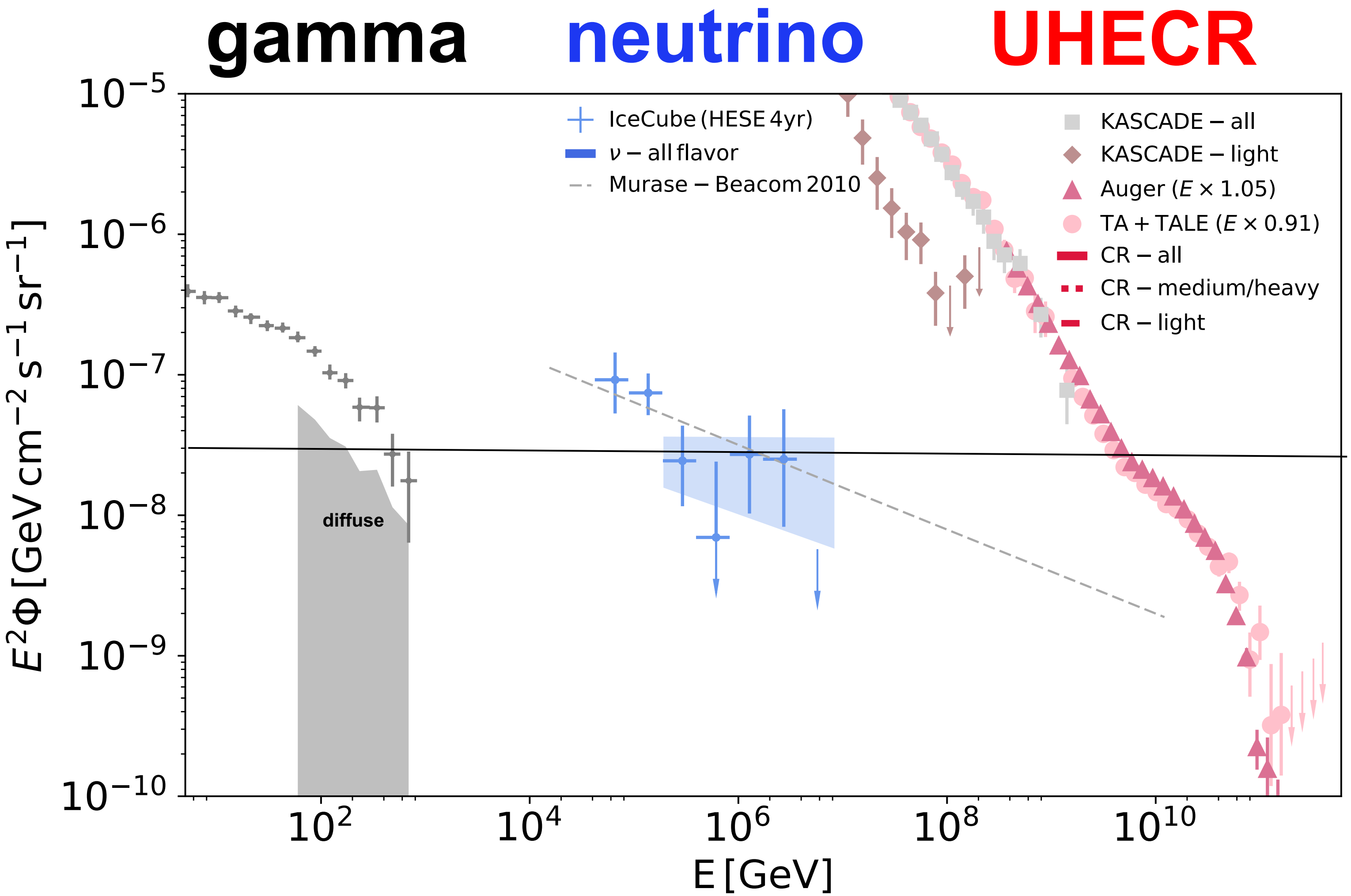
High-Energy Neutrinos from Active Galactic Nuclei

Kohta Murase (PSU/IAS-Princeton)

September 2022
KM3Net Town Hall Meeting 2022

Multi-Messenger Astro-Particle "Backgrounds"

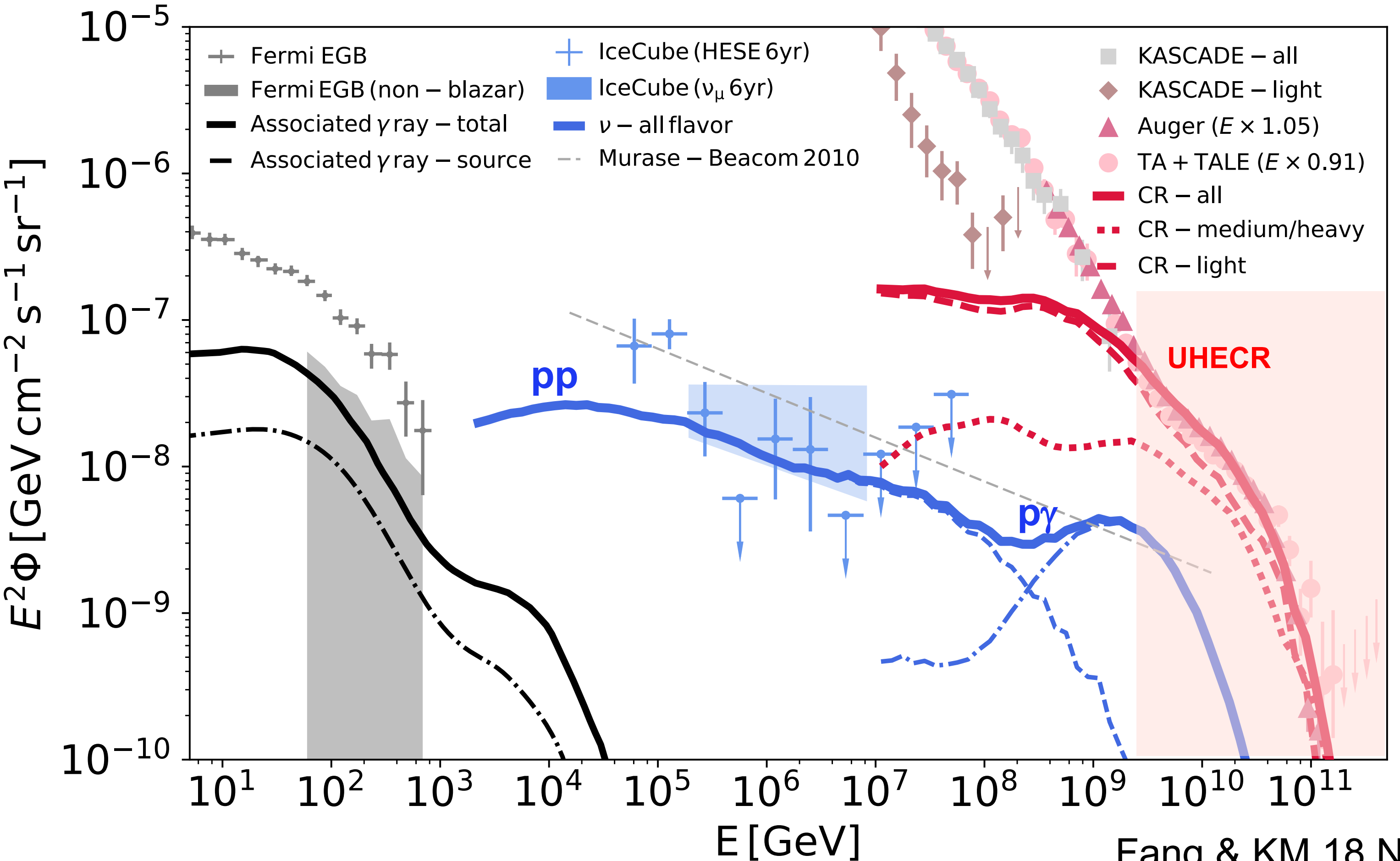


Energy generation rate densities of 3 messengers are all comparable

AGN are promising as the origins (e.g., KM & Fukugita 19 PRD)

Multi-Messenger Astro-Particle Grand-Unification?

Concrete example of the "grand-unification" scenario with detailed simulations

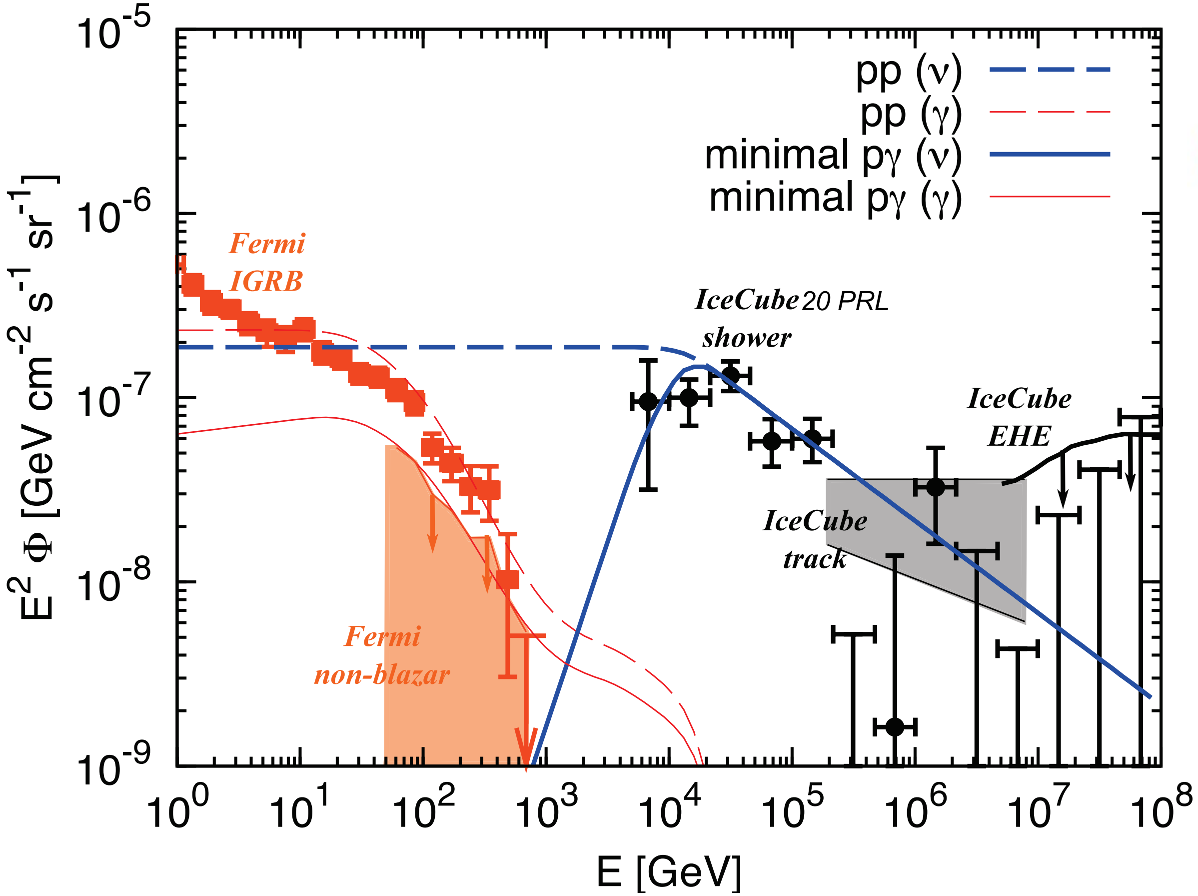


Fang & KM 18 Nature Phys.
(see also Kachelriess+ 17)

- Jetted AGN as "UHECR" accelerators
- Neutrinos from confined CRs & UHECRs from escaping CRs

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

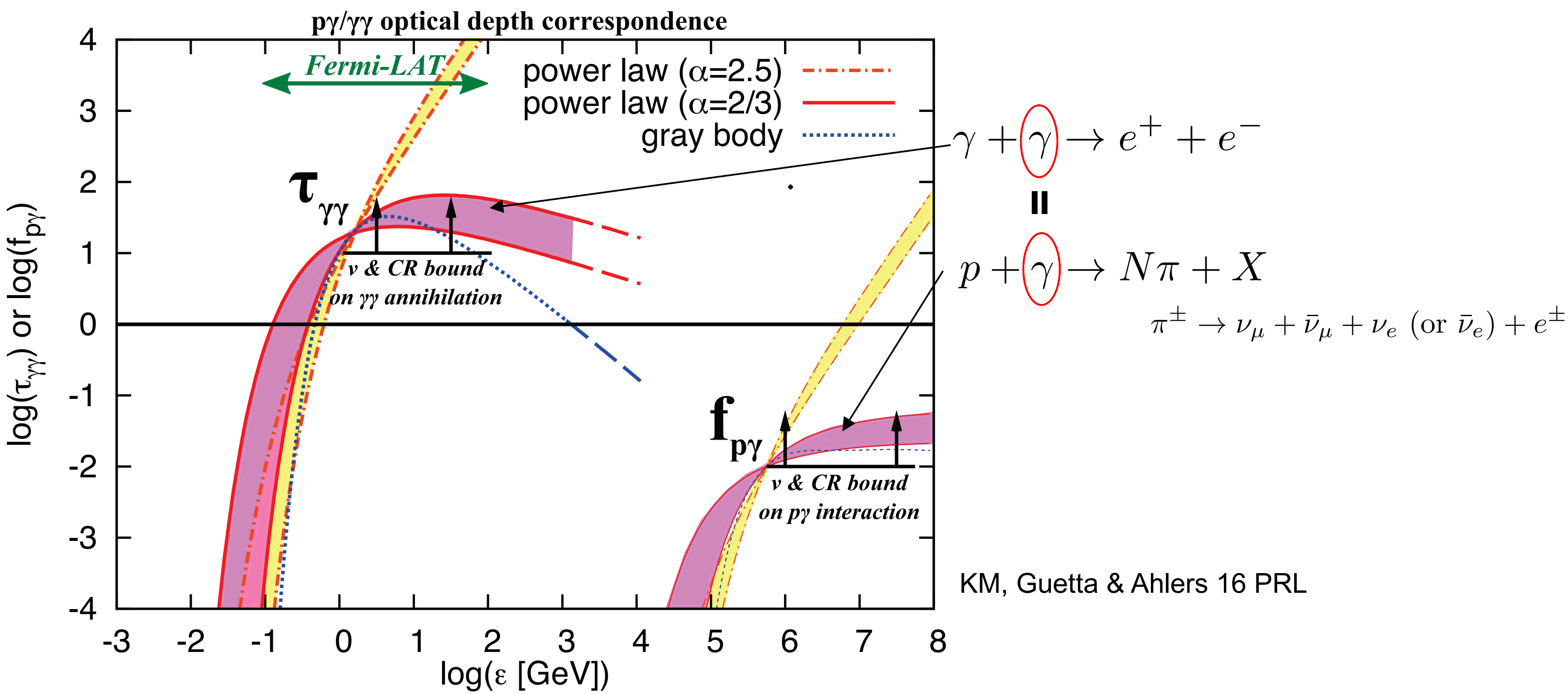
Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent
→ Requiring hidden (i.e., γ-ray opaque) cosmic-ray accelerators
(Galactic components are not sufficient: see also Ahlers & KM 14 PRD, Fang & KM 21 ApJ)

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



KM, Guetta & Ahlers 16 PRL

What Have We Learned?

