MPIK Heidelberg
Astroparticle Physics seminar
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HE Neutrinos beyond Standard Model: steriles and secret interactions

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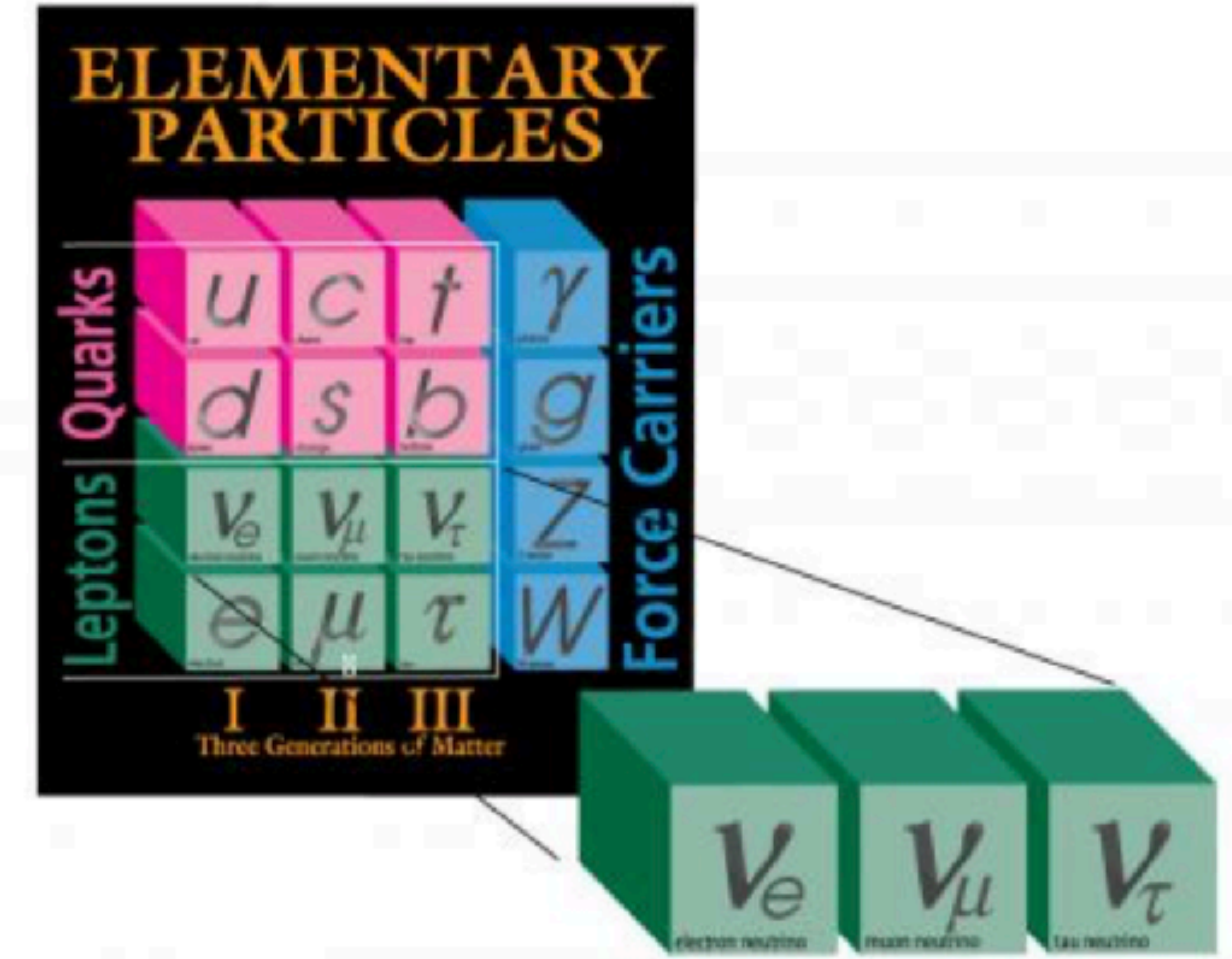
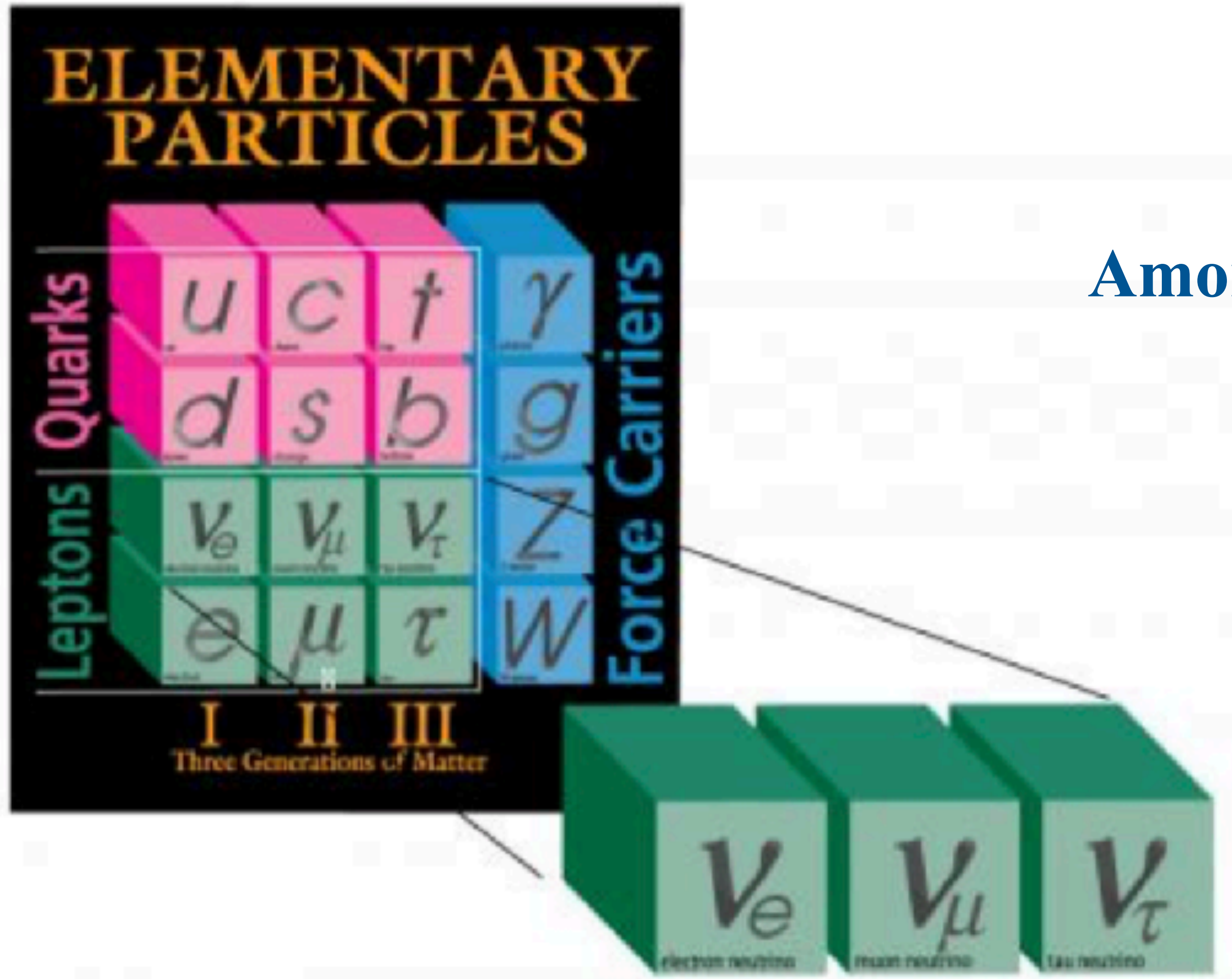
Standard Model and Beyond



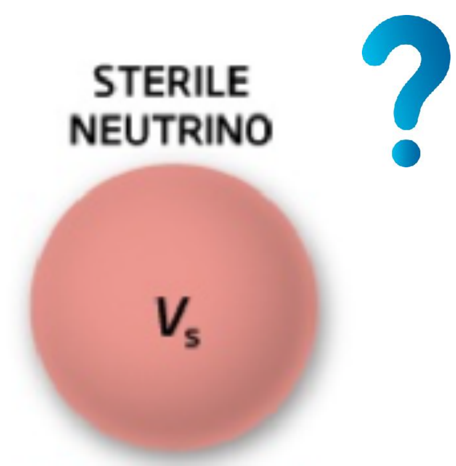
What else?

MASS	< 1 electronvolt
FORCES THEY RESPOND TO	Weak force Gravity
DIRECTION OF SPIN	All three "left handed"

Standard Model and Beyond



Among possible extensions:



MASS	< 1 electronvolt	>1 electronvolt
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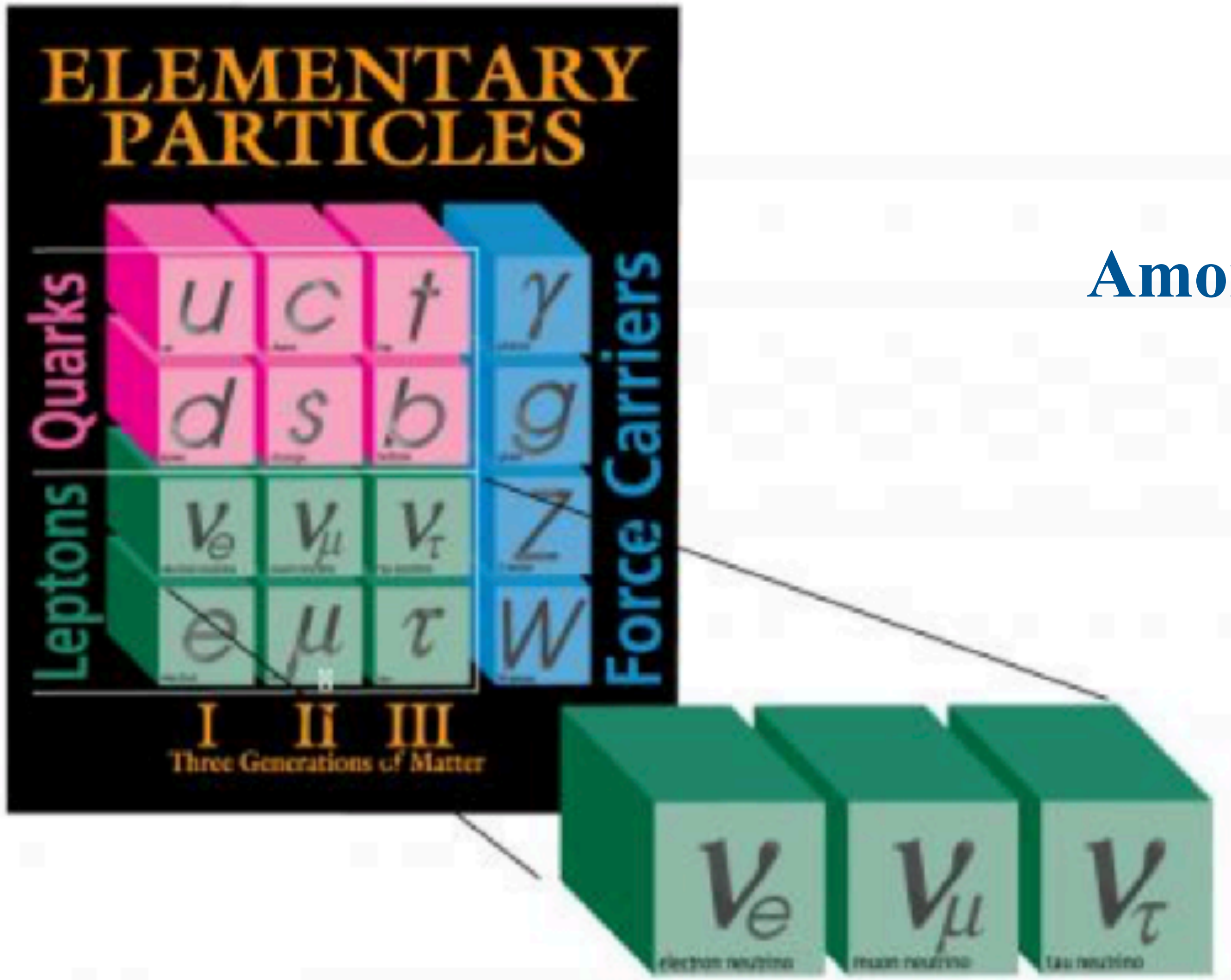
DIRECTION OF SPIN	All three "left handed"	"Right handed"

Standard Model and Beyond



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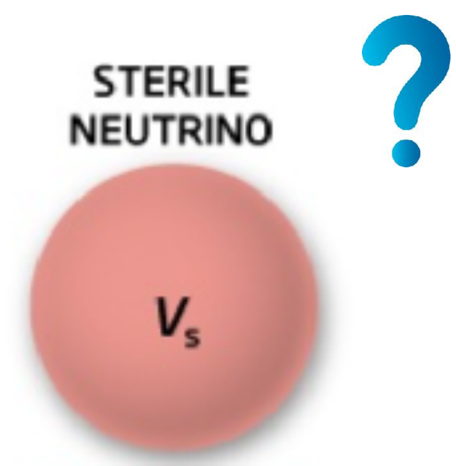

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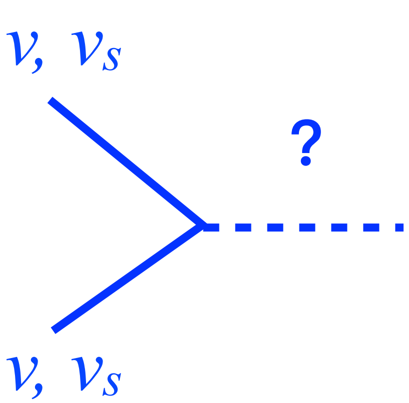
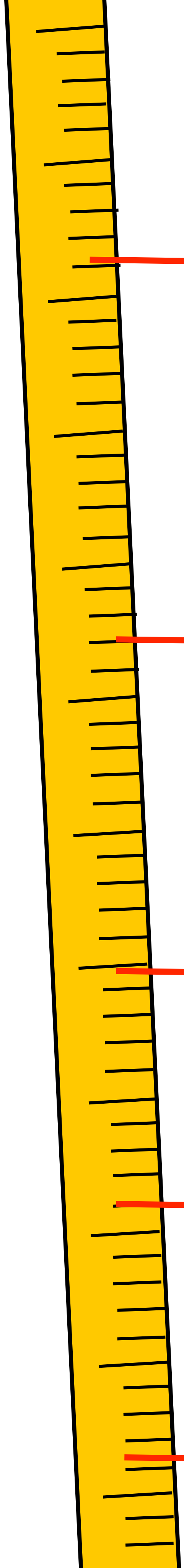
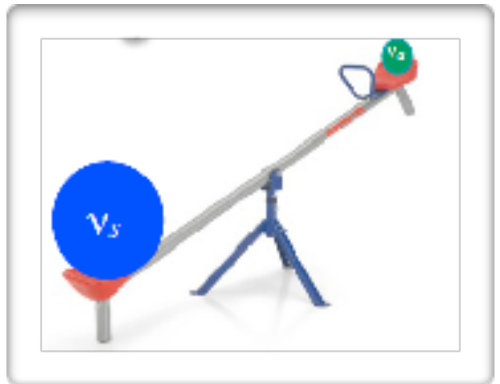


