Multi-Messenger Implications for Cosmic-Ray Sources and Heavy Dark Matter

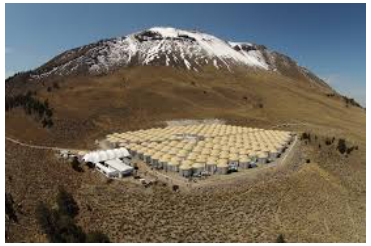
Kohta Murase (Penn State)

June 22 2017 @ WIN 2017

Era of Multi-Messenger Astroparticle Physics

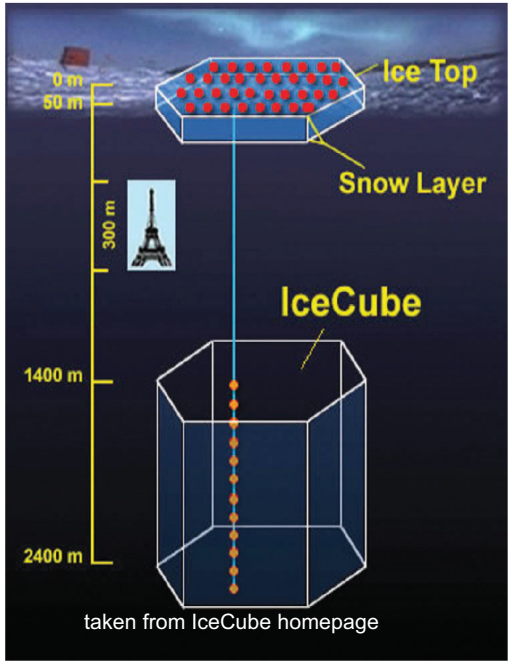
Gamma Rays

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

This Talk

"Multi-messenger approaches"

different particles, different energies, different physics, different objects…

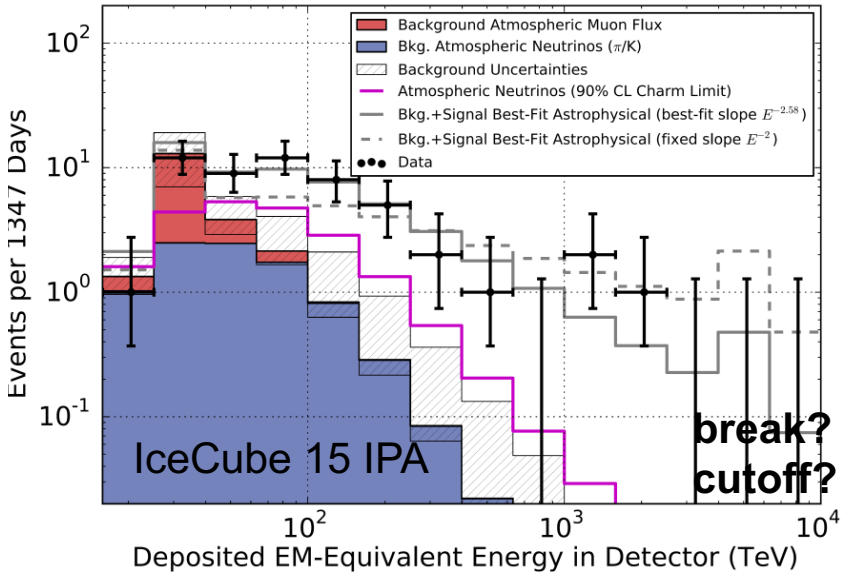
ex. cosmic-ray origin, dark matter indirect searches, counterparts of gravitational wave sources etc.

Focus:

multi-messenger implications for cosmic-ray sources

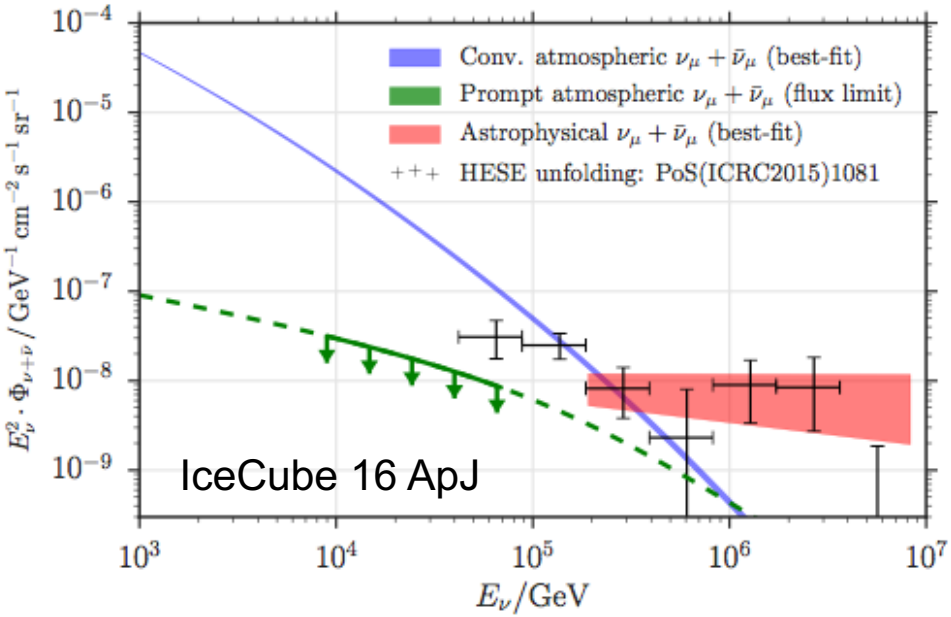
multi-messenger constraints on heavy dark matter

High-Energy Neutrinos



- 4-yr HESE data: 54 events (6.5 σ)
  E_{dep}: 20 TeV-2 PeV
  - Best fit: s_ν=2.58+-0.25
  - $E_\nu^2\ \Phi_\nu$=(2.2±0.7)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV (per flavor)

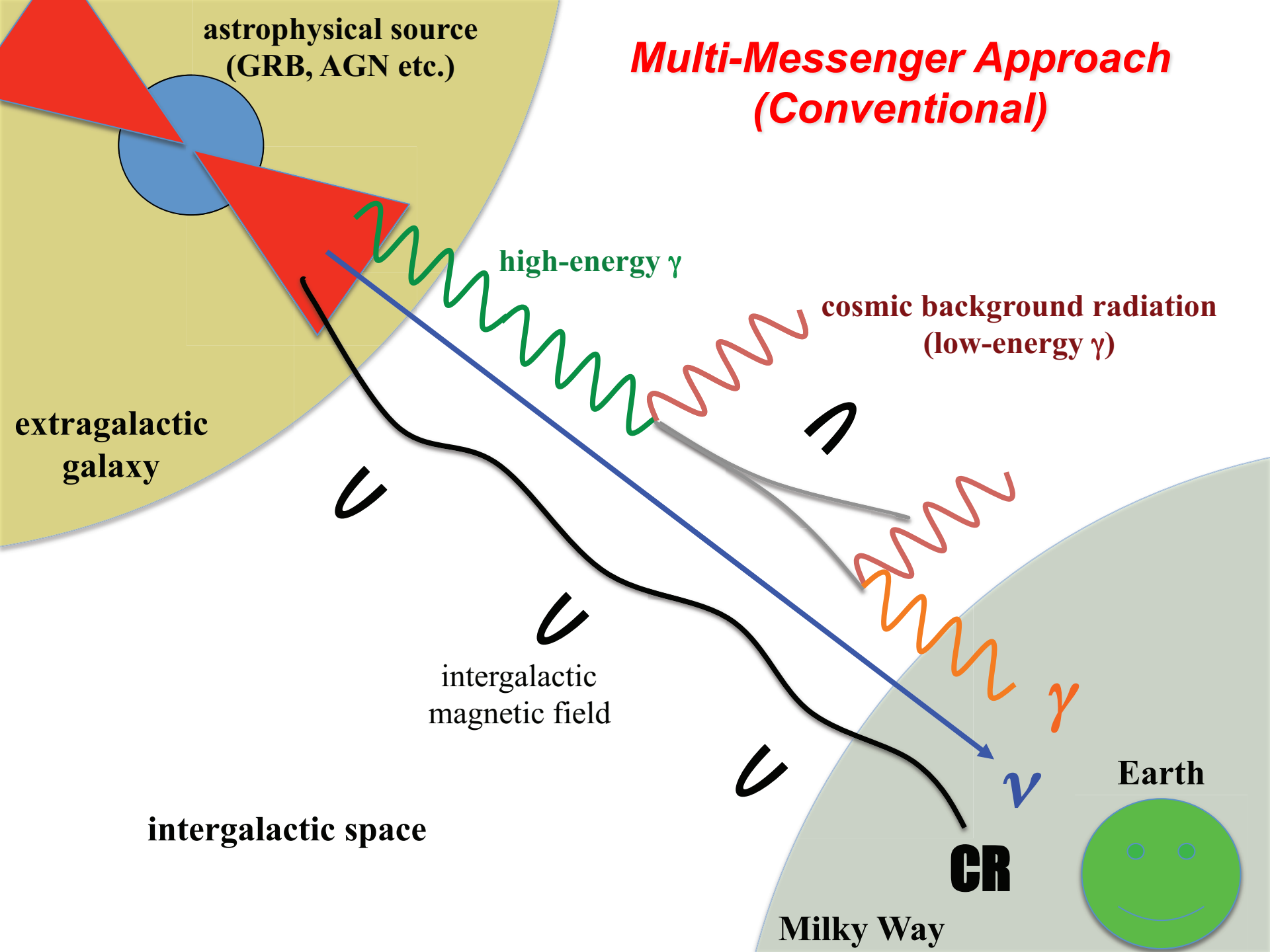
cf. 3-yr HESE data: 37 events (5.7 σ)
E_{dep}: 30 TeV-2 PeV
- Best fit (no cutoff): s_ν=2.3+-0.3



- 6-yr upgoing ν_μ "track"
  29 events at >200 TeV (5.9σ)

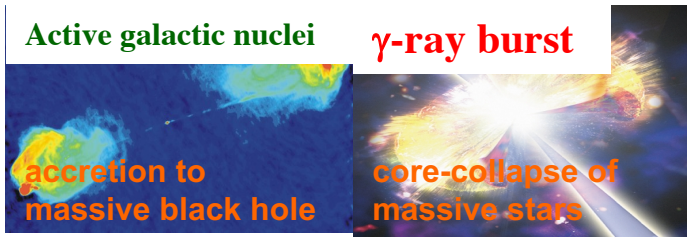
- Best-fit: s=2.13±0.13
- ν_μ flux above 100 TeV:
  $E_\nu^2\Phi_\nu$=(0.82+0.3-0.26)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

Multi-Messenger Approach (Conventional)

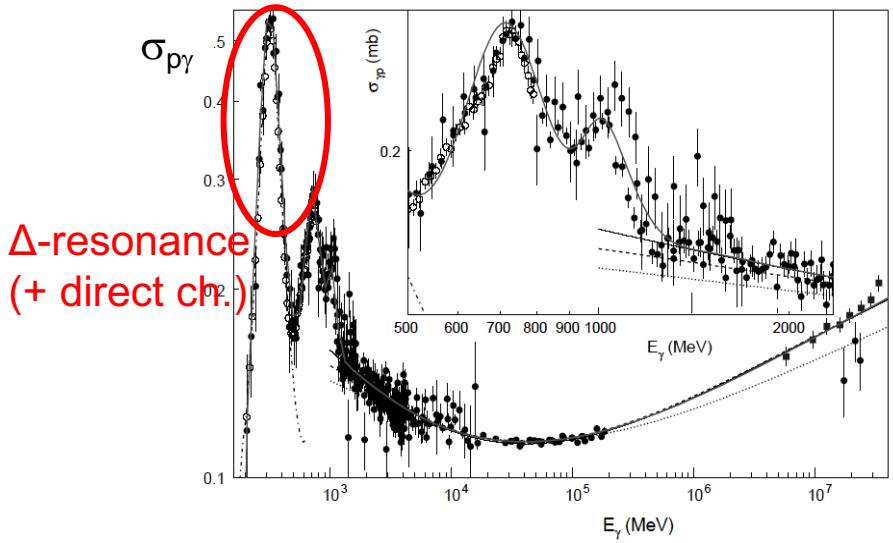


Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. UHECR candidate sources)



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

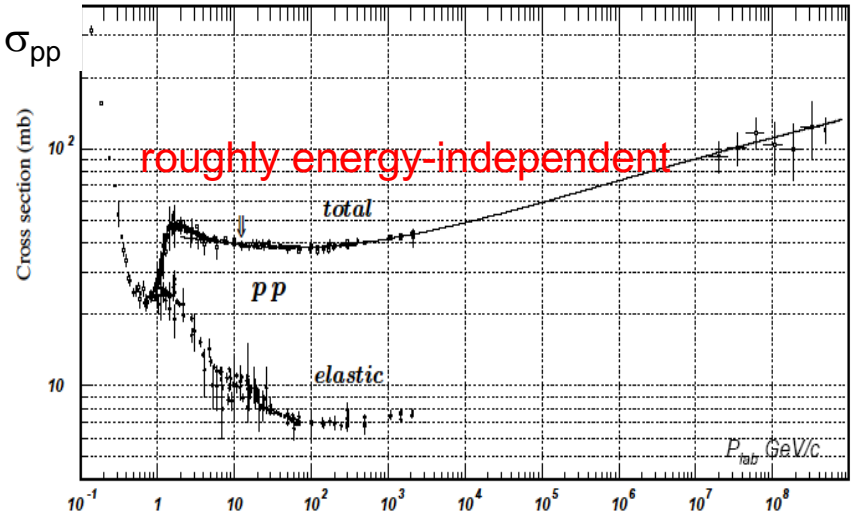


$$\sigma_{p\gamma} \sim \alpha\sigma_{pp} \sim 0.5 \text{ mb}$$

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

Cosmic-ray Reservoirs

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



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

Fate of High-Energy Gamma Rays

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

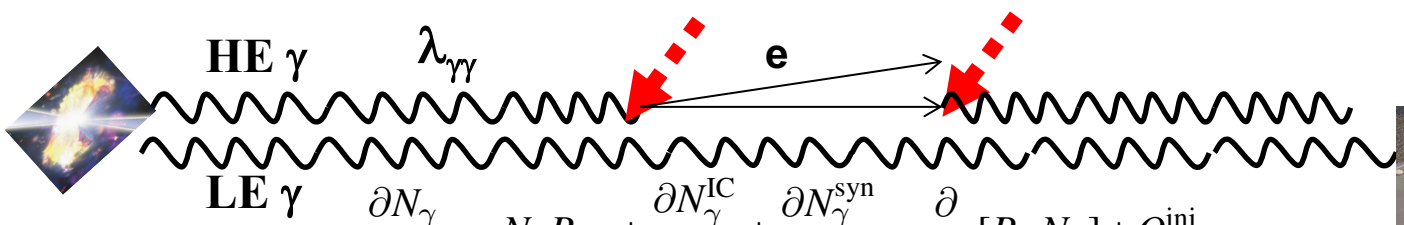
$p + \gamma \rightarrow N\pi + X$ $\quad$ $\pi^{\pm}:\pi^0 \sim 1:1 \rightarrow$ **$E_\gamma^2\,\Phi_\gamma \sim (4/3)\,E_\nu^2\,\Phi_\nu$**

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

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

$\gamma + \gamma_{\mathrm{CMB/EBL}} \rightarrow e^+ + e^-$ $\quad$ ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc

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



Fermi satellite

airshower detectors

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

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

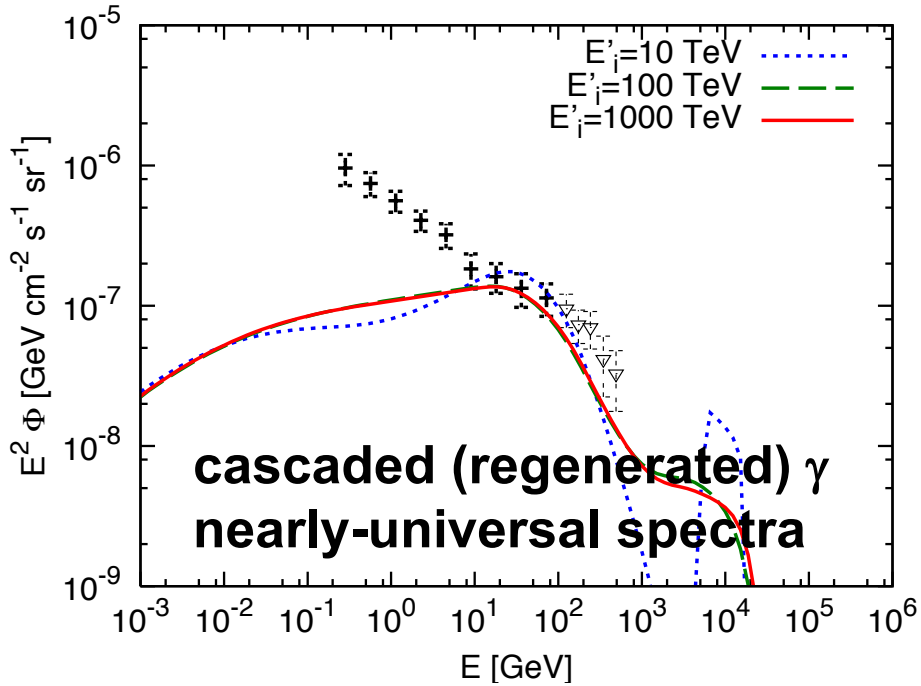
Fate of High-Energy Gamma Rays

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

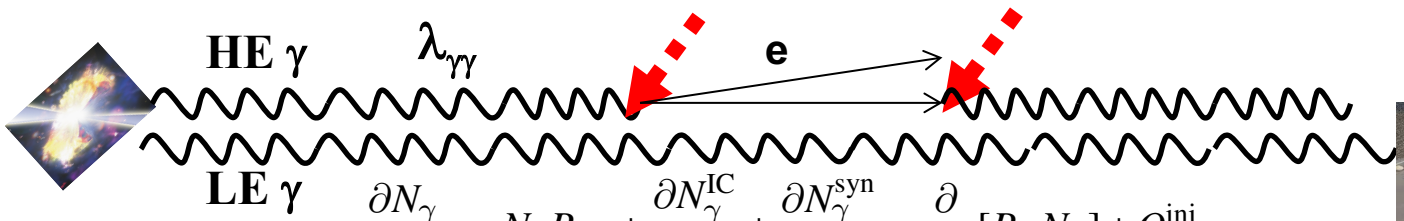
$p+p \rightarrow$ 2/3) $E_\nu^2\ \Phi_\nu$

>TeV γ rays int ound light (EBL)

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



cosmic photon bkg. cosmic photon bkg.



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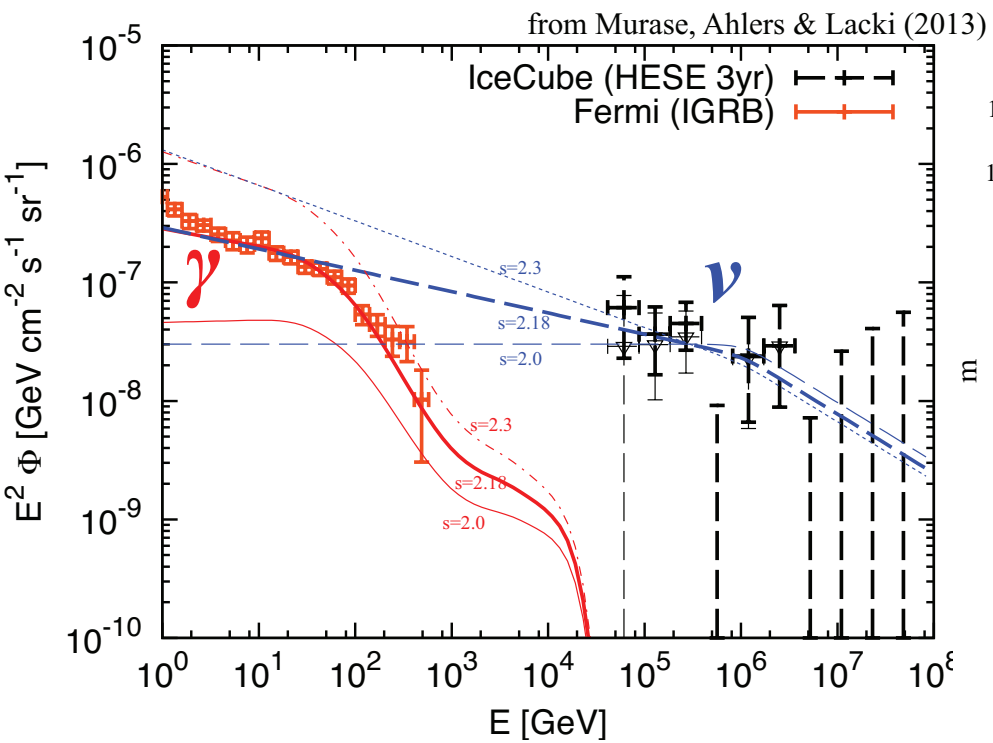
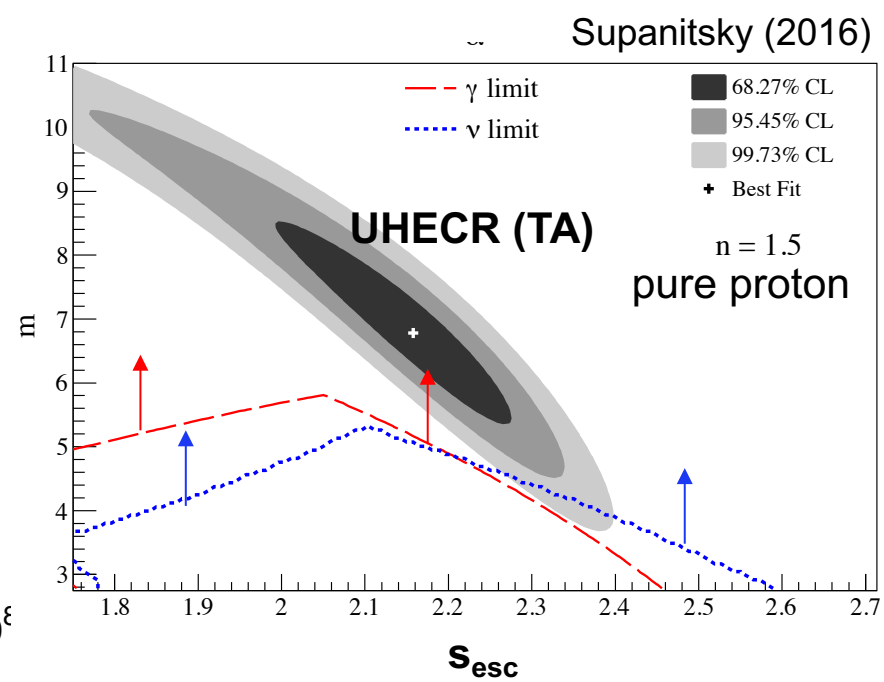
Multi-Messenger Constraints on CR Sources

Constraints on high-energy ν sources



- **spectral index s < 2.1-2.2**
- **significant contribution to Fermi γ-ray bkg.**

Constraints on UHECR sources (cosmogenic/GZK ν & γ)

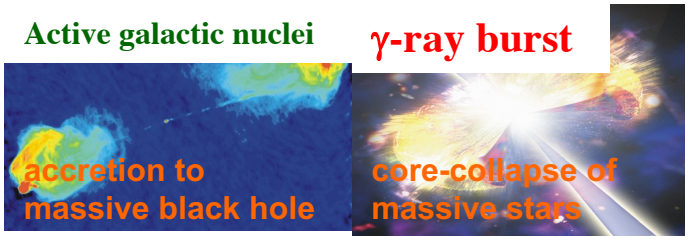


- **UHECR sources cannot be strongly evolving** (redshift evolution ∝ $(1+z)^m$)
- γ & ν give competitive limits

Astrophysical Extragalactic Scenarios

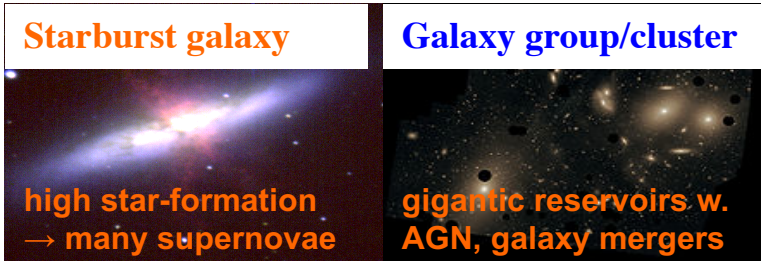
$E_\nu \sim 0.04\ E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-ray Accelerators (ex. UHECR candidate sources)



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

Cosmic-ray Reservoirs



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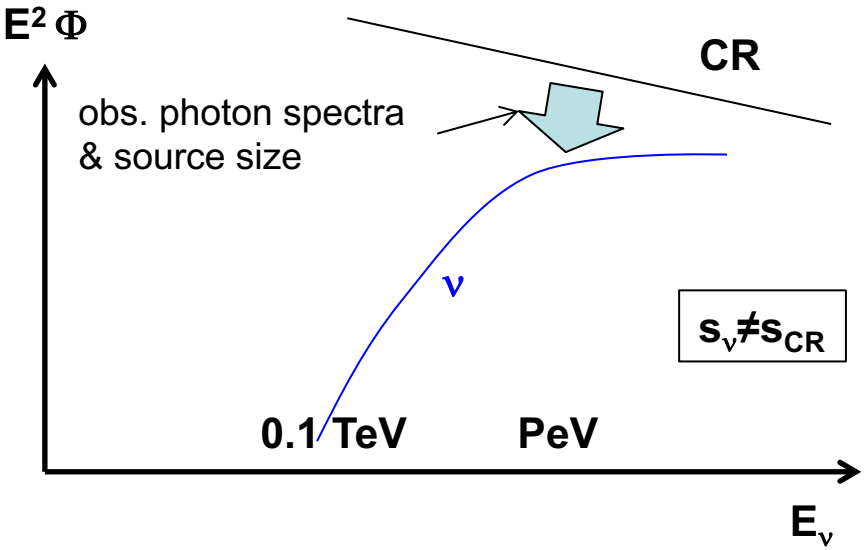

