High-Energy Neutrino Astrophysics in the Multimessenger Era

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L'Aquila Astroparticle Colloquium

Introduction

Astrophysical Implications

New Physics Implications

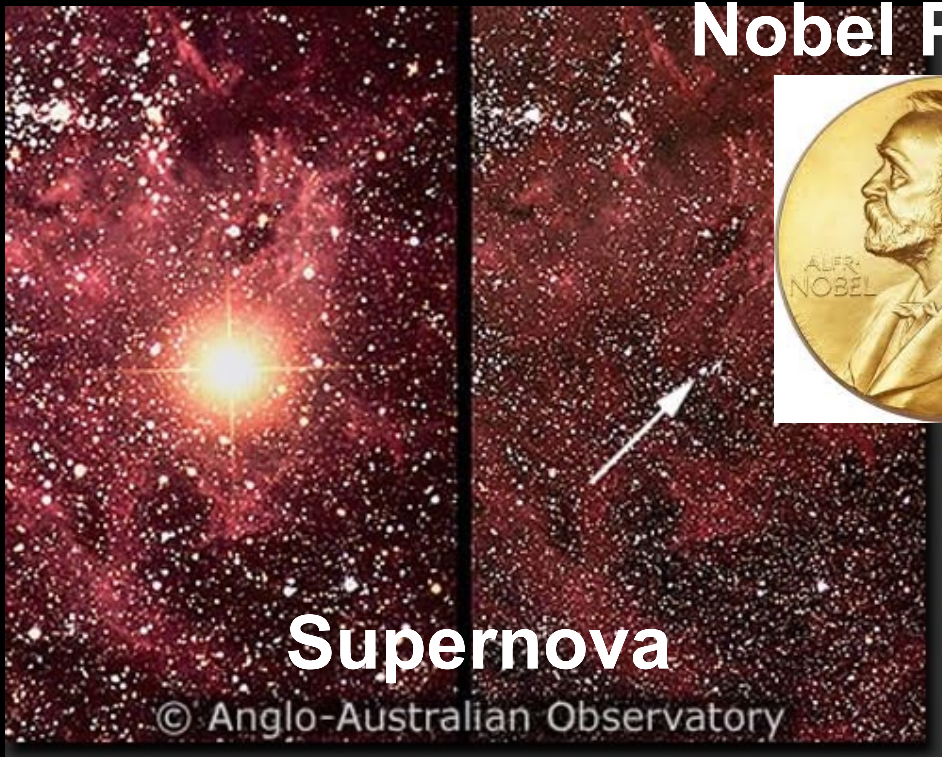
Neutrino?

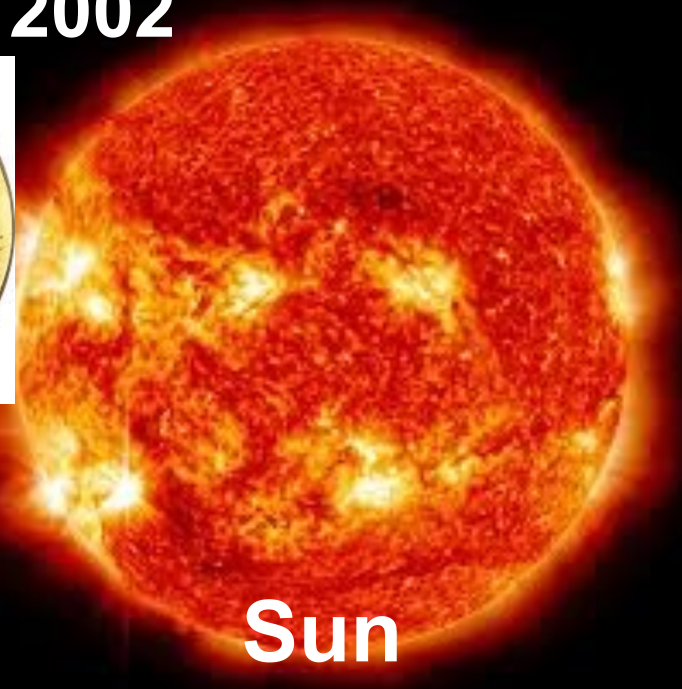
- Elementary particle (lepton): "ν"
- Electrically neutral
- Weak interaction: "ghost particle"
  ex: hundreds of trillion (a fewx10^{14}) ν/sec from the Sun go through a human
- Almost massless but tiny mass (<1/10^{6} electron mass)

three types
(flavors)

Neutrinos for Astrophysics

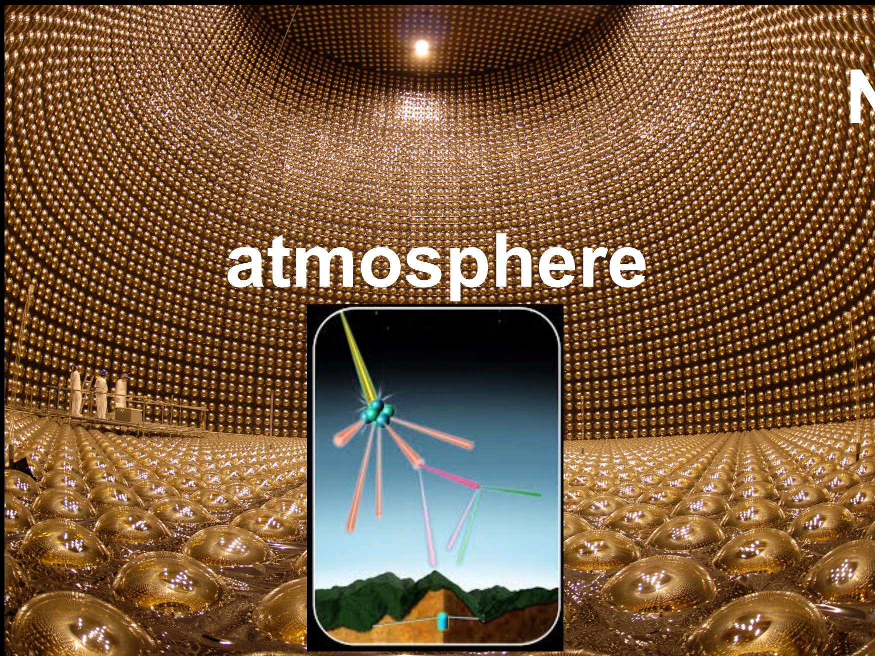
Nobel Prize 2002



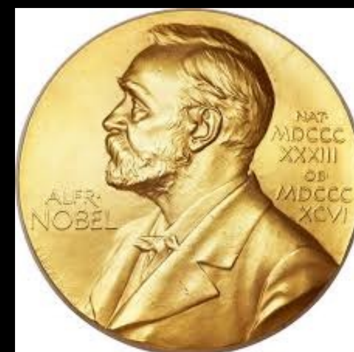


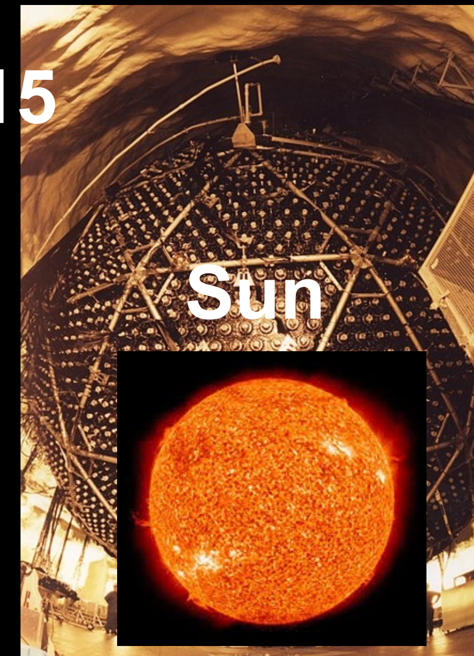
"ν" enables us to see dense regions invisible with light

Neutrinos for Fundamental Physics



Novel Prize 2015





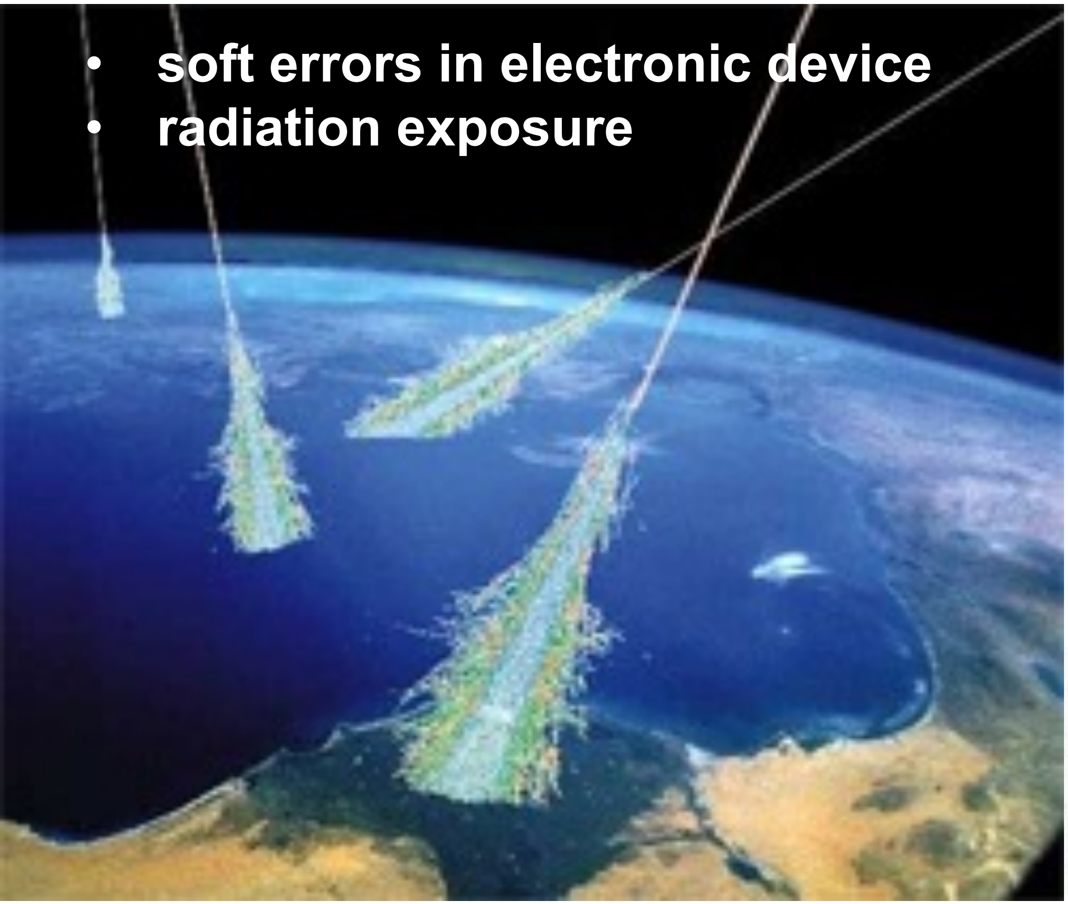
Neutrino oscillation

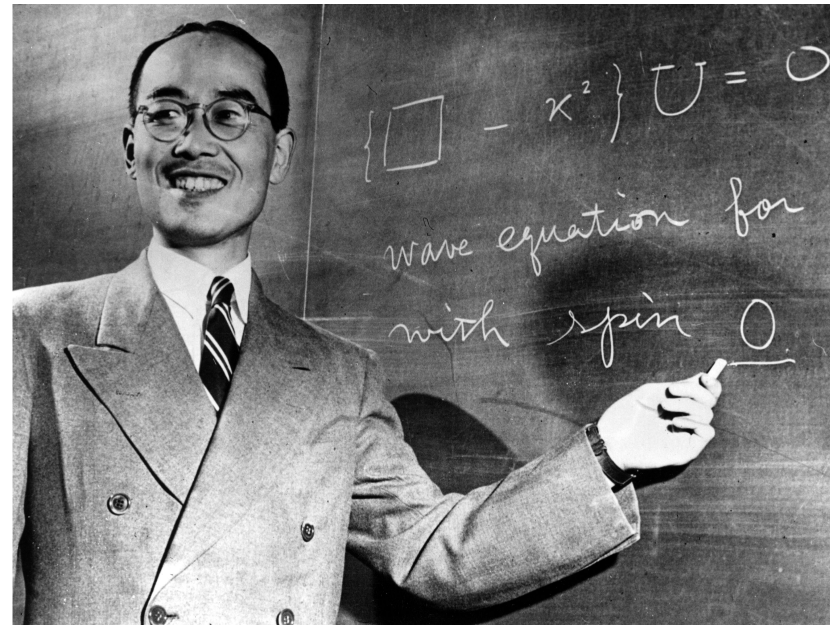
non-zero neutrino mass suggests new physics beyond the Standard Model

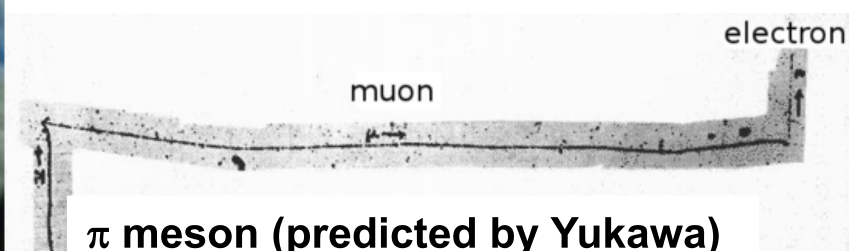
Prof. Kajita: “I want to thank the neutrinos, of course. And since neutrinos are created by cosmic rays, I want to thank them, too"

Cosmic Rays

Energetic charged particles coming from space

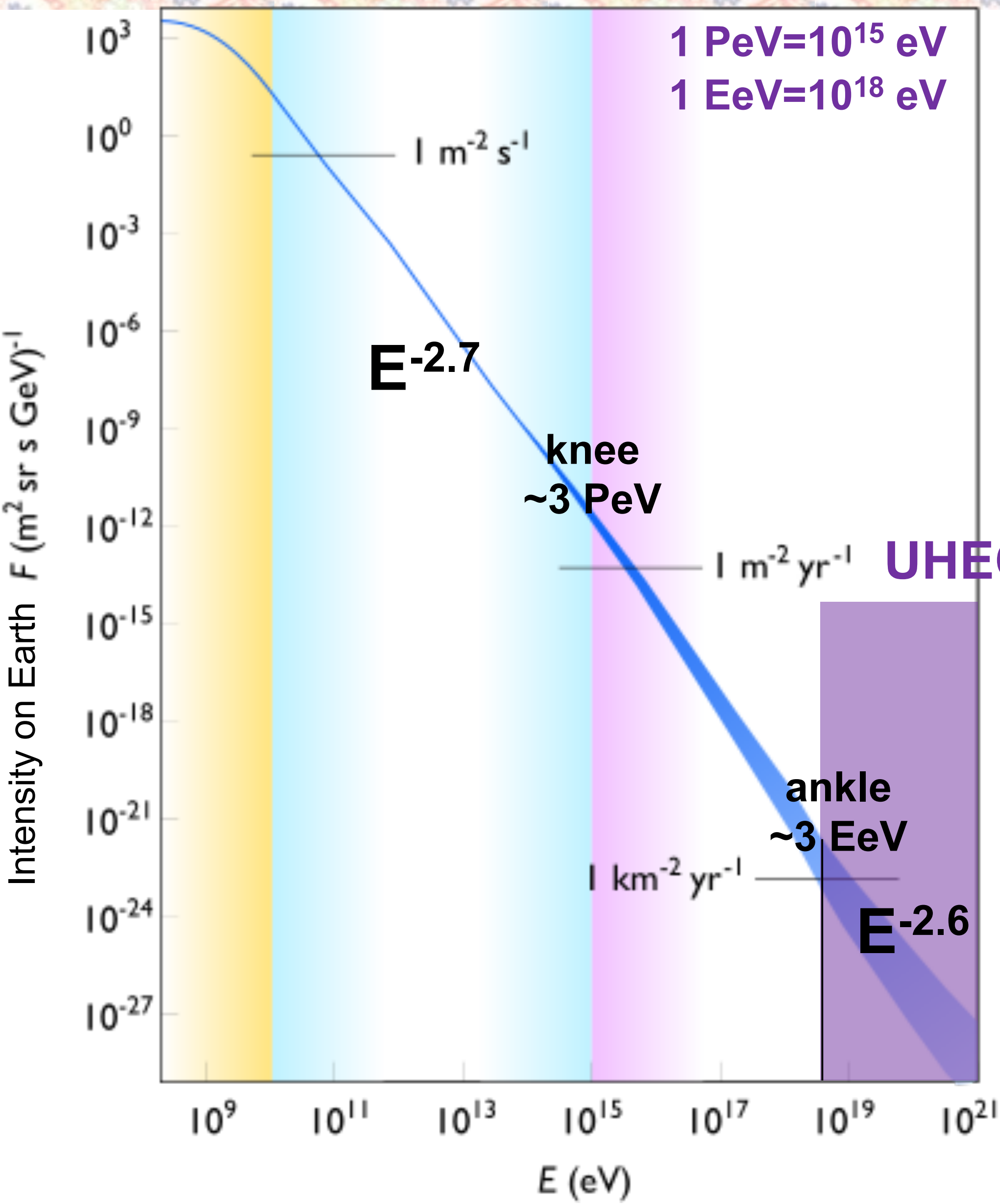






Cosmic "gifts": crucial roles in particle physics/astronomy

Cosmic-Ray Origin – A Century Old Puzzle



power-law spectrum

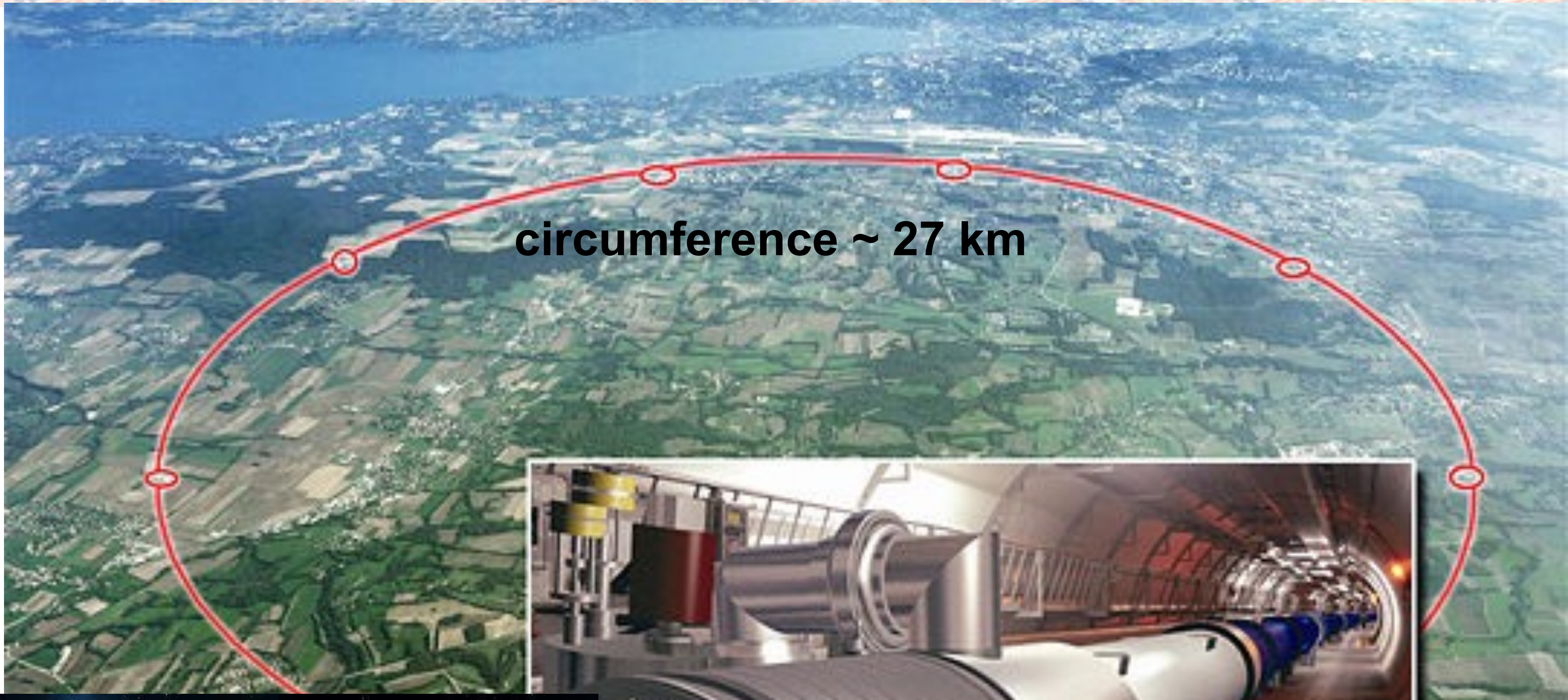
$$\frac{dN_{\rm CR}}{dE} \propto E^{-s_{\rm CR}}$$

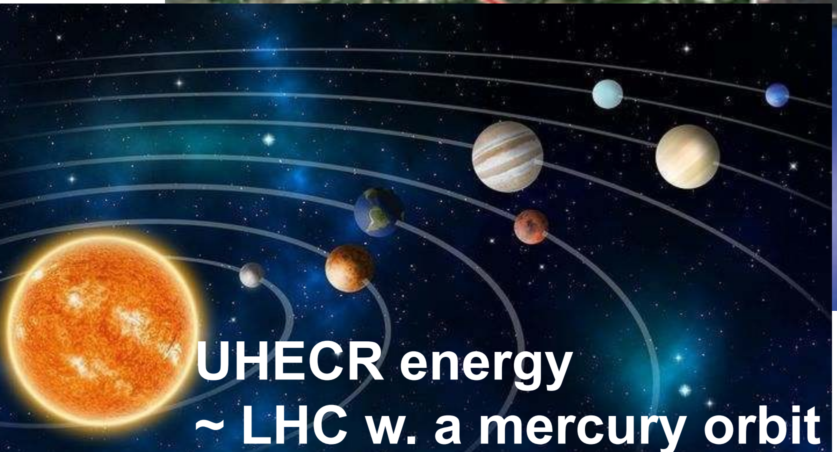
acceleration mechanisms?
propagation processes?

UHECR = ultrahigh-energy cosmic rays

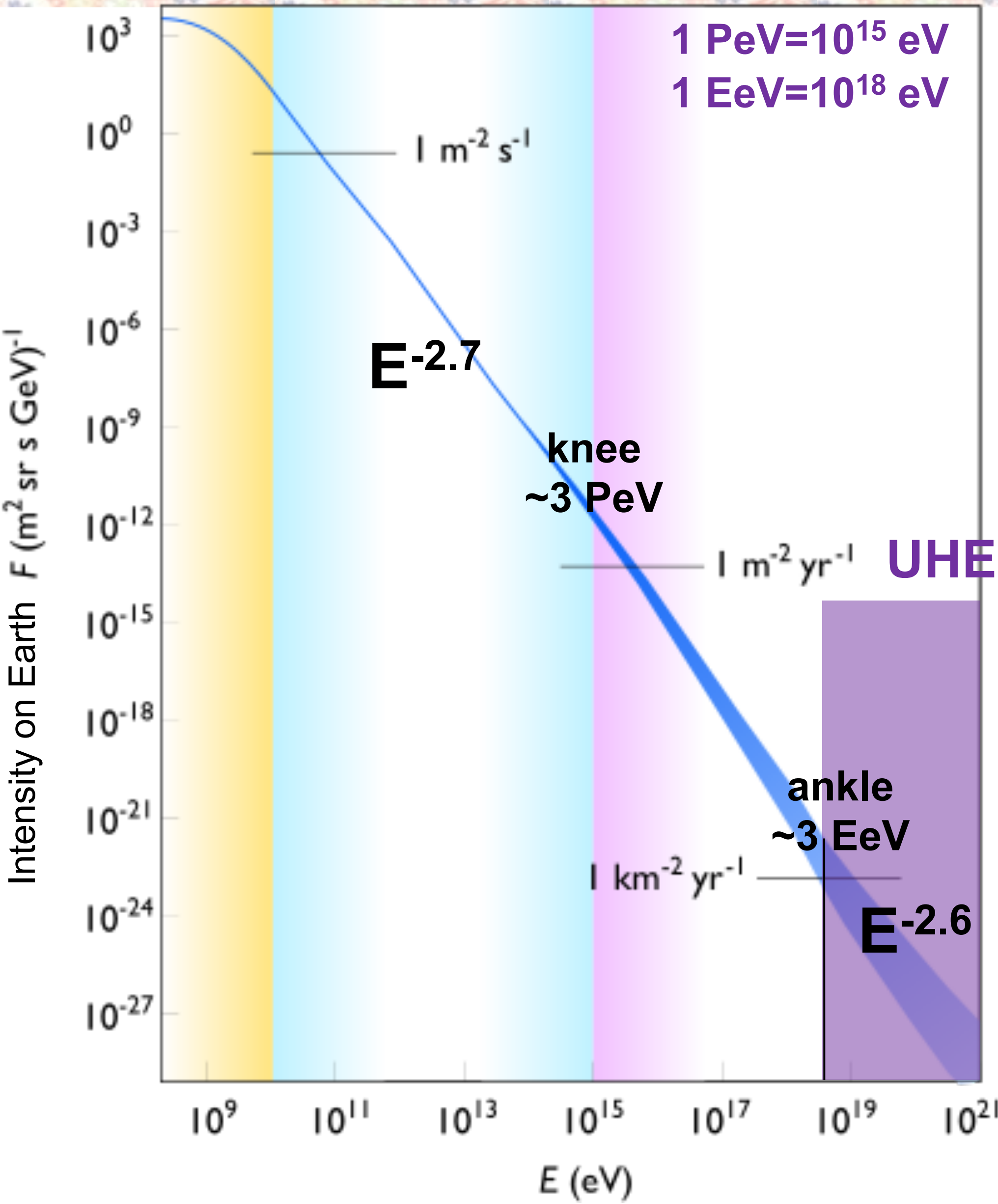
$3\text{x}10^{20}$ eV ~ 50 J ~ kinetic energy of a tennis ball with 160km/h!

UHECR vs Large Hadron Collider (LHC)





Cosmic-Ray Origin – A Century Old Puzzle



power-law spectrum

$$\frac{dN_{\rm CR}}{dE} \propto E^{-s_{\rm CR}}$$

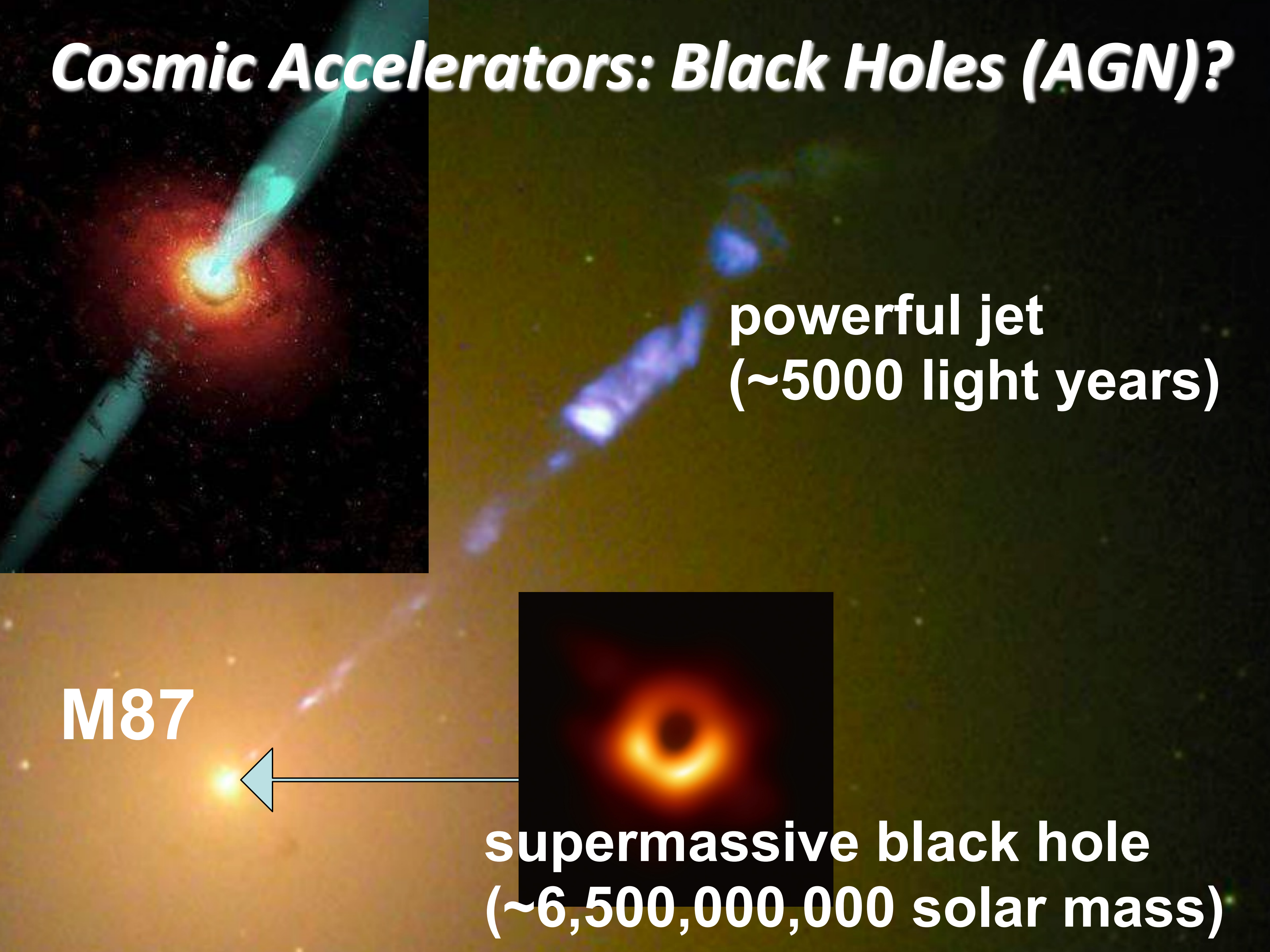
acceleration mechanisms?
propagation processes?

UHECR = ultrahigh-energy cosmic rays

3×10^{20} eV ~ 50 J ~ kinetic energy of a tennis ball with 160km/h!

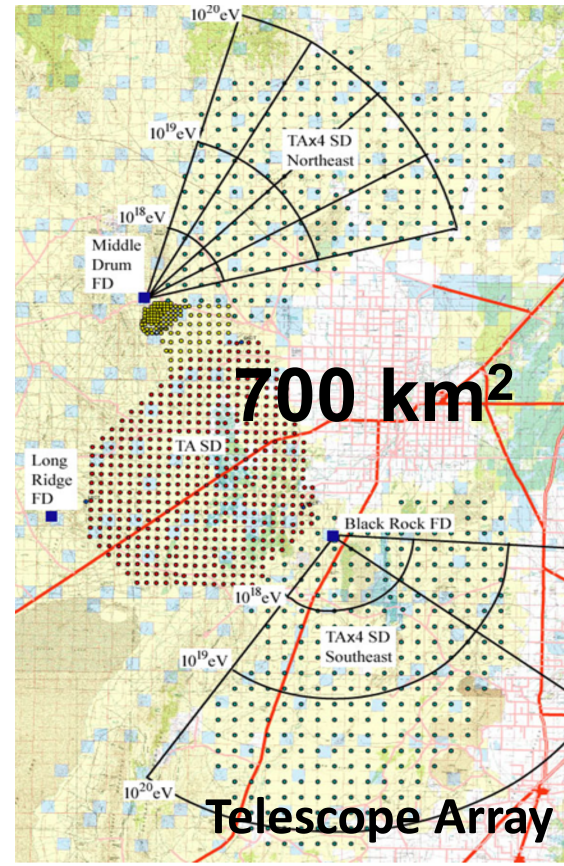
"What is the origin?"

Cosmic Accelerators: Black Holes (AGN)?

