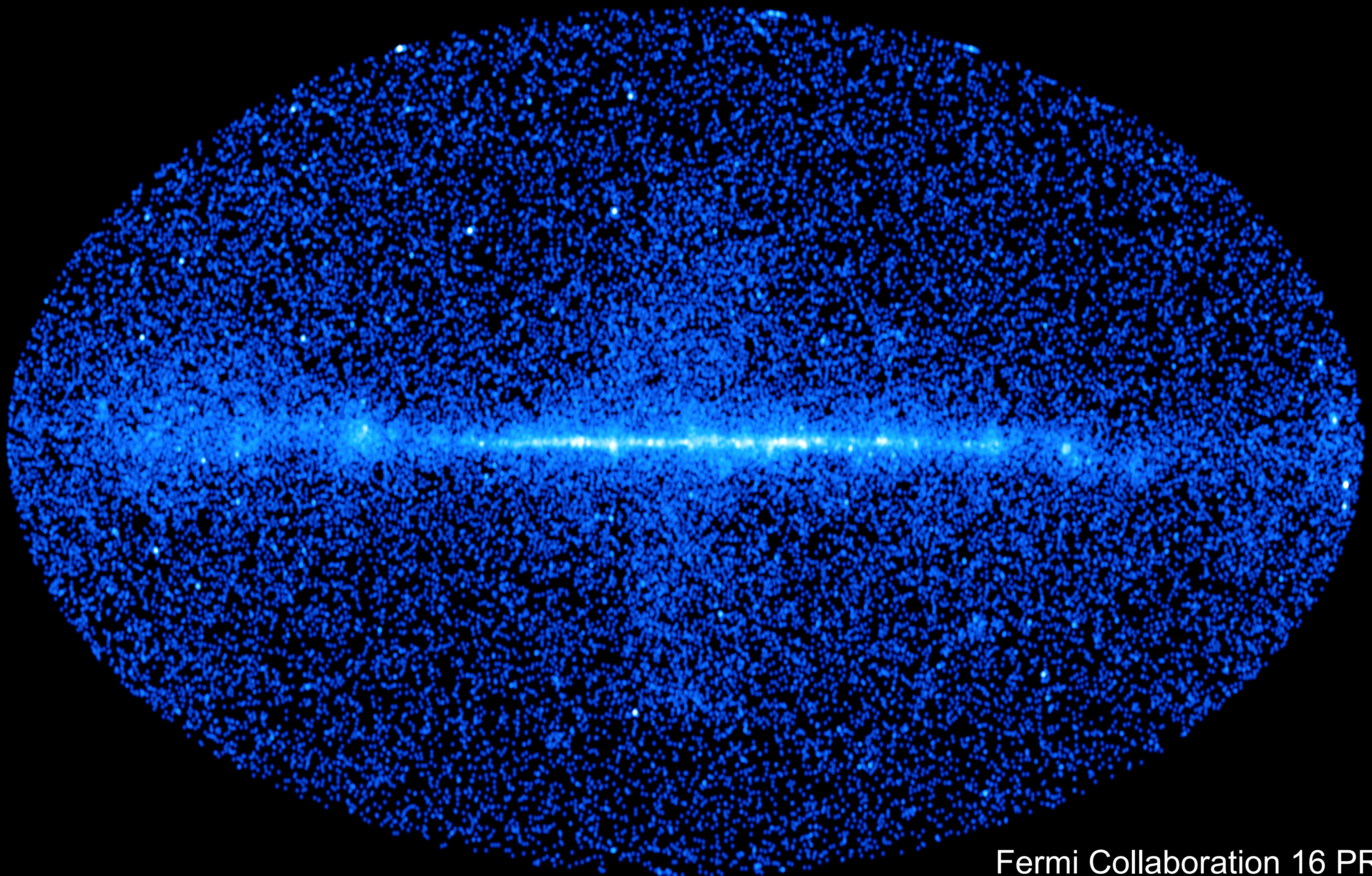


"Catches" (~3σ) exist but none have reached the discovery level

Multi-Messenger Approaches?

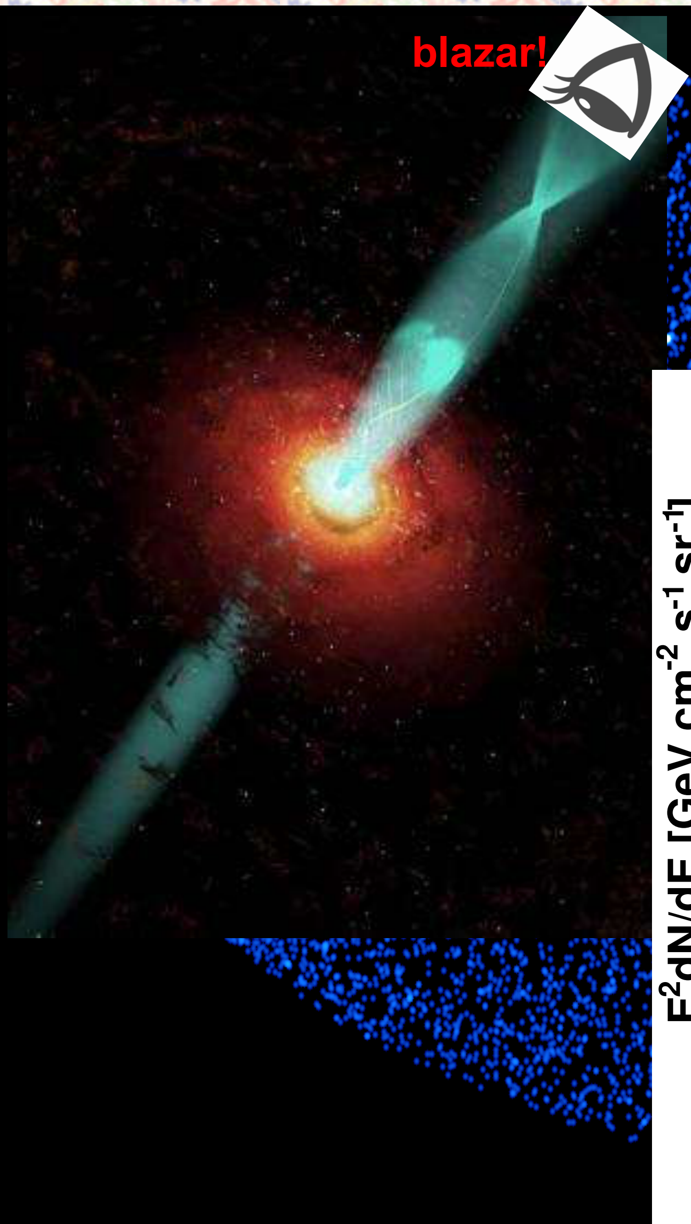


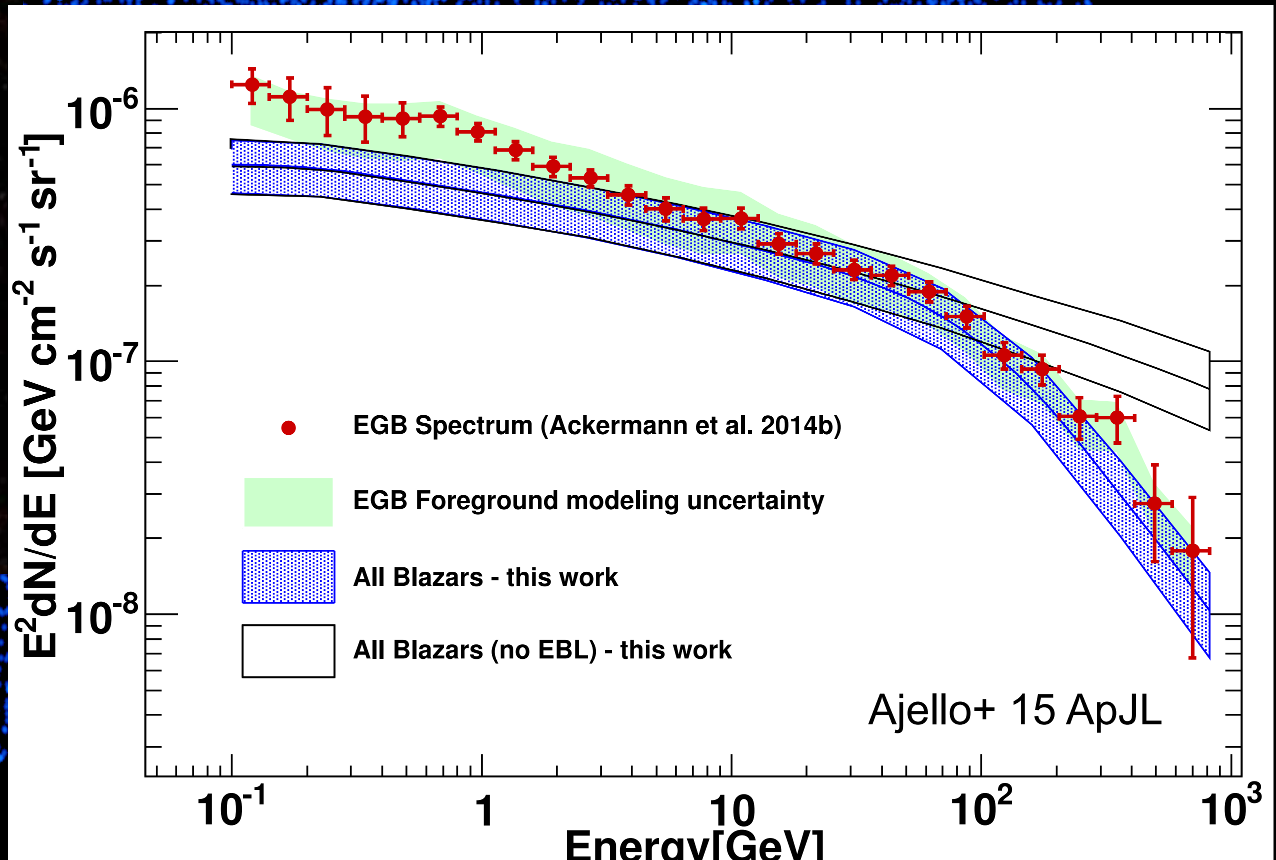
Extragalactic Gamma-Ray Sky: Dominated by Jetted AGN



Fermi Collaboration 16 PRL

Extragalactic Gamma-Ray Sky: Dominated by Jetted AGN

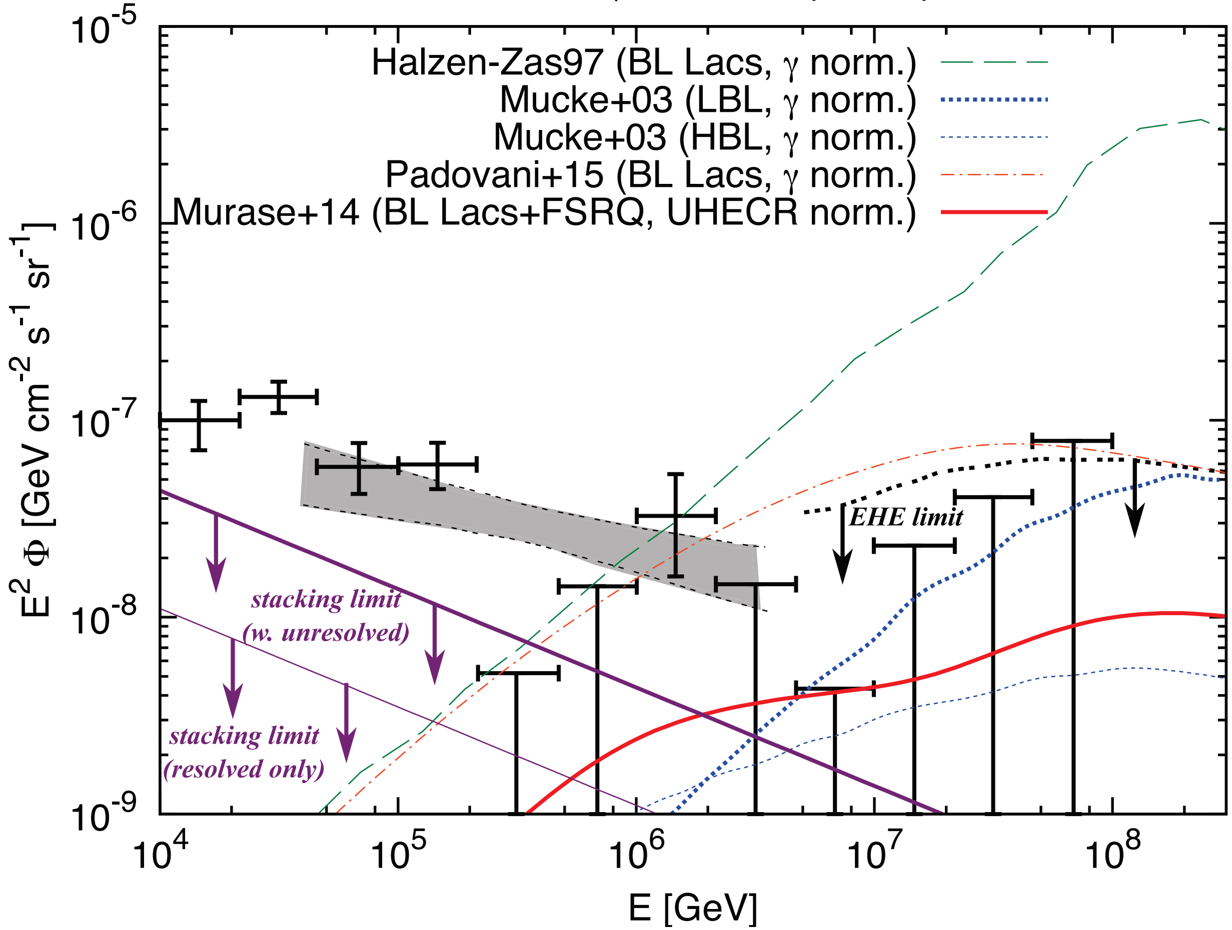




Can Blazars be the Origin of IceCube Neutrinos?

