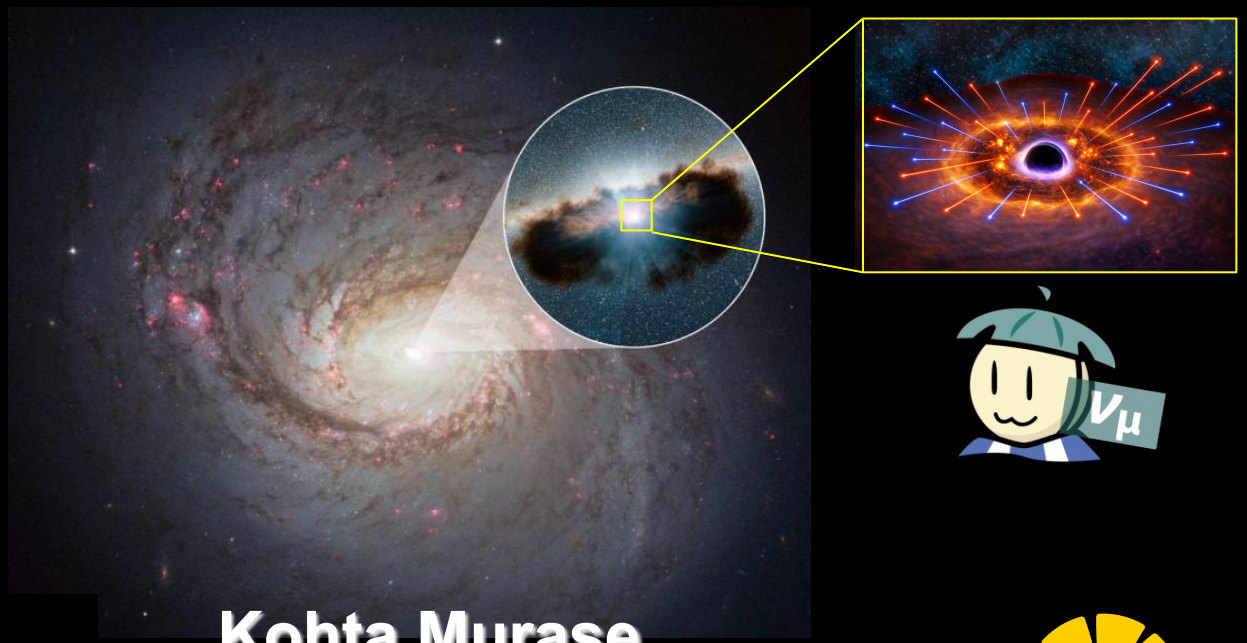
The High-Energy Neutrino Universe

- What We Have Learned and the Next Frontiers -



PENNSTATE
1855

Kohta Murase
(Penn State/U. Tokyo)

October 14
IPA 26 @ Madison

UTokyo

Huge congratulations to Francis & the entire IceCube Collaboration!



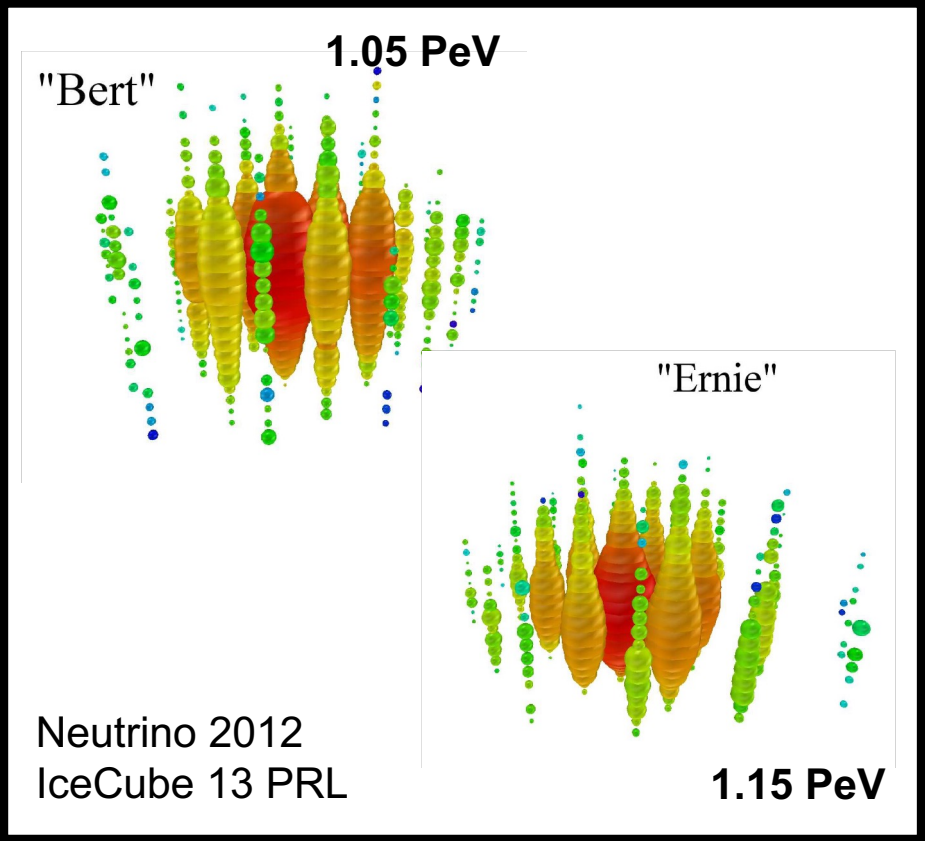




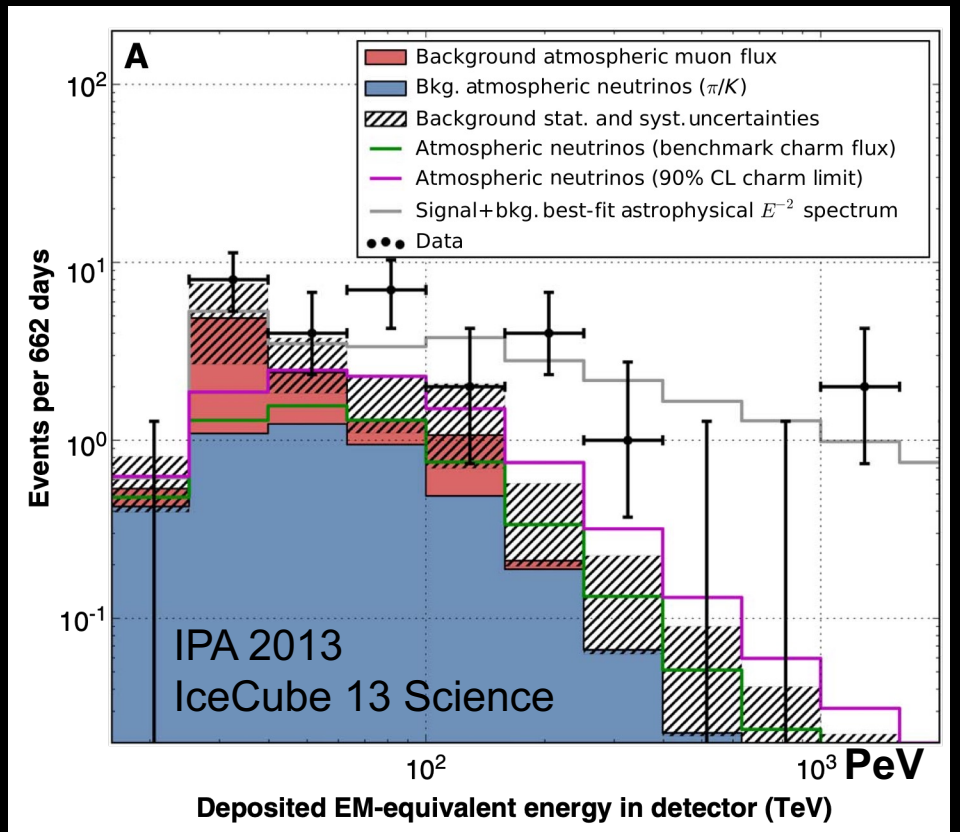


2013: Dawn of High-Energy Neutrino Astrophysics

First detection of PeV events (~3σ)



HESE analysis (~4σ)



- Flux: $E_\nu^2 \Phi_\nu \sim 3\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}@ 0.1 PeV
- Spectrum: E_ν^{-2} w. a cutoff or softer than $E_\nu^{-2.2}$
- Flavor: consistent w. flavor ratio 1:1:1
- Arrival direction: consistent w. isotropic distribution

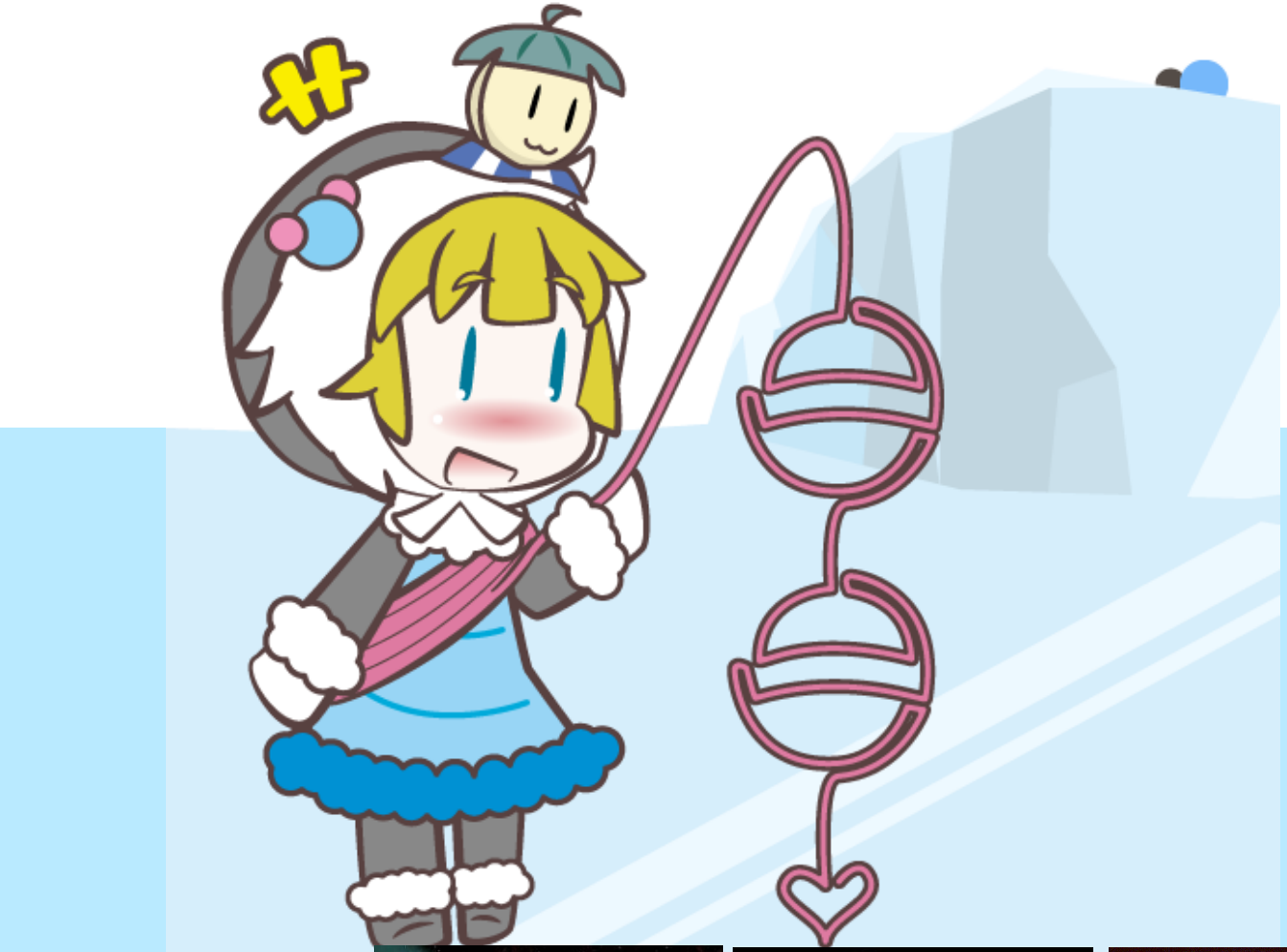
High-Energy Cosmic ν : Questions

- 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?



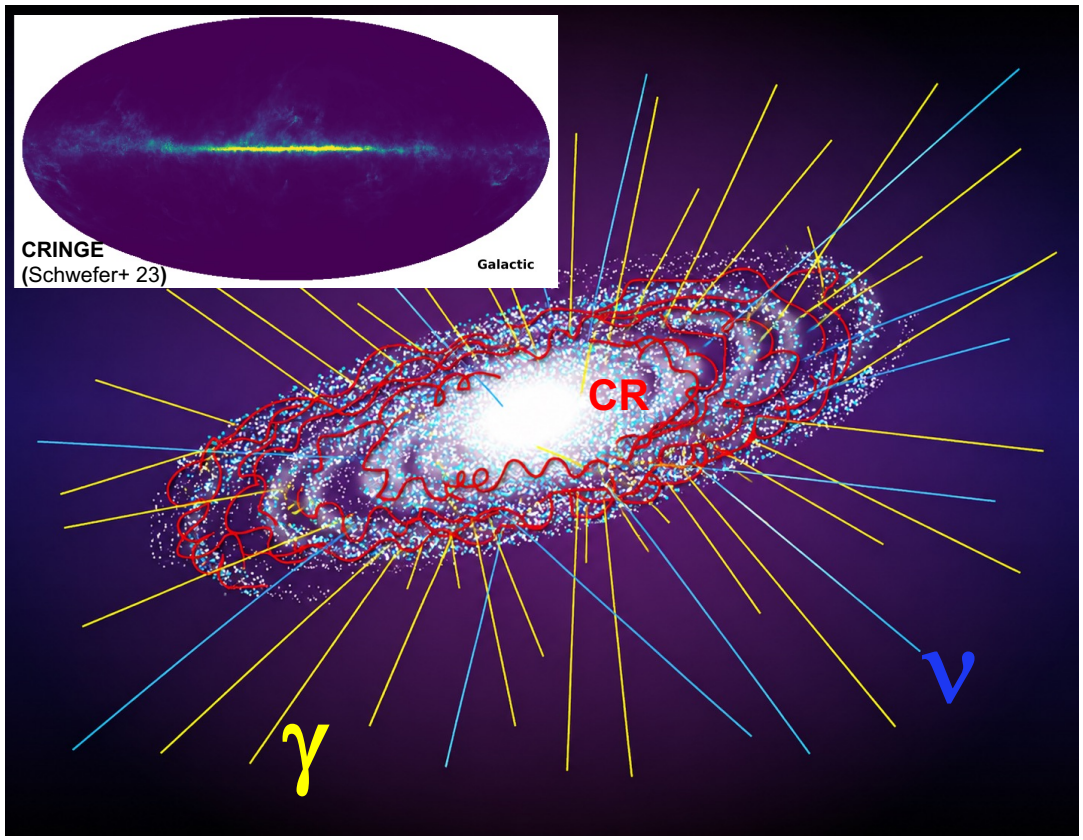








Galactic Diffuse Neutrinos and Gamma Rays



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

CR interactions w. interstellar gas

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

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

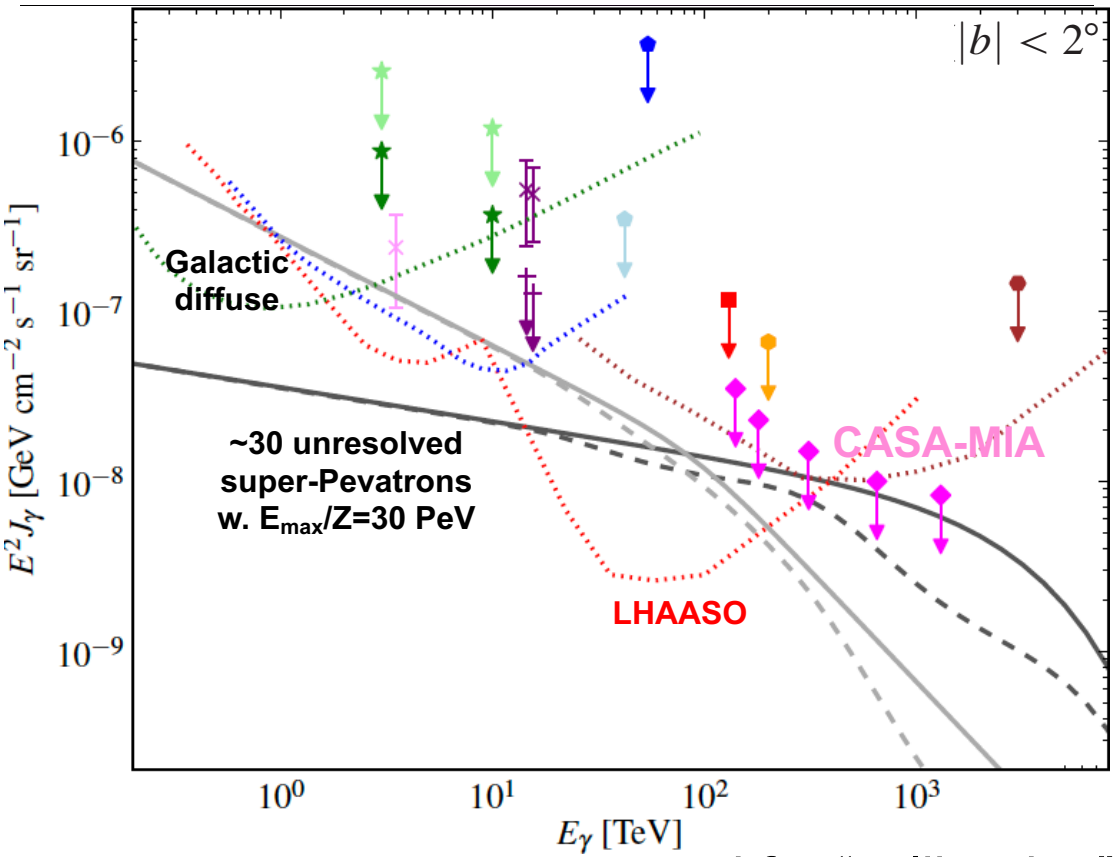
$$\pi^0 \rightarrow \gamma + \gamma$$

π^0:$\pi^{\pm}$~1:2

γ-ray measurements are used for "calibrating" ν fluxes (after γγ de-absorption)

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

Galactic Diffuse Neutrinos and Gamma Rays



Ahlers & KM 14 PRD

CR interactions w. interstellar gas

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

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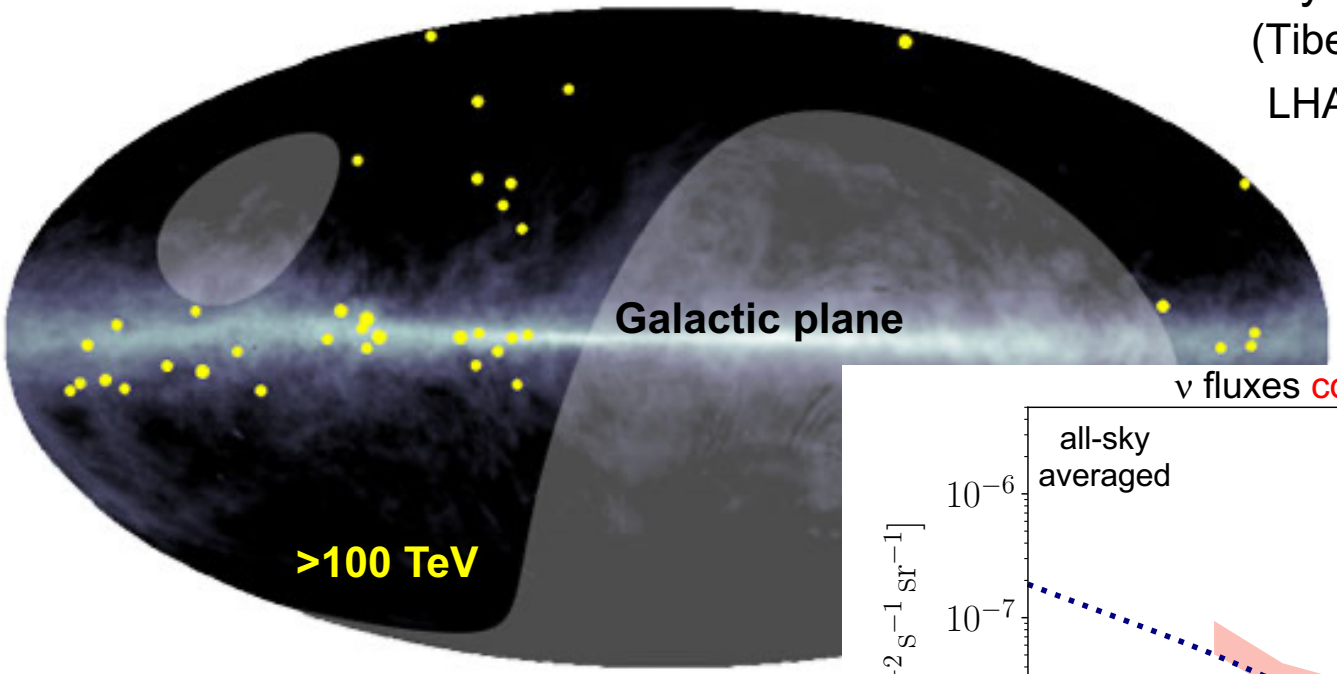
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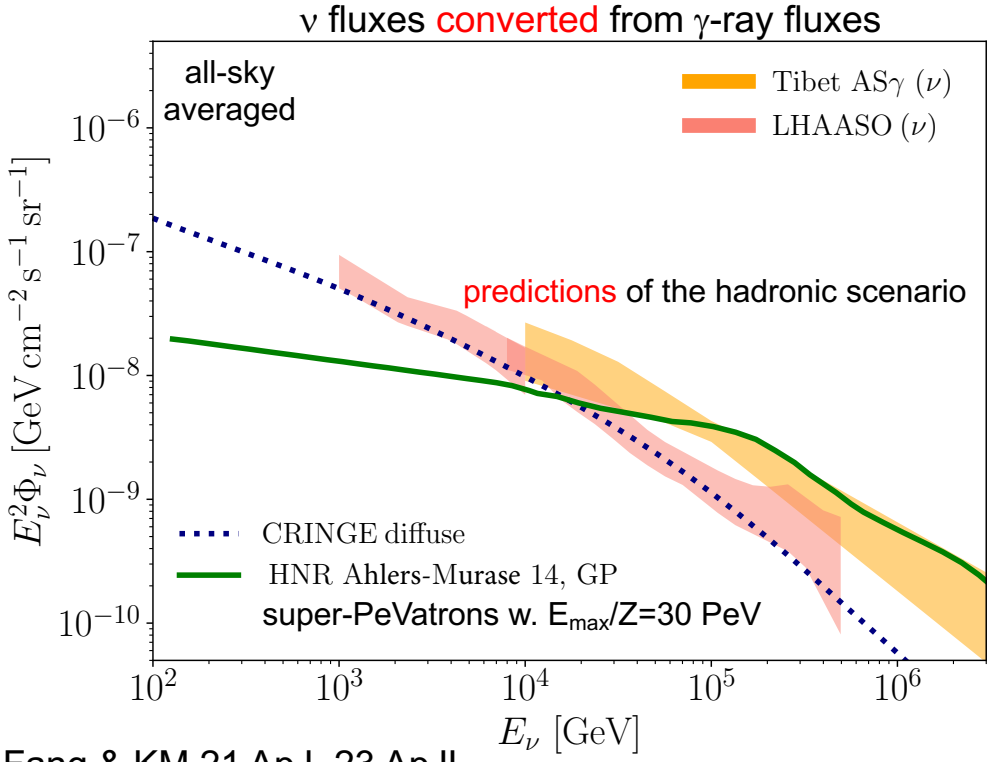
Only upper limits at sub-PeV γ rays existed in 2013, but the Galactic ν contribution is **subdominant**

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)



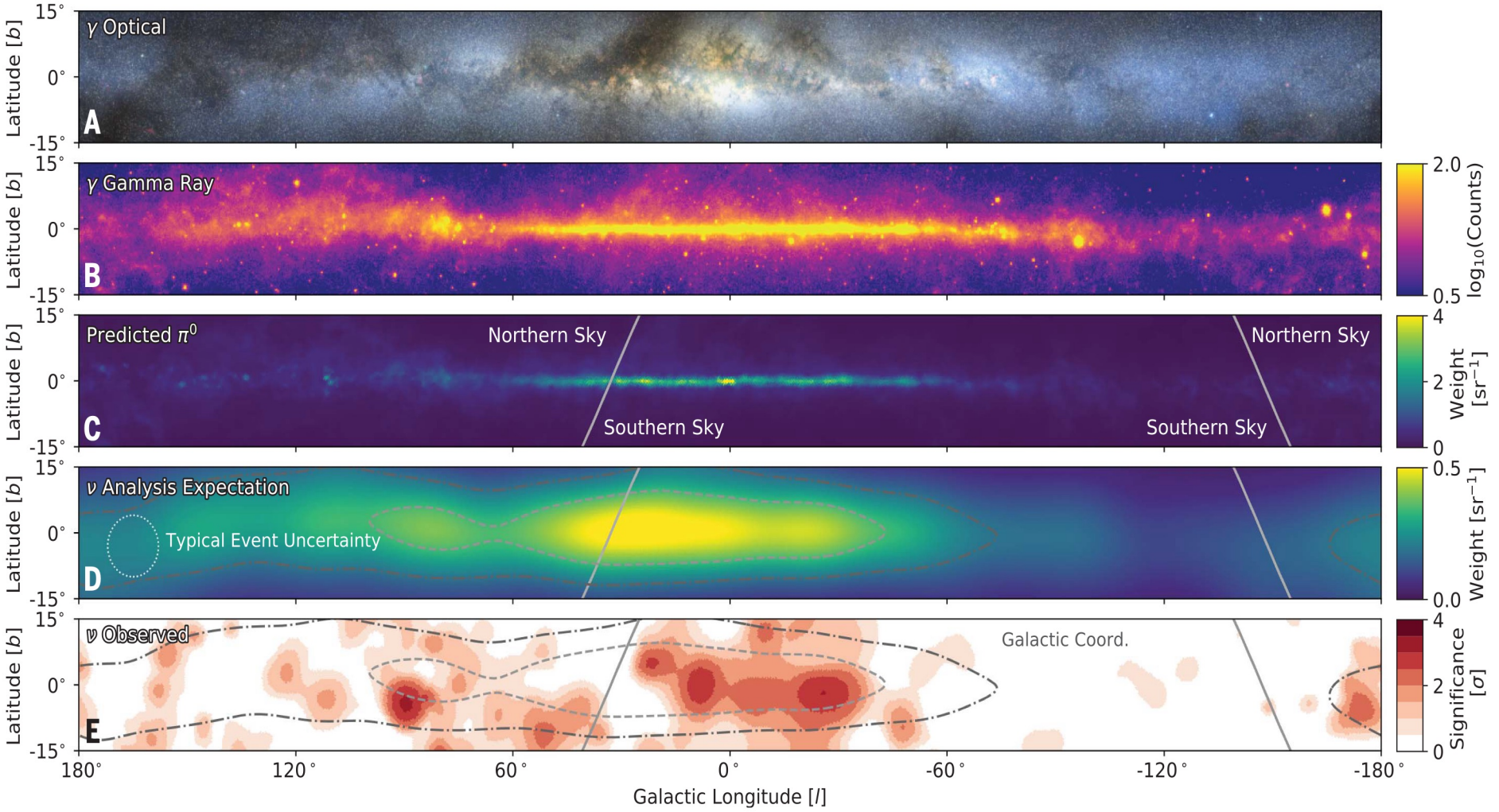




Fang & KM 21 ApJ, 23 ApJL

Discovery of Galactic Diffuse Neutrinos

IceCube 23 Science

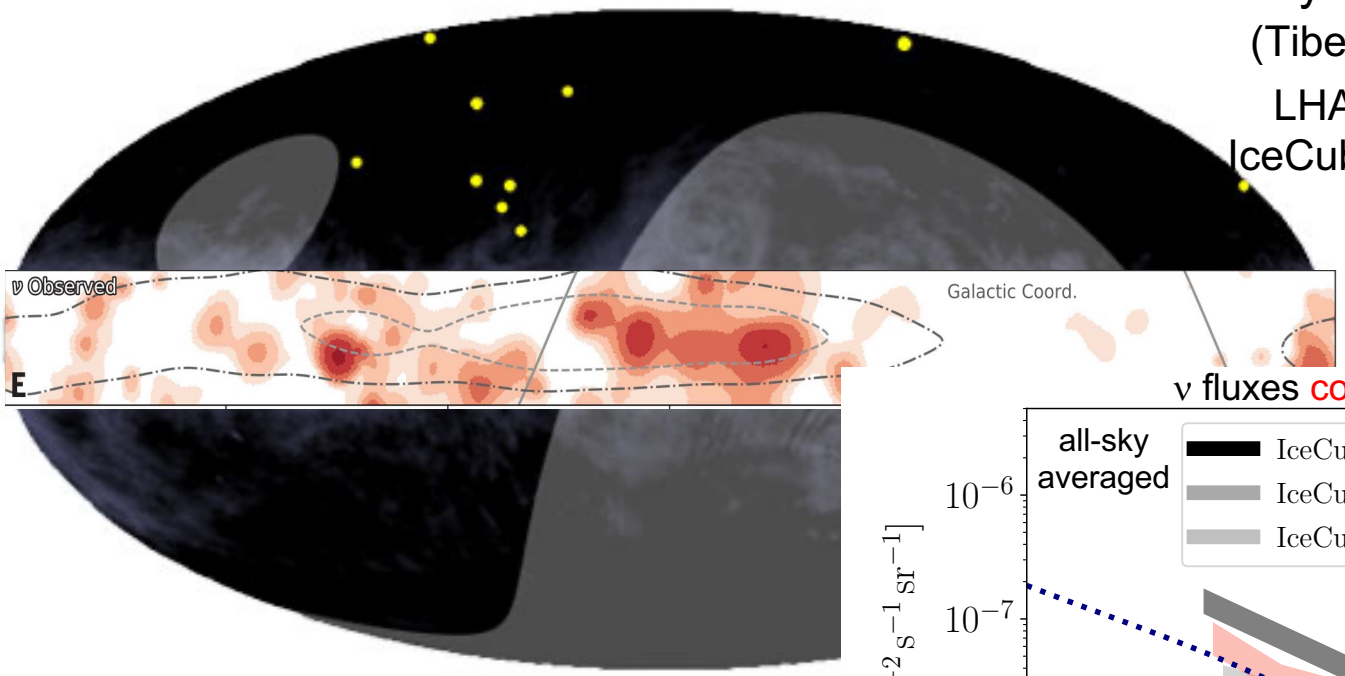


Now ν emission from the Milky Way (~10% of total) has been observed w. >5σ

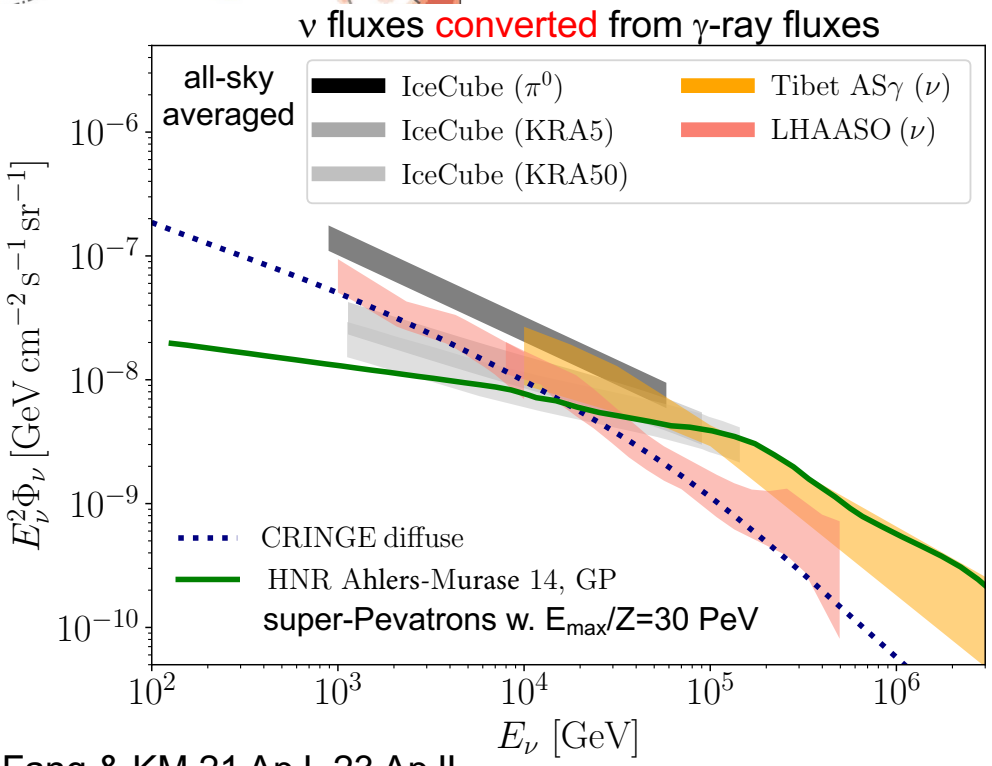
(IceCube 26)

Galactic Multimessenger Connection

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



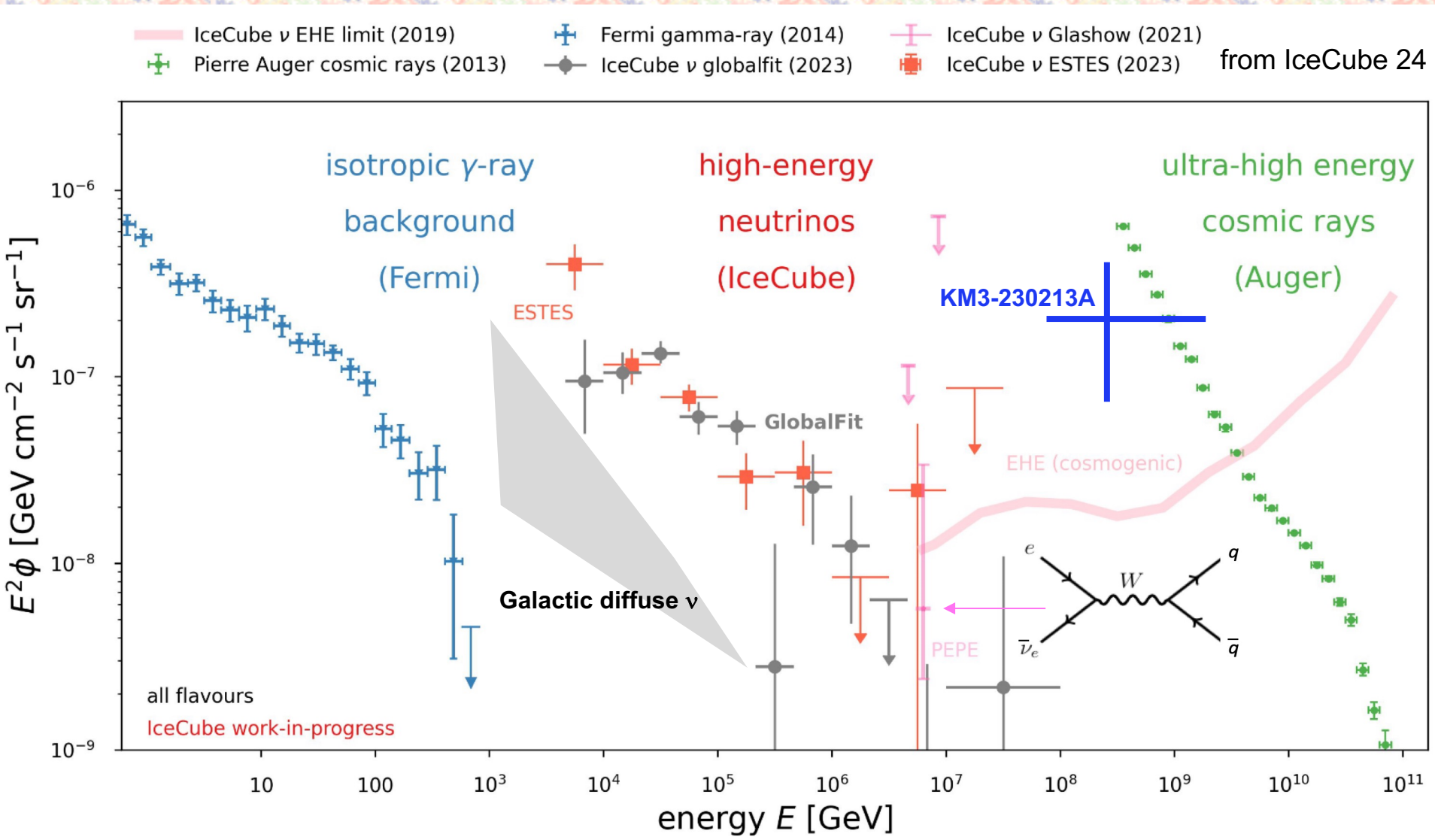
ν-γ supports hadronic (pp) origin



Fang & KM 21 ApJ, 23 ApJL

Open questions
- Truly diffuse vs unresolved sources?
  → better angular resolution
- Super-PeVatron accelerators?
  → larger statistics at higher energies

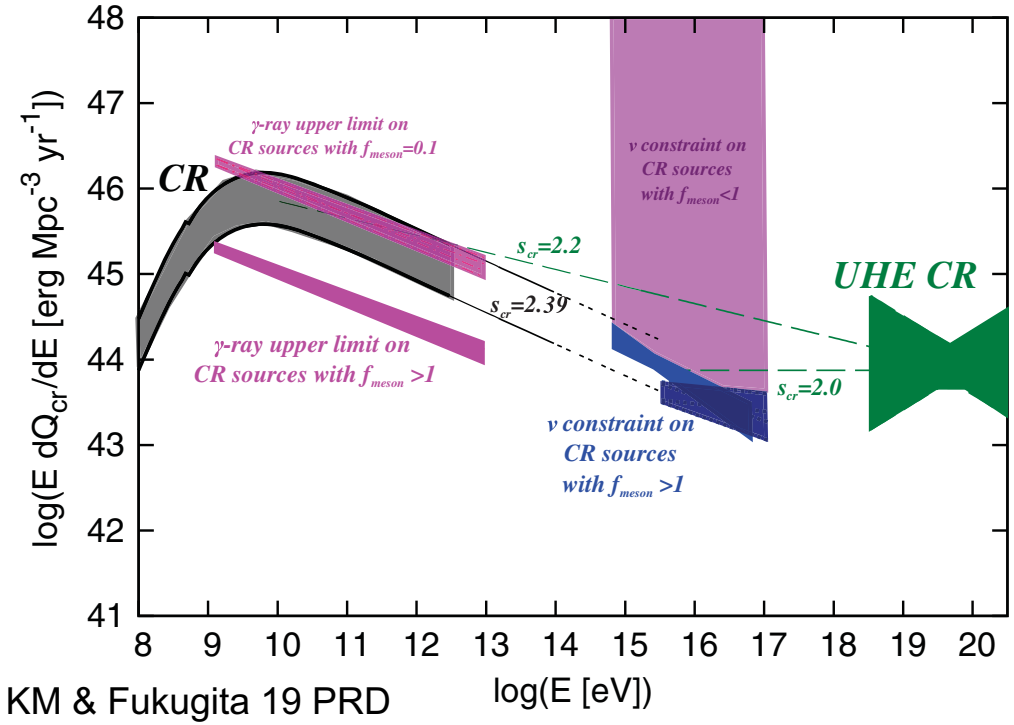
All-Sky Multimessenger Flux & Spectrum



Dominant Sources:* extragalactic *(unlike Milky-Way galaxies)

Multimessenger Particle Energetics

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



KM & Fukugita 19 PRD

redshift evolution (order of unity)

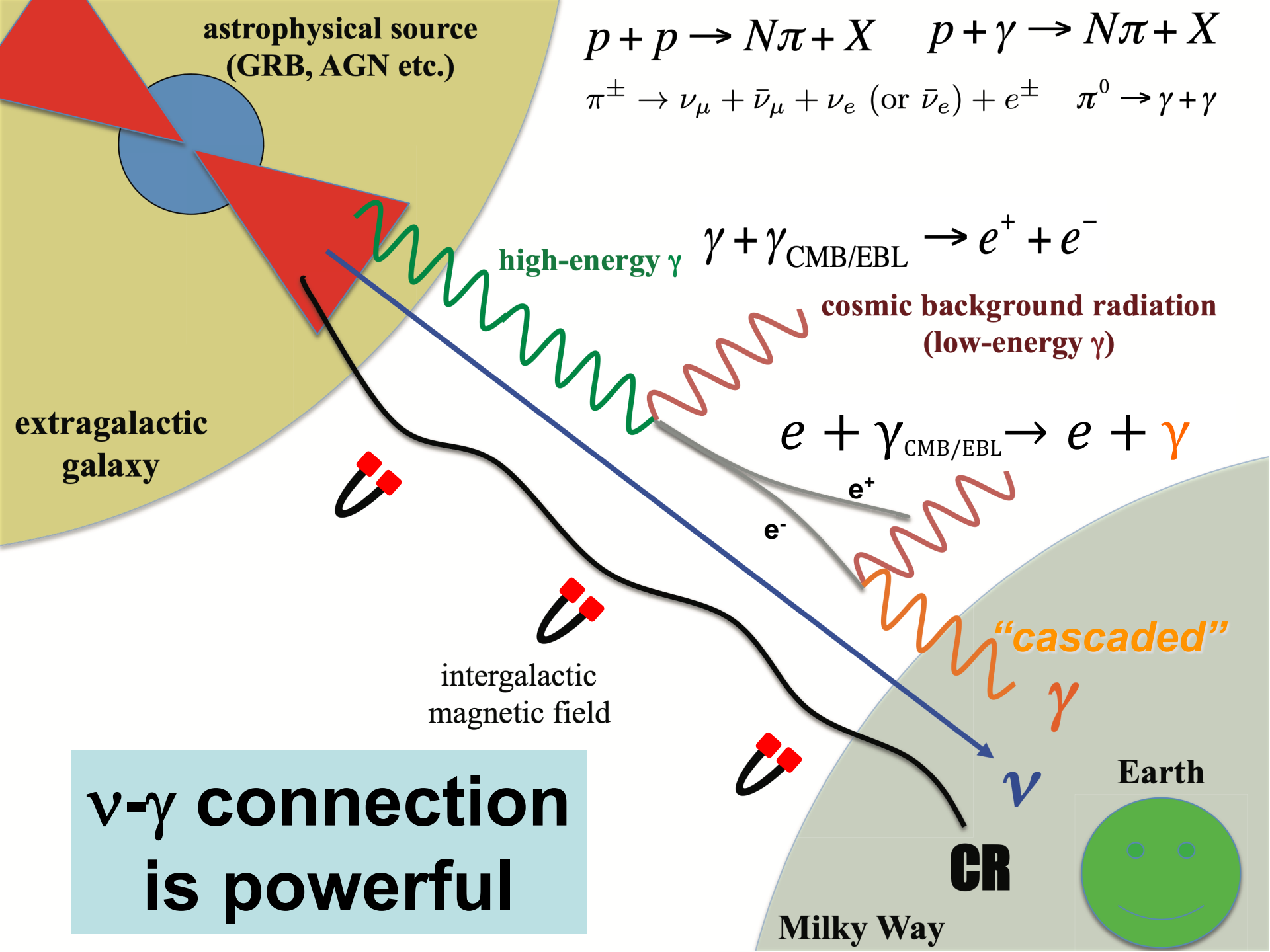
propagation & losses

$$E^2\Phi \approx \frac{ct_H}{4\pi}\varepsilon Q_\varepsilon \xi_z g(E)$$

energy generation rate density

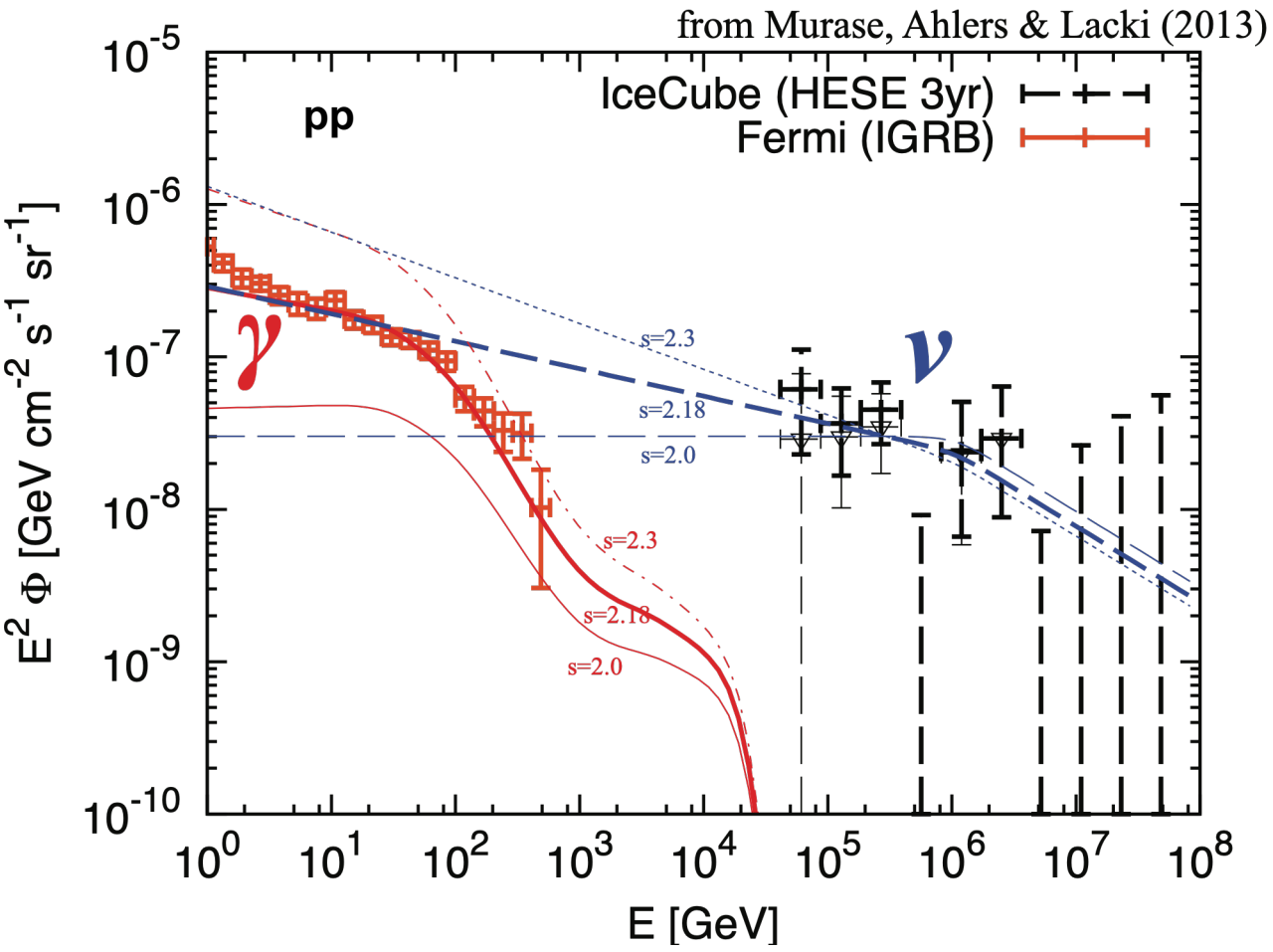
Are 3 messengers connected? (Grand-)unification? (KM & Waxman 16, Fang & KM 18)