Extra "secret" interactions

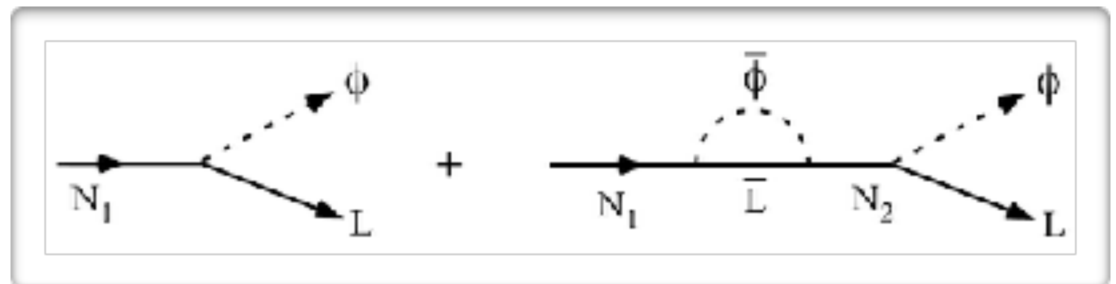
Sterile Neutrinos



MGUT



TeV

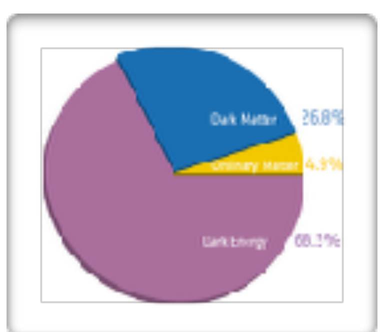


MeV

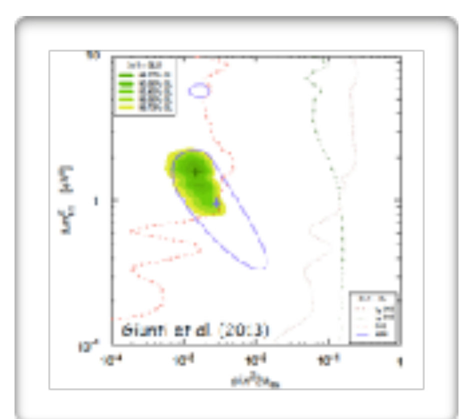
νMSM

Dynamical electroweak symmetry breaking

keV

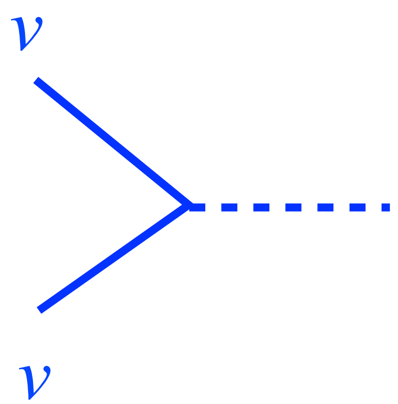


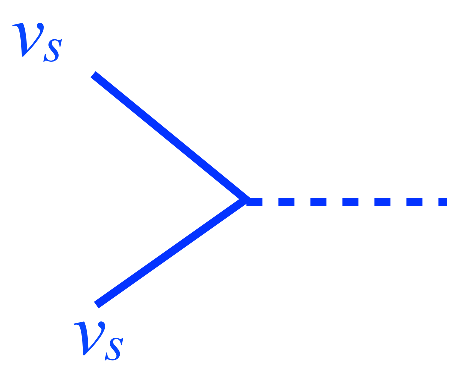
eV

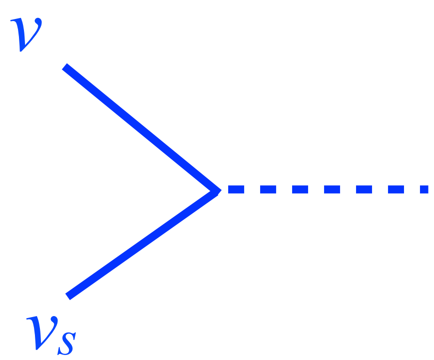


Secret Interactions

The term "secret neutrino interactions" (νSI) indicates new physics that couples only ν to ν (included steriles)







Several models have been studied involving vector, scalar, pseudo-scalar boson, for a large range of the new mediator and sterile masses and in different contexts (Early Universe, supernova, High energy neutrinos..)

Incomplete list:

Early Universe:

Archidiacono and Hannestad, 2014; Forastieri, Lattanzi e Natoli 2019; Hannestad, Hansen, Tram 2014,

Dasgupta and Kopp, 2014; Saviano et al 2014, Archidiacono et al., 2016; Cherry, Friedland and Shoemaker 2016;

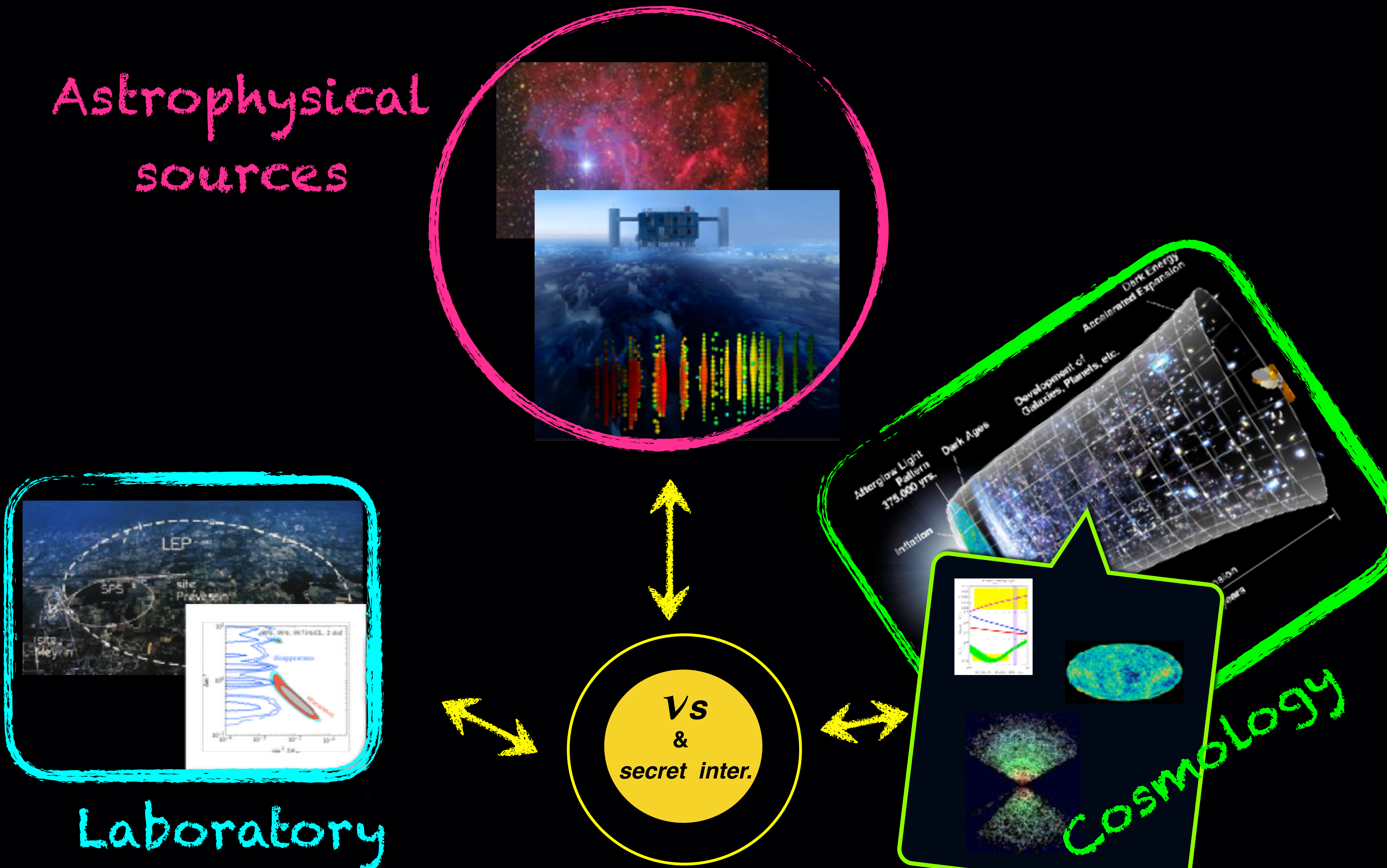
Forastieri…Saviano, 2017; Chu, Dasgupta, Dentler, Kopp and Saviano, 2018; Mirizzi et al, 2015,…

Astrophysics:

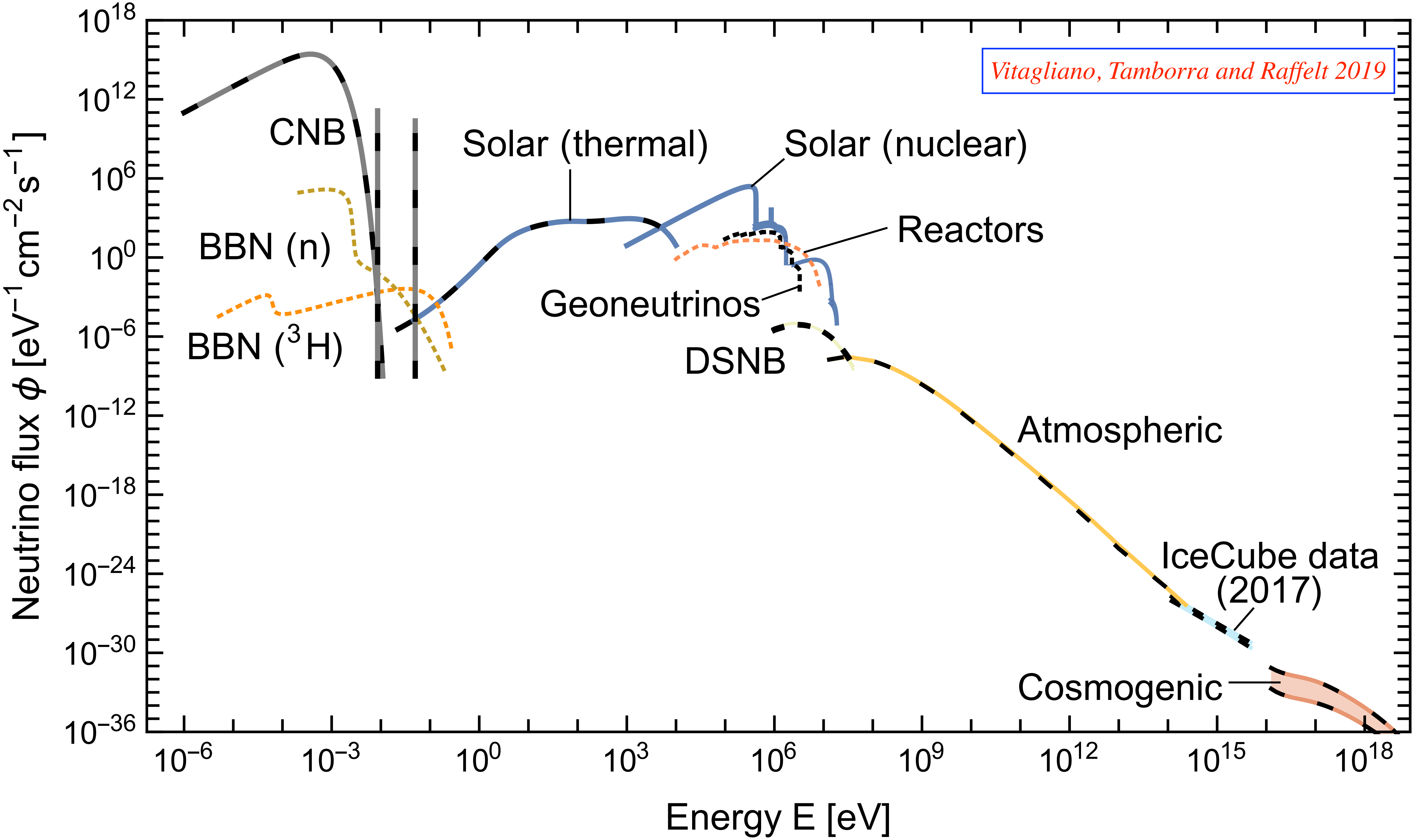
Kolb and Turner 1987; Ng and Beacom 2014; Ioka and Murase 2014;

Cherry, Friedland and Shoemaker 2016, Bustamante et al 2019, Shoemaker and Murase 2016…

How to corner sterile ν and secret interactions



Neutrino Spectrum at Earth



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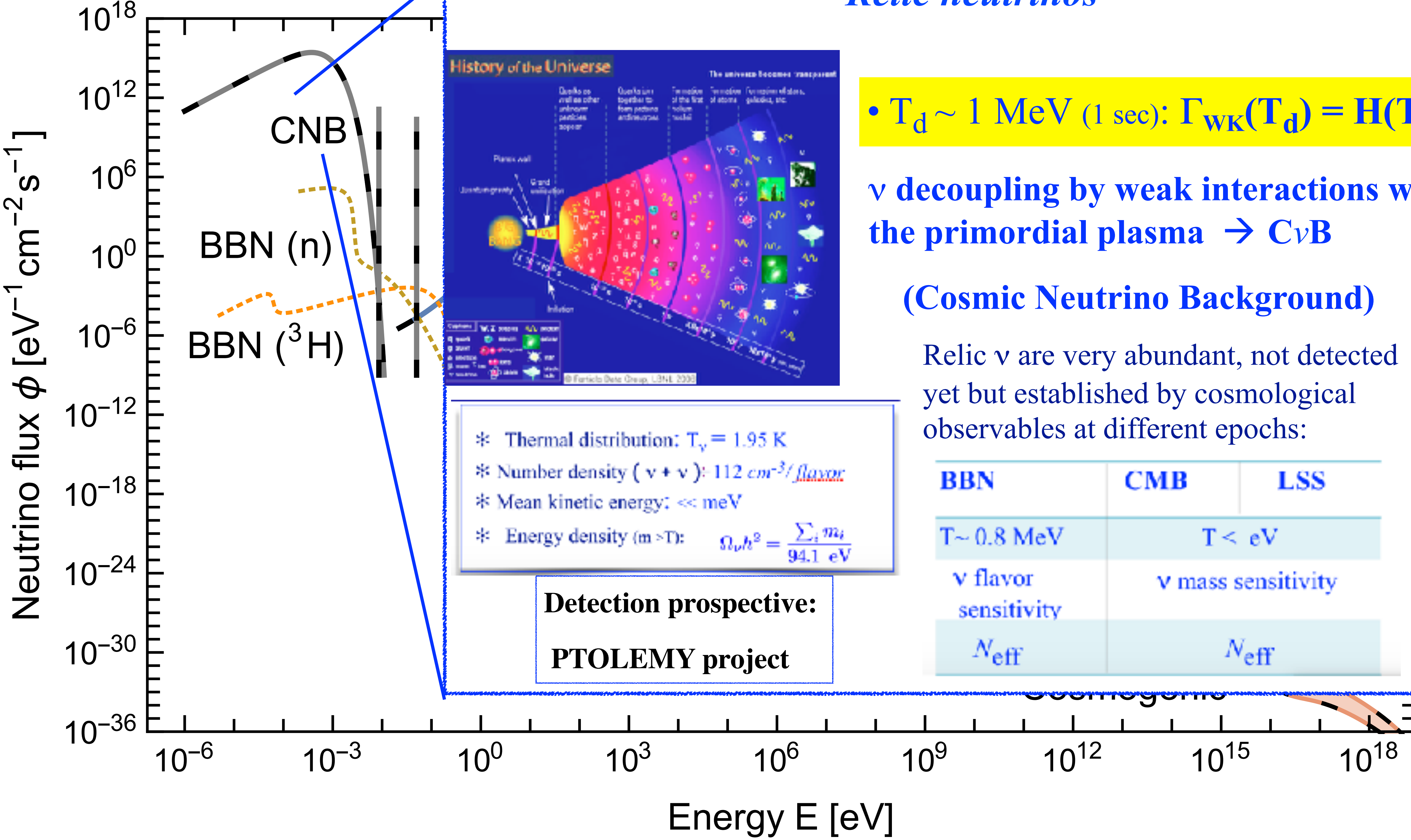


Relic neutrinos

• $T_d \sim 1$ MeV (1 sec): $\Gamma_{WK}(T_d) = H(T_d)$

ν decoupling by weak interactions with the primordial plasma → CνB

(Cosmic Neutrino Background)

Relic ν are very abundant, not detected yet but established by cosmological observables at different epochs:

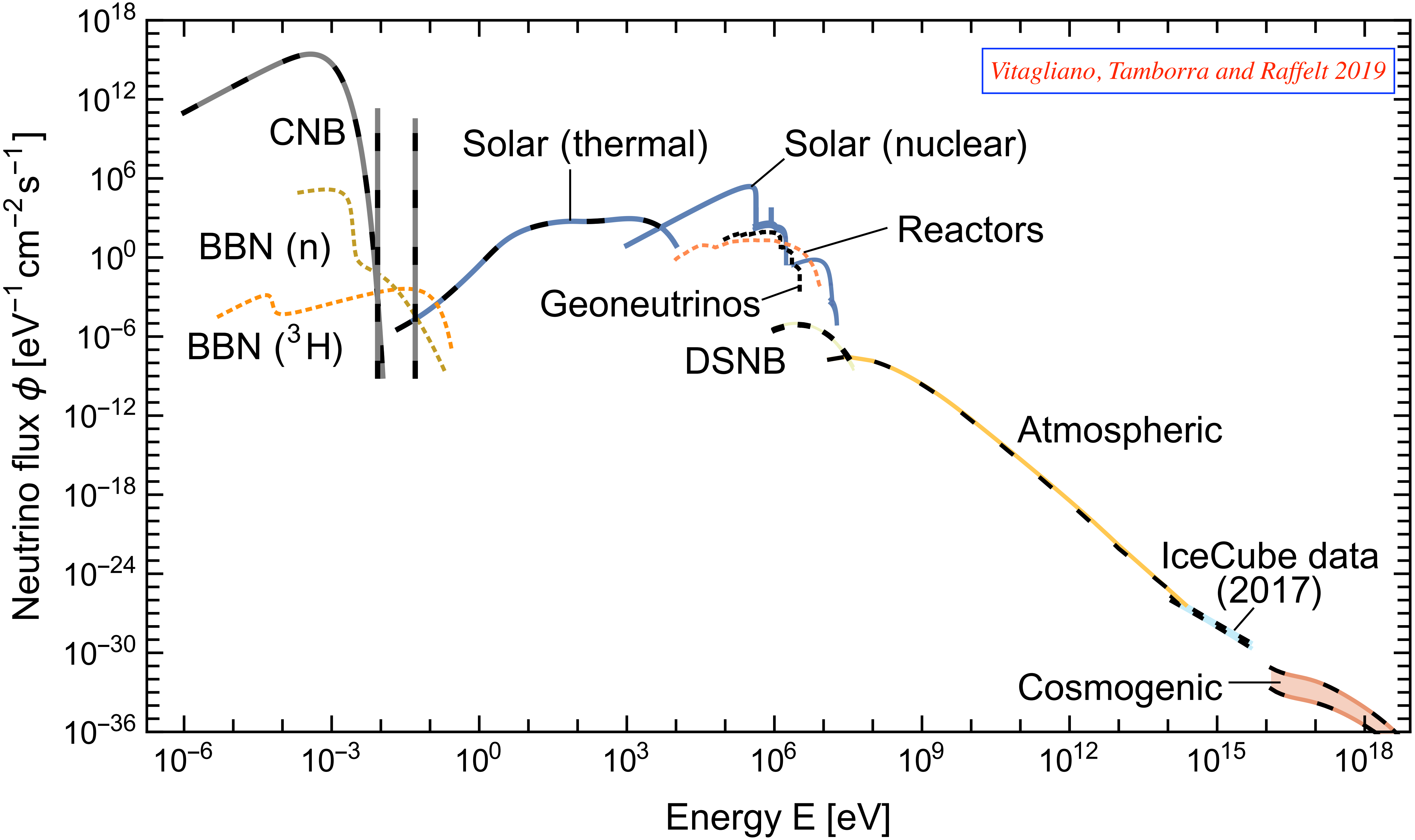
BBN	CMB	LSS
T~ 0.8 MeV	T < eV	
ν flavor sensitivity	ν mass sensitivity	
N_{eff}	N_{eff}	

