Z-bursts from the Virgo cluster

[revealing the cosmic neutrino background with EHE neutrinos]

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in collaboration with

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[PRD in press, astro-ph/0505563]

COSMO 2005, Bonn

The inevitable Z-burst… …the basics

A standard model interaction:

$$\nu_{\mathrm{EHE}\nu} + \bar{\nu}_{\mathrm{C}\nu\mathrm{B}} \xrightarrow{\sqrt{2E_\nu m_\nu}=m_Z} Z \xrightarrow{70\ \%} \text{hadrons} \tag{1}$$

- Cosmic neutrino background (CνB) $\Leftarrow$ fundamental prediction like CMB.
- Extremely high energy neutrinos (EHEν) $\Leftarrow$ possible, natural in GUTs.
- Neutrino mass (m_ν) $\Leftarrow$ oscillations experiments, $m_\nu \gtrsim 0.05$ eV.

$$E_{\nu_i}^{\mathrm{res}} = \frac{m_Z^2}{2m_{\nu_i}} = 4.2 \times 10^{21} \left(\frac{\mathrm{eV}}{m_{\nu_i}}\right) \ \mathrm{eV}. \tag{2}$$

(cf. $E_{\mathrm{UHECR}} \sim 10^{20}$ eV.)

Observables:

- Emission features: nucleons & photons, "Z-bursts".
- Absorption features in EHEν flux, "Z-dips".

Z phenomenology: unique sensitivity to the CνB! [Weiler 1982]

The inevitable Z-burst... ...more basics

Emissions, $\psi = N, \gamma$:

$$F_{\psi|Z}(E,\theta,\phi) \simeq \sum_i \mathrm{Br}(Z \to \text{hadrons}) \, \langle \sigma_{\text{ann}} \rangle \, E_{\nu_i}^{\text{res}} \, F_{\nu_i}^{\text{res}} \times \tag{3}$$

$$\int dE_\psi \int dr \, [1+z(r)]^\alpha \, n_{\nu_i}(r,\theta,\phi) \, \frac{2}{E_{\nu_i}^{\text{res}}} Q(y) \, \left| \frac{\partial P_\psi(r, E_\psi; E)}{\partial E} \right| .$$

CνB: $n_{\nu_i}(r,\theta,\phi) \simeq \langle n_{\nu_i} \rangle \simeq \langle n_{\bar{\nu}_i} \rangle \simeq 56 \text{ cm}^{-3}$ (??)

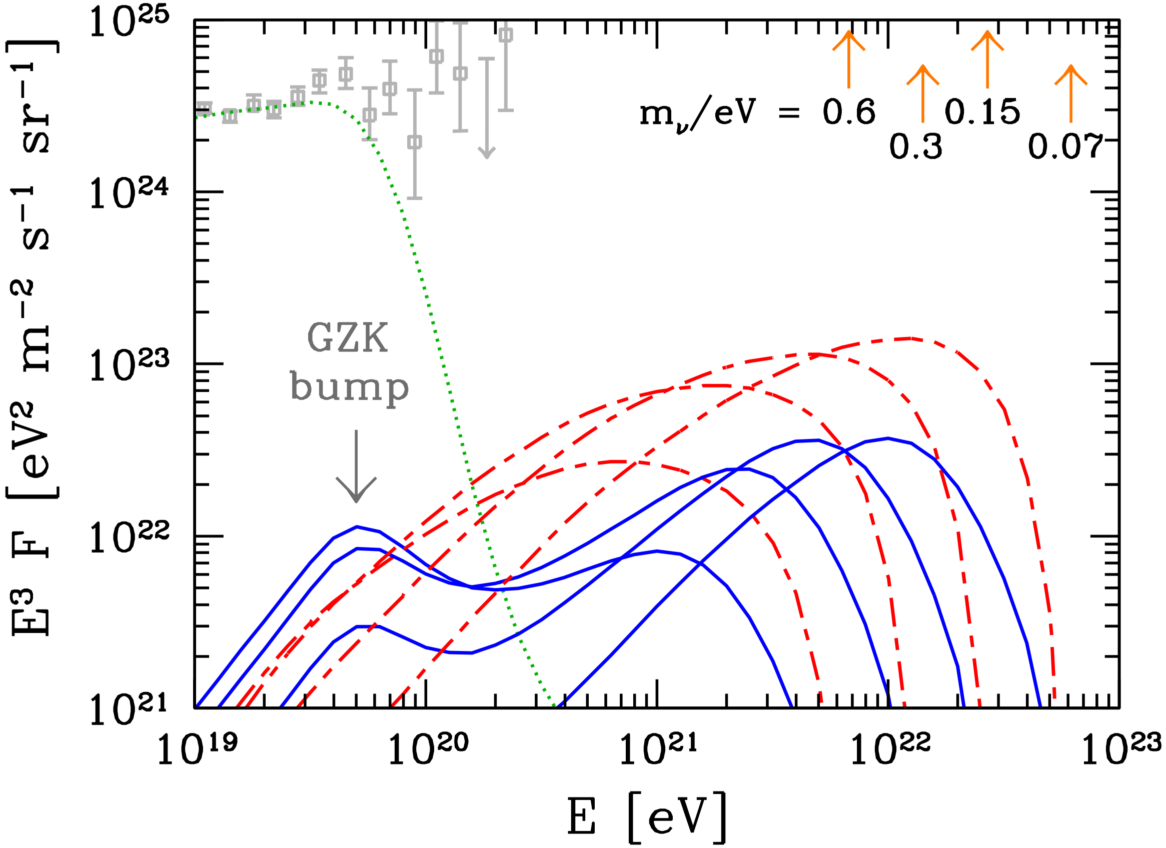
EHEν flux:

- $\star$ $F_\nu^{\text{res}} \equiv F_\nu(E_\nu^{\text{res}}) + F_{\bar{\nu}}(E_{\bar{\nu}}^{\text{res}})$.
- $\star$ Source evolution, $F_\nu(E_\nu, r) = F_\nu(E_\nu, 0)[1+z(r)]^\alpha$, e.g., TD: $\alpha = 3/2$.

Z-decay products:

- $\star$ Boosted momentum distribution, $Q(y = 4m_\nu E_\psi / m_Z^2) \Rightarrow$ observed spectral shape.
- $\star$ Propagation, $P_\psi(r, E_\psi; E) \Leftarrow p\gamma_{\text{BG}} \to N\pi,\ pe^+e^- \Rightarrow$ GZK cut-off.
  $\Leftarrow \gamma\gamma_{\text{BG}} \to e^+e^-,\ e\gamma_{\text{BG}} \to e\gamma$; BG = CMB/IRB/URB.

The inevitable Z-burst. . . . . . the flux



- ⋆ Cascade/EGRET limit EHEν flux.
- ⋆ Z-burst nucleons.
- ⋆ Z-burst photons; URB/EG magnetic field dependent.
- ⋆ EG nucleons; data fit $E \in [10^{8.6}, 10^{11}]$ GeV, $z_{\rm min} = 0.012$, $z_{\rm max} = 2$, $E_{\rm max} = 10^{12.5}$ GeV.

  [Ahlers et al. 2005]
- ⋆ Akeno+AGASA data.

- $m_\nu \lesssim 1$ eV $\Rightarrow$ post-GZK emissions; ideal for new UHECR experiments!
- We are not trying to explain the AGASA excess with Z-bursts! [Fargion, Fodor, Gelmini, Kalashev, Katz, Kusenko, Kuzmin, Lee, Mele, Ringwald, Salis, Semikoz, Sigl, Weiler, Yoshida, etc.]

