Absolute neutrino masses from the highest energy cosmic rays

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1. Introduction

- **Big Bang Cosmology:**

  ⇒ Cosmic microwave background (**CMB**) radiation

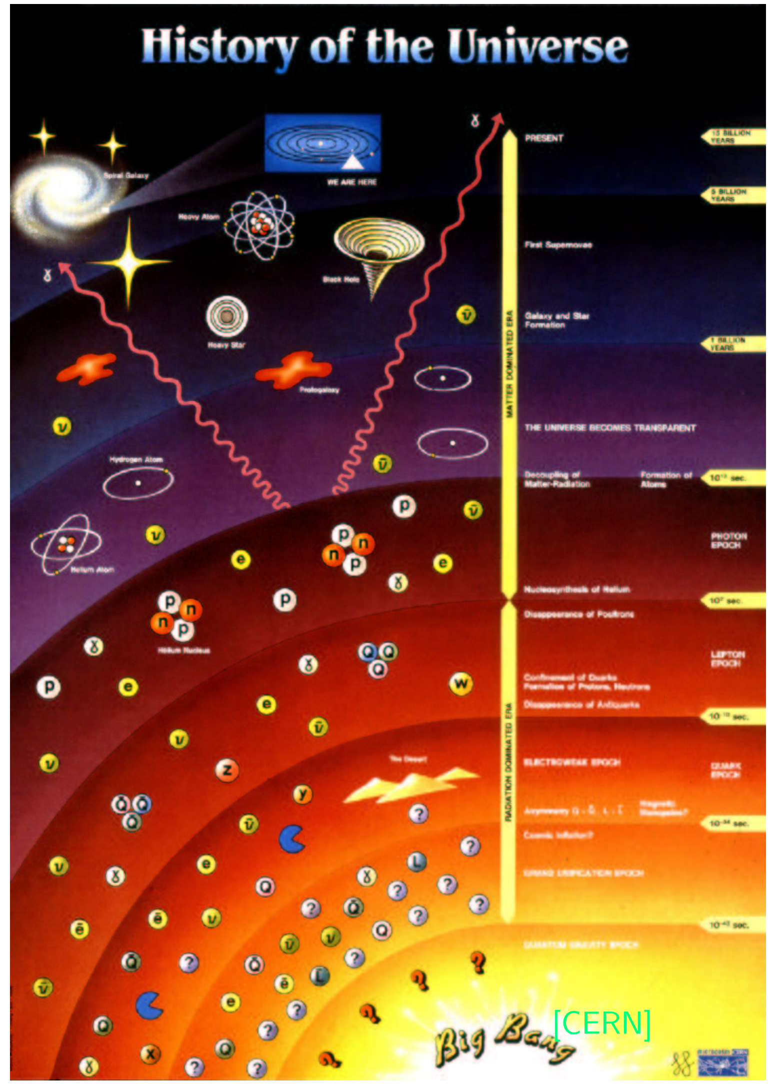
  ⇒ **Cosmological background of relic neutrinos (Rν)**, with

$$\langle n_{\nu_i}\rangle_0 = \langle n_{\bar{\nu}_i}\rangle_0 = \frac{3}{22}\underbrace{\langle n_\gamma\rangle_0}_{\text{CMB}} \simeq 56\ \text{cm}^{-3}\,,$$

  for neutrino types with $m_{\nu_i} < 1$ MeV.

  – **Not detected until now.**

  ⇐ **Neutrinos interact only weakly.**



- Indirect detection possibility:

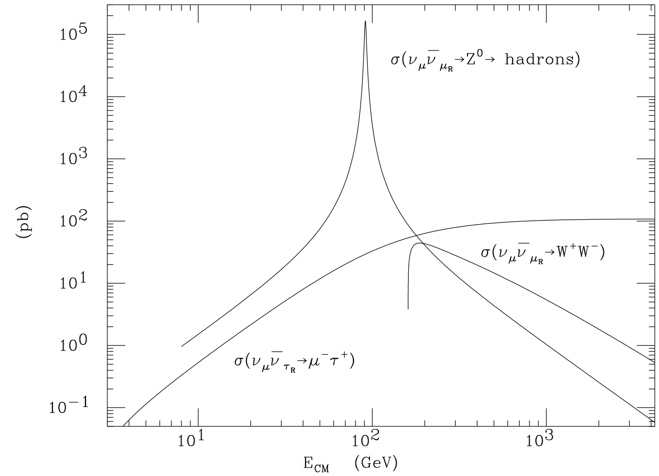
[Fargion,Mele,Salis '99; Weiler '99]

Resonant annihilation of ultrahigh energy cosmic neutrinos (**UHECν**) with relic neutrinos

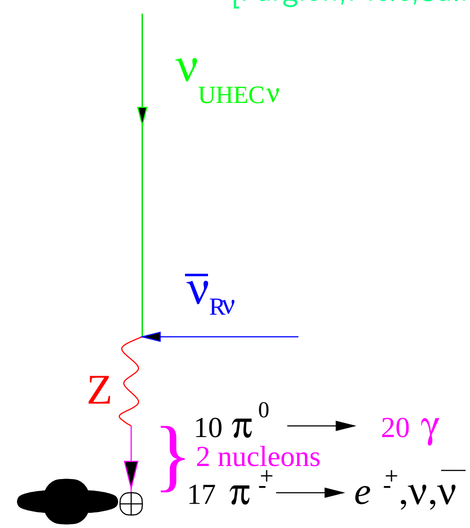
$$\underbrace{\nu_{\rm UHEC\nu}}_{E_\nu^{\rm res}} + \underbrace{\bar\nu_{\rm R\nu}}_{m_\nu} \to Z$$

at **resonant energies**

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



[Fargion,Mele,Salis '99]



- Resonant annihilation detectable in the spectrum of ultrahigh energy cosmic rays (**UHECR**)?

