# Neutrinos on the Earth and from the Sky

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IFIC, CSIC-U. Valencia

7th NeXT Workshop
Abingdon, UK

# Plan of lectures

- I From the beginning...
- II Neutrino oscillations
- III High-energy neutrinos
- IV New physics with neutrino telescopes

# New physics

effects on the energy spectrum

effects on the angular distribution

production of special features (dips, bumps)

non-standard flavor composition

connection to other type of physics

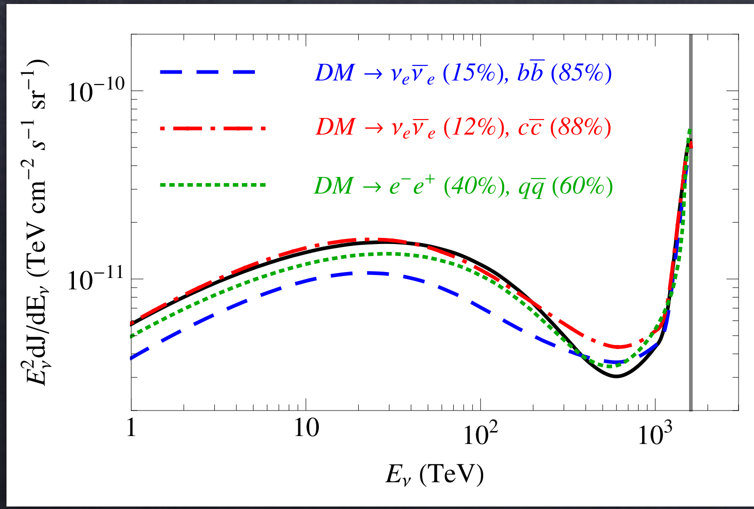
# Dark matter decays

Can the highest energy IceCube neutrinos be explained by heavy dark matter decays?

$$\text{Rate} \sim V\, N_N\, \sigma_N\, L_{MW} \frac{\rho_{DM}}{m_{DM}} \frac{1}{\tau_{DM}} \sim 10/\text{year} \rightarrow \left(\frac{\tau_{DM}}{10^{28}\,\text{s}}\right)\left(\frac{m_{DM}}{1\ \text{PeV}}\right) \sim 1$$

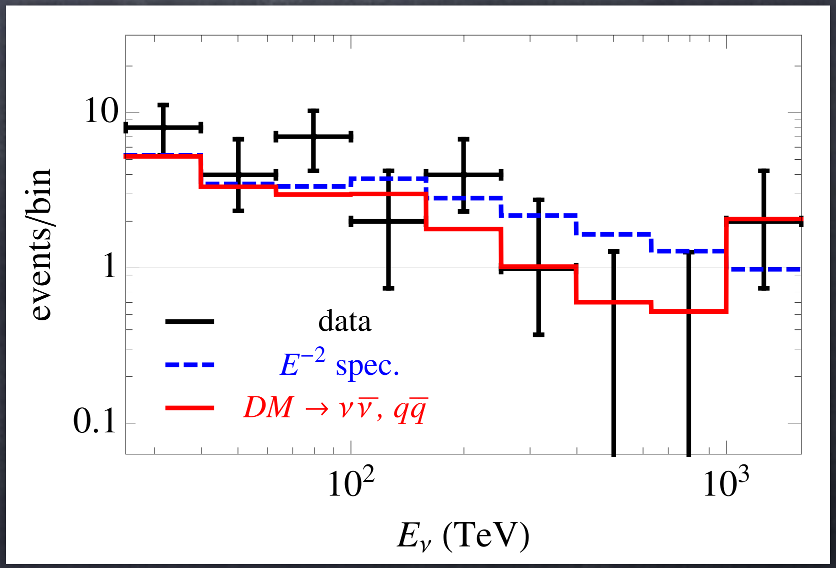
B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, Phys, Rev. D88:015004, 2013

Can ALL IceCube neutrinos be explained by heavy dark matter decays?




combination of soft and hard channels

2-year HESE data




A. Esmaili and P. D. Serpico, JCAP 1311:054, 2013

# NEUTRINOS FROM DARK MATTER DECAYS

**Two components**

GALACTIC    EXTRA-GALACTIC

$$\frac{d\Phi_{\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu}$$

$$\frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} = \frac{1}{4\pi m_{DM}\tau_{DM}} \frac{dN_{\nu_\alpha}}{dE_\nu} \int_0^\infty \rho\left[r(s,b,l)\right] ds$$

$$\frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu} = \frac{\Omega_{DM}\rho_c}{4\pi m_{DM}\tau_{DM}} \int_0^\infty dz \frac{1}{H(z)} \frac{dN_{\nu_\alpha}}{dE_\nu}\left[(1+z)E_\nu\right]$$

DM mass

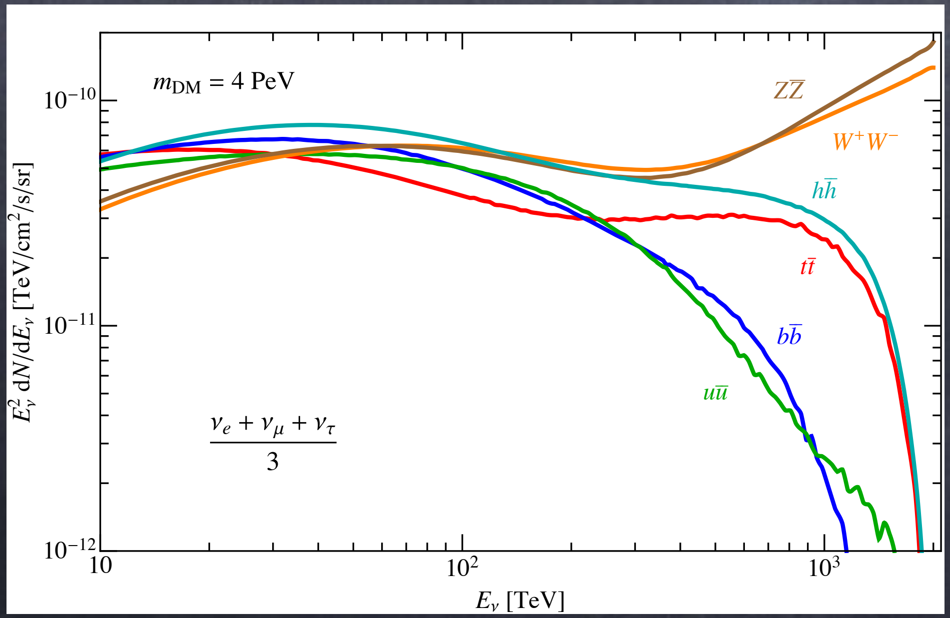
DM lifetime

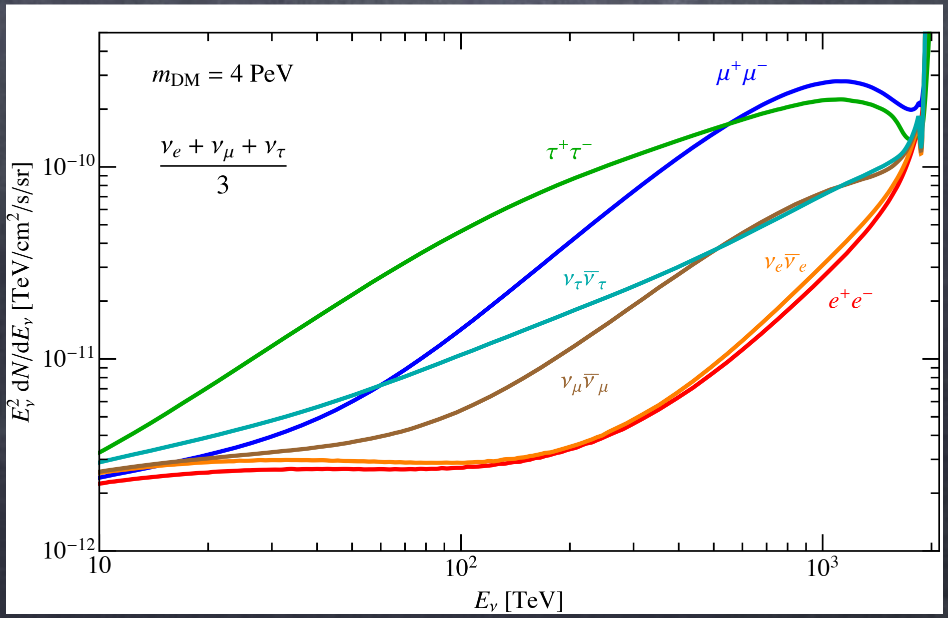
neutrino flux at production

DM galactic density

DM density of the Universe

Hubble function



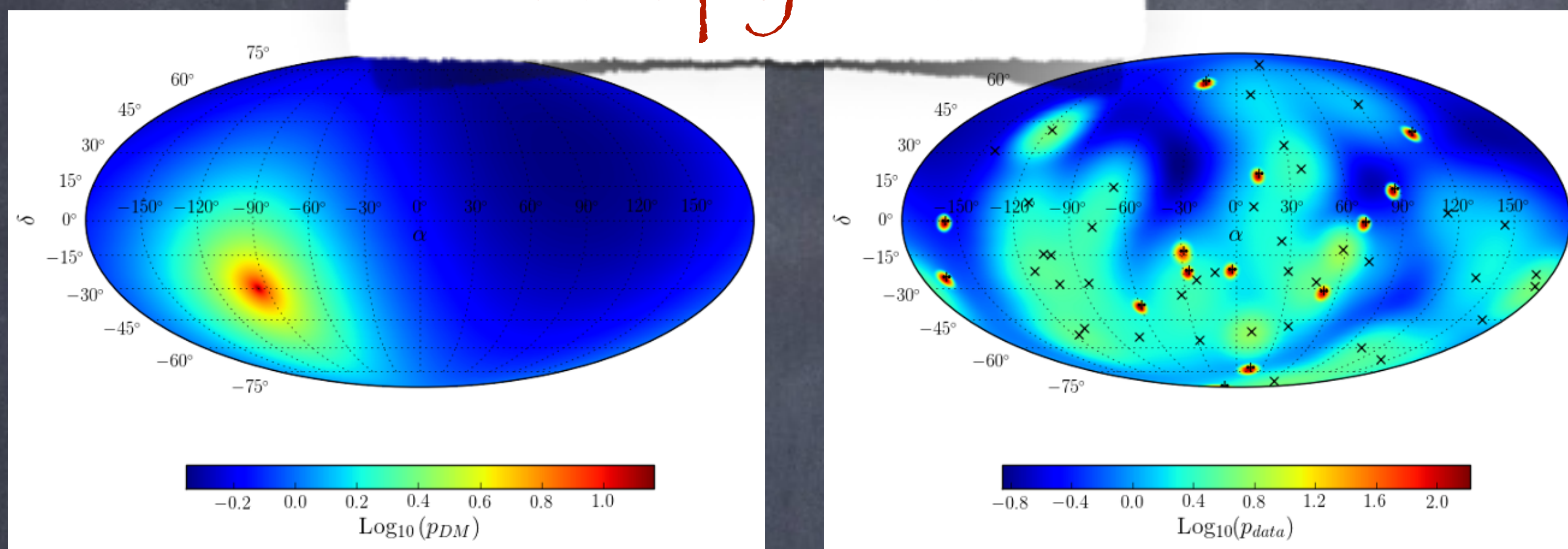

A. Bhattacharya, A. Esmaili SPR and I. Sarcevic, arXiv:1706.05746

# Dark matter decays

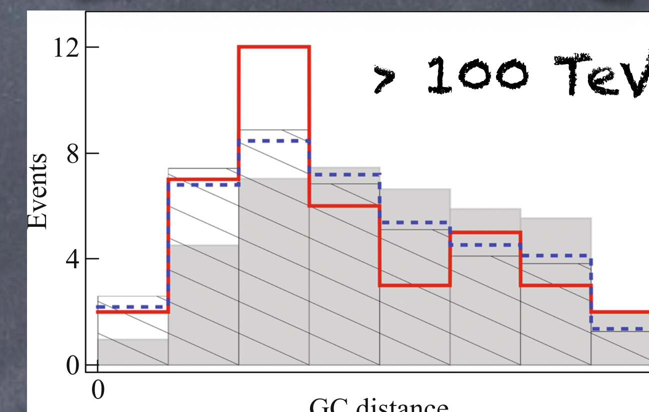
## Are neutrinos from DM decays compatible with the angular distribution of the IceCube events?

is isotropy better?

is DM better?

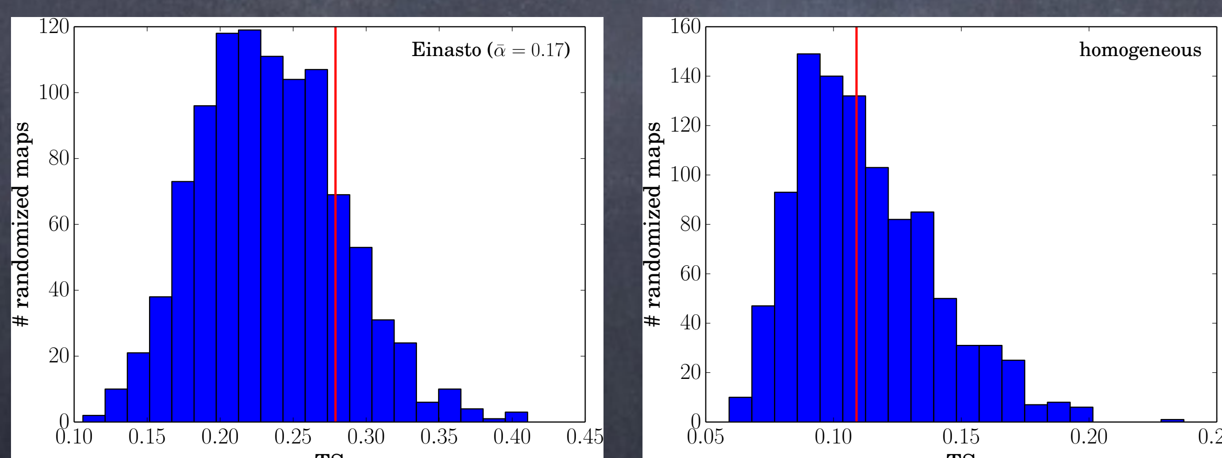



Y. Bai, R. Lu and J. Salvadó, JHEP 1601:161, 2016




S. V. Troitsky, JETP Letters 102:785, 2015

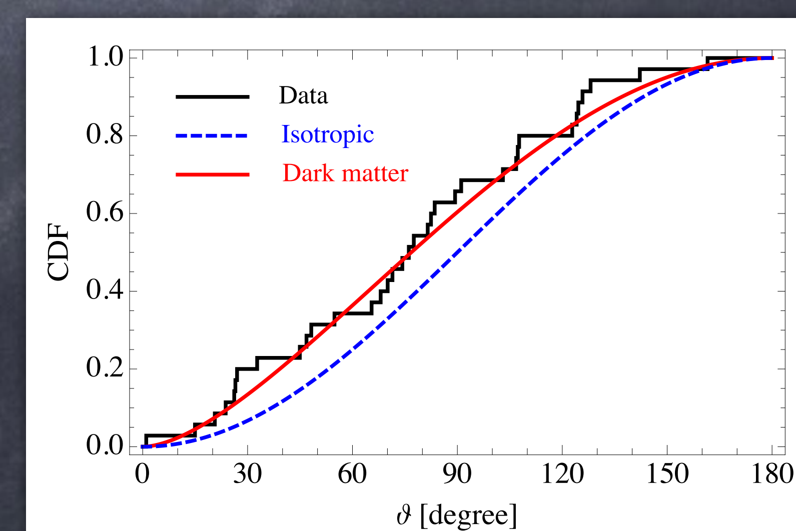
only galactic contribution




| Scenario | | KS |
|---|---|---|
| Astrophysics | Gal. plane | 0.007–0.008 |
| | Iso. dist. | 0.20–0.55 |
| DM decay | NFW | 0.06–0.16 |
| | Isoth. | 0.08–0.22 |

