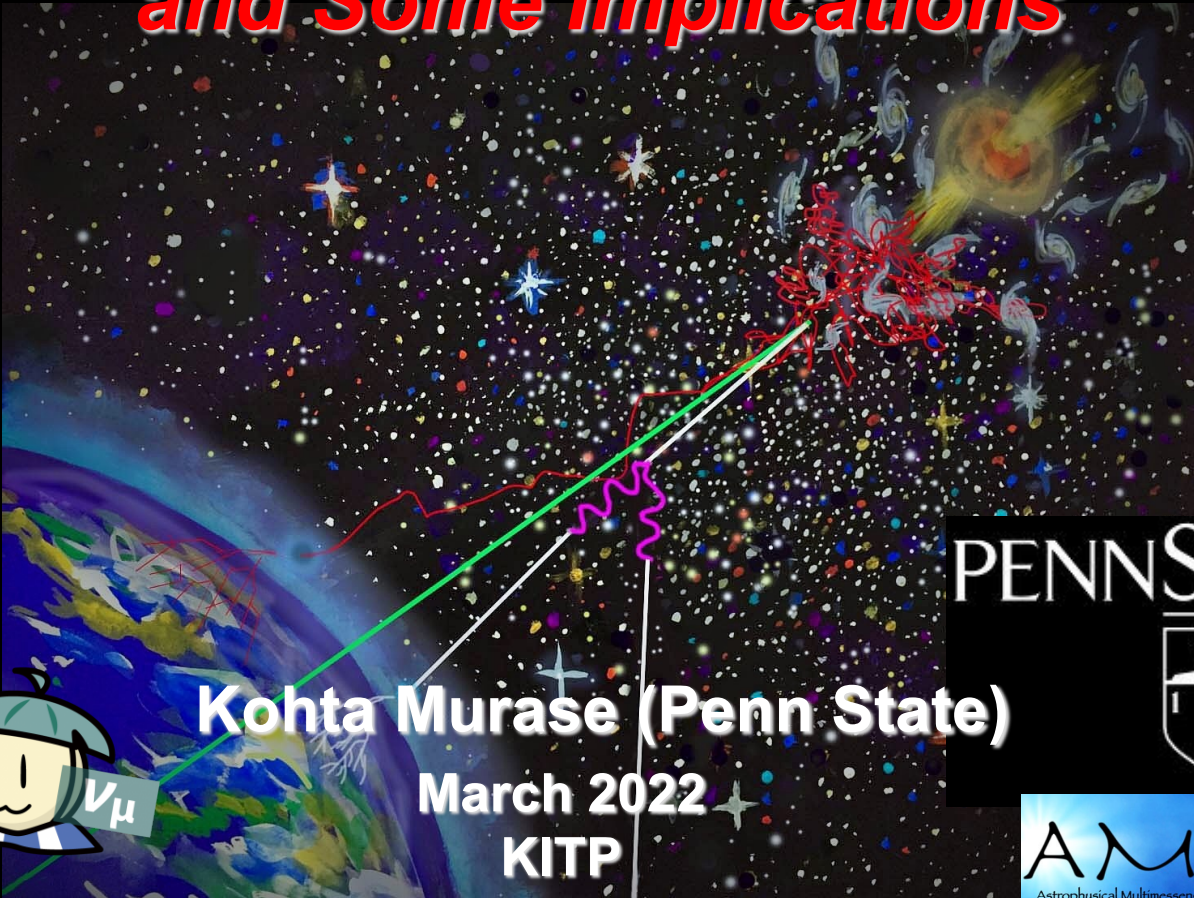


# Promising Sources of High-Energy Neutrinos and Some Implications



Kohta Murase (Penn State)

March 2022

KITP

PENNSTATE



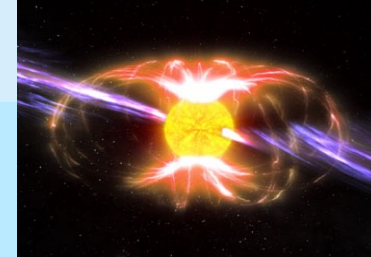
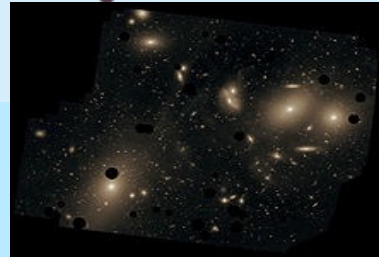
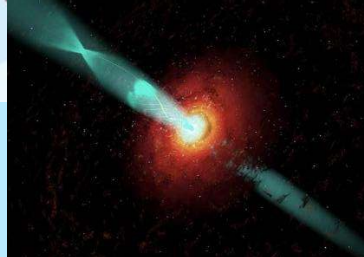
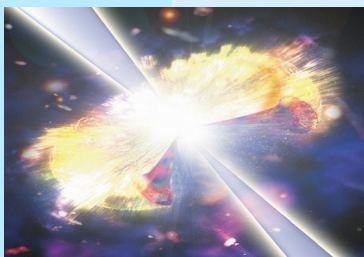
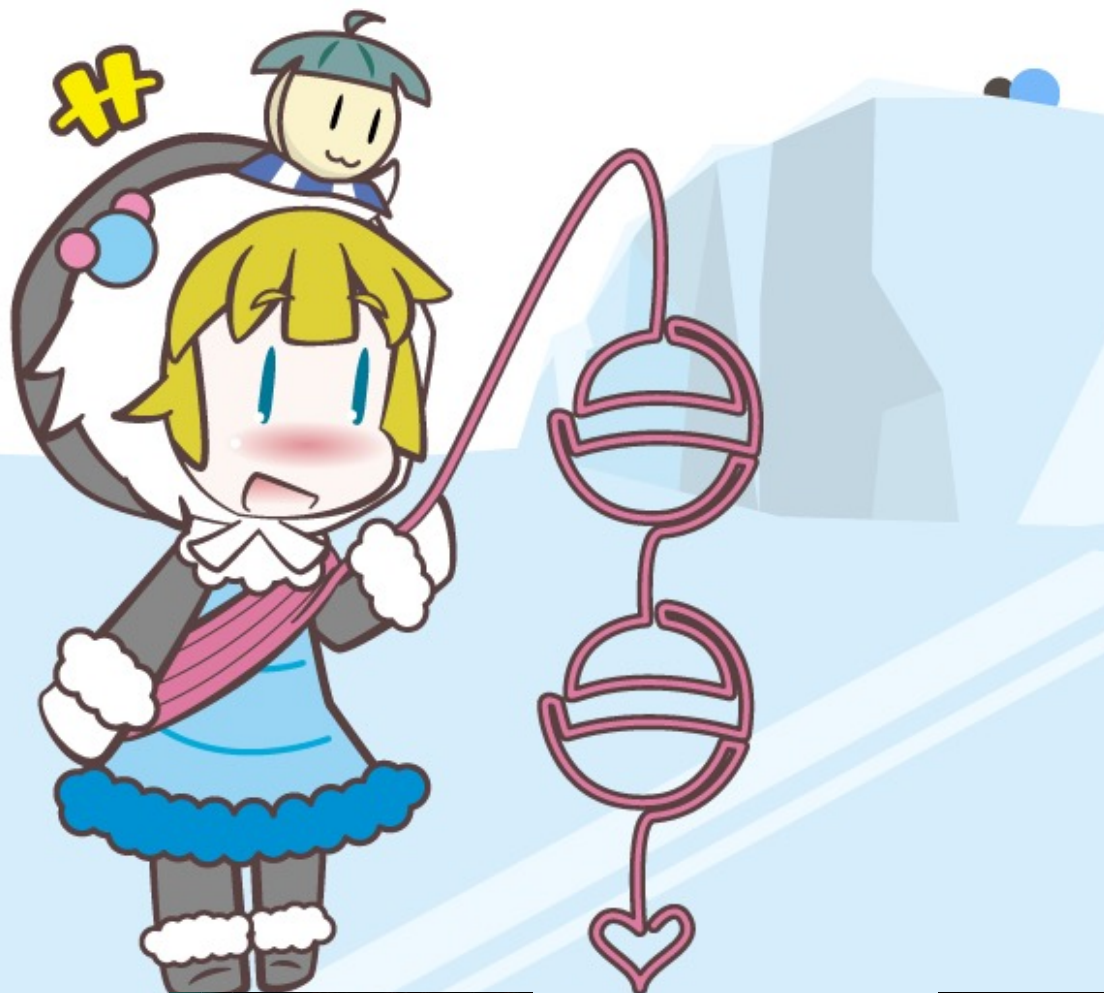
AMON

Astrophysical Multimessenger Observatory Network



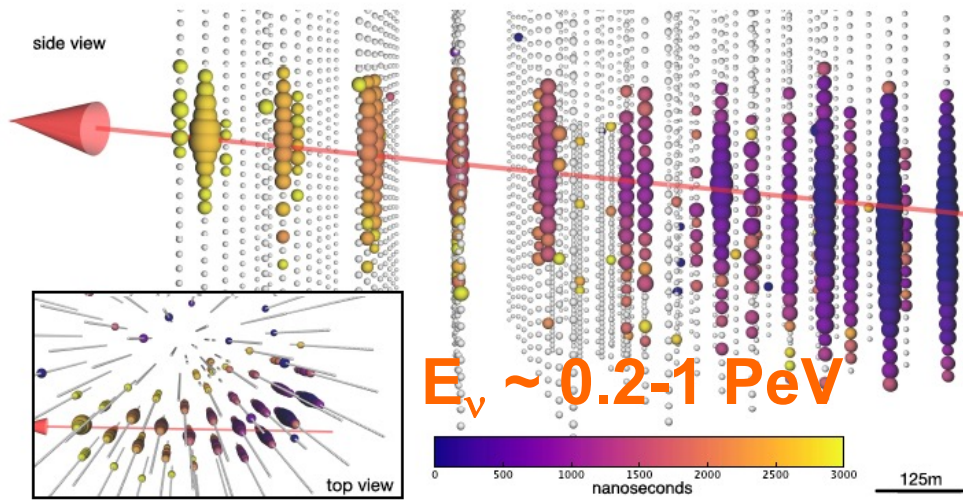
# Sources?

monster  
fishing!!



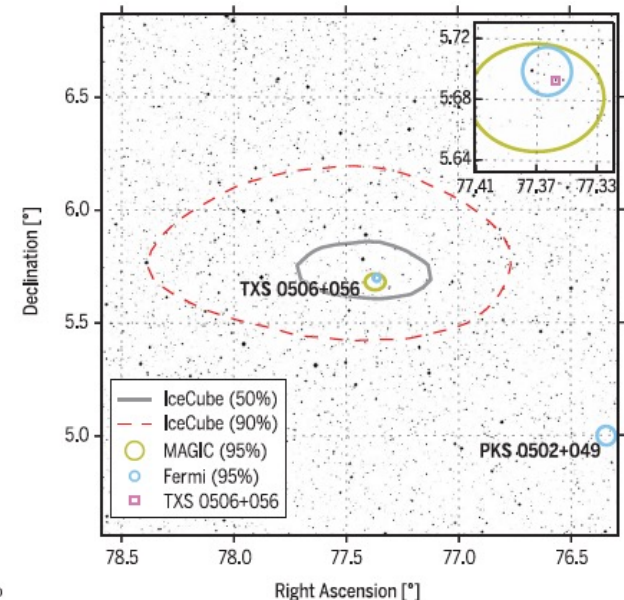
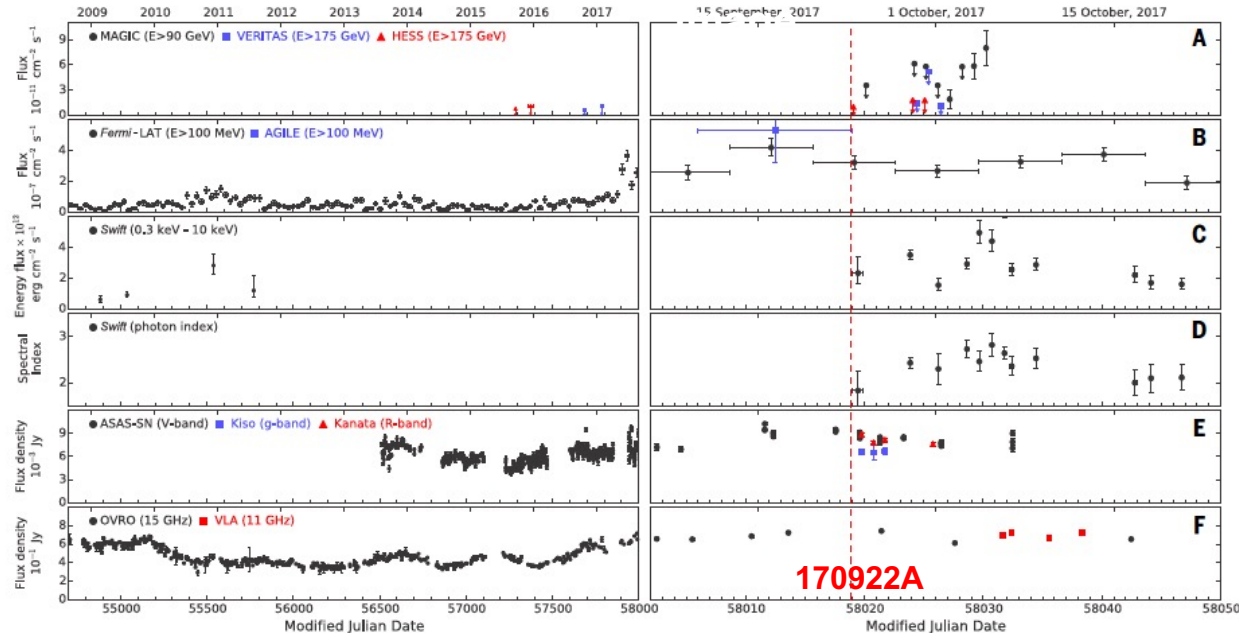


# IceCube 170922A & TXS 0506+056



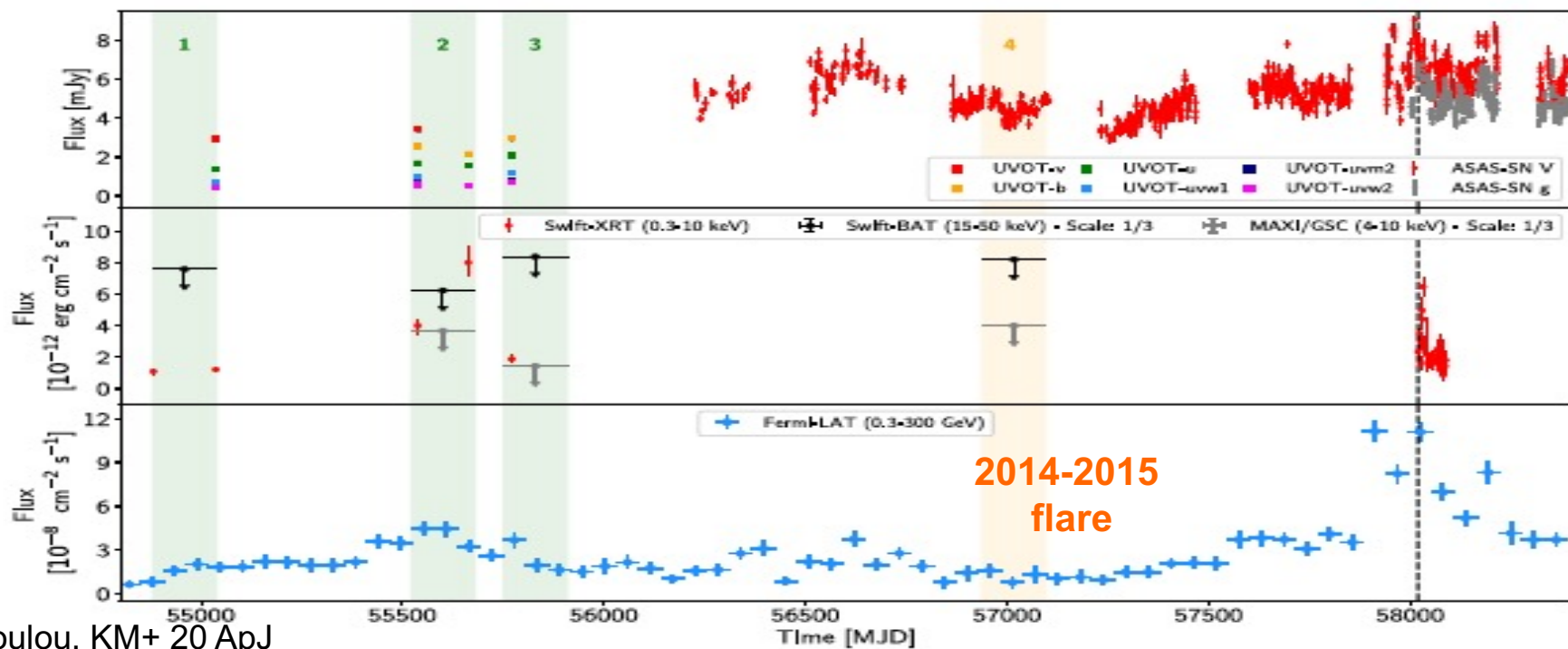
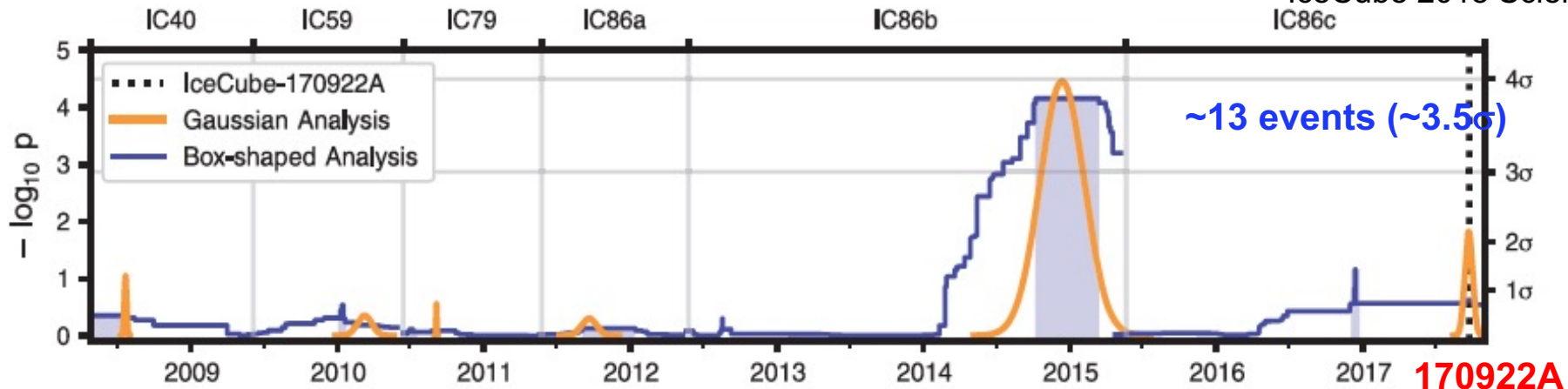
- IceCube EHE alert pipeline
- Automatic alert (via AMON/GCN)
- Kanata observations of blazars  
-> Fermi-LAT (Tanaka et al.)  
ATel #10791 (Sep/28/17)
- Swift (Keivani et al.)  
GCN #21930, ATel #10942  
NuSTAR (Fox et al.) ATel #10861
- **$\sim 3\sigma$  coincidence**

