Astrophysical sources of high-energy neutrinos

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Neutrino Astrophysics

Top questions in astrophysics in the pre-cosmology era:

- How do stars work?
  - Thermonuclear [illegible] disagree with neutrino deficit
  - Central [illegible] K confirmed by helioseismology
  - Neutrino [illegible] oscillations seen by SNO

Davis

- How do stars evolve?
  - Core collapse produced neutrino bursts
  - Confirmed by observation of SN1987A

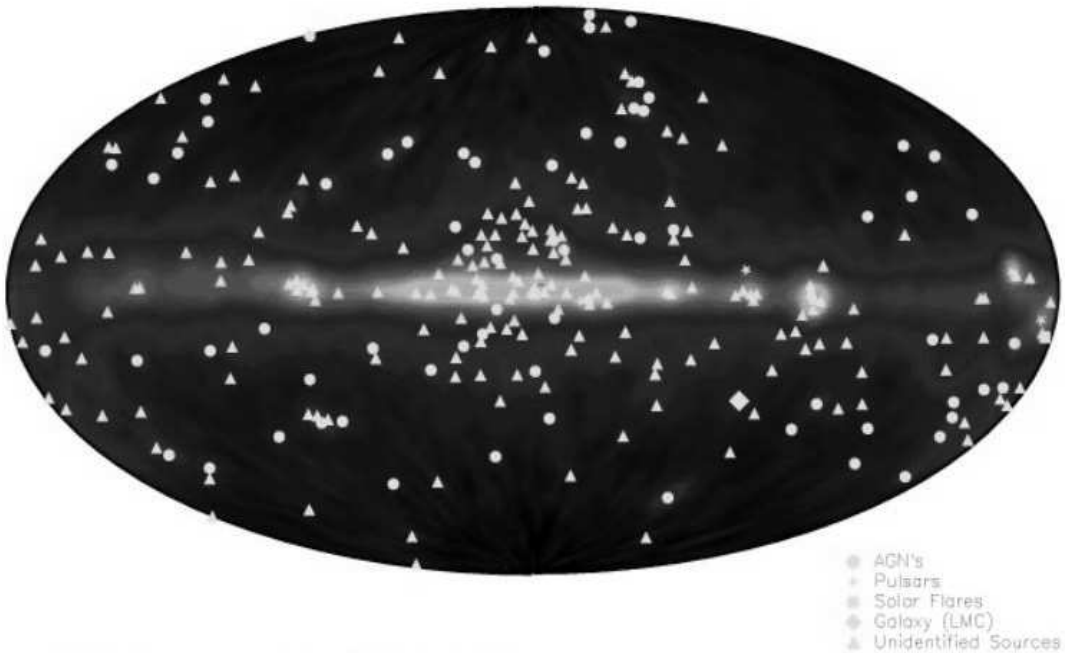
Koshiba

Top questions in cosmology era

- How do first stars form (PopIII)?
  - Collapse of massive metal-poor stars involves accretion disk/jet phase
    - GRBs with nonthermal neutrino production (Schneider et al. 2002)
    - Enhanced neutrino flux due to progenitor shell (Razzaque et al. 2004)
- What is dark matter?
  - Massive weakly interacting relics → top-down production of neutrinos
    - Cosmogenic SUSY (Elsässer & Mannheim 2004)
    - Supermassive dark matter (Crotty 2002)
- What is dark energy?
  - Coupling with scalar field
    - Energy scale of dark energy same as Δm_ν (Paes et al. 2004)
    - Modified neutrino mixing over Gpc baselines (Barenboim & Quigg 2003)
- Where do cosmic rays come from?
    - Pulsar wind nebulae (Nagataki 2004)
    - AGN jets
      - disk photon target (Atoyan & Dermer 2004)
      - synchrotron photon target (Mücke et al. 2002)
    - GRB jets
      - Neutrinos from internal and external shock waves (Dermer 2000)
      - Neutrinos from dirty fireballs (Dermer 2000)

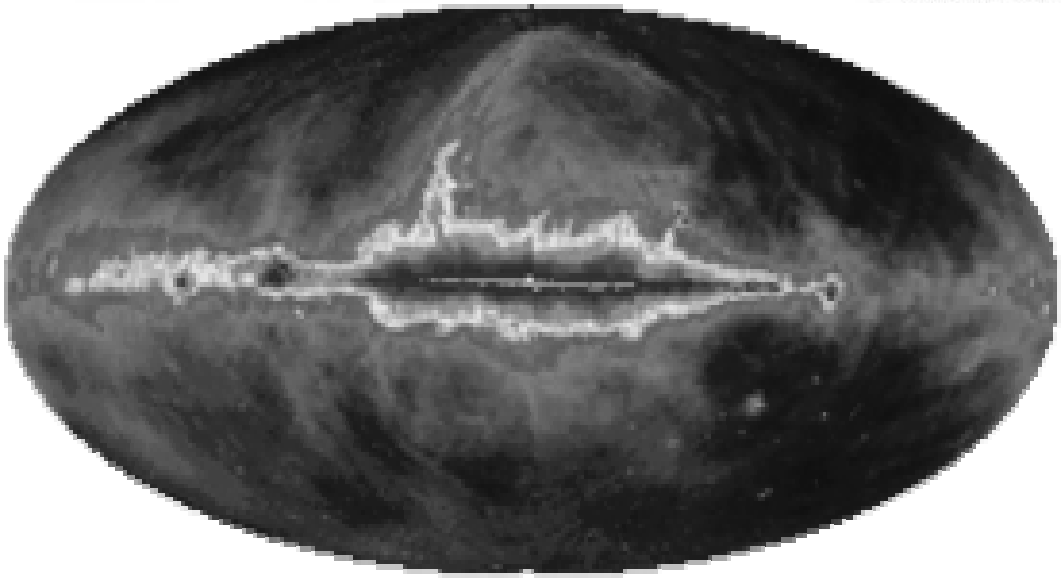
Guaranteed Sources ?