* Thermal distribution: $T_\nu = 1.95$ K
* Number density (ν + ν): 112 cm^{-3}/ flavor
* Mean kinetic energy: << meV
* Energy density (m >T): $\Omega_\nu h^2 = \frac{\sum_i m_i}{94.1 \text{ eV}}$

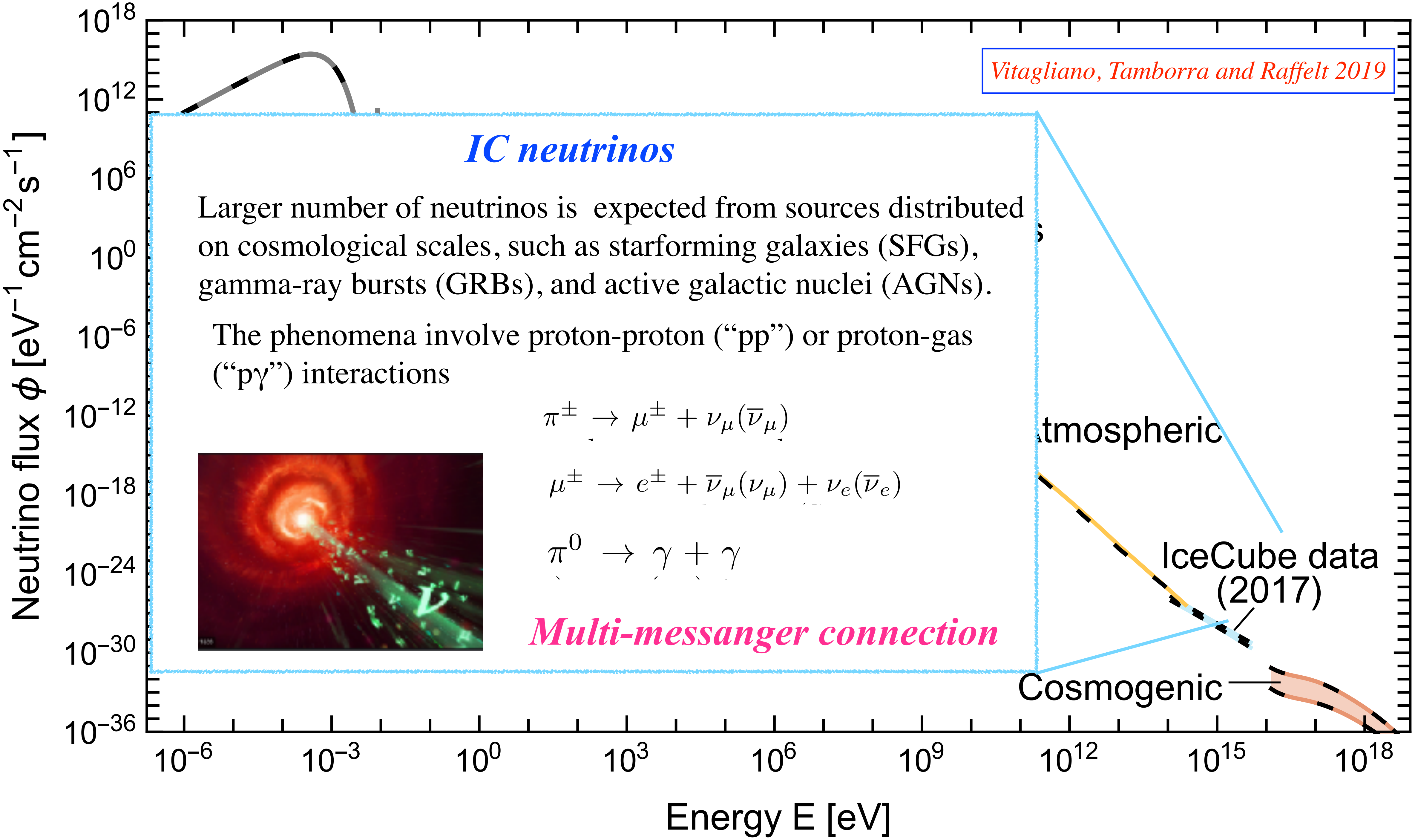
Detection prospective:

PTOLEMY project

Neutrino Spectrum at Earth



Neutrino Spectrum at Earth



IC neutrinos

Larger number of neutrinos is expected from sources distributed on cosmological scales, such as starforming galaxies (SFGs), gamma-ray bursts (GRBs), and active galactic nuclei (AGNs).

The phenomena involve proton-proton ("pp") or proton-gas ("pγ") interactions

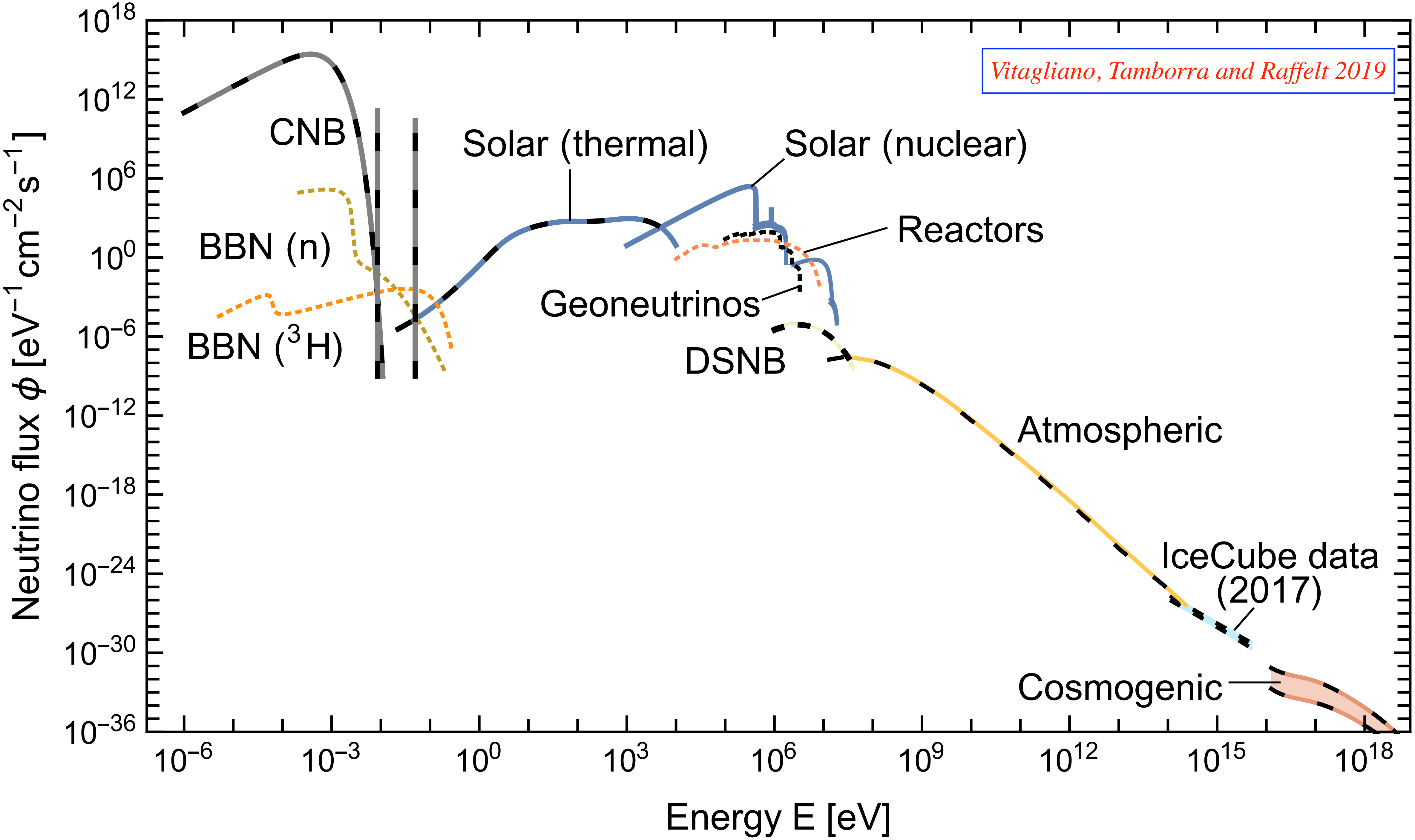
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \overline{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\overline{\nu}_{e})$$

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

Multi-messanger connection

Neutrino Spectrum at Earth



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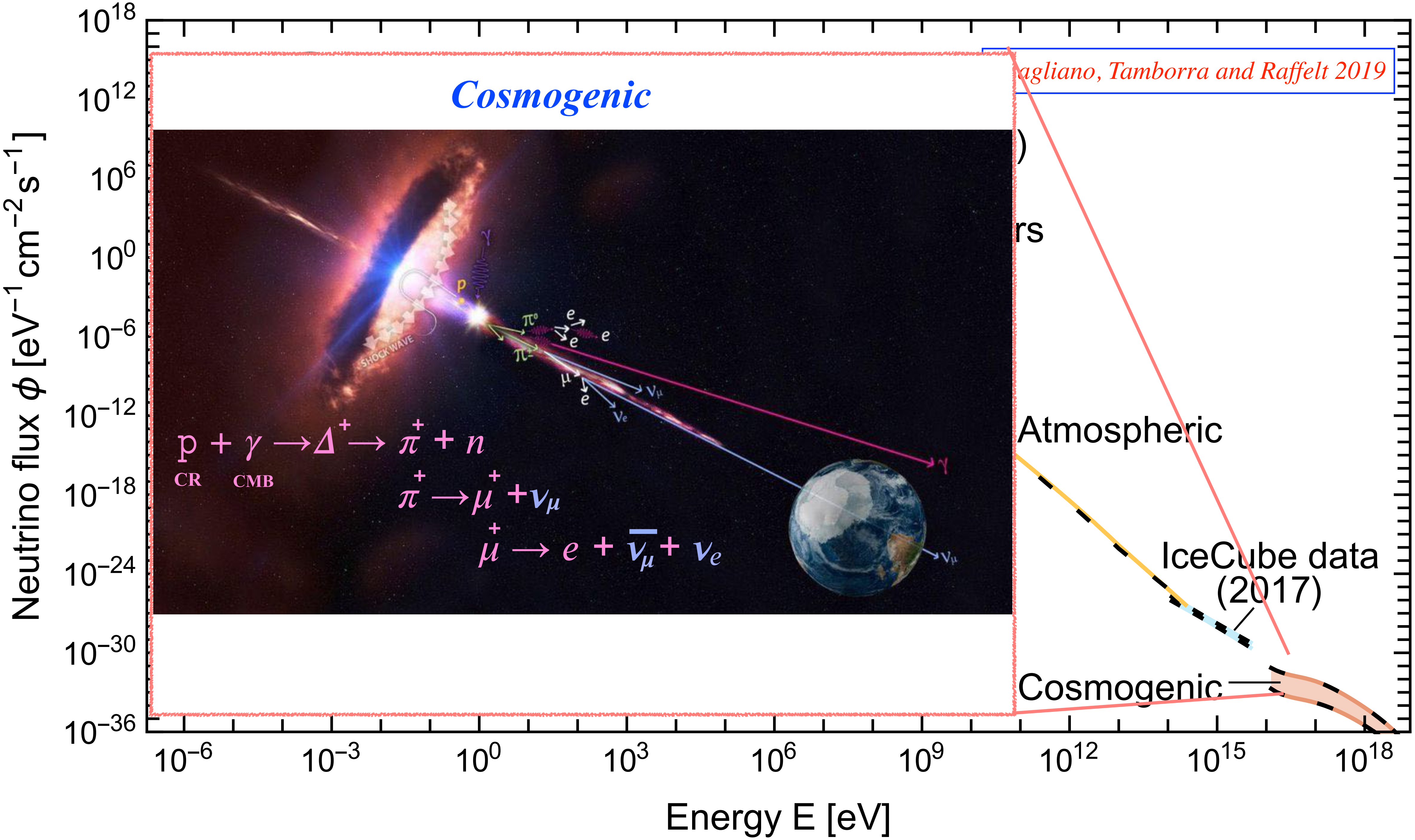


(Ultra-)High ν flux at Earth

IceCube ν: **PL spectrum**

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

$g \equiv \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} + \phi_{\overline{\nu}_e} + \phi_{\overline{\nu}_\mu} + \phi_{\overline{\nu}_\tau}$, γ 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

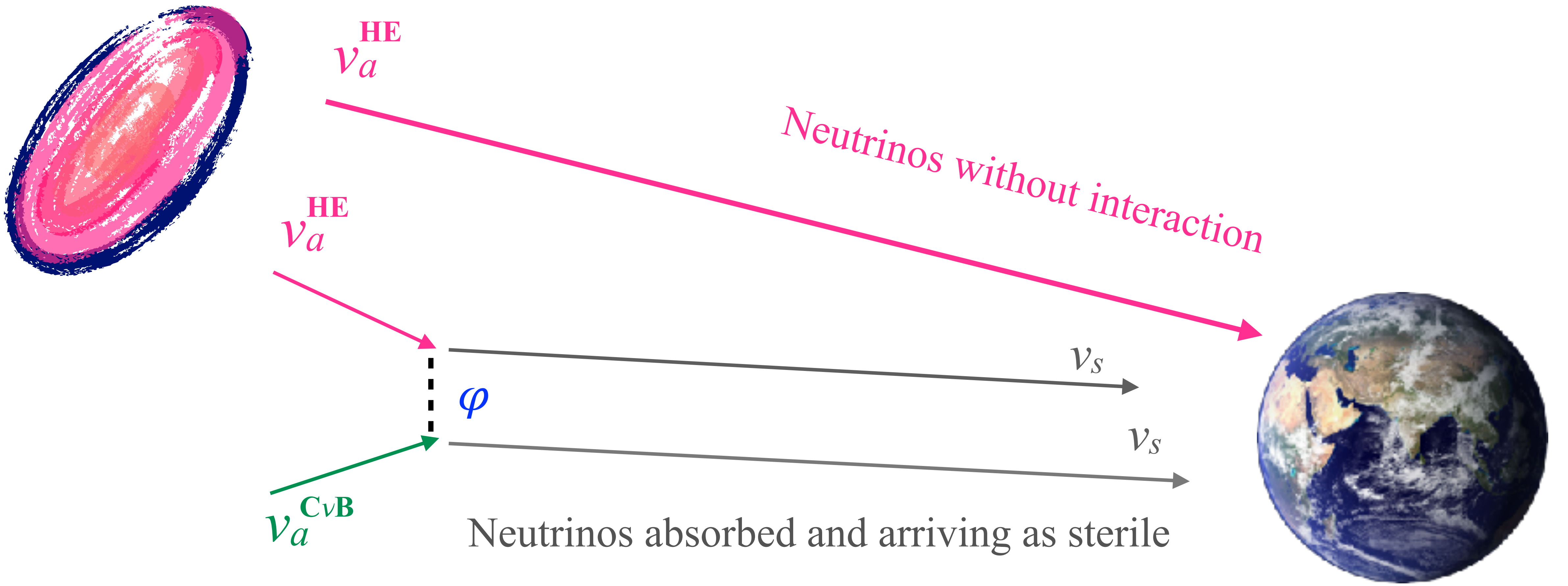
$$\frac{d\phi_\nu}{dE d\Omega} = \int \frac{dz'}{H(z')} \rho(z') f[E(1+z')]$$

where ρ(z) is the Star Forming Rate

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

Our model

We consider a scheme of SI where the new interaction, mediated by a new pseudoscalar mediator, involves both active and sterile neutrinos: $\mathcal{L}_{\rm SI} = \lambda\,\overline{\nu}\gamma_5\nu_s\varphi$



