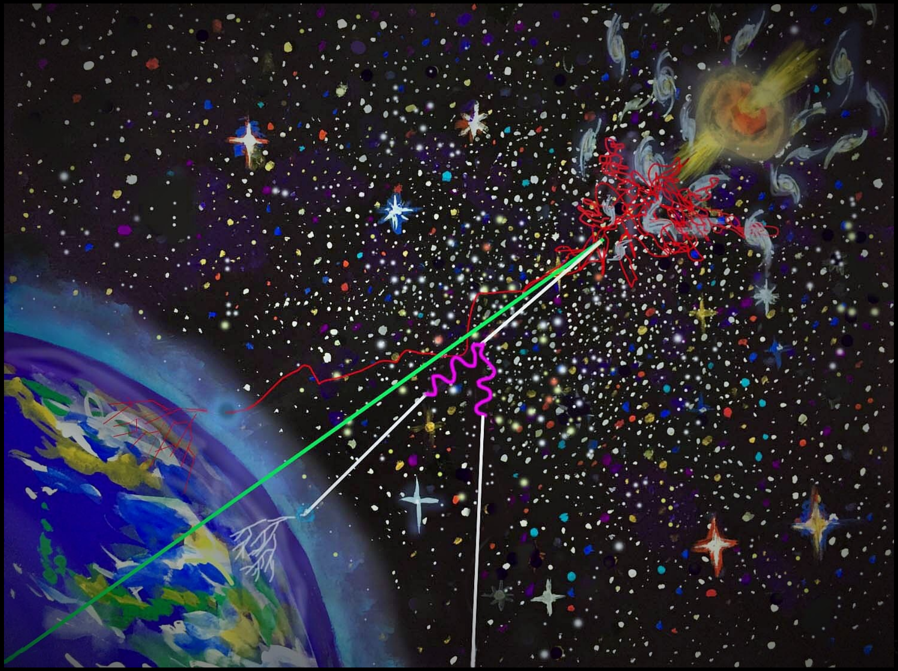
Cosmic Particles in the Multi-Messenger Era



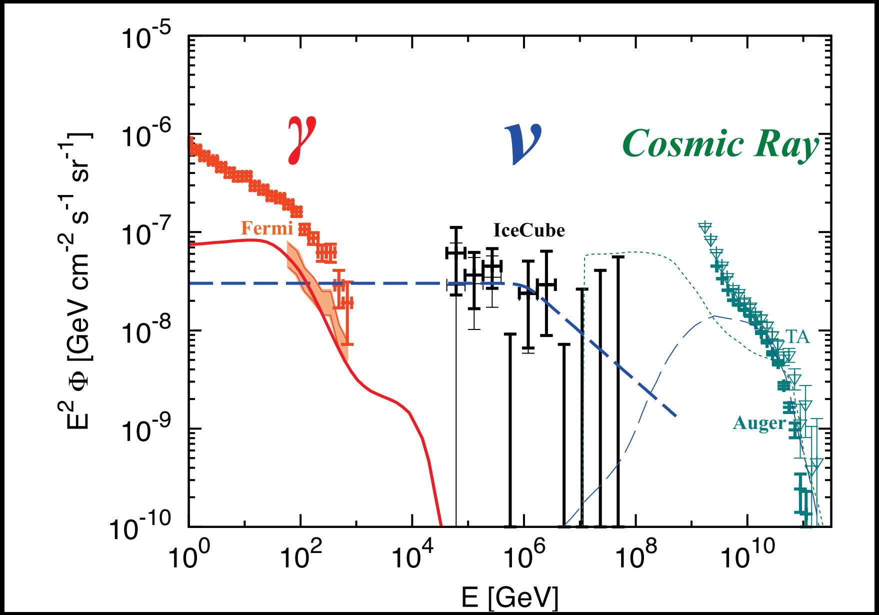
Kohta Murase

Penn State University

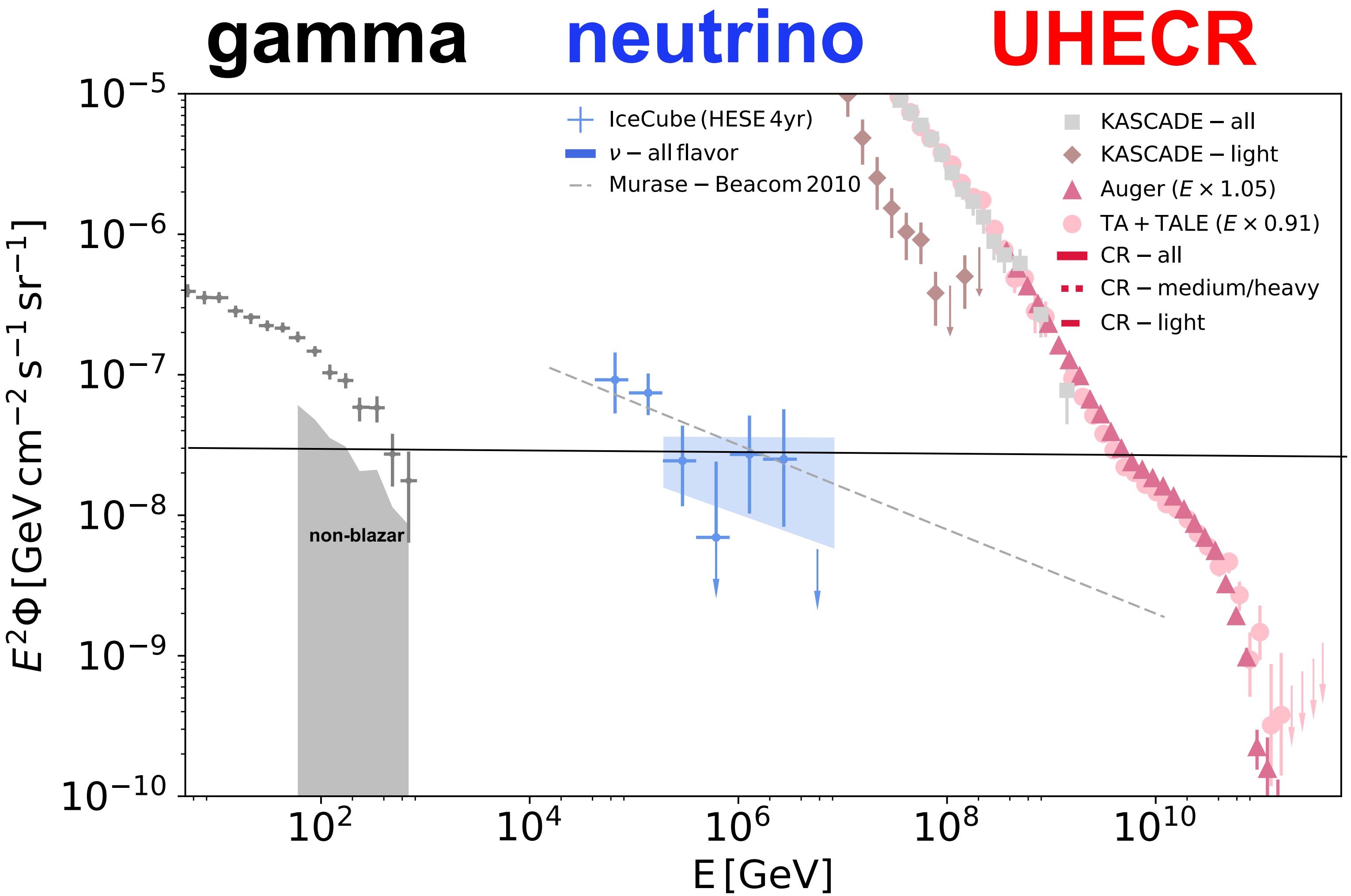
PENNSTATE

1 8 5 5

Multi-Messenger Implications



Multi-Messenger Cosmic Particle Backgrounds



Energy budgets are all comparable (a few x 10^{43} erg Mpc^{-3} yr^{-1})

Astrophysical Extragalactic Scenarios

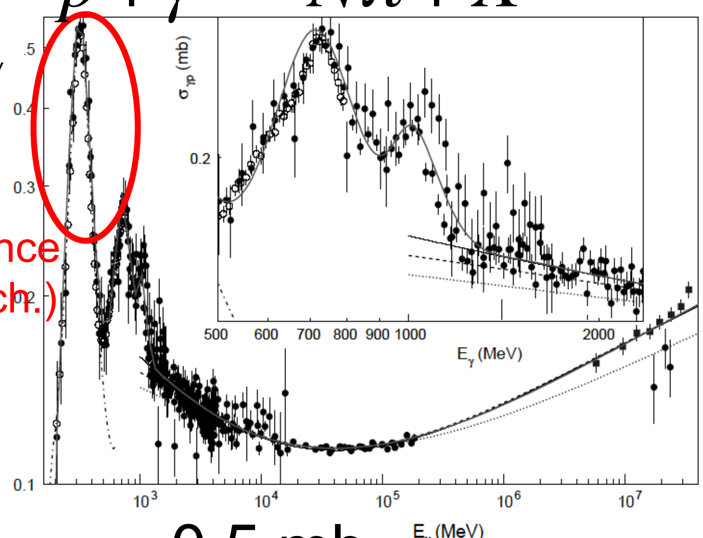
$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-ray Accelerators (ex. UHECR candidate sources)

Active galactic nuclei

γ-ray burst

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

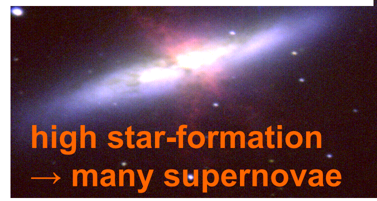


$$\sigma_{p\gamma} \sim \alpha \sigma_{pp} \sim 0.5\ \mathrm{mb}$$

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

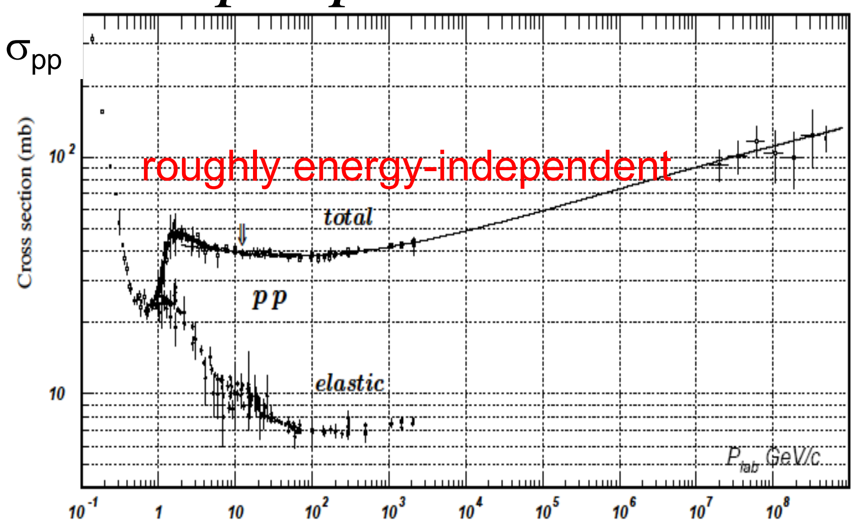
Cosmic-ray Reservoirs

Starburst galaxy



Galaxy group/cluster

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



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

Fate of High-Energy Gamma Rays

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

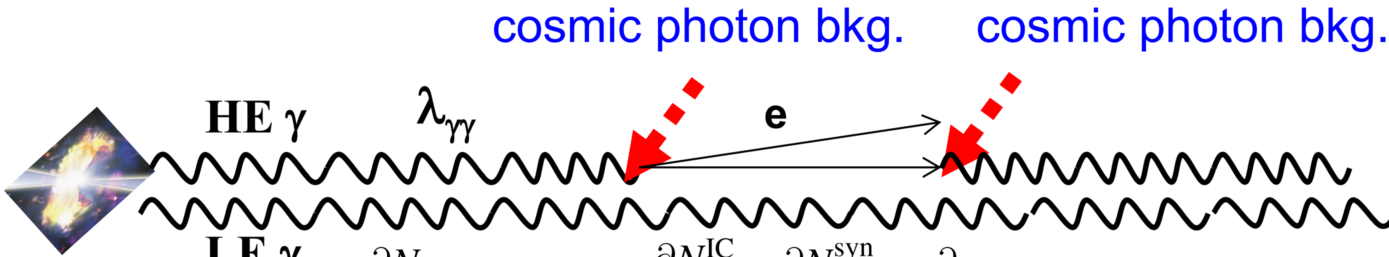
$p + \gamma \rightarrow N\pi + X$ $\quad \pi^{\pm}:\pi^0 \sim 1:1 \rightarrow$ **$E_\gamma^2\, \Phi_\gamma \sim (4/3)\, E_\nu^2\, \Phi_\nu$**

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

>TeV γ rays interact with CMB & extragalactic background light (EBL)

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

ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc
$\lambda_{\gamma\gamma}$(PeV) ~ 10 kpc ~ distance to Gal. Center



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

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

Fermi satellite

airshower detectors

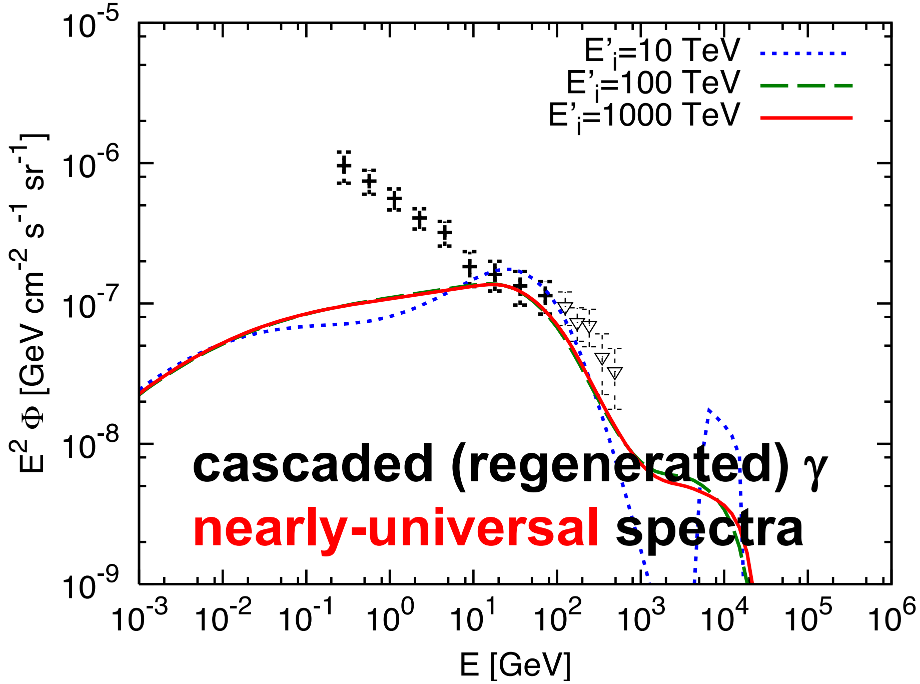
Fate of High-Energy Gamma Rays

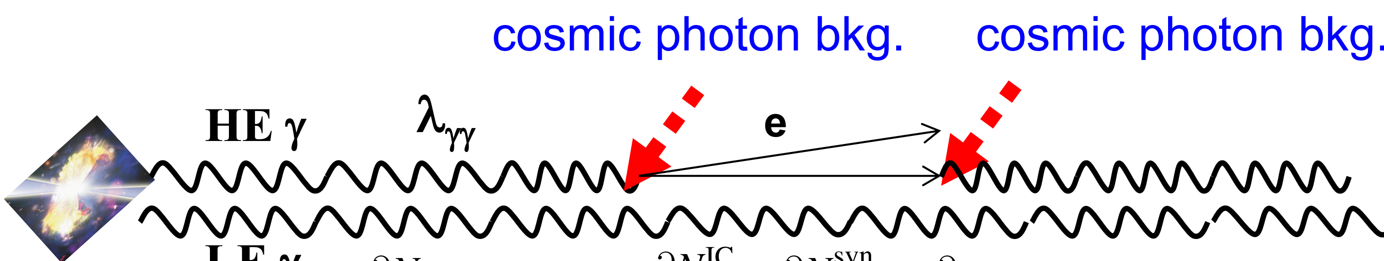
$p+\gamma \rightarrow$ … 4/3) $E_\nu^2\,\Phi_\nu$

$p+p \rightarrow$ … 2/3) $E_\nu^2\,\Phi_\nu$

>TeV γ rays int … **und light (EBL)**

$\gamma+\gamma_{\rm CMB/EB}$ … ce to Gal. Center





Fermi satellite

airshower detectors

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

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Astrophysical Extragalactic Scenarios

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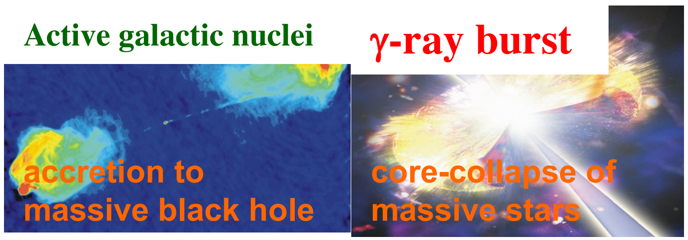
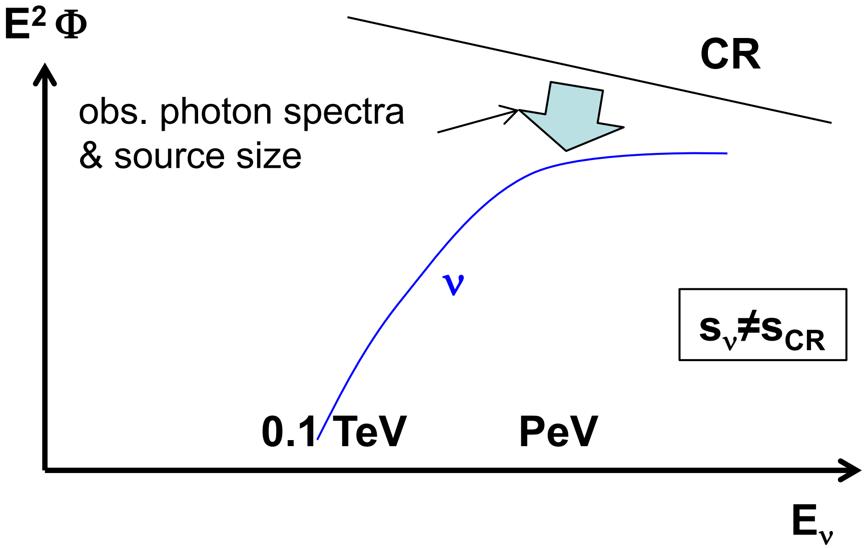
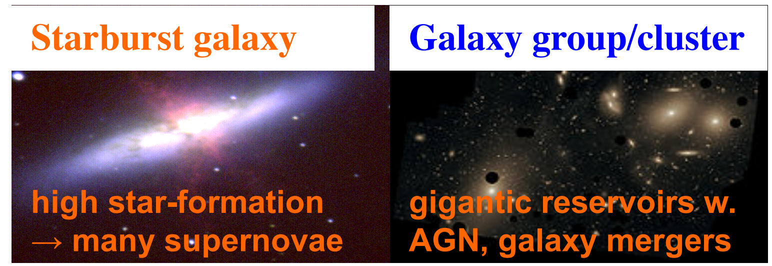
Cosmic-ray Accelerators (ex. UHECR candidate sources)



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

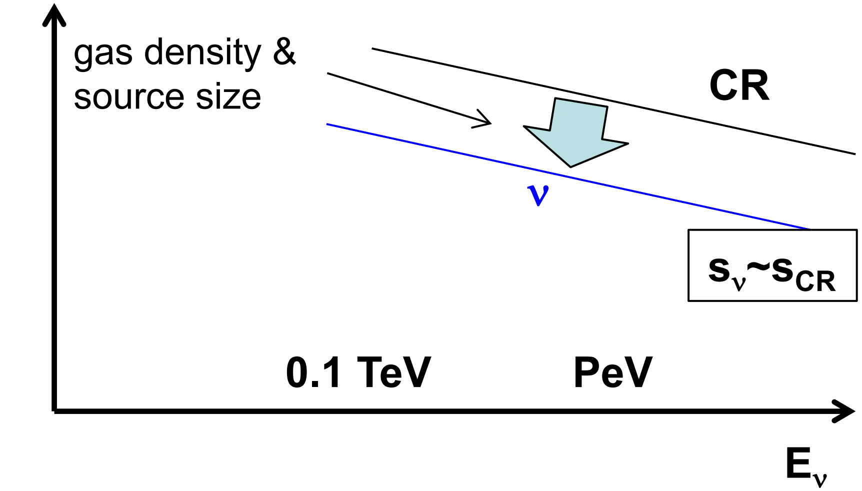


Cosmic-ray Reservoirs



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

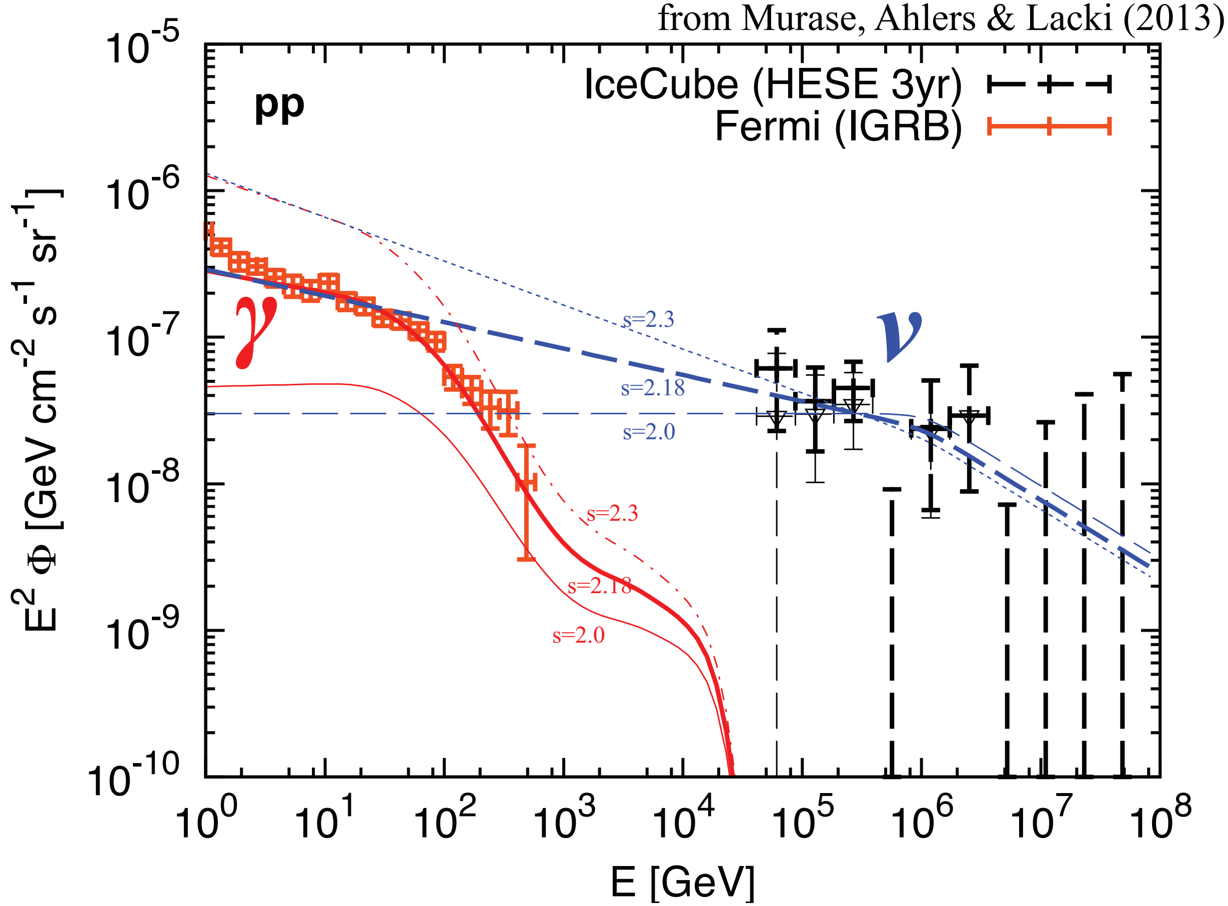
$\Phi \propto E^{-s}$



Neutrino-Gamma Connection?

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

from Murase, Ahlers & Lacki (2013)



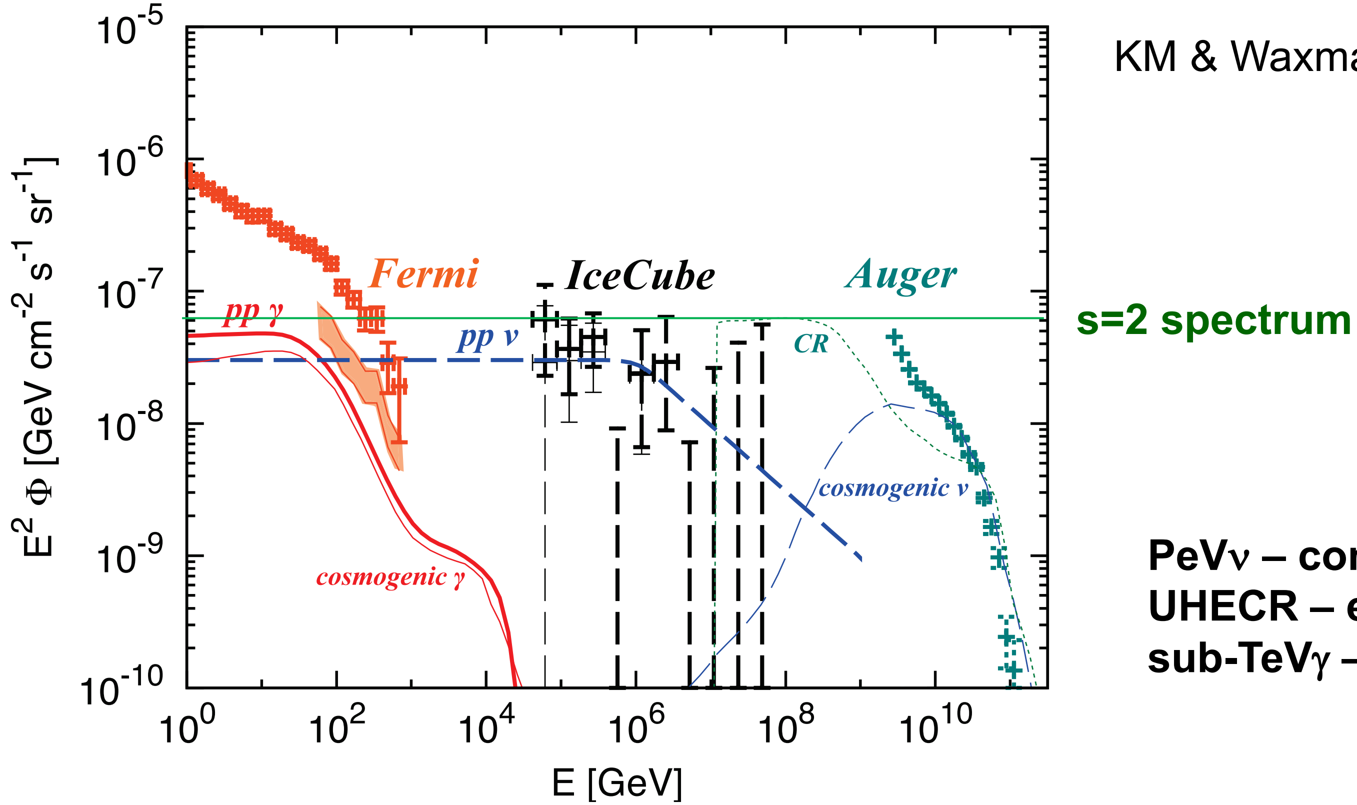
- **s_ν<2.1-2.2 (for extragal.); insensitive to evolution & EBL models**
- **contribution to diffuse sub-TeV γ: >30%(SFR evol.)-40% (no evol.)**
- s_ν<2.0 for nearly isotropic Galactic emission (e.g., Galactic halo)

Neutrino-Gamma-UHECR Connection?