> 100 MeV



GeV protons

408 MHz



GeV electrons

Infering neutrino fluxes

Unknown magnetic field

$$\Phi(\mathbf{p})/\Phi(\mathbf{e})$$

em . cascading

$$\Phi(\gamma)/\Phi(\nu)$$

isotropy

$$\Phi(\mathbf{p})/\Phi(\nu)$$

Cosmic ray escape in magnetically confined sources by „neutron bomb“

$$\Phi_p \sim E^{-s}$$

$$p\gamma \rightarrow \Delta^+$$

$$\pi^0 p \rightarrow \gamma\gamma$$

$$\pi^+ n \rightarrow p\, e^- \bar{\nu}_e$$

$$\mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$pp \rightarrow \ldots$$

Maximum neutrino flux associated with cosmic rays

$$E_\nu = \frac{4}{3} E_\gamma$$

$$\frac{\Phi_\gamma}{\Phi_{\nu_\mu}} = \frac{2}{1}$$

$$\frac{\Phi_{\nu_\mu}}{\Phi_{\bar{\nu}_\mu}} = \frac{1}{1}$$

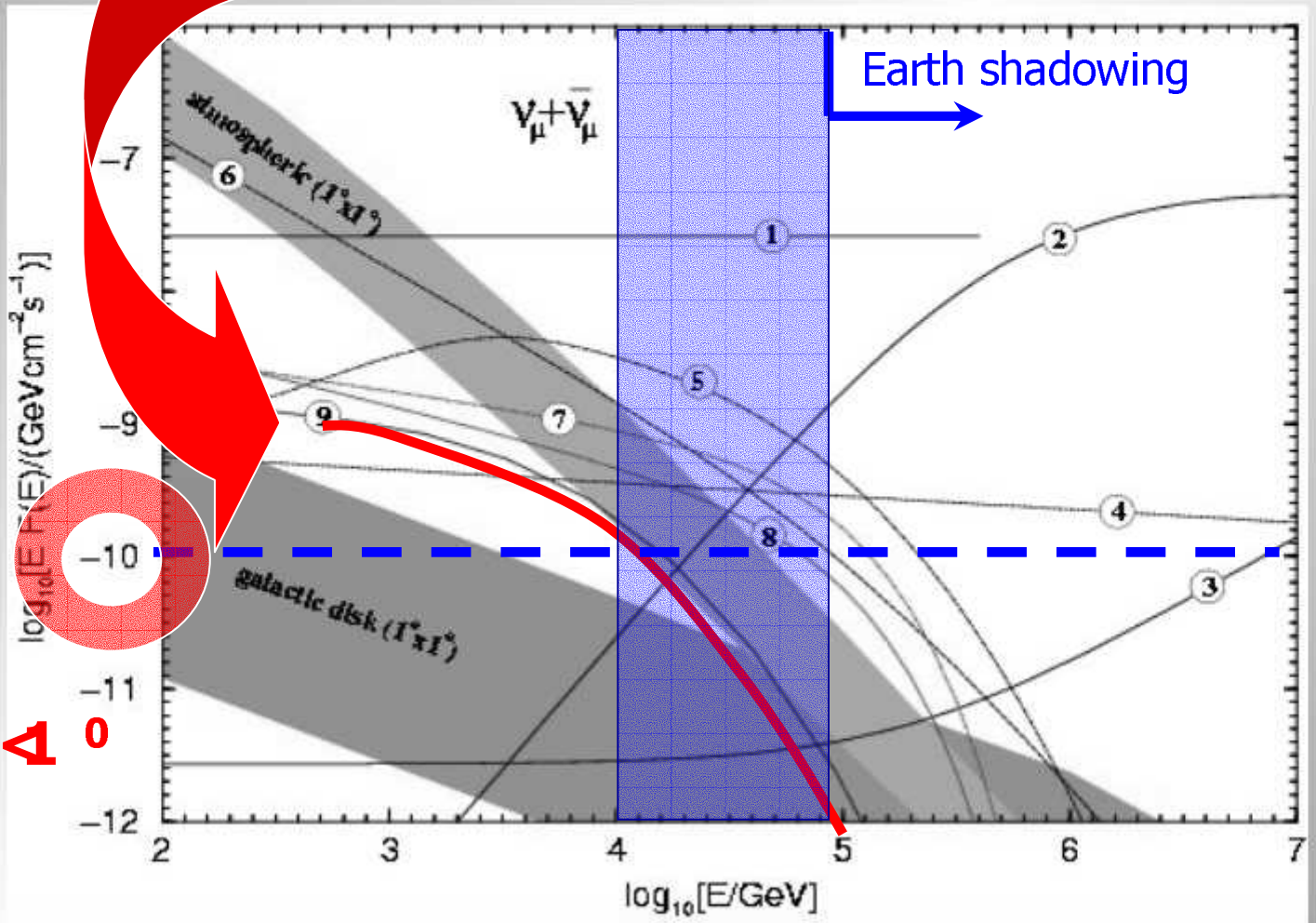
$$\frac{\Phi_{\nu_\mu}}{\Phi_{\nu_e}} = \frac{1}{1}$$

Galactic sources

- Chemical composition, absence of intergalactic IC, and diffuse Galactic gamma ray emission supports Galactic origin of CRs up to knee
- Candidates
  - Sun
  - OB associations with stellar winds
  - ISM
  - GC
  - SNR
  - Microquasars
  - PWN