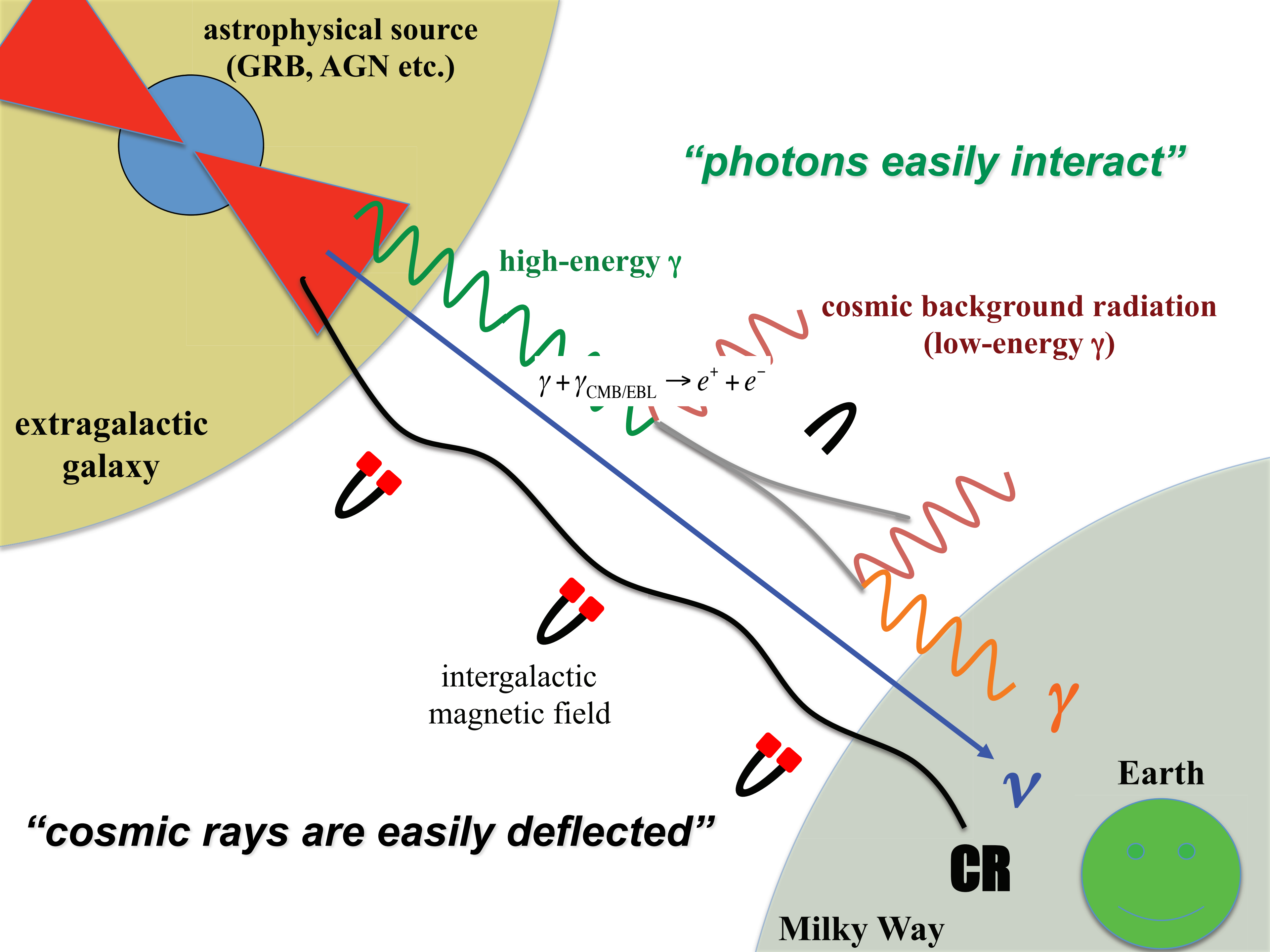


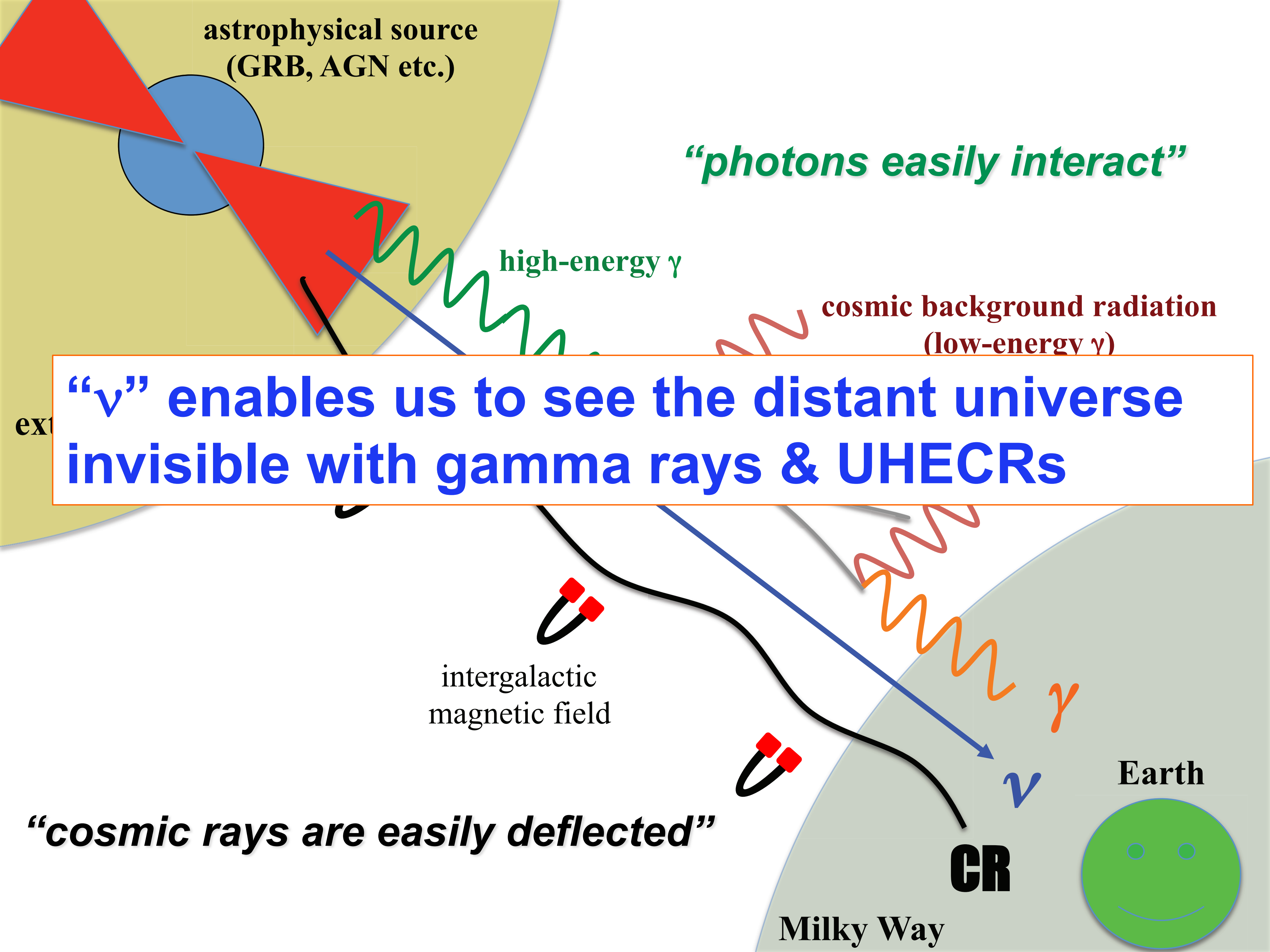
UHECR Observations

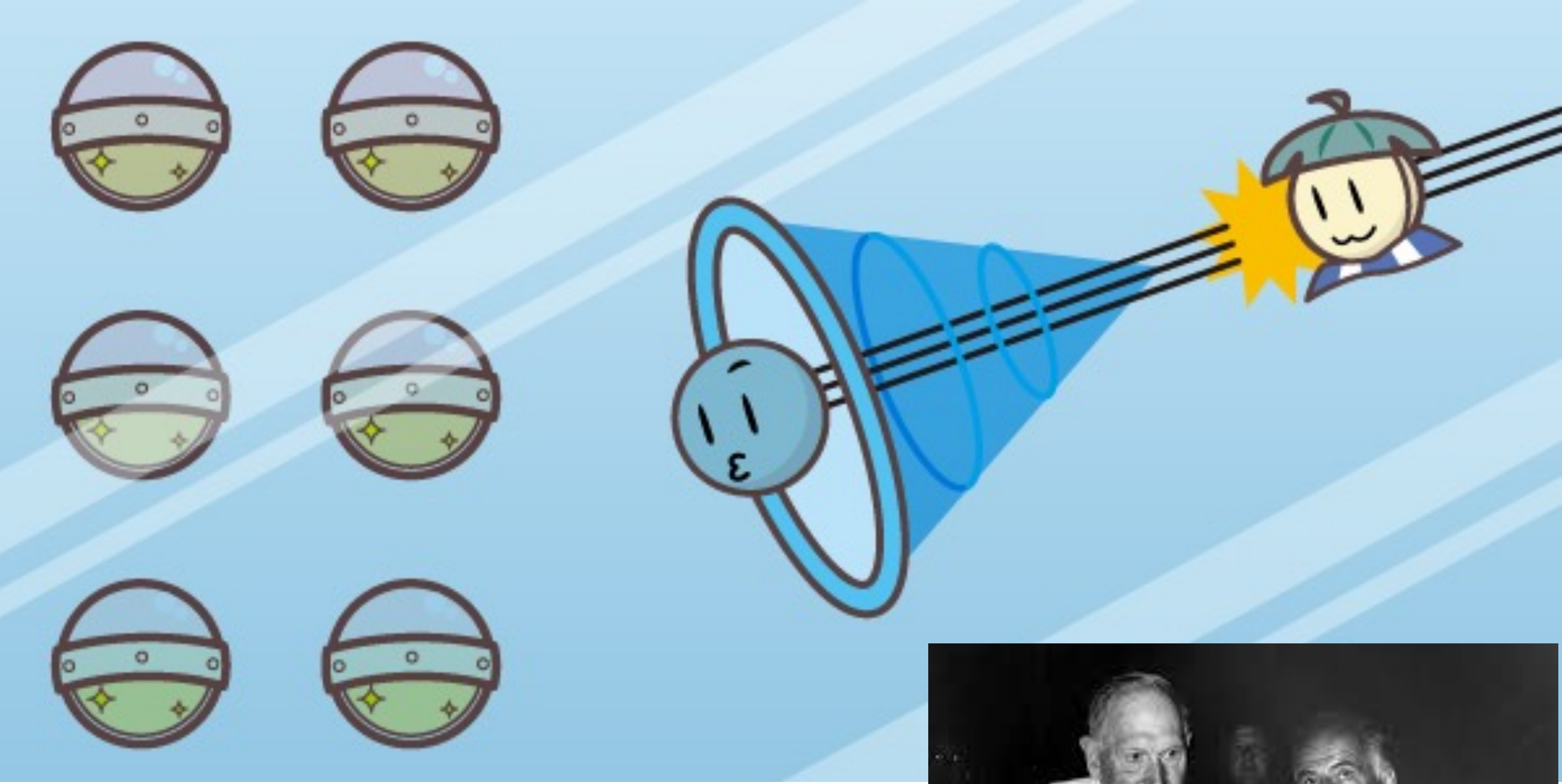
Need large detectors ← ~1 event/km^2/300yr



No source has been found so far…


astrophysical source
(GRB, AGN etc.)
"photons easily interact"
high-energy γ
cosmic background radiation
(low-energy γ)
$\gamma + \gamma_{CMB/EBL} \rightarrow e^{+} + e^{-}$
extragalactic
galaxy
intergalactic
magnetic field
γ
ν
Earth
"cosmic rays are easily deflected"
CR
Milky Way

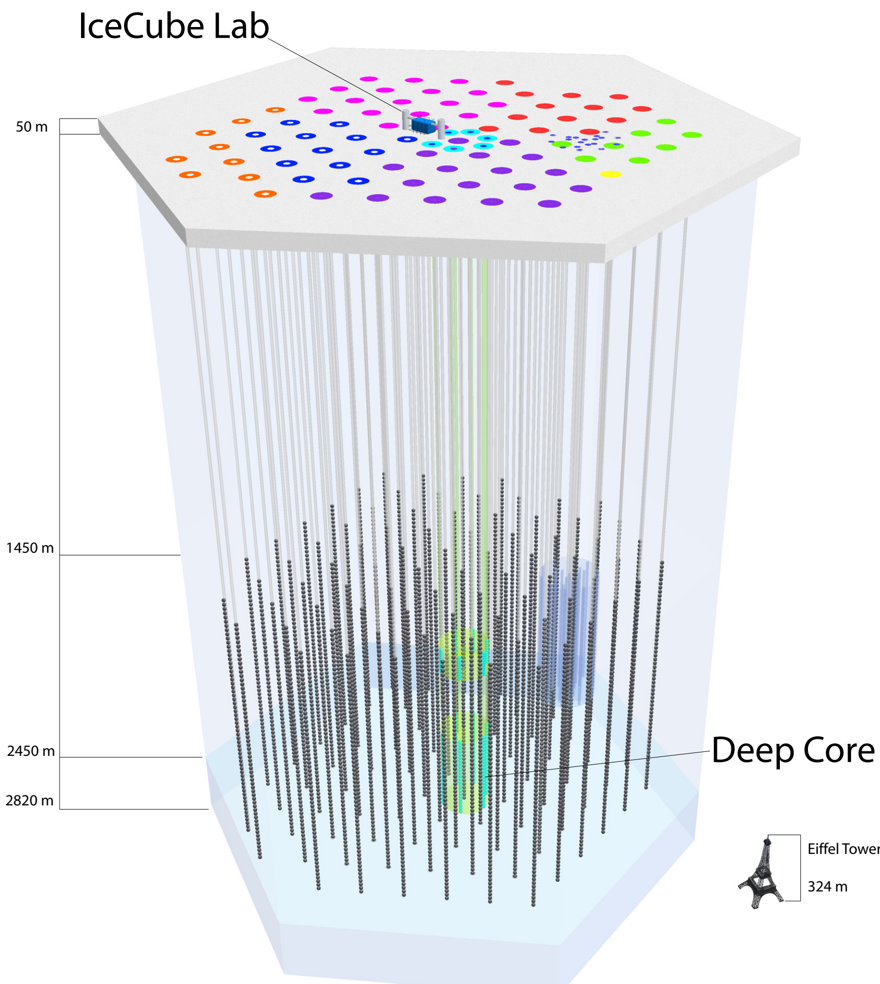

astrophysical source
(GRB, AGN etc.)
"photons easily interact"
high-energy γ
cosmic background radiation
(low-energy γ)
"ν" enables us to see the distant universe
invisible with gamma rays & UHECRs
intergalactic
magnetic field
γ
ν
Earth
CR
"cosmic rays are easily deflected"
Milky Way



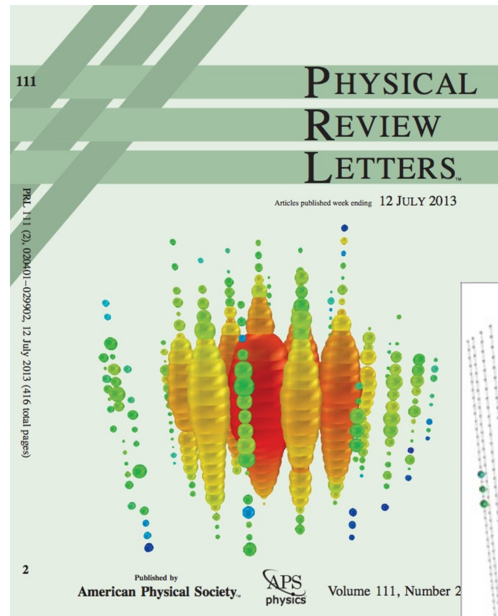
proposal by M. Markov (1960)
“…to install detectors deep in a lake or a sea and to determine the location of charged particles with the help of Cherenkov radiation”

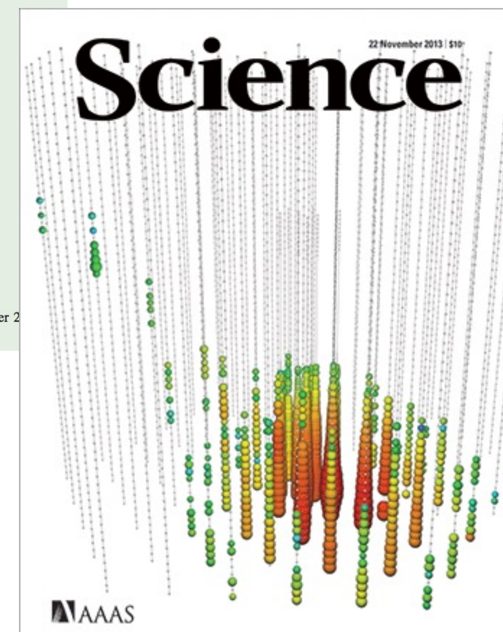
IceCube & Discovery of High-Energy Cosmic Neutrinos

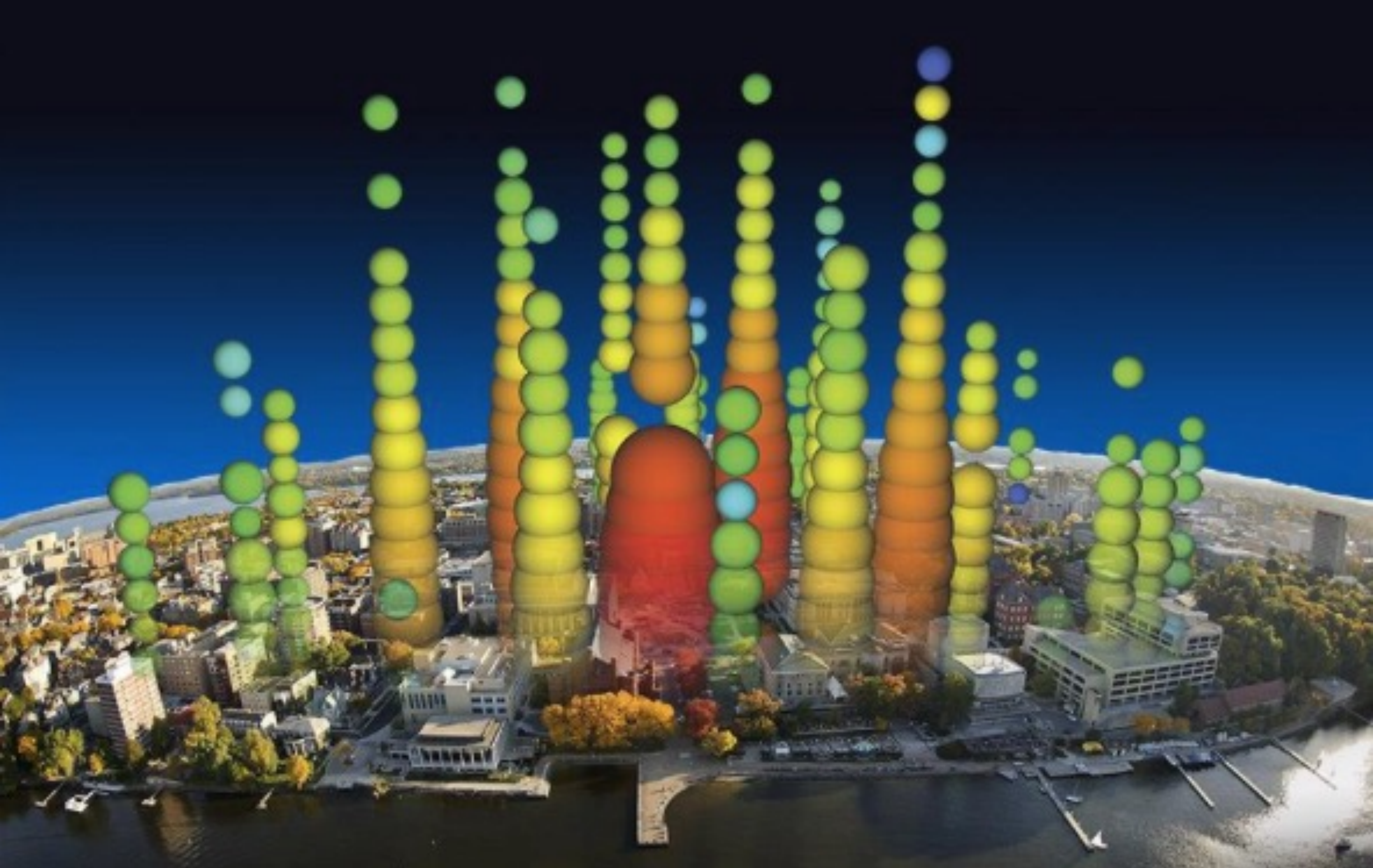
IceCube: 1km^3 detector @ south pole completed in 2010



2012-2013: evidence of high-energy cosmic ν





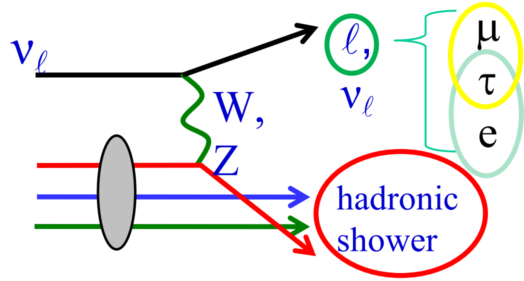


~ 1 PeV = 10^{15} eV

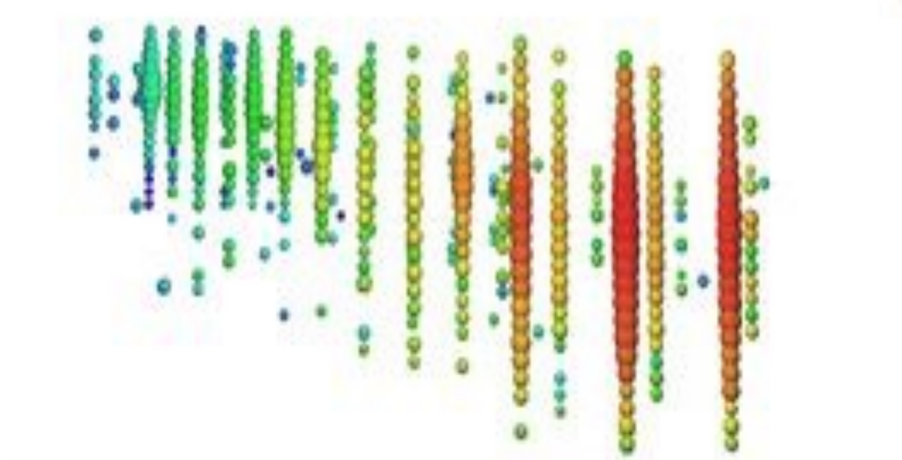
>> 1–10 MeV (supernova/Solar ν)

Neutrino Event Types

2 "main" event types



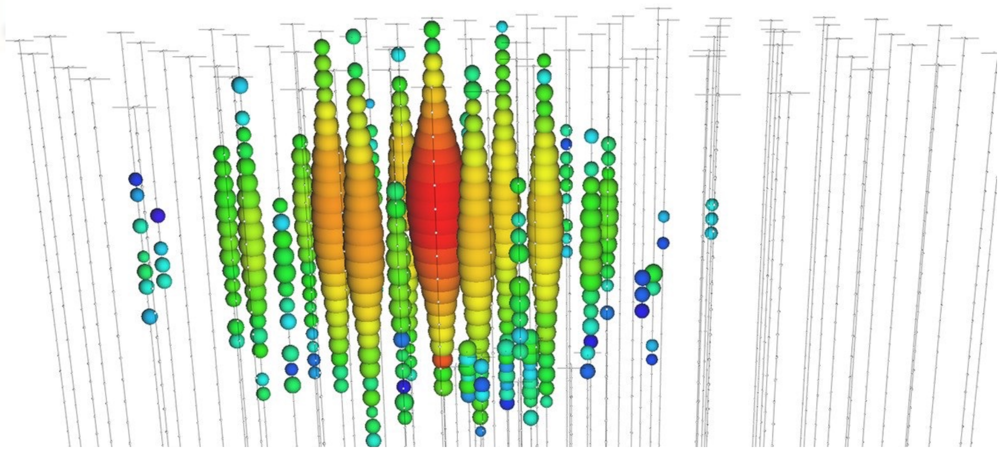
"ν_μ track"



ν_μ+N → μ+X

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

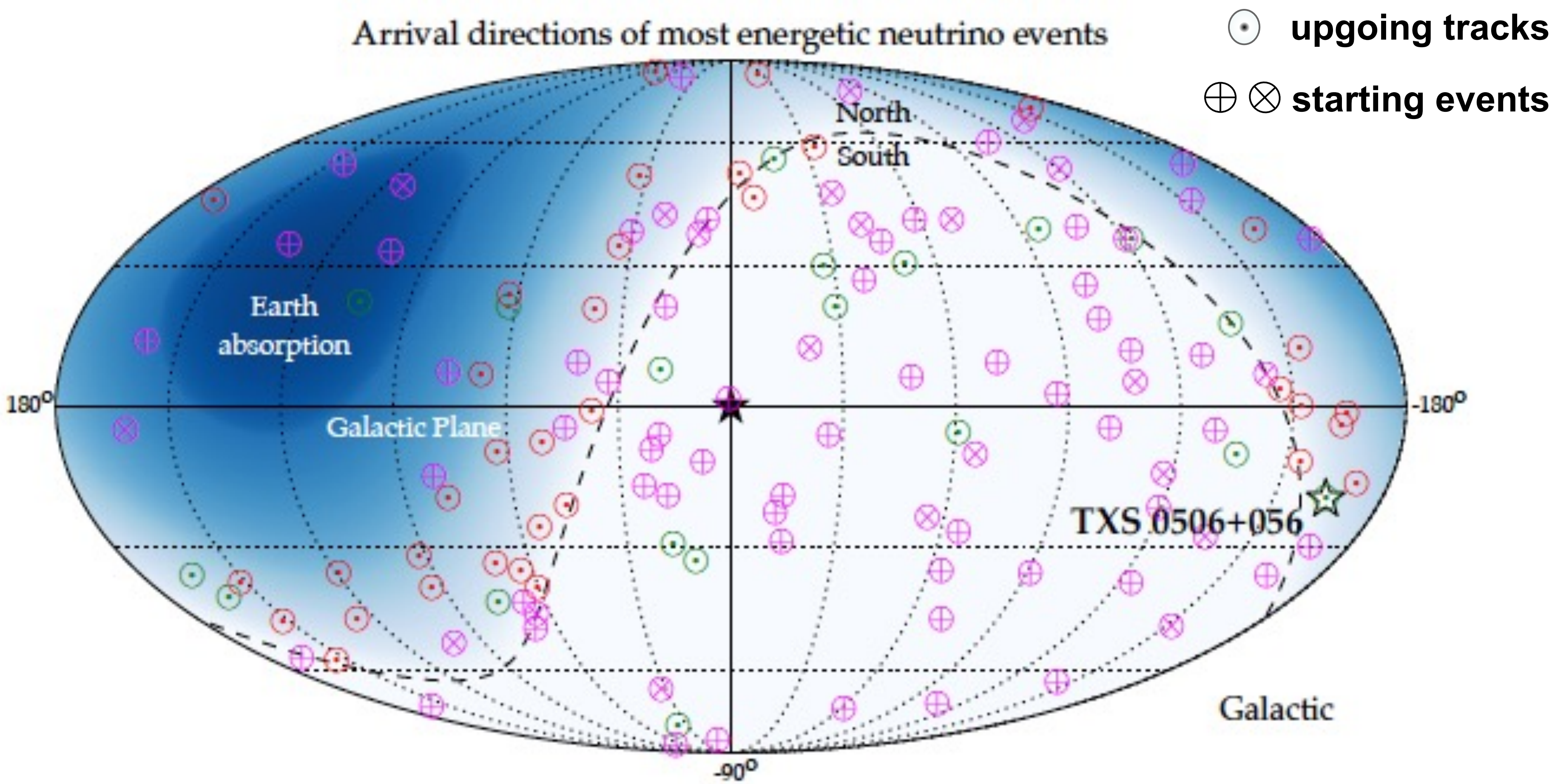
"shower"