excess at 60-100 TeV

M. Chianese, G. Miele, S. Morisi and E. Vitagliano, Phys. Lett. B757:251, 2016

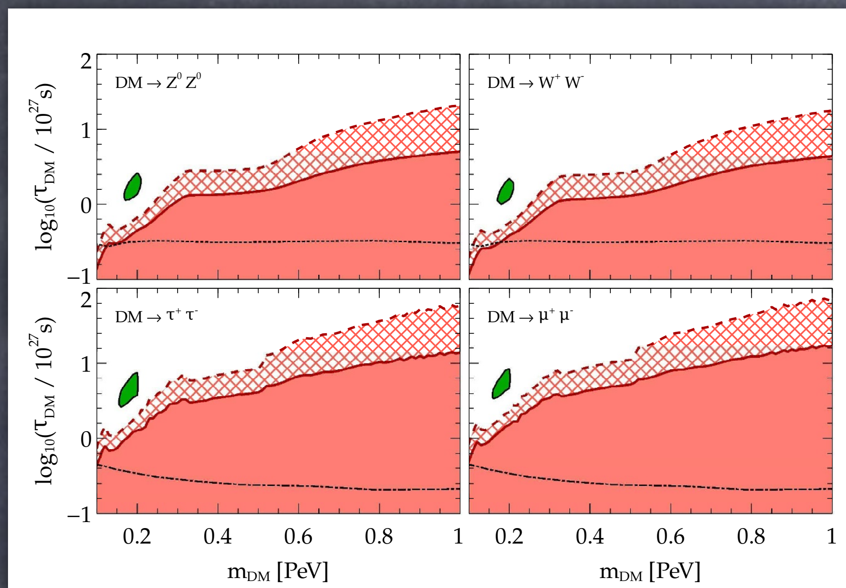



A. Esmaili, S. K. Kang and P. D. Serpico, JCAP 1412:054, 2014

# Dark matter decays

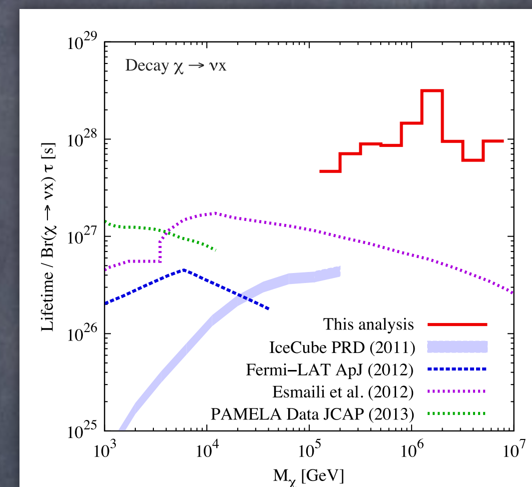
## several energy spectrum analyses

### Low energies: DM+astro (index=2)

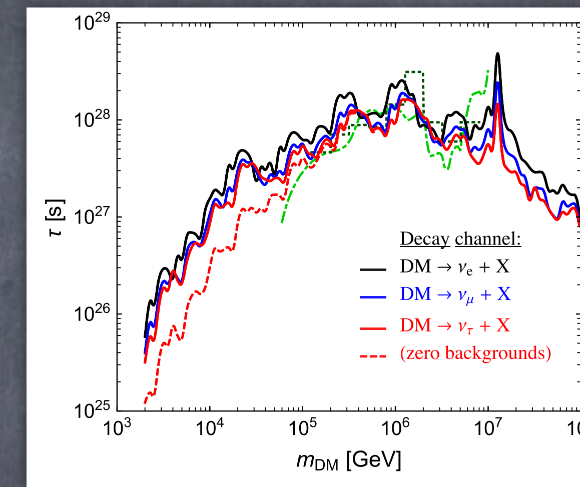



A. Bhattacharya, M. H. Reno and I. Sarcevic, JHEP 1406:110, 2014

### limits on monochromatic decays

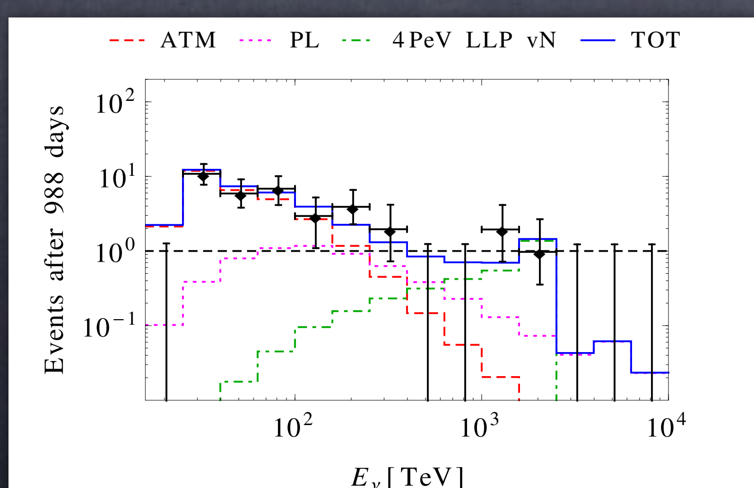



C. Rott, K. Kohri and S. C. Park, Phys. Rev. D92:023529, 2015



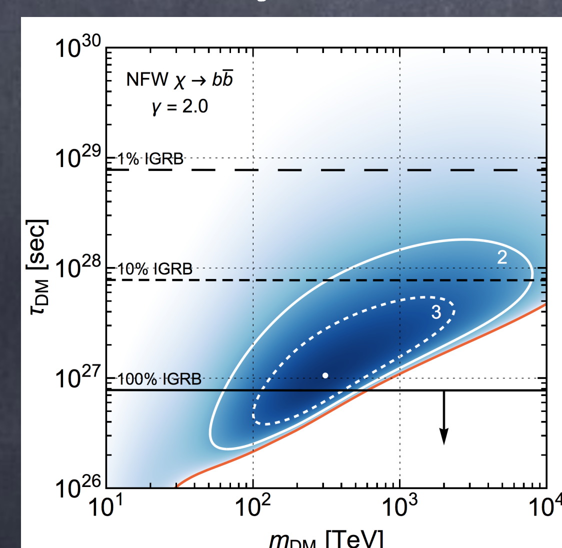

C. El Aisati, M. Gustafsson and T. Hambye, Phys. Rev. D92:123515, 2015

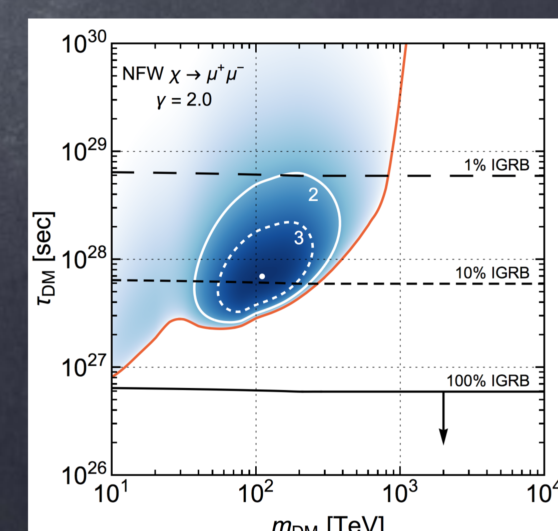
### Fixing PeV mass, some channels




C. S. Fong, H. Minakata, B. Panes and R. Z. Funchal, JHEP 1502:189, 2015

### Low energies (MESE), fixing astro index




M. Chianese, G. Miele and S. Morisi, JCAP 1701:007, 2017

# Dark matter decays: gamma-ray bounds

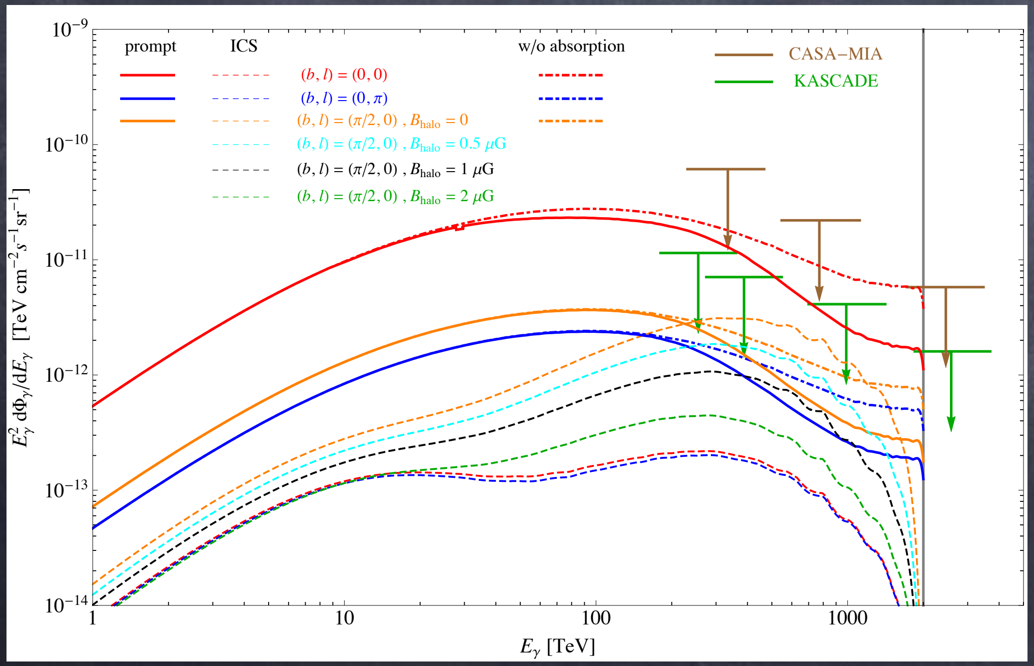
The neutrino spectrum from DM decays is accompanied by a gamma-ray spectrum

However, at energies E > 10-100 TeV, the Universe is opaque to gamma-rays due to the interaction with the background radiation field (IR or CMB):

gamma-rays produce $e^{\pm}$ pairs, which produce further gamma-rays via inverse Compton onto CMB photons, until the energies fall below ~100 GeV

**different absorption for extragalactic and galactic signals**

It seems to work....




A. Esmaili and P. D. Serpico, JCAP 1510:014, 2015

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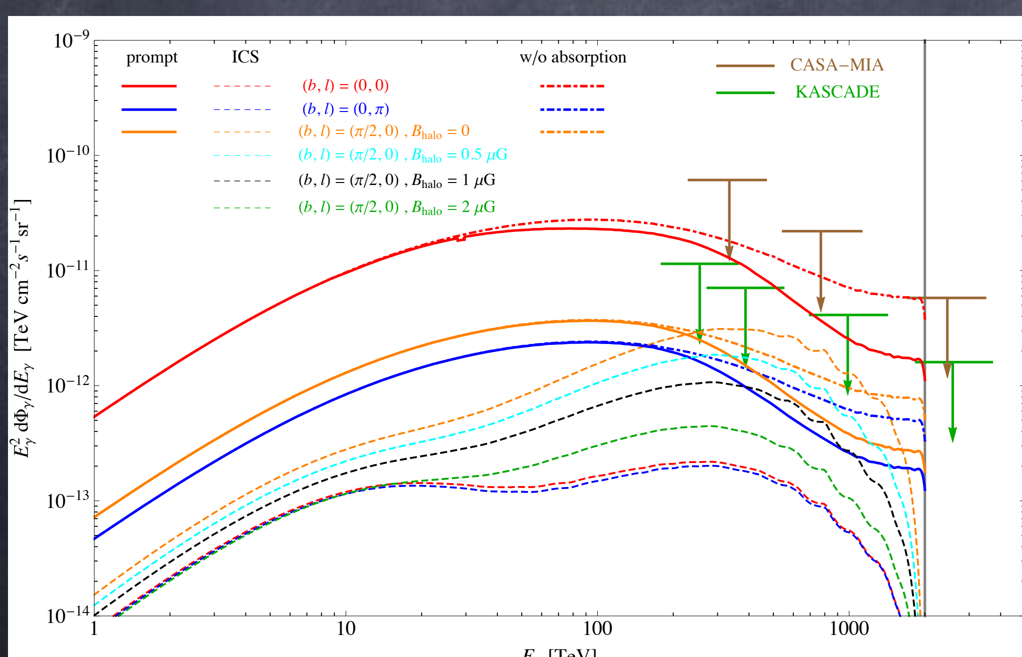
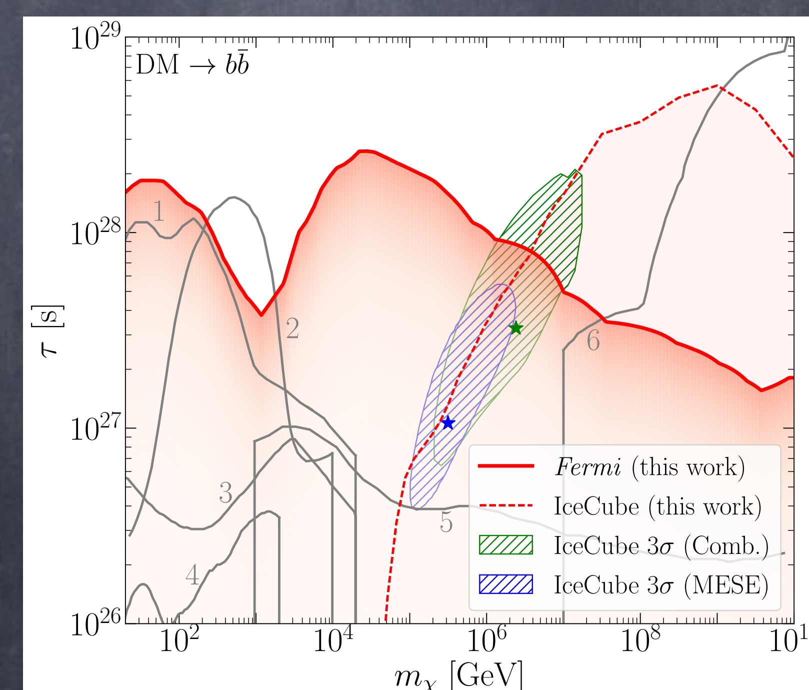



A. Esmaili and P. D. Serpico, JCAP 1510:014, 2015

maybe some tension with some channels....

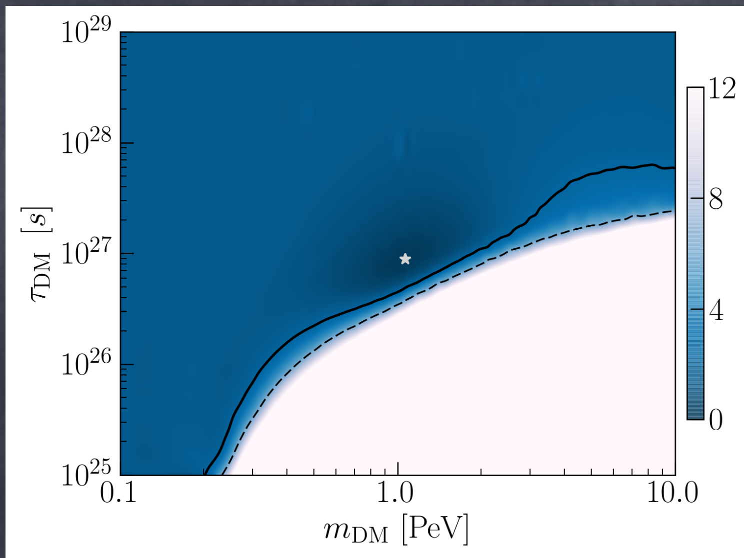



T. Cohen et al., arXiv:1612.05638

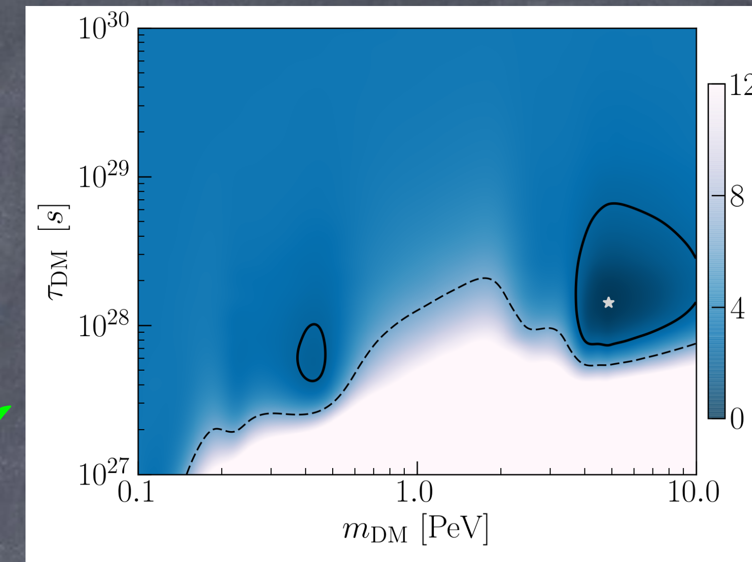
See also: K. Murase and J. F. Beacom, JCAP 1201:043, 2012

K. Murase, R. Laha, S. Ando and M. Ahlers, Phys. Rev. Lett. 115:071301, 2015

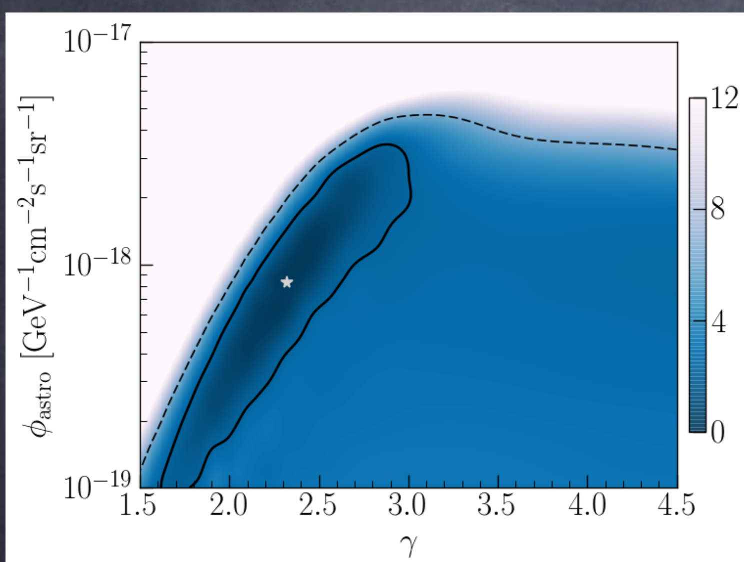
# DM decays + Astro: HESE analysis



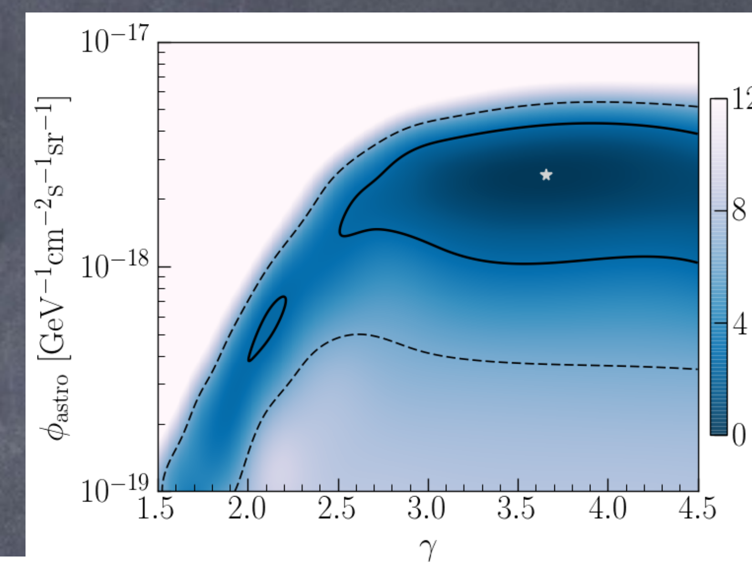

short lifetimes ✗
(problem with gamma-rays)