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

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



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

Complementary constraints from neutrino clustering limits (KM & Waxman 16 PRD)

High-Energy Neutrino Production

Cosmic-ray Accelerators

Active galaxy

γ-ray burst

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

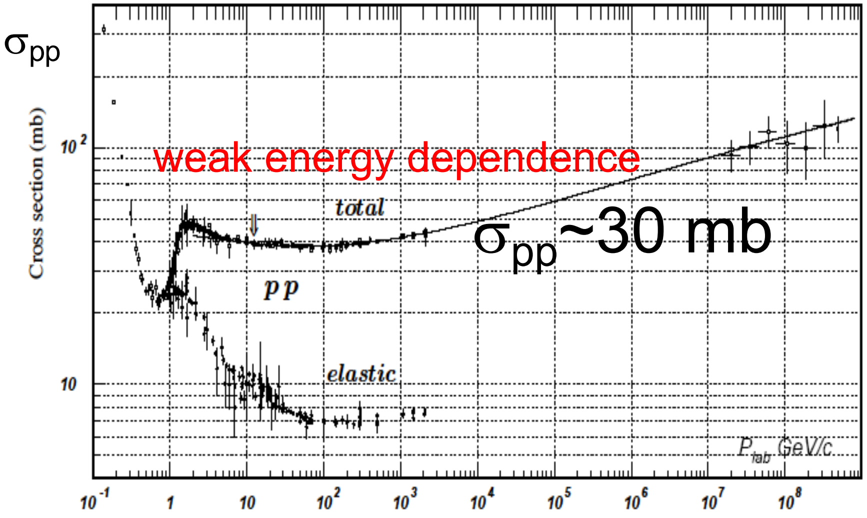
stacking or other searches disfavor blazar-type AGN and classical γ-ray bursts as the "dominant" ν origin
(important results of multi-messenger approaches)

Cosmic-ray Reservoirs

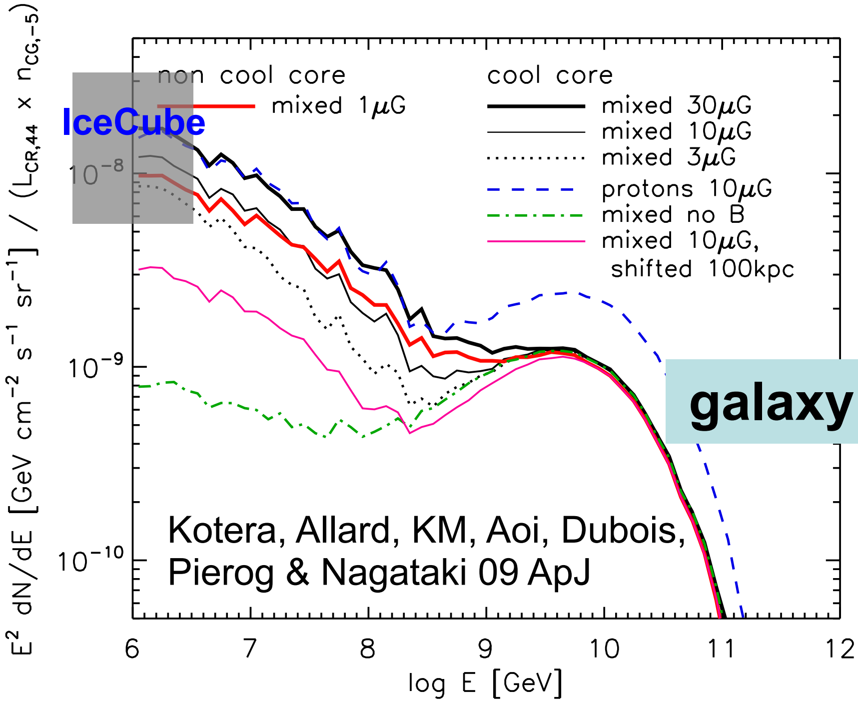
Starburst galaxy

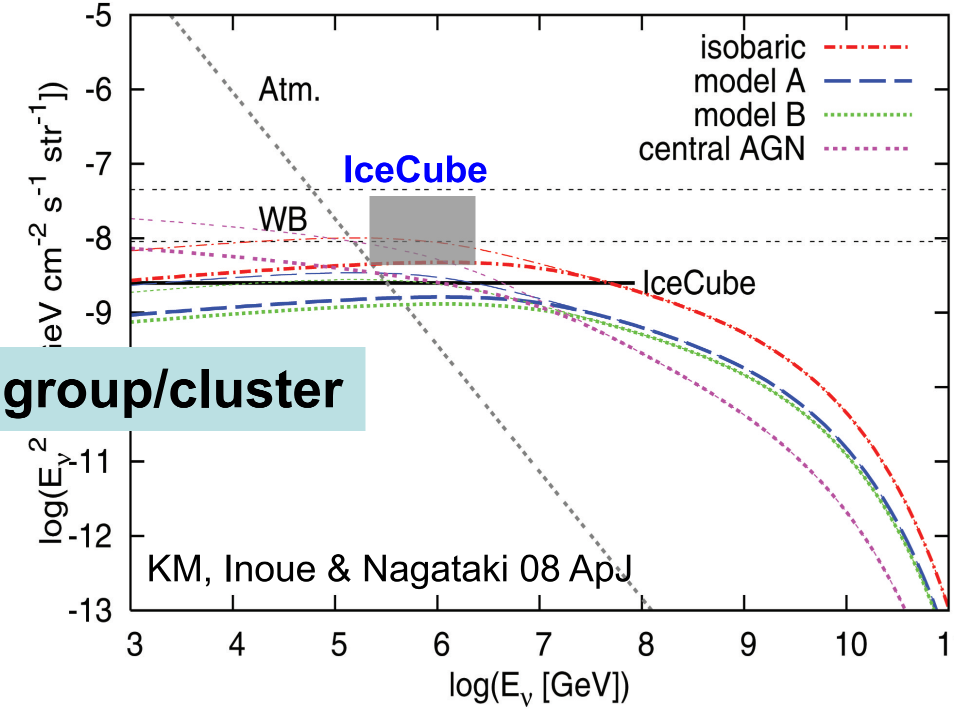
Galaxy cluster

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

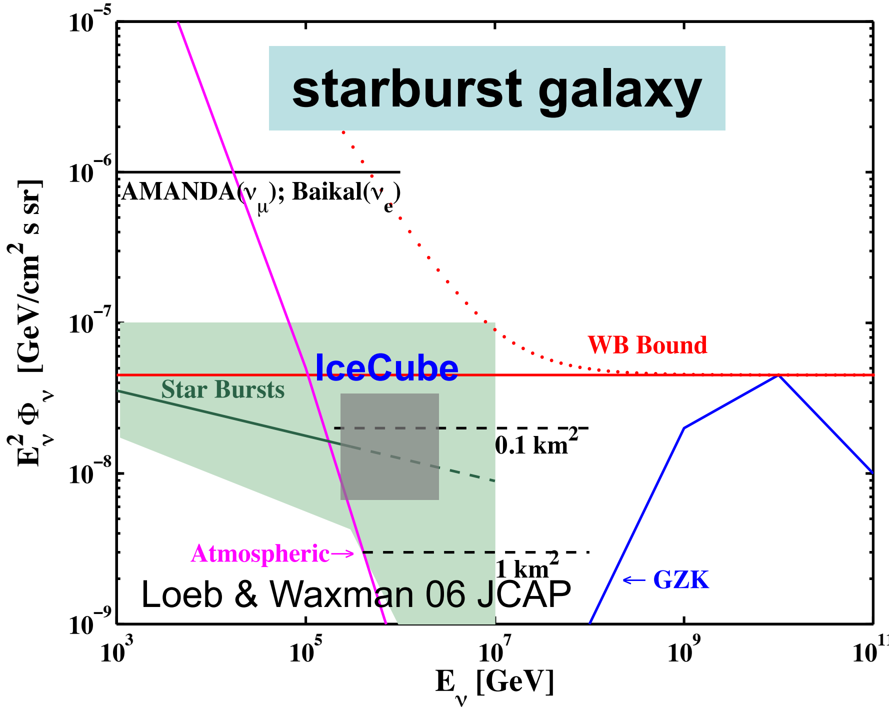


$$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e \ (\mathrm{or}\ \bar{\nu}_e) + e^{\pm}$$





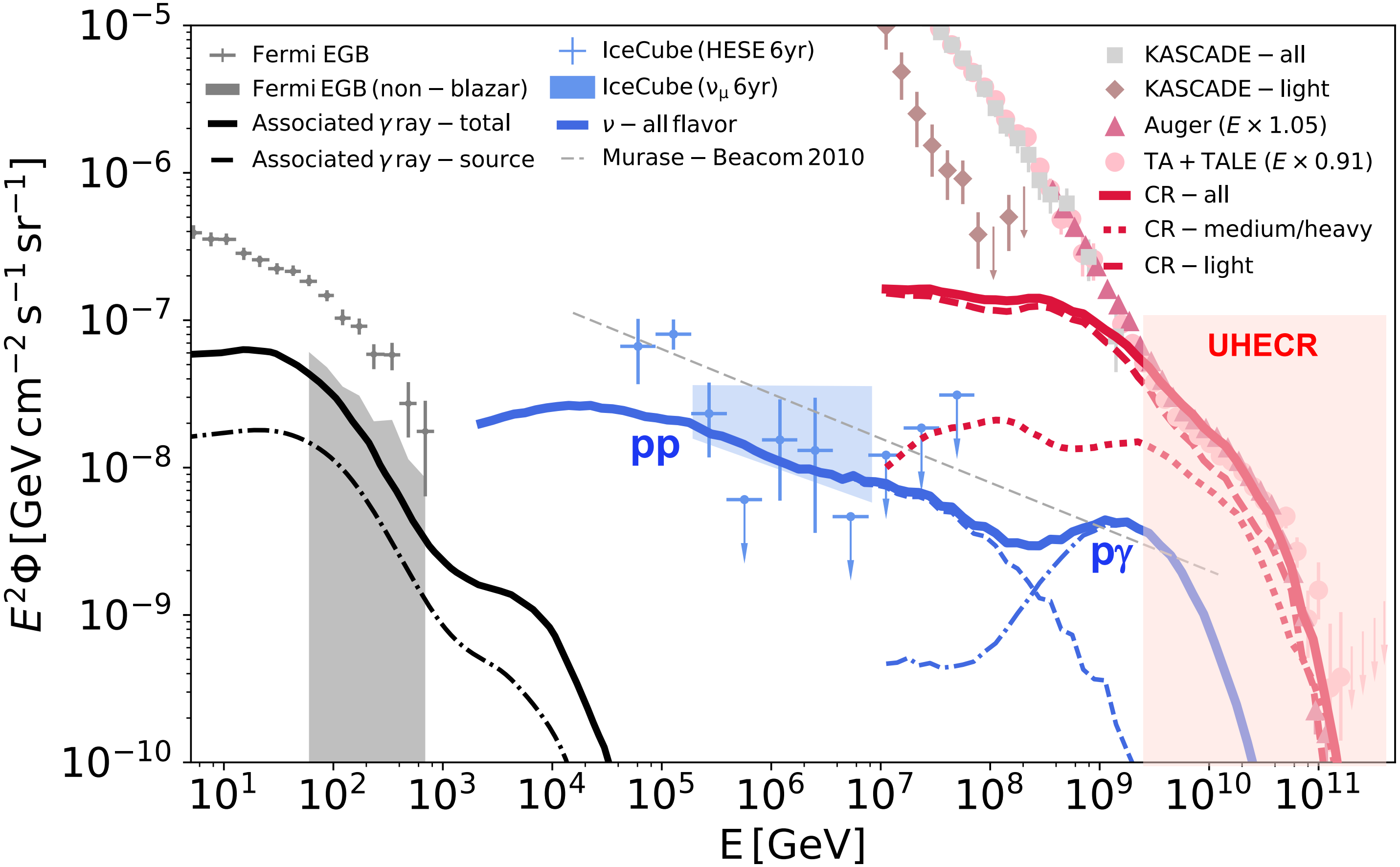
galaxy group/cluster



>0.1 PeV IceCube data: consistent w. earlier theoretical predictions

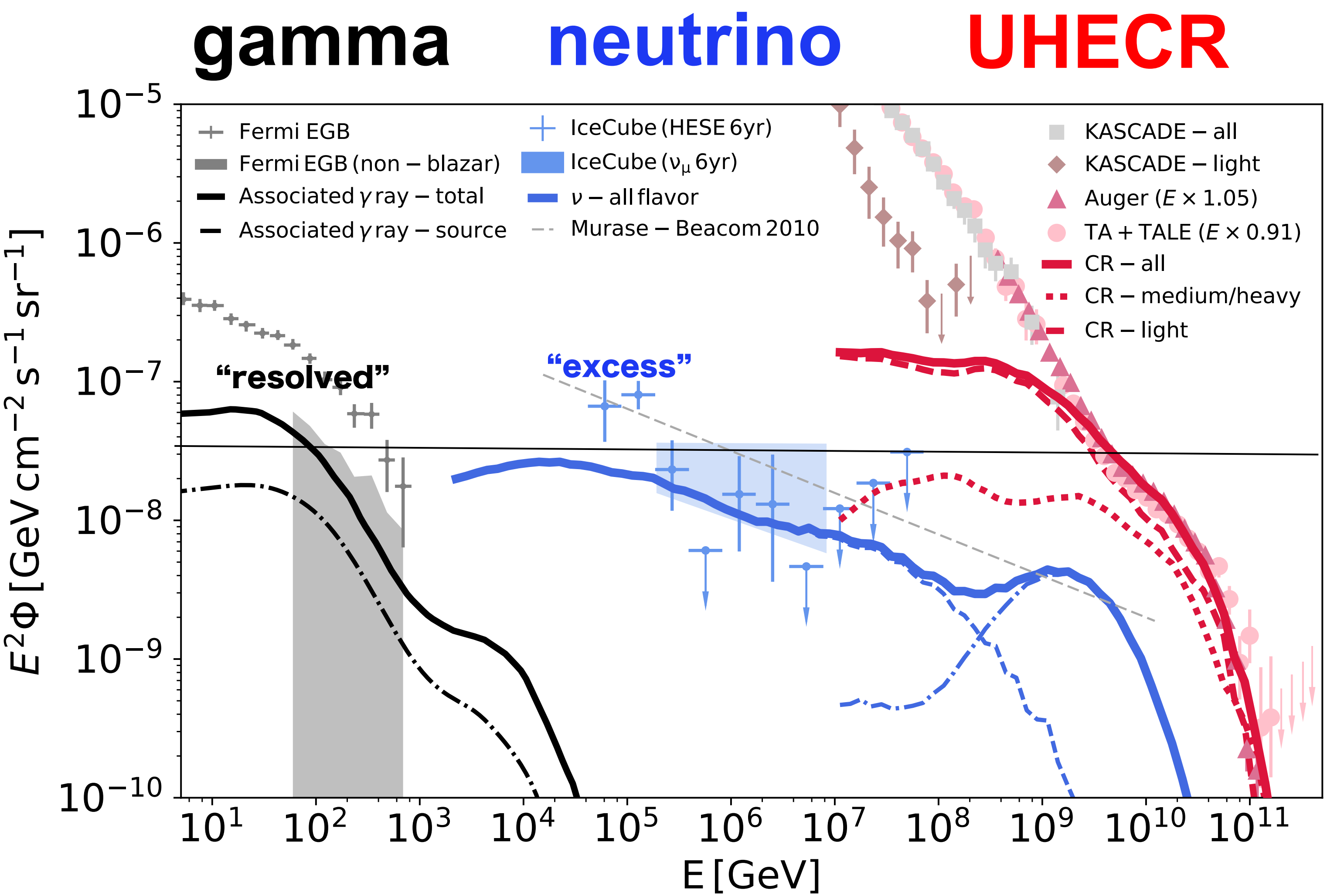
High-Energy Astro-Particle “Grand-Unification”?

Fang & KM 18 Nature Phys.