- Multi-messenger connection is important
  (hidden neutrino sources, constraints on Galactic emission)
- ν-γ-UHECR connection?: interesting open question
- AGN are leading candidates in terms of energy budget
  But many other source classes are not excluded

AGN have "diverse" classes and involve "multi-scale" physics

Dangerous to over-interpret results relying on the diffuse data
(Model systematics are often larger than data errors.
ex. CR spectra will not be exact power laws
Photon/matter density has distributions in space/sources)

Multi-messenger picture for individual sources are necessary
Brightest sources do not have to be the dominant sources

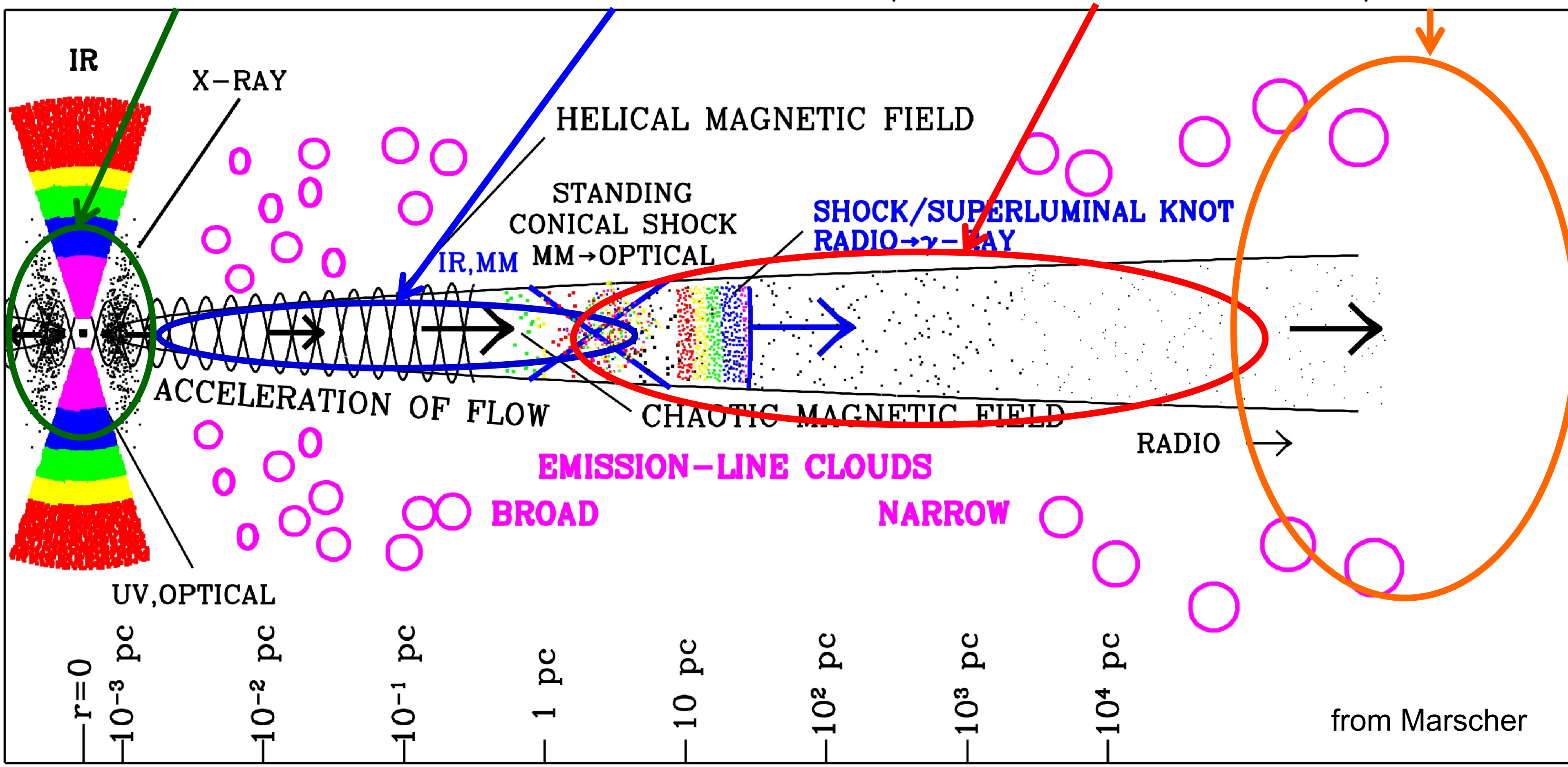
AGN Multi-Scale Particle Production

Black hole vicinity
$r \sim$ 1-100 Rs,
$B \sim 10\text{-}10^4$ G, $\Gamma \sim 1$

Inner jet (blazar zone)
$r \sim 10^{16}\text{-}10^{18}$ cm,
$B \sim 0.1\text{-}100$ G, $\Gamma \sim 10$

Large-scale jet/cocoon
$r \sim 10^{20}\text{-}10^{21}$ cm,
$B \sim 1\mu$G -1 mG, $\Gamma \sim 1$

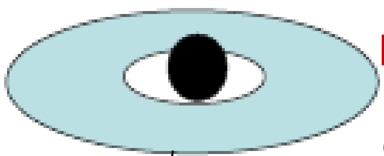
Intracluster medium
$r \sim 10^{23}\text{-}10^{25}$ cm,
$B \sim 0.1\text{-}1\mu$G



Hillas condition: $E_{max} \sim ZeBr\Gamma \sim 3\text{x}10^{19}$ eV Z (Γ/10) (B/0.1 G) (r/10^{17} cm)

AGN Diversity

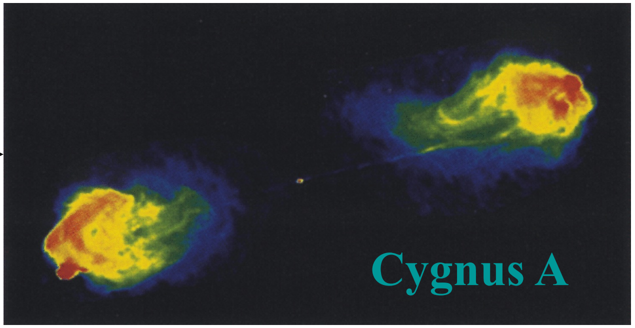
BH + accretion disk



~ 10%
powerful jets
(Γ~1-10)
elliptical gal.

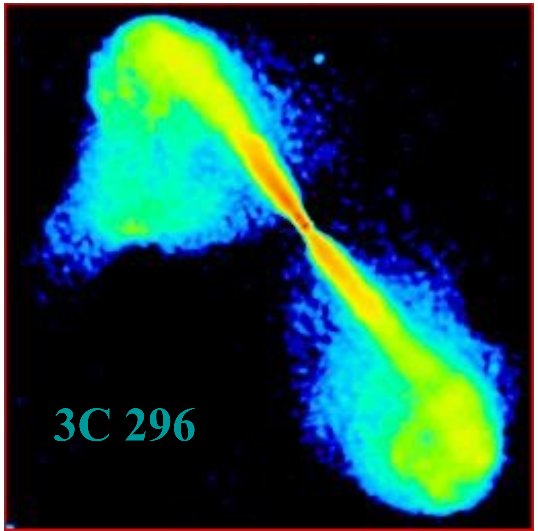
~ 1 %
$L_{radio} > 5 \times 10^{41}$ erg/s

FR-II radio galaxy
Flat spectrum radio quasar (FSRQ)
Steep spectrum radio quasar (SSRQ)



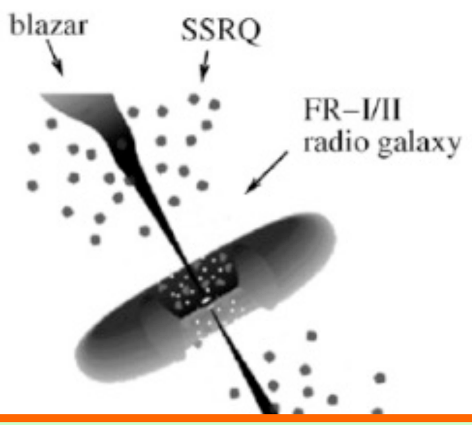
~ 9%
$L_{radio} < 5 \times 10^{41}$ erg/s

FR-I radio galaxy
BL Lacertae object (BL Lac)



~ 90%
jet-quiet
spiral gal.

Seyfert galaxy
Radio quiet quasar
Low-luminosity AGN



"blazar" (FSRQ+BL Lac)
= on-axis jets

- Flares (e.g., T ~ day)

FR=Fanaroff-Riley

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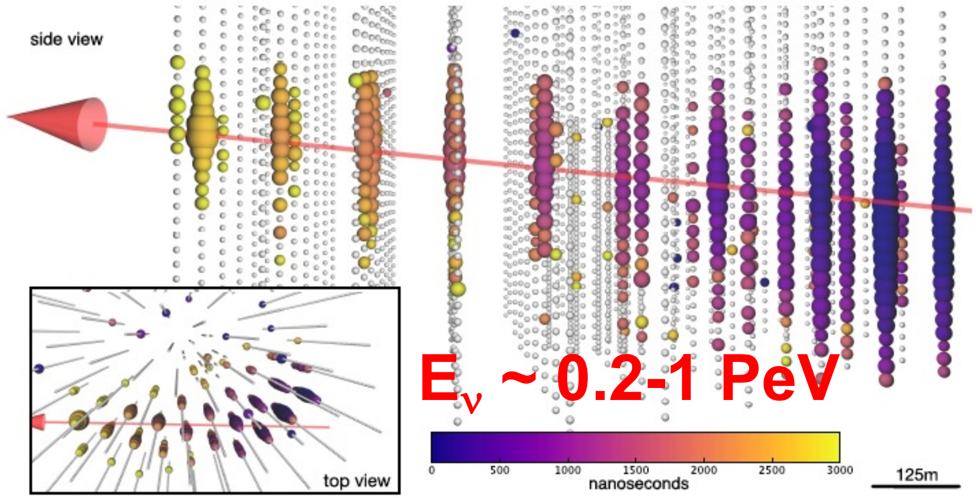
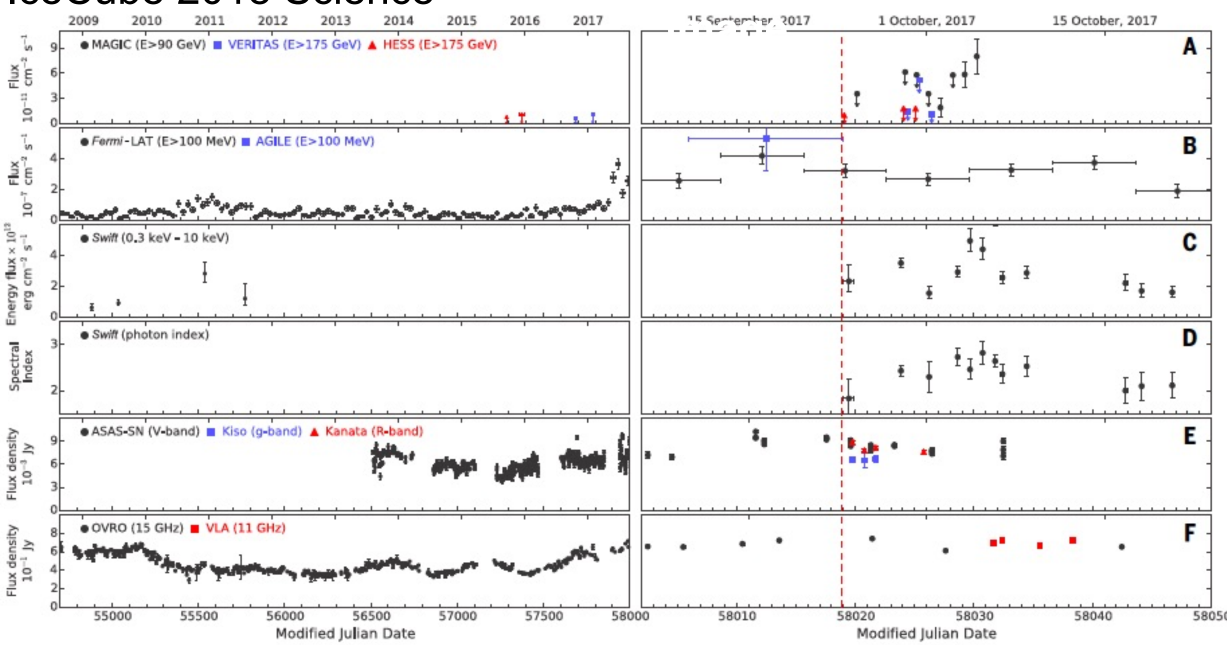
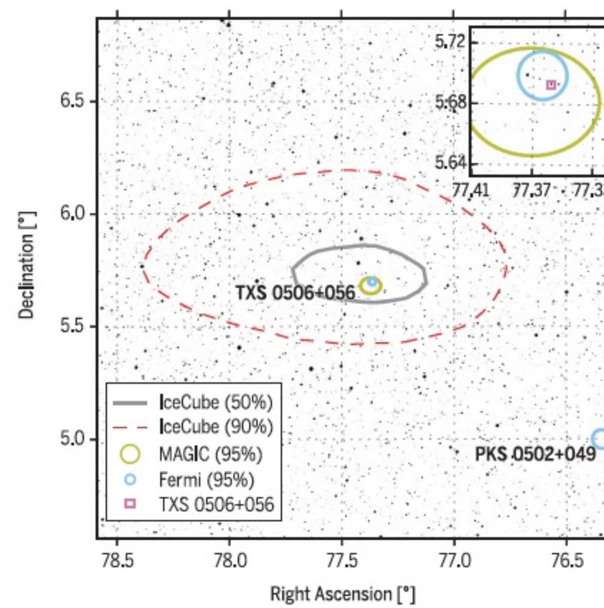
IceCube 170922A & TXS 0506+056



- 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

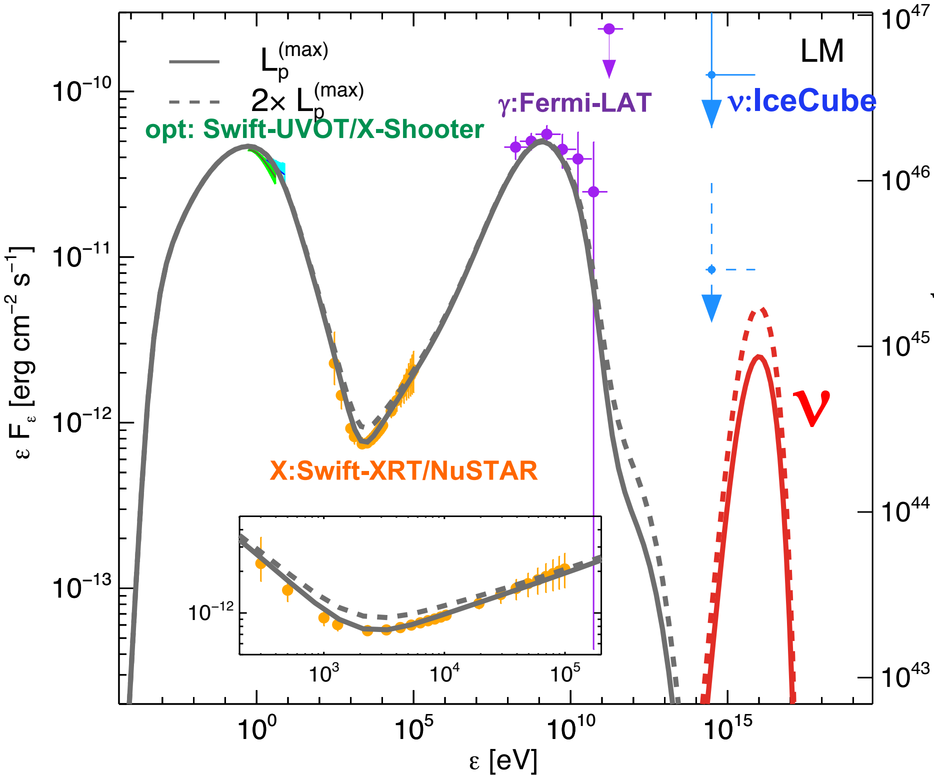




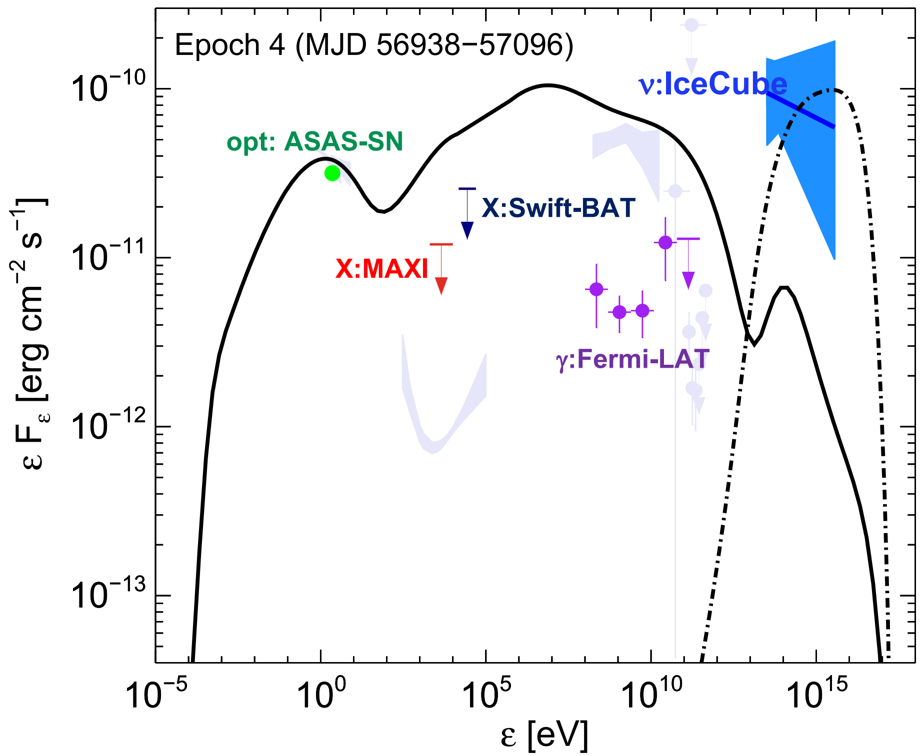
"Power" of Multi-Messenger Approaches

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

Foteini's nice talk!

