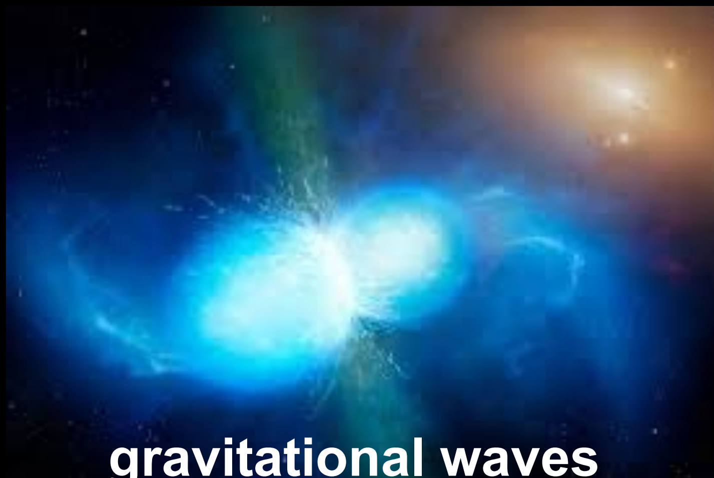
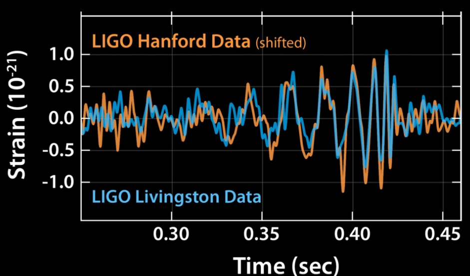
Black-Hole Disk Coronae and High-Energy Neutrinos

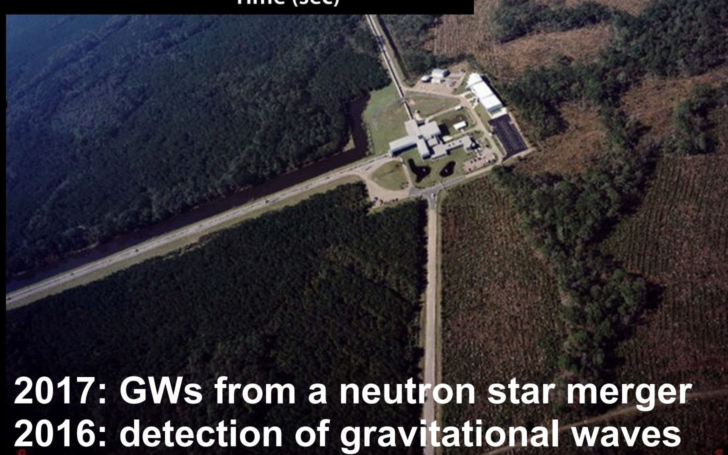
Kohta Murase
(Penn State/YITP)

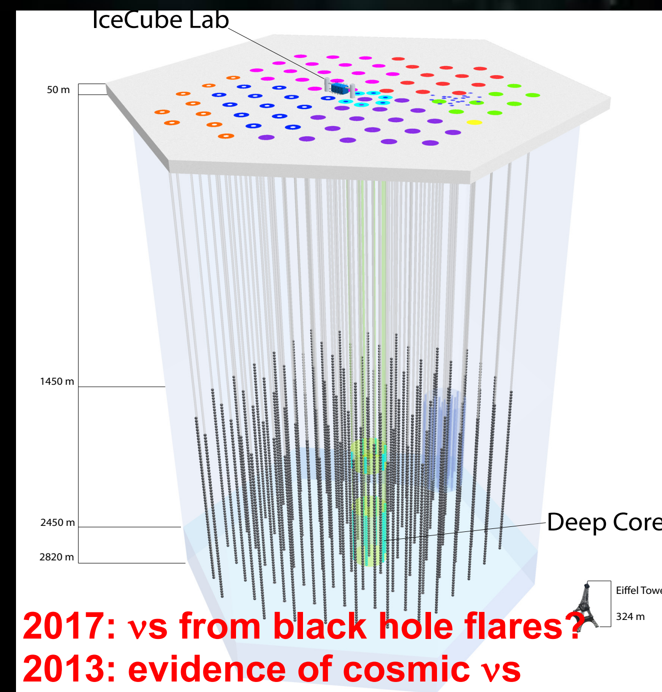
Les Houches workshop 2025

New Era of Multimessenger Astrophysics



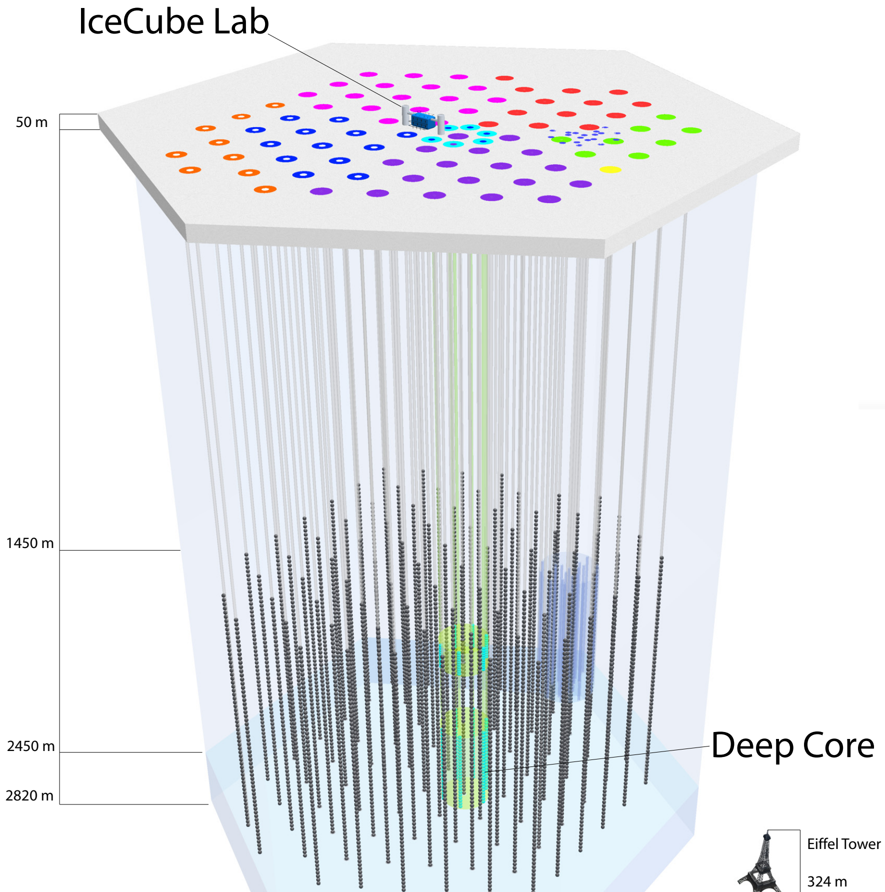






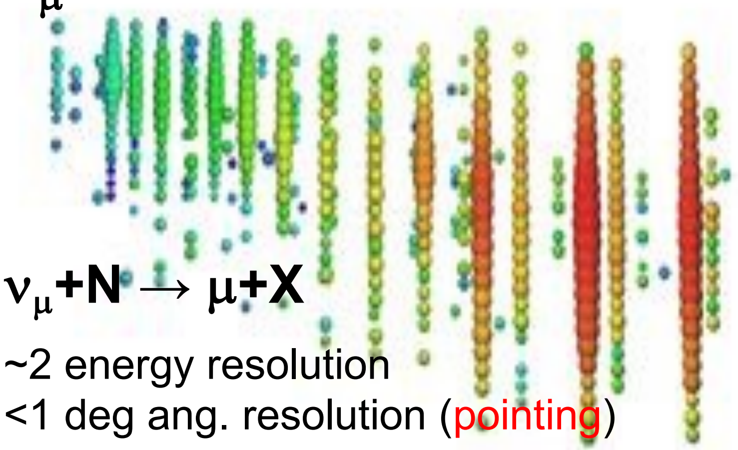
IceCube & Discovery of High-Energy Cosmic Neutrinos

IceCube @ south pole
completed in 2010



- volume~1 km^3, mass~Gton
- 86 strings (120 m spacing)
- 5160 PMTs (17 m spacing)

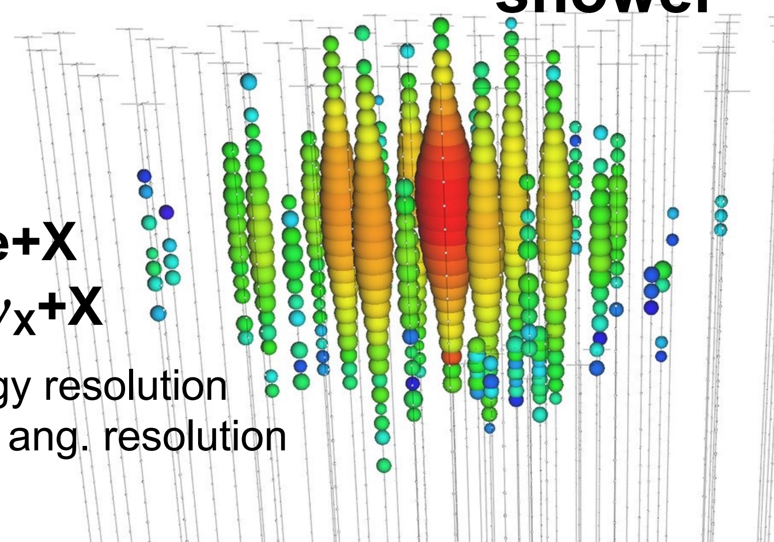
"ν_μ track"



ν_μ**+N** $\rightarrow$ μ**+X**

~2 energy resolution
<1 deg ang. resolution (pointing)

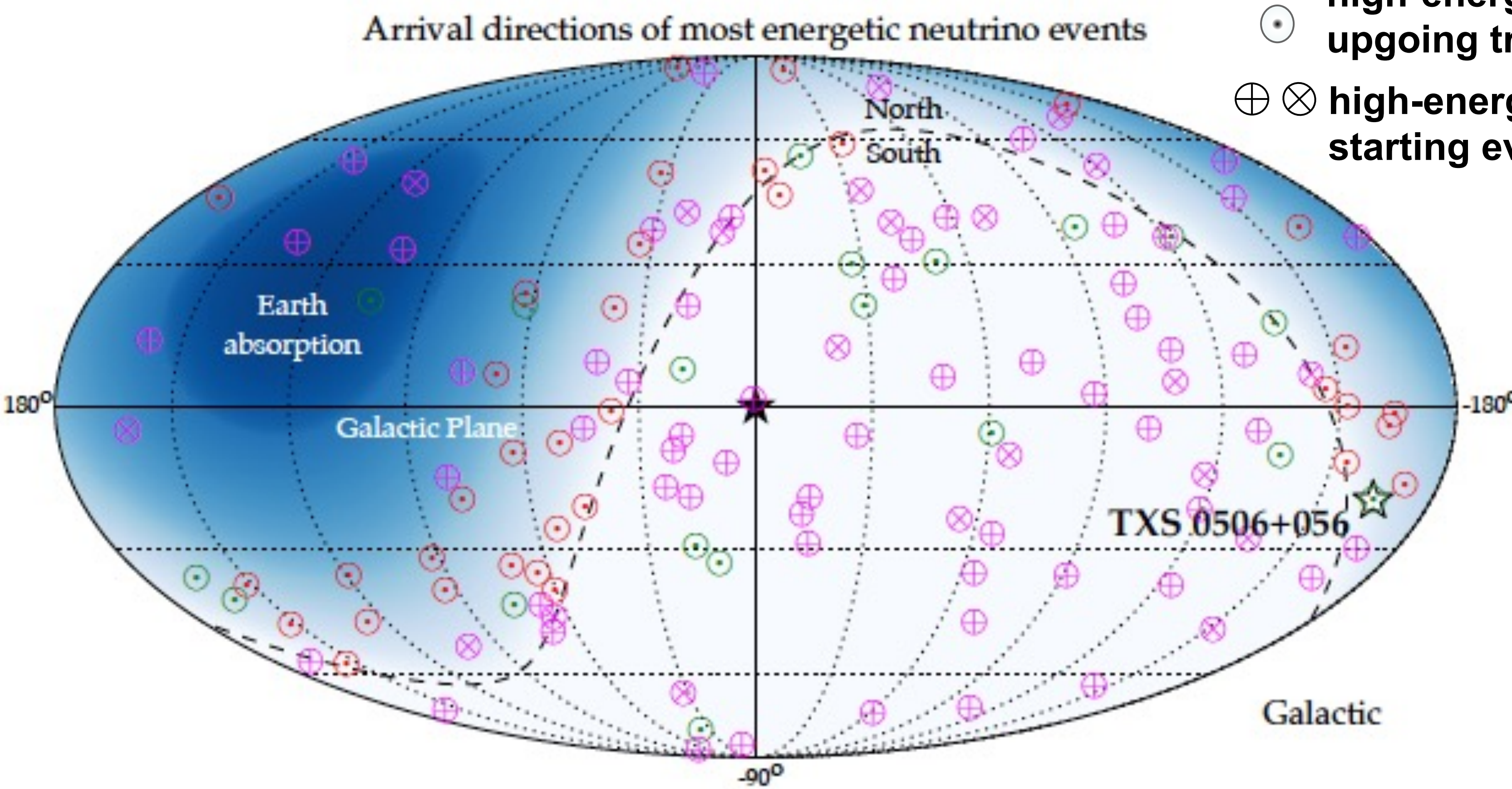
"shower"



ν_e**+N** $\rightarrow$ **e+X**
ν_X**+N** $\rightarrow$ ν_X**+X**

~15% energy resolution
~10-15 deg ang. resolution

High-Energy Neutrino Sky



⊙ high-energy upgoing tracks

⊕ ⊗ high-energy starting events

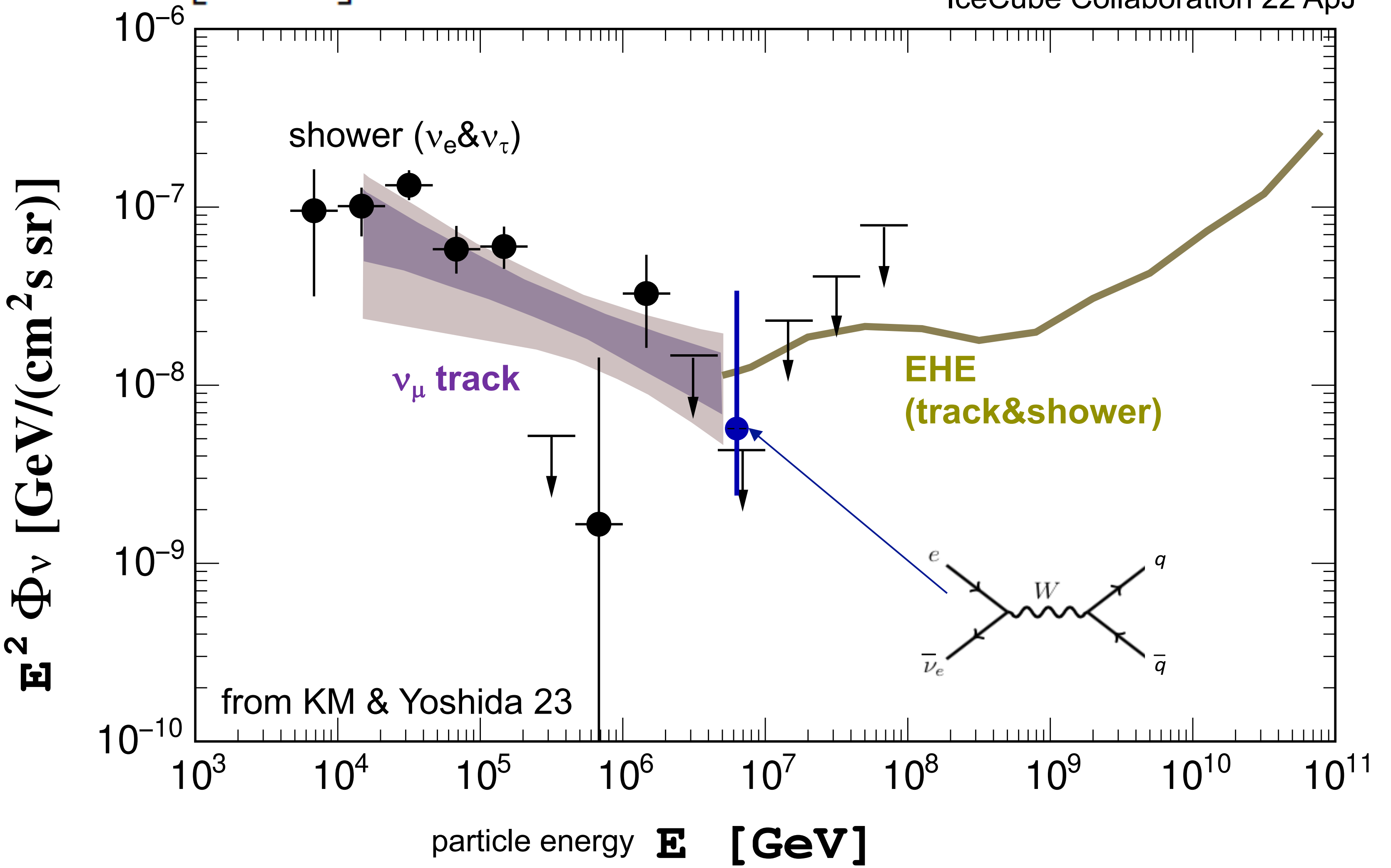
consistent w. isotropic distribution/extragalactic origins

All-Sky Neutrino Flux & Spectrum

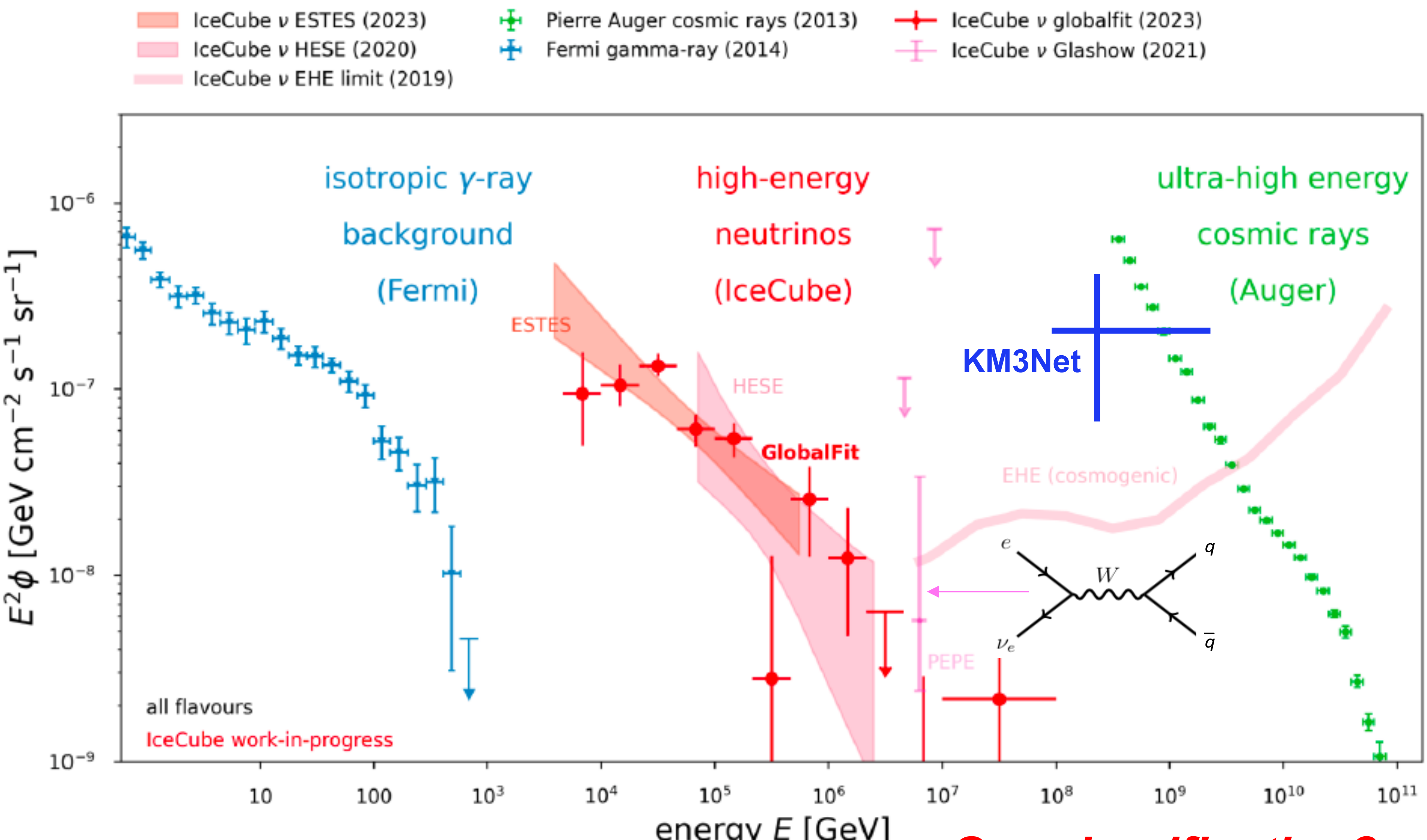
$$E^2\Phi \approx \frac{ct_H}{4\pi}\xi_z\left[\frac{dQ}{d\ln E}\right]$$

Q_ν: energy generation rate density

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



All-Sky Multimessenger Flux & Spectrum

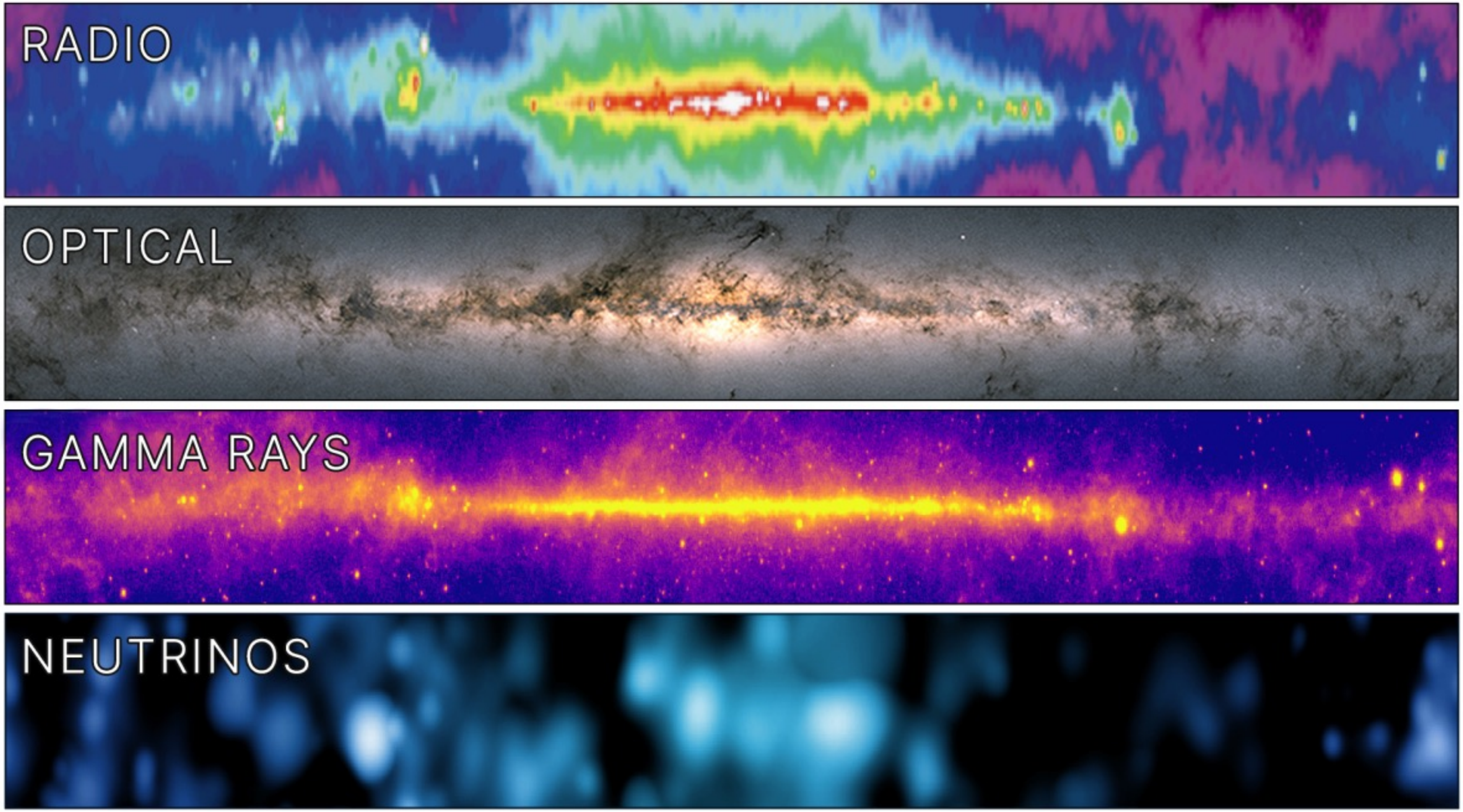


IceCube Collaboration 18 PRD, 20 PRL, 21 Nature, 22 ApJ

Grand-unification?