Flux Predictions

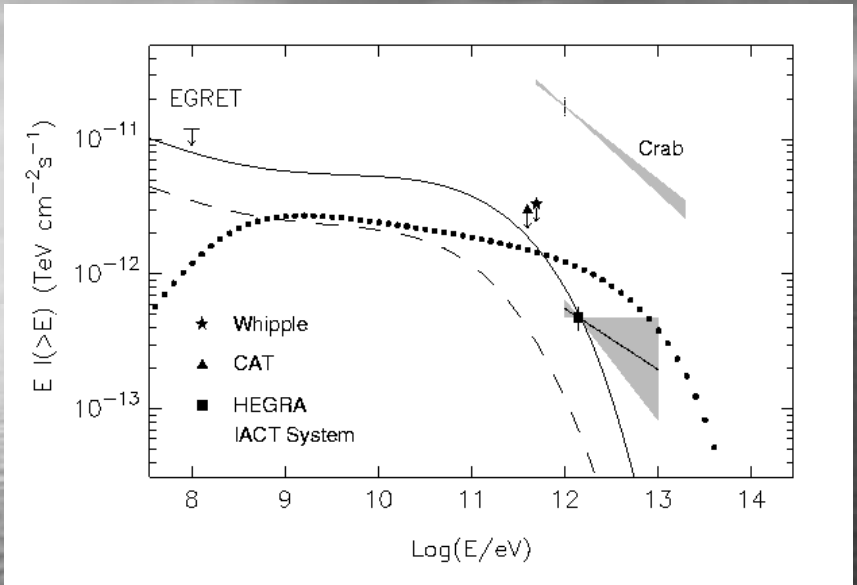
Model 9 → Cas A (Atoyan et al. 2000)

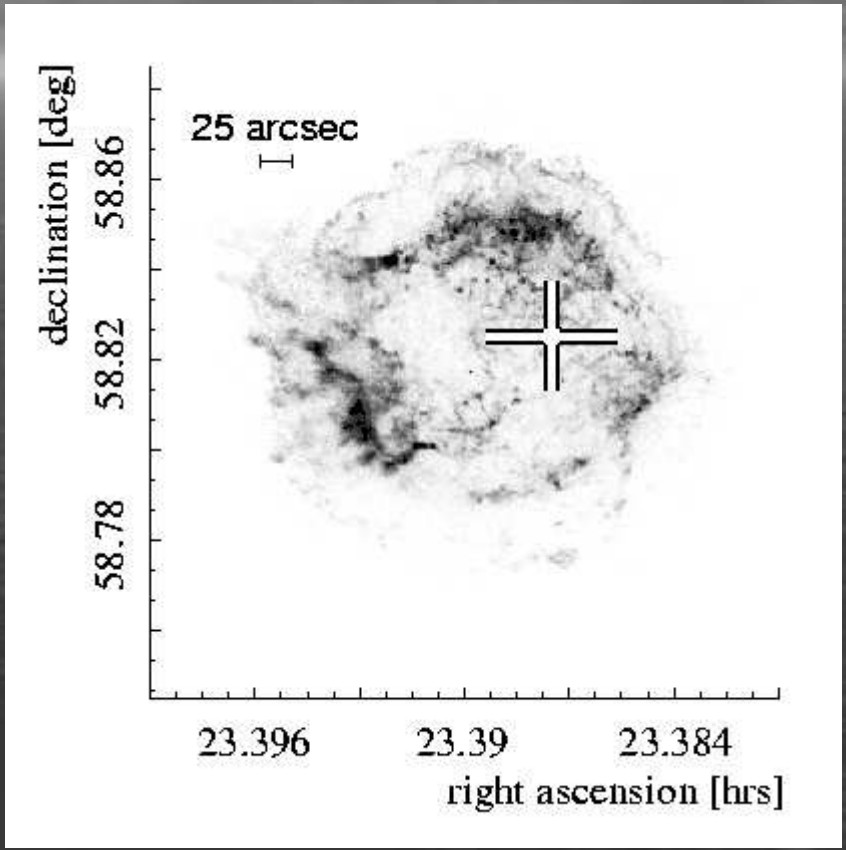


@ Δθ◄ 0

Learned & Mannheim, Ann. Rev. of Nuc. and Part. Sci. **50**, 679 (2000)

