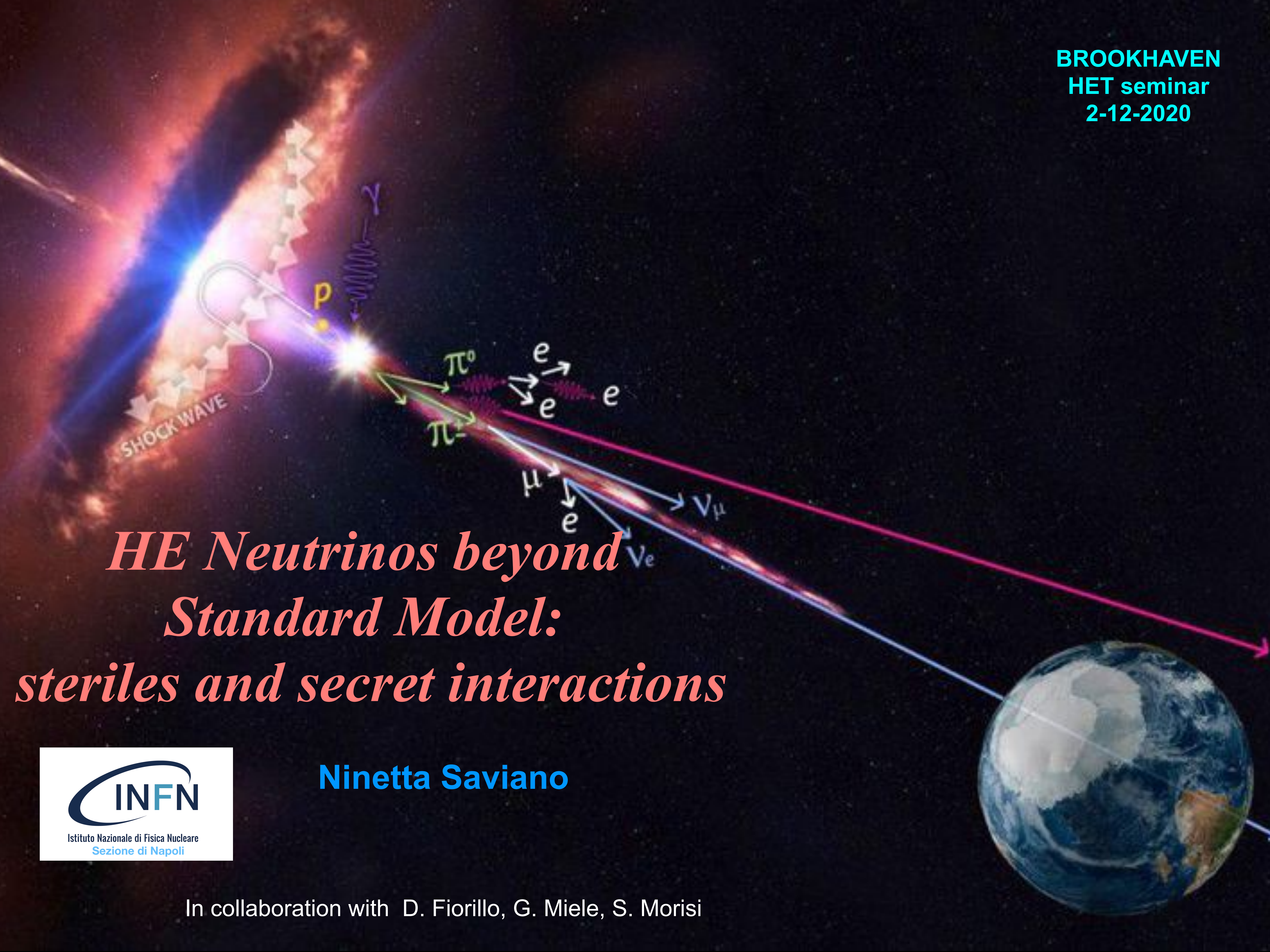
BROOKHAVEN
HET seminar
2-12-2020



HE Neutrinos beyond Standard Model: steriles and secret interactions

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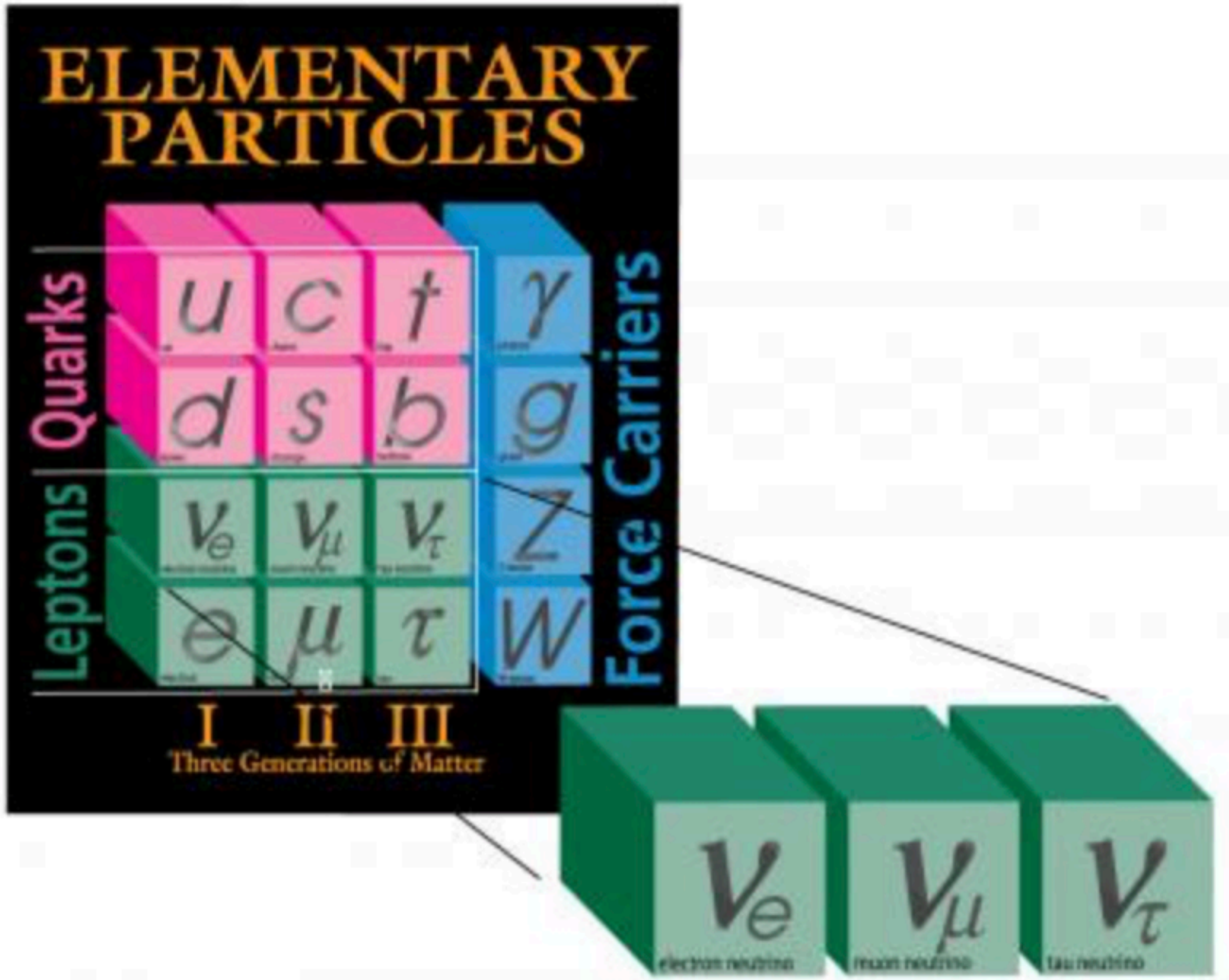
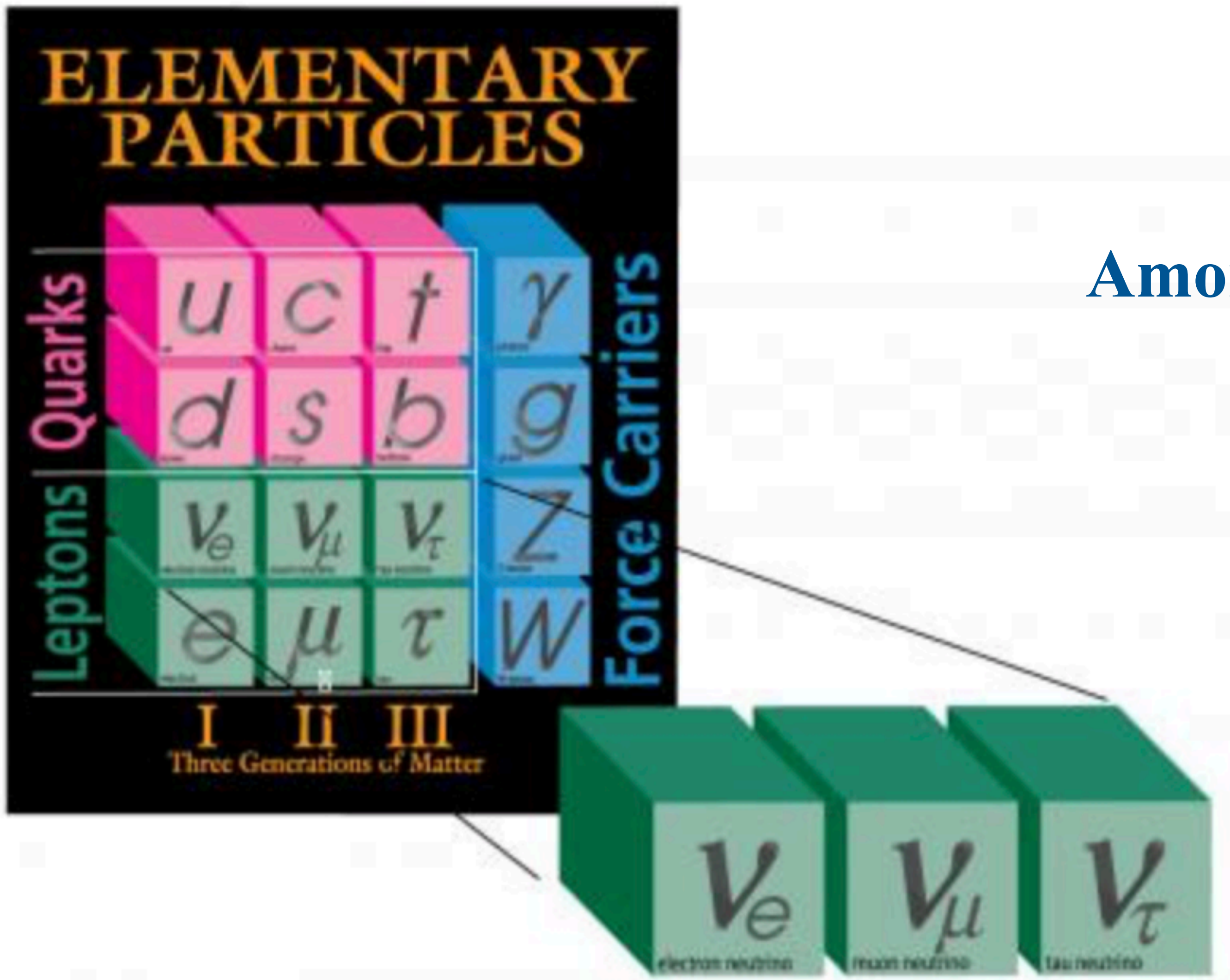
Standard Model and Beyond



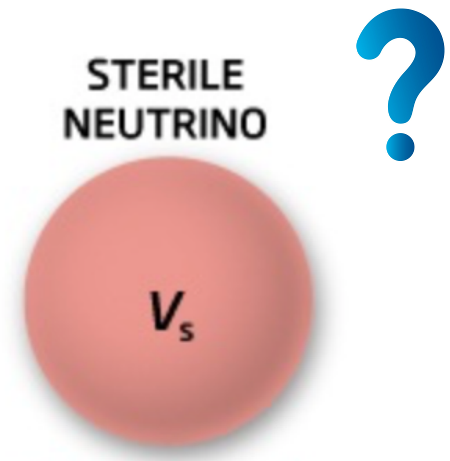
What else?

MASS	< 1 electronvolt $\neq 0$
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
FORCES THEY RESPOND TO	Weak force Gravity	Gravity ?
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Standard Model and Beyond

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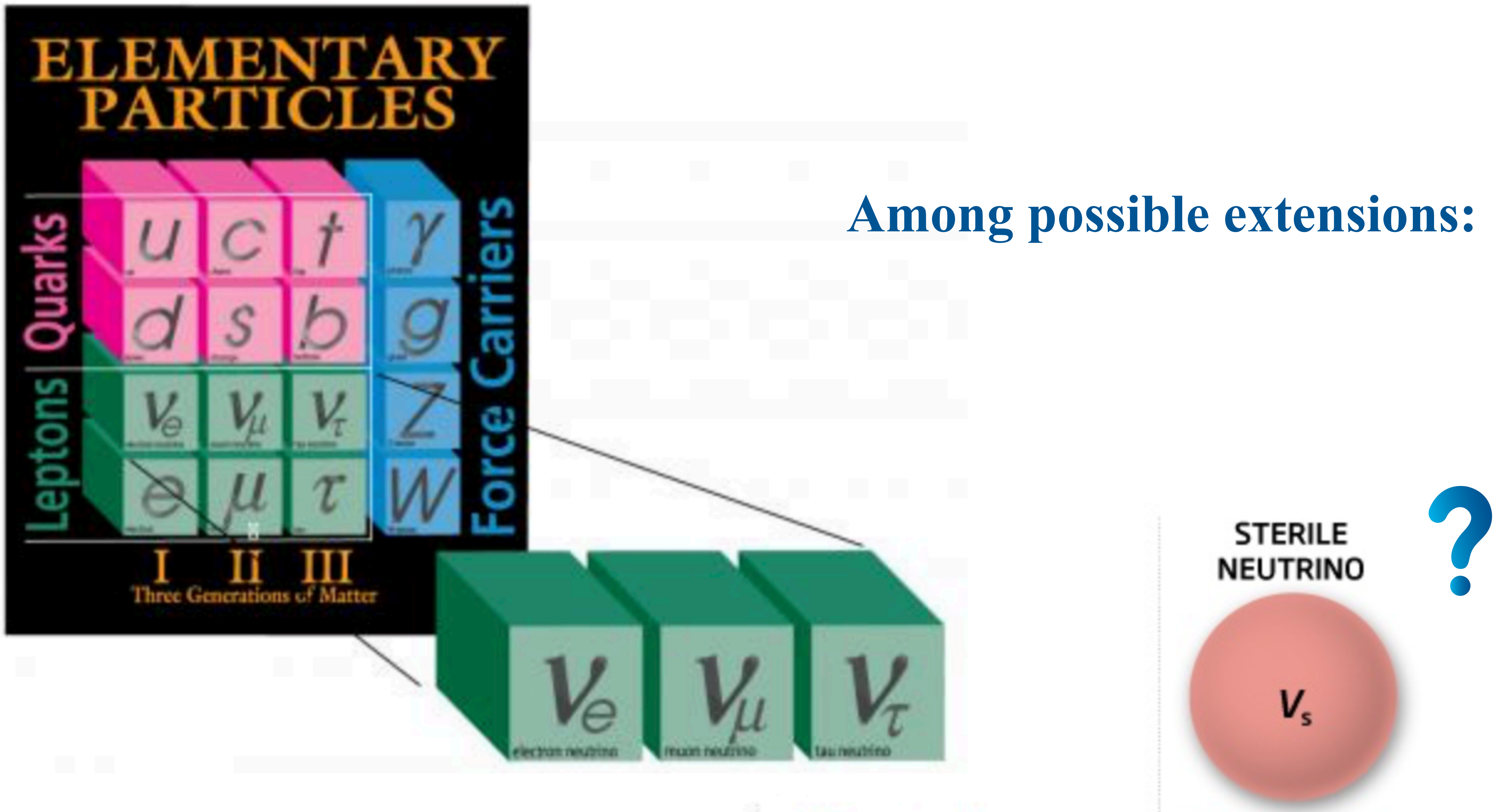

