High-Energy Multimessenger Emission from Supermassive Black Holes

Kohta Murase

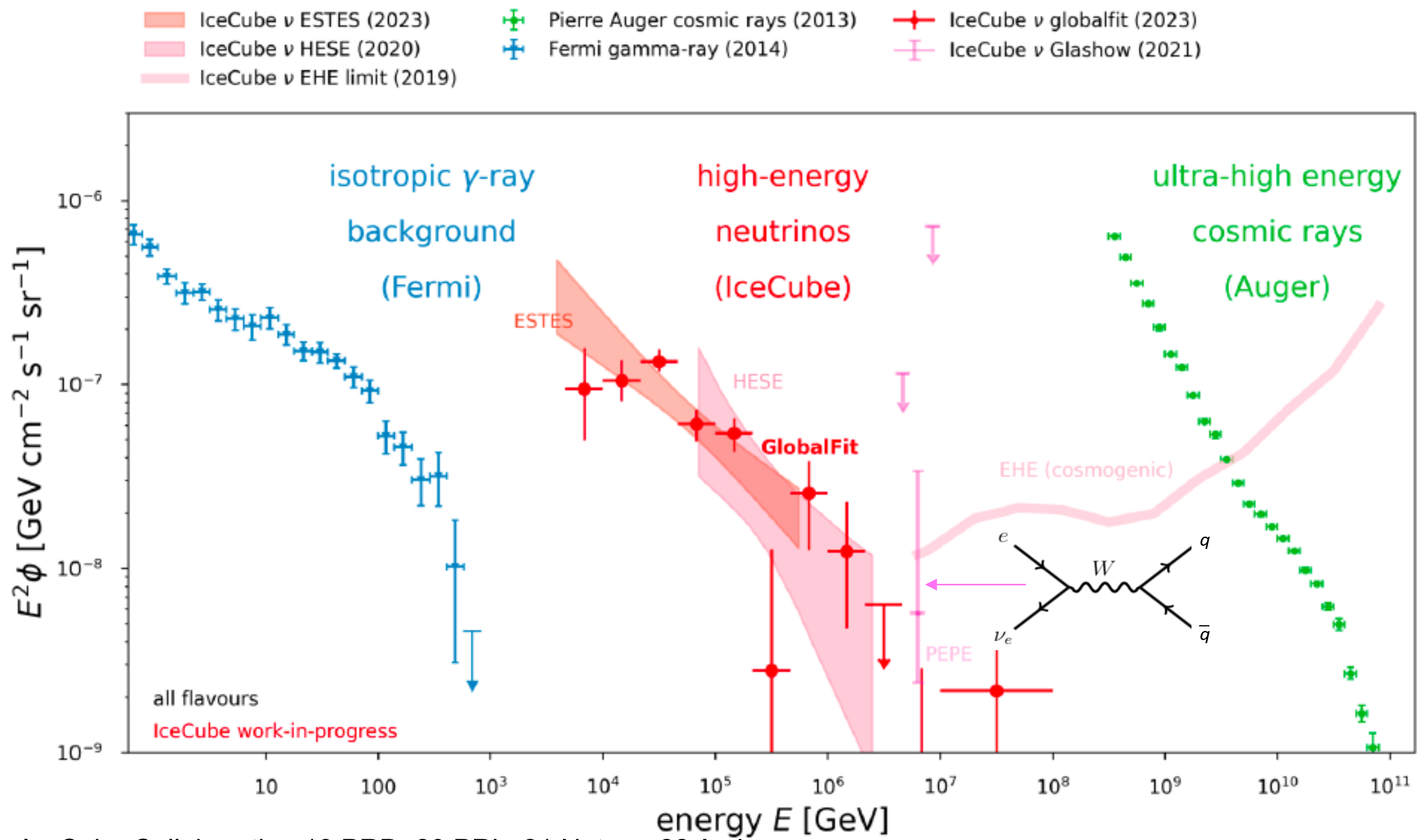
(Penn State/YITP)

CRs & νs in the MM Era

PENNSTATE

1855

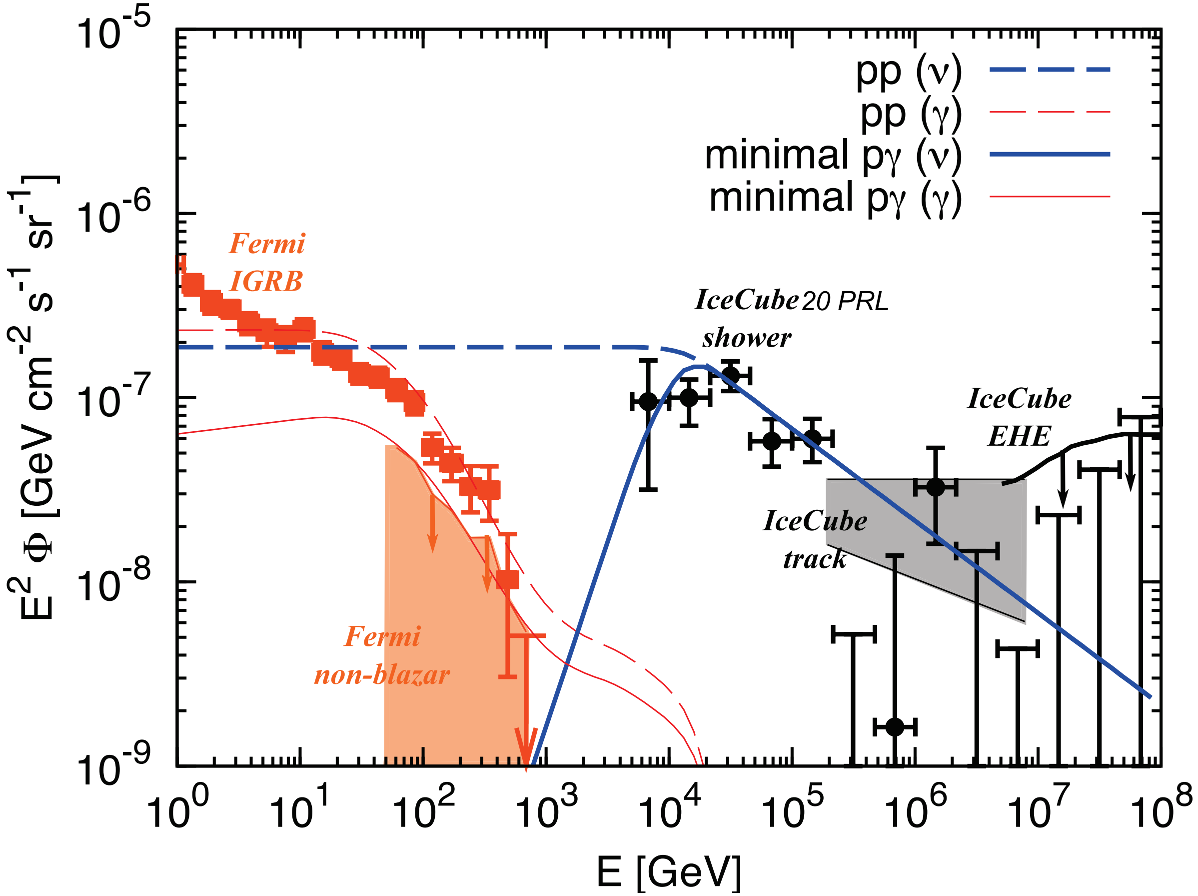
All-Sky Multimessenger Flux & Spectrum



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

Extragalactic Multimessenger Connection

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



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

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

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

$$\pi^0 \rightarrow \gamma + \gamma$$

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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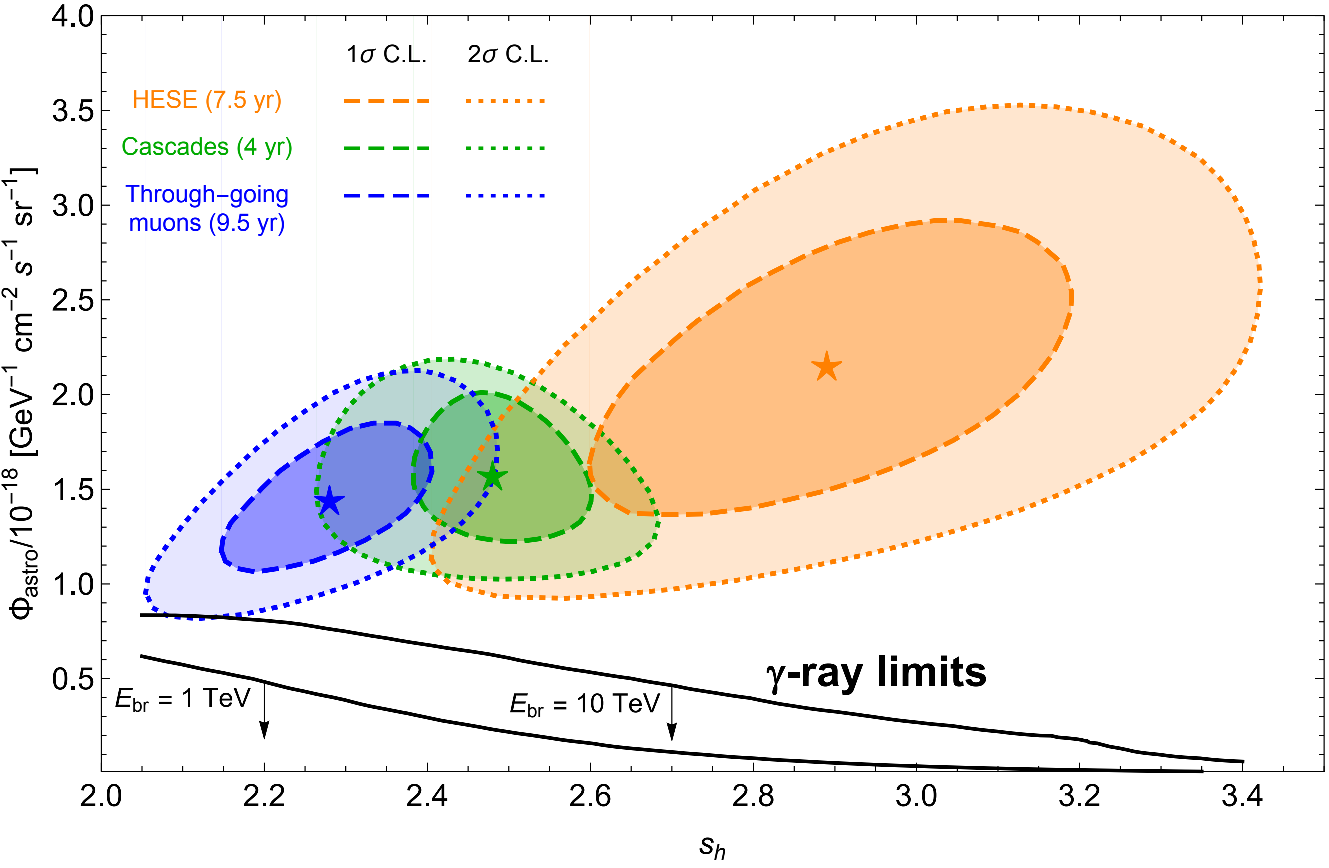

Capanema, Esmaili & KM 20
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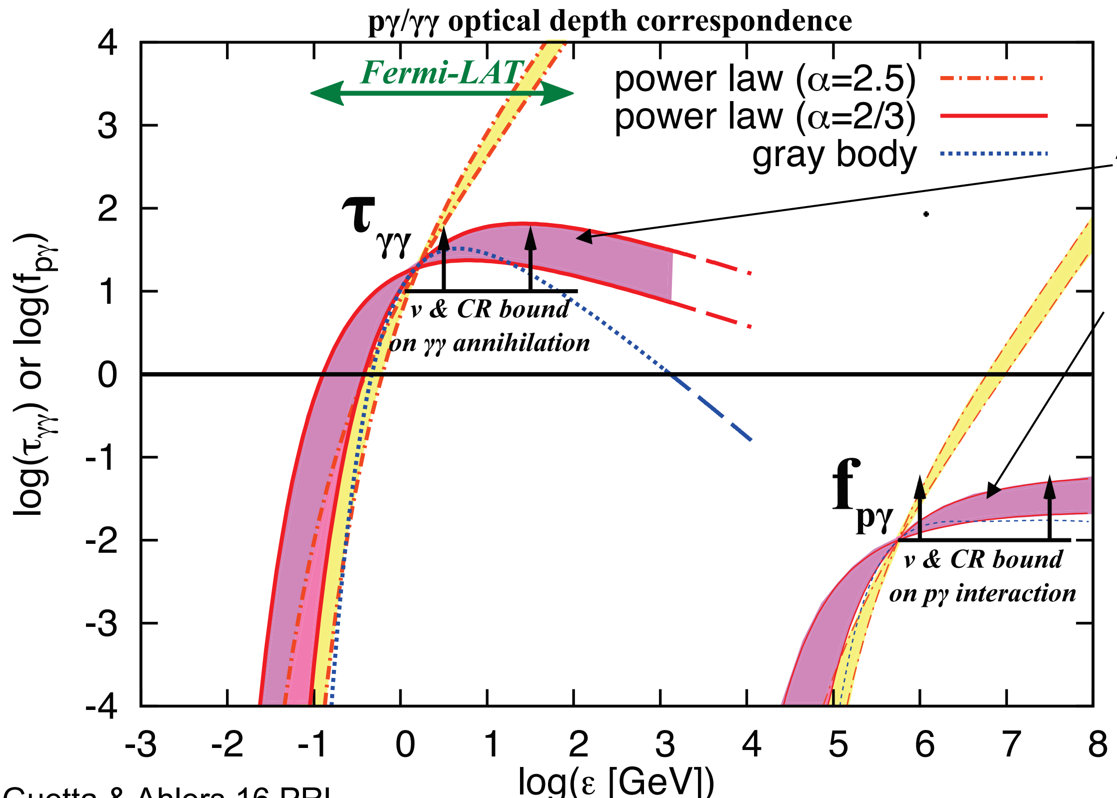
Opacity Argument

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

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

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



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

II

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

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

KM, Guetta & Ahlers 16 PRL

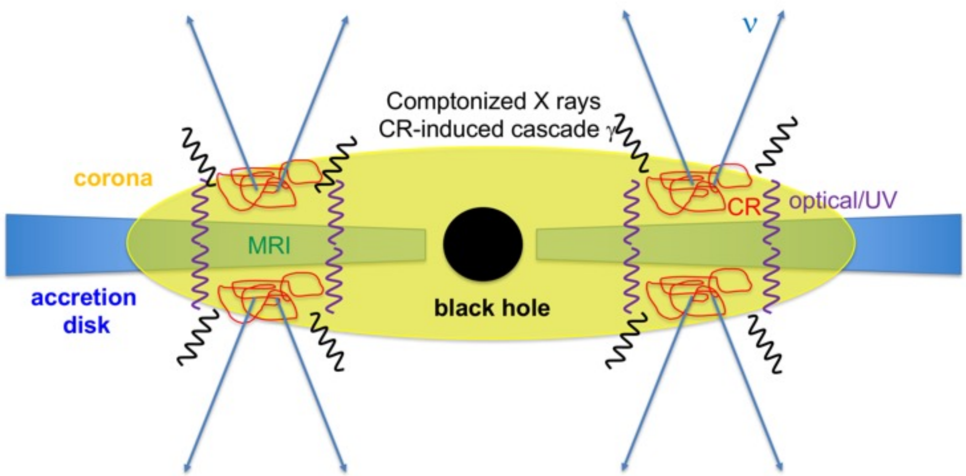
Necessity of Hidden Neutrino Sources for Medium-Energy ν

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

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

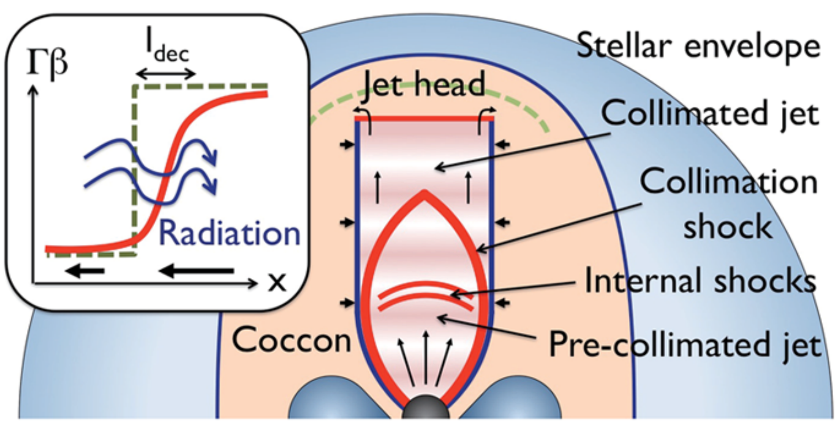
implying that >TeV-PeV γ rays are cascaded down to GeV or lower energies

vicinity of supermassive black holes



(from KM, Kimura & Meszaros 20 PRL)

supernovae/hypernovae w. hidden jets



(from KM & Ioka 13 PRL)

Not many sources can explain 10-100 TeV ν data (KM, Guetta & Ahlers 16 for various possibilities)