ν_e+N → e+X **ν_X+N → ν_X+X**

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

High-Energy Neutrino Sky



consistent w. isotropic distribution/extragalactic origins

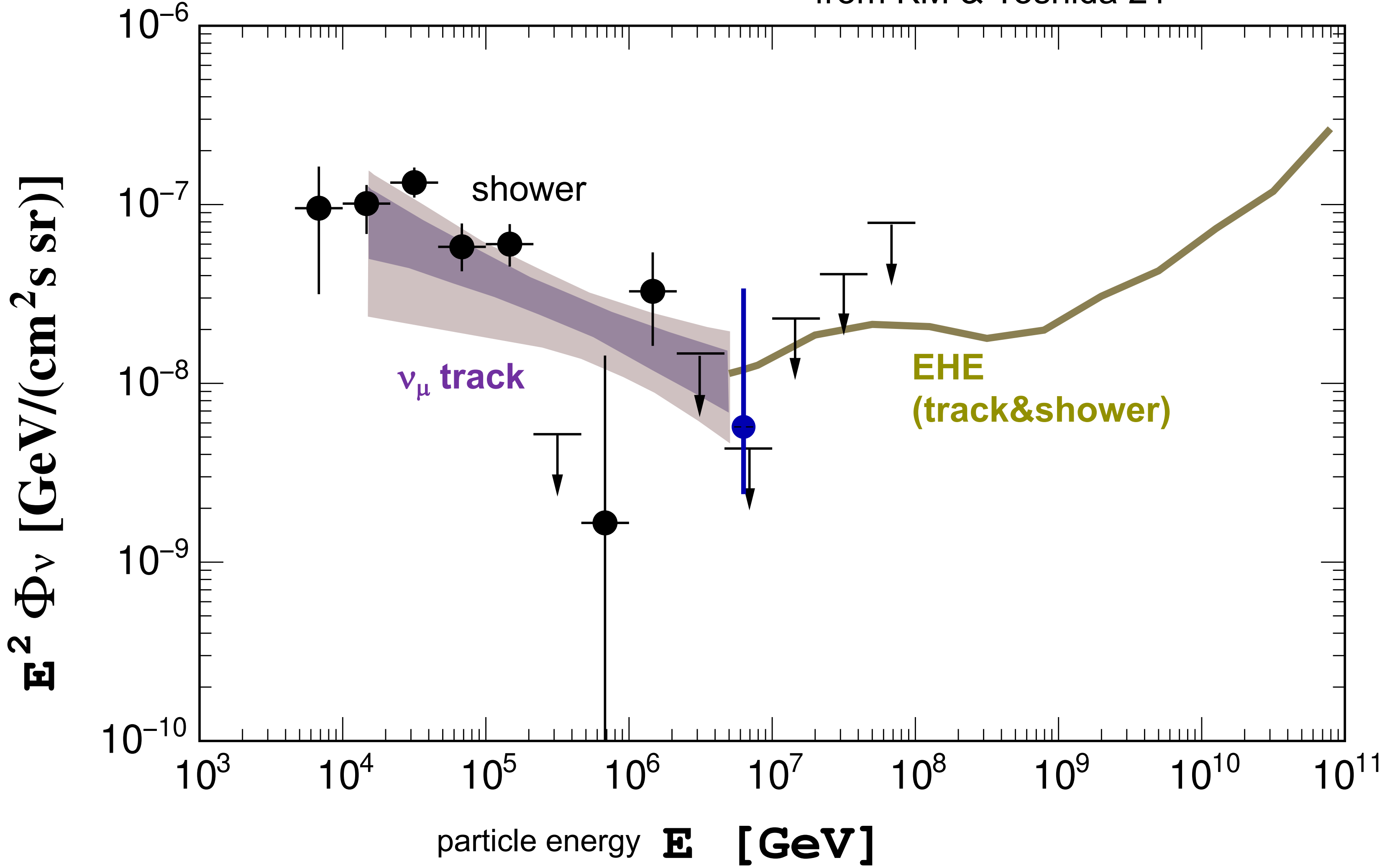
All-Sky Neutrino Flux & Spectrum

all-sky ν flux at E_ν ~200 TeV

$E_\nu^2\Phi_\nu$ ~ 3×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

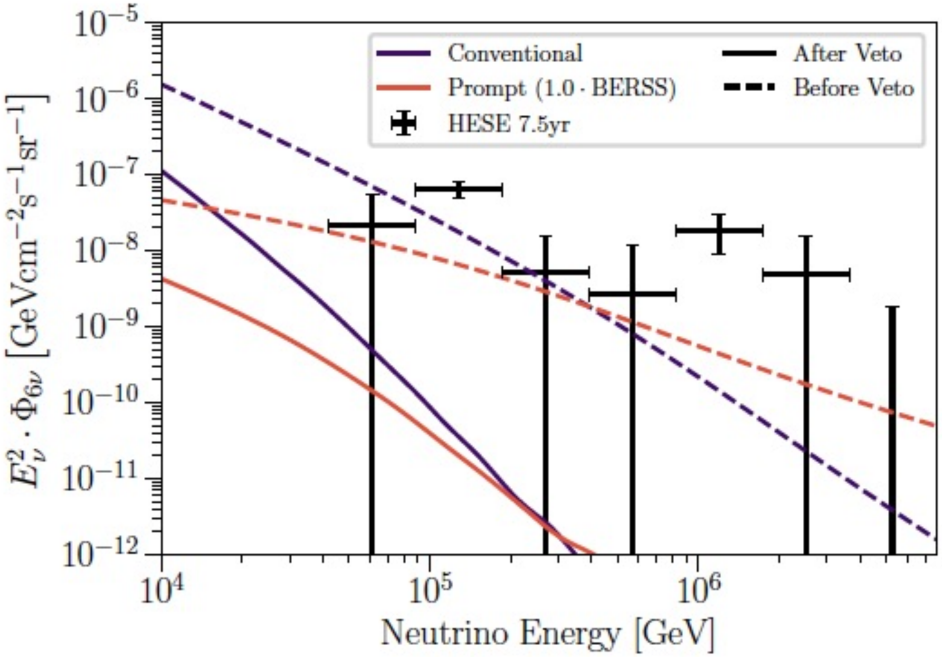
IceCube Collaboration @ Neutrino 2020
IceCube Collaboration 20 PRL

from KM & Yoshida 21

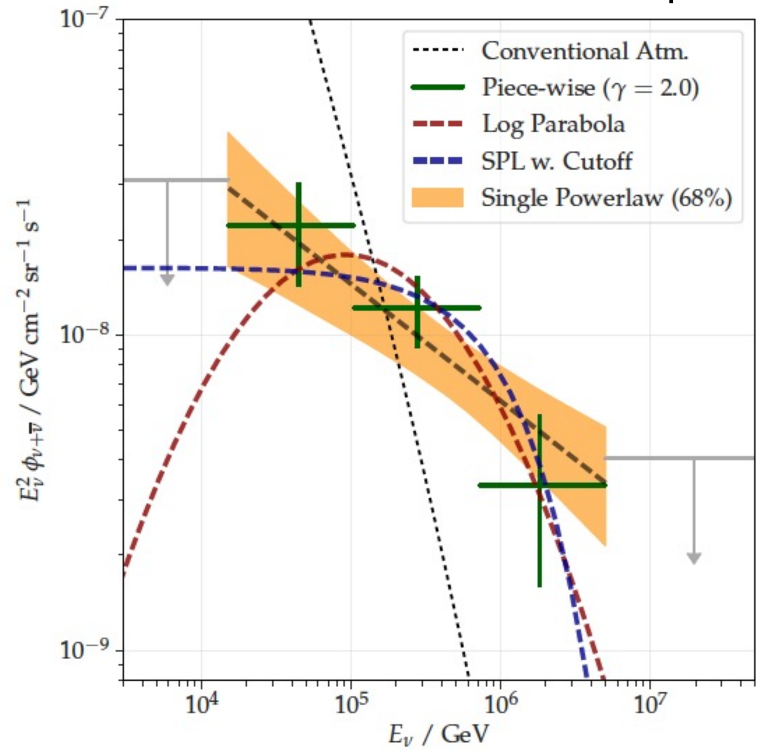


Latest Results on High-Energy Neutrinos

IceCube Collaboration 21 PRD



IceCube Collaboration 22 ApJ

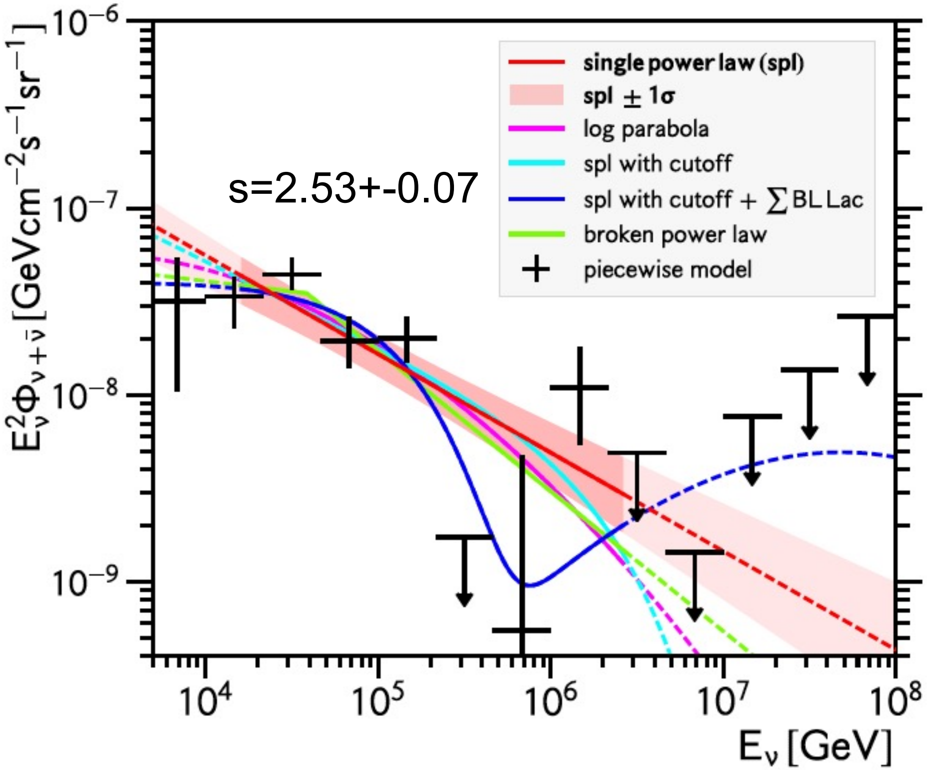


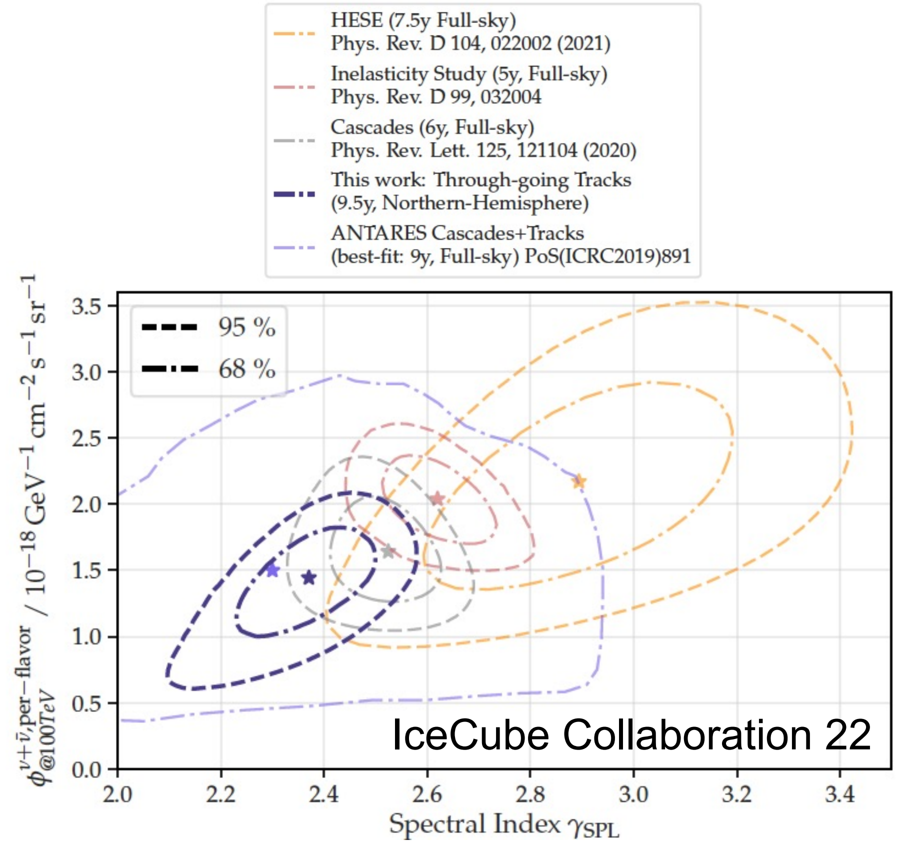
- 7.5-yr "HESE" (tracks & showers) 102 starting events (60 events > 60 TeV) Best-fit: s=2.87+0.20-0.19
- 9.5-yr "upgoing" ν_μ tracks 35 events at >200 TeV (5.6σ) (updated reconstruction) Best-fit: s=2.37$\pm$0.09 softening at PeV w. ~2σ level

Latest Results on Medium-Energy Neutrinos

shower analyses (E_{dep}=0.4 TeV-10 PeV (2010-2015), 4740 events)

IceCube Collaboration 20 PRL





$E_\nu^2\ \Phi_\nu$=(1.66+0.25-0.27)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV (per flavor)

No evidence for north-south asymmetry (supporting the extragalactic origin)

Not conclusive but perhaps a structure in the neutrino spectrum?

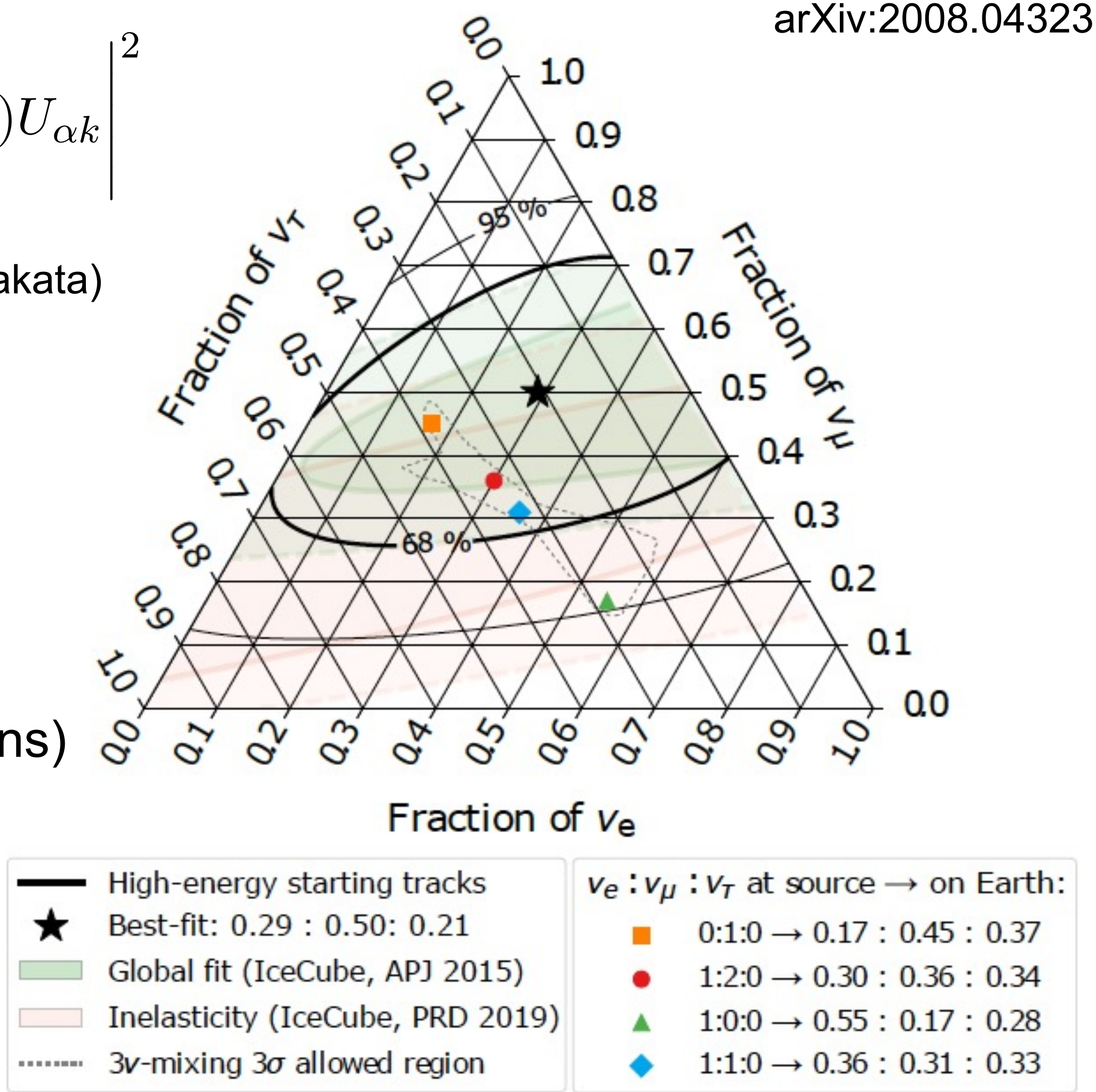
Neutrino Flavors

Neutrino oscillation

arXiv:2008.04323

$$P_{\alpha\to\beta}(t) = \left| \sum_{k=1}^{n} U^*_{\beta k} \exp(-iEt) U_{\alpha k} \right|^2$$

U: lepton mixing matrix
(Pontecorvo-Maki-Nakagawa-Sakata)



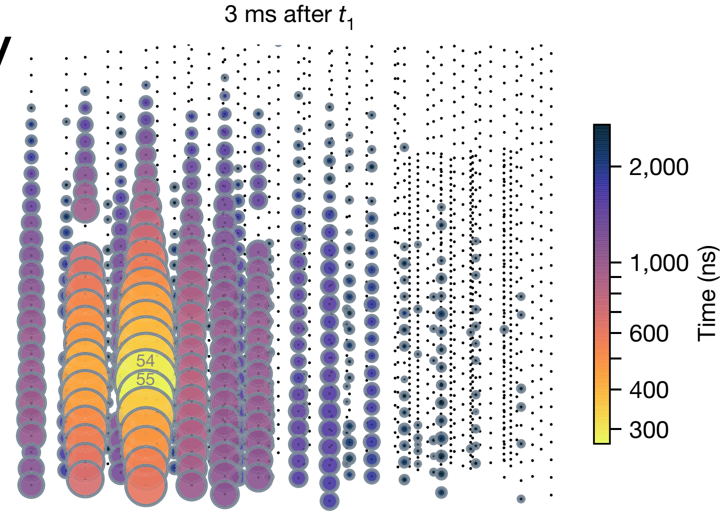
long baseline limit:

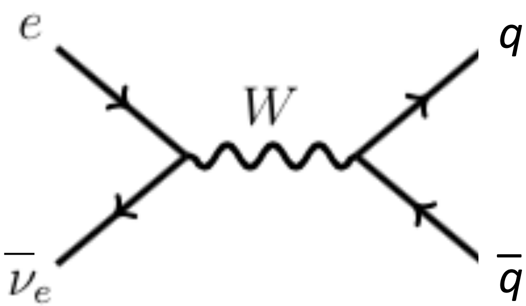
$\nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$

(if no astrophysical complications)

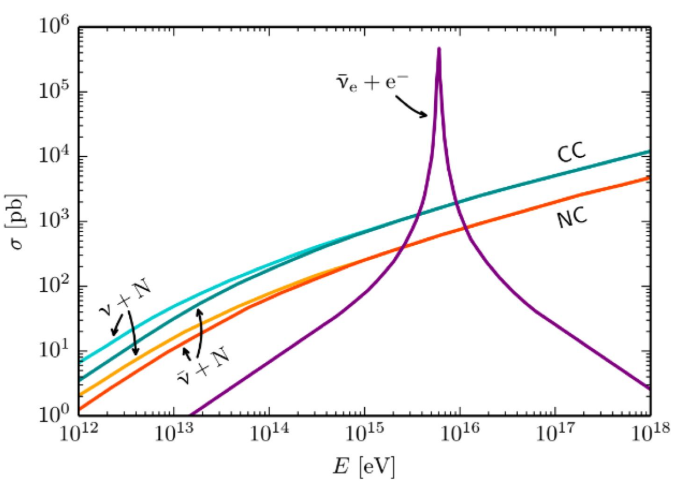
Anti-Neutrino Detection

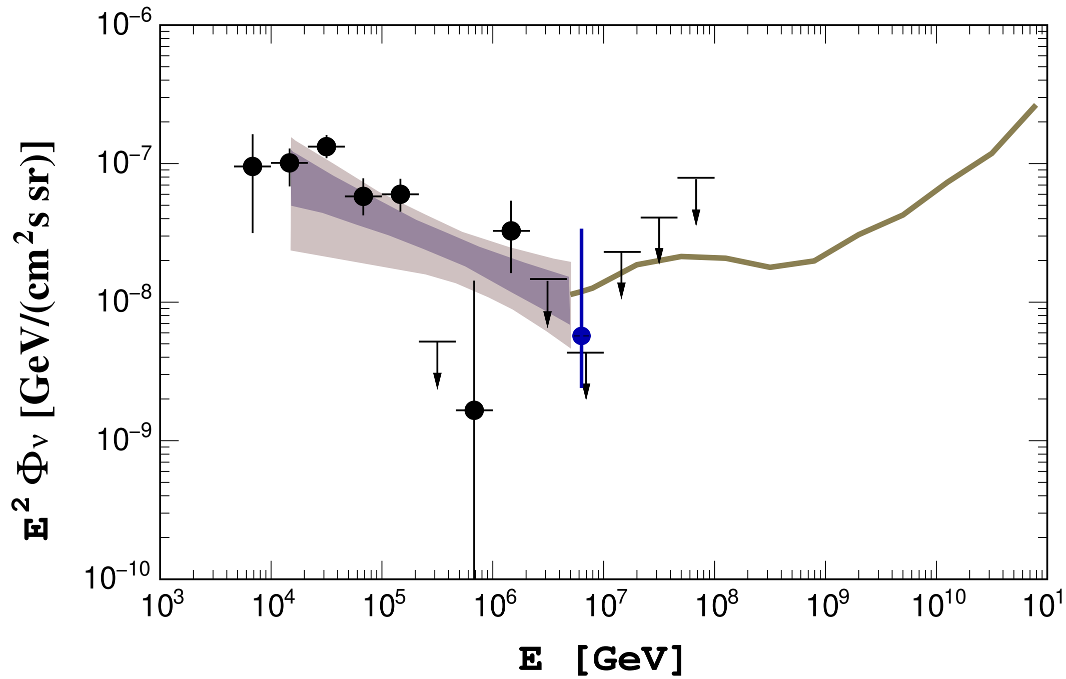
- Shower deposited energy = 6.05 PeV
- Glashow resonance (GR) event at E=6.3 PeV (~2.3σ) (predicted in 1959 by Glashow)





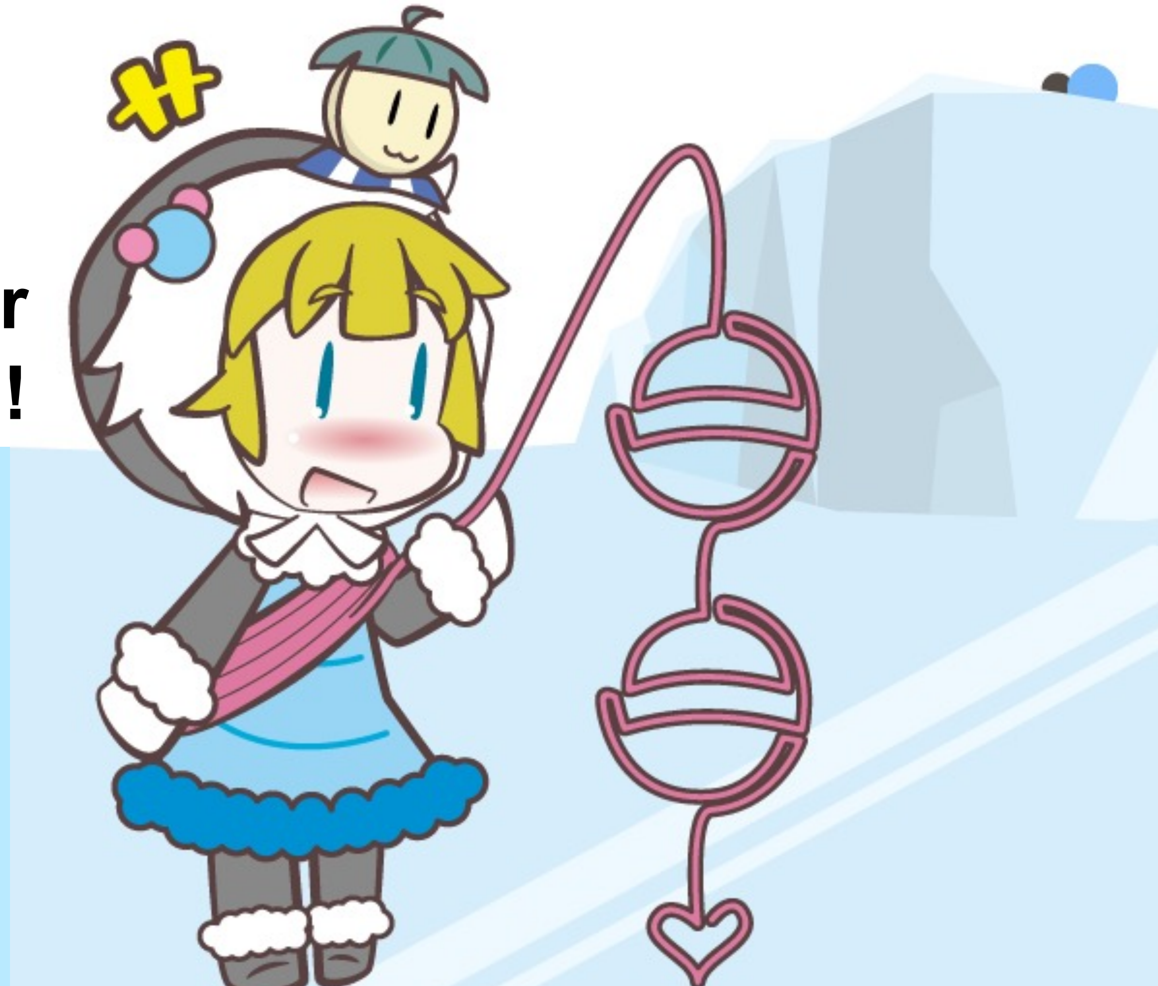
IceCube 21 Nature

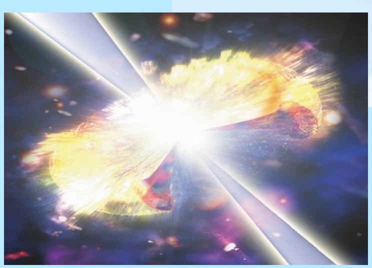


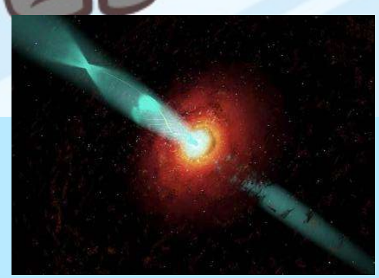


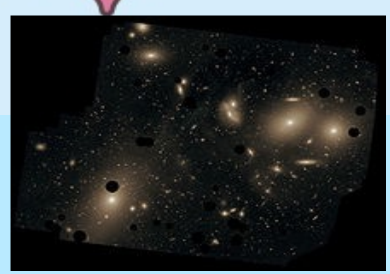
Where do neutrinos mainly come from?

monster fishing!!



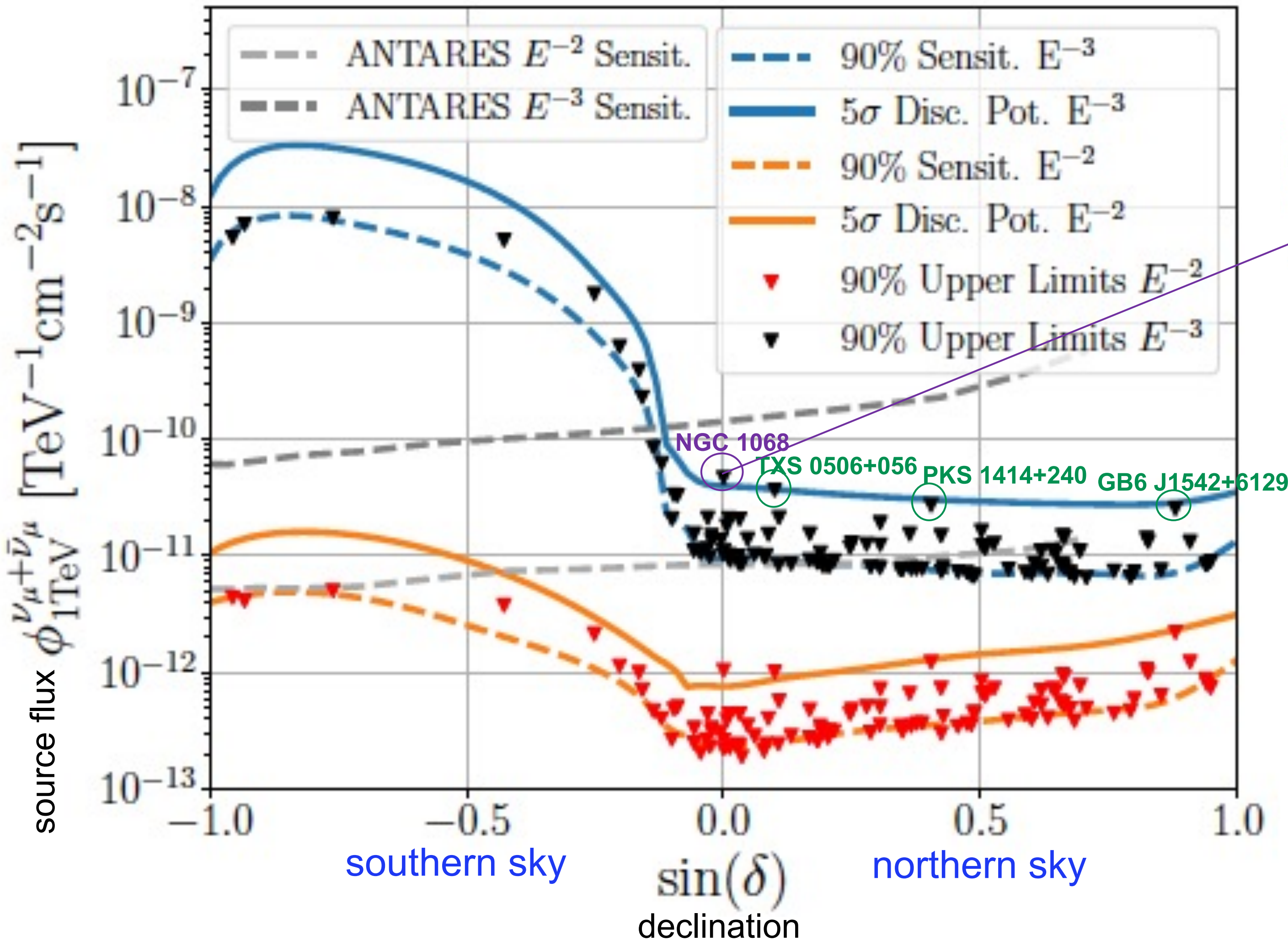




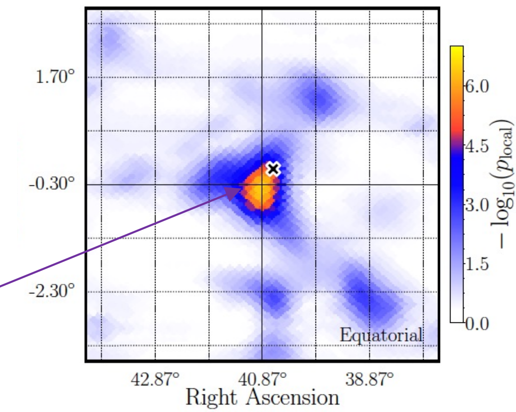


IceCube Source Searches

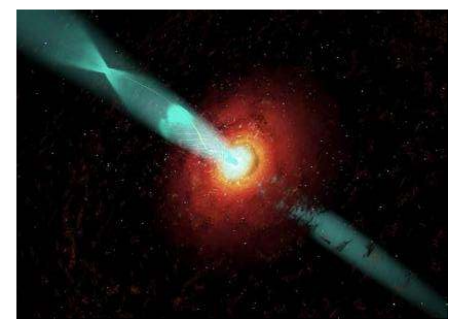
IceCube Collaboration 20 PRL



AGN/starburst galaxy



Jetted AGN



"Catches" (~3σ) exist but none have reached the discovery level

Introduction

Astrophysical Implications

New Physics Implications

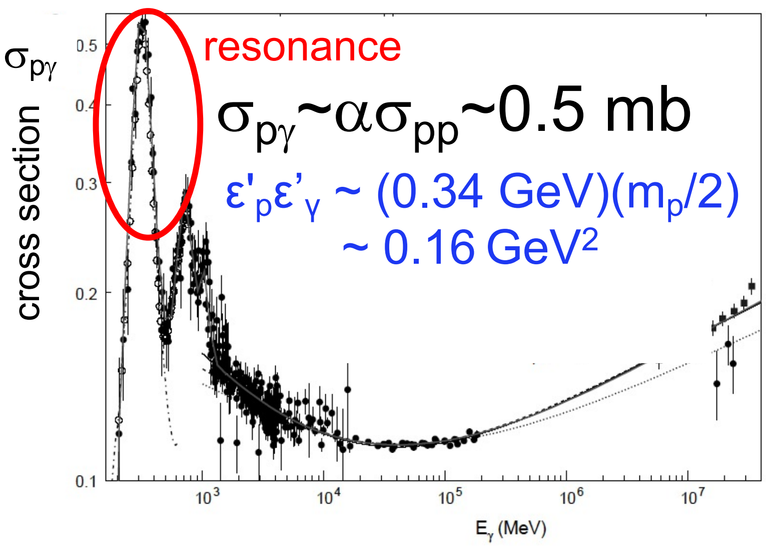
High-Energy Neutrino Production

Cosmic-ray Accelerators

Active galaxy

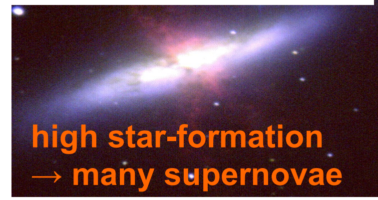
γ-ray burst

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



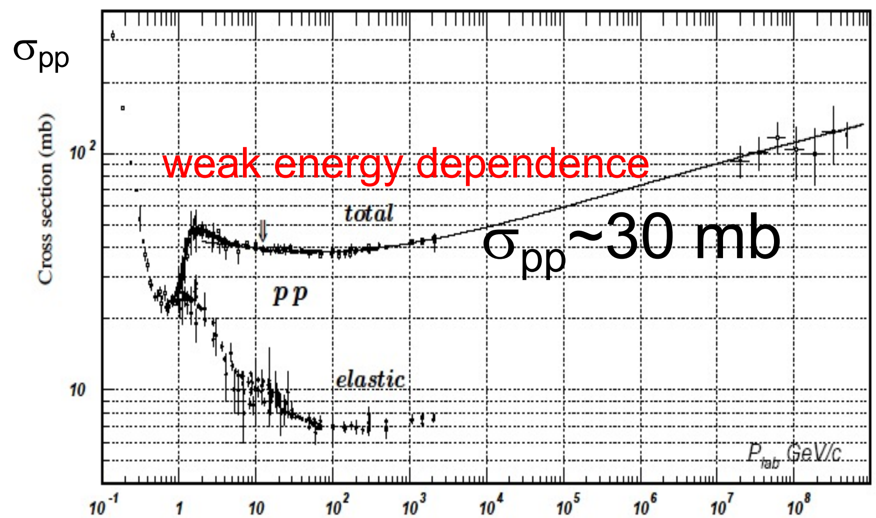
Cosmic-ray Reservoirs

Starburst galaxy



Galaxy cluster

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



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

Fate of High-Energy Gamma Rays

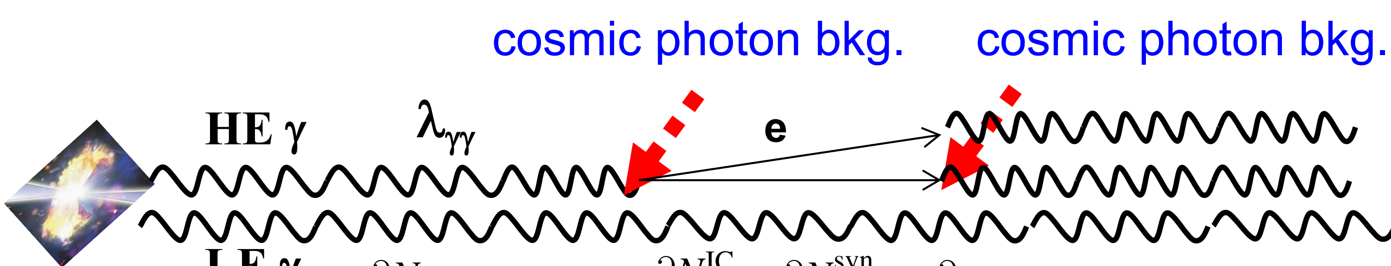
$$\pi^0 \rightarrow \gamma + \gamma$$

$p + \gamma \rightarrow N\pi + X$ $\quad \pi^0:\pi^{\pm} \sim 1:1 \rightarrow$ $\mathbf{E_\gamma^2\,\Phi_\gamma : E_\nu^2\,\Phi_\nu} \sim 4:3$