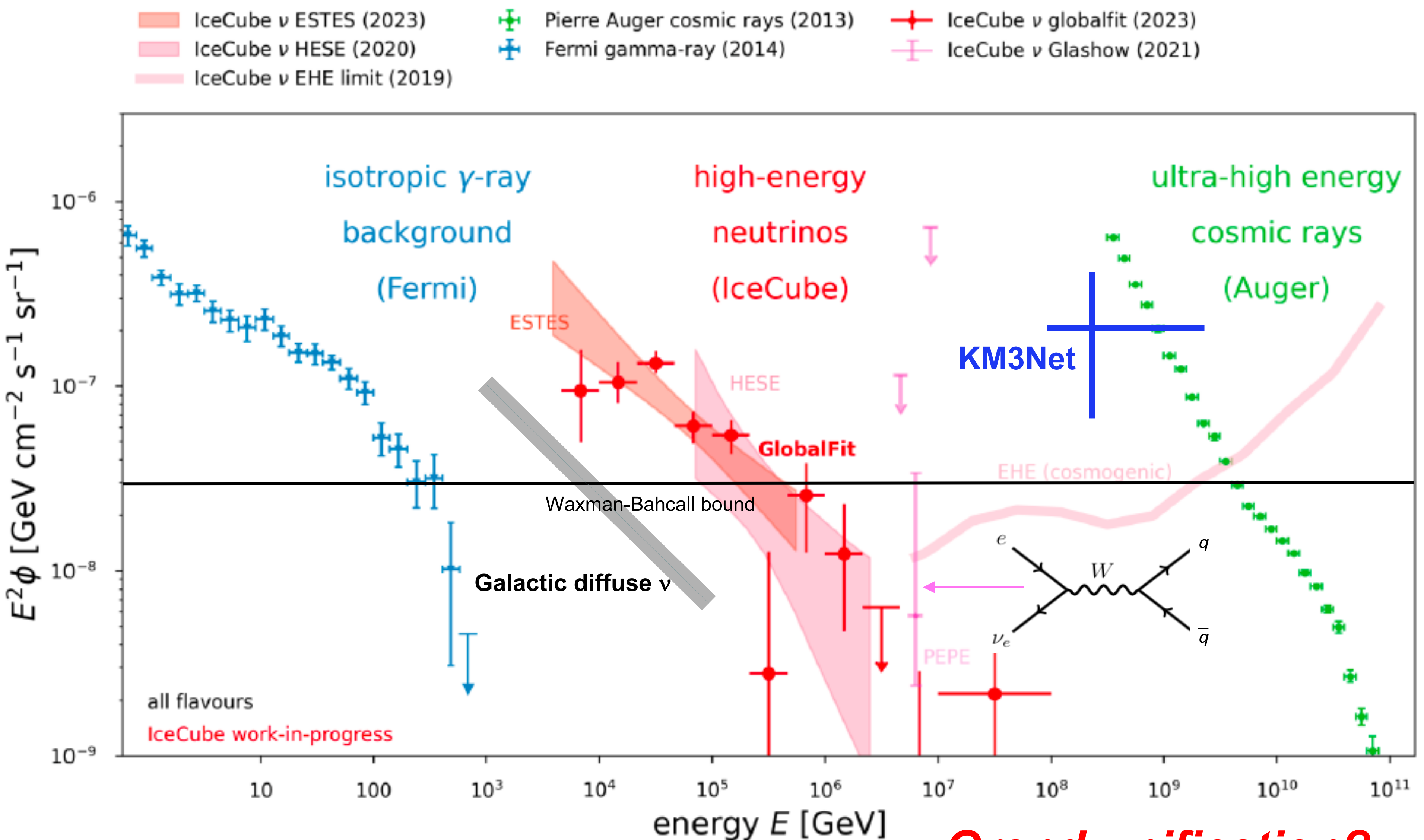
2023: Evidence of Neutrinos from the Milky Way

IceCube 23 Science



Neutrino emission from the Milky Way (~10% of total) has been observed w. 4.5σ

All-Sky Multimessenger Flux & Spectrum

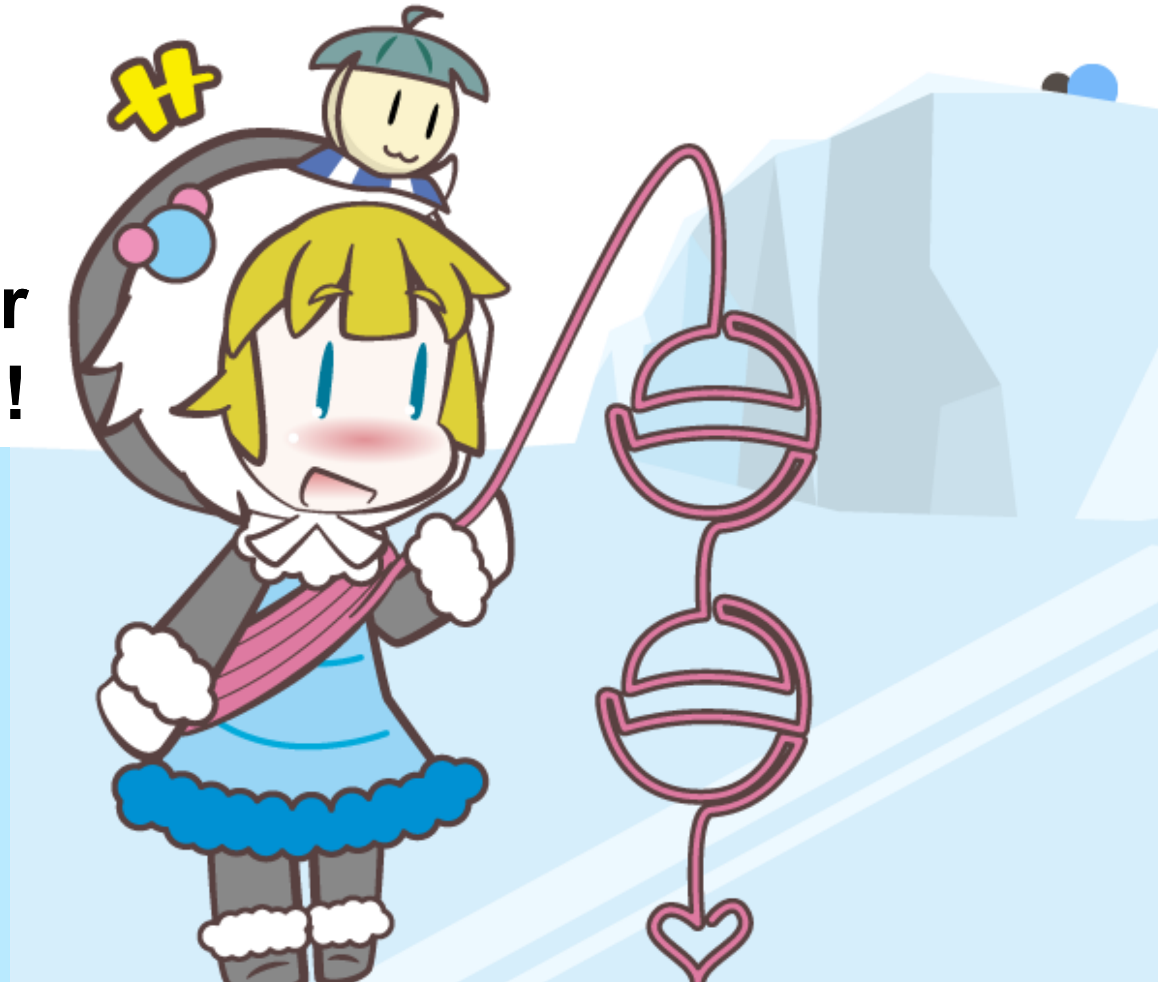


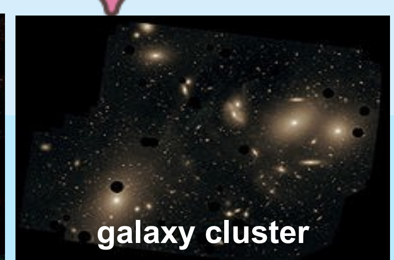
IceCube Collaboration 18 PRD, 20 PRL, 21 Nature, 22 ApJ

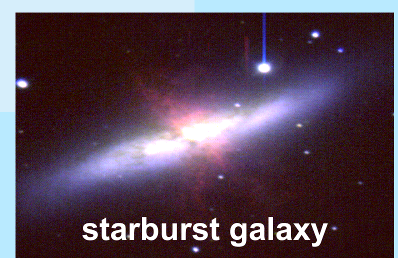
Grand-unification?

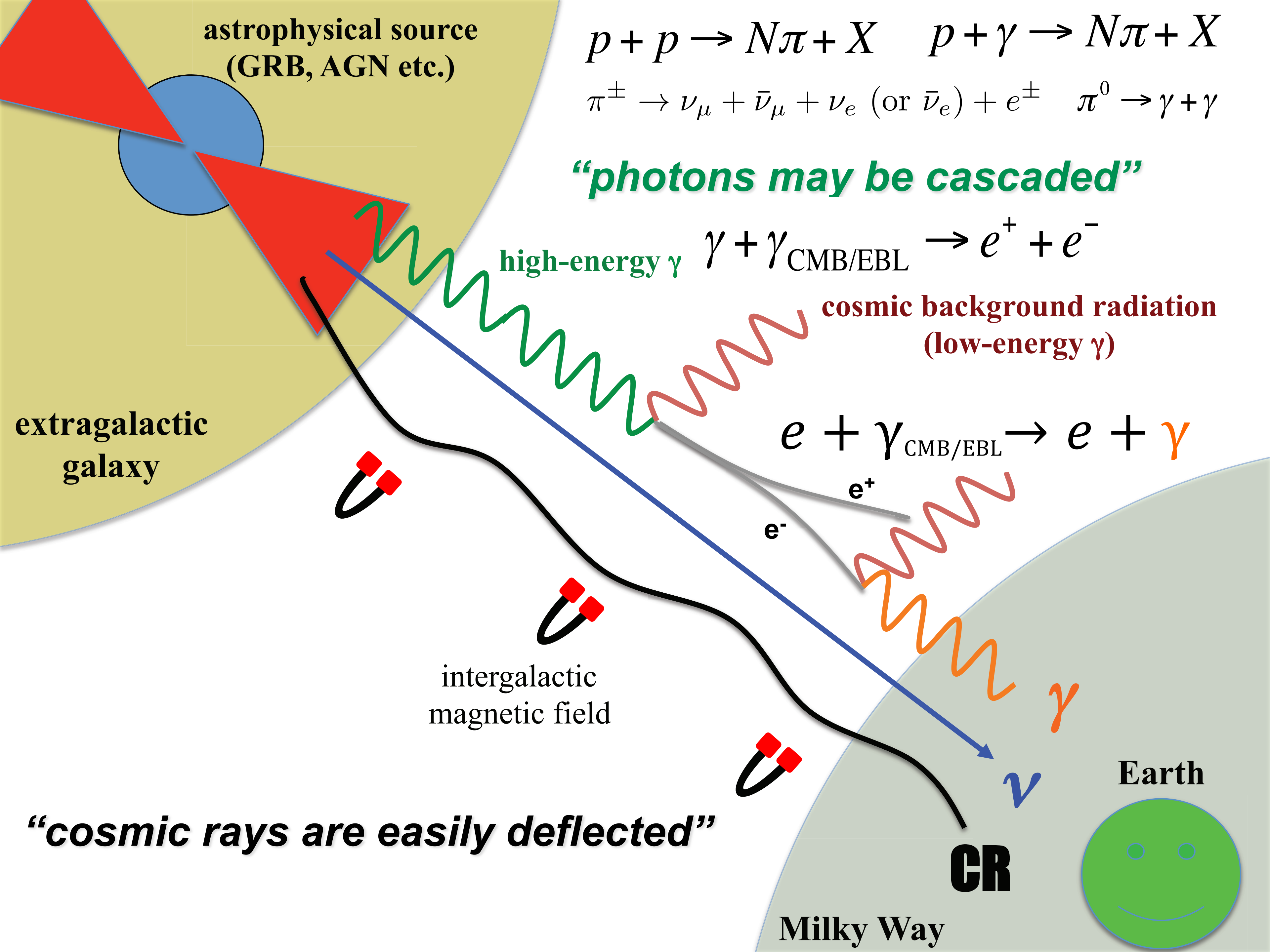
Where do neutrinos mainly come from?

monster fishing!!



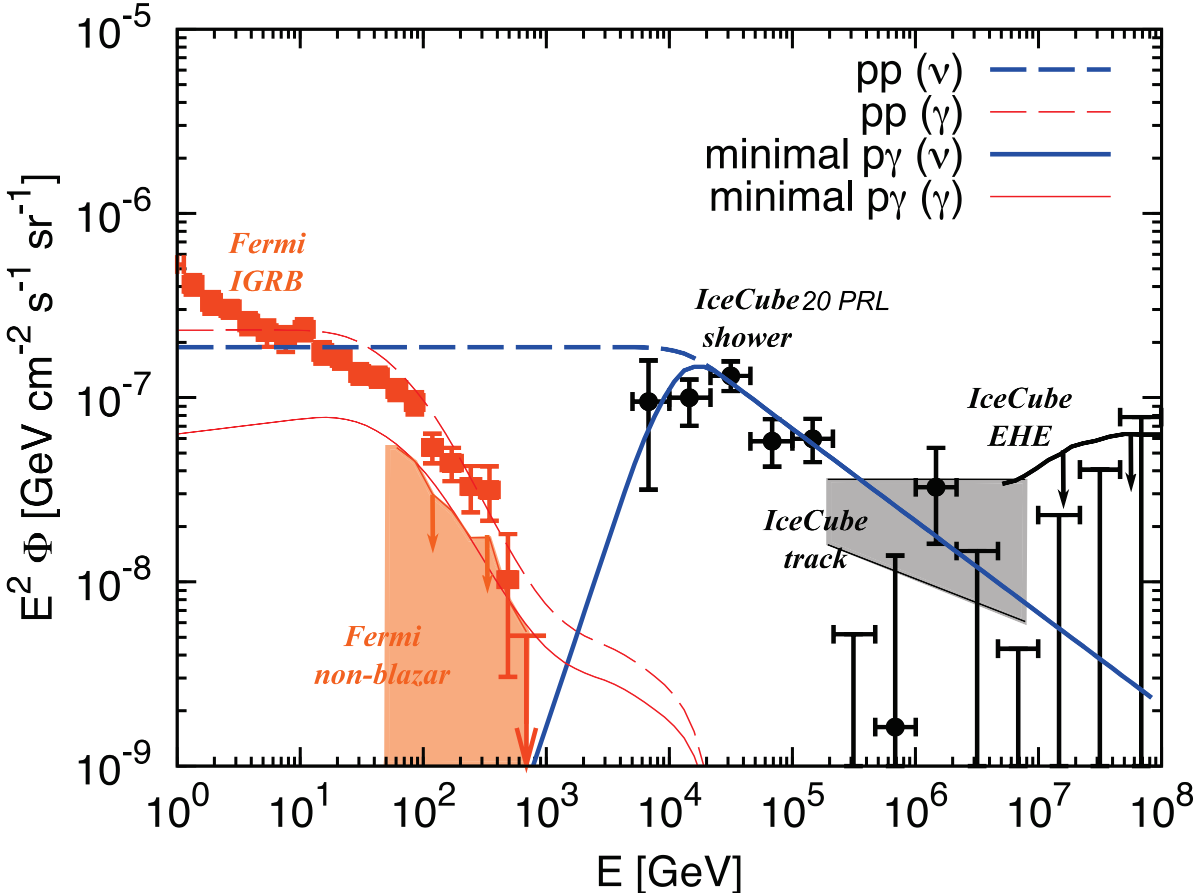





astrophysical source
(GRB, AGN etc.)
$p + p \rightarrow N\pi + X$
$p + \gamma \rightarrow N\pi + X$
$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e \text{ (or } \bar{\nu}_e) + e^{\pm}$
$\pi^0 \rightarrow \gamma + \gamma$
"photons may be cascaded"
high-energy γ
$\gamma + \gamma_{\mathrm{CMB/EBL}} \rightarrow e^+ + e^-$
cosmic background radiation
(low-energy γ)
extragalactic
galaxy
$e + \gamma_{\mathrm{CMB/EBL}} \rightarrow e + \gamma$
e^+
e^-
intergalactic
magnetic field
γ
ν
Earth
"cosmic rays are easily deflected"
CR
Milky Way

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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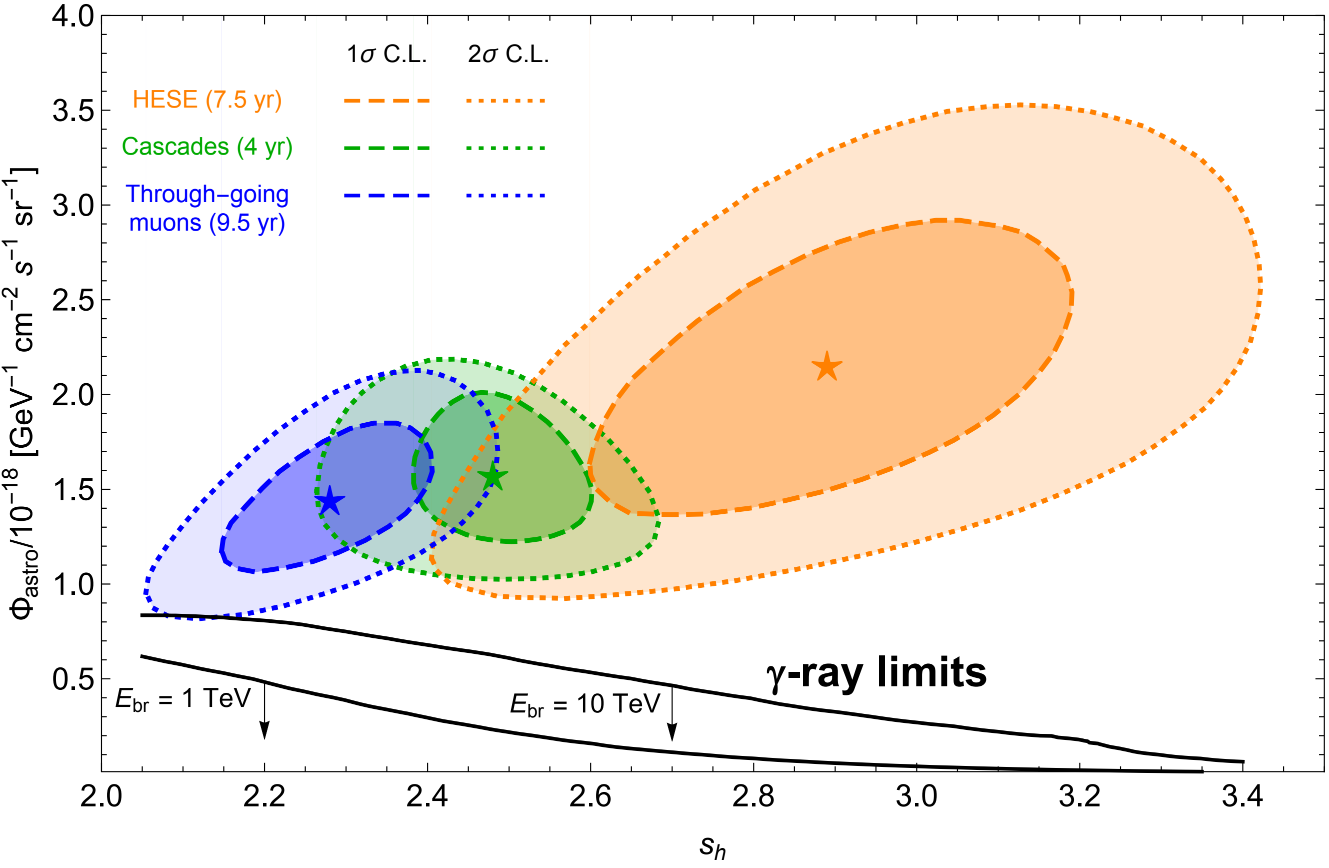

Capanema, Esmaili & KM 20
Capanema, Esmaili & Serpico 21

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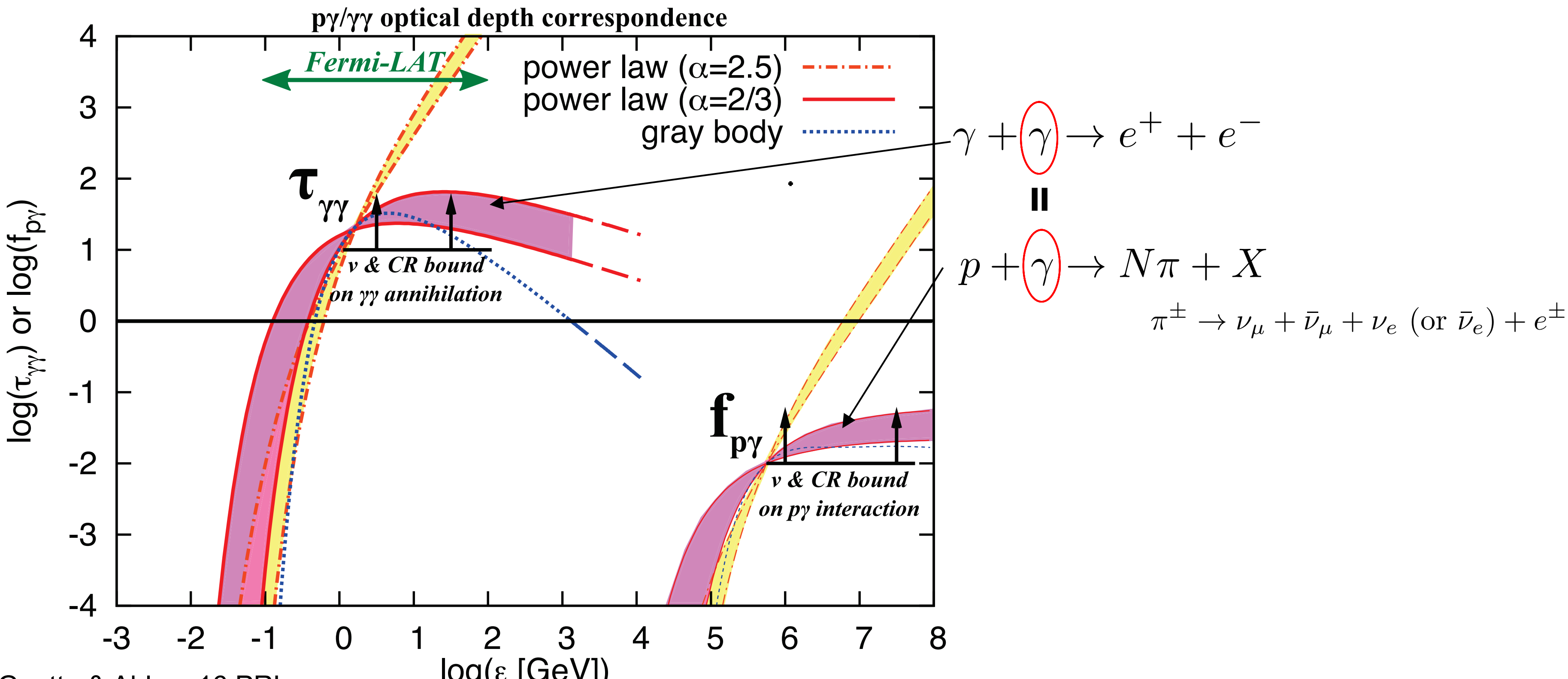
(ν data above 100 TeV can still be explained by γ-ray transparent sources)

Opacity Argument

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

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



KM, Guetta & Ahlers 16 PRL

Prediction of Hidden Neutrino Sources for Medium-Energy ν

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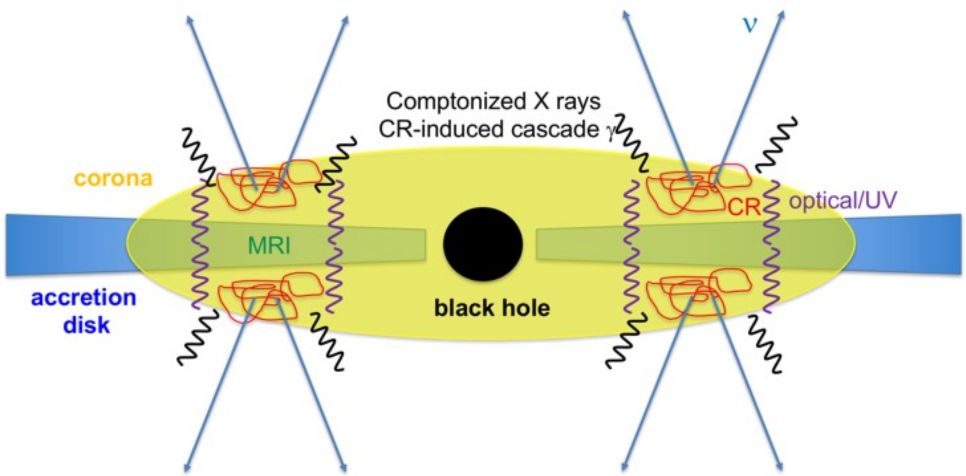
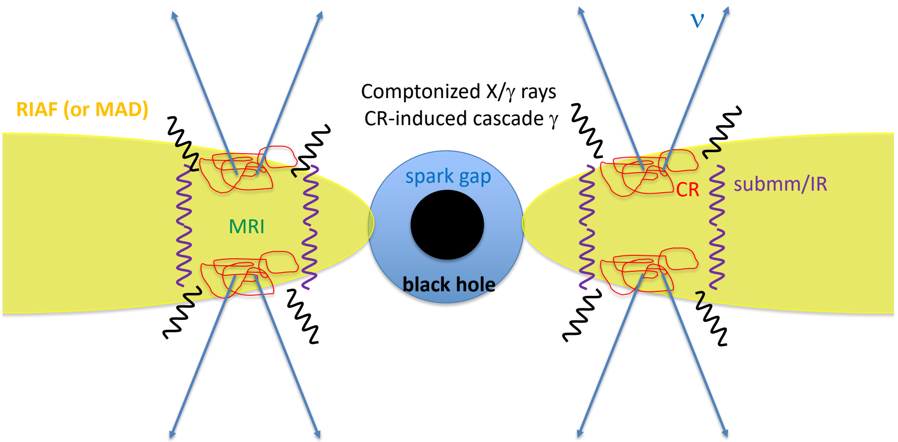
active galactic nuclei coronae



