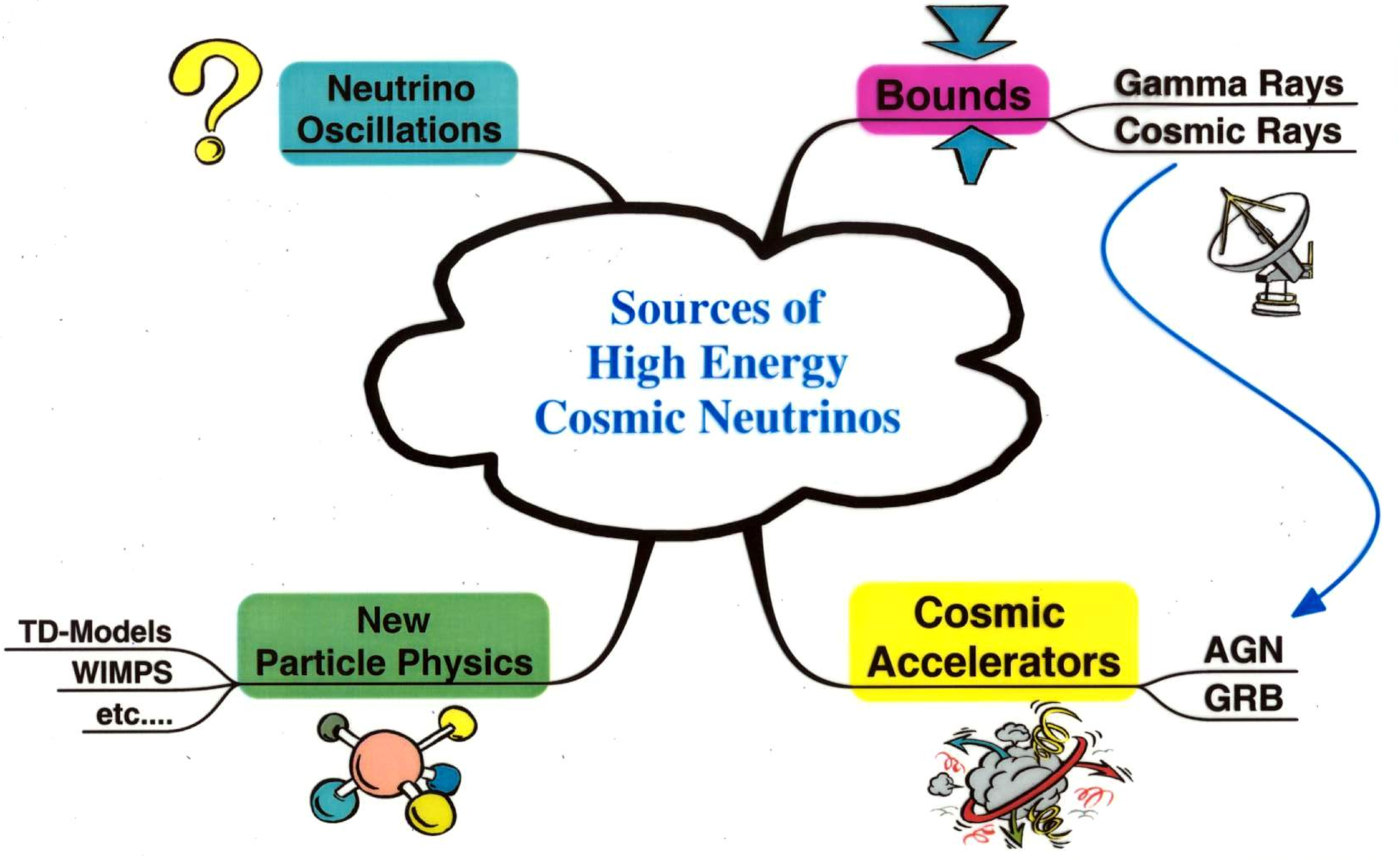


Sources of High Energy Cosmic Neutrinos

Neutrino Oscillations

Bounds
- Gamma Rays
- Cosmic Rays

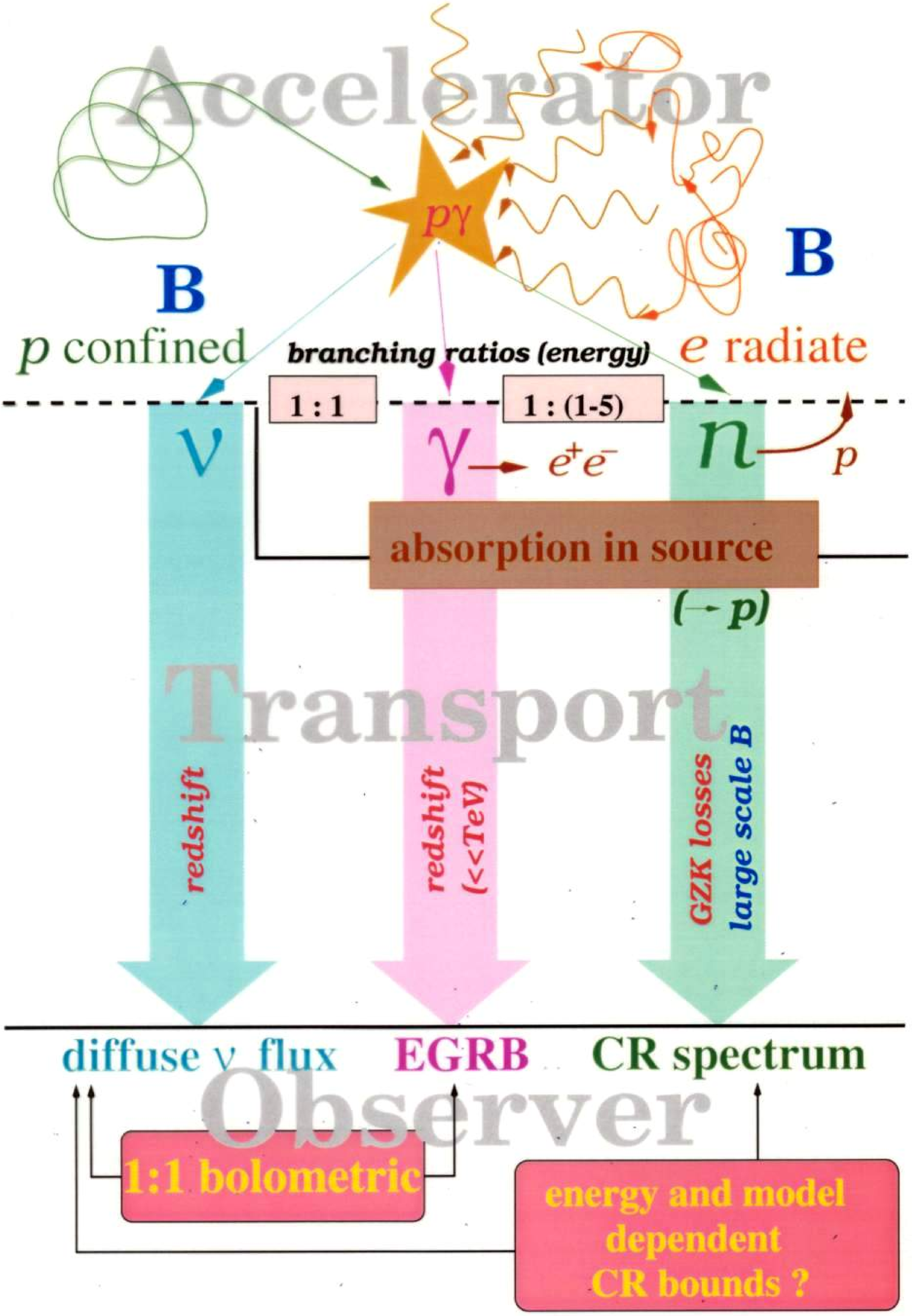
New Particle Physics
- TD-Models
- WIMPS
- etc....

Cosmic Accelerators
- AGN
- GRB

Cosmic Neutrino Model Cookbook

- High energy particle population
  1. Heavy particles (Dark Matter, Topological Defects)
     - → decay into hadron spectrum
  2. Accelerated protons
     - → accelerator particle spectrum
     - → interactions with target
     - (a) matter ($N_\nu \propto N_p$)
     - (b) photons ($N_\nu \propto N_p/N_\gamma$)

- Normalize at other branches
  - → photons from point sources
  - → diffuse γ or UHECR flux



Accelerator

$p\gamma$

B

B

p confined

branching ratios (energy)

e radiate

1 : 1

1 : (1-5)

ν

$\gamma \rightarrow e^+e^-$

$n \rightarrow p$

absorption in source

($\rightarrow p$)

Transport

redshift

redshift (<<TeV)