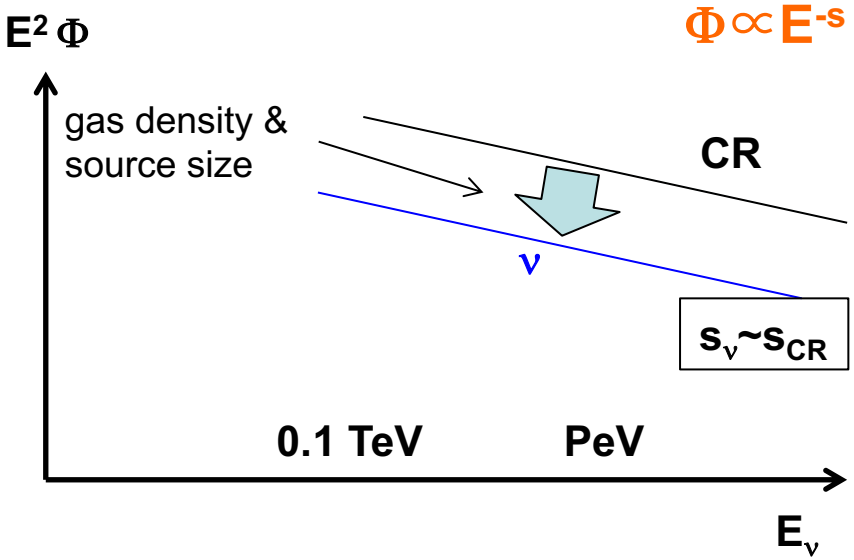

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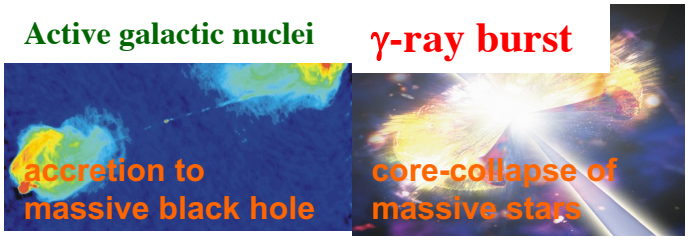

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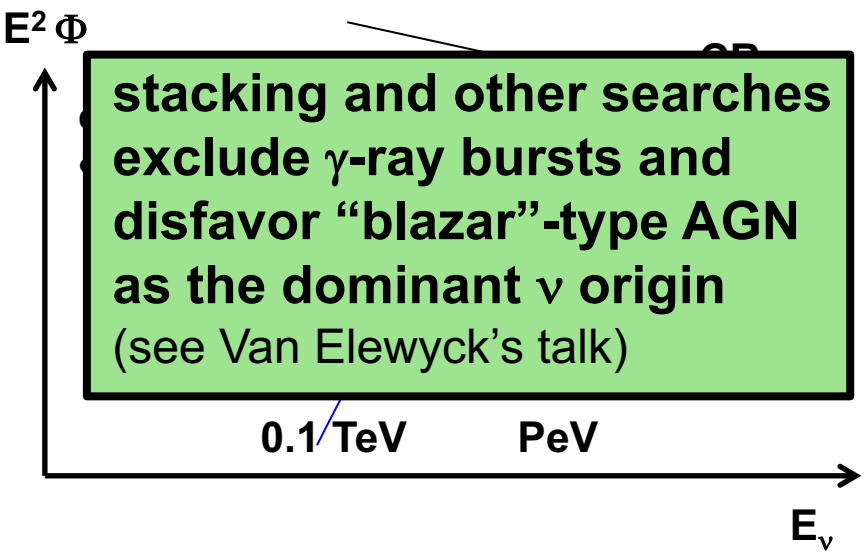
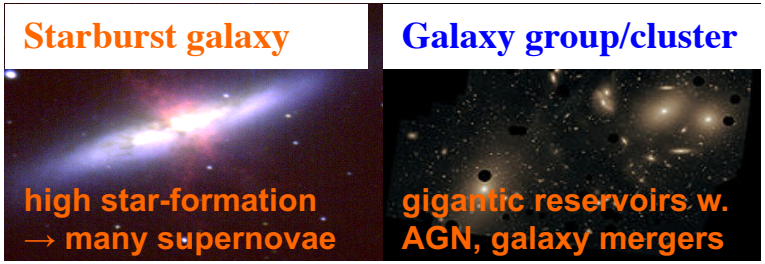


stacking and other searches exclude γ-ray bursts and disfavor "blazar"-type AGN as the dominant ν origin
(see Van Elewyck's talk)

Cosmic-ray Reservoirs



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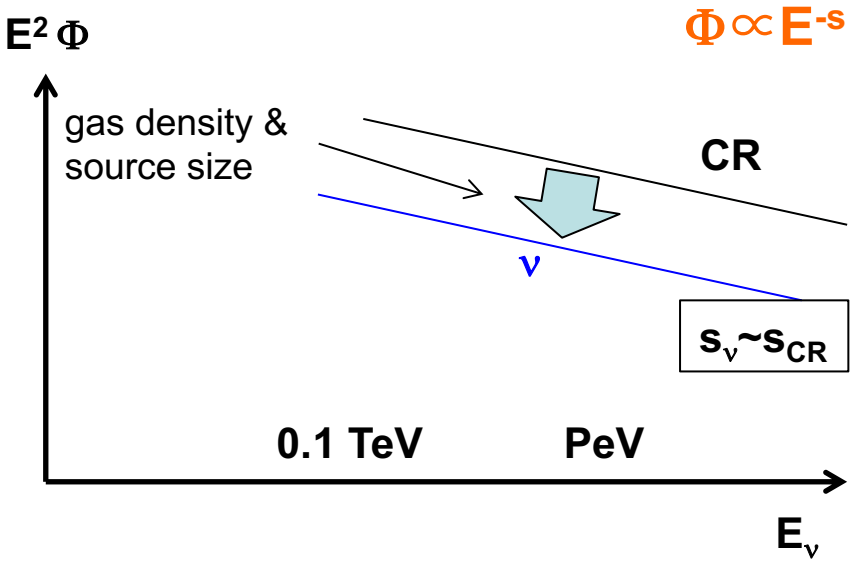
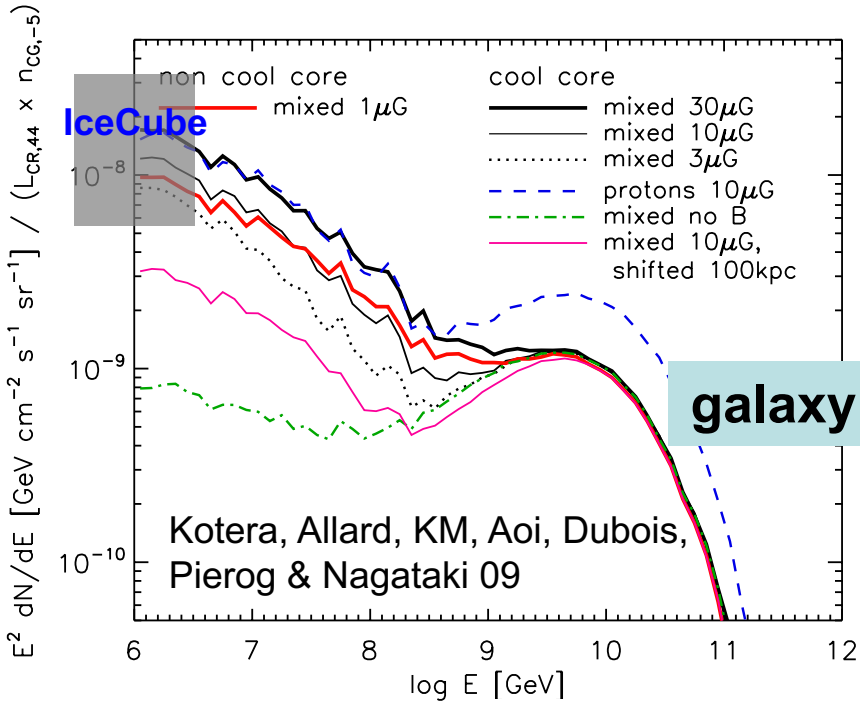
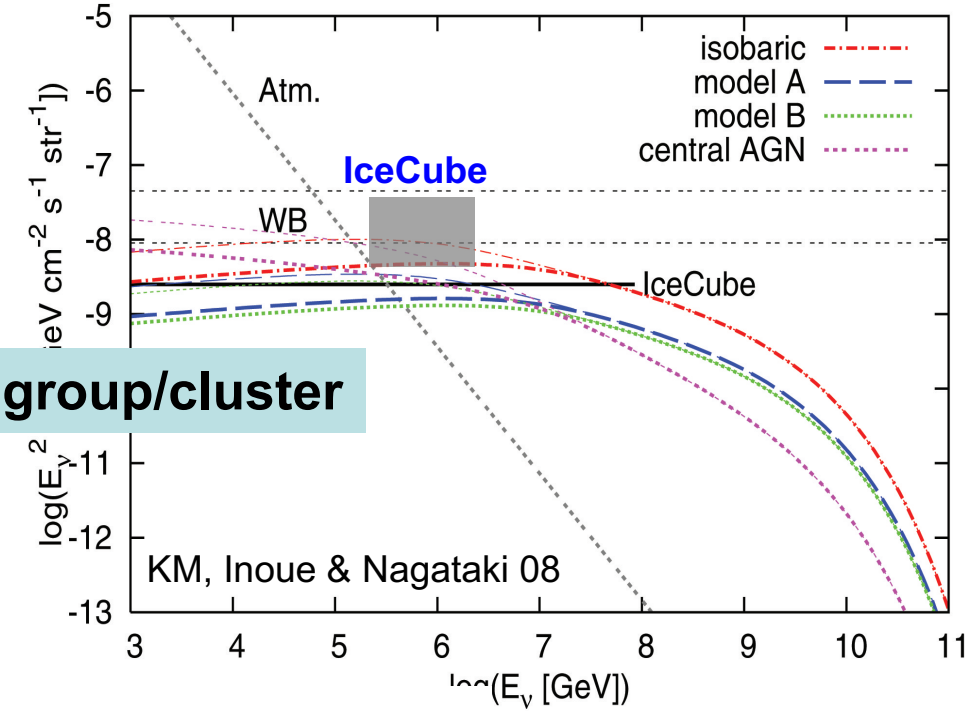
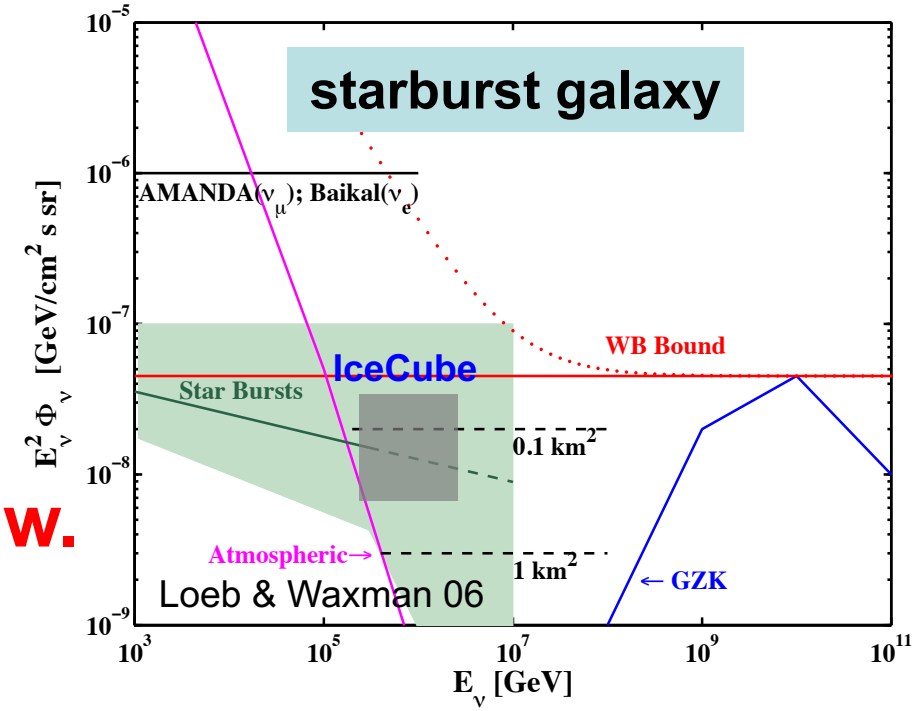






galaxy group/cluster

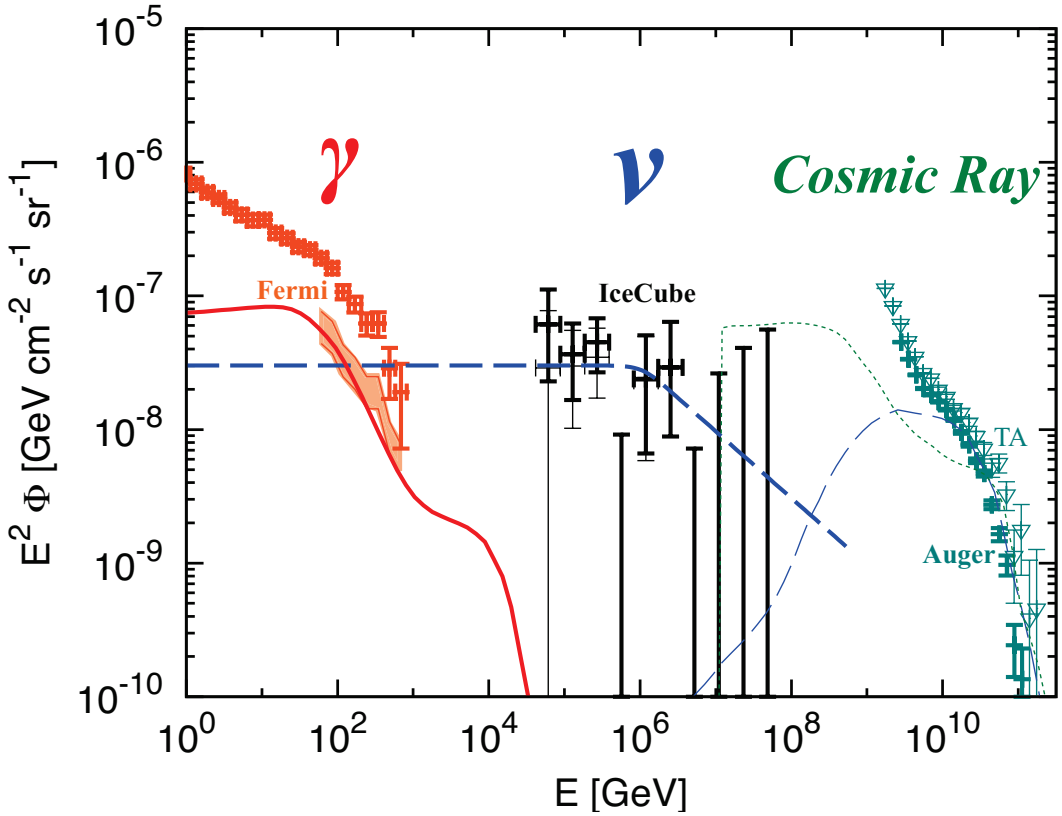


starburst galaxy

Cconsistent w. predictions

Neutrino-Gamma-UHECR Connection

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



KM & Waxman 16 PRD
see also Fang & KM 17

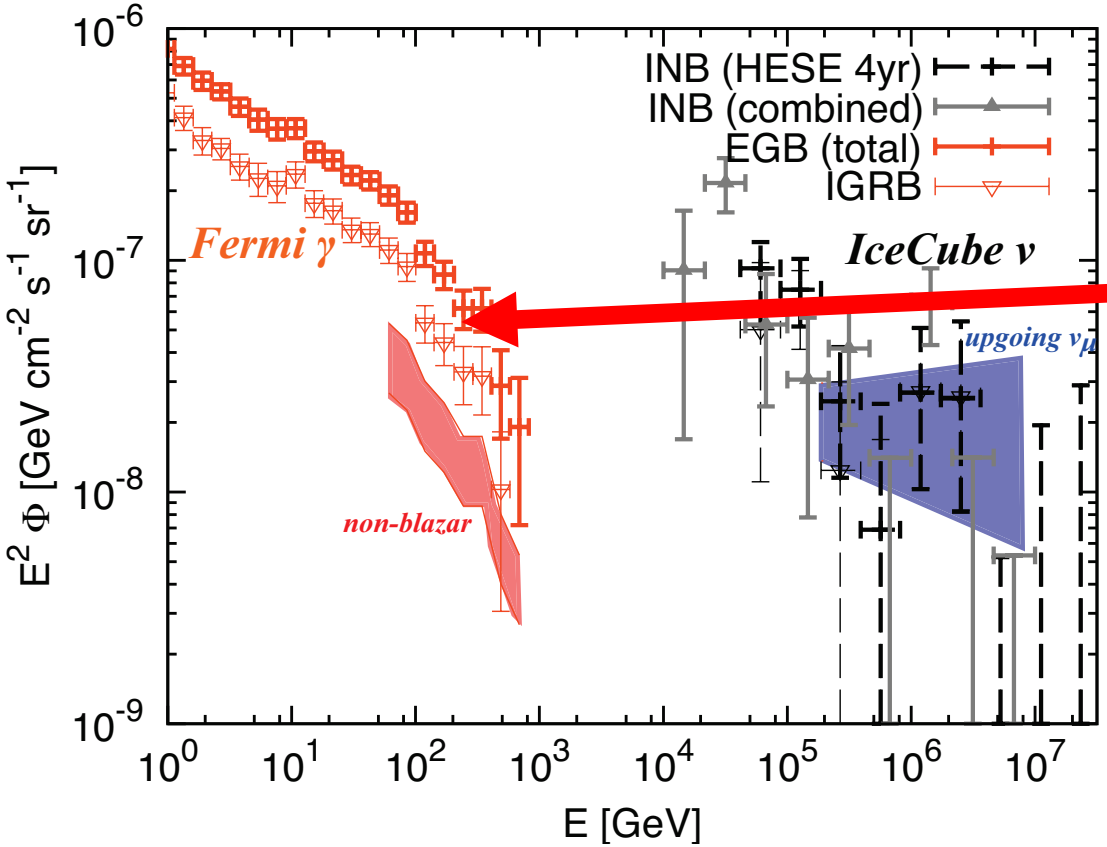
PeVν – confined CR
UHECR – escaping CR
sub-TeVγ – "both"

Grand-unification of neutrinos, gamma rays & UHECRs

※cosmogenic ν flux does not violate the latest EHE limit by IceCube

Multi-Messenger Connections: Physical or Conspiracy?

Proposed tests (2013): 1. (Stacking) searches for neutrinos & γ rays for nearby sources
2. Decomposing the diffuse γ-ray bkg.
3. Measurements of neutrino data below 100 TeV

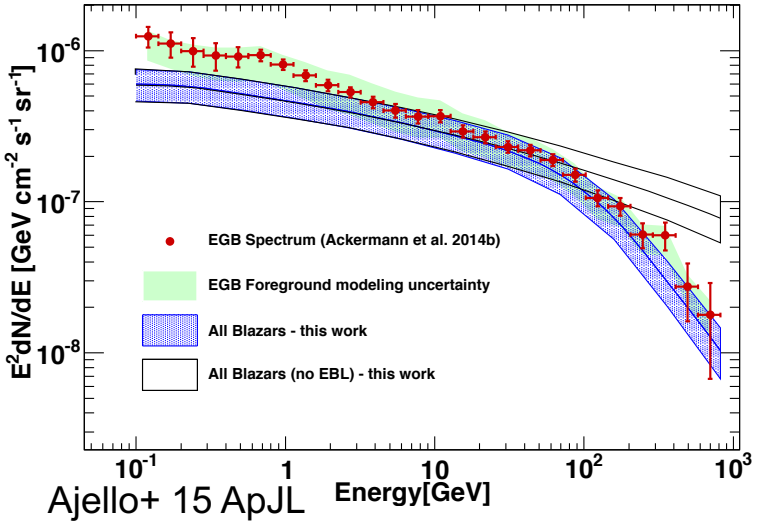


dedicated analyses based on pixel-photon count distribution

unresolved point sources

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

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



Ajello+ 15 ApJL

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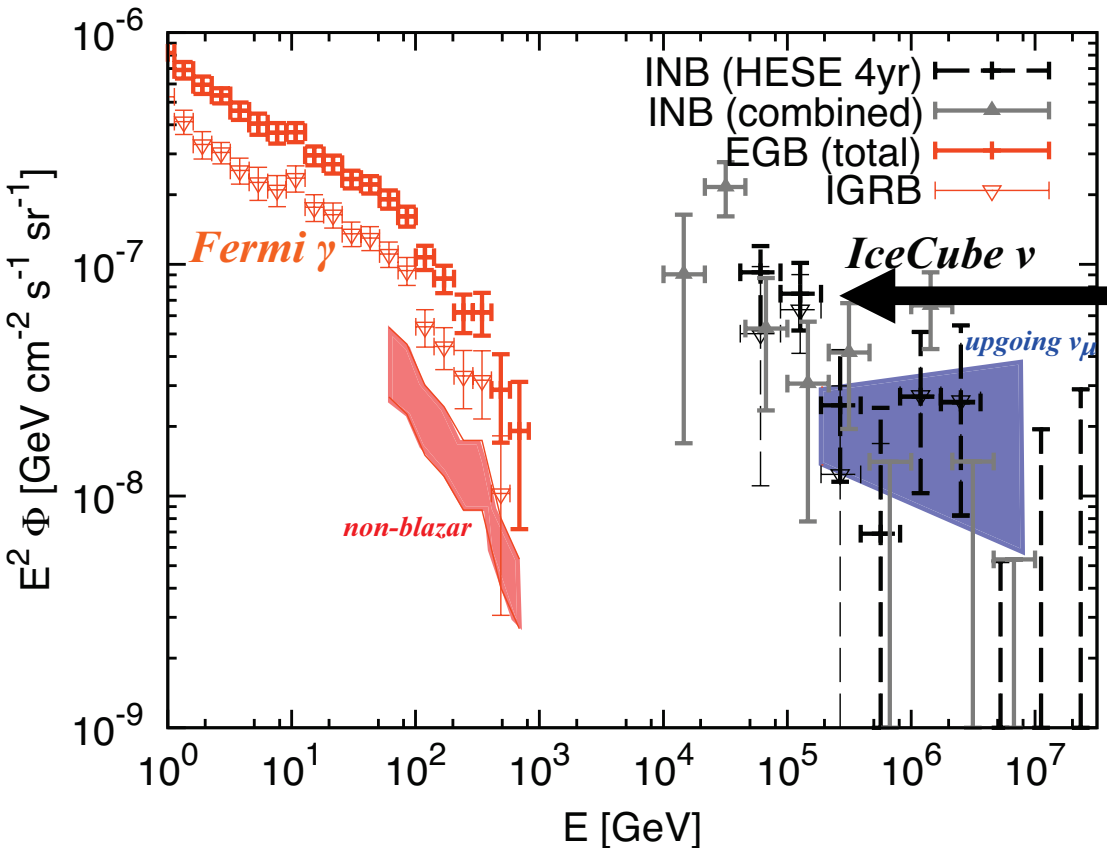
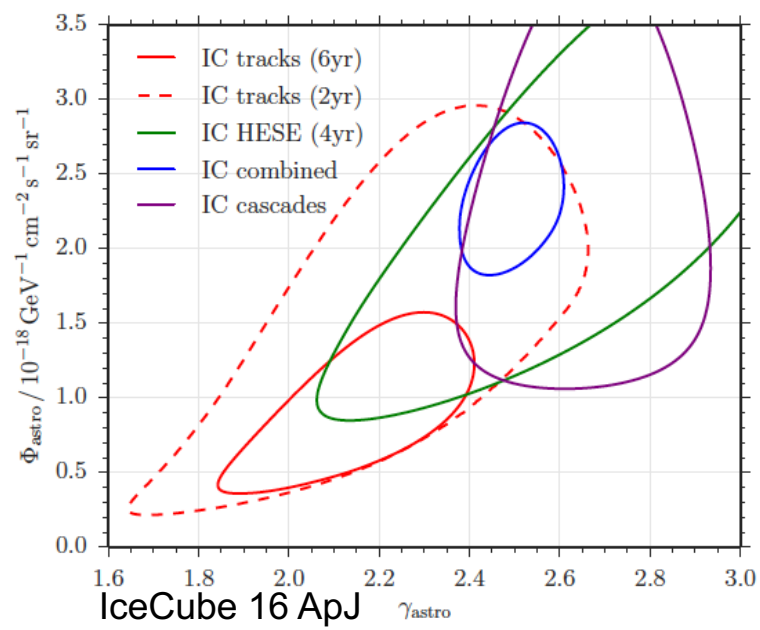


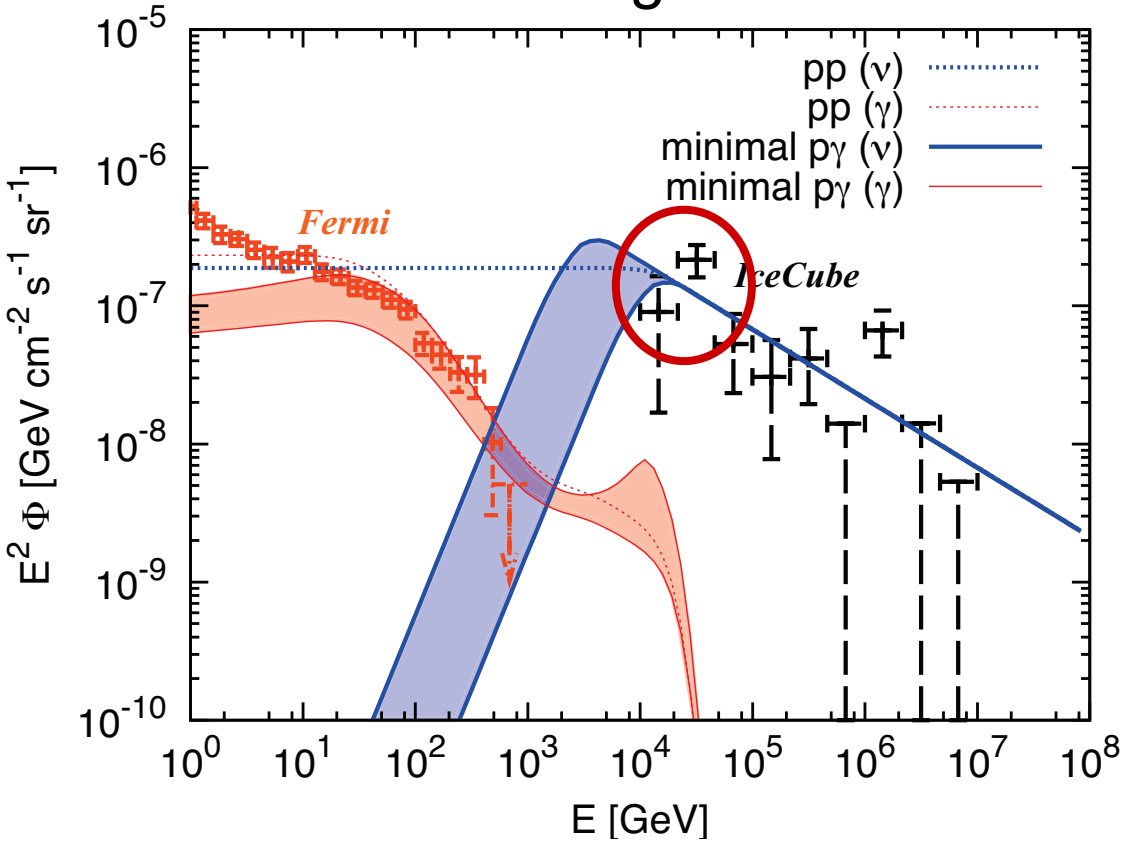
track analysis (>200 TeV) is consistent w. HESE, medium-energy, and shower analyses but there is a 3.3σ tension



