Relic neutrinos and the Early Universe

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The Highest Energy Physics

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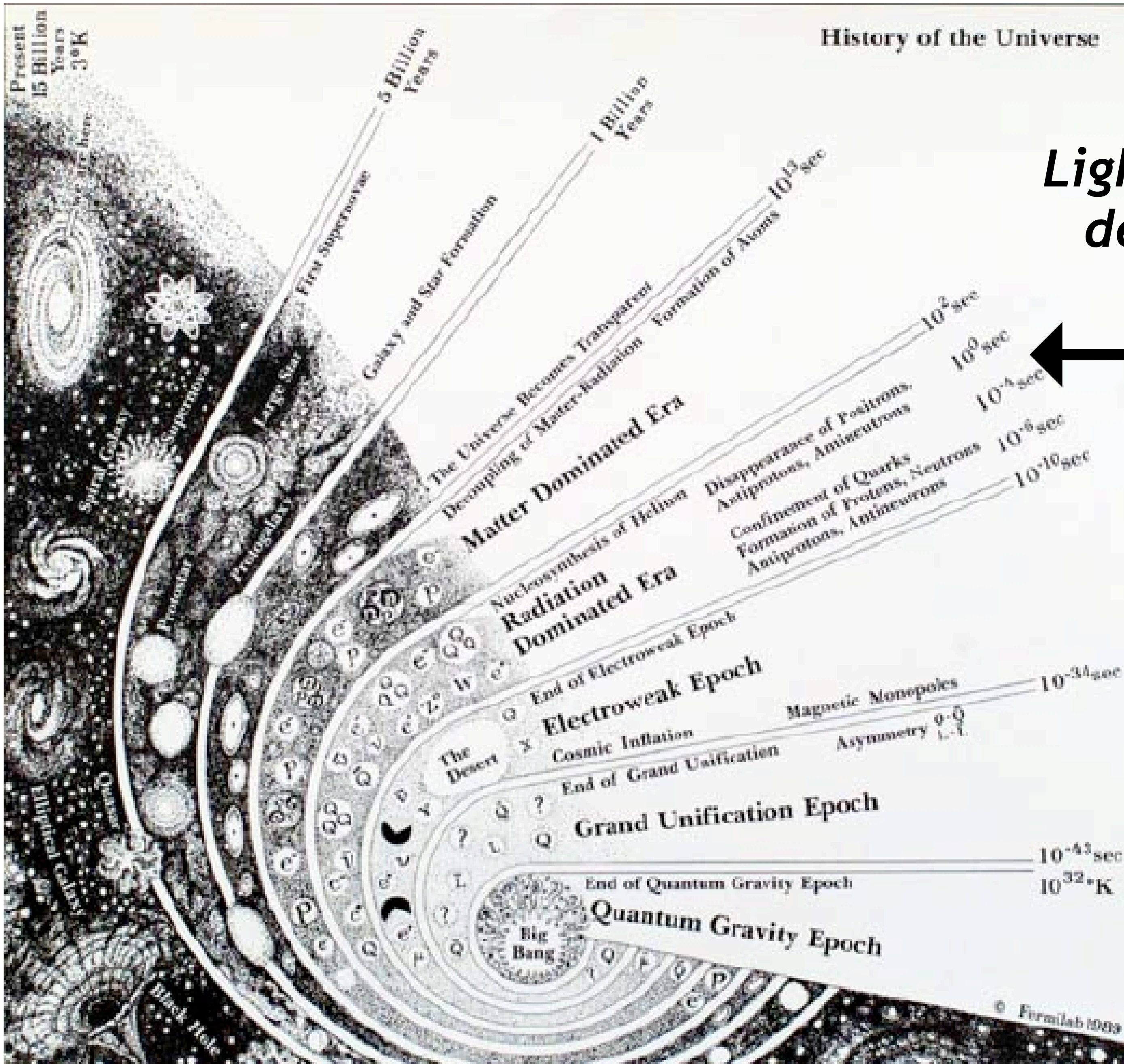
According to standard cosmology, neutrinos should be **the most abundant particles in the Universe**, after CMB photons. The **CMB neutrino** is the **oldest relic**, present since the **BBN era.**



Light neutrino decoupling

According to standard cosmology, neutrinos should be the most abundant particles in the Universe, after CMB photons. The CMB neutrino is the oldest relic, present since the BBN era.

What are the components of the *relic neutrino background*?

(?) Three active massive neutrinos Dirac or Majorana with (WMAP+LSS)

$$\Sigma_i m_{\nu_i} \lesssim 1 \text{ eV}$$

and from neutrino oscillation experiments:

$$m_1 \equiv m_\ell \quad m_2 \equiv \sqrt{m_\ell^2 + \delta m_{solar}^2} > 0.008 \text{ eV} \quad m_3 \equiv \sqrt{m_2^2 + \delta m_{atmos}^2} > 0.05 \text{ eV}$$

(?) Less neutrinos: decays, non standard couplings (light bosons): *Neutrinoless universe*.

(?) More neutrinos: sterile neutrinos, lepton asymmetry.

The relic neutrino background has never been detected (!)

Cosmic-neutrino Spectroscopy

T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982) E. Roulet, Phys. Rev. D 47, 5247 (1993)

$$\nu\bar{\nu} \rightarrow Z^0$$

Outline

Quick review:

*"From the lowest to the highest energies:
The standard relic neutrino background and UHE neutrinos"*

Cosmic neutrino Spectroscopy

An idealized experiment

Absorption lines in an expanding universe

Effect of the relic neutrino temperature

Cosmic Summation

The *standard* relic neutrino background

Neutrinos decouple from the thermal soup when the temperature of the Universe is ~ MeV, keeping then perfect Fermi-Dirac distributions:

$$z \simeq \mathcal{O}(10^{10}) \qquad \frac{dn_{\nu_i}(T_\nu)}{d^3p} = \frac{dn_{\nu_i^c}(T_\nu)}{d^3p} = \frac{1}{(2\pi)^3}\,\frac{1}{\exp\left(p/T_\nu\right)+1}$$

They do not inherit any of the energy associated to e^+e^- annihilation:

$$T_{\nu 0} = \left(\tfrac{4}{11}\right)^{1/3} T_0 = 1.945\ \mathrm{K} \rightsquigarrow 1.697 \times 10^{-4}\ \mathrm{eV}$$

In the present universe the number density of *each active neutrino species*

$$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$$

is (*the lower bound on the effective target mass*):

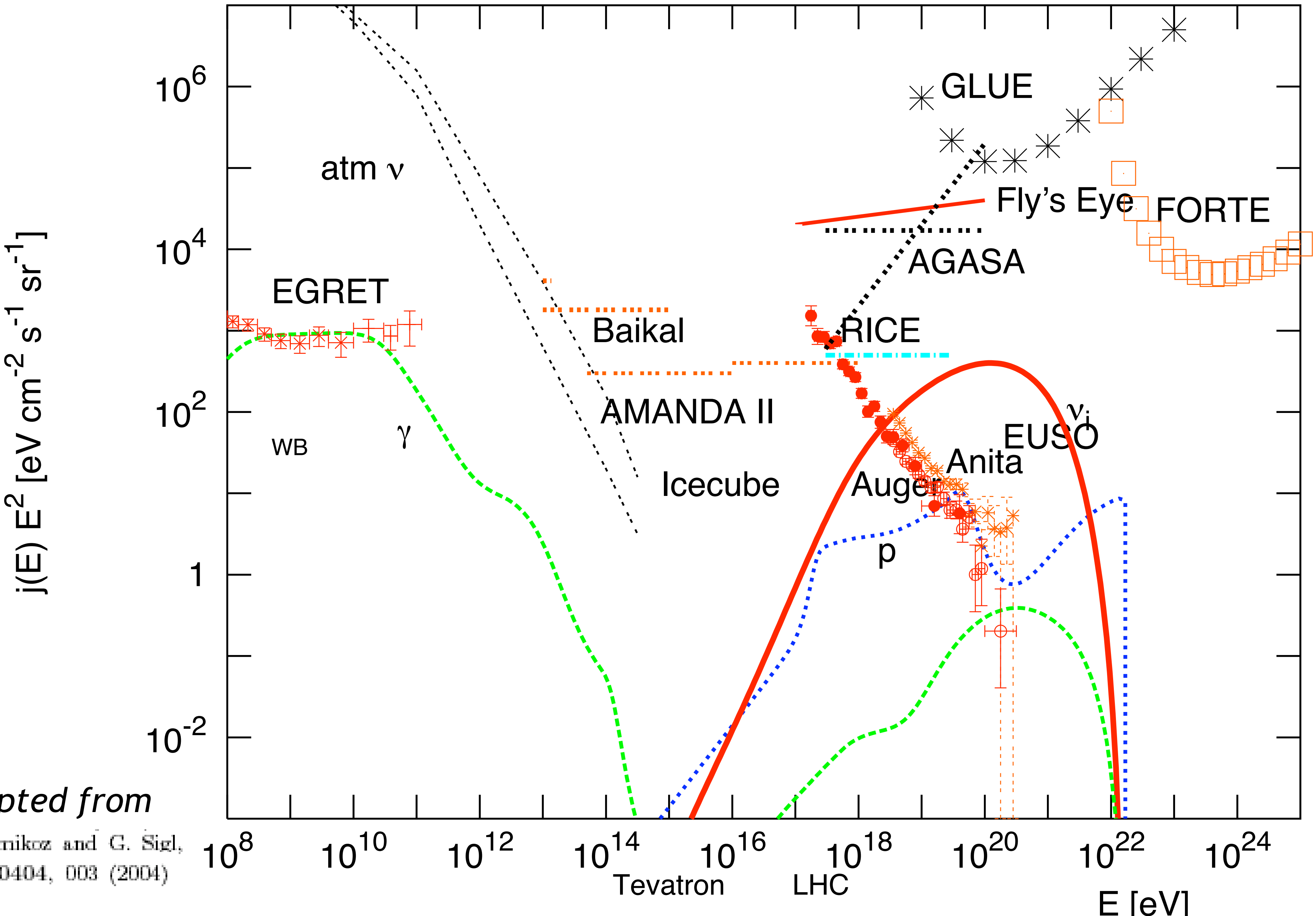
$$n_{\nu_i 0} = n_{\nu_i^c 0} \equiv n_{\nu_i}(T_{\nu 0}) \approx 56\ \mathrm{cm}^{-3}$$