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*

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

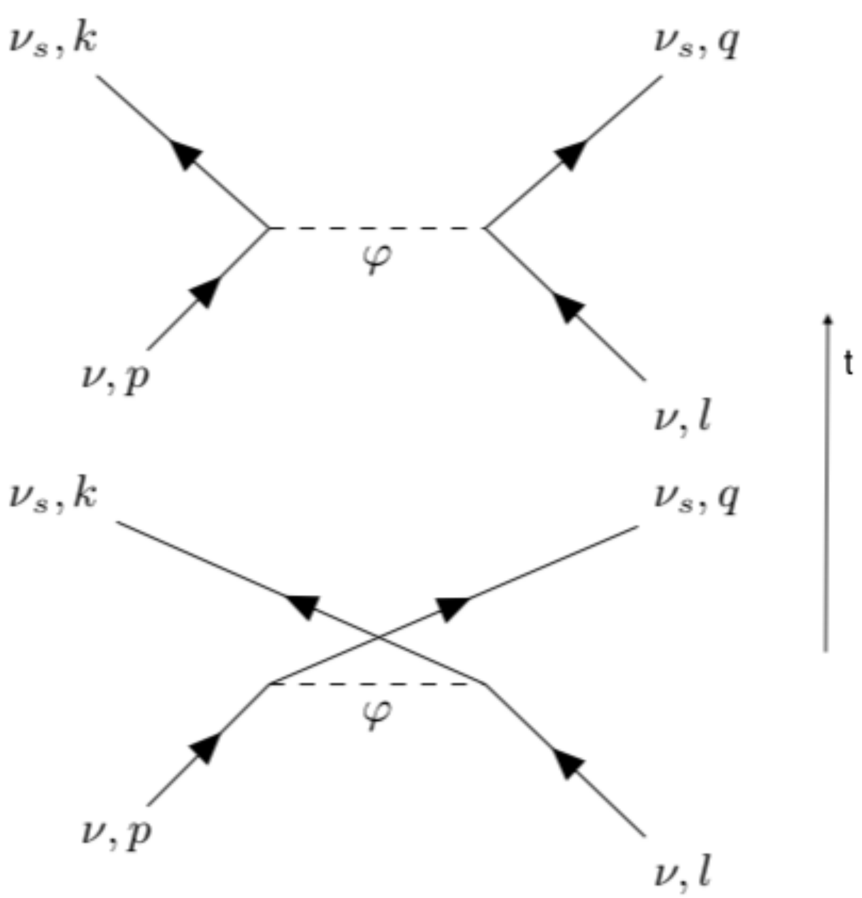
Exploratory investigation: case 1

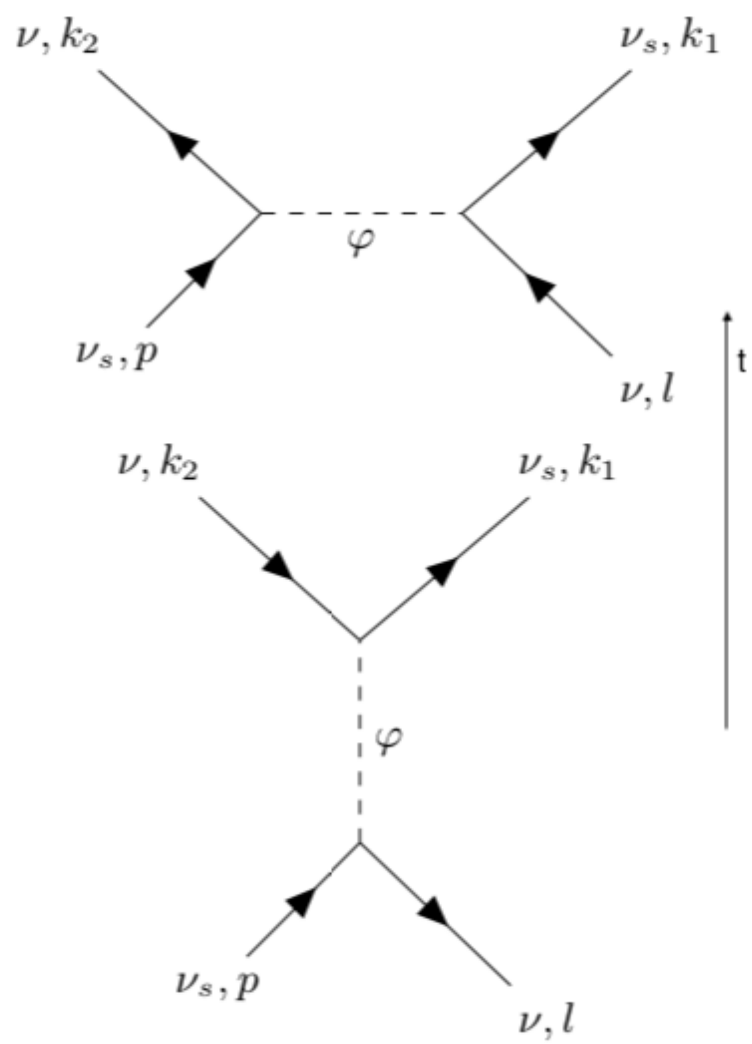
***case 1:* simplified scenario *1 & 1* (1 active and 1 sterile, *negligible active-sterile mixing*)**

$$\mathcal{L}_{\rm SI} = \lambda\,\overline{\nu}\gamma_5\nu_s\varphi$$

At tree level the new processes introduced by our new interaction are the four particle collisions

$\nu + \nu \to \nu_S + \nu_S$, $\quad$ $\nu + \nu_S \to \nu + \nu_S$, $\quad$ $\nu_S + \nu_S \to \nu + \nu$





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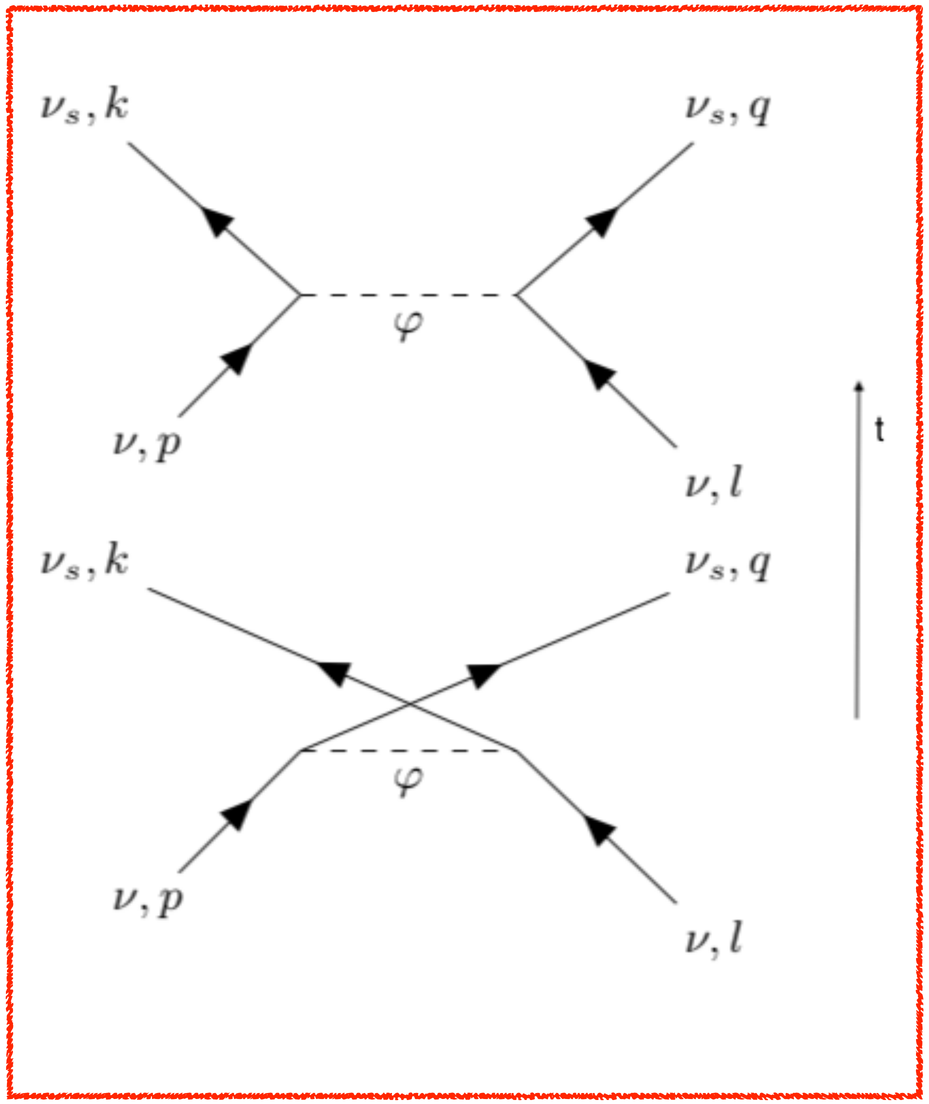

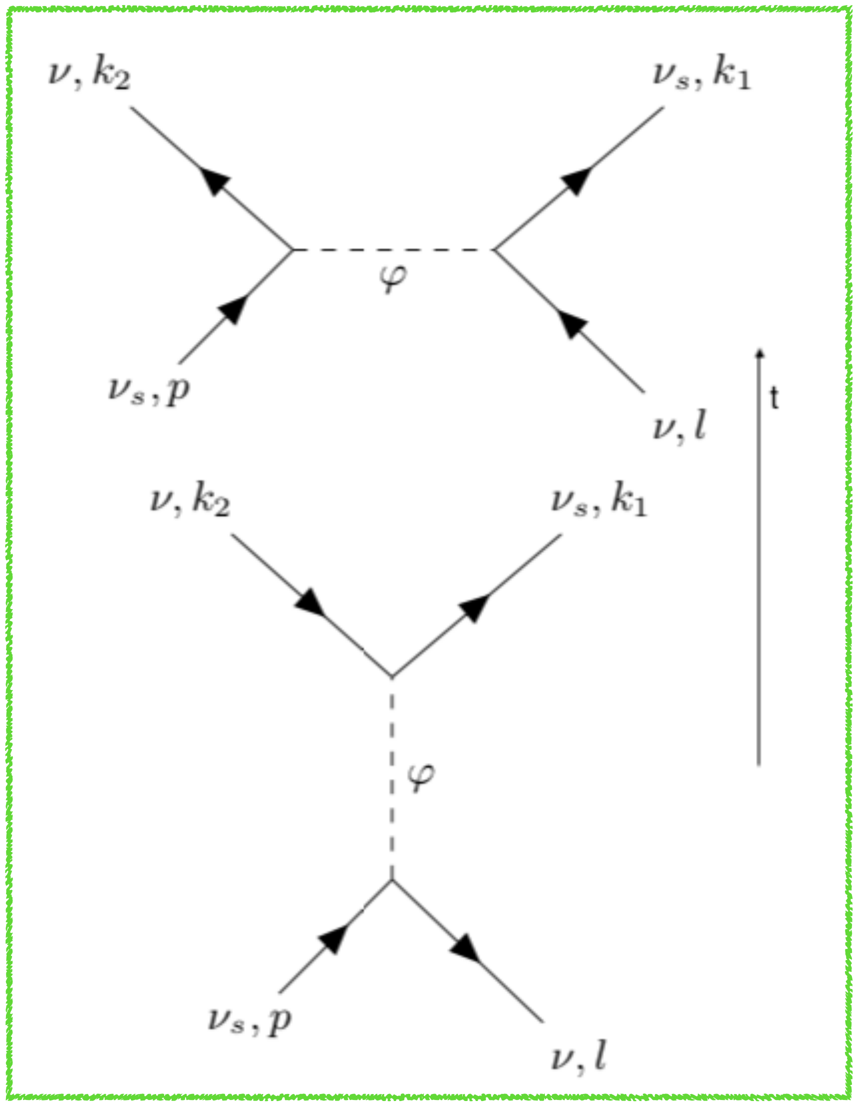

relevant for the experimental signatures

Transport Equations

$\Phi_a(z, E)$ flux of active neutrinos per unit energy interval per unit solid angle at a redshift z $\left(\Phi = \frac{d\phi}{dE d\Omega}\right)$

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

The transport set of equations is:

- $H(z)(1+z)\left(\frac{\partial \Phi_a}{\partial z} + \frac{\partial \Phi_a}{\partial E}\frac{E}{1+z}\right) = n(z)\sigma_a(E)\Phi_a - \int dE' \Phi_s(E') \frac{d\sigma_{sa}}{dE}(E' \to E) n(z) - \rho(z)(1+z) f(E)$

  $\sigma_a \to \sigma_{aa\to ss}$

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  $\sigma_s \to \sigma_{as\to as}$

$n(z) = n_0(1+z)^3$ number density of CNB neutrinos with $n_0 = 116\mathrm{cm}^{-3}$

$f(E)$ number of neutrinos emitted per unit energy interval per unit time per unit solid angle

ρ(z) is the density of sources taken to evolve with the Star Formation Rate

$\frac{d\sigma_{as}}{dE}$ $\frac{d\sigma_{sa}}{dE}$ partial cross section for the production of other neutrinos as consequence of collisions

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…simplifications

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1) In absence of mixing between active and sterile neutrinos ⇛ NO interest in the sterile flux at Earth, not detectable anyway

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absorption   regeneration

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2) An active neutrino can be produced through regeneration by a sterile neutrino, which has to be produced itself by an active neutrino. The latter has to have an energy at least as high as 10^{10} GeV. Due to the rapid decrease with energy of the input flux, this correction turns out to be much smaller than the original flux ⇛ the regeneration term can be neglected

Transport Equations…
…simplifications

The transport set of equations is:

absorption — regeneration

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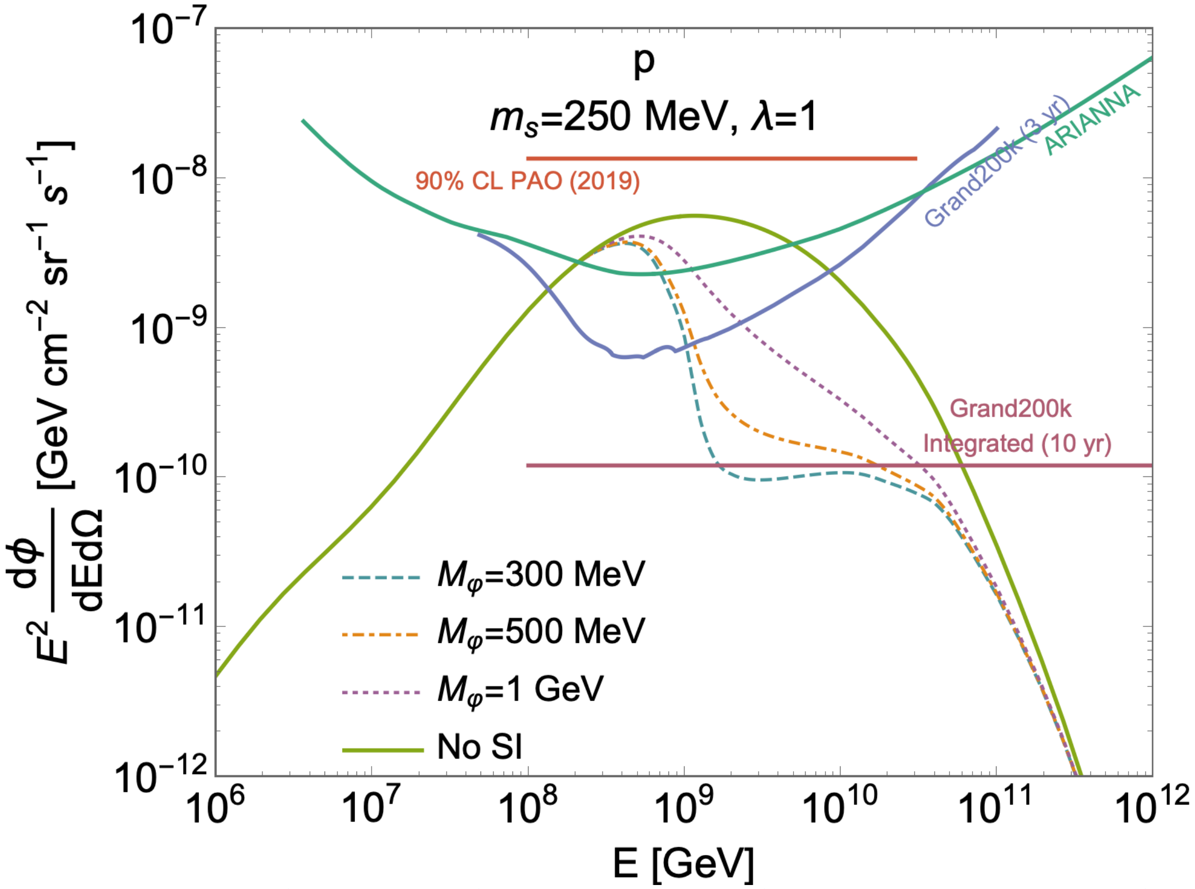
The transport equation admits now an analytical solution for the flux at Earth

