# Probing Neutrino Dark Energy with Extremely High-Energy Cosmic Neutrinos

(astro-ph/0606316, accepted at JCAP, A. Ringwald, L.Schrempp)

Lily Schrempp

DESY Hamburg

# Outline

1. Motivation
2. The Mass Varying Neutrino (MaVaN) Scenario
3. Signatures of Ultra-Energetic MaVaNs in the Sky?

## Neutrino Dark Energy (Mass Varying Neutrinos)

[Fardon,Nelson,Weiner '03]

Idea of varying neutrino masses in other contexts

[Kawasaki,Murayama,Yanagida '92,Stephenson et al '97]

- Attractive scalar force between Big Bang relic neutrinos (the analog of the Cosmic Microwave Background (CMB) photons)$\rightarrow$ smooth background, can form a negative pressure fluid
- $\rightarrow$ acts as a form of Dark Energy $\rightarrow$ accelerated expansion
- $\rightarrow$ neutrino mass $m_\nu$ becomes a function of neutrino energy density $\rho_\nu(z)$ which evolves on comological timescales (here parametrized in terms of cosmic redshift $z$)

$\rightarrow$ Neutrino mass not constant but promoted to a dynamical quantity $m_\nu(z)$!

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# The non-SM neutrino interaction mediated by a scalar field

A concrete realization as preferred in the literature which implemets the 'seesaw mechanism'

$\rightarrow$ indirect coupling of neutrinos to the mediator of the scalar force, $\rightarrow$ light active neutrino masses

[FNW '03,FNW '05,Peccei '04,Barbieri,Hall,Oliver,Strumia '04,Takahashi,Tanimoto '05/'06...]

## Introduce the 'Dark Sector' ($\rightarrow$ Standard Model singlets)

- A light scalar field, the acceleron $\mathcal{A}$, where $H \sim 10^{-33}\mathrm{eV} \ll m_{\mathcal{A}} < 10^{-4}\,\mathrm{eV}$
- A scalar potential $V_0(\mathcal{A})$
- Right-handed/sterile neutrinos N
- Yukawa couplings $\kappa\ \mathcal{A}$ N N$\rightarrow M_N(\mathcal{A}) = \kappa\mathcal{A}$

## 'Our Sector' contains:

- Active neutrinos $\nu$
- The Higgs field H
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# 'Mini-Seesaw'-MaVaN model

## Light active neutrino masses $m_\nu$

- Scalar force of the 'Dark Sector' transmitted to the active neutrino sector via the seesaw mechanism
- Low energy effective theory for $M_N(\mathcal{A}) \gg m_D$ (after integrating out the Higgs and the $N$) $\rightarrow \mathcal{L} \supset \frac{m_D^2}{M_N(\mathcal{A})}\nu^2 + h.c. + V_0(\mathcal{A})$

[seesaw:Yanagida '79,Gell-Mann,Ramond '79,Minkowski' 80,Mohapatra,Senjanovic' 80]

**Active neutrinos interact through a non-SM scalar force!**

VEV of the acceleron, $\mathcal{A}$, generates light neutrino masses

$$m_\nu(\mathcal{A}) = \frac{m_D^2}{M_N(\mathcal{A})}$$

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# Dynamics of the MaVaN Scenario

Complex interplay between the neutrinos and the acceleron:

- Neutrino energy density $\rho_\nu$ is a function of neutrino mass $m_\nu(\mathcal{A})$ $\longrightarrow \rho_\nu(m_\nu(\mathcal{A}))$
- $\longrightarrow \rho_\nu(m_\nu(\mathcal{A}))$ can stabilize $\mathcal{A}$ by contributing to its effective potential $V_{\text{eff}}(\mathcal{A}) = \rho_\nu(m_\nu(\mathcal{A})) + V_0(\mathcal{A})$, the total energy density of the coupled system
- Take cosmic expansion into account: $\rho_\nu\Big(z, m_\nu(\mathcal{A})\Big) \sim (1+z)^3$
- $V_{\text{eff}}\Big(\rho_\nu(z, m(\mathcal{A}))\Big)$ evolves on cosmological time scales!
- For a homogeneous configuration, in the adiabatic limit $H^2 \ll V''_{\text{eff}}(\mathcal{A}) = m^2_{\mathcal{A}}$, the equilibrium value $\mathcal{A}$ tracks the minimum of $V_{\text{eff}}(\mathcal{A}, z)$

Crucial effect:

$\mathcal{A}$ condensate, $\mathcal{A}(z)$, varies on cosmological time scales (i.e. slowly)!