	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}	$10^{-4} - 10^{-3}$	$10^{-7} - 10^{-6.5}$	$10^{-9} - 10^{-8}$	$10^{-5} - 10^{-4}$	$10^{-6} - 10^{-5}$


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

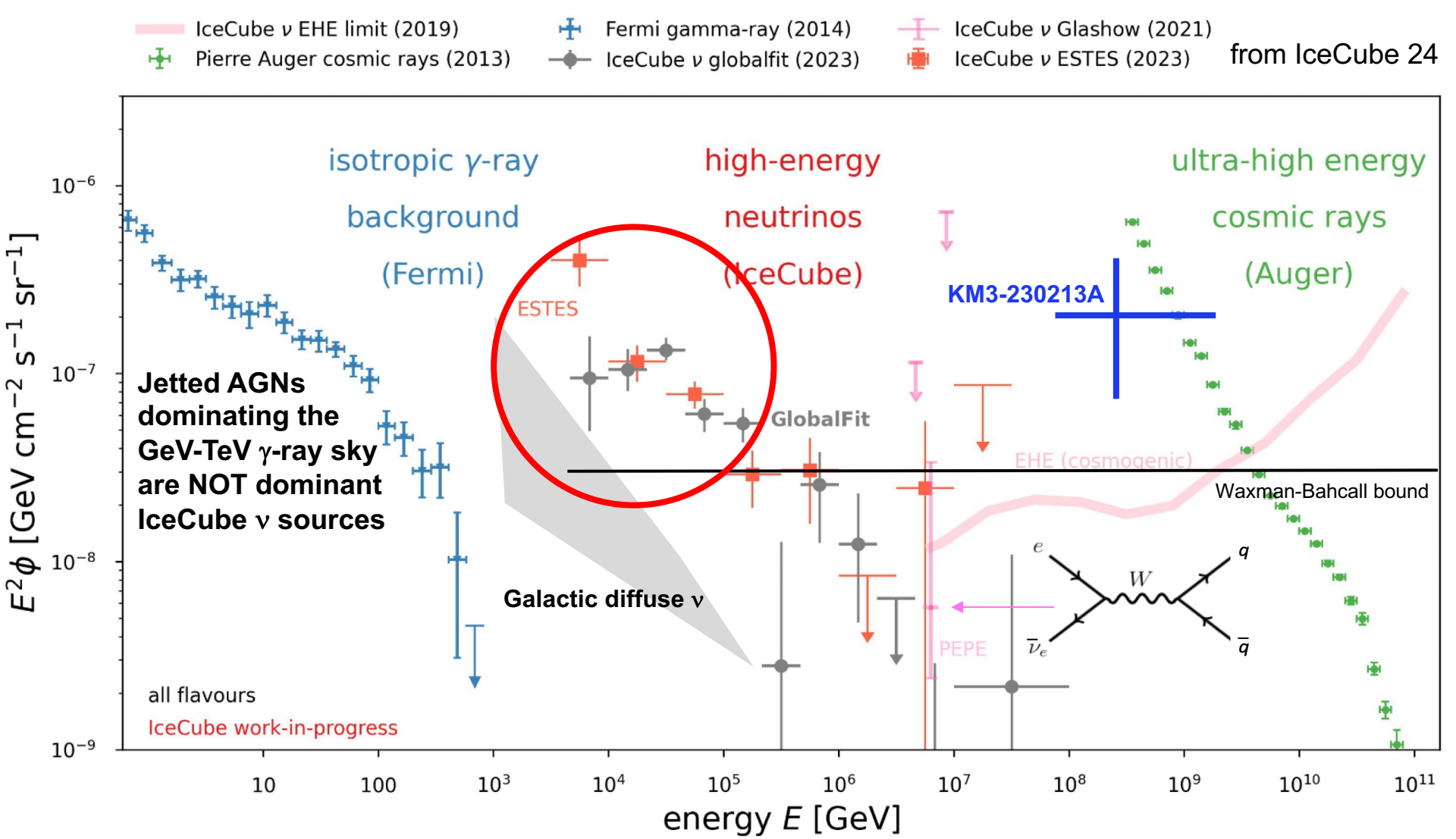
Extragalactic Multimessenger Connection

Generic power-law spectrum ν sources transparent to GeV-TeV γ rays



- **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.)

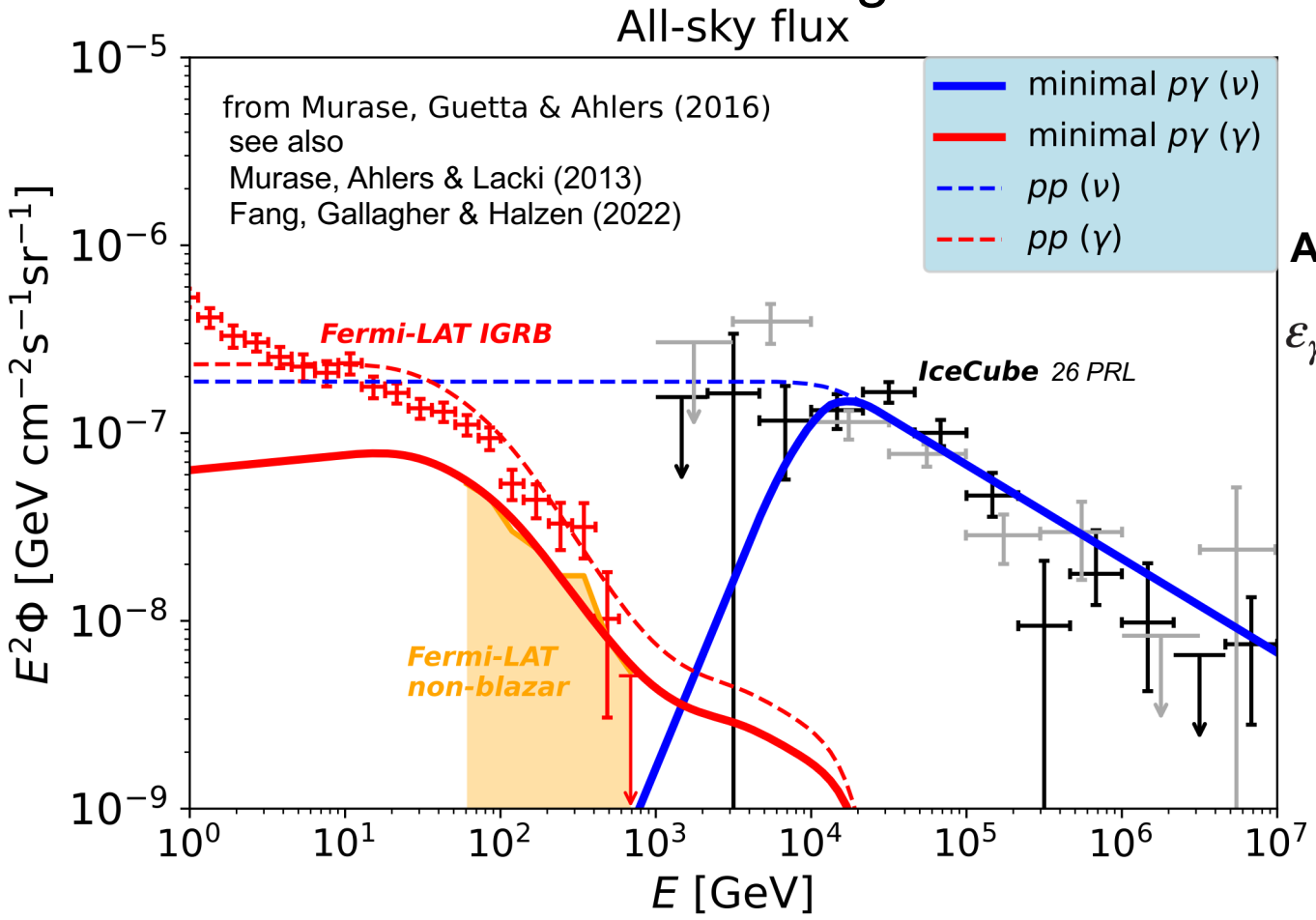
All-Sky Multimessenger Flux & Spectrum



- 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)

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

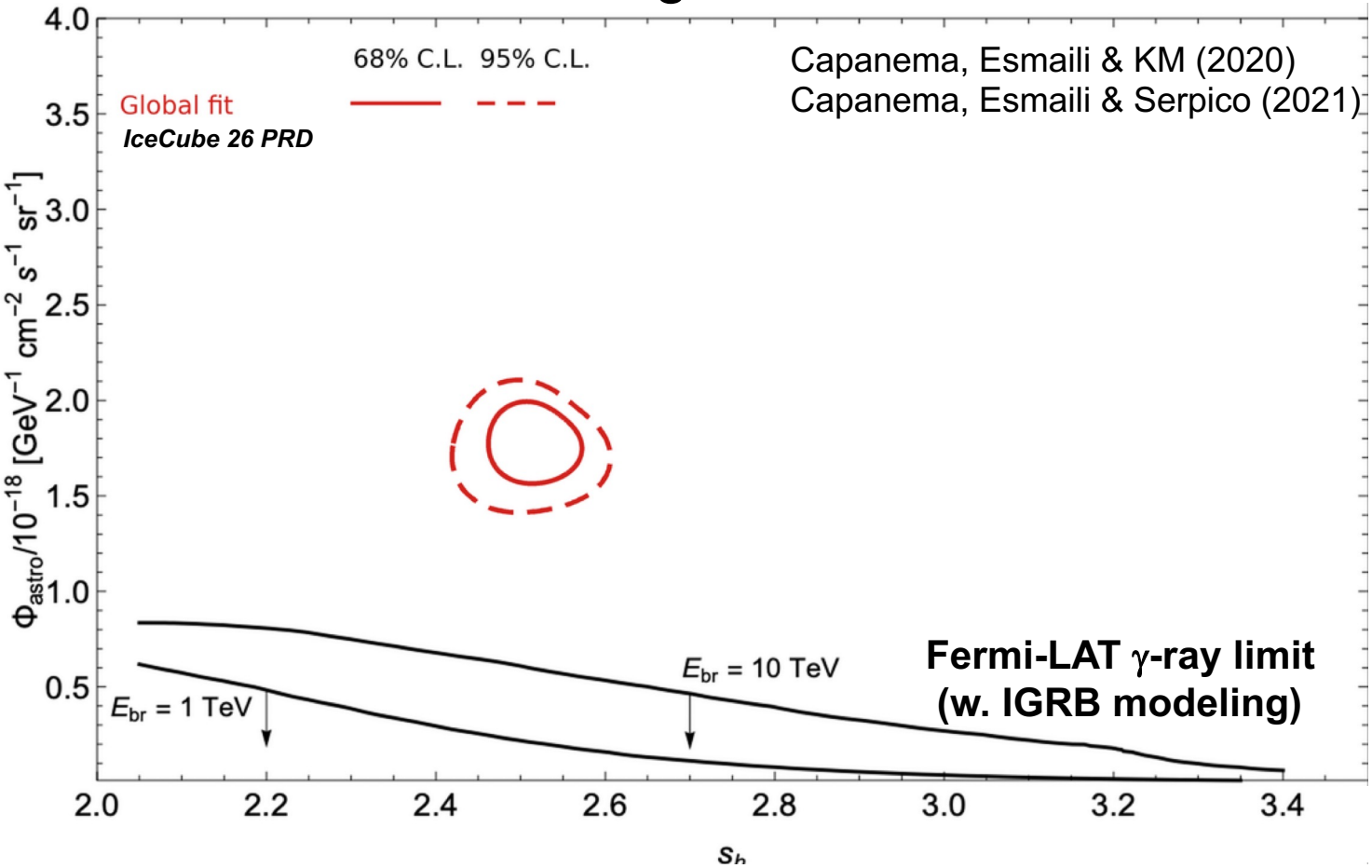
pp scenarios (e.g., star-forming galaxies) are excluded if γ-ray transparent

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}

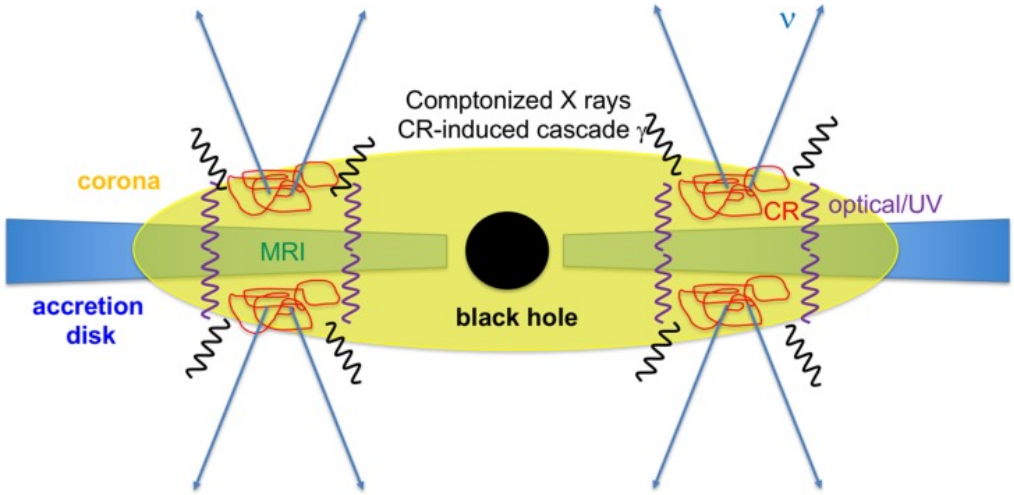


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→ majority of ~30 TeV νs: hidden (i.e., γ-ray opaque) cosmic-ray accelerators

Prediction of Hidden Neutrino Sources

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

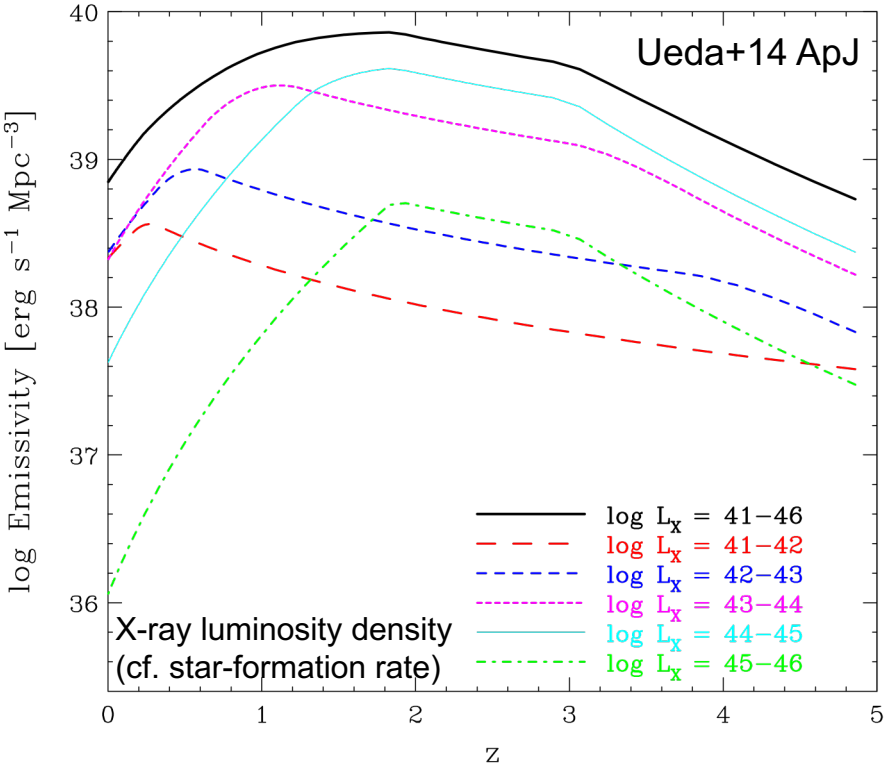
γγ→e⁺e⁻ optical depth $\tau_{\gamma\gamma} \approx \frac{\sigma_{\gamma\gamma}^{\rm eff}}{\sigma_{p\gamma}^{\rm eff}} f_{p\gamma} \sim 1000 f_{p\gamma} \gtrsim 10$



disk-corona

opt/UV=multi-temperature blackbody from disks

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

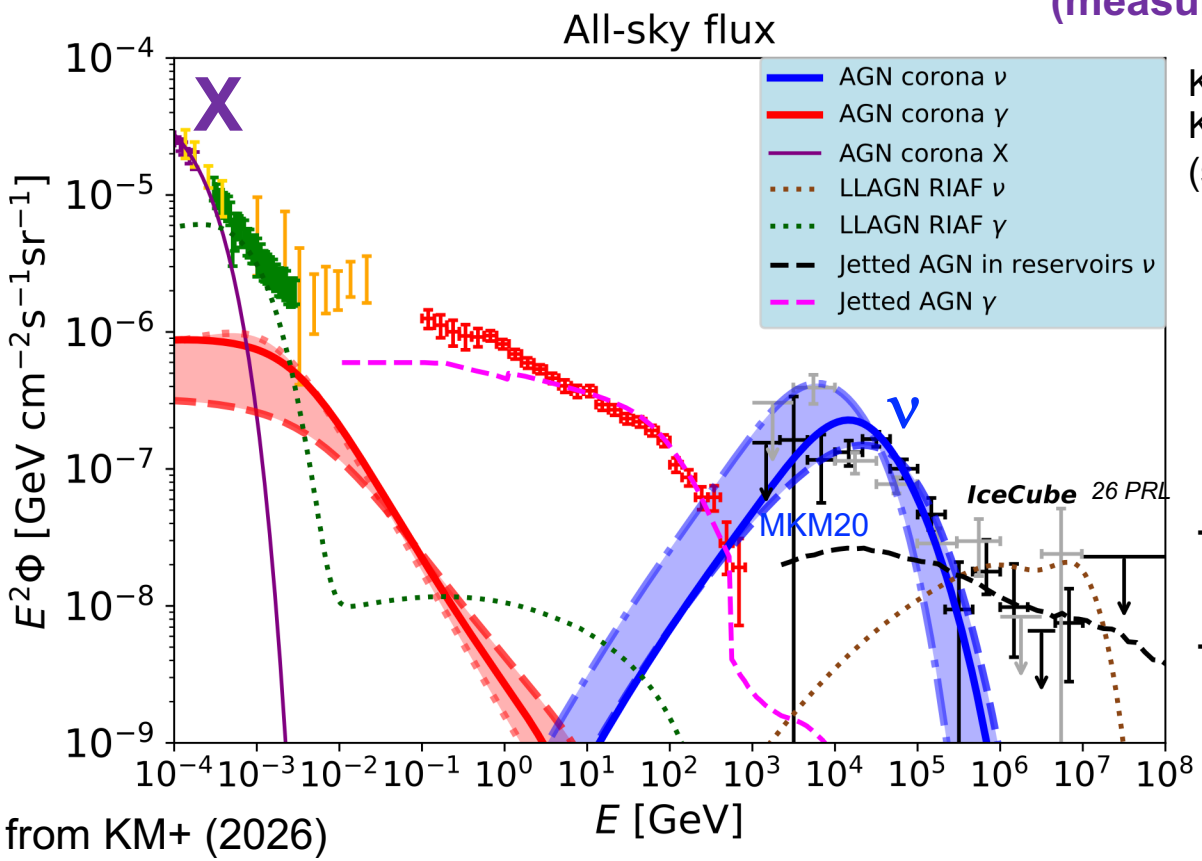


The X-ray background originates from jet-quiet AGNs (coronae)

Prediction of Hidden Neutrino Sources

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

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



from KM+ (2026)

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

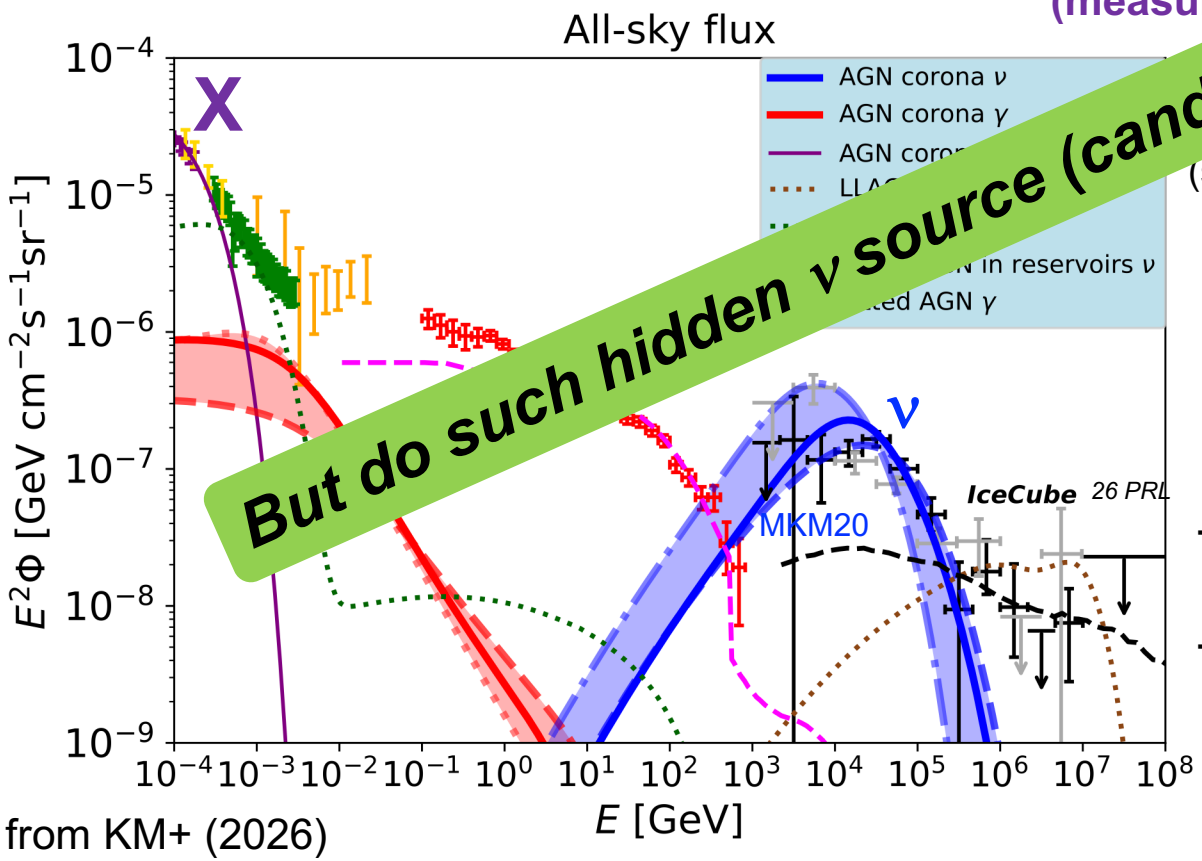
- Simultaneous explanation for the all-sky ν and X-ray fluxes
- Predicting a spectral curvature consistent w. a ~10-30 TeV break in the ν data

Basu's talk

Prediction of Hidden Neutrino Sources

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

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

...a & Meszaros 20 PRL
...ara, 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

Basu's talk

from KM+ (2026)

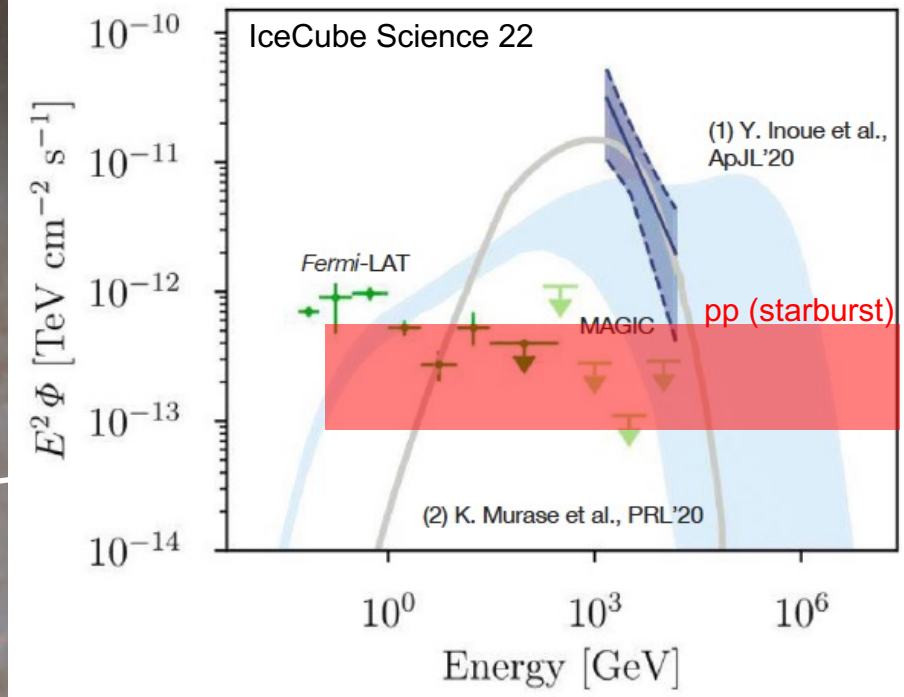
NGC 1068

one of the powerful AGNs in the local universe

distance: ~10 Mpc

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

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



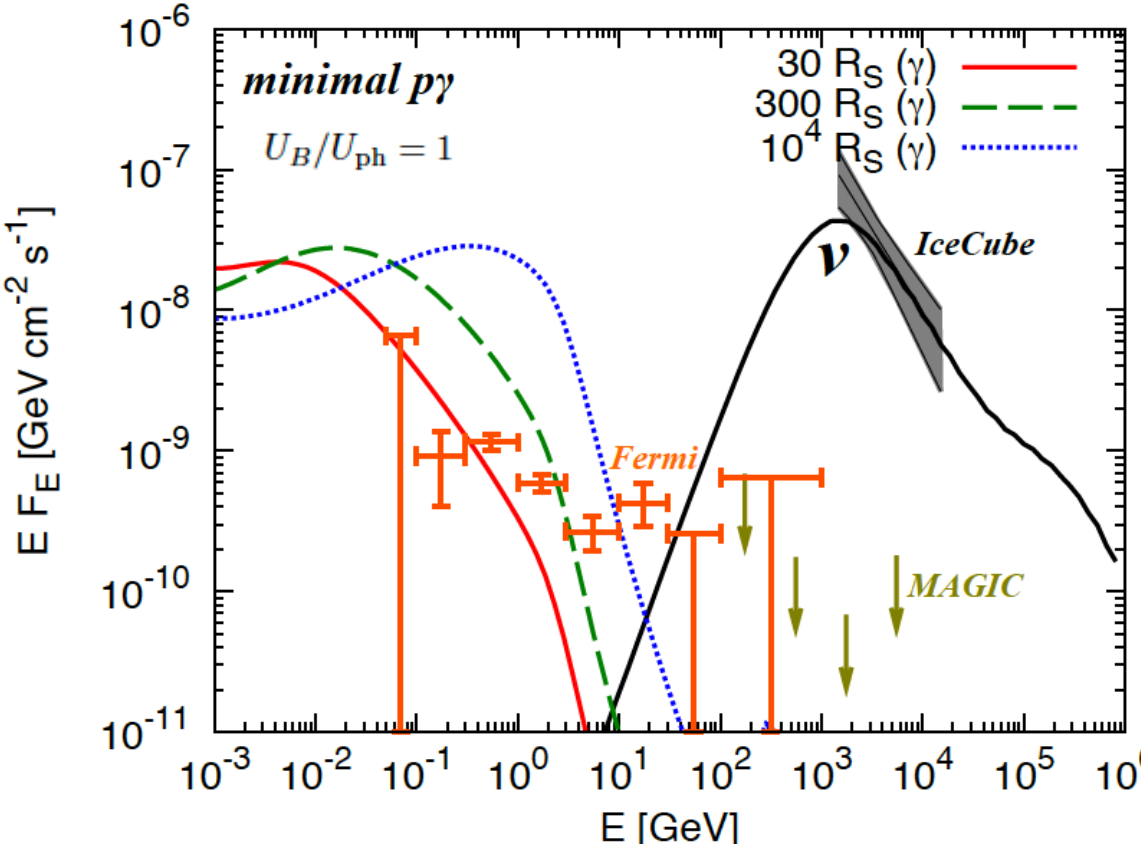


Where Do Neutrinos Come from?

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

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 < (15-30) R_S

KM 22 ApJL
see also
Das, Zhang & KM 24 ApJ
Blanco, Hooper, Linden & Pinetti 25 PRD
Das, KM & Zhang 26 ApJL

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

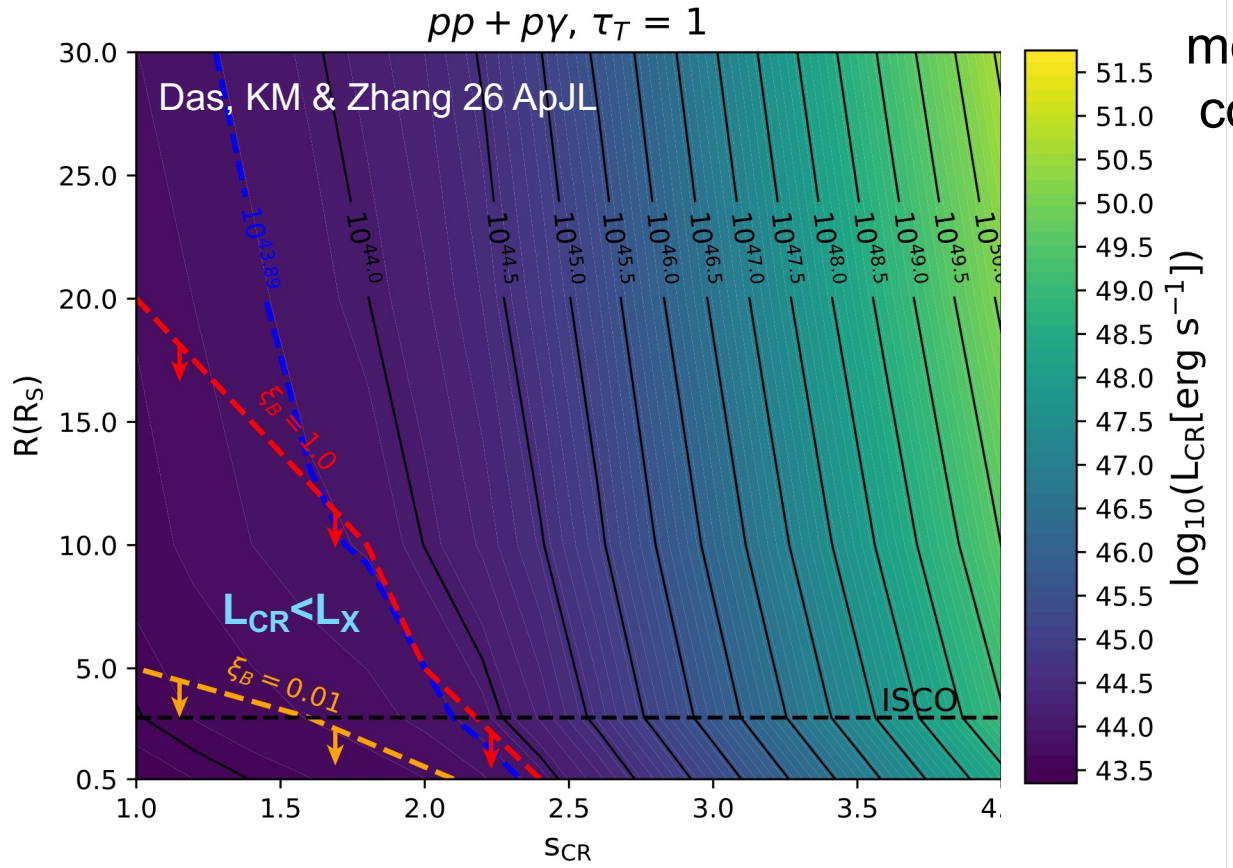
Massive black hole: sub-PeV proton accelerator & ideal beam dump

What Can We Learn from NGC 1068?

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

for 0.1-300 GeV γ rays

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



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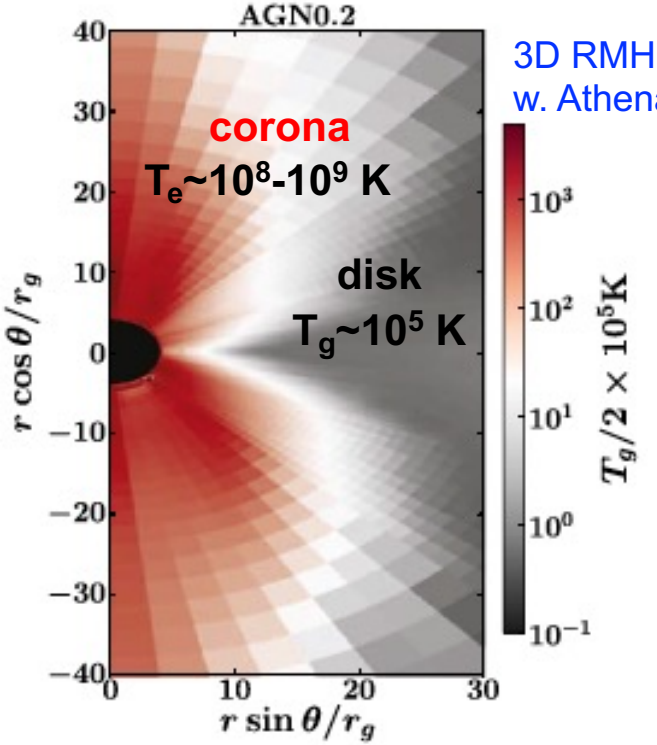
- CR spectrum: hard (**s_{CR} <~ 2**)
- Emission region: strongly magnetized **$\xi_B = U_B/U_{ph}$ >~ 0.01**
- ν production mechanism: $p\gamma$/pp ($\gamma\gamma \rightarrow \mu^+\mu^-$ & β-decay scenarios ruled out by γ-rays/CRs/flavors)

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

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

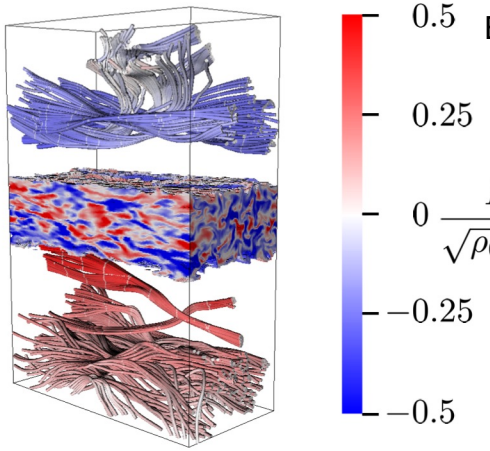
High-Energy Phenomena in the Vicinity of Black Holes

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



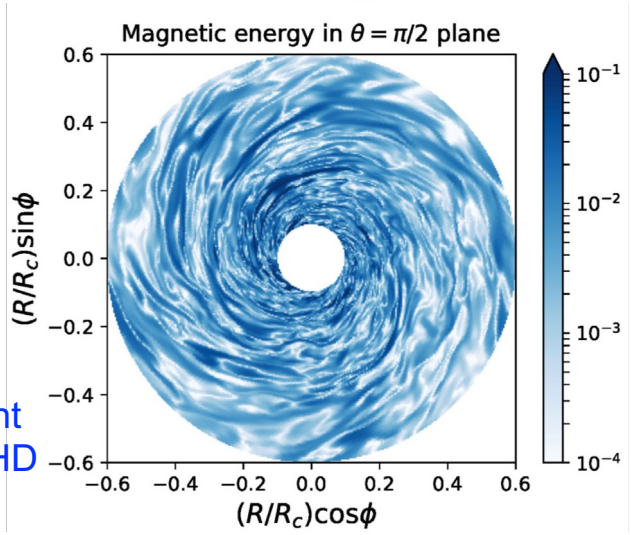
3D RMHD simulation
w. Athena++

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



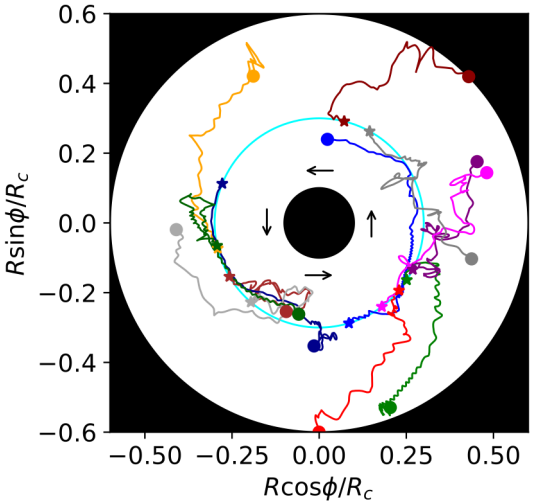
Bambic, Quataert & Kunz 23 MNRAS

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)

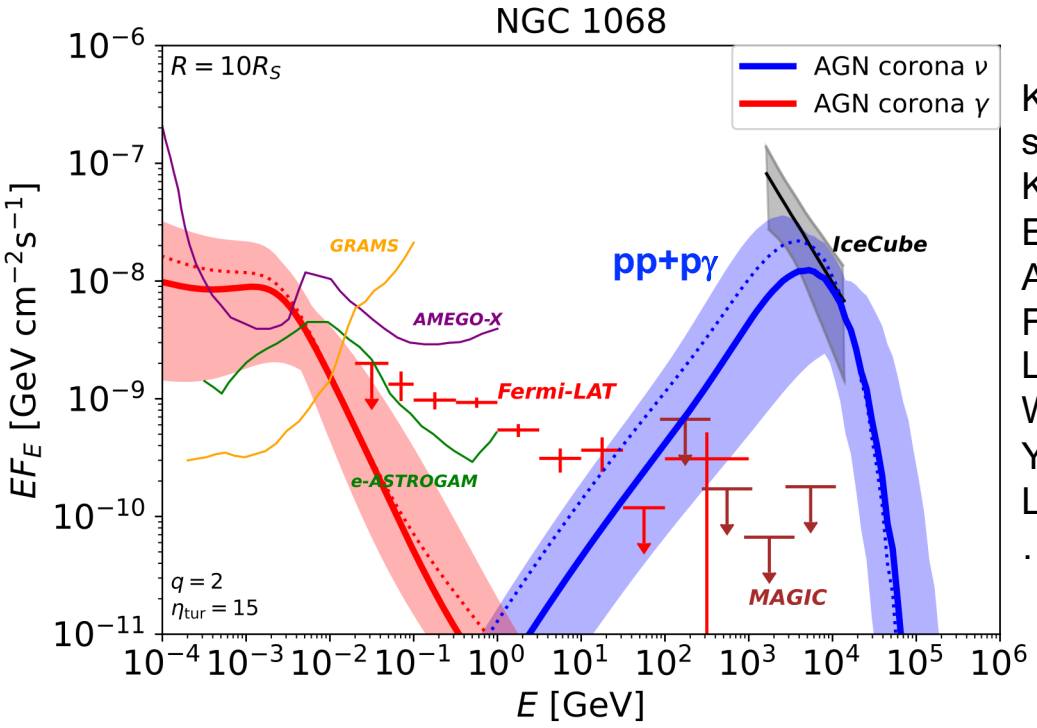


High-energy neutrinos now meet the frontier of astroplasma physics

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
- Cosmic-ray parameters (particle acceleration):
  injection efficiency, acceleration efficiency (η_{tur}), spectral index (q)

