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# *HE Neutrinos beyond Standard Model: steriles and secret interactions*

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In collaboration with D. Fiorillo, G. Miele, S. Morisi

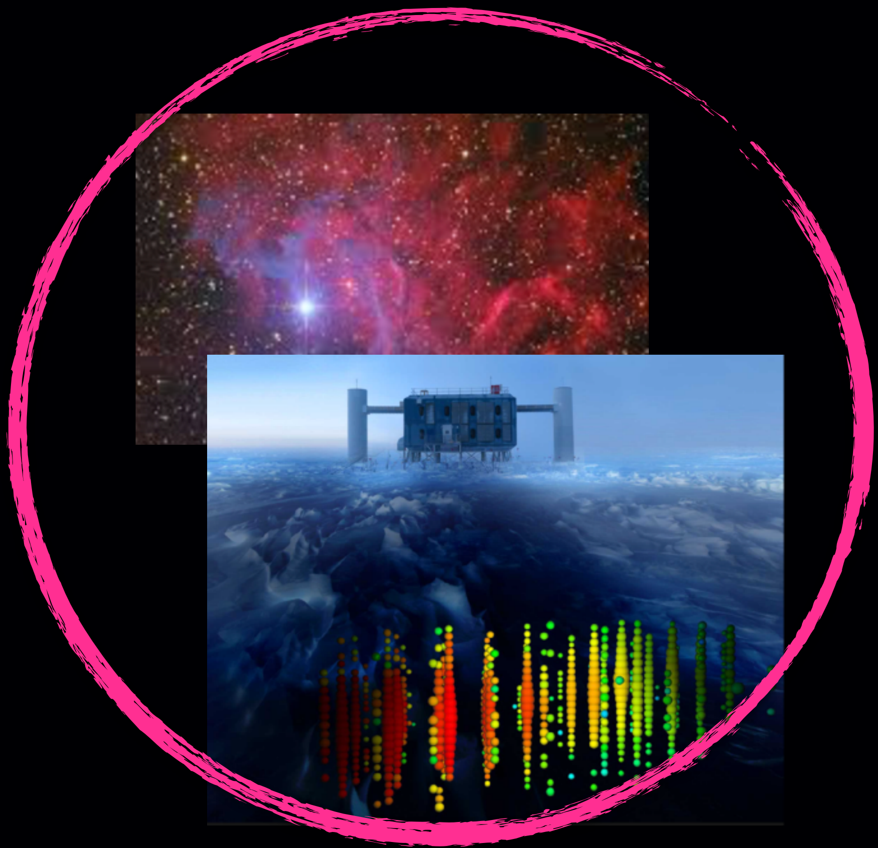
Based on: *Fiorillo, Miele, Morisi, **Saviano** 2020, **PRD 101,083024**, arXiv:2002.10125,*

*Fiorillo, Miele, Morisi, **Saviano** 2020, **PhysRevD 102.083014**, arXiv:2007.07866*

# *How to corner sterile ν and secret interactions*

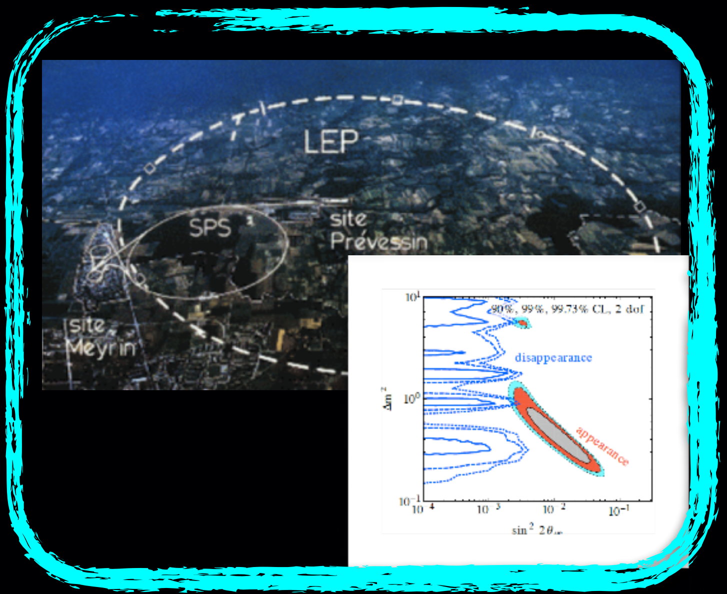
## Astrophysical sources

*Kolb and Turner 1987; Ng and Beacom 2014; Ioka and Murase 2014; Cherry, Friedland and Shoemaker 2016, Bustamante et al 2019, Shoemaker and Murase 2016…*



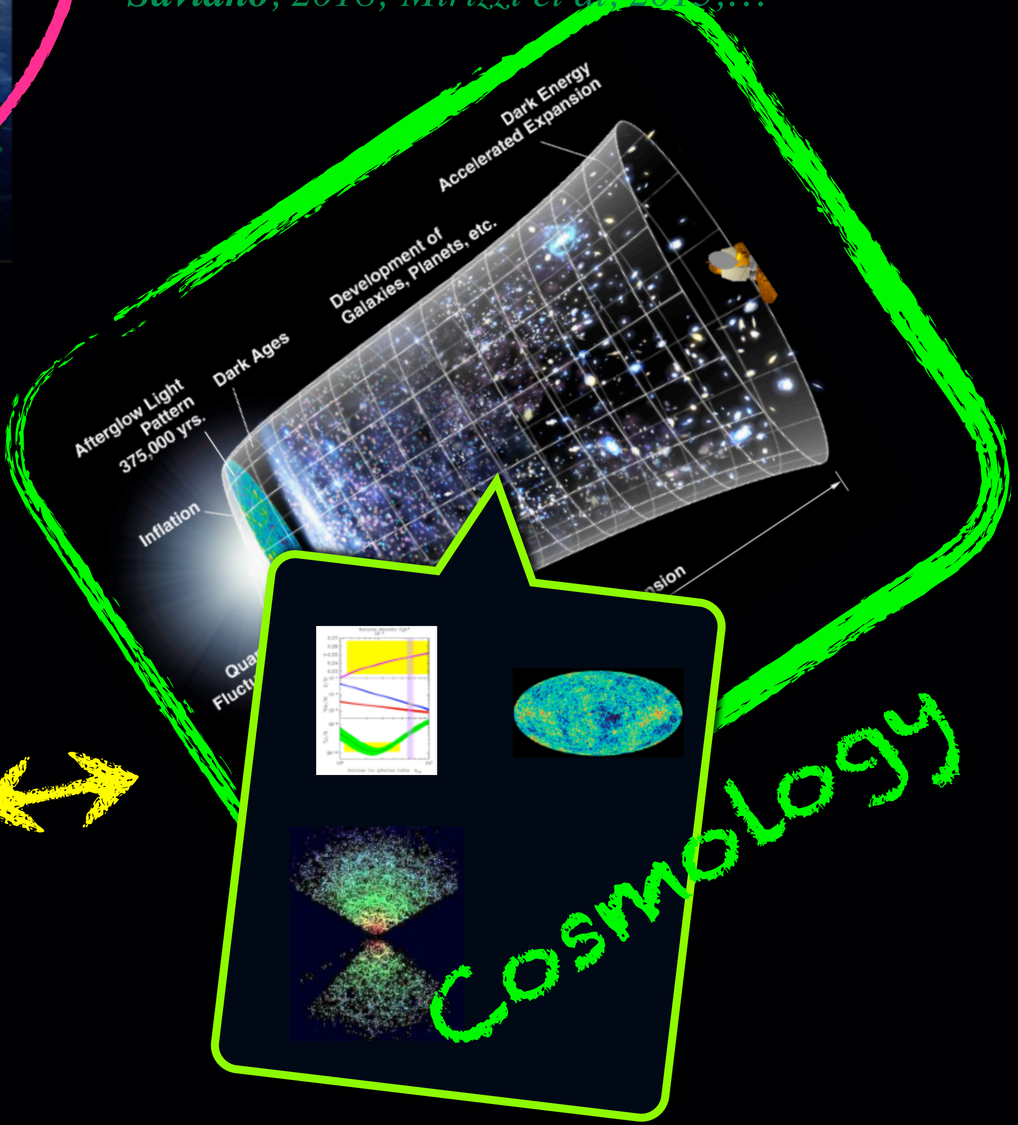
*Archidiacono and Hannestad, 2014; Forastieri, Lattanzi e Natoli 2019;,Dasgupta and Kopp, 2014;* ***Saviano*** *et al 2014, Archidiacono et al., 2016; Cherry, Friedland and Shoemaker 2016; Forastieri…* ***Saviano****, 2017; Chu, Dasgupta, Dentler, Kopp and* ***Saviano****, 2018; Mirizzi et al, 2015,…*