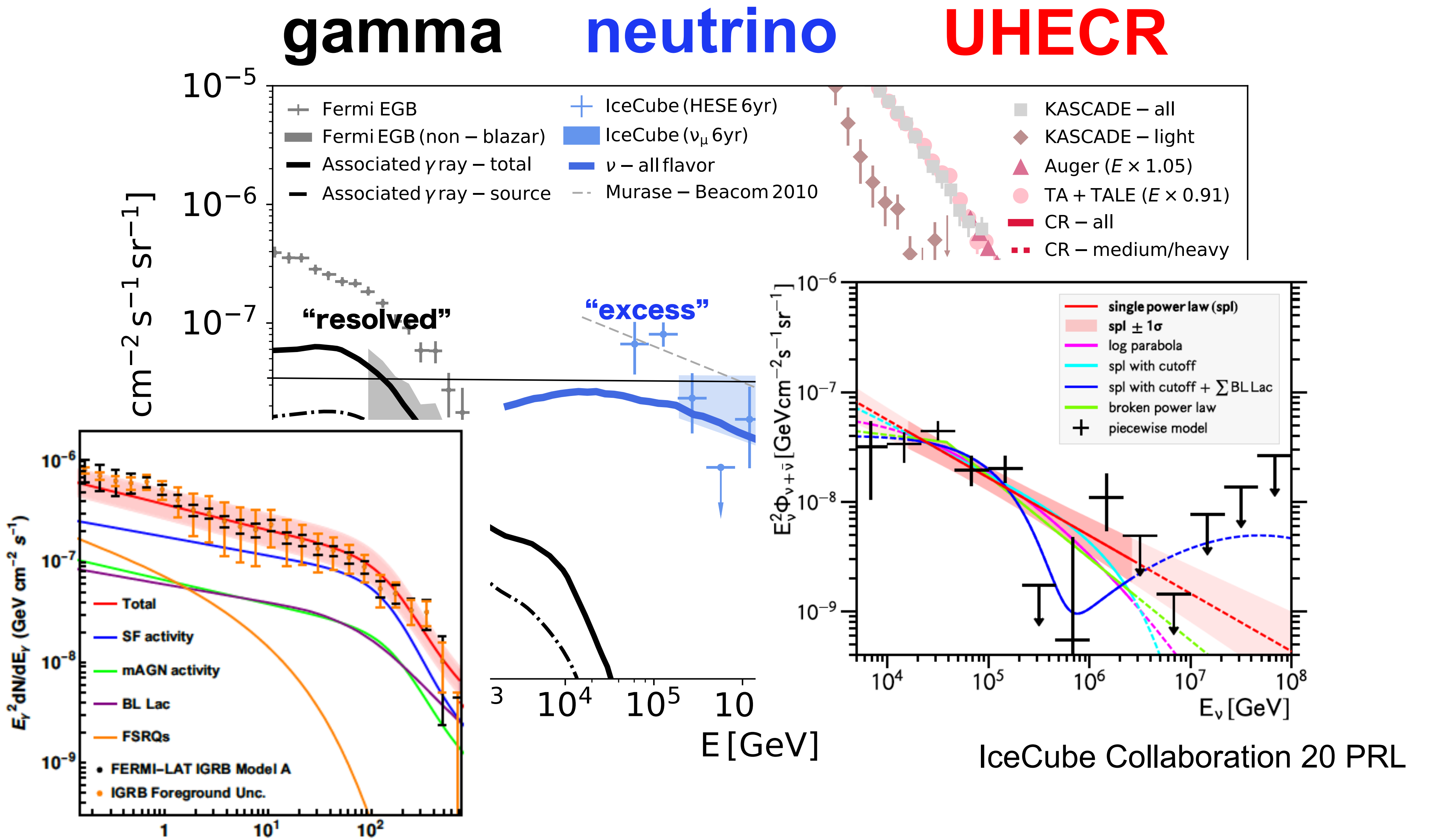


- Jetted AGN as “UHECR” accelerators
- Neutrinos from confined CRs & UHECRs from escaping CRs
- Prediction: smooth transition from source ν (at PeV) to cosmogenic ν (at EeV)

Reality Seems More Complicated (& Interesting)



Reality Seems More Complicated (& Interesting)



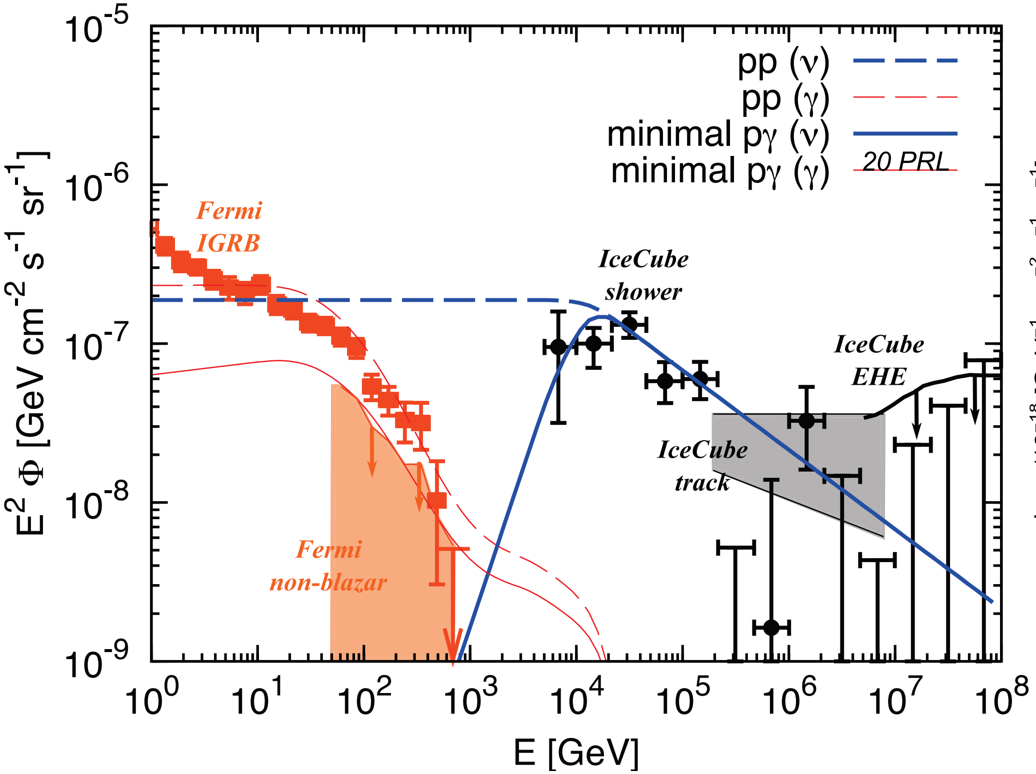
Blanco & Linden 21

IceCube Collaboration 20 PRL

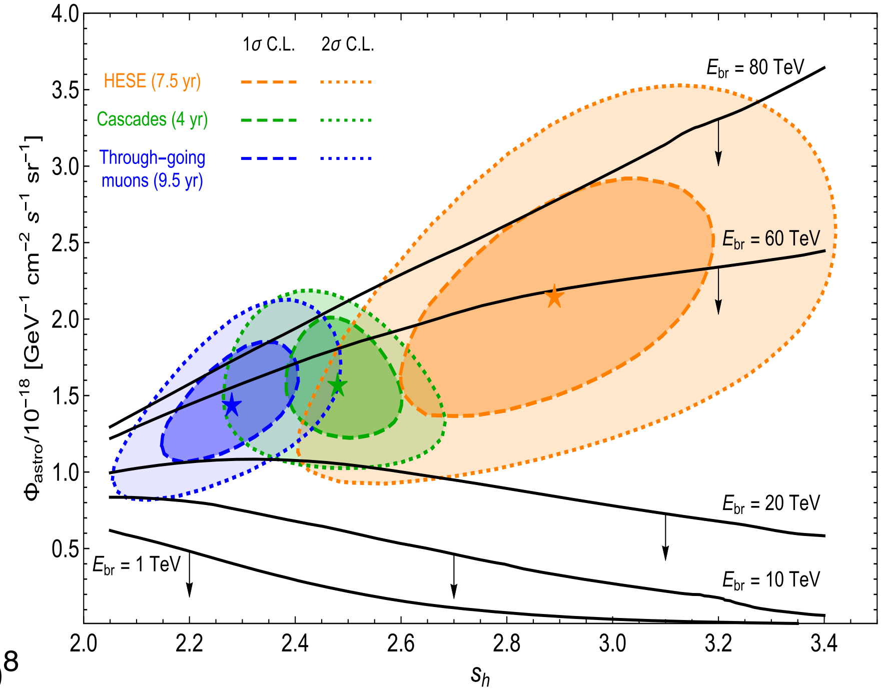
Multi-Messenger Implications of 10-100 TeV ν All-Sky Flux

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

KM, Guetta & Ahlers 16 PRL
see also KM, Ahlers & Lacki 13 PRDR



Capanema, Esmaili & KM 20 PRD
see also Capanema, Esmaili & Serpico 21 JCAP



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

Solutions to "Excessive" All-Sky Neutrino Flux?

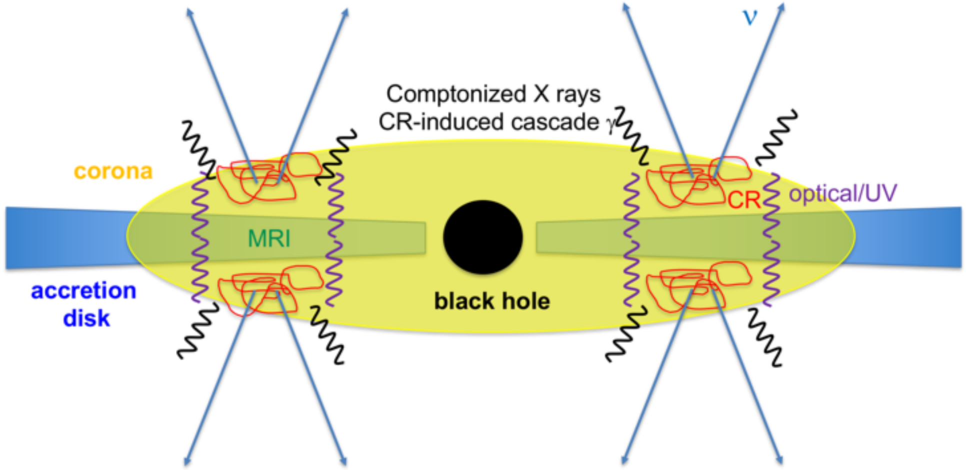
Hidden (i.e., γ-ray opaque) ν sources are actually natural in $p\gamma$ scenarios

(KM, Guetta & Ahlers 16 PRL)

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

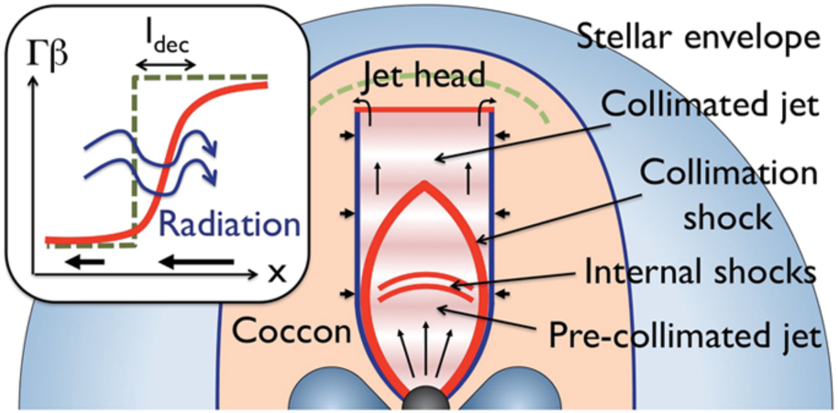
implying that >TeV-PeV γ rays are cascaded down to GeV or lower energies

vicinity of black holes



(from KM, Kimura & Meszaros 20 PRL)

choked jets in supernovae

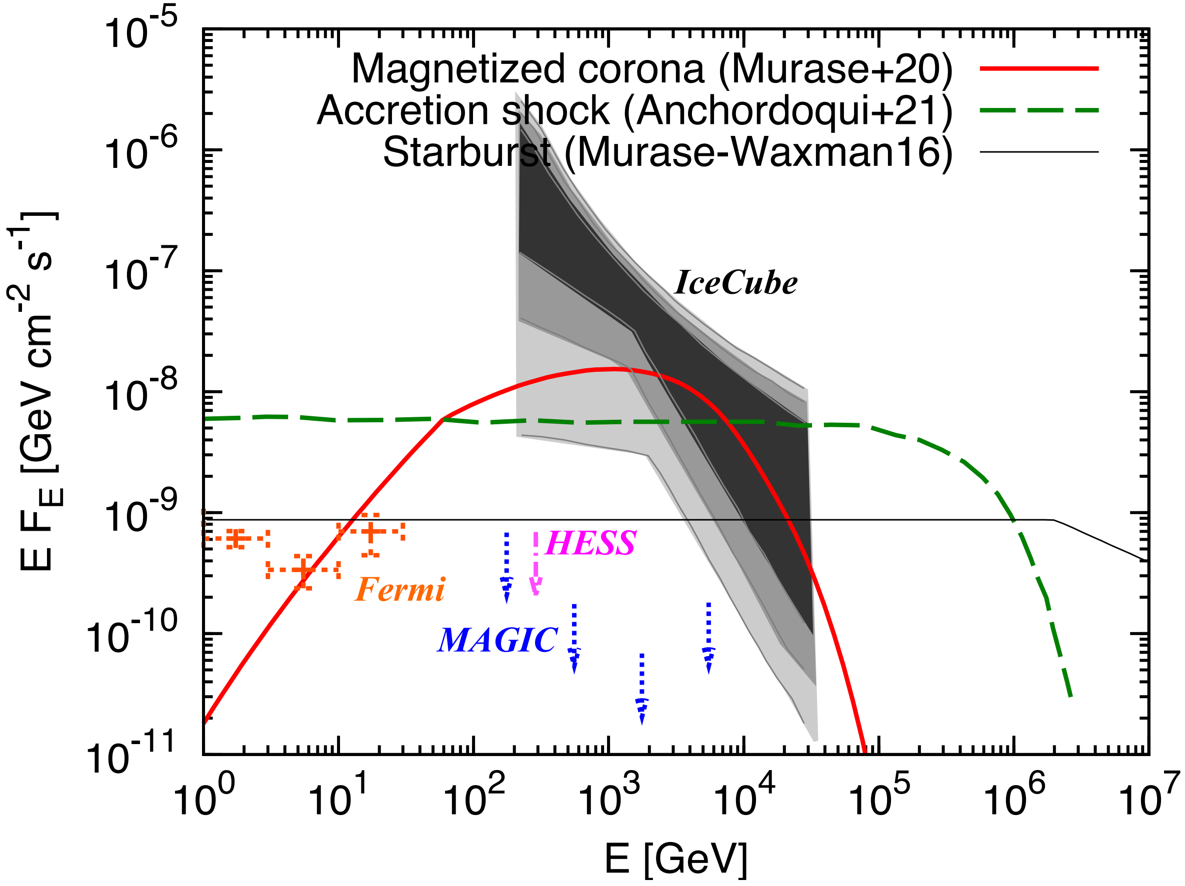


(from KM & Ioka 13 PRL)

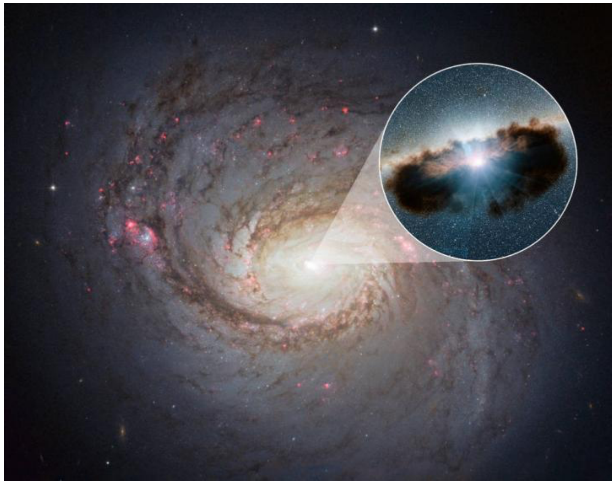
or exotic scenarios w. new physics (ex. dark matter, ν decay)?