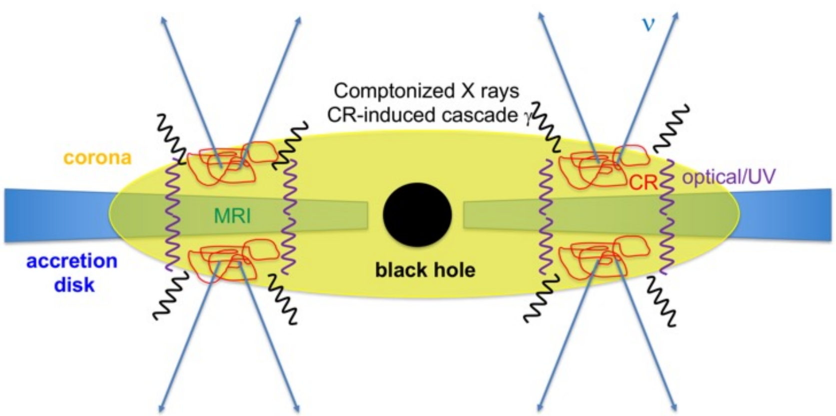
AGN seem to have more energy budget to spare: $Q_{CR} <\sim Q_X \sim 2 \times 10^{46}$ erg Mpc^{-3} yr^{-1}

Prediction of Hidden Neutrino Sources

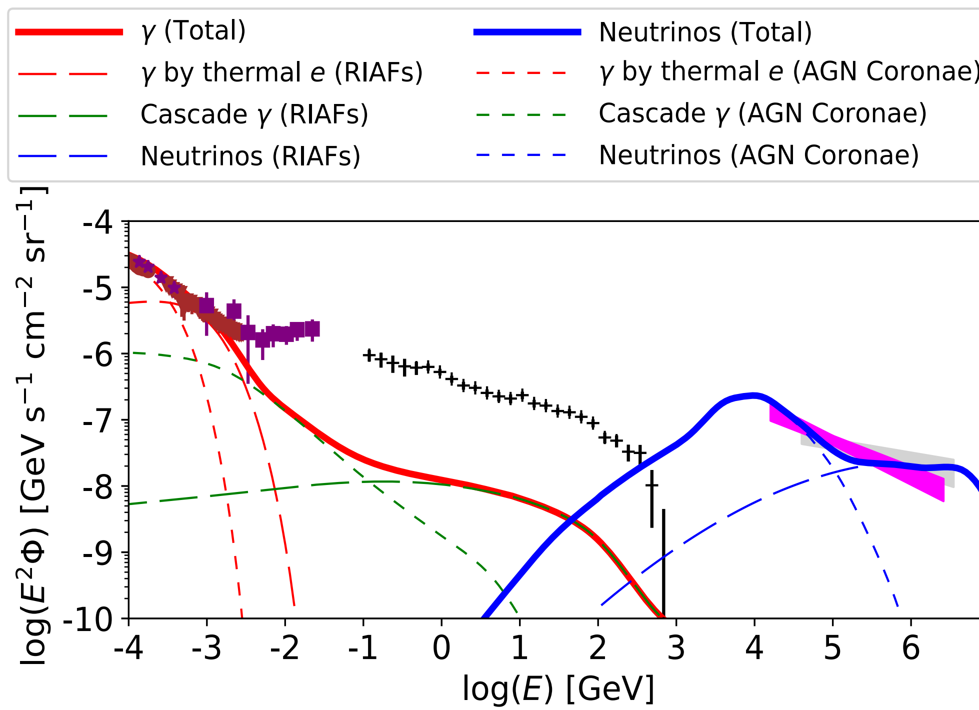
Hidden (i.e., γ-ray opaque) ν sources are actually "natural" in pγ scenarios

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*

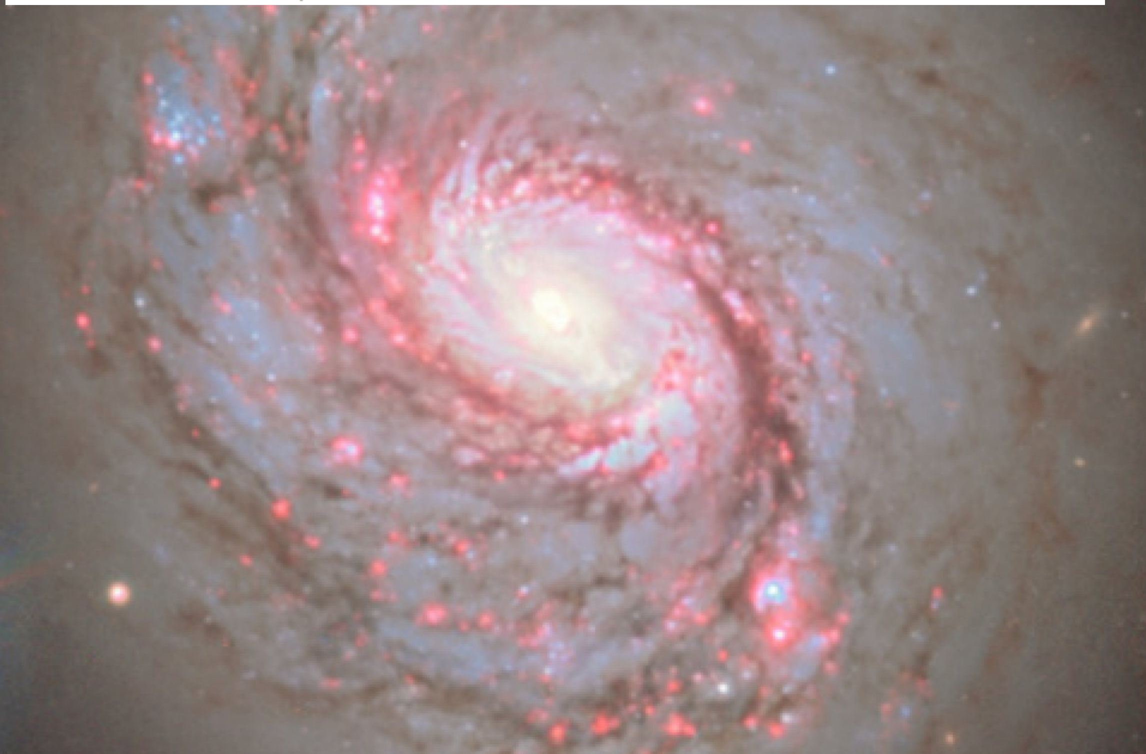
But do such hidden ν source (candidates) exist??

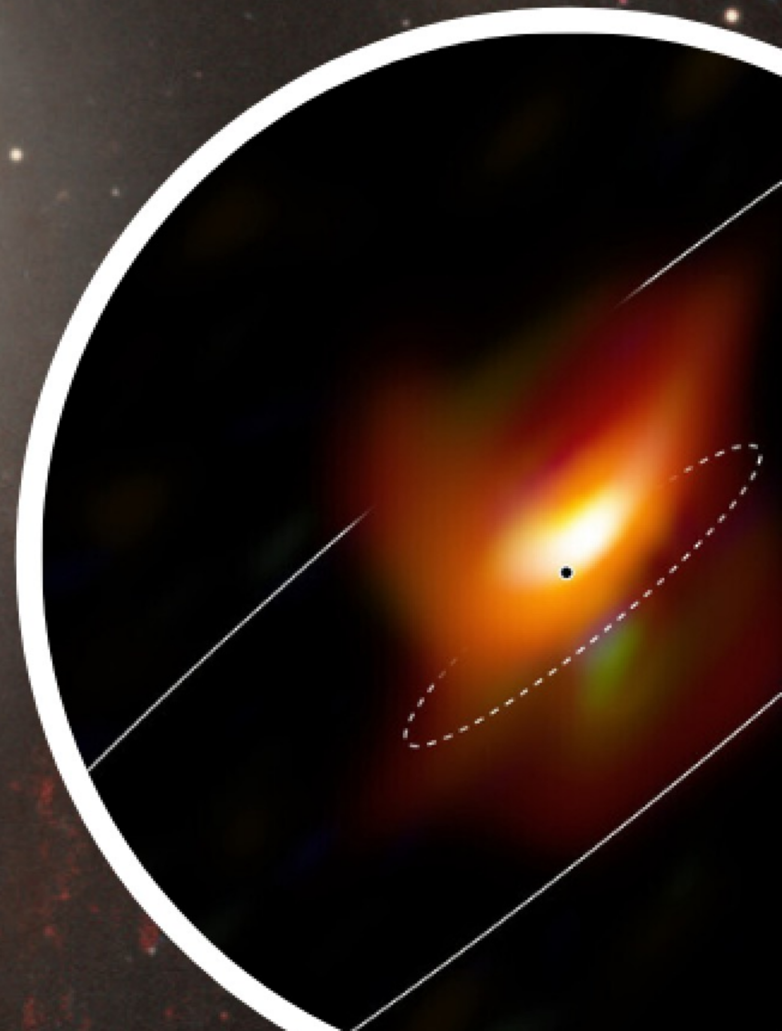
NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

Science
JOURNALS AAAS

IceCube Collaboration*†





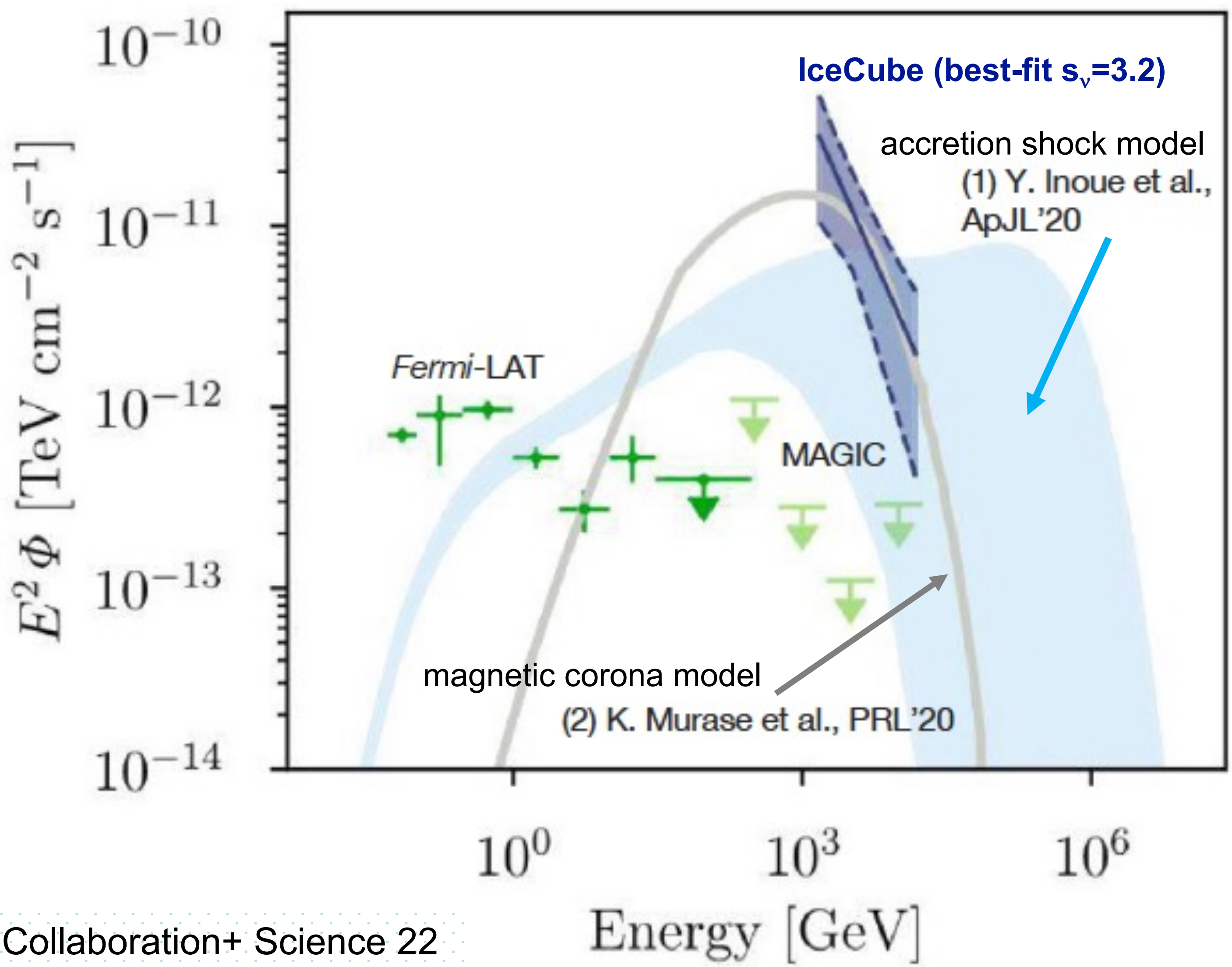
ASTRONOMY

Neutrinos unveil hidden galactic activities

By Kohta Murase[1,2,3]