longer lifetimes ✓

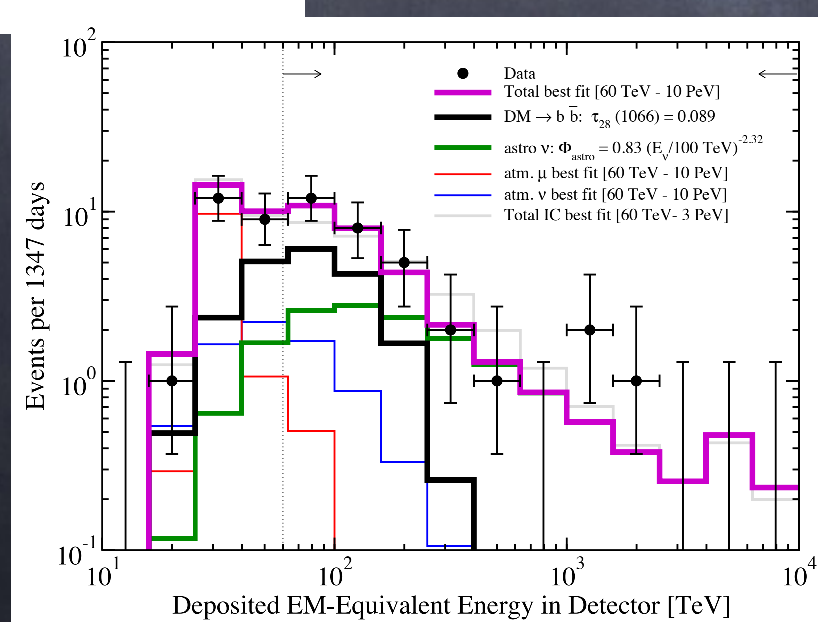


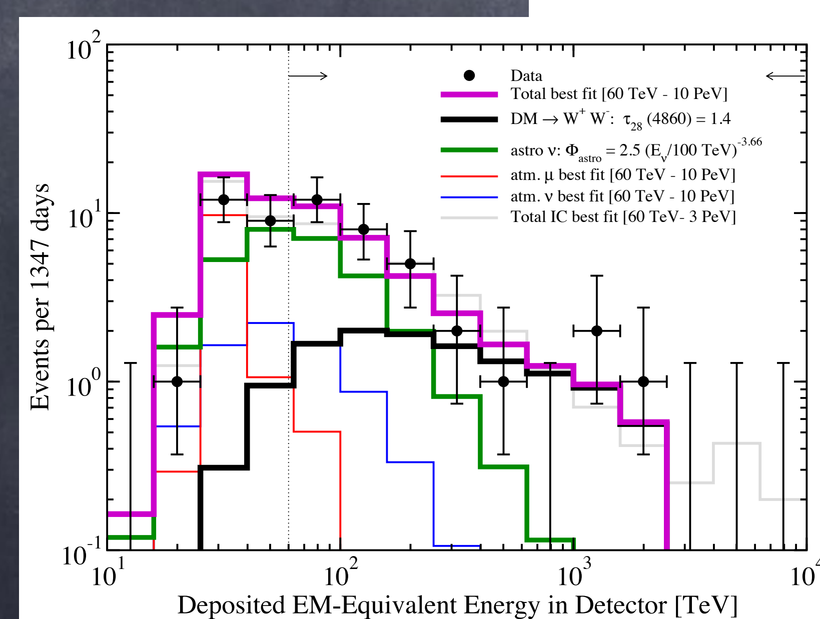

relatively hard astro spectrum ✓




very soft astro spectrum ✗

$DM \to b\bar{b}$

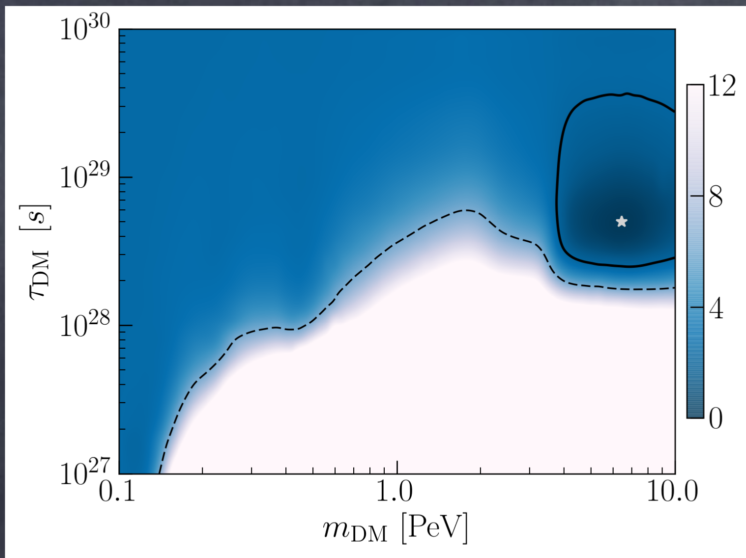


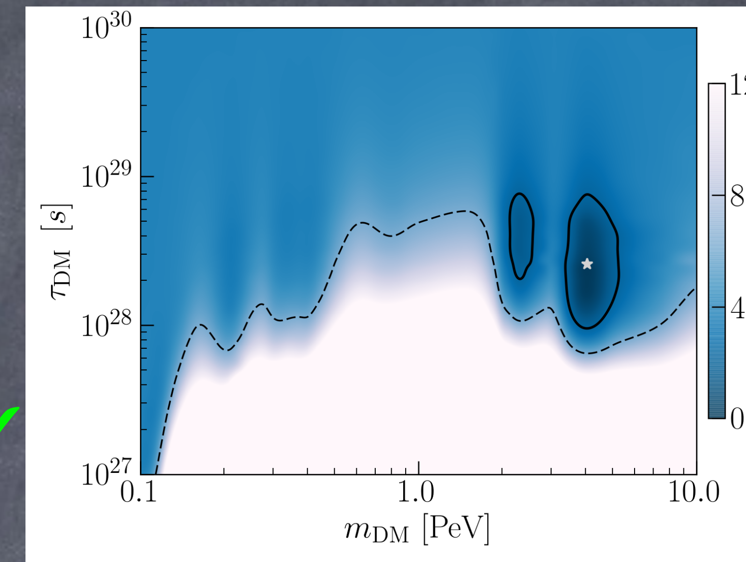

$DM \to W^+W^-$

A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, arXiv:1706.05746

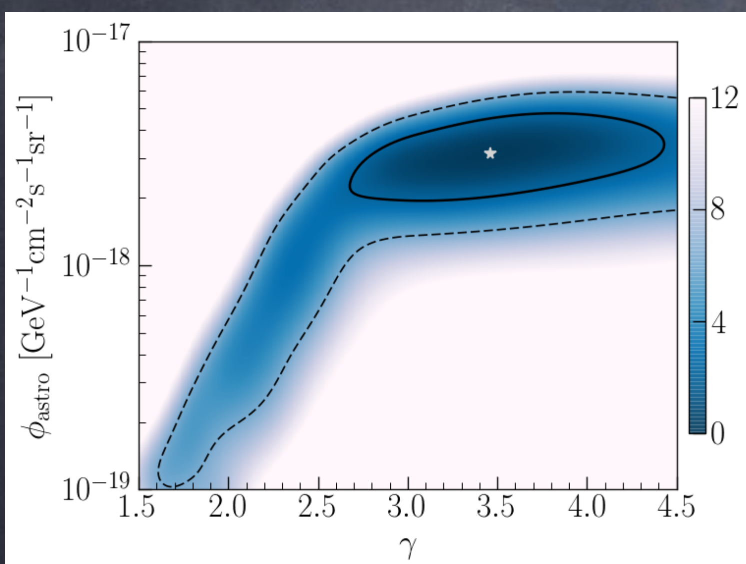
# DM decays + Astro: HESE analysis



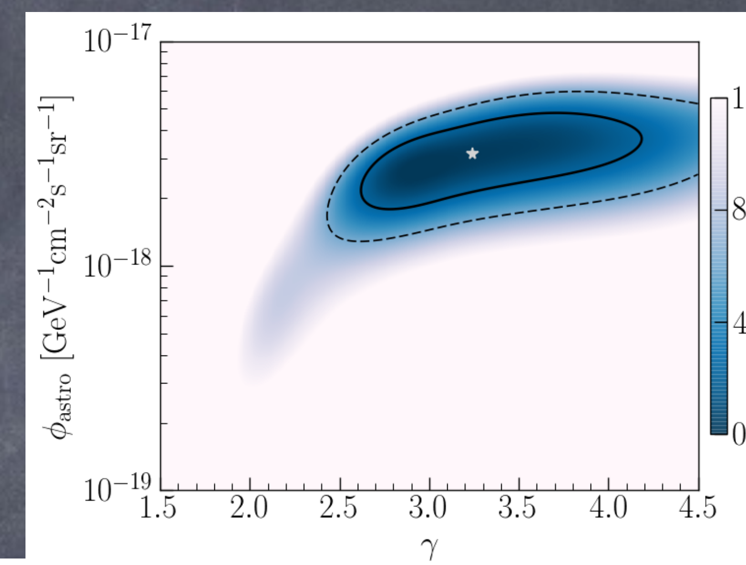

long lifetimes ✓




long lifetimes ✓

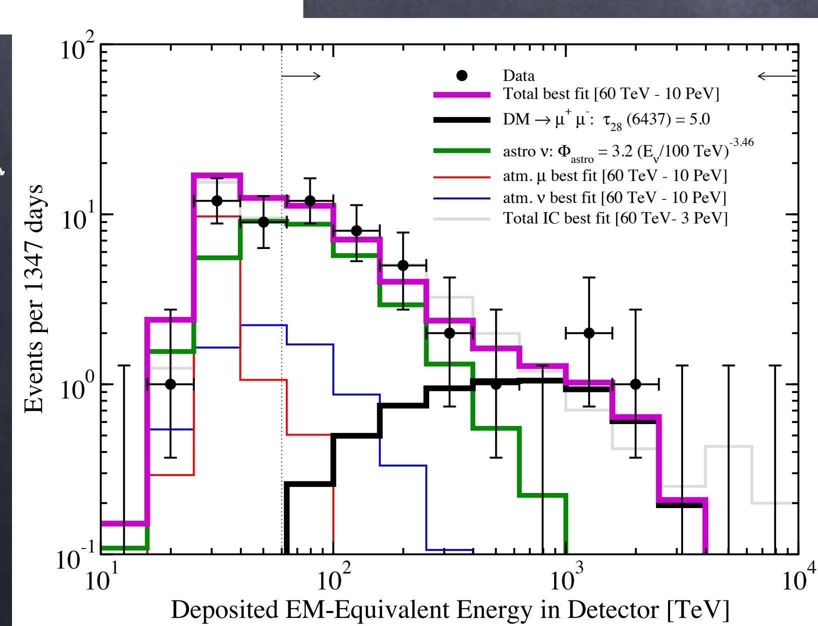


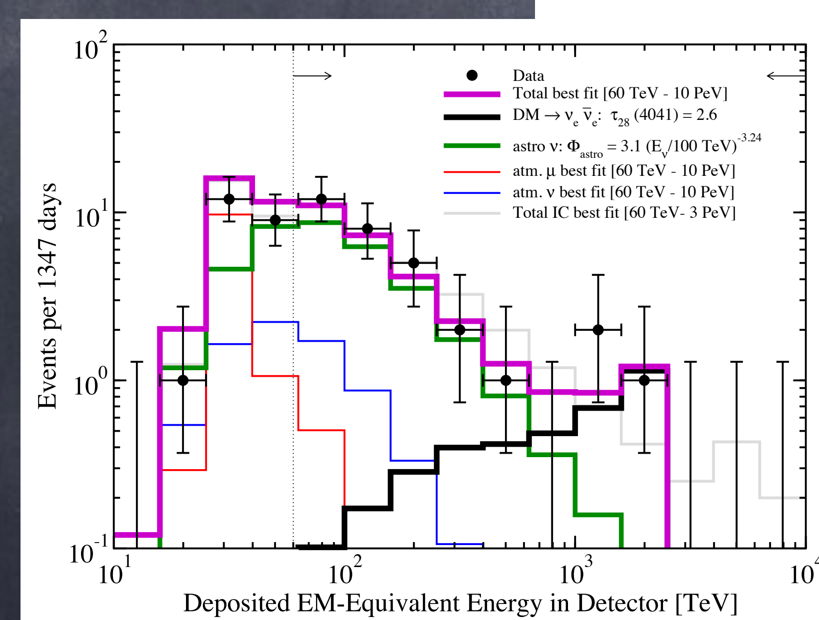

very soft astro spectrum ✗




very soft astro spectrum ✗

$\mathrm{DM} \rightarrow \mu^+\mu^-$




$\mathrm{DM} \rightarrow \nu_e \bar{\nu}_e$

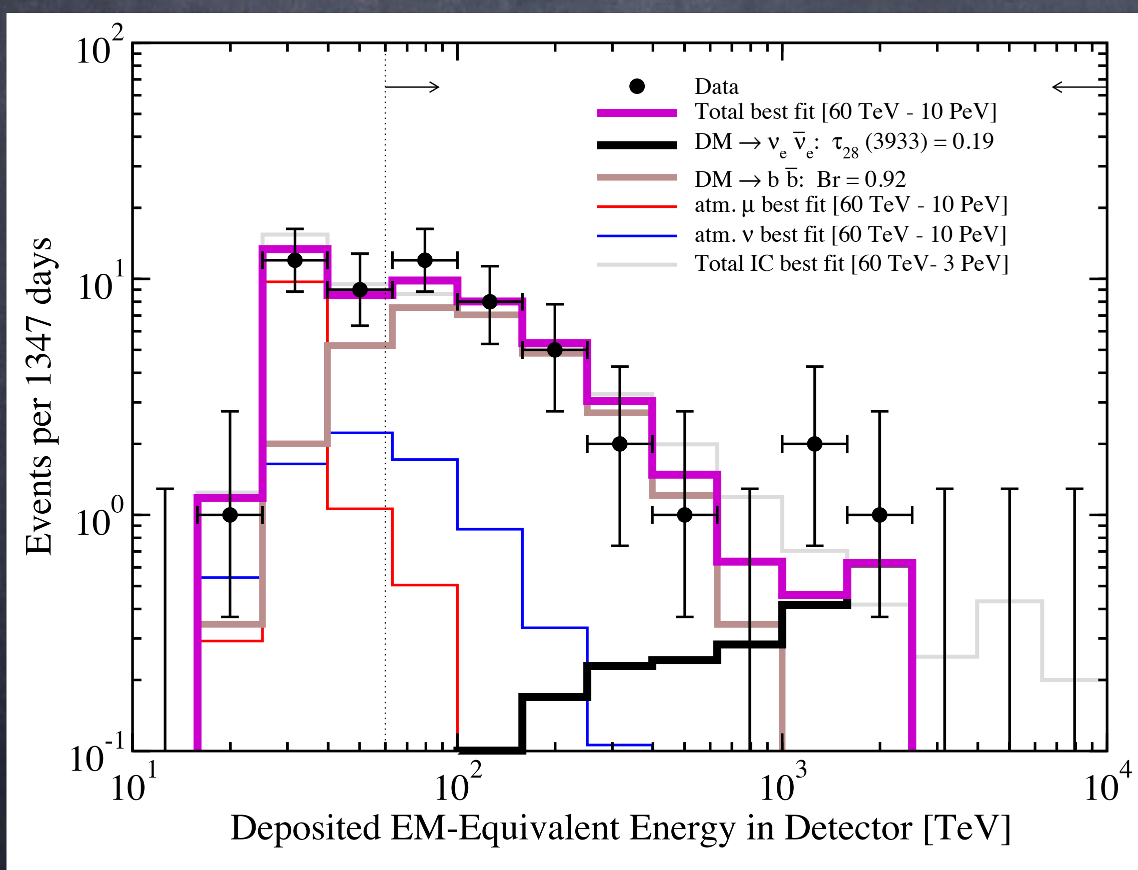
A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, arXiv:1706.05746

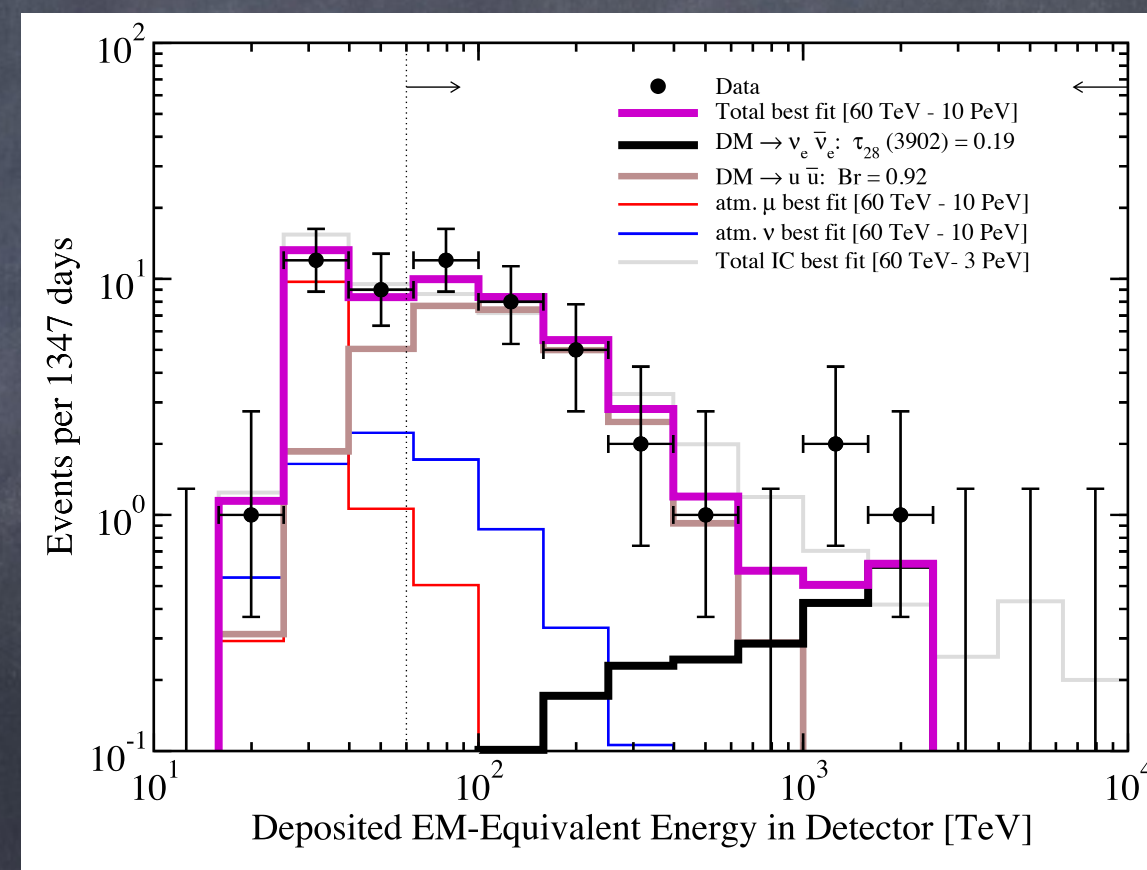
# Only DM decays: HESE analysis

Only DM?
Two decay channels

but too much contribution from soft channels?