Z-burst hypothesis:

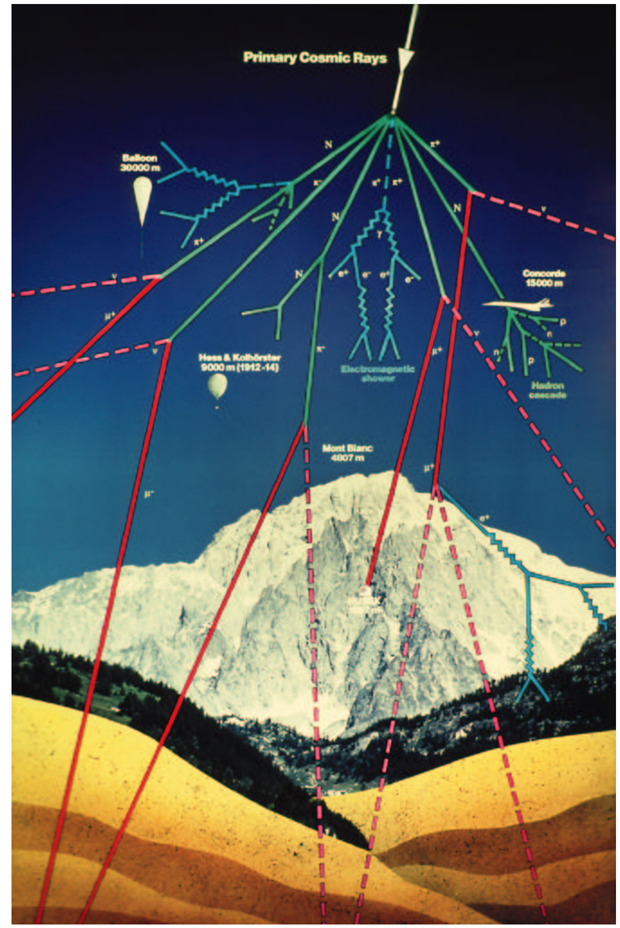
[Fargion, Mele, Salis '99; Weiler '99]

UHECR at energies above the Greisen-Zatsepin-Kuzmin-cutoff $\approx 4 \cdot 10^{19}$ eV are **protons and photons from Z-decay**.

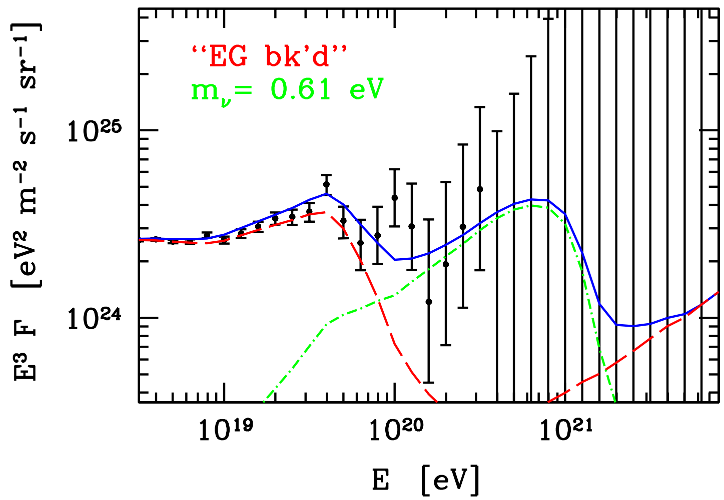
Various investigations:

[Waxman '98; Yoshida, Sigl, Lee '98; Gelmini, Kusenko '99, '00; Blanco-Pillado, Vásquez, Zas '00; Päs, Weiler '01; Fodor, Katz, Ringwald '01; Kalashev, Kuzmin, Semikoz, Sigl '01; . . .]

Extended air shower



[CERN]

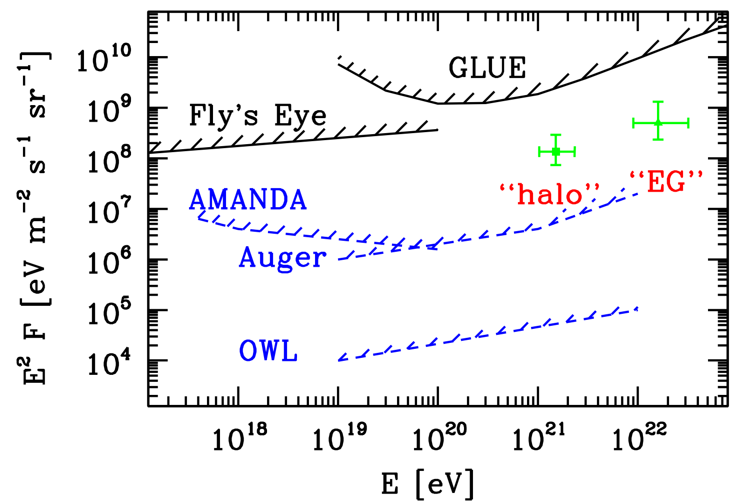


- Discuss here: [Fodor,Katz,Ringwald '01, in prep.]
  Comparison of the Z-burst spectrum + normal cosmic rays with **observed UHECR spectrum** (**AGASA, Fly's Eye, Haverah Park, HIRES**),

$$F(E) = F_{p|\rm normal}(E) + F_{p+\gamma|Z}(E; m_\nu, F_\nu)\,,$$

[Fodor,Katz,Ringwald, in prep.]

allows, in principle, determination of the **neutrino mass** m_ν and of the necessary **UHECν**-flux F_ν.



Neutrino oscillations and masses

- **Solar and atmospheric neutrino data:**

[Homestake,..., Gallex,..., SuperKamiokande, SNO,...]