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

Blazar Coincidences: Pros & Cons

Pros:

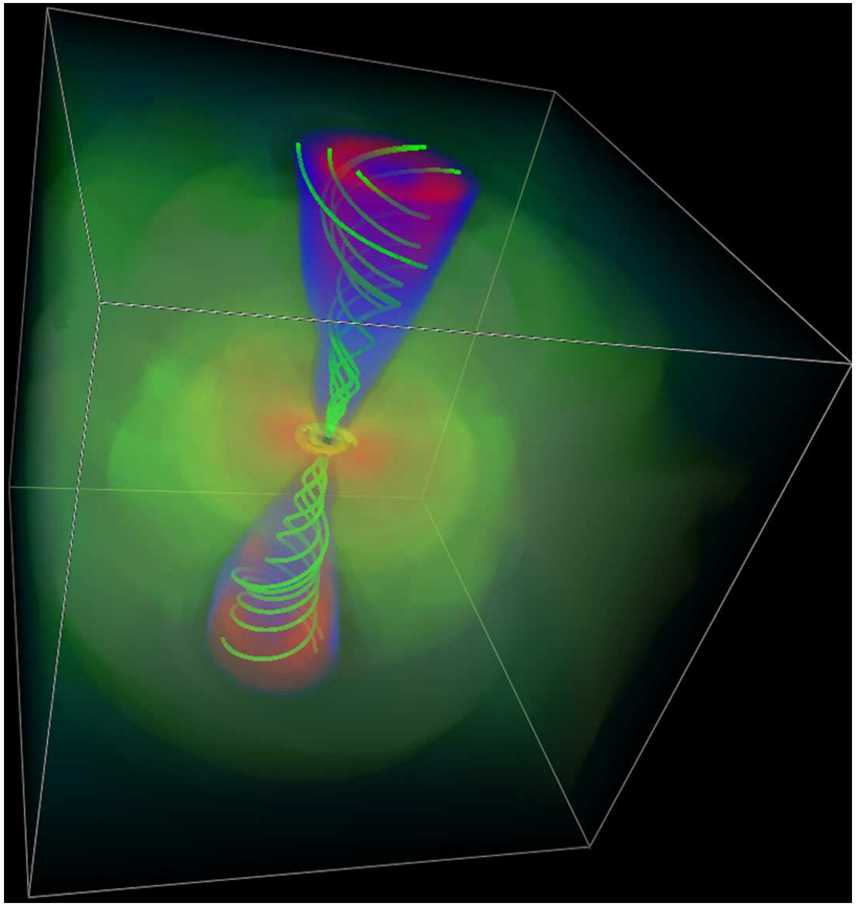
- More coincidences from ν alerts
- Stacking with radio-selected AGN (Plavin+ 20, 21)
  and BZCat blazars (Buson+ 22)
  (correlation level is consistent with theory even if subdominant)

Cons: Lack of concordance for multi-messenger data

- Cascade constraints limit allowed ν fluxes
- Not clear to explain why TXS or another is the brightest blazar
- Energetics issue
  $L_{CR}>L_{Edd}$ is often obtained
  $\varepsilon_p/\varepsilon_e > 300$ for the TXS 2017 multi-messenger flare

Particle Acceleration in Jets?

Origin of relativistic particles is under debate



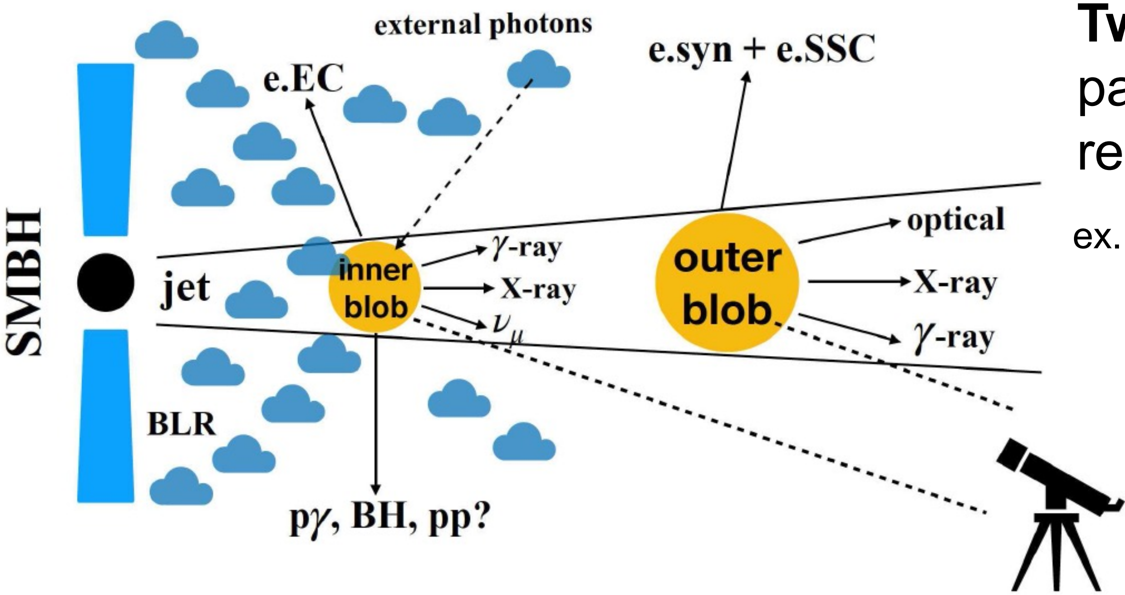
McKinney & Blandford 09

- Jet: launched as Poynting-dominated (e.g., Blandford-Znajek mechanism)
- Maybe copious pairs ($1<n_e/n_p<1000$)
- Emission region: particle-dominated but magnetized
- Toroidal-dominated at larger distances -> quasi-perpendicular shocks
- Relativistic magnetized shocks: acceleration is inefficient unless parallel (Sironi et al. 13, Bell et al. 18 etc.)

→ magnetic reconnection?

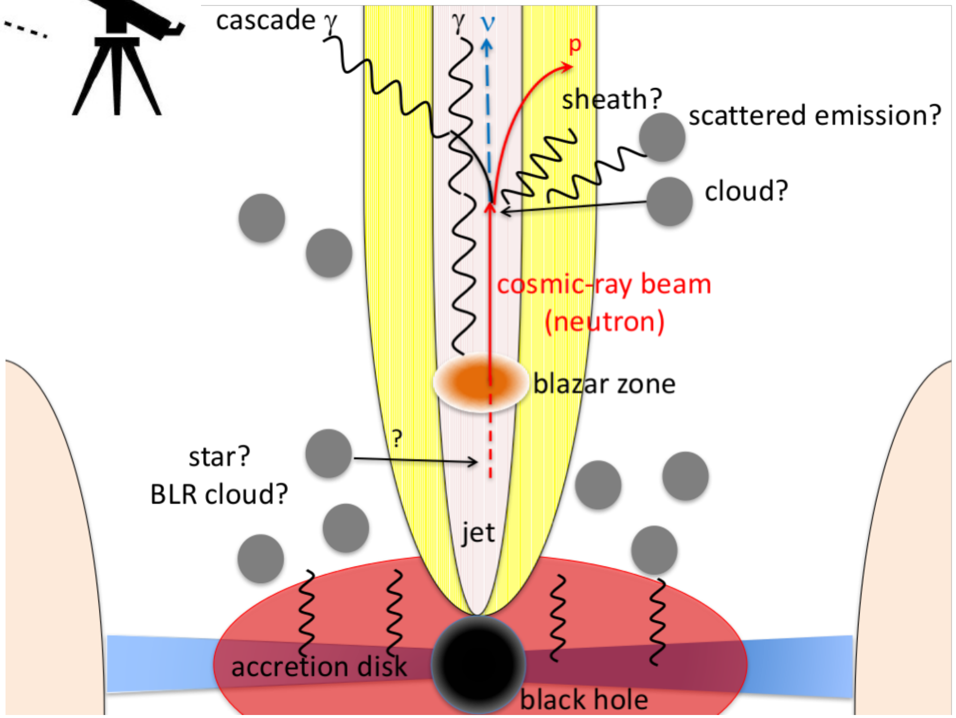
but $\varepsilon_p/\varepsilon_e$ may not be large

Beyond the Canonical Single-Zone Emission Model



Two-zone model:
parameters are doubled,
relaxing energetics requirement

ex. Gao+ 19 Nature Astron., Xue+ 19 ApJ

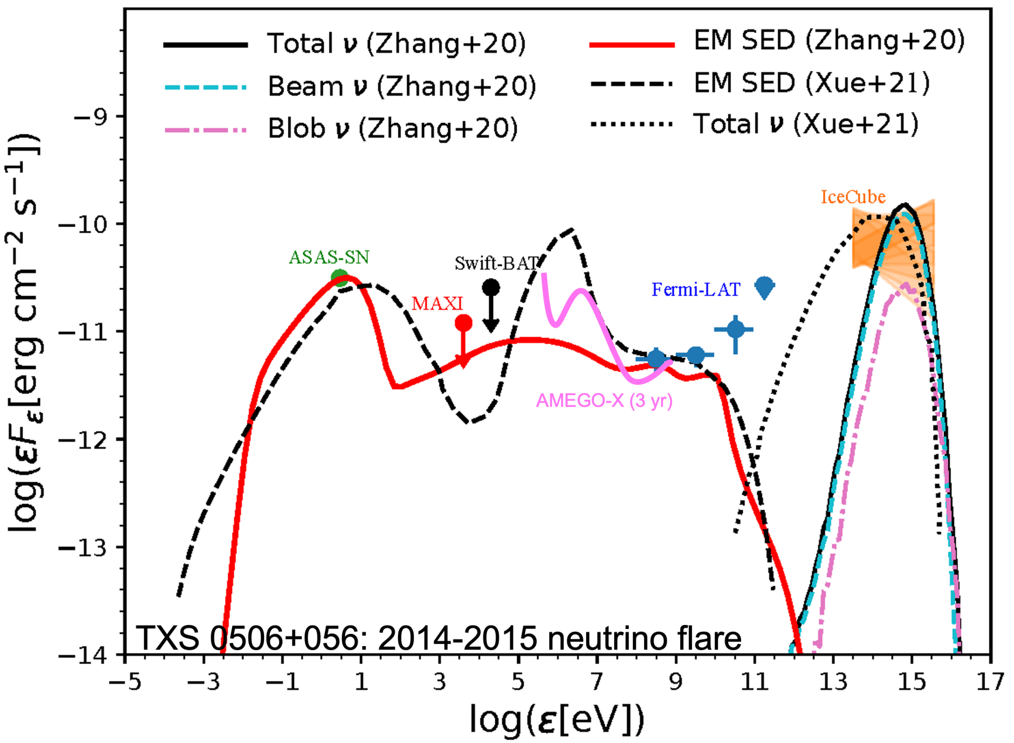


cosmic-ray beam model:
minimum extension,
relaxing cascade constraints
due to time delay & isotropization