$DM \to \{92\%\ b\bar{b};\ 8\%\ \nu_e\bar{\nu}_e\}$ $DM \to \{92\%\ u\bar{u};\ 8\%\ \nu_e\bar{\nu}_e\}$



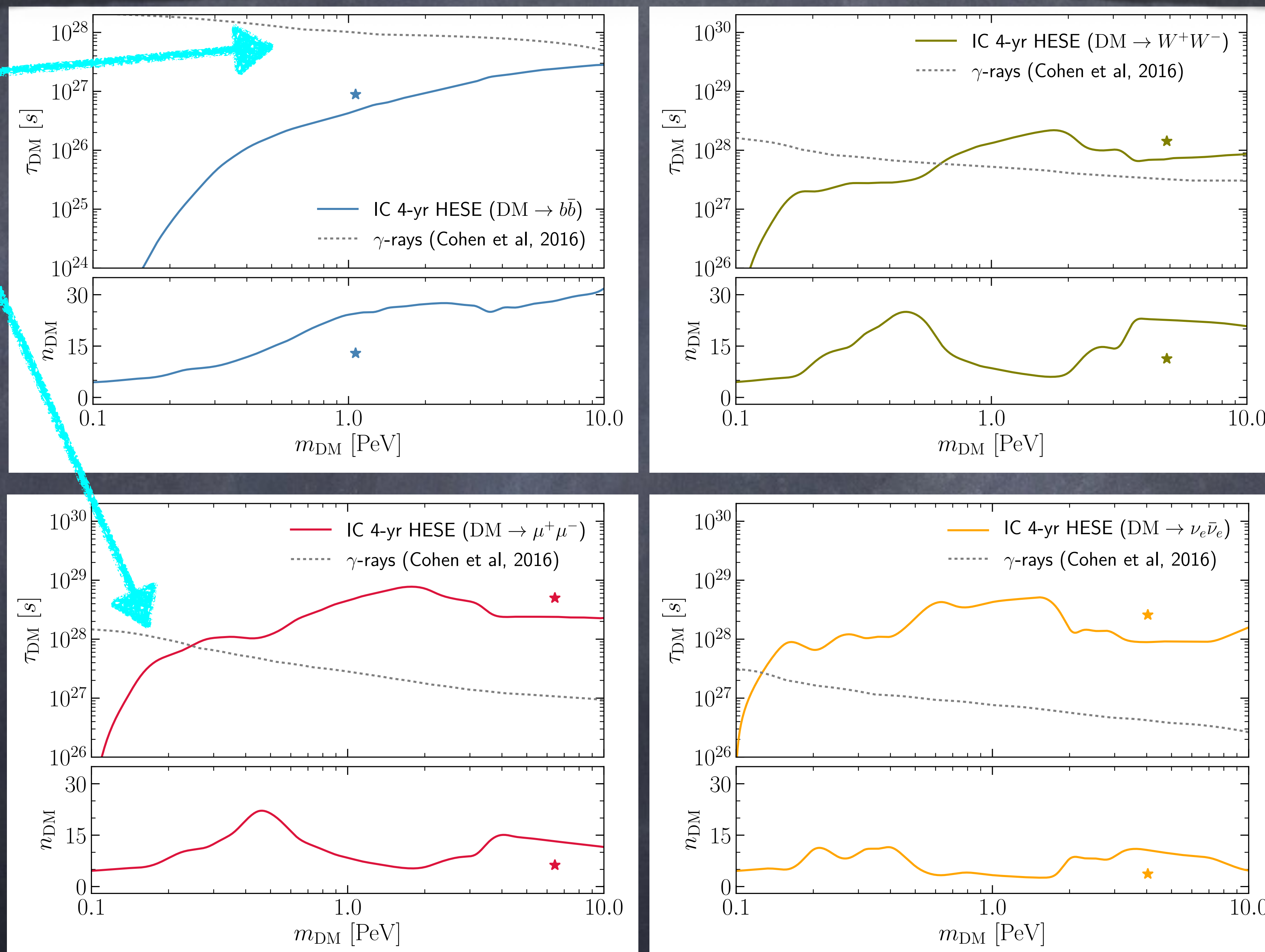




A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, arXiv:1706.05746

# DM decays + Astro: HESE analysis

**Neutrino limits are better than gamma-ray ones for relatively hard channels**

GAMMA-RAY LIMITS




A. Bhattacharya, A. Esmaili, SPR and I. Sarcevic, arXiv:1706.05746

# Dark matter decay models

## A unified solution for the matter-antimatter asymmetry and dark matter?

In the standard see-saw scenario the decays of right-handed neutrinos can explain the baryon asymmetry via leptogenesis... but the decays are too fast so that none of them is a good dark matter candidate

If one is decoupled (vanishing Yukawas), it can play the role of dark matter

$$m_D = \begin{pmatrix} 0 & (m_D)_{e2} & (m_D)_{e3} \\ 0 & (m_D)_{\mu 2} & (m_D)_{\mu 3} \\ 0 & (m_D)_{\tau 2} & (m_D)_{\tau 3} \end{pmatrix}$$

But how is it produced then? RH-LH mixing is too small

via Higgs portal interactions (non-diagonal couplings) $\frac{\lambda_{ij}}{\Lambda} \phi^\dagger \phi \, \bar{N}_i^c N_j$

A. Anisimov and P. Di Bari, Phys, Rev. D80:073017, 2009

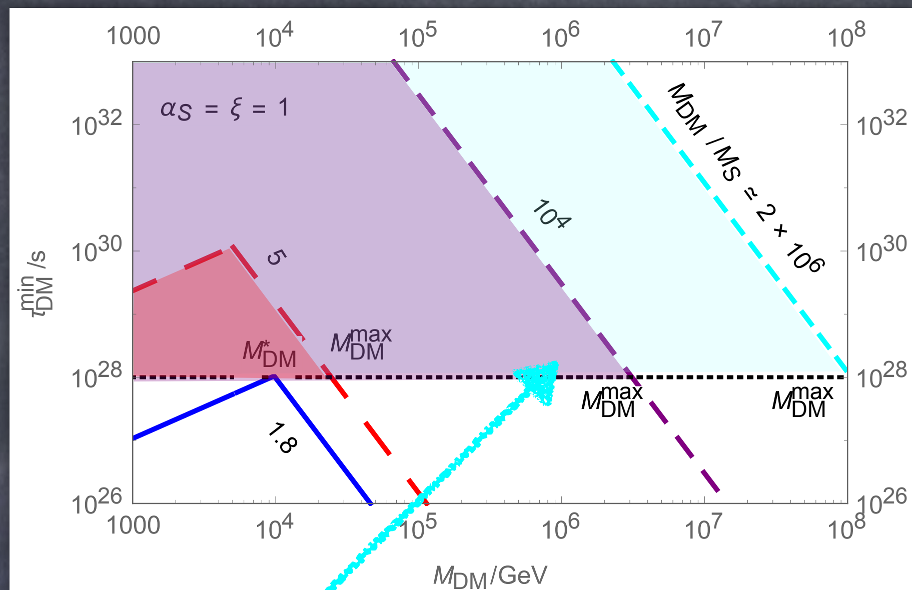
via medium effects DM can be produced non-adiabatically from RH-RH neutrino mixing

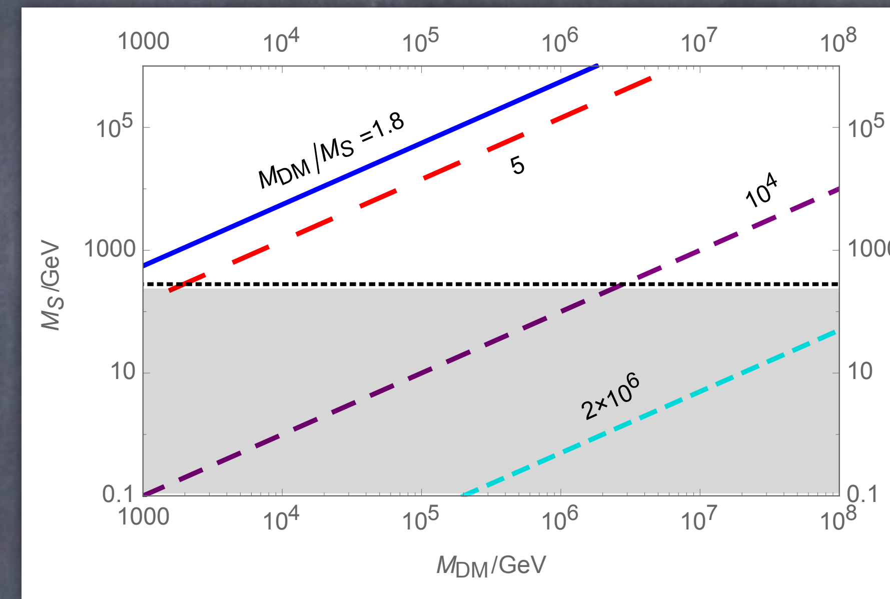
$$\Delta H \simeq \begin{pmatrix} -\frac{\Delta M^2}{4E} - \frac{T^2}{16E} h_s^2 & \frac{T^2}{12\tilde{\Lambda}} \\ \frac{T^2}{12\tilde{\Lambda}} & \frac{\Delta M^2}{4E} + \frac{T^2}{16E} h_s^2 \end{pmatrix}$$

P. Di Bari, O. Ludl and SPR, JCAP 1611:044, 2016

# Dark matter decay models

These small couplings induce long lifetimes



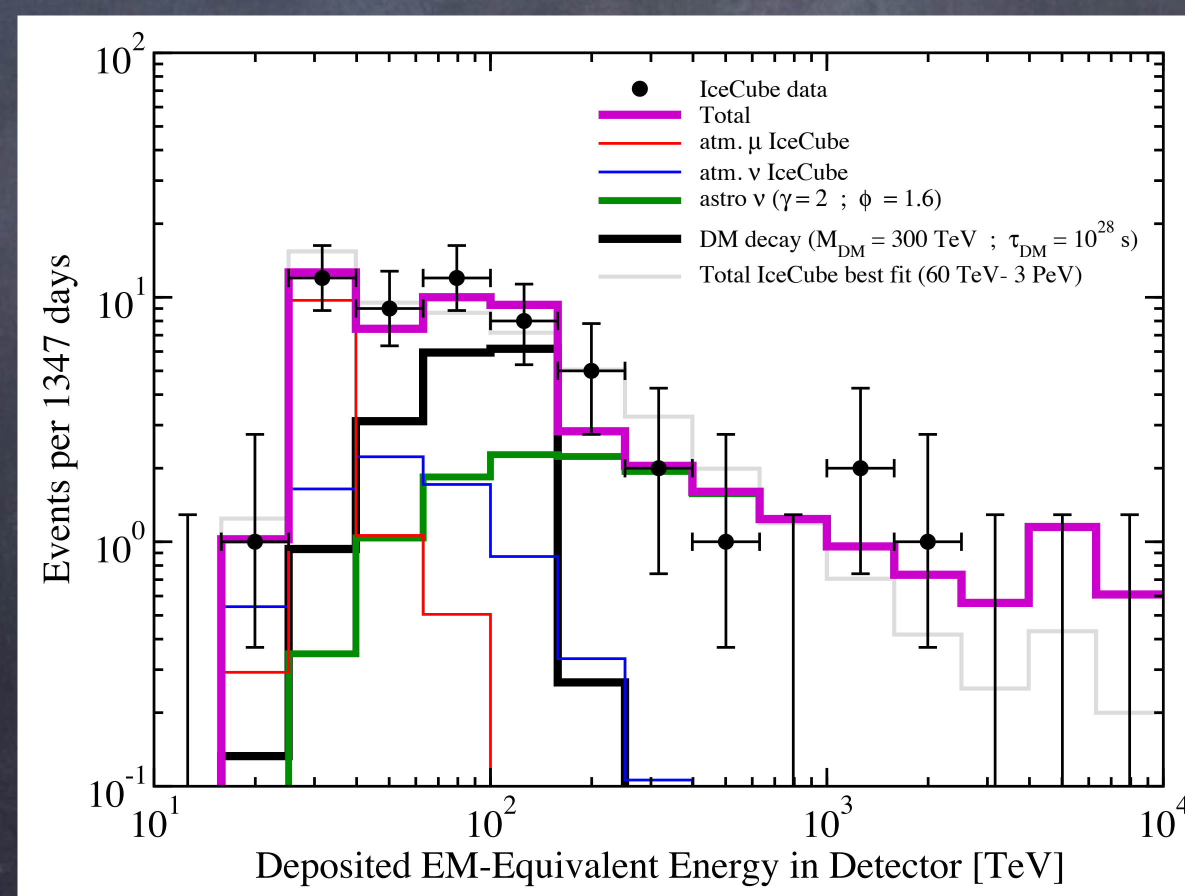

P. Di Bari, O. Ludl and SPR, JCAP 1611:044, 2016

testable at IceCube

$$50\% : N \rightarrow \ell^{\pm} W^{\mp}$$

$$25\% : N \rightarrow \nu_\alpha Z, \bar{\nu}_\alpha Z$$

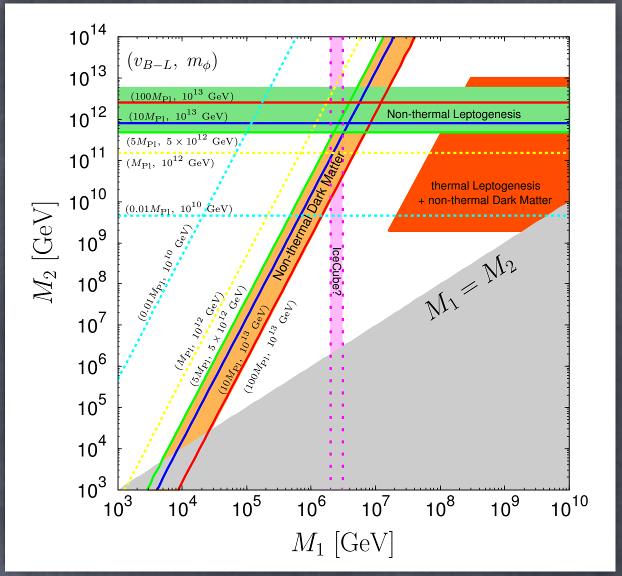
$$25\% : N \rightarrow \nu_\alpha h, \bar{\nu}_\alpha h$$



# Dark matter decay models

Extended SM with an $U(1)_{B-L}$ symmetry, 3 RHN and new Higgs: can explain leptogenesis, dark matter and neutrino masses

after $U(1)_{B-L}$ symmetry breaking RHN acquire mass, then impose one of them is almost decoupled. Same Yukawa structure as in Anisimov and Di Bari, 2009, although the production mechanism (via inflaton decay) is different




T. Higaki, R. Kitano and R. Sato, JHEP 1407:044, 2014

PeV RH neutrino in an $S_4$ flavor symmetric extra U(1) model: resonant leptogenesis, non-thermal production of the heaviest RHN, signatures at colliders (new colored particles)

Y. Daikoku and H. Okada, Phys. Rev. D91:075009, 2015

U(1) dark gauge symmetry with a dark fermion (DM) and a RH neutrino that connects with SM. DM decays into three particles

P. Ko and Y. Tang, Phys. Lett. B751:81, 2015

# Dark matter decay models

Leptophilic DM as a fermion singlet with a dim-6 portal

$$\frac{y_{\alpha\beta\gamma}}{M_{Pl}^2}\left(\bar{L}_\alpha \ell_\beta\right)\left(\bar{L}_\gamma \chi\right) \qquad \cancel{y\, \bar{L}_\alpha \tilde{\phi} \chi}$$