IceCube 16 ApJ

New Component?: Medium-Energy "Excess" Problem

- Best-fit spectral indices tend to be as soft as s~2.5
- 10-100 TeV data: large fluxes of ~10^{-7} GeV cm^{-2} s^{-1} sr^{-1}



KM, Guetta & Ahlers 16 PRL

$$\varepsilon_\nu Q_{\varepsilon_\nu} \propto \begin{cases} \varepsilon_\nu^{2-s} & (\varepsilon_\nu \le \varepsilon_\nu^b) \\ \varepsilon_\nu^{2-s'} & (\varepsilon_\nu^b < \varepsilon_\nu) \end{cases} \quad (pp)$$

$$\varepsilon_\nu Q_{\varepsilon_\nu} \propto \begin{cases} \varepsilon_\nu^{2} & (\varepsilon_\nu \le \varepsilon_\nu^b) \\ \varepsilon_\nu^{2-s'} & (\varepsilon_\nu^b < \varepsilon_\nu) \end{cases} \quad (\text{minimal } p\gamma)$$

(cutoff due to the π production threshold)

Fermi γ-ray bkg. is violated if ν sources are γ-ray transparent

→ **"hidden (γ-ray dark) sources"**

(CR reservoirs can explain the neutrino data only above 100 TeV)

New Component?: Medium-Energy "Excess" Problem

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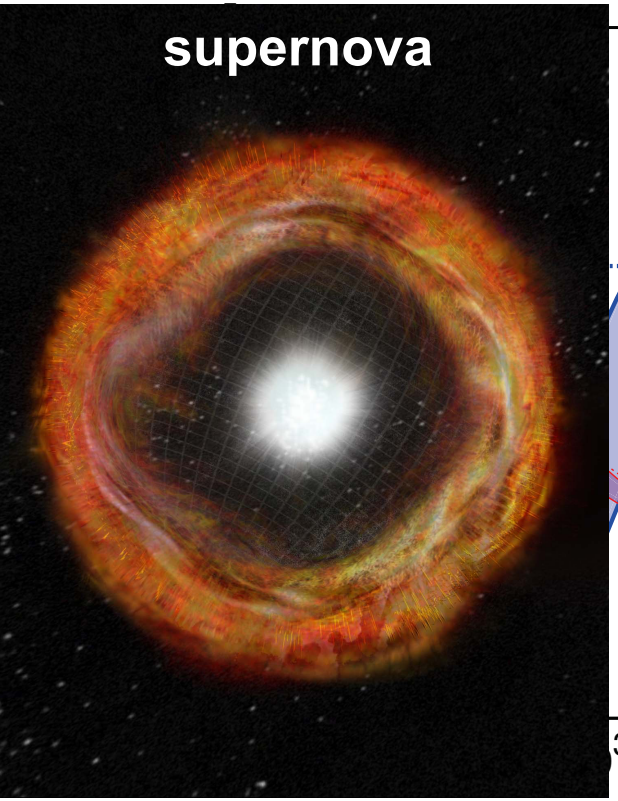
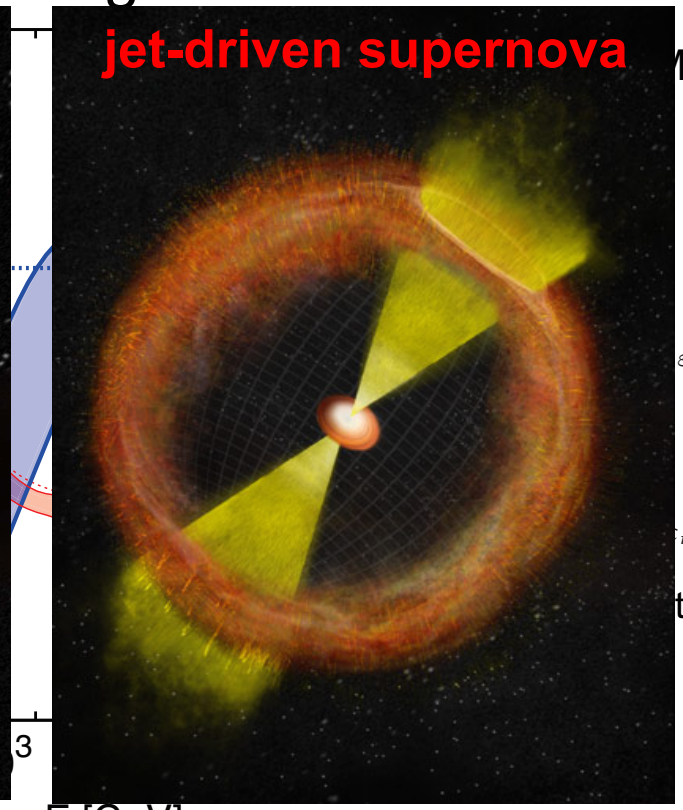
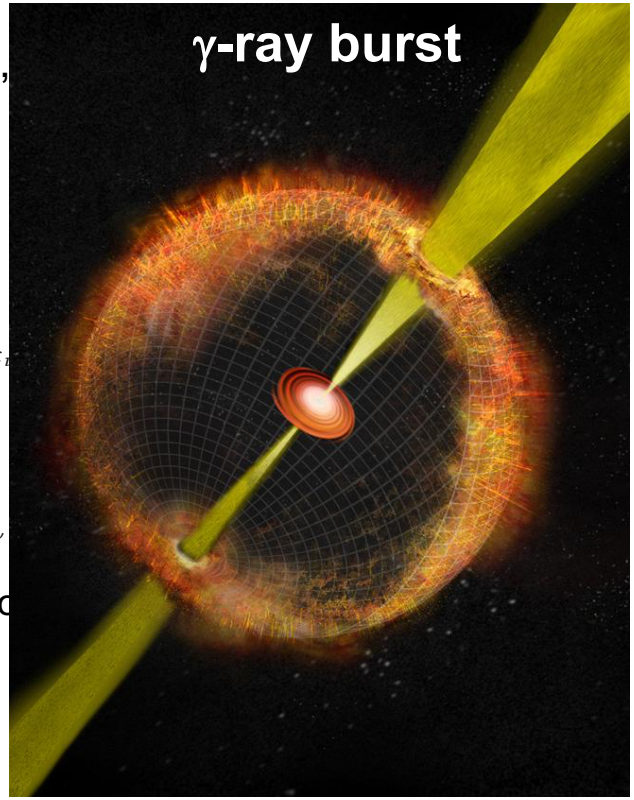




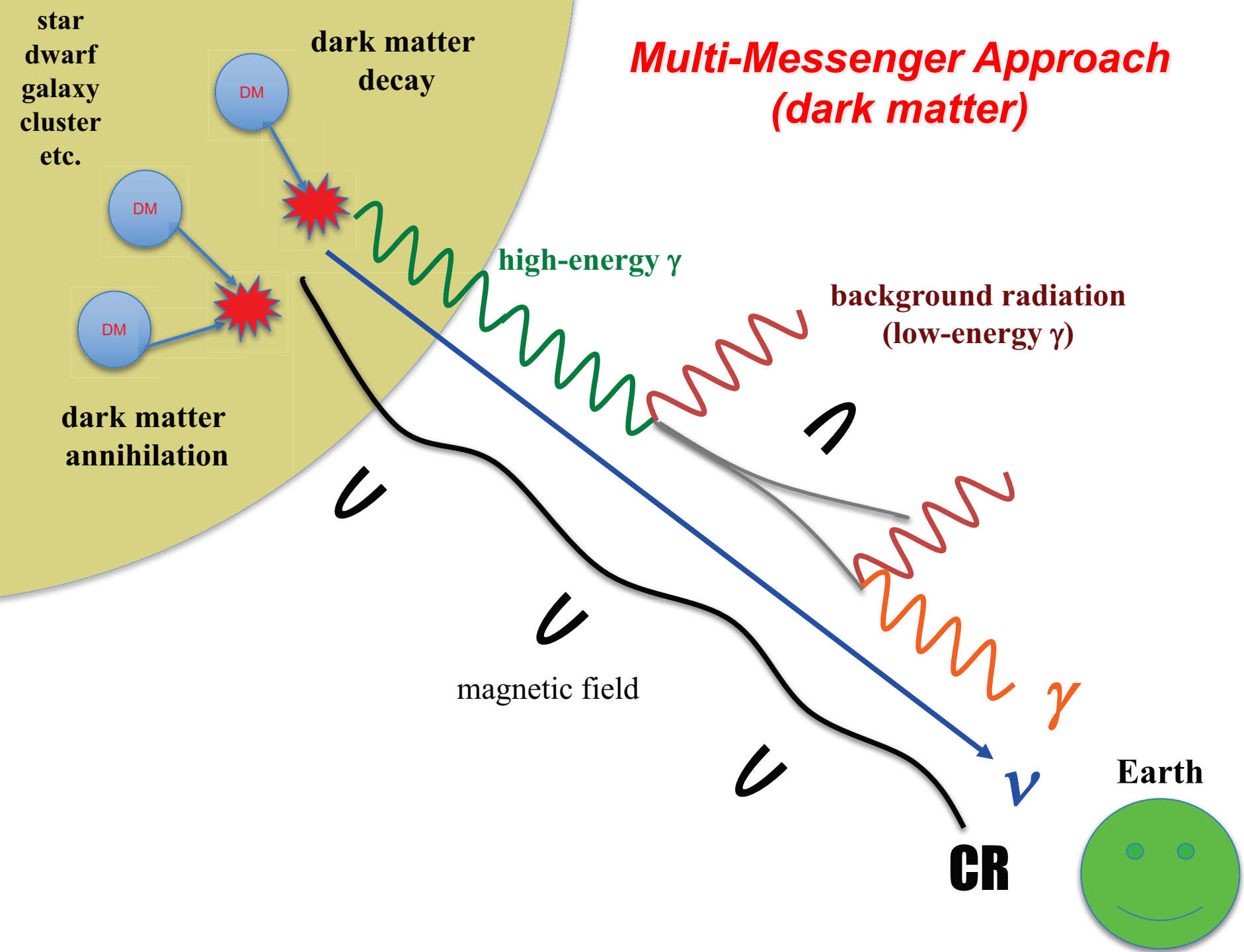


E [GeV]

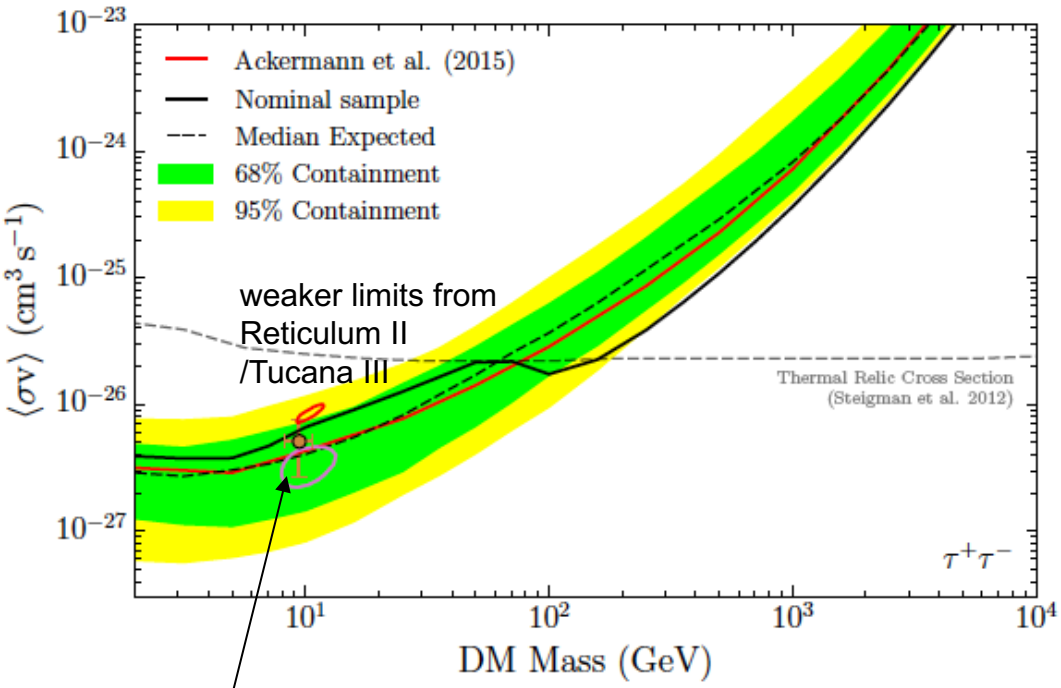
Fermi γ-ray bkg. is violated if ν sources are γ-ray transparent

→ **"hidden (γ-ray dark) sources" (e.g., jet-driven supernovae)**
(CR reservoirs can explain the neutrino data only above 100 TeV)

Multi-Messenger Approach (dark matter)



Gamma-Ray Limits on Annihilating Dark Matter

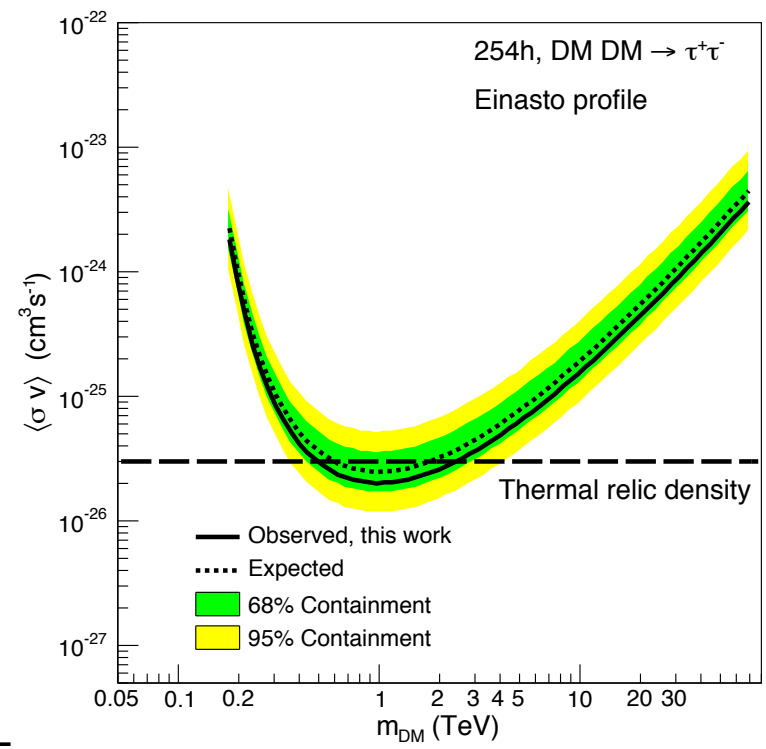


2σ best-fit regions for
Galactic center excess
(not excluded by dwarf analyses)

Dwarf & dwarf candidates

45 sources w. 6 year LAT data

Fermi Collaboration 17 ApJ



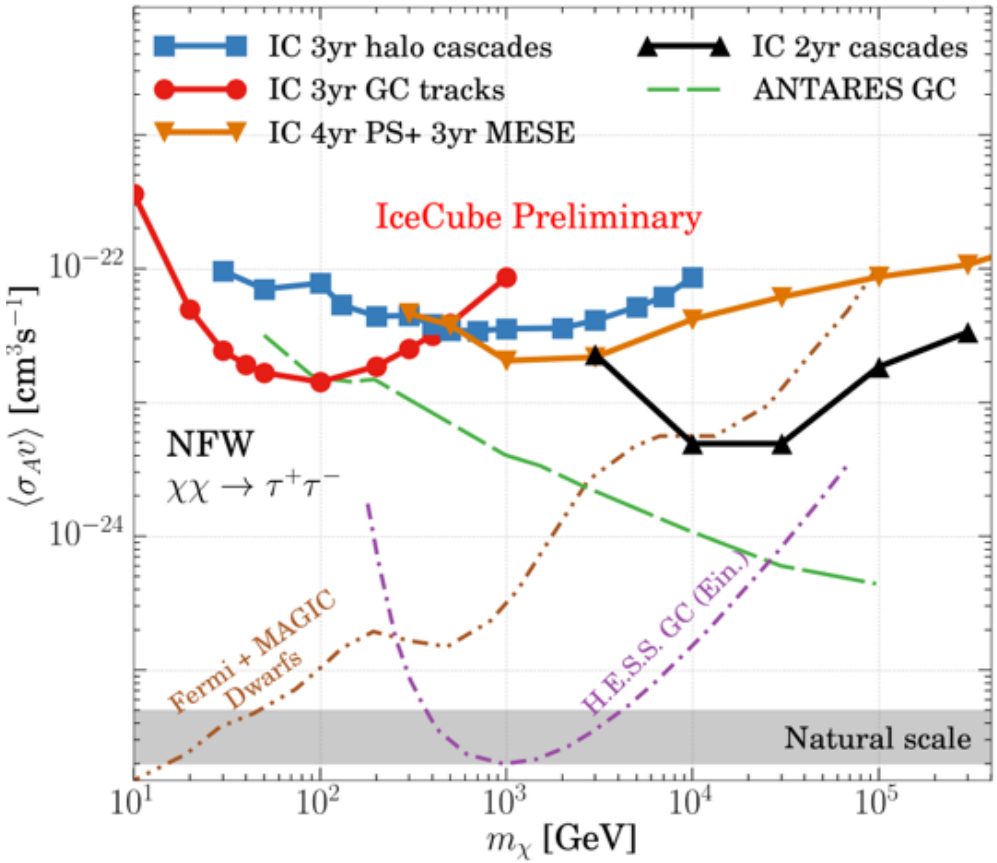
Galactic center region

inner 300 pc w. 10 year data

HESS Collaboration 16 PRL

CR & ν Limits on Annihilating Dark Matter

IceCube Collaboration 1705.08103
talk by Capone and Medici

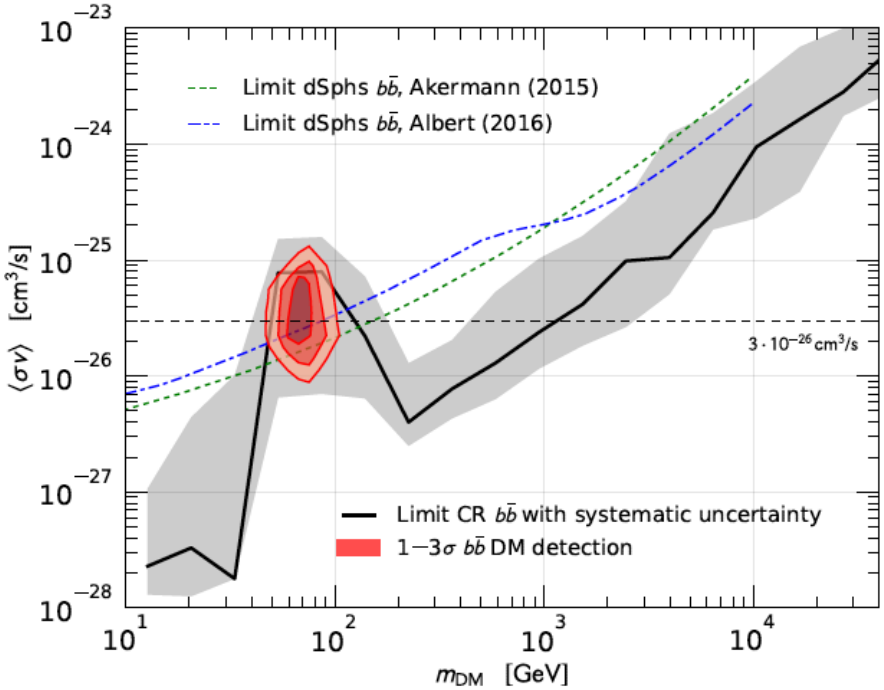


ν from Galactic halo and center

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

Heavy Dark Matter for IceCube Neutrinos?

Decaying dark matter

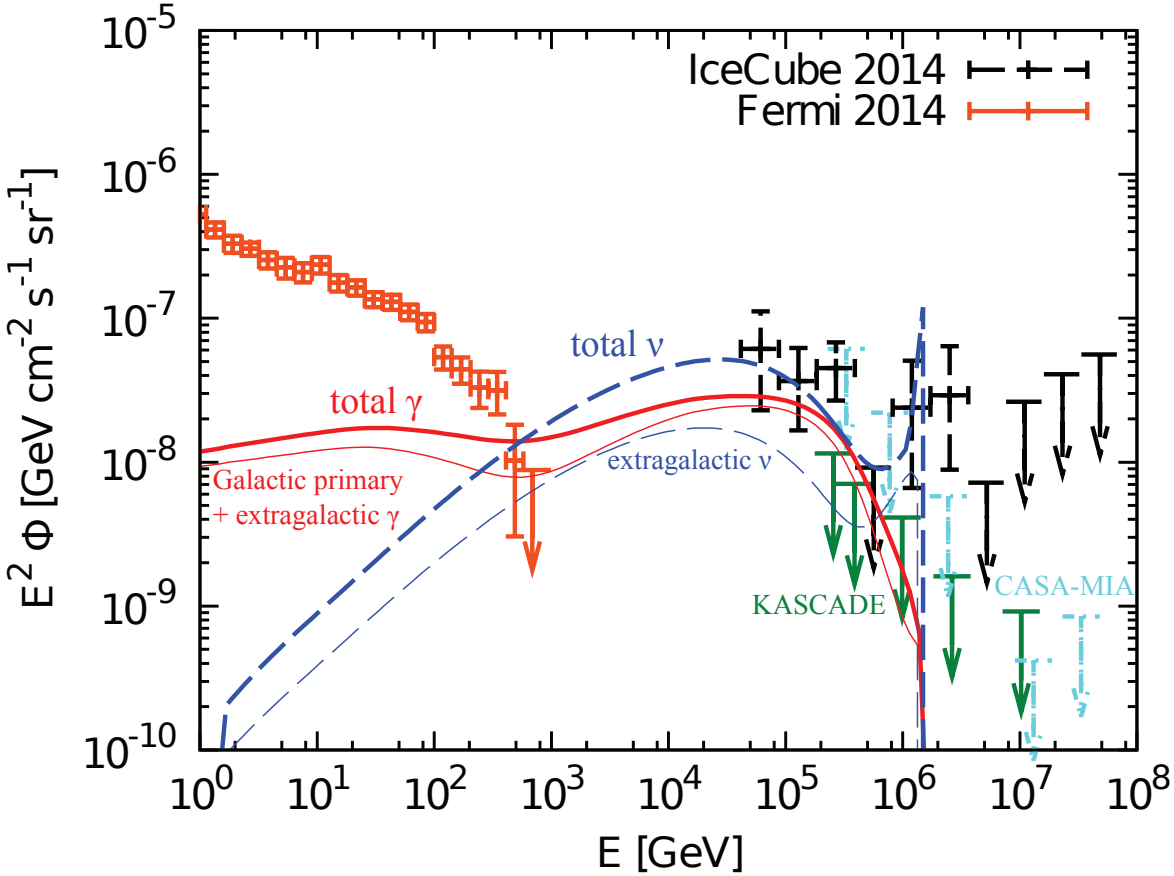
- General constraints: KM & Beacom 12, Esmaili, Ibarra & Peres 12, KM et al. 15
  Chianese et al. 16, Cohen et al. 16, Bhattacharya et al. 17
- Neutrino lines:
  Feldstein et a. 13, Dudas, Mambrini & Olive 15, Roland et al. 15, Aisati et al. 15
- Portal type, R-parity violating gravitino, RH ν, glueball 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, Boucenna et al. 15, Ko & Tang 15, Dev et al. 16, Bari, Ludl & Palomares-Ruiz 16, Cohen et al. 16, Borah et al. 17, Hiroshima+ 17

Other models

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

Multi-Messenger Emission of Decaying Dark Matter

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



KM, Laha, Ando & Ahlers 15

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

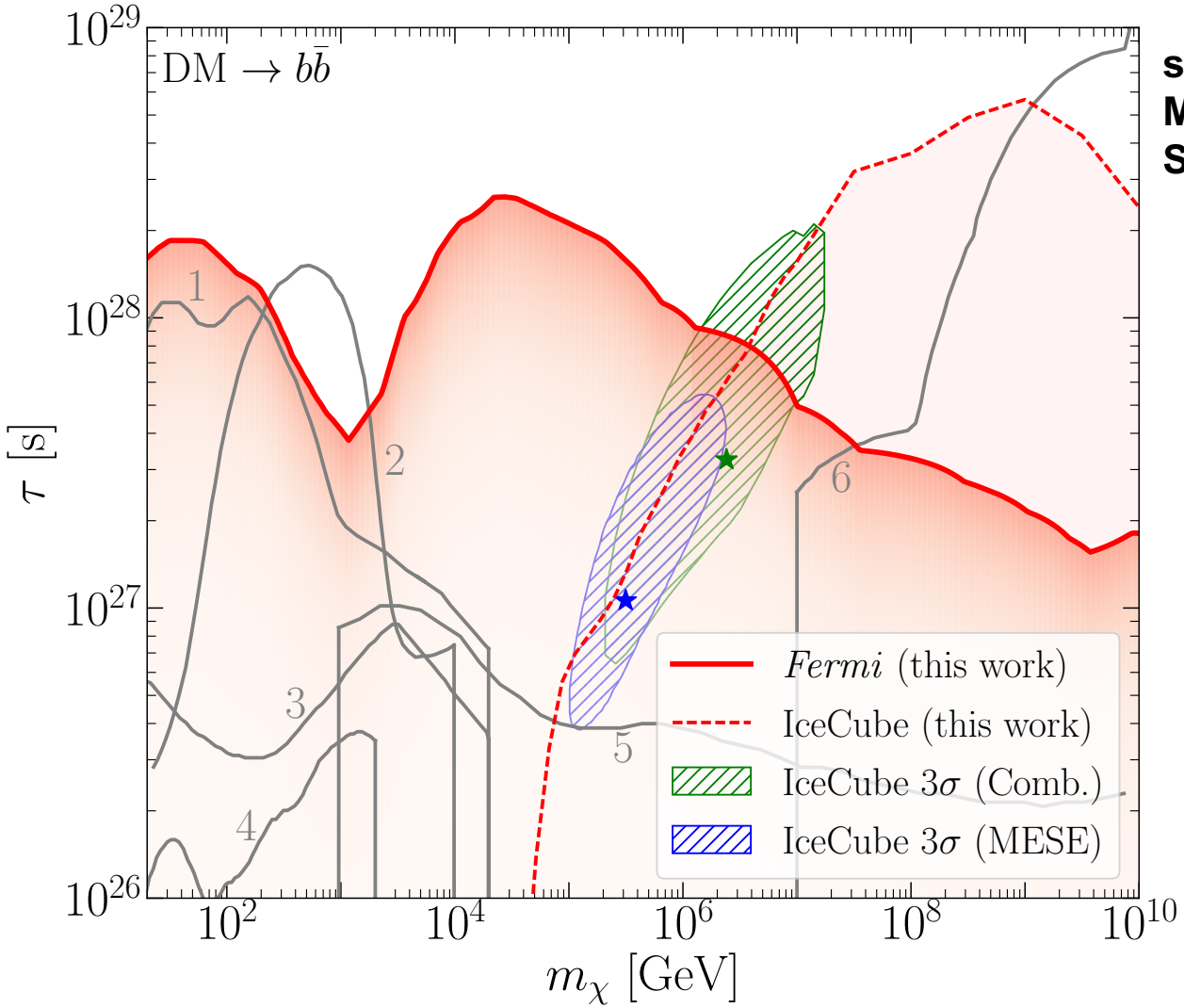
DM → ν_e+ν_e (12%)
DM → b+bbar (88%)