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

comparable

Moreover, accelerated electrons make γ rays by synchrotron & Compton processes



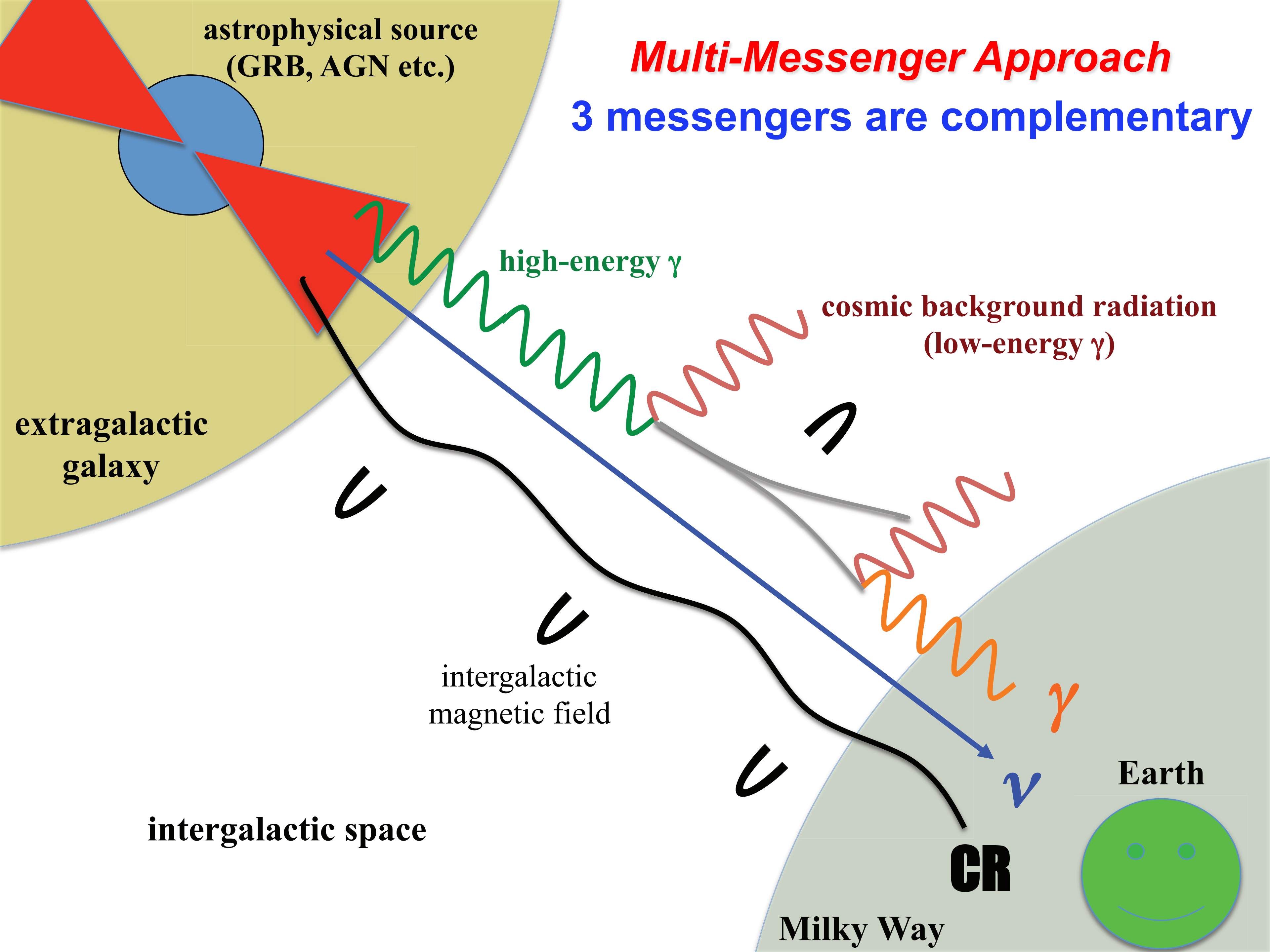
Fermi satellite

airshower detectors

$$\frac{\partial N_\gamma}{\partial x} = -N_\gamma R_{\gamma\gamma} + \frac{\partial N_\gamma^{\rm IC}}{\partial x} + \frac{\partial N_\gamma^{\rm syn}}{\partial x} - \frac{\partial}{\partial E}[P_{\rm ad} N_\gamma] + Q_\gamma^{\rm inj},$$

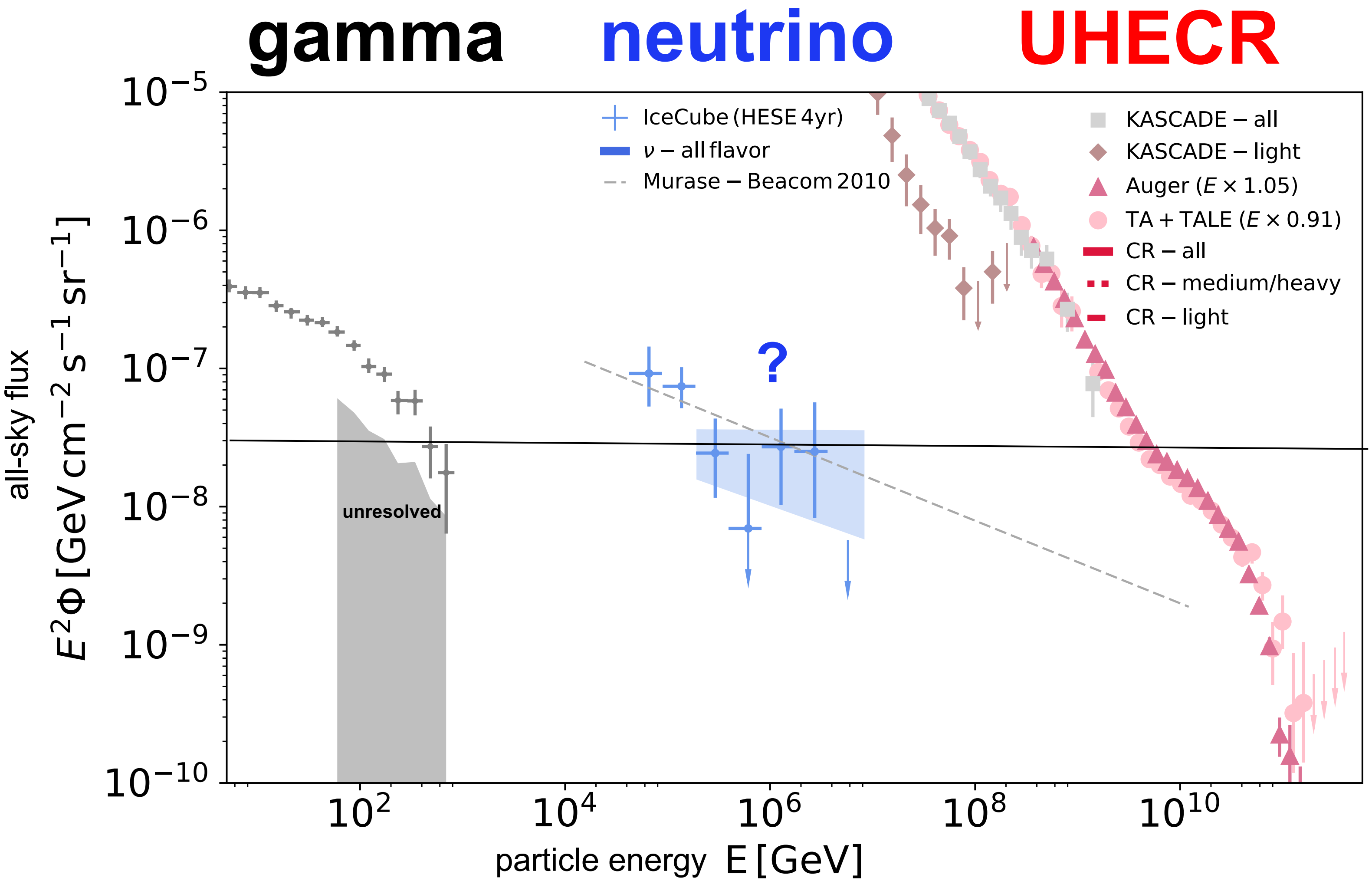
$$\frac{\partial N_e}{\partial x} = \frac{\partial N_e^{\gamma\gamma}}{\partial x} - N_e R_{\rm IC} + \frac{\partial N_e^{\rm IC}}{\partial x} - \frac{\partial}{\partial E}[(P_{\rm syn} + P_{\rm ad}) N_e] + Q_e^{\rm inj},$$

>TeV-PeV γ rays are cascaded to GeV-TeV γ rays



Multi-Messenger Approach
3 messengers are complementary
astrophysical source
(GRB, AGN etc.)
high-energy γ
cosmic background radiation
(low-energy γ)
extragalactic
galaxy
intergalactic
magnetic field
γ
ν
Earth
CR
intergalactic space
Milky Way

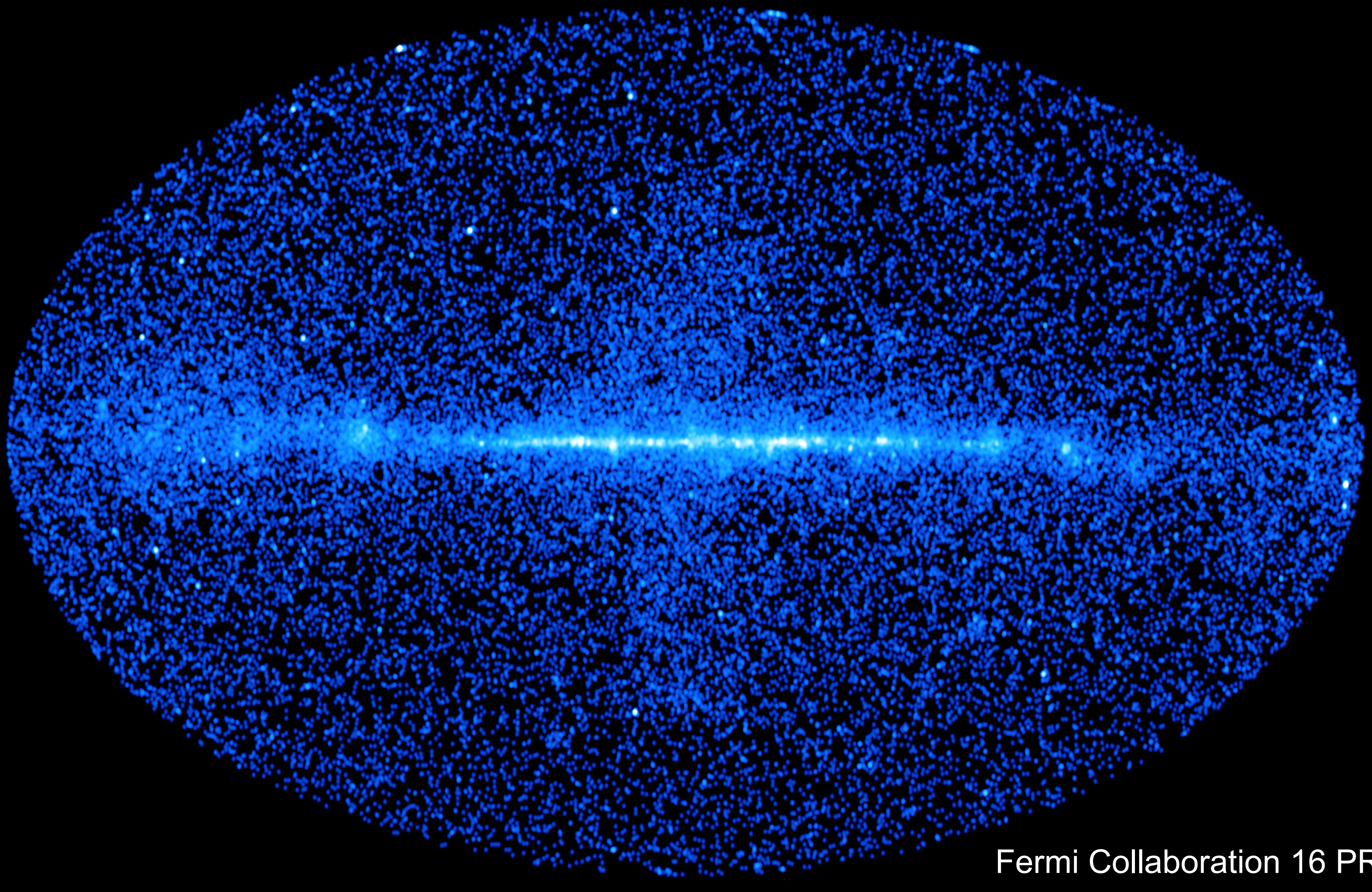
Multi-Messenger Astro-Particle "All-Sky Flux"



Energy generation rate per volume in the Universe are all "comparable"

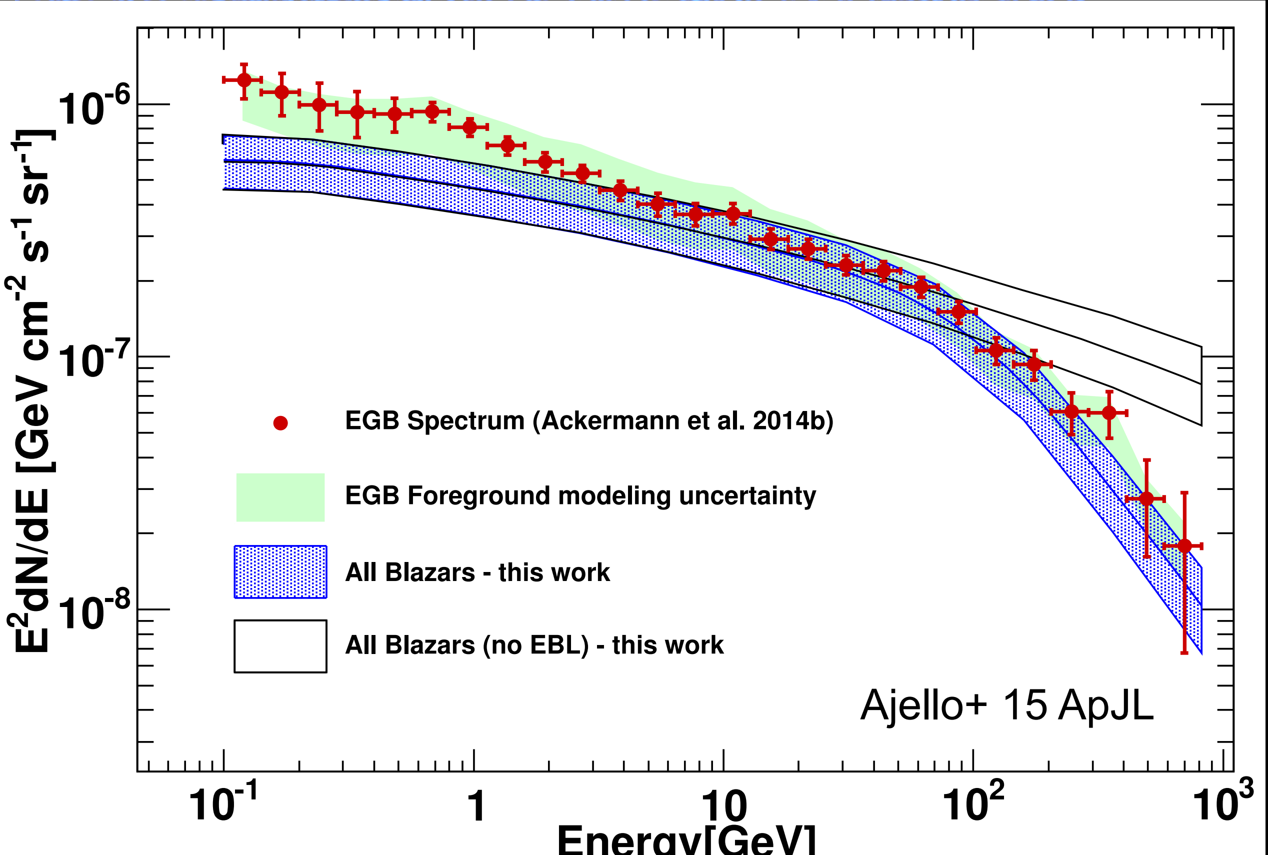
(e.g., KM & Fukugita 19 PRD)

Extragalactic Gamma-Ray Sky: Dominated by Jetted AGN



Fermi Collaboration 16 PRL

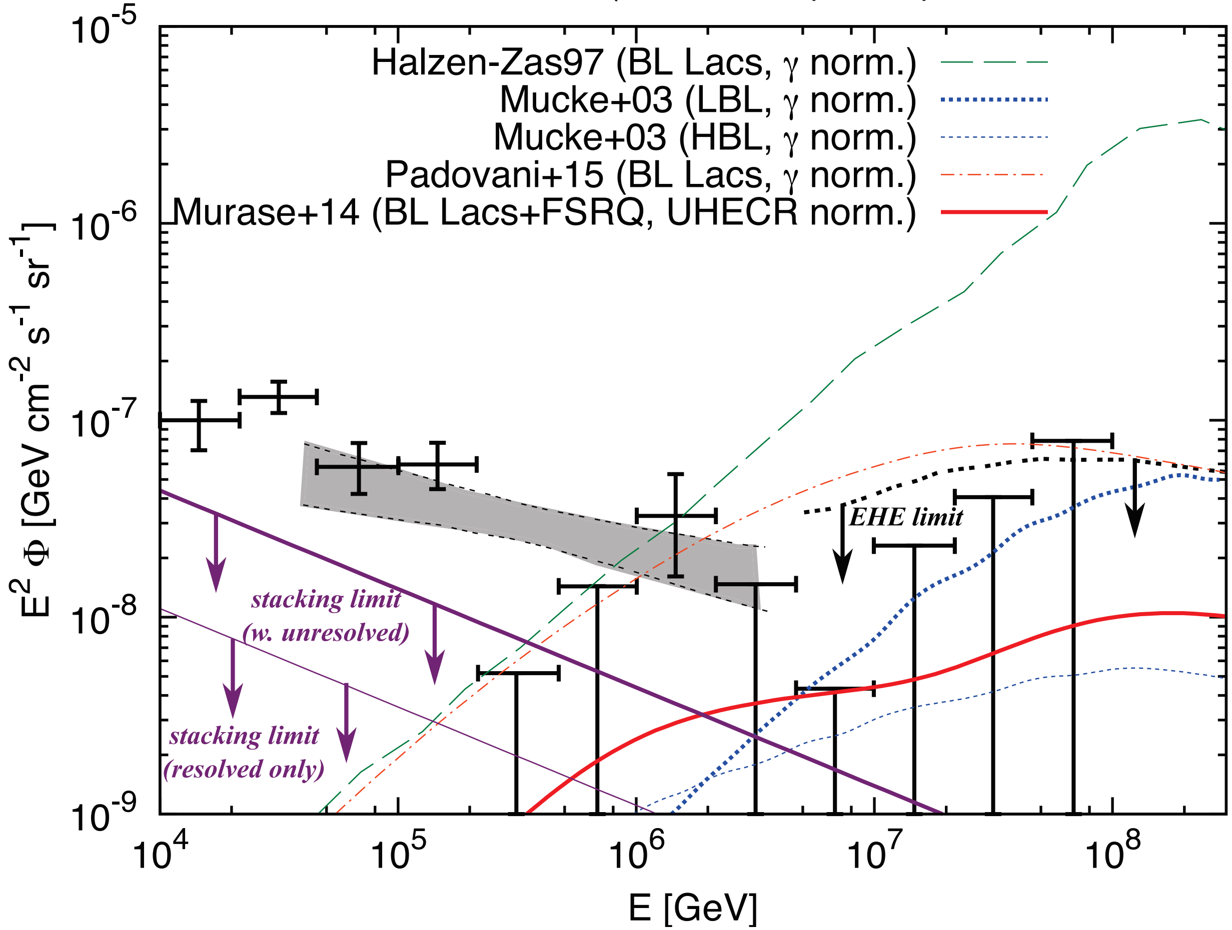
Extragalactic Gamma-Ray Sky: Dominated by Jetted AGN



Can Blazars be the Origin of IceCube Neutrinos?

γ-ray bright blazars are largely resolved -> stacking analyses are powerful

(IceCube 17 ApJ, Hooper+ 19 JCAP, Yuan, KM & Meszaros 20 ApJ)



Blazars are subdominant in all parameter space (most likely <~ 30%)

Similar conclusion from neutrino anisotropy limits (KM & Waxman 16 PRD)

High-Energy Neutrino Production

Cosmic-ray Accelerators

Active galaxy

γ-ray burst

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

stacking or other searches disfavor blazar-type AGN and classical γ-ray bursts as the "dominant" ν origin
(important results of multi-messenger approaches)

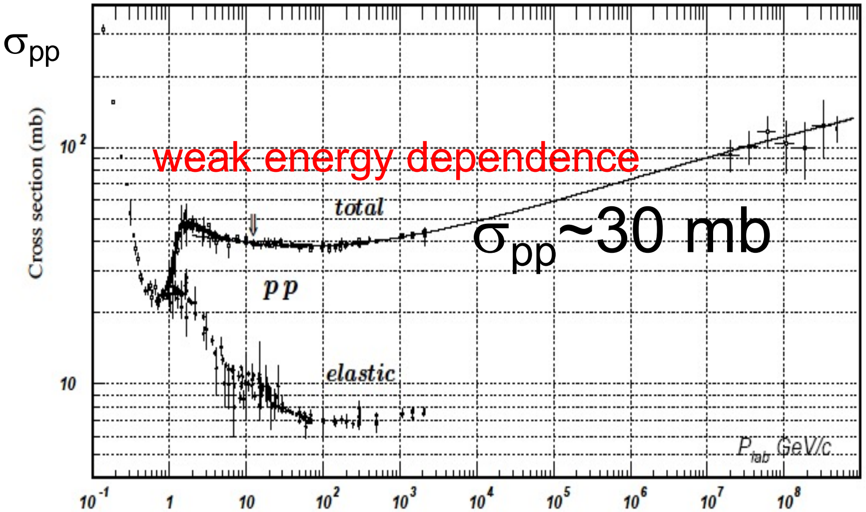
E_γ (MeV)

Cosmic-ray Reservoirs

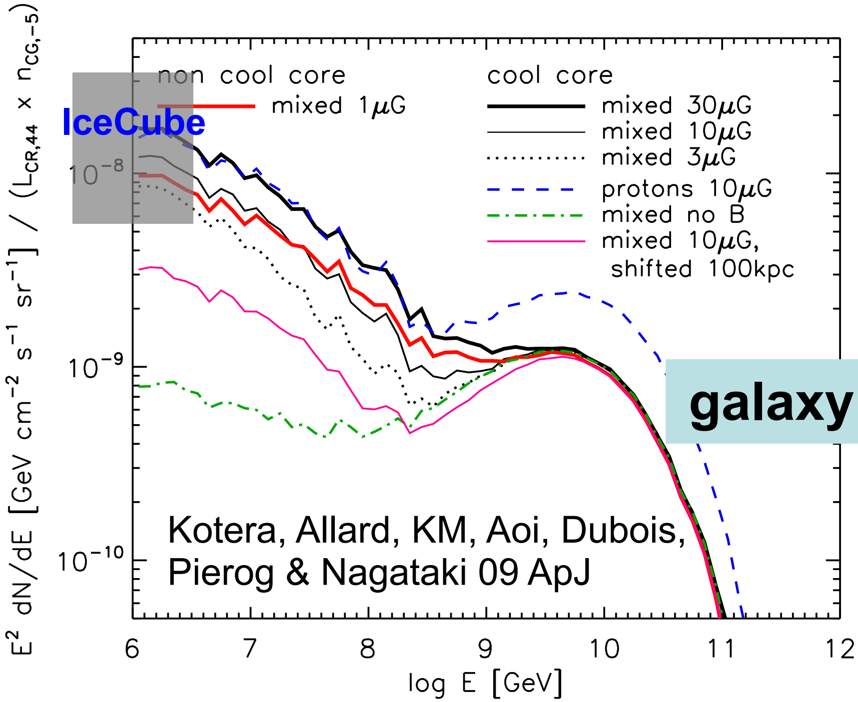
Starburst galaxy

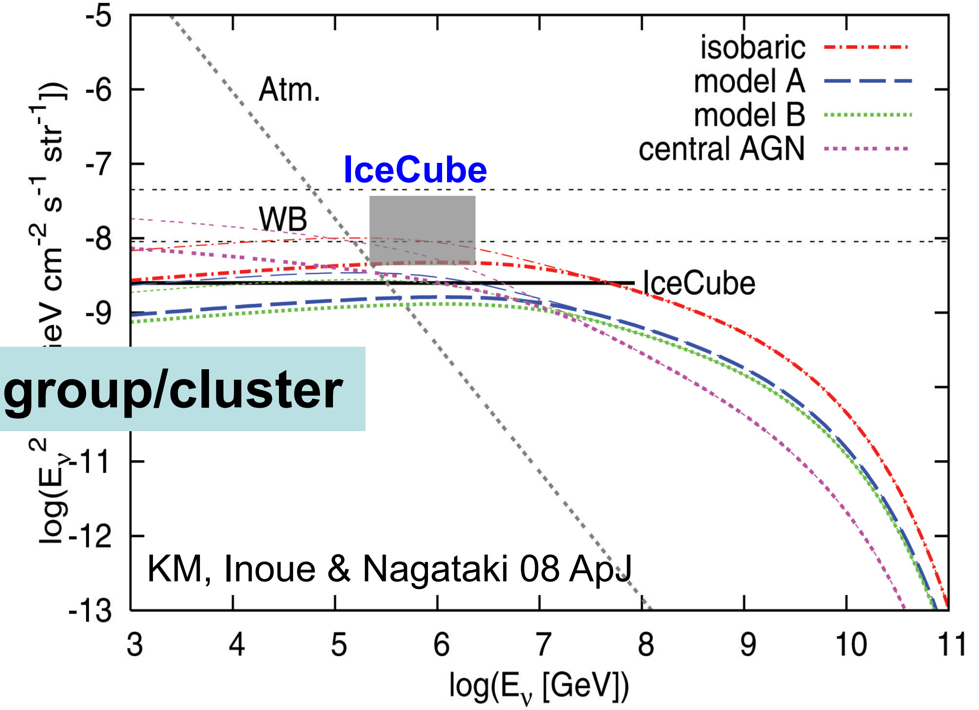
Galaxy cluster

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

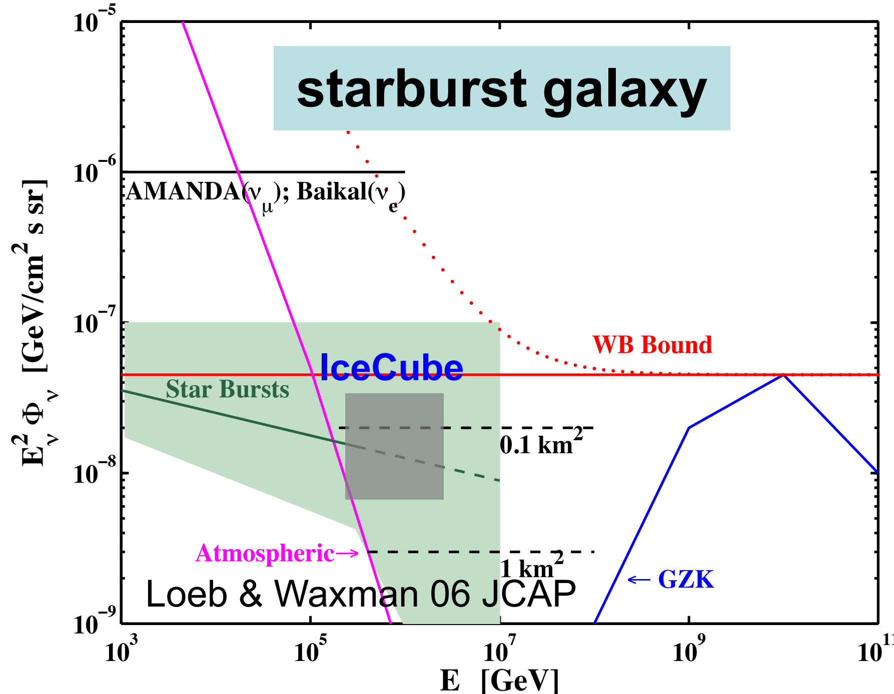


$$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e \; (\text{or } \bar{\nu}_e) + e^{\pm}$$

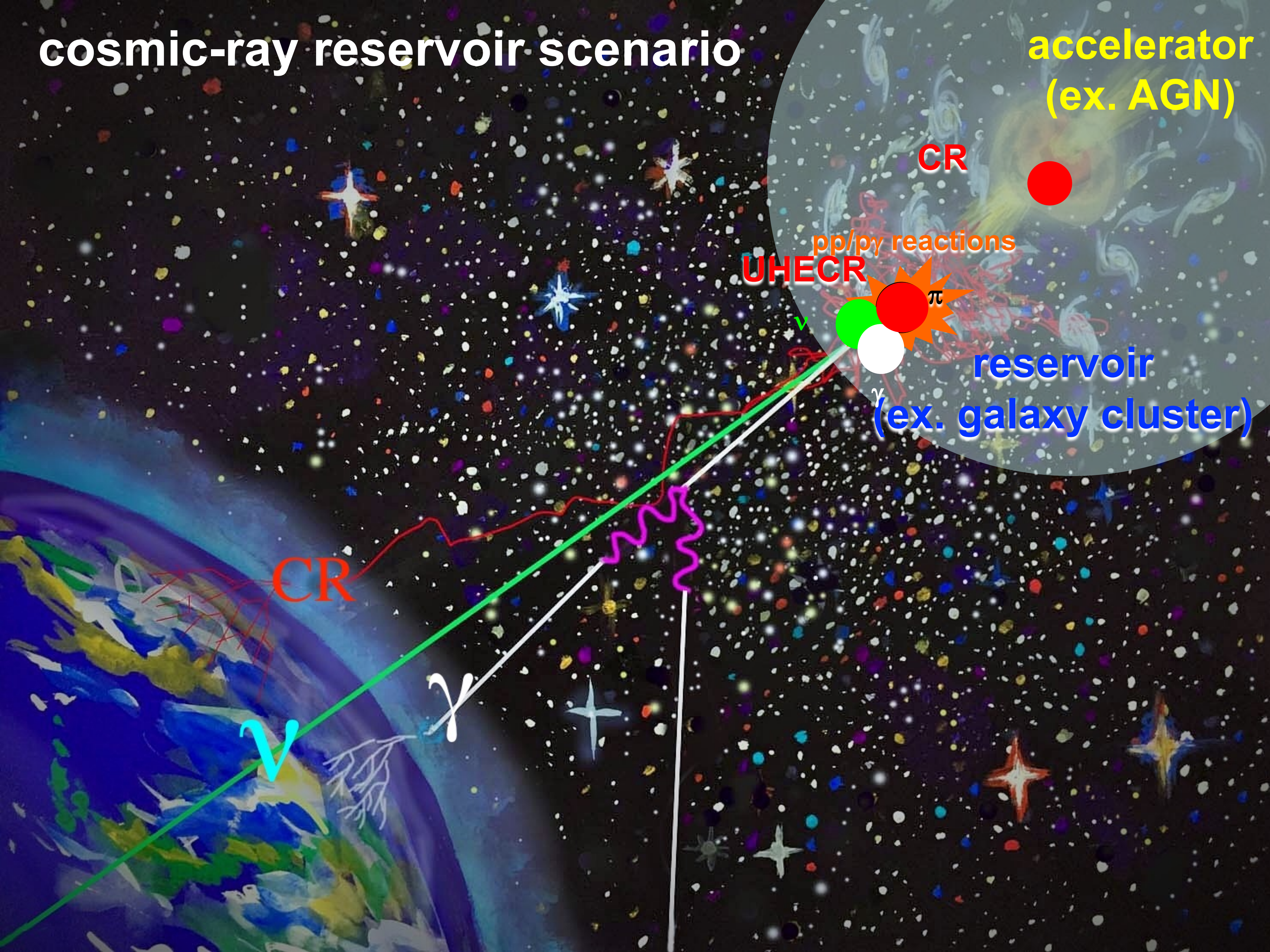




galaxy group/cluster

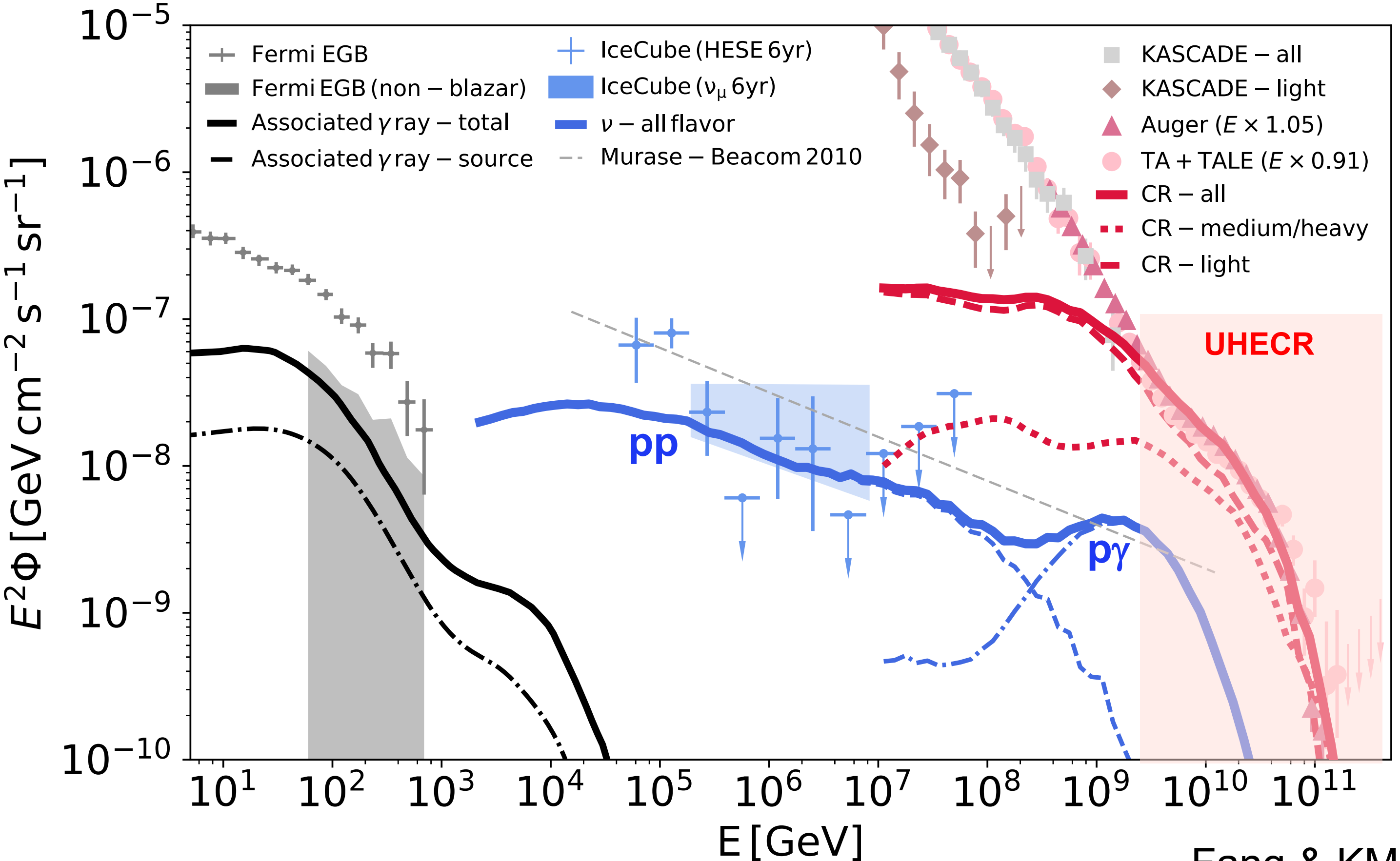


>0.1 PeV IceCube data: consistent w. earlier theoretical predictions


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

High-Energy Astro-Particle Grand-Unification?