$\Rightarrow$ Growing evidence for $m_{\nu_i} \neq 0$

$\Leftarrow$ Interpretation in terms of **neutrino oscillations**:

$$\triangle m^2_{\rm atm} = 10^{-2} \div 10^{-3}\ {\rm eV}^2$$
$$\triangle m^2_{\rm sol} = 10^{-11} \div 10^{-4}\ {\rm eV}^2$$

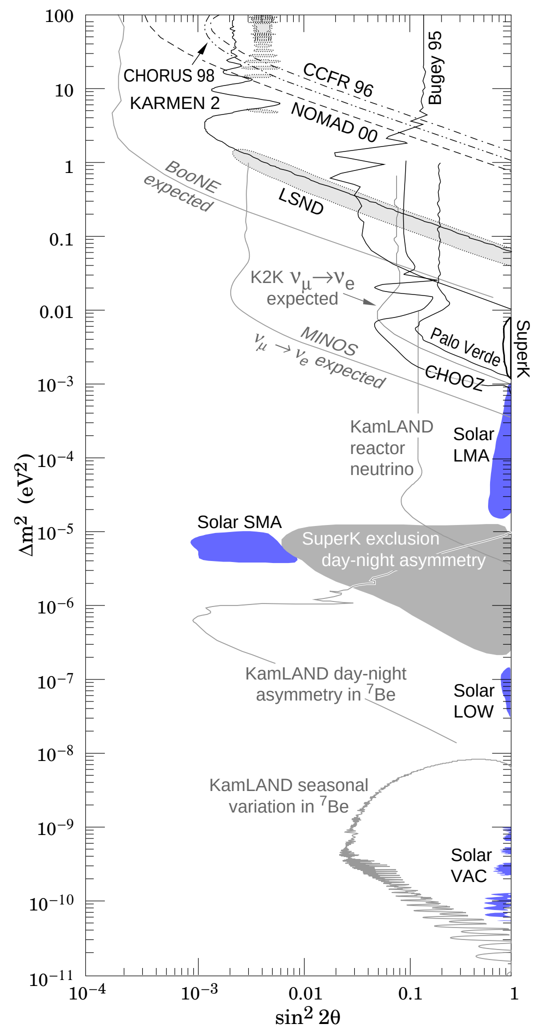
– Observations determine **only mass^2 differences**,

$$\triangle m^2_{ij} = m^2_{\nu_i} - m^2_{\nu_j}\ ,$$

but not absolute neutrino masses.

– Relations between neutrino masses, $m_{\nu_3} > m_{\nu_2} > m_{\nu_1}$, e. g. $m^2_{\nu_3} = m^2_{\nu_1} + \triangle m^2_{\rm atm}$, $m^2_{\nu_2} = m^2_{\nu_1} + \triangle m^2_{\rm sol}$, with **lower limit on heaviest neutrino**,

$$m_{\nu_3} > \sqrt{\triangle m^2_{\rm atm}} \sim 0.05\ {\rm eV}\ .$$



[Groom *et al.* '00]

Absolute neutrino masses

- **Cosmology** (**relic neutrinos:** $\Omega_\nu h^2 = \sum_i m_{\nu_i}/(94\text{ eV})$)

$$\sum_i m_{\nu_i} < 4.4 \text{ eV}$$

Future sensitivity: 0.3 eV [Hu,Eisenstein,Tegmark '98]

- **Astrophysics** (**supernovae explosions**)

Future sensitivity: 1 eV [Beacom *et al.* '00; Arnaud *et al.* '01]

- **Tritium β decay:** [Lobashev '99,Weinheimer '99,Mainz Exp. '00]

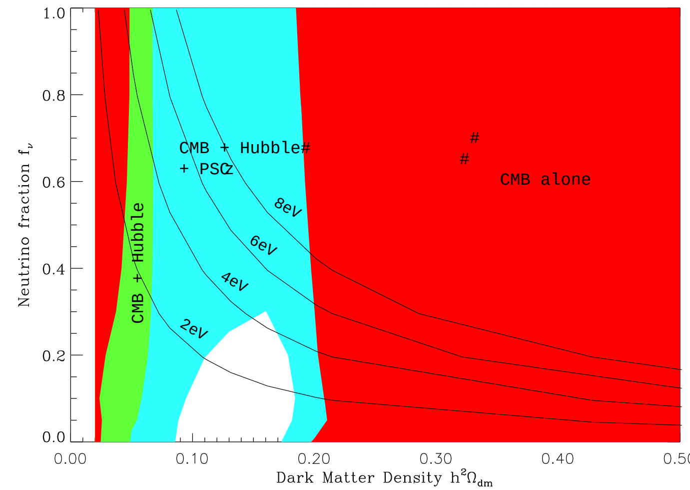
$$m_{\nu_e} = \sqrt{\sum_j |U_{ej}|^2 m_{\nu_j}^2} < 2.2 \text{ eV}$$

Future sensitivity: 0.3 eV [KATRIN]

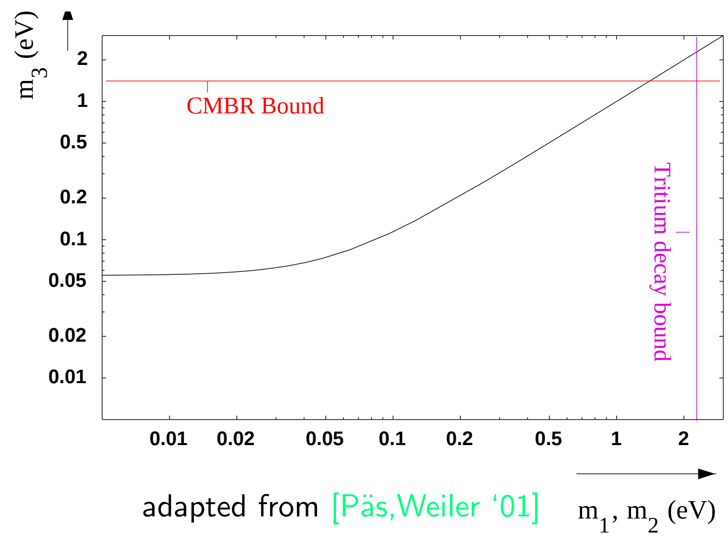
- **$0\nu\beta\beta$ decay:** [Klapdor-Kleingrothaus *et al.* '00]

$$m_{ee} = \left|\sum_j U_{ej}^2 m_{\nu_j}\right| < 0.27 \text{ eV}$$

Future sensitivity: 0.01 eV [GENIUS,EXO]



