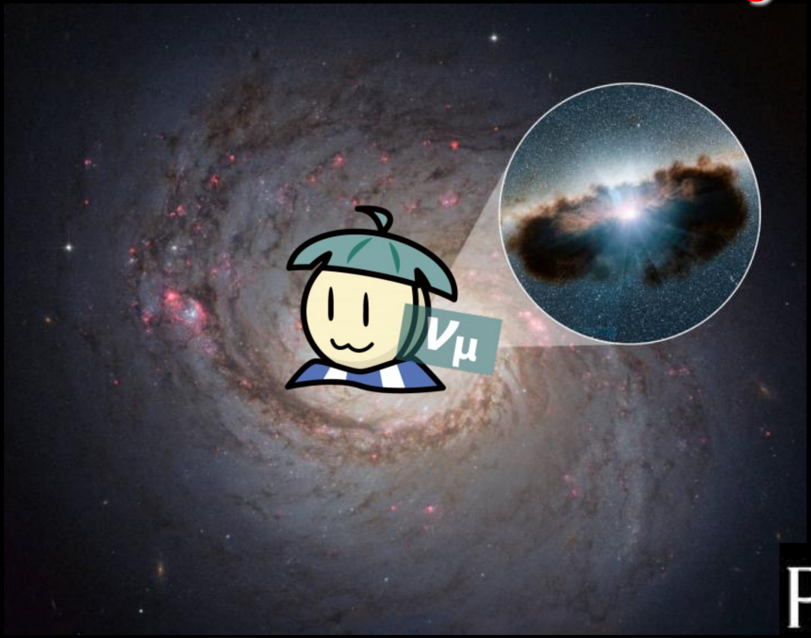
High-Energy Cosmic Neutrinos as Probes of New Physics



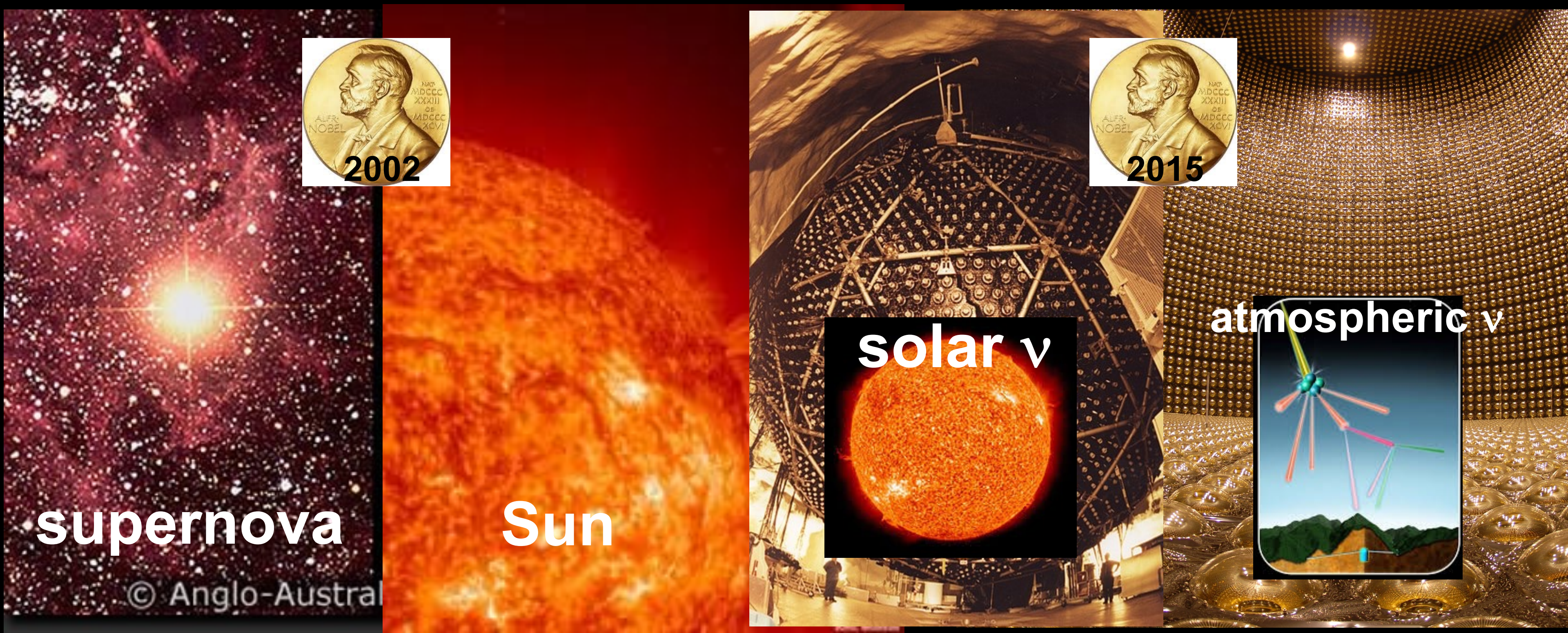
Kohta Murase (PSU/YITP)

June 16

The Frontier of Particle Physics

Why Cosmic ν ?

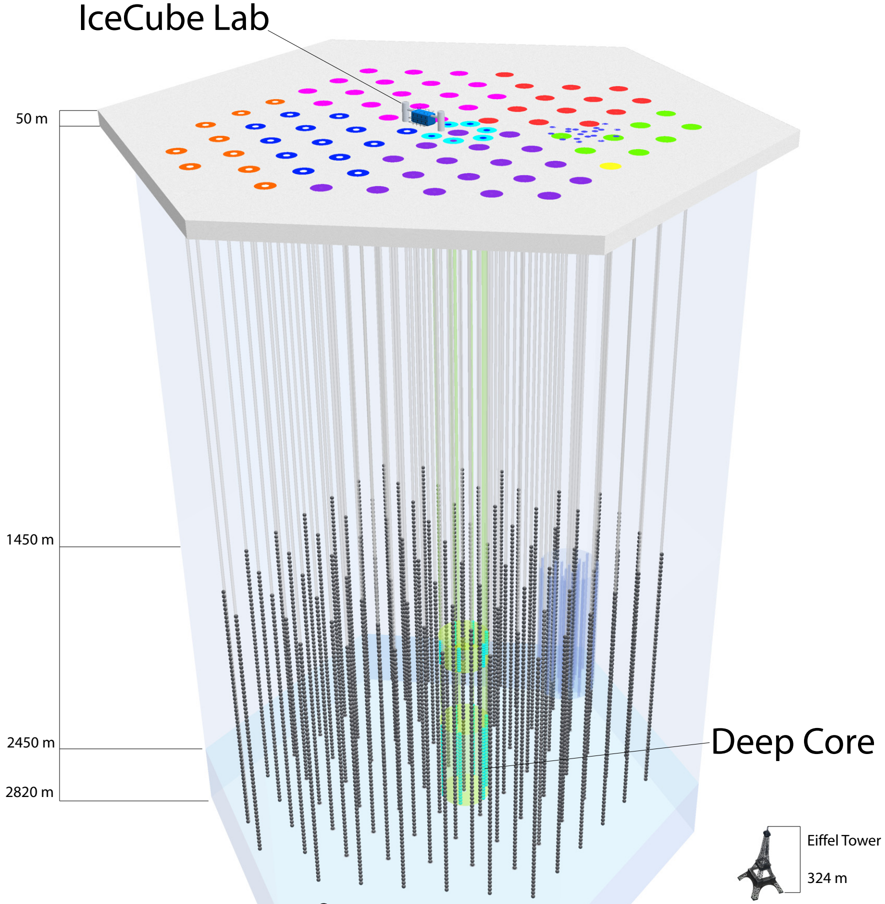
- Electrically neutral lepton
- Weak interaction: ghost particle
- Almost massless but tiny mass ($<1/10^6$ electron mass)



Astrophysics ***Particle Physics***

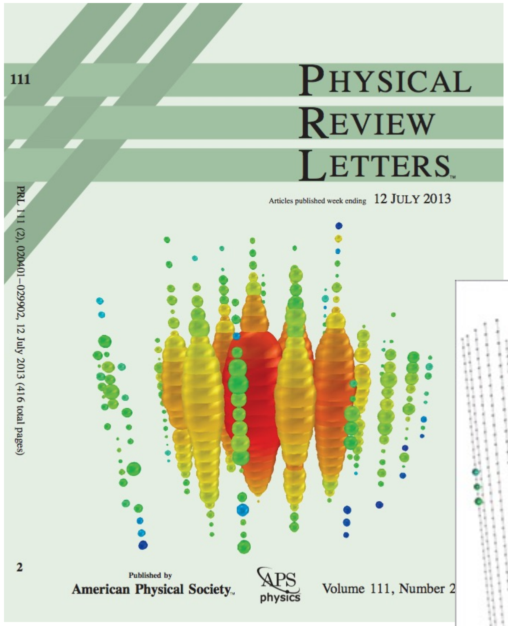
IceCube & Discovery of High-Energy Cosmic Neutrinos

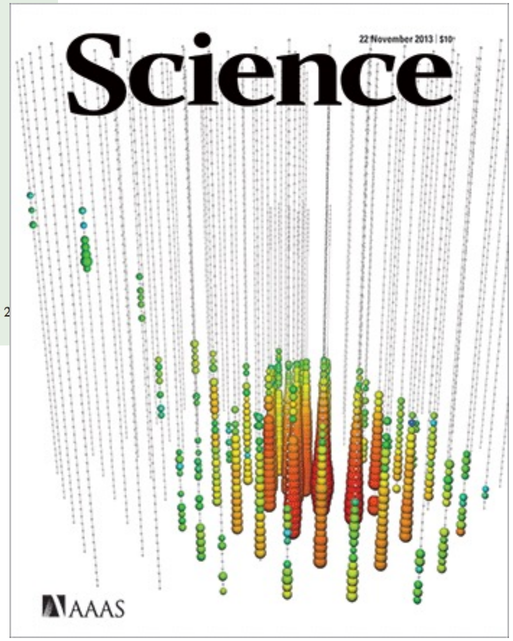
IceCube @ south pole completed in 2010

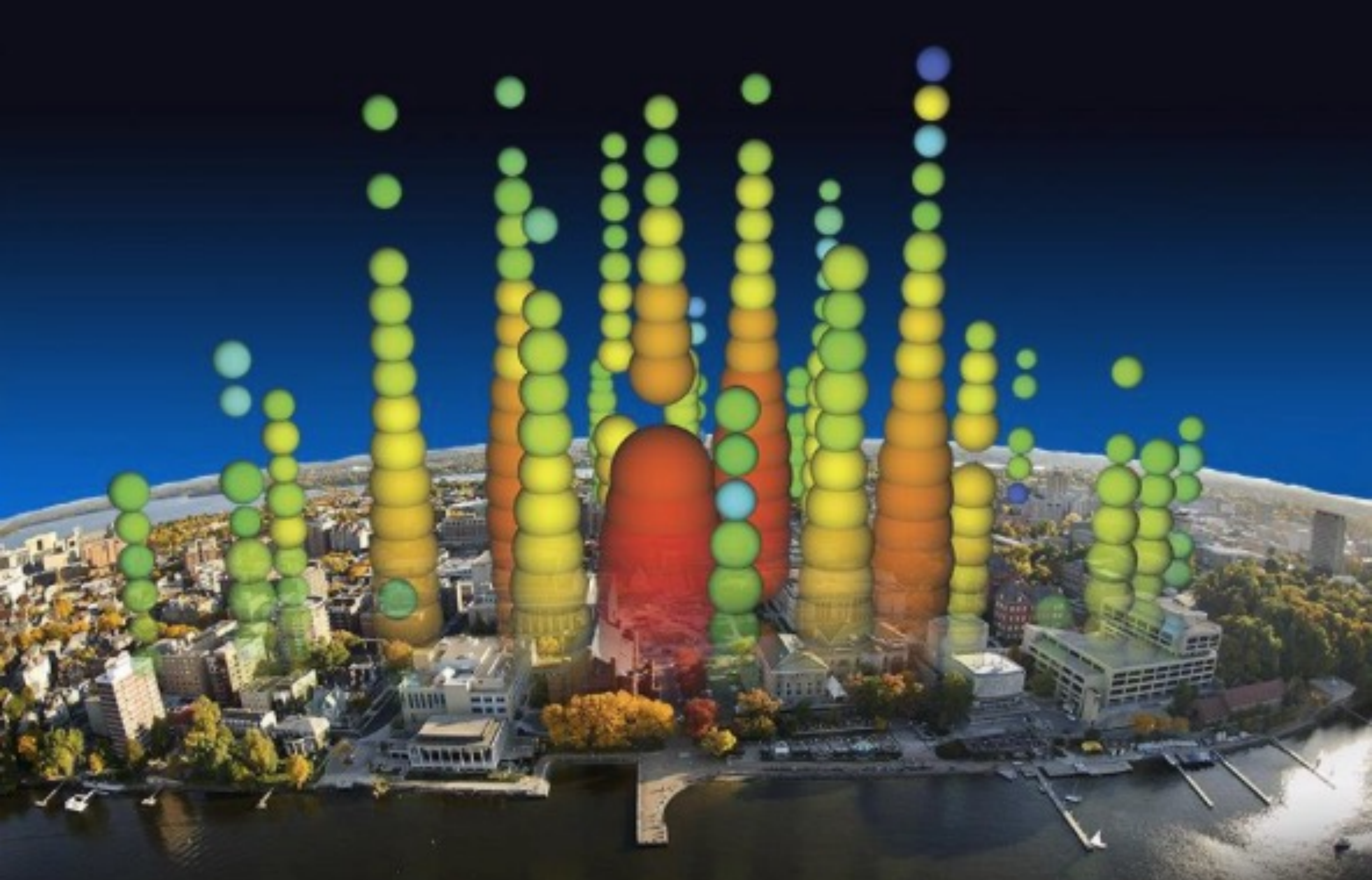


- volume~1 km^3, mass~Gton
- 86 strings (120 m spacing)
- 5160 PMTs (17 m spacing)

2012-2013: evidence of high-energy cosmic ν

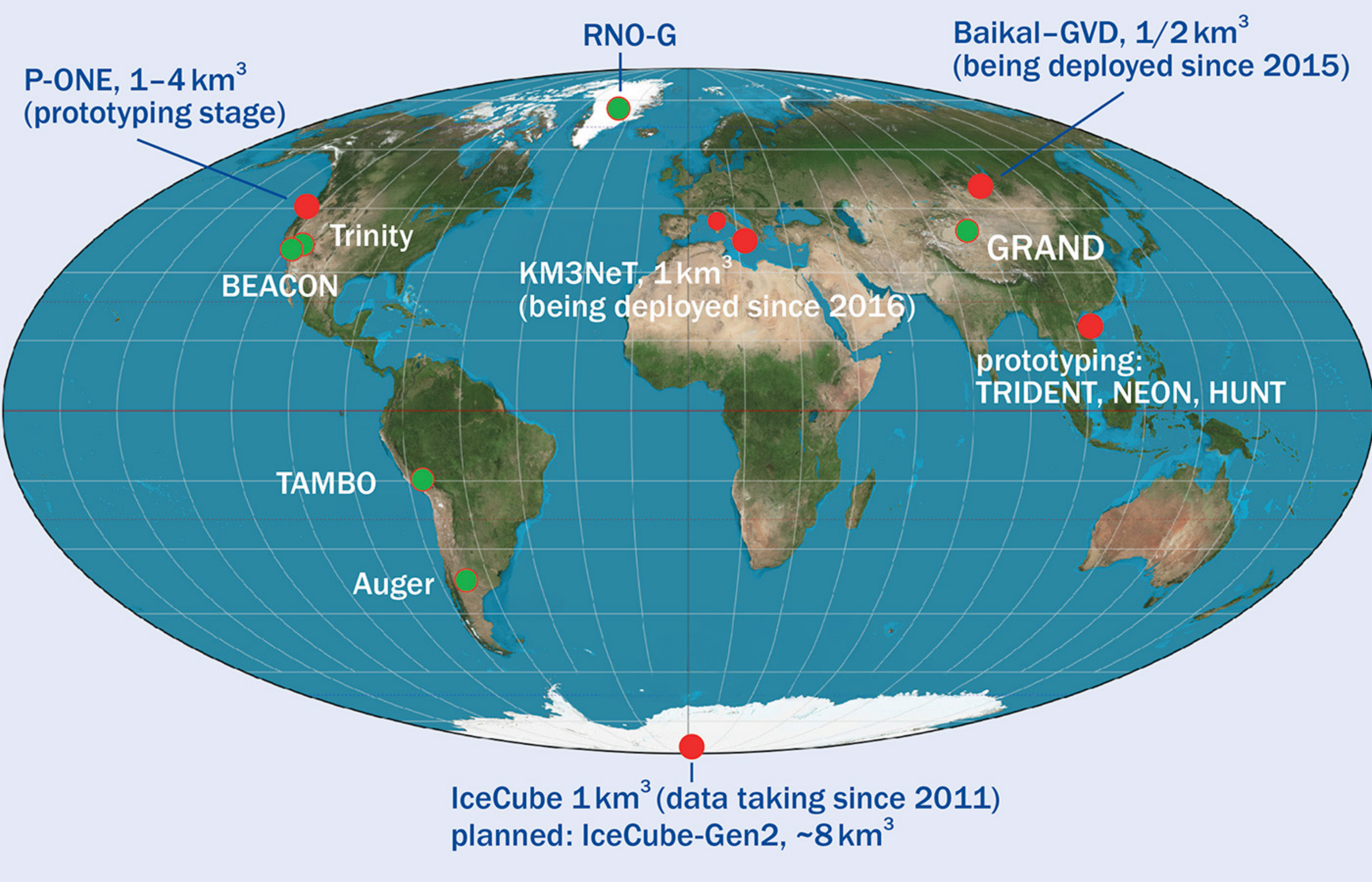






~ 1 PeV = 10^{15} eV >> $1\text{–}10$ MeV (supernova/solar ν)
L ~ 1 Gpc ~ $3\text{x}10^{22}$ km >> 295 km (T2K)

Global Neutrino Detector Network



Plan of Talk

High-energy cosmic neutrinos can be unique as probes of new physics

- natural high-energy ν beams that are hard to create with ground accelerators
- unique advantages (ex. long travel distance, high dark matter density)

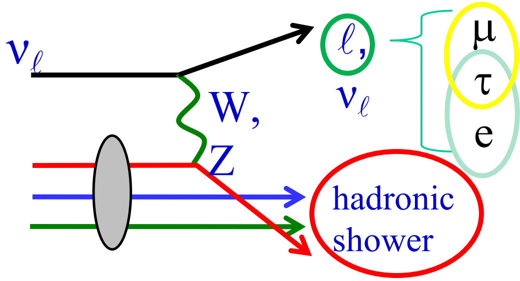
- **Review of high-energy cosmic neutrino observations and implications**

- **New physics search**
  - **new ν interactions**
  - **SM-DM interactions**
  - pseudo-Dirac ν
  - ν decay
  - conventional DM search

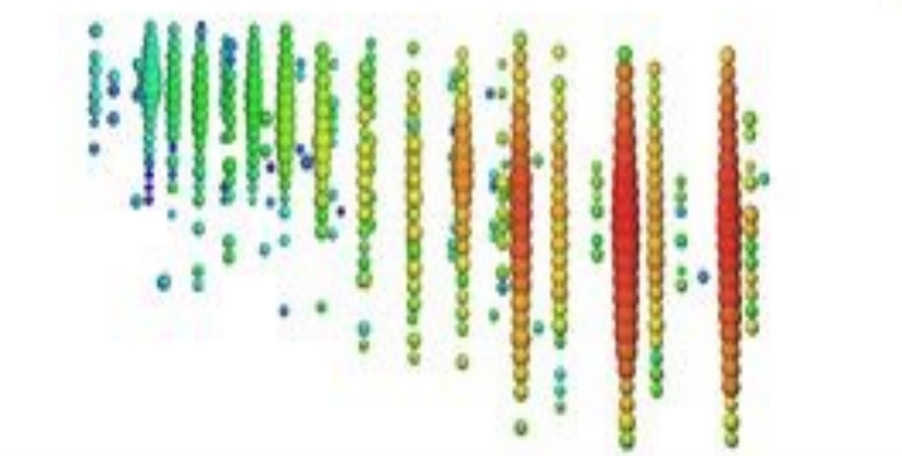
Disclaimer:
There are many things that cannot be covered...
DM-SM interaction in the Sun, atmospheric neutrino oscillation,
sterile neutrinos, ν mag. moment, Lorentz variance violation etc.

Neutrino Event Types

2 “main” event types



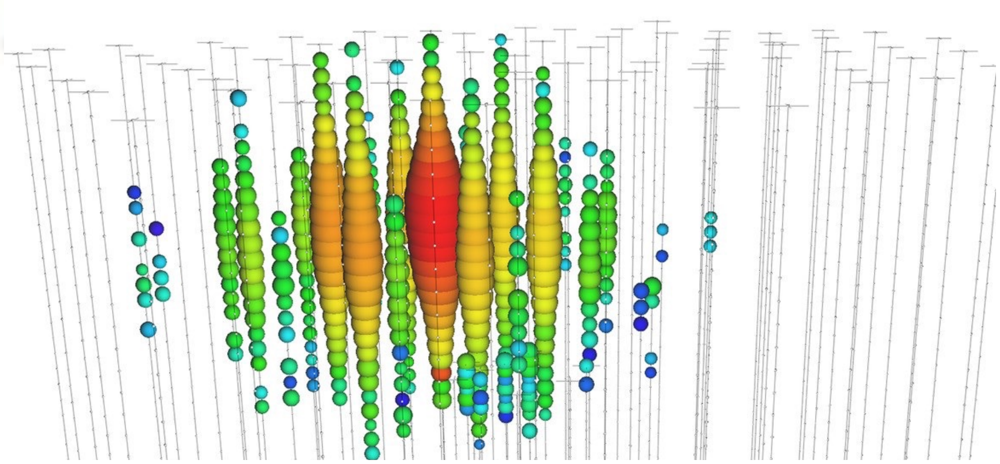
“ν_μ track”



ν_μ+N → μ+X

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

“shower”



ν_e+N → e+X

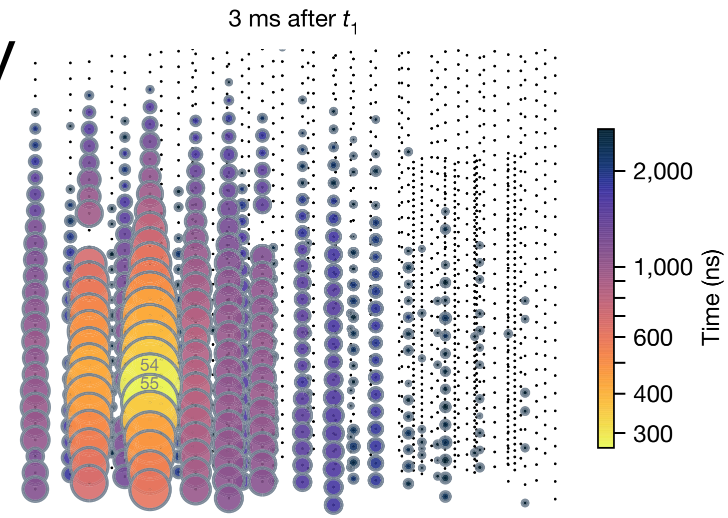
ν_τ+N → τ+X

ν_X+N → ν_X+X

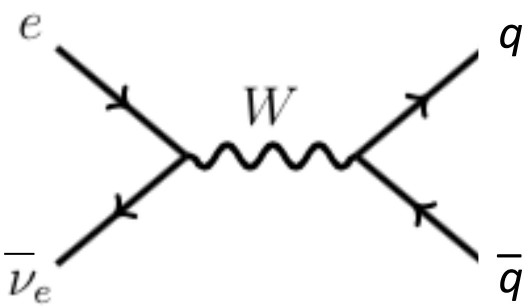
~10% energy resolution
~5-10 deg ang. resolution

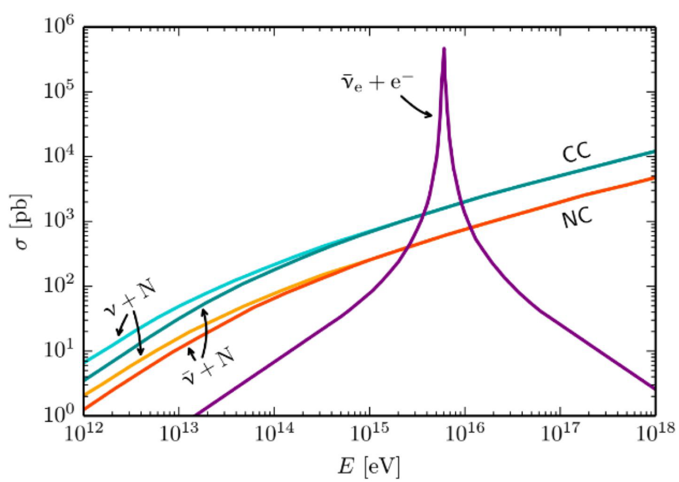
Anti-Neutrino Detection

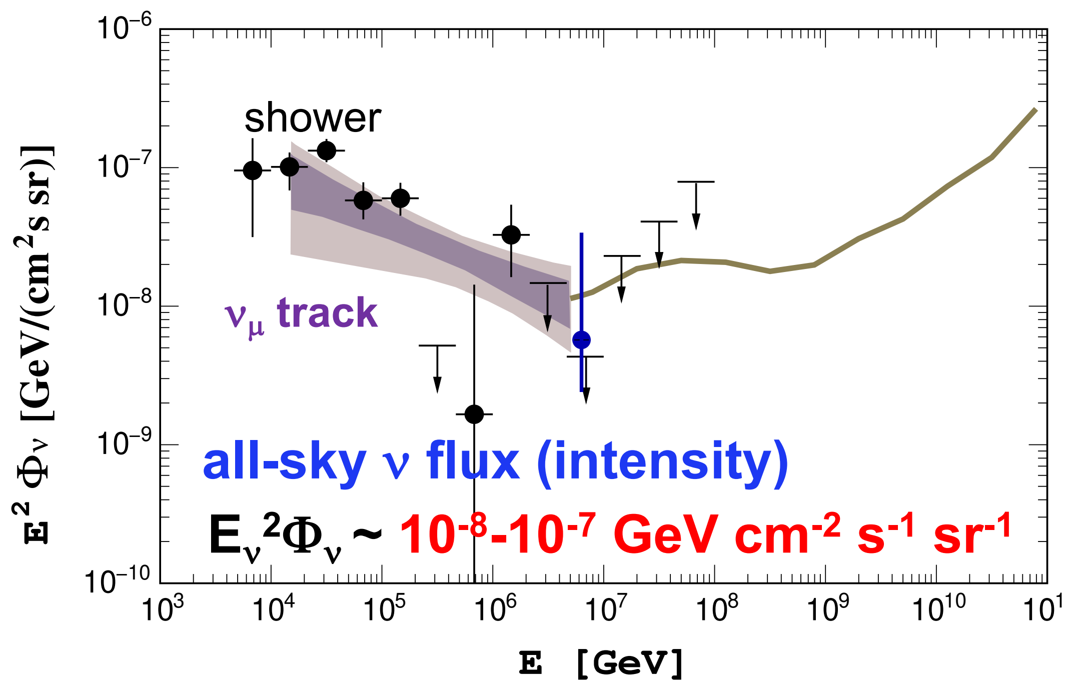
- Shower deposited energy = 6.05 PeV
- Glashow resonance (GR) event at E=6.3 PeV (~2.3σ) (predicted in 1959 by Glashow)



IceCube 21 Nature



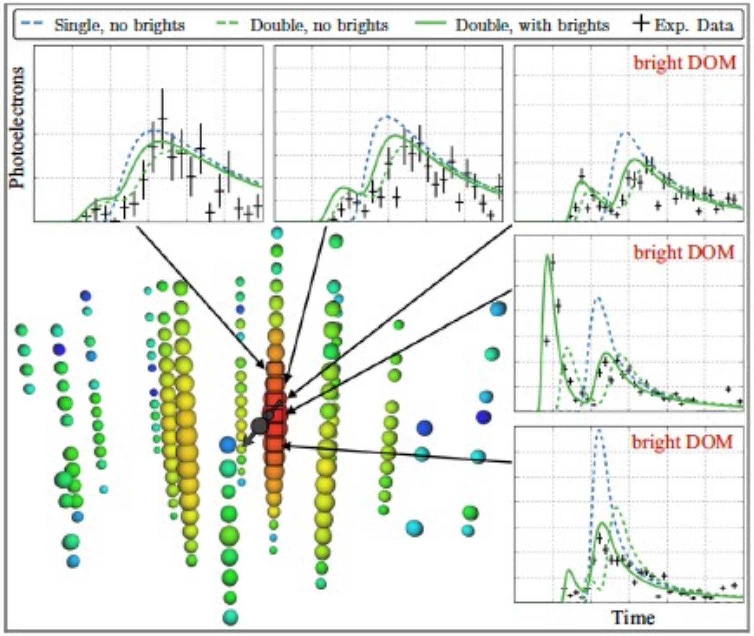




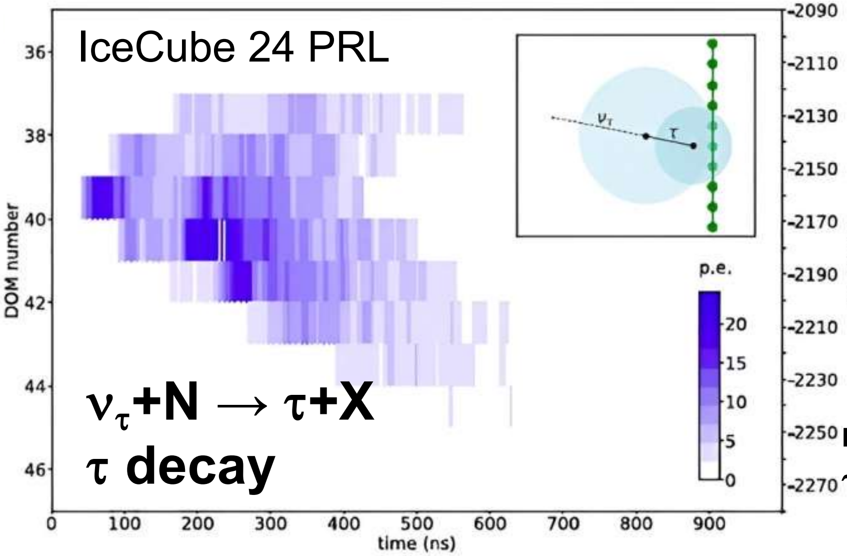
Tau Neutrino Candidates

m_τ=1.77 GeV

τ_τ=2.9 × 10^{-13} s ~50 m at ~PeV



IceCube 22 EPC

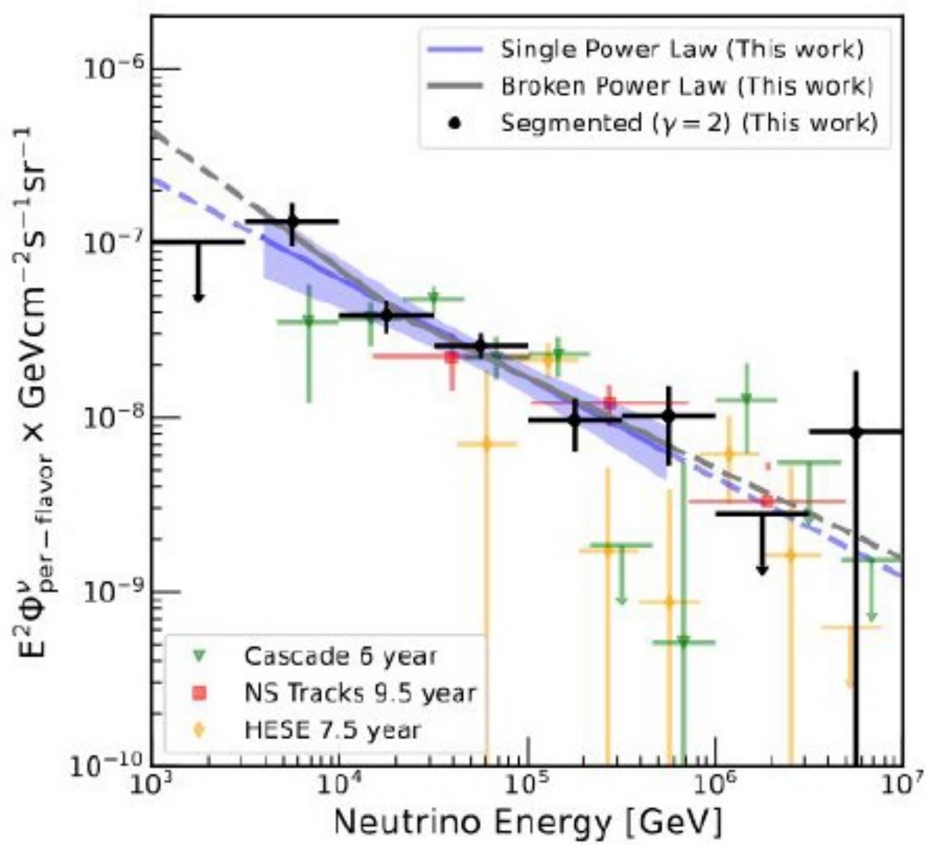


m_τ=1.77 GeV
τ_τ=2.9 × 10^{-13} s

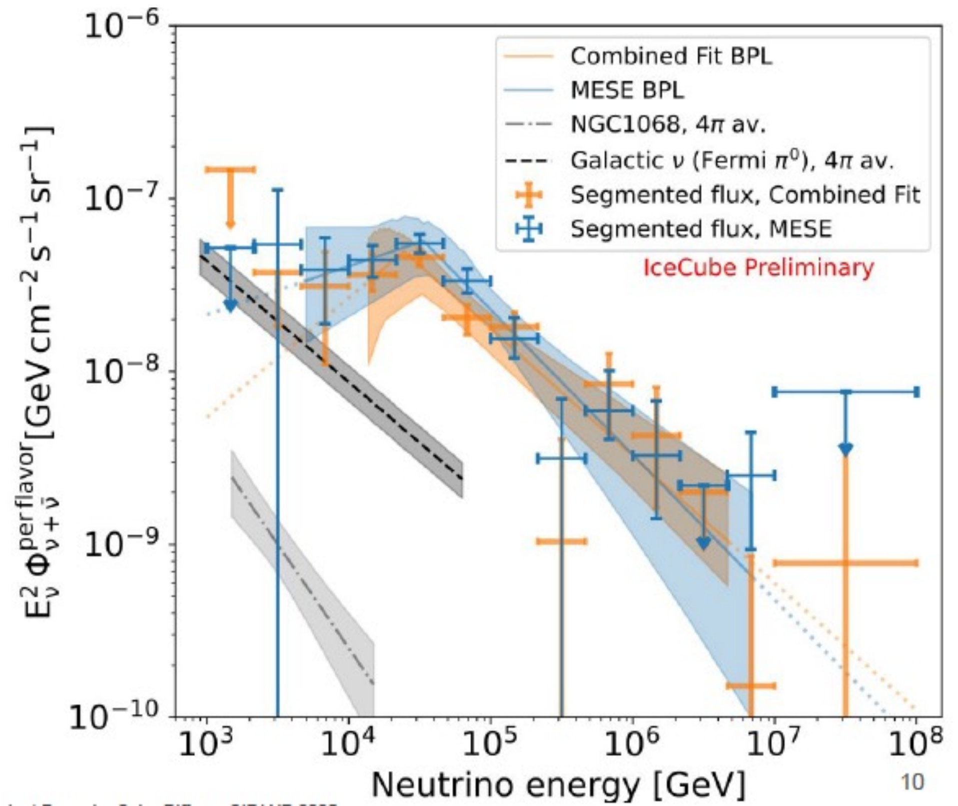
7 candidates found though neutral network (>5σ)