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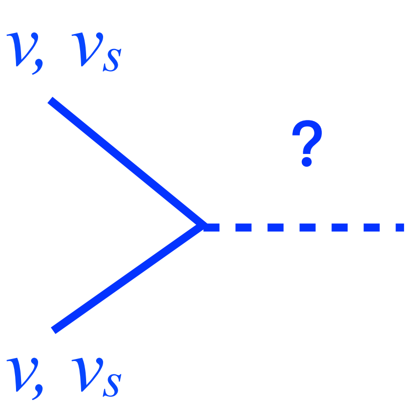
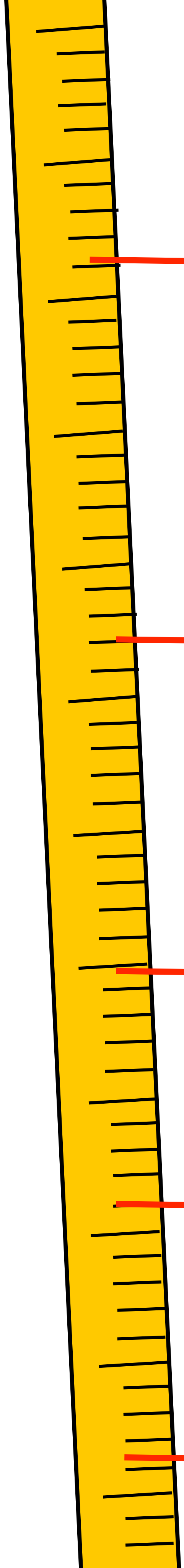


Extra "secret" interactions

Sterile Neutrinos



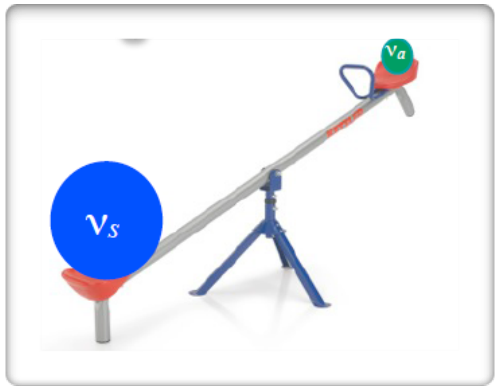
M_{GUT}

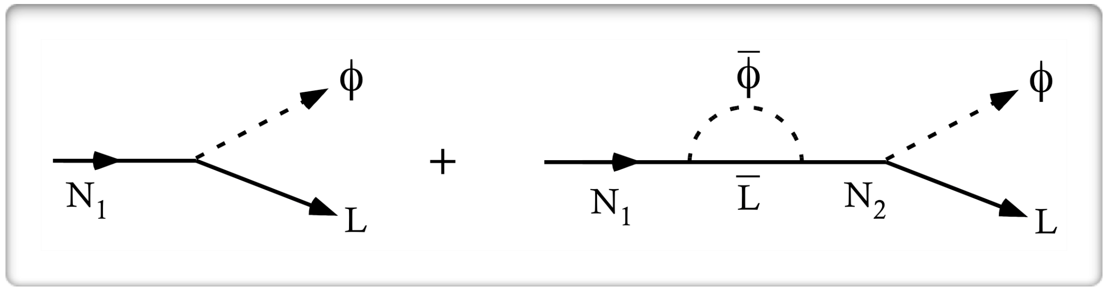
TeV

MeV

keV

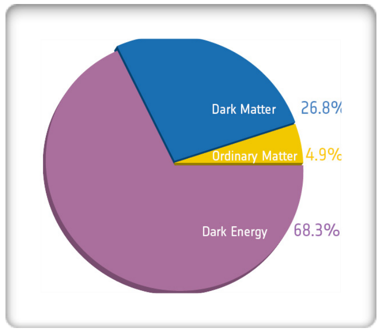
eV

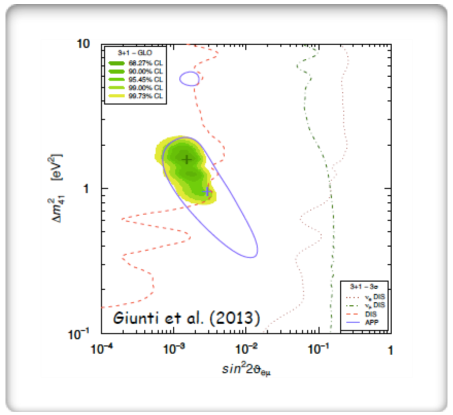




νMSM

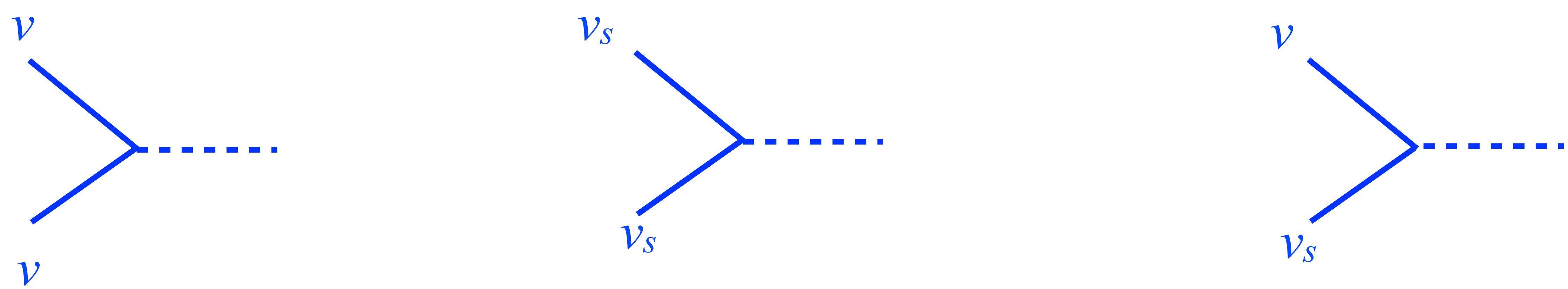
Dynamical electroweak symmetry breaking





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,…

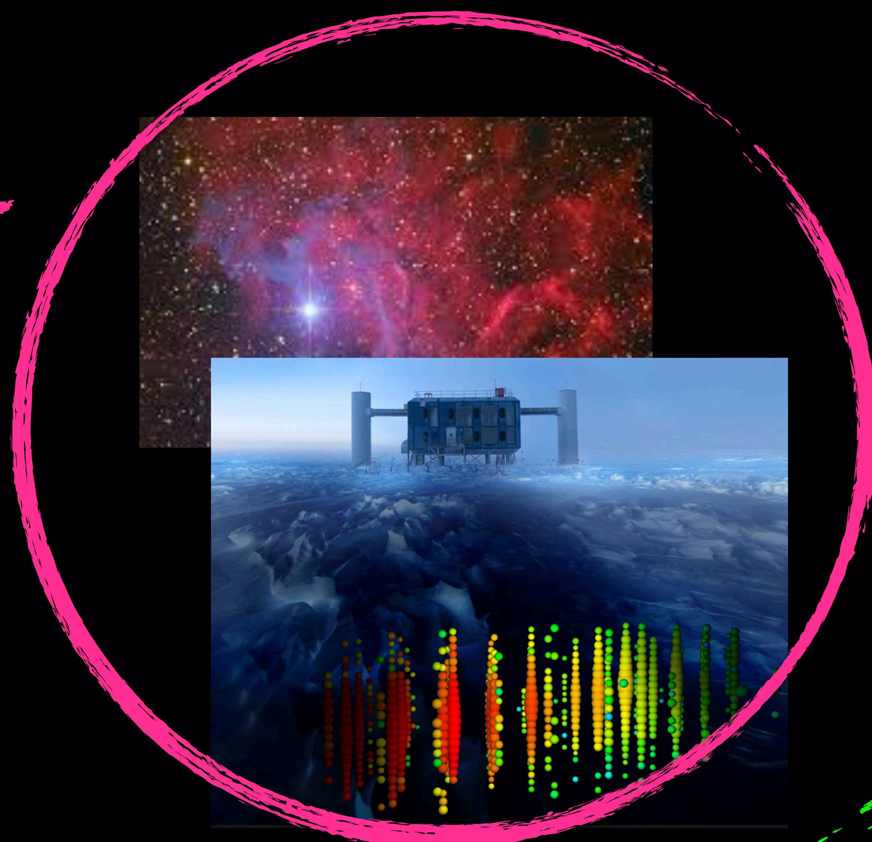
Astrophysics:

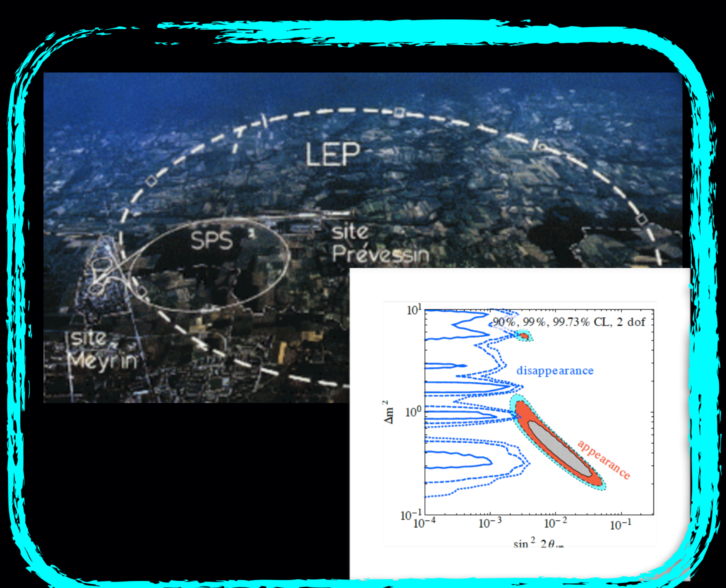
Kolb and Turner 1987; Ng and Beacom 2014; Ioka and Murase 2014;