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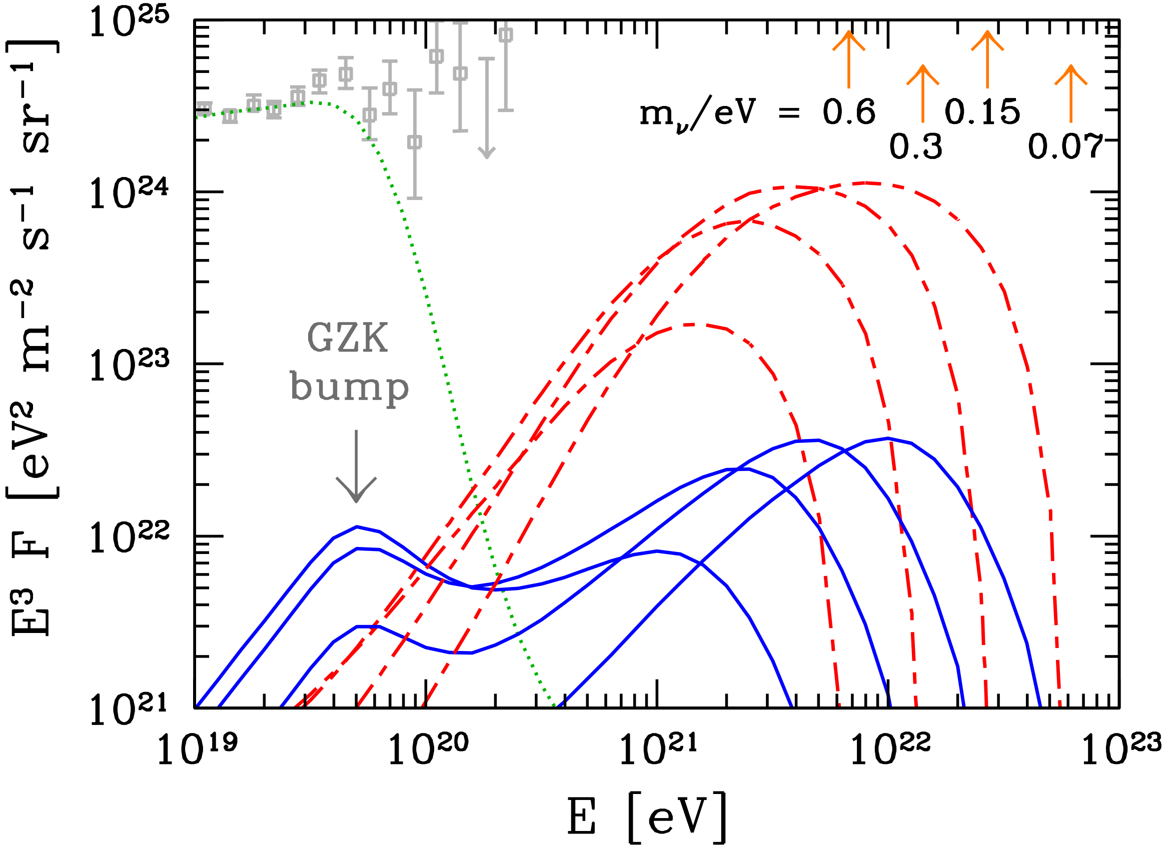

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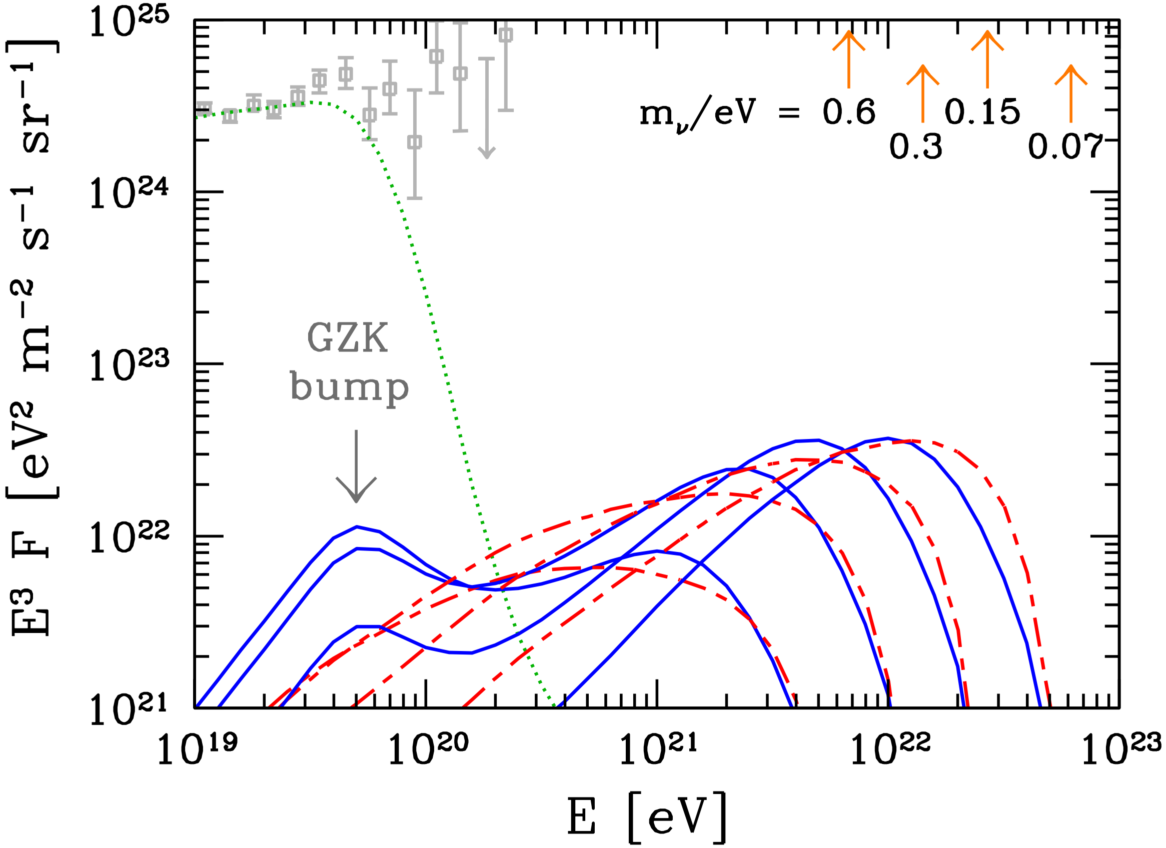

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CνB & galaxy clusters. . . . . . gravitational clustering

Mean velocity of CνB:

$$\langle v \rangle \simeq 1.6 \times 10^2 \ (1+z) \left(\frac{\text{eV}}{m_\nu} \right) \ \text{km s}^{-1}. \tag{4}$$

- cf. velocity dispersions of galaxy clusters (~ 1000 km s^{-1}).
- $m_\nu \lesssim 1$ eV $\Rightarrow$ CνB clustering in galaxy clusters at $z \lesssim 2$.

$\Rightarrow$ Direction dependent Z-burst emission rates.

How much clustering??

- Solve the non-relativistic Vlasov equation:

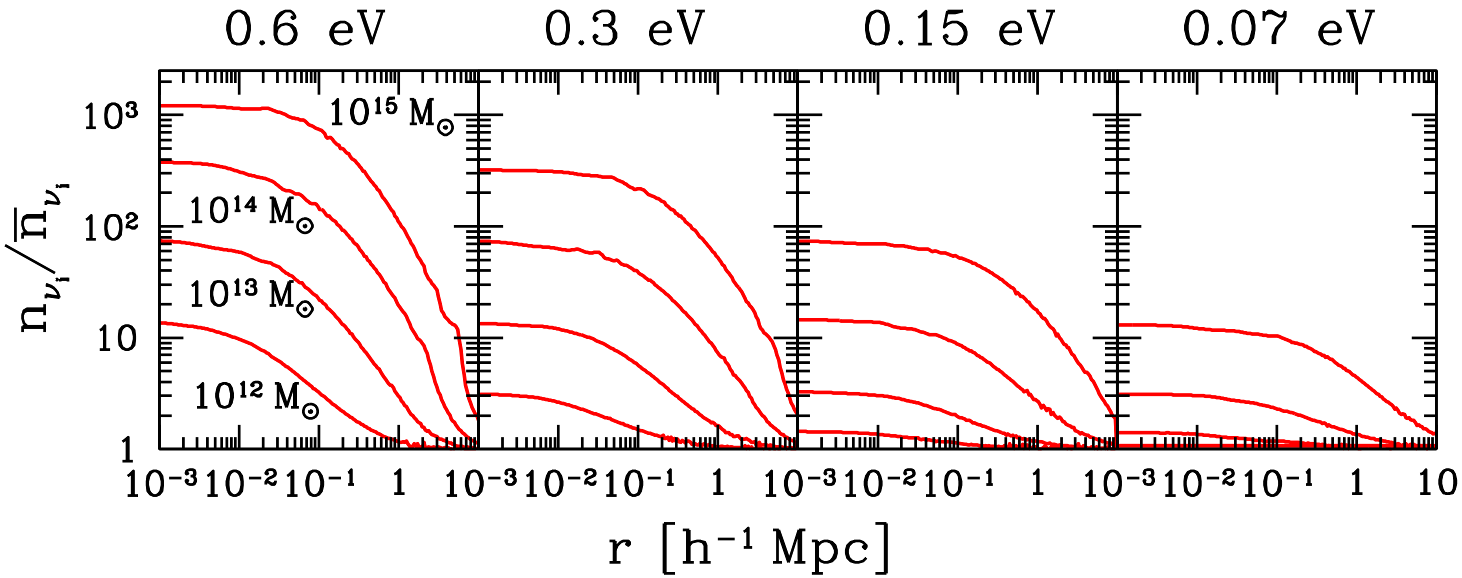
$$\frac{\partial f_\nu}{\partial \tau} + \frac{\boldsymbol{p}}{a m_\nu} \cdot \frac{\partial f_\nu}{\partial \boldsymbol{x}} - a m_\nu \nabla \phi \cdot \frac{\partial f_\nu}{\partial \boldsymbol{p}} = 0, \tag{5}$$

$$\nabla^2 \phi = 4\pi G a^2 [\rho_m(\boldsymbol{x}, \tau) - \bar{\rho}_m(\tau)] \, . \tag{6}$$

- CνB number density, $n_\nu(\boldsymbol{x}, \tau) = (1/a^3) \int d^3p \ f_\nu(\boldsymbol{x}, \boldsymbol{p}, \tau)$.
- Some form of numerical simulation required.

CνB & galaxy clusters. . . . . . ν overdensities

CνB overdensities:



[Ringwald & Y^{3}W 2004; Ringwald, Weiler & Y^{3}W 2005]

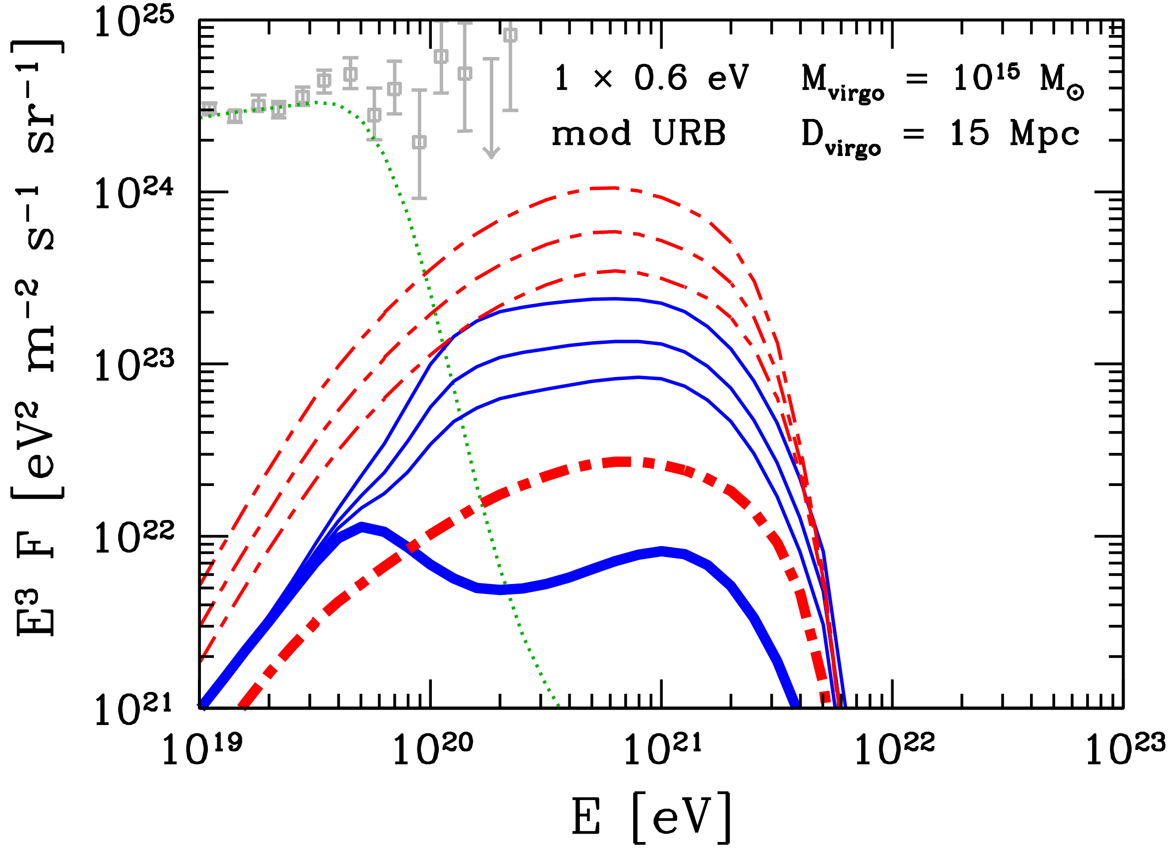
- Cosmological parameters, $\{\Omega_m, \Omega_\Lambda, h, \sigma_8\} = \{0.3, 0.7, 0.7, 0.9\}$.
- Assume NFW halo density profile: [Navarro, Frenk & White 1995]

$$\rho_m(r, M) = \frac{\rho_s(M)}{[r/r_s(M)][1 + r/r_s(M)]^2}. \tag{7}$$

- Incidentally, late-time CνB clustering may have some observable effects for large-scale weak lensing surveys. [Abazajian et al. 2004, Hannestad, Ringwald, Tu & Y^{3}W 2005]

CνB & galaxy clusters. . . . . . enhanced fluxes

- Enhanced Z-burst emissions in the direction of galaxy clusters within the GZK zone ($D \lesssim 50$ Mpc).
- Consider the Virgo cluster, $M \sim 10^{15}\ M_{\odot}$, $D \sim 15 \rightarrow 20$ Mpc, $\theta_d \sim 10°$.



[Ringwald, Weiler & Y^{3}W 2005]

- ⋆ Cascade/EGRET limit EHEν flux.
- ⋆ Nucleons.
- ⋆ Photons (moderate URB).
- ⋆ Thick = no CνB clustering.
- ⋆ Thin = CνB clustering (0, 4, 10 degrees from cluster centre).
- ⋆ Enhancements depend on m_ν ⇐ minimum: ×2.