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

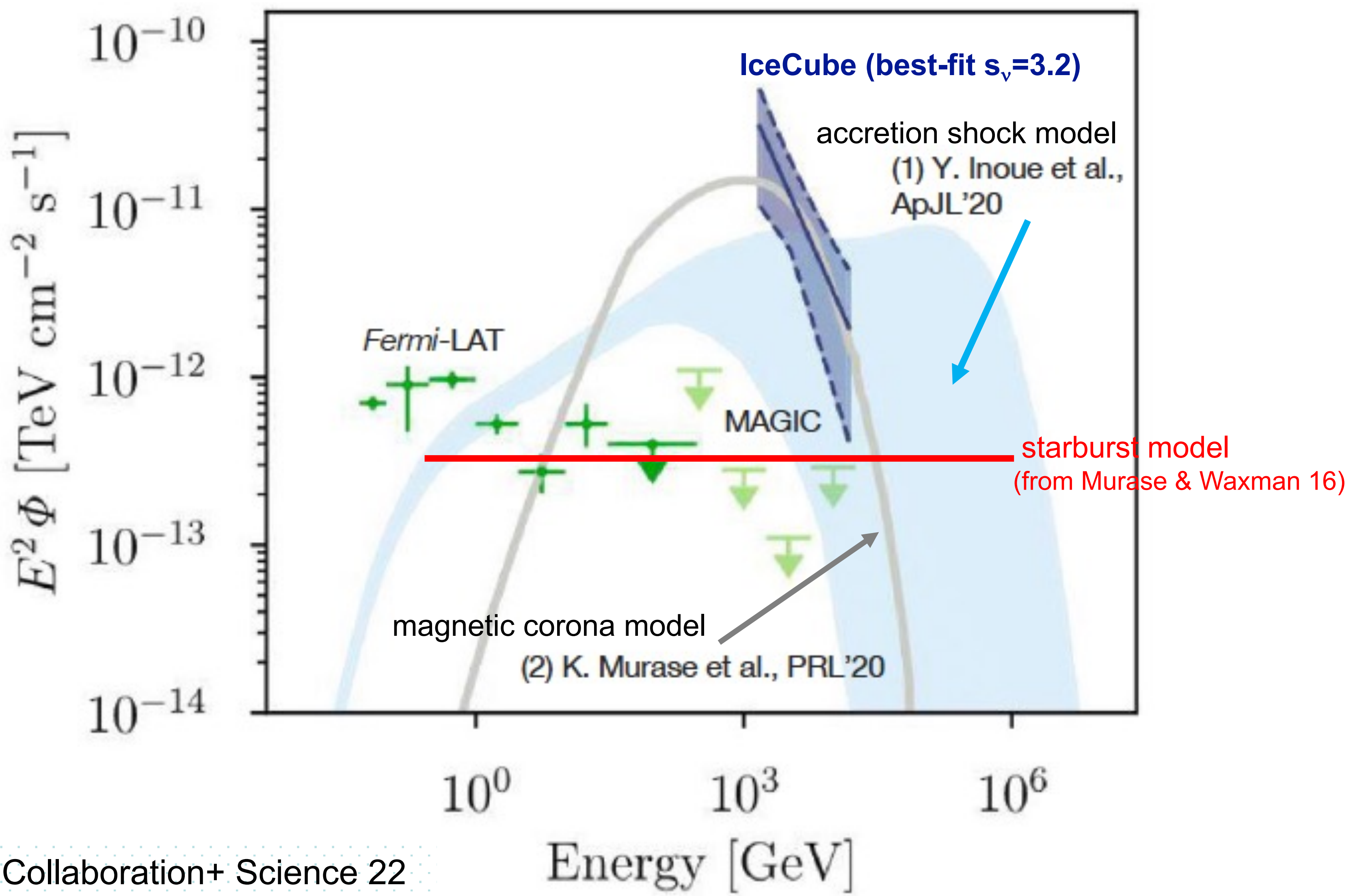
NGC 1068 as a Hidden Neutrino Source



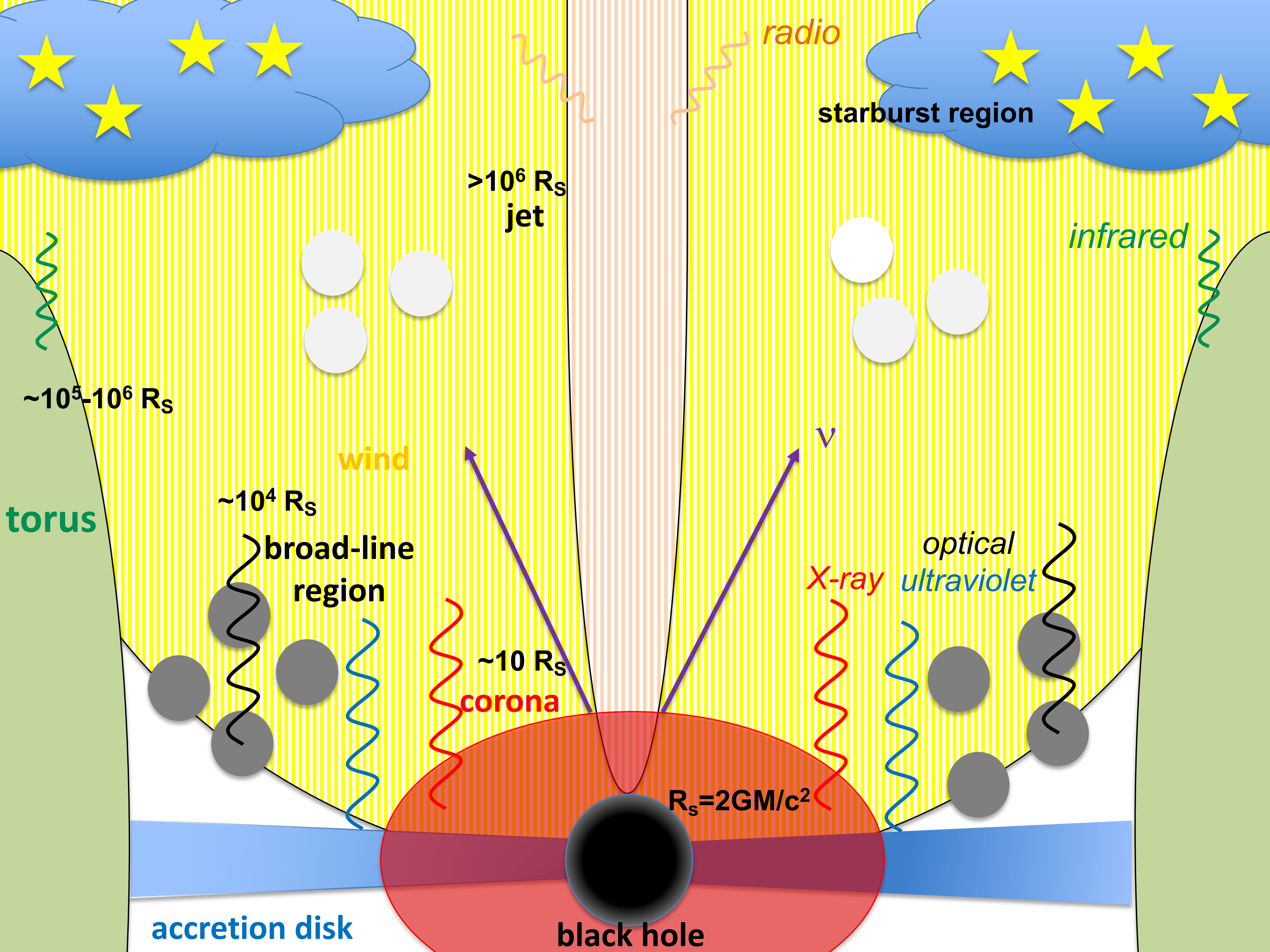
IceCube Collaboration+ Science 22

NGC 1068 as a Hidden Neutrino Source

L_ν~2x10^{42} erg/s << L_{bol} ~ 10^{45} erg/s <~ L_{Edd} ~ 10^{45} erg/s: reasonable energetics



IceCube Collaboration+ Science 22



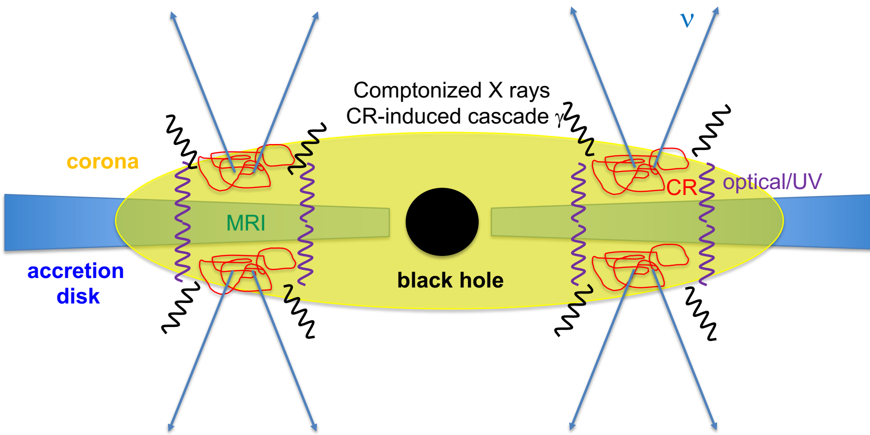
radio
starburst region
>10⁶ Rs
jet
infrared
~10⁵-10⁶ Rs
ν
wind
~10⁴ Rs
torus
broad-line
region
optical
X-ray
ultraviolet
~10 Rs
corona
Rs=2GM/c²
accretion disk
black hole

Neutrino Production Models

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

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

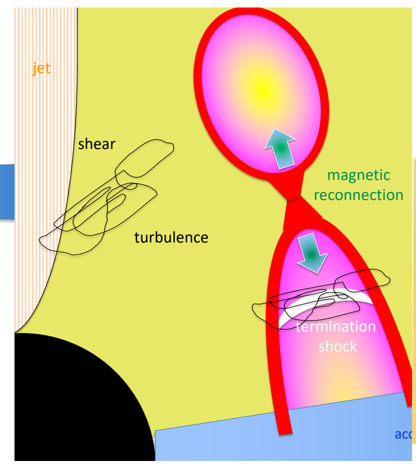
magnetically-powered corona or jet base
(KM+ 20, Kheirandish, KM & Kimura 21)

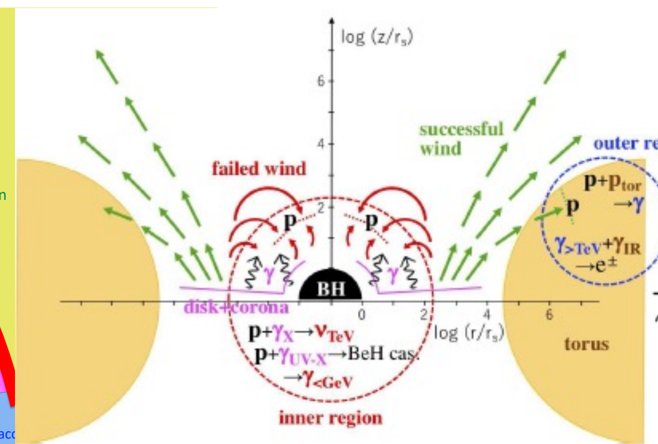


turbulence
magnetic reconnection

$\beta = P_g/P_B < 0.1\text{-}1 \rightarrow B > 10^3$ G
$L_{CR} <\sim L_X <\sim L_B$ (turbulent)

failed-wind or accretion shock
(S. Inoue, Cerruti, KM+ 22, Y. Inoue+ 20)
shear at the base of jets
(KM 22, Lemoine & Rieger 25)





shocks

submm → B~10-100 G
$\beta = P_g/P_B >\sim 100$
$L_B, L_{CR} <\sim L_X$

Facts & Questions, Implications?

ν facts:

- $L_\nu \sim 2 \times 10^{42}$ erg/s << $L_X \sim 7 \times 10^{43}$ erg/s, $L_{bol} \sim 10^{45}$ erg/s <~ L_{Edd}
- Hidden source $L_\nu >> L_\gamma$
- d=10 Mpc, $M_{BH} \sim 10^7$ M_{sun}, Compton-thick ($N_H \sim 10^{25}$ cm^{-2})
- NGC 1068 (~4σ), NGC 4151 (~3σ)

Where and how are νs are produced?

- Cosmic-ray energetics
  L_{CR} >~ 10^{43} erg/s (>~5×10^{42} erg/s for pp, >~5×10^{43} erg/s for pγ): reasonable
  But challenging for s>~2 L_{CR} >~ 0.5×10^{44} erg/s (and more for pγ)
- Properties of emission regions
  (size, magnetization etc.)
- Production mechanisms (pp or pγ)

How typical is NGC 1068 as a neutrino active galaxy?

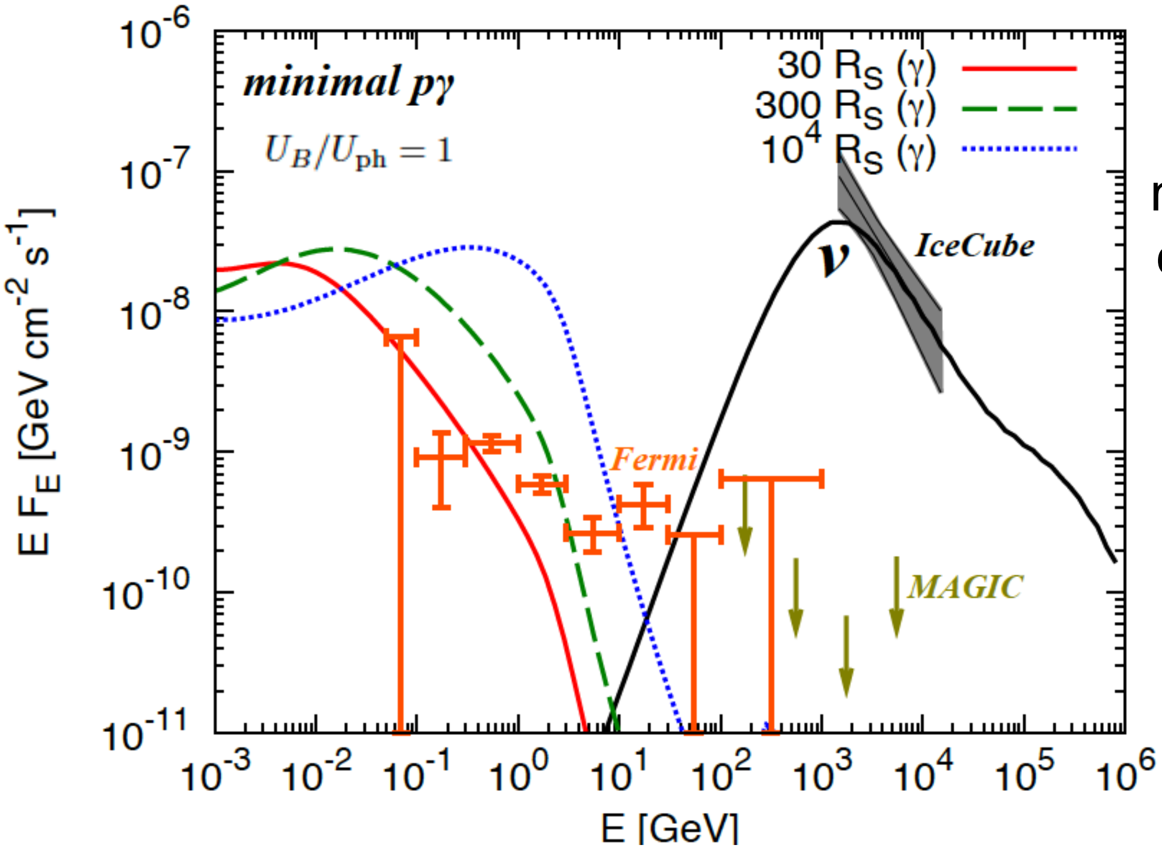
- Why is NGC 1068 ν-brightest? How about other AGNs?
- Is the all-sky neutrino flux explained by jet-quiet AGNs?

Where Do Neutrinos Come from?

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

for 0.1-300 GeV γ rays

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



model-independent constraint considering elemag. cascade

R < (30-100) R_S

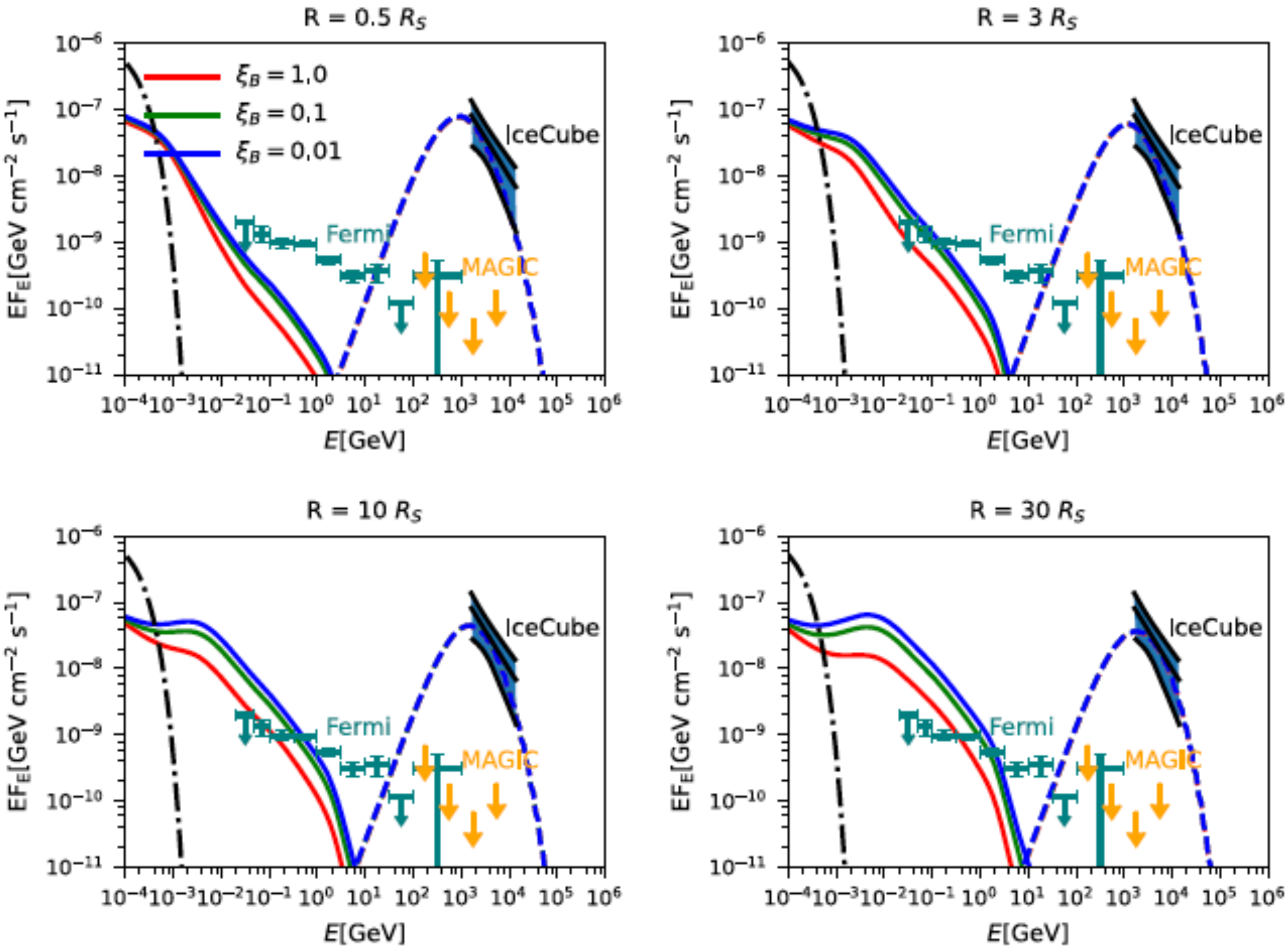
KM 22 ApJL

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

Black hole: sub-PeV proton accelerator & efficient beam dump

Updated Fermi Analysis & Impacts of Magnetic Fields

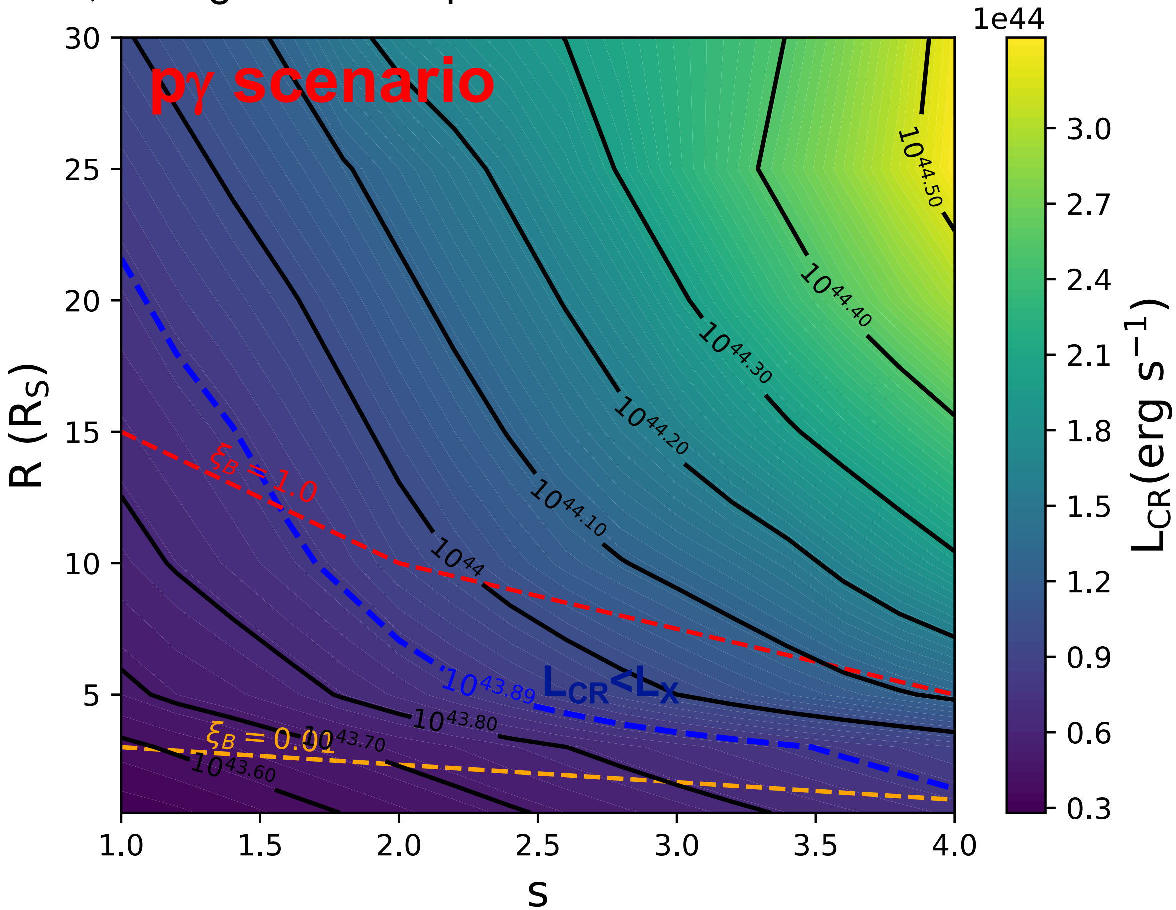
Das, Zhang & KM 24 ApJ (see Ajello, KM & McDaniel 23 ApJL for updated Fermi-LAT analysis)



magnetization $\xi_B = U_B/U_{ph}$ (cf. corona model: $\xi_B \sim 1$, shock model: ξ_B <~ 0.01)