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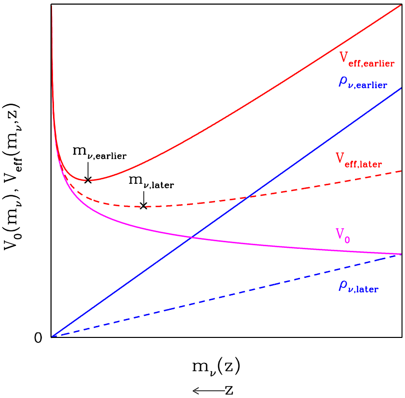
- $\rightarrow \frac{\partial V_{\rm eff}(\mathcal{A})}{\partial \mathcal{A}} = \frac{\partial m_\nu}{\partial \mathcal{A}} \frac{\partial V_{\rm eff}(m_\nu)}{\partial m_\nu} = 0$
- Neutrino mass variation determined by $V'_{\rm eff}(m_\nu, z) = 0 = \rho'(m_\nu, z) + V'_0(m_\nu)$
- $\rightarrow$ in the non-relativistic limit, $\rho_\nu(z) = m_\nu n_\nu(z)$ ($n_\nu(z) \equiv$ neutrino number density)
- Neutrino acceleron fluid has dynamical Eq. of State

$$\omega(z) + 1 = -\frac{m_\nu(z) V'_0(m_\nu)}{V_{\rm eff}(m_\nu(z))}$$



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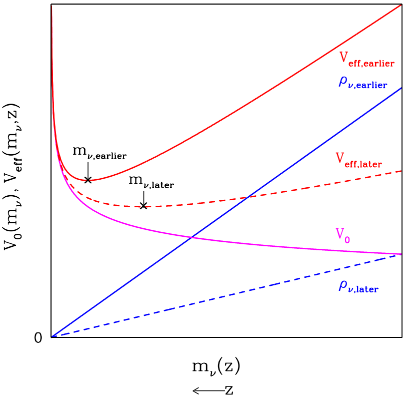


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# Stability of the MaVaN Scenario

## Possible Instabilities?

- Phenomenon similar to gravitational instabilities of cold dark matter possible for MaVaNs?
- Attractive scalar force mediated by the acceleron $\mathcal{A}$
- For relativistic neutrinos, random motions prevent collapse
- However, when neutrinos turn non-relativistic formation of ‘neutrino nuggets’?

Note: Outcome of instability inherently non-linear process

... but if nuggets really form, neutrino fluid redshifts similar to cold dark matter with $\omega \sim 0 \not\approx -1 \rightarrow$ no acceleration

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# Stability of the MaVaN Scenario

## Ways out of catastrophic instability!

- Relativistic neutrino responsible for dark energy $\longrightarrow$ $m_{\nu_1} \leq T_{\nu_0} = 1.69 \times 10^{-4}$ eV

[Afshordi,Zaldarriaga,Kohri '05, Fardon,Nelson,Weiner '05]

- Certain constraints on the scalar acceleron potential $V_0(\mathcal{A})$ can lead to stable MaVaN models also in the highly-non-relativistic regime

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# A Hybrid Model of MaVaNs

## Acceleration mechanism known from inflation

- Two light scalar fields $\rightarrow$ one is kept in a metastable minimum due to the large value of the other
- Energy density stored in the false minimum drives accelerated expansion

[Linde '93]

## Supersymmetrization of MaVaN model naturally sets the stage!

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- Scalar partner $\mathcal{N}$ of lightest neutrino kept in false minimum until $\mathcal{A} < \mathcal{A}_{\rm crit}$
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## MaVaN mass evolution with redshift, $m_\nu(z)$