## IceCube 2018 Science

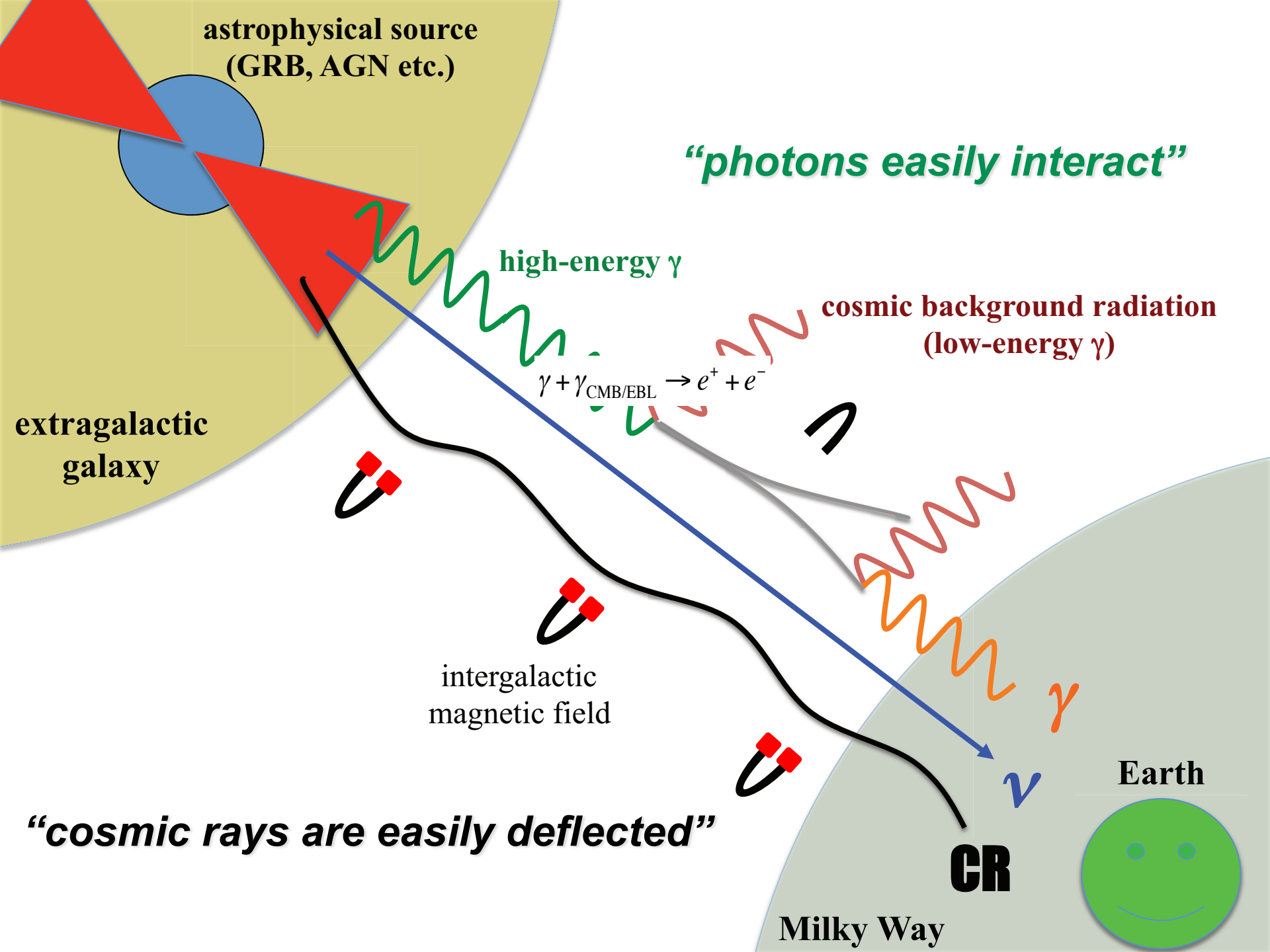


# 2014-2015 Neutrino Flare

IceCube 2018 Science







astrophysical source  
(GRB, AGN etc.)

**"photons easily interact"**

high-energy  $\gamma$

cosmic background radiation  
(low-energy  $\gamma$ )

$$\gamma + \gamma_{\text{CMB/EBL}} \rightarrow e^+ + e^-$$

extragalactic  
galaxy

intergalactic  
magnetic field

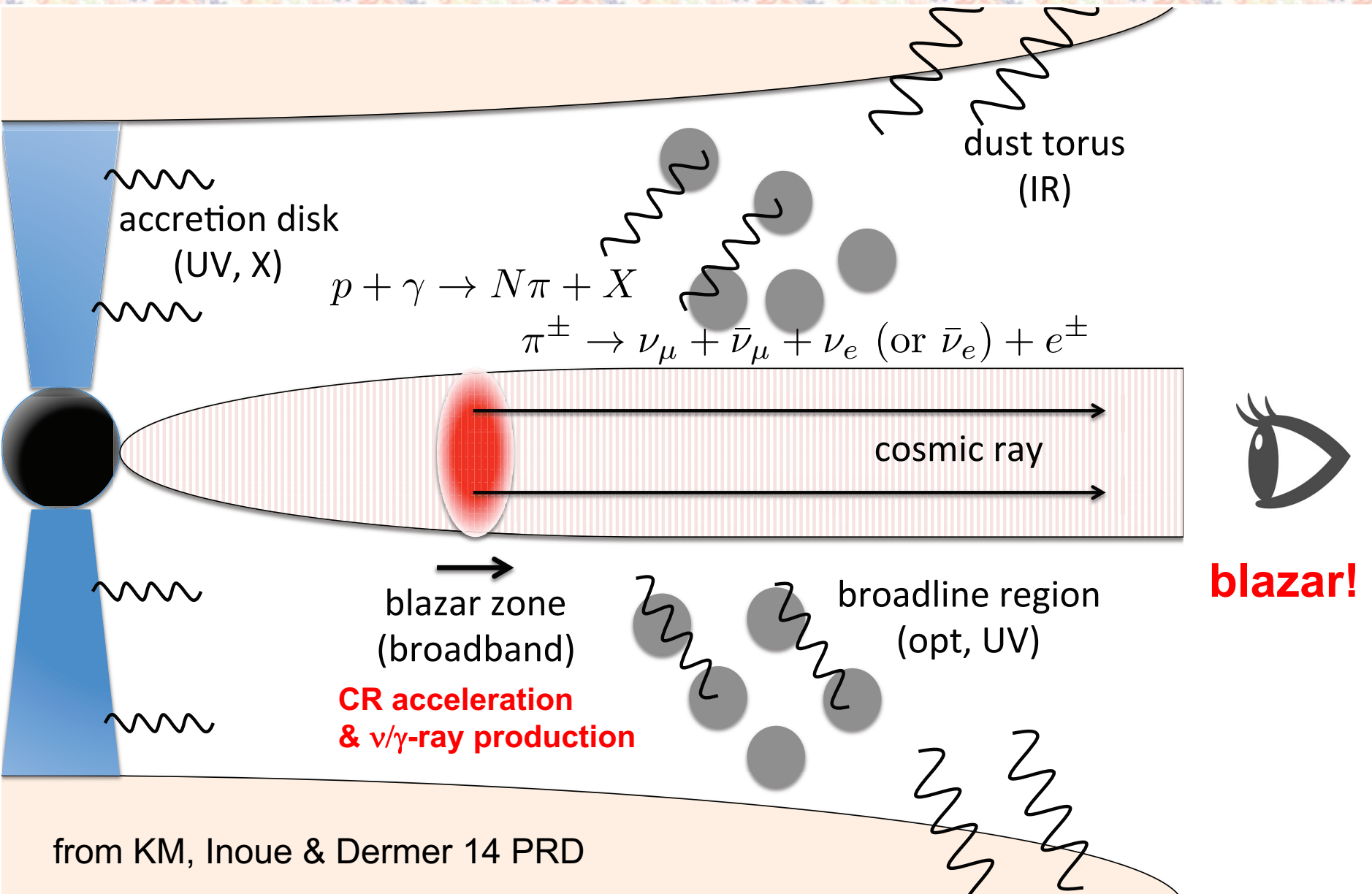
**"cosmic rays are easily deflected"**

Earth

**CR**

Milky Way

# Neutrino Production in AGN Jets





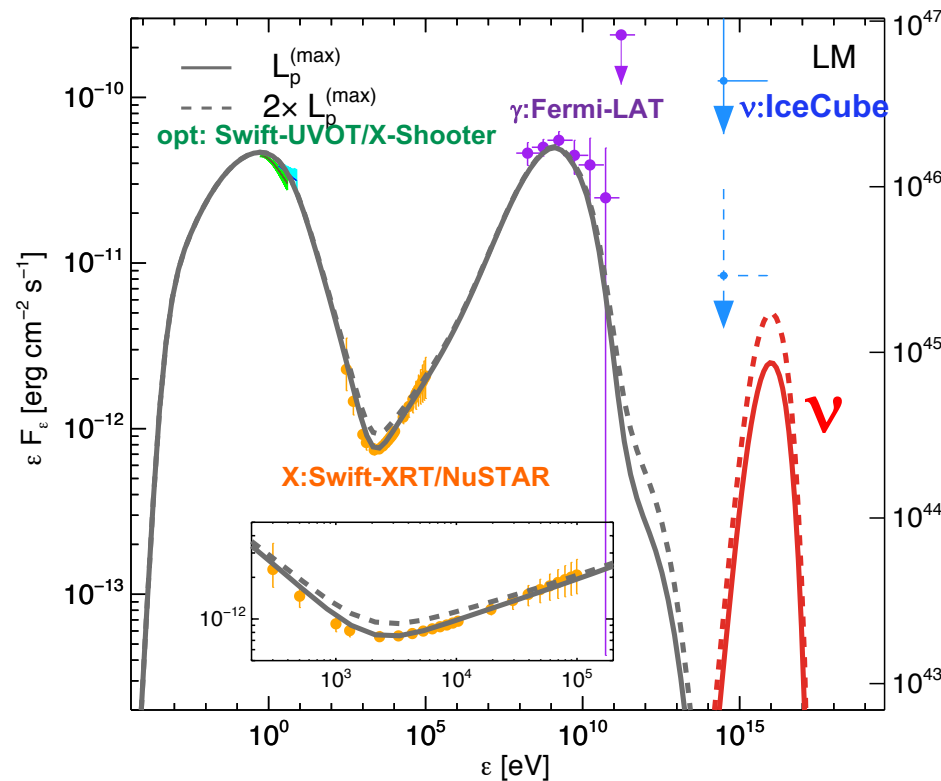
# “Power” of Multi-Messenger Approaches

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

electromagnetic energy must appear at keV-MeV

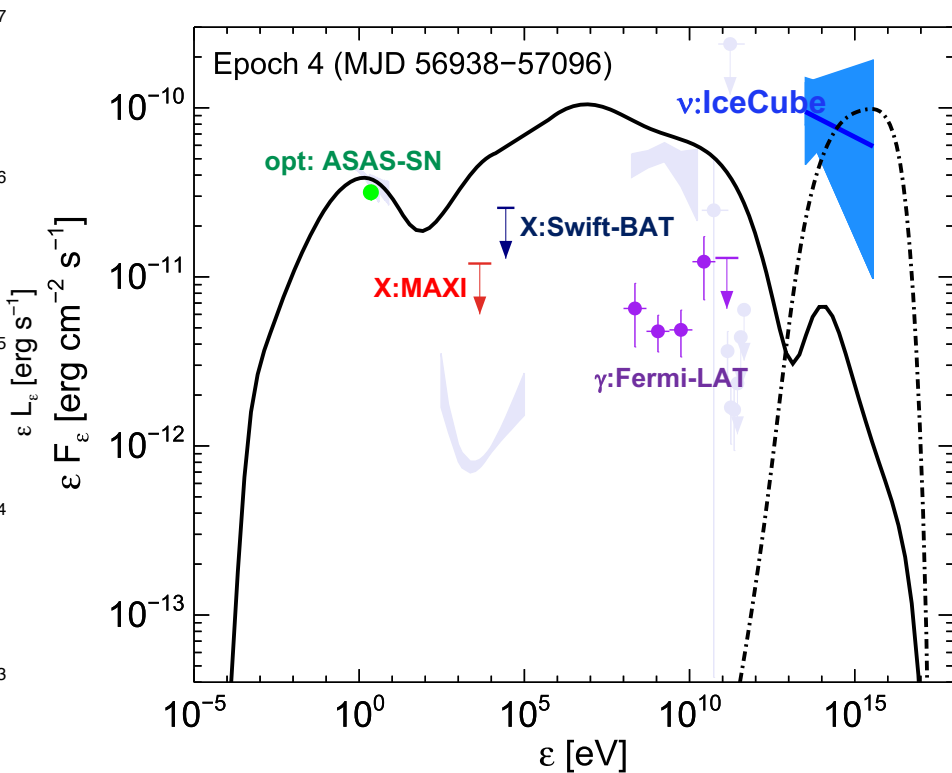
2017 multi-messenger flare

Keivani, KM et al. 18 ApJ



2014-2015 neutrino flare

Petropoulou, KM et al. 20 ApJ

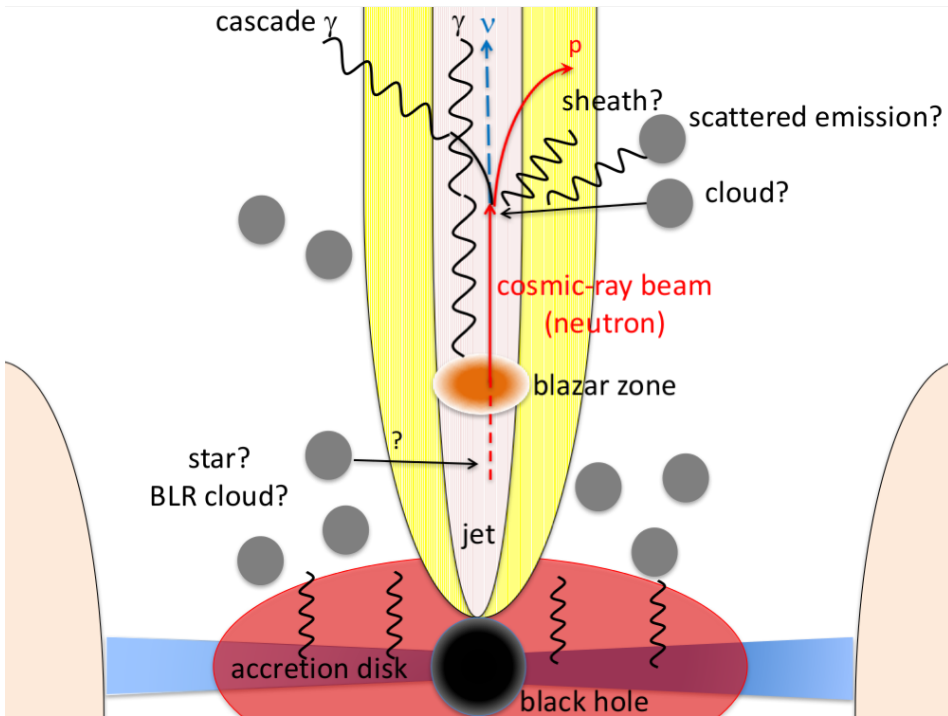


**Puzzling:** standard single-zone models do NOT give a concordance picture

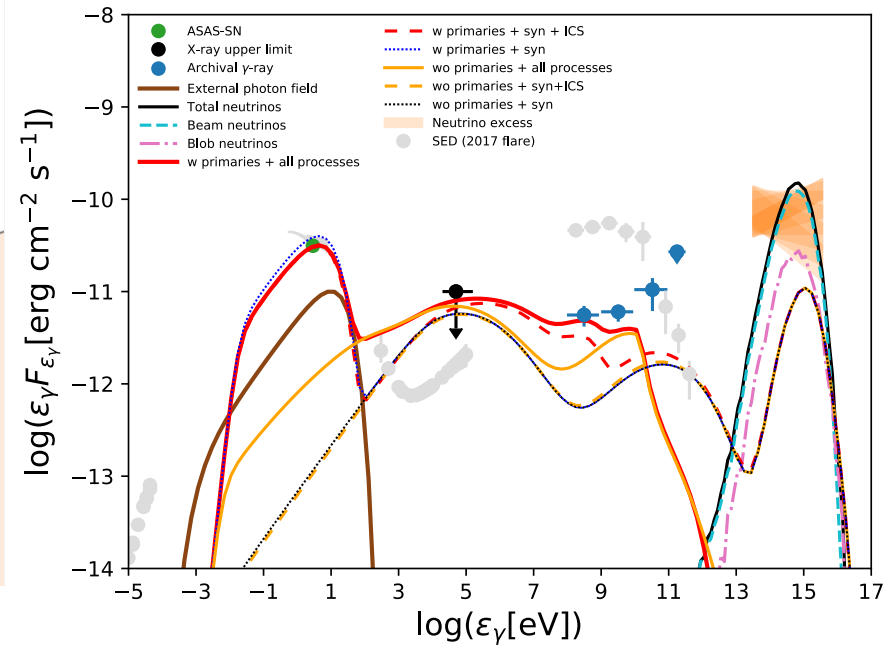
# Beyond the Canonical Single-Zone Emission Model

We presented the most detailed multi-messenger analyses and modeling.  
→ “If the association is physical, multi-zone emission models are necessary.”