The temperature of a massless decoupled species scales as (1+z)

The relic neutrino number density (*the effective target mass at a fixed redshift*) will be redshifted as

$$n_{\nu 0}\ (1+z)^3$$

The highest energy particles in Nature

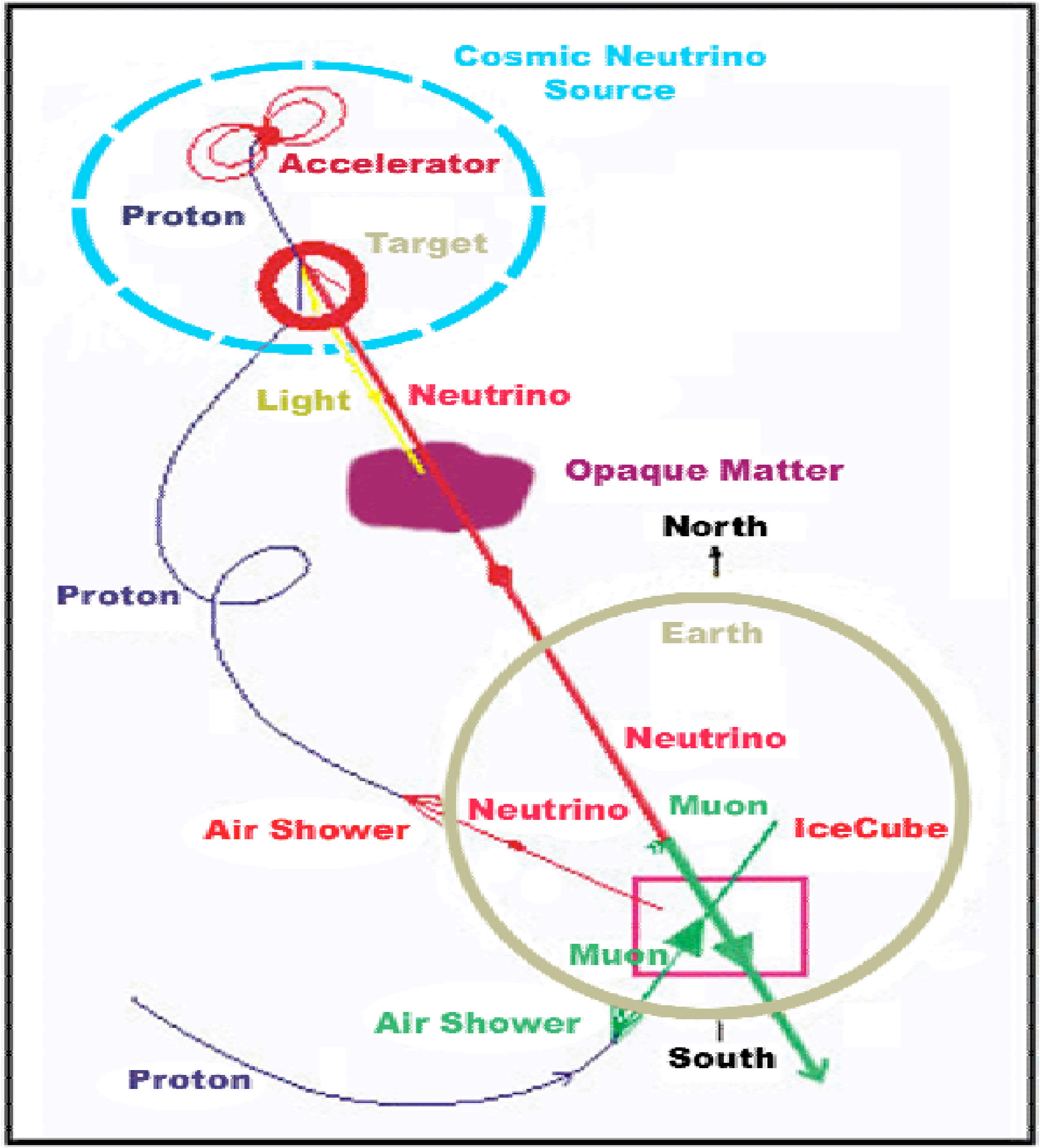


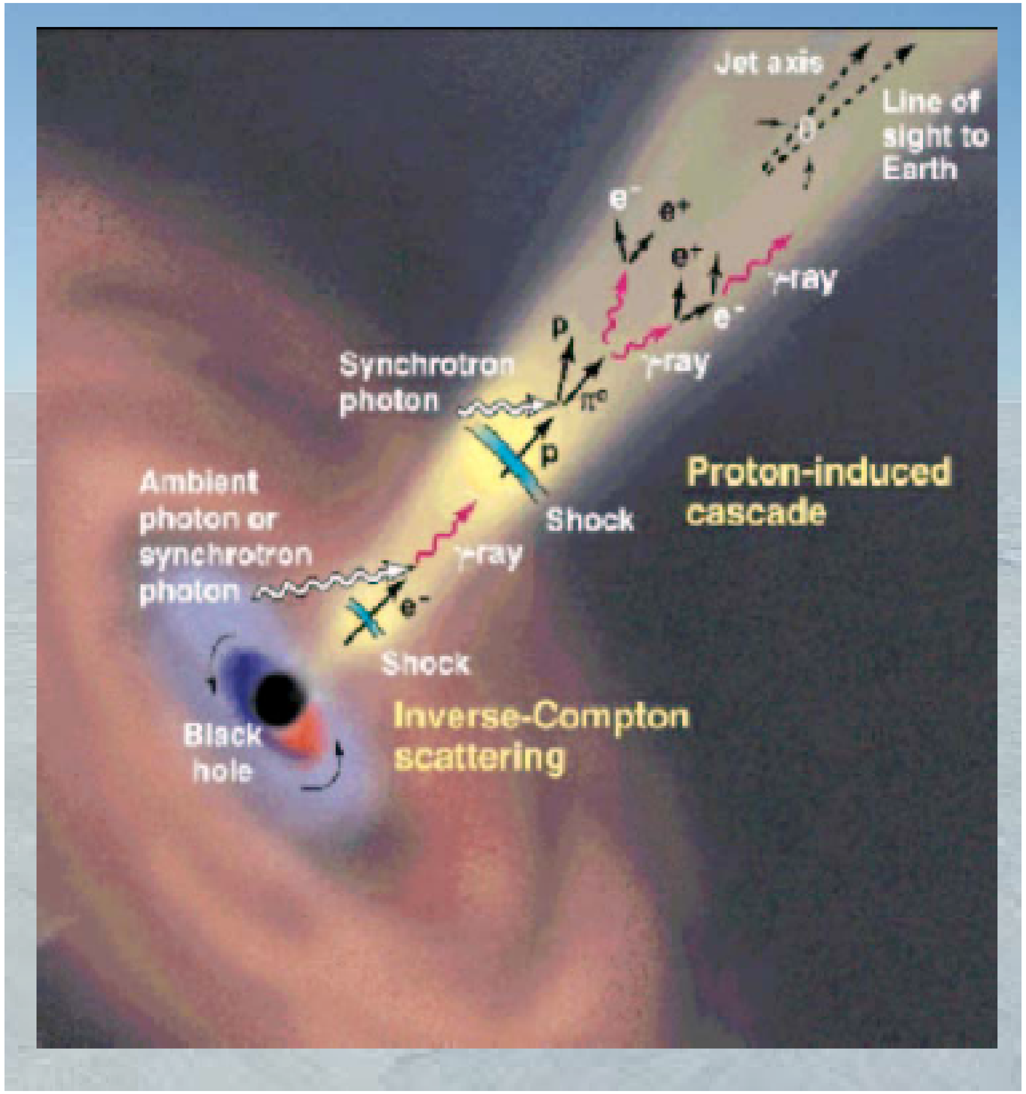
adapted from

D. V. Semikoz and G. Sigl, JCAP 0404, 003 (2004)

To go beyond these limits, one must turn to cosmic accelerators that Nature has provided to us!