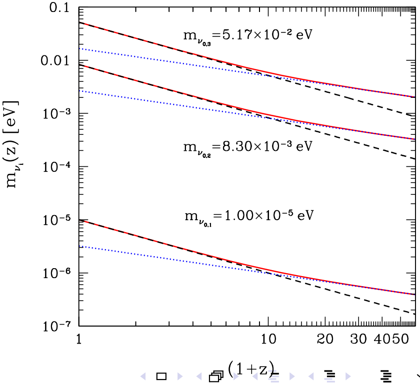
- Hybrid Model$\to$ Microscopic origin for quadratic acceleron potential $V_0(\mathcal{A}) \sim A^2 \to V_0(m_\nu) \sim m_\nu^{-2}$

**$V_0$ fixes mass evolution $m_\nu(z)$!**

Recall:
$V'_{\rm eff}(m_\nu) = 0 = \rho'(m_\nu) + V'_0(m_\nu)$

- Mass behaviour in the low-redshift regime approximated by a simple power law $m_{\nu_i} \approx m_{\nu_{0,i}} (1+z)^{-1}$, $i = 1, 2, 3$

$\to$ MaVaN phenomenology



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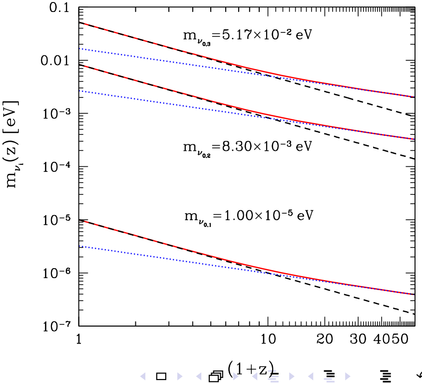
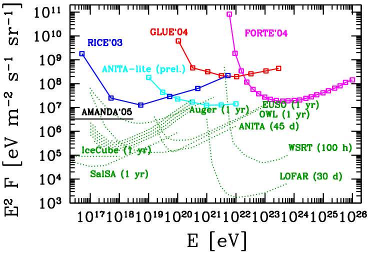


# Extremely High Energy Cosmic Neutrinos (EHEC$\nu$'s)

## EHEC$\nu$'s in reach!

- Existing and planned observatories have a combined sensitivity of
  $10^7\,\mathrm{GeV} < E < 10^{17}\,\mathrm{GeV}$
- Appreciable event samples
- Fluxes to be detected at earth contain valuable information on particle physics and cosmology




## Absorption of EHEC$\nu$'s by the Cosmic $\nu$ Background (C$\nu$B)

Most direct evidence for the existence of the C$\nu$B so far $\rightarrow$ confirmation of standard cosmology back to $\approx$ 1 s after the Big Bang!

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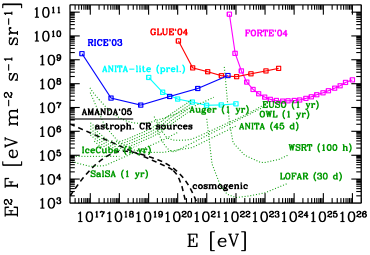


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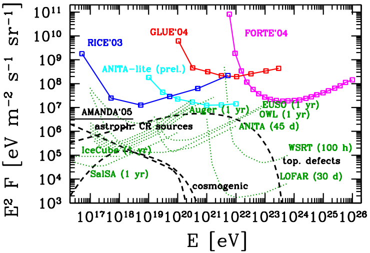


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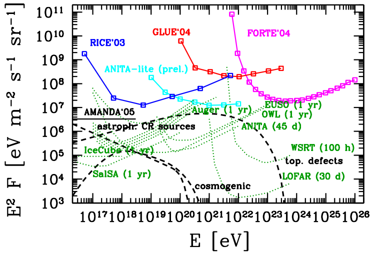


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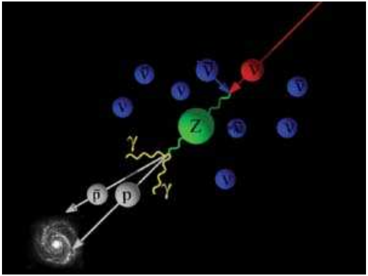
# Signatures of ultra-energetic MaVaNs in the sky?