**cosmic-ray beam model:** minimum extension, relaxing cascade constraints



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



Other coincidences w. flares? - yes

3HSP J095507.9 +355101 (Petropoulou+ KM 20 ApJ), PKS 1502+106 (Oikonomou+ KM 21)

However, more follow-up campaigns and/or larger statistics in  $\nu$  data are necessary



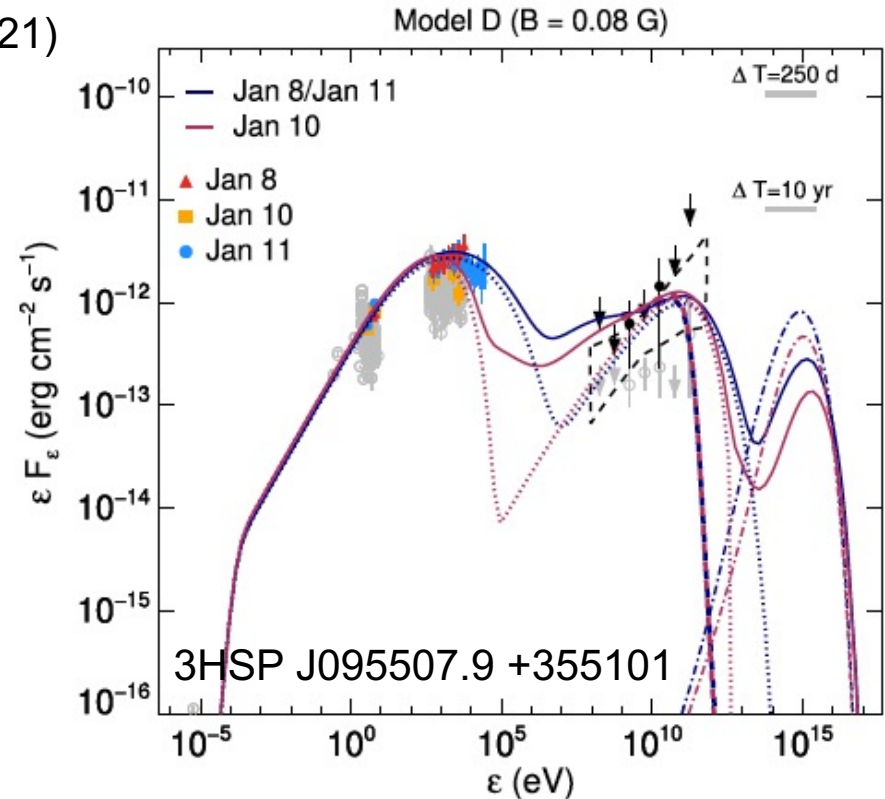
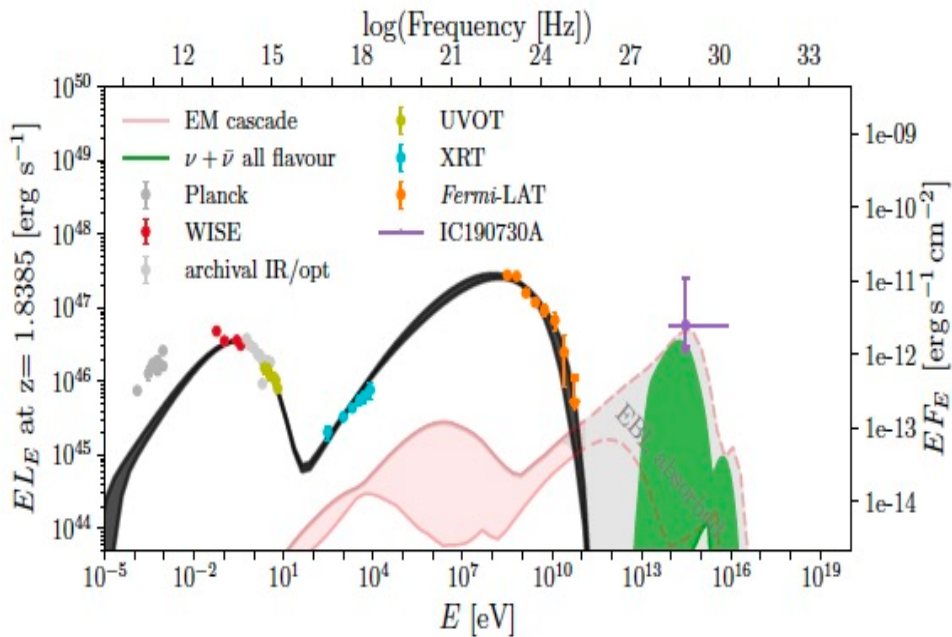
# Other Coincidences?

More follow-up campaigns and/or larger statistics in  $\nu$  data are necessary  
 But the situation is still puzzling...

IceCube-200107A

(Petropoulou, Oikonomou, Mastichiadis, KM+ 20)

IceCube-190730A (Oikonomou, Petropoulou, KM+ 21)



- PKS 1502 +106: FSRQ

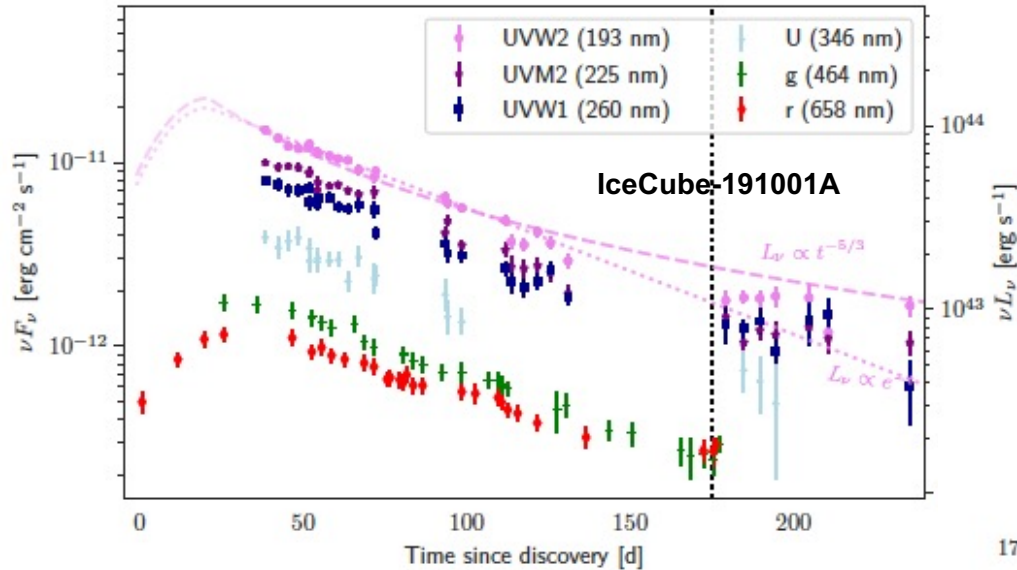
promising but no coincidence w.  $\gamma$ -ray flaring, unseen in  $\nu$  point-source search

- 3HSP J095507.9 +355101: extreme BL Lac

coincidence w. X-ray flaring but the alert rate is at most  $\sim 1-3\%$  in 10 years

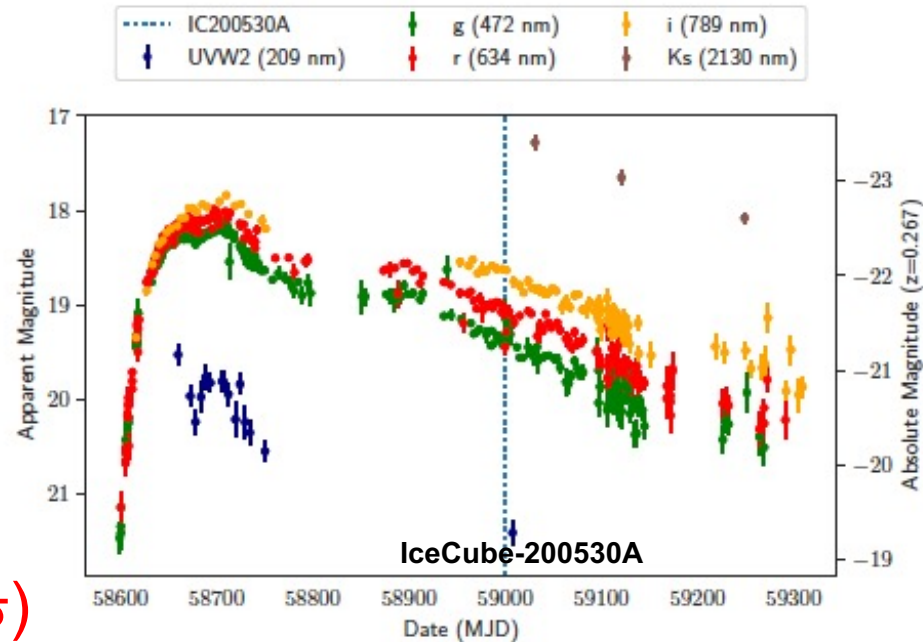
# More Coincidences?

Blazars: IceCube-190730A & PKS 1502 +106, IceCube-200107A & 3HSP J095507.9 +355101



IceCube-191001A  
& AT 2019dsg  
(Stein+ 21 Nature Astron.)

IceCube-200530A  
& AT 2019fdr  
(Reusch+ KM 21 PRL accepted)



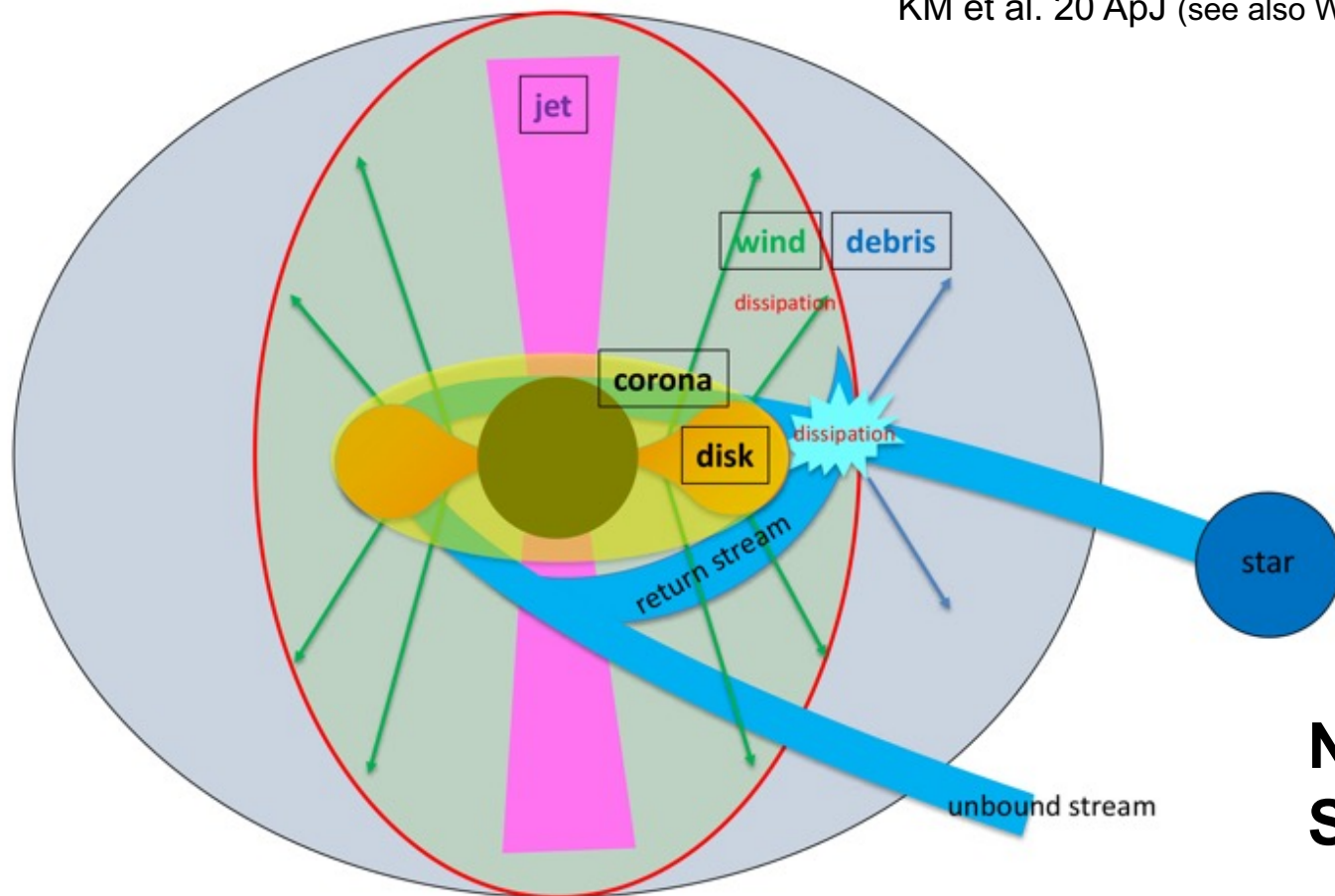
Both are rare optical transients  
with strong radio emission ( $>3.4\sigma$ )



# Neutrinos from Black Hole “Flares”?

- AT 2019dsg & AT 2019fdr = tidal disruption event (TDE)
- TDE and AGN  $\nu$  emission may share common mechanisms (disk-corona? jet? stellar debris as a cosmic-ray reservoir?)

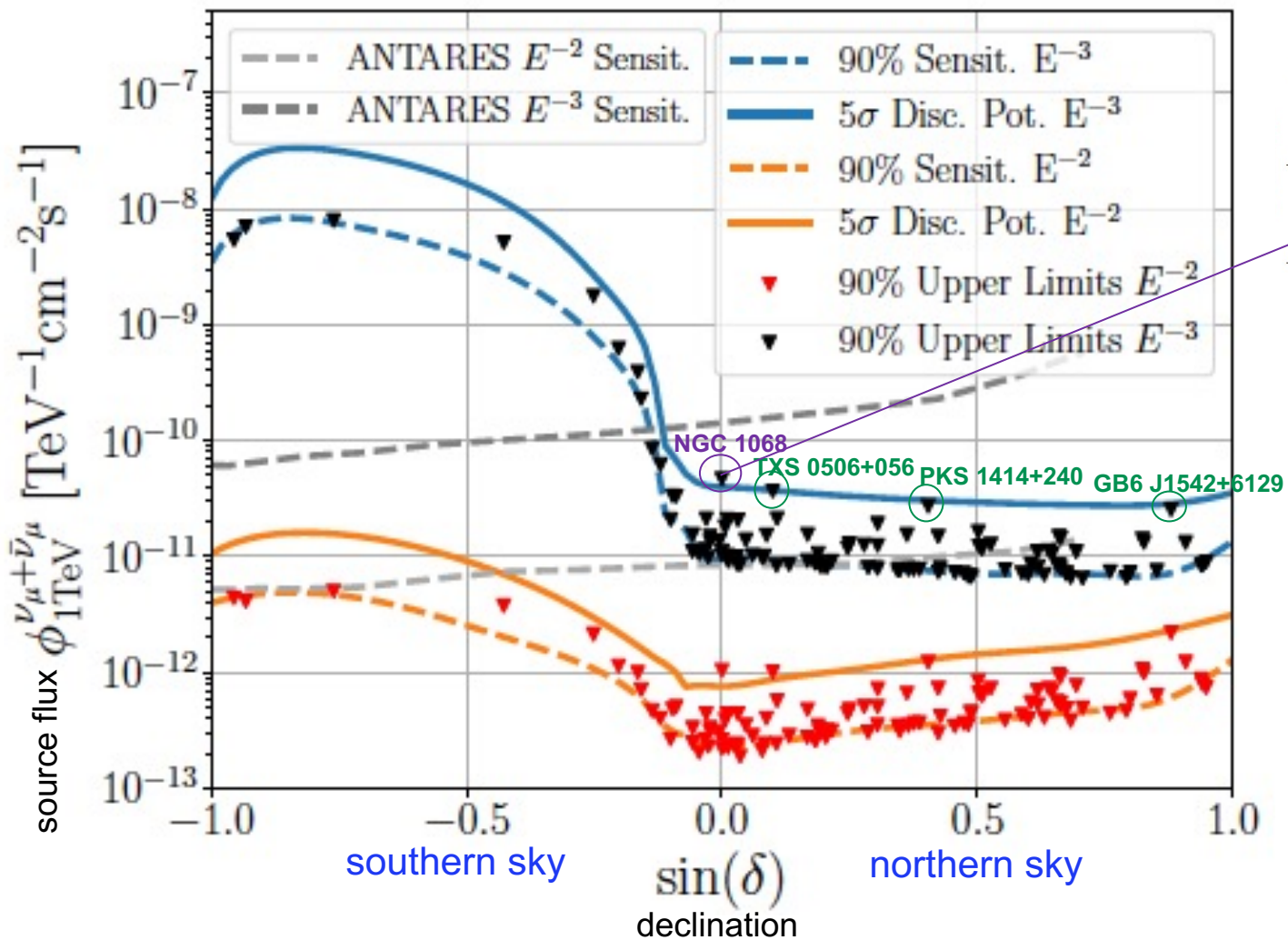
KM et al. 20 ApJ (see also Winter & Lunardini Nature Astron. 21)