(from KM, Kimura & Meszaros 20)

radiatively inefficient accretion disks



(from KM & Stecker 23)

Not many sources can explain 10-100 TeV ν data (KM, Guetta & Ahlers 16 for various possibilities)
Jet-quiet AGN: best in view of energy budget to spare: Q_{CR} <~ Q_X ~ 2×10^{46} erg $\rm Mpc^{-3}\ yr^{-1}$

Prediction of Hidden Neutrino Sources for Medium-Energy ν

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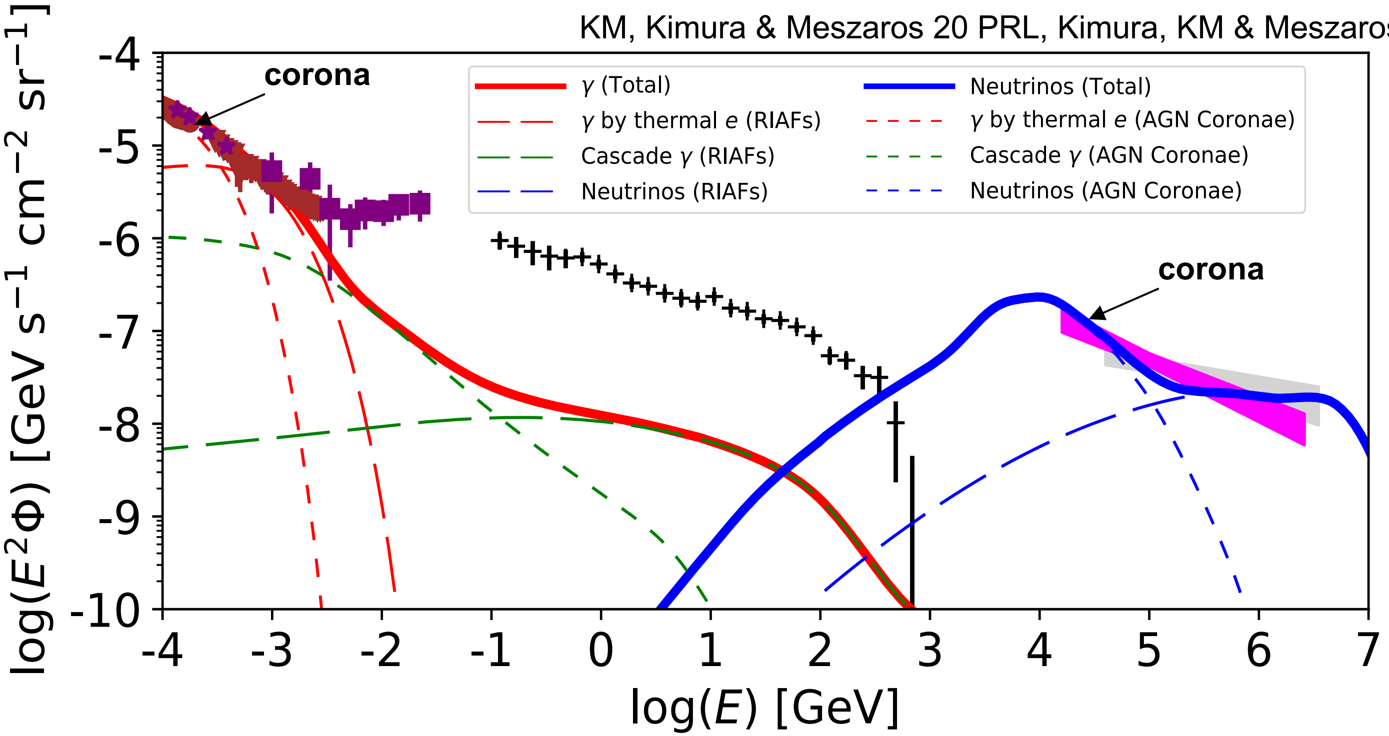
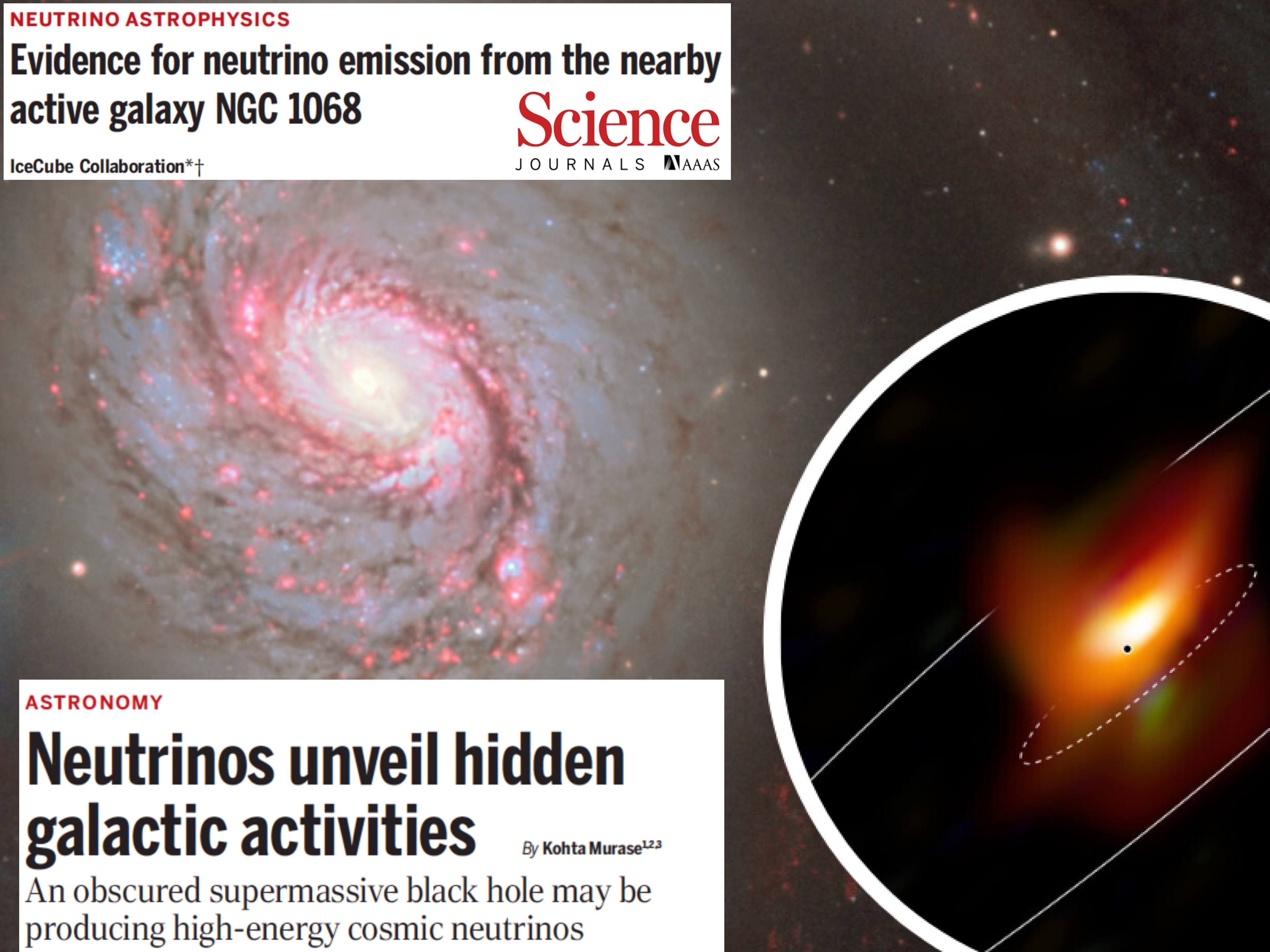
KM, Kimura & Meszaros 20 PRL, Kimura, KM & Meszaros 21 Nature Comm.



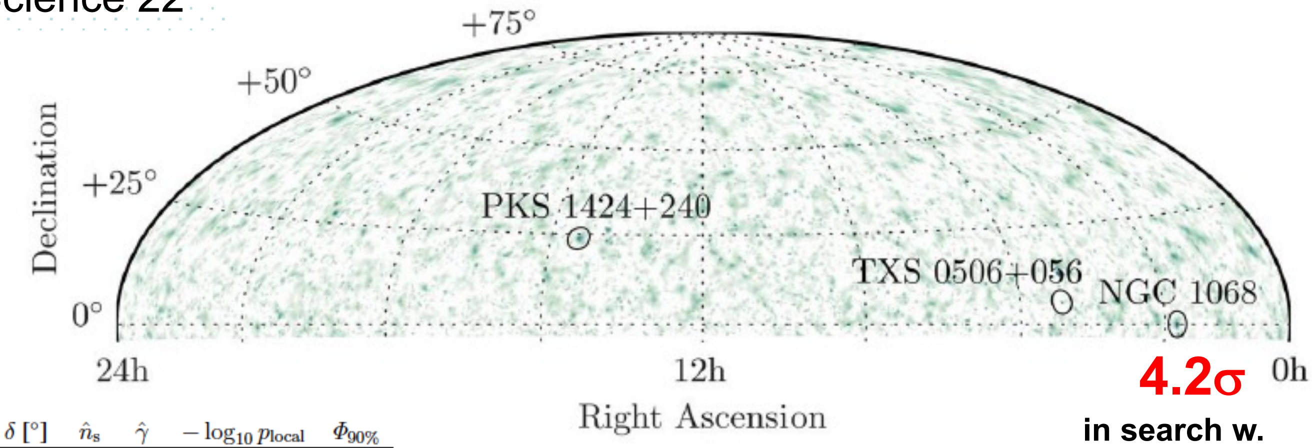
All-sky (diffuse) neutrino flux can be explained by AGN

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 Murase1,2,3
An obscured supermassive black hole may be producing high-energy cosmic neutrinos

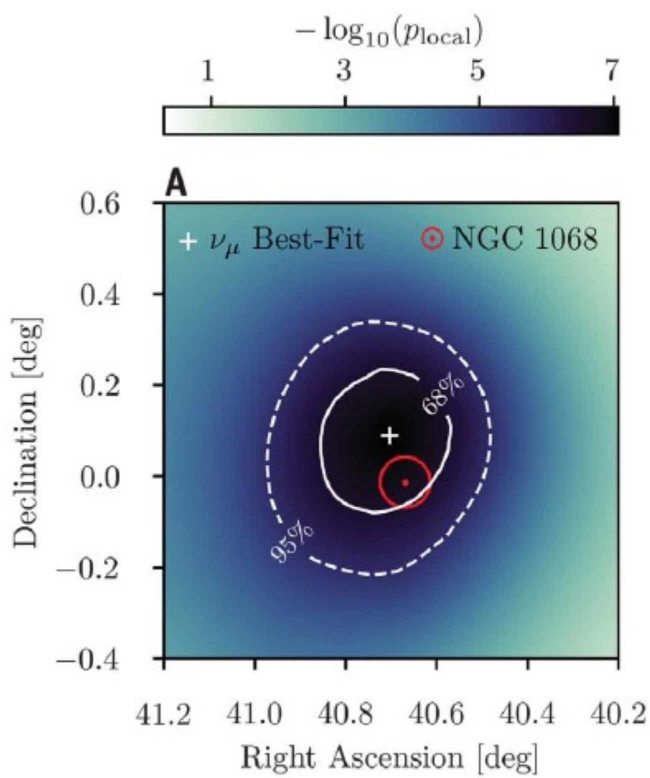
IceCube Collaboration+ Science 22

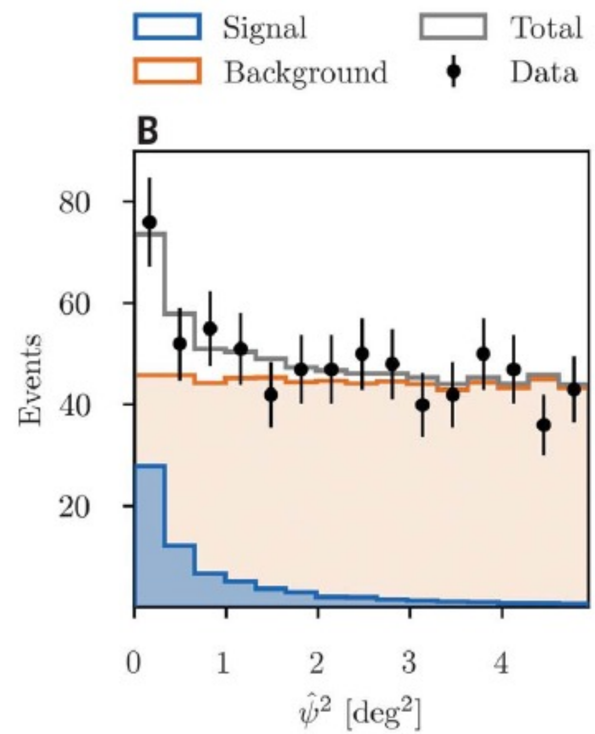
2011-2020
10 year track data



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

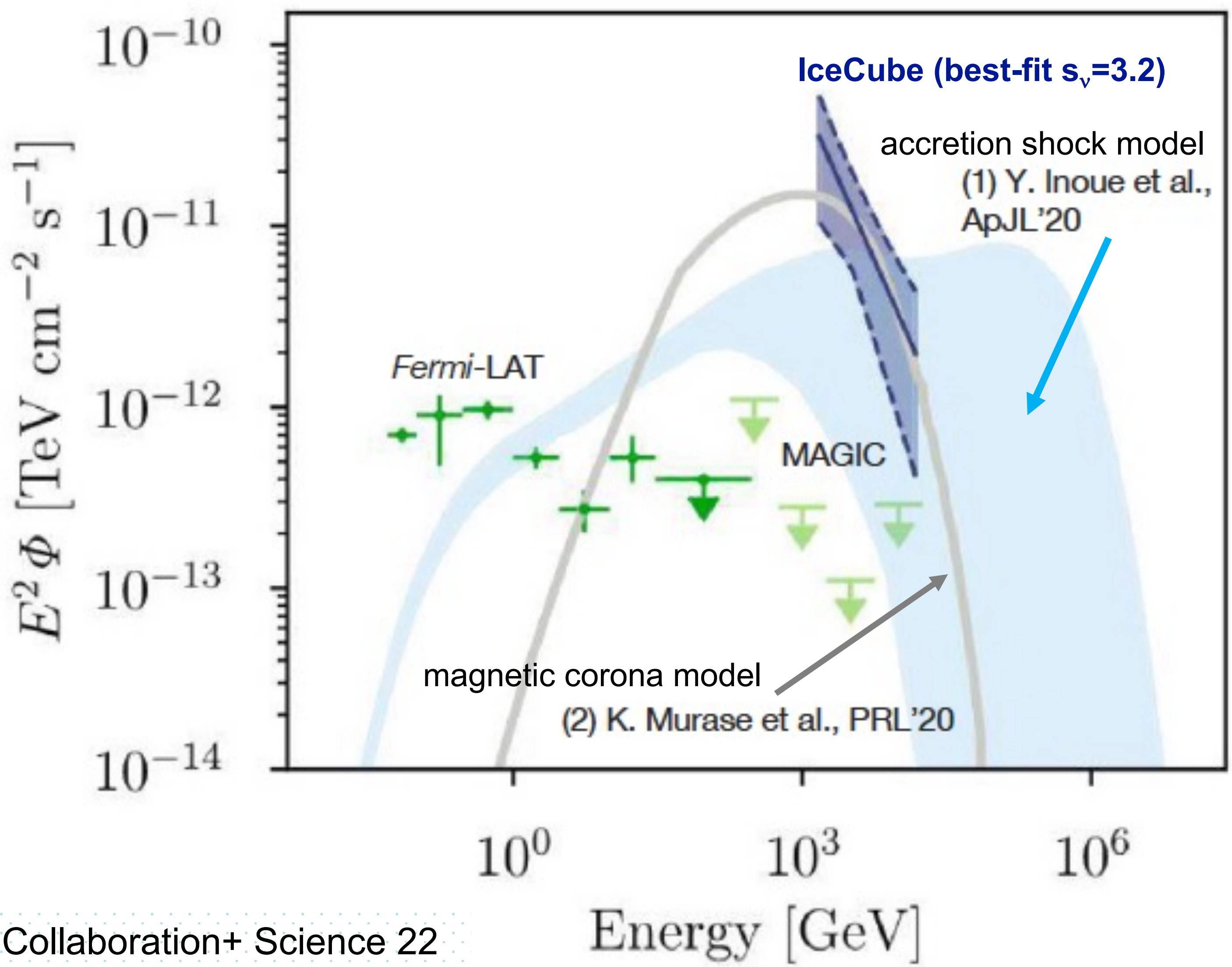
Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\text{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5





~80 excess events

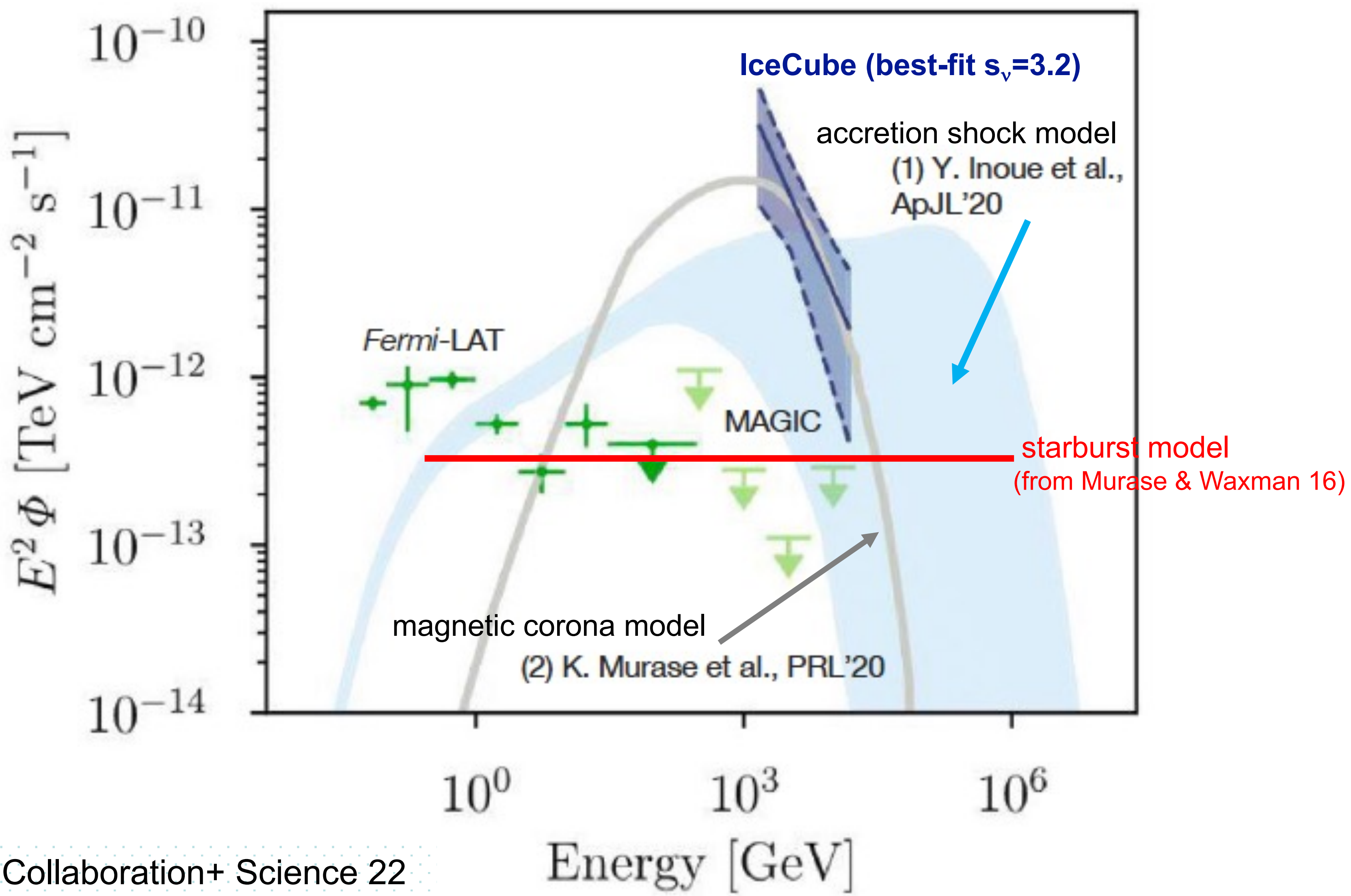
NGC 1068 as a Hidden Neutrino Source



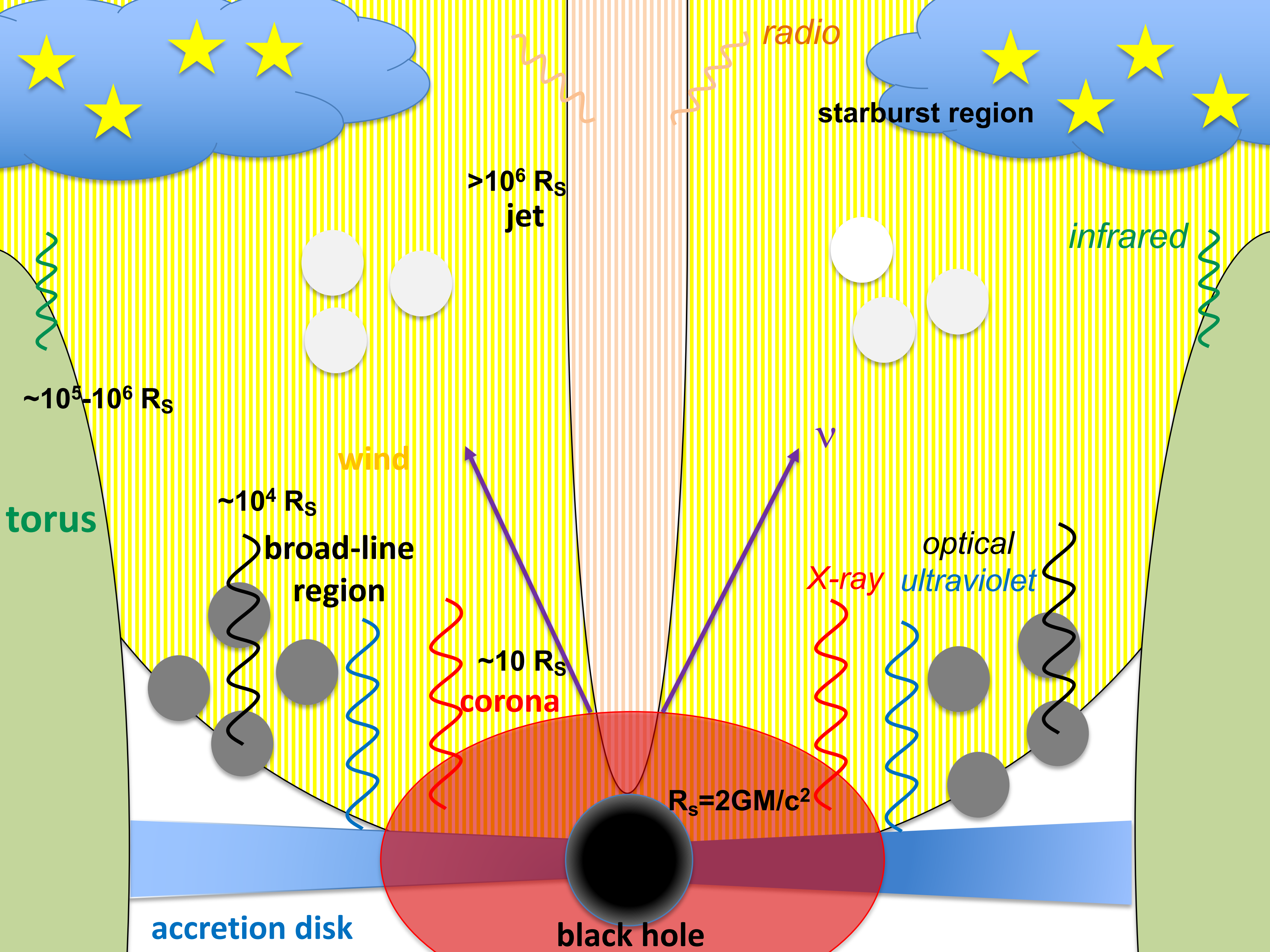
IceCube Collaboration+ Science 22

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
>10^6 R$_S$
jet
infrared
~10^5-10^6 R$_S$
wind
ν
~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

Facts & Questions, Implications?