(grand-)unification of neutrinos, gamma rays & UHECRs

simple Fermi acc. spectrum w. s~2 can fit all diffuse fluxes

- Explain >0.1 PeV ν data with a few PeV break (theoretically expected)
- Escaping CRs may contribute to the observed UHECR flux



KM & Waxman 16 PRD

PeVν – confined CR
UHECR – escaping CR
sub-TeVγ – "sum"

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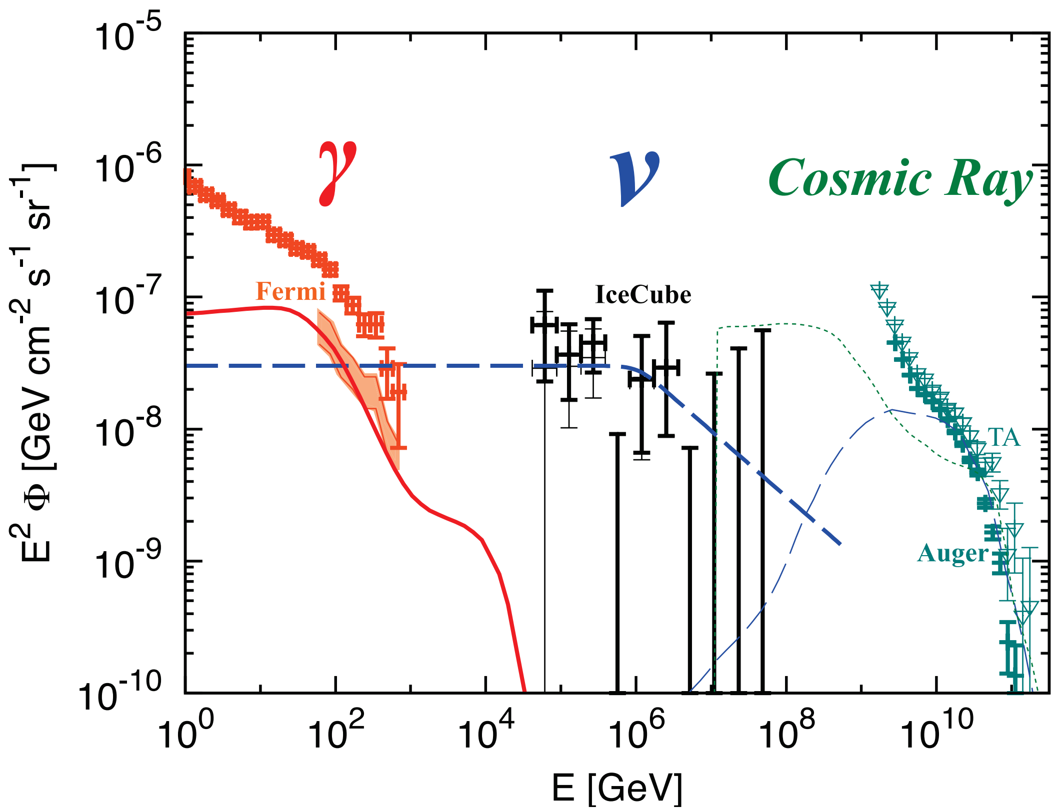

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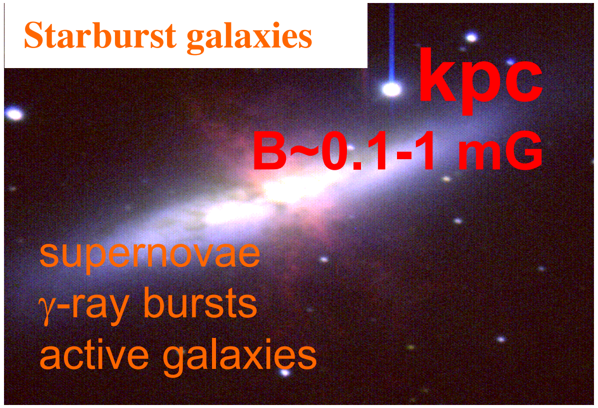
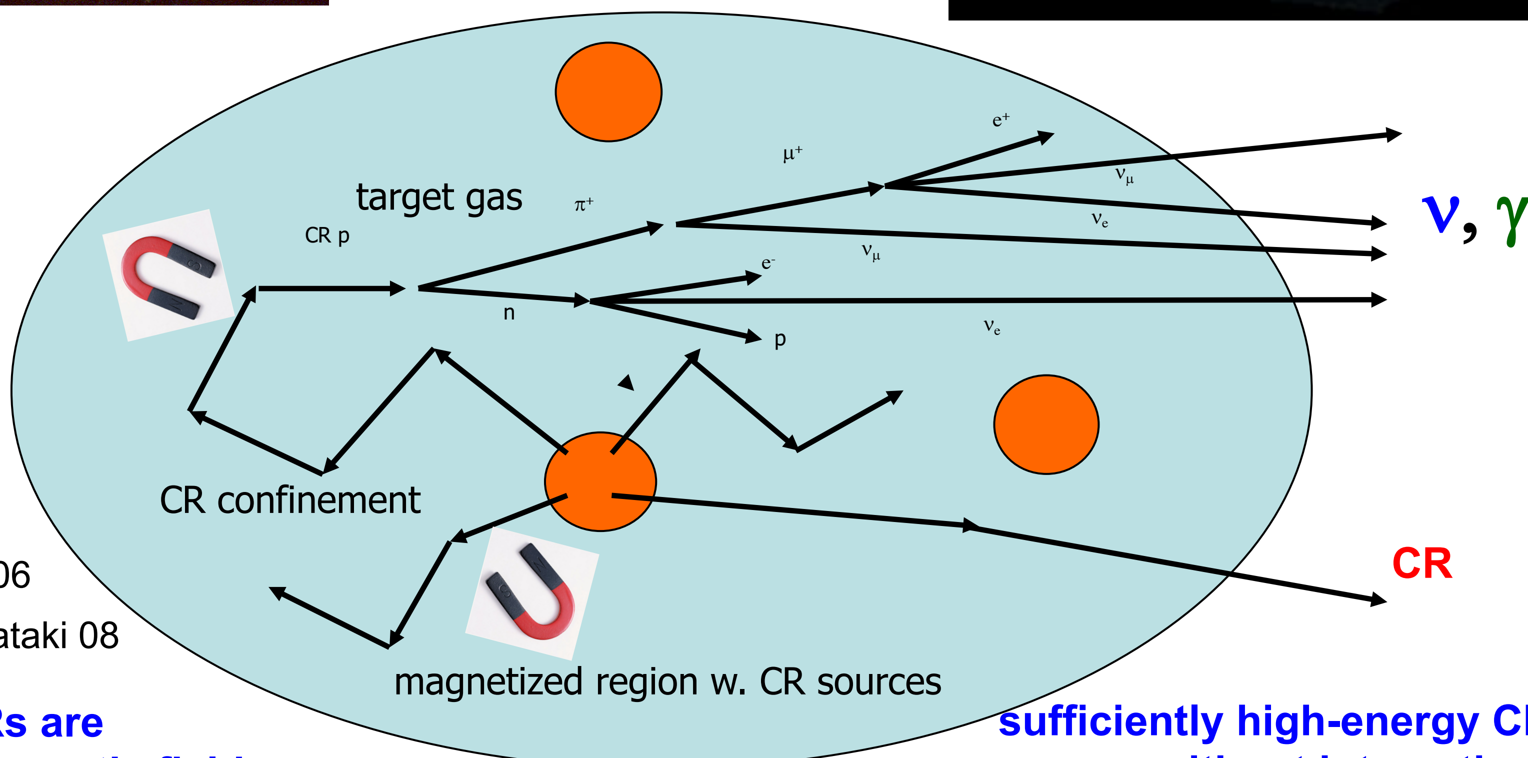
Cosmic-Ray Reservoirs



“cosmic-ray reservoirs”



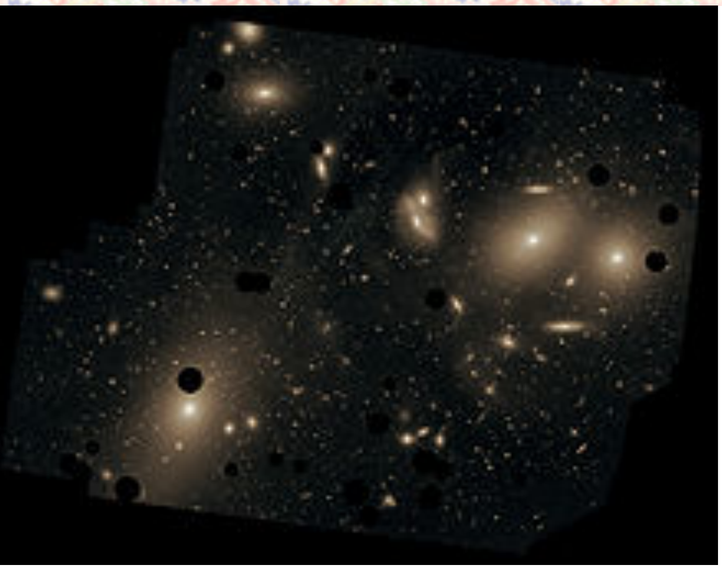
Loeb & Waxman 06

KM, Inoue & Nagataki 08

low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions

Example: Galaxy Groups and Clusters



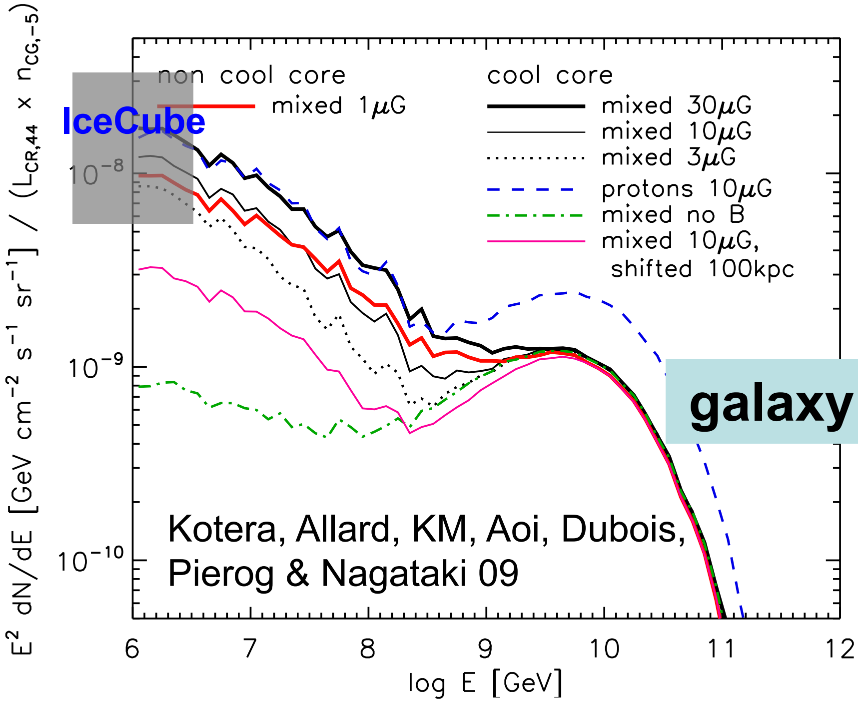
- Intracluster gas density (known)
  n~10^{-4} cm^{-3}, a fewx10^{-2} cm^{-3} (center)
- CR accelerators
  active galactic nuclei
  accretion shocks (massive clusters)
  galaxy/cluster mergers

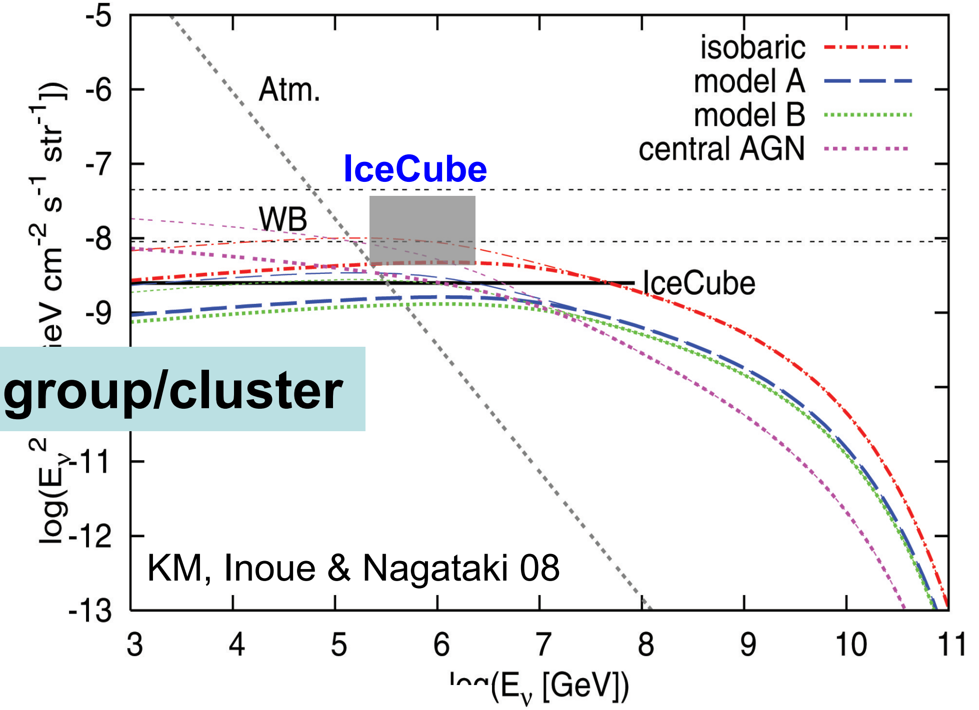
AGN jet luminosity density $Q_{\rm cr} \sim 3.2 \times 10^{46}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}\ \epsilon_{{\rm cr},-1} L_{j,45} \rho_{{\rm GC},-5}$

cluster luminosity density $Q_{\rm cr} \sim 1.0 \times 10^{47}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}\ \epsilon_{{\rm cr},-1} L_{{\rm ac},45.5} \rho_{{\rm GC},-5}$

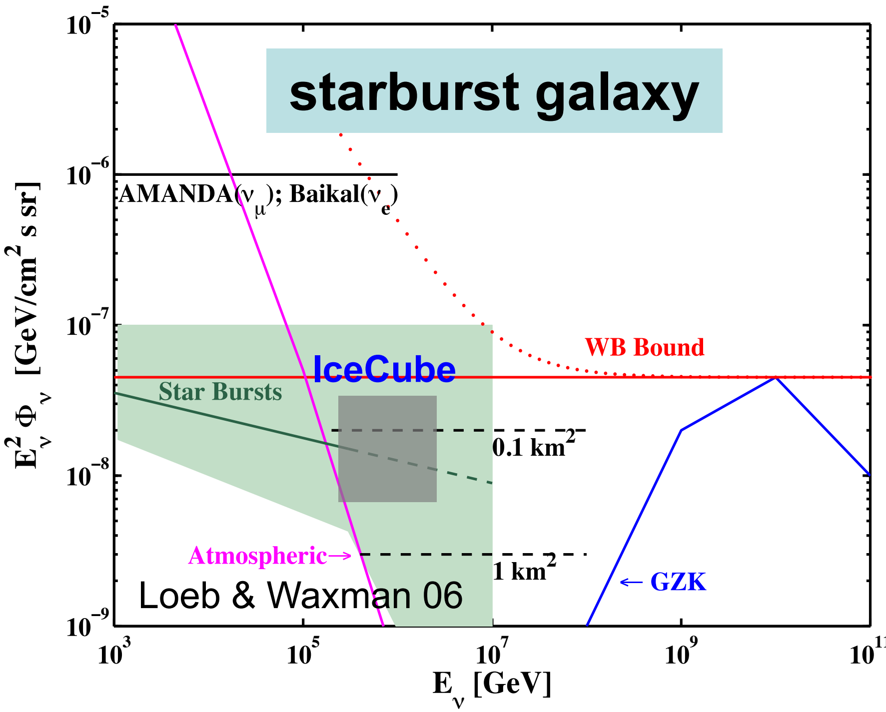
pp efficiency $f_{pp} \approx \kappa_p \sigma_{pp} n c t_{\rm int} \simeq 0.76 \times 10^{-2}\ g \bar{n}_{-4} (t_{\rm int}/2\ {\rm Gyr})$

$$E_\nu^2 \Phi_{\nu_i} \sim 10^{-9}\text{–}10^{-8}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$





galaxy group/cluster



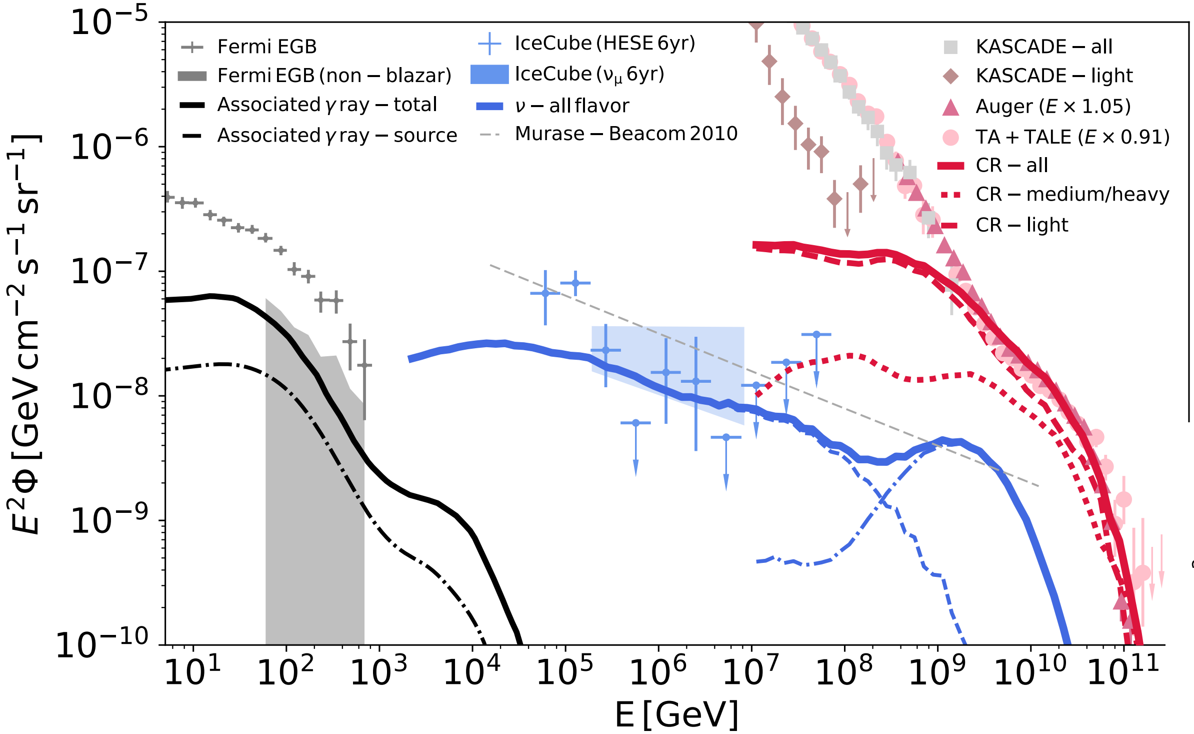
starburst galaxy

consistent w. observations but uncertain

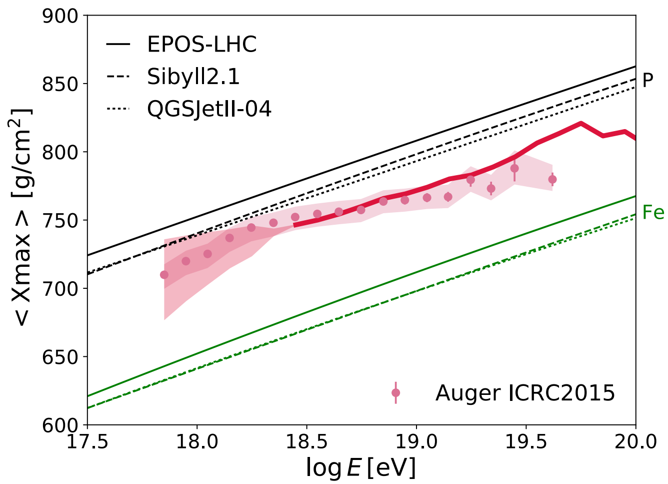
Neutrino-Gamma-UHECR Connection?

Grand-unification of neutrinos, gamma rays & UHECRs

- Explain ν data by confined CRs with energies less than a few PeV
- Escaping CRs may contribute to the observed UHECR flux



Fang & KM 18 Nature Physics

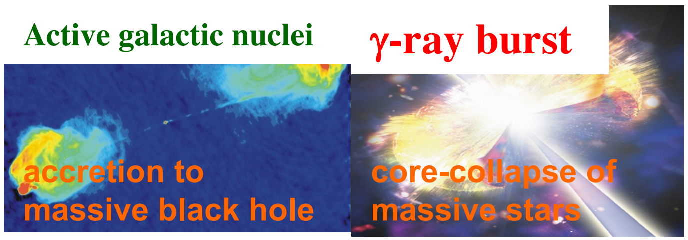


- AGN as "UHECR" accelerators
- CR nuclei: harder than CR protons due to photodisintegration inside clusters

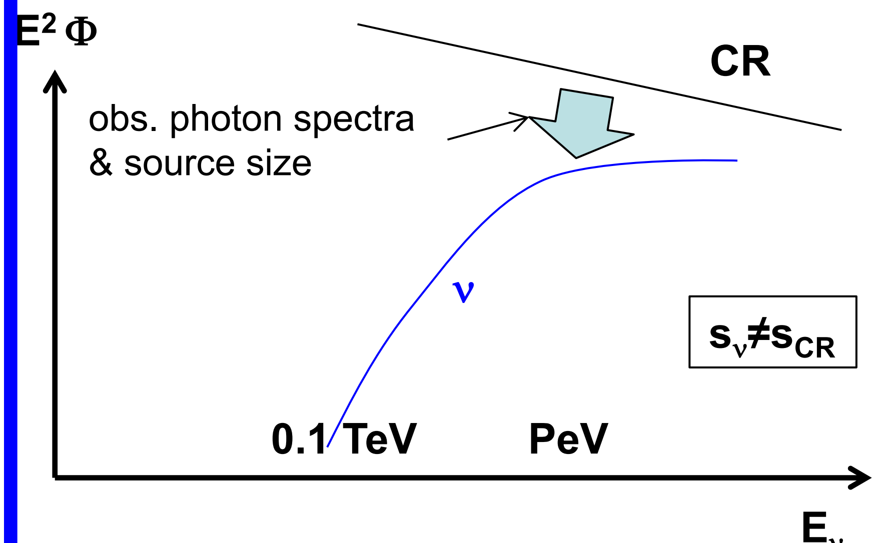
Astrophysical Extragalactic Scenarios

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

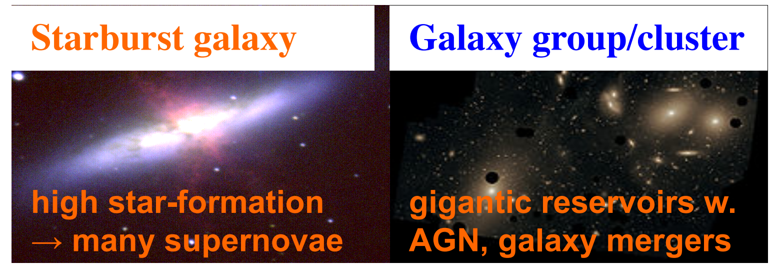
Cosmic-ray Accelerators (ex. UHECR candidate sources)