Updated Multimessenger Implications for ν Production Sites and Coronae

Das, Zhang & KM 24 ApJ



γ-ray constraint

ξ_B>~0.1
synchrotron cascade
→ **R <~ (5-15) R_S**

ξ_B<~0.1
inverse-Compton cascade
→ **R < R_{ISCO} unlikely**

CR energetics constraint

L_{CR} < L_X
→ **R <~ (1-20) R_S**

If ν emission comes from X-ray coronae, plasma should be magnetically dominated

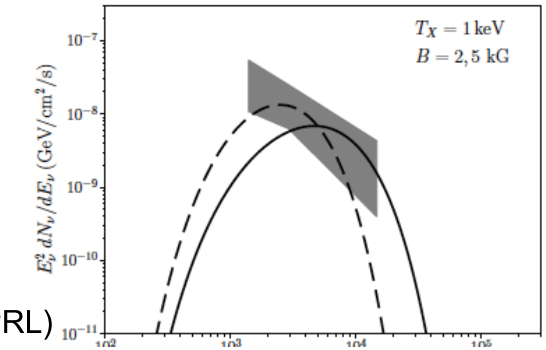
$$\beta = \frac{8\pi n_p k_B T_p}{B^2} \approx \frac{\tau_T G M_{\rm BH} m_p}{\sqrt{3}\zeta_e \sigma_T R^2 U_\gamma}\xi_B^{-1} \approx \left(\frac{\tau_T}{\sqrt{3}\zeta_e \lambda_{\rm Edd}}\right)\xi_B^{-1}$$

τ_T~0.1-1 for X-ray corona, λ_{Edd}~0.5
ξ_B >~ 0.1 leads to **β <~ 1**

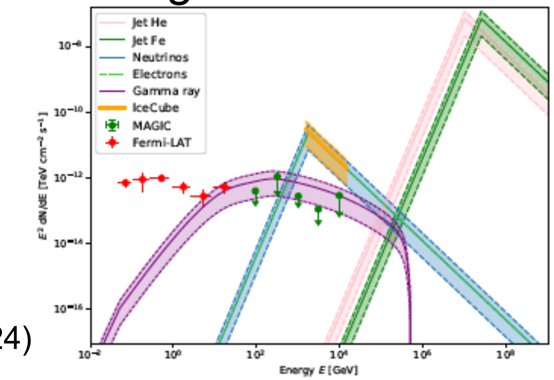
Multimessenger Implications for Neutrino Production Mechanisms

- Multimessenger connection is robust and must be considered
- Exotic models are excluded if relevant processes are consistently included
- Also unlikely by the energetics requirement: $L_{CR} < L_{bol} \sim L_{Edd} \sim 10^{45}$ erg/s

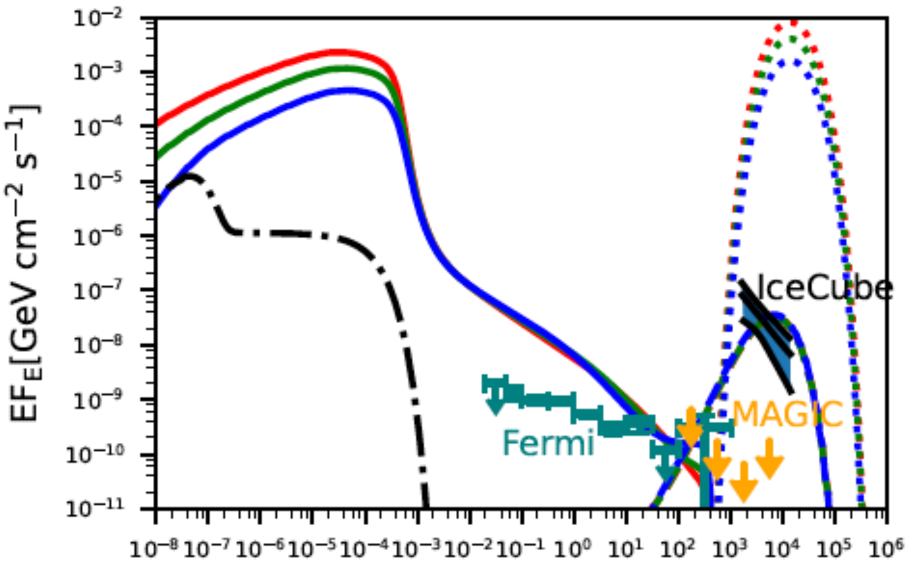
Neutrinos from $\gamma\gamma \rightarrow \mu^+\mu^-$
(Hooper & Plant 23 PRL)



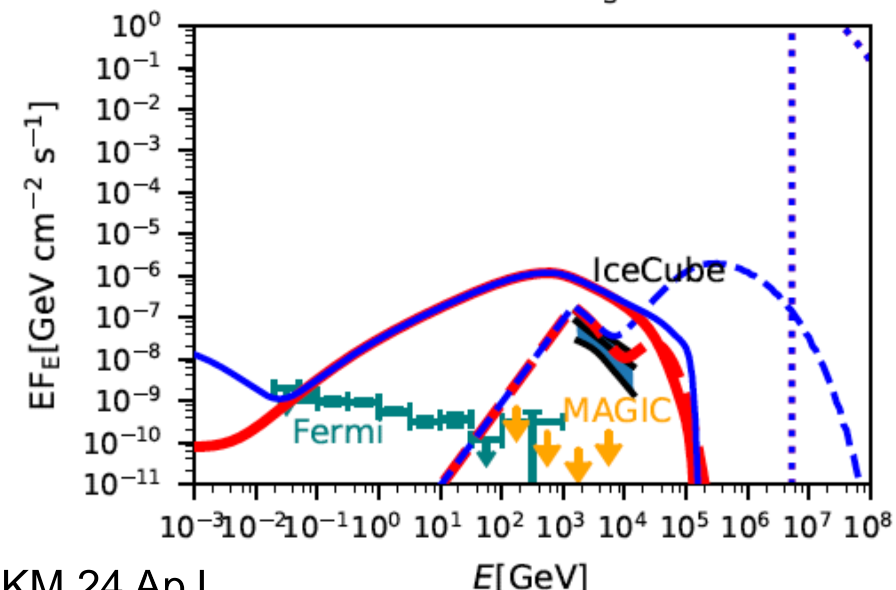
Neutrons from photodisintegration
(Yasuda, Inoue & Kusenko 24)



R = 10 R_S



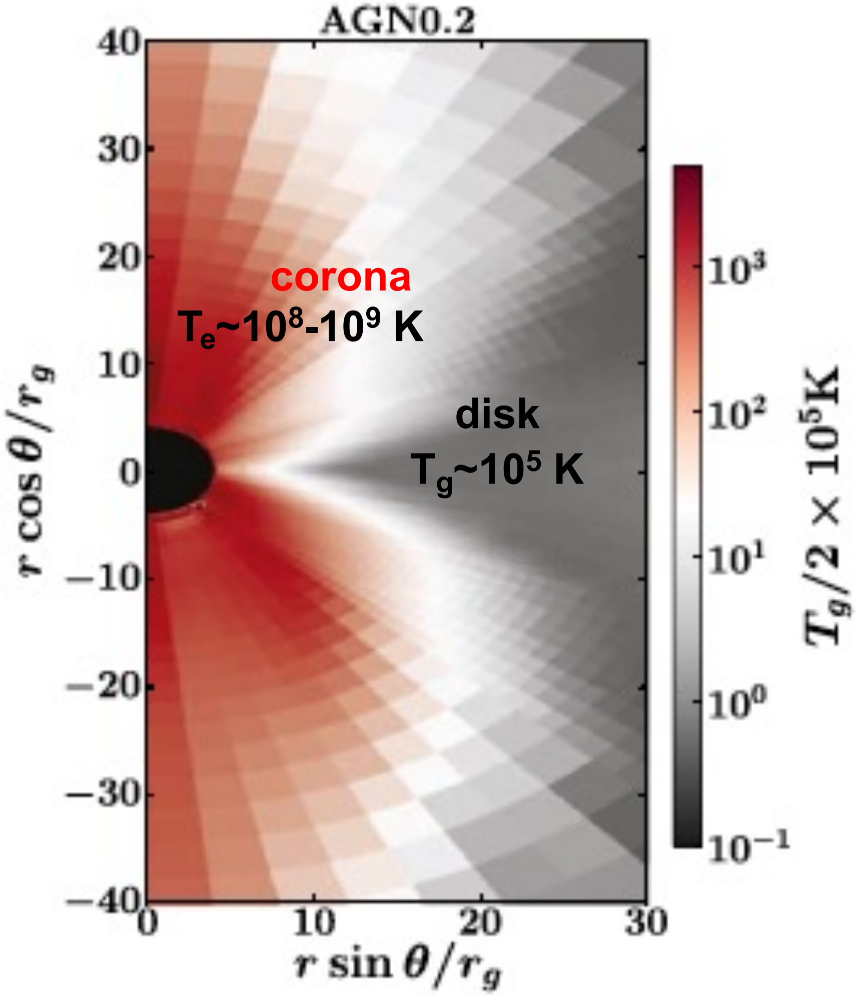
R = 10^8 R_S



Das, Zhang & KM 24 ApJ

Coronal Regions: Magnetized & Collisionless

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



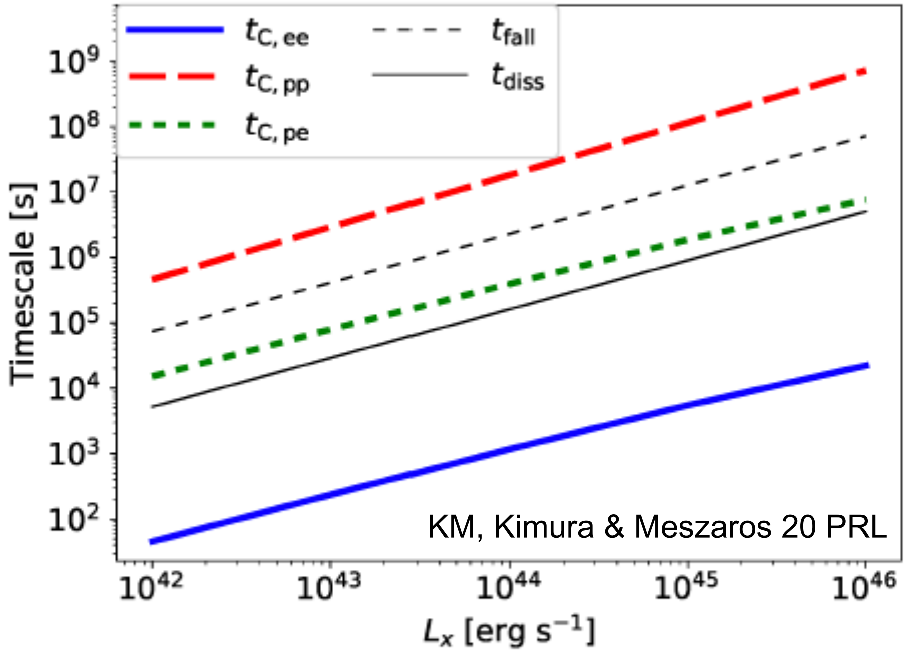
3D RMHD simulation w. Athena++

$T_p \sim T_{vir} \sim 10^{11}$-$10^{12}$ K @ R~10 R_S

$\boldsymbol{\beta = P_g/P_B < 0.1}$**-1** ($\sigma_p$ >~ 0.01)

→ **B > 10^3 G**

$T_e \sim 10^8$-10^9 K (← $t_{Comp} \sim t_{heat}$)



$T_e < T_p$ (two-temperature corona)
collisionless for protons

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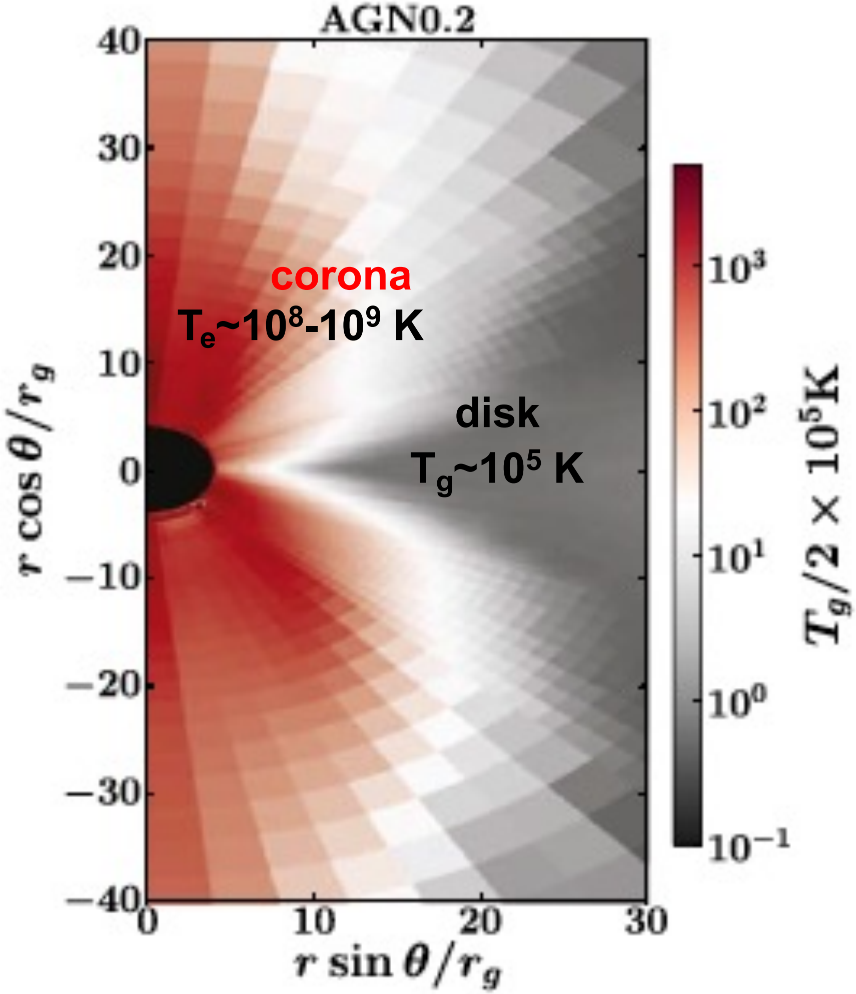


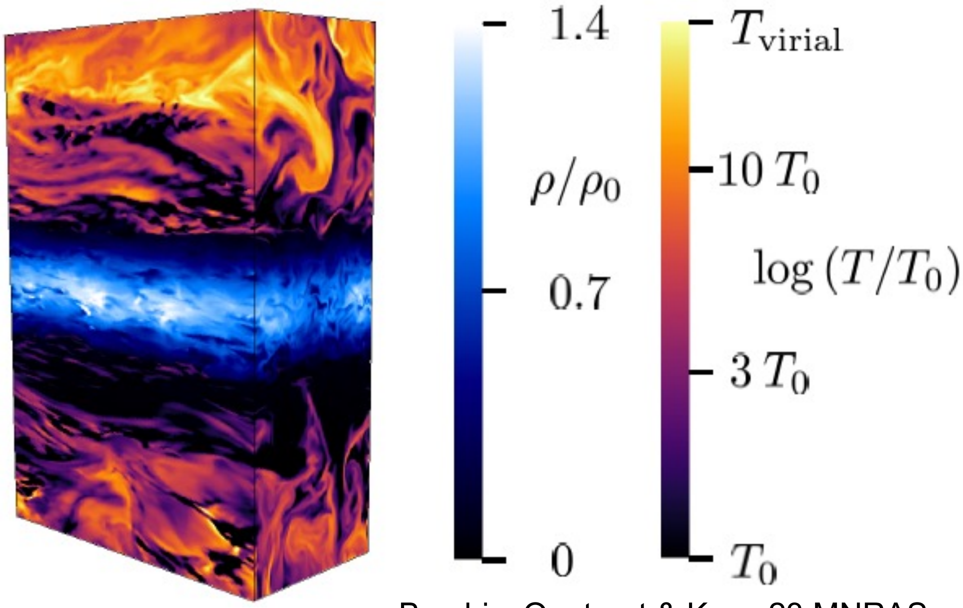
3D RMHD simulation w. Athena++

T_p~T_{vir}~10^{11}-10^{12} K @ R~10 R_S

β=P_g/P_B < 0.1-1 (σ_p >~ 0.01)

→ **B > 10^3 G**

T_e ~ 10^8-10^9 K (← t_{Comp} ~ t_{heat})