KM, Oikinomou & Petropoulou 18 ApJ
Zhang, Petropoulou, KM & Oikonomou 20 ApJ

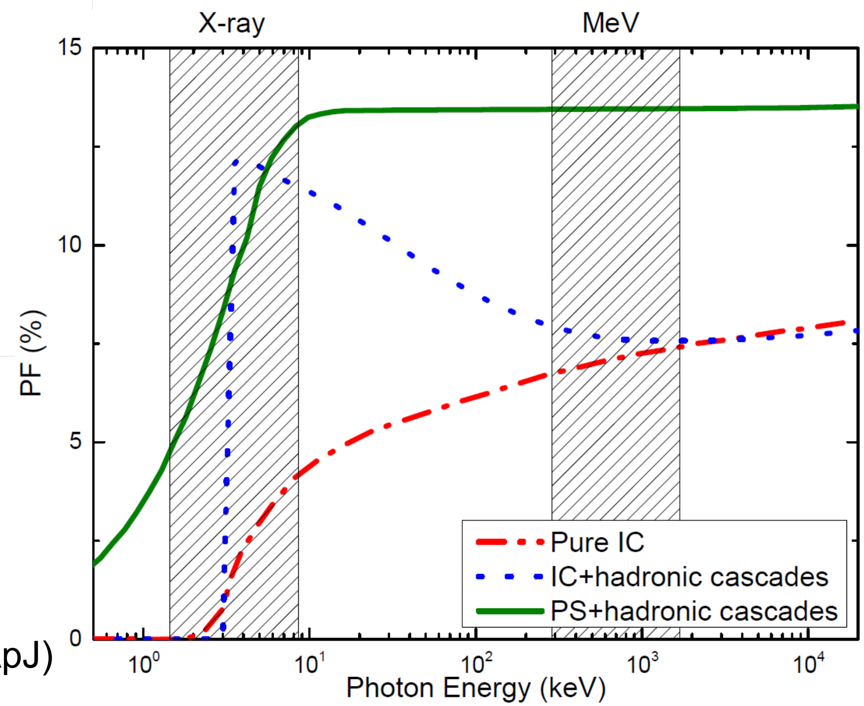
Possible Observational Signatures

MeV γ-ray signatures



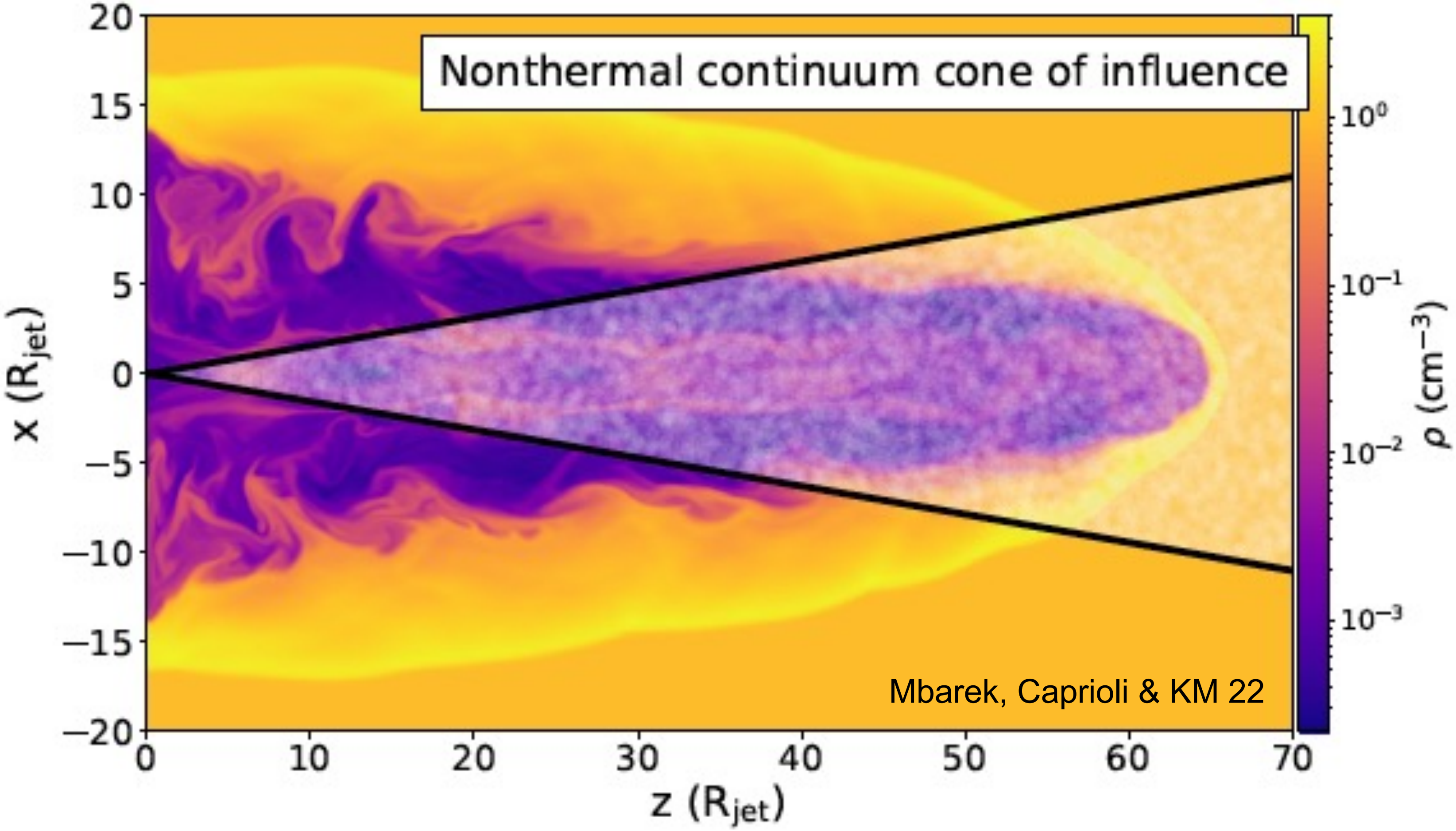
TXS 0506+056: 2017 multimessenger flare (Zhang+ 19 ApJ)

polarization



Toward More Realistic Acceleration Models

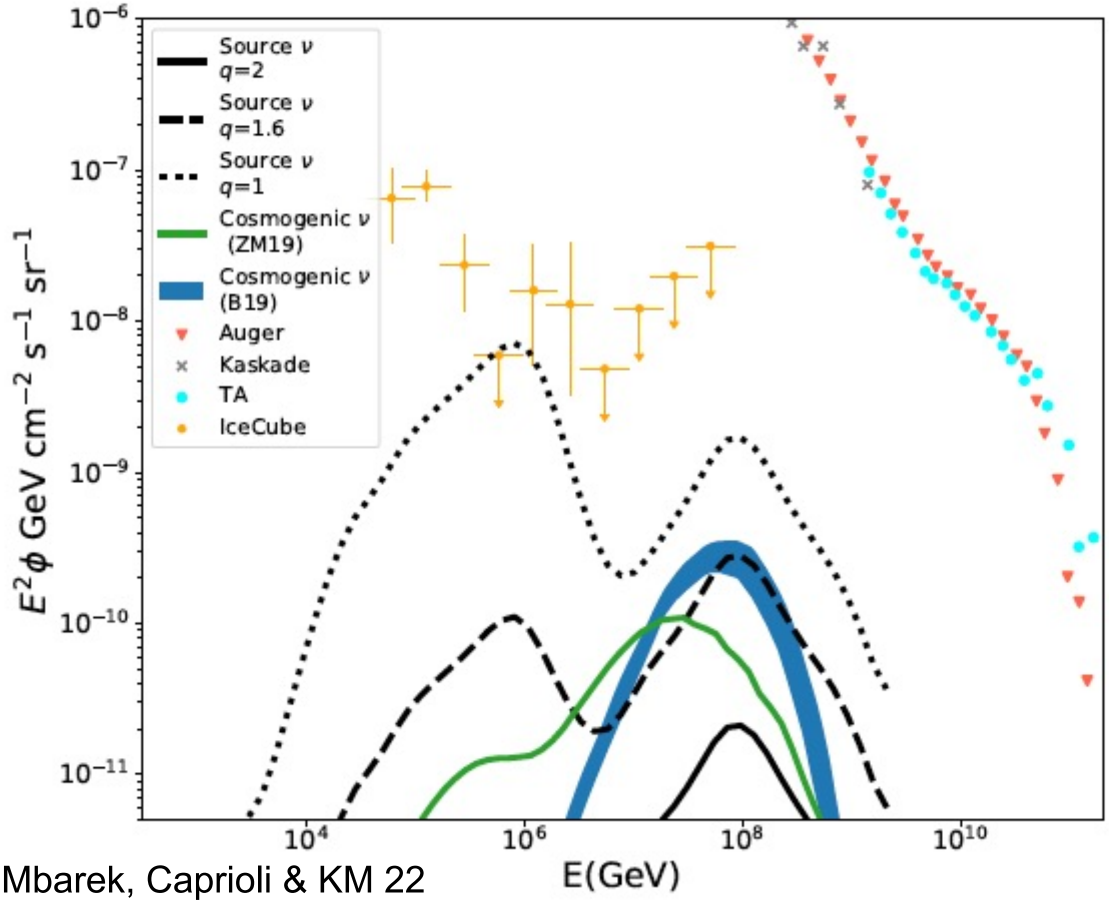
CR acceleration & ν production occur at multi-scales



ex. UHECR via reaceleration (Carprioli 15 ApJL, Kimura, KM & Zhang 18 PRD)

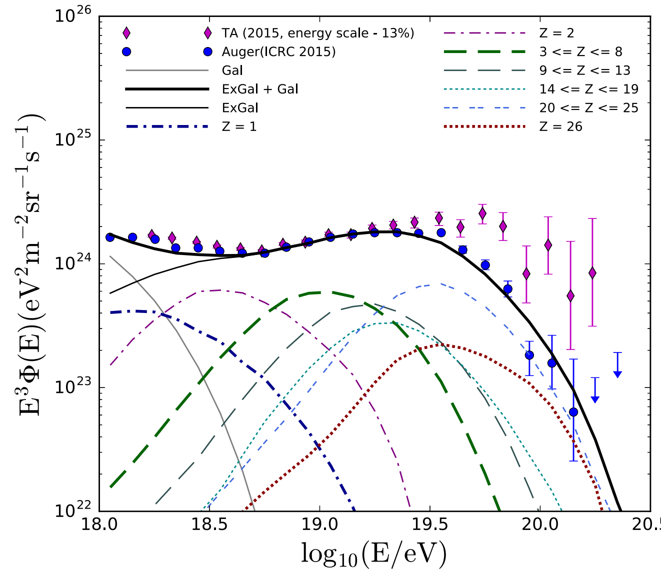
Toward More Realistic Acceleration Models

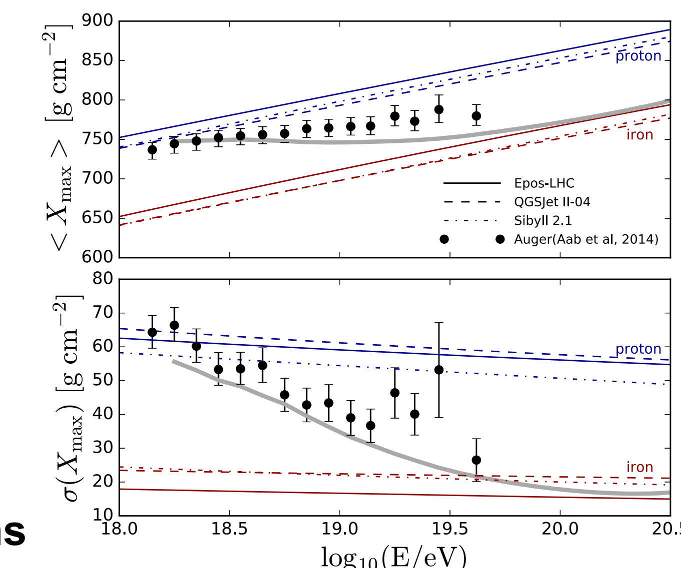
Test-particle simulations with MHD



Mbarek, Caprioli & KM 22

Kimura, KM & Zhang 18 PRD

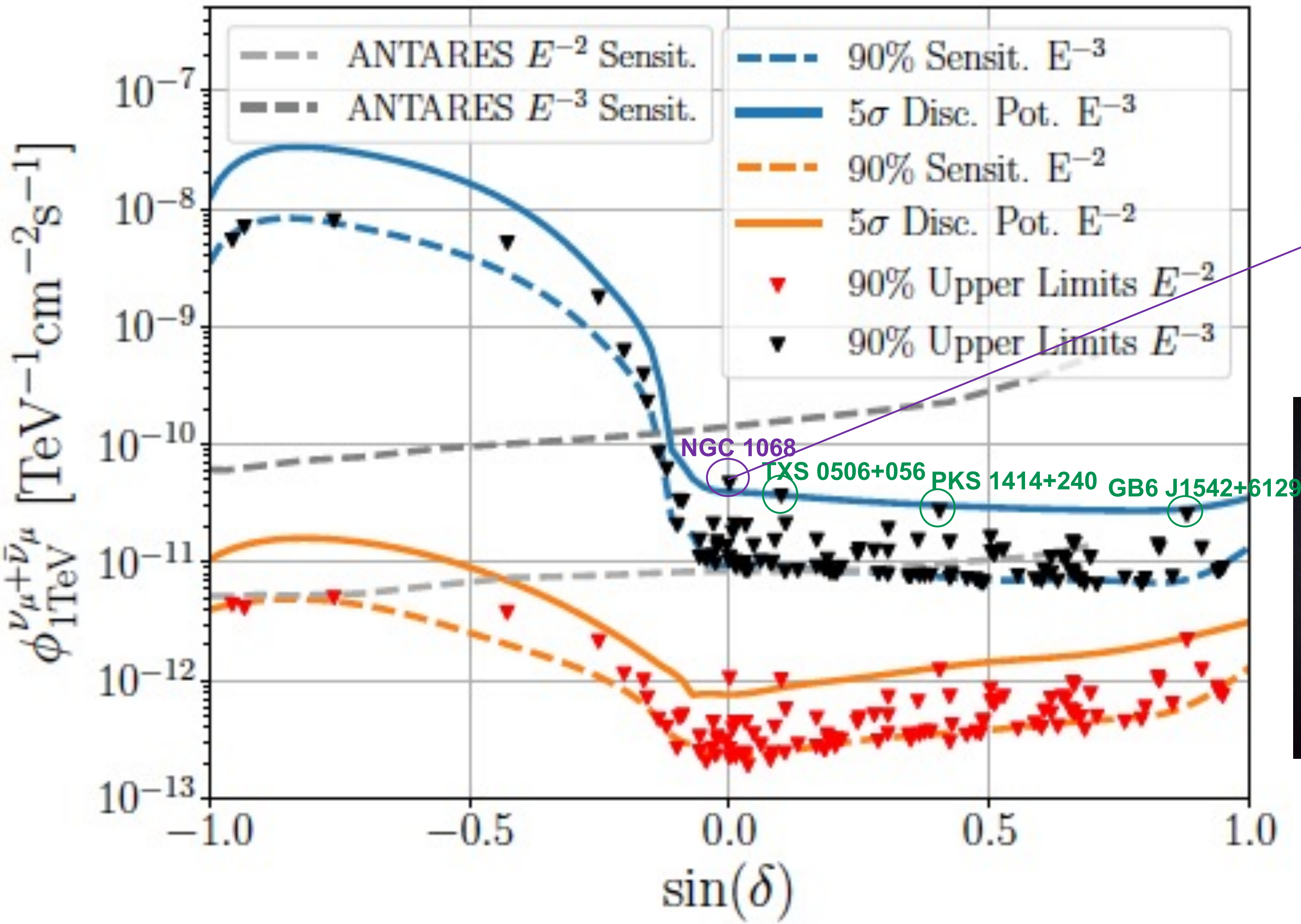




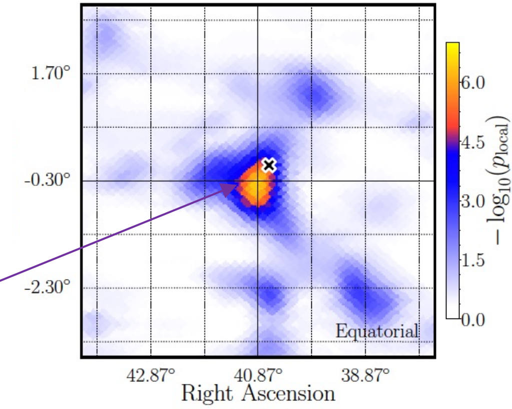
Monte-Carlo simulations

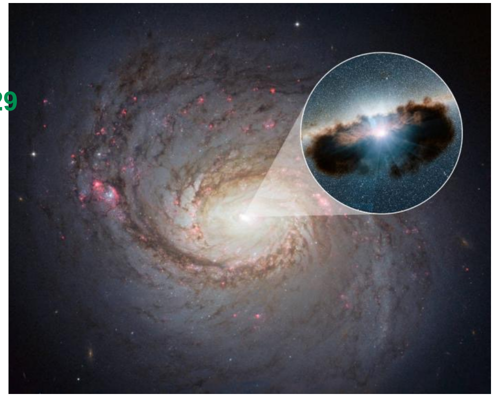
IceCube Point Source Searches

IceCube Collaboration 20 PRL



starburst galaxy/AGN



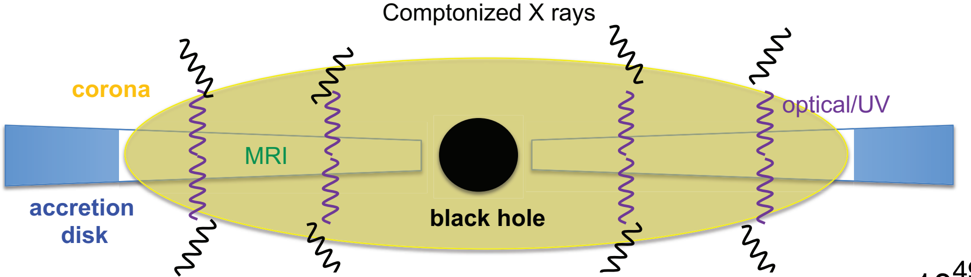


Yoshi's nice talk!

