High-Energy Cosmic Neutrinos (Theory)

Kohta Murase (Penn State/YITP)

June 25
Neutrino 2026 @ Irvine

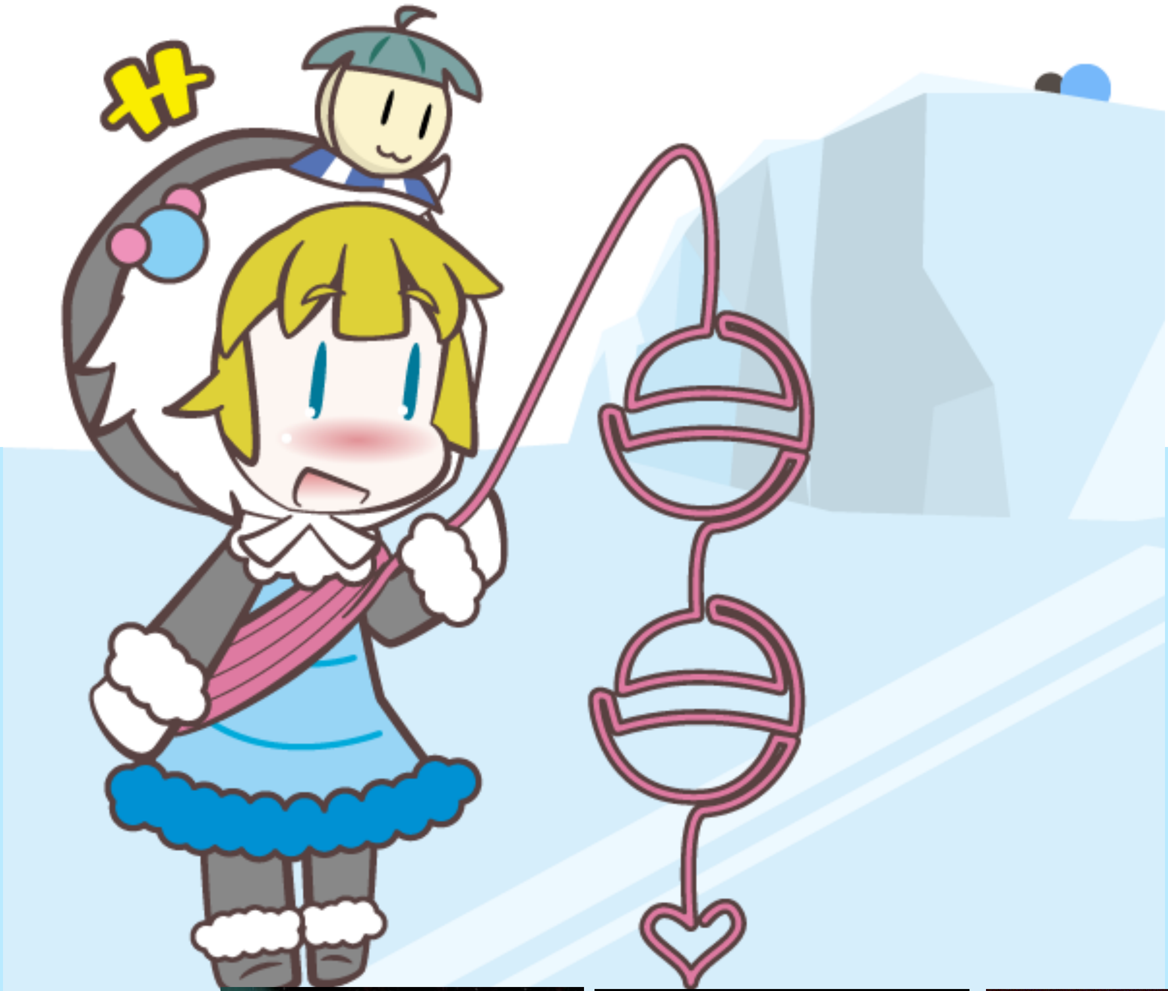
HE Cosmic ν Background Has Been Measured: Questions

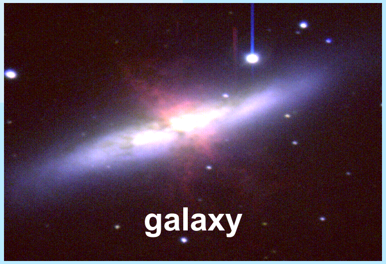
- Origin of high-energy cosmic neutrinos
- Neutrino production mechanisms: pp/pγ or else
- Connection to γ rays and/or cosmic rays?
- Origin of UHECRs (extragalactic CR accelerators)
- Origin of Galactic CRs (Galactic PeVatrons)

- Particle acceleration mechanisms
- Physics in dense environments and high-z sources

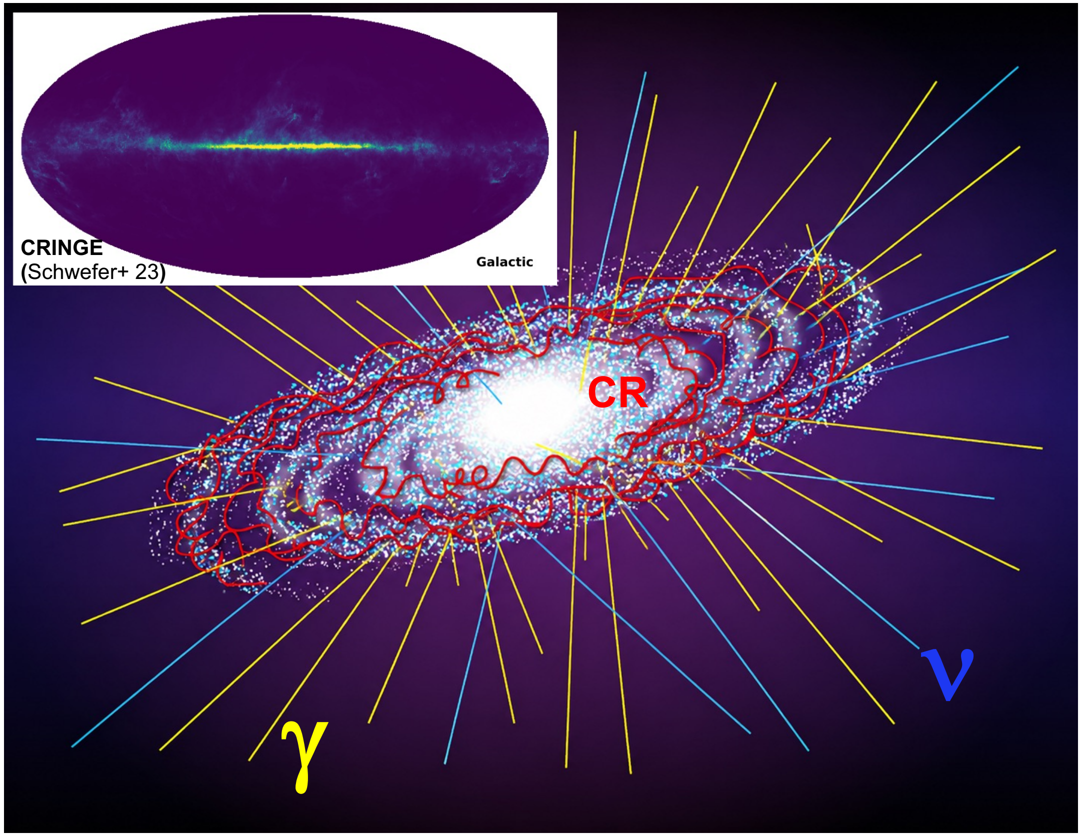
- Neutrino properties
- Physics beyond the Standard Model

Where do neutrinos come from?





Galactic Diffuse Neutrinos and Gamma Rays



(Hayakawa−Hutchinson−Morrison)
(Berezinsky-Smirnov-Stecker)

CR interactions w. interstellar gas

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

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

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

$\pi^0:\pi^{\pm}\sim 1:2$

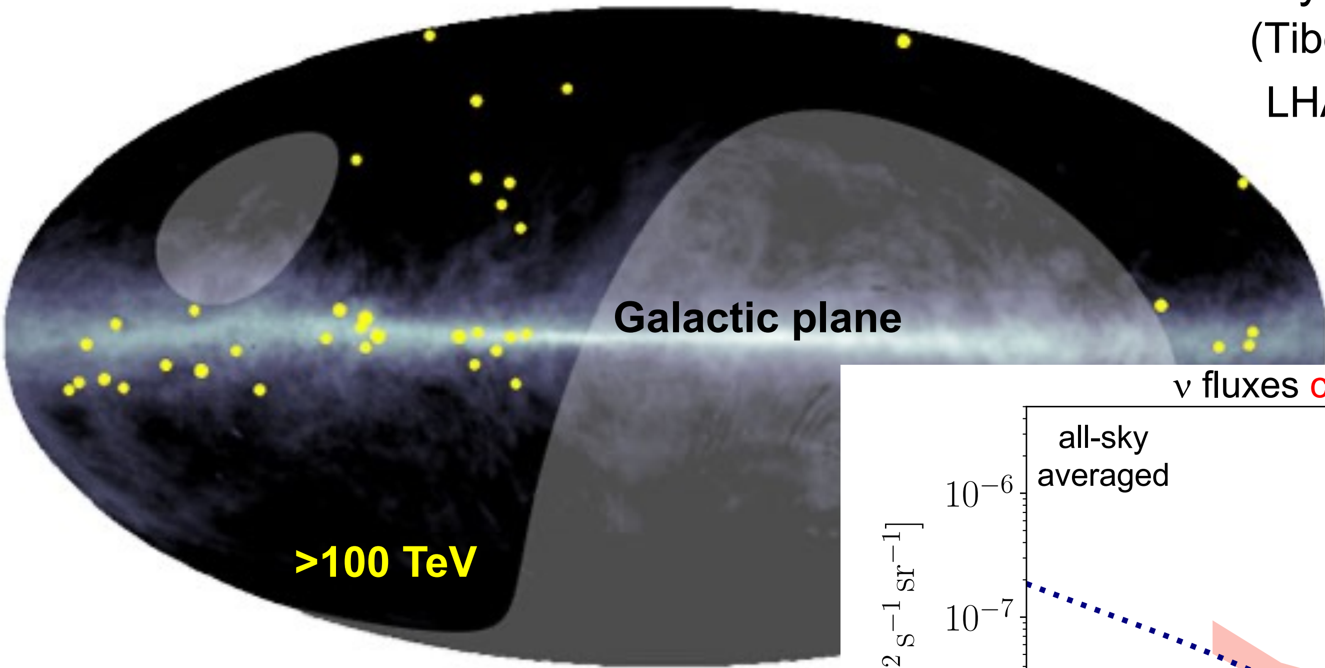
γ-ray measurements can be used for "calibrating" ν fluxes (after γγ correction)

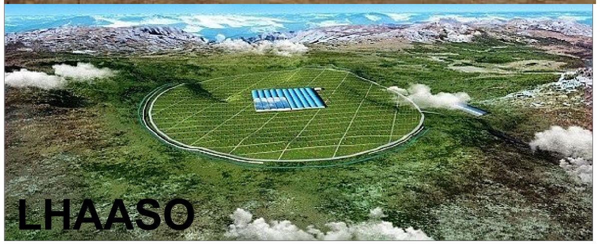
$$E_{\nu}^{2} F_{\nu}^{\Omega} \approx \frac{3}{2}(E_{\gamma}^{2} F_{\gamma}^{\Omega})|_{E_{\gamma}=2E_{\nu}} \times \frac{\int ds \int \cos b\, db \int dl\, n_{s}(s,\, b,\, l)}{\int ds \int \cos b db \int dl\, n_{s} P_{\gamma,\mathrm{surv}}(E_{\gamma} = 2E_{\nu},\, s,\, b,\, l)}$$

Even in 2013, γ-ray limits implied the Galactic ν contribution is subdominant (Ahlers & KM 14 PRD)

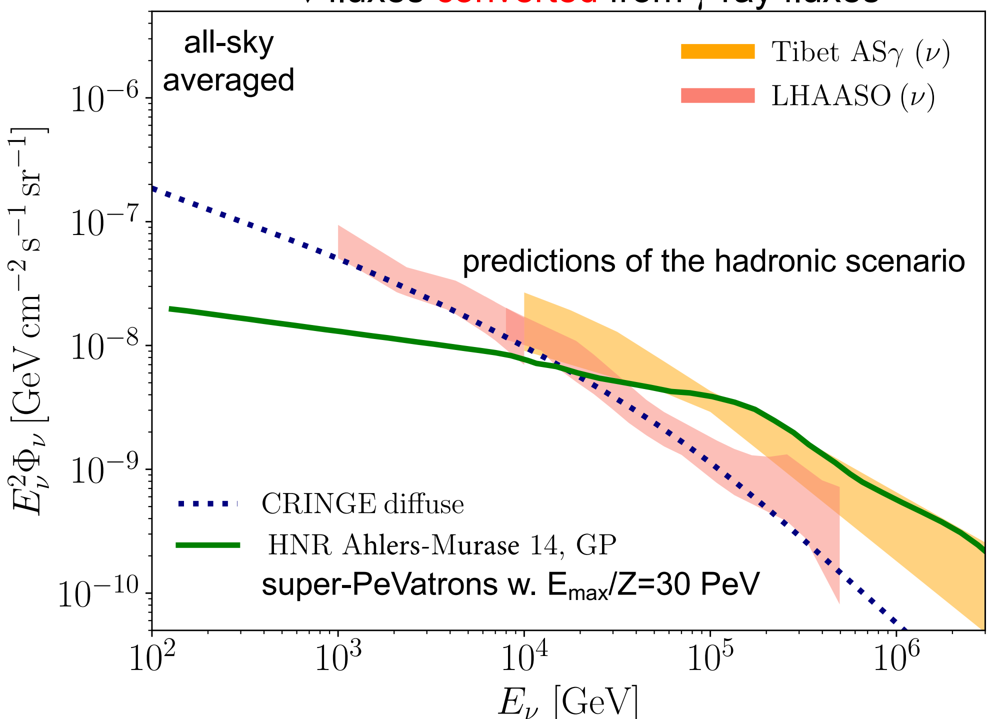
Galactic Diffuse Sub-PeV Gamma Rays Are Measured

Discovery of sub-PeV γ rays in 2021
(Tibet ASγ Collaboration 21 PRL
LHAASO Collaboration 23 PRL)





ν fluxes converted from γ-ray fluxes

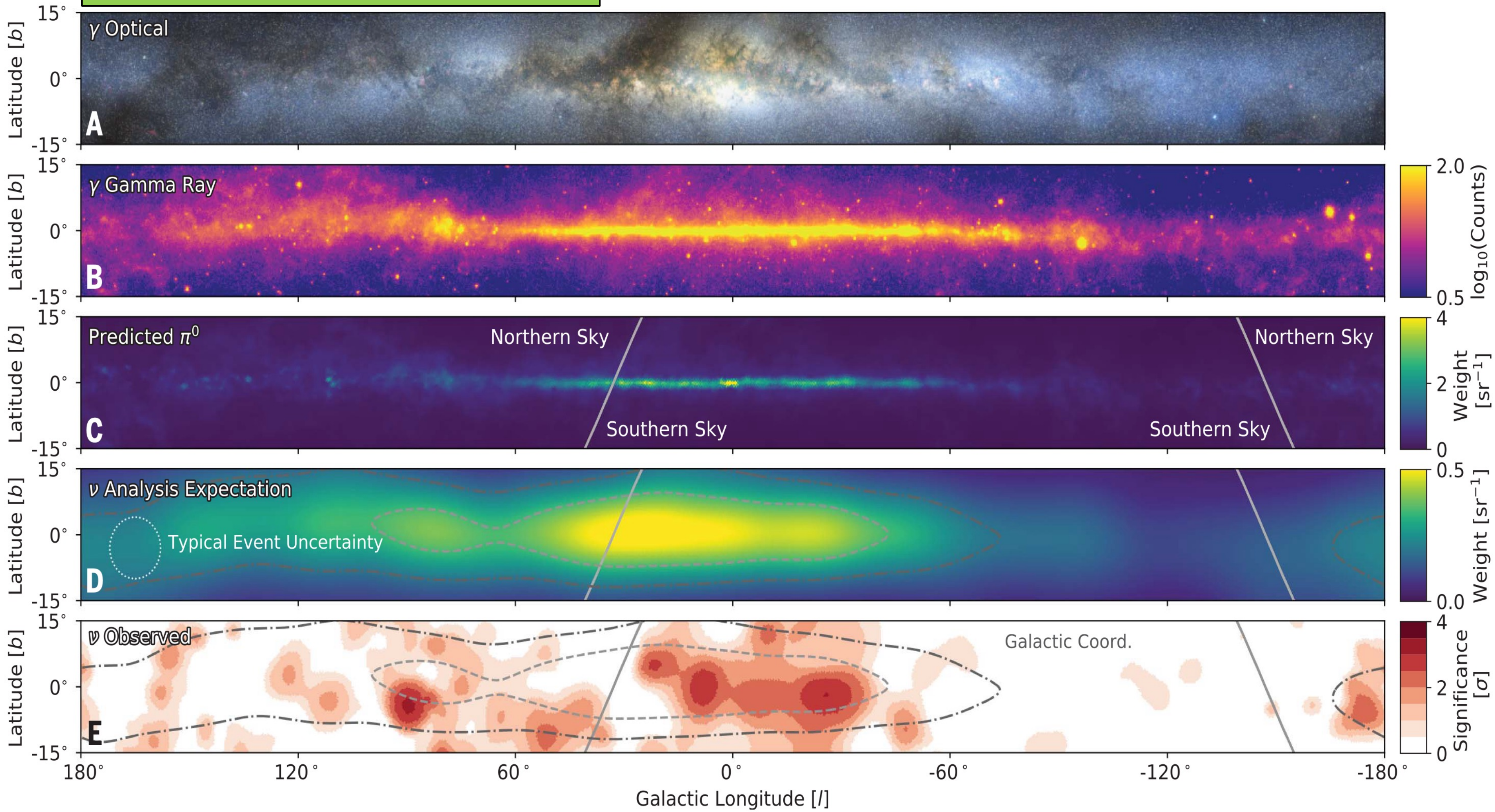


Fang & KM 21 ApJ, 23 ApJL

Evidence for Galactic Diffuse Neutrinos

Kheirandish's talk on Wed

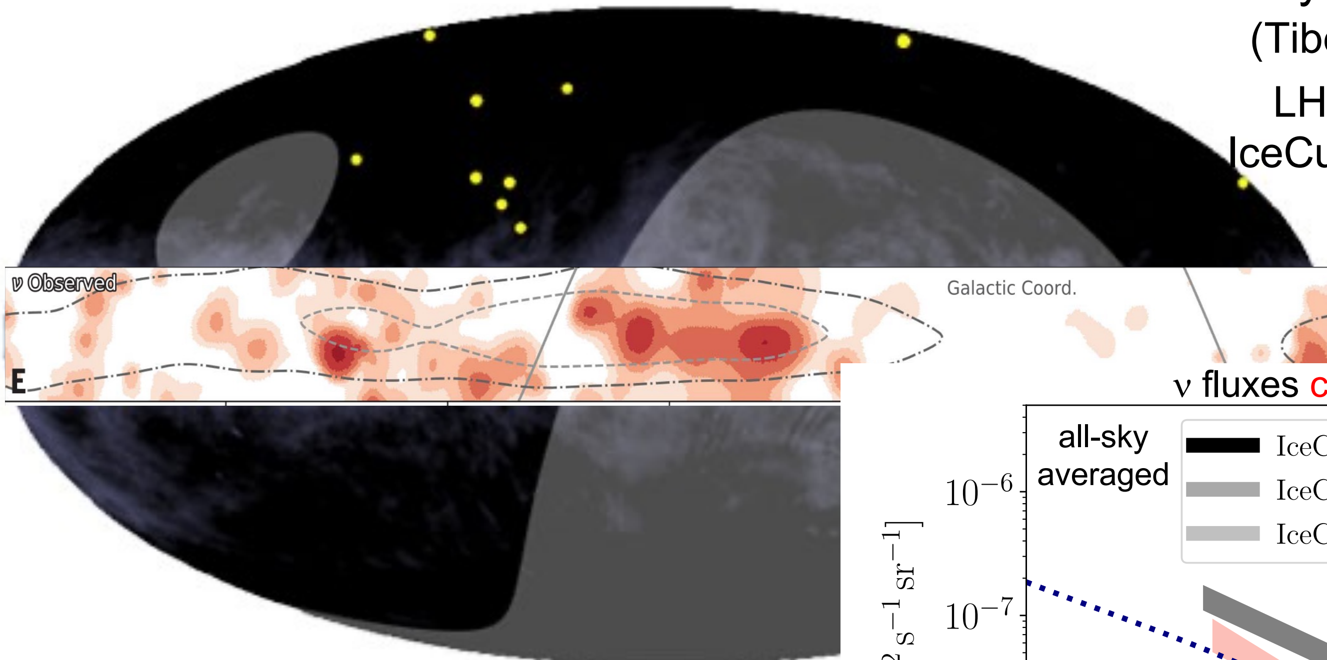
IceCube 23 Science



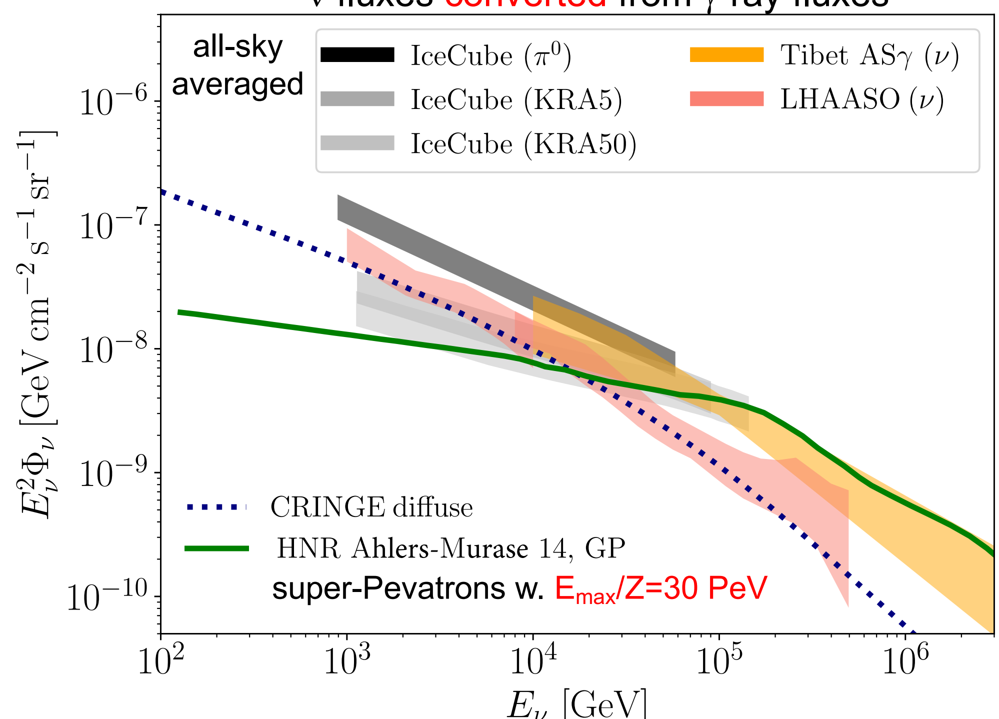
Now ν emission from the Milky Way (~10% of total) has been observed w. >5σ

Galactic Multimessenger Connection is Now Seen

Discovery of sub-PeV γ rays in 2021
(Tibet ASγ Collaboration 21 PRL
LHAASO Collaboration 23 PRL
IceCube Collaboration 23 Science)



ν fluxes converted from γ-ray fluxes



Fang & KM 21 ApJ, 23 ApJL

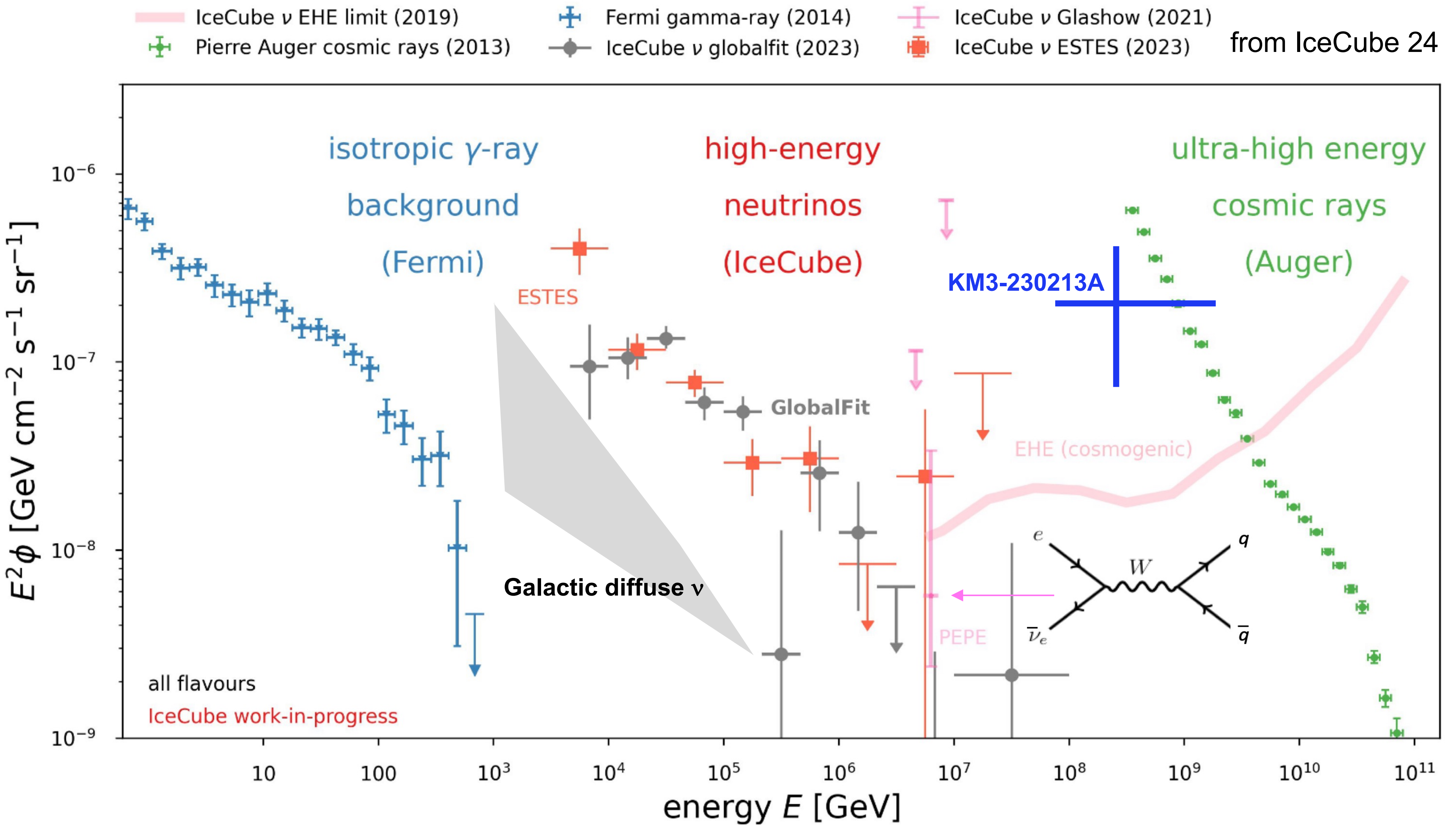
Supporting hadronic (pp) origin

Open questions
- Truly diffuse vs unresolved sources?
- Super-PeVatron accelerators?

(Schwefer+ 23, Vecchiotti+ 23, Shao+ 23, Ambrosone+ 24, Yan+ 24, Kato+ 24, 25, Lipari & Vernetto 25, Kaci+ 25, Espinosa Castro, KM+ 26, Moghadam+ 26, Roberts+ 26 etc.)

All-Sky Multimessenger Flux & Spectrum

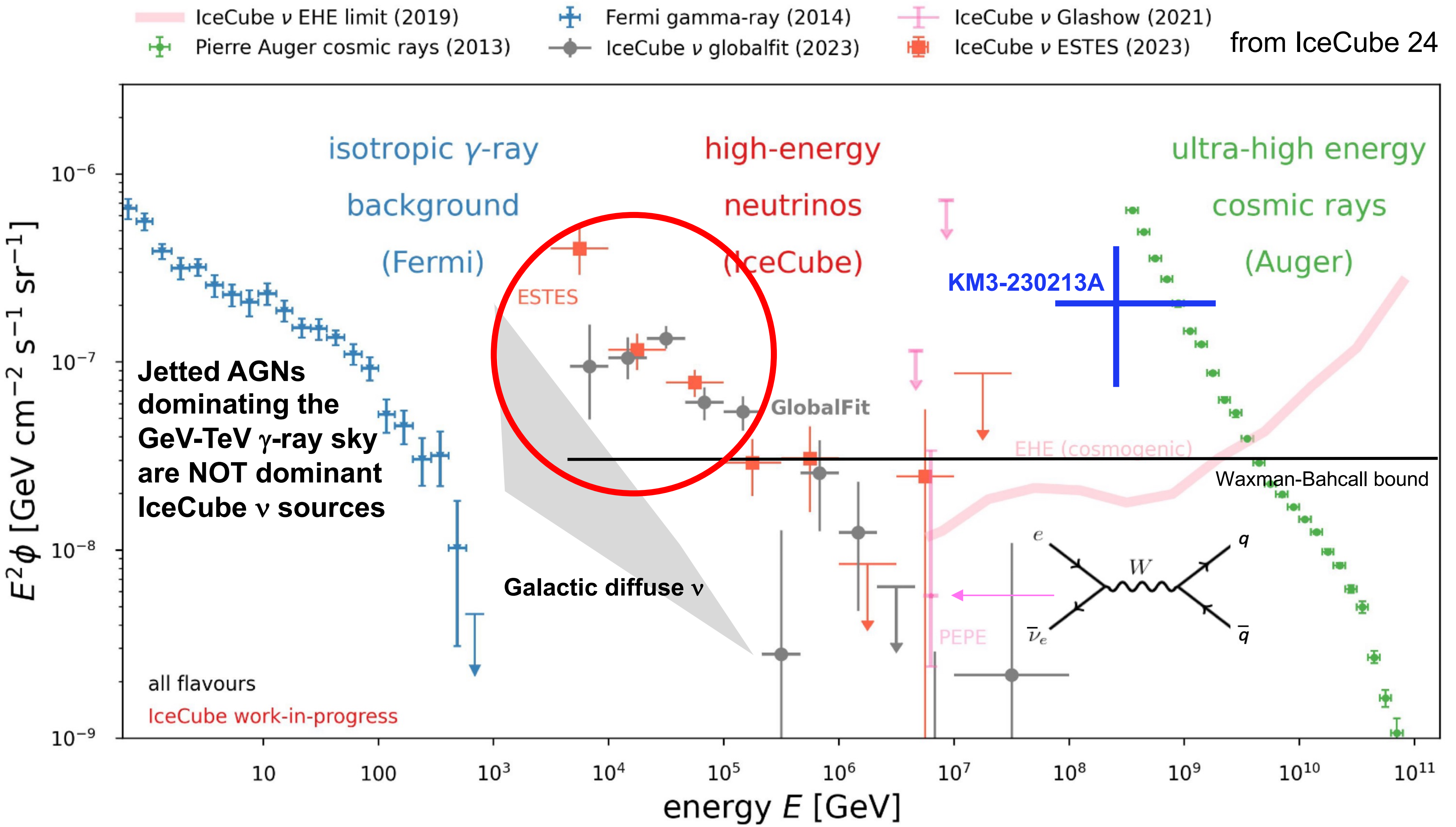
from IceCube 24



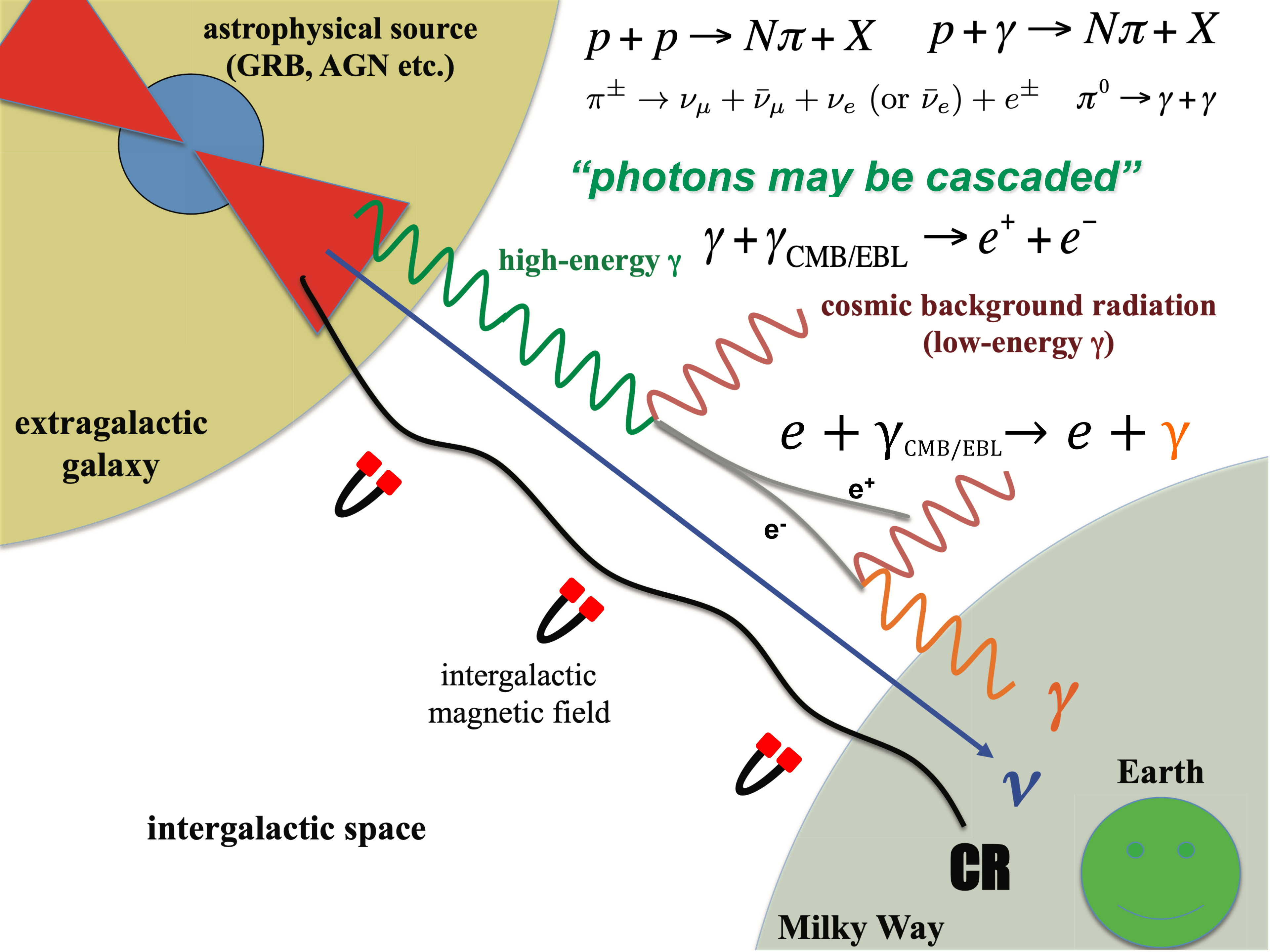
(Grand-)unified multimessenger picture?