(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 in press

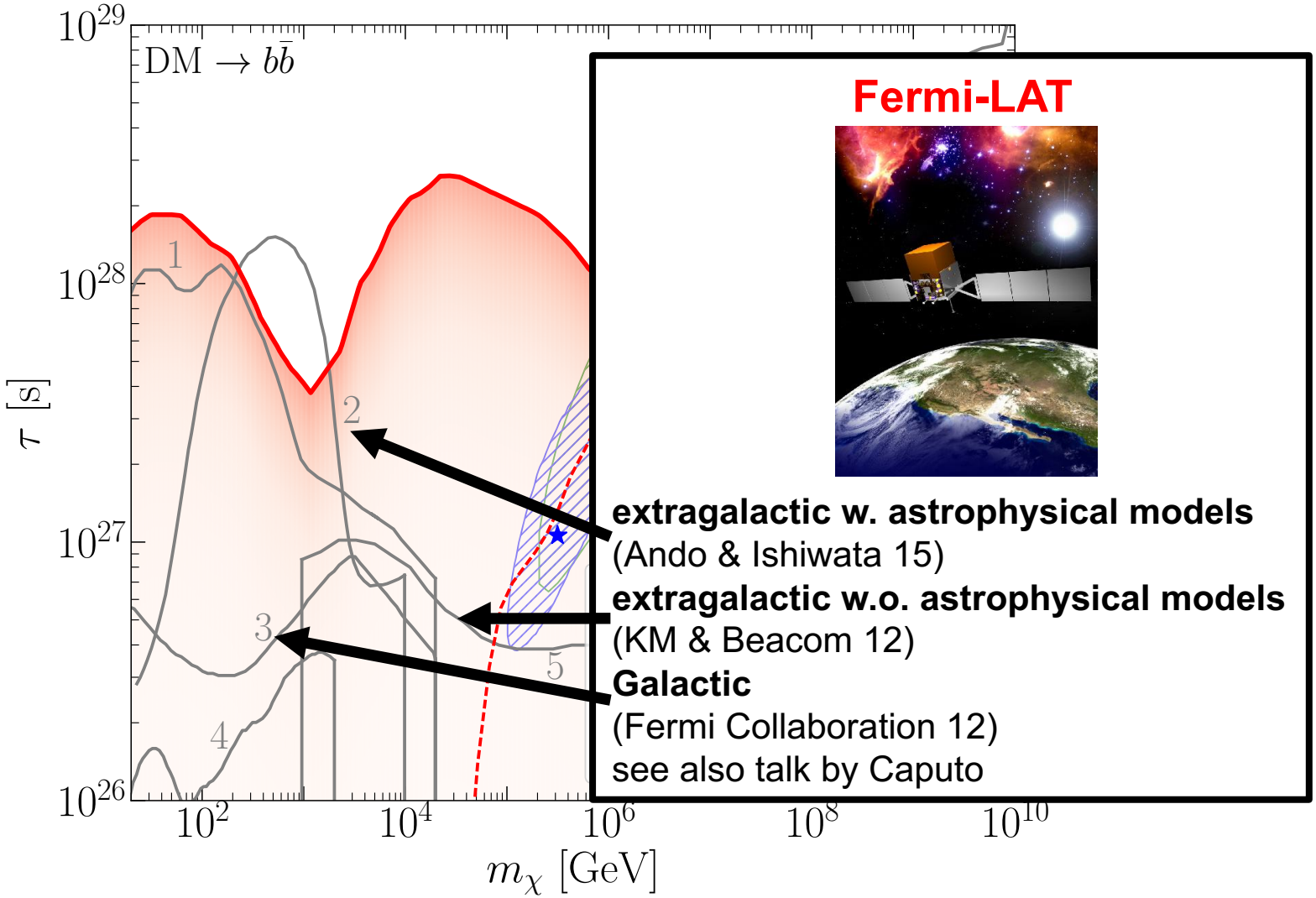


see also talks by Medici (IceCube) Sarcevic (HESE)

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

Multi-Messenger Constraints on Decaying DM

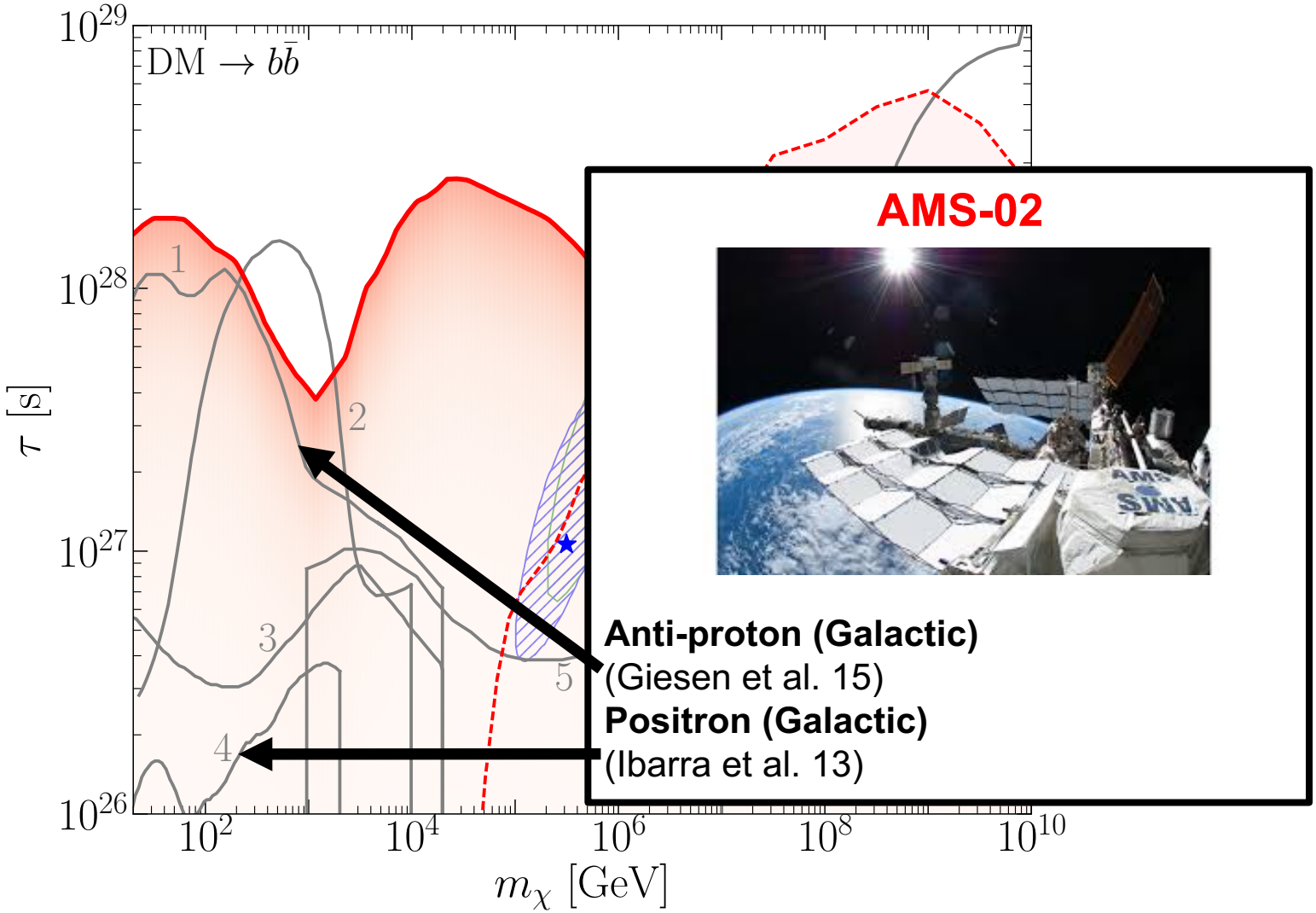
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL in press



Gamma-ray limits are improved independently of astrophysical modeling

Multi-Messenger Constraints on Decaying DM

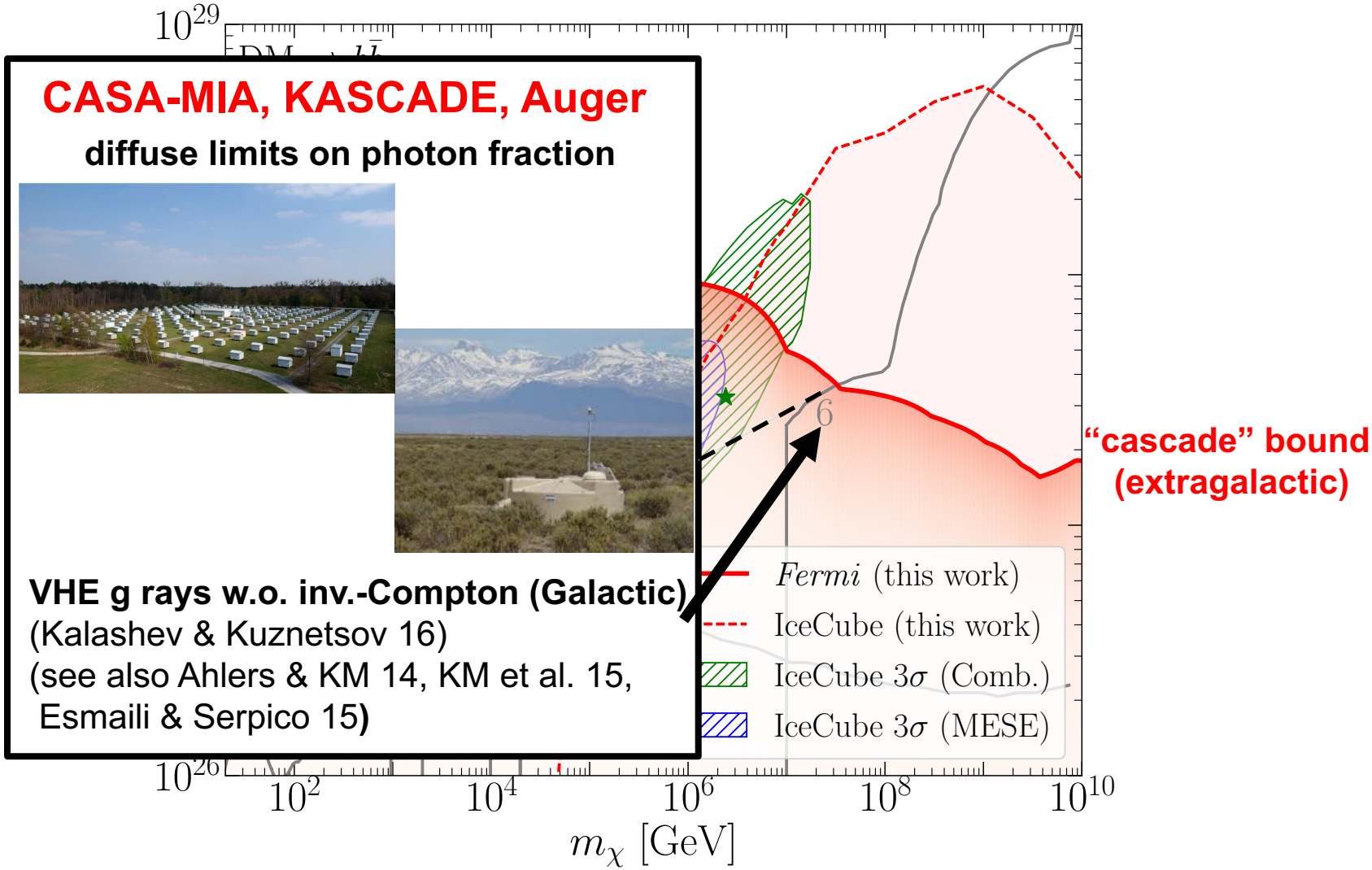
Cohen, KM, Rodd, Safdi, and Soreq 17 PRL in press



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

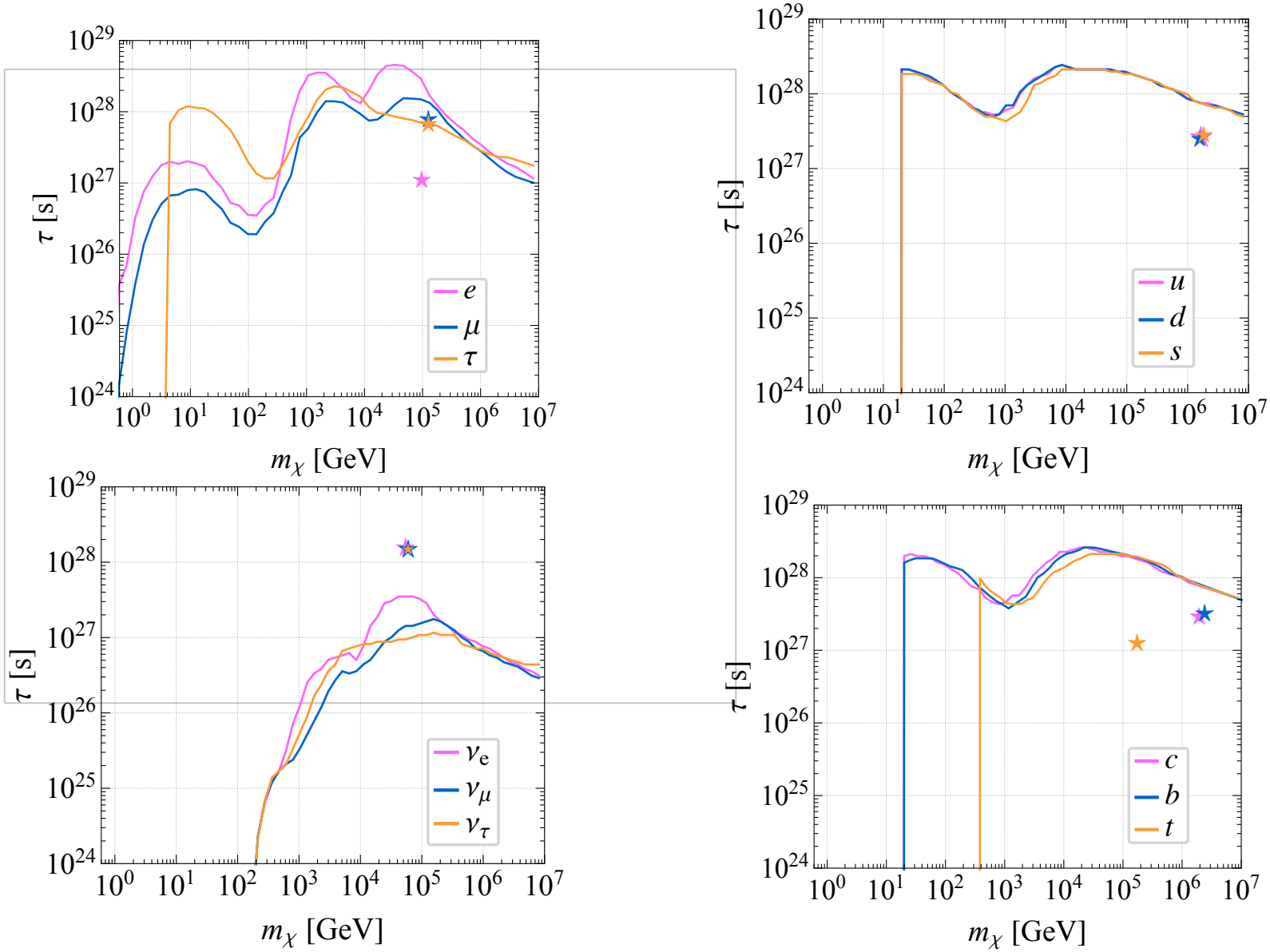
Multi-Messenger Constraints on Decaying DM

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



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

Other Final States



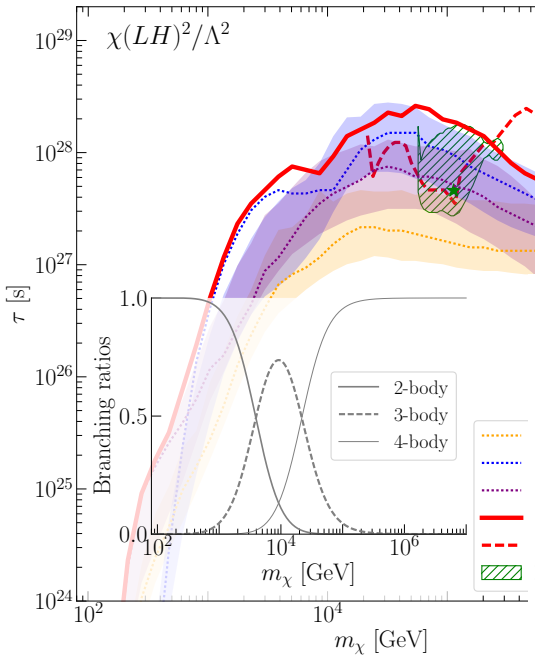
Examples of Models (EFT)

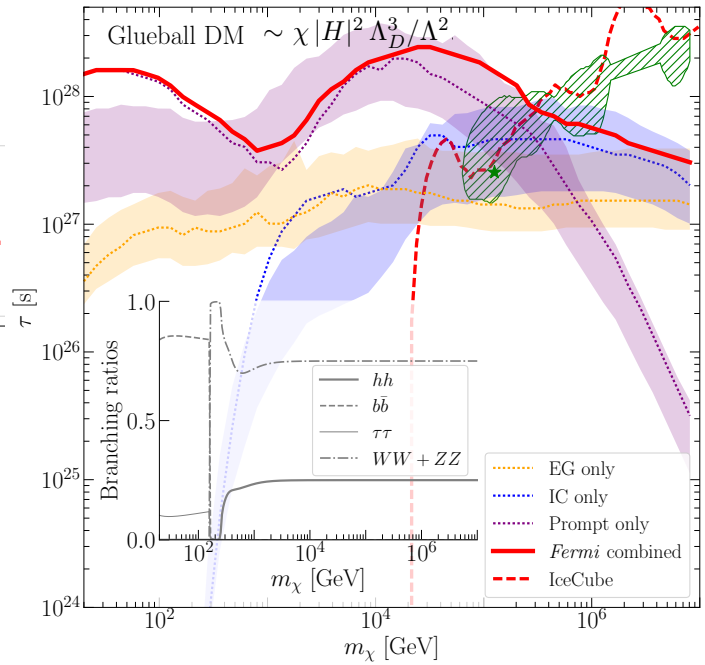
EFT (up to dimension 6)

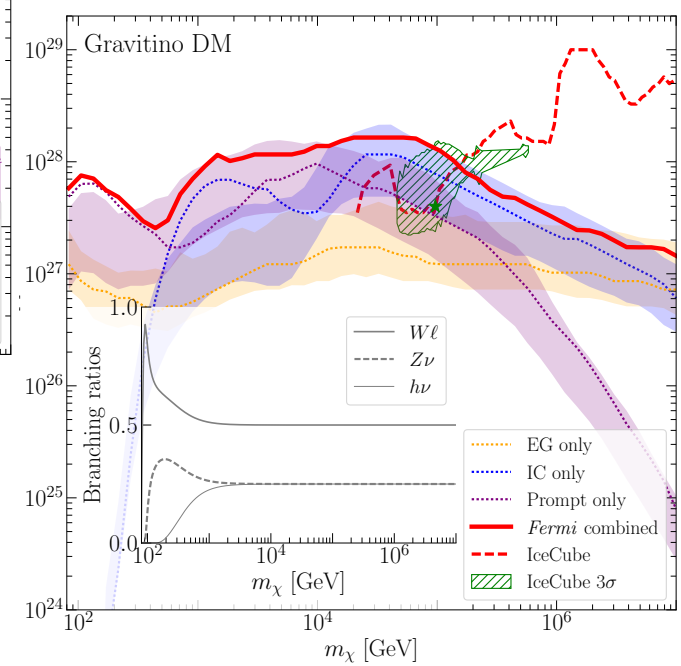
$\left(R_{SU(2)}\right)_Y$	operator	final states	ratios of BR's, $m_\chi \gg$ TeV	$\tau \gtrsim 10^{27}$ [s]
		spin 0		
$(0)_0$	$\chi H^\dagger H$	hh, Z^0Z^0,W^+W^-,$f\bar{f}$	$1:1:2:16N_c y_f^2 \frac{v^2}{m_\chi^2}$	$\bar{m}_\chi/\bar{\Lambda}^2 \gtrsim 9\times 10^{79\,a}$
	$\chi\,(LH)^2$	$\nu\nu hh$, $\nu\nu Z^0Z^0$, $\nu\nu Z^0h$, $\nu e^- hW^+$, $\nu e^- Z^0W^+$, $e^-e^-W^+W^+$, $\nu\nu h$, $\nu\nu Z^0$, $\nu e^- W^+$, $\nu\nu$	$1:1:2:2:2:4:24\pi^2\frac{v^2}{m_\chi^2}\left(1:1:1:768\pi^2\frac{v^2}{m_\chi^2}\right)$	$\bar{\Lambda}^4/\bar{m}_\chi^5 \gtrsim 1$
	$\chi H\bar{L}E$	$h\ell^+\ell^-$, $Z^0\ell^+\ell^-$, $W^\pm\ell^\mp\nu$, $\ell^+\ell^-$	$1:1:2:32\pi^2\frac{v^2}{m_\chi^2}$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 4\times 10^{29}$
	$\chi\tilde{H}\bar{Q}U$, $\phi H\bar{Q}D$	$hq\bar{q}$, $Z^0q\bar{q}$, $W^\pm q'\bar{q}$, $q\bar{q}$	$1:1:2:32\pi^2\frac{v^2}{m_\chi^2}$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 1\times 10^{30}$
	$\chi B_{\mu\nu}\overset{(\sim)}{B}{}^{\mu\nu}$	$\gamma\gamma$, γZ, ZZ	$c_W^4 : 2c_W^2 s_W^2 : s_W^4$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 2\times 10^{31}$
	$\chi W_{\mu\nu}\overset{(\sim)}{W}{}^{\mu\nu}$	$\gamma\gamma$, γZ^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]	$V_{\tilde{\lambda}}$ [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		
$(1)_0$	$\tilde{H}\bar{L}\psi$	νh, νZ^0, $\ell^\pm W^\mp$	$1:1:2$	$g^2\bar{m}_\chi \lesssim 2\times 10^{-56}$
$(2)_{1/2}$	$\tilde{H}\bar{\psi}E$	νh, νZ^0, $\ell^\pm W^\mp$	$1:1:2$	$g^2\bar{m}_\chi \lesssim 2\times 10^{-56}$
$(3)_0$	$H\bar{L}\sigma^a\psi^a$	νh, νZ^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

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







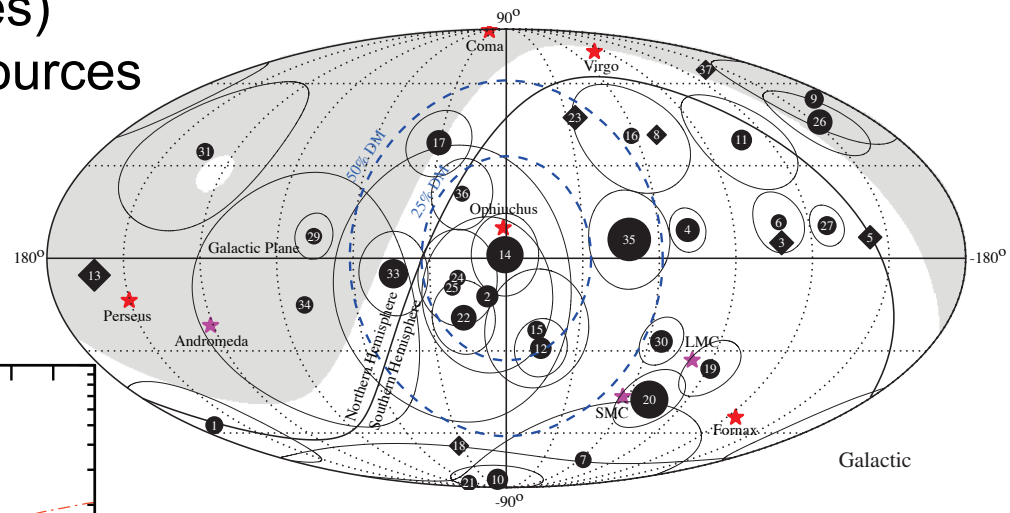
high-energy (>100 TeV) data could be consistent
<100 TeV (e.g., MESE) data cannot be explained
(see also Bhattacharya et al. 17)

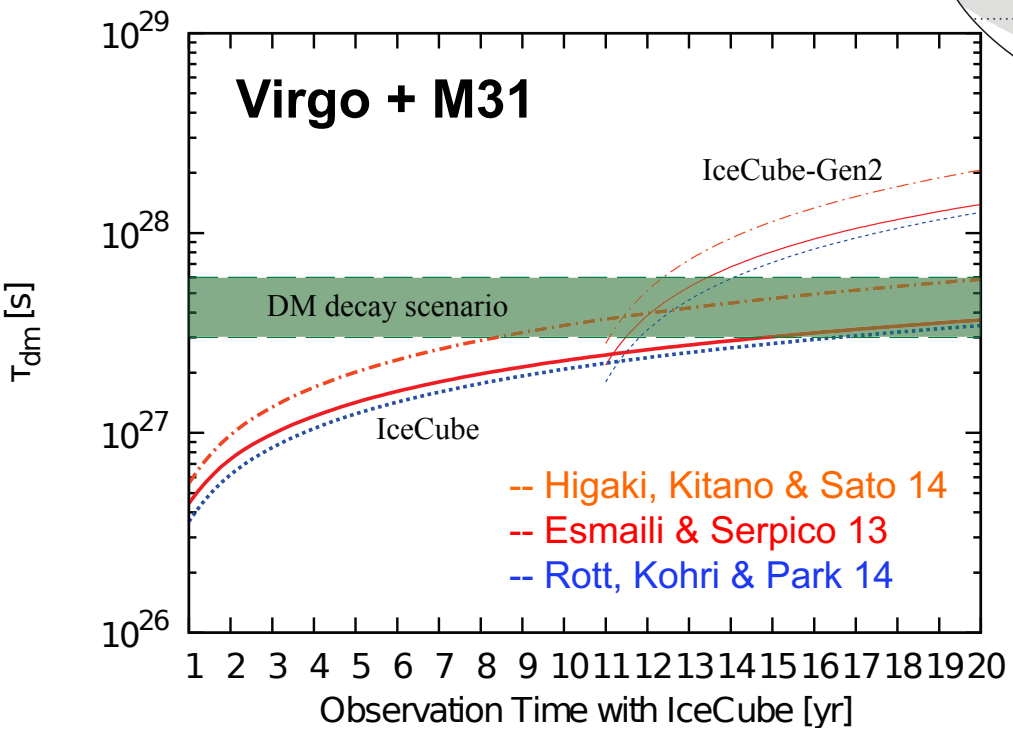
Muon Neutrino Tests w. Nearby DM Halos

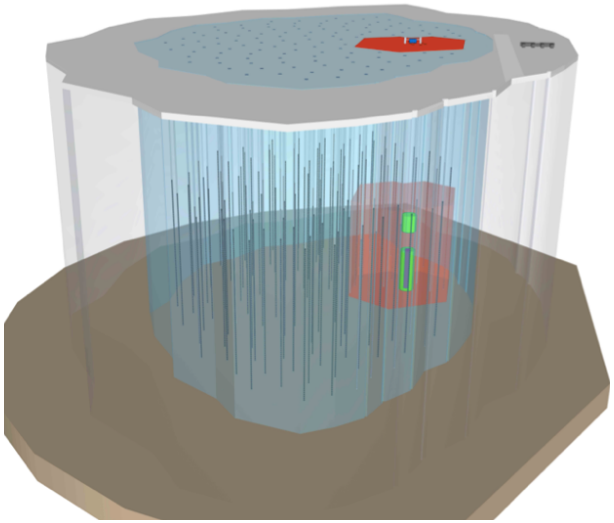
Nearby DM halos (clusters & galaxies) should be seen as point/extended sources

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

stacking or cross-correlation independent of γ–ray limits







KM, Laha, Ando & Ahlers 15 PRL

Summary

Powerful combination of all messengers to reveal CRs & DM

γ-ray flux ~ ν flux ~ CR flux

- multi-messenger limits are now critical for the CR origins
- complementary/competing limits on dark matter at TeV-ZeV

IceCube neutrinos?

pp scenarios: cosmic particle unification?

s<2.1-2.2 & significant contribution to Fermi γ-ray bkg.