[Wang,Tegmark,Zaldarriaga '01]



adapted from [Päs,Weiler '01]

- **Further content:**

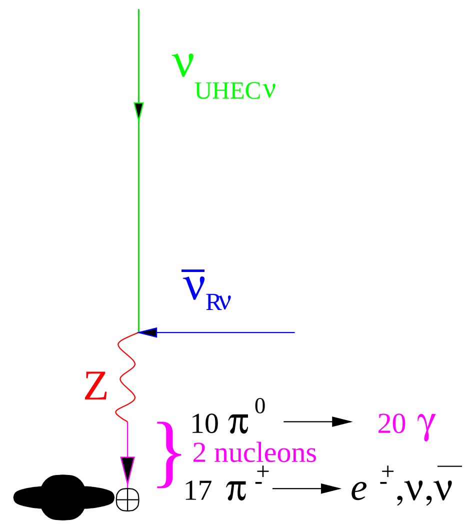
  2. **Z-burst spectrum**
  3. **Determination of m_ν and UHECν flux**
  4. **Conclusions**

2. Z-burst spectrum

- **Differential proton flux from Z-bursts, $\frac{\mathrm{d}N_{p|Z}}{\mathrm{d}E\,\mathrm{d}A\,\mathrm{d}t\,\mathrm{d}\Omega} = F_{p|Z}(E)$:**

$$F_{p|Z}(E) = \sum_i \int_0^\infty \mathrm{d}E_p \int_0^{R_0} \mathrm{d}r \int_0^\infty \mathrm{d}\epsilon\, F_{\nu_i}(E_{\nu_i}, r) n_{\nu_i}(r) \sigma(\epsilon) \mathcal{Q}(E_p) (-) \frac{\partial P(r, E_p; E)}{\partial E}$$

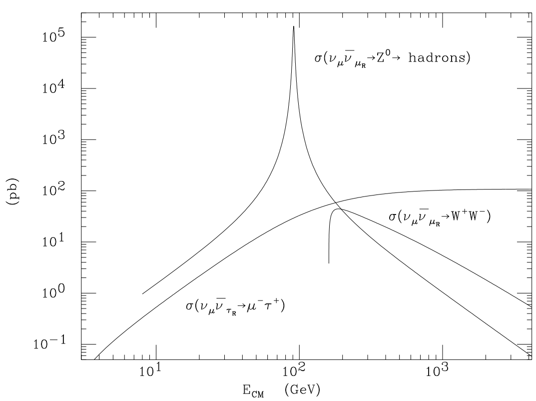
- **Ingredients:**
  - **UHECν** fluxes $F_{\nu_i}(E_{\nu_i}, r)$ at $E_{\nu_i} \approx E_{\nu_i}^{\rm res}$ at distance r
  - **Rν** number densities $n_{\nu_i}(r)$
  - Z production cross section $\sigma(\epsilon)$ at CM energy $\epsilon = \sqrt{2 m_{\nu_i} E_{\nu_i}}$
  - Energy distribution $\mathcal{Q}(E_p)$ of the protons produced with energy E_p
  - Probability $P(r, E_p; E)$, that a proton, produced at distance r with energy E_p, arrives at Earth above the threshold energy E
- **Similar for photons from Z-bursts**



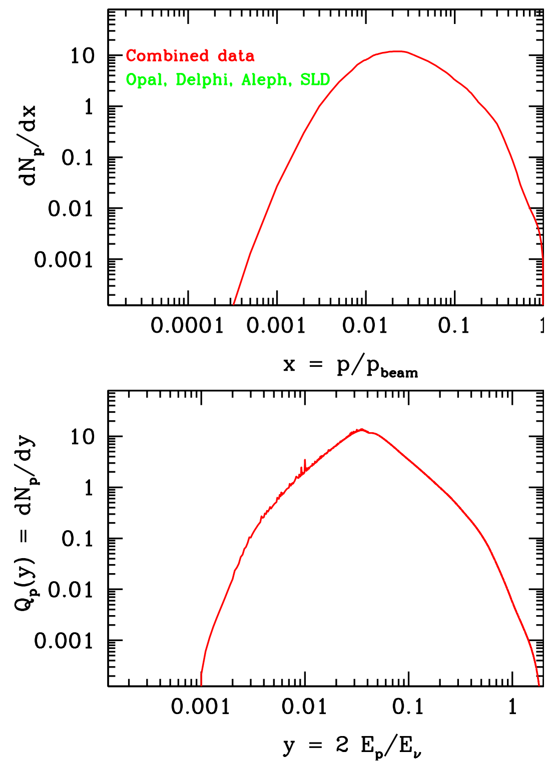
$$F_{p|Z}(E) = \sum_i \int_0^\infty \mathrm{d}E_p \int_0^{R_0} \mathrm{d}r \int_0^\infty \mathrm{d}\epsilon\, F_{\nu_i}(E_{\nu_i}, r) n_{\nu_i}(r) \sigma(\epsilon) \mathcal{Q}(E_p) (-) \frac{\partial P(r, E_p; E)}{\partial E}$$

- Energy distribution of protons $\mathcal{Q}(E_p)$ and π^0's ($\rightarrow \gamma$'s) from **precision data** (**LEP, SLC**)