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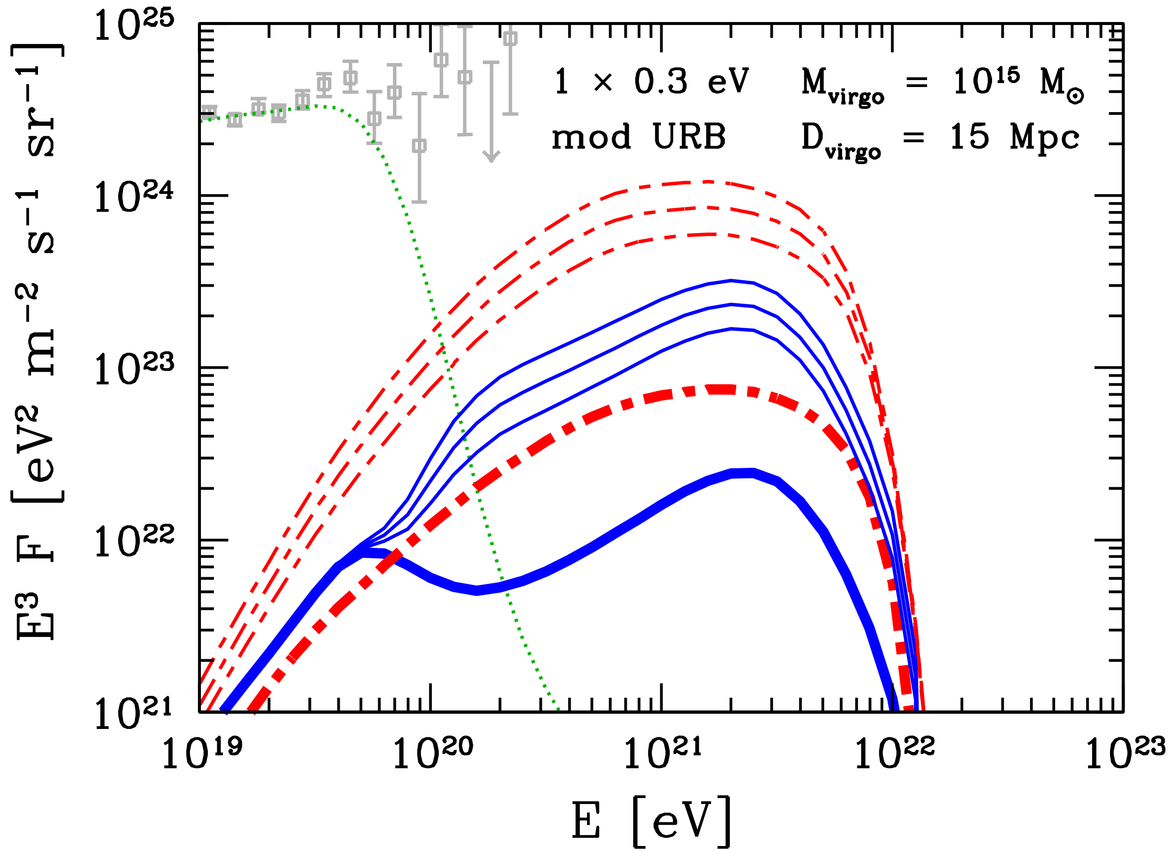

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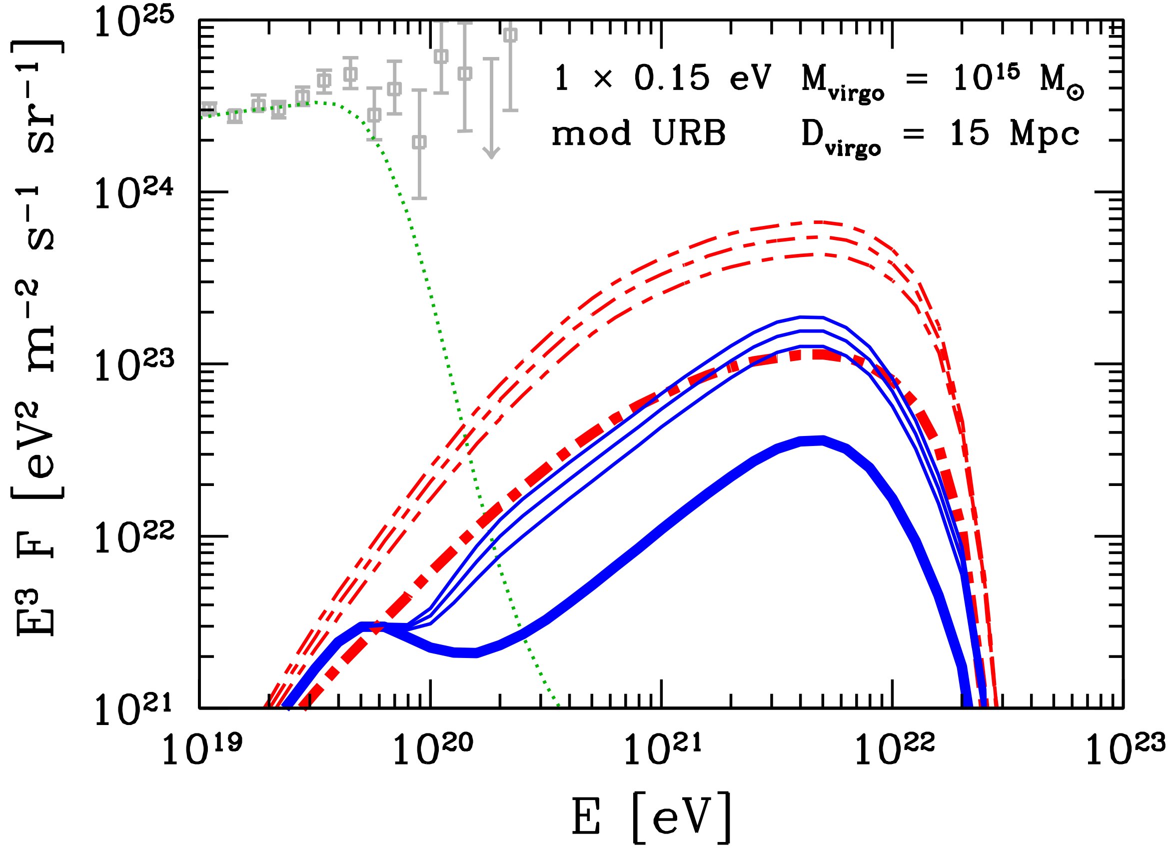

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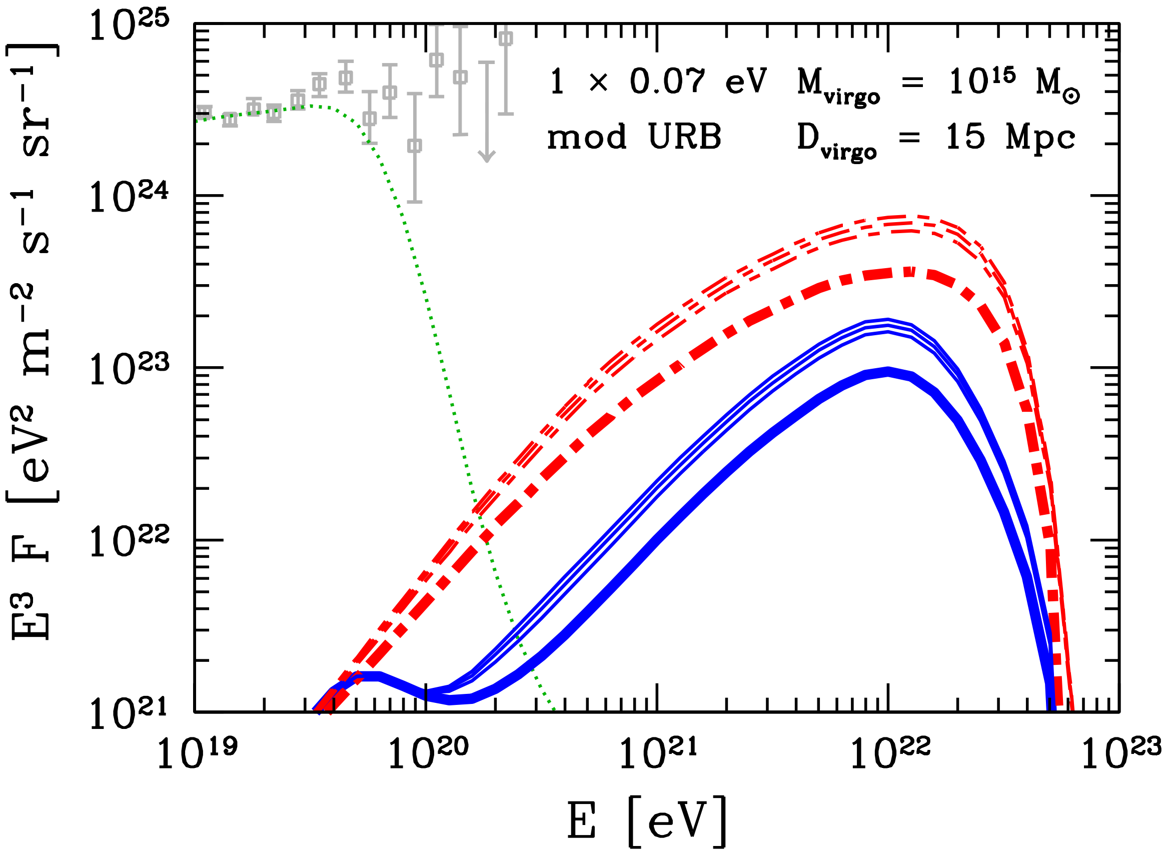

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[Ringwald, Weiler & Y^{3}W 2005]

Experimental prospects. . . . . . general considerations

For Virgo Z-bursts:

1. Angular resolution??

$\Rightarrow$ A few degrees (all exps OK).

