Absorption Dips - Detection of the Cosmic Neutrino Background

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see also: Relic Neutrino Absorption Spectroscopy, hep-ph/0401203

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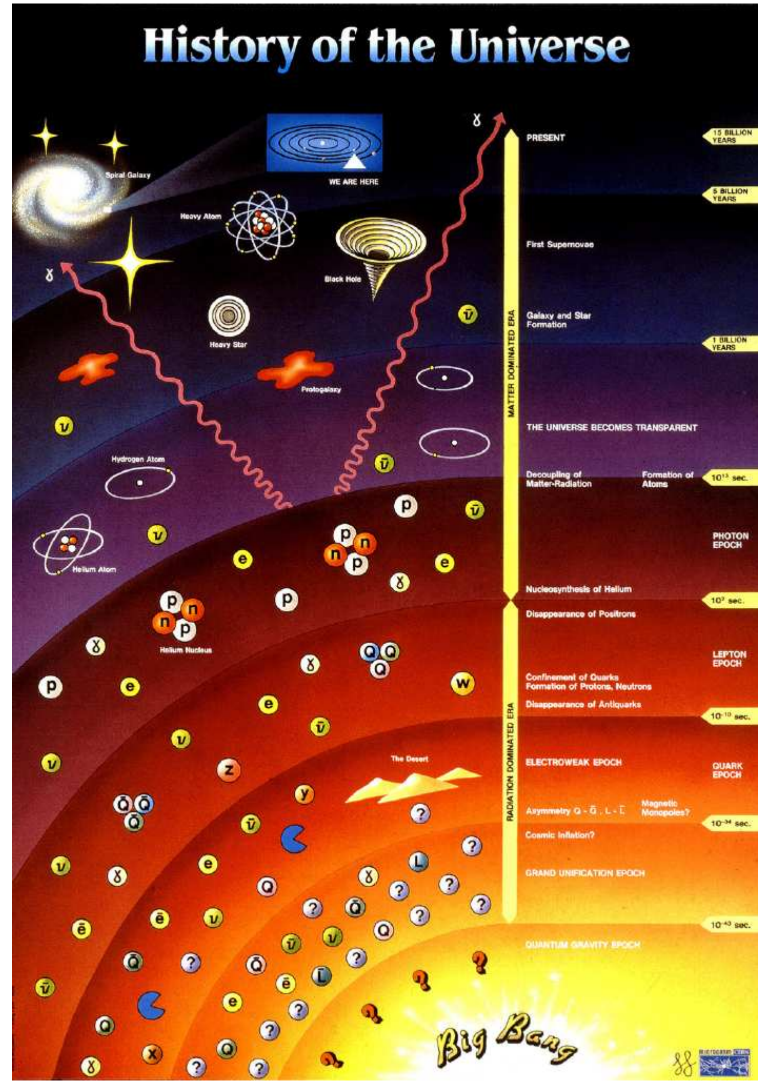
Big Bang - the relic ν story

- Big Bang: all particles in thermal equilibrium
- $\Gamma_{\mathrm{INT.}} < \Gamma_{\mathrm{EXP}} \rightarrow$ decoupling; for **Cosmic neutrino Background** (**CνB**) at $t \sim 1$ s

  $\rightarrow$ CνB gives glimpse to **early universe**!
- since decoupling, wavelength of relic ν's expanding in proportion to size of Universe
- subsequent e^+e^- annihilation reheats the photon gas, such that $(T_\nu/T_\gamma)^3 = 4/11$.



[CERN]

thus we can deduce for the **CνB**:

- **density** $\quad \langle n_{\nu_i} \rangle_0 = \dfrac{3}{22} \langle n_\gamma \rangle_0 \simeq 56 \ \mathrm{cm}^{-3}$
- **momentum**

$$\langle |\vec{p}_{\nu_i}| \rangle_0 \simeq 3 \left(\frac{4}{11} \right)^{1/3} T_{\gamma\,0} \simeq 5 \cdot 10^{-4} \ \mathrm{eV}$$

Well predicted - but no direct evidence!

CνB - why so difficult to detect?

- ν's interact only weakly - for $s \ll M_Z^2\,, M_W^2$: **small cross section**:

$$\sigma_{\nu_i}^{\mathrm{NC,CC}} \sim G_F^2\, s \, \simeq 10^{-55}\,\mathrm{cm}^2\,(\,s\,/\mathrm{eV}^2\,)$$

- ν's have mass - $m_{\nu_3} > \langle |\vec{p}_\nu| \rangle \simeq 5 \cdot 10^{-4}\,\mathrm{eV}$, leading to a **small velocity**.
- ν mass is small - $m_{\nu_3} < 1\,\mathrm{eV}$, **no substantial clustering** $n(r) \simeq \langle n_\nu \rangle_0$

Event rate for incoherent scattering

$$R_{\nu_i}^{\mathrm{ic}} = V\, n_{\mathrm{T/b}}\, \langle n_{\nu_i} \rangle_0\, \langle |\vec{v}\,| \rangle\, \sigma_{\nu_i}^{\mathrm{NC,CC}}$$

▷ detecting **CνB flux** - incoherent scattering - kton targets

$$R_{\nu_i}^{\mathrm{ic}} = N_T\, \langle |\vec{v}_{\nu_i}| \rangle_0\, \langle n_{\nu_i} \rangle_0\, \sigma_{\nu_i} \sim 3 \cdot 10^{-8}\ \mathrm{yr}^{-1}\, \left(\frac{m_{\nu_i}}{0.1\ \mathrm{eV}}\right) \left(\frac{N_T}{10^{33}}\right)$$

▷ using **CνB** as a **target** - collider experiment - TESLA, LHC, VLHC

$$R_{\nu_i\,\mathrm{beam}} \sim 10^{-11}\ \mathrm{yr}^{-1}\, \left(\frac{I}{\mathrm{Ampere}}\right) \left(\frac{L}{10\ \mathrm{km}}\right) \left(\frac{m_{\nu_i}}{0.1\ \mathrm{eV}}\right) \left(\frac{E_{\mathrm{beam}}}{1\ \mathrm{TeV}}\right) \left(\frac{\langle n_{\nu_i} \rangle_0}{56\ \mathrm{cm}^3}\right)$$

Mission impossible? $\Rightarrow$ **ways out**:

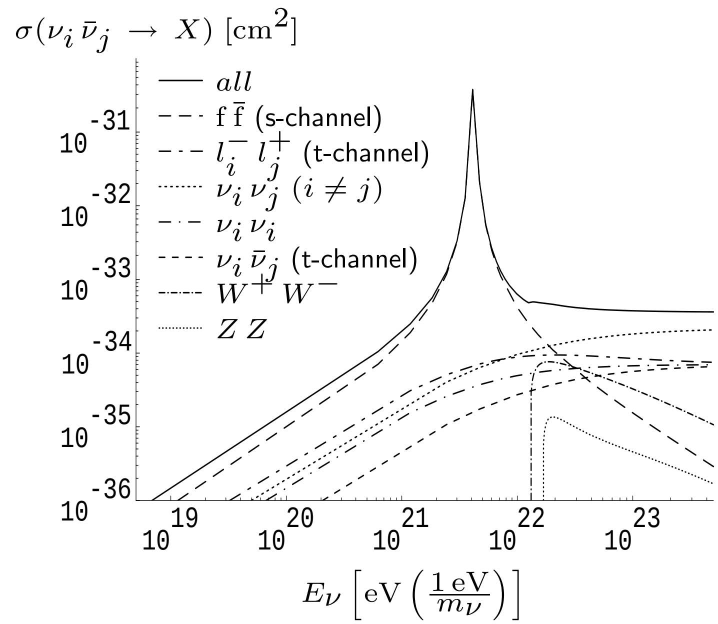
- **coherent scattering** - then: $R_\nu^{\mathrm{coh}} \propto N_T^2$
- **CνB as target** for **E**xtreme **E**nergy **C**osmic **R**ays (EECR), $\boldsymbol{E > 10^{19}}\,\mathrm{eV}$

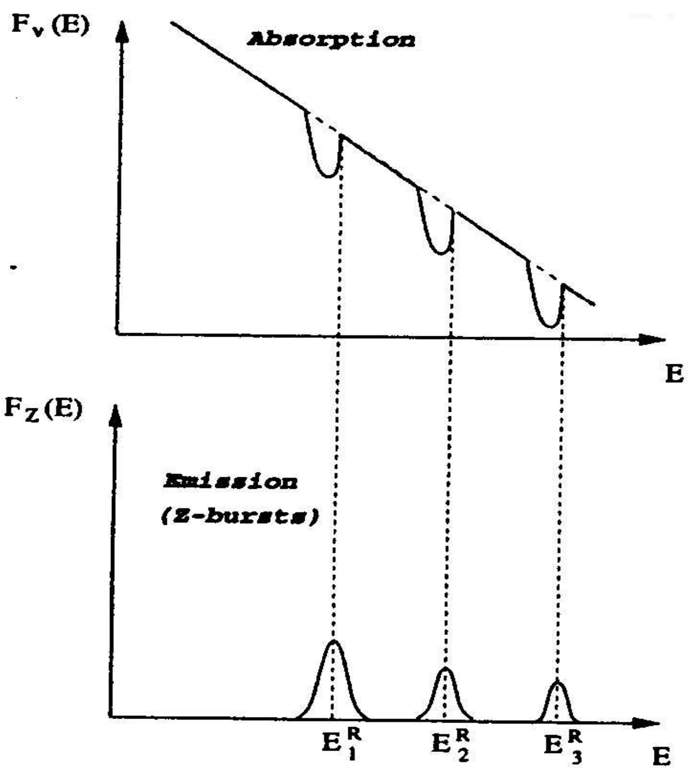
EECν scattering on the CνB

The annihilation of a cosmic ray ν with a relic $\bar{\nu}$ (or vice versa) on the Z-resonance

$\Rightarrow$ **large cross-section** at **resonant energies**

$$E_{\nu_i}^{\rm res} = M_Z^2/(2\,m_{\nu_i}) = 4.2\cdot 10^{21}\ {\rm eV}\,(1\ {\rm eV}/m_{\nu_i})$$





- **Absorption features (dips)** in the extreme energy cosmic neutrino spectrum at the **resonant energies**

  [Weiler '82; '84; Roulet '93; ...]

- **Emission features (Z-bursts)** as protons (or photons) above the Greisen-Zatsepin-Kuzmin-cutoff

  [Fargion,Mele,Salis '99; Weiler '99; . . . ; Fodor,Katz,Ringwald '01; '02]

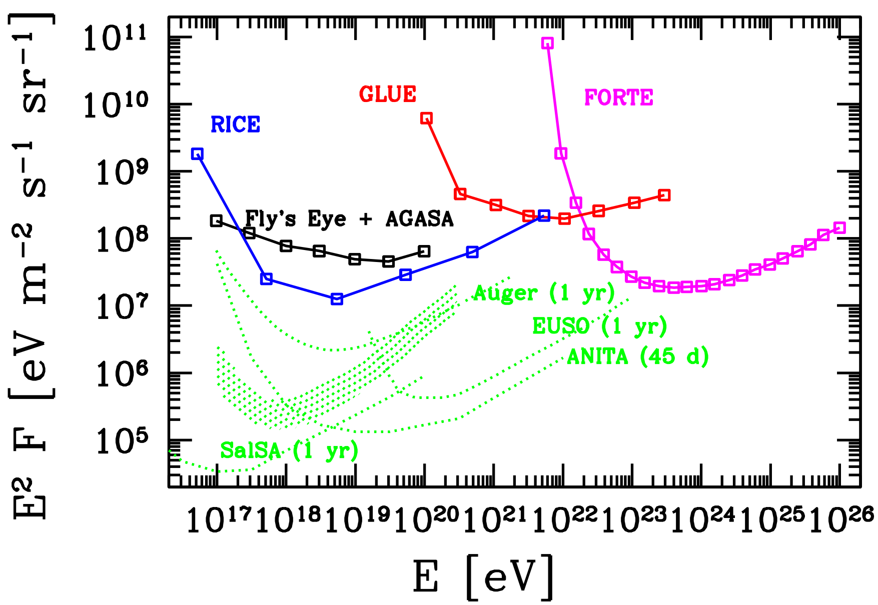
At present time - best opportunities for absorption dips