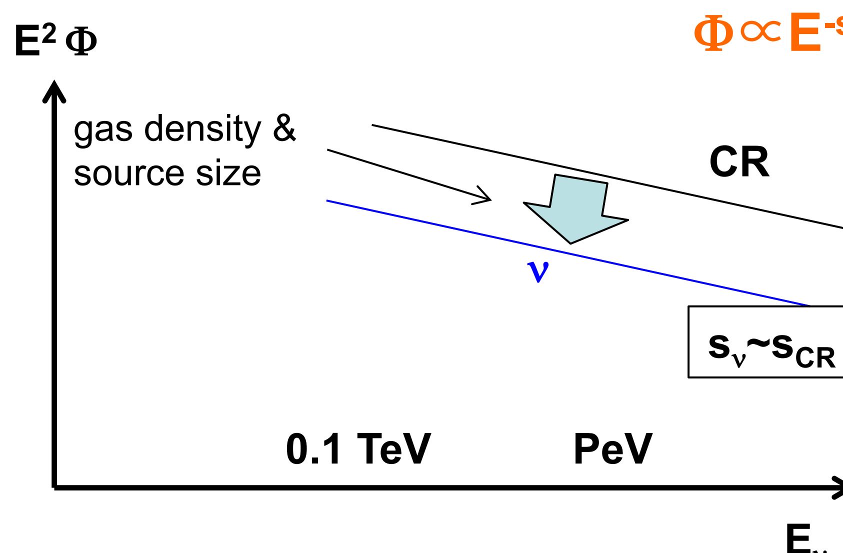
$$p + \gamma \rightarrow N\pi + X$$



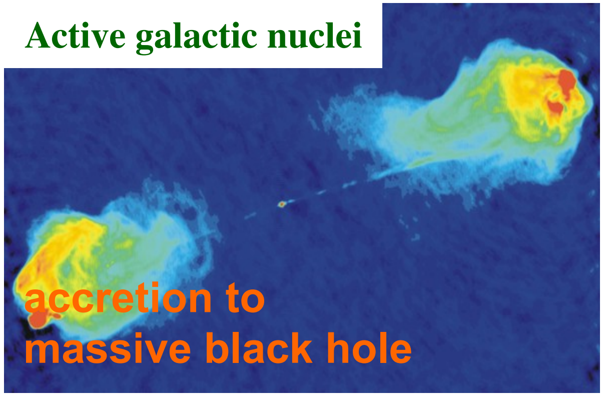
Cosmic-ray Reservoirs



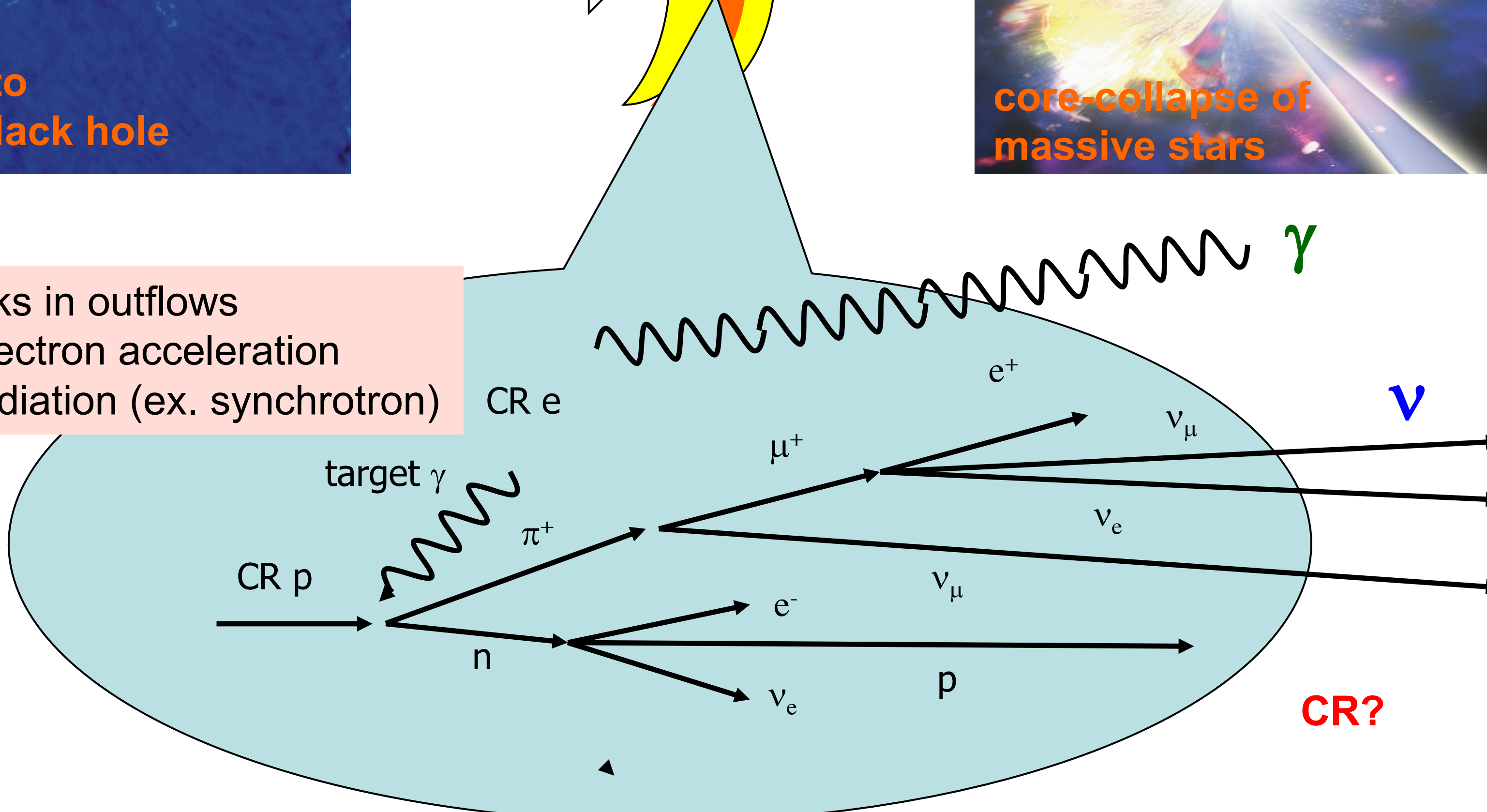
$$p + p \rightarrow N\pi + X$$



Cosmic-Ray Accelerators



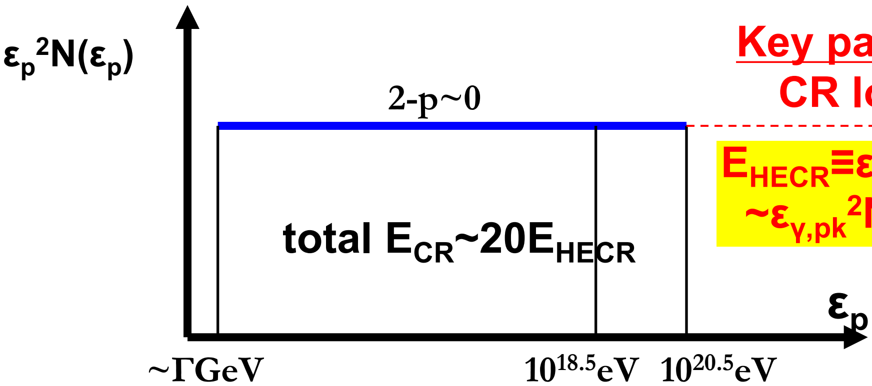
ex. shocks in outflows
→ electron acceleration
→ radiation (ex. synchrotron)



CRs may or may not escape

Basics of ν and γ-ray Emission

CR Spectrum (Fermi mechanism)

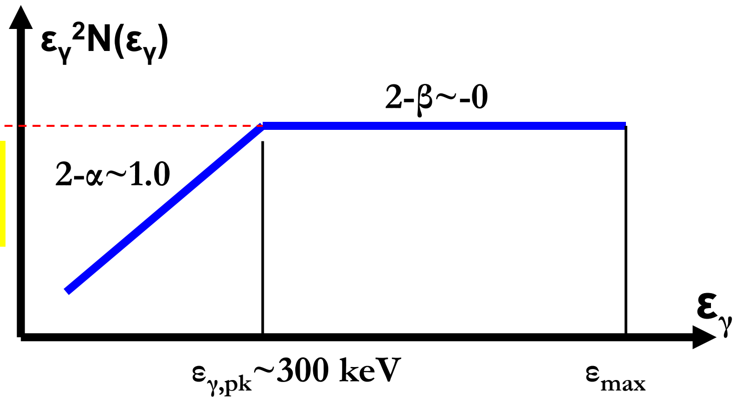


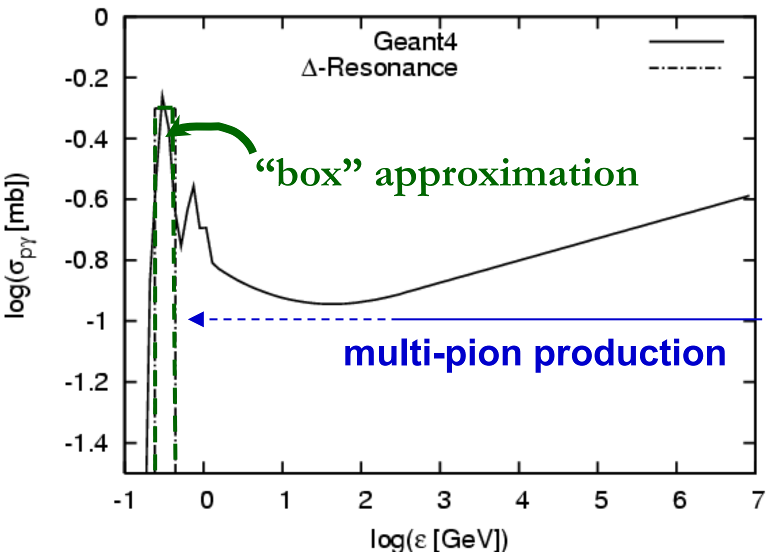
Key parameter

CR loading

$E_{HECR} \equiv \varepsilon_p^2 N(\varepsilon_p)$
$\sim \varepsilon_{\gamma,pk}^2 N(\varepsilon_{\gamma,pk})$

Photon Spectrum (observed)





(in proton rest frame)

Photomeson Production

$$p + \gamma \rightarrow n + \pi^+ \quad \kappa_p \sim 0.2$$

$$p + \gamma \rightarrow N\pi^\pm + X \quad \kappa_p \sim (0.4 - 0.7)$$

at Δ-resonance ($\varepsilon_p\ \varepsilon_\gamma \sim 0.3\ \Gamma^2\ \mathrm{GeV}^2$)

$\varepsilon_p^b \sim 0.15\ \mathrm{GeV}\ m_p c^2\ \Gamma^2/\varepsilon_{\gamma,pk} \sim 50$ PeV

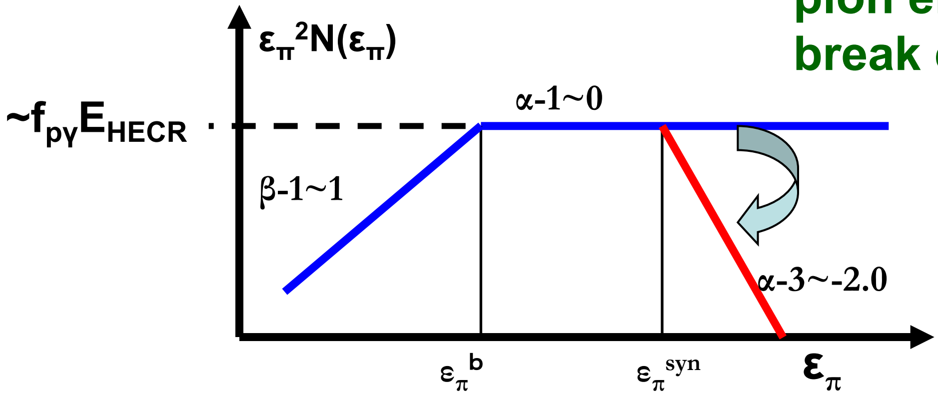
Photomeson production efficiency

~ effective optical depth for pγ process

$f_{p\gamma} \sim 0.2\ n_\gamma \sigma_{p\gamma}\ (r/\Gamma)$ $\propto r^{-1}\ \Gamma^{-2}$

$\propto \Gamma^{-4}\ \delta t^{-1}$ (if $r \sim \Gamma^2\ \delta t$)

Meson Spectrum



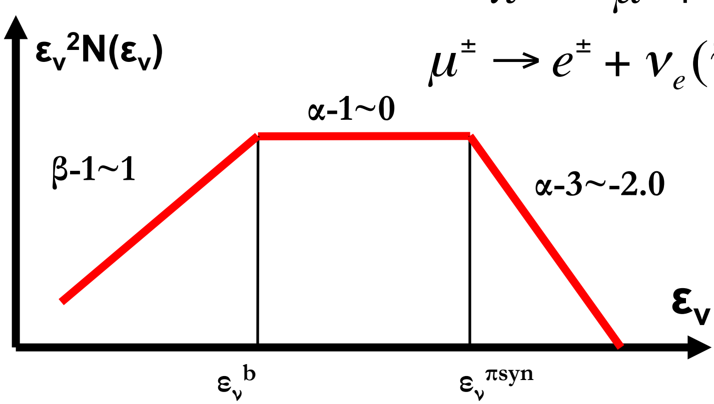
pion energy $\varepsilon_\pi \sim 0.2\ \varepsilon_p$
break energy $\varepsilon_\pi^b \sim 0.07\ \mathrm{GeV}^2\ \Gamma^2/\varepsilon_{\gamma,pk} \sim 10$ PeV

HE charged mesons
(meson cooling time) < (meson life time)
→ suppression at high energies

Waxman & Bahcall, PRL (1997)

Neutrino Spectrum

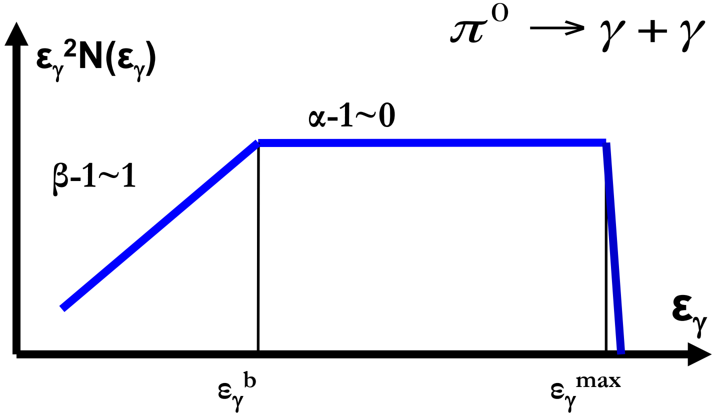
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$
$$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$



neutrino energy $\varepsilon_\nu \sim 0.25\ \varepsilon_\pi \sim 0.05\ \varepsilon_p$
• ν lower break energy $\varepsilon_\nu^b \sim 2.5$ PeV
• ν higher break energy $\varepsilon_\nu^{\pi syn} \sim 25$ PeV

Gamma-Ray Spectrum

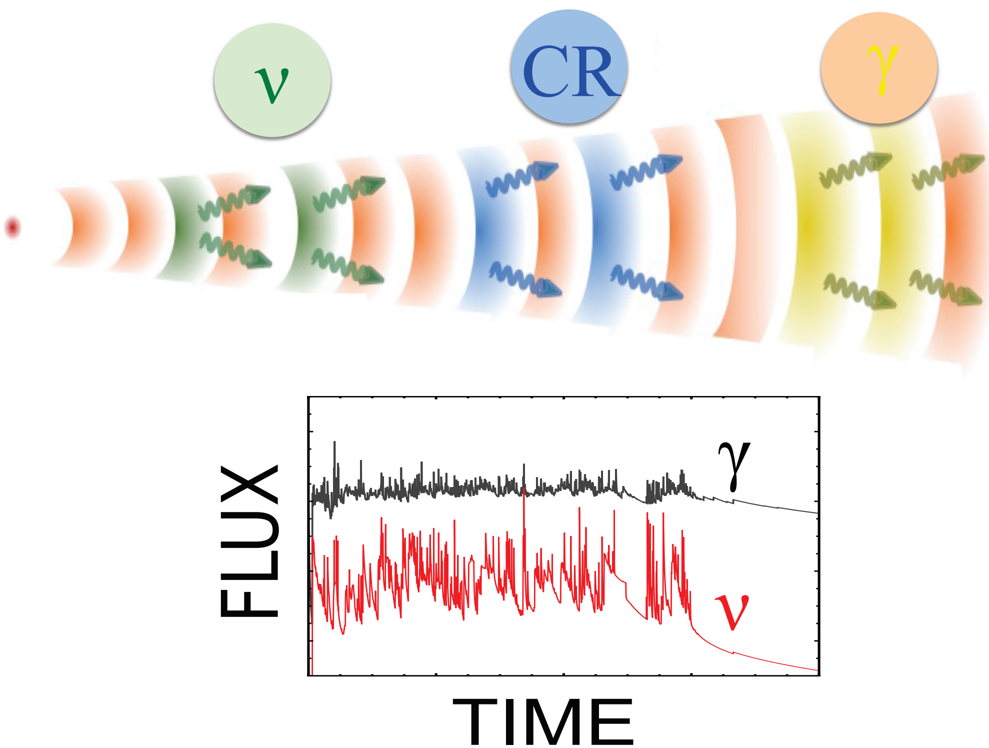
$$\pi^0 \rightarrow \gamma + \gamma$$



γ-ray energy $\varepsilon_\gamma \sim 0.5\ \varepsilon_\pi \sim 0.1\ \varepsilon_p$
• γ lower break energy $\varepsilon_\gamma^b \sim 5$ PeV
• γ maximum energy $\varepsilon_\gamma^{max} \sim 0.1\ \varepsilon_p^{max}$

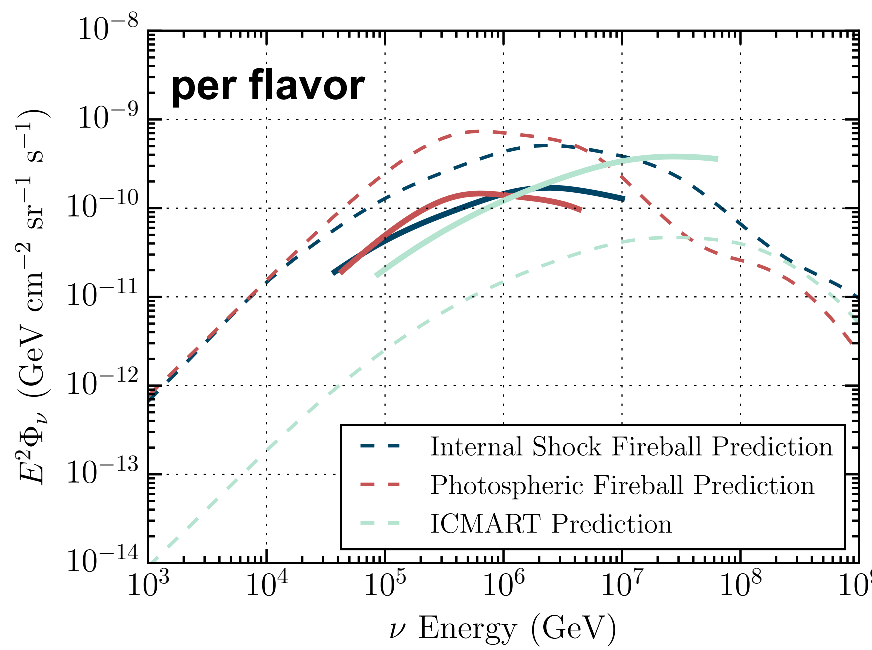
HE Neutrinos from GRBs: Constraints

Standard jet models as the dominant origin: excluded by multimessenger obs.
- Classical GRBs: constrained by stacking analyses **<~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}**
 ※ space- and time-coincidence (duration~30 s → background free)
- Low-luminosity GRBs and supernovae are allowed



Bustamante, Baerwald, KM, & Winter 15 Nature Comm.

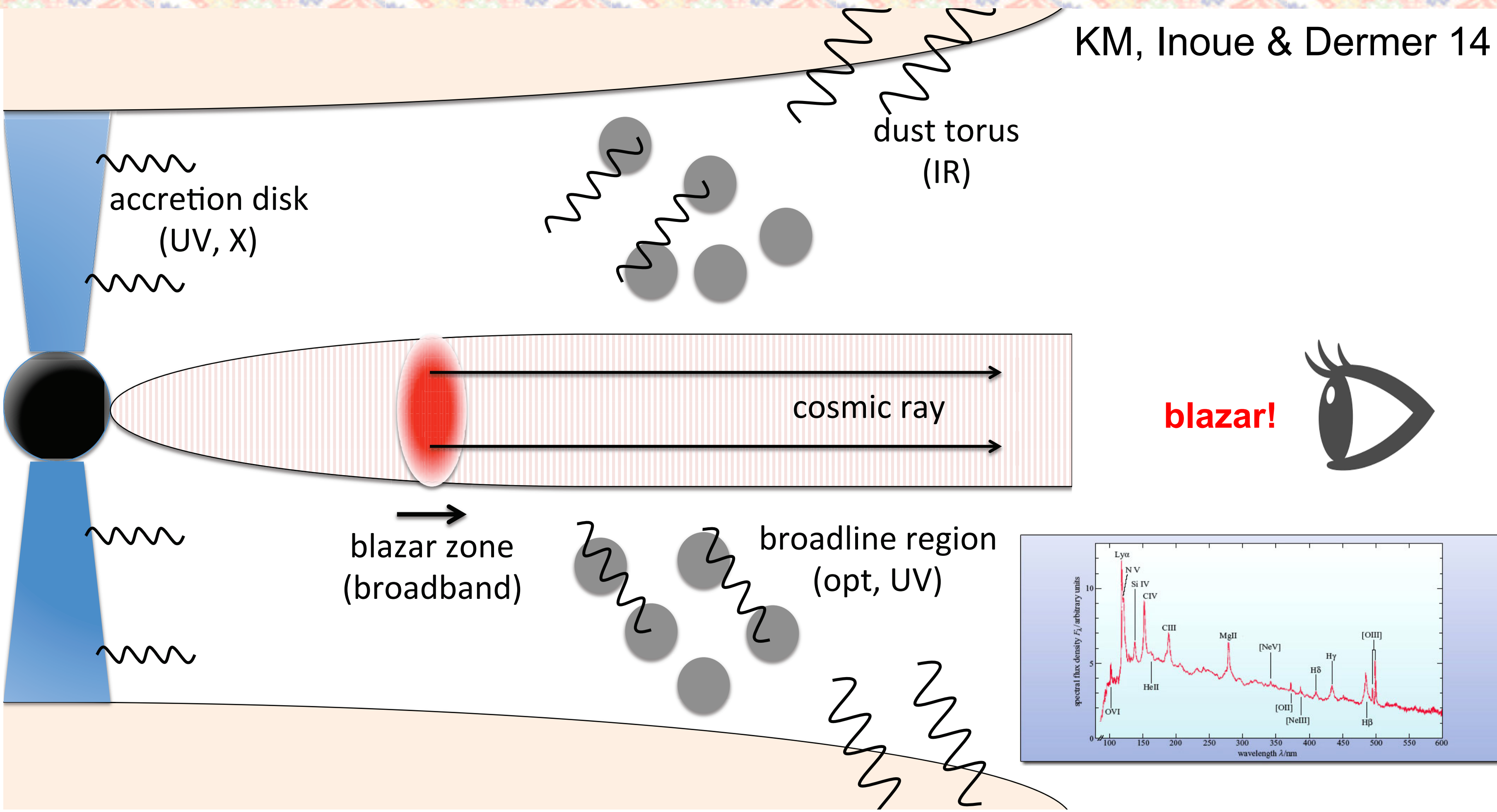
Classical GRBs (prompt)



IceCube 2017 ApJ

Photomeson Production in AGN Jets

KM, Inoue & Dermer 14



$E'^{b}_{\nu} \approx 0.05 E'^{b}_{p} \simeq 80 \text{ PeV } \Gamma_1^2 (E'_s/10 \text{ eV})^{-1}$ **inner jet photons**

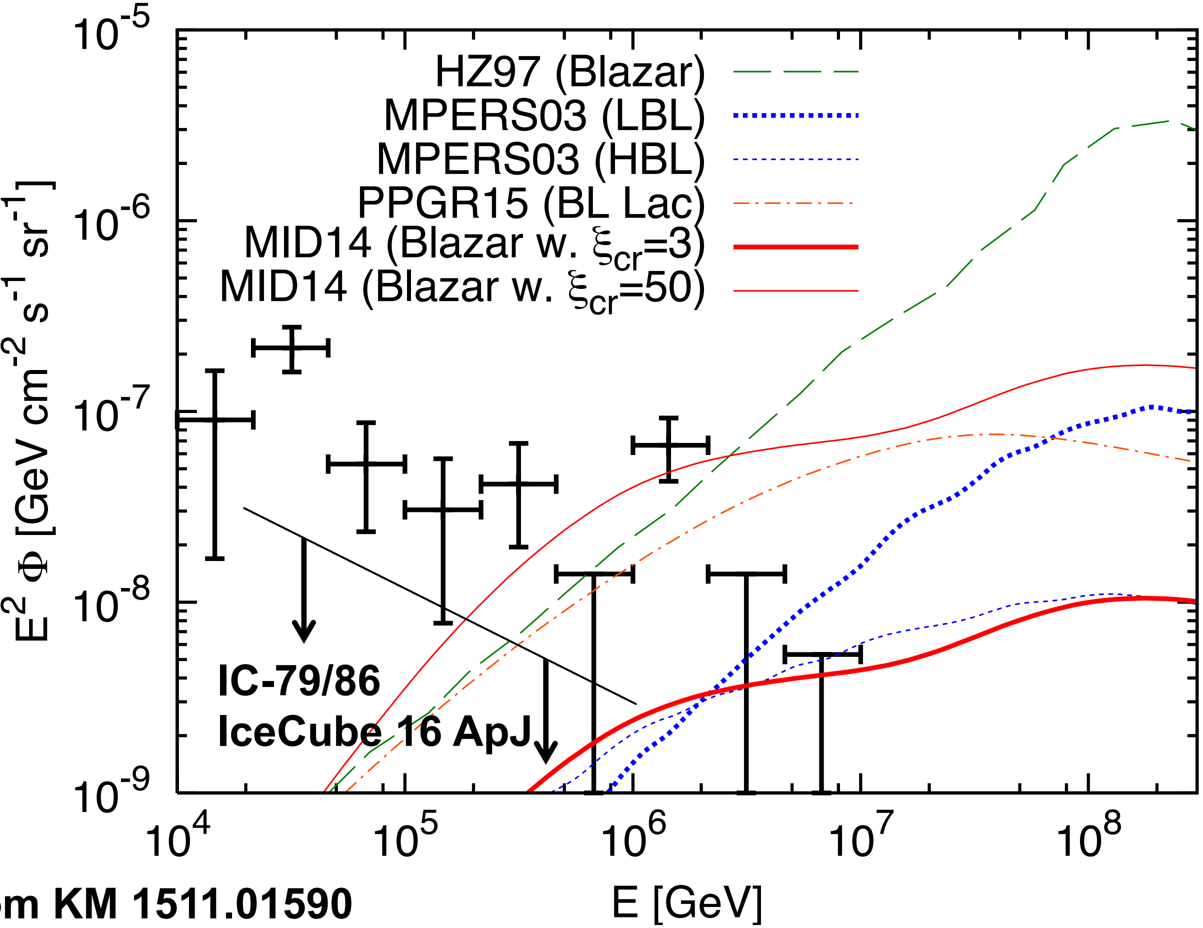
$E'^{b}_{\nu} \approx 0.05 (0.5 m_p c^2 \bar{\varepsilon}_{\Delta} / E'_{\rm BL}) \simeq 0.78 \text{ PeV}$ **BLR photons**

$E'^{b}_{\nu} \simeq 0.066 \text{ EeV} (T_{\rm IR}/500 \text{ K})^{-1}$ **IR dust photons**