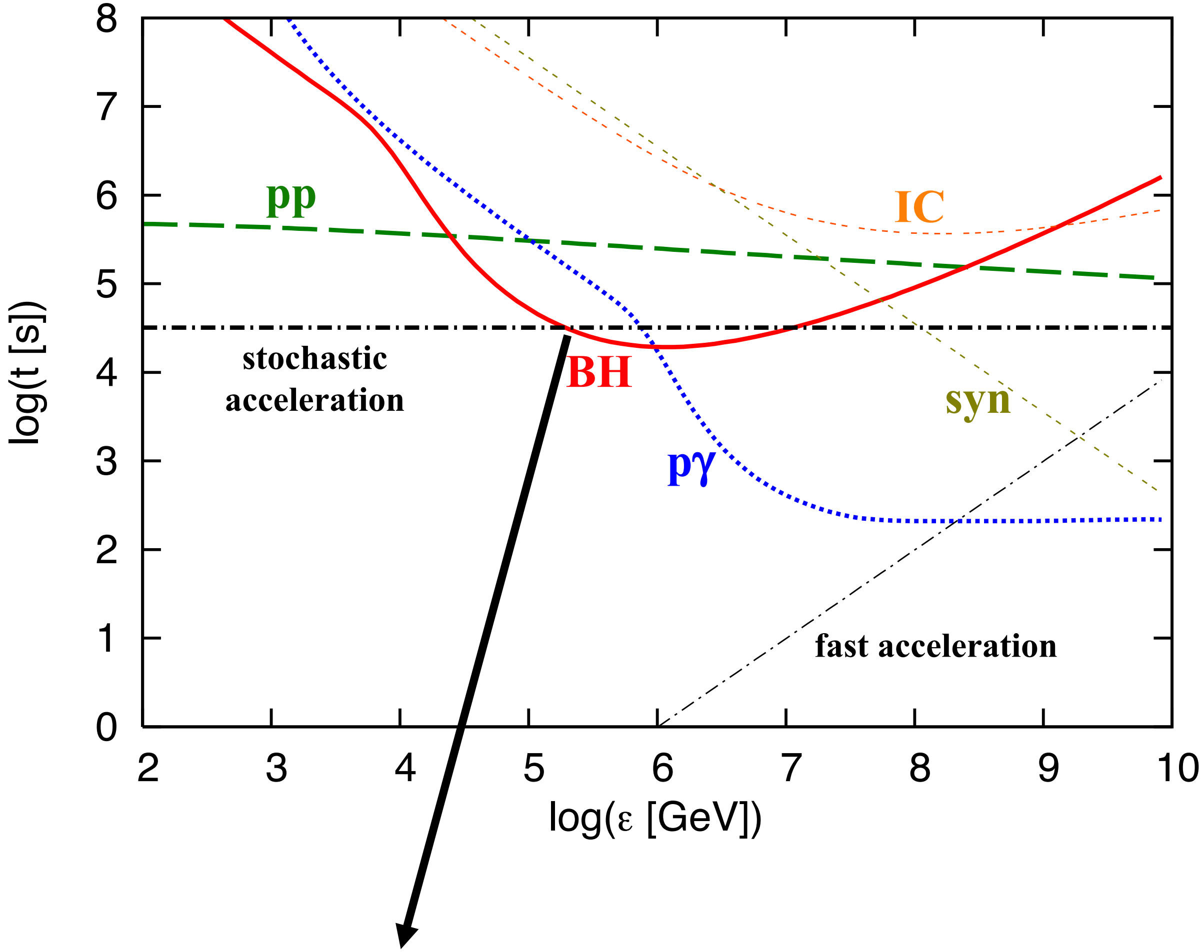
Bambic, Quataert & Kunz 23 MNRAS

T_e < T_p (two-temperature corona)
collisionless for protons

Particle Acceleration: Fast or Slow?

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

(KM, Kimura & Meszaros 20 PRL)

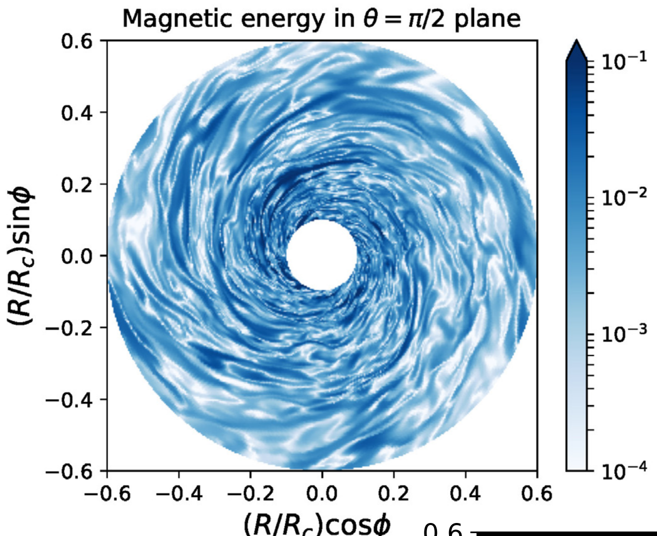


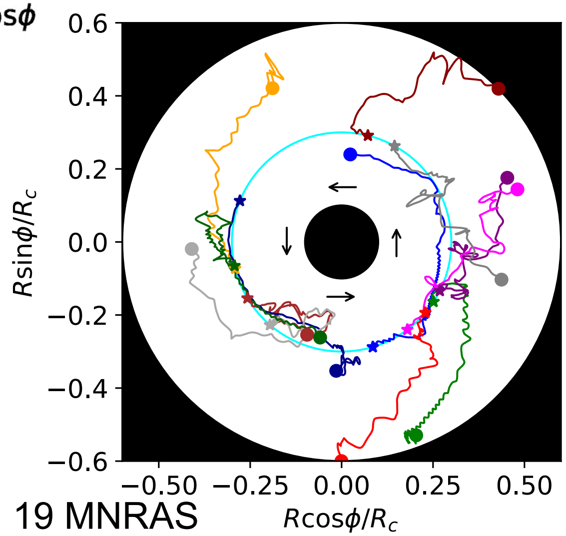
ε_p^{max} **~ 100 TeV** → ε_ν^{max} **~ 20 TeV** (consistent w. IceCube)

Simulating Particle Acceleration in Turbulence

stochastic acc. in 3D global MHD simulations

test particle sim. w. Athena++



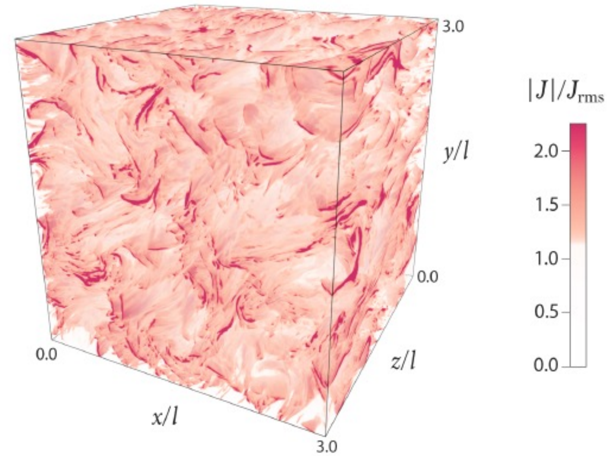


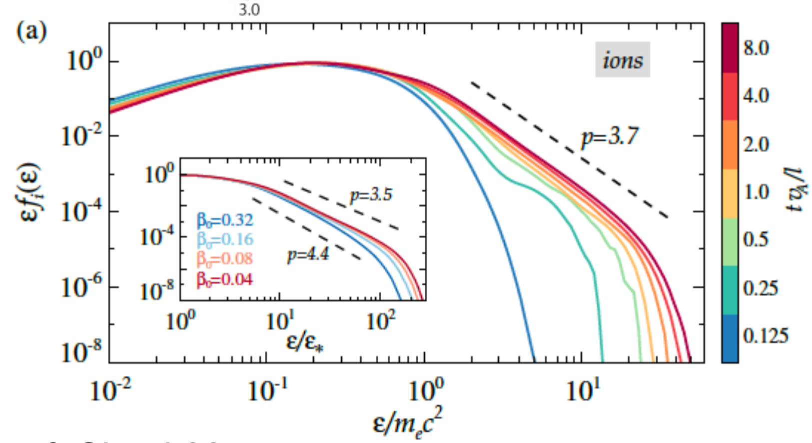
Kimura, Tomida & KM 19 MNRAS

Sun & Bai 21 MNRAS

stochastic acc. in 3D PIC simulations

- acceleration by electric fields at X point
- subsequent acceleration in turbulence
- Electron acceleration is more difficult

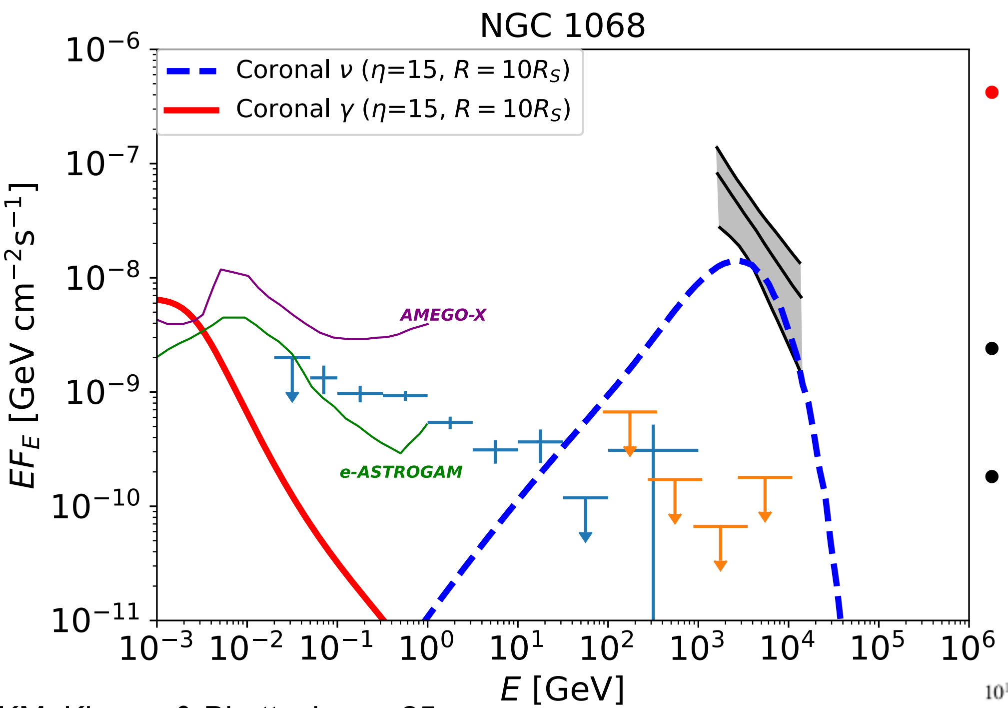




Comisso & Sironi 22

see also Hoshino 15 PRL, Zhdankin+ 17 PRL

NGC 1068: Corona Model with Stochastic Acceleration

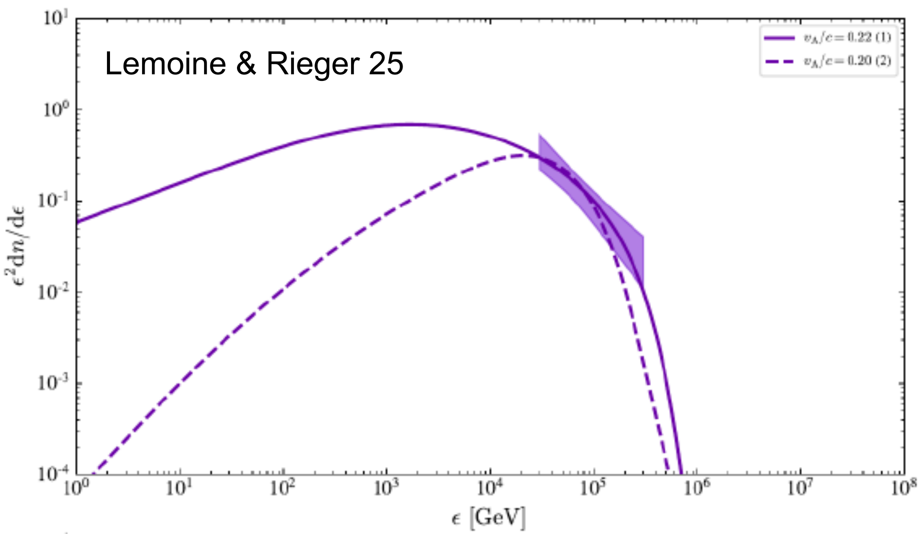


KM, Kimura & Bhattacharya 25
see also KM, Kimura & Meszaros 20, Fiorillo, Comisso+ 24

- Model-independent prediction: CR-induced cascade γ rays should appear at MeV

- PIC/MHD simulations suggest nonresonant nature: $D_{\varepsilon\varepsilon} \propto \varepsilon^2$
- CR pressure ~ 0.1 virial pressure

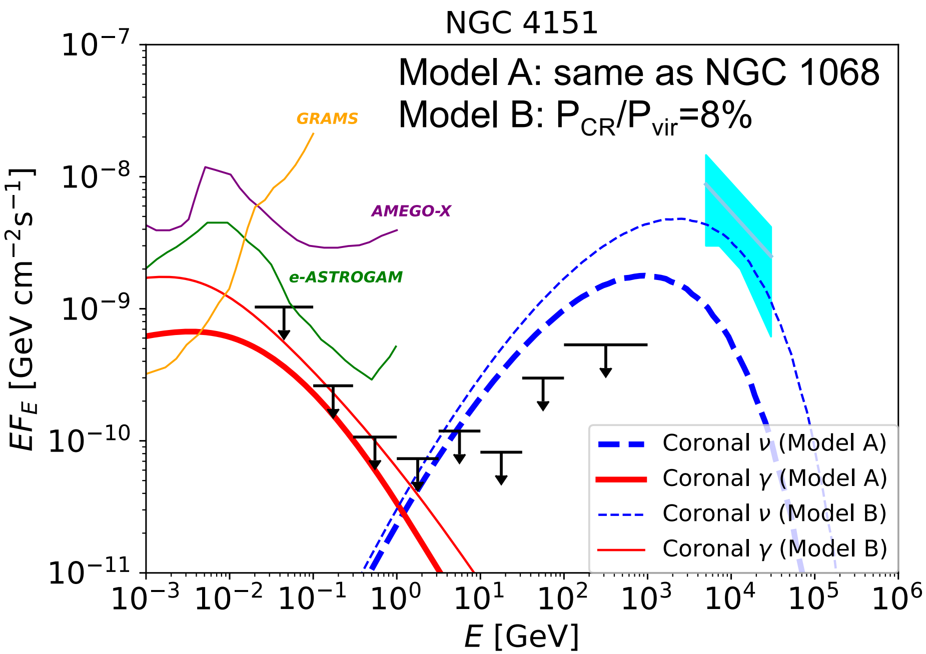
- Generalized Fermi process
  (Lemoine 21 PRD, 22 PRL)
- CR feedback on turbulence
  (Lemoine, KM & Riger 24 PRD)



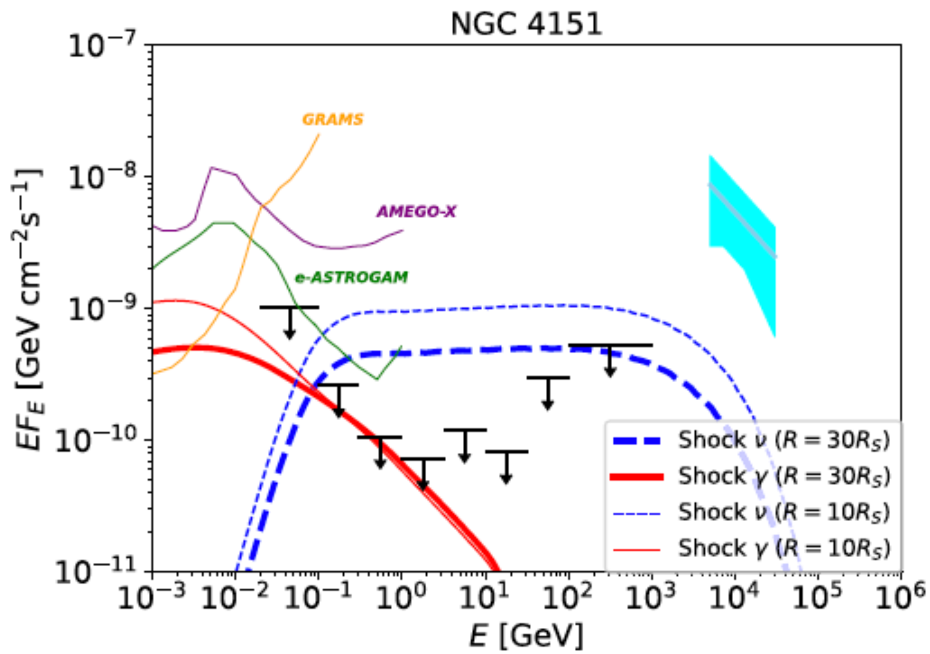
Why NGC 1068? How about Others?