- Precise best fits of **cosmological values** determining the expansion rate

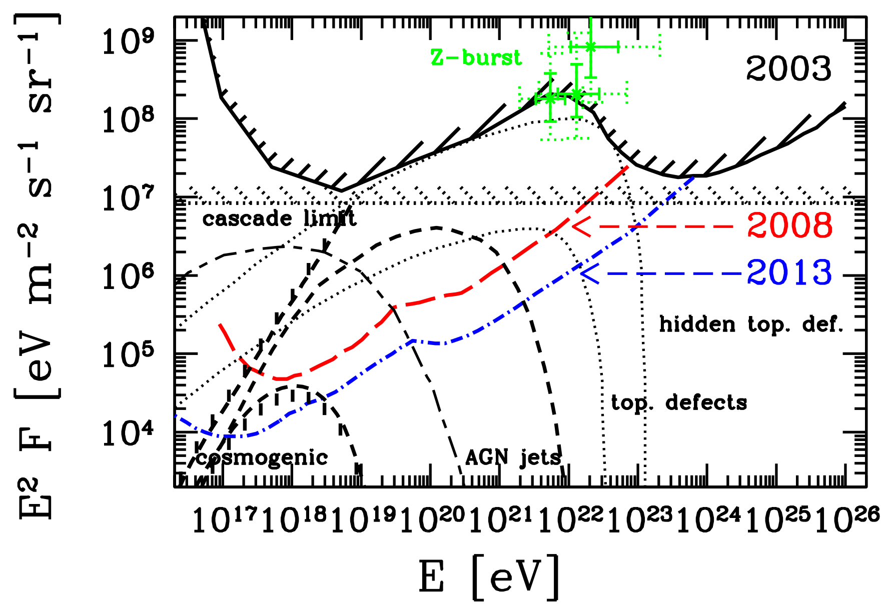
- **ν_3-mass** known to lie within an order of magnitude range

$$0.04 \text{ eV} \leq m_{\nu_3} \lesssim 0.4 \text{ eV} \quad \leftrightarrow \quad 1 \times 10^{22} \text{ eV} \lesssim E_{\nu_3}^{\text{res}} \leq 1 \times 10^{23} \text{ eV}$$

- **Experiments**: next decade - building phase for a lot of EECν detectors!



Current upper limits and future sensitivities



Current upper bound, improvement of the next decade, various proposals for fluxes

Outline of the talk

- Introduction
- Mathematical preparation:
  formulas, simplifications and parameterizations
- Results
- Conclusions

Flux formulae I

$$F_{\nu_\alpha}(E) \equiv \frac{\mathrm{d}^4 N_{\nu_\alpha}}{\mathrm{d}E\,\mathrm{d}A\,\mathrm{d}t\,\mathrm{d}\Omega} =$$

$$\frac{1}{4\pi}\int_0^\infty \mathrm{d}E_i \int_0^\infty \underbrace{\frac{\mathrm{d}z}{(1+z)\,\mathbf{H(z)}}}_{\mathrm{d}r} \sum_\beta \frac{-\,\partial \mathbf{P}_{\nu_\alpha|\nu_\beta}(\mathbf{E};\mathbf{E_i},\mathbf{z})}{\partial E}\;\mathcal{L}_{\nu_\beta}(\mathbf{z},\mathbf{E_i})$$

EECν source emissivity distribution:

$$\mathcal{L}_{\nu_\beta}(\mathbf{z},\mathbf{E_i}) \equiv \frac{\mathrm{d}^3 N_{\nu_\beta}}{\mathrm{d}V_{\mathrm{comov.}}\,\mathrm{d}t\,\mathrm{d}E_i}$$ injected at z from Earth with energy E_i

Propagation function:

$\mathbf{P}_{\nu_\alpha|\nu_\beta}(\mathbf{E};\mathbf{E_i},\mathbf{z}) \equiv$ expected N_{ν_α} above E if one ν_β started at z with E_i

Evolving Hubble parameter:

$$\mathbf{H(z)} = H_0\,\left[\Omega_M\,(1+z)^3 + \Omega_k\,(1+z)^2 + \Omega_\Lambda\right]^{1/2}$$

Assumptions and simplifications

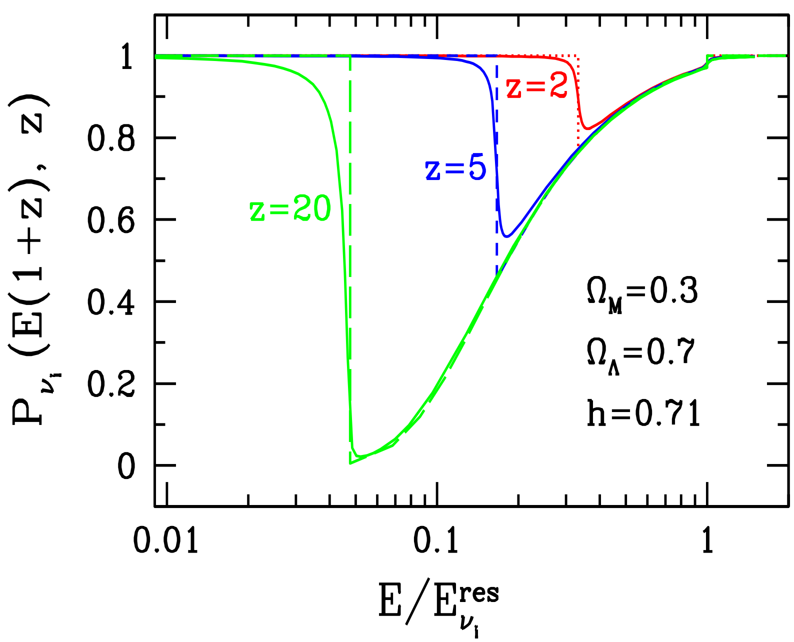
- Cross section **Z-resonance dominated**
- **Interaction = absorption**

  $\rightarrow$ energy loss only due to expansion, $E_i = E\,(1+z)$
- **Cosmological parameters**: $\Omega_M = 0.3,\ \Omega_\Lambda = 0.7$
- $\sum$ of flux detected $\rightarrow$ $\sum$ **leptonic mixing matrices** equal to **unity**