(ex. KM & Waxman 16, Fang & KM 18, Kachelriess+ 17, KM & Fukugita 19)

All-Sky Multimessenger Flux & Spectrum

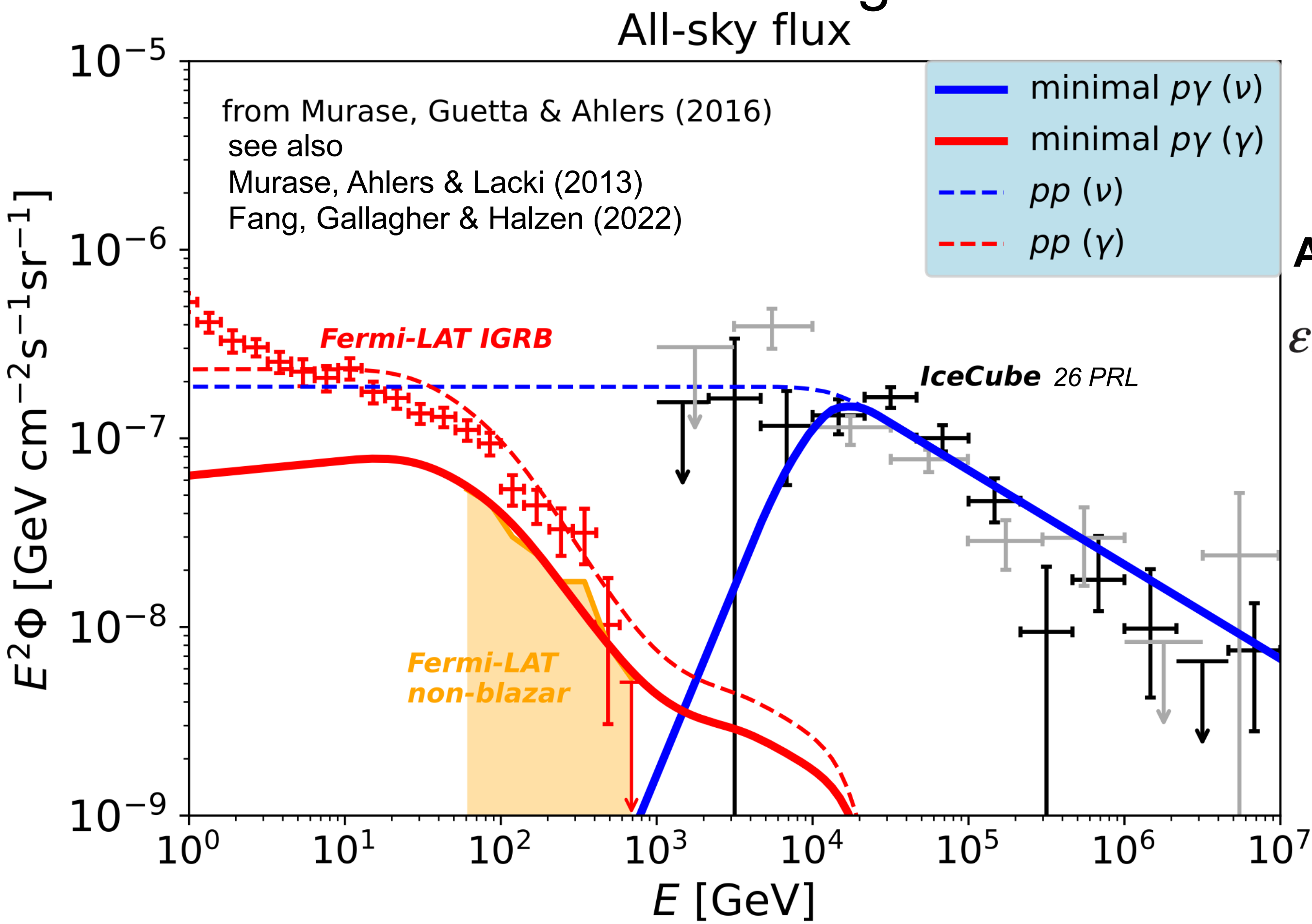


- 10-100 TeV ν flux is larger than the benchmark ν flux from UHECR sources
- 10-100 TeV ν flux mainly originates from sources other than jetted AGNs (blazars)


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

Extragalactic Multimessenger Connection

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



At sources

$$\varepsilon_\gamma Q_{\varepsilon_\gamma} \approx \frac{4}{3K}(\varepsilon_\nu Q_{\varepsilon_\nu})|_{\varepsilon_\nu=\varepsilon_\gamma/2}$$

$K=\pi^\pm/\pi^0$

pp: K~2

pγ: K~1

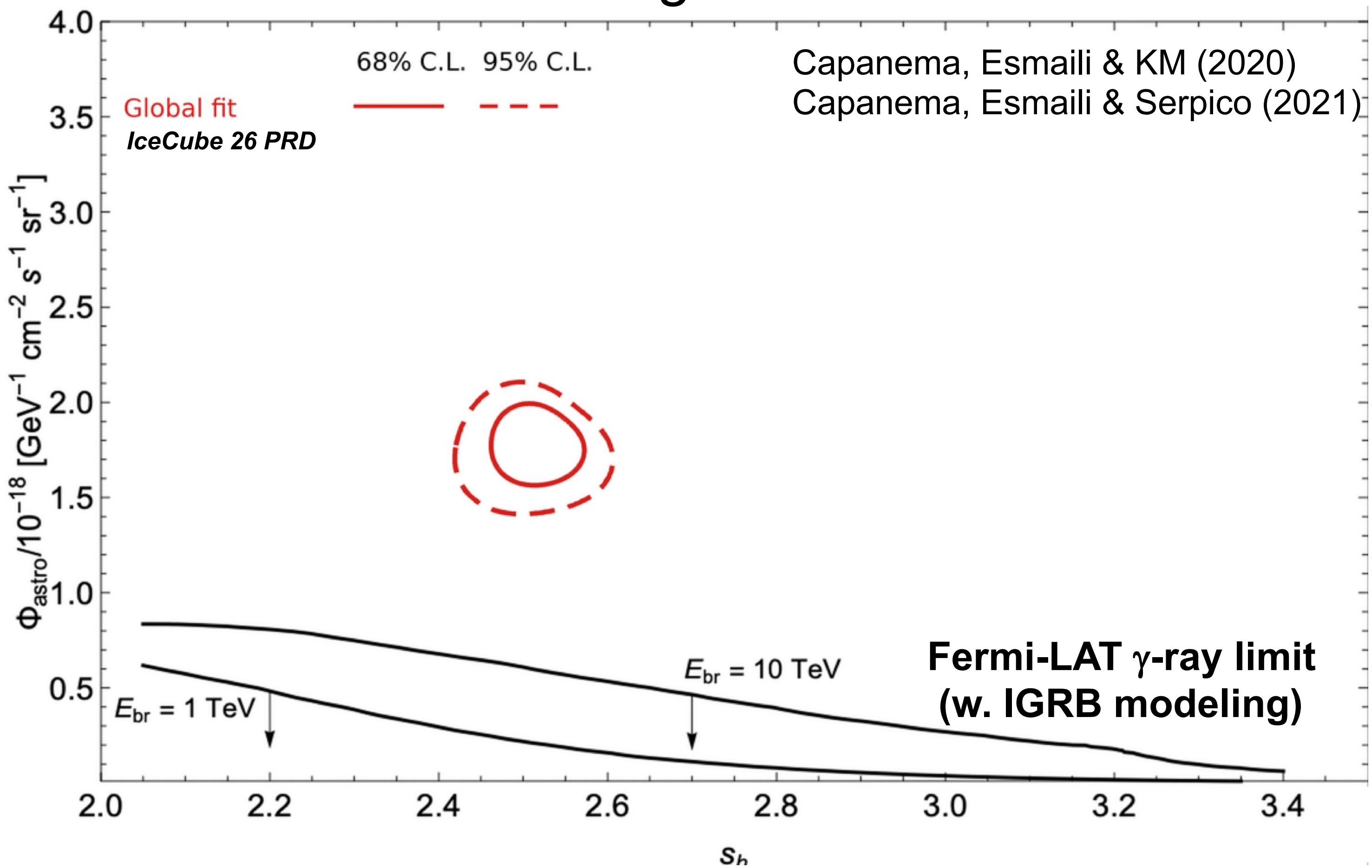
pp scenarios (e.g., star-forming galaxies) are excluded if γ-ray transparent

tension w. γ-ray data (>~3σ) even for the minimal pγ scenario if γ-ray transparent

→ majority of ~30 TeV νs: hidden (i.e., γ-ray opaque) cosmic-ray accelerators

Extragalactic Multimessenger Connection

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

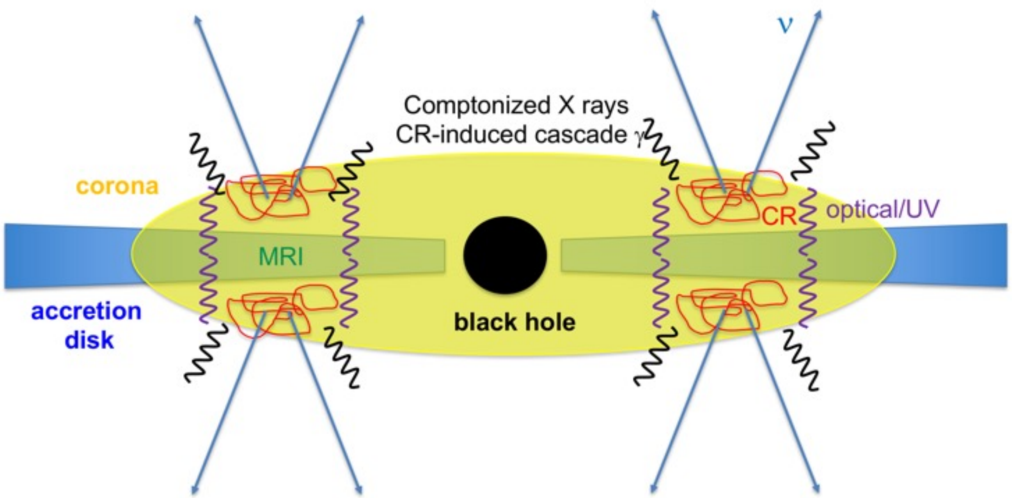


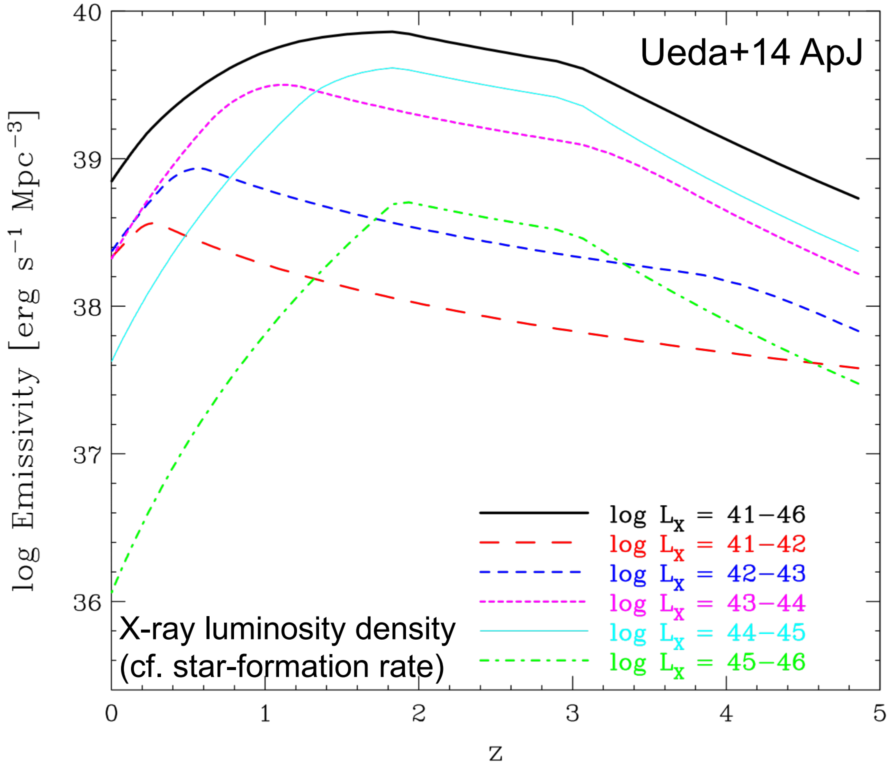
pp scenarios (e.g., star-forming galaxies) are excluded if γ-ray transparent
tension w. γ-ray data (>~3σ) even for the minimal pγ scenario if γ-ray transparent
→ majority of ~30 TeV νs: hidden (i.e., γ-ray opaque) cosmic-ray accelerators

Prediction of Hidden Neutrino Sources

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

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





disk-corona

opt/UV=multi-temperature blackbody from disks

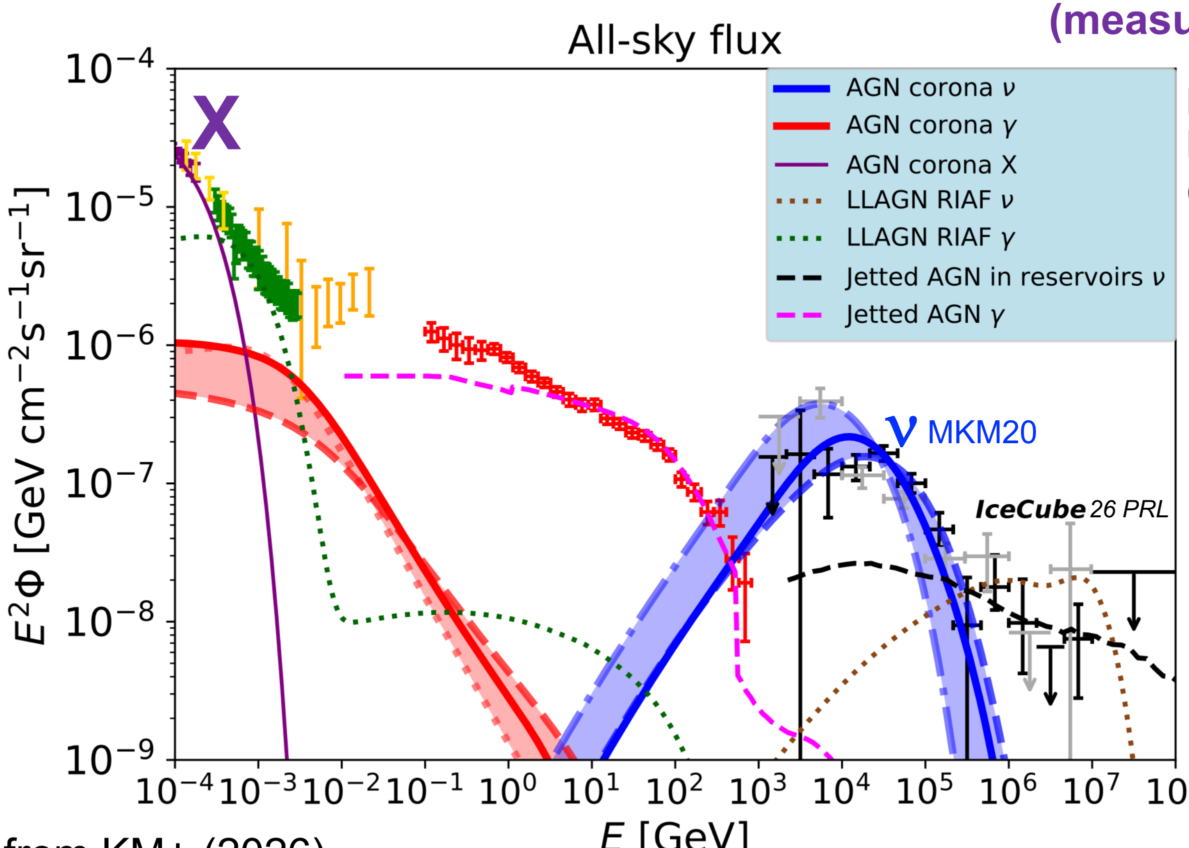
X-ray=Comptonization by hot electrons in coronae (kT_e ~ 10-100 keV)

→ The X-ray background originates from jet-quiet AGNs (coronae)

Prediction of Hidden Neutrino Sources

all-sky ν intensity of extragalactic ν sources (cf. DSNB)

$$\Phi_\nu = \underbrace{\frac{c}{4\pi H_0}\int_{z_{\rm min}}^{z_{\rm max}} dz \frac{1}{\sqrt{(1+z)^3\Omega_m+\Omega_\Lambda}}}_{\textbf{cosmology}} \underbrace{\int dL_X \frac{d\rho_{\rm AGN}}{dL_X}(L_X,z,\bar{\lambda})}_{\textbf{X-ray data (measured)}} \underbrace{\int d\lambda \frac{d\Pi}{d\lambda}\frac{L_{\varepsilon_\nu}(L_X,\lambda)}{\varepsilon_\nu}}_{\textbf{theory } (\lambda\textbf{: model parameters})}$$



from KM+ (2026)

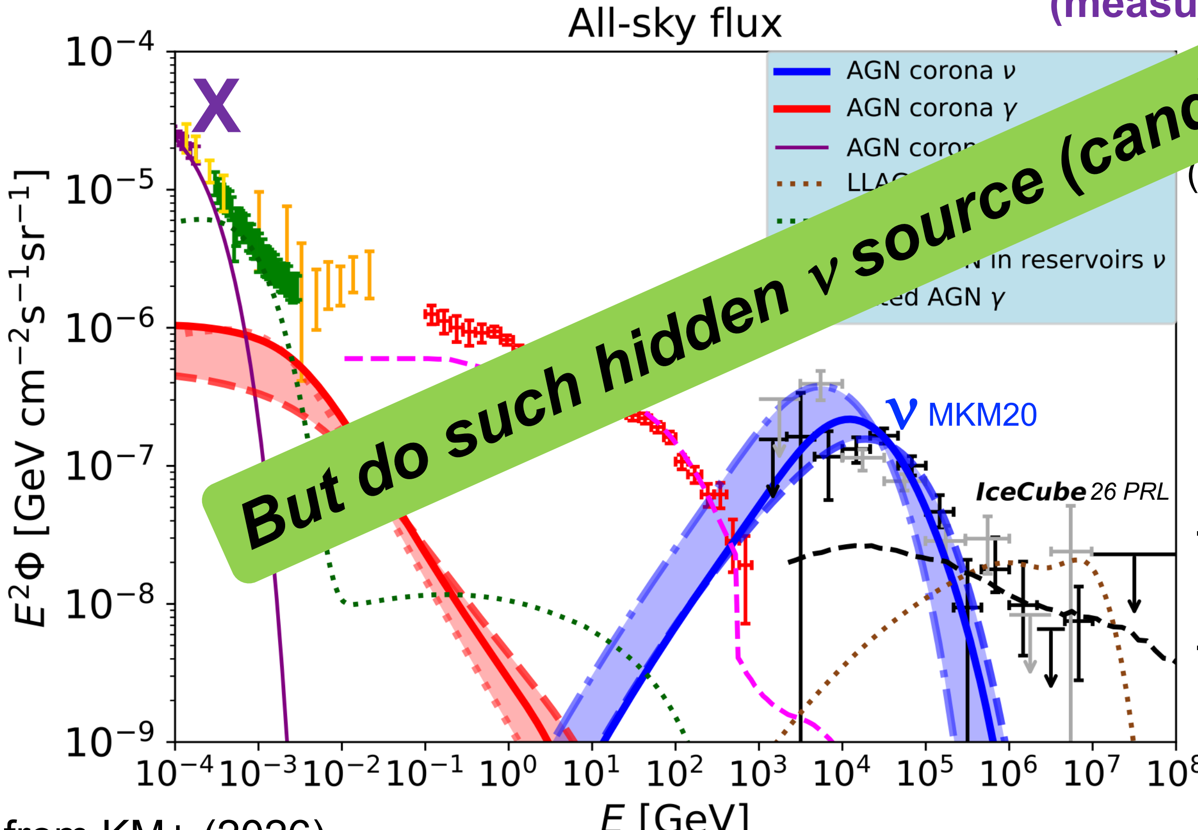
KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.
(see also Padovani et al. 24 A&A)

- Simultaneous explanation for the all-sky ν and X-ray fluxes
- Predicting a spectral curvature consistent w. a ~10-30 TeV break in the ν data (IceCube PRL 26)

Prediction of Hidden Neutrino Sources

all-sky ν intensity of extragalactic ν sources (cf. DSNB)

$$\Phi_\nu = \underbrace{\frac{c}{4\pi H_0}\int_{z_{\rm min}}^{z_{\rm max}} dz \frac{1}{\sqrt{(1+z)^3\Omega_m+\Omega_\Lambda}}}_{\text{cosmology}} \underbrace{\int dL_X \frac{d\rho_{\rm AGN}}{dL_X}(L_X,z,\bar\lambda)}_{\text{X-ray data (measured)}} \underbrace{\int d\lambda \frac{d\Pi}{d\lambda}\frac{L_{\varepsilon_\nu}(L_X,\lambda)}{\varepsilon_\nu}}_{\text{theory (model parameters)}}$$



from KM+ (2026)

a & Meszaros 20 PRL
ura, KM & Meszaros 21 Nature Comm.
(see also Padovani et al. 24 A&A)

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

- Simultaneous explanation for the all-sky ν and X-ray fluxes
- Predicting a spectral curvature consistent w. a ~10-30 TeV break in the ν data (IceCube PRL 26)

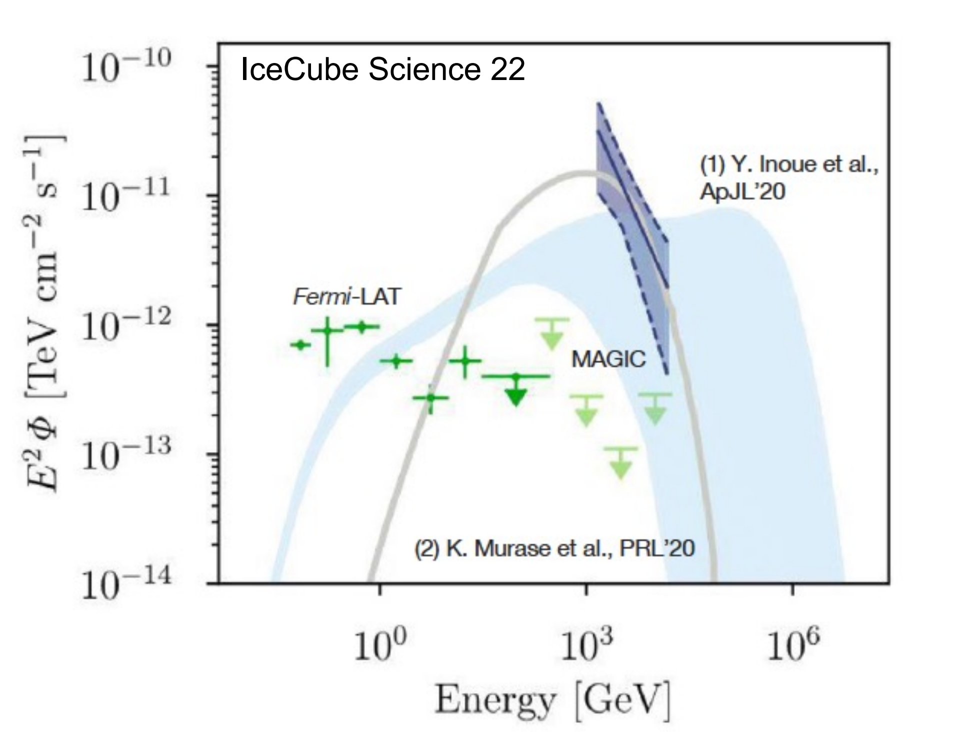
NGC 1068

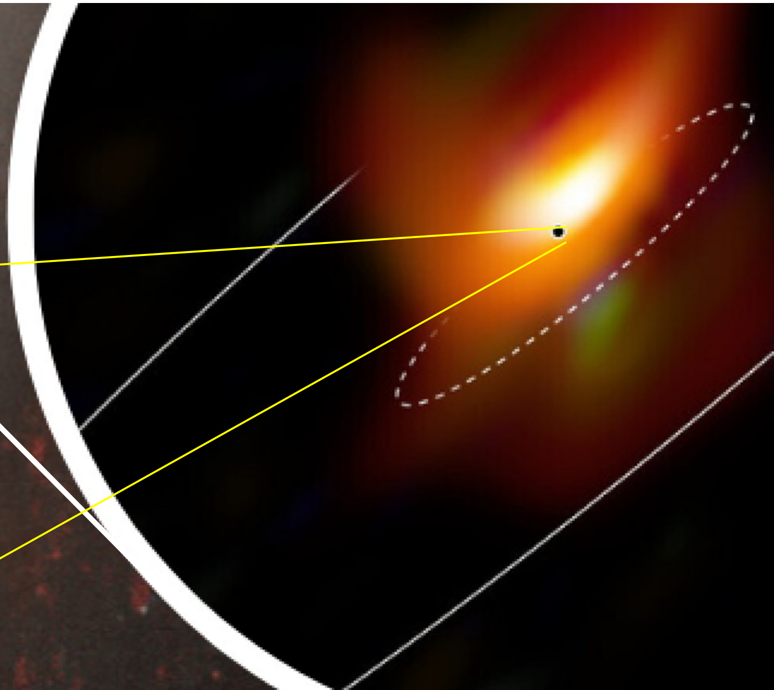
one of the powerful AGNs in the local universe

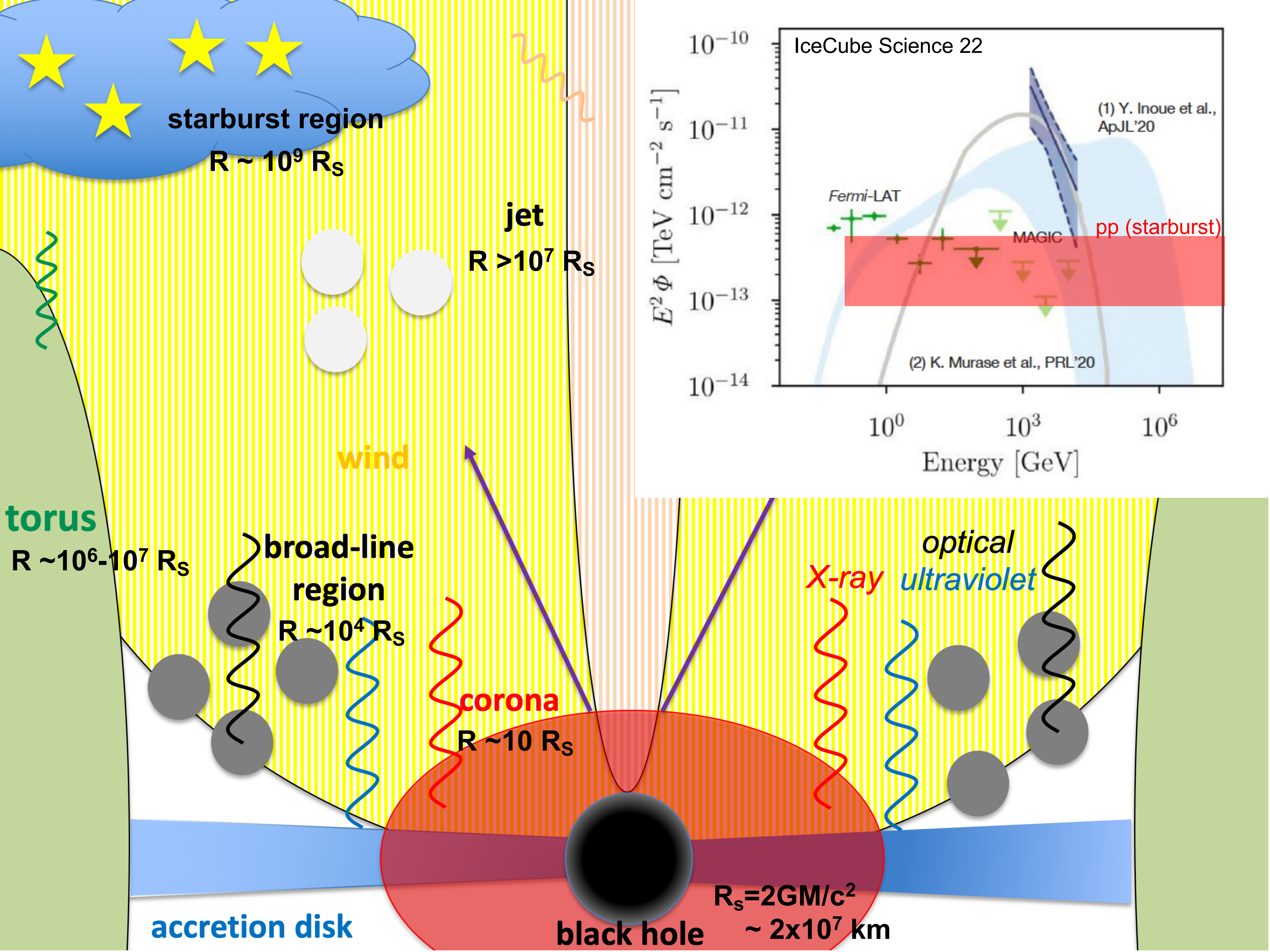
distance: ~10 Mpc

$L_{\nu} \sim 10^{42}$ erg/s $\ll L_{corona} \sim 8\times10^{43}$ erg/s

$\ll L_{bol} \sim L_{Edd} \sim 10^{45}$ erg/s





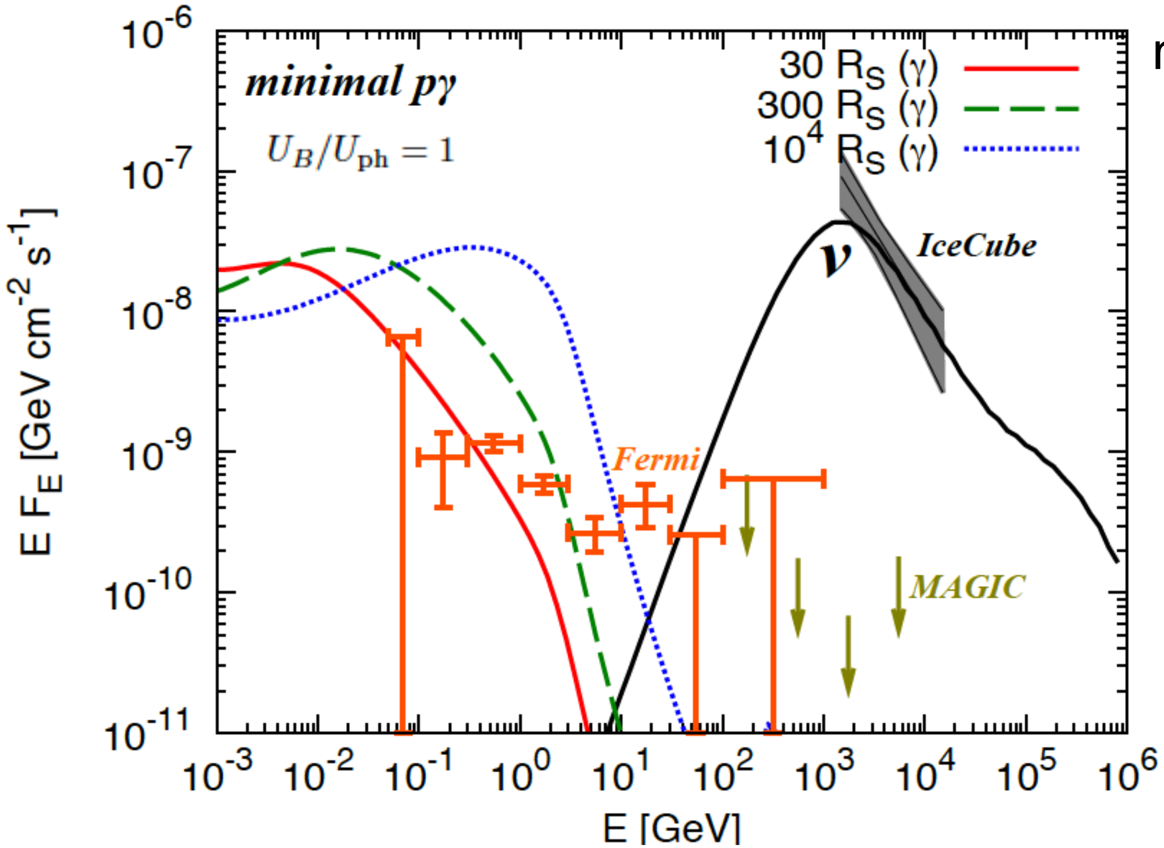


starburst region
R ~ 10^9 R_S
jet
R >10^7 R_S
wind
torus
R ~10^6-10^7 R_S
broad-line
region
R ~10^4 R_S
corona
R ~10 R_S
optical
X-ray
ultraviolet
accretion disk
black hole
R_S=2GM/c^2
~ 2x10^7 km
IceCube Science 22
(1) Y. Inoue et al., ApJL'20
(2) K. Murase et al., PRL'20
Fermi-LAT
MAGIC
pp (starburst)
E^2 Φ [TeV cm^-2 s^-1]
Energy [GeV]

Where Do Neutrinos Come from?

$\gamma + \gamma \to e^+ + e^-$
for 0.1-300 GeV γ rays

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



model-independent constraint considering elemag cascade
R < (15-30) R_S

KM 22 ApJL
see also
Das, Zhang & KM 24 ApJ
Blanco, Hooper, Linden & Pinetti 25 PRD

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

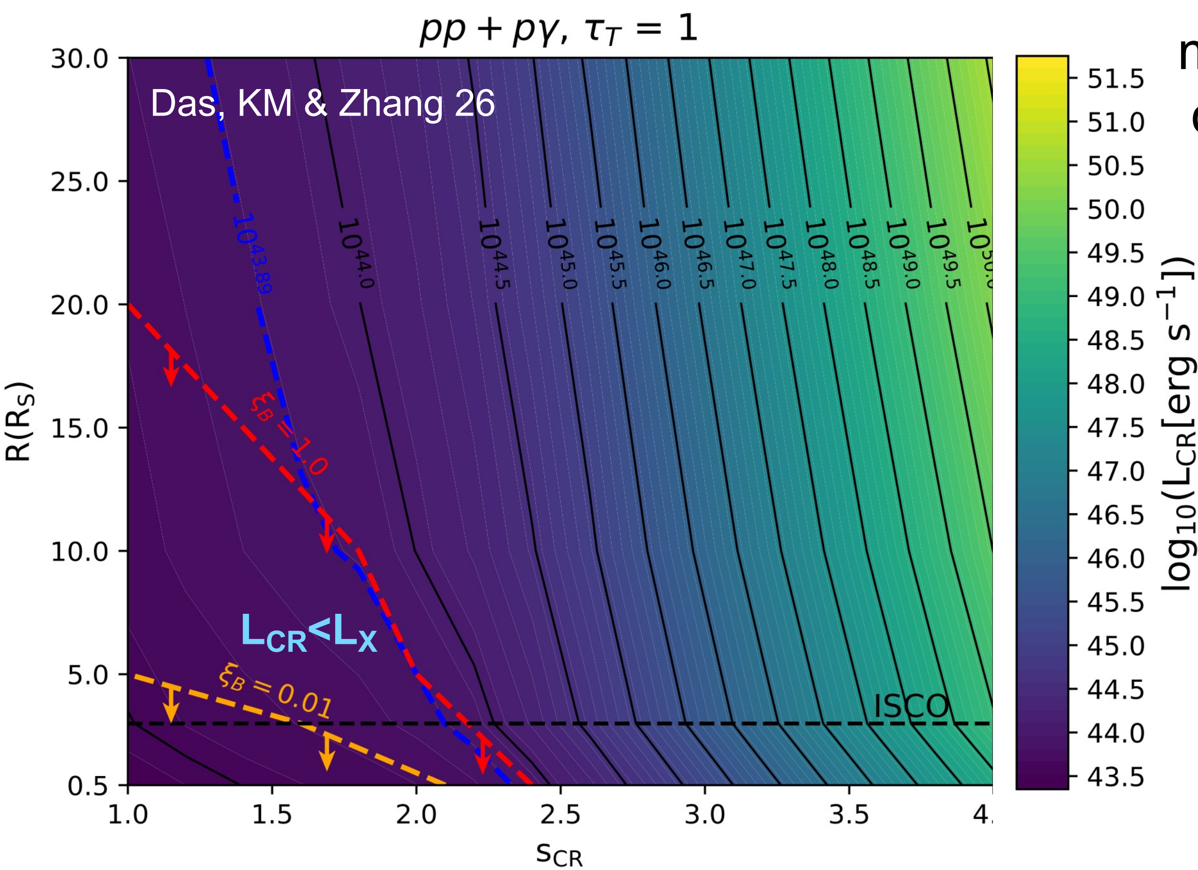
Massive black hole: sub-PeV proton accelerator & ideal beam dump

What Can We Learn from NGC 1068?