The UHE neutrino beam





UHE neutrinos...

Unlike charged particles are undeflected by magnetic fields and *unlike photons* they interact weakly.

Two classes of models of UHE neutrino production:

1) Acceleration mechanisms (UHECR connection:"guaranteed"): Cosmogenic neutrino fluxes.

$$p + (N,\gamma) \rightarrow \pi + \text{anything} \qquad \pi^0 \rightarrow \gamma\gamma \qquad \pi^+ \rightarrow \mu^+\nu_\mu, \quad \mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$

These neutrino sources switched on at a time characterized by z< 20.
They can trace back the astrophysical source (proton acceleration).

2) Top down scenarios (Cosmological remnants):
UHE neutrinos from decay/annihilation of SuperHeavy-Dark Matter
Topological Defects (formed in SB phase transitions predicted by GUT)

C. T. Hill, Nucl. Phys. B 224, 469 (1983). P. Bhattacharjee, C. T. Hill and D. N. Schramm, Phys. Rev. Lett. 69, 567 (1992).

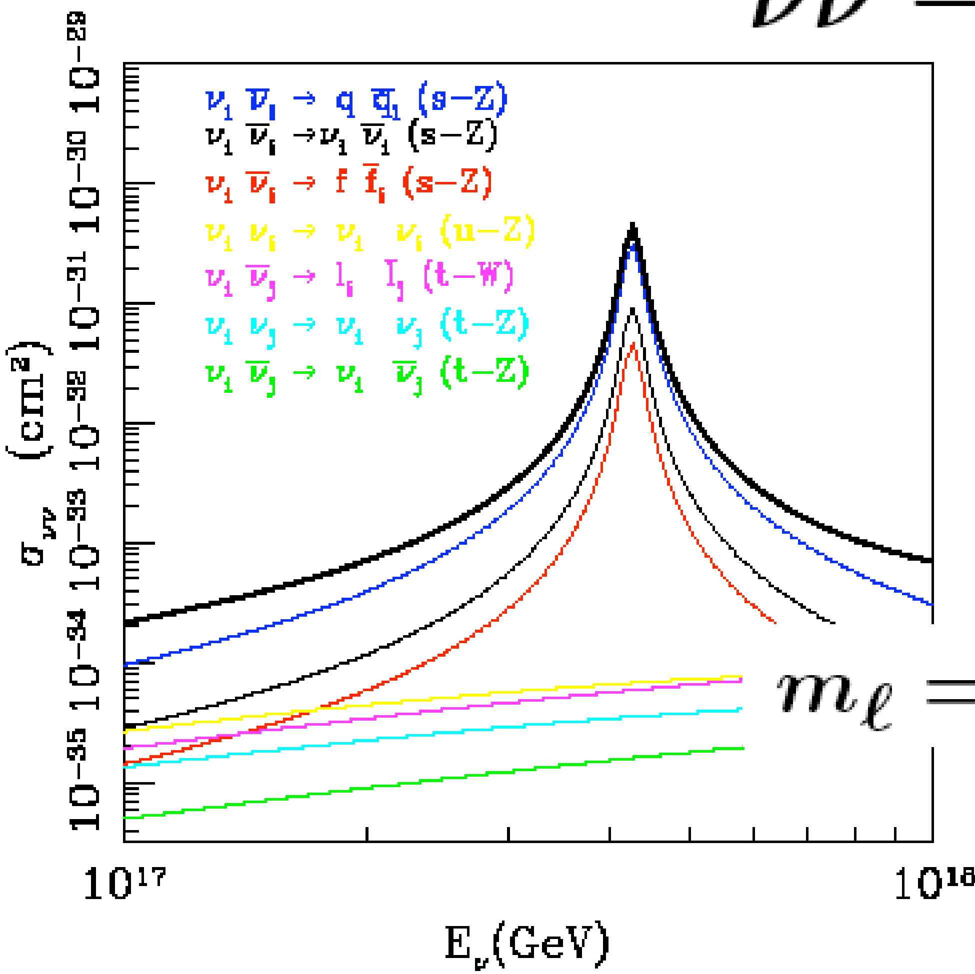
They have been decaying all the way back to very large z,

$$z \sim \mathcal{O}(10^{10})$$

Cosmic Neutrino Spectroscopy

Resonant annihilation of UHEν's with the relic neutrino background:

$$\nu\bar{\nu} \longrightarrow Z^0$$



$$m_\ell = 10^{-5}\ \text{eV}$$

$$s \simeq 2E_\nu m_\nu = M_Z^2$$

$$E_\nu^{Z\text{res}} \simeq \frac{4{\cdot}10^{21}}{m_\nu}\ \text{eV}$$

The location of the absorption lines in the UHEν spectrum points to neutrino masses:

$$m_\nu = M_Z^2/2E_\nu^{Z\text{res}}$$

Cosmic Neutrino Spectroscopy

Is it possible to determine the absolute neutrino masses
and the flavor composition of the mass eigenstates
through the detection of the "dips"?

It could be, assuming perfect energy resolution and flavor tagging:
the ideal experiment.

Our universe is far away from an ideal laboratory experiment!

Integration over cosmic time (redshift), CMB-neutrino temperature,
unconventional neutrino histories.

Absorption lines are sensitive to the thermal history of the universe.

An idealized experiment

Ideal laboratory: We neglect the expansion of the universe and relic neutrino temperature.

Ideal target: The cosmic neutrino attenuator is a very long uniform column of length L with the current relic density for each species,

$$n_{\nu 0} = 56 \text{ cm}^{-3}$$

$$\mathcal{P}(E_{\nu 0}) = \exp\left[-\sigma_{\nu\nu}(E_{\nu 0})\, n_{\nu_i}\, L\right]$$

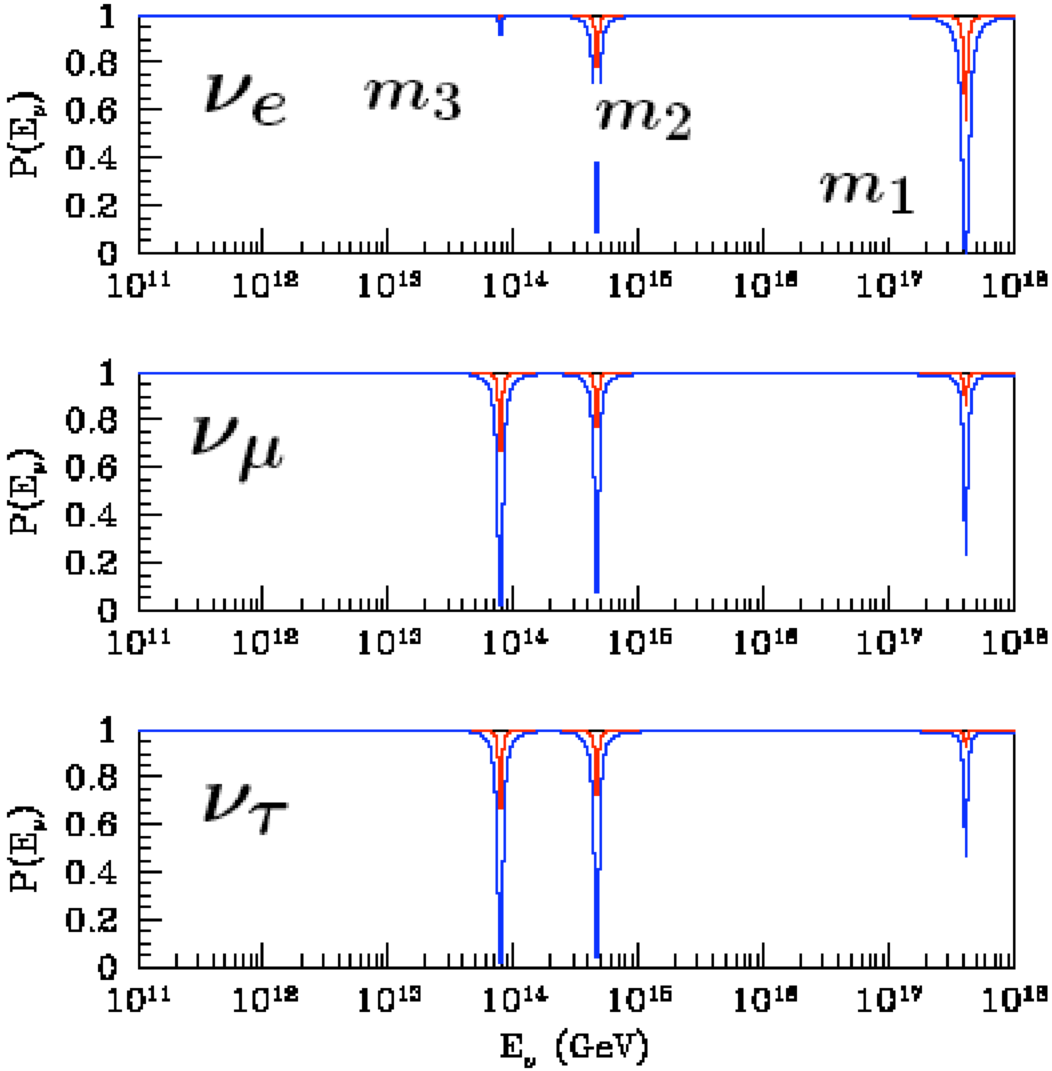
Ideal beam: The UHE neutrino beam is originated >100 Mpc .
It contains all (anti) neutrino flavors in sufficient numbers.
Oscillation length<<distance to the source: Averaged oscillations.