TeV-detection of Cas A with HEGRA IACT array



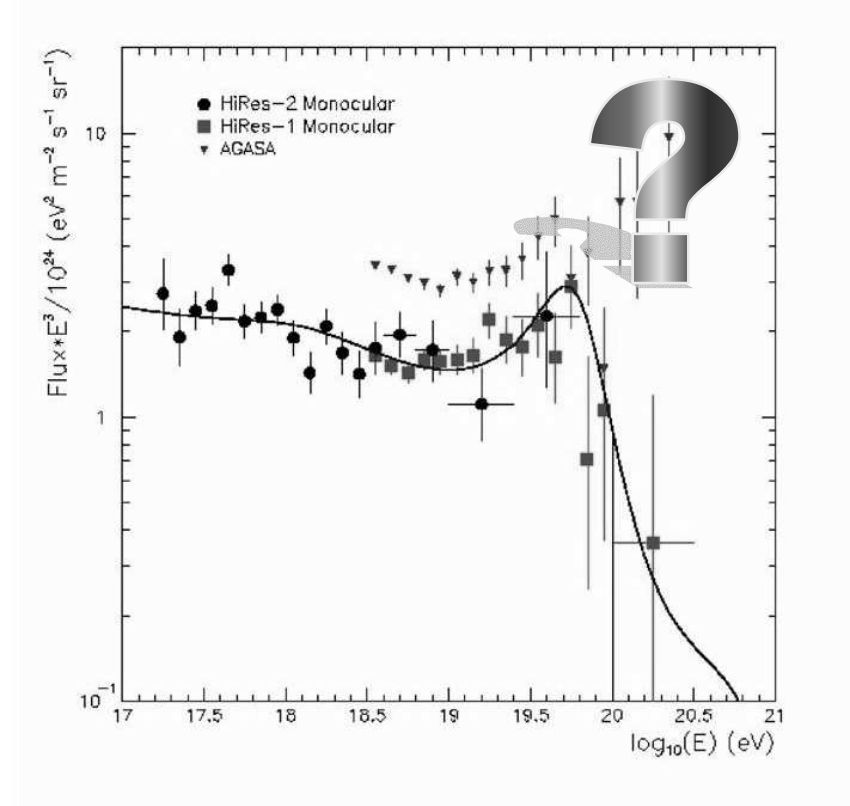


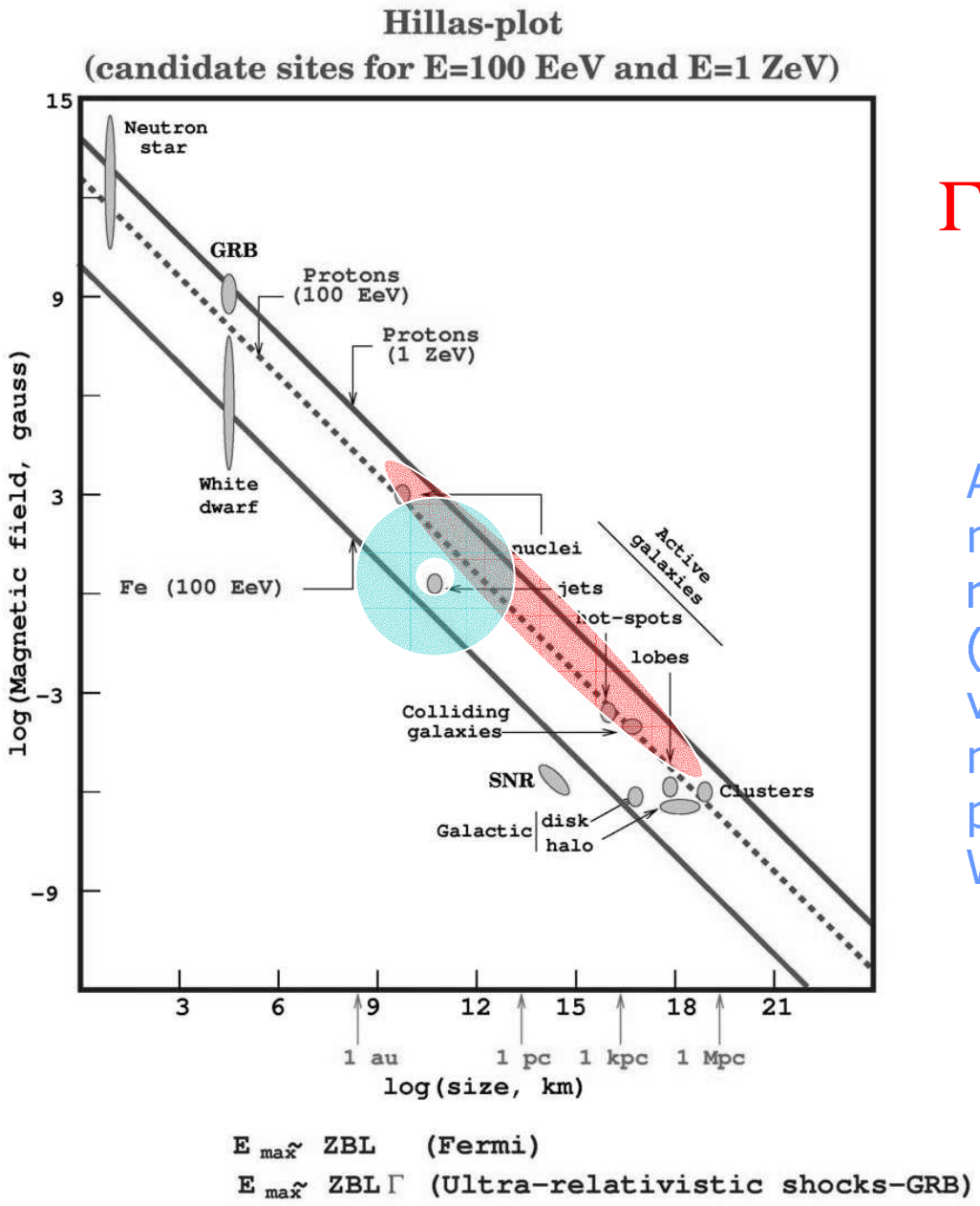
Shell-type SNR fluxes generally on the low side when compared with expectations-

Pulsar wind nebulae or microquasars may do better (Nagataki 2004, Bednarek, Waxman)

Extragalactic sources

- GZK cutoff
- Hillas Plot
- Isotropy at > 10^{18} eV
- Light chemical composition (?)
- Gamma-ray sources
  - AGN jets
  - GRBs
- Bolometric gamma ray limit due to cascading





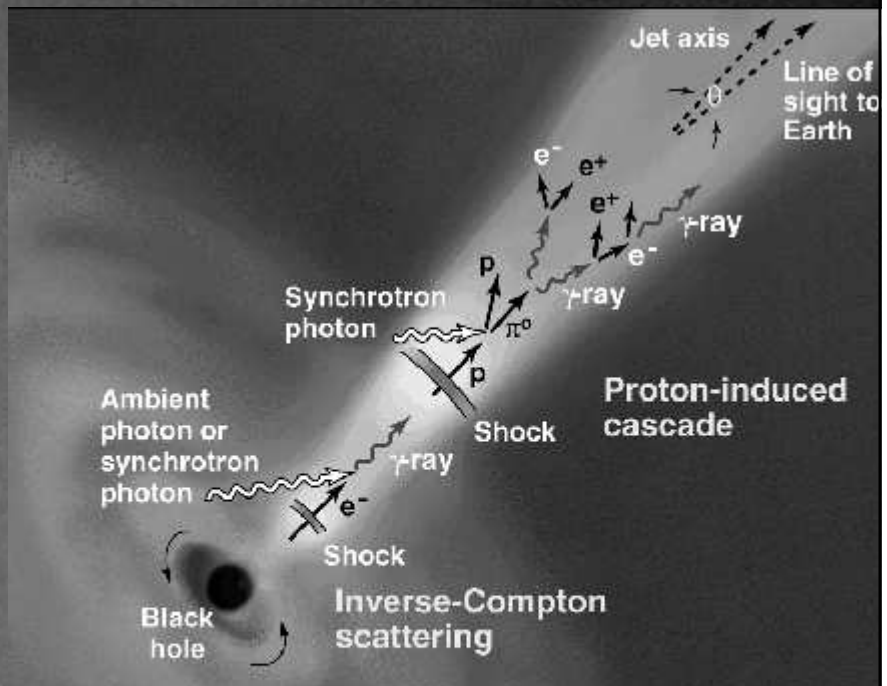
$E_{max} \sim ZBL$ (Fermi)

$E_{max} \sim ZBL\Gamma$ (Ultra-relativistic shocks-GRB)