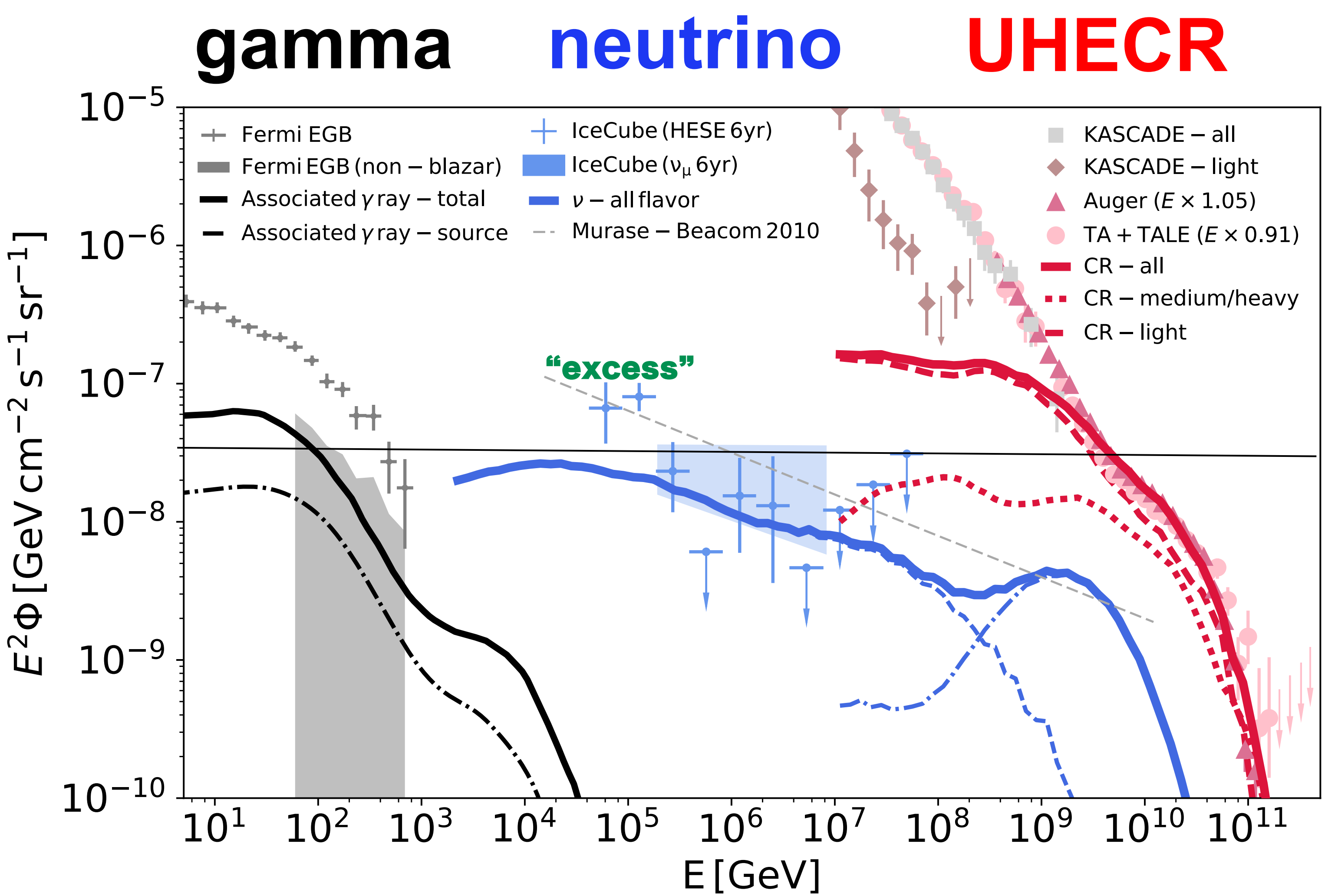
First concrete example of the "grand-unification" scenario with detailed simulations



Fang & KM 18 Nature Phys.

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

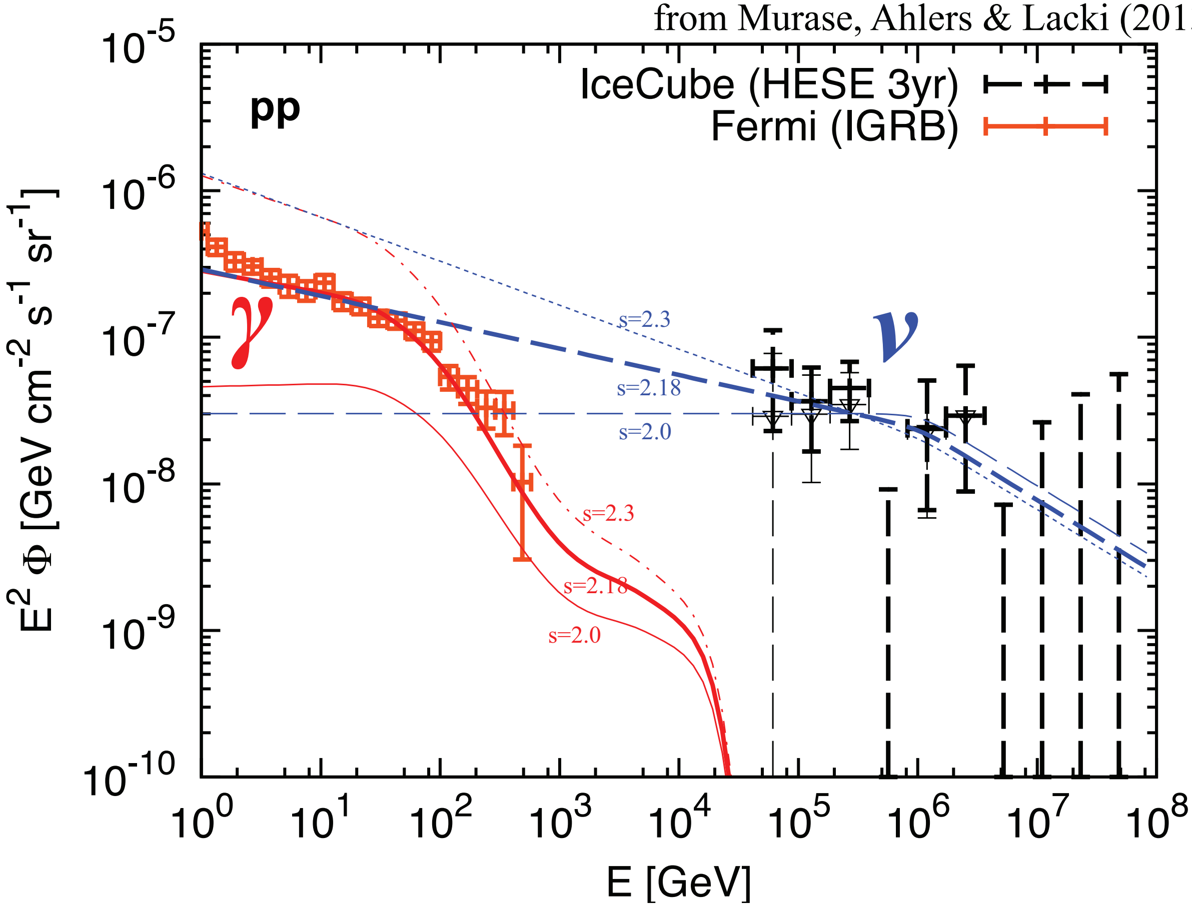
However the Reality Seems More Complicated (& Interesting)



Neutrino-Gamma Connection

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

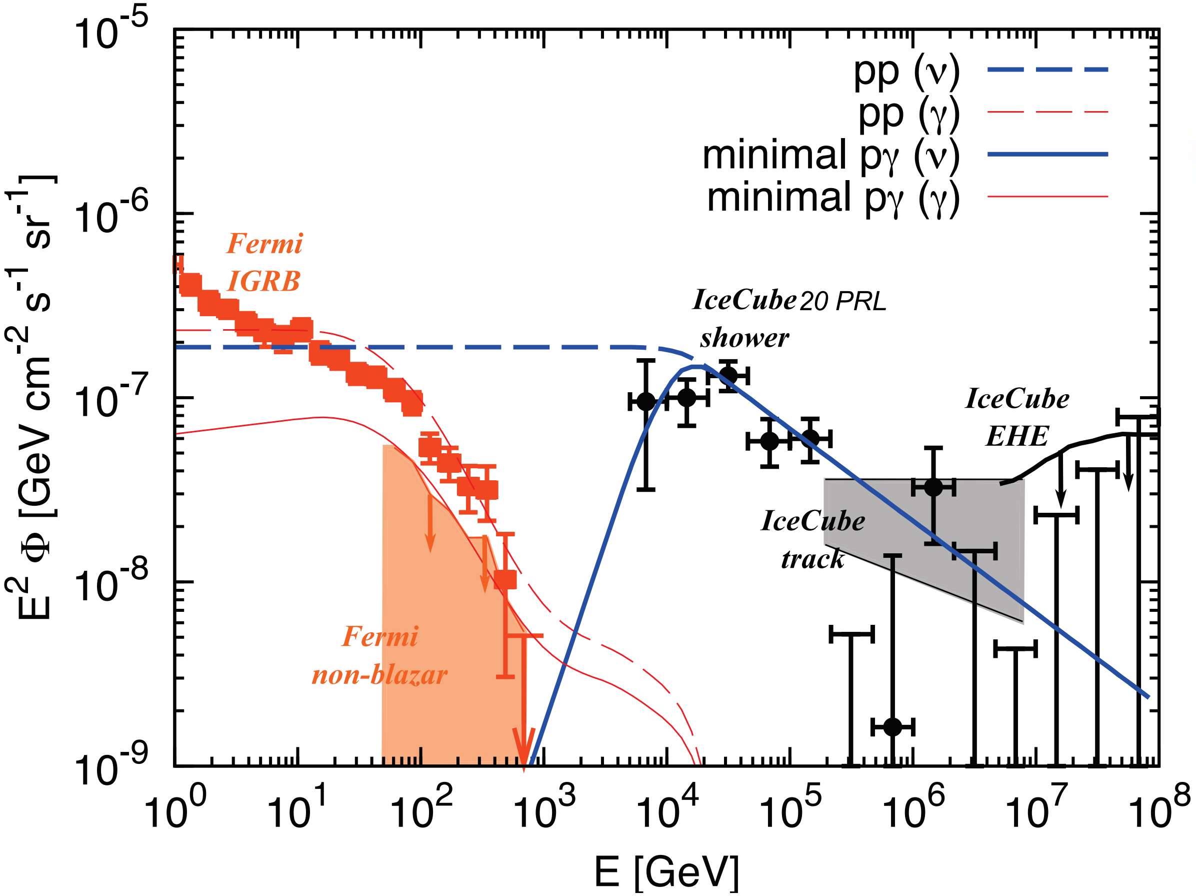
from Murase, Ahlers & Lacki (2013)



- **s_ν<2.1-2.2 (for extragal.); insensitive to redshift evolution of sources**
- **physical connection between ν & γ backgrounds?**
  contribution to diffuse sub-TeV γ: >30%(SFR evol.)-40% (no evol.)

Multi-Messenger Implications of 10-100 TeV ν All-Sky Flux

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



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

K=1 (pγ), K=2 (pp)

KM, Guetta & Ahlers 16 PRL
see also
KM, Ahlers & Lacki 13 PRDR
Capanema, Esmaili & KM 20 PRD
Capanema, Esmaili & Serpico 21 JCAP

Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent
→ Requiring hidden (i.e., γ-ray opaque) cosmic-ray accelerators

Solutions to "Excessive" All-Sky Neutrino Flux?

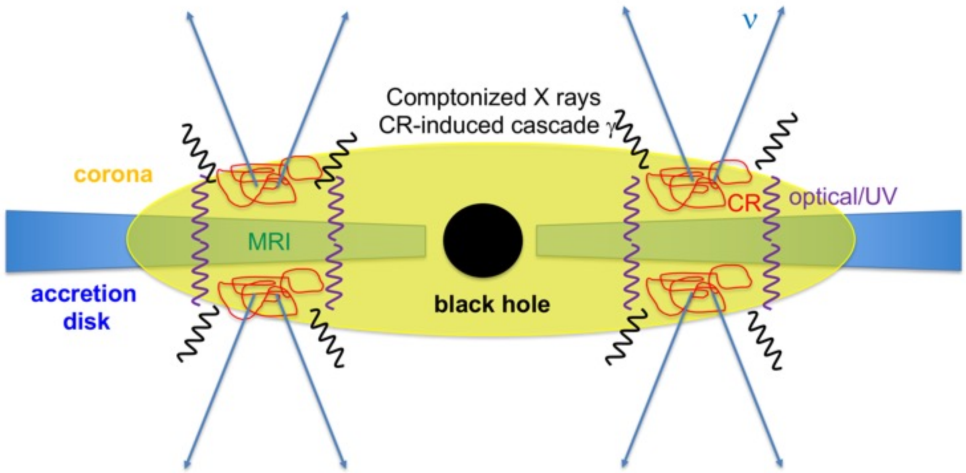
Hidden (i.e., γ-ray opaque) ν sources are actually natural in $p\gamma$ scenarios

(KM, Guetta & Ahlers 16 PRL)

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

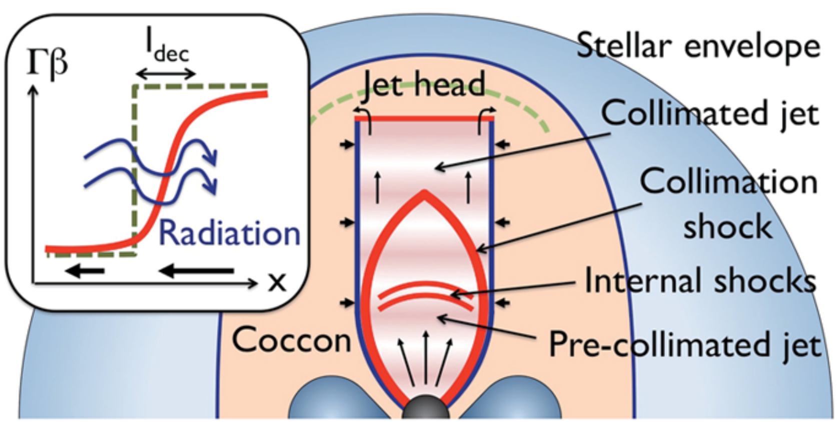
implying that >TeV-PeV γ rays are cascaded down to GeV or lower energies

vicinity of black holes



(from KM, Kimura & Meszaros 20 PRL)

choked jets in supernovae

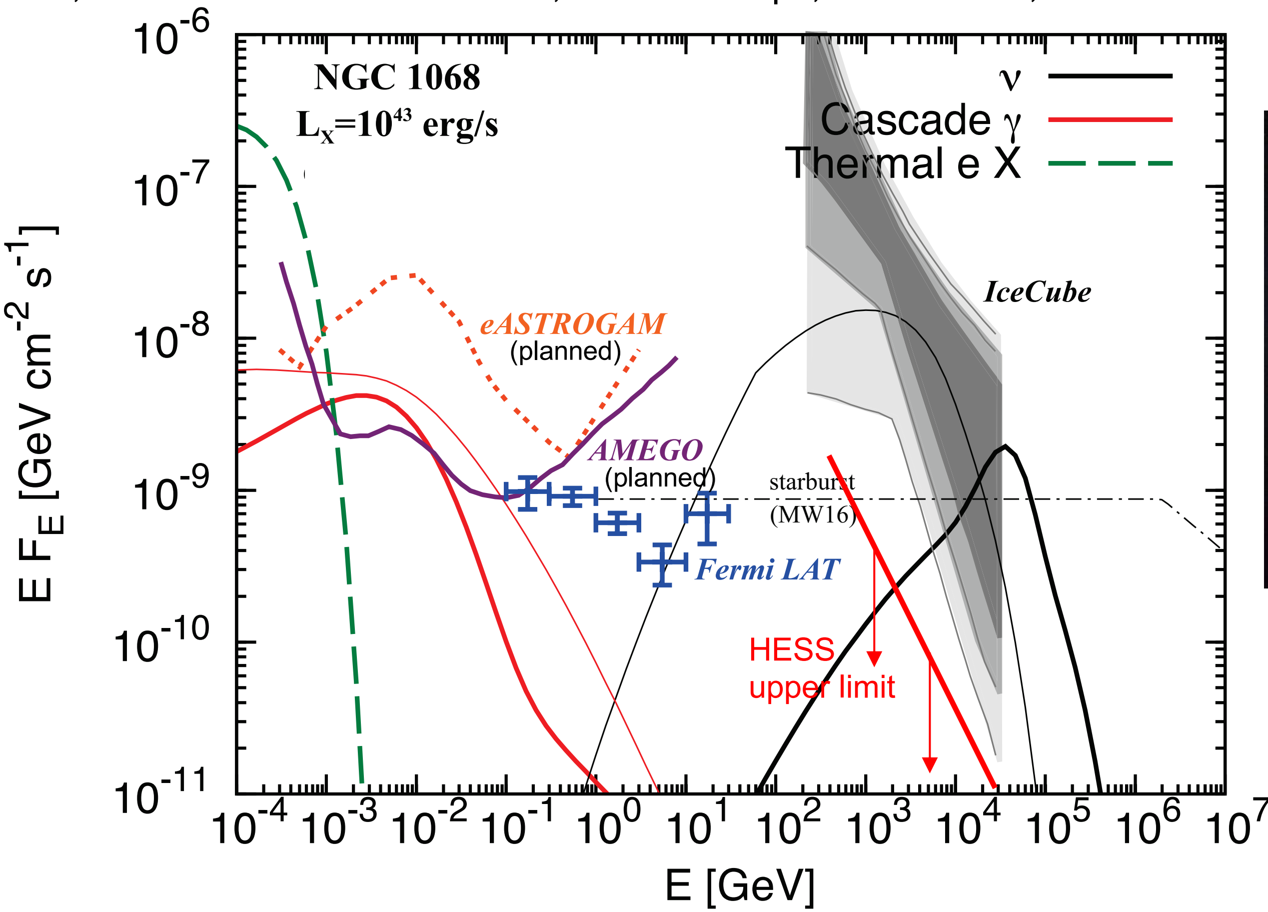


(from KM & Ioka 13 PRL)

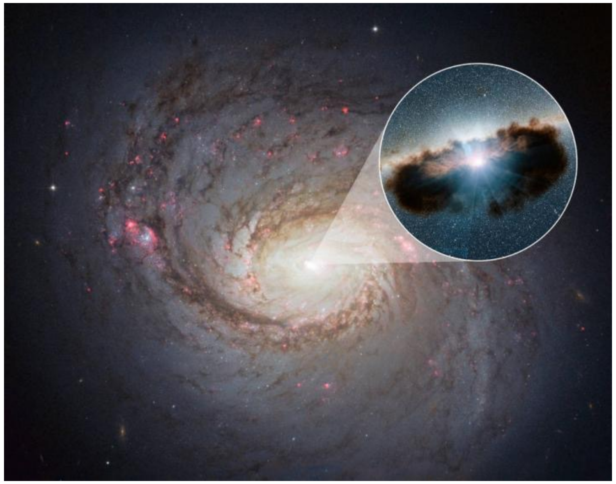
or exotic scenarios invoking new physics (ex. dark matter)…???

NGC 1068: Support for Hidden ν Sources

KM, Kimura & Meszaros 20 PRL, Inoue+ 20 ApJ, Kheirandish, KM & Kimura 21 ApJ



NGC 1068: "obscured AGN"

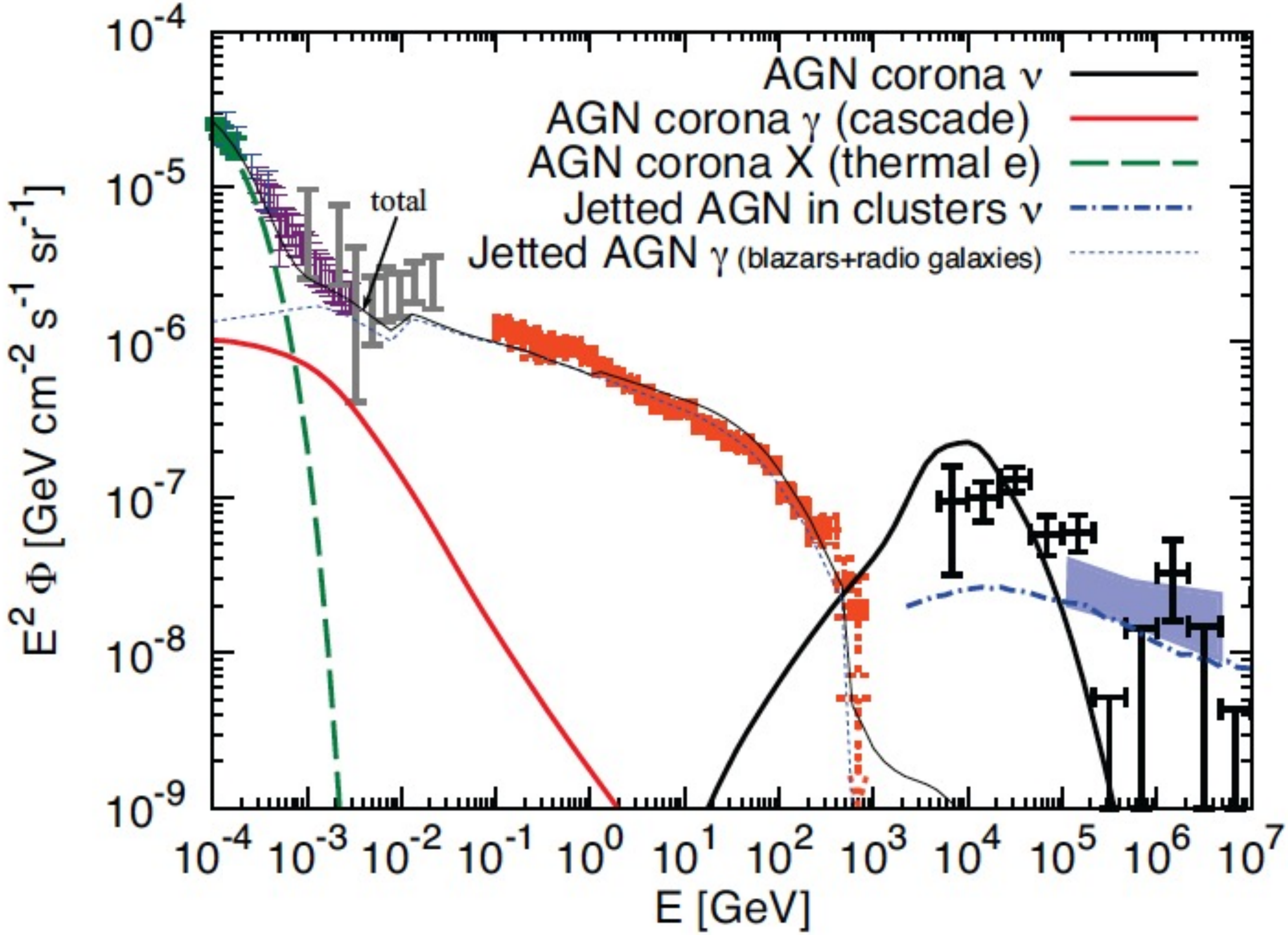


- particle acceleration in coronae (supported by recent simulations)
- ν production via pp & pγ processes

- Theory predicts NGC 1068 to be the brightest ν source in the northern sky
- GeV-TeV γ rays are hidden but MeV γ rays should appear (prediction)

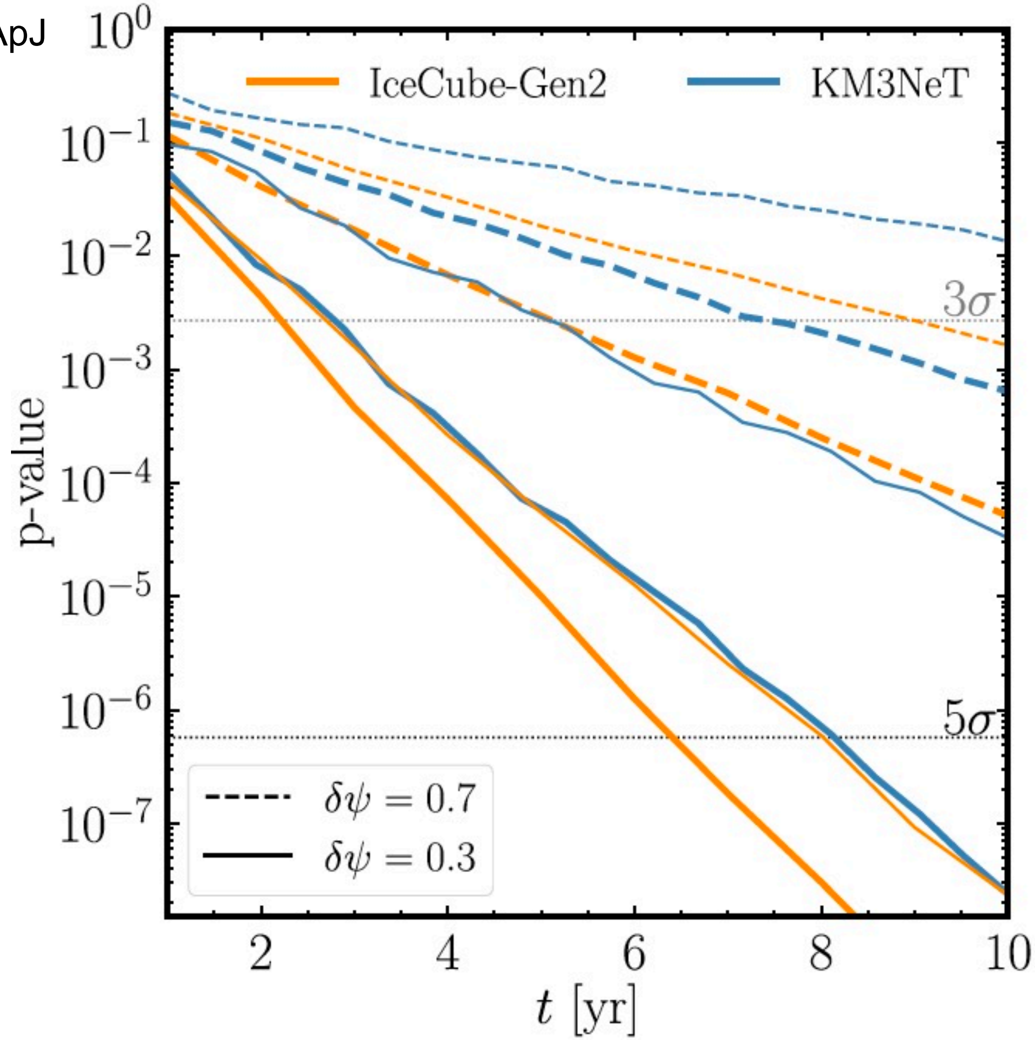
AGN Manifesting in the Multi-Messenger Sky?