Latest Results on High-Energy Neutrinos

IceCube Collaboration 24 PRD



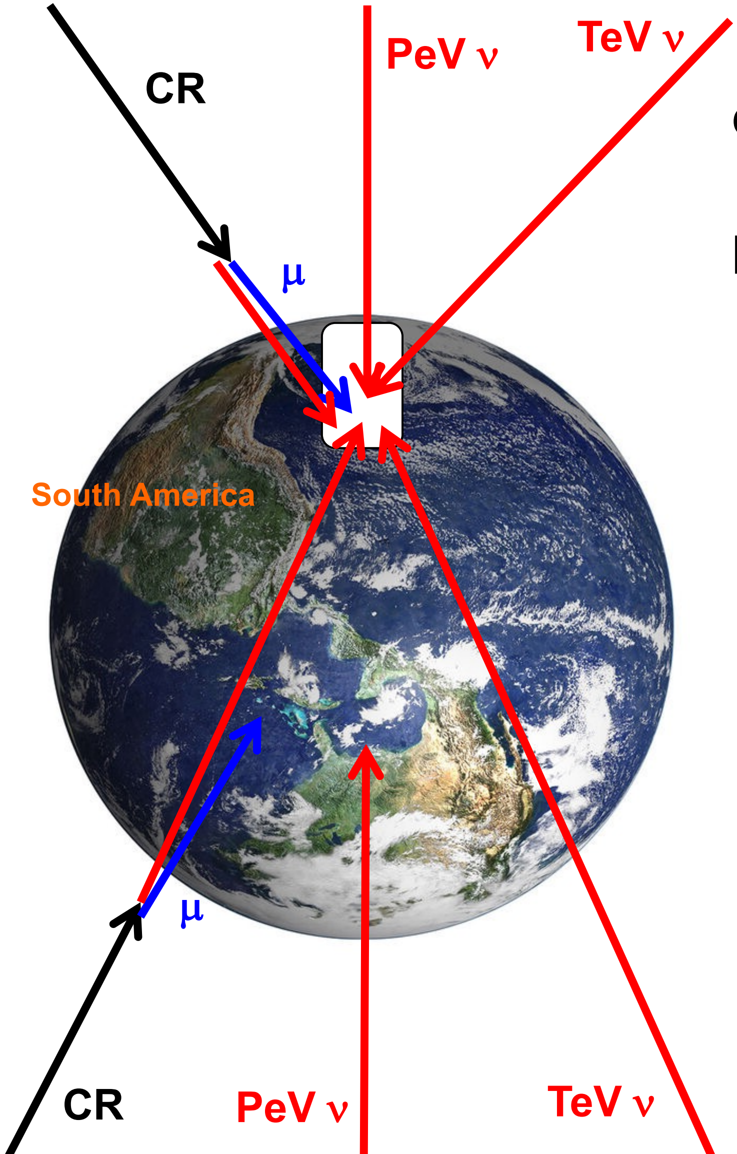
IceCube Collaboration 25



- "ESTES" (10.3 yr)
  (Enhanced Starting Track Event Selection)
- Best-fit: s=2.58+0.10-0.09

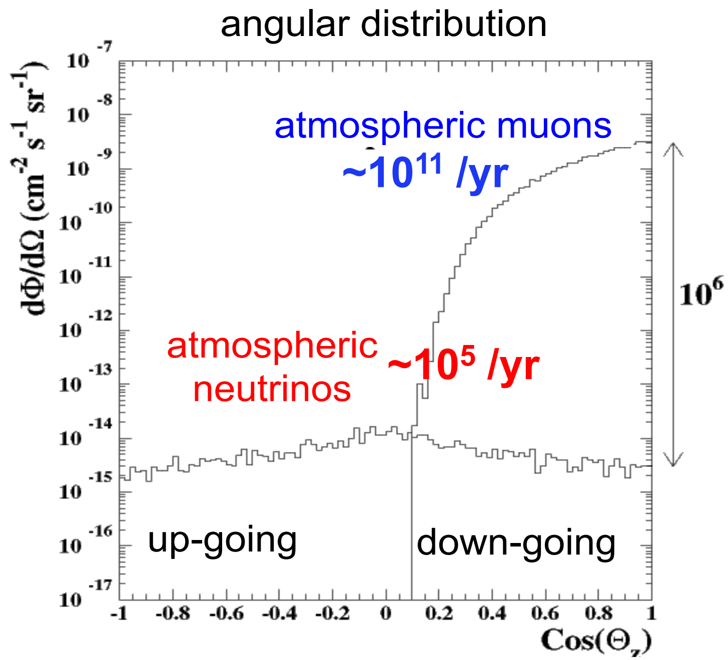
- "MESE" & Combined Fit
  (Medium Energy Starting Events)
- Simple power law excluded w. ~4σ level

Upgoing vs Downgoing



Downgoing events

cons: atm. muons (rapidly decreasing as E)
(can be cut by veto)
pros: avoid attenuation by Earth

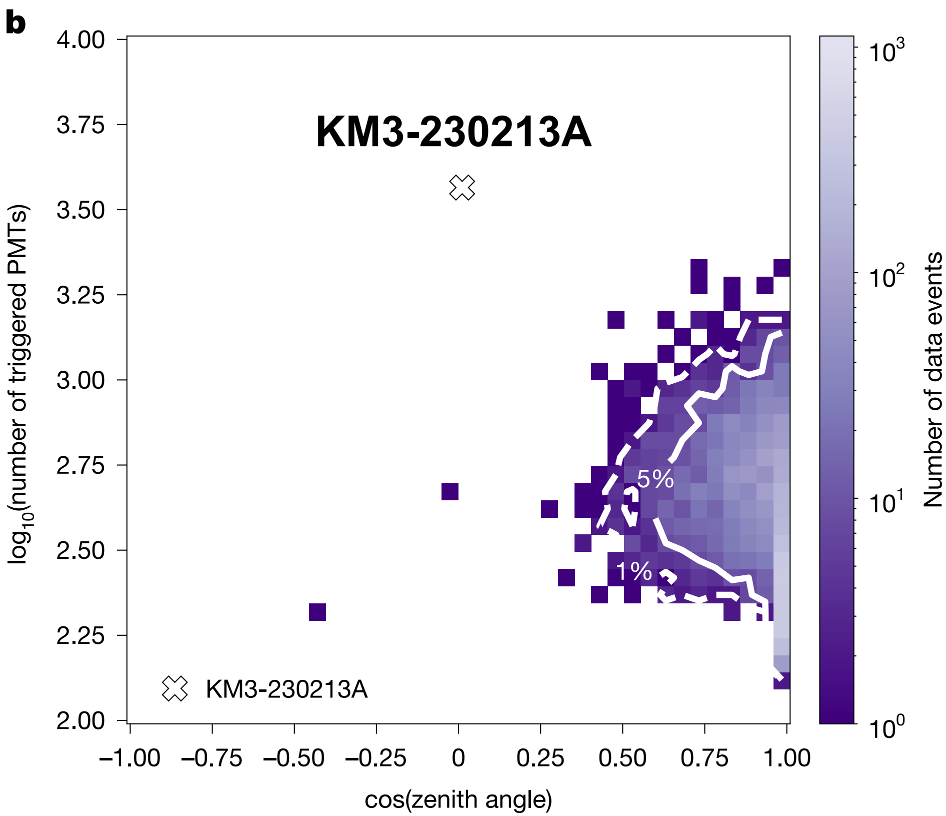


Upgoing events

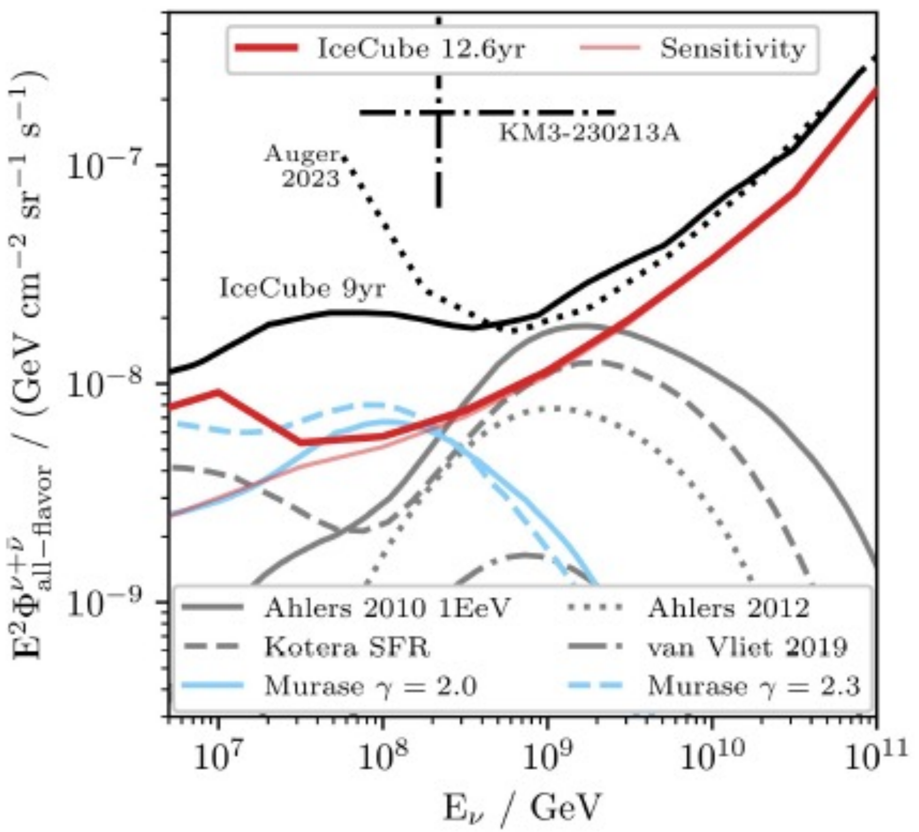
pros: avoid atmospheric "muons"
cons: attenuation by Earth at > 0.1-1 PeV

Ultrahigh-Energy Neutrino Observations

KM3Net Collaboration 25 Nature



IceCube Collaboration 25 PRL



- KM3Net: E_ν=220 PeV from 0.6 deg above the horizon (21 lines & 287.4 d)
- IceCube: no extremely high-energy events in downgoing/horizontal direction
- 2.9σ tension between KM3Net and IceCube measurements

Neutrino Flavors

Neutrino oscillation

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

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

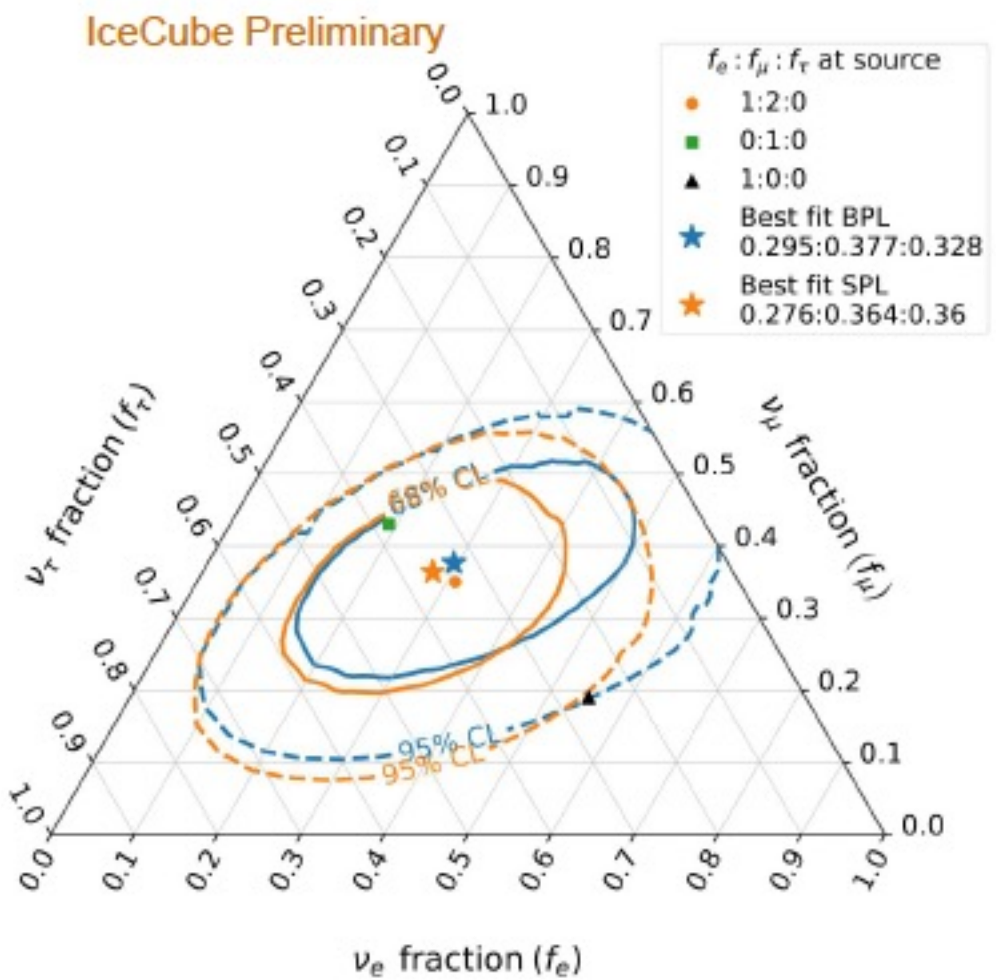
long baseline limit:

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

Modifications
- matter effect
- muon cooling/damp
(Kashti & Waxman 05 PRL)
- ν-ν forward scattering
(Abbar, Carpio & KM 22)
- Beyond Standard Model
(e.g., Bustamante, Beacom & Winter 15 PRL)
Arguelles, Katori & Salvado 15 PRL
Shoemaker & KM 16 PRD)

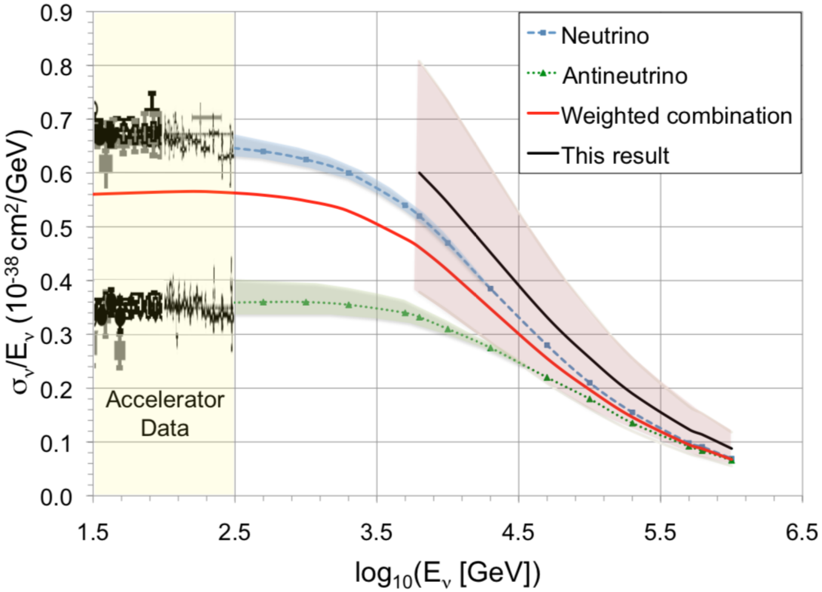
IceCube 25 & CNAPAP

MESE

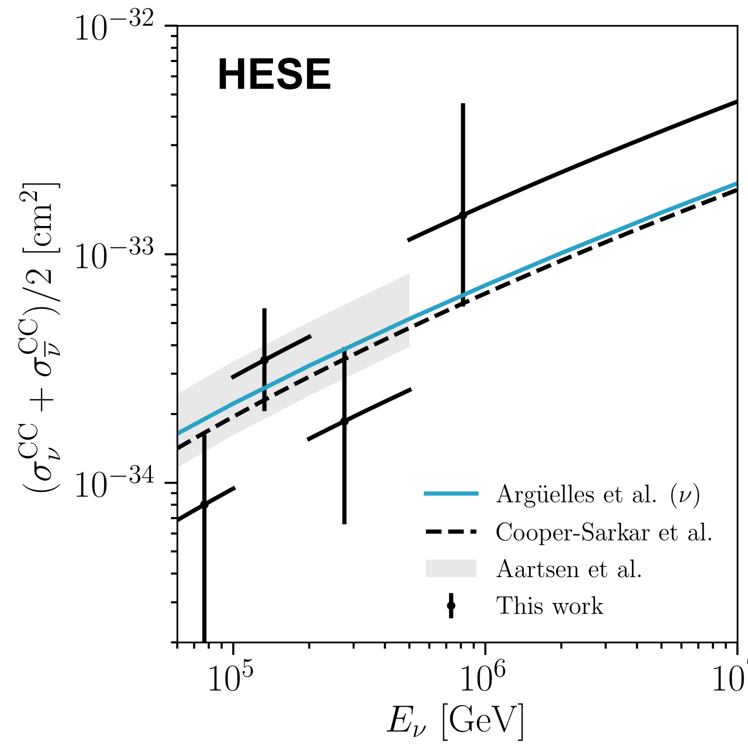


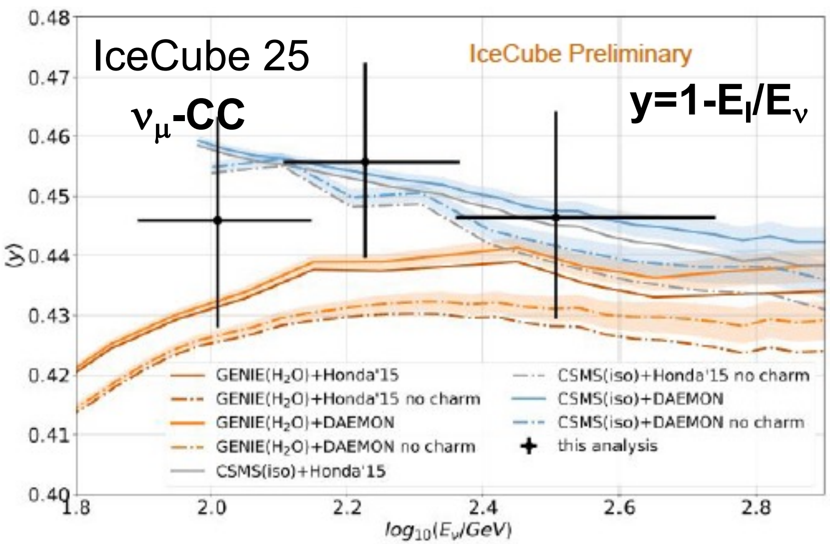
Neutrino Interactions

IceCube Collaboration 17 Nature



IceCube Collaboration 21 PRD

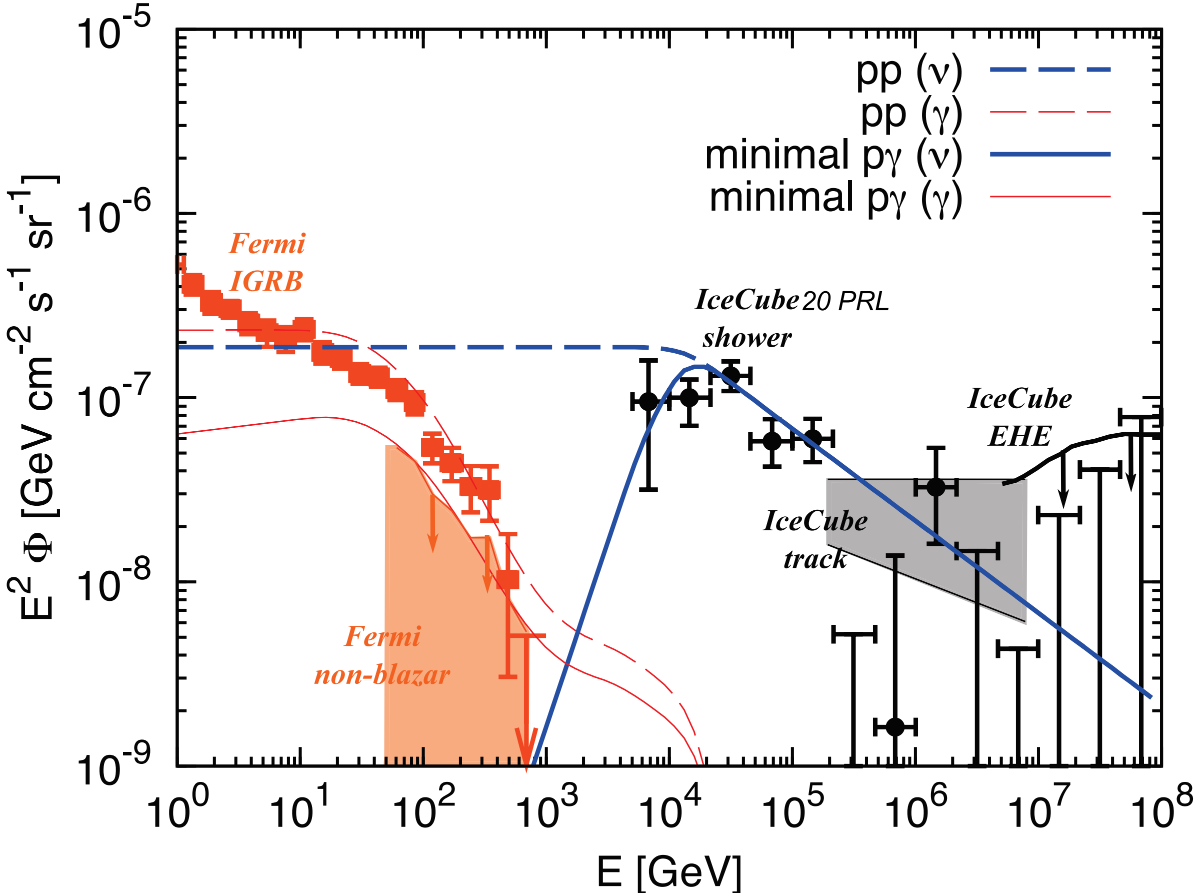




- Consistent w. SM cross section
- Inelasticity measurements from 80-560 GeV (w. DeepCore)
- Can be used for constraining the ratio of antineutrinos to neutrinos

Extragalactic Multimessenger Connection: Current

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



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

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

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

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

KM, Guetta & Ahlers 16 PRL
see also
KM, Ahlers & Lacki 13 PRDR
Capanema, Esmaili & KM 20 PRD
Capanema, Esmaili & Serpico 21 JCAP
Fang, Gallagher & Halzen 22 ApJL

Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent

→ Requiring hidden (i.e., γ-ray opaque) cosmic-ray accelerators

(ν data above 100 TeV can still be explained by γ-ray transparent sources)

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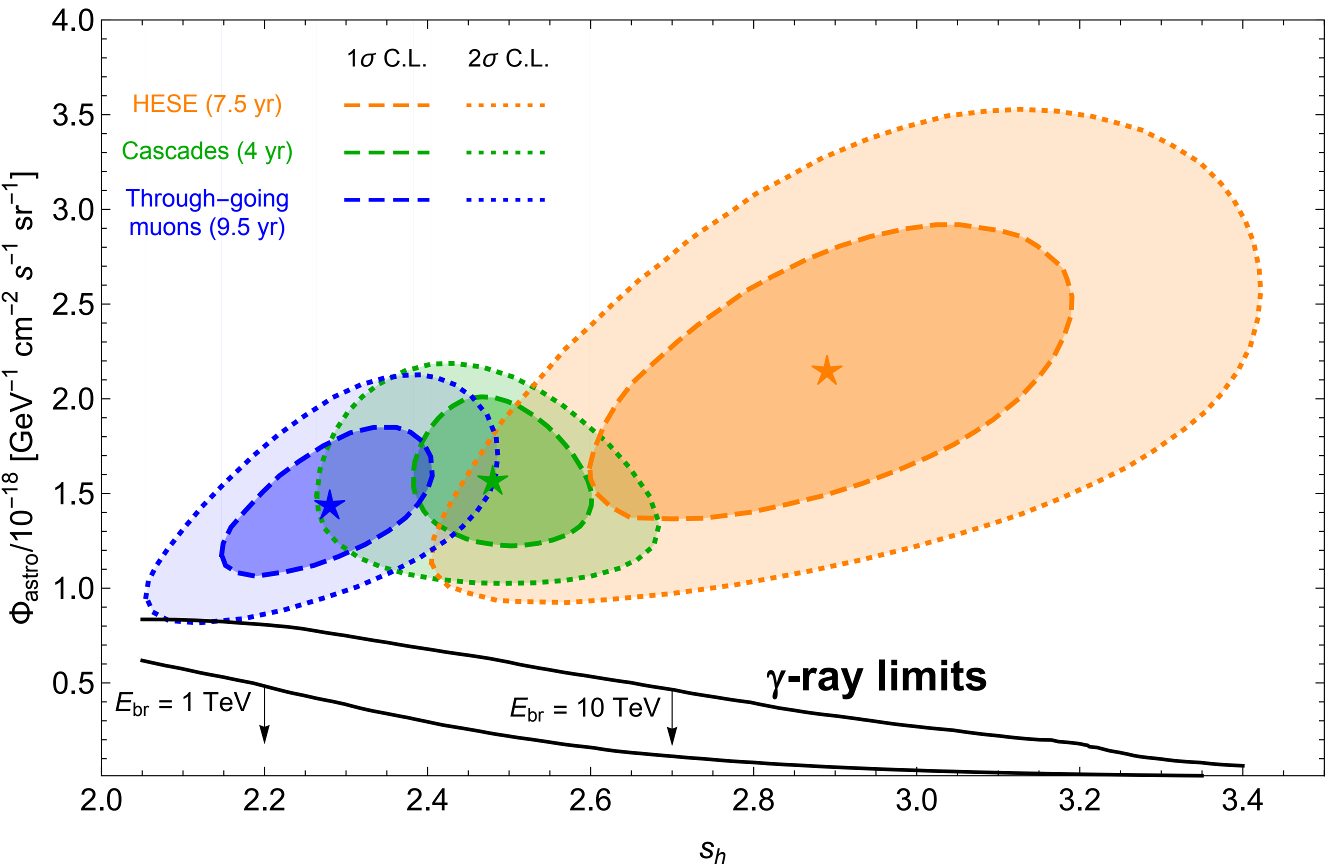

Capanema, Esmaili & KM 20
Capanema, Esmaili & Serpico 21

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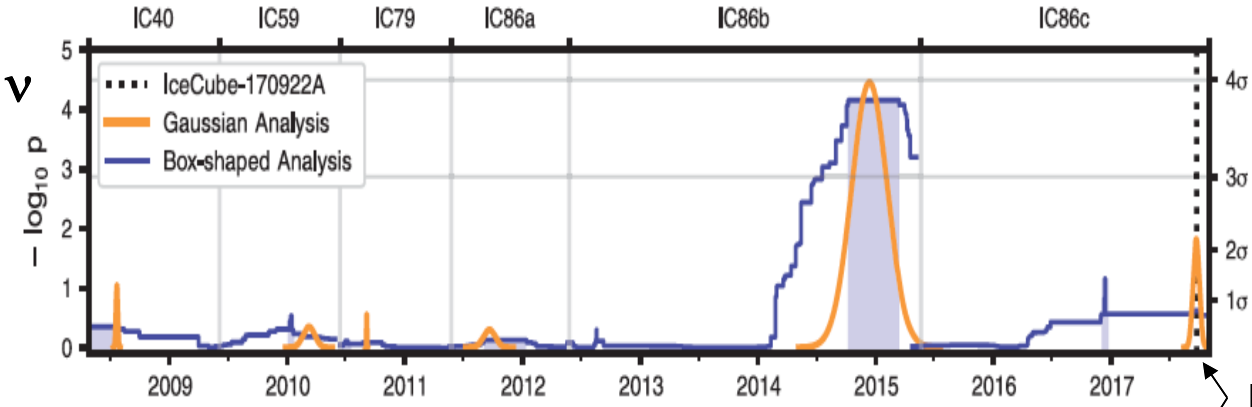
Flares from Supermassive Black Hole Jets?

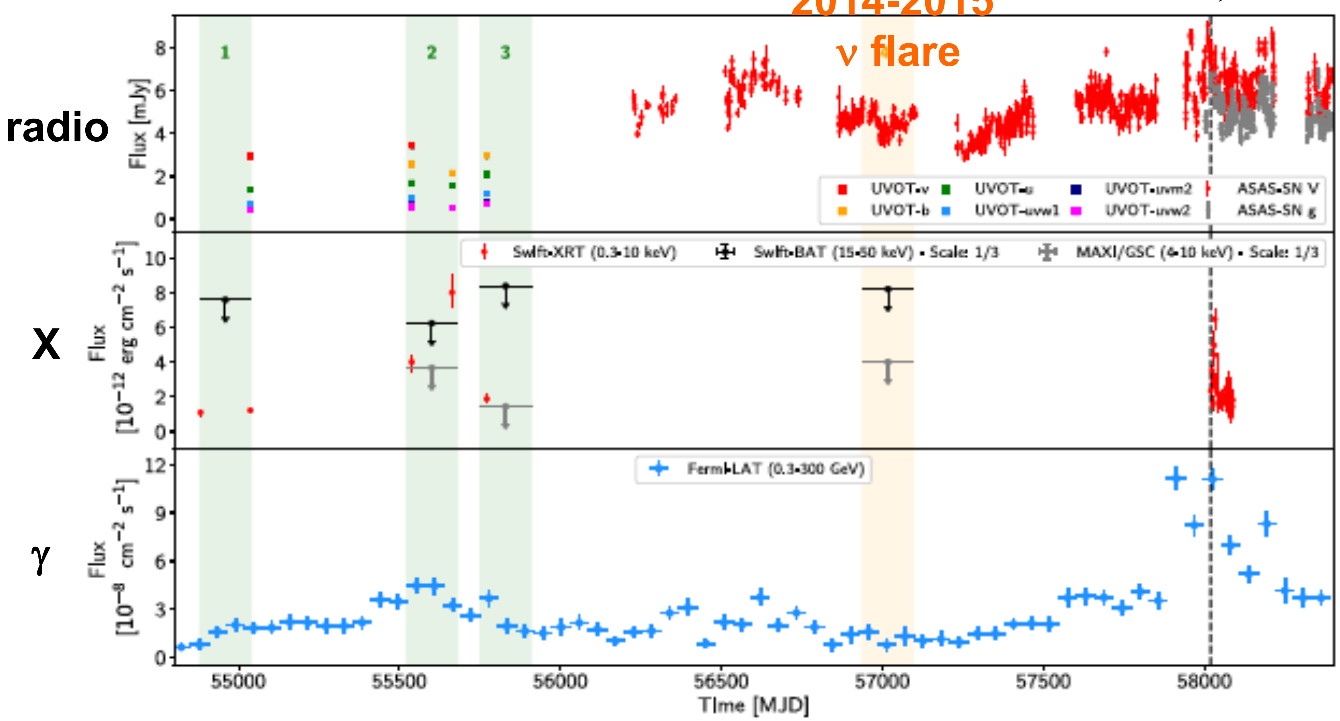
IceCube 2018 Science

~13 events (~3.5σ): 2014-2015 neutrino orphan flare



TXS 0506+056
"jetted AGN"

IceCube-170922A (E_ν~0.2-1 PeV)



2017 multimessenger flare

- IceCube EHE alert pipeline
- Automatic alert (via AMON/GCN)
- γ/X/UV/opt/radio counterparts
- **~3σ coincidence**

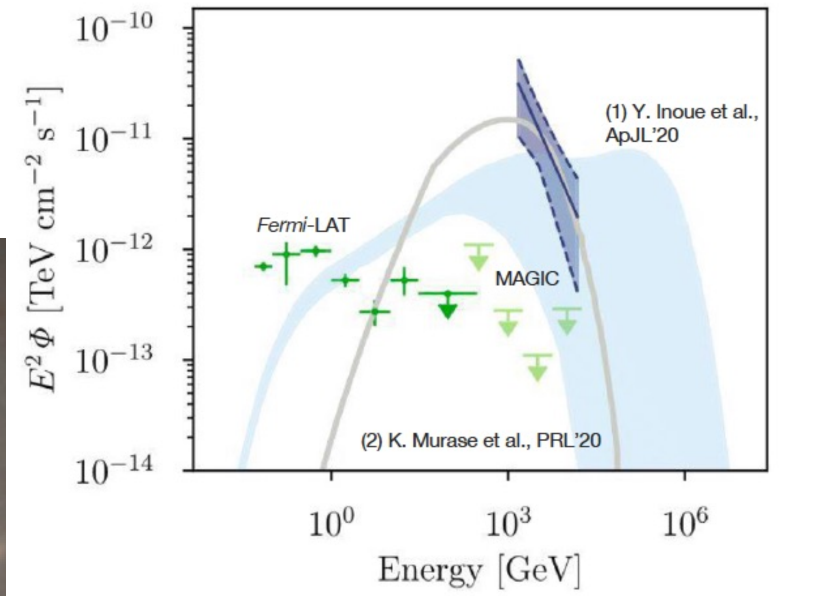
Petropoulou, KM+ 20 ApJ

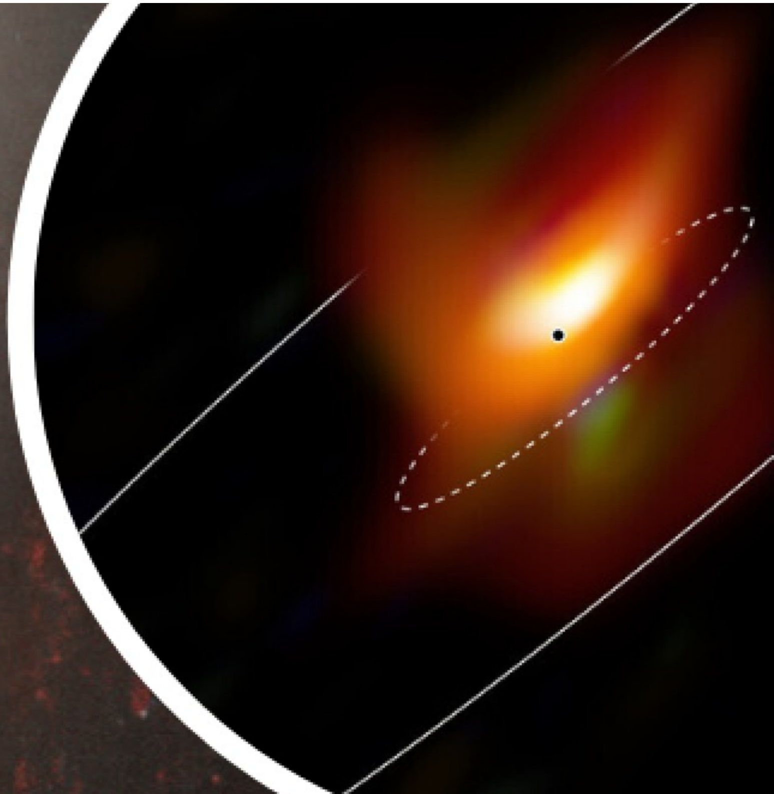
NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

Science
JOURNALS AAAS

IceCube Collaboration*†





ASTRONOMY

Neutrinos unveil hidden galactic activities

By Kohta Murase[1,2,3]

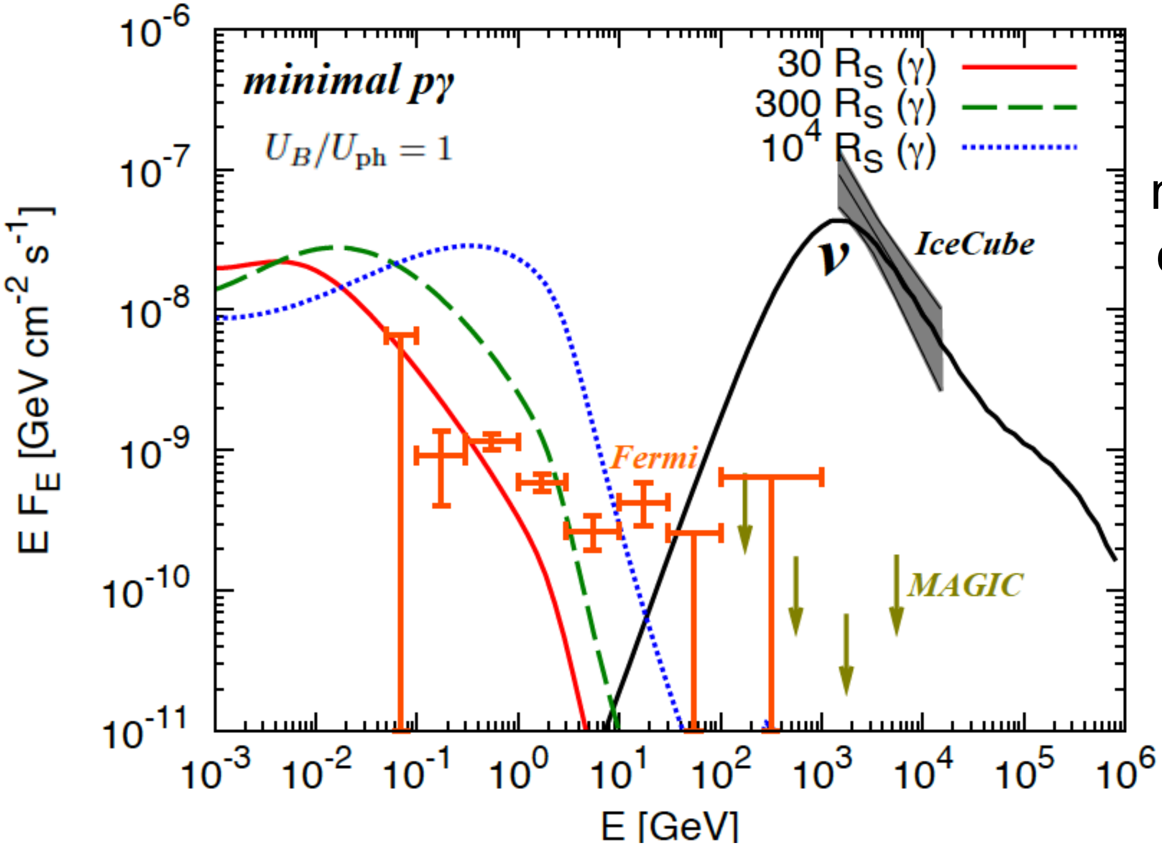
An obscured supermassive black hole may be producing high-energy cosmic neutrinos

Where Do Neutrinos Come from?