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

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

$R < (15\text{-}30)\ R_S$

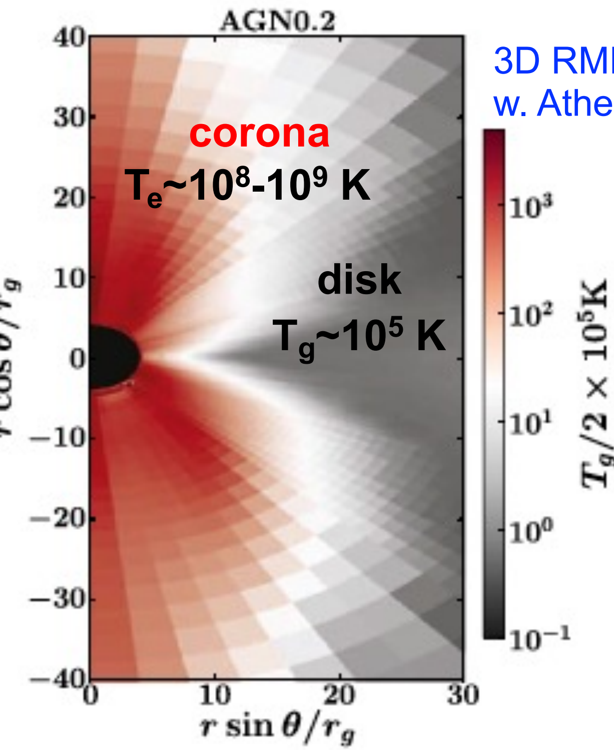
- CR spectrum is hard
  s_{CR} <~ 2
- Emission region is likely to be strongly magnetized
  $\xi_B = U_B/U_{ph}$ >~ 0.01
- ν production mechanism should be pp or pγ
  ($\gamma\gamma \rightarrow \mu^+\mu^-$ & β-decay scenarios are ruled out by γ-ray/CR overproduction & flavor studies)

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

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

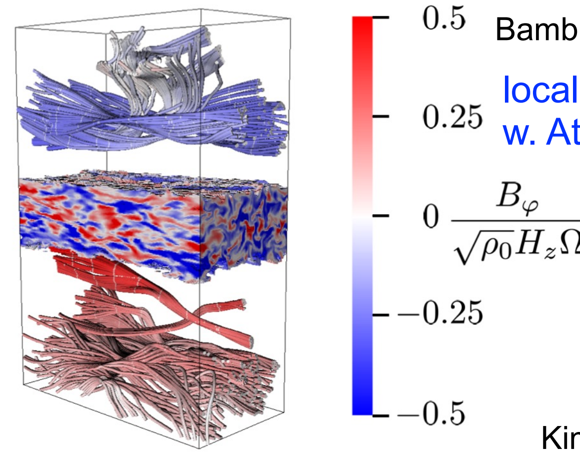
High-Energy Phenomena in the Vicinity of Black Holes

"Hot", "strongly magnetized", "turbulent" regions around a black hole (coronae)
→ promising sites for particle acceleration (Fermi mechanism)



Jiang, Blaes, Stone & Davis 19 ApJ
(see also Liska+ 22 ApJ)

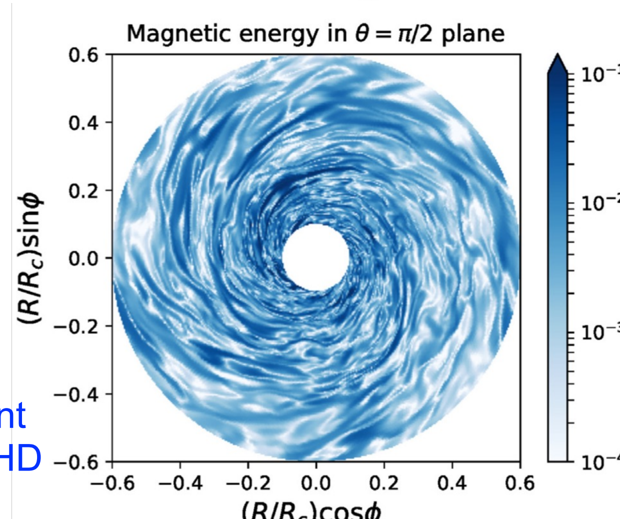
3D RMHD simulation
w. Athena++



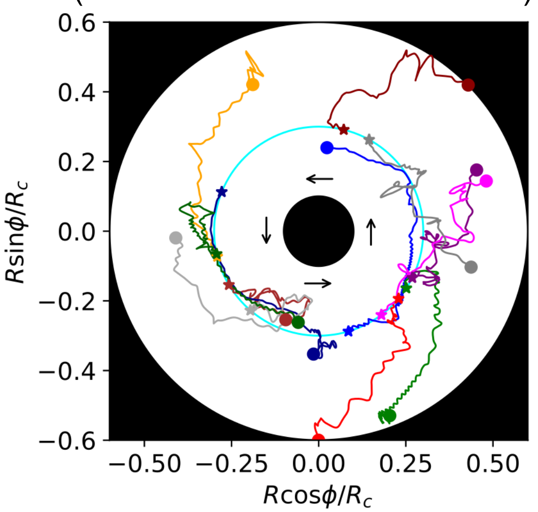
Bambic, Quataert & Kunz 23 MNRAS

local MHD simulation
w. Athena++

Test-particle simulations of turbulent
acceleration based on 3D global MHD



Kimura, Tomida & KM 19 MNRAS
(see also Sun & Bai 21 MNRAS)

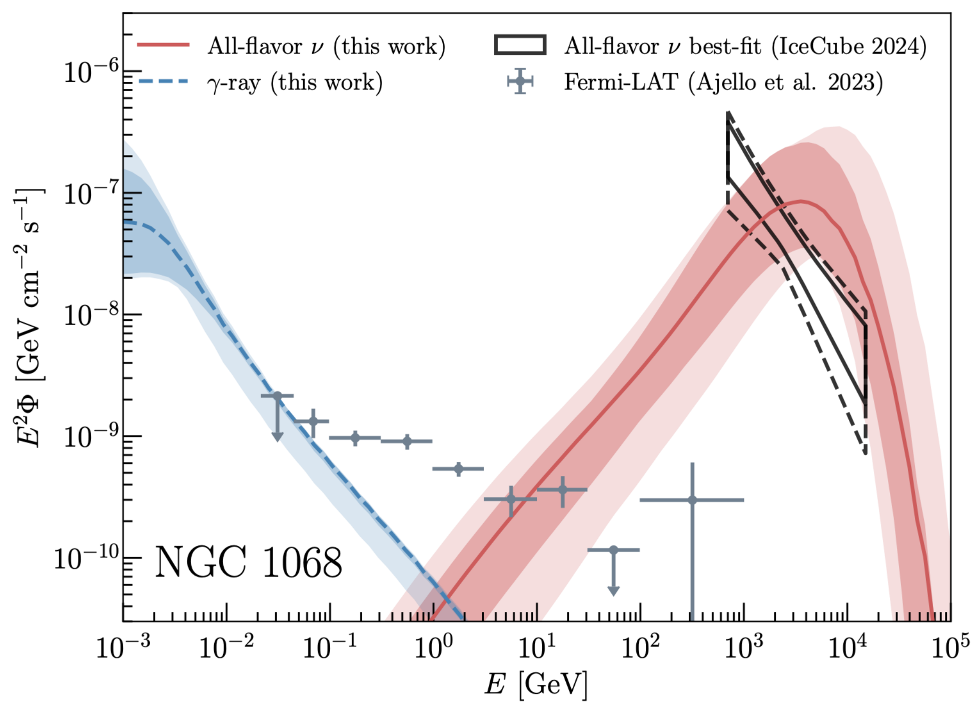


High-energy neutrinos now meet the frontier of astroplasma physics

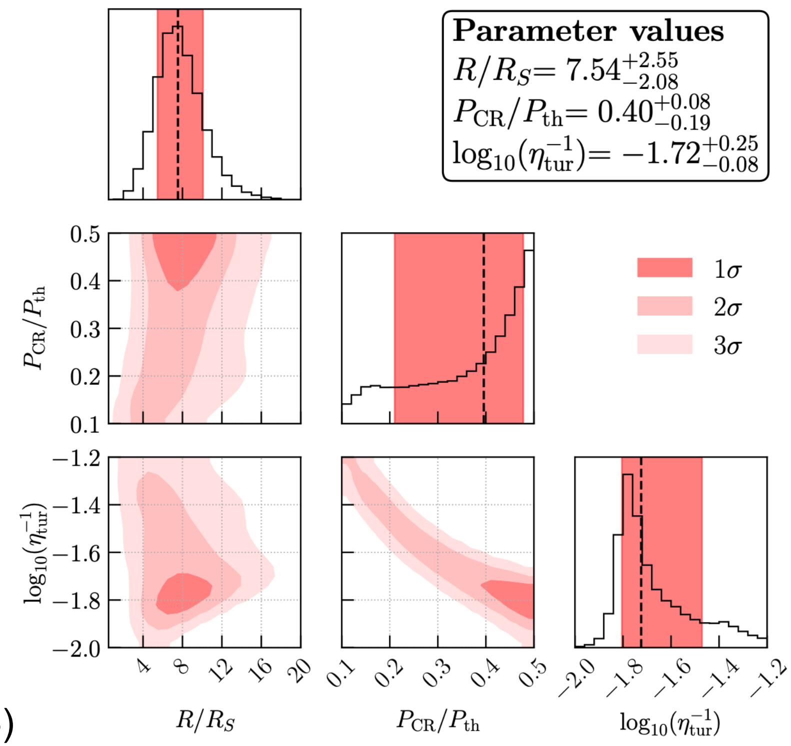
Magnetically Powered Turbulent Corona Model

- Astrophysical data (NGC 1068):
  luminosity (L_X~$3x10^{43}$ erg/s), mass (M_{BH}~$6x10^6$ M_{sun}), optical depth (τ_T~0.4)
- Coronal parameters (data & magnetohydrodynamics):
  emission region size (R/R_S), magnetic fields, viscosity
- CR parameters (particle acceleration):
  Injection efficiency (P_{CR}/P_{th}), acceleration efficiency (η_{tur}), spectral index (q)

(KM+ 20, see also Kheirandish, KM+ 21, Eichman+ 22, Fiorillo+ 24, Lemoine & Rieger 25, Wang+ 26, Yang+ 26…)



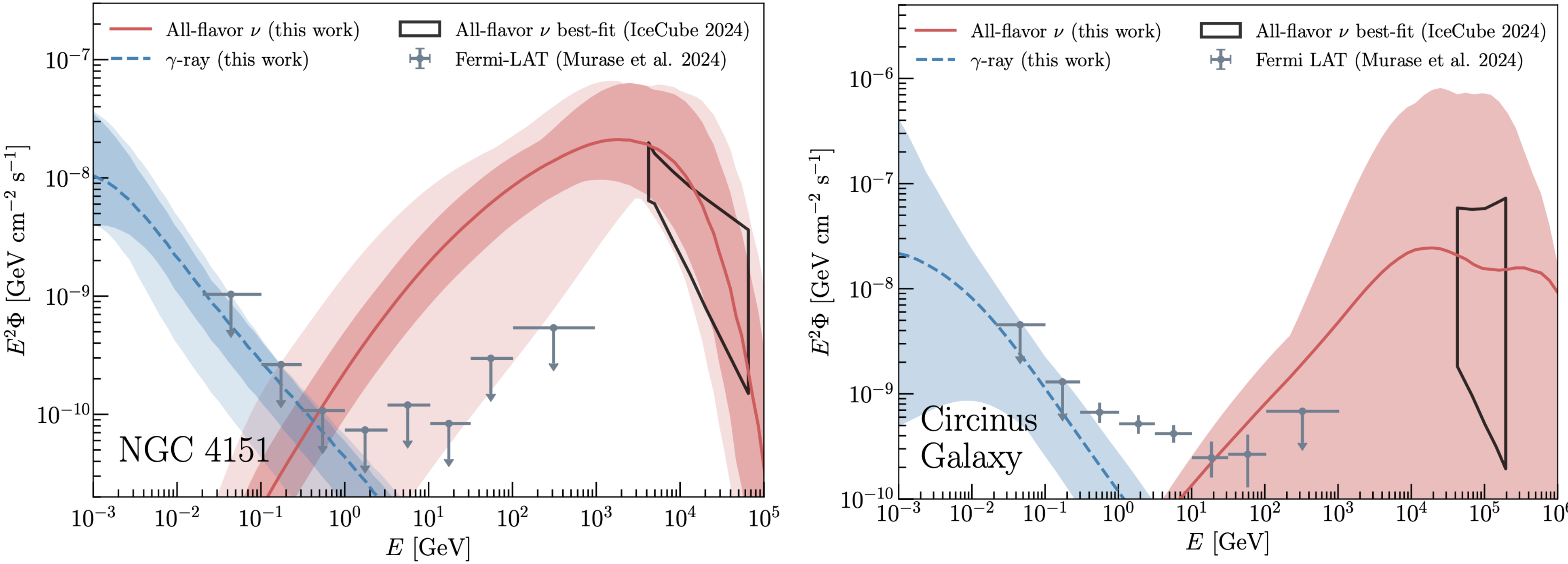
Carpio, Kheirandish & KM 26 (see also Ajello, KM & McDaniel 23)



Corona Model: Predictions and Hints

- Theory prediction: ν luminosity ~ intrinsic X-ray luminosity (KM+ 20 PRL, 24 ApJL)
  brightest for IceCube: NGC 1068, NGC 4151
  brightest in the southern sky: Circinus, NGC 4945
- IceCube ν evidences/hints: (IceCube Collaboration 22, 25a, 25b, 26a, 26b)
  NGC 1068 (~4σ), NGC 4151 (~3σ),
  14 AGNs in the south incl. Circinus (~3σ)
  consistent w. the theoretical picture

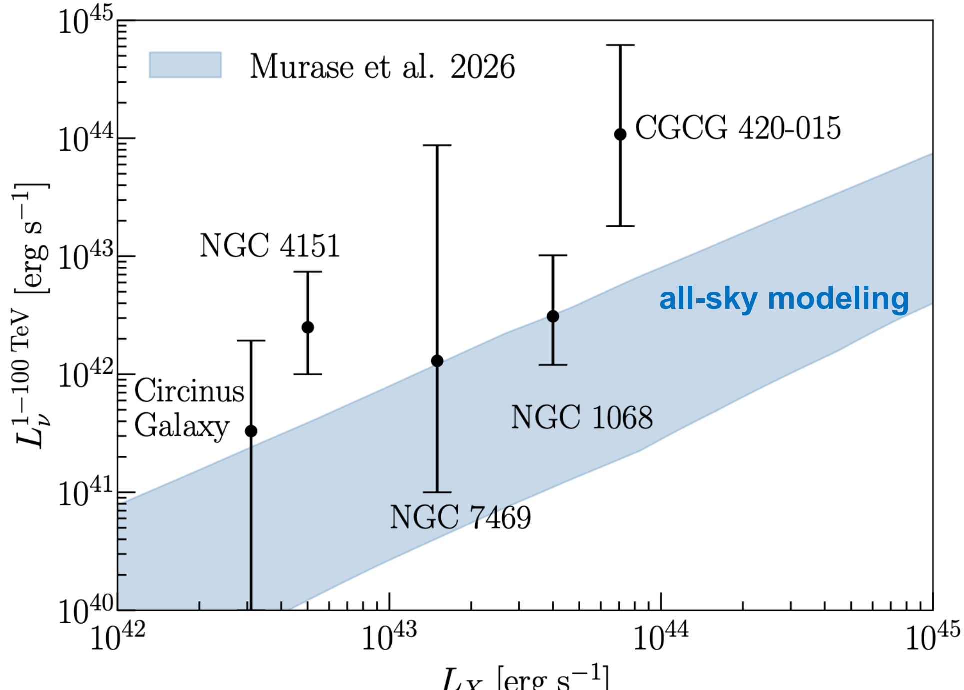
Kheirandish's talk on Wed



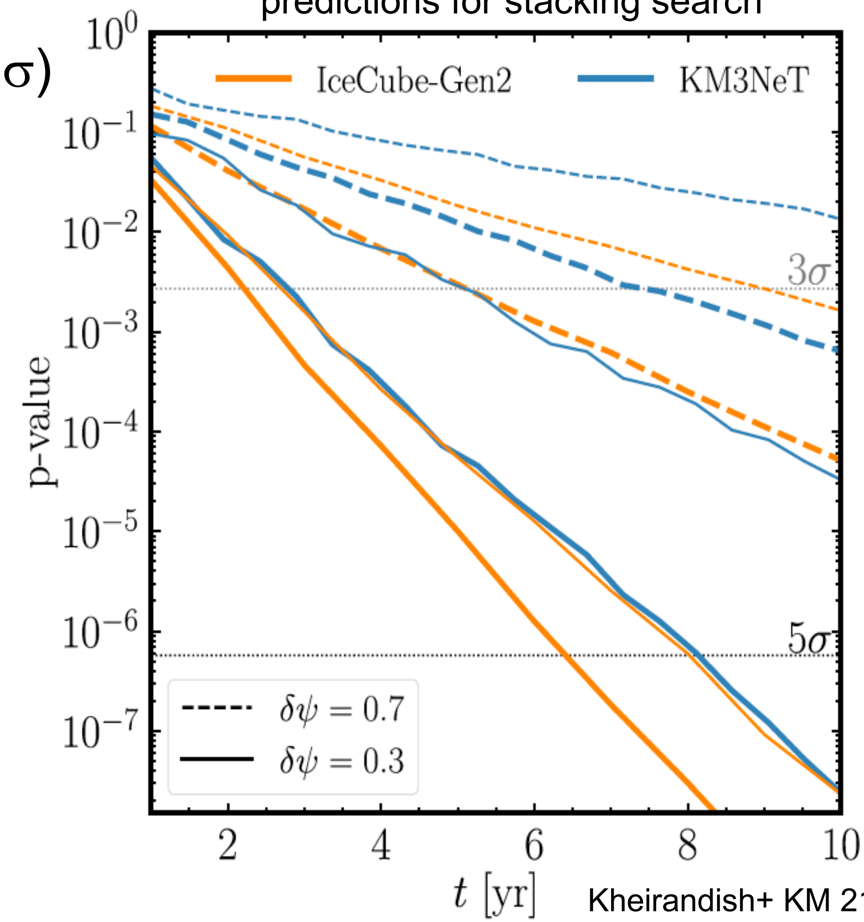
Carpio, Kheirandish & KM 26 ApJ (see also KM et al. 24 ApJL, Saurenhaus et al. 26 PRD)

Corona Model: Predictions and Hints

- Theory prediction: ν luminosity ~ intrinsic X-ray luminosity (KM+ 20 PRL, 24 ApJL)
  brightest for IceCube: NGC 1068, NGC 4151
  brightest in the southern sky: Circinus, NGC 4945
- IceCube ν evidences/hints: (IceCube Collaboration 22, 25a, 25b, 26a, 26b)
  NGC 1068 (~4σ), NGC 4151 (~3σ),
  14 AGNs in the south incl. Circinus (~3σ)
- Population studies are important



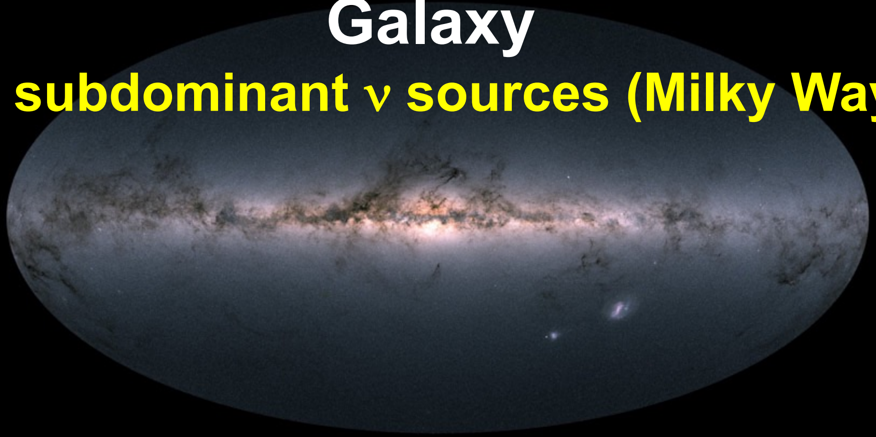
predictions for stacking search

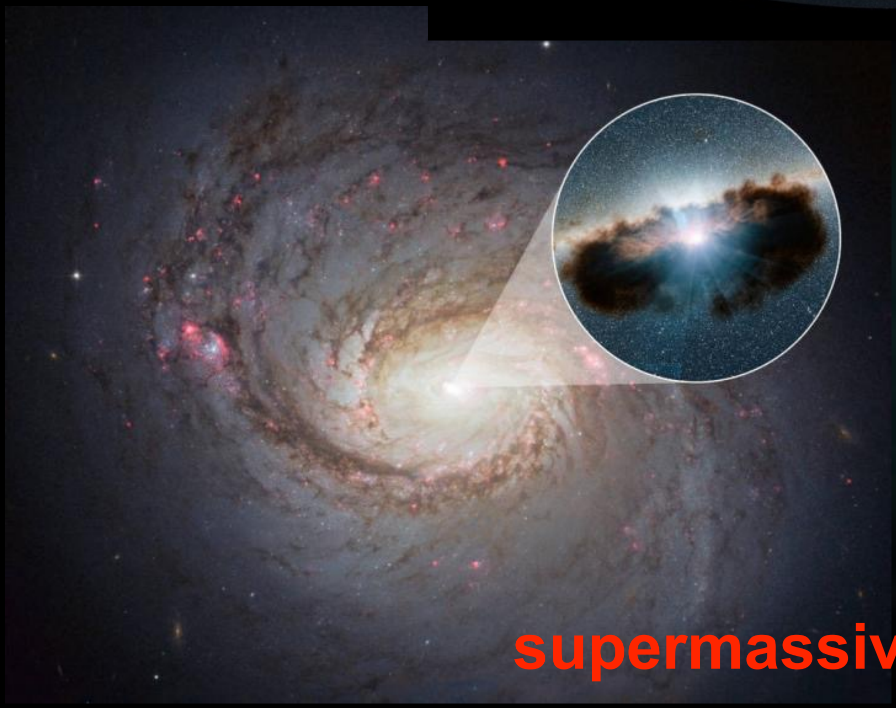


Kheirandish+ KM 21

Galaxy

subdominant ν sources (Milky Way)





supermassive black holes

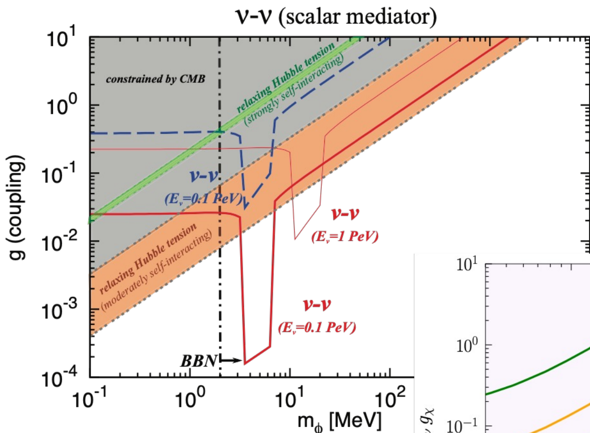
Jet-quiet AGN

hidden ν sources
(NGC 1068…)

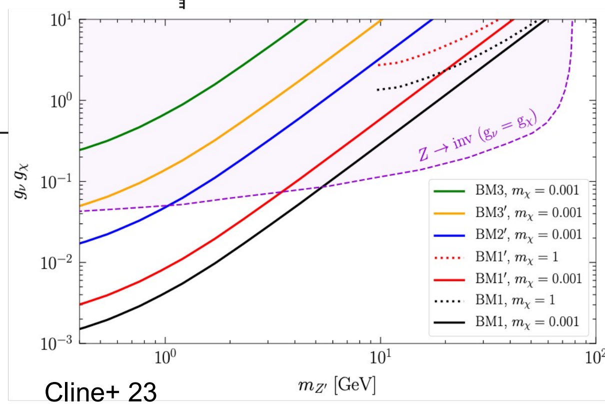
Jet-loud AGN

>100 TeV ν sources?
(TXS 0506+056?)

Probing New Physics with Identified ν "Sources"



KM & Shoemaker 19



Cline+ 23

Dev's talk today

nonstandard ν interactions

Kelly & Machado 18,
Choi+ 19,
Koren 19,
Ferrer+ 23,
Cline & Puel 23,
Doring & Vogl 24 etc.

Babu's talk today

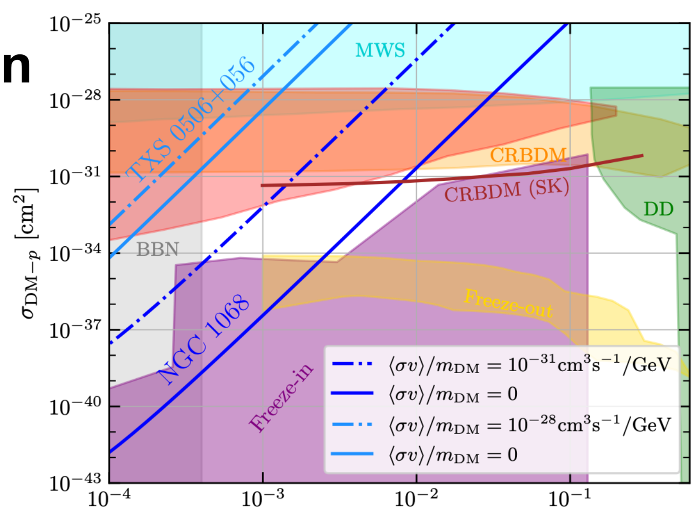
pseudo-Dirac ν

Beacom+ 04,
Shoemaker & KM 16,
Brdar & Hansen 19,
Rink & Sen 24,
Carloni+ 24,
Dixit+ 25
MacDonald+ 25 etc.

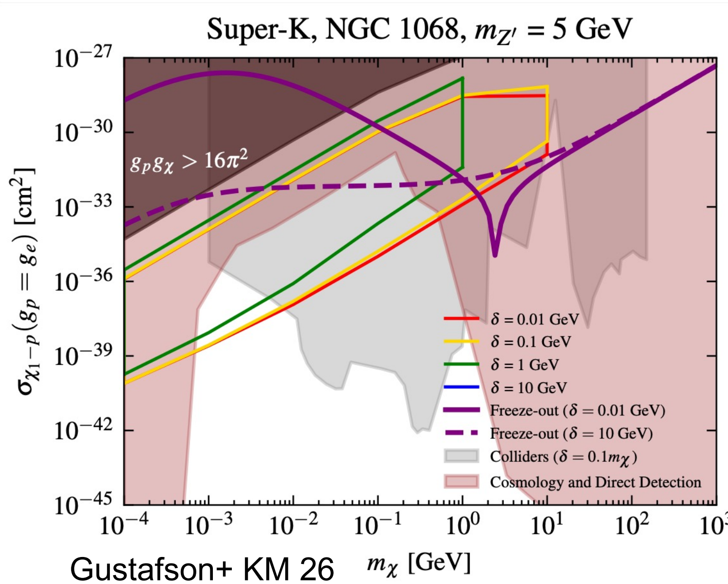
CR-DM interaction

- CR cooling by BSM
- CR-boosted DM

Guo+ 20
Wang+ 22,
Granelli+ 22,
Cappiello+ 24,
Gustafson+ KM 25,
De Marchi+ 25 etc.



Herrera & KM 24



Gustafson+ KM 26

Since the Discovery of HE Cosmic Neutrinos…

Evidences/hints for the association of high-energy νs with sources

Since the Discovery of HE Cosmic Neutrinos…

Evidences/hints for the association of high-energy νs with sources

- Source identification may not be easy
  (ex. starbursts: horizon of an average source ~ 1 Mpc)
- promising cases: "bright transients (GRBs, AGN flares)",
  "rare bright sources (powerful AGN)", "Galactic sources"
- Not guaranteed but remember the success of γ-ray astrophysics

from Murase's talk @ Neutrino 2014

Since the Discovery of HE Cosmic Neutrinos…

Evidences/hints for the association of high-energy νs with sources

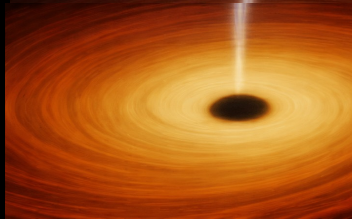
WANTED

~~Diffuse or~~ Associated

ν

- Source identification may not be easy
  (ex. starbursts: horizon of an average source ~ 1 Mpc)
- promising cases: "bright transients (TXS 0506+056? s)",
  "rare bright sources (powerful AGN)", "Galactic sources"
- Not guaranteed but re NGC 1068 e succ Galactic Plane strophysics

from Murase's talk @ Neutrino 2014



Since the Discovery of HE Cosmic Neutrinos…

Evidences/hints for the association of high-energy νs with sources
Multimessenger analyses are powerful and necessary

Galactic: multimessenger connection is now observed
- Supporting the hadronic origin of the Galactic diffuse γ-ray flux

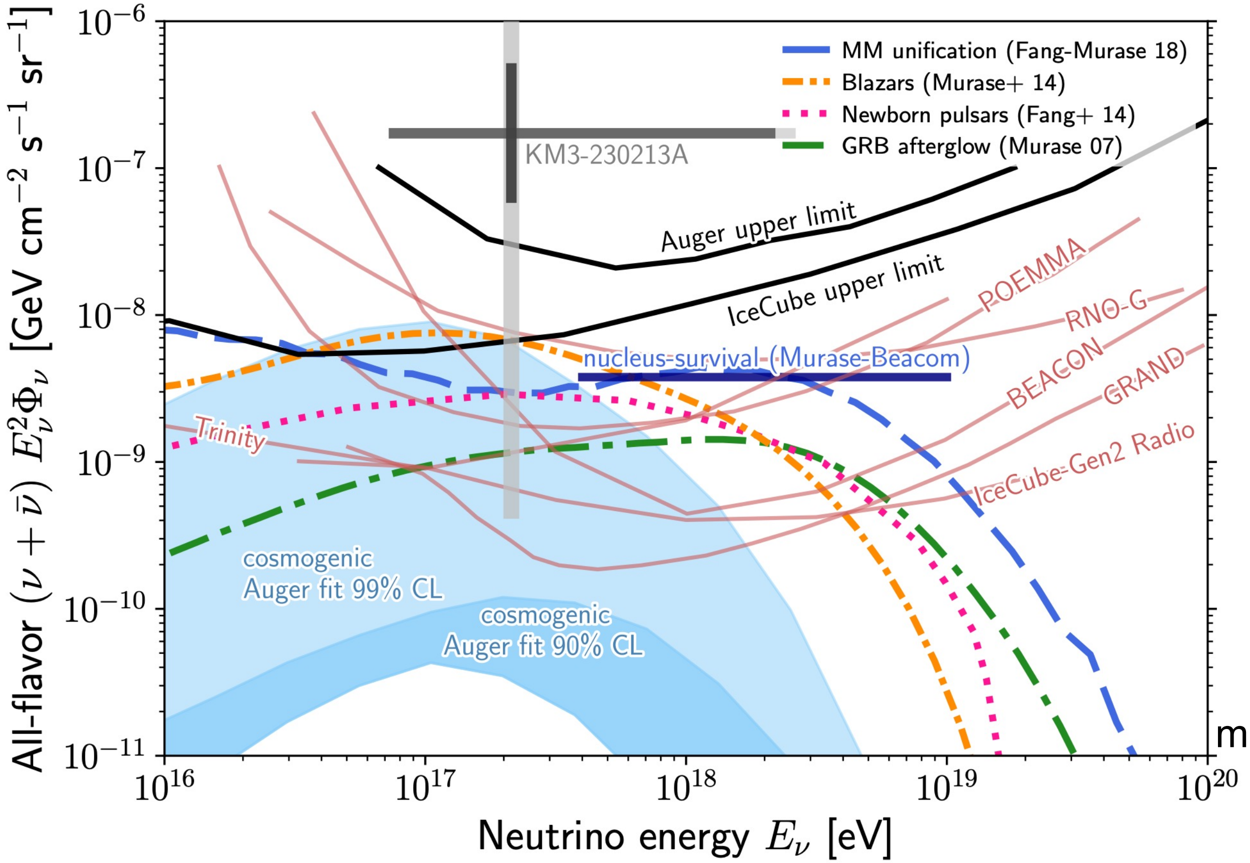
Extragalactic: multimessenger connection requires hidden ν sources
- AGN (jet-quiet): can be the dominant sources of the all-sky neutrino flux
- Associated AGNs: hidden ν sources
  NGC 1068 $\rightarrow$ νs from pp or pγ produced within 10-30 Schwarzschild radii
  Unique probe of high-energy phenomena powered by black holes

New physics: better understanding properties of ν sources is relevant

Looking forward to
- Galactic: unveiling diffuse emission and study extreme Galactic CR accelerators
- Extragalactic: establishing NGC 1068 and source population w. multiple ν detectors
- Energy frontier:
- Time domain:

Energy Frontier: Ultrahigh-Energy Cosmic-Ray Accelerators?

- Auger data: UHECRs are largely "nuclei" → $E^2\Phi_\nu$ <~ 3×10^{-9} GeV cm^{-2} s^{-1} sr^{-1}
- Many models consistent w. IceCube limits: $E^2\Phi_\nu$ <~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}



IceCube 25, Li+ 25, Yuan & Lu 25
KM3Net 25, 26, Yuan+ 25
Mukhopadhyay & Kimura 26
KM3Net 26, Yu & Zhang 26…

modified from Kotera+ KM 26 JCAP

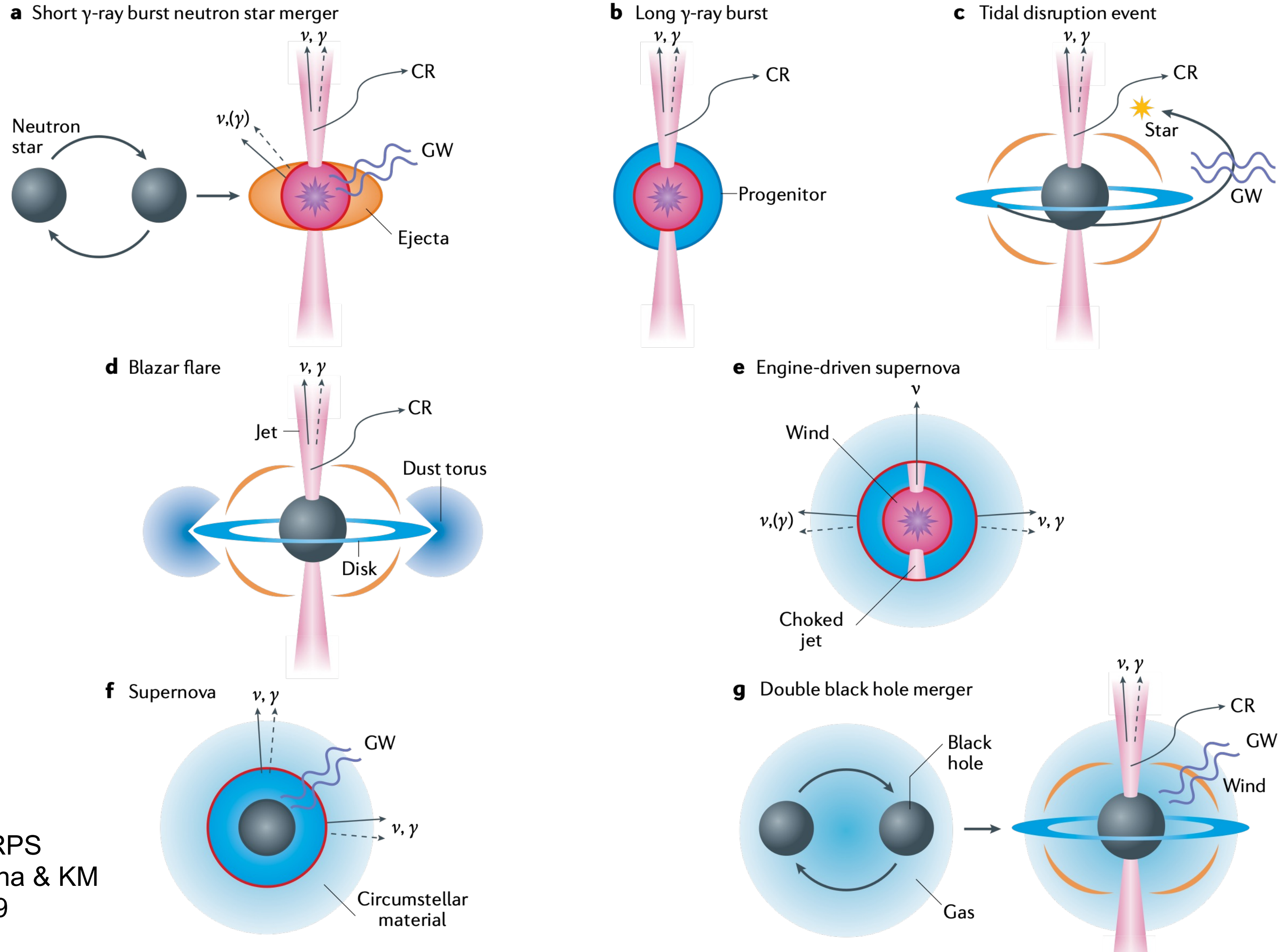
Next-generation UHE ν detectors can probe many models for UHECR nuclei
KM3Net event? encouraging

Celli's talk on Fri

Viergg's talk this afternoon

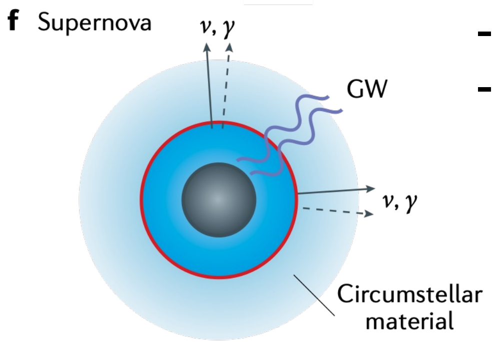
Time-Domain Frontier: Multimessenger/Multienergy ν Transients?

pointing & timing → good chance to discover ν sources

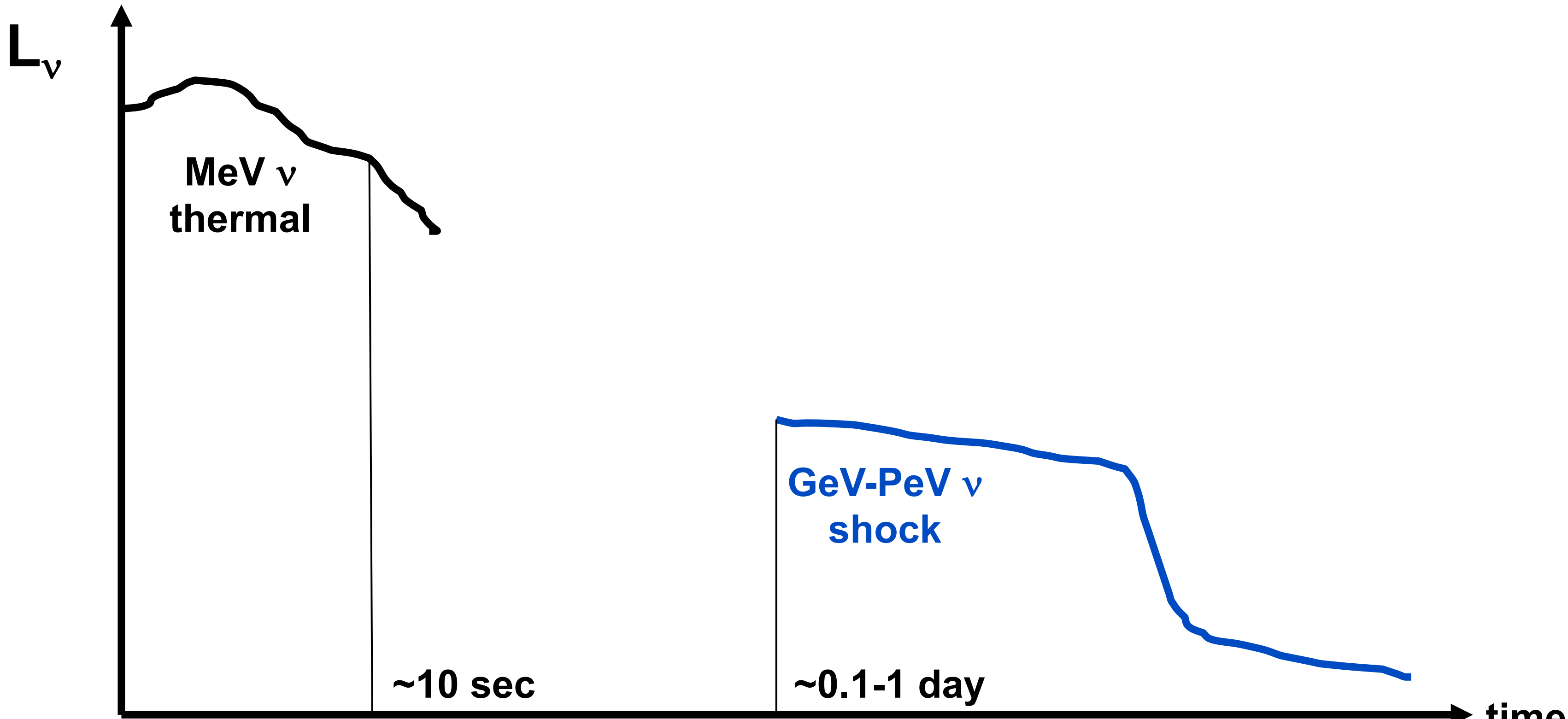


KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

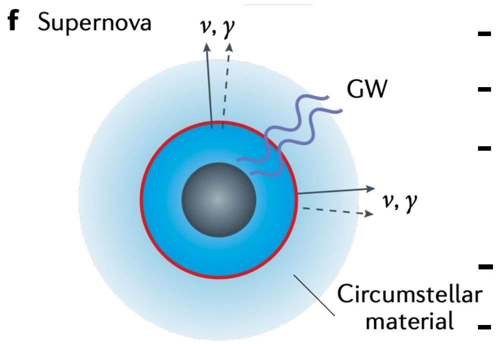
High-Energy Supernova Neutrinos



- SN progenitors commonly have "confined" circumstellar material
- Explosion → shock → Fermi acceleration → ν & γ-ray production

