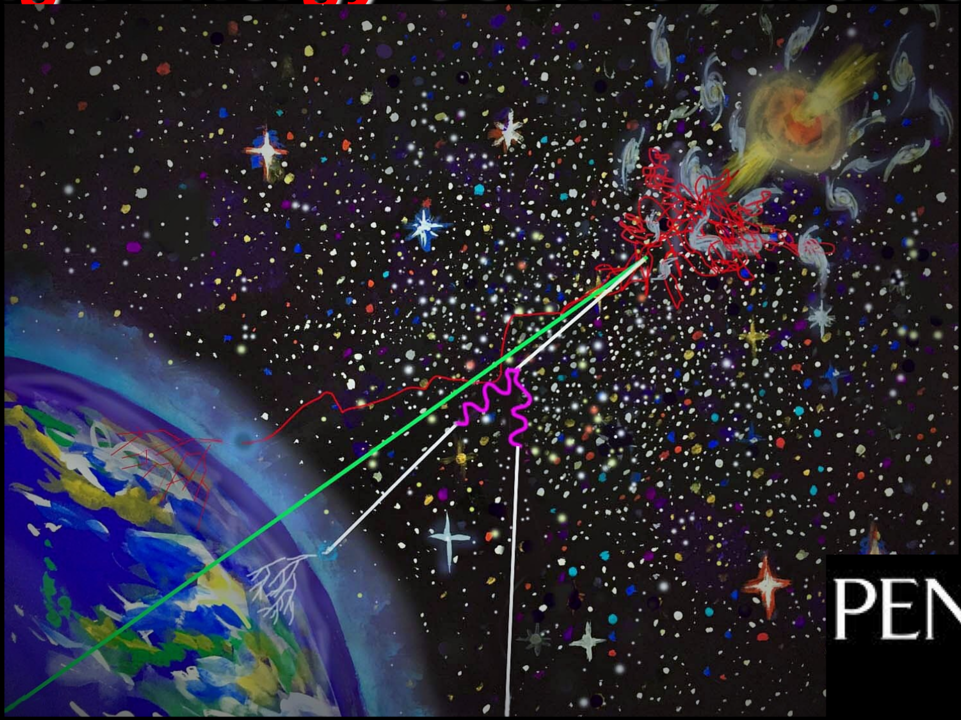
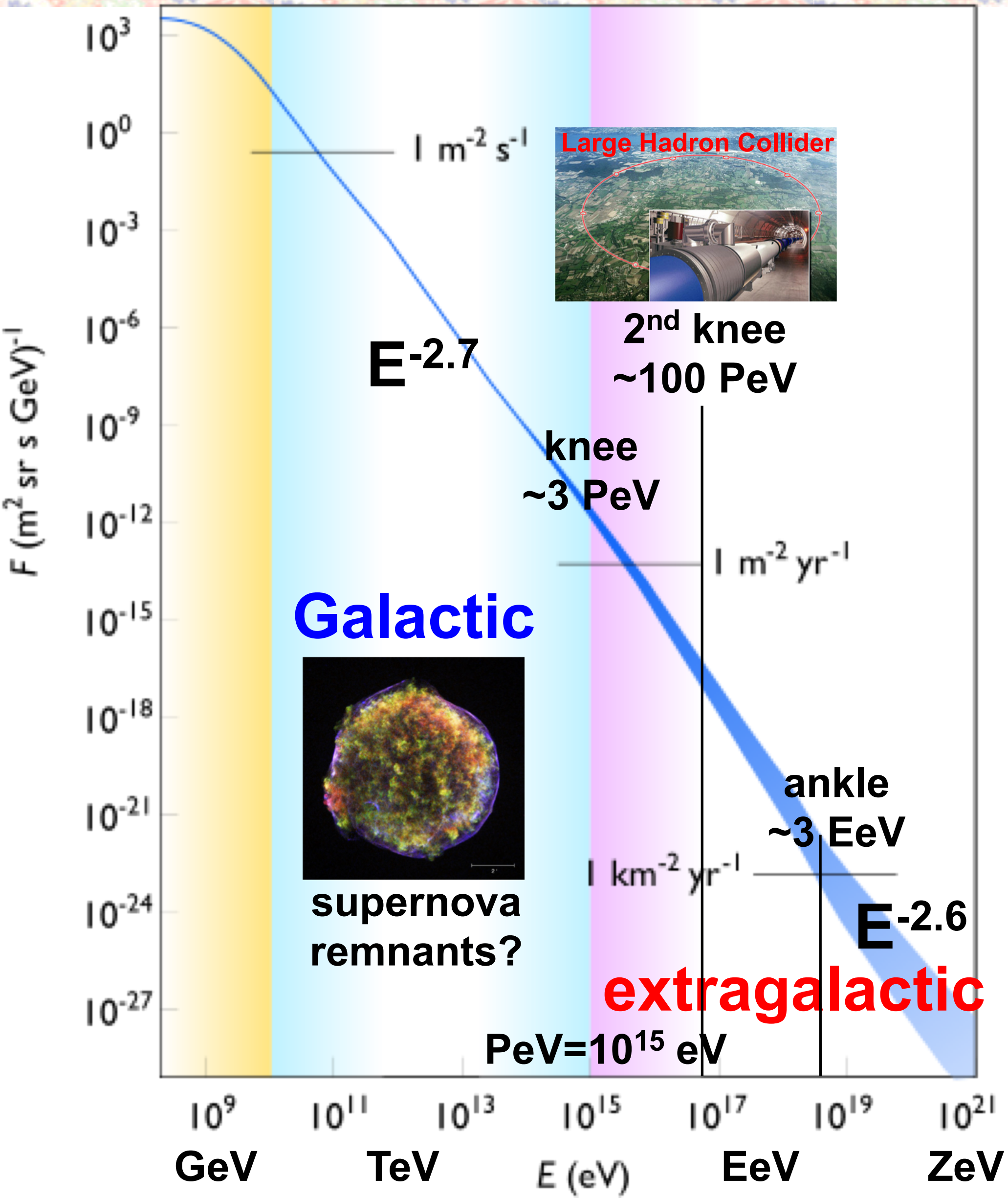
Multi-Messenger Connection of High-Energy Cosmic Particles



Kohta Murase (Penn State)

Feb 18 2018 @ VHEPA 2019

Motivation: Cosmic Rays – A Century Old Puzzle



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

Open problems

- How is the spectrum formed?
 (ex. transition to extragalactic)

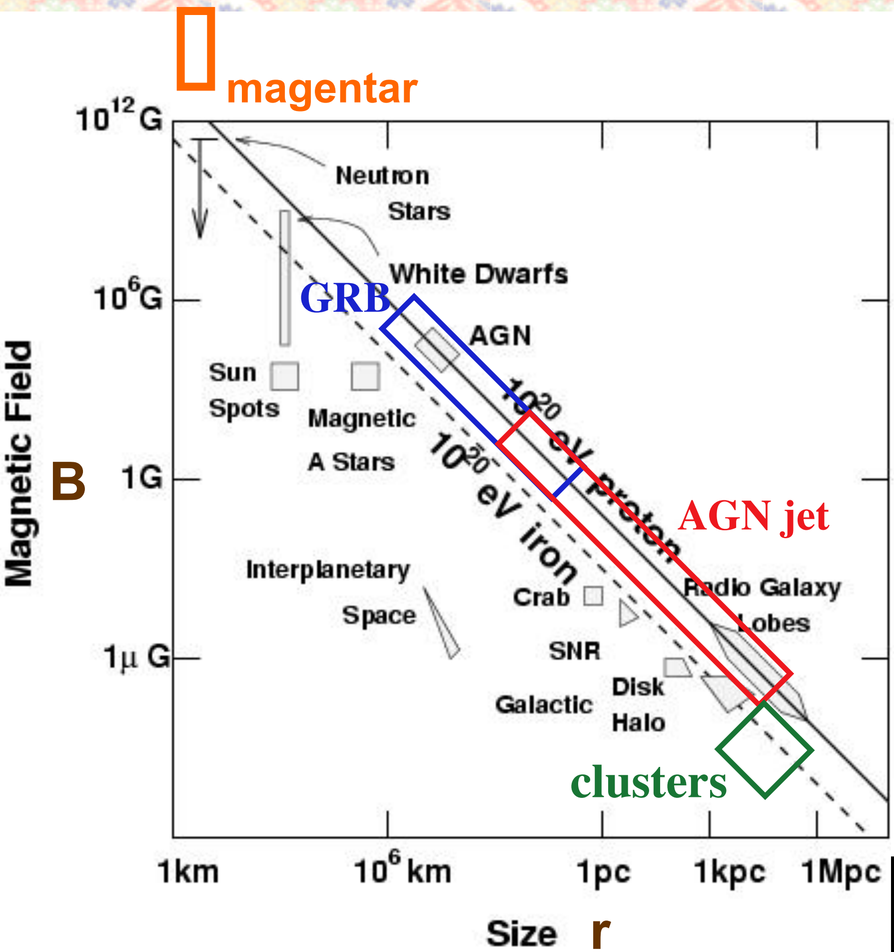
- How are CRs accelerated?
 (ex. Fermi mechanism: s_{CR}~2)

- How do CRs propagate?
 (diffusion, rectilinear, or?)

…

"What is the origin?"

UHECR Source Candidates: Cosmic Monsters



Hillas condition

$E < e B r \beta$

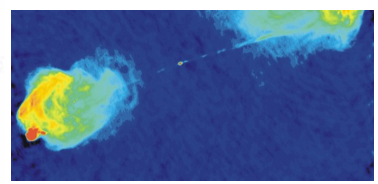
Magnetar

The **strongest** mag. fields
$B \sim 10^{15}$ G

γ-ray burst (GRB)

The **brightest** explosions
$L_{\gamma} \sim 10^{52}$ erg/s

Active galaxy (AGN)



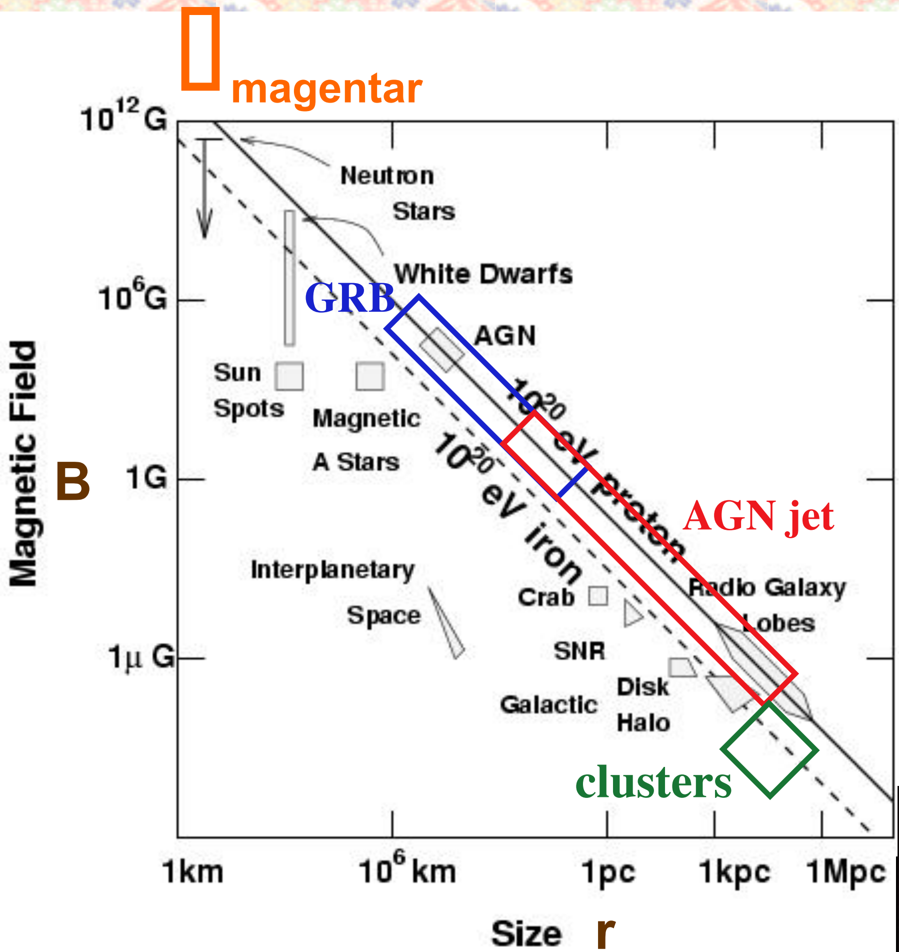
The **most massive** black holes
$M_{BH} \sim 10^{8\text{-}9} M_{sun}$

Galaxy cluster

The **largest** gravitational object
$R_{vir} \sim$ a few Mpc

cf. $B_{sun} \sim 1$ G, $L_{sun} \sim 4 \times 10^{33}$ erg/s,
$M_{sun} \sim 2 \times 10^{33}$ g, $R_{sun} \sim 7 \times 10^{10}$ cm

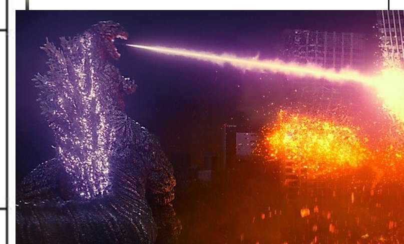
UHECR Source Candidates: Cosmic Monsters



Hillas condition

$E < e\, B\, r\, \beta$

The **strongest** mag. fields
$B \sim 10^{15}$ G



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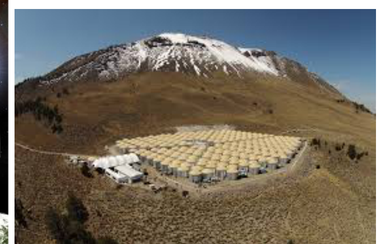
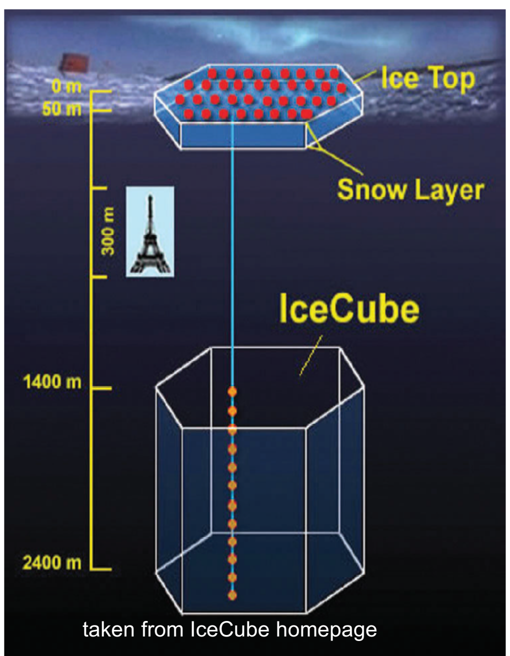
Era of Multi-Messenger Astroparticle Physics

Gamma Rays
Fermi, HAWC,
HESS, MAGIC, VERITAS, CTA etc.



Neutrinos
IceCube, KM3Net
Super-K etc.

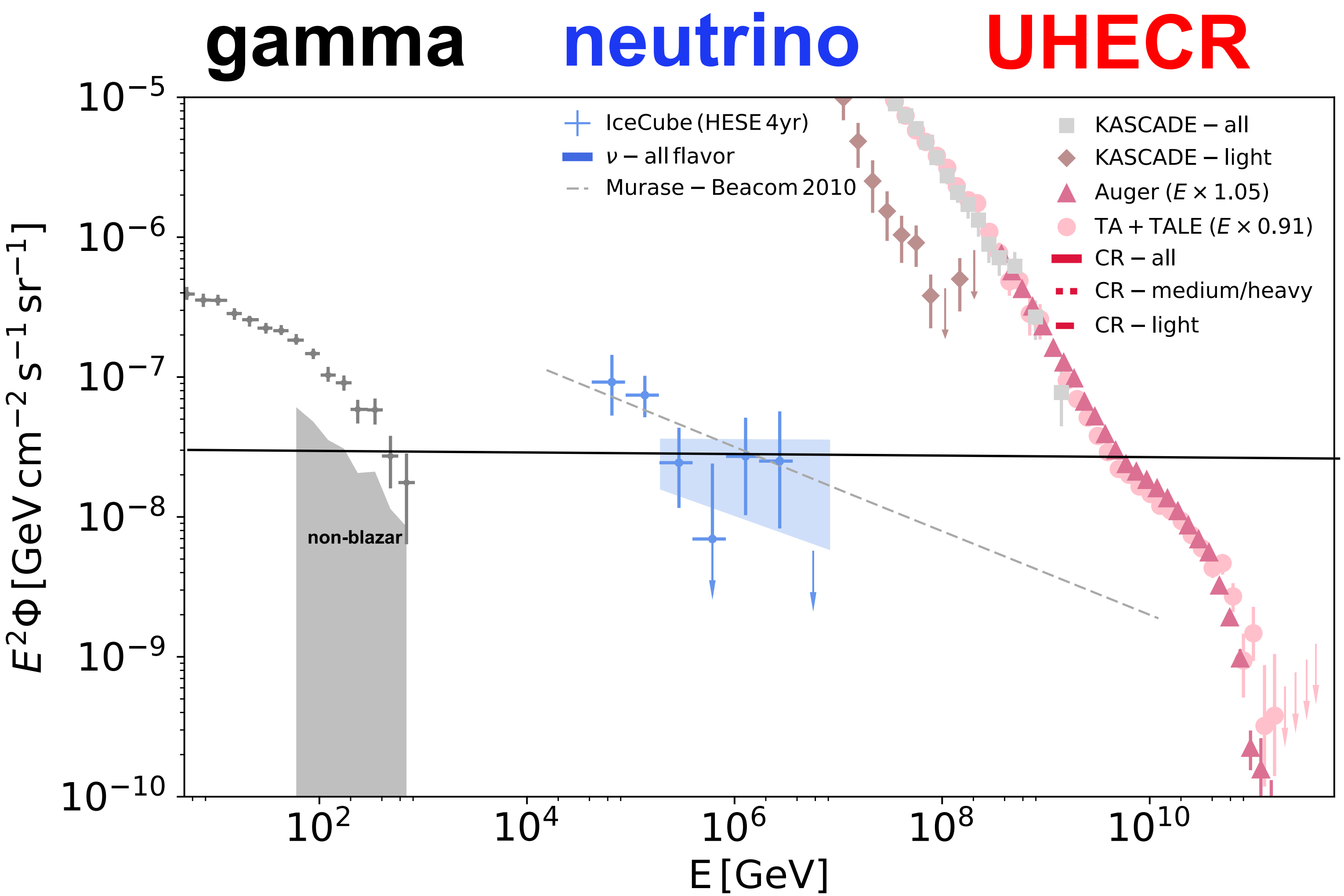


taken from IceCube homepage

Cosmic Rays
PAMELA, AMS-02
Auger, TA etc.

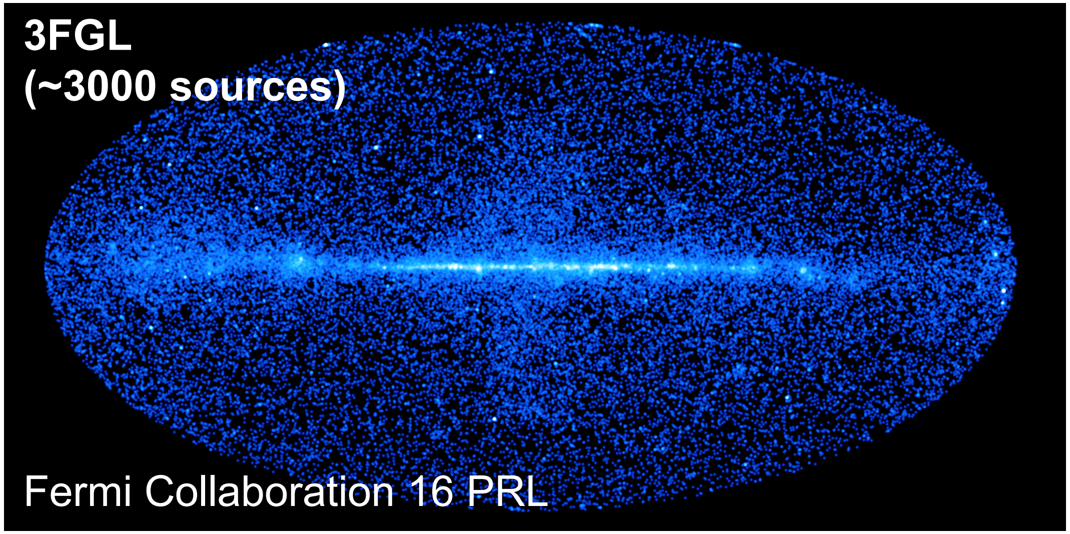
Gravitational Waves
LIGO, Virgo, KAGRA

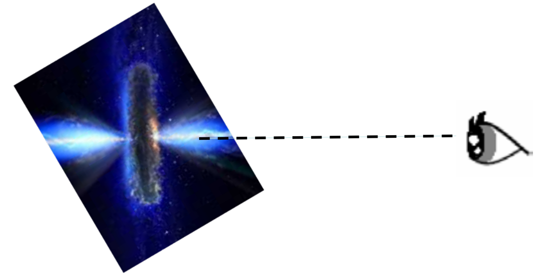
Multi-Messenger Cosmic Particle Backgrounds



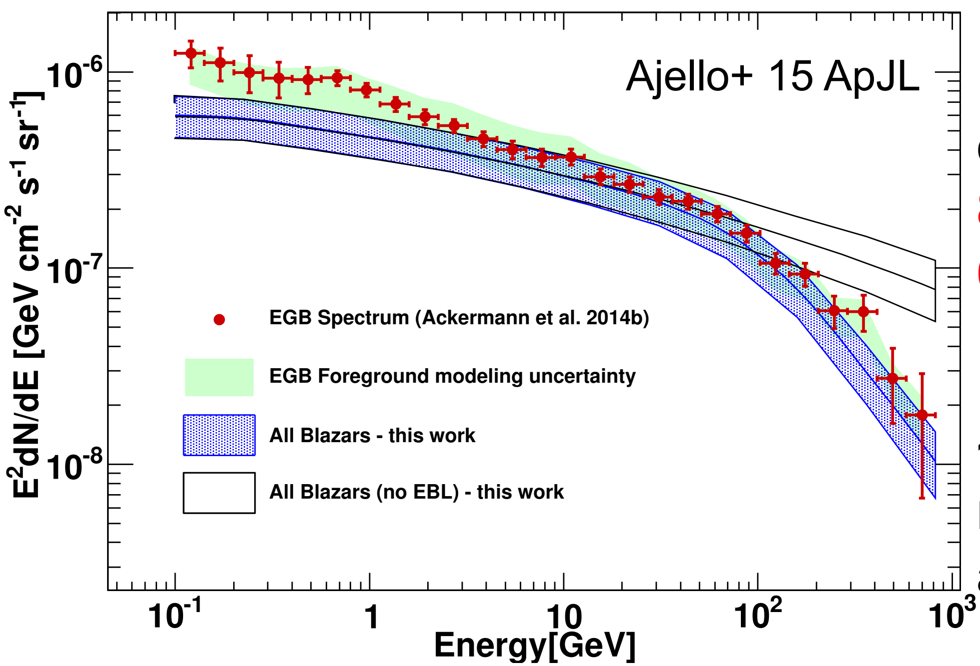
Energy generation rates are all comparable to a few x 10^{43} erg Mpc^{-3} yr^{-1}

Extragalactic Gamma-Ray Sky: Dominated by Blazars





48 months of observations :
3LAC: 1563 sources
1444 AGNs in the clean sample
most of them are blazars



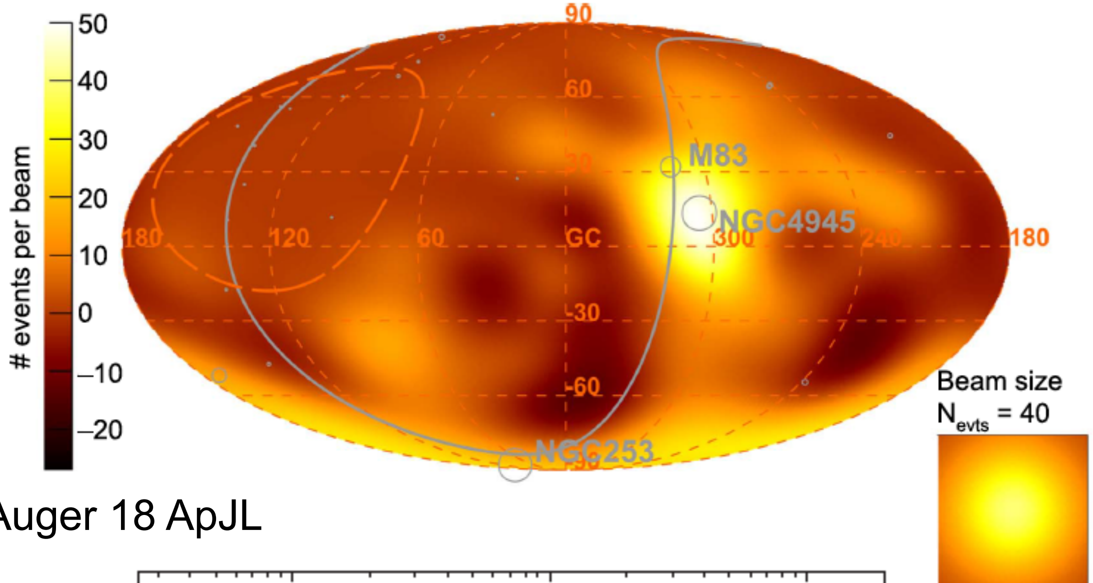
Blazar (point-source) contribution to extragalactic γ-ray background (EGB)

86%+16%-14% (Fermi 16 PRL)

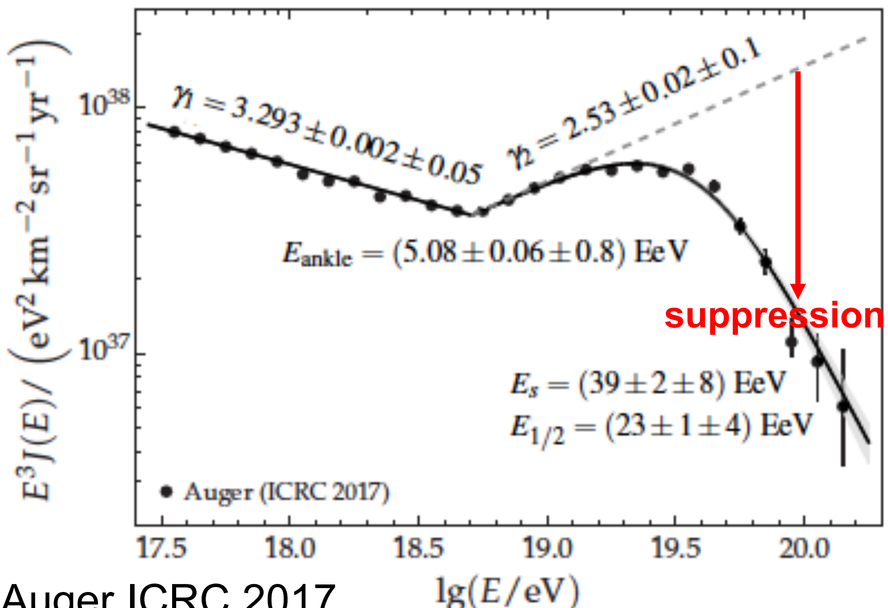
68%+9%-8% (Lisanti+ 16 ApJ)

~15-30% of the EGB at > 50 GeV may come from something else and more rooms at lower energies

UHECR Sky: Unknown (but Hint?)



Auger 18 ApJL

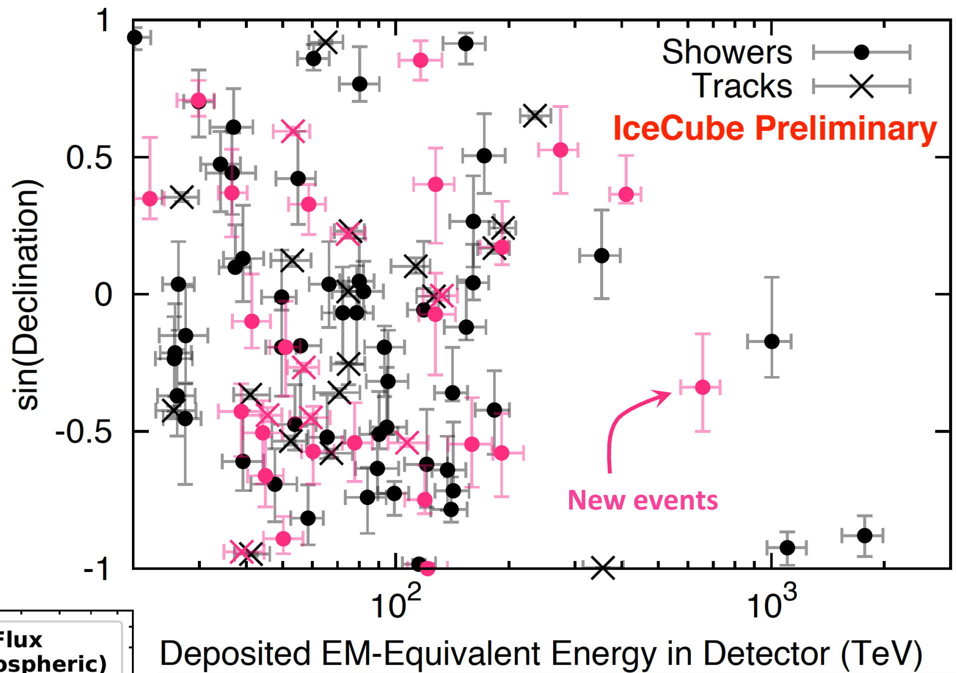


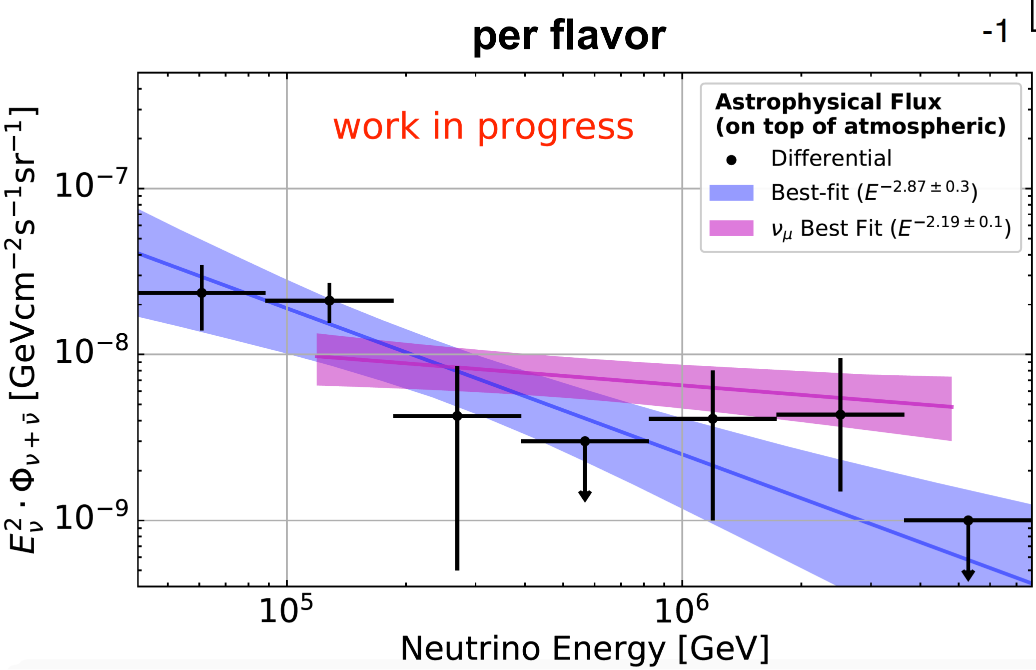
Auger ICRC 2017

- No established source yet
- Tentative correlation?
  starbursts: ~4σ
  AGN: ~3σ
  TA hotspot: ~3σ
- Dipole anisotropy established
  -> supporting extragalactic
  (Auger 17 Science)
- Spectrum:
  suppression at ~40 EeV can be explained by interactions with CMB during the propagation OR maximum energy at the sources
- Composition:
  heavier nuclei beyond the ankle?