Prediction: cascaded γ rays in the MeV range

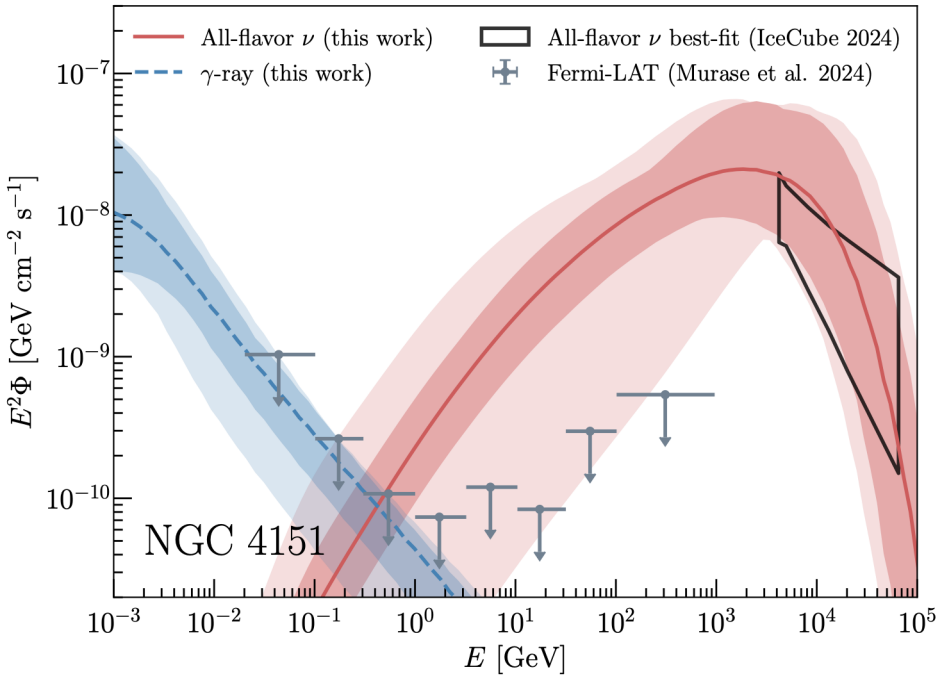


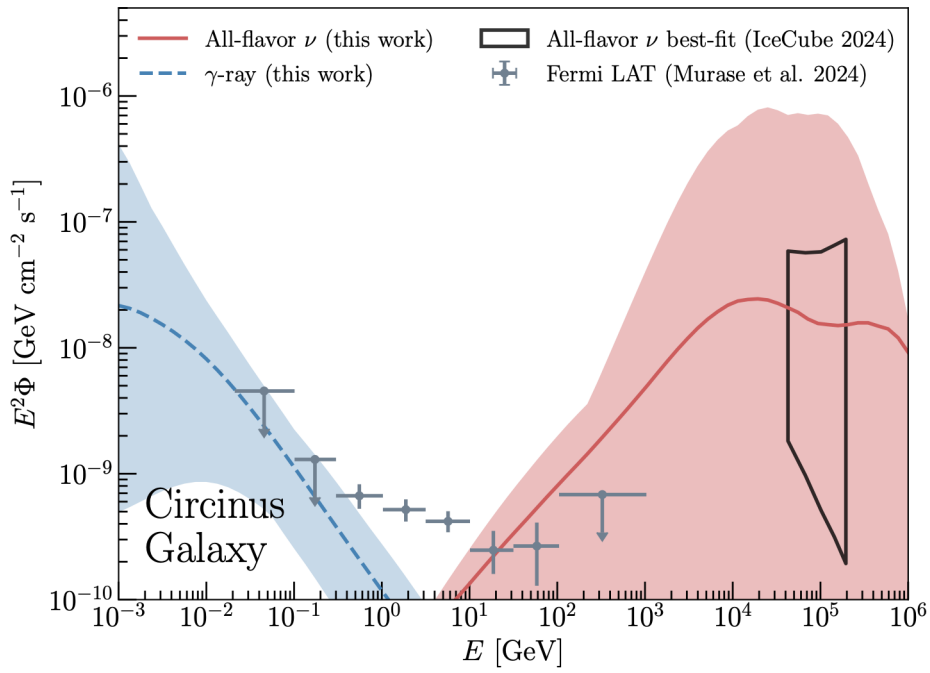
KM+ 20
see also
Kheirandish, KM & Kimura 21
Eichman+ 22
Ajello, KM & McDaniel 23
Fiorillo+ 24
Lemoine & Rieger 25
Wang+ 26
Yang+ 26
Li & Halzen 26
…

https://github.com/pegasuskmurase/ModelTemplates/tree/main/AGNcoronaMM_MKM20model

Corona Model: Predictions and Hints

- Theory prediction: ν luminosity ~ intrinsic X-ray luminosity (KM+ 20, 24, 26)
  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

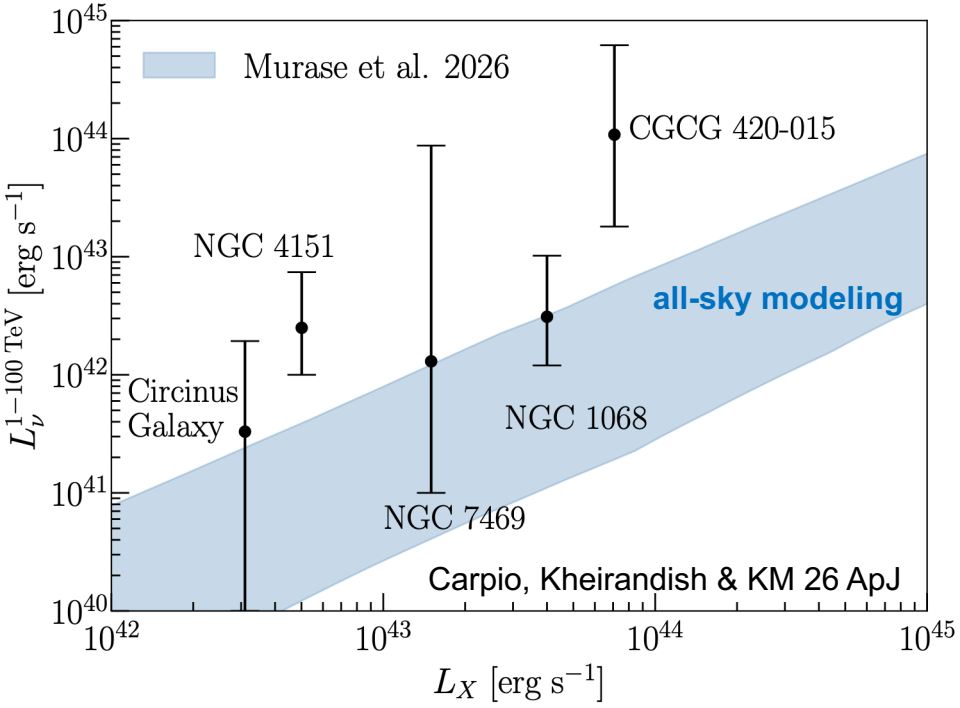


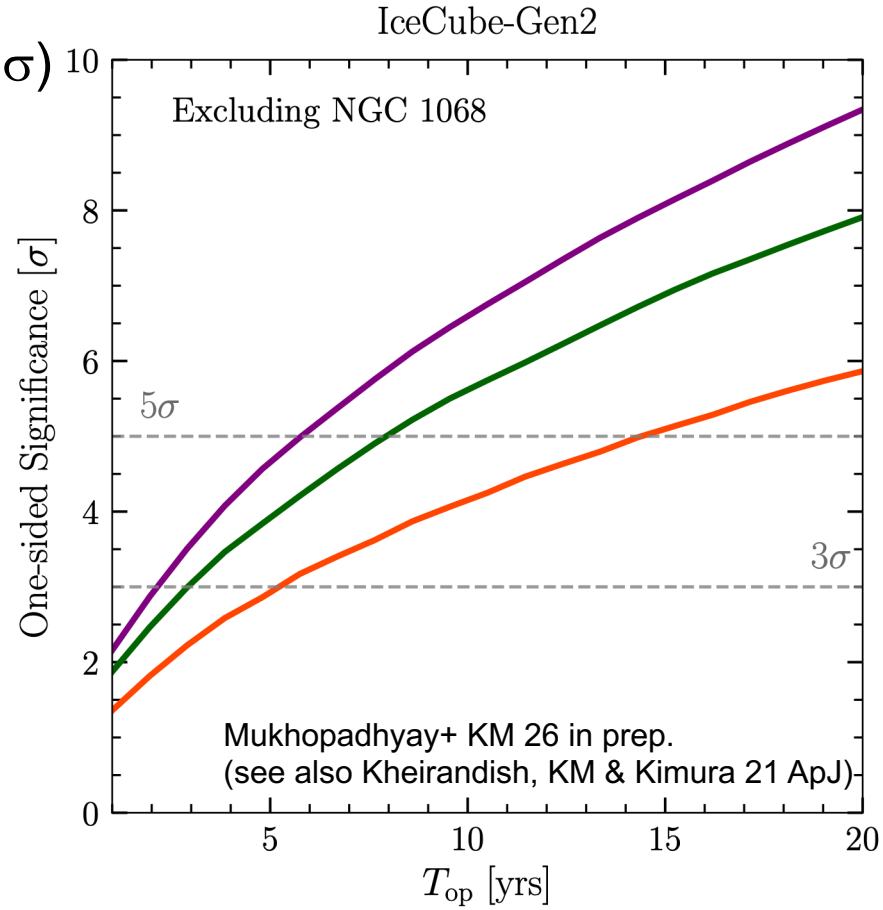


Carpio, Kheirandish & KM 26 ApJ (see also KM et al. 24 ApJL, Saurenhaus et al. 26 PRD)

Corona Model: Predictions and Hints

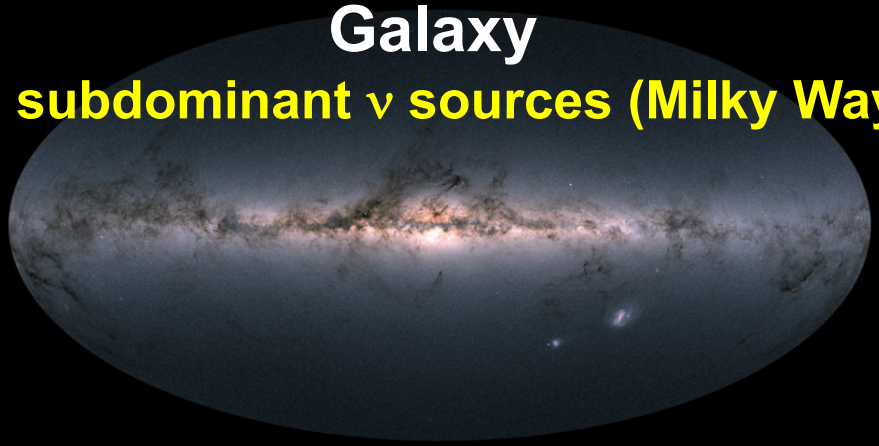
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  NGC 1068 (~4σ), NGC 4151 (~3σ),
  14 AGNs in the south incl. Circinus (~3σ)
- Population studies are important

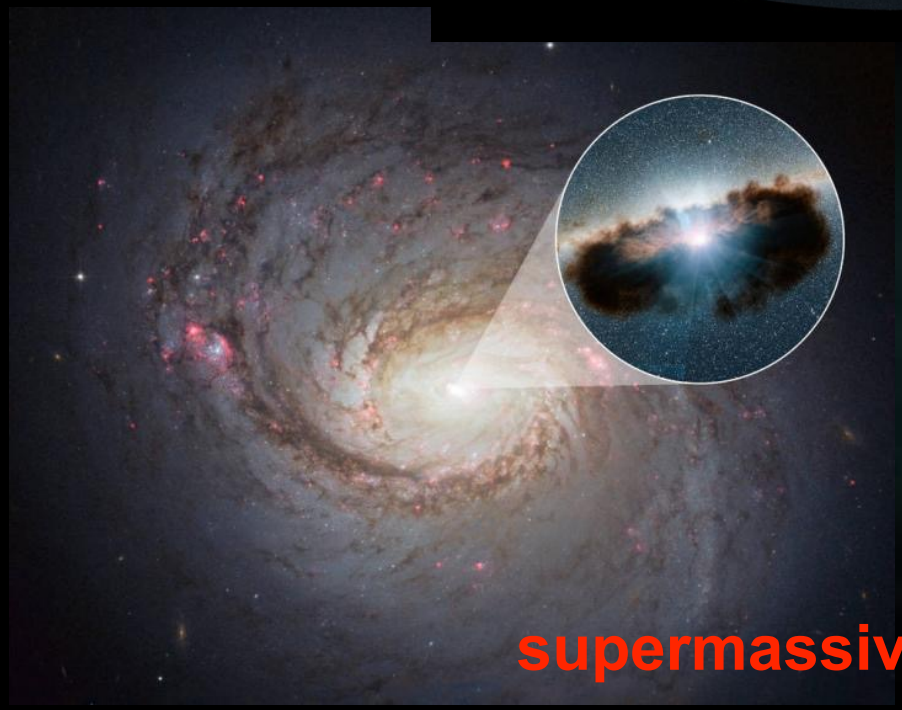




Galaxy

subdominant ν sources (Milky Way)







supermassive black holes

Jet-quiet AGN

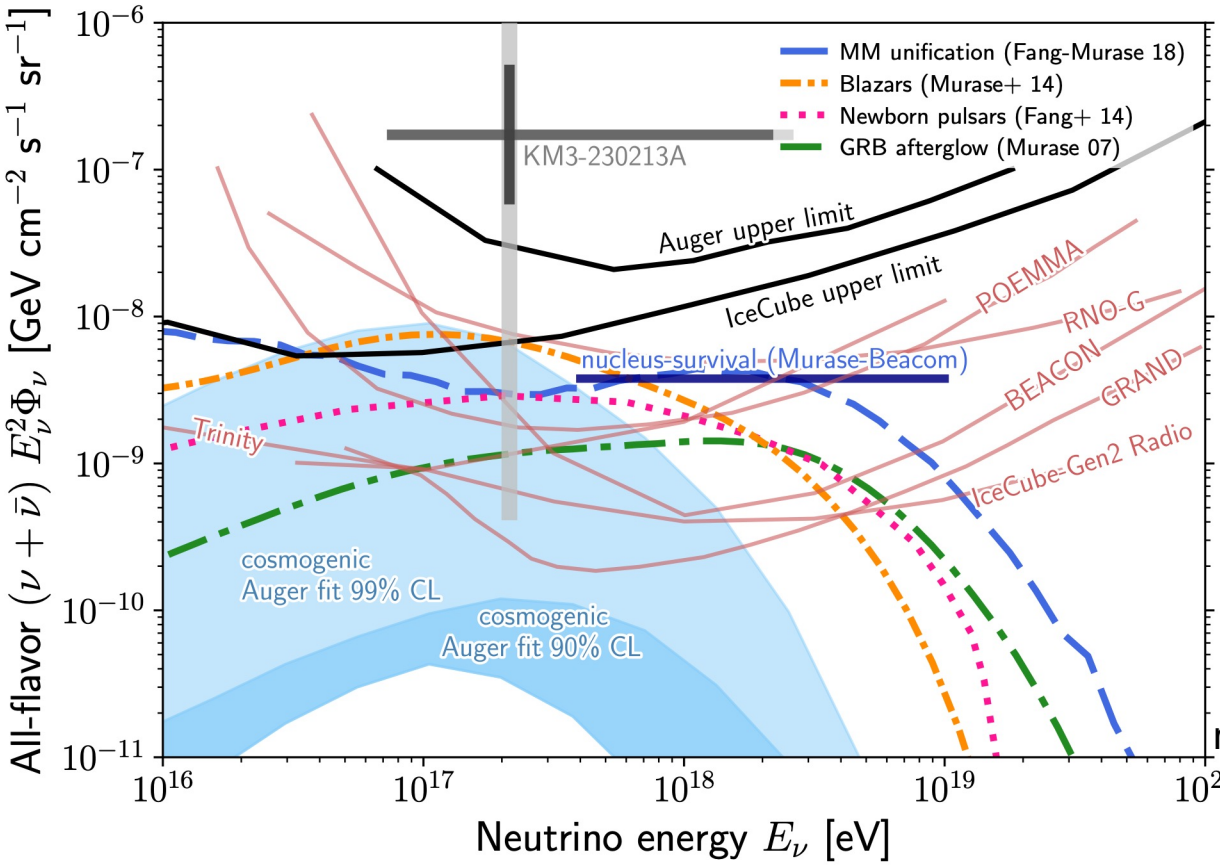
hidden ν sources
(NGC 1068…)

Jet-loud AGN

>100 TeV ν sources?
(TXS 0506+056?)

Hunting Extragalactic Cosmic-Ray Accelerators

UHECRs w. E/Z > $10^{18.5}$ eV → UHE ν w. E_ν >~ 100 PeV



Many models proposed in the past are consistent with KM3Net+IceCube:
$E^2\Phi_\nu$ <~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

modified from Kotera+ KM 26 JCAP

-Auger composition data: UHECRs are largely "nuclei"
nucleus survival (semi-transparency) → $E^2\Phi_\nu$ <~ 3x10^{-9} GeV cm^{-2} s^{-1} sr^{-1}
-CR reservoirs (connected to IceCube)? UHECR accelerators? Cosmogenic νs?

Summary

Multimessenger clues to the origins of high-energy ν sources

all-sky sub-TeV γ-ray flux ~ all-sky sub-PeV ν flux ~ all-sky UHECR flux

Galactic multimessenger connection → observed

- Supporting the hadronic origin of the Galactic diffuse γ-ray flux

Extragalactic multimessenger connection → hidden ν sources

- AGN (jet-quiet): promising as the major sources of the all-sky neutrino flux
- Associated AGNs: hidden ν sources

  NGC 1068 → 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 important

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. blazars/TDEs/supernovae)
- Some surprises…

Backup Slides

Since the Discovery of HE Cosmic Neutrinos…

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



from Murase's talk @ Neutrino 2014

Since the Discovery of HE Cosmic Neutrinos…

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



from Murase's talk @ Neutrino 2014

Since IPA 2015…

Implications remain unchanged but more progress on sources

Summary

What is the origin of cosmic ν signals?

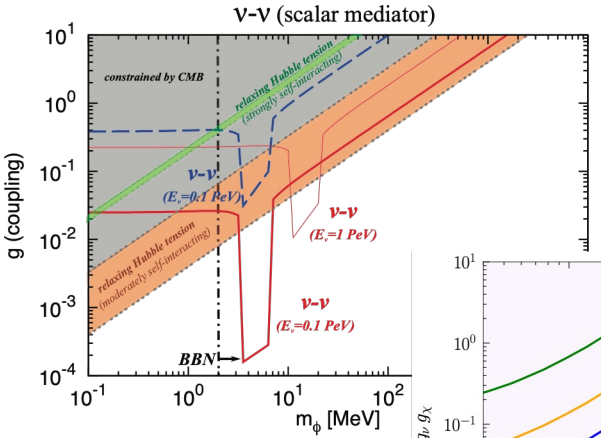
Implications:

mostly isotropic & diffuse TeV-PeV γ-ray limits → extragalactic
pp scenarios: s<2.2 & >30% to the diffuse sub-TeV γ-ray bkg.
s~2.5 → another component below ~100 TeV?
pγ scenarios: not explained by classical GRBs & blazars
→ hidden sources (ex. low-power GRBs/AGN)?

Requests for future:

IceCube-Gen2: $n_0 > 10^{-5}$ Mpc^{-3}, testing CR reservoirs & PeV DM
Fermi: ~2-3 improvements can rule out or support pp scenarios & PeV DM
CTA: CR reservoirs as s<2.2 γ-ray sources, DM emission from galaxy clusters
HAWC/air-shower arrays: γ-ray counterparts if significant Galactic contributions
Importance of theories: "multi-messenger" approach (ex. AMON)
especially for pγ scenarios (ex. low-power GRBs w. hard X-ray sky monitors)

Probing New Physics with Identified ν "Sources"



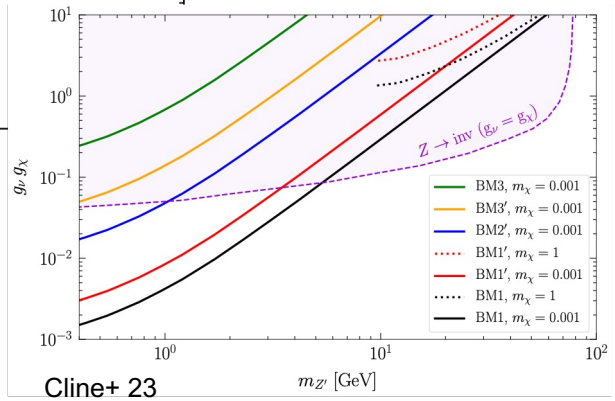
KM & Shoemaker 19

nonstandard ν interactions

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

pseudo-Dirac ν

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

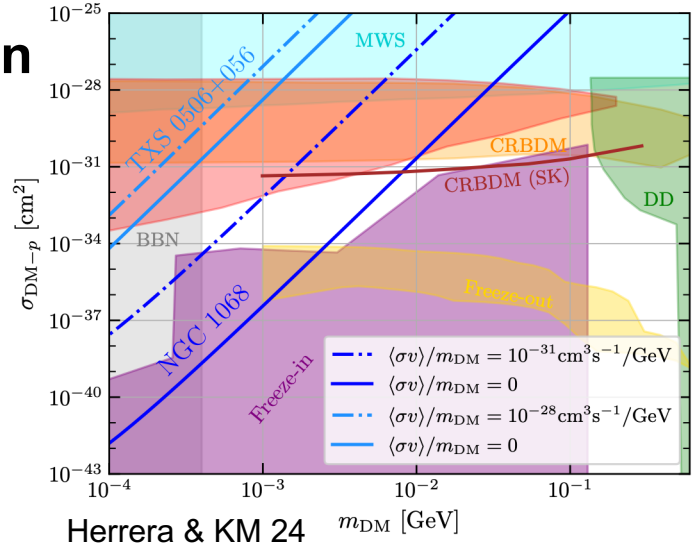


Cline+ 23

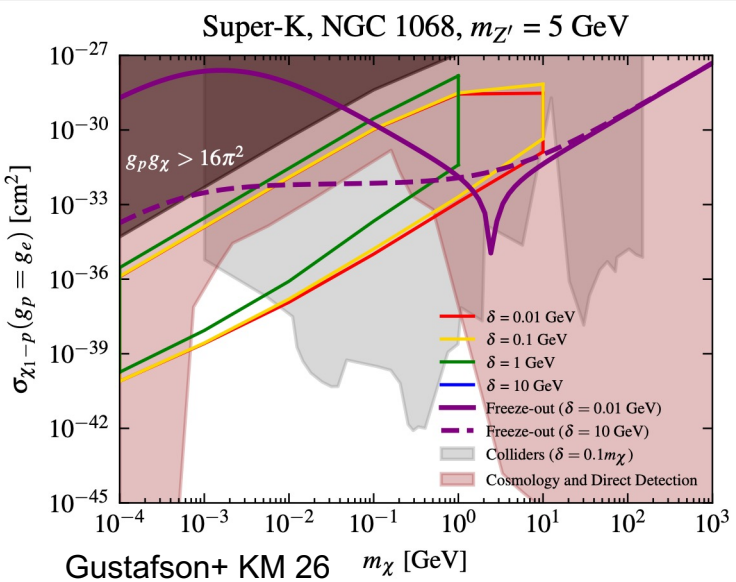
CR-DM interaction

- CR cooling by BSM
- CR-boosted DM

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



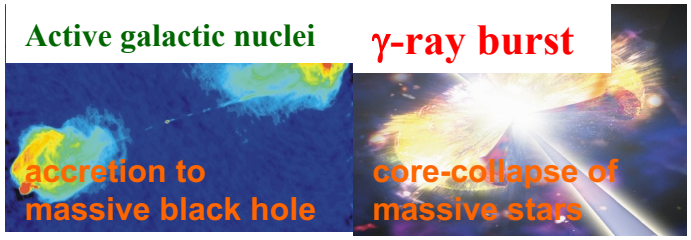
Herrera & KM 24



Gustafson+ KM 26

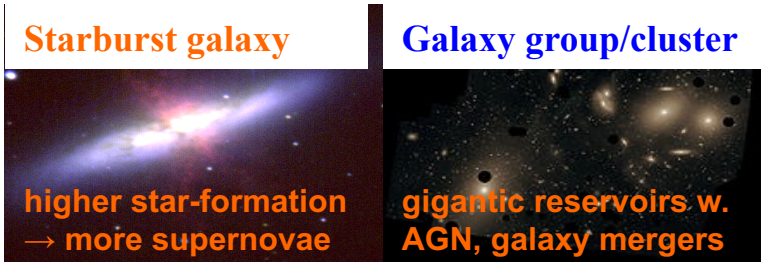
Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators
(ex. UHECR candidate sources)

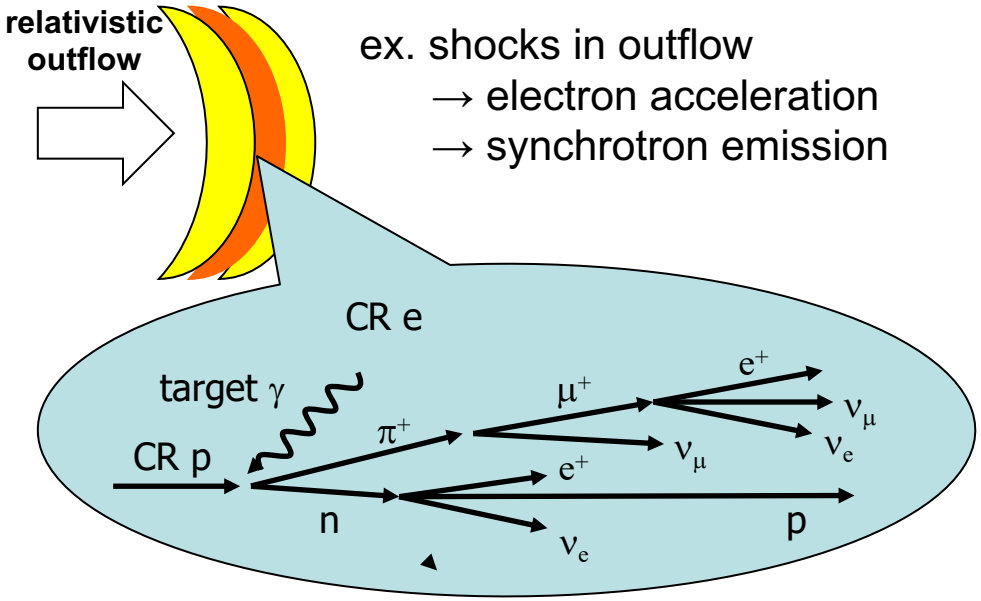


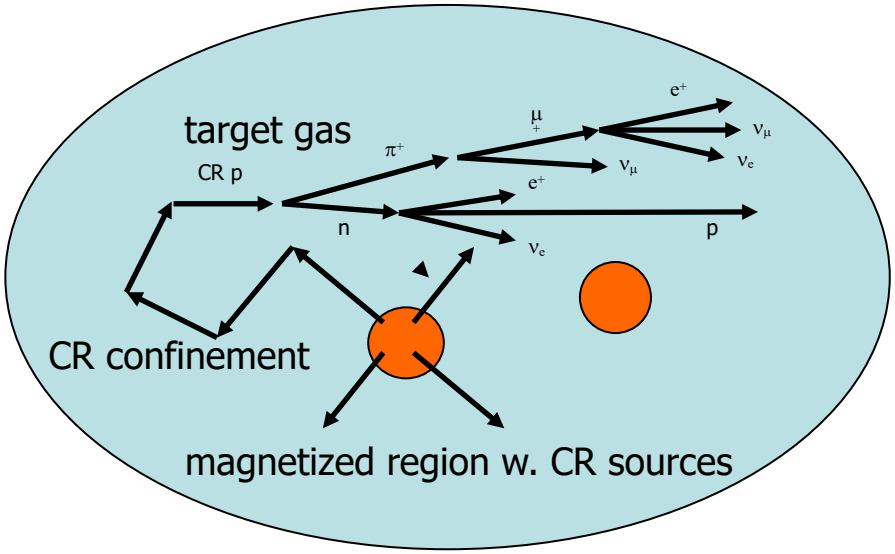
$$p + \gamma \rightarrow N\pi + X$$

Cosmic-ray Reservoirs



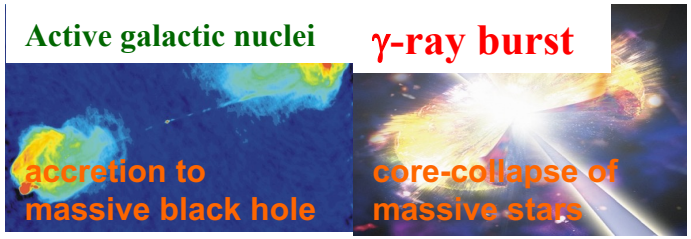
$$p + p \rightarrow N\pi + X$$



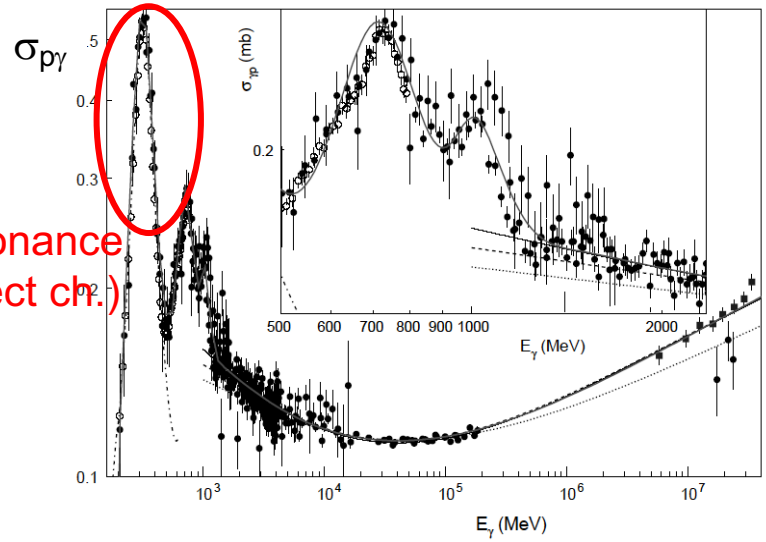


Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators
(ex. UHECR candidate sources)



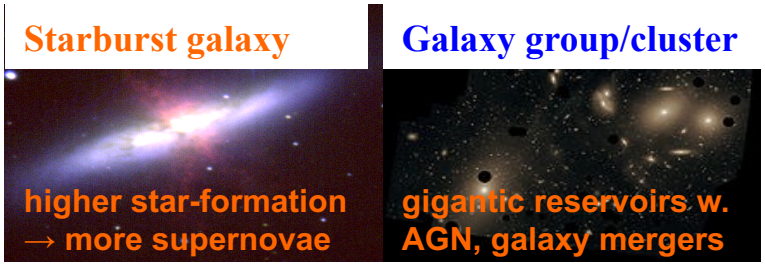
$$p + \gamma \rightarrow N\pi + X$$



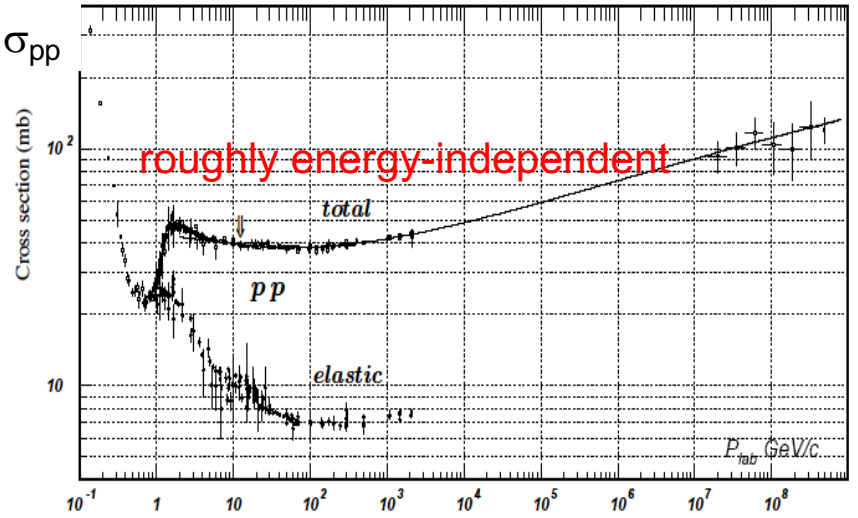
$$\sigma_{p\gamma} \sim \alpha\sigma_{pp} \sim 0.5 \text{ mb}$$

$$\varepsilon'_p \varepsilon'_\gamma \sim (0.34 \text{ GeV})(m_p/2) \sim 0.16 \text{ GeV}^2$$

Cosmic-ray Reservoirs



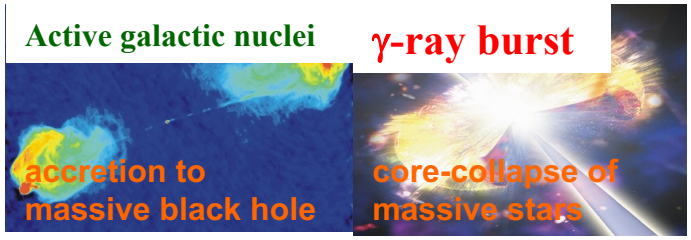
$$p + p \rightarrow N\pi + X$$



$$\sigma_{pp} \sim 1/m_\pi^2 \sim 30 \text{ mb}$$

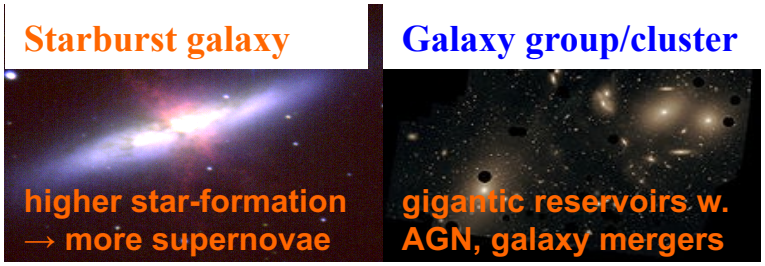
Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators
(ex. UHECR candidate sources)

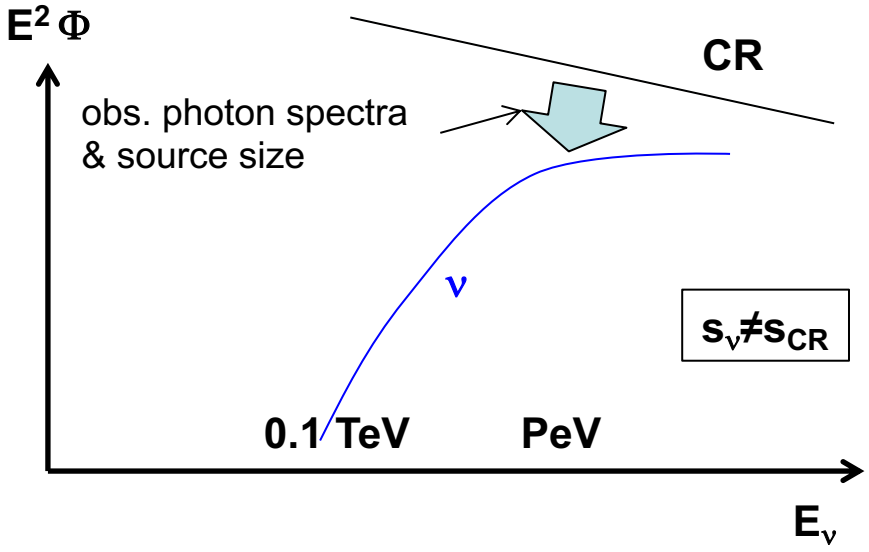


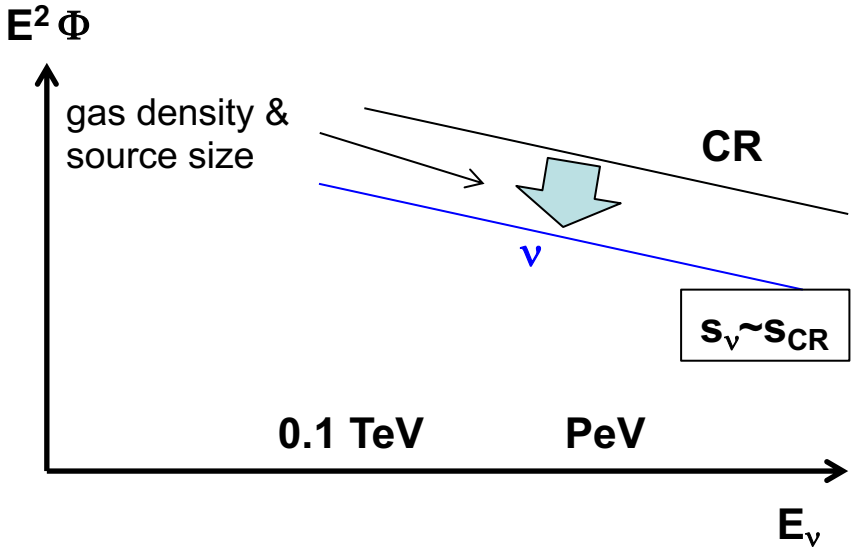
$$p + \gamma \rightarrow N\pi + X$$

Cosmic-ray Reservoirs



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





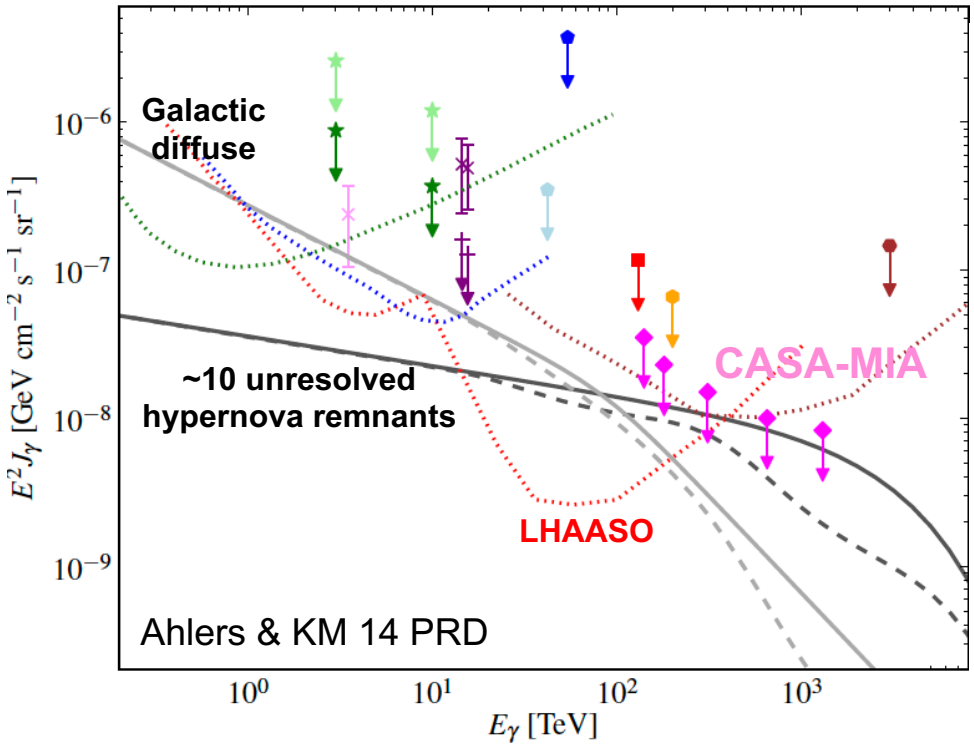
$E_\nu \sim 0.04\ E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Importance of Multimessenger Connection – Milky Way Case

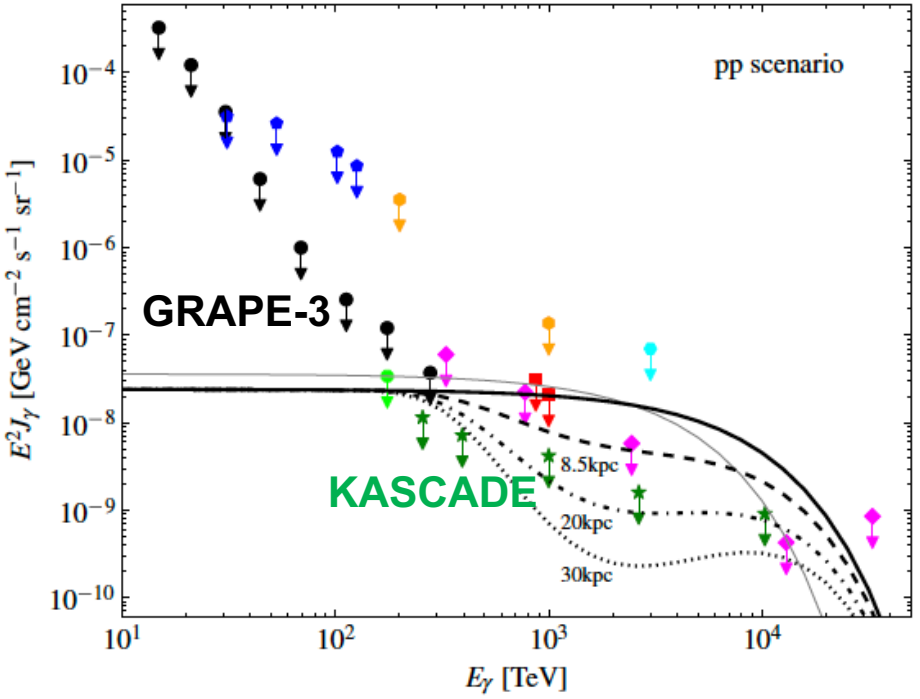
A decade ago, neither γ rays NOR νs were observed in the sub-PeV range.
(Note that most γ rays from Galactic sources reach Earth.)
But we already learned that Galactic contribution to IceCube νs is subdominant.