ν facts:

- NGC 1068 (~4σ): d=10 Mpc, M_{BH}~10^7 M_{sun}, Compton-thick (N_H~10^{25} cm^{-2})
- L_ν~2×10^{42} erg/s << L_X~7×10^{43} erg/s, L_{bol}~10^{45} erg/s <~ L_{Edd}
- Hidden source L_ν >> L_γ
- Other hints: NGC 4151 (~3σ), CGCG 420-015, NGC 3079, Circinus, stacking search (but none of them reach 5σ)…

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 if s>~2, due to 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?

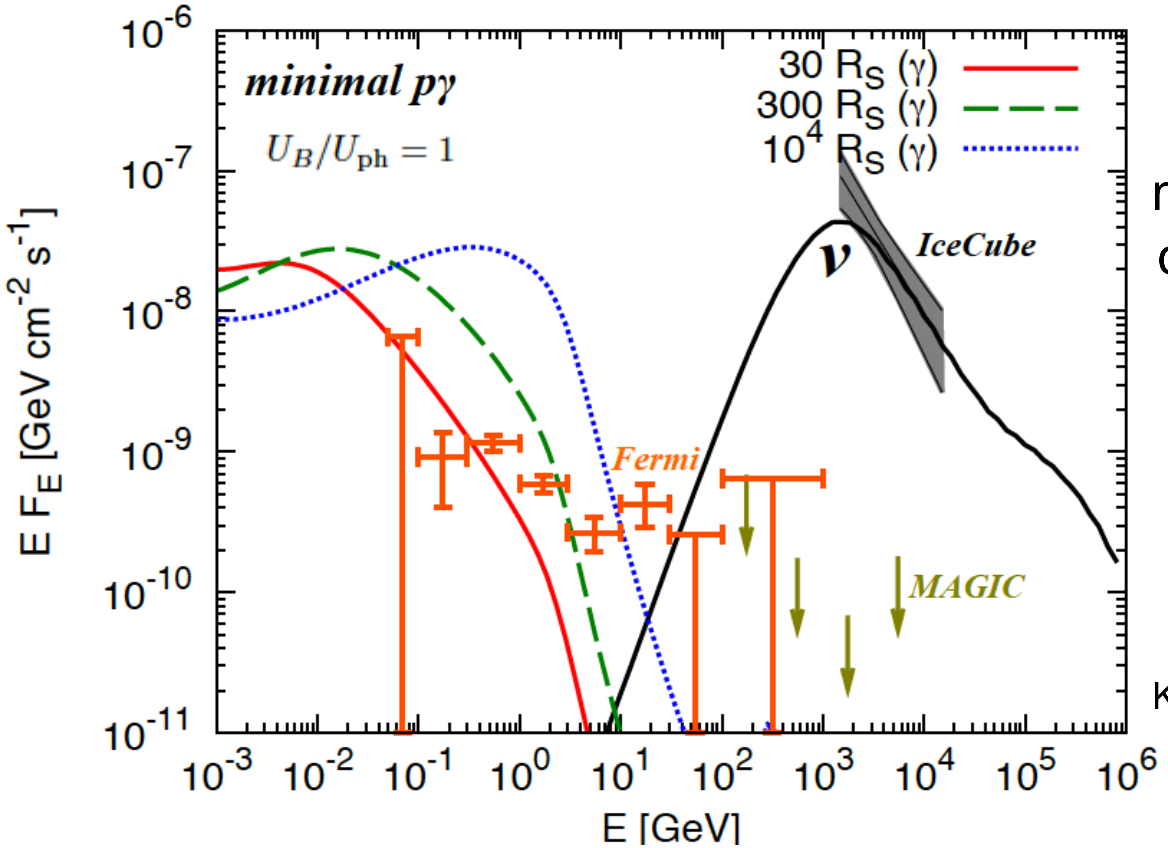
- Why is NGC 1068 ν-brightest? How about other AGNs?
- Is the all-sky neutrino flux explained by jet-quiet AGNs?

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 < (10-30) R_S

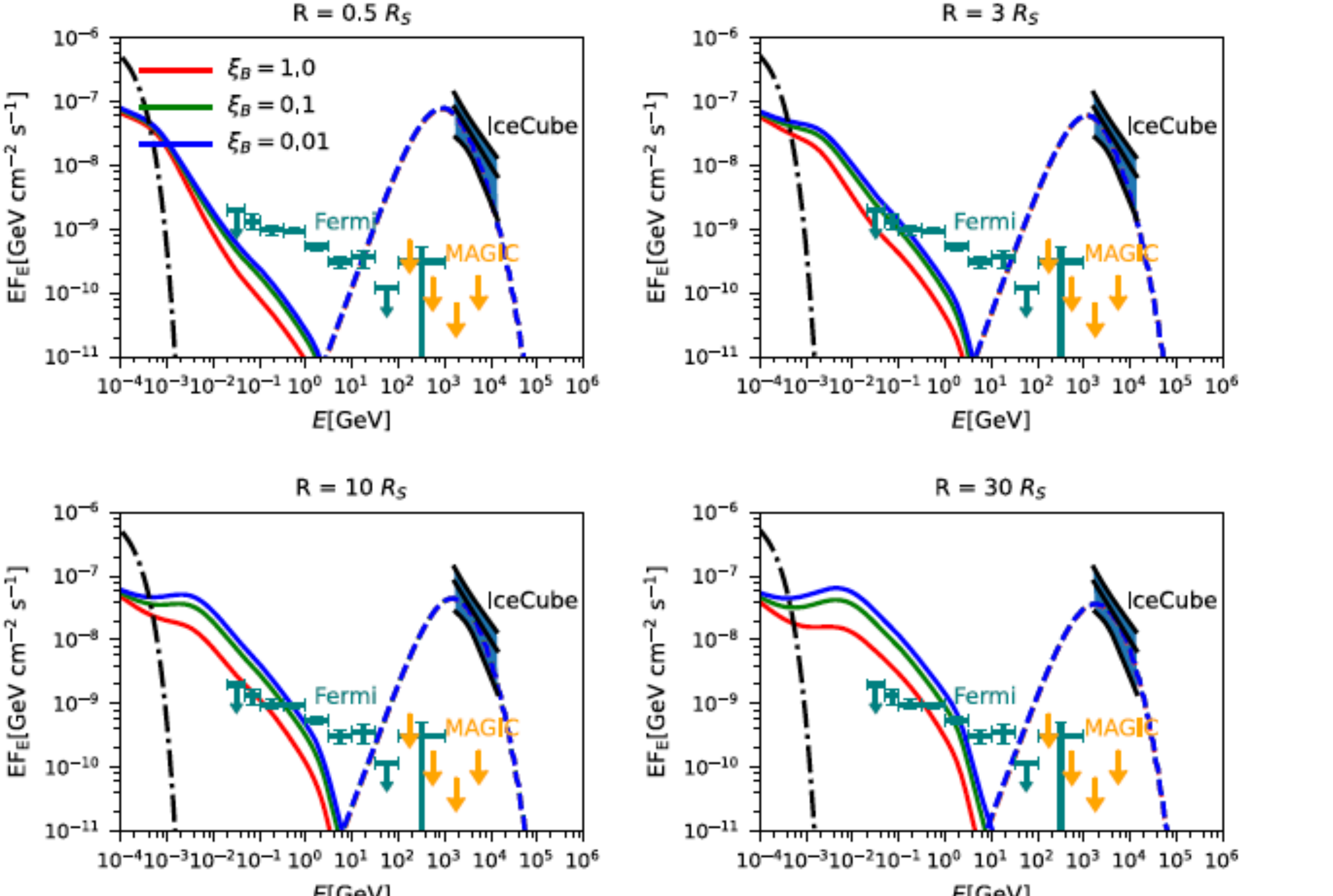
KM 22 ApJL, Das, Zhang & KM 24 ApJ

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

Massive black hole: sub-PeV proton accelerator & ideal beam dump

Updated Fermi Analysis & Impacts of Magnetization

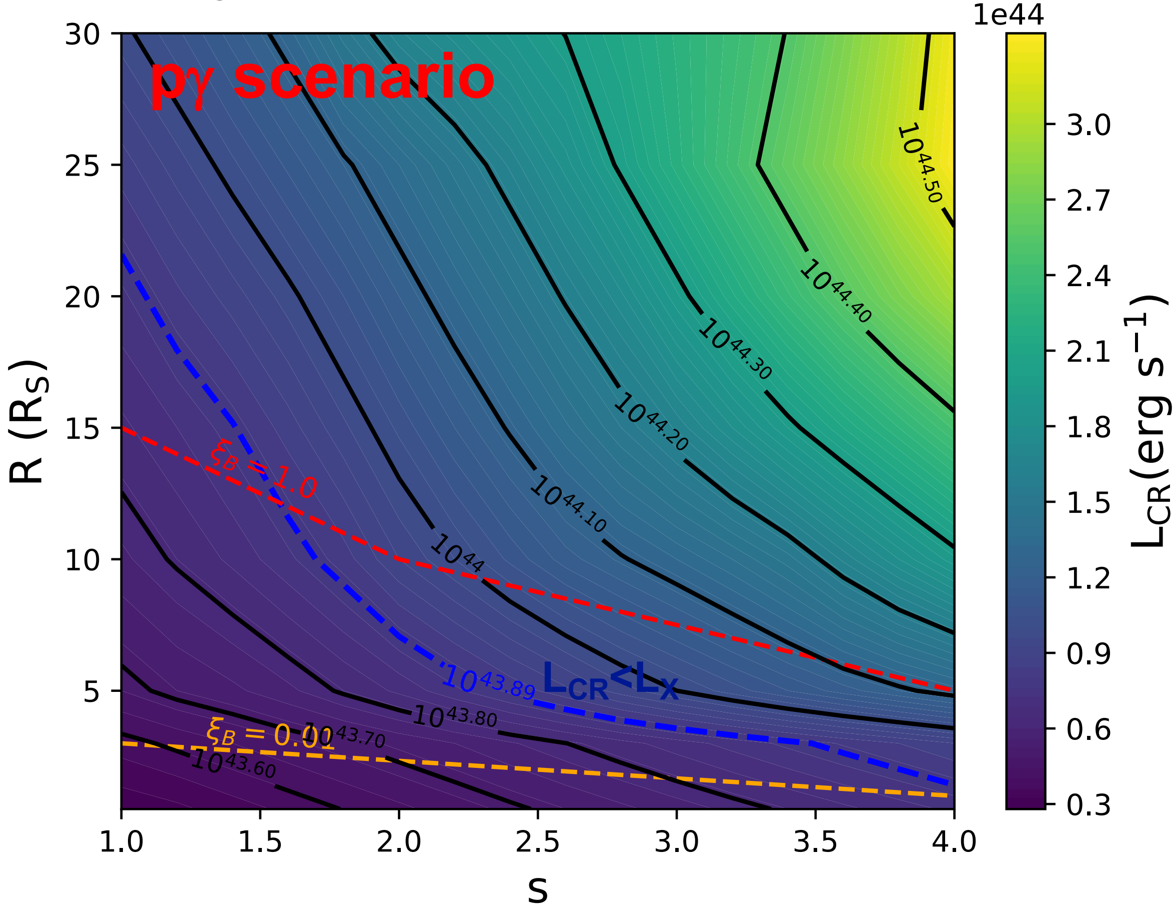
Das, Zhang & KM 24 ApJ (see Ajello, KM & McDaniel 23 ApJL for updated Fermi-LAT analysis)



magnetization $\xi_B = U_B/U_{ph}$ (cf. magnetically-powered corona: $\xi_B \sim 1$)

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

$L_{CR} < L_X$=7x10^{43} erg/s
→ **R <~ (1-20) R_S**

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

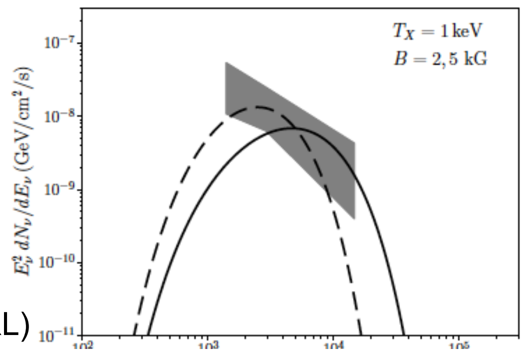
$$\beta = \frac{8\pi n_p k_B T_p}{B^2} \approx \frac{\tau_T G M_{\rm BH} m_p}{\sqrt{3}\zeta_e \sigma_T R^2 U_\gamma}\xi_B^{-1} \approx \left(\frac{\tau_T}{\sqrt{3}\zeta_e \lambda_{\rm Edd}}\right)\xi_B^{-1}$$

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

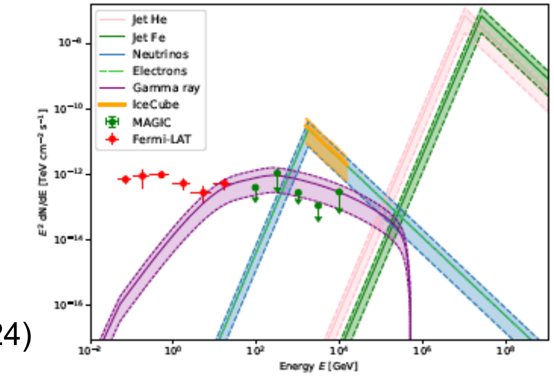
Multimessenger Implications for Neutrino Production Mechanisms

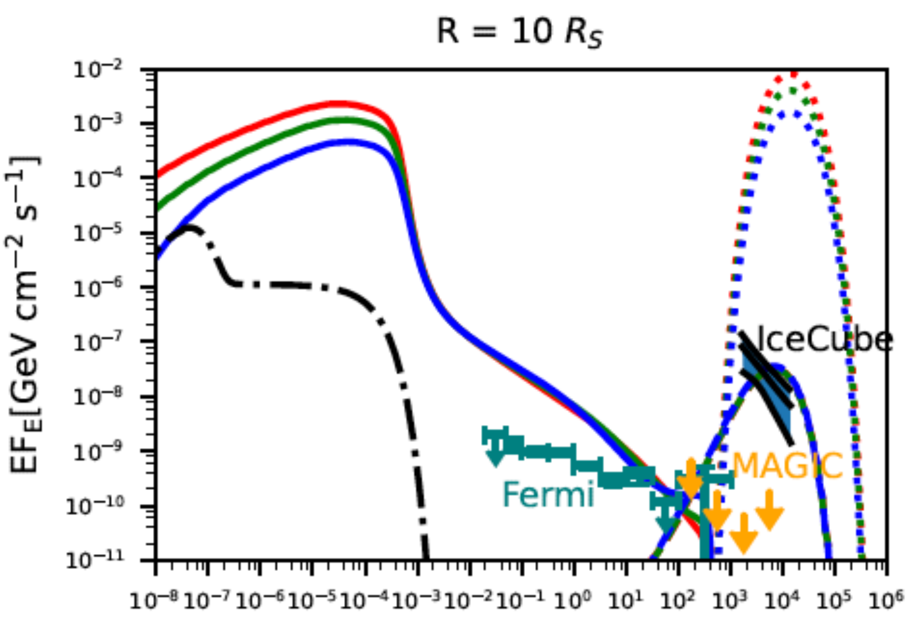
- Multimessenger connection must be considered and exotic models are excluded.
- Also unlikely by the energetics requirement: $L_{CR} < L_{bol} \sim L_{Edd} \sim 10^{45}$ erg/s

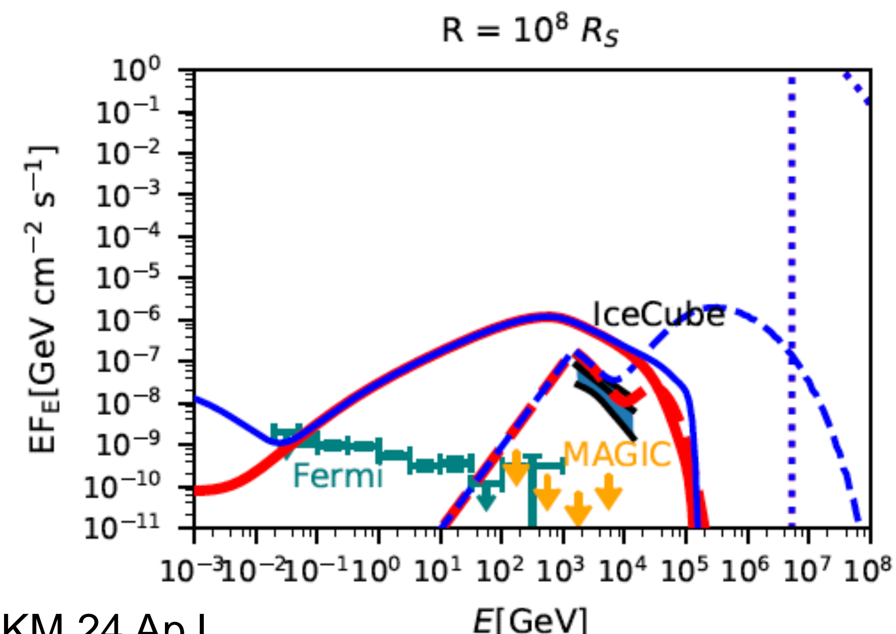
Neutrinos from $\gamma\gamma \rightarrow \mu^+\mu^-$
(Hooper & Plant 23 PRL)



Neutrons from photodisintegration
(Yasuda, Inoue & Kusenko 24)







Das, Zhang & KM 24 ApJ

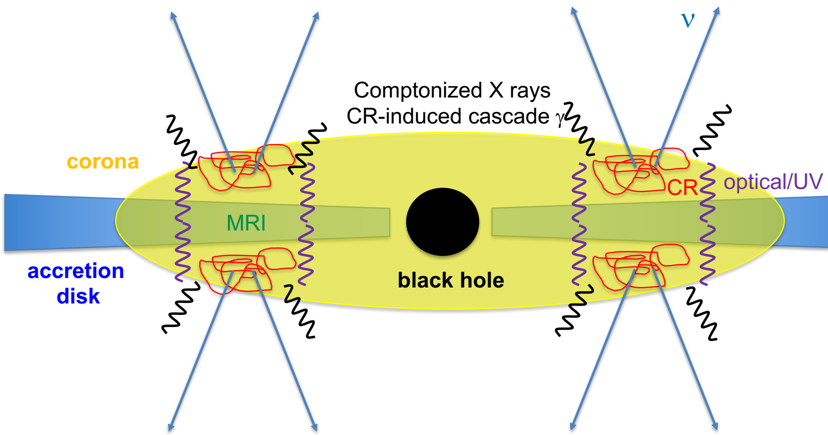
Particle Acceleration/Production Sites

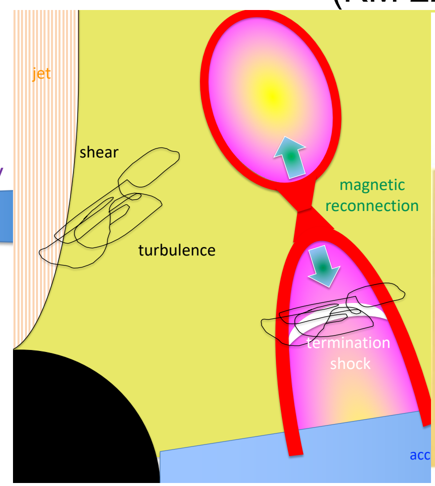
$$p + \gamma \rightarrow N\pi + X$$

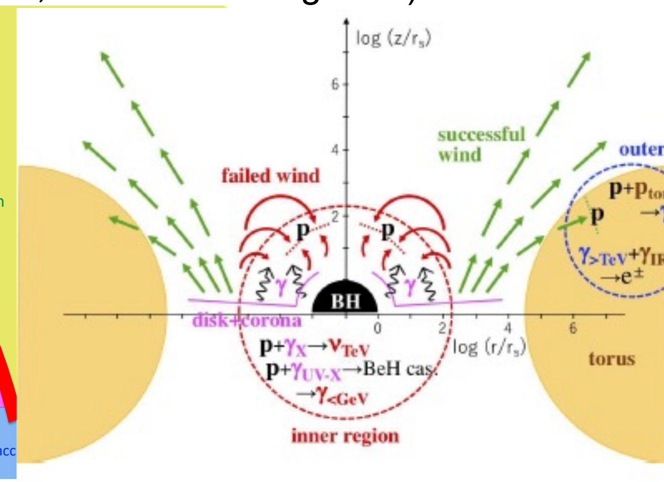
$$p + p \rightarrow N\pi + X$$

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

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







turbulence
magnetic reconnection

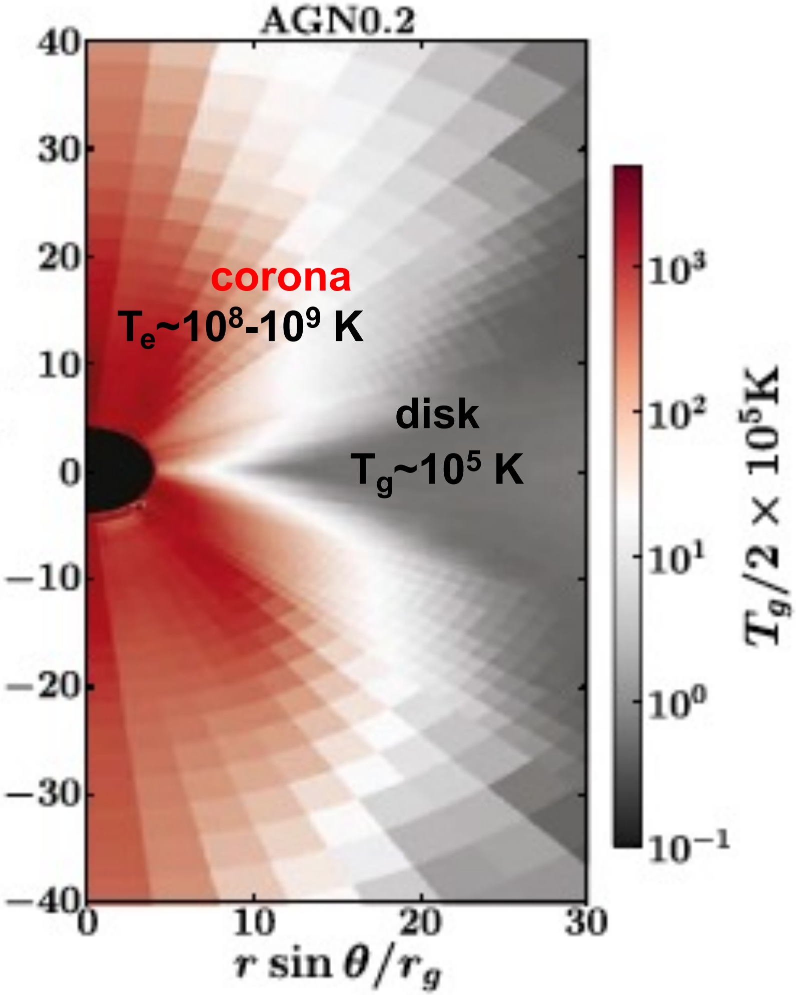
$\beta = P_g/P_B < 0.1\text{-}1 \rightarrow B > 10^3$ G
$L_{CR} <\sim L_X <\sim L_B$ (turbulent)

shocks

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

Coronal Regions: Magnetized & Collisionless

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



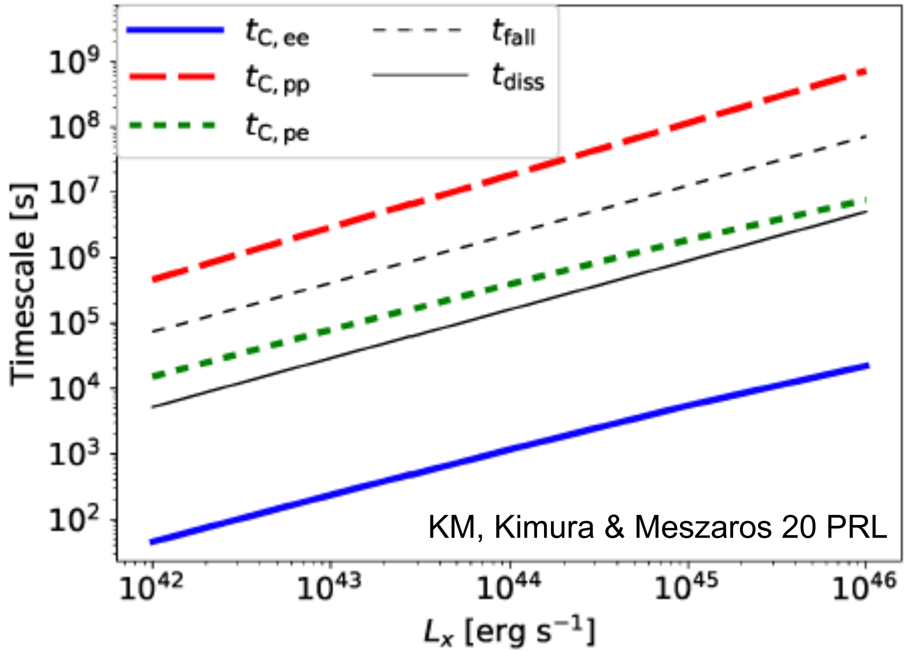
3D RMHD simulation w. Athena++

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

$\beta = P_g/P_B$ < 0.1-1 (σ_p >~ 0.01)