## The process $\nu_{\mathrm{EHEC}}\,\bar{\nu}_{\mathrm{relic}} \rightarrow Z$

- At the resonance energies $E_{\nu_i}^{res} = \frac{M_Z^2}{2m_{\nu_i}} \simeq 4 \times 10^{21}\ \mathrm{eV}\left(\frac{eV}{m_{\nu_i}}\right)$ EHEC$\nu$'s can annihilate with relic $\bar{\nu}_i$'s (and vice versa) into $Z$ bosons
- Exceptional loss of transparency of the C$\nu$B for EHEC$\nu$'s $\rightarrow$ absorption dips in the EHEC$\nu$ spectra
- Annihilation process sensitive to $m_{\nu_i}$ and possible time variation $m_{\nu_i}(z)$




Relic Neutrino Absorption Spectroscopy as a Test of Neutrino Dark Energy (MaVaNs)!

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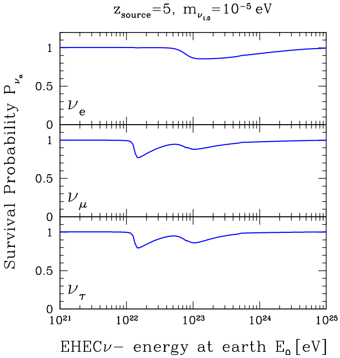


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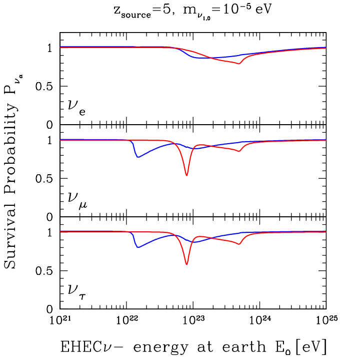



**Relic Neutrino Absorption Spectroscopy as a Test of Neutrino Dark Energy (MaVaNs)!**

# Relic Neutrino Absorption Spectroscopy

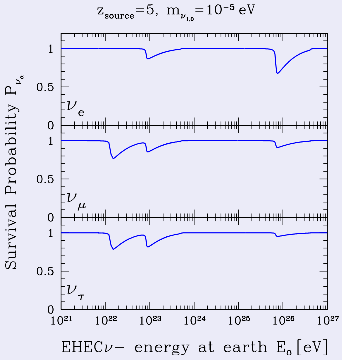
## Energy loss due to cosmic redshift!

Source injects EHEC$\nu$ at $z_s > 0$ with energy $E \rightarrow$
EHEC$\nu$ arrives at earth at $z = 0$ with energy $E_0 = \frac{E}{1+z_s} < E$

## Interpretation of absorption dips for $m_\nu = \text{const.}$

As a first step, assume the relic neutrinos to be at rest, $p_{relic} = 0$, to disentangle different influences on the Survival Probability

- Why are the dips in the Survival Probability not sharply peaked at $E \sim E^{res}_{\nu_i}$?
- Consider effect of cosmic redshift $\sim (1+z)^{-1}$ on $E \rightarrow$ Survival Probability $P_{\nu_\alpha}$ reduced in the interval $\frac{E^{res}_{\nu_i}}{1+z_s} \leq E_0 \leq E^{res}_{\nu_i} \rightarrow$ redshift distortion



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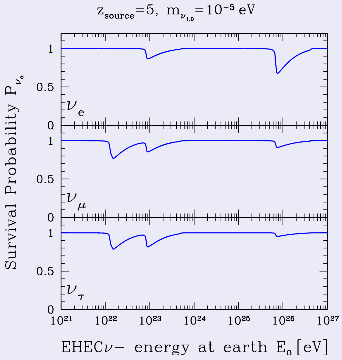