KM, Kimura & Meszaros 20 PRL



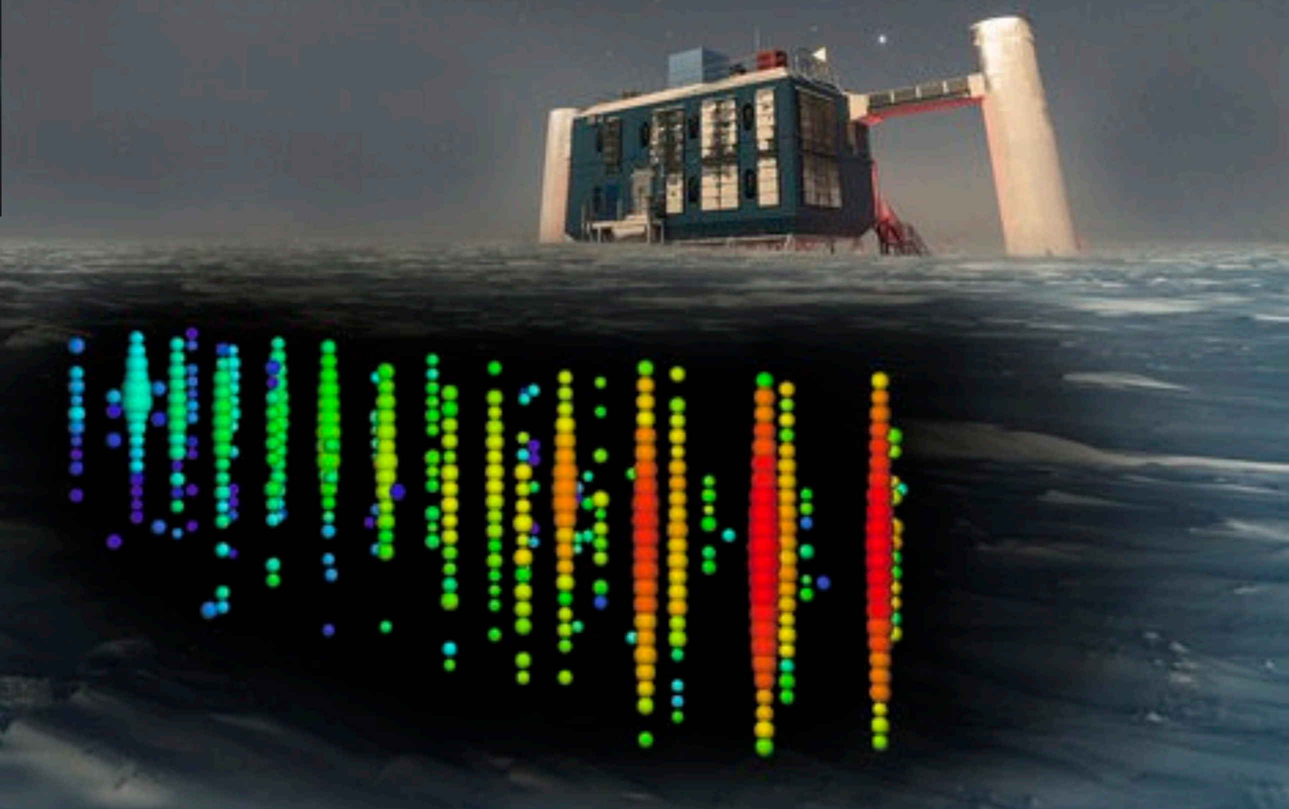
Detectability of Coronal Neutrinos from Nearby AGN

Kheirandish, KM & Kimura 21 ApJ



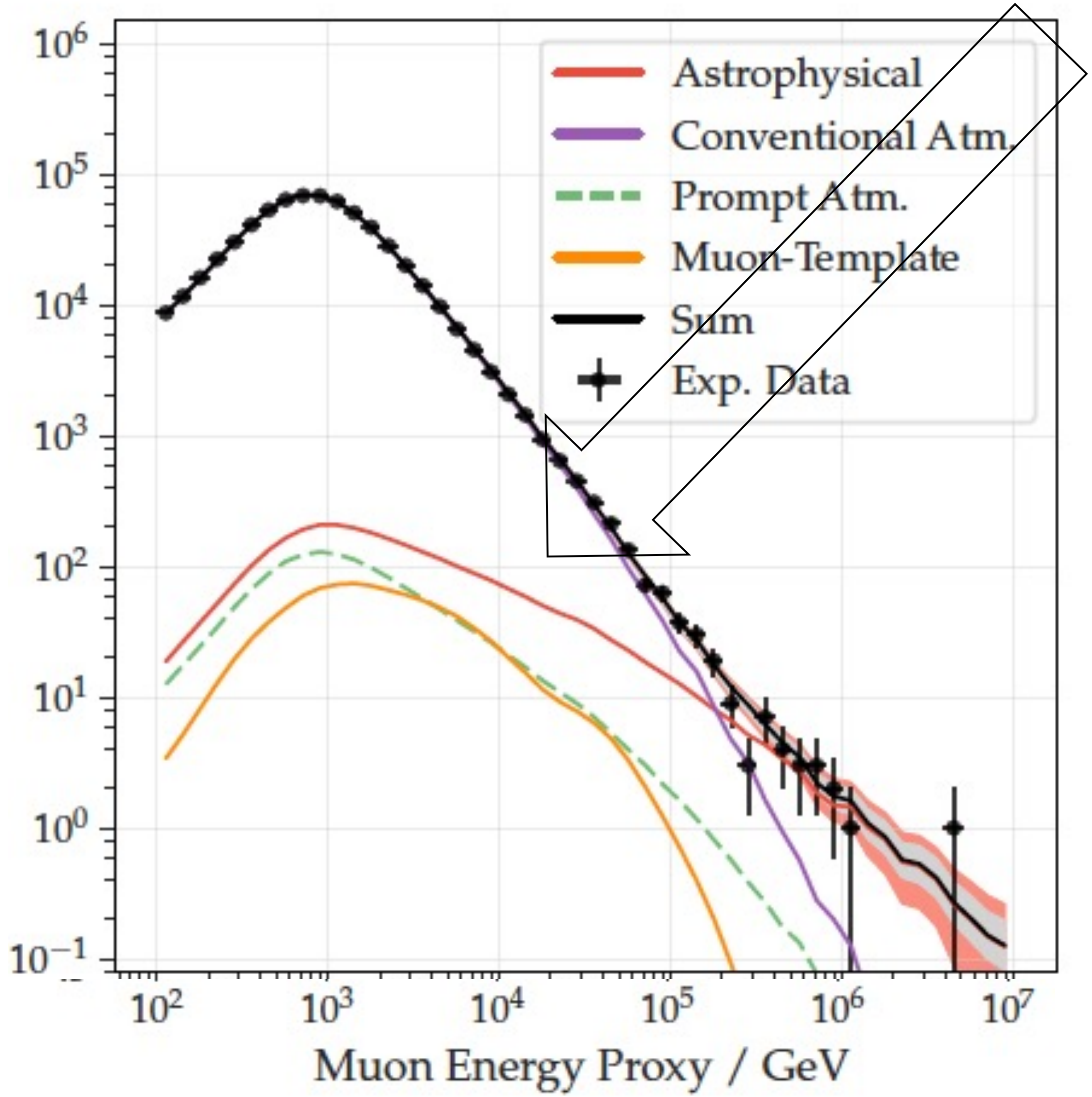
- More in the southern sky (Circinus, ESO 138-1, NGC 758)
- Testable w. near-future IceCube data or by IceCube-Gen2 & KM3Net

Neutrino Transients



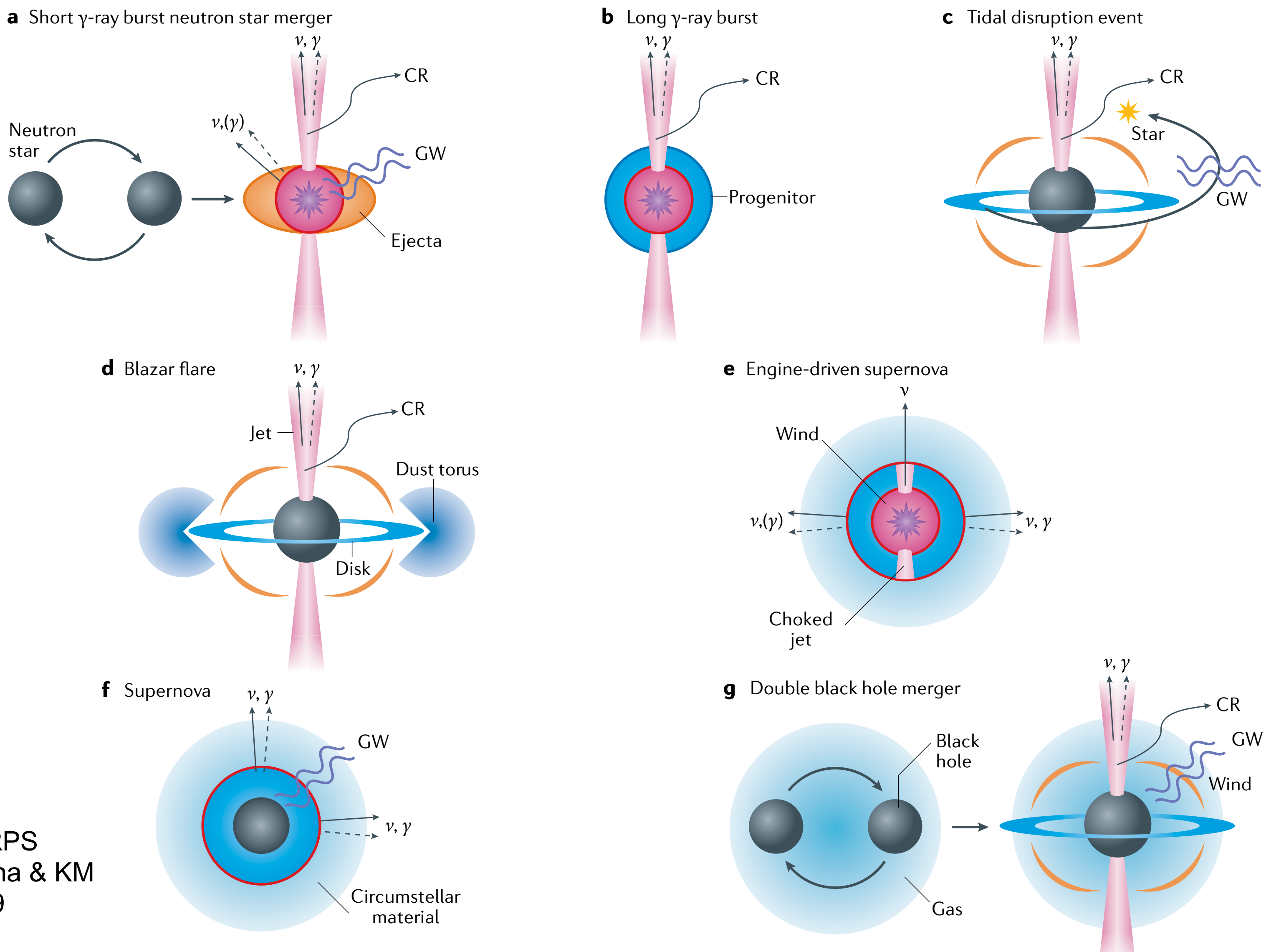
High-Energy Neutrino Transients

pointing & timing → good chance to discover ν sources



High-Energy Neutrino Transients

Diverse explosive/flaring phenomena in the Universe!



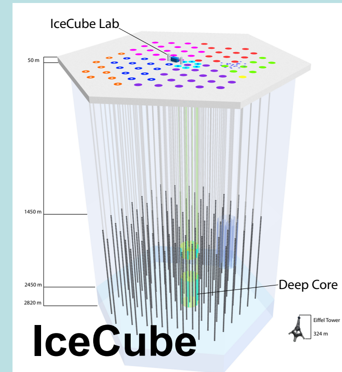
KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

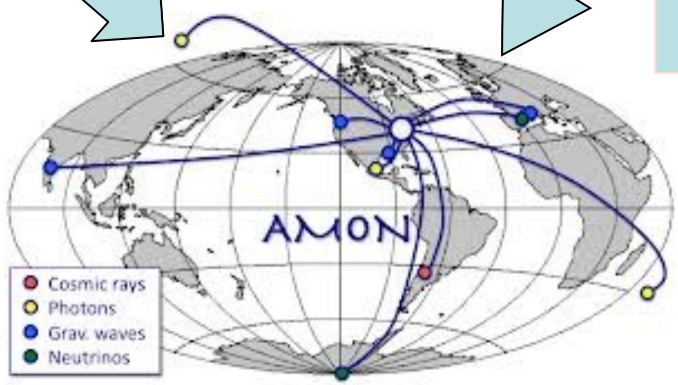
Ongoing "Multi-Messenger" Attempts

Light
(electromagnetic)

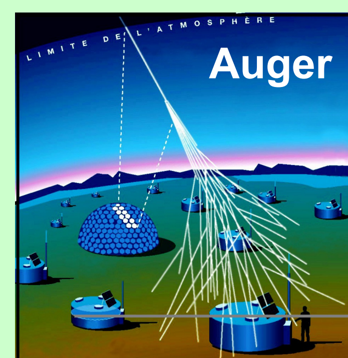
Astrophysical multi-messenger observatory network (AMON)
(led by Penn State)

Neutrino (weak force)





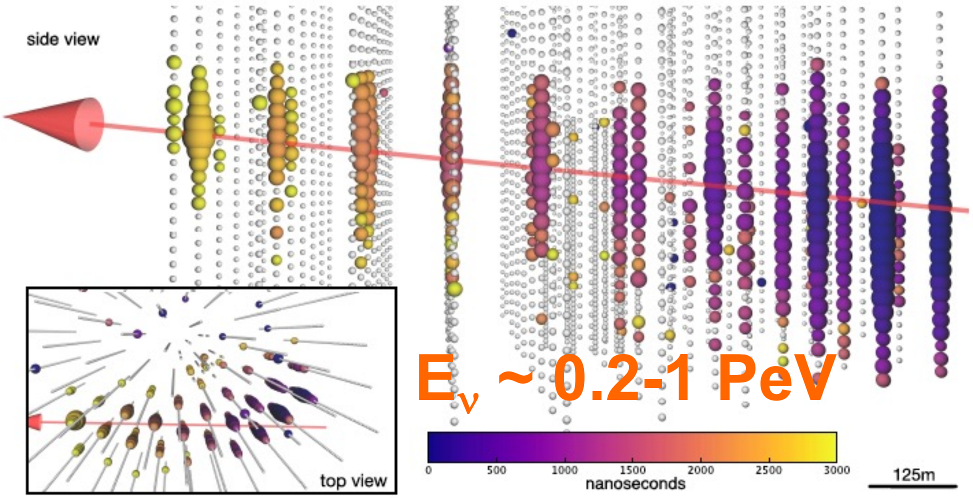
Cosmic-ray
(strong force)



Gravitational wave
(gravity)

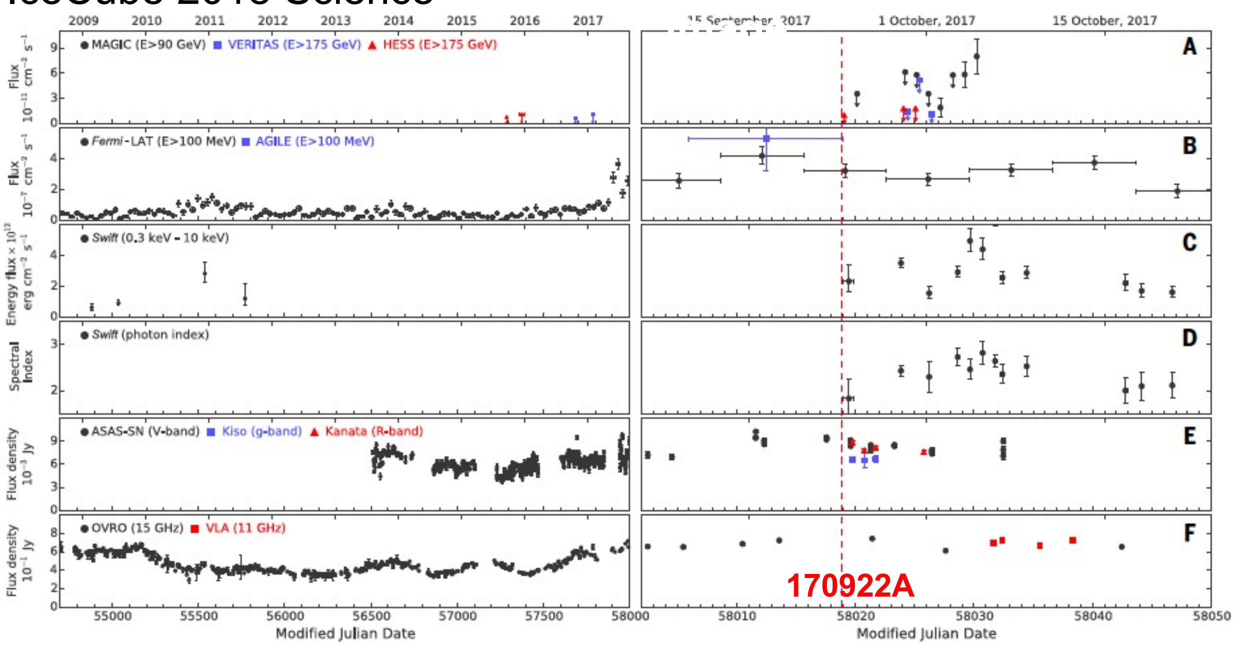
Don't miss interesting ν & GW events!
- **Realtime coincident searches**
- **Prompt data-sharing for follow-ups**

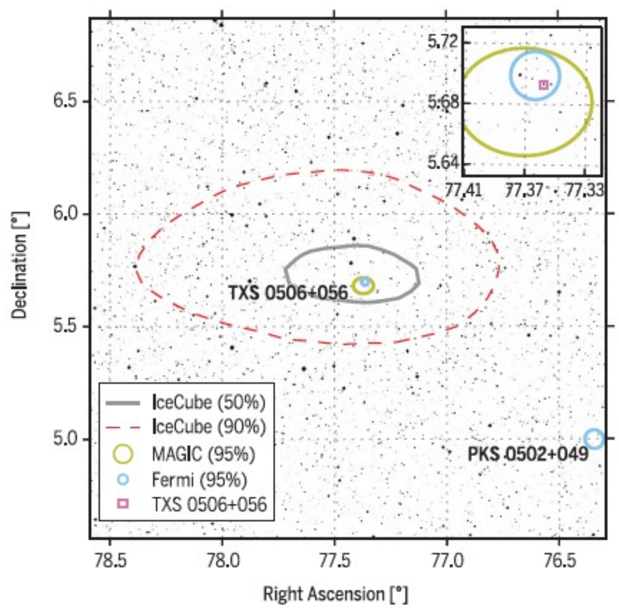
IceCube 170922A & TXS 0506+056



- 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
- **~3σ coincidence**

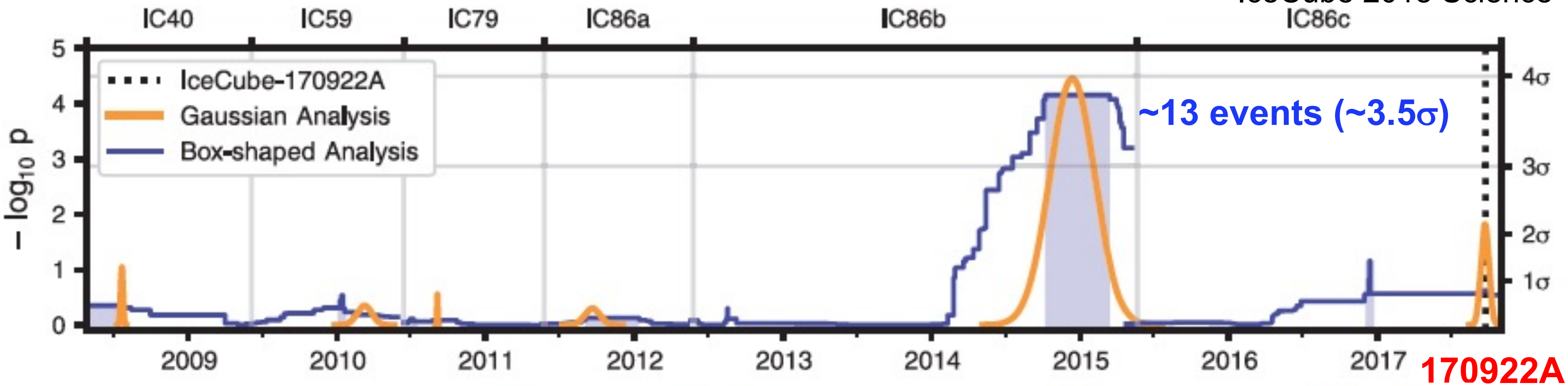
IceCube 2018 Science

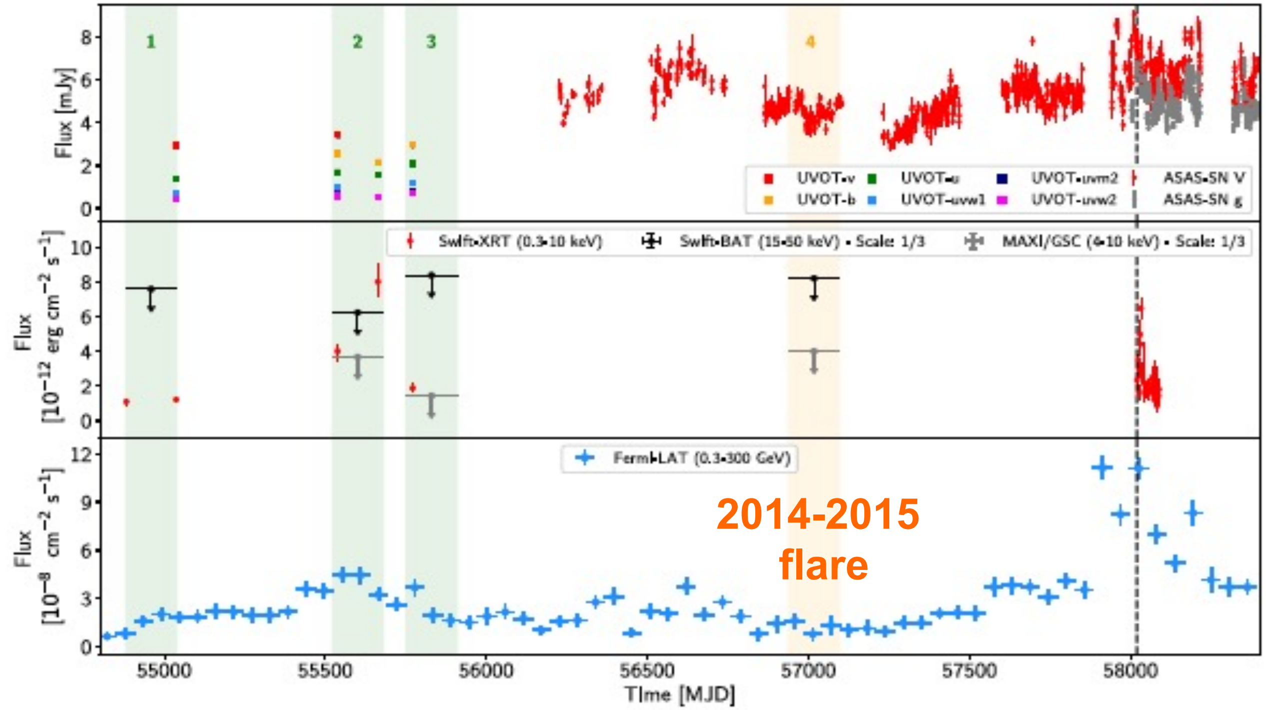




2014-2015 Neutrino Flare

IceCube 2018 Science

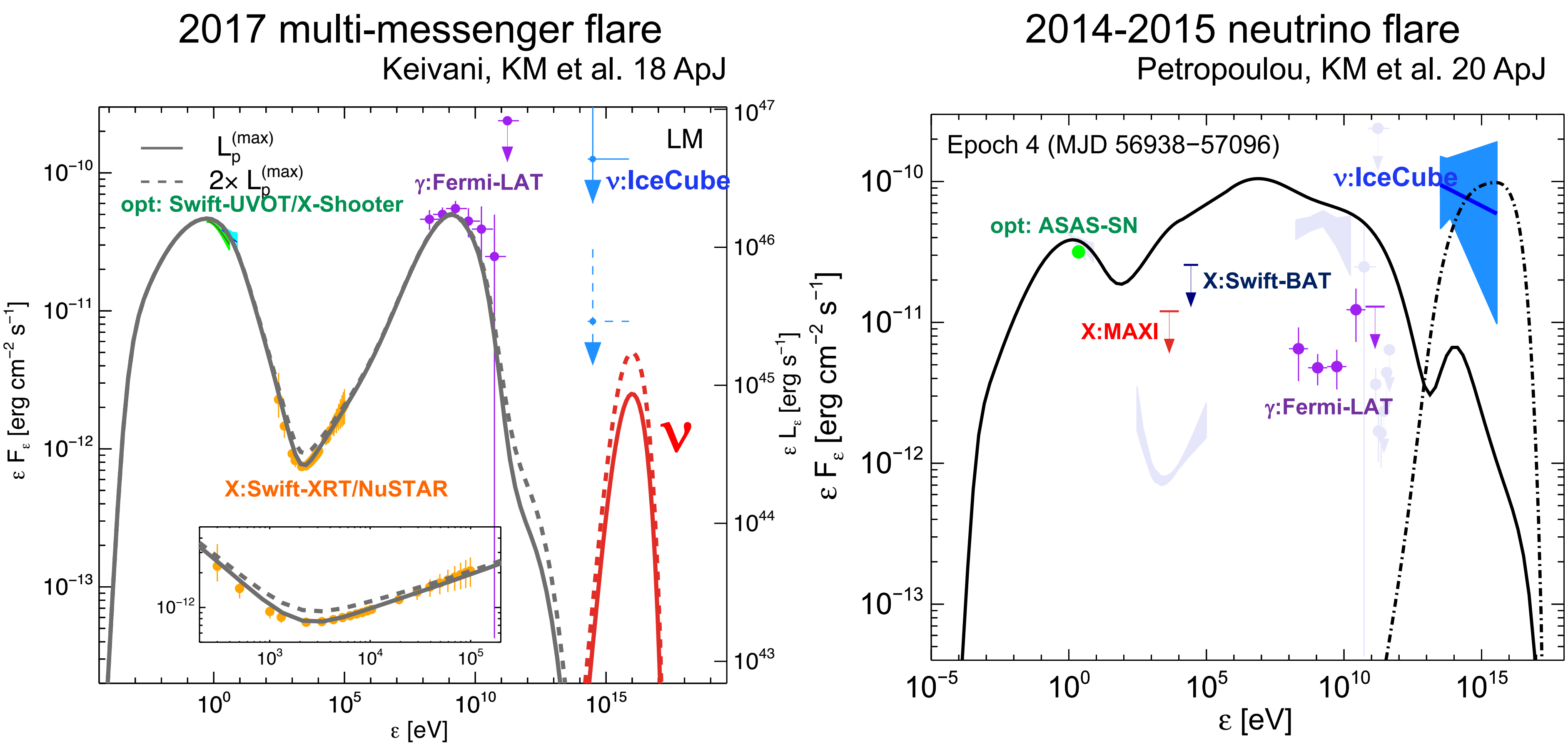




Petropoulou, KM+ 20 ApJ

"Power" of Multi-Messenger Approaches

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



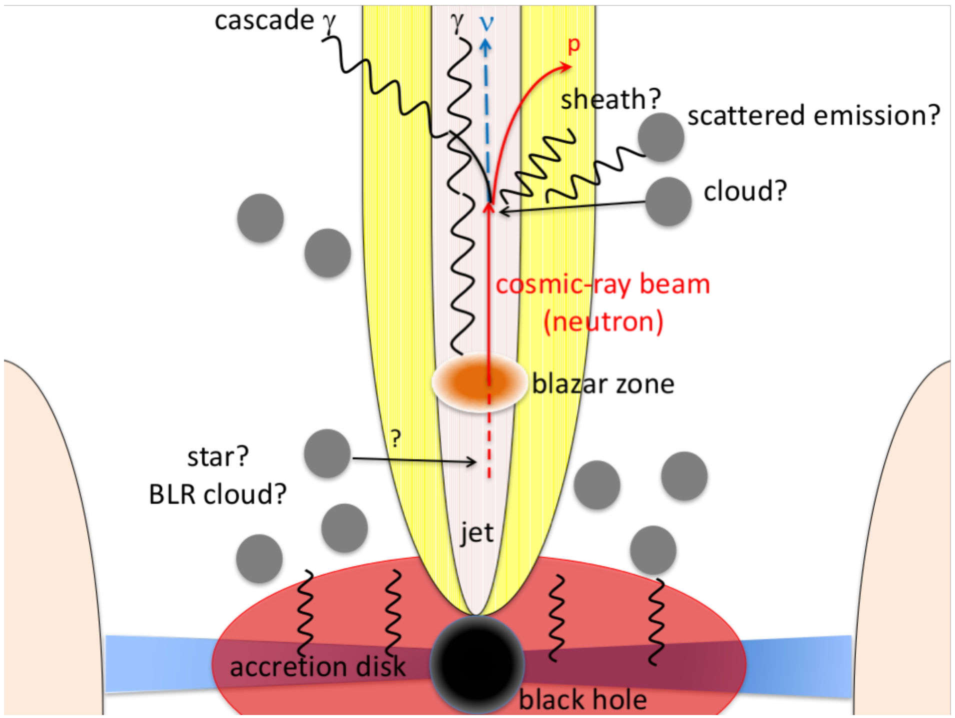
Puzzling: standard single-zone models do NOT give a concordance picture

see also KM, Oikonomou & Petropoulou 18, Ansoldi+ 18, Cerutti+ 19, Gao+ 19, Rodriguez+ 19, Reimer+ 19

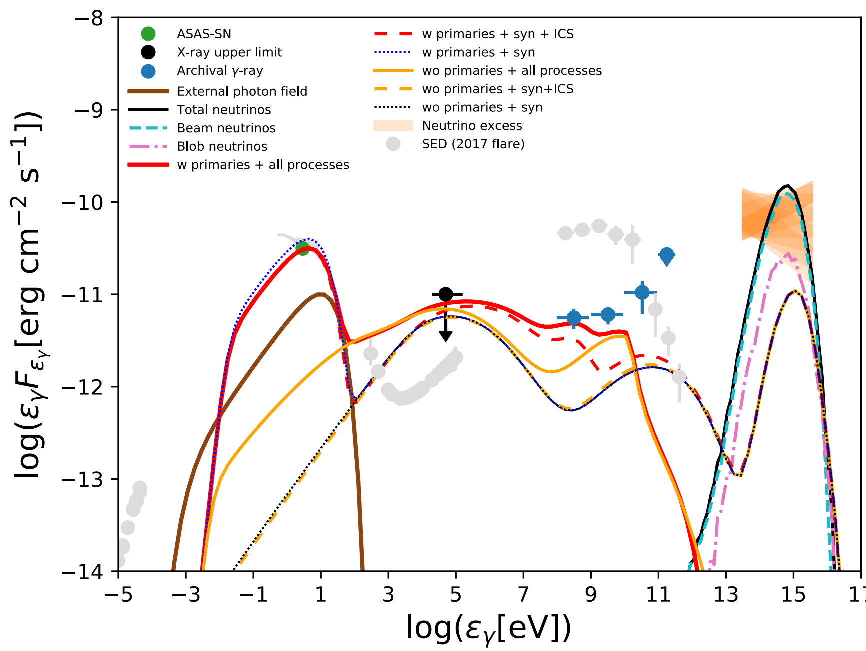
Beyond the Canonical Single-Zone Emission Model

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



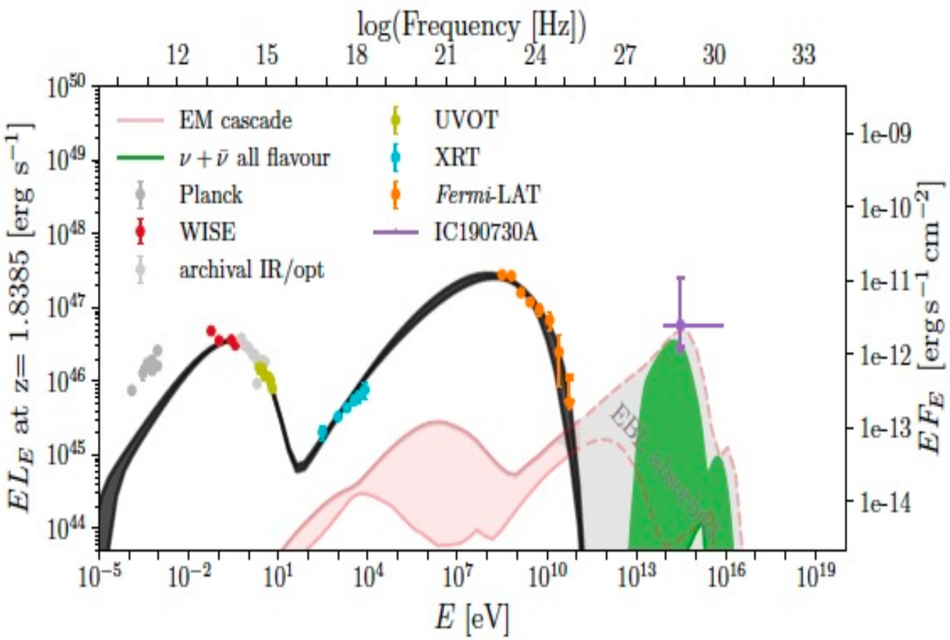
Other coincidences w. flares?: 3HSP J095507.9 +355101 (Petropoulou+ KM 20 ApJ), PKS 1502+106 (Oikonomou+ KM in prep.), AT2019dsg (KM+ 20 ApJ)
However, more follow-up campaigns and/or larger statistics in ν data are necessary

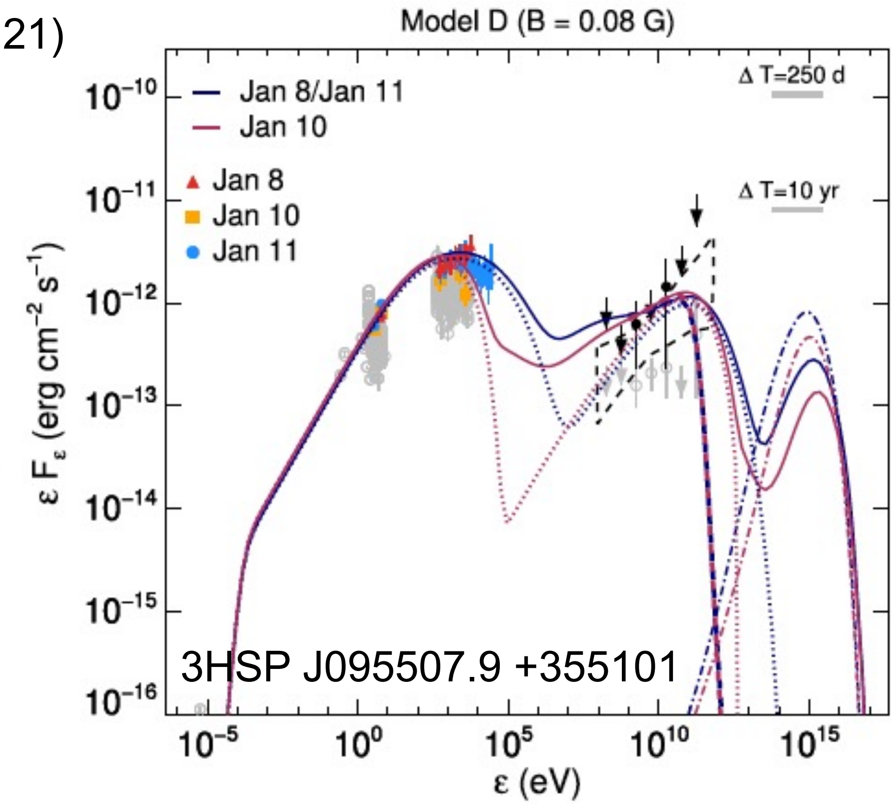
Other Coincidences?