Non-thermal production (during reheating) requires low reheating temperature

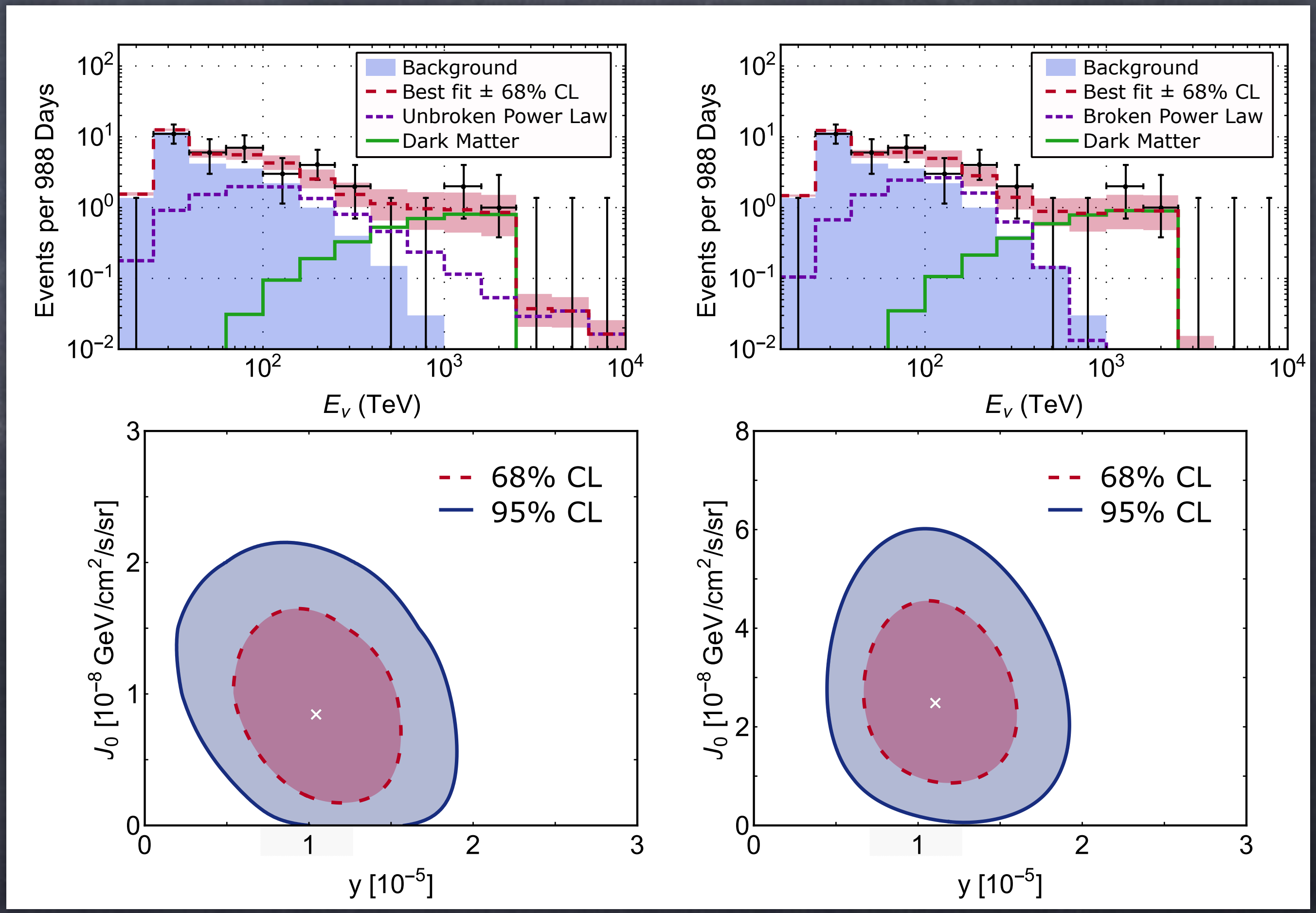
DM explains high-energy IceCube events

3-year HESE data

$m_{DM}$ = [1,10] PeV

**best fit: $m_{DM}$ = 5 PeV**

spectral index = [2,3]




S. M. Boucenna et al, JCAP 1510:055, 2015

# Dark matter decay models

Leptogenesis-DM scenario within a left-right model:
DM produced thermally via interactions with $SU(2)_R$ gauge bosons, negligible production from RH-RH mixing

M. Re Fiorentin, V. Niro and N. Fornengo, JHEP 1611:022, 2016

PeV RH neutrino with extra $SU(2)'$ gauge interactions and a softly broken $Z_2$ symmetry, which allows for DM decays

P. S. B. Dev, D. Kazanas, R. N. Mohapatra, V. L. Teplitz and Y. Zhang, JCAP 1608:034, 2016

Left-right model with two DM candidates (decays into light DM and neutrinos) and thermal production of DM via s-channel annihilations with extra fields

D. Borah, A. Dasgupta, U. K. Dey, S. Patra and G. Tomar, arXiv:1704.04138

Secluded DM, decaying into neutrinos and dark fermions.
The larger the number of fermions the broader the spectrum

N. Hiroshima, R. Kitano, K. Kohri and K. Murase, arXiv:1705.04419

# Boosted Dark matter

A. Bhattacharya, R. Gandhi and A. Gupta, JCAP 1503:027, 2015

DM composed of two particles:

a dominant contribution with a mass $m_\phi$= few PeV

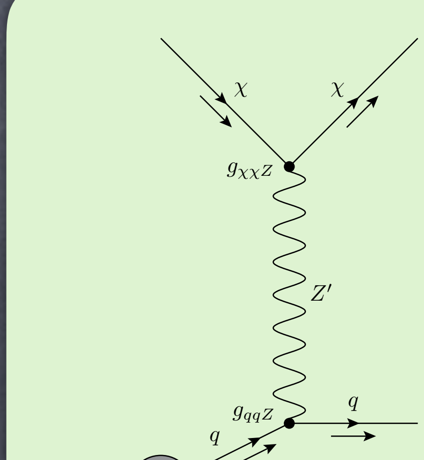
a lighter one $\chi$ ($m_\chi \ll m_\phi$) produced from decays of $\phi$

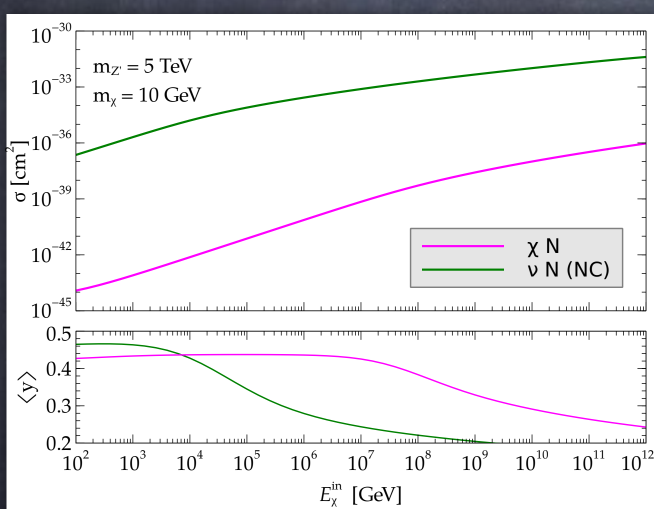
**Signal:**

scatterings of highly relativistic $\chi$

with nucleons of the detector

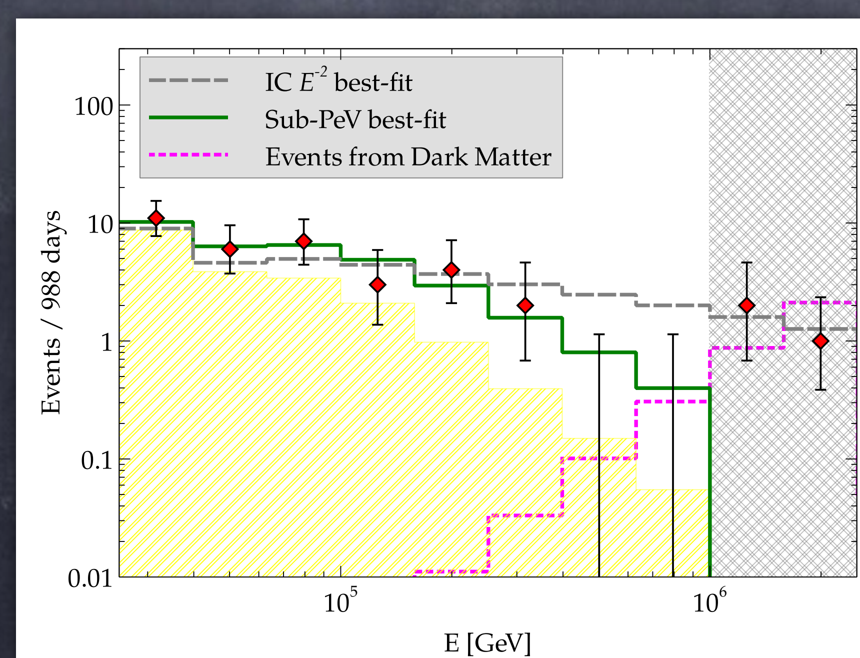
undistinguishable from NC neutrino interactions



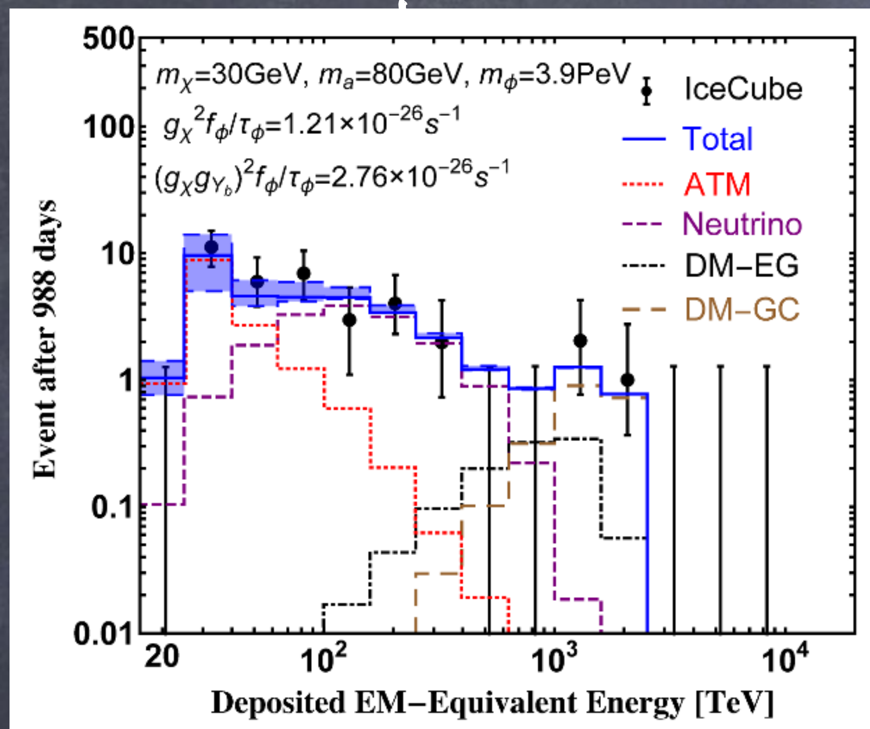

To explain PeV events

$$\frac{\tau}{G^2} \sim 2 \times 10^{24}\,\mathrm{s}$$



# Boosted Dark matter

Adding bremsstrahlung of the (pseudo-scalar) mediator, produces also a low-energy neutrino flux

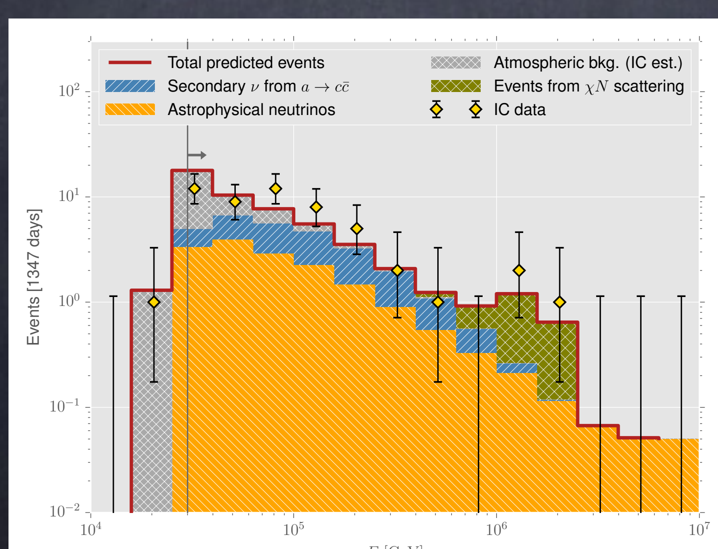



no need of astro neutrinos
DM could explain all events!

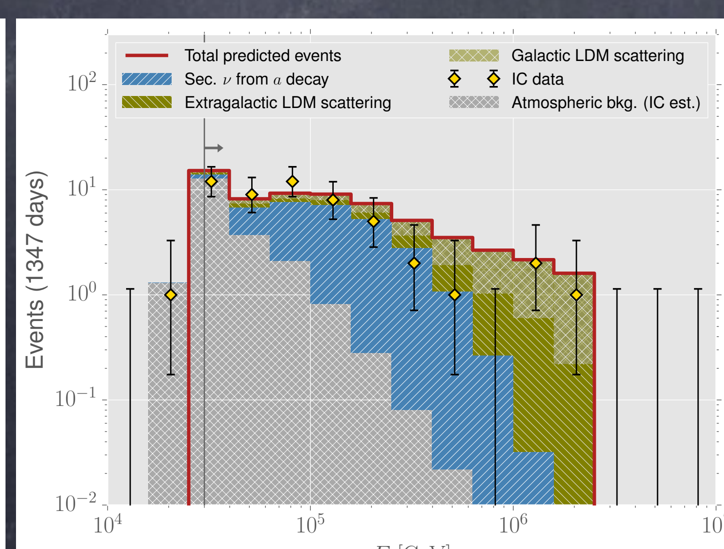
may even explain GC gamma-ray excess

J. Kopp, J. Liu and X.-P. Wang, JHEP 1504:105, 2015

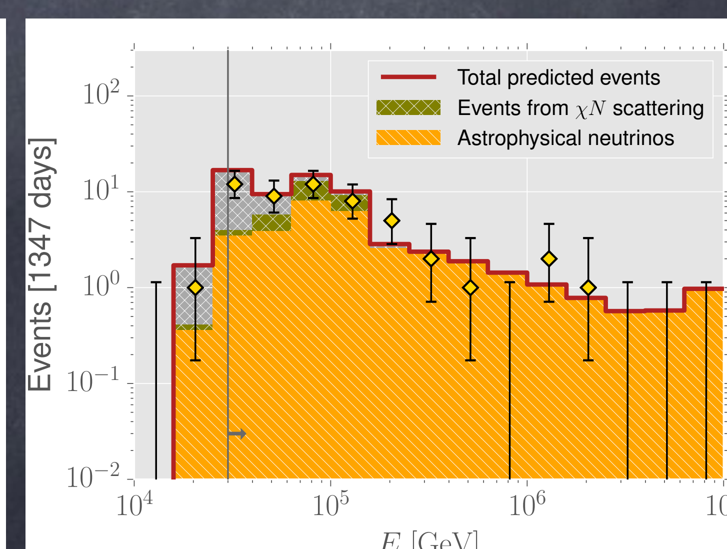
**SCALAR MEDIATOR**




**LIGHT VECTOR MEDIATOR**




**PSEUDO-SCALAR MEDIATOR LOWER DM MASS**



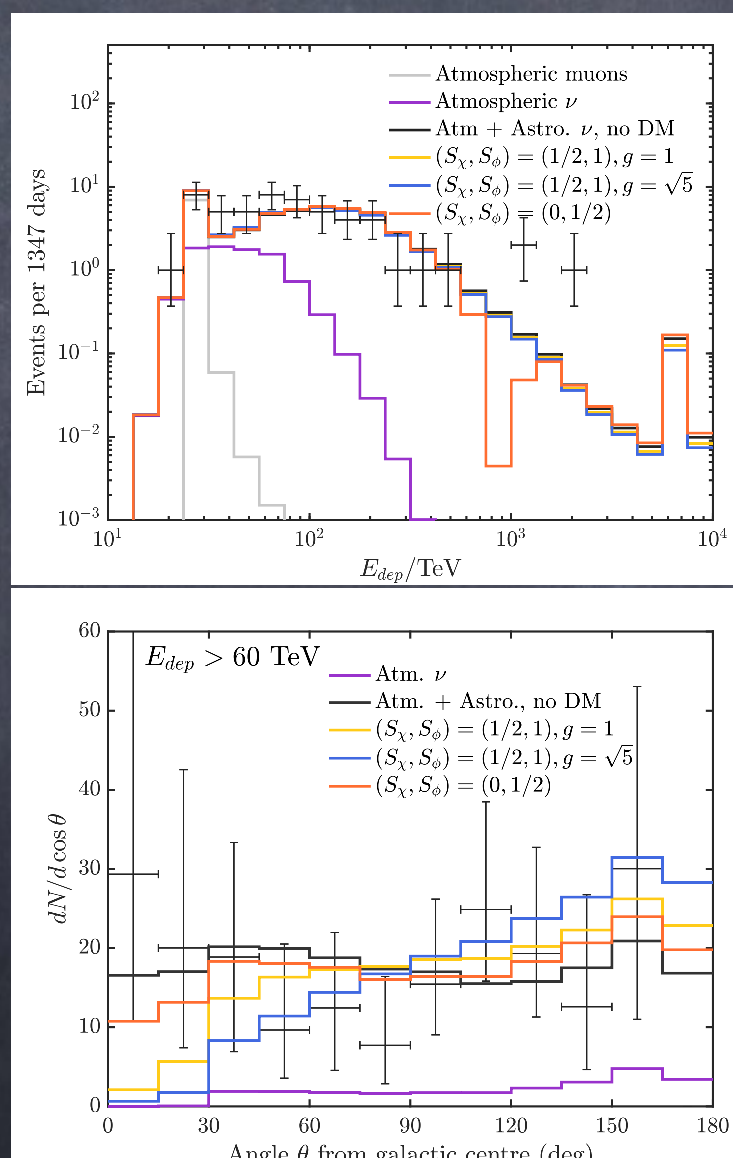

A. Bhattacharya, R. Gandhi, A. Gupta and S. Mukhopadhyay, JCAP 1705:002, 2017

# Neutrino-DM interactions

As neutrinos pass through the Milky Way, they would be more attenuated in the direction of the GC

↓

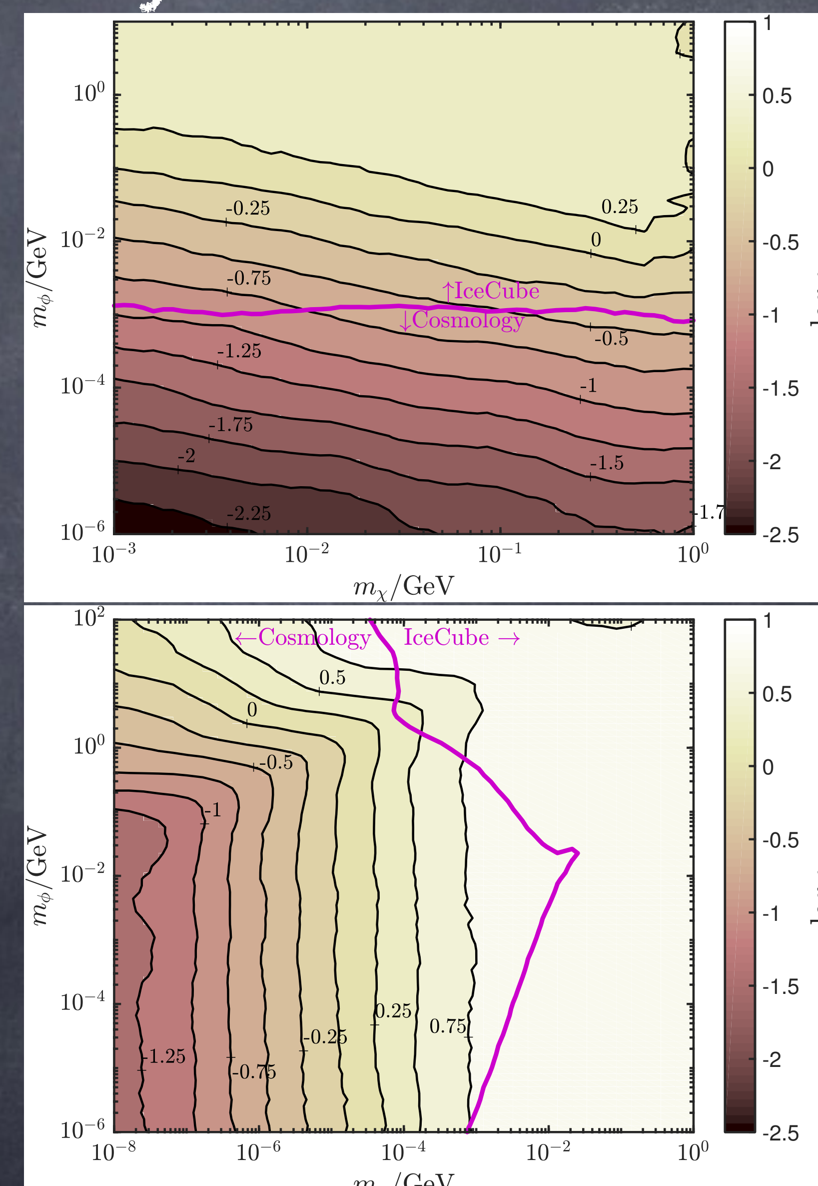
energy-dependent anisotropy in the (otherwise isotropic) neutrino sky




suppression in the CG direction

FERMIONIC DM/ VECTOR MEDIATOR

SCALAR DM/ FERMION MEDIATOR




C. A. Argüelles, A. Kheirandish, A. C. Vincent, arXiv:1703.00451

# What about flavor?

# What about flavor?

It carries information about the mechanism of production...