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

How to corner sterile ν and secret interactions

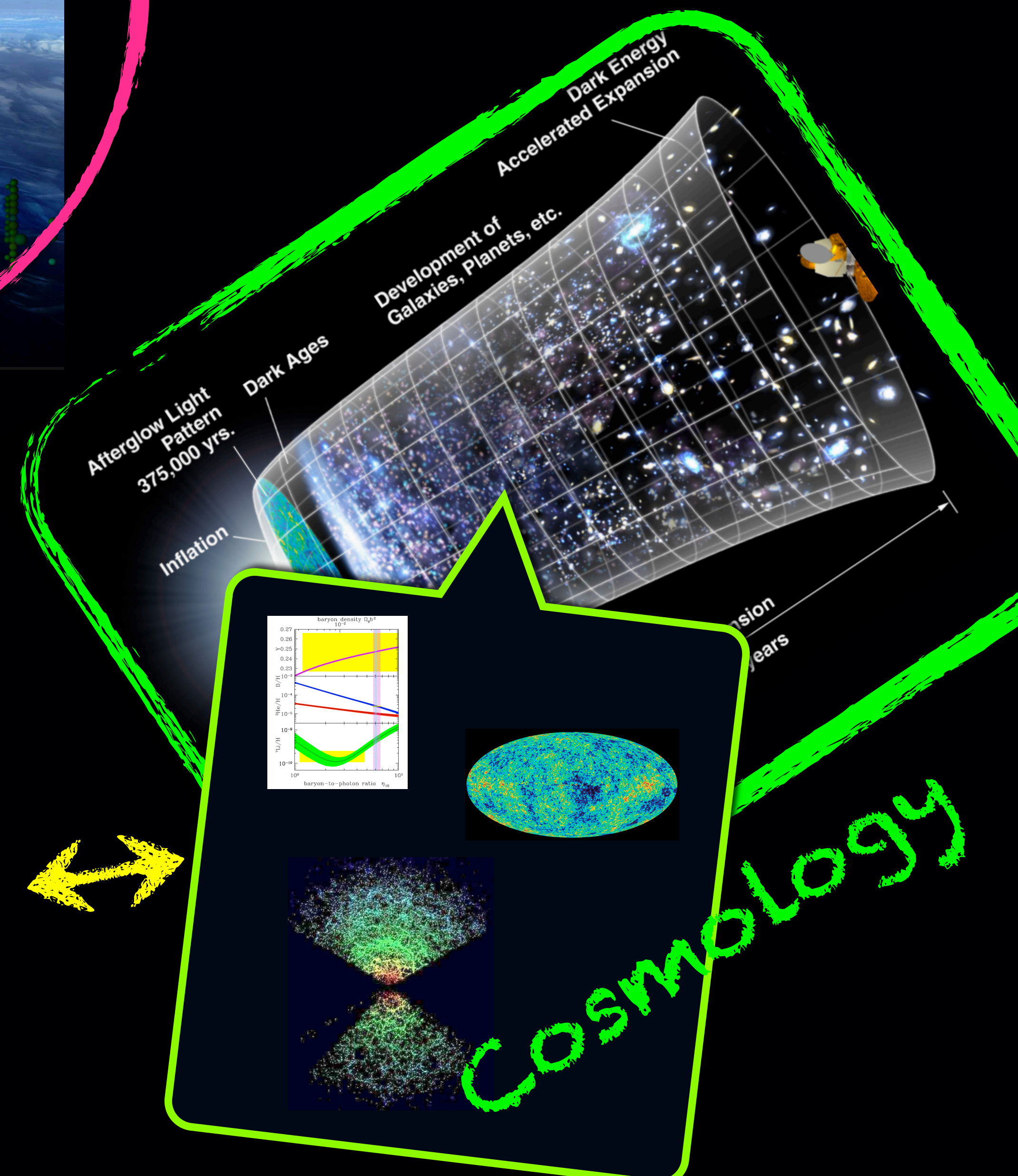
Astrophysical sources





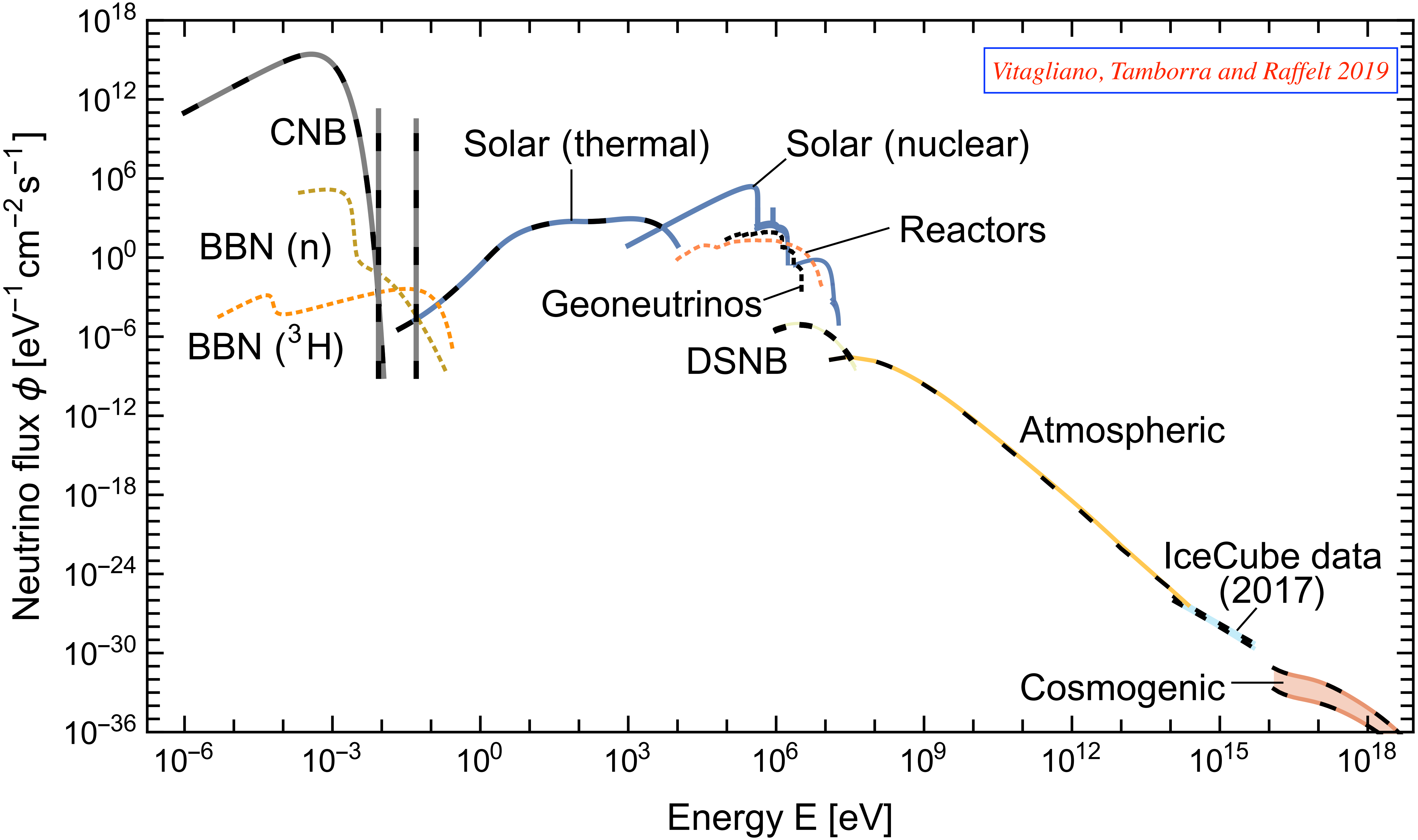
Laboratory

νs & secret inter.

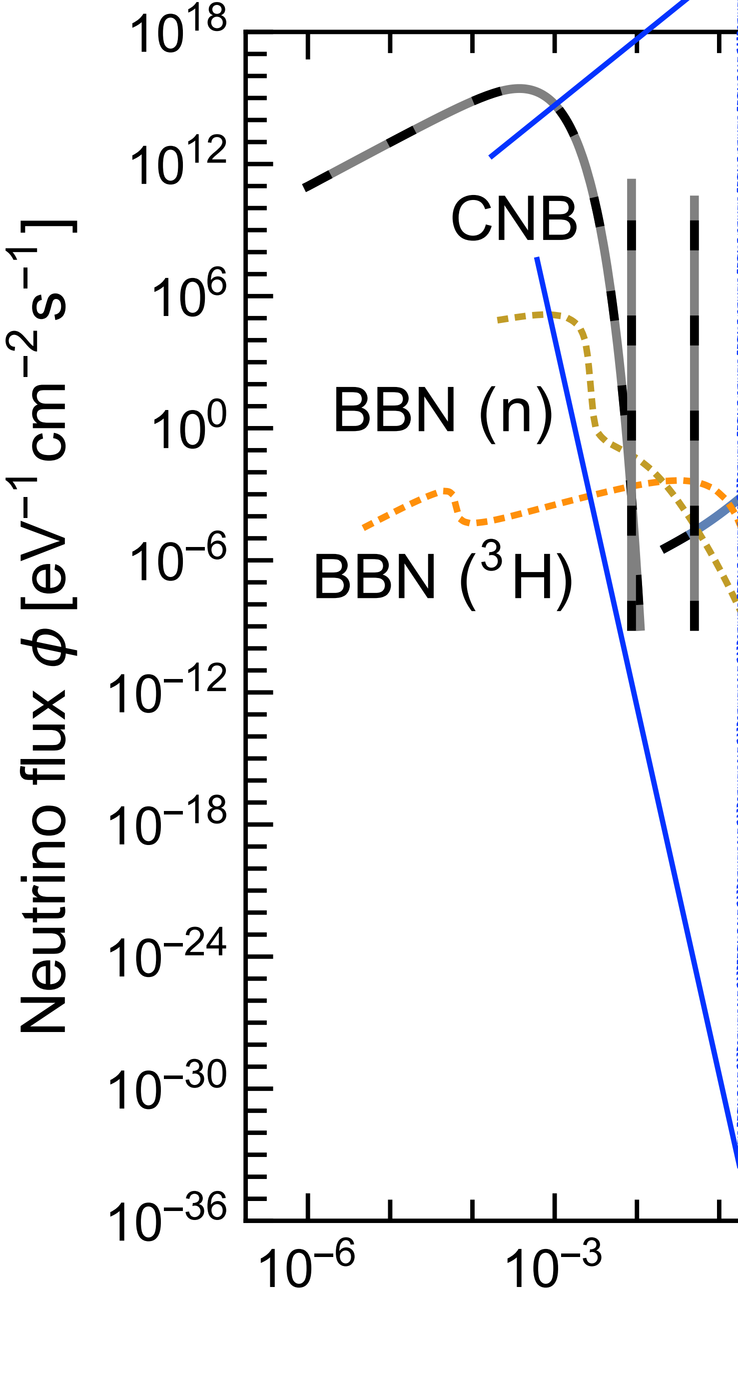


Cosmology

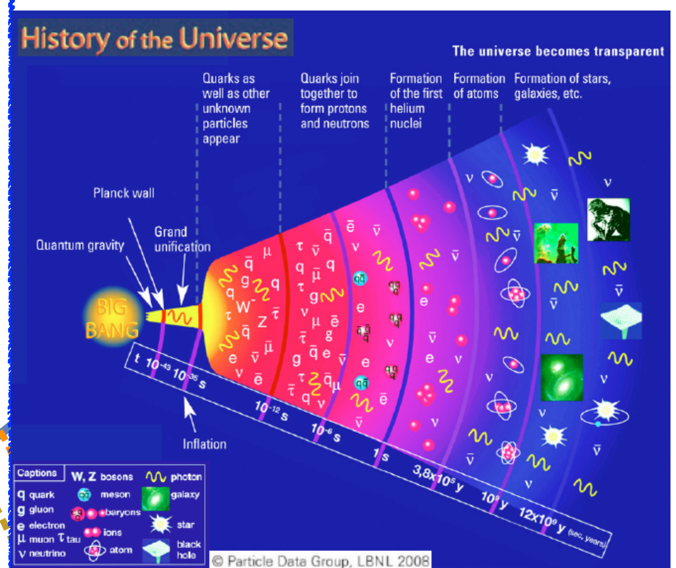
Neutrino Spectrum at Earth



Neutrino Spectrum at Earth



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:

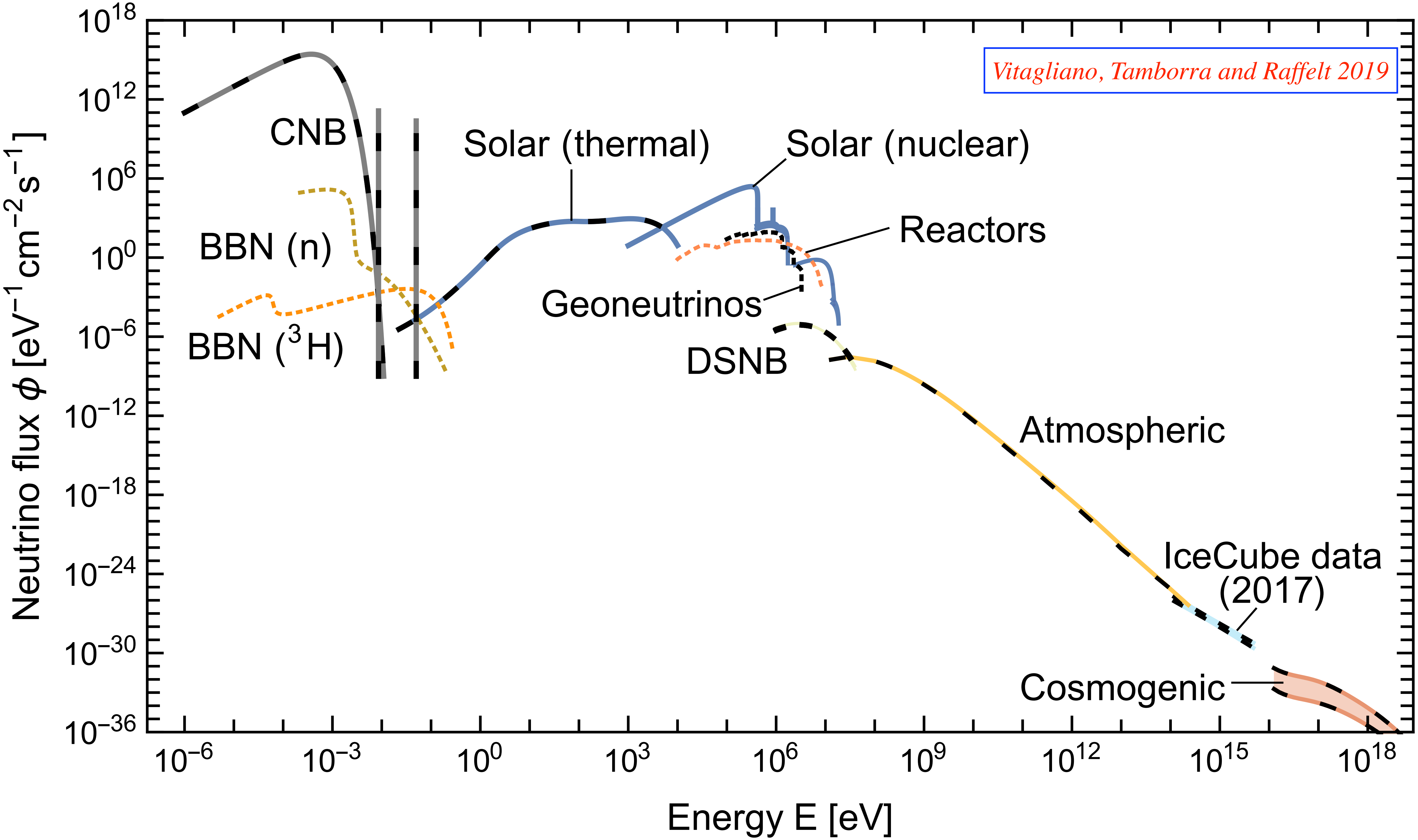
BBN	CMB	LSS
T~ 0.8 MeV	T < eV	
ν flavor sensitivity	ν mass sensitivity	
N_{eff}	N_{eff}	

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

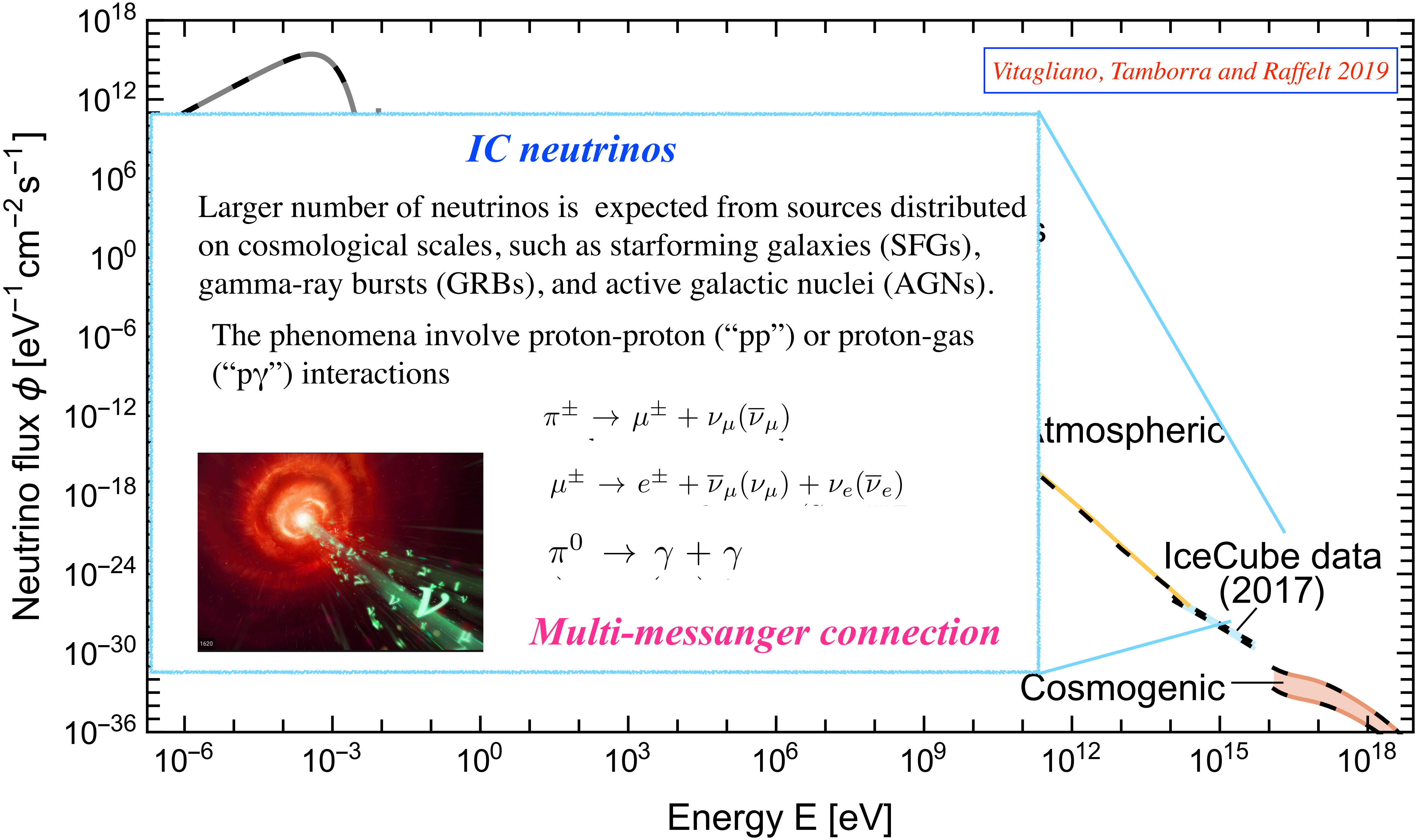
Detection prospective:

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

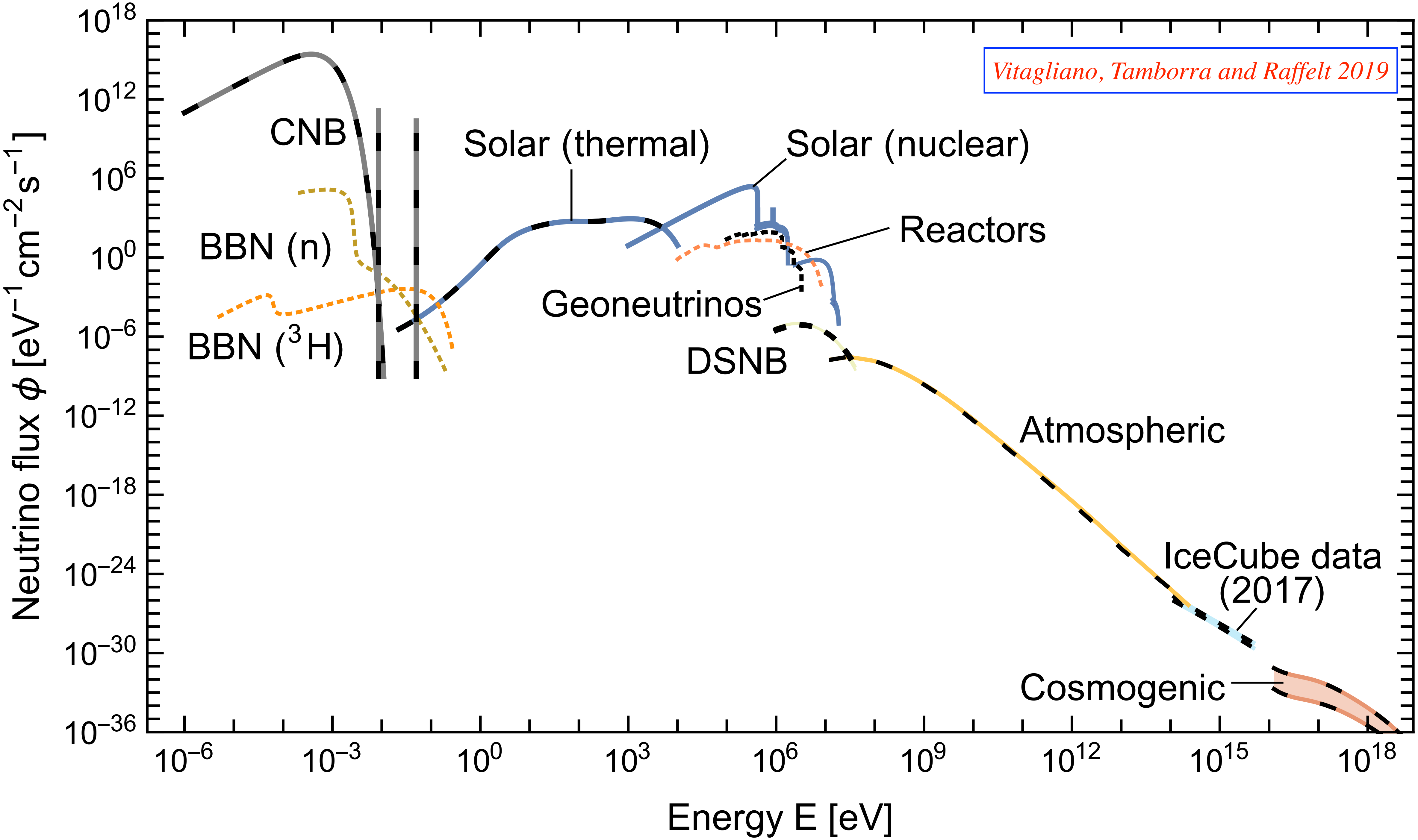
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$$

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

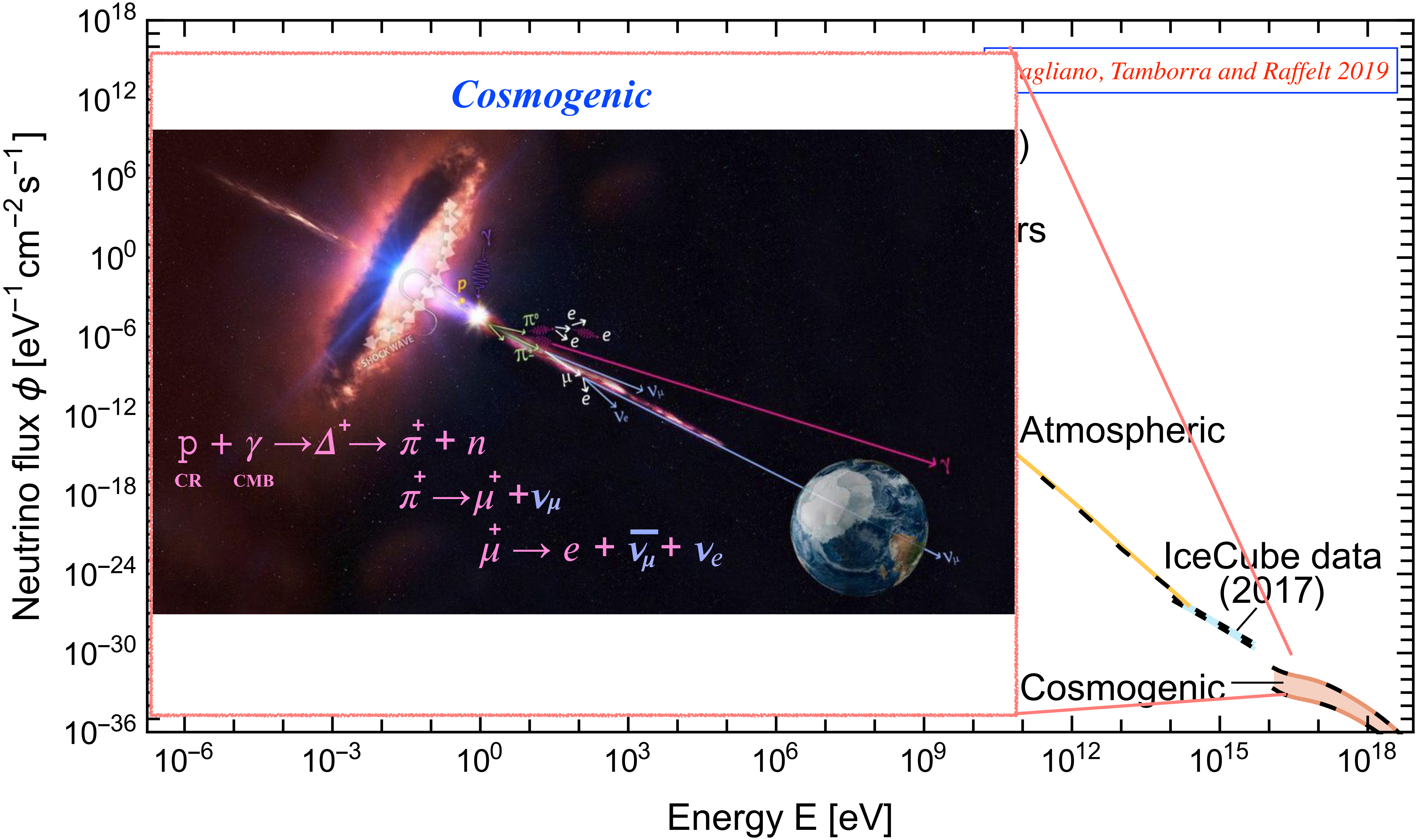
$$\pi^0 \rightarrow \gamma + \gamma$$

Multi-messanger connection

Neutrino Spectrum at Earth

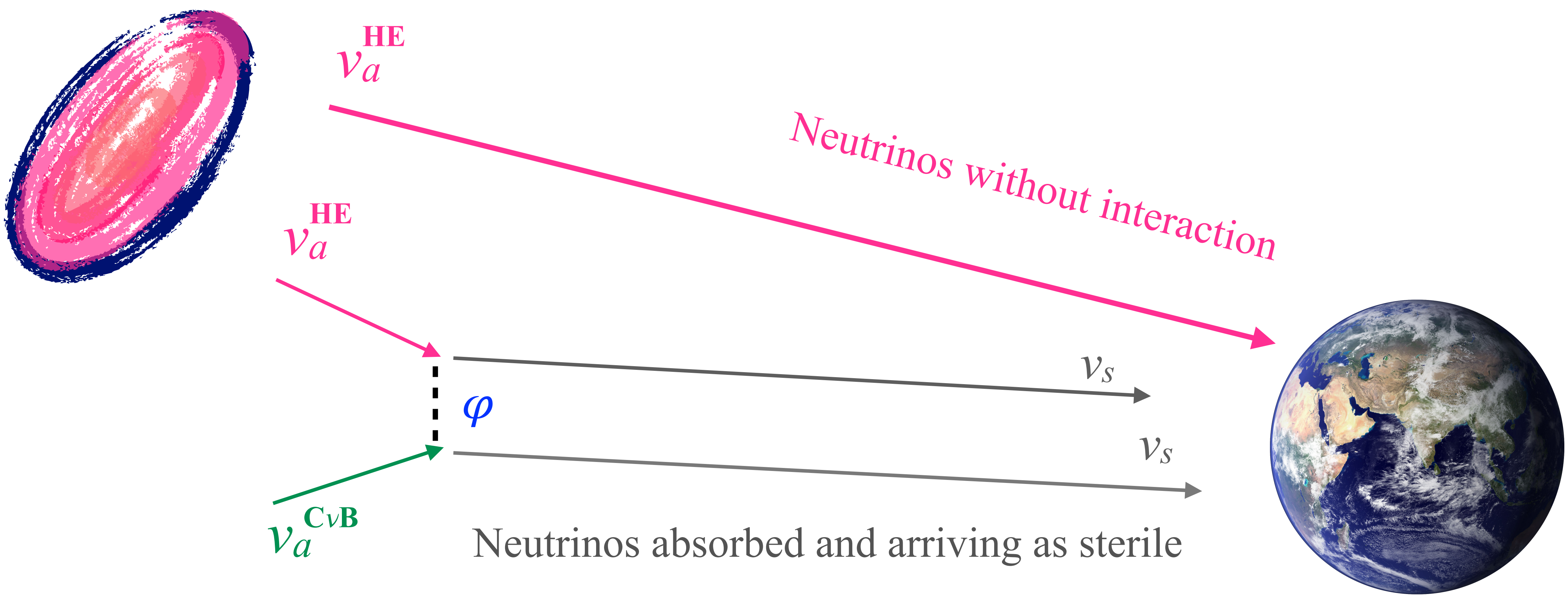


Neutrino Spectrum at Earth



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.

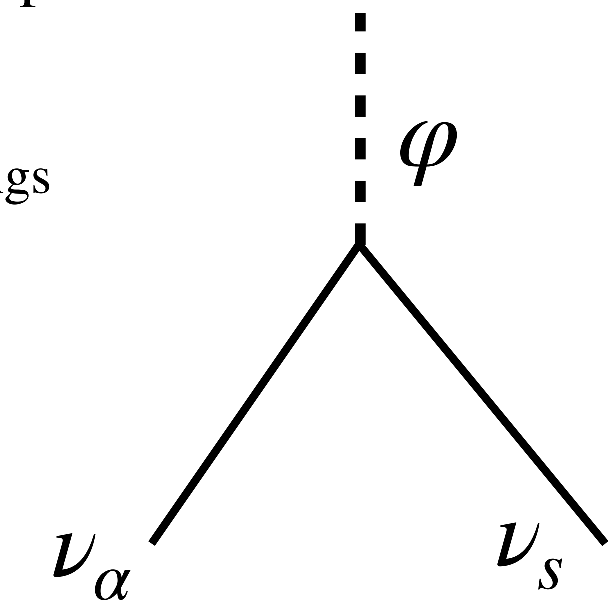
*Fiorillo, Miele, Morisi, **Saviano** 2020, **PRD 101,083024**, arXiv:2002.10125*

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

Active-sterile secret interactions

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

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



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

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

λ_α dimensionless free couplings

- Majorana neutrinos

- For the simplest choice,

  φ is a pseudoscalar

Parameter space:

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

Ample freedom of choice for our model:

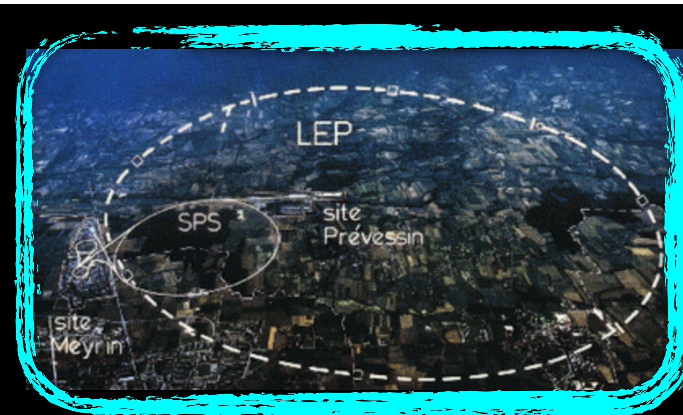
- The most natural possibility is $\lambda_e = \lambda_\mu = \lambda_\tau$

- Very interesting case only $\lambda_\tau \neq 0$

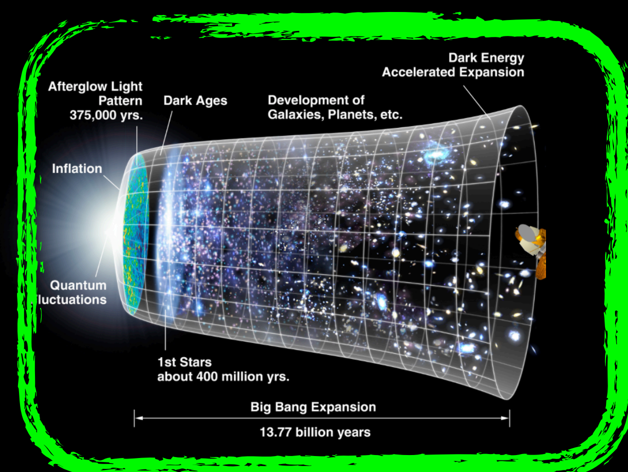
Allowed parameter space

Restrictions of the free parameter space can derive from :

- Laboratory experiments



- Cosmology



- Supernovae

The results of this analysis suggest a region of interest in the parameters **10 MeV < m_S, M_ϕ < 1 GeV**