Flux formulae II - now simple

$$\sum_\alpha F_{\nu_\alpha}(E) \simeq \frac{1}{4\pi}\int_0^\infty \frac{\mathrm{d}z}{H(z)}\,\frac{1}{3}\,\mathcal{L}_\nu^{\rm tot}(z, E\,(1+z)) \times \sum_{j=1}^{3} P_{\nu_j}(E\,(1+z), z)$$

with



$$P_{\nu_j}(E\,(1+z), z) \simeq$$

$$\exp\left[-\left(\frac{\langle n_\nu\rangle_0\,\langle\sigma^{\rm ann}_{\nu\bar\nu}\rangle}{H_0}\right)\frac{\left(\frac{E^{\rm res}_{\nu_j}}{E}\right)^3}{\left[\Omega_M\left(\frac{E^{\rm res}_{\nu_j}}{E}\right)^3+\Omega_\Lambda\right]^{1/2}}\right]$$

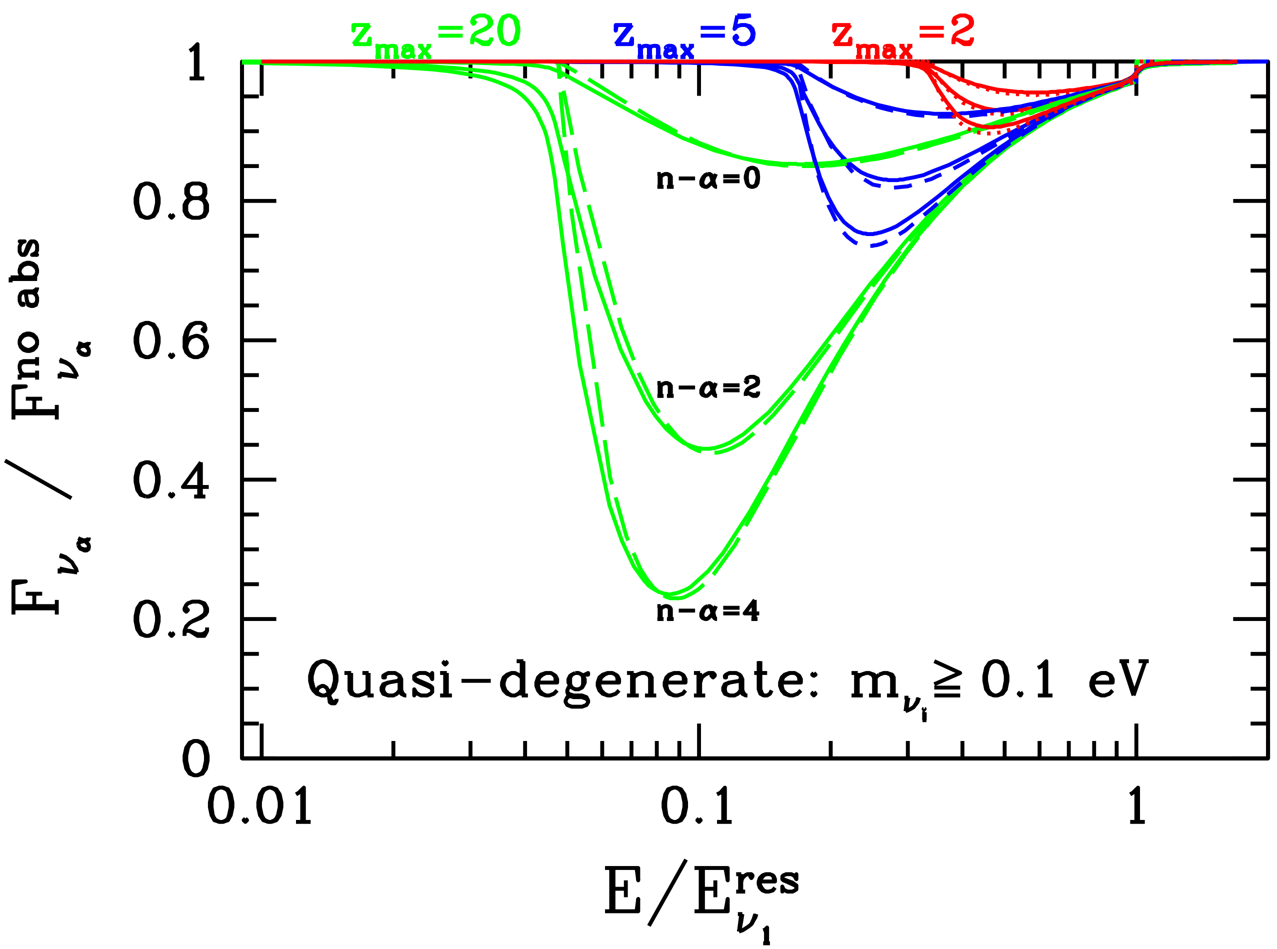
for $\frac{1}{1+z} < \frac{E}{E^{\rm res}_{\nu_j}} < 1\,,$