$\Gamma = 2 - 15$ (AGN jets)

Adiabatic expansion of magnetic field in jets requires stronger values (consistent with hot spot values and recent measurements of circular polarisation in the optical, Wagner et al., SPIE 2000)

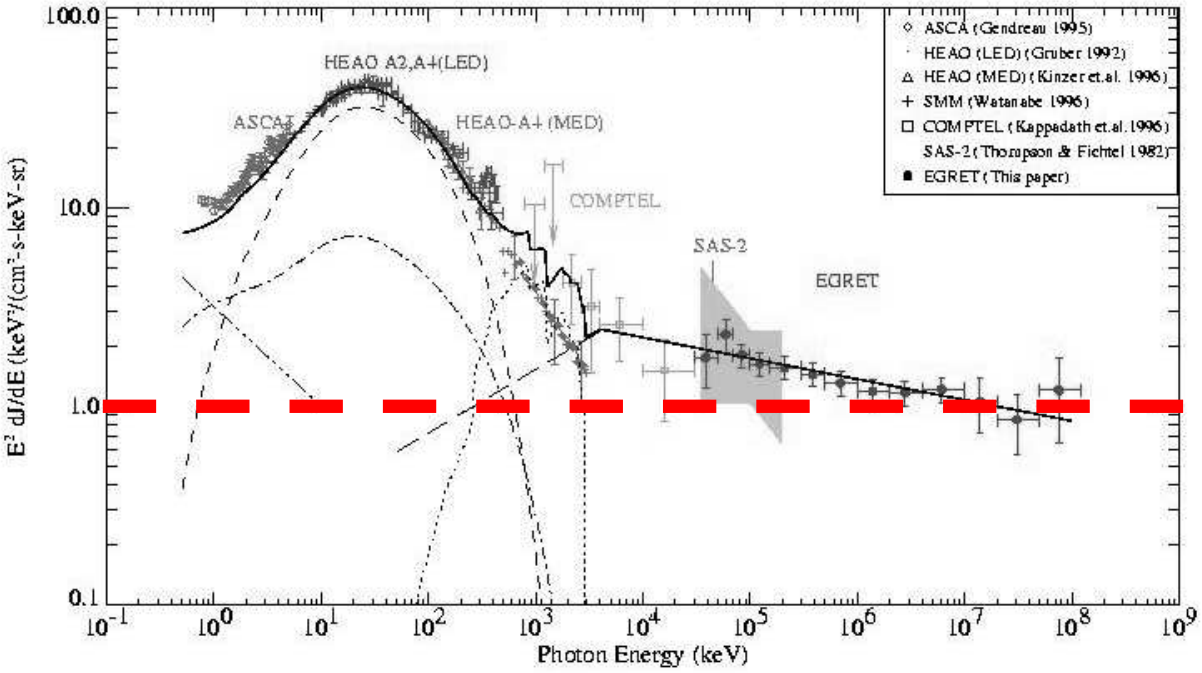
AGN jets: cosmic accelerators of UHE cosmic rays?



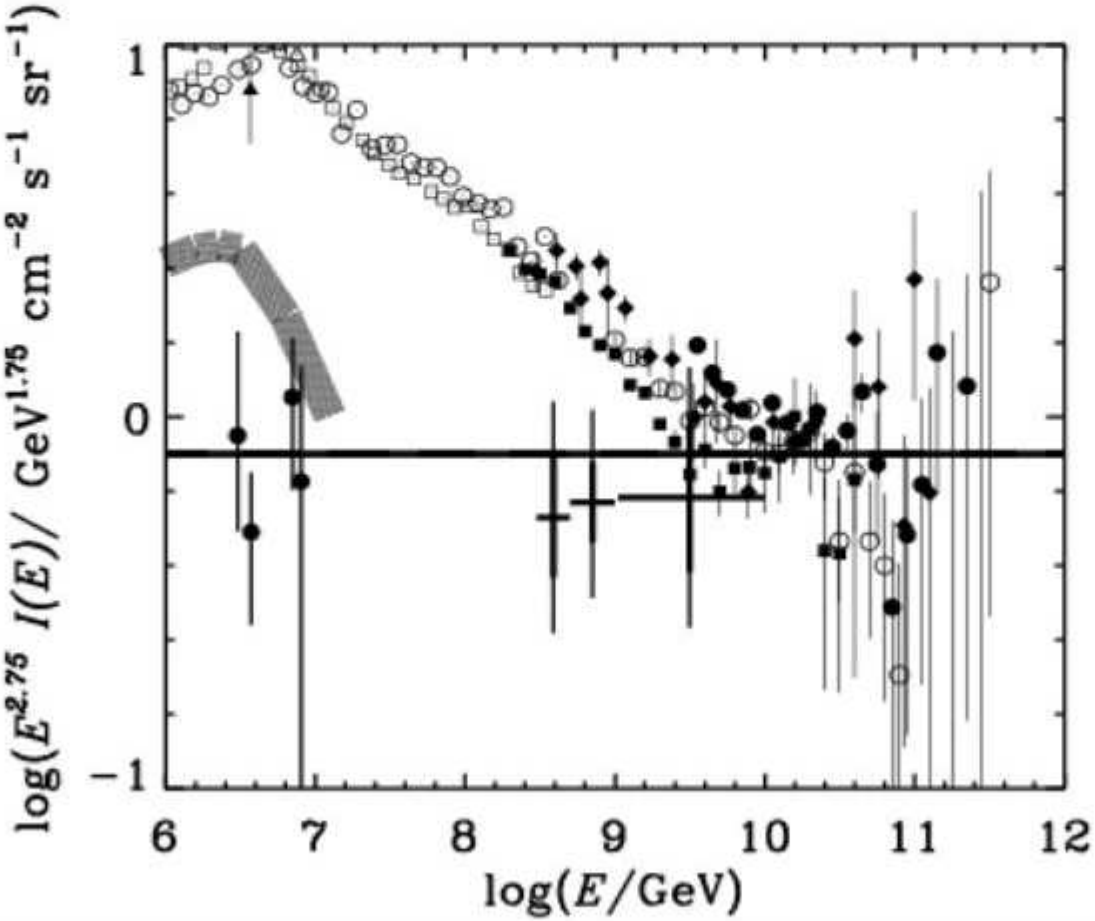
Predicted cascade spectrum up to multi-TeV in agreement with detections (see discussion in Mannheim, 1998, Sci. 279, 684)