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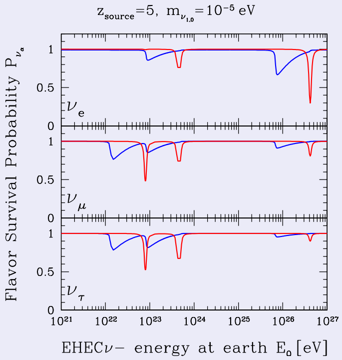
1) Recall: $m_{\nu_i}(z) = m_{\nu_{0,i}}\,(1+z)^{-1}$ in the low redshift regime
2) Recall: $E^{res}_{\nu_i} = \frac{M_Z^2}{2m_{\nu_i}} \rightarrow$ employ 1)

- $\rightarrow E^{res}_{\nu_i}(z) = E^{res}_{\nu_{0,i}}\,(1+z)$
- Mass induced $z$ dependence compensates the effect of cosmic redshift $\rightarrow$ all annihilations at $0 \leq z \leq z_s$ contribute to the absorption peak at $E^{res}_{\nu_{0,i}} = \frac{E^{res}_{\nu_i}(z)}{1+z}$



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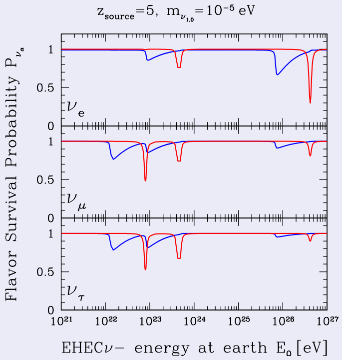

# Relic Neutrino Absorption Spectroscopy

## Energy loss due to cosmic redshift!

Source injects EHEC$\nu$ at $z_s > 0$ with energy $E \rightarrow$
EHEC$\nu$ arrives at earth at $z = 0$ with energy $E_0 = \frac{E}{1+z_s} < E$

## Interpretation of absorption dips for $m_\nu(z) \neq$ const.

? How does the mass variation $m_\nu(z)$ affect the absorption features?

1) Recall: $m_{\nu_i}(z) = m_{\nu_{0,i}}\,(1+z)^{-1}$ in the low redshift regime
2) Recall: $E^{res}_{\nu_i} = \frac{M_Z^2}{2m_{\nu_i}} \rightarrow$ employ 1)

- $\rightarrow E^{res}_{\nu_i}(z) = E^{res}_{\nu_{0,i}}\,(1+z)$
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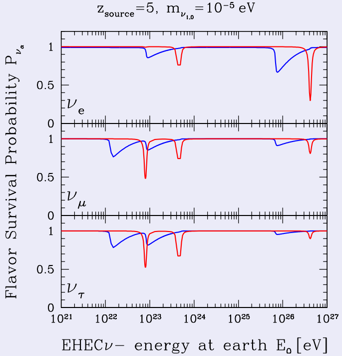

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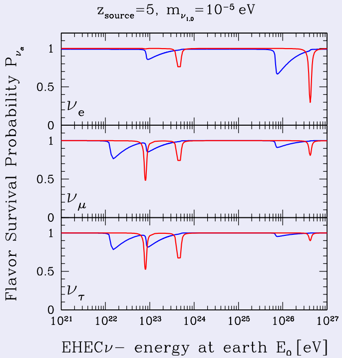

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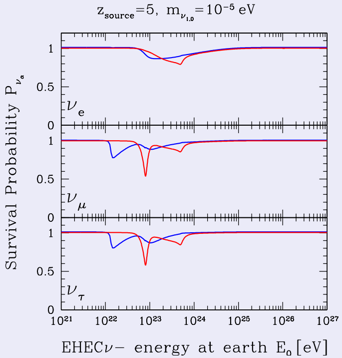
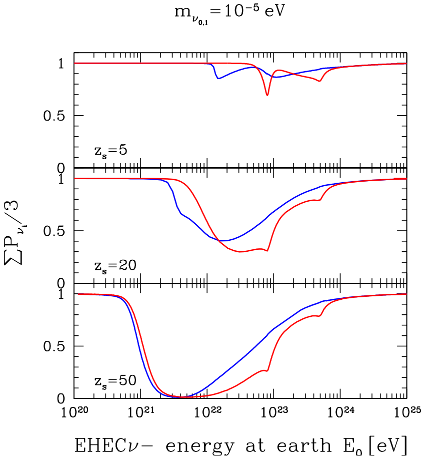