2. Statistics??

   ⋆ Limited EHEν flux.

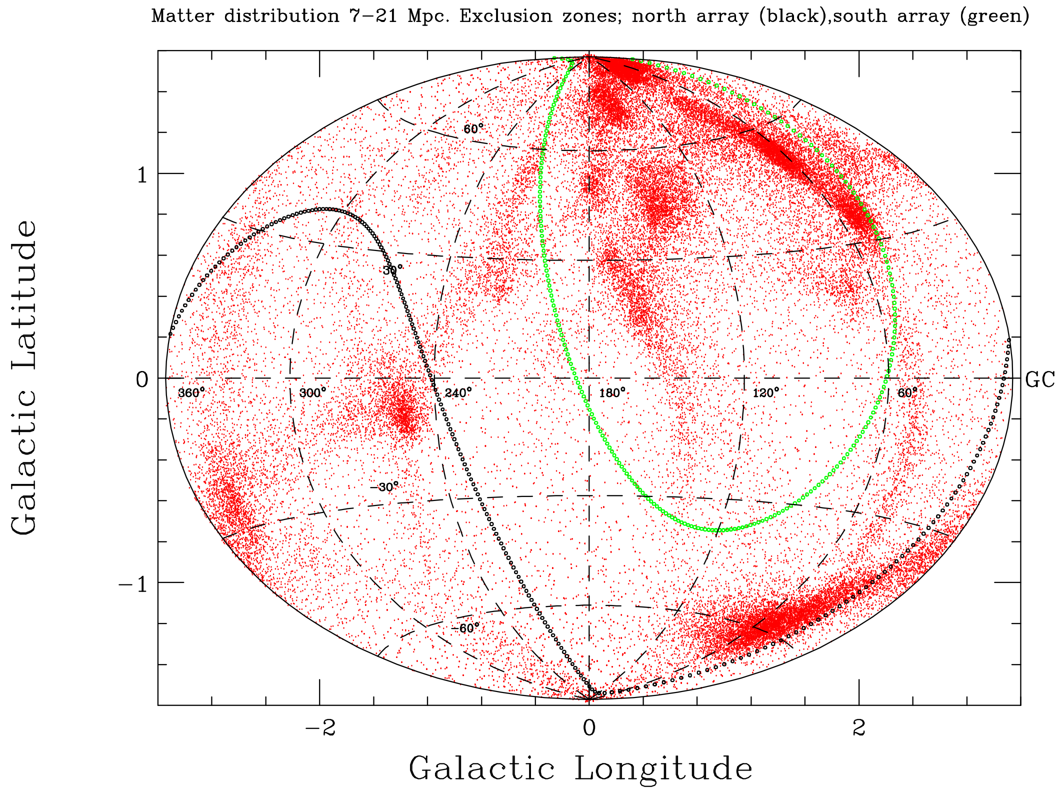
   ⋆ Small solid angle.

$\Rightarrow$ Very large exposure.

3. Direction??

   ⋆ Fig: exclusion zones for observatories at 35° S&N (zenith angle $\leq 60°$).

$\Rightarrow$ Auger South misses bulk of Virgo.

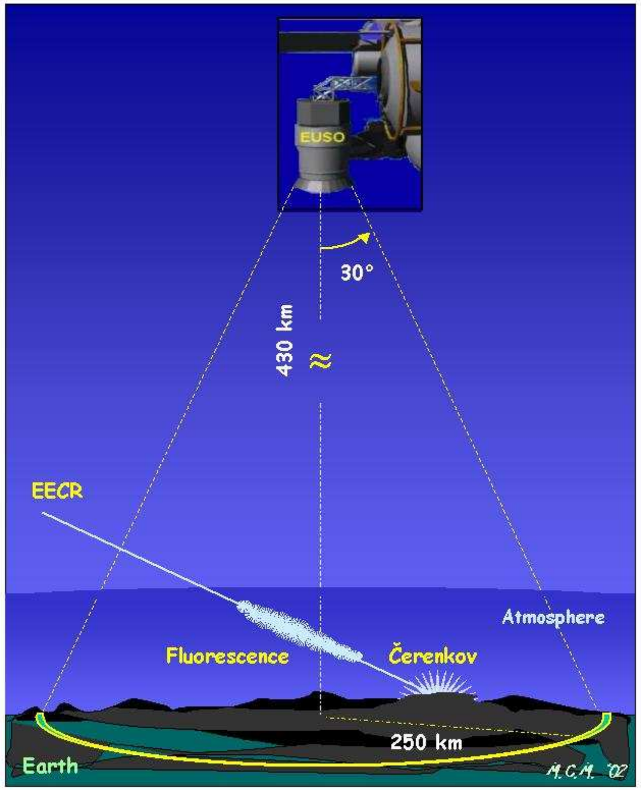


[Cronin 2004]

- Best bet: space-based experiments like EUSO and OWL/Multi-OWL.

Extreme Universe Space Observatory (EUSO)...

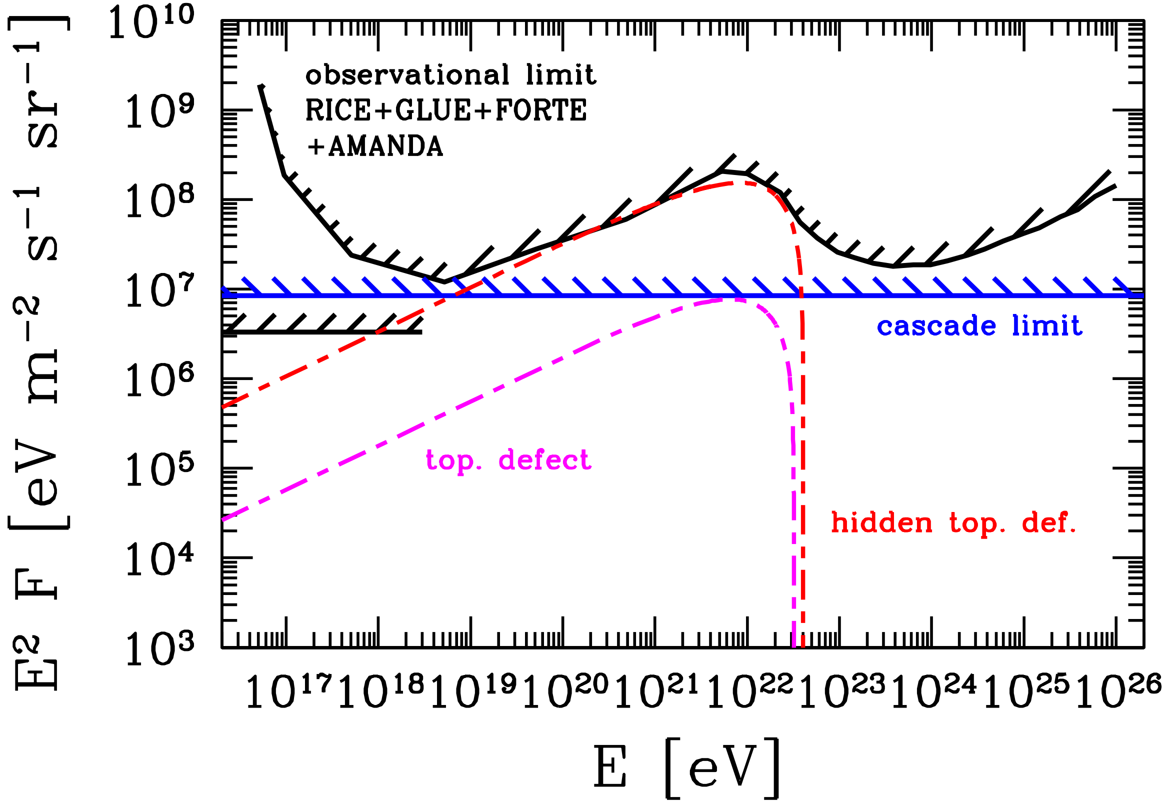
- ⋆ Lens docked on the ISS.
- ⋆ Detect fluorescence emitted from N_2 produced by air showers from primary CR interactions with the atmosphere.
- ⋆ Field of view: $\sim 10^5$ km^2.
- ⋆ Duration: three years.
- ⋆ Angular resolution: ~ 1 degrees.
- ⋆ Energy threshold: $\sim 5 \times 10^{19}$ eV; $\gtrsim E_{\rm GZK}$.
- ⋆ Energy resolution: ~ 10 % at 10^{20} eV.
- ⋆ Sensitivity: EUSO 3yr $\sim 10^3\times$ AGASA, HiRes,
  $\sim$ Auger South 10yr,
  $\lesssim 0.1\times$ OWL.