10-100 TeV data are NOT explained by CR reservoirs

pγ scenarios: dim or hidden CR accelerators? (ex. jet-driven supernovae)

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

10-100 TeV data are NOT readily explained

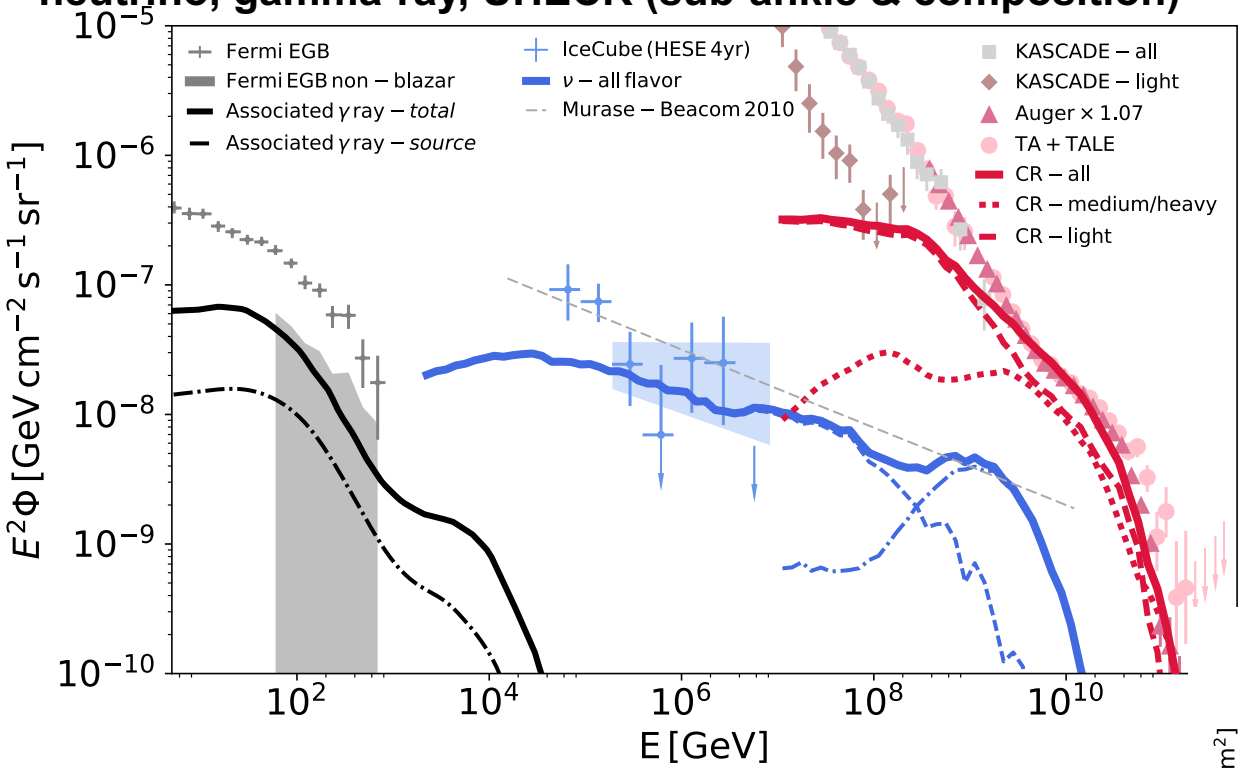
Other new physics probed by neutrinos?

- sterile neutrinos, self-interactions, neutrino decay, pseudo-Dirac neutrinos, neutrino dark matter interactions, Lorentz invariance violation etc.

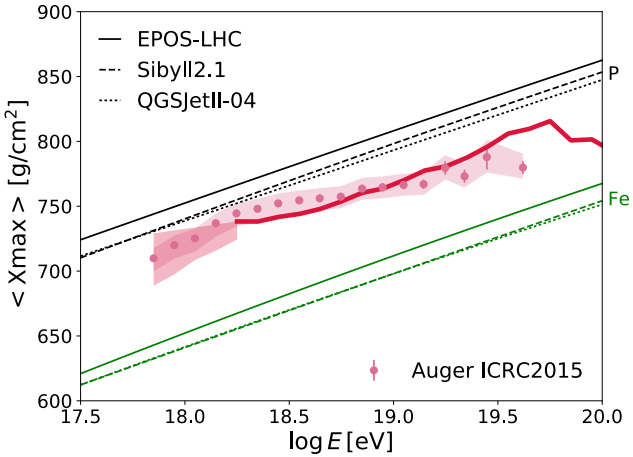
AGN Embedded in Galaxy Clusters/Groups

"cosmic particle-unification"

neutrino, gamma-ray, UHECR (sub-ankle & composition)



Fang & KM 17

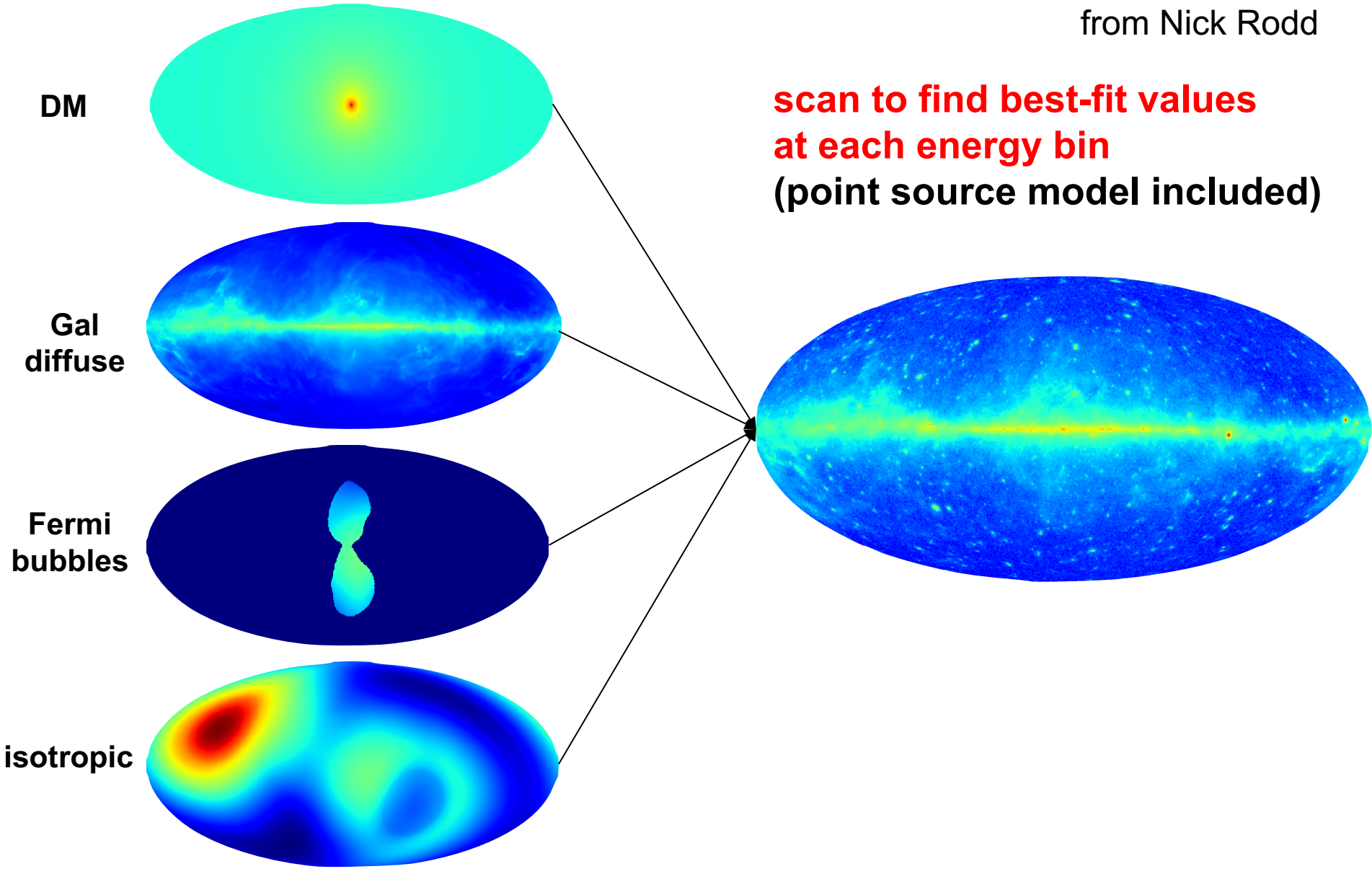


- AGN as "UHECR" accelerators
- confinement in cocoons & clusters
- Escaping CR nuclei may have s < 2

Profile Likelihood Technique

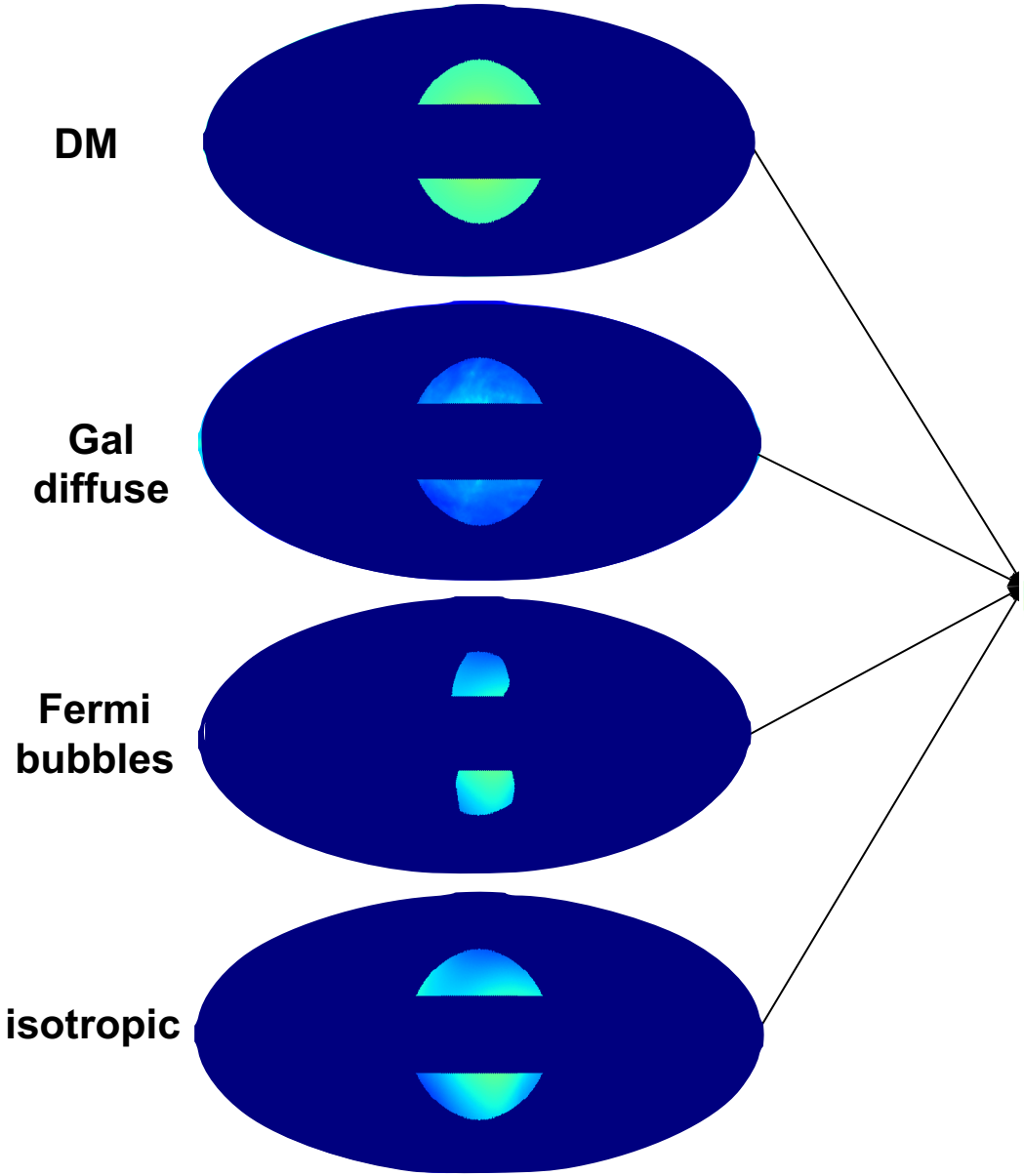
from Nick Rodd

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



Profile Likelihood Technique

from Nick Rodd



scan to find best-fit values at each energy bin

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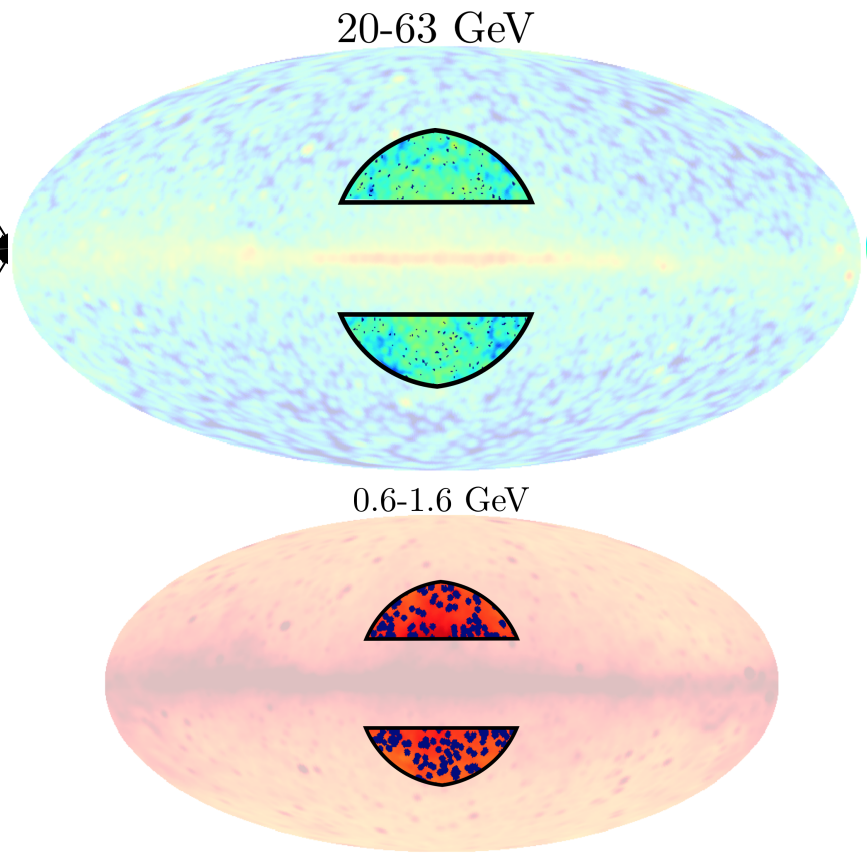
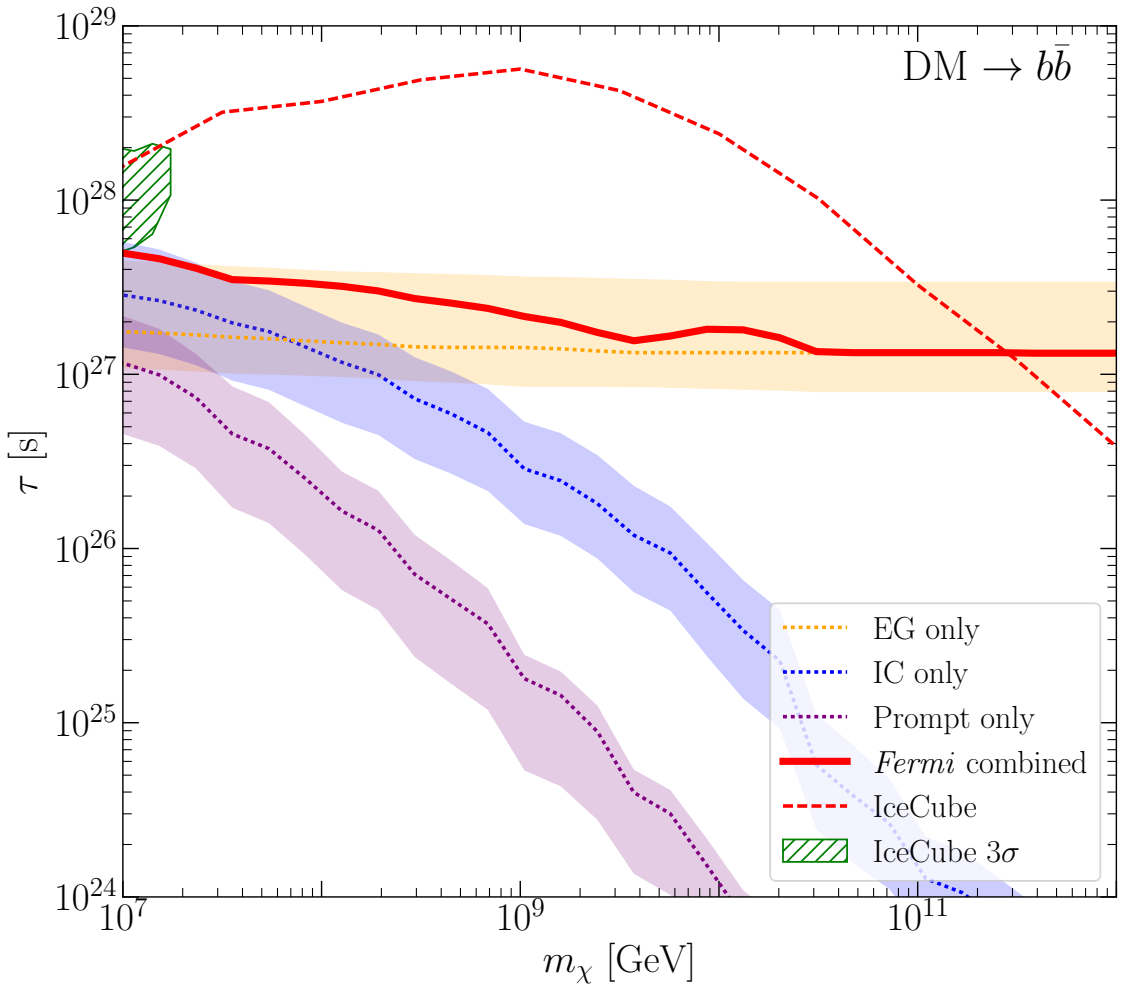


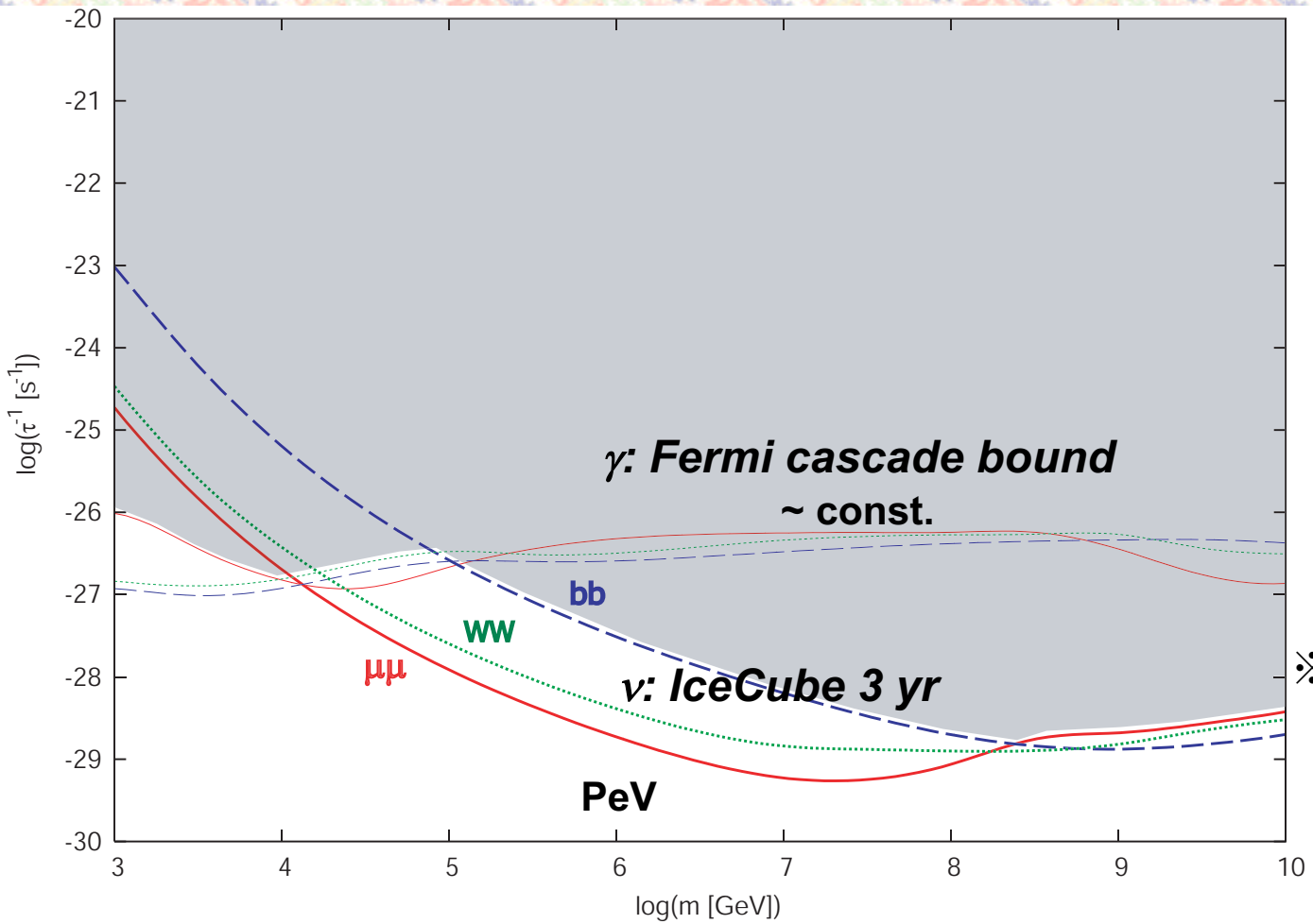
Extension to Superheavy Dark Matter?