1 otherwise

Open parameters

- **Source emissivity parameters**
- ν**-mass spectrum**

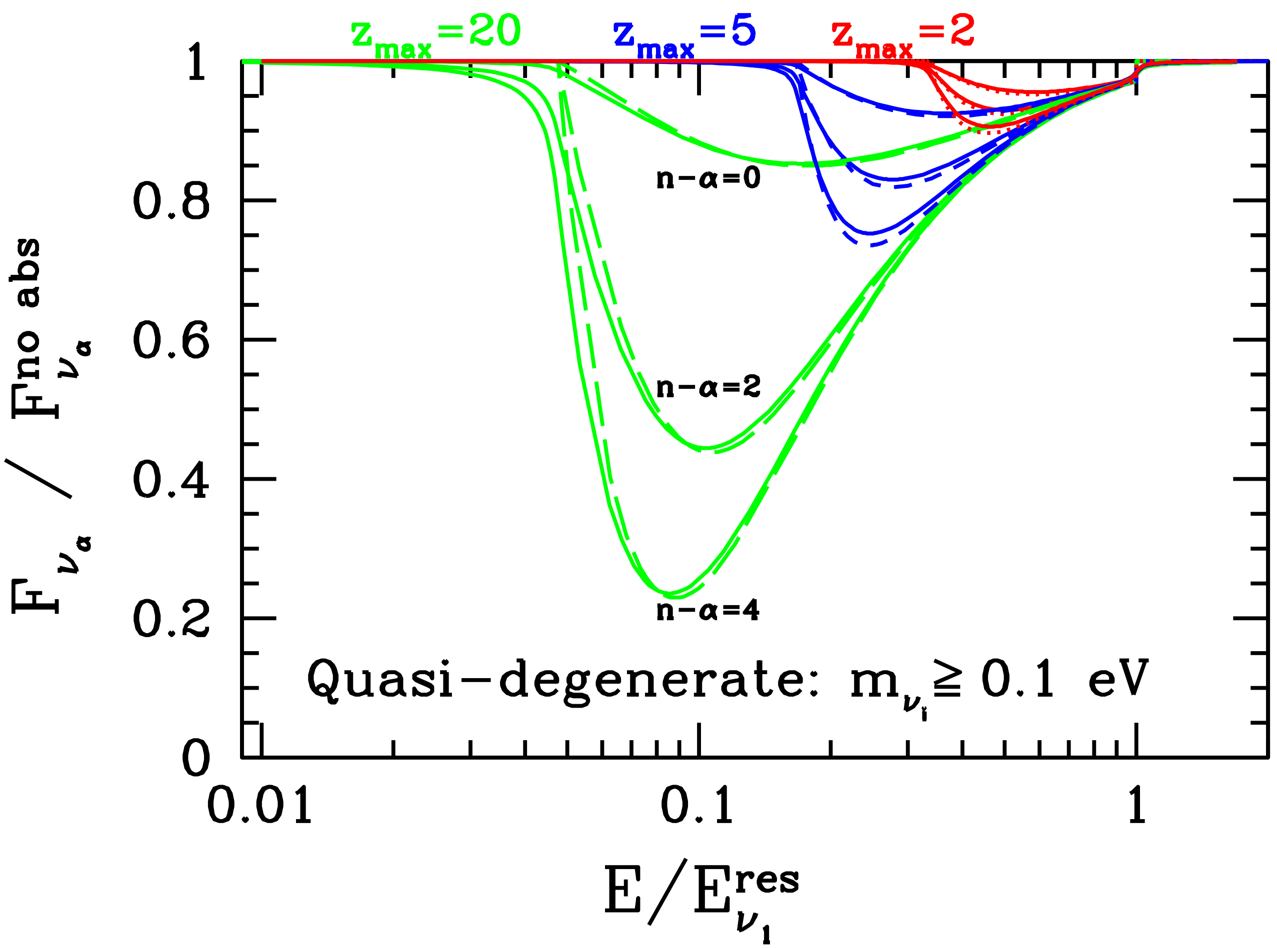
Case study - source emissivity



General features of the dip:

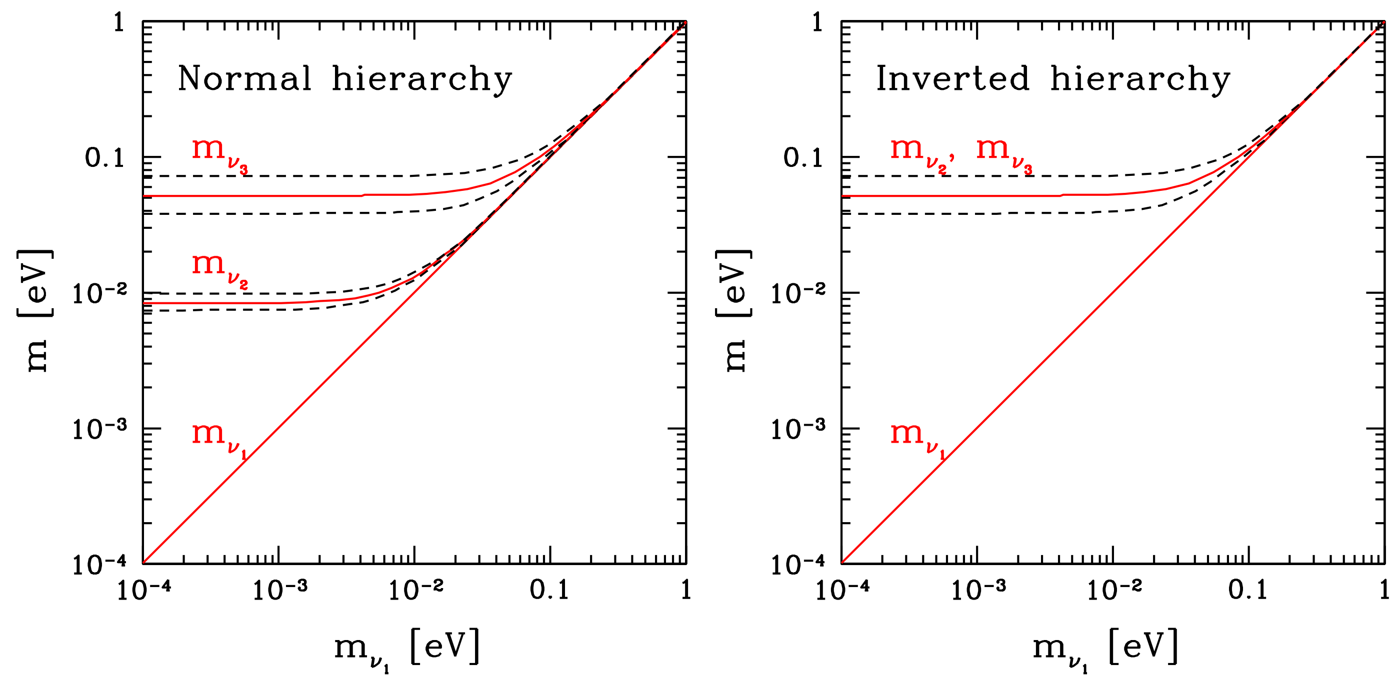
- $\frac{\langle n_\nu \rangle_0 \, \langle \sigma^{\rm ann}_{\nu\bar{\nu}} \rangle}{H_0} \simeq$ **3.0 %**
- **Depth**: large source evolution & flat energy spectrum
- **Magnification**: starts at early times & high cutoff energy

Open parameters - source emissivity: what is realized in Nature?