[www.euso-mission.org]

- Our results indicative only; scale up and down for your favourite experiment!

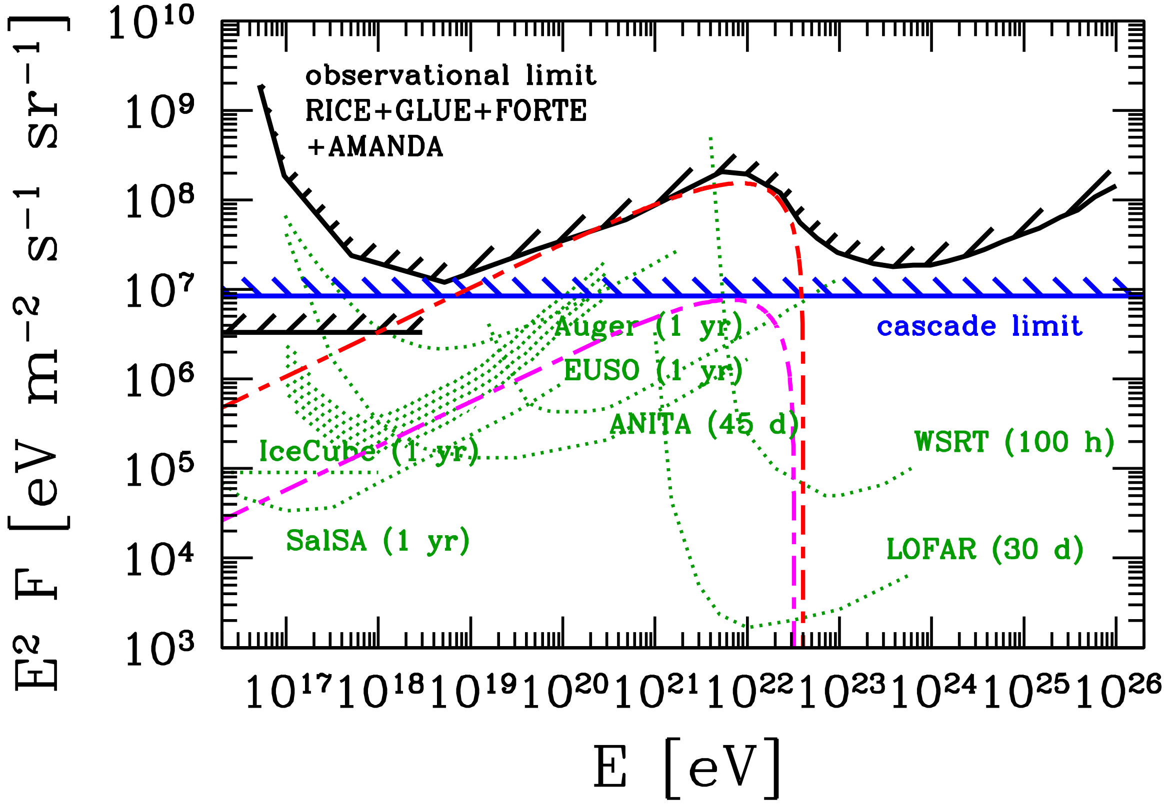
Benchmark EHE neutrino fluxes. . .



- ⋆ Observational limit.
- ⋆ Cascade/EGRET limit.
- ⋆ Sample EHEν fluxes.

1. Observational limit: firm; applies to all sources.
2. Cascade/EGRET limit: source-dependent; applies only to sources emitting also nucleons and $\gtrsim 100$ MeV photons.

Benchmark EHE neutrino fluxes...



- ⋆ Observational limit.
- ⋆ Cascade/EGRET limit.
- ⋆ Sample EHEν fluxes.
- ⋆ Planned/running experiments.

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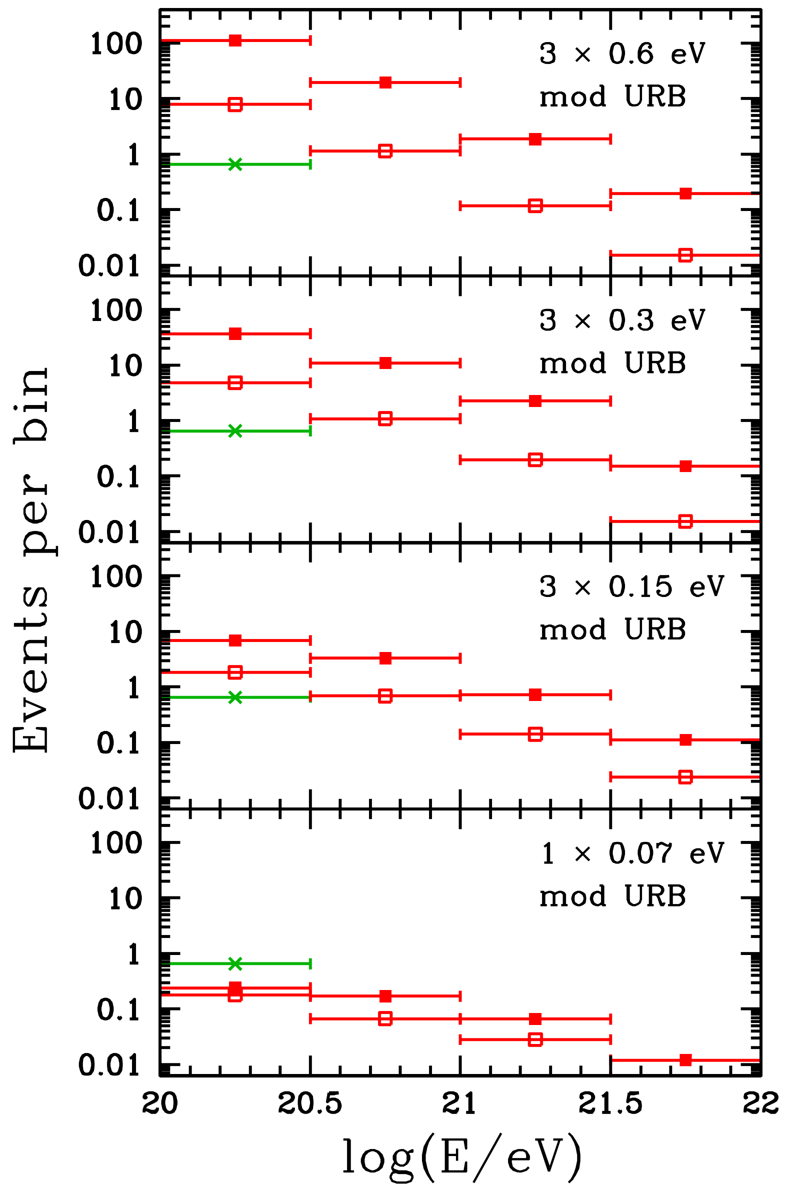
Case one: hidden sources... ... < observational limit