→ B > 10^3 G

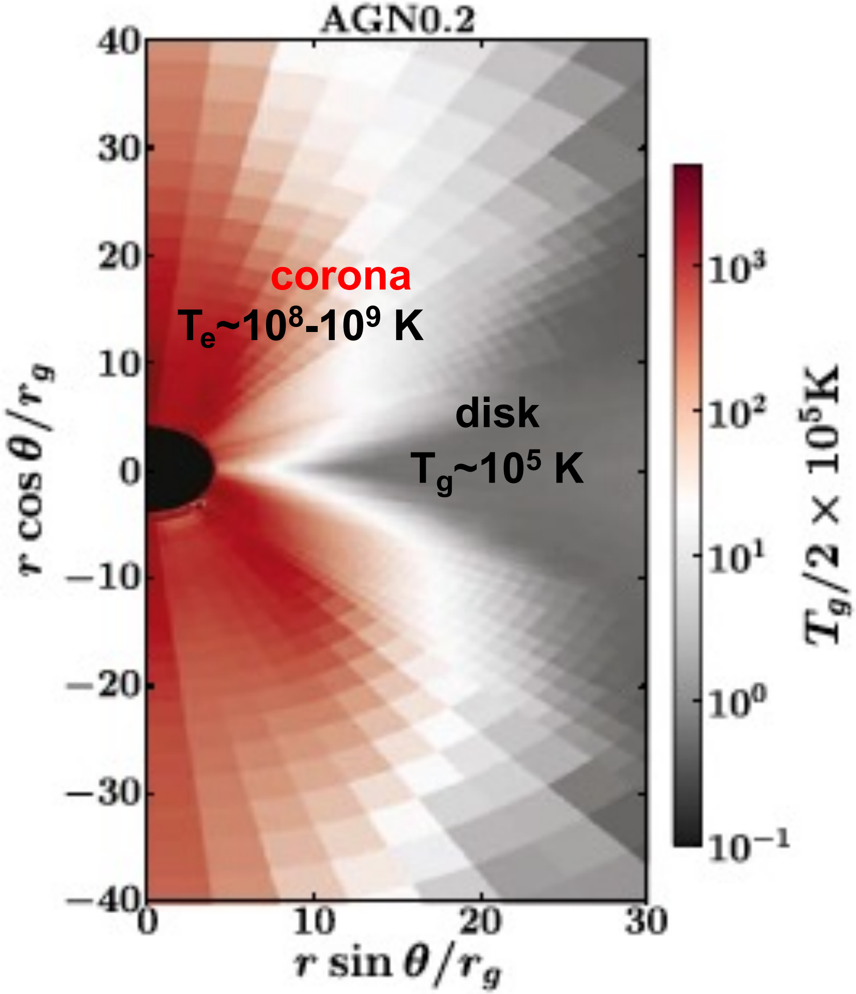
T_e ~ 10^8-10^9 K (← t_{Comp} ~ t_{heat})



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

Coronal Regions: Magnetized & Collisionless

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



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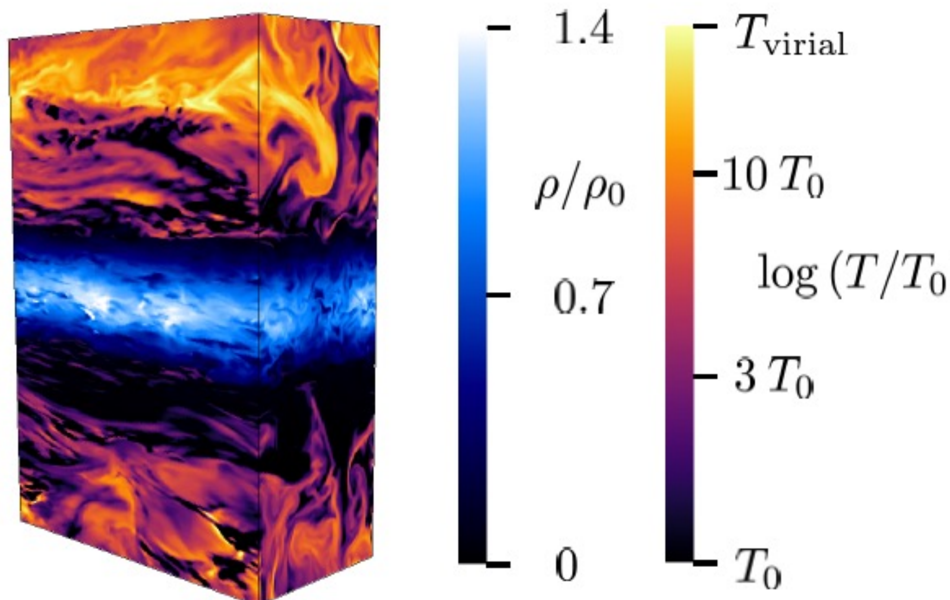
→ B > 10^3 G

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



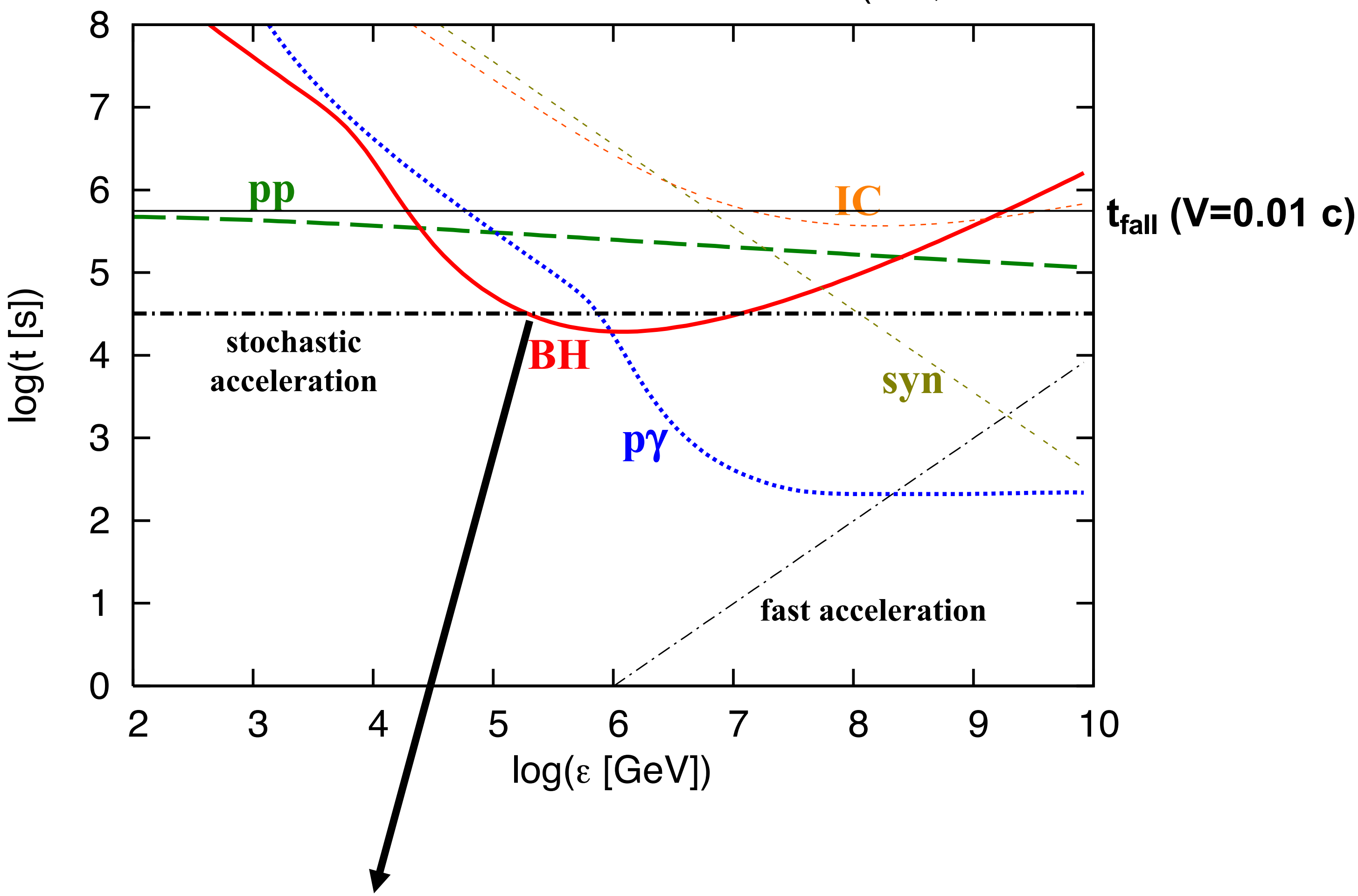
Bambic, Quataert & Kunz 23 MNRAS

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

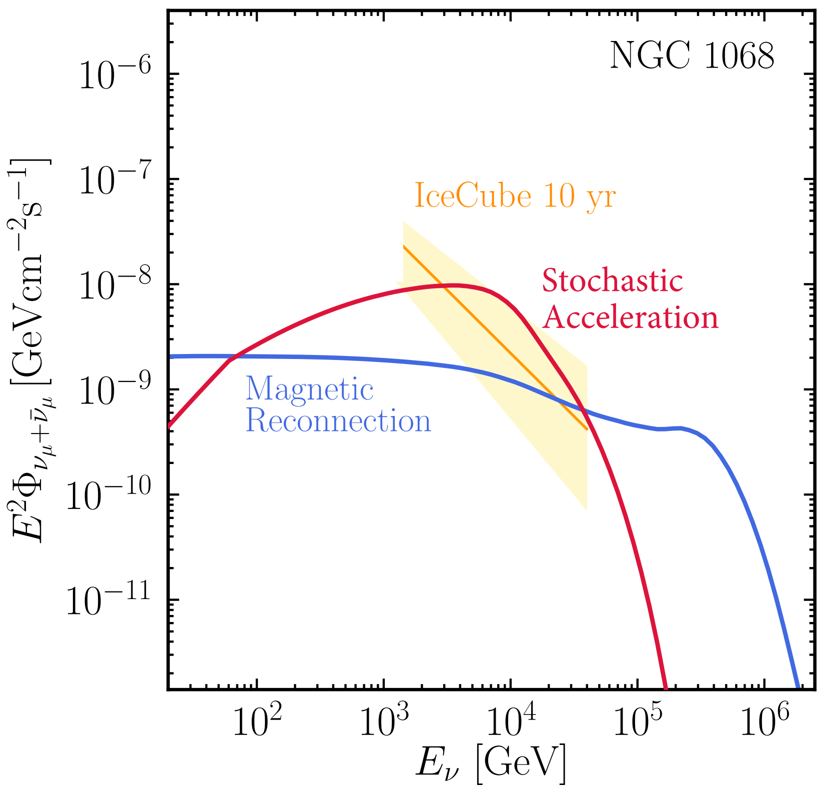
(KM, Kimura & Meszaros 20 PRL)

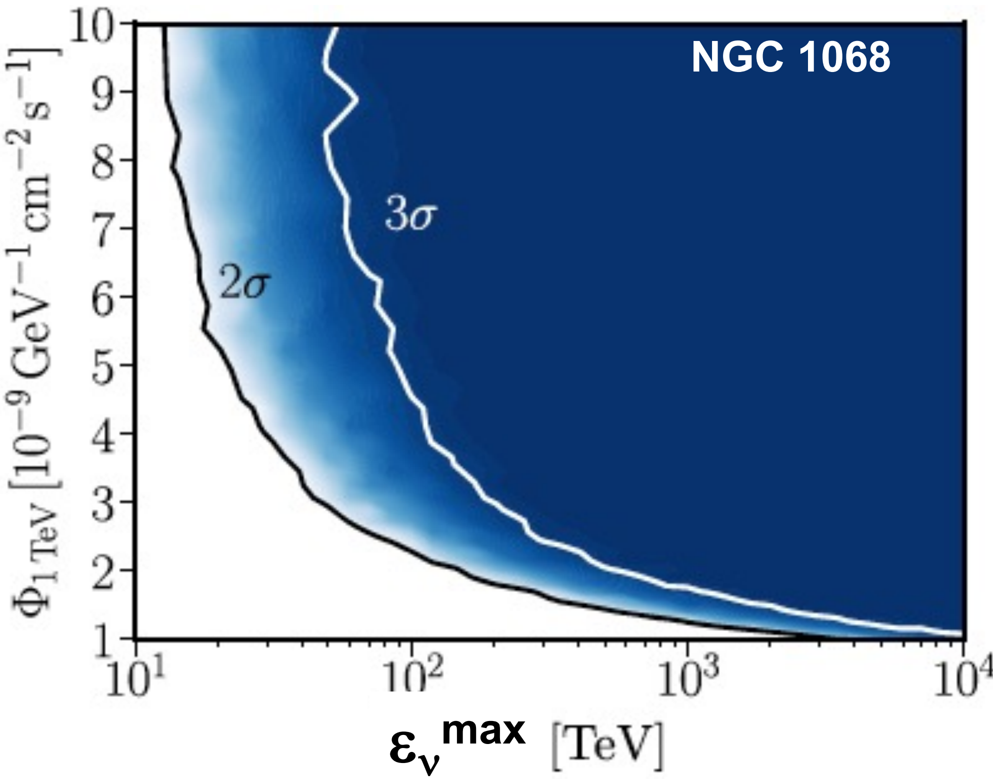


ε_p^{max} ~ 100 TeV → ε_ν^{max} ~ 2 TeV (consistent w. IceCube)

Neutrinos Can Probe Particle Acceleration in Coronae

Kheirandish, KM & Kimura 21 ApJ





$E_\nu^2\Phi_{\nu\mu}$ ~ 10^{-8} GeV cm^{-2} s^{-1} @ 1 TeV
constraints for an E_ν^{-2} spectrum
ε_ν^{max} < 10 TeV (ε_p^{max} < 200 TeV)

broken power-law by reconnections?
$\varepsilon_p^b = \sigma_p m_p c^2$ w. σ_p~10^5 (Fiorillo+ 24 ApJ)

Fokker-Planck Model for Turbulent Coronae

stochastic acceleration (Fokker-Planck eq.)

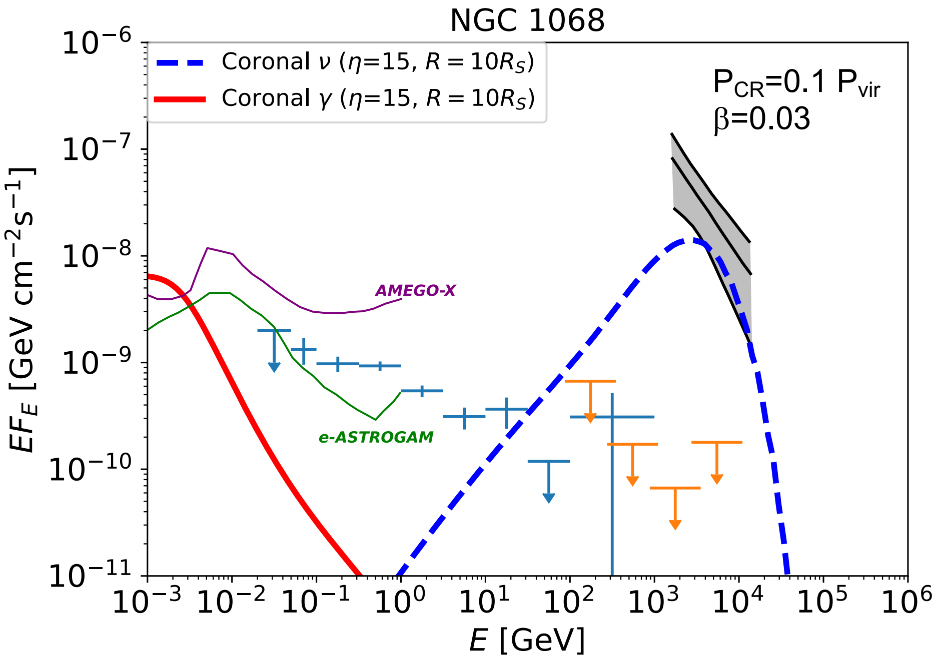
$$\frac{\partial \mathcal{F}_p}{\partial t} = \frac{1}{\varepsilon_p^2}\frac{\partial}{\partial \varepsilon_p}\left(\varepsilon_p^2 D_{\varepsilon_p}\frac{\partial \mathcal{F}_p}{\partial \varepsilon_p} + \frac{\varepsilon_p^3}{t_{p-\rm cool}}\mathcal{F}_p\right) - \frac{\mathcal{F}_p}{t_{\rm esc}} + \dot{\mathcal{F}}_{p,\rm inj},$$

(KM, Kimura & Meszaros 20 PRL, KM+ 24 ApJL, Fiorillo, Comisso+ 24 ApJ, Lemoine & Rieger 25 A&A)

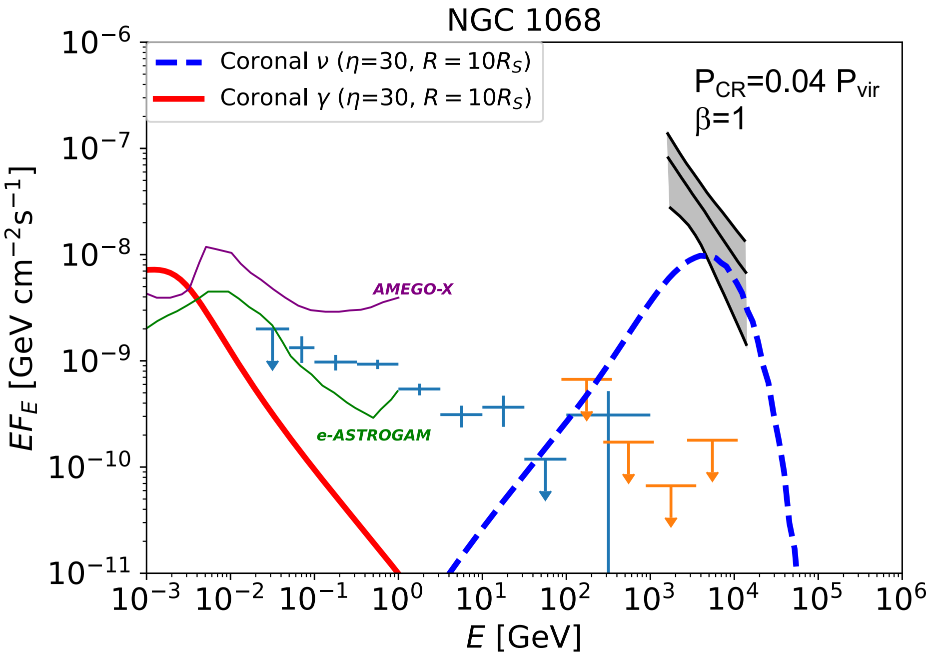
- Power-law dependence $D_{\varepsilon\varepsilon} \propto \varepsilon^q$
- CR pressure ~ 1-10% virial pressure

$n_e=\tau_T/(H\sigma_T)\sim 8\times10^{10}\ \mathrm{cm^{-3}}\ (\tau_T/0.5)(10^{13}\ \mathrm{cm}/H)$

$B = (8\pi\, n_p k_B T_{vir}/\beta)^{1/2} \sim 7\ \mathrm{kG}\ (\tau_T/0.5)^{1/2}\ (10R_S/R)\ \beta^{-1/2} \rightarrow r_L \sim 5\times10^7\ \mathrm{cm}\ (\varepsilon_p/100\ \mathrm{TeV})(B/7\ \mathrm{kG})^{-1}$



q=2 (hard-sphere)

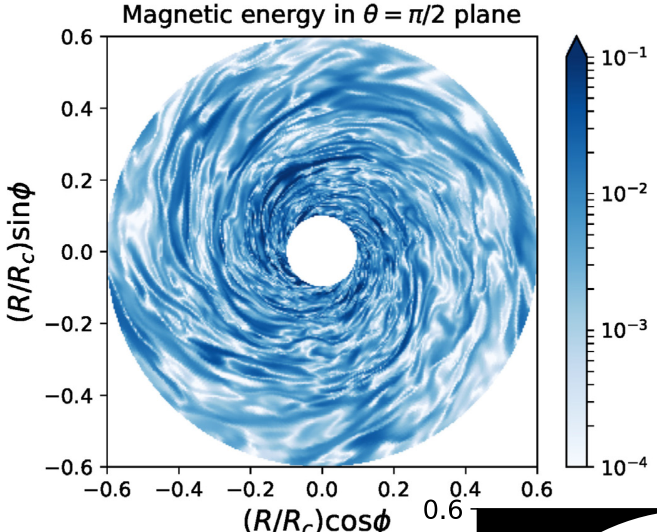


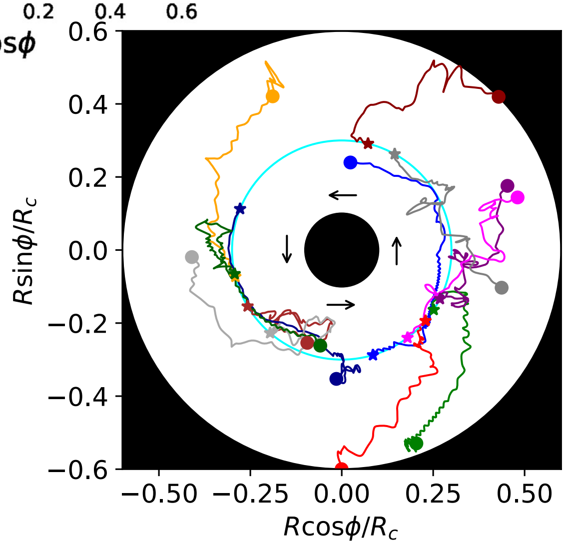
q=5/3 (Kolmogorov)

Simulating Particle Acceleration in Turbulence

stochastic acc. in 3D global MHD simulations

test particle sim. w. Athena++

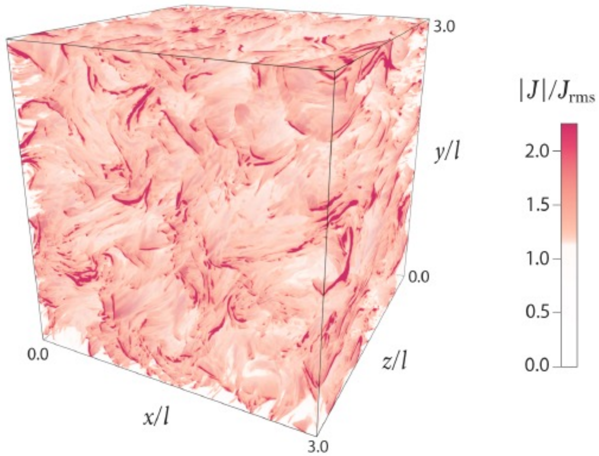


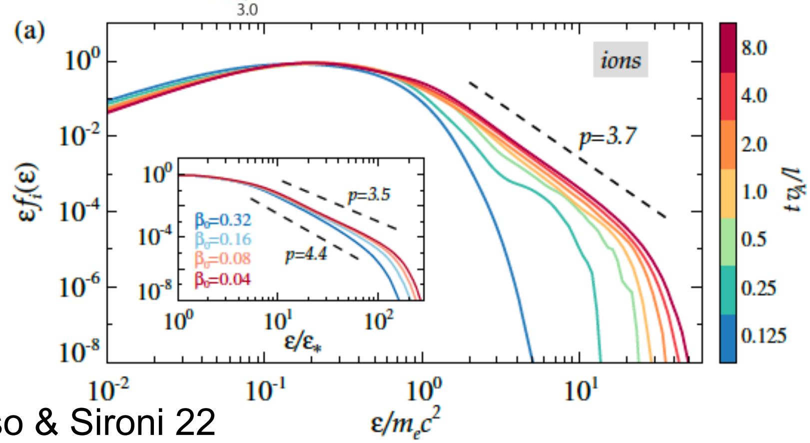


Kimura, Tomida & KM 19 MNRAS
Sun & Bai 21 MNRAS

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
Hoshino 15 PRL, Zhdankin+ 17 PRL, Lemoine 22 PRL