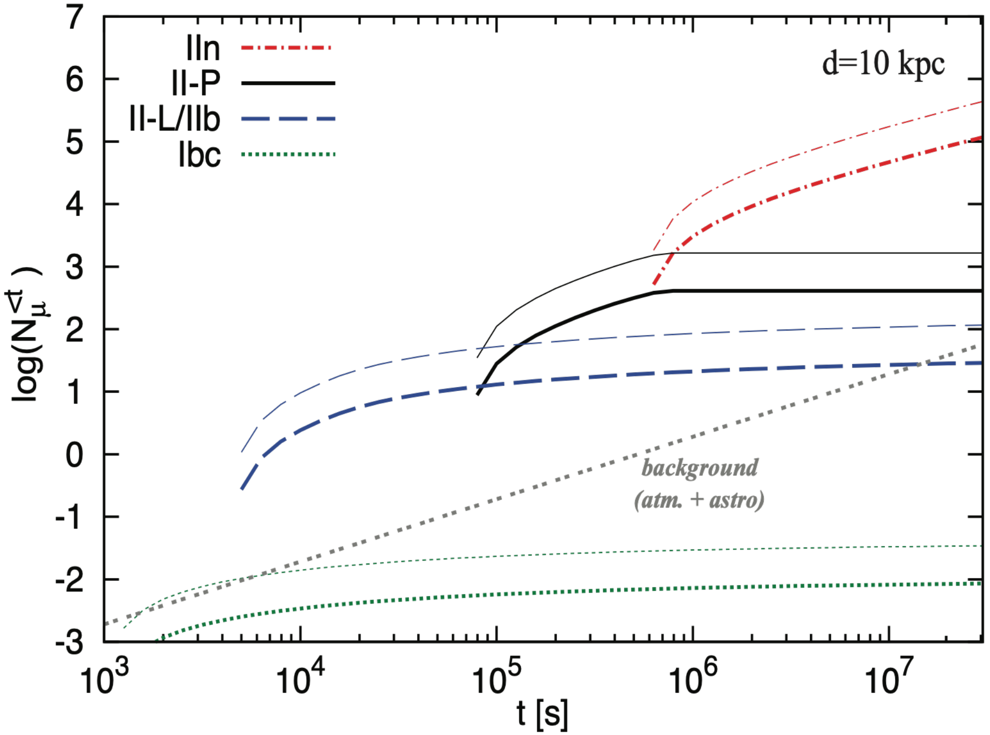


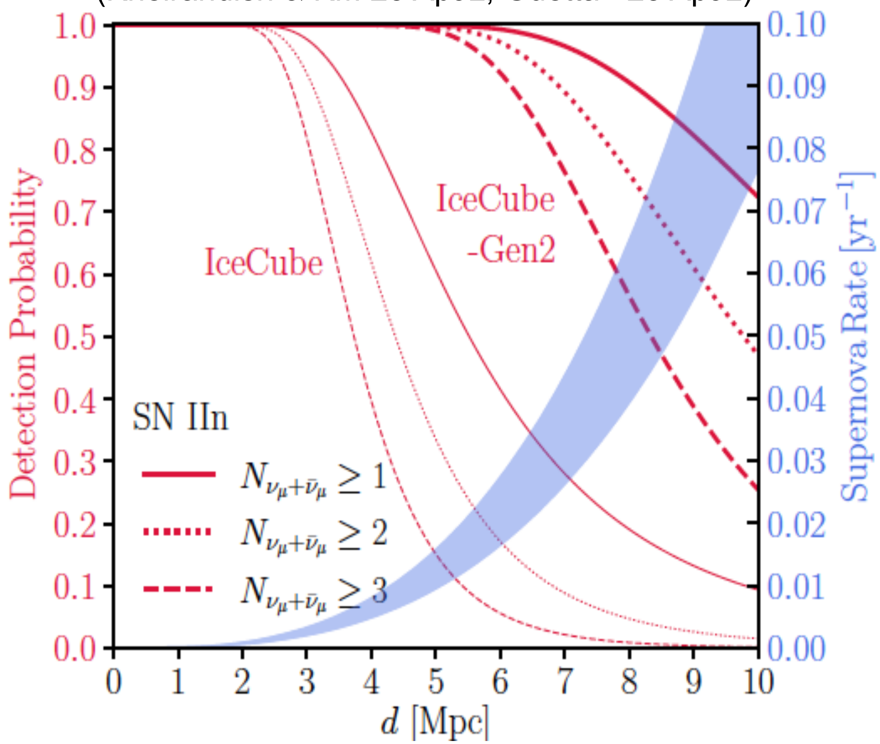
High-Energy Supernova Neutrinos

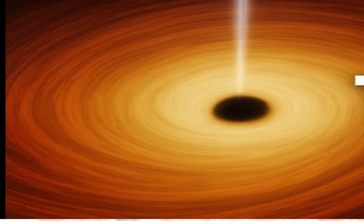


- SN progenitors commonly have "confined" circumstellar material
- Explosion → shock → Fermi acceleration → ν & γ-ray production
- Galactic SN → large statistics for IceCube etc. (KM 18 PRDR, 24 PRD)
  possible targets for HK, ATLAS etc. (Wen+ KM 24 PRL)
- "multimessenger" & "multi-energy" ν sources
- Real-time observations of CR acceleration, Galactic CR origin
- Extragalactic "minibursts": global ν detector network will be useful

(Kheirandish & KM 23 ApJL, Guetta+ 23 ApJL)







Thank you for your attention

Evidences/hints for the association of high-energy νs with sources
Multimessenger analyses are powerful and necessary

Galactic: multimessenger connection is now observed
- Supporting the hadronic origin of the Galactic diffuse γ-ray flux

Extragalactic: multimessenger connection requires hidden ν sources
- AGN (jet-quiet): can be the dominant sources of the all-sky neutrino flux
- Associated AGNs: hidden ν sources

  NGC 1068 $\rightarrow$ νs from pp or pγ produced within 10-30 Schwarzschild radii

  Unique probe of high-energy phenomena powered by black holes

New physics: better understanding properties of ν sources is relevant

Looking forward to
- Galactic: unveiling diffuse emission and study extreme Galactic CR accelerators
- Extragalactic: establishing NGC 1068 and source population w. multiple ν detectors
- Energy frontier: dawn of ultrahigh-energy ν astrophysics
- Time domain: ν–multiplet transients w. counterparts (ex. supernovae/novae/flares)
- Some surprises…

Backup Slides

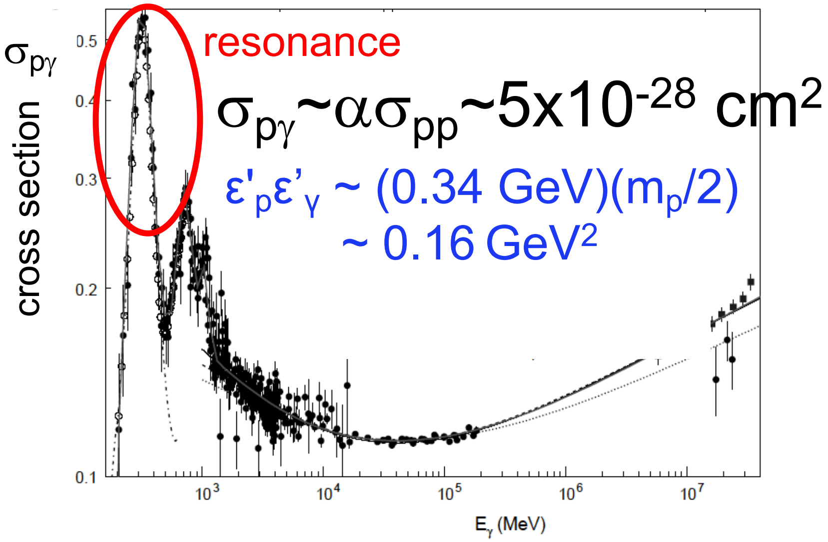
Neutrino and Gamma-Ray Production by Cosmic Rays

Cosmic-ray Accelerators

Active galaxy

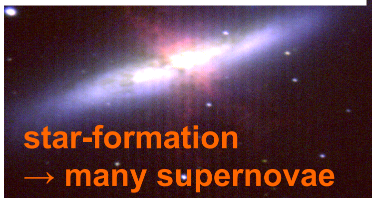
γ-ray burst

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



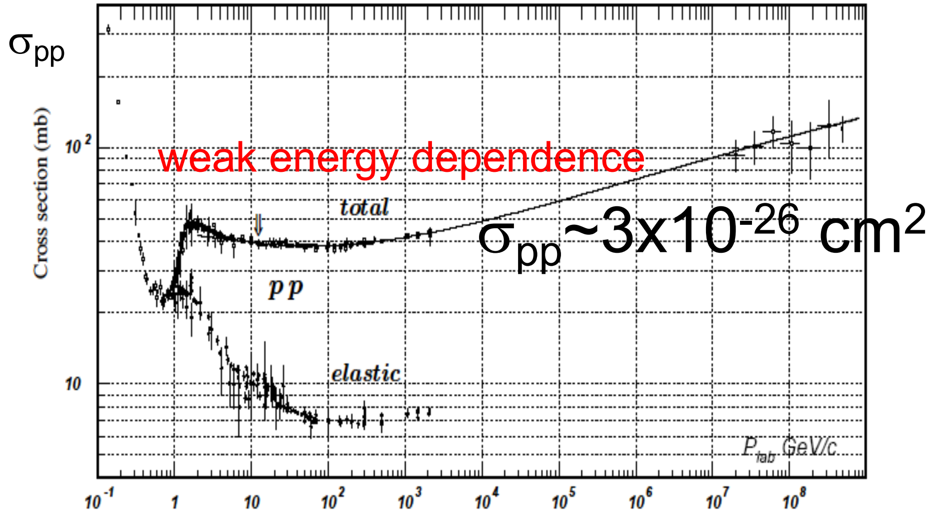
Cosmic-ray Reservoirs

Galaxy



Galaxy cluster

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



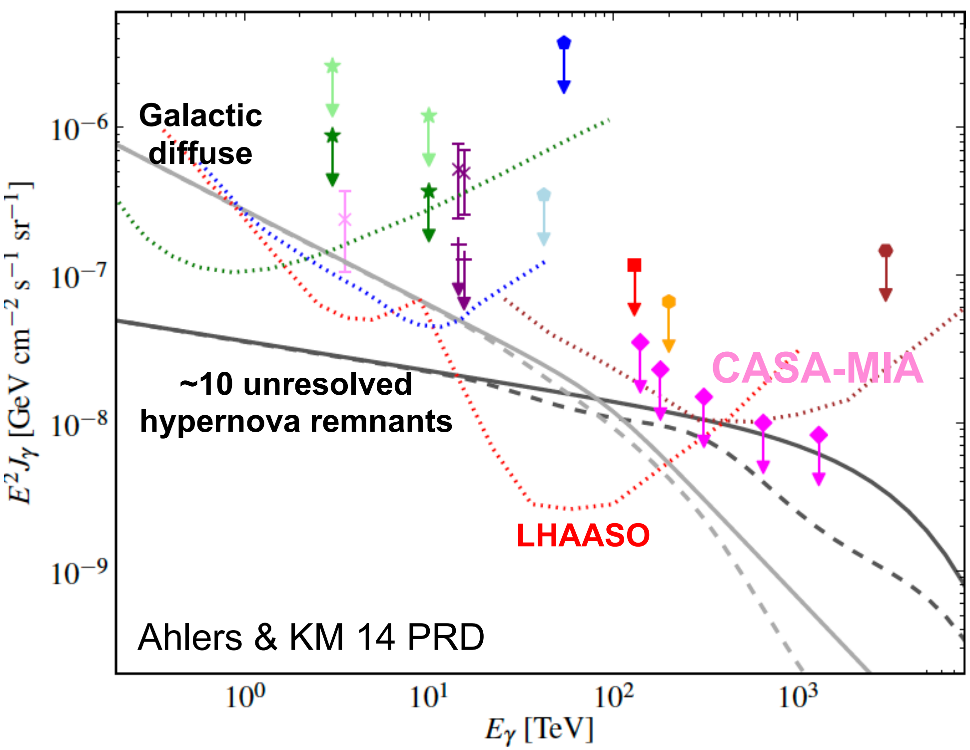
$$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e \ (\text{or } \bar{\nu}_e) + e^{\pm}$$

Importance of Multimessenger Connection – Milky Way Case

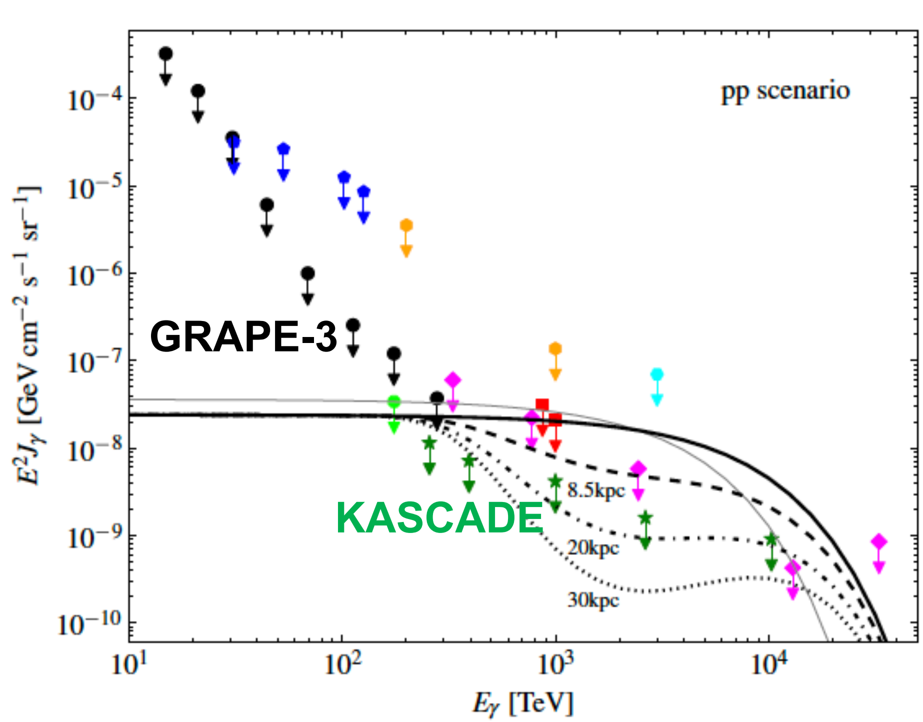
A decade ago, neither γ rays NOR νs were observed in the sub-PeV range.
(Note that most γ rays from Galactic sources reach Earth.)
But we already learned that Galactic contribution to IceCube νs is subdominant.

$p + p \rightarrow N\pi + X \quad \pi^0:\pi^{\pm} \sim 1:2 \rightarrow \mathbf{E_\gamma^2\,\Phi_\gamma : E_\nu^2\,\Phi_\nu} \sim 2:3$ (comparable)

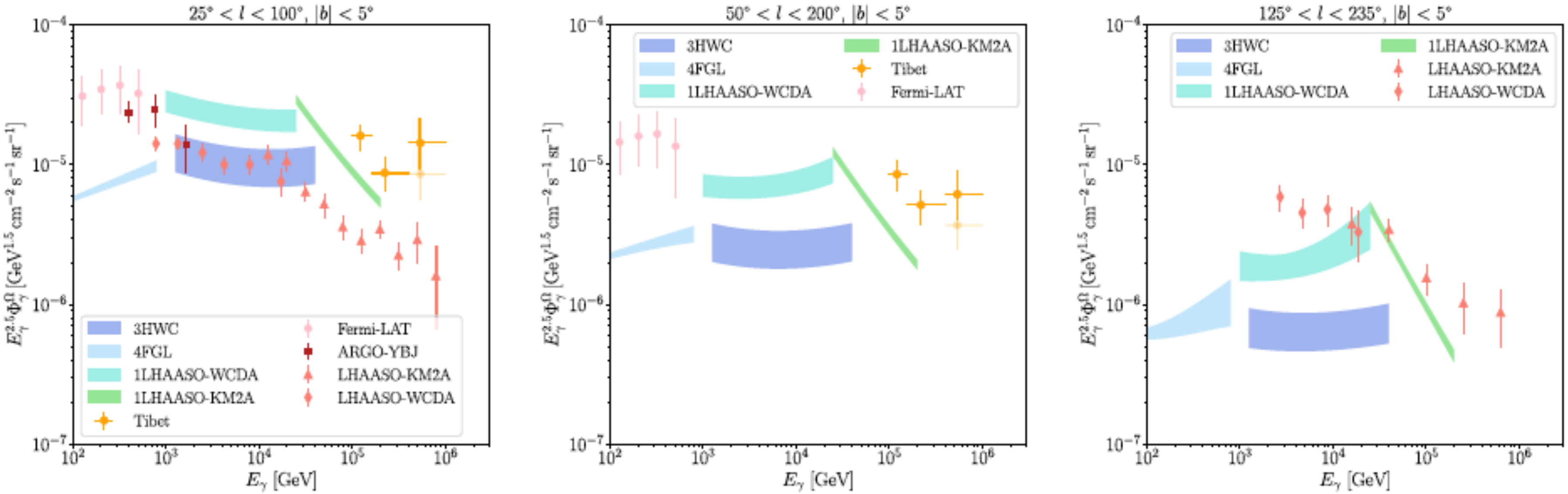
Galactic Plane $|b| < 2^\circ$

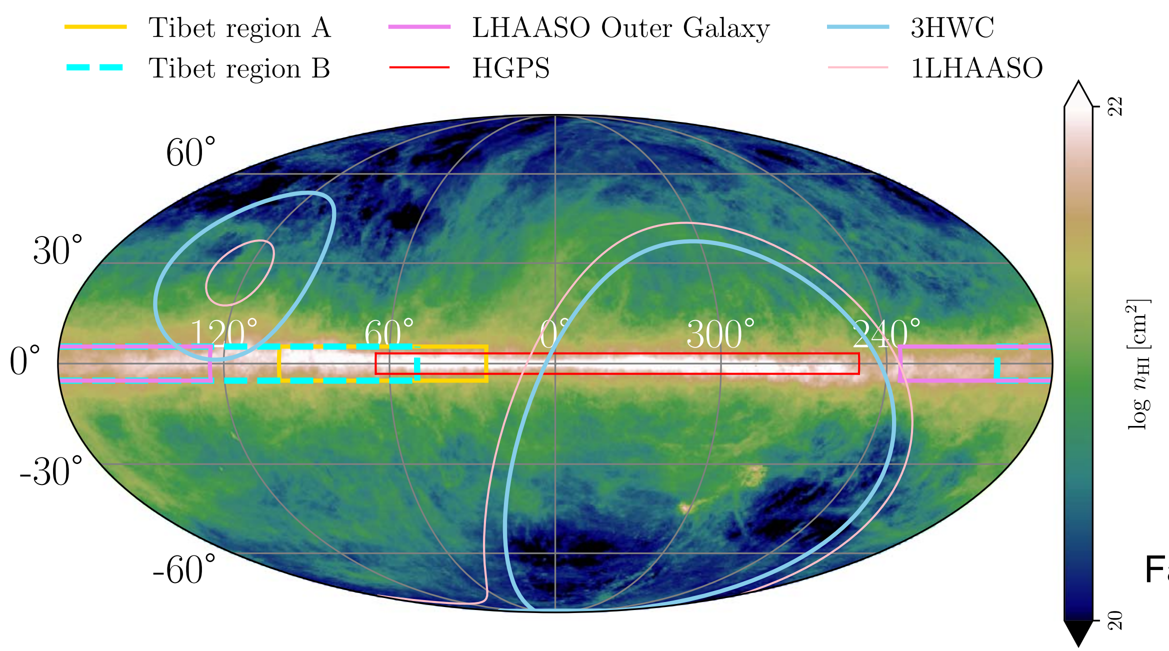


Galactic Halo (quasi-isotropic)



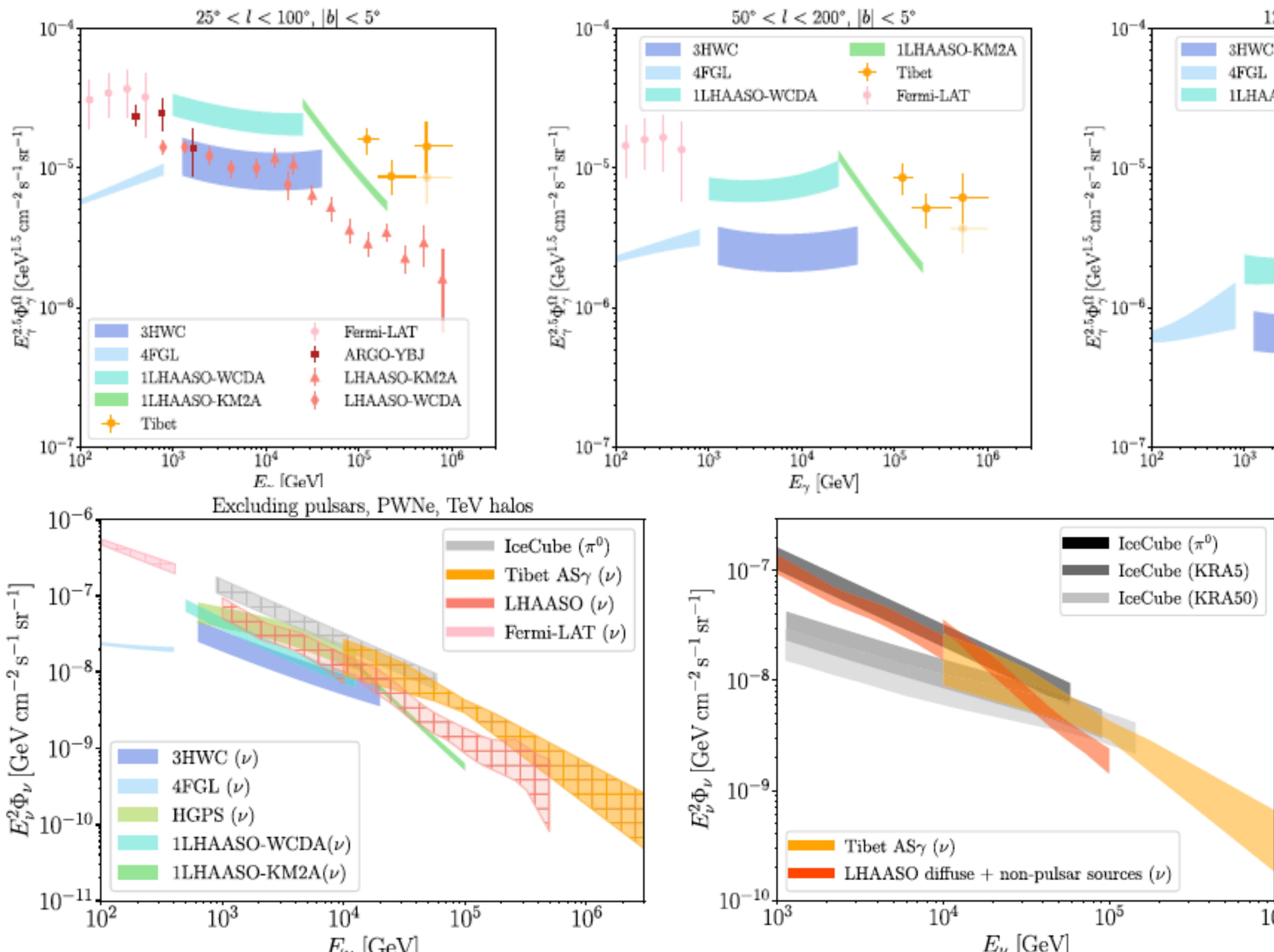
Importance of Improved Measurements





Fang & KM 23 ApJL

Importance of Improved Measurements



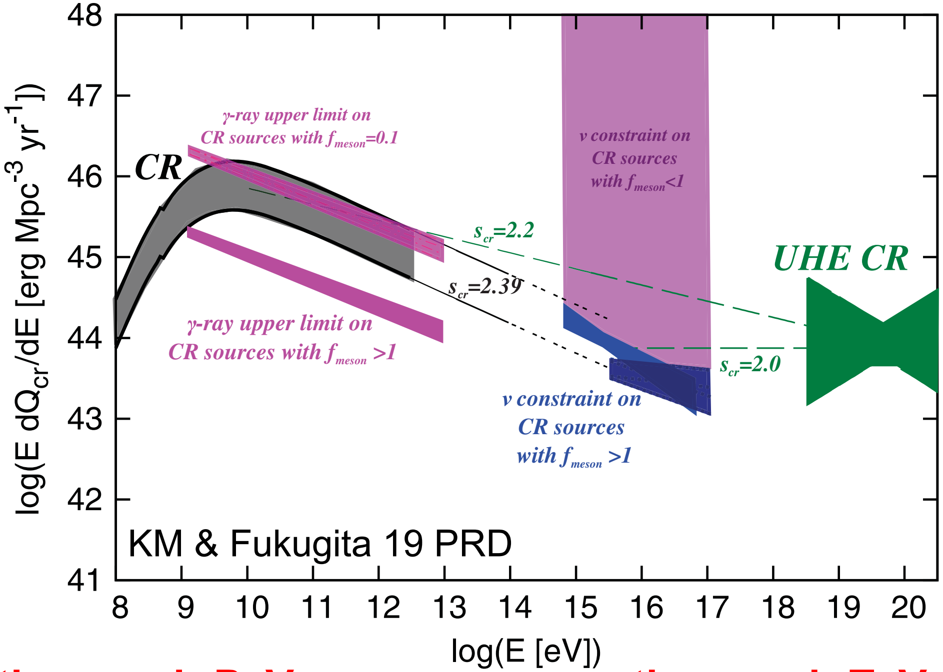
Fang & KM 23 ApJL

Sources may significantly contribute to the Tibet data in the inner region (see also Kato+ 24 ApJL). Unresolved sources at >100 TeV? “Resolved” sources could also contribute to the IceCube data.

What Can We Learn from All-Sky Data? - Energetics

$$E^2\Phi \approx \frac{ct_H}{4\pi}\varepsilon Q_\varepsilon \xi_z g(E)$$ ∝ **(Q: energy generation rate density)**

propagation

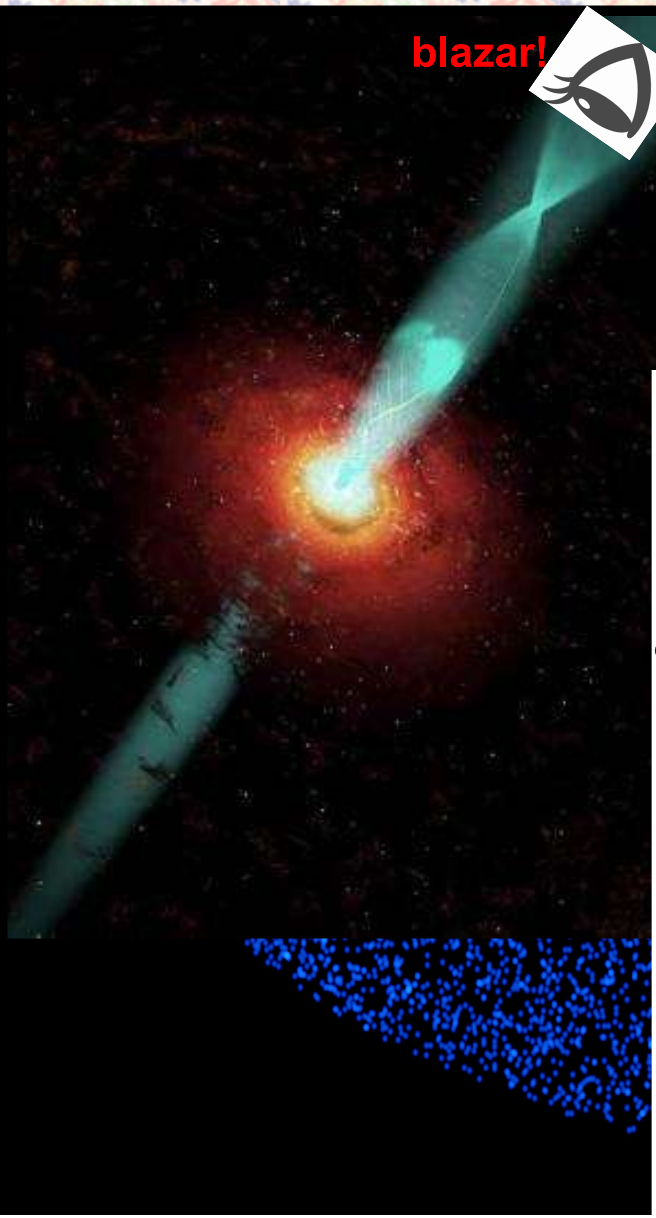


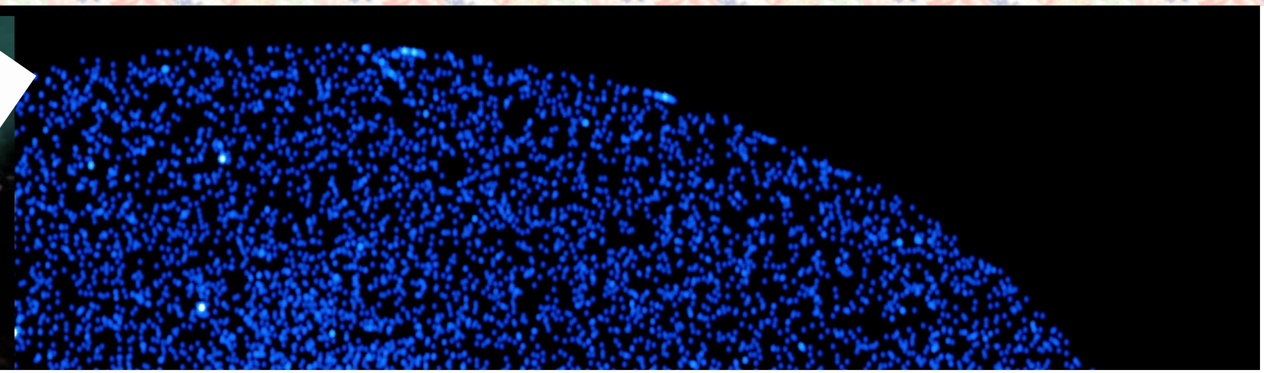
UHECR energy generation ~ sub-PeV ν energy generation ~ sub-TeV γ-ray energy generation

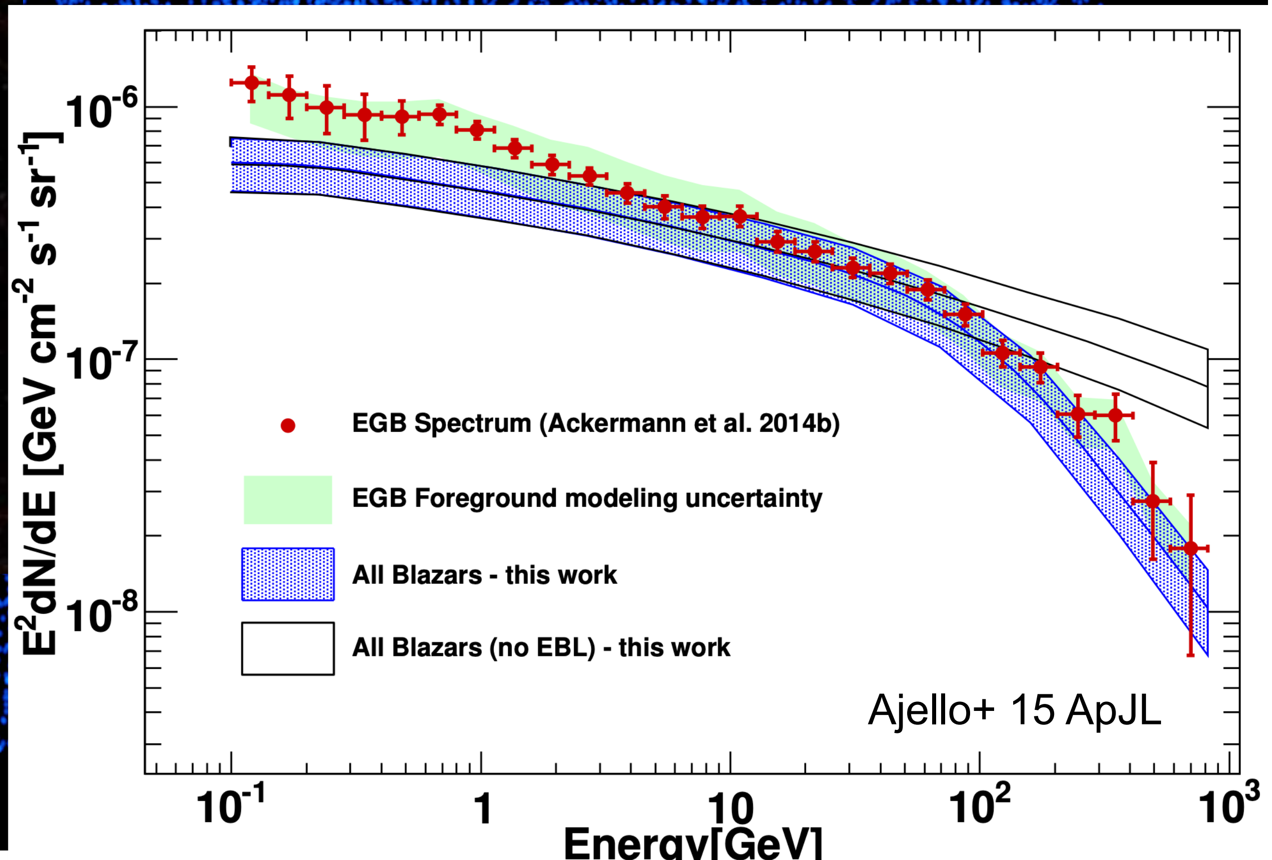
	ccSN (CR)	HN (CR)	DNS (CR)	GRB (γ)	LL GRB (γ)	TDE (γ)
Q [erg Mpc^{-3} yr^{-1}]	$10^{46.6}$	$10^{45.5}$	$10^{44.5}$	$10^{43.6}$	$10^{43.5}$	$10^{43.5}$
ρ [Mpc^{-3} yr^{-1}]	10^{-4}	$10^{-5.5}$	$10^{-5.8}$	10^{-9}	$10^{-6.5}$	$10^{-10.5}$

	SBG (γ)	AGN (X)	BL Lac (γ)	FSRQ (γ)	RG (γ)	Accr/Mger (CR)
Q [erg Mpc^{-3} yr^{-1}]	$10^{44.5}$	$10^{46.3}$	$10^{45.4}$	$10^{44.3}$	$10^{44.6}$	$10^{46.5}$
n [Mpc^{-3}]	10^{-4}	$10^{-4}-10^{-3}$	$10^{-7}-10^{-6.5}$	$10^{-9}-10^{-8}$	$10^{-5}-10^{-4}$	$10^{-6}-10^{-5}$

Extragalactic γ-Ray Sky: Dominated by On-Axis Jetted AGN



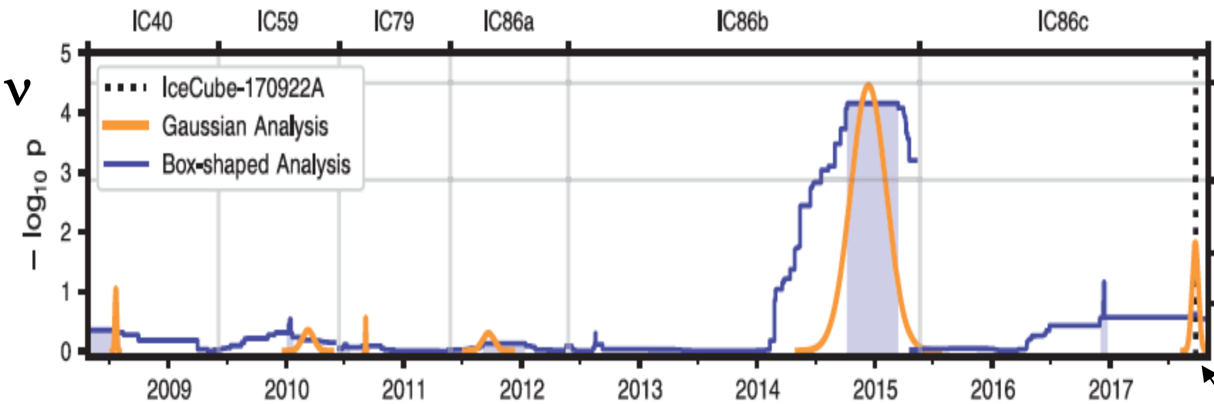




2017: Hints of Neutrinos from On-Axis Jetted AGN?