- Prediction of the coronal model: X-ray bright AGN ~ ν bright AGN
  brightest AGN in north: NGC 1068, NGC 4151
  brightest AGN in south: NGC 4945, Circinus (KM+ 20 PRL, KM+ 24 ApJL)
- 2.7σ excess of νs from NGC 4151 and CGCG 420-015
  2.9σ excess of νs from NGC 4151 (IceCube Collaboration 24a, 24b, Neronov+ 24)
- Unobscured AGNs like NGC 4151 are relevant for model discrimination

magnetically-powered corona model



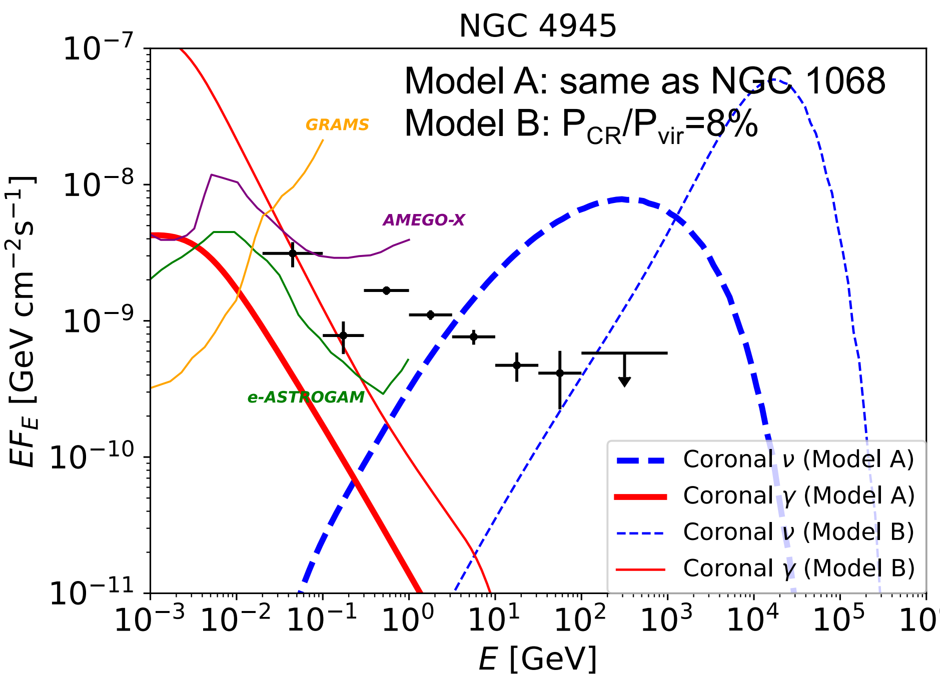
accretion shock model

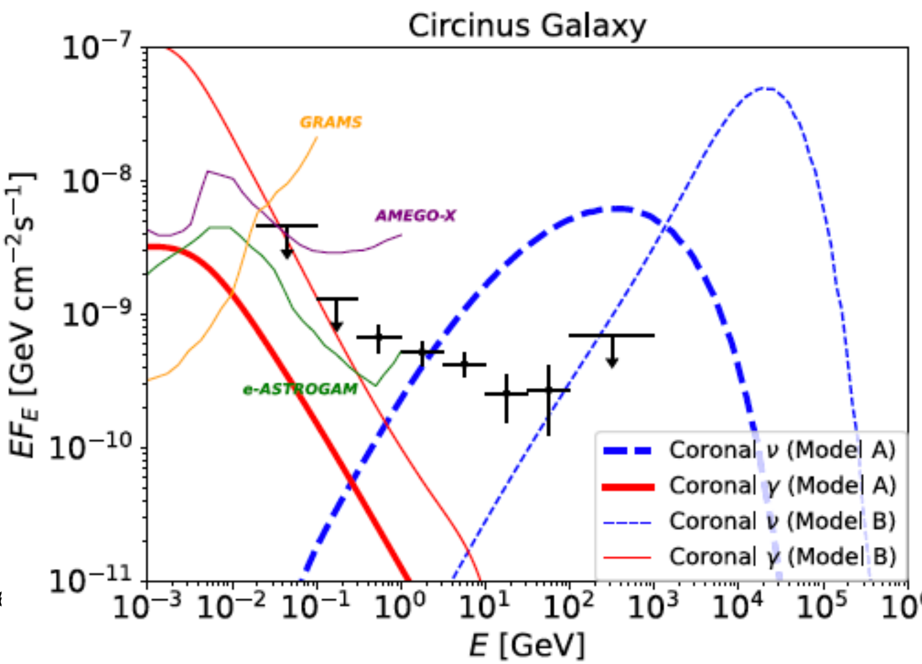


KM, Karwin, Kimura, Ajello & Buson 24 ApJL

Why NGC 1068? How about Others?

- Prediction of the coronal model: X-ray bright AGN ~ ν bright AGN
  brightest AGN in north: NGC 1068, NGC 4151
  brightest AGN in south: NGC 4945, Circinus (KM+ 20 PRL, KM+ 24 ApJL)
- 3.0σ excess of νs from Seyferts in south (IceCube Collaboration 24c)
- Promising targets for neutrino detectors in the northern hemisphere (KM3Net, Baikal-GVD, P-ONE, Trident), as well as IceCube-Gen2

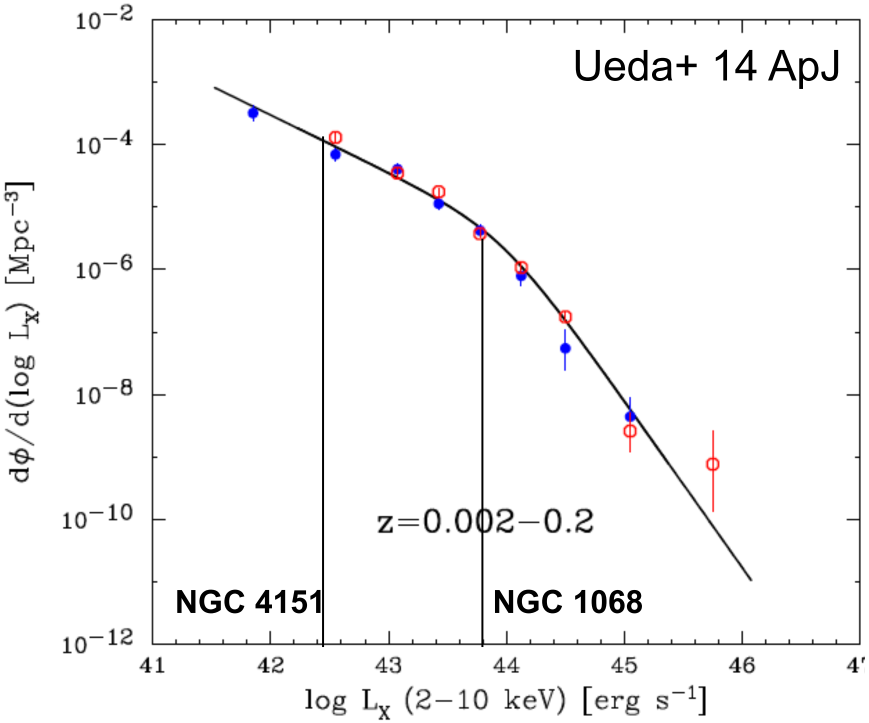


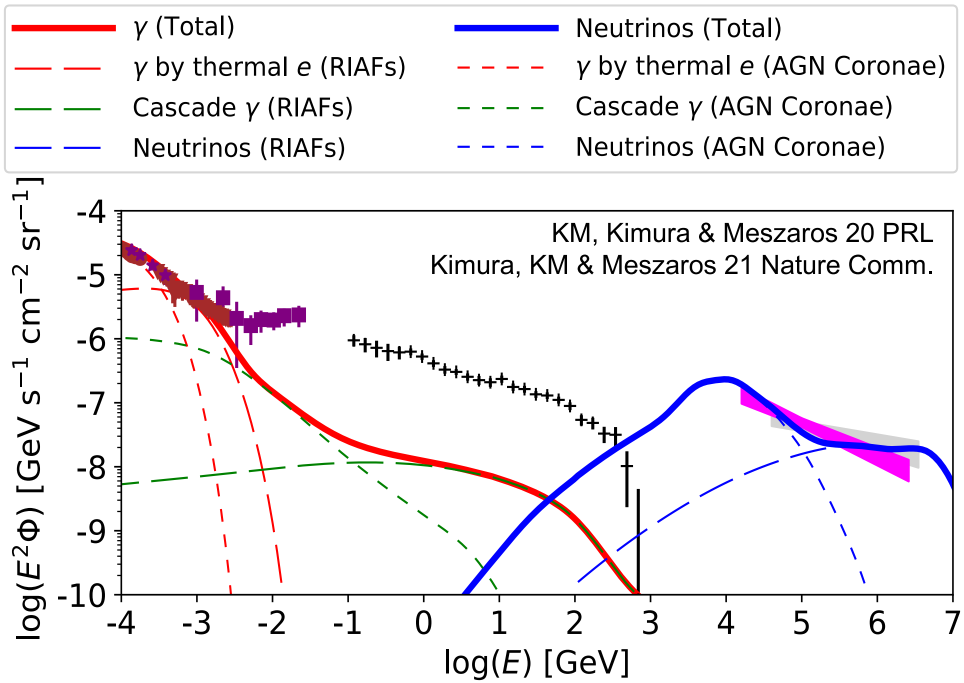


KM, Karwin, Kimura, Ajello & Buson 24 ApJL

Jet-Quiet AGN Can Successfully Explain the All-Sky ν Flux

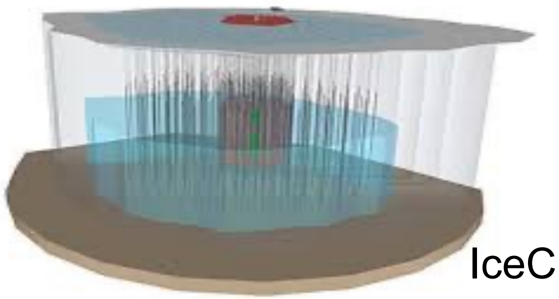
- The all-sky ν flux has been explained by the AGN corona model (KM+20 PRL) (ex. X-ray luminosity function is used in the MKM20 corona model)
- Differential ν flux at 10 TeV: ~10^{-8} GeV cm^{-2} s^{-1} → EL_E ~ 2×10^{41} erg/s
- NGC 1068-like AGNs are rare: n~10^{-5} Mpc^{-3} → EQ_E ~ 6×10^{43} erg Mpc^{-3} yr^{-1}
- Comparable to the required energy budget: EQ_E ~ 5×10^{43} erg Mpc^{-3} yr^{-1}
- Possible to "simultaneously" to explain the all-sky ν flux within uncertainty
- Higher-energy neutrinos originate from lower-luminosity AGN



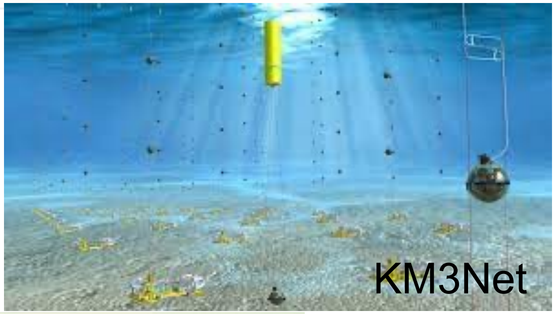


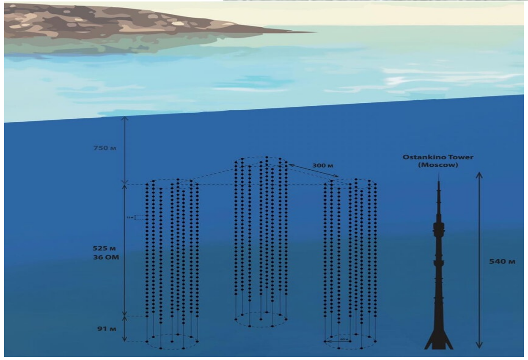
Neutrinos: More Hints & More Tests

- 2.6σ with 8 yr upgoing ν_μ events and IR-selected AGN (IceCube 22 PRD)
- Good news for KM3Net/Baikal-GVD/P-ONE: many bright AGN in south



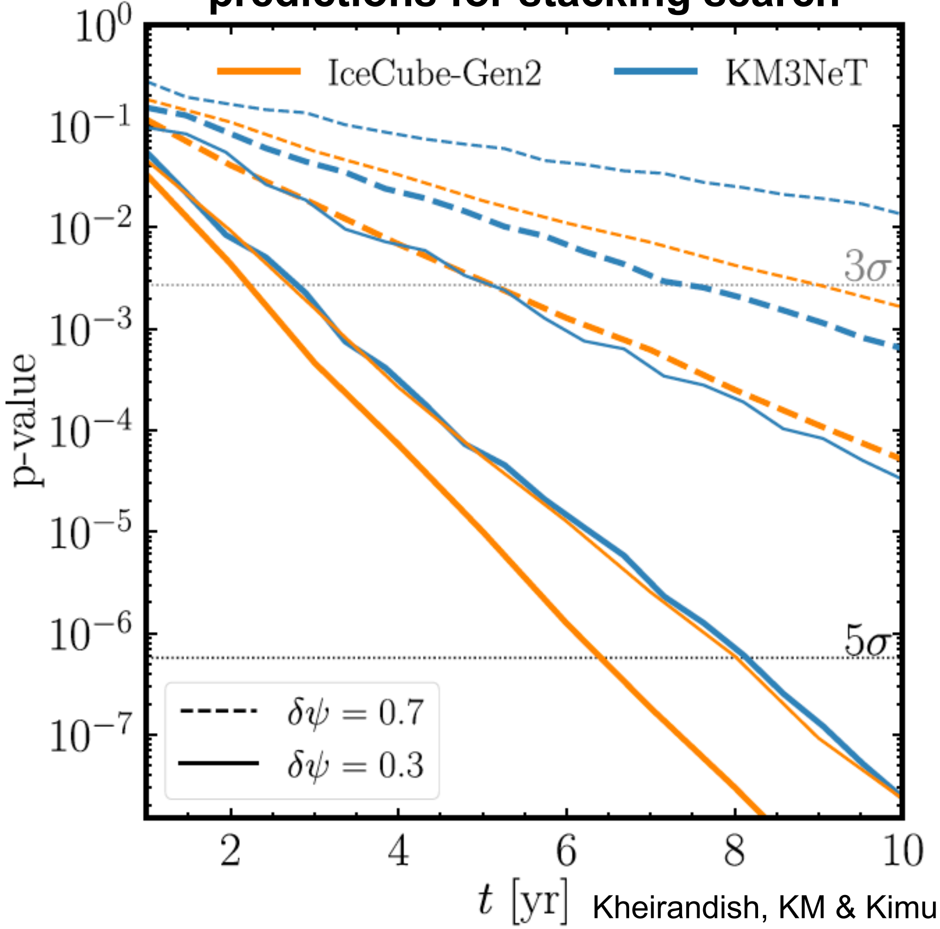
IceCube-Gen2





Baikal-GVD

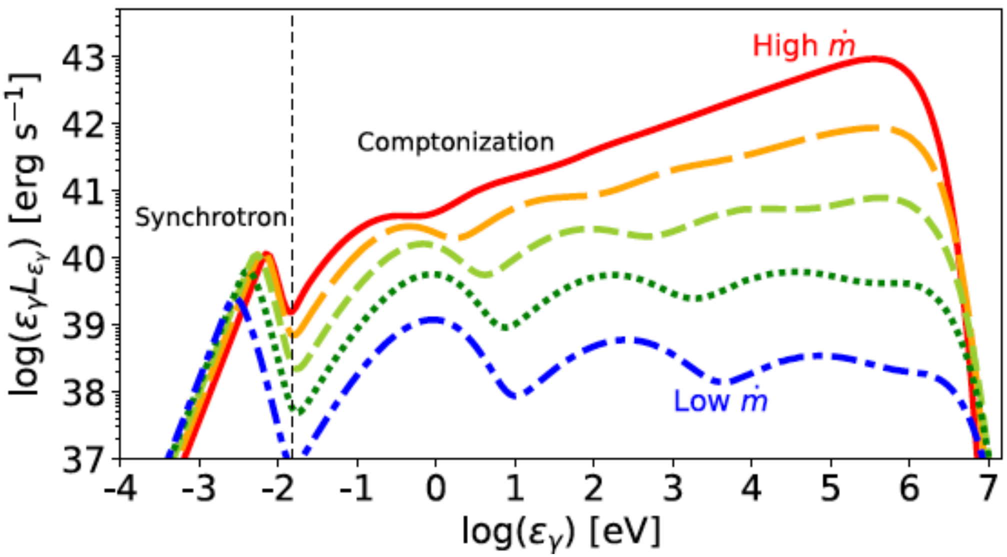
predictions for stacking search



Kheirandish, KM & Kimura 21 ApJ

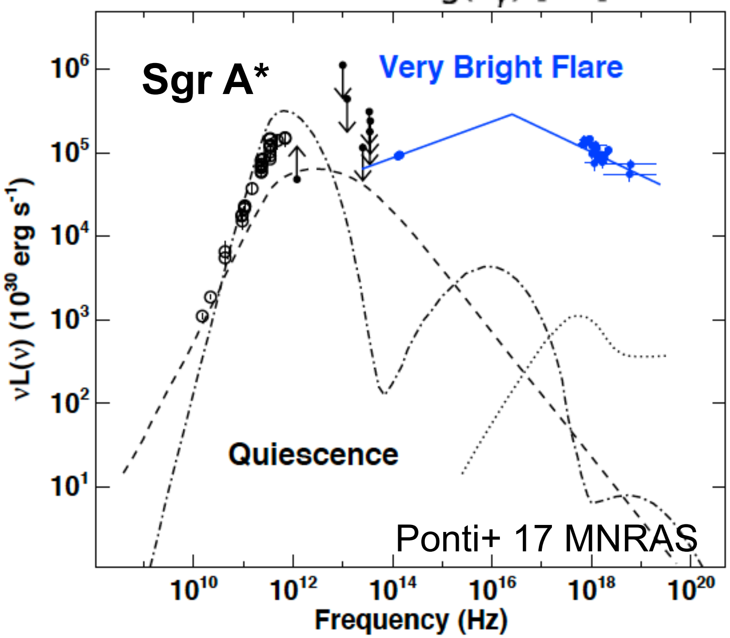
testable w. near-future data or by next-generation neutrino detectors