Ideal detection: Detector with perfect energy resolution and flavor tagging.

An idealized experiment

L = 10^5 Mpc L = 10^4 Mpc

Normal



$$m_\ell = 10^{-5}\ \text{eV}$$

$$m_2 = \sqrt{m_\ell^2 + \delta m^2_{solar}} \sim 0.01\ \text{eV}$$

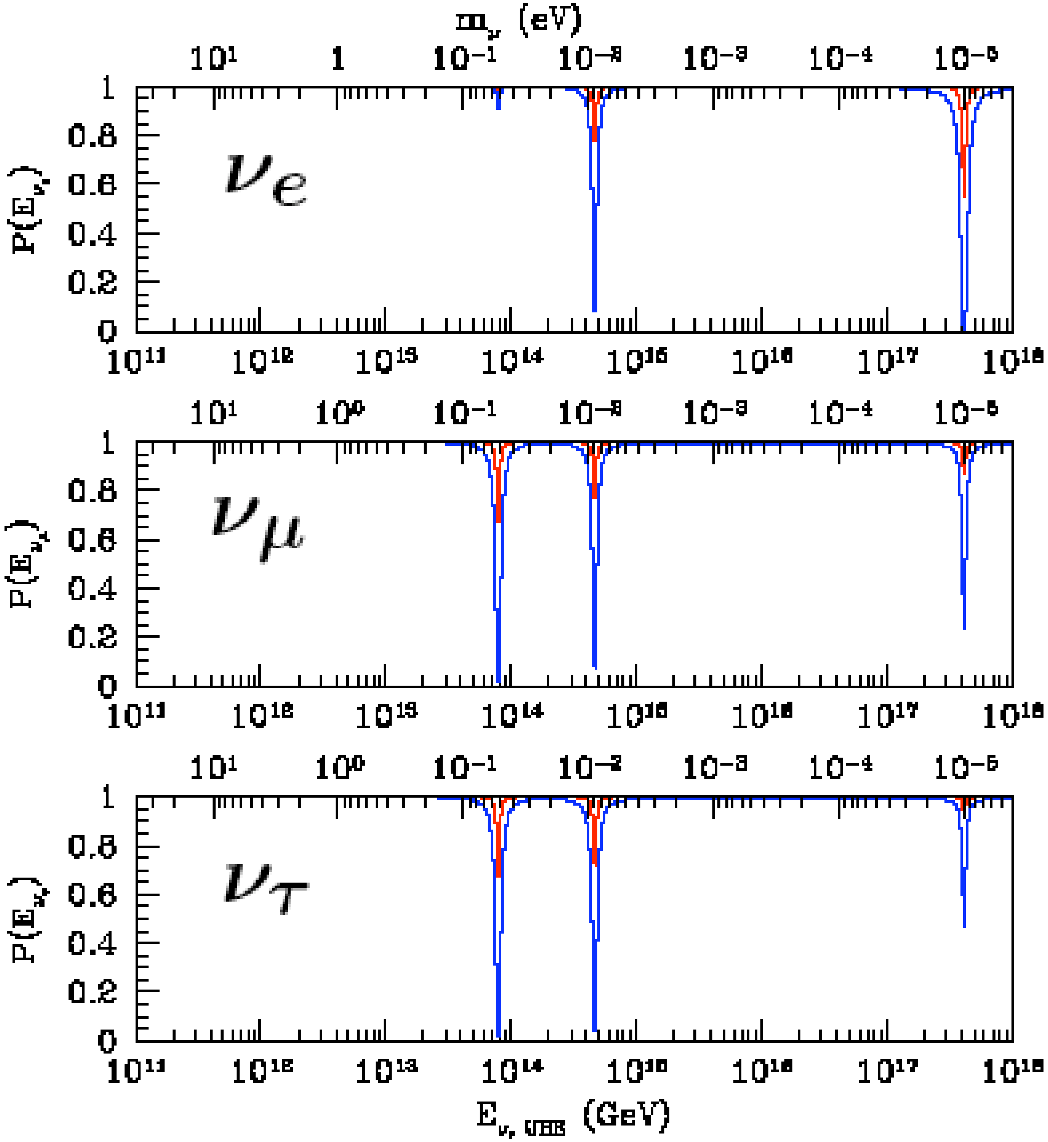
$$m_3 = \sqrt{m_2^2 + \delta m^2_{atmos}} \sim 0.05\ \text{eV}$$