# Relic Neutrino Absorption Spectroscopy

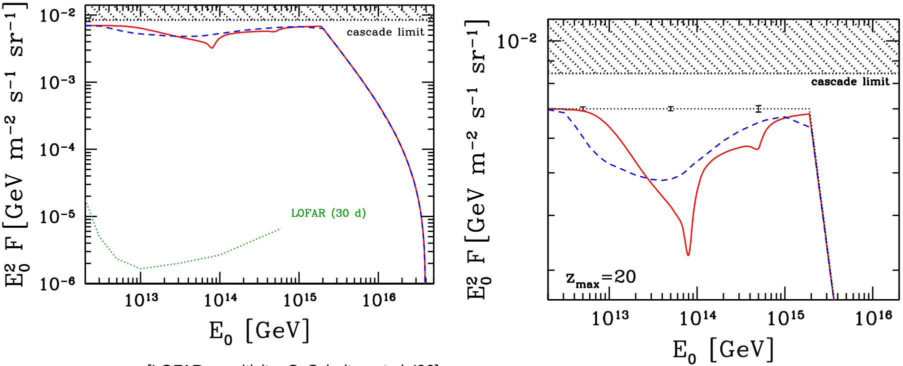
Sum of Survival Probabilites $\frac{1}{3}\sum P_{\nu_i}$

- What happens if the EHEC$\nu$ source is farther away ($\rightarrow z_s$ larger)?
- $\rightarrow$ Dips get deeper and thermal broadening is more pronounced
- MaVaN absorption features (red) clearly shifted to higher energies
- MaVaN absorption features (red) clearly deeper$\rightarrow$ better to detect



# Relic Neutrino Absorption Spectroscopy

## Flavor Summed EHEC$\nu$ Flux $\sum F_{\nu_\alpha}$ to be observed at Earth for an Astrophysical Source at $z_s = 20$




[LOFAR sensitivity: O. Scholten et al. '06]

## Outlook

Relic Neutrino Absorption Spectroscopy as a Test of Neutrino Dark Energy (MaVaNs) within the next decade?!

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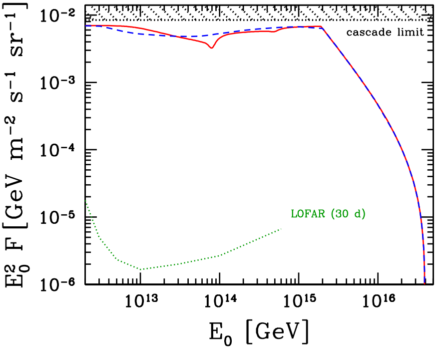