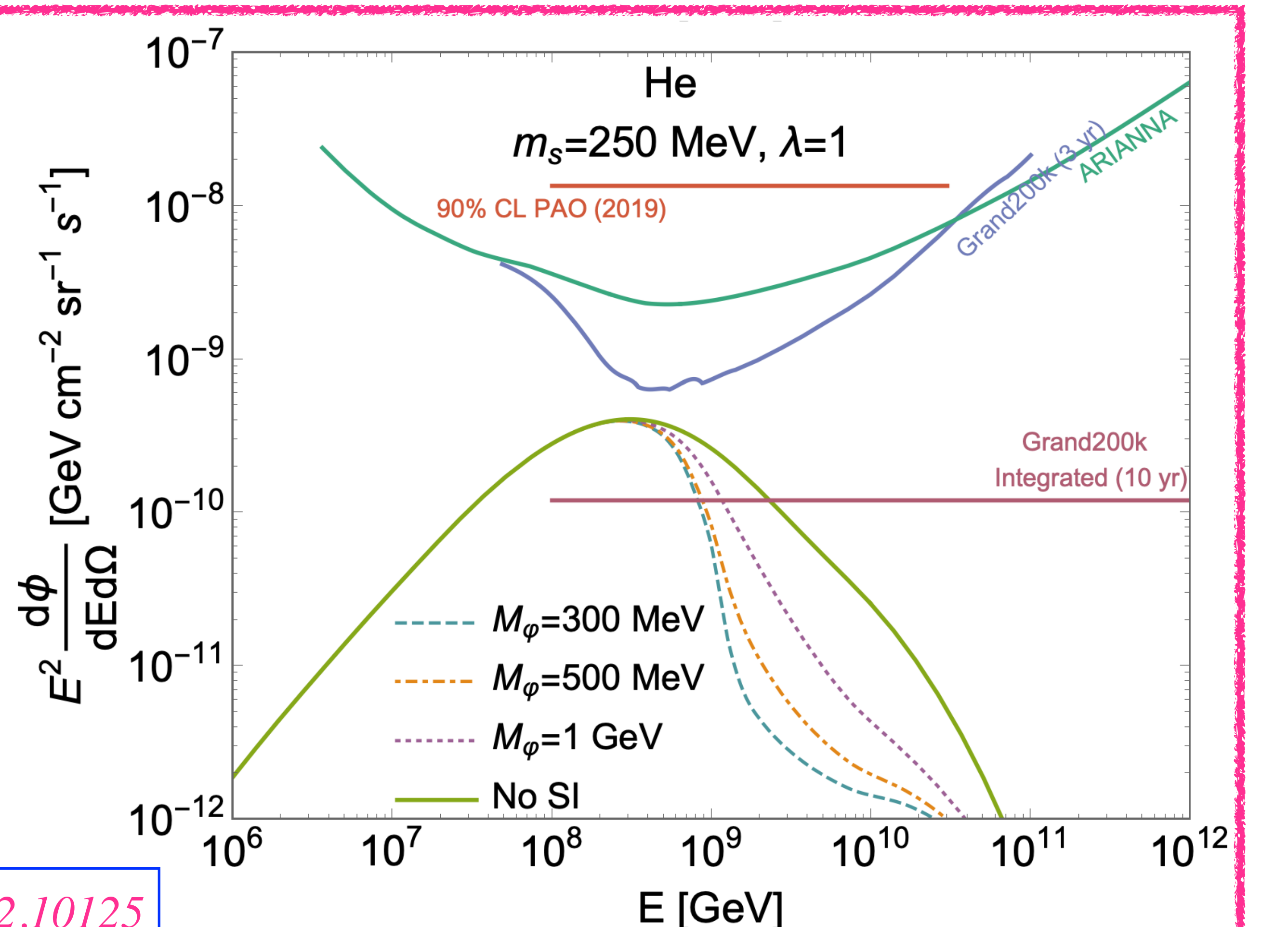
$$\Phi_a(E)=\int_0^{+\infty}\frac{dz}{H(z)}\rho(z)f\left[E(1+z)\right]\times\exp\left[-\int_0^z\frac{dz'}{H(z')}n(z')\sigma_a\left[E(1+z')\right]\right]$$

Results and detection chances



proton cosmic rays

helium cosmic rays



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

Compatibility with lab, cosmo and astro constraints

Our model is in principle subject to a number of constraints from laboratory experiments, cosmology and astrophysics

Laboratory bound

Secret interactions can introduce new decay channels for mesons (in particular Kaon decays).

In particular, the kaon can decay into $K \rightarrow \mu\nu_s\phi$ or $K \rightarrow \mu\nu_s\nu_s\nu$.

If we restrict to the range of masses $m_S \geq 250$ MeV and $M_\phi \geq 250$ MeV, these reactions are kinematically forbidden,

→ absence of constraints from these decays.

Cosmological bound

BBN : The new particles could count as extra degree of freedom at BBN time (~1 MeV).

However with the choice M_ϕ, $m_S \geq 250$ MeV, the interactions between active and sterile neutrinos and scalar mediator remain effective. → the sterile neutrino and the scalar mediator are Boltzmann suppressed.

Supernovae bound

Since neutrinos in the core of supernovae have energies of order of tenth or hundredth of MeV, they are sufficiently energetic to produce sterile neutrinos which could escape the supernova, giving rise to an energy loss with observable consequences.

However, the produced sterile neutrinos would not be able to escape the supernova, since trapped by the secret interaction with the active neutrinos inside the core (mean free path of 10^{-11} m, clearly << than the characteristic distances of a supernova). This is true for $m_S \geq 250$ MeV, $M_\phi \geq 300$ MeV and $\lambda = 1$.

More detailed investigation: case 2

***Case2:* more general case *3 & 1* (3 *active and* 1 *sterile, negligible active-sterile mixing*)**

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

$$\mathcal{L}_{\rm SI} = \sum_{\alpha} \lambda_\alpha \, \overline{\nu}_\alpha \gamma_5 \nu_s \varphi \qquad \alpha = e, \mu, \tau$$

λ_α dimensionless free couplings

Ample freedom of choice for our model:

- The most natural possibility is $\lambda_e = \lambda_\mu = \lambda_\tau$
- Very interesting case only $\lambda_\tau \neq 0$ (very weakly constrained by mesons decay)

We examine in detail the constraints on the parameter space of the secret interaction, coming both from laboratory experiments and from cosmological observations.

We find that new regions for the parameters are allowed compared to the safe one we had investigated in the previous paper.

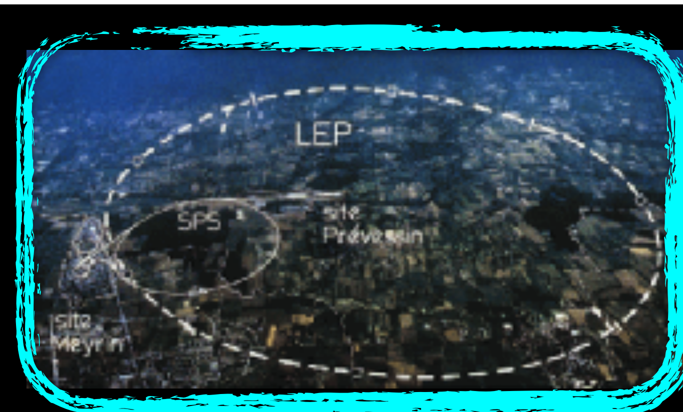
*Fiorillo, Miele, Morisi, **Saviano** 2020, arXiv:2007.07866*

Allowed parameter space

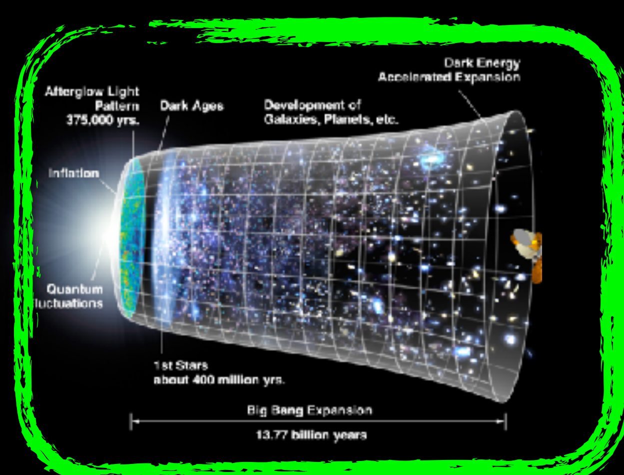
Our model is parametrized by the set $(\lambda_\alpha,\, M_\varphi,\, m_s)$

Restrictions of the free parameter space can derive from :

- Laboratory experiments



- Cosmology



- Supernovae

• Laboratory constraints

Mesons can decay leptonically as $M \rightarrow \nu_\ell \ell$, where M represents a meson (π^+, K^+, D^+) and $\ell = e, \mu, \tau$

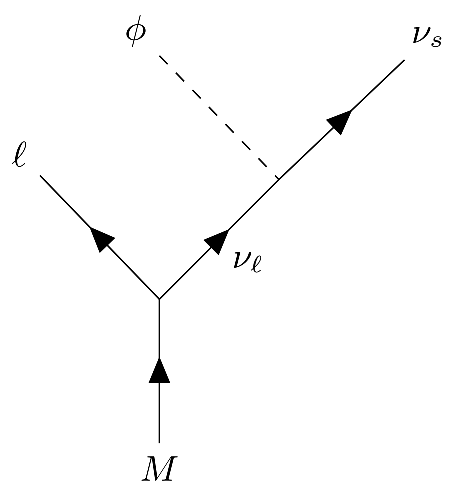
The new interaction opens the possibility of new leptonic decay channels $M \rightarrow \nu_s \ell \varphi$ and $M \rightarrow \nu_s \ell \overline{\nu}_{\ell'} \nu_s$

$M \rightarrow \nu_s \ell \varphi$ conditions:

$$\begin{cases} \lambda_\ell \neq 0 \\ \lesssim m_s + M_\varphi \lesssim m_M - m_\ell \end{cases}$$

from BBN

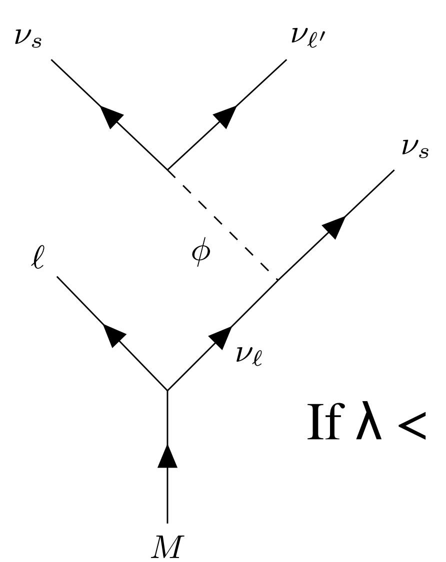
kinematic



Meson	$(m_s + M_\varphi)_{\max}$(MeV)
$\pi^+ \rightarrow e\varphi\nu_s$	140
$\rightarrow \mu\varphi\nu_s$	35
$\rightarrow \tau\varphi\nu_s$	–
$K^+ \rightarrow e\varphi\nu_s$	493
$\rightarrow \mu\varphi\nu_s$	388
$\rightarrow \tau\varphi\nu_s$	–
$D^+ \rightarrow e\varphi\nu_s$	1870
$\rightarrow \mu\varphi\nu_s$	1765
$\rightarrow \tau\varphi\nu_s$	93

$M \rightarrow \nu_s \ell \overline{\nu}_{\ell'} \nu_s$ conditions:

$$\begin{cases} \lambda_\ell \neq 0 \\ 2m_s \lesssim m_M - m_\ell \end{cases}$$



If $\lambda < 1$, the rate for four-body decay will be smaller by a factor of λ^2 compared to the three-body decay

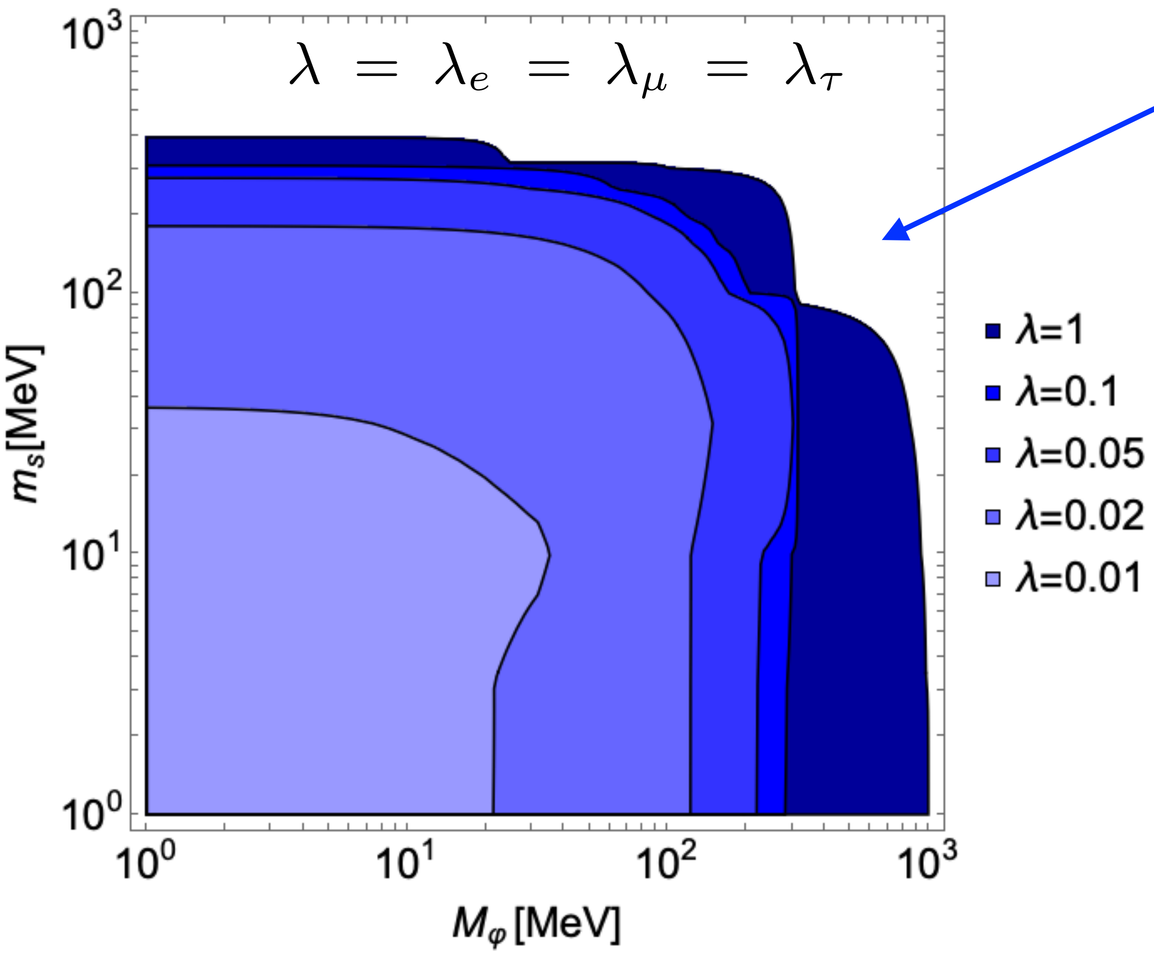
• Laboratory constraints

Examples: $K^+ \to \mu\varphi\nu_s$ and $K^+ \to \mu\nu_s\nu_s\overline{\nu}'_\ell$, they should be observed as