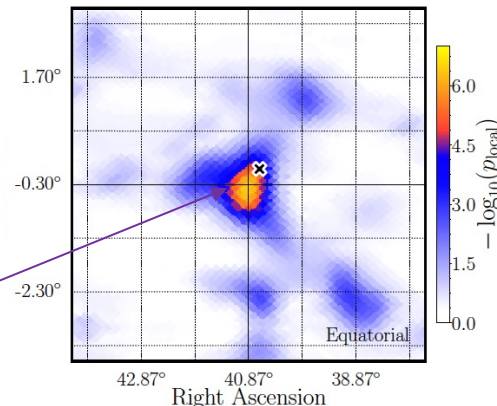
**Need more data  
Stay tuned!!!**

# IceCube Point Source Searches

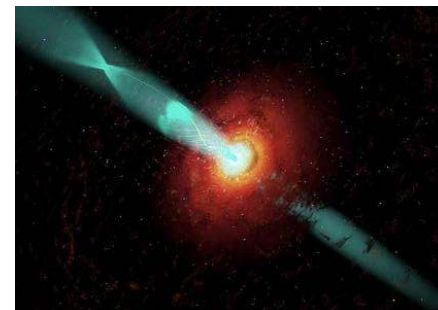
IceCube Collaboration 20 PRL



AGN/starburst galaxy



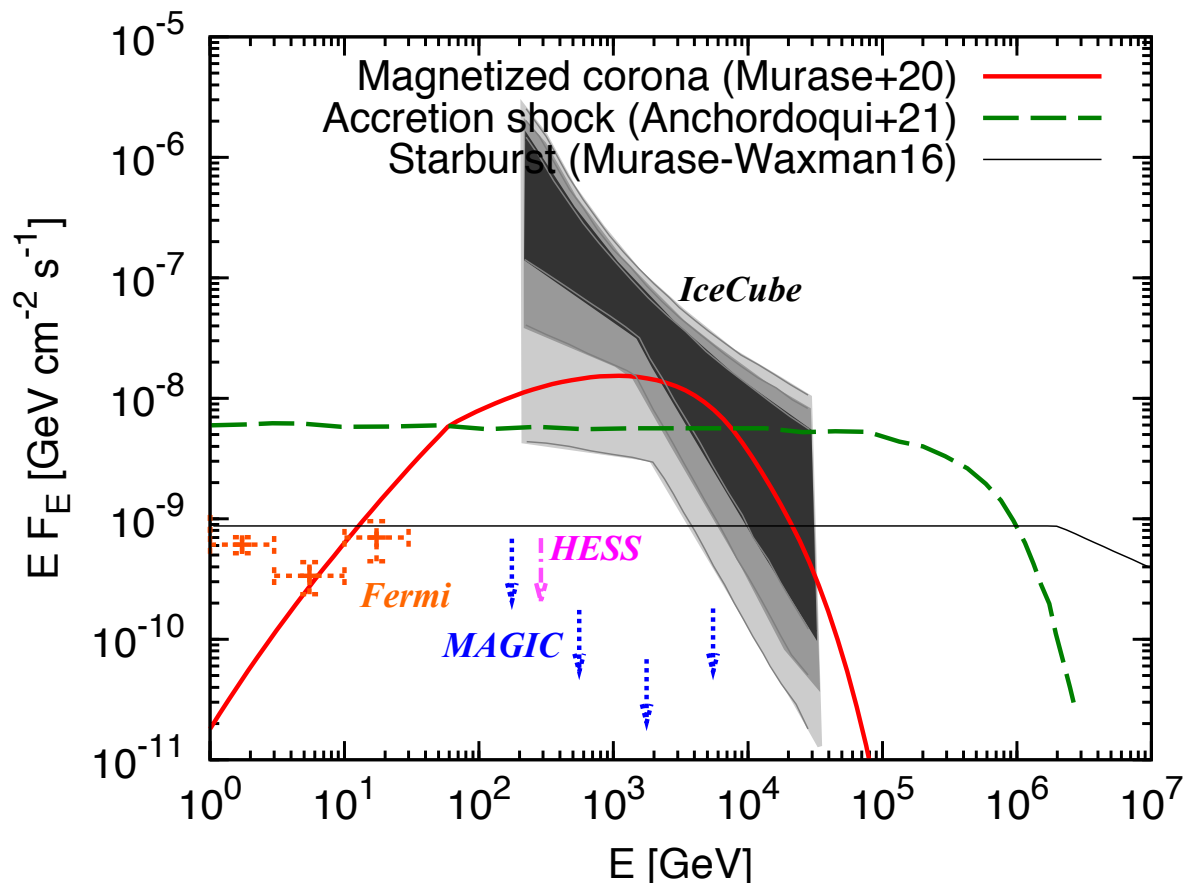
Jetted AGN



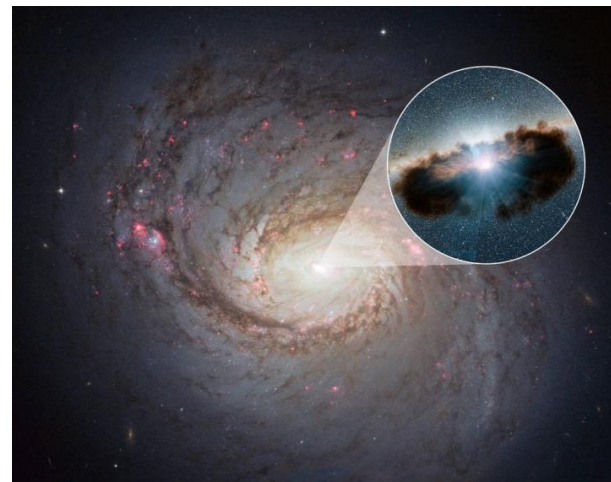
“Catches” ( $\sim 3\sigma$ ) exist but none have reached the discovery level

# NGC 1068: Promising Hidden $\nu$ Sources

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



## NGC 1068: “obscured AGN”



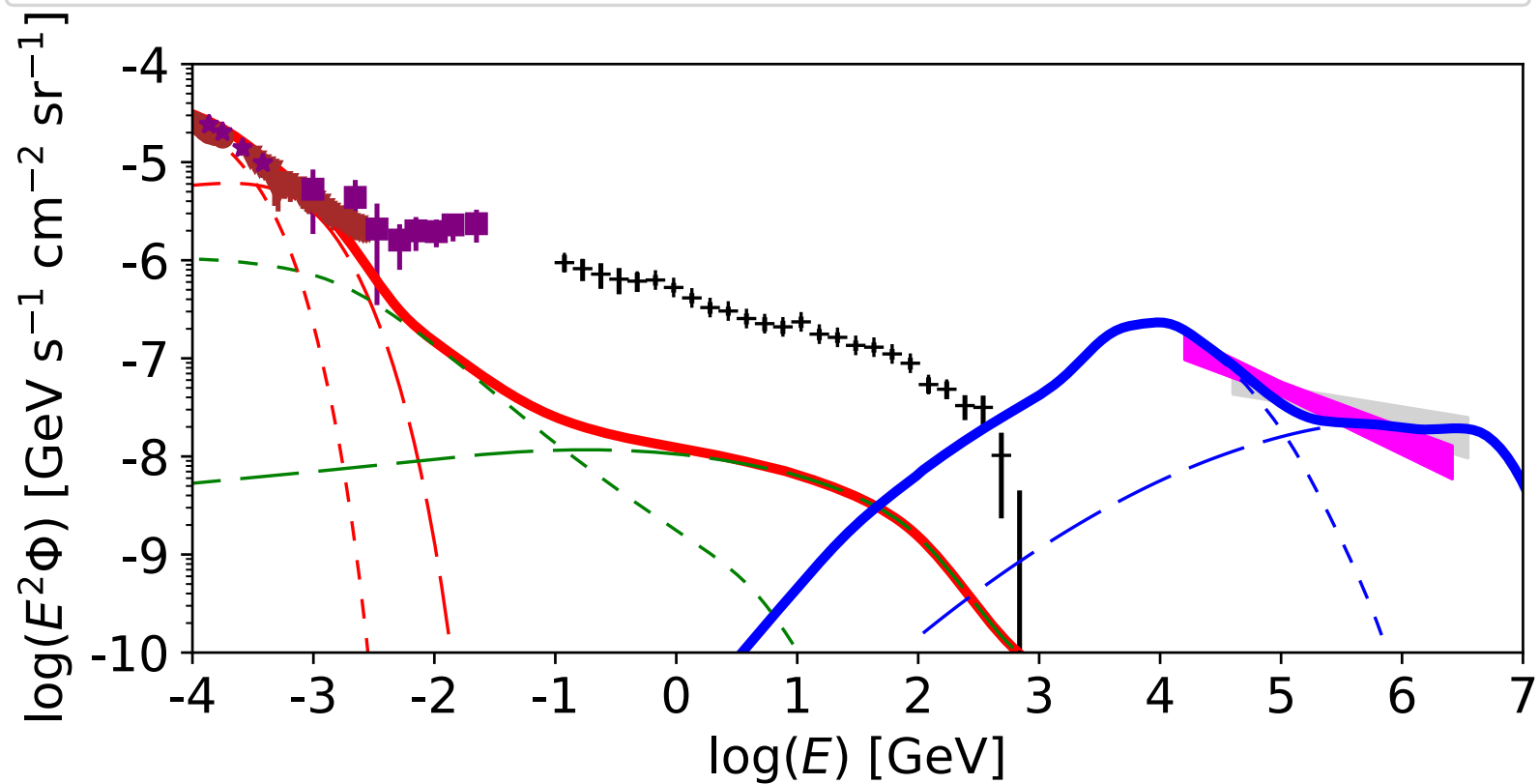
- particle acceleration in coroneae (supported by recent simulations)
- $\nu$  production via pp & p $\gamma$  processes

- Theory predicts NGC 1068 to be the **brightest**  $\nu$  source in the northern sky
- “Concordance picture”: possible to explain the all-sky neutrino flux
- Supporting multimessenger results from diffuse  $\nu$  (KM, Guetta & Ahlers 16 PRL)



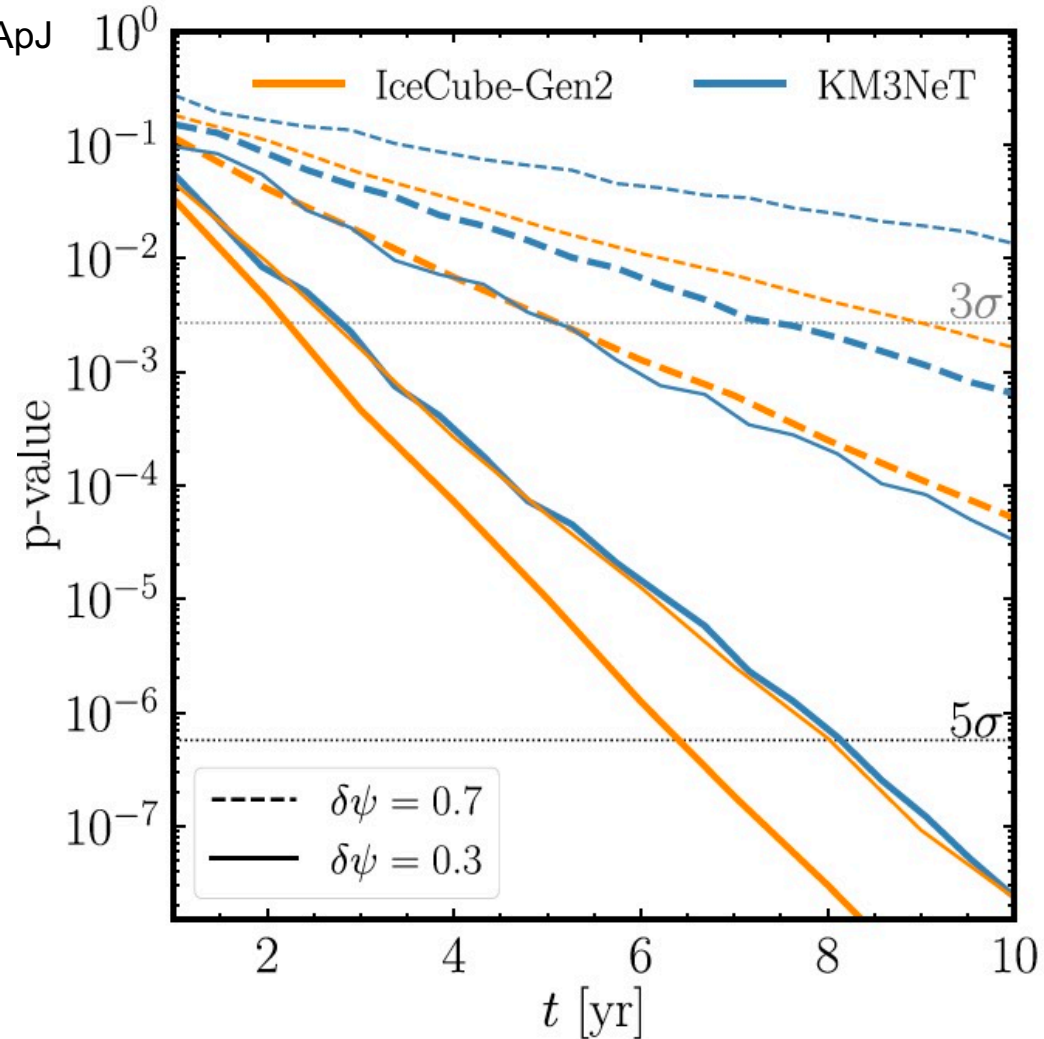
# AGN Manifesting in the Multi-Messenger Sky?

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



# Detectability of Coronal Neutrinos from Nearby AGN

Kheirandish, KM & Kimura 21 ApJ

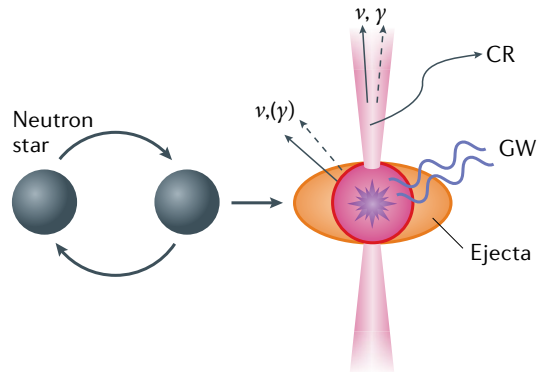


- More in the southern sky (Circinus, ESO 138-1, NGC 758)
- Testable w. near-future data or by next-generation neutrino detectors

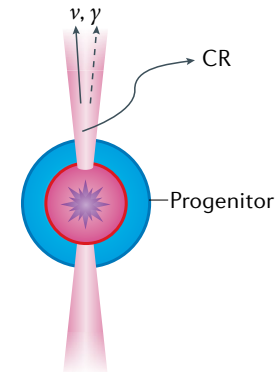
# High-Energy Neutrino Transients

## Diverse explosive/flaring phenomena in the Universe

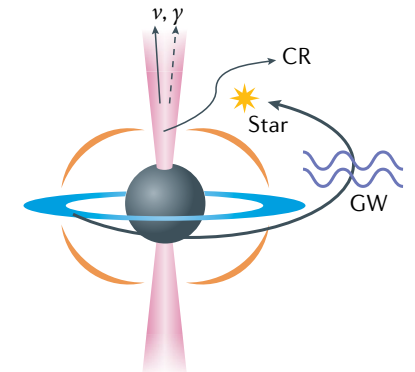
**a** Short  $\gamma$ -ray burst neutron star merger