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

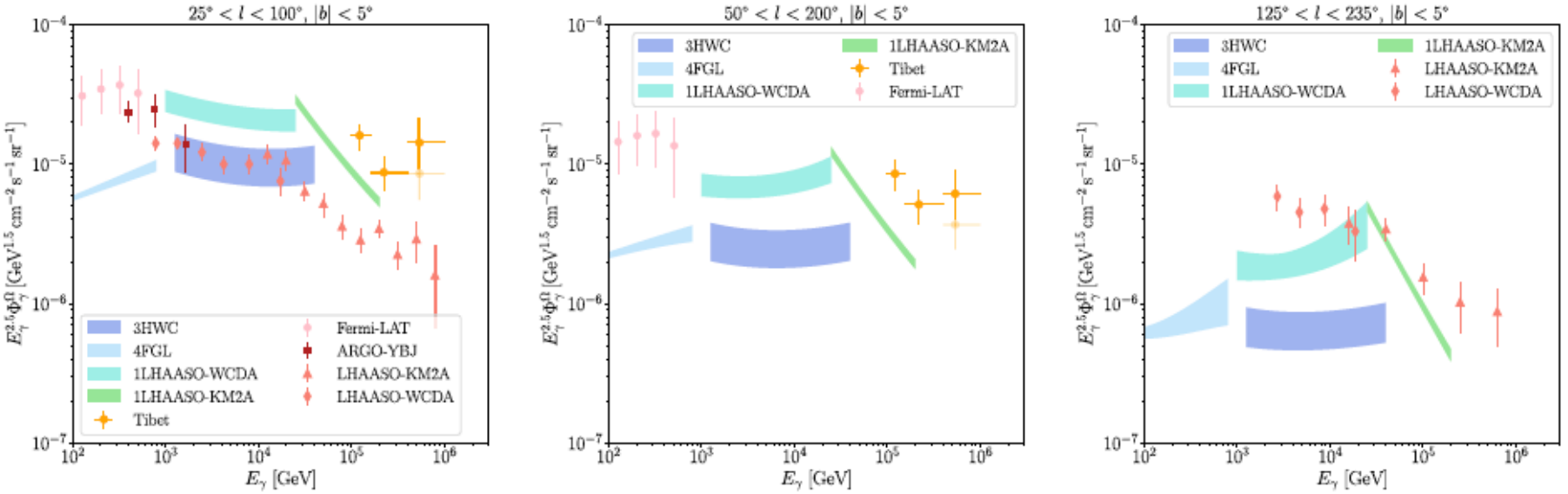
Galactic Plane $|b| < 2°$

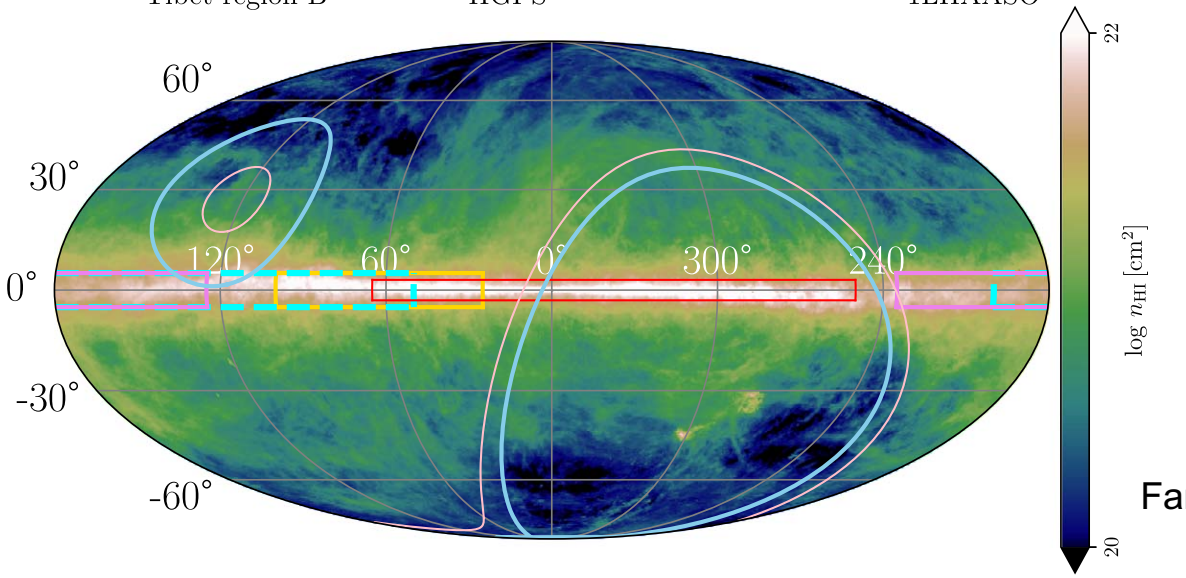


Galactic Halo (quasi-isotropic)



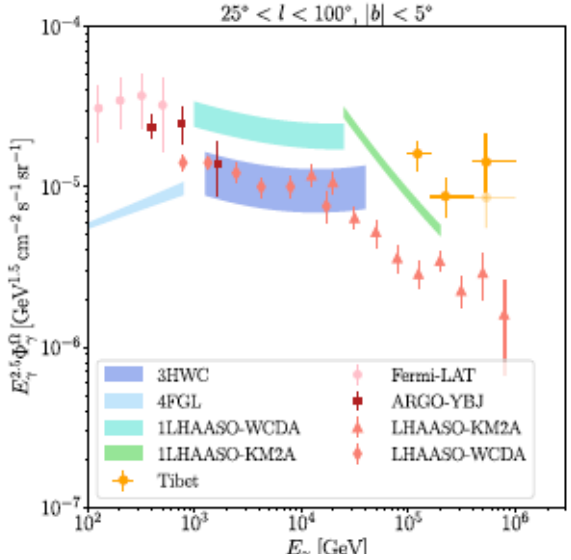
Importance of Improved Measurements

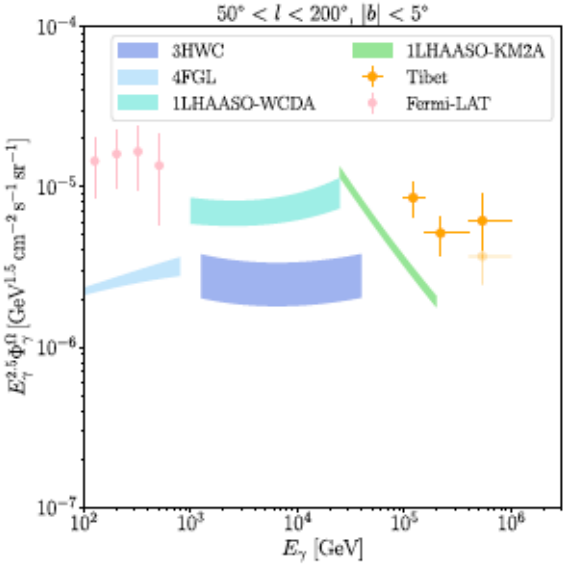


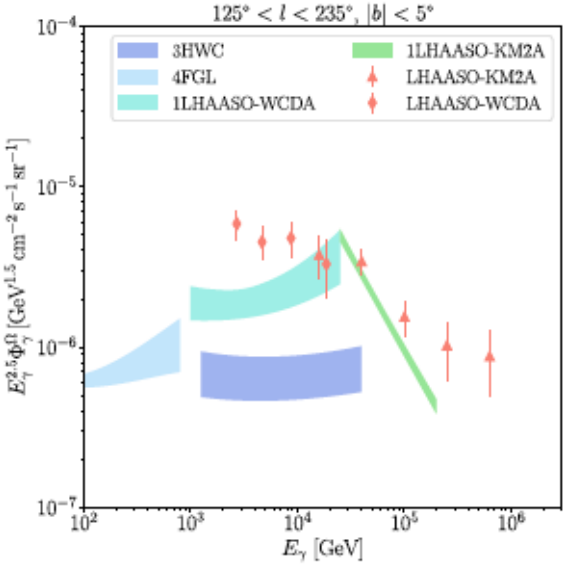


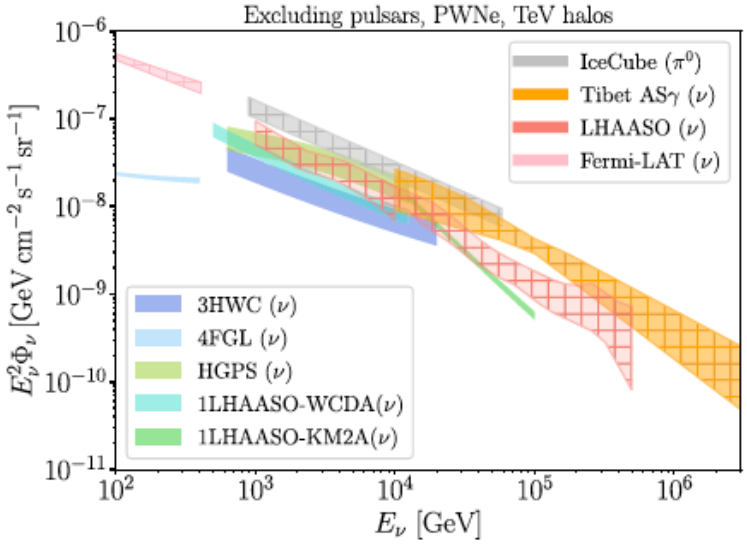
Fang & KM 23 ApJL

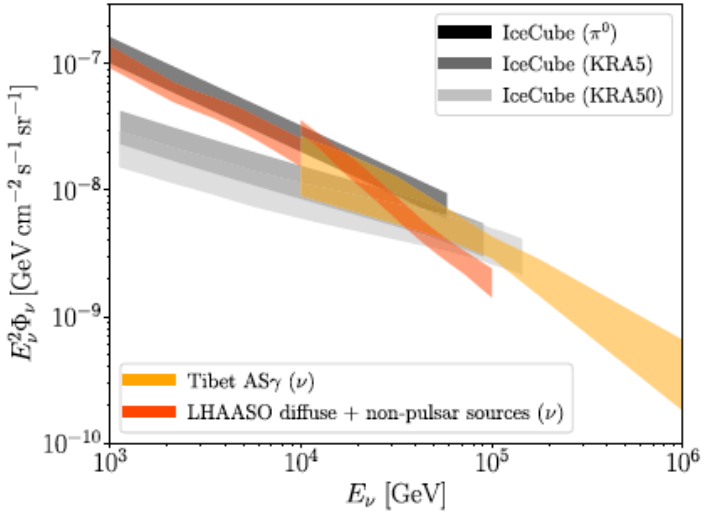
Importance of Improved Measurements







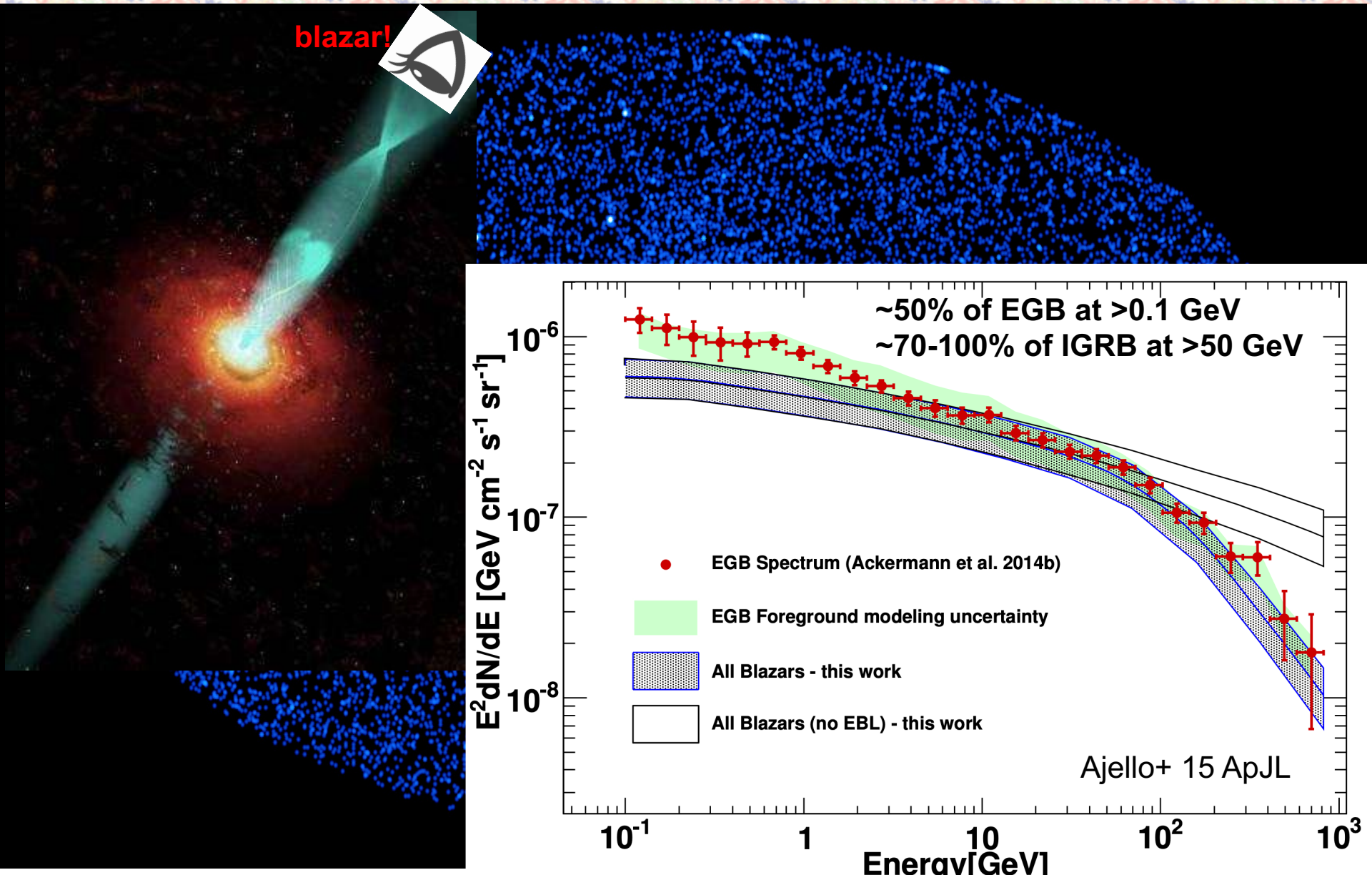




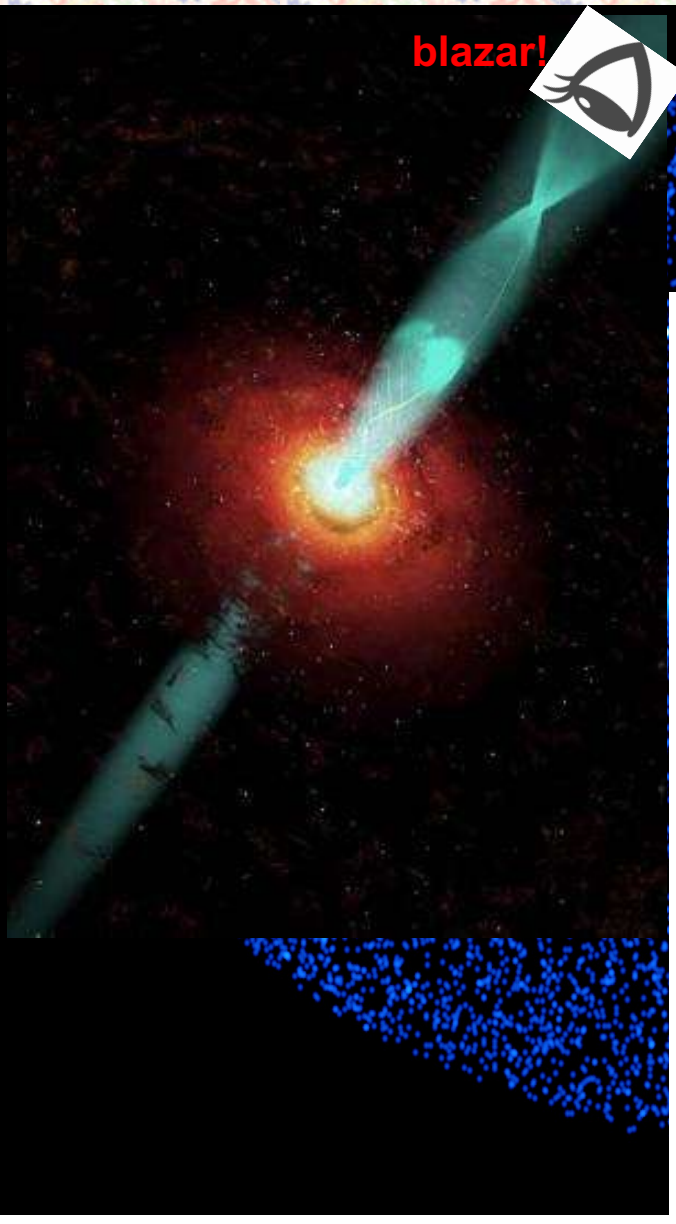
Fang & KM 23 ApJL

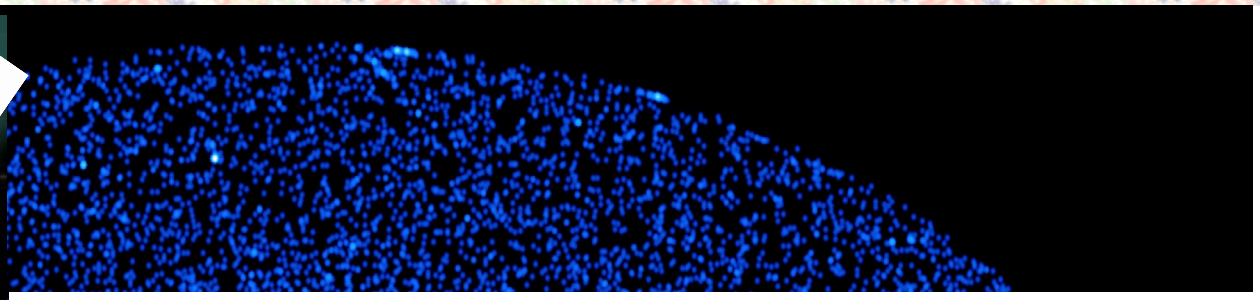
Sources may significantly contribute to the Tibet data in the inner region (see also Kato+ 24 ApJL).
Unresolved sources at >100 TeV? “Resolved” sources could also contribute to the IceCube data.

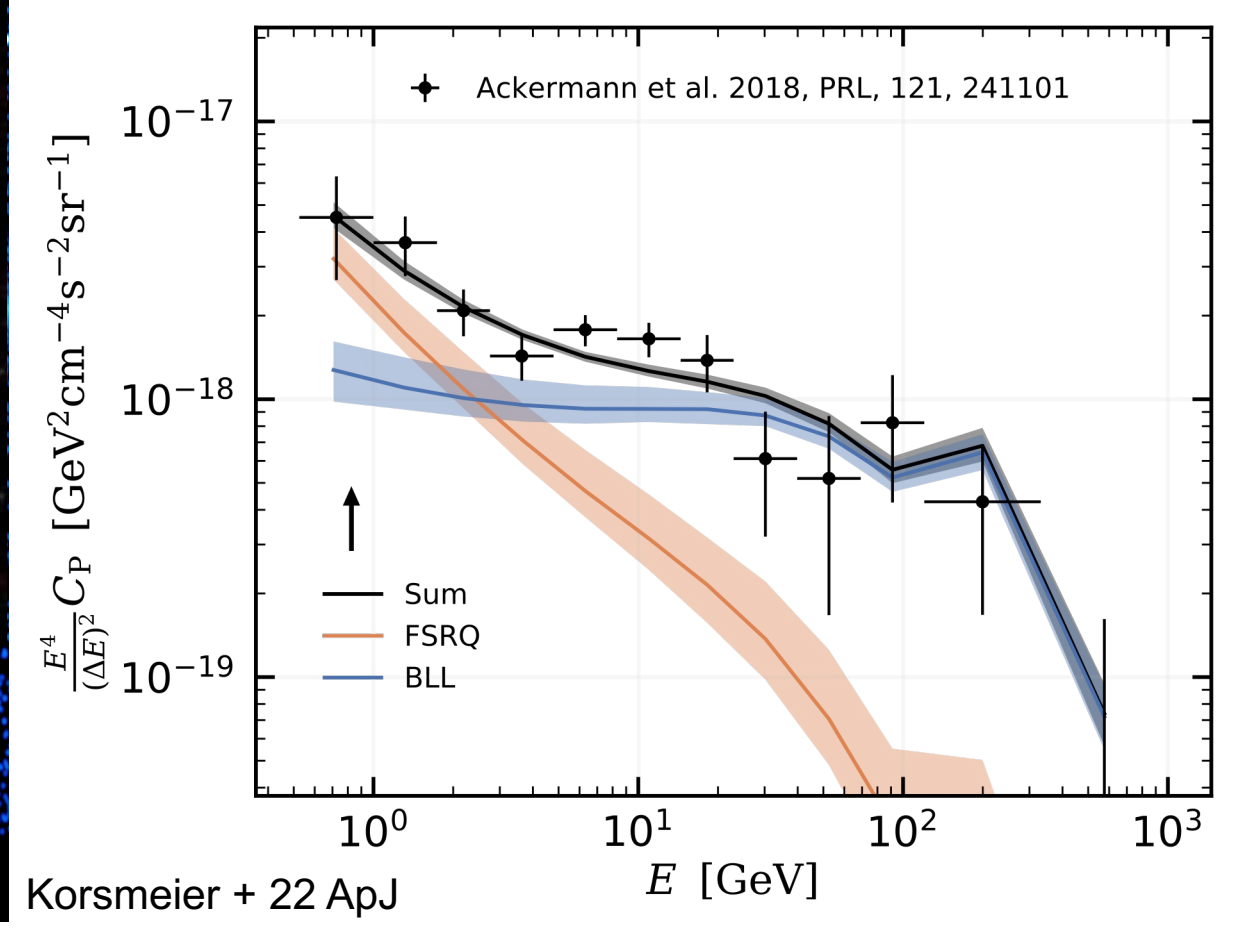
Extragalactic γ-Ray Sky: Dominated by On-Axis Jetted AGN



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

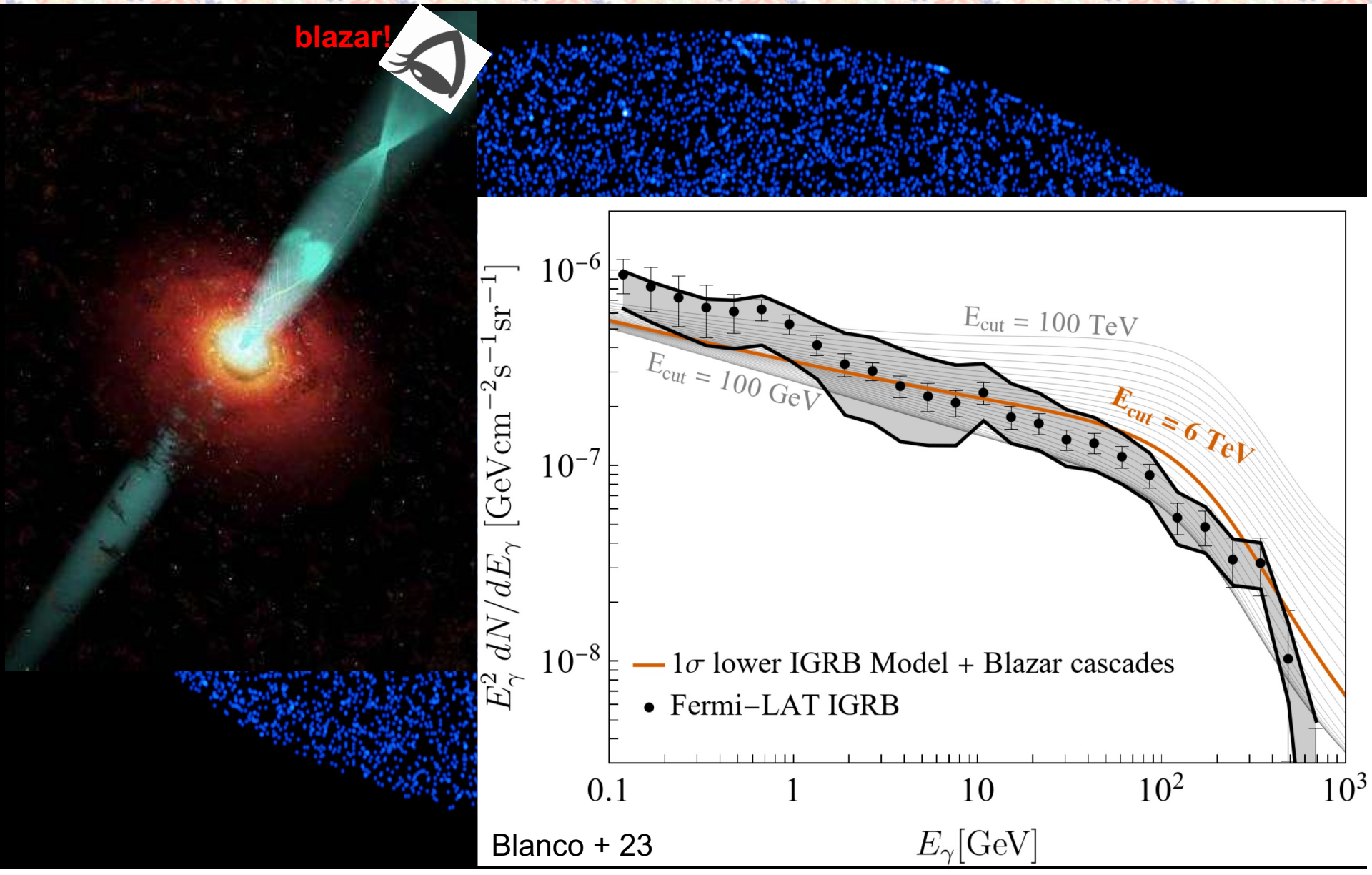






Korsmeier + 22 ApJ

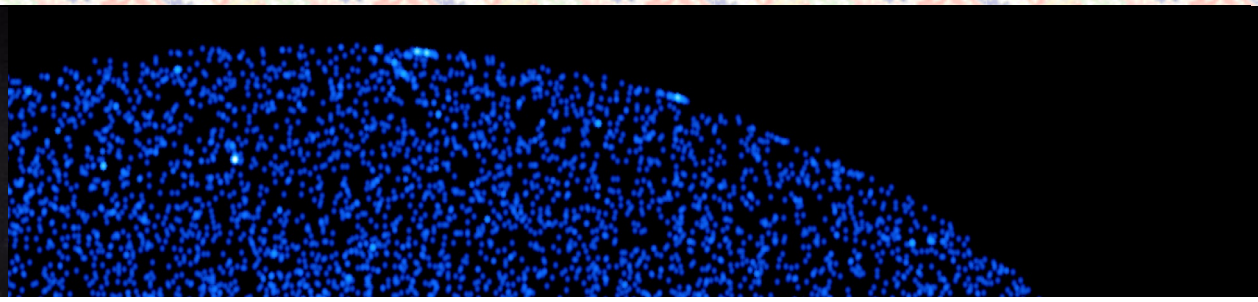
Extragalactic γ-Ray Sky: Dominated by On-Axis Jetted AGN

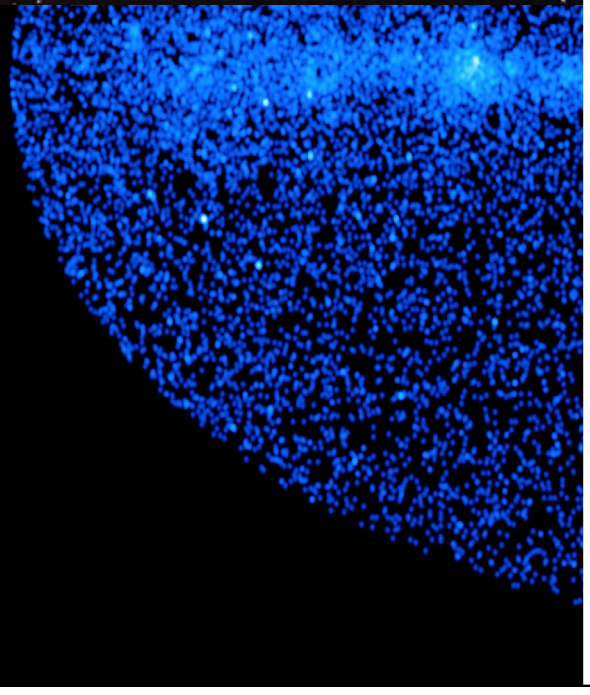


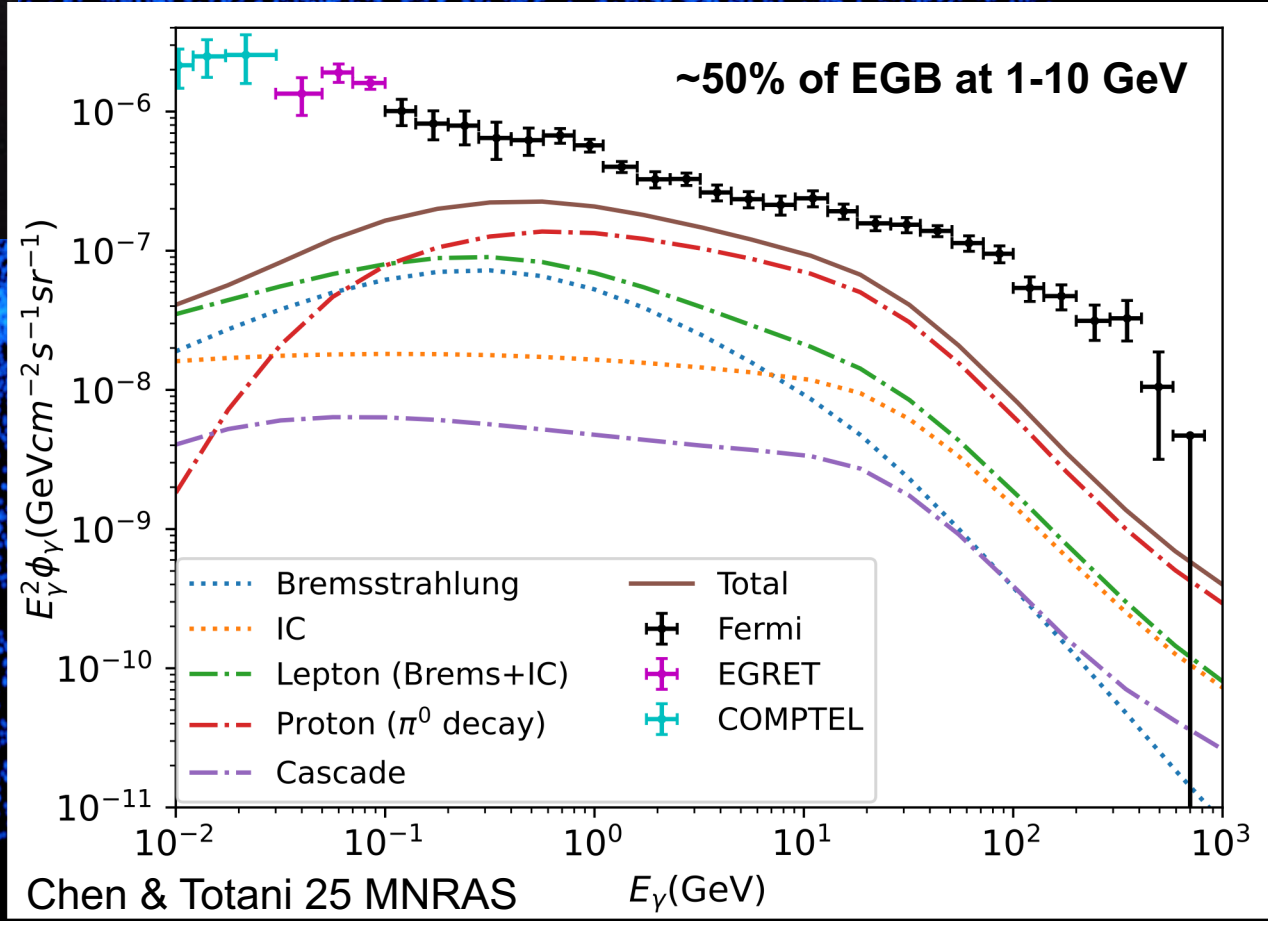
Blanco + 23

Extragalactic γ-Ray Sky: Star-Forming Galaxies at GeV



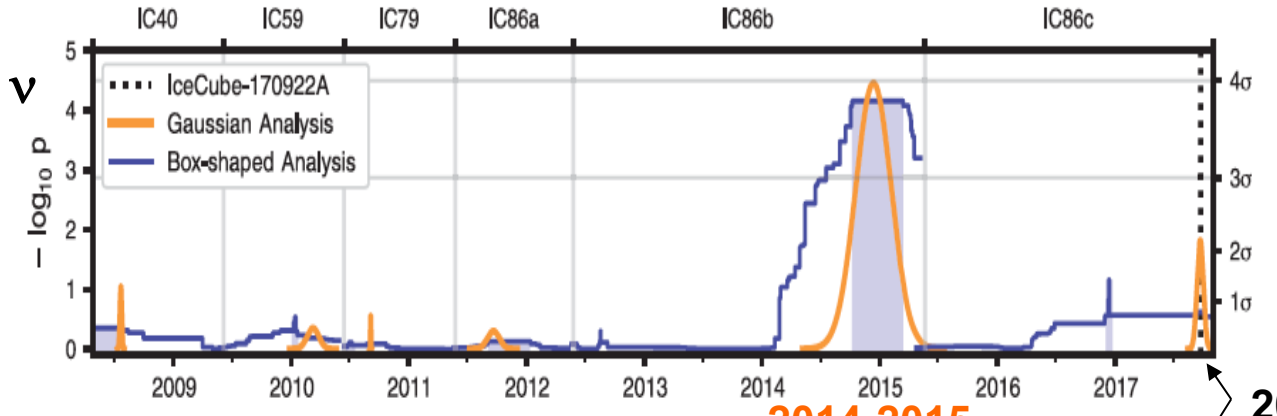






2017: Hints of Neutrinos from On-Axis Jetted AGN?

IceCube 2018 Science

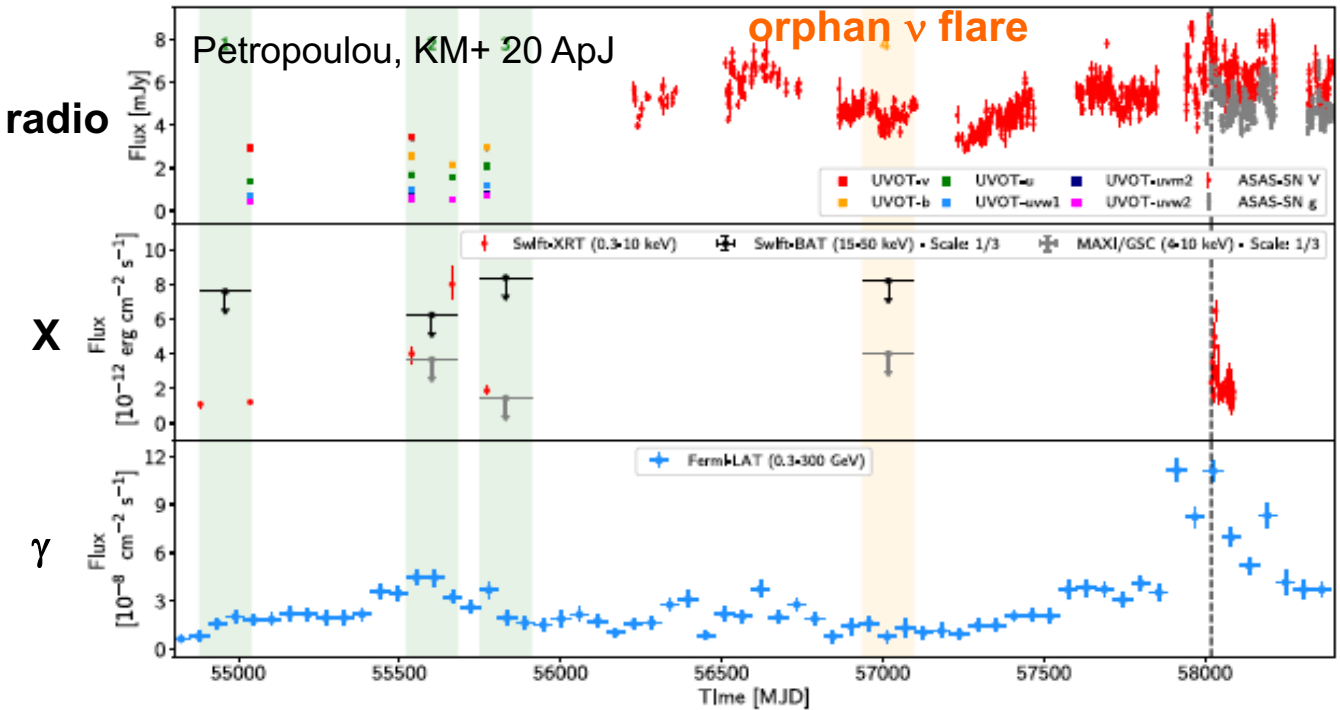


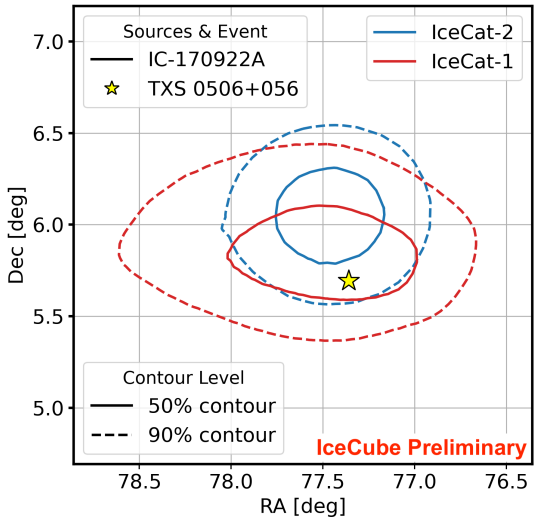
TXS 0506+056
"blazar"

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

2017 multimessenger flare

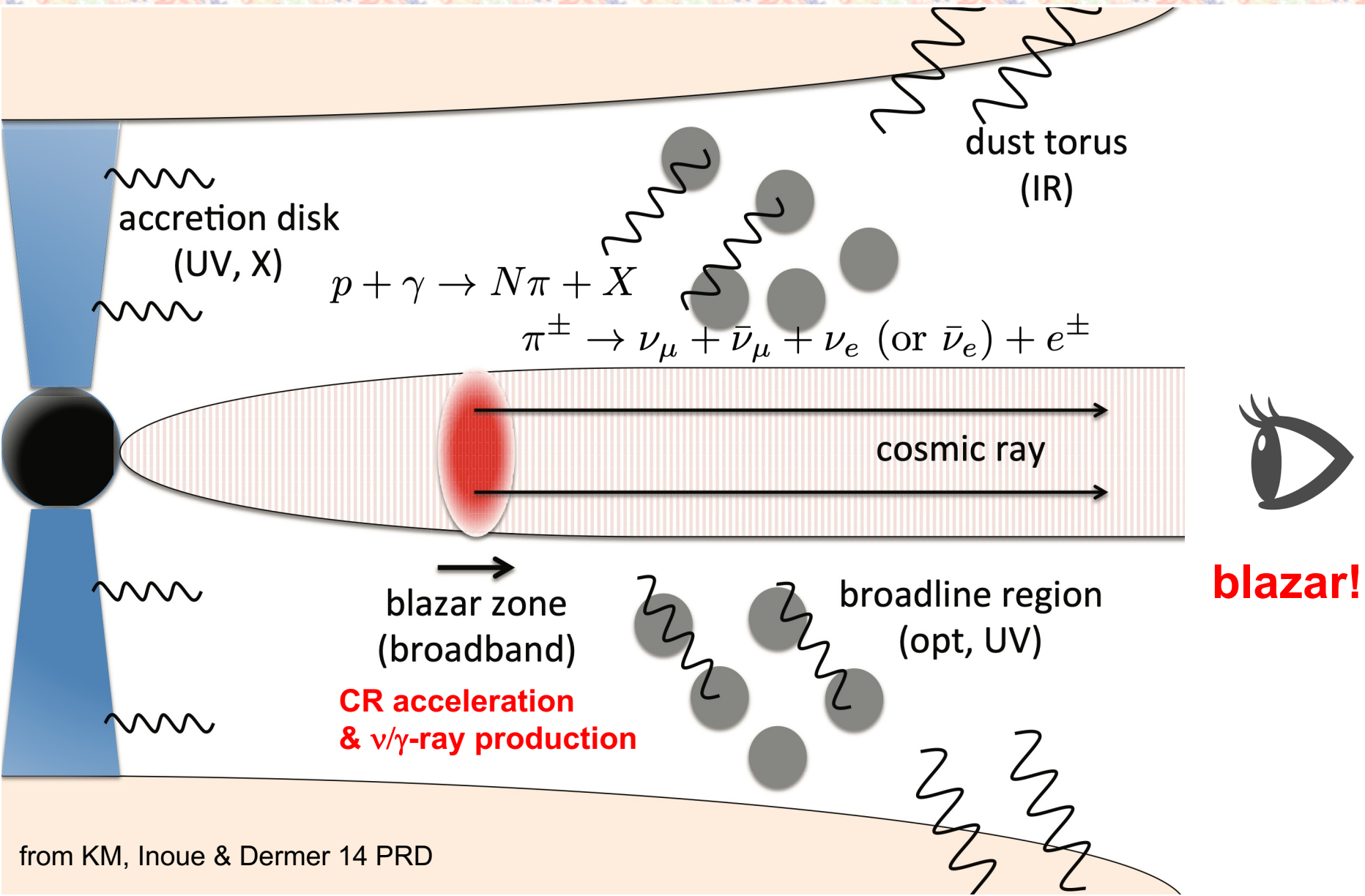
2014-2015
orphan ν flare





IceCube 25 ICRC

Neutrino Production in AGN Jets



blazar!