Neutrino Sky: Latest Updates

- HESE 7.5 year
  103 events
  (60 events > 60 TeV)
  Best-fit: s=2.87±0.3

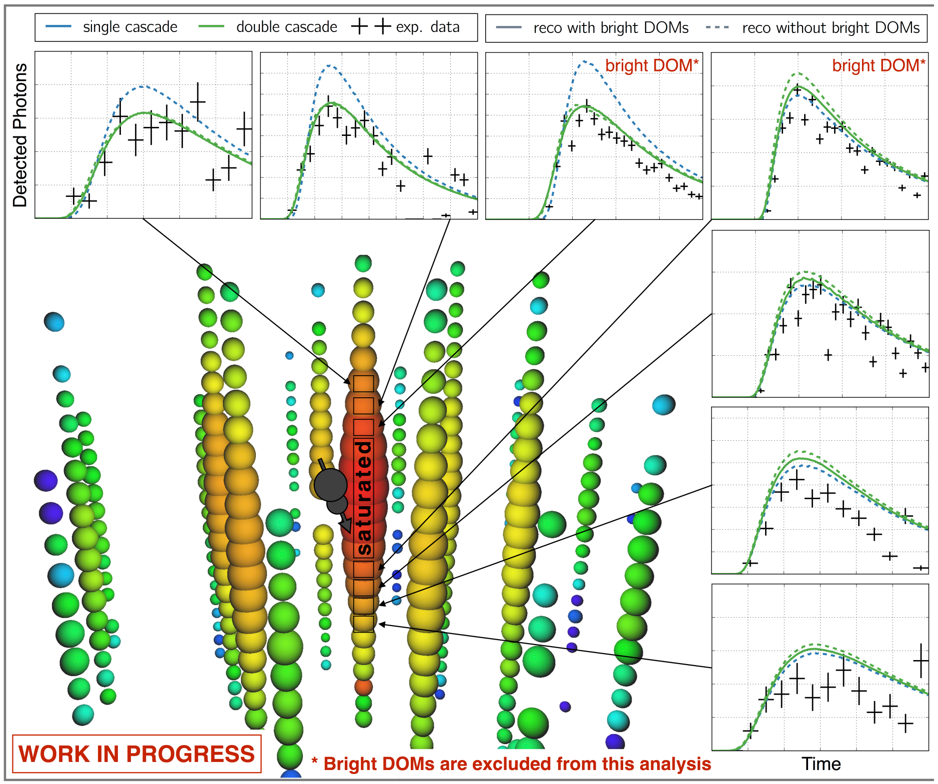




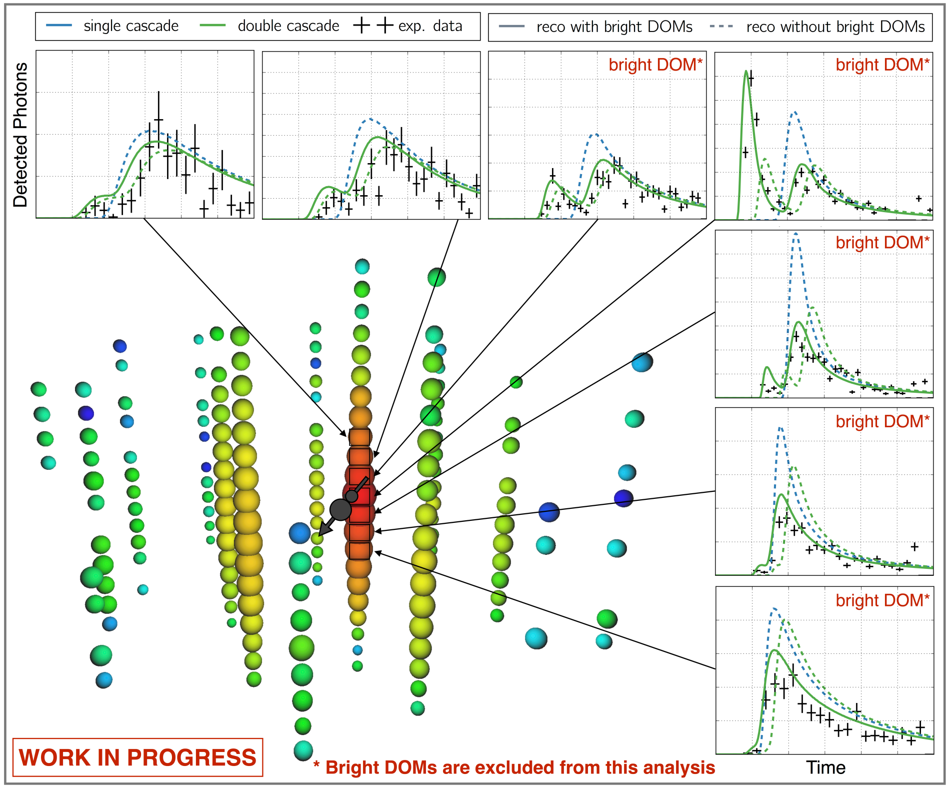
- 8-yr upgoing ν_μ "track"
  36 events at >200 TeV (6.7σ)
- Best-fit: s=2.19±0.10
- ν_μ flux above 100 TeV:
  $E_\nu{}^2\Phi_\nu$=(1.01+0.26-0.23)
  x10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

Neutrino Sky: Latest Updates

- Two double bang candidates (not settled yet) could be CC interaction by ν_τ



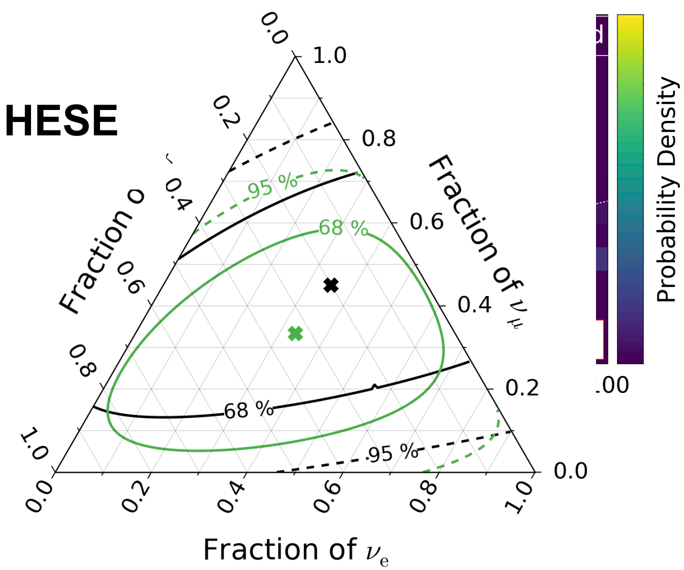
Double cascade Event #1

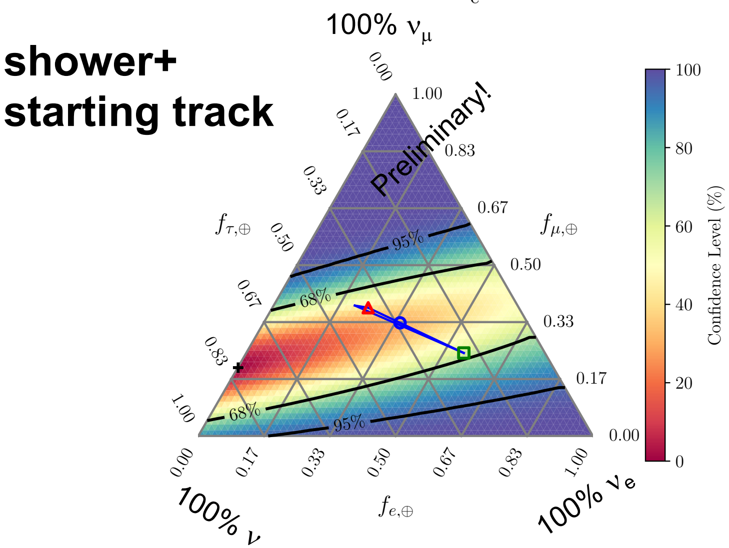


Double cascade Event #2

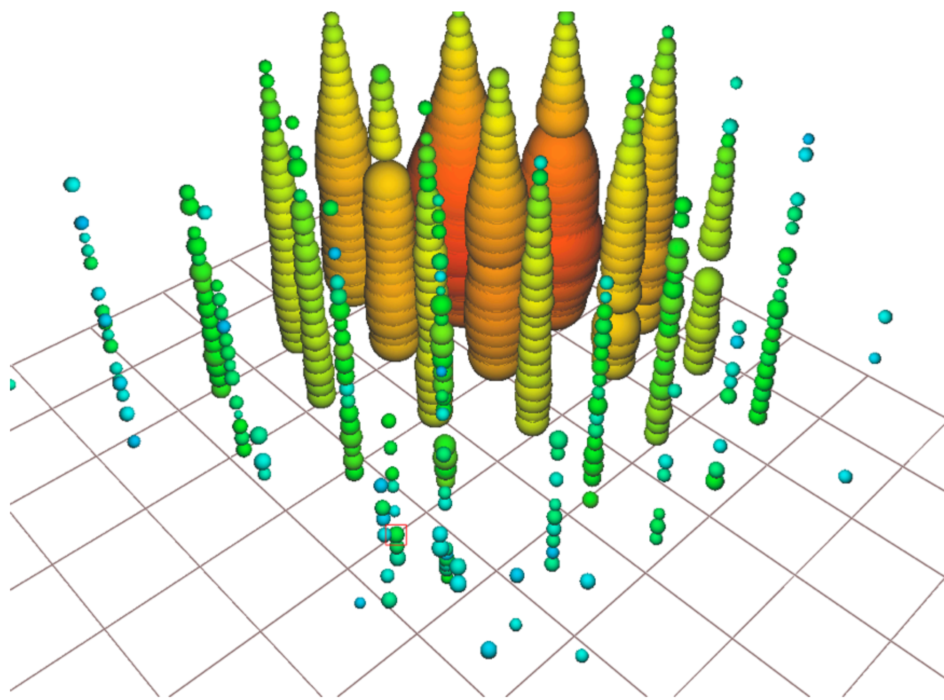
Neutrino Sky: Latest Updates

- Neutrino flavor

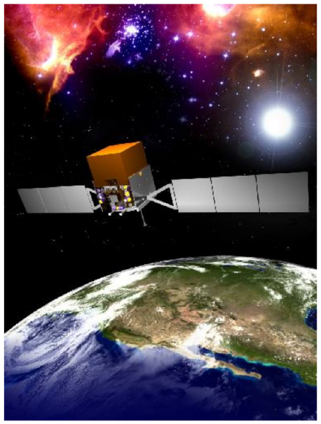


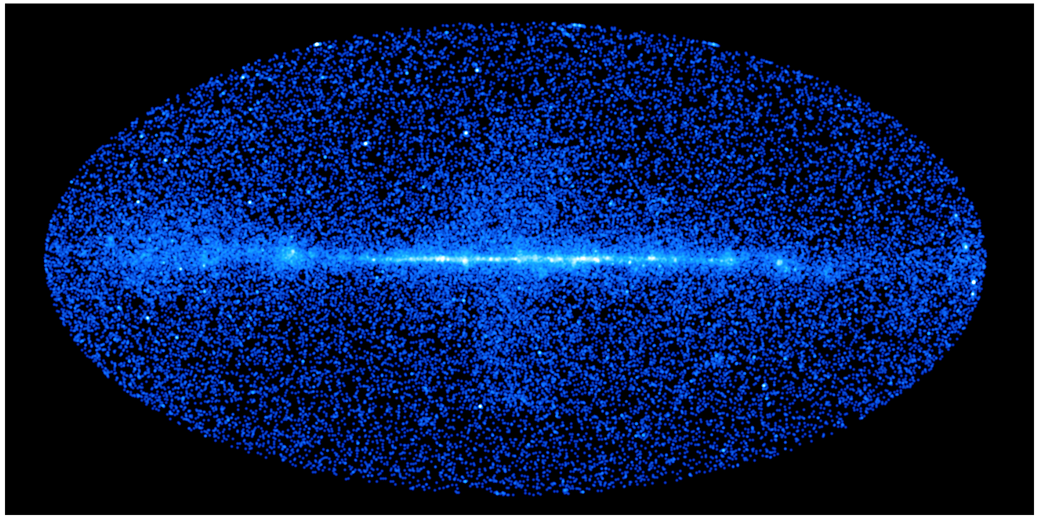


- 5.9 PeV event (deposited) in PEPE (PeV Energy Partially-contained Events)
- Could be a Glashow event at E=6.3 PeV?

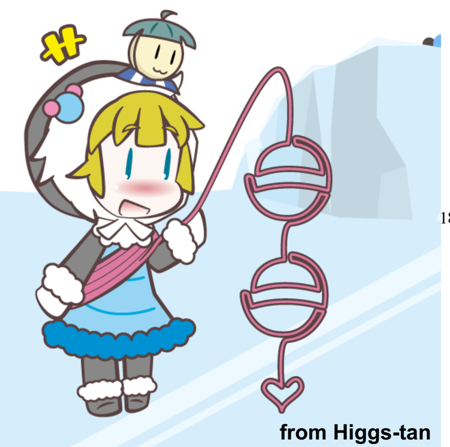


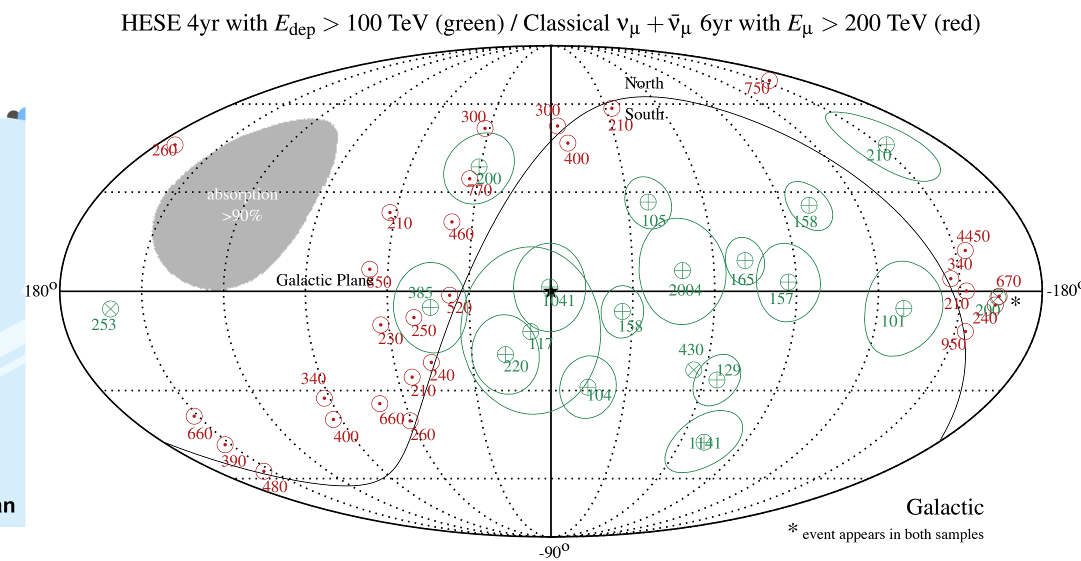
Sources?





~3000 sources (3FGL)

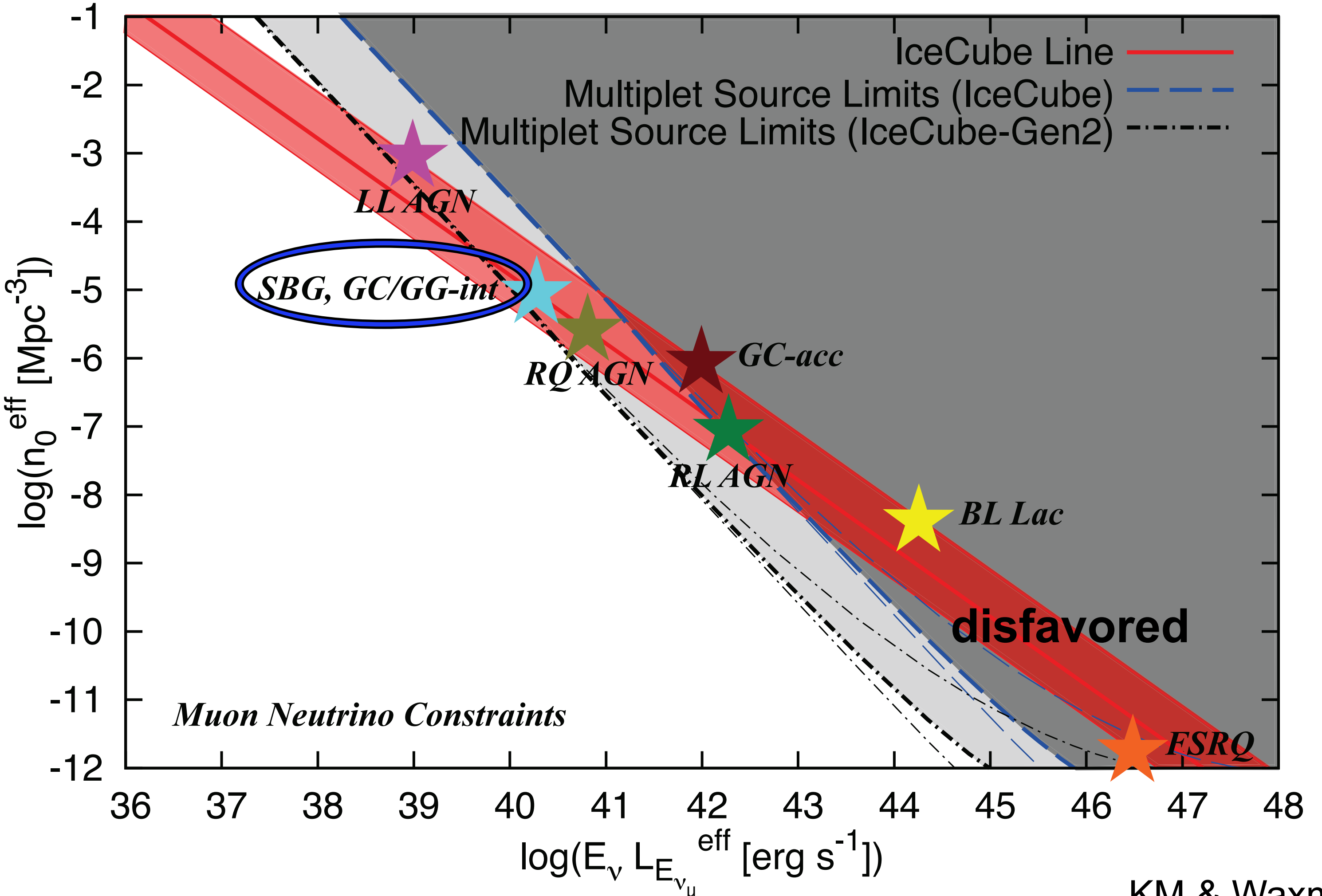




0 source yet

(maybe fishy one?)

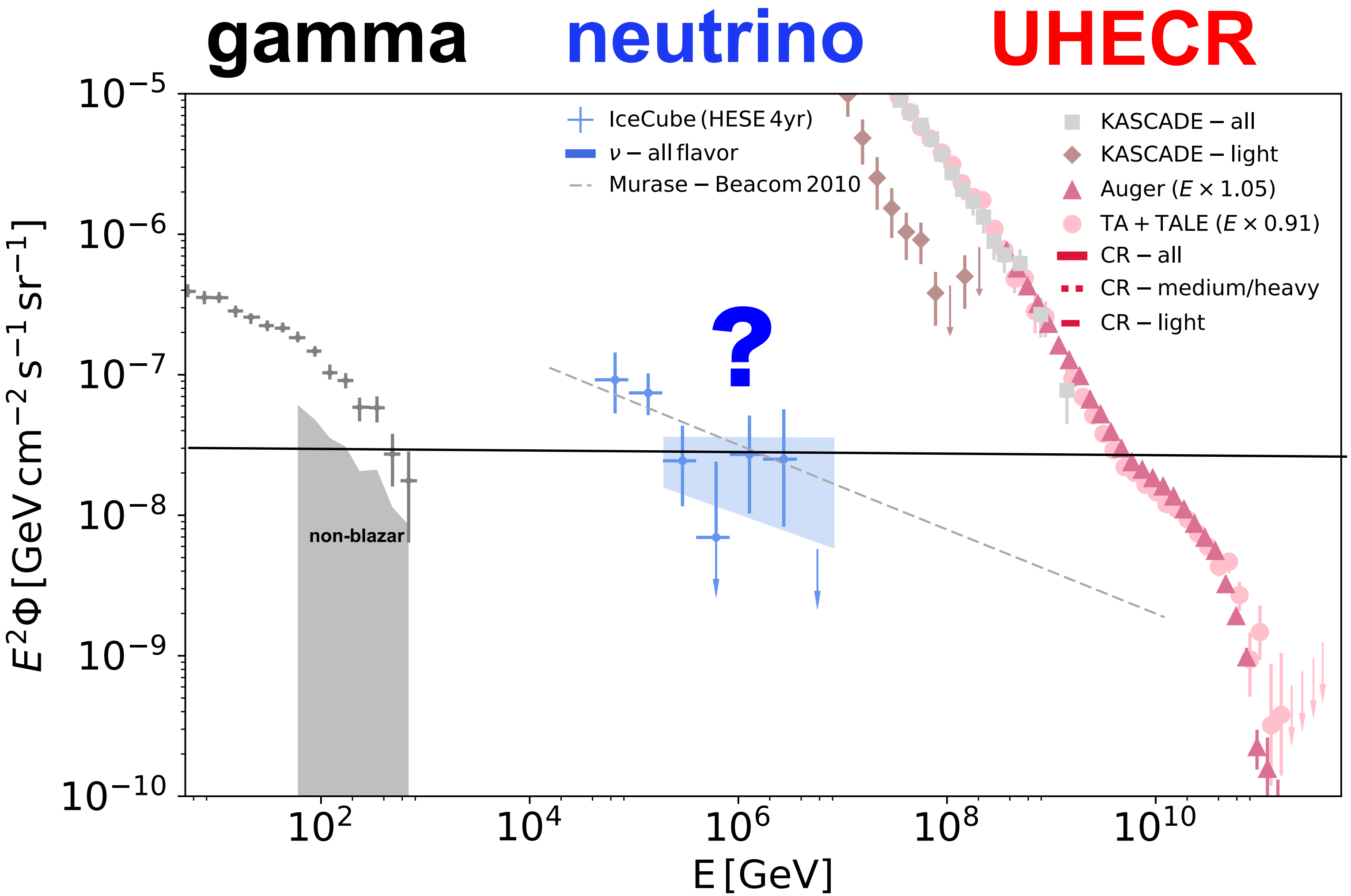
Constraints from Non-Detection of Neutrino Clustering



KM & Waxman 16 PRD

Non-detection of "multiplet" neutrino sources give limits on the number density
Source-identification is possible with Gen2 for known astrophysical candidates

Multi-Messenger Cosmic Particle Backgrounds



Energy generation rates are all comparable to a few x 10^{43} erg Mpc^{-3} yr^{-1}

Astrophysical Extragalactic Scenarios

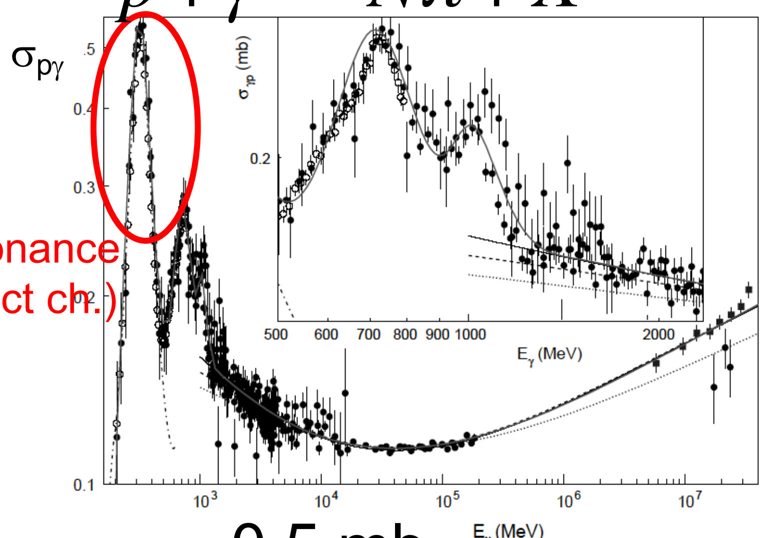
$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-ray Accelerators (ex. UHECR candidate sources)

Active galactic nuclei

γ-ray burst

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

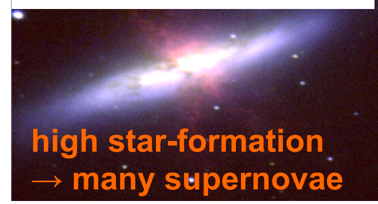


$\sigma_{p\gamma} \sim \alpha \sigma_{pp} \sim 0.5$ mb

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

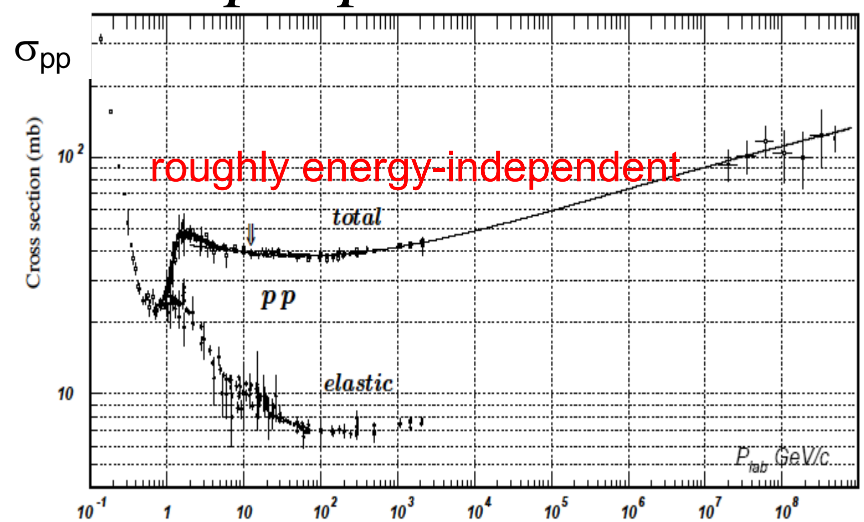
Cosmic-ray Reservoirs

Starburst galaxy



Galaxy group/cluster

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



$\sigma_{pp} \sim 30$ mb

Fate of High-Energy Gamma Rays

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

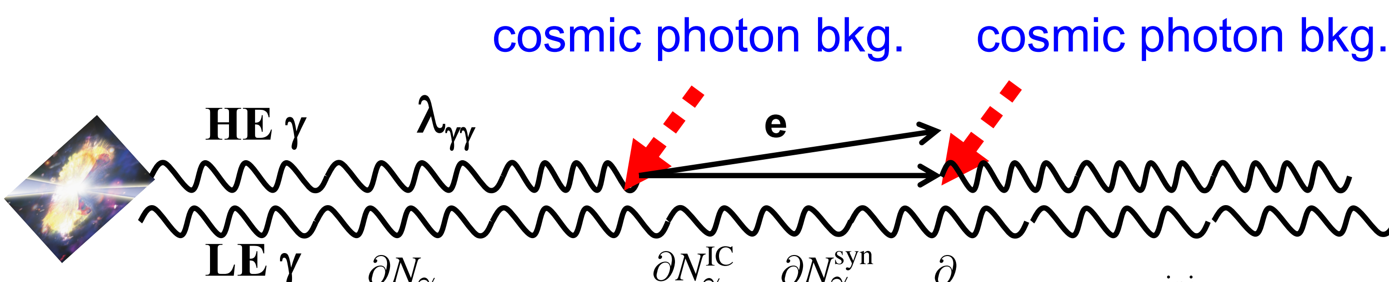
$p + \gamma \rightarrow N\pi + X$ $\pi^{\pm}:\pi^0 \sim 1:1 \rightarrow$ **$E_\gamma^2 \Phi_\gamma \sim (4/3)\, E_\nu^2 \Phi_\nu$**

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

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

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

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



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

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

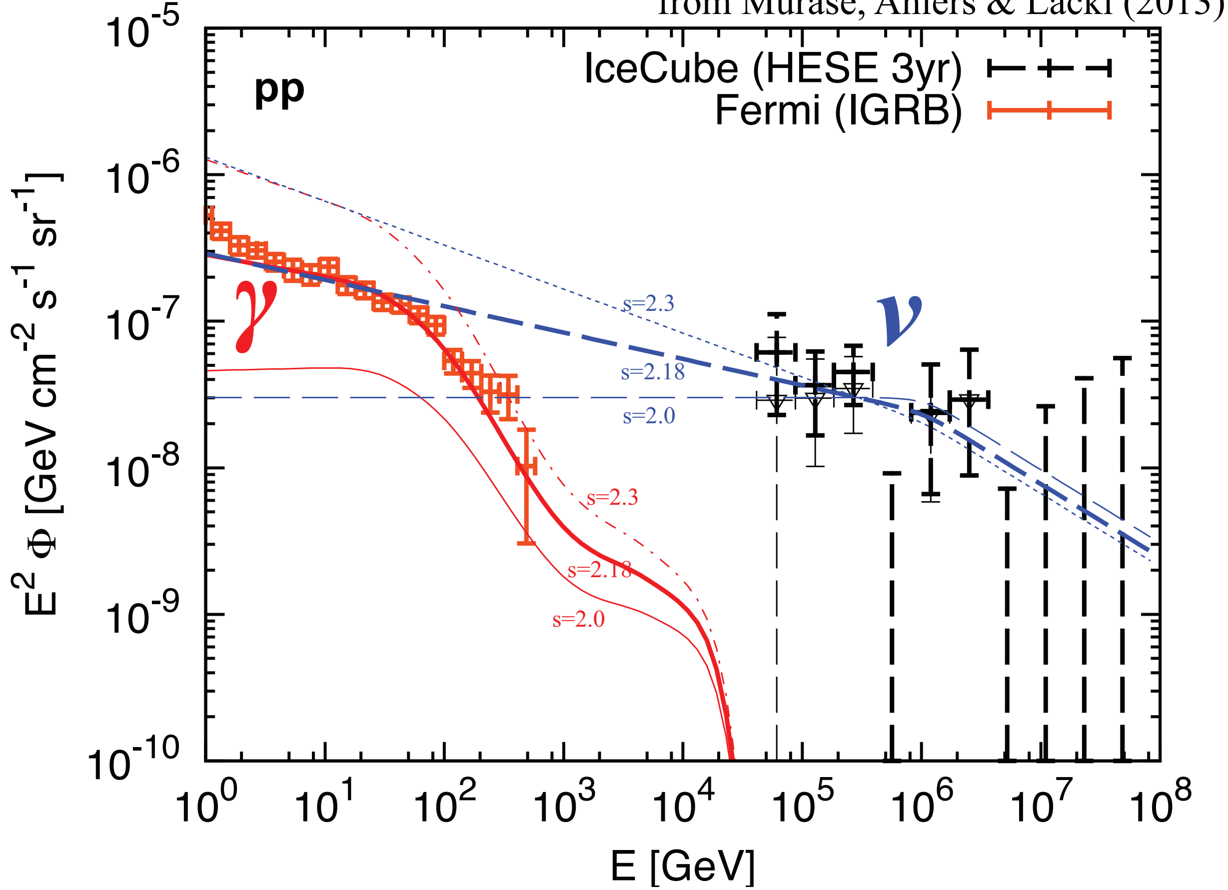
Fermi satellite

airshower detectors

Generic Neutrino and Gamma-Ray 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)

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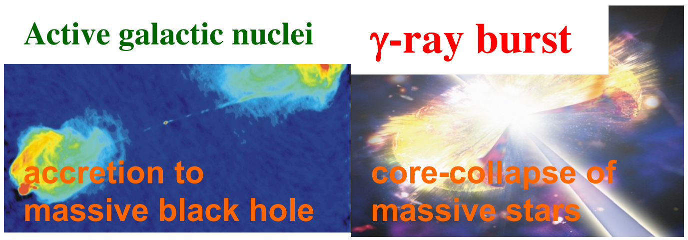
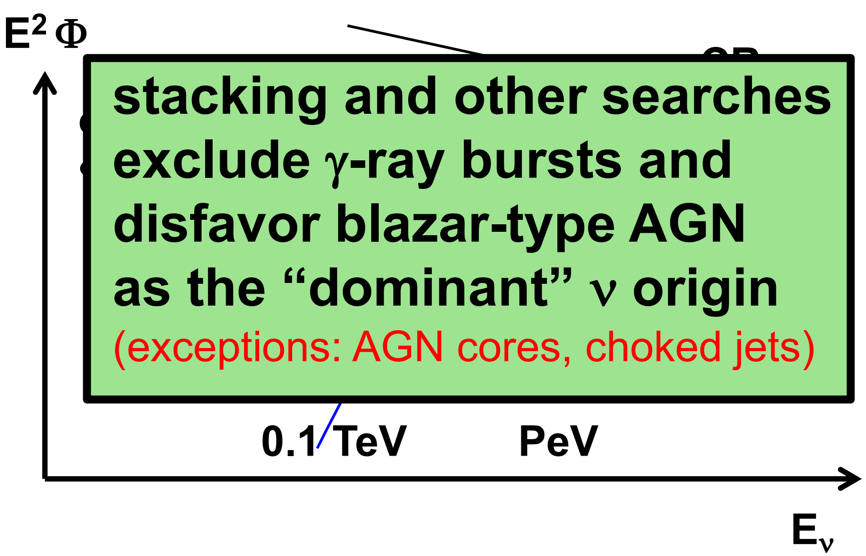


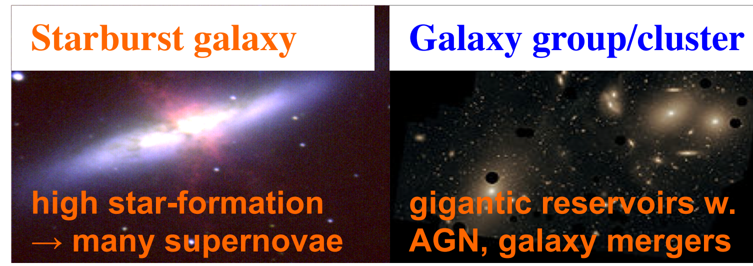
$$p + \gamma \rightarrow N\pi + X$$



stacking and other searches exclude γ-ray bursts and disfavor blazar-type AGN as the "dominant" ν origin

(exceptions: AGN cores, choked jets)

Cosmic-ray Reservoirs



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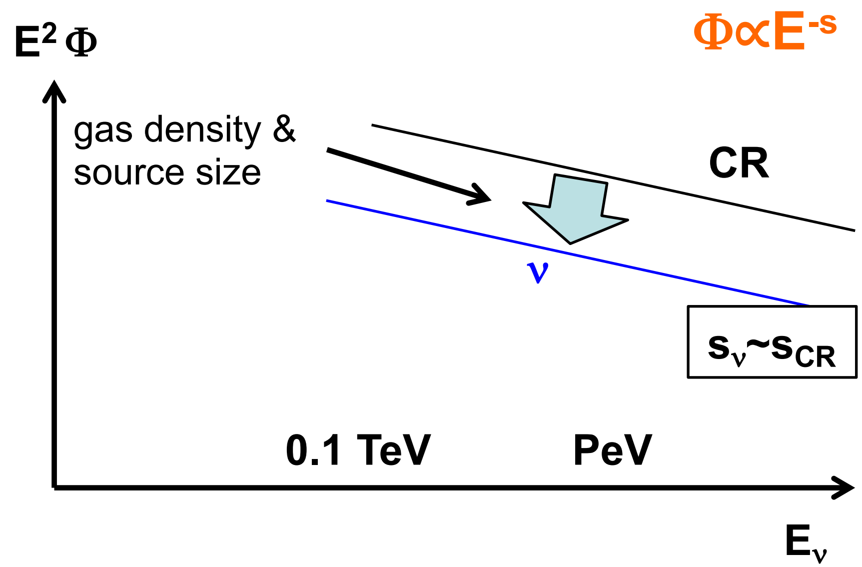
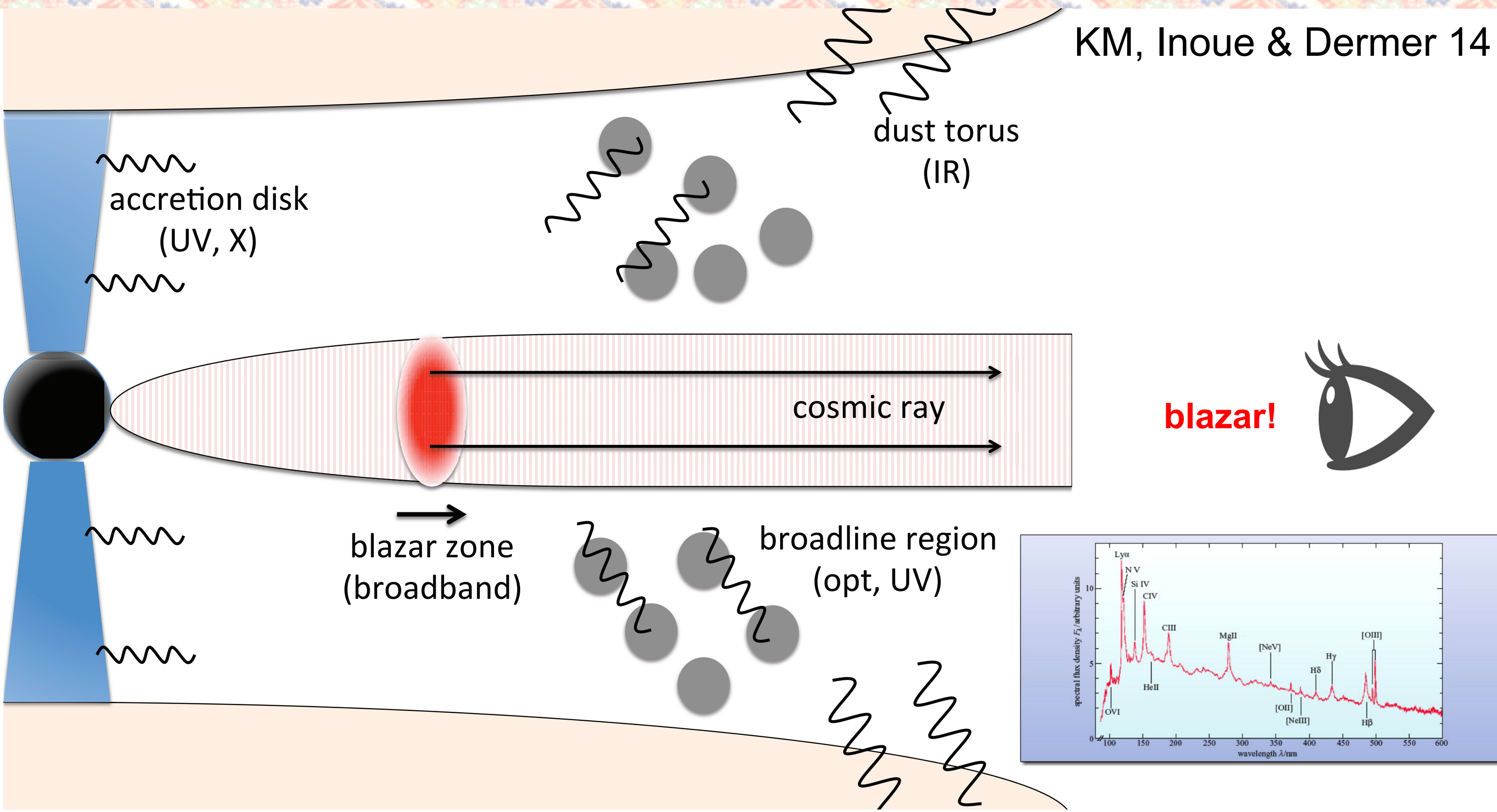