- **topological defects:**
  - low source evolution
  - starts at early times
  - cutoff energy large
- **astrophysical sources:**
  - large source evolution
  - starts at redshift time $z_{\max} = 2 \div 5$
  - cutoff energy low

Open parameters - neutrino masses

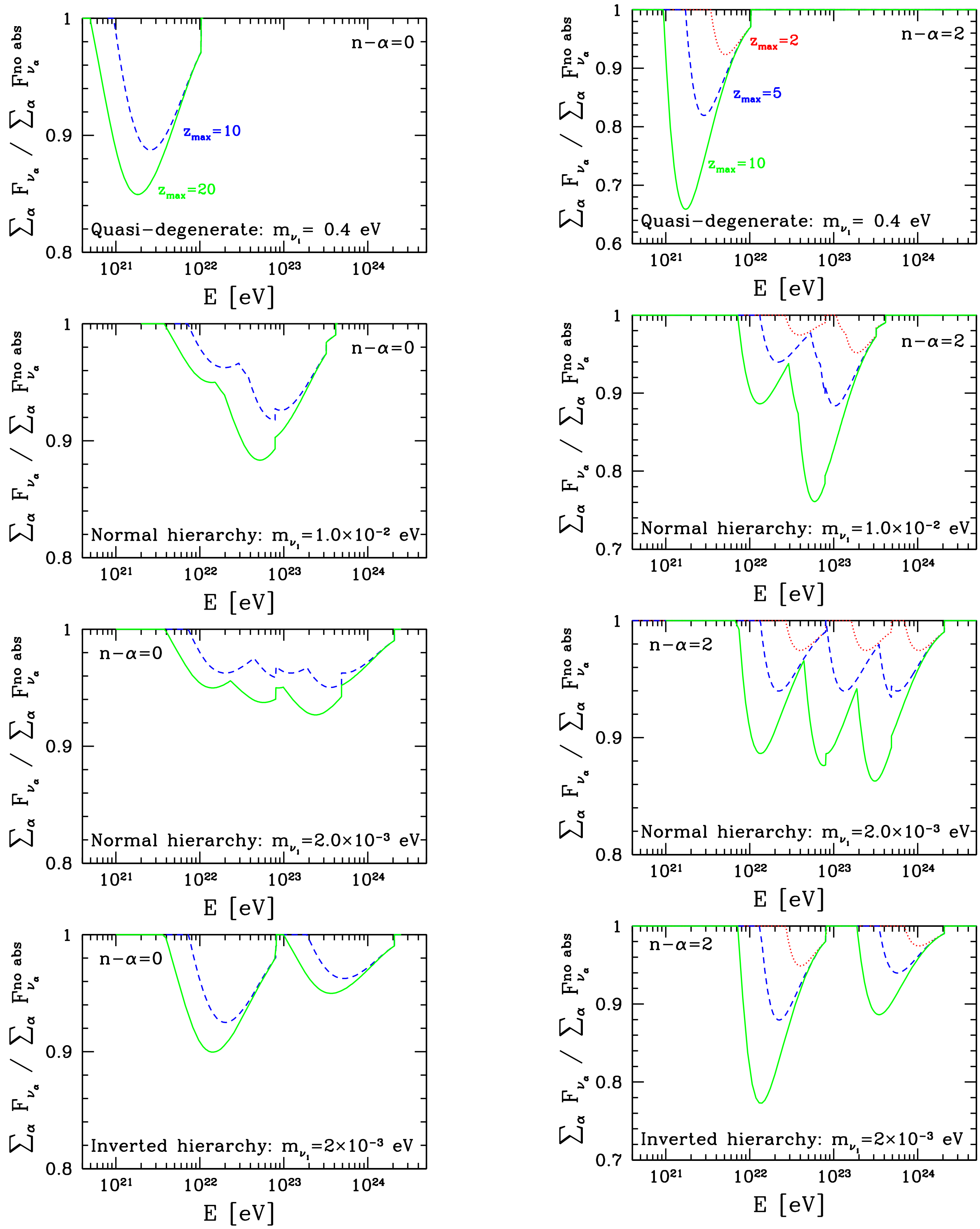


Allowed ranges for three neutrino masses in normal and inverted hierarchy

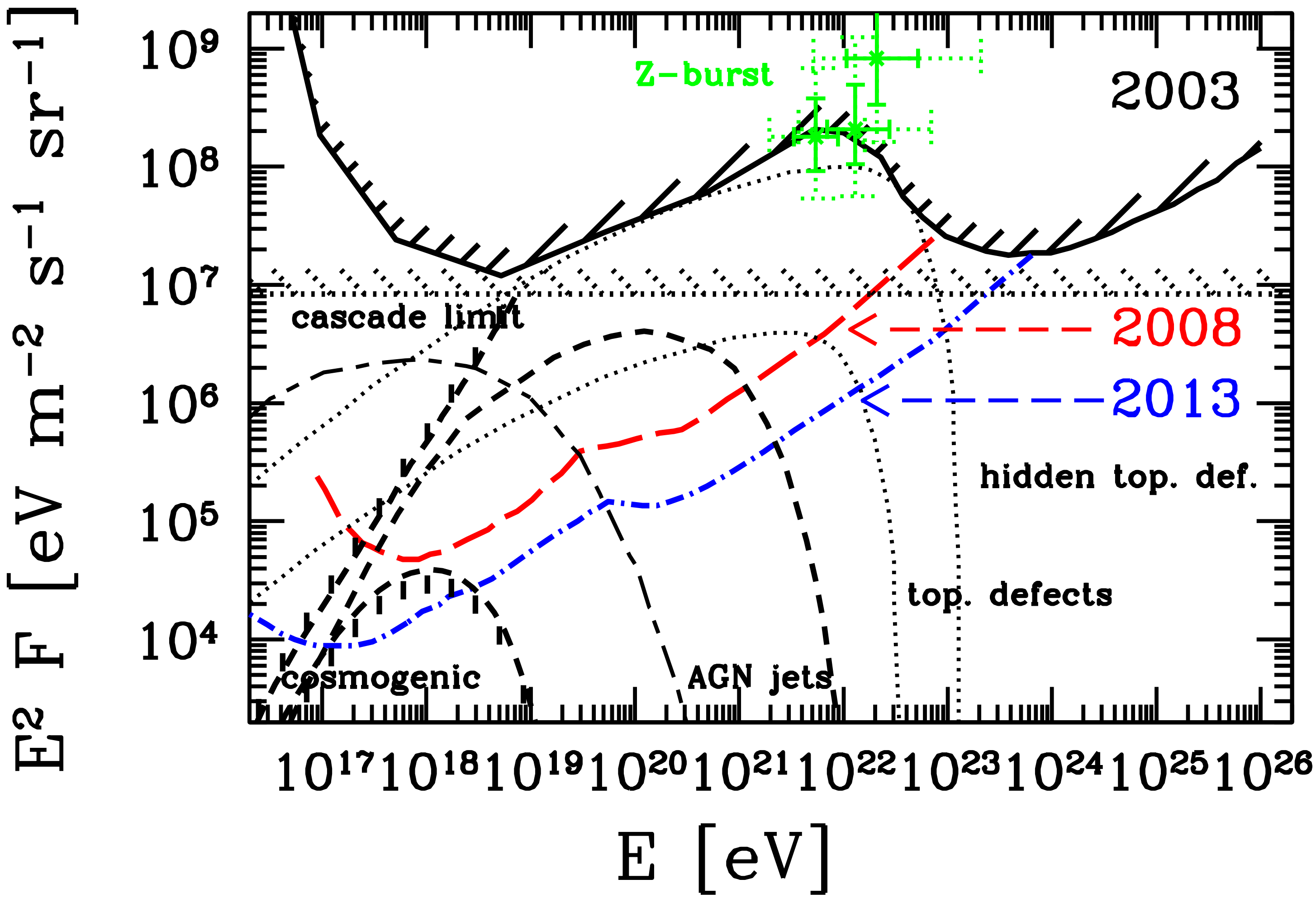
Case studies - different ν mass patterns