$p\gamma \rightarrow \Delta^{+} \rightarrow \pi + N$

HE Neutrinos from AGN Jets: Constraints

Standard simplest jet models as UHECR accelerators: many constraints…
- Blazars: power-law CR spectra & known SEDs→ hard spectral shape



leptonic w, neutrino norm,
BL Lacs + FSRQs

lepto-hadronic w. γ-ray norm.
BL Lacs (w.o. external fields)

leptonic w. UHECR norm.
BL Lacs + FSRQs

from KM 1511.01590

HE Neutrinos from AGN Jets: Constraints

Standard simplest jet models as UHECR accelerators: many constraints…

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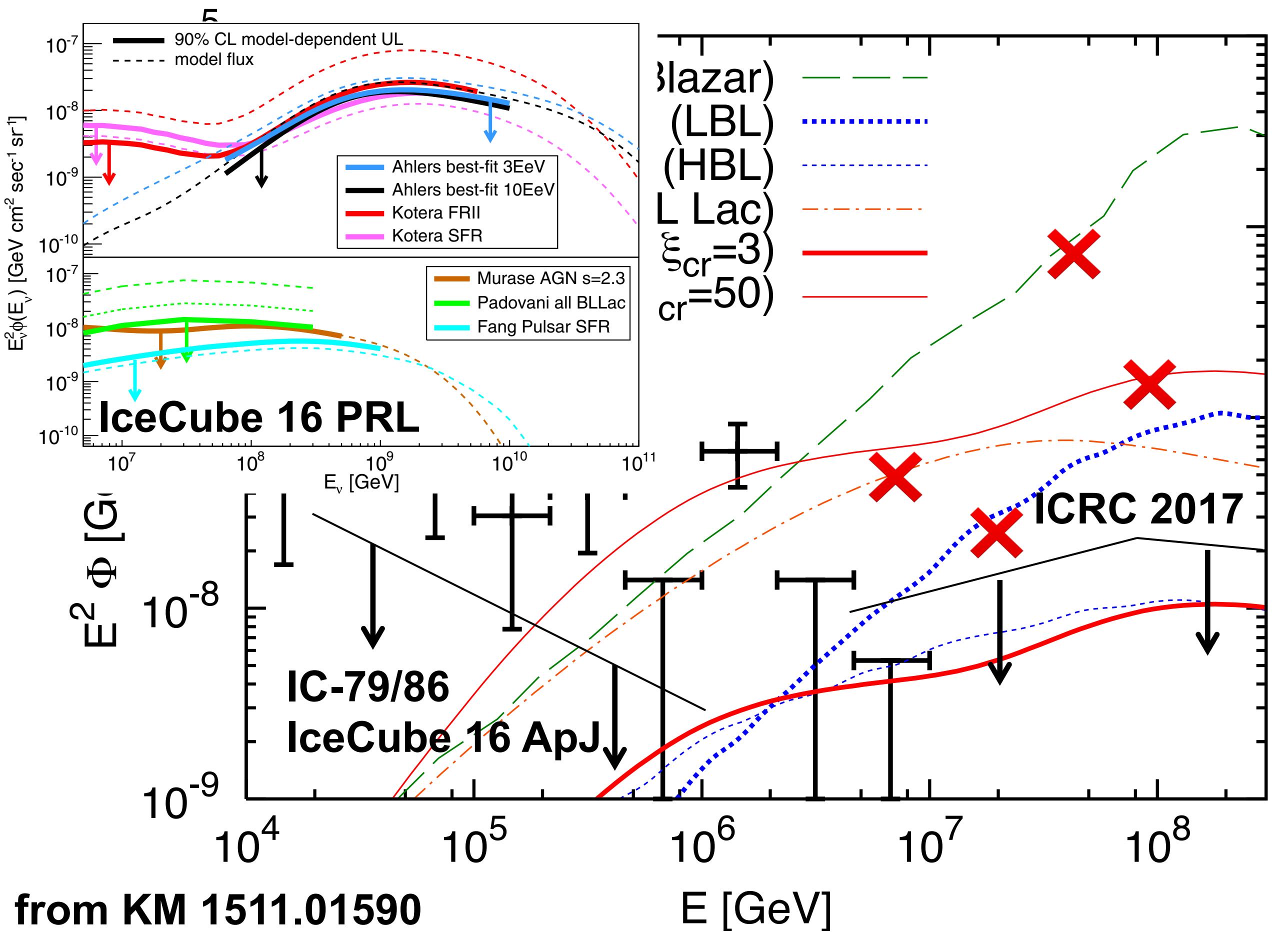
  IceCube 9-yr EHE analyses give a limit of $<10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} at 10 PeV



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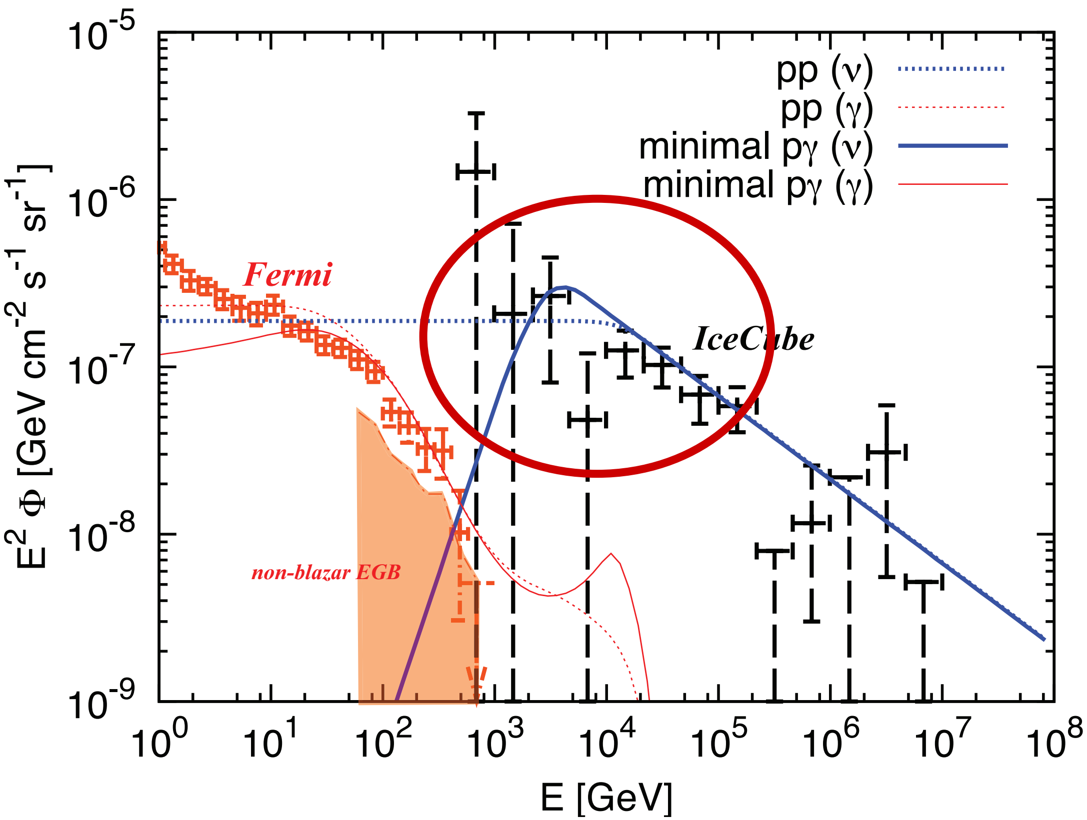
BL Lacs + FSRQs

lepto-hadronic w. γ-ray norm.
BL Lacs (w.o. external fields)

leptonic w. UHECR norm.
BL Lacs + FSRQs
(This model is still OK!)

Neutrinos May Come from Dense Environments

- If γ-ray transparent → contradiction with the gamma-ray and CR data whatever the mechanism is a pp or pγ process



Multimessenger approach poses questions for cosmic neutrinos

HIGH ENERGY The IceCube Neutrino Observatory in Antarctica has detected high-energy cosmic neutrinos, but the corresponding high-energy gamma-rays from their source regions have not been found by the Fermi Gamma-ray Space Observatory.

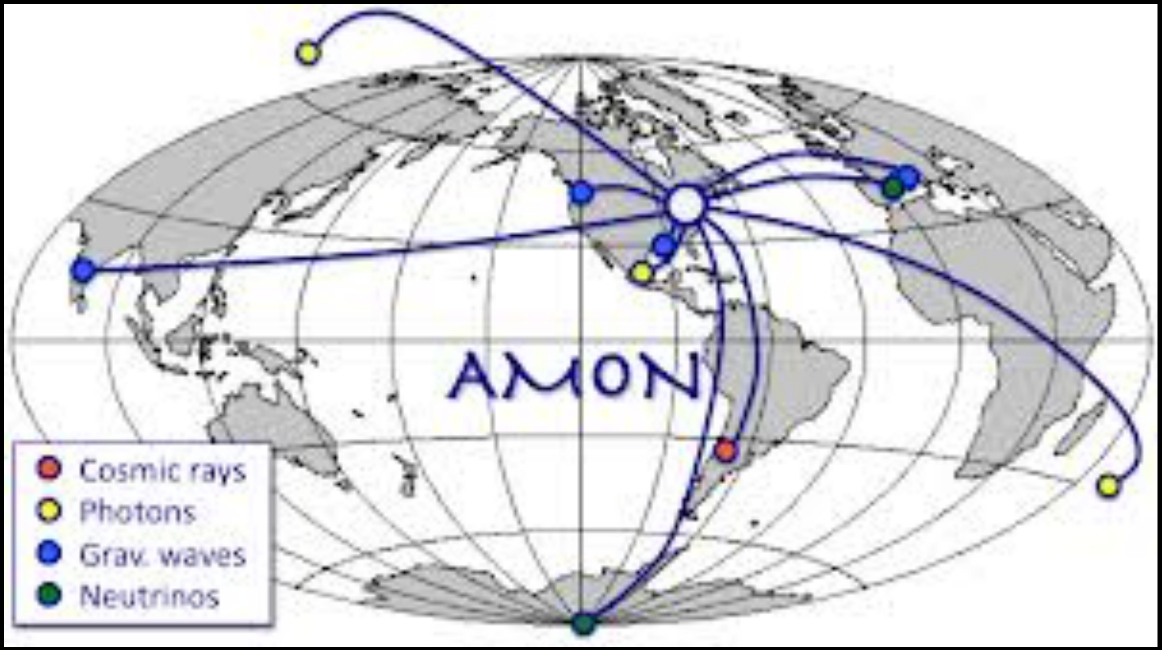
The high-energy cosmic neutrinos are believed to originate in supermassive black holes and some gamma-ray bursts. These processes should produce gamma-rays detectable by Fermi. Looking at both detectors – a multimessenger approach – indicates that there is some unknown "hidden accelerator" process producing neutrinos without gamma radiation, or something in the source is absorbing gamma-rays. "We found that that the suppression of high-energy gamma-rays should naturally occur when neutrinos are produced via proton–photon interactions," said Kohta Murase of Penn State University, lead author of the paper in *Physical Review Letters*.
http://bit.ly/1Szr2eT

KM, Guetta & Ahlers 16 PRL

High-energy neutrinos come from γ-ray dark sources?

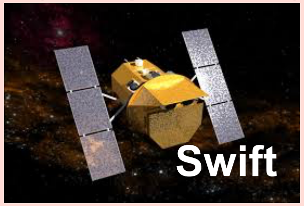
Unexpected but in pγ scenarios γ rays are naturally masked by the γγ process

Transients?



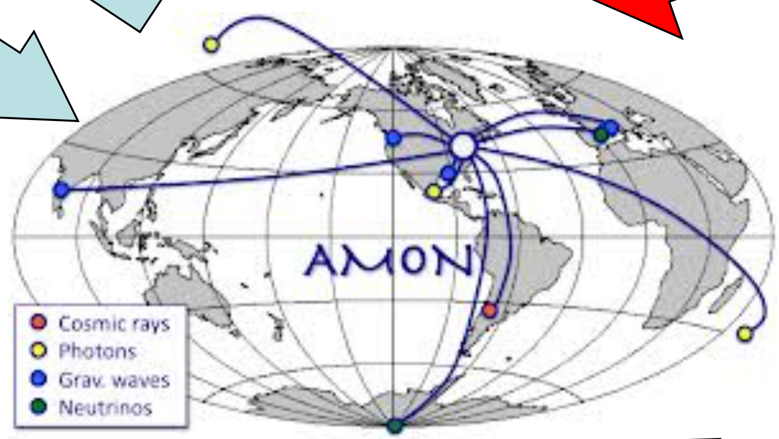
Real-Time Neutrino Alerts

Light (elemag)

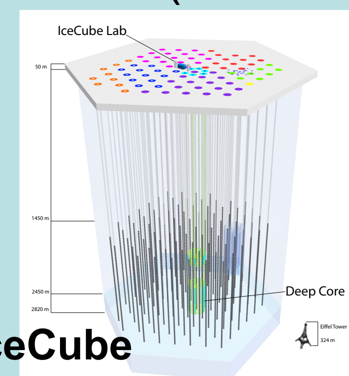


DO NOT miss interesting ν & GW events!

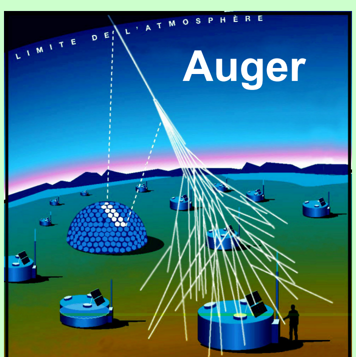
Astrophysical Multimessenger Observatory Network (AMON)
- pipelines to send "public" alerts
- ν–γ subthreshold events (in near future)



Neutrino (weak force)



Cosmic-ray
(strong force)



PENNSTATE
1855

Gravitational wave
(gravity)

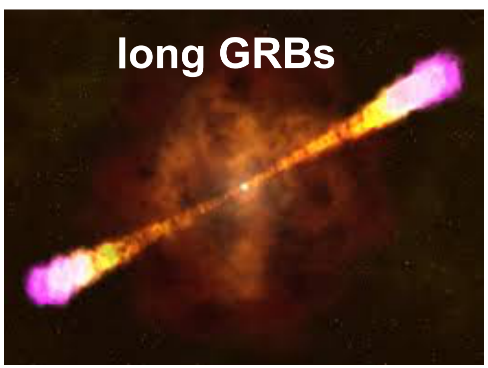
Neutrino Transient Sources?

Remember: UHECR accelerators may be transients

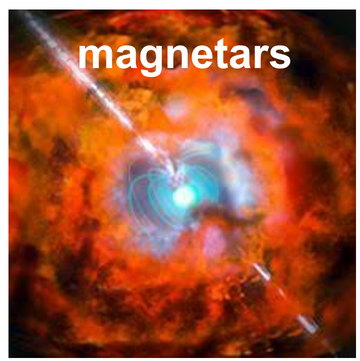
$$L_B \equiv \epsilon_B L \gtrsim 2 \times 10^{45} \frac{\Gamma^2 {E_{20}}^2}{Z^2 \beta} \text{ erg s}^{-1}$$

PeV-EeV ν

PeV-EeV ν



TeV-PeV ν (prompt)
EeV ν (afterglow)
GW source



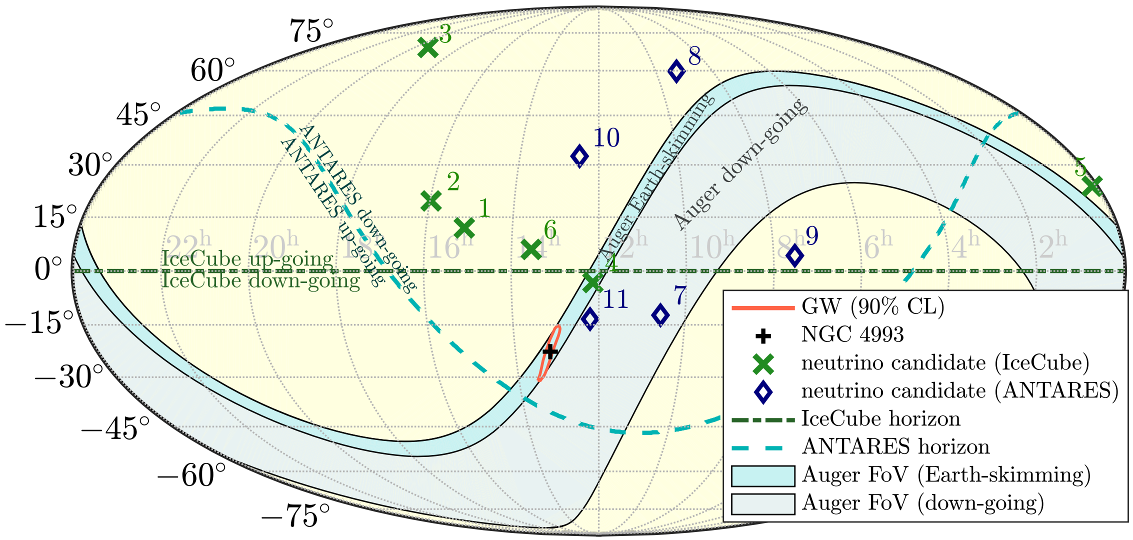
EeV ν
GW source

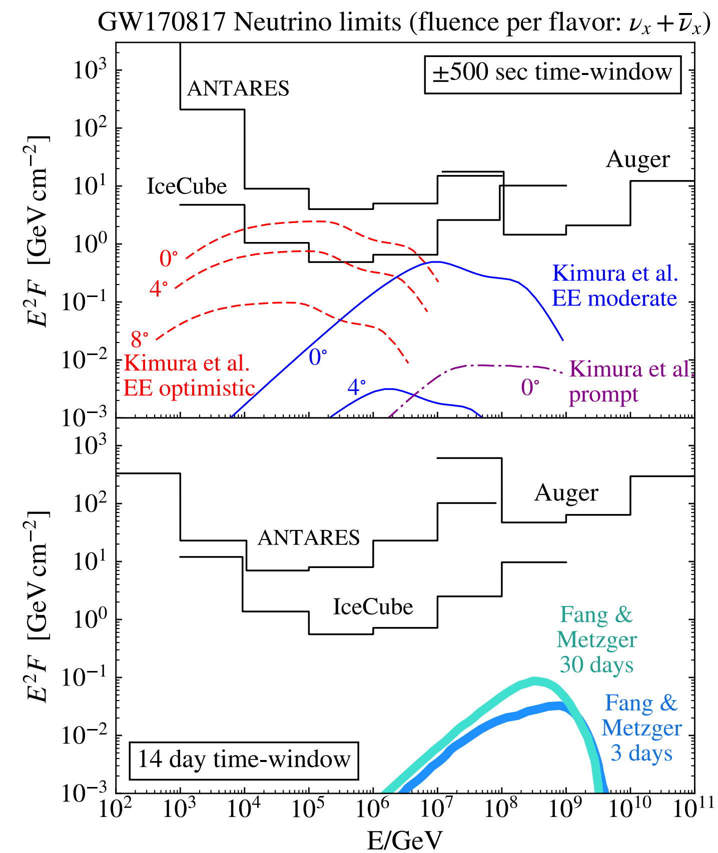
TeV-EeV ν
GW source

Neutrinos Coinciding w. Gravitational Waves?

GW170817: supporting the NS merger origin of short GRBs

ANTARES, IceCube, Auger, & LIGO-Virgo ApJL 17





theoretical models

short GRB jets (Kimura, KM, Meszaros & Kiuchi 17)

magnetar in the ejecta (Fang & Metzger 17)

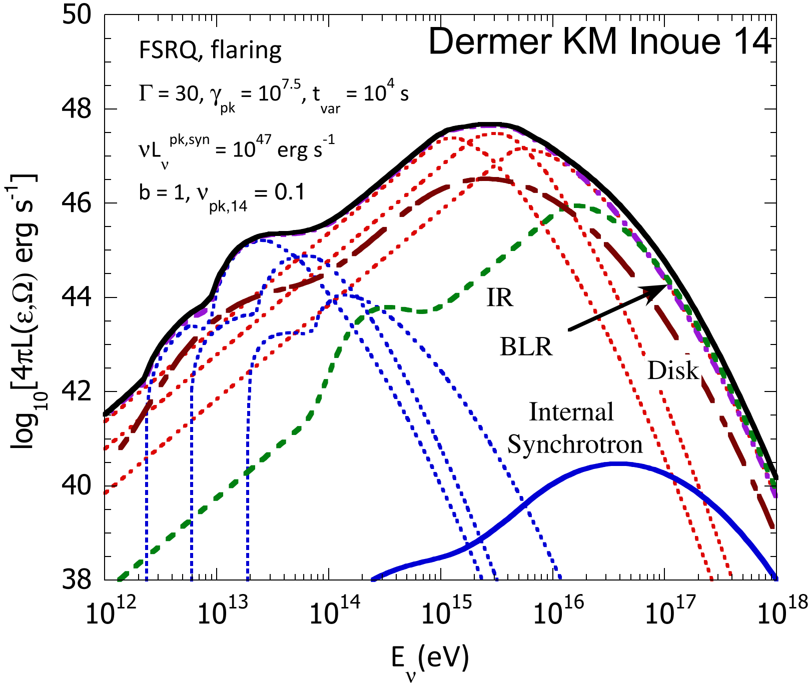
(see also KM, Zhang & Meszaros 09)

- GW170817: off-axis (~30 deg): the models are still consistent
- On-axis events coinciding w. GW signals could be seen

Blazar Flares?

Flares: NOT well-constrained: good chances to see them even if subdominant

(ex. KM & Waxman 16)

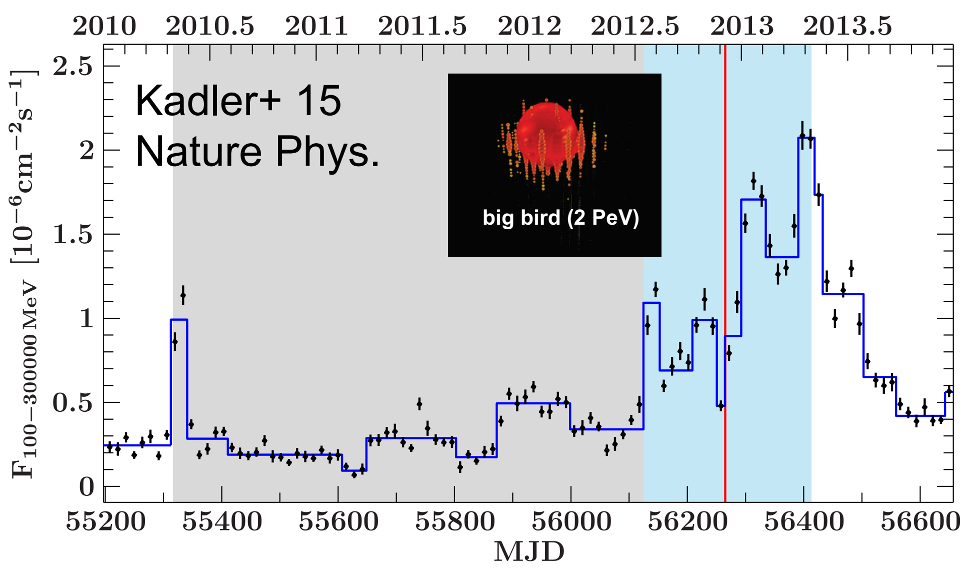


neutrino flares: even brighter

$f_{p\gamma} \propto L_\gamma$

$L_{cr} \propto L_\gamma$ ⇒ $L_\nu \propto L_\gamma^2$

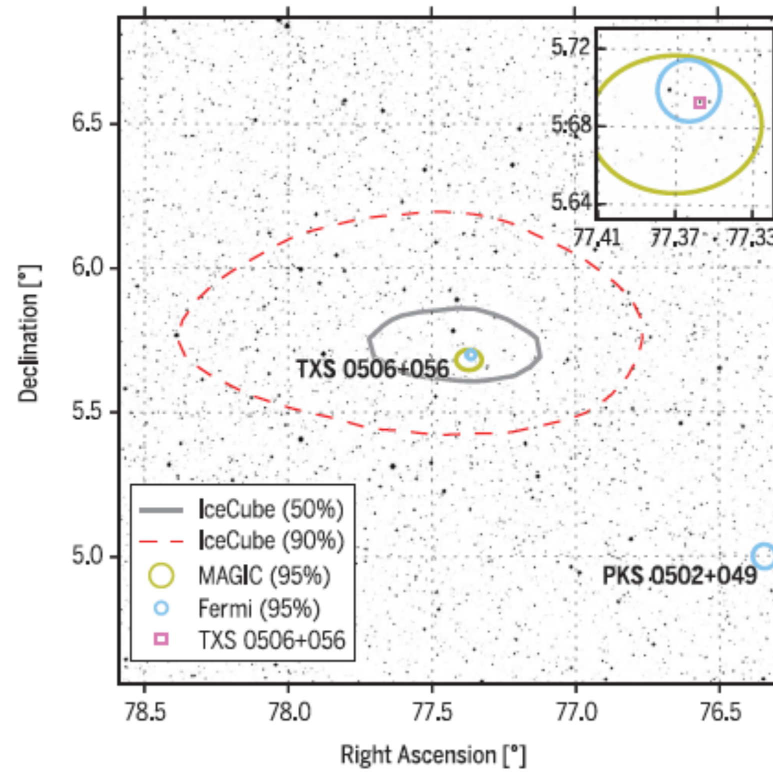
Association between 2 PeV event and FSRQ PKS B-1424-418 (z=1.522)
Low significance (~2σ)



IceCube 170922A & TXS 0506+056

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```

IceCube 2018 Science

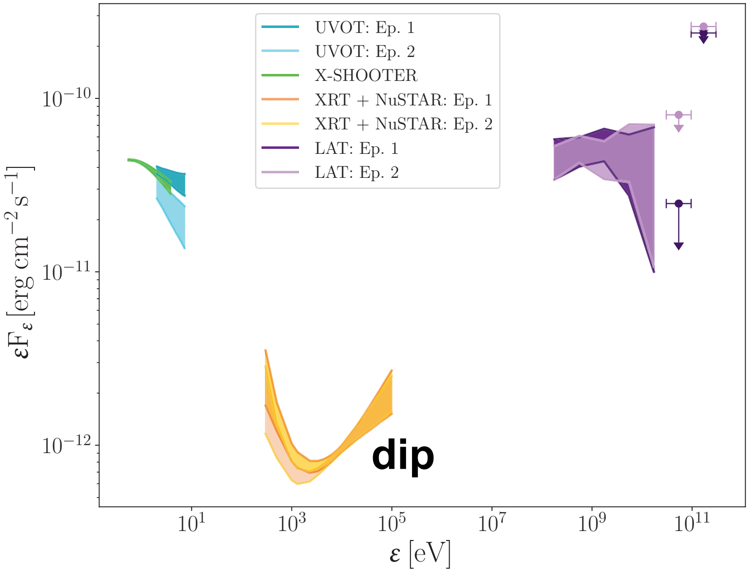


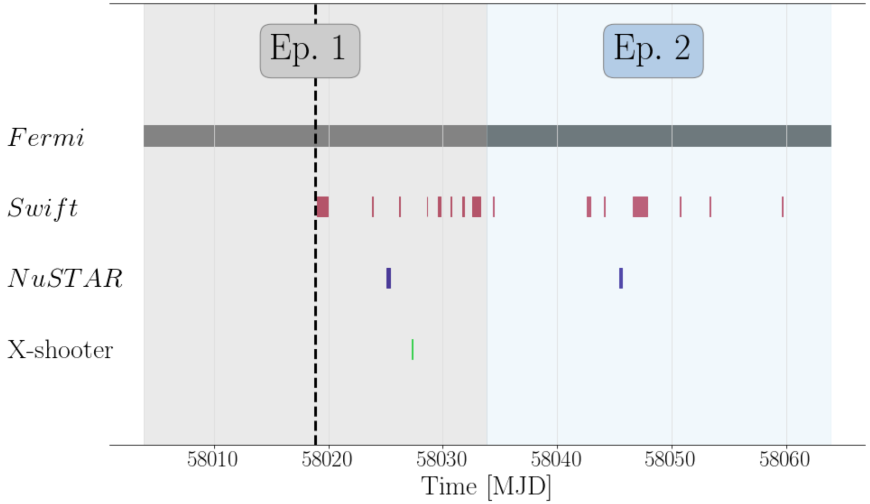
- EHE alert pipeline: from the Chiba group
- Automatic public alert: through AMON
  Track w. E_{ν} ~ 300 TeV
  (ang. res. < 1 deg)
- Kanata -> Fermi analysis (Tanaka et al.)
  ATel #10791 (Sep/28/17)

- X-ray observations were first reported by the AMON team from Penn State
- Swift observations (Keivani et al.)
  GCN #21930, ATel #10942 (Sep/26/17)
- NuSTAR observations (Fox et al.)
  ATel #10861 (Oct/12/17)