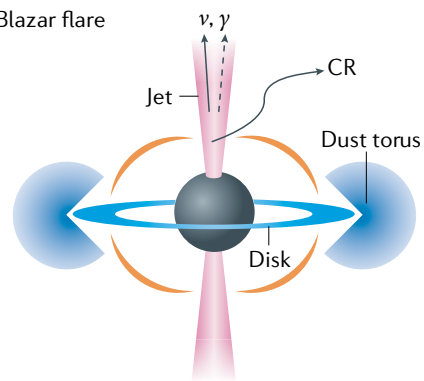
**b** Long  $\gamma$ -ray burst



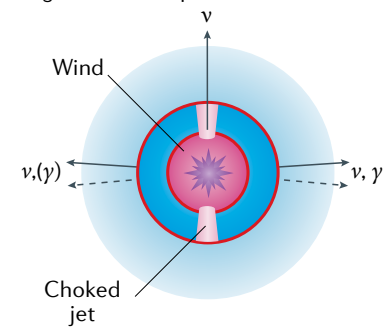
**c** Tidal disruption event



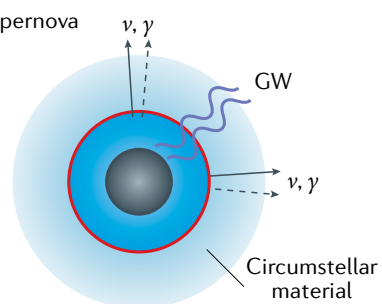
**d** Blazar flare



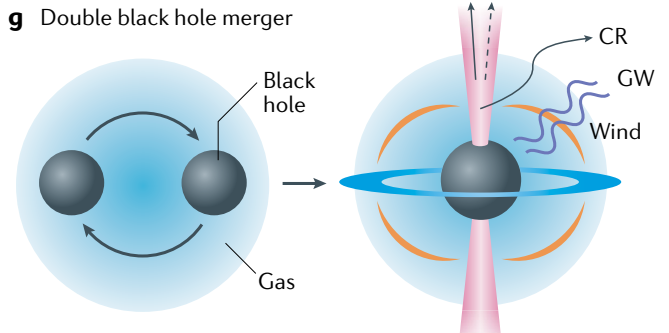
**e** Engine-driven supernova



**f** Supernova



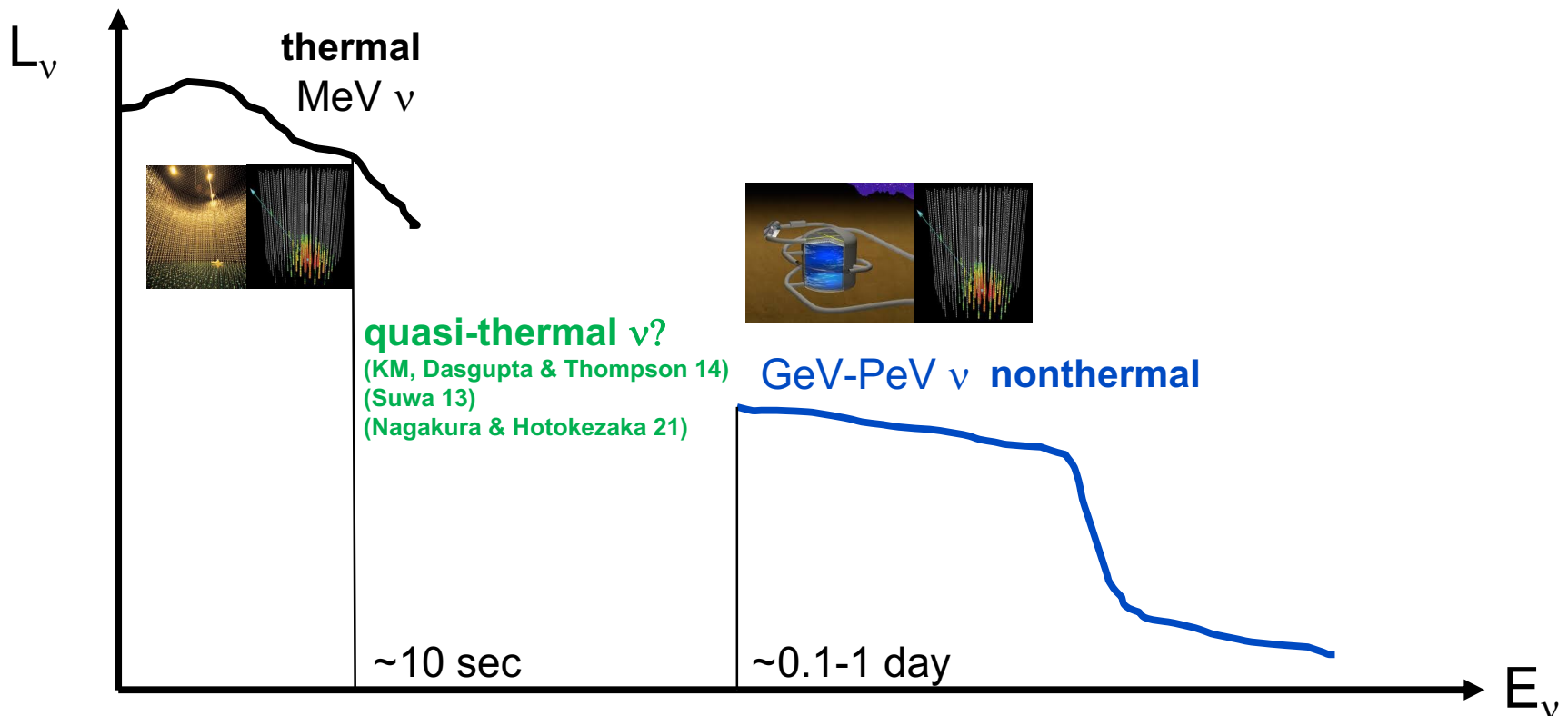
**g** Double black hole merger





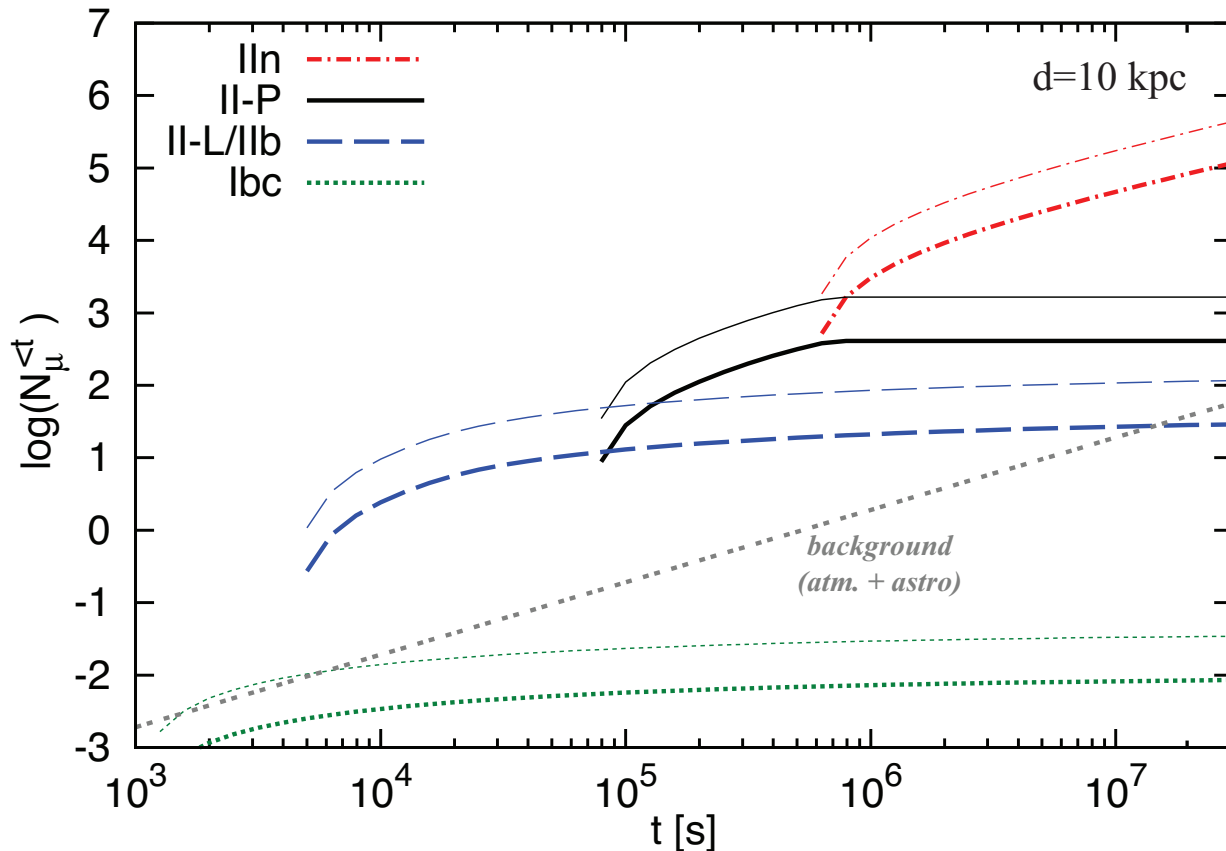
# Next Galactic SN: **Multi-Messenger** & **Multi-Energy $\nu$ Source**

- Not only MeV  $\nu$ s but also GeV  $\nu$ s could be detected by Hyper-K & IceCube
- TeV-PeV  $\nu$ s will be detected by IceCube-like detectors w. large statistics  
ex. Betelgeuse:  $\sim 10^3$ - $3 \times 10^6$  events, Eta Carinae:  $\sim 10^5$ - $3 \times 10^6$  events  
→ **real-time** observation of **cosmic-ray ion acceleration**  
testing the cosmic-ray origin & applications to neutrino physics



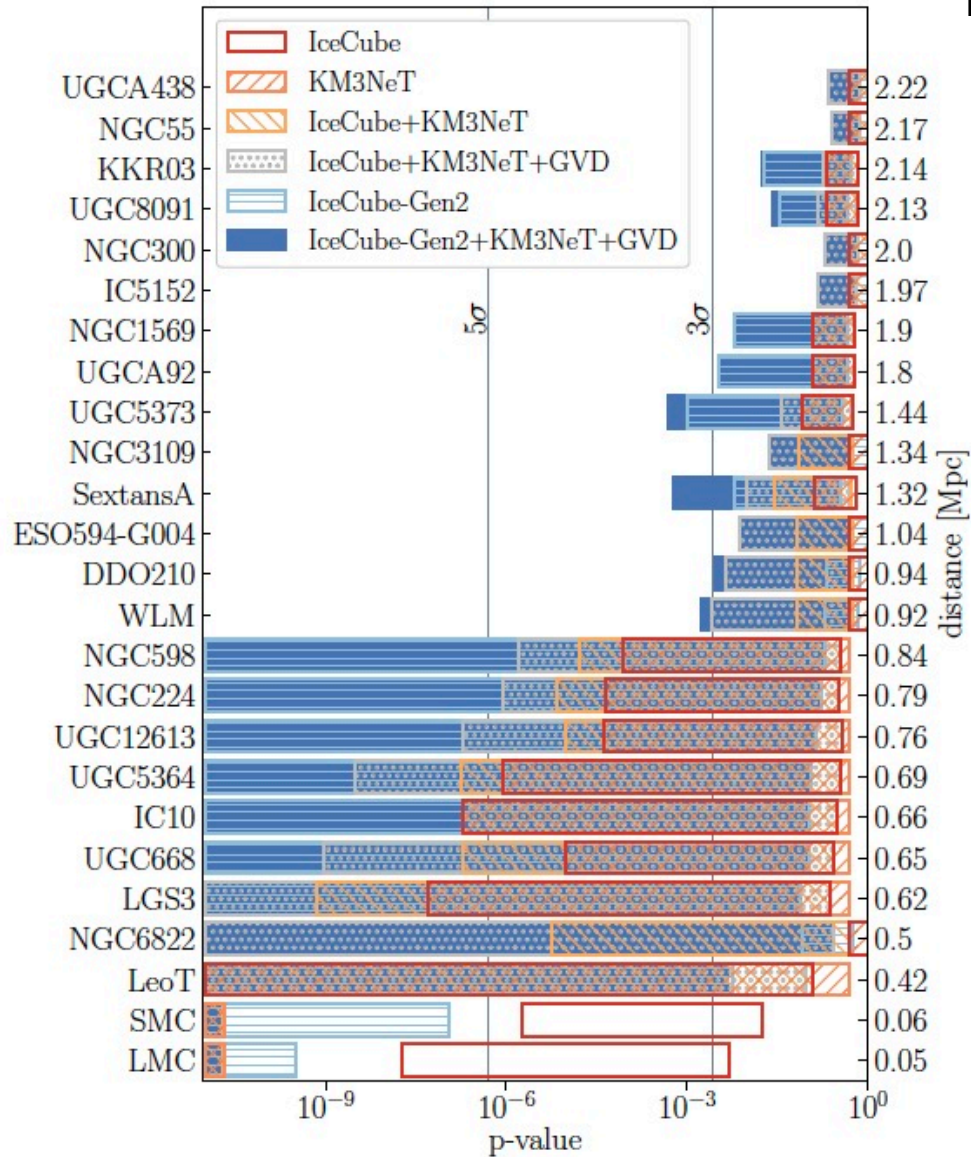
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testing the cosmic-ray origin & applications to neutrino physics



# Detectability of Minibursts

Kheirandish & KM 22

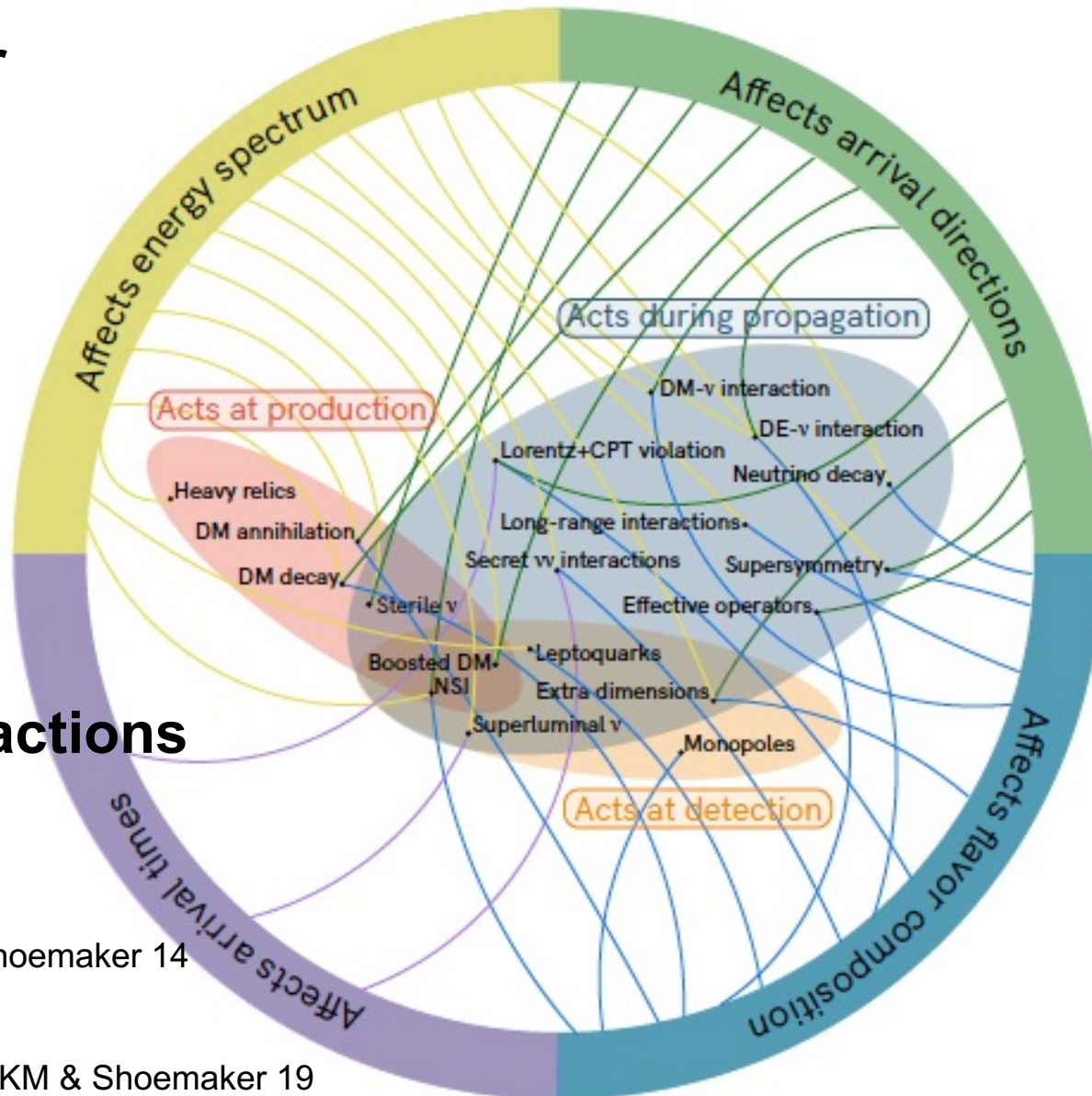




# Testing Fundamental Physics

## Dark matter

Feldstein+ 13  
Esmaili & Serpico 13  
Bai, Lu & Salvado 13  
Bhattacharya+ 14  
Higaki+ 14  
Esmaili+14,  
Rott+ 15  
Fong+ 15  
KM+ 15  
Boucenna+ 15  
Ko & Tang 15  
Chianese+ 16...



## Secret interactions

Ioka & KM 14  
Ng & Beacom 14  
Ibe & Kaneta 14  
Blum, Hook & KM 14  
Cherry, Friedland & Shoemaker 14  
Araki et al. 15  
Kamada & Yu 15  
Shoemaker & KM 16, KM & Shoemaker 19

# Secret Neutrino Interactions

$$\mathcal{L} \supset G \nu \nu \phi$$

$$\mathcal{L} \supset G \bar{\nu} \not{Z}' \nu$$

Bardin, Bilenyk & Pontecorvo 70

Applications to IceCube

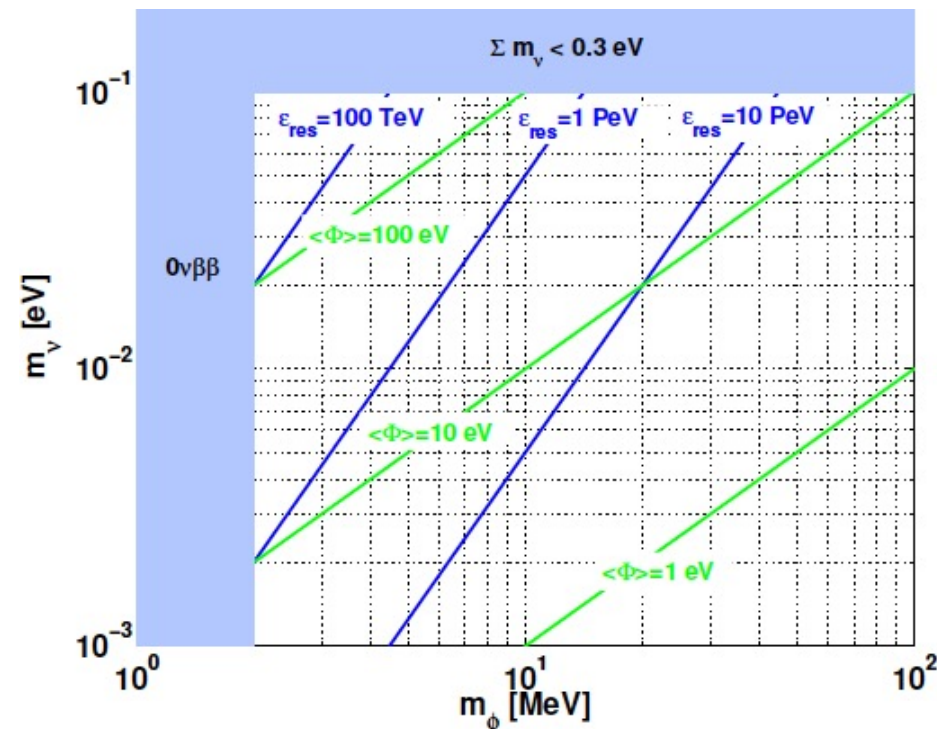
Ioka & KM 14 PTEP

Ng & Beacom 14 PRD

Cherry+ 14

ex. Majorana  $\nu$  self-interactions via a scalar (e.g., Blum, Hook & KM 14)

$$\mathcal{L} = -\frac{g}{\Lambda^2} \Phi (HL)^2 + cc. \quad \begin{array}{c} \text{SSB} \\ \text{lepton \# violation} \end{array} \quad \mathcal{L} = -\frac{1}{2} \sum_i (m_{\nu_i} + \mathcal{G}_i \phi) \nu_i \nu_i + cc + \dots, \quad m_{\nu_i} = \frac{g_i \mu \nu^2}{\Lambda^2}$$