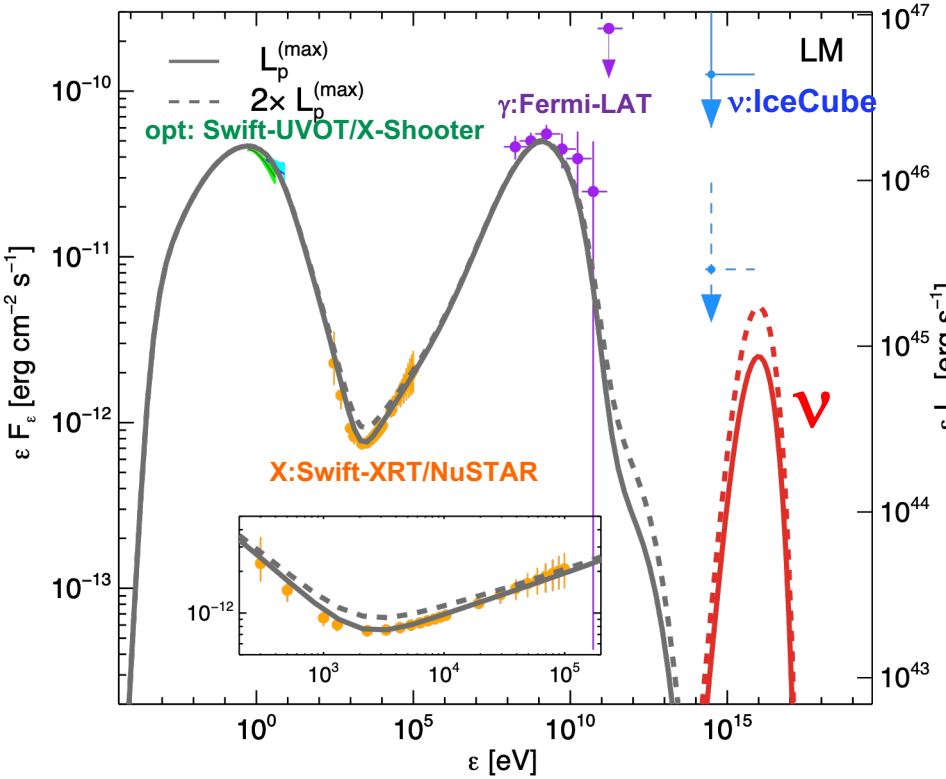
from KM, Inoue & Dermer 14 PRD

"Power" of Multimessenger Approaches

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

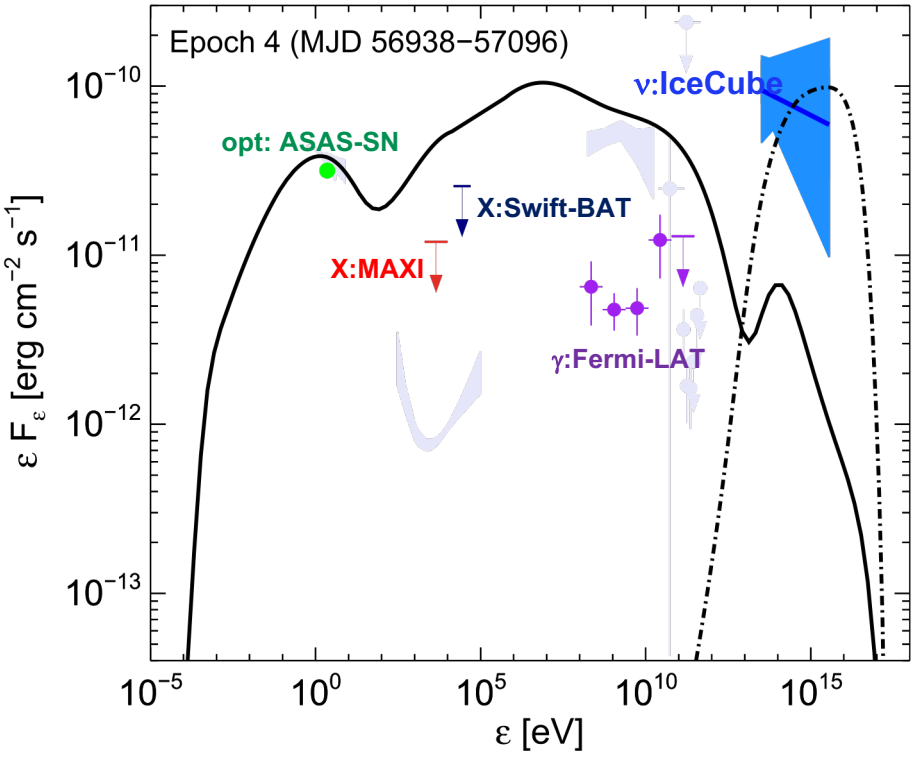
2017 multi-messenger flare

Keivani, KM, Petropoulou Fox et al. 18 ApJ



2014-2015 neutrino flare

Petropoulou, KM et al. 20 ApJ

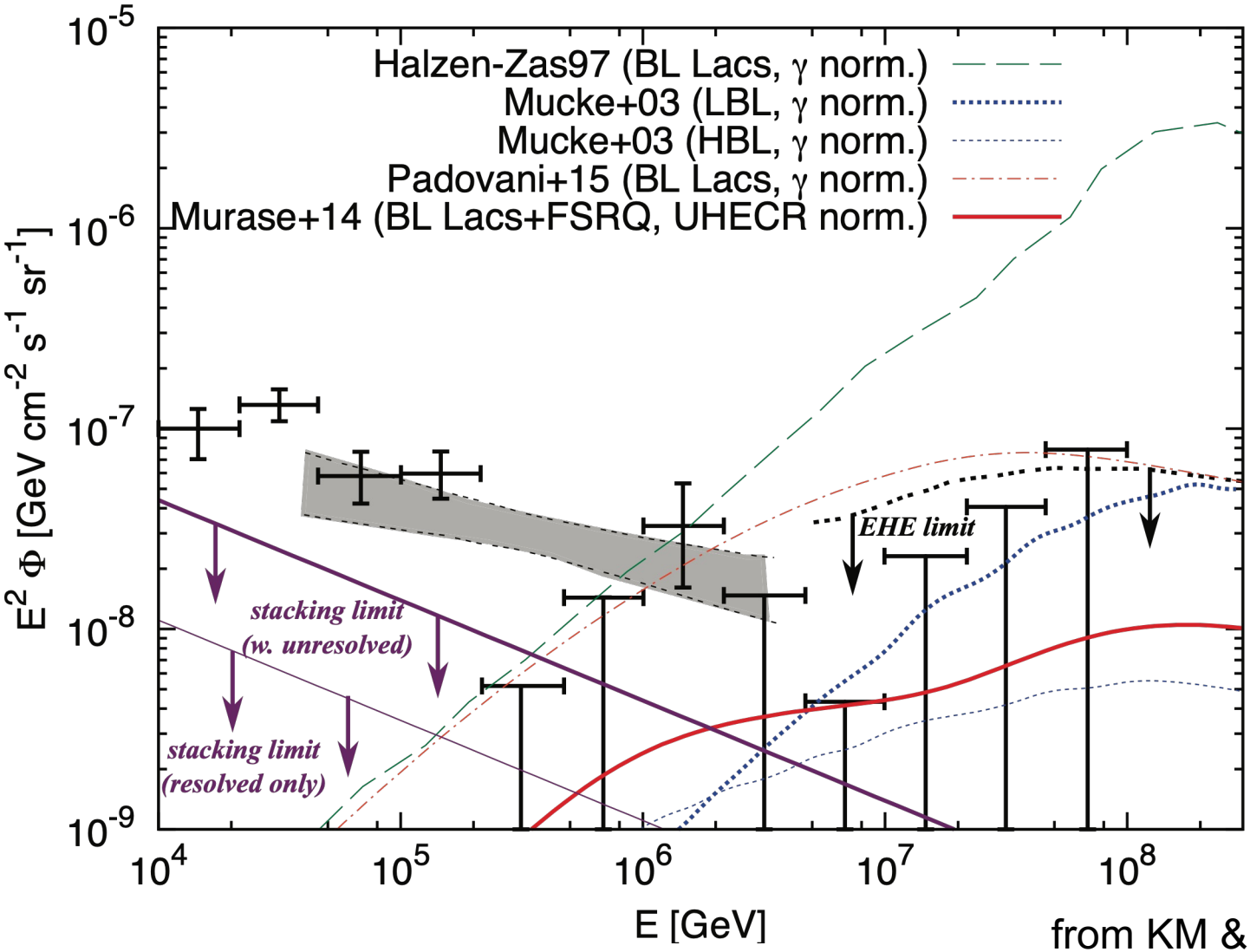


$F_{\nu theory} \sim F_{EMtheory} < F_{EMobs} < F_{\nu obs}$

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



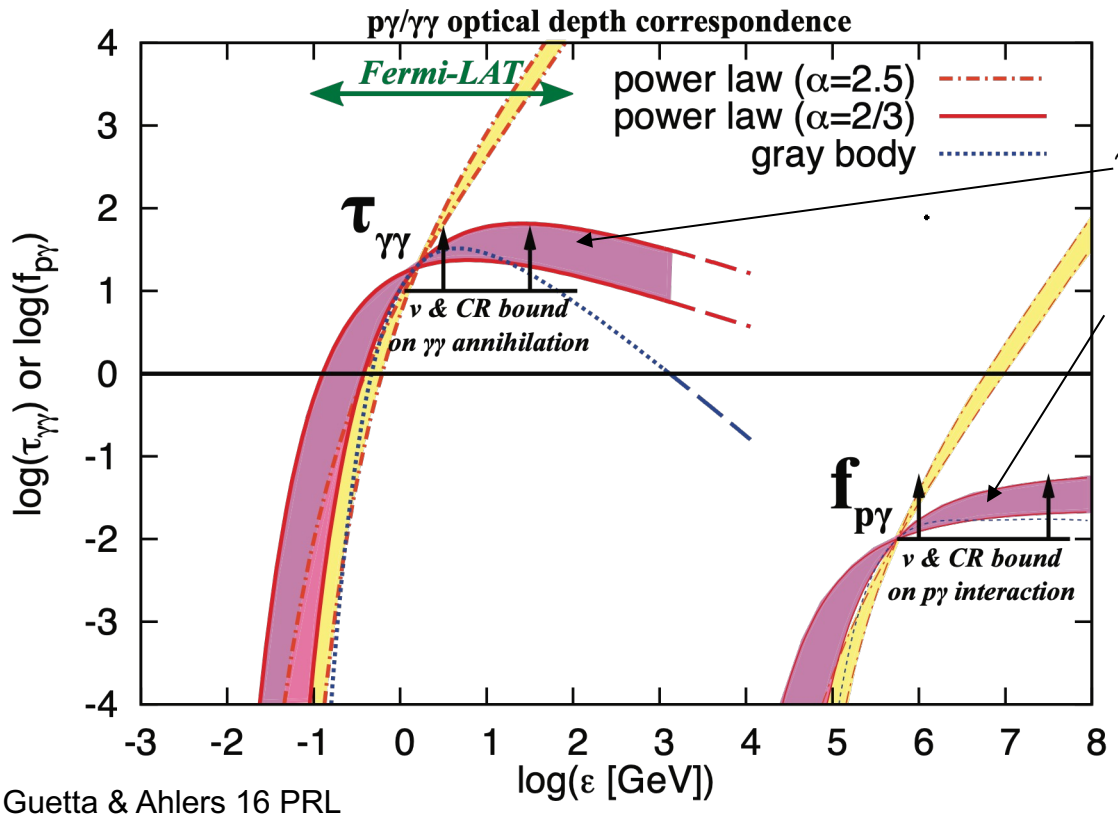
from KM & Stecker 23

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

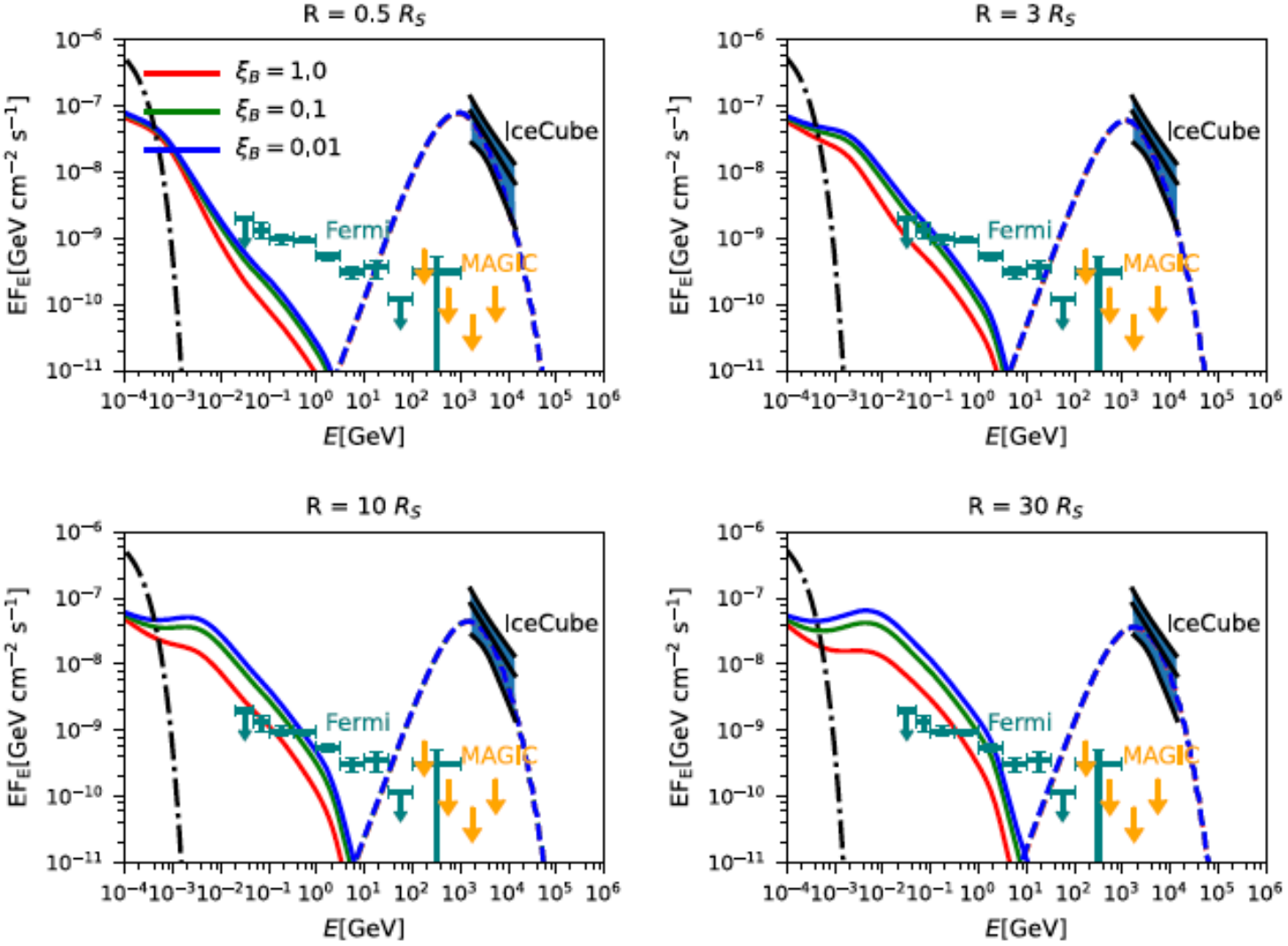
$p + \gamma \rightarrow N\pi + X$

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

KM, Guetta & Ahlers 16 PRL

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)

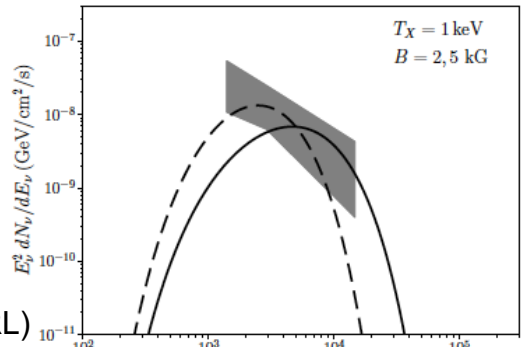


magnetization $\xi_B = U_B/U_{ph}$ (cf. corona model: $\xi_B \sim 1$, shock model: $\xi_B <\sim 0.01$)

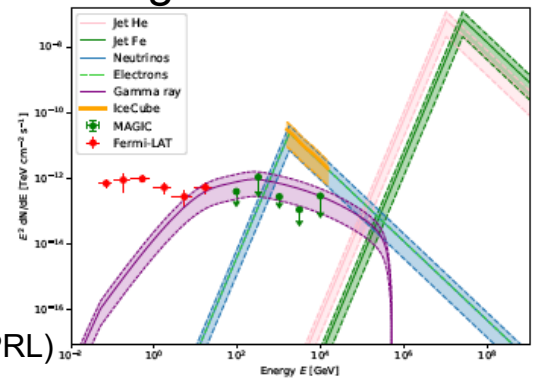
Neutrino Production Mechanisms: pp & pγ

- 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

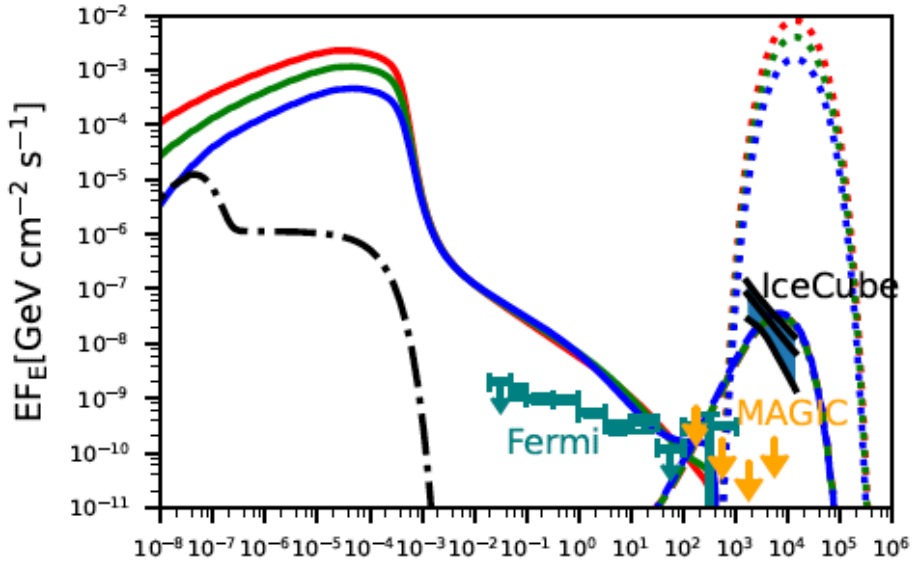
Neutrinos from $\gamma\gamma \rightarrow \mu^+\mu^-$ (Hooper & Plant 23 PRL)



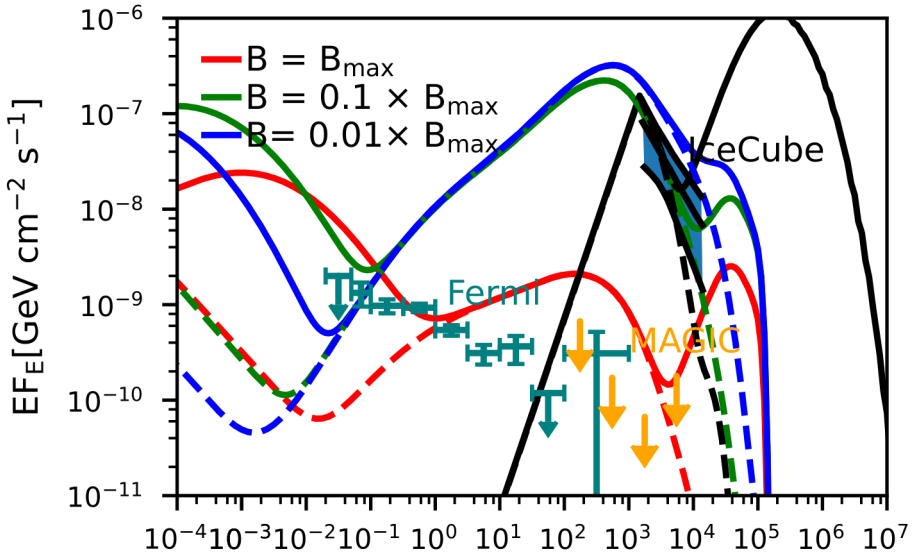
Neutrons from photodisintegration (Yasuda, Inoue & Kusenko 25 PRL)



R = 10 R_S



R = 10^8 R_S



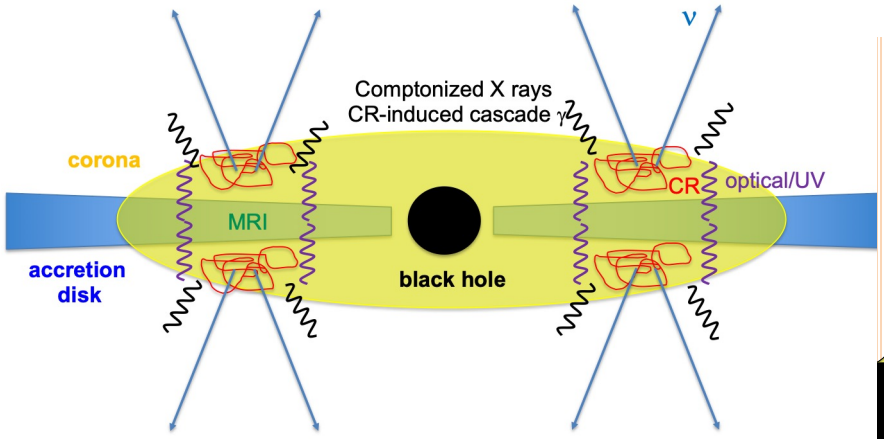
Das, Zhang & KM 24 ApJ, Das, KM & Zhang 26

Neutrino Production Models

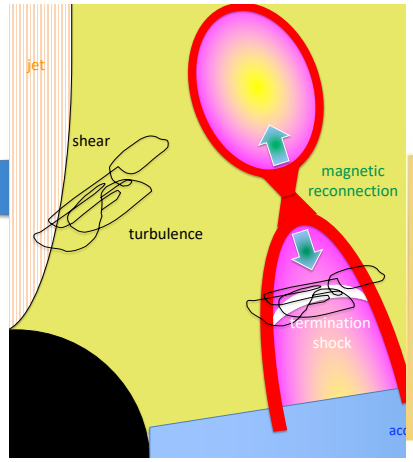
$$p+\gamma \rightarrow N\pi+X$$

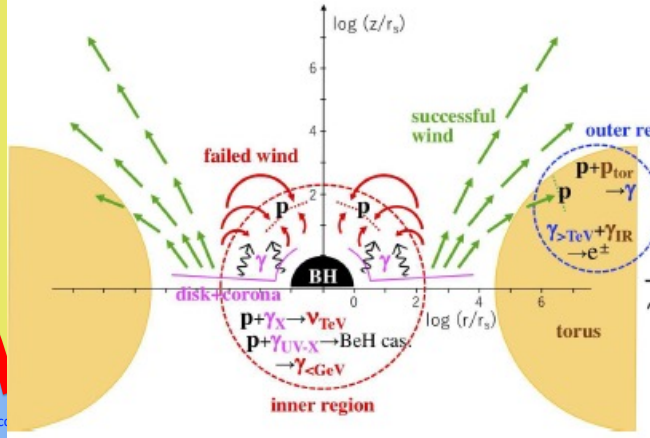
$$p+p \rightarrow N\pi+X$$

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



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





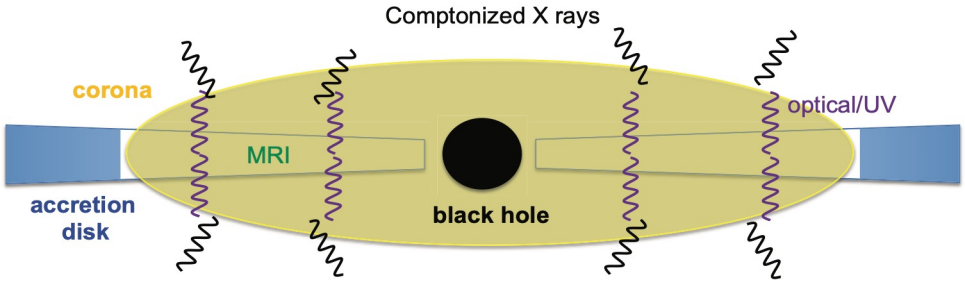
turbulence
magnetic reconnection

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

shocks

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

Coronal Regions: Births and Deaths of Cosmic Rays

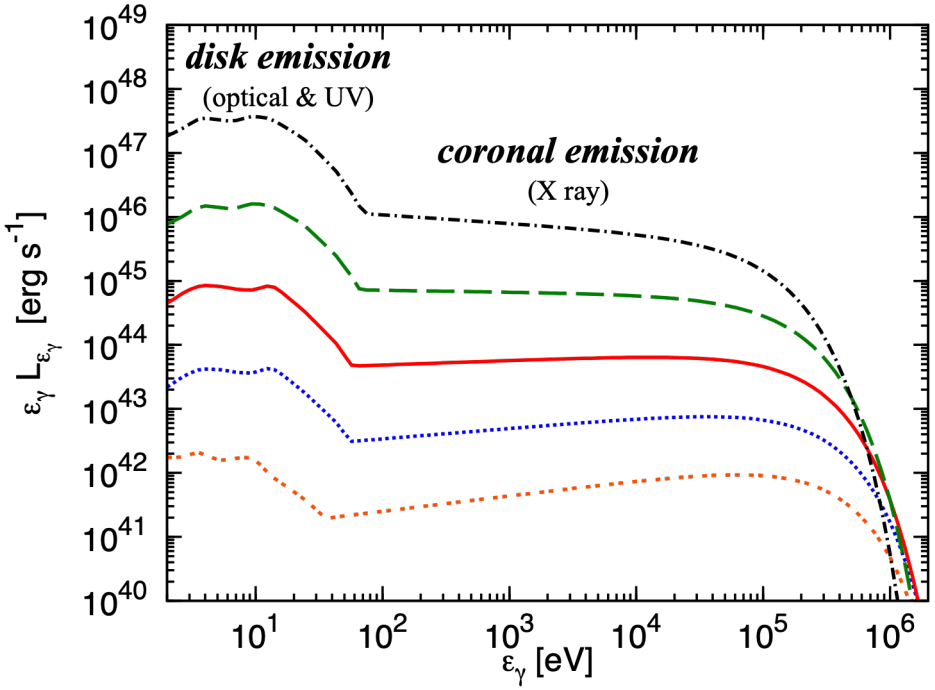


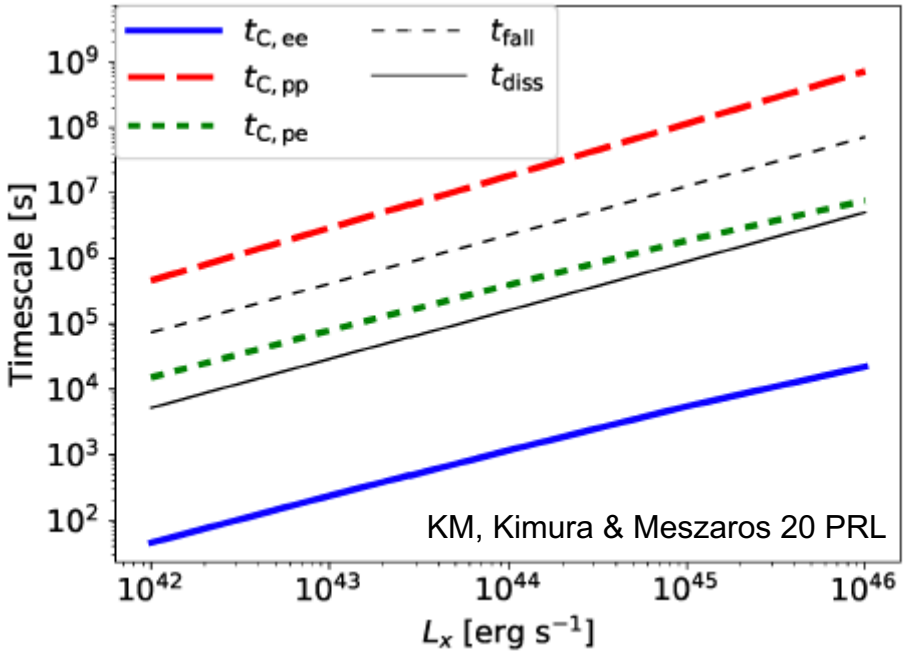
$T_p \sim T_{vir} \sim 10^{11}$-$10^{12}$ K @ R~10 R_S

$\beta = P_g/P_B < 0.1$-1 ($\sigma_p >\sim 0.01$)

$\rightarrow$ B > 10^3 G

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



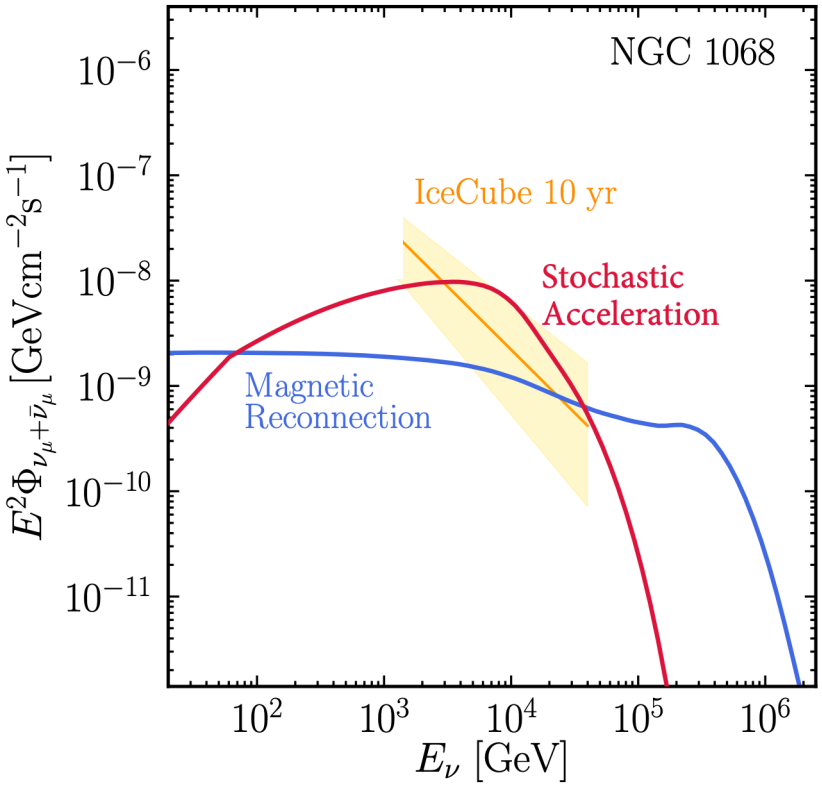


effective optical depth: both **f_{pp} & $f_{p\gamma}$ > 1**
("nearly calorimetric")

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

Neutrinos Can Probe Particle Acceleration in Coronae

Kheirandish, KM & Kimura 21 ApJ

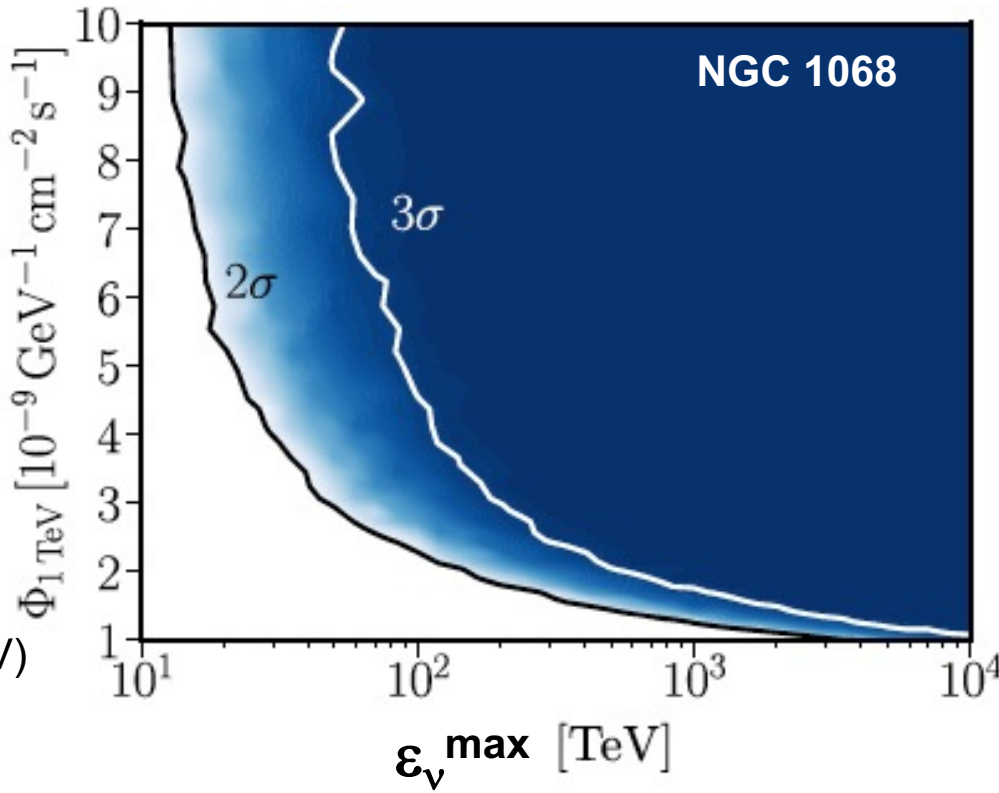


$E_\nu^2\Phi_{\nu\mu}$ ~ 10^{-8} GeV cm^{-2} s^{-1} @ 1 TeV

constraints for an E_ν^{-2} spectrum

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

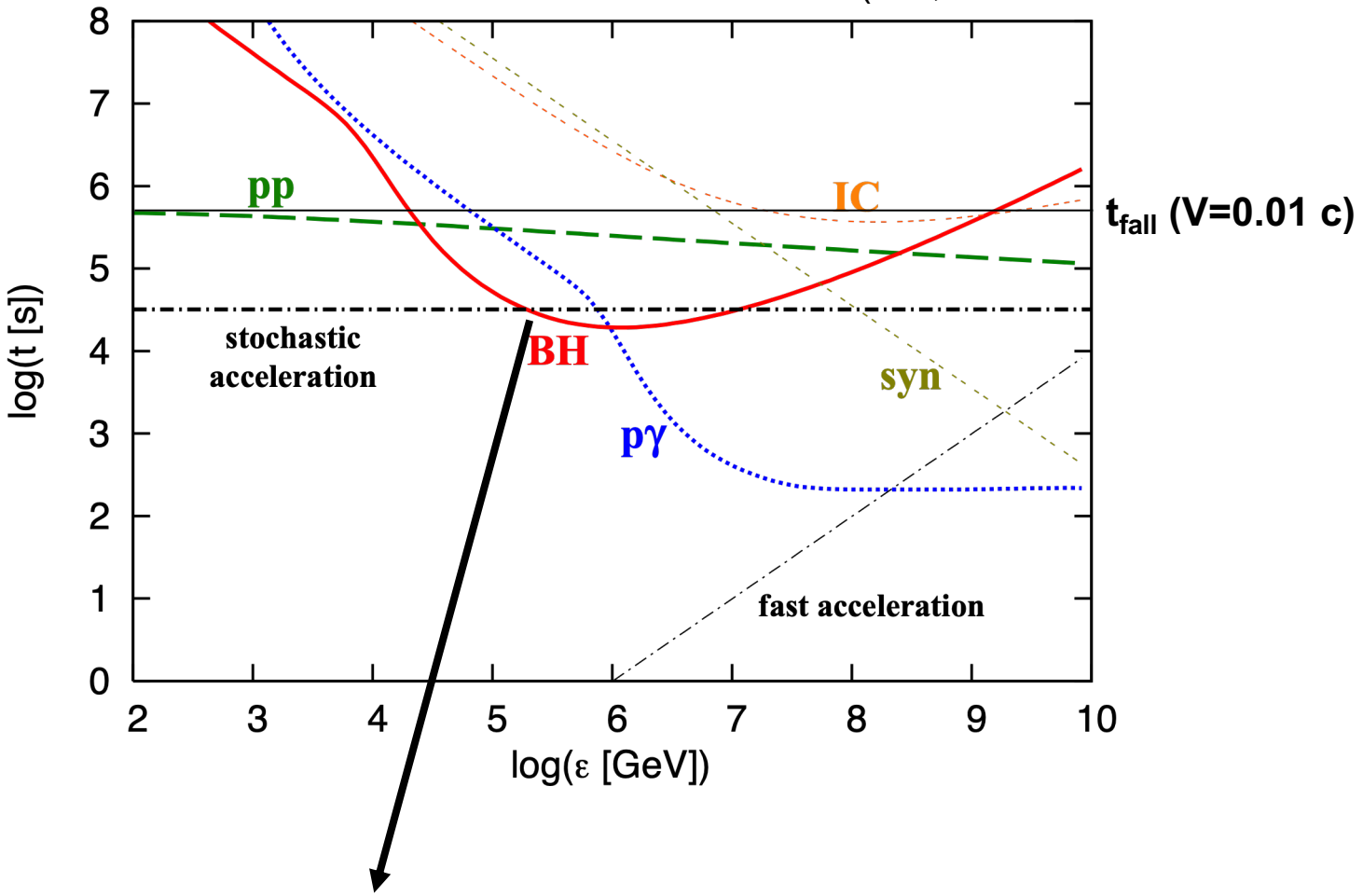
(cf. acceleration w. $t_{acc}=r_L/c \rightarrow \varepsilon_p^{max}$~10-100 PeV)



Particle Acceleration: Fast or Slow?

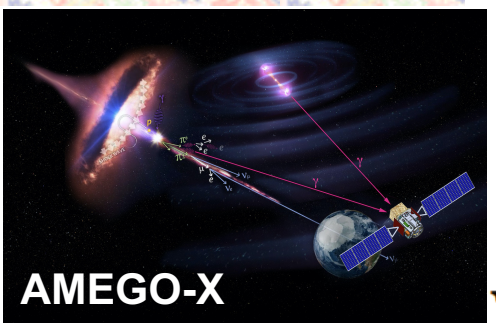
$p\gamma \rightarrow pe^+e^-$ (Bethe-Heitler process) is important for protons producing 1-10 TeV νs

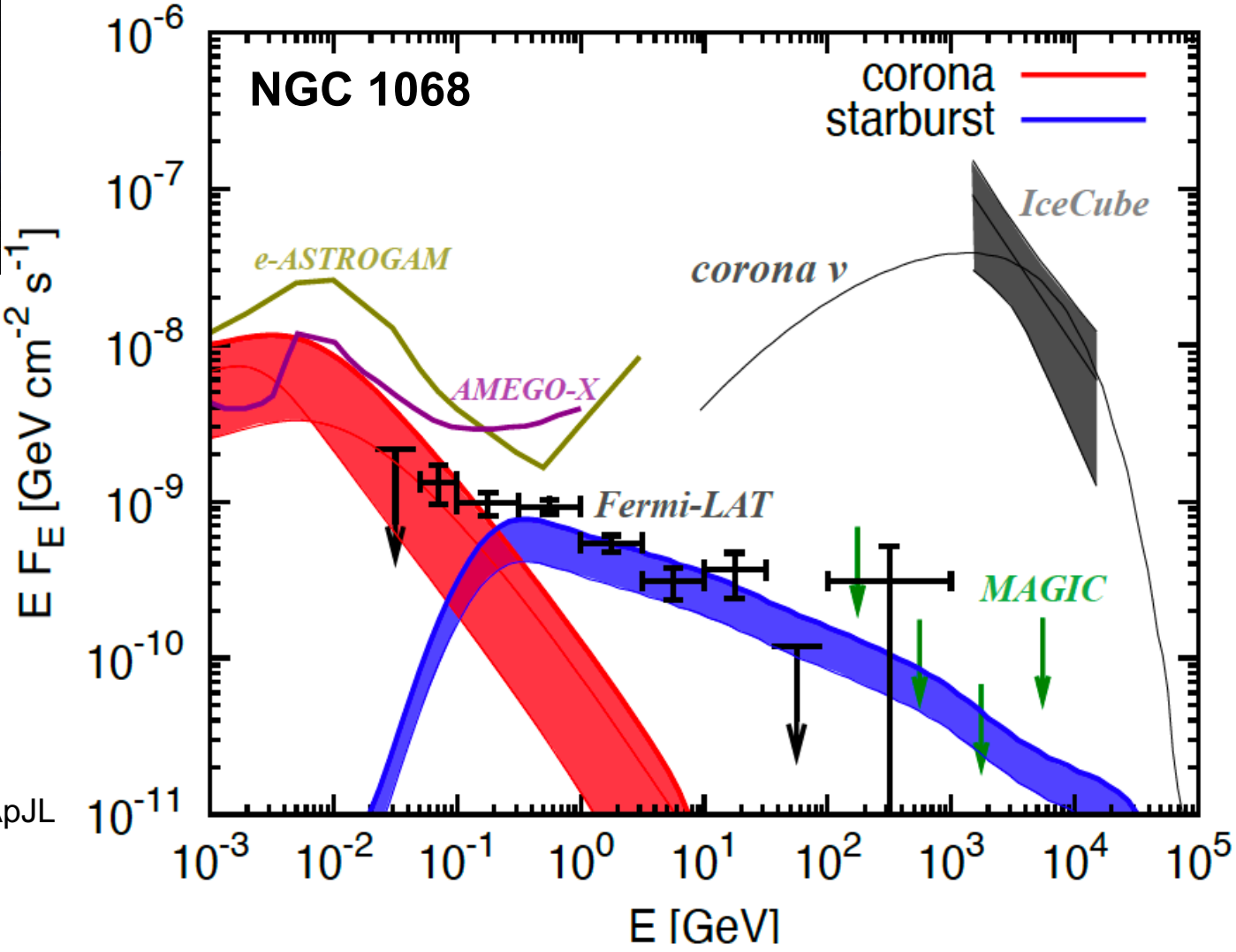
(KM, Kimura & Meszaros 20 PRL)



$\varepsilon_p^{max} \sim 100$ TeV $\rightarrow \varepsilon_\nu^{max} \sim 5$ TeV (consistent w. IceCube)

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



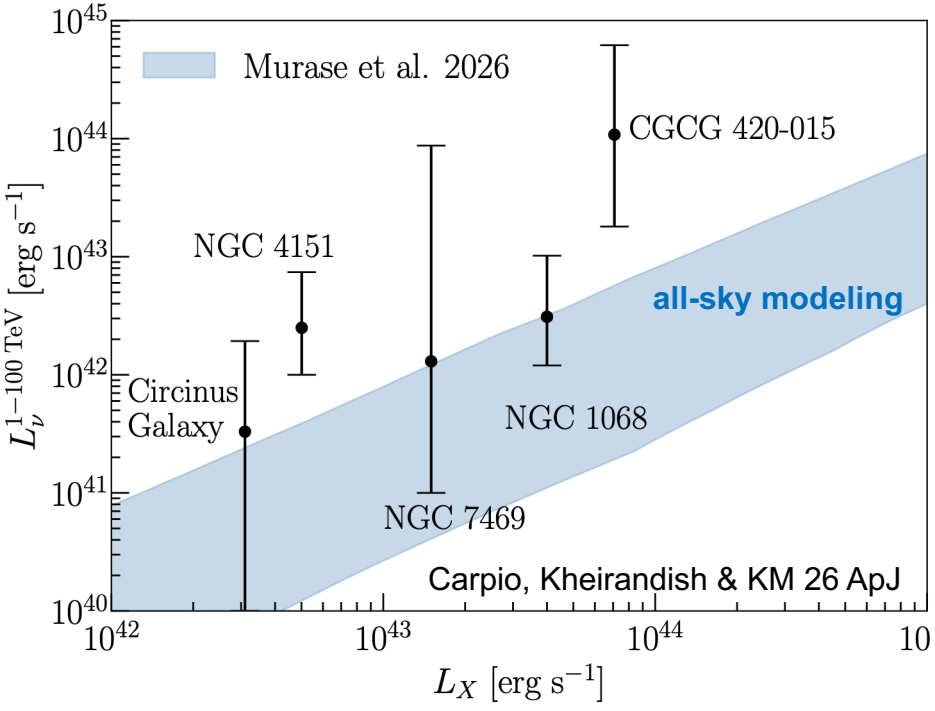


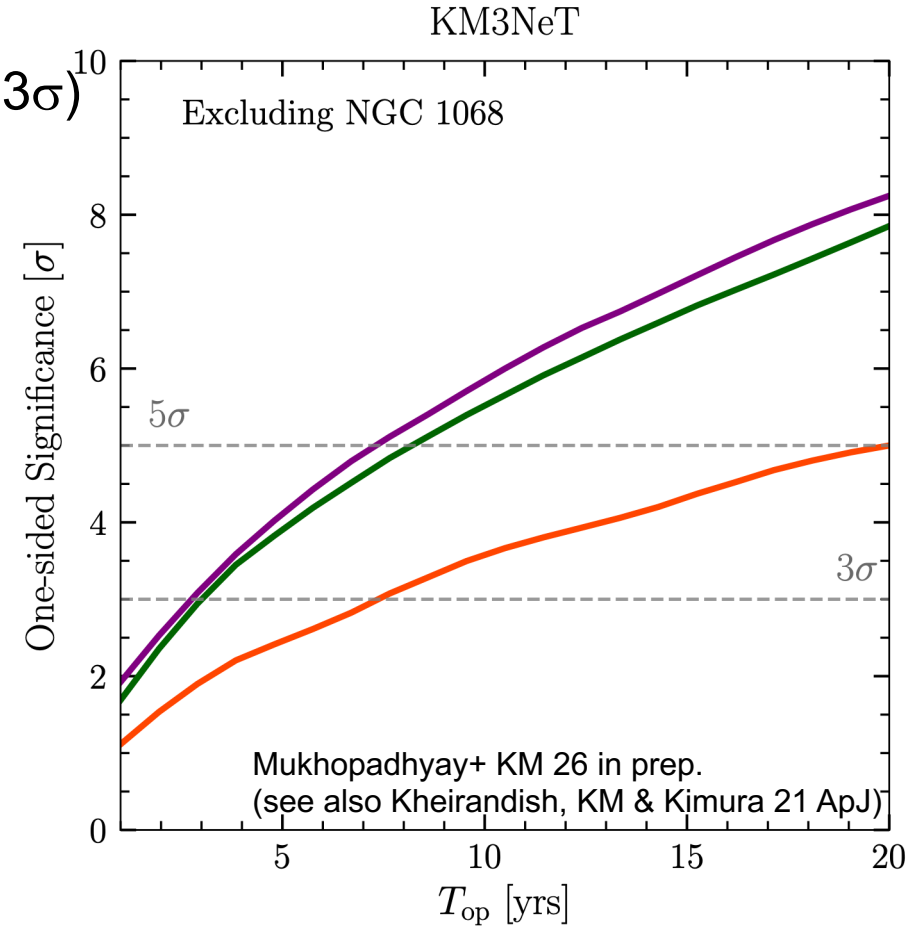
Ajello, KM & McDaniel 23 ApJL

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

Corona Model: Predictions and Hints

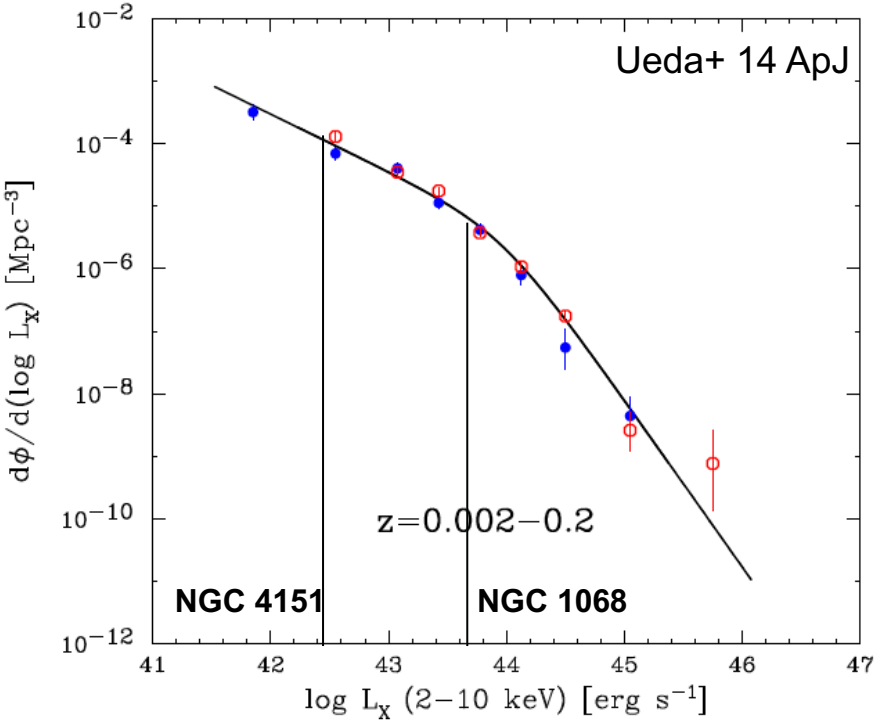
- Theory prediction: ν luminosity ~ intrinsic X-ray luminosity (KM+ 20, 24, 26)
  brightest for IceCube: NGC 1068, NGC 4151
  brightest in the southern sky: Circinus, NGC 4945
- IceCube ν evidences/hints: (IceCube Collaboration 22, 25a, 25b, 26a, 26b)
  NGC 1068 (~4σ), NGC 4151 (~3σ),
  14 AGNs in the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



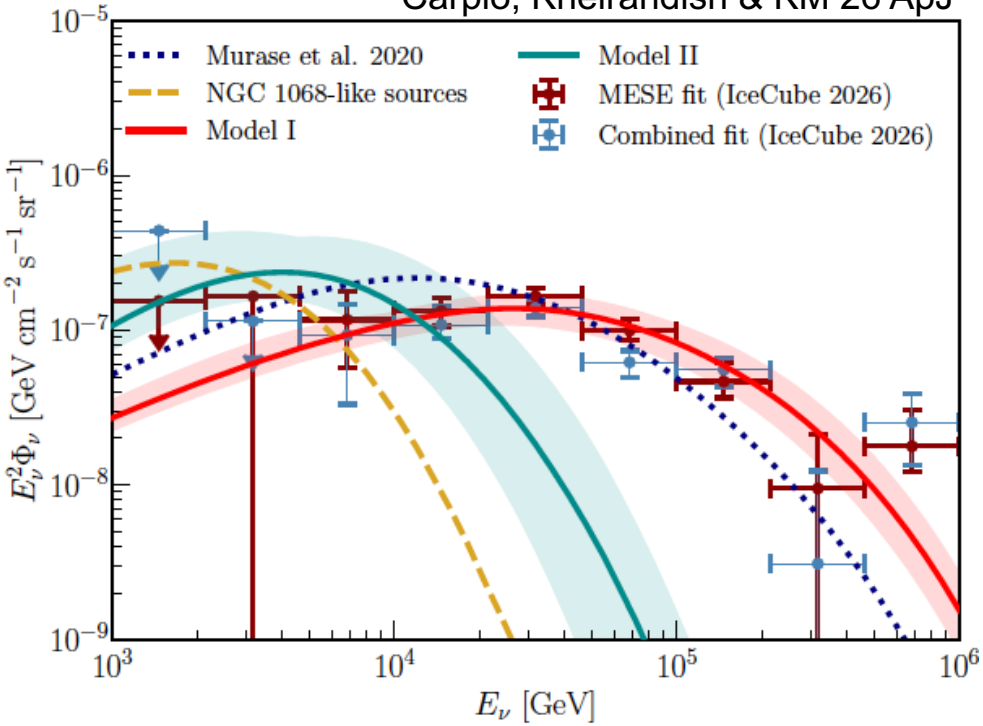


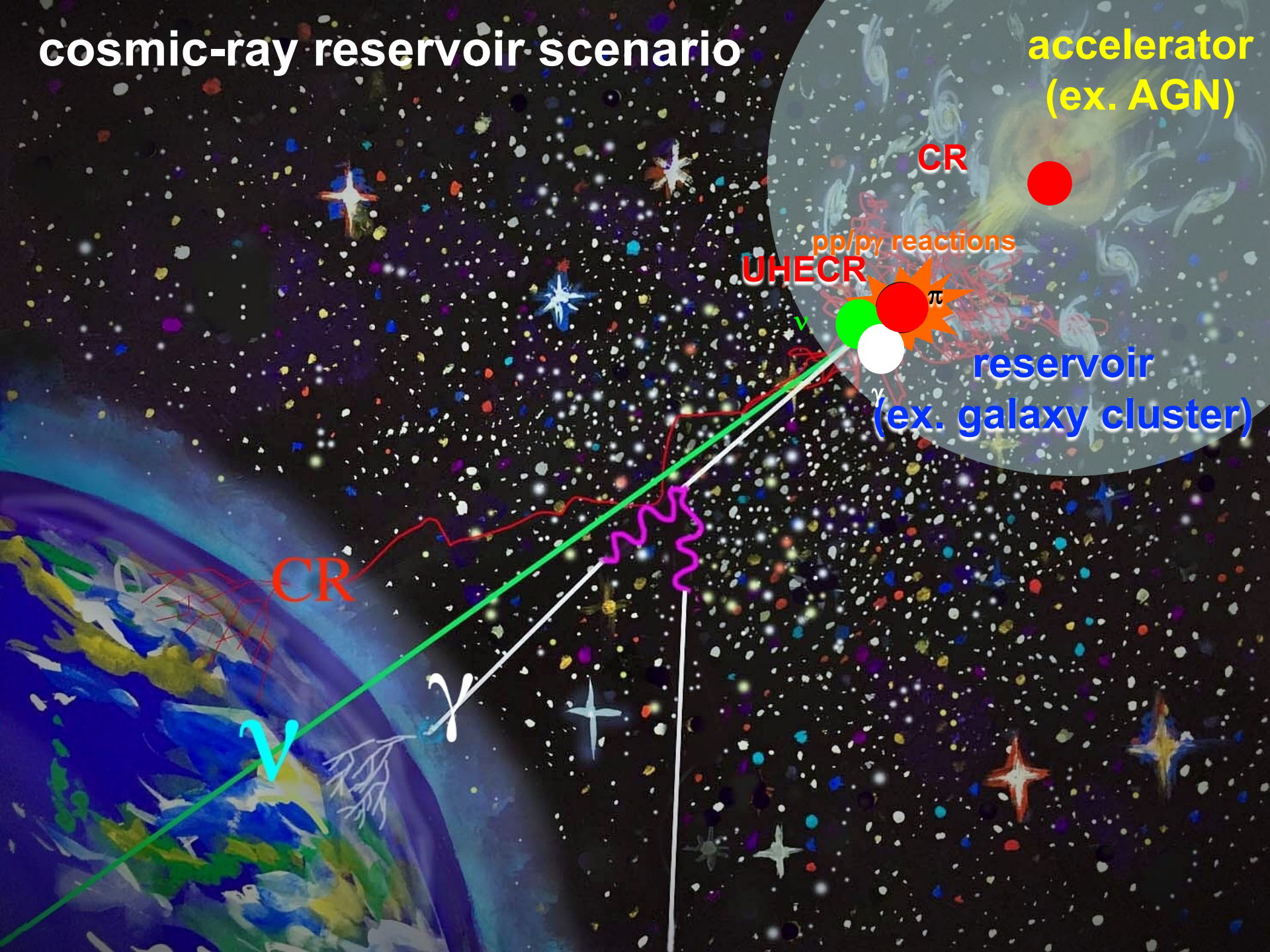
Guaranteed AGN Contribution to the All-Sky Neutrino Flux?