*Berryman et al., 2018…*



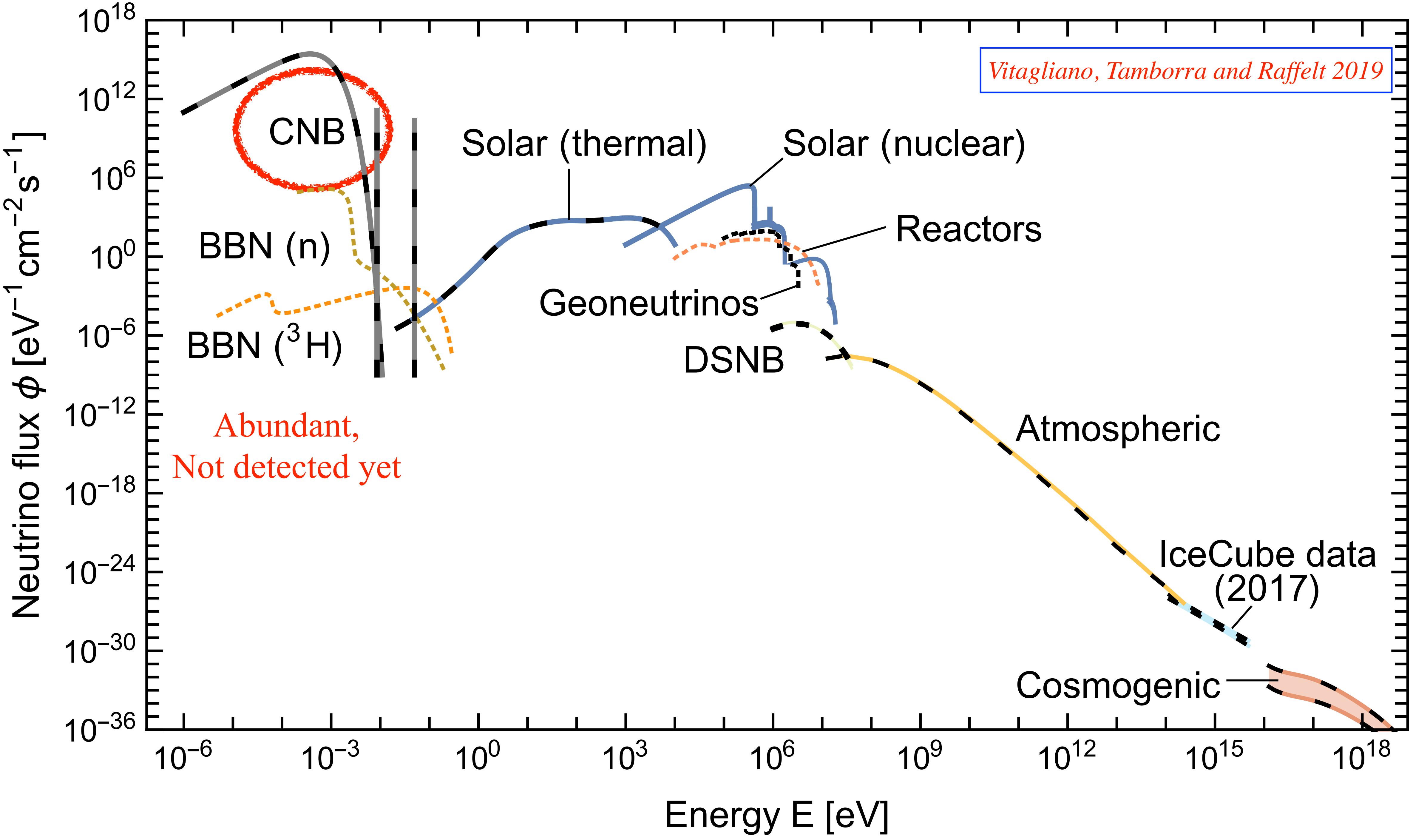
## Laboratory

**νs**
**&**
**secret inter.**



## Cosmology

# *Neutrino Spectrum at Earth*



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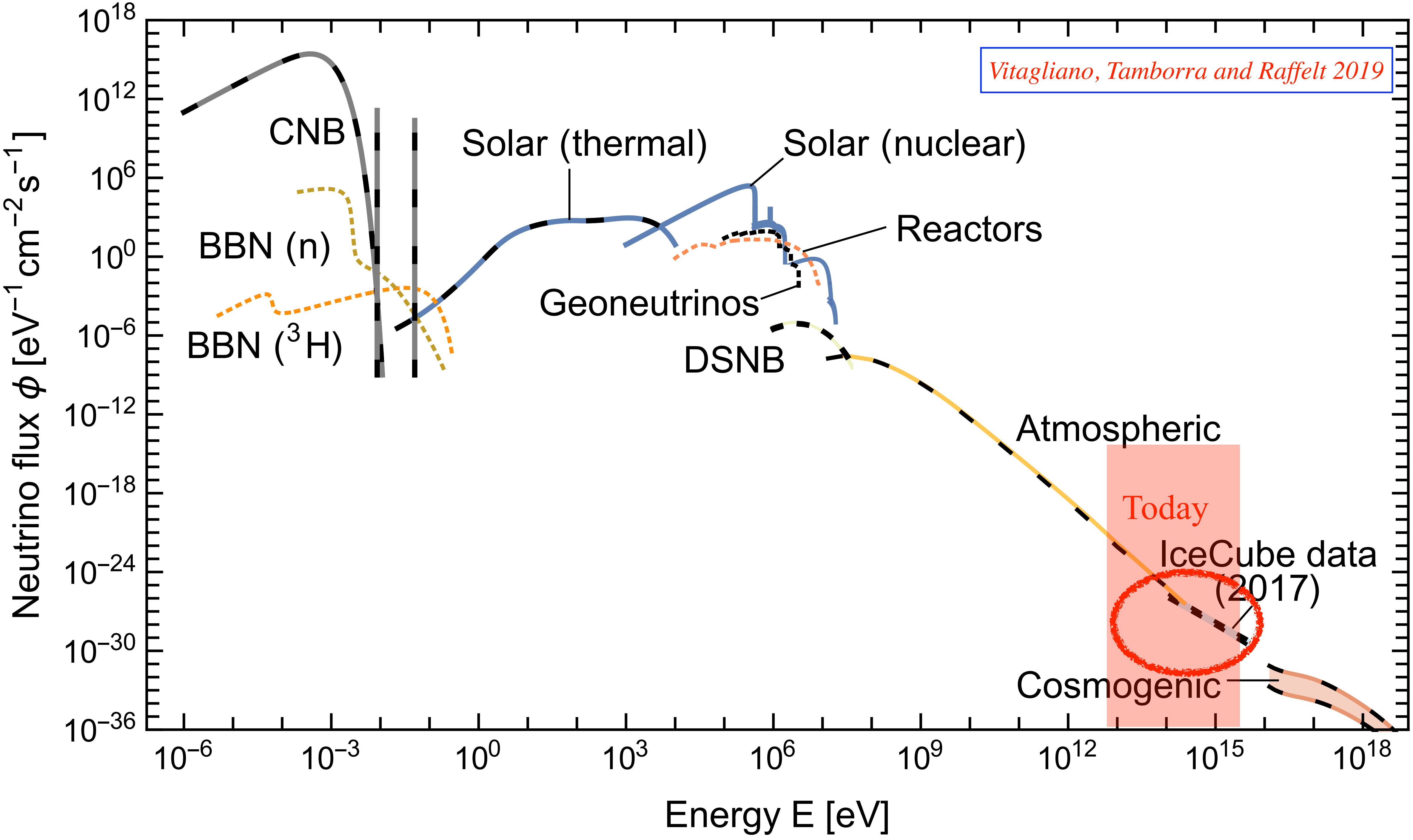

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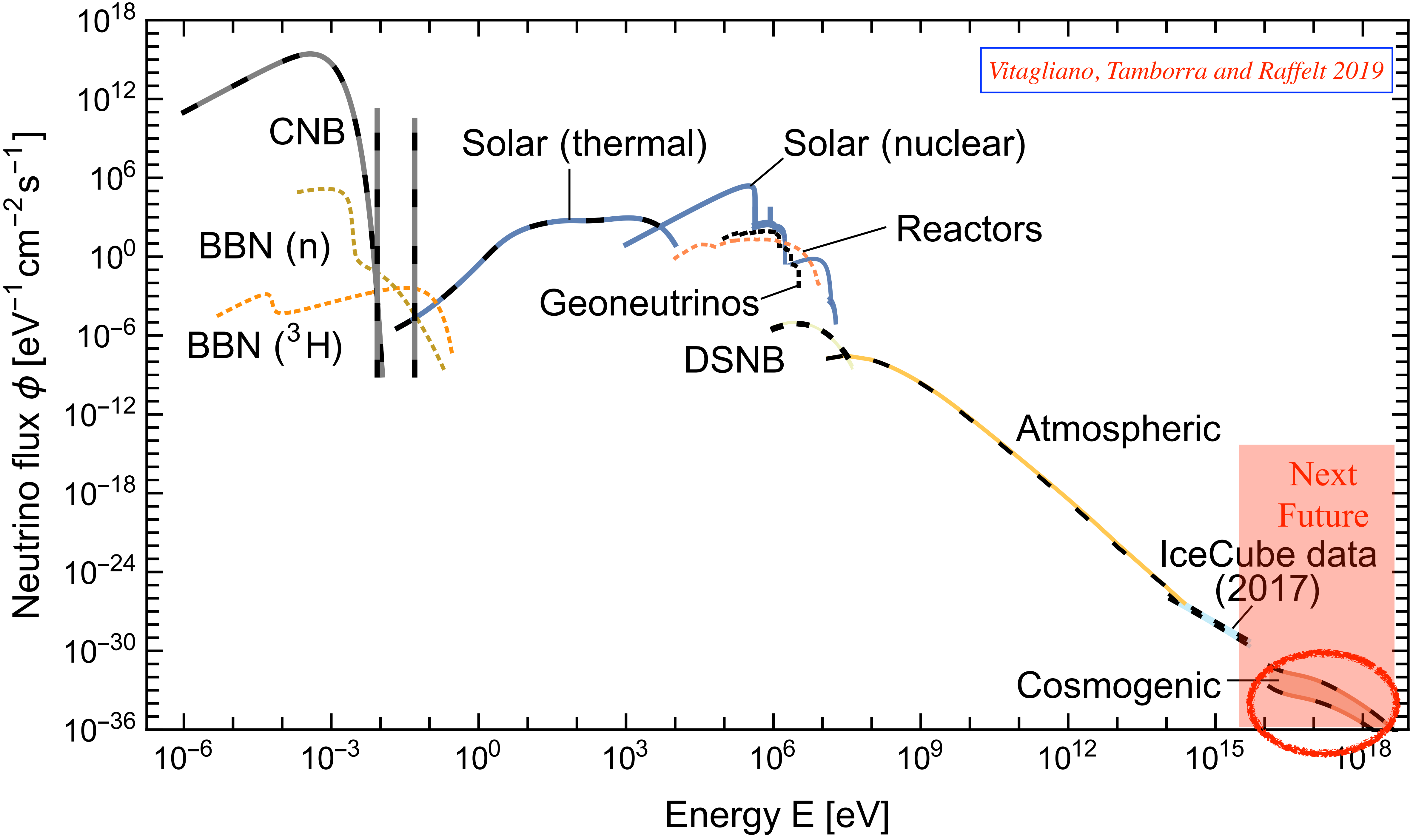
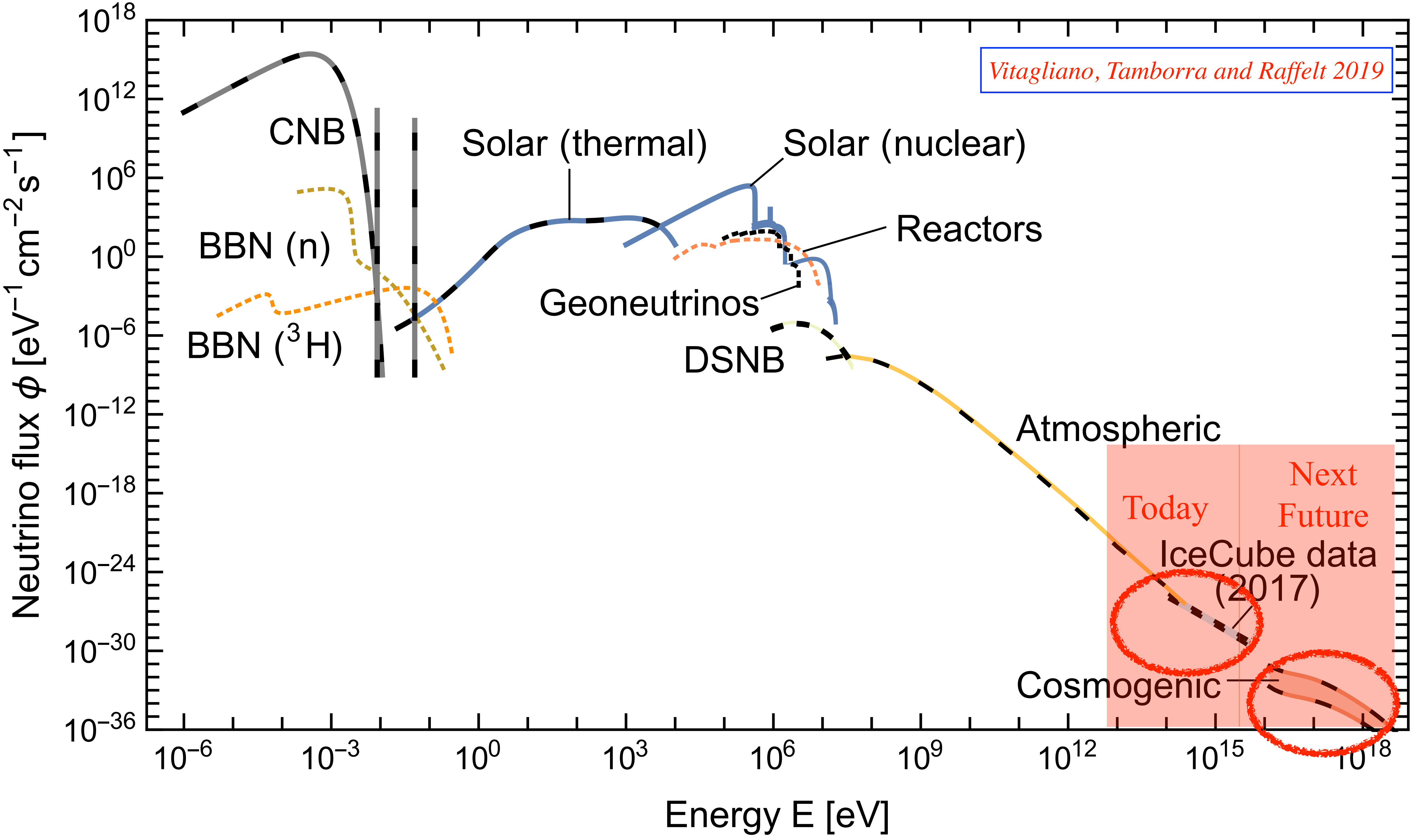