$\gamma + \gamma \rightarrow e^+ + e^-$

for 0.1-300 GeV γ rays

$$\tau_{\gamma\gamma} \sim \left(\frac{1}{4\pi}\right)\left(\frac{\sigma_{\gamma\gamma}}{R}\right)\left(\frac{L_X}{m_e c^3}\right)\left(\frac{\varepsilon_\gamma}{m_e c^2}\right) \gtrsim 10$$



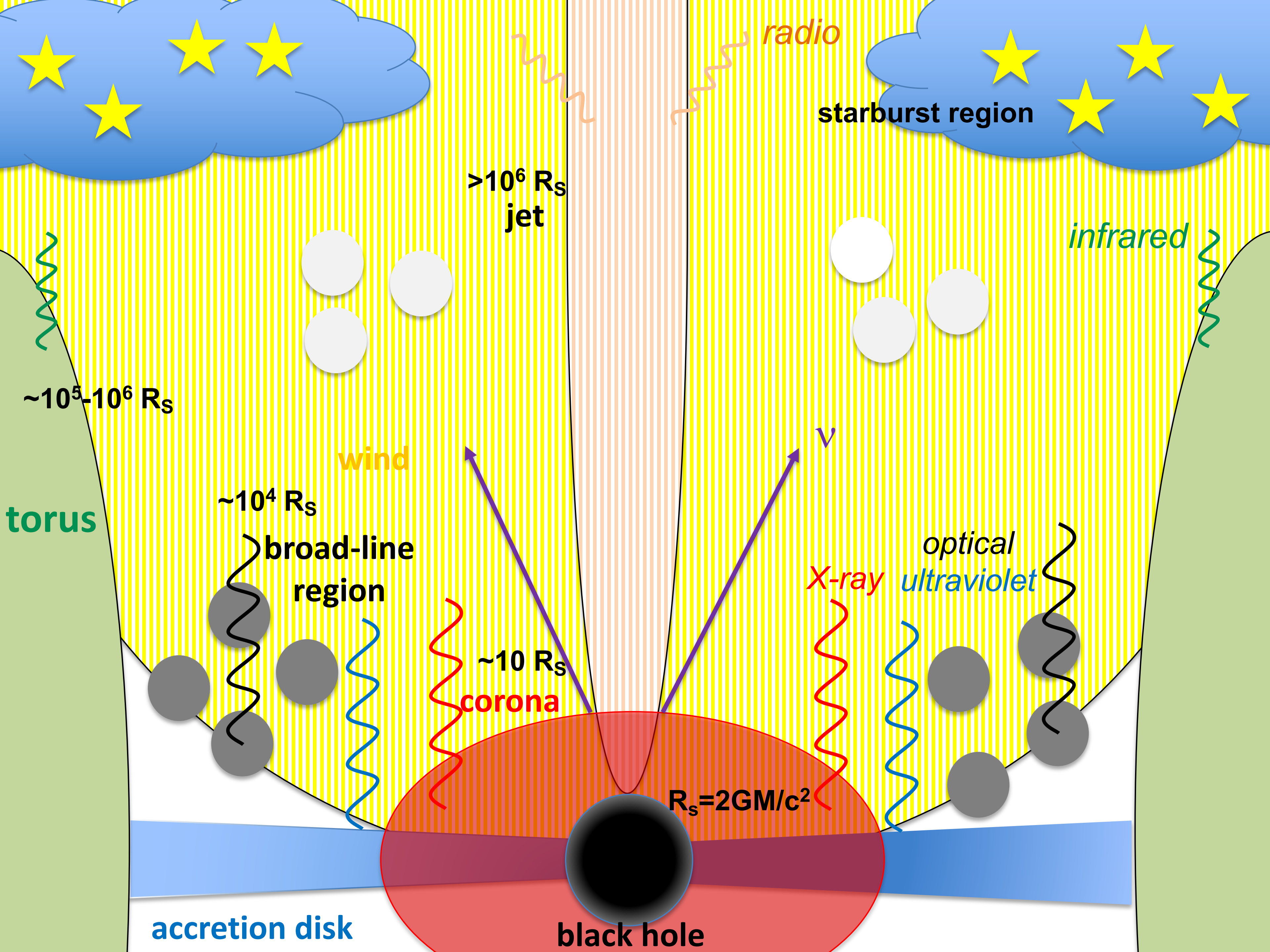
model-independent constraint considering elemag. cascade

$R < (15\text{-}30)\ R_S$

KM 22 ApJL

compatible w. pγ calorimetry ($f_{p\gamma}$>1) condition: **$R < 30\text{-}100\ R_S$**

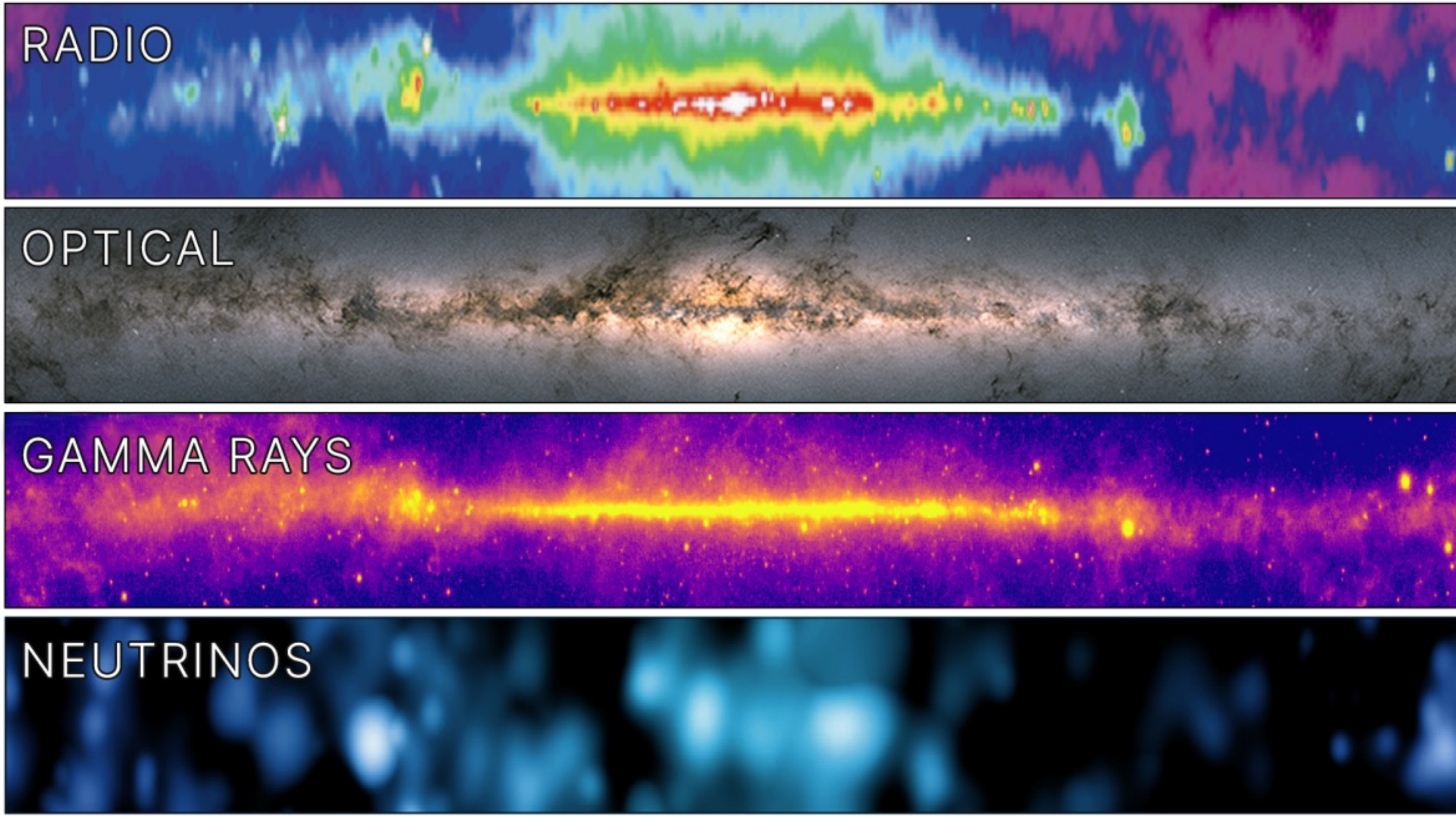
Black hole: sub-PeV proton accelerator & ideal beam dump



radio
starburst region
>10⁶ Rs
jet
infrared
~10⁵-10⁶ Rs
wind
ν
~10⁴ Rs
torus
broad-line
region
optical
X-ray
ultraviolet
~10 Rs
corona
Rs=2GM/c²
accretion disk
black hole

Multimessenger View of the Milky Way

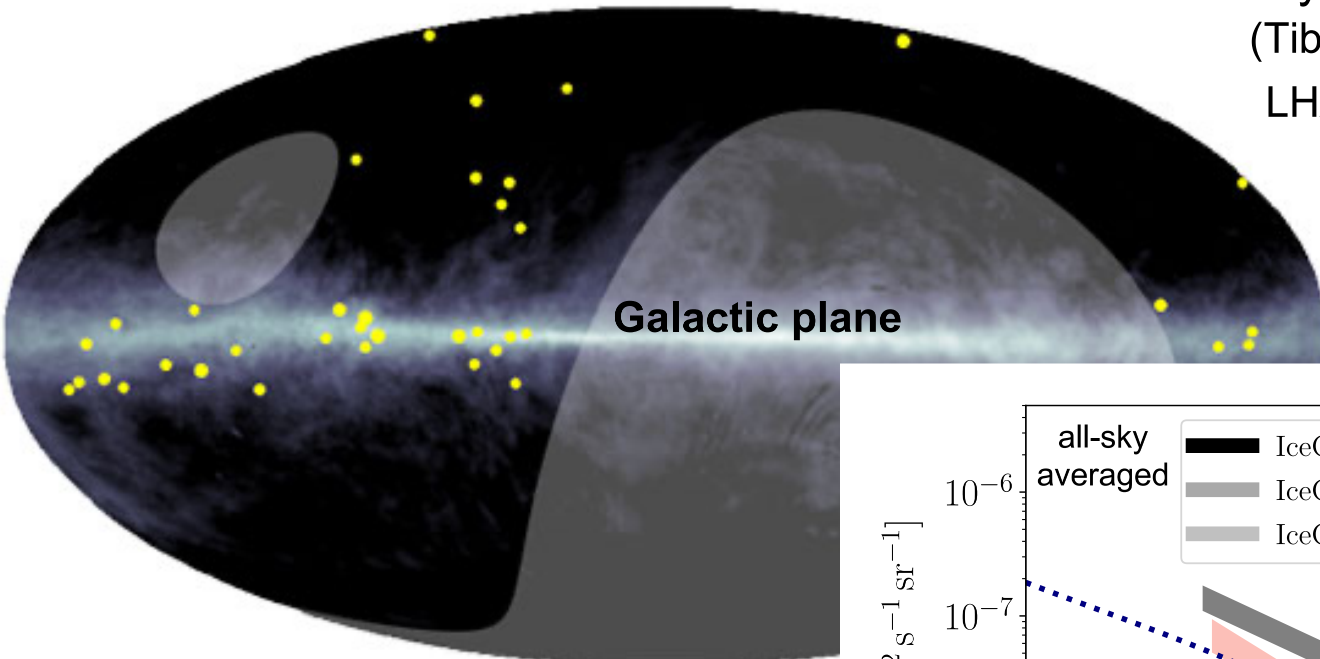
IceCube 23 Science

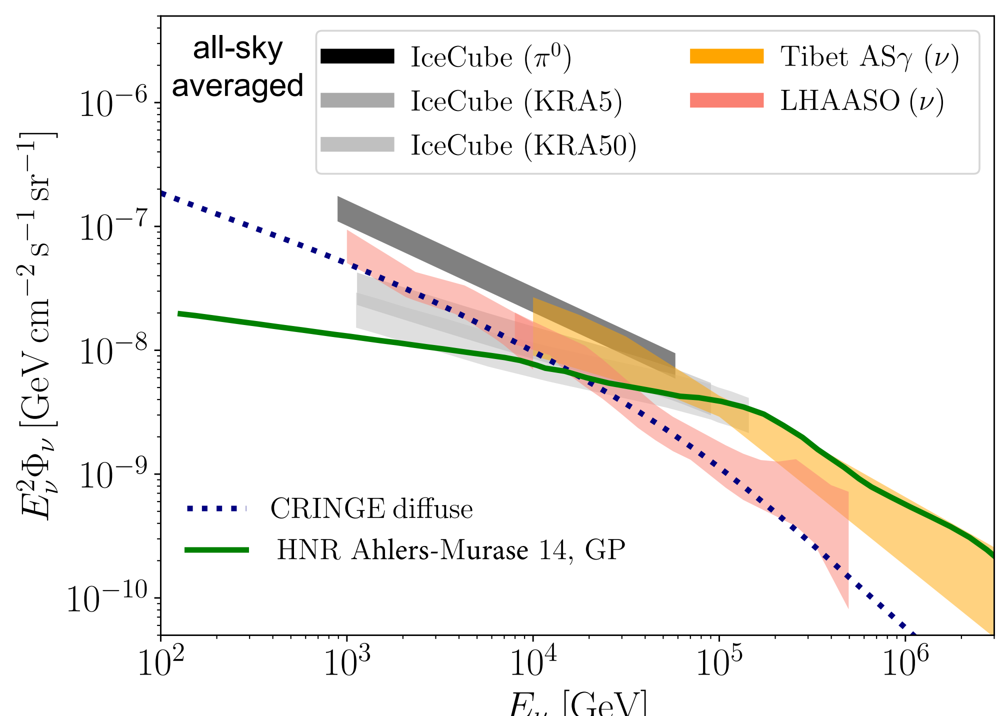


Neutrino emission from the Milky Way (~10% of total) has been observed w. 4.5σ

Galactic Multimessenger Connection

Discovery of sub-PeV γ rays in 2021
(Tibet ASγ Collaboration 21 PRL
LHAASO Collaboration 23 PRL)





Fang & KM 21 ApJ, 23 ApJL

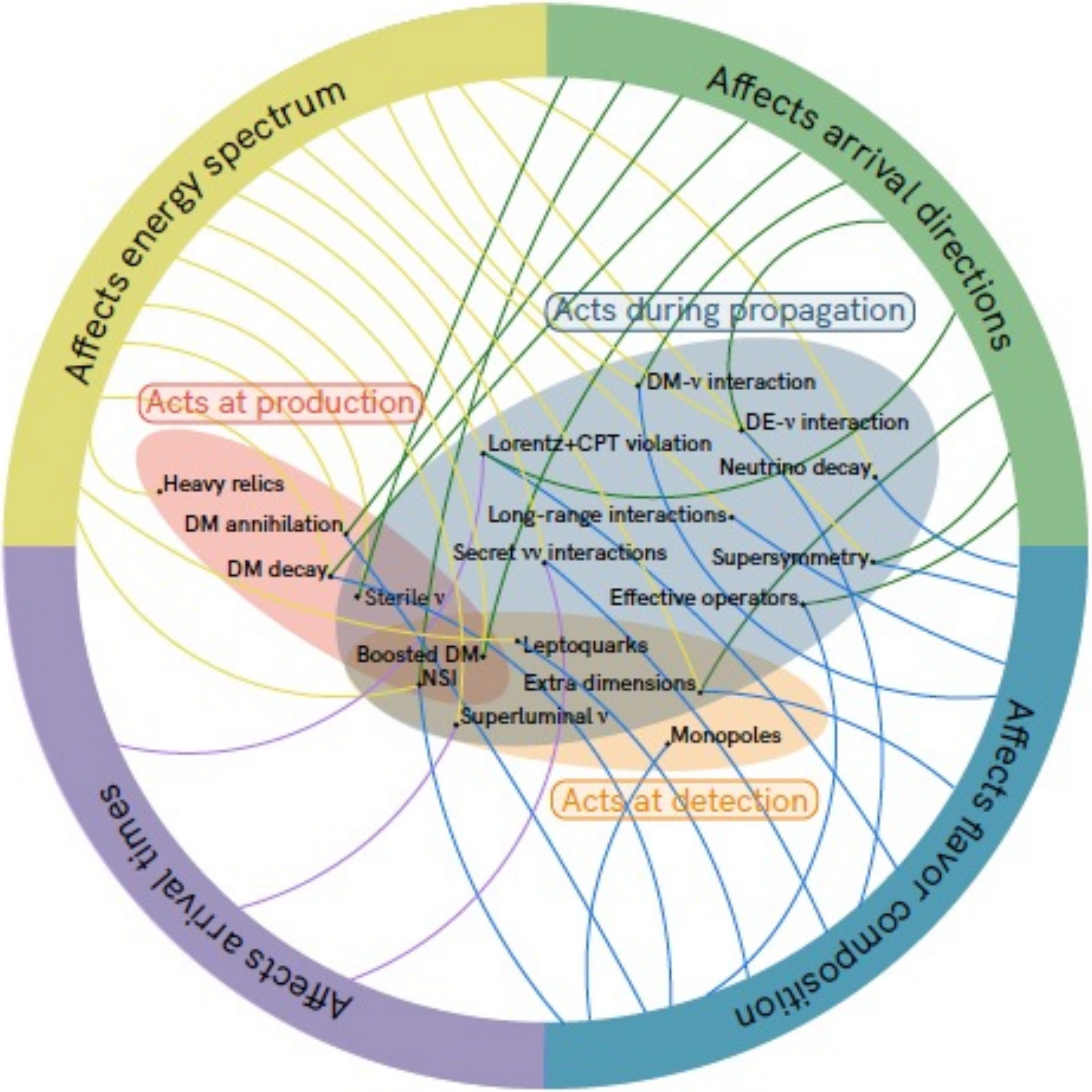
- **Supporting hadronic (pp) origin**
- **Truly diffuse emission**

vs

Unresolved (extended) sources

→ SWGO, KM3Net, Gen2 etc.
relevance of templates

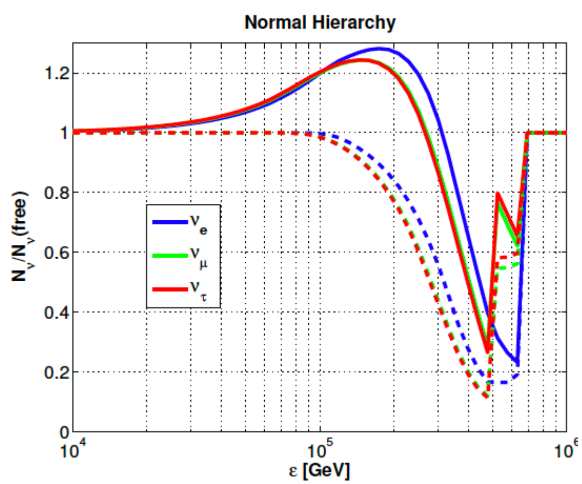
High-Energy Cosmic Neutrino as Probes of BSM Physics



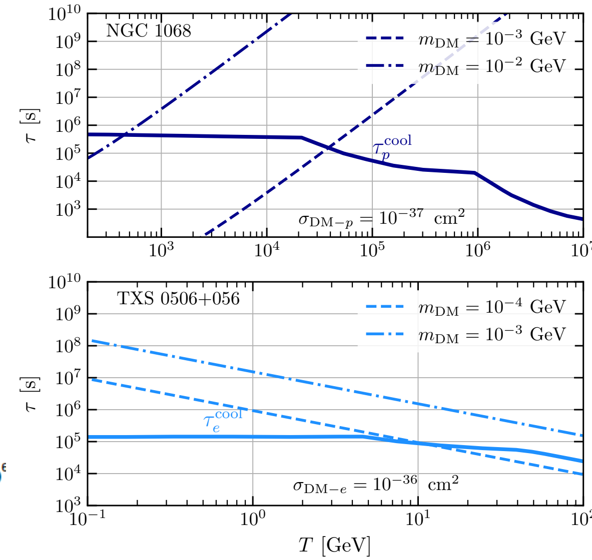
BSM Imprints on Spectra/Flavors

nonstandard interactions

Blum, Hook & KM 14

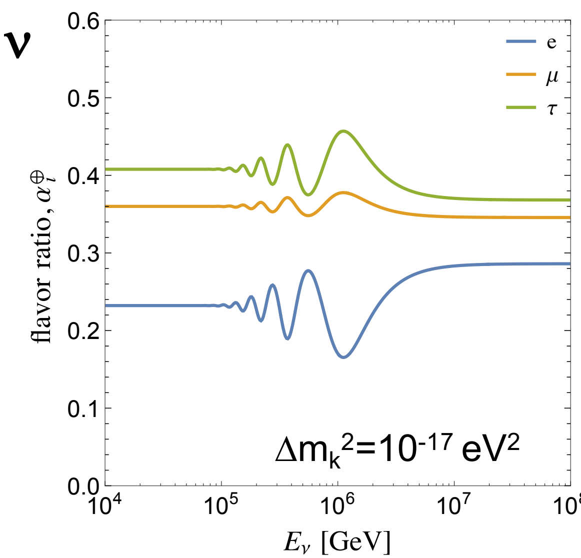


Herrera & KM 24



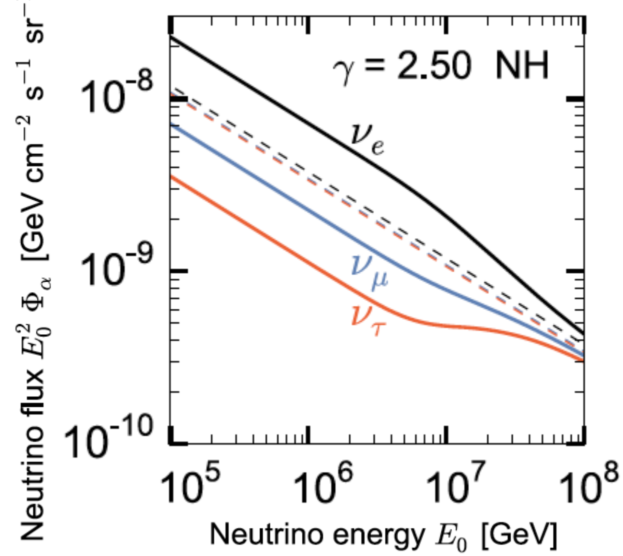
pseudo-Dirac ν

Shoemaker & KM 16



ν decay

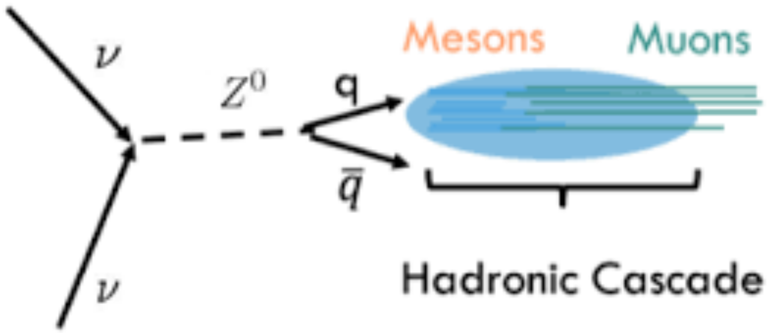
Bustamante, Beacom & KM 17

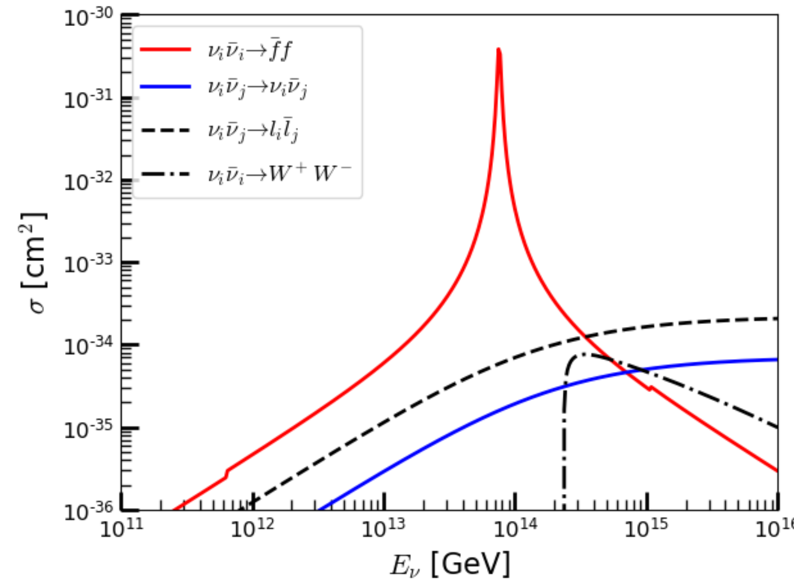


Standard Model Resonances

Z burst (Weiler 82 PRL)

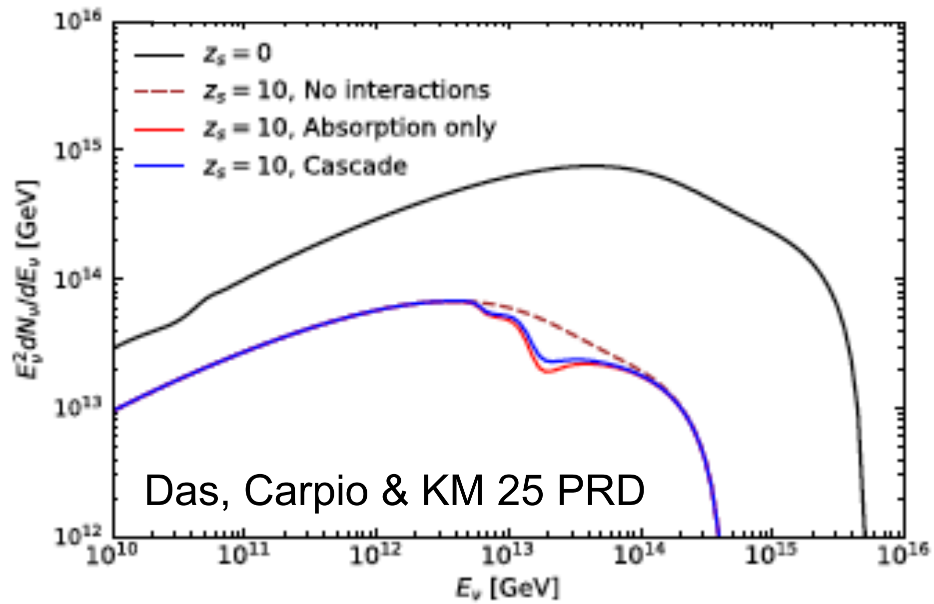
$$\varepsilon_{\rm res} = \frac{m_Z^2}{2m_\nu} = 8.3 \times 10^{13}\ {\rm GeV} \left(\frac{m_Z}{91\ {\rm GeV}}\right)^2 \left(\frac{m_\nu}{0.05\ {\rm eV}}\right)^{-1}$$





- Not realistic to expect in astrophysical scenarios
- BSM scenarios required (ex. superheavy DM)
- Neutrino cascades

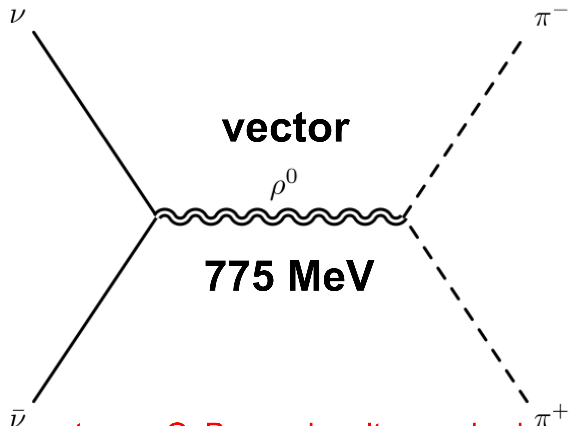
  (Yoshida 94 APh)



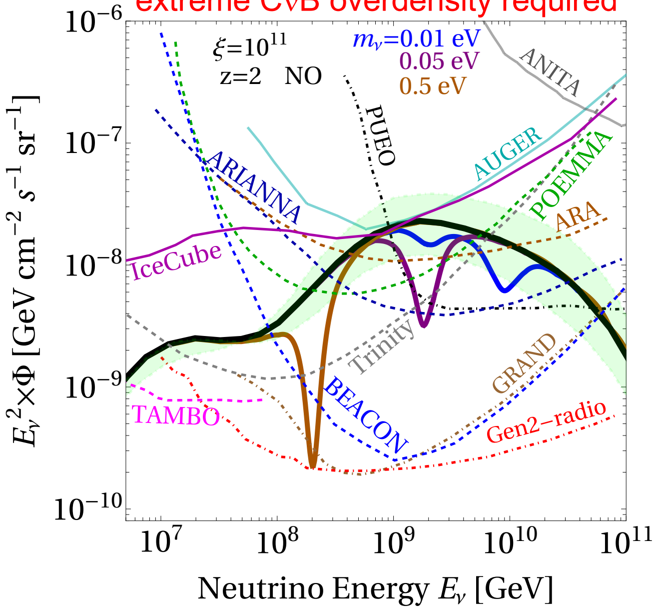
Other Possible Resonances

vector meson resonance

(Paschos and Lalakulich 02)

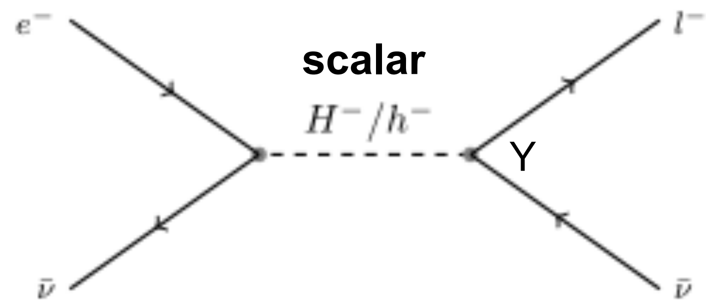


extreme CνB overdensity required

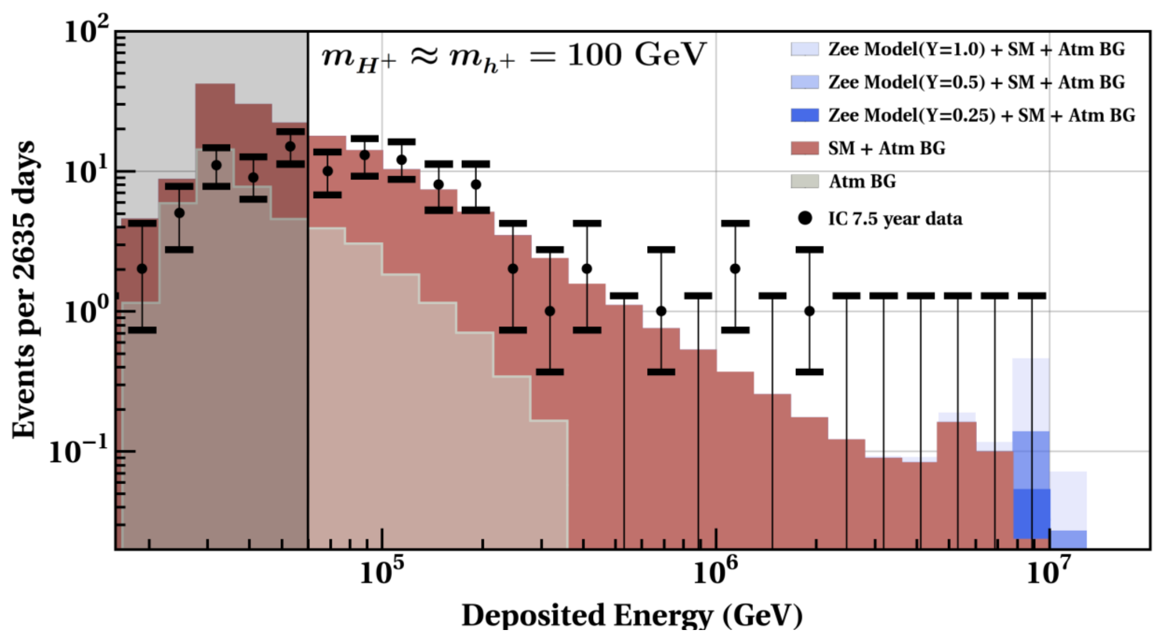


Brdar+ 22 PLB

Zee burst (Babu+ 20 PRL)



motivated by the Zee model (Zee 80 PLB)