NGC 1068: Support for Hidden ν Sources

KM, Kimura & Meszaros 20 PRL, Inoue+ 20 ApJ, Anchordoqui+ 21



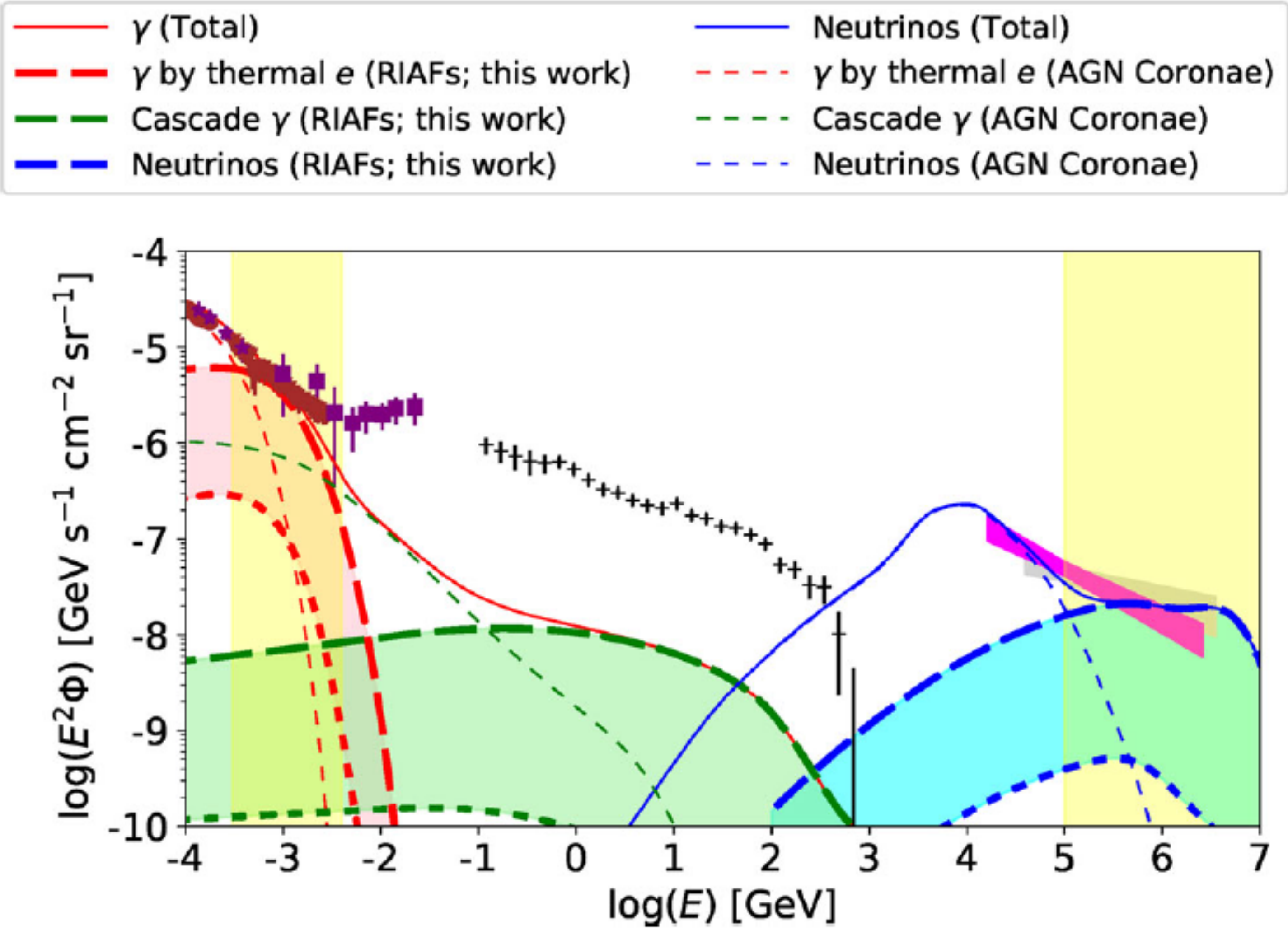
- particle acceleration in coronae (supported by recent simulations)
- ν production via pp & pγ processes
- γ-ray opaque → cascade



- IceCube ν data can be explained by emission from AGN disk-coronae
- NGC 1068 is predicted to be the brightest ν source in the northern sky
- Opaque for GeV-TeV γ rays → must be cascaded down to MeV (prediction)

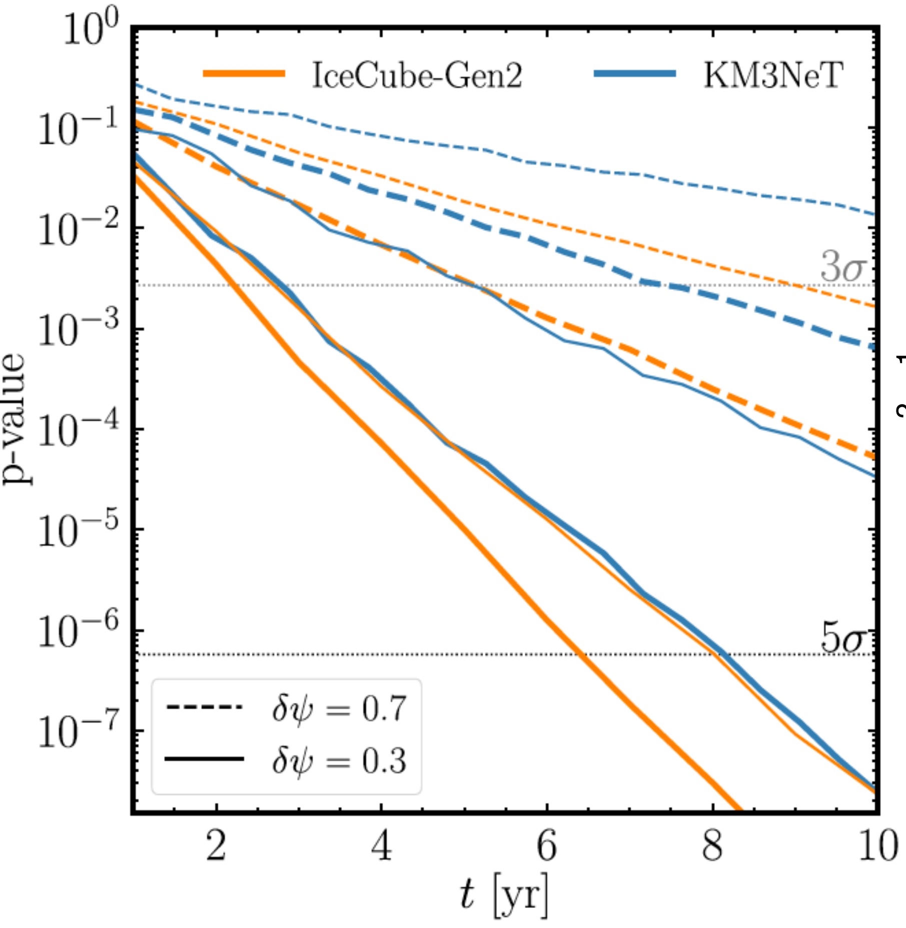
AGN Manifesting in the Multi-Messenger Sky?

KM, Kimura & Meszaros 20 PRL   Kimura, KM & Meszaros 21 Nature Communications

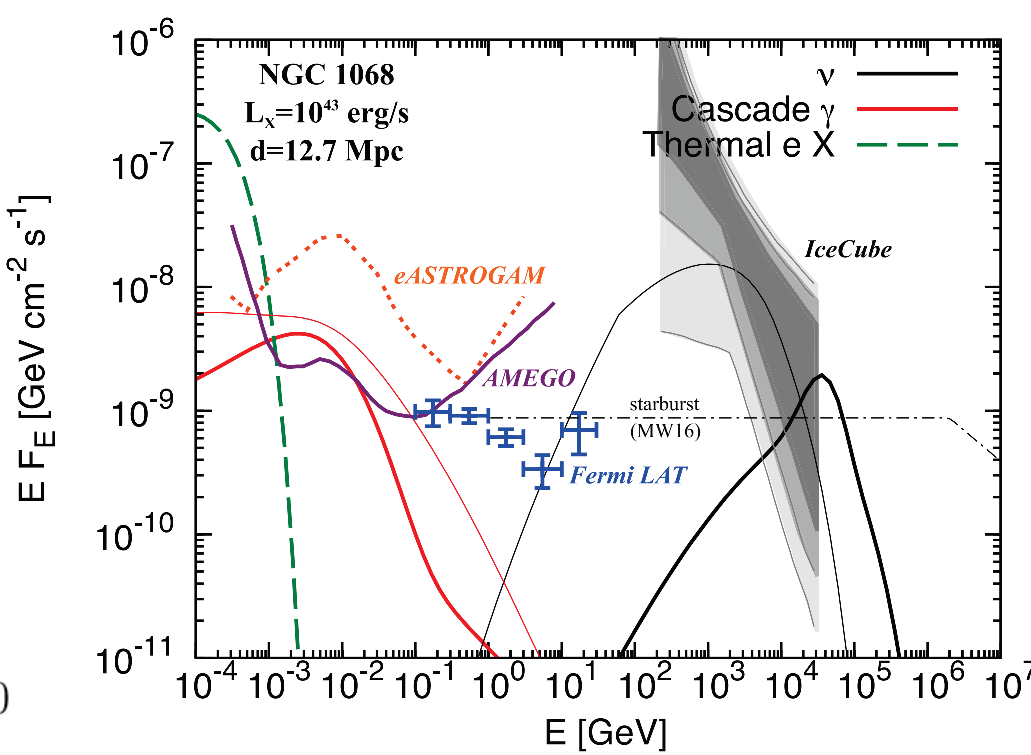


#~2.6σ hint of IR-selected AGN correlation reported (IceCube Collaboration 21)

Detectability of Nearby AGN is Promising

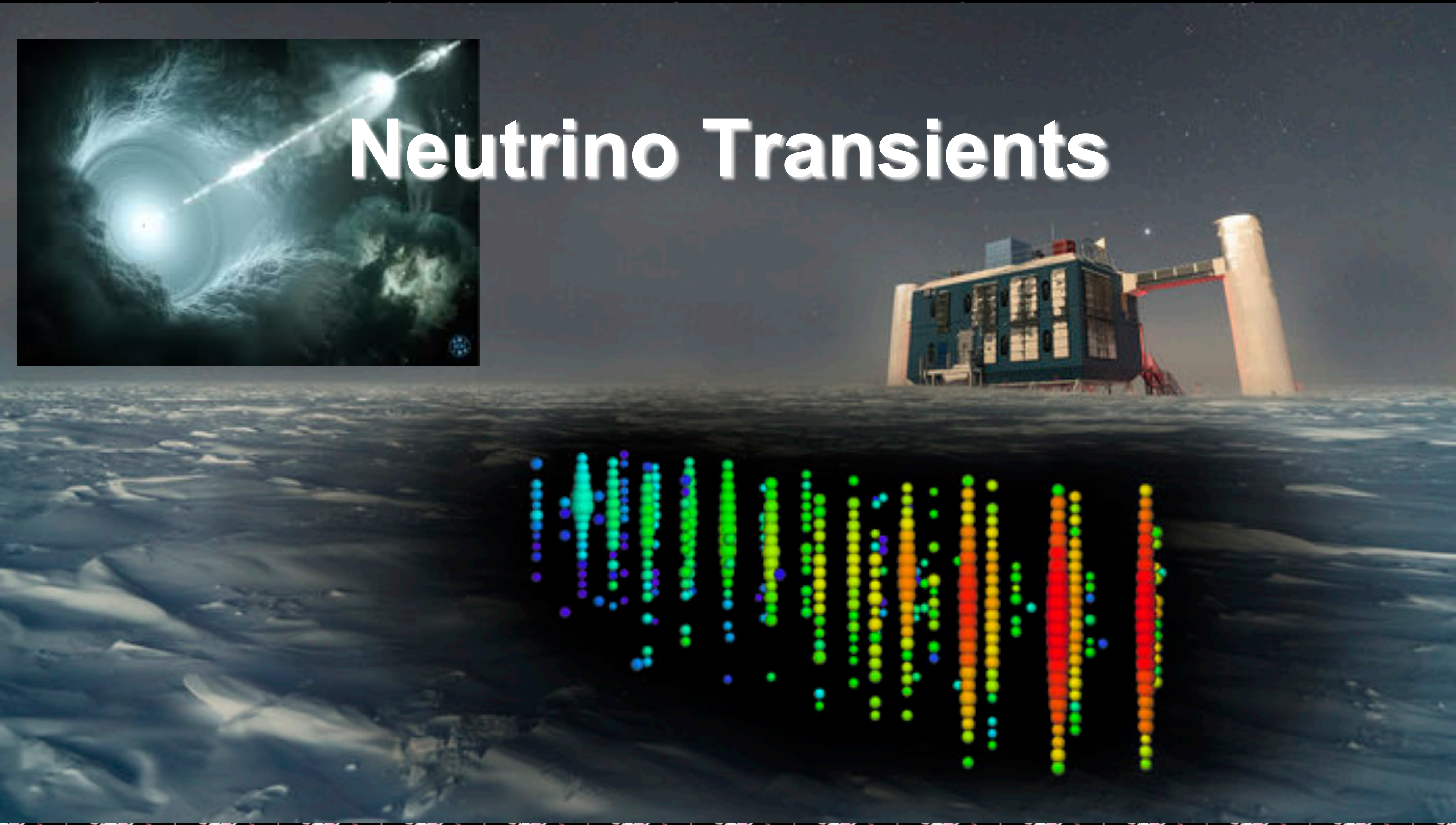


Kheirandish, KM & Kimura 21 ApJ
KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.



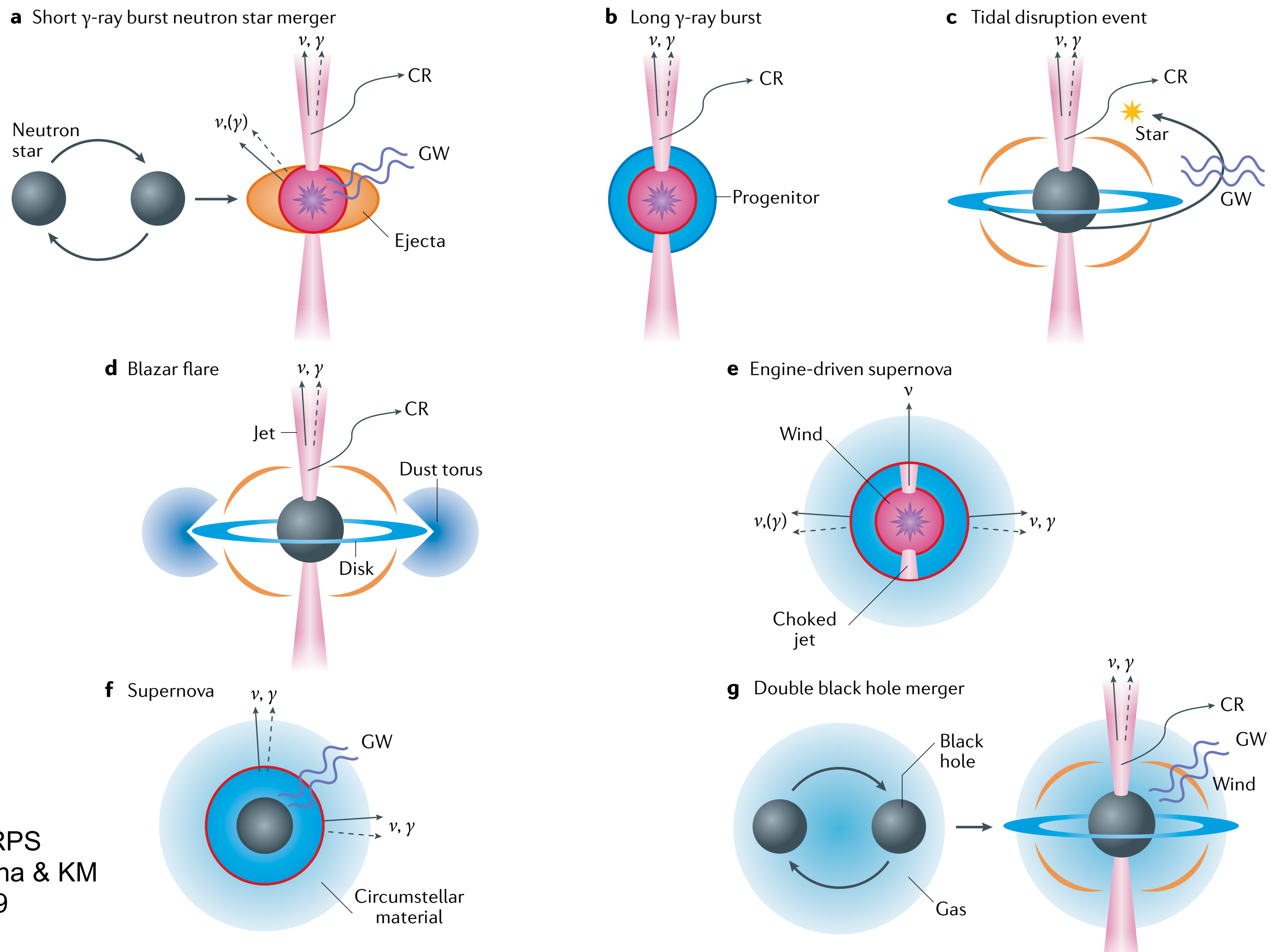
- Testable w. upcoming neutrino detectors & MeV gamma-ray telescopes
- More in the southern sky (Circinus, ESO 138-1, NGC 758)
- Nearby low-luminosity AGN should also be detectable as well