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

Vicinity of Supermassive Black Holes

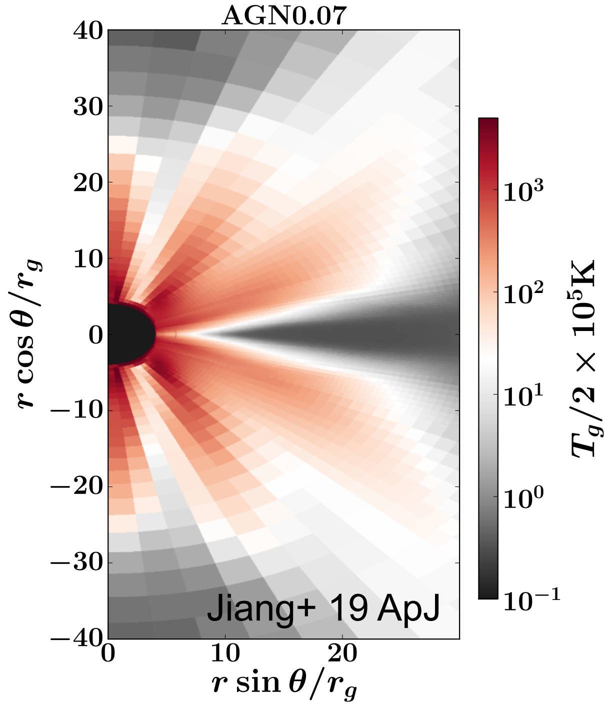
cores of active galactic nuclei (mainly jet-quiet AGNs)

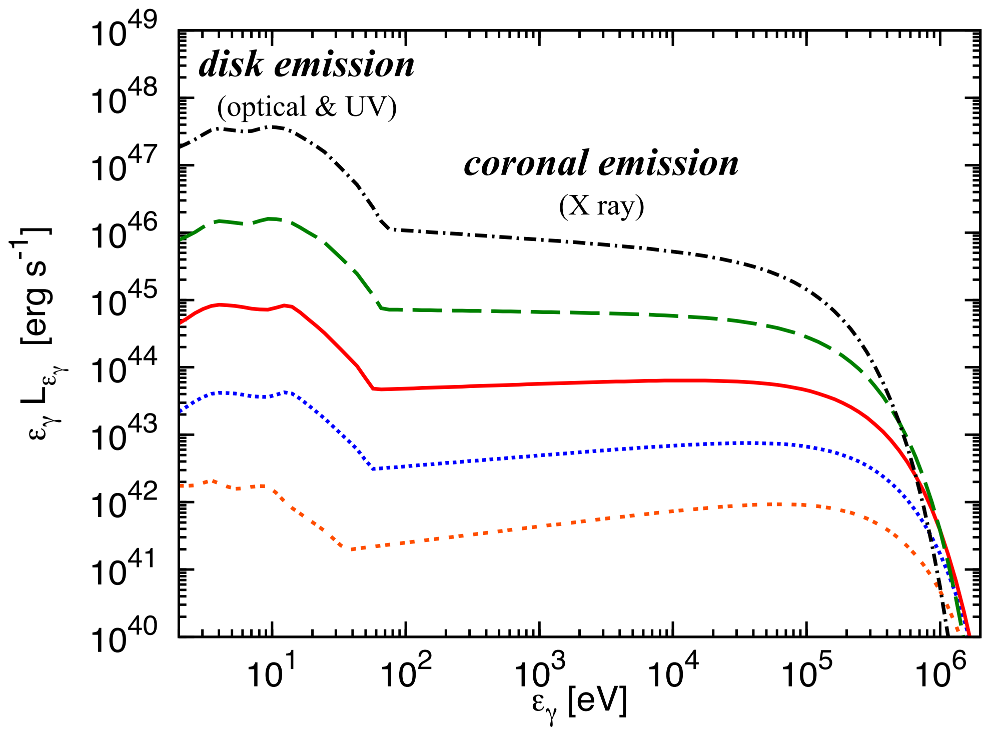


disk-corona model

opt/UV=multi-temp. blackbody

X-ray=Compton by thermal e





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

NGC 1068: Pros & Cons

Pros:

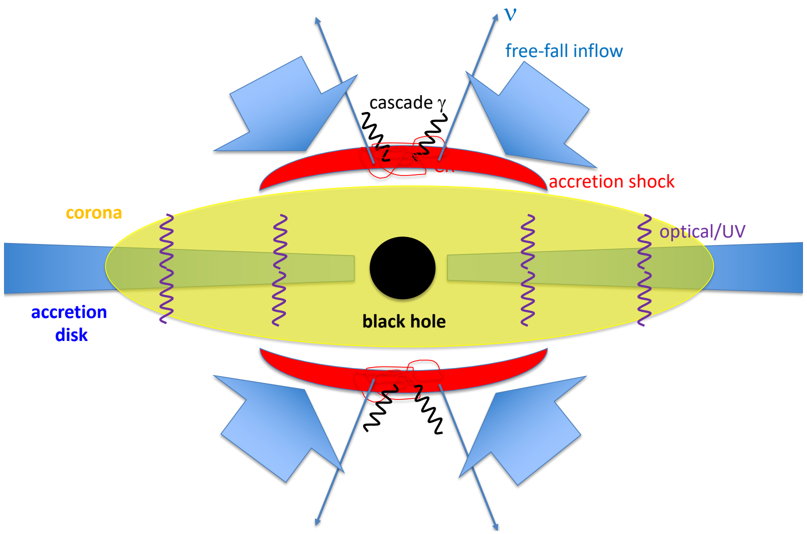
- L_ν~3x10^{42} erg/s vs L_{bol}~10^{45} erg/s & L_X~10$^{43-44}$ erg/s reasonable energetics: energy fraction of CRs: ~10%
- Obscured AGN & high-density (calorimetric) environments
- The brightest Seyfert in intrinsic X-rays in the IceCube sky (For PeV νs, the most promising starburst in the IceCube sky)
- Hidden sources motivated by both theory and diffuse ν-γ
- Hints from stacking with IR/radio-selected AGN (2.6σ)

Cons:

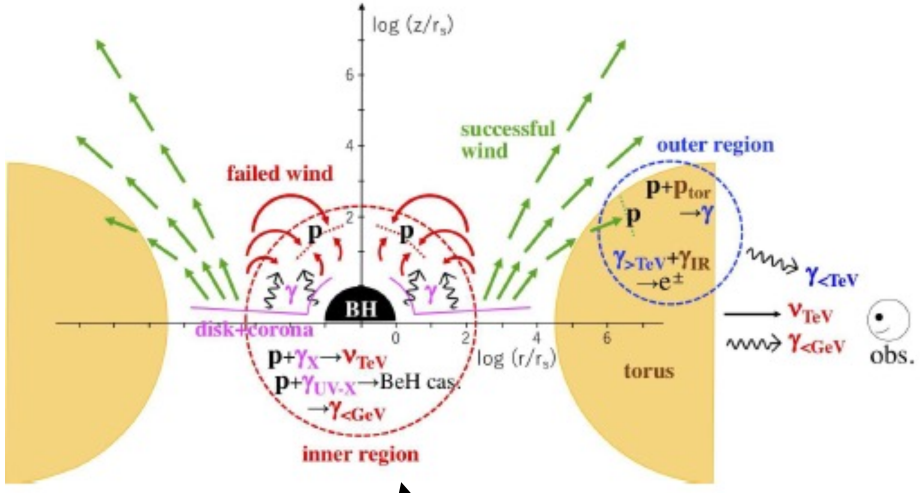
- More statistics are necessary (~3σ in the cataloged search)
- Particle acceleration mechanisms are unclear (but much progress has been made theoretically)

AGN Models

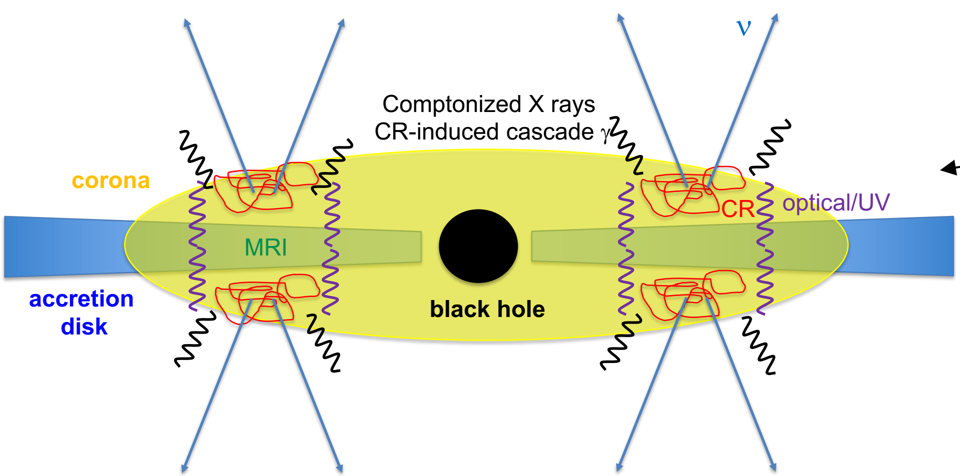
Accretion shock model
(ex. Stecker+ 91, Y. Inoue+ 20 ApJ)



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



supported/motivated by state-of-art simulations

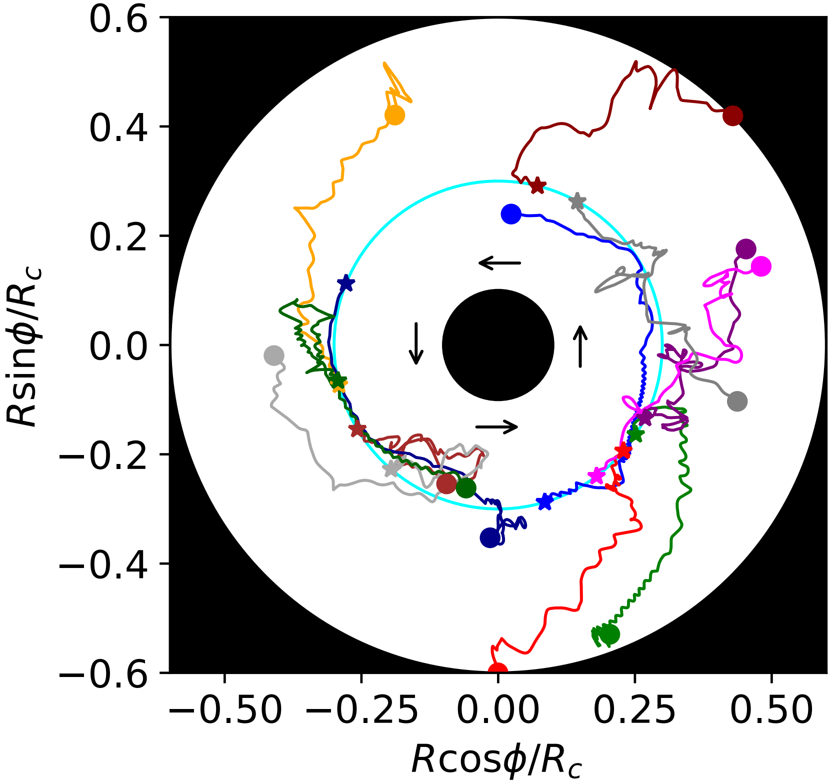


Magnetically-powered corona model
(KM+ 20 PRL, Eichmann+ 22)

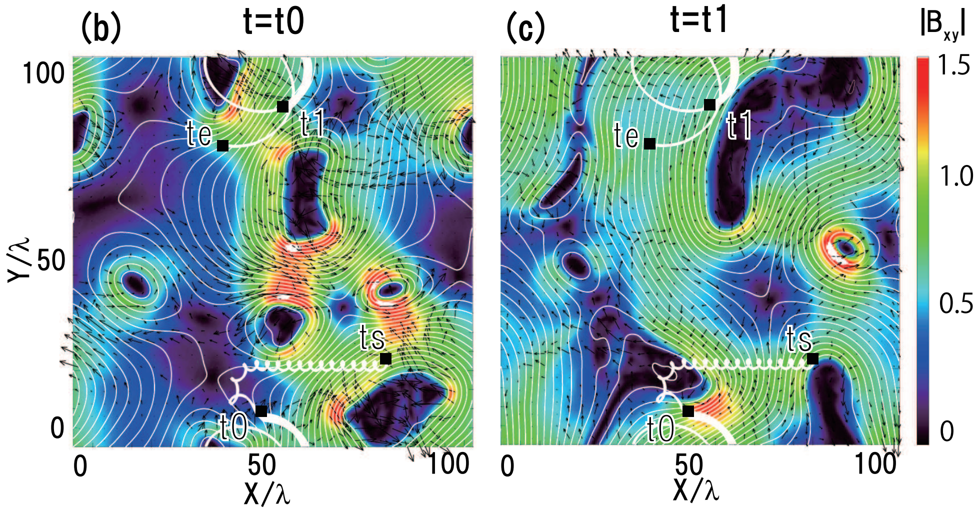
Particle Acceleration in Hot Accretion Flows

Magnetorotational Instability (MRI) -> turbulence & reconnection

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



reconnection/stochastic acc. in PIC simulations



Hoshino 12 PRL

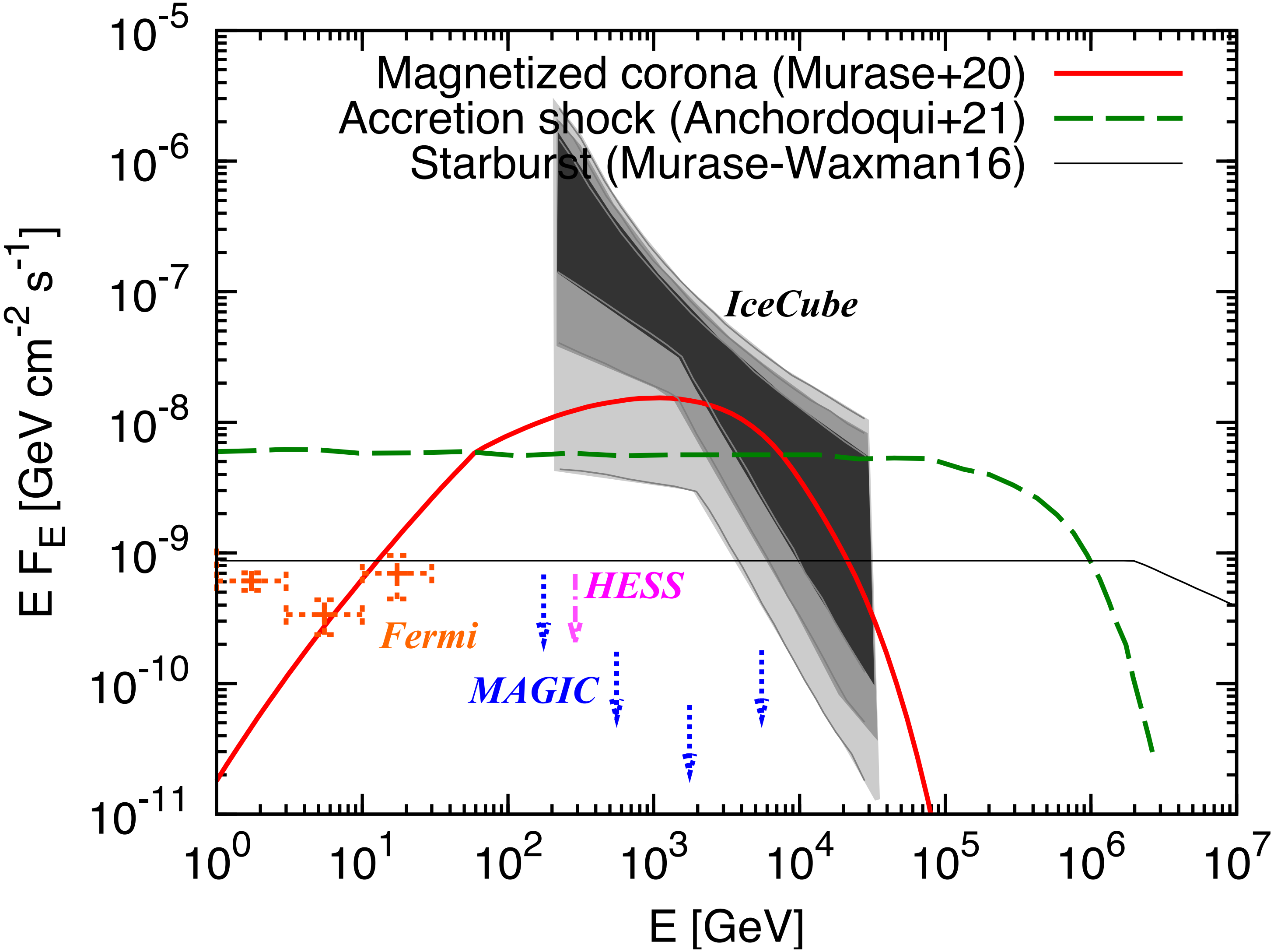
magnetic reconnections
- acceleration by electric fields at X point
- subsequent stochastic acceleration via collisions w. islands or reconnection flows