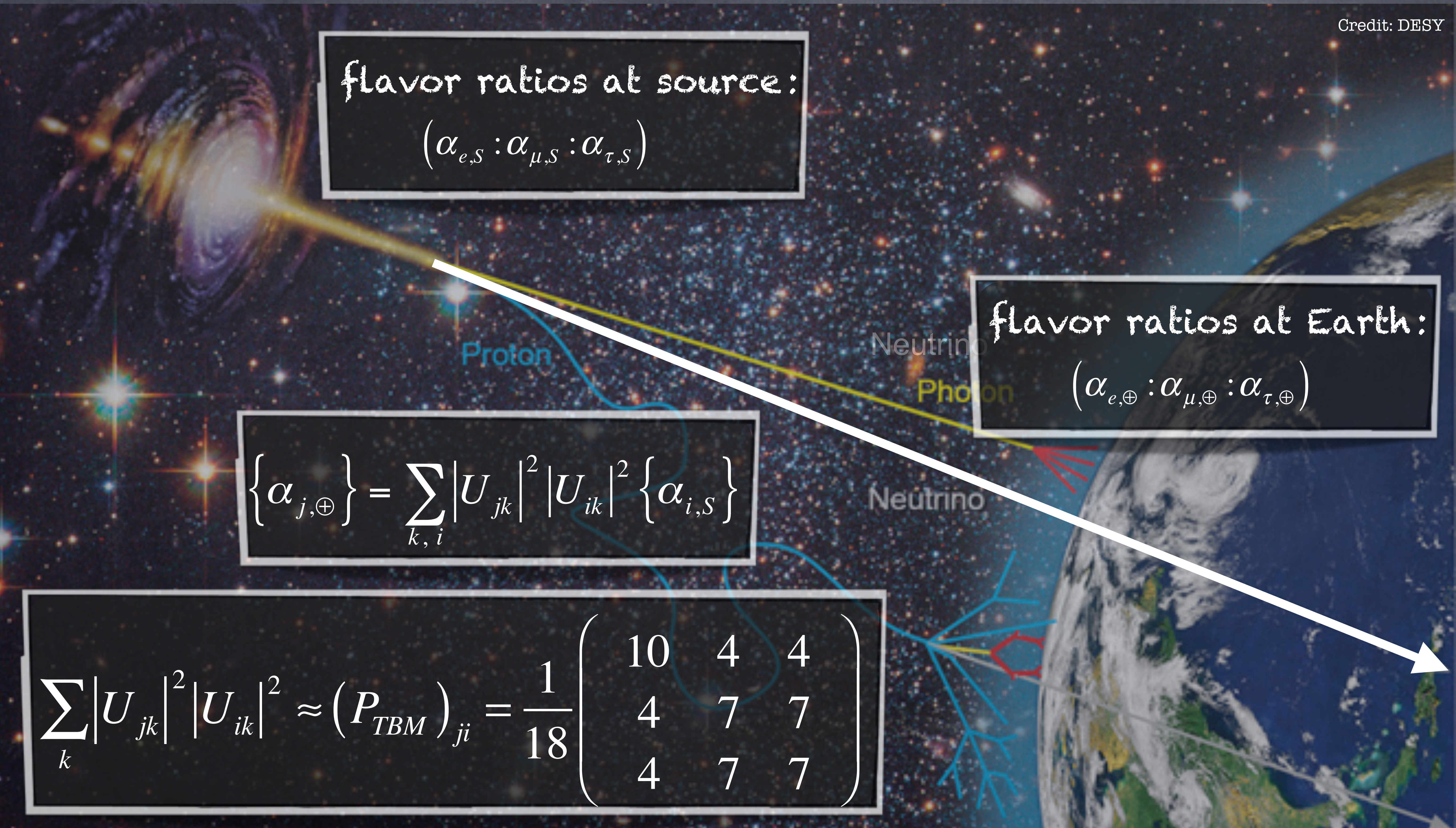
# What about flavor?

It carries information about the mechanism of production...

...but also about the way neutrinos propagate from the sources to the detector

Exotic physics could produce deviations from the standard expectations

# STANDARD COSMIC PROPAGATION




flavor ratios at source:

$$\left(\alpha_{e,S} : \alpha_{\mu,S} : \alpha_{\tau,S}\right)$$

flavor ratios at Earth:

$$\left(\alpha_{e,\oplus} : \alpha_{\mu,\oplus} : \alpha_{\tau,\oplus}\right)$$

$$\left\{\alpha_{j,\oplus}\right\} = \sum_{k,\,i} \left|U_{jk}\right|^2 \left|U_{ik}\right|^2 \left\{\alpha_{i,S}\right\}$$

$$\sum_k \left|U_{jk}\right|^2 \left|U_{ik}\right|^2 \approx \left(P_{TBM}\right)_{ji} = \frac{1}{18}\begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

# Flavor ratios at source and Earth

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

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

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

Pion sources $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:2:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (1:1:1)$

Muon damped sources $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (0:1:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (4:7:7)$

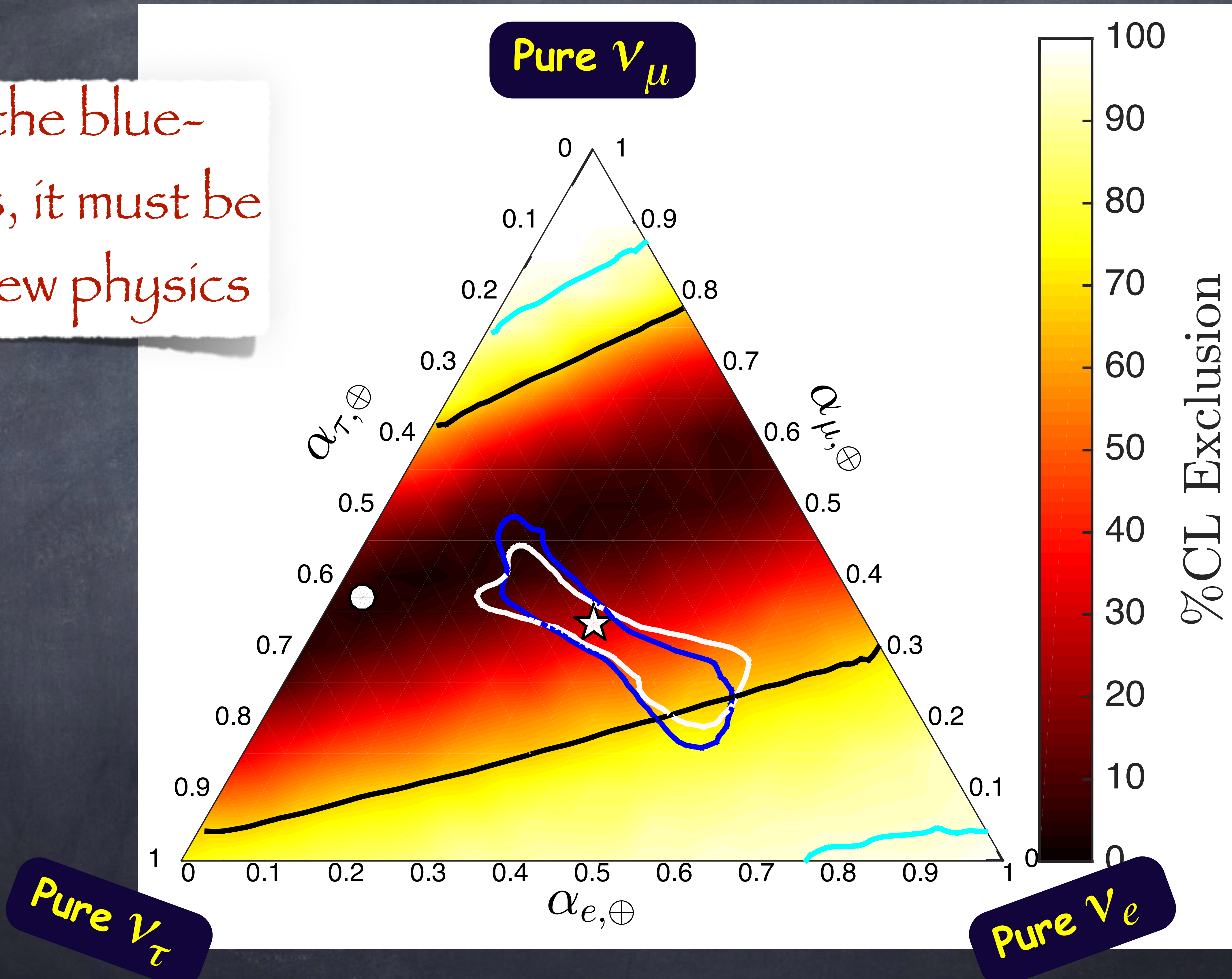
Muon sources $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:1:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (14:11:11)$

Neutron sources $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:0:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (5:2:2)$

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

# Flavor triangles

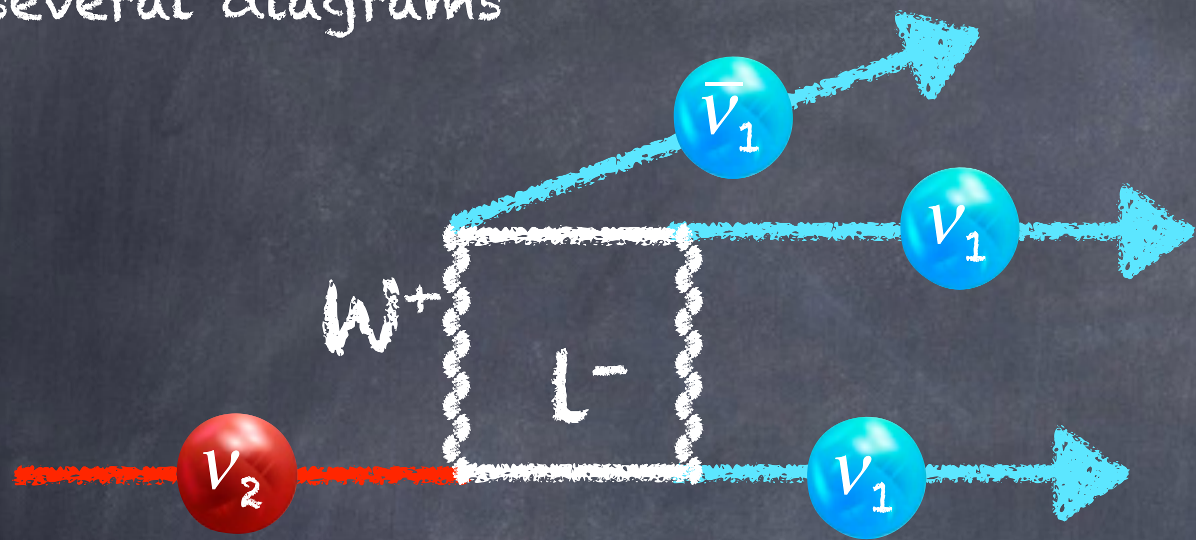
If outside the blue-white regions, it must be caused by new physics



# Neutrino decay

## Lepton flavor violation implies neutrino decays

several diagrams




$$\Gamma_{3\nu} = \varepsilon_{SM}^2 \Gamma \approx 10^{-36}\, s^{-1} \left(\frac{\sin^2(2\theta)}{0.1}\right)\left(\frac{m_2}{1\ \text{eV}}\right)^5 \varepsilon_{SM}^2$$

$$\Gamma = \sin^2(2\theta) G_F^2 \left(\frac{m_2^5}{768\pi^3}\right)$$

$$\varepsilon_{SM}^2 \leq 10^{-11}$$


$$\Gamma_\gamma = \frac{27\alpha}{8\pi} \Gamma \tilde{\varepsilon}_{SM}^2 \approx 10^{-38}\, s^{-1} \left(\frac{\sin^2(2\theta)}{0.1}\right)\left(\frac{m_2}{1\ \text{eV}}\right)^5 \tilde{\varepsilon}_{SM}^2$$

$$\tilde{\varepsilon}_{SM}^2 \leq 10^{-7}$$

huge lifetime
detection: NEW PHYSICS

**Early computations**

S. T. Petcov, Phys, Sov. J. Nucl. Phys. 25:340, 1977

T. Goldman and G. J. Stephenson, Phys. Rev. D16:2256, 1977

E. Ma and A. Pramudita, Phys. Rev. D24:1410, 1981

Y. Hosotani, Nucl. Phys. B191:411, 1981

**Radiative decays: general computation**

P. B. Pal and L. Wolfenstein, Phys. Rev. D25:766, 1981

# Astrophysical neutrino decay

J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, Phys, Rev. Lett. 90:181301, 2003

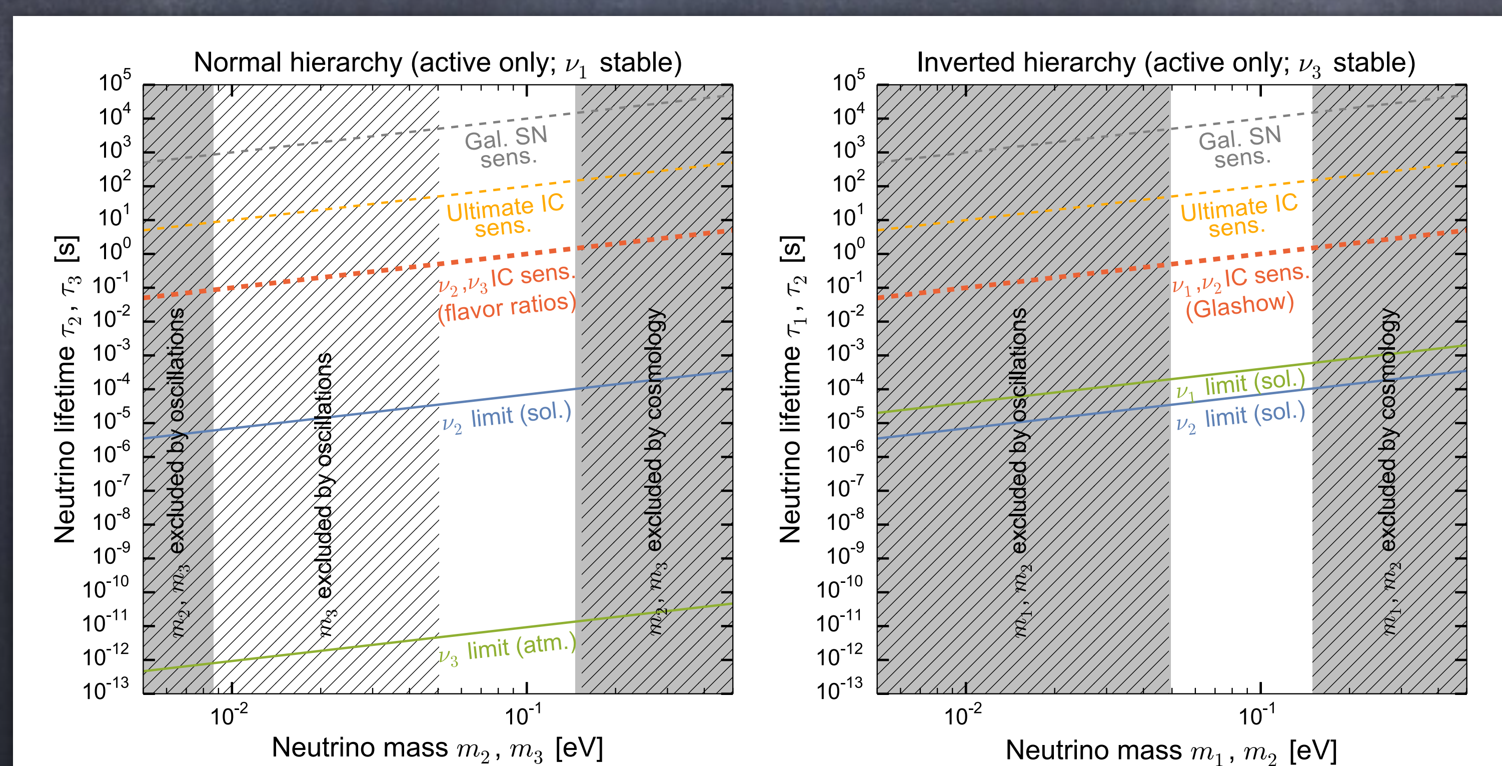
$$\mathcal{L} = g_{ij}\bar{\nu}_i \nu_j X + h_{ij}\bar{\nu}_i \gamma_5 \nu_j X$$

$$\nu_i \rightarrow \nu_j + X$$

decay rates depend on:

$$e^{-\frac{L}{E}\frac{m}{\tau}}$$

$$\frac{\tau}{m} \sim 10^3 \left(\frac{L}{\mathrm{Gpc}}\right)\left(\frac{100\ \mathrm{TeV}}{E}\right) \mathrm{s/eV}$$