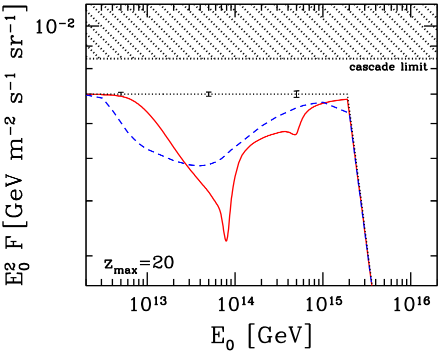


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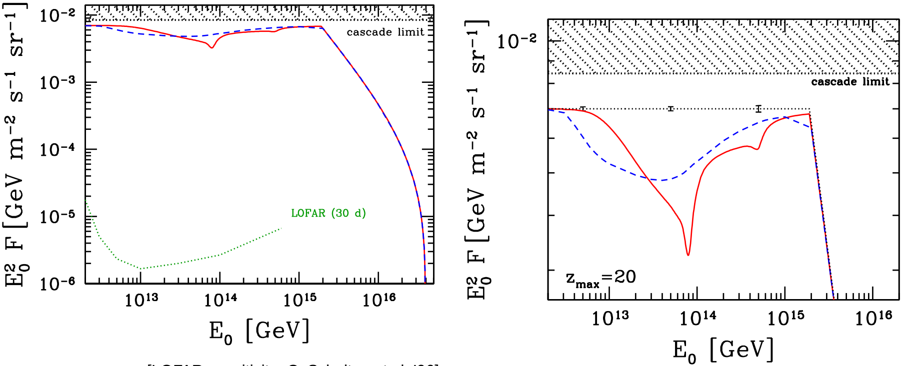


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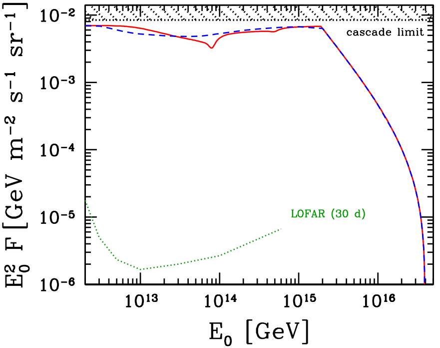


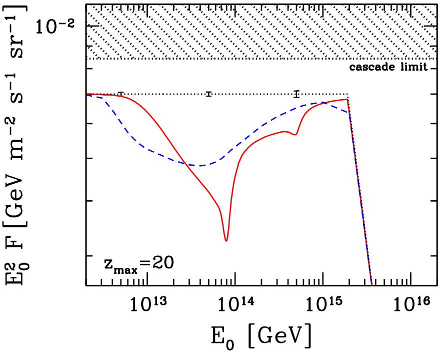


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### Outlook

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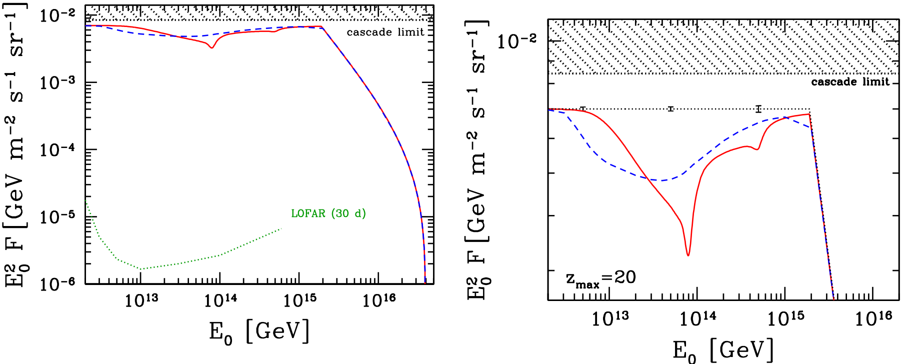


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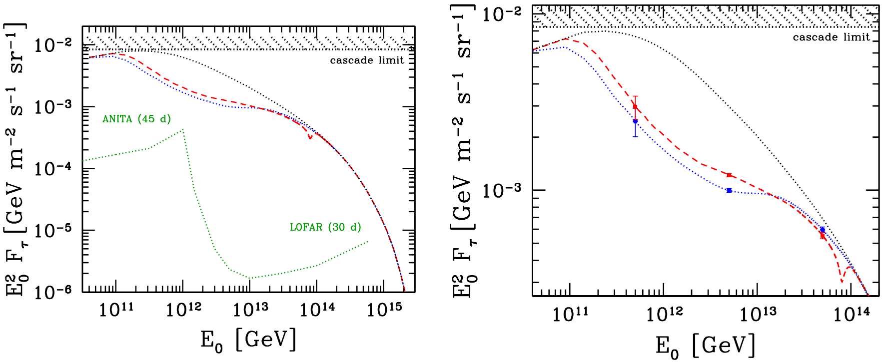
### Outlook

Relic Neutrino Absorption Spectroscopy as a Test of Neutrino Dark Energy (MaVaNs) within the next decade?!