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

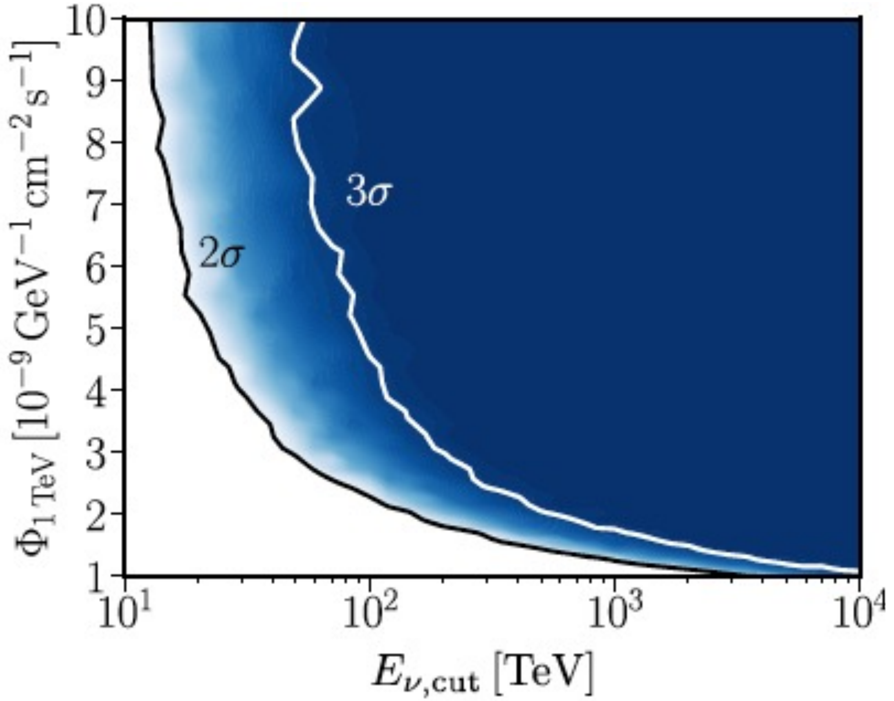
see also Hoshino 15 PRL, Sironi & Spitkovsky 14 ApJ, Ball, Sironi & Ozel 19 ApJ

NGC 1068: Promising Hidden ν Sources

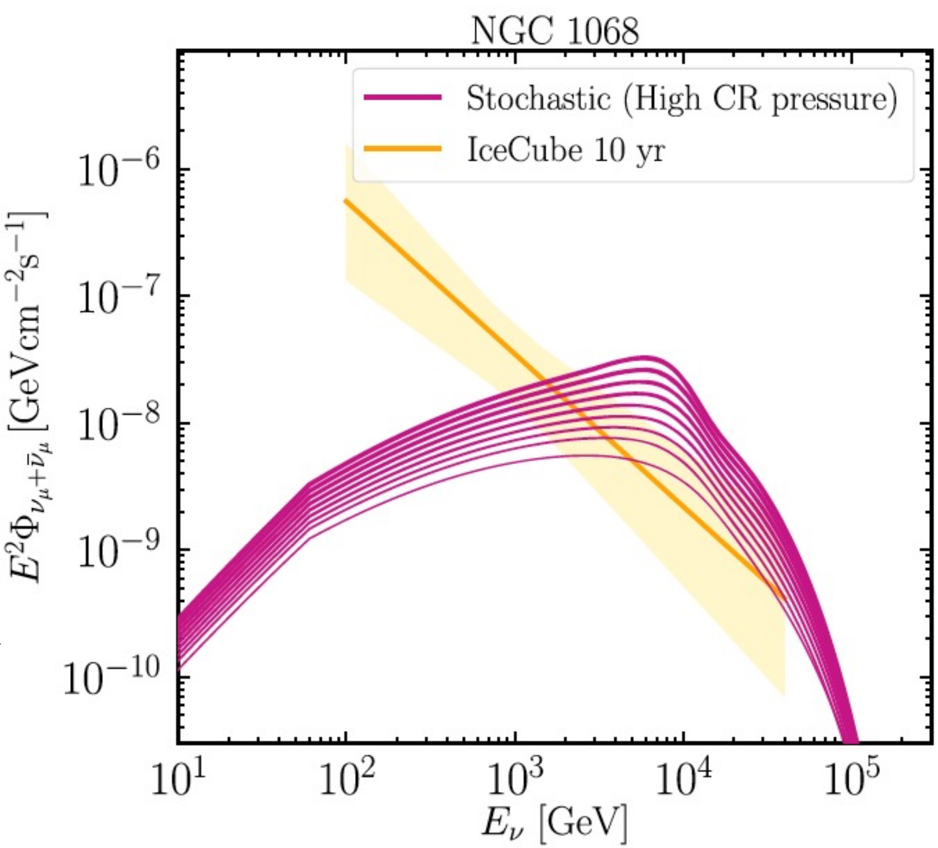
KM, Kimura & Meszaros 20 PRL, Inoue, Anchordoqui, Krizmanic & Stecker 21



NGC 1068: Constraints & Uncertainty



Constraints on E_{cut} for E^{-2} spectrum (Bohm diffusion is excluded for the accretion shock model)

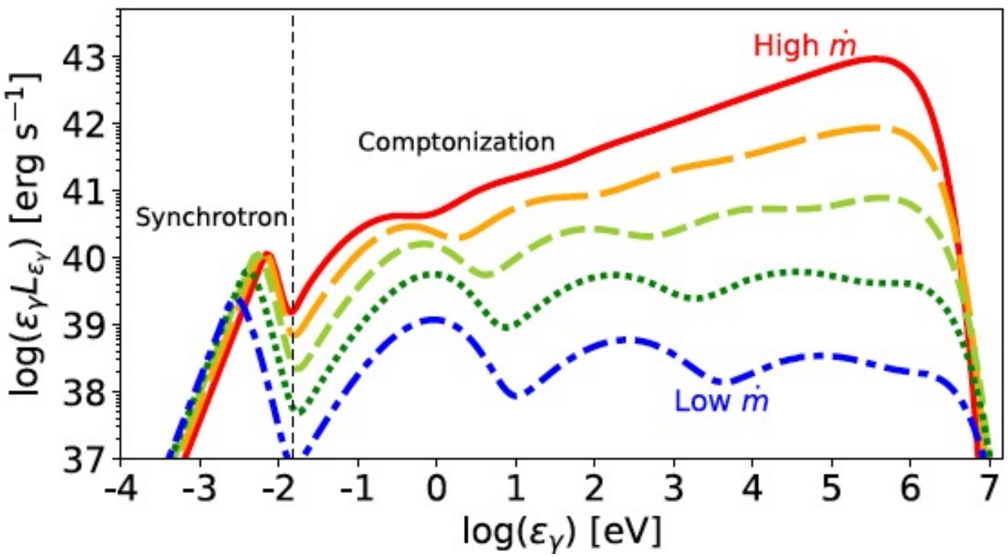


Uncertainty from “intrinsic” X-ray flux

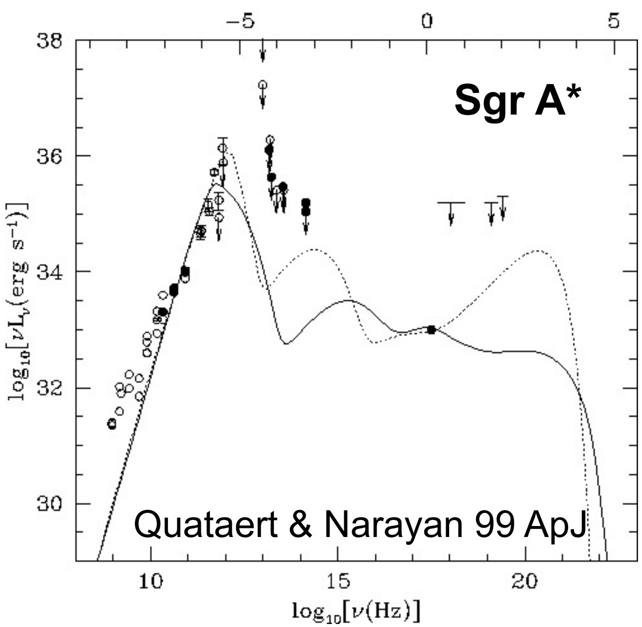
Kheirandish, KM & Kimura 21 ApJ

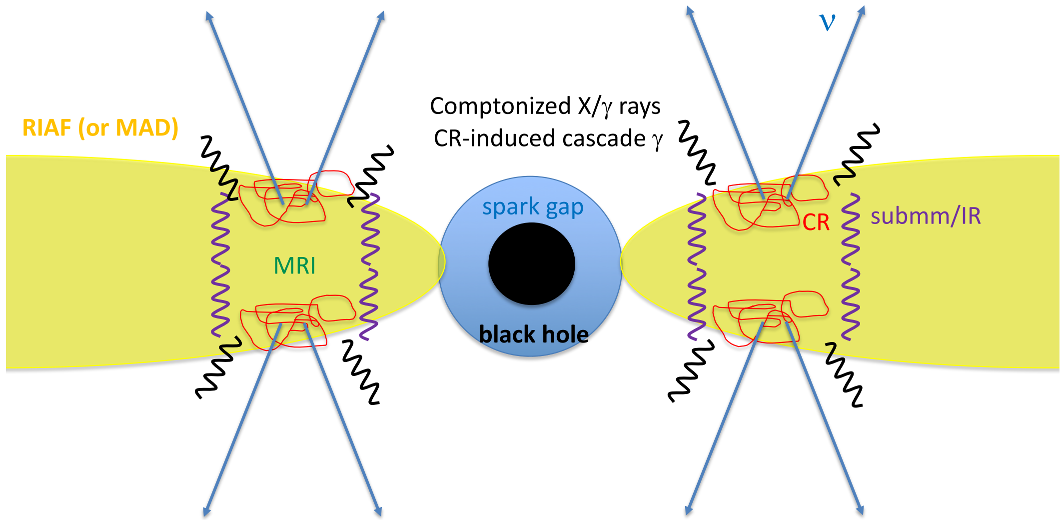
Applications to Low-Luminosity AGNs

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



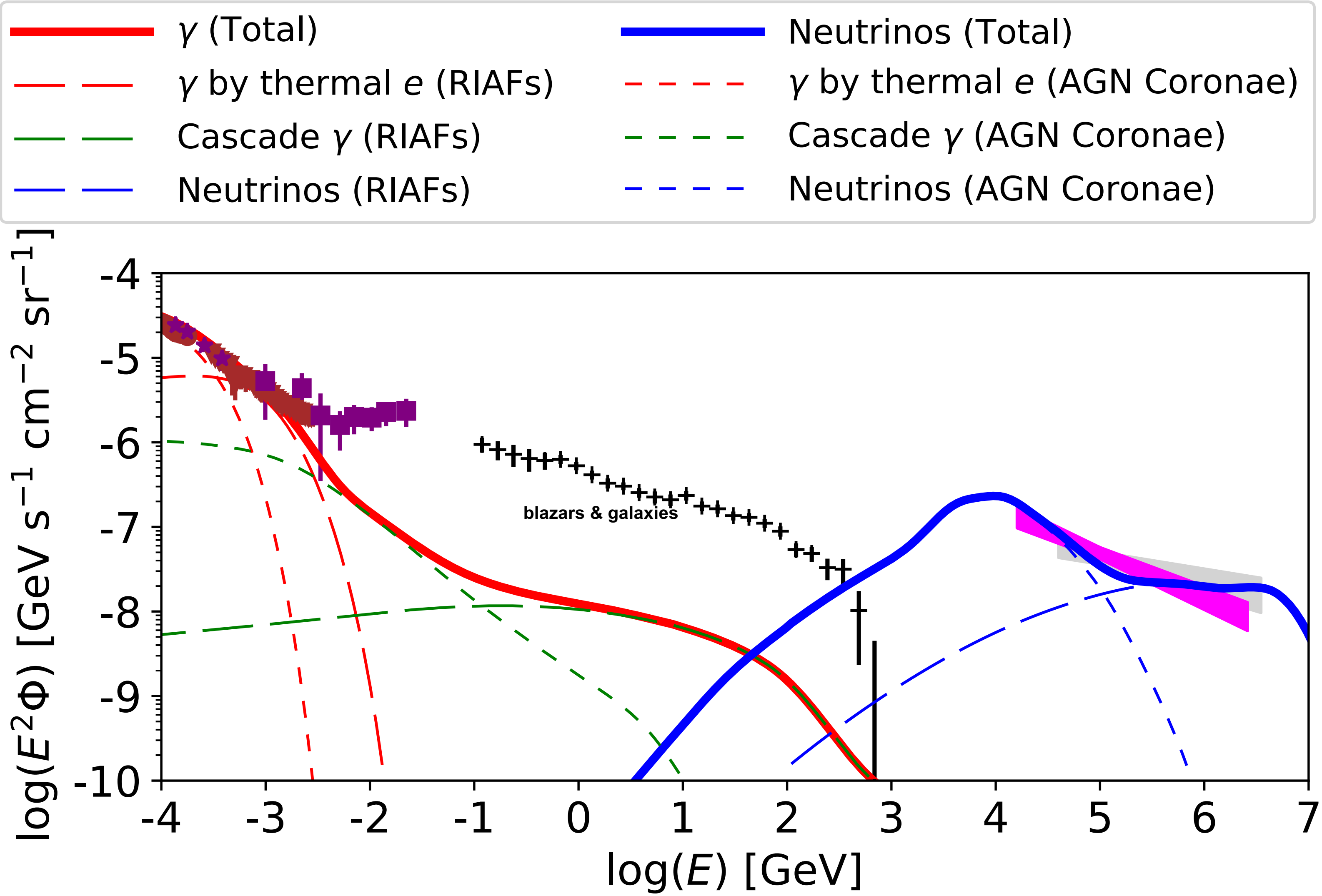
- RIAF for mdot<0.03
- Electrons are mostly thermal (collisional for electrons but collisionless for protons)



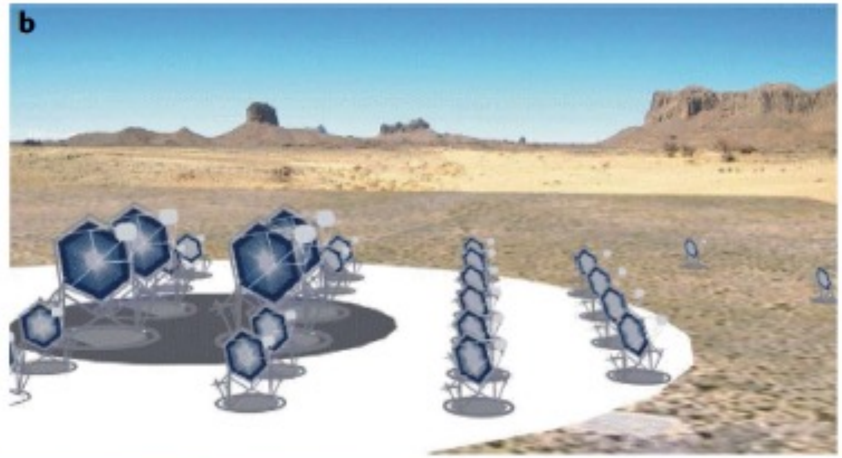


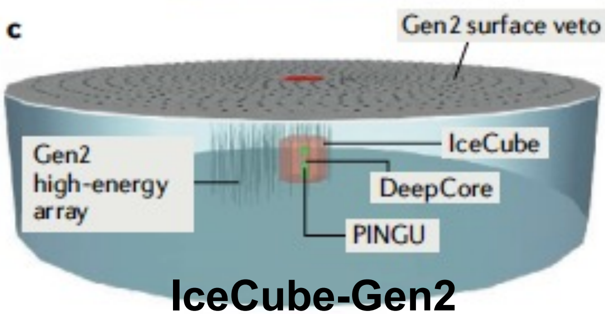
AGN Manifesting in the Multi-Messenger Sky?