# *Neutrino Spectrum at Earth*



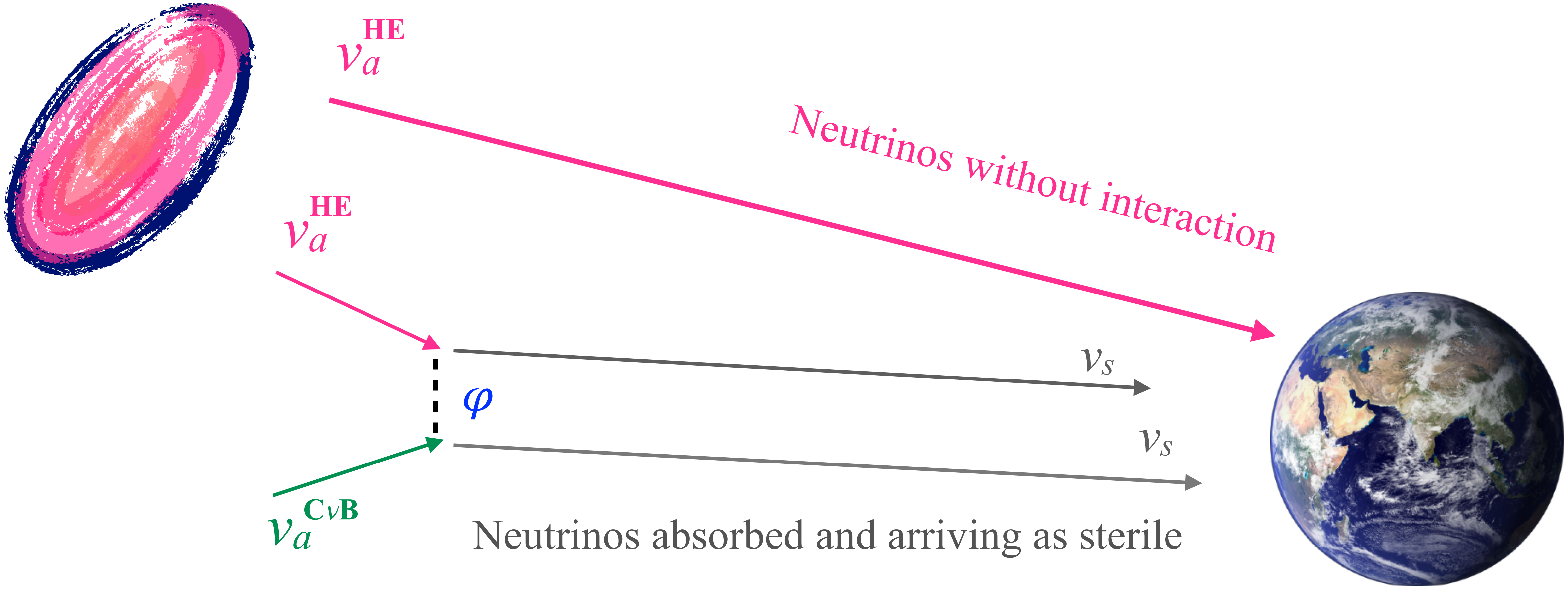
**High-Energy cosmic nu very exciting:** {

they have the highest energies

they travel the longest distances

# Our model

We consider a scheme of SI where the new interaction, mediated by a new pseudoscalar mediator, involves both active and sterile neutrinos:



We study the modifications on the expected (ultra-)high neutrino fluxes at Earth implied by the new coupling, estimating the possibility to measure this effect in present and future apparatus, depending on the neutrino energies.

*Fiorillo, Miele, Morisi, **Saviano** 2020, **PRD 101,083024**, arXiv:2002.10125*

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# *Active-sterile secret interactions*

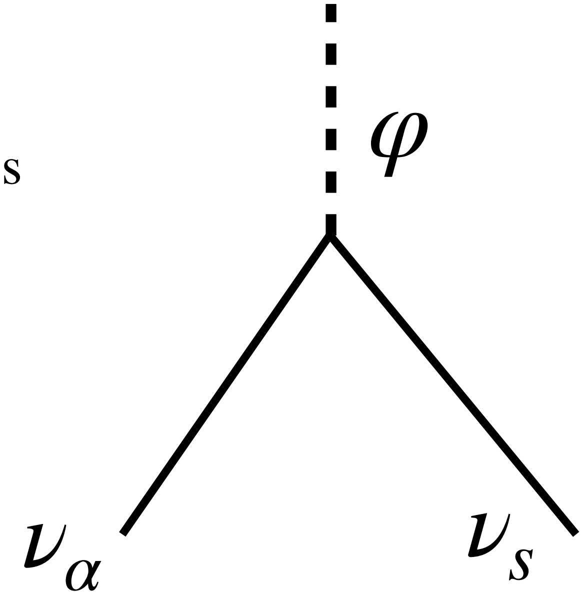
## *General case: 3 & 1 (3 active and 1 sterile)*

The interaction is flavor dependent and mediated by a pseudoscalar particle.

$$\mathcal{L}_{\mathrm{SI}} = \sum_{\alpha} \lambda_\alpha \, \overline{\nu}_\alpha \gamma_5 \nu_s \varphi$$

$\alpha = e, \mu, \tau$

$\lambda_\alpha$ dimensionless free couplings



- Majorana neutrinos
- For the simplest choice,

  $\varphi$ is a pseudoscalar

**Parameter space:**

$M_\varphi, m_s, \lambda_\alpha$

Ample freedom of choice for our model:

- The most natural possibility is $\lambda_e = \lambda_\mu = \lambda_\tau$
- Very interesting case only $\lambda_\tau \neq 0$

# *Allowed parameter space*

The proposed model is subject to different constraints from:

laboratory experiments

Cosmological observations

Astrophysical observations

# *Allowed parameter space (1)*

- Laboratory constraints

**The new interaction opens new leptonic decay channels** $M \to \nu_s \ell \varphi$ and $M \to \nu_s \ell \overline{\nu}_{\ell'} \nu_s$

Examples: $\boxed{K^+ \to \mu \varphi \nu_s}$ and $\boxed{K^+ \to \mu \nu_s \nu_s \overline{\nu}'_\ell}$ should be observed as $\underline{K \to \mu + \text{missing energy}}$

In the standard sector the closer Kaon decay process is $K \to \mu \nu \overline{\nu} \nu$ with BR= $2.4 \times 10^{-6}$