  $\Rightarrow$ Uncertainties from Z production and Z decay negligible



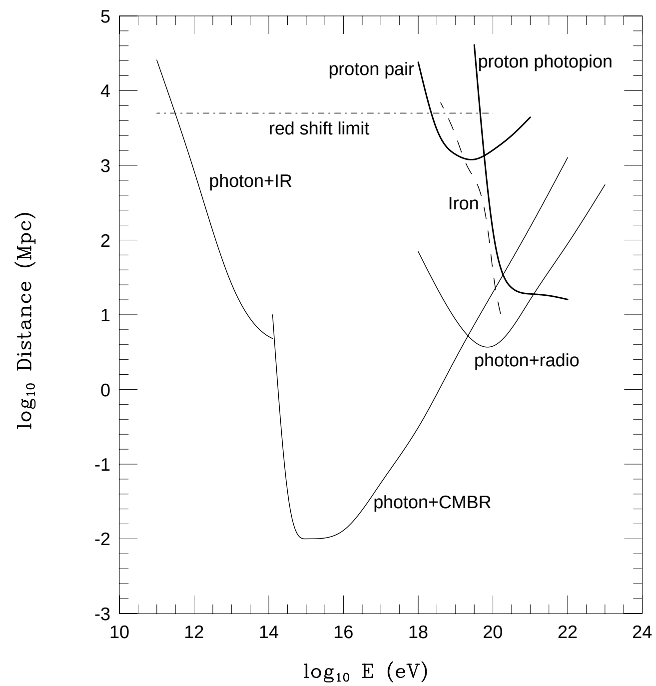
[Fargion,Mele,Salis '99]



[Fodor,Katz,Ringwald '01]

$$F_{p|Z}(E) = \sum_i \int_0^\infty \mathrm{d}E_p \int_0^{R_0} \mathrm{d}r \int_0^\infty \mathrm{d}\epsilon\, F_{\nu_i}(E_{\nu_i}, r) n_{\nu_i}(r) \sigma(\epsilon) \mathcal{Q}(E_p)(-)\frac{\partial P(r, E_p; E)}{\partial E}$$

- Probability $P(r, E_p; E)$, that a proton, produced at distance r with energy E_p, arrives at Earth above the threshold energy E [Bahcall,Waxman '00; Fodor,Katz '01]
  - Energy losses through
    - scattering on CMB
      - e^+e^- pair production
      - pion production (**GZK**)
    - redshift



[Pierre Auger Project Design Report]

- Similar quantity $P_\gamma(r, E_\gamma; E)$ for photon propagation [Fodor, Katz, Ringwald, in prep.]

Data: http://www.desy.de/~uhecr

$$F_{p|Z}(E) = \sum_i \int_0^\infty \mathrm{d}E_p \int_0^{R_0} \mathrm{d}r \int_0^\infty \mathrm{d}\epsilon \, F_{\nu_i}(E_{\nu_i}, r) n_{\nu_i}(r) \sigma(\epsilon) \mathcal{Q}(E_p) (-) \frac{\partial P(r, E_p; E)}{\partial E}$$

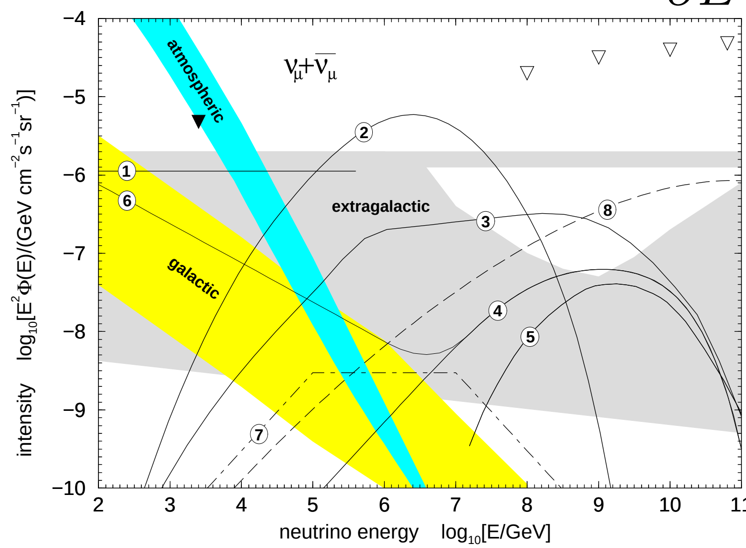
- **UHECν** fluxes $F_{\nu_i}(E_{\nu_i}, r)$ at $E_{\nu_i} \approx E^{\rm res}_{\nu_i}$ at distance r

- **Not known!** Therefore **ansatz**:

  $$F_{\nu_i}(E_{\nu_i}, r) = F_{\nu_i}(E_{\nu_i}) \, (1+z)^\alpha$$

  z ... redshift; $R_0 \leftrightarrow z = 2$

- Flux at zero redshift, $F_Z = \sum_i F_{\nu_i}(E^{\rm res}_{\nu_i})$, from later fit on **UHECR** data

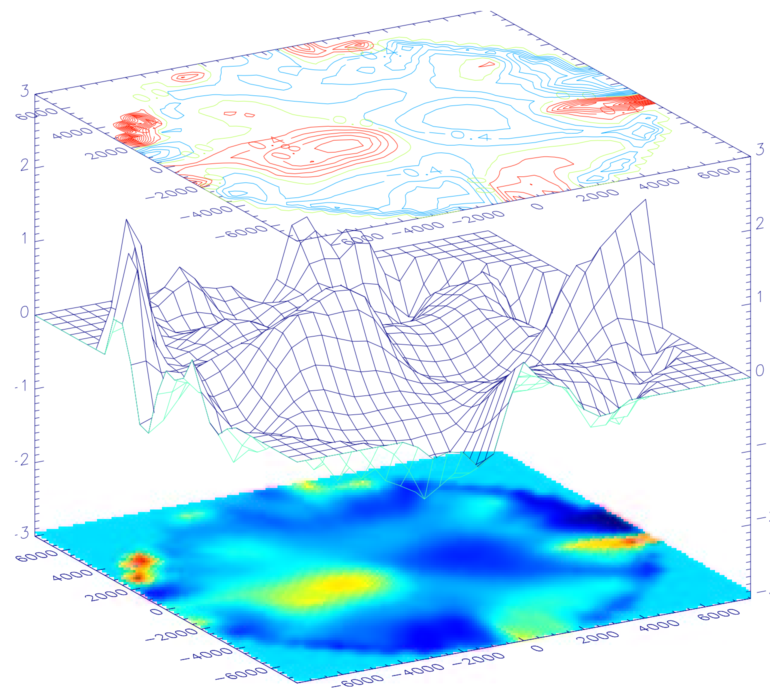


[Learned,Mannheim '00]