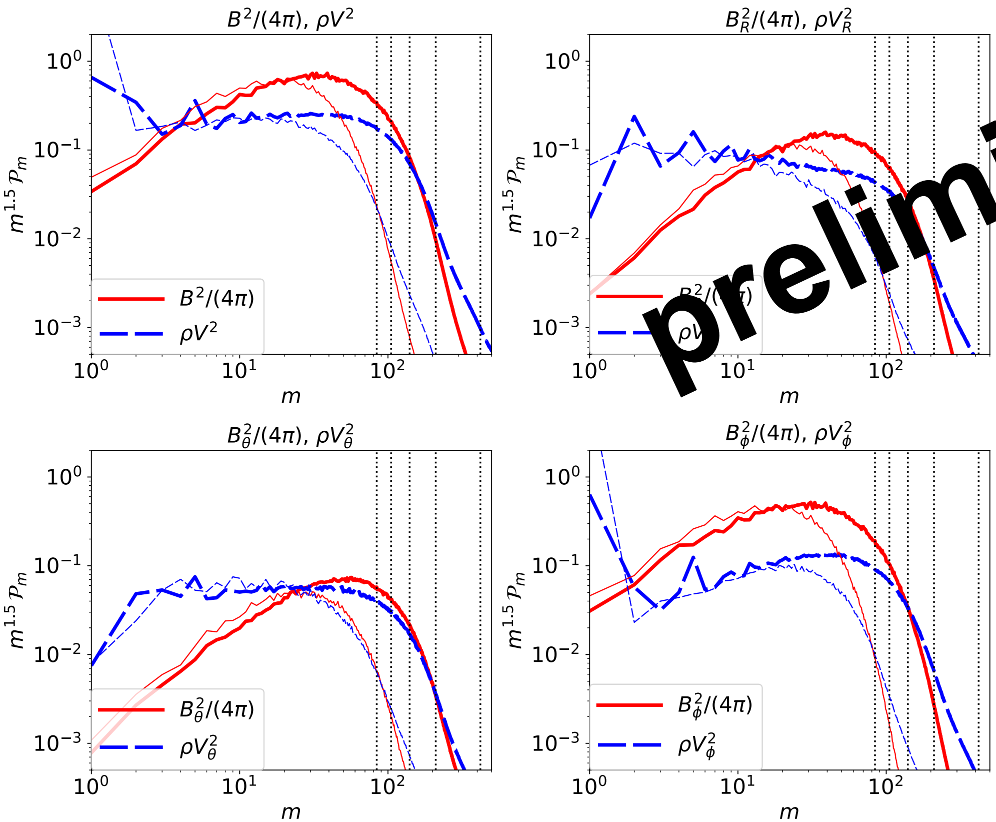
High-energy neutrinos now meet the frontier of astroplasma physics

Simulating Particle Acceleration in Turbulence

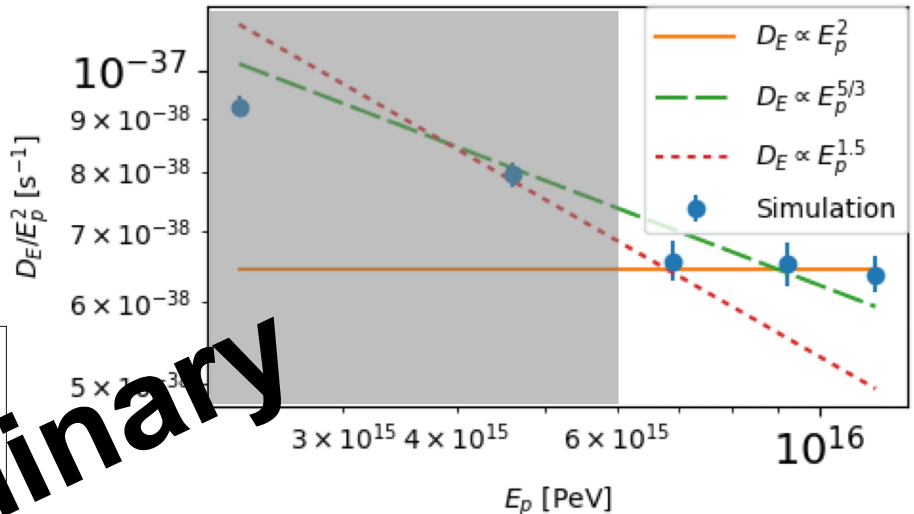
consistent w. $P_B(k) \propto k^{-1.5}$

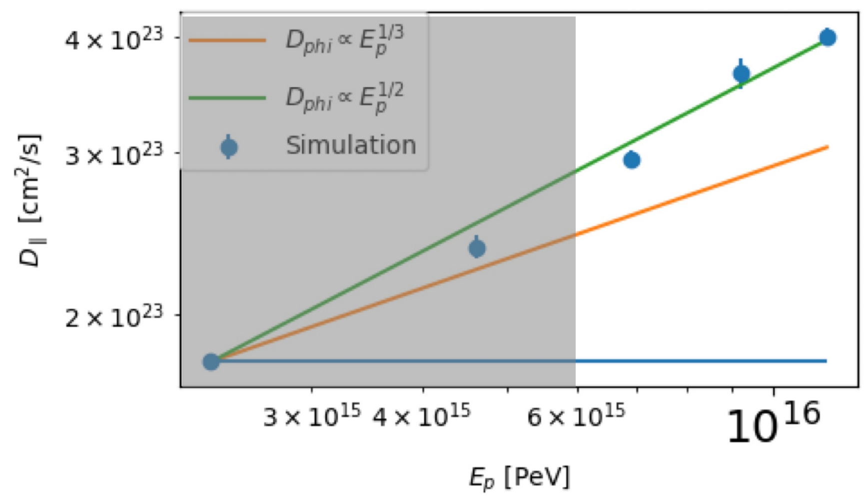
(Kawazura & Kimura 24 Science Adv.)

Kimura, KM et al. in prep.



preliminary



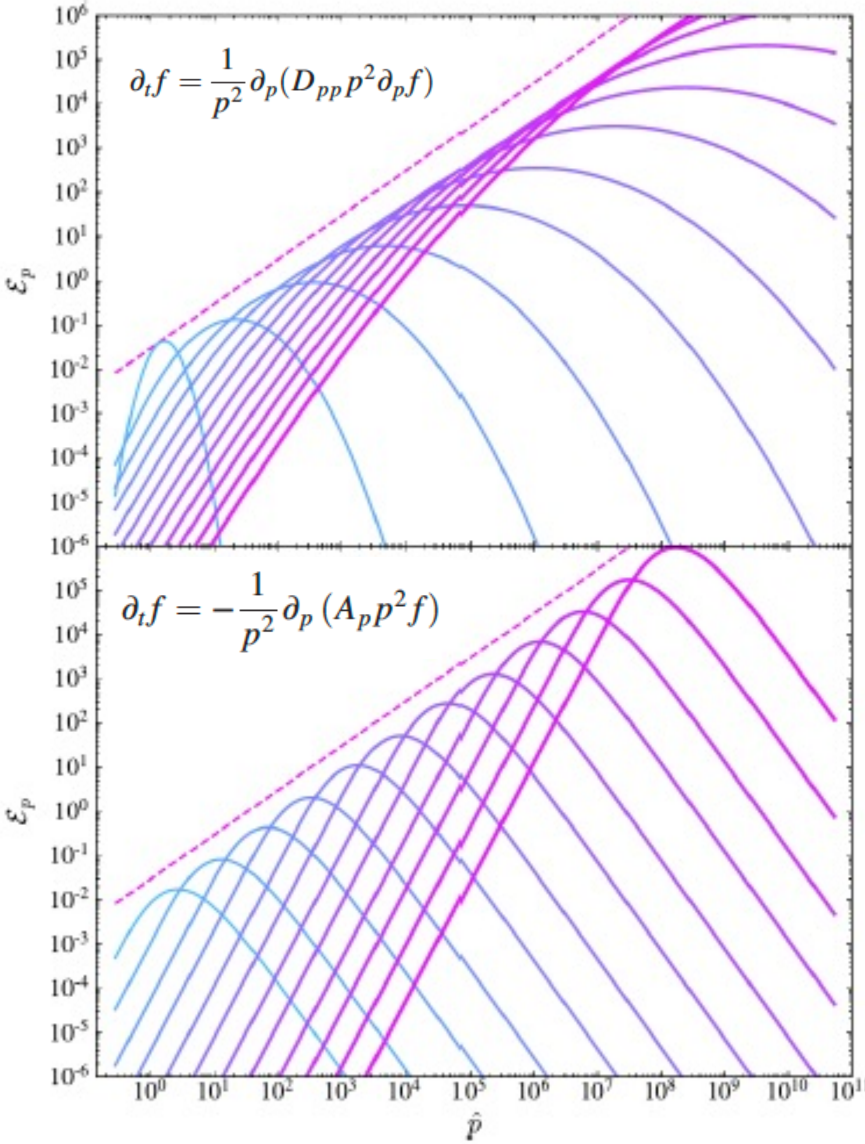


But we need higher-resolution simulations

magnetic reconnections are likely to be relevant for injections (ex. Mbarak+ 24 PRD)

Beyond the Fokker-Planck Model

Lemoine, KM & Rieger 24 PRD

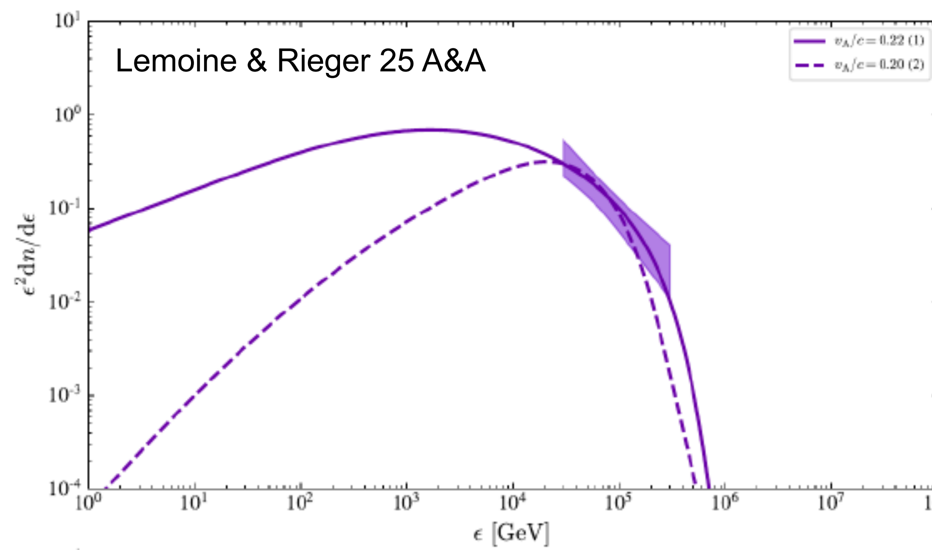


- PIC simulations suggest power-law distributions, localized interactions w. intense, intermittent structures (Wong+ 20 ApJL, Lemoine 21 PRD, 22 PRL)

- The time scale of driving turbulence is longer than the eddy turn-over time at the MHD scale etc.

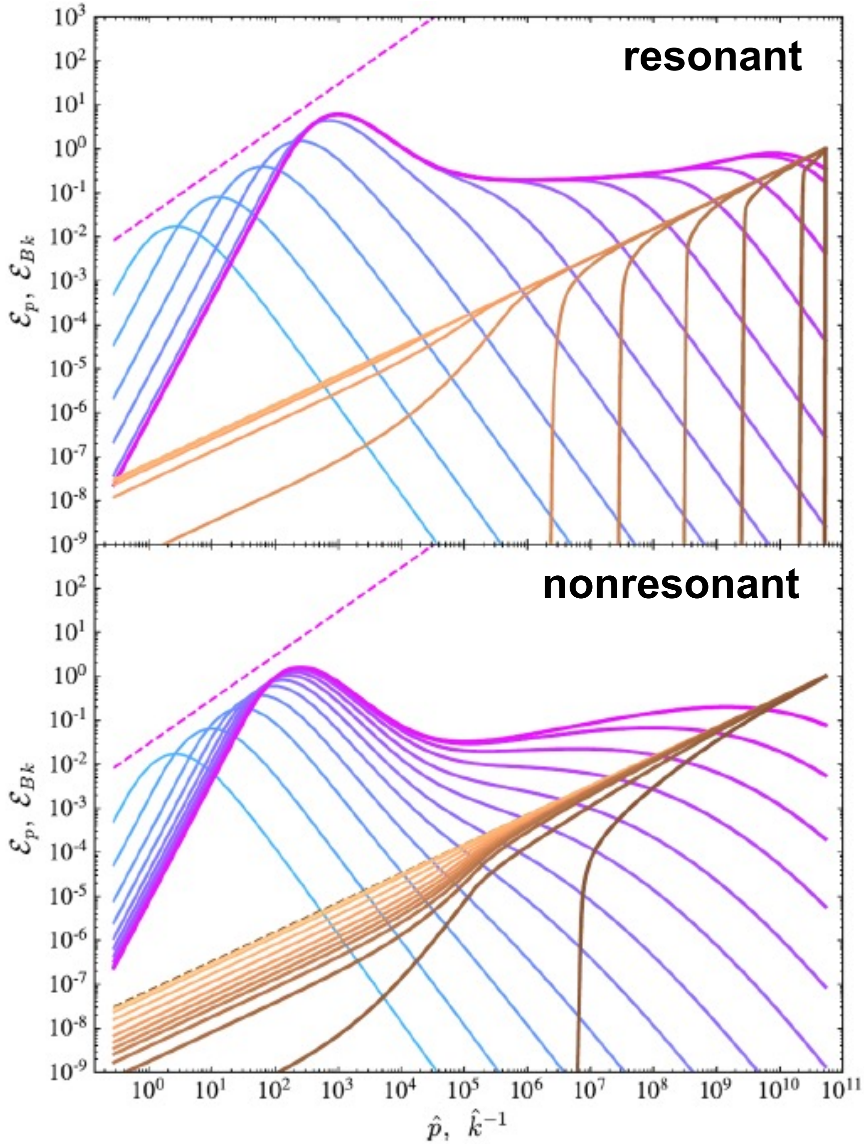
- In the corona setup, the peak is determined by the balance between acceleration and cooling. (KM+ 20)

- Good news for modeling:
  The resulting ν spectra are more or less similar.



Cosmic-Ray Feedback on MHD Turbulence

Lemoine, KM & Rieger 24 PRD

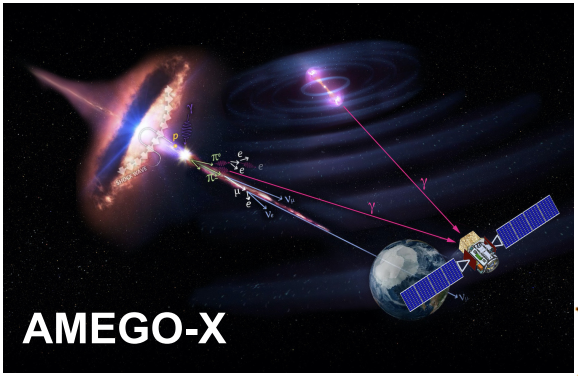


- NGC 1068: L_{CR} <~ L_X <~ L_B
- (CR energy) ~ (turbulence energy) may happen

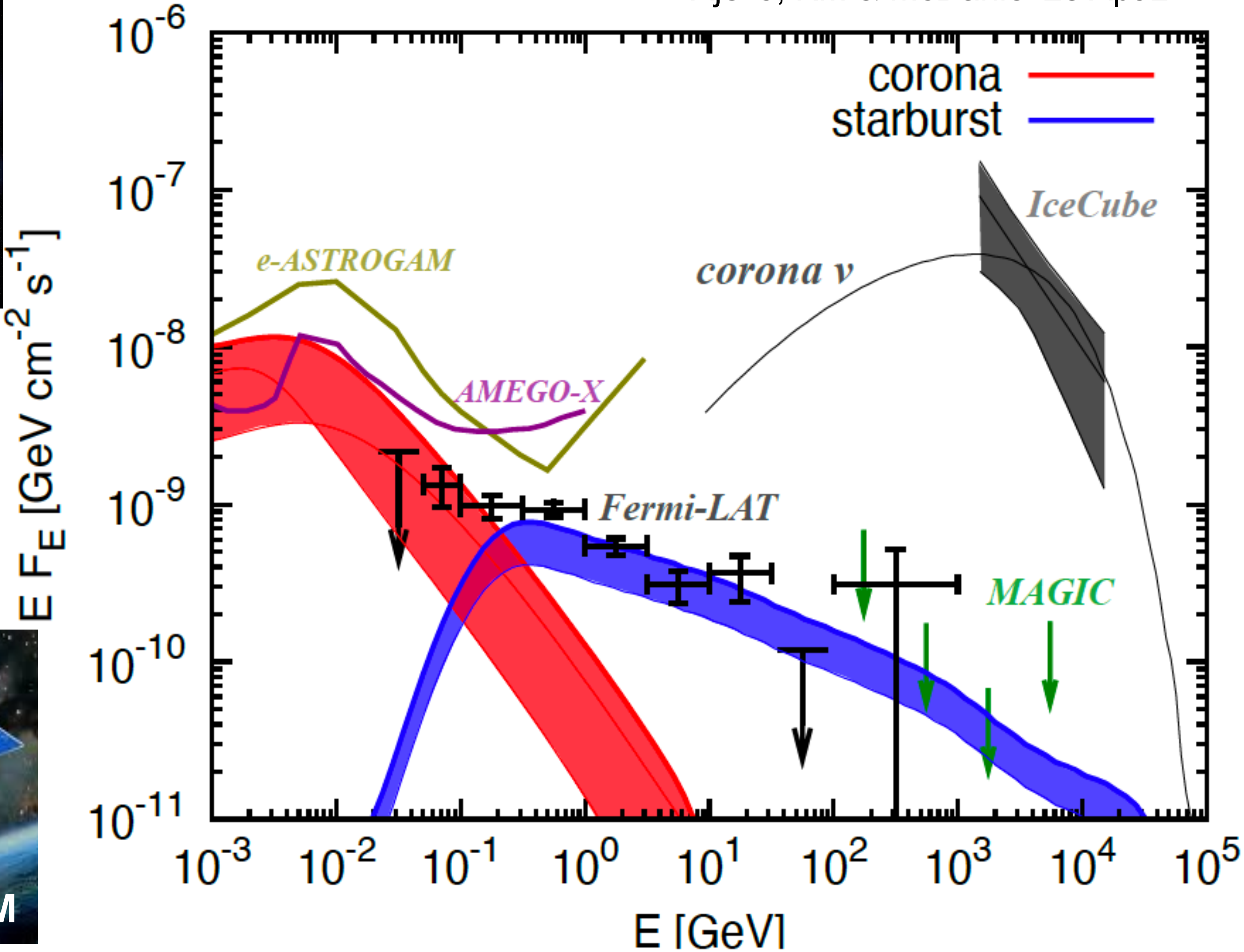
$$\partial_t \mathcal{E}_{Bk} = -k\partial_k(\gamma_k \mathcal{E}_{Bk}) - \int \mathrm{d}\ \ln\ p\,\Phi(k;p)\partial_t \mathcal{E}_p + \gamma_{\rm inj}\mathcal{E}_{\rm ext} k_{\rm inj}\delta(k-k_{\rm inj}) - \gamma_{\rm kin}\mathcal{E}_{k_{\rm kin}} k_{\rm kin}\delta(k-k_{\rm kin})$$

- CR energy spectra w.o. CR cooling can be flat (but CR cooling would lead to a bump)
- Just a toy model but potentially relevant for regulating the CR energy budget
- In any case we need to know energy flows… What powers coronae?

γ Rays Must Not Be Gone: Hints & Future MeV γ-Ray Tests



Ajello, KM & McDaniel 23 ApJL

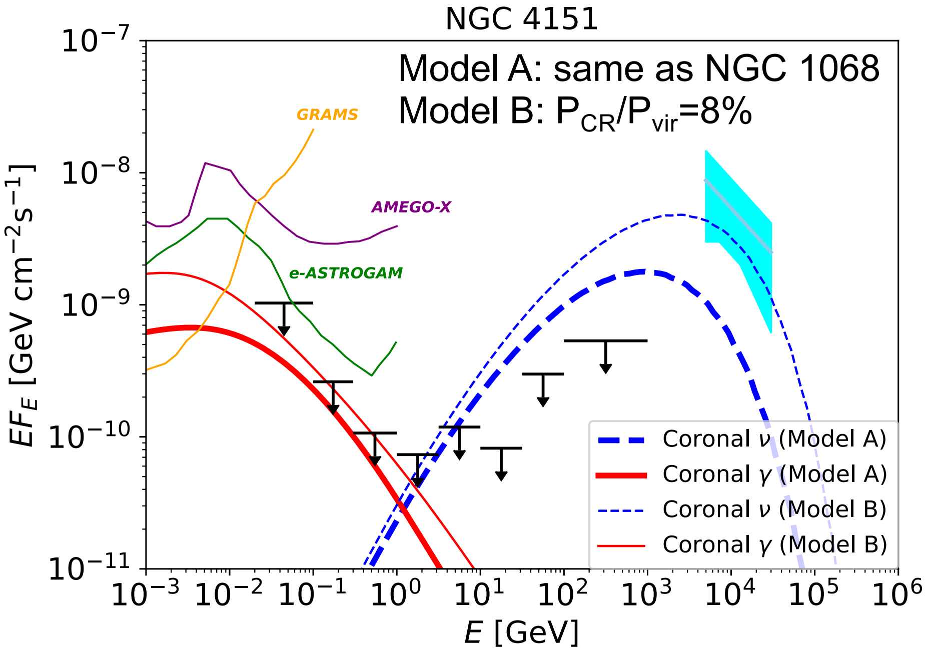


- Corona model prediction: cascade γ rays should appear in the MeV range
- Fermi γ-ray observation: sub-GeV “excess” over the starburst component

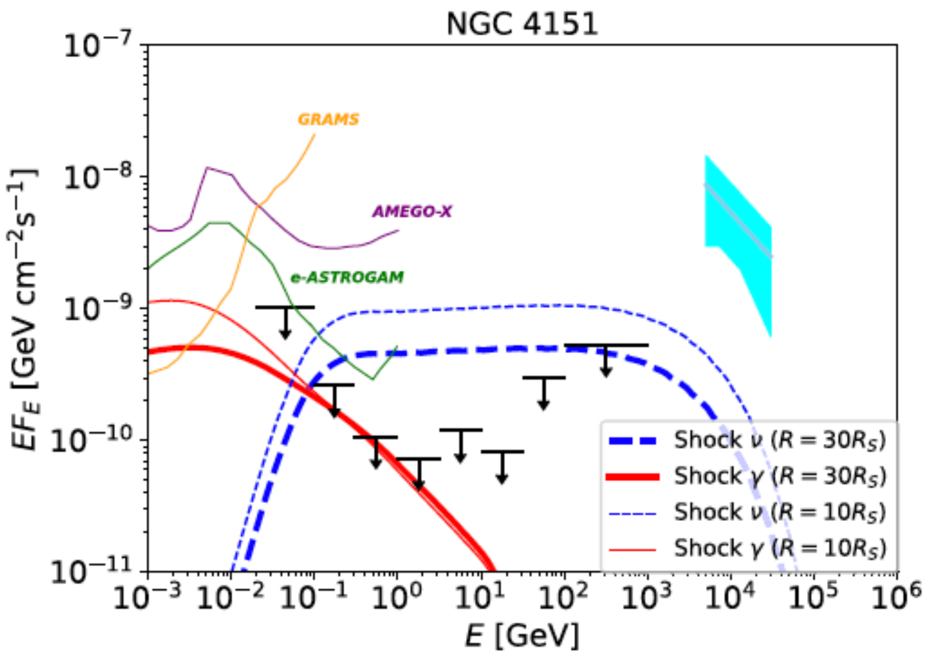
How about Others?: NGC 4151

- Prediction of the coronal model: X-ray bright AGN ~ ν bright AGN (KM+ 20 PRL)
  brightest AGN in north: NGC 1068, NGC 4151
  brightest AGN in south: NGC 4945, Circinus
- 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 understanding physics

stochastic acceleration



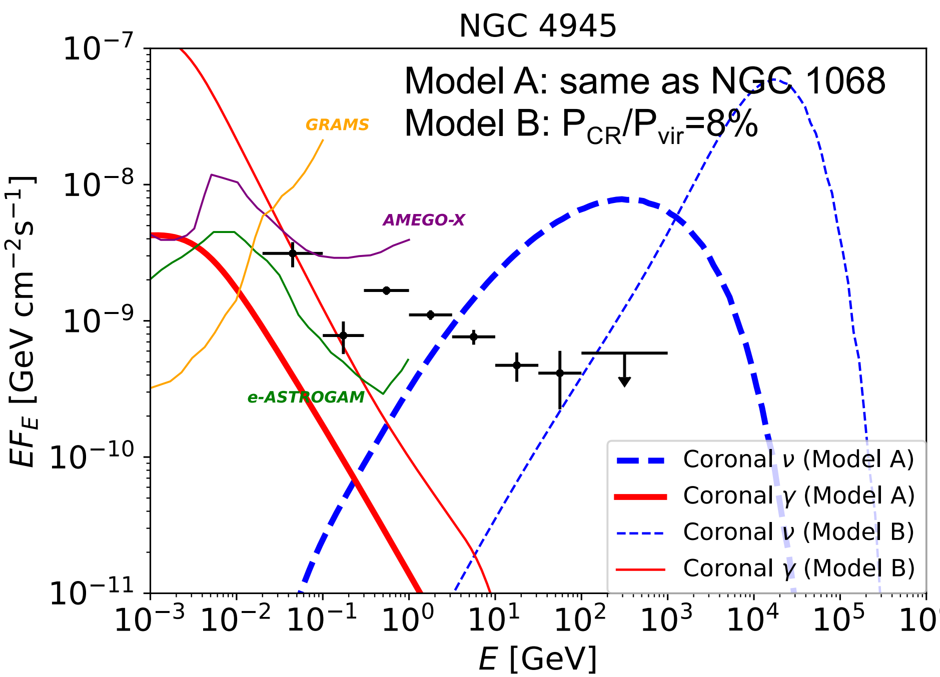
fast acceleration (E^{-2} injection)