GZK losses

large scale B

diffuse ν flux

EGRB

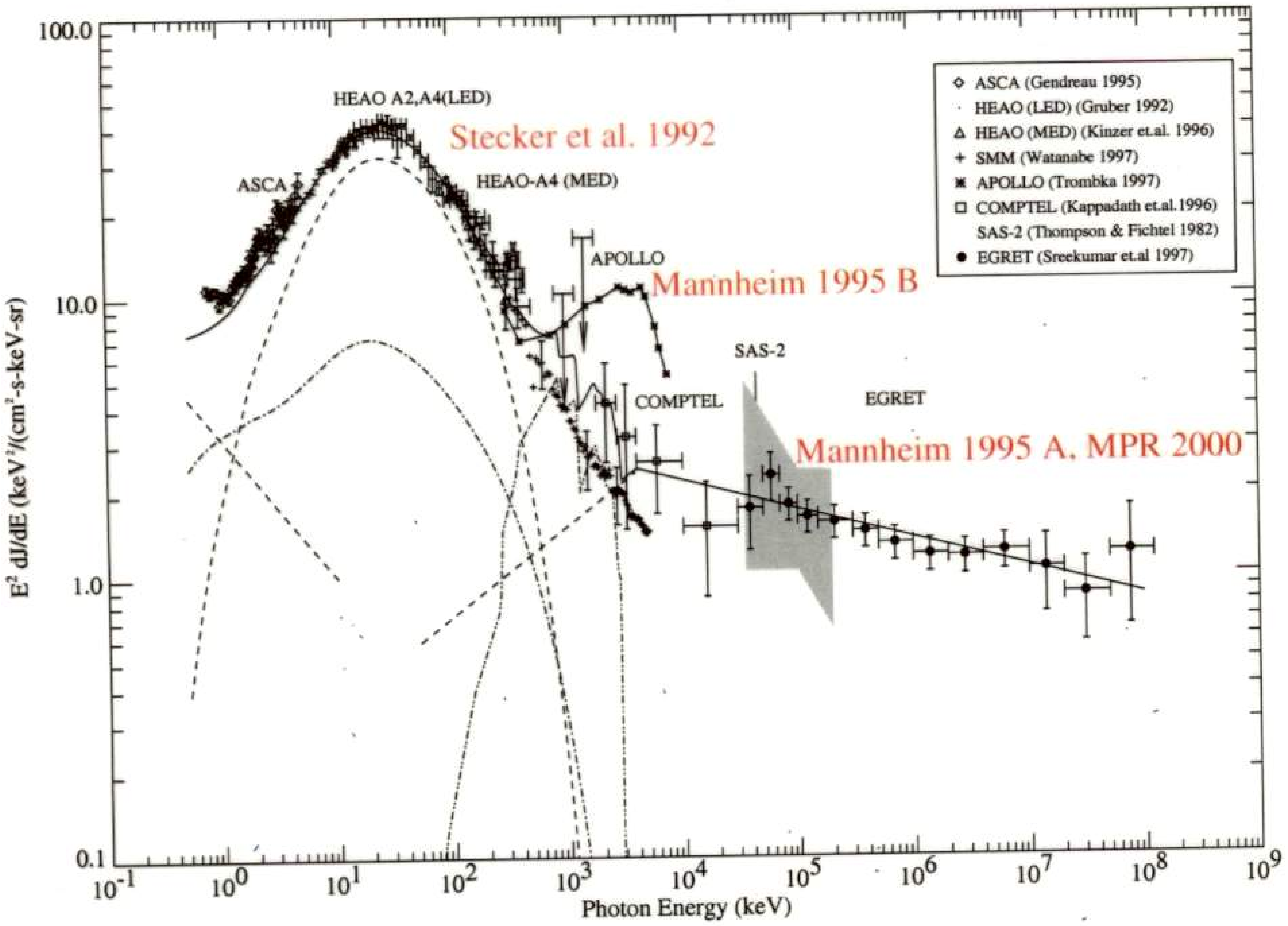
CR spectrum

Observer

1:1 bolometric

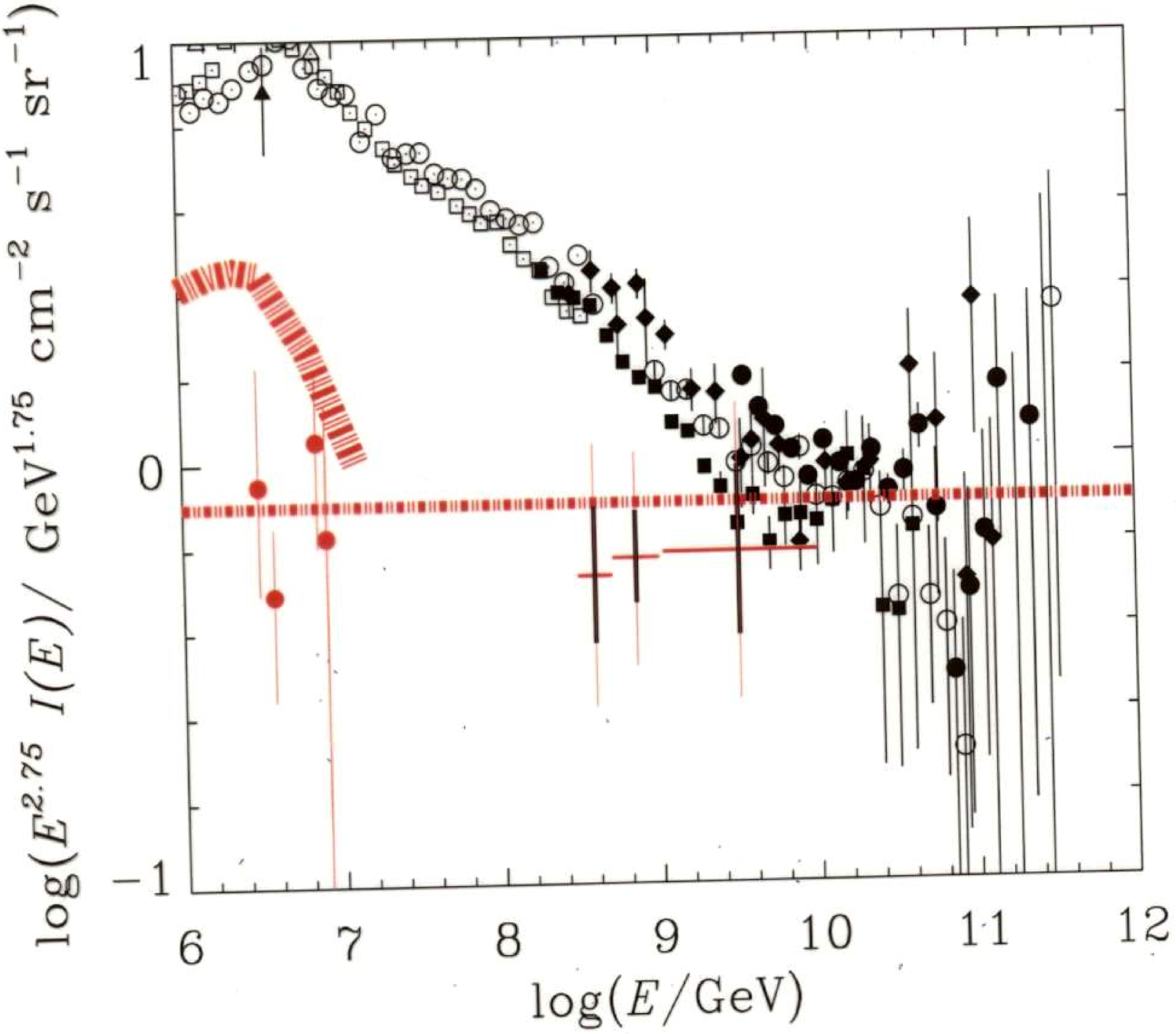
energy and model dependent CR bounds ?