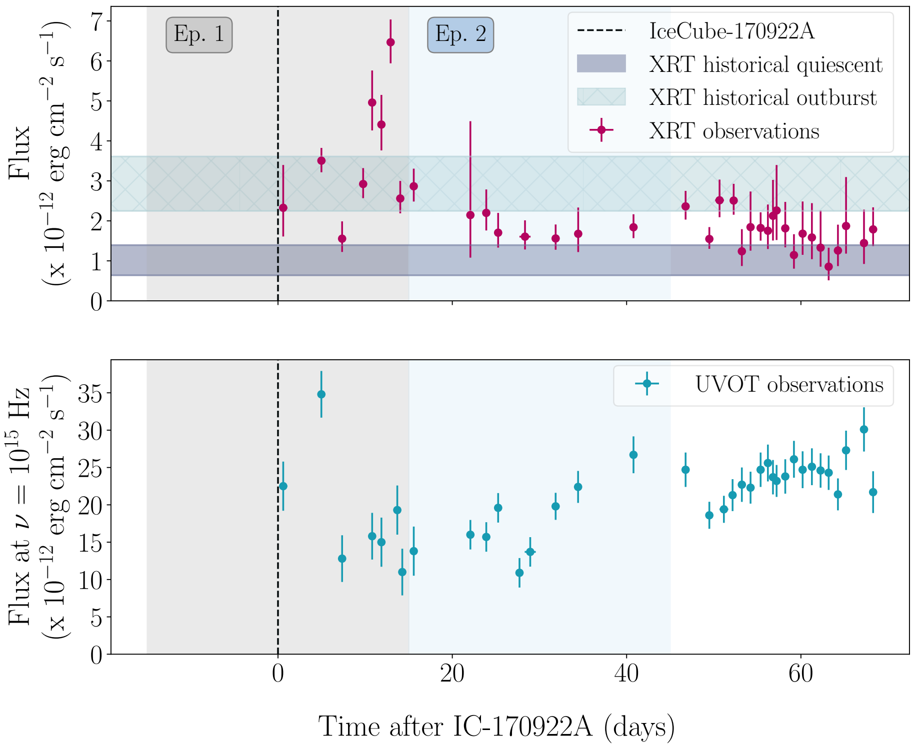
Our Observations of TXS 0506+056

Quasi-simultaneous SED





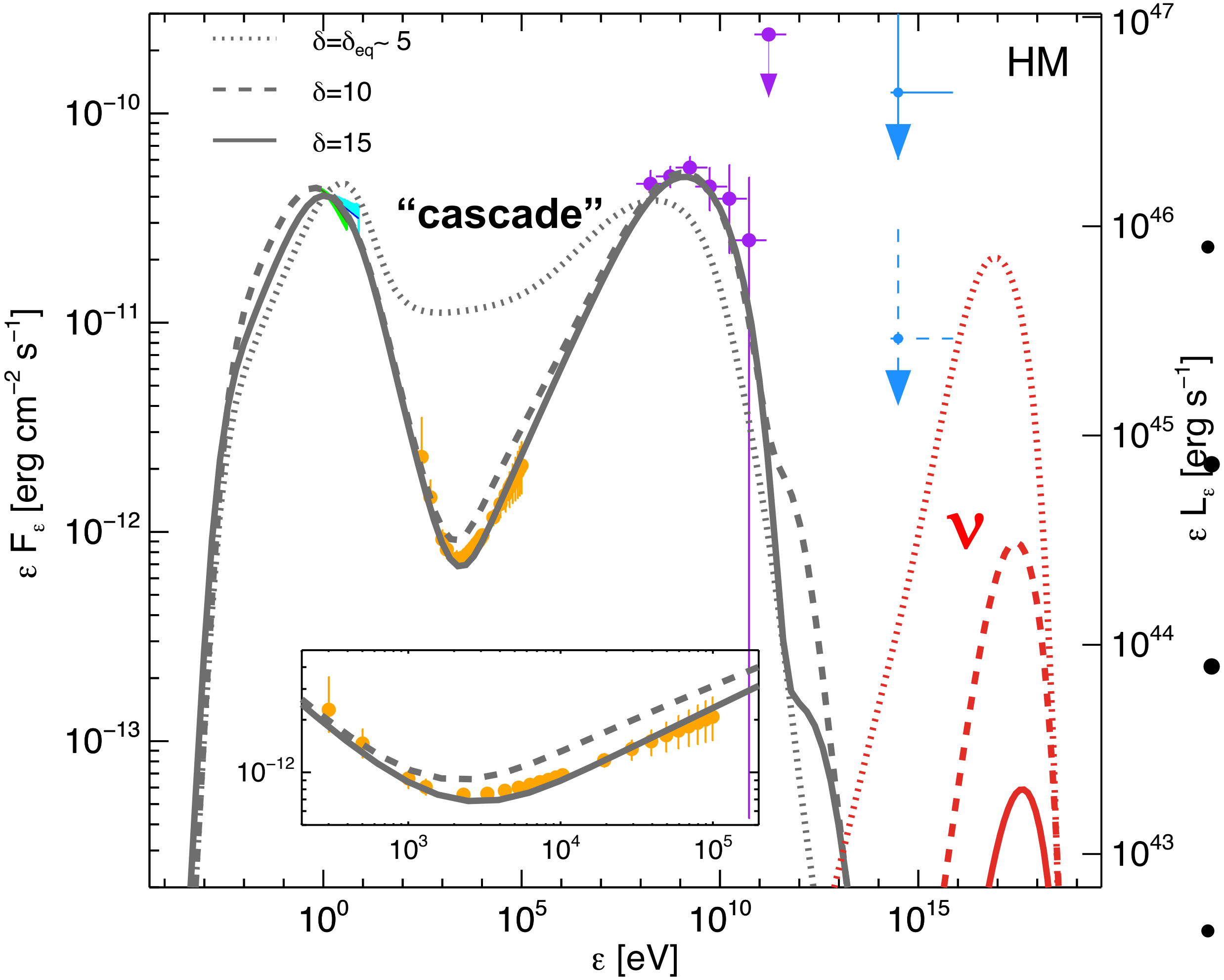
XRT & UVOT light curves



Keivani, KM, Petropoulou, Fox et al. 2018

TXS 0506+056 SED Modeling: Hadronic

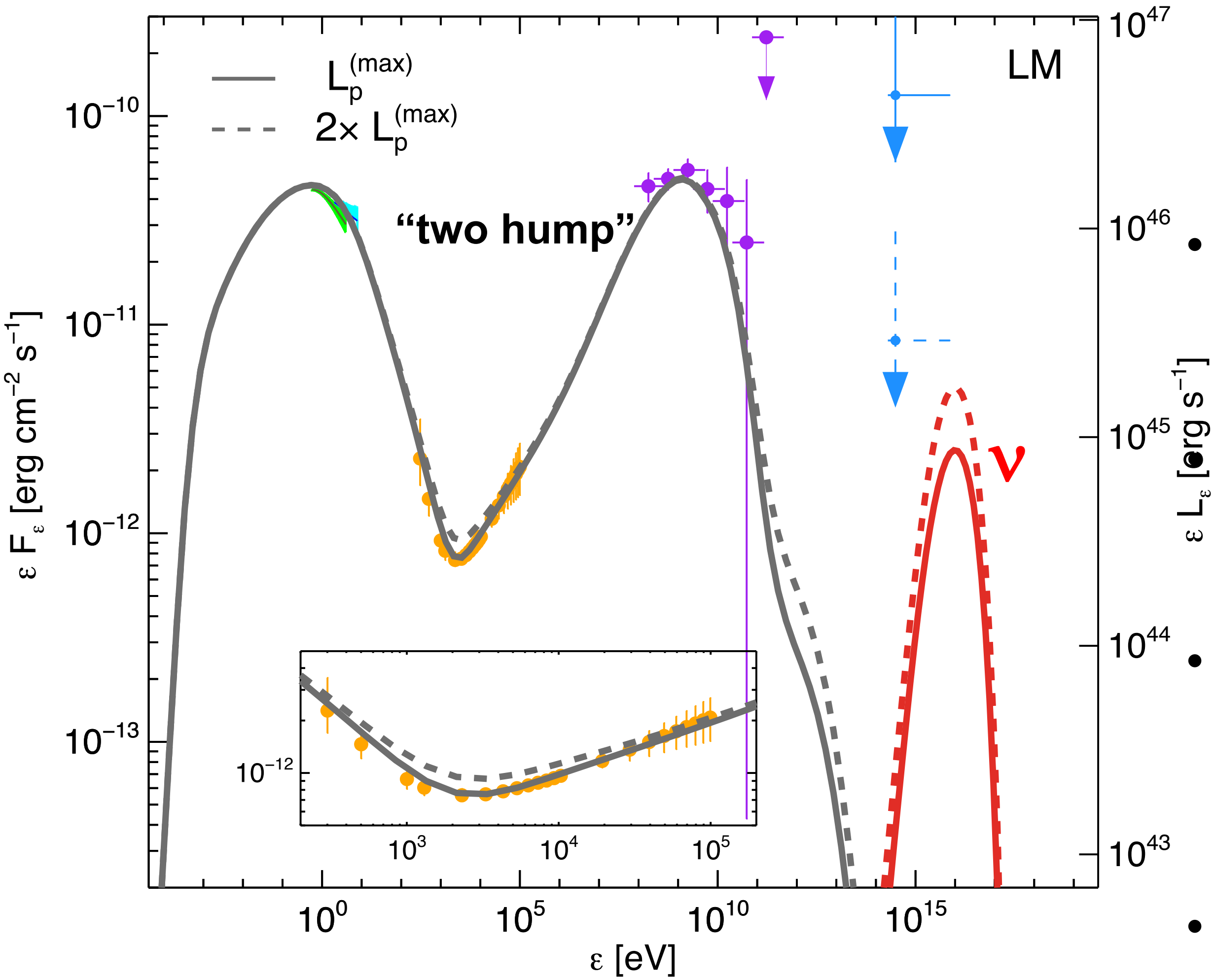
Keivani, KM, Petropoulou, Fox et al. 2018



- Swift-UVOT/X-SHOOTER, Swift-XRT/NuSTAR, and Fermi-LAT data
- UVOT/X-SHOOTER $\nu_{pk}<10^{14}$ Hz (ISP - LSP)
- γ = π-induced cascade
  $F_\nu \sim F_\gamma$: ruled out
- γ = p-syn. from UHECRs
  very low F_ν at 0.1-1 PeV
  $P_p < 10^{44}$ erg/s
- IC-170922A event CANNOT be explained

TXS 0506+056 SED Modeling: Leptonic

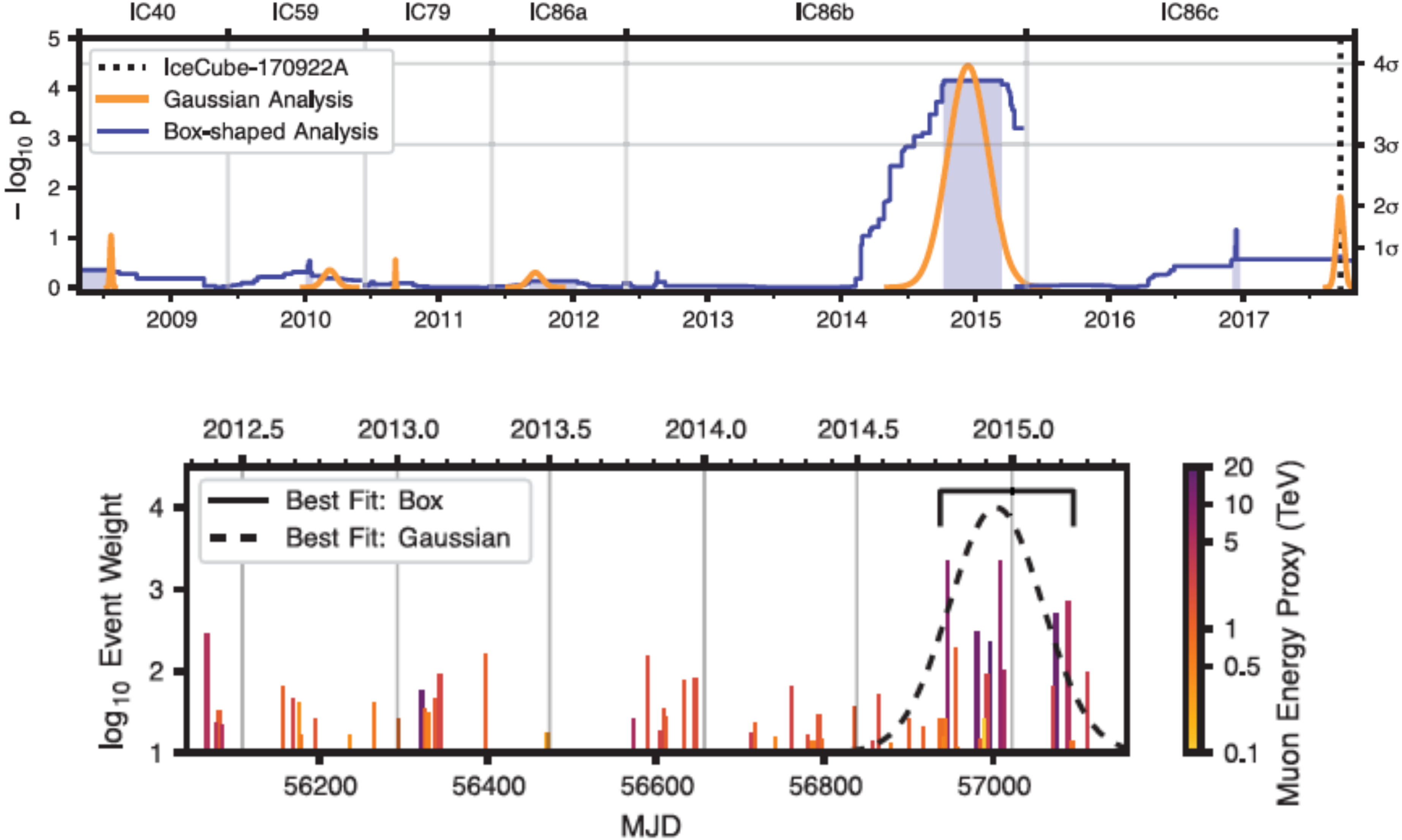
Keivani, KM, Petropoulou, Fox et al. 2018



- Swift-UVOT/X-SHOOTER, Swift-XRT/NuSTAR, and Fermi-LAT data
- UVOT/X-SHOOTER $\nu_{pk}<10^{14}$ Hz (ISP - LSP)
- Leptonic scenario γ = external IC emission
- Upper limits on ν & CR $F_\nu < (1\text{-}2)\text{x}10^{-12}$ erg/cm^2/s $P_p < 10^{45}$ erg/s
- $<N_\nu>\sim 0.01\text{-}0.03$ for a duration of $T=10^7$ s ~< 1-3 % to see 1 event

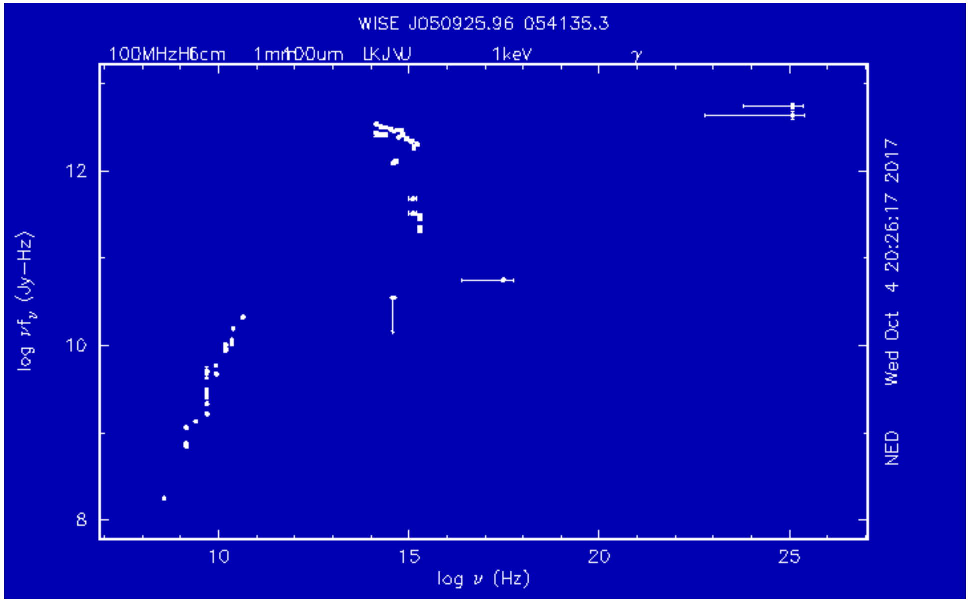
2014-2015 Neutrino Flare

IceCube 2018 Science

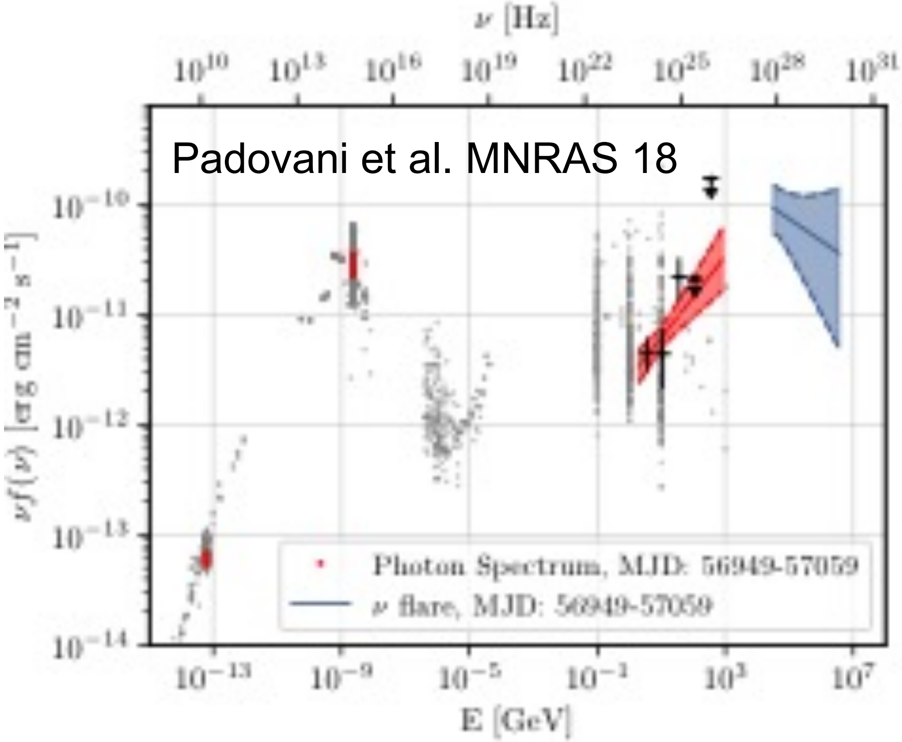


Observations of TXS 0506+056

Archival SED

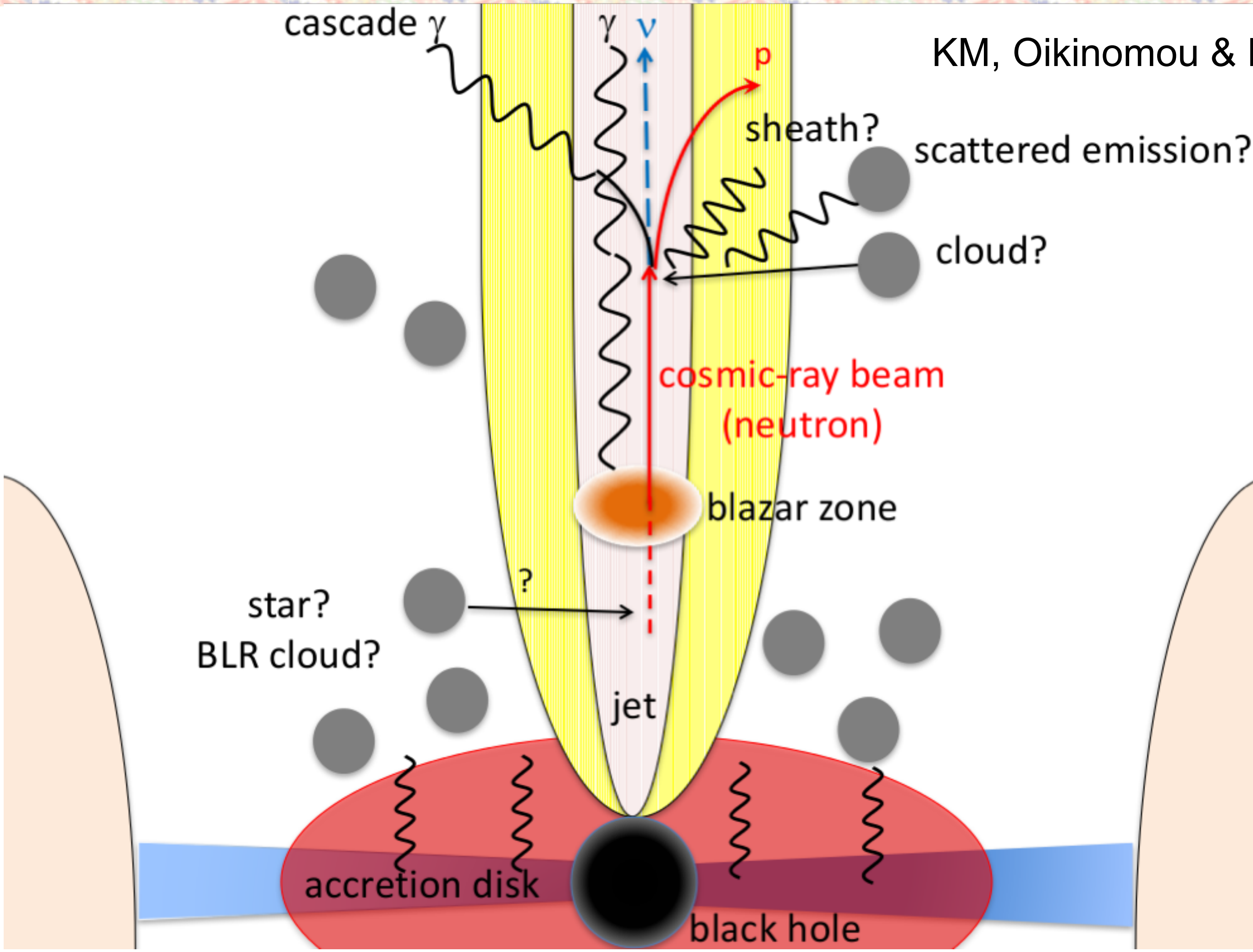


X-ray flux ~ 10^{-12} erg/cm^2/s
γ-ray flux ~ a fewx10^{-11} erg/cm^2/s



No indication of strong X-ray enhancement

How to Mask X rays?

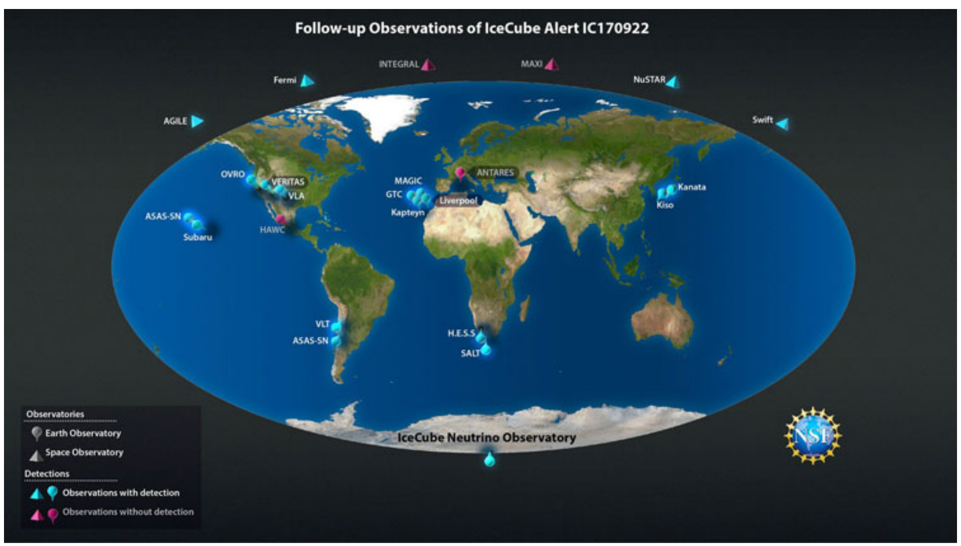


KM, Oikinomou & Petropoulou 18

- Not easy (cascade results from energy conservation)
- 1. de-beaming 2. fine tuning in the core region 3. photoelectric absorption

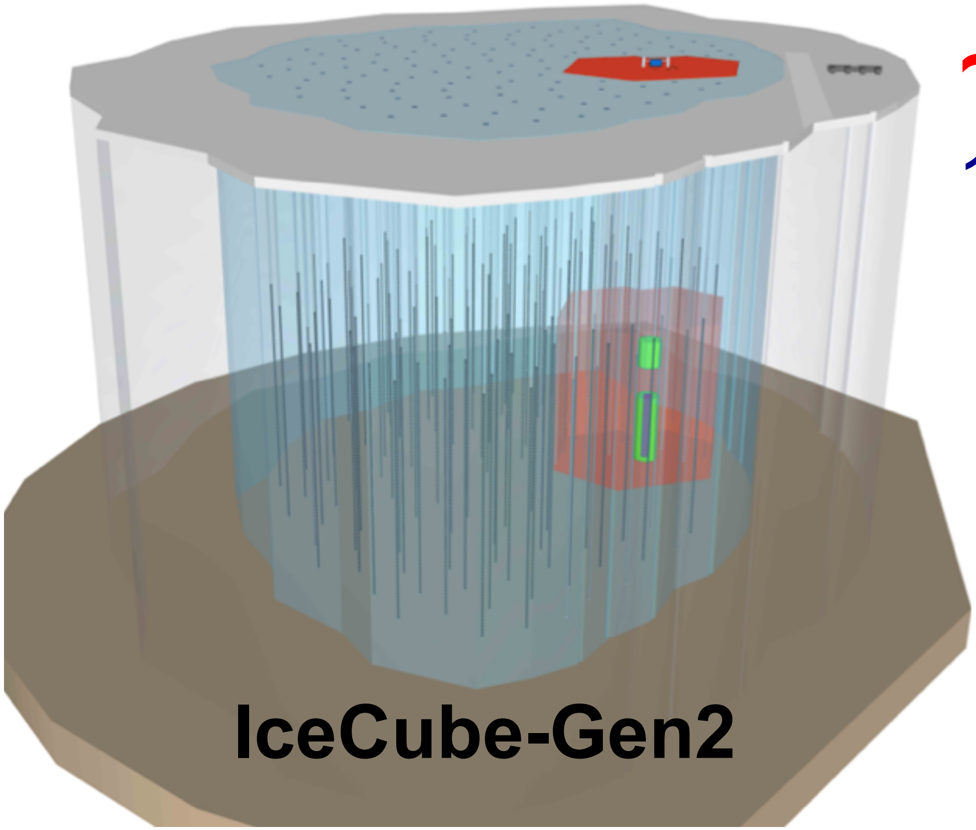
Implications

- Still ~3-4σ so it could be merely a chance…
  But possible to detect bright transients like this blazar flare even if the sources are sub-dominant in the diffuse ν flux
- If the association is physical:
  A. If the single-zone scenario is correct, robust cascade bounds imply that:
     Probability to explain 1 event is <~a few %
     Ironically, the leptonic scenario is supported by neutrinos
  B. Multi-zone or more complicated models may be required