An idealized experiment

L = 10^5 Mpc   L = 10^4 Mpc

$$m_\nu = M_Z^2 / 2E_\nu^{Z\,\mathrm{res}}$$

Normal



$$m_\ell = 10^{-5}\ \mathrm{eV}$$

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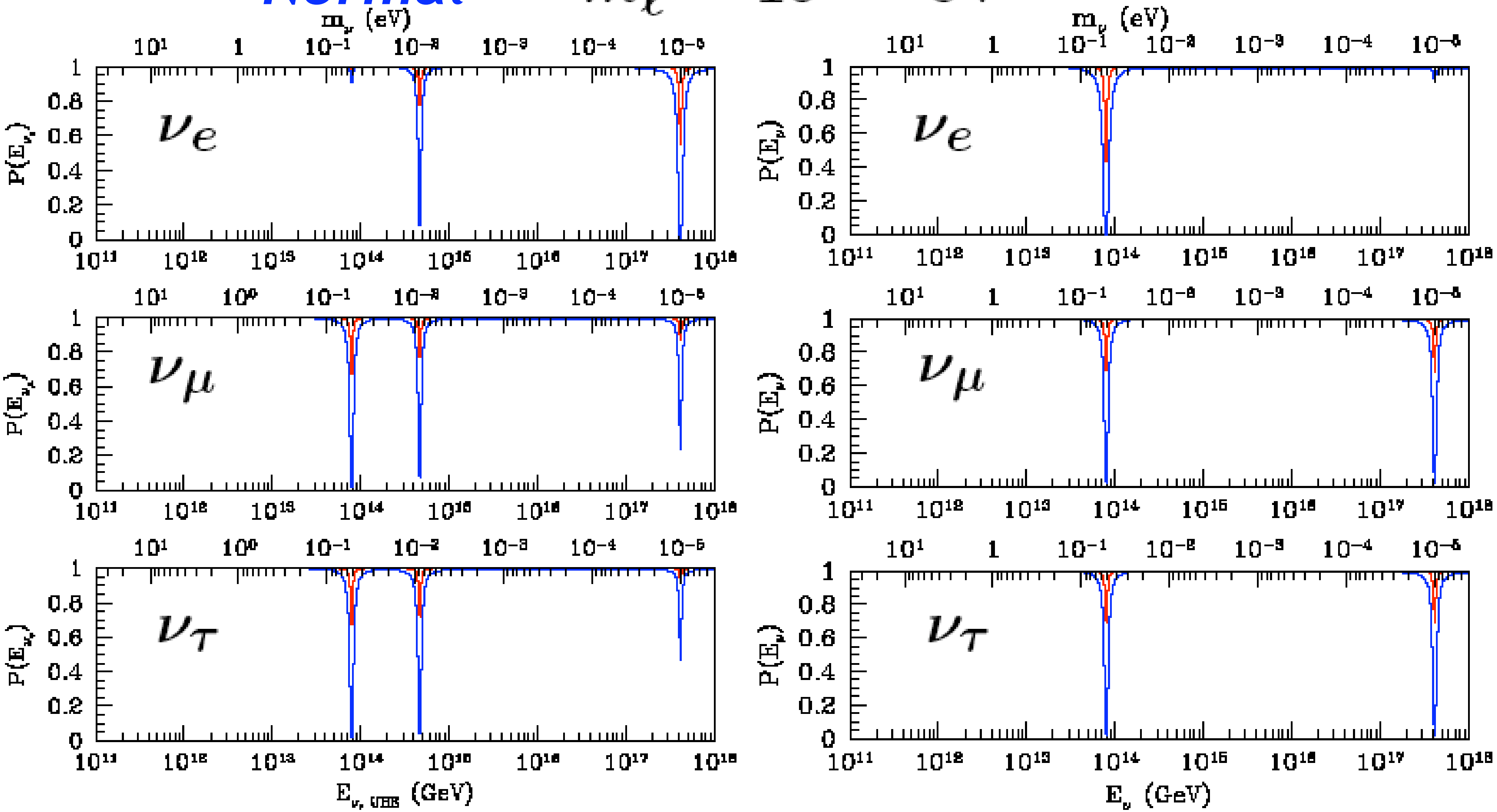
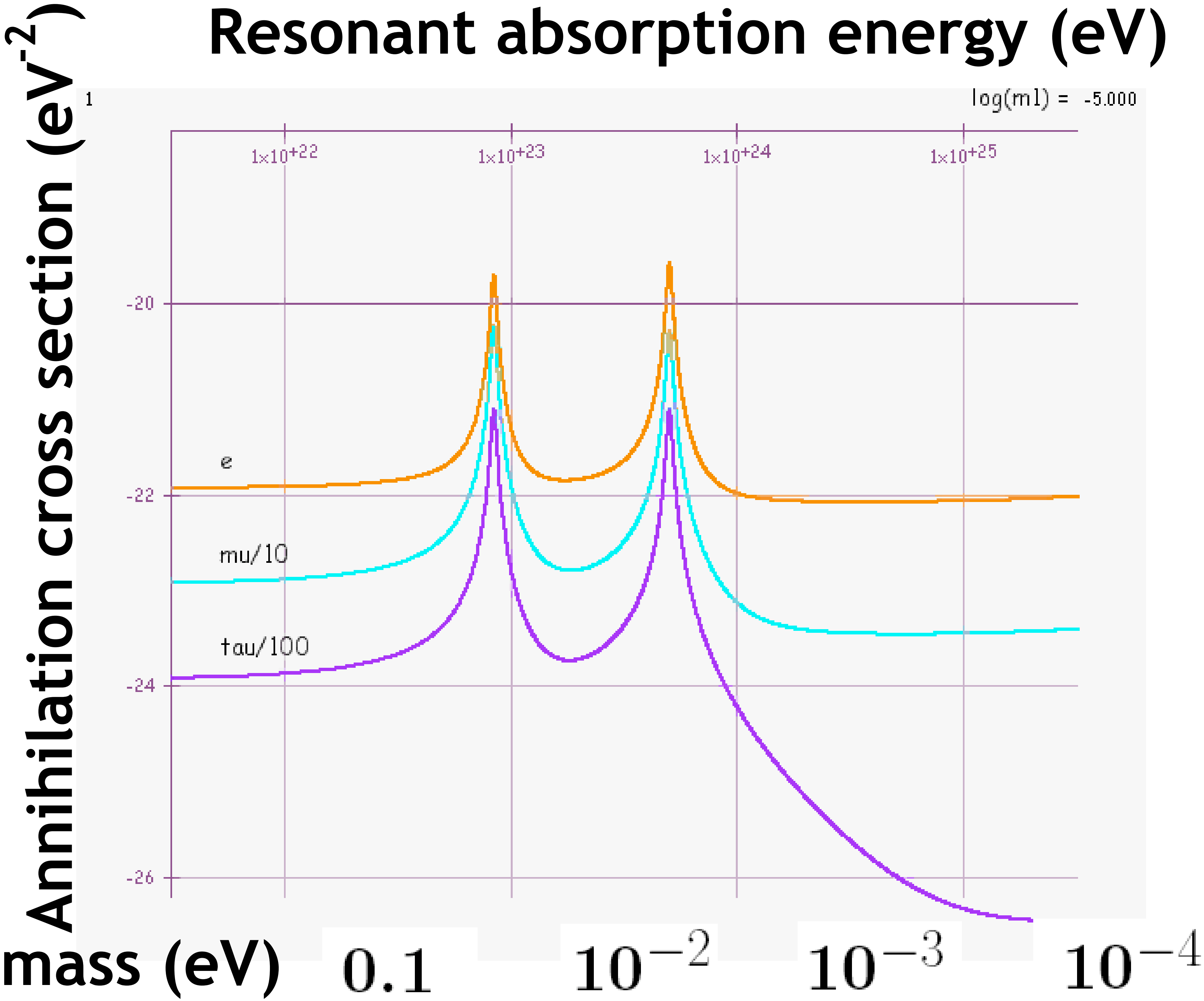
An idealized experiment

L = 10^5 Mpc   L = 10^4 Mpc

Normal $m_\ell = 10^{-5}$ eV   **Inverted**



Resonant absorption energy (eV)



What could be extracted from the dips?

Normal or inverted hierarchical spectrum?

Majorana or Dirac neutrino characters?

Unstable relics?

Lepton asymmetry? (BBN constraints)

Neutrinoless universe?

The time to traverse one interaction length for the annihilation on the current relic neutrino density exceeds the age of the universe!

$$1.2 \times 10^4 \ \mathrm{Mpc} = 39 \ \mathrm{Gly}$$

We should consider UHE neutrinos traversing the universe over the cosmic time:

Evolution in the redshift!

Absorption lines in an expanding universe

Evolution of the relic neutrino number density changes (dips depth):

$$n_\nu(z) = n_{\nu 0}(1+z)^3$$

The energy of the UHE neutrino (dips location):

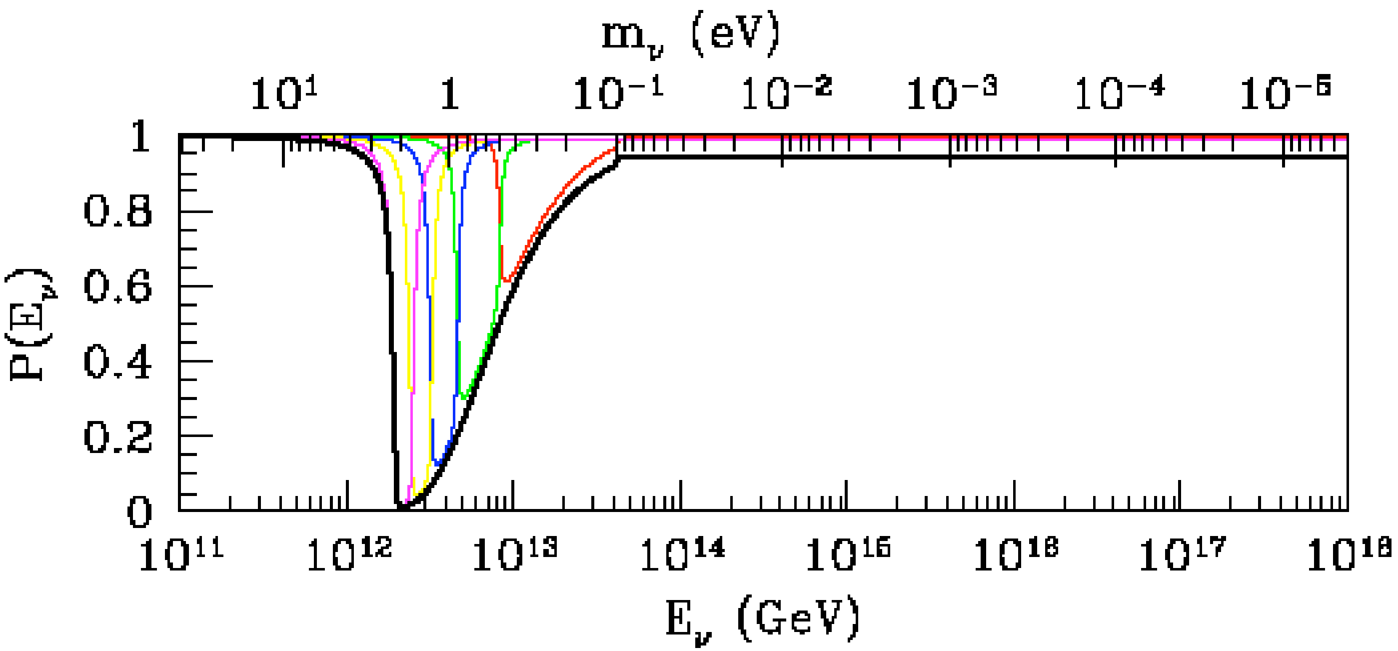
$$E_\nu(z) = E_{\nu 0}\,(1+z) \qquad E_{\nu 0}^{Z\,\mathrm{res:z}} = \frac{M_Z^2}{2m_{\nu_i}(1+z)}$$

$$\mathcal{P}(E_{\nu 0}) = \exp\left[-\int_0^z dz\, \sigma_{\nu\nu}((1+z)E_{\nu 0})\,\frac{d\bar{n}_{\nu_i}(z)}{dz}\right]$$