Photomeson Production in AGN Jets

KM, Inoue & Dermer 14



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

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

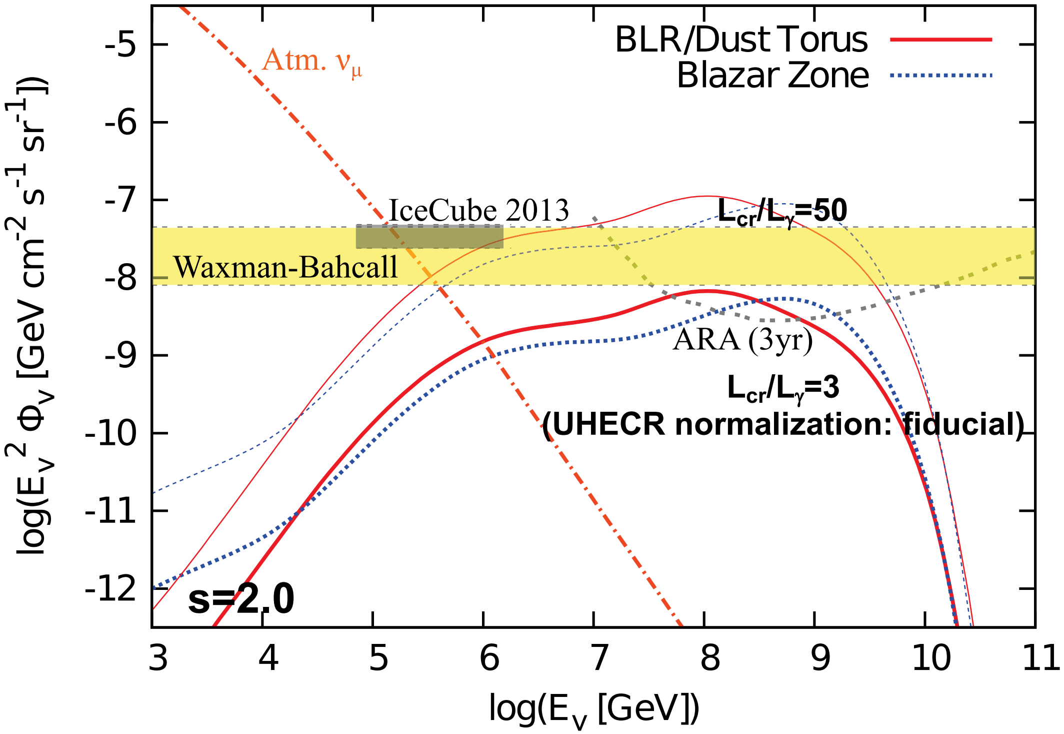
$$E'^{b}_{\nu} \approx 0.05 (0.5 m_p c^2 \bar{\varepsilon}_\Delta / E'_{\rm BL}) \simeq 0.78 \text{ PeV}$$ **BLR photons**

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

Blazars as Powerful EeV ν Sources

Blazar (radio galaxy) = BL Lacs (FR-I) + FSRQs (FR-II)

- FSRQs: efficient ν production, dominant in the neutrino sky
- BL Lacs: inefficient ν production, dominant in the UHECR sky as FR-I

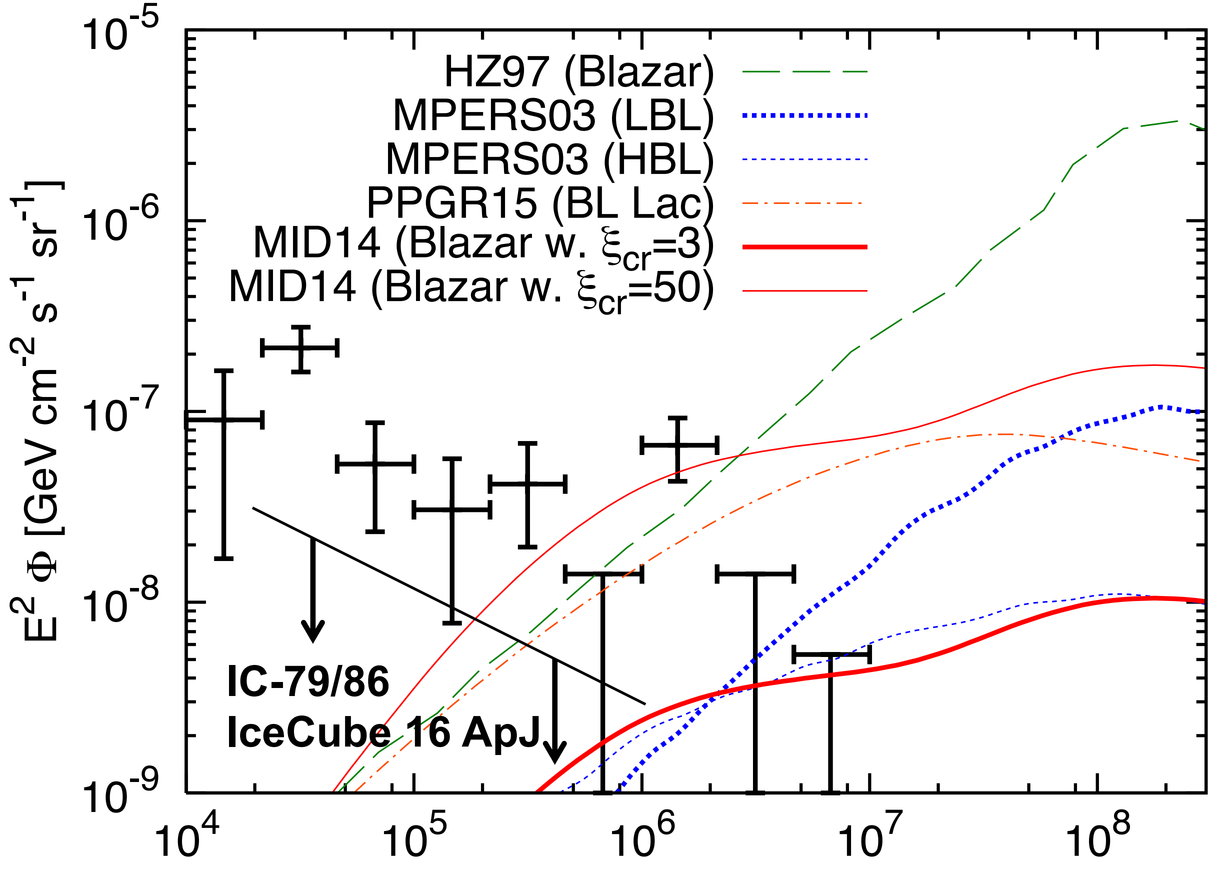


KM, Inoue & Dermer 14 PRD

- Unique ν spectrum: PeV ν by BLR photons & EeV ν by dust IR photons
- Only bright FSRQs are dominant -> promising source identification
- Consistent w. IceCube (1-10% at PeV), UHECRs are isotropized at kpc-Mpc

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)

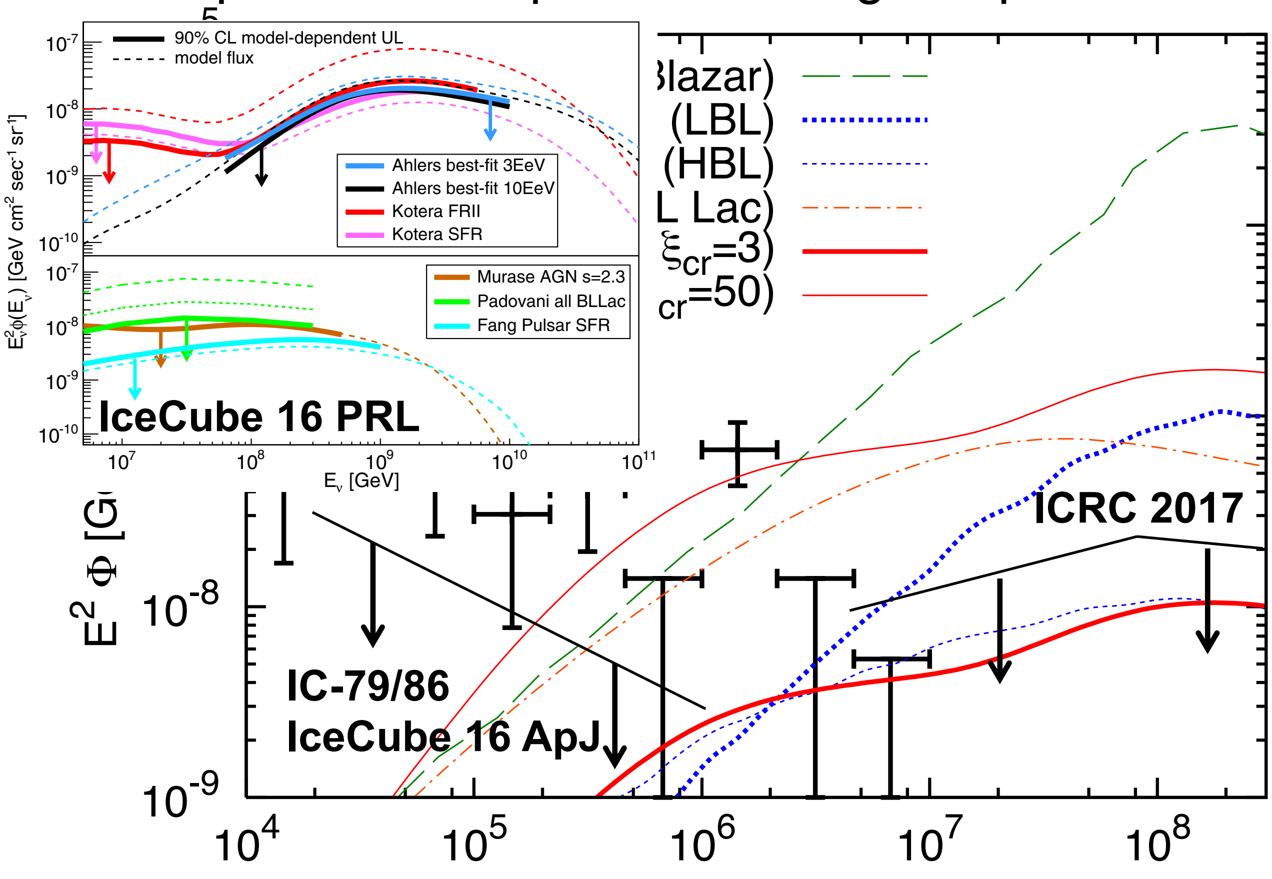
leptonic w. UHECR norm. BL Lacs + FSRQs

from KM 1511.01590

HE Neutrinos from AGN Jets: Constraints

Standard simplest jet models as UHECR accelerators: many constraints…

- Blazars: power-law CR spectra & known SEDs→ hard spectral shape
  IceCube 9-yr EHE analyses give a limit of $<10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} at 10 PeV
- Give up IceCube explanation OR give up UHECRs (ex. Dermer, KM & Inoue 14
  Tavecchio+14,
  Tavecchio & Ghisellini 15)



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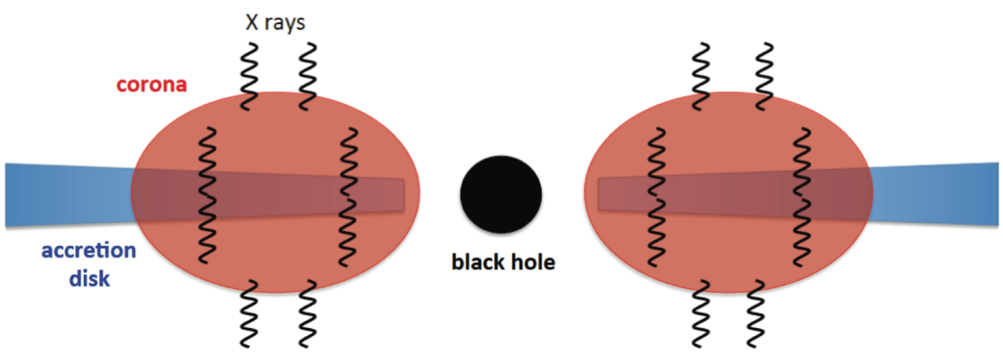
lepto-hadronic w. γ-ray norm.
BL Lacs (w.o. external fields)

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

from KM 1511.01590

AGN Cores as Neutrino Factories



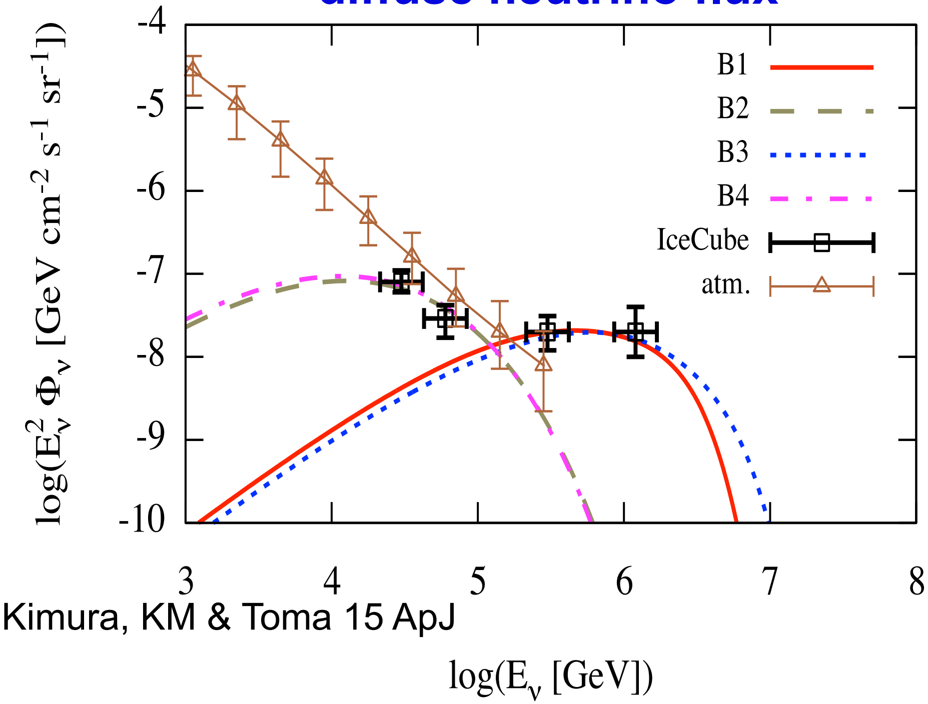
Seyfert/Quasar AGN

standard accretion disk -> collisional
CR acceleration is inefficient

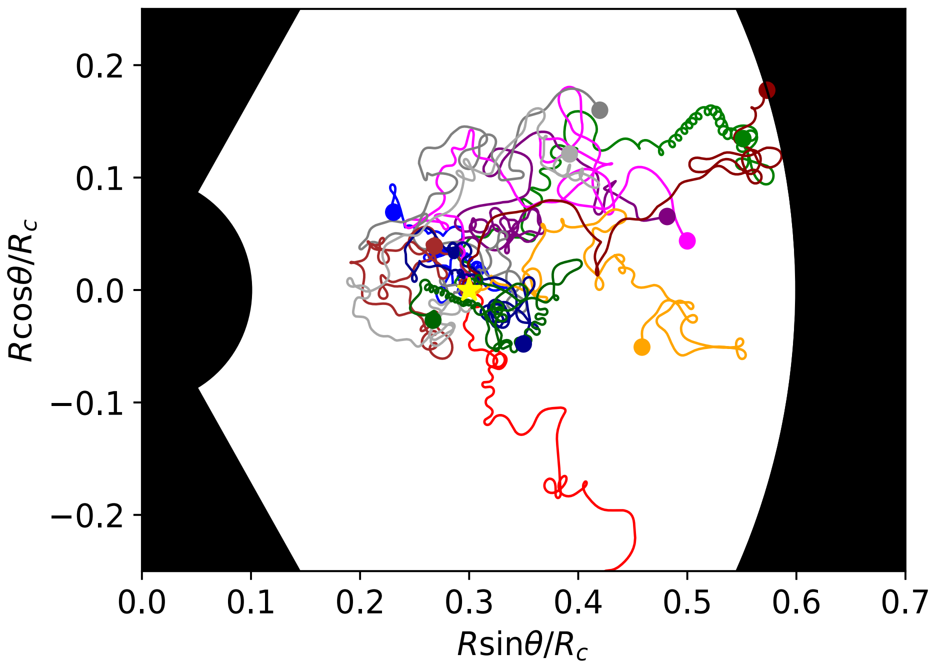
Low-luminosity AGN

accretion disk is “radiatively inefficient”
collisionless -> promising CR acceleration
supported by simulations & observations

diffuse neutrino flux



Kimura, KM & Toma 15 ApJ



Kimura, KM & Tomida 19 MNRAS

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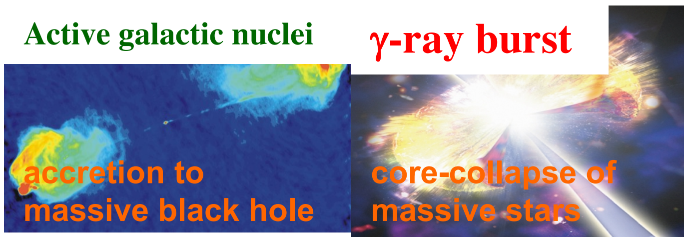

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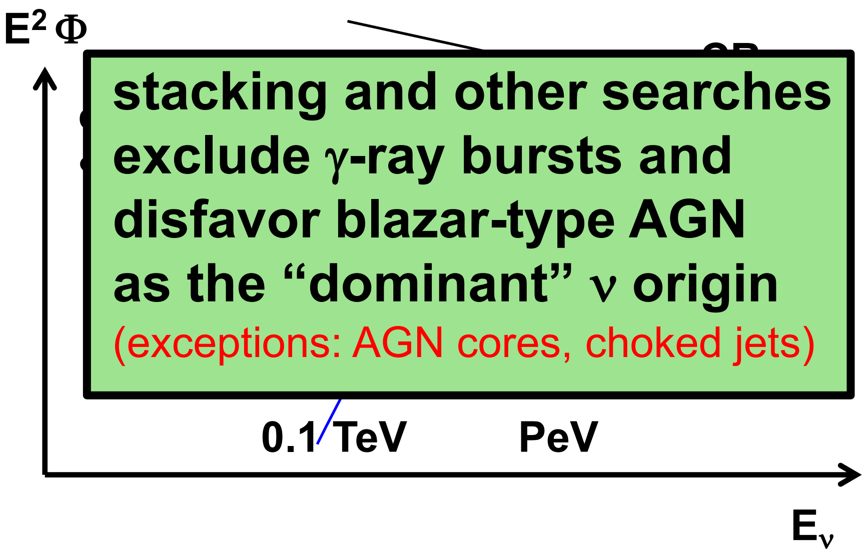

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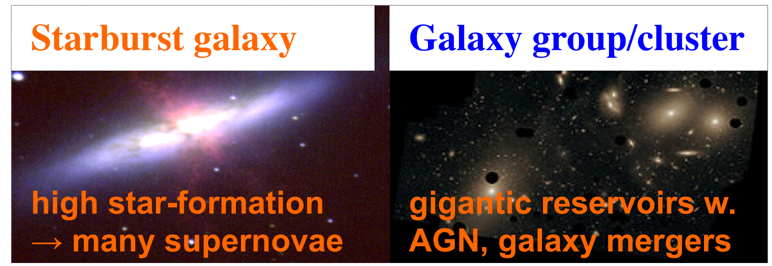
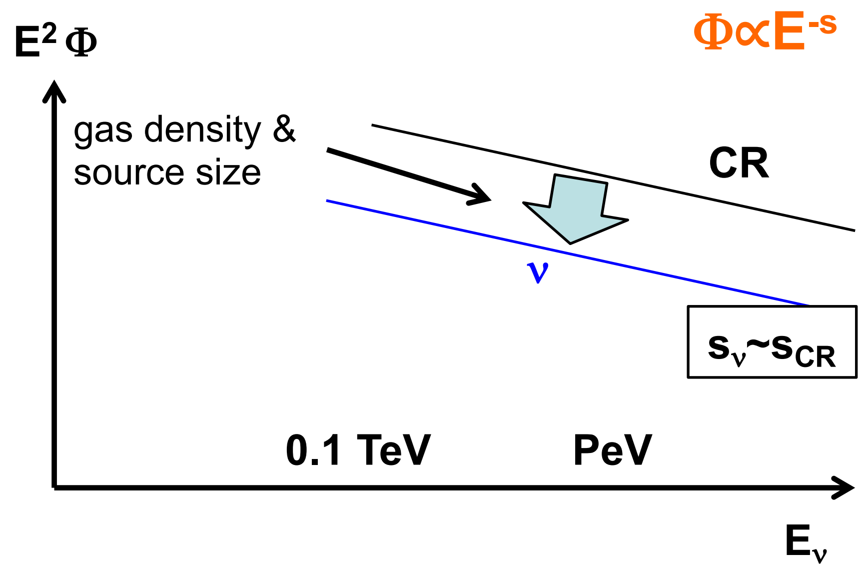
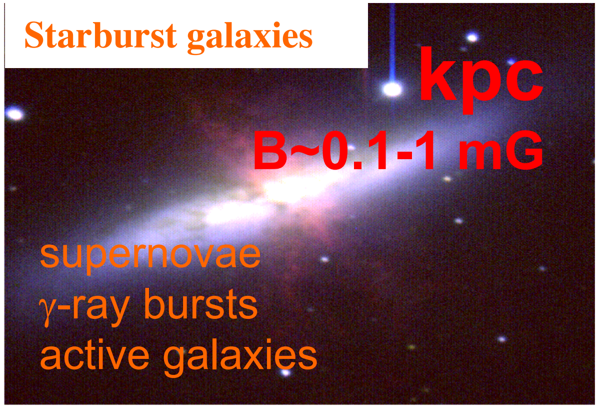
Cosmic-ray Reservoirs



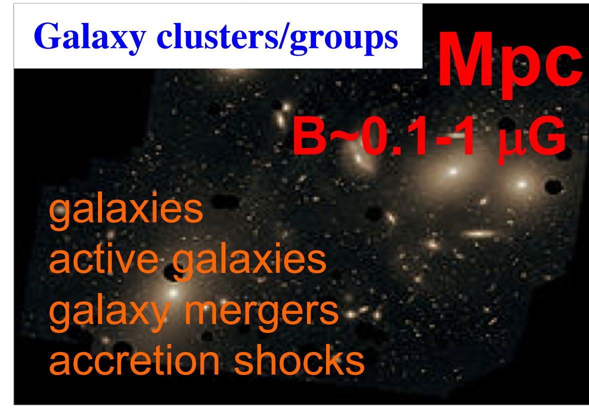
$$p + p \rightarrow N\pi + X$$

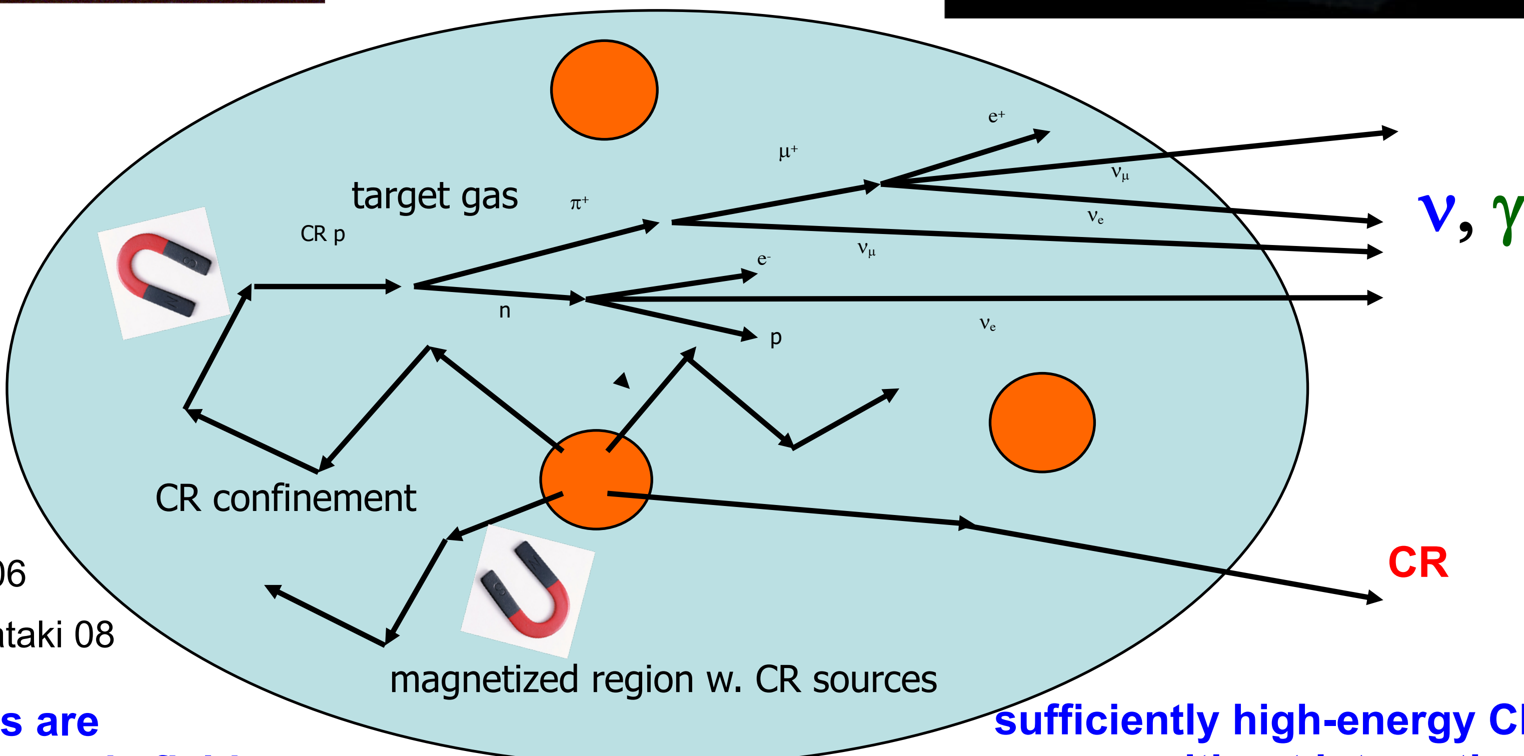


Cosmic-Ray Reservoirs



"cosmic-ray reservoirs"



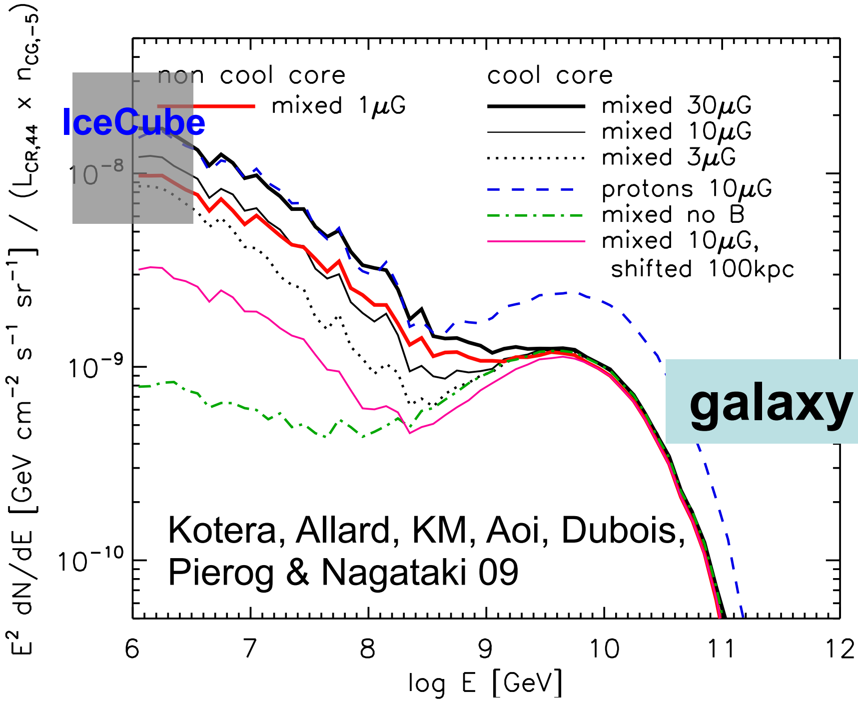


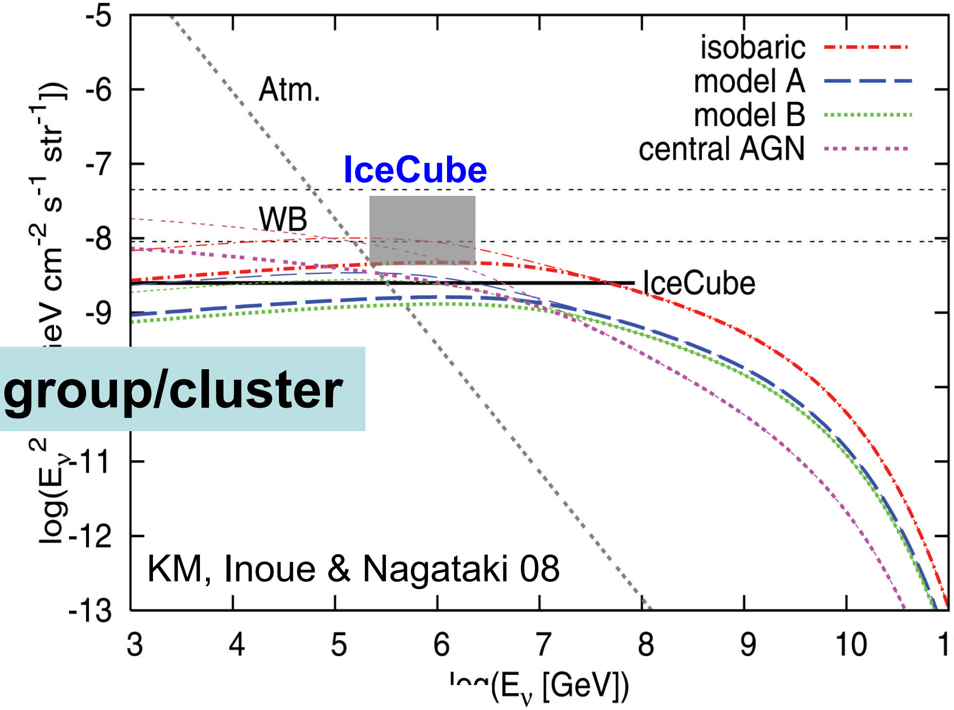
Loeb & Waxman 06

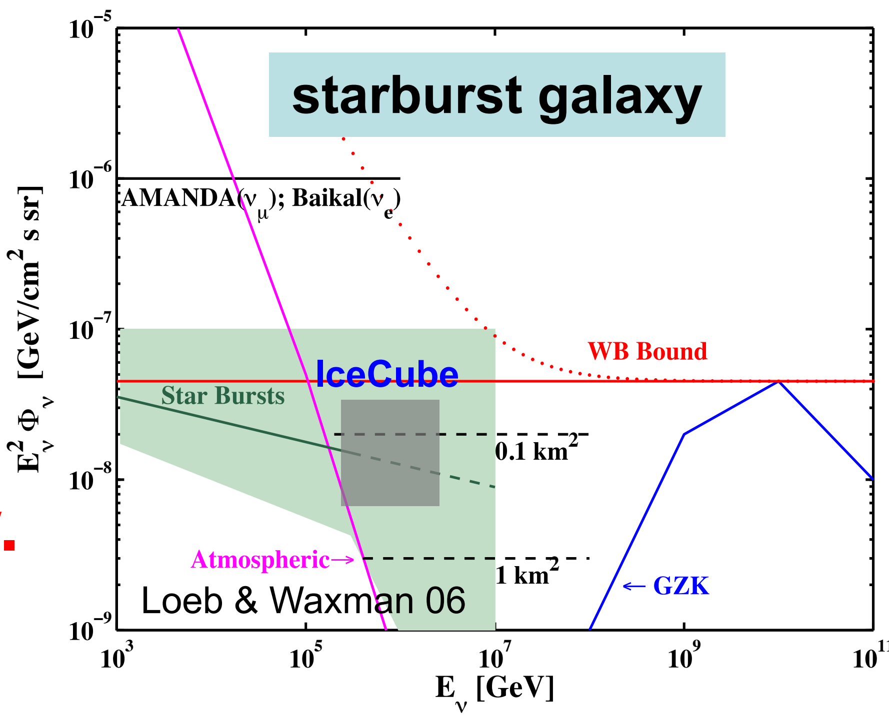
KM, Inoue & Nagataki 08

low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions







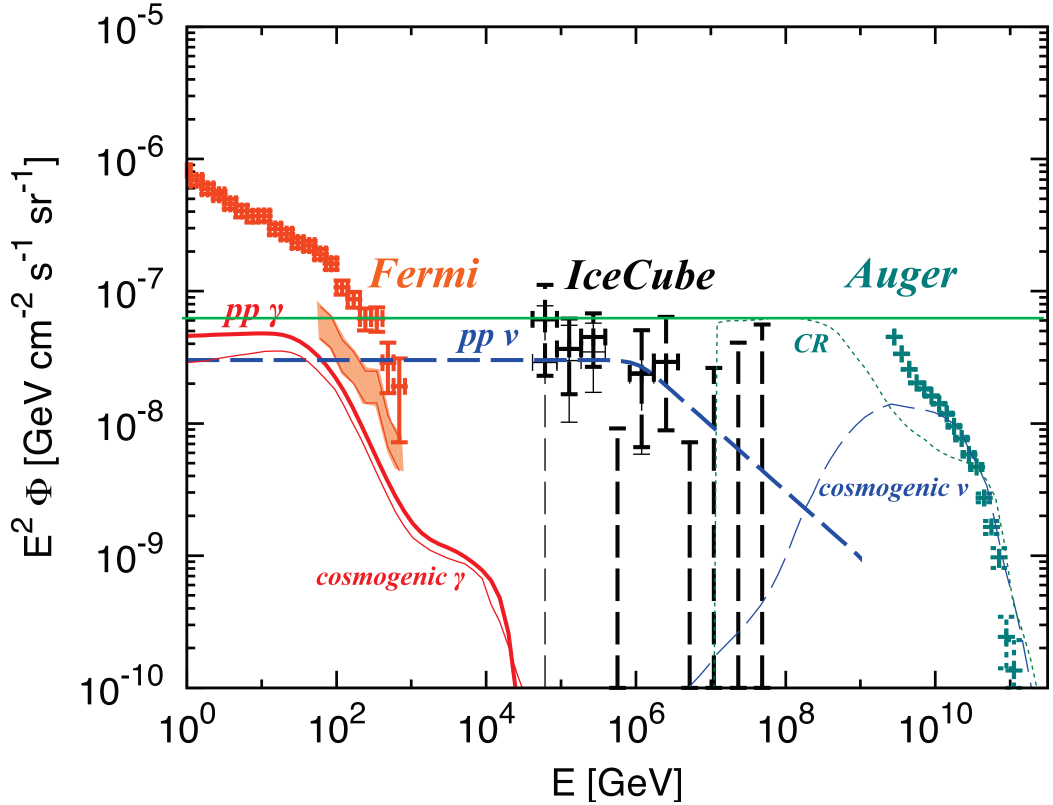
Consistent w. predictions

Neutrino-Gamma-UHECR Connection?