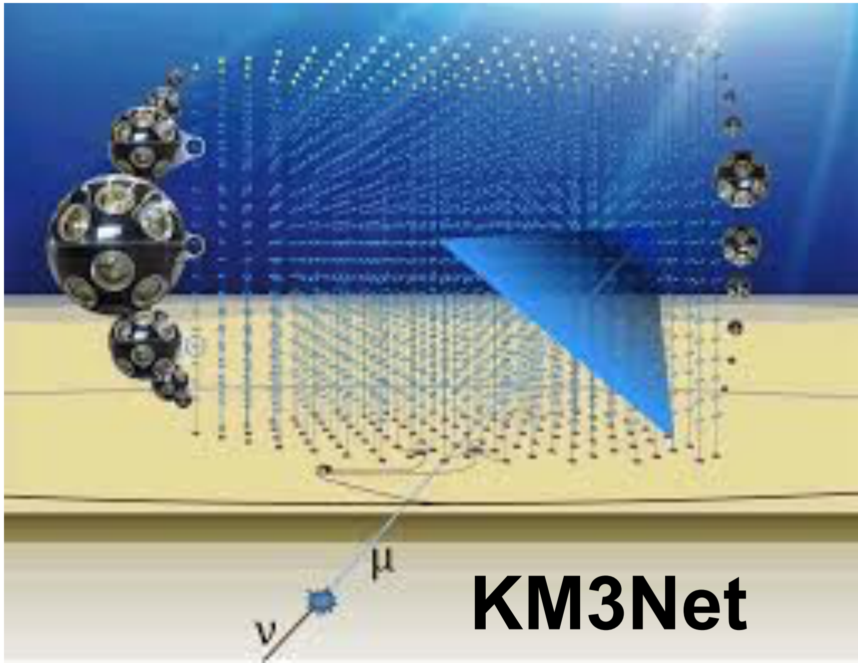
Demonstration of the feasibility of ν-triggered multi-messenger campaigns

Future Detectors



$\sim$10 km^3

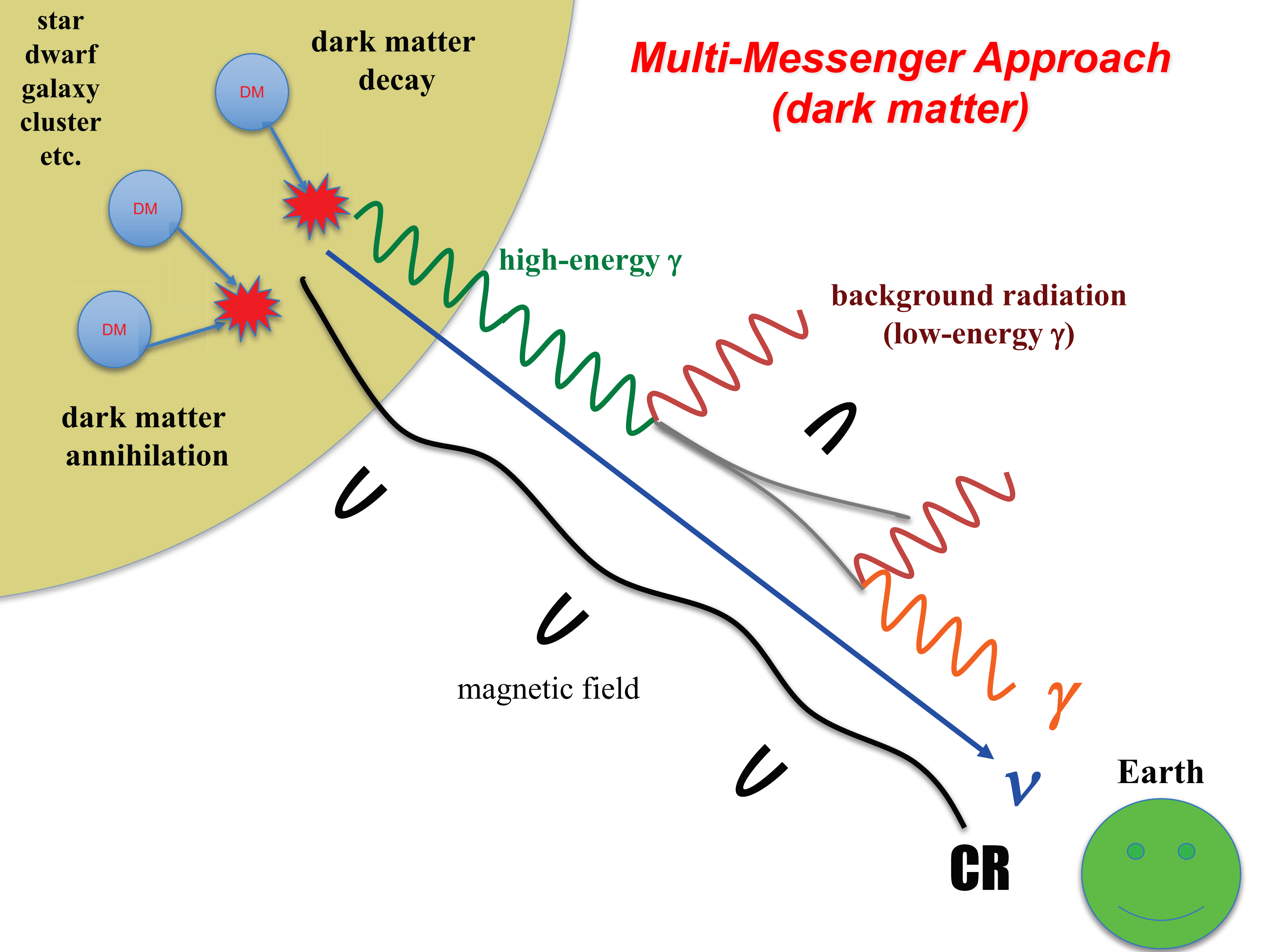
120m→240m spacing



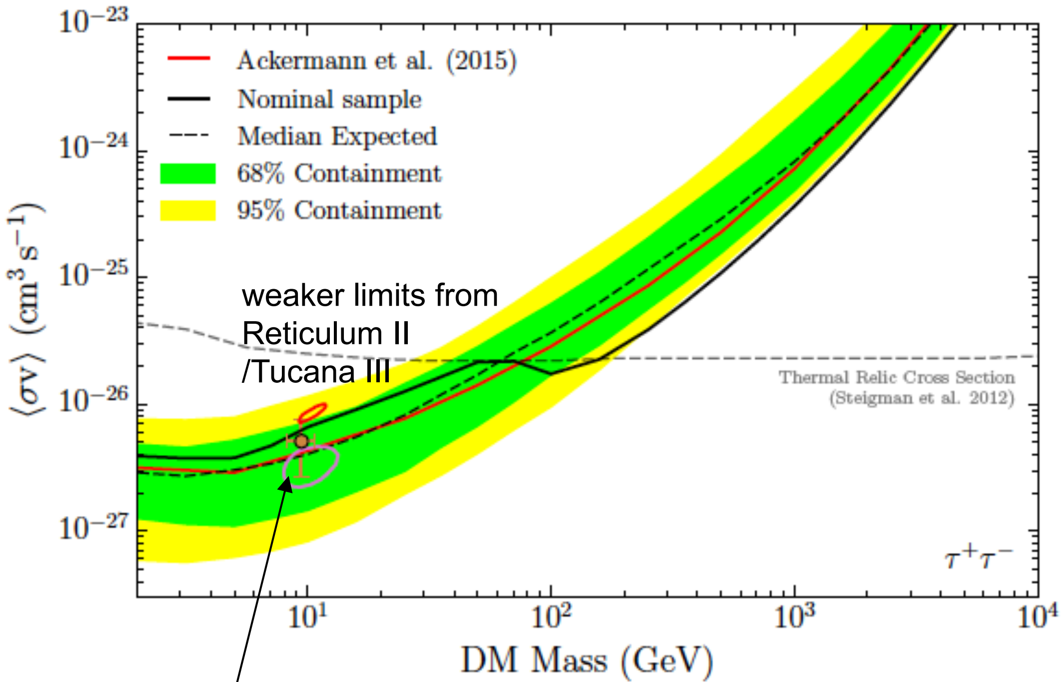
$\sim$1 km^3

better angular resolution

BSM Search


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
CR
Earth

Gamma-Ray Limits on Annihilating Dark Matter

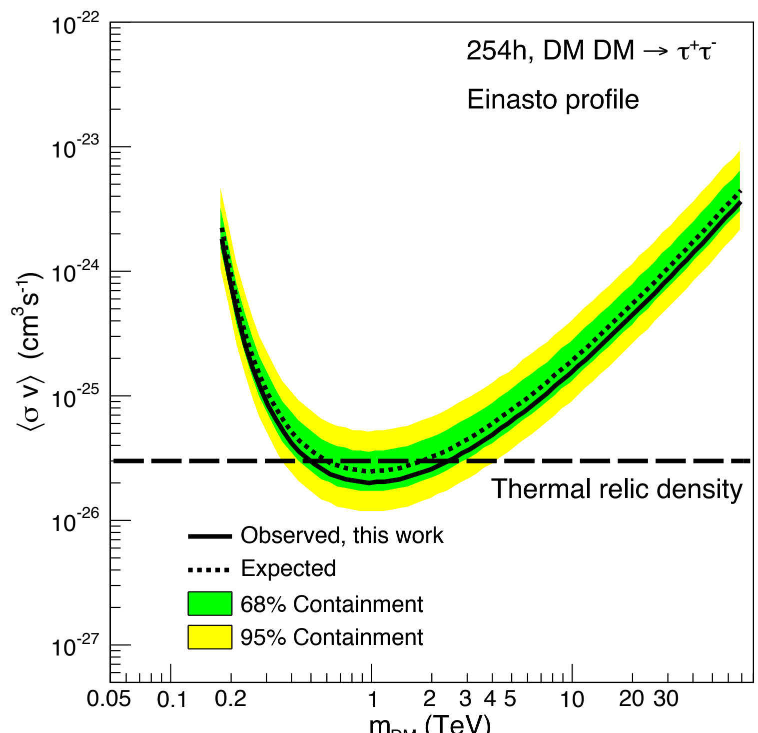


Dwarf & dwarf candidates

45 sources w. 6 year LAT data

Fermi Collaboration 17 ApJ

2σ best-fit regions for
Galactic center excess
(not excluded by dwarf analyses)

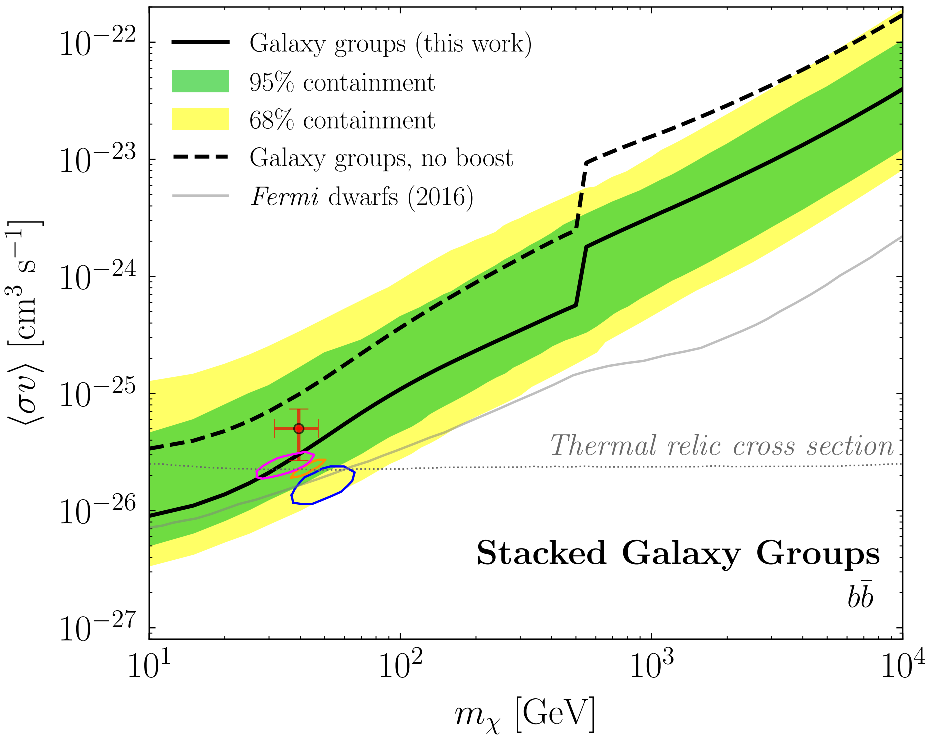


Galactic center region

inner 300 pc w. 10 year data

HESS Collaboration 16 PRL

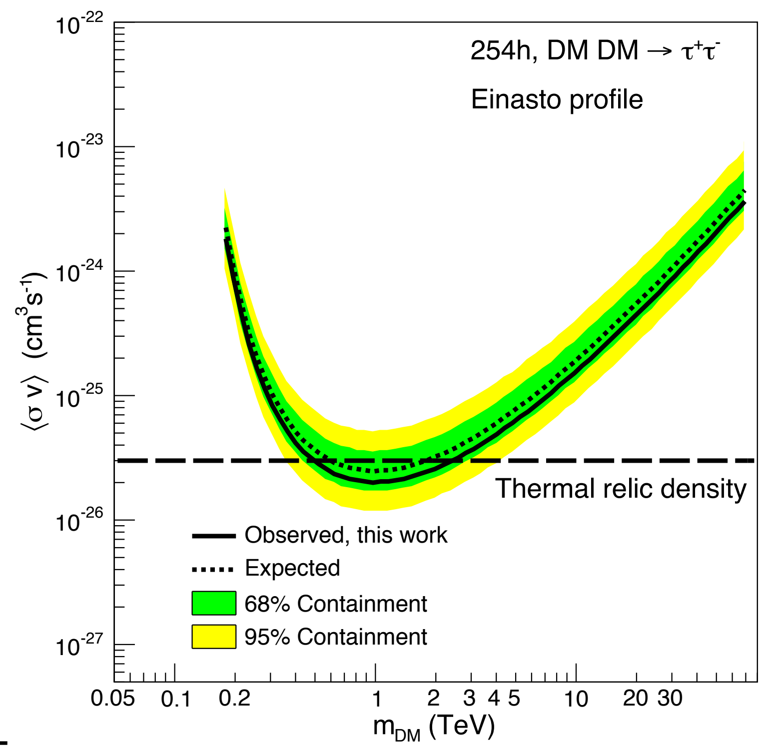
Gamma-Ray Limits on Annihilating Dark Matter



Galaxy groups & clusters

~500 sources out to z~0.03

Mishra-Sharma et al. 17 PRL



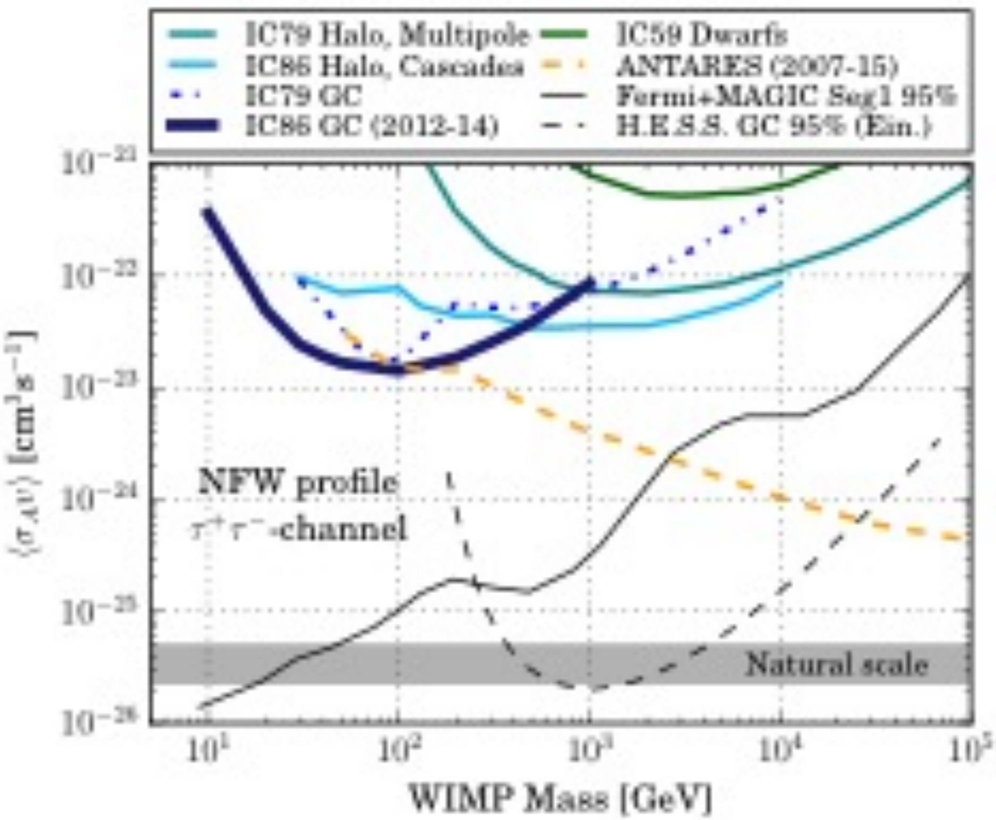
Galactic center region

inner 300 pc w. 10 year data

HESS Collaboration 16 PRL

CR & ν Limits on Annihilating Dark Matter

IceCube Collaboration EPJ 17

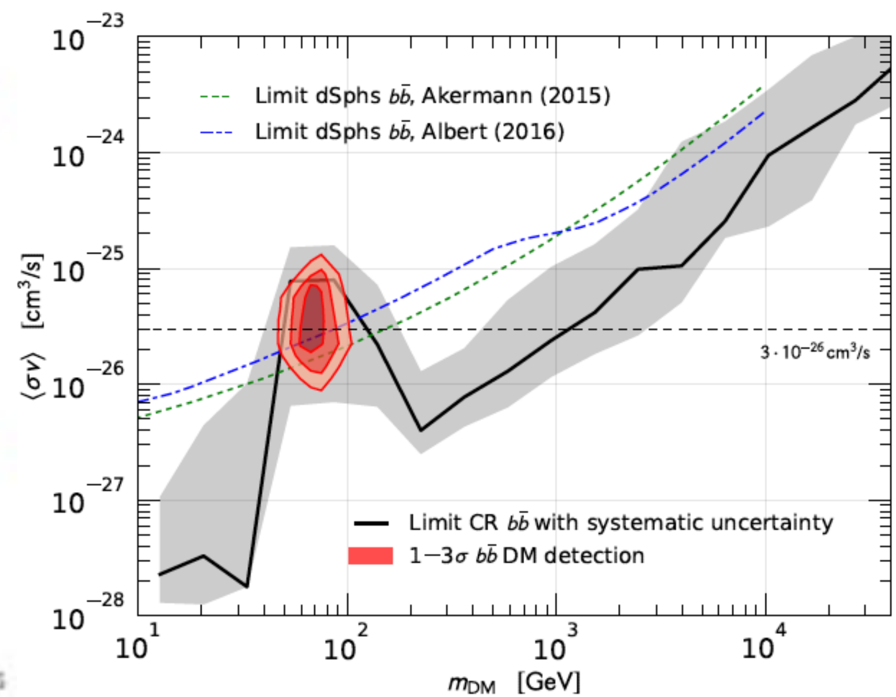


ν **from Galactic halo and center**

complementary to γ-ray limits

Cuoco et al. PRL 17
Cui et al. PRL 17

DM+DM → b+bbar



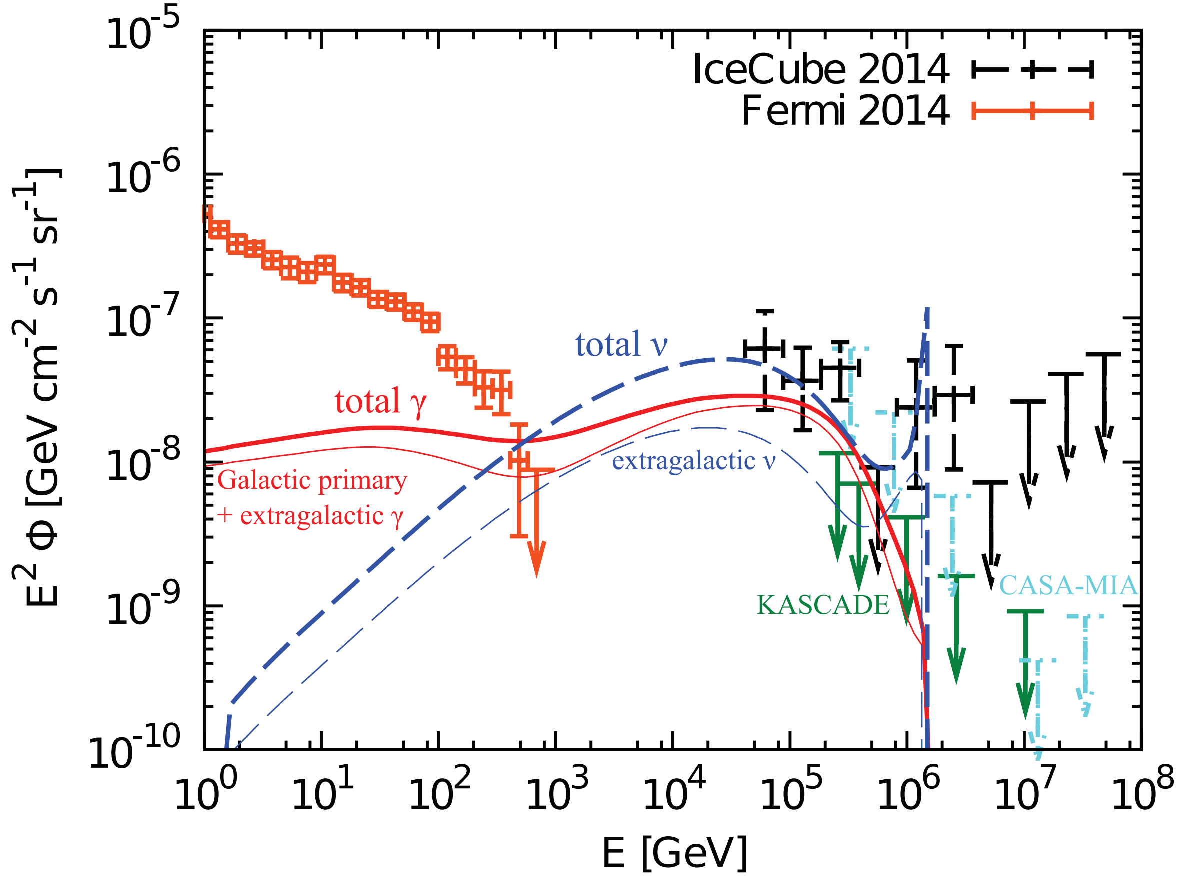
anti-proton w. AMS-02 data

stronger than dwarf limits for bb

anomaly compatible w. GC excess

Dark Matter as an Explanation for IceCube

$$E_\nu^2\Phi_\nu = E_\nu^2\Phi_\nu^{\rm EG} + E_\nu^2\Phi_\nu^{\rm G} \sim 4\times10^{-8}\ {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}\ \left[\frac{1+1.6(\mathcal{J}_\Omega/2)}{2.6}\right]\tau_{\rm dm,27.5}^{-1}(\mathcal{R}_\nu/15)^{-1}$$



KM, Laha, Ando & Ahlers 15

ex. Feldstein et al. 13,
Esmaili & Serpico 13,
Higaki+ 14, Fong+ 15,
Bai+ 14, Rott+ 15

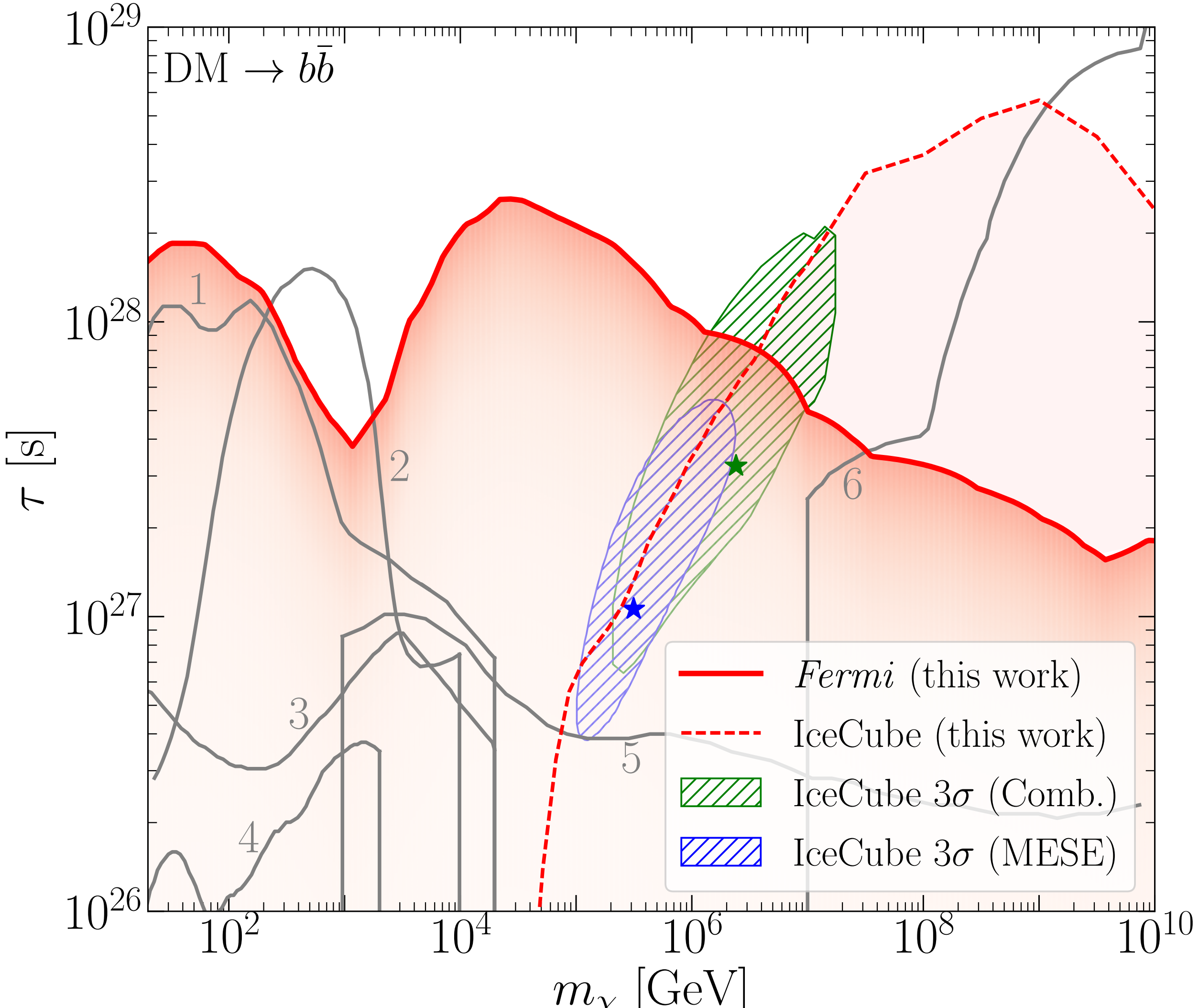
DM → ν_e+ν_e (12%)
DM → b+bbar (88%)

(similar results in other models that are proposed)