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



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

Neutrino Constraints on Dark Matter Decay



KM & Beacom 12 JCAP

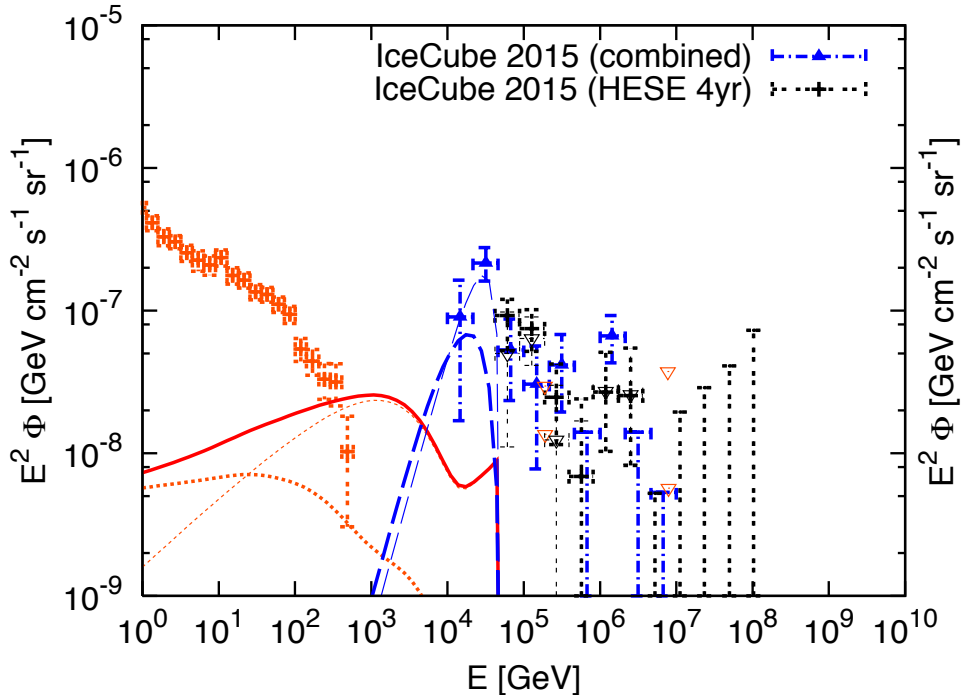
※Annihilating heavy dark matter scenarios are difficult due to the unitarity bound

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

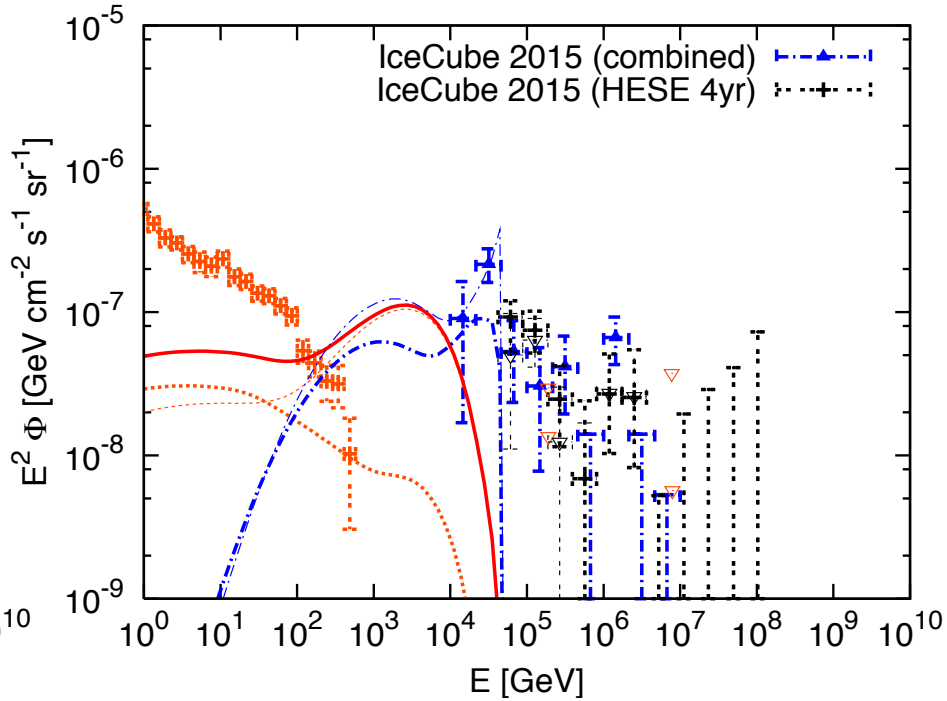
Can DM Explain MESE Excess?

- Most DM models belong to γ-ray transparent sources
- Most DM models are invented to explain only the PeV data

DM → μ+μbar



DM → W⁺+W⁻



(based on KM & Beacom 12 JCAP with the updated data)

Only models w. small γ/ν ratio (<~0.1) or high-z are allowed

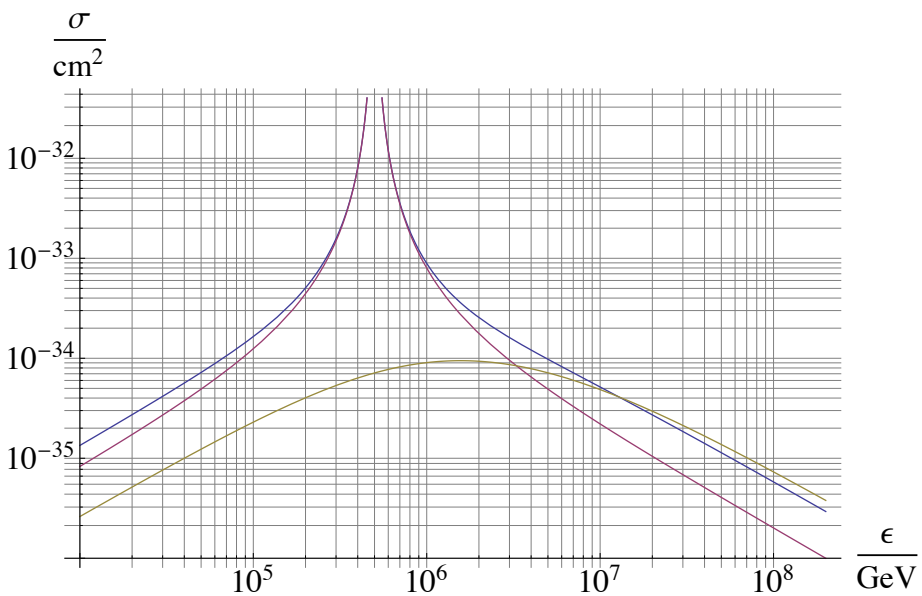
Secret Neutrino Interactions

Majorna neutrino self-interactions via a scalar

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

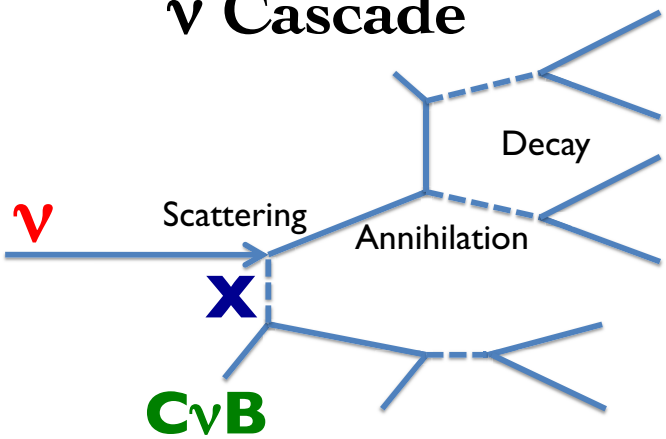
SSB, LNV $\Uparrow$ $m_{\nu_i} = \frac{g_i \mu v^2}{\Lambda^2}$

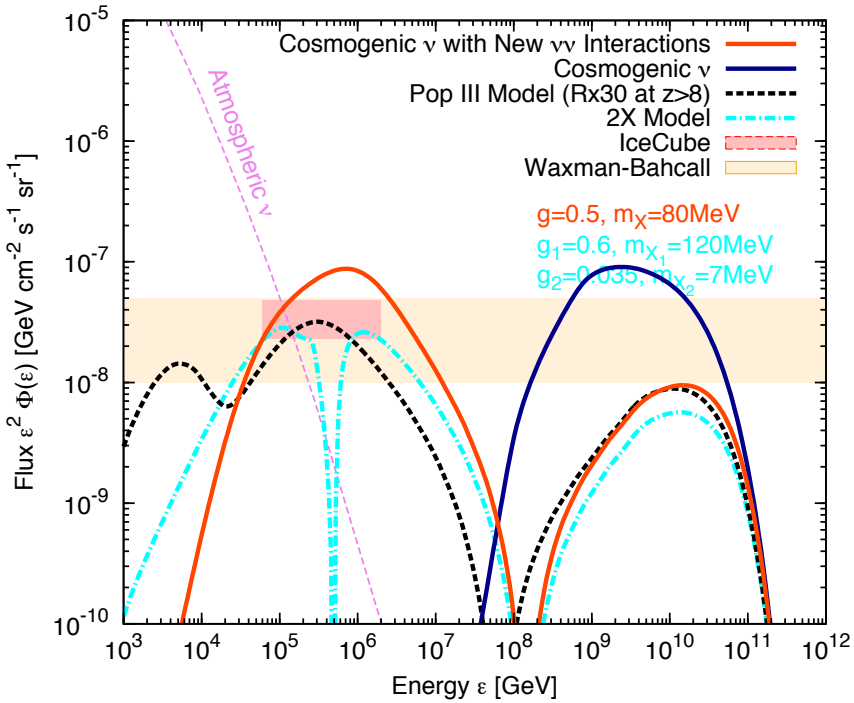
$$\mathcal{L} = -\frac{g}{\Lambda^2}\Phi(HL)^2 + cc.$$



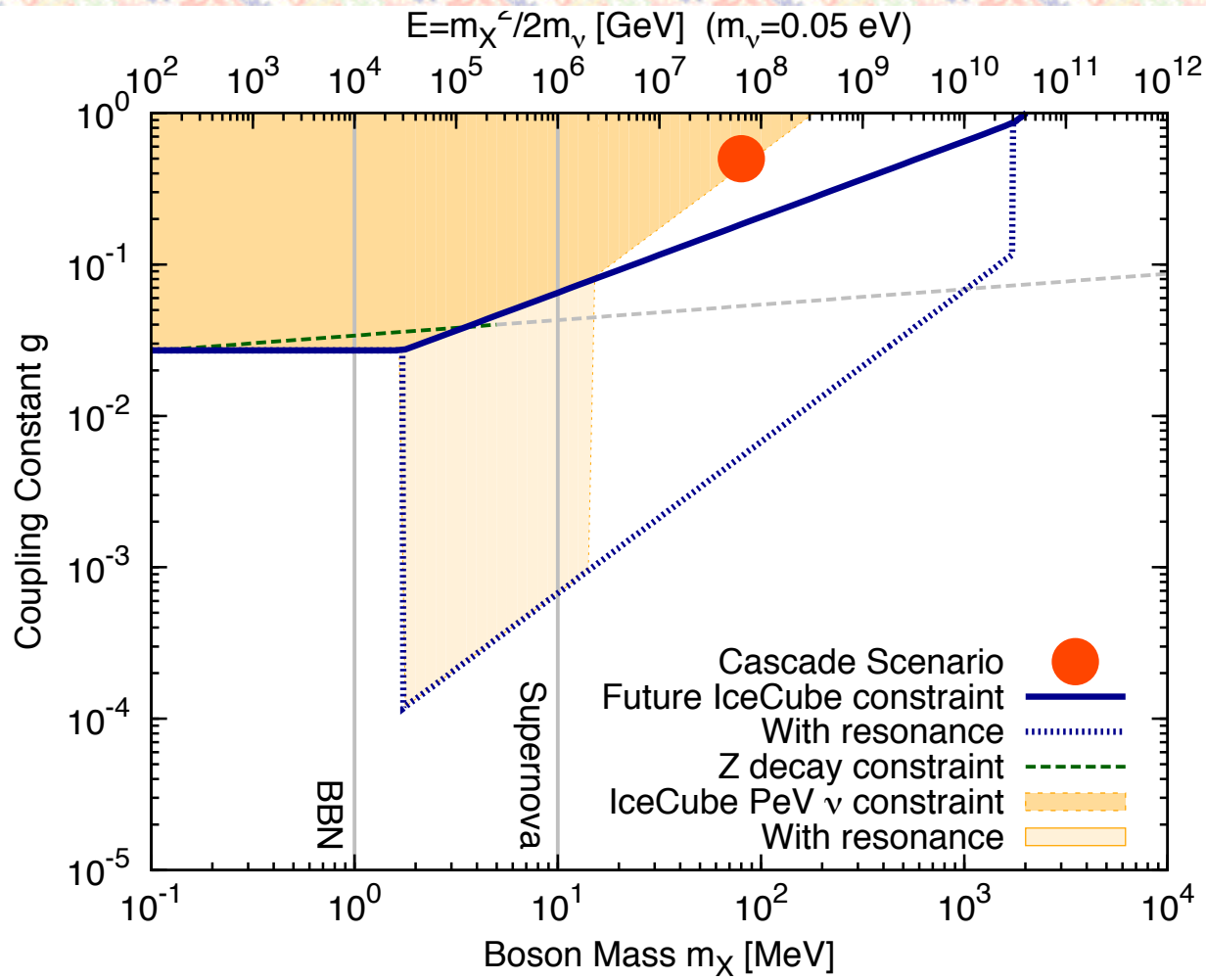
Blum. Hook & KM 14, Ioka & KM 14 PTEP

ν Cascade





Constraints on Self-Interactions



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

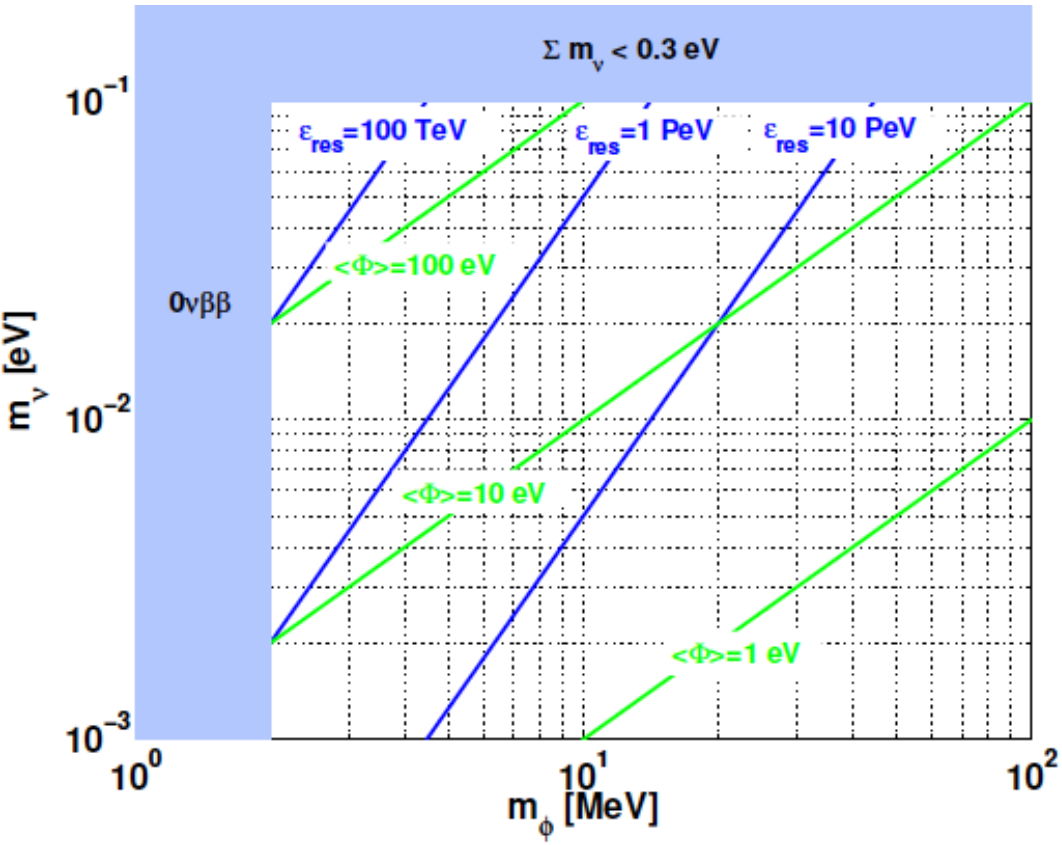
- An example that IceCube can be used for testing nonstandard interactions
- Can be more powerful than laboratory tests

Secret Neutrino Interactions

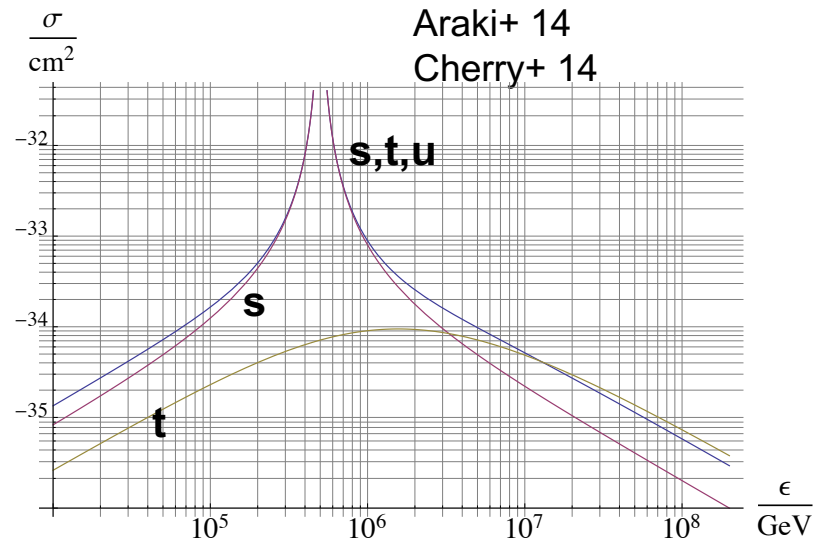
Applications to IceCube
Ioka & KM 14 PTEP
Ng & Beacom 14 PRD
see also
Ibe & Kaneta 14
Araki+ 14
Cherry+ 14

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

Bardin, Bilenky & Pontecorvo 70



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



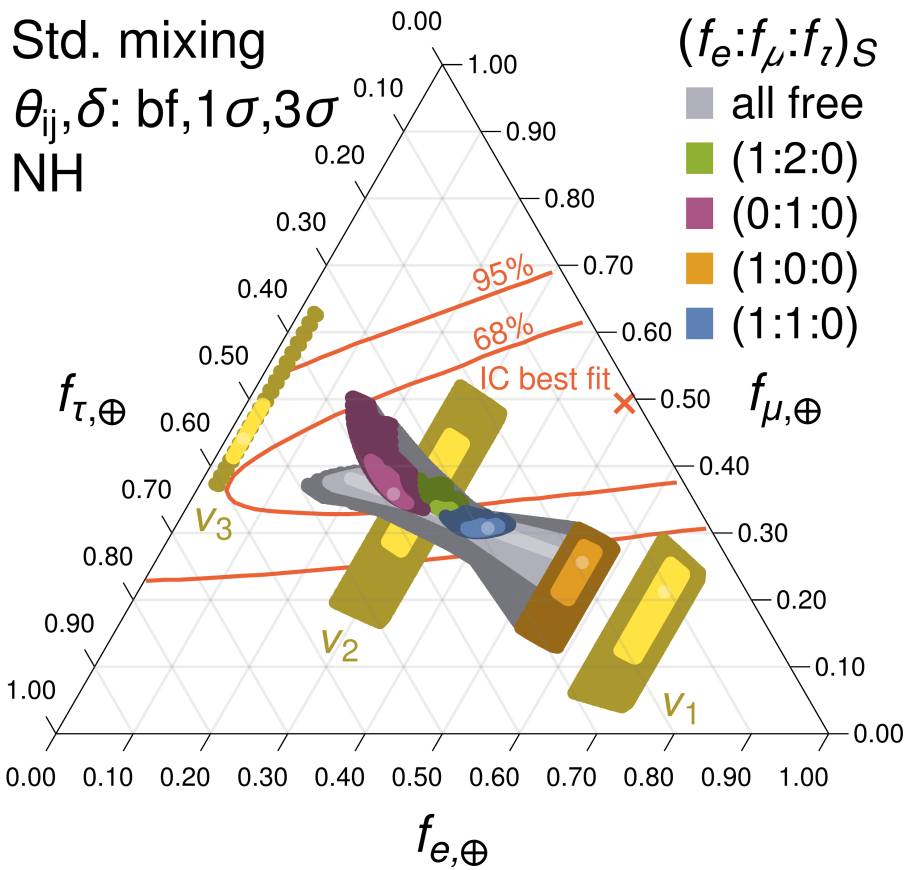
$$\sigma_{ii\to jj} \approx \frac{|\mathcal{G}_i|^2|\mathcal{G}_j|^2}{64\pi\Gamma_\phi^2}\frac{m_\phi^2\Gamma_\phi^2/(4m_{\nu_i}^2)}{\left(\epsilon - \frac{m_\phi^2}{2m_{\nu_i}}\right)^2 + m_\phi^2\Gamma_\phi^2/(4m_{\nu_i}^2)}$$

$$\Gamma_\phi = \frac{m_\phi}{32\pi}\sum_i |\mathcal{G}_i|^2$$

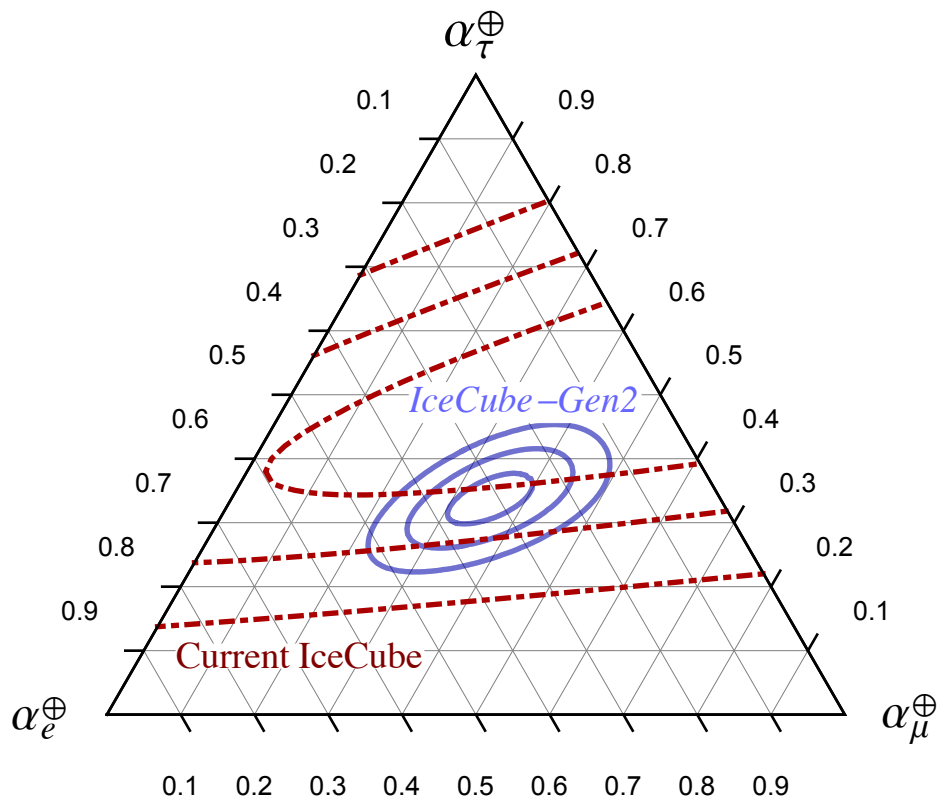
Blum. Hook & KM 14

Flavors

Bustamante et al. PRL



Shoemaker & KM

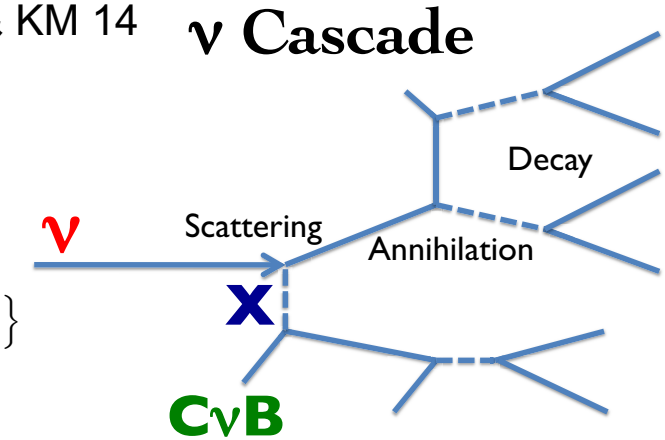


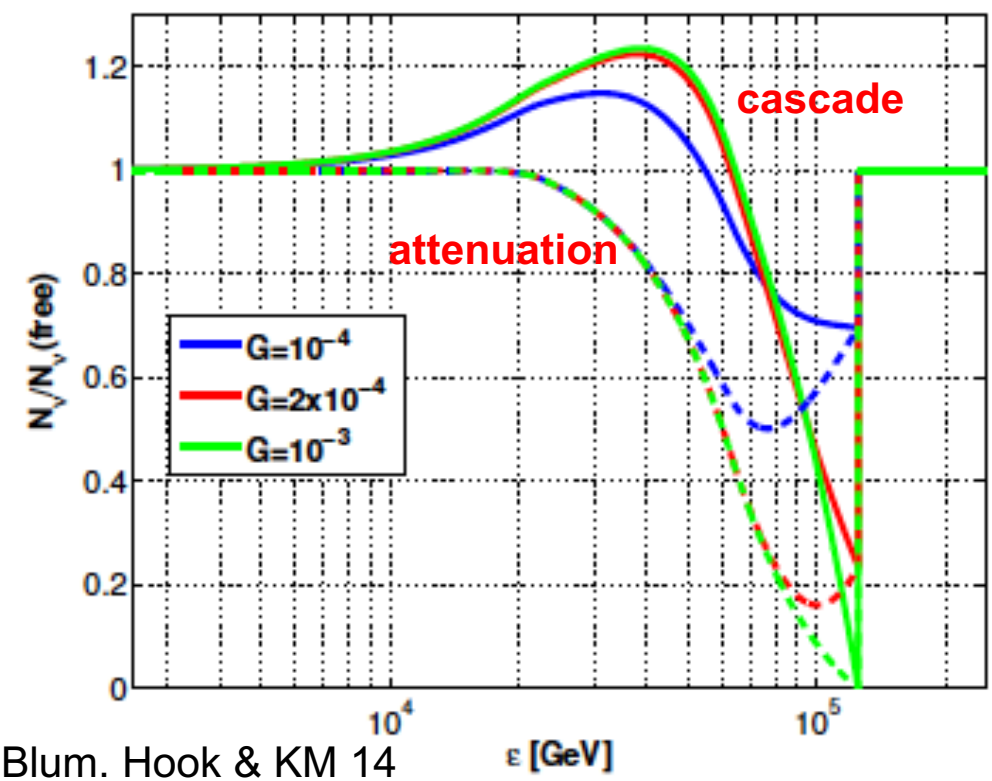
Flavor constraints are improved in the Gen2 era