M. Bustamante, J. F. Beacom and K. Murase, Phys. Rev. D95:063013, 2017

# Astrophysical neutrino decay

J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, Phys, Rev. Lett. 90:181301, 2003

$$\nu_i \to \nu_j + X$$

## Invisible daughters

$$\Phi_{\nu_\alpha} = \sum_{i\beta} |U_{\beta i}|^2 |U_{\alpha i}|^2 \Phi_{\nu_\beta}^{source} e^{-L m_i / E\tau_i} \xrightarrow{L \gg E\tau_i/m_i} \sum_{i(stable),\beta} |U_{\beta i}|^2 |U_{\alpha i}|^2 \Phi_{\nu_\beta}^{source}$$

## Daughters with full energy (quasi-degenerate)

$$\Phi_{\nu_\alpha} = \sum_{i\beta} |U_{\beta i}|^2 |U_{\alpha i}|^2 \Phi_{\nu_\beta}^{source} e^{-L m_i / E\tau_i} \xrightarrow{L \gg E\tau_i/m_i} \sum_{i(stable),\beta} |U_{\beta i}|^2 |U_{\alpha i}|^2 \Phi_{\nu_\beta}^{source} + \sum_{i(stable),j,\beta} |U_{\beta i}|^2 |U_{\alpha j}|^2 Br_{j\to i} \Phi_{\nu_\beta}^{source}$$

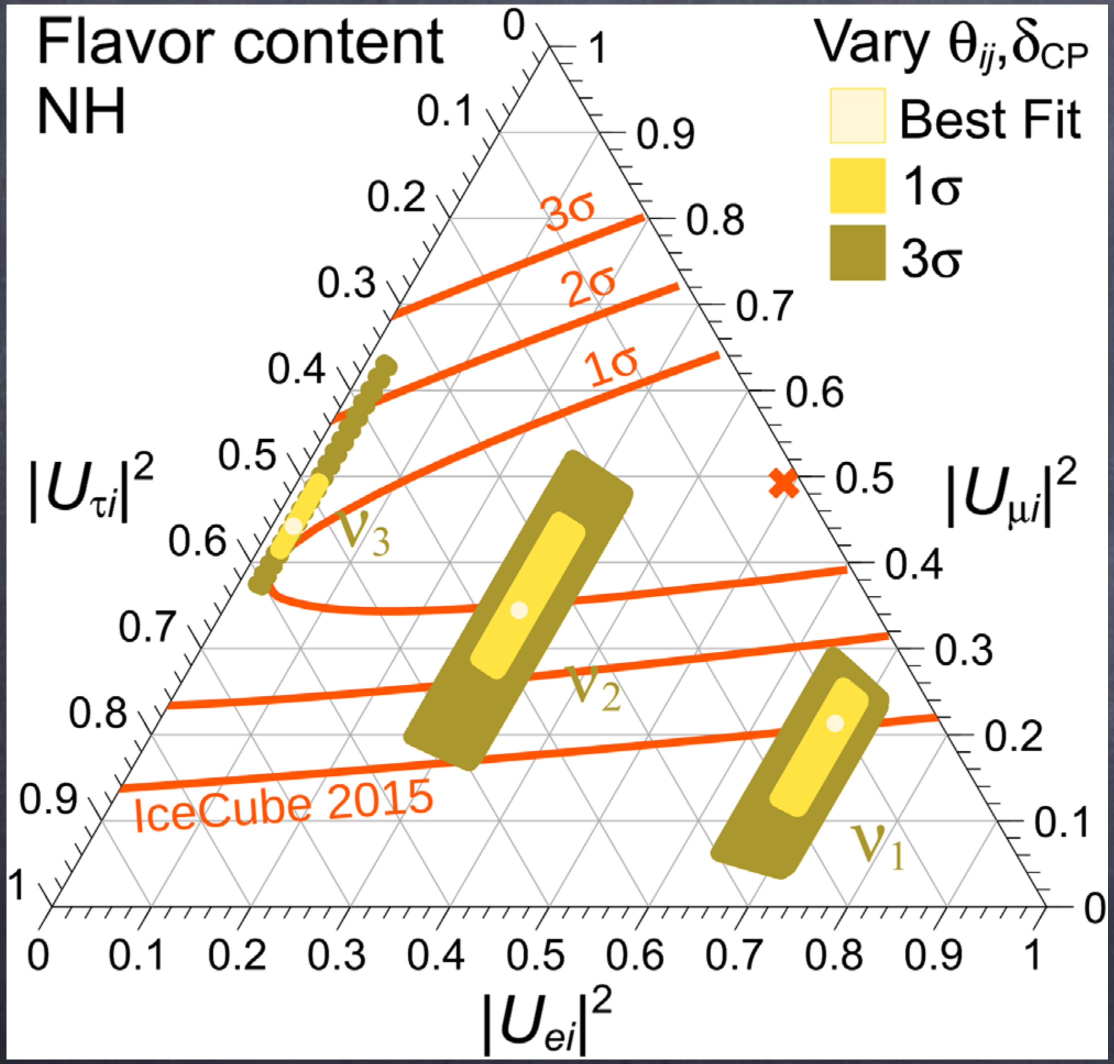
| Unstable | Daughters | Branchings | $\phi_{\nu_e}:\phi_{\nu_\mu}:\phi_{\nu_\tau}$ |
|---|---|---|---|
| $\nu_2$, $\nu_3$ | anything | irrelevant | 6:1:1 |
| $\nu_3$ | sterile | irrelevant | 2:1:1 |
| $\nu_3$ | full energy | $B_{3\to 2} = 1$ | 1.4:1:1 |
| | degraded ($\alpha = 2$) | | 1.6:1:1 |
| $\nu_3$ | full energy | $B_{3\to 1} = 1$ | 2.8:1:1 |
| | degraded ($\alpha = 2$) | | 2.4:1:1 |
| $\nu_3$ | anything | $B_{3\to 1} = 0.5$ | 2:1:1 |
| | | $B_{3\to 2} = 0.5$ | |

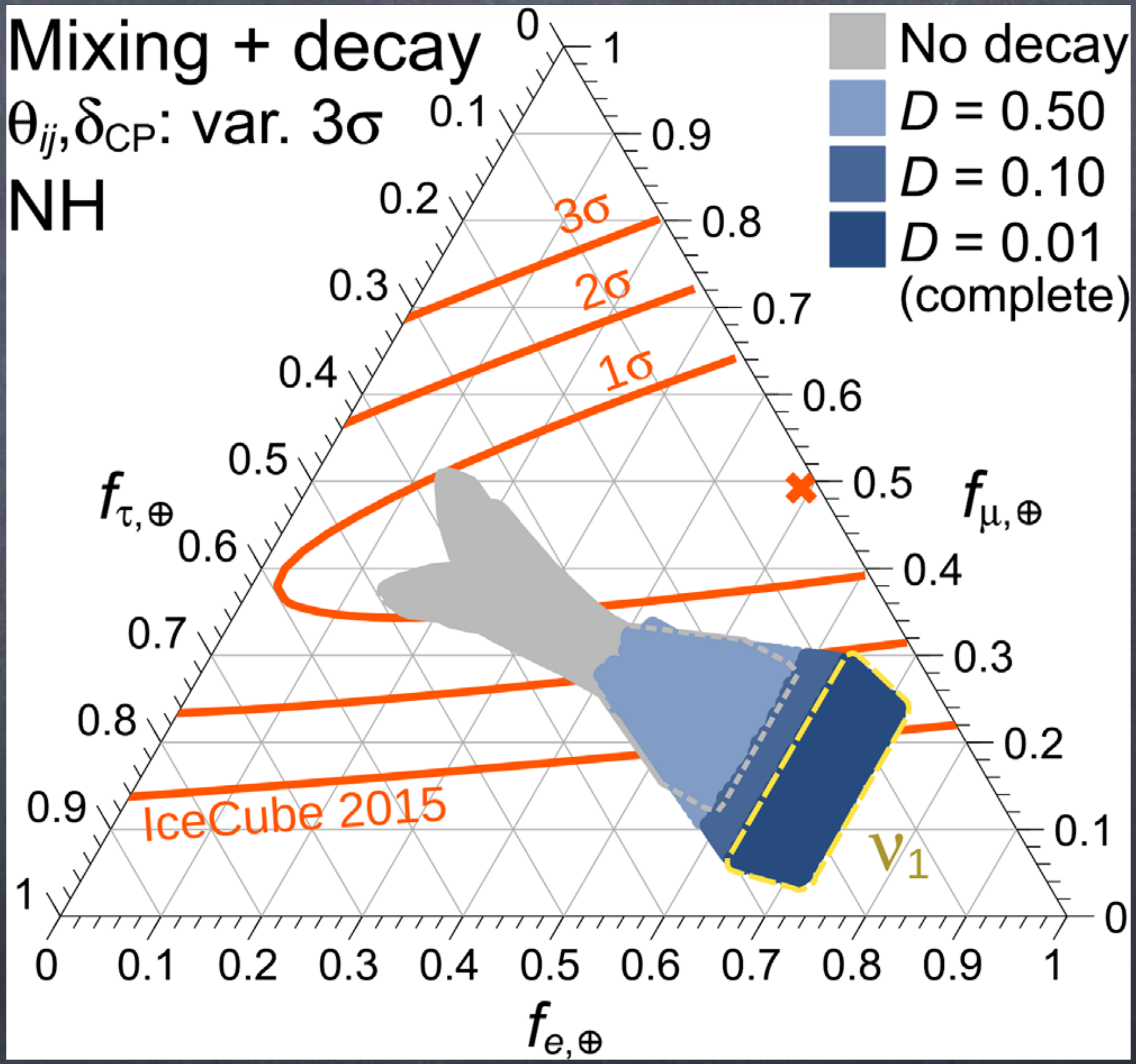
# Astrophysical neutrino decay

## Using flavor ratios in IceCube

complete decay of $\nu_2$ and $\nu_3$ is disfavored at $2\sigma$

$\tau/m > 10$ s/eV




M. Bustamante, J. F. Beacom and K. Murase, Phys. Rev. D95:063013, 2017

See also: G. Pagliaroli, A. Palladino, F. L. Villante and F. Vissani, Phys. Rev. D92:113008, 2015

# Pseudo-Dirac neutrinos

R. M. Crocker, F. Melia and R. R. Volkas, Astrophys. J. Suppl. 130: 339, 2000; and 141:147, 2002

J. F. Beacom, N. F. Bell, D. Hooper, J. G. Learned, S. Pakvasa and T. J. Weiler, Phys, Rev. Lett. 92:011101, 2004

$$M_\nu = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

Dirac neutrino: $m_L = m_R = 0$

Pseudo-Dirac neutrinos: $m_L, m_R \ll m_D$

maximal mixing: $\tan 2\theta = 2m_D/(m_R - m_L) \gg 1$

$$\Phi_\alpha = \sum_{\beta i} |U_{\alpha i}|^2 |U_{\beta i}|^2 \Phi_\beta^{source} \left[1 - \sin^2\left(\frac{\Delta m_i^2 L}{4E}\right)\right]$$

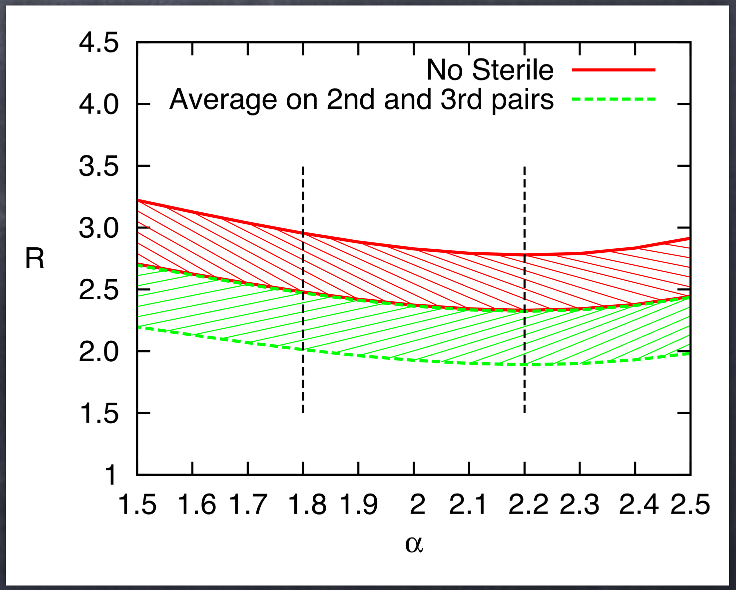
Testable:

$$\left(\frac{\Delta m^2}{10^{-14}\,eV^2}\right) \sim \left(\frac{Mpc}{L}\right)\left(\frac{E}{100\ TeV}\right)$$

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 : 1 | $\xrightarrow[3]{}$ | 4/3 : 1 | $\xrightarrow[2,3]{}$ | 14/9 : 1 | $\xrightarrow[1,2,3]{}$ | 1 : 1 |
| 1 : 1 | $\xrightarrow[1]{}$ | 2/3 : 1 | $\xrightarrow[1,2]{}$ | 2/3 : 1 | $\xrightarrow[1,2,3]{}$ | 1 : 1 |
| 1 : 1 | $\xrightarrow[2]{}$ | 14/13 : 1 | $\xrightarrow[2,3]{}$ | 14/9 : 1 | $\xrightarrow[1,2,3]{}$ | 1 : 1 |
| 1 : 1 | $\xrightarrow[1]{}$ | 2/3 : 1 | $\xrightarrow[1,3]{}$ | 10/11 : 1 | $\xrightarrow[1,2,3]{}$ | 1 : 1 |
| 1 : 1 | $\xrightarrow[3]{}$ | 4/3 : 1 | $\xrightarrow[1,3]{}$ | 10/11 : 1 | $\xrightarrow[1,2,3]{}$ | 1 : 1 |
| 1 : 1 | $\xrightarrow[2]{}$ | 14/13 : 1 | $\xrightarrow[1,2]{}$ | 2/3 : 1 | $\xrightarrow[1,2,3]{}$ | 1 : 1 |

J. F. Beacom et al., Phys, Rev. Lett. 92:011101, 2004

R=tracks/showers




A. Esmaili, Phys, Rev. D81:013006, 2010

**Some models:**

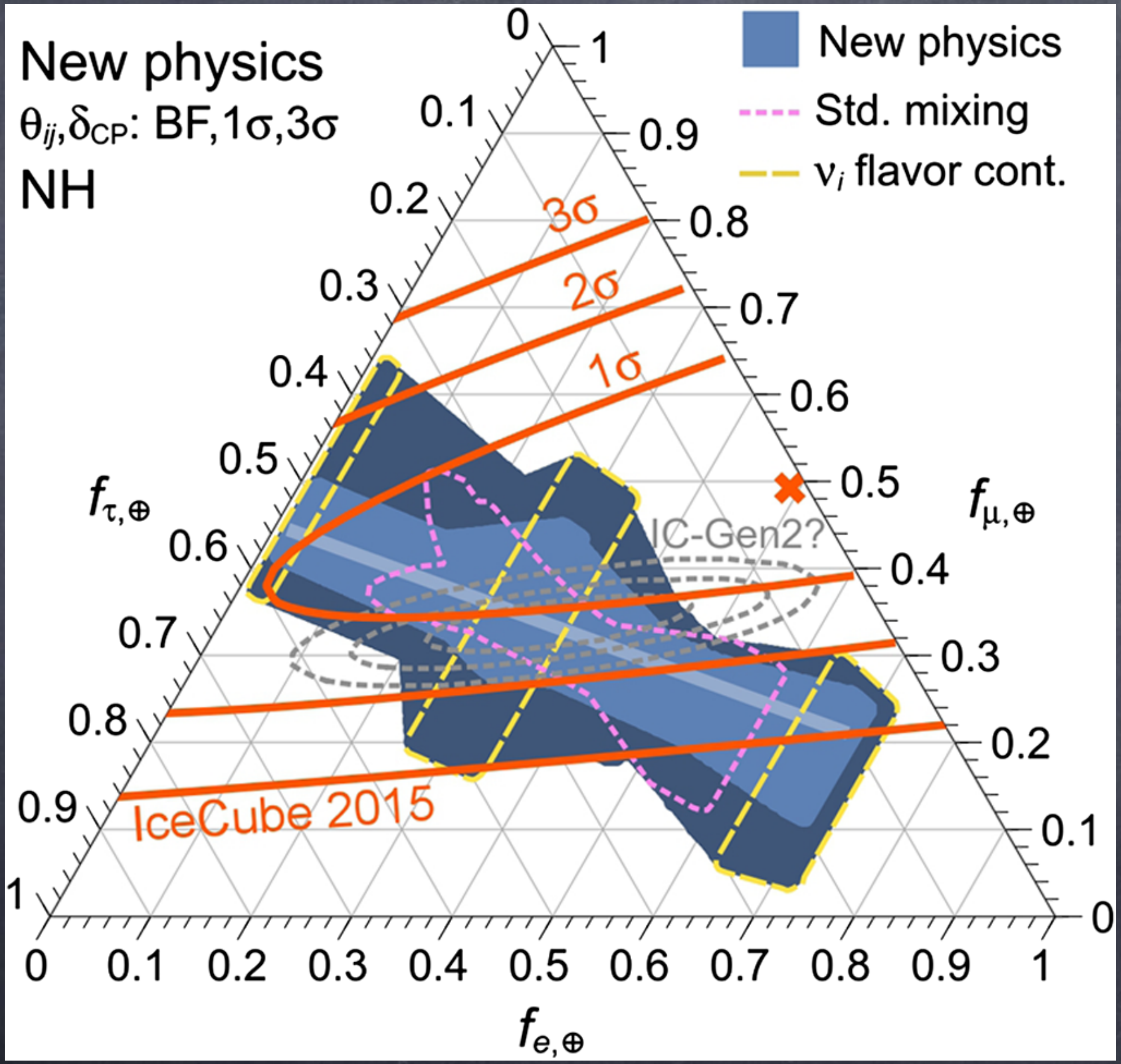
A. S. Joshipura and S. Mohanty and S. Pakvasa, Phys. Rev. D89:033003, 2014

Y. H. Ahn, S. K. Kang and C. S. Kim, JHEP 1610:092, 2016

# OTHER SCENARIOS

What if any incoherent mixture of mass eigenstates is possible?

neutrino decays, pseudo-Dirac neutrinos... or neutrino secret interactions, Planck-scale decoherence




Yet, flavor triangle not fully covered!