Sreekumar et al., 1997



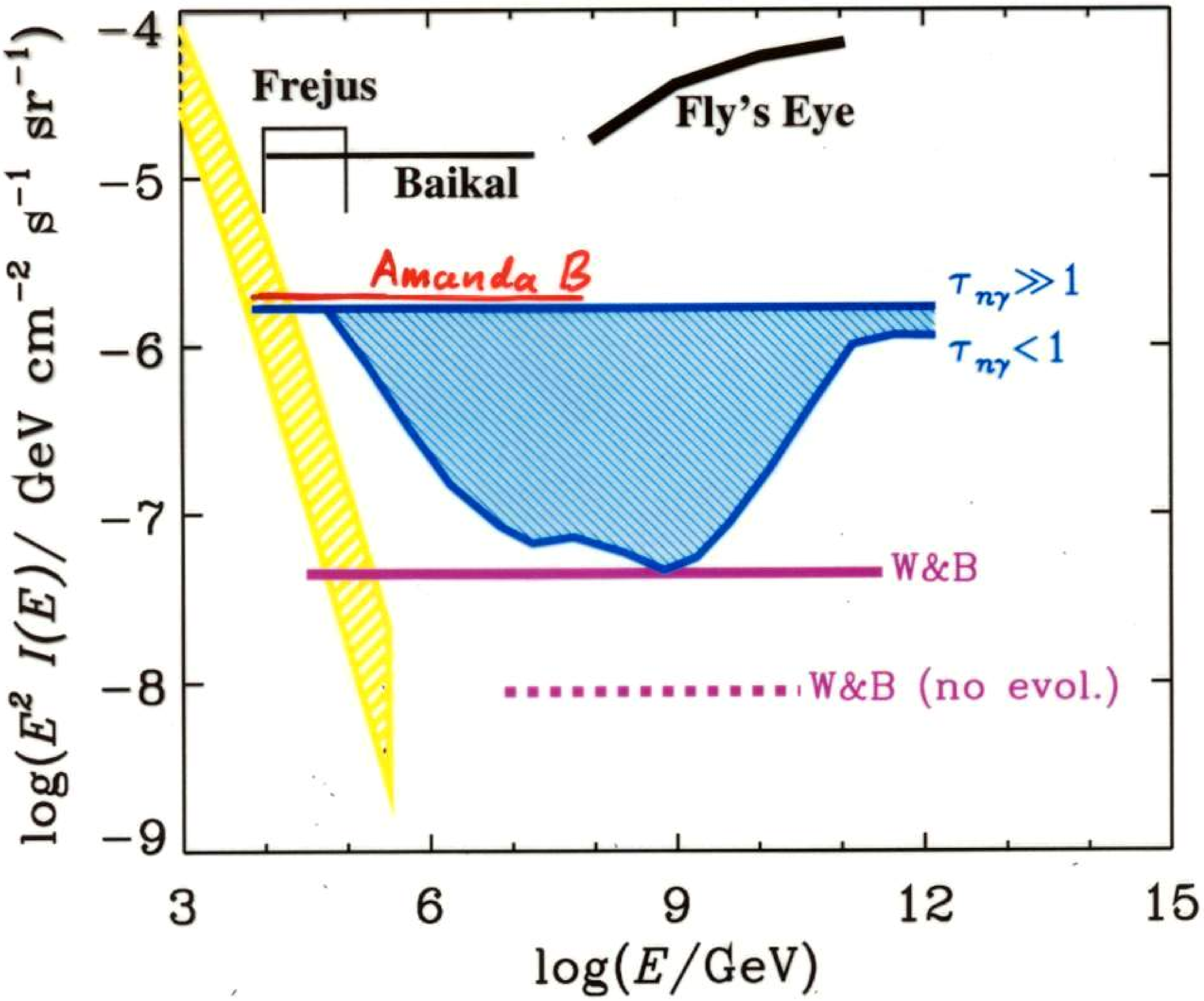
Diffuse extragalactic gamma ray background

Normalization of several neutrino models



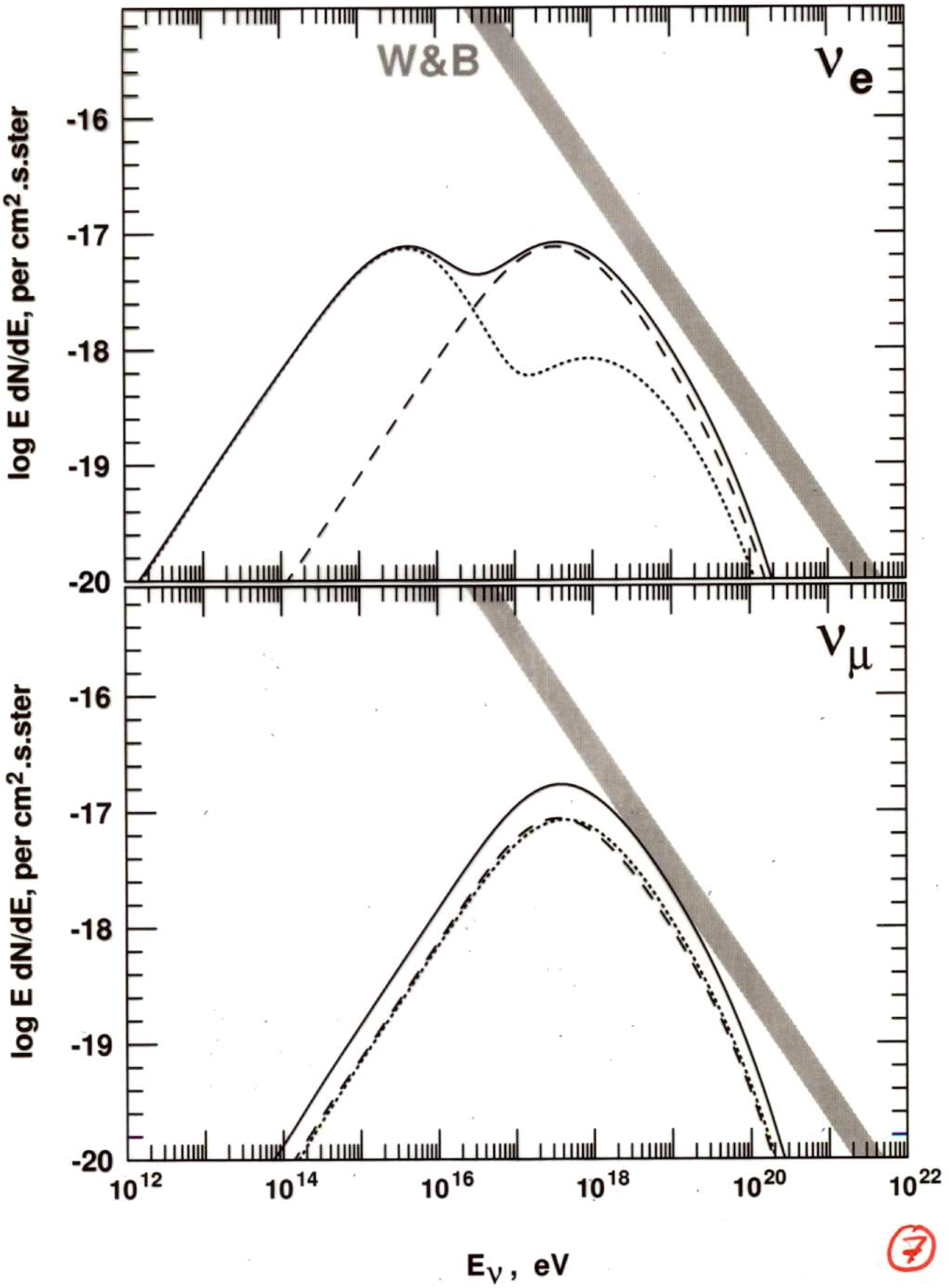
Cosmic ray spectrum (proton contribution)