$K \to \mu +$ missing energy

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

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



Bump produced by the four-body decay

the region below the contours is excluded

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

the correction to Kaon decay is within the experimental bound

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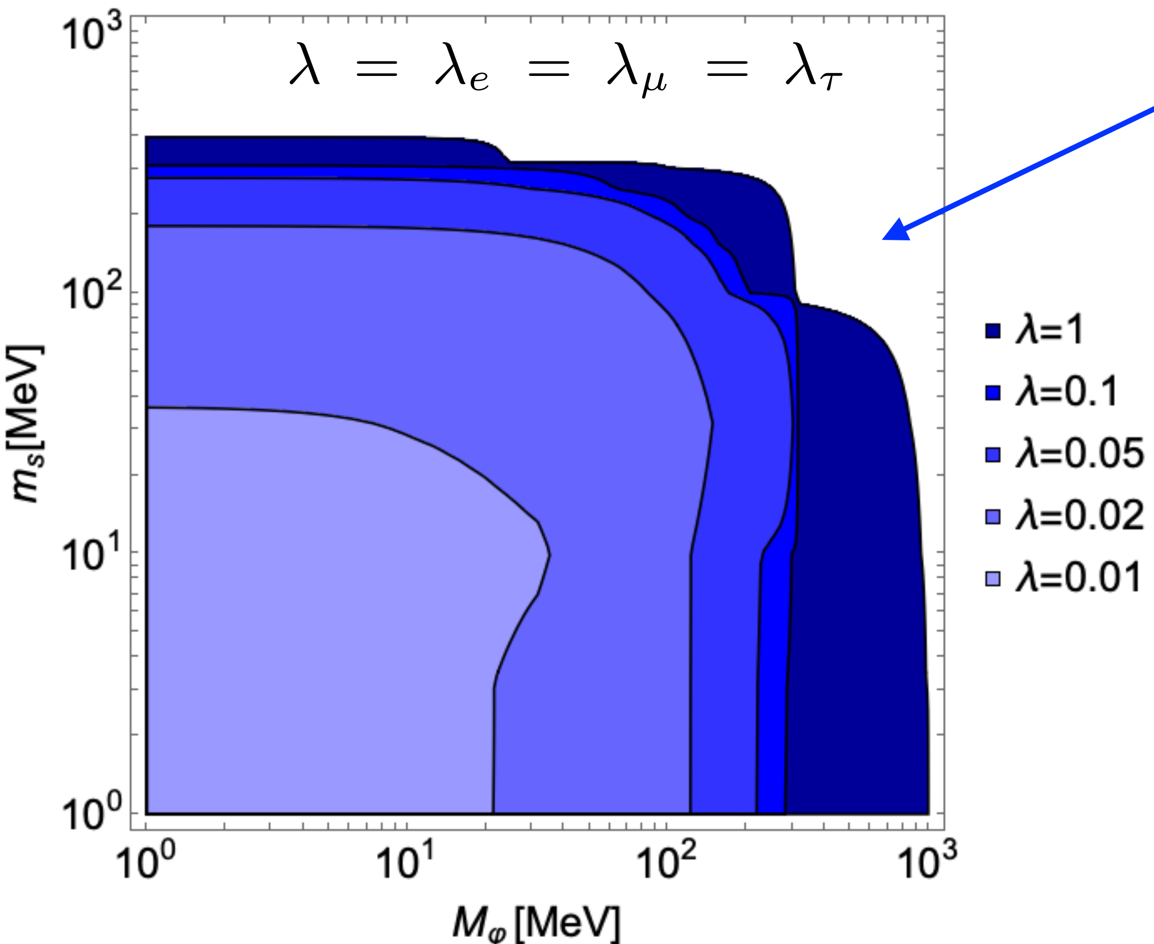

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the region below the contours is excluded

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

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

• Cosmological constraints 1

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

1) ***the newly introduced species are non relativistic at the time of the BBN***

2) ***they remain in kinetic and chemical equilibrium at this epoch***

• Cosmological constraints 1

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

1) the newly introduced species are non relativistic at the time of the BBN

This is naturally met if both **M_ϕ and m_S >10 MeV**:

in this way, the Boltzmann factor is exp[-M/T] < 10^{-4} and we can safely assume that the species are non relativistic

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$$\Gamma_{SI}\,(T) > H\,(T) \Rightarrow \;\; \textit{equilibrium}, \quad \Gamma_{SI}\,(T) = H\,(T) \Rightarrow \;\; \textit{decoupling}$$

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$\Gamma_{SI}(T) > H(T) \Rightarrow$ *equilibrium*, $\Gamma_{SI}(T) = H(T) \Rightarrow$ *decoupling*

$$H(T) \sim \frac{T^2}{M_{pl}}$$

Approximative estimate:

$\nu_\alpha \nu_s \to \nu_\alpha \nu_s$ and $\nu_s \nu_s \to \nu_\alpha \nu_\alpha$:

$$\Gamma(T) \sim T^3 \frac{T^2 \lambda^4}{M_\varphi^4}$$

$$T^{\rm dec}_{\nu_s\nu_s} = \left(\frac{M_\varphi^4}{\lambda^4 M_{\rm pl}}\right)^{1/3} \simeq 0.3 {\rm MeV} \left(\frac{M_\varphi}{1{\rm GeV}}\right)^{4/3} \left(\frac{\lambda}{0.01}\right)^{-4/3}$$

$\varphi\varphi \to \nu_s \nu_s$

$$\Gamma(T) \sim T^3 \frac{\lambda^4}{m_\alpha^2}$$

$$T_\varphi = \frac{m_\alpha^2}{\lambda^4 M_{\rm pl}} \simeq 4 \times 10^{-28} MeV \left(\frac{m_\alpha}{0.1{\rm eV}}\right)^2 \left(\frac{\lambda}{0.01}\right)^{-4}$$

Requirement **:** $T_{dec} < T_{BBN}$ satisfied for **M_ϕ and m_s >10 MeV**:

• Cosmological constraints 2

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

Active neutrinos can secretly interact through the reactions $\nu_\alpha \nu_{\alpha'} \rightarrow \nu_\beta \nu_{\beta'}$ at next-to-leading order *via* the box diagram.

$$\Gamma \sim T^3 \frac{\lambda^8 T^{10}}{M_\varphi^8 m_s^4}$$

$$T^{\rm dec}_{\nu_\alpha \nu'_\alpha} = \left(\frac{M_\varphi^8 m_s^4}{\lambda^8 M_{\rm pl}}\right)^{1/11} \simeq 10^5 {\rm eV} \left(\frac{M_\varphi}{10{\rm MeV}}\right)^{8/11} \left(\frac{m_s}{10{\rm MeV}}\right)^{4/11} \lambda^{-8/11}$$

Requirement **:** $T_{\rm dec} > T_{\rm CMB}$ **satisfied for all the parameter space we considered.**

• 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.

Our model could be in conflict with SN 1987A data if both the following conditions would simultaneously met

1) the mean free path $\mathcal{L}$ of the ν_s inside the SN core should be larger than the radius of the supernova

$$\mathcal{L} = (\sigma_{sa} n_a)^{-1} > \mathrm{R}(\mathcal{O}\ 10\ \mathrm{km})$$

Mastrototaro, Mirizzi, Serpico, Esmaili, 202o

2) ν_s should be copiously produced in the SN core and that the energy injected into sterile neutrinos have to exceed the threshold luminosity for the SN 1987A

$$L_s > L_{1987A}$$

$$L_s = \int \frac{d\sigma_{a\to s}}{dE} E dE f(E', r) f(E'', r) dE' dE'' 4\pi r^2 dr \qquad L_{1987A} \simeq 2\times 10^{52}\ \mathrm{erg/s}$$

For **M_ϕ and ms >10 MeV, the 2 conditions are never simultaneously 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 φ.

The energy at which the absorption over neutrinos from the Cosmic Neutrino Background (CNB) is most relevant is of the order of M_φ^2/m_α

In the selected parameter space, this energy scale corresponds to a **range of energy [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 in the region 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 power law flux in the range below 100 PeV, and a cosmogenic flux, in the Ultrahigh energy range

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

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

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

$n(z) = n_0(1+z)^3$ number density of CNB neutrinos with $n_0 = 116\text{cm}^{-3}$

$f(E)$ neutrino spectrum produced at the source

ρ(z) is the density of sources taken to evolve with the Star Formation Rate

$\frac{d\sigma_{as}}{dE}$ $\frac{d\sigma_{sa}}{dE}$ partial cross section for the production of other neutrinos as consequence of collisions

ξ_i the fraction of neutrinos produced at the source in the *i-th* mass eigenstate

ν Fluxes with SI and Transport Equation

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$\Phi_i(z,E)$ 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

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

- $$H(z)(1+z)\left(\frac{\partial\Phi_i}{\partial z} + \frac{\partial\Phi_i}{\partial E}\frac{E}{1+z}\right) = n(z)\sigma_i(E)\Phi_i - \int dE'\Phi_s(E')\frac{d\sigma_{sa}}{dE}(E' \to E)n(z) - \rho(z)(1+z)f(E)\xi_i$$
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Is the regeneration term unimportant for the full parameter space we consider?

ν Fluxes with SI and Transport Equation

In the generalized multiflavor case:

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absorption   regeneration

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Regeneration term:

We analyzed this question adopting a perturbative approach in which the regeneration processes are treated as a perturbation

Both astrophysical and cosmogenic fluxes are practically unaffected by regeneration *(never larger than* ~10%*)*

In addition to energy argument, an important role is played by the redshift:

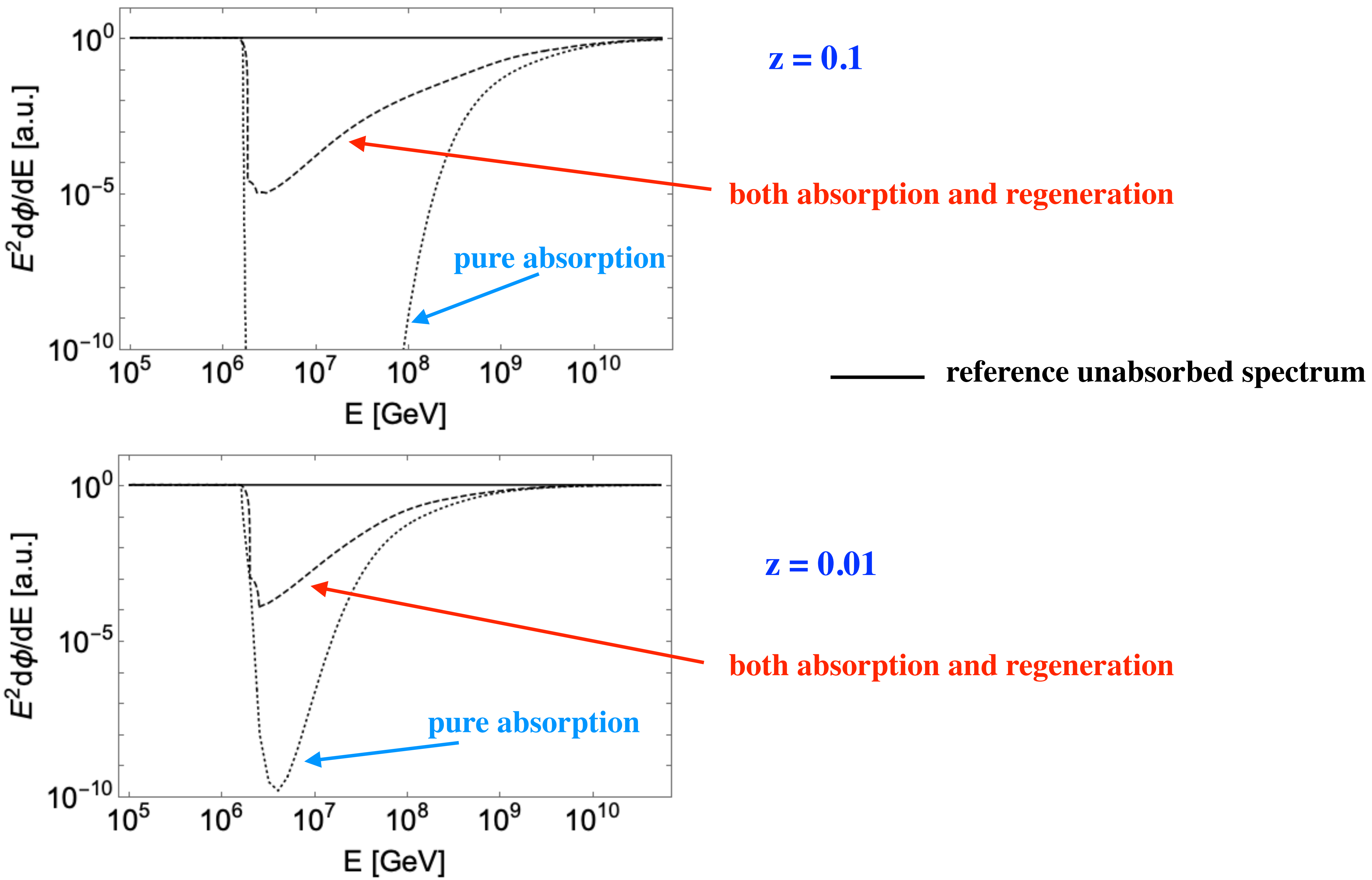
z > 0.1, the produced neutrinos are severely suppressed due to the absorption on the CNB

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.

Regeneration term for point-like sources at large redshift:

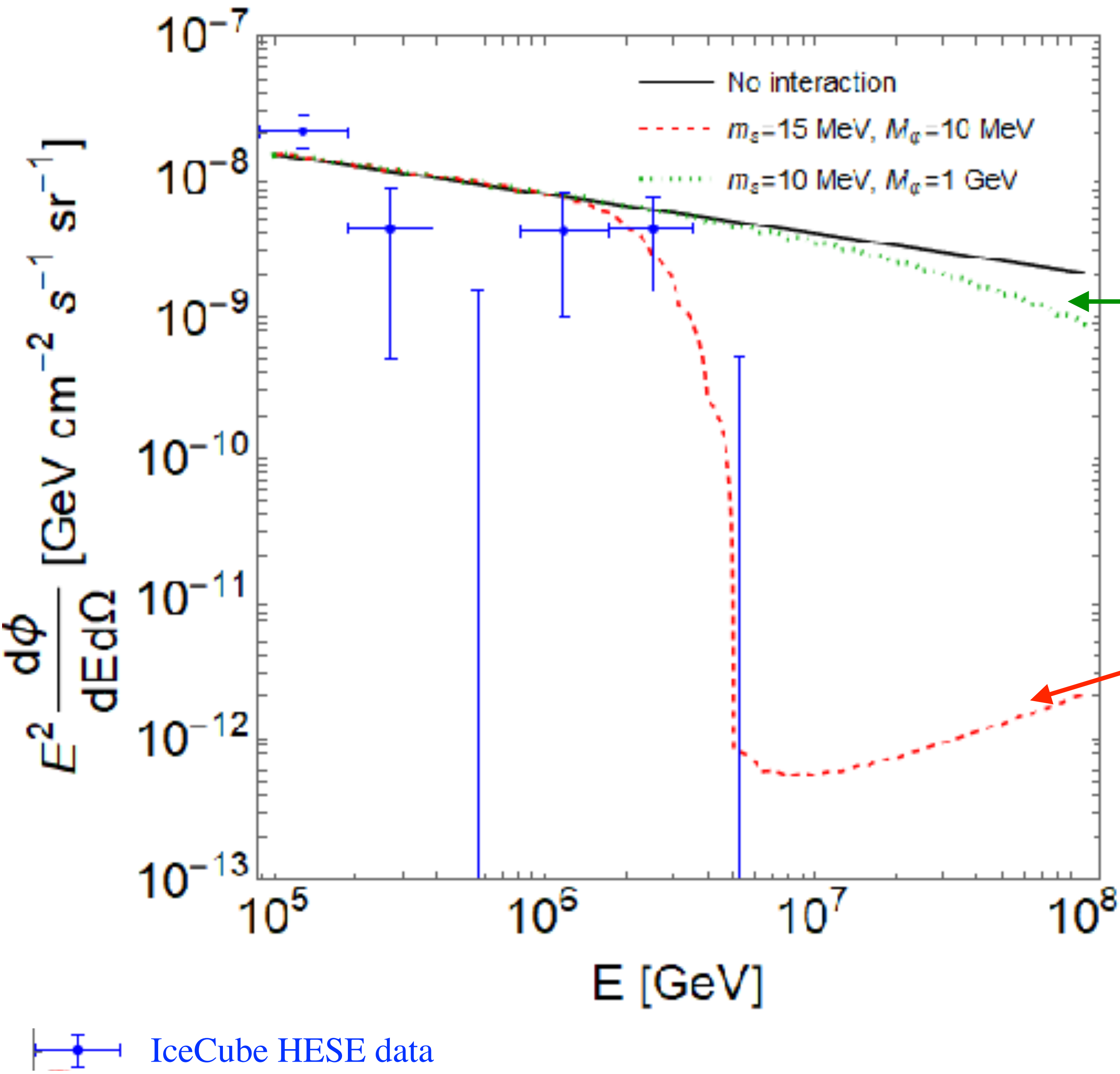
Expected spectra at Earth for a generic source at two fixed redshift values z with an E^{-2} reference spectrum.