- Galactic: γ → direct (w. some attenuation), $e^\pm$ → sync. + inv. Compton
- Extragalactic → EM cascades during cosmological propagation

Multi-Messenger Constraints on Decaying DM

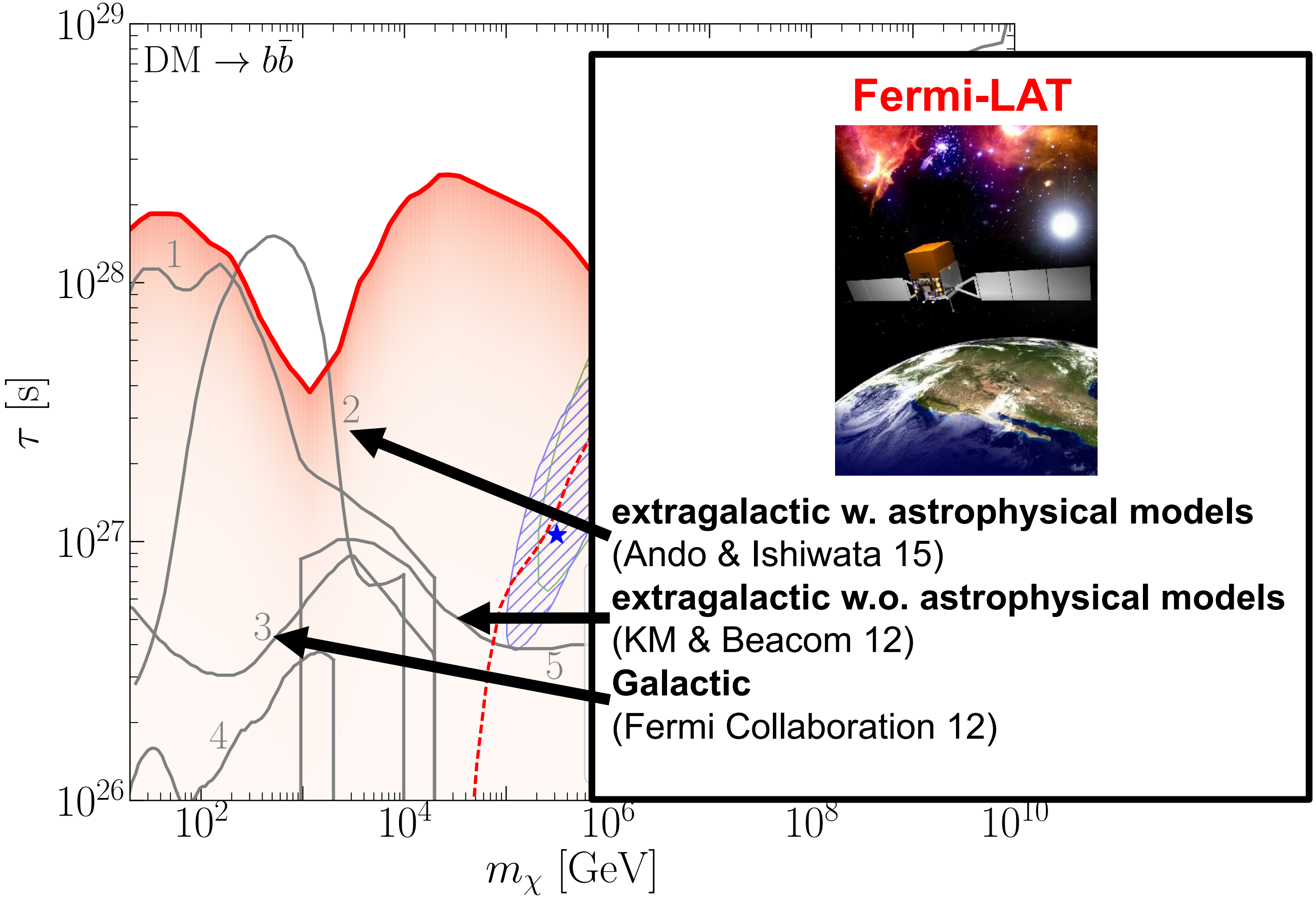
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



Pass 8, eight-year Fermi data w. non-Poissonian template fitting method

Multi-Messenger Constraints on Decaying DM

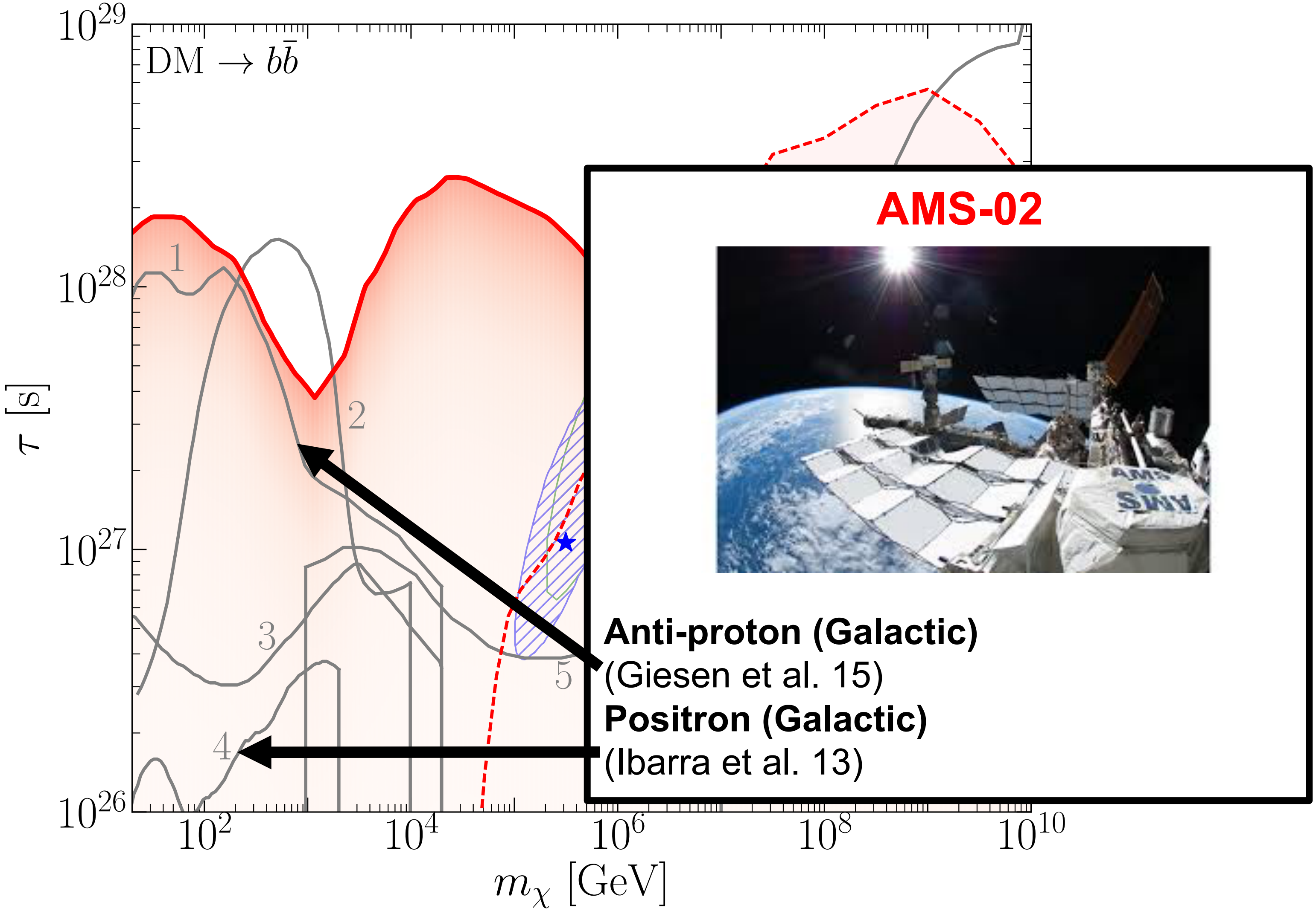
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



Gamma-ray limits are improved independently of astrophysical modeling

Multi-Messenger Constraints on Decaying DM

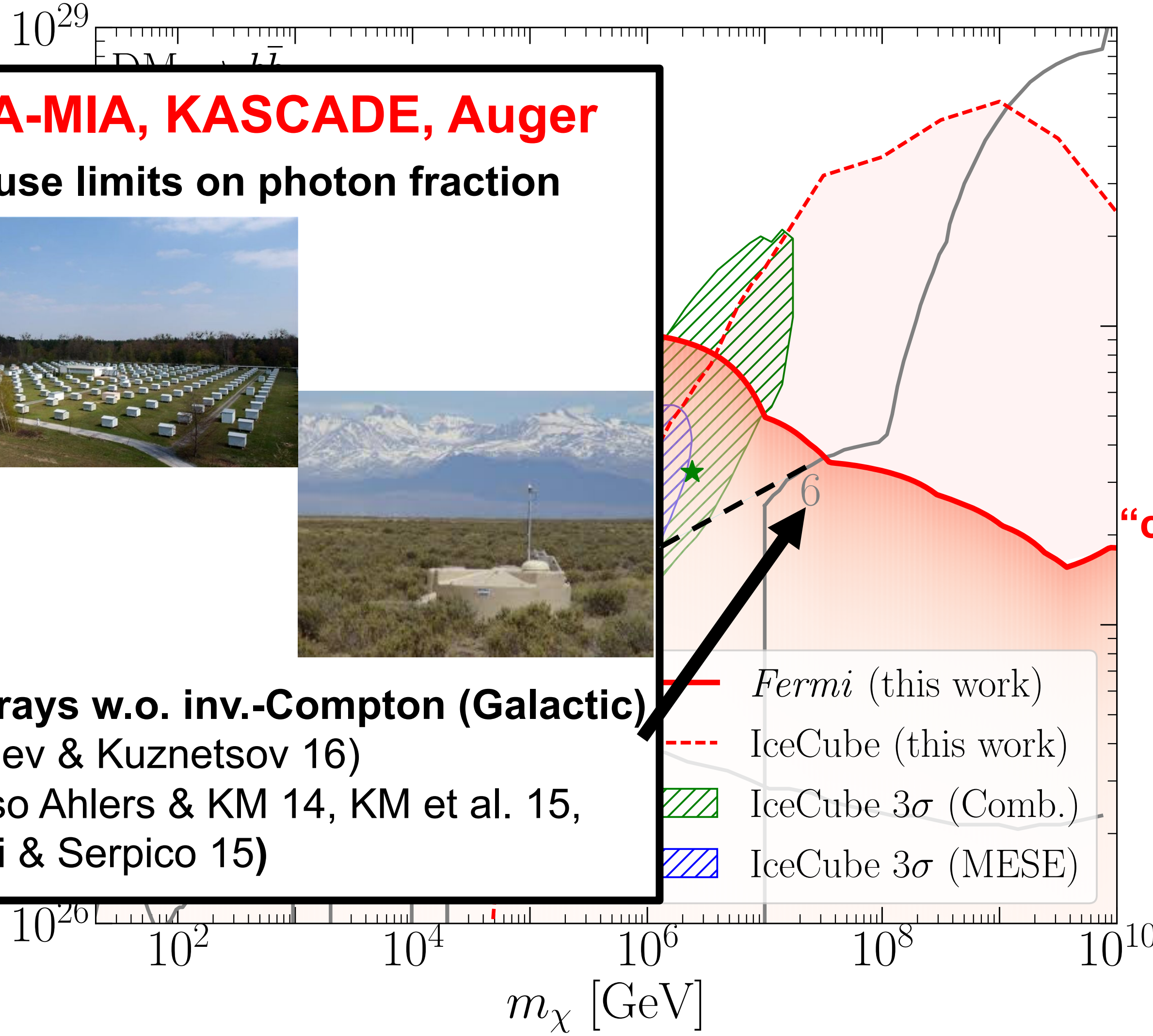
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



Anti-proton constraints are competing for soft channels such as DM→bb

Multi-Messenger Constraints on Decaying DM

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



CASA-MIA, KASCADE, Auger

diffuse limits on photon fraction

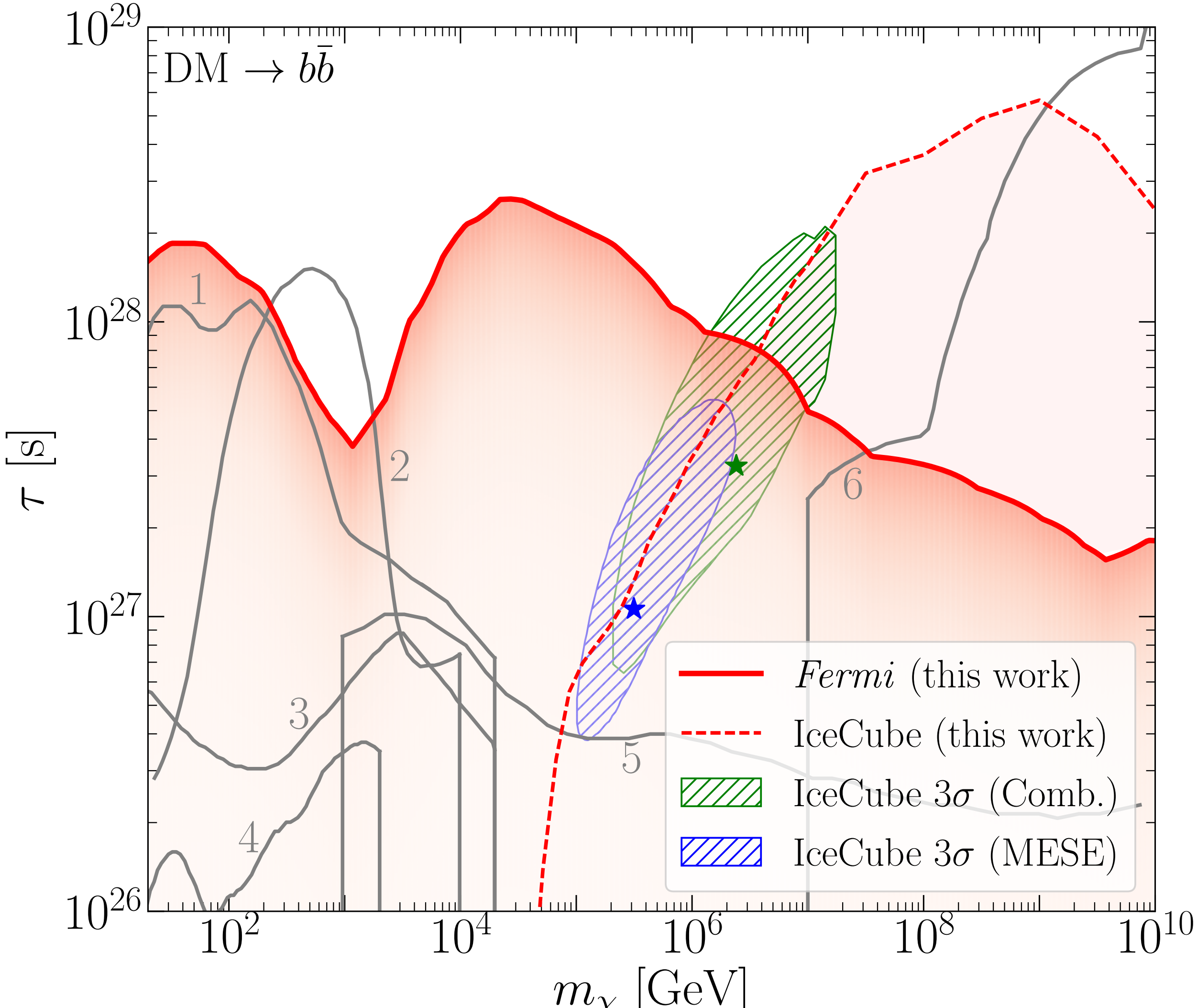
VHE g rays w.o. inv.-Compton (Galactic)
(Kalashev & Kuznetsov 16)
(see also Ahlers & KM 14, KM et al. 15,
Esmaili & Serpico 15)

“cascade” bound (extragalactic)

tension w. diffuse VHE γ-ray limits that are important at ultrahigh energies

Multi-Messenger Constraints on Decaying DM

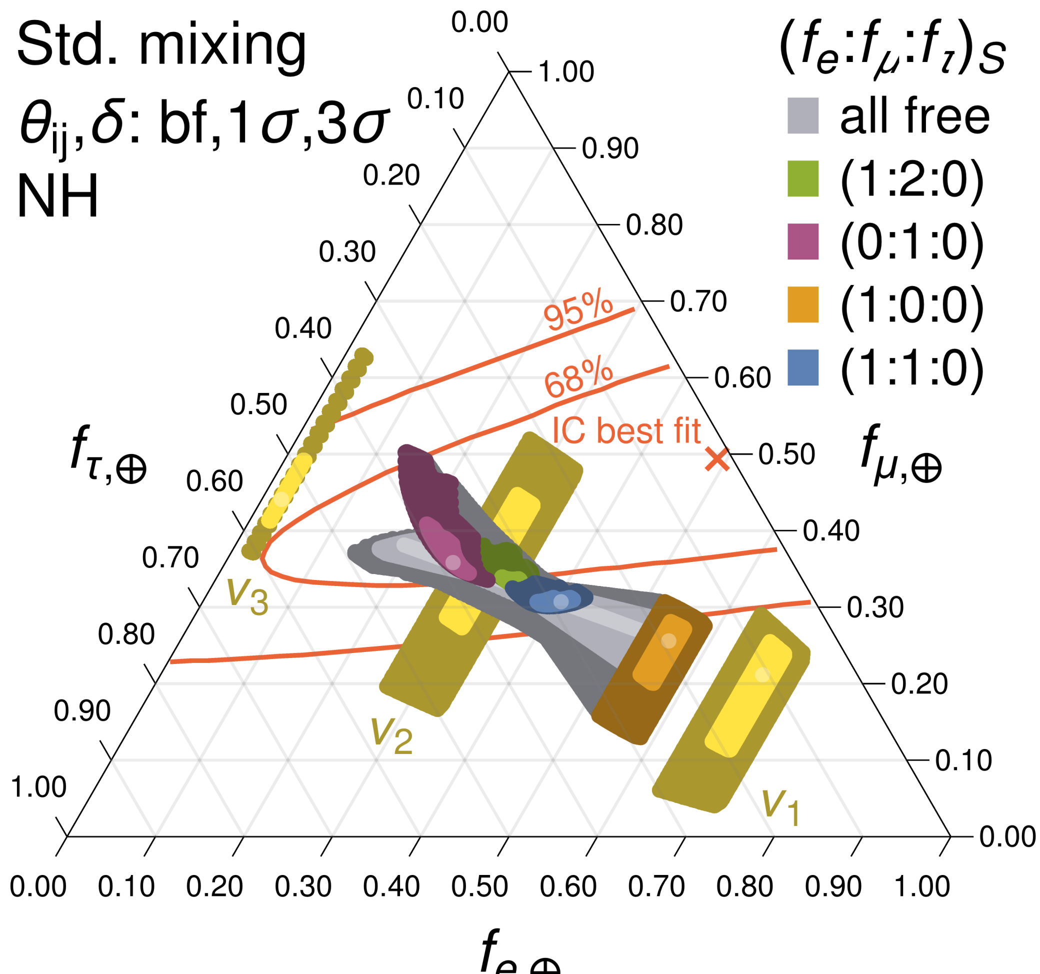
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



Pass 8, eight-year Fermi data w. non-Poissonian template fitting method

Flavor Constraints on Neutrinos

Shower-to-track ratio -> flavor information (ex. IceCube Collaboration 15 ApJ)



Bustamante, Beacom & Winter 15 PRL
see also Arguelles, Katori & Salvado 15 PRL, Shoemaker & KM 16 PRD

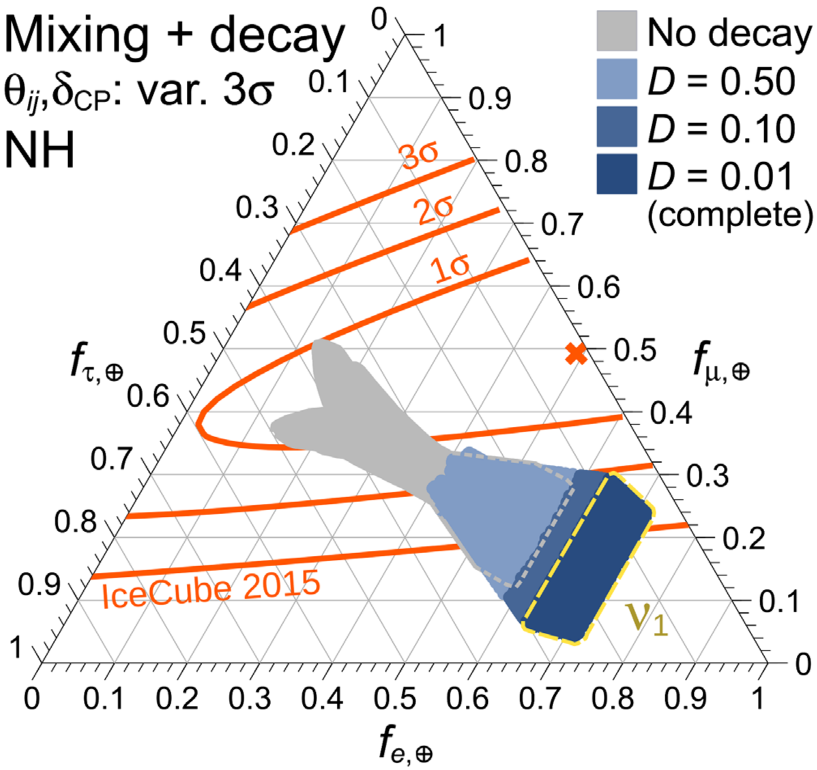
Neutrino Decay: Normal Hierarchy

- Neutrinos may decay via BSM processes
- HE cosmic neutrinos provide a special way to test BSM decay

$$\frac{dN_i}{dt} = -\left(\frac{m_i}{\tau_i}\frac{1}{E_\nu}\right)N_i$$

$$\kappa_i^{-1} \equiv \tau_i/m_i$$

$$L_{\rm dec} \simeq 0.01 \cdot \kappa^{-1}\left[{\rm s\ eV^{-1}}\right] E_\nu\,[{\rm TeV}]\ \ {\rm Mpc}$$



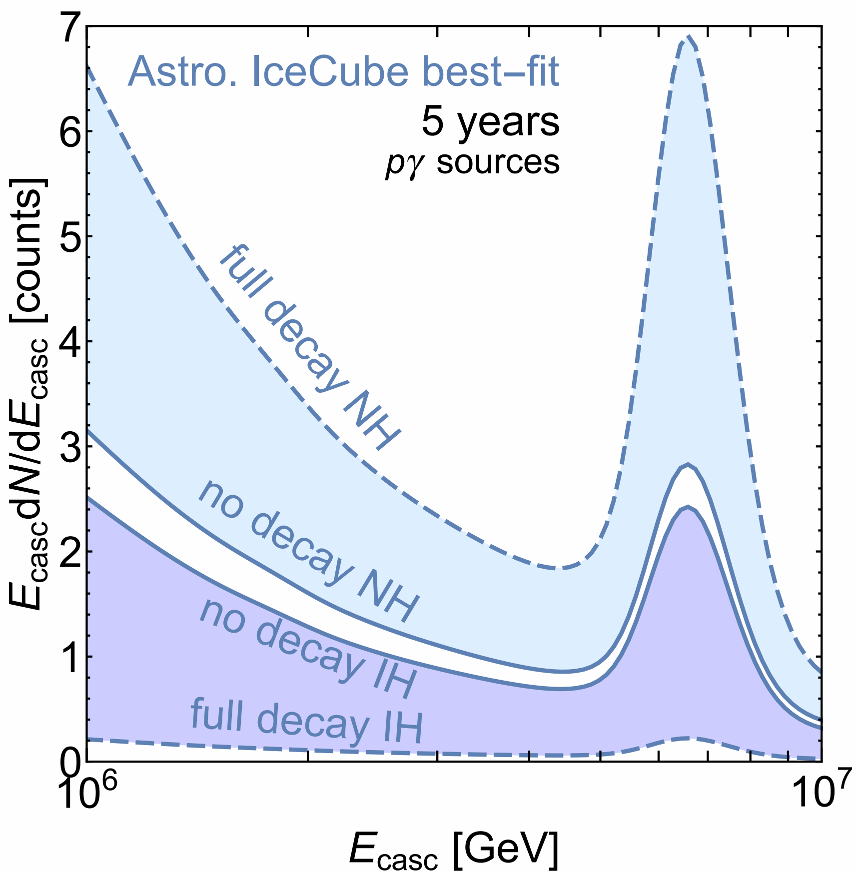
Bustamante, Beacom & KM 17 PRD
(see also Pagliaroli+ 15 PRD)

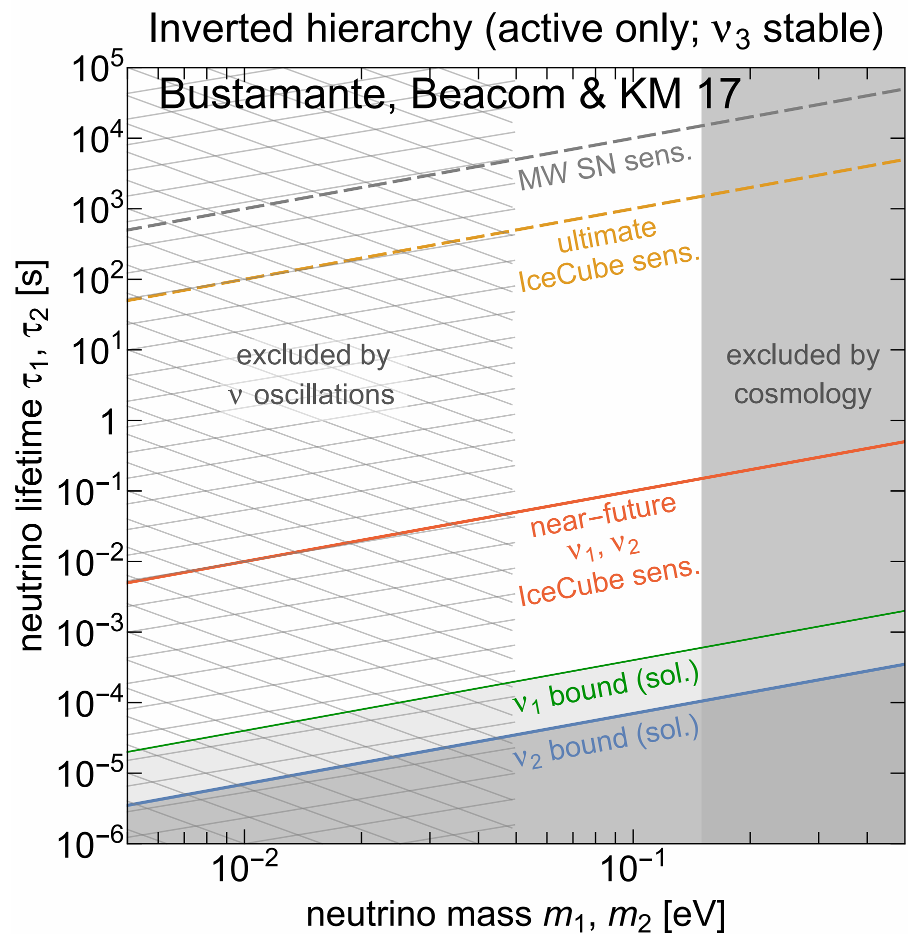
complete decay of ν_2, ν_3 disfavored only by flavors

$$\tau_2/m_2, \qquad \tau_3/m_3 \gtrsim 10\ {\rm s\,eV^{-1}}\,(\gtrsim 2\sigma, {\rm NH})$$