## Flux $F_{\nu_\tau}$ to be observed at Earth for a Topological Defect Source



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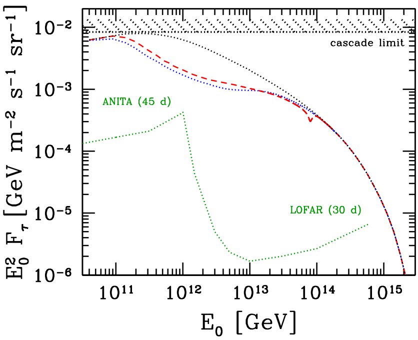
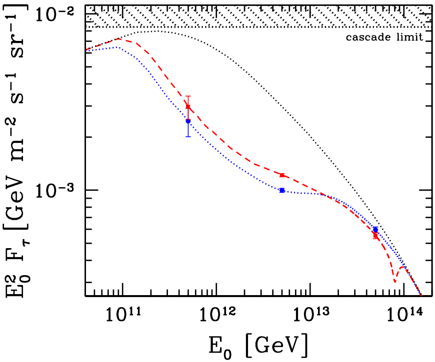
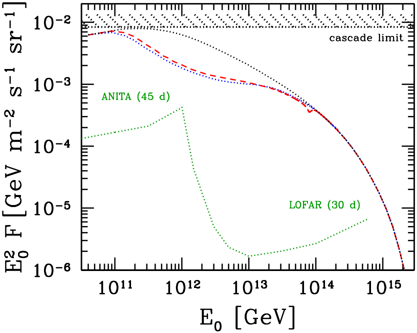
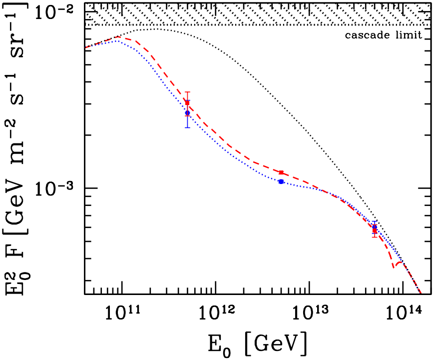


Total EHEC$\nu$ Flux $\sum F_{\nu_\alpha}$ to be observed at Earth for a TD Source



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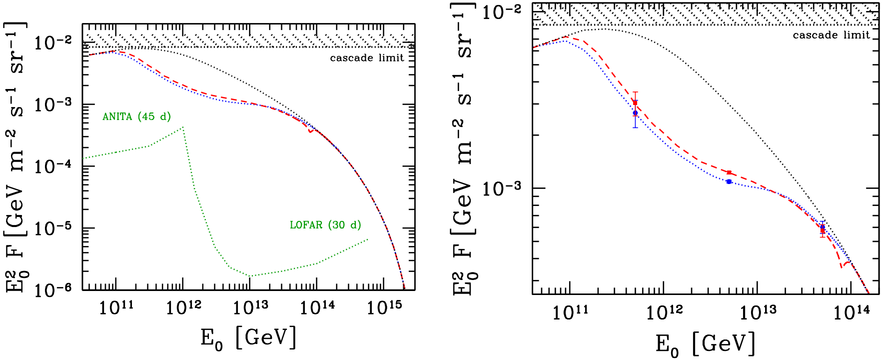

## Light active neutrino masses $m_\nu$:

- Allow tiny coupling $\lambda H N \nu$, $\mathcal{O}(10^{-12})$, linking 'Our Sector' to the 'Dark Sector'
- At scales $\ll$ 100 GeV $\rightarrow \mathcal{L} \supset m_D \nu N + M_N(\mathcal{A}) N N + h.c. + V_0(\mathcal{A})$, with $m_D = \lambda \langle H \rangle < 1$ eV
- Low energy effective theory $\rightarrow \mathcal{L} \supset \frac{m_D^2}{M_N(\mathcal{A})} \nu^2 + h.c. + V_0(\mathcal{A})$ for $M_N(\mathcal{A}) \gg m_D$ (after integrating out $N$)

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