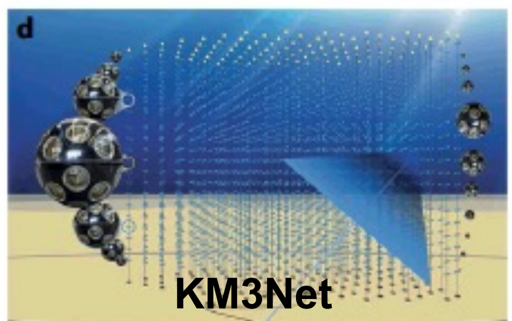
KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.

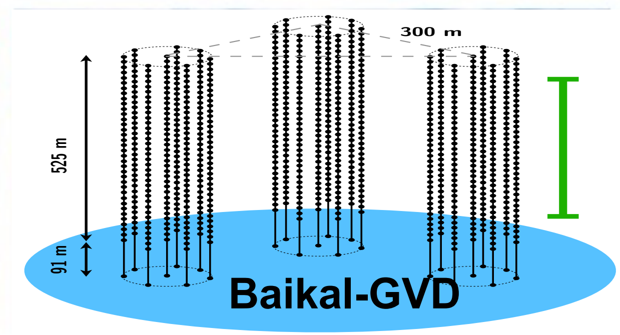


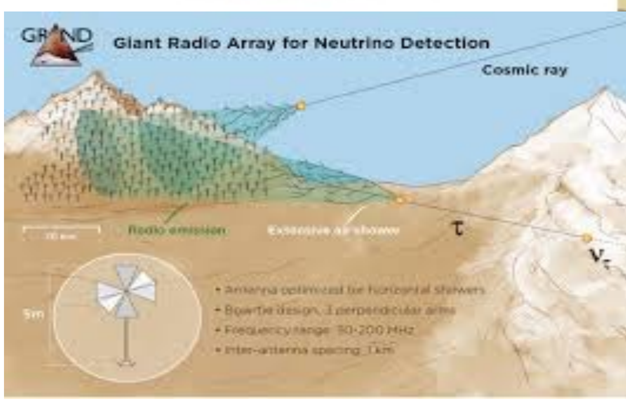
Good Testability











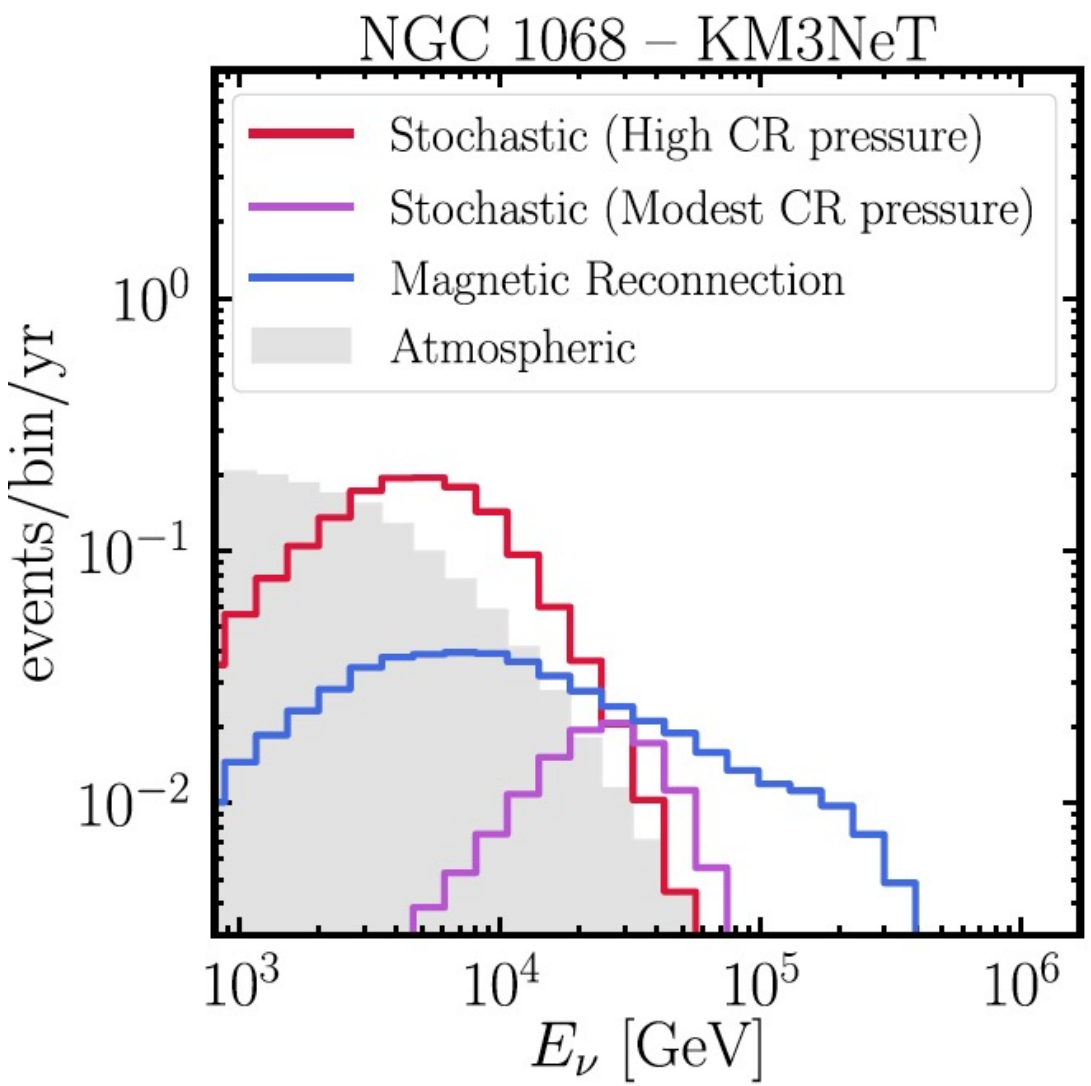
More multi-messenger data in the next decade will enable us to test the proposed models

Importance of KM3Net Observations

Kheirandish, KM & Kimura 21 ApJ

Top 10 sources for KM3Net

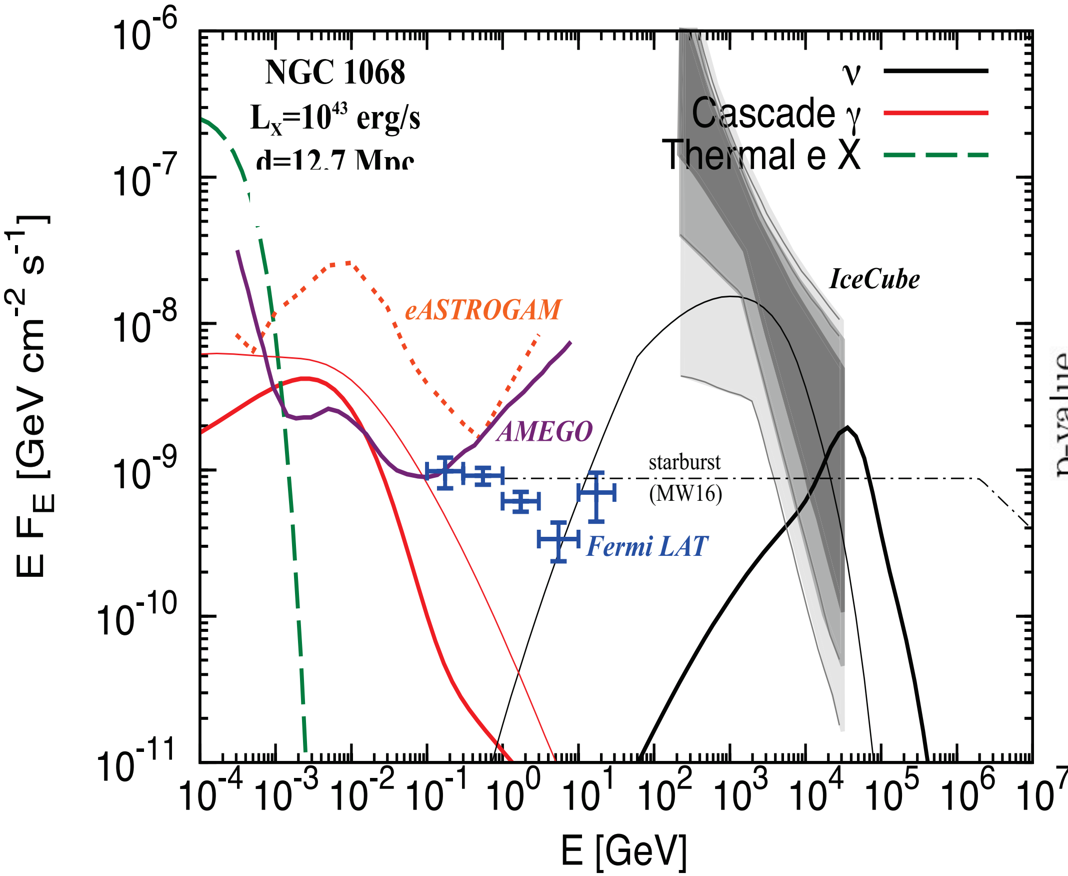
1. *Cen A
2. Circinus Galaxy
3. ESO 138-1
4. NGC 7582
5. NGC 1068
6. NGC 4945
7. NGC 424
8. UGC 11910
9. CGCG 164-019
10. *NGC 1275



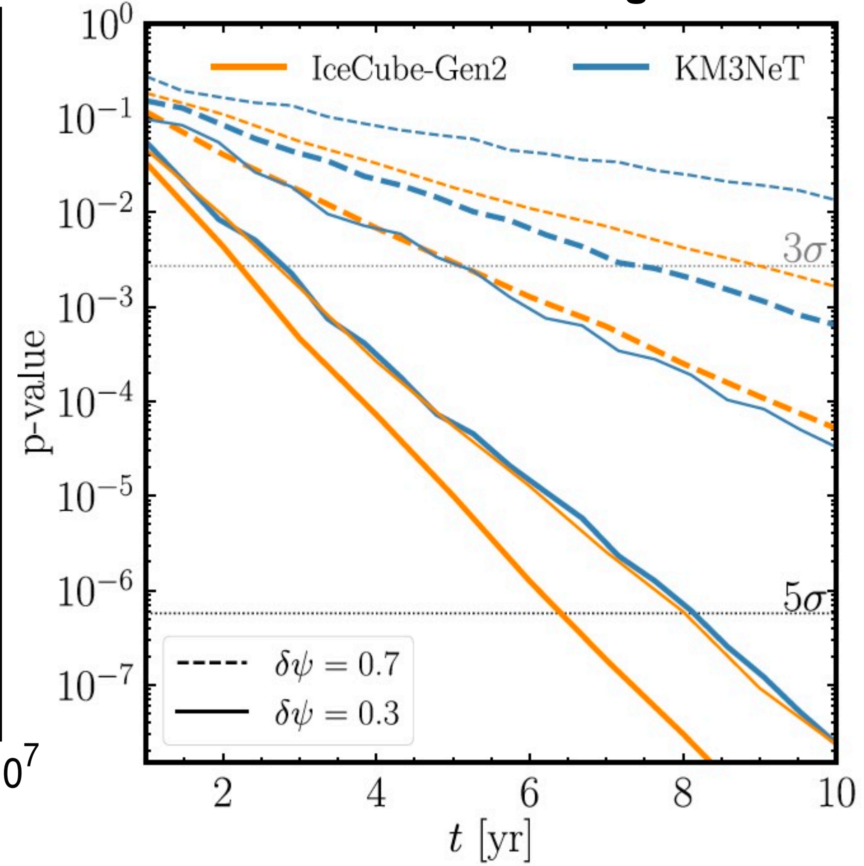
*** may belong to different classes**

Detectability of Nearby Seyfert Galaxies

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



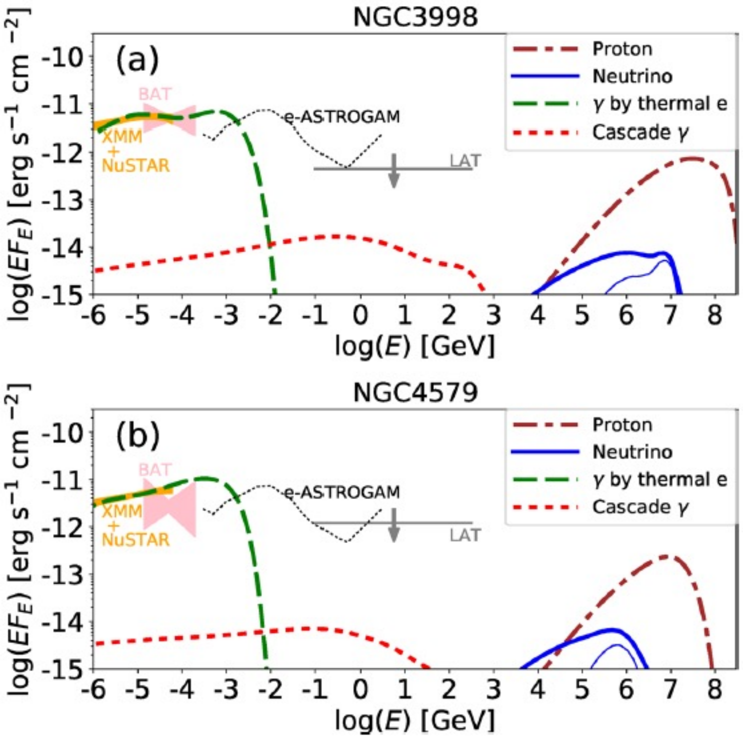
Predictions for stacking search

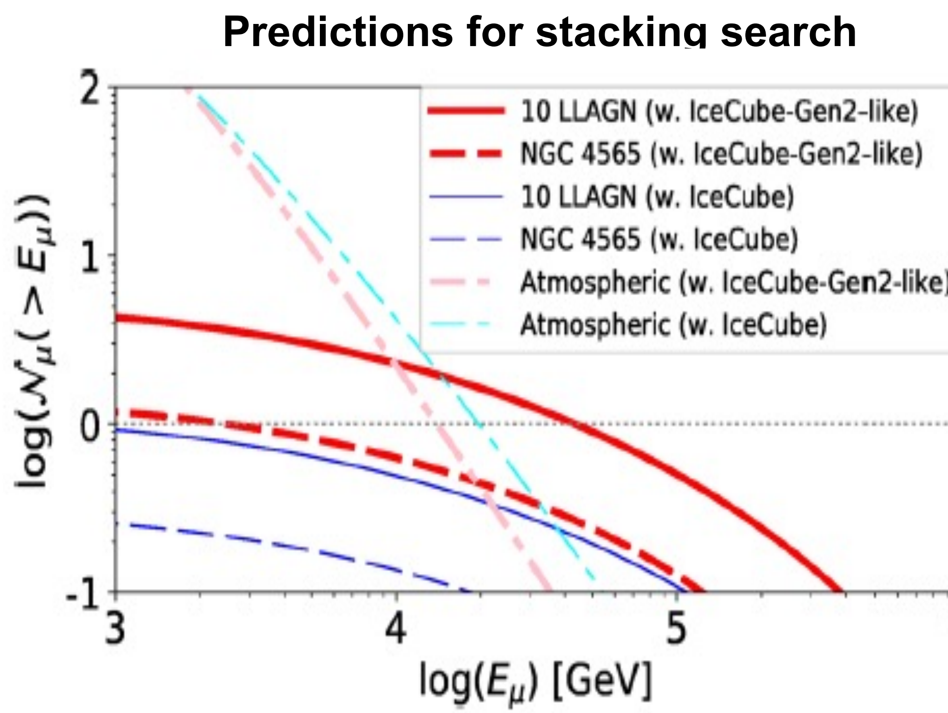


- CR-induced cascade γ rays are promising in the MeV range
- Testable w. near-future data or by next-generation neutrino detectors given that the angular resolution is <0.3 deg