• Laboratory constraints

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

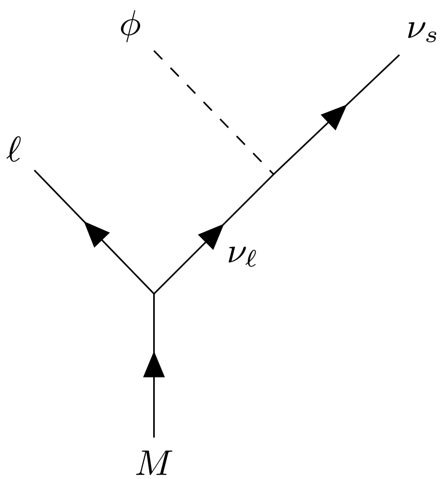
The new interaction opens the possibility of new leptonic decay channels $M \to \nu_s \ell \varphi$ and $M \to \nu_s \ell \overline{\nu}_{\ell'} \nu_s$

$\boxed{M \to \nu_s \ell \varphi}$ conditions:

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

from BBN

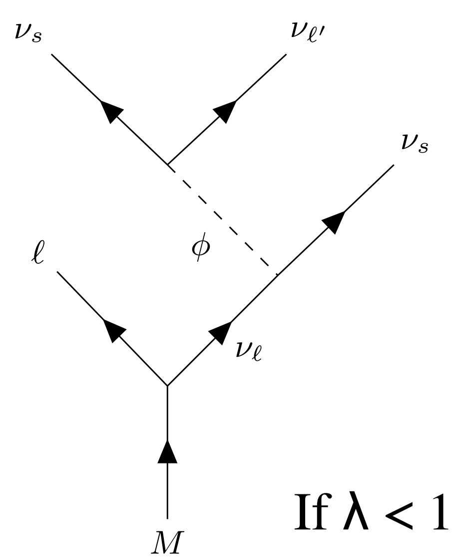
kinematic



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

$\boxed{M \to \nu_s \ell \overline{\nu}_{\ell'} \nu_s}$ 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

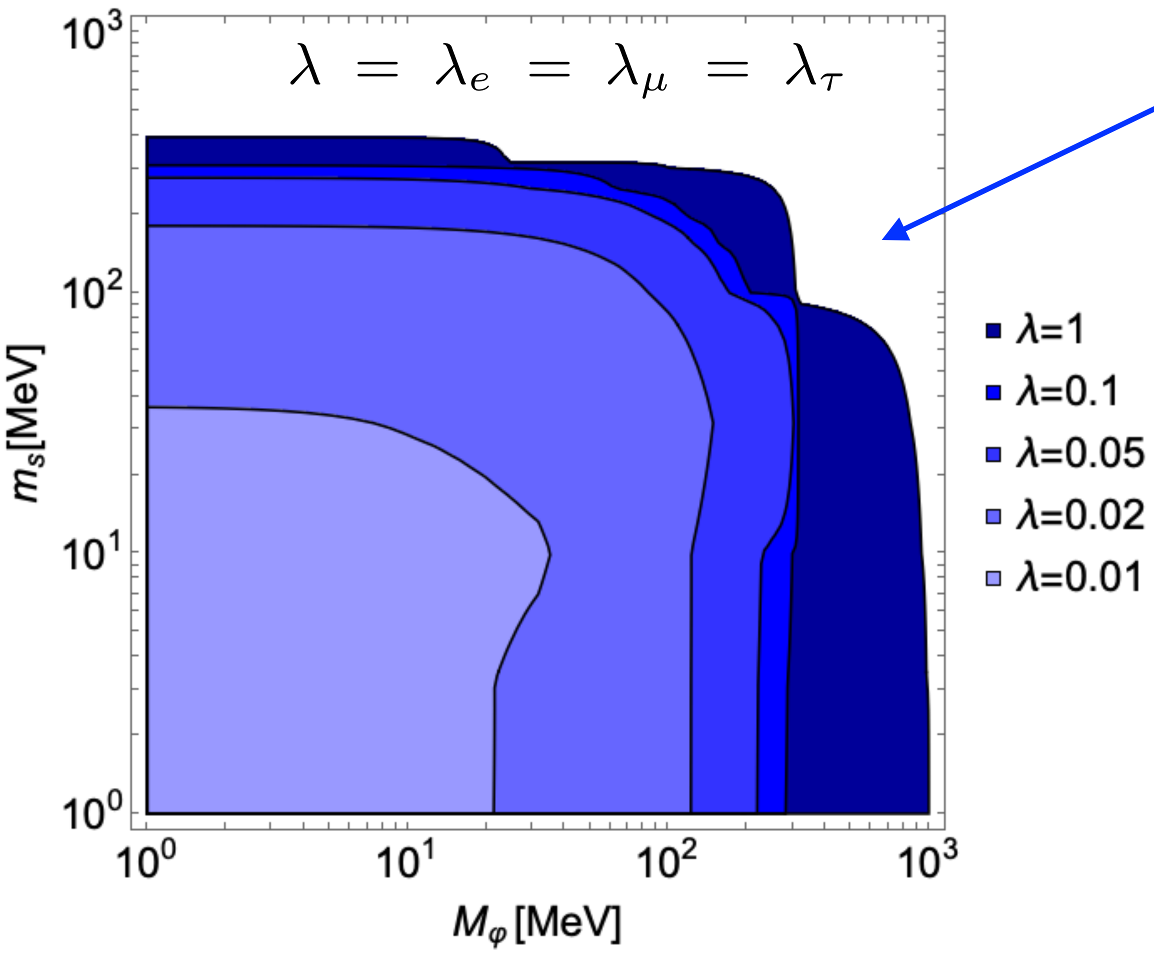
• Laboratory constraints

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

$$K \to \mu + \text{missing energy}$$

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

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

• Laboratory constraints

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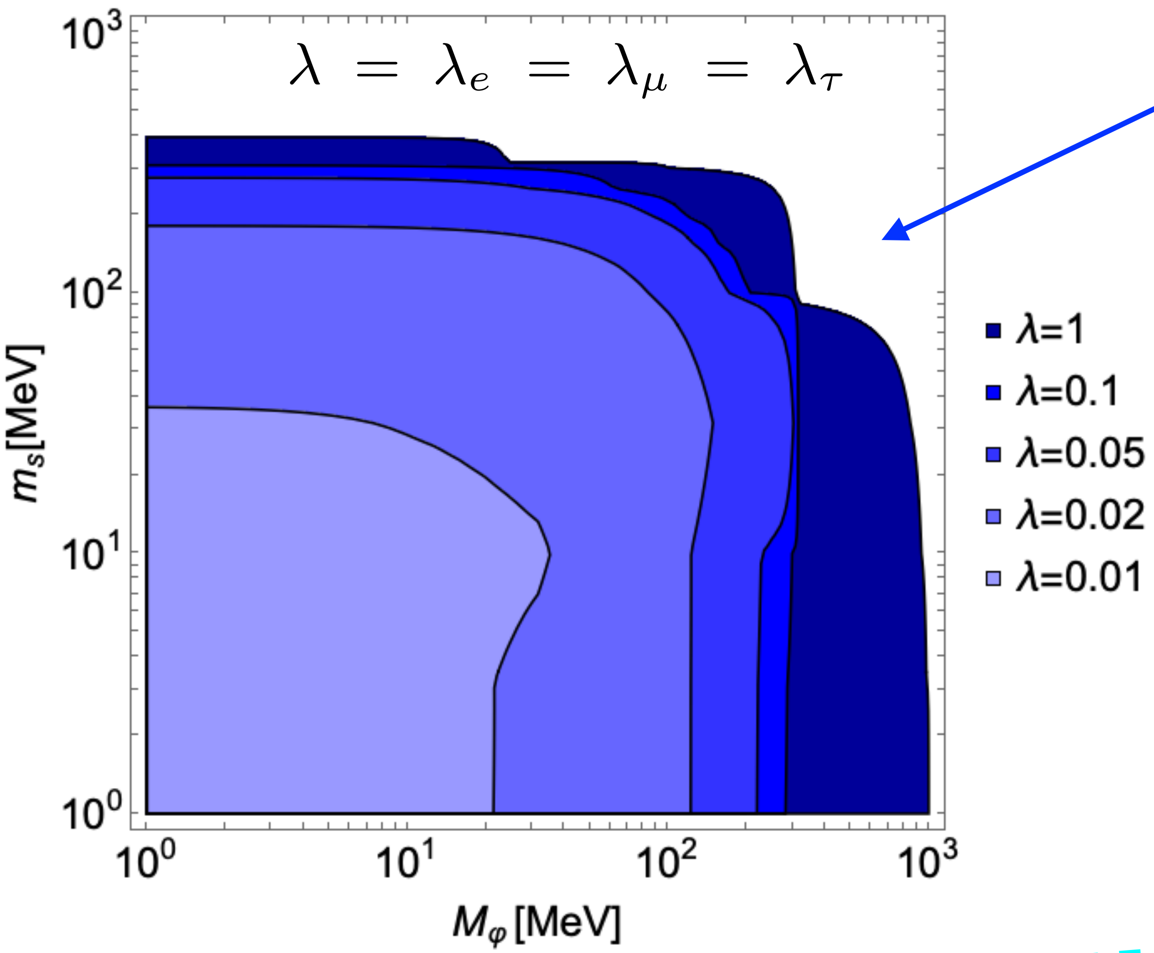

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the correction to Kaon decay is within the experimental bound

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

• Cosmological constraints 1

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

2 conditions for non relativistic species at BBN epoch

newly species are non relativistic

kinetic and chemical equilibrium

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2 conditions for non relativistic species at BBN epoch

newly species are non relativistic

kinetic and chemical equilibrium

This is naturally met if both **Mϕ and ms >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

• Cosmological constraints 1

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

2 conditions for non relativistic species at BBN epoch

newly species are non relativistic

kinetic and chemical equilibrium

$$n\sigma(T) > H(T) \;\Rightarrow\; \textit{equilibrium},$$

$$n\sigma(T) \sim H(T) \sim \frac{T^2}{M_{Pl}} \;\Rightarrow\; \textit{decoupling}$$

• Cosmological constraints 1

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

2 conditions for non relativistic species at BBN epoch

newly species are non relativistic

kinetic and chemical equilibrium

$$n\sigma(T) > H(T) \;\Rightarrow\; equilibrium, \qquad n\sigma(T) \sim H(T) \sim \frac{T^2}{M_{Pl}} \;\Rightarrow\; decoupling$$

Approximative estimate:

$$\boxed{\nu_\alpha \nu_s \to \nu_\alpha \nu_s \text{ and } \nu_s \nu_s \to \nu_\alpha \nu_\alpha:} \longrightarrow \quad T_s \sim \frac{m_s}{\log\left[\frac{M_{\rm Pl} m_s^3 \lambda^4}{M_\varphi^4}\right]} \sim \frac{m_s}{10}$$

$$\sigma \sim \frac{\lambda^4 T^2}{M_\varphi^4}$$

$$\boxed{\varphi\varphi \;\to\; \nu_s \nu_s} \longrightarrow \quad T_\varphi \sim \frac{M_\varphi}{\log\left[\frac{M_\varphi M_{\rm Pl} \lambda^4}{m_\alpha^2}\right]} \sim \frac{M_\varphi}{10}$$

$$\sigma \sim \frac{\lambda^4}{m_\alpha^2}$$

• Cosmological constraints 1

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

2 conditions for non relativistic species at BBN epoch

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Requirement **:** $T_{dec} < T_{BBN}$

satisfied for **M_ϕ and ms >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 $\nu_\alpha \nu_{\alpha'} \to \nu_\beta \nu_{\beta'}$ 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

$$L_s > L_{1987A}$$

$$L_s = \int \frac{d\sigma_{a\to s}}{dE} E dE f(E', r) f(E'', r) dE' dE'' 4\pi r^2 dr$$

$$L_{1987A} \simeq 2\times 10^{52}\ \mathrm{erg/s}$$

For **M_ϕ and m_s >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

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

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

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

σ cross sections for the collision of an ith mass eigenstate and a sterile neutrino with a CNB neutrino

$f(E)$ 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

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)

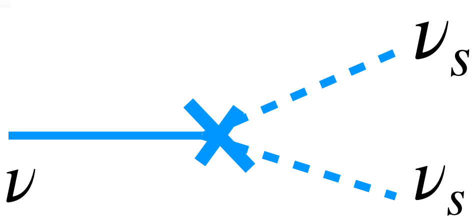
$\Phi_s(z,E)$ flux of sterile neutrino

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

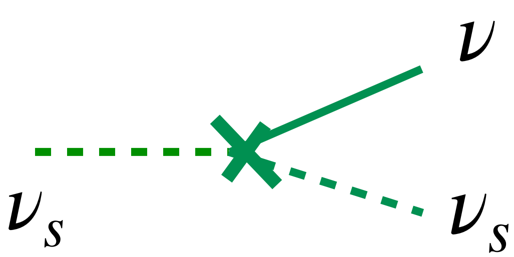
absorption

regeneration

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



absorption



regeneration

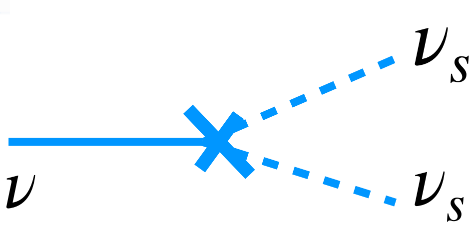
ν Fluxes with SI and Transport Equation

In the generalized multiflavor case:

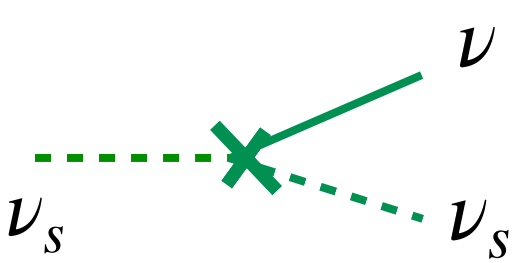
$\Phi_i(z,E)$ flux of active neutrinos per unit energy interval per unit solid angle at a redshift z ($(i=1,2,3)$ mass eigenstate)

$\Phi_s(z,E)$ flux of sterile neutrino $\qquad \frac{d\phi_\nu}{dE d\Omega} = \Phi(0,E)$

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

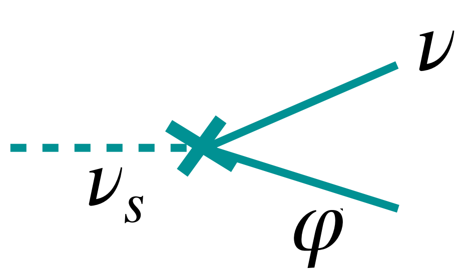


absorption



regeneration

CAVEAT:



possible decay of the sterile neutrinos if $\mathbf{m_S > M_\phi}$

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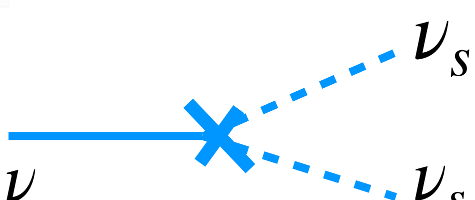
absorption regeneration $\frac{d\phi_\nu}{dE d\Omega} = \Phi(0,E)$