## BSM $\nu$ - $\nu$ and $\nu$ -DM interactions via MeV mediators:

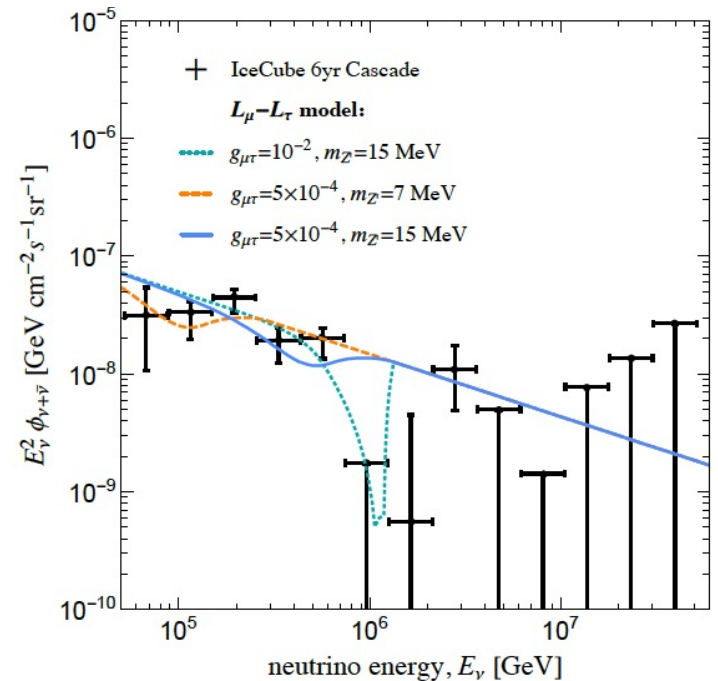
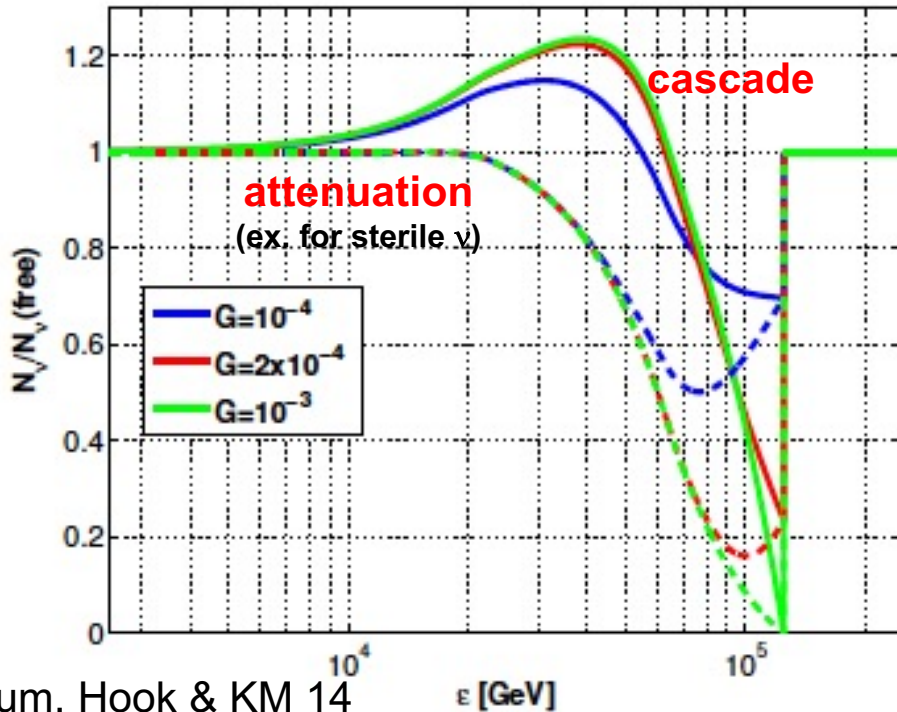
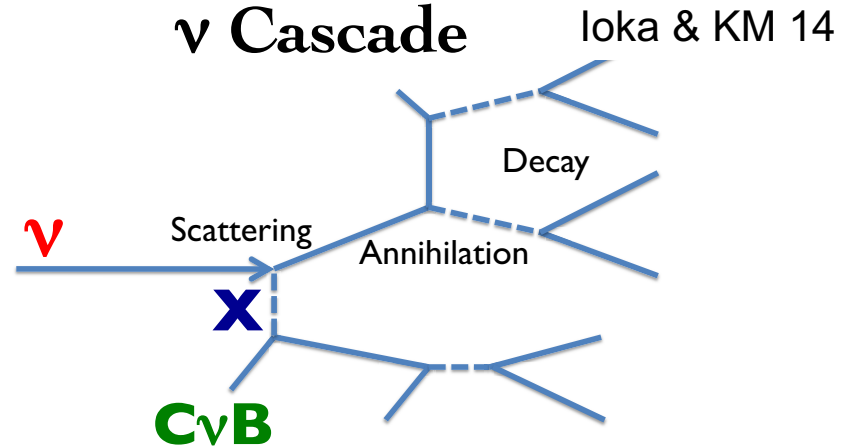
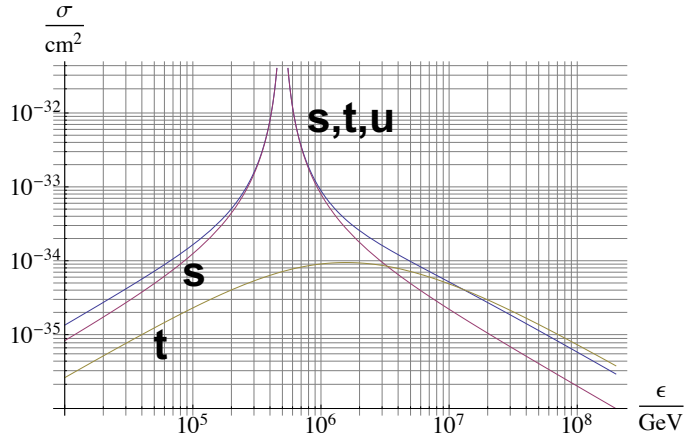
1. Hubble tension
2. small-scale structure problems

HE neutrinos interact w. cosmic neutrino background or dark matter

$$\epsilon_{\text{res}} = \frac{m_\phi^2}{2m_\nu} = 1 \text{ PeV} \left( \frac{m_\phi}{10 \text{ MeV}} \right)^2 \left( \frac{m_\nu}{0.05 \text{ eV}} \right)^{-1}$$

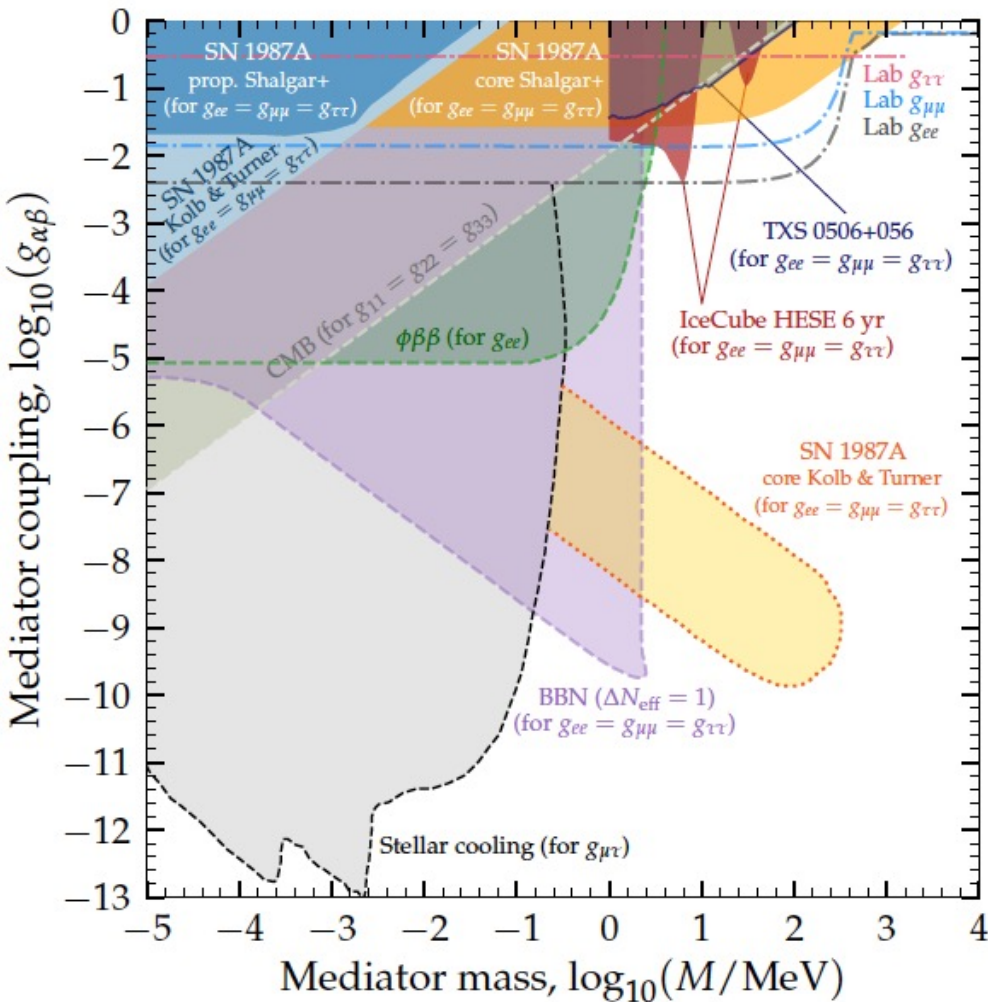
→ modulation in neutrino spectra

# Effects on Cosmic Neutrino Spectra



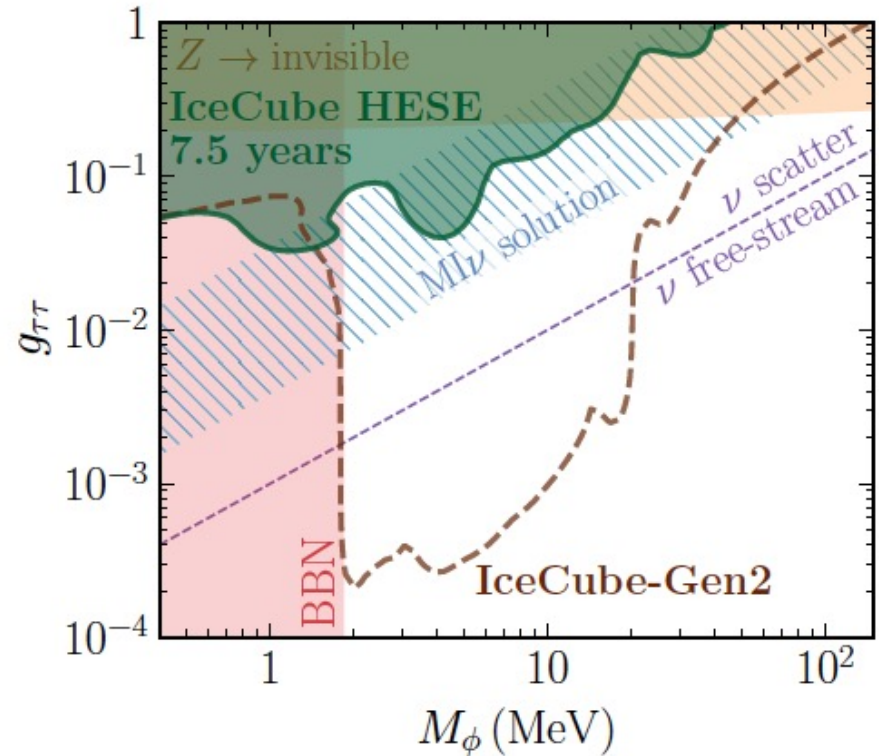


# Current Constraints



from 2203.01955  
see also Shoemaker & KM 16 PRD for Gen2

↓ only  $\nu_\tau$  coupling

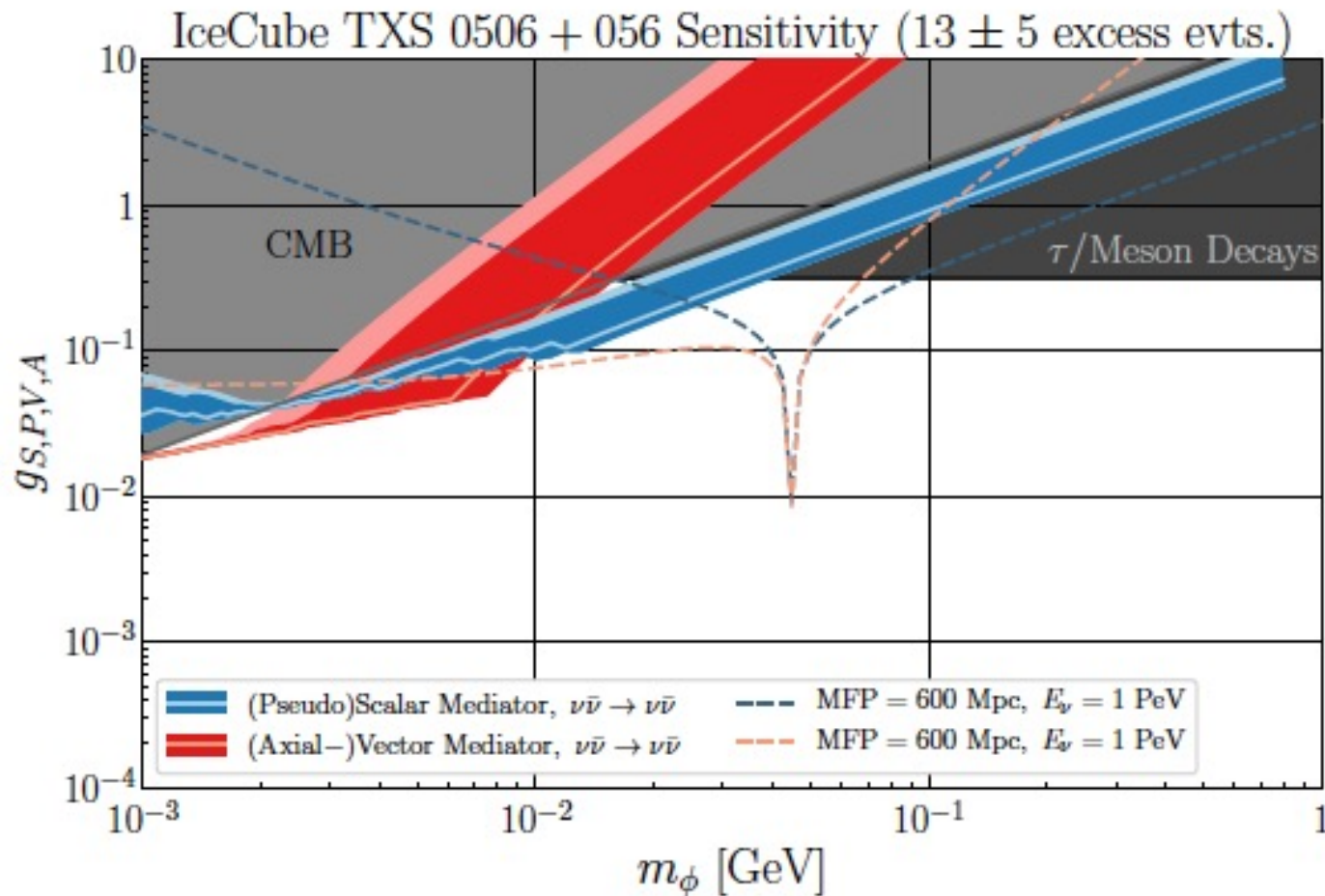


**Diffuse neutrino observations could give the best constraints but the limits depend on spectra that may not be power law**



# Current Constraints

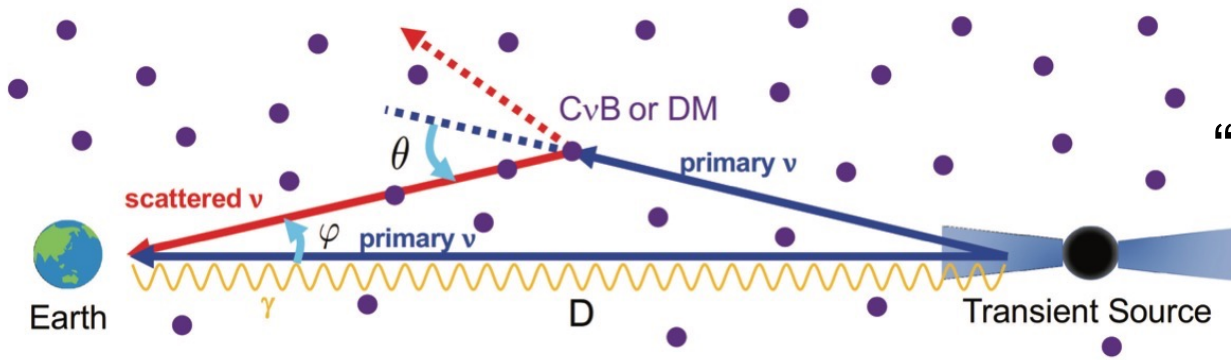
Kelly & Machado 18 JCAP



Multimessenger observations imply the  $\nu$  mean free path  $> 1.3$  Gpc  
But the limits depend on source models predicting non-power laws