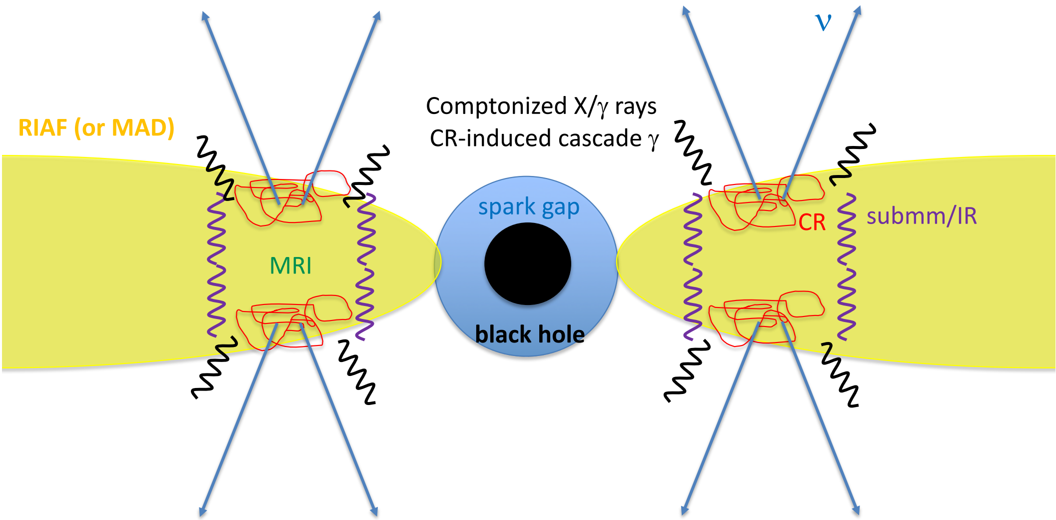
Radiative Inefficient Accretion Flows



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

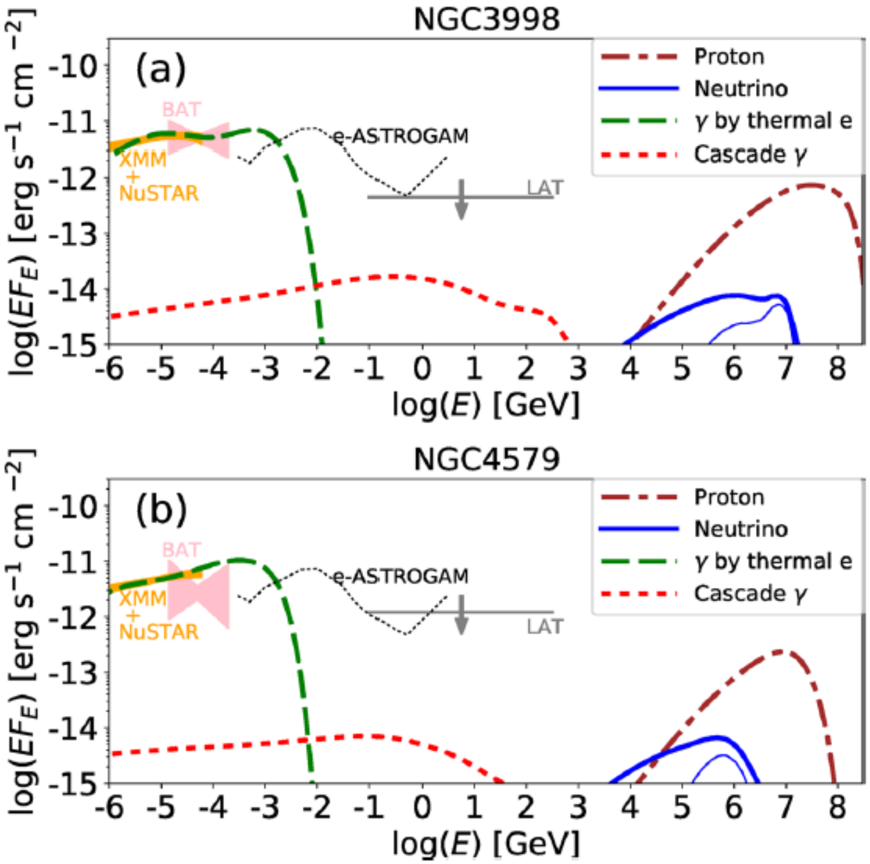
- RIAF for mdot<0.03
- Hot plasma
- Electrons are mostly thermal (collisional for electrons collisionless for protons)

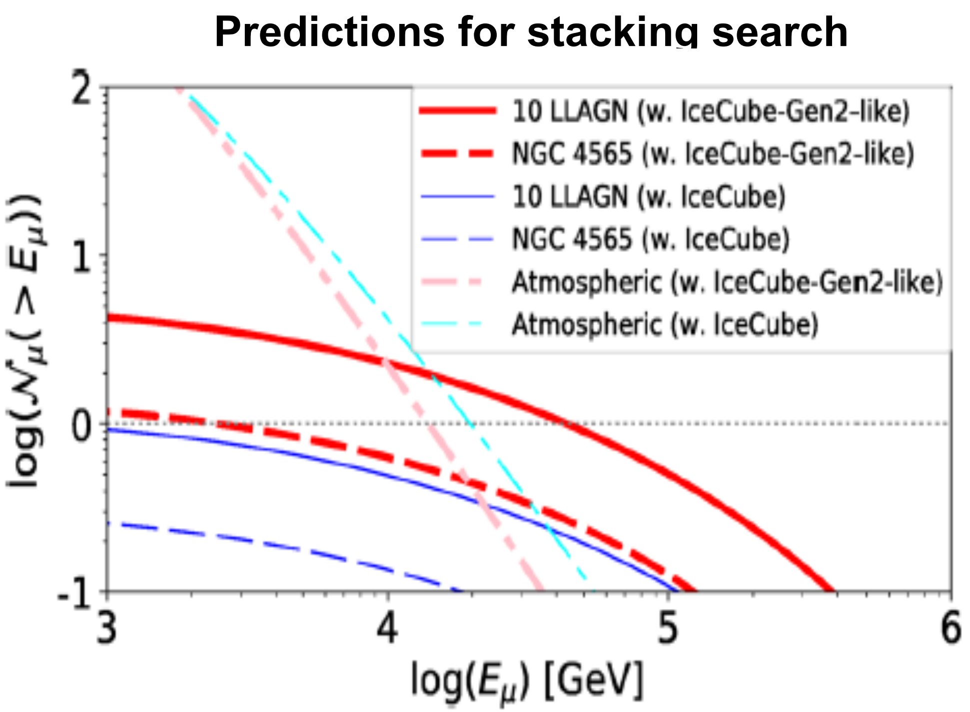




Detectability of Nearby Low-Luminosity AGN

Kimura, KM & Meszaros 21 Nature Comm.



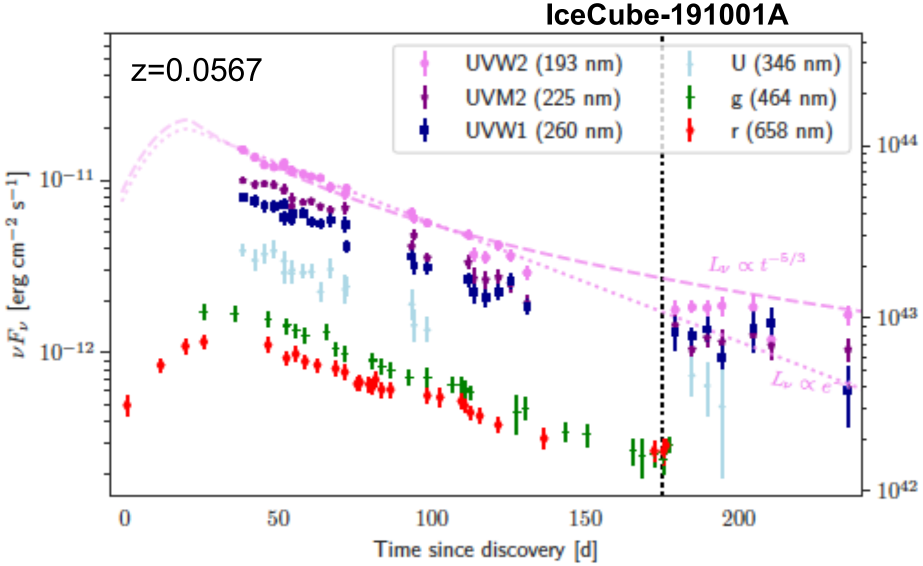


- Detection of MeV γ due to thermal electrons is promising (CR-induced cascade γ rays are difficult to observe)
- Nearby LL AGN can be seen by IceCube-Gen2/KM3Net

Coincidences w. Optical Transients

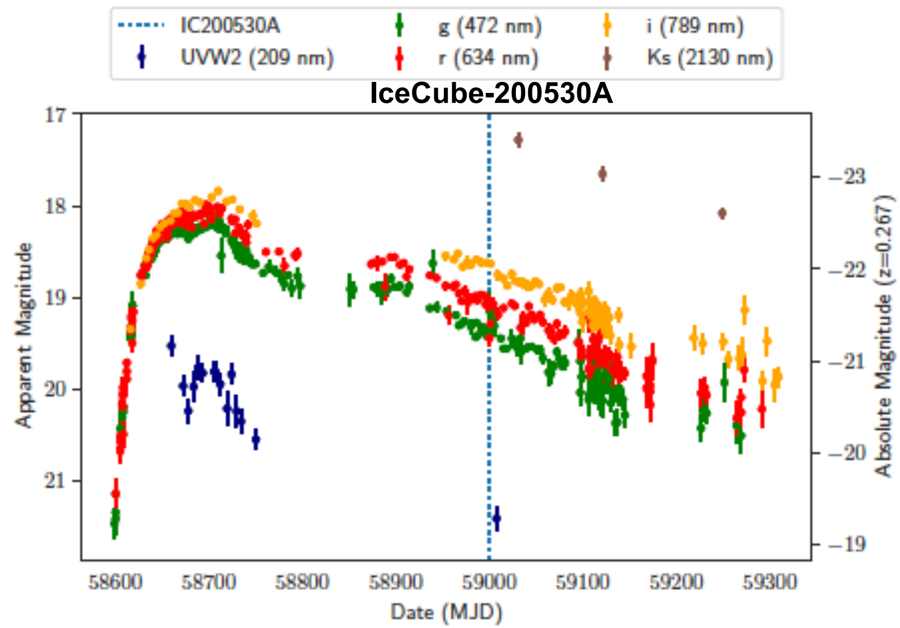
Tidal disruption events (TDEs) – supermassive black hole flares

IceCube-191001A & AT 2019dsg



Stein+ 21 Nature Astron.

IceCube-200530A & AT 2019fdr

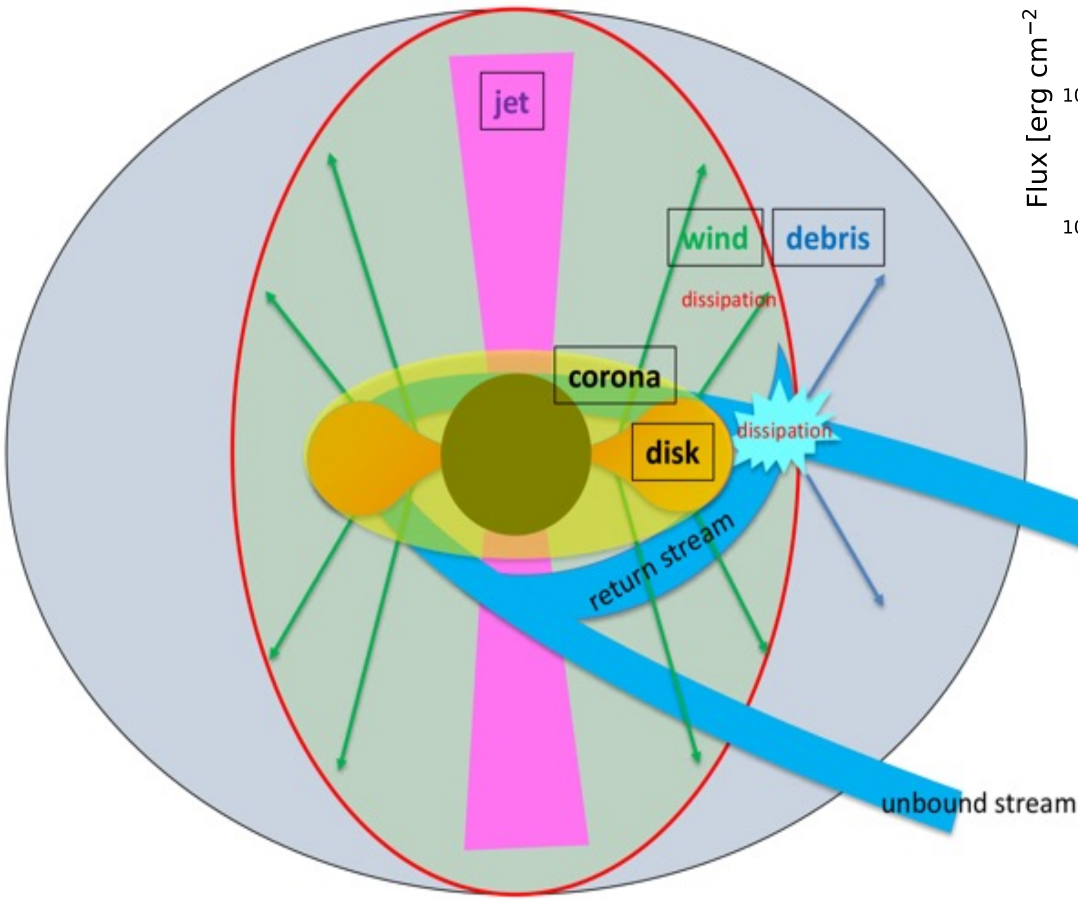


Reusch+ KM 21 PRL

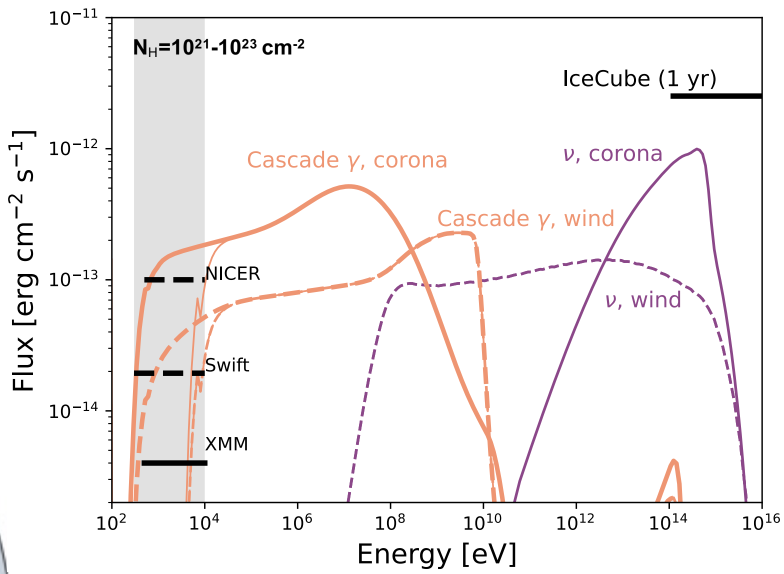
- 5 TDE coincidences have been reported (van Velzen+ 23, Jiang+ 23)
- All are rare optical transients w. strong infrared echoes
- Possible neutrino time delays w. ~150-300 day

Neutrinos from Tidal Disruption Events?