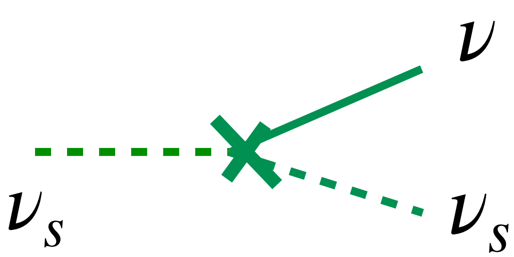
- $H(z)(1+z)\left(\frac{\partial \Phi_i}{\partial z} + \frac{\partial \Phi_i}{\partial E}\frac{E}{1+z}\right) = n(z)\sigma_i(E)\Phi_i - \int dE' \Phi_s(E')\frac{d\sigma_{sa}}{dE}(E' \to E) n(z) - \rho(z)(1+z) f(E)\xi_i$

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

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



absorption



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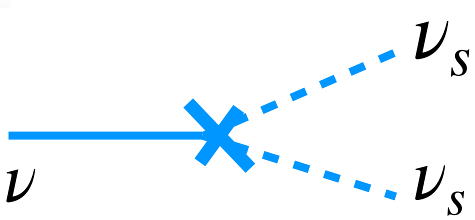
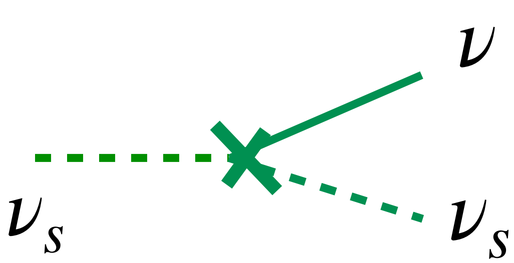


absorption



regeneration

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%

ν Fluxes with SI and Transport Equation

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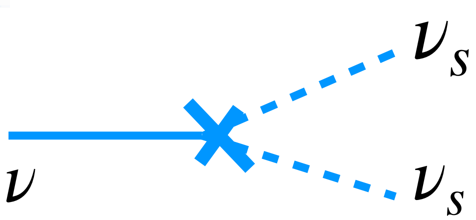
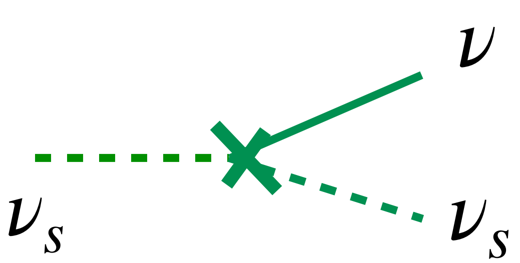
$$\cancel{-\int dE'\,\Phi_s(E')\frac{d\sigma_{ss}}{dE}(E'\to E)\,n(z)}$$



absorption



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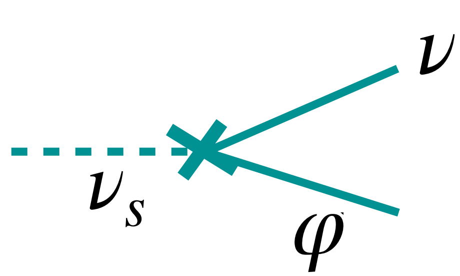
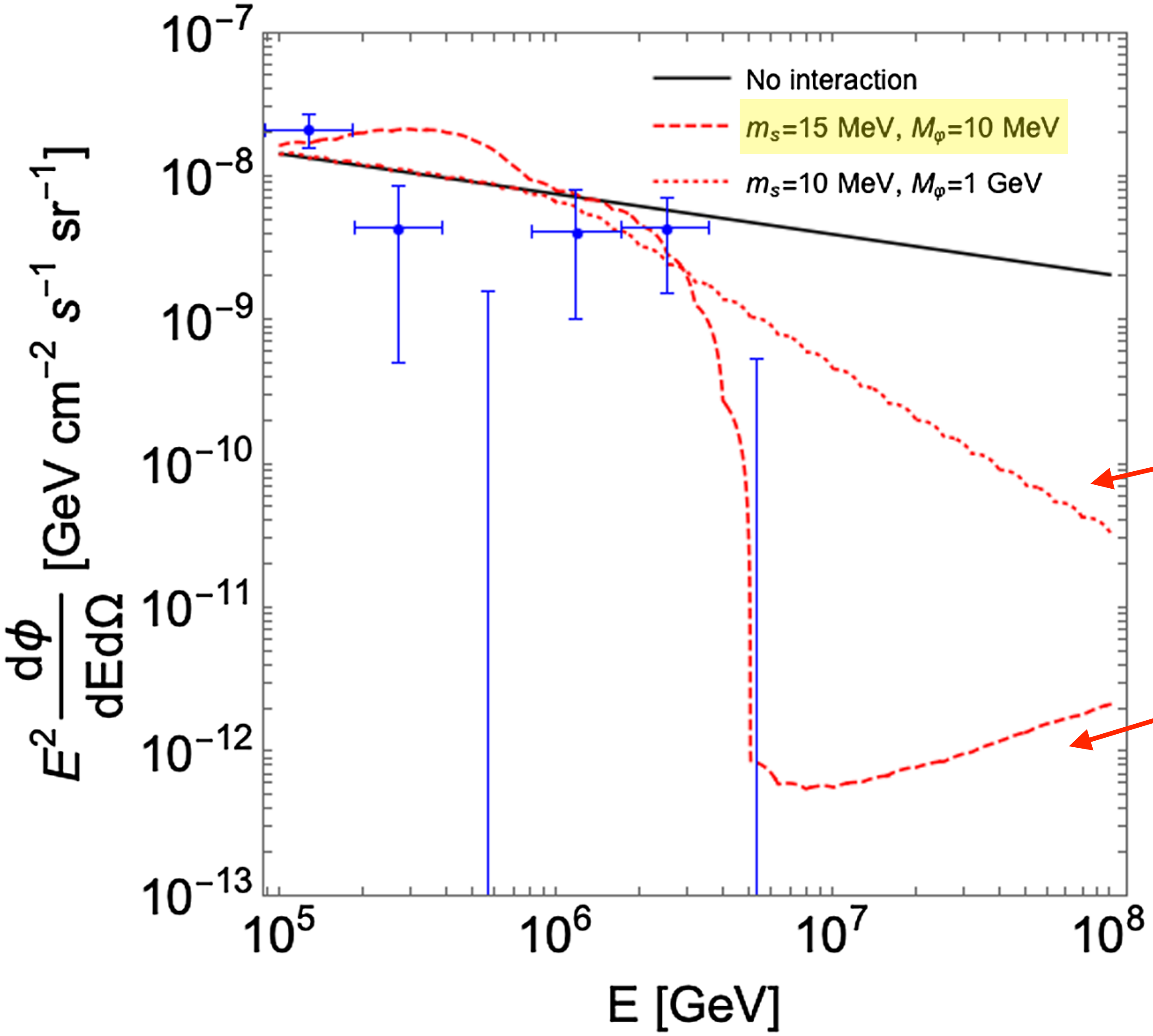


the results of the first order perturbation theory may cause small but non-negligible changes to the spectrum

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_φ=1 GeV

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

m_s=15 MeV, M_φ=10 MeV

the constraints from mesons decay are irrelevant

⇨ also lower masses for Mφ

IceCube HESE data

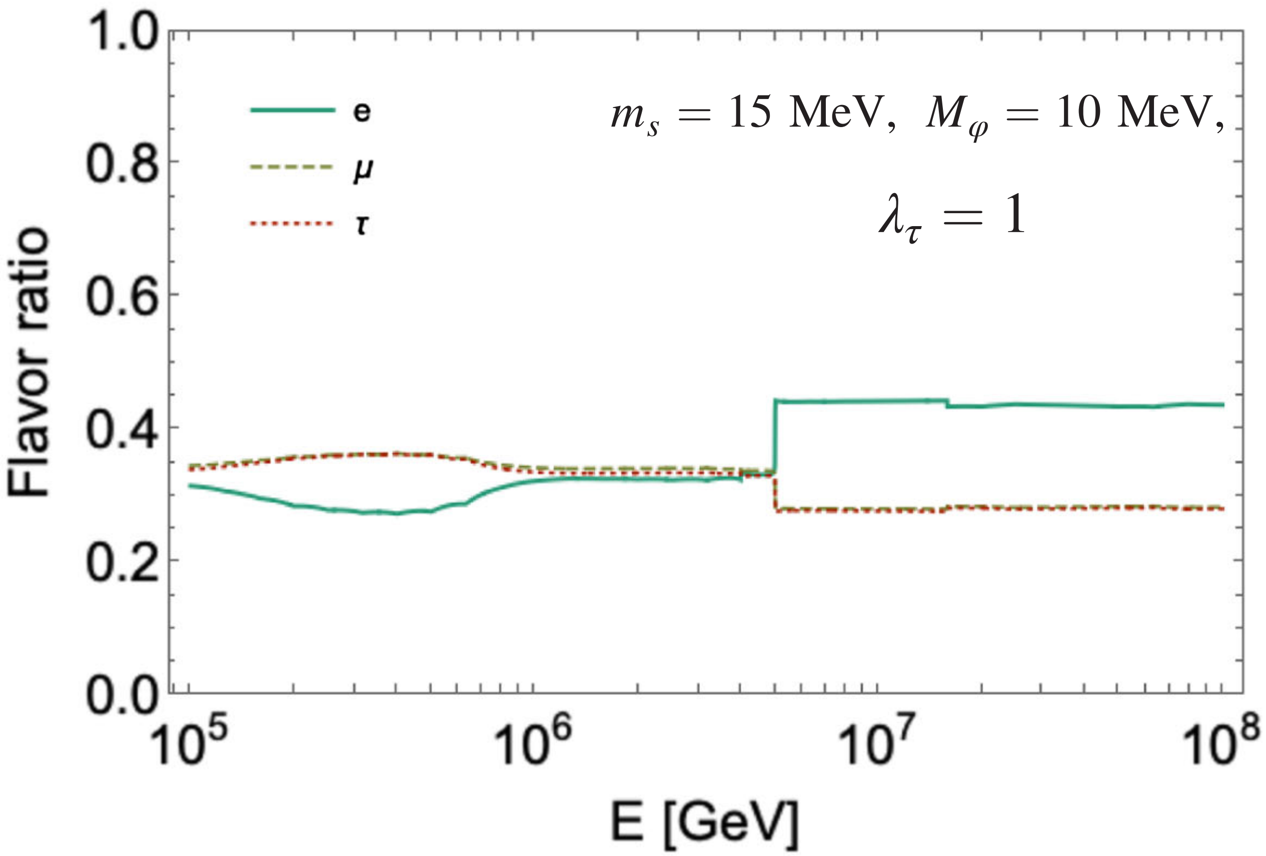
The new interaction causes a cutoff-like feature in the spectrum in the range between 1 PeV and 10 PeV

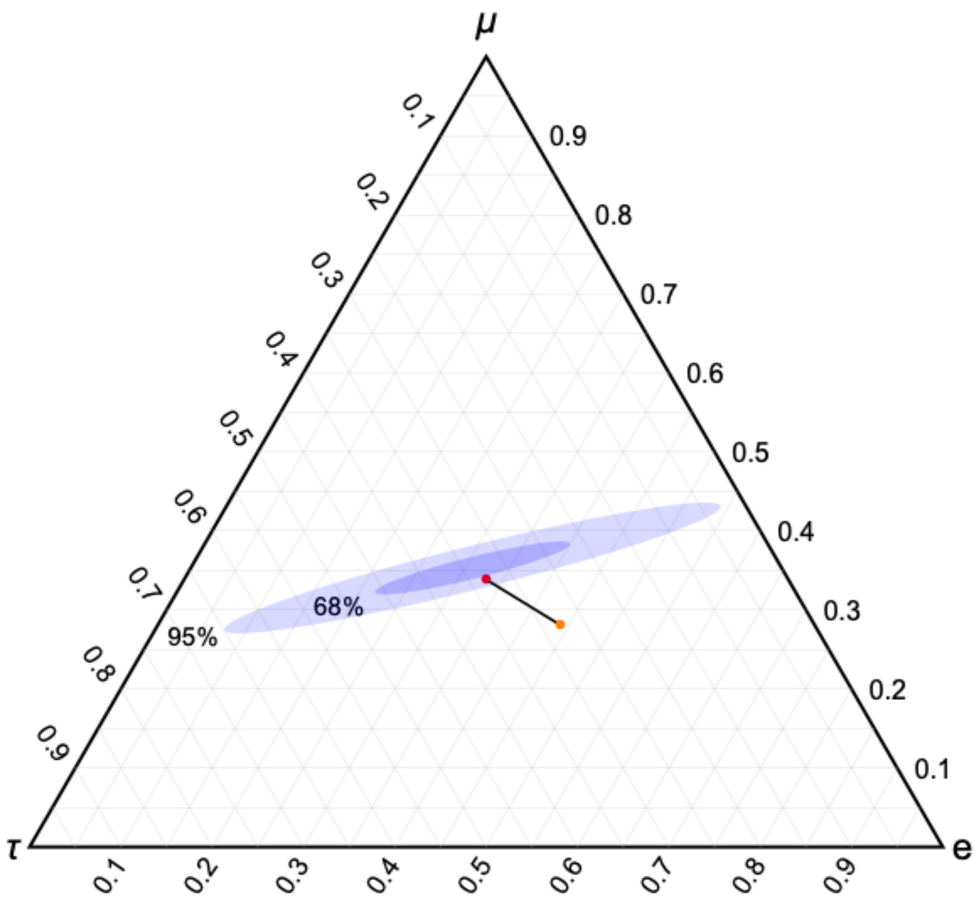
Fiorillo, Miele, Morisi, ***Saviano*** *2020,* ***PhysRevD 102.083014****, arXiv:2007.07866*