Neutrino Transients



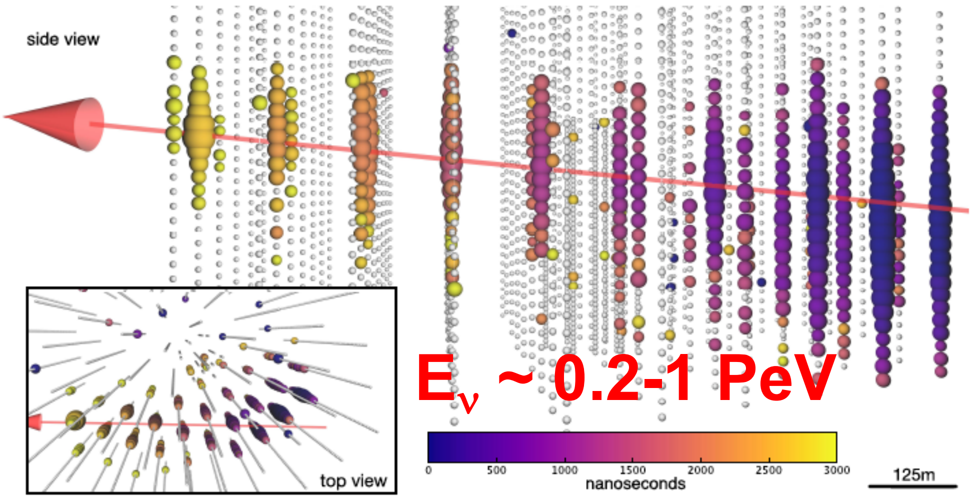
High-Energy Neutrino Transients

Diverse explosive/flaring phenomena in the Universe!



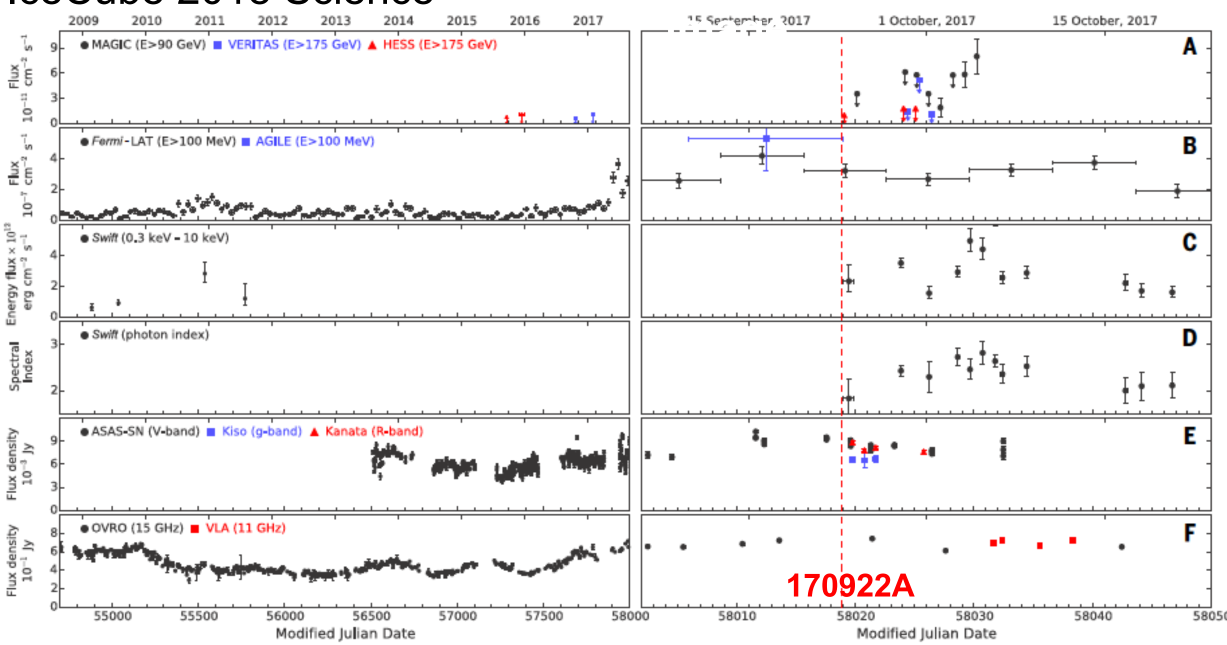
KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

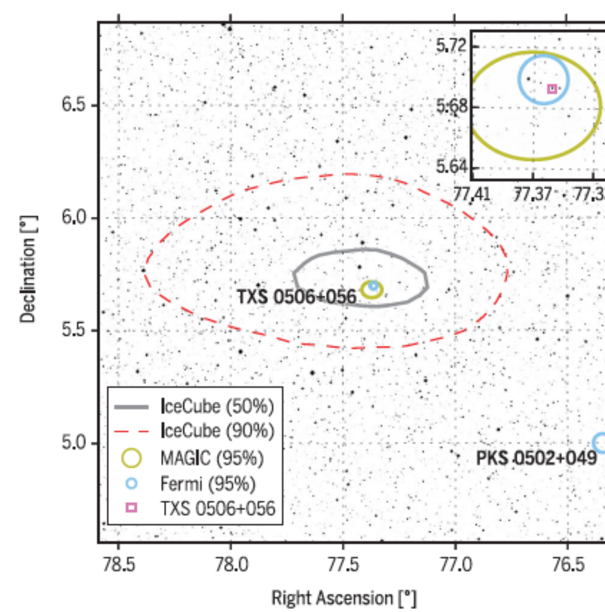
IceCube 170922A & TXS 0506+056



- 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**

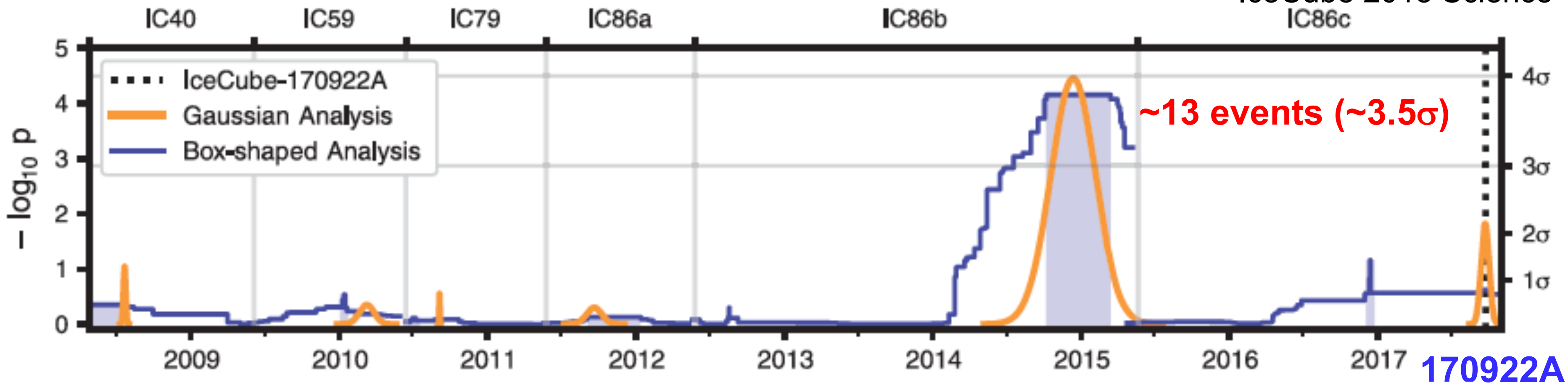
IceCube 2018 Science

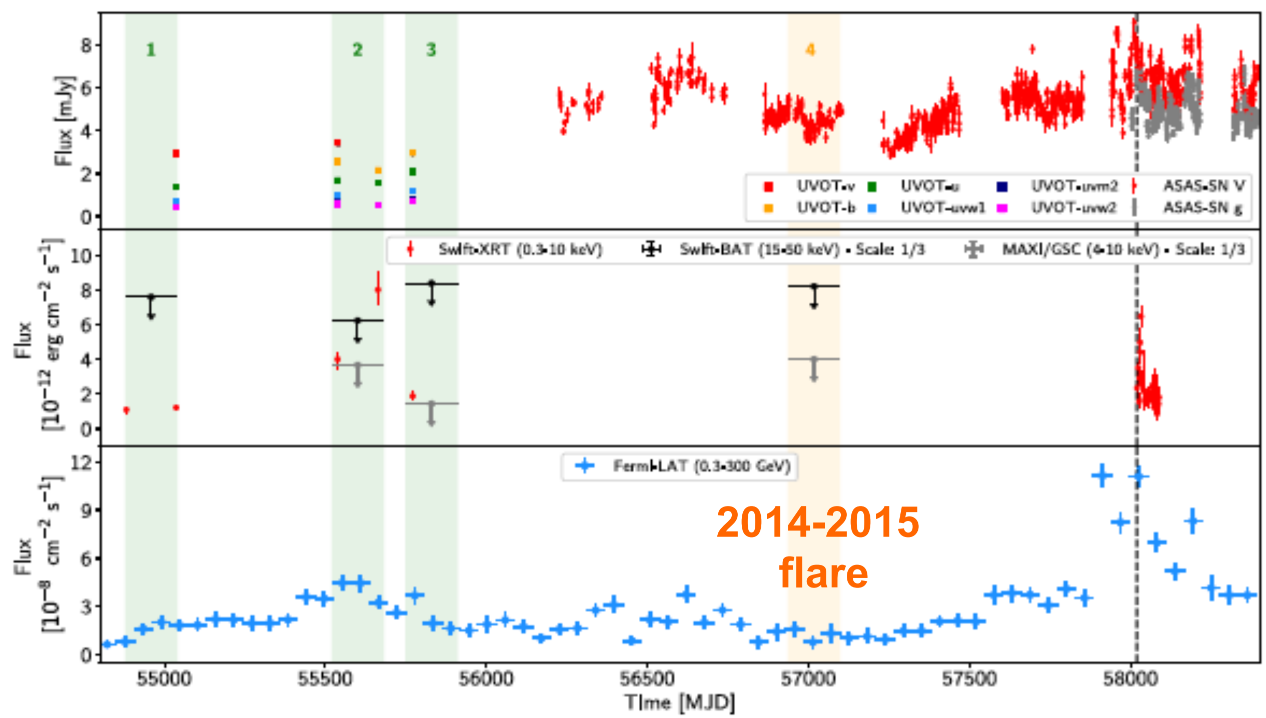




2014-2015 Neutrino Flare

IceCube 2018 Science



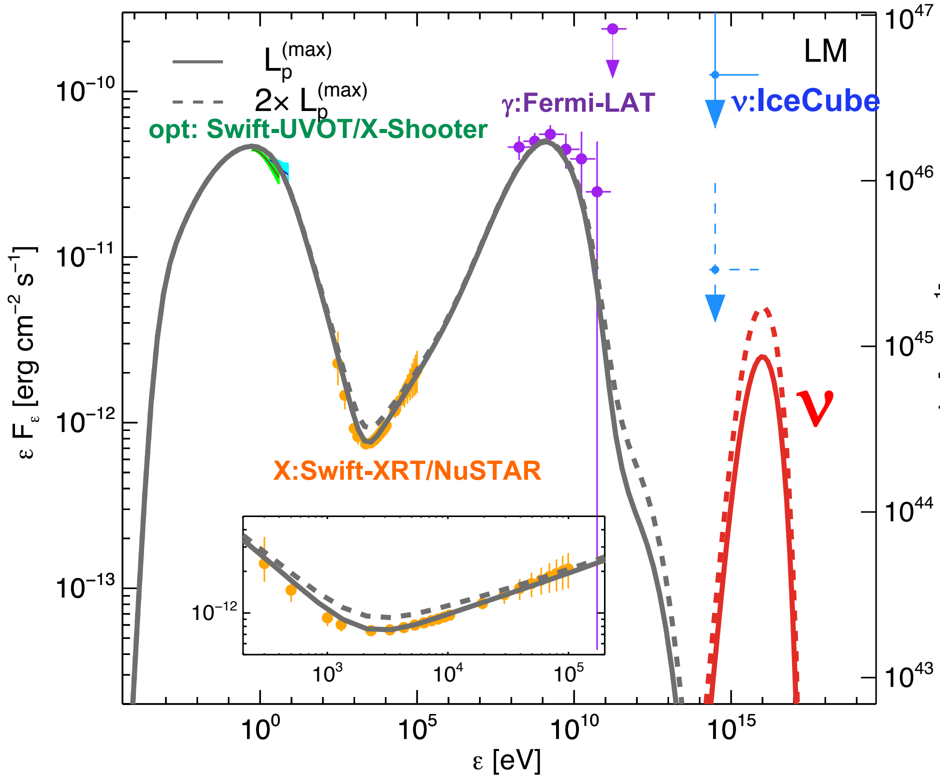


Petropoulou, KM+ 20 ApJ

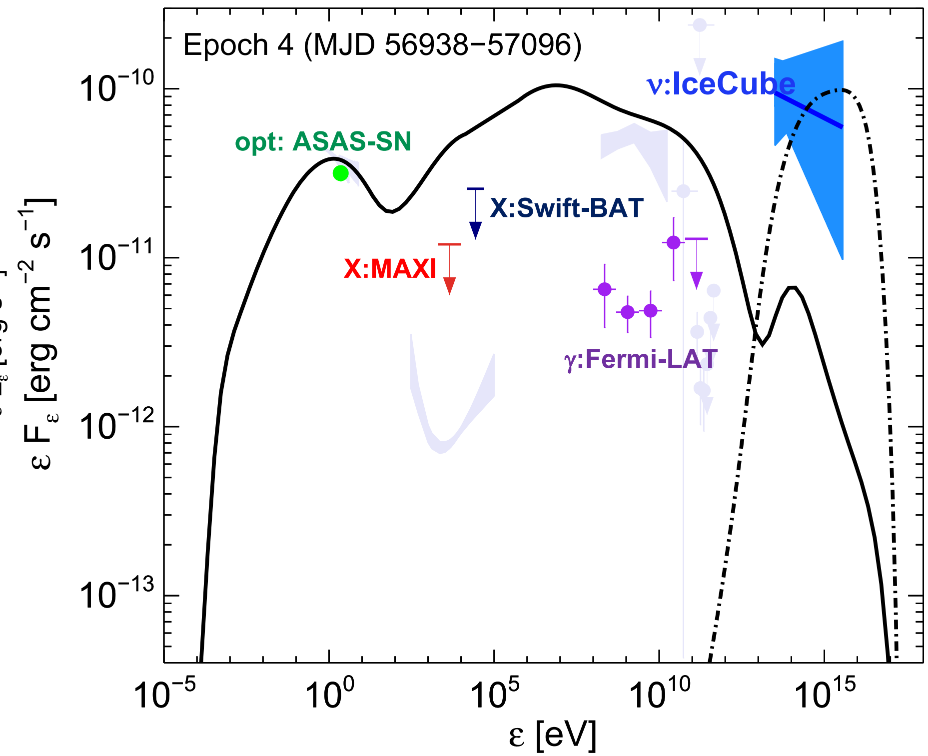
"Power" of Multi-Messenger Approaches

$p\gamma \rightarrow \nu, \gamma + e$ **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