- **Expected neutrino fluxes:**
  - Active galactic nuclei (**AGN**): 1-4, 6
  - Interaction of **UHECR**s with **CMBR**: 5
  - Gamma ray burst (**GRB**) model: 7
  - Neutrinos from topological defects: 8
  - Theoretical bounds on fluxes: shaded

$$F_{p|Z}(E) = \sum_i \int_0^\infty \mathrm{d}E_p \int_0^{R_0} \mathrm{d}r \int_0^\infty \mathrm{d}\epsilon\, F_{\nu_i}(E_{\nu_i}, r) n_{\nu_i}(r) \sigma(\epsilon) \mathcal{Q}(E_p)(-)\frac{\partial P(r, E_p; E)}{\partial E}$$

- **Rν** number densities $n_{\nu_i}(r)$
  - **Rνs hot dark matter $\Rightarrow$ less clustered** than cold dark matter
  - For $r < 100$ Mpc:
    Vary shape between homogeneous case and $\mathcal{M}_{\rm tot}(r)$ from measurements of peculiar velocities; **overdensities at most a factor $2 \div 3$**
  - For $r > 100$ Mpc:
    $n_{\nu_i} = 56 \cdot (1+z)^3$ cm^{-3}



[Da Costa *et al.* '96]

3. Determination of m_ν and UHECν flux

- Compare Z-burst spectrum with **observed UHECR** spectrum

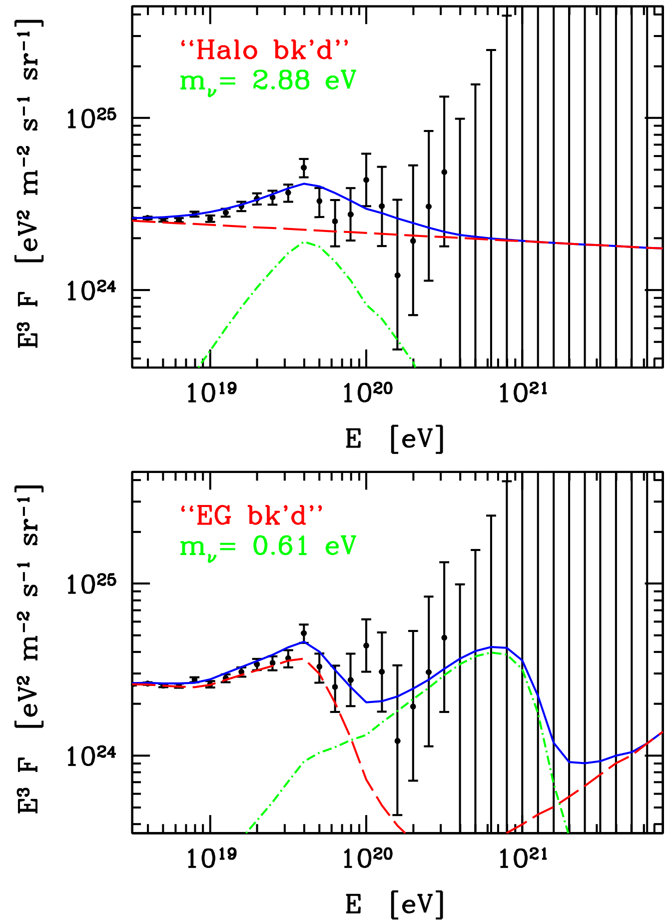
$$F_{\rm pred}(E) =$$

$$F_{p|{\rm norm}}(E) + F_{p+\gamma|Z}(E; m_\nu, F_Z)$$

  - **Halo:** $F_{p|{\rm norm}}(E) = A \cdot E^{-\beta}$
  - **Extragalactic (EG):** $A \cdot E_p^{-\beta}$ as **injektion** spectrum; modified through $P(r, E_p; E)$

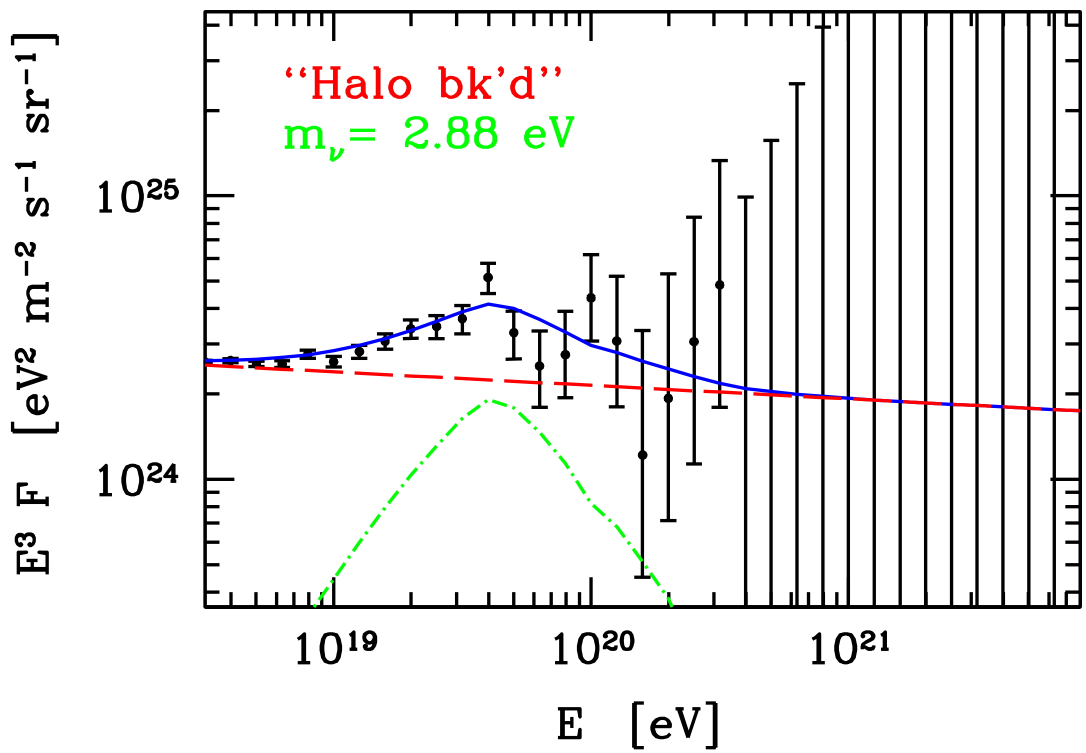
- **UHECR** data: **AGASA, Fly's Eye, Haverah Park, HIRES** 17/03/01