Grand-unification of neutrinos, gamma rays & UHECRs

simple hard CR 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
EeVν – cosmogenic ν
sub-TeVγ – confined CR
cosmogenic γ

Neutrino-Gamma-UHECR Connection?

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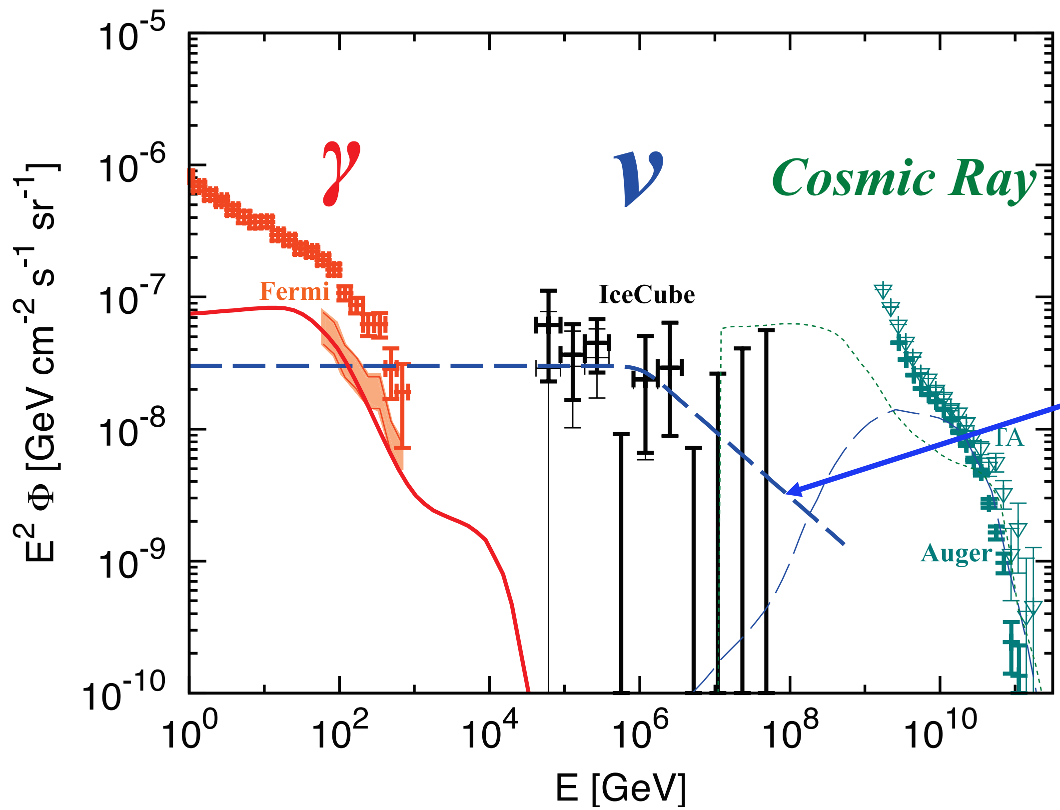


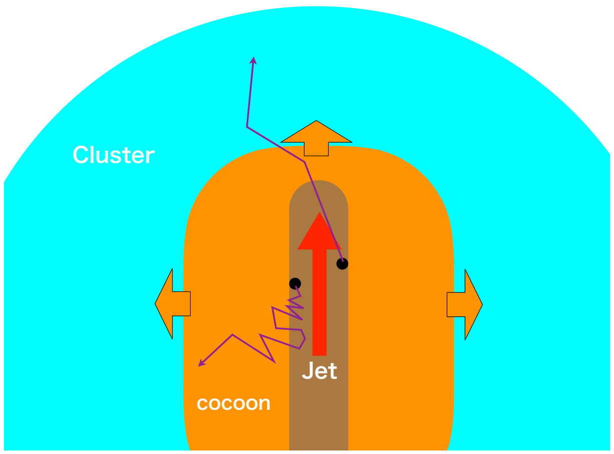
KM & Waxman 16 PRD

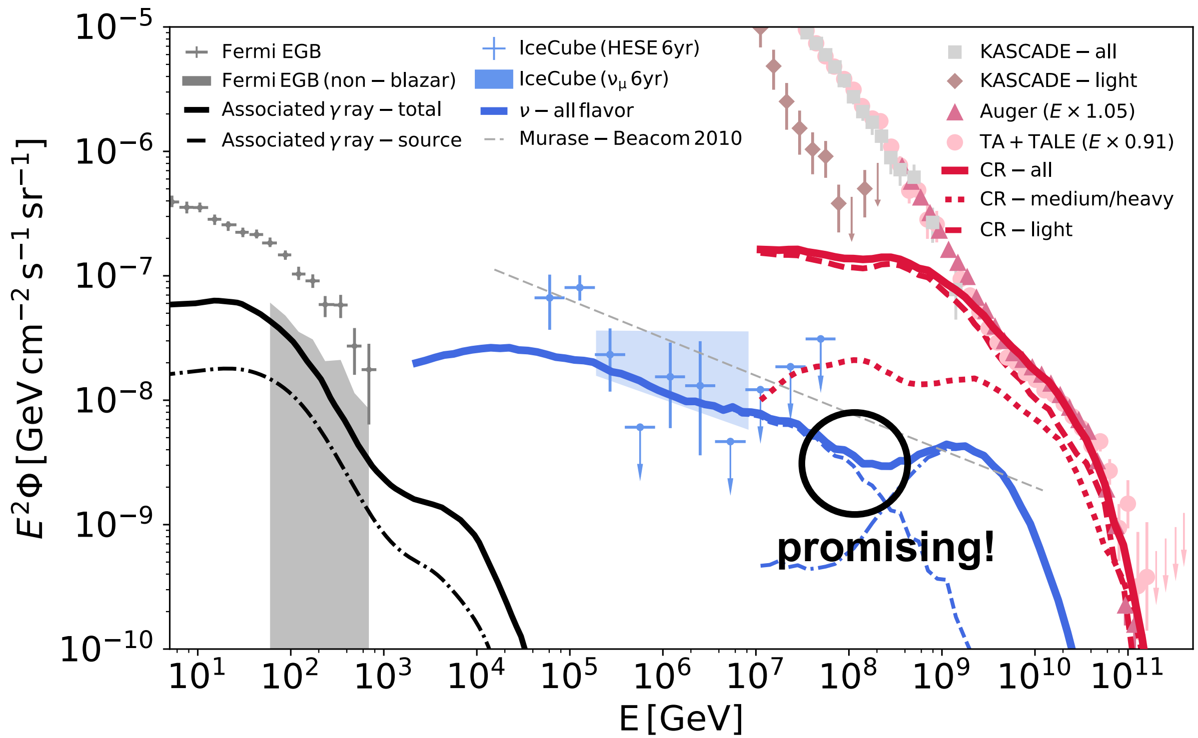
~3x10^{-9} GeV/cm^2/s/sr at ~100 PeV

PeVν – confined CR
UHECR – escaping CR
EeVν – cosmogenic ν
sub-TeVγ – confined CR
cosmogenic γ

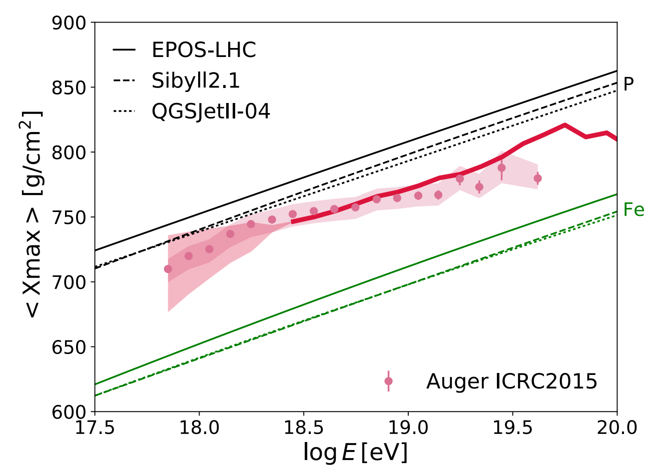
Ex. AGN Embedded in Galaxy Clusters/Groups

- AGN as "UHECR" accelerators
- confinement in cocoons & clusters
- escaping CR nuclei: harder than CR protons
- smooth transition from source ν to cosmogenic ν





Fang & KM 18 Nature Physics

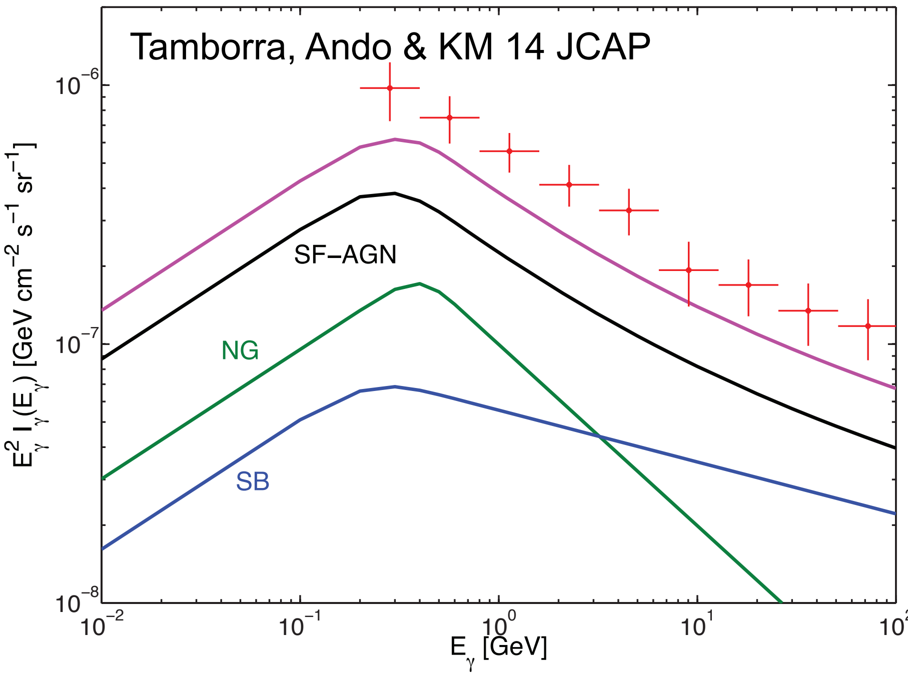


Unifying >0.1 PeV ν, sub-TeV γ, and UHECRs
(including proton ankle at 100 PeV & composition)

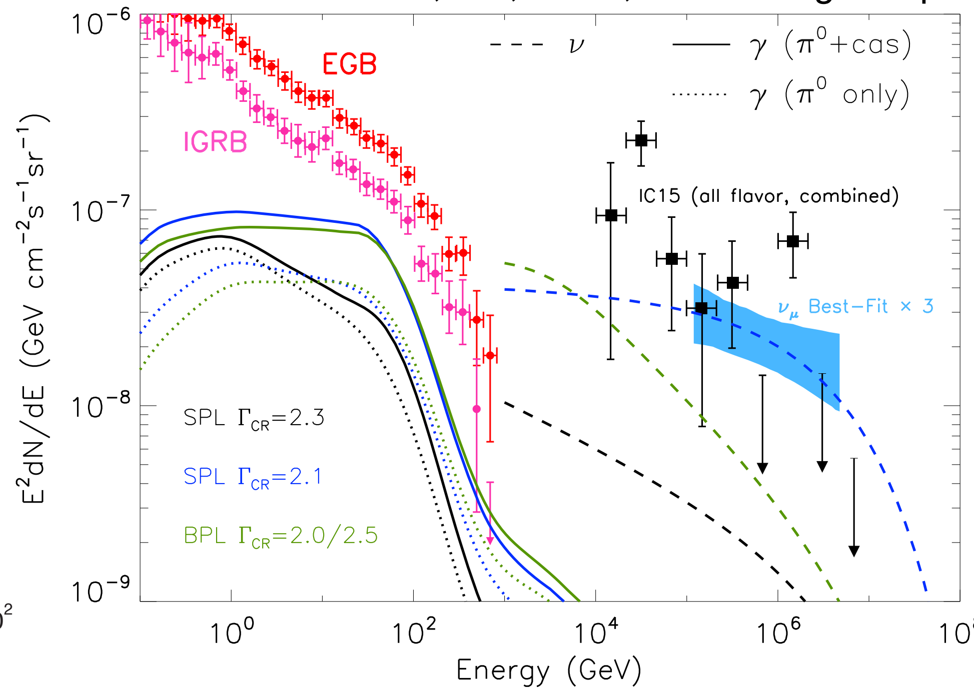
Ex. Star-Forming Galaxies w. AGN

Starbursts can potentially explain ν and γ simultaneously but...

1. CR accelerators are more powerful than supernovae (beyond the knee)
2. Diffusion should be much slower than expected from that of our Galaxy
3. Tension with Fermi and IACT data (normalization & photon index)



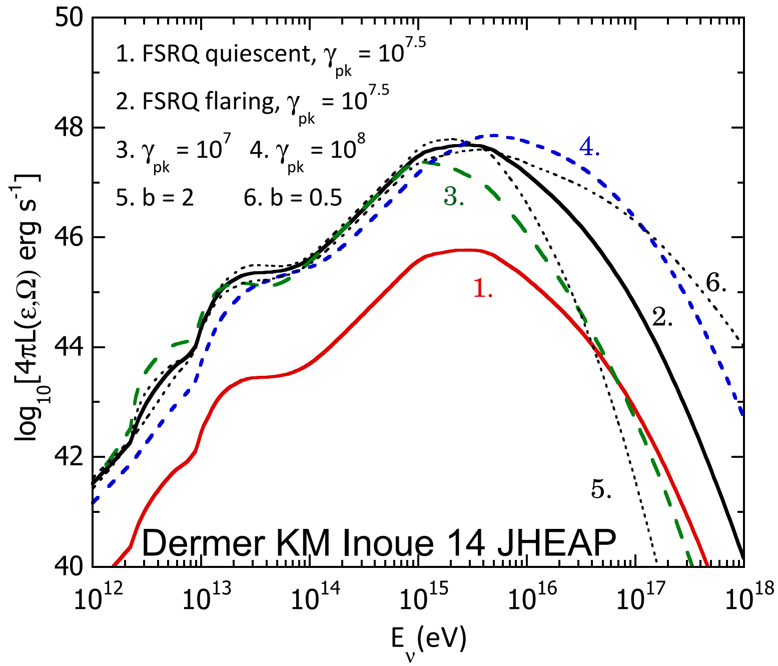
Liu, KM, Inoue, Ge & Wang 18 ApJ



1. Disk-driven winds are likely to accelerate CRs up to ~10-100 PeV
2. Diffusion coefficients can be smaller from those of star-forming galaxies
3. Consistent w. Fermi limits and CR spectra can be harder

Blazar Flares?

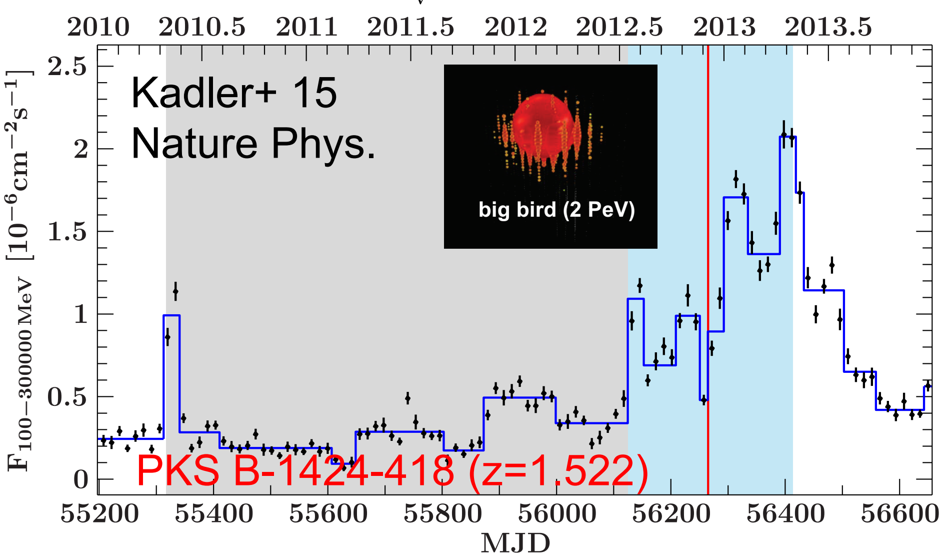
Blazar Flares?

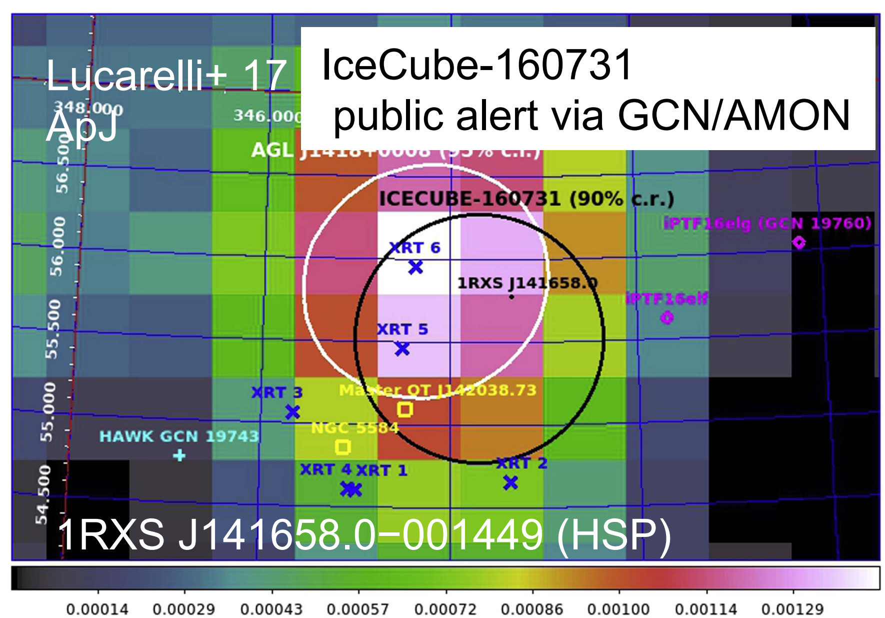


Good chances to detect them
even if subdominant in the diffuse ν sky

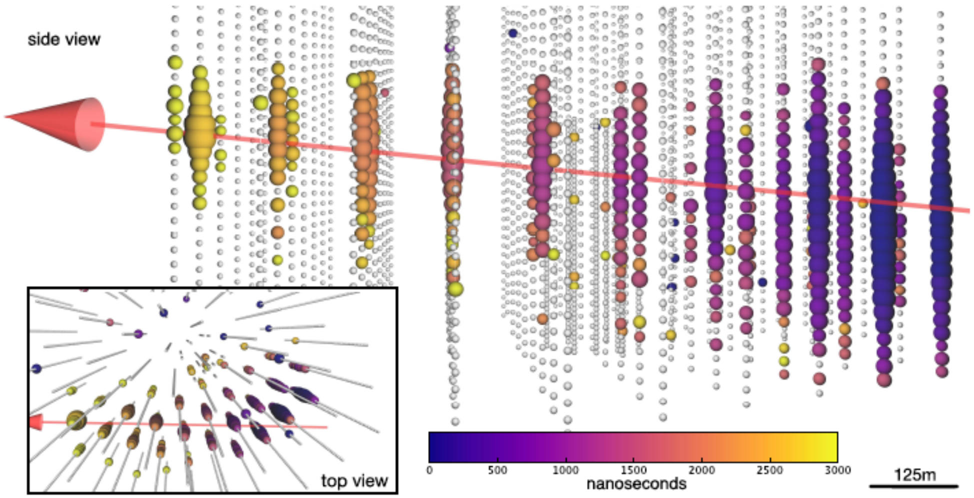
1. Observational reason:
   temporal & spatial coincidence
2. Theoretical reason
   “enhanced“ jet power + target photons

(see e.g., KM & Waxman 16, KM et al.18)

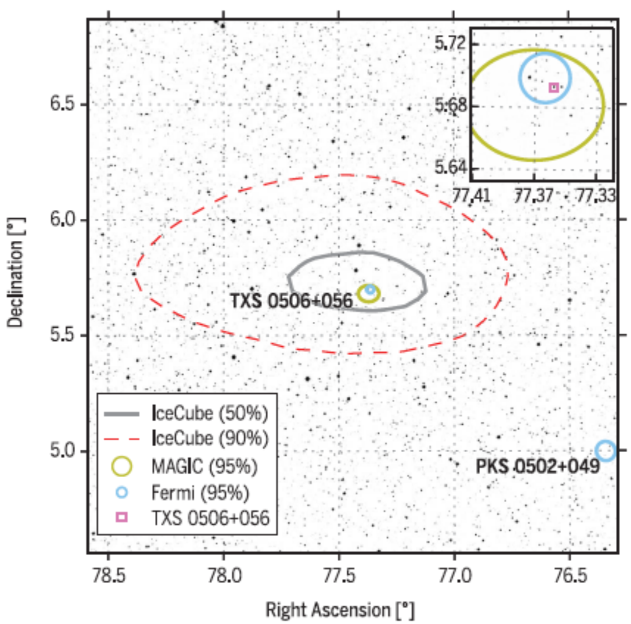




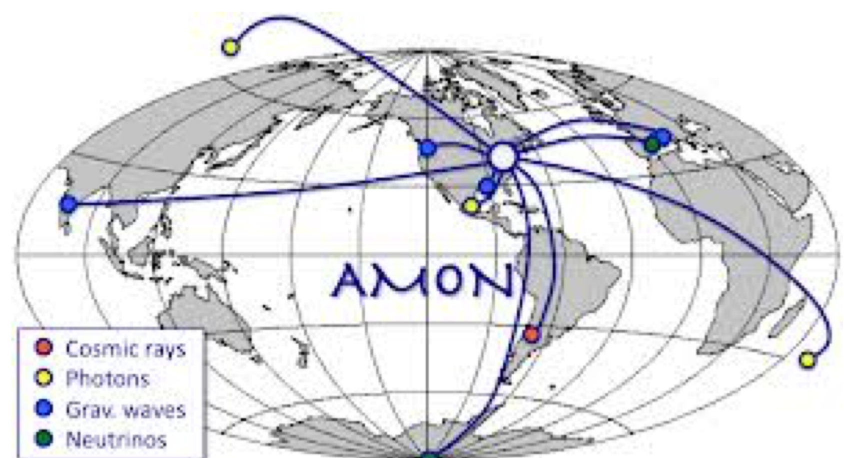
IceCube 170922A & TXS 0506+056



IceCube 2018 Science

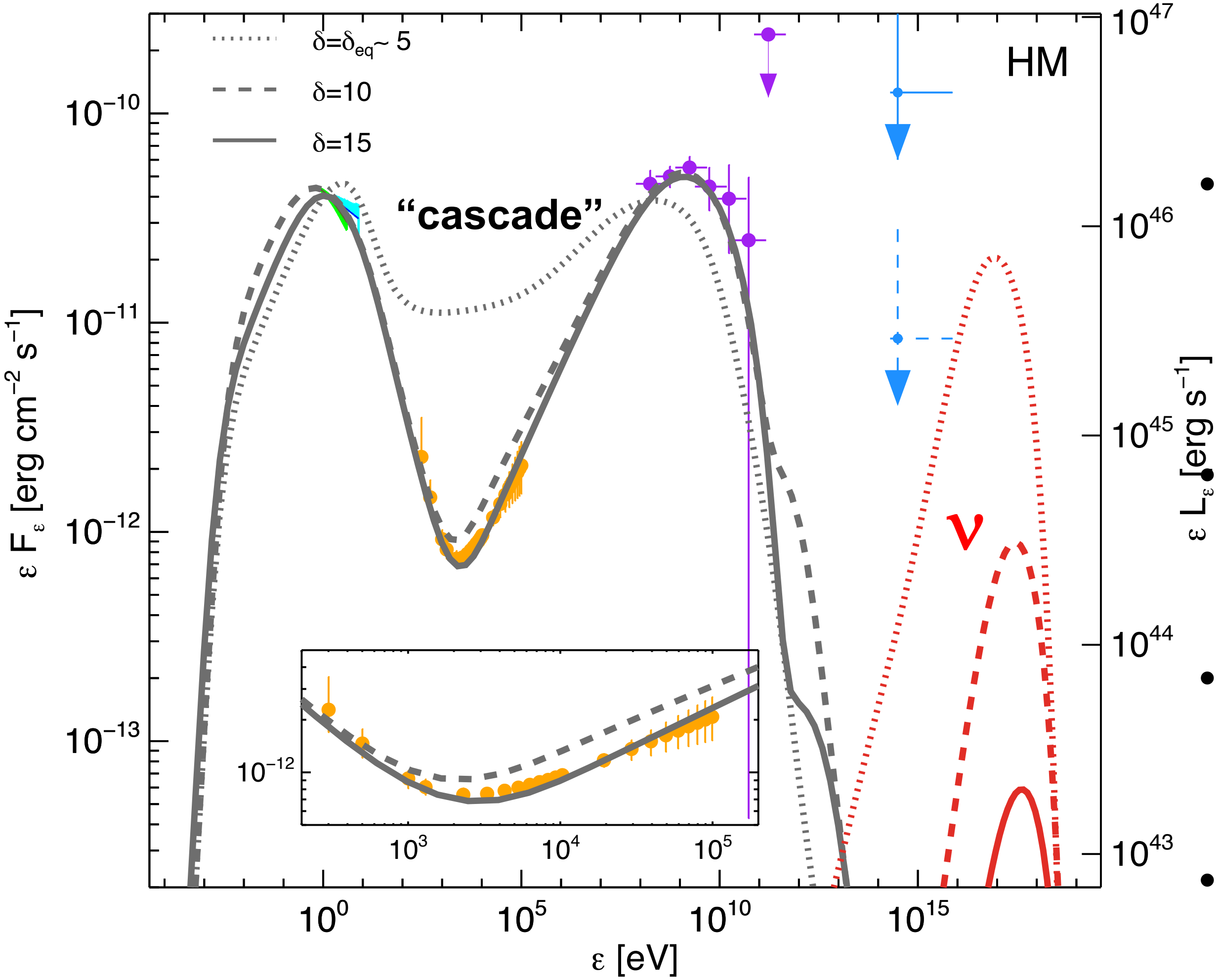


- IceCube EHE alert pipeline
- Automatic public alert (through AMON/GCN)
- Kanata observations of blazars -> Fermi-LAT (Tanaka et al.) ATel #10791 (Sep/28/17)
- X-ray observations reported by members of Penn State people
- Swift (Keivani et al.) GCN #21930, ATel #10942 NuSTAR (Fox et al.) ATel #10861



TXS 0506+056 SED Modeling: Hadronic

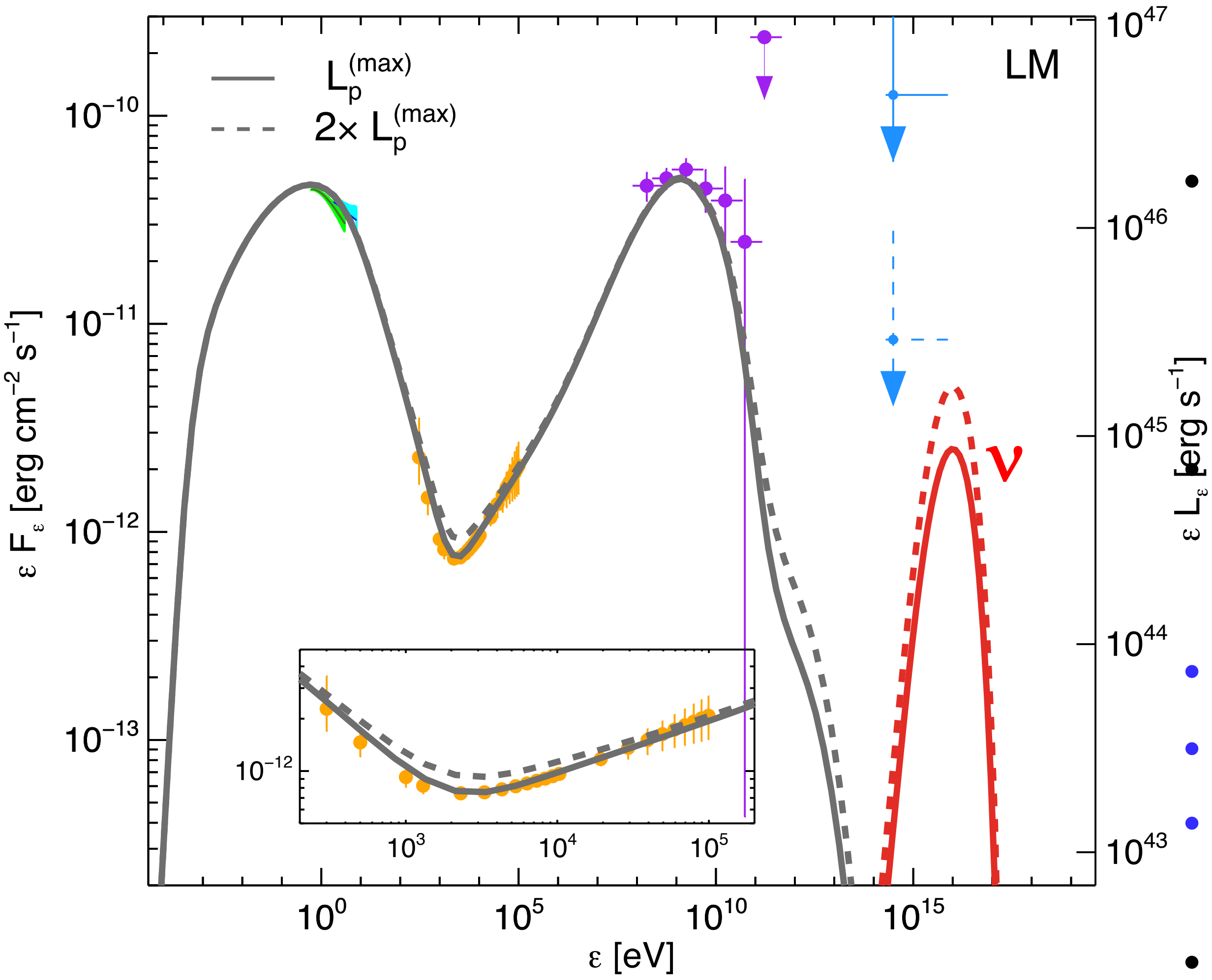
Keivani, KM, Petropoulou, Fox et al. 2018 ApJ



- Swift-UVOT/X-Shooter, Swift-XRT/NuSTAR Fermi-LAT data
- UVOT/X-Shooter $\nu_{syn}<3\times10^{14}$ 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
- IC-170922A event CANNOT be explained by the hadronic scenario

TXS 0506+056 SED Modeling: Leptonic

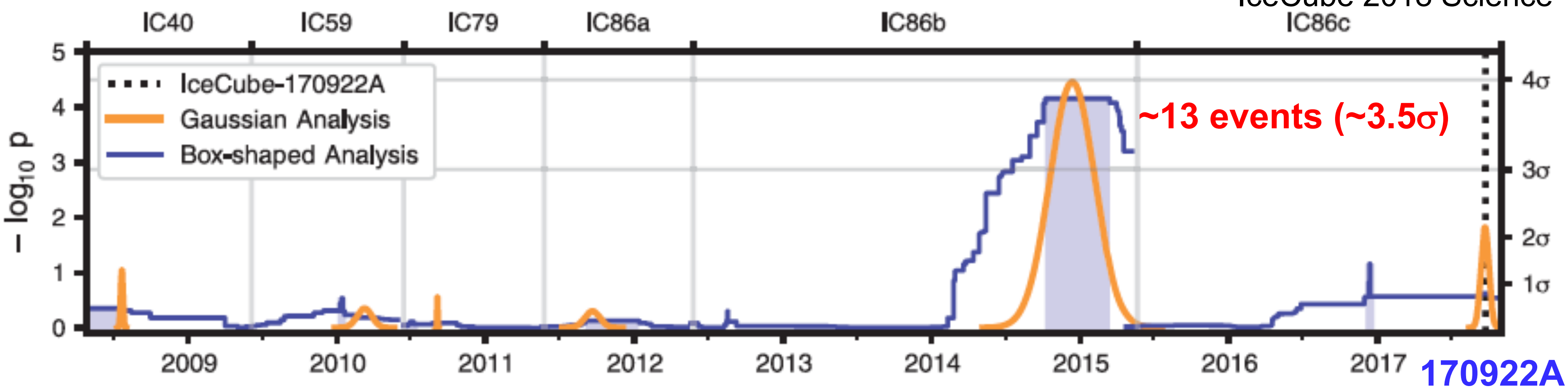
Keivani, KM, Petropoulou, Fox et al. 2018 ApJ



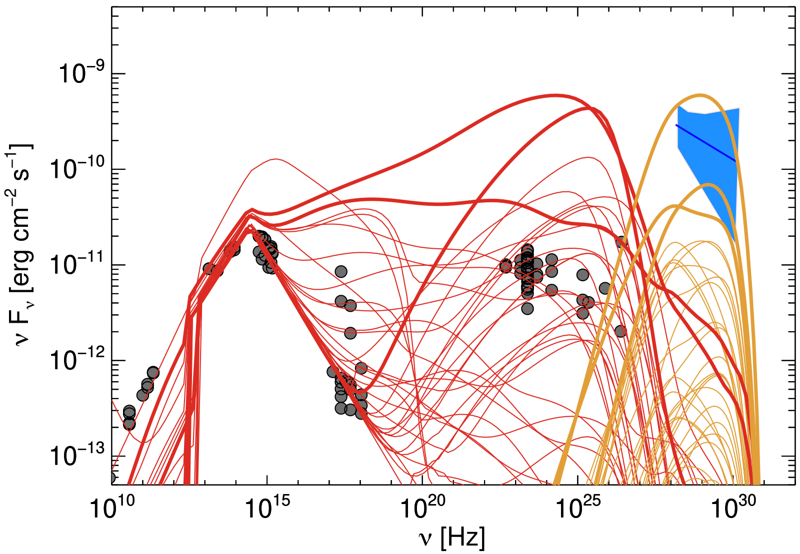
- Swift-UVOT/X-Shooter, Swift-XRT/NuSTAR Fermi-LAT data
- UVOT/X-Shooter ν_{syn}<3x10^{14} Hz: ISP/LSP
- Leptonic scenario γ = external IC emission
- F_ν < (1-2)x10^{-12} erg/cm^2/s
- $\varepsilon_p/\varepsilon_e$ > 300
- E_{max} < 0.3 Z EeV
- N_ν~0.02/yr (real-time) N_ν~0.2/yr (point-source)

2014-2015 Neutrino Flare

IceCube 2018 Science



Single-zone models predict **$F_x \sim 10^{-10}$ erg/cm^2/s by cascades** (violating Swift-BAT limit)



Petropoulou, KM+ in prep.