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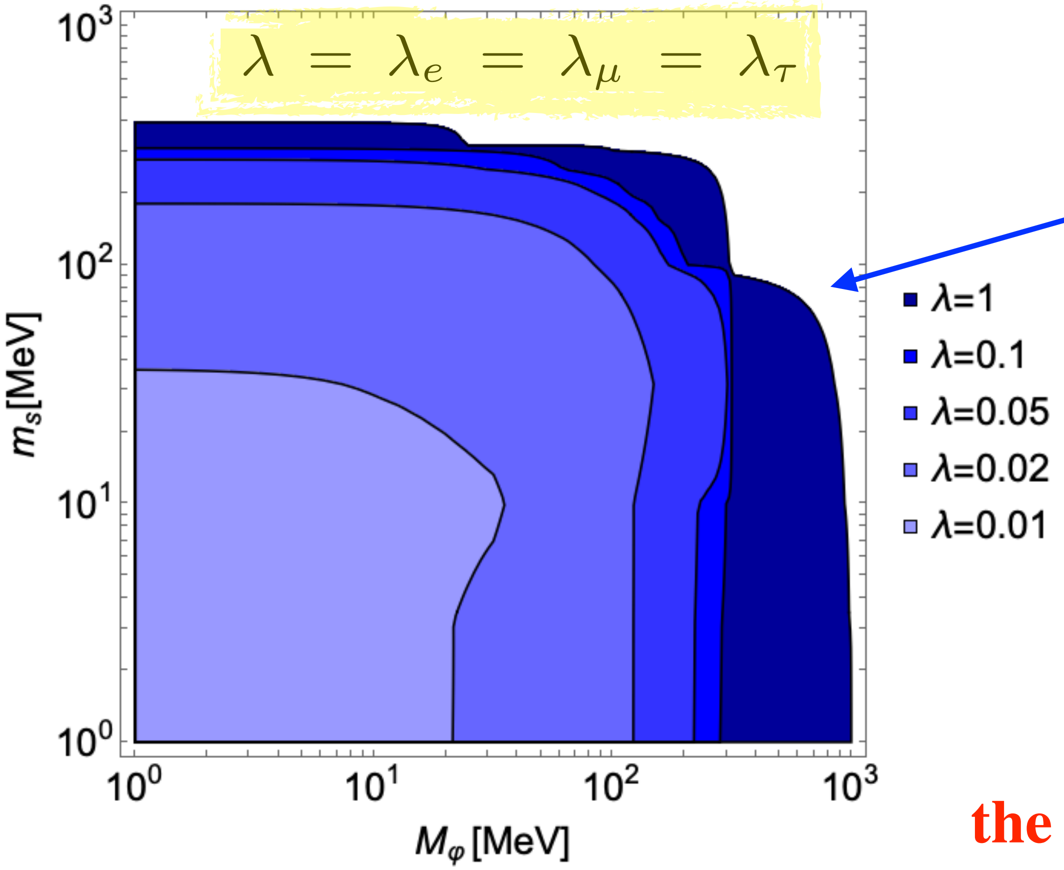

We impose $\boxed{\mathrm{BR}\left(\begin{smallmatrix} K^+ \to \mu \varphi \nu_s \\ K^+ \to \mu \nu_s \nu_s \overline{\nu}'_\ell \end{smallmatrix}\right) < 2.4 \times 10^{-6}}$

Bump produced by the four-body decay

**the region below the contours is excluded**

For $\lambda \geq 0.01$ and $(m_s \text{ or } M_\varphi) \gtrsim 30\, MeV$

**the correction to Kaon decay is within the experimental bound**

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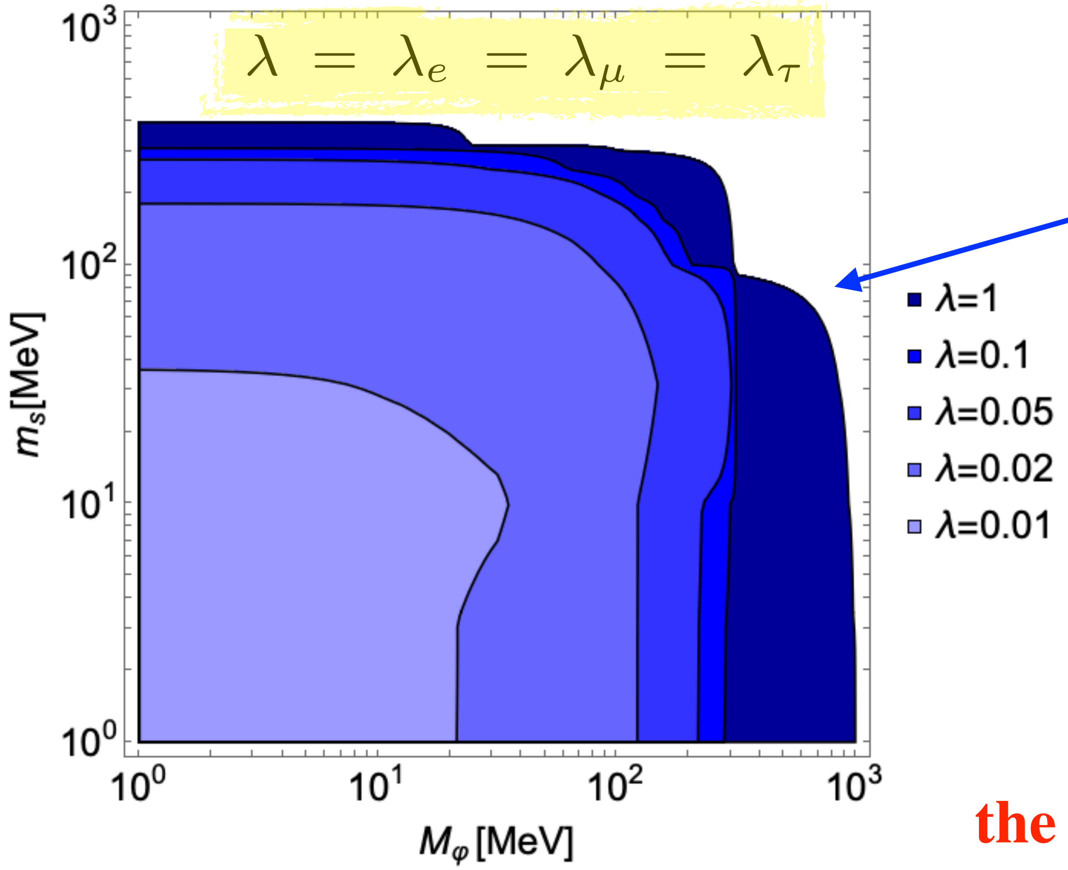

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⬇

**the correction to Kaon decay is within the experimental bound**

The choice of only $\lambda_\tau \neq 0$ (which involves the D decay) is practically unconstrained from meson physics and even for value of λτ~ O(1), the only relevant bound in the $M_\varphi - m_s$ plane comes from BBN

# *Allowed parameter space (2)*

- Cosmological constraints

BBN requirement: no extra relativistic d.o.f. at the BBN-time (~1 MeV)

CMB requirement: free-streaming active ν at the CMB-time (~1 eV)

Both satisfied for **Mϕ and ms >10 MeV**

- Supernovae constraints

Supernovae neutrinos with energy of 10-100 MeV can produce non relativistic sterile neutrinos via secret interactions.

These sterile neutrinos might, depending on their interaction, escape the SN giving rise to an observable energy loss.

For **Mϕ and ms >10 MeV, this situation is never verified and so our model is not subjected to SN constrains**

# *Neutrino Fluxes without SI*

Active-sterile neutrino interaction can become relevant at very different energy scales depending on the mass of the scalar mediator $\varphi$.

The energy at which the absorption over neutrinos from the Cosmic Neutrino Background (CNB) is most relevant is of the order of $M_\varphi^2/m_\alpha$

In the selected parameter space, this energy scale corresponds to a **range of [PeV -$10^4$ PeV]**

## PeV scale

The dominant source of neutrinos is expected to be constituted by galactic and extragalactic astrophysical sources (Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB))

A good fit to the observed IceCube data below the PeV is represented by a simple PL spectrum

We discuss the effect of the new interaction on a **PL spectrum** with parameters obtained by the fit to the IceCube data *D.R. Williams (IceCube), 2018*

## 100 PeV

It is expected that a dominant source of neutrinos should have **cosmogenic** origin.

A competing source of neutrinos could still be of astrophysical nature, provided for example by blazars and Flat Spectrum Radio Quasar *Murase et al. 2014* *Righi et al. 2020*

***We consider two benchmark fluxes:***

***- an astrophysical PL flux in the range below 100 PeV***

***- a cosmogenic flux, in the Ultrahigh energy range***

# ν Fluxes with SI and Transport Equation

In the generalized multiflavor case:

$\Phi_i(z,E)$ flux of active neutrinos per unit energy interval per unit solid angle at a redshift z ($(i=1,2,3)$ mass eigenstate )

$\Phi_s(z,E)$ flux of sterile neutrino

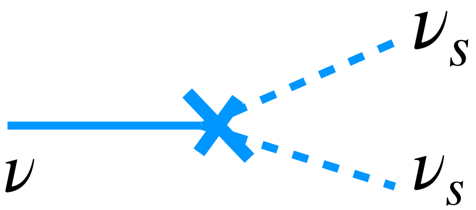
absorption

regeneration

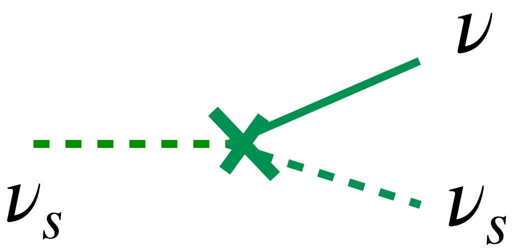
$$\frac{d\phi_\nu}{dEd\Omega} = \Phi(0,E)$$

- $H(z)(1+z)\left(\frac{\partial\Phi_i}{\partial z}+\frac{\partial\Phi_i}{\partial E}\frac{E}{1+z}\right) = \boxed{n(z)\sigma_i(E)\Phi_i} - \int dE'\,\Phi_s(E')\frac{d\sigma_{sa}}{dE}(E'\to E)\,n(z) - \rho(z)(1+z)f(E)\xi_i$
- ~~$H(z)(1+z)\left(\frac{\partial\Phi_s}{\partial z}+\frac{\partial\Phi_s}{\partial E}\frac{E}{1+z}\right) = n(z)\sigma_s(E)\Phi_s - \int dE'\,\Phi_i(E')\frac{d\sigma_{is}}{dE}(E'\to E)\,n(z)$~~

  ~~$-\int dE'\,\Phi_s(E')\frac{d\sigma_{ss}}{dE}(E'\to E)\,n(z)$~~



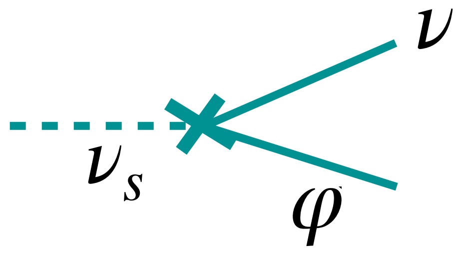
absorption



regeneration terms

unimportant for the full parameter space we consider.