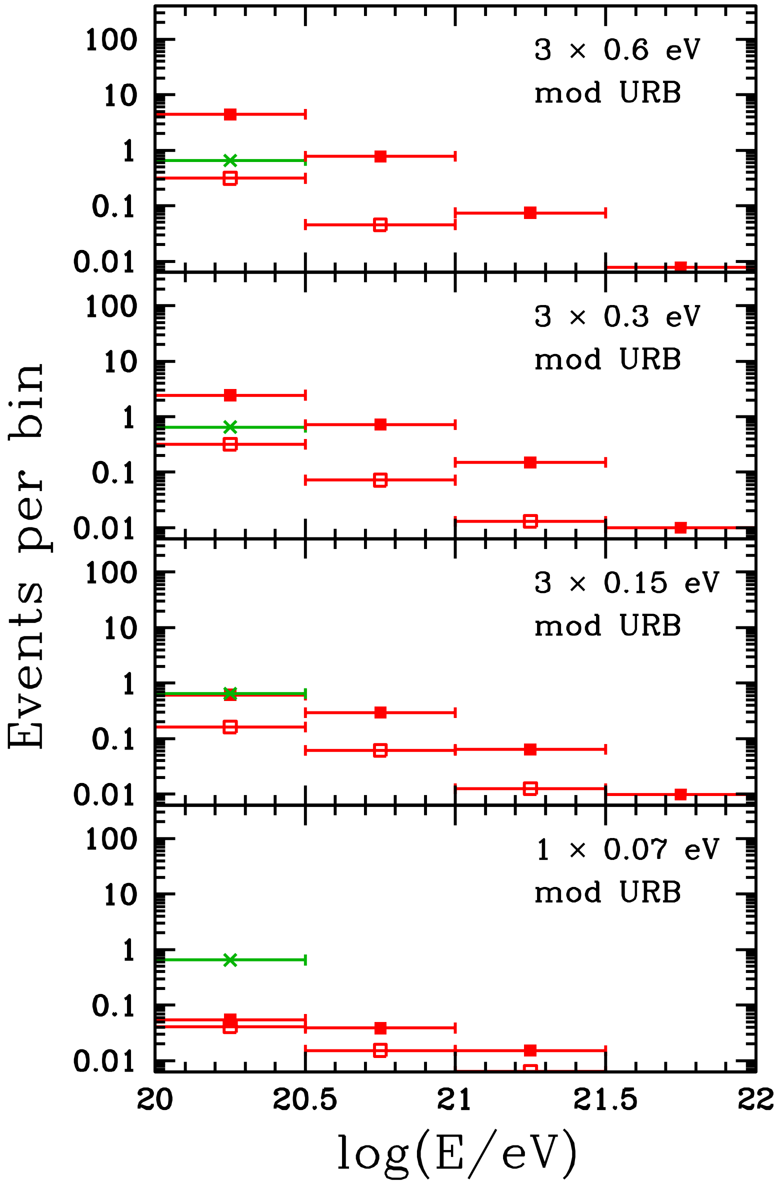
- EHEν from sources emitting neutrinos only can exceed cascade limit.
- Hidden sources:
  - ⋆ Not astrophysical accelerators.
  - ⋆ Beyond SM sources ⇒ must curb photon and nucleon emissions.
  - ⋆ Proof-of-principle models exist (hidden sectors, mirror sectors, etc.).
- Fig: events within 10° from cluster centre (EHEν ~ obs. limit):
  - ⋆ ■ $N+\gamma$ clustered; □ $N+\gamma$ unclustered; × EG nucleons.
  - ⋆ Degenerate m_ν (top 3): looks good!
  - ⋆ Hierarchical m_ν (bottom): difficult.
- EHEν ⇐ EUSO, ANITA, WSRT...



[Ringwald, Weiler & Y[3]W 2005]

Case two: transparent sources. . . . . . < cascade limit

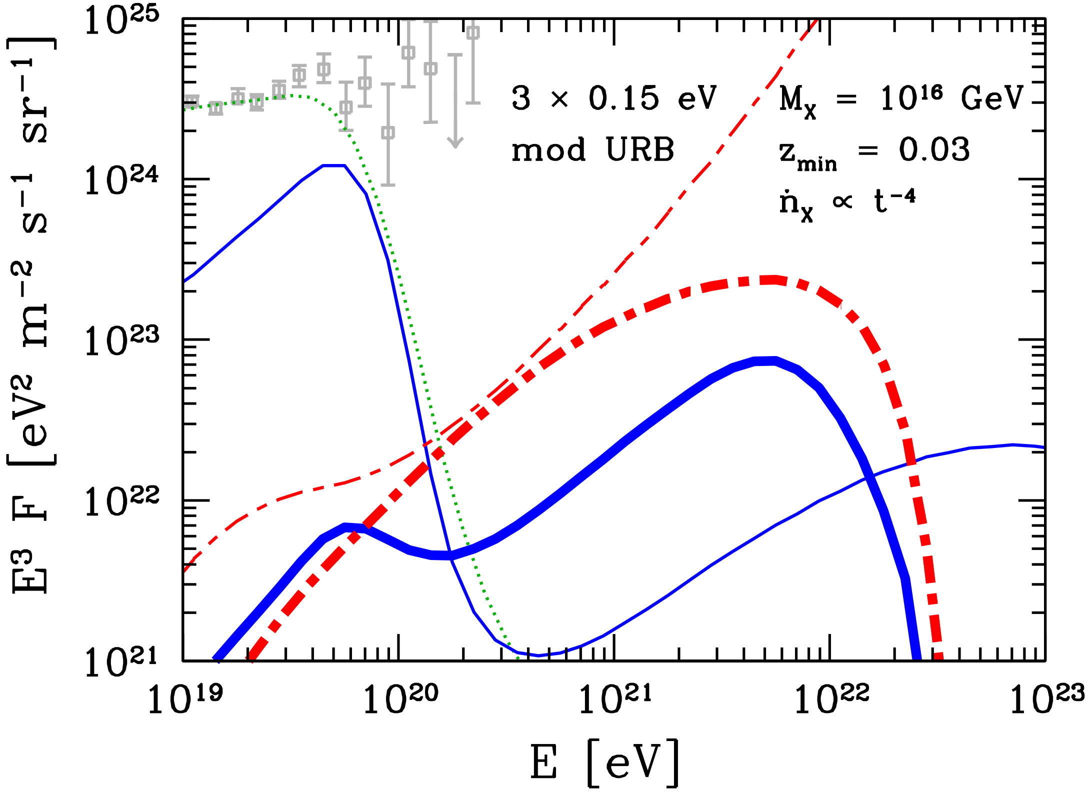
- Z, W, π-decay $\Rightarrow \nu, \gamma$.
- EM cascade of γ down to energies probed by EGRET (MeV $\rightarrow$ GeV) $\Rightarrow$ Cascade/EGRET limit on EHEν.
- Transparent sources:
  - ⋆ (Yet unknown) astro accelerators.
  - ⋆ Beyond SM sources; usually involve superheavy particle decay.
- Fig: events within 10° from cluster centre (EHEν $\sim$ cascade limit):
  - ⋆ ■ $N+\gamma$ clustered; □ $N+\gamma$ unclustered; × EG nucleons.
  - ⋆ Difficult even for degenerate m_ν.
  - ⋆ Widen angle, improve statistics??
  - ⋆ Bigger exp! 20× EUSO 3yr. OWL?



[Ringwald, Weiler & Y^{3}W 2005]

Swamped. . . . . . or not??

- Intrinsic $p + n$, γ fluxes from transparent sources $\Rightarrow$ swamp Z-bursts??
- Answer: model-dependent.
- Fig: X-particle decay:
  - ⋆ Nucleons.
  - ⋆ Photons (mod URB).
  - ⋆ Thin = intrinsic flux.
  - ⋆ Thick = Z-burst.
  - ⋆ Uniform CνB.
- Evolution:
  - ⋆ Most TD, $\dot{n}_X \propto t^{-3}$.
  - ⋆ SCS, $\dot{n}_X \propto t^{-4}$.