Neutrino Bounds

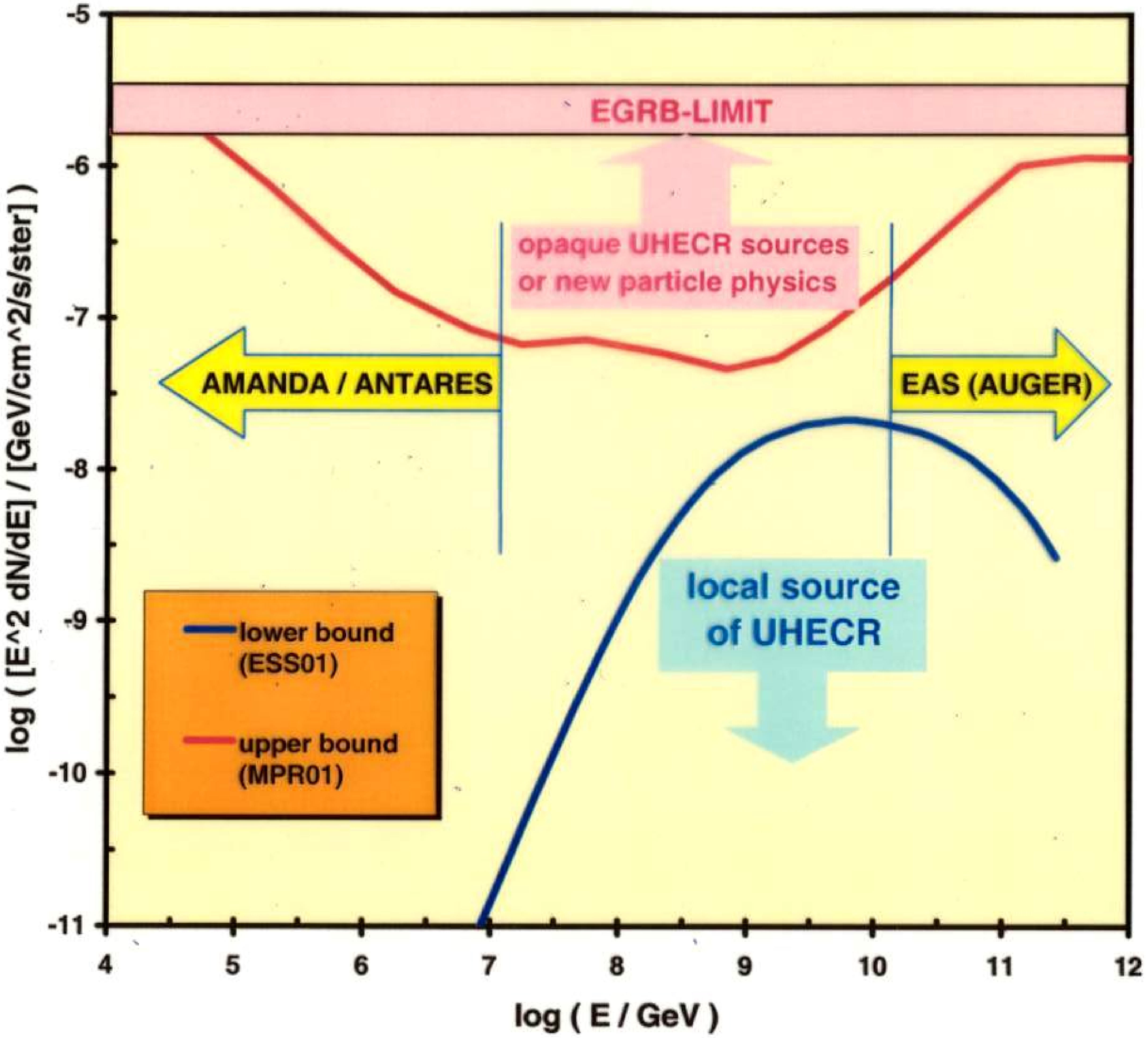


- "Robust" bound by EGRB
  - → experimental upper limit may soon be lower!
- Cosmic ray bound stricter at UHE
  - ... but dependent on many unknowns!