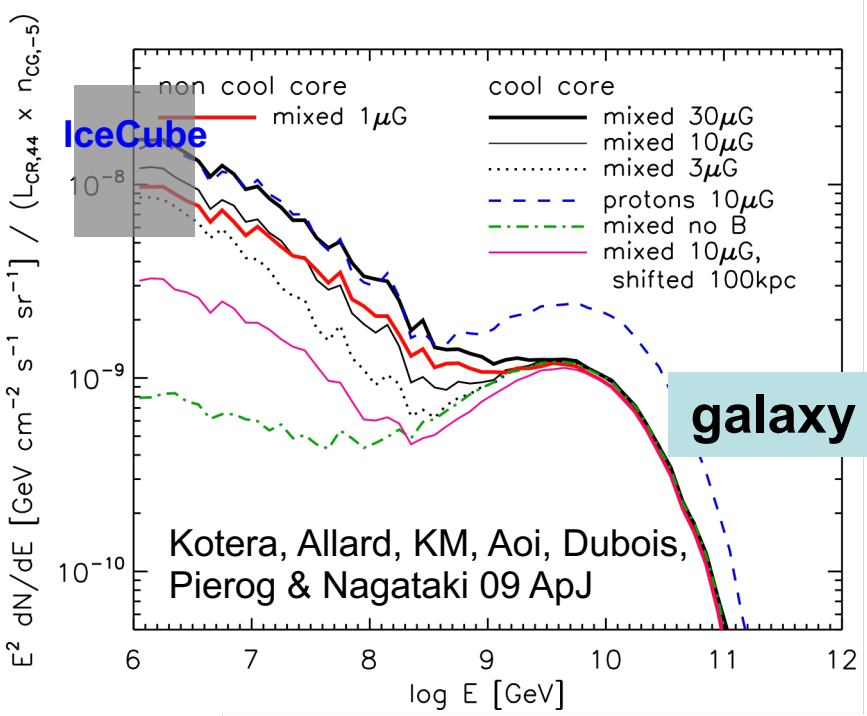
- AGN corona model was proposed to explain the all-sky ν flux (KM+20 PRL)
  (ex. X-ray luminosity function is used in the MKM20 corona model)
- Differential ν flux at 10 TeV: ~10^{-8} GeV cm^{-2} s^{-1} → EL_E ~ 2x10^{41} erg/s
- NGC 1068-like AGNs are rare: n~10^{-5} Mpc^{-3} → EQ_E ~ 6x10^{43} erg Mpc^{-3} yr^{-1}
- Comparable to the required energy budget: EQ_E ~ 5x10^{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

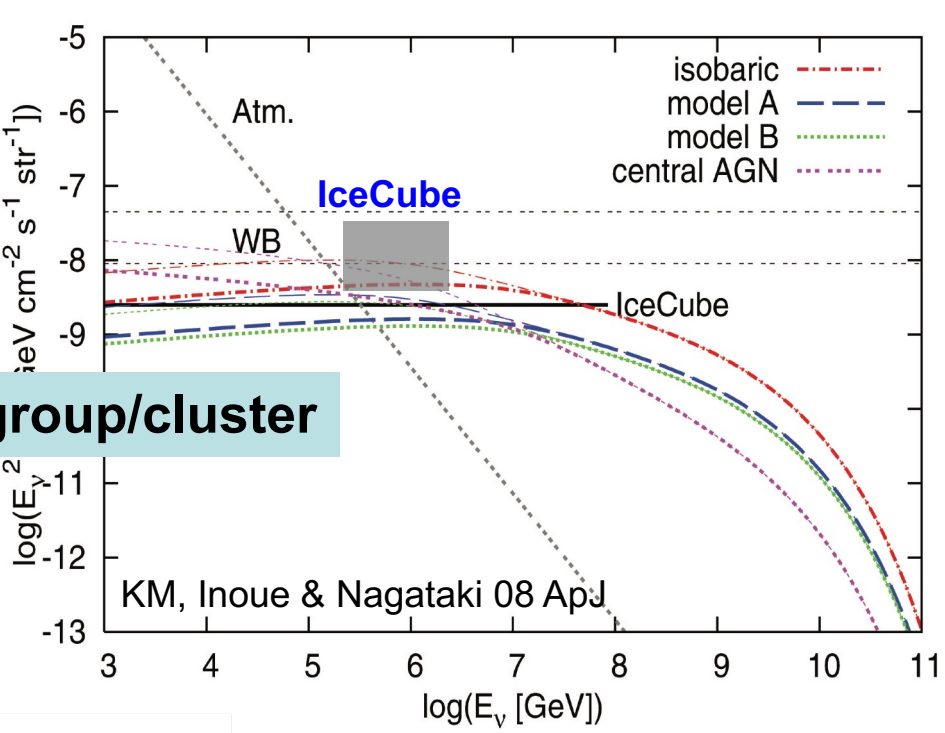


Carpio, Kheirandish & KM 26 ApJ

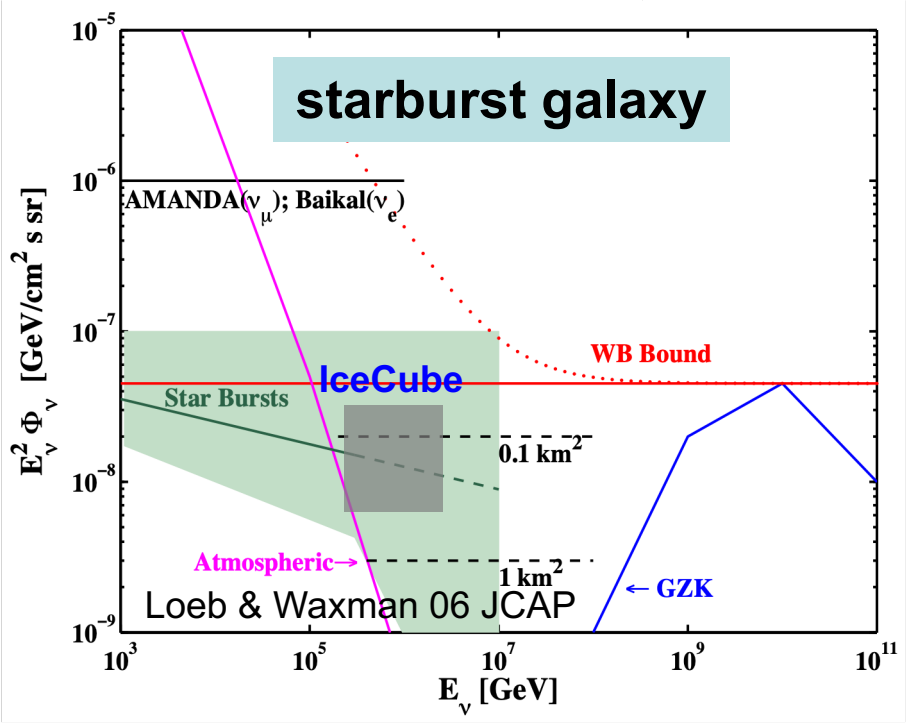



cosmic-ray reservoir scenario
accelerator
(ex. AGN)
CR
pp/pγ reactions
UHECR
π
ν
γ
reservoir
(ex. galaxy cluster)
CR
ν
γ





galaxy group/cluster

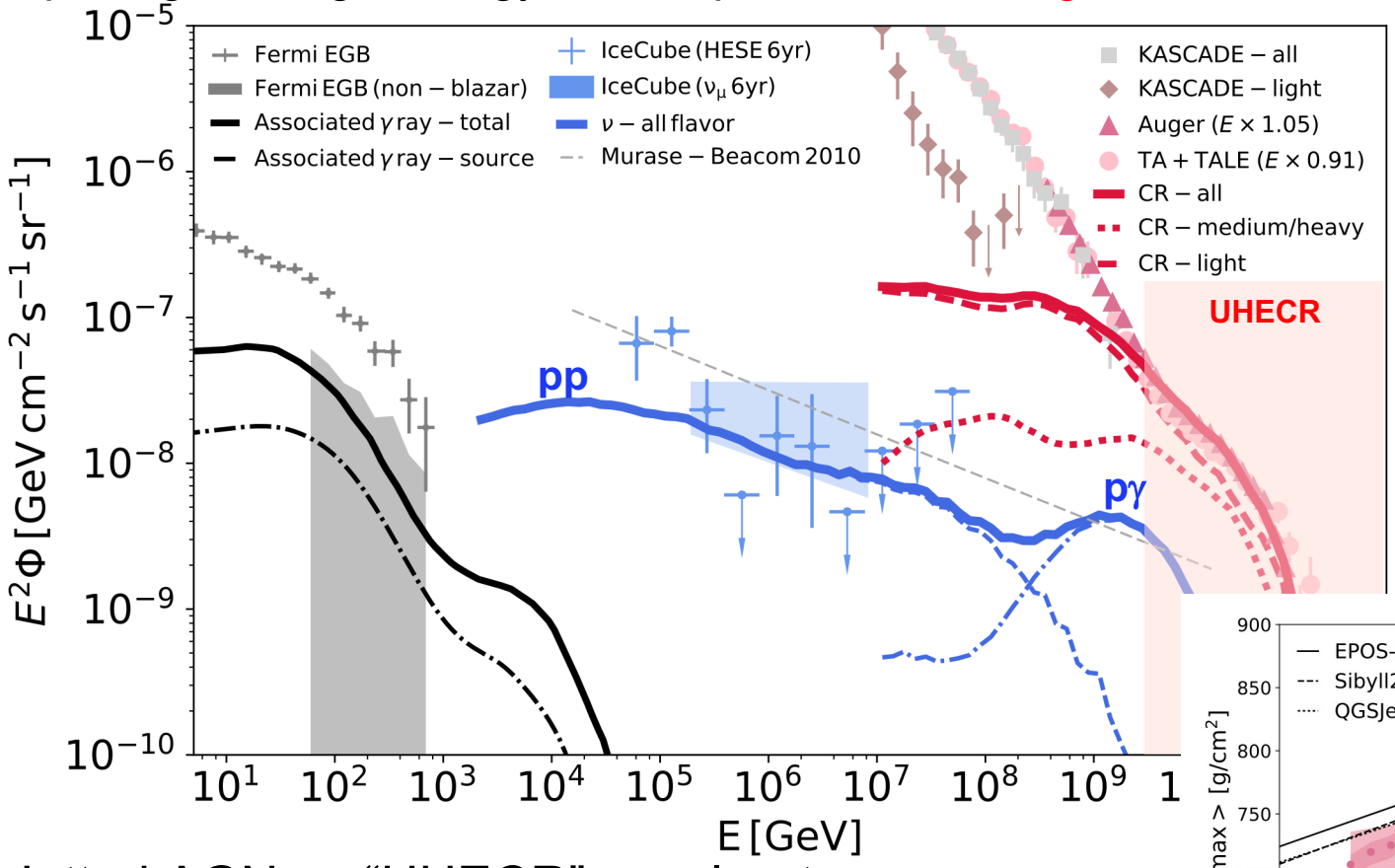


starburst galaxy

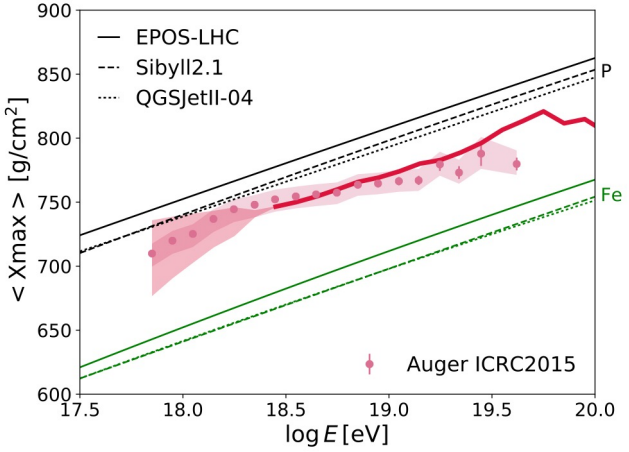
>0.1 PeV IceCube data: consistent w. earlier theoretical predictions

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



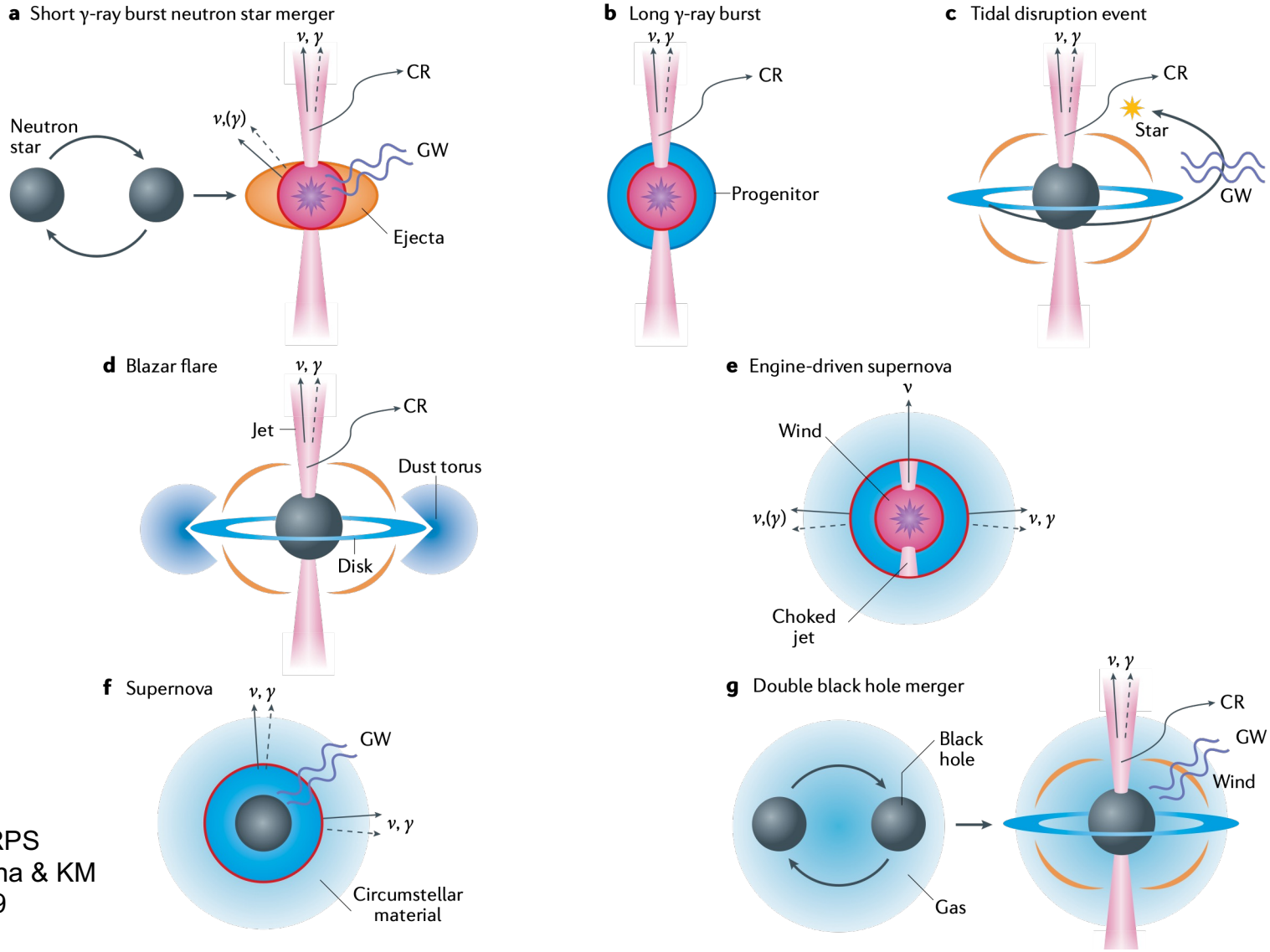
Fang & KM 18 Nature Phys.
(cf. Unger et al. 15 PRD)



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

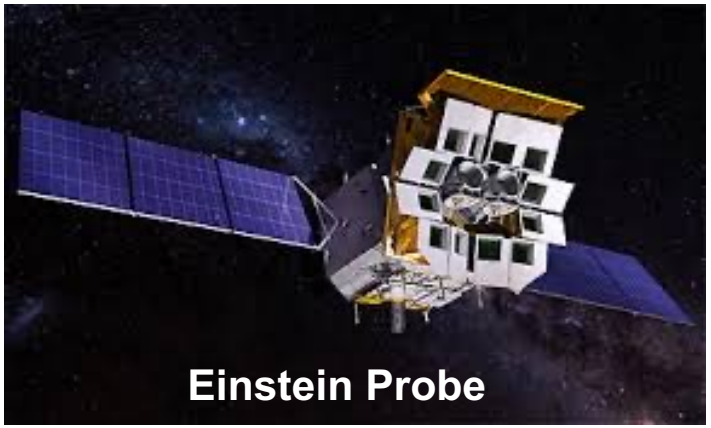
Time-Domain Frontier: Multimessenger/Multienergy ν Transients?

pointing & timing → good chance to discover ν sources



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

Optical, Infrared and X Rays: New ν Transient Searches



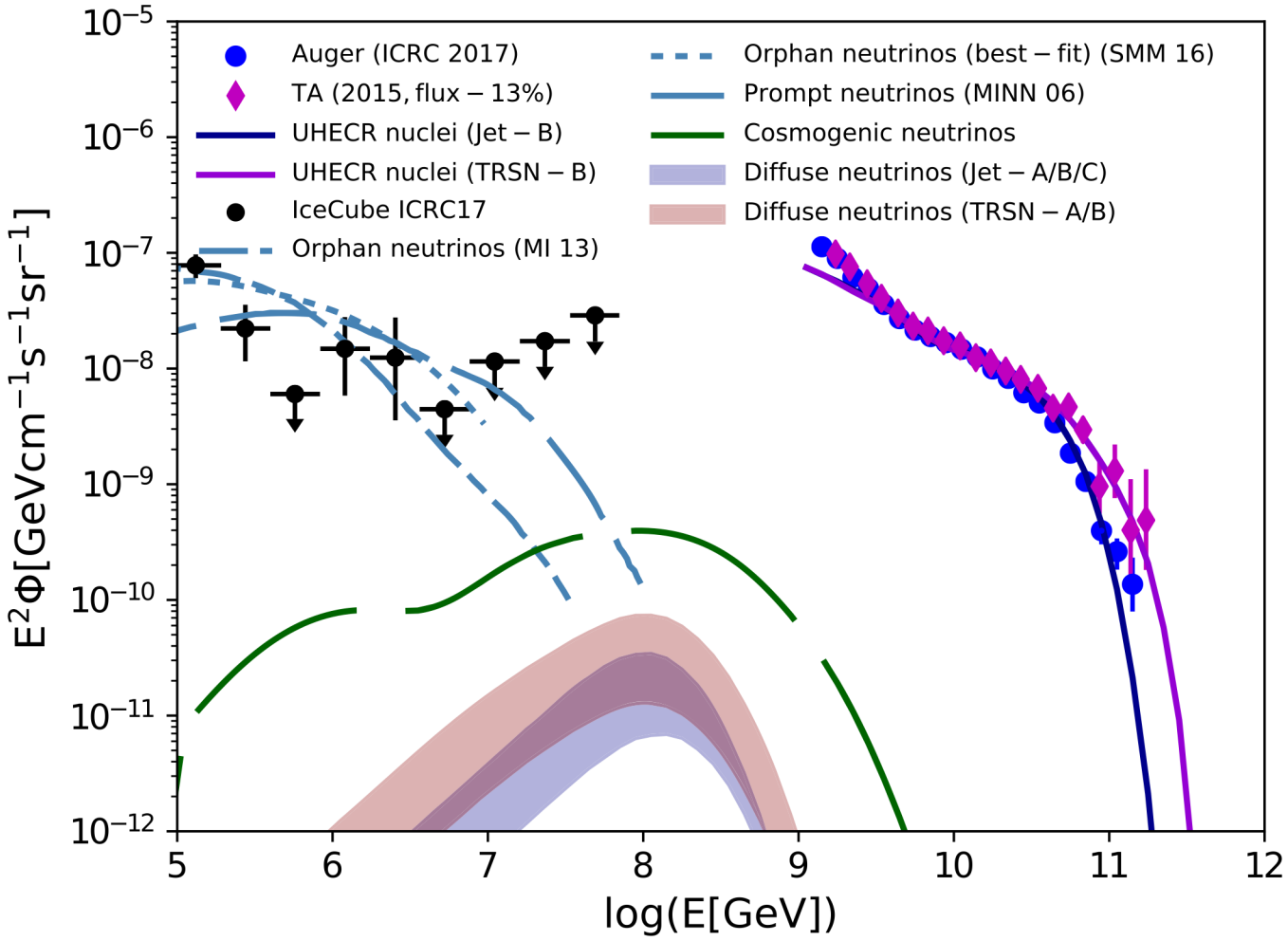


- Supernovae, tidal disruption events, low-luminosity gamma-ray bursts…
  (e.g., Stein+ 21 Nature Astronomy, Reusch+ KM 21 PRL)
- Testability of models have been limited by the number of detected transients
- Stacking searches
- Neutrino multiplet followups
- Multimessenger alert followups

  # Neutrino singlet followups would need spectroscopic information



Neutrinos from Engine-Driven Supernovae



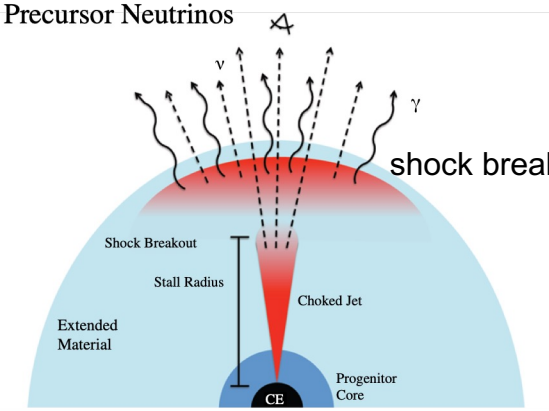
Zhang & KM 19 PRD

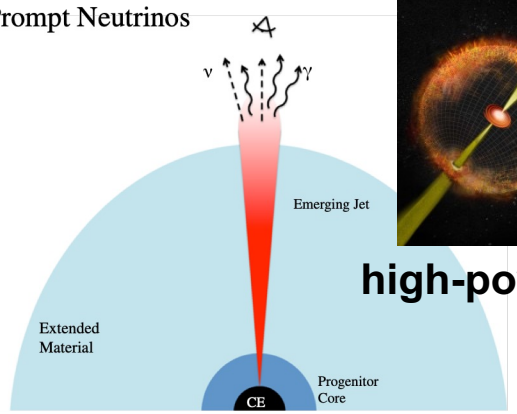
- EeV: cosmogenic neutrinos overwhelm source neutrinos
- TeV-PeV νs may also be produced (KM+ 06, Senno, KM & Meszaros 16)

Stacking Searches w. Optical Supernovae



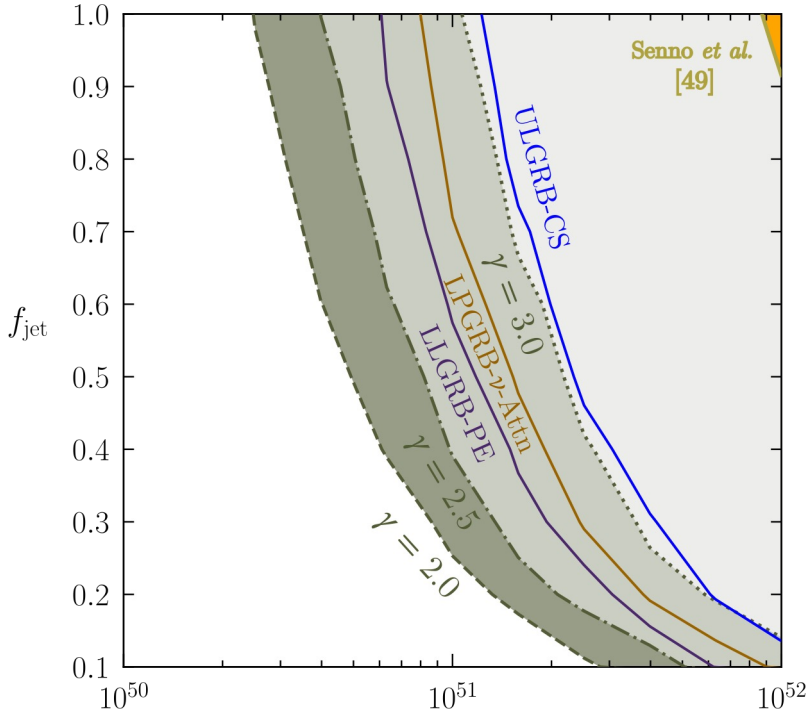
low-power

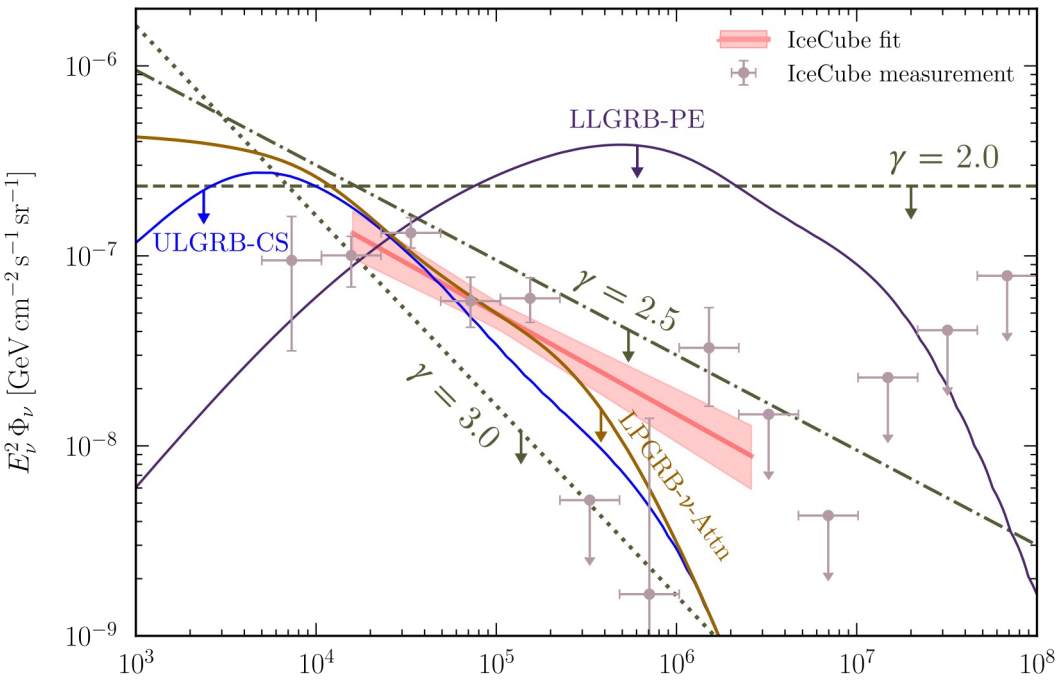




high-power

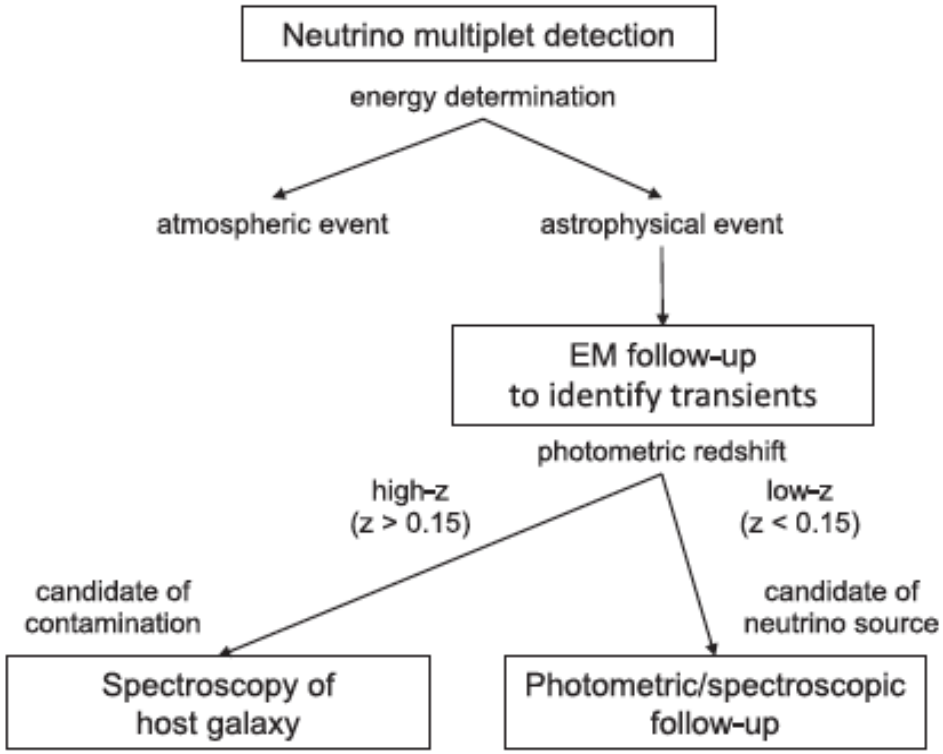
from Senno, KM & Meszaros 16 PRD

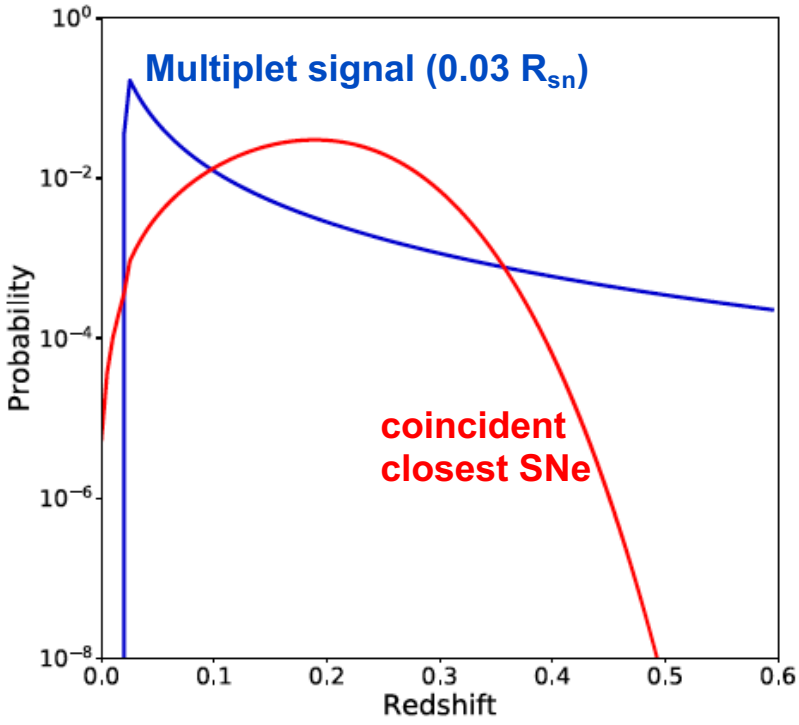


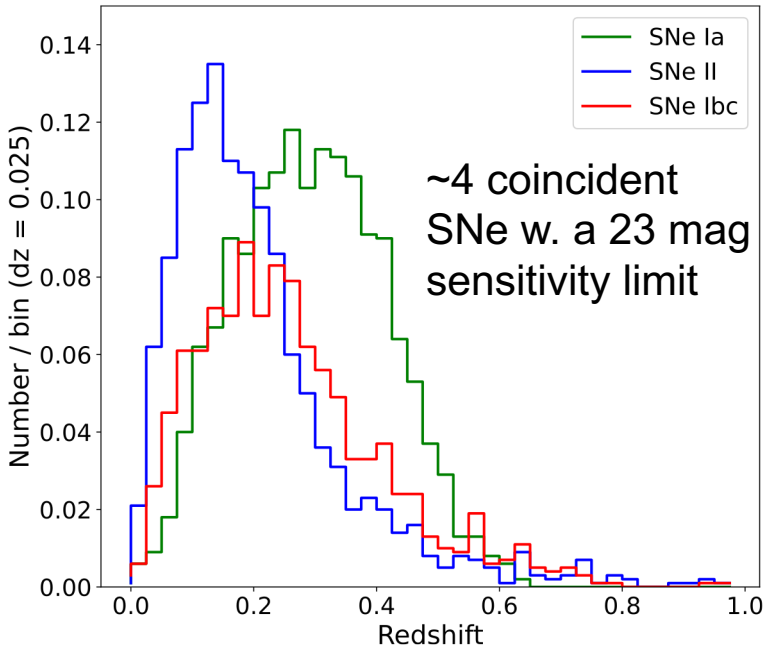


Chang, Zhou, KM & Kamionkowski 24 PRD

Yoshida, KM+ 22 ApJ







- Need for long-duration multiplet alerts
  lower FAR (< 1/yr)
  likely to be low redshifts if SN-like

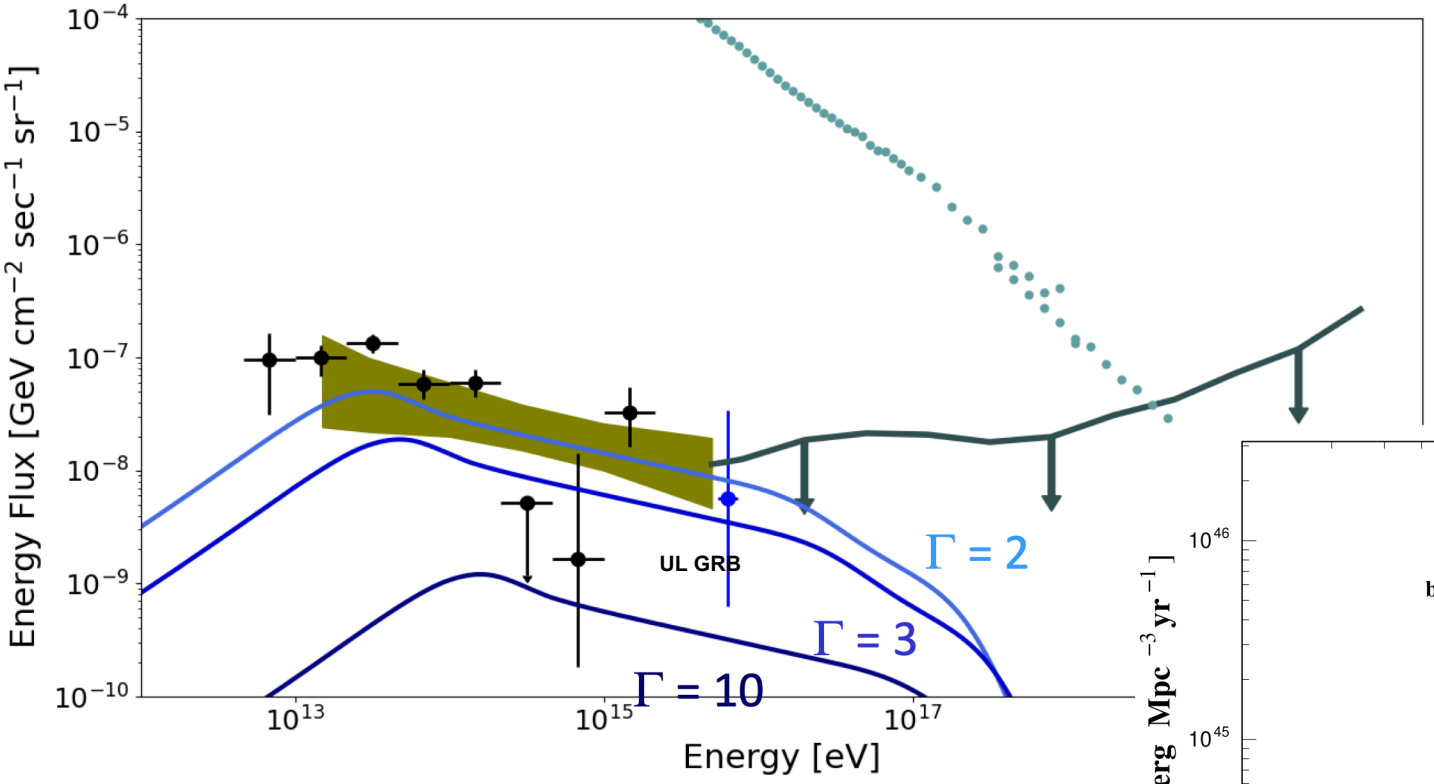
- Discriminating optical transients is a key

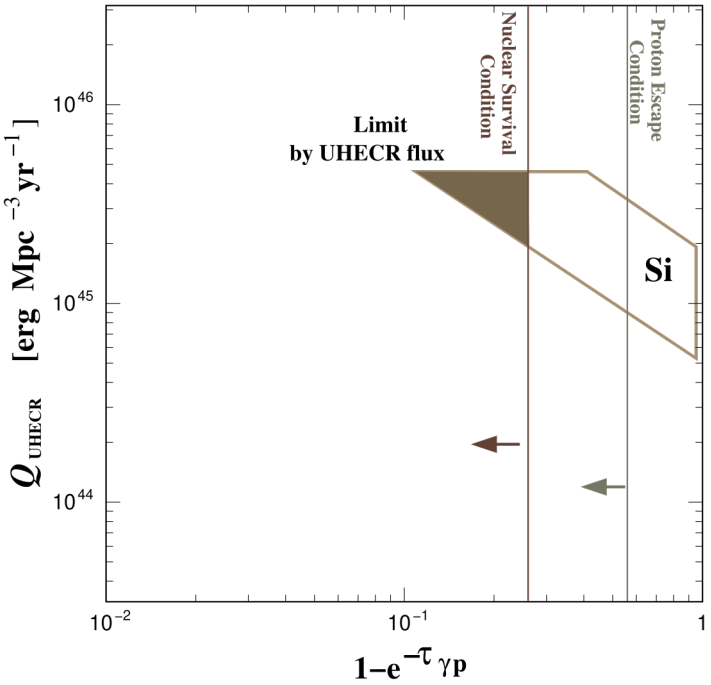
- Sensitivity: ~(30-3000) Gpc^{-3} yr^{-1}
  more improved w. KM3Net/IceCube-Gen2