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



KM, Kimura, Zhang et al. 20 ApJ



Summary

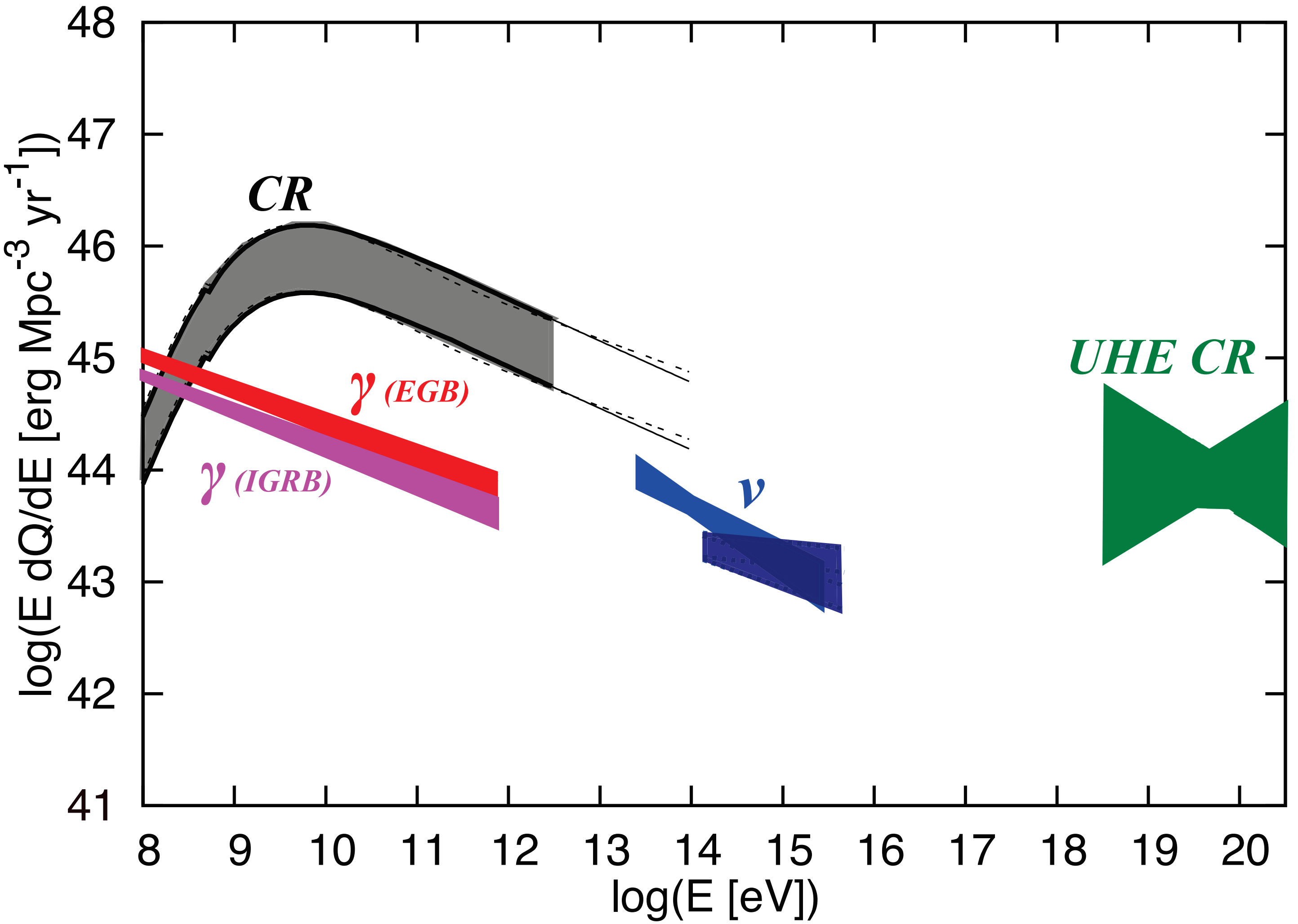
- Multimessenger analyses on 10 TeV ν data require hidden CR accelerators
- Jet-quiet AGNs: the most promising origin (whether ~3-4σ is real or not)

- NGC 1068 & NGC 4151: indications of hidden ν sources

Implications:
- ν emission regions should be compact: $R < 10\text{-}30\ R_S$
- Low-energy cosmic-ray spectrum should be hard ($s <\sim 2$) to satisfy $L_{CR} <\sim L_X$
- Strongly magnetized: $\xi_B >\sim 0.1$ (supporting low-β coronae)
- NGC 4151 may be a key for discriminating models (corona vs shock)
- Relevance of AGNs in the southern sky (NGC 4945, Circinus)
- Consistent with the measured all-sky ν flux in the 10-100 TeV range
- Physical connections to LL AGNs and TDEs

Future:
- More statistics, next-generation ν detectors (KM3Net, Baikal, P-ONE, Gen2)
- Synergy w. hard X-ray and MeV γ-ray observations
- Understanding coronal plasma & CR acceleration in the vicinity of black holes

Multi-Messenger Astro-Particle "Backgrounds"

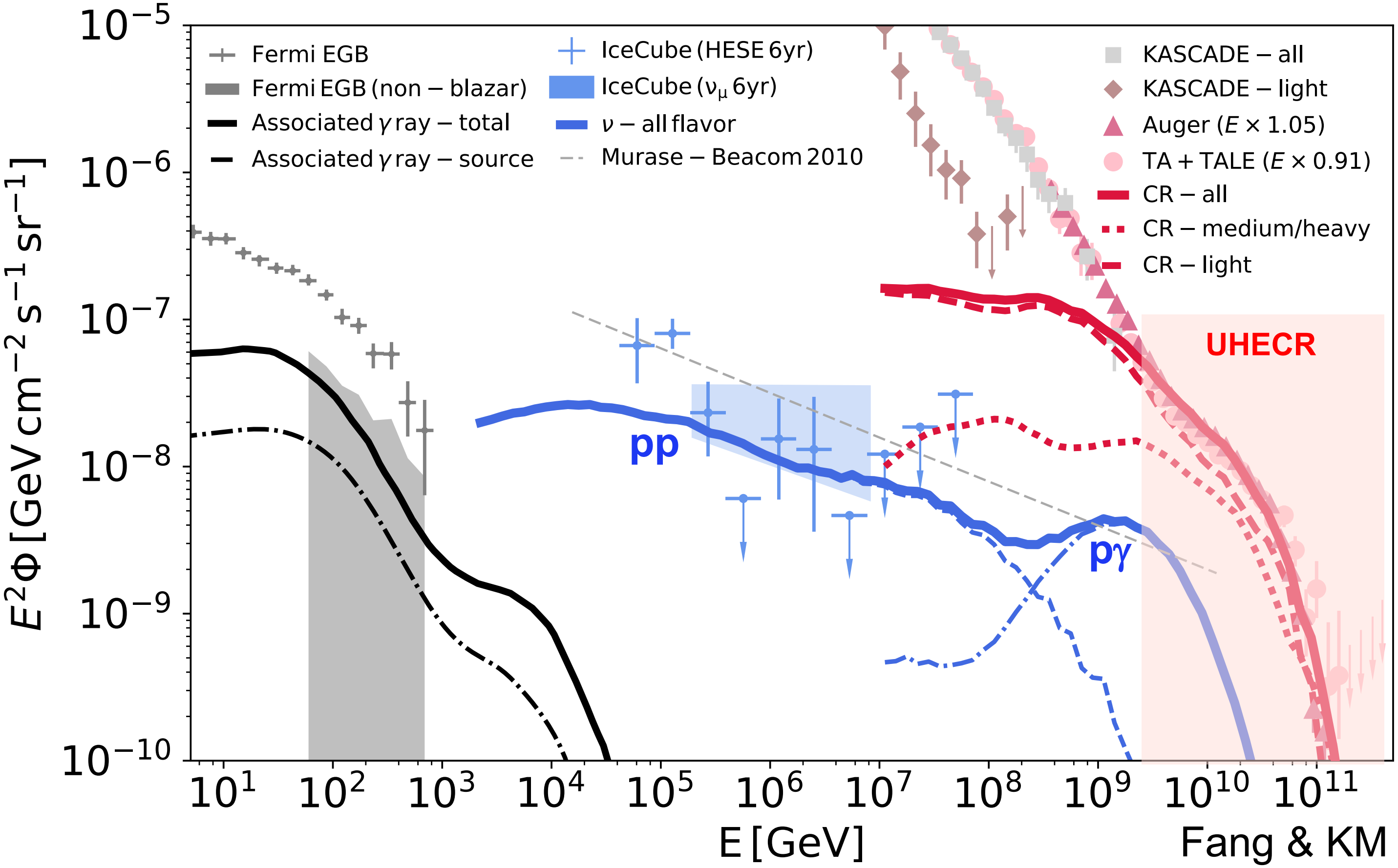


Energy generation rate densities of 3 messengers are all comparable

(KM & Fukugita 19, Yu, Zhang & KM 20)

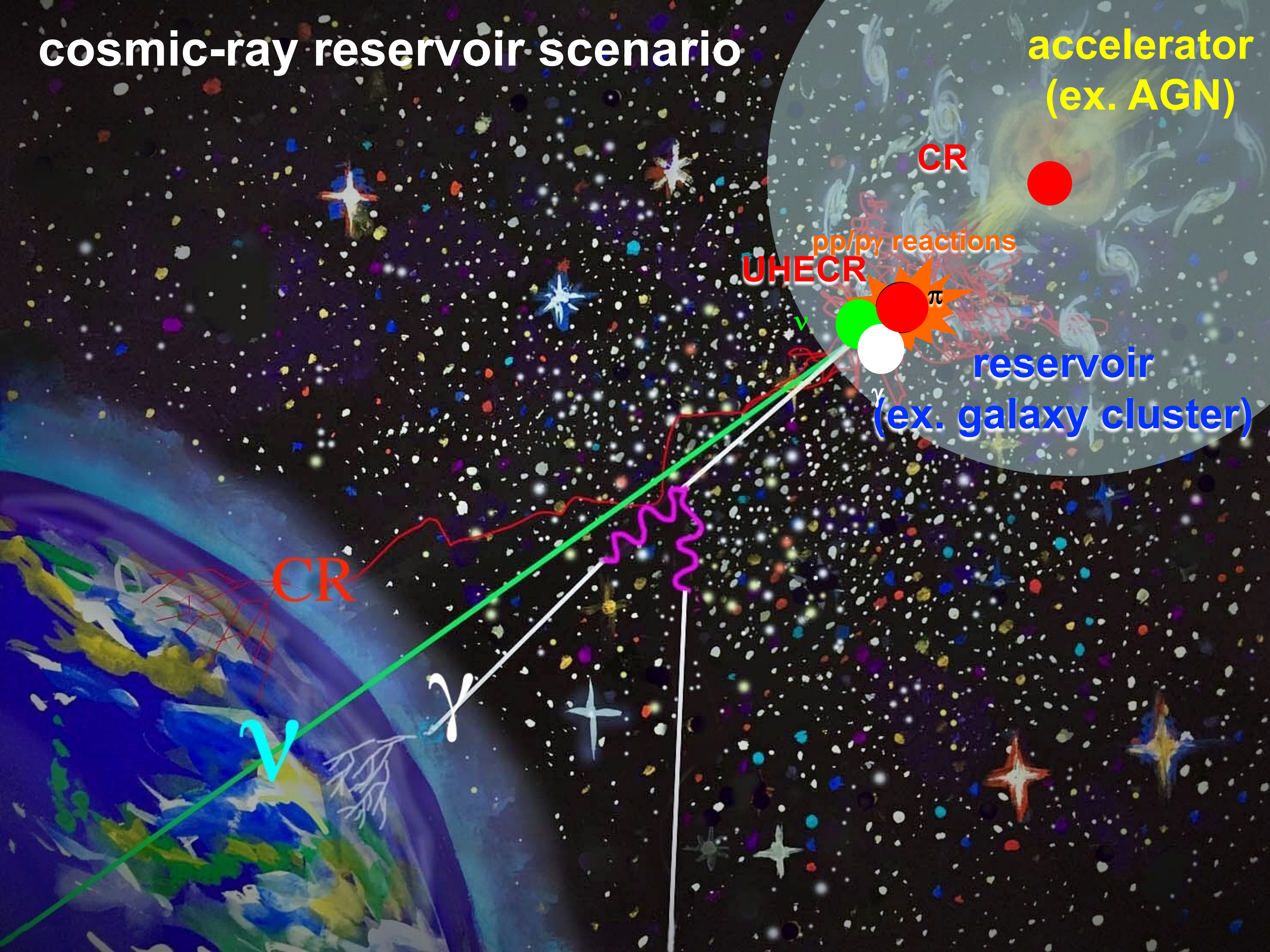
High-Energy Astro-Particle Grand-Unification?

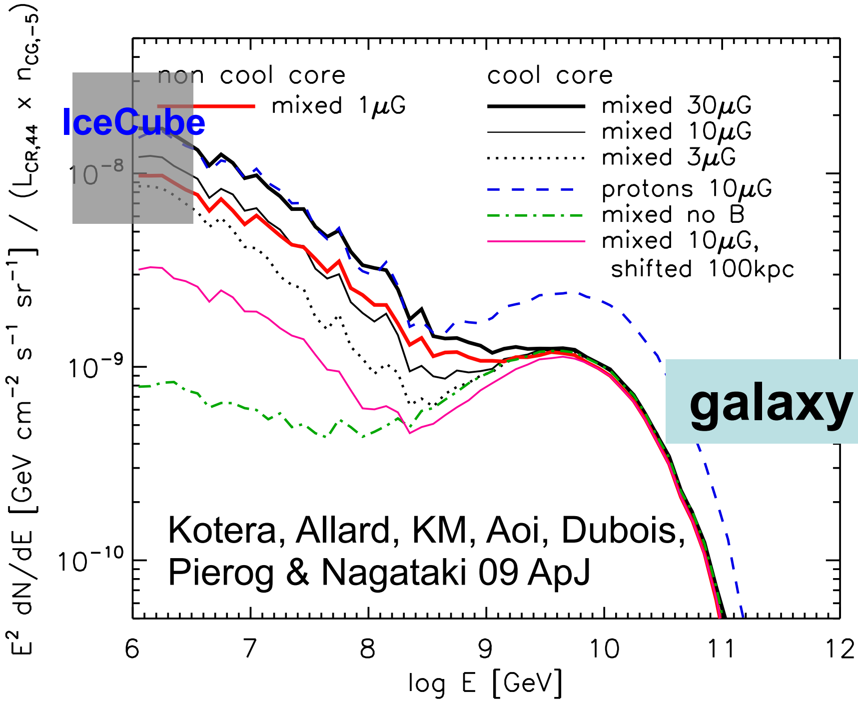
First concrete example of the "grand-unification" scenario with detailed simulations

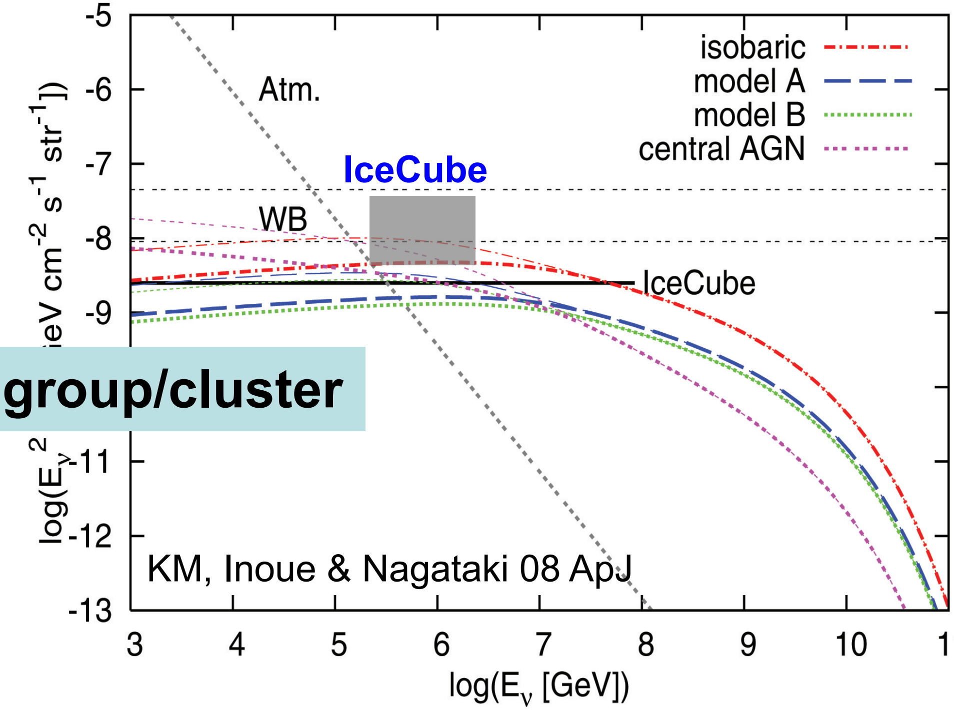


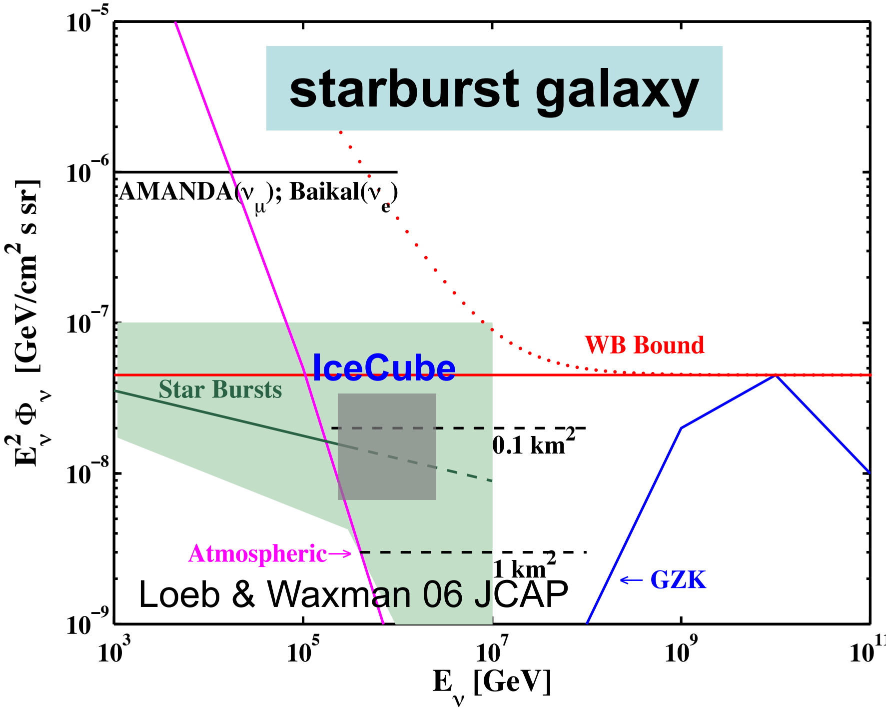
Fang & KM 18 Nature Phys.
(see also KM & Waxman 16)

- Jetted AGN as "UHECR" accelerators
- Neutrinos from confined CRs & UHECRs from escaping CRs
- Smooth transition from PeV (source ν) to EeV (cosmogenic ν)


cosmic-ray reservoir scenario
accelerator
(ex. AGN)
CR
pp/pγ reactions
UHECR
π
ν
reservoir
(ex. galaxy cluster)
γ
CR
γ
ν







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