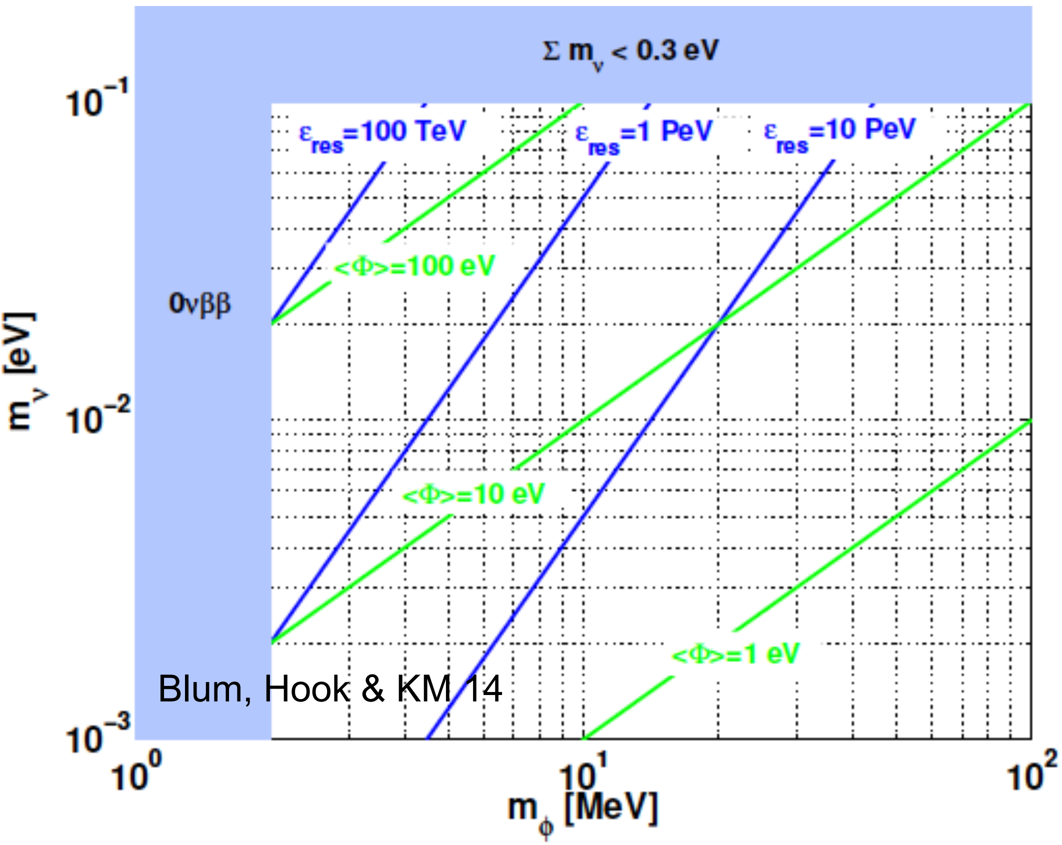


Secret Neutrino Interactions

Bardin, Bilenky & Pontecorvo 70

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

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



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

ex1. Majorana ν self-interactions via a scalar

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

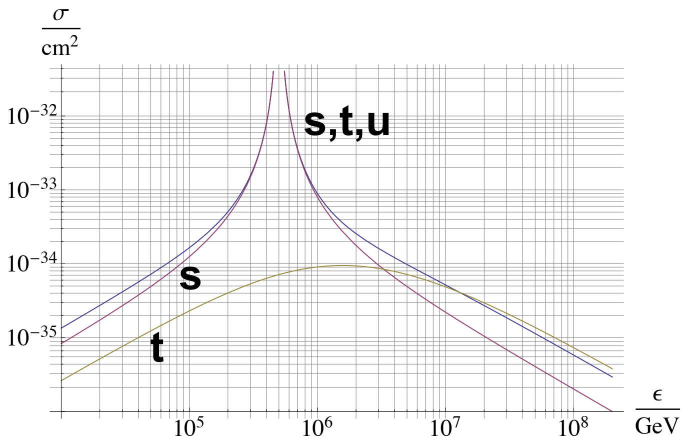
SSB
lepton # violation

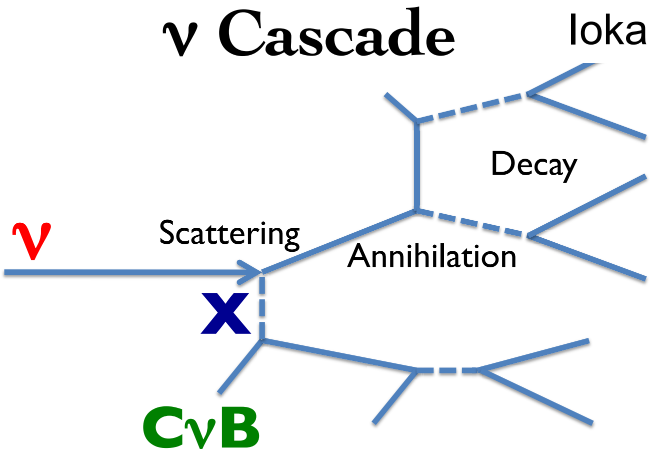
$$m_{\nu_i} = \frac{g_i\mu v^2}{\Lambda^2}$$

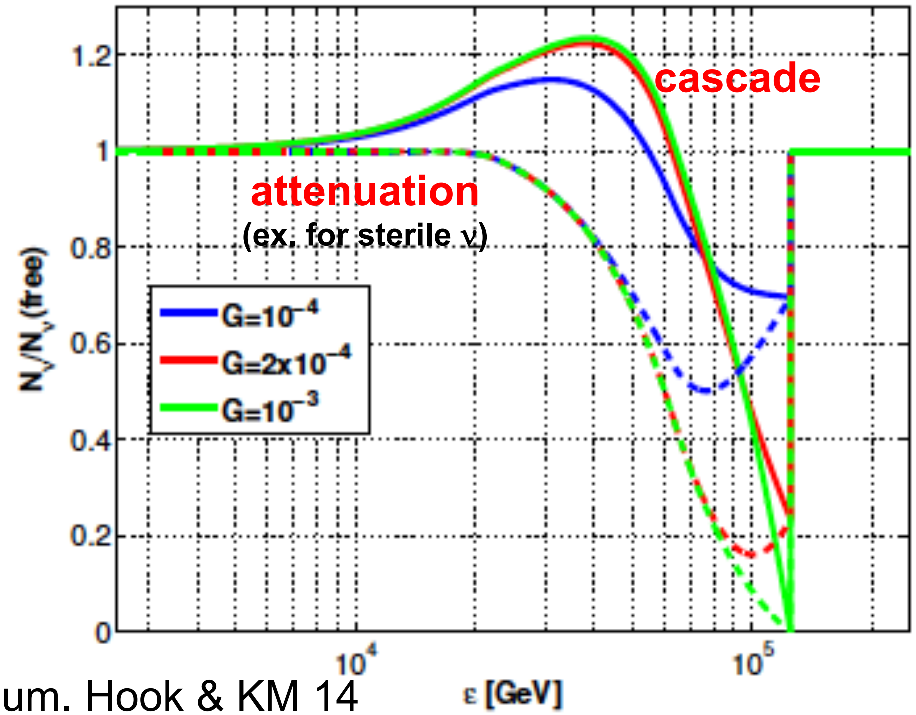
$$\mathcal{L} = -\frac{g}{\Lambda^2}\Phi(HL)^2 + cc$$

ex2. L_μ-L_τ gauged
ex3. interaction w. "sterile" neutrinos
- m_ν is replaced with m_s
- limits are weaker due to $\sin\theta_s$

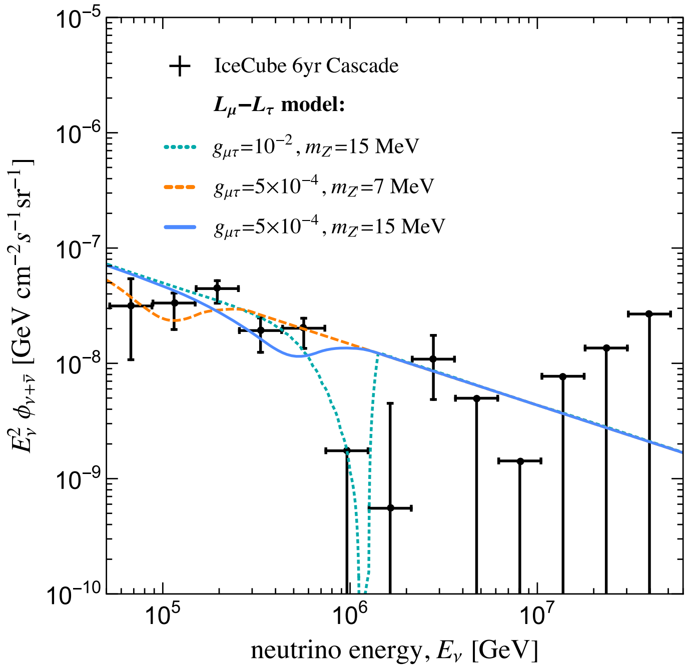
Effects on Cosmic Neutrino Spectra





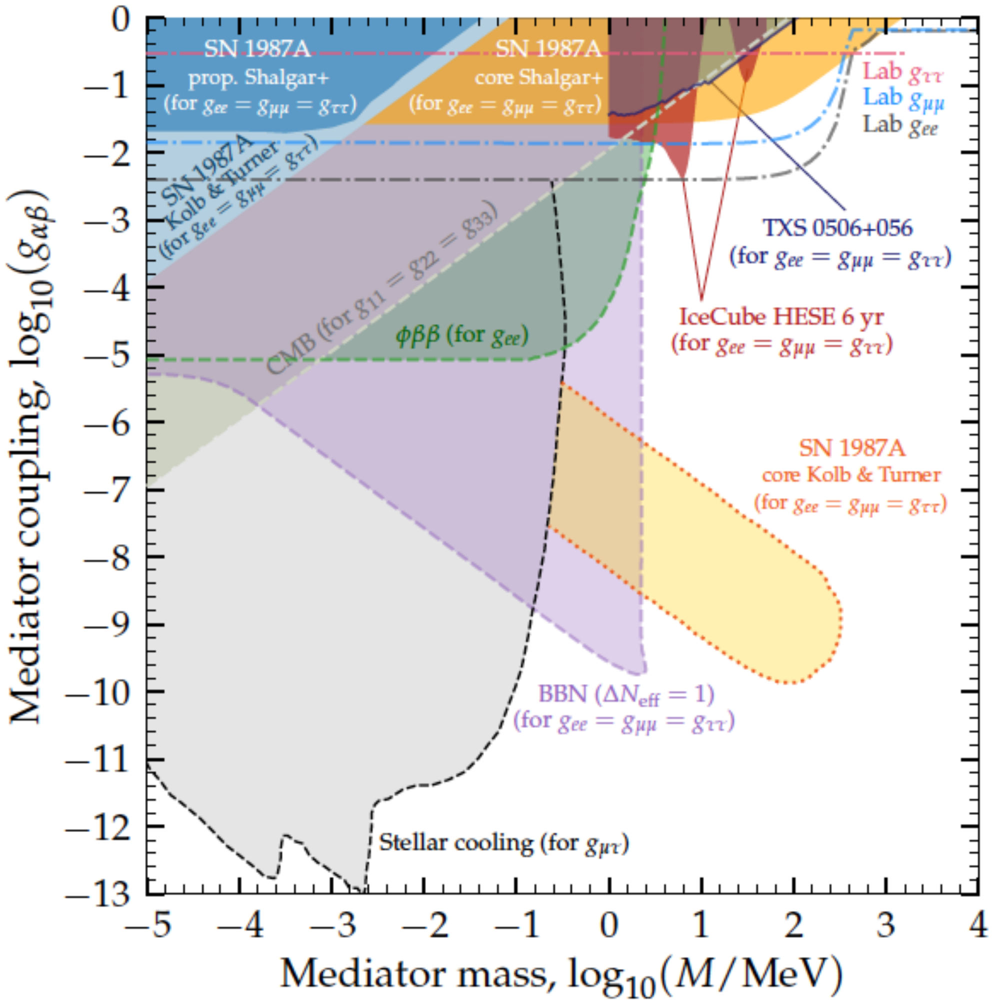


Blum. Hook & KM 14



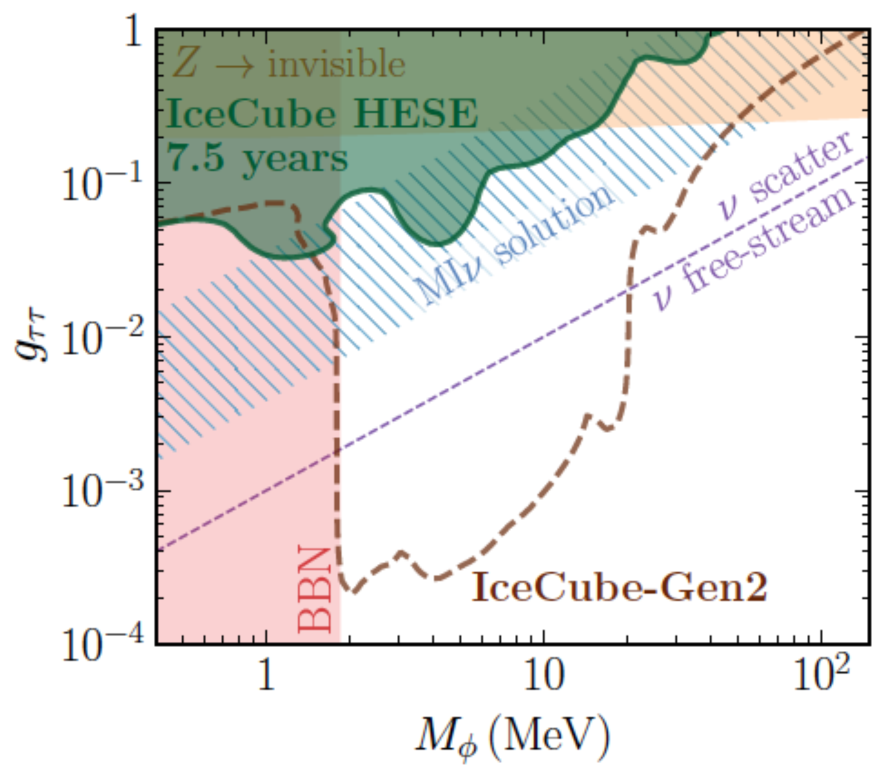
Carpio, KM, Shoemaker & Tabrizi 23 PRD

Scalar Mediator Case



from 2203.01955
see also Shoemaker & KM 16 PRD for Gen2

↓ only ν_τ coupling



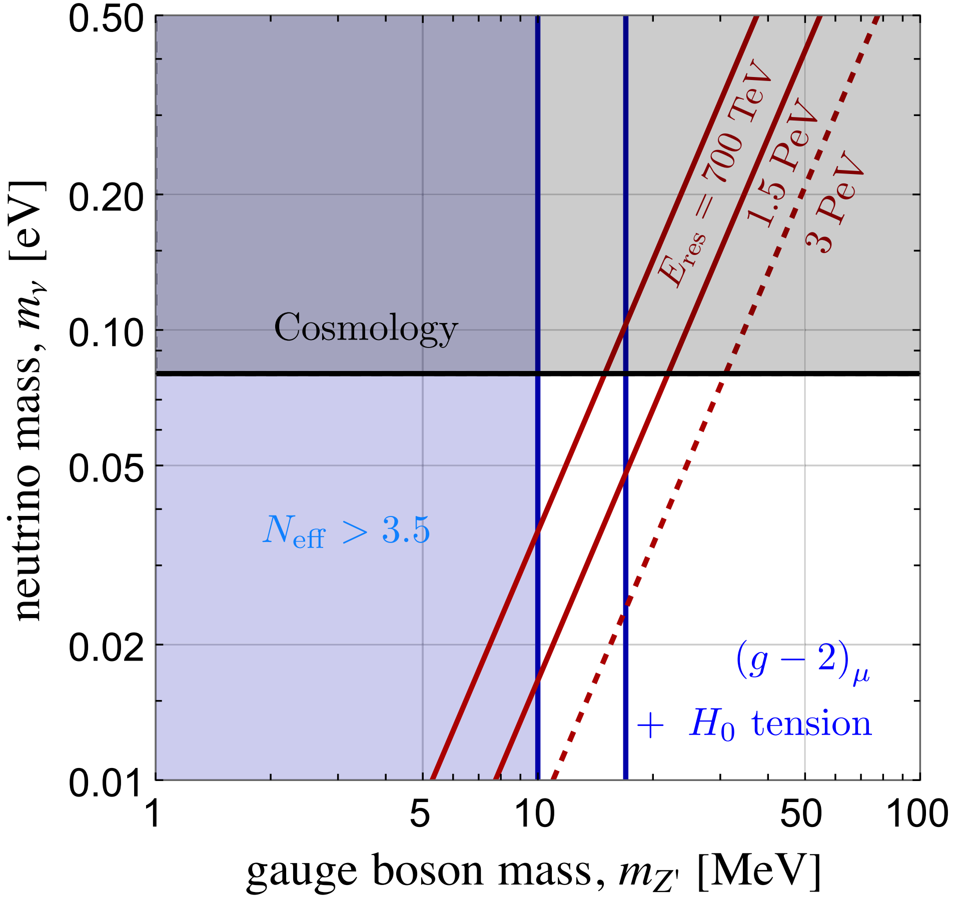
synergy w. Muon Collider (Adhikary+ 25 PRD)

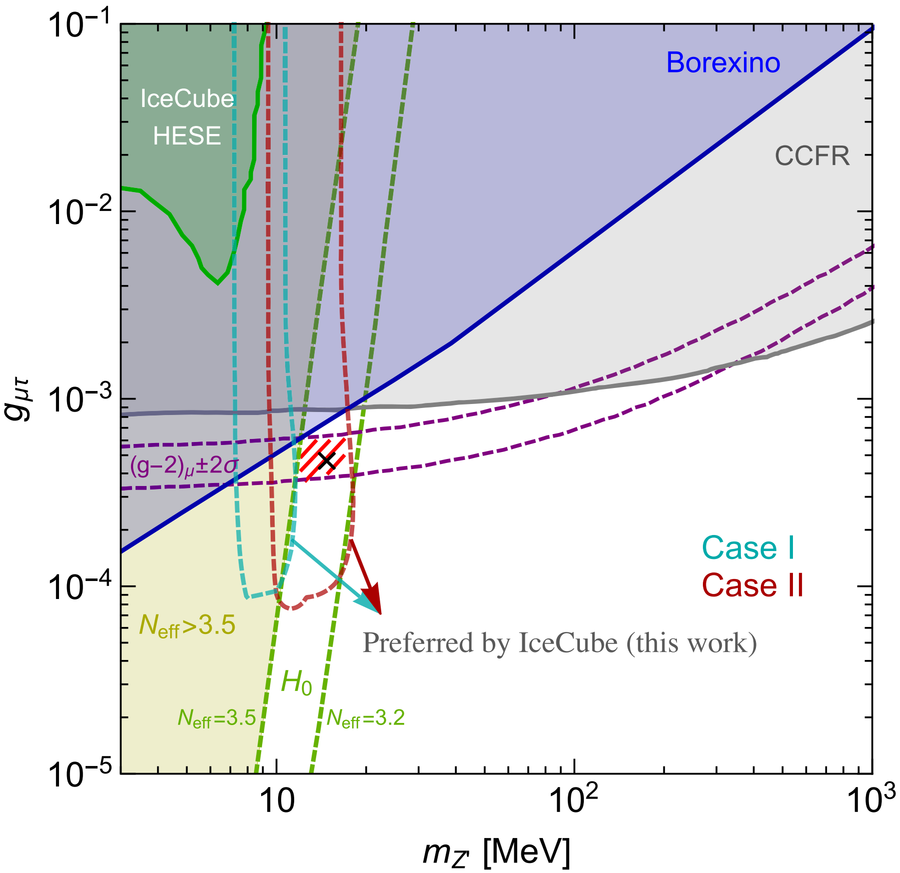
Diffuse neutrino observations could give the best constraints but the limits depend on spectra that may not be power law

Vector Mediator Case

Example of a Z' model – gauged L_μ-L_τ (ex. Araki+14)

$$\mathscr{L} \supset g_{\mu\tau} j^{\alpha}_{\mu-\tau} Z'_{\alpha} - \frac{m^2_{Z'}}{2} Z'_{\alpha} Z'^{\alpha}$$

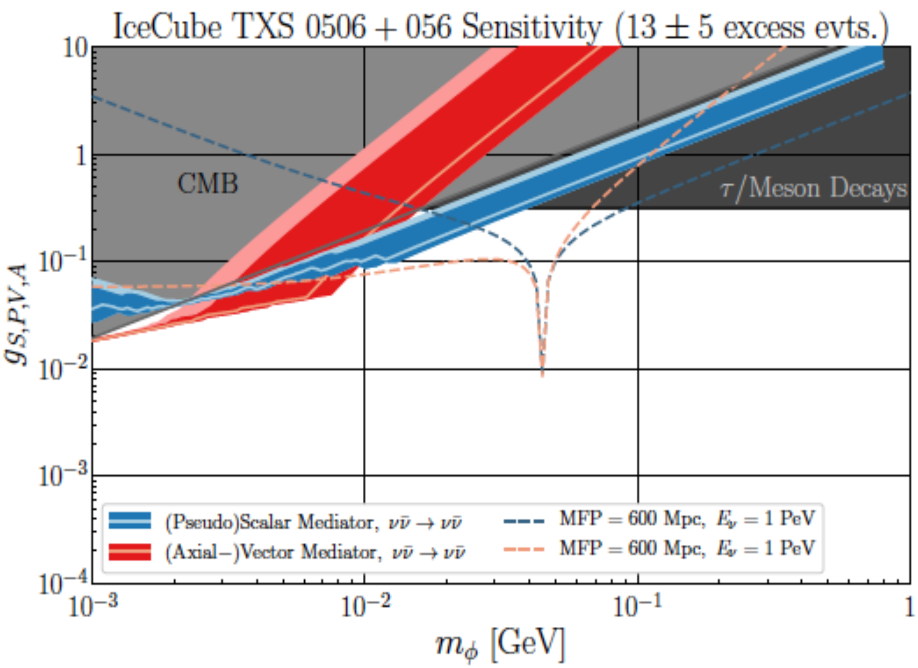




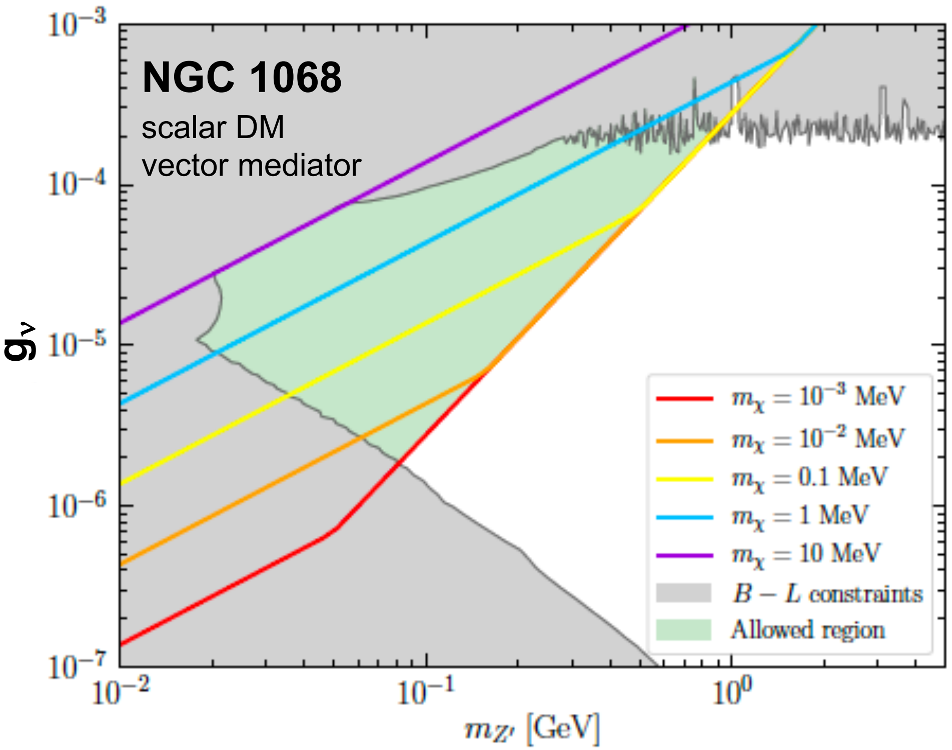
Carpio, KM, Shoemaker & Tabrizi 23 PRD

Probing ν-ν/ν-DM Interactions

Kelly & Machado 18 JCAP



Cline & Puel 23 JCAP

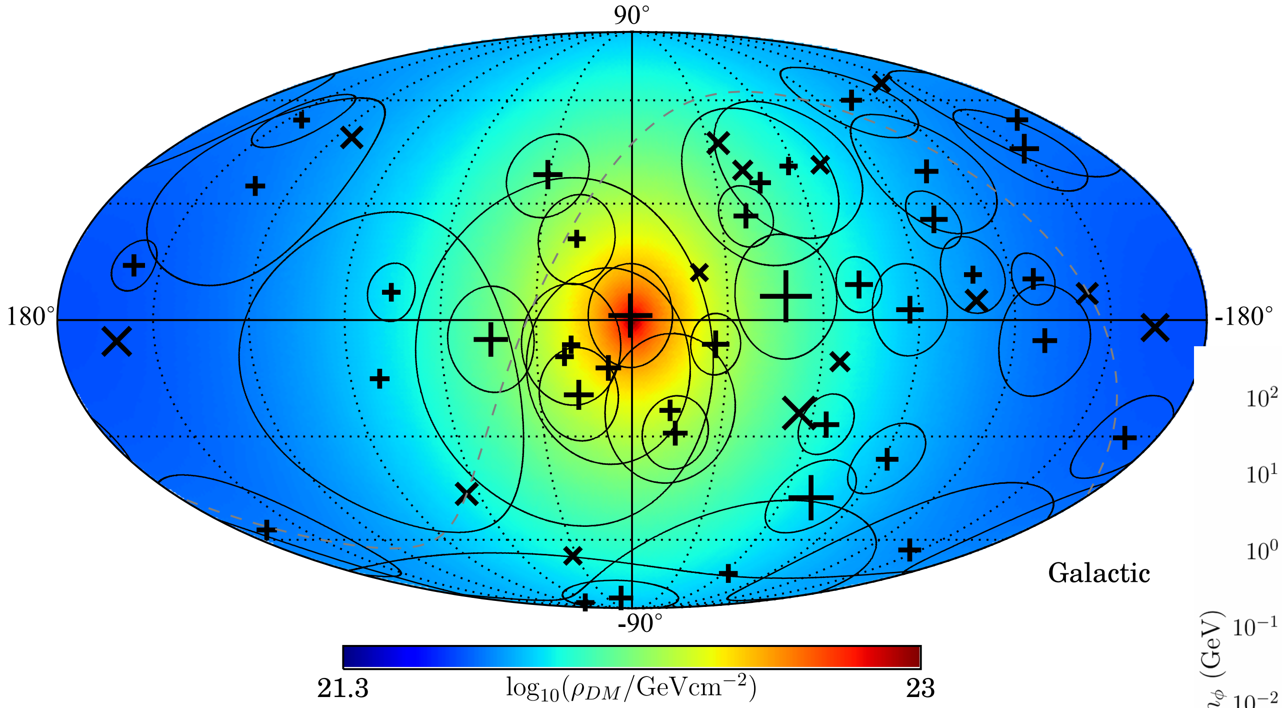


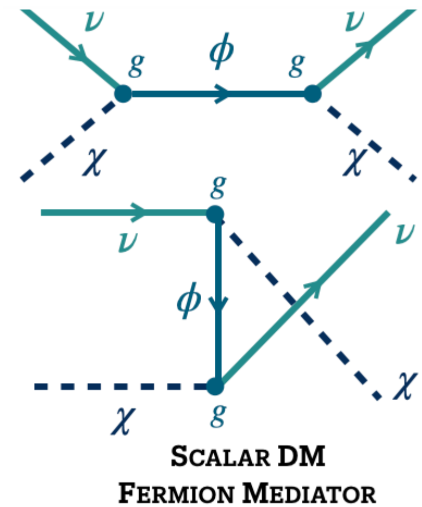
#essentially relying on τ~nσD <~ 1

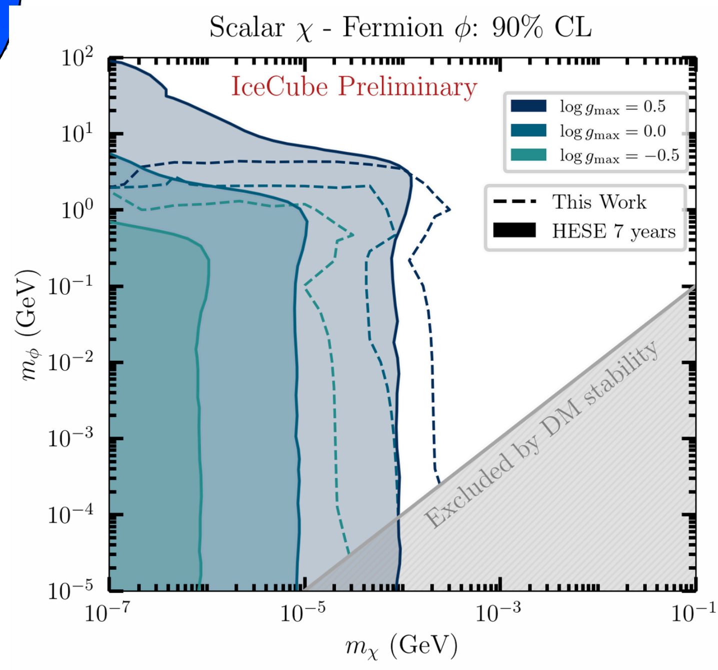
subject to large uncertainty (e.g., unknown astrophysical spectrum)

Distortion by BSM Scattering

ν-DM scatterings induce deflection (attenuation)
-> limits complementary to laboratory constraints
(neutrino telescopes can provide the best constraints)



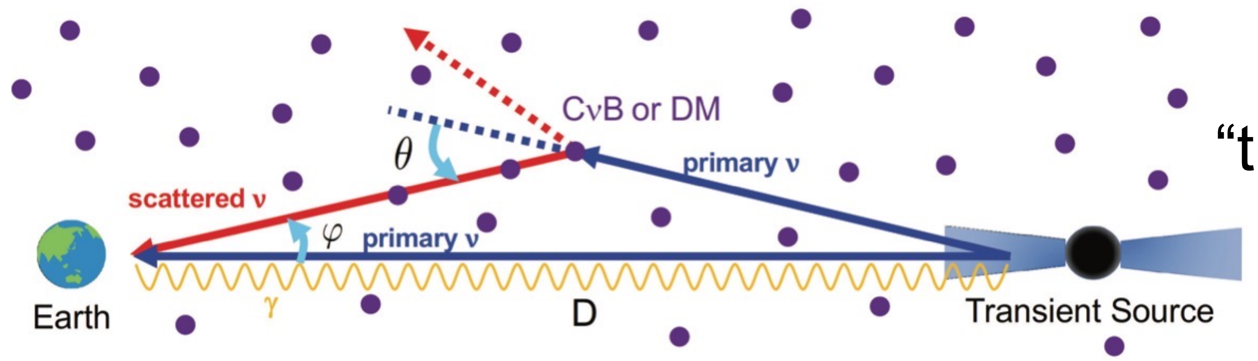




Arguelles et al. 17 PRL
IceCube Collaboration 23

BSM & Time-Domain Multi-Messenger Astrophysics

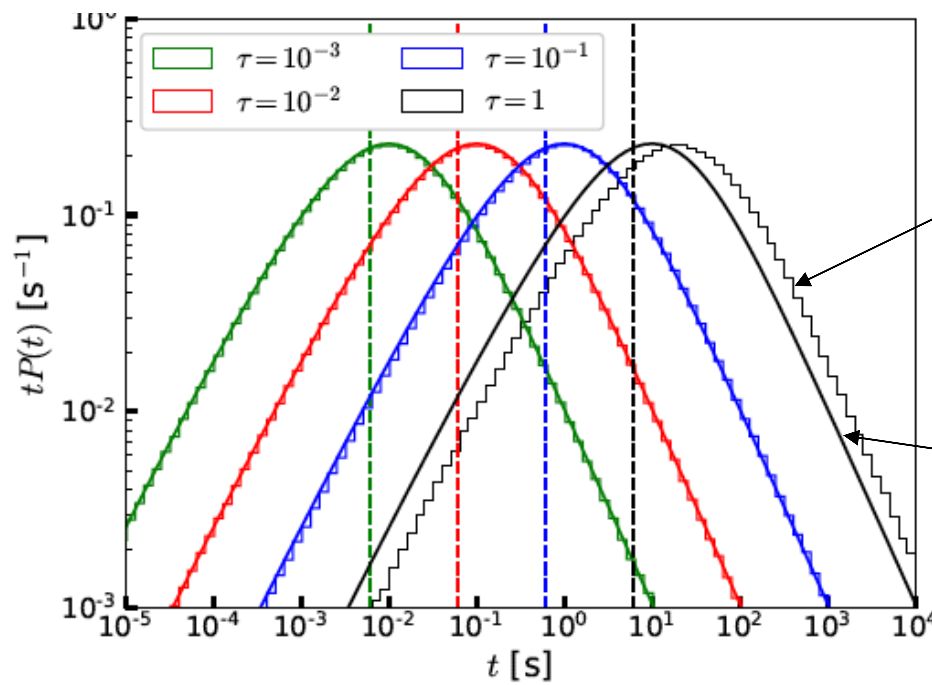
KM & Shoemaker 19 PRL



"time delay" signatures
(neutrino echoes)

general $$P(t,\varphi;D) = J(t,\varphi)\frac{1}{\sigma_\nu}\left(\frac{d\sigma_\nu}{d\cos\theta}\right)$$

small-angle scattering limit $$P(t,\varphi;D) \approx \frac{1}{t+(D\varphi^2/2)}\frac{1}{\sigma_\nu}\left(\frac{d\sigma_\nu}{d\theta}\right)_{\theta=\varphi+2t/(D\varphi)}$$