IceCube 2018 Science

ν



TXS 0506+056

"blazar"

But "disputed" by theory...
(e.g., KM+ 18 ApJ)

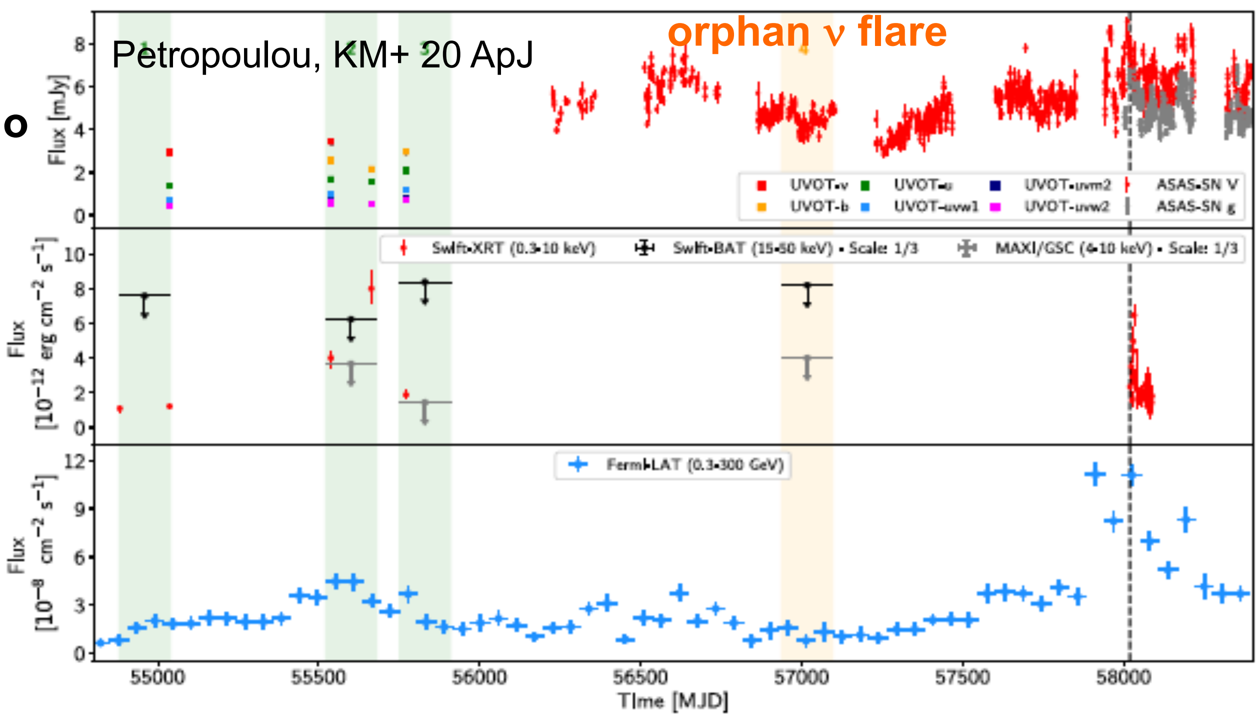
2017 multimessenger flare

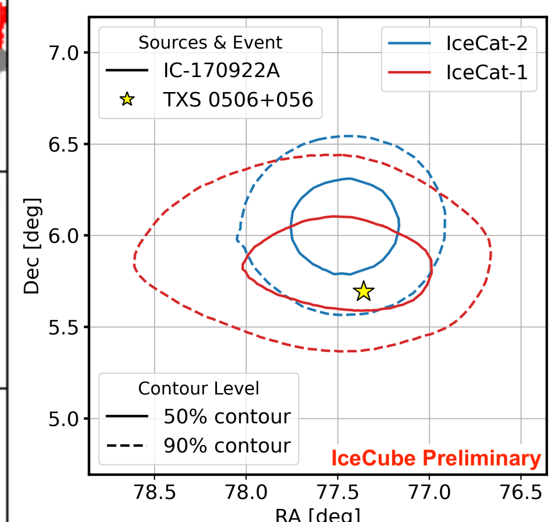
2014-2015
orphan ν flare

radio

X

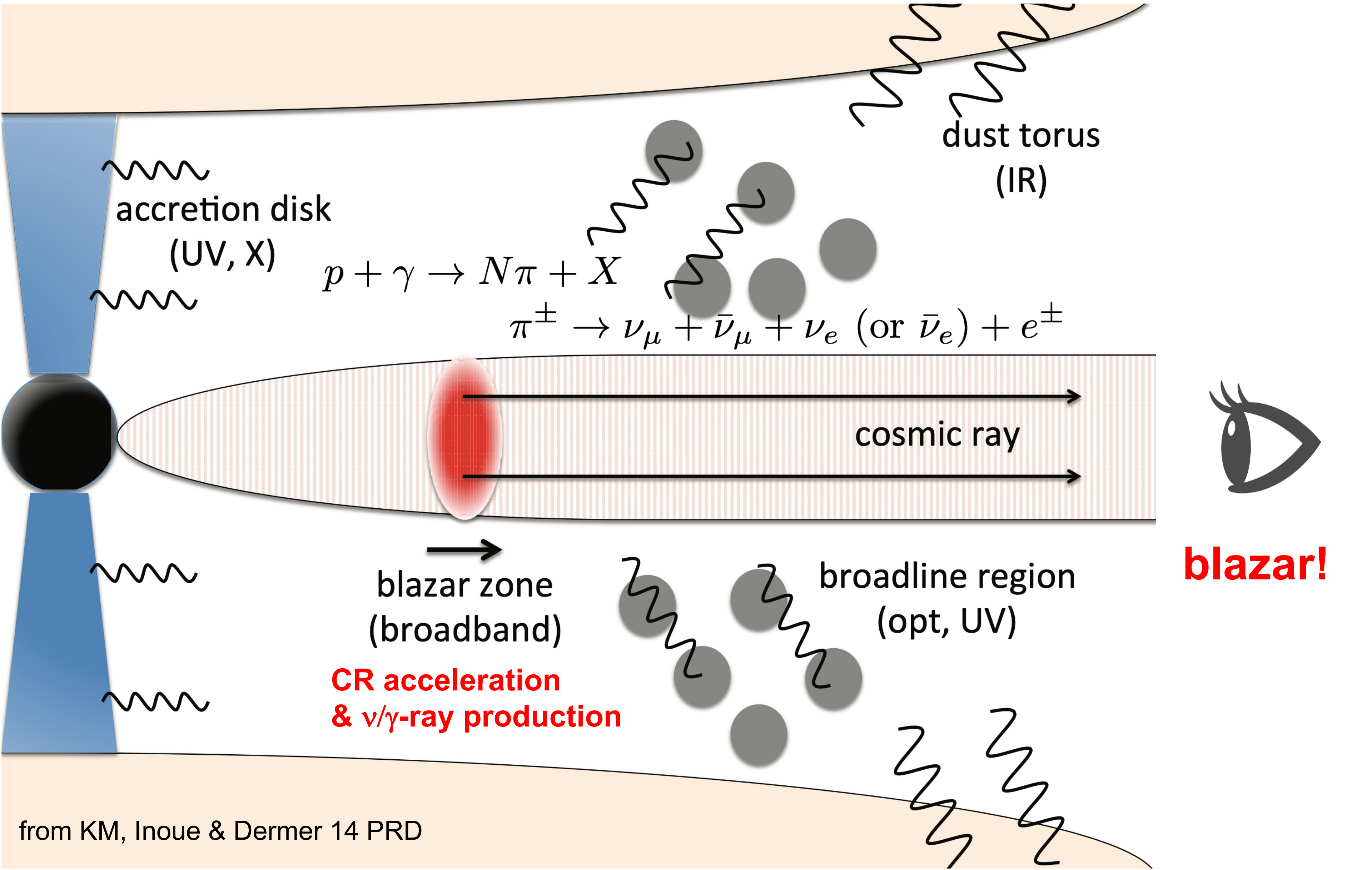
γ





IceCube 25 ICRC

Neutrino Production in AGN Jets

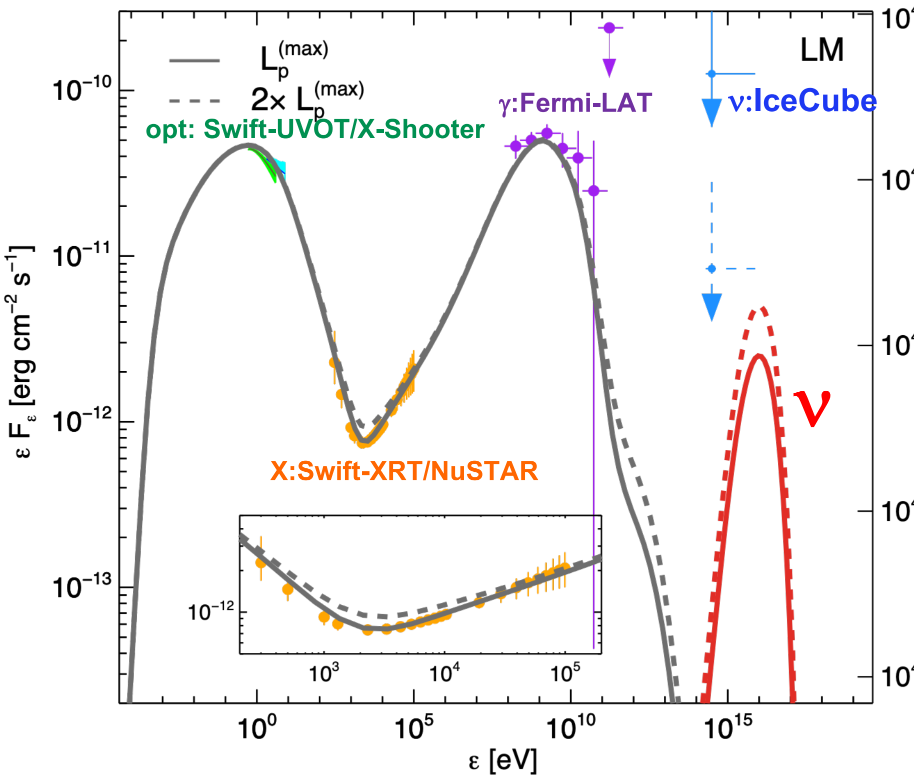


from KM, Inoue & Dermer 14 PRD

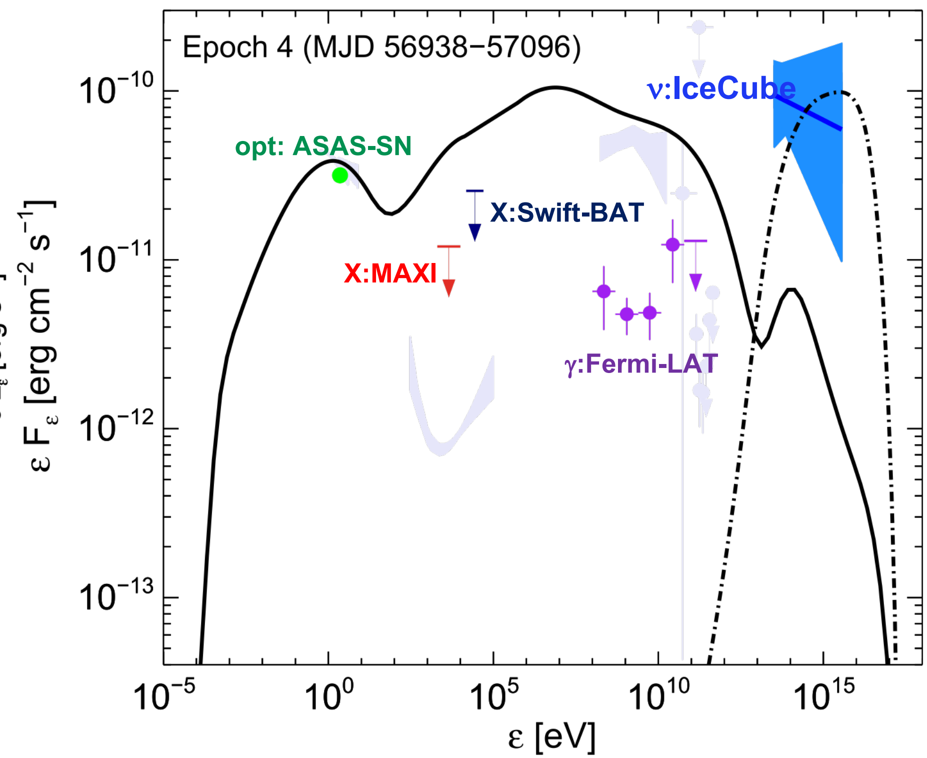
"Power" of Multimessenger Approaches

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

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



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

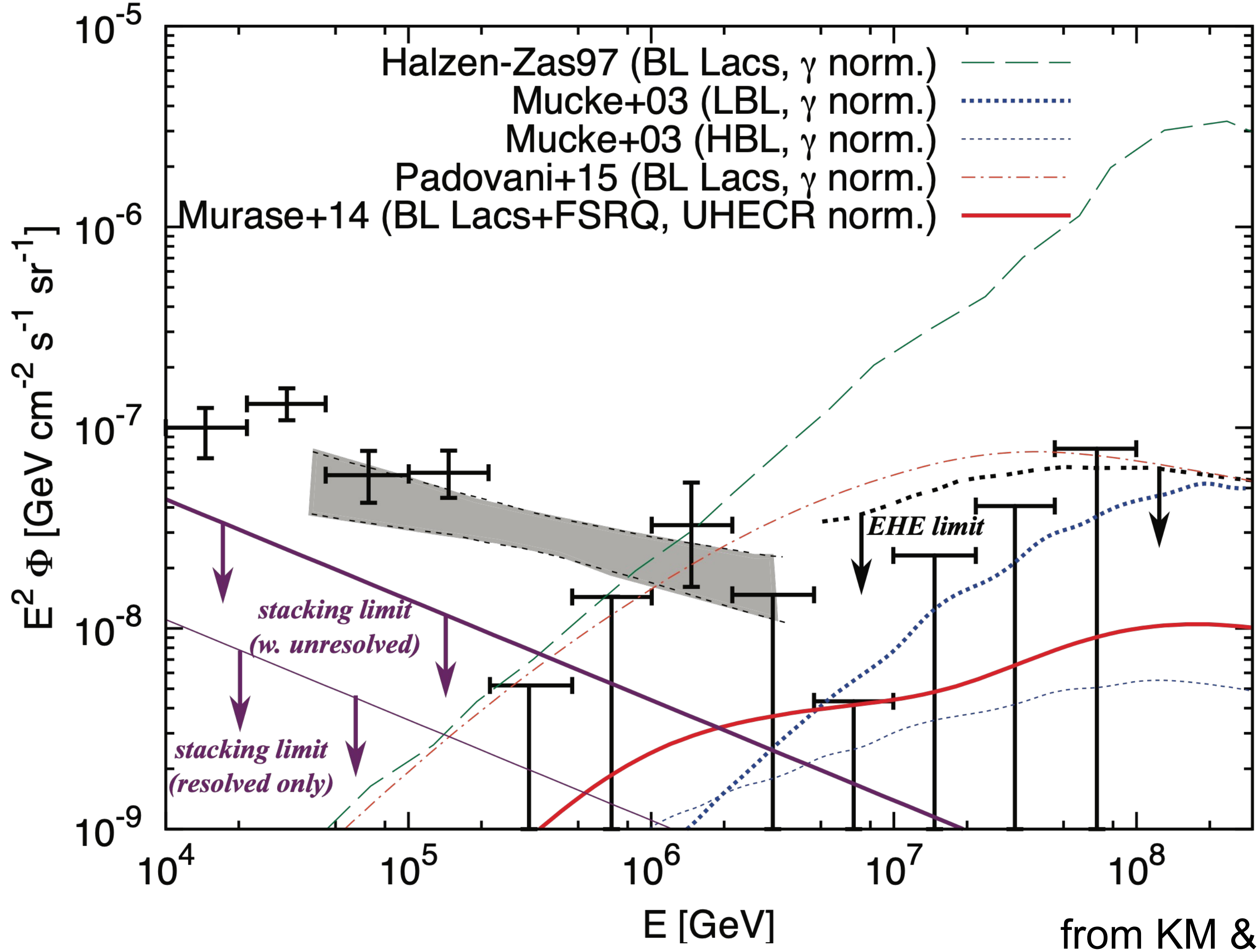


$F_{\nu\mathrm{theory}} \sim F_{\mathrm{EMtheory}} < F_{\mathrm{EMobs}} < F_{\nu\mathrm{obs}}$

associations are questioned by multimessenger analyses

Extragalactic ν Sky: NOT Dominated by On-Axis Jetted AGN

Stacking searches are powerful to constrain νs from on-axis jetted AGN

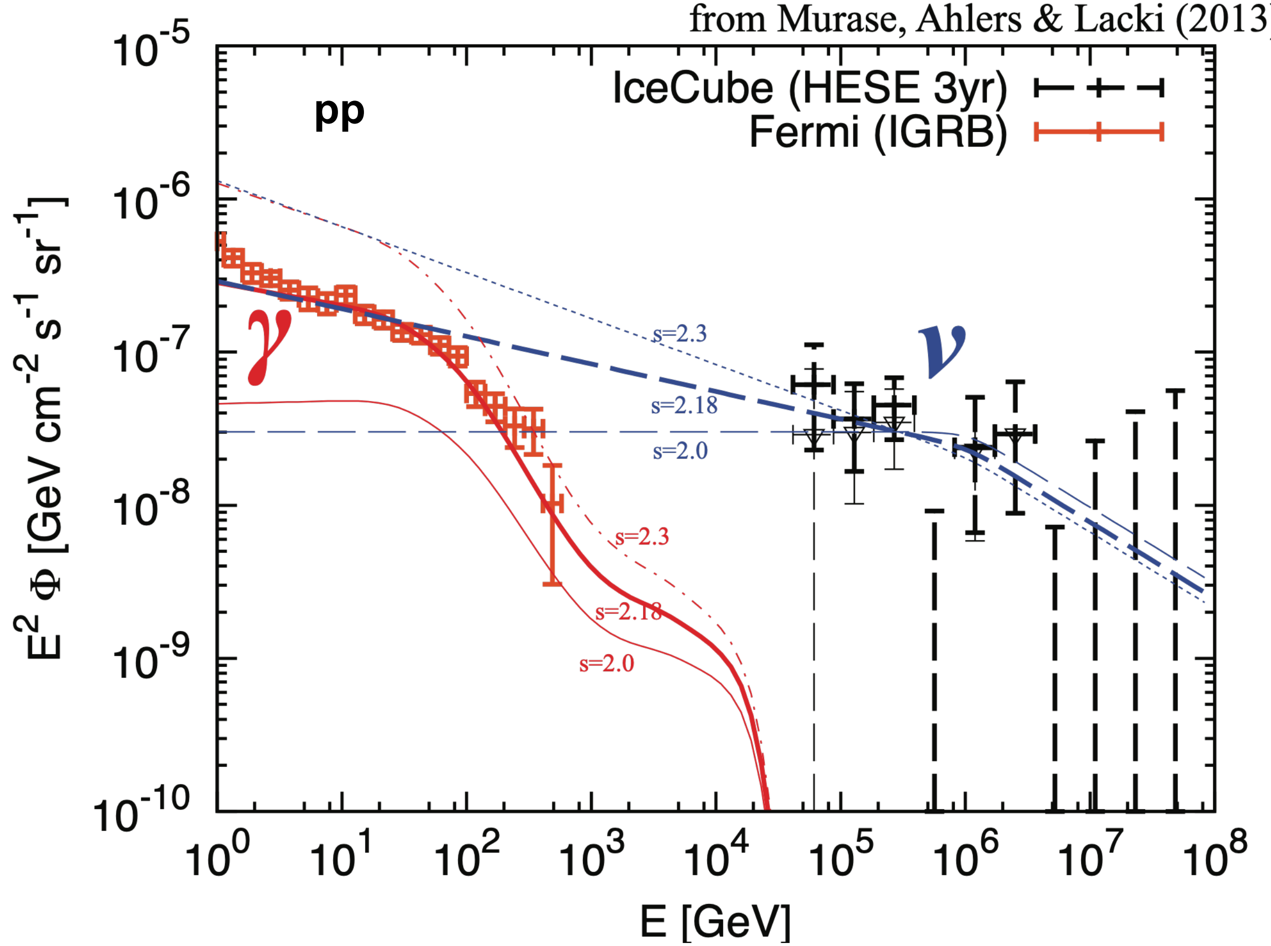


from KM & Stecker 23

What Can We Learn from Multimessenger Connection?

Generic power-law spectrum: $\propto \varepsilon^{2-s}$, transparent to GeV-TeV γ

from Murase, Ahlers & Lacki (2013)



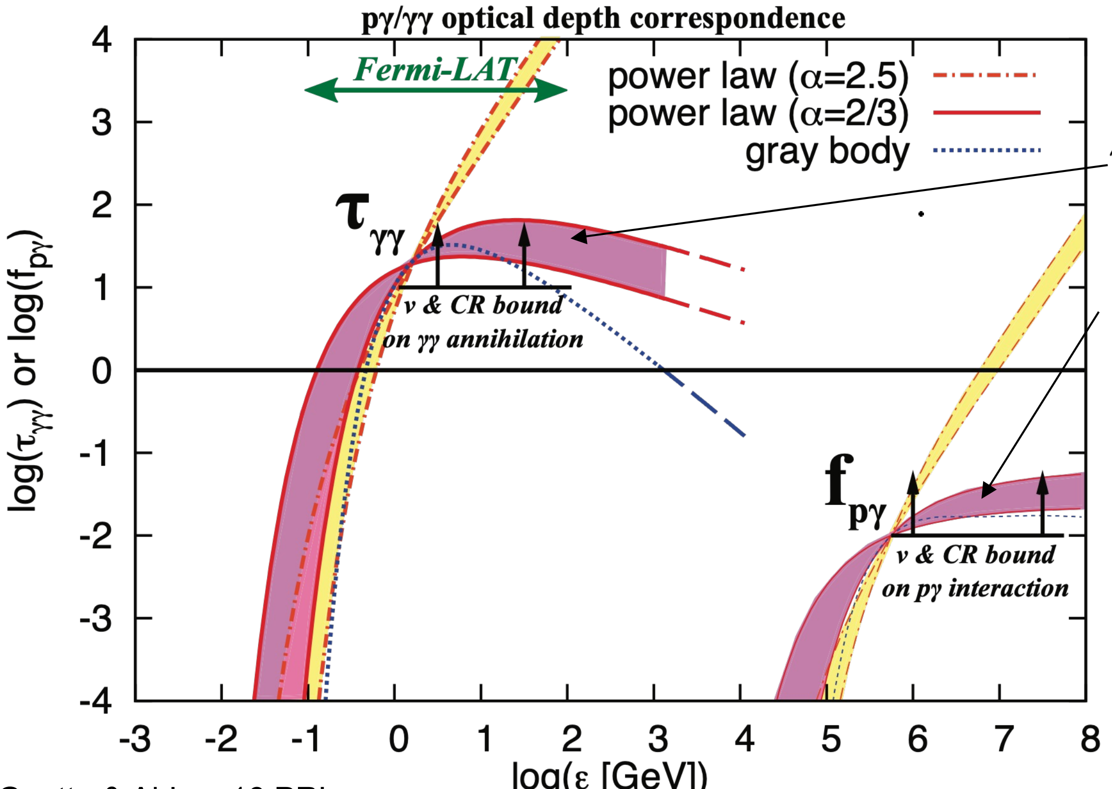
- **s_ν<2.1-2.2 (for extragal.); insensitive to redshift evolution of sources**
- Large contribution to diffuse sub-TeV γ: >30%(SFR evol.)-40% (no evol.)

Opacity Argument

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

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

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



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

II

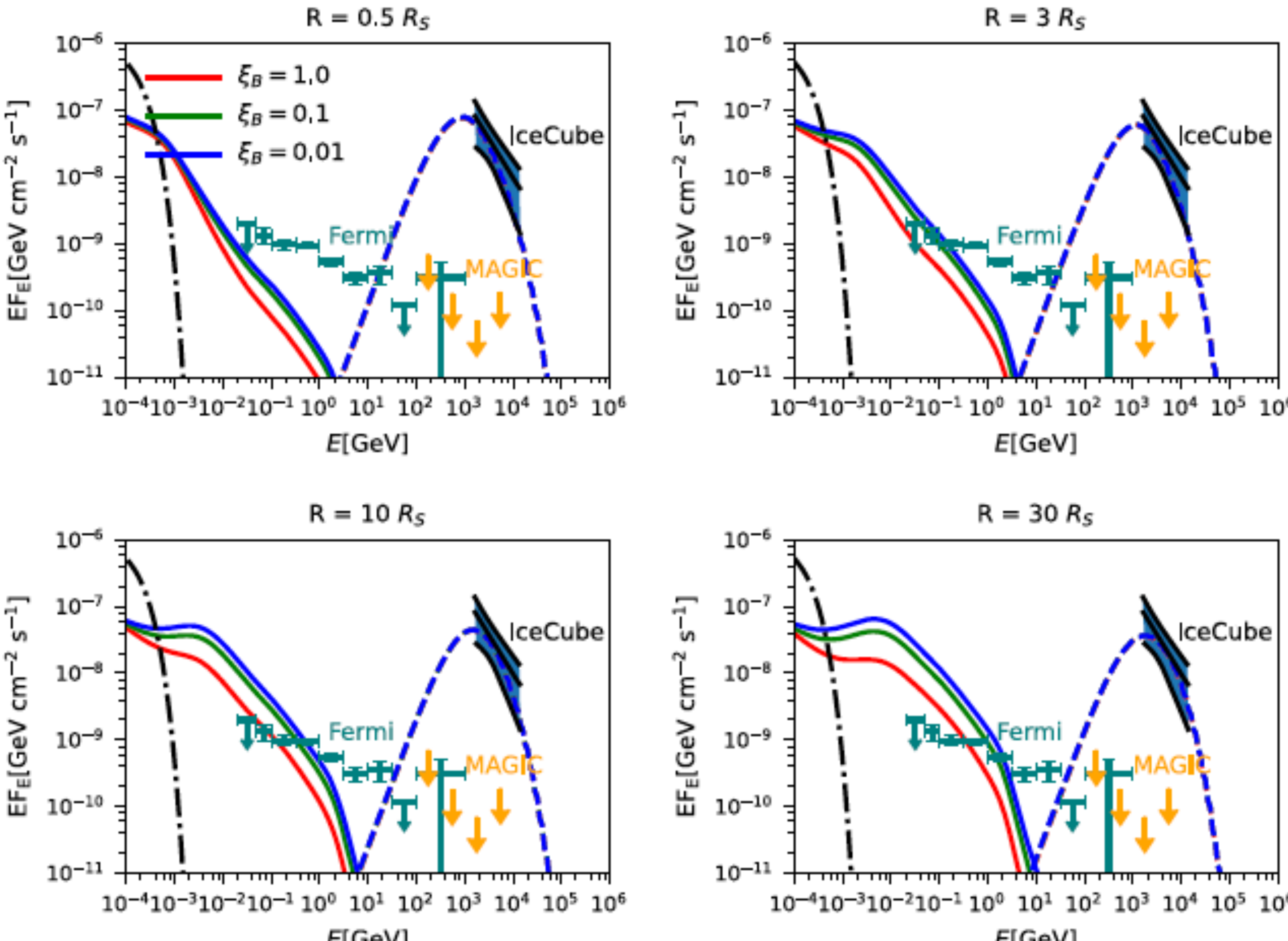
$$p + \gamma \to N\pi + X$$

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

KM, Guetta & Ahlers 16 PRL

Updated Fermi Analysis & Impacts of Magnetic Fields

Das, Zhang & KM 24 ApJ, Das, KM & Zhang 26 (see Ajello, KM & McDaniel 23 ApJL for updated Fermi analysis)

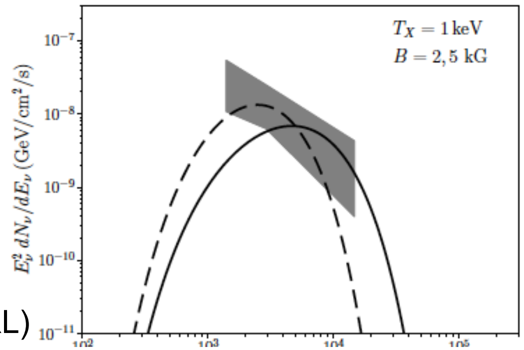


magnetization $\xi_B = U_B/U_{ph}$ (cf. corona model: $\xi_B \sim 1$, shock model: ξ_B <~ 0.01)

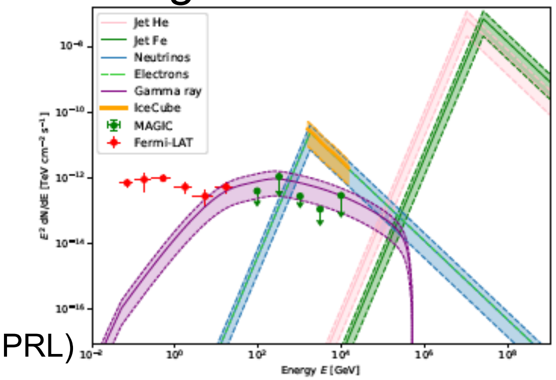
Neutrino Production Mechanisms: pp & pγ

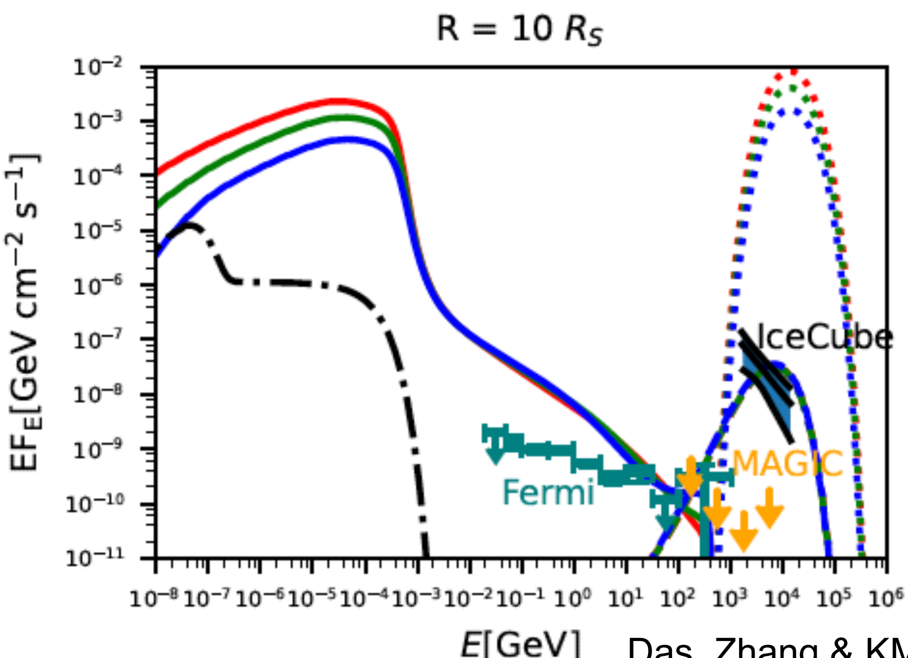
- Multimessenger connection must be considered
- Exotic models are excluded if relevant processes are consistently included
- Also unlikely by the energetics requirement: $L_{CR} < L_{bol} \sim L_{Edd} \sim 10^{45}$ erg/s

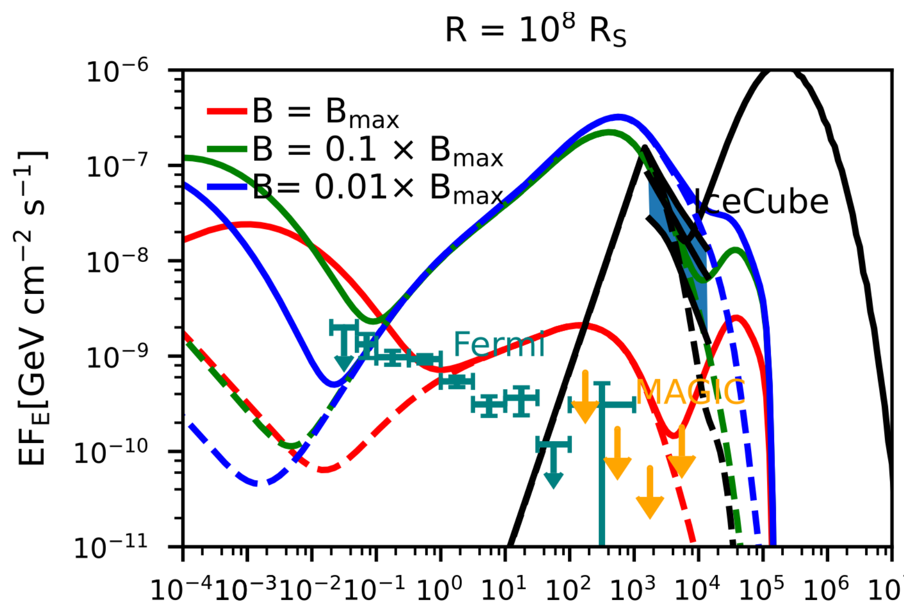
Neutrinos from $\gamma\gamma \rightarrow \mu^+\mu^-$
(Hooper & Plant 23 PRL)



Neutrons from photodisintegration
(Yasuda, Inoue & Kusenko 25 PRL)







Das, Zhang & KM 24 ApJ, Das, KM & Zhang 26

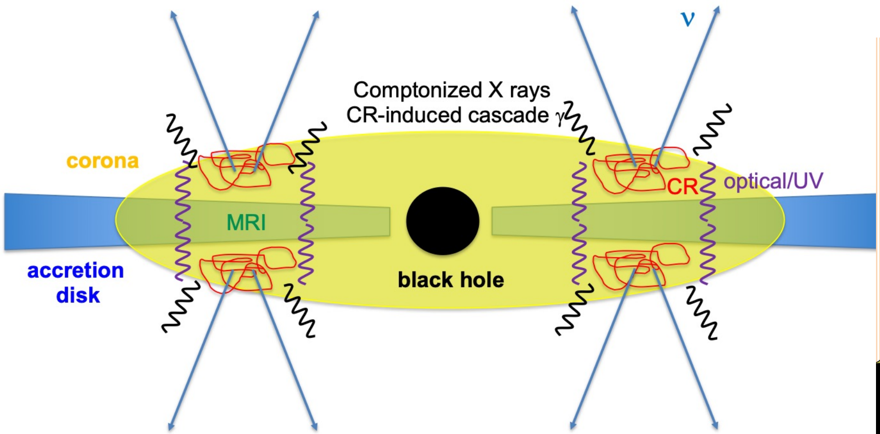
E[GeV]

Neutrino Production Models

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

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

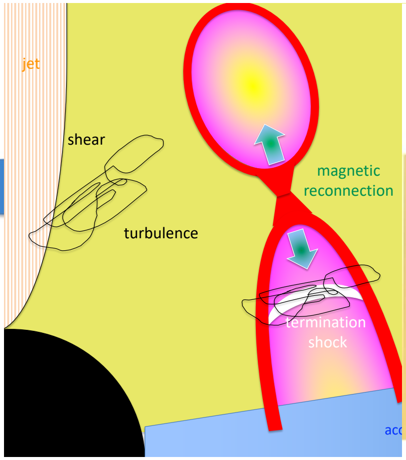
magnetically-powered corona or jet base
(KM+ 20, Kheirandish, KM & Kimura 21)

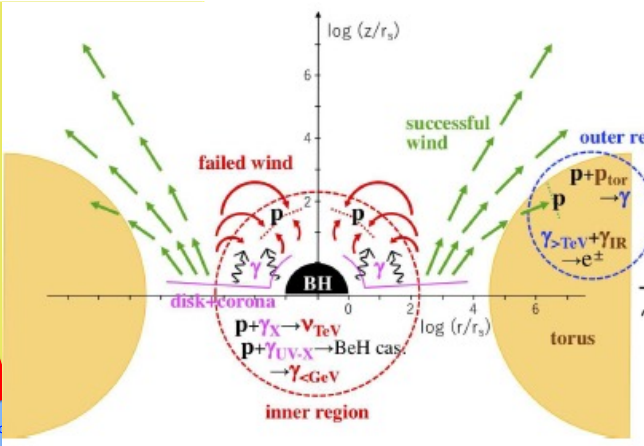


turbulence
magnetic reconnection

$\beta = P_g/P_B < 0.1\text{-}10 \rightarrow B \gtrsim 10^2$ G
$L_{CR} \lesssim L_X \lesssim L_B$ (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)

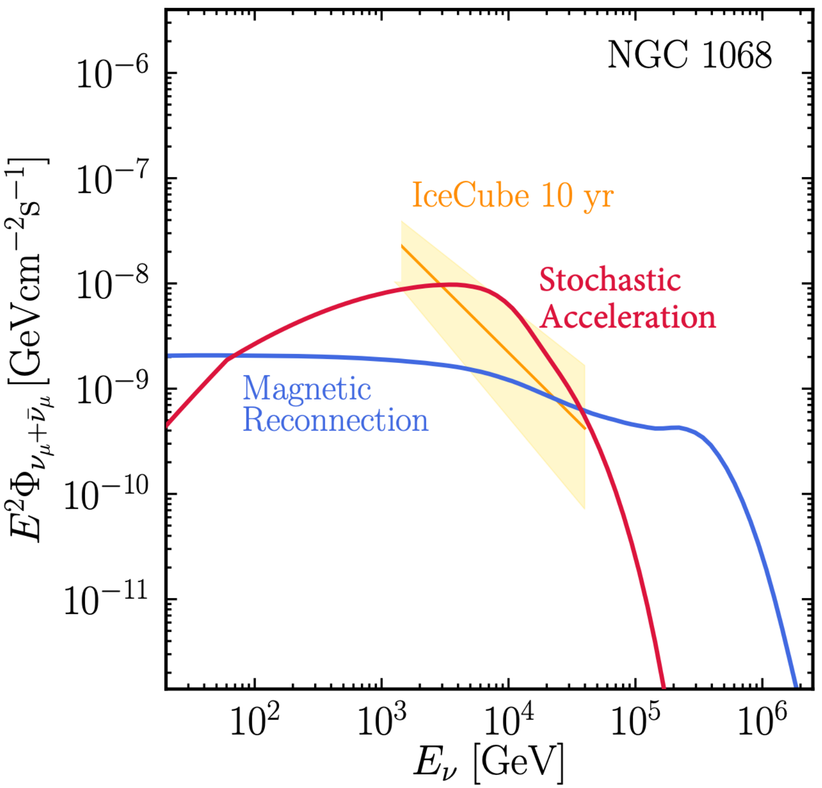




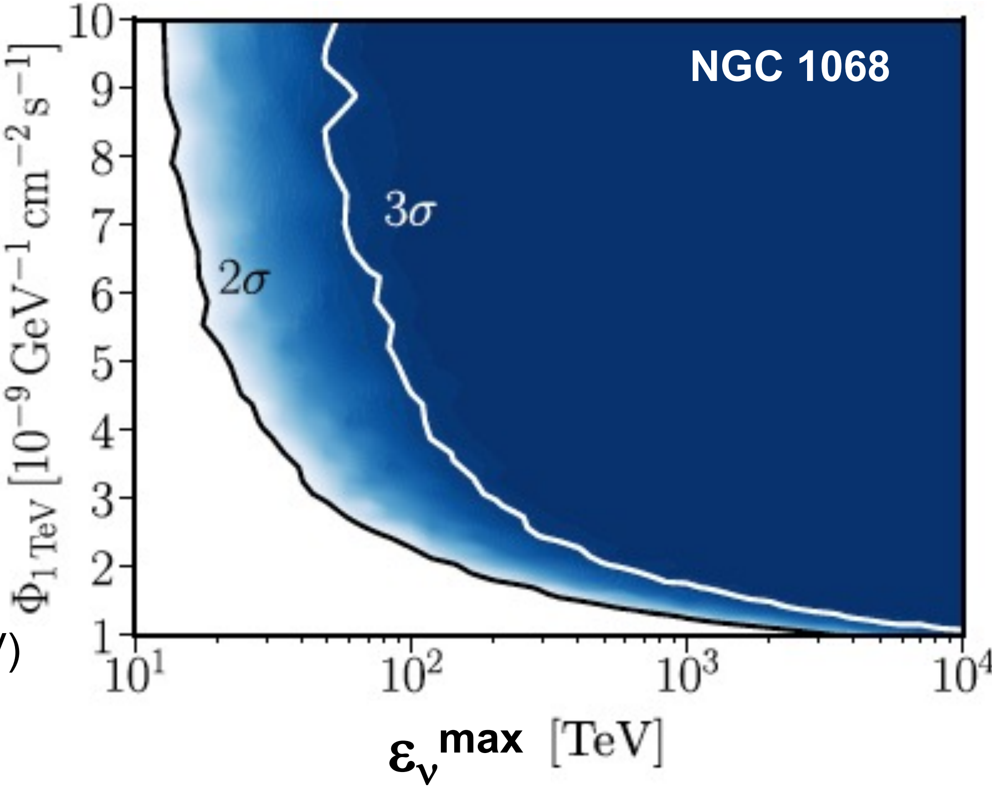
shocks

submm → B~10-100 G
$\beta = P_g/P_B \gtrsim 10\text{-}100$
$L_B, L_{CR} \lesssim L_X$