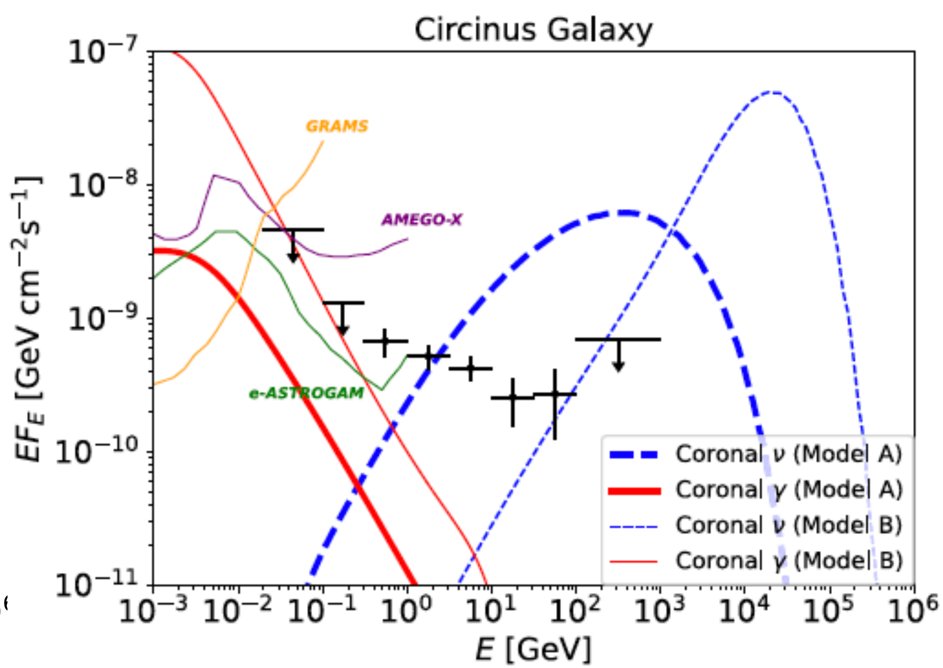


KM, Karwin, Kimura, Ajello & Buson 24 ApJL

How about Others?: AGN in South

- Prediction of the coronal model: X-ray bright AGN ~ ν bright AGN (KM+ 20 PRL)
  brightest AGN in north: NGC 1068, NGC 4151
  brightest AGN in south: NGC 4945, Circinus
- 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

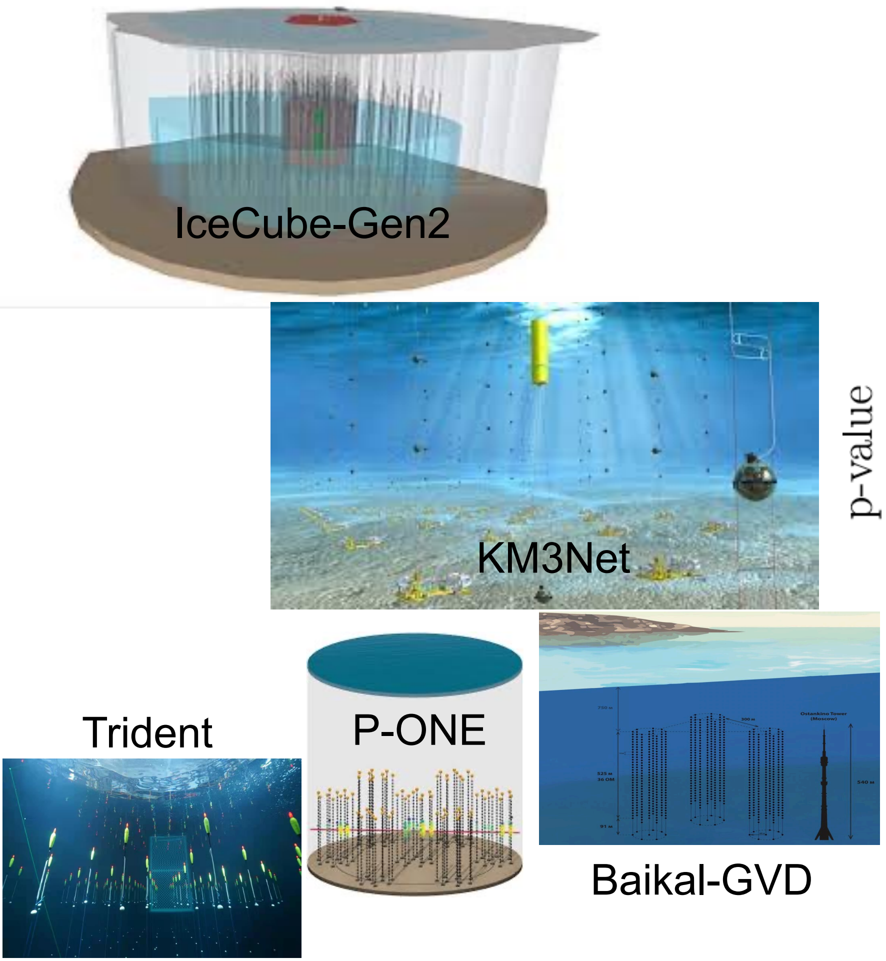


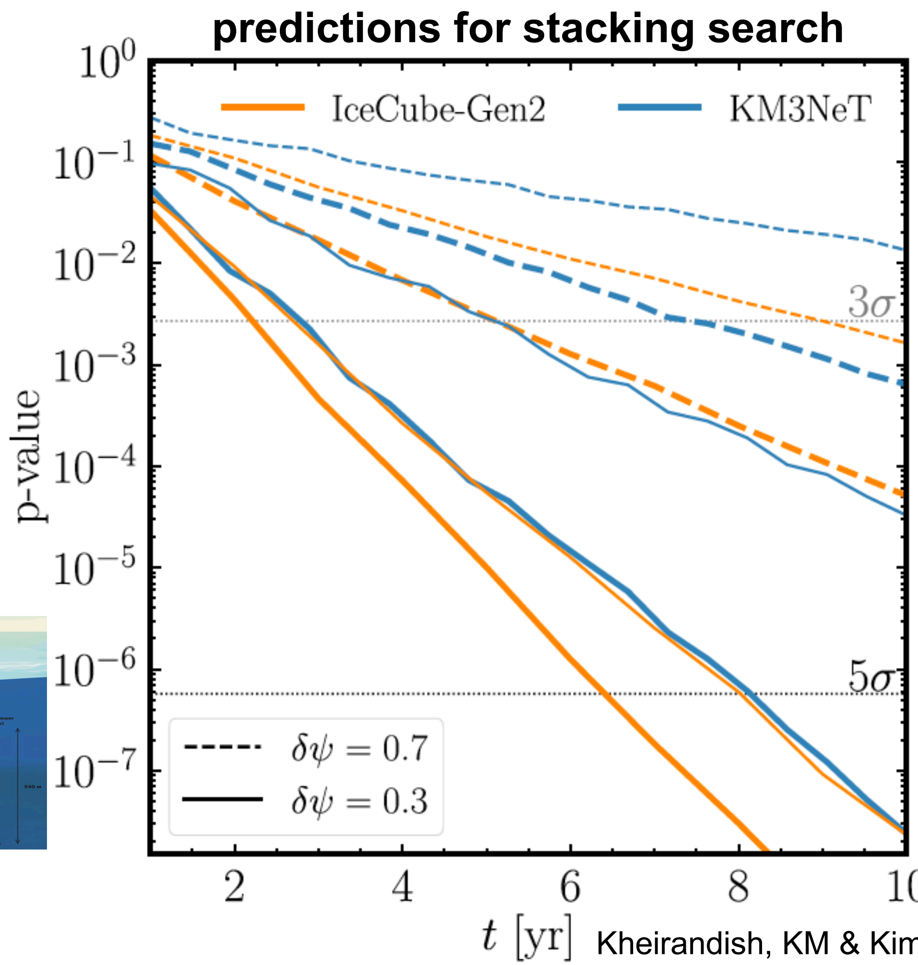


KM, Karwin, Kimura, Ajello & Buson 24 ApJL

Further Tests with Neutrinos

- 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



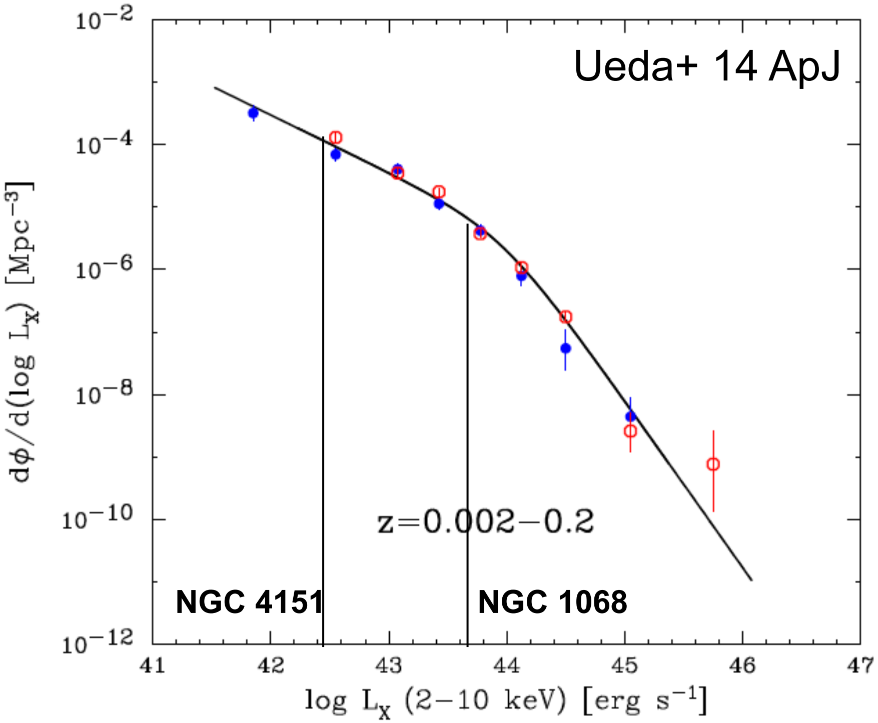


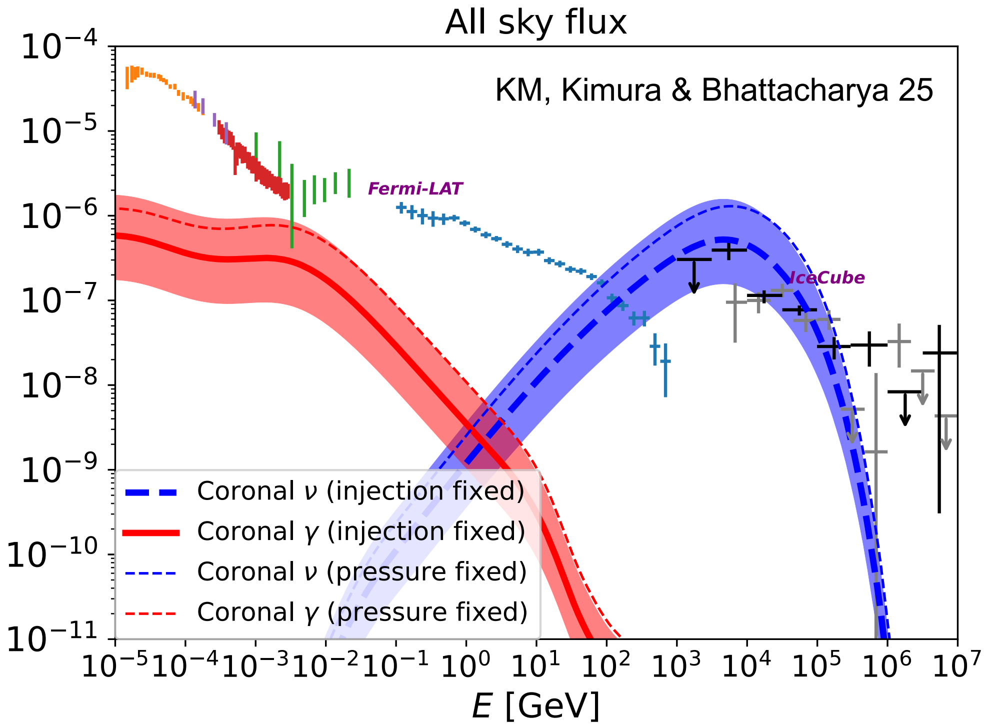
Kheirandish, KM & Kimura 21 ApJ

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

Contribution to the All-Sky Neutrino Flux

- AGN corona model was proposed to explain the all-sky ν flux (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}
- The all-sky ν flux can be explained simultaneously within uncertainty
- Higher-energy neutrinos originate from lower-luminosity AGN





Summary

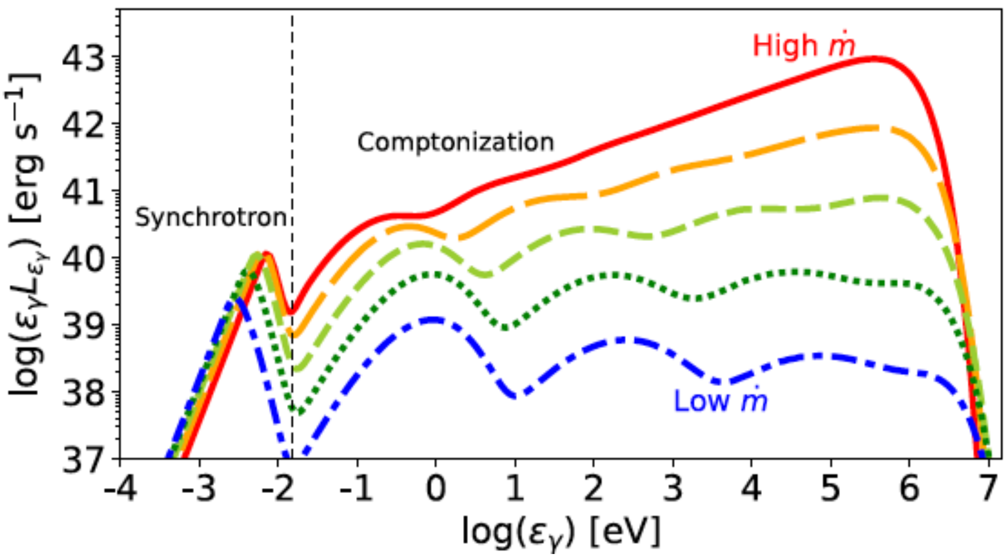
- Multimessenger analyses on 10 TeV ν data require hidden CR accelerators
- Jet-quiet AGN: the most promising by energetics (whether ~3-4σ is real or not)

- NGC 1068 & NGC 4151:
  indications of hidden ν sources, predicted to be the top 2 sources for IceCube

If the associations are physical…
- 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 (Compton-thin) may be better for testing the theory
- Relevance of AGNs in the southern sky (NGC 4945, Circinus)
- Consistent with the measured all-sky ν flux in the 10-100 TeV range

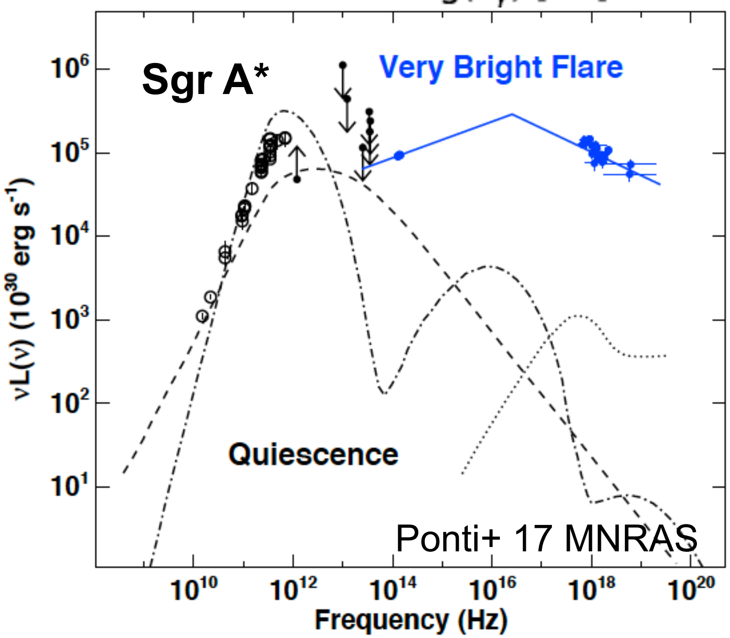
Future:
- More statistics, next-generation ν detectors (KM3Net, Baikal, P-ONE, Gen2)
- Synergy w. MeV γ-ray, hard X-ray, and millimeter observations
- Physical connections to LL AGNs (RIAFs/MADs)
- Theory: Multimessenger, Multiscale, Magnetic in the vicinity of black holes

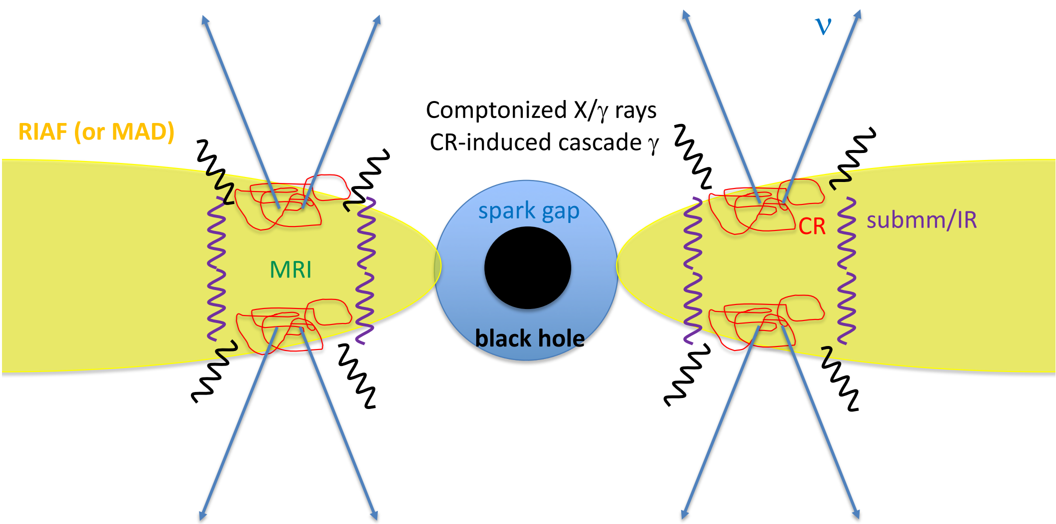
Radiative Inefficient Accretion Flows



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

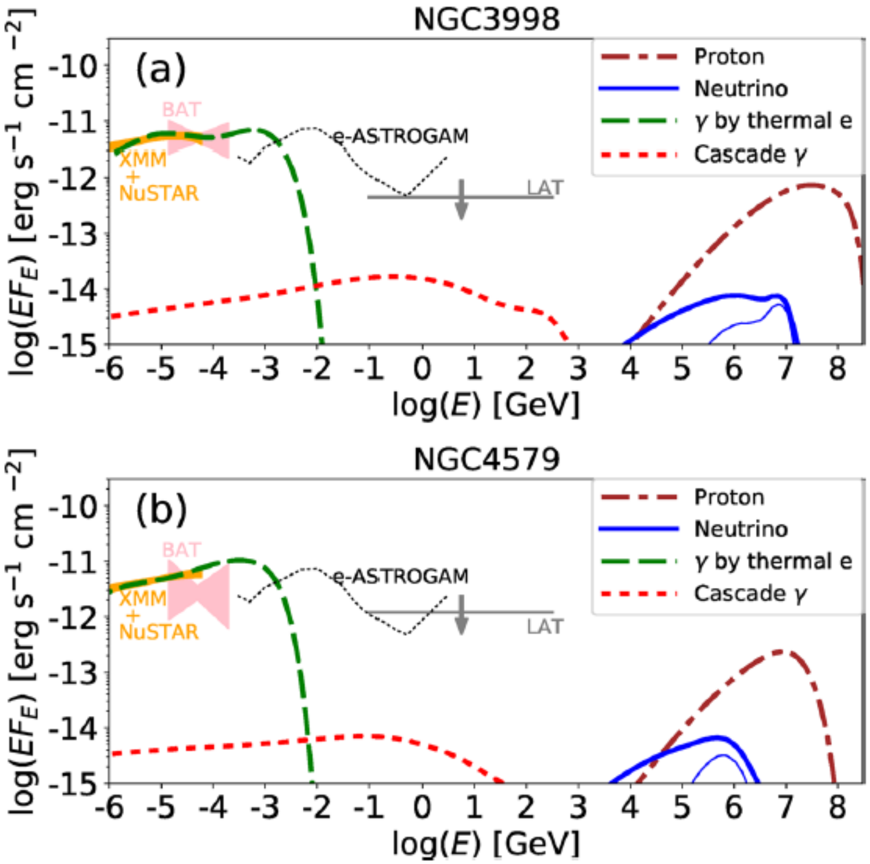
- RIAF for mdot<0.03
- Hot plasma
- Electrons are mostly thermal (collisional for electrons collisionless for protons)

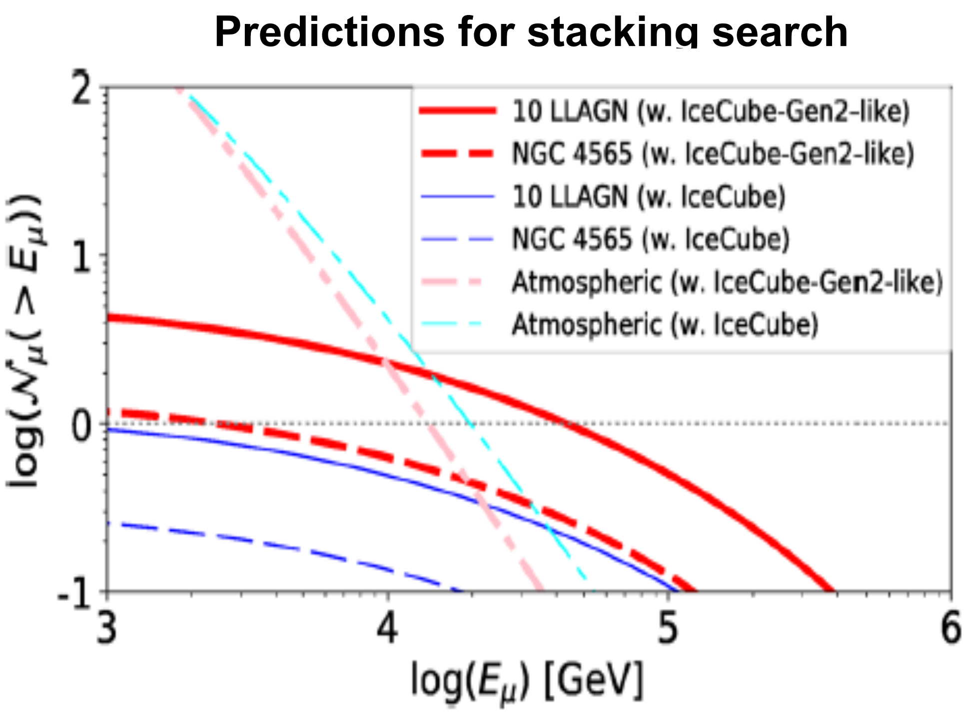




Detectability of Nearby Low-Luminosity AGN

Kimura, KM & Meszaros 21 Nature Comm.



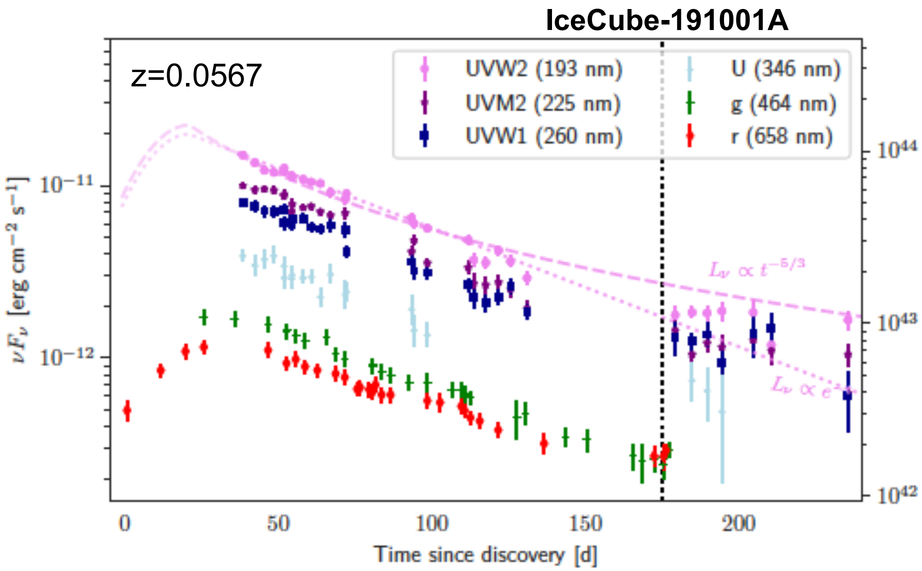


- Detection of MeV γ due to thermal electrons is promising (CR-induced cascade γ rays are difficult to observe)
- Nearby LL AGN can be seen by IceCube-Gen2/KM3Net

Coincidences w. Optical Transients

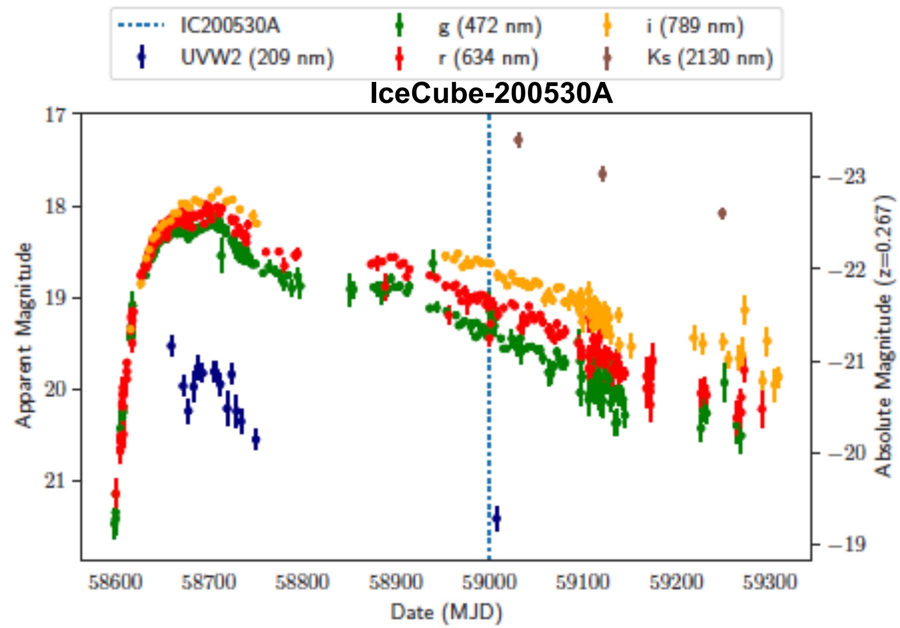
Tidal disruption events (TDEs) – supermassive black hole flares

IceCube-191001A & AT 2019dsg



Stein+ 21 Nature Astron.