Gamma-ray background energy flux

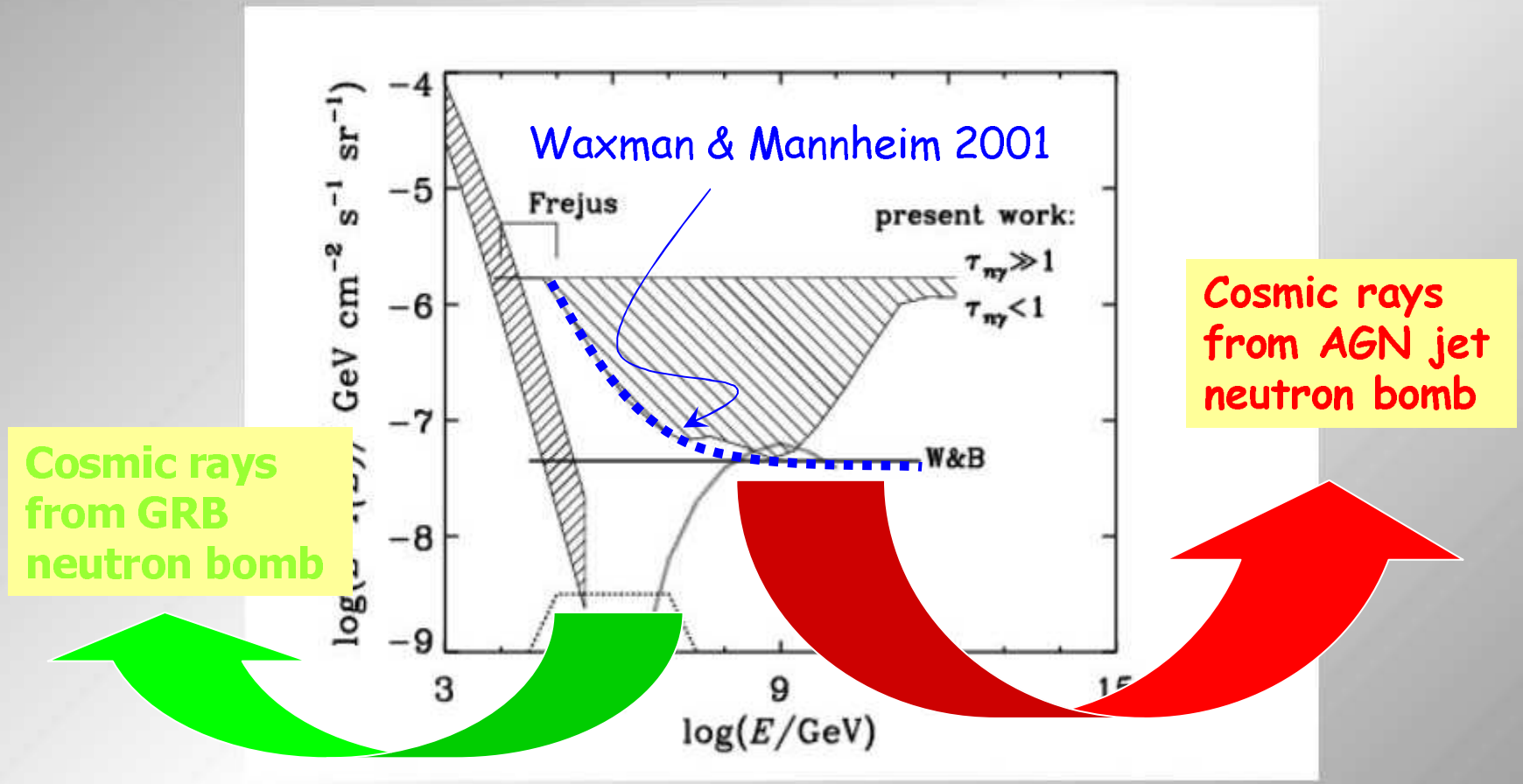
→ $\Phi(\gamma) \sim 10^{-6}$ GeV/(cm^2 s sr)



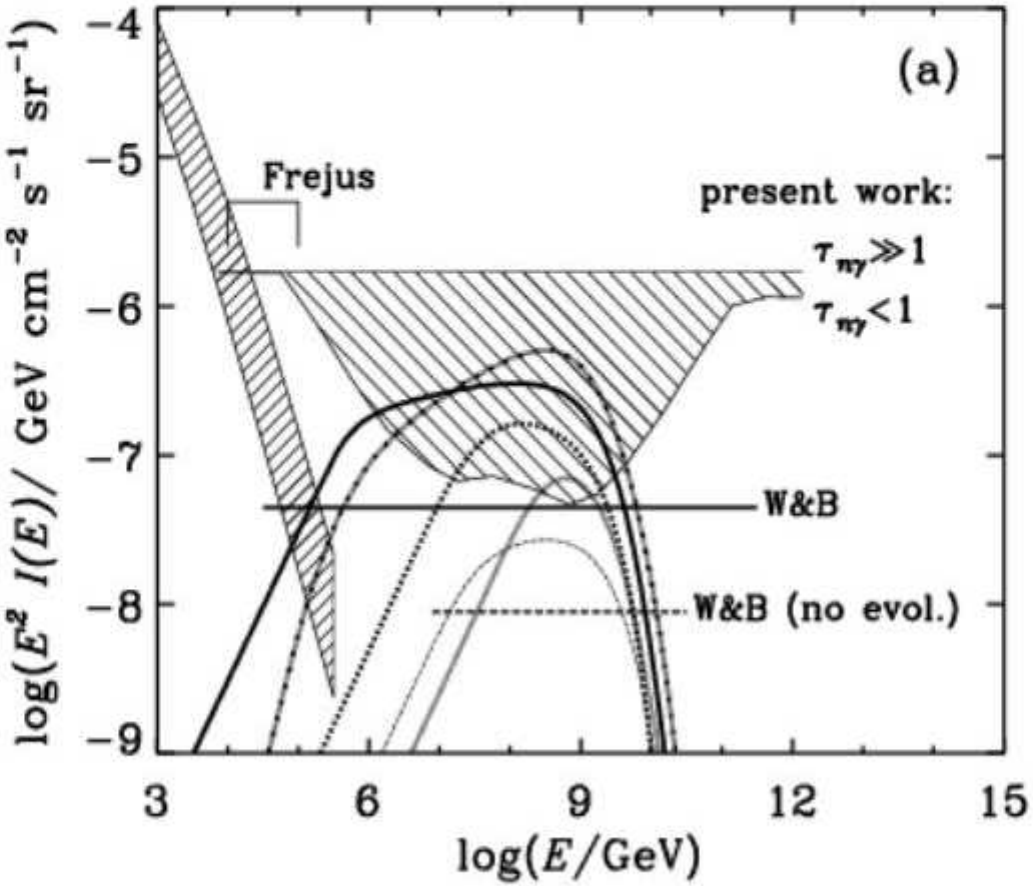
Experimental Limit on Cosmic Ray Protons