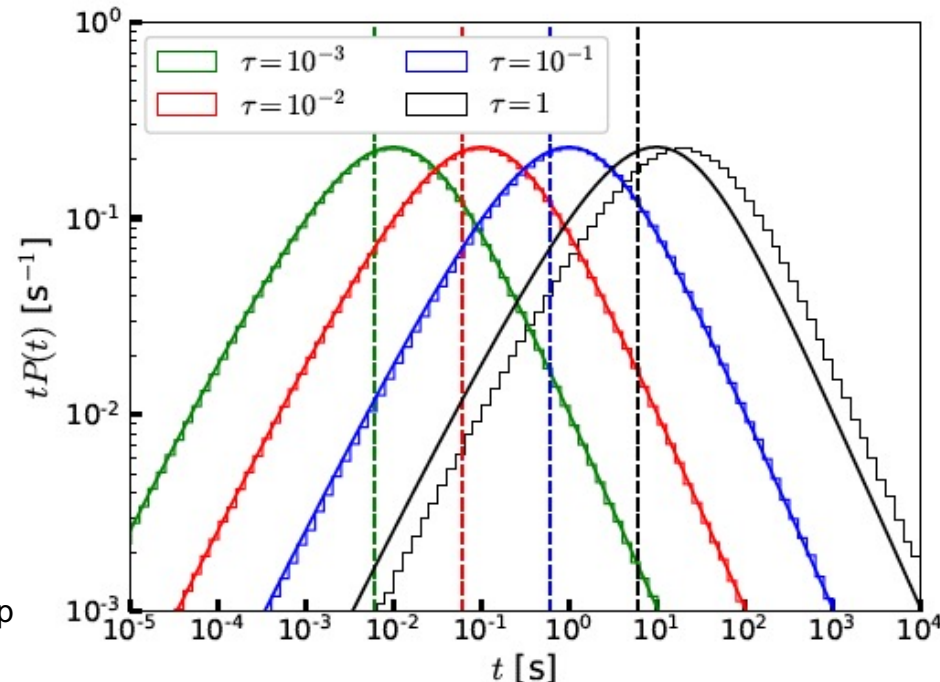
# BSM & *Time-Domain Multi-Messenger Astrophysics*

KM & Shoemaker 19 PRL



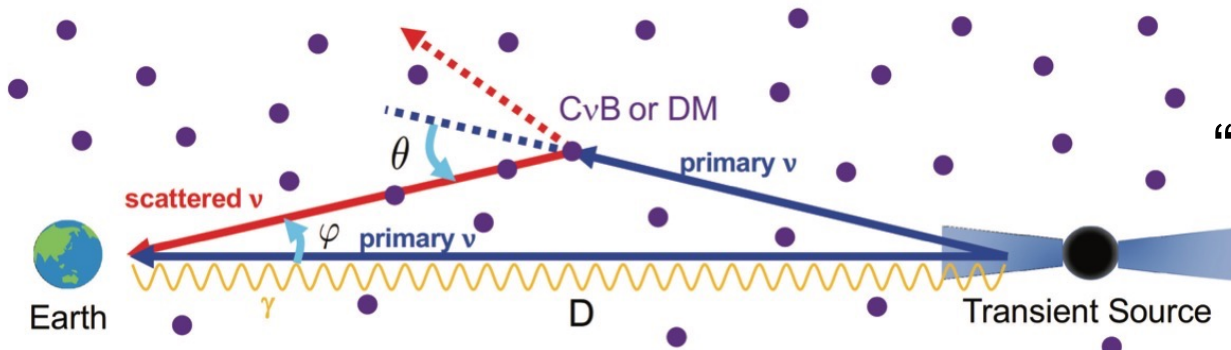
“time delay” signatures  
(**neutrino echoes**)

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



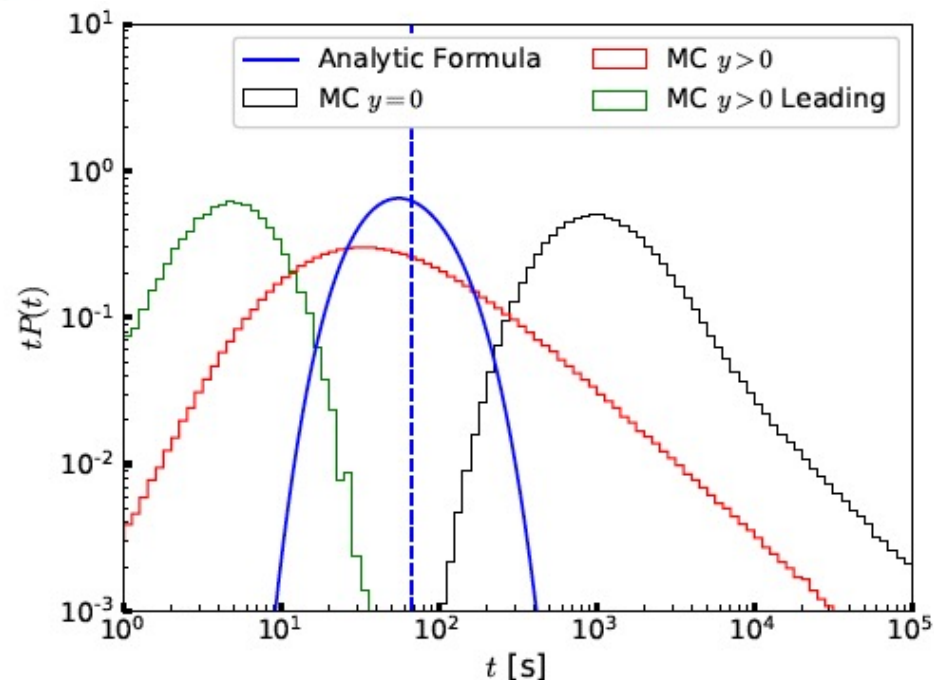
# BSM & *Time-Domain Multi-Messenger Astrophysics*

KM & Shoemaker 19 PRL



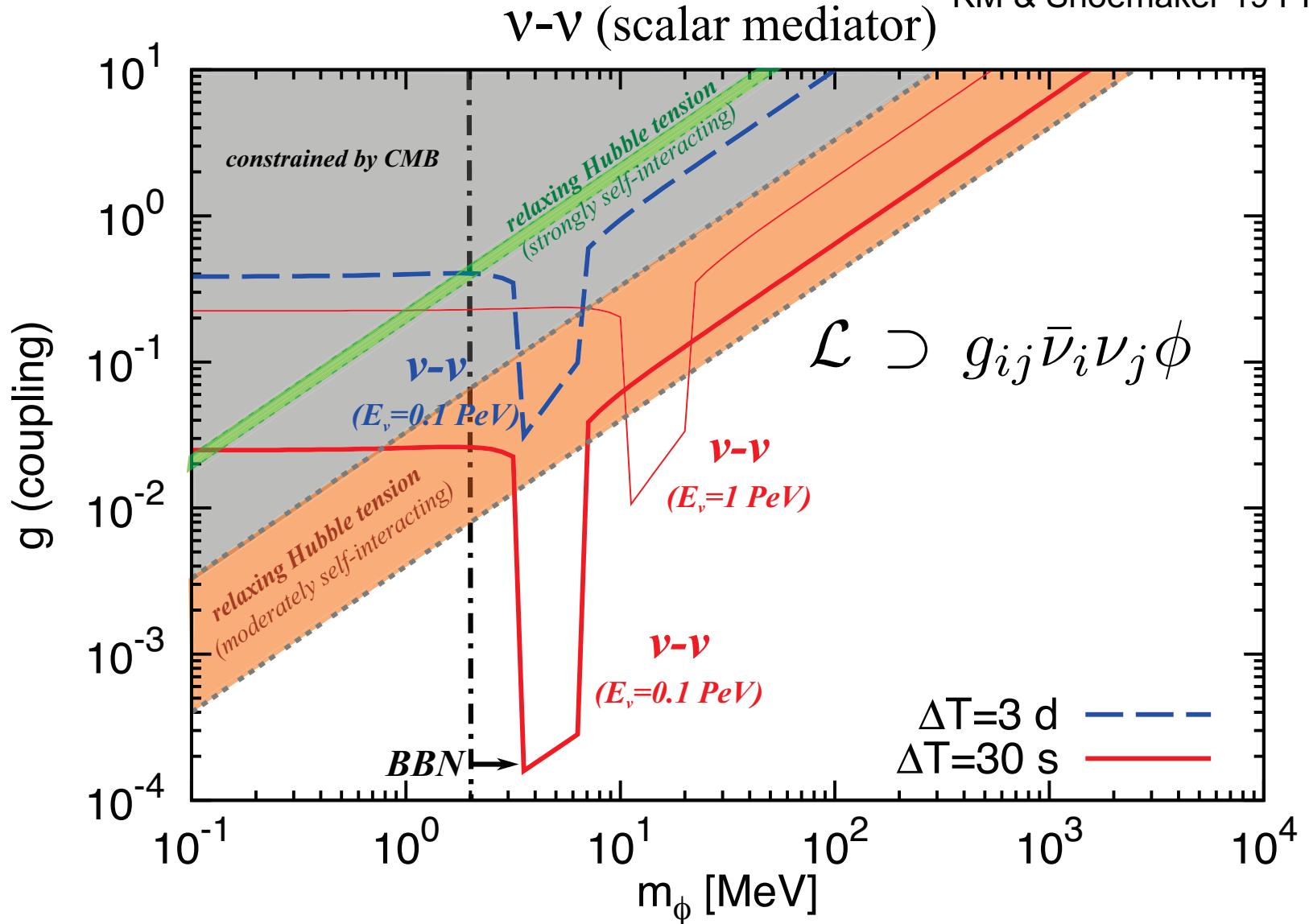
“time delay” signatures  
(**neutrino echoes**)

$$\Delta t \approx \frac{1}{4} \langle \varphi^2 \rangle D \simeq 500 \text{ s} \left( \frac{\tau_\nu}{10} \right) \left( \frac{D}{3 \text{ Gpc}} \right) C^2 \left( \frac{m_\nu}{0.1 \text{ eV}} \right) \left( \frac{0.1 \text{ PeV}}{E_\nu} \right)$$



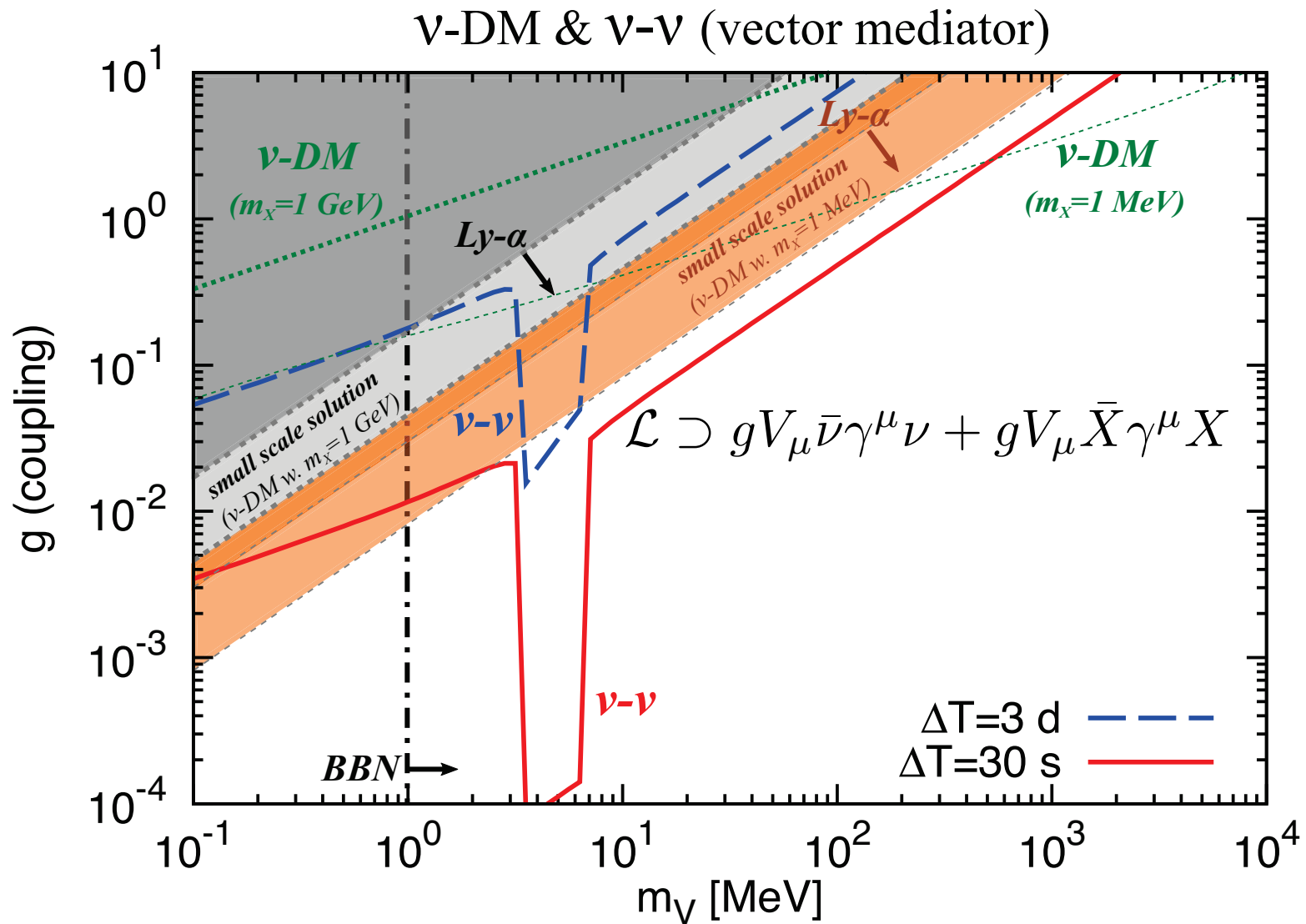
# BSM & Time-Domain Multi-Messenger Astrophysics