KM, Oikinomou & Petropoulou 18 ApJ

confirmed by numerical studies:

Rodrigues et al. 18

Reimer et al. 18

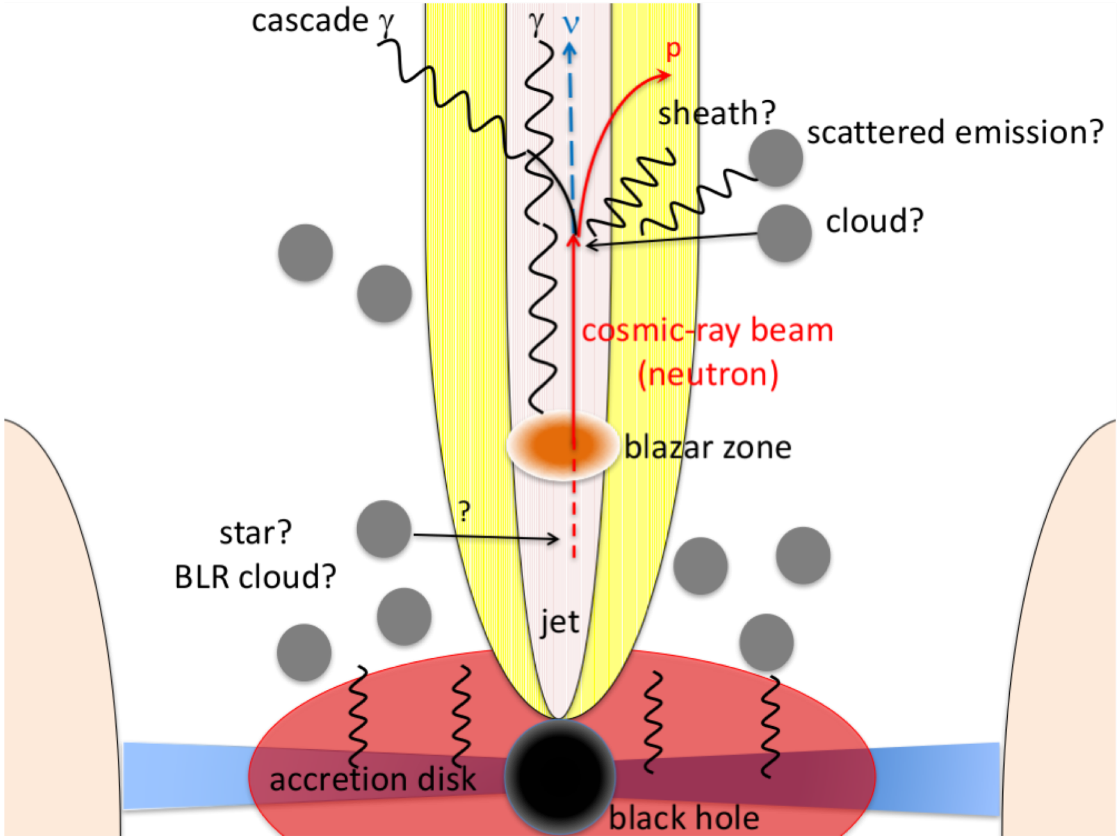
Petropoulou, KM et al. in prep.

No simple picture

Multi-Zone Picture?

Problems

- Severe X-ray constraints on the maximum neutrino flux
- Severe CR power requirement for low ν production efficiency



Relaxing X-ray suppression?

1. Anisotropic cascades (isotropization & time delay)
2. Avoiding Bethe-Heitler (for neutron beams)
3. Scattering ($N_H > 10^{25}$ cm^{-2})

Efficient ν production?

1. External radiation fields
2. pp interactions w. clouds

see
KM, Oikinomou & Petropoulou 18 ApJ

Need more information: X-ray/γ-ray monitoring, X-ray/γ-ray polarization

Summary

γ-ray flux ~ ν flux ~ CR flux

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

Cosmic-ray sources (above 100 TeV)?

CR accelerators: blazars are likely to be subdominant at sub-PeV energies
but they can be dominant in the 10-100 PeV energy range
AGN core models are viable given that CRs are accelerated

CR reservoirs: s<2.1-2.2 & significant contribution to Fermi γ-ray bkg.
cosmic particle unification is possible with s~2

Blazar flares?

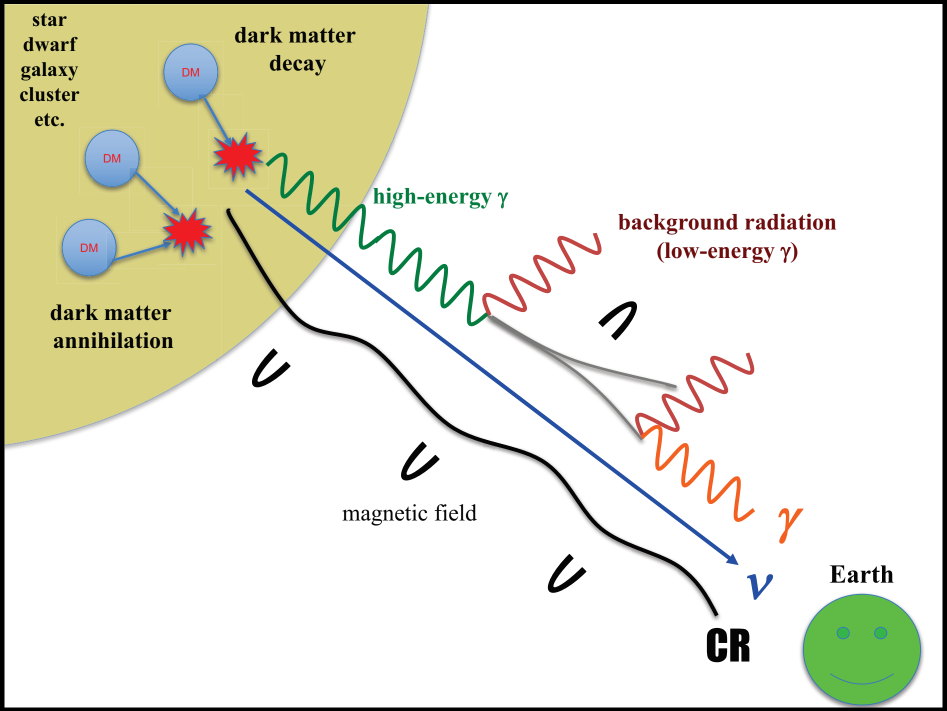
TXS 0506+056 flares: no simple convincing picture – stay tuned….

BSM?

decaying dark matter: constrained by Fermi-LAT and CR experiments

various possibilities are discussed (neutrino decay, pseudo-Dirac neutrinos, neutrino-neutrino self-interactions, neutrino-dark matter interactions, Lorentz invariance violation)

BSM Explanations?



BSM Signatures in Neutrino Spectra

Decaying dark matter ("dominant" in terms of the number of papers)

$$E_\nu^2 \Phi_\nu = E_\nu^2 \Phi_\nu^{\rm EG} + E_\nu^2 \Phi_\nu^{\rm G} \sim 4 \times 10^{-8}\ {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \left[\frac{1 + 1.6(\mathcal{J}_\Omega/2)}{2.6}\right] \tau_{\rm dm,27.5}^{-1} (\mathcal{R}_\nu/15)^{-1}$$

- Neutrino lines:

Feldstein et al. 13, Dudas, Mambrini & Olive 15, Roland et al. 15, Aisati et al. 15, Aisati et al. 16

- Portal type, R-parity violating gravitino, RH ν, glueball DM etc.

Feldstein, Kusenko, Matsumoto & Yanagida 13, Esmaili & Serpico 14, Bai, Lu & Salvado 13, Bhattacharya, Reno & Sarcevic 14, Higaki, Kitano & Sato 14, Esmaili, Kang & Serpico 14, Rott, Kohri & Park 15, Fong et al. 15, KM et al. 15, Boucenna et al. 15, Ko & Tang 15, Chianese et al. 16, Bhupal Dev et al. 16, Bari, Ludl & Palomares-Ruiz 16, Borah et al. 17, Hiroshima, KM et al. 17 etc.

Other models

- Annihilation in low-velocity sub-halos: Zavala 14
- Early time particle decay: Ema, Jinno & Moroi 14, Anchordoqui et al. 15, Ema & Moroi 16
- Boosted dark matter: Bhattacharya, Gandi & Gupta 15, Kopp, Liu & Wang 15, Bhattacharya et al. 17

Secret interactions

Ioka & KM 14, Ng & Beacom 14, Ibe & Kaneta 14, Blum, Hook & KM 14, Cherry, Friedland & Shoemaker 14, Araki et al. 15, DiFranzo & Hooper 15, Kamada & Yu 15, Araki et al. 16, Shoemaker & KM 16, Yin 17

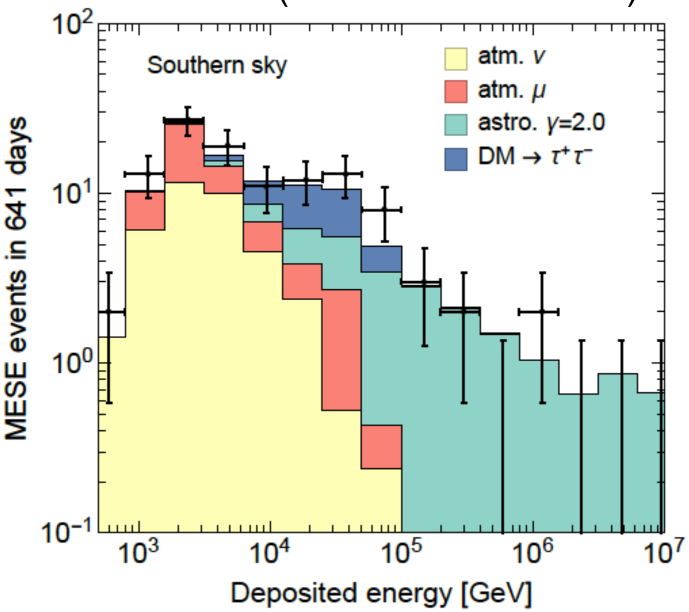
Neutrino decay

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

BSM Explanations for Neutrino Spectra?

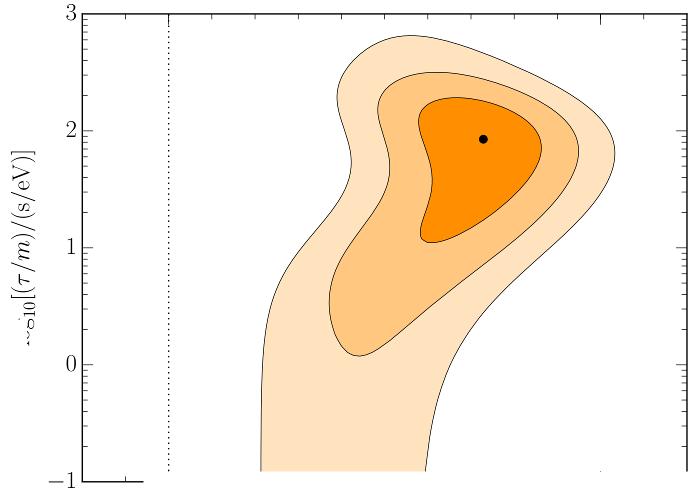
dark matter decay

(Chianese+ 17 JCAP)

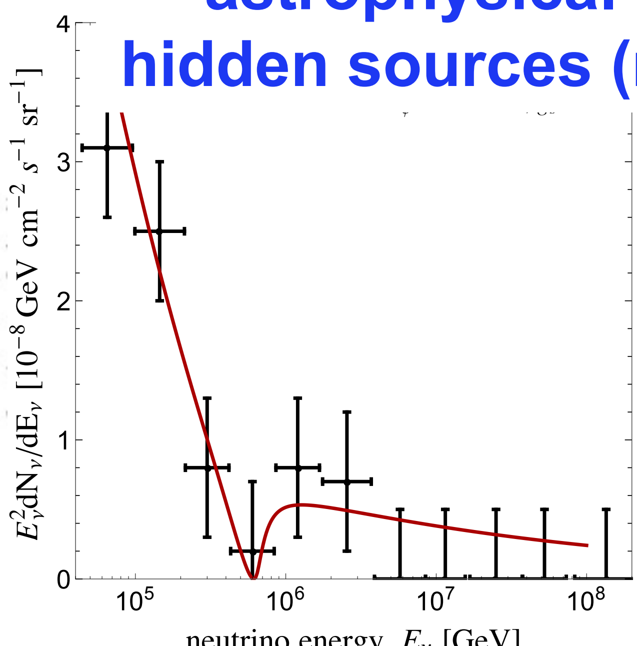


Invisible neutrino decay

(Denton & Tamborra 18 PRL)



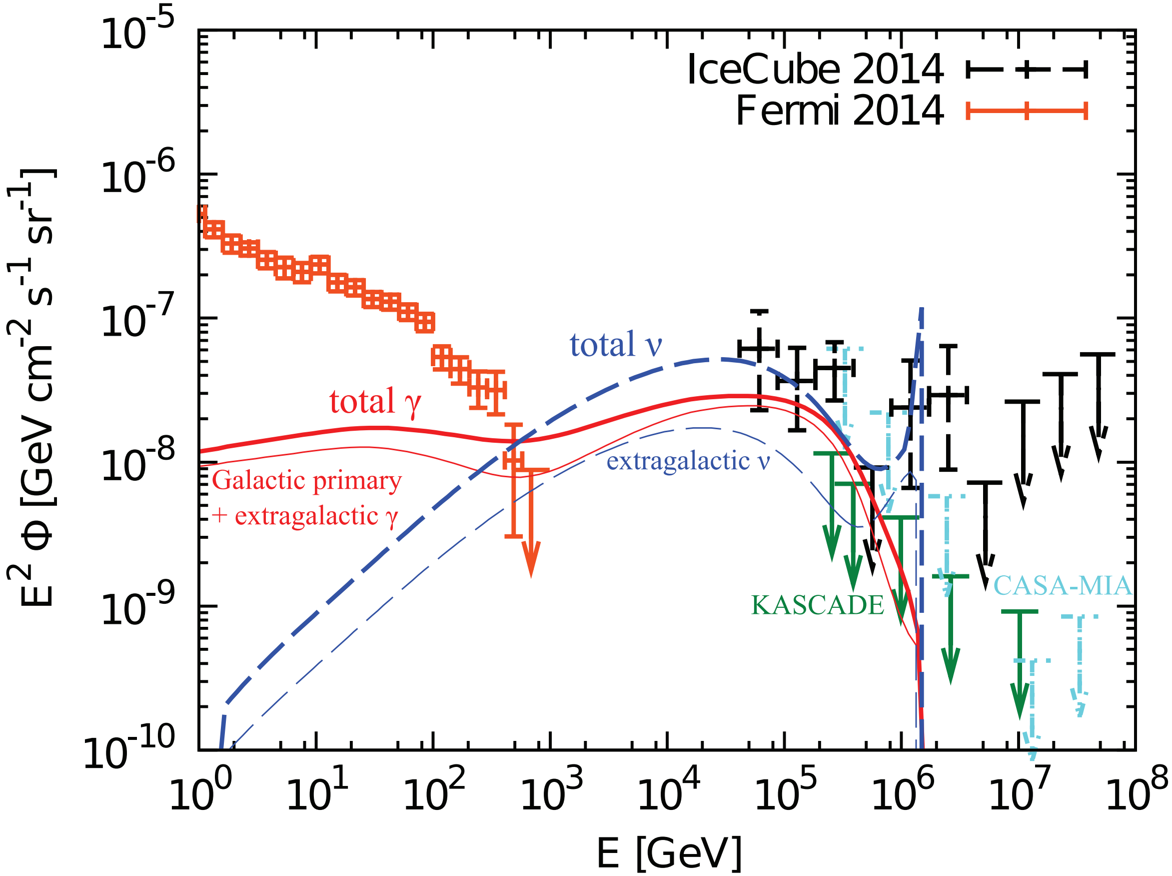
astrophysical ν necessary
hidden sources (more) required



neutrino-neutrino self-interactions

(e.g., Blum, Hook & KM Cherry+ 14)

Multi-Messenger Emission of Decaying Dark Matter



KM, Laha, Ando & Ahlers 15

see also:
KM & Beacom 12
Esmaili & Serpico 15

DM → ν_e+ν_e (12%)
DM → b+bbar (88%)

(similar results in other models that are proposed)

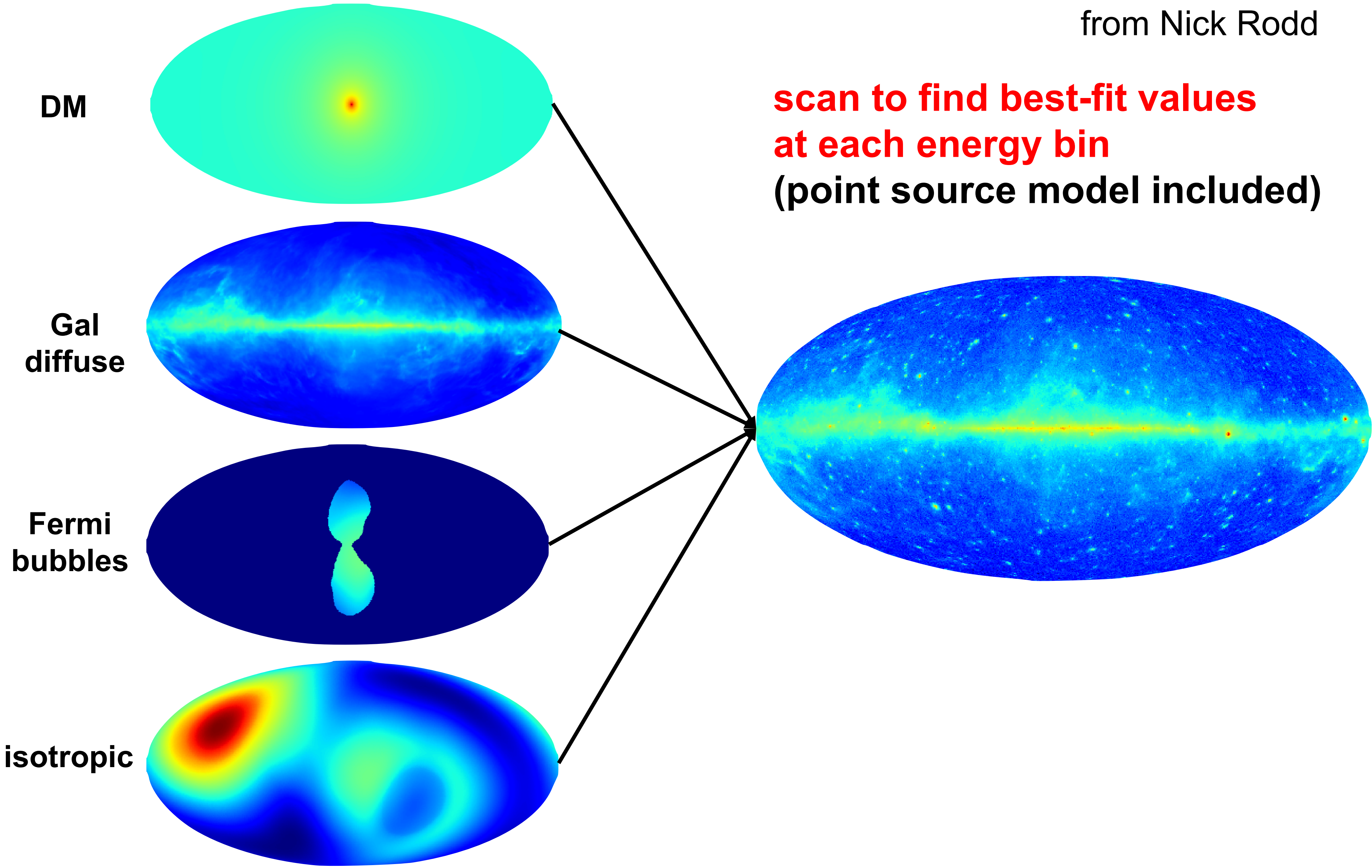
- Galactic: γ → direct (w. some attenuation), e$^{\pm}$ → sync. + inv. Compton
- Extragalactic → EM cascades during cosmological propagation

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

Profile Likelihood Technique

from Nick Rodd

scan to find best-fit values
at each energy bin
(point source model included)



Profile Likelihood Technique

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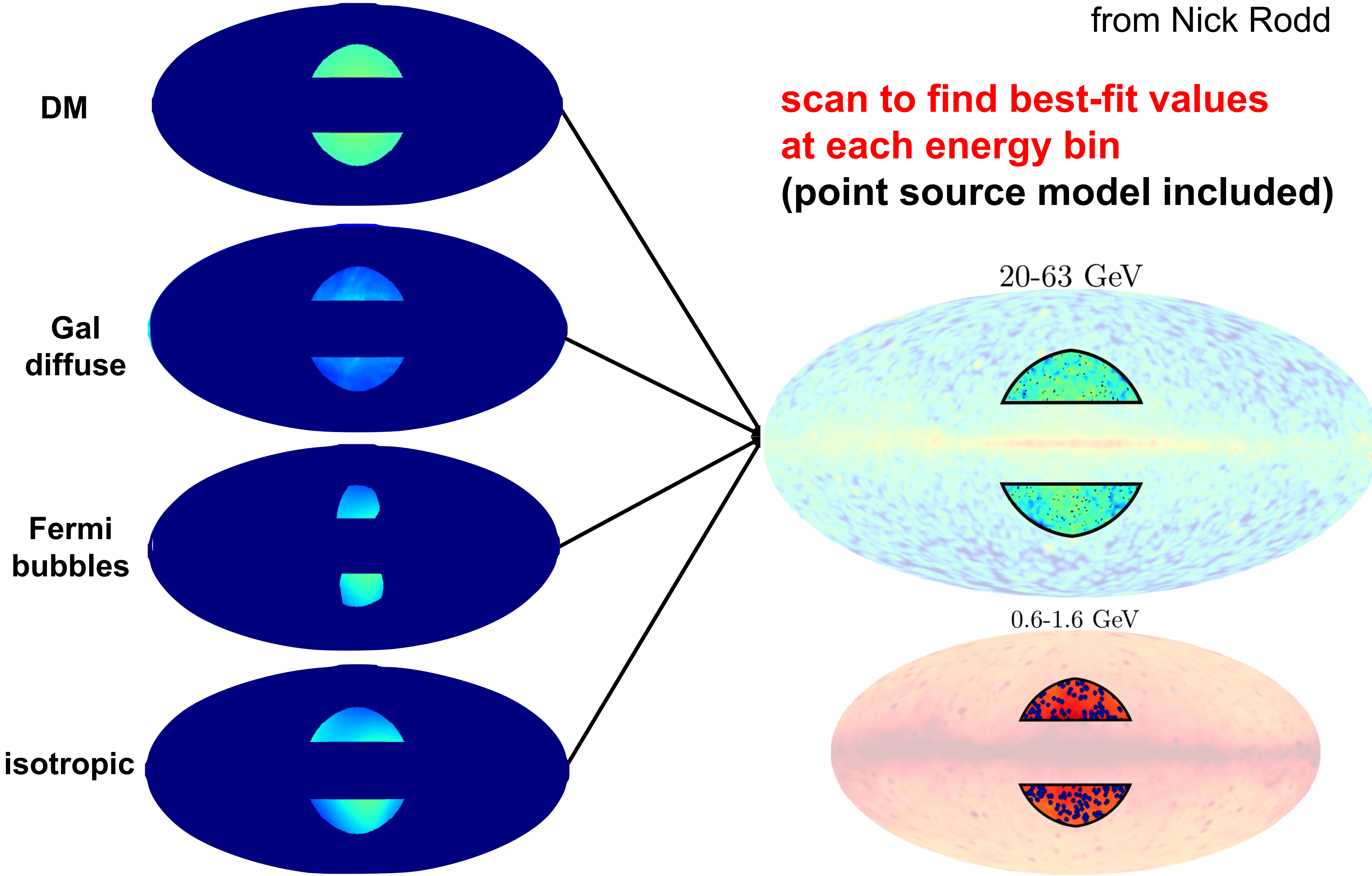
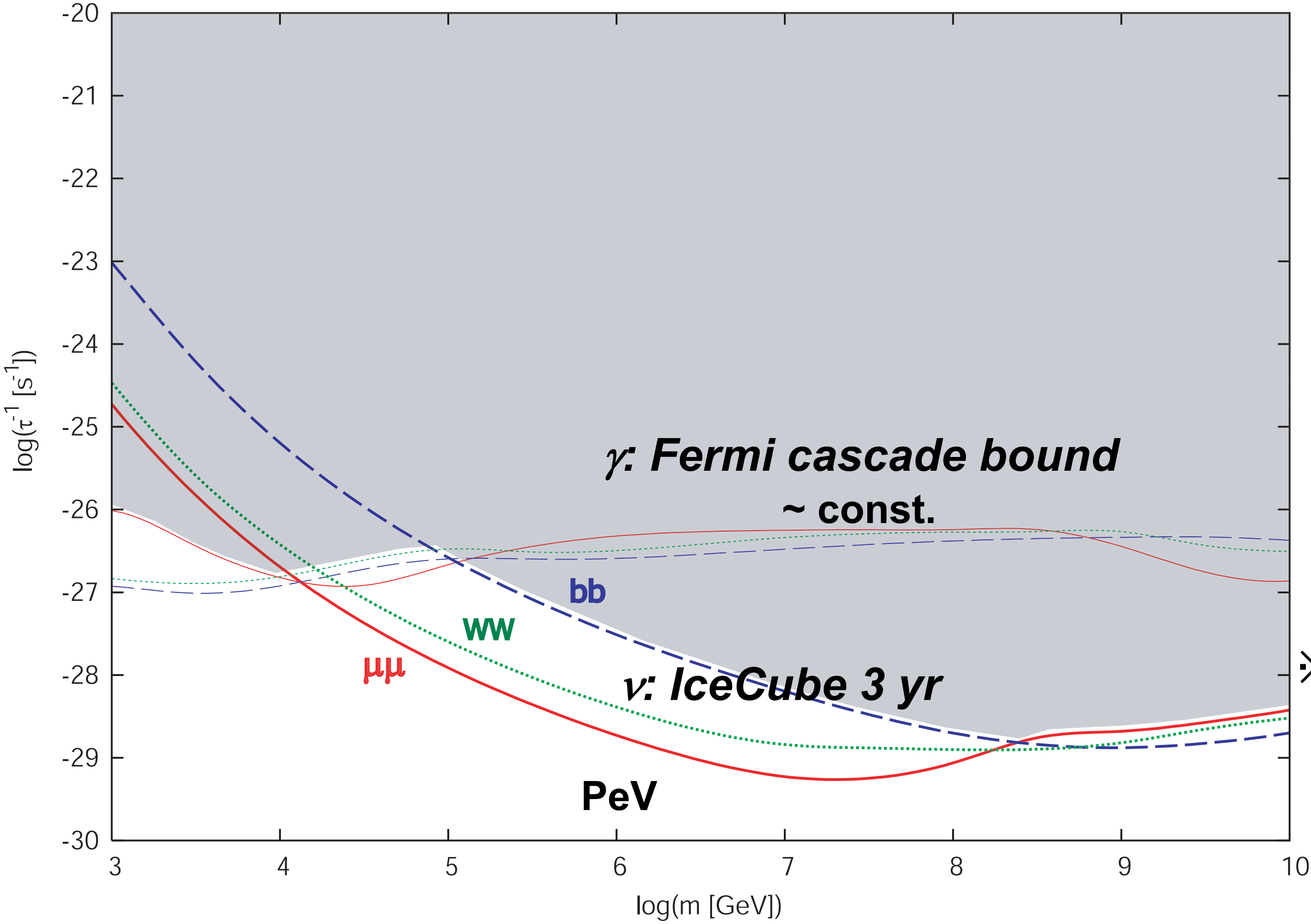


scan to find best-fit values
at each energy bin
(point source model included)

Neutrino Constraints on Dark Matter Decay



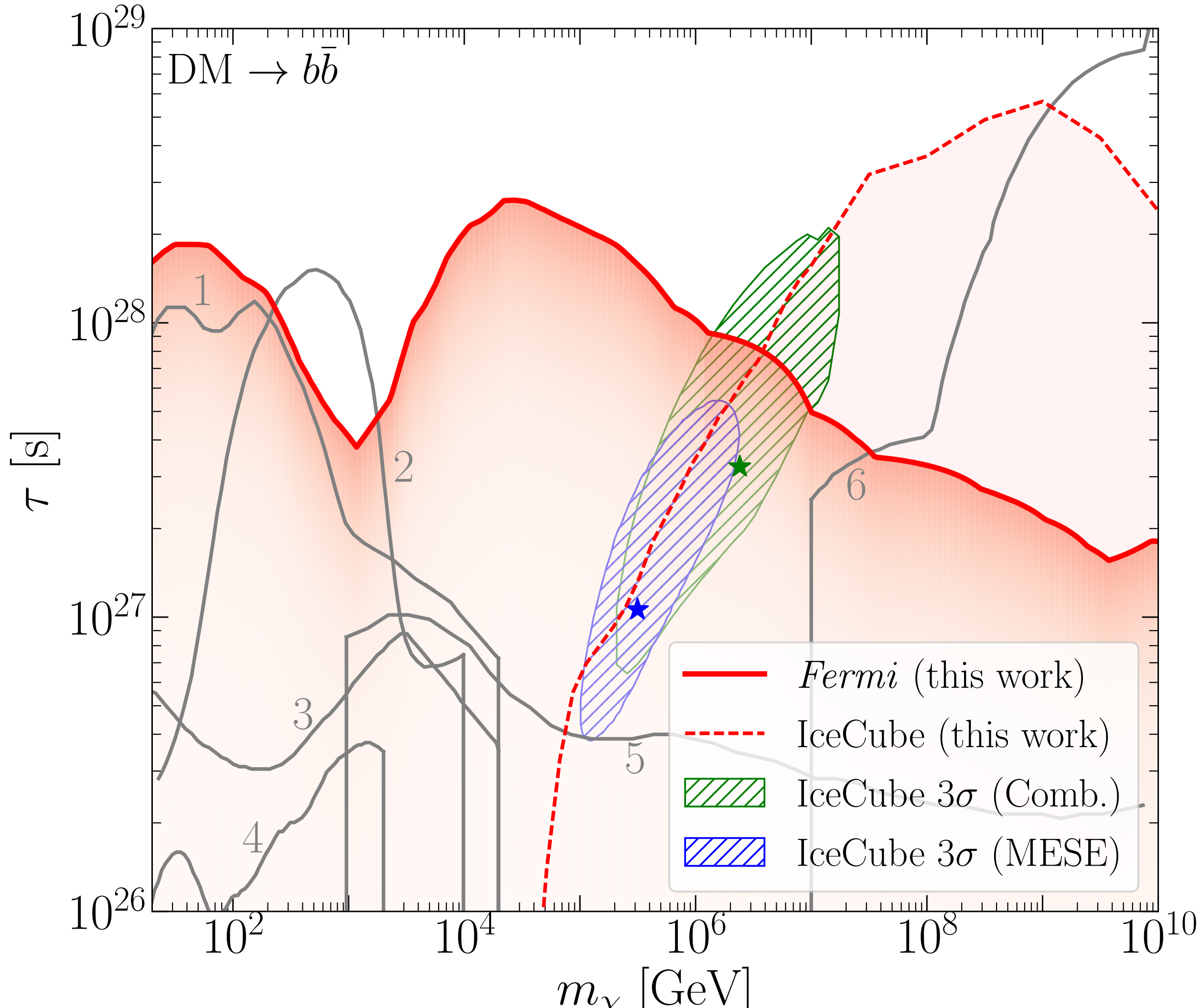
KM & Beacom 12 JCAP

※Annihilating heavy dark matter scenarios are difficult due to the unitarity bound

- Neutrino bound is very powerful at high energies
- Cascade γ-ray bound: more conservative/robust at high m_{dm}