- Maximum-likelihood analysis with four parameters, $\chi^2(A, \beta, F_Z, m_\nu)$



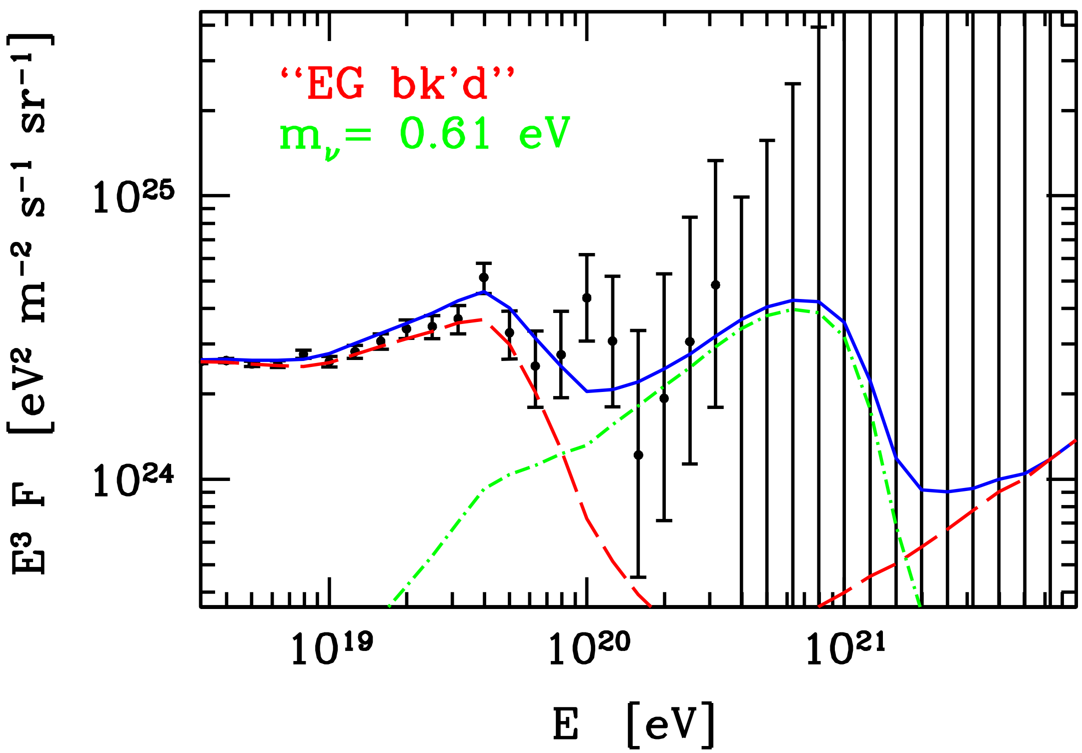
- **Halo:**

$m_\nu = 2.88^{+1.25(3.01)}_{-0.43(0.55)}$ eV; $\beta = 3.048$; $\chi^2_{\min} = 19.17$



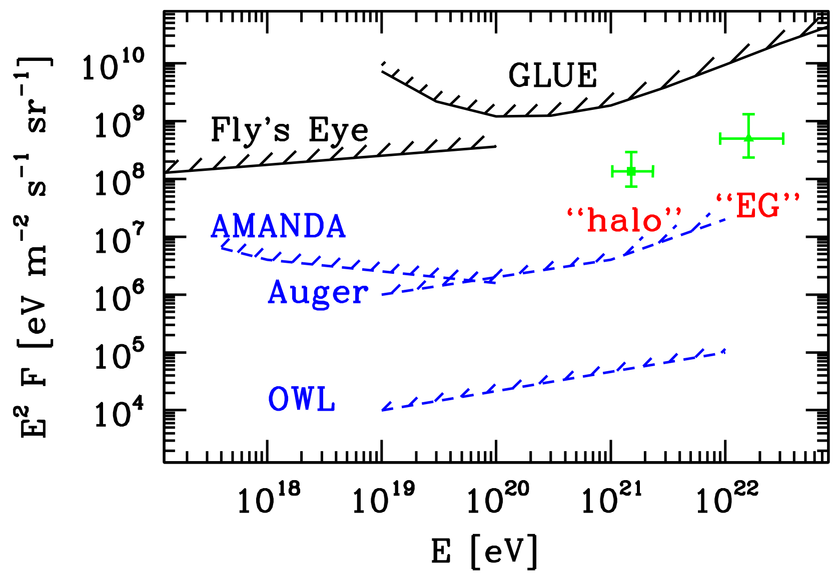
- **EG:**

$m_\nu = 0.61^{+0.25(0.59)}_{-0.24(0.43)}$ eV; $\beta = 2.526$; $\chi^2_{\rm min} = 25.21$



- **Best fits:**

Halo UHECR background	
with UHEγ	w'out UHEγ
$2.88^{+1.25(3.01)}_{-0.43(0.55)}$ eV	$2.75^{+1.28(3.15)}_{-0.97(1.89)}$ eV
EG UHECR background	
with UHEγ	w'out UHEγ
$0.61^{+0.25(0.59)}_{-0.24(0.43)}$ eV	$0.26^{+0.20(0.50)}_{-0.14(0.22)}$ eV