$$m_\ell = 0.1\ \mathrm{eV}$$

degenerate spectrum

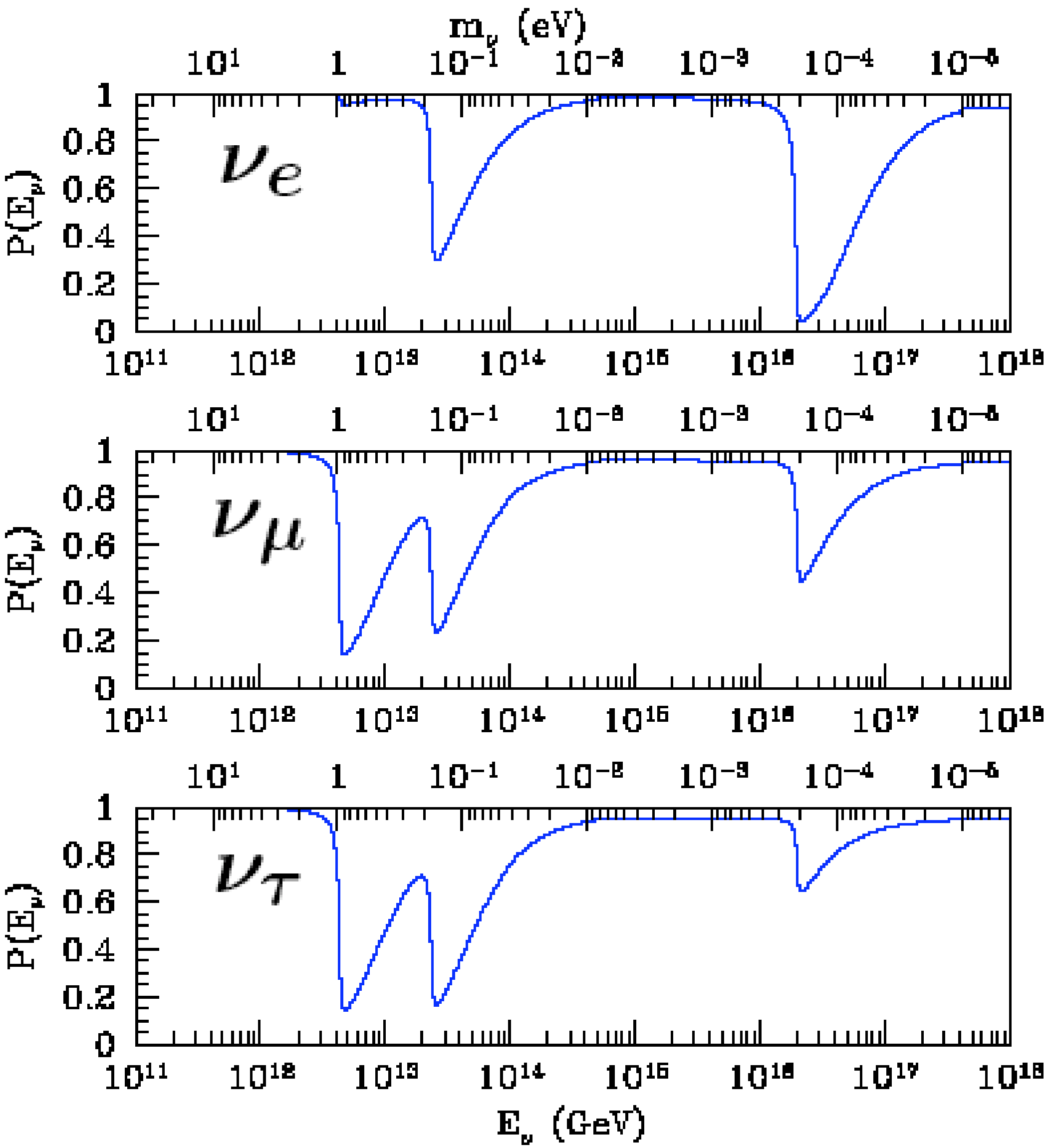
$$0 \le z \le 20$$



Absorption lines in an expanding universe

Normal

$$m_\nu = M_Z^2 / 2E_\nu^{\mathrm{Zres}}$$



$$m_\ell = 10^{-5} \ \mathrm{eV}$$

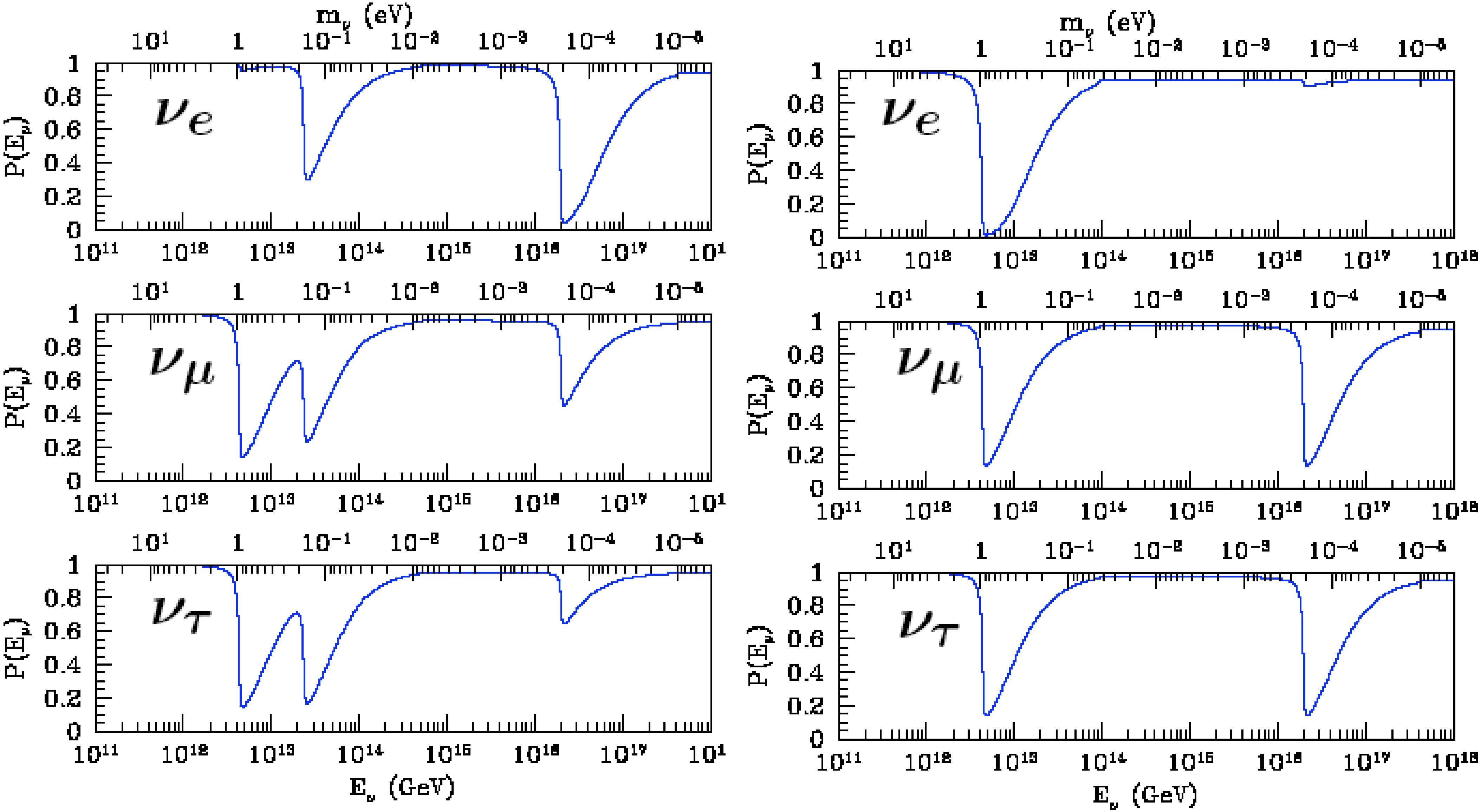
$$m_2 = \sqrt{m_\ell^2 + \delta m_{solar}^2} \sim 0.01 \ \mathrm{eV}$$