More extreme scenarios are required!

M. Bustamante, J. F. Beacom and W. Winter, Phys. Rev. Lett. 115:161302, 2015

# MORE EXTREME SCENARIOS

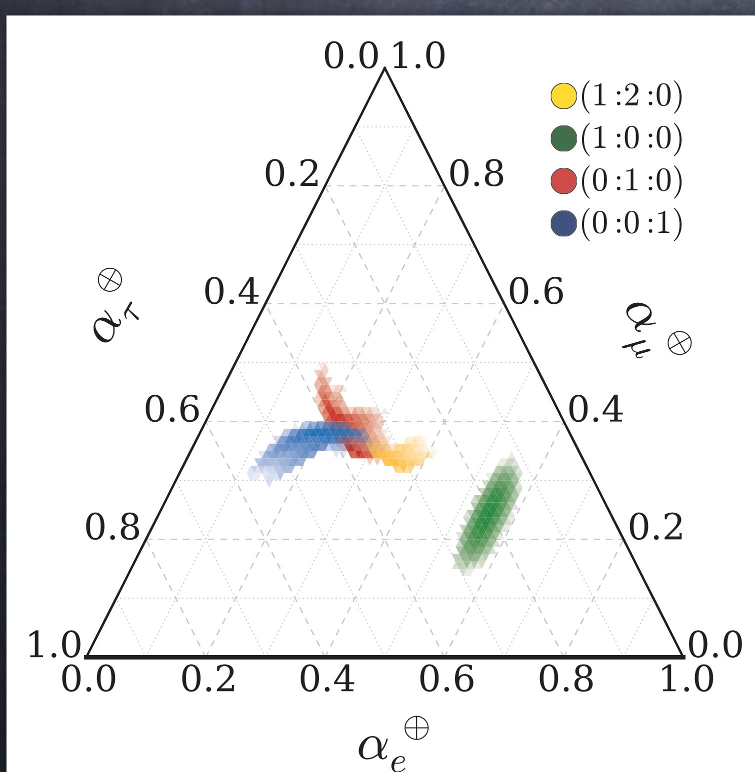
Using effective operators:
general evolution hamiltonian

flavor structure of new physics

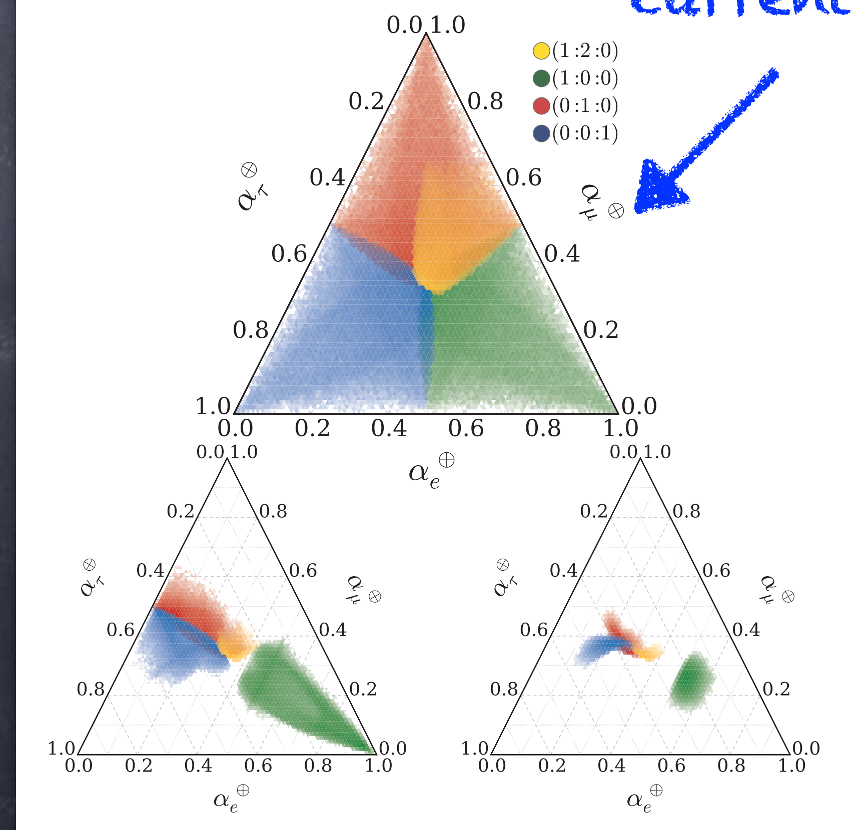
$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_n \left( \frac{E}{\Lambda_n} \right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger$$

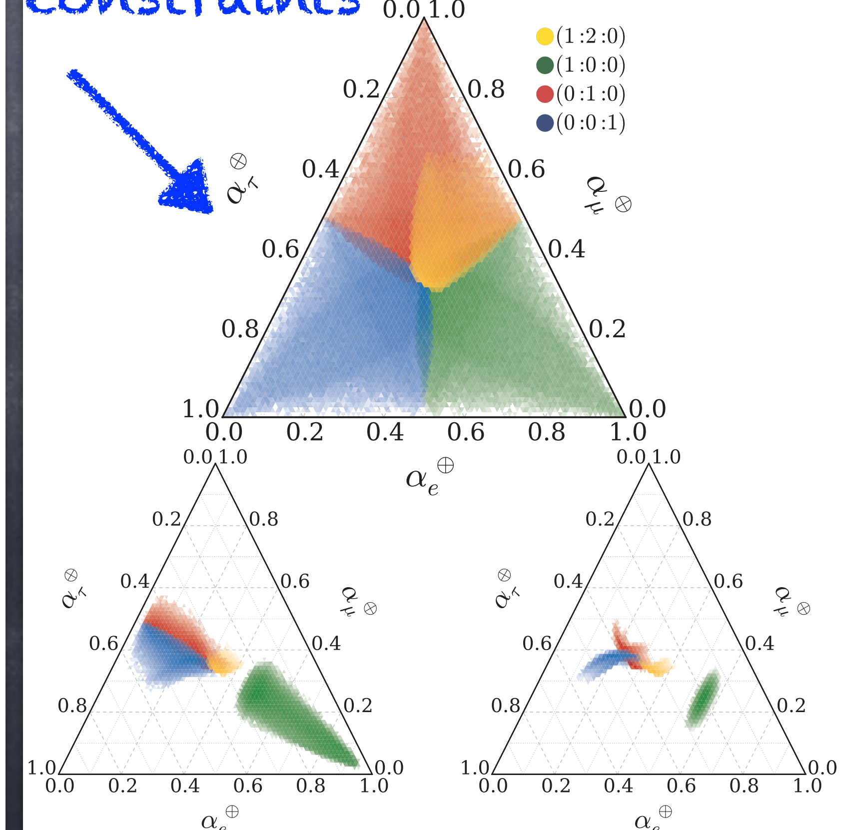
n=0 : neutrino couplings to spacetime torsion, CPT-odd Lorentz violation, NSI

n=1 : CPT-even Lorentz violation, equivalence principle violation




current constraints



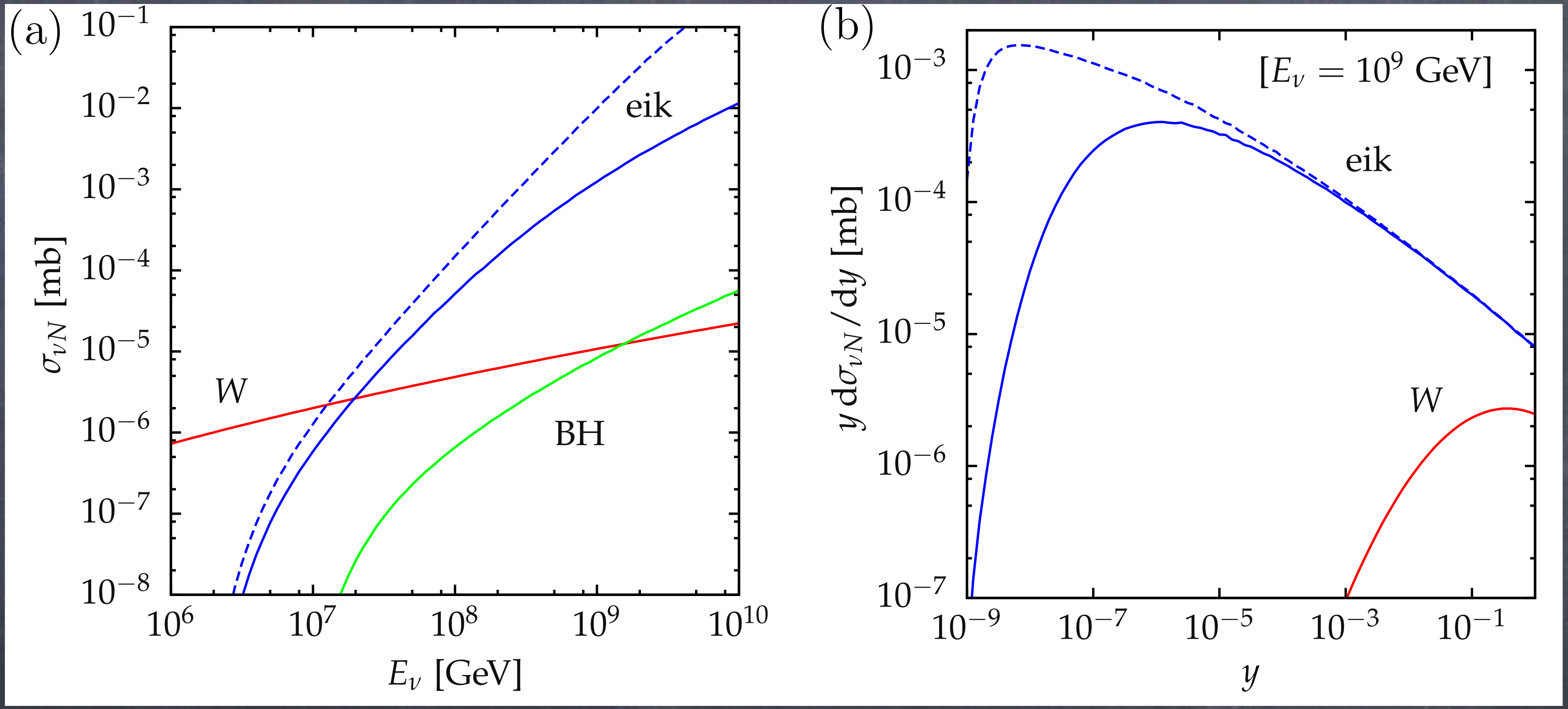

C. A. Argüelles, T. Katori and J. Salvadó, Phys. Rev. Lett. 115:161303, 2015

# TeV Gravity model

One extra dimension with a fundamental scale at $M_S$ ~ TeV and a mass > 50 MeV for the first KK mode (graviton)

enhancement of the cross section at high energies ($s>M_S^2$)

very soft interaction




J. I. Illana, M. Masip and D. Meloni, Astropart. Phys. 65:64, 2015

interactions of downgoing cosmogenic neutrinos would **only produce showers** (like NC interactions) and might explain the lack of tracks

# Leptoquarks

A. Anchordoqui, C. A. García Canal, H. Goldberg, D. Gómez Dumm and F. Halzen, Phys. Rev. D74:125021, 2006

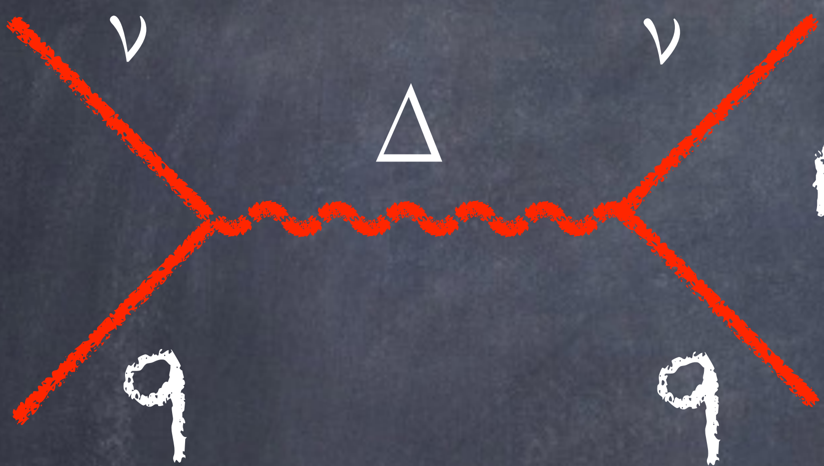
Leptoquarks are colored particles with lepton and baryon number that appear in GUTs and recently can solve some flavor anomalies

See also:

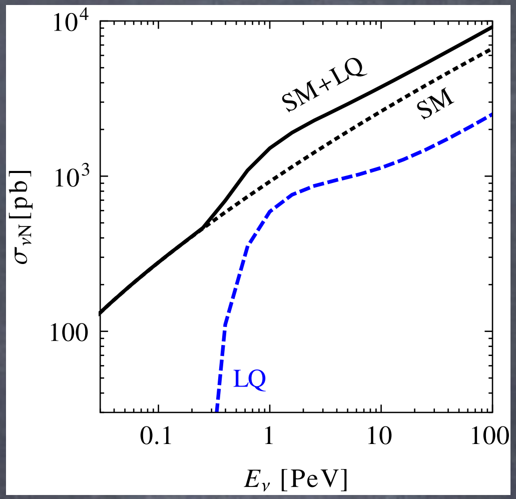
V. Barger and W.-Y. Keung, Phys. Lett. B727:190, 2013

N. Mileo, A. de la Puente and A. Szynkman, JHEP 1611:124, 2016

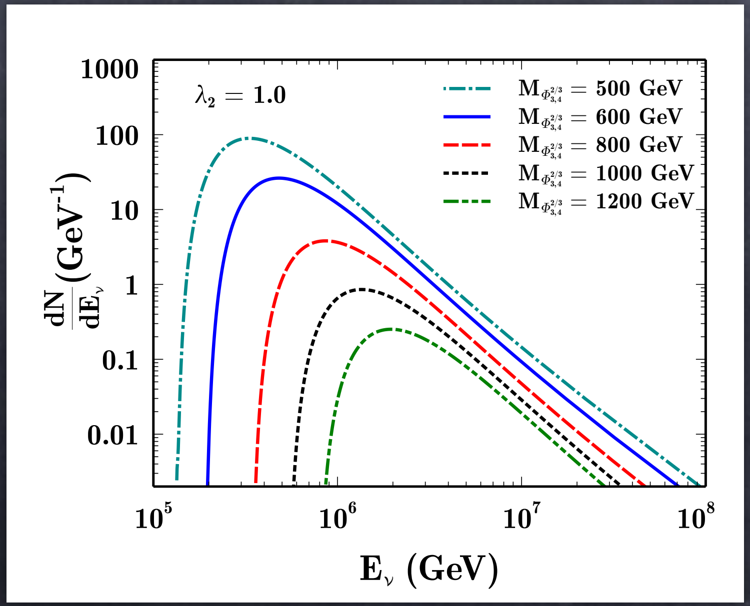
$\bar{Q}\ \Delta\ L$



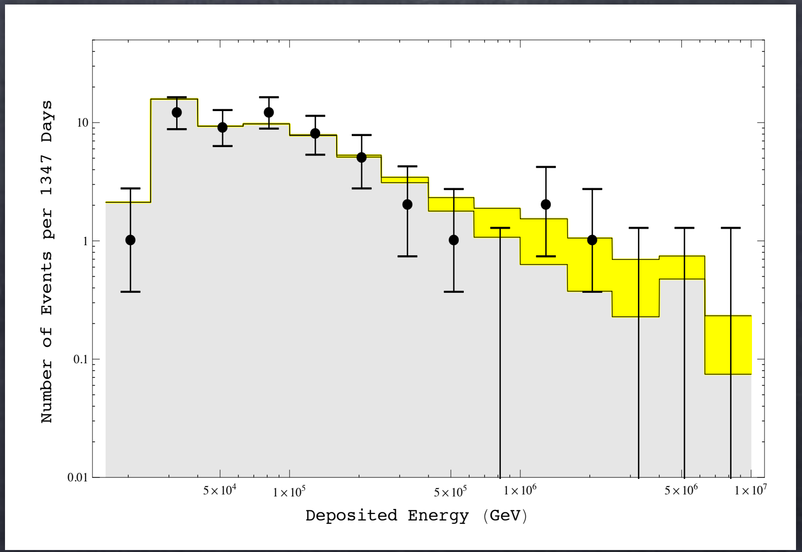

$E = M_\Delta^2 / 2m_N$




B. Dutta, Y. Gao, T. Li, C. Rott and L. E. Strigari, Phys. Rev. D91:125015, 2015




U. K. Dey and S. Mohanty, JHEP 1604:187, 2016




B. Chauhan, B. Kindra and A. Narang , arXiv:1706:04598

# OTHER EXOTIC SCENARIOS

Lorentz-violating scenarios

shortcuts in extra dimensions

secret neutrino interactions
via a MeV mediator

decays of a O(100) PeV particle

non-standard neutrino interactions

your proposal?

# FINAL COMMENTS

Neutrinos opened a window to build the Standard Model

A lot has been learnt... but a lot more yet to be learnt

Neutrinos could be the right tool to understand the missing blocks

A huge range of energies,
a huge variety of phenomenology,
a lot to be tested

# THANK YOU FOR YOUR ATTENTION!