Multi-Messenger Constraints on Decaying DM

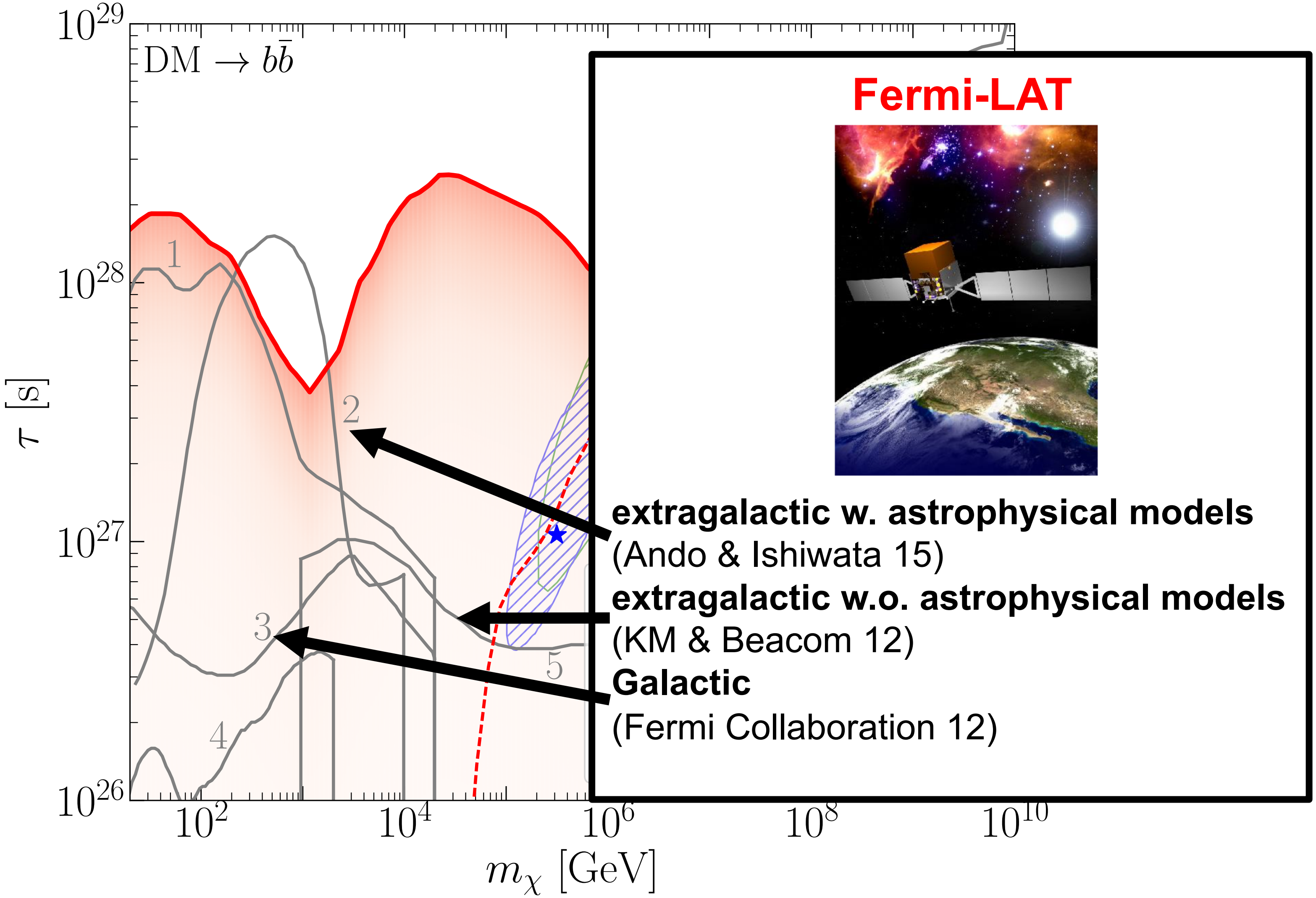
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



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

Multi-Messenger Constraints on Decaying DM

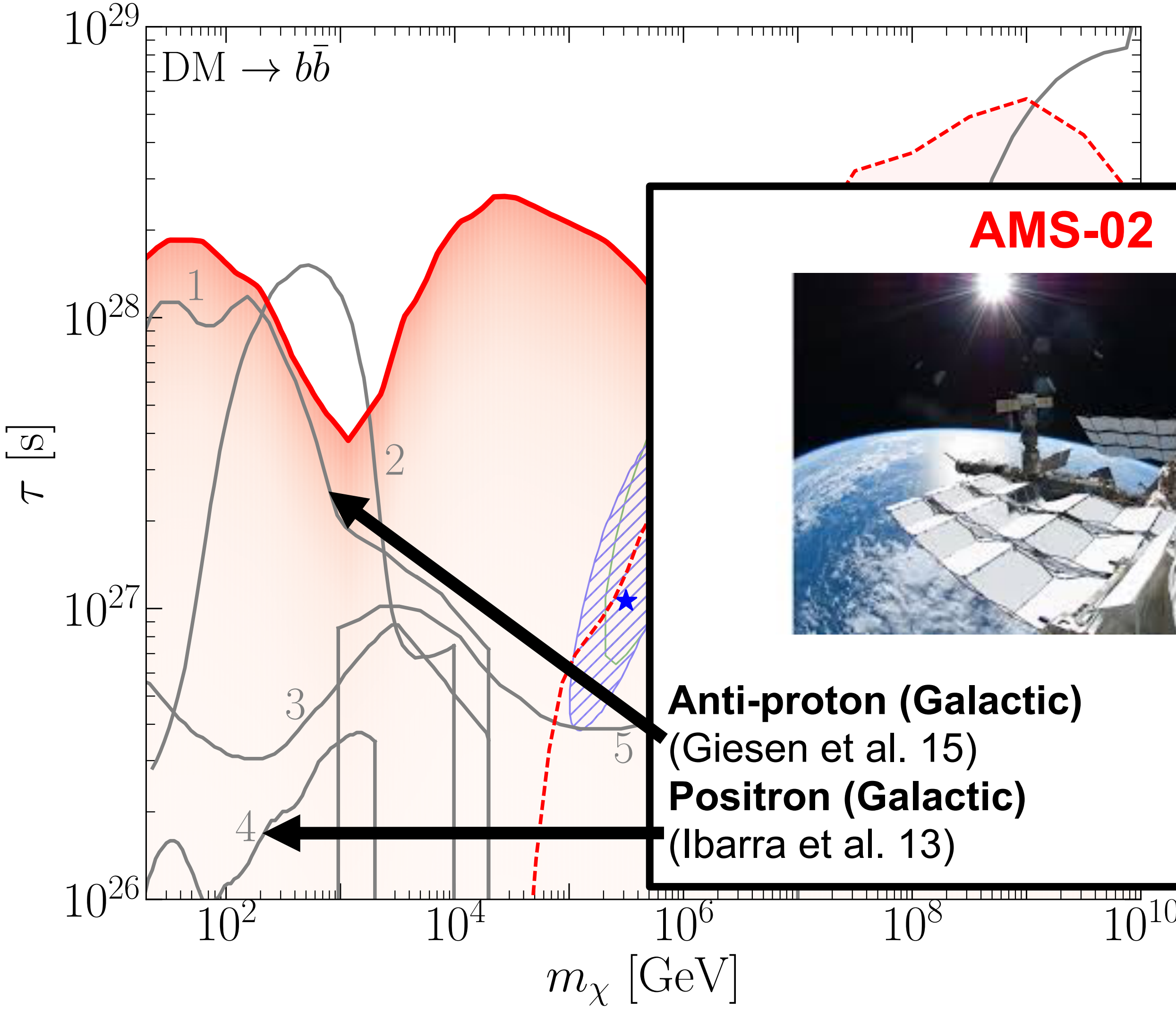
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



Gamma-ray limits are improved independently of astrophysical modeling

Multi-Messenger Constraints on Decaying DM

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



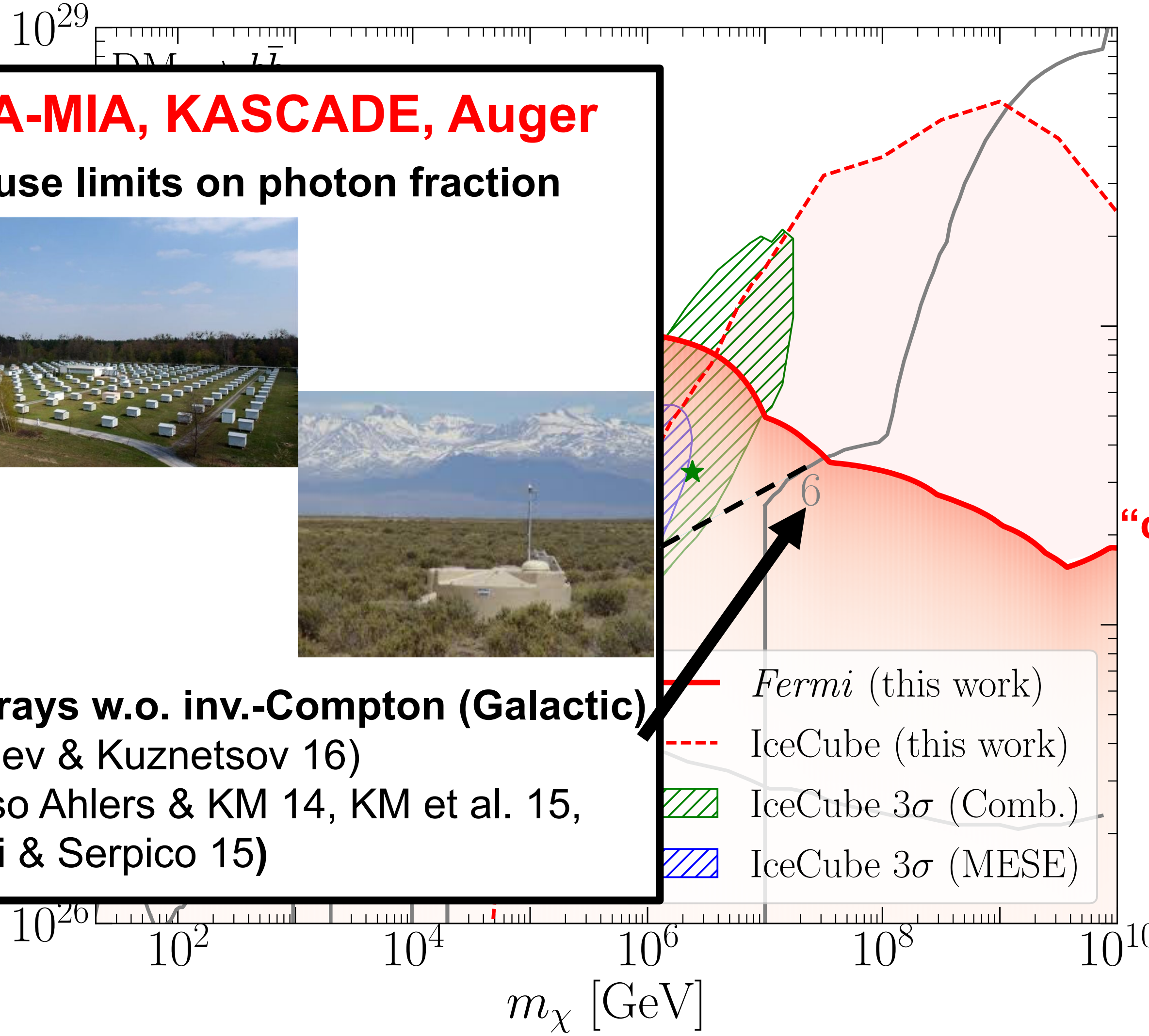
AMS-02

Anti-proton (Galactic)
(Giesen et al. 15)
Positron (Galactic)
(Ibarra et al. 13)

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

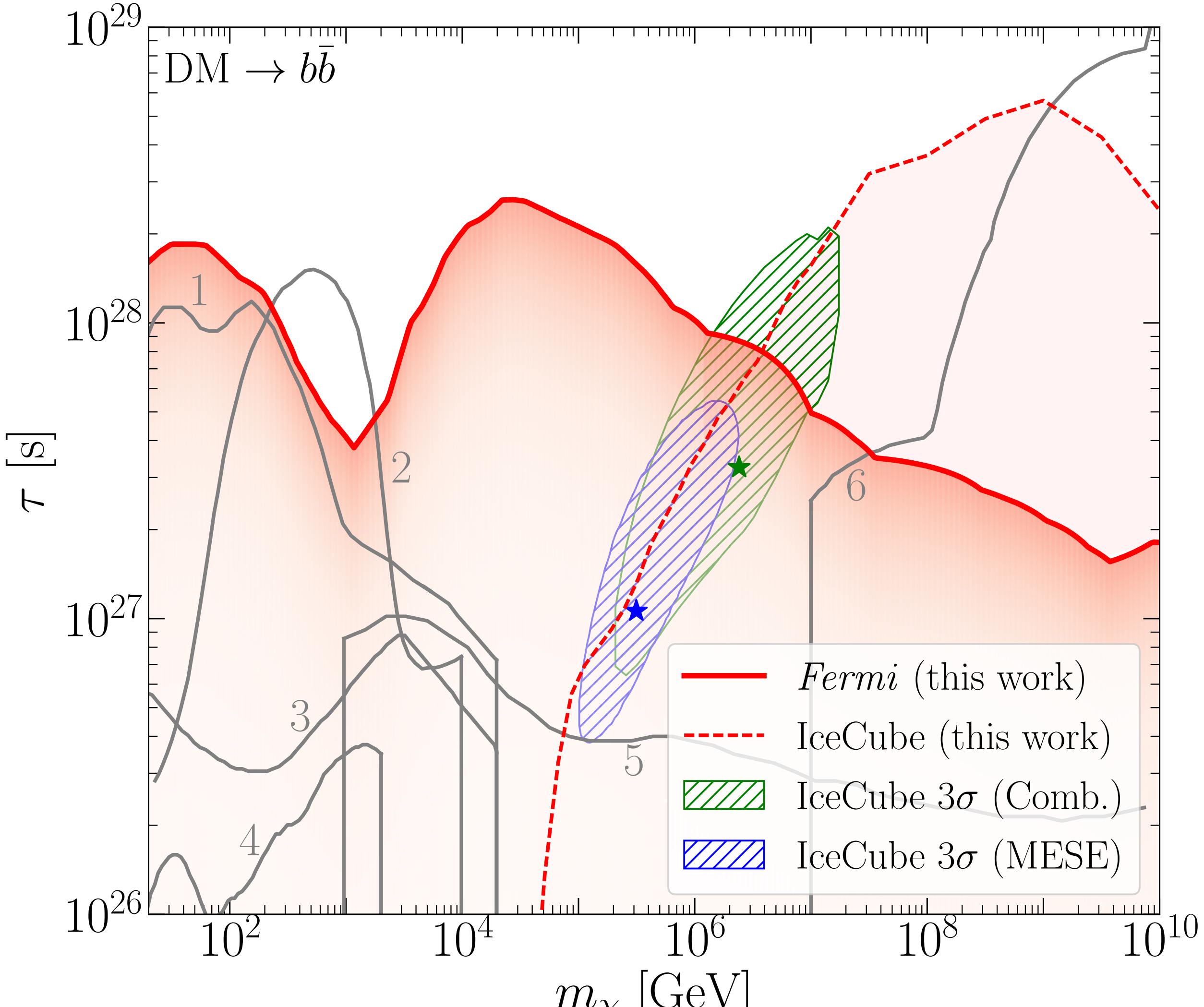
VHE g rays w.o. inv.-Compton (Galactic)
(Kalashev & Kuznetsov 16)
(see also Ahlers & KM 14, KM et al. 15,
Esmaili & Serpico 15)

"cascade" bound (extragalactic)

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

Multi-Messenger Constraints on Decaying DM

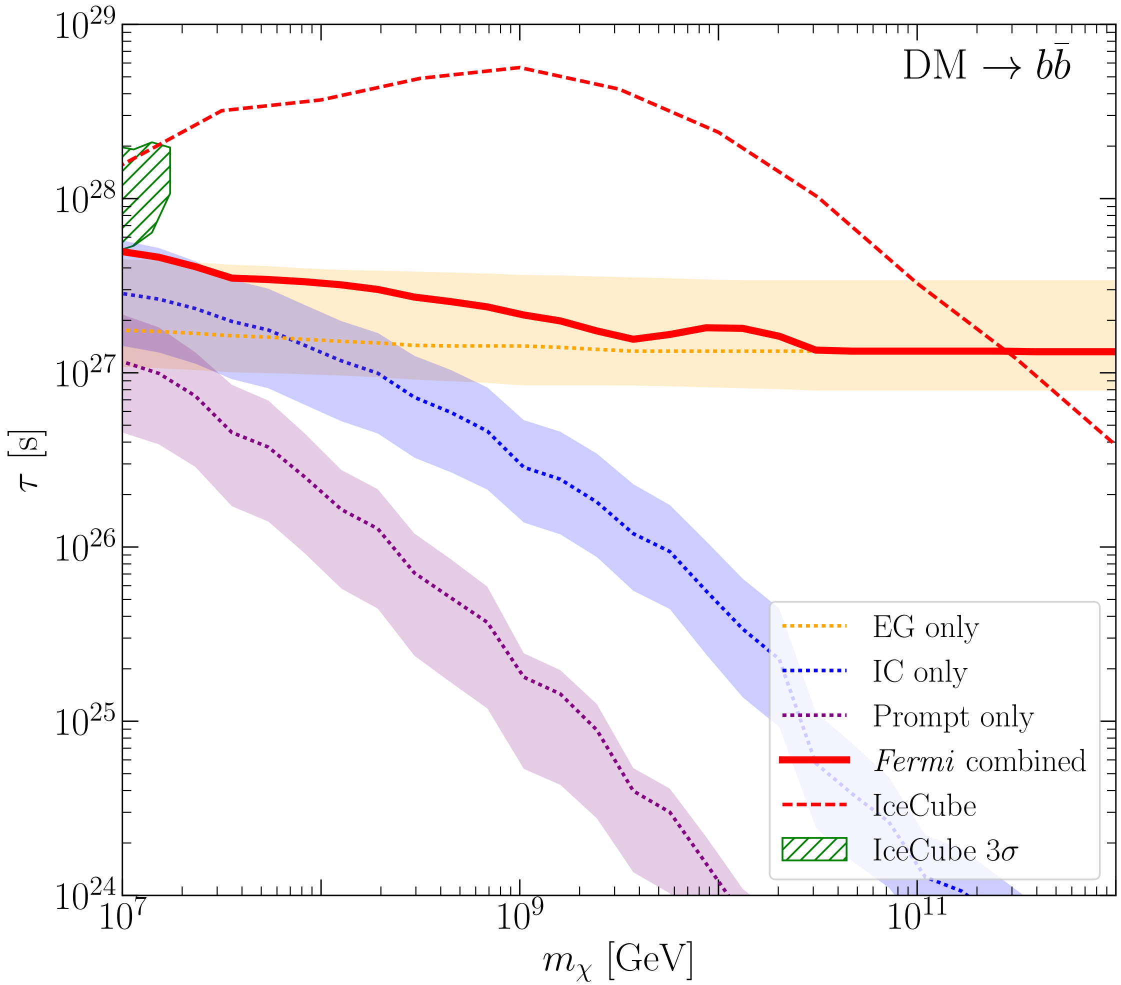
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL



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

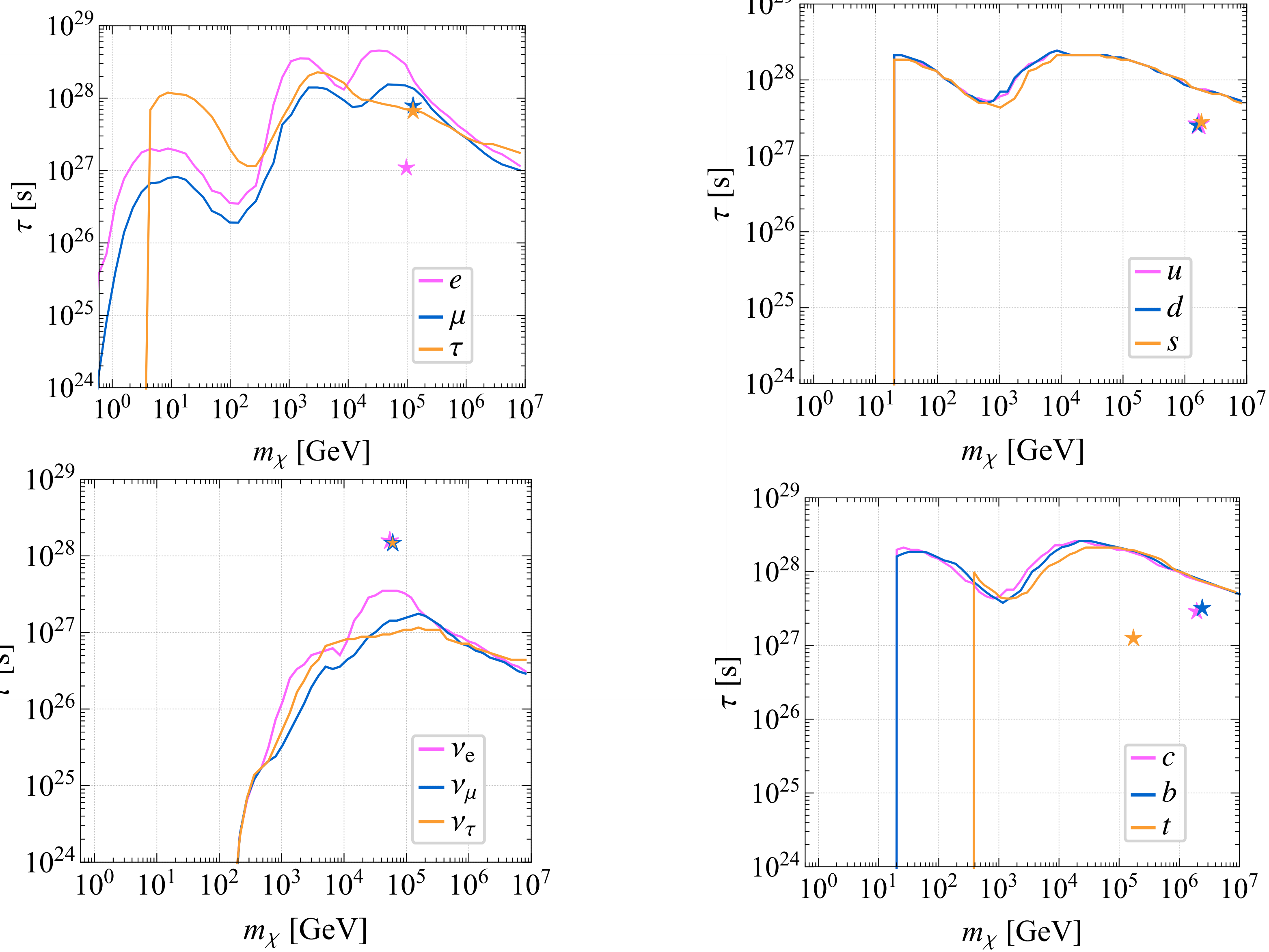
Extension to Superheavy Dark Matter?

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



Constraints up to ~10^{11} GeV thanks to “cascade” bounds

Other Final States

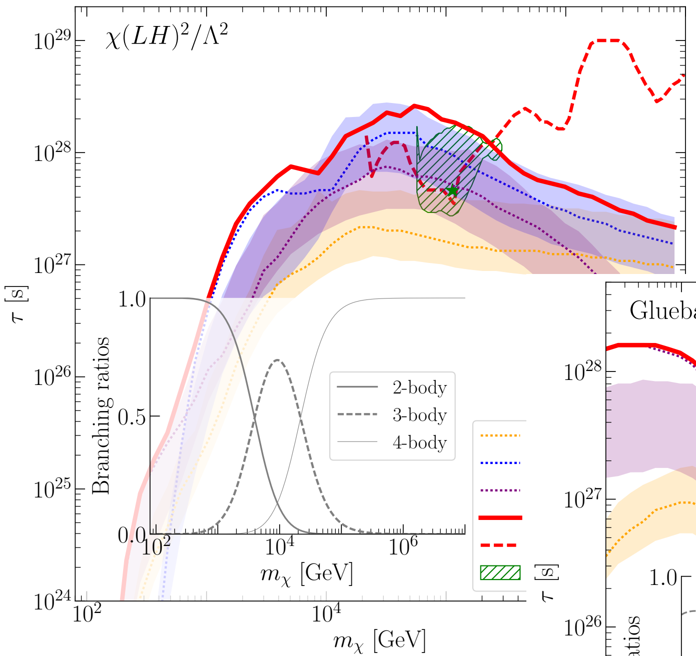


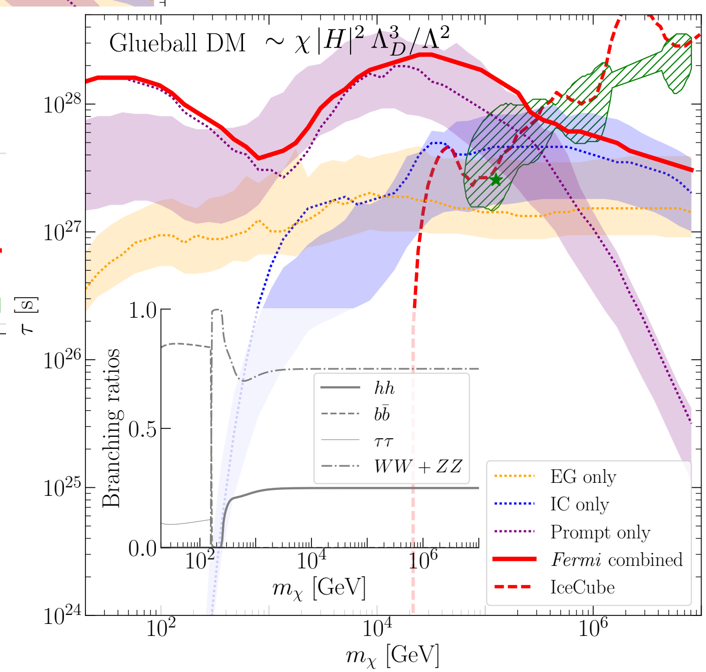
Examples of Models (EFT)

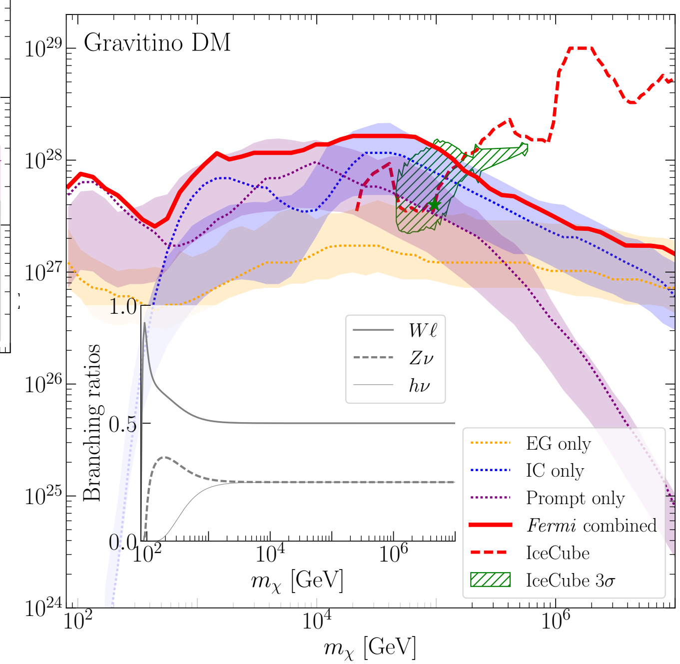
EFT (up to dimension 6)

$\left(R_{SU(2)}\right)_Y$	operator	final states	ratios of BR's, $m_\chi \gg$ TeV	$\tau \gtrsim 10^{27}$ [s]
spin 0				
$(0)_0$	$\chi H^\dagger H$	$hh,\ Z^0Z^0, W^+W^-, f\bar{f}$	$1:1:2:16N_c y_f^2 \frac{v^2}{m_\chi^2}$	$\bar{m}_\chi/\bar{\Lambda}^2 \gtrsim 9\times 10^{79}$ [a]
	$\chi\,(LH)^2$	$\nu\nu hh,\ \nu\nu Z^0Z^0,\ \nu\nu Z^0 h,$ $\nu e^- hW^+,\ \nu e^- Z^0 W^+,\ e^-e^-W^+W^+,$ $\nu\nu h,\ \nu\nu Z^0,\ \nu e^- W^+,\ \nu\nu$	$1:1:2:$ $2:2:4:$ $24\pi^2\frac{v^2}{m_\chi^2}\left(1:1:1:768\pi^2\frac{v^2}{m_\chi^2}\right)$	$\bar{\Lambda}^4/\bar{m}_\chi^5 \gtrsim 1$
	$\chi H\bar{L}E$	$h\ell^+\ell^-,\ Z^0\ell^+\ell^-,\ W^\pm\ell^\mp\nu,\ \ell^+\ell^-$	$1:1:2:32\pi^2\frac{v^2}{m_\chi^2}$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 4\times 10^{29}$
	$\chi\tilde{H}\bar{Q}U,\ \phi H\bar{Q}D$	$hq\bar{q},\ Z^0q\bar{q},\ W^\pm q'\bar{q},\ q\bar{q}$	$1:1:2:32\pi^2\frac{v^2}{m_\chi^2}$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 1\times 10^{30}$
	$\chi B_{\mu\nu}\overset{(\sim)}{B}{}^{\mu\nu}$	$\gamma\gamma,\ \gamma Z,\ ZZ$	$c_W^4 : 2c_W^2 s_W^2 : s_W^4$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 2\times 10^{31}$
	$\chi W_{\mu\nu}\overset{(\sim)}{W}{}^{\mu\nu}$	$\gamma\gamma,\ \gamma Z^0,\ Z^0Z^0,\ W^+W^-$ [b]	$s_W^4 : 2c_W^2 s_W^2 : c_W^4 : 2$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 6\times 10^{31}$
	$\chi G_{\mu\nu}\overset{(\sim)}{G}{}^{\mu\nu}$	hadrons	1	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 2\times 10^{32}$
	$\chi D_\mu H^\dagger D^\mu H$	$hh,\ Z^0Z^0,\ W^+W^-$ [c]	$1:1:2$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 3\times 10^{30}$
$(2)_{1/2}$ [d]	$V_{\hat{\lambda}}$ [114][e]	$hhh,\ hZ^0Z^0,\ hW^+W^-$	$1:1:2$	$g^2\bar{m}_\chi \lesssim 2\times 10^{-53}$
	$V_{c_{\beta-\alpha}}$ [114][e,f]	$hh,\ Z^0Z^0,\ W^+W^-$	$\left(1+(\lambda_T-2\lambda_A)/\lambda\right)^2 : 1 : 2$	$\bar{m}_\chi/c_{\beta-\alpha}^2 \gtrsim 4\times 10^{48}$
	$\phi\bar{L}E$	$\ell^+\ell^-$	1	$g^2\bar{m}_\chi \lesssim 2\times 10^{-56}$
	$\tilde{\phi}\bar{Q}U,\ \phi\bar{Q}D$	$q\bar{q}$	1	$g^2\bar{m}_\chi \lesssim 6\times 10^{-57}$
$(3)_0$	$\phi^a\tilde{H}\sigma^a H$	$hh,\ Z^0Z^0, W^+W^-, f\bar{f}$	$1:1:2:16N_c y_f^2 \frac{v^2}{m_\chi^2}$	$\bar{m}_\chi/\bar{\Lambda}^2 \gtrsim 9\times 10^{79}$
	$\phi^a W^a_{\mu\nu}B^{\mu\nu}$	$\gamma\gamma,\ Z^0\gamma,\ Z^0Z^0$	$c_W^2 s_W^2 : 2\left(c_W^2 - s_W^2\right)^2 : c_W^2 s_W^2$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 1\times 10^{31}$
	$\phi^a\bar{L}E\sigma^a H$	$h\ell^+\ell^-,\ Z^0\ell^+\ell^-,\ W^\pm\ell^\mp\nu,\ \ell^+\ell^-$	$1:1:2:32\pi^2\frac{v^2}{m_\chi^2}$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 4\times 10^{29}$
	$\phi^a\bar{Q}U\sigma^a\tilde{H},\ \phi^a\bar{Q}D\sigma^a H$	$hq\bar{q},\ Z^0q\bar{q},\ W^\pm q'\bar{q},\ q\bar{q}$	$1:1:2:32\pi^2\frac{v^2}{m_\chi^2}$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 1\times 10^{30}$
$(3)_1$	$\phi^a L^T\sigma^a\sigma^2 L$	$\nu\nu$	1	$g^2\bar{m}_\chi \lesssim 2\times 10^{-56}$
spin 1/2				
$(1)_0$	$\tilde{H}\bar{L}\psi$	$\nu h,\ \nu Z^0,\ \ell^\pm W^\mp$	$1:1:2$	$g^2\bar{m}_\chi \lesssim 2\times 10^{-56}$
$(2)_{1/2}$	$\tilde{H}\bar{\psi}E$	$\nu h,\ \nu Z^0,\ \ell^\pm W^\mp$	$1:1:2$	$g^2\bar{m}_\chi \lesssim 2\times 10^{-56}$
$(3)_0$	$H\bar{L}\sigma^a\psi^a$	$\nu h,\ \nu Z^0,\ \ell^\pm W^\mp$	$1:1:2$	$g^2\bar{m}_\chi \lesssim 2\times 10^{-56}$
spin 1				
$(0)_0$	$\bar{f}\gamma_\mu V'^\mu f$	$f\bar{f}$	see text	$N_c g^2\bar{m}_\chi \lesssim 2\times 10^{-56}$
	$B_{\mu\nu}F'^{\mu\nu}/2$	$f\bar{f}$	see text	$g^2\bar{m}_\chi \lesssim 4\times 10^{-56}$

Model-Dependent Results







high-energy (>100 TeV) data could be consistent

<100 TeV (e.g., MESE) data cannot be explained

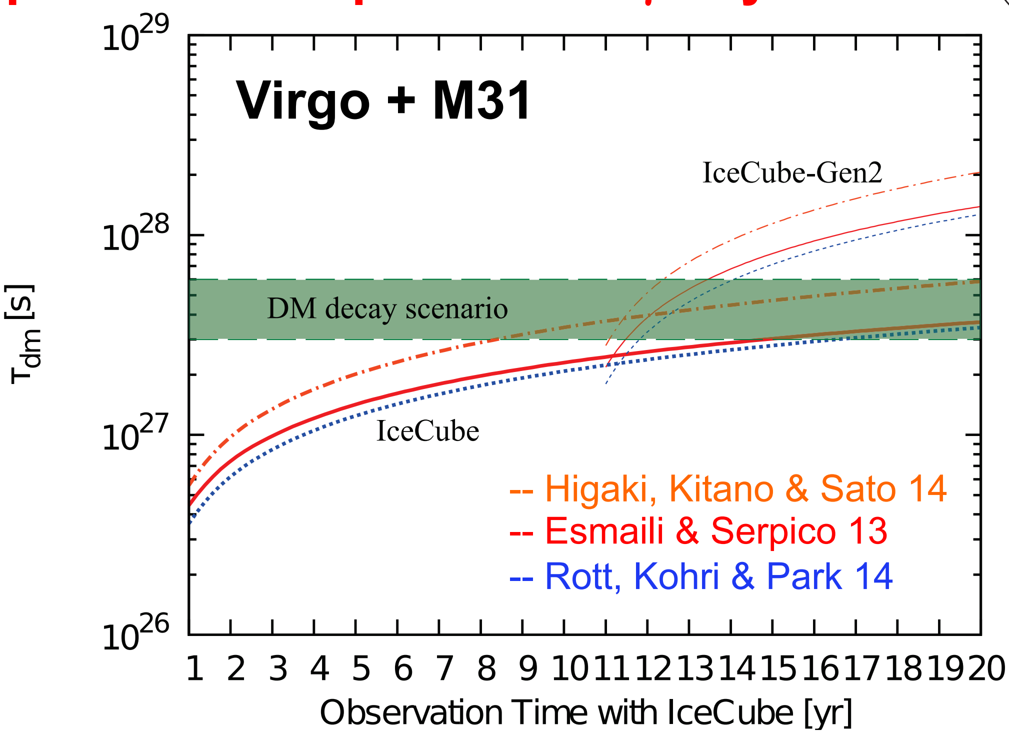
(see also Bhattacharya et al. 17)