topol. defect source

acceleration source



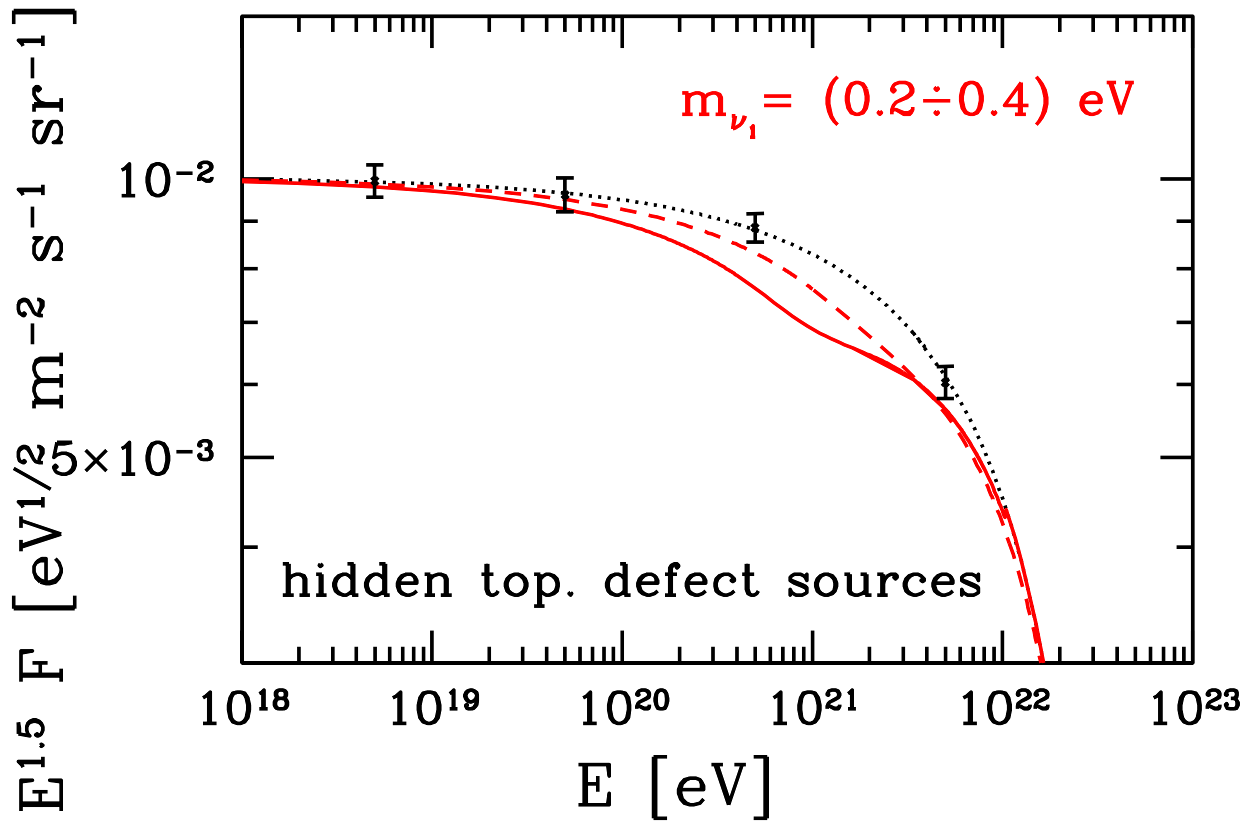
Open parameters - absolute scale of source emissivity



current observational upper bound, experimental sensitivities of 2008/2013, predictions of various EECν fluxes