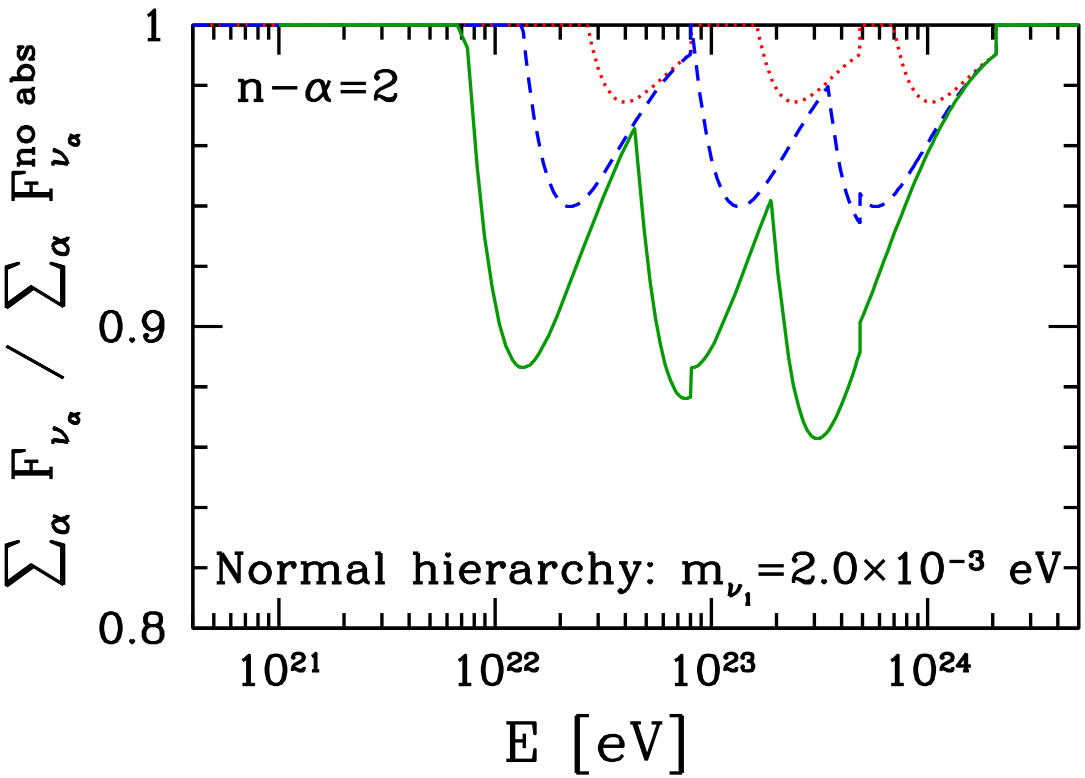


[Eberle, Ringwald, Weiler & Y^{3}W, in prep.]

- Evolving sources and/or high redshift sources favour Z-burst observation.

A complementary probe. . . . . . Z-dips

- Look for absorption features in the EHEν flux due to $\nu\bar{\nu} \to Z$.



[Eberle, Ringwald, Song & Weiler 2004]

⋆ Right edge ⇒ E_ν^{res} ⇒ m_ν.

⋆ Shape of dip:

⇒ source redshift and evolution.

⇒ cosmology.

⋆ If experiment flavour sensitive ⇒ neutrino mixing.

- Perfectly resolved dips contain a wealth of information on neutrino properties, source properties, cosmology, etc.. [Eberle, Ringwald, Song & Weiler 2004; Barenboim, Mena Requejo & Quigg 2005; D'Olivo, Nellen, Sahu & Van Elewyck 2005]

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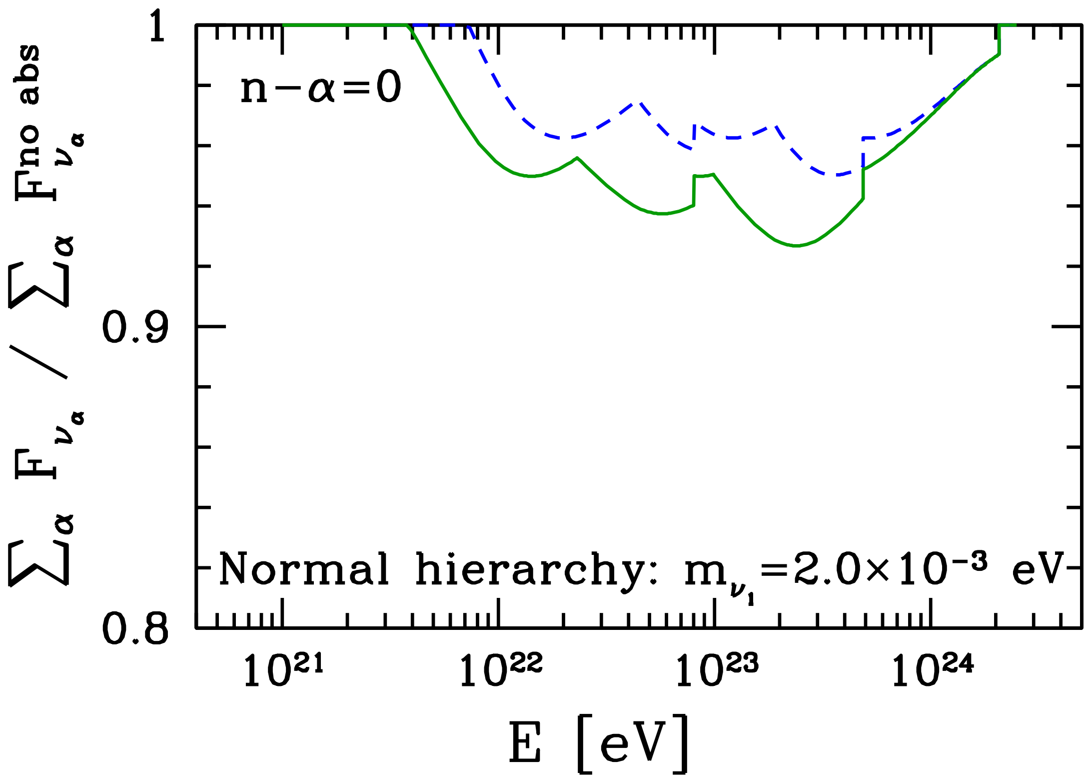

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Summary...

- We live in exciting times.
- Many experiments to look for UHECR and EHEν in the next decade.
- If there is EHEν $\Rightarrow$ resonant annihilation $\nu_{\mathrm{C}\nu\mathrm{B}} + \bar{\nu}_{\mathrm{EHE}\nu} \rightarrow Z$ inevitable.

  $\Rightarrow$ A unique process with sensitivity to the CνB.
- Several ways to look for resonant annihilation:
  - ⋆ Absorption dips in EHEν flux.
  - ⋆ Z-decay products:
    - Spectral shape of post-GZK cosmic rays.
    - Spatial distribution due to CνB clustering in nearby galaxy clusters.
- Enhanced Z-burst emissions from the Virgo cluster:
  - ⋆ Likely within reach of proposed UHECR experiments (OWL, if not EUSO), if degenerate neutrino masses and cascade limit EHEν flux.
  - ⋆ If hierarchical neutrino masses...

UHECR experiments. . .

Experiment	Method	Effective area [km s^{-1}]	Duty factor [%]	Effective aperture [km^2 str]	Energy threshold [eV]	Energy resol. [%]	Angular resol. [Deg]	Start year
Fly's Eye	FD	300	10	100	$\sim 10^{17}$	~ 20	~ 2	1986
AGASA	SD	100	100	250	$\sim 3 \times 10^{18}$	~ 20	~ 2	1992
HiRes	FD	10,000	10	1000	$\sim 3 \times 10^{18}$	~ 10	~ 0.5	1999
Auger-S	SD Hybrid	3,000 3,000	100 10	7,000 700	$\sim 10^{19}$ $\sim 3 \times 10^{18}$	~ 10 ~ 5	~ 1 ~ 0.4	2005
Auger-S&N	SD Hybrid	6,000 6,000	100 10	14,000 1,400	$\sim 10^{19}$ $\sim 3 \times 10^{18}$	~ 10 ~ 5	~ 1 ~ 0.4	2007 2007
EUSO	FD	500,000	10	50,000	$\sim 5 \times 10^{19}$	~ 30	~ 2	~ 2010
OWL	FD	5,000,000	10	500,000	$\sim 10^{20}$	~ 30	~ 2	> 2015