Effects on Cosmic Neutrino Spectra

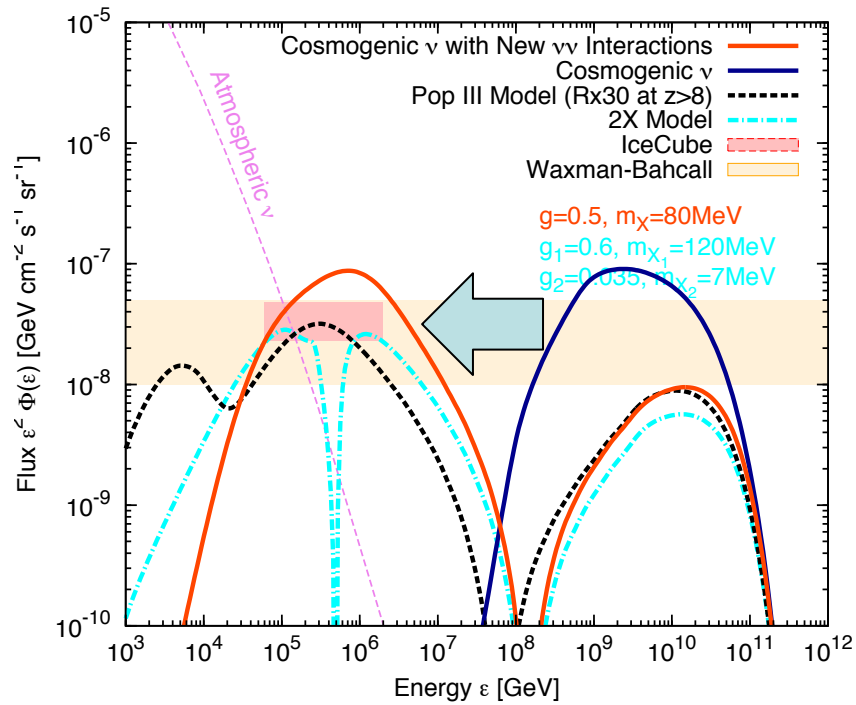
$$
\begin{aligned}
\partial_\eta N_i[q;\eta] &= aQ_i[q,\eta] \\
&- acN_i[q;\eta]\Big\{\sum_j n_i(\eta)\sigma_{ii\to jj}[2m_{\nu_i}q] + \sum_{j\neq i} n_j(\eta)\sigma_{ij\to ij}[2m_{\nu_j}q]\Big\} \\
&+ ac\int_0^1 \frac{dx}{x}\Big\{\sum_j \frac{d\sigma_{jj\to ii}\left[\frac{2m_{\nu_j}q}{x},x\right]}{dx} N_j\left[\frac{q}{x},\eta\right] n_j(\eta) \\
&+ \sum_{j\neq i}\frac{d\sigma_{ij\to ij}\left[\frac{2m_{\nu_j}q}{x},x\right]}{dx} N_i\left[\frac{q}{x},\eta\right] n_j(\eta) + \sum_{j\neq i}\frac{d\sigma_{ji\to ji}\left[\frac{2m_{\nu_i}q}{x},x\right]}{dx} N_j\left[\frac{q}{x},\eta\right] n_i(\eta)\Big\}
\end{aligned}
$$

Ioka & KM 14





Blum. Hook & KM 14



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)

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

Example 2

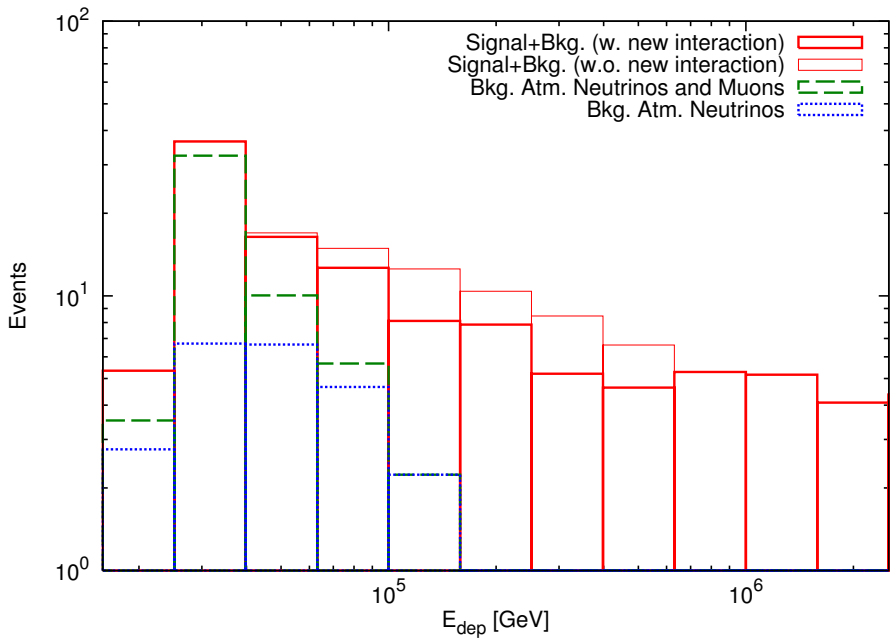
$$V_{UV} = \left\{M\psi\psi^c + y'\Phi\psi^c\psi^c + y(HL)\psi + Y_l H^\dagger L e^c + cc\right\} + m_\phi^2|\Phi|^2 + \lambda_\phi|\Phi|^4 + V_{\mathrm{U}(1)_{\not{L}}}$$

Observational Features

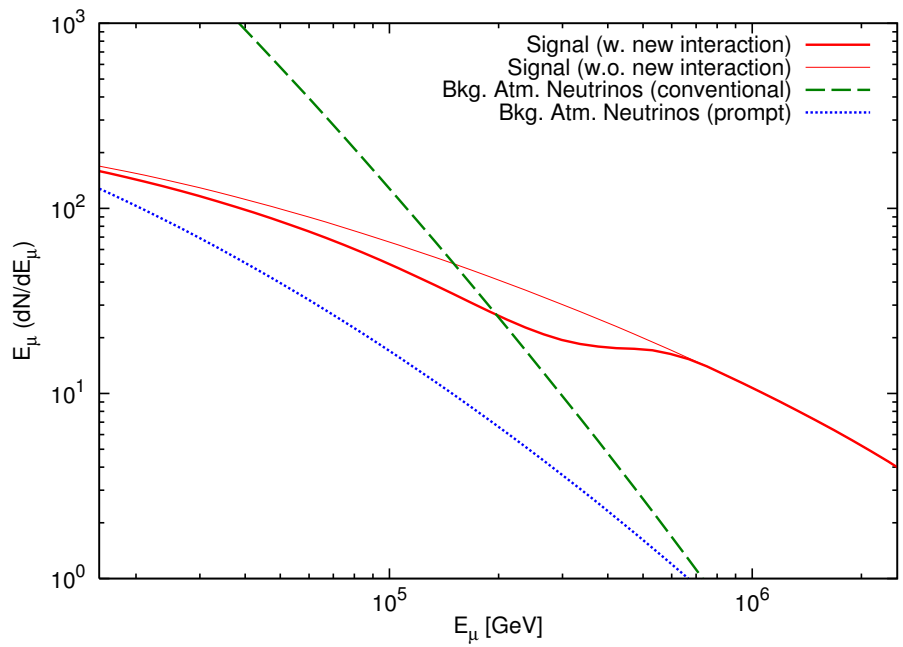
To see a sizable effect in IceCube, we need

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

shower



upgoing muon



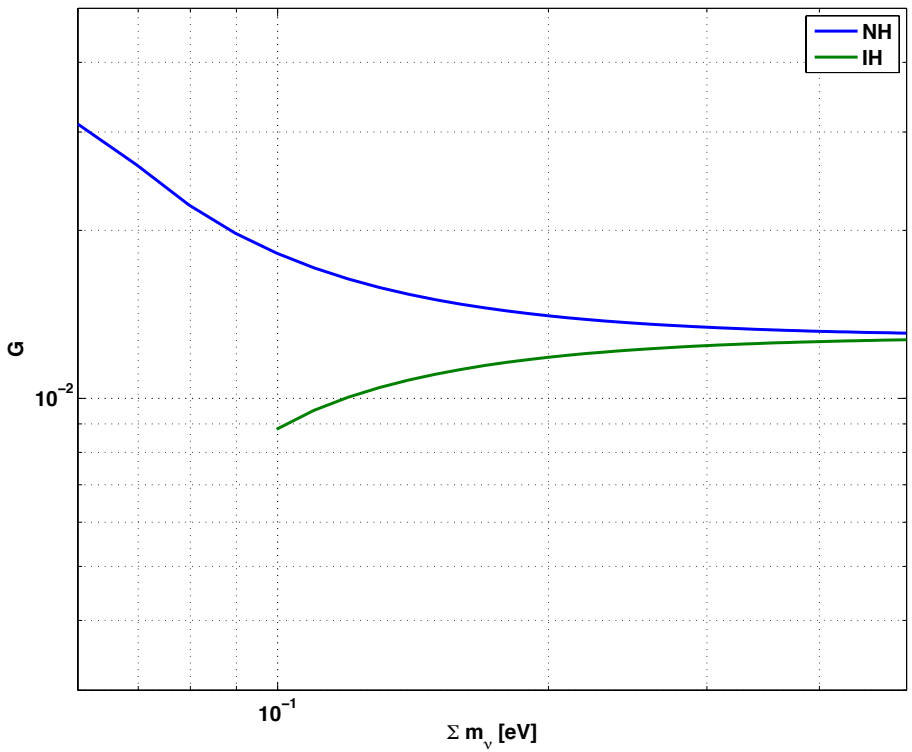
general cautions: deposited energy, muon energy < neutrino energy

unfolded spectrum derived a flavor ratio 1:1:1

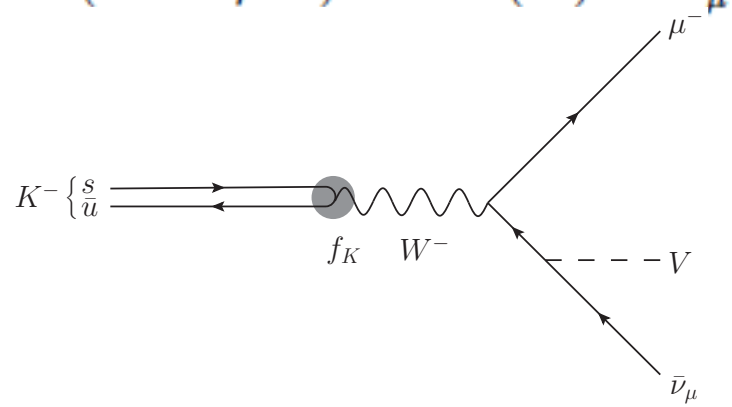
Experimental Constraints

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

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



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



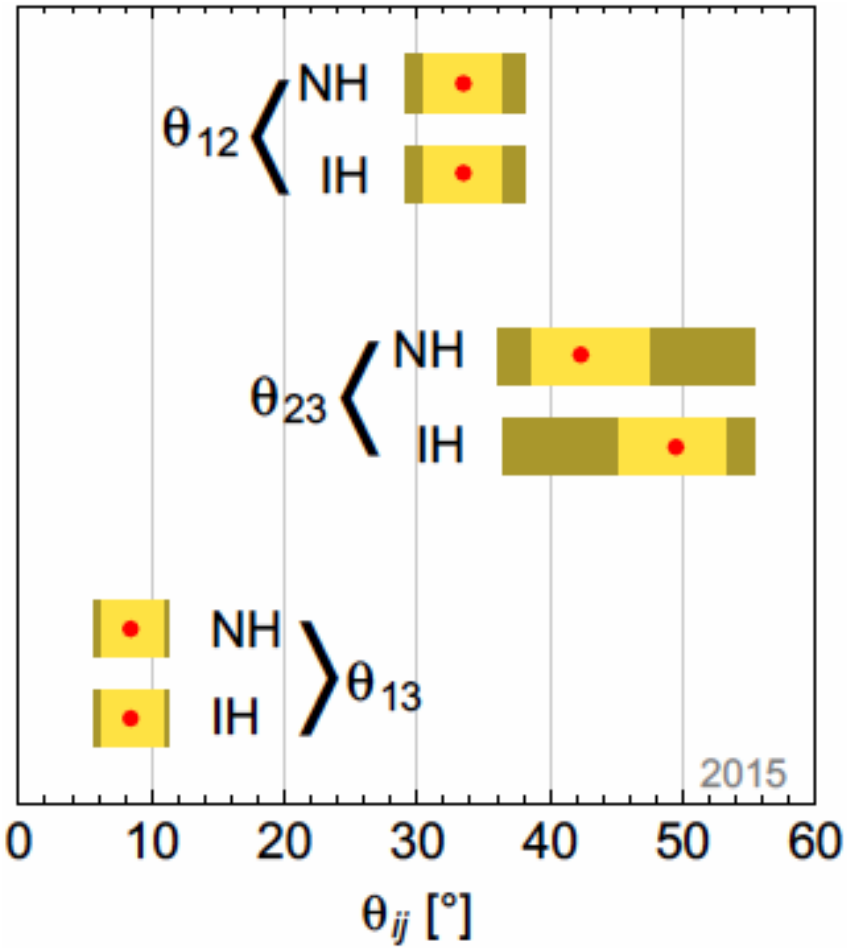
∗ **helicity-unsuppressed decay $e\nu\phi$ leads to comparable limits**

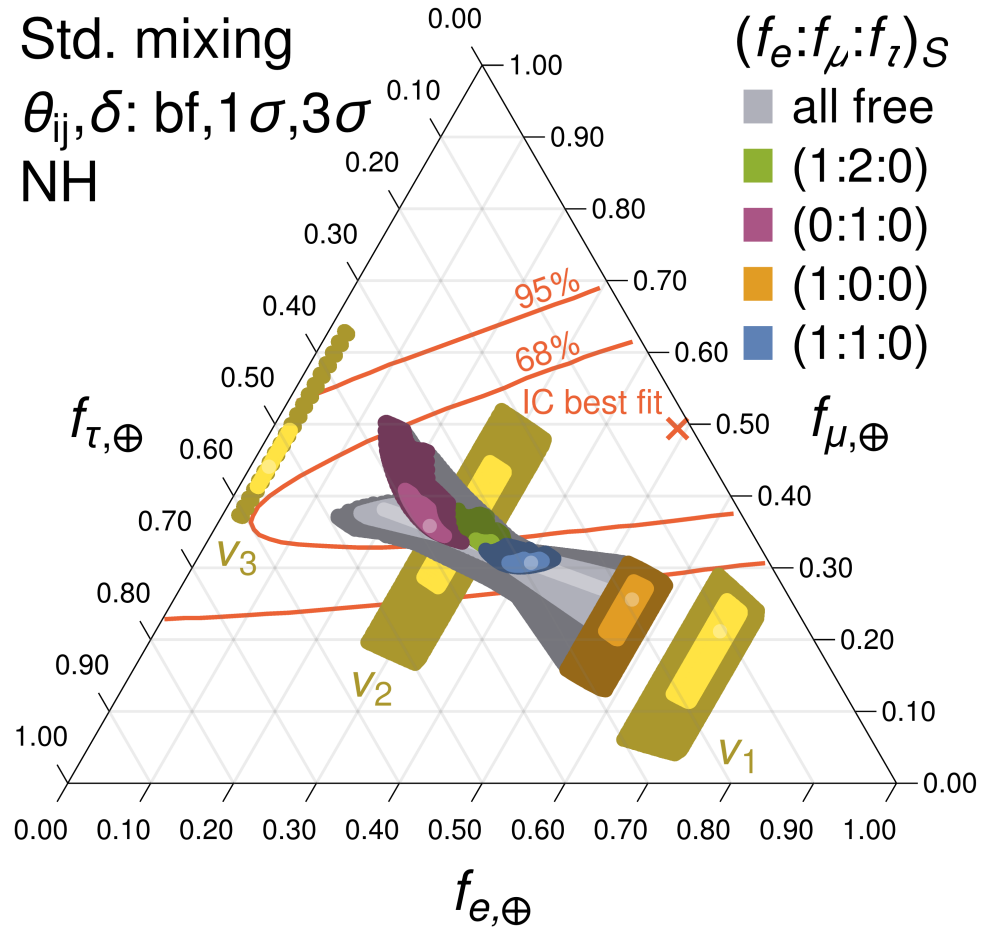
(Blum, Hook & KM 14
see also, e.g., Laha, Dasgupta & Beacom 14)

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

Measuring Flavors

from NUFIT2.0 (2014)





Deviation from gray regions indicates BSM physics

Bustamante, Beacom & KM 17 PRD
Bustamante, Beacom & Winter 15 PRL

Example: 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

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

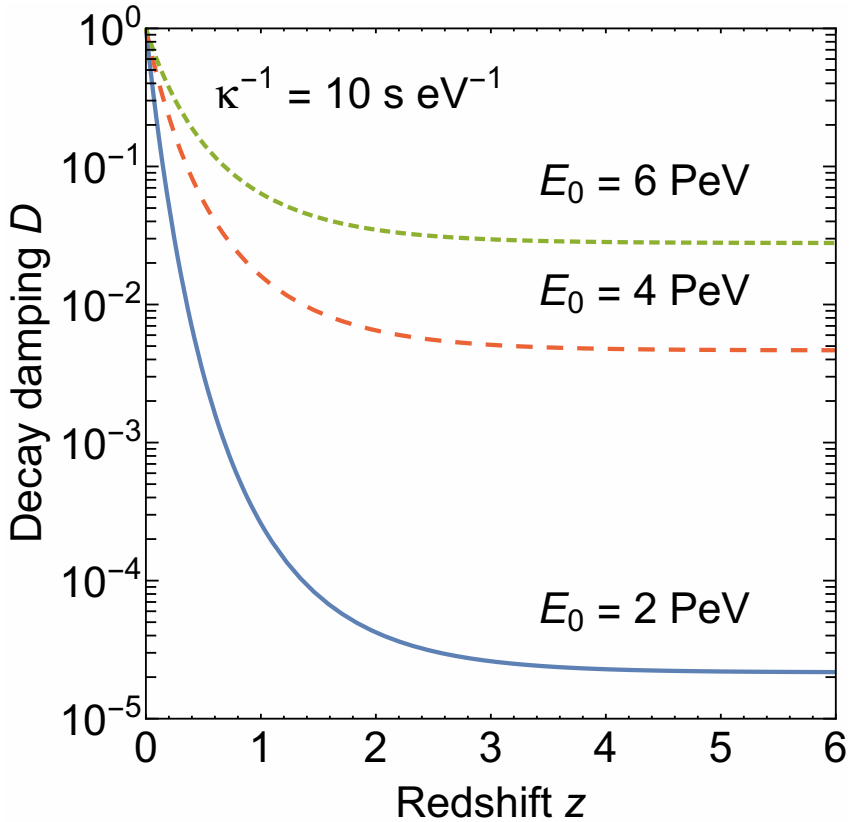
Visible decay (decay into the lowest mass eigenstate)

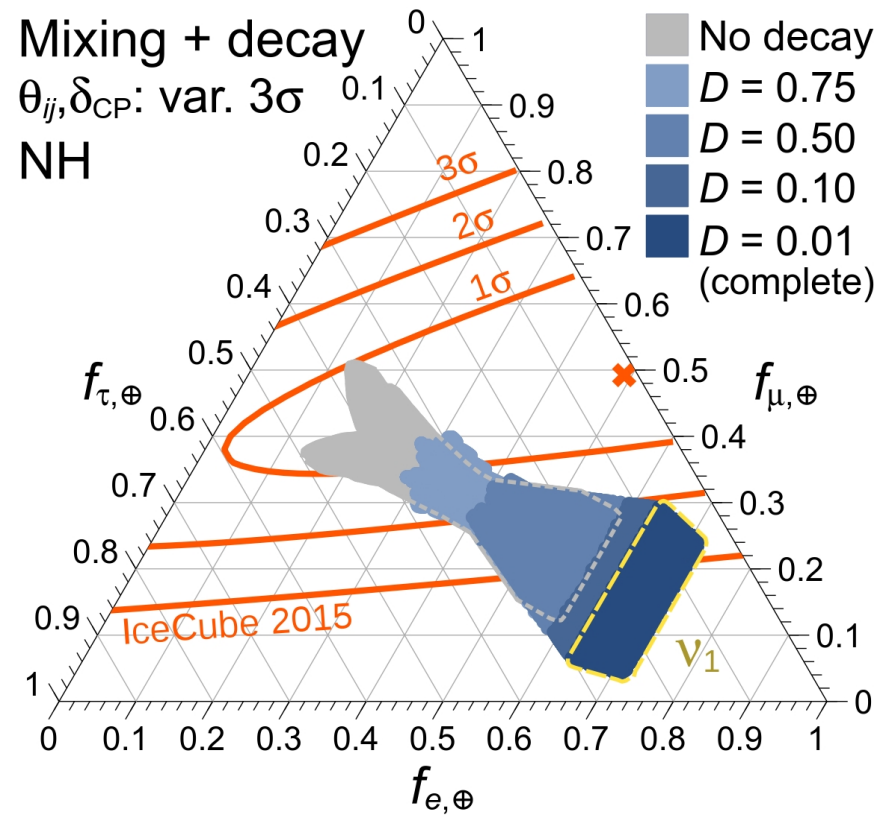
$$P^{\mathrm{vis,NH}}_{\alpha\beta} = |U_{\alpha 1}|^2 \, |U_{\beta 1}|^2 \left[\frac{N_1 + \left(\hat{N}_2 - N_2\right) + \left(\hat{N}_3 - N_3\right)}{\hat{N}_1}\right] + |U_{\alpha 2}|^2 \, |U_{\beta 2}|^2 \, \frac{N_2}{\hat{N}_2} + |U_{\alpha 3}|^2 \, |U_{\beta 3}|^2 \, \frac{N_3}{\hat{N}_3}$$

Neutrino Decay: Normal Hierarchy

$$D\left(E_0, z, \kappa^{-1}\right) = \left[\mathcal{Z}\left(z\right)\right]^{-\frac{\kappa L_H}{E_0}} \qquad \mathcal{Z}\left(z\right) \simeq a + be^{-cz}$$

redshift evolution



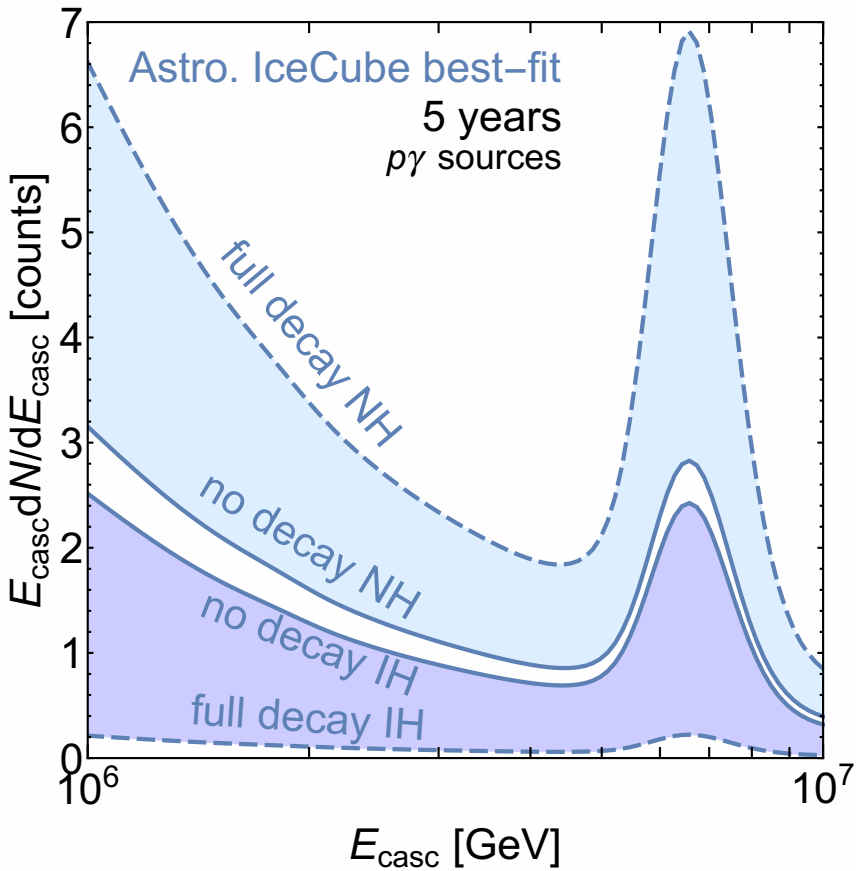


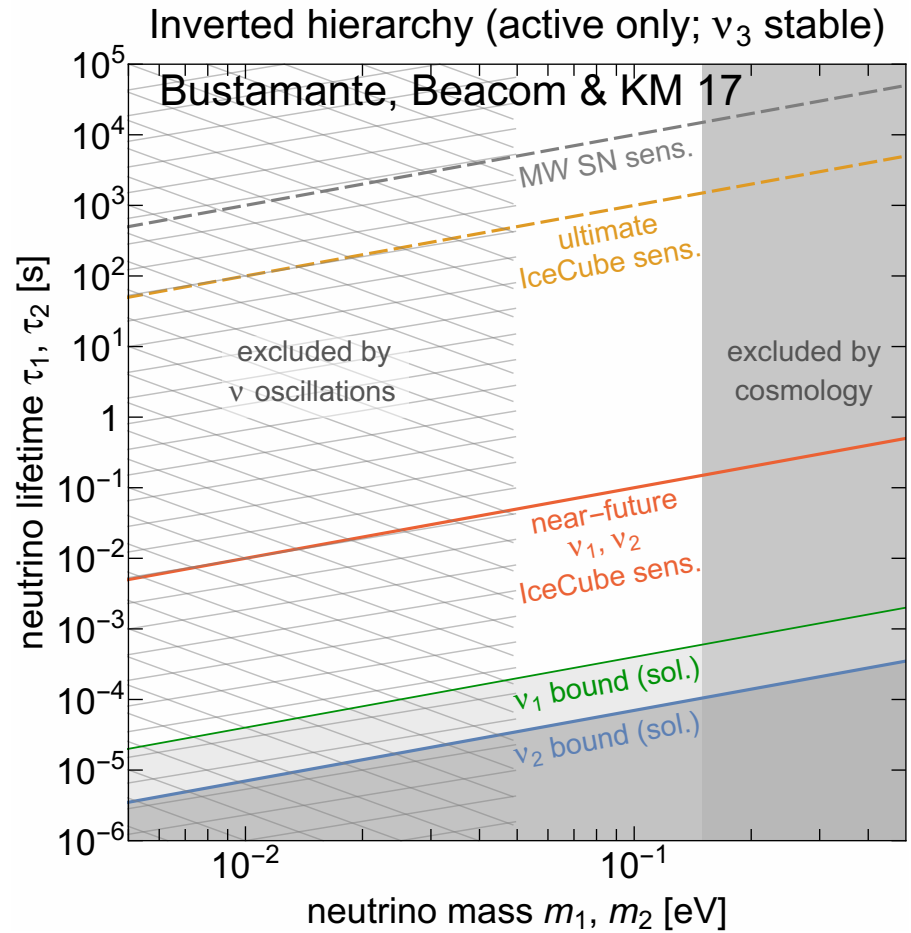
complete decay of ν_2, ν_3 is ruled out w. 2σ only by flavor information

$$\kappa_2^{-1}, \kappa_3^{-1} \gtrsim 10 \text{ s eV}^{-1} \; (\gtrsim 2\sigma)$$

Neutrino Decay: Inverted Hierarchy

IH is not ruled out by the flavor information

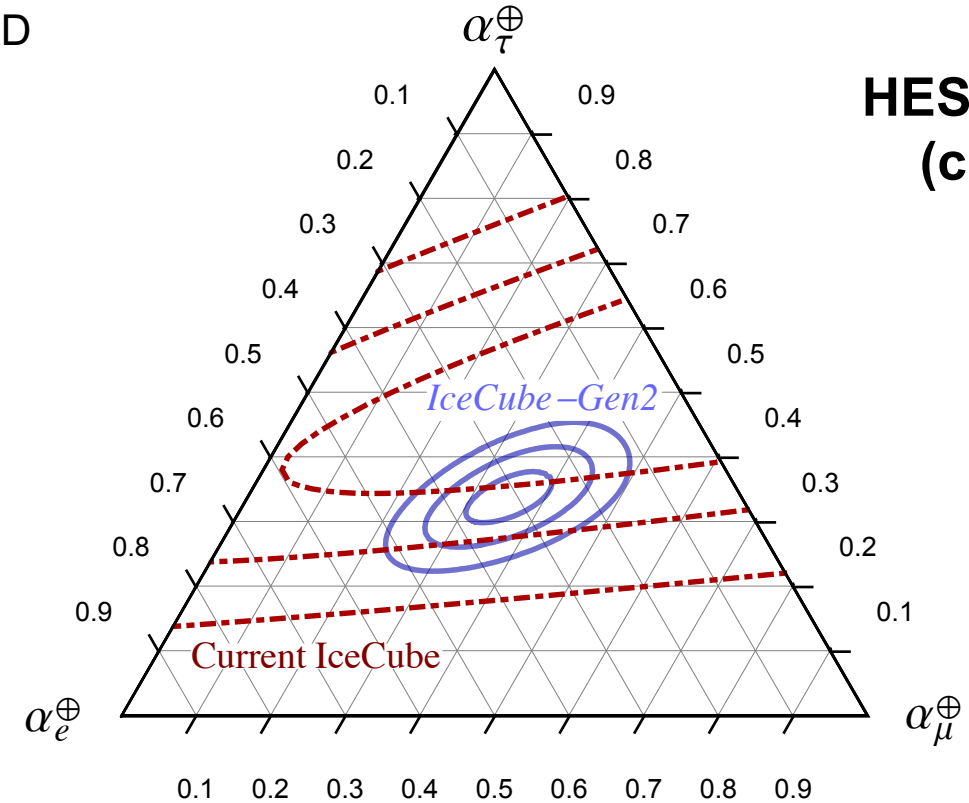




Observing just one Glashow resonance event improves the limit by 2-3 orders of magnitudes: $\kappa >\sim 1$ s eV^{-1}

Improvements in Future?