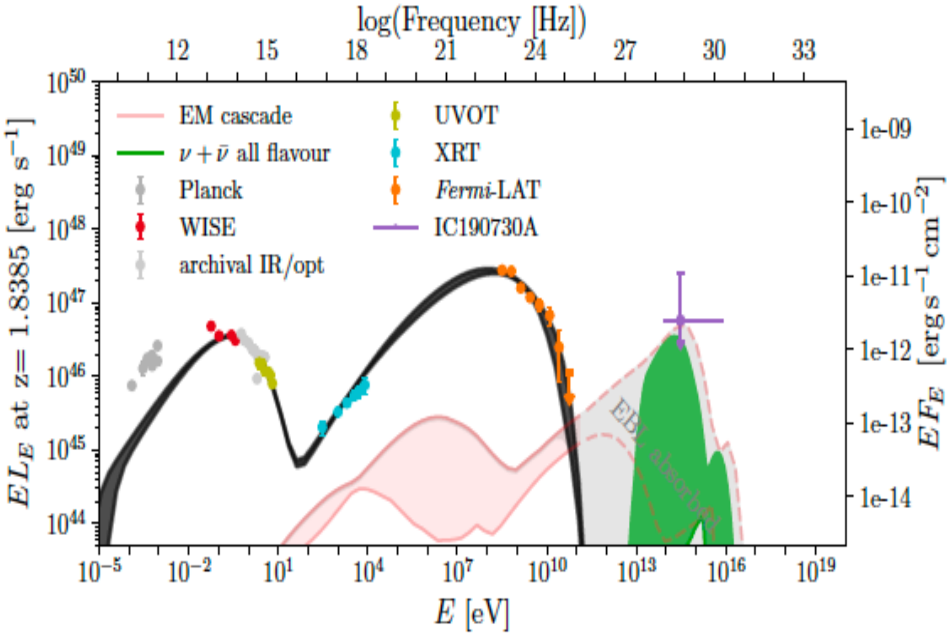
Puzzling: standard single-zone models do NOT give a concordance picture

see also KM, Oikonomou & Petropoulou 18, Ansoldi+ 18, Cerutti+ 19, Gao+ 19, Rodriguez+ 19, Reimer+ 19

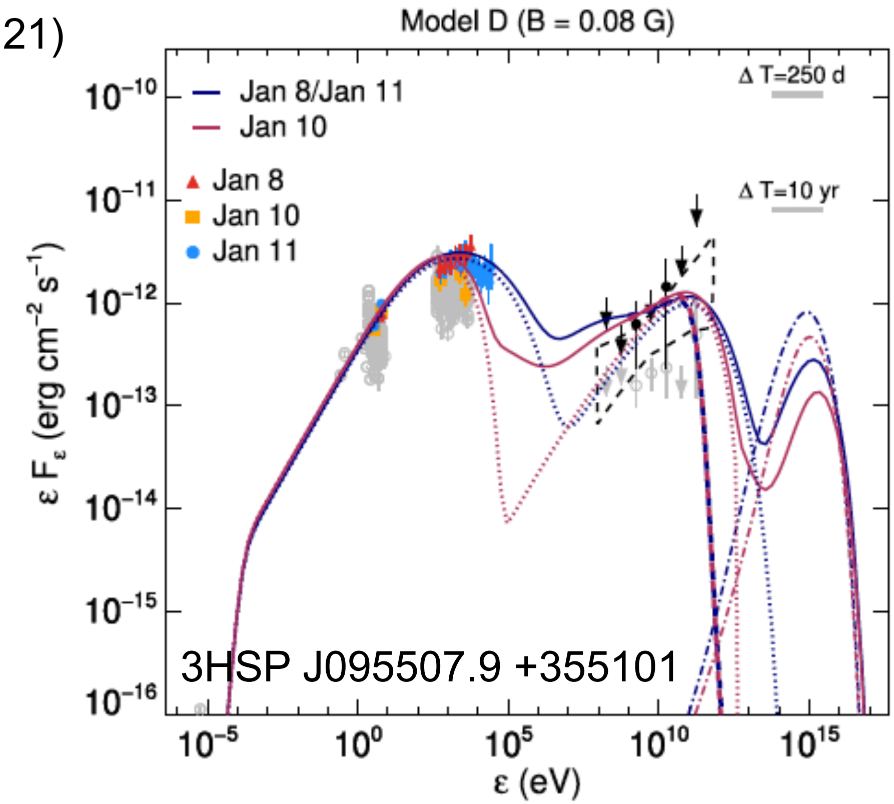
Other Coincidences w. Neutrino Alerts?

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)



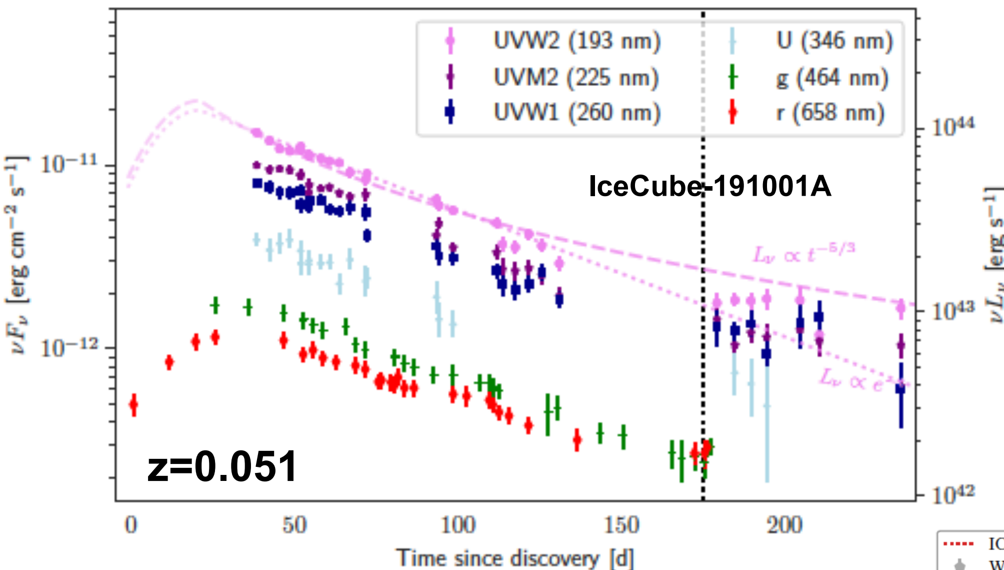
IceCube-200107A
(Petropoulou, Oikonomou, Mastichiadis , KM+ 20)



- 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

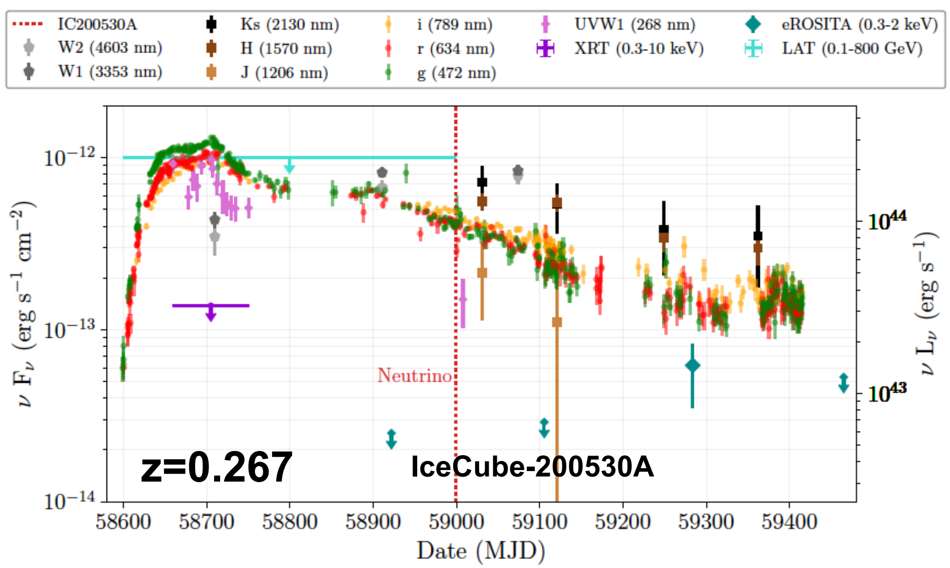
More Coincidences? – Yes…

Blazars: IceCube-190730A & PKS 1502 +106, IceCube-200107A & 3HSP J095507.9 +355101



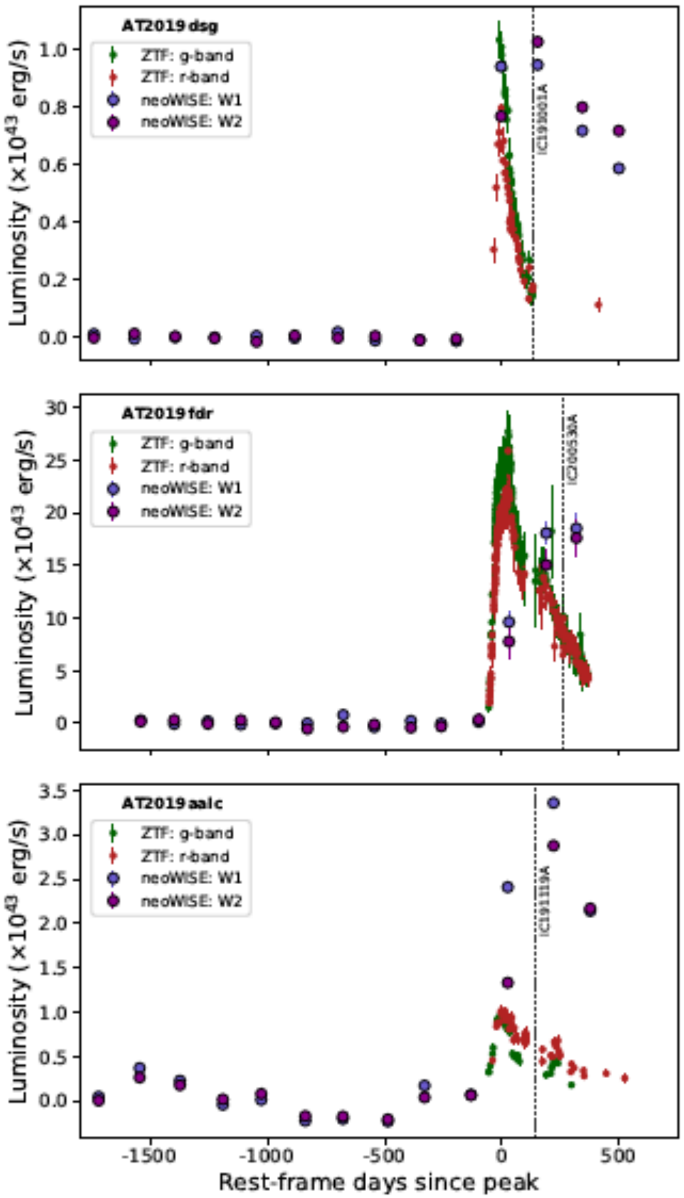
IceCube-191001A
& AT 2019dsg
(Stein+ 21 Nature Astron.)

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

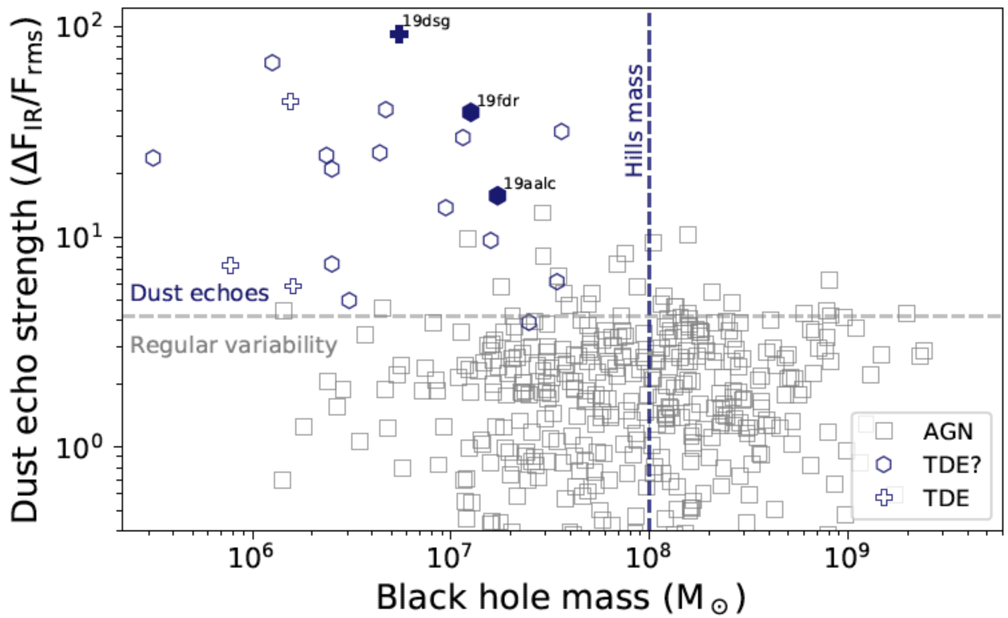


Both are rare optical transients with strong radio emission (~3σ)

Correlation w. IR Dust Echoes?