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

Summary

γ-ray flux ~ ν flux ~ CR flux

AGN may contribute to all 3 messengers but from different regions

Blazars/Jetted AGN

- Dominant in the extragalactic γ-ray sky but seems subdominant in the ν sky
- TXS 0506+056 and other coincidences: no simple convincing picture
- Intriguing ν-radio correlations are reported but implications are unclear
- Beyond handwavy models: simulations of jets & particle acceleration
- UHECR & EeV ν (UHECRs may rather be produced by large scale jets)

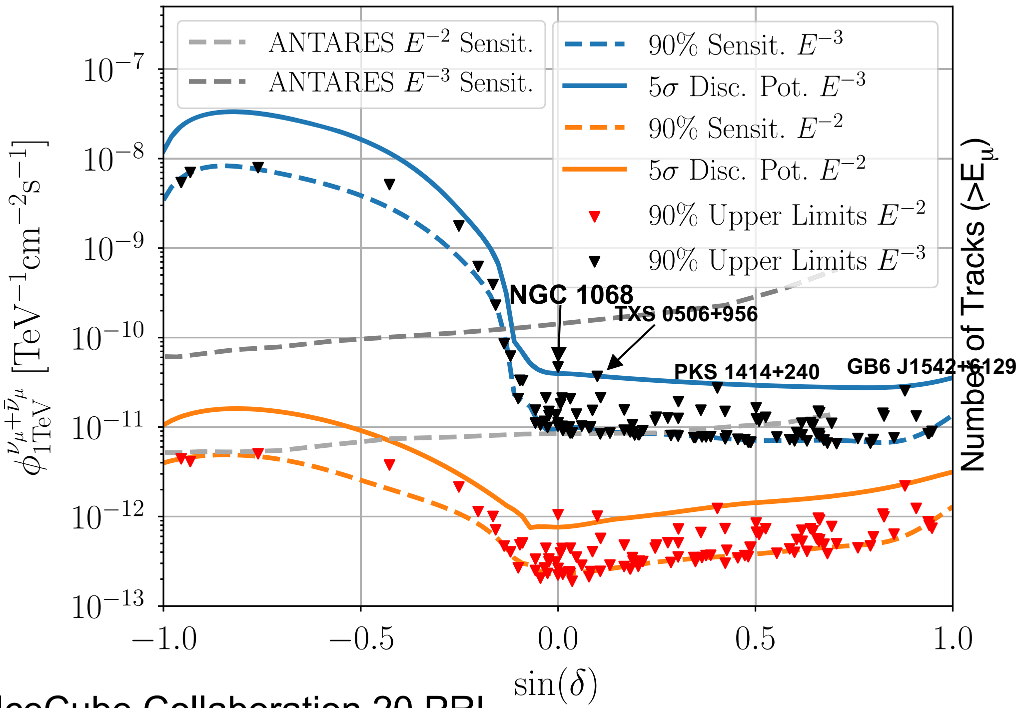
Jet-quiet AGN

- All-sky 10 TeV νs can be explained as γ-ray hidden sources
- Tight connection w. X rays and MeV γ rays (plus millimeter/radio emission)
- Nearby Seyferts: NGC 1068 (IceCube) & more in south (KM3Net)
- Nearby LL AGN: detected by Gen2 if they contribute to the diffuse ν sky

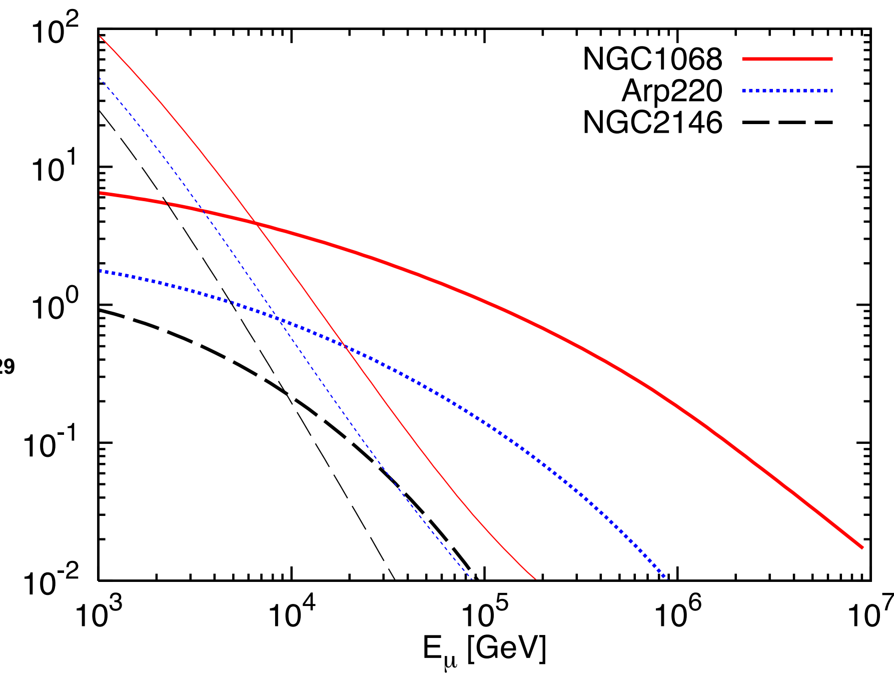
Point-Source Search & NGC 1068

IceCube's 10-year point-source search

predicted νs for the brightest starbursts (10 years in IceCube)



IceCube Collaboration 20 PRL



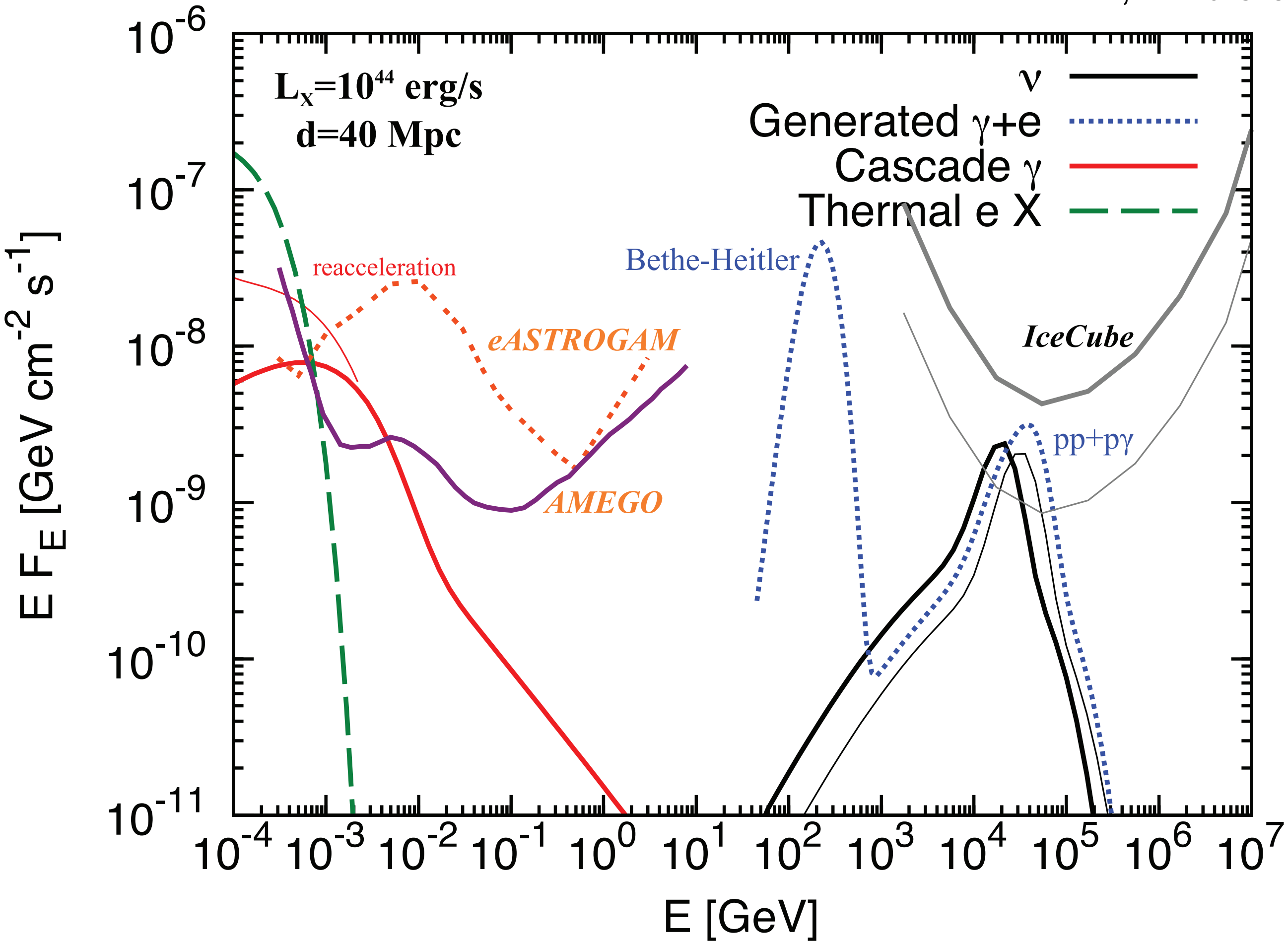
KM & Waxman 16 PRD

- ~3σ excess emission from NGC 1068 (starbursts w. Seyfert)
- Predicted to be among the most promising starbursts

(see also Tambrra, Ando & KM 14, Liu, KM+ 18 ApJ)

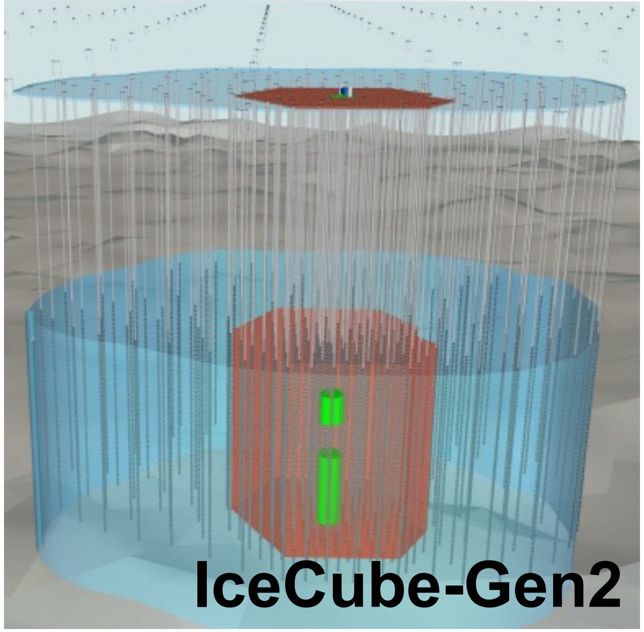
Detectability of Nearby Radio-Quiet AGN

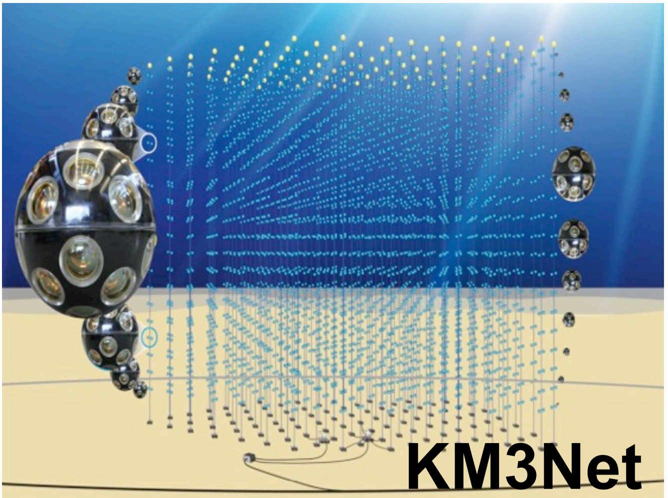
KM, Kimura & Meszaros 20 PRL



- Bethe-Heitler dominance (interactions w. UV disk photons limit CR acc.) synchrotron/IC cascades → "robust" MeV γ-ray connection
- ν: interactions w. accreting matter & coronal X-rays (rather than disk photons)

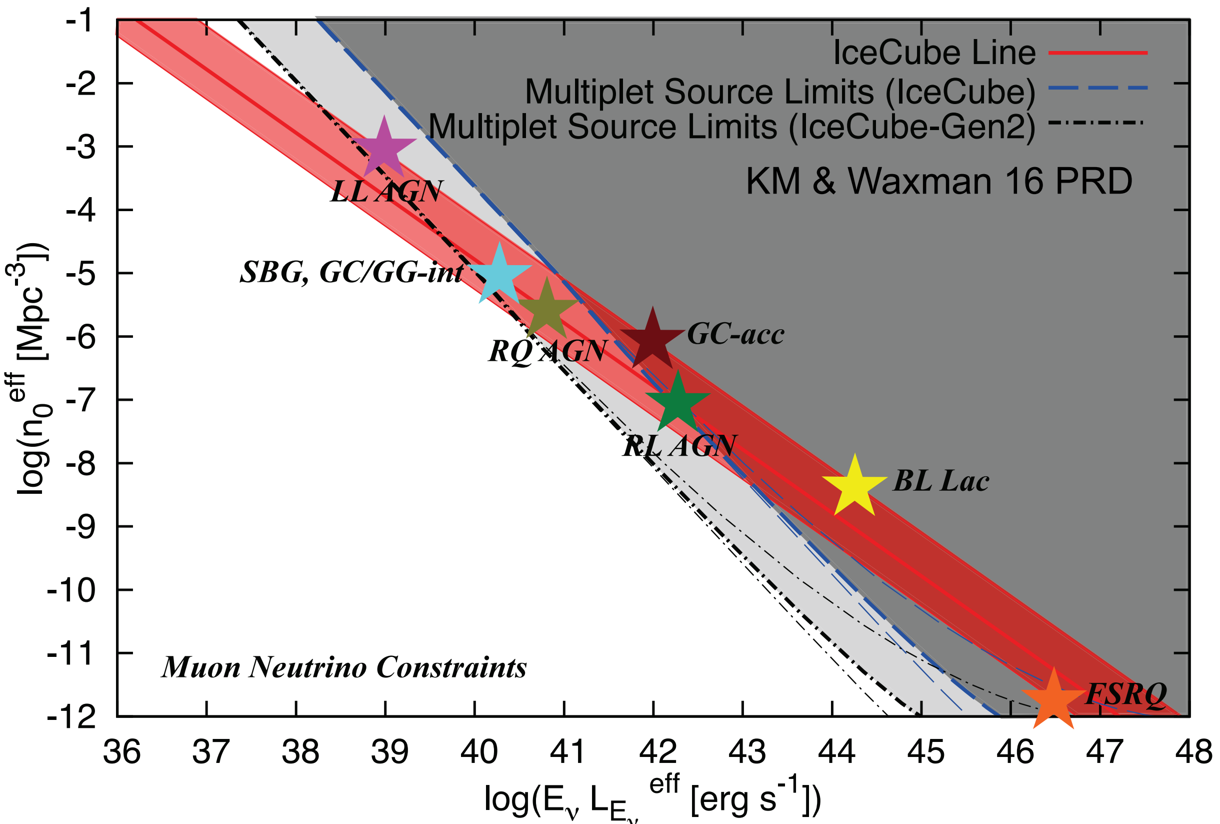
What's Next?





IceCube-Gen2

- 10 x IceCube in volume
- better angular resolution



All source candidates will be critically tested given that the angular resolution is ~0.1-0.2 deg