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 at 10^5 GeV

Flavor at 10^8 GeV

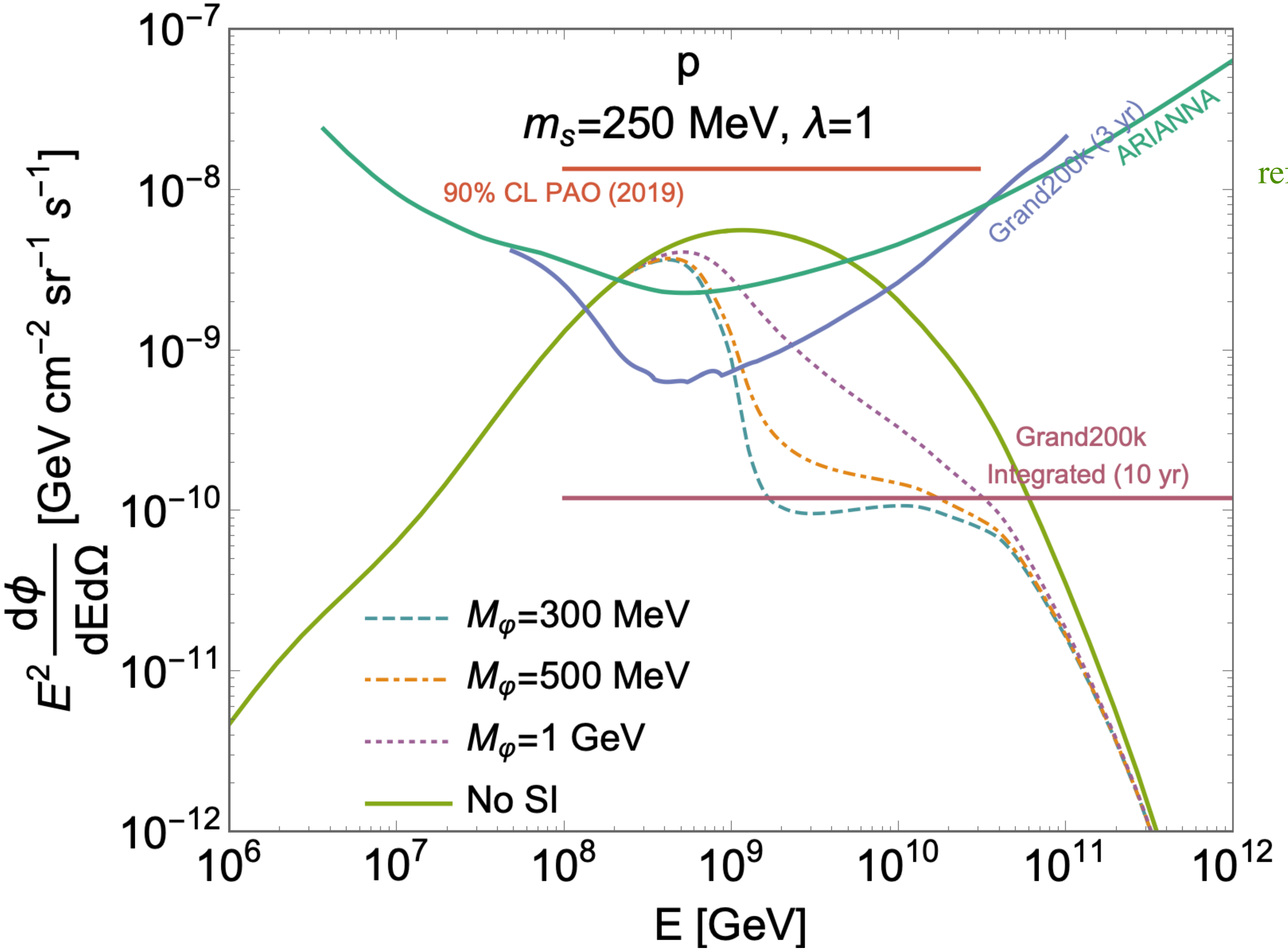
flavor ratio at the source (1 : 2 : 0)

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

forecasted sensitivity of IceCube-Gen2

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

Results and detection chance for Cosmogenic Spectrum (1)



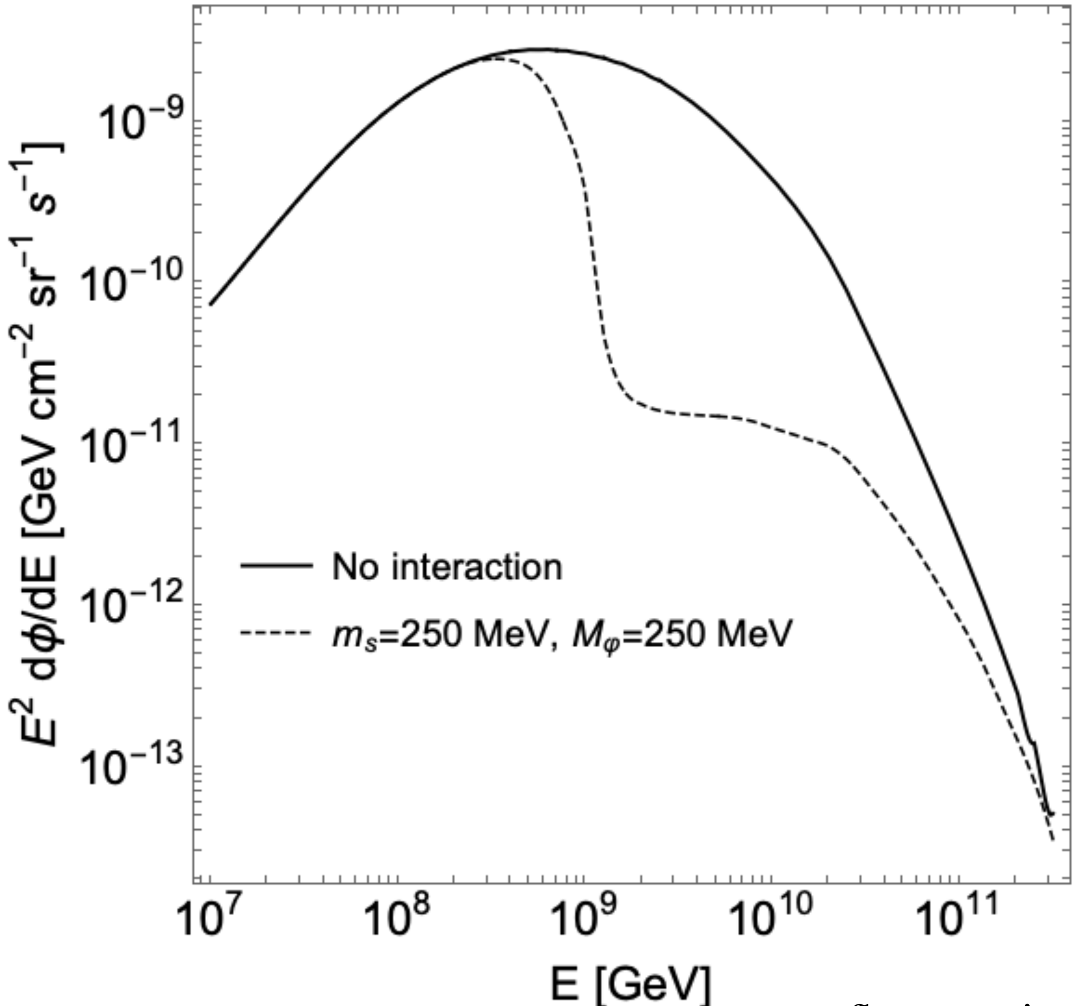
proton cosmic rays

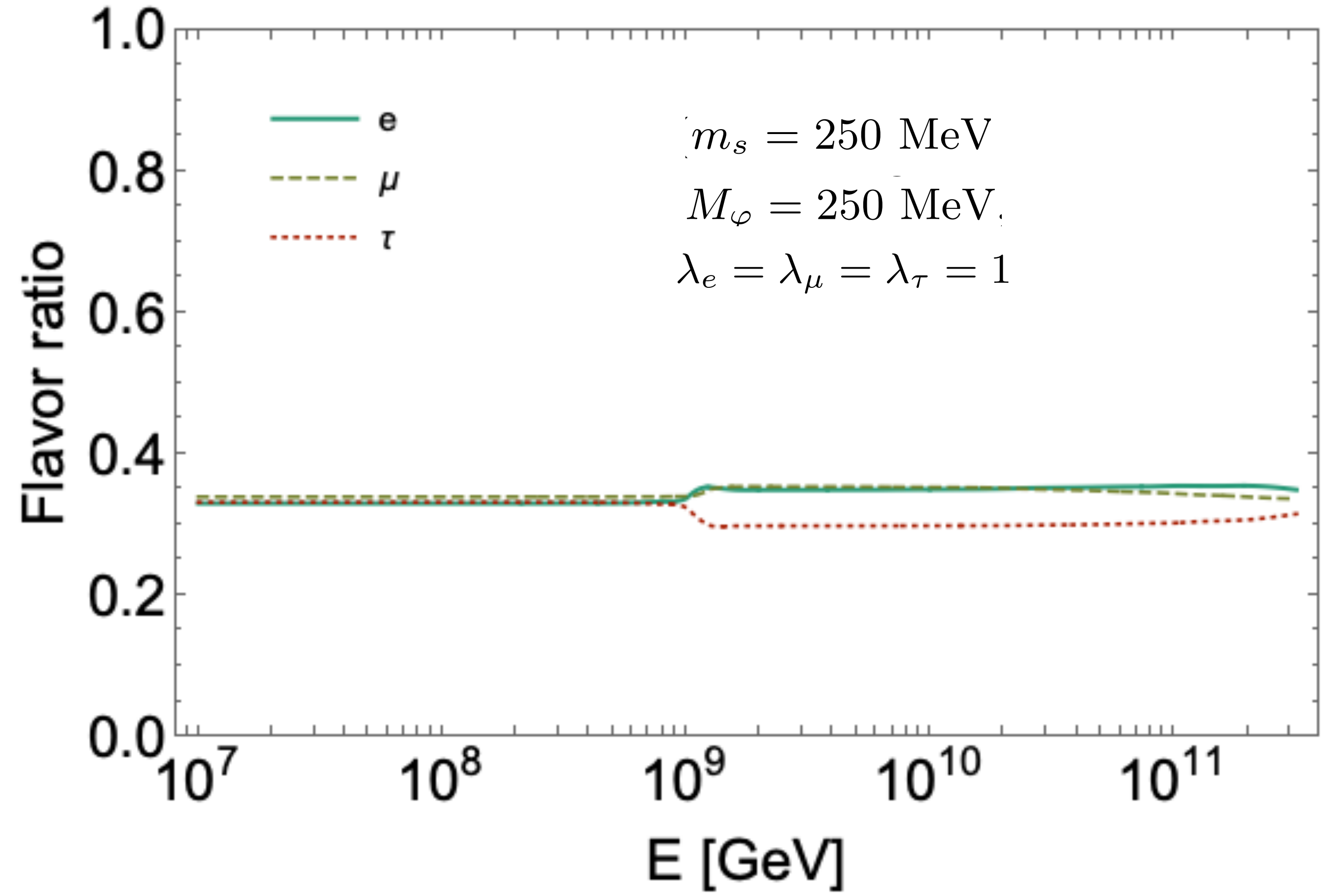
reference spectrum given in *Ahlers & Halzen 2012*

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

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

Results and detection chance for Cosmogenic Spectrum (2)





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

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

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

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.

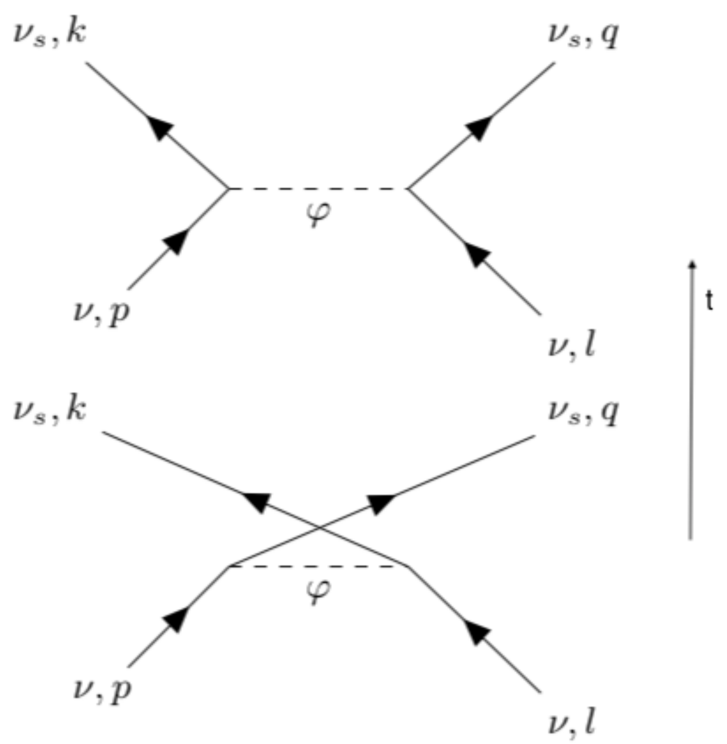
Another interesting phenomenological aspect of active-sterile secret interactions is represented by the changing in the flavor ratio as a function of neutrino energy. This effect could be interesting for next generation of neutrino telescopes.


γ
p
SHOCK WAVE
π⁰
e
e
e
π±
μ
e
ν_μ
ν_e
γ
ν_μ
Thank you

Backup slides

Cross sections

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



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

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

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

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

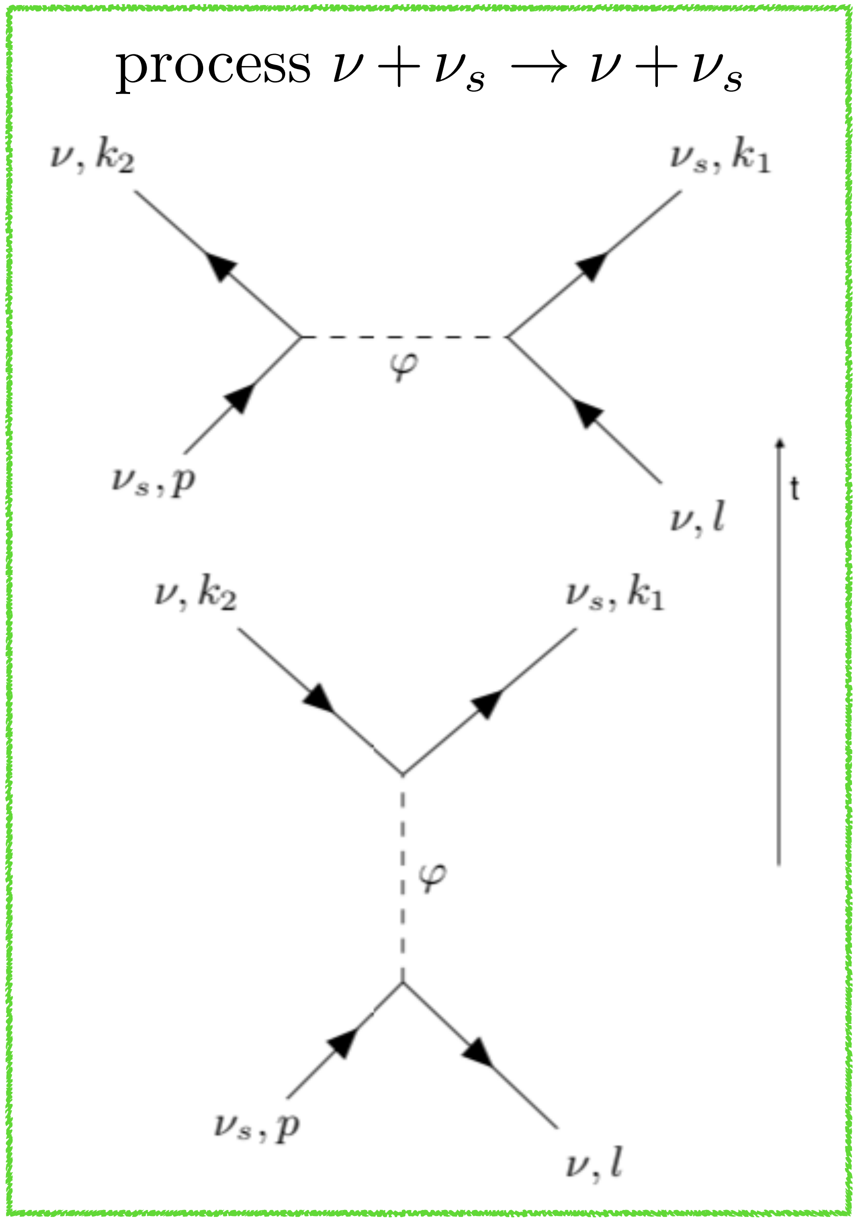
$$I = \sqrt{\frac{2m^4 + s^2 - 4sm^2}{2}}$$

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:

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

Cross sections in multiflavor case

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

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

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

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 E_s:

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

E is the energy of the incident cosmogenic active neutrino

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 $M_\phi > m_S$.