The perturbative approach shows in fact that the corrections coming from regeneration, both for cosmogenic and astrophysical fluxes, are typically not larger than about 10%

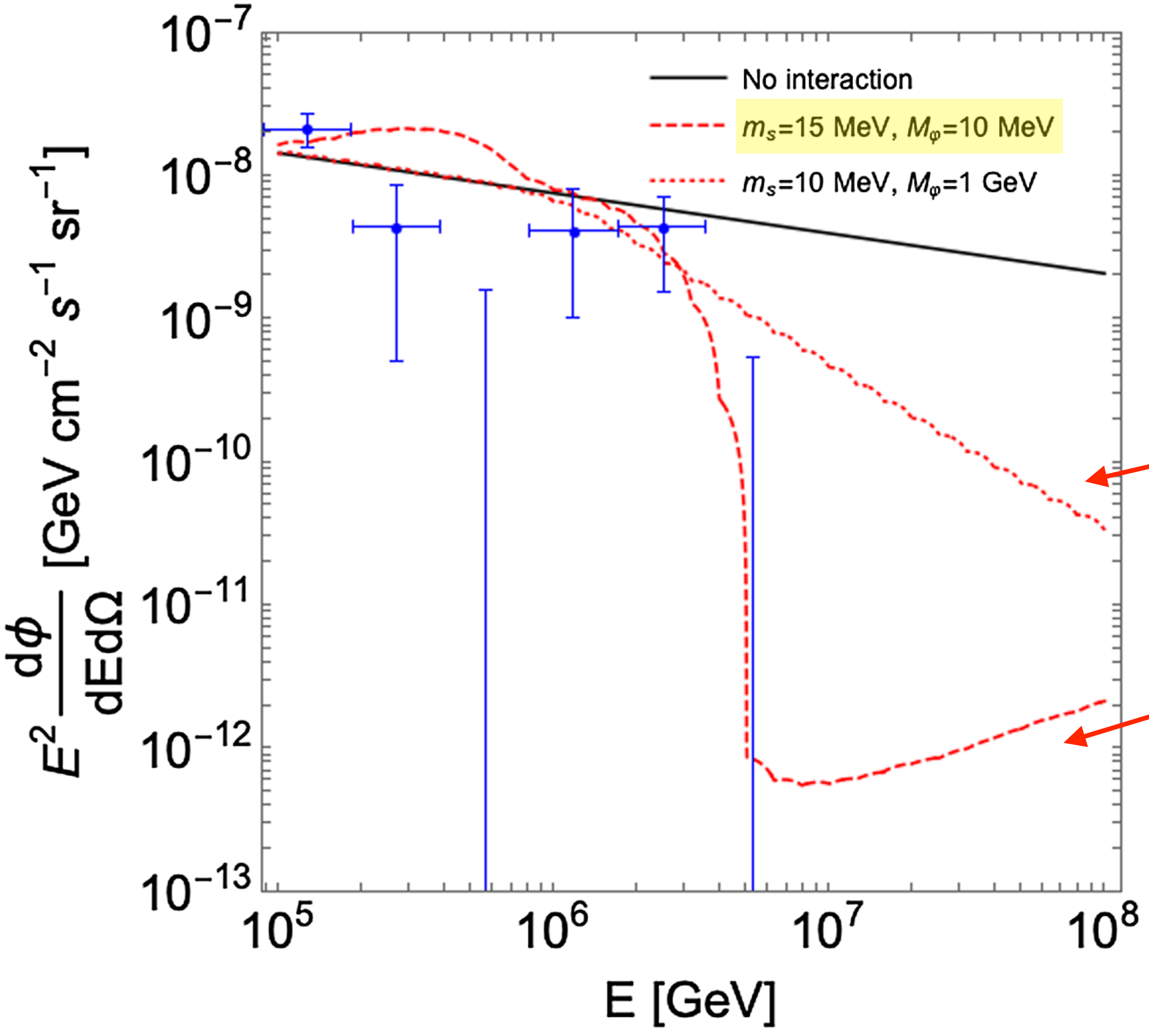


the results of the first order perturbation theory may cause small but non-negligible changes to the spectrum

# *Results and detection chances for PL Spectrum* (1)

*Cutoff-like feature in the spectrum:*

Energy range roughly below 100 PeV



$\lambda_e = \lambda_\mu = \lambda_\tau = \lambda_{af}$ (where $af$ denotes all flavors)

$\lambda_{af} = 1$

small sterile masses, large scalar masses

$m_s$=10 MeV, $M_\varphi$=1 GeV

$\lambda_e = \lambda_\mu = 0$ and $\lambda_\tau \neq 0$ =1

$m_s$=15 MeV, $M_\varphi$=10 MeV

the constraints from mesons decay are irrelevant

⇨ also lower masses for M$\varphi$

IceCube HESE data

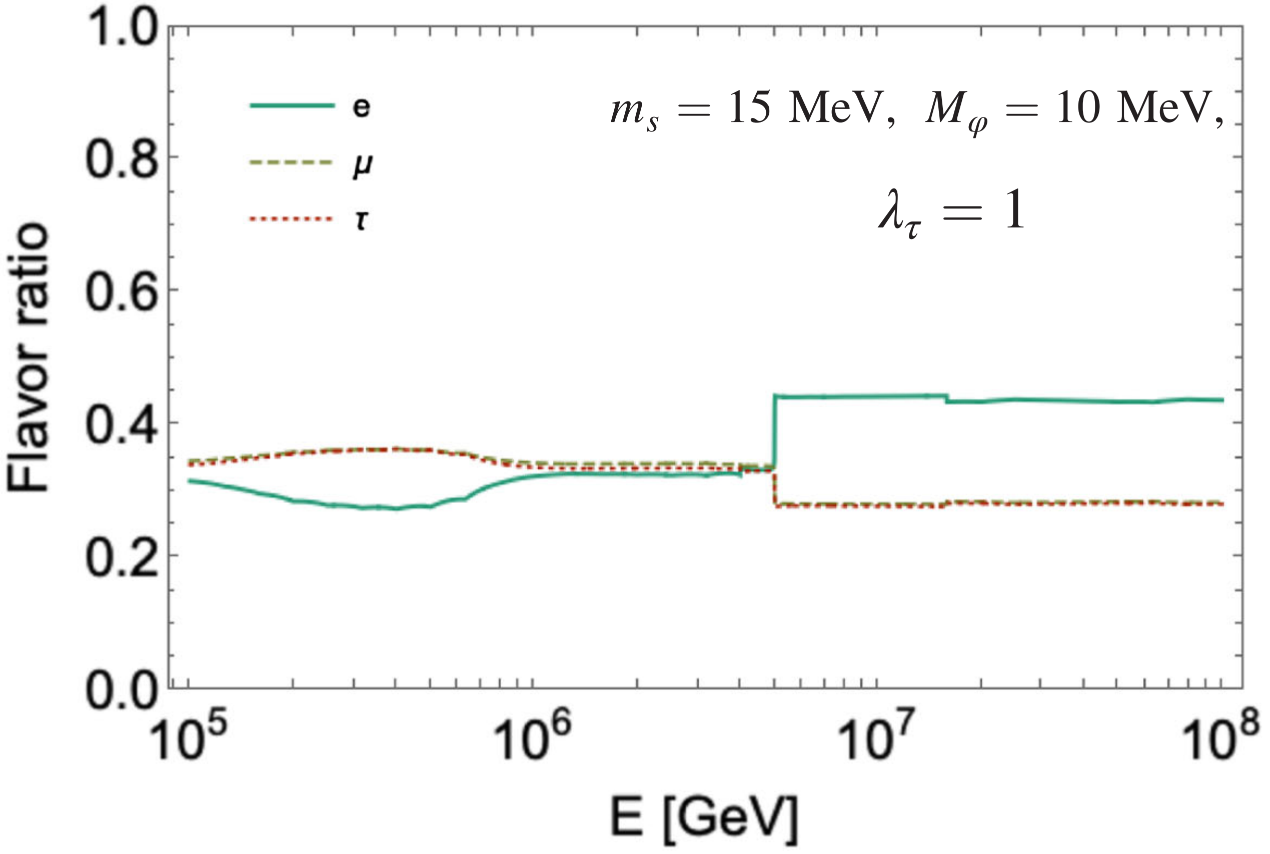
The new interaction causes a cutoff-like feature in the spectrum in the range between 1 PeV and 10 PeV

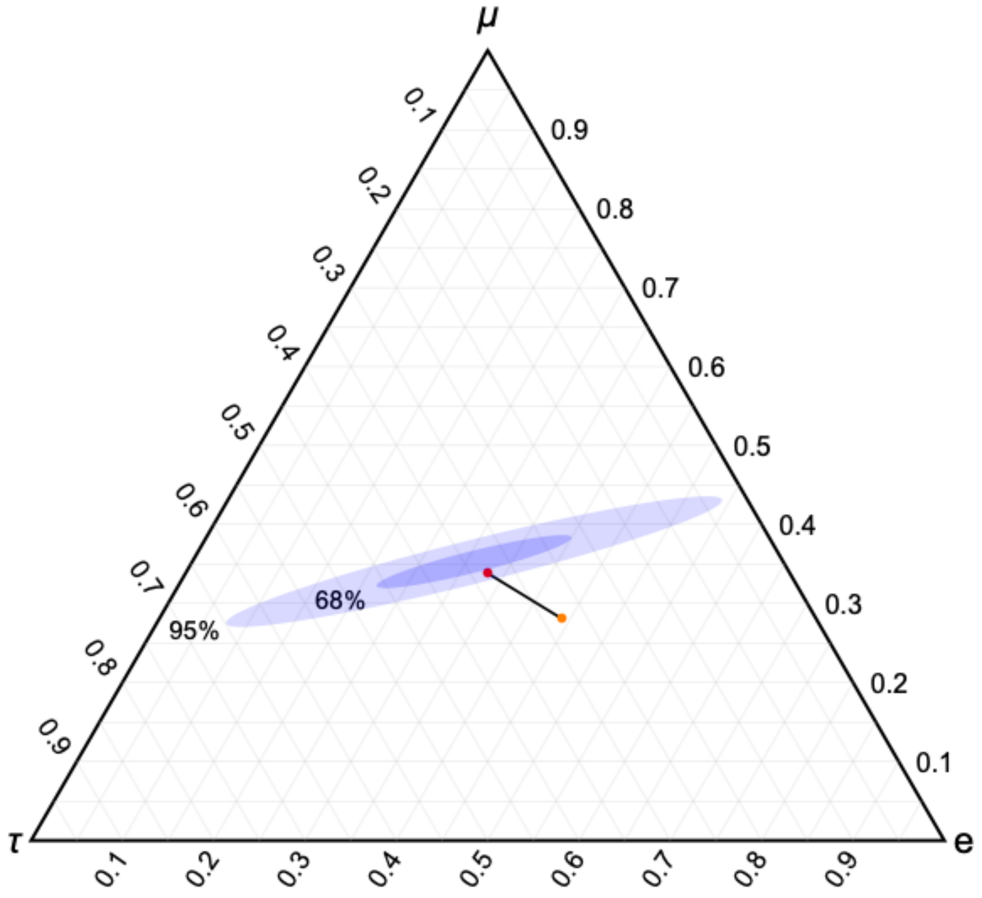
*Fiorillo, Miele, Morisi, **Saviano** 2020, **PhysRevD 102.083014**, arXiv:2007.07866*