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

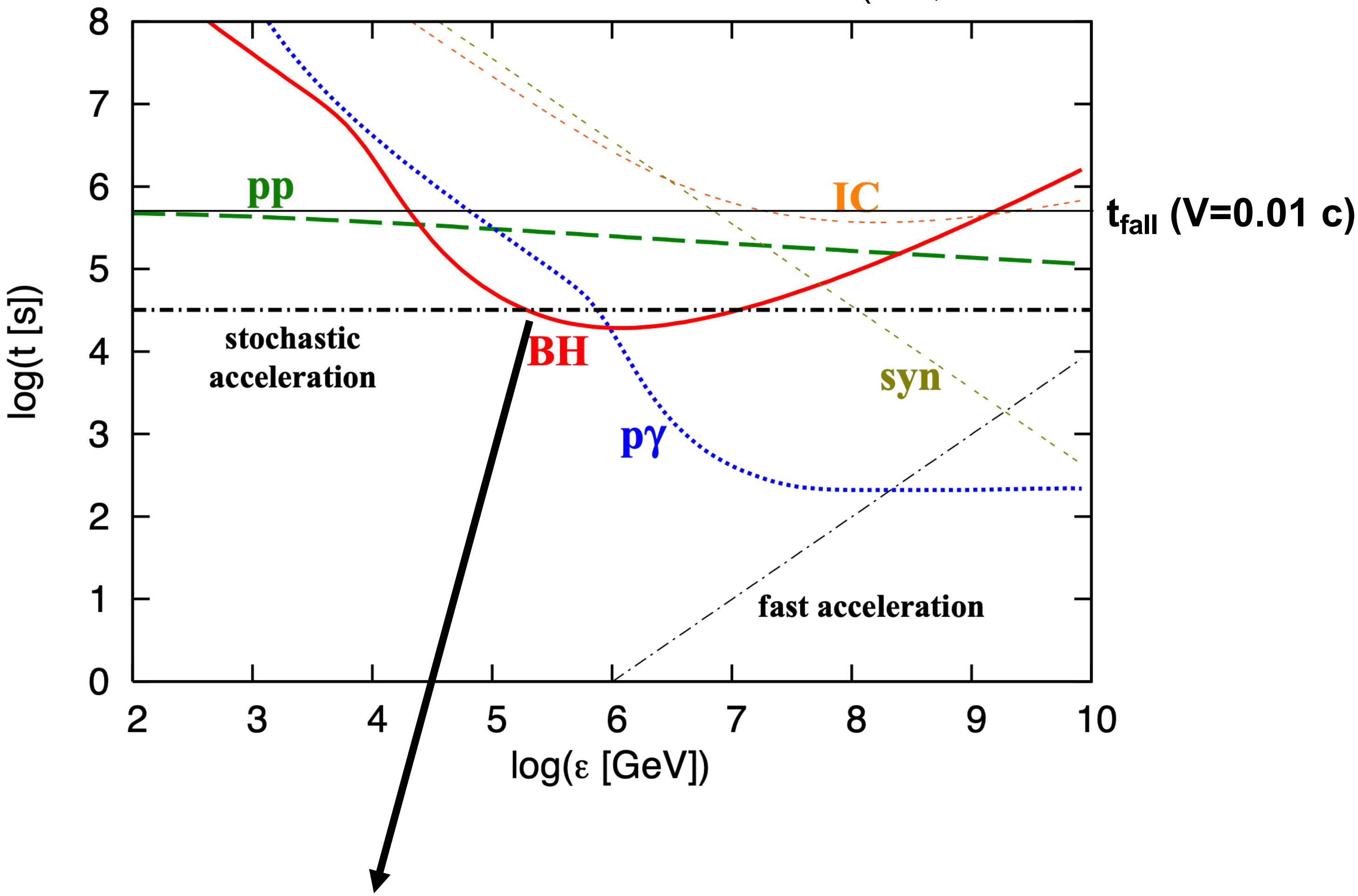
ε_ν^{max} < 10 TeV (ε_p^{max} < 200 TeV)

(cf. acceleration w. $t_{acc}=r_L/c \rightarrow \varepsilon_p^{max}$~10-100 PeV)

Particle Acceleration: Fast or Slow?

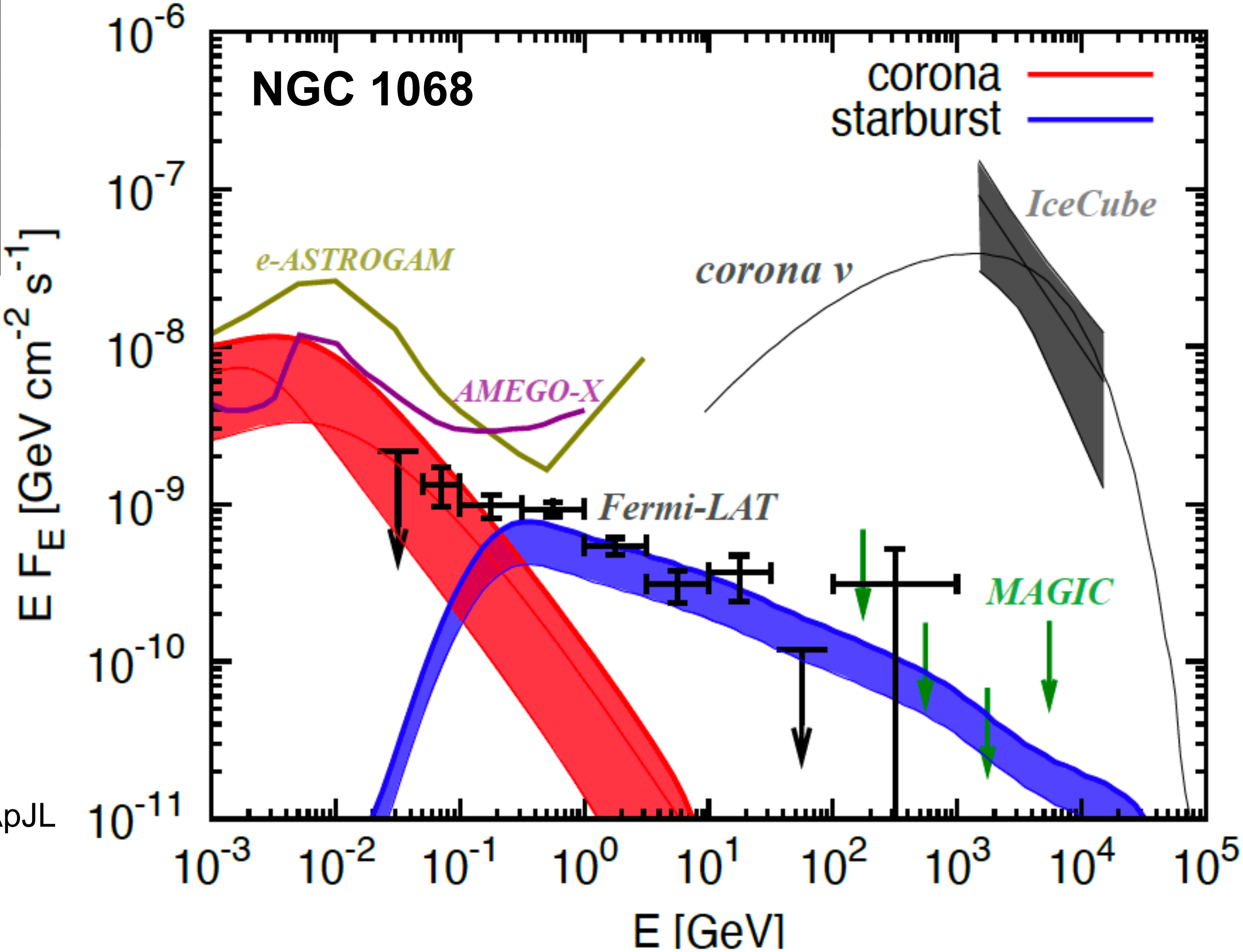
$p\gamma \rightarrow pe^+e^-$ (Bethe-Heitler process) is important for protons producing 1-10 TeV νs

(KM, Kimura & Meszaros 20 PRL)



ε_p^{max} **~ 100 TeV** $\rightarrow$ ε_ν^{max} **~ 2 TeV** (consistent w. IceCube)

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

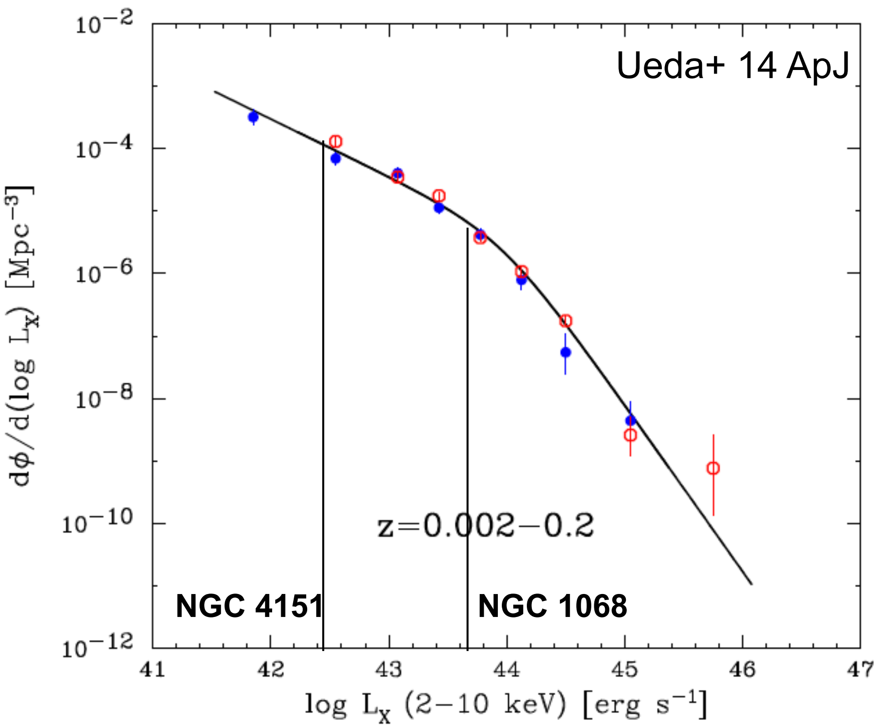


Ajello, KM & McDaniel 23 ApJL

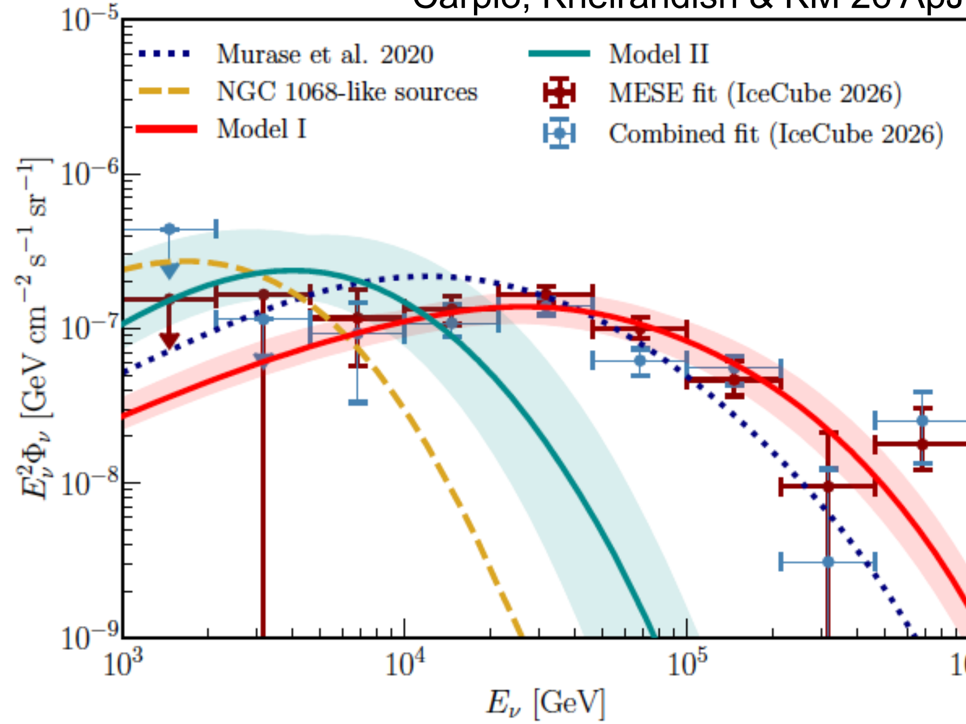
- Corona model prediction: cascade γ rays should appear in the MeV range
- Hint?: sub-GeV γ-ray “excess” over the starburst component

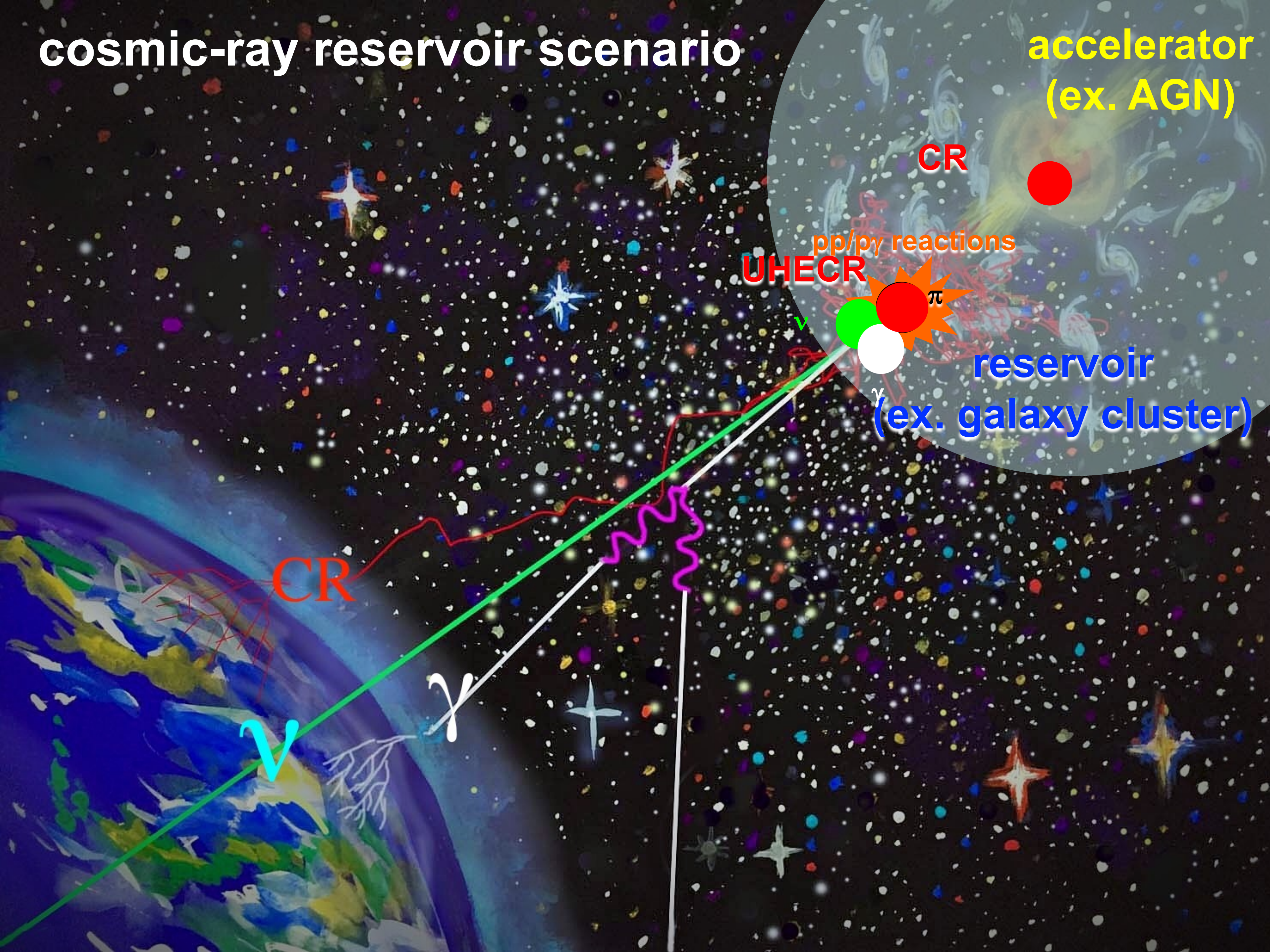
Guaranteed AGN Contribution to the All-Sky Neutrino Flux?

- 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}
- NGC 1068-like sources give the minimal contribution to the all-sky ν flux
- Higher-energy neutrinos come from AGNs with lower luminosities

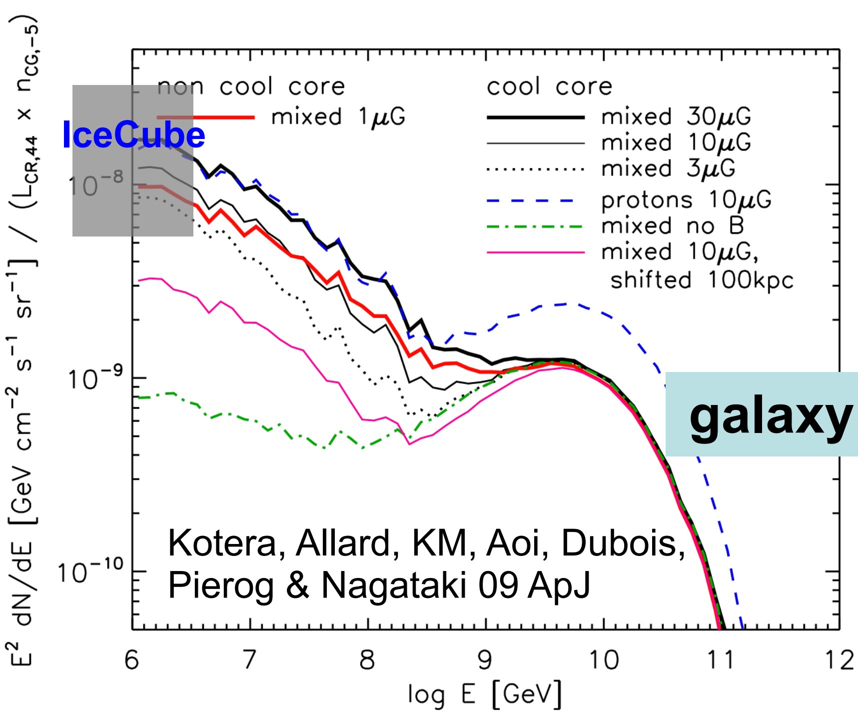


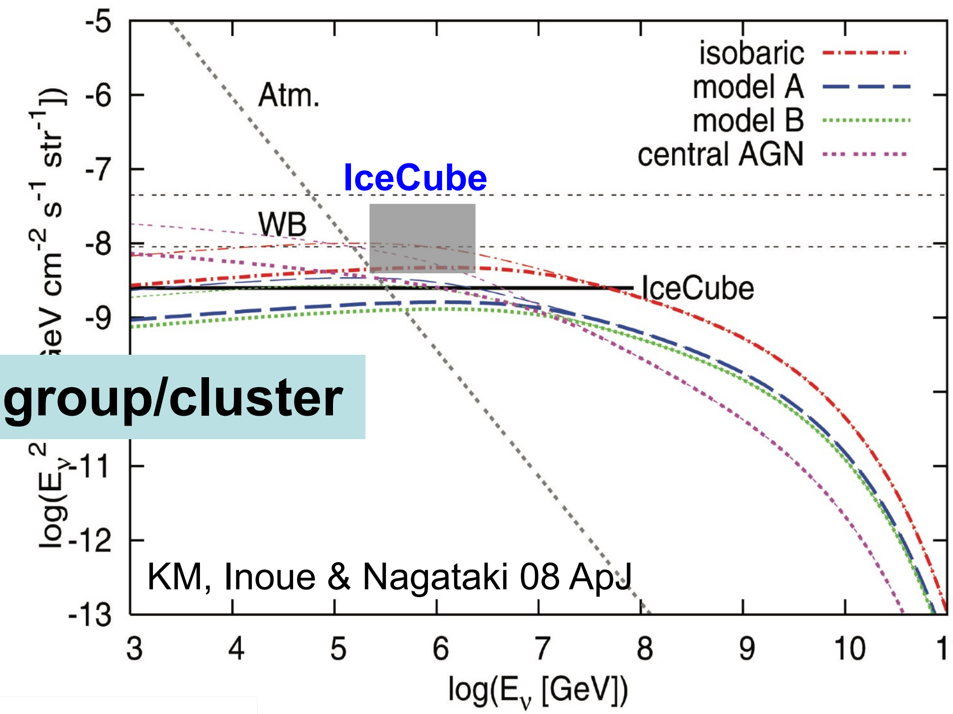
Carpio, Kheirandish & KM 26 ApJ



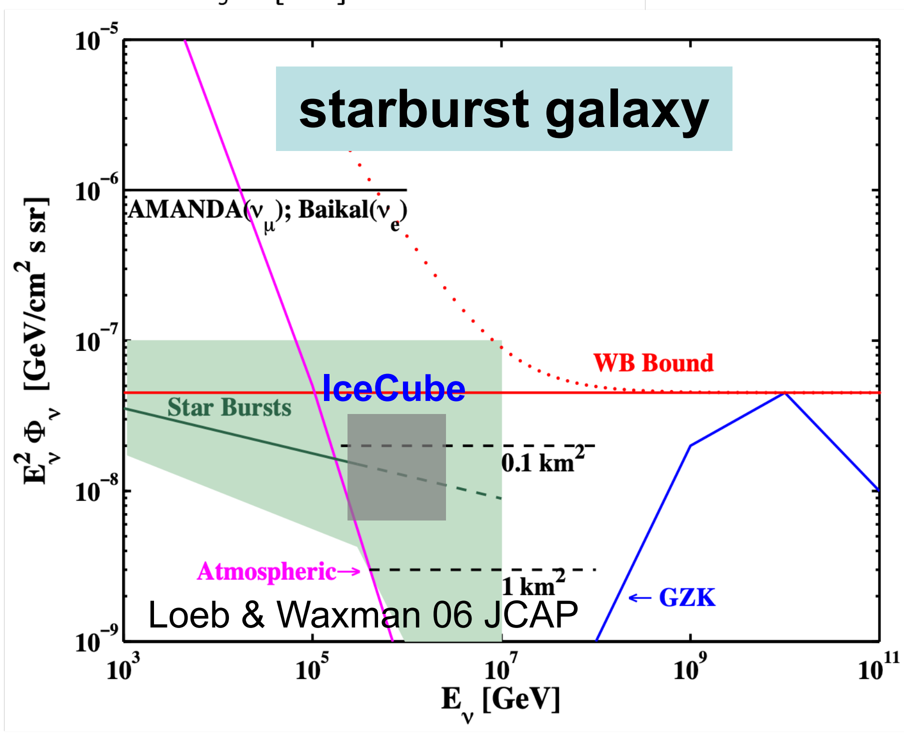


cosmic-ray reservoir scenario
accelerator
(ex. AGN)
CR
pp/pγ reactions
UHECR
π
ν
γ
reservoir
(ex. galaxy cluster)
CR
γ
ν





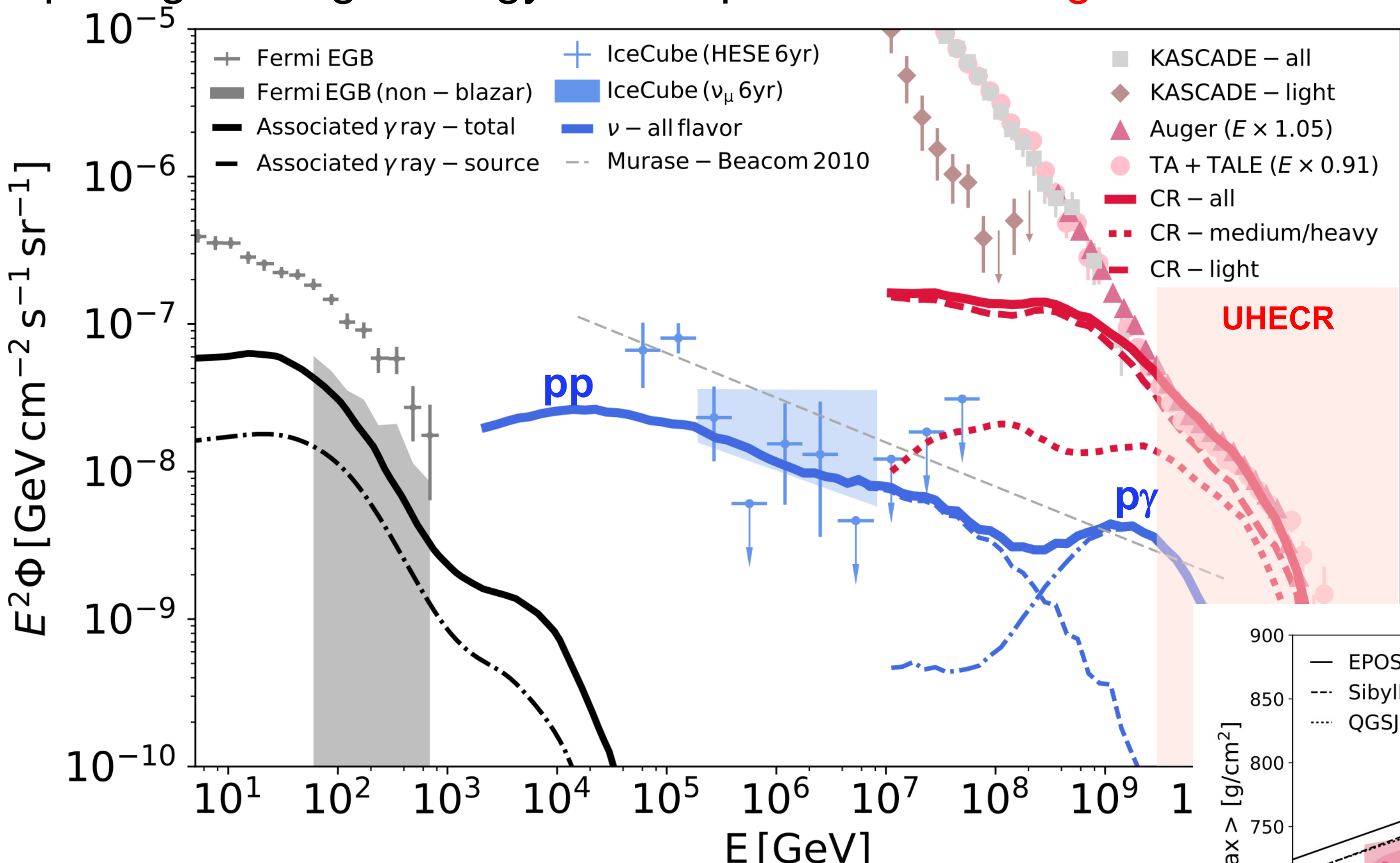
galaxy group/cluster



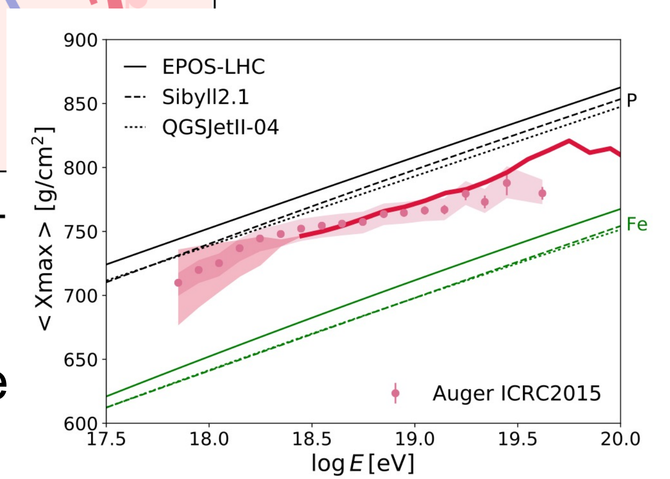
>0.1 PeV IceCube data: consistent w. earlier theoretical predictions

High-Energy Astro-Particle Grand-Unification?

> PeV νs may be physically related to UHECRs and isotropic diffuse γ rays (unification)
Exploring ultrahigh-energy νs is important for testing the ν-UHECR connection

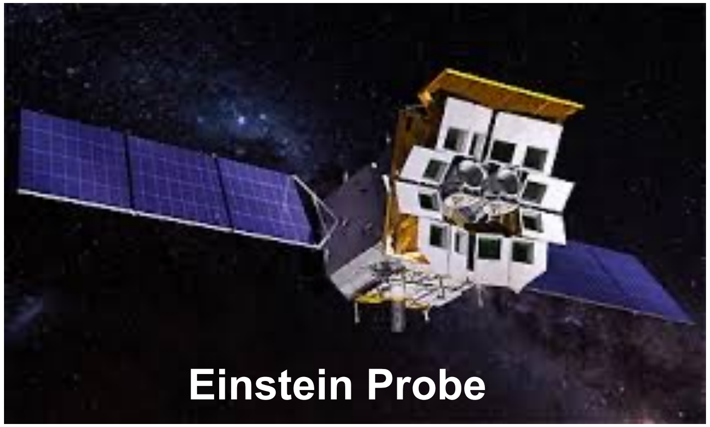


Fang & KM 18 Nature Phys.
(cf. Unger et al. 15 PRD)

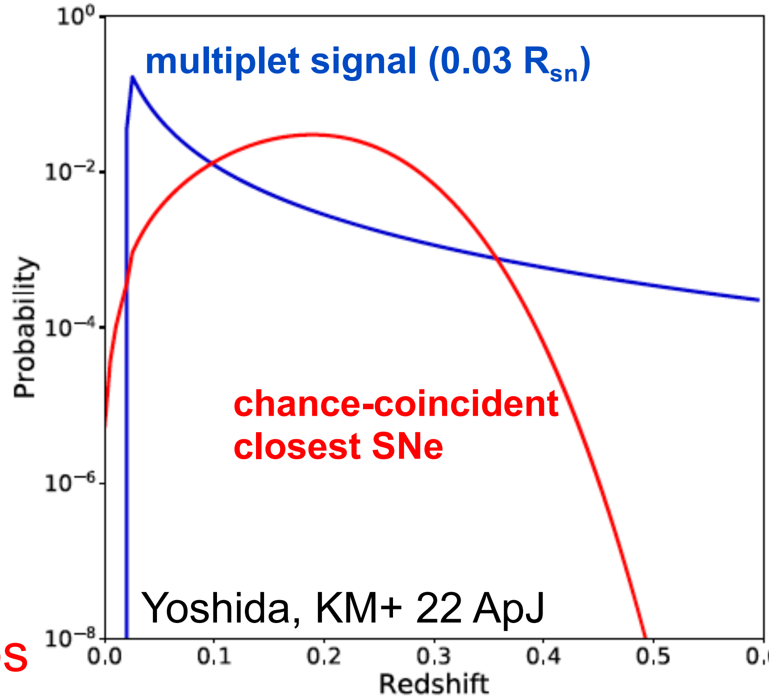


- Jetted AGN as "UHECR" accelerators
- νs from confined CRs & UHECRs from CR escape
- Predicting the smooth transition from pp ν to pγ ν

No Patience? Game Changing in ν Transient Searches

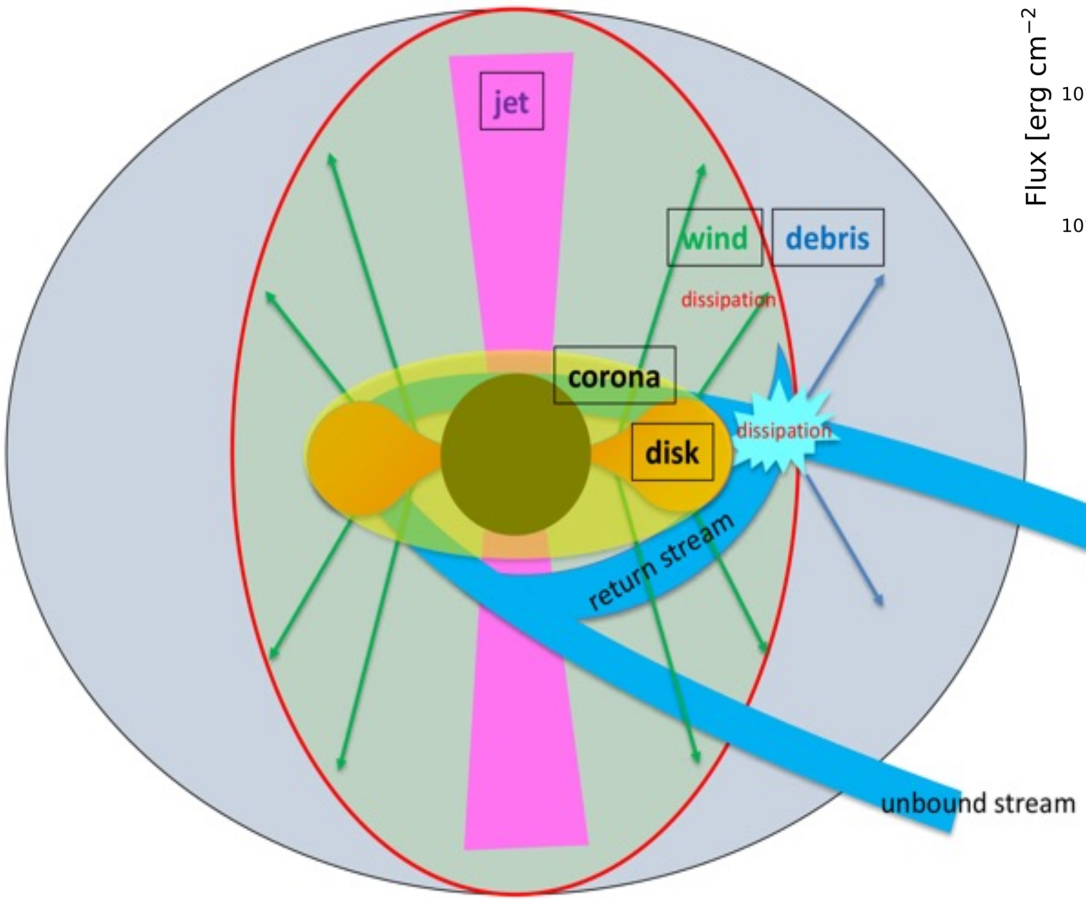


- Supernovae, tidal disruption events, low-luminosity gamma-ray bursts…
  (e.g., Stein+ 21 Nature Astronomy, Reusch+ KM 21 PRL)
- Testability of models have been limited by the number of detected transients
- Neutrino singlet followups would need spectroscopic information
- Neutrino multiplet followups
- Multimessenger alert (e.g., AMON) followups

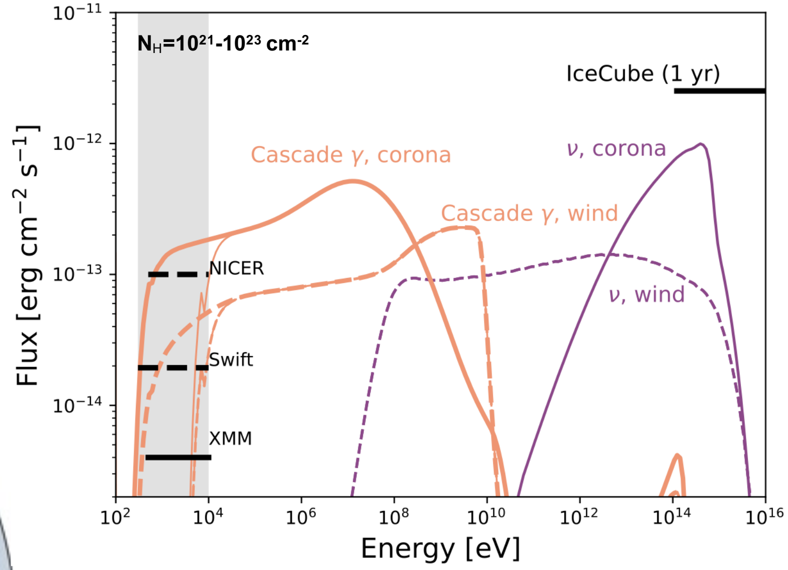


Tidal Disruption Events – Bare Black Hole Model

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



KM, Kimura, Zhang et al. 20 ApJ

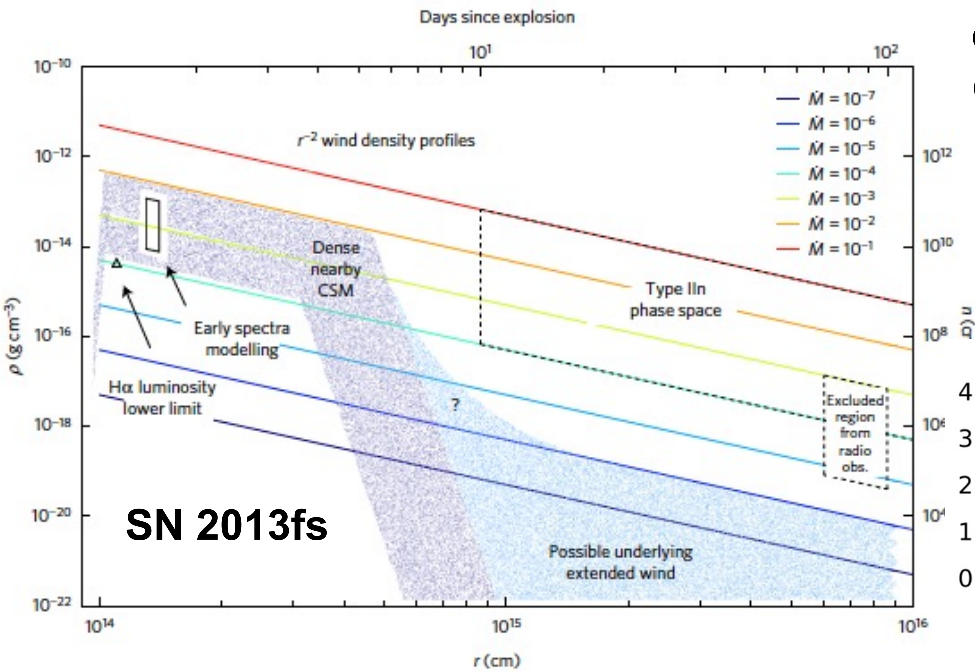


Vera C. Rubin Observatory

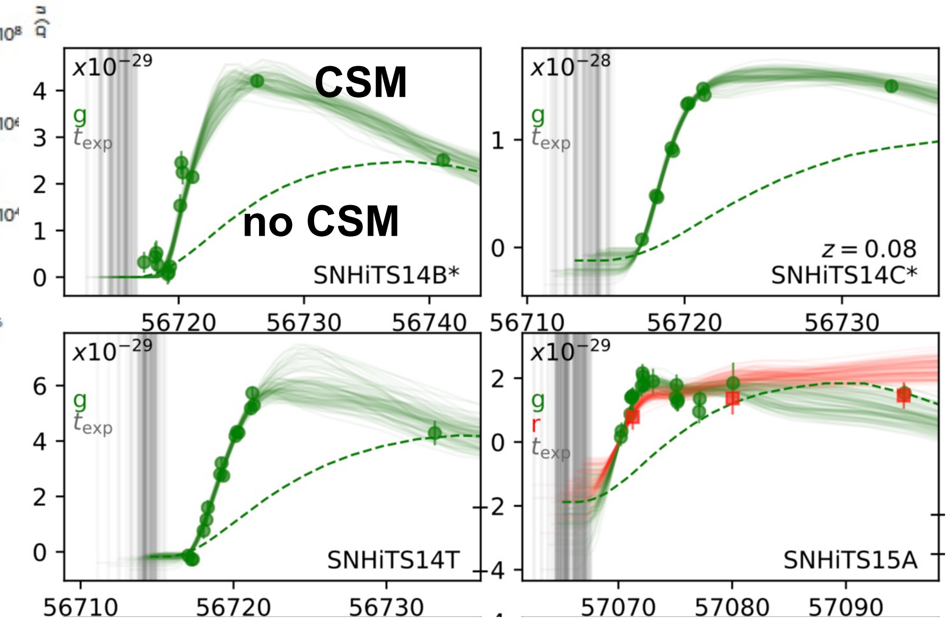
Interacting Supernovae as Multimessenger Transients

- Confined CSM (R_{cs} <~ 10^{15} cm): mass ejection or extended envelope
- May be common even for Type II-P SNe
  $dM_{cs}/dt \sim 10^{-3}$-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)
- Shock accelerated cosmic rays produce cosmic rays, νs and γs
  (KM+ 11 PRD, KM 18 PRDR, KM 24 PRD)

Evidence for "Confined" CSM around Progenitors



early spectroscopy
(Yaron+ 16 Nature Phys.)