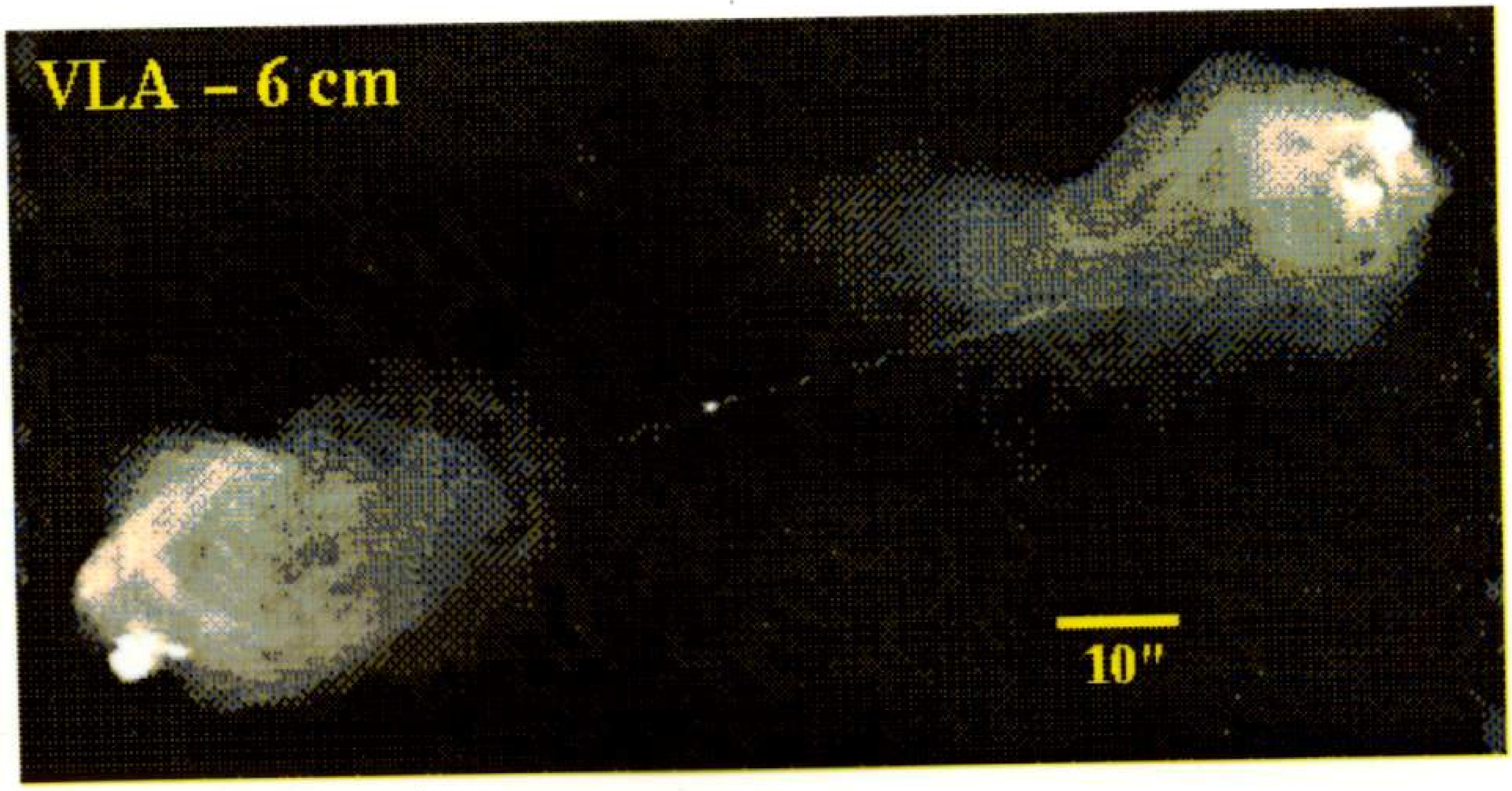
Engel, Seckel & Stanev, 2001



Bounds on extragalactic neutrinos



Cosmic Accelerators

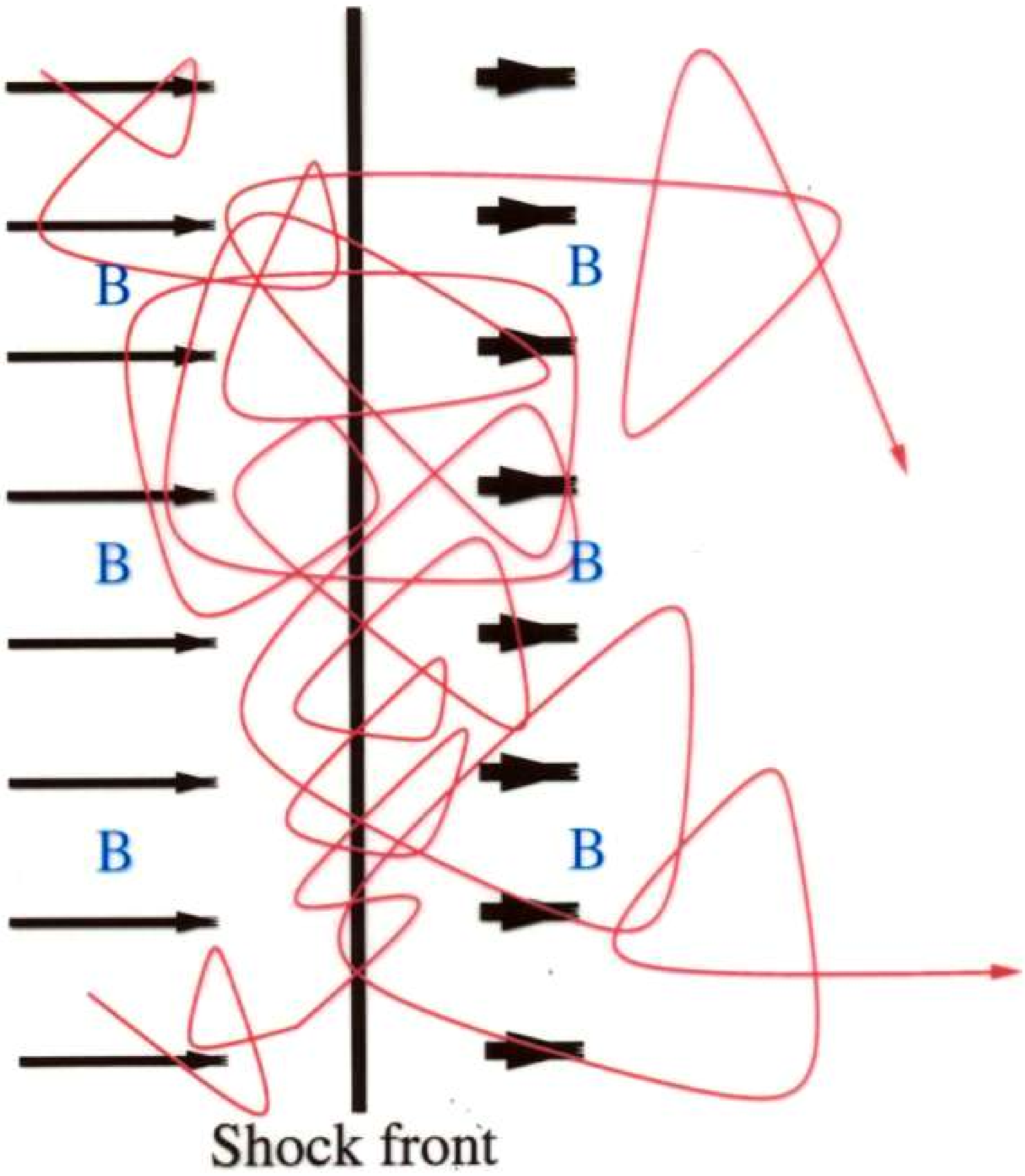


Jets and hot spots in the radio galaxy Cygnus A

- **Hot spots in FR-II radio galaxies (like