(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:

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

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

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

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 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').

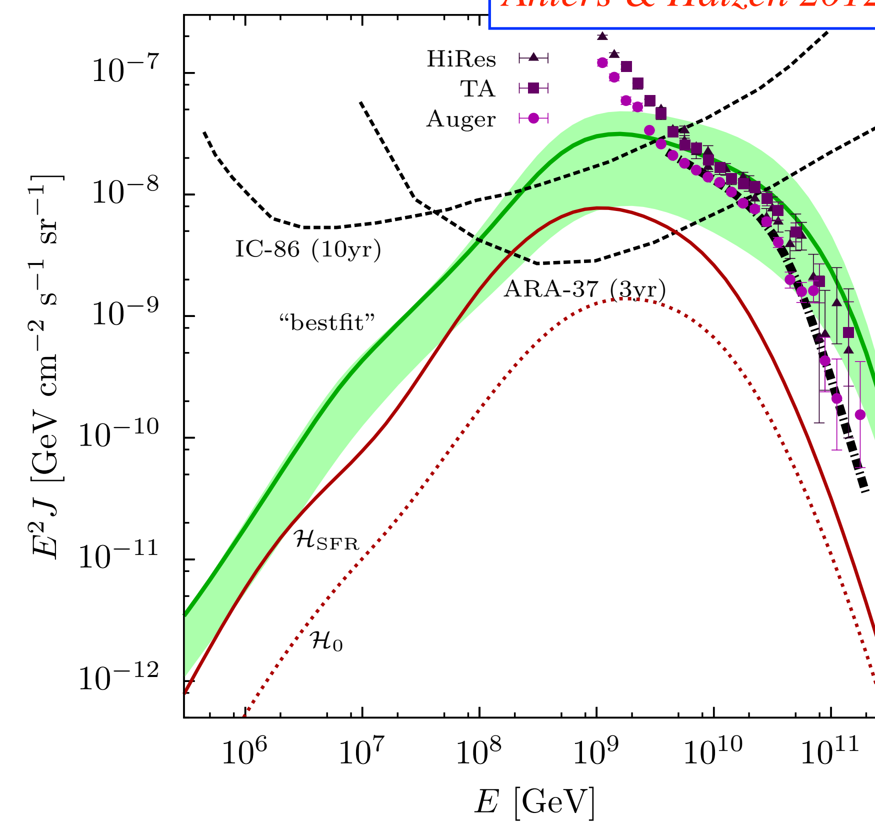
Using as a reference the spectrum proposed in *Ahlers & Halzen 2012*, which constitutes a lower bound for the cosmogenic neutrino spectrum,

We adopt the following **ansatz for F**

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

where ρ(z) is the Star Forming Rate
$$\begin{cases} (1+z)^{3.4} & z \leq 1; \\ N_1(1+z)^{-0.3} & 1 < z \leq 4; \\ N_1 N_4 (1+z)^{-3.5} & z > 4, \end{cases}$$

Ahlers & Halzen 2012



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

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

absorption regeneration

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

$\boxed{\text{Regeneration term:}}$

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 $\sim 10\%$)*

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

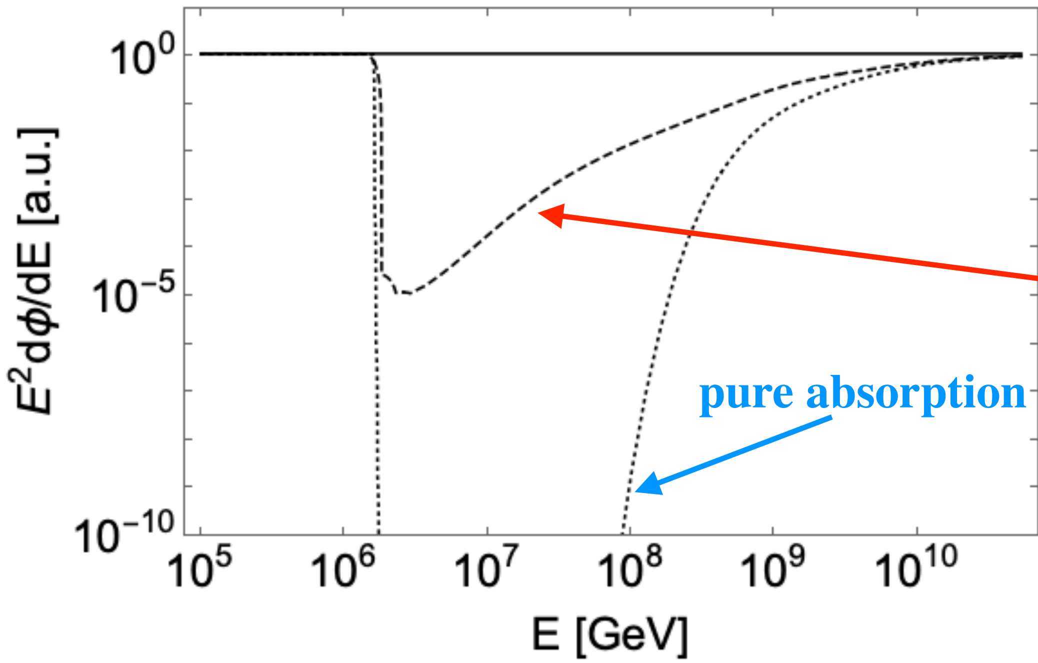
z > 0.1, the produced neutrinos are severely suppressed due to the absorption on the CNB

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:

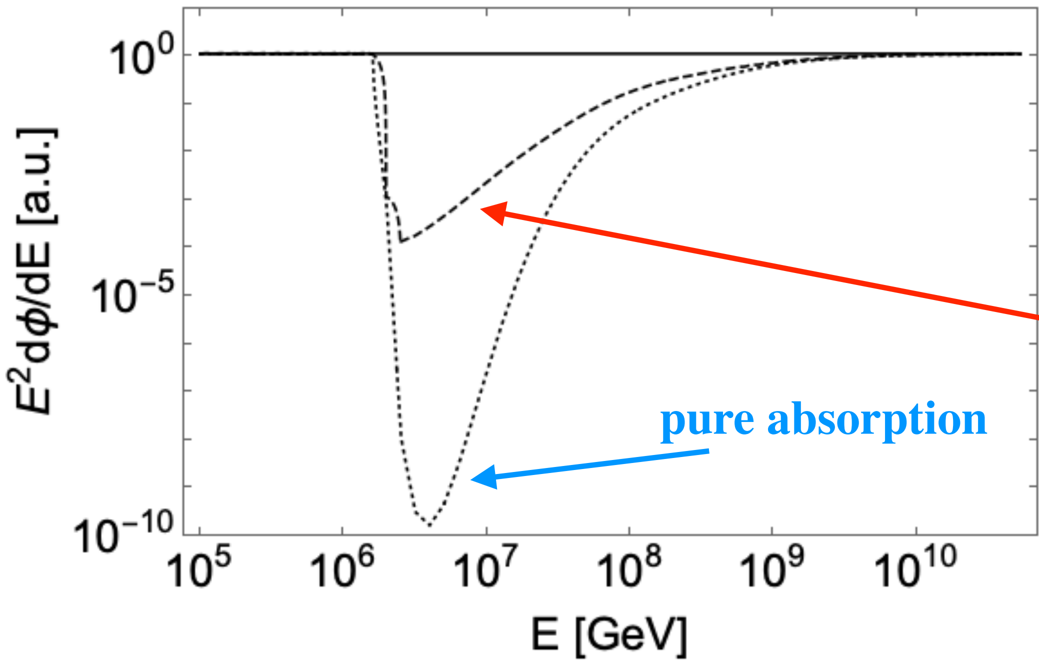
Expected spectra at Earth for a generic source at two fixed redshift values z with an E^{-2} reference spectrum.



z = 0.1

both absorption and regeneration

reference unabsorbed spectrum

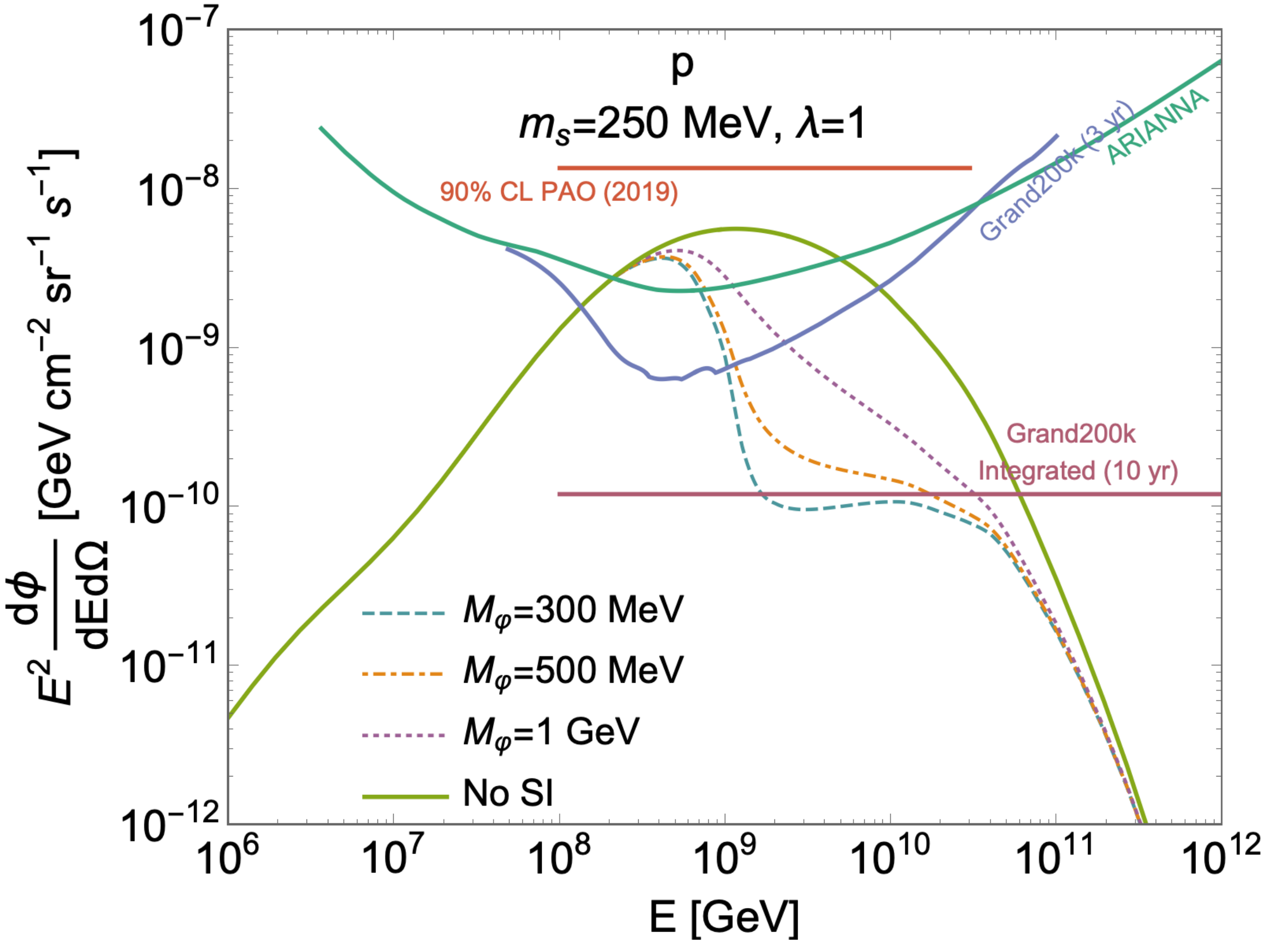


z = 0.01

both absorption and regeneration

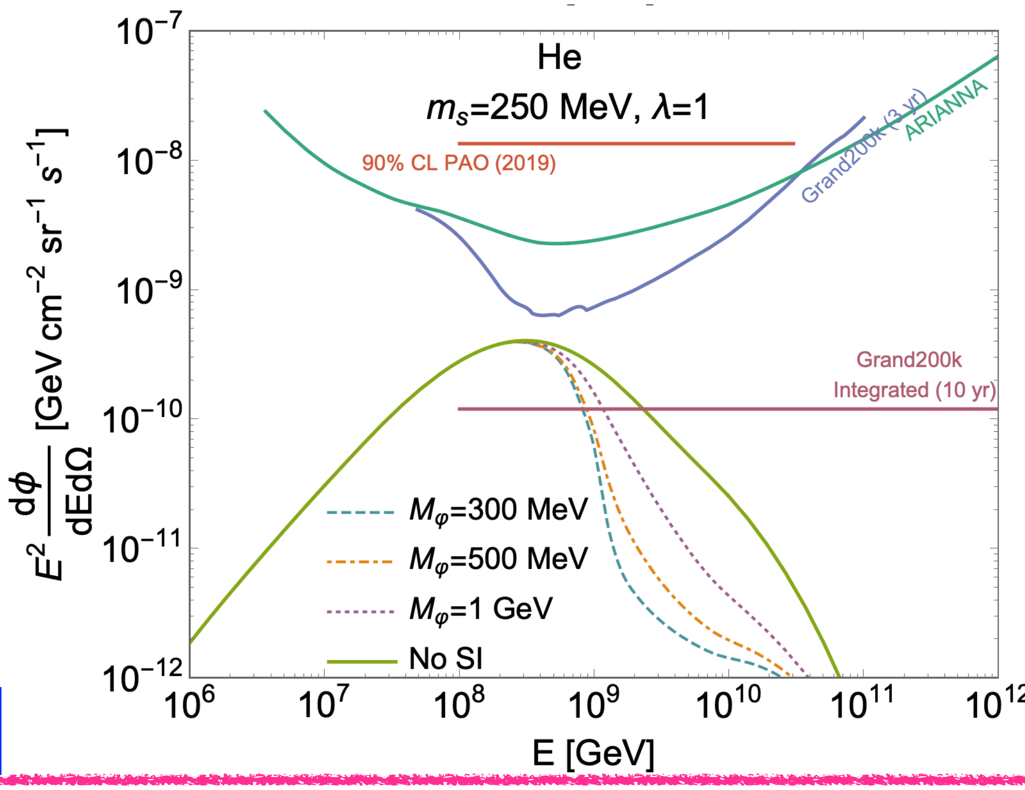
The effects of regeneration are more important for larger redshifts of the source and can drastically change the results.

Results and detection chance for Cosmogenic Spectrum (1)



proton cosmic rays

helium cosmic rays



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