More follow-up campaigns and/or larger statistics in ν data are necessary
But the situation is still puzzling…

IceCube-200107A
(Petropoulou, Oikonomou, Mastichiadis , KM+ 20)

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

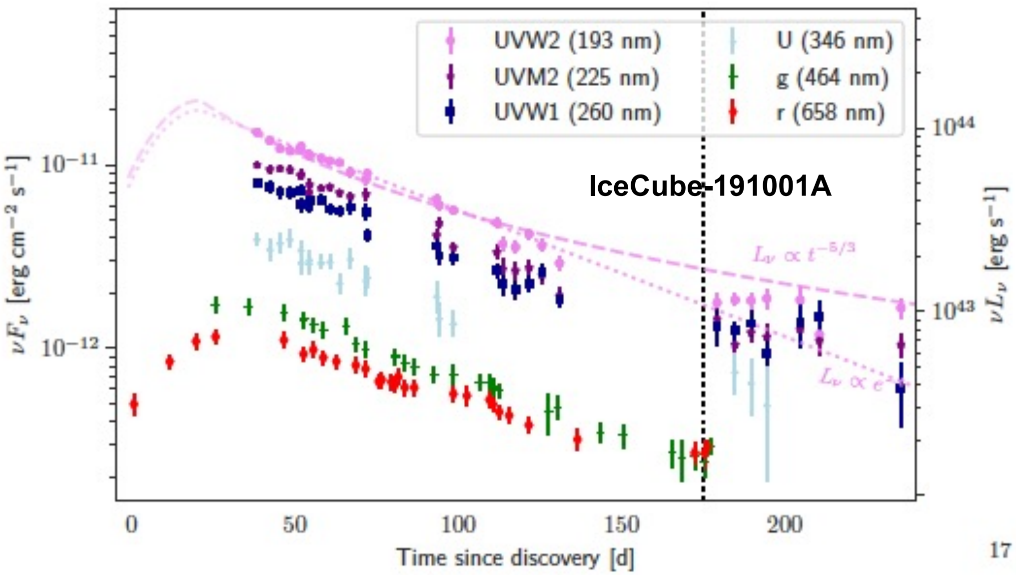




- PKS 1502 +106: FSRQ
  promising but no coincidence w. γ-ray flaring, unseen in ν point-source search
- 3HSP J095507.9 +355101: extreme BL Lac
  coincidence w. X-ray flaring but the alert rate is at most ~1-3% in 10 years

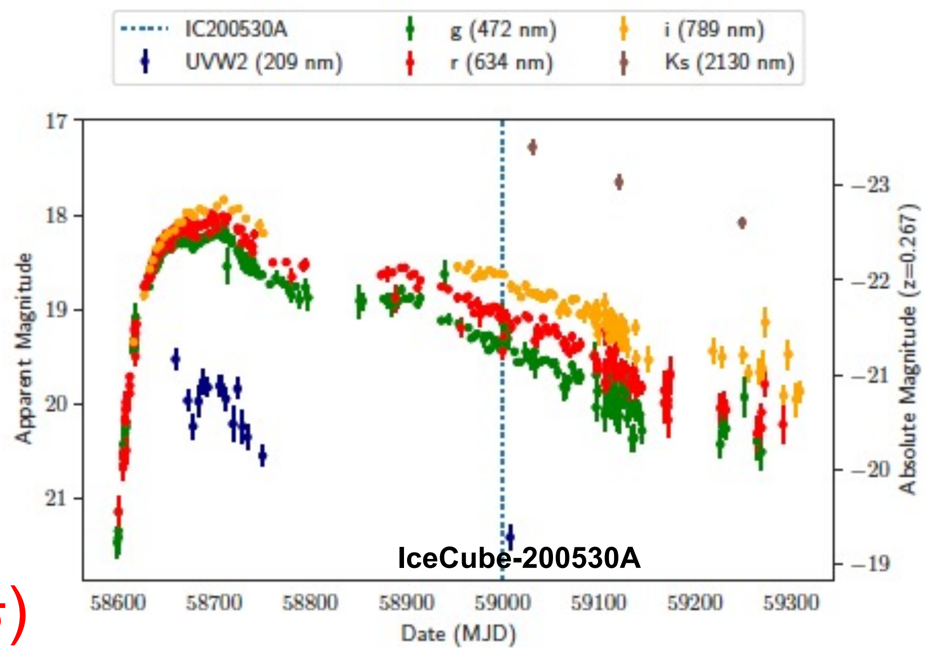
More Coincidences?

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)

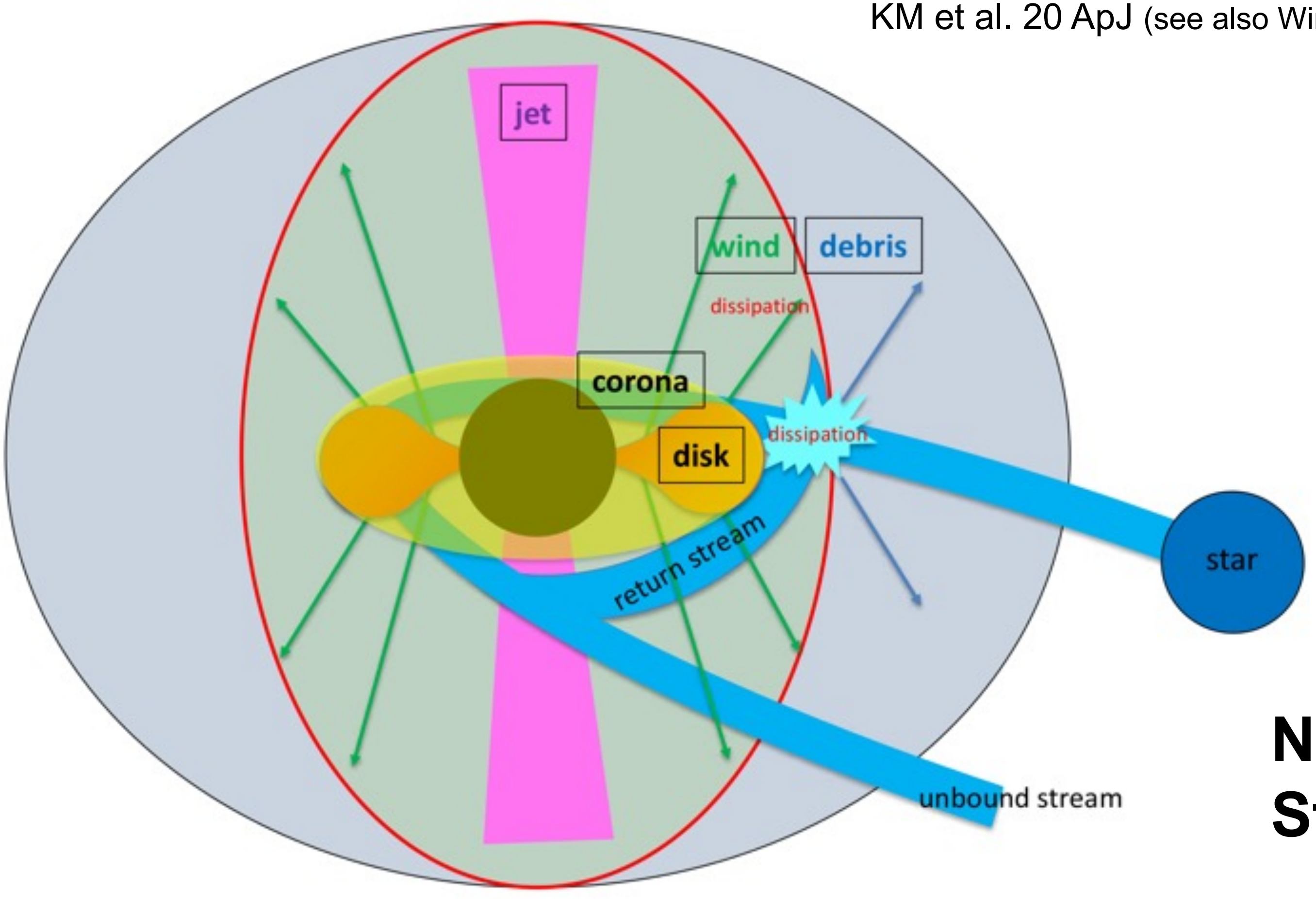


Both are rare optical transients with strong radio emission (>3.4σ)

Neutrinos from Black Hole "Flares"?

- AT 2019dsg & AT 2019fdr = tidal disruption event (TDE)
- TDE and AGN ν 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!!!

Introduction

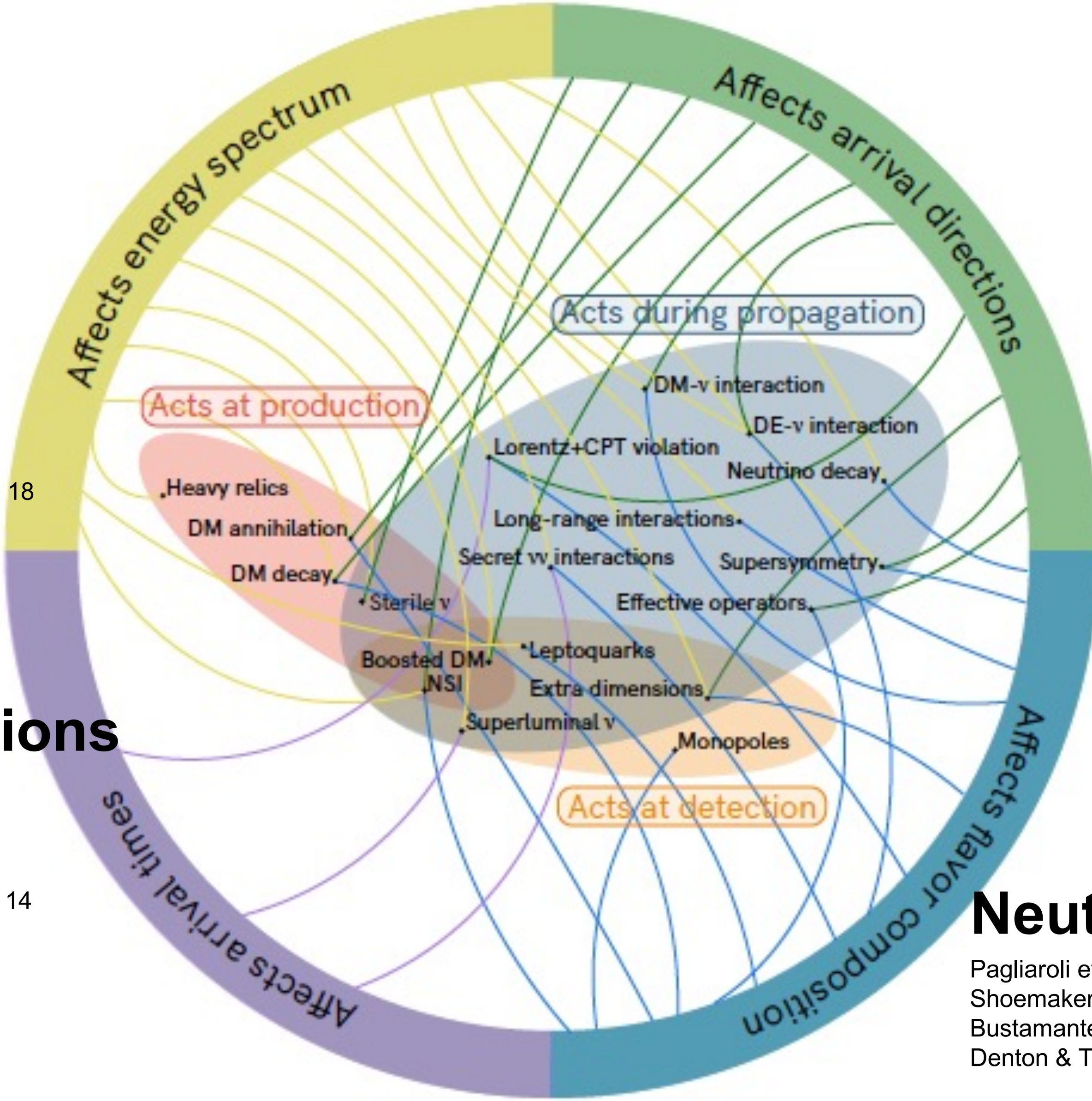
Astrophysical Implications

New Physics Implications

Testing Physics Beyond the Standard Model

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
Bhupal Dev+ 16
Chianese+ 16
Hiroshima, Kitano, Kohri & KM 18
…

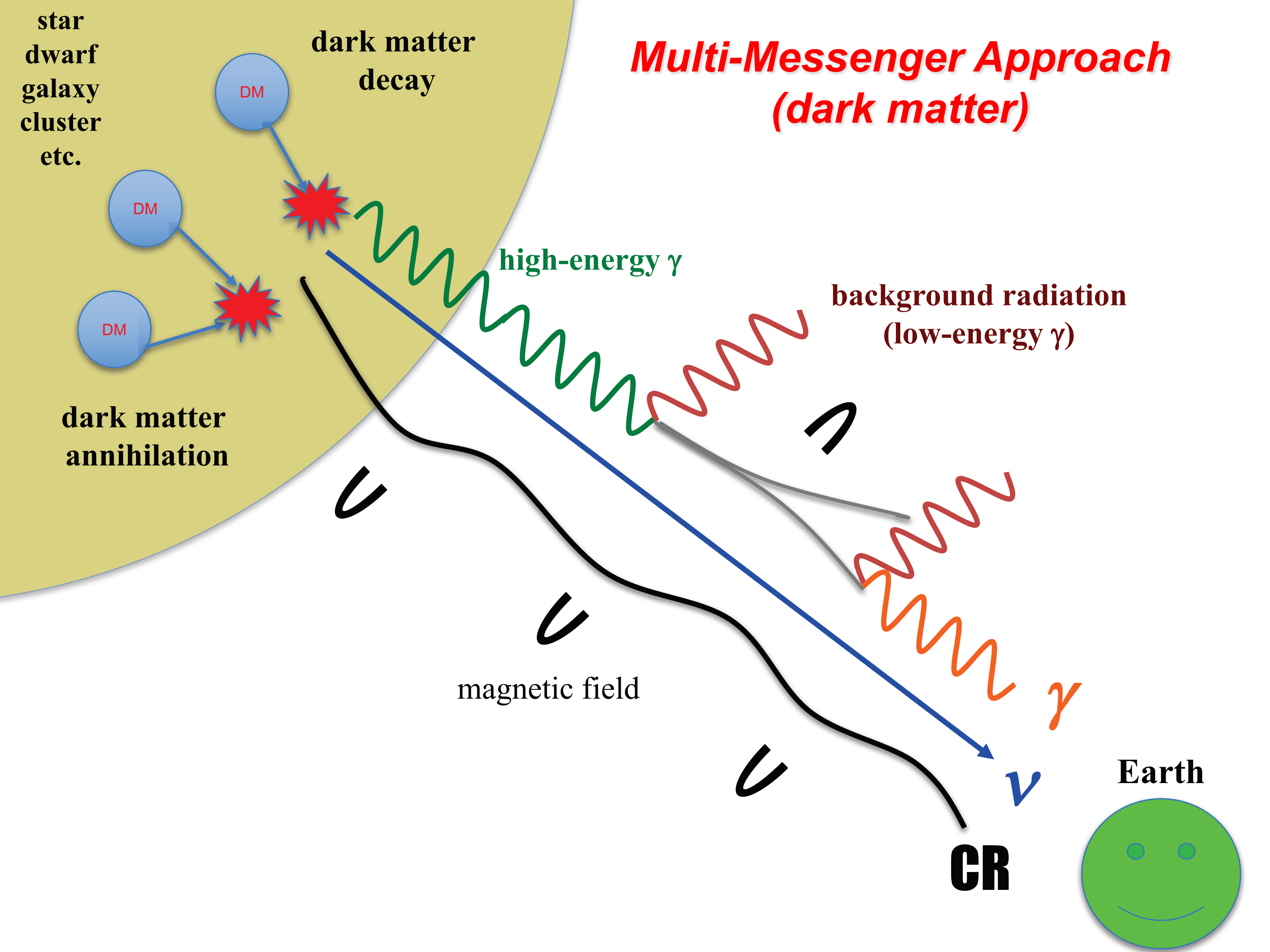


New interactions

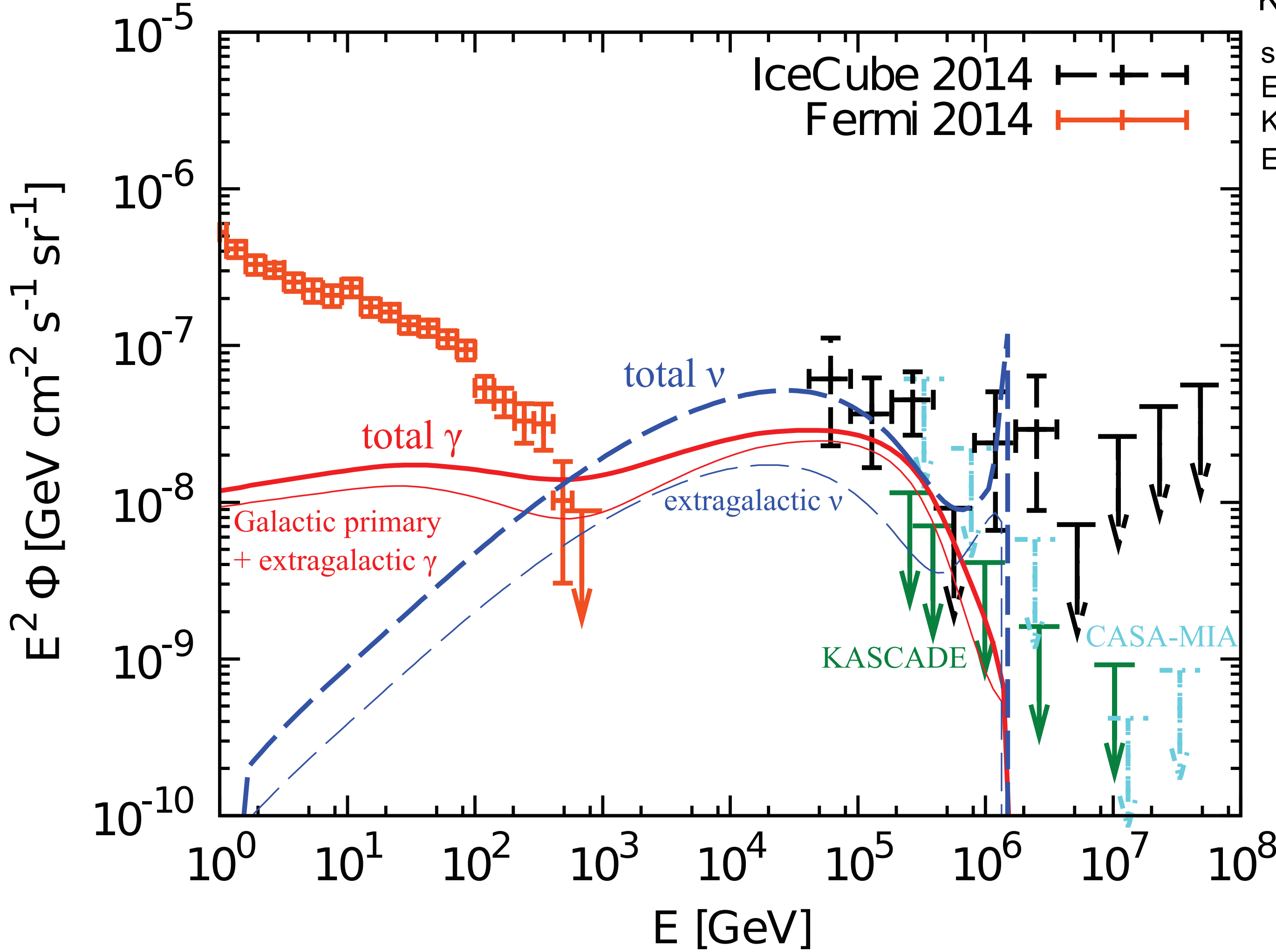
Ioka & KM 14
Ng & Beacom 14
Ibe & Kaneta 14
Blum, Hook & KM 14
Cherry, Friedland & Shoemaker 14
Araki et al. 15
Kamada & Yu 15
Shoemaker & KM 16
KM & Shoemaker 19…

Neutrino decay

Pagliaroli et al. 15
Shoemaker & KM 16
Bustamante, Beacom & KM 17
Denton & Tamborra 18…


Multi-Messenger Approach
(dark matter)
star
dwarf
galaxy
cluster
etc.
dark matter
decay
DM
DM
DM
dark matter
annihilation
high-energy γ
background radiation
(low-energy γ)
magnetic field
γ
ν
Earth
CR

Multi-Messenger Emission of Decaying Dark Matter



KM, Laha, Ando & Ahlers 15 PRL

see also:
Ellis+ 92, Gondolo 92, Gondolo+ 93
KM & Beacom 12
Esmaili & Serpico 15

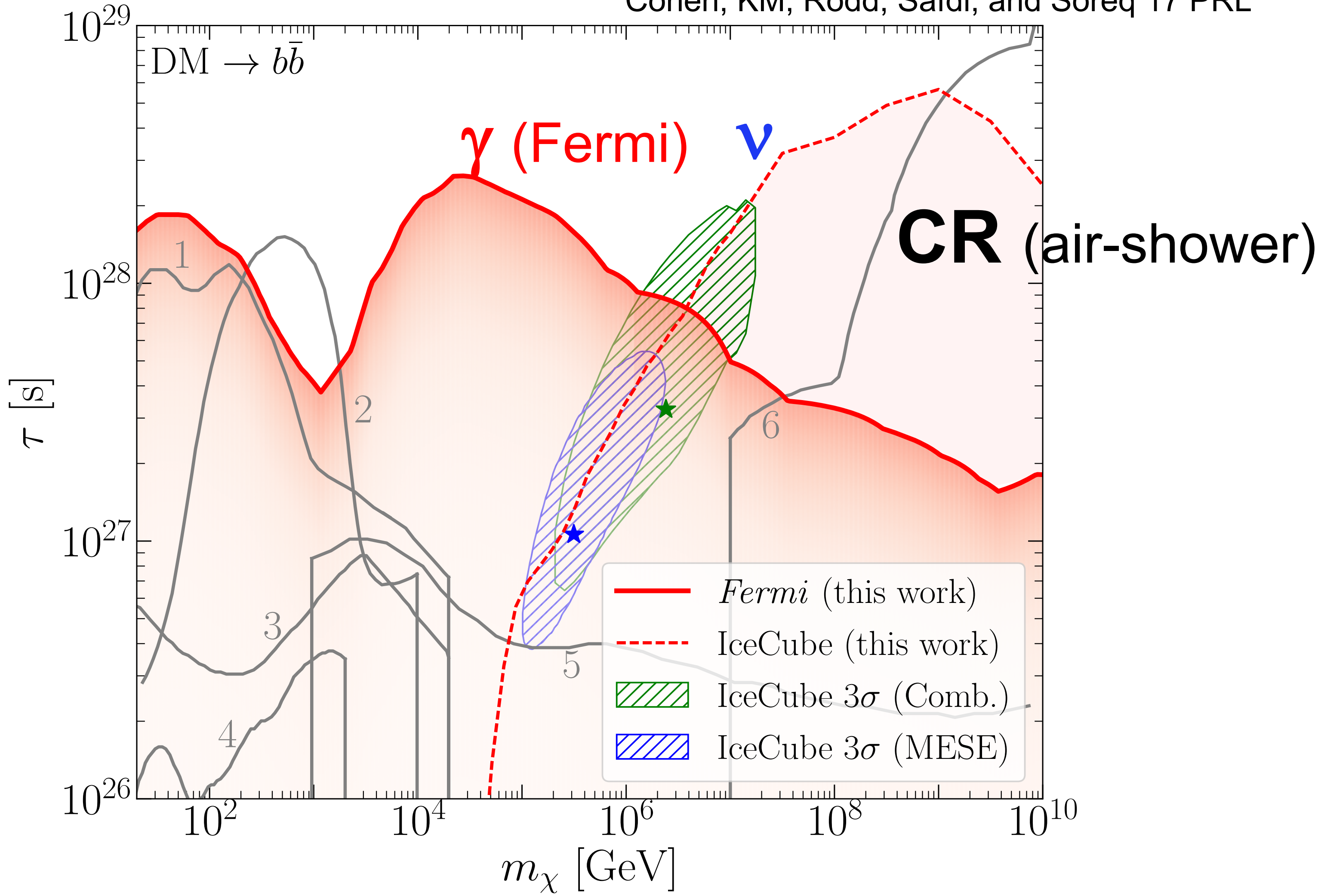
DM → ν_e+ν_e (12%)
DM → b+bbar (88%)

(similar results in other models that are proposed)

tension with existing Fermi (sub-TeV γ) and air-shower (sub-PeV γ) data

Multi-Messenger Constraints on Decaying DM

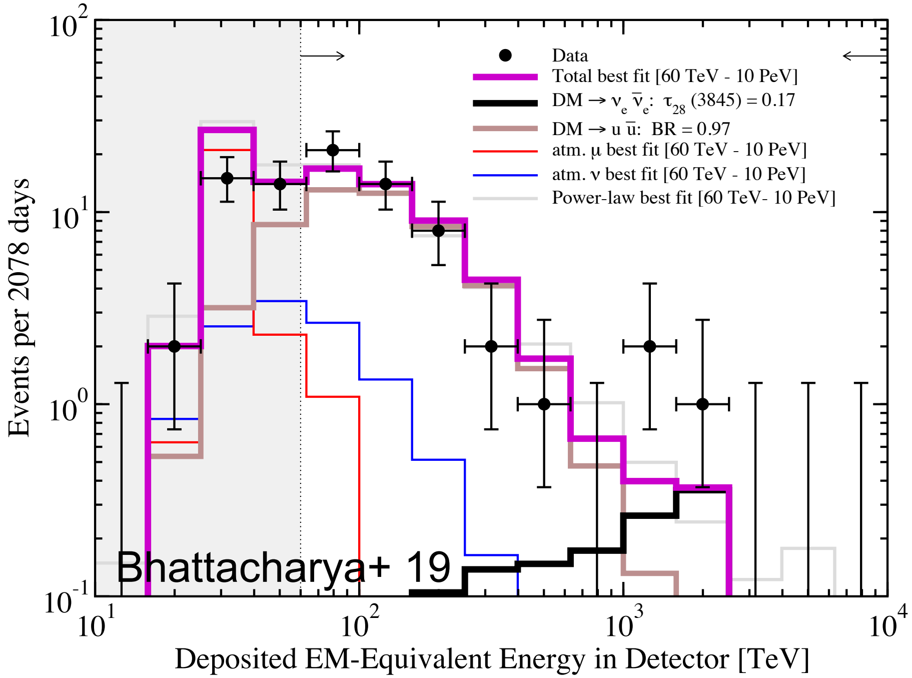
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



- Disfavoring DM scenarios to explain the excessive 10-100 TeV ν data
- Unique probes of superheavy dark matter that is difficult to directly test

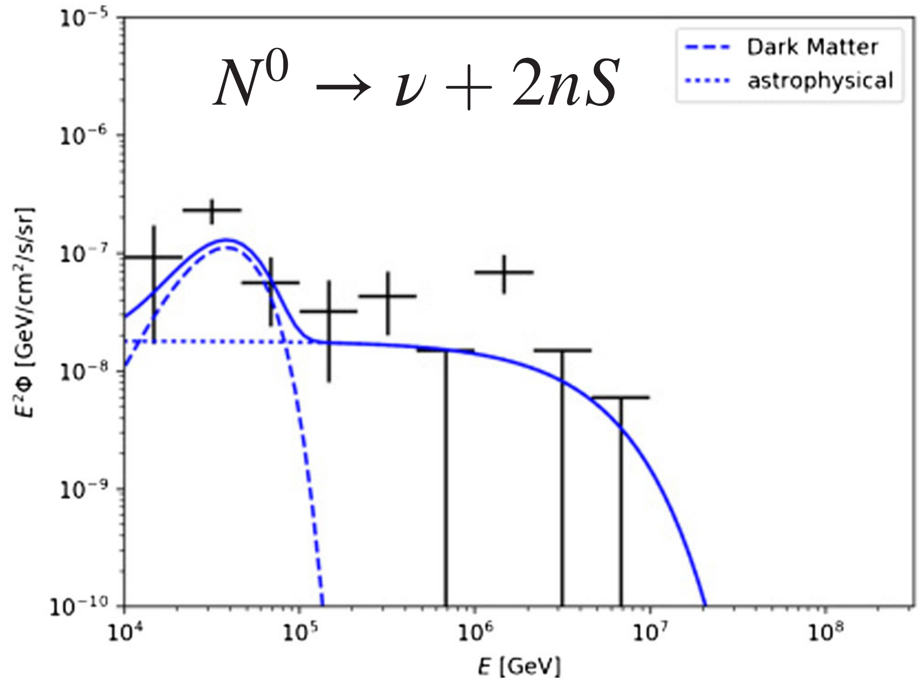
Viable DM Scenarios?