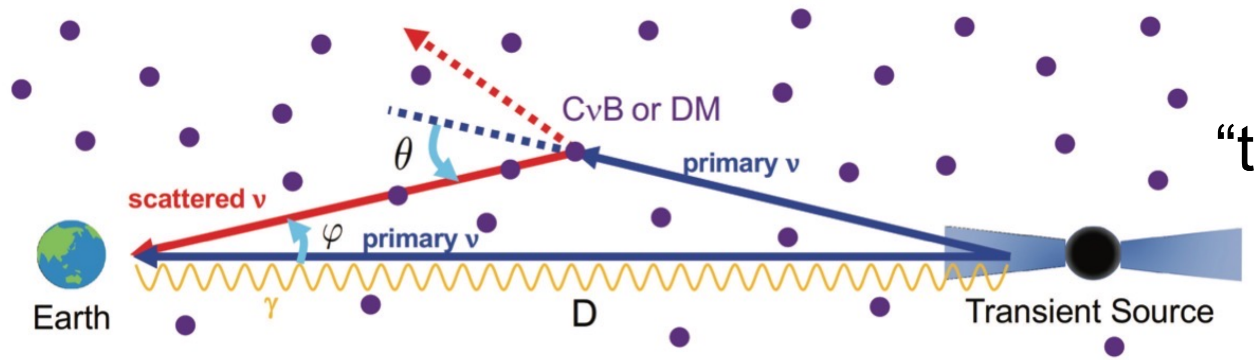
Monte Carlo simulation

analytical formula

Eskenasy, Kheirandish & KM 23 PRD
Carpio & Murase 23 JCAP

BSM Tests with Multi-Messenger Transients

KM & Shoemaker 19 PRL

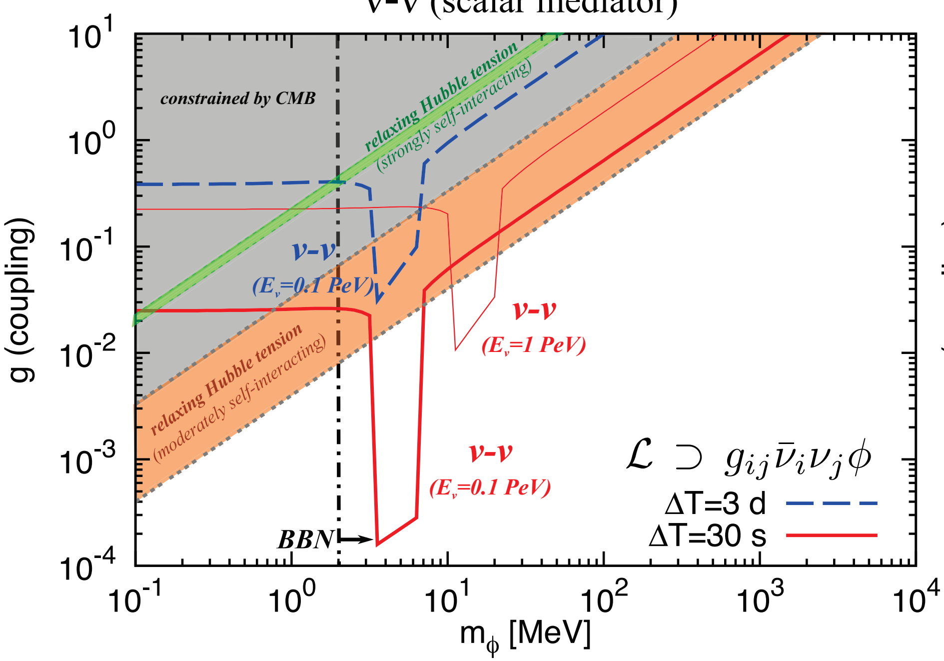


"time delay" signatures
(**neutrino echoes**)

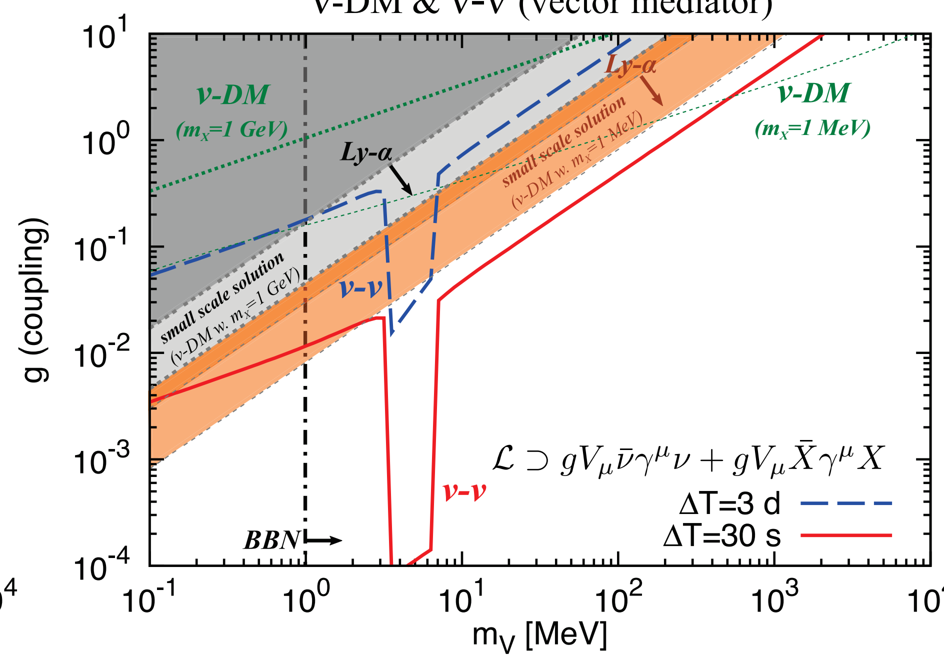
$$\Delta t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4} D \simeq 77\ \mathrm{s}\ \left(\frac{D}{3\ \mathrm{Gpc}}\right) C^2 \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

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

ν-ν (scalar mediator)

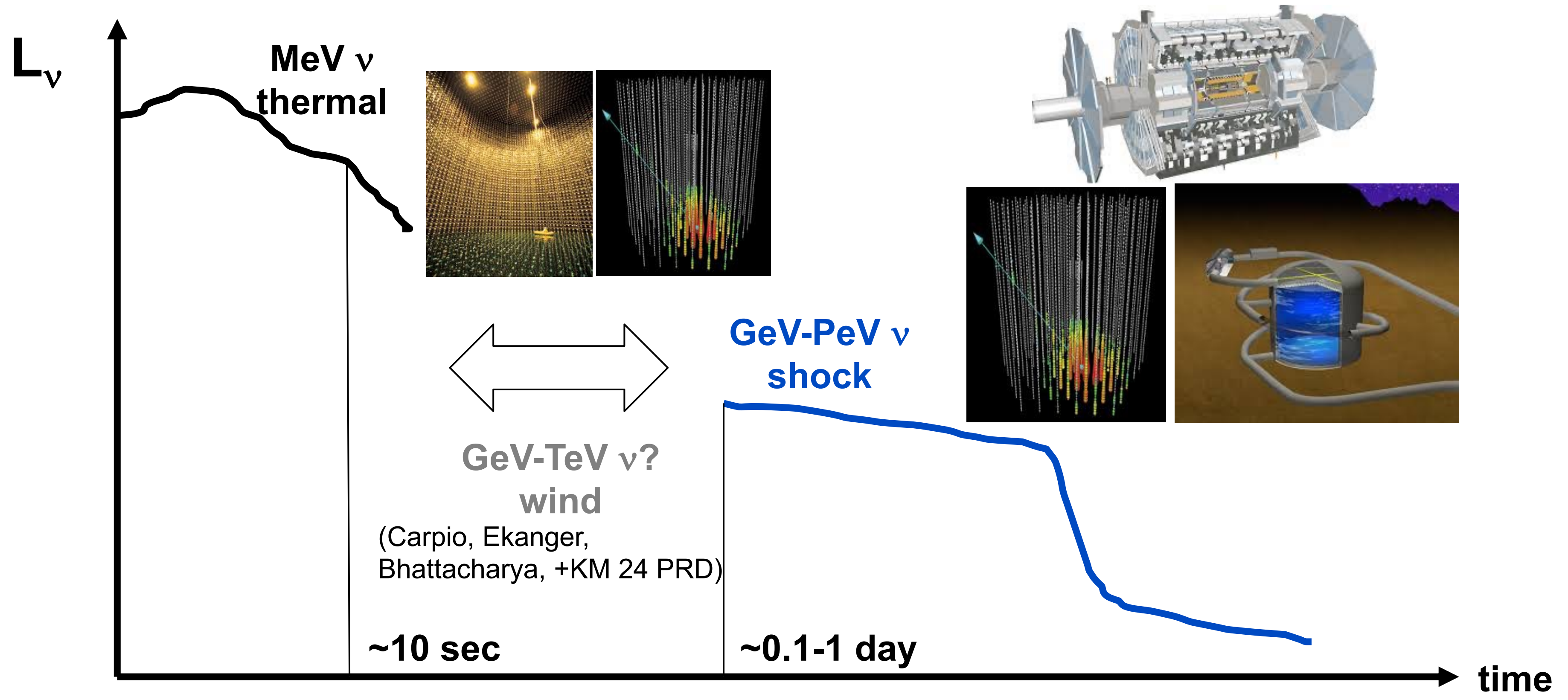


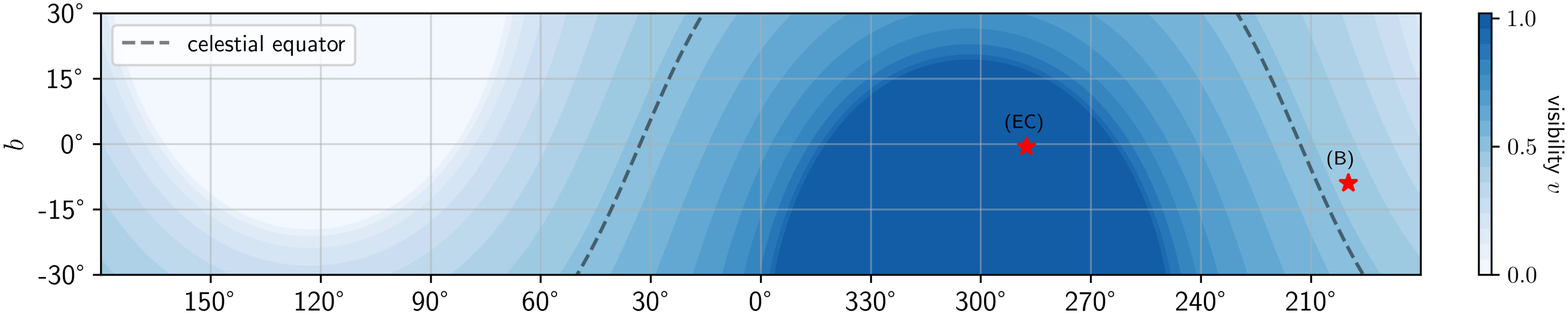
ν-DM & ν-ν (vector mediator)



Supernovae as High-Energy Neutrino Sources

- SNe as “multimessenger” & “multi-energy” neutrino source
- Importance of ”global ν detector network” (Kheirandish & KM 23 ApJL)
- ~1000 events of TeV ν from the next Galactic SNe (KM 18, 24 PRD)
- LHC ATLAS/CMS as cosmic ν detectors (Wen, Arguelles, Kheirandish & KM 24 PRL)

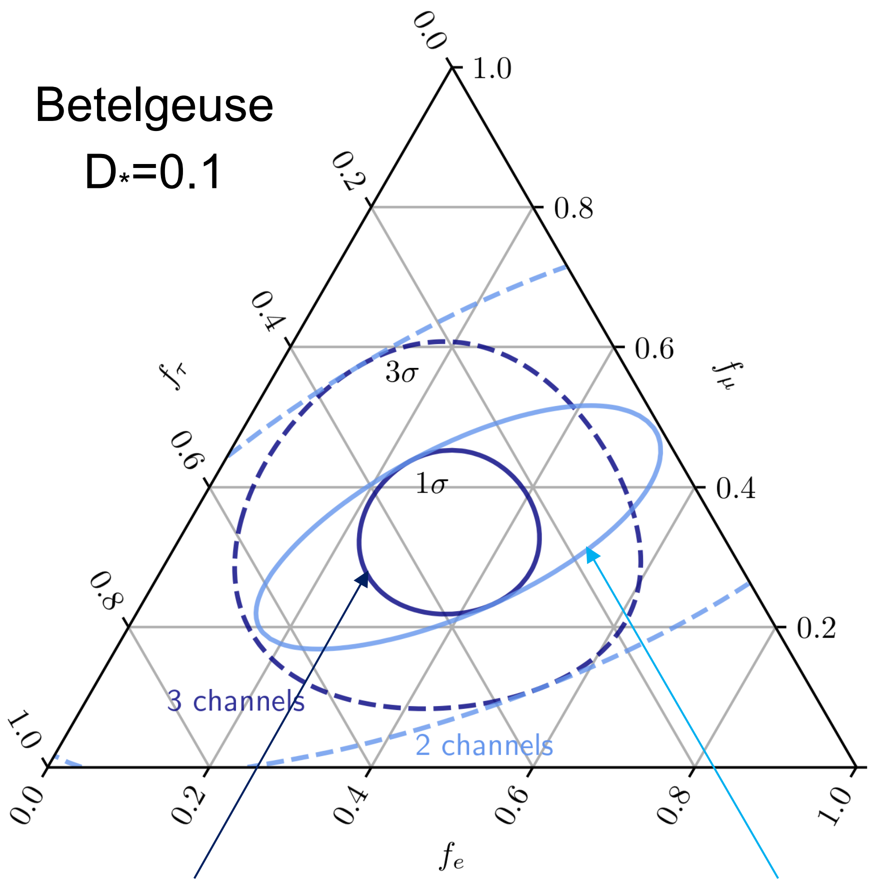




B: Betelgeuse
EC: Eta Carinae

Betelgeuse

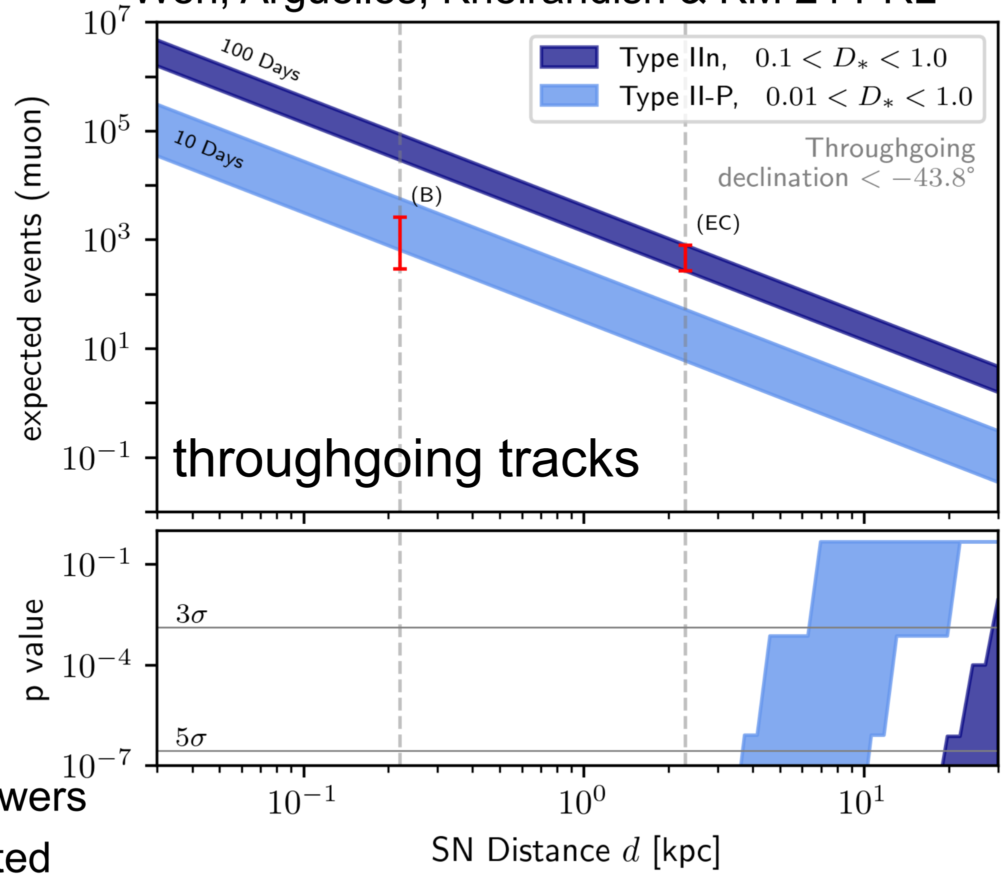
D*=0.1



2 hadronic showers discriminated

2 hadronic showers undiscriminated

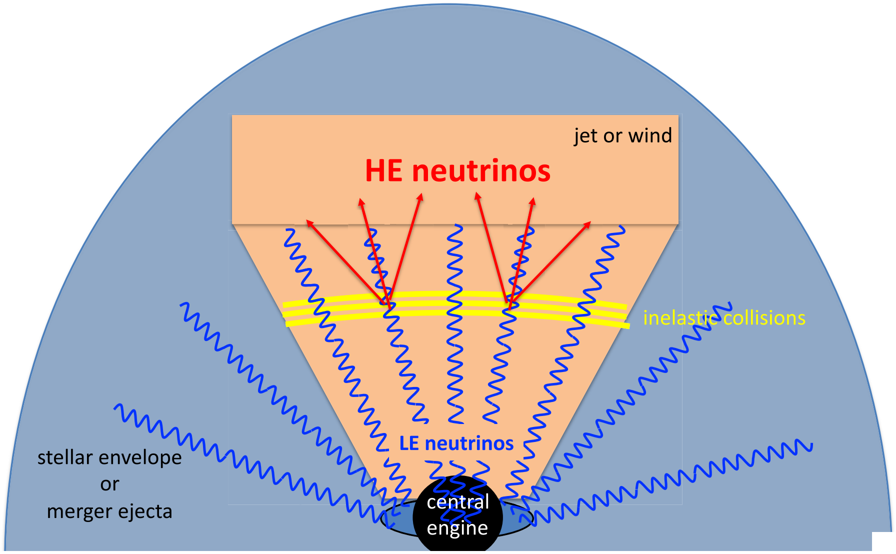
Wen, Arguelles, Kheirandish & KM 24 PRL

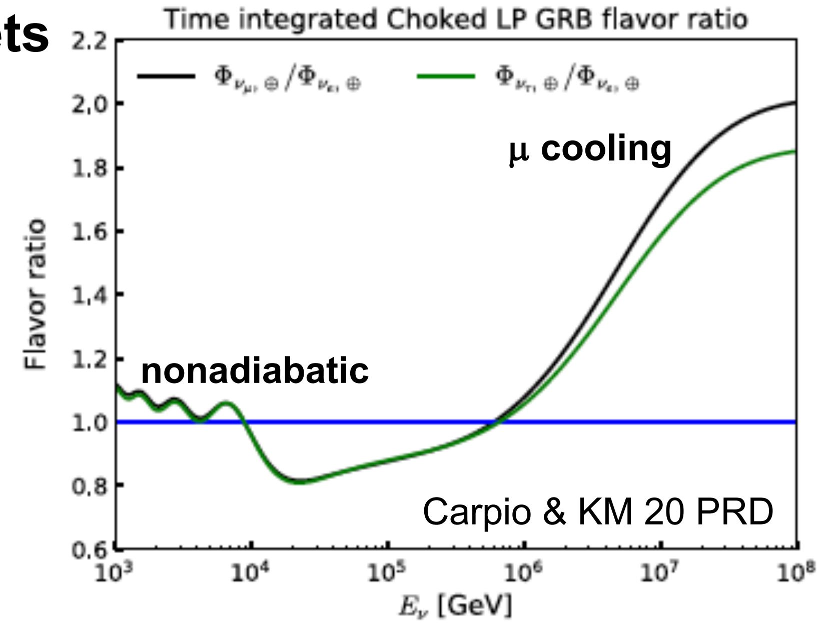


Jetted Supernovae as High-Energy Neutrino Sources

High-energy ν production in choked jets

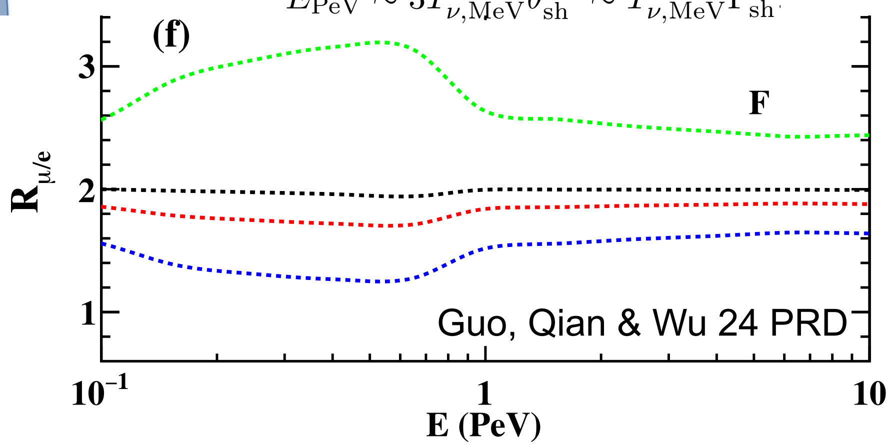
(Meszaros & Waxman 01 PRL,
Razzaque, Meszaros & Waxman 04 PRL
Ando & Beacom 05 PRL, KM & Ioka 13 PRL)





- Pion/muon cooling
- Matter effect
- On-shell Z production w. MeV νs
  (though difficult to have PeV νs)

$$E_{\rm PeV} \sim 3T_{\nu,{\rm MeV}}^{-1}\theta_{\rm sh}^{-2} \sim T_{\nu,{\rm MeV}}^{-1}\Gamma_{\rm sh}^{2}$$



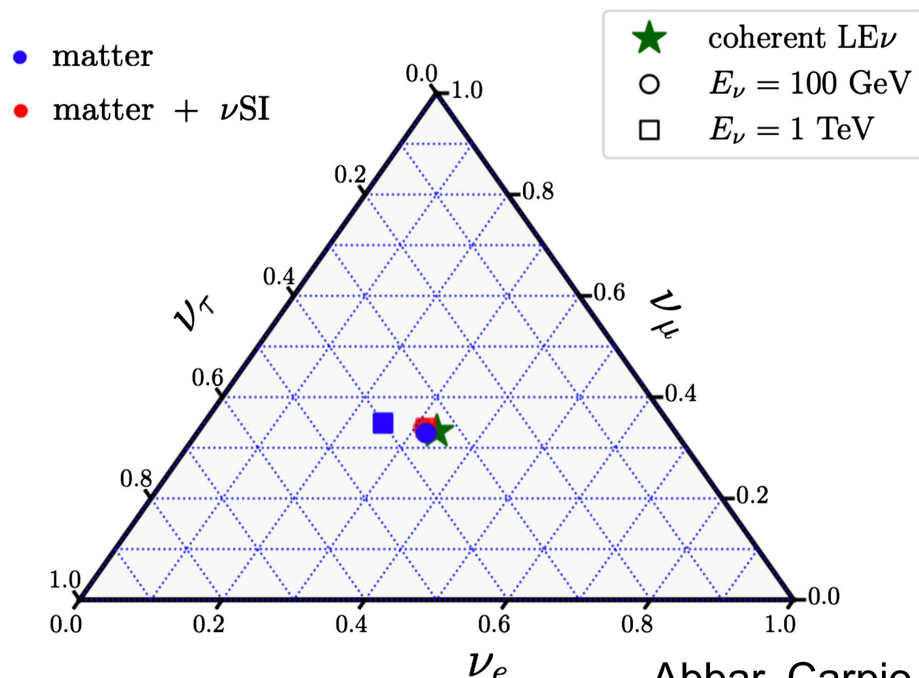
Flavor Impacts of High-Energy Neutrino Self-Interactions

High-energy ν & MeV ν : self-interactions (forward scattering)

$$i d_t \varrho_{\mathbf{p}} = \left[\frac{\mathsf{UM}^2\mathsf{U}^\dagger}{2E_\nu} + \mathsf{H}_{\mathrm{m}} + \mathsf{H}_{\nu\nu,\mathbf{p}}, \varrho_{\mathbf{p}}\right] \qquad \mathsf{H}_{\nu\nu,\mathbf{p}} = \sqrt{2}G_{\mathrm{F}} \int \frac{d^3 p'}{(2\pi)^3}(1 - \mathbf{v}\cdot\mathbf{v}')(\varrho_{\mathbf{p}'} - \bar{\varrho}_{\mathbf{p}'})$$

$$\mu \approx \sqrt{2}G_{\mathrm{F}} n_\nu \hbar^2 c^2 \xi \simeq 6.4 \times 10^{-6}\ \mathrm{cm}^{-1}\left(\frac{n_\nu}{10^{27}\ \mathrm{cm}^3}\right)\xi \qquad \xi \approx \Theta^2/2 \sim 1/(2\Gamma^2)$$

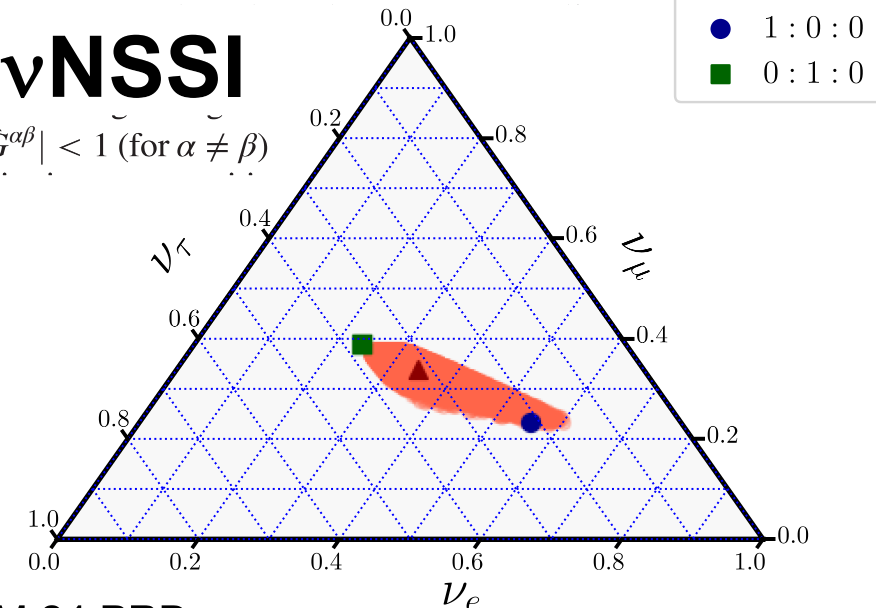
short-scale conversions rapidly lead to the flavor mixing



$$\mathcal{L}_{\mathrm{eff}} \supset G_{\mathrm{F}}[\hat{G}^{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\nu_\beta][\hat{G}^{\xi\eta}\bar{\nu}_\xi\gamma_\mu\nu_\eta]$$

νNSSI

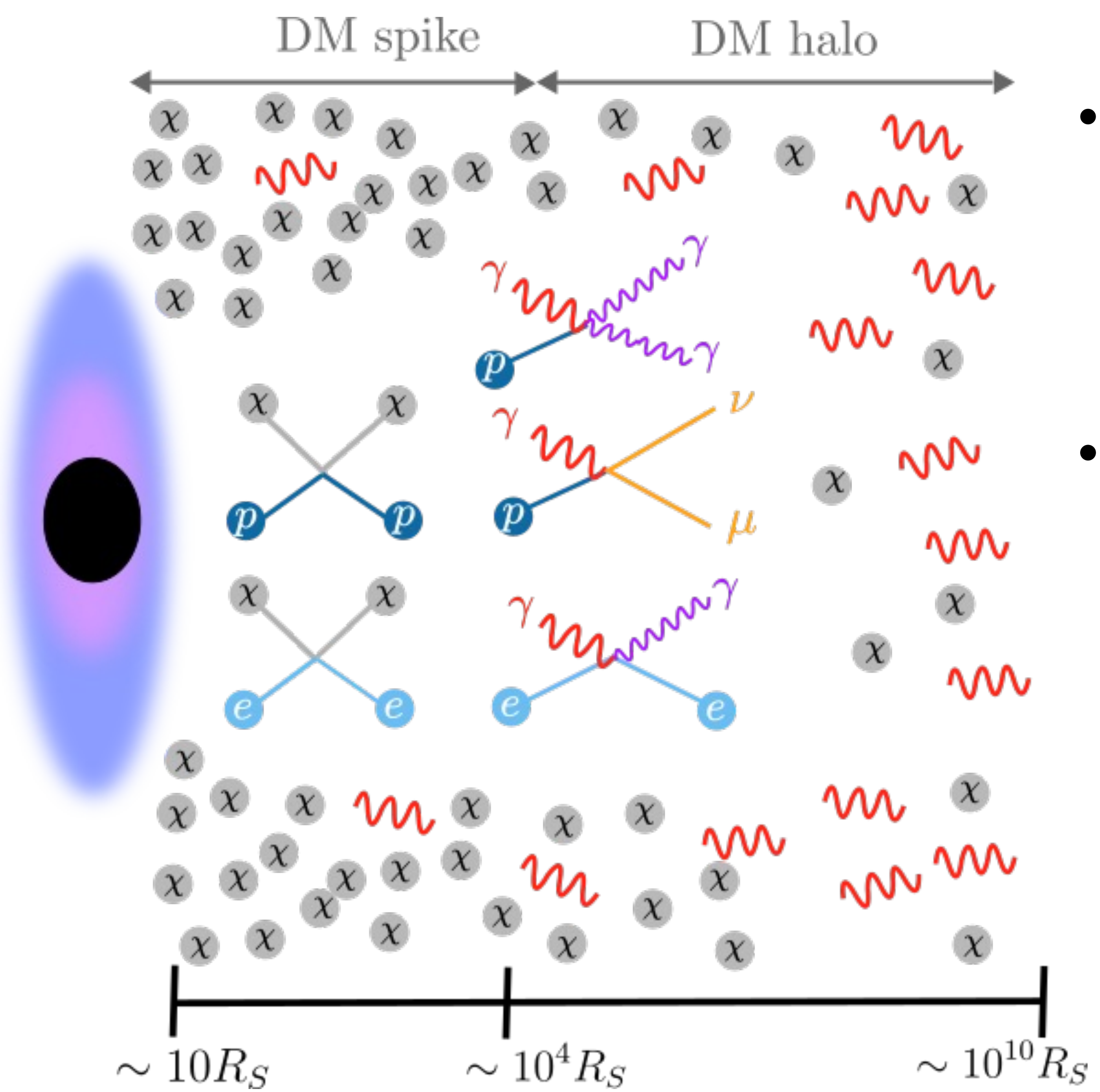
$|\hat{G}^{\alpha\beta}| < 1$ (for $\alpha \neq \beta$)



Abbar, Carpio & KM 24 PRD

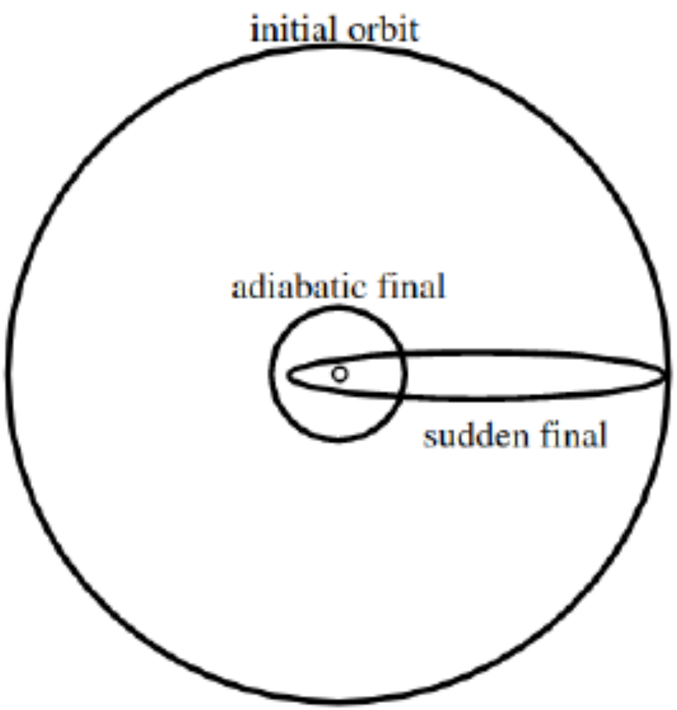
BSM CR-DM Interactions

Herrera & KM 24 PRDL



- ν-DM/ ν-ν interaction: High-energy cosmic νs as a natural beam
- CR-DM interaction: Complementarity to the low-energy frontier of direct detection experiments
  - CR cooling due to BSM
  - CR-boosted DM

Dark Matter Spike Around Black Holes



$$\rho_{\rm sp}(r) = \rho_R \, g_\gamma(r) \left(\frac{R_{sp}}{r} \right)^{\gamma_{\rm sp}}$$

$$g_\gamma(r) \simeq (1 - \frac{4R_S}{r})$$

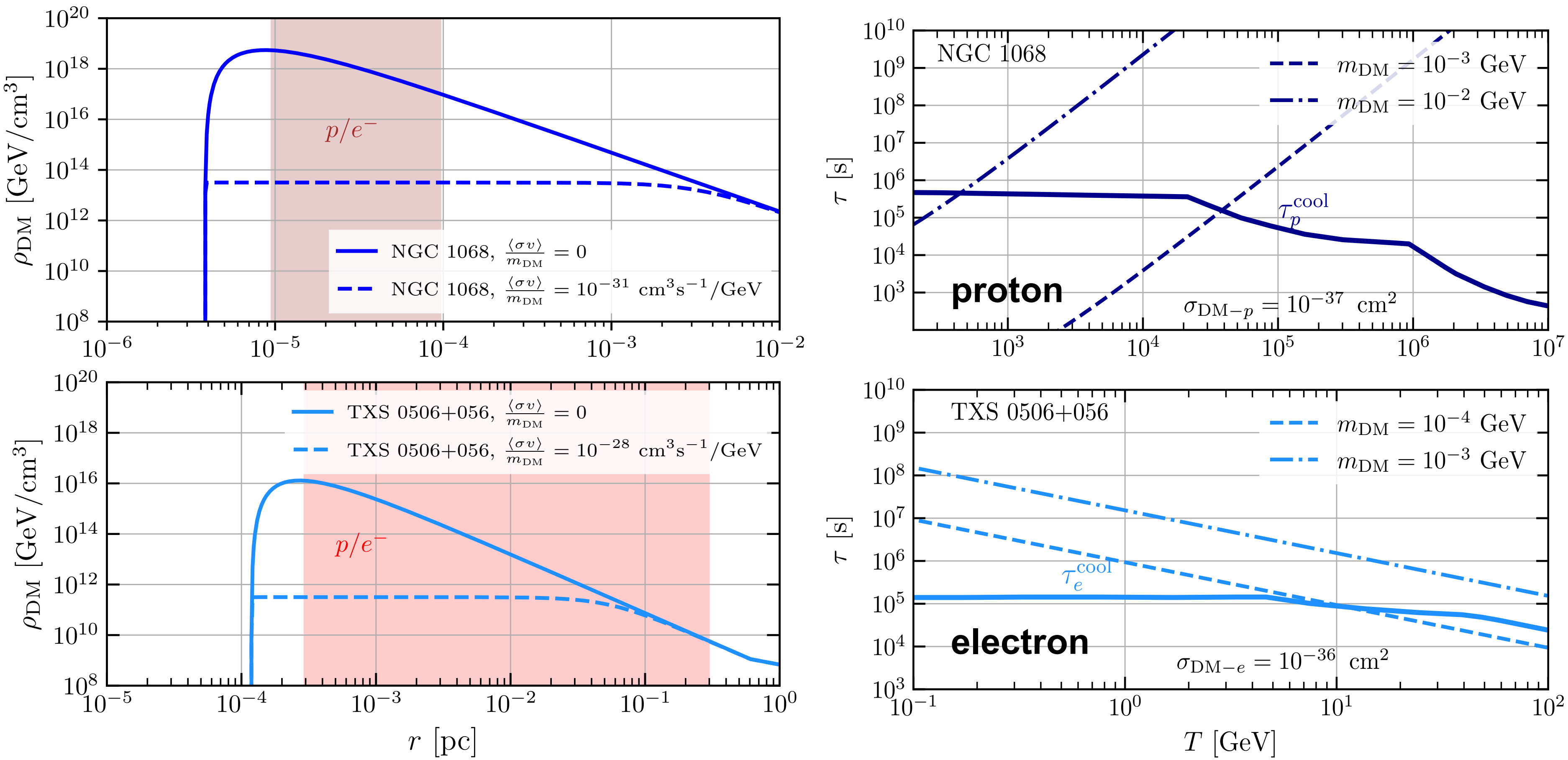
$$R_{\rm sp} = \alpha_\gamma r_0 (M_{\rm BH}/(\rho_0 r_0^3))^{\frac{1}{3-\gamma}}$$ **spike size**

$$\gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma}$$ **cuspiness, γ=1 (NFW)**

modification necessary for annihilating DM

- Adiabatic growth
  A substantial increase in the black hole mass takes place after its initial formation, and the mass accretes slowly to the pre-existing seed black hole. (e.g., Peebles 72, Quinlan+ 95)
- NGC 1068: dynamical time < Salpeter time is justified