IceCube-200530A & AT 2019fdr

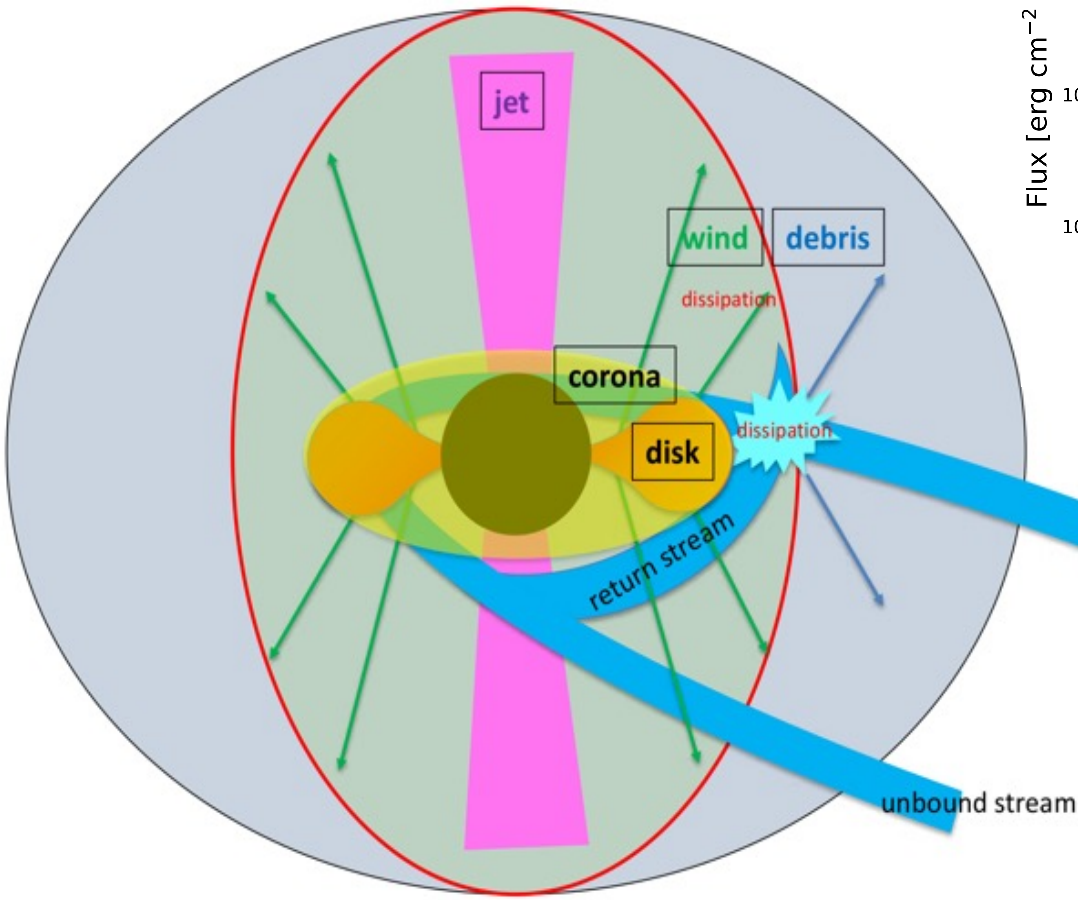


Reusch+ KM 21 PRL

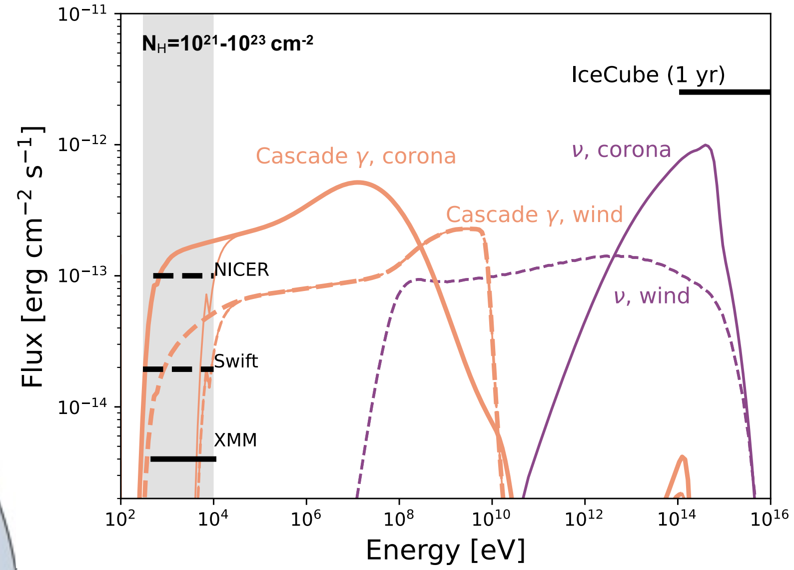
- 5 TDE coincidences have been reported (van Velzen+ 23, Jiang+ 23)
- All are rare optical transients w. strong infrared echoes
- Possible neutrino time delays w. ~150-300 day

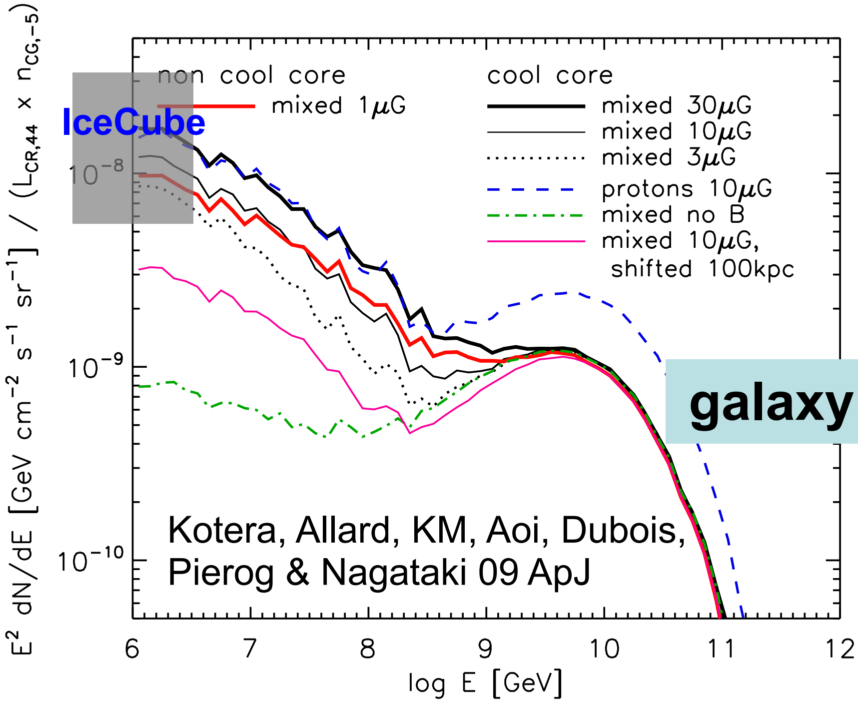
Neutrinos from Tidal Disruption Events?

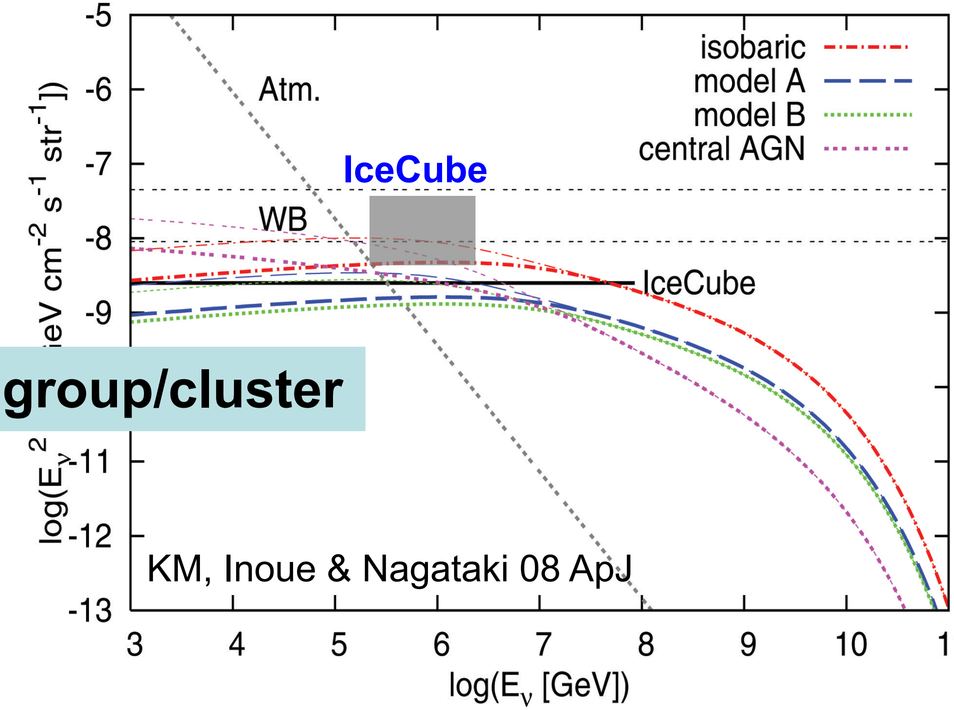
TDE and AGN νs could come from "common" mechanisms
(disk-corona, hidden wind, hidden jet)



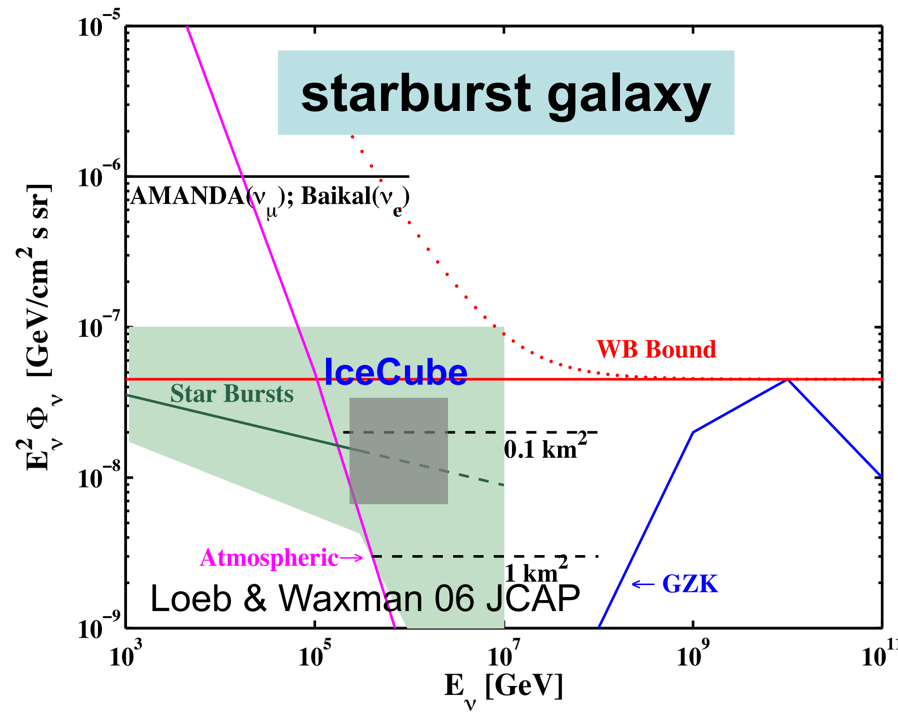
KM, Kimura, Zhang et al. 20 ApJ







galaxy group/cluster

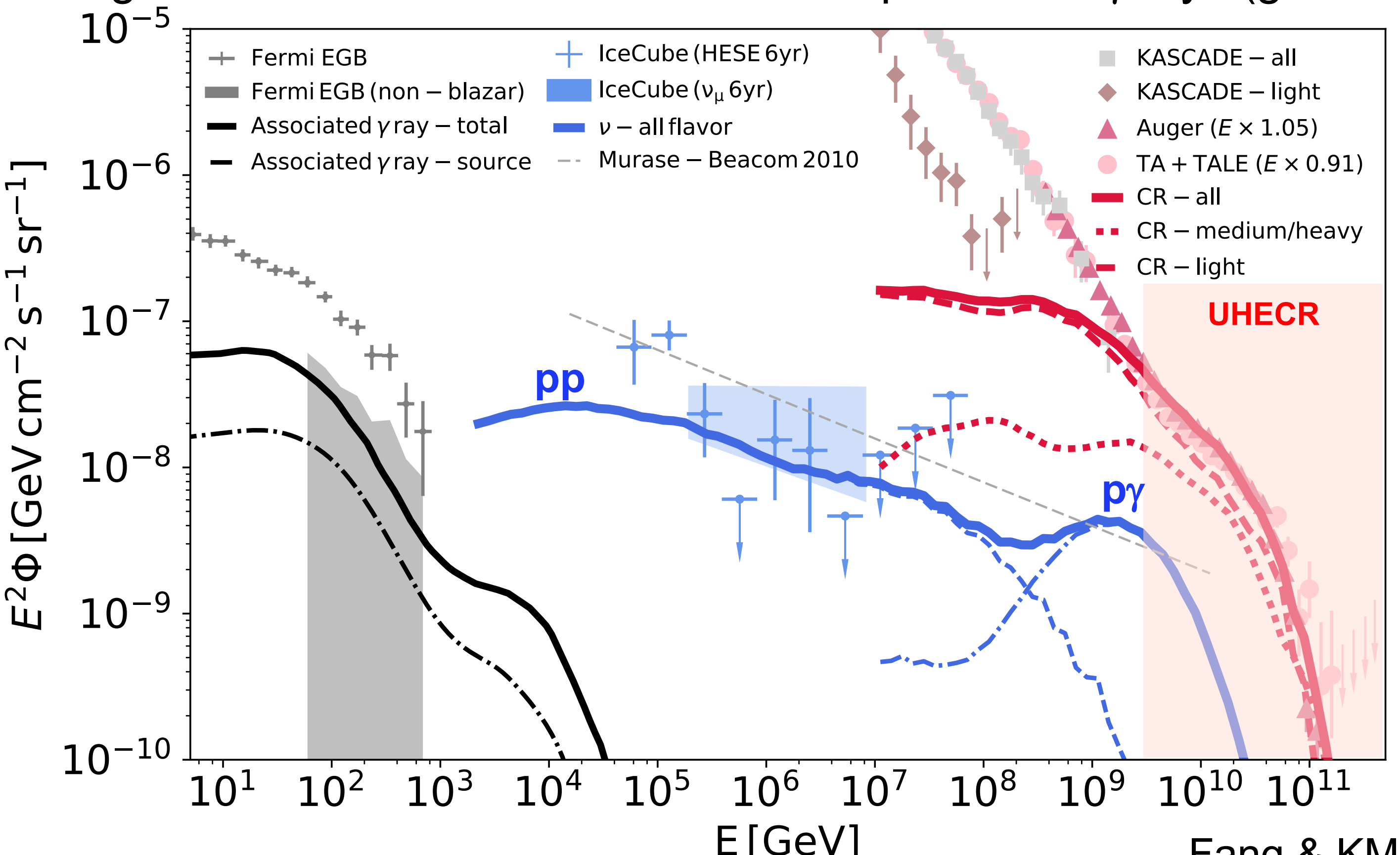


starburst galaxy

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

High-Energy Astro-Particle Grand-Unification?

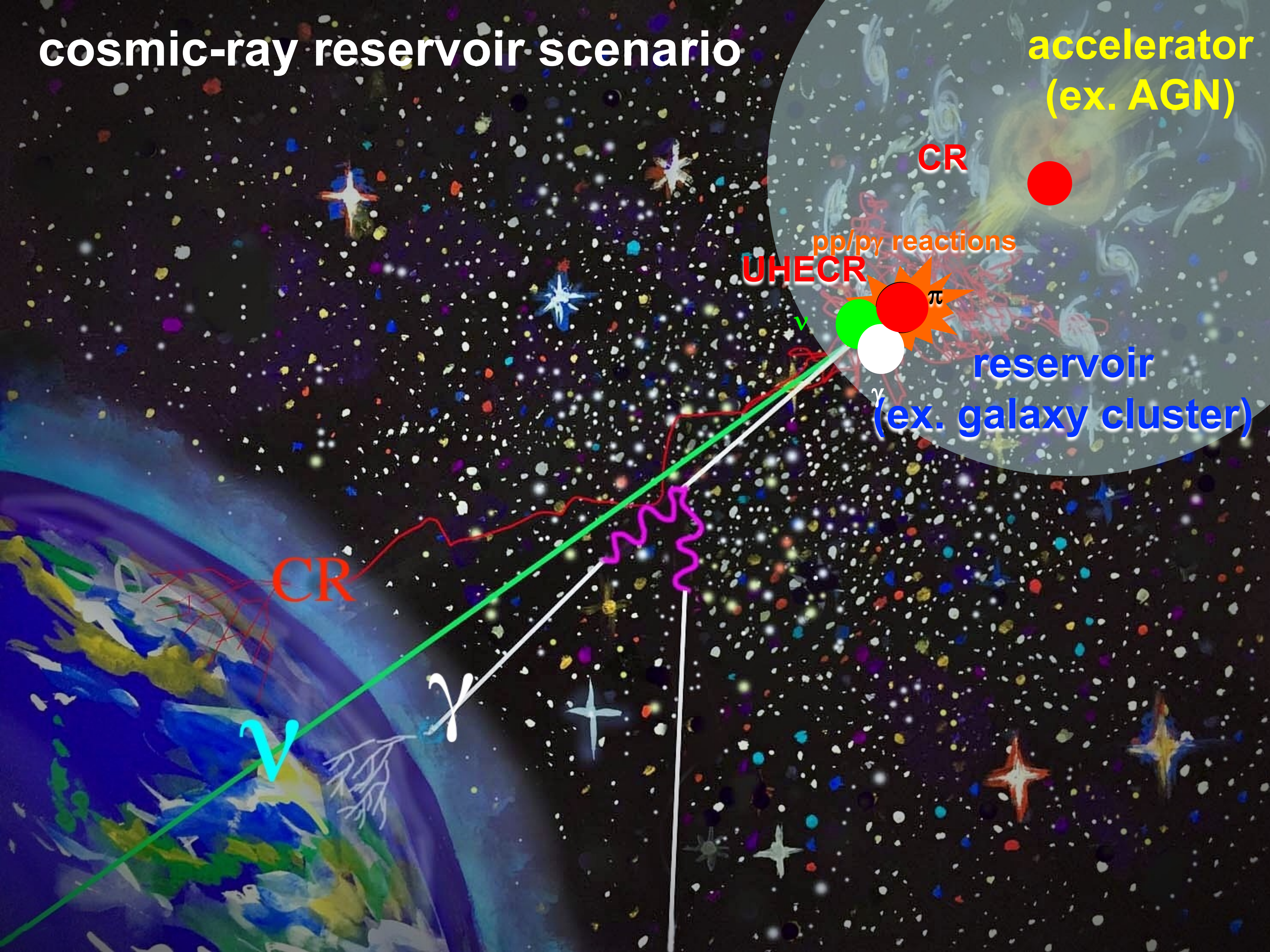
>100 TeV νs may originate from GeV γ-ray transparent sources including CR reservoirs
> PeV νs might be related to UHECRs and isotropic diffuse γ rays (grand-unification)



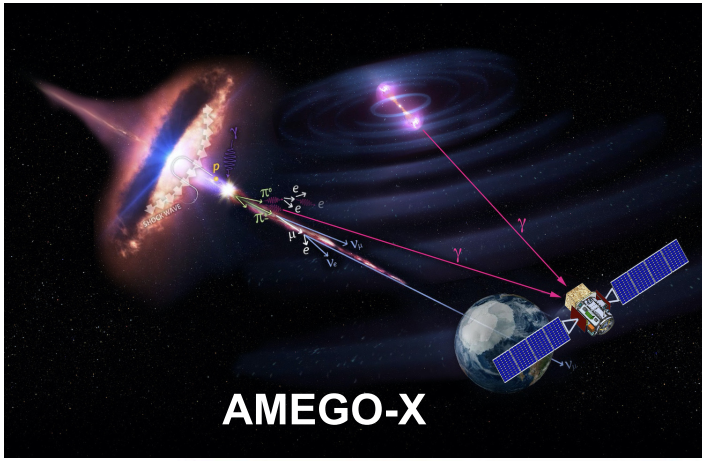
Fang & KM 18 Nature Phys.
(see also Kachelriess+ 17)

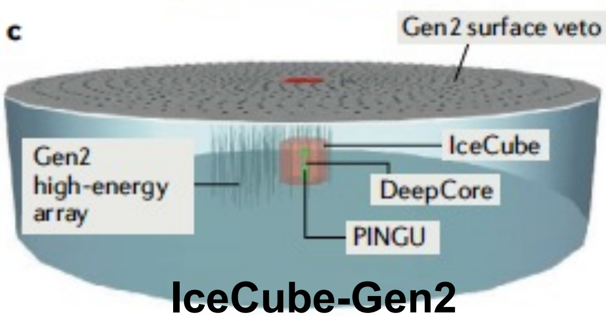
- Jetted AGN as “UHECR” accelerators
- Neutrinos from confined CRs & UHECRs from escaping CRs
- Smooth transition from PeV (source ν) to EeV (cosmogenic ν)

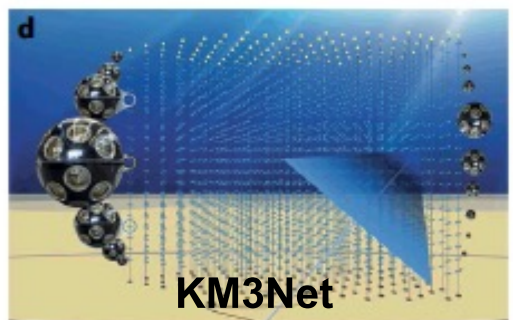
cosmic-ray reservoir scenario

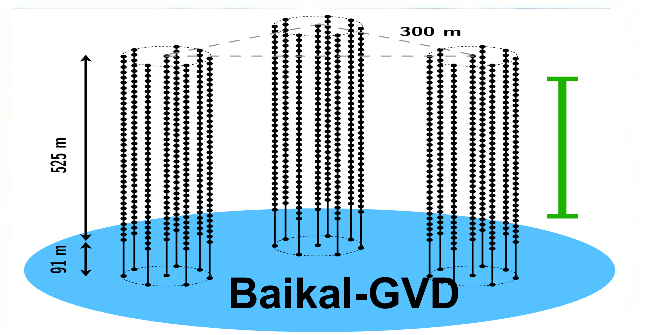


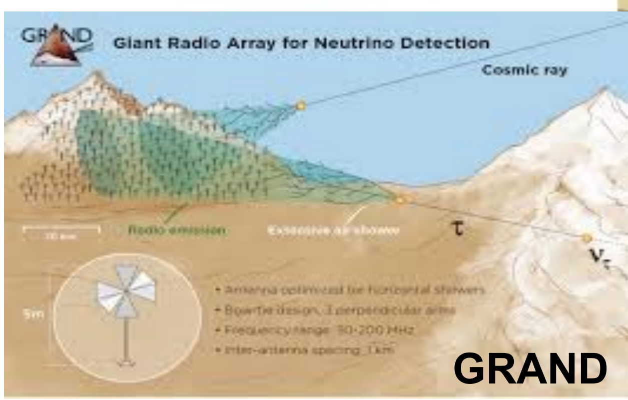
Bright Future











More multimessenger data in the next decade will enable us to test the proposed models


Thank you very much!