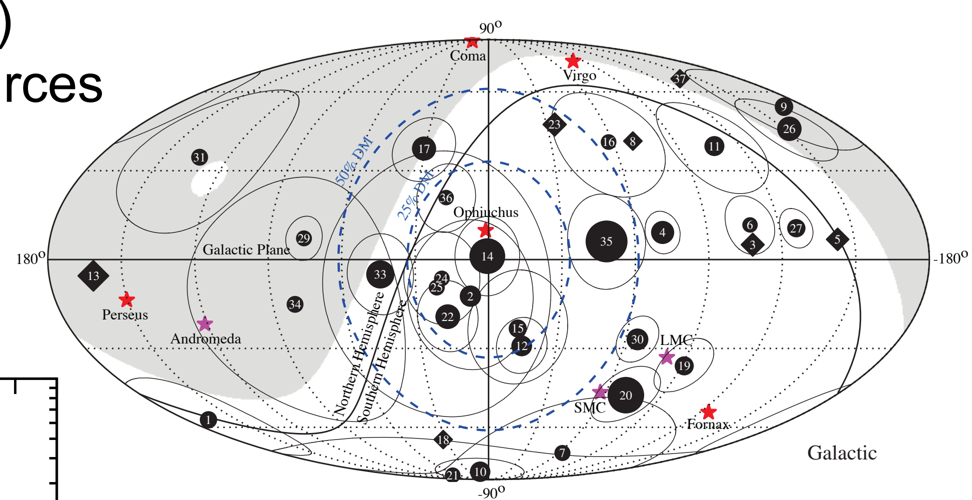
Other Tests? Search for Nearby DM Halos

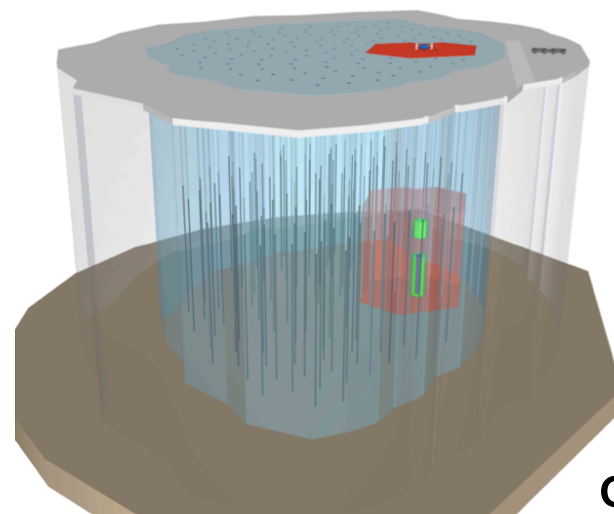
Nearby DM halos (clusters & galaxies) should be seen as point/extended sources

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

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





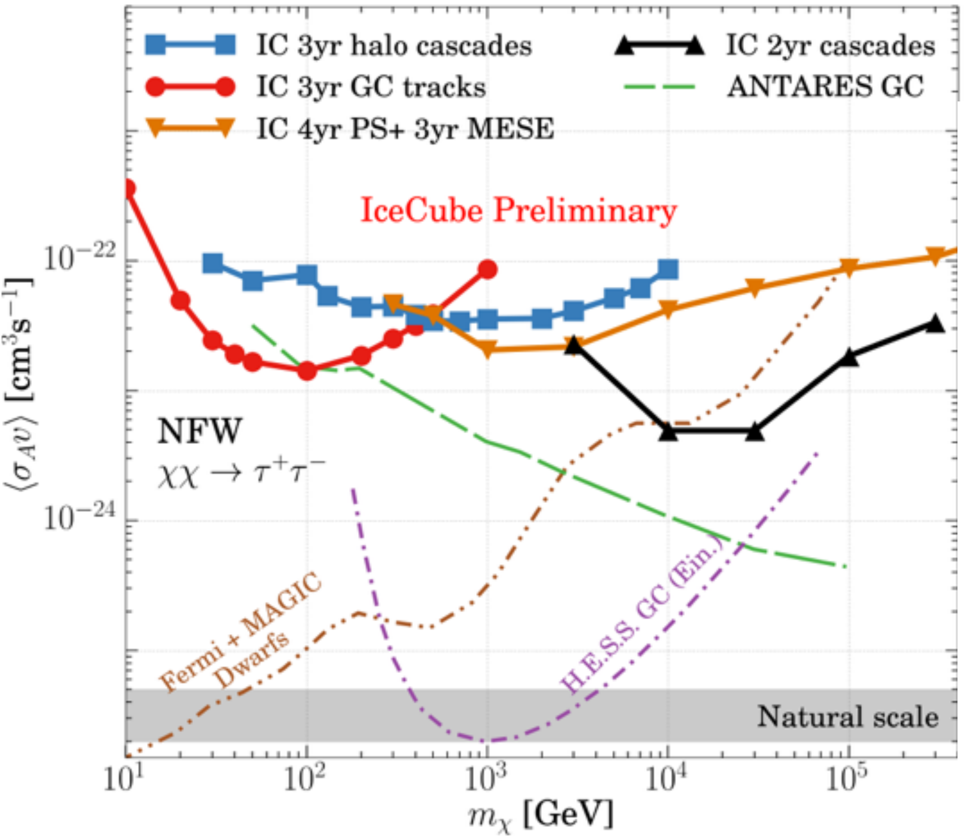


Gen2

KM, Laha, Ando & Ahlers 15 PRL

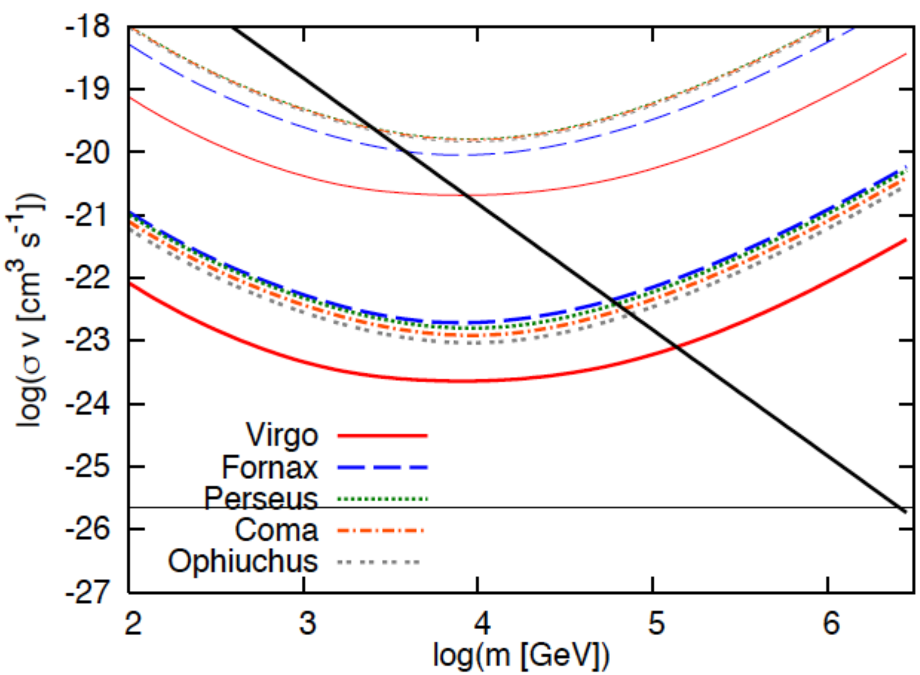
ν Limits on Annihilating Dark Matter

IceCube Collaboration 1705.08103



KM & Beacom 13 JCAP

DM+DM → $\mu^+\mu^-$



ν from Galactic halo and center

complementary to γ-ray limits

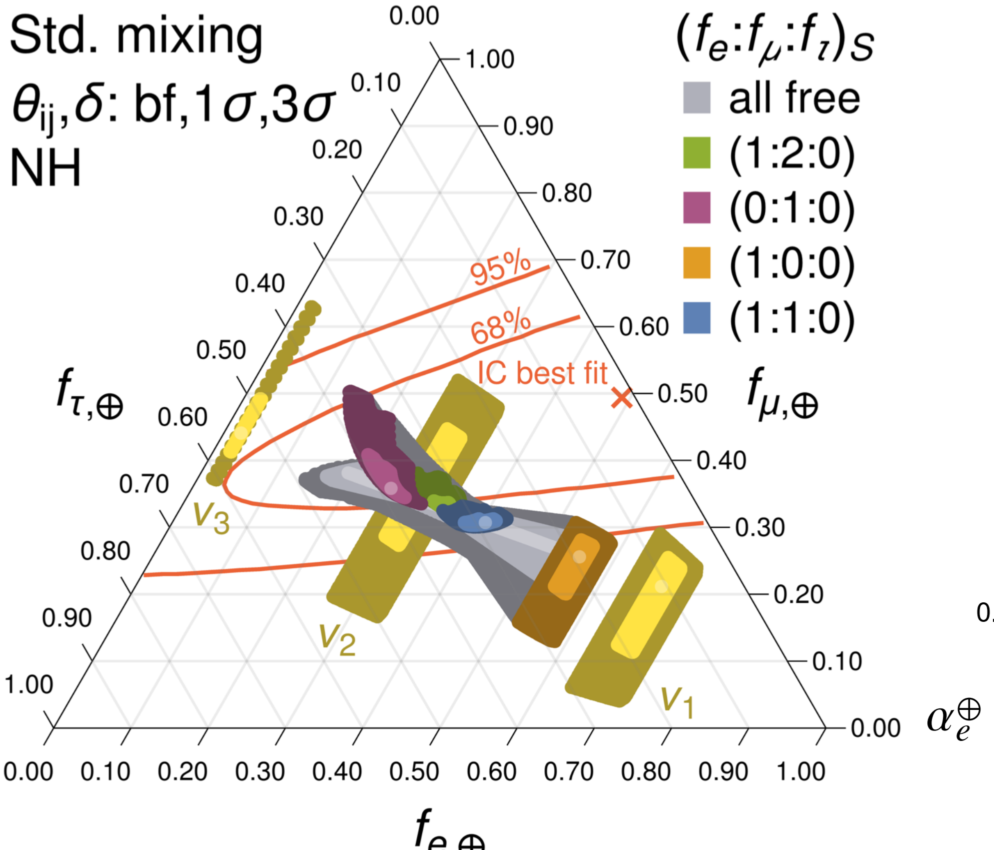
ν from Galactic clusters

complementary to γ-ray limits

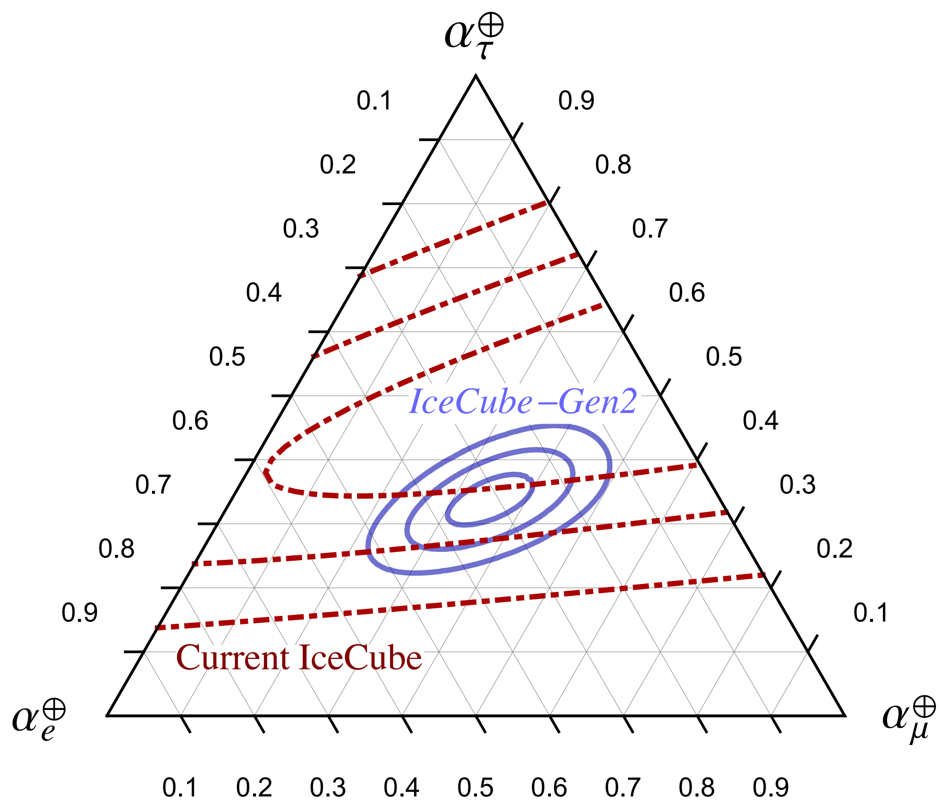
Constraints from Neutrino Flavors

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

BSM physics tests w. sufficient statistics (especially by Gen2)



Bustamante, Beacom & Winter 15 PRL
see also Arguelles, Katori & Salvado 15 PRL

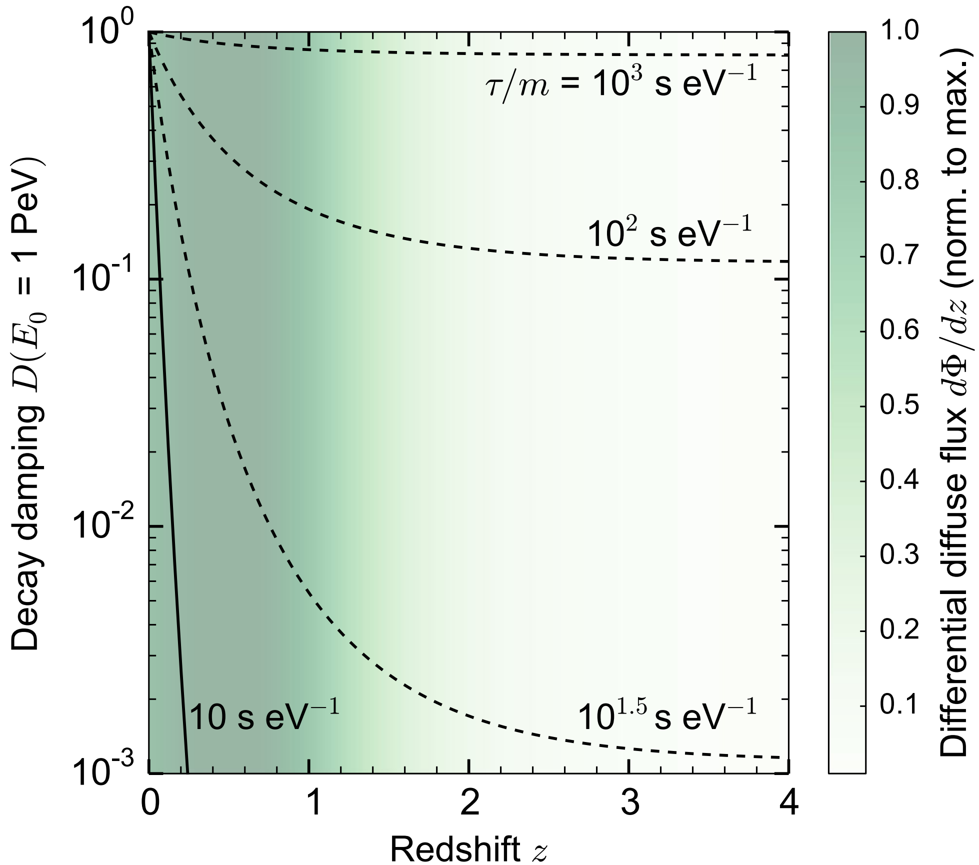


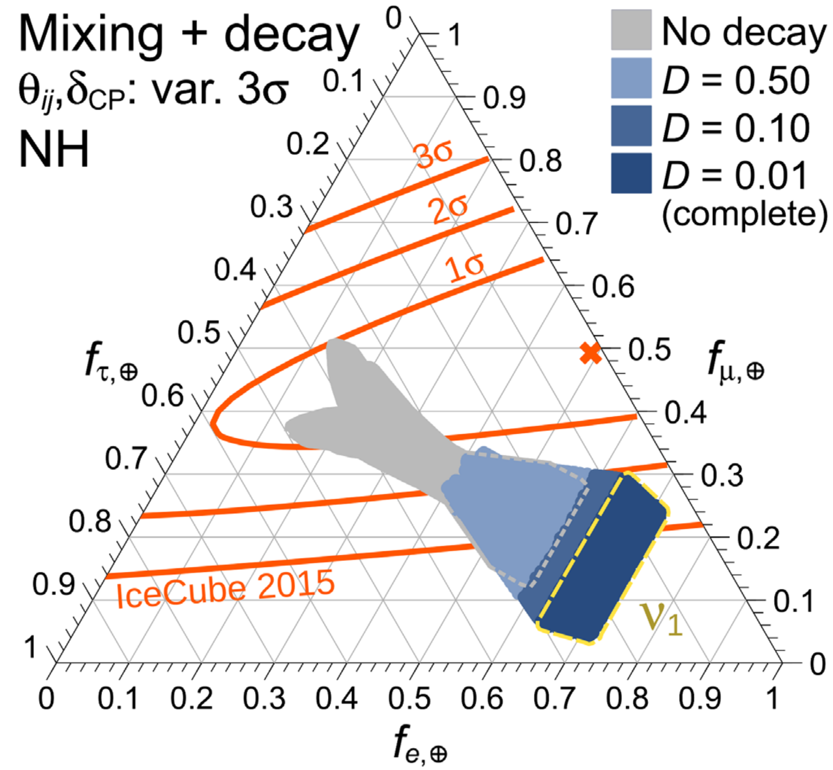
Shoemaker & KM 16 PRD

Neutrino Decay: Normal Hierarchy

$$D(E_0, z, \tau/m) = [\mathcal{Z}(z)]^{-\frac{m}{\tau}\cdot\frac{L_H}{E_0}}$$

$$\mathcal{Z}(z) \simeq a + be^{-cz}$$ **redshift evolution**





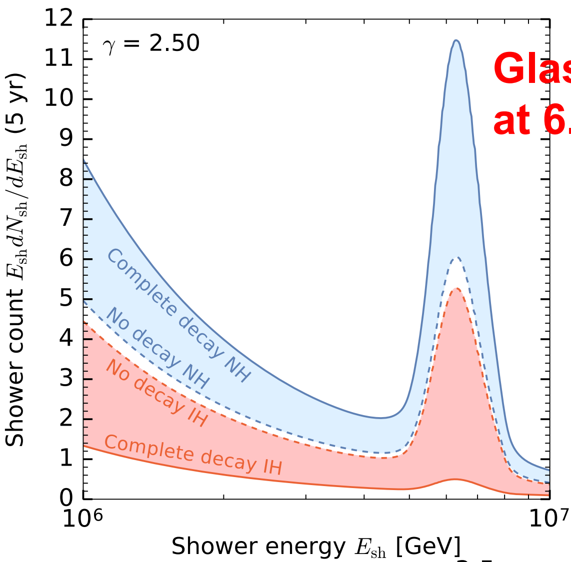
Bustamante, Beacom & KM 17 PRD
(see also Pagliaroli+ 15 PRD)

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

complete decay of ν_2, ν_3 disfavored only by flavors

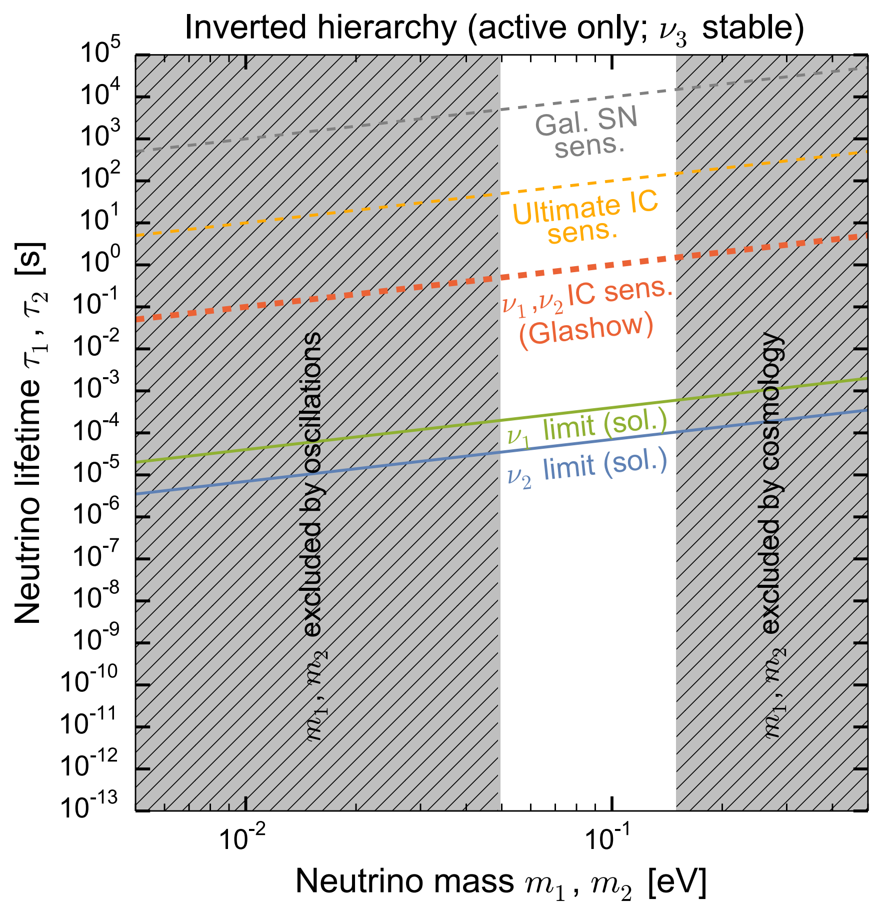
Neutrino Decay: Inverted Hierarchy

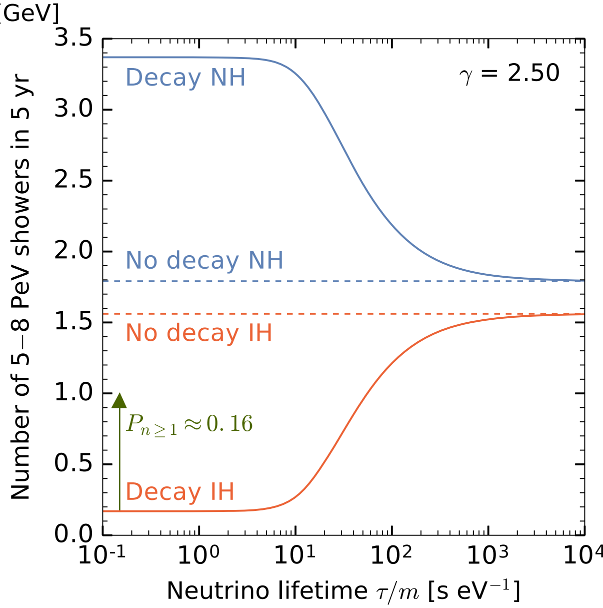
IH is not disfavored yet by the flavor information



Glashow resonance at 6.3 PeV

Bustamante, Beacom & KM 17 (see also Shoemaker & KM 16)





one Glashow event (for γ=2.5)

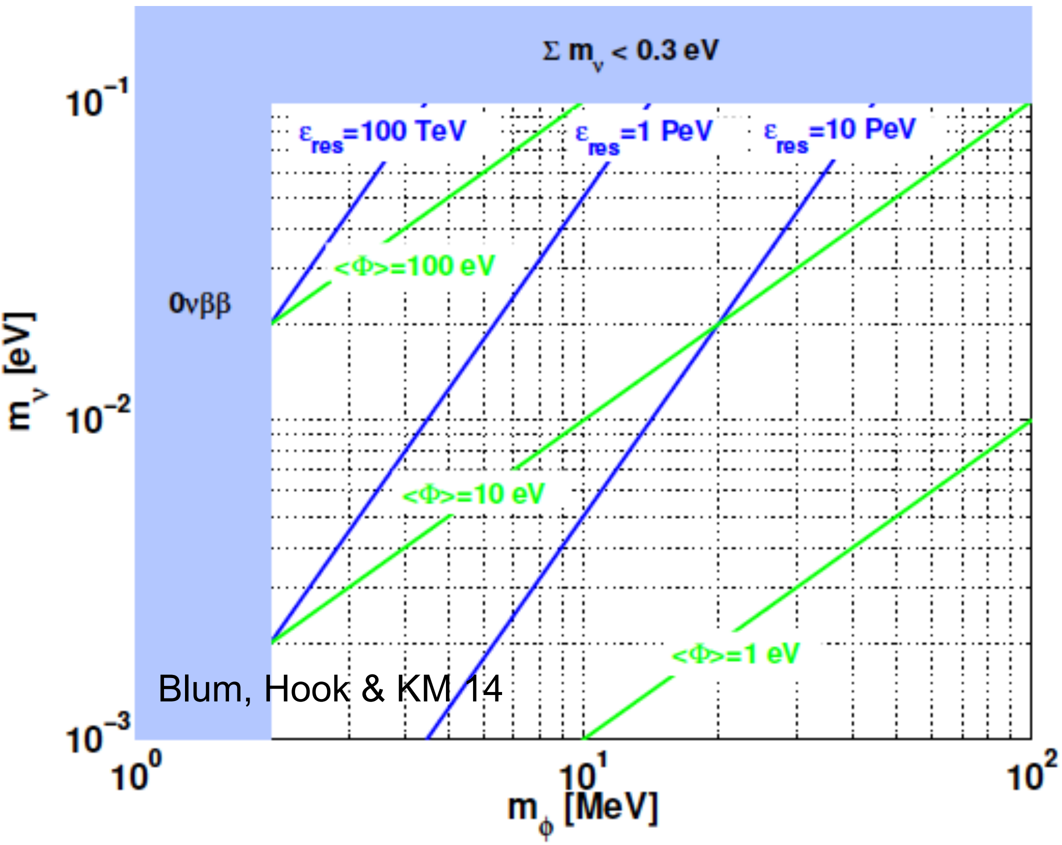
$$\tau_1/m_1, \quad \tau_2/m_2 \gtrsim 10 \text{ s eV}^{-1} \quad (\sim 2\sigma, \mathrm{IH})$$

Secret Neutrino Interactions

Bardin, Bilenky & Pontecorvo 70

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

Applications to IceCube
Ioka & KM 14 PTEP
Ng & Beacom 14 PRD
see also
Ibe & Kaneta 14 PRD
Araki+ 14 PRD
Cherry+ 14 JHEP



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

ex. Majorana ν self-interactions via a scalar

$$\mathcal{L} = -\frac{1}{2}\sum_i \left(m_{\nu_i} + \mathcal{G}_i\phi\right)\nu_i\nu_i + cc + \ldots,$$

SSB
lepton # violation

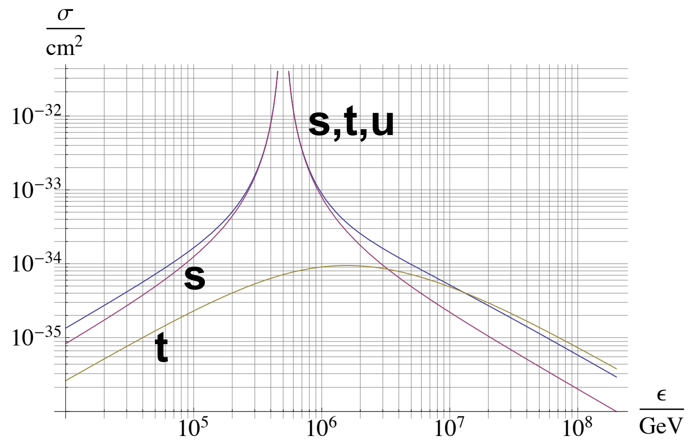
$$m_{\nu_i} = \frac{g_i \mu v^2}{\Lambda^2}$$

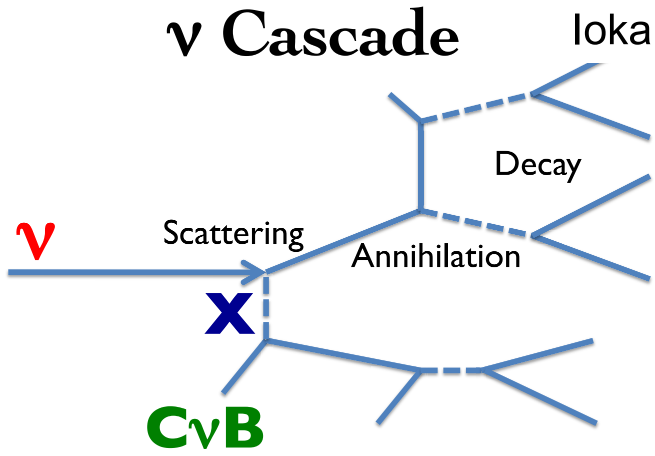
$$\mathcal{L} = -\frac{g}{\Lambda^2}\Phi(HL)^2 + cc.$$

ex. gauged L_μ-L_τ model
see also Kaneta's talk

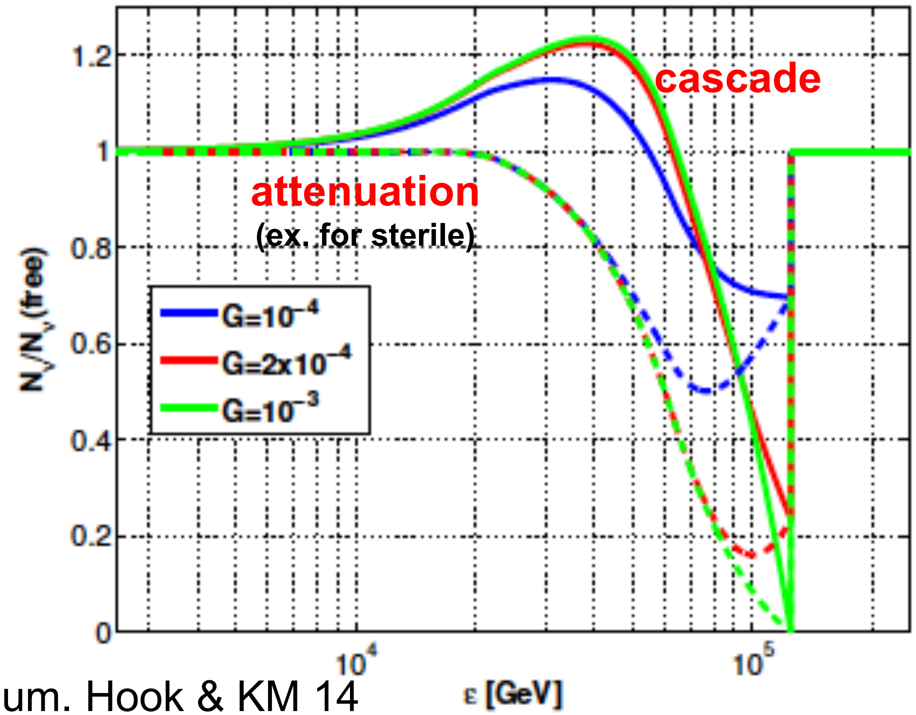
ex. interaction w. "sterile" neutrinos
- m_ν is replaced with m_s
- limits are weaker due to $\sin\theta_s$