Dark Matter Distribution & Cosmic-Ray Cooling

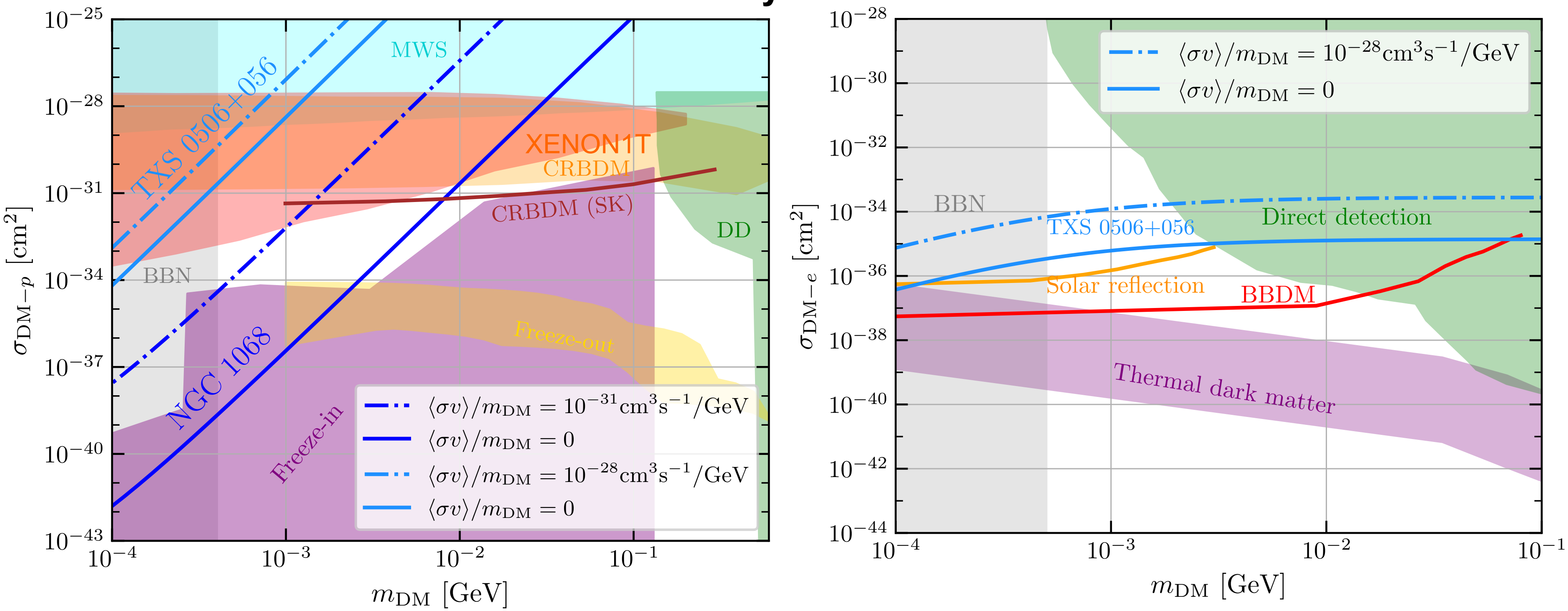


- DM density can be very high at the center of AGN (“DM spike”)
- NGC 1068 νs originate from CRs within ~30-100 Schwarzschild radii
- Neutrino emission would not be seen if DM-p scattering was too efficient
- γ-ray emission would not be seen if DM-e scattering was too efficient

CR Cooling Limits on DM-p and DM-e Interactions

Herrera & KM 24 PRDL

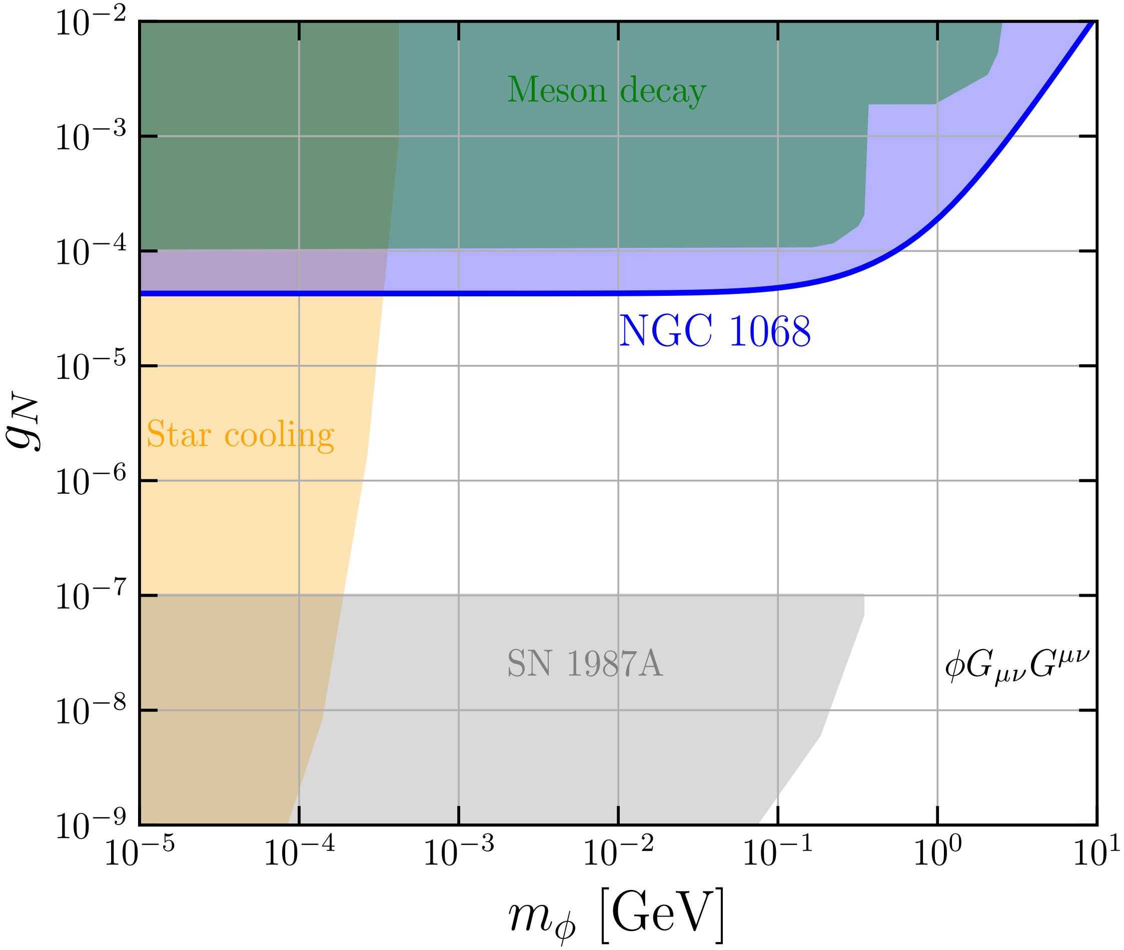
heavy mediator



- Most stringent constraints for dark matter in the MeV range
- Important for freeze-in DM (ex. Elor+ 23 PRL) & thermal DM (ex. Boehm & Fayet 03)
- Complementary to CR-boosted DM limits with XENON/LZ and Super-K

Example of Scalar-Mediated DM-Nucleon Interactions

Herrera & KM 24 PRDL



$$\mathcal{L} \supset -m_\chi \bar{\chi}\chi - g_N \phi \bar{N} N - g_\chi \phi \bar{\chi}\chi$$

$$\frac{d\sigma^{\phi}_{\mathrm{DM-CR}i}}{dT_{\mathrm{DM}}} = \frac{m_\phi^4}{\left(q^2 + m_\phi^2\right)^2} \frac{d\sigma_{\mathrm{DM-CR}i}}{dT_{\mathrm{DM}}},$$

non-relativistic DM cross section

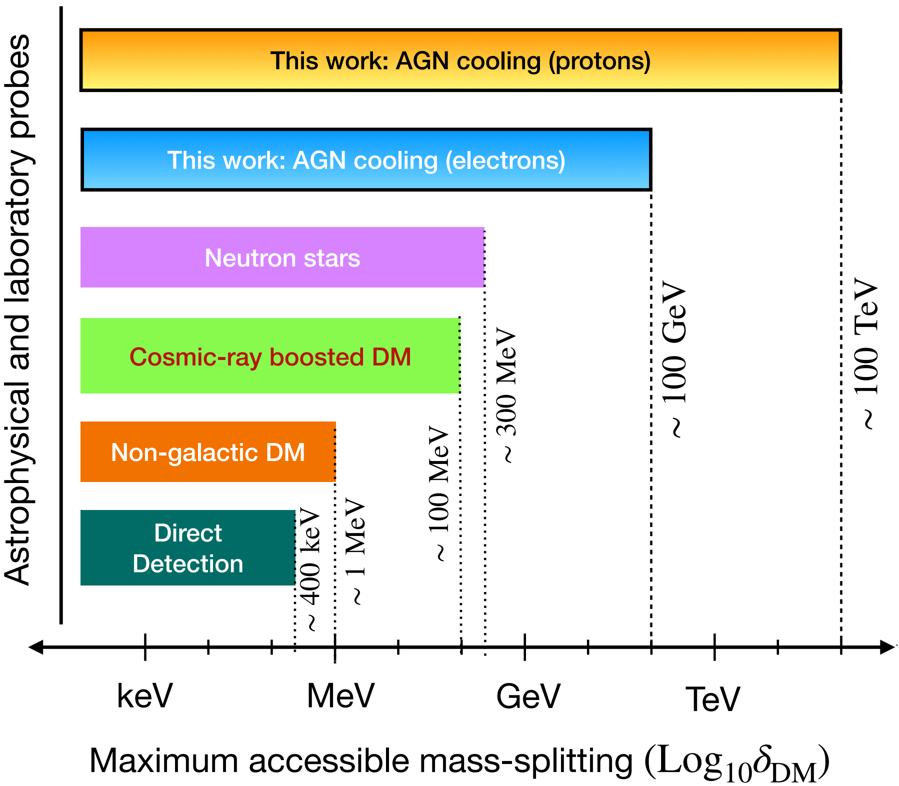
$$\sigma_{\mathrm{DM}-N} = \frac{g_\chi^2 g_N^2 \mu_{\chi-N}^2}{\pi m_\phi^4}.$$

- NGC 1068 observations enable us to probe new parameter space

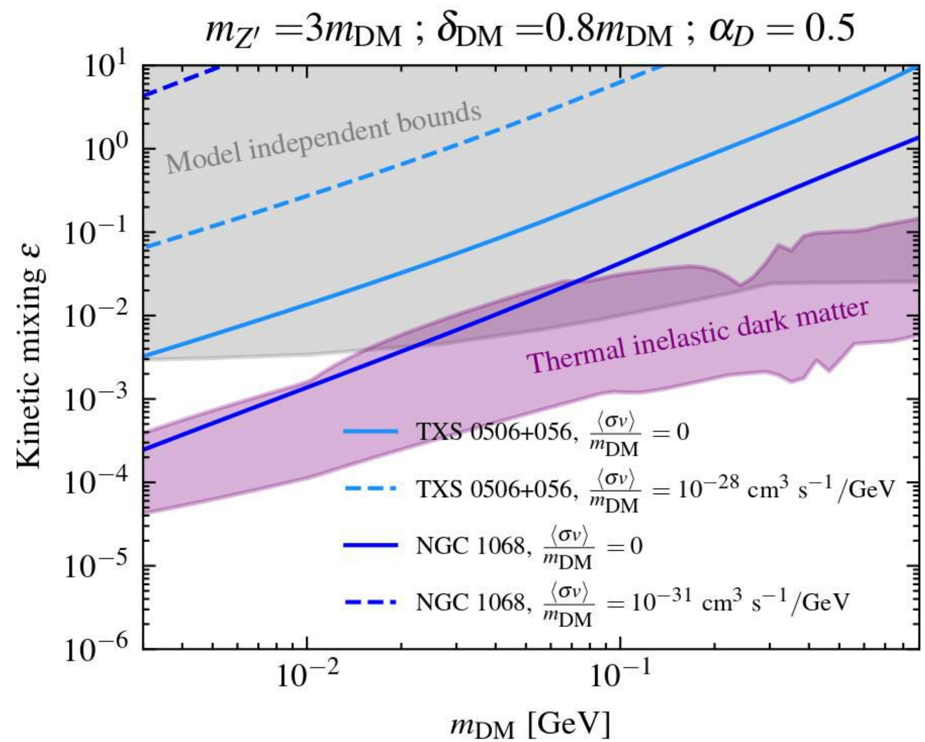
Application to Inelastic Dark Matter

$$\chi_1 + i \to \chi_2 + i$$

DM may be inelastic (ex. pseudo-Dirac)



CR cooling

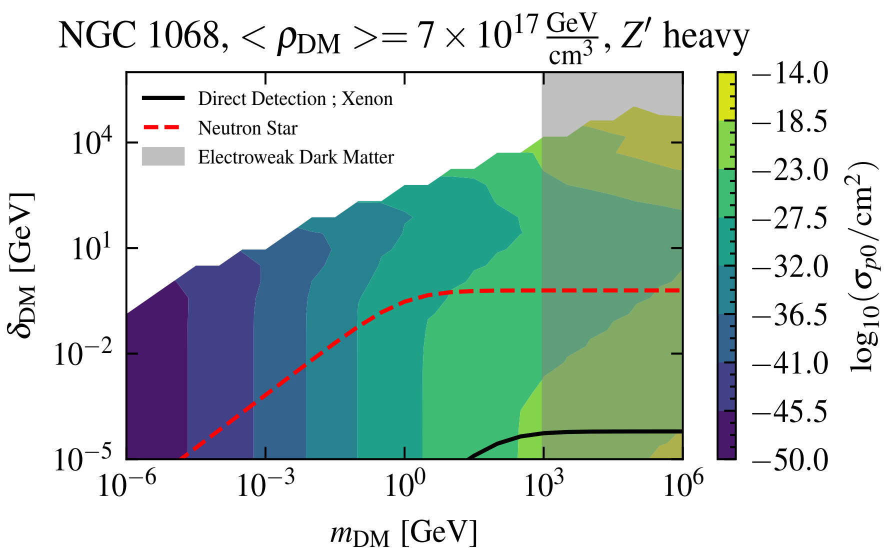


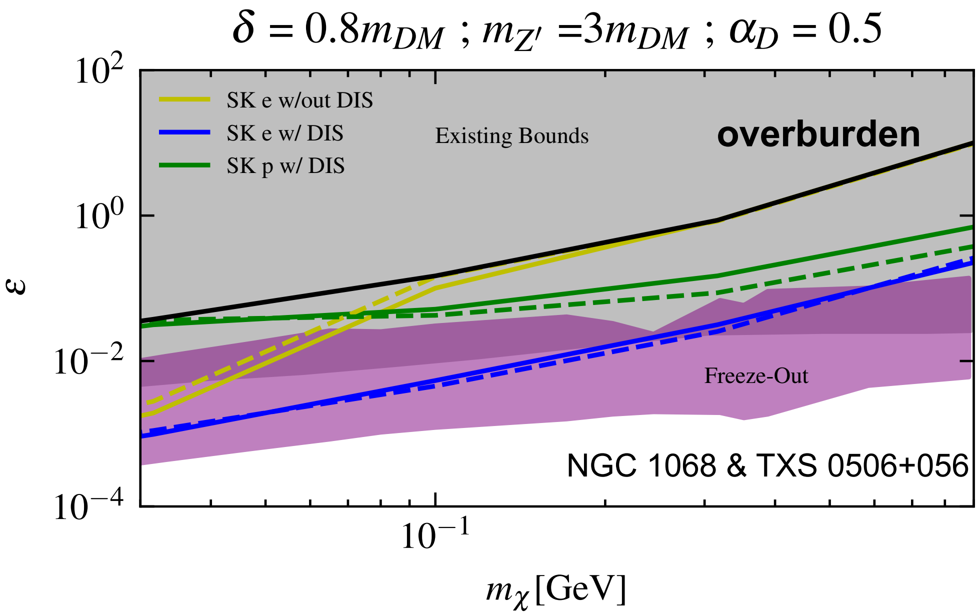
$$m^*_{\mathrm{DM}} = m_{\mathrm{DM}} + \delta_{\mathrm{DM}}$$

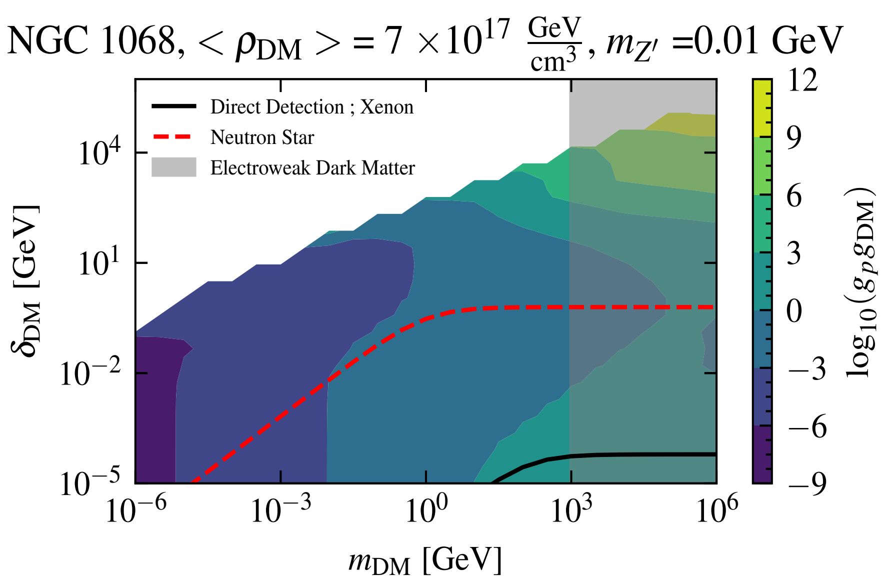
$$\epsilon = g_{\mathrm{SM}}/e \qquad \sigma_0 = \frac{g^2_{\mathrm{SM}} g^2_{\mathrm{DM}} \mu^2_{\mathrm{DM-SM}}}{\pi m^4_{Z'}}$$

Gustafson, Herrera, Mukhopadhyay, KM & Shoemaker 2408.08947, 2505.xxxxx

Constraints on Inelastic DM



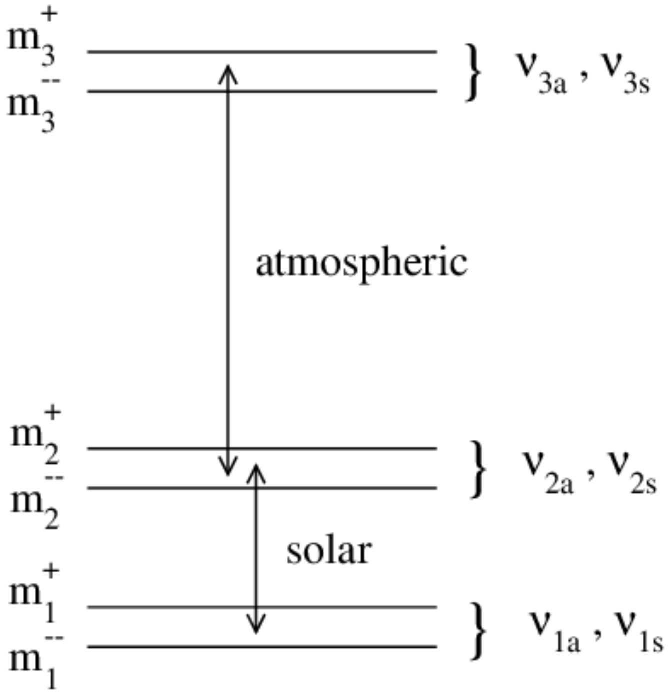




Complementarity
different (nontrivial) systematics

- CR cooling
  More robust and/or conservative
- Boosted DM
  Limits can be improved with larger detectors and paleodetectors
- DIS helps

Pseudo-Dirac Neutrinos



$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- M_R=0 (Dirac)
- $|M_R|$>>$|m_D|$ (Type-I seesaw)
- $|M_R|$<<$|m_D|$ (pseudo-Dirac)

- Tiny mass splitting w. sterile neutrinos

Wolfenstein 81, Petcov 82

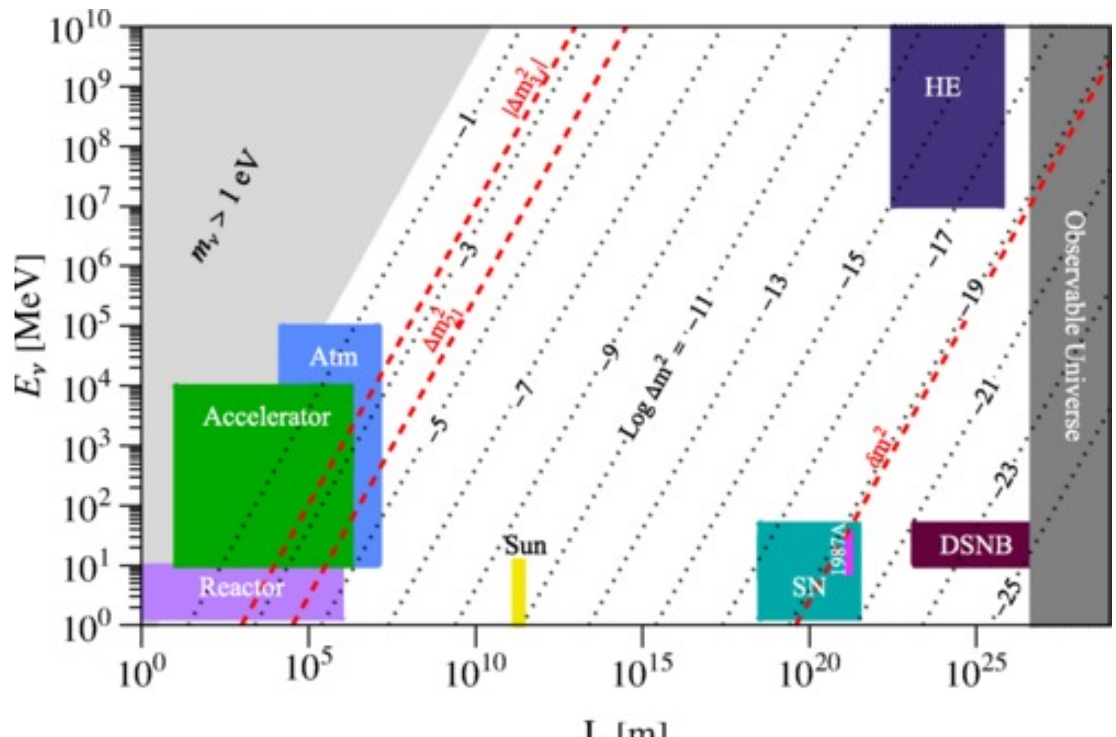
- Cosmic neutrinos can be used as a probe

Beacom et al. 04, Karanen et al. 03

- Motivated by the Swampland conjecture

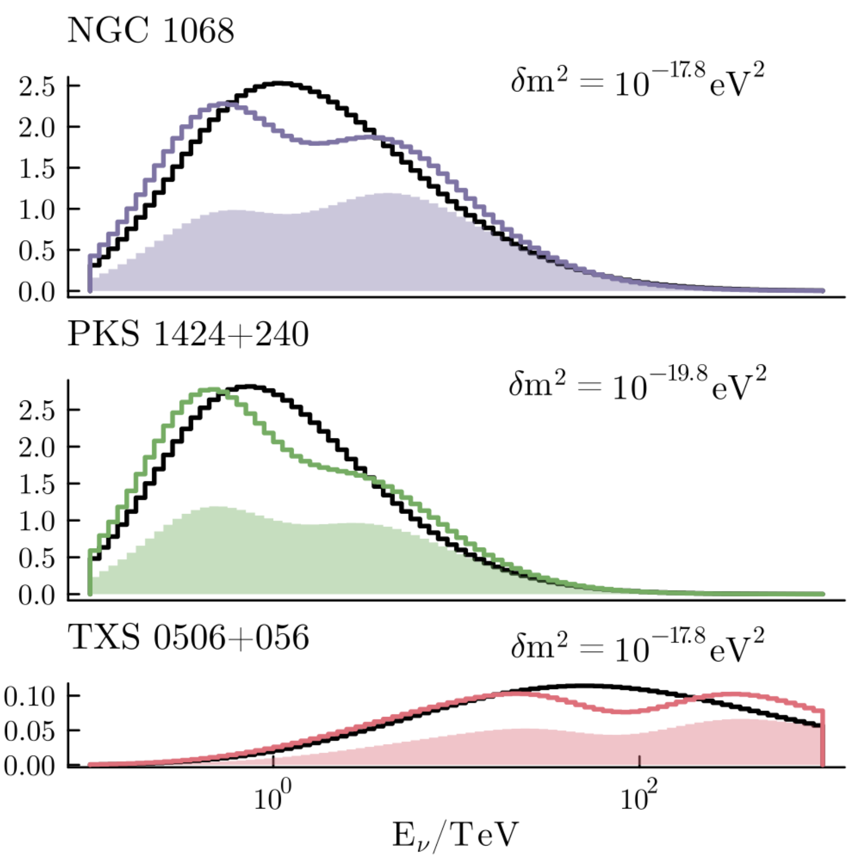
Gonzalo et al. 22 JHEP

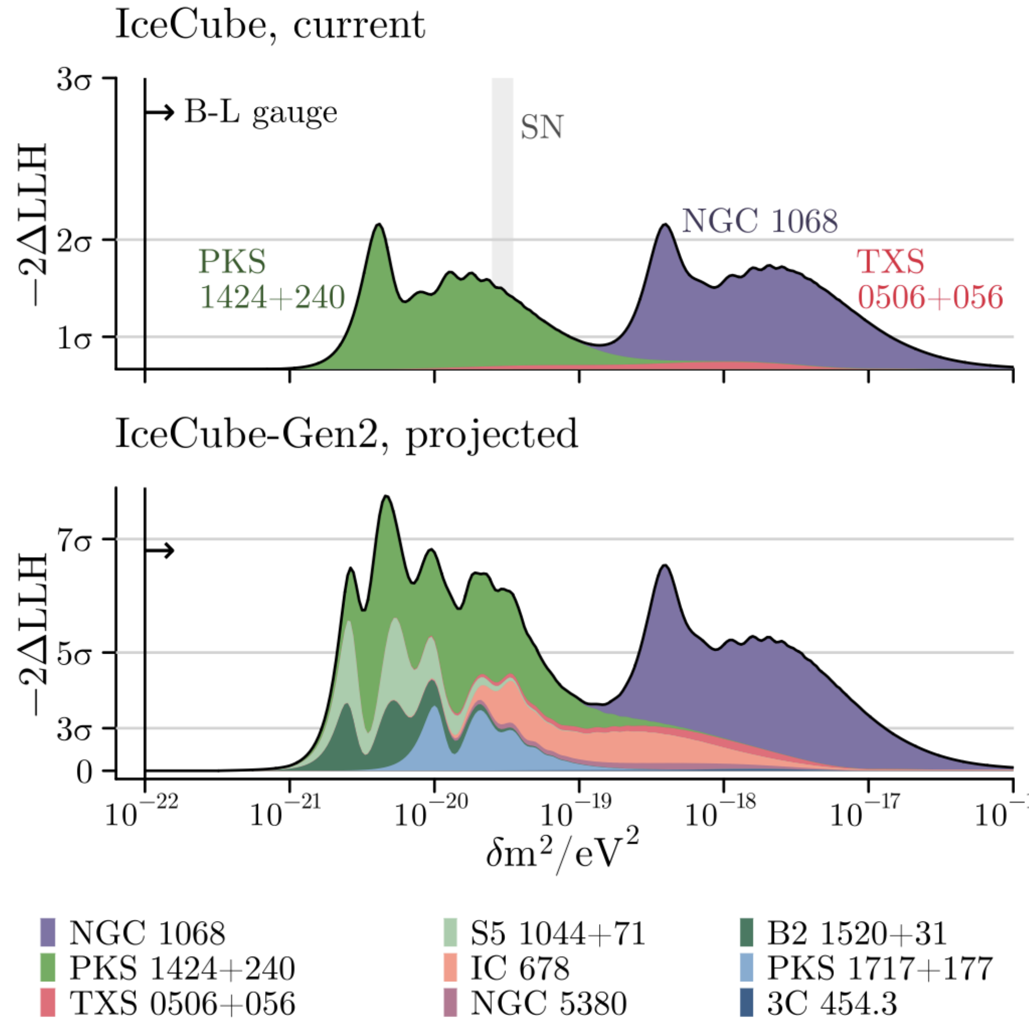
- Planck-suppressed operators, loop generation



Constraints from Point Sources

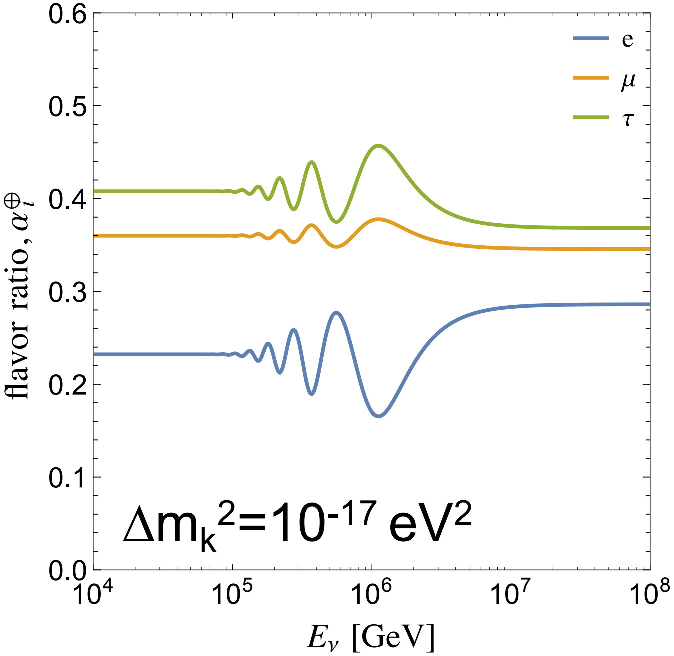
Carloni+ 24 PRDL, Rink & Sen 24 PLB

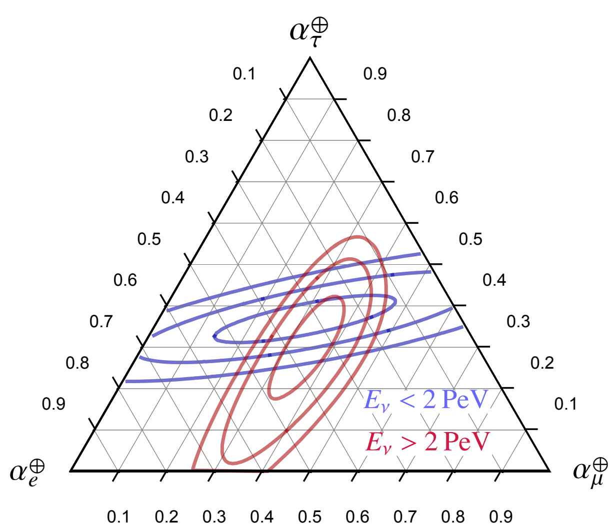




Meaningful limits by IceCube-Gen2 but astro-model dependent

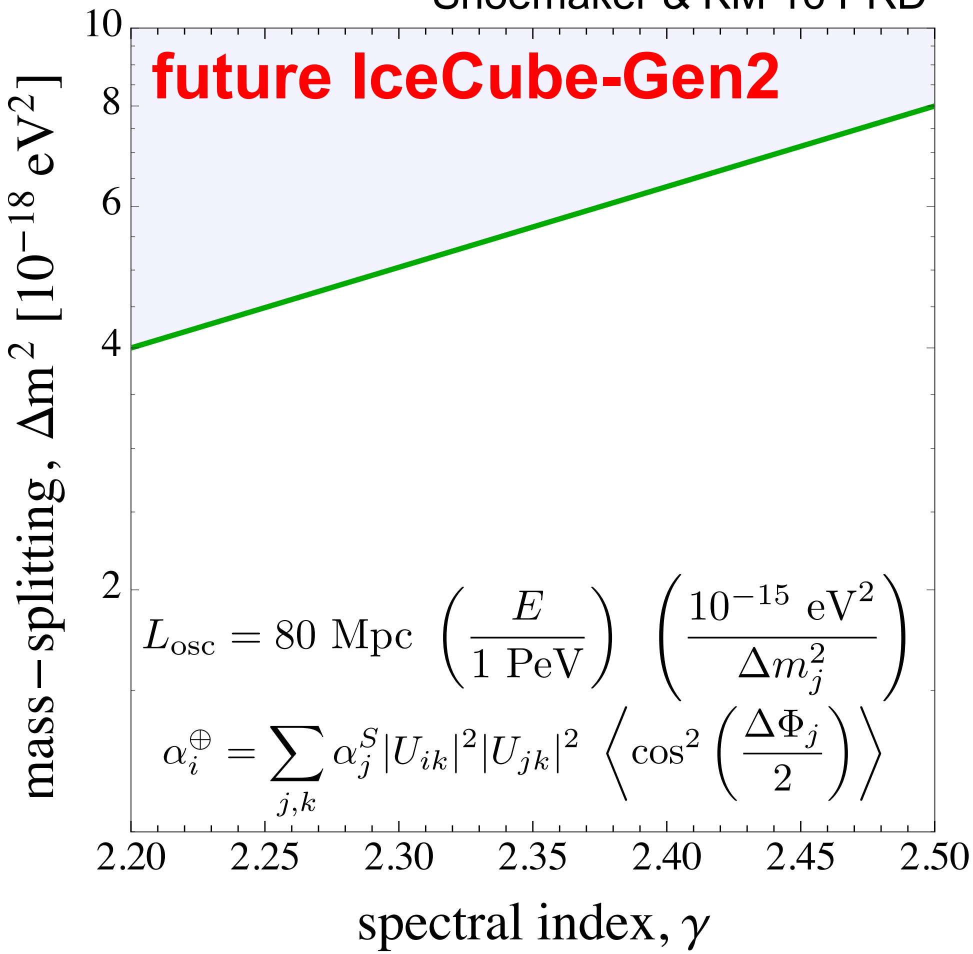
Diffuse Neutrino Constraints (Future)





- Spectral modulation may be caused
- Energy-dependent flavor constraints would be more model independent

Shoemaker & KM 16 PRD



Summary

General Implications

- τ candidates, hints of the ν spectral curvature, debate on the KM3Net event
- Multimessenger analyses on 10 TeV ν data require hidden CR accelerators
- NGC 1068 (AGN): evidence of a hidden ν source
- Milky Way: multimessenger connection now observed