Benchmark fluxes - optimistic scenario

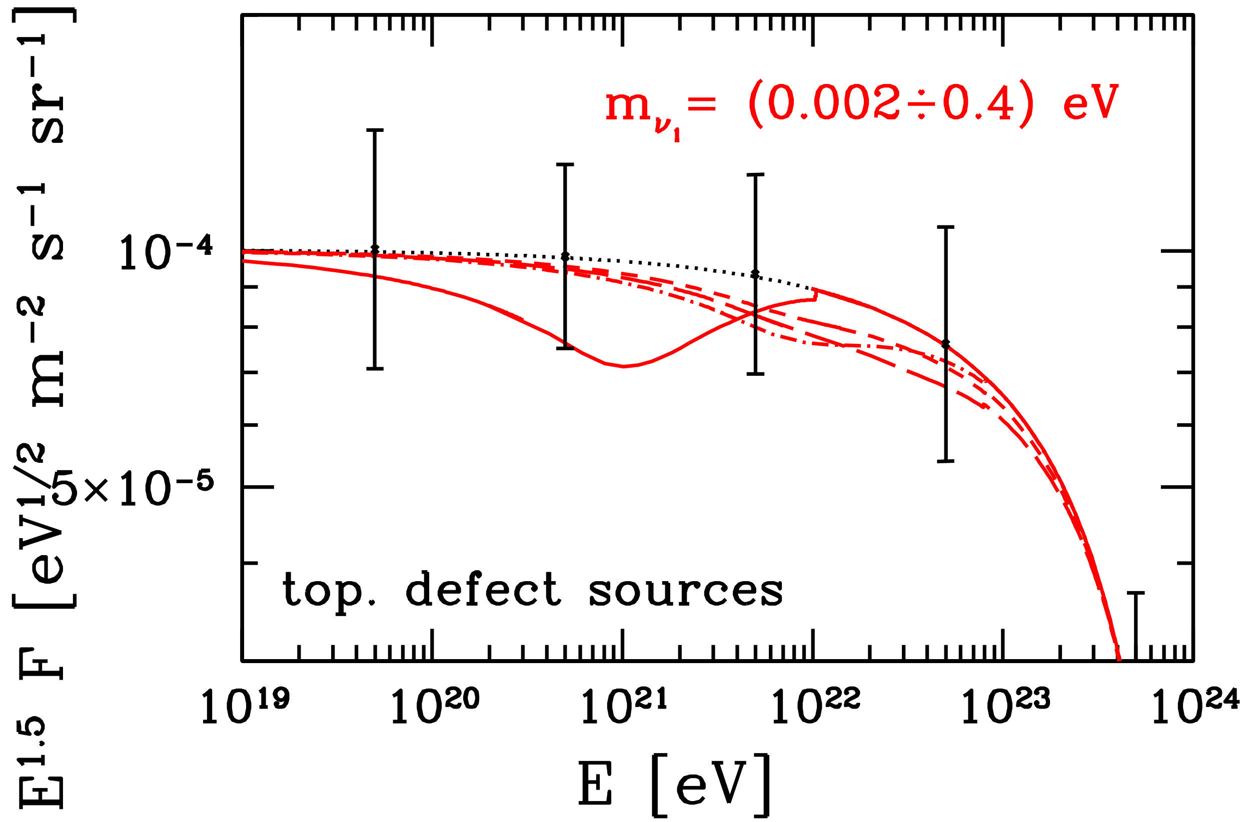
- **"Hidden" source:** ν flux touches the todays observational upper bound
- **Quasi degenerated** neutrino masses



$\rightarrow$ **observable by 2013!**

Benchmark fluxes - less optimistic scenario

- **Transparent source**: ν flux touches the cascade limit
- Different mass scenarios



→ looks nice, but statistics worse

Benchmark fluxes - less optimistic scenario

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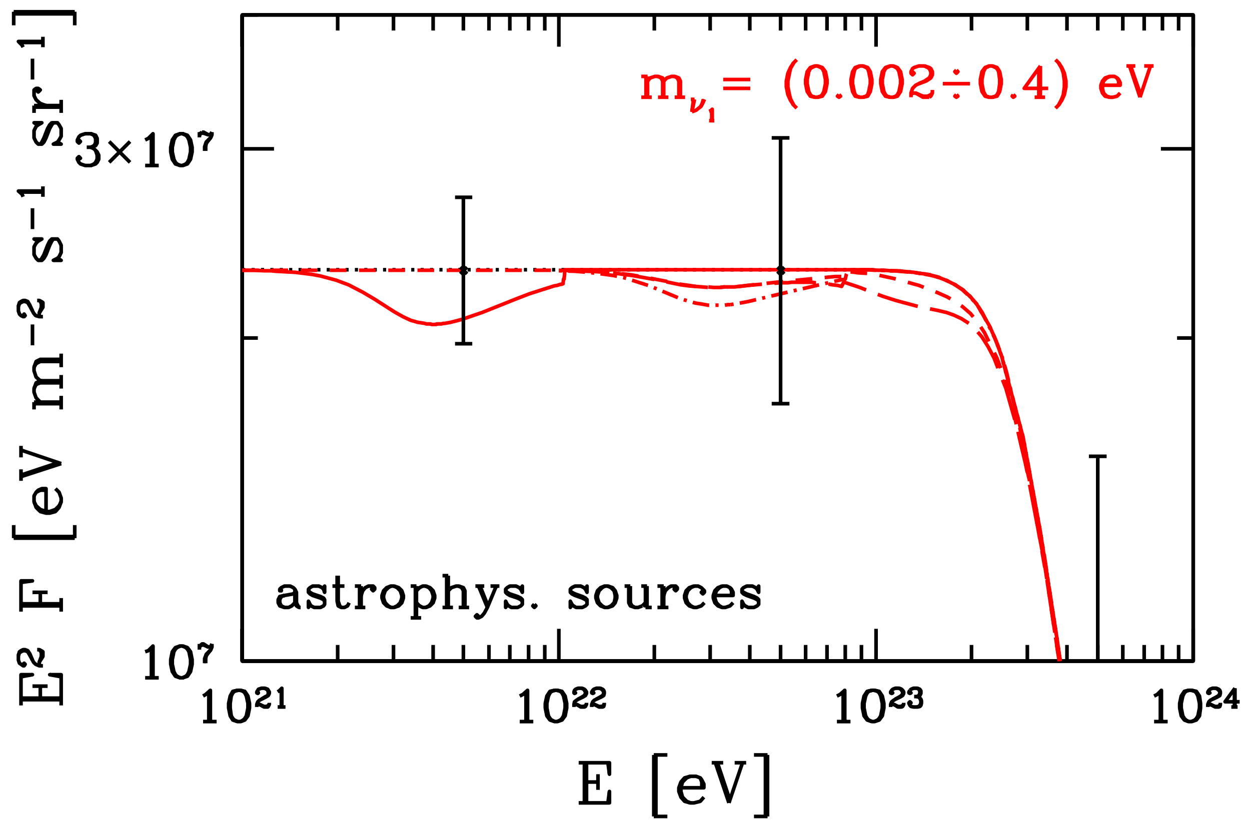

→ looks nice, but statistics worse

Conclusion

Detection of **CνB** might be feasible, furthermore:

absorption dips rich in **particle and astrophysical information**

- High energy edge of dip: ν mass
- Shape, depth: Cosmol.param., activity, inj. spectrum and ν mass pattern
- Width: source evolutionary history and ν mass spectrum

However, detection strongly dependent on statistics:

On the magnitude of the ν flux:
Flux needed: should touch cascade limit - better higher flux
$\rightarrow$ **Auger** should detect it within next few years

And on the depth of the dip:
ν **mass spectrum** - quasi deg. $\leftrightarrow m_{\nu_1} \gtrsim 0.1$ eV
$\rightarrow$ measures **KATRIN** in upcoming decade

In any case - next decade **exciting** and decisive for CνB detection!