# *Results and detection chances for PL Spectrum* (2)

***Changing in the flavour ratio:***

the depletion is energy dependent ⇨ energy dependent flavor ratio at Earth





flavor ratio at the source (1 : 2 : 0)

Expected flavor ratio at Earth (1 : 1 : 1)

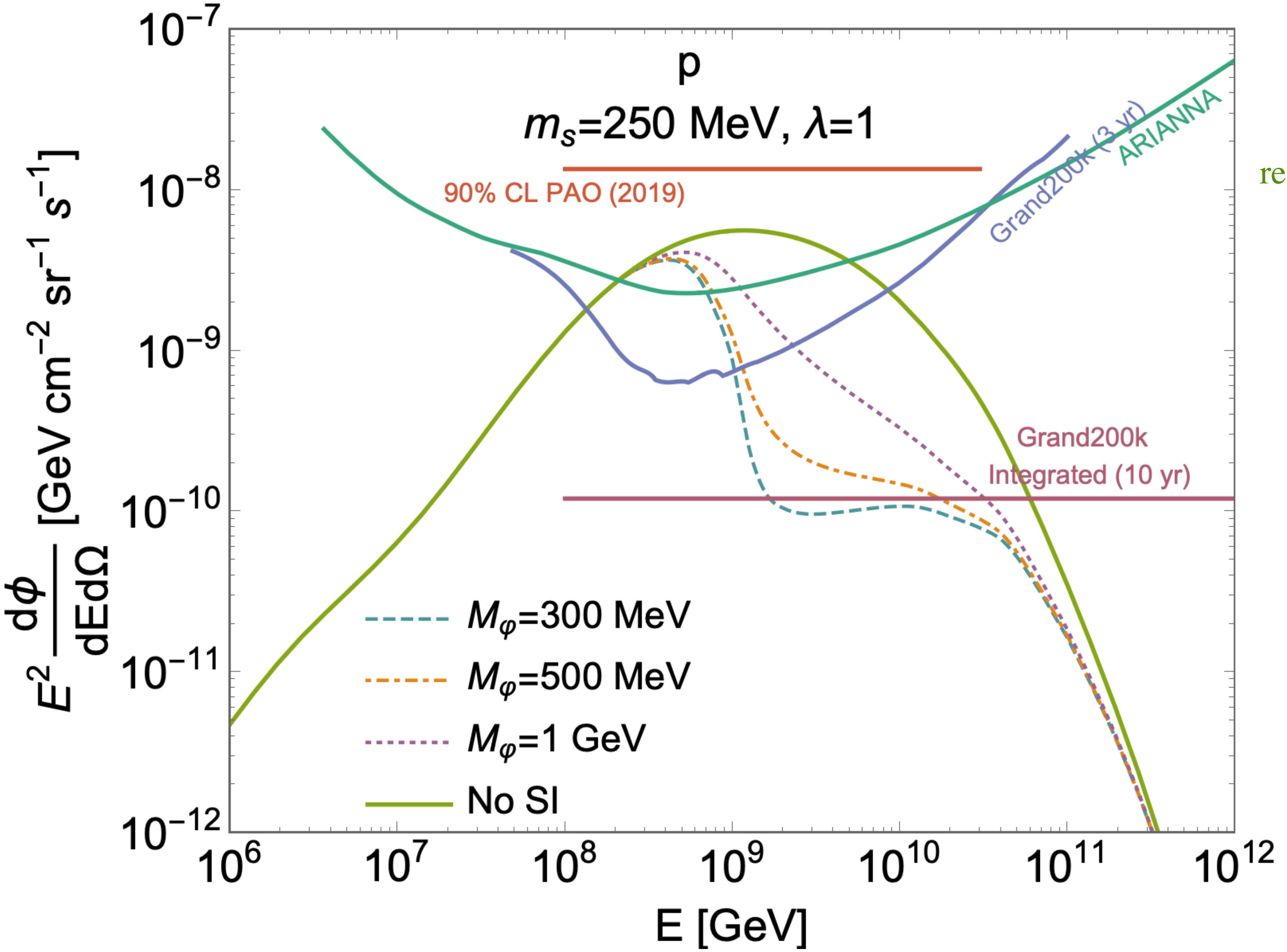
Flavor at $10^5$ GeV

Flavor at $10^8$ GeV

forecasted sensitivity of IceCube-Gen2

*Fiorillo, Miele, Morisi, **Saviano** 2020, **PhysRevD 102.083014**, arXiv:2007.07866*

# Results and detection chance for Cosmogenic Spectrum



***proton cosmic rays***

reference spectrum given in *Ahlers & Halzen 2012*

The effect is maximal around $10^{9\div10}$ GeV

*Fiorillo, Miele, Morisi, **Saviano** 2020, **PRD 101,083024**, arXiv:2002.10125*

# *Conclusions*

We have investigated the effects on high- and ultra high- energy active neutrino fluxes due to active-sterile secret interactions mediated by a new pseudoscalar particle.

Active-sterile neutrino interactions become relevant at very different energy scales depending on the masses of the scalar mediator and of sterile neutrino.

The final active fluxes can present a measurable depletion (absorption) observable in future experiments.

The flux depletion can occur both at lower energy, around the PeV, depending on the choice for the coupling, and at higher energy involving the cosmogenic neutrino flux.

Another interesting phenomenological aspect of active-sterile secret interactions is represented by the changing in the flavor ratio as a function of neutrino energy. This effect could be interesting for next generation of neutrino telescopes.

**Thank you**

# *(Ultra-)High$\nu$ flux at Earth*

## IceCube *ν*: **PL spectrum**

Collection of astrophysical neutrino sources, each one producing a power law spectrum in energy $g(E) = \mathcal{N}\, E^{-\gamma}$

$g \equiv \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} + \phi_{\overline{\nu}_e} + \phi_{\overline{\nu}_\mu} + \phi_{\overline{\nu}_\tau}$ , $\gamma$ the spectral index $= 2.28$ , $\mathcal{N}$ normalization

*Schneider, 2020*

Adopting the Star Forming Rate ρ(z) for the cosmological evolution of these sources, the ***diffuse astrophysical spectrum*** is:

$$\frac{d\phi_\nu}{dE d\Omega} = \int \frac{dz'}{H(z')} \rho(z') g[E(1+z')]$$

Flavor structure at the source (1 : 2 : 0), corresponding to pion beam sources

## Cosmogenic spectrum

Cosmogenic neutrinos are produced by the scattering of high energy protons from the cosmic rays with the CMB photons.

Following the work of *Ahlers and Halzen 2012*, we reproduce their results parameterizing the ***cosmogenic neutrino spectrum*** as

$$\frac{d\phi_\nu}{dE d\Omega} = \int \frac{dz'}{H(z')} \rho(z') f[E(1+z')]$$

where ρ(z) is the Star Forming Rate

Flavor structure at the source (1 : 2 : 0)

# *Cosmogenic ν flux at Earth without SI*

Cosmogenic neutrinos are produced by the scattering of high energy protons from the cosmic rays with the CMB photons, while propagating between their sources and Earth.

The cosmogenic neutrino flux $\phi_\nu$, expected to be isotropic, can be parameterized in the form

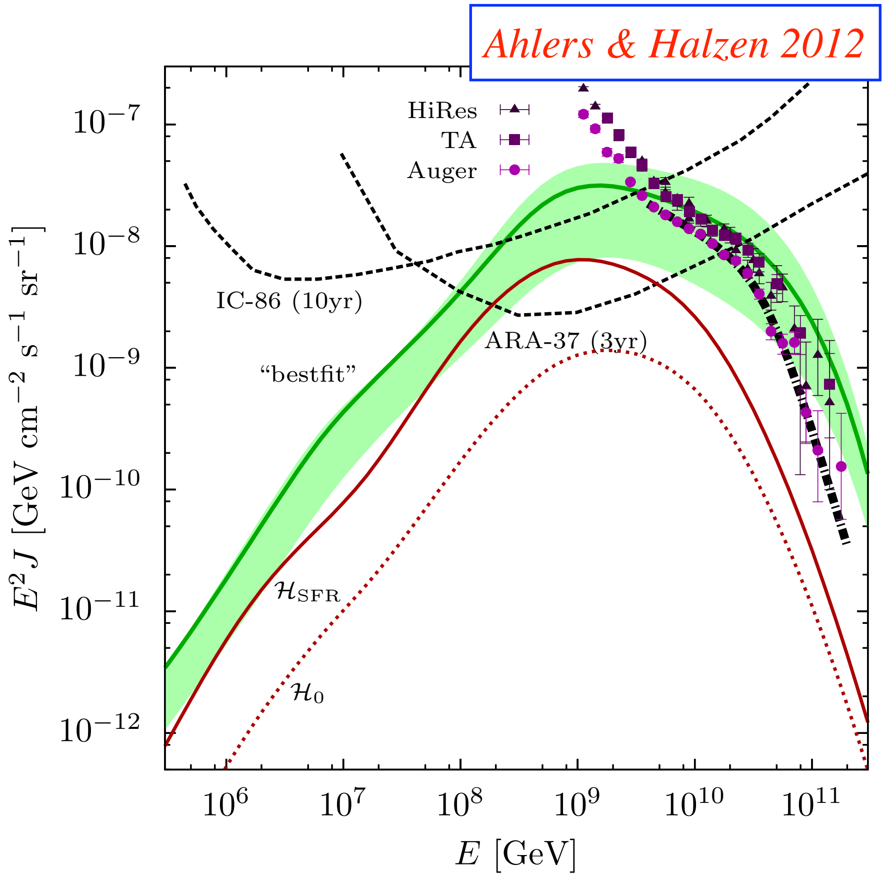
$$\frac{d\phi_\nu}{dE\,d\Omega} = \int \frac{dz'}{H(z')} F\left[z', E(1+z')\right]$$

where $F\,[z', E(1+z')]$ is the number of neutrinos produced per unit time per unit energy interval per unit solid angle per unit volume at redshift z’ and with comoving energy E(1 + z’).