Shoemaker & KM 16 PRD



HESE-like analysis (conservative)

$$N_S^{\mathrm{NC,all}}(E_1,E_2) = p_{NC} \sum_{i=e,\mu,\tau} 4\pi T \int_{E_1/\beta_{NC}}^{E_2/\beta_{NC}} dE\ (\alpha_\oplus^i + \bar{\alpha}_\oplus^i)\Phi_\nu(E) A_i(E)$$

$$N_S^{\mathrm{CC},\tau_{\mathrm{had}}}(E_1,E_2) = (1-p_{NC})\, p_{had} 4\pi T \int_{E_1/\beta_{had}}^{E_2/\beta_{had}} dE\ (\alpha_\oplus^\tau + \bar{\alpha}_\oplus^\tau)\Phi_\nu(E) A_\tau(E)$$

$$N_S^{\mathrm{CC},\tau_{\mathrm{lep}}}(E_1,E_2) = (1-p_{NC})\,(1-p_{had}) 4\pi T \int_{E_1/\beta_{lep}}^{E_2/\beta_{lep}} dE\ (\alpha_\oplus^\tau + \bar{\alpha}_\oplus^\tau)\Phi_\nu(E) A_\tau(E)$$

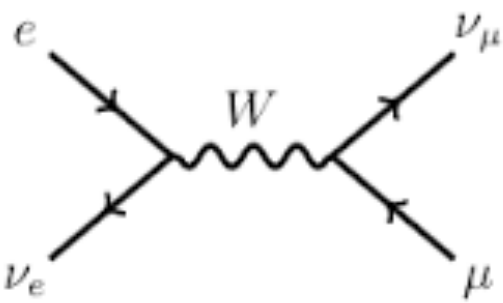
$$N_S^{\mathrm{CC,e}}(E_1,E_2) = (1-p_{NC})\, 4\pi T \int_{E_1}^{E_2} dE\ (\alpha_\oplus^e + \bar{\alpha}_\oplus^e)\Phi_\nu(E) A_e(E)$$

$$N_T = 4\pi T \int_{E_1/\beta_\mu}^{E_2/\beta_\mu} dE\ (1-p_{NC})\ (\alpha_\oplus^\mu + \bar{\alpha}_\oplus^\mu)\ \Phi_\nu(E)\ A_\mu(E)$$

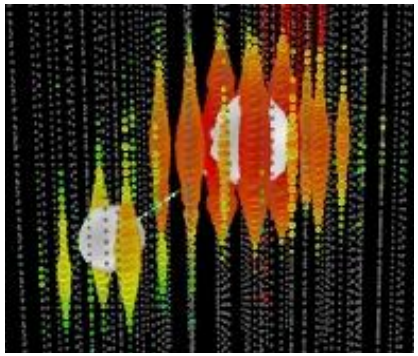
likelihood analysis for mocked data combining flavor & spectral information

Improvements in Future?

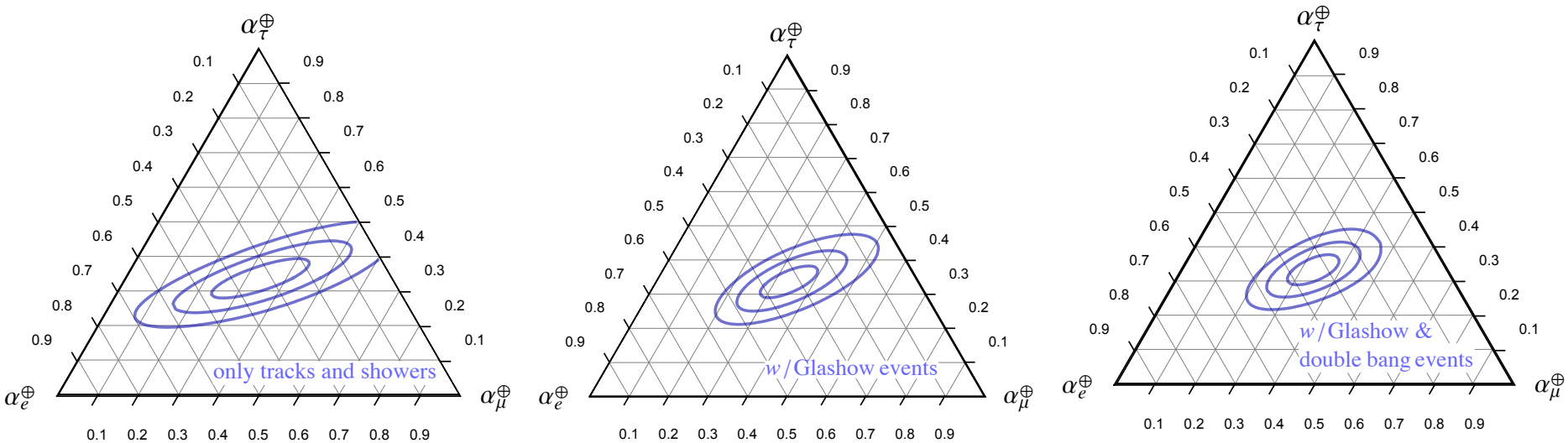
$\bar{\nu}_e + e^- \longrightarrow W^-$



$\nu_\tau + N \rightarrow \tau + X$

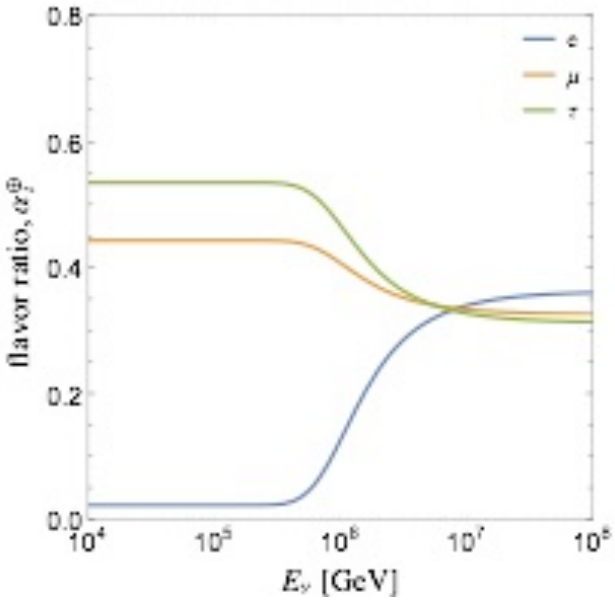


$[N_{GR}, N_{DB}]$	$\Phi \propto E^{-2.2}$	$\Phi \propto E^{-2.5}$
pp	$[23, 5]$	$[8, 2]$
pp (with μ^+ damping)	$[15, 6]$	$[6, 2]$
$p\gamma$ (canonical π^-)	$[11, 6]$	$[4, 2]$
neutron decay	$[73, 4]$	$[28, 1]$



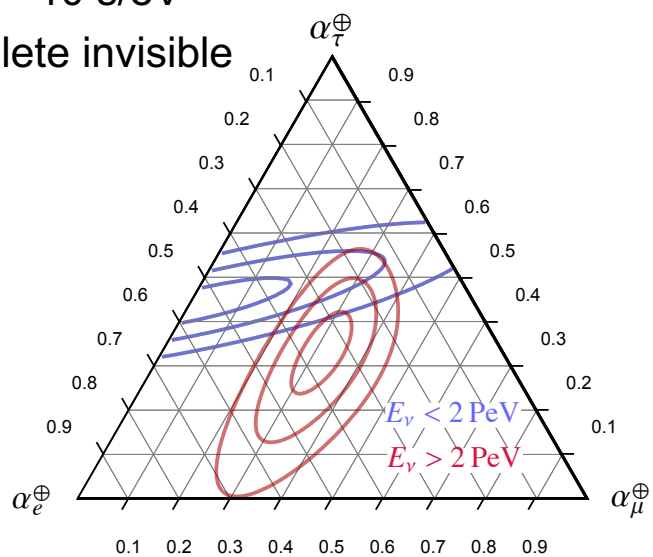
Shoemaker & KM 16 PRD

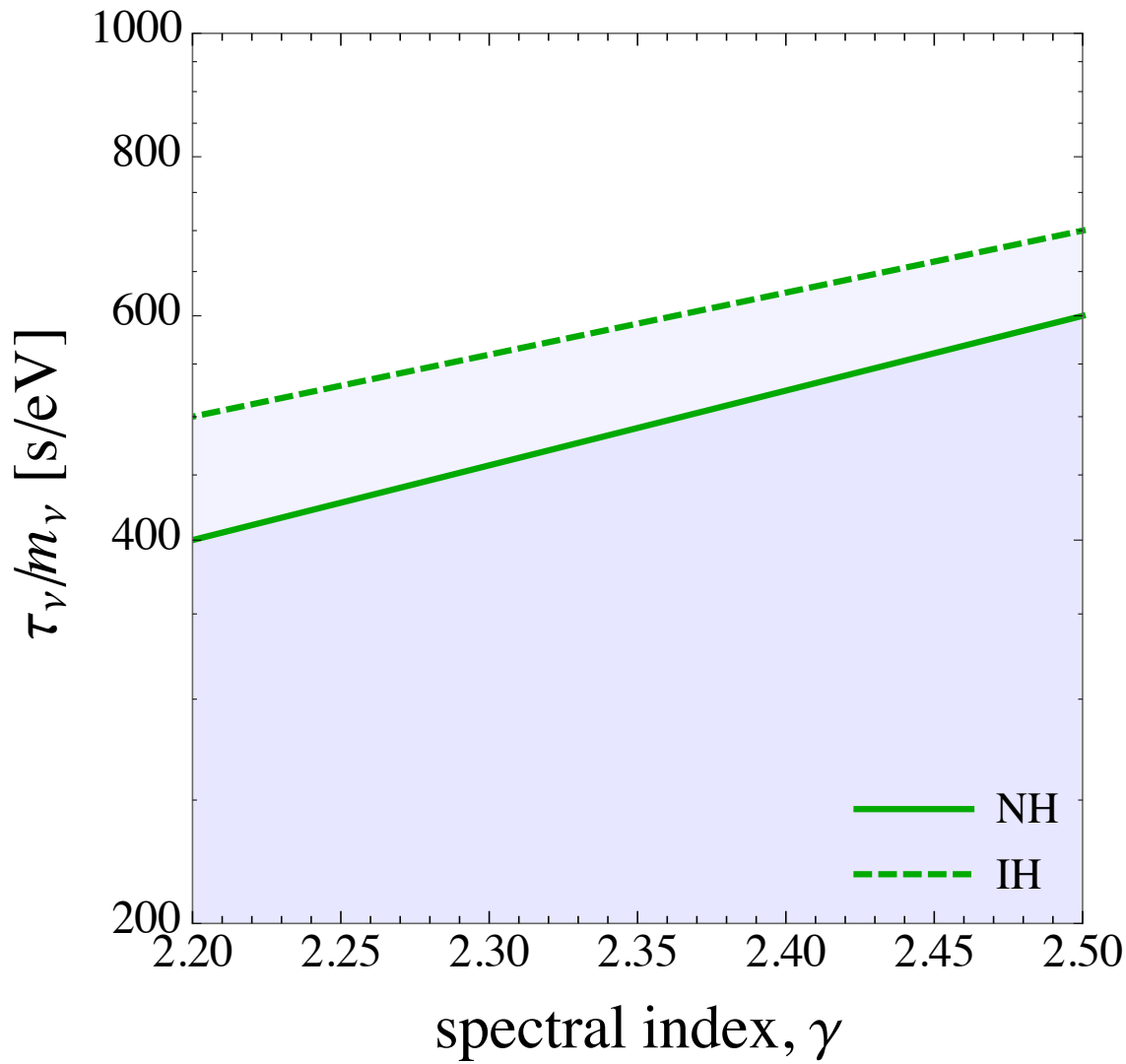
Future Constraints: Neutrino Decay



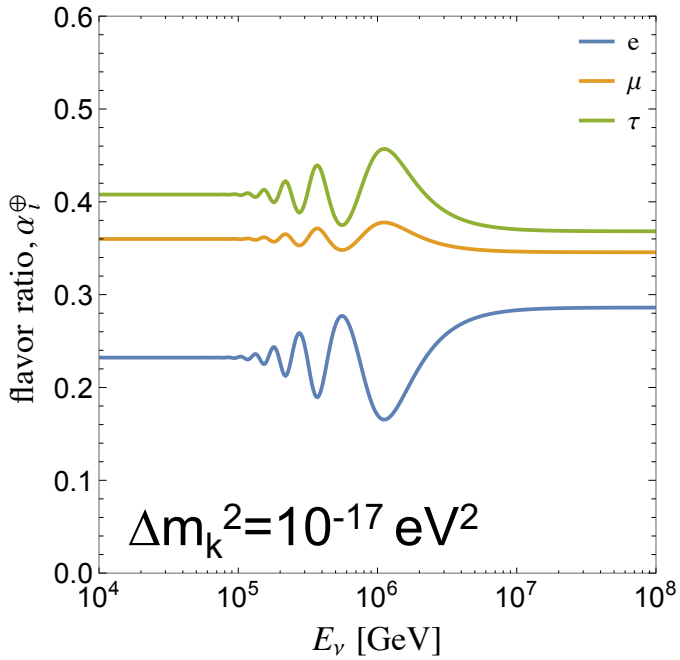
IH: κ^{-1}=10 s/eV

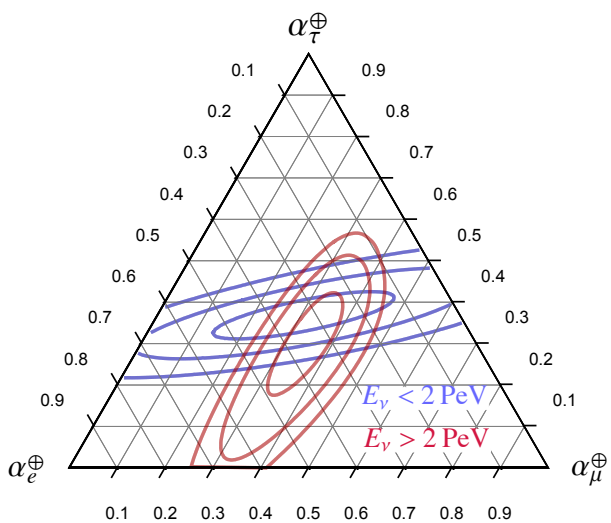
complete invisible





Future Constraints: Pseudo-Dirac Neutrinos



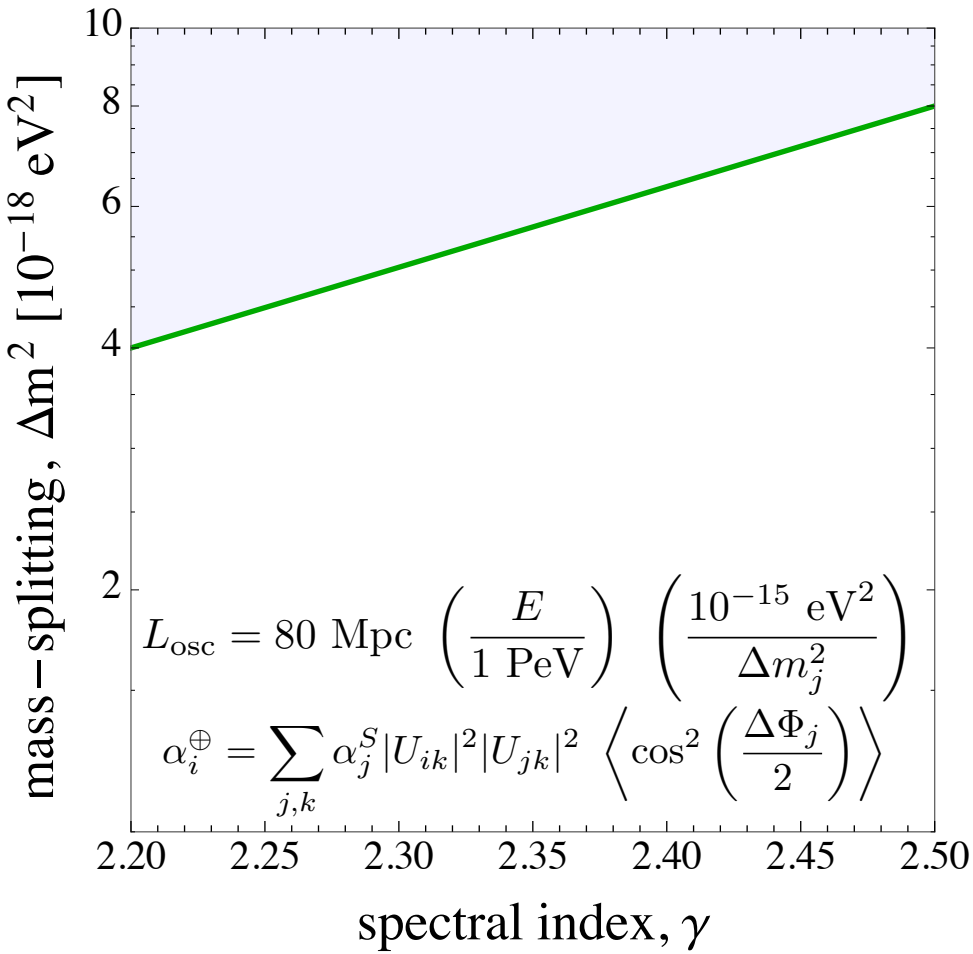


- Tiny mass splitting w. sterile neutrinos

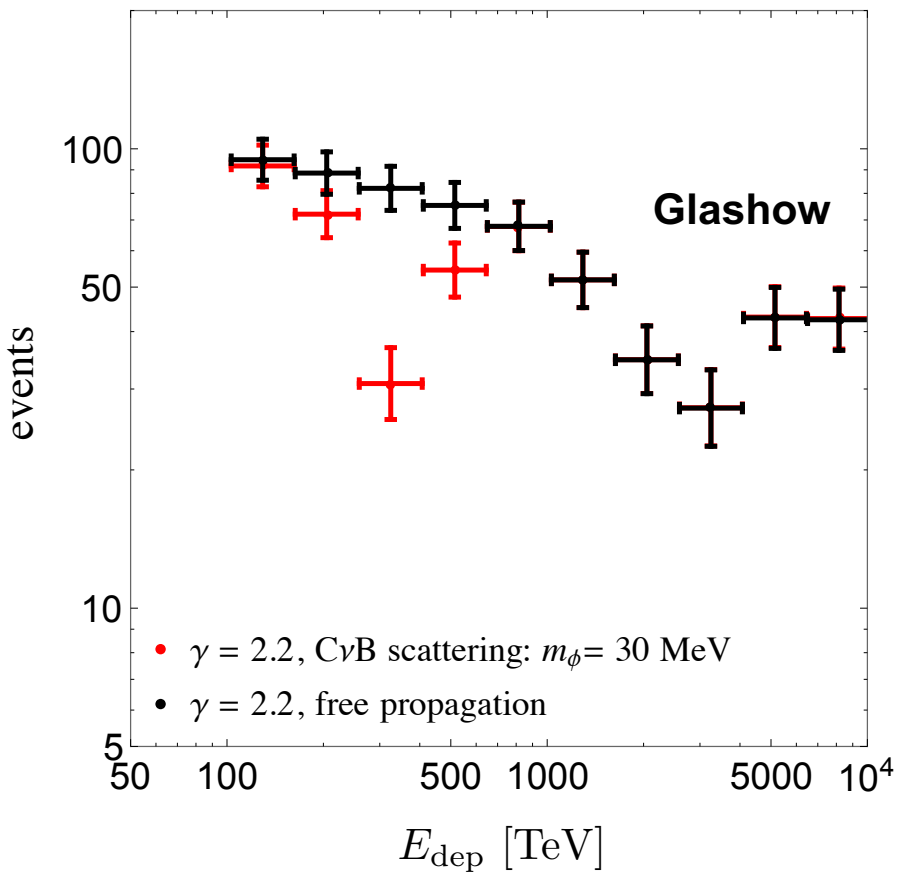
Wolfenstein 81, Petcov 81

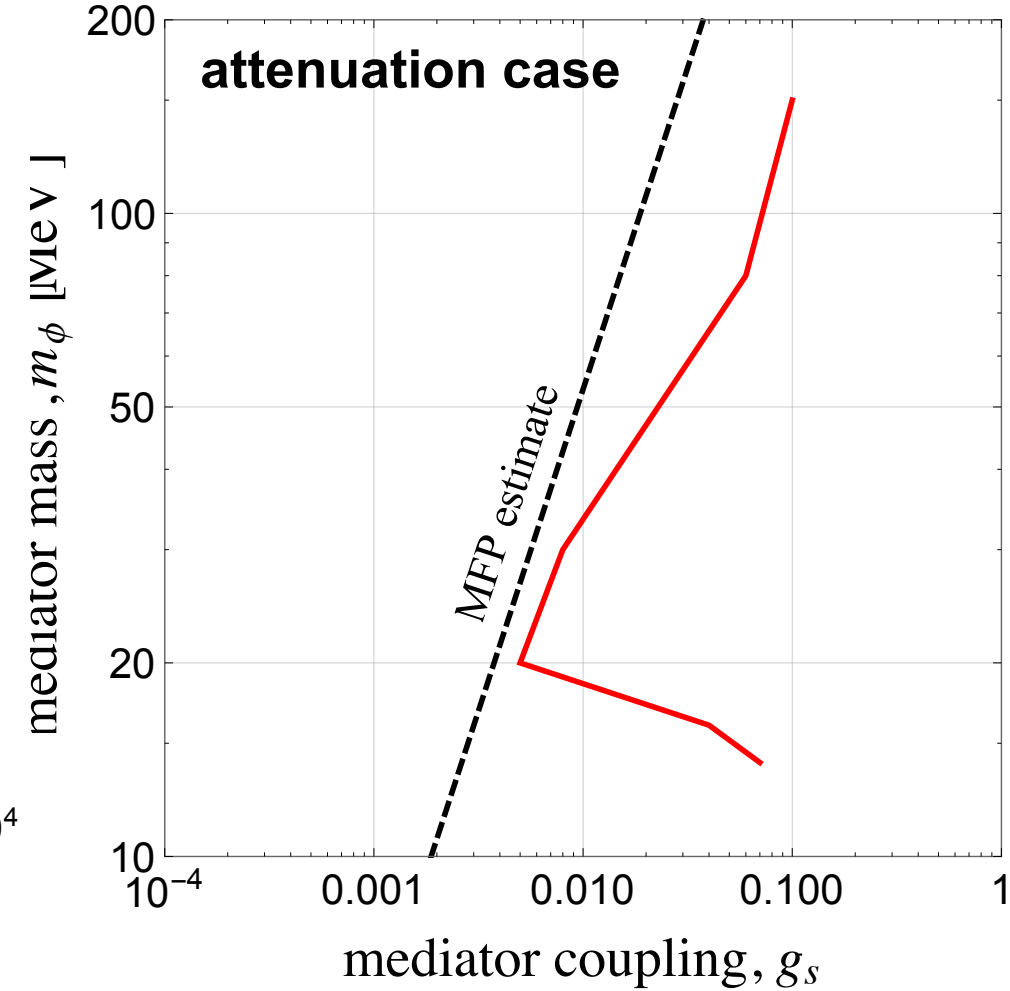
- Cosmic neutrinos can be used as a probe

Beacom et al. 04, Karanen et al. 03



Future Constraints: Secret Interactions





$$\sigma_{\nu\nu}(\varepsilon_\nu) > \frac{H_0}{c n_\nu} \sim 1.4 \times 10^{-30}\,\mathrm{cm}^2, \quad (s \simeq 2 m_\nu \varepsilon_\nu)$$