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

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

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

the constraints from mesons decay are irrelevant

⇨ also lower masses for Mφ

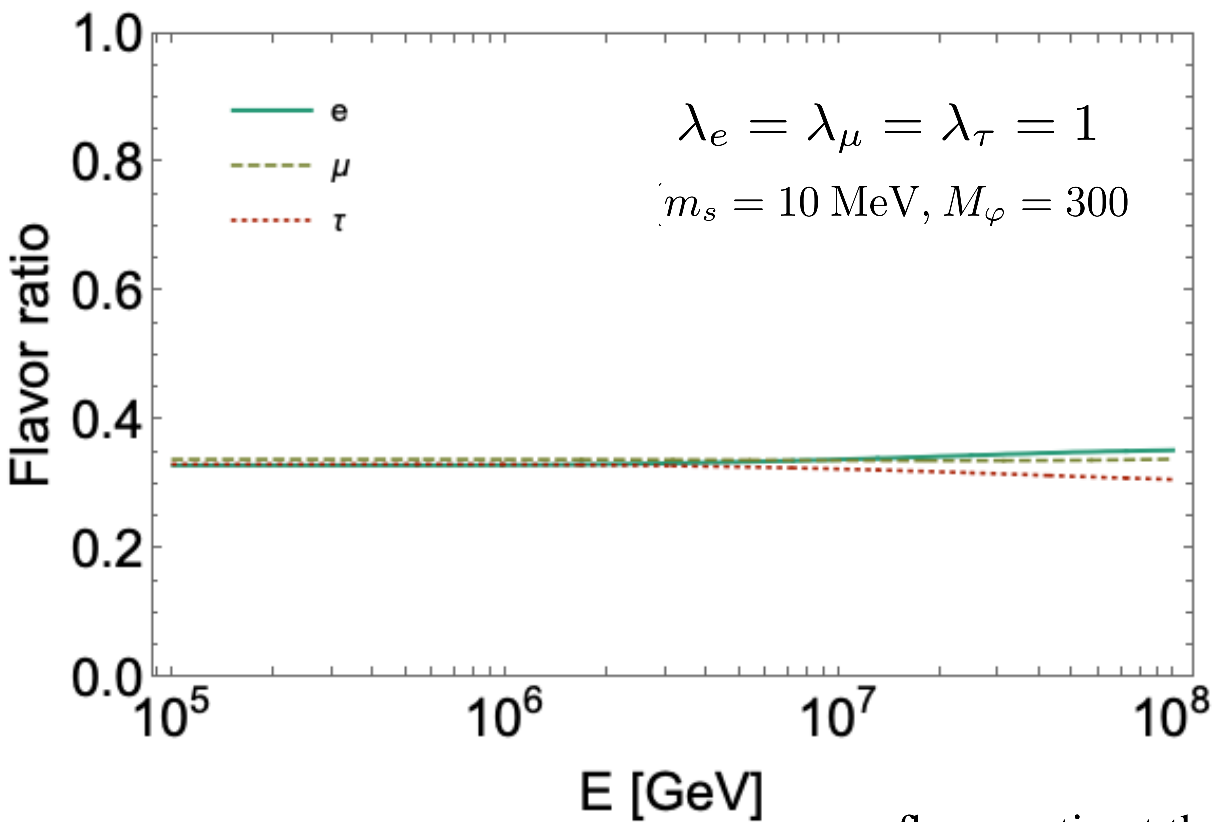
The new interaction causes a cutoff-like feature in the spectrum in the range between 1 PeV and 10 PeV

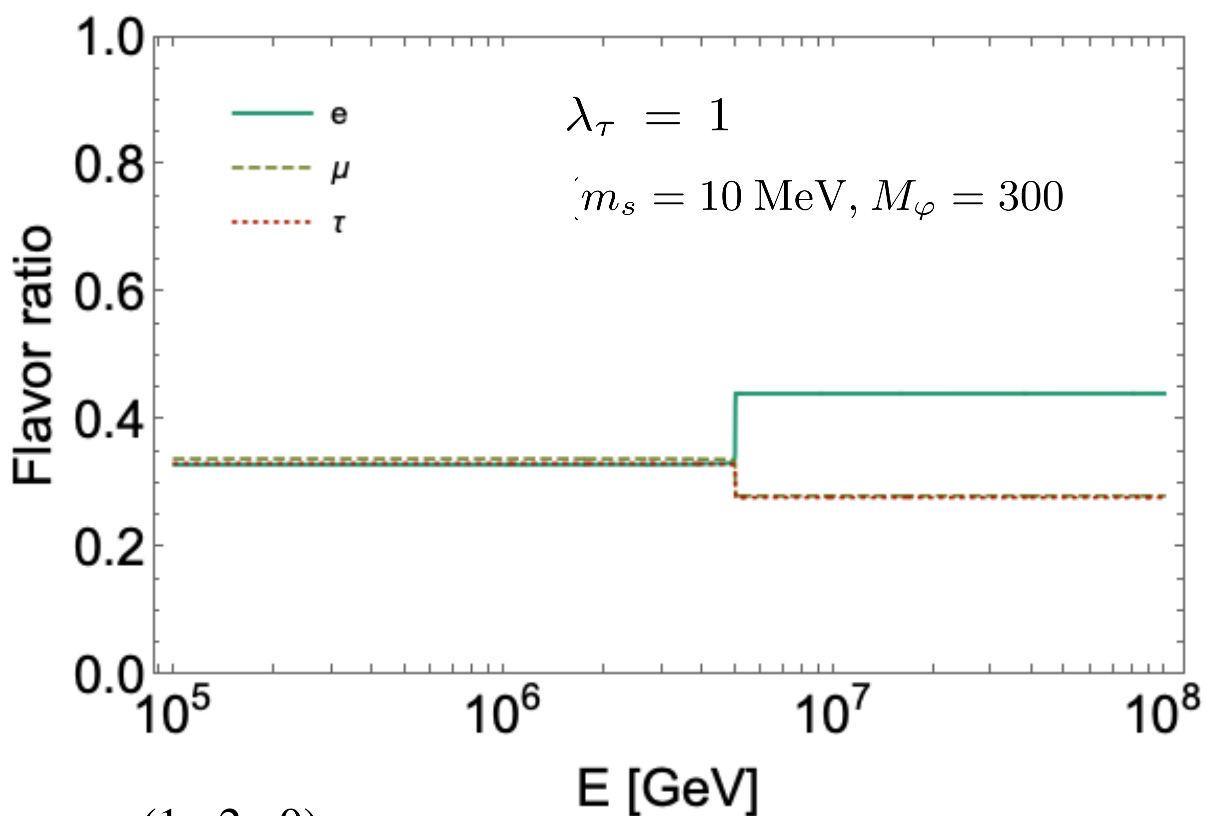
*Fiorillo, Miele, Morisi, **Saviano** 2020, arXiv:2007.07866*

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)

Results and detection chances for PL Spectrum (2)

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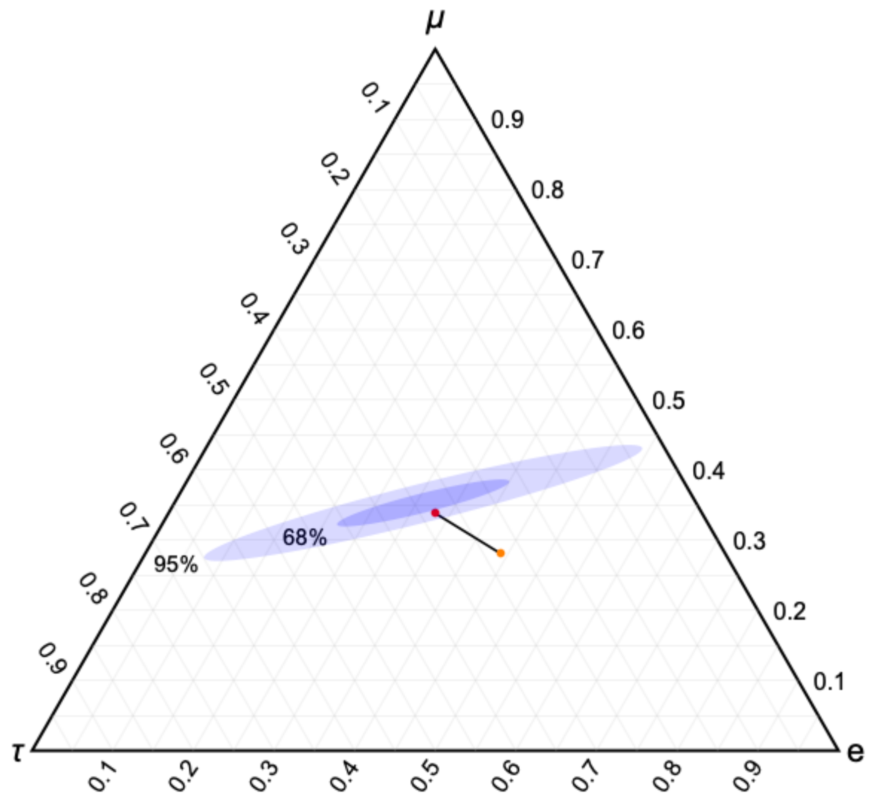
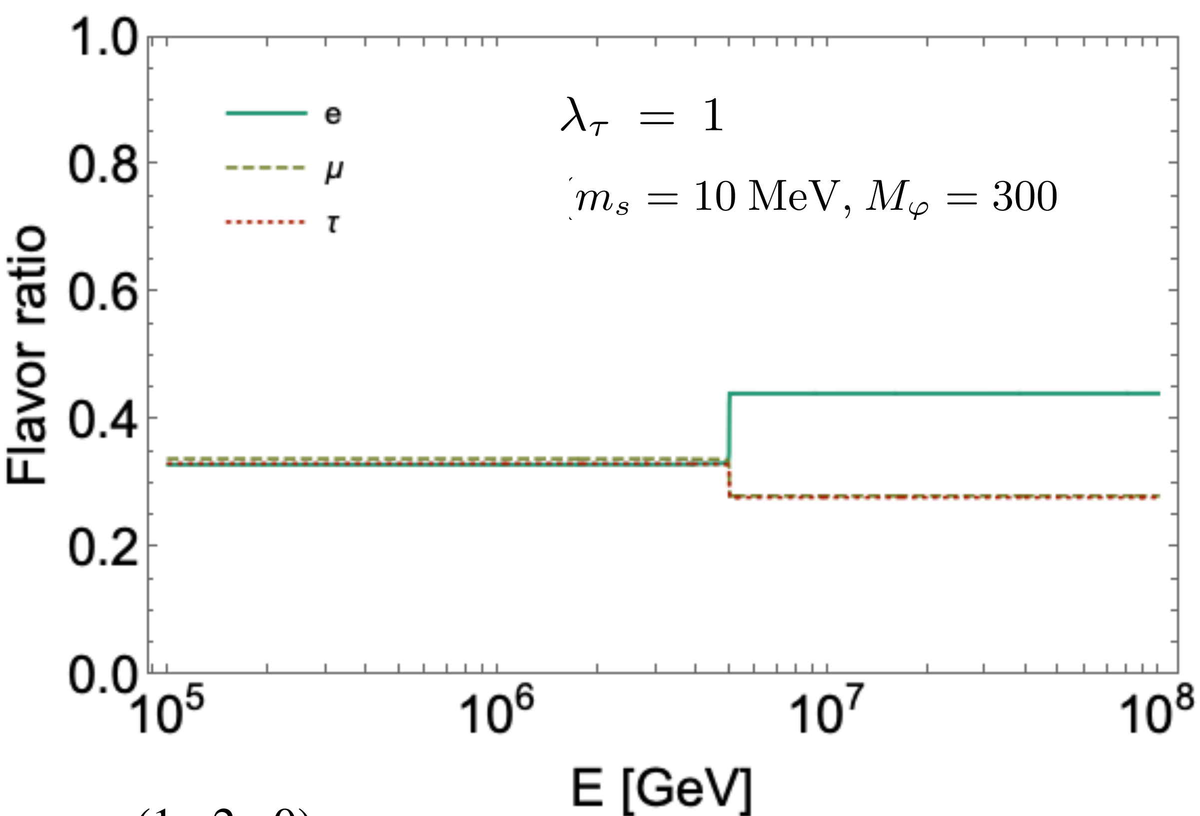




flavor ratio at the source (1 : 2 : 0)

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

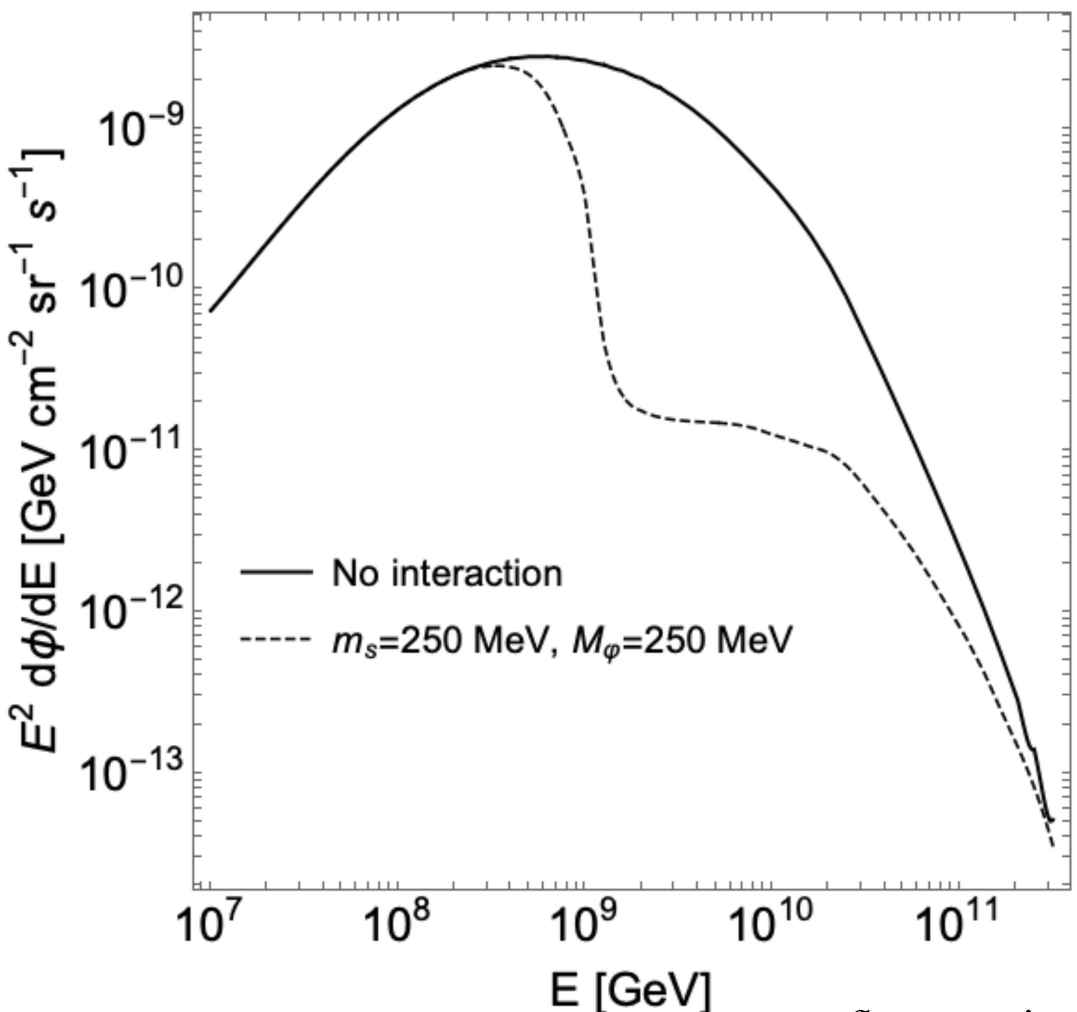
red point 10^5 GeV

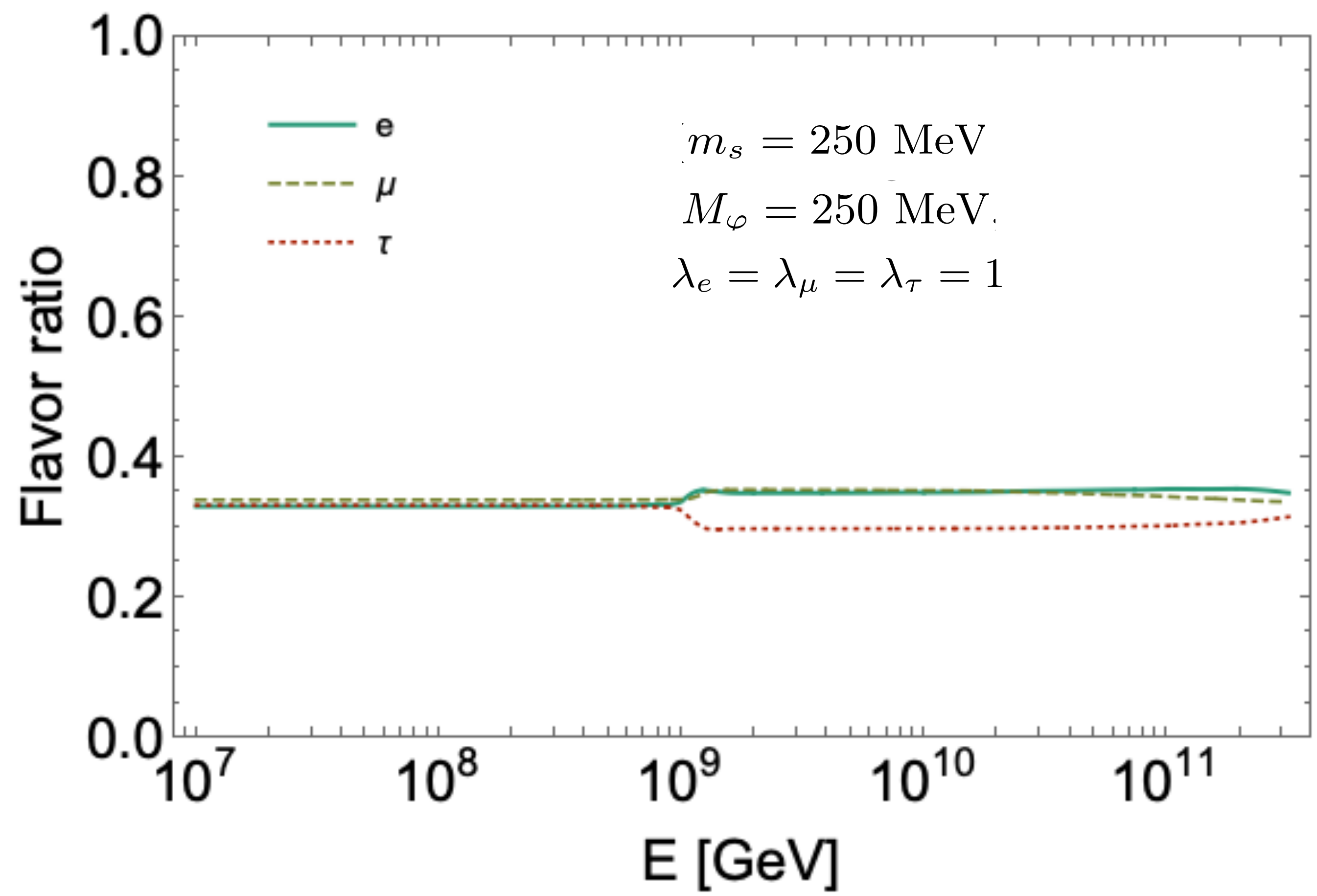
orange point 10^8 GeV

forecasted sensitivity of IceCube-Gen2

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

Results for Cosmogenic Spectrum (2)





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

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

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 observable in future experiments.