$$m_3 = \sqrt{m_2^2 + \delta m_{atmos}^2} \sim 0.05 \ \mathrm{eV}$$

$$E_{\nu 0}^{\mathrm{Zres:z}} = \frac{M_Z^2}{2m_{\nu_i}(1+z)}$$

Absorption lines in an expanding universe

Normal $m_\ell = 10^{-5}$ eV **Inverted**



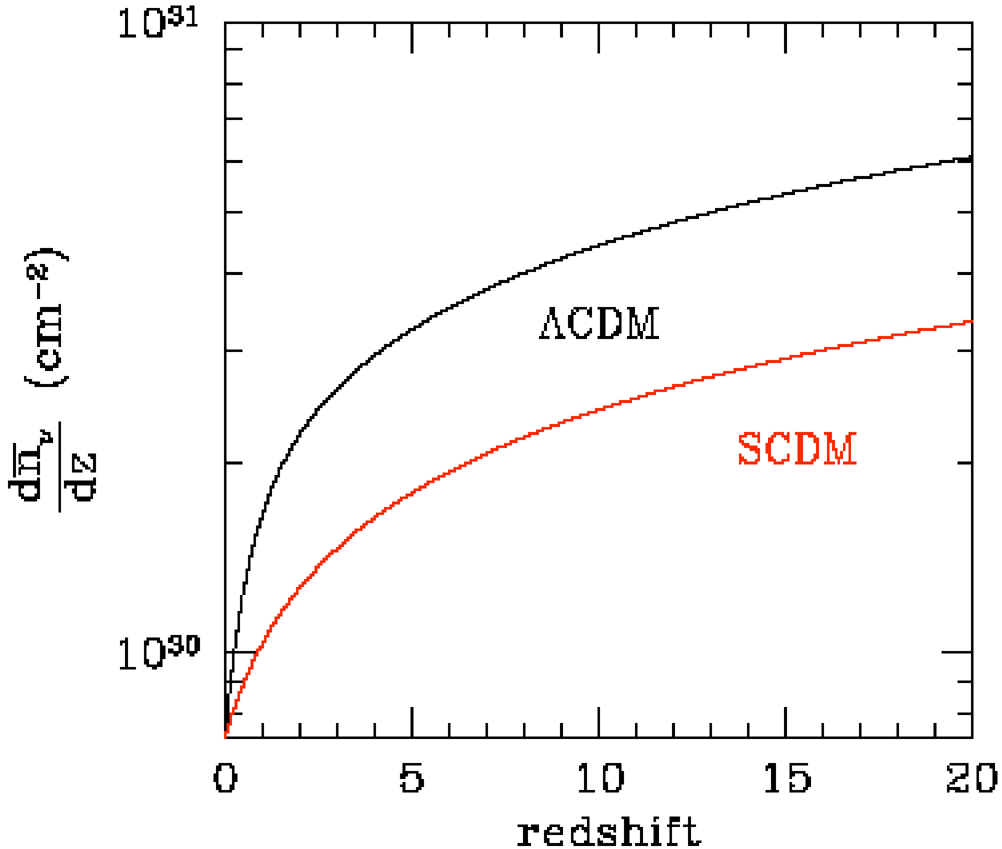
Are the dips sensitive to different cosmologies?

Yes!

$$\frac{d\bar{n}_{\nu_i}(z)}{dz} = \frac{n_{\nu 0}\;(1+z)^3 dz}{(1+z)\;H(z)}$$

UHEν's sources as "standard candles" = SN I-a.

UHEν's are more attenuated = distant SN I-a photons are fainter in a dark energy dominated universe than in a matter dominated one.



And to the equation of state of the dark energy ?

Yes!

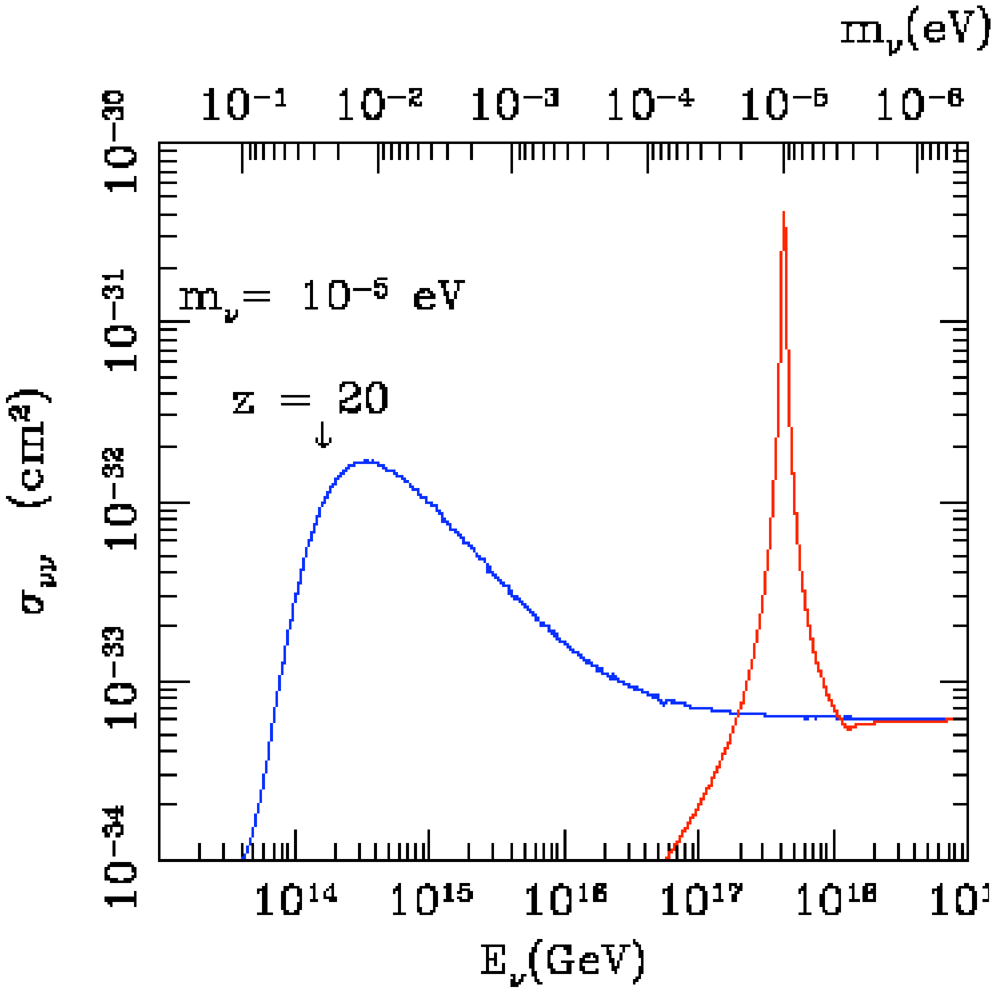
The effect grows with the redshift.

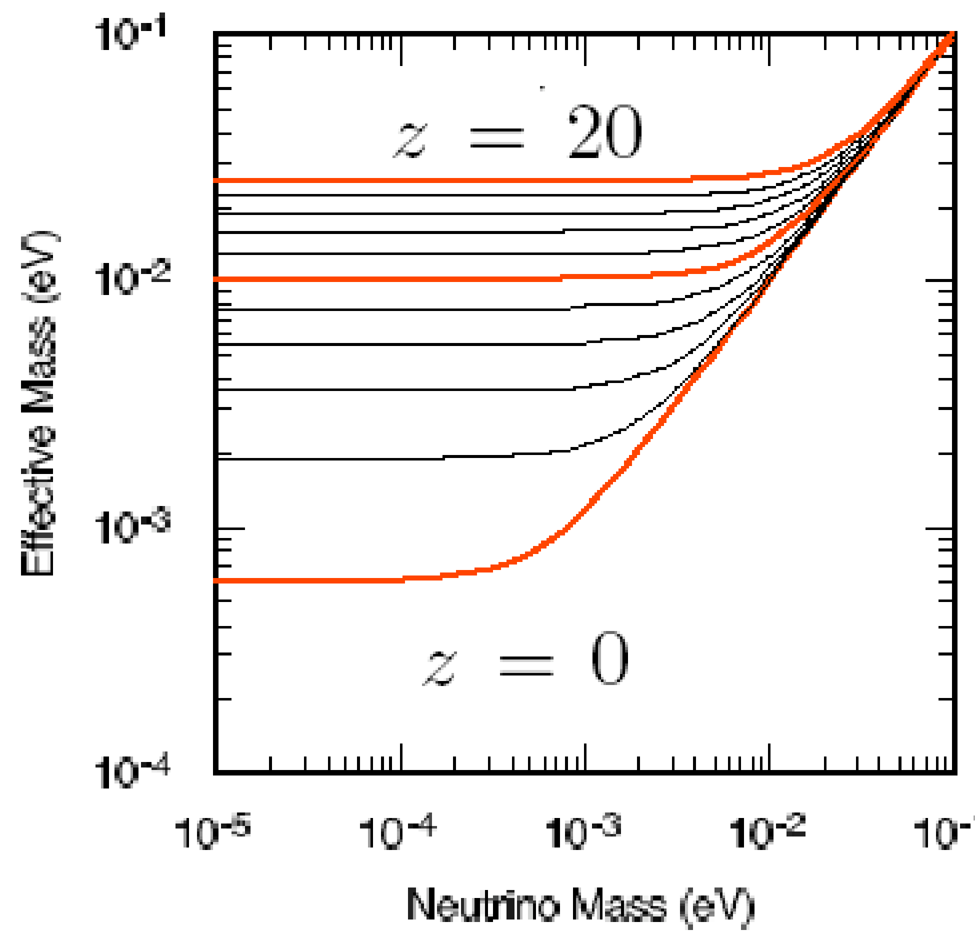
Dramatic differences for TD UHE sources for different quintessence models.