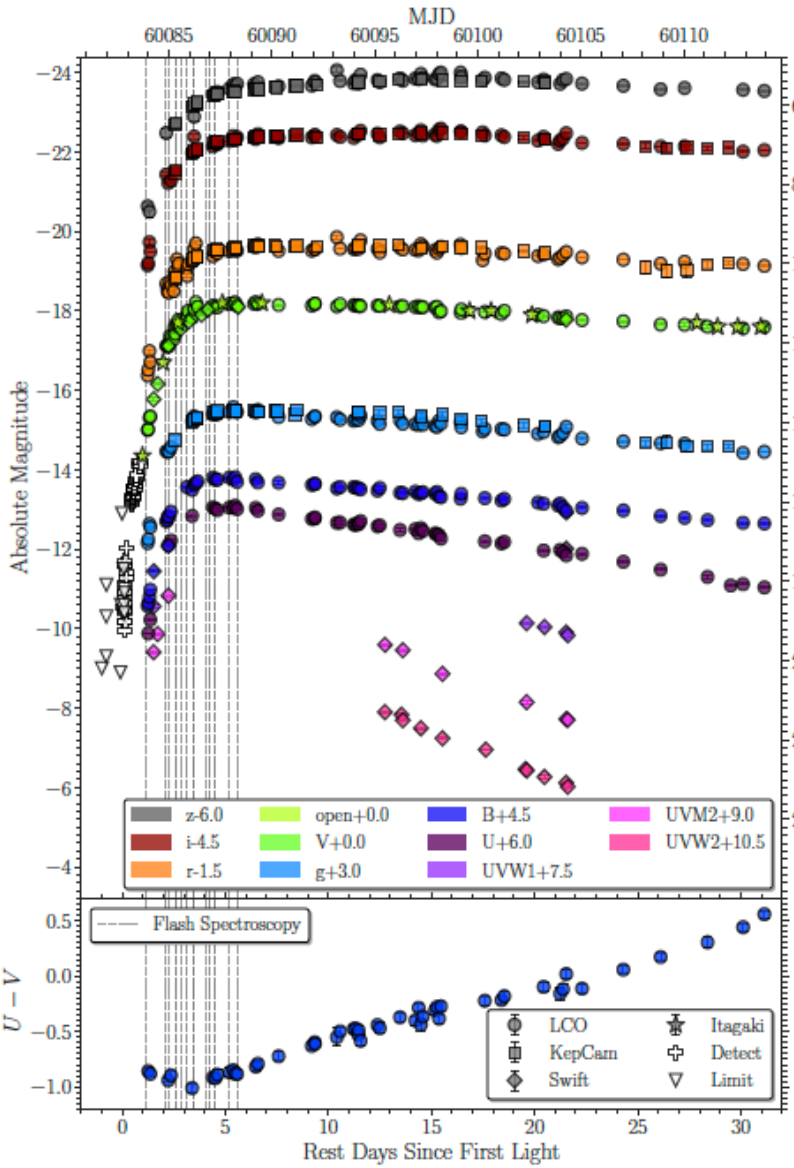


light curve modeling
(Forster+ 18 Nature Astronomy
see also Morozova+ 17 ApJ)

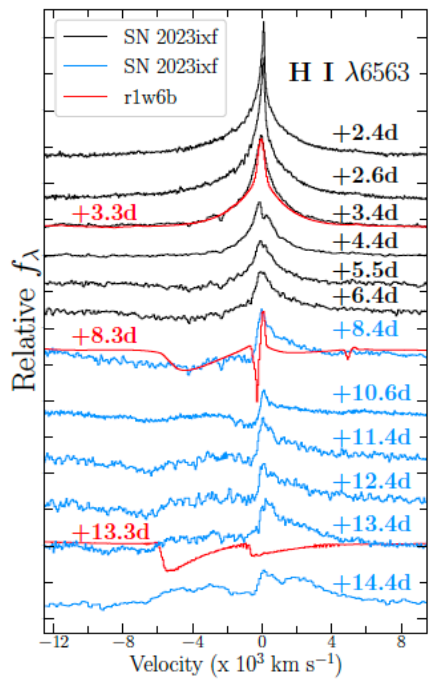
- **May be common even for Type II-P SNe**
  $dM_{cs}/dt \sim 10^{-3}$-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)
- **Confined CSM** (R_{cs} <~ 10^{15} cm): mass ejection or inflation

Latest Example: SN 2023ixf

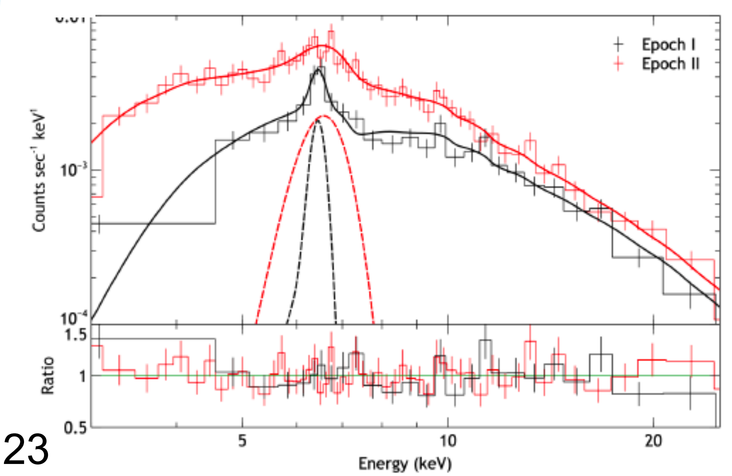
Hiramatsu+ 23



Jacobson-Galan+ 23



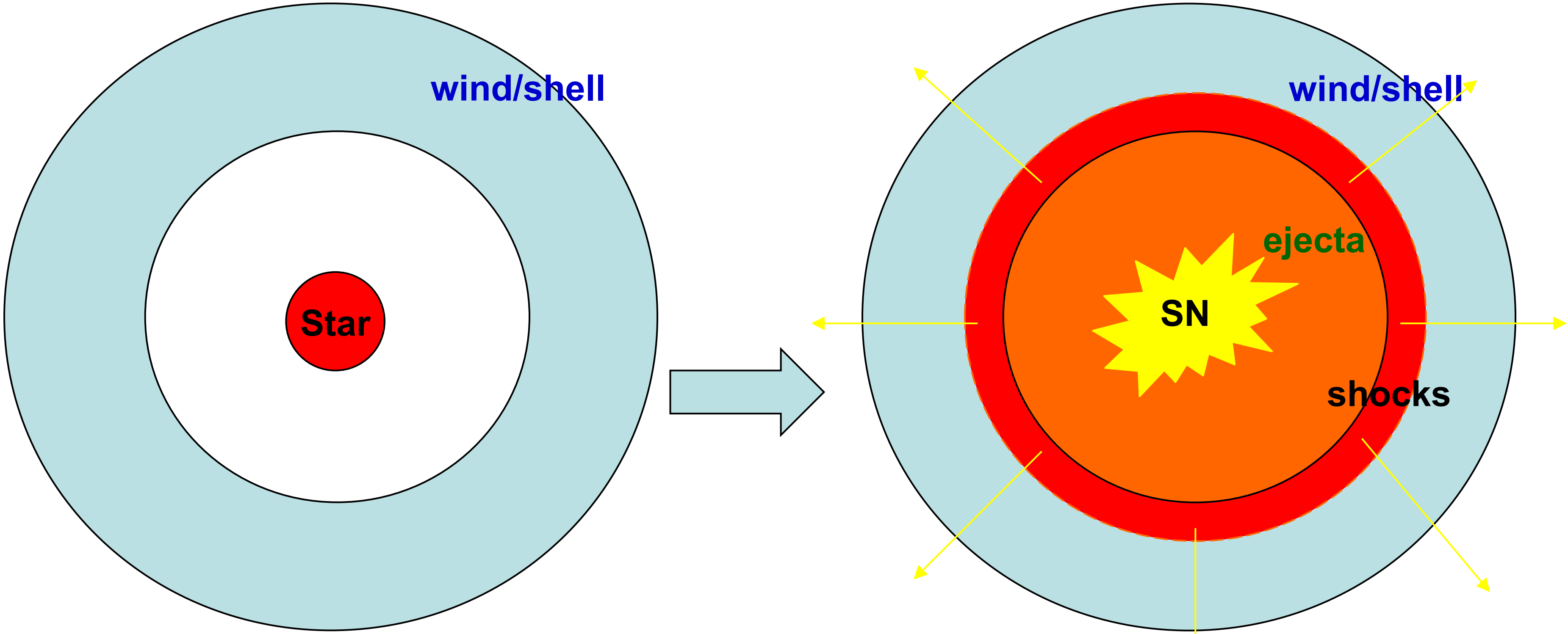
- M101 @ 6.9 Mpc
- Optical
  $dM_{cs}/dt \sim 10^{-2}$-10^{-1} M_{sun} yr^{-1}
  R_{cs} ~ a few x 10^{14} cm
- X-ray
  $dM_{cs}/dt \sim (0.3$-$1) \times 10^{-3}$ M_{sun} yr^{-1}
  R_{cs} ~ 10^{15} cm
- Radio
  VLA detection at ~30 d



Grefenstette+ 23

Multimessenger Emission from Interacting SNe

KM, Thompson, Lacki & Beacom 11 PRD, KM & Thompson & Ofek 14 MNRAS



kinetic energy → thermal + non-thermal via shocks

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

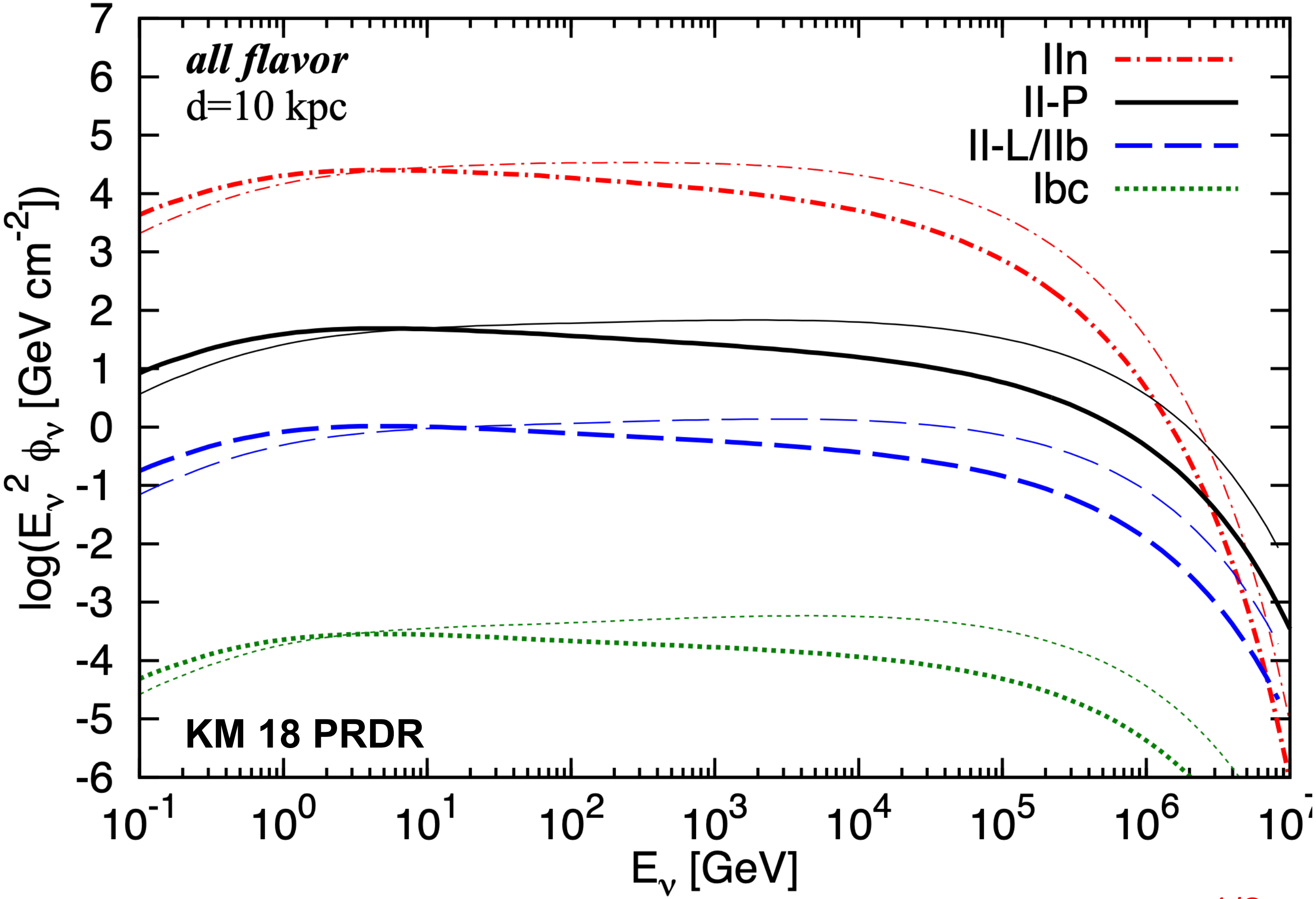
$$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}(\bar{\nu}_{e}) + e^{\pm}$$

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

dense environments = efficient ν emitters (calorimeters)

Neutrino Fluence

First prediction of HE neutrinos from SN w. confined CSM (KM 18 PRDR)

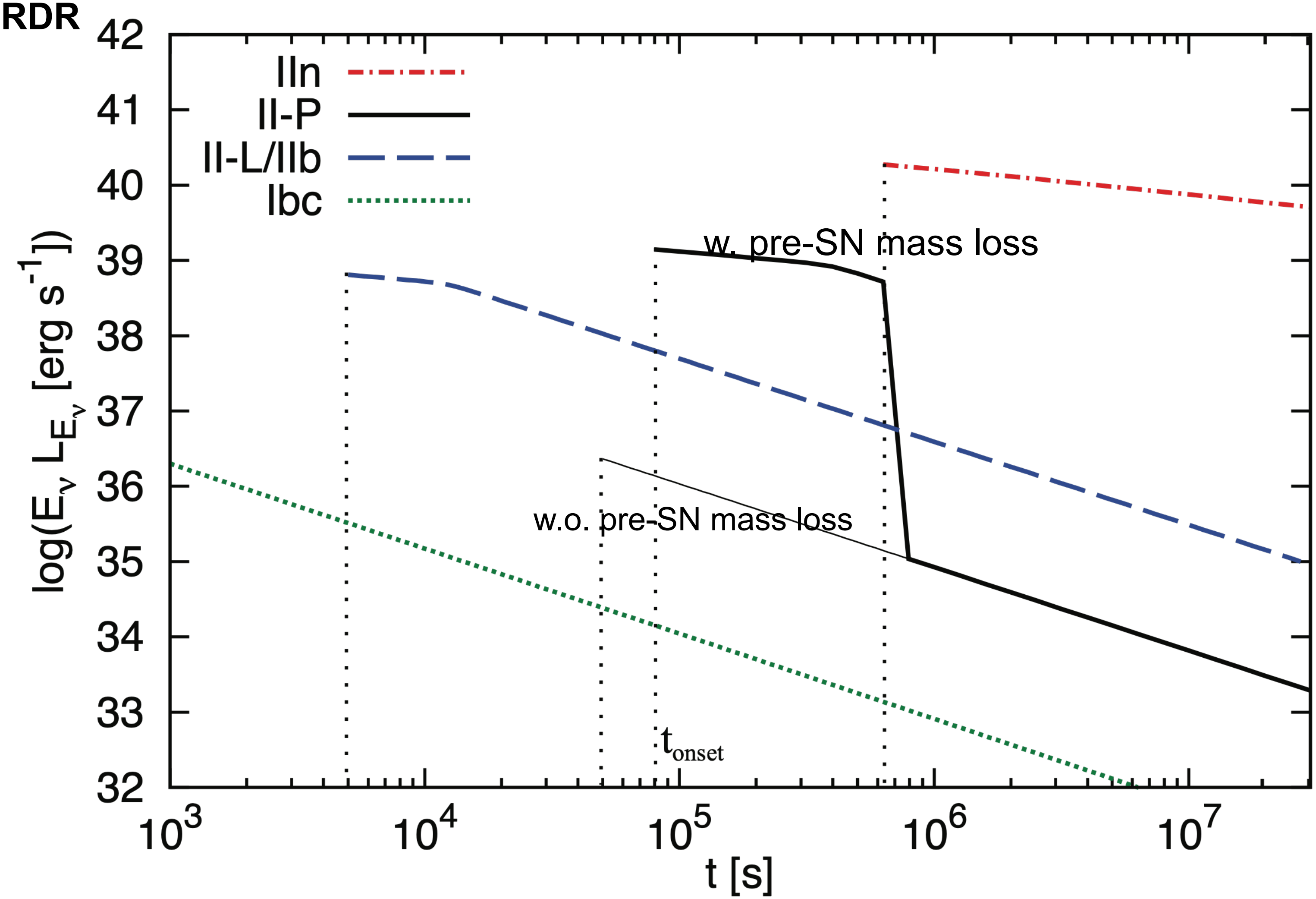


thick: s=2.2
thin: s=2.0

Fluence for an integration time at which $S/B^{1/2}$ is maximal (determined by the detailed time-dependent model)

Neutrino Light Curve

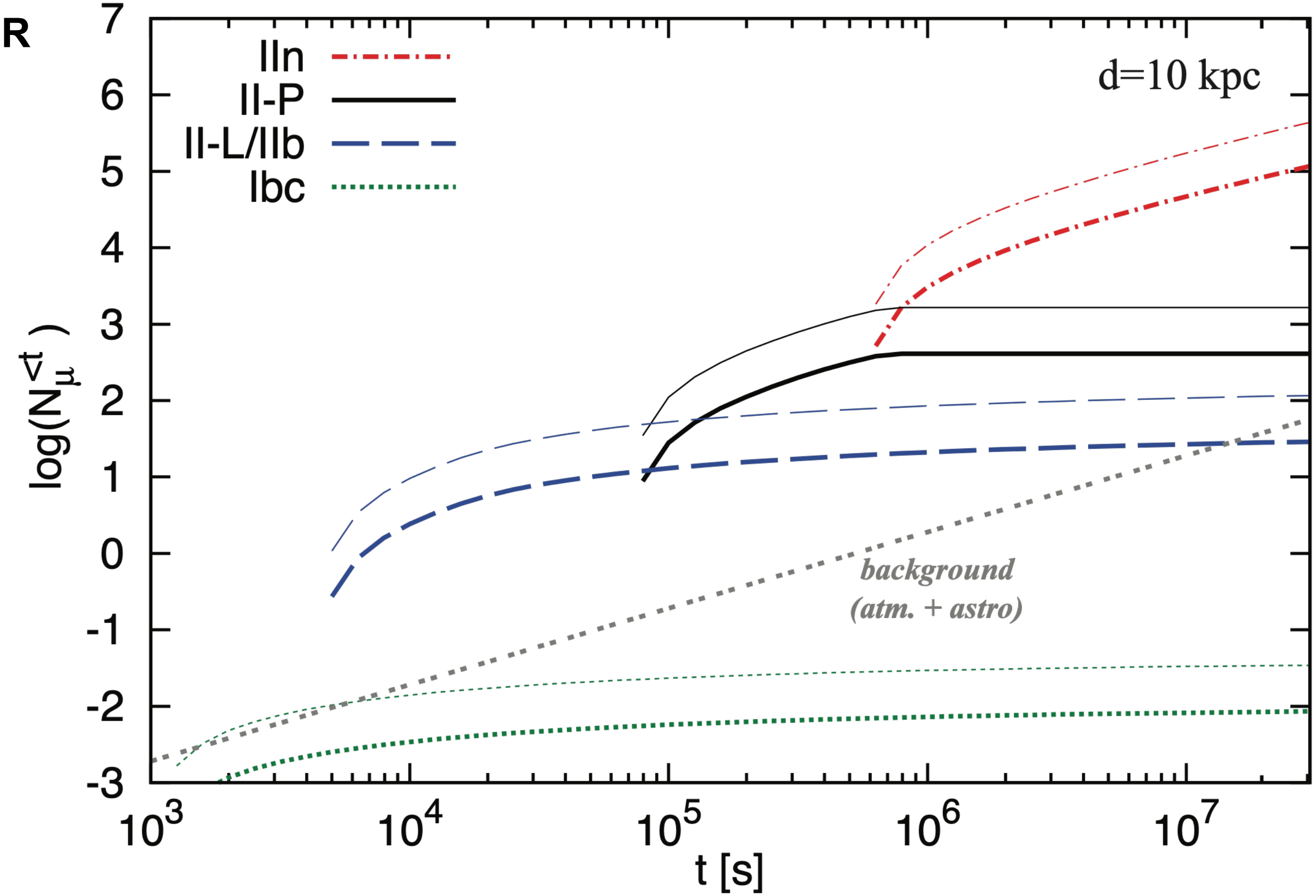
KM 18 PRDR



slowly declining light curves while pion production efficiency ~ 1

Next Galactic Supernova?

KM 18 PRDR



- Type II: ~100-1000 events of TeV ν from the next Galactic SN
  ex. Betelgeuse: ~10^3-3×10^6 events, Eta Carinae: ~10^5-3×10^6 events
- SNe as "multi-messenger" & "multi-energy" neutrino source
- "Real-time" detection of CR acceleration, testing Pevatrons, neutrino physics

Key Points

- Testable & clear predictions (no need for jets/winds)
  free parameters: ε_{CR} & s (typical values: ε_{CR}~0.1 & s~2.0-2.3)
- Time window:
  duration ~ calorimetry ($f_{pp} \sim t_{dyn}/t_{pp} > 1$)
  e.g., ~days to weeks for SNe II (II-P/II-L/IIb), ~hours (Ibc), ~months (IIn)
- Energy range: multi-energy
  IceCube/KM3Net: TeV-PeV (even Glashow resonance anti-ν_e & ν_τ events)
  Hyper-K/IceCube-Upgrade/KM3Net-ORCA: GeV-TeV
- Astrophysical implications
  a. Pre-explosion mass-loss mechanisms
     How does a dense wind/shell form around the star ?
  b. PeVatron origin
     Are supernovae the origin of CRs up to the knee energy at $10^{15.5}$ eV?
  c. Real-time observation of ion acceleration for the first time
     Onset of CR ions acceleration & collisionless shock formation
  d. Particle physics implications – large statistics
     flavor studies, BSM searches

Detection w. Large Hadron Collider

diameter 22m

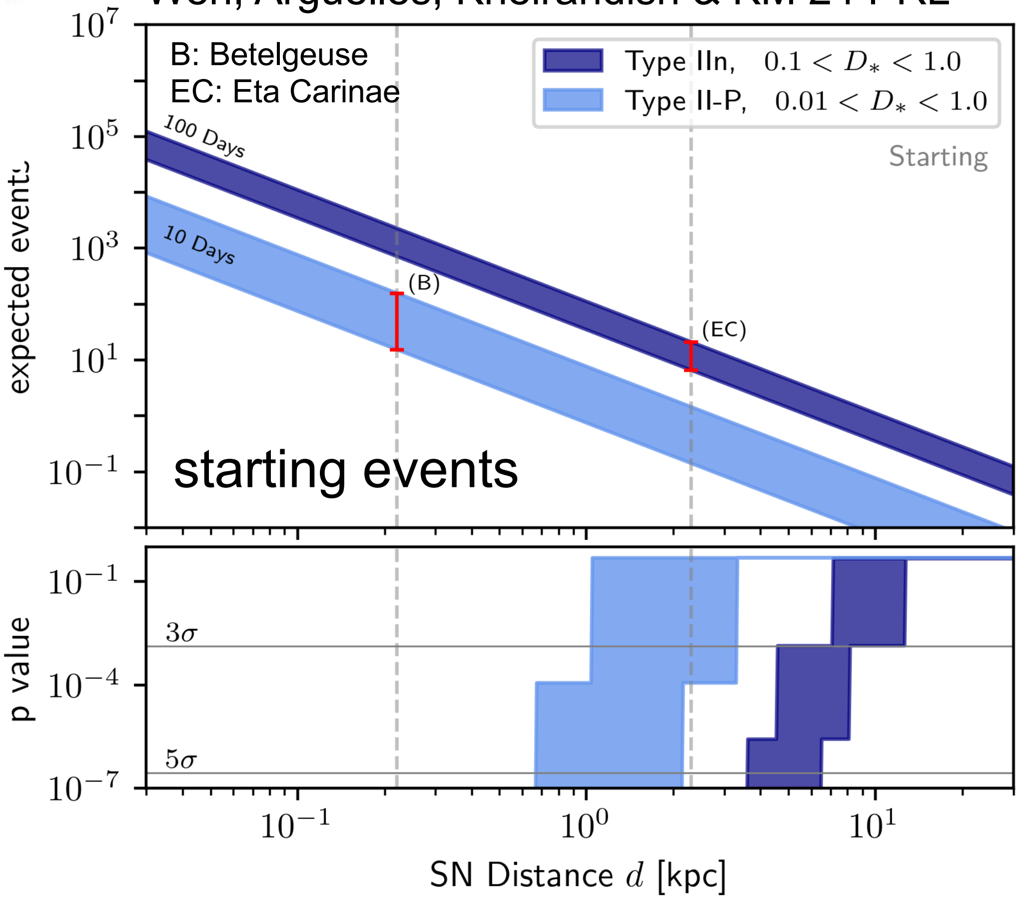
length 40m

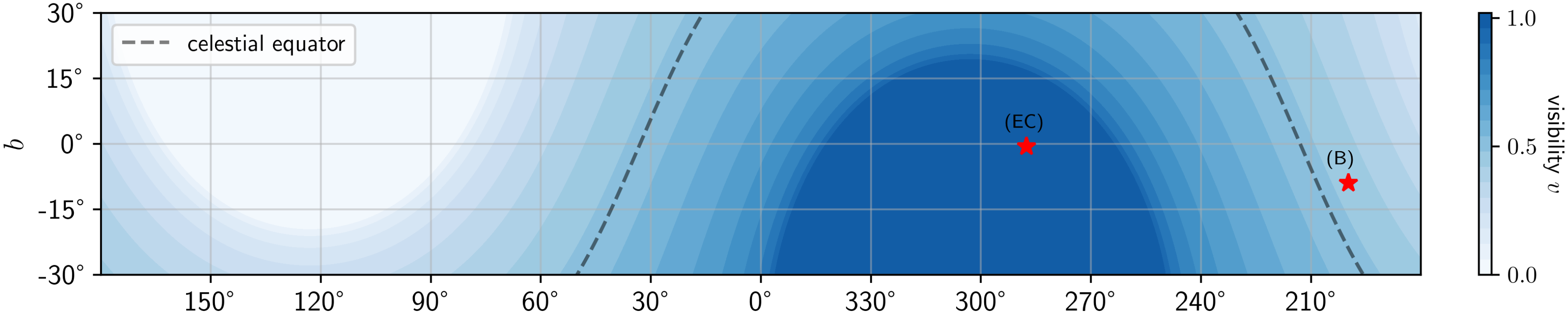
LHC ATLAS

calorimeter ρV=4 kt

$$N \sim \rho V N_A \sigma_{\nu N} E_\nu \Phi_\nu$$
$$\sim 3\times10^{-3} E_\nu \Phi_\nu$$
$$\sim 1 \, (E_\nu \Phi_\nu / 300 \text{ cm}^{-2})$$

Wen, Arguelles, Kheirandish & KM 24 PRL

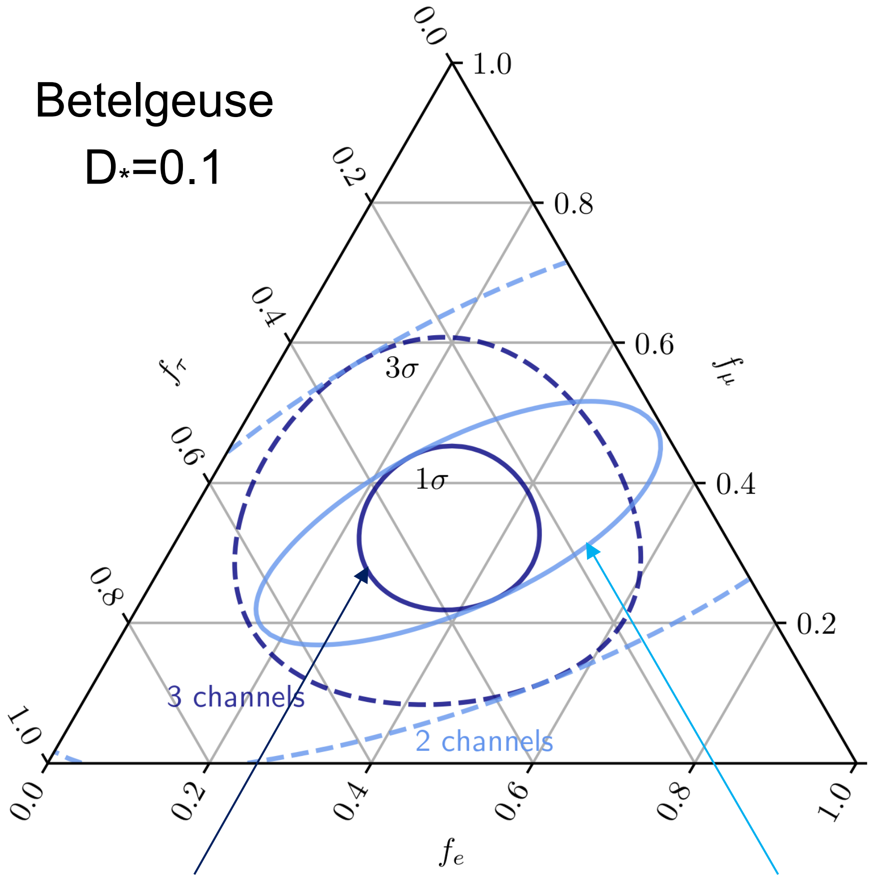




B: Betelgeuse
EC: Eta Carinae

Betelgeuse

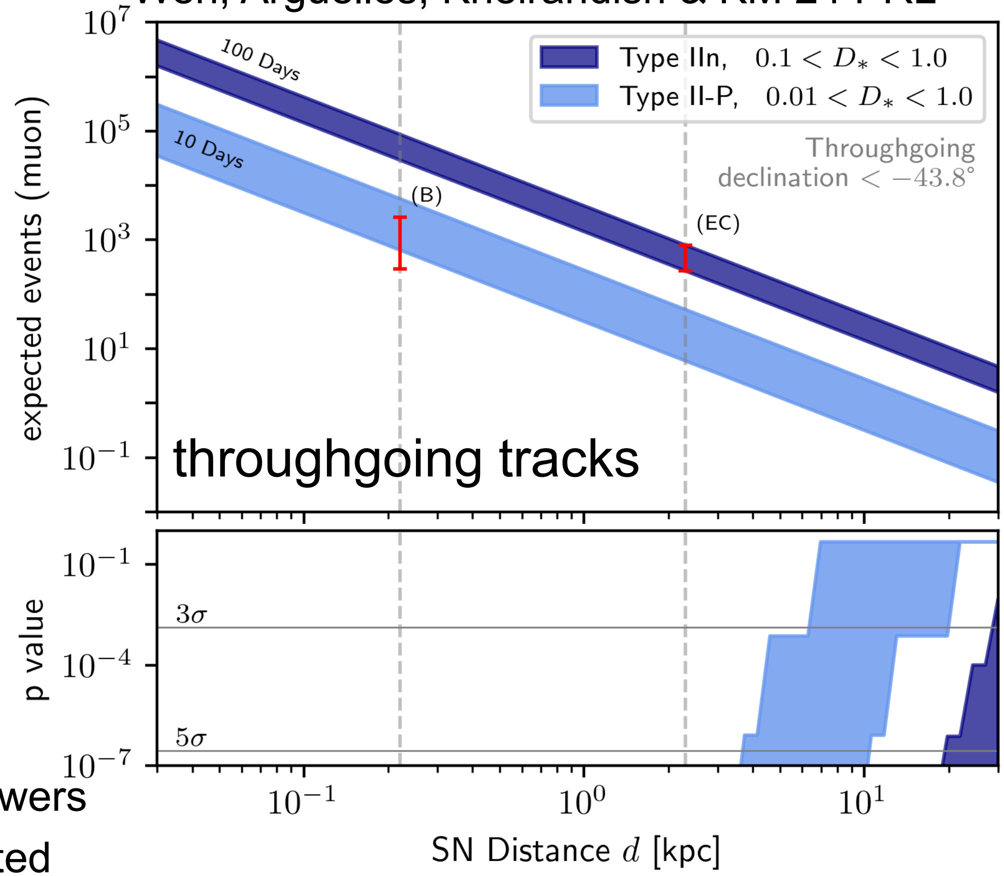
D*=0.1



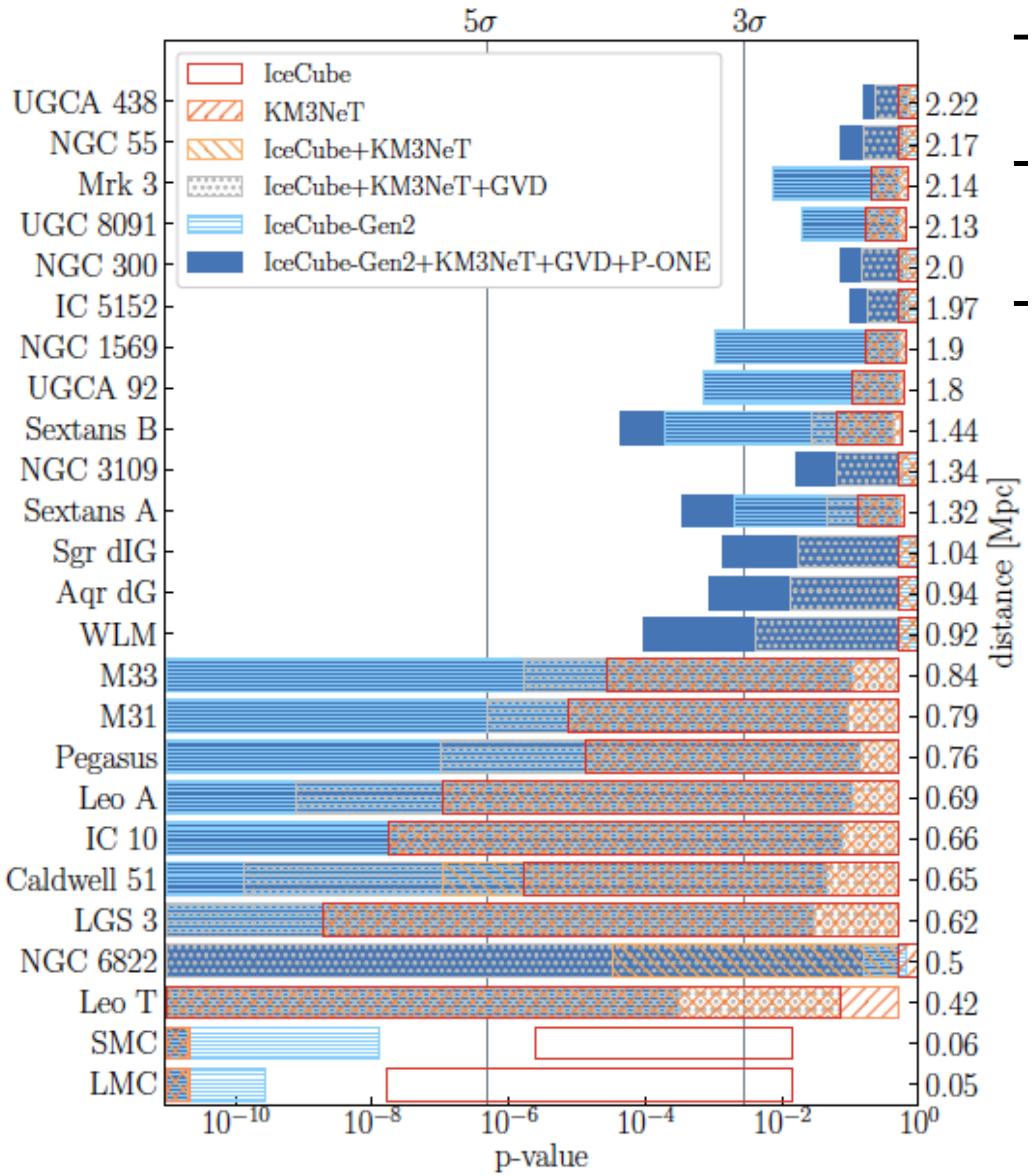
2 hadronic showers discriminated

2 hadronic showers undiscriminated

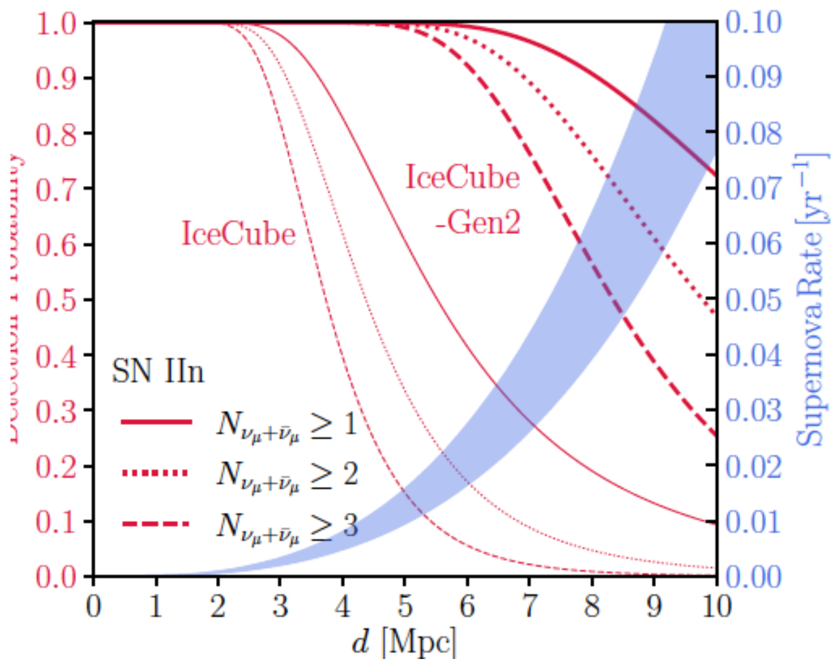
Wen, Arguelles, Kheirandish & KM 24 PRL



Detectability of "Miniburts"