Cyg A) show electrons of Lorentz factors $\gamma > 10^5$**

- **They can accelerate protons to $> 10^{20}$ eV.**

Shock acceleration



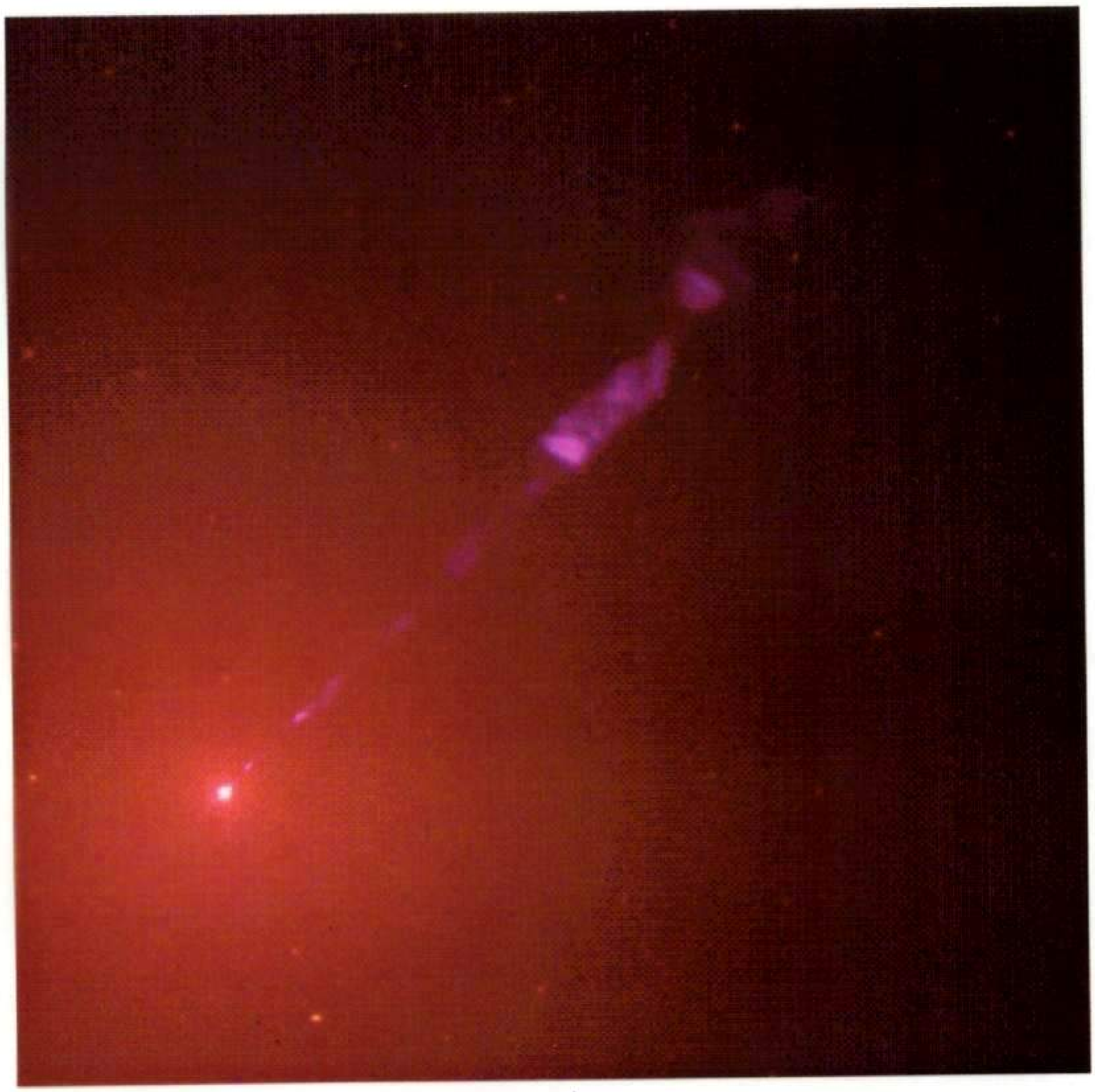
$$\boxed{\left\langle \frac{\Delta E}{E} \right\rangle \approx \beta_{\mathsf{sh}}}$$