The flux depletion can also 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

Backup slides

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 ϕ_ν, expected to be isotropic, can be parameterized in the form

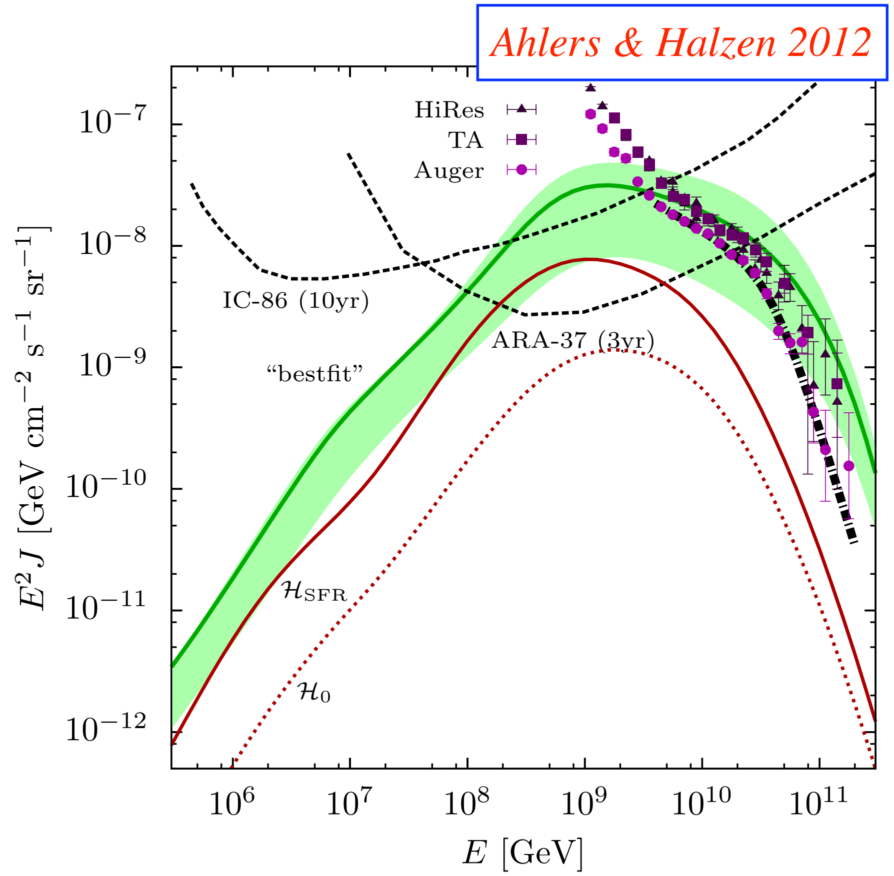
$$\frac{d\phi_\nu}{dE d\Omega} = \int \frac{dz'}{H(z')} F\left[z', E(1+z')\right]$$

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**

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

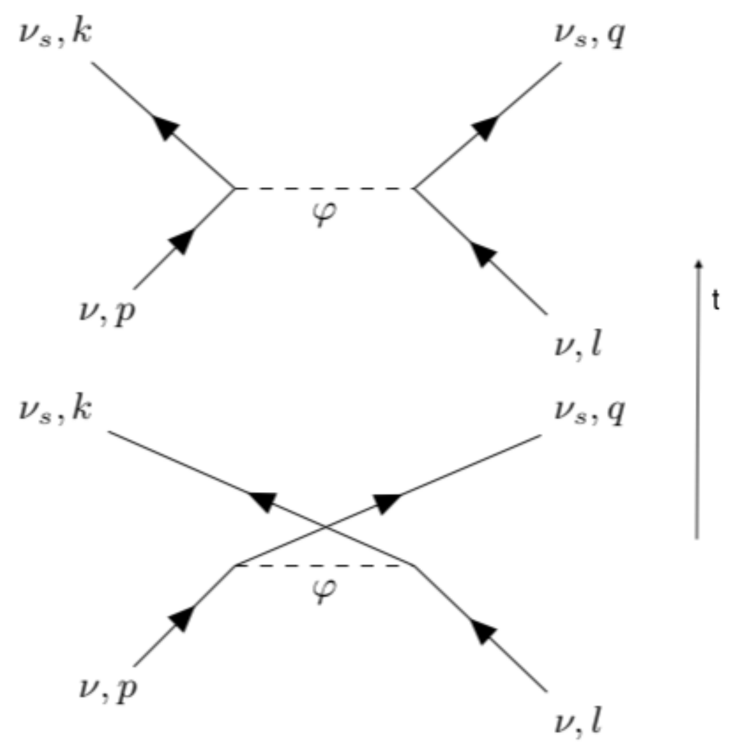


where ρ(z) is the Star Forming Rate

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

Cross sections

process $\nu + \nu \to \nu_s + \nu_s$



$s = (p+l)^2$, $t = (p-k)^2$ and $u = (p-q)^2$

$$|\mathcal{M}_{aa\to ss}|^2 = \lambda^4 \Bigg[\frac{[t-(m-m_s)^2]^2}{(t-M_\varphi^2)^2+\Gamma^2 M_\varphi^2} + \frac{[u-(m-ms)^2]^2}{(u-M_\varphi^2)^2+\Gamma^2 M_\varphi^2} - \frac{2[(t-M_\varphi^2)(u-M_\varphi^2)+\Gamma^2 M_\varphi^2]}{[(t-M_\varphi^2)^2+\Gamma^2 M_\varphi^2][(u-M_\varphi^2)^2+\Gamma^2 M_\varphi^2]} \times \left(\frac{(t-m^2-m_s^2)^2}{4} + \frac{(u-m^2-m_s^2)^2}{4} - \frac{s^2}{4} + s(m^2+m_s^2-m\,m_s) - 2m^2 m_s^2 \right) \Bigg]$$

m is the mass of the active neutrino ν of CνB

m_s is the mass of the sterile neutrino

$M\varphi$ mass of the scalar mediator

λ coupling

Γ is the decay rate of the scalar mediator

Total cross section: $$\sigma_{aa\to ss} = \frac{1}{64\pi I^2} \int_{t_1}^{t_2} |\mathcal{M}_{aa\to ss}|^2 (s,t)\, dt$$

$$t_{1,2} = m^2 + m_s^2 - \frac{s}{2} \pm \sqrt{s}\sqrt{\frac{s}{4} - m_s^2}$$

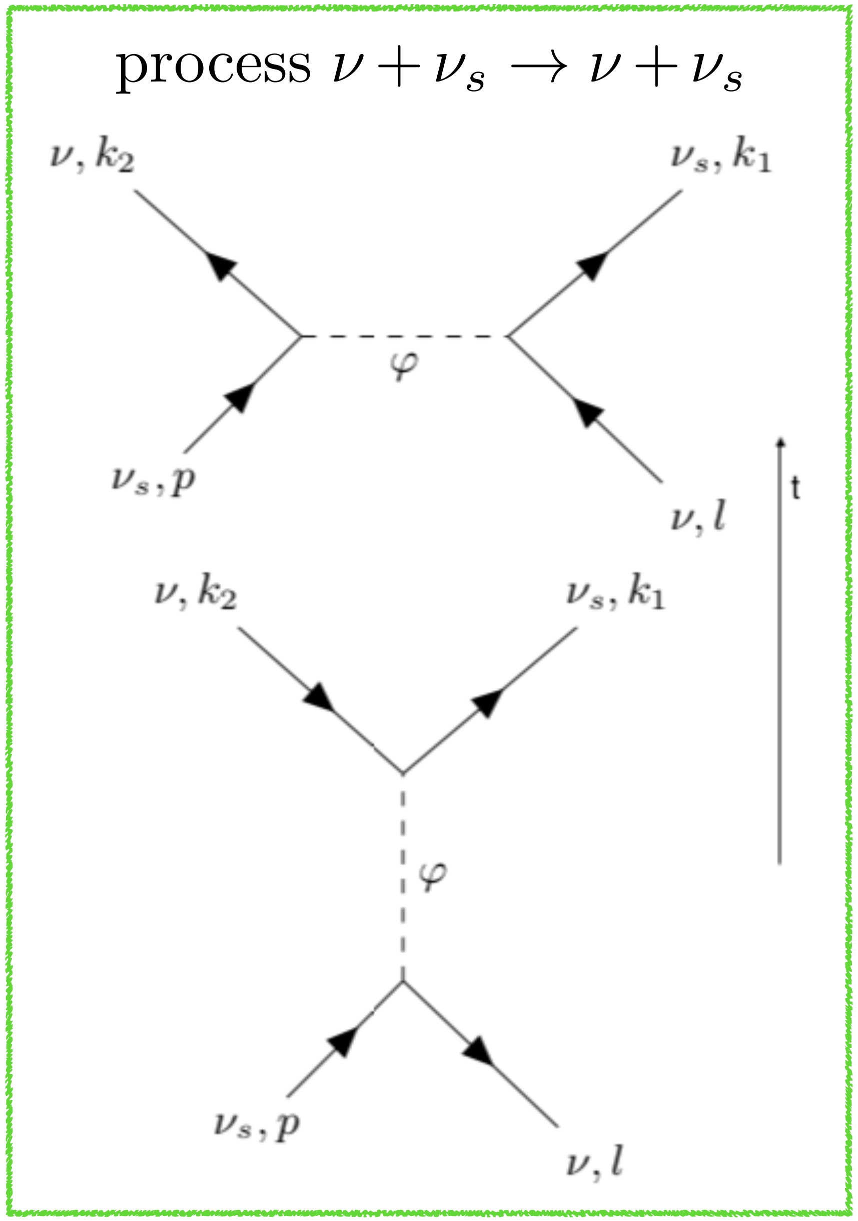
$$I = \sqrt{\frac{2m^4 + s^2 - 4sm^2}{2}}$$

Differential cross section for the production of a sterile neutrino with energy Es:

$$\frac{d\sigma_{aa\to ss}}{dE_s} = \frac{|\mathcal{M}_{aa\to ss}|^2[2pm, m^2+m_s^2-2m(E-E_s)]}{32\pi E I} \times \theta\left(E - \frac{2mE_s^2}{2mE_s - m_s^2}\right) \theta\left(E_s - \frac{m_s^2}{2m}\right)$$

E is the energy of the incident cosmogenic active neutrino

Cross sections



the squared amplitude $|\mathcal{M}_{as\to as}|^2$ is identical to one given for the process $|\mathcal{M}_{aa\to ss}|^2$ with the s and the u parameters exchanged in the corresponding equation.

$$t = (p - k_2)^2 = (l - k_1)^2$$

Total cross section:

$$\sigma_{as\to as} = \frac{1}{64\pi J^2}\int_{t_1}^{t_2} |\mathcal{M}_{aa\to ss}|^2(m_s^2 + 2mE, t)dt$$

$$J = \sqrt{\frac{m^4 + m_s^4 + s^2 - 2sm^2 - 2sm_s^2}{2}}$$

Differential cross section for the production of an active neutrino of energy E_2:

$$\frac{d\sigma_{as\to as}}{dE_2} = \frac{1}{32\pi EJ}\theta\left(\frac{2mE^2}{2mE + m_s^2} - E_2\right) \times |\mathcal{M}|^2[m^2 + m_s^2 + 2mE, m^2 + m_s^2 - 2m(E - E_2)]$$

Differential cross section for the production of a sterile neutrino of energy E_1:

$$\frac{d\sigma_{as\to as}}{dE_1} = \frac{1}{32\pi EJ}\theta\left((E - E_1)(2mEE_1 - m_s^2(E - E_1)\right) \times |\mathcal{M}|^2[m^2 + m_s^2 + 2mE, m^2 + m_s^2 - 2mE_1]$$

Mediator Decay

The decay rate of the pseudoscalar mediator is given by

$$\Gamma = \frac{\lambda^2 \xi (m m_s + \sqrt{\xi^2 + m^2}\sqrt{\xi^2 + m_s^2} + \xi^2)}{2\pi M_\varphi (\sqrt{\xi^2 + m^2} + \sqrt{k^2 + m_s^2})} \theta(M_\varphi - m - m_s)$$

$$\xi = \frac{\sqrt{m^4 - 2m^2 M_\varphi^2 + M_\varphi^4 - 2m^2 m_s^2 - 2M_\varphi^2 m_s^2 + m_s^4}}{2M_\varphi}$$

For $m_S \geq M_\phi$, the decay rate of the scalar mediator vanishes, since there is no decay channel kinematically allowed $\Longrightarrow$

$\Longrightarrow$ the resonances in the cross sections become unregulated.

While this is not a problem for the s-resonance, which can never be reached in the physical space of parameters of the collision, the t- and u-resonance exhibit instead a singular behavior. This behavior needs to be regulated taking into account the finite transverse amplitude of the scattering beams.

In order to avoid this difficulty, we have restricted to the case $M_\phi > m_S$.

Cross sections in multiflavor case

process $\nu_i + \nu_j \to \nu_s + \nu_s$

$s = (p+l)^2$, $t = (p-k)^2$ and $u = (p-q)^2$

$$|\mathcal{M}_{ij\to ss}|^2 = |\sum_{\alpha,\beta} U^*_{\alpha i} U^*_{\beta j} \lambda_\alpha \lambda_\beta|^2$$
$$\times \left[\frac{[t-(m-m_s)^2]^2}{(t-M_\varphi^2)^2+\Gamma^2 M_\varphi^2} + \frac{[u-(m-ms)^2]^2}{(u-M_\varphi^2)^2+\Gamma^2 M_\varphi^2} \right.$$
$$- \frac{2[(t-M_\varphi^2)(u-M_\varphi^2)+\Gamma^2 M_\varphi^2]}{[(t-M_\varphi^2)^2+\Gamma^2 M_\varphi^2][(u-M_\varphi^2)^2+\Gamma^2 M_\varphi^2]}$$
$$\times \left(\frac{(t-m^2-m_s^2)^2}{4} + \frac{(u-m^2-m_s^2)^2}{4} \right.$$
$$\left.\left. - \frac{s^2}{4} + s(m^2+m_s^2-m\,m_s) - 2m^2 m_s^2 \right) \right]$$

m is the mass of the active neutrino , m_s is the mass of the sterile neutrino,
$M\varphi$ mass of the scalar mediator, λ couplings
Γ is the decay rate of the scalar mediator

Total cross section:

$$\sigma_i = \frac{1}{64\pi I^2} \sum_j \int_{t_1}^{t_2} |\mathcal{M}_{ij\to ss}|^2(s,t)dt$$

$$t_{1,2} = m^2 + m_s^2 - \frac{s}{2} \pm \sqrt{s}\sqrt{\frac{s}{4} - m_s^2}$$

$$I = \sqrt{\frac{2m^4 + s^2 - 4sm^2}{2}}$$

Differential cross section for the production of a sterile neutrino with energy Es:

$$\frac{d\sigma_{aa\to ss}}{dE_s} = \frac{|\mathcal{M}_{aa\to ss}|^2[2pm, m^2+m_s^2-2m(E-E_s)]}{32\pi E I} \times \theta\left(E - \frac{2mE_s^2}{2mE_s - m_s^2}\right)\theta\left(E_s - \frac{m_s^2}{2m}\right)$$

E is the energy of the incident cosmogenic active neutrino