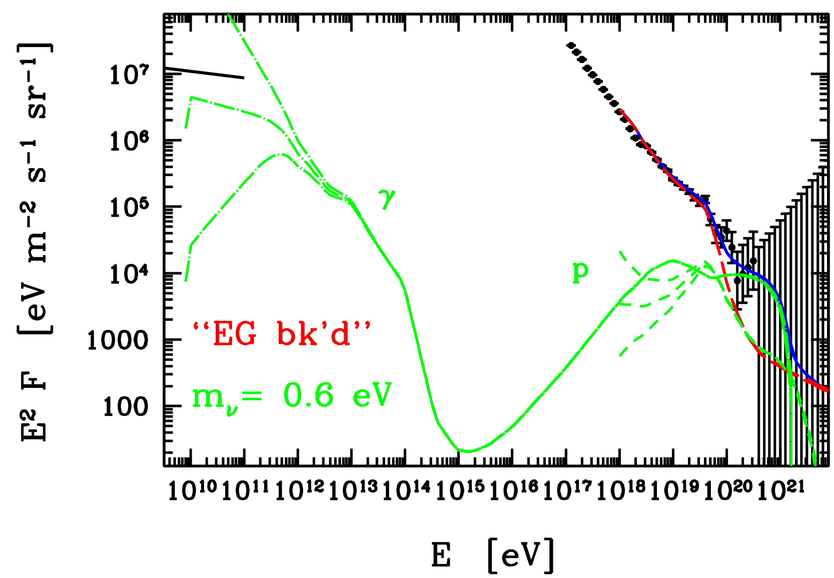


- **UHECν fluxes from F_Z:**

  Necessary fluxes well below present upper bounds, but in reach of **AMANDA, Auger, OWL**

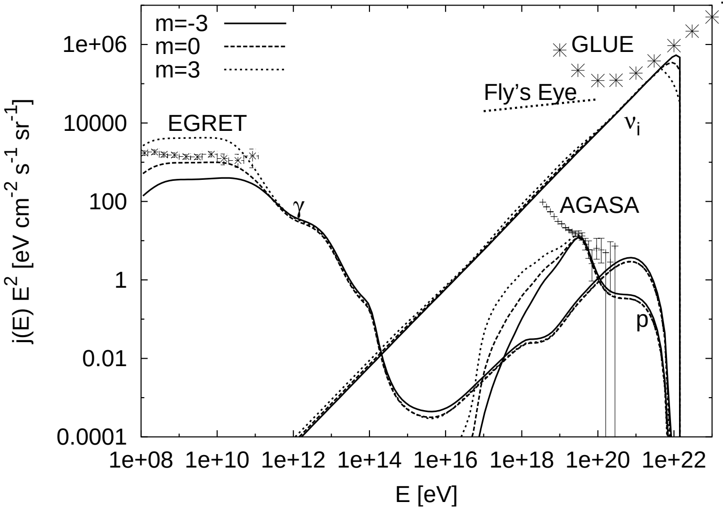
- **Photon flux**:

  Below observation in **EGRET** region (30 MeV $\div$ 100 GeV), as long as cosm. evolution parameter $\alpha \lesssim 0$

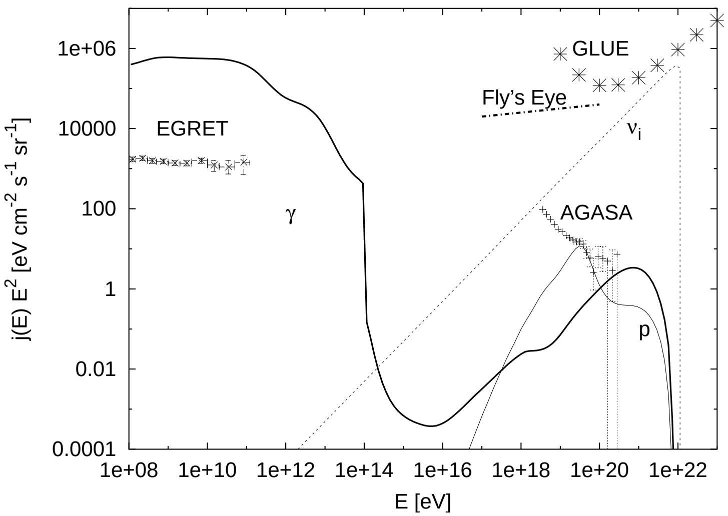


- Quantitative agreement with recent numerical calculations of Z-burst spectra: [Kalashev,Kuzmin,Semikoz,Sigl '01]
  - Z-burst scenario works without unrealistic neutrino clustering for $m_\nu = \mathcal{O}(1)$ eV.
  - Tremendous **UHECν** flux required:
    - ∗ **Astrophysical sources** should
      - · have distribution with $\alpha \lesssim 0$,
      - · acc. protons to $\gtrsim 10^{23}$ GeV,
      - · be opaque to primary protons,
      - · emit secondary photons only in sub-MeV region.
    - ∗ Alternatively, invoke **superheavy relic particle decay as source**

[Gelmini,Kusenko '00]



[Kalashev *et al.* '01]



[Kalashev *et al.* '01]

4. Conclusions

- **Z-burst hypothesis**, **if** true:
  - Indirect detection of relic neutrinos.
  - Absolute determination of the mass of the heaviest neutrino.
  - Determination of the neutrino-flux at ultrahigh energies.
- Future tests:
  - **UHECν-flux:**
    - ∗ Detection at neutrino-telescopes (**AMANDA**, . . .) or at air shower experiments (**Auger**, . . .)
  - **Mass:**
    - ∗ Compatibility with neutrino oscillation experiments ($\Rightarrow \triangle m_{ij}^2$)
    - ∗ Laboratory experiments (**EXO, GENIUS, KATRIN**) on neutrino mass with projected sensitivities of $m_\nu \approx 0.01 \div 0.3$ eV.
    - ∗ Cosmological investigations (large scale cosmic structure) with projected sensitivities of $\sum m_\nu \approx 0.3$ eV.