Testing UHECR-PeV ν Unification Scenarios

Yoshida & KM 24 PRD

ξ_{CR}=10

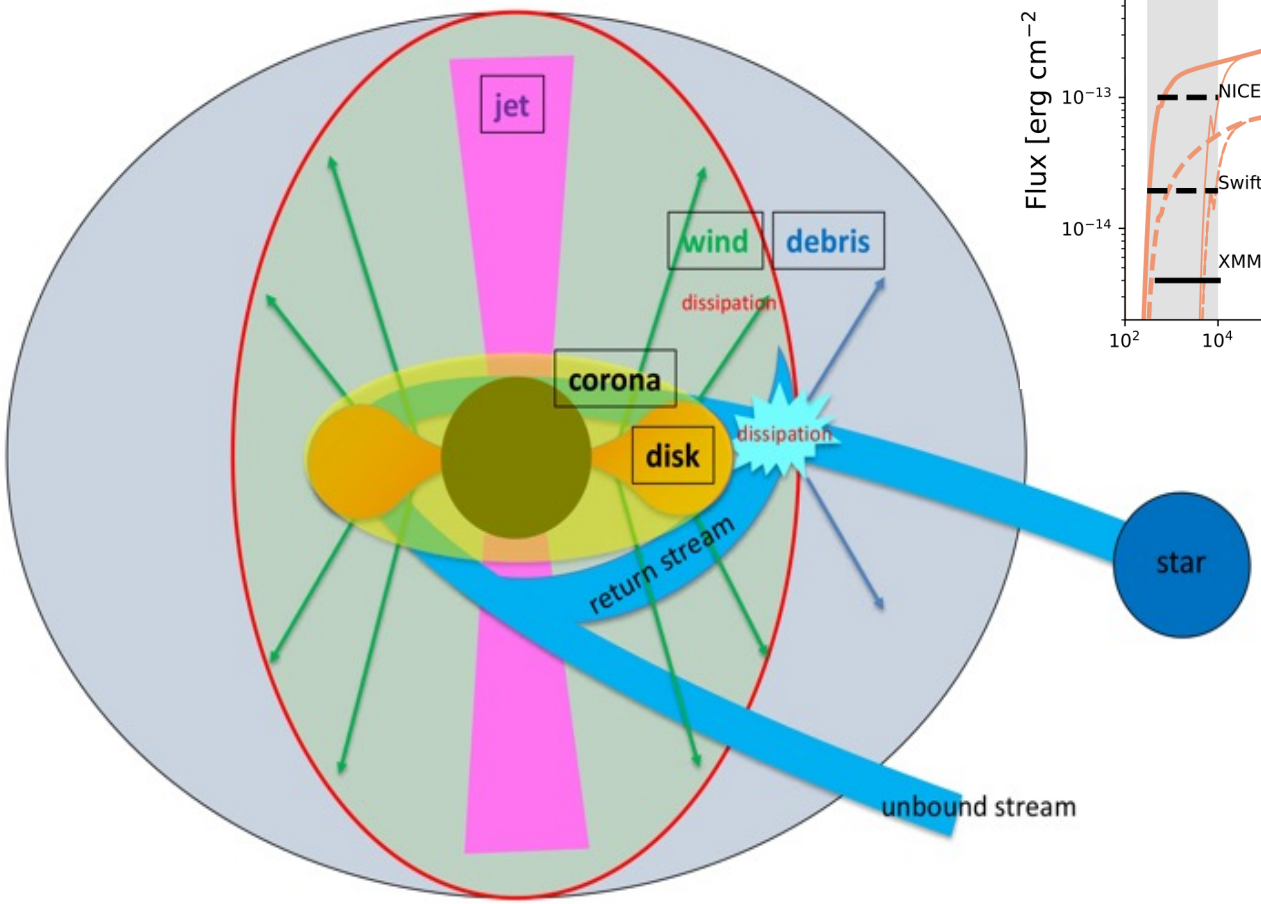




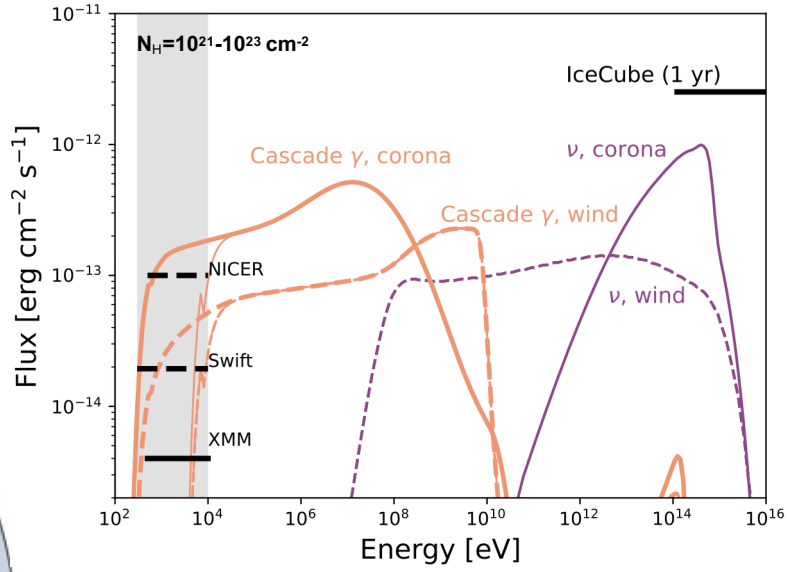
- Common origin of PeV νs and UHECRs requires narrow parameter space for sources
- Viable models include LLGRBs and TDEs
  → optical & X-ray transient searches

Tidal Disruption Events – Bare Black Hole Model

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



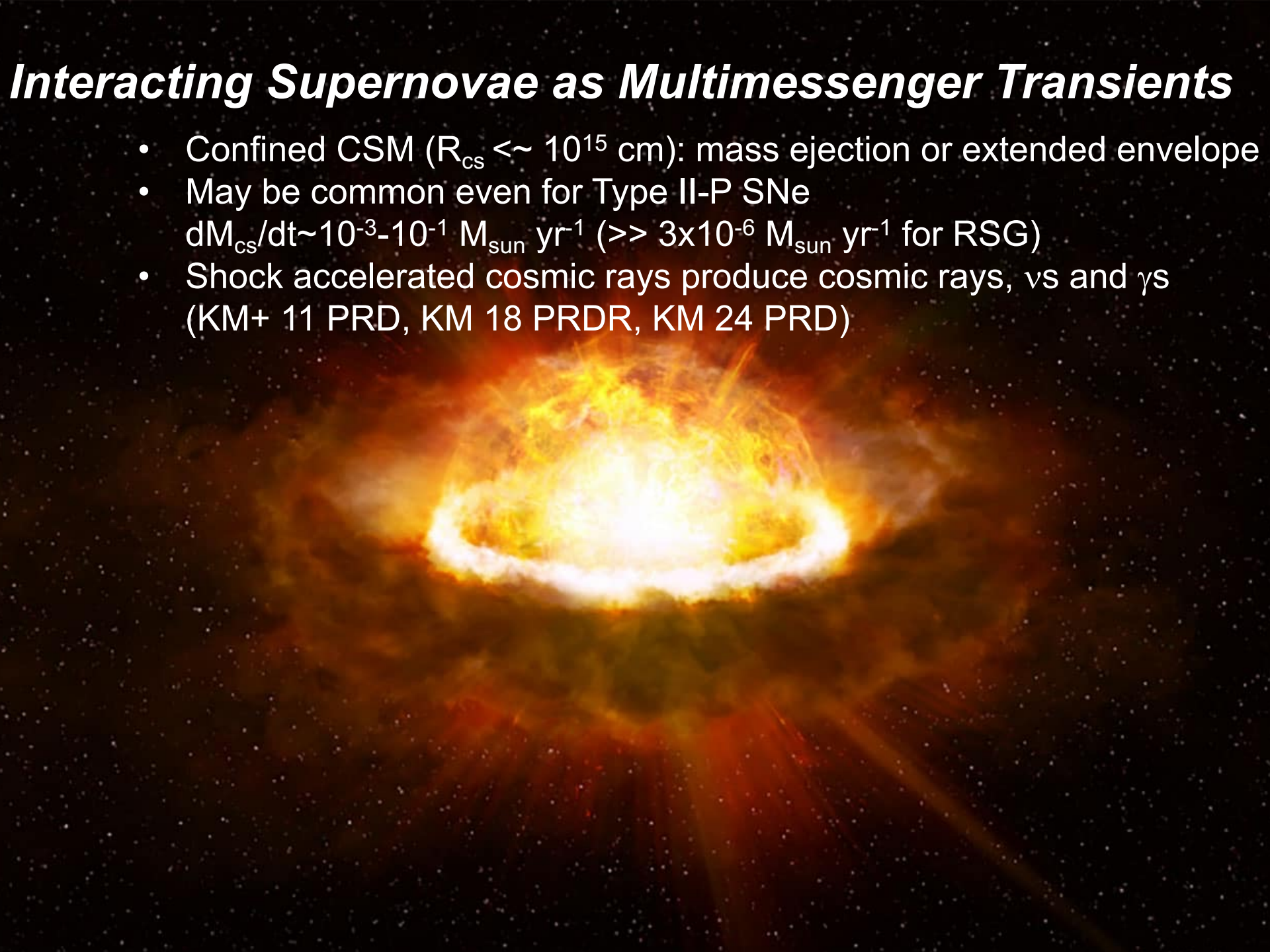
KM, Kimura, Zhang et al. 20 ApJ



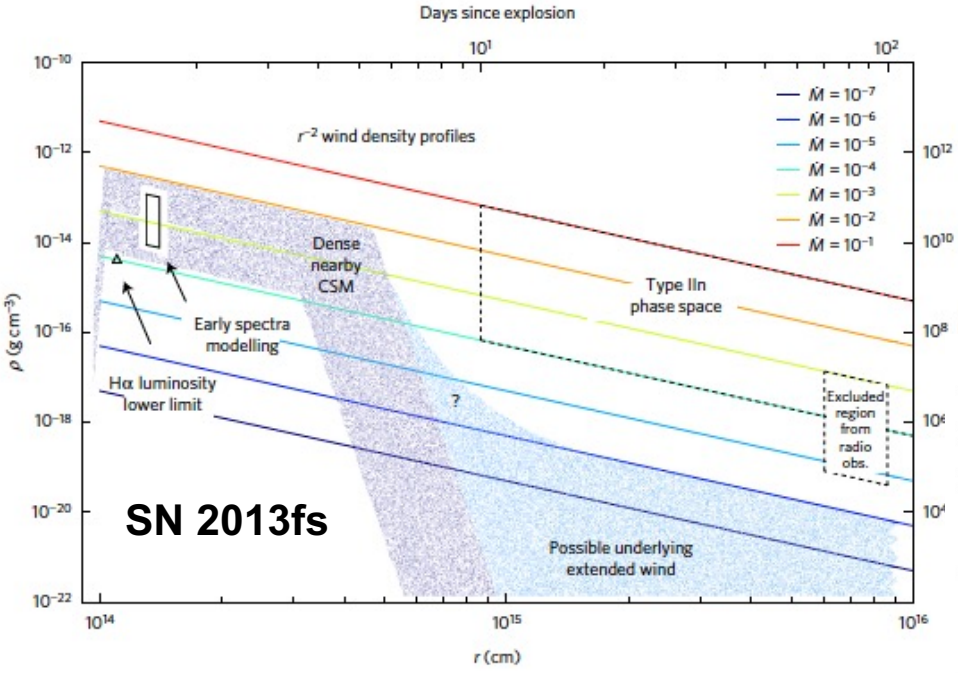


Interacting Supernovae as Multimessenger Transients

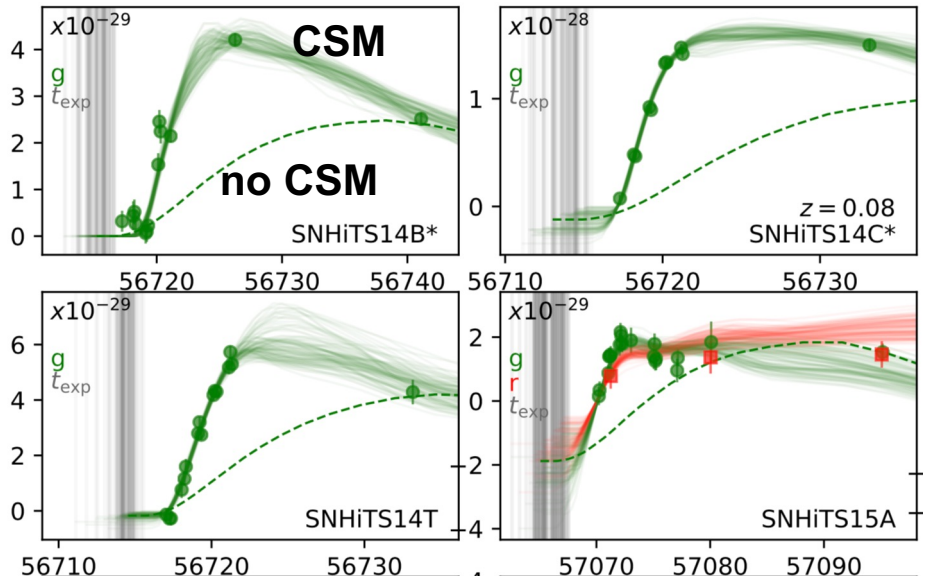
- Confined CSM (R_{cs} <~ 10^{15} cm): mass ejection or extended envelope
- May be common even for Type II-P SNe
  $dM_{cs}/dt \sim 10^{-3}$-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)
- Shock accelerated cosmic rays produce cosmic rays, νs and γs
  (KM+ 11 PRD, KM 18 PRDR, KM 24 PRD)



Evidence for "Confined" CSM around Progenitors



early spectroscopy
(Yaron+ 16 Nature Phys.)

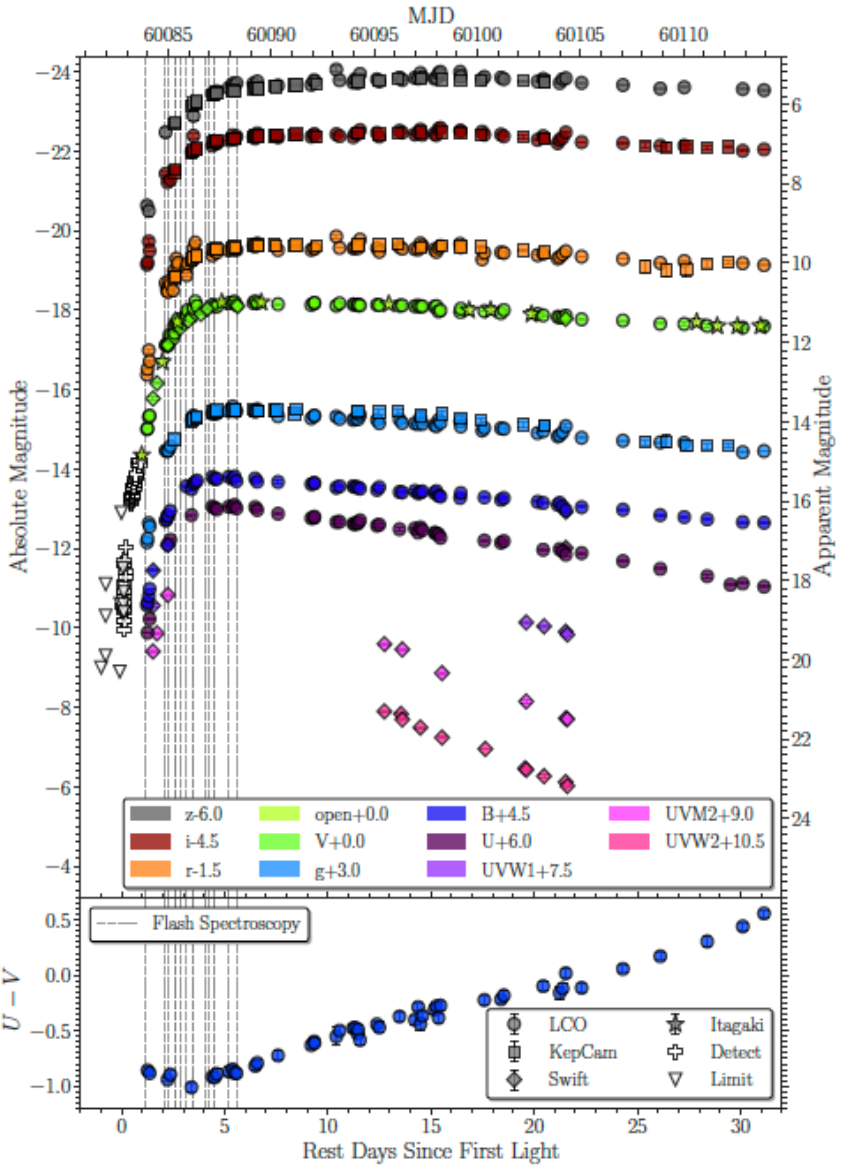


light curve modeling
(Forster+ 18 Nature Astronomy
see also Morozova+ 17 ApJ)

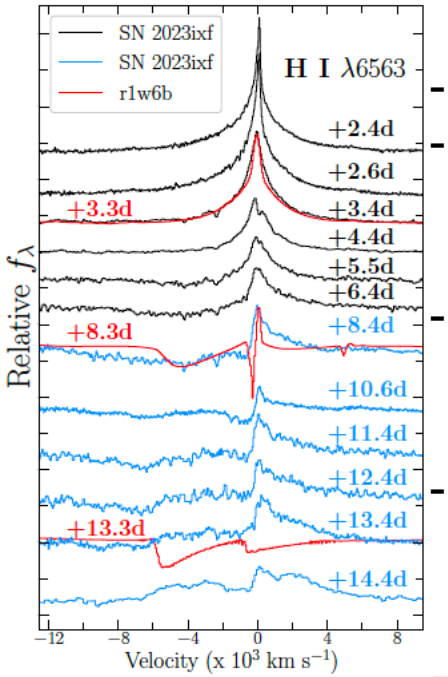
- **May be common even for Type II-P SNe**
  $dM_{cs}/dt \sim 10^{-3}$-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)
- **Confined CSM** (R_{cs} <~ 10^{15} cm): mass ejection or inflation

Latest Example: SN 2023ixf

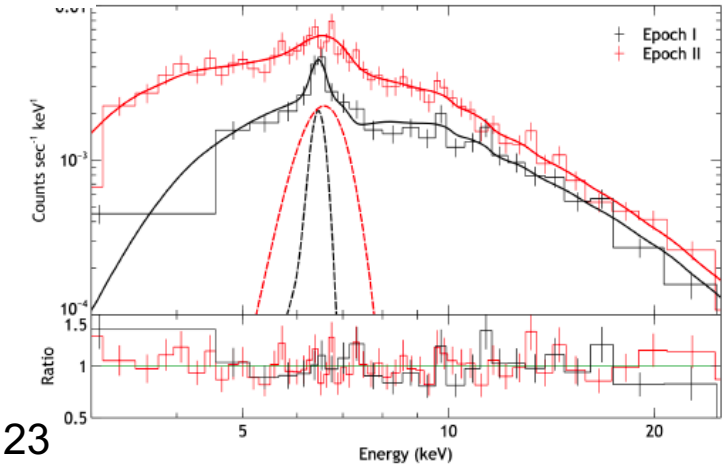
Hiramatsu+ 23



Jacobson-Galan+ 23



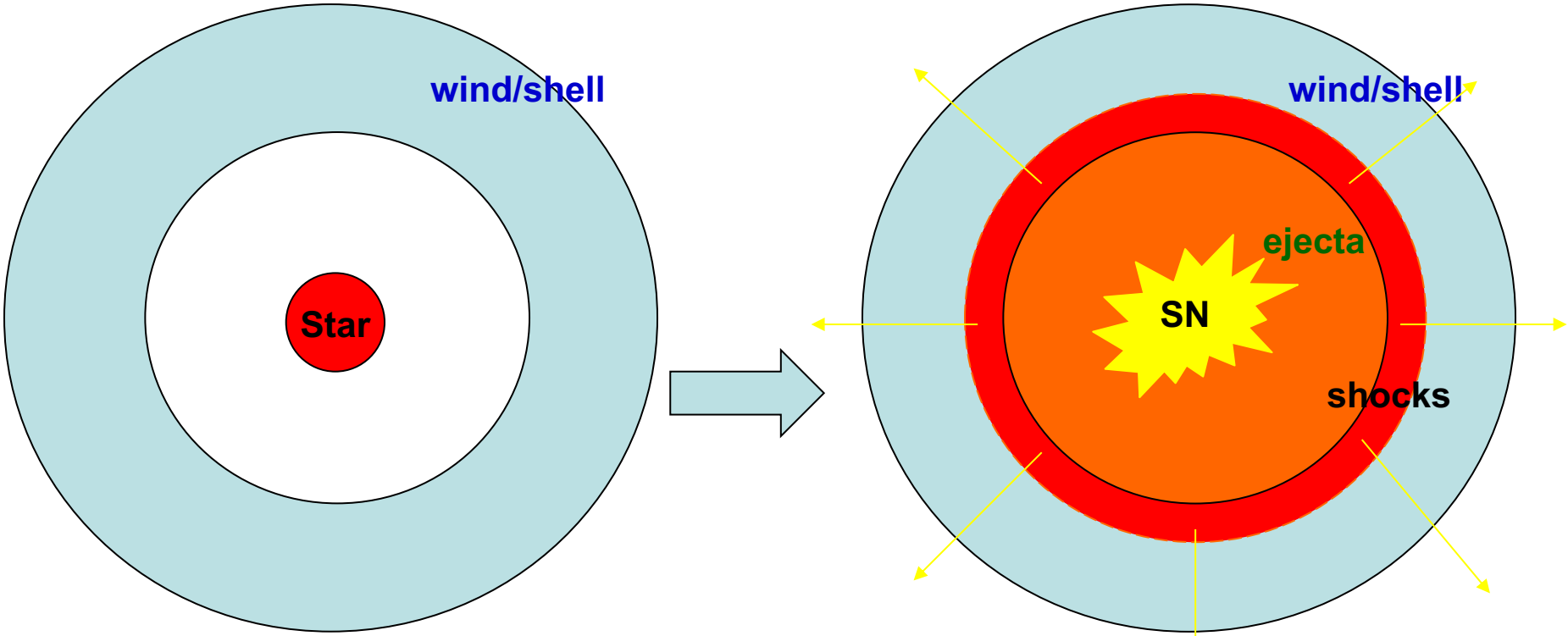
- M101 @ 6.9 Mpc
- Optical
  $dM_{cs}/dt \sim 10^{-2}$-10^{-1} M_{sun} yr^{-1}
  R_{cs} ~ a few x 10^{14} cm
- X-ray
  $dM_{cs}/dt \sim (0.3\text{-}1)\times10^{-3}$ M_{sun} yr^{-1}
  R_{cs} ~ 10^{15} cm
- Radio
  VLA detection at ~30 d



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

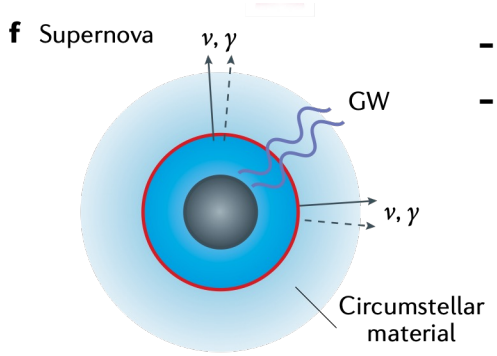
$$p + p \rightarrow N\pi + X$$

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

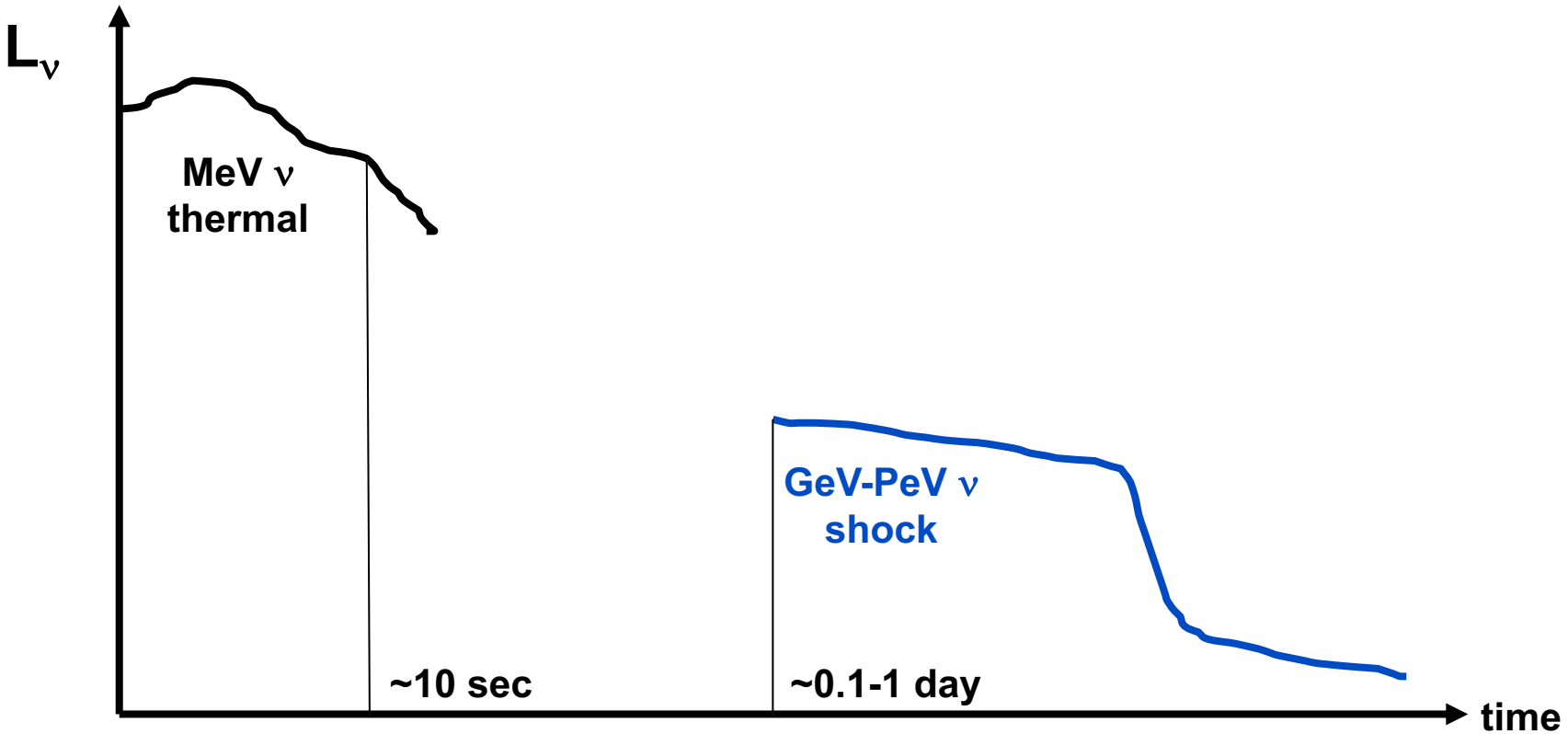
$$\pi^{0} \rightarrow \gamma + \gamma$$

dense environments = efficient ν emitters (calorimeters)

High-Energy Supernova Neutrinos

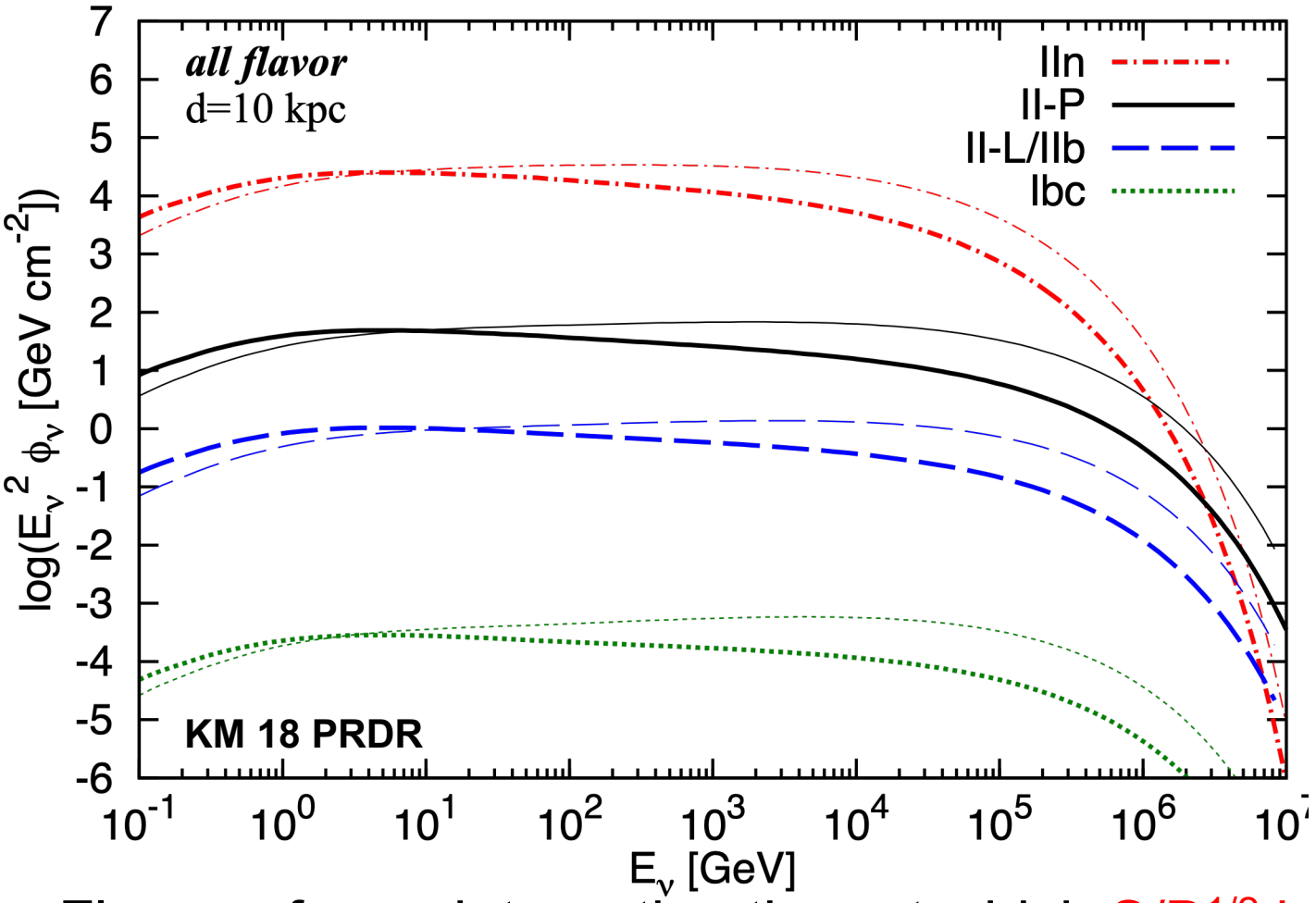


- SN progenitors commonly have “confined” circumstellar material
- Explosion → shock → Fermi acceleration → ν & γ-ray production



Neutrino Fluence

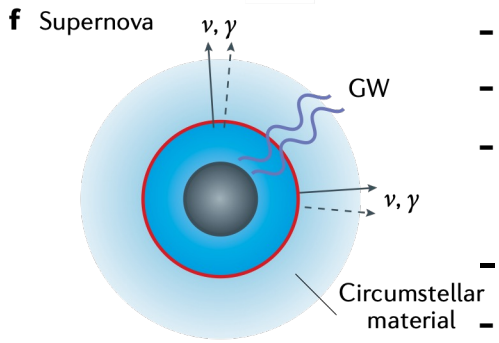
First prediction of HE neutrinos from SN w. confined CSM (KM 18 PRDR)



thick: s=2.2
thin: s=2.0

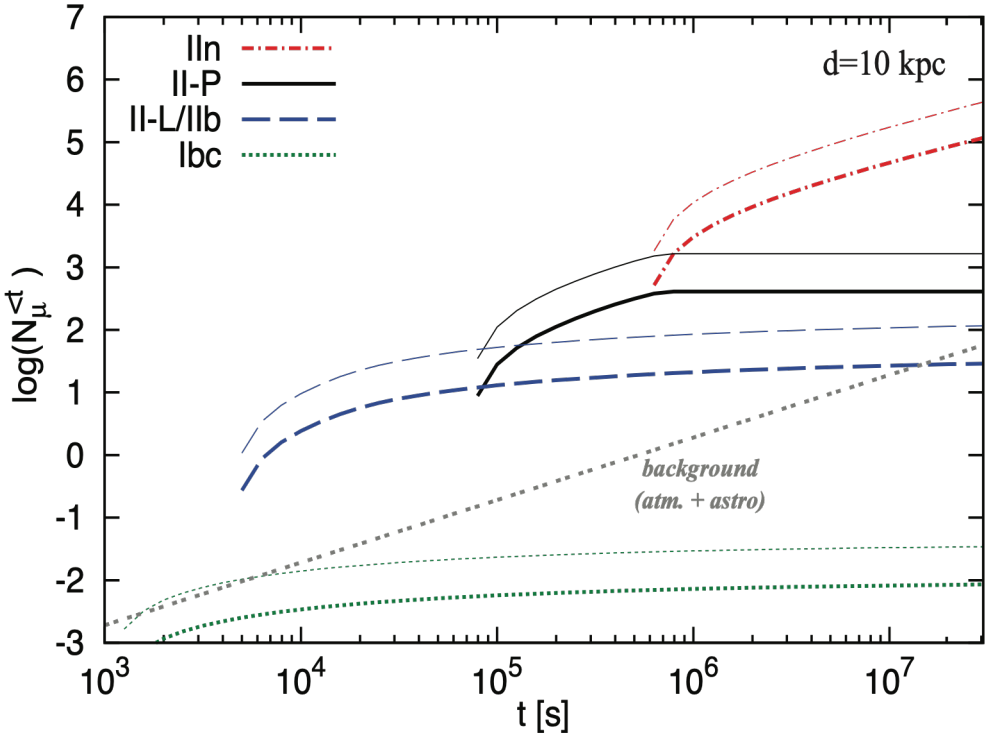
Fluence for an integration time at which $S/B^{1/2}$ is maximal (determined by the detailed time-dependent model)

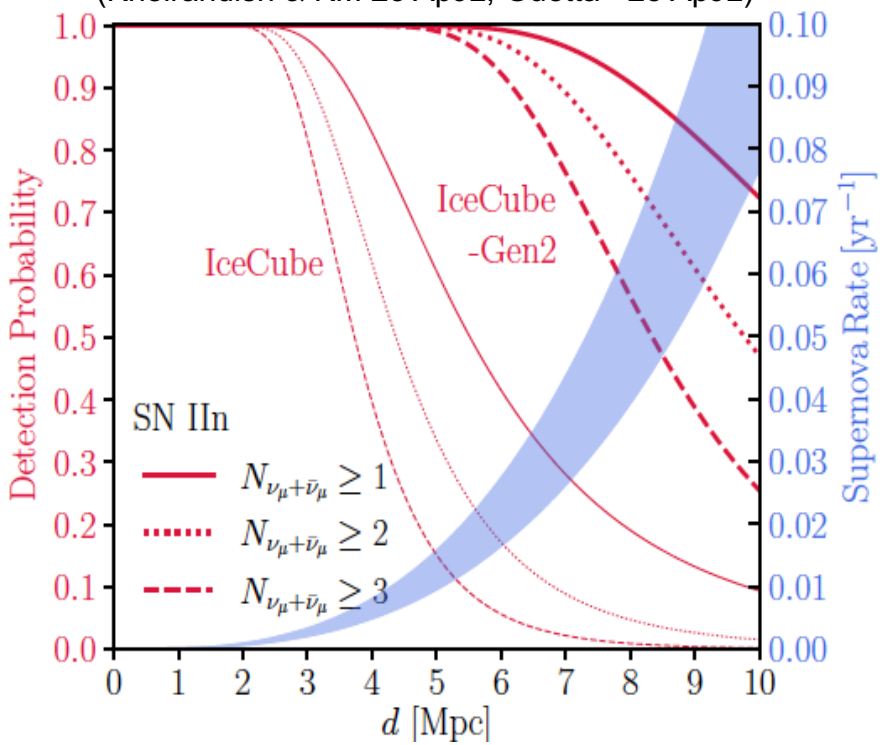
High-Energy Supernova Neutrinos



- 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)





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}~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



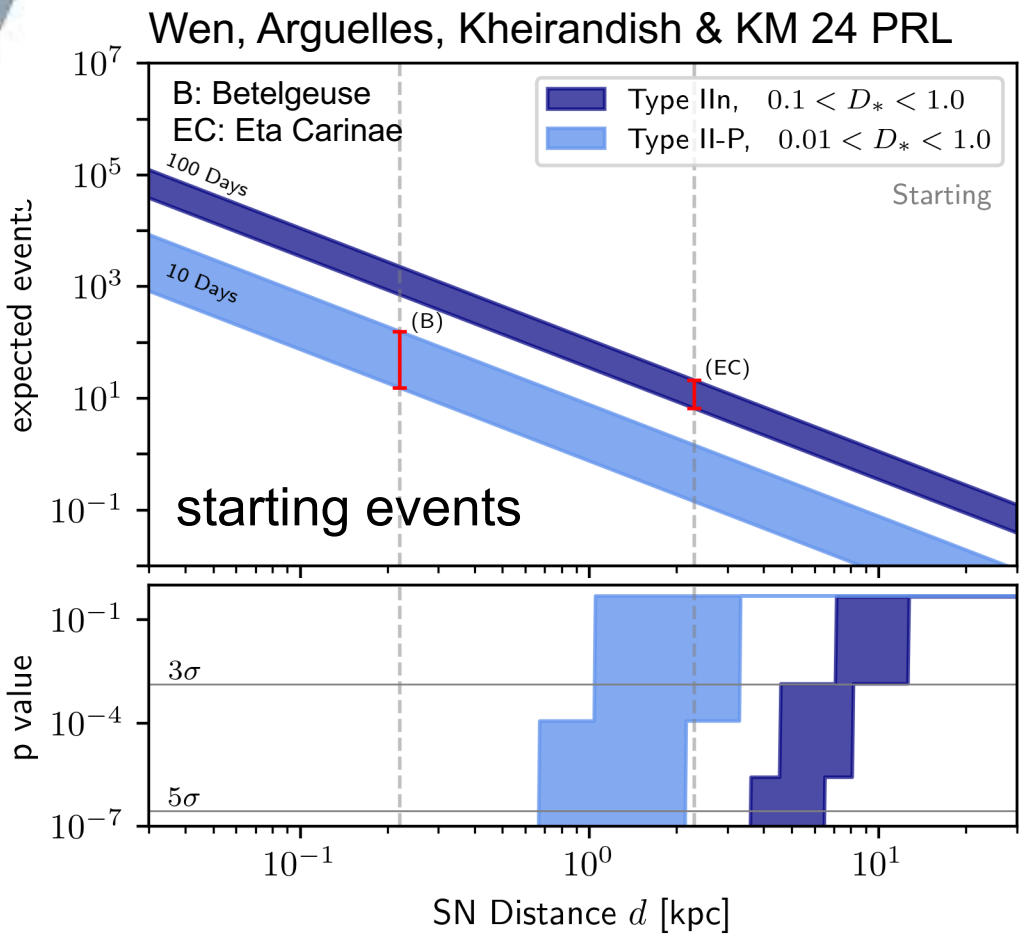
diameter 22m

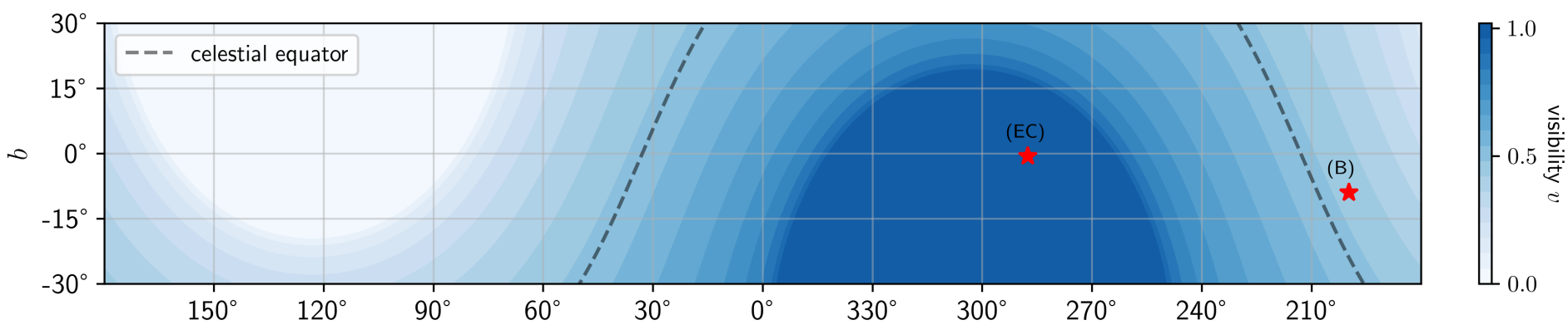
length 40m

LHC ATLAS

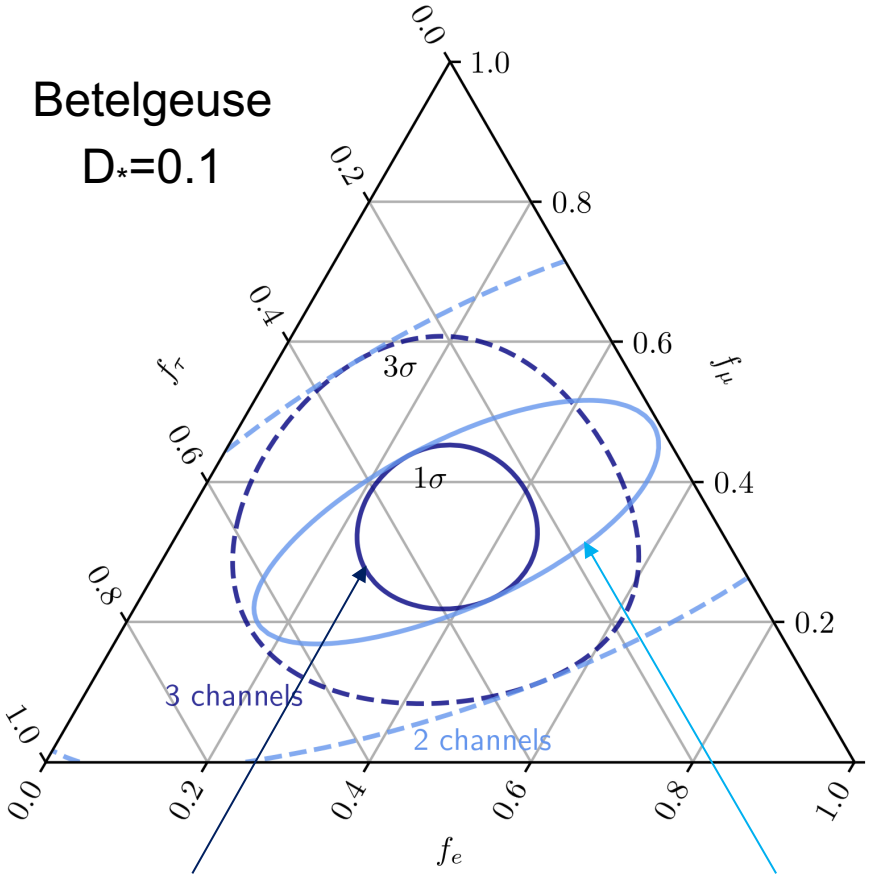
calorimeter ρV=4 kt

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



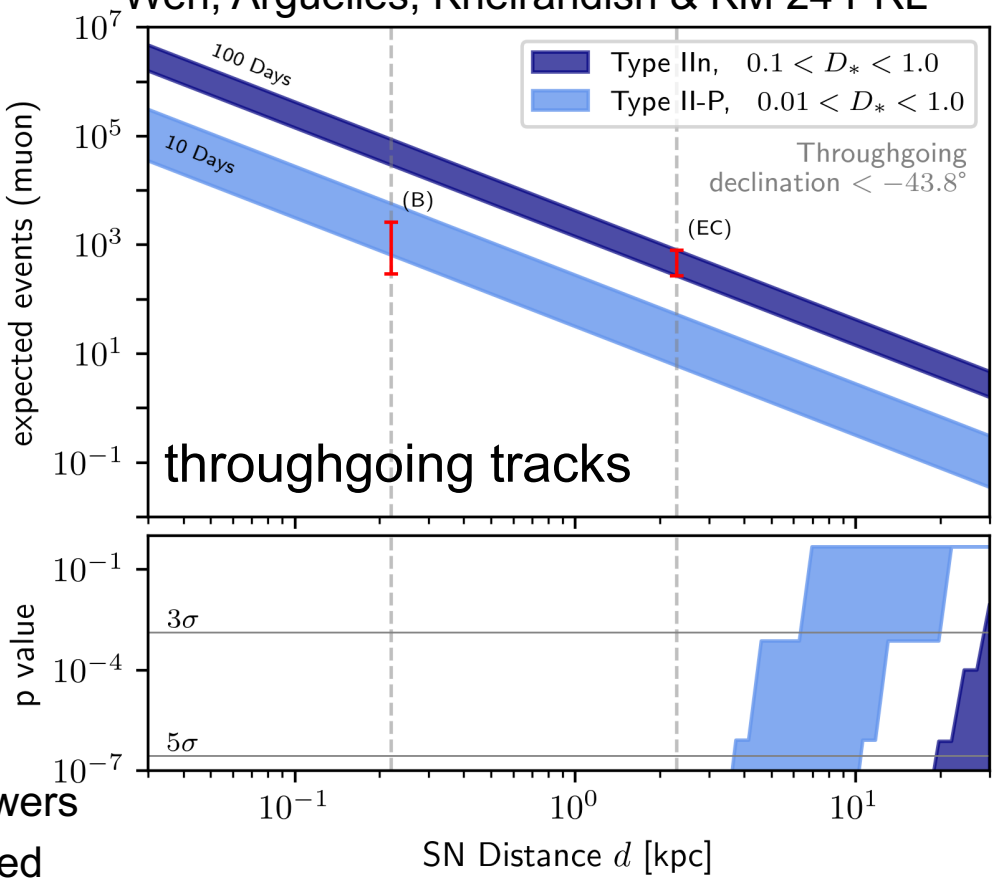


B: Betelgeuse
EC: Eta Carinae



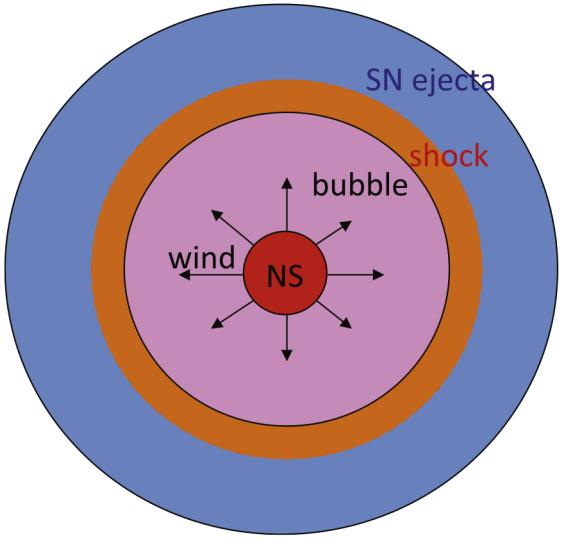
2 hadronic showers discriminated

2 hadronic showers undiscriminated

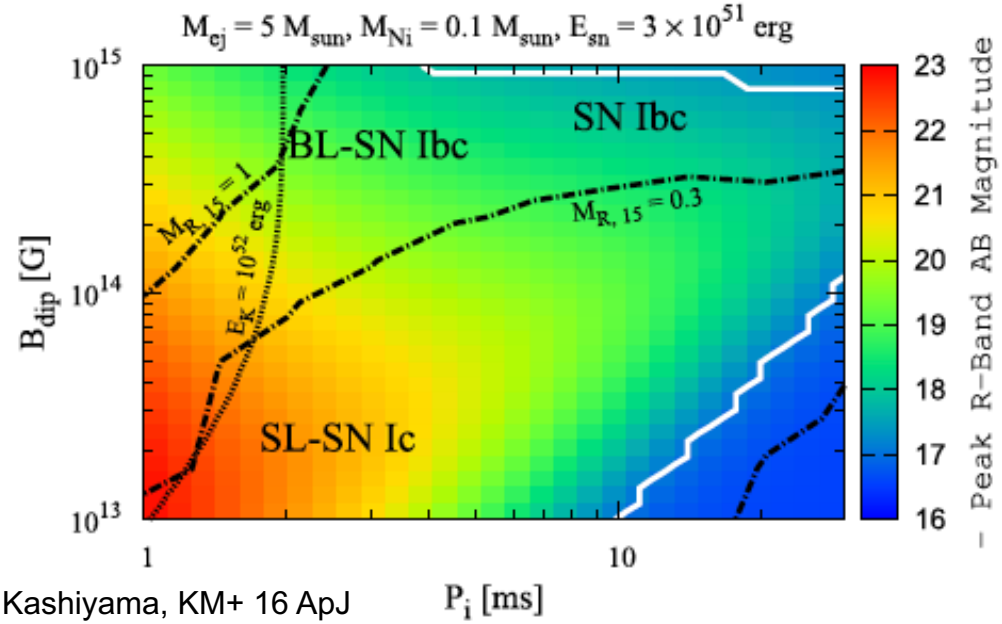


Newborn Pulsars/Magnetars as UHECR Sources?