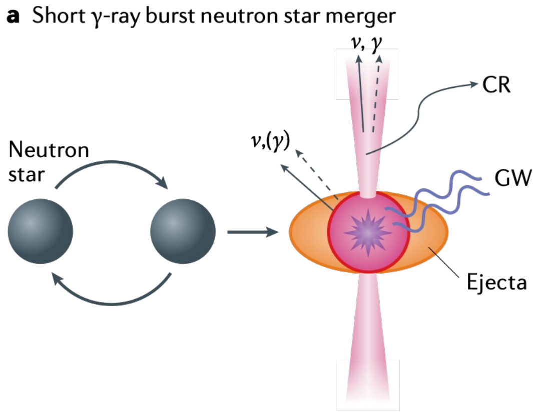


- CCSN rate enhancement in local galaxies (ex. Ando+ 05 PRL)
- Neutrino telescope networks are beneficial for nearby SNe at Mpc
- II (CCSM): detectable to ~3-4 Mpc
  IIn: detectable to ~10 Mpc

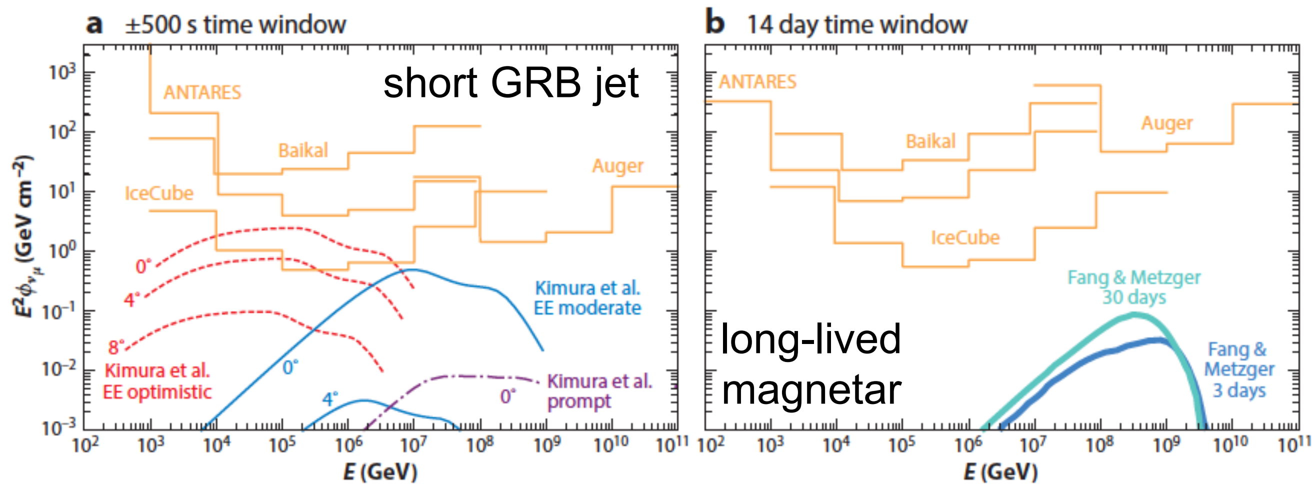


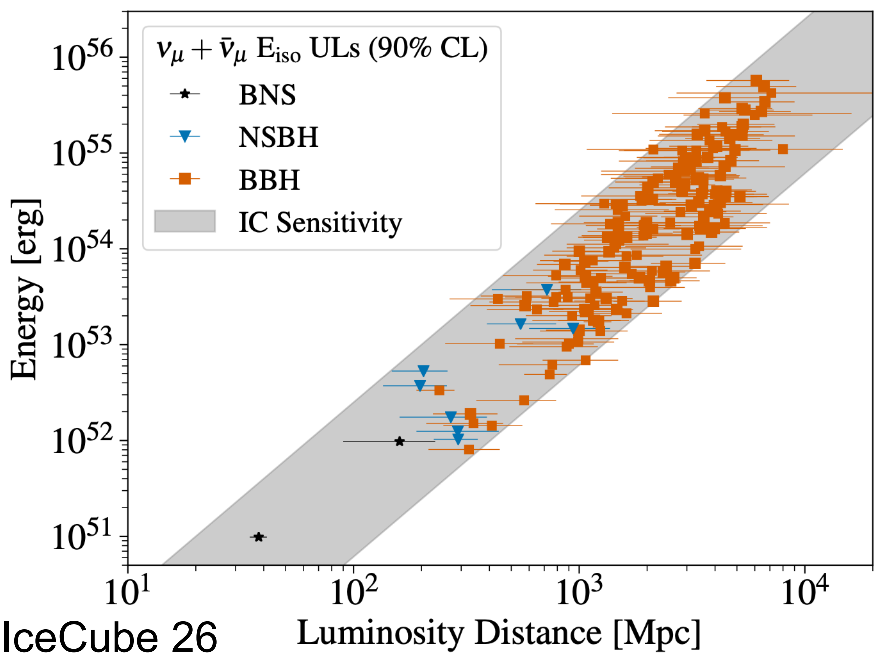
Kheirandish & KM 23 ApJL

High-Energy Neutrino – Gravitational Wave Transients?



GW170817 (ANTARES-IceCube-Auger-LIGO-VIRGO 17)



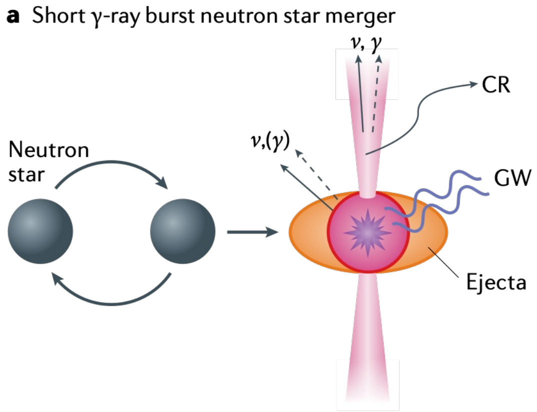


IceCube 26

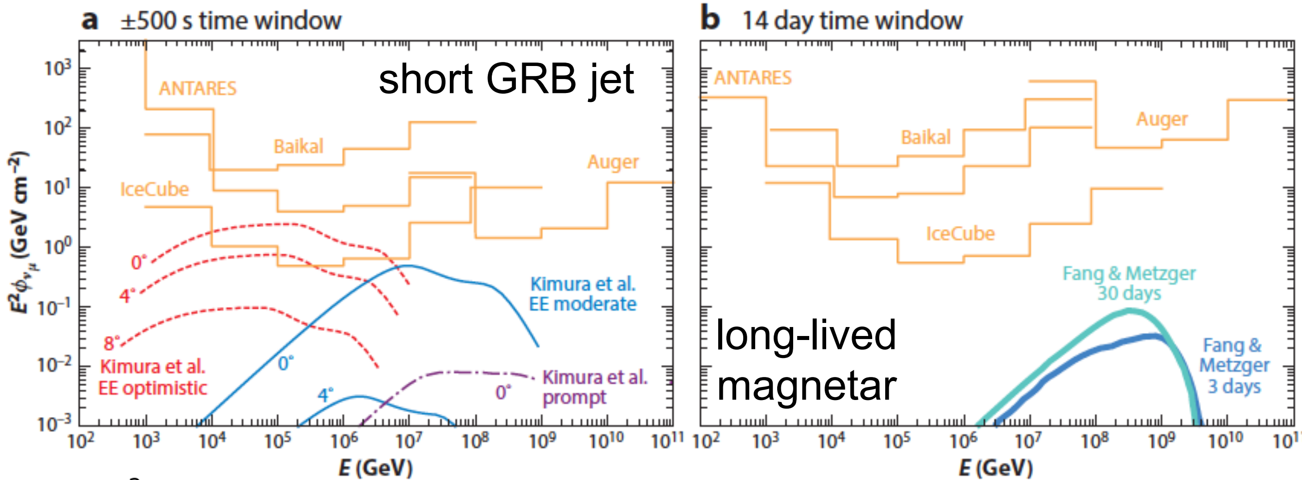
- No statistically significant coincident ν emission from significant GW sources (164 BH-BH + 10 NS-BH + 2 NS-NS) during O1-O4a run

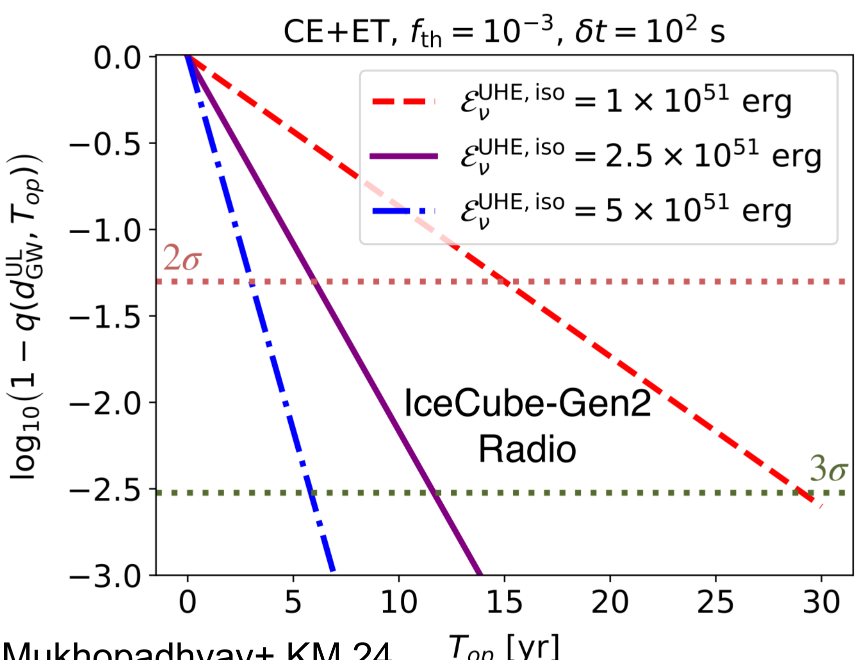
- Consistent w. theoretical expectations

High-Energy Neutrino – Gravitational Wave Transients?



GW170817 (ANTARES-IceCube-Auger-LIGO-VIRGO 17)





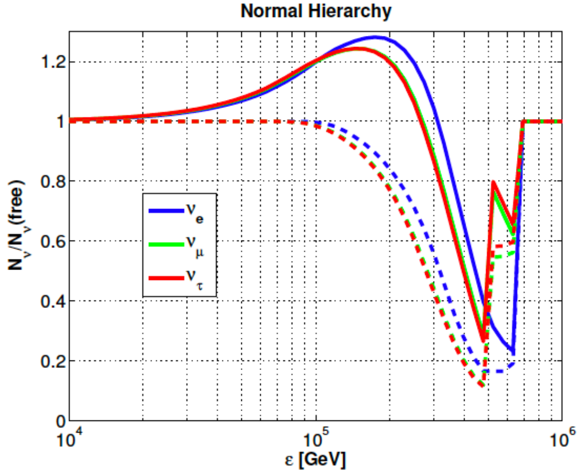
Mukhopadhyay+ KM 24

- No statistically significant coincident ν emission from significant GW sources (164 BH-BH + 10 NS-BH + 2 NS-NS) during O1-O4a run
- Consistent w. theoretical expectations
- Could be detected w. next-generation neutrino and GW detectors

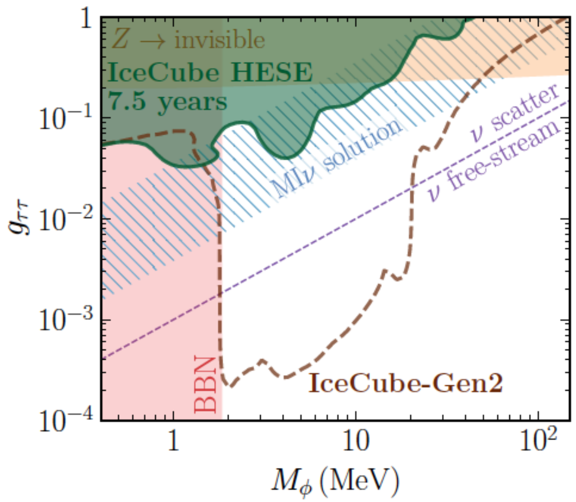
BSM Imprints on Spectra/Flavors

nonstandard interactions

Blum, Hook & KM 14

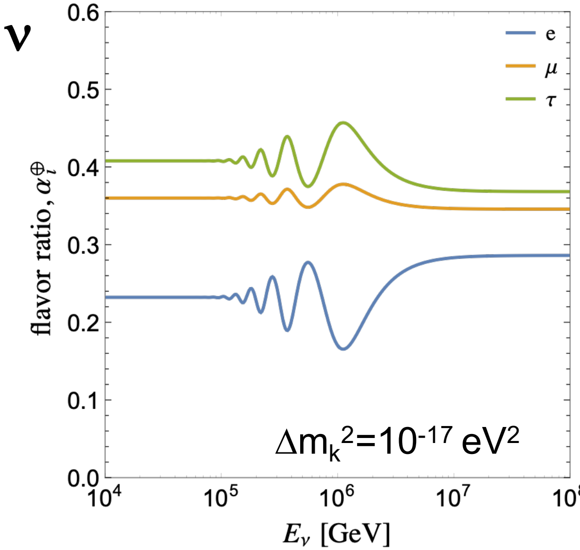


Esteban+ 21



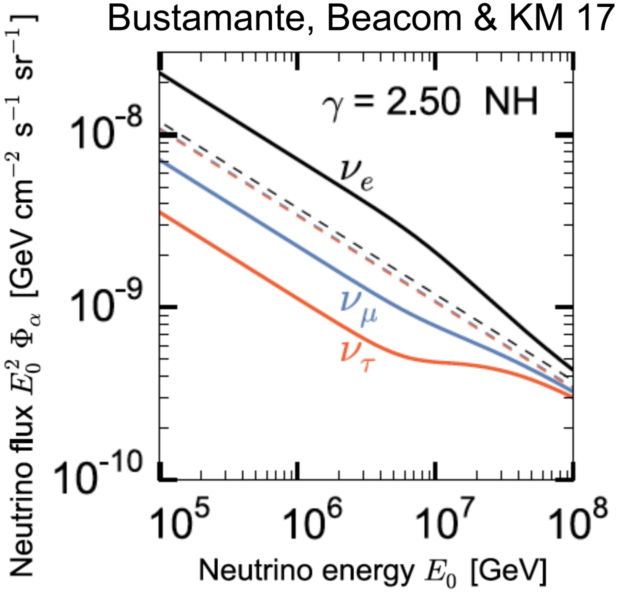
pseudo-Dirac ν

Shoemaker & KM 16



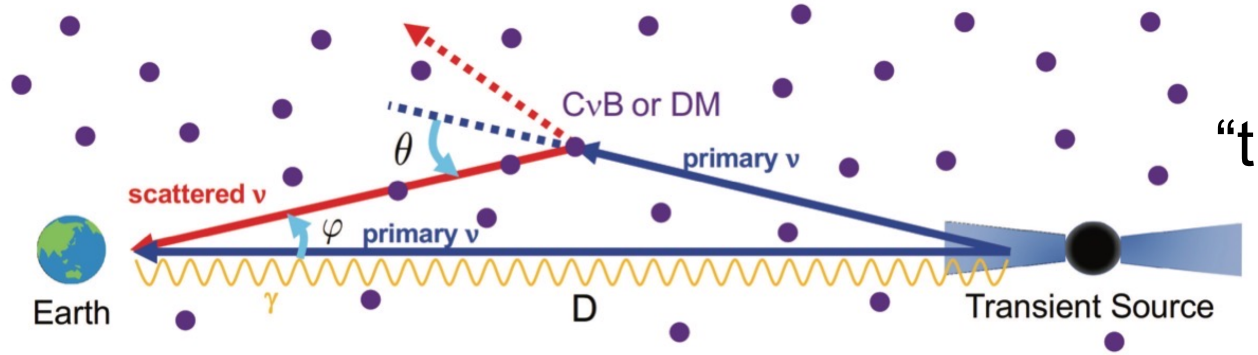
ν decay

Bustamante, Beacom & KM 17



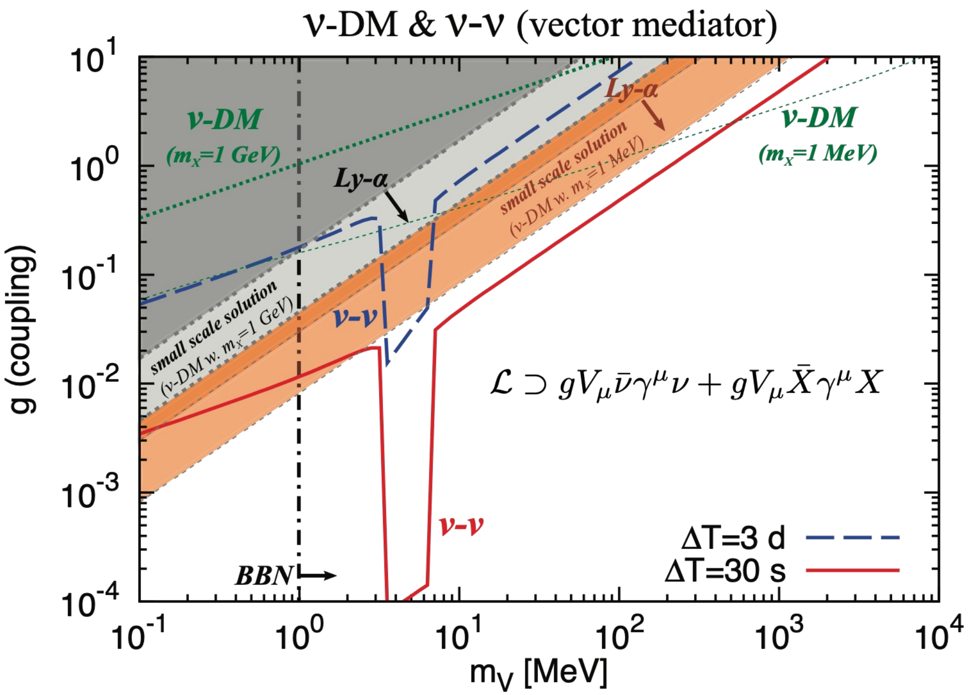
BSM & Time-Domain Multimessenger Astrophysics

KM & Shoemaker 19 PRL

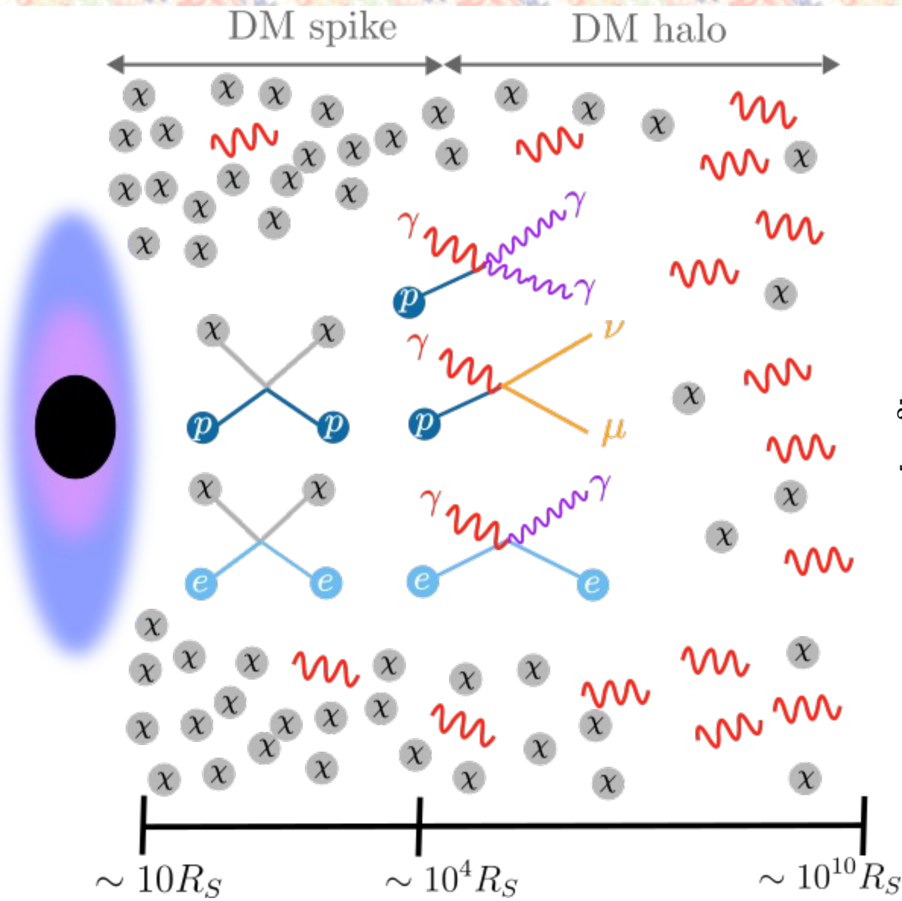


"time delay" signatures
(**neutrino echoes**)

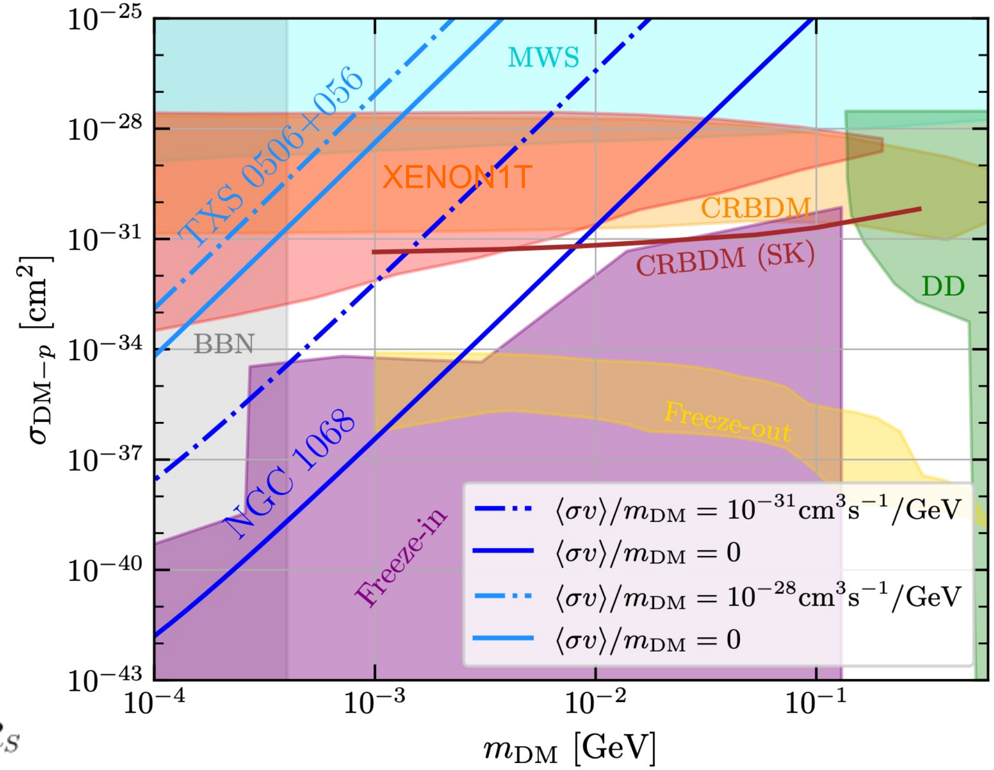
$$\Delta t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4}D \simeq 77\,\mathrm{s}\,\left(\frac{D}{3\ \mathrm{Gpc}}\right)C^2\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$



Supermassive Black Hole Neutrinos as a Probe of Dark Matter



Herrera & KM 24 PRDL
Gustafson, Herrera, Mukhopadhyay, KM & Shoemaker
2408.08947

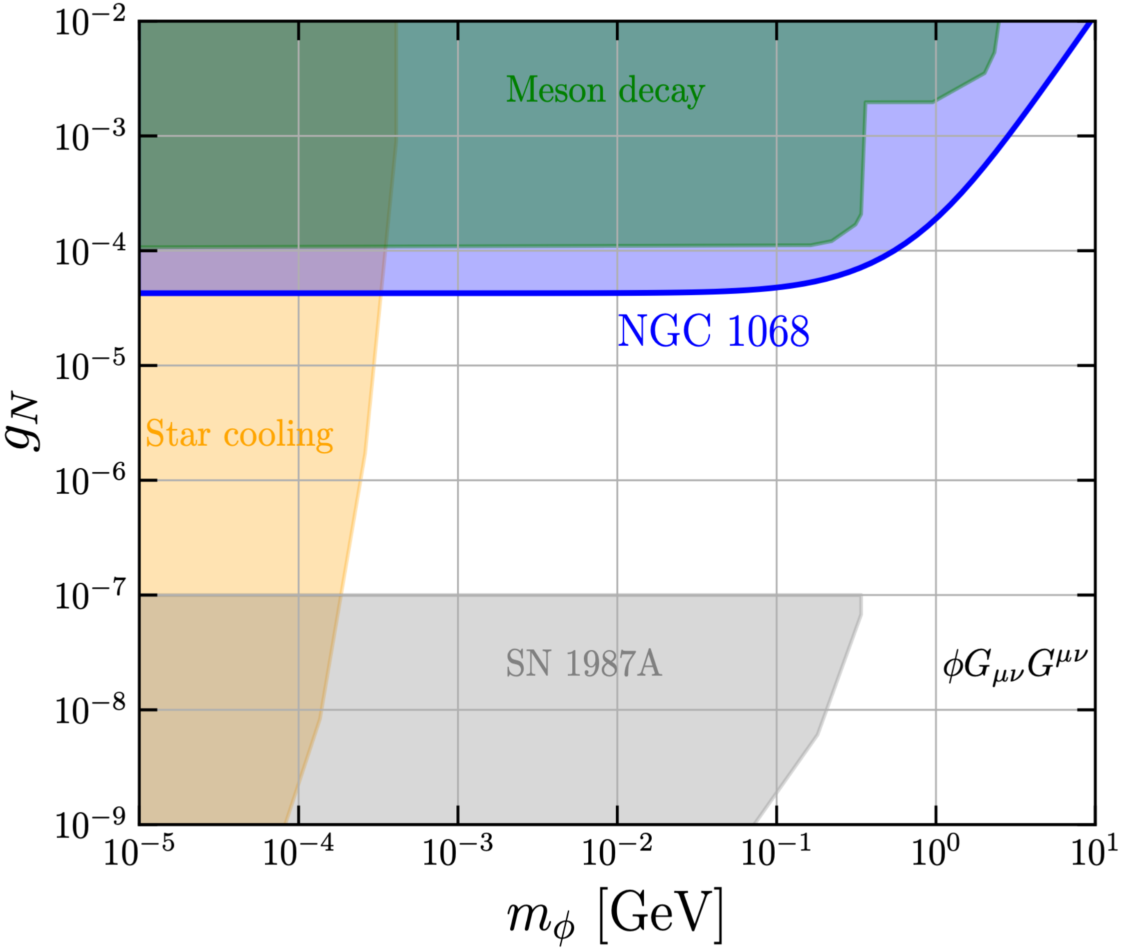


- AGN νs originate from CRs within 10-30 Schwarzschild radii
- High DM density at the center of AGN ("DM spike")
- CR cooling due to DM-SM scattering

  Most stringent constraints on DM-p scattering for DM in the MeV range

Example of Scalar-Mediated DM-Nucleon Interactions

Herrera & KM 24 PRDL



$$\mathcal{L} \supset -m_\chi \bar{\chi}\chi - g_N \phi \bar{N} N - g_\chi \phi \bar{\chi}\chi$$

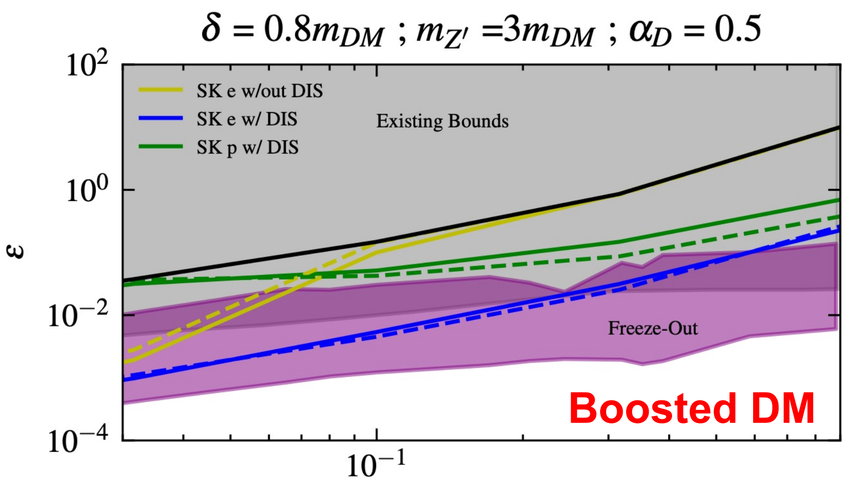
$$\frac{d\sigma^{\phi}_{\mathrm{DM-CR}i}}{dT_{\mathrm{DM}}} = \frac{m_\phi^4}{\left(q^2 + m_\phi^2\right)^2} \frac{d\sigma_{\mathrm{DM-CR}i}}{dT_{\mathrm{DM}}}$$

non-relativistic DM cross section

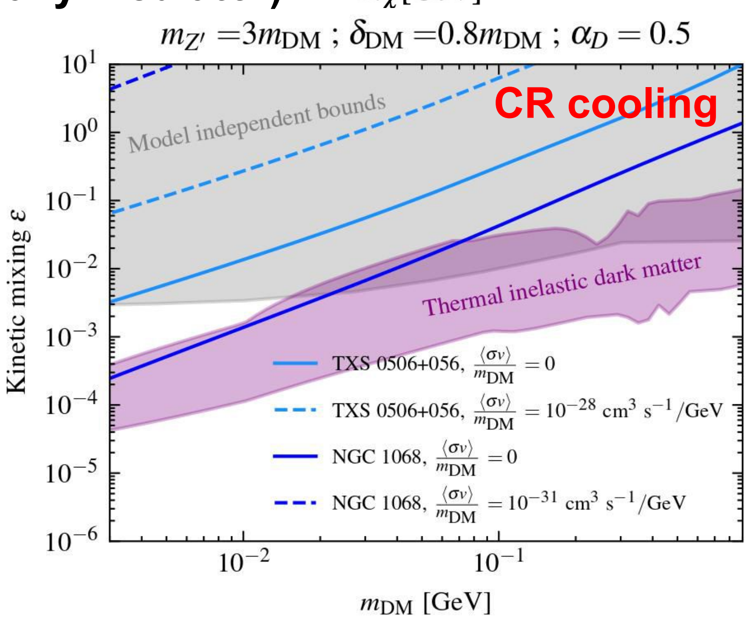
$$\sigma_{\mathrm{DM}-N} = \frac{g_\chi^2 g_N^2 \mu_{\chi-N}^2}{\pi m_\phi^4}.$$

- NGC 1068 observations enable us to probe new parameter space

Application to Inelastic Dark Matter

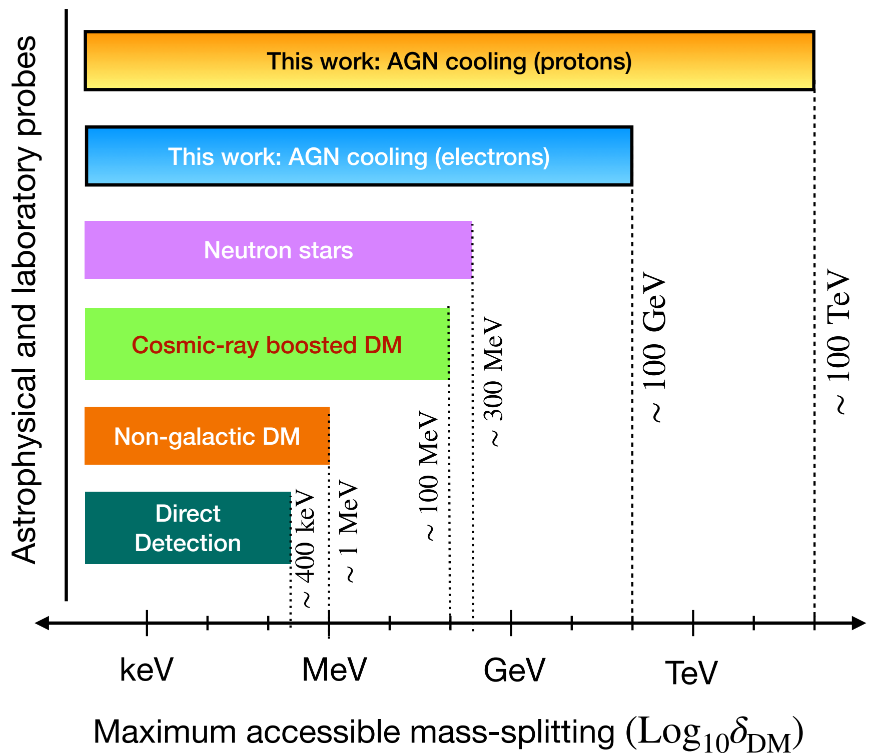


(heavy mediator)



$$\chi_1 + i \to \chi_2 + i'$$

- DM may be inelastic (ex. pseudo-Dirac)
- DIS can be important!
- CR cooling limits (IceCube)
- Boosted DM limits (Super-K)



Gustafson, Herrera, Mukhopadhyay, KM & Shoemaker 2408.08947