van Velzen+ 22

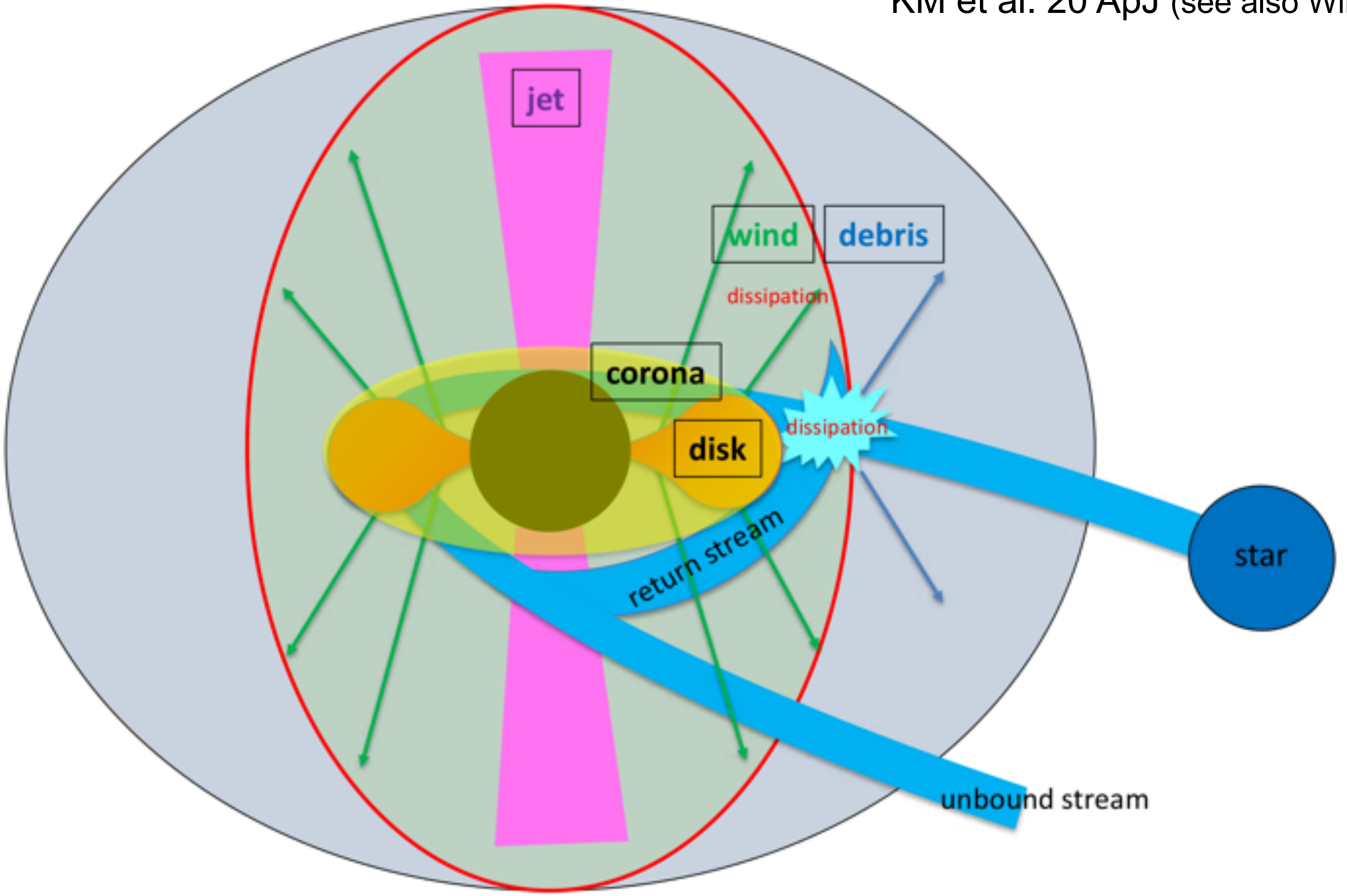


- Correlation w. accretion flares w. dust echoes (63 samples; ~3.7σ)
- One more source (2019aalc) found
- Interpretations are controversial

Neutrinos from Black Hole “Flares”?

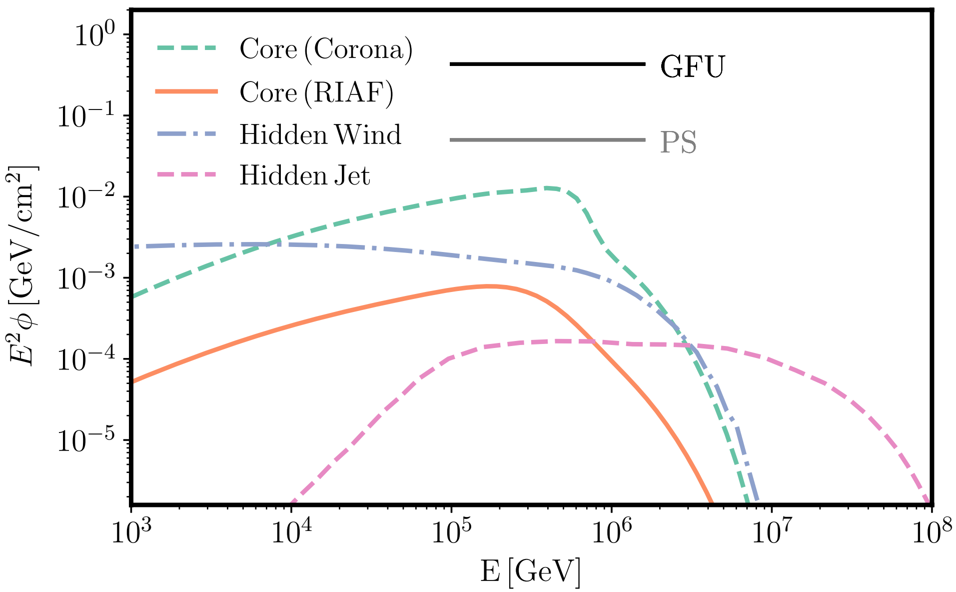
- AT 2019dsg & AT 2019fdr = tidal disruption event (TDE)
- TDE and AGN ν emission mechanisms may be similar (disk-corona? jet? stellar debris as a cosmic-ray reservoir?)

KM et al. 20 ApJ (see also Winter & Lunardini Nature Astron. 21)



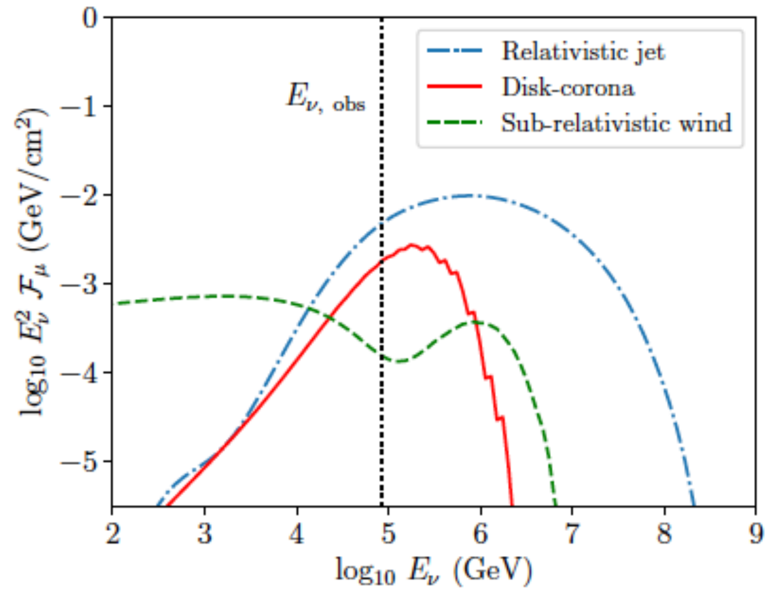
Implications for AT2019dsg & AT2019fdr

AT 2019dsg



KM, Kimura, Zhang, Oikonomou & Petropoulou 20 ApJ

AT 2019fdr



Reusch+ KM 21
see also Pitik+ 21

N_ν ~ 0.001-0.1 events (GFU)

N_ν ~ 0.001-0.1 events (GFU)

No evidence of jets for both TDEs

Multi-Messenger Picture is Crucial

Neutron star merger
GW170817- GRB 170817A

Black hole "flares"
IceCube-170922A - TXS 0506+056
IceCube-191001A – AT 2019dsg
and several more…

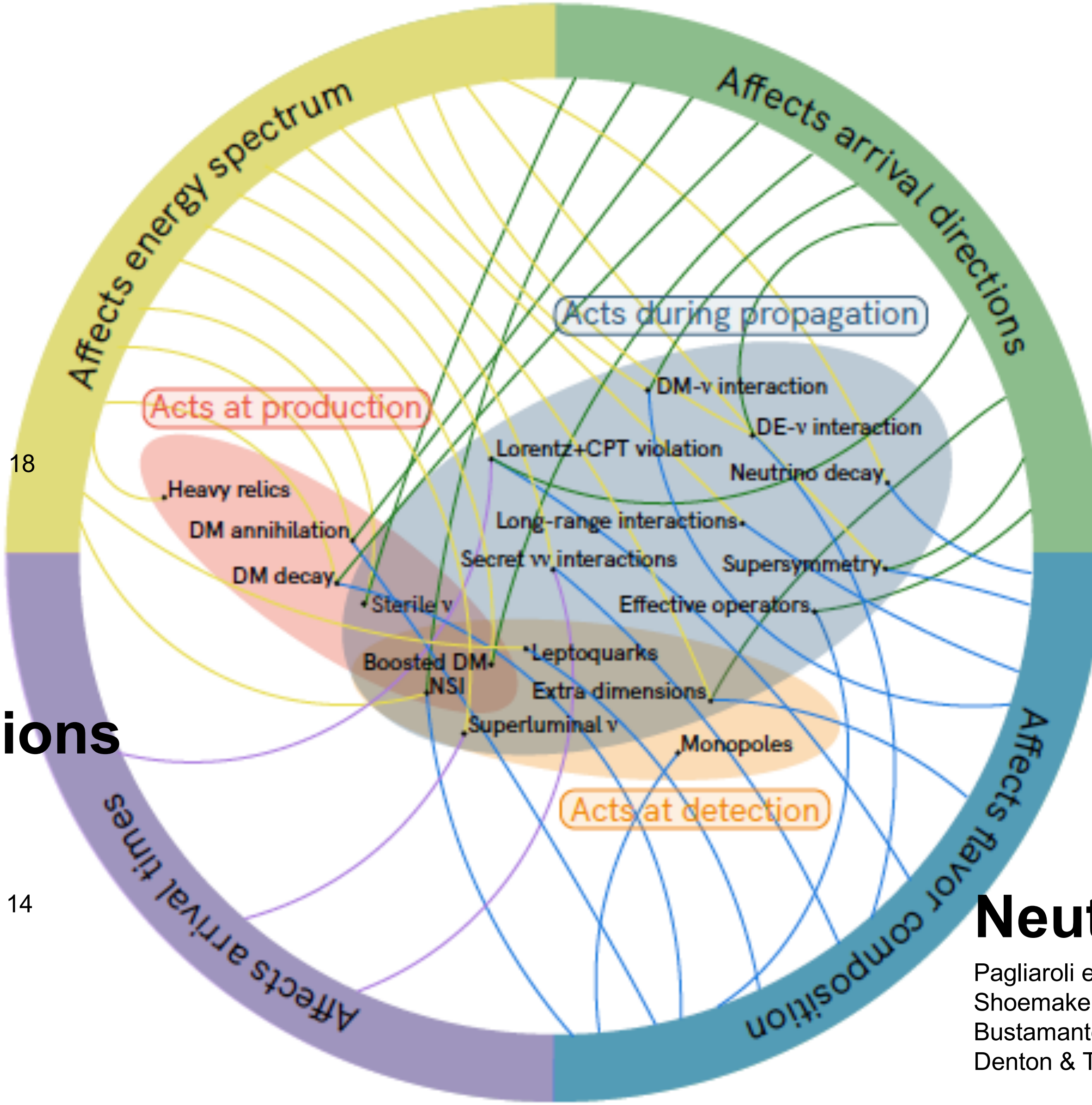
"concordance"

"puzzling"

Testing Physics Beyond the Standard Model

Dark matter

Feldstein+ 13
Esmaili & Serpico 13
Bai, Lu & Salvado 13
Bhattacharya+ 14
Higaki+ 14
Esmaili+14,
Rott+ 15
Fong+ 15
KM+ 15
Boucenna+ 15
Ko & Tang 15
Chianese+ 16
Hiroshima, Kitano, Kohri & KM 18
…



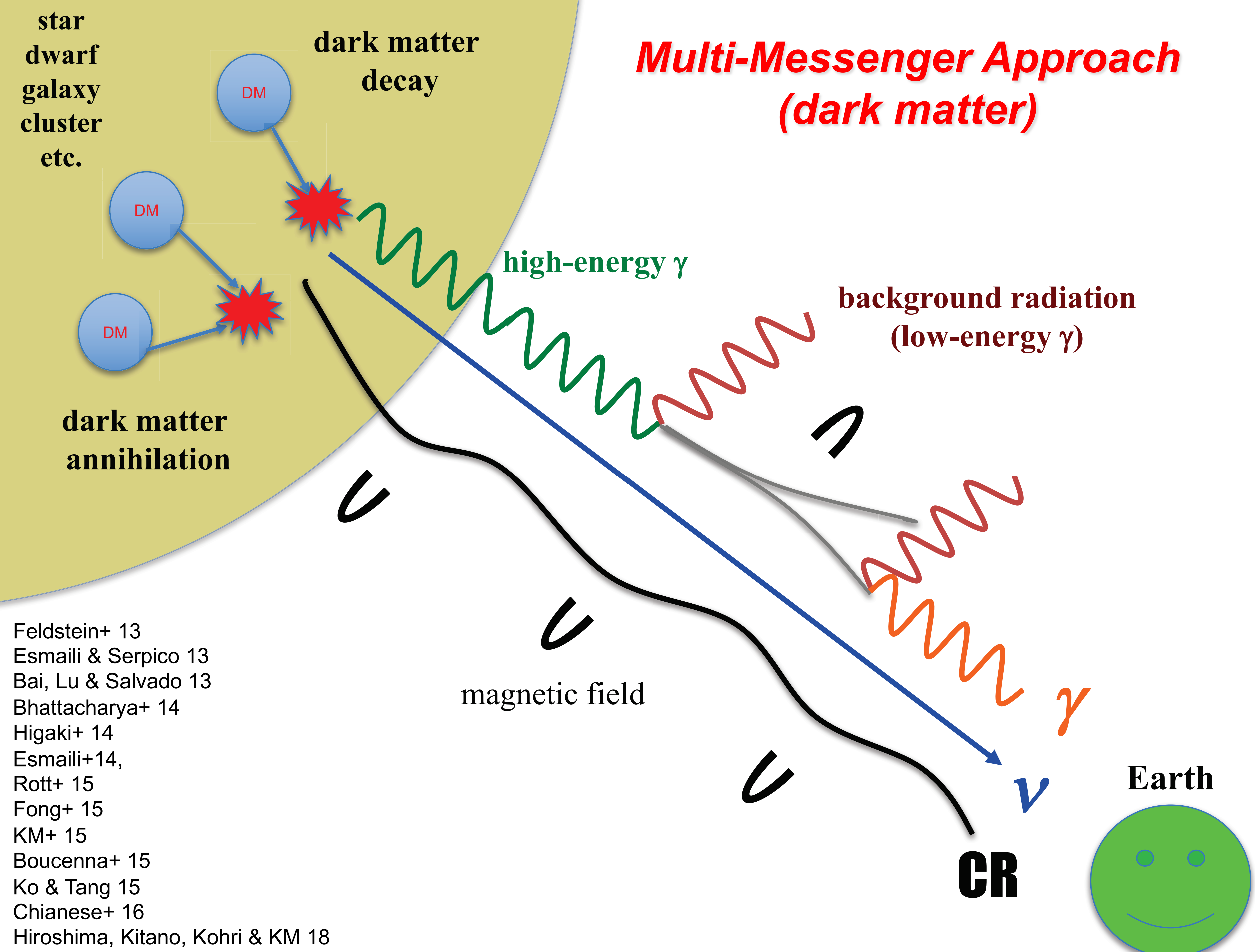
New interactions

Ioka & KM 14
Ng & Beacom 14
Ibe & Kaneta 14
Blum, Hook & KM 14
Cherry, Friedland & Shoemaker 14
Araki et al. 15
Kamada & Yu 15
Shoemaker & KM 16
KM & Shoemaker 19…

Neutrino decay

Pagliaroli et al. 15
Shoemaker & KM 16
Bustamante, Beacom & KM 17
Denton & Tamborra 18…