KM & Shoemaker 19 PRL

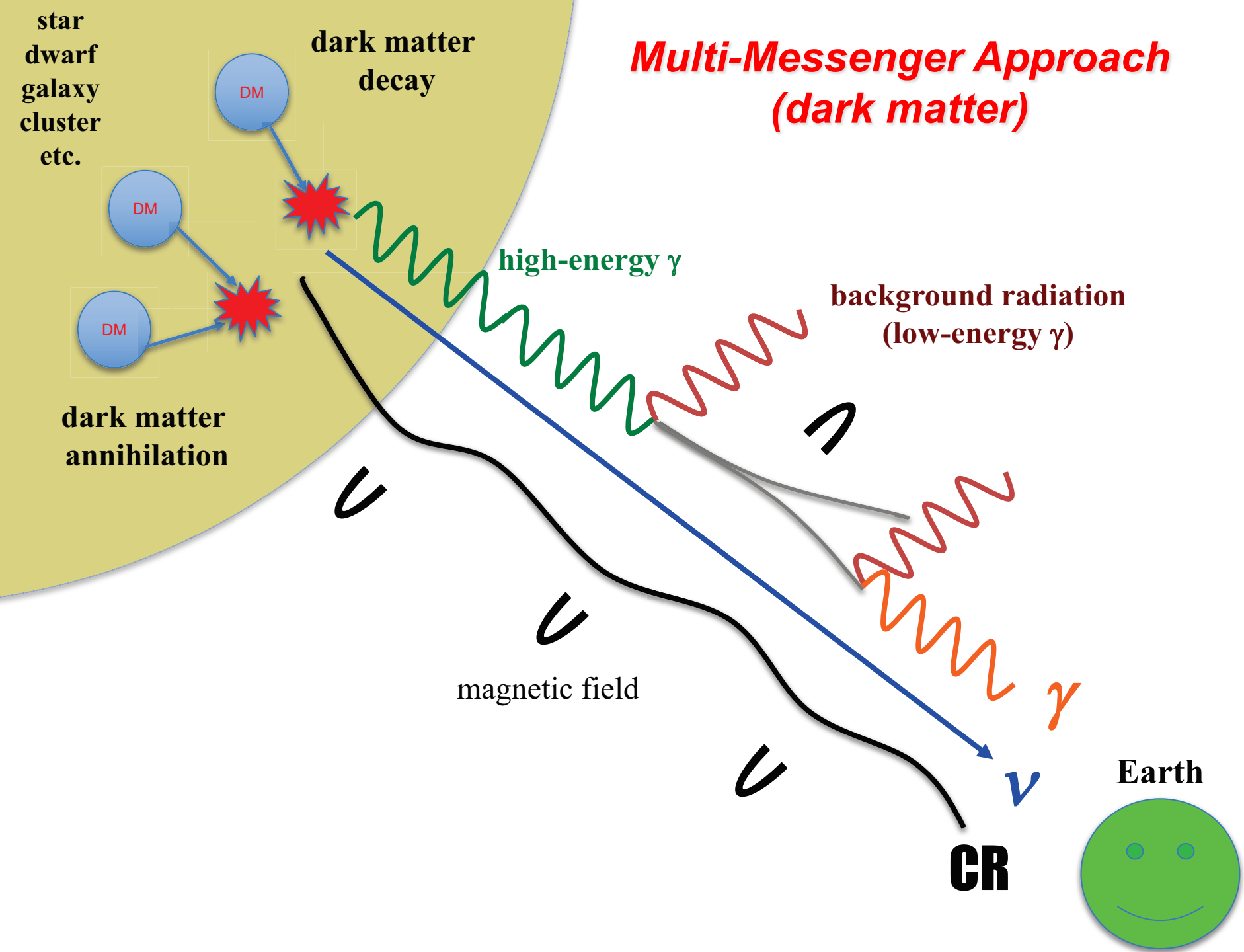




# Application to Neutrino-DM Scatterings

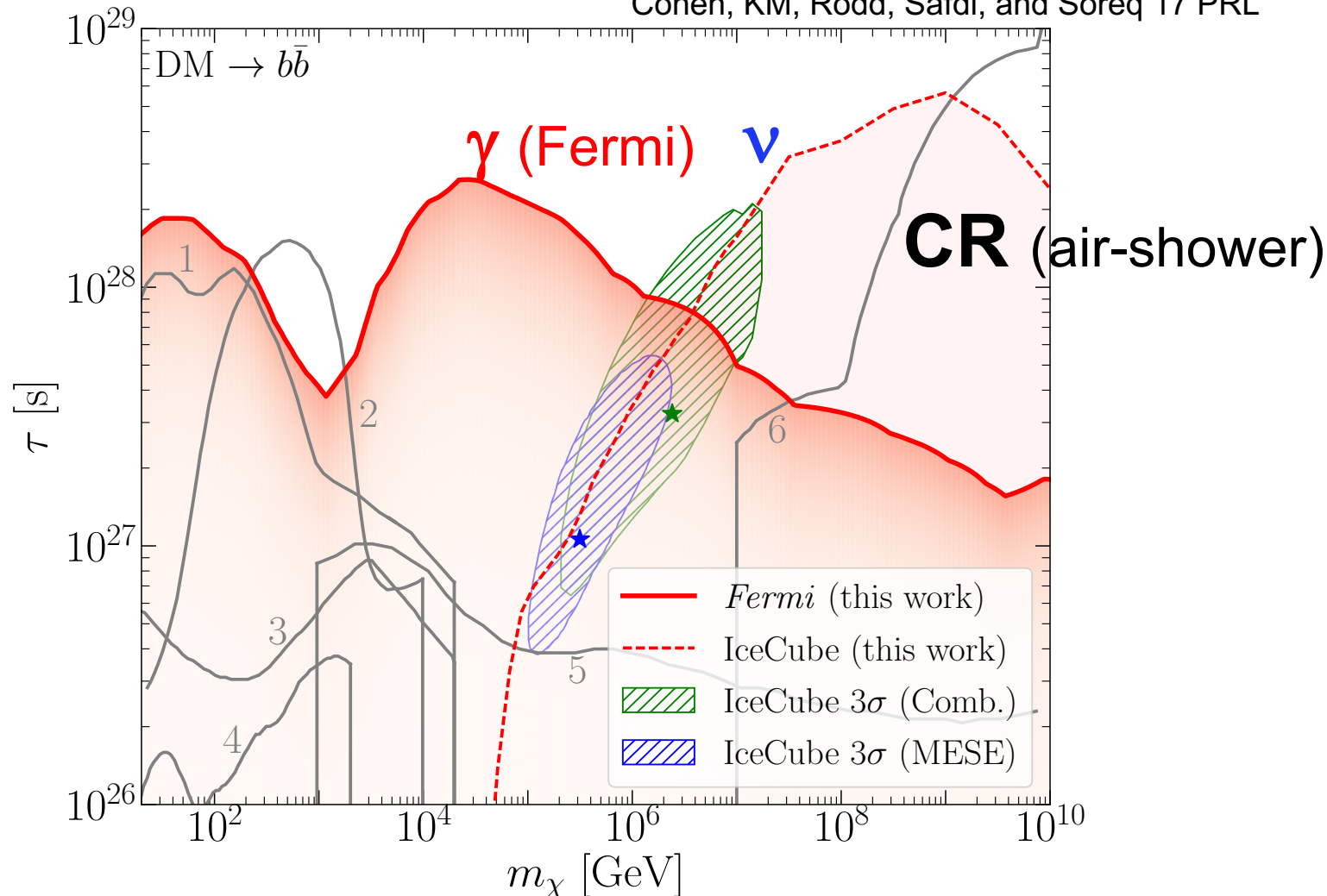


# Multi-Messenger Approach (dark matter)



# Multi-Messenger Constraints on Decaying DM

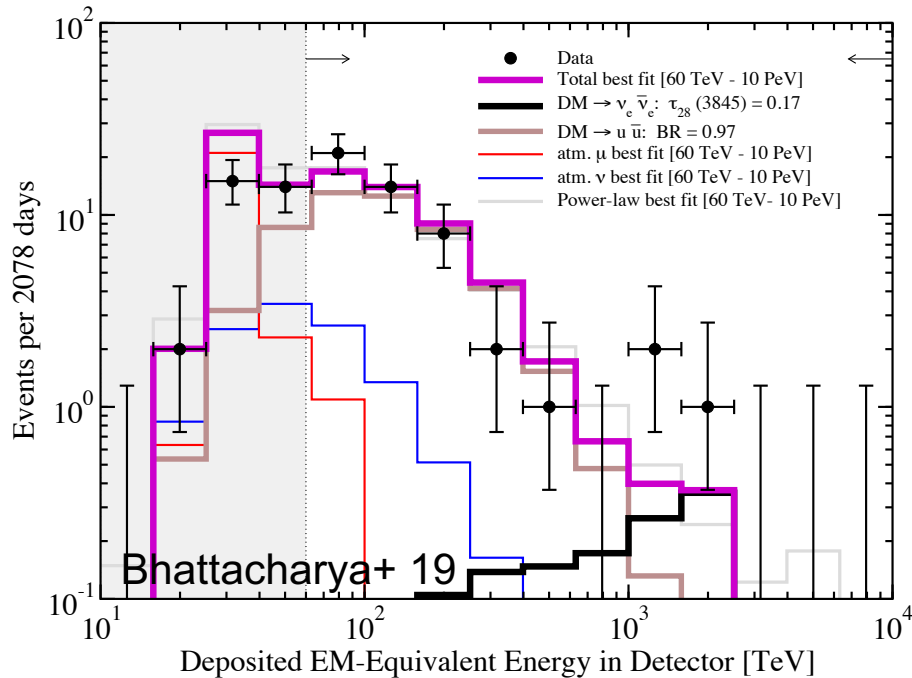
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



- Disfavoring DM scenarios to explain the excessive 10-100 TeV  $\nu$  data
- Neutrinophilic DM and/or two components (DM+astro)

# Viability DM Scenarios?

- High-energy diffuse neutrino data can be explained by multiple final states
- Medium energy diffuse neutrino data in the 10-100 TeV range can only be explained by neutrinophilic DM



Hiroshima, Kitano, Kohri & KM 18

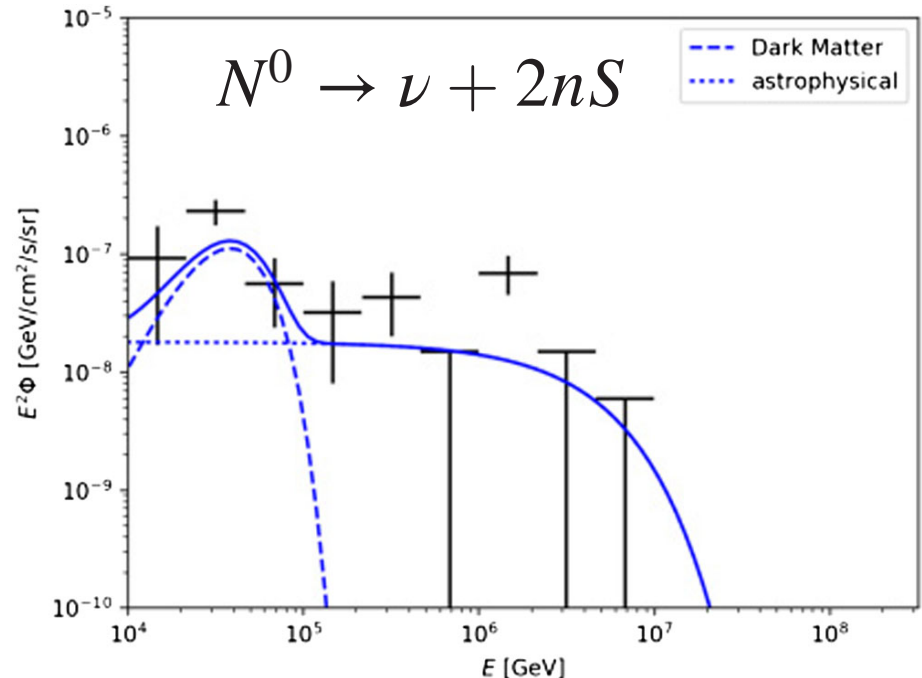
see also:

Chianese+ 17

Anchordoqui+ 20

$$\mathcal{L}_{\text{int}} = \mathcal{L}_X + \frac{1}{M^{3n-3}} X S^{2n} + \frac{1}{M_*^{3n-1}} \bar{L} \ell S^{2n} + \text{H.c.}$$

$$\mathcal{L}_X = -m_{\text{DM}} \bar{L} L + (\epsilon \bar{L} \ell X + \text{H.c.})$$



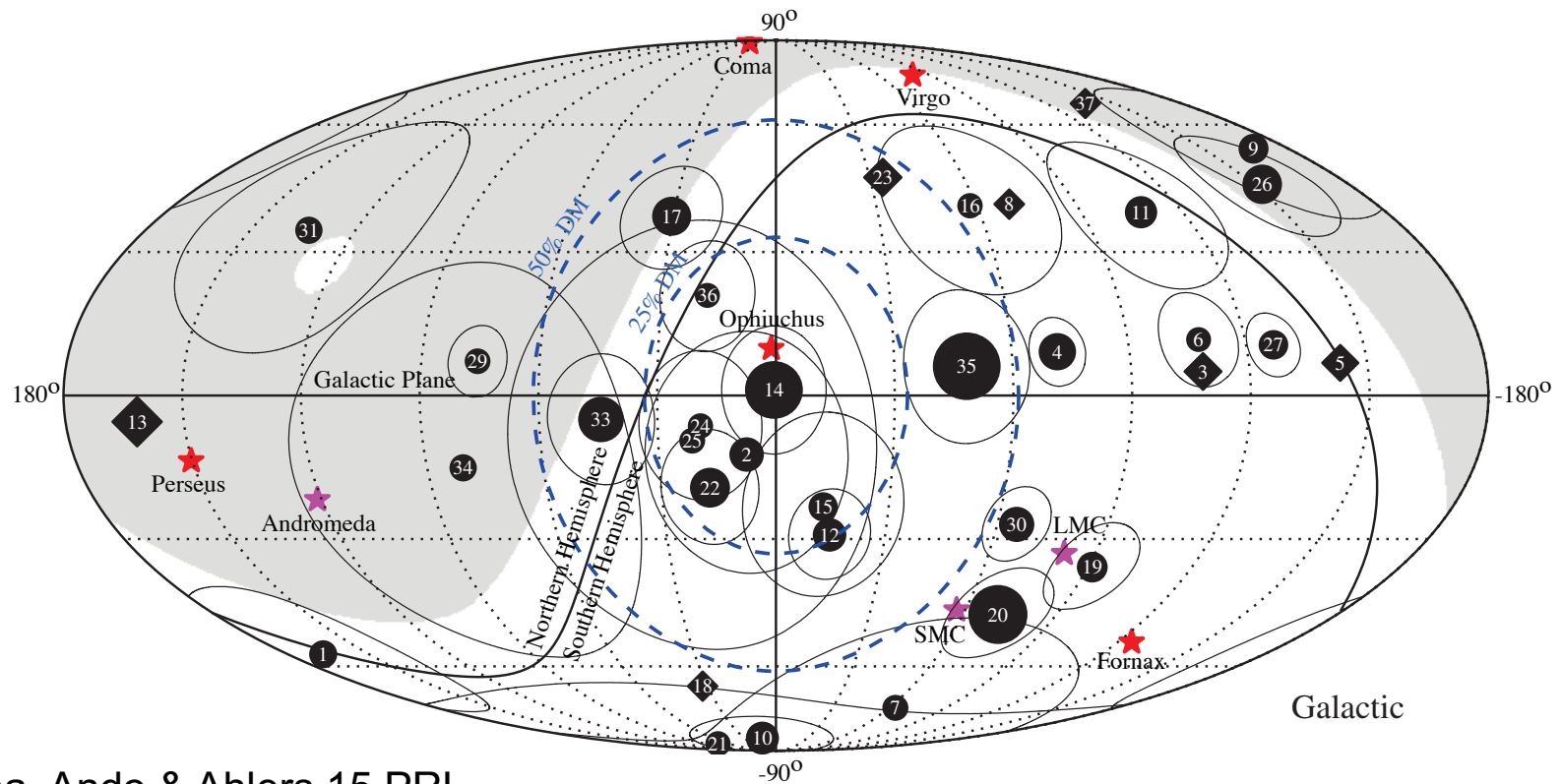


# Search for Nearby DM Halos

- Galactic DM halo (e.g., Bai+ 14 PRD)
  - Nearby DM halos (clusters & galaxies)
- “point/extended” sources

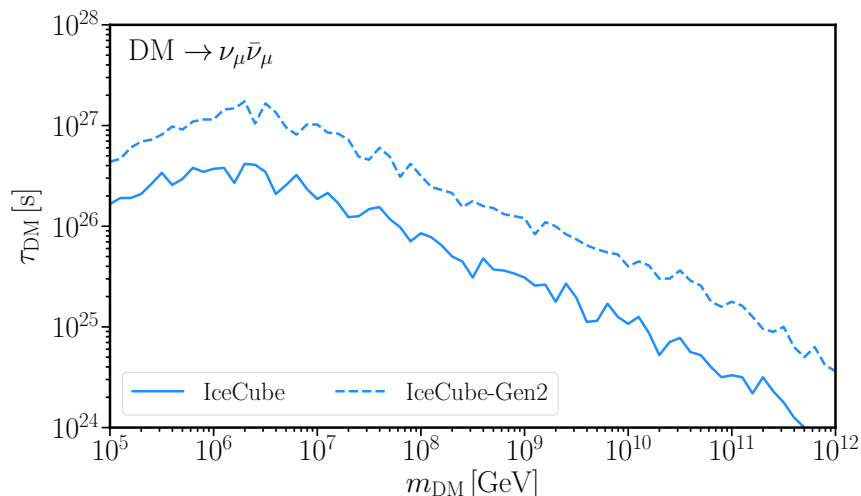
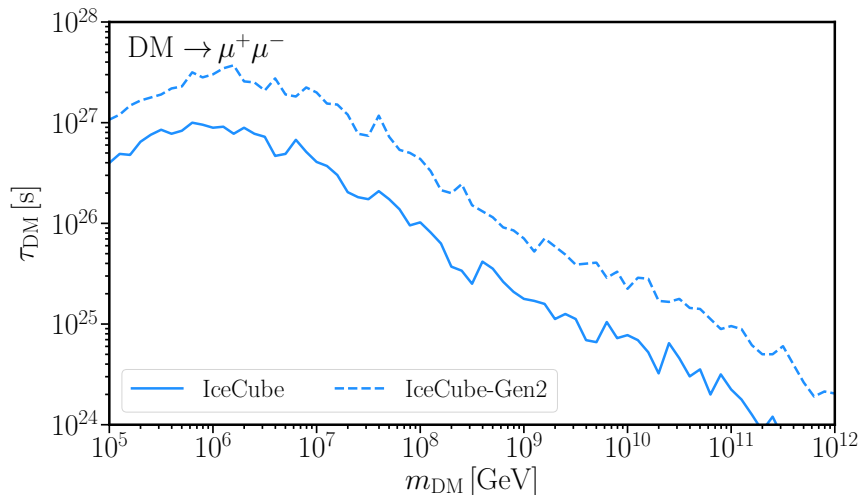
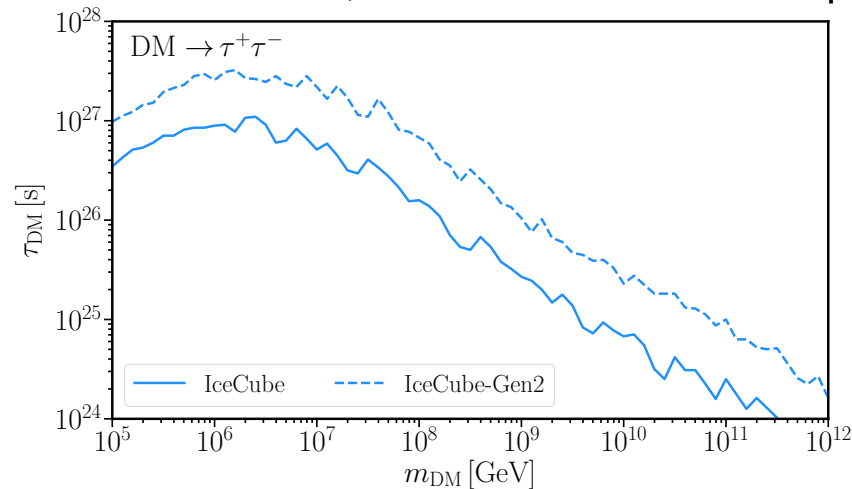
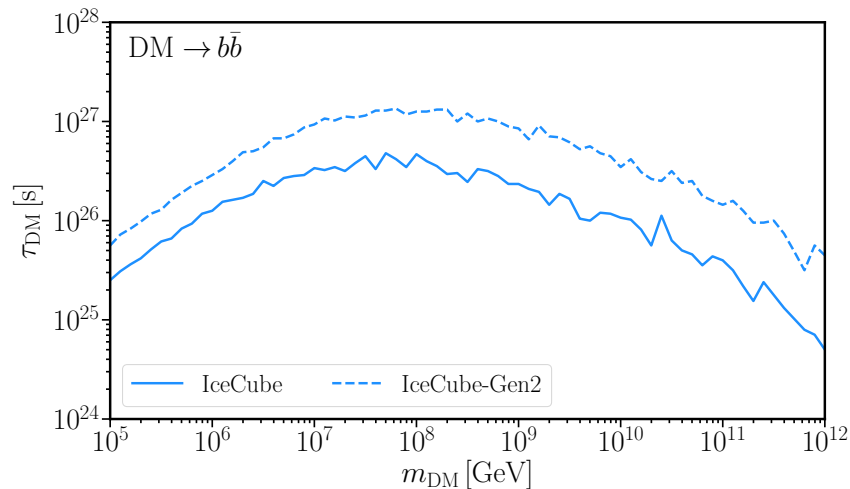
$$\text{source flux} \propto M_{\text{dm}}/\tau_{\text{dm}}/d^2$$

stacking/cross-correlation  
“independent” of  $\gamma$ -ray bounds



# Search for Nearby DM Halos

Chianese, Kheirandish & KM 22 in prep.



In the Gen2-era, stacking w. more clusters may overwhelm diffuse  $\nu$  limits

# Summary

## ***Neutrino Sources?***

Intriguing coincidences with **black hole flares** have been found  
NGC 1068 (AGN) supports **active black holes** as hidden  $\nu$  sources

Future is bright: IceCube-Gen2, KM3Net & other next-generation facilities  
Establishing the multimessenger picture is critical → stay tuned  
Transients: unique chances → strategic multi-messenger searches (ex. AMON)  
High-statistics HE  $\nu$  detection is promising for e.g., Galactic supernovae

## ***Tests for New Physics?***

Heavy dark matter, neutrino-neutrino/DM interactions etc.  
Multimessenger searches are powerful and very important

HE neutrino sources (including transients) provide tests for neutrino NSIs  
Dedicated cataloged/stacking searches to test heavy DM models