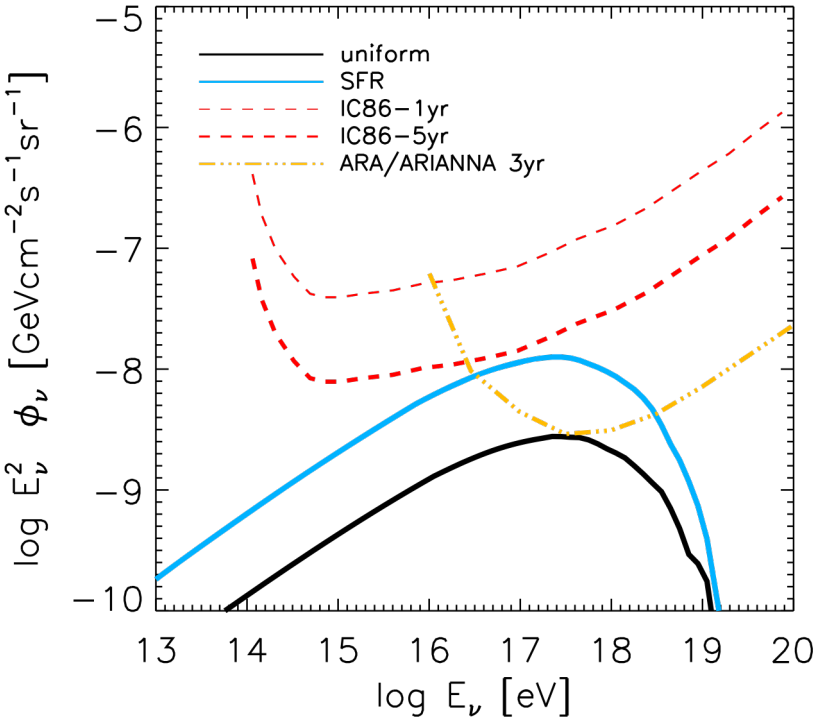
Blasi, Epstein & Olinto 00 ApJ
Arons 03 ApJ
KM, Meszaros & Zhang 09 PRD
Fang, Kotera & Olinto 12 ApJ
Fang, Kotera, KM & Olinto 14 PRD



- Shaping the diversity in transients (supernova, merger-nova, SLSN, FBOT, GRB, FRB…)
- CRs should interact with ejecta and nebular photons
- Nuclei can be supplied from the neutron star surface

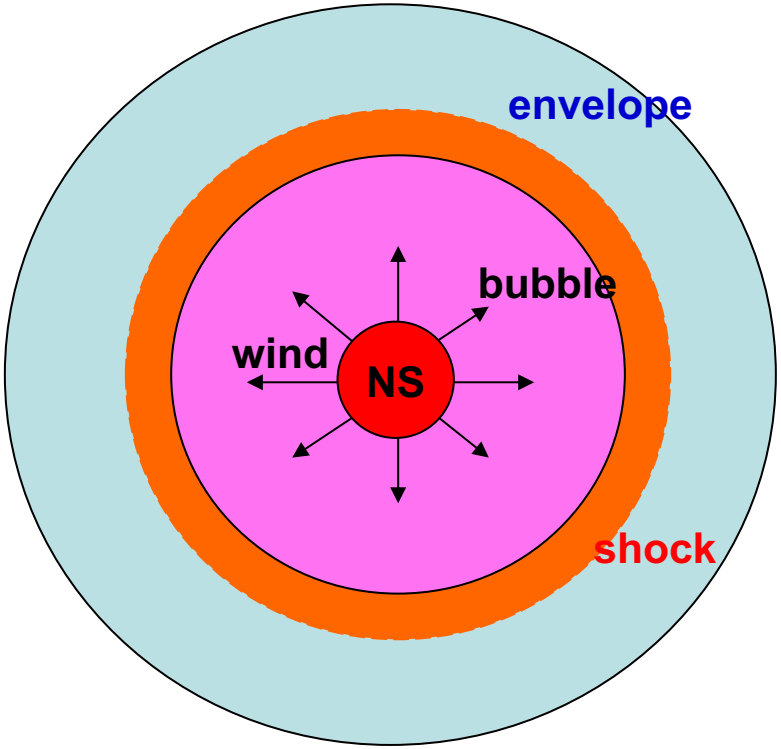


Kashiyama, KM+ 16 ApJ

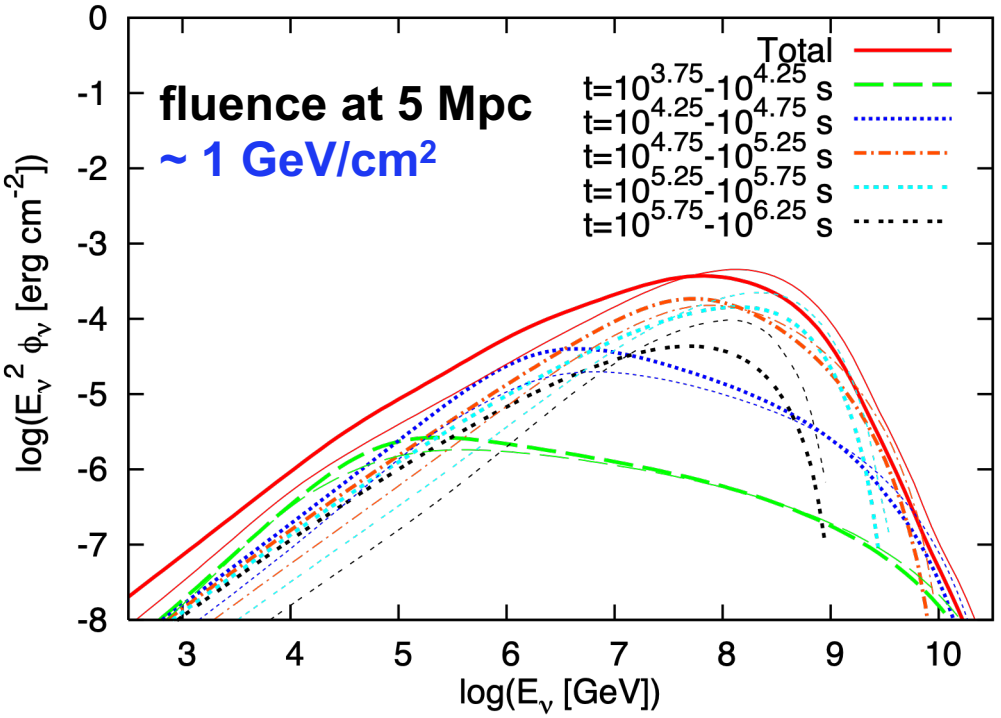


HE Neutrino Transients from Fast-Spinning Magnetars?

- Ion acceleration (<~10%) has been speculated (ex. Blasi et al. 00, Arons 03)
- Efficient ν production must occur due to interactions w. ejecta/photons
- ν signals arrive earlier -> "ν alerts" will be followed by a supernova



KM, Meszaros & Zhang 09 PRD

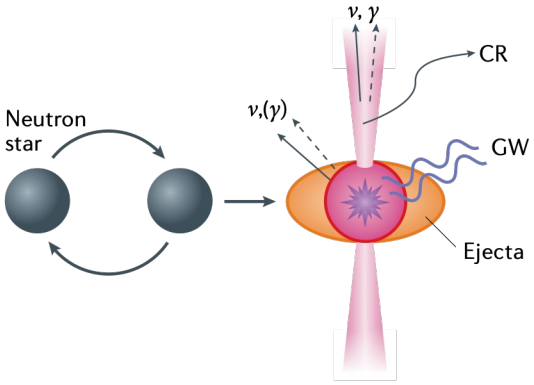


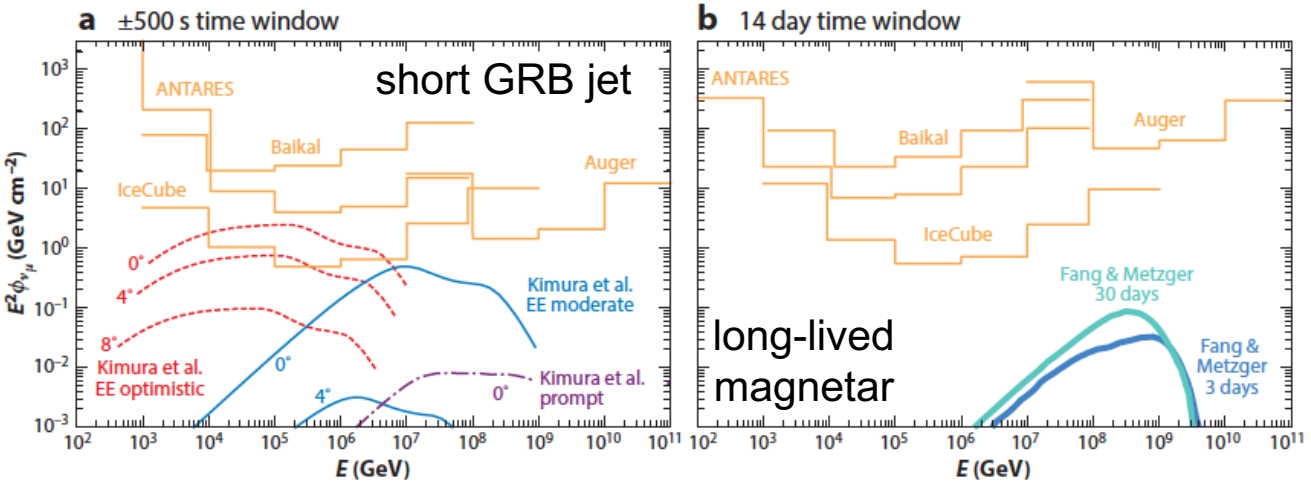
Recent developments:

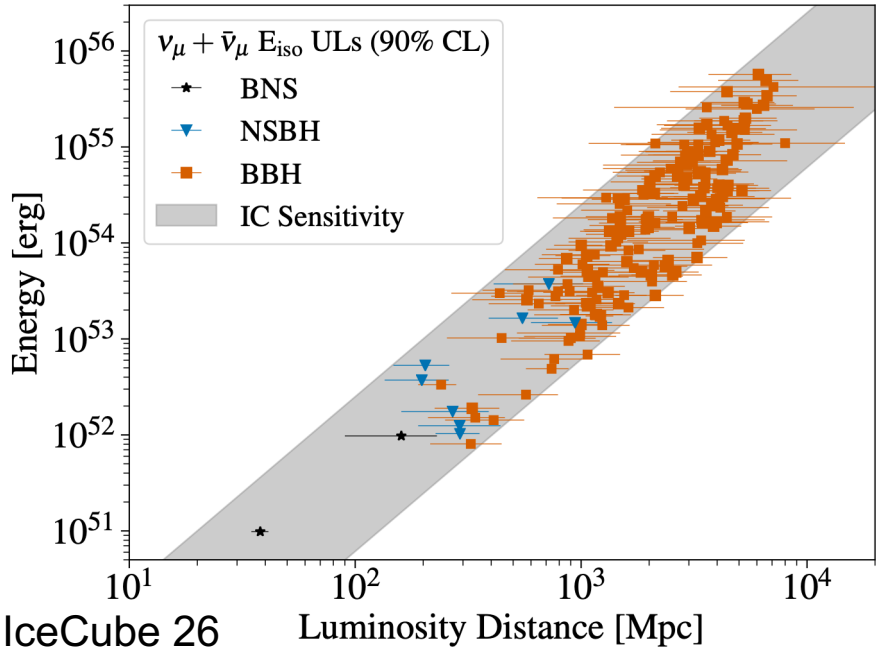
- Possible to explain the UHECR data including X_{max} (Fang et al. 13)
- Similar spectrum for NS merger ejecta (but rarer) (Fang & Metzger 17)

High-Energy Neutrino – Gravitational Wave Transients?

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





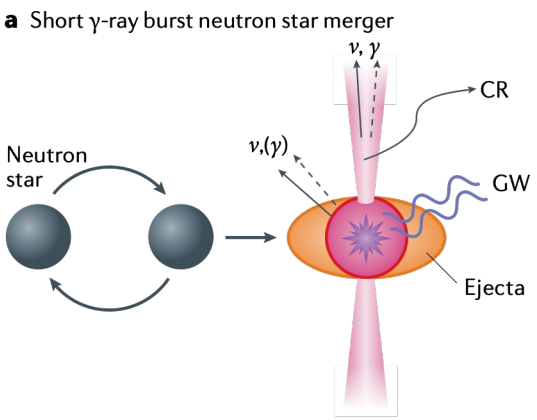


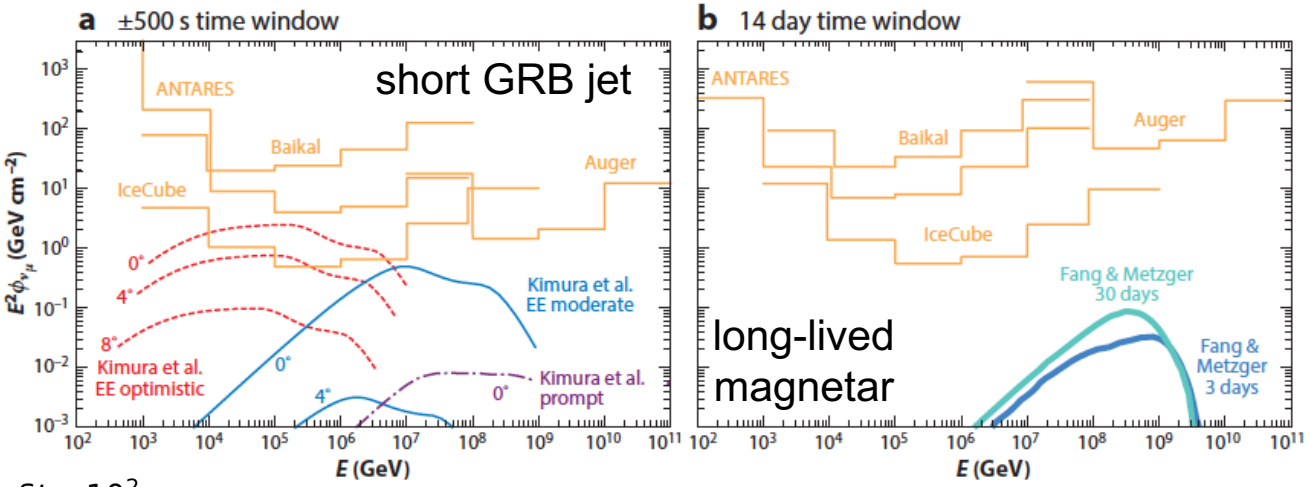
- No statistically significant coincident ν emission from significant GW sources (164 BH-BH + 10 NS-BH + 2 NS-NS) during O1-O4a run

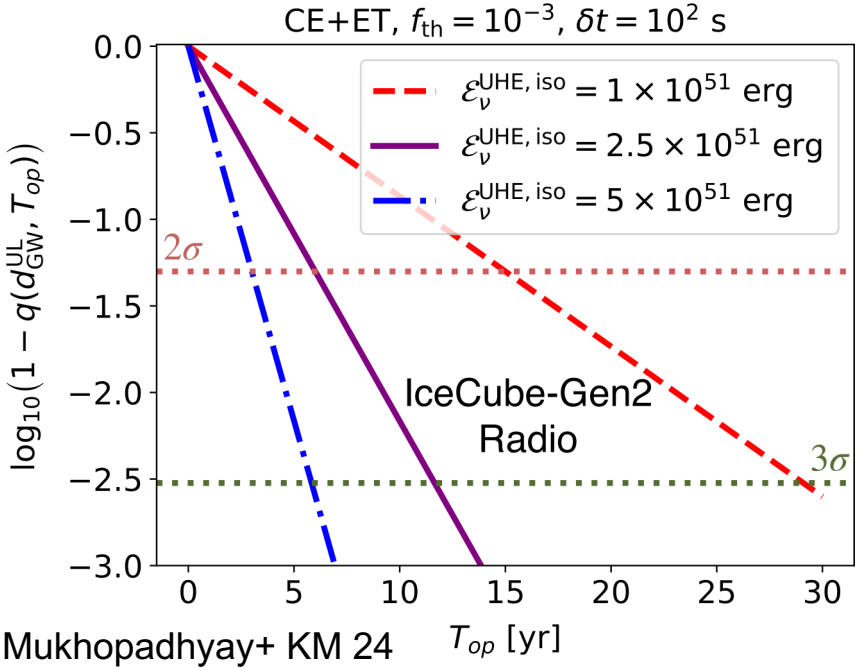
- Consistent w. theoretical expectations

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

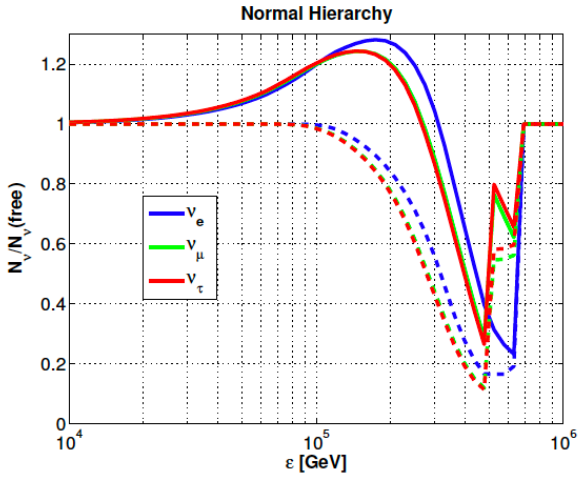
- Consistent w. theoretical expectations

- Could be detected w. next-generation neutrino and GW detectors

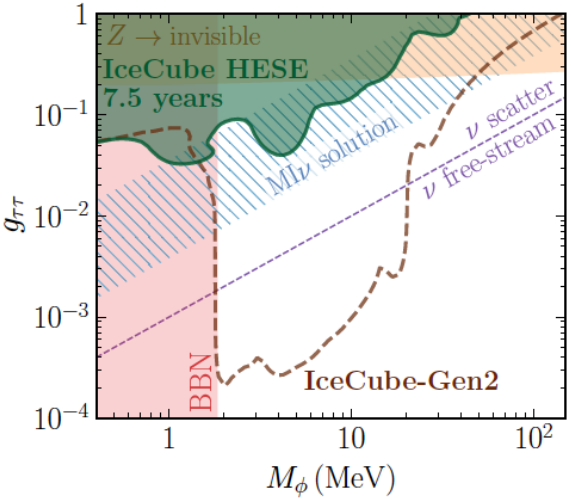
BSM Imprints on Spectra/Flavors

nonstandard interactions

Blum, Hook & KM 14

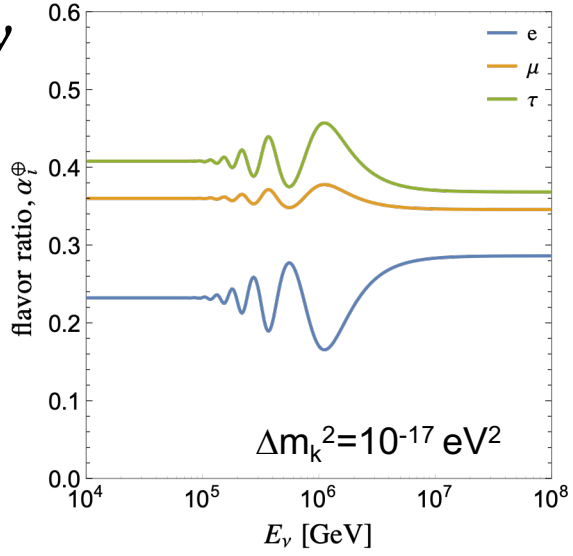


Esteban+ 21



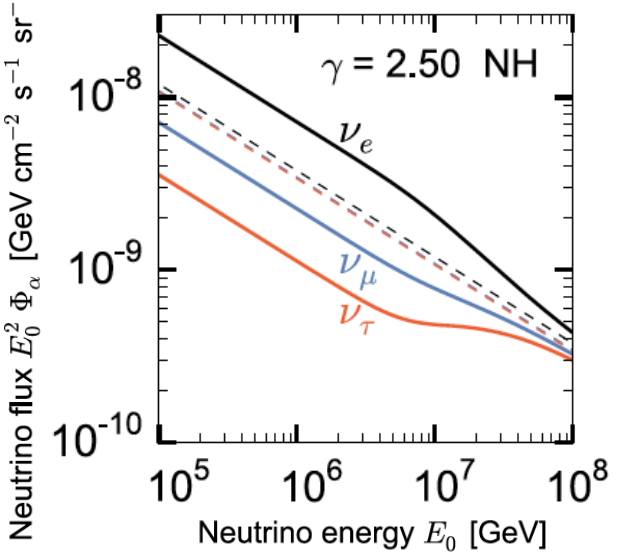
pseudo-Dirac ν

Shoemaker & KM 16



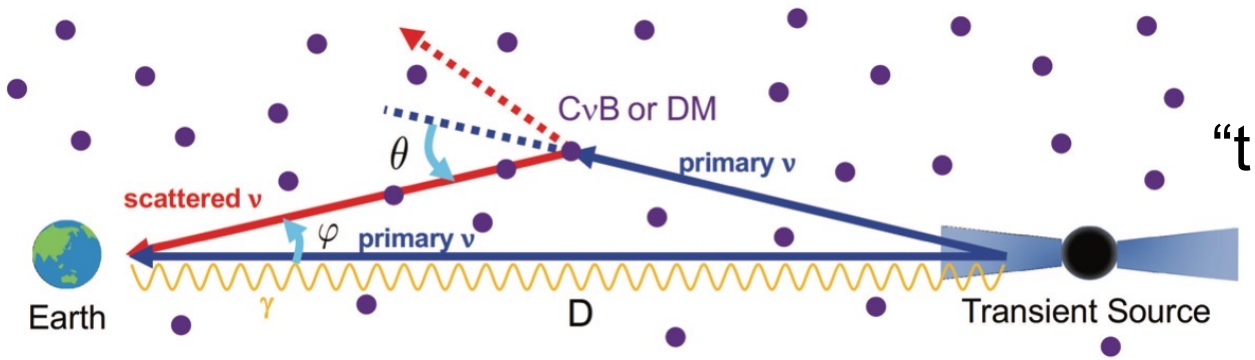
ν decay

Bustamante, Beacom & KM 17



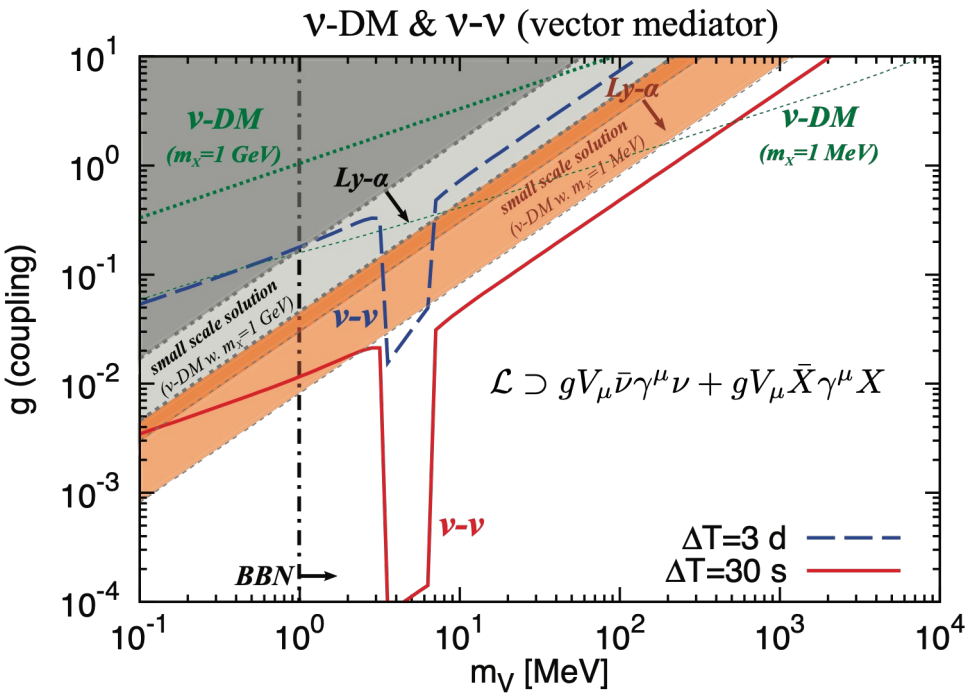
BSM & Time-Domain Multimessenger Astrophysics

KM & Shoemaker 19 PRL

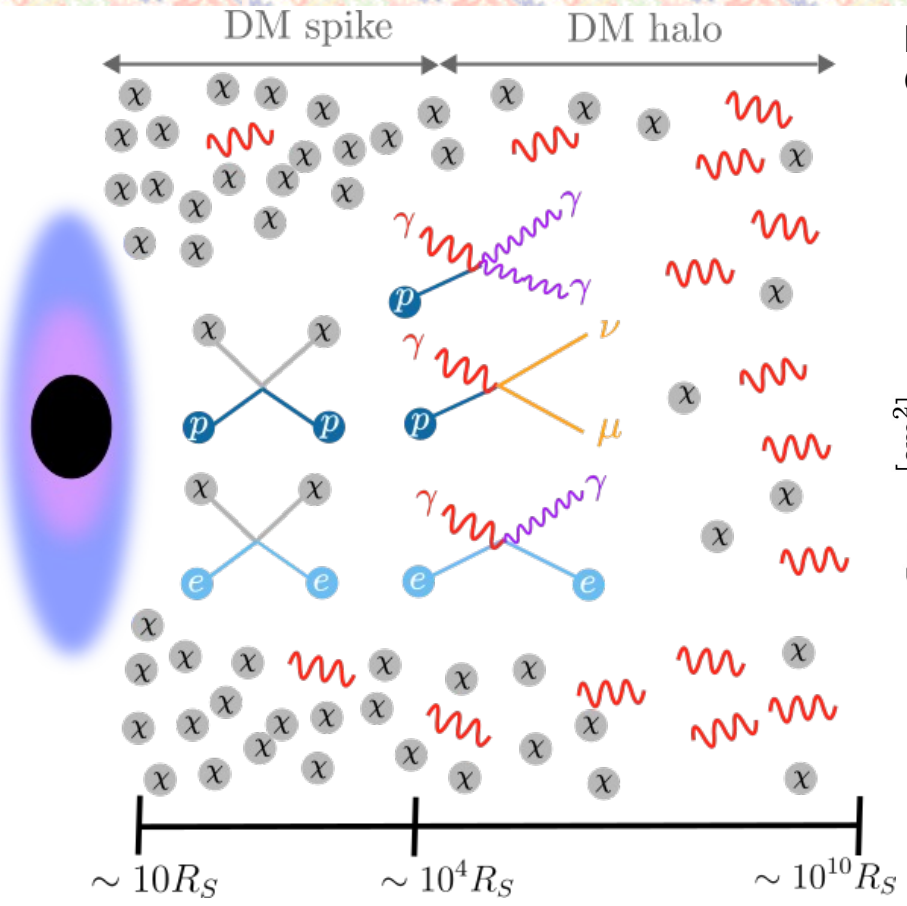


"time delay" signatures
(**neutrino echoes**)

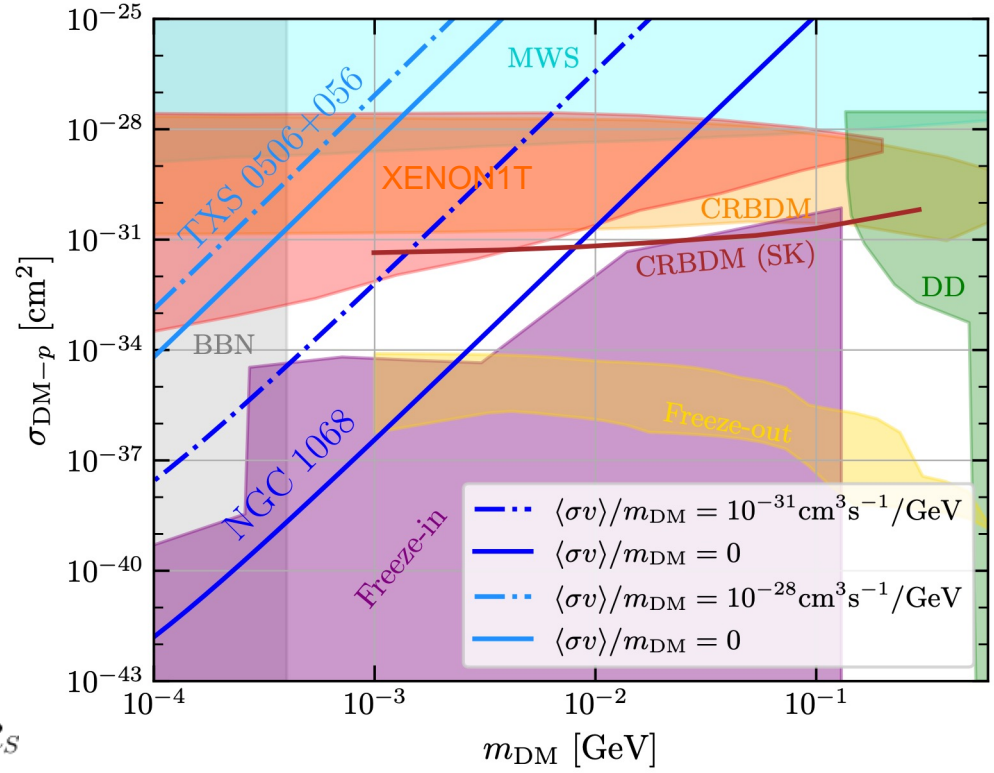
$$\Delta t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4} D \simeq 77\,\mathrm{s}\left(\frac{D}{3\ \mathrm{Gpc}}\right) C^2 \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$



Supermassive Black Hole Neutrinos as a Probe of Dark Matter



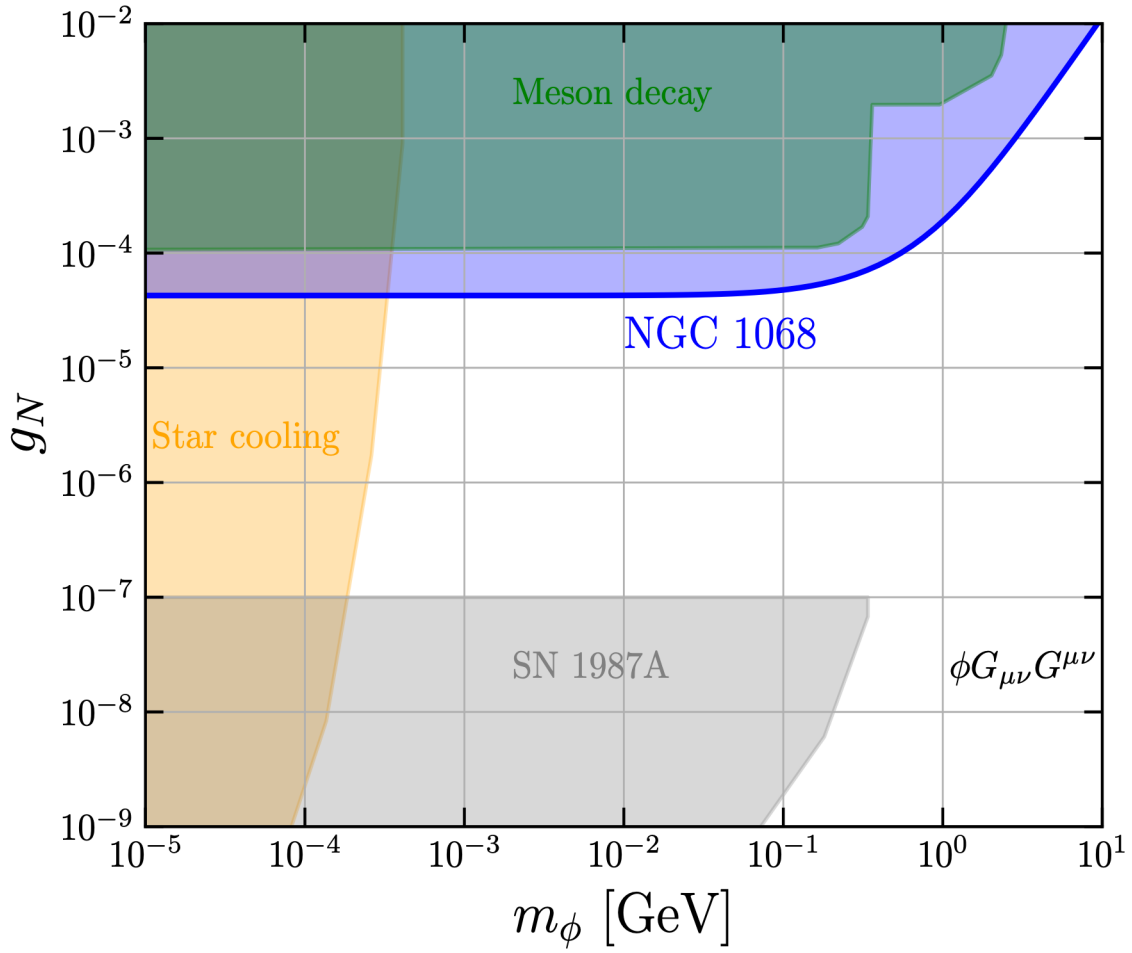
Herrera & KM 24 PRDL
Gustafson, Herrera, Mukhopadhyay, KM & Shoemaker 2408.08947



- 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



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

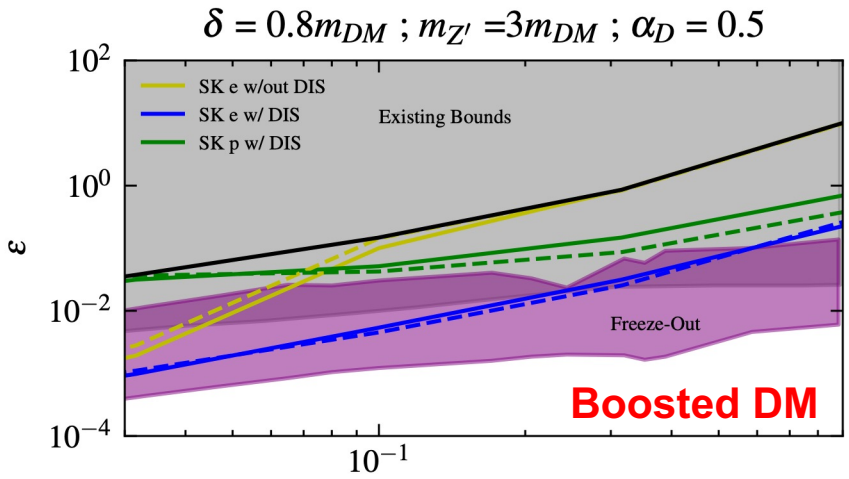
$$\frac{d\sigma^{\phi}_{\mathrm{DM-CR}i}}{dT_{\mathrm{DM}}} = \frac{m_\phi^4}{\left(q^2 + m_\phi^2\right)^2} \frac{d\sigma_{\mathrm{DM-CR}i}}{dT_{\mathrm{DM}}}$$

non-relativistic DM cross section

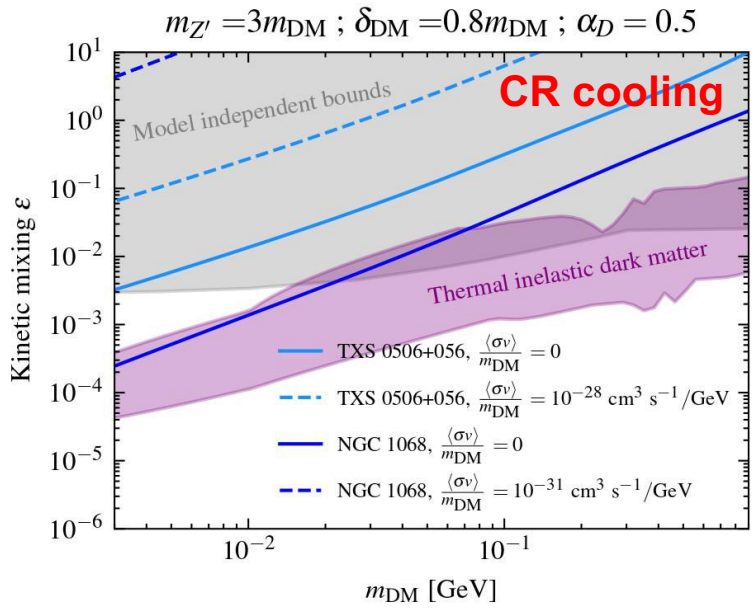
$$\sigma_{\mathrm{DM}-N} = \frac{g_\chi^2 g_N^2 \mu_{\chi-N}^2}{\pi m_\phi^4}$$

- NGC 1068 observations enable us to probe new parameter space

Application to Inelastic Dark Matter

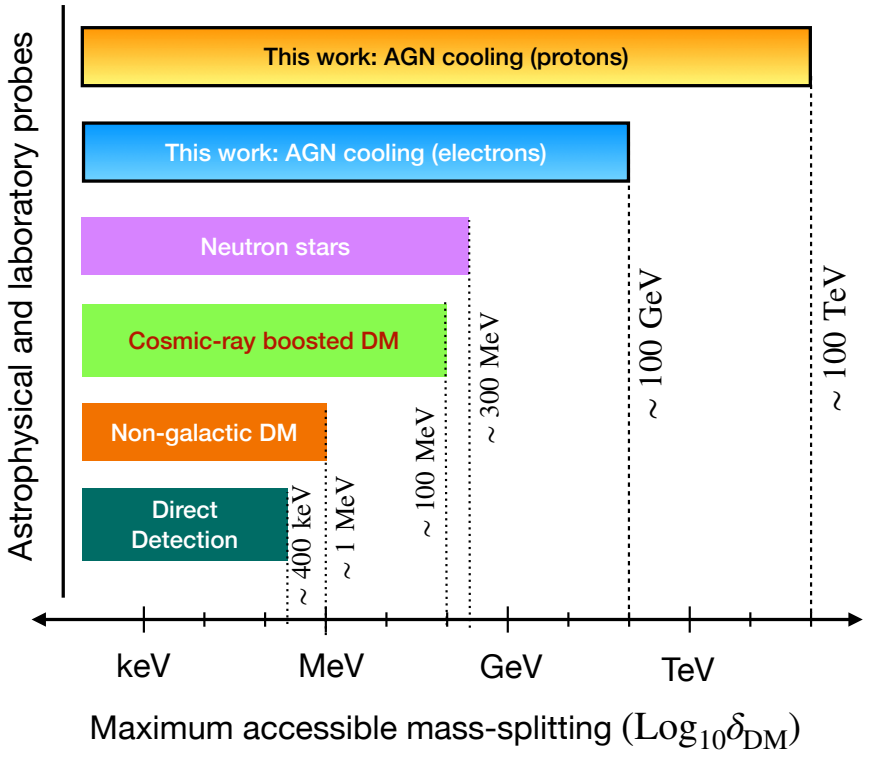


(heavy mediator)



$$\chi_1 + i \rightarrow \chi_2 + i$$

- 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