Using as a reference the spectrum proposed in *Ahlers & Halzen 2012*, which constitutes a lower bound for the cosmogenic neutrino spectrum,

We adopt the following **ansatz for F**

$$\boxed{F[z', E(1+z')] = \rho(z') f[E(1+z')]}$$


*Ahlers & Halzen 2012*

where ρ(z) is the Star Forming Rate

$$\begin{cases} (1+z)^{3.4} & z \le 1; \\ N_1(1+z)^{-0.3} & 1 < z \le 4; \\ N_1 N_4 (1+z)^{-3.5} & z > 4, \end{cases}$$

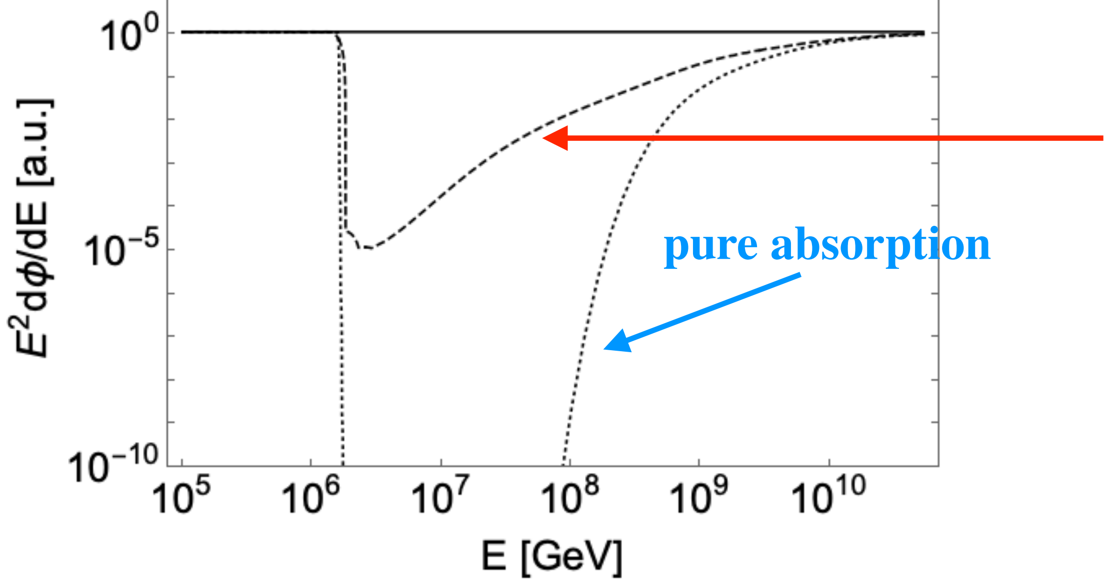
# Regeneration term for point-like sources at large redshift:

**$z > 0.1$**, the produced neutrinos are severely suppressed due to the absorption on the CNB

**$z < 0.1$**, the produced neutrinos are only weakly absorbed

The flux has always a component, produced at low redshift, which is roughly unabsorbed and which dominates against the small regenerated flux produced at high redshifts, masquerading the effect.

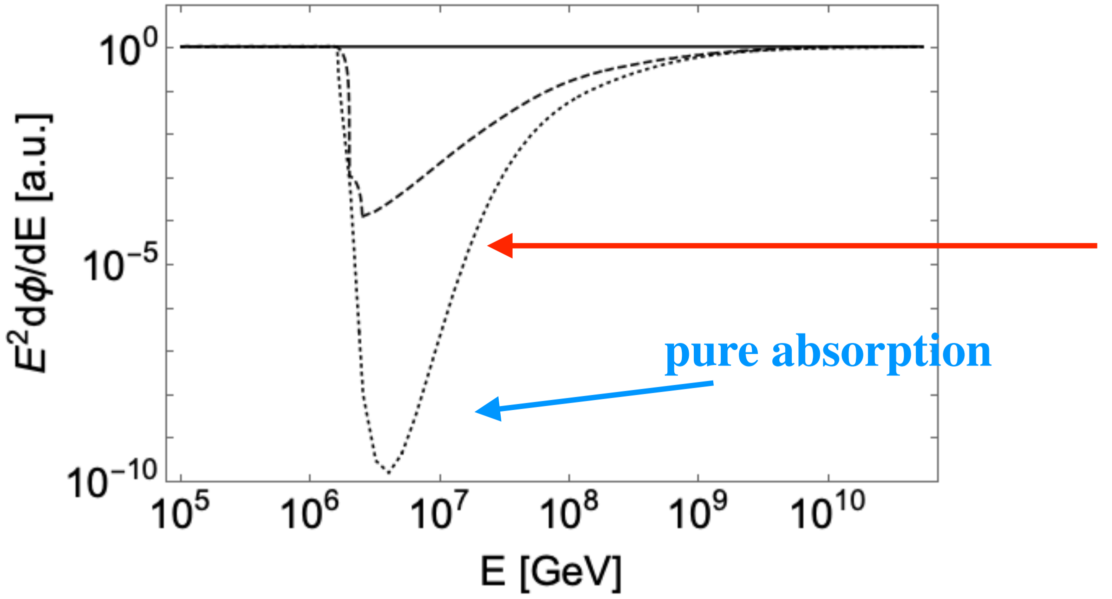
Expected spectra at Earth for a generic source at two fixed redshift values z with an $E^{-2}$ reference spectrum.