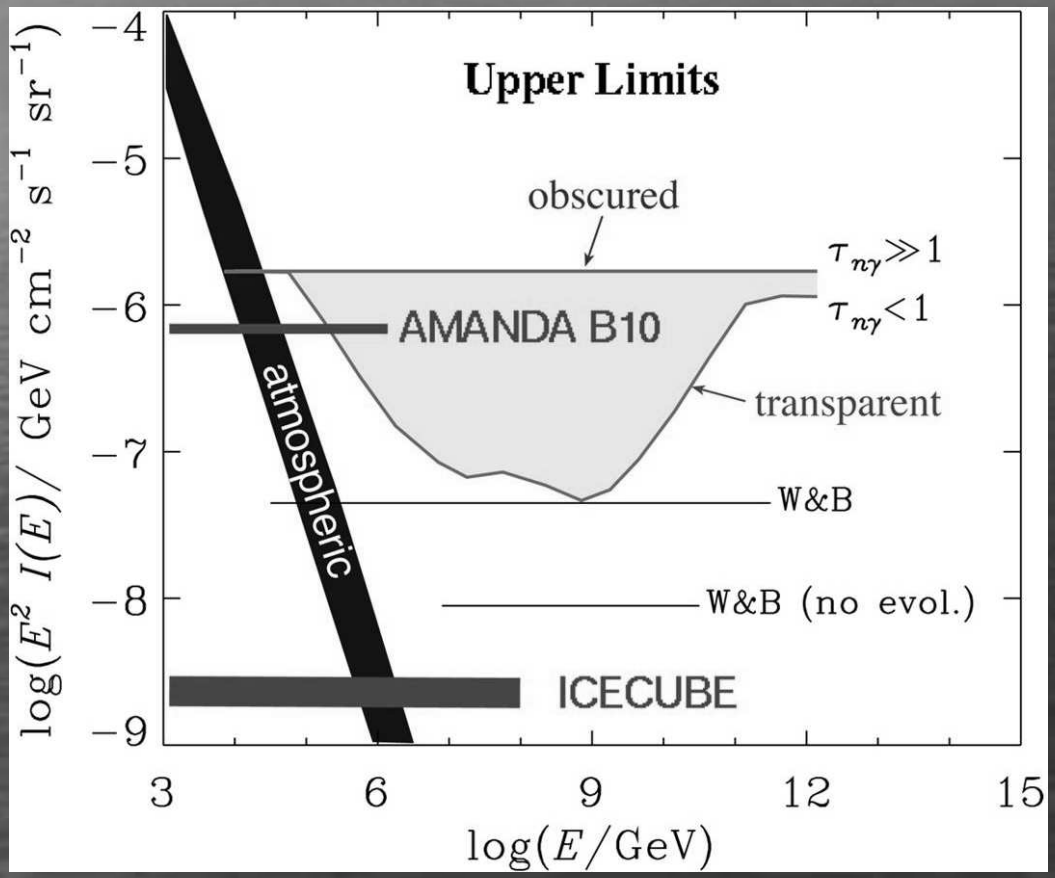
Bound for Thin Sources including Effects of Evolution andPropagation