Neutrino Decay: Inverted Hierarchy

IH is not ruled out by the flavor information





Observing just one Glashow resonance event improves the limit by 2-3 orders of magnitudes: $\tau/m >\sim 1\ \mathrm{s\ eV^{-1}}$

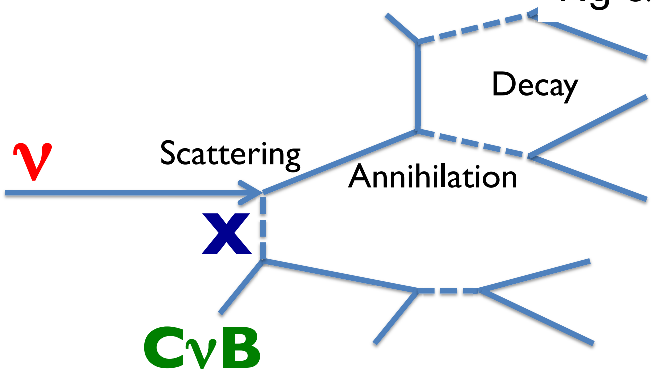
Neutrino-Neutrino Self-Interactions

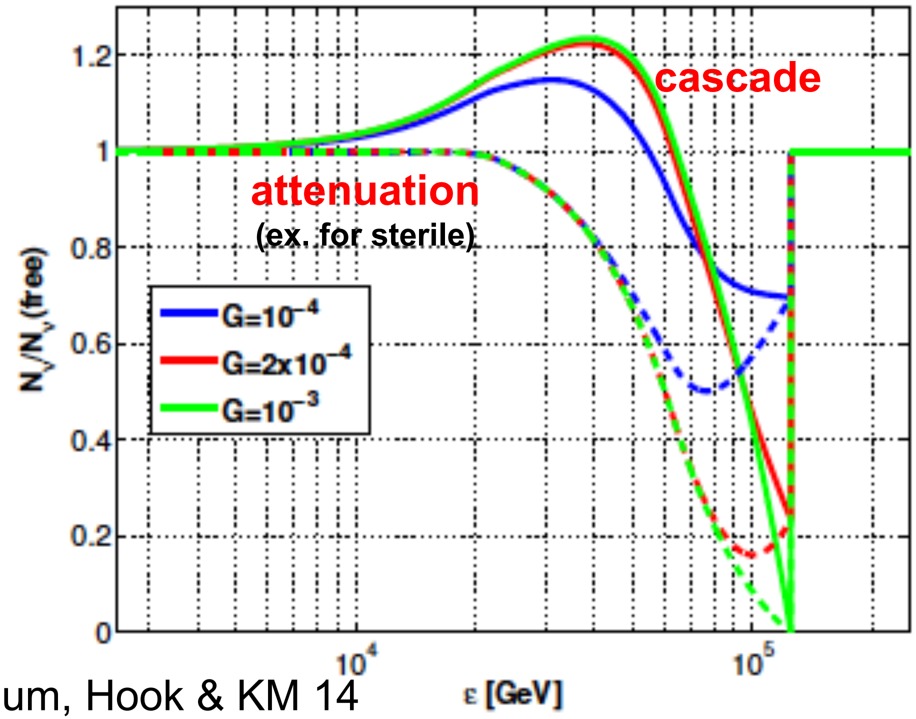
$$\mathcal{L} \supset G\nu\nu\phi$$

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

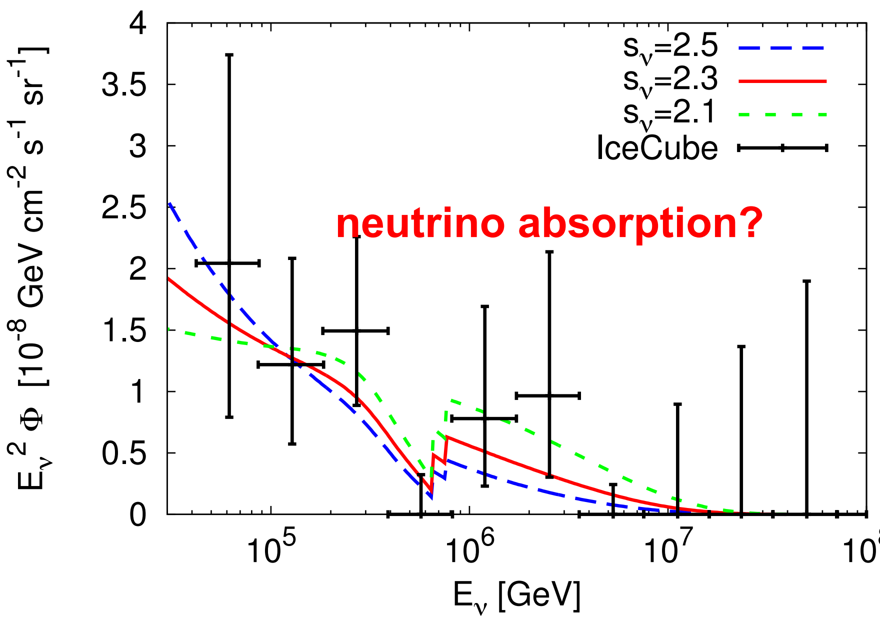
mediator mass ~ 10 MeV

Ioka & KM 14
Ng & Beacom 14





Blum, Hook & KM 14



Araki et al. 16

Summary

γ-ray flux ~ ν flux ~ CR flux

multi-messenger limits are now critical for CR and DM models

Cosmic-ray sources?

pp scenarios: s<2.1-2.2 & significant contribution to Fermi γ-ray bkg.
cosmic particle unification is possible with s~2
10-100 TeV data are NOT explained by CR reservoirs

pγ scenarios: hidden CR accelerators?

Neutrino Transients?

TXS 0506+056 flare: the simple model does not work – need more events

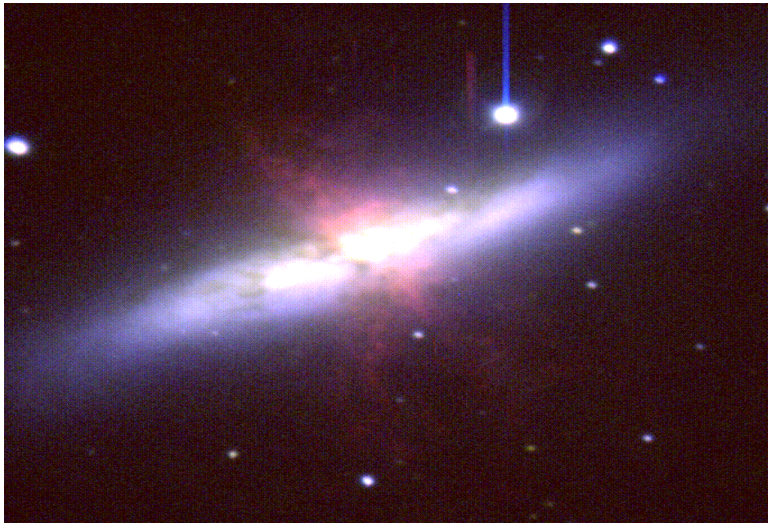
BSM?

dark matter: constrained by Fermi-LAT and CR experiments
10-100 TeV data are NOT readily explained

various possibilities (ex. neutrino decay, neutrino-neutrino self-interactions)


Thanks!

Starburst/Star-Forming Galaxies: Basics



- High-surface density

  M82, NGC253: Σ_g~0.1 gcm^{-3} → n~200 cm^{-3}

  high-z MSG: Σ_g~0.1 g cm^{-3} → n~10 cm^{-3}

  submm gal. Σ_g~1 gcm^{-3} → n~200 cm^{-3}
- CR accelerators

  Supernovae, hypernovae, GRBs,

  Super-bubbles (multiple SNe)

  Galaxy mergers, AGN

SBG CR luminosity density $Q_{\rm cr} \sim 8.5 \times 10^{44}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}\ \epsilon_{{\rm cr},-1} \varrho_{{\rm SFR},-3}$

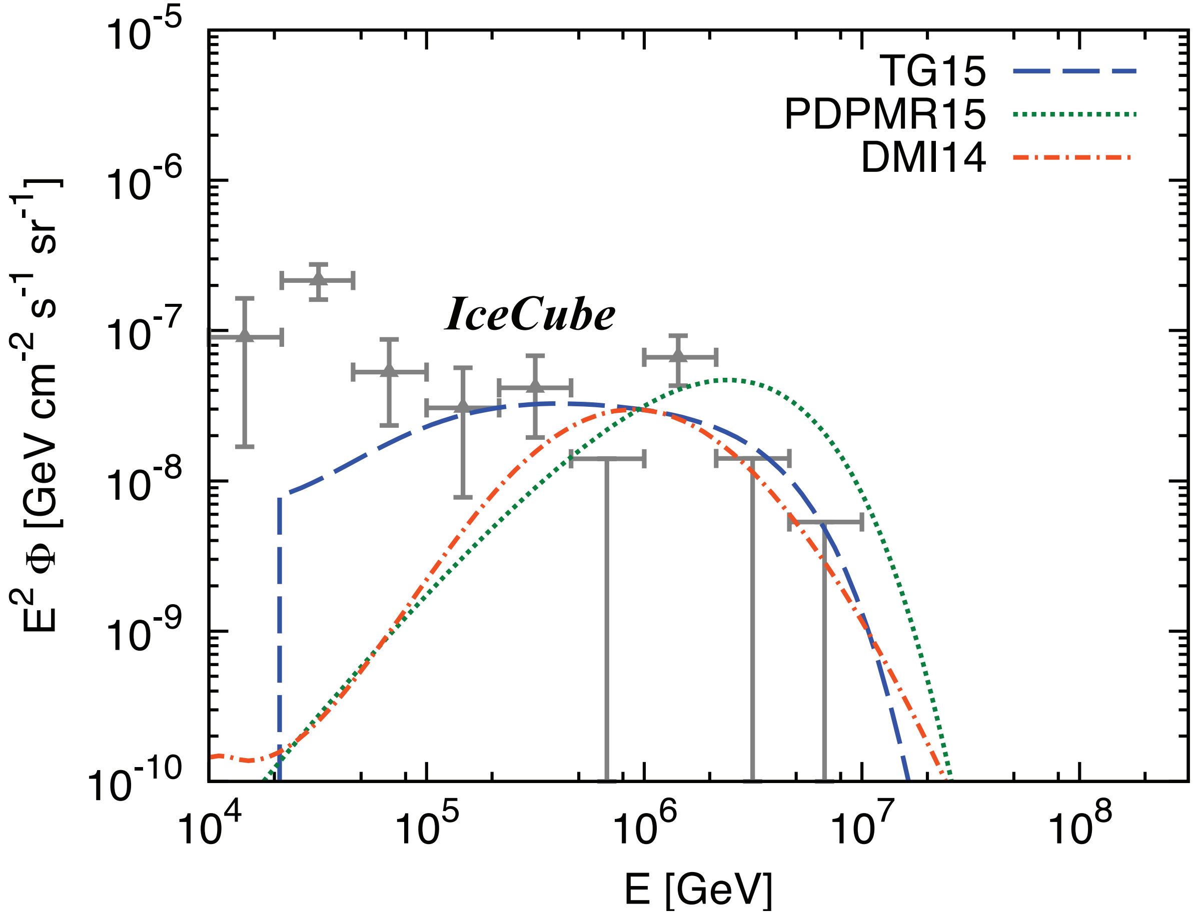
(SFG CR energy budget ~ Milky Way CR budget is ~10 times larger)

advection time (Gal. wind) $t_{\rm esc} \approx t_{\rm adv} \approx h/V_w \simeq 3.1\ {\rm Myr}\ (h/{\rm kpc}) V_{w,7.5}^{-1}$

pp efficiency $f_{pp} \approx \kappa_p \sigma_{pp} n c t_{\rm esc} \simeq 1.1\ \Sigma_{g,-1} V_{w,7.5}^{-1} (t_{\rm esc}/t_{\rm adv})$

$$E_\nu^2 \Phi_{\nu_i} \sim 10^{-9}\text{–}10^{-7}\ {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Can Blazars Explain the IceCube Data?



BL Lac – two-zone
BL Lac – one-zone
FSRQ – external field

KM & Waxman 16 PRD

- Cutoff or steepening around a few PeV (ex. stochastic acceleration)
  But the models give up the simultaneous explanation of UHECRs
- Neutrino data at <~100 TeV are not explained by proposed models and there are constraints from stacking and clustering analyses

Galactic Neutrino Sources?

~200 TeV is coincident w. "neutrino ankle" of Galactic CRs
Galactic scenarios are not ruled out but fine tuning is needed

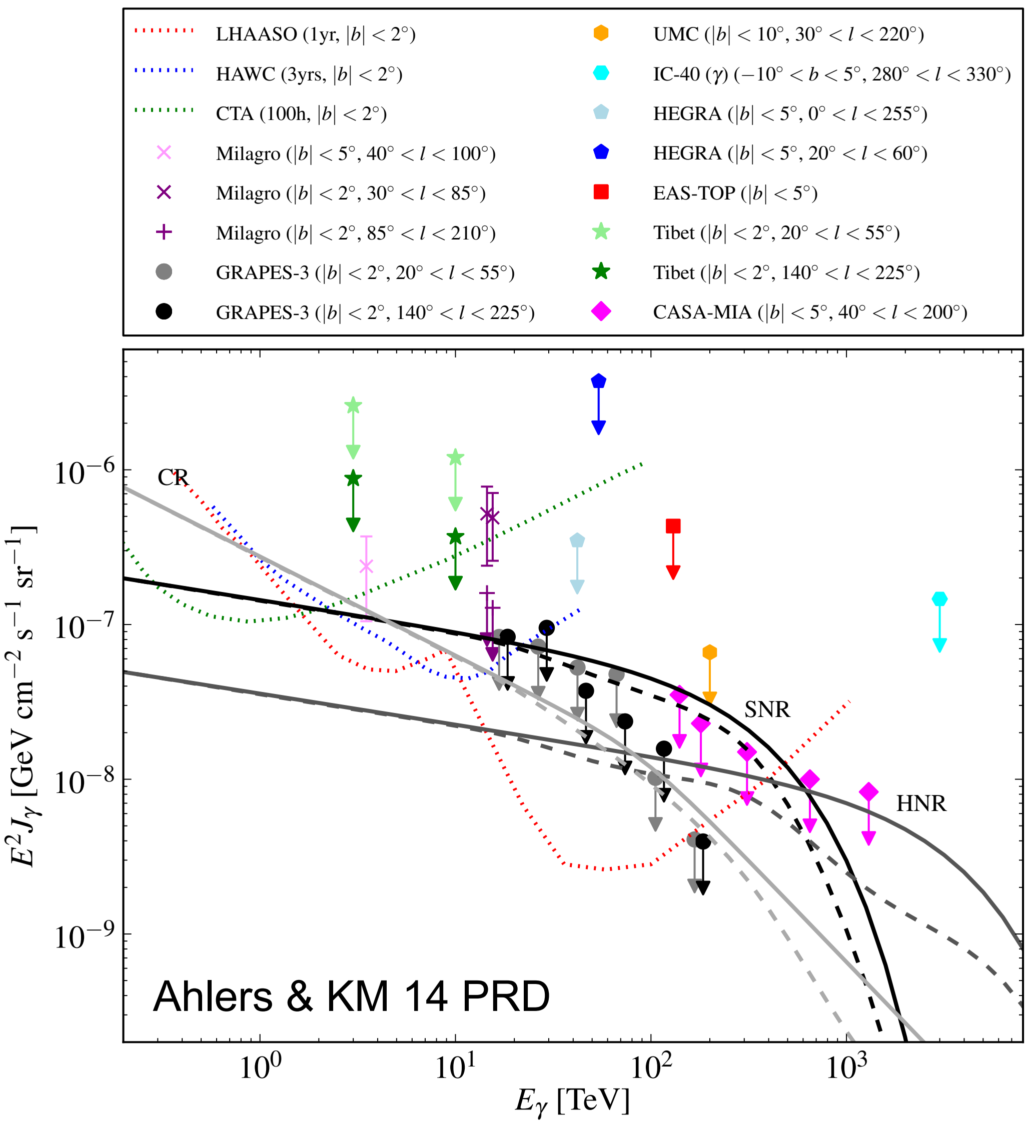
- Why the Gal and extragalactic have the similar flux at this energy?
  If the same source population is responsible

$$\frac{\Delta\Omega E_\nu^2 \Phi_\nu^{\rm G}}{4\pi E_\nu^2 \Phi_\nu^{\rm EG}} \approx \frac{\Delta\Omega \langle r_{\rm los}\rangle}{4\pi c t_H \xi_z n_0^g \mathcal{V}} \sim 310 \left(\frac{\Delta\Omega}{4\pi}\right)\left(\frac{\langle r_{\rm los}\rangle}{3~{\rm kpc}}\right)^{-2} \xi_z^{-1}$$

- Muon neutrino constraints (Ahlers, Bai+ 15 PRD)
  Galactic diffuse emission: <50% (<20% from IceCube Collab. 17)
  Unresolved sources in the Galactic plane: <65%
  Fermi bubbles, un-ID TeV sources: <25%
  DM decay: unconstrained

- Diffuse gamma-ray constraints (Ahlers & KM 14 PRD, KM+ 16 PRL, Kistler 16)
  Galactic diffuse emission: <3(ΔΩ/1 sr)%
  Galactic center: <40-50(ΔΩ/1 sr)%
  HAWC will improve the limits soon

Subdominant Sources in the Galactic Plane?



CASA-MIA limit $|b| < 5^\circ$ and $50^\circ < l < 200^\circ$

$$E_\nu^2 \Phi_\nu \lesssim 2 \times 10^{-9} \ (\Delta\Omega/1 \text{ sr}) \ \text{GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

CASA-MIA limit at the Galactic center

$$E_\nu^2 \Phi_\nu \lesssim 3 \times 10^{-8} \ (\Delta\Omega/1 \text{ sr}) \ \text{GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

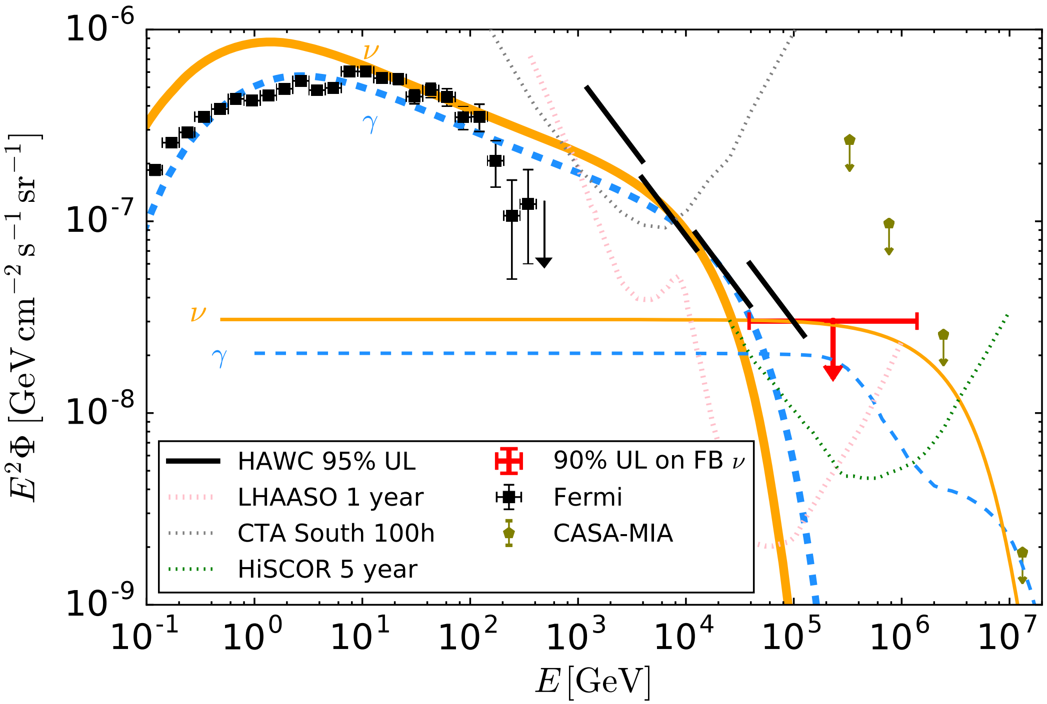
<u>constraints on proposed models</u>

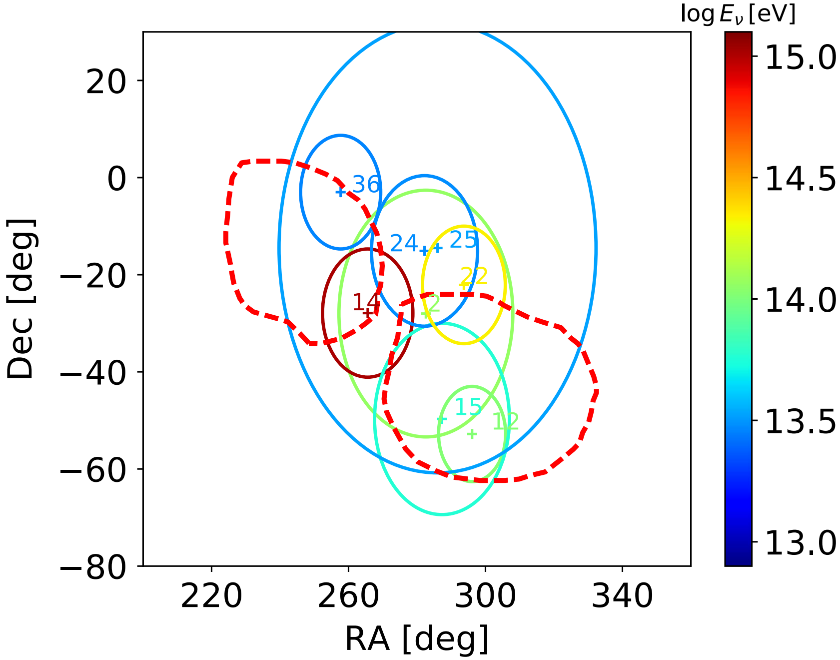
- diffuse Galactic emission
  (Anchordoqui+ 14, Neronov+ 14, Joshi+14)
  too steep spectra
- supernova/hypernova remnants
  (Fox+ 13)
  gamma limits look violated

Association of many events w. the Galactic plane is unlikely

Example: Fermi Bubbles?

Fang, Su, Linden & KM 17 PRD
updated from Ahlers & KM 14 PRD



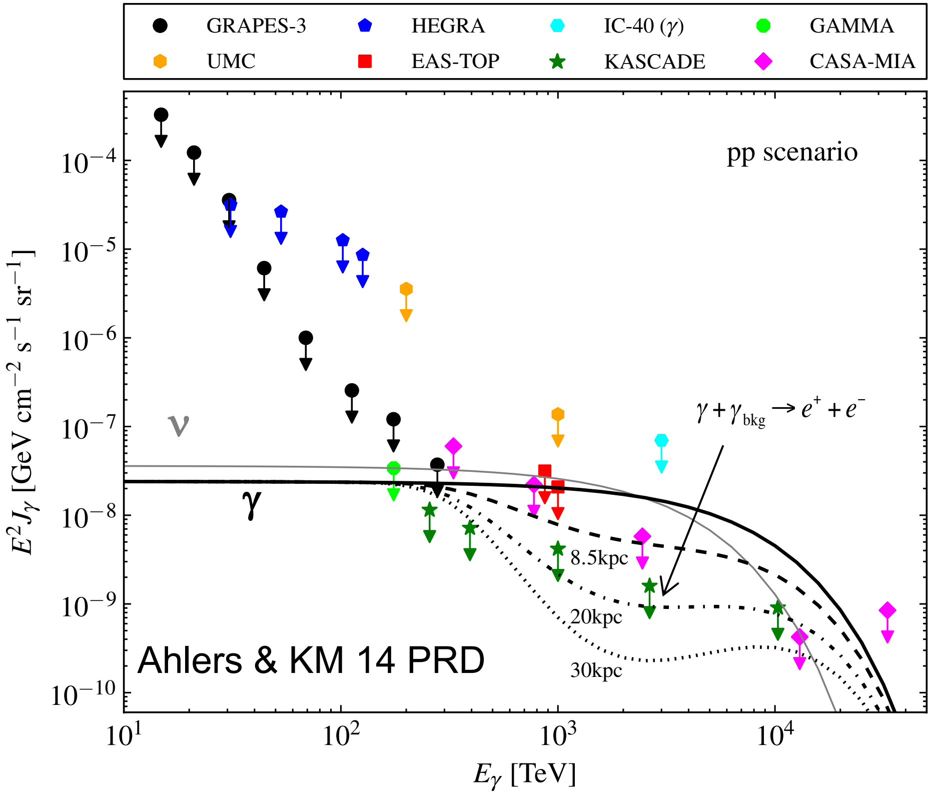


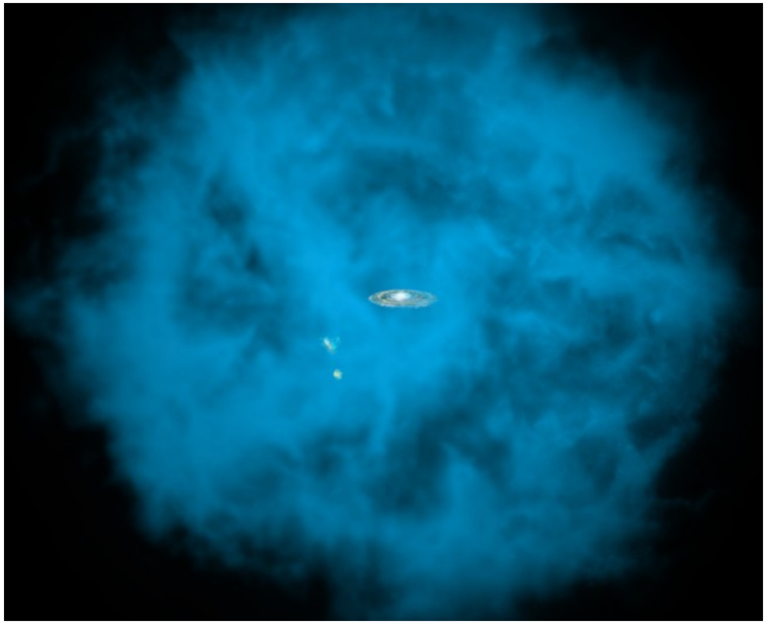
- consistent w. Γ>2.2 (although the cutoff is indicated by Fermi)
- Contribution to diffuse neutrino flux is subdominant

Example: Galactic Halo?

Airshower arrays have placed diffuse γ-ray limits at TeV-PeV

Isotropic limits (Galactic halo CR model)





$$n_H = (10^{-4.2\pm0.25})(R/R_{vir})^{-0.8\pm0.3}$$

- Existing old TeV-PeV γ-ray limits are close to predicted fluxes
  → Need deeper TeV-PeV γ-ray observations (relatively not expensive)

※ Fermi γ-ray data imply $s_\nu < 2.0$ → support extragalactic scenarios