- 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



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

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



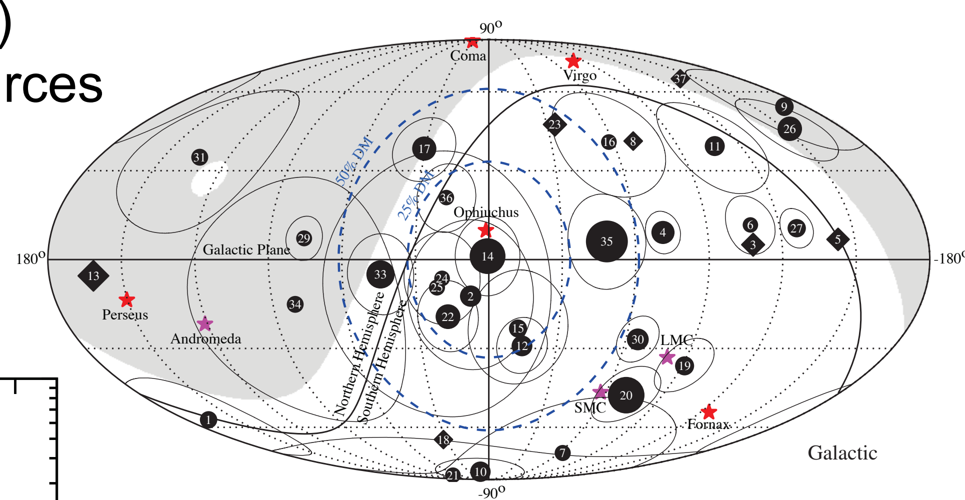
Hiroshima, Kitano, Kohri & KM 18
see also:
Chianese+ 17
Anchordoqui+ 20

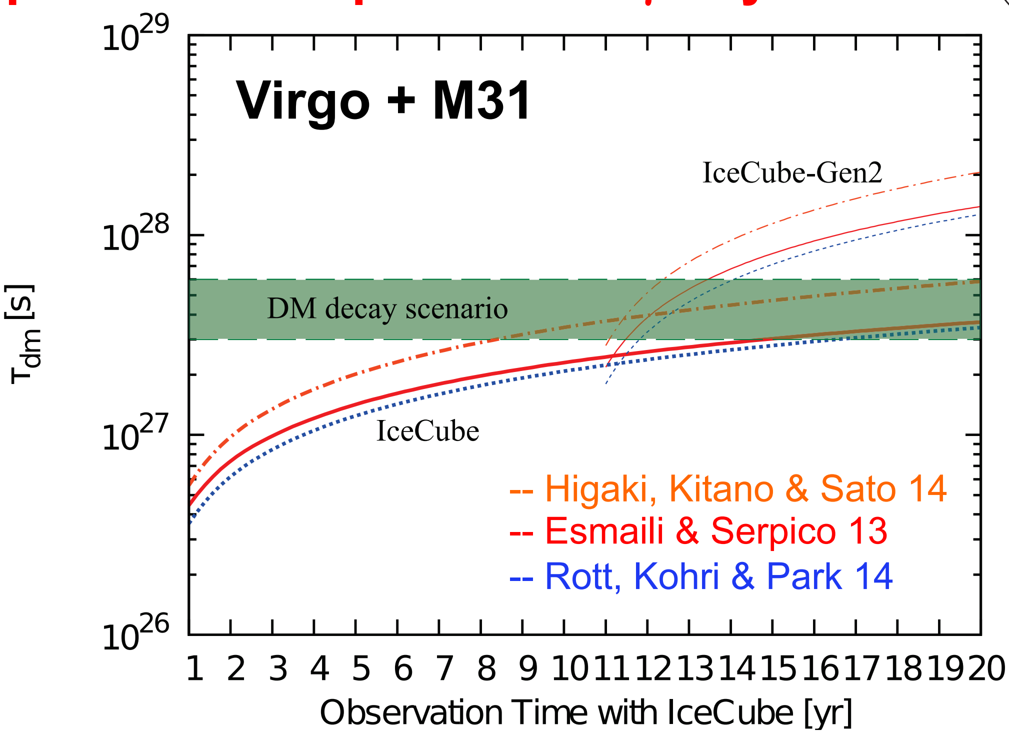
Future Tests for Dark Matter Scenarios

Nearby DM halos (clusters & galaxies) should be seen as point/extended sources

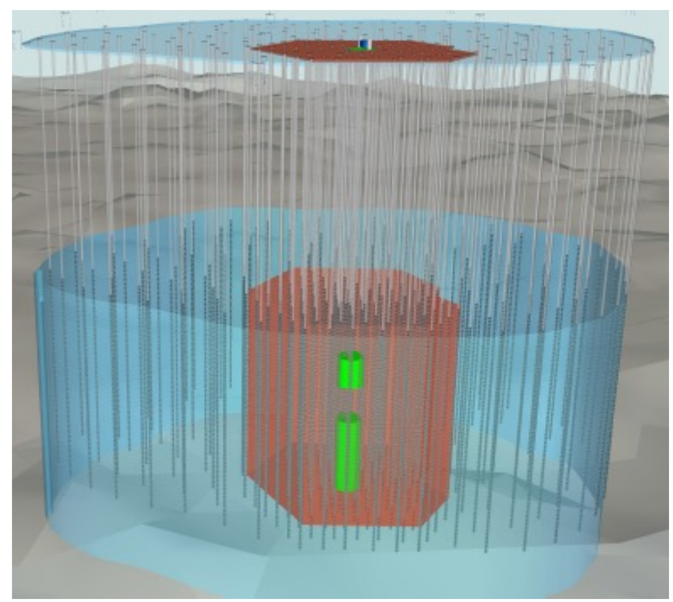
$$\text{flux} \propto M_{dm}/\tau_{dm}/d^2$$

stacking or cross-correlation
powerful independent of γ–ray limits





KM, Laha, Ando & Ahlers 15 PRL



Secret Neutrino Interactions

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

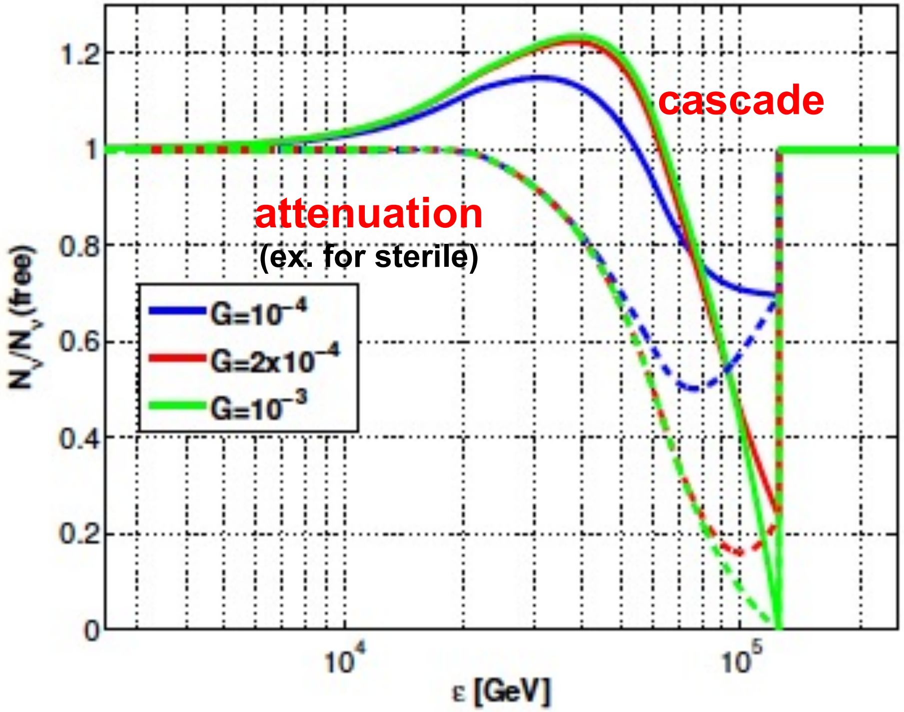
Bardin, Bilenky & Pontecorvo 70

Applications to IceCube
Ioka & KM 14 PTEP
Ng & Beacom 14 PRD

ex. Majorana ν self-interactions via a scalar (Blum, Hook & KM 14)

$$\mathcal{L} = -\frac{g}{\Lambda^2}\Phi(HL)^2 + cc. \xrightarrow{\text{SSB}} \mathcal{L} = -\frac{1}{2}\sum_i \left(m_{\nu_i} + \mathcal{G}_i\phi\right)\nu_i\nu_i + cc + ..., \quad m_{\nu_i} = \frac{g_i\mu v^2}{\Lambda^2}$$

lepton # violation



BSM ν–ν and ν-DM interactions via MeV mediators:

1. small-scale structure problems
2. Hubble tension

HE neutrinos interact w. cosmic neutrino background or dark matter

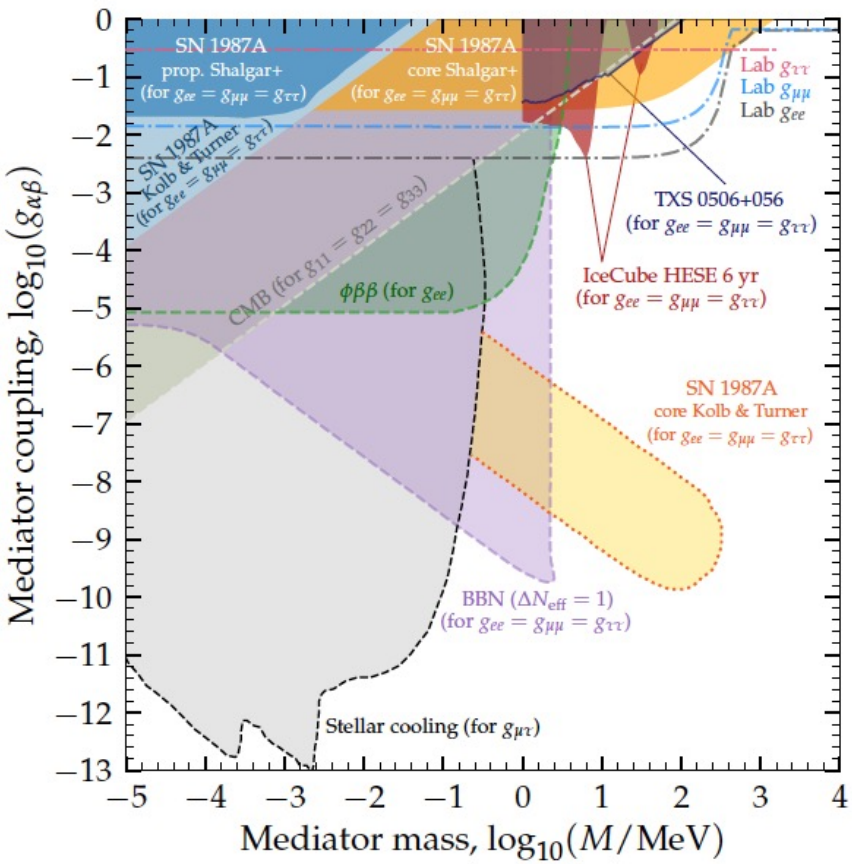
$$\epsilon_{\rm res} = \frac{m_\phi^2}{2m_\nu} = 1\ \mathrm{PeV}\left(\frac{m_\phi}{10\ \mathrm{MeV}}\right)^2\left(\frac{m_\nu}{0.05\ \mathrm{eV}}\right)^{-1}$$

→ **modulation in neutrino spectra**

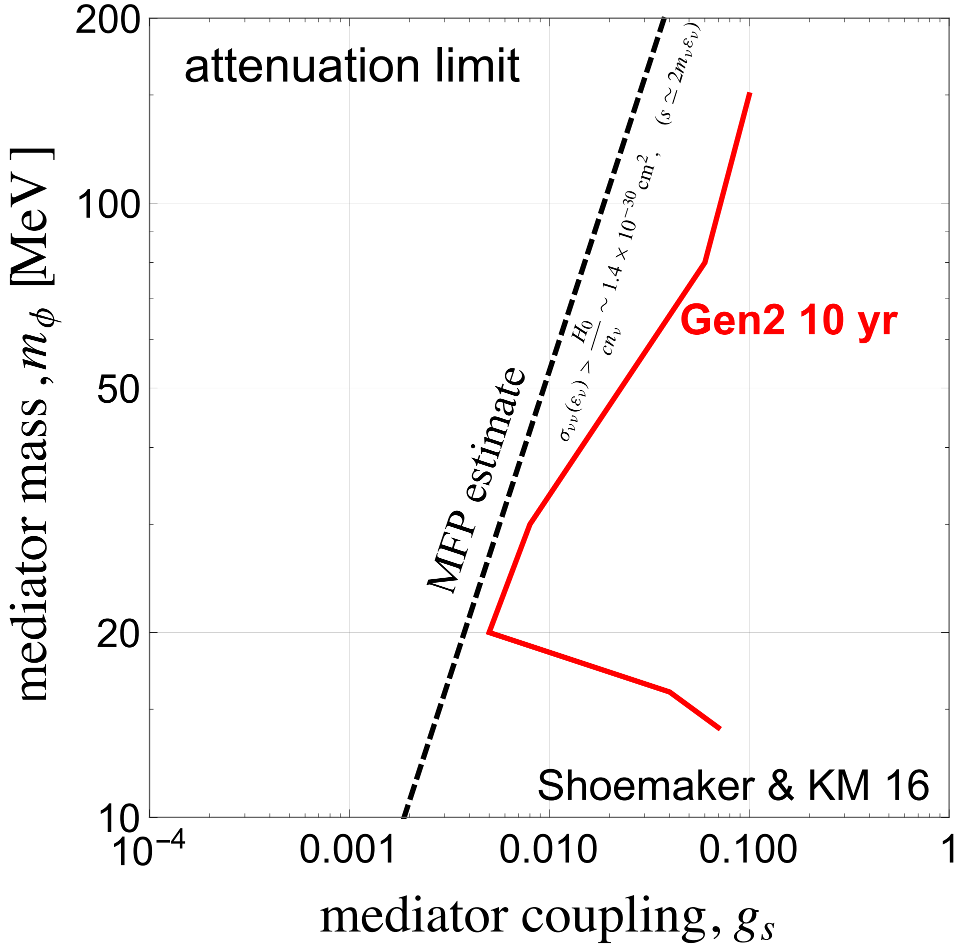
ex. Blum. Hook & KM 14, Araki+ 14 PRD, Shoemaker & KM 16 PRD…

Current & Future Constraints

current IceCube



future IceCube-Gen2

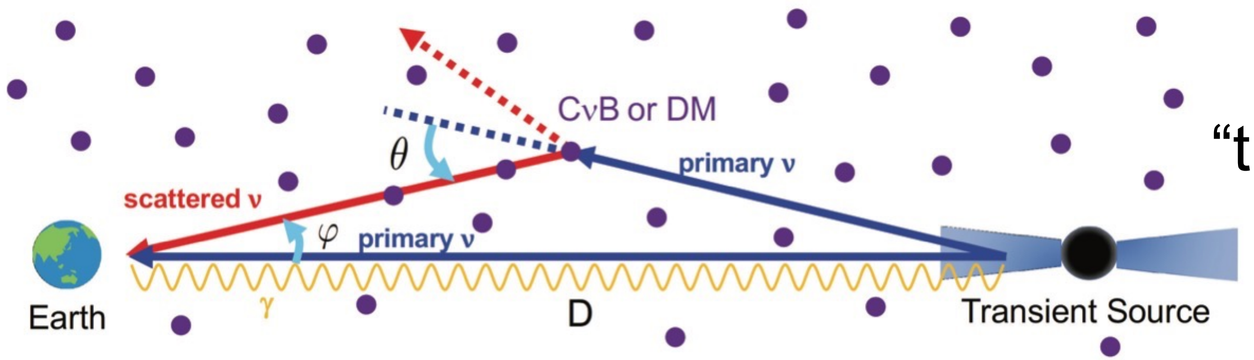


HE neutrino observations can give the best constraints

(cf. π/K decay: g < 0.01, Z decay: g <~ 0.1, 0νββ decay etc. but **model-dependent)**

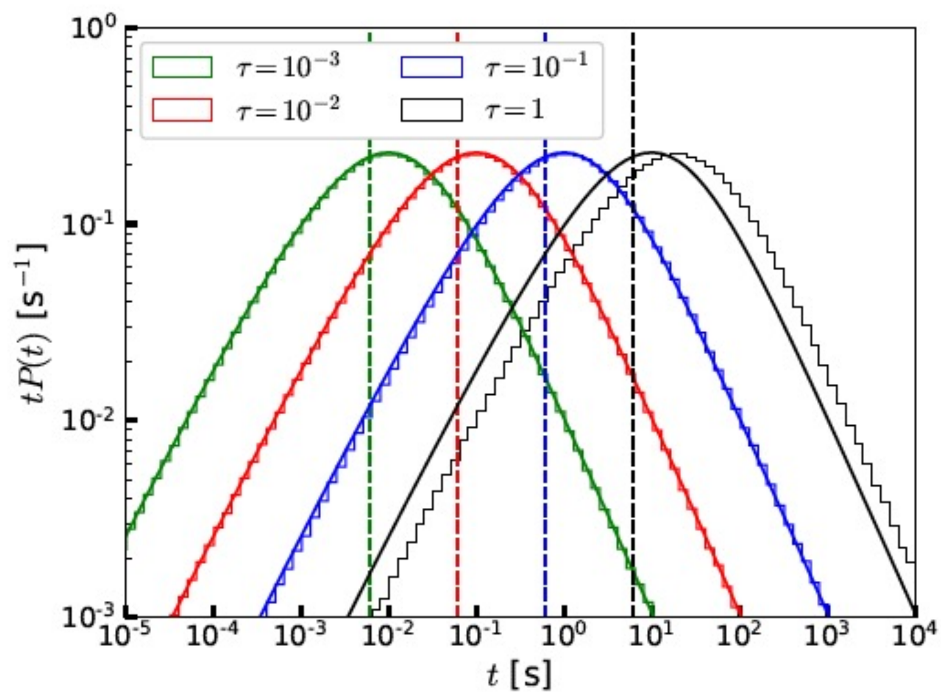
BSM & Time-Domain Multi-Messenger Astrophysics

KM & Shoemaker 19 PRL



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

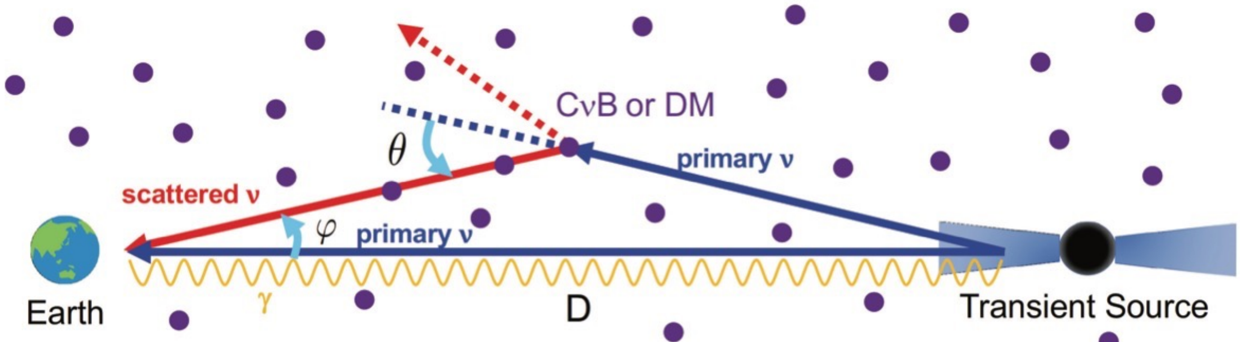
$$\Delta t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4} D \simeq 77\,\mathrm{s}\left(\frac{D}{3\ \mathrm{Gpc}}\right) C^2 \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$



Eskenasy, Kheirandish & KM 22
Carpio & Murase 22

BSM Tests with Multi-Messenger Transients

BSM ν-ν/ν-DM interactions could alleviate H_0 tension & small-scale issues

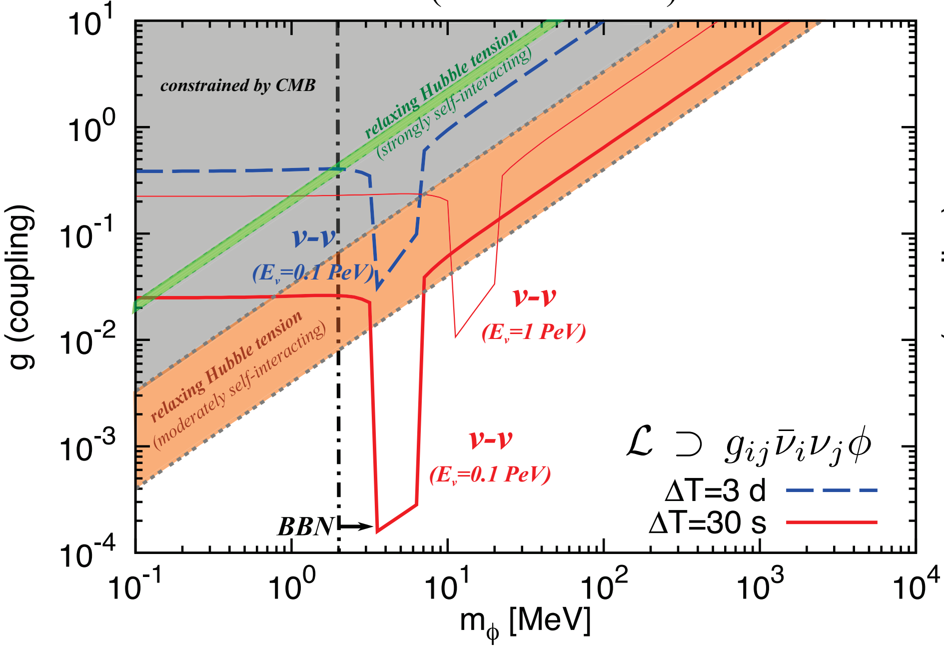


"time delay" signatures
(**neutrino echoes**)

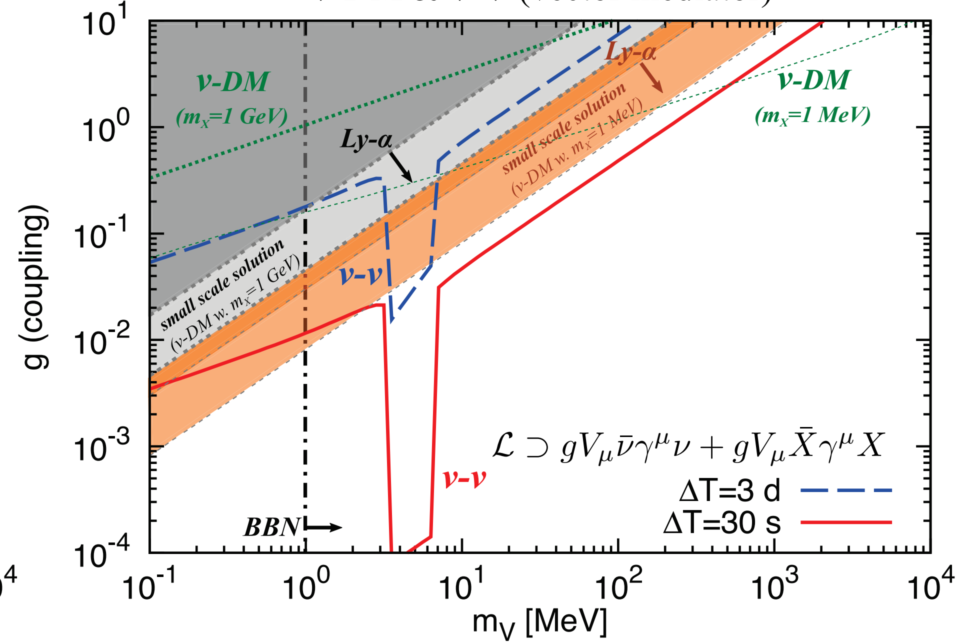
$$\Delta t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4} D \simeq 77\ \mathrm{s}\left(\frac{D}{3\ \mathrm{Gpc}}\right) C^2 \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

KM & Shoemaker 19 PRL

ν-ν (scalar mediator)



ν-DM & ν-ν (vector mediator)



Summary

ν budget ~ γ-ray budget ~ UHECR budget

Where do neutrinos mainly come from?

CR accelerators: blazars & GRBs: likely subdominant in the neutrino sky
CR reservoirs: astro-particle grand-unification is possible
Multi-messenger analyses w. 10-100 TeV ν data imply hidden CR accelerators
NGC 1068 (AGN) supports active black holes as hidden ν sources

Neutrino Transients?

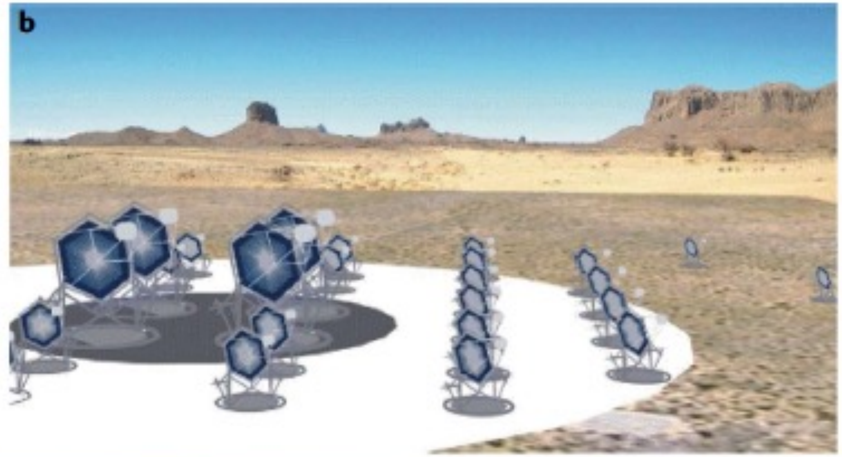
Transients: unique chances -> strategic multi-messenger searches (ex. AMON)
Intriguing coincidences with black hole flares have been found
Establishing the multi-messenger picture is critical → stay tuned

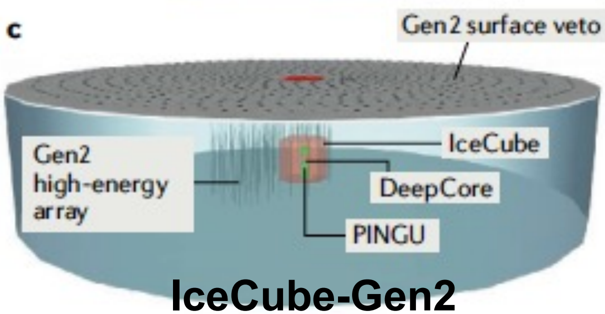
Tests for New Physics?

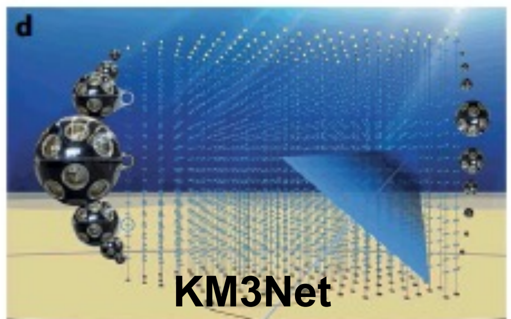
heavy dark matter, neutrino-neutrino/DM interactions etc.
multi-messenger searches are complementary and powerful

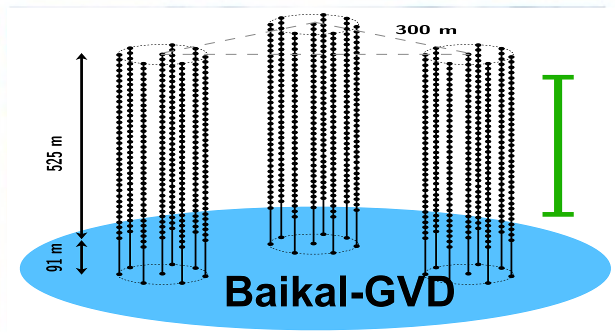
Future is bright: IceCube-Gen2, KM3Net & other next-generation facilities

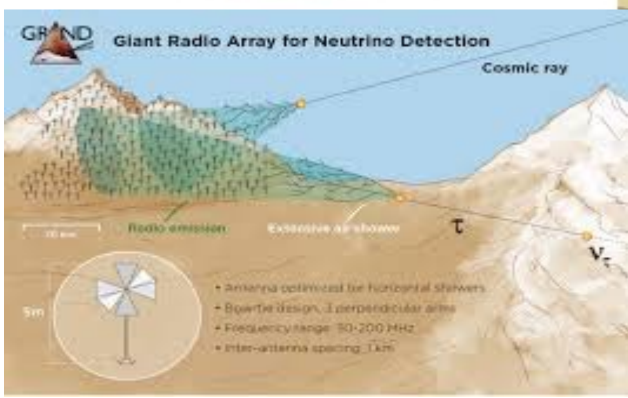
Bright Future









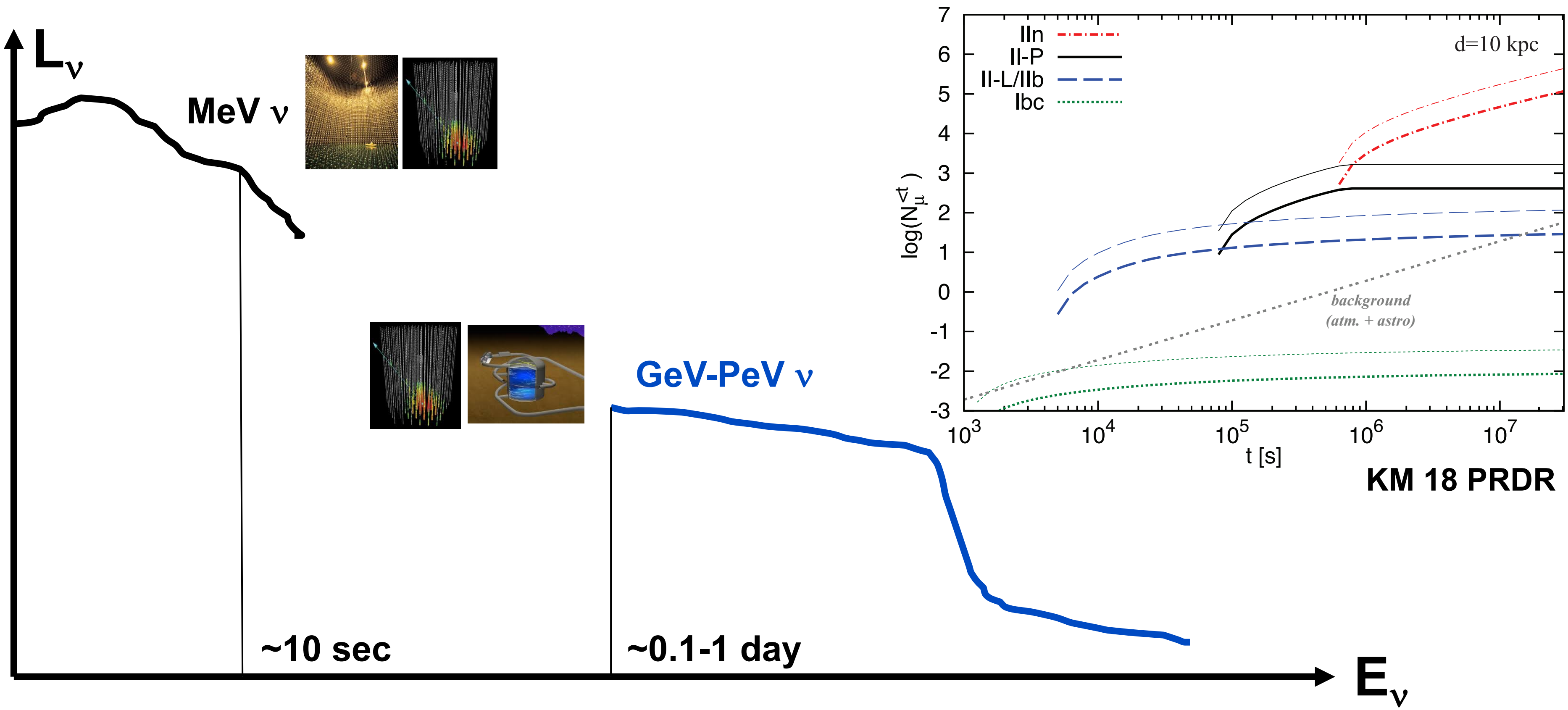


More multi-messenger data in the next decade will enable us to test the proposed models


Thank you very much!

Example of Promising ν Transients: Supernovae

- Enhanced circumstellar material: ubiquitous for supernova progenitors
- Type II: ~100-1000 events of TeV ν from the next Galactic SN
  ex. Betelgeuse: ~10^3-3×10^6 events, Eta Carinae: ~10^5-3×10^6 events
- SNe as "multi-messenger" & "multi-energy" neutrino source
- Real-time monitoring of CR ion acceleration & new physics tests



KM 18 PRDR