Effects on Cosmic Neutrino Spectra

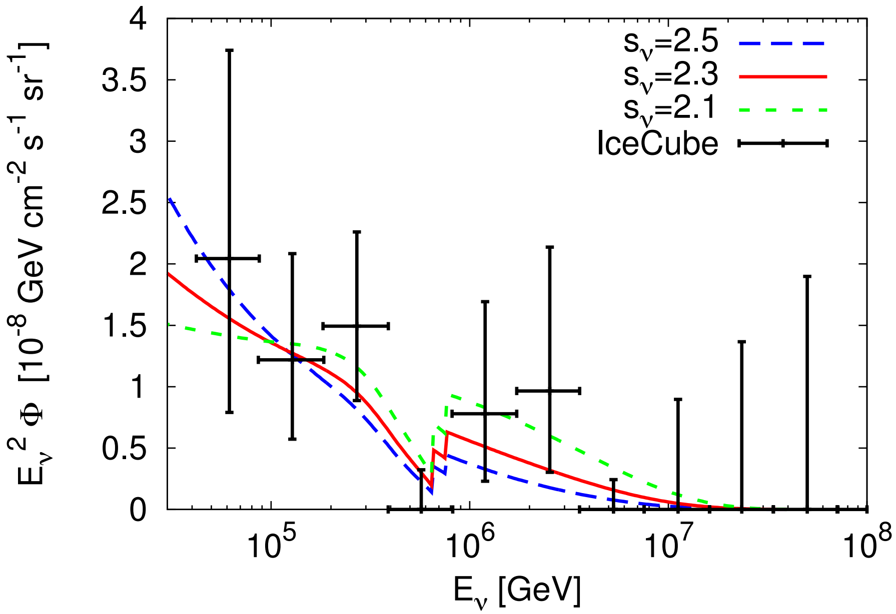




Ioka & KM 14

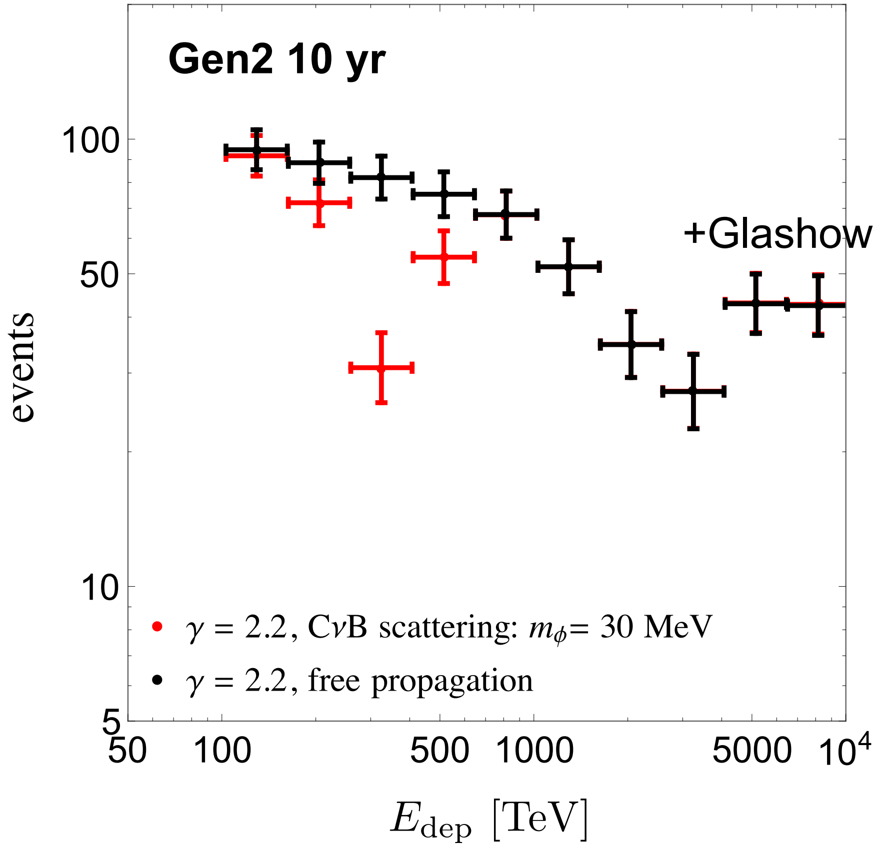


Blum. Hook & KM 14



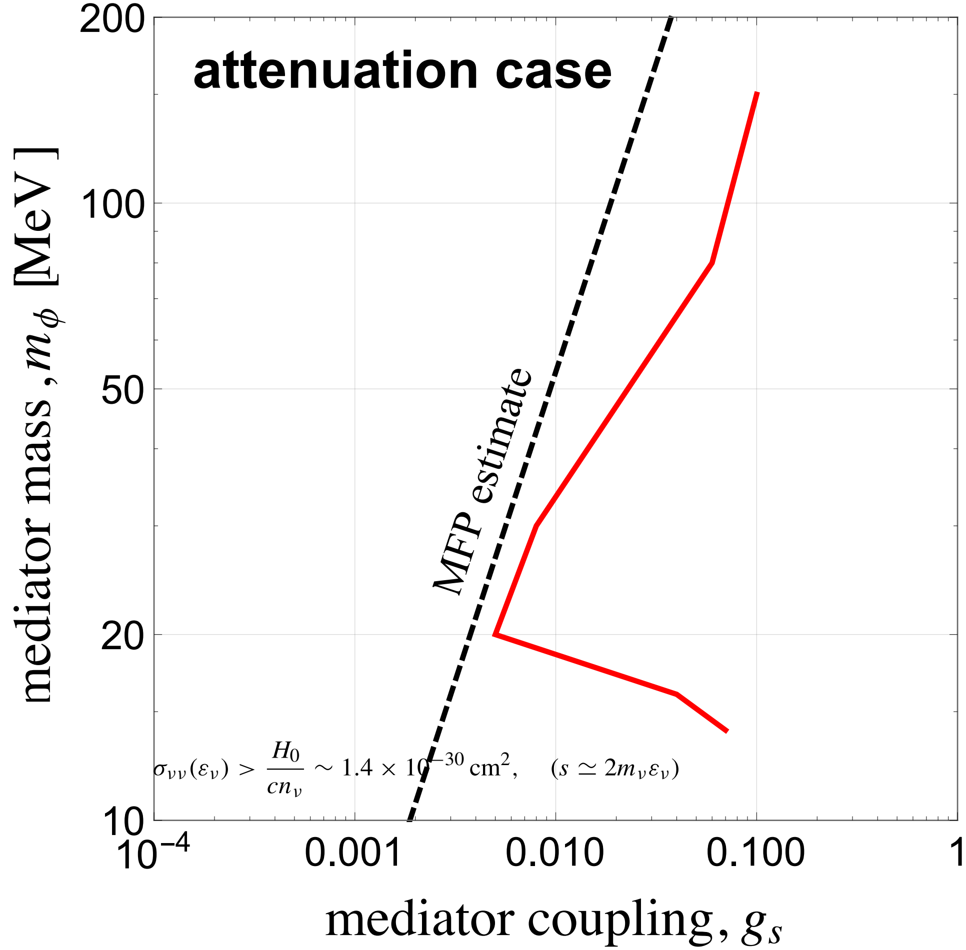
Araki et al. 16

Hunting Gaps & Future Constraints

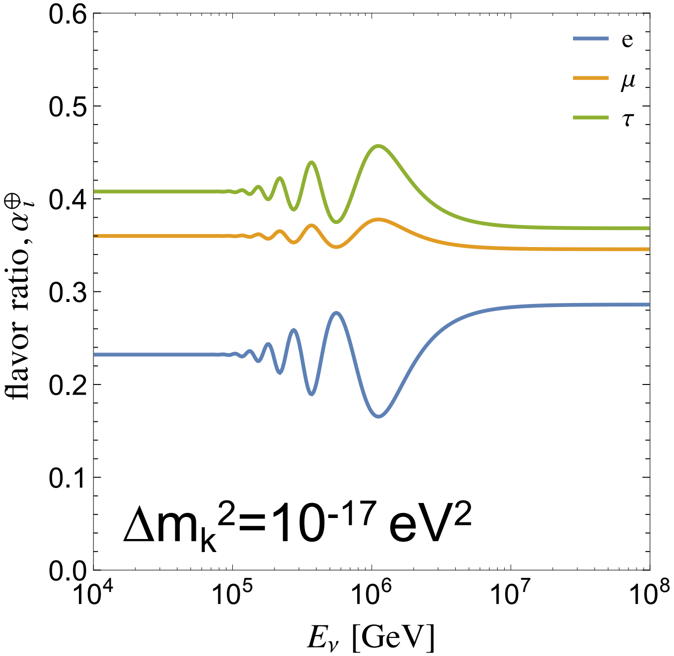


gap features can be tested with feature experiments

HE neutrinos can give the best limits
cf. π/K decay: G < 0.01
Z decay: G <~ 0.1
0νββ decay etc. but **model-dependent**



Pseudo-Dirac Neutrinos

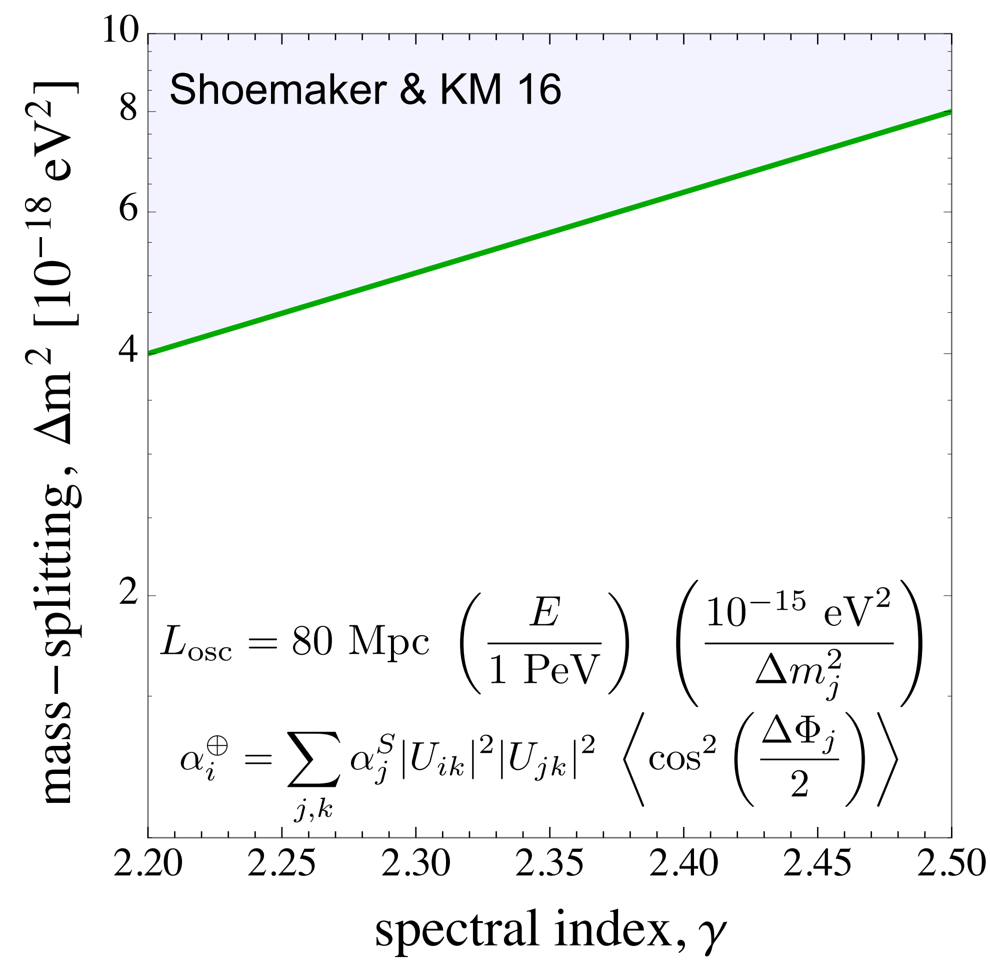


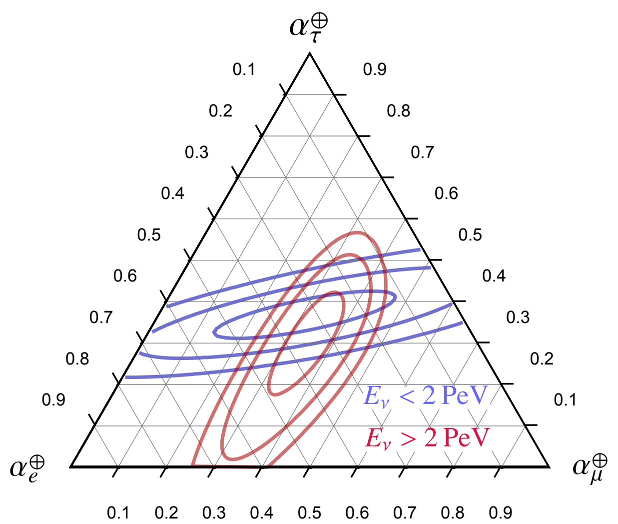
- Tiny mass splitting w. sterile neutrinos

Wolfenstein 81, Petcov 81

- Cosmic neutrinos can be used as a probe

Beacom et al. 04, Karanen et al. 03





Neutrino Decay

Neutrinos may decay (as studied in Majoron models)

HE cosmic neutrinos provide a special way to test for m_ν~0.1 eV

Beacom, Bell, Hooper, Pakvasa & Weiler 04

$$\frac{dN_i}{dt} = -\left(\frac{m_i}{\tau_i}\frac{1}{E_\nu}\right) N_i \qquad \kappa_i^{-1} \equiv \tau_i / m_i$$

$$\kappa^{-1}\left[\frac{\mathrm{s}}{\mathrm{eV}}\right] \simeq 10^2 \, \frac{L\,[\mathrm{Mpc}]}{E_\nu\,[\mathrm{TeV}]}$$

or

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

Complete decay of all eigenstates: SN 1987A $\quad \kappa^{-1} \gtrsim 10^5\ \mathrm{s\ eV}^{-1}$

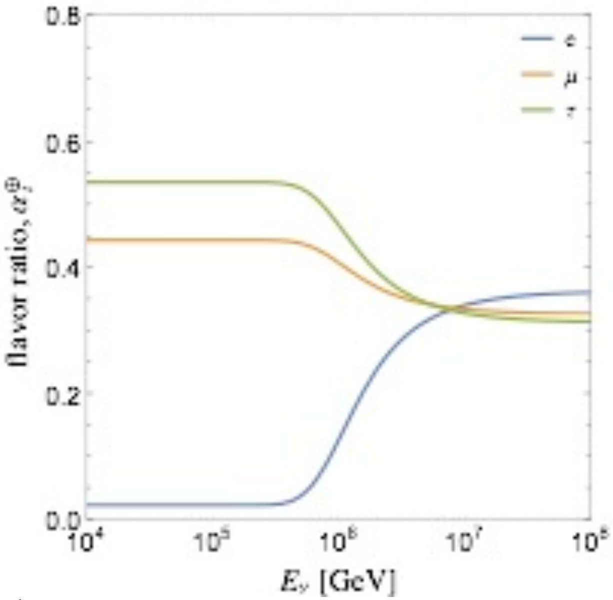
Invisible decay

$$P_{\alpha\beta}^{\mathrm{inv}}(E_0, z) = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \frac{N_i\left(E_0, z, \kappa_i^{-1}\right)}{\hat{N}_i}$$

Visible decay (decay into the lowest mass eigenstate)

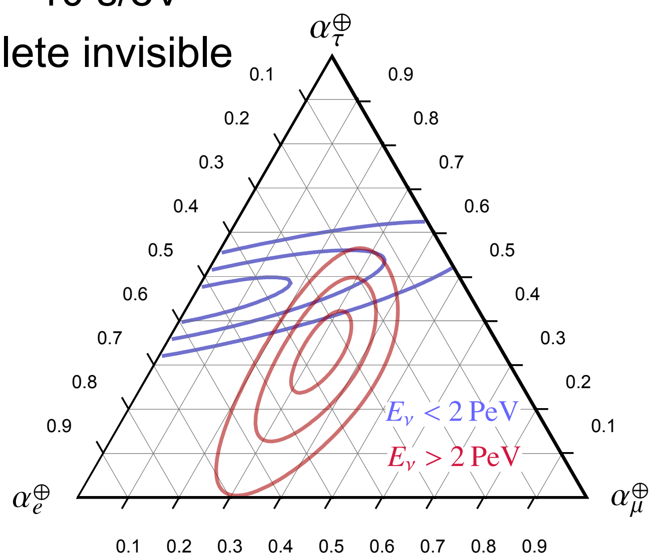
$$P_{\alpha\beta}^{\mathrm{vis,NH}} = |U_{\alpha 1}|^2 |U_{\beta 1}|^2 \left[\frac{N_1 + \left(\hat{N}_2 - N_2\right) + \left(\hat{N}_3 - N_3\right)}{\hat{N}_1}\right] + |U_{\alpha 2}|^2 |U_{\beta 2}|^2 \frac{N_2}{\hat{N}_2} + |U_{\alpha 3}|^2 |U_{\beta 3}|^2 \frac{N_3}{\hat{N}_3}$$

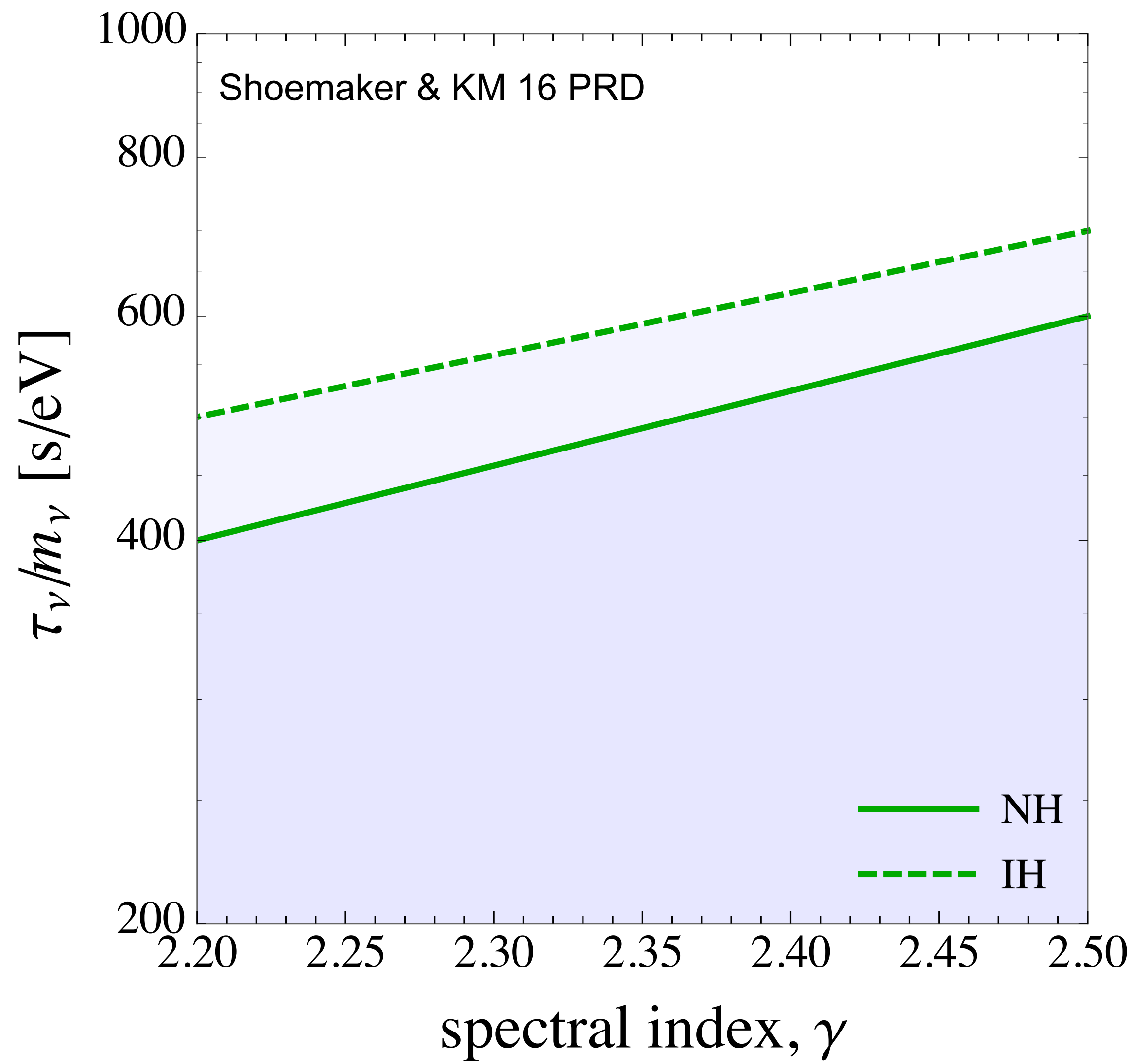
Future Constraints on Neutrino Decay



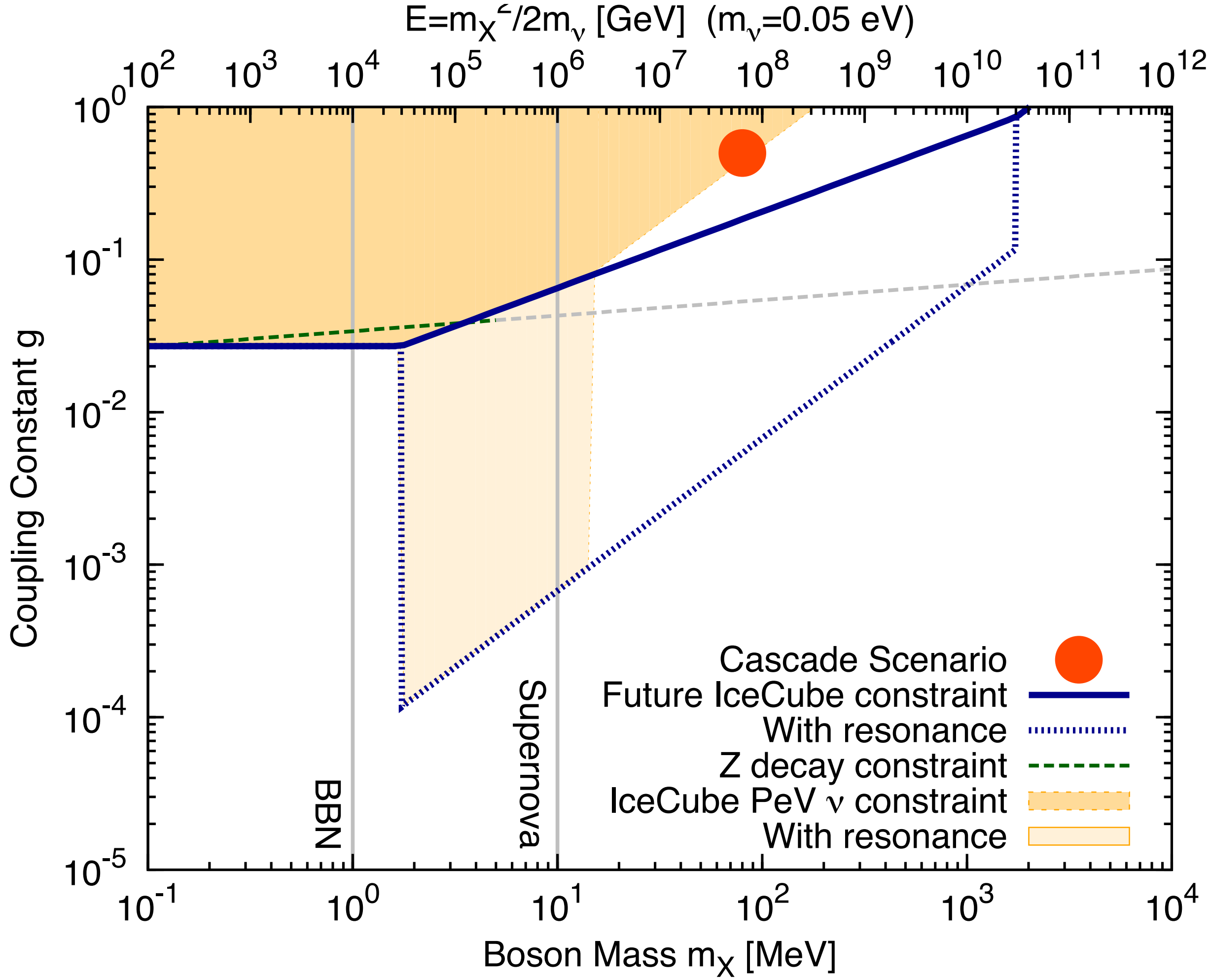
IH: κ^{-1}=10 s/eV

complete invisible





Constraints on Self-Interactions



ex. s-channel resonance:
$s=2m_\nu E_\nu \sim m_X^2$

- An example that IceCube can be used for testing nonstandard interactions
- Can be more powerful than laboratory tests

A Phenomenological Model

6-dimensional operator

$$\mathcal{L} = -\frac{g}{\Lambda^2}\Phi(HL)^2 + cc,$$

EW SSB & LN explicit breaking

$$\Phi = \phi + \mu \quad \langle\Phi\rangle = \mu.$$

$$\mathcal{L} = -\frac{1}{2}\sum_i \left(m_{\nu_i} + \mathcal{G}_i\phi\right)\nu_i\nu_i + cc + \ldots,$$

$$m_{\nu_i} = \frac{g_i\mu v^2}{\Lambda^2}, \qquad g = \mathrm{diag}(g_1, g_2, g_3), \qquad \mathcal{G}_i = \frac{m_{\nu_i}}{\mu} = \frac{g_i v^2}{\Lambda^2}$$

There are many possibilities to induce neutrino-neutrino scattering

Example 1 (type II seesaw)

$$V_{UV} = \left\{\lambda\Phi^*\Delta^a H^\dagger\sigma^a\epsilon H^* + \Delta^a L^T\epsilon\sigma^a y L + Y_l H^\dagger L e^c + cc\right\} + M^2\Delta^{a*}\Delta^a + m_\phi^2|\Phi|^2 + \lambda_\phi|\Phi|^4 + V_{\mathrm{U}(1)_{\not L}}$$

Example 2

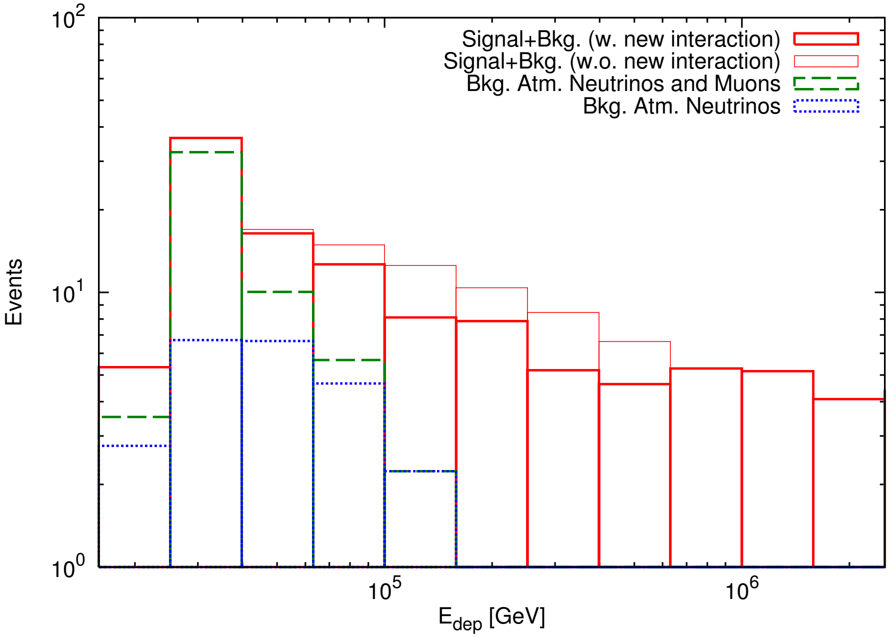
$$V_{UV} = \left\{M\psi\psi^c + y'\Phi\psi^c\psi^c + y(HL)\psi + Y_l H^\dagger L e^c + cc\right\} + m_\phi^2|\Phi|^2 + \lambda_\phi|\Phi|^4 + V_{\mathrm{U}(1)_{\not L}}$$

Observational Features

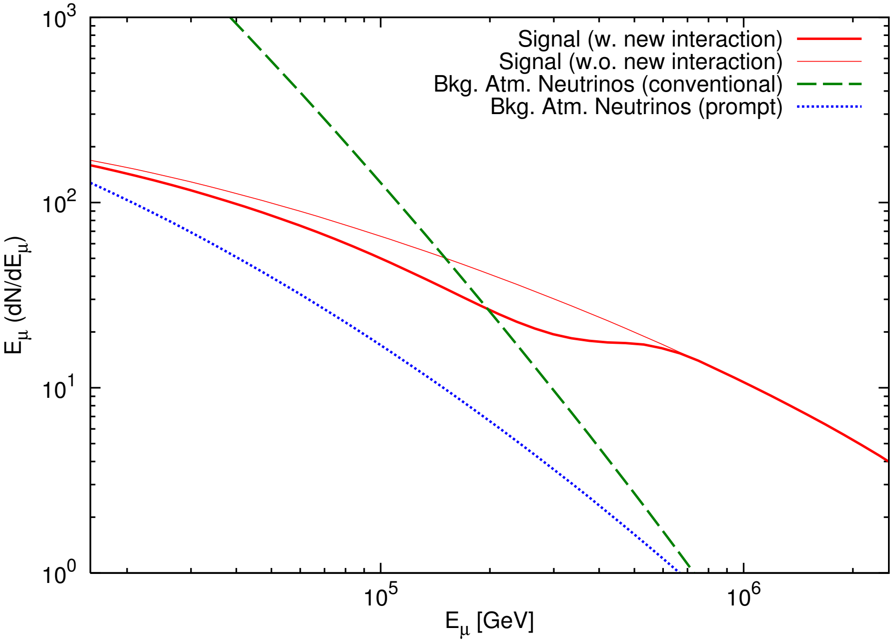
To see a sizable effect in IceCube, we need

$$\mathcal{G} \gtrsim 10^{-3} \left(\frac{m_\phi}{10 \text{ MeV}} \right) \quad \text{or} \quad \Lambda \lesssim 8 \text{ TeV} \times \left(\frac{m_\phi}{10 \text{ MeV}} \right)^{-\frac{1}{2}} g^{\frac{1}{2}}$$

shower



upgoing muon

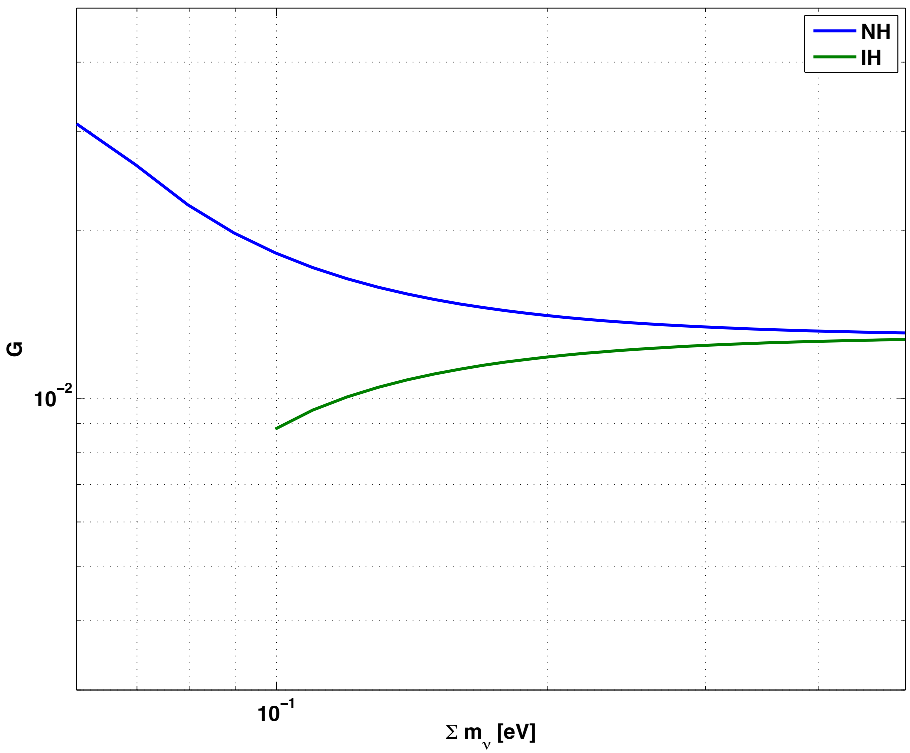


general cautions: deposited energy, muon energy < neutrino energy
unfolded spectrum derived a flavor ratio 1:1:1

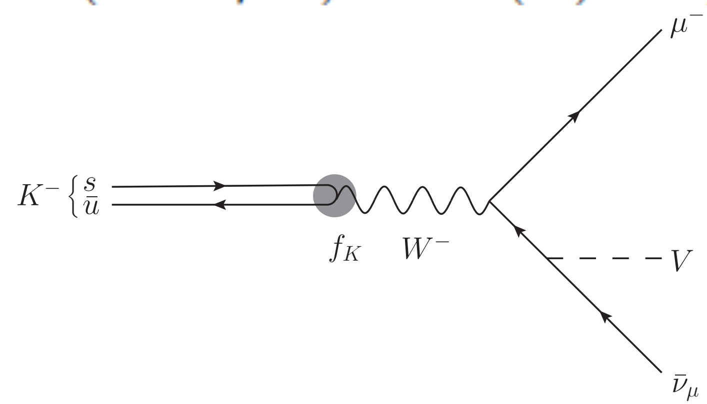
Experimental Constraints

Constraints: light meson decay, Z invisible width, $0\nu\beta\beta$ decay

(& non-unitarity mixing, LFV processes, cosmology…)



$$\frac{BR(K^+ \to \mu^+ \nu \phi)}{BR(K^+ \to \mu^+ \nu)} = \frac{\sum_i G_i^2 |U_{\mu i}|^2}{12(4\pi)^2} \frac{m_K^2}{m_\mu^2}$$



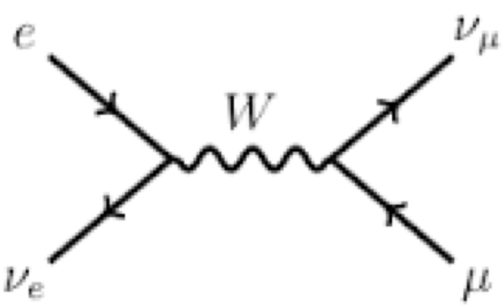
*** helicity-unsuppressed decay $e\nu\phi$ leads to comparable limits**

(Blum, Hook & KM 14
see also, e.g., Laha, Dasgupta & Beacom 14)

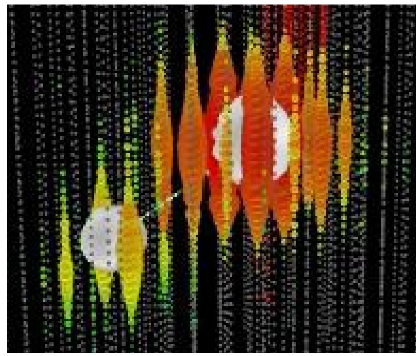
- Active ν scattering: $G < 0.01$ (i.e. $10^{-3} < G < 0.01$ needed)
- Sterile ν scattering: constraints can be weaker due to $\sin\theta_m$

Improvements in Future?

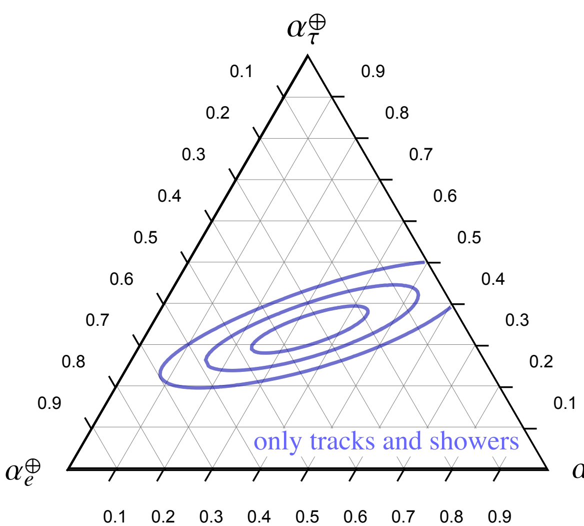
$$\bar{\nu}_e + e^- \longrightarrow W^-$$

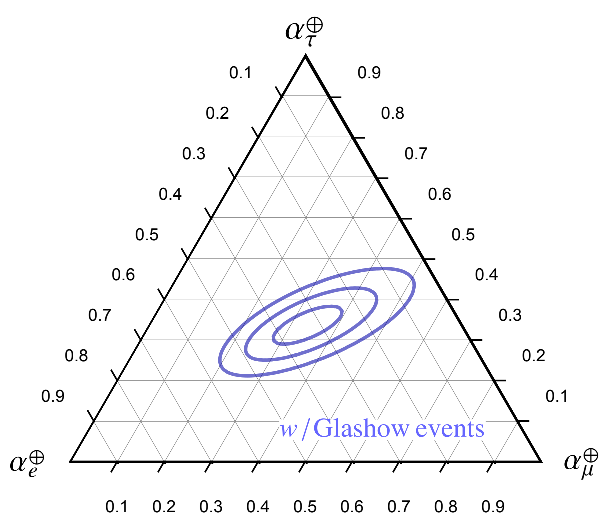


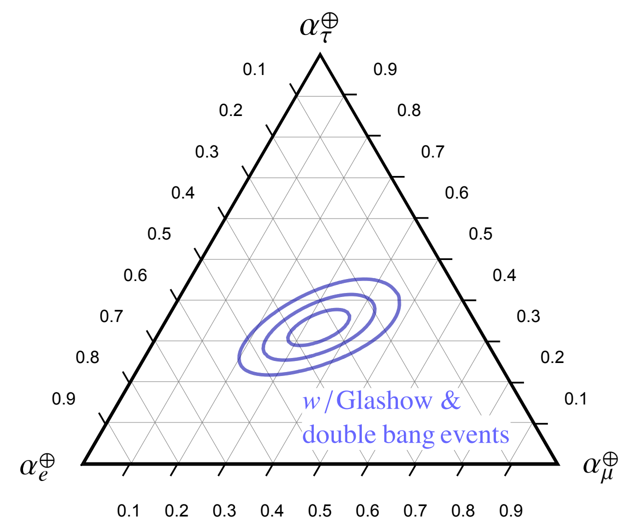
ν_τ+N → τ+X



$[N_{GR}, N_{DB}]$	$\Phi \propto E^{-2.2}$	$\Phi \propto E^{-2.5}$
pp	$[23, 5]$	$[8, 2]$
pp (with μ^+ damping)	$[15, 6]$	$[6, 2]$
$p\gamma$ (canonical π^-)	$[11, 6]$	$[4, 2]$
neutron decay	$[73, 4]$	$[28, 1]$







Shoemaker & KM 16 PRD