Effect of the relic neutrino temperature

Relic neutrinos are moving targets:
thermal motion will induce a "Fermi-smearing".

$$E_\nu^{Z\mathrm{res}} = \frac{M_Z^2}{2(\varepsilon_\nu - p_\nu \cos\theta)} \sim \frac{M_Z^2}{2\langle\varepsilon_\nu\rangle} \qquad \langle\varepsilon_\nu\rangle = [\langle p_\nu^2\rangle + m_\nu^2]^{1/2}$$





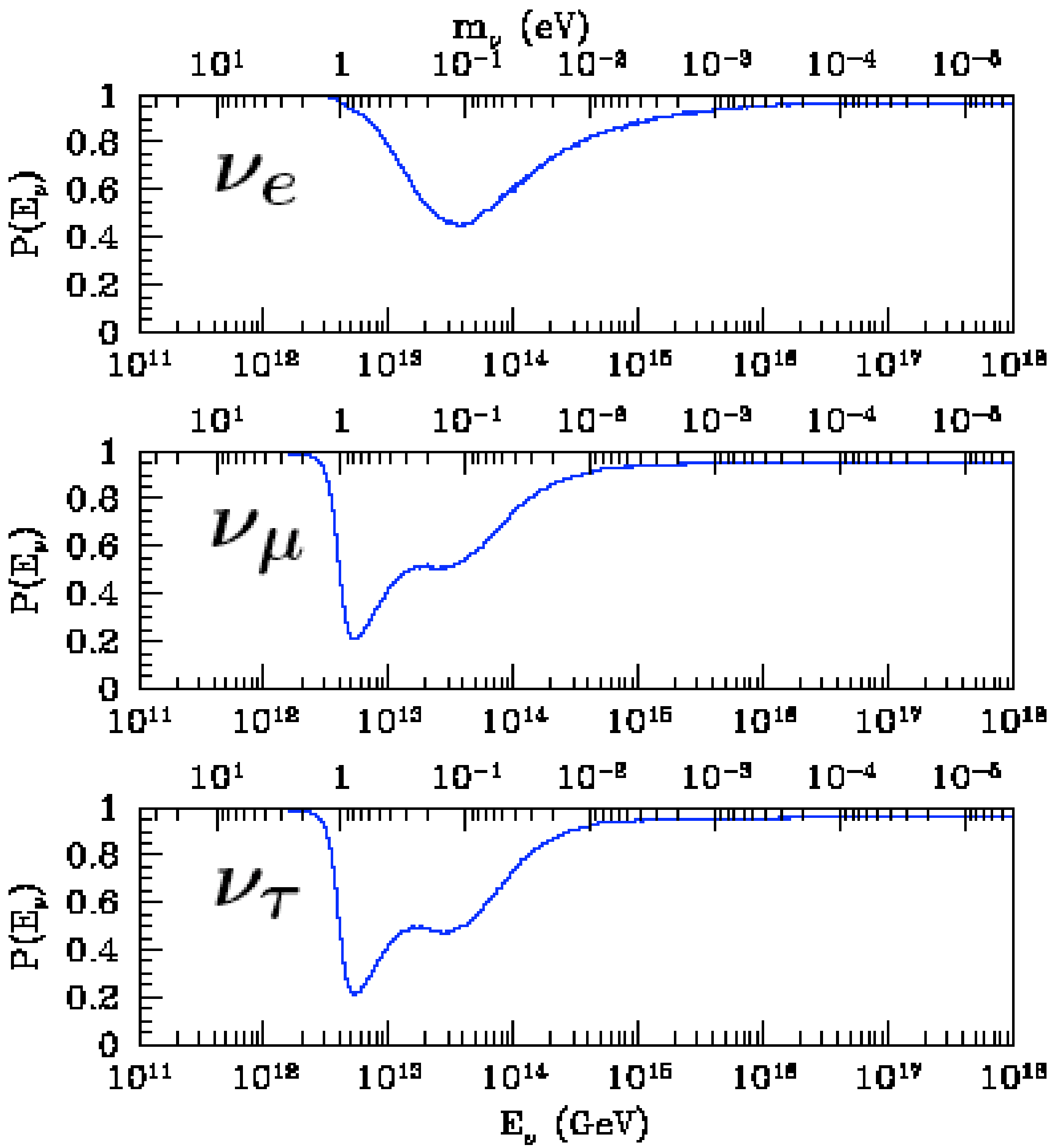
When considering cosmic evolution the thermal motion has to be considered unless m~0.1eV

The three very different dips have merged into one!

Impossible to determine the distinct neutrino masses.

Normal

$$m_\nu = M_Z^2 / 2E_\nu^{\mathrm{Zres}}$$



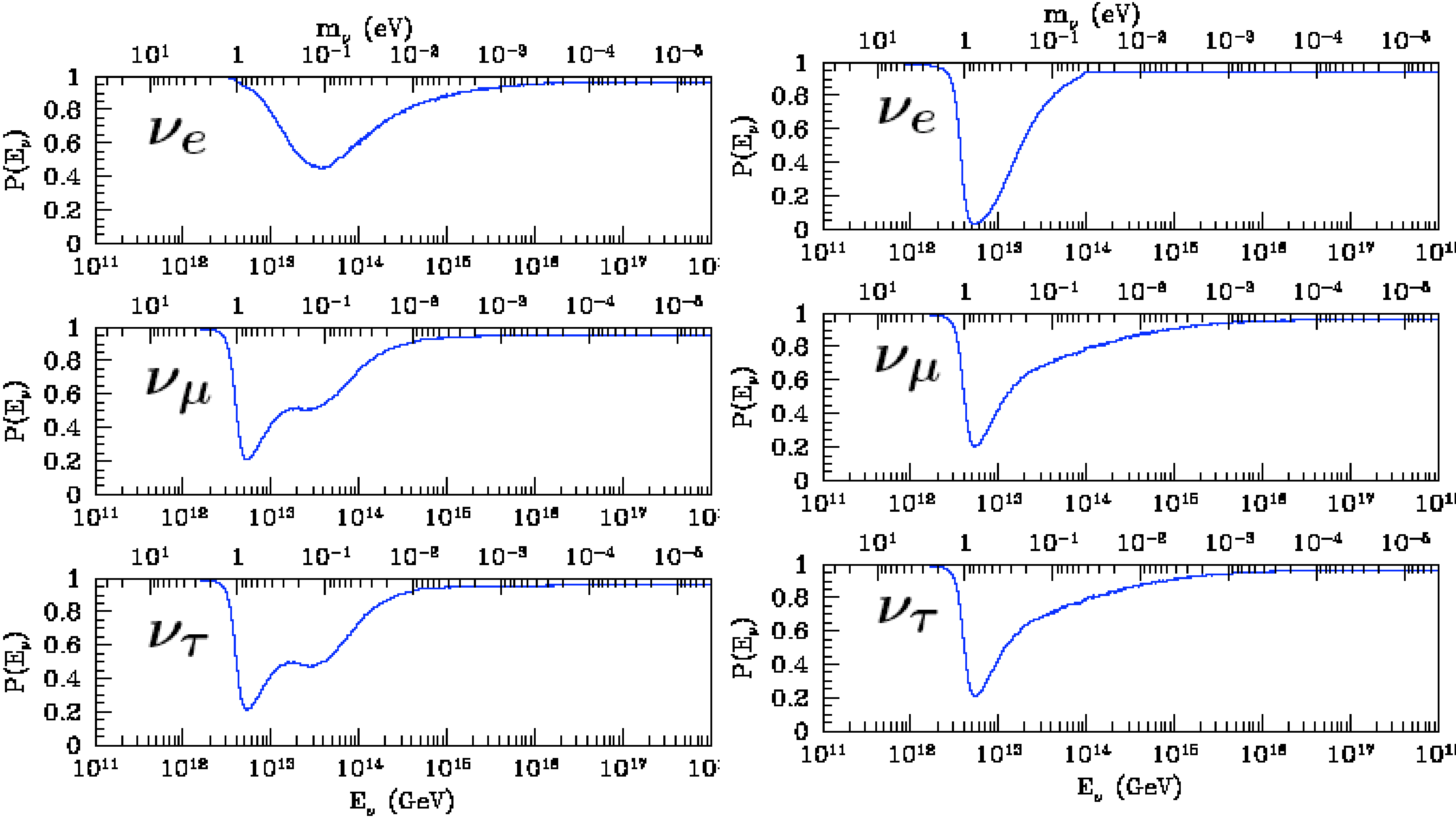
$$m_\ell = 10^{-5}\ \mathrm{eV}$$

The three very different dips have merged into one!

Impossible to determine the distinct neutrino masses.

The determination of the hierarchy still remains at reach.

Normal ***Inverted***



Diagnostic Potential of Cosmic-Spectroscopy

Needs the existence of SuperGZK ν's and future detectors with vast effective volumes and/or long exposure times.
The detection of the relic neutrinos would be a major discovery!

As a byproduct, *in principle*, cosmic neutrino spectroscopy could provide the value of the individual neutrino masses, unveiling neutrino properties, or unconventional neutrino histories and the thermal history of the universe.

The redshift dependence is both a *blessing* and a *curse*...
Dips at much lower energies: evidence of non accelerator sources?
Future cosmic data may provide our first real evidence for GUTs!
Unfortunate because it means more smearing/distortion of the dips.
It compromises the dream of the determination of neutrino masses!

The first dip could determine/verify the spectrum mass hierarchy.
The more "external" information, the more cosmic neutrino spectroscopy can tell us about the thermal history of the universe!