New ν Interactions

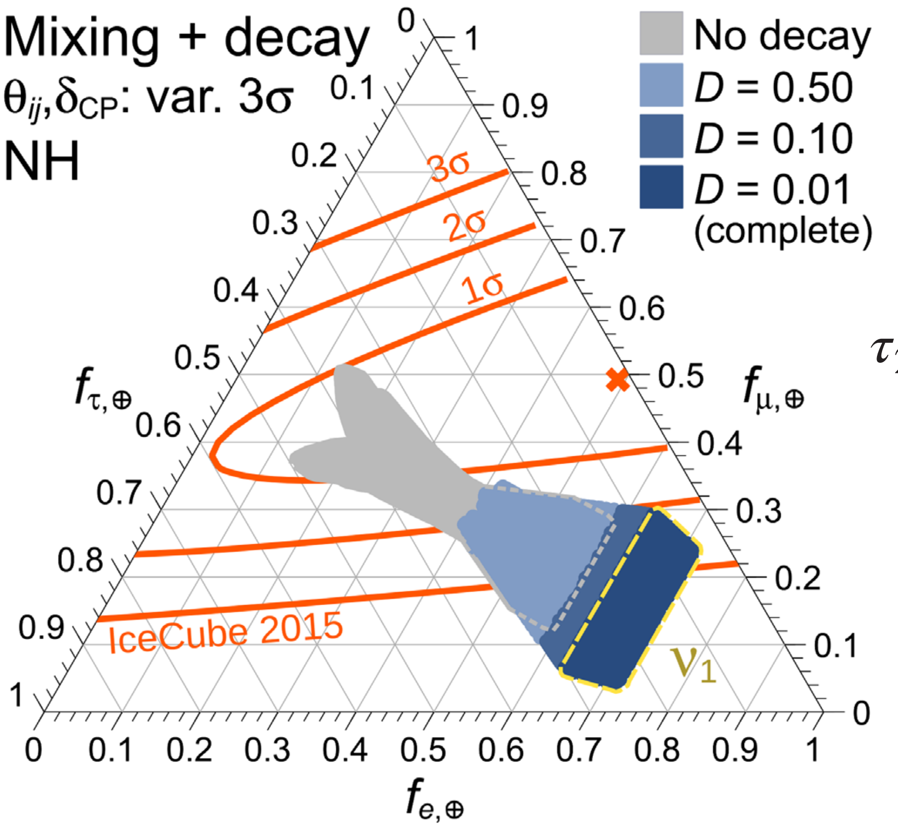
- Spectral & flavor modulations
- Time delays (& arrival directions) can also be used
- Useful as probes of ν-ν & ν-DM interactions
- Supernovae high-energy νs allow us to measure ν flavors
- CR cooling & CR-boosted DM er provide power probes of MeV-GeV DM
- Advantage of super-long baseline $\rightarrow$ ex. pseudo-Dirac νs, ν decay

Indirect Search for Dark Matter

- Multimessenger constraints on DM models explaining n observations
- Beyond the IceCube energy range
- Nearby DM halos provide more direct tests

Neutrino Decay: Normal Hierarchy

$$\frac{dN_i}{dt} = -\left(\frac{m_i}{\tau_i}\frac{1}{E_\nu}\right)N_i \qquad \tau_i/m_i\ \left[\frac{\mathrm{s}}{\mathrm{eV}}\right] \simeq 10^2\ \frac{L\,[\mathrm{Mpc}]}{E_\nu\,[\mathrm{TeV}]}$$



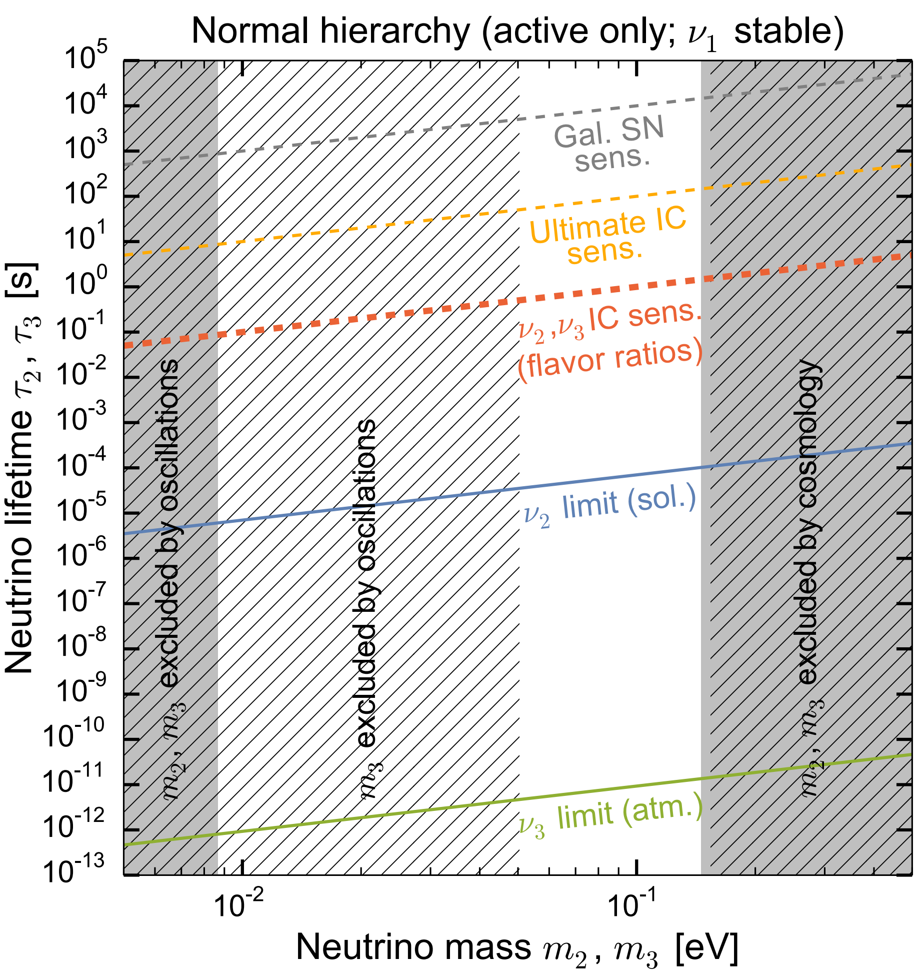
Bustamante, Beacom & KM 17 PRD
(see also Pagliaroli+ 15 PRD)

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

"complete" decay of ν_2, ν_3 disfavored only by flavors

Neutrino Decay: Normal Hierarchy

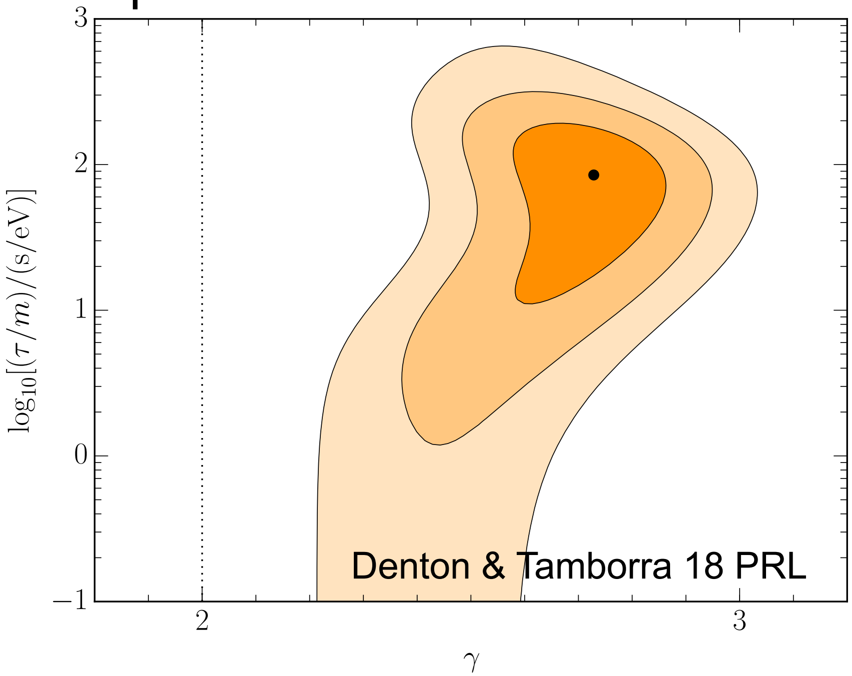
complementary to atm. & solar ν

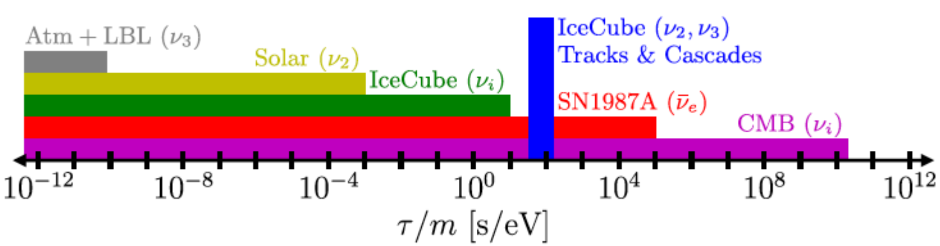


Partial decay solution

–> ν_2, ν_3 are lost at low energies

-> possible tension alleviated



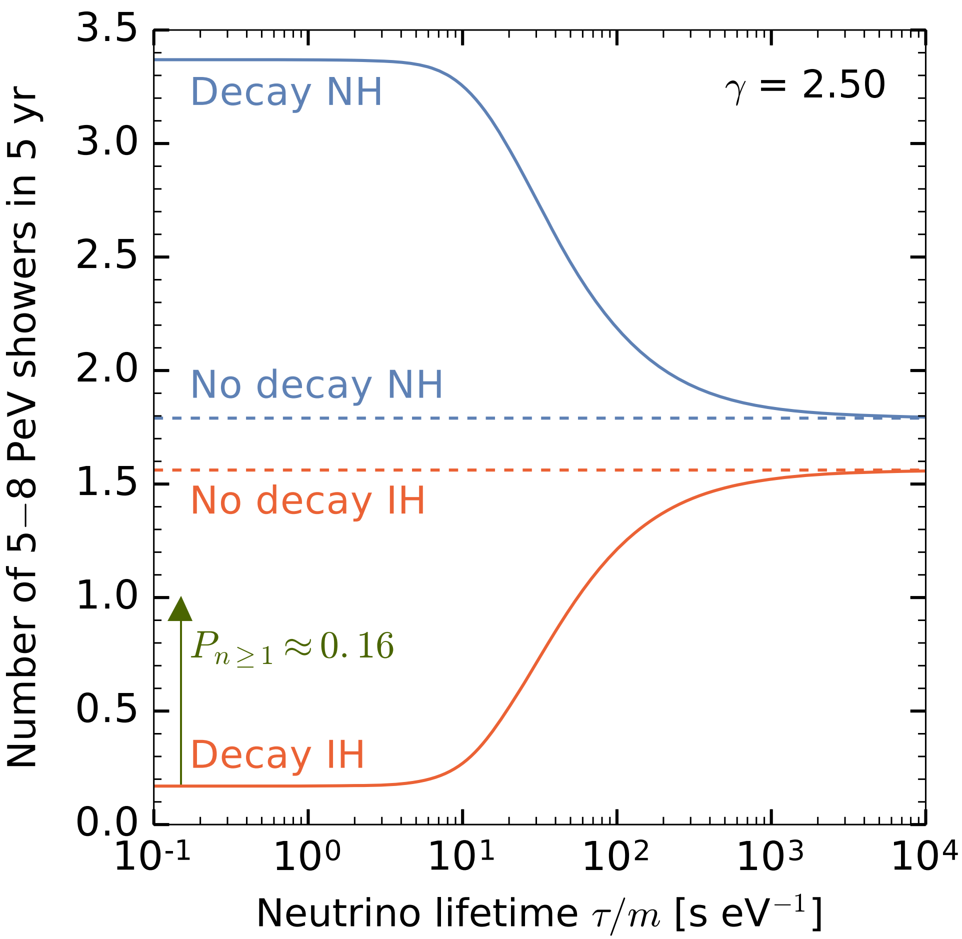


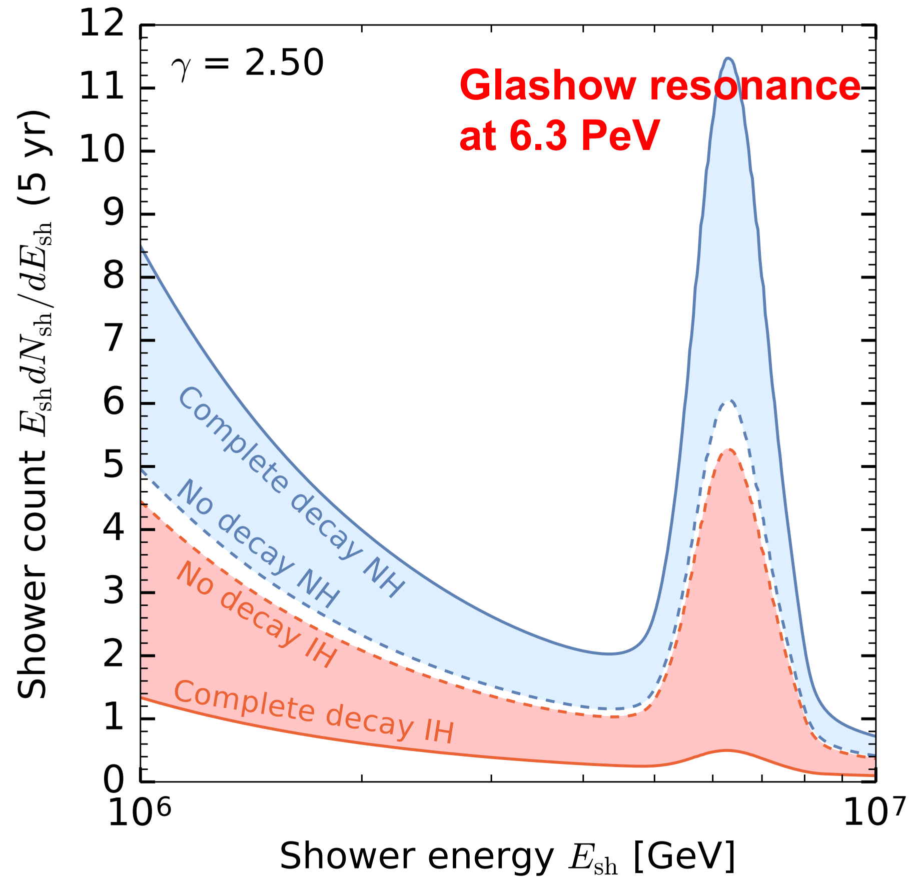
Bustamante, Beacom & KM 17 PRD, Abdullahi & Denton 21 PRD

Neutrino Decay: Inverted Hierarchy

IH is not disfavored yet by the flavor information

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



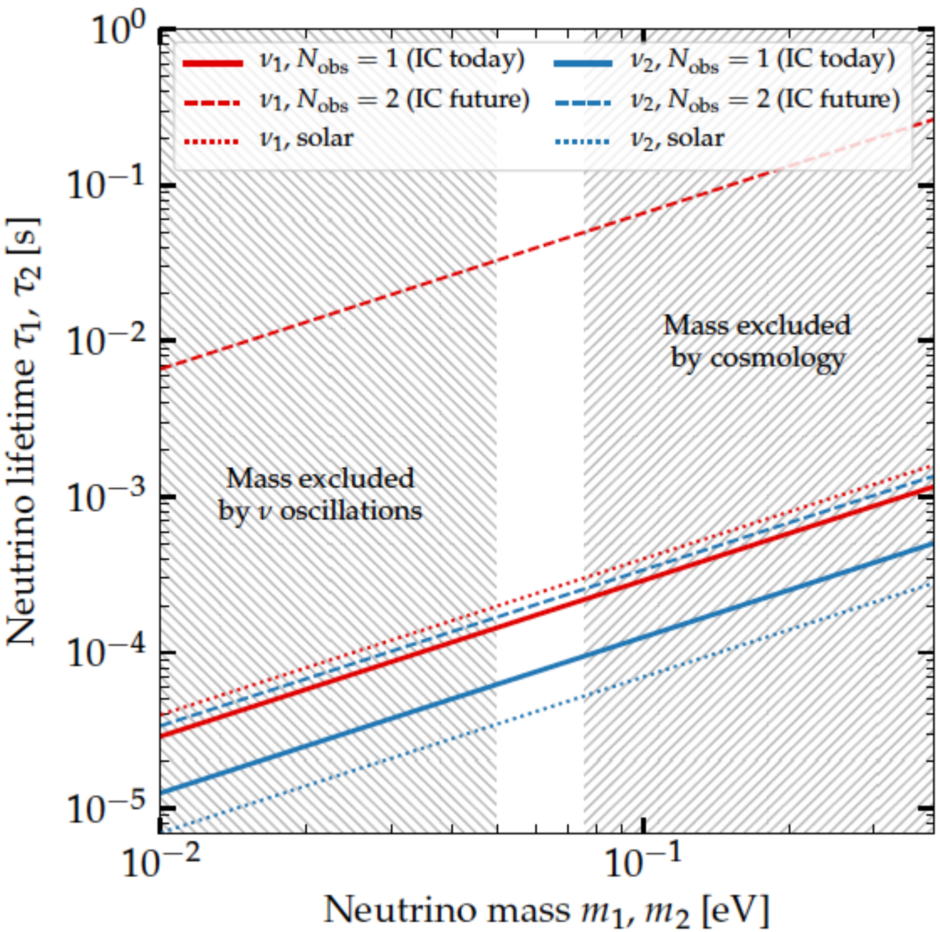


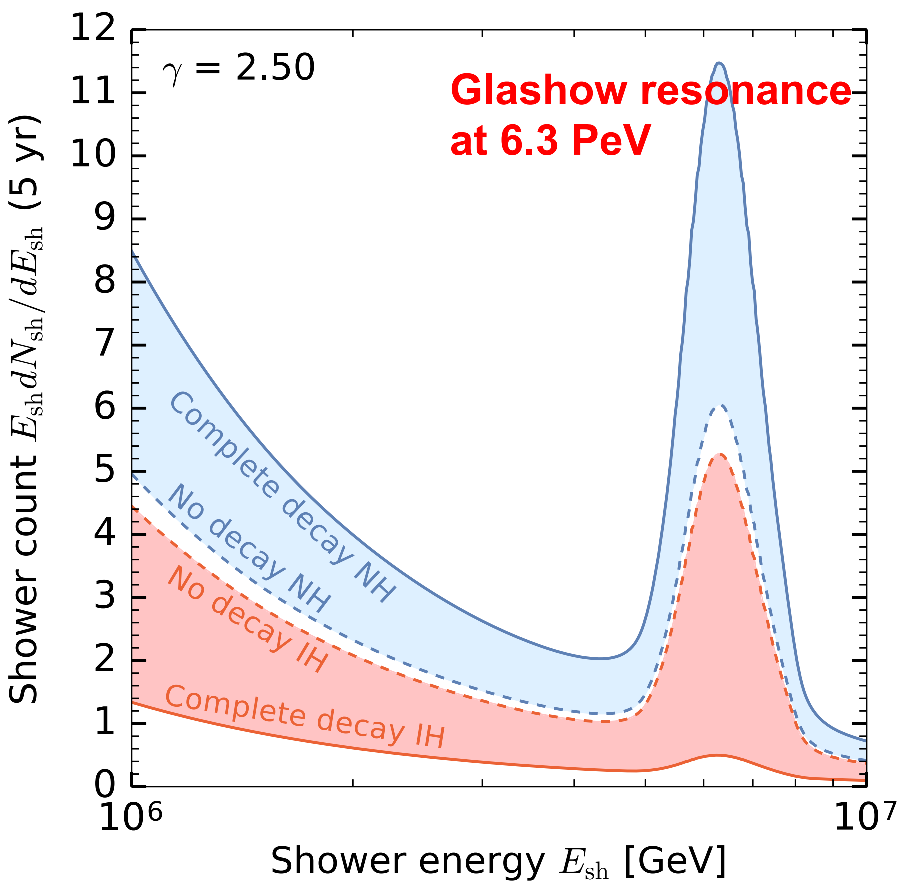
Neutrino Decay: Inverted Hierarchy

GR detection can give the best constraints in the IH case

IH, visible decay

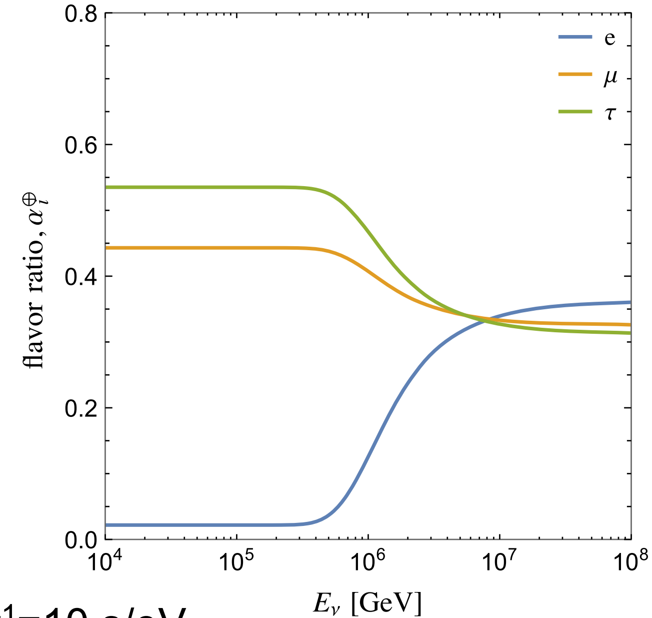
Bustamante, Beacom & KM 17 PRD
(see also Shoemaker & KM 16 PRD)



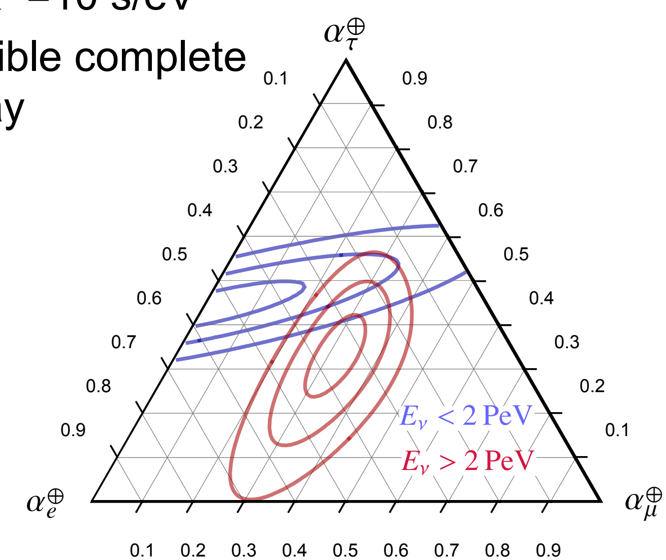


Bustamante 20

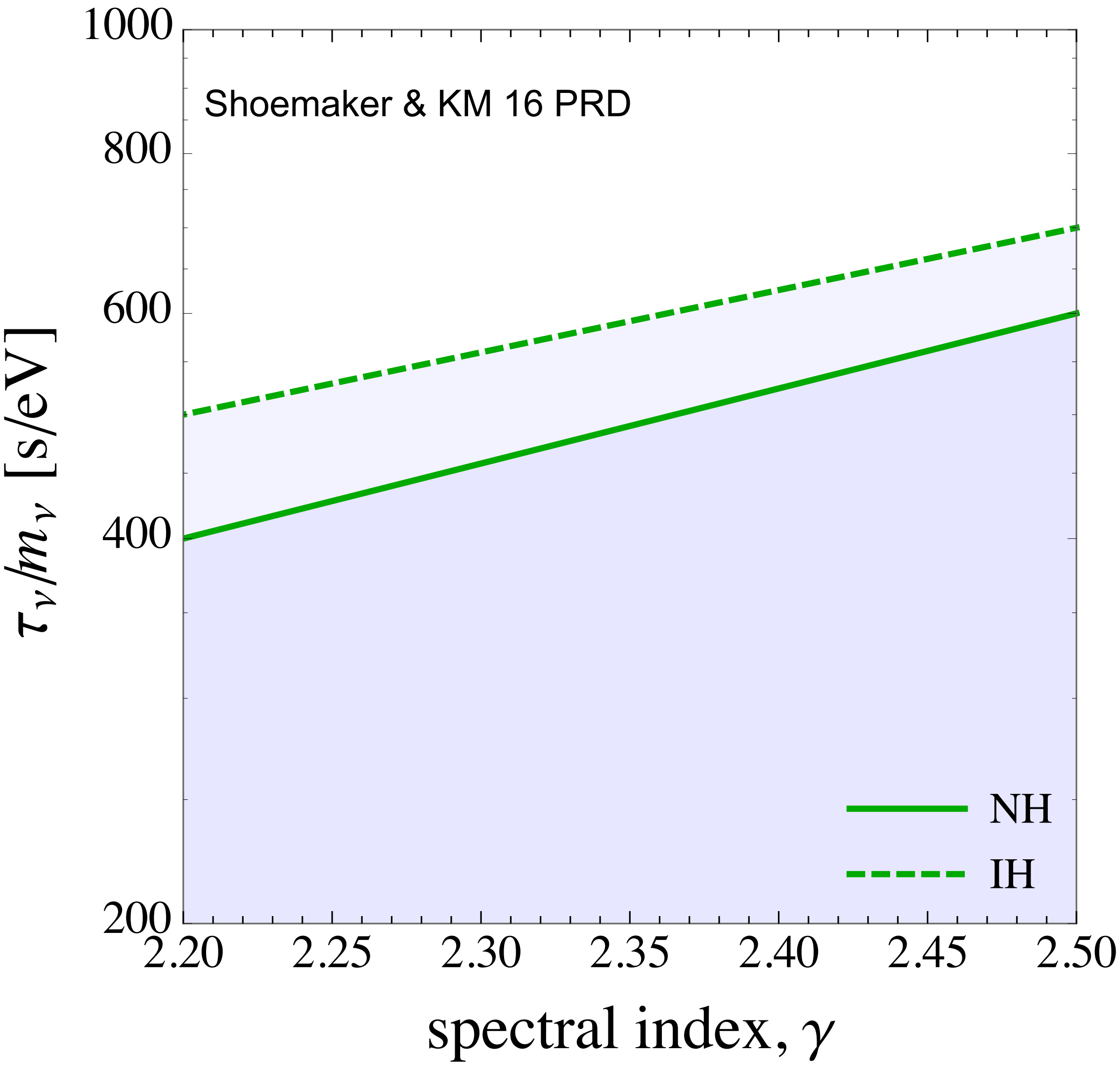
Future Constraints on Neutrino Decay

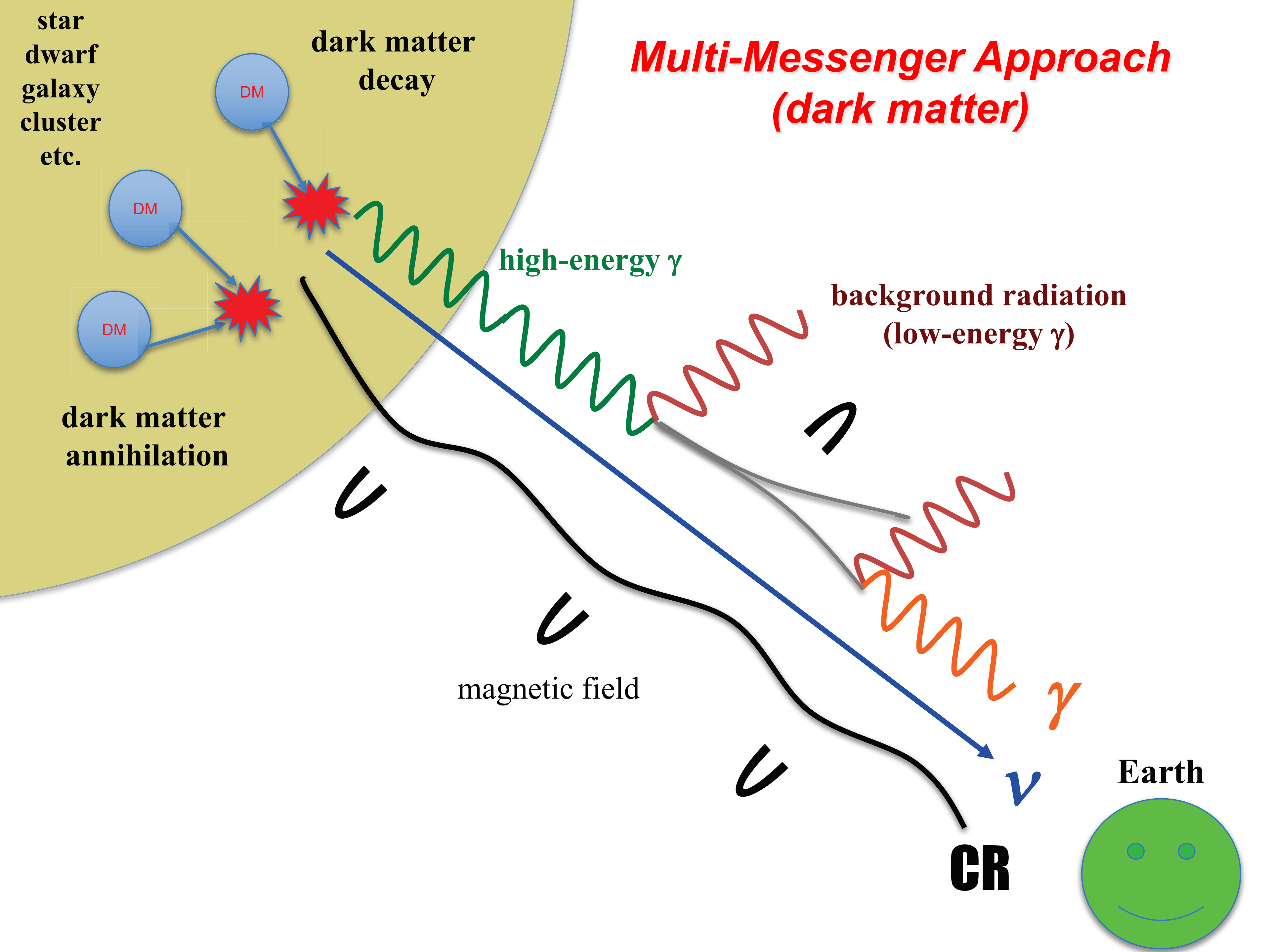


IH: κ^{-1}=10 s/eV
invisible complete decay



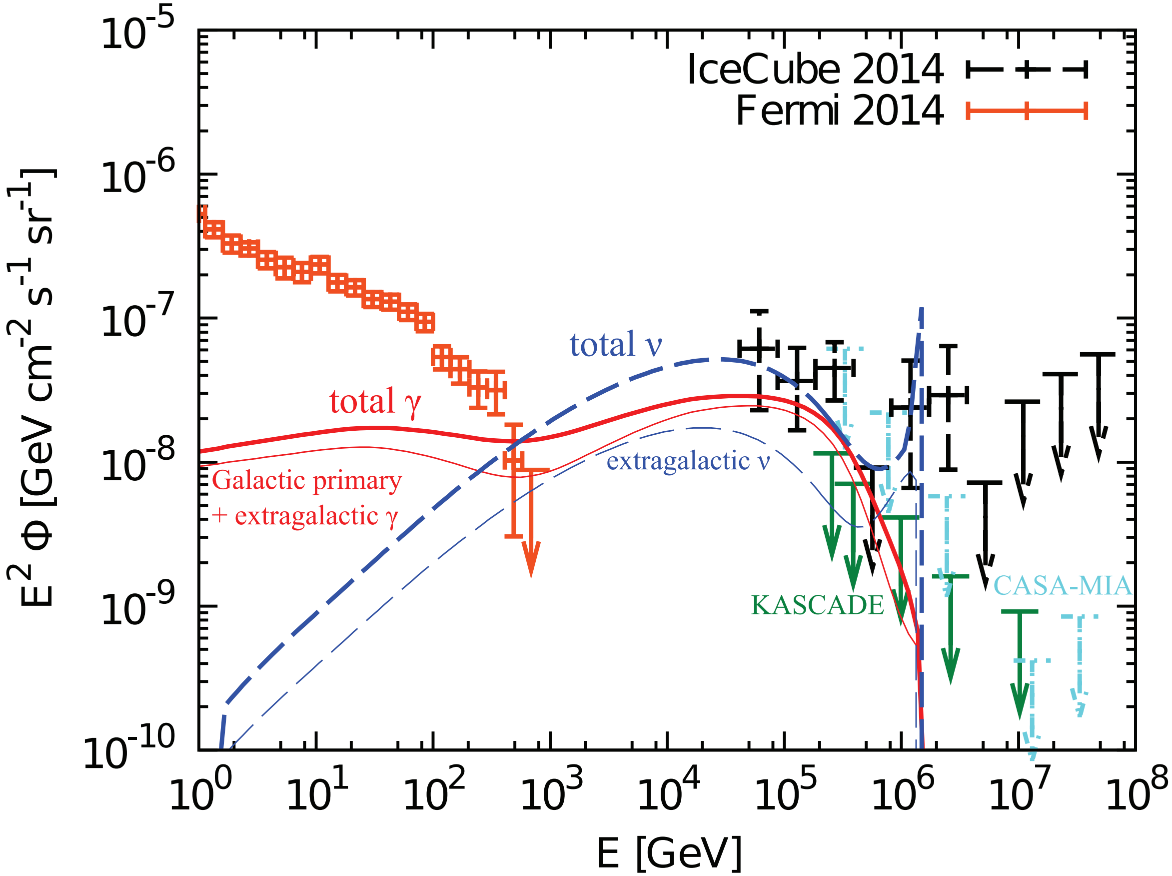
future IceCube-Gen2





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

Multimessenger Emission of Decaying Dark Matter



KM, Laha, Ando & Ahlers 15 PRL

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

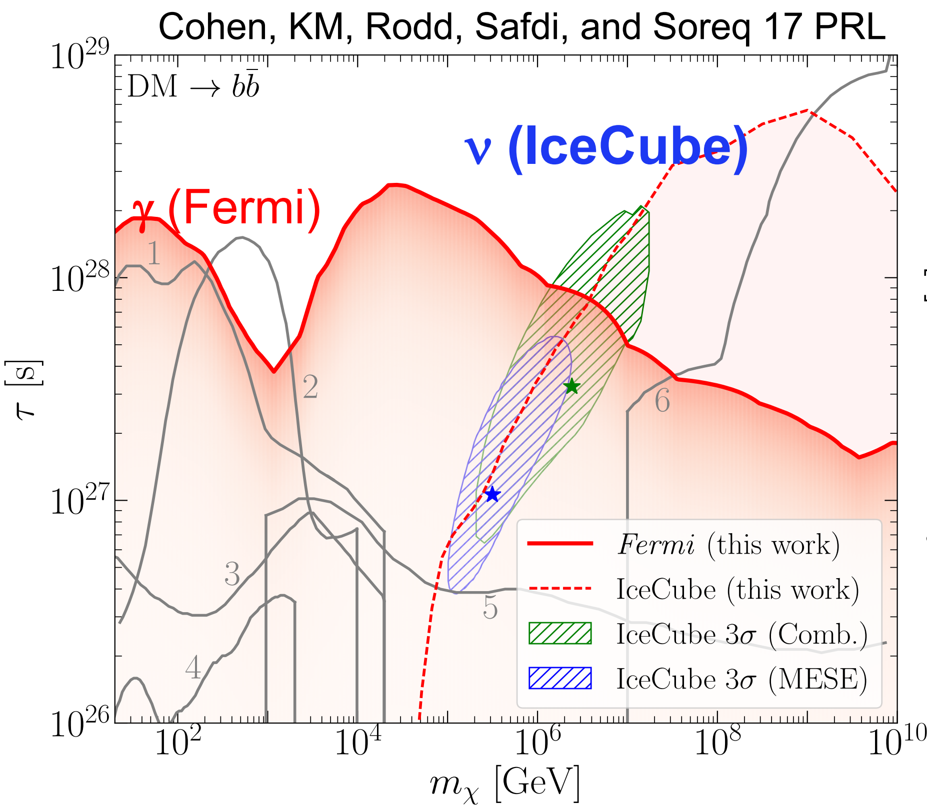
DM → b+bbar (88%)
DM → ν_e+ν_e (12%)