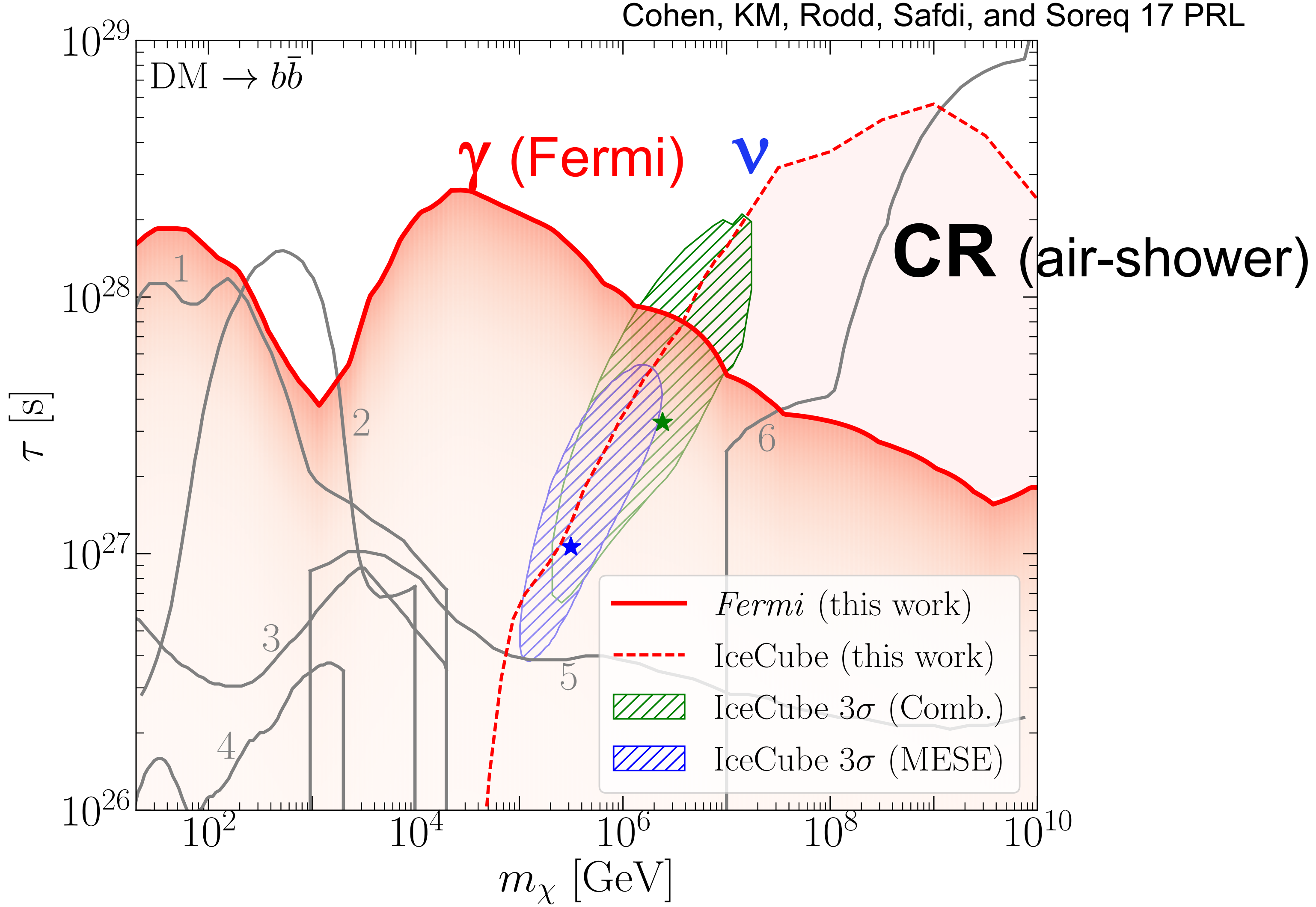
Multi-Messenger Approach (dark matter)



Feldstein+ 13
Esmaili & Serpico 13
Bai, Lu & Salvado 13
Bhattacharya+ 14
Higaki+ 14
Esmaili+14,
Rott+ 15
Fong+ 15
KM+ 15
Boucenna+ 15
Ko & Tang 15
Chianese+ 16
Hiroshima, Kitano, Kohri & KM 18

Multi-Messenger Constraints on Decaying DM

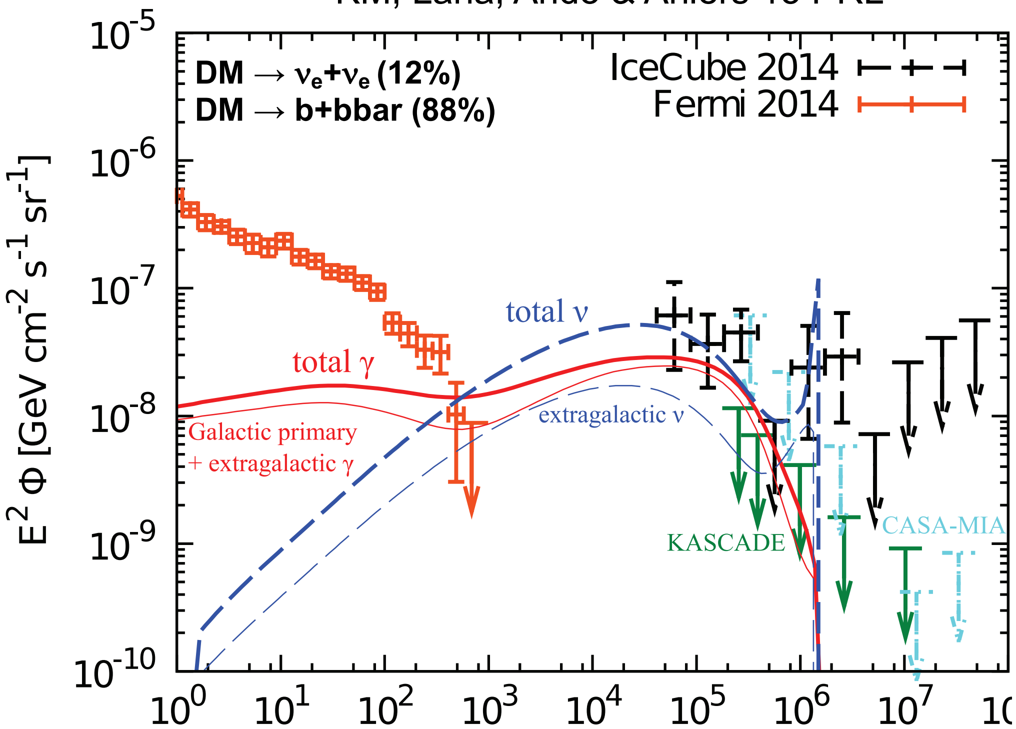
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



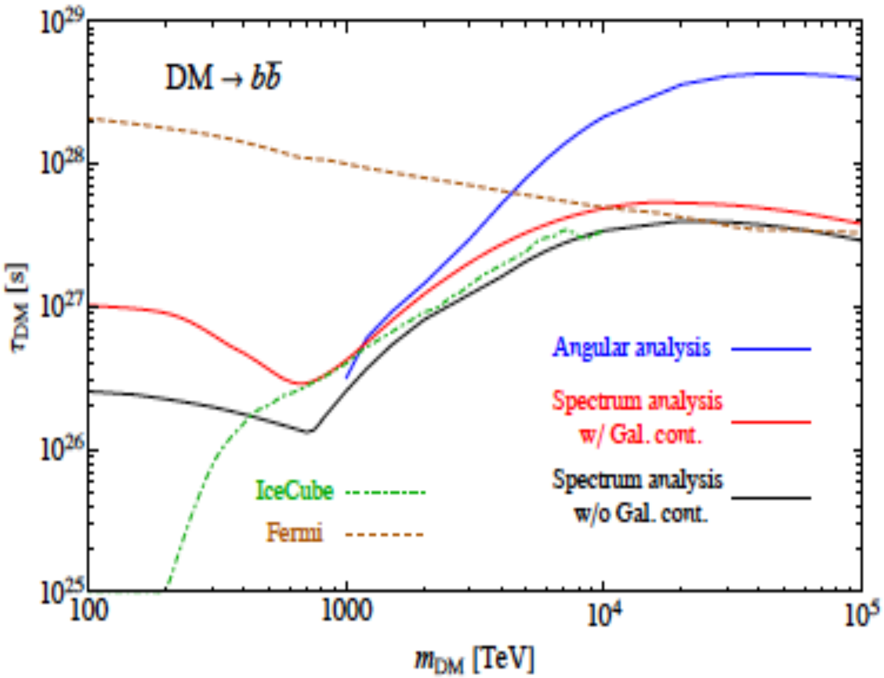
- Disfavoring DM scenarios to explain the excessive 10-100 TeV ν data
- Unique probes of superheavy dark matter that is difficult to directly test

Sub-PeV Gamma-Ray Limits

KM, Laha, Ando & Ahlers 15 PRL



Esmaili & Serpico 21 PRD

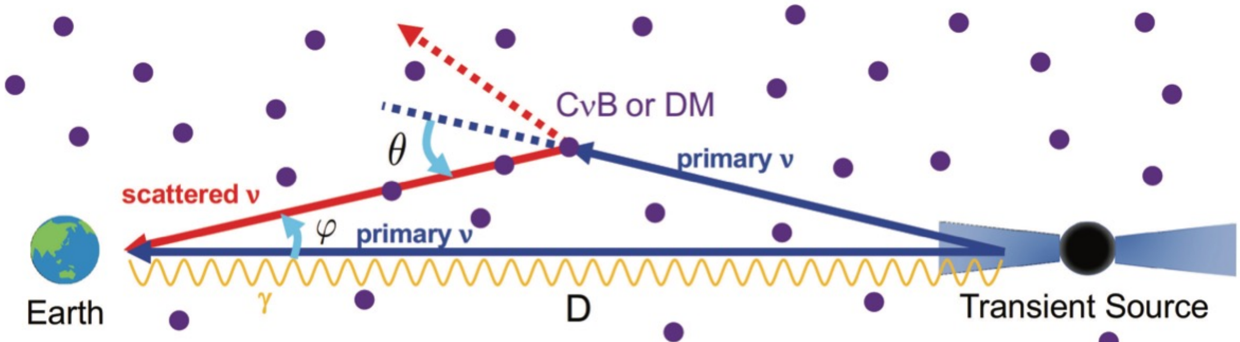


see also:
Ellis+ 92, Gondolo 92, Gondolo+ 93
KM & Beacom 12
Esmaili & Serpico 15

- Tibet AS-γ detected Galactic sub-PeV γ rays (Tibet Collaboration 21 PRL)
- Further tension with air-shower (sub-PeV γ) data and improved with LHAASO

BSM Tests with Multi-Messenger Transients

BSM ν-ν/ν-DM interactions could alleviate H_0 tension & small-scale issues

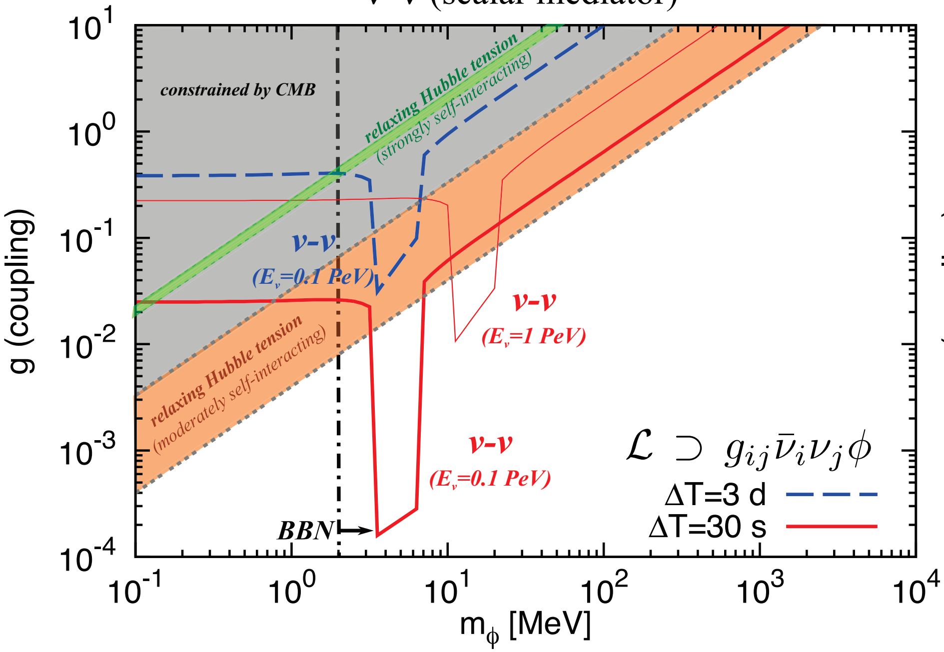


"time delay" signatures
(**neutrino echoes**)

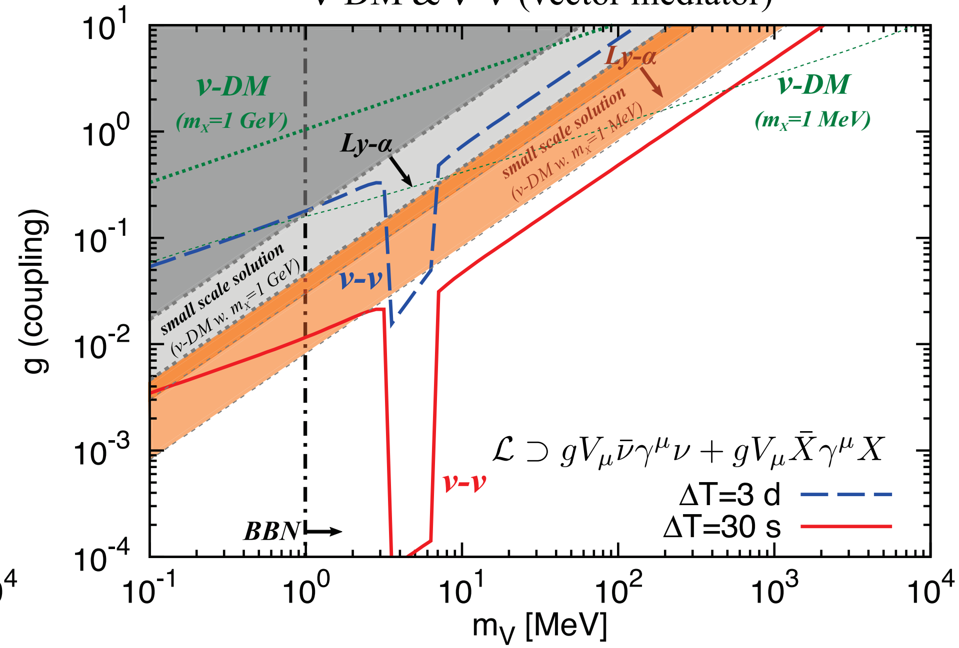
$$\Delta t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4}D \simeq 77\ \mathrm{s}\left(\frac{D}{3\ \mathrm{Gpc}}\right)C^2\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

KM & Shoemaker 19 PRL

ν-ν (scalar mediator)



ν-DM & ν-ν (vector mediator)



Summary

ν flux ~ γ-ray flux ~ CR flux

importance of multi-messenger connections

Where do neutrinos mainly come from?

CR accelerators: blazars & GRBs: likely subdominant in the neutrino sky
CR reservoirs: astro-particle grand-unification is possible
Multi-messenger analyses w. 10-100 TeV ν data imply hidden CR accelerators
Non-jetted AGN – some hints, critically testable with near-future detectors

Neutrino Transients?

Transients: unique chances -> strategic multi-messenger searches (ex. AMON)
Intriguing coincidences with black hole flares have been found (hidden sources)
Establishing the multi-messenger picture is critical → stay tuned

Tests for New Physics?

multi-messenger searches are complementary and powerful (ex. heavy DM)

Future is bright: IceCube-Gen2, KM3Net & other next-generation facilities