Maximum AGN Jet Model

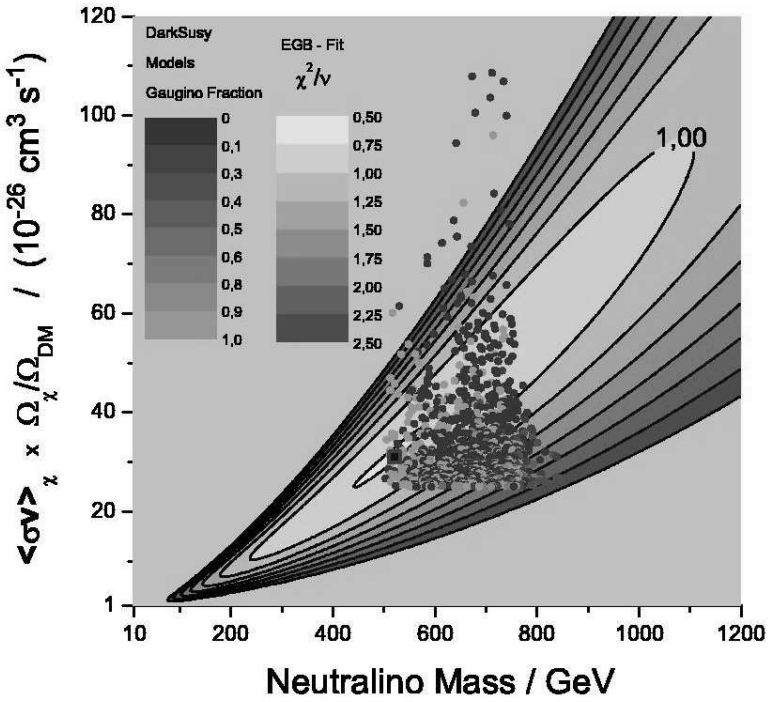


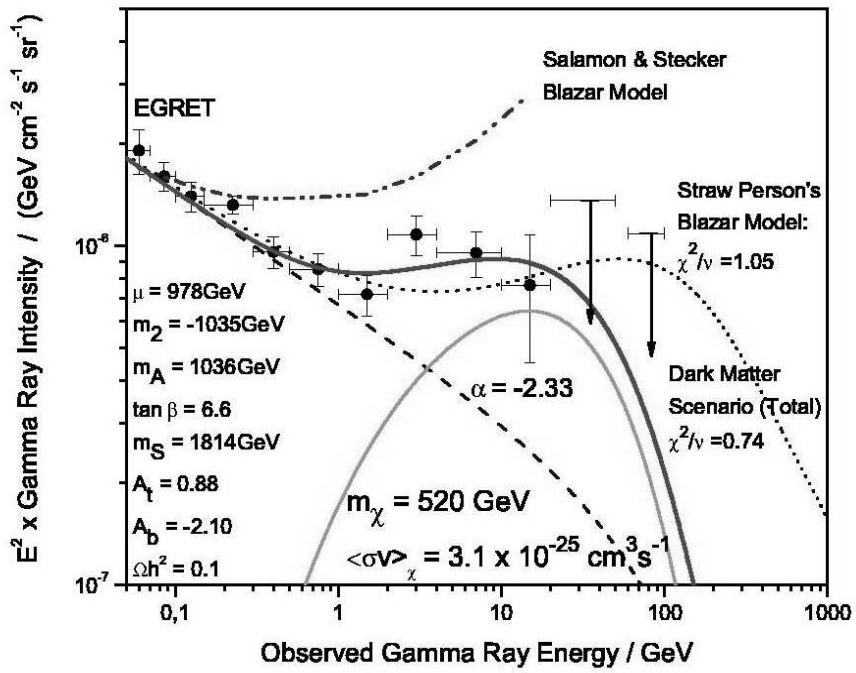
Experimental upper limits



Structure in spectrum of extragalactic gamma ray background due to 500 GeV neutralinos ?

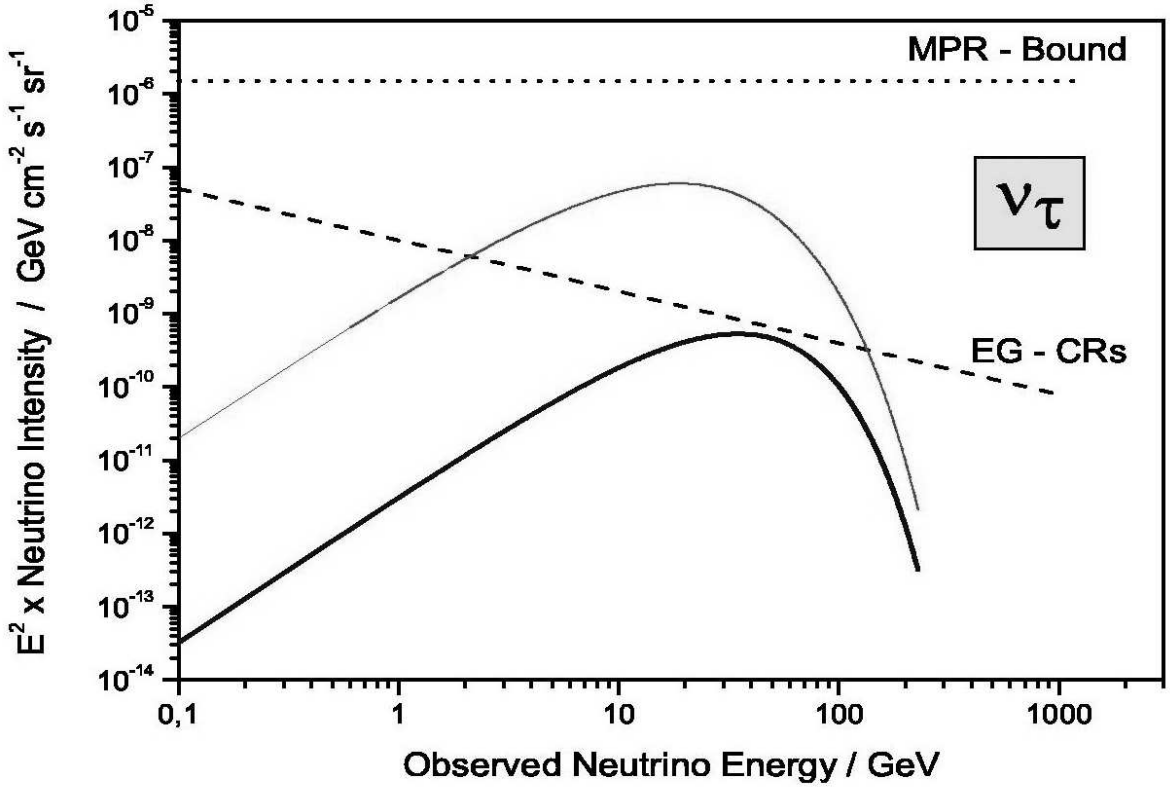
(Elsässer&Mannheim2004, PRL submitted)





Cosmogenic high-energy neutrino background

(Elsässer & Mannheim 2004, Aph, in press)



Summary

I. Guaranteed sources (Galactic disk, Sun, GZK)

II. Likely steady sources at 100 TeV (Knee-CR sources, AGN)

$\Phi_\nu \sim [10^{-9}\text{-}10^{-10}]$ GeV/(cm2 s)

III. Omnidirectional intensity from 100 TeV to GZK energies

$I_\nu \sim [5\ 10^{-8} - 5\ 10^{-7}]$ GeV/(cm2 s sr)

(due to sources of extragalactic cosmic rays and γ-ray background)

IV. GRB contribution to I_ν small (unless splendid TeV emitters), nevertheless likely neutrino sources

V. Neutralino-induced cosmogenic tau-neutrino flux at ~50-100 GeV