**$z = 0.1$**

**both absorption and regeneration**

**reference unabsorbed spectrum**

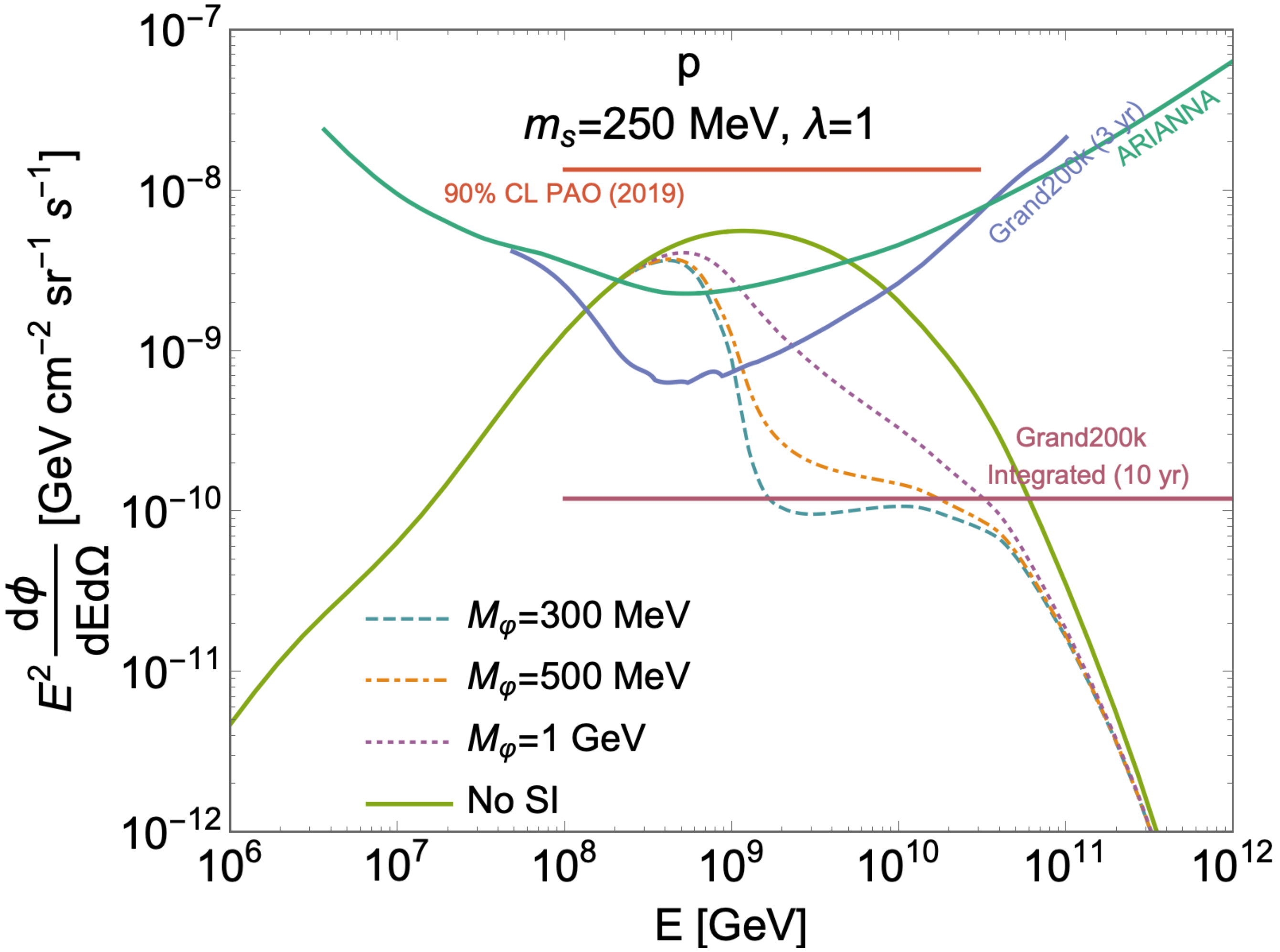


**$z = 0.01$**

**both absorption and regeneration**

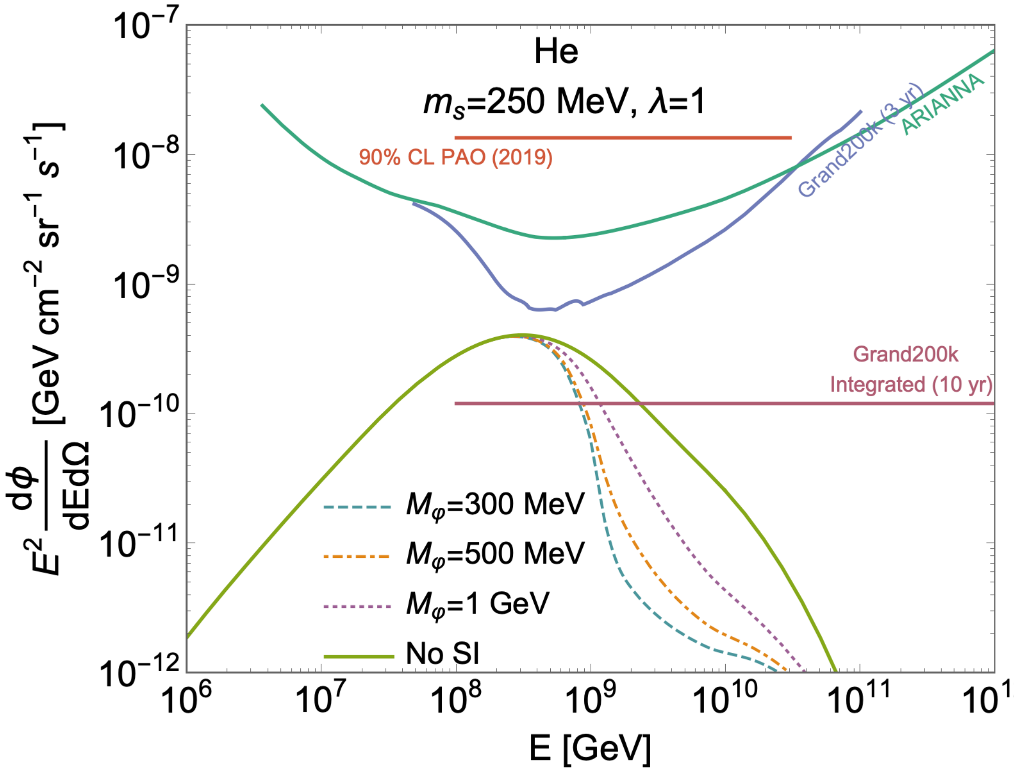
The effects of regeneration are more important for larger redshifts of the source and can drastically change the results.

# *Results and detection chance for Cosmogenic Spectrum*



*proton cosmic rays*

*helium cosmic rays*



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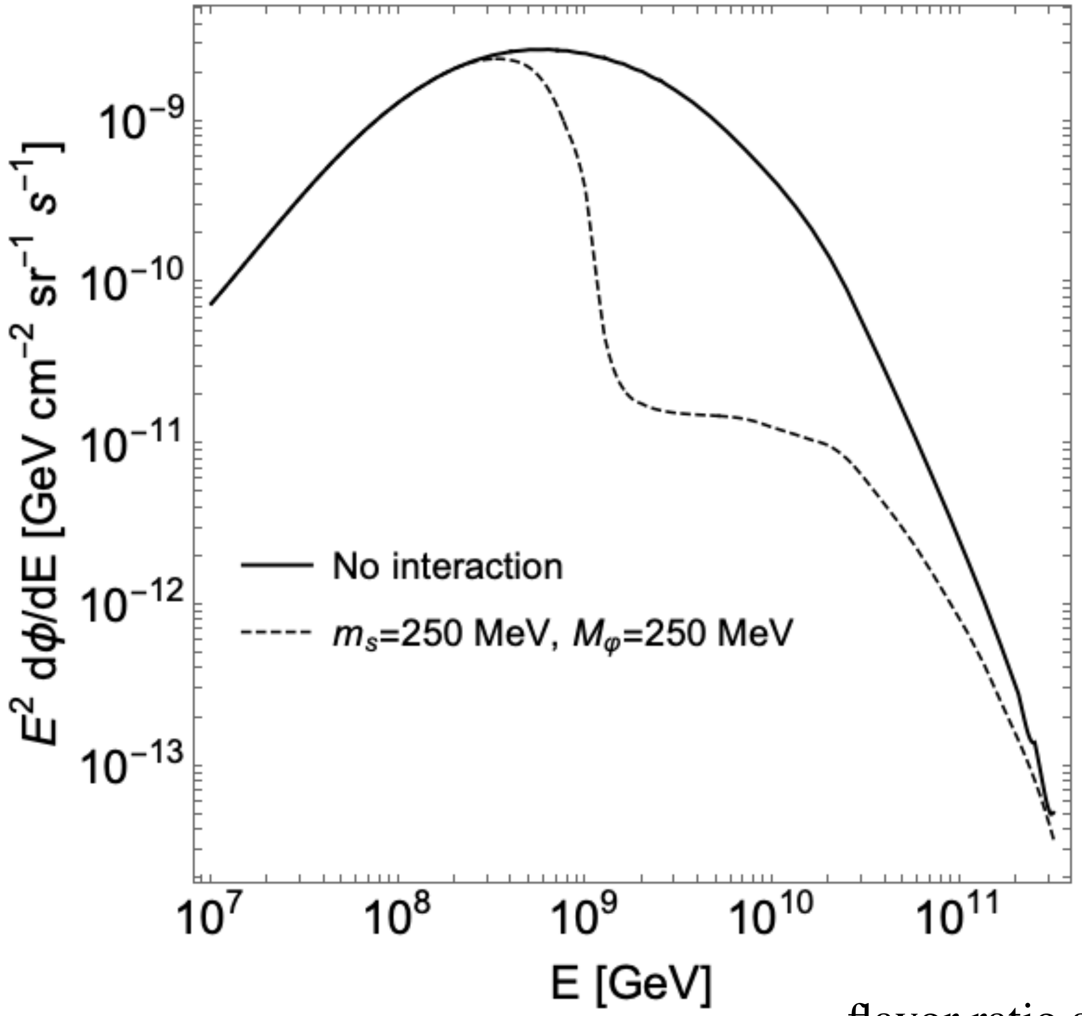
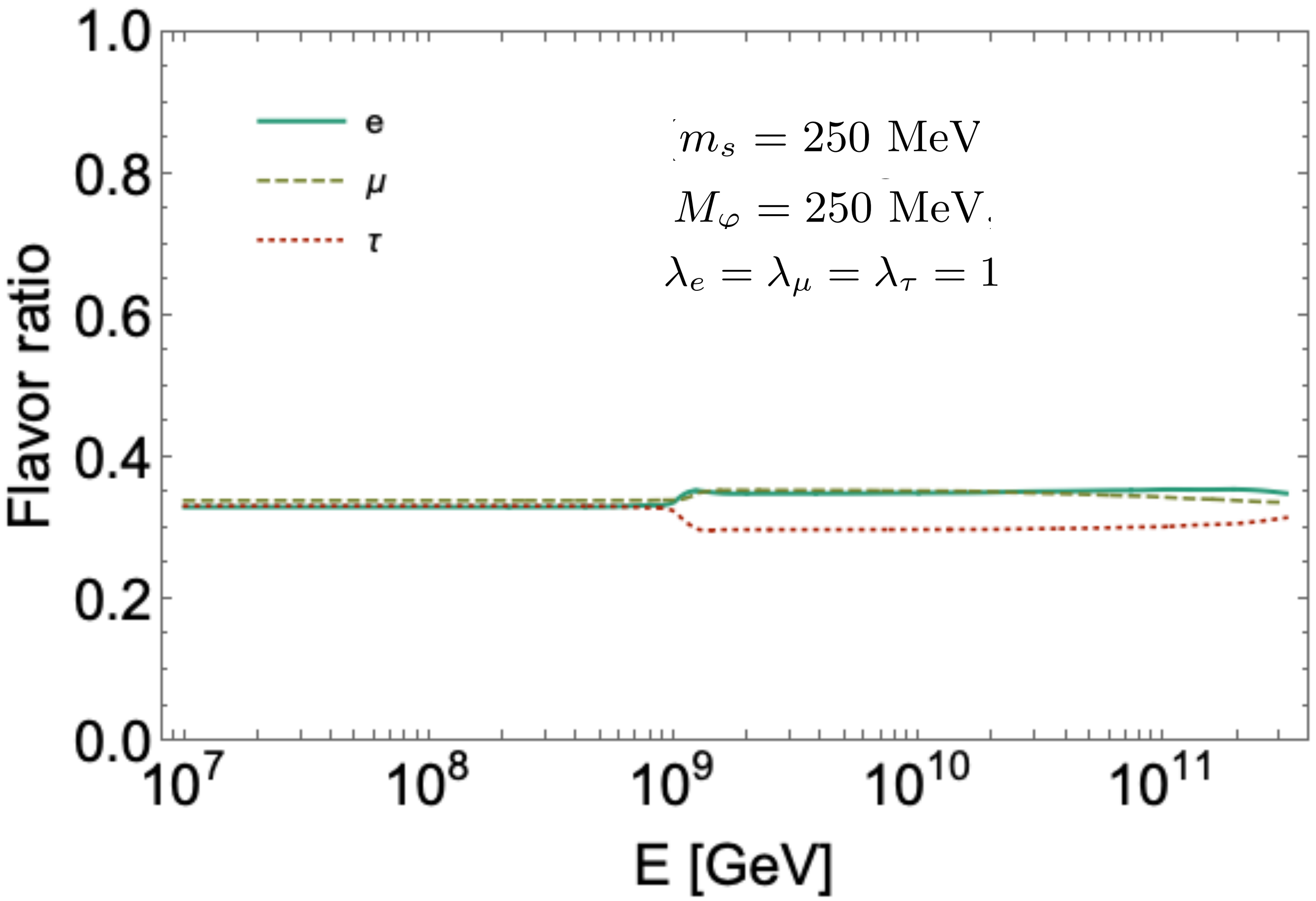
# *Results and detection chance for Cosmogenic Spectrum (2)*





flavor ratio at the source (1 : 2 : 0)

Expected flavor ratio at Earth (1 : 1 : 1)

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