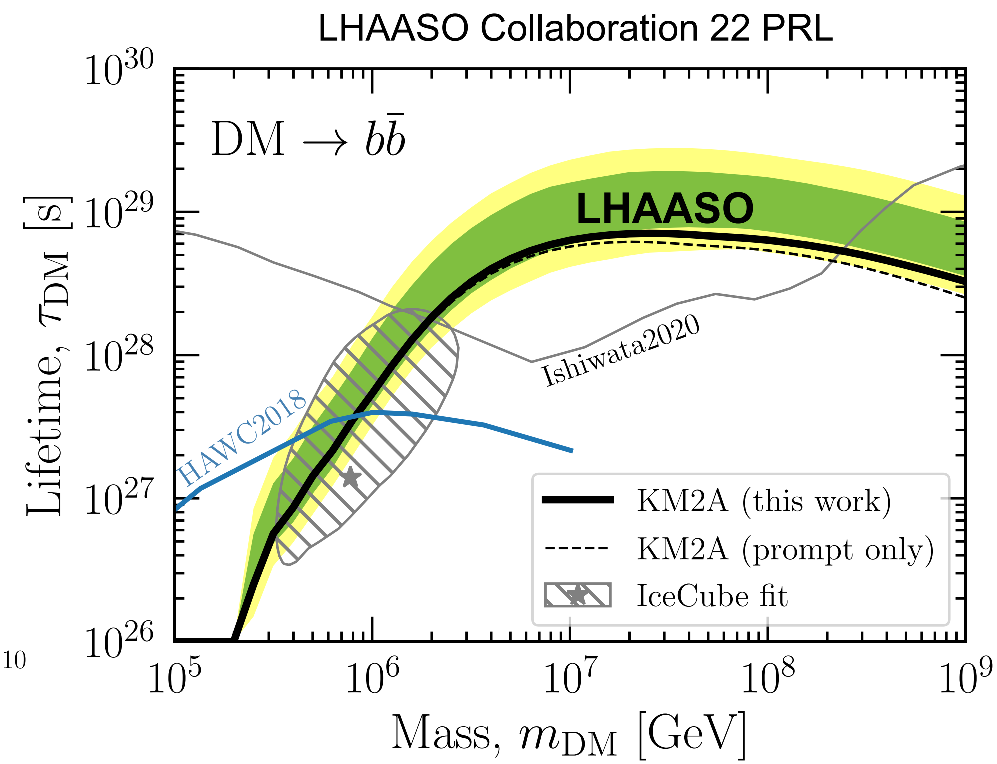
(similar results in other models that are proposed)

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

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

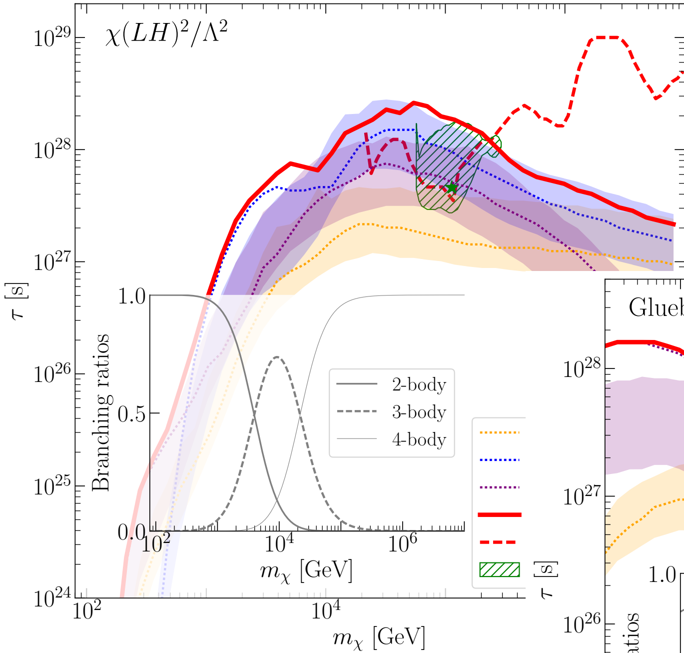
Multimessenger Search for TeV-EeV Scale Dark Matter

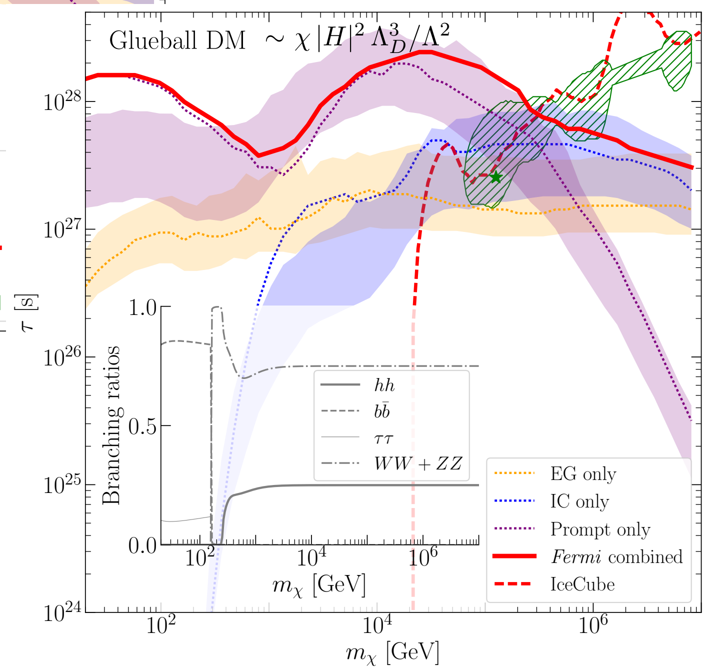


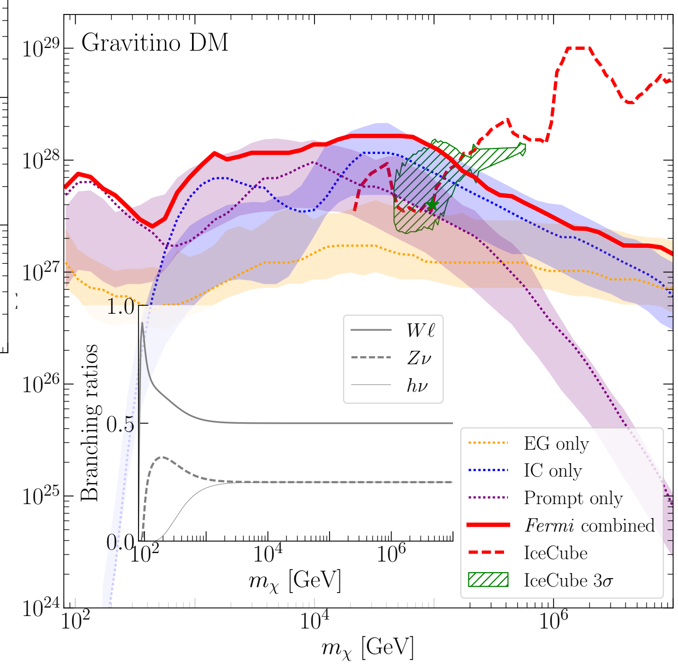


- IceCube, LHAASO and Fermi limits are complementary and comparable
- Nearly excluding dark matter scenarios to explain the all-sky IceCube ν data
- Unique probes of superheavy dark matter that is difficult to directly test

Model-Dependent Results







dark glueball case

$$\tau \simeq 5\times 10^{27}\ \mathrm{s}\left(\frac{3}{N_D}\frac{1}{4\pi\lambda_D}\right)^2\left(\frac{\Lambda}{m_{\rm Pl}}\right)^4\left(\frac{0.1\ \mathrm{PeV}}{\Lambda_D}\right)^5$$

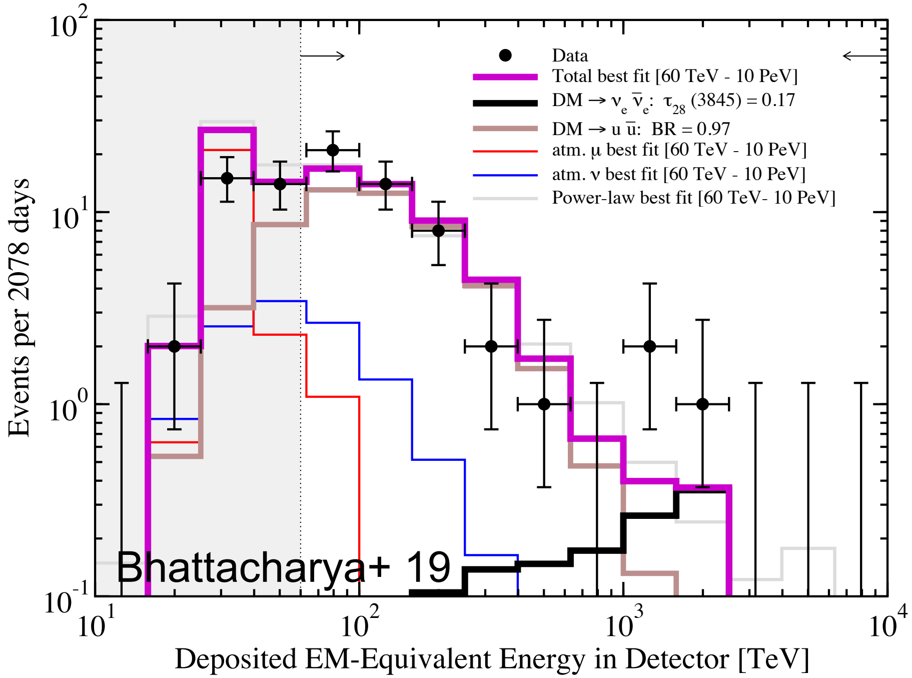
Examples of Models (EFT)

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	$g^2\bar{m}_\chi \lesssim 6\times 10^{-57}$
$(3)_0$	$\phi^a\tilde{H}\sigma^a H$	$hh,\ Z^0Z^0, W^+W^-, f\bar{f}$	$1:1:2:16N_c y_f^2\frac{v^2}{m_\chi^2}$	$\bar{m}_\chi/\bar{\Lambda}^2 \gtrsim 9\times 10^{79}$
	$\phi^a W_{\mu\nu}^a B^{\mu\nu}$	$\gamma\gamma,\ Z^0\gamma,\ Z^0Z^0$	$c_W^2 s_W^2 : 2\left(c_W^2 - s_W^2\right)^2 : c_W^2 s_W^2$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 1\times 10^{31}$
	$\phi^a\bar{L}E\sigma^a H$	$h\ell^+\ell^-,\ Z^0\ell^+\ell^-,\ W^\pm\ell^\mp\nu,\ \ell^+\ell^-$	$1:1:2:32\pi^2\frac{v^2}{m_\chi^2}$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 4\times 10^{29}$
	$\phi^a\bar{Q}U\sigma^a\tilde{H},\ \phi^a\bar{Q}D\sigma^a H$	$hq\bar{q},\ Z^0q\bar{q},\ W^\pm q'\bar{q},\ q\bar{q}$	$1:1:2:32\pi^2\frac{v^2}{m_\chi^2}$	$\bar{\Lambda}^2/\bar{m}_\chi^3 \gtrsim 1\times 10^{30}$
$(3)_1$	$\phi^a L^T\sigma^a\sigma^2 L$	$\nu\nu$	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	$g^2\bar{m}_\chi \lesssim 4\times 10^{-56}$

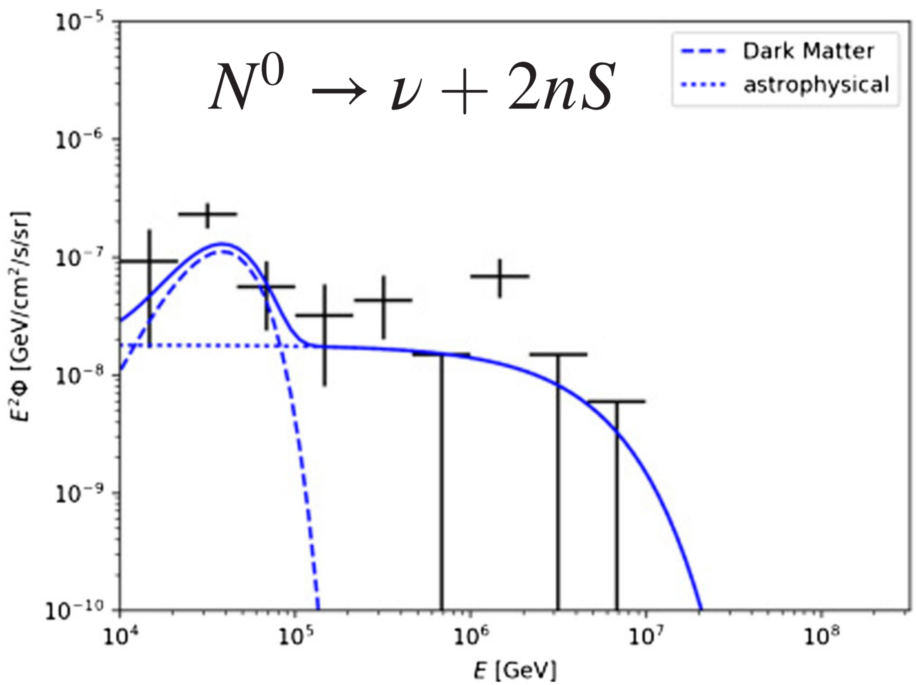
Viable DM Scenarios?

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



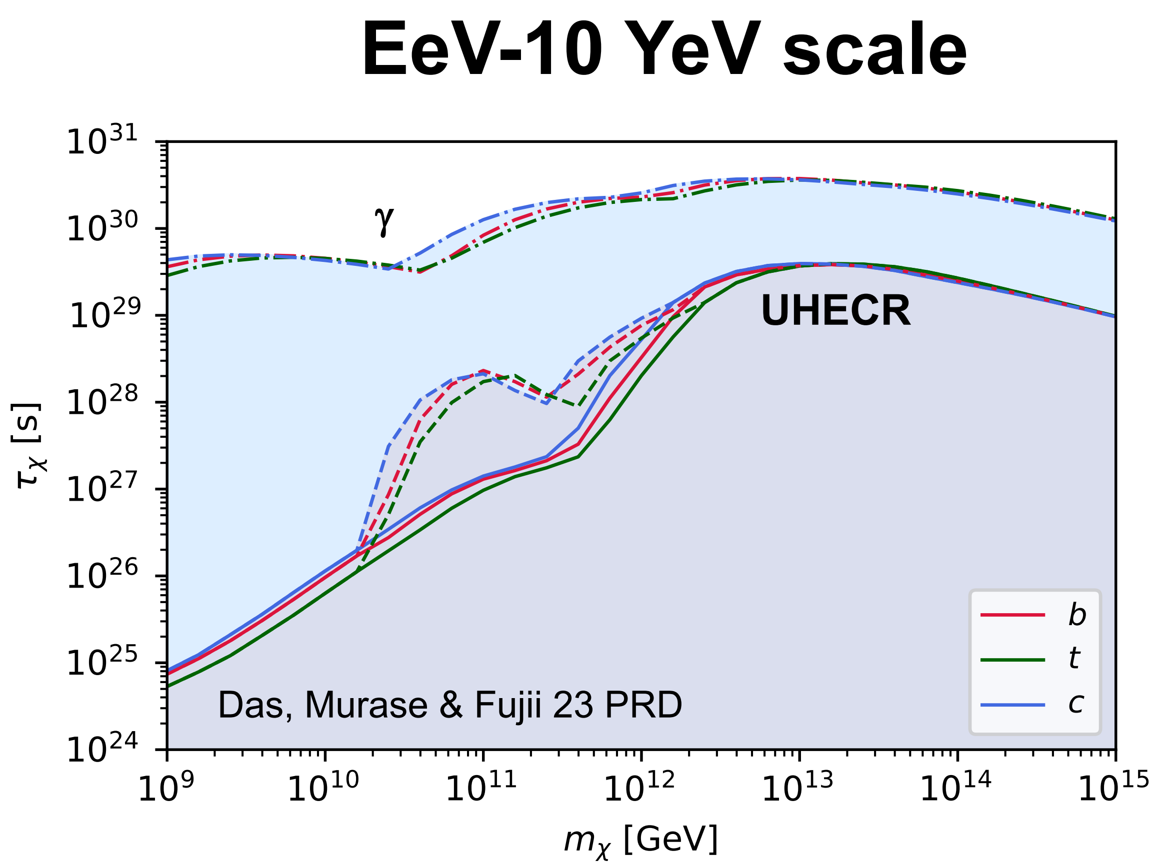
$$\mathcal{L}_{\rm int} = \mathcal{L}_X + \frac{1}{M^{3n-3}} X S^{2n} + \frac{1}{M_*^{3n-1}} \bar{L}\ell S^{2n} + \text{H.c.}$$

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



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

Current Energy Frontier in Space

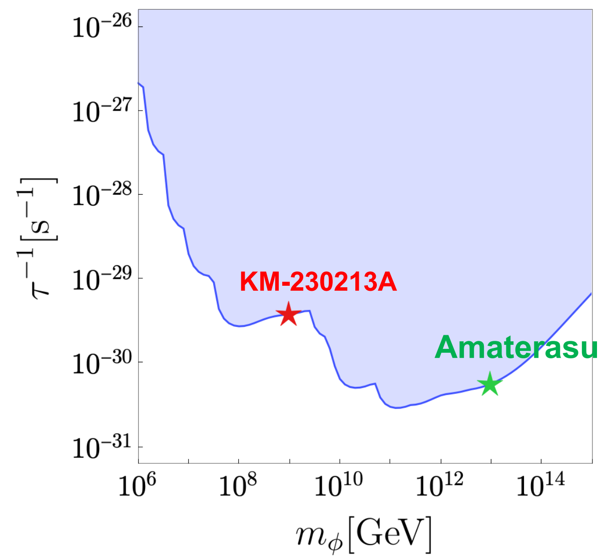


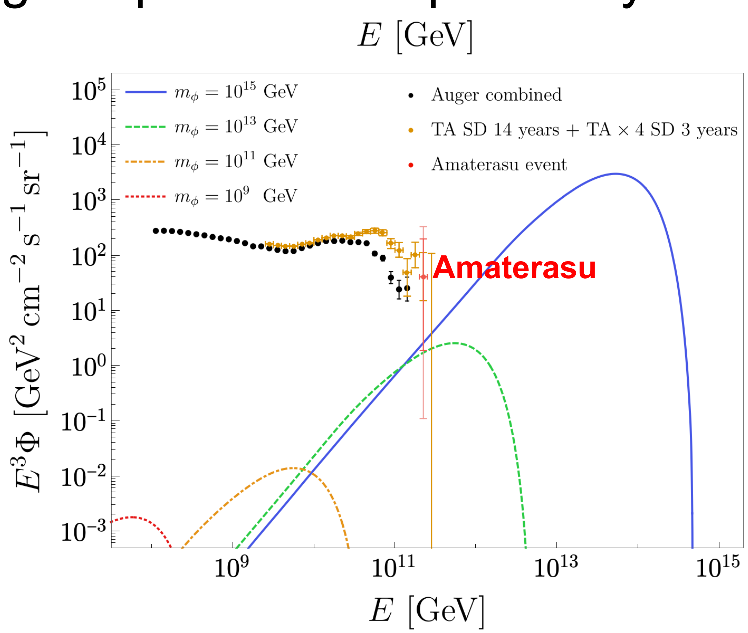
- UHECR measurement & UHE photon limits:
  $\tau_{DM} > 10^{30}$ s up to GUT scale: world-best limits for EeV or higher

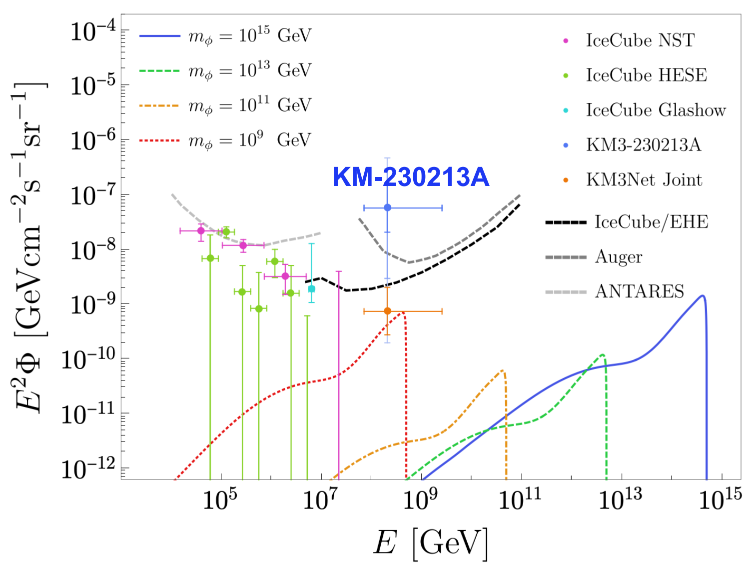
The Highest-Energy Particles & Inflaton DM

- Collaboration w. A01
- Inflaton DM models
  in (modified) natural inflation
  (entropy dilution necessary)
- Scalar DM
  $\phi \to H\bar{q}q,\ \bar{H}\bar{l}l,\ \bar{H}H,\ gg,\ AA,\ BB,$
- UHE neutrons can also be used
  as good probes of superheavy DM

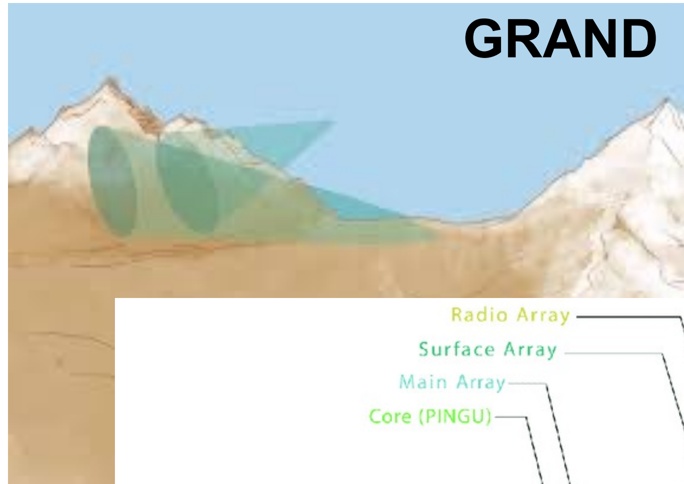
KM, Narita & Yin 2504.15272

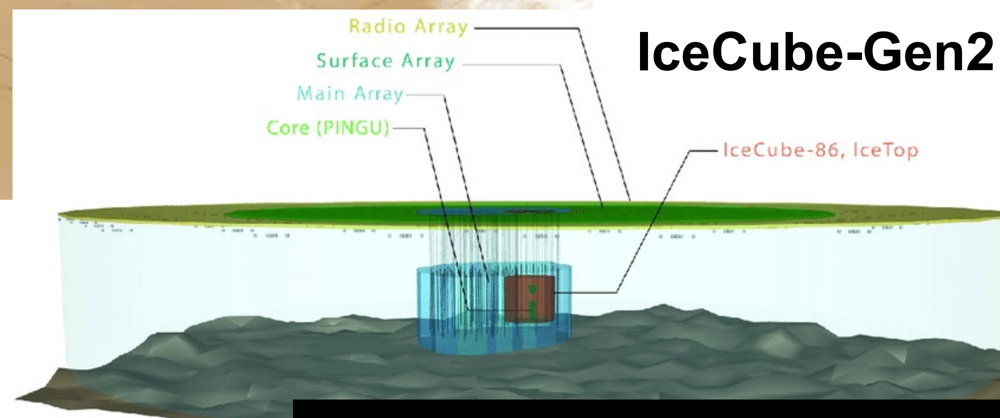


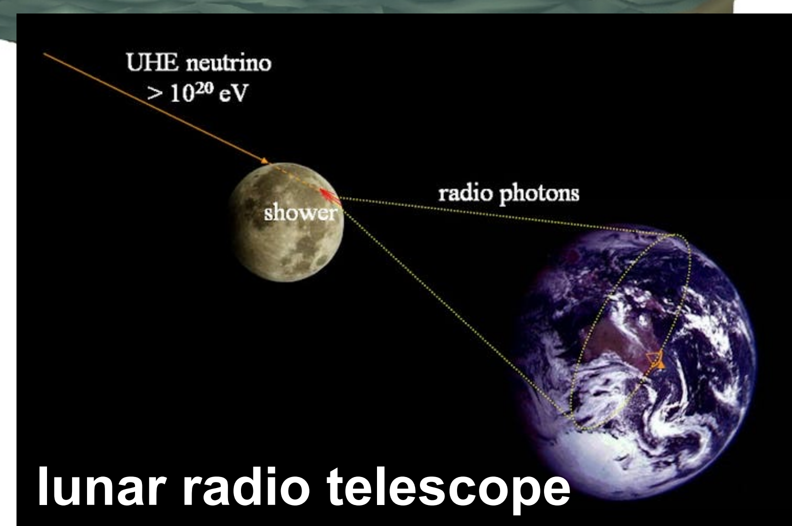




Future Energy Frontier in Space







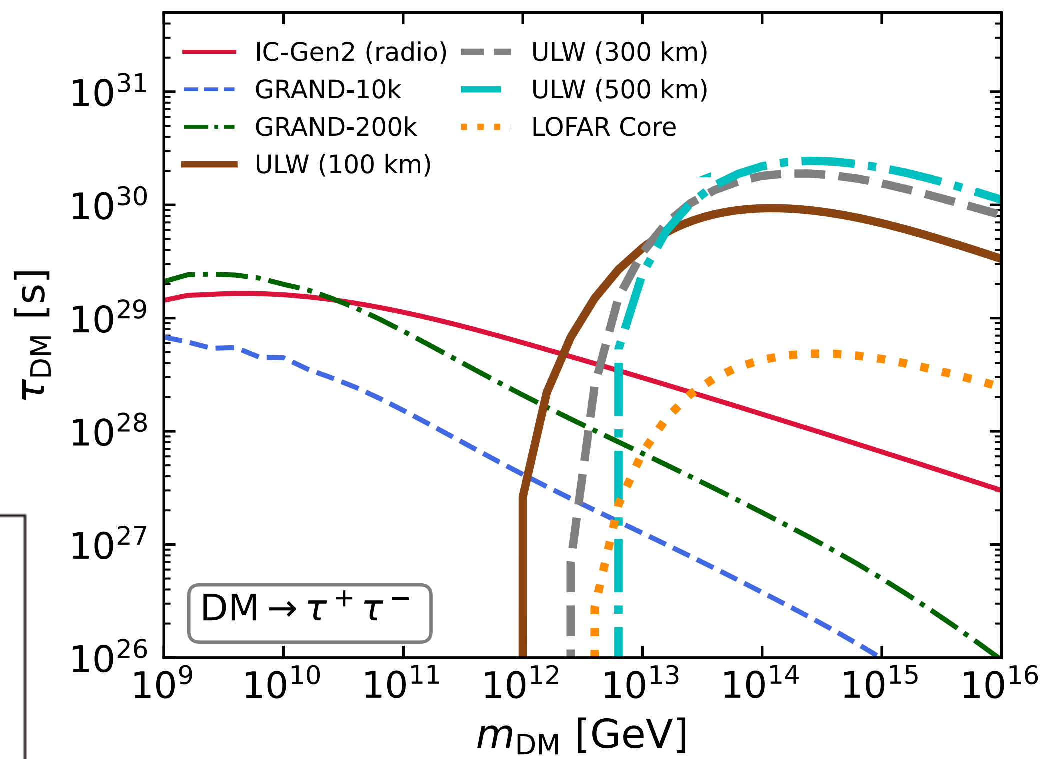
- UHE neutrino observations will be drastically improved in future
- Essentially no atmospheric ν bkg.

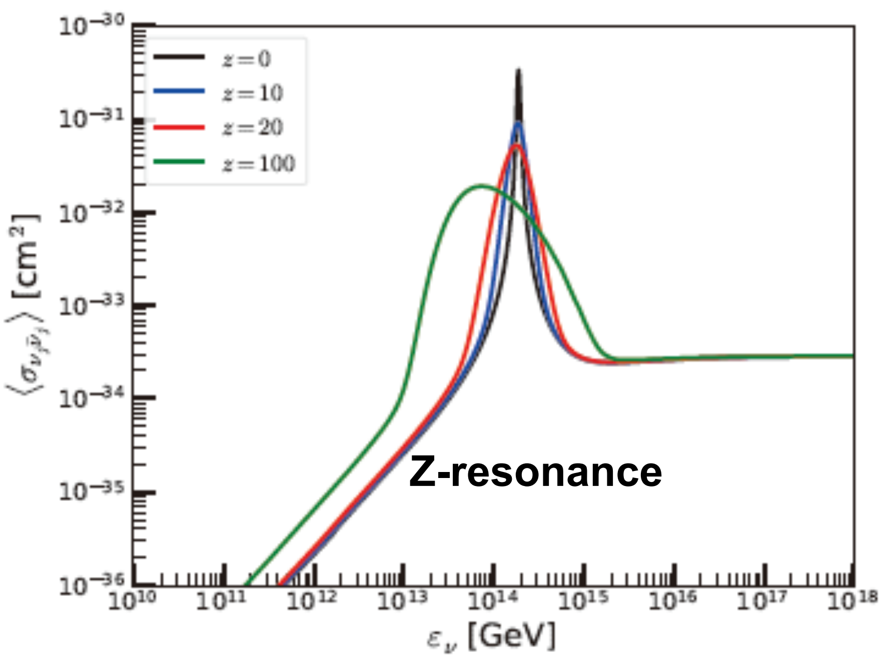
Future Neutrino Search for Superheavy Dark Matter

Das, Carpio & Murase 25 PRD

Future UHE ν detectors

- τ_{DM} >~ 10^{30} s up to GUT scale
- Best probe for leptonic channels
- No astrophysical neutrinos for GUT-scale DM (range of lunar radio telescopes)





BONUS

- Neutrino self-interaction considered
- Will be public in the **AMES** code
- Applicable to BSM (ex. Z' physics)

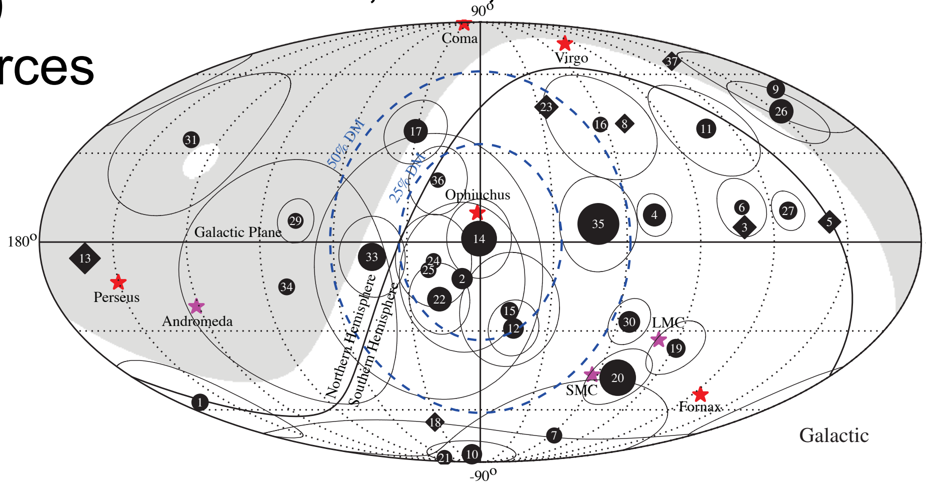
Future Tests for Dark Matter Scenarios

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

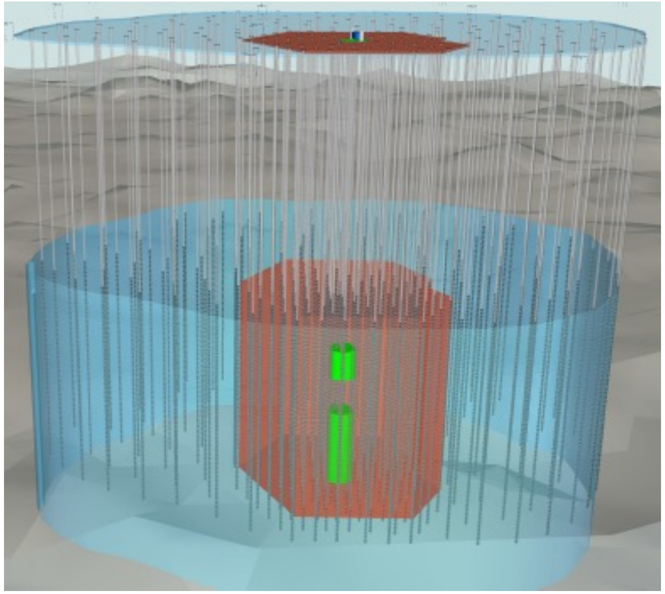
$$\mathbf{flux} \propto M_{dm}/\tau_{dm}/d^2$$

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

KM, Laha, Ando & Ahlers 15 PRL



Name	Galaxy	$\log j^{\rm dec}$ [GeVcm^{-2}sr]	Decl. [deg]	d_c [Mpc]	$M_{\rm vir}$ [$M_\odot$]	$r_{\rm vir}$ [kpc]	θ [deg]
Andromeda	–	20.76	41.06	0.75	12.44	369.96	28.26
NGC 4472	Virgo	20.33	12.41	15.82	14.66	2023.32	7.33
NGC 5128	–	19.9	-45.53	3.63	12.95	546.68	8.62
NGC 0253	–	19.76	-25.21	3.49	12.78	477.98	7.84
Maffei 1	–	19.68	59.61	3.46	12.69	447.79	7.41
NGC 6822	–	19.42	-14.8	0.48	10.71	97.91	11.69
NGC 3031	–	19.57	69.22	3.65	12.63	427.63	6.71
NGC 4696	Centaurus	19.55	-41.22	37.27	14.62	1971.53	3.03
NGC 1399	–	19.42	-35.39	18.16	13.87	1105.77	3.49
IC0356	–	19.36	69.78	13.9	13.57	881.97	3.63
NGC 4594	–	19.32	-11.49	11.34	13.36	751.37	3.8
ESO 137-G 006	Norma	19.42	-60.91	75.25	15.1	2842.43	2.16
NGC 4736	–	19.07	41.36	4.43	12.3	331.68	4.29
NGC 1275	Perseus	19.37	41.51	77.64	15.08	2796.52	2.06
NGC 3627	–	19.12	13.13	9.71	13.02	578.85	3.42
NGC 1316	Fornax	19.1	-37.11	18.42	13.56	873.63	2.72
NGC 4565	–	19.01	25.92	13.19	13.18	651.34	2.83
13000812+2758370	Coma	19.24	27.98	107.61	15.23	3132.32	1.67
NGC 1553	Dorado	19.02	-55.78	17.76	13.45	799.85	2.58
NGC 3311	Hydra	19.13	-27.56	48.01	14.42	1687.23	2.01
NGC 4261	–	19.02	5.89	31.61	13.95	1179.31	2.14



Neutrino Search for Galaxy Clusters

Chianese, Kheirandish & KM 24