$$\boxed{P_{\mathsf{esc}} \approx \beta_{\mathsf{sh}}}$$

- Shock acceleration is 1st order Fermi acceleration: every encounter increases particle energy.

- Universal spectral index: $s = \frac{P_{\text{esc}}}{\langle \Delta E/E \rangle} \approx 1$

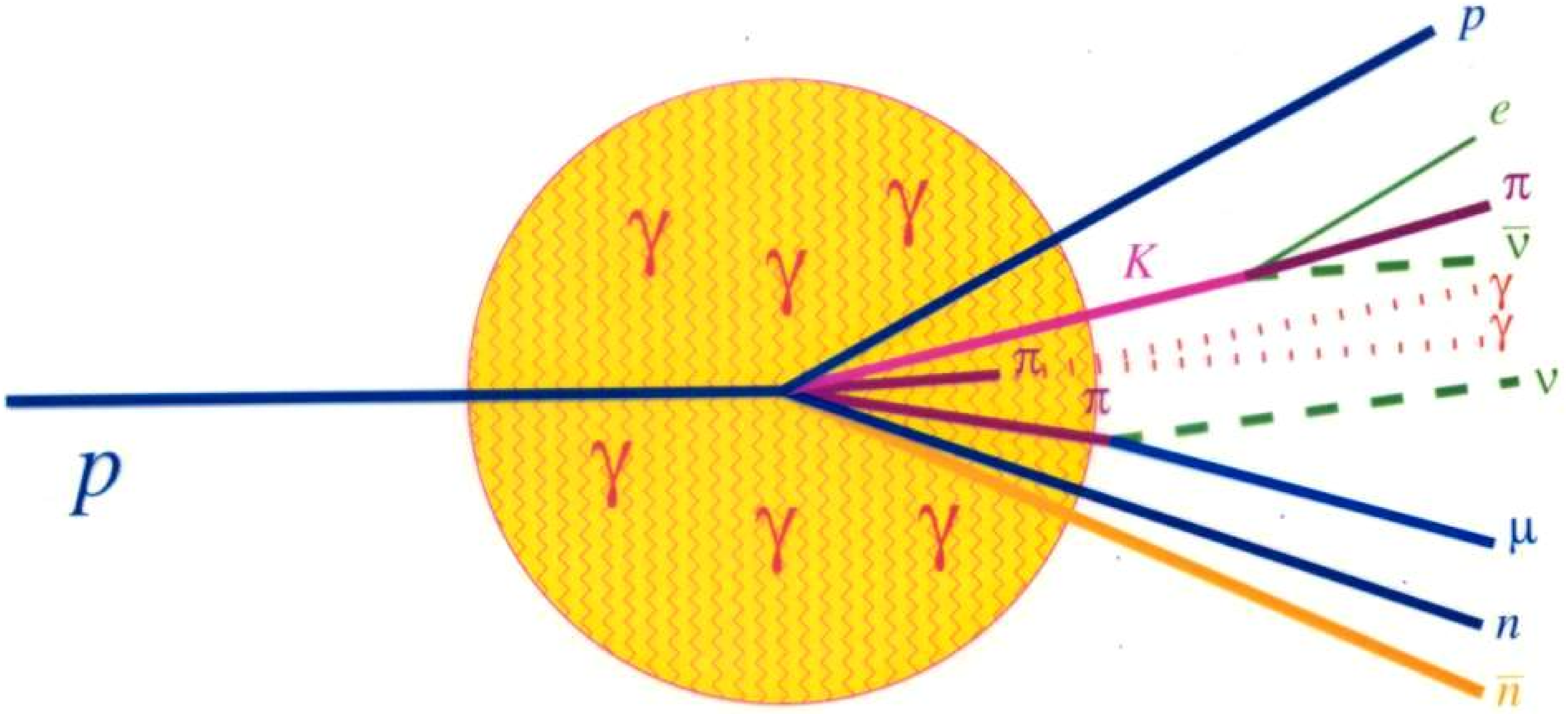
power-per-decade energy independent



The M87 jet: internal shocks in an unsteady flow

- **Internal shocks can occur deep inside the flow** (high compactness!)
- **They are assumed to create also Gamma Ray Bursts (just smaller, faster, brighter, ...)**

Photomeson production



- Interactions of energetic protons with (soft) ambient photons

- Interaction efficiency:

$$\boxed{\zeta_{p\gamma}(E_p) = \frac{t_{\text{cool}}}{t_{p\gamma}} \leq 1}$$

  - Depends on dominant cooling process

Transient neutrino sources

- **Relativistic shocks: lifetime $\sim$ size$/c$**
  - Variability: $T_{\text{var}}^{\text{obs}} \sim R/(cD)$,
    $D =$ Doppler factor

$$\boxed{\mathcal{P}_\nu \propto \zeta_{p\gamma} T_{\text{var}} \propto T_{\text{var}}^{-1}}$$

for $\zeta_{p\gamma} < 1$

→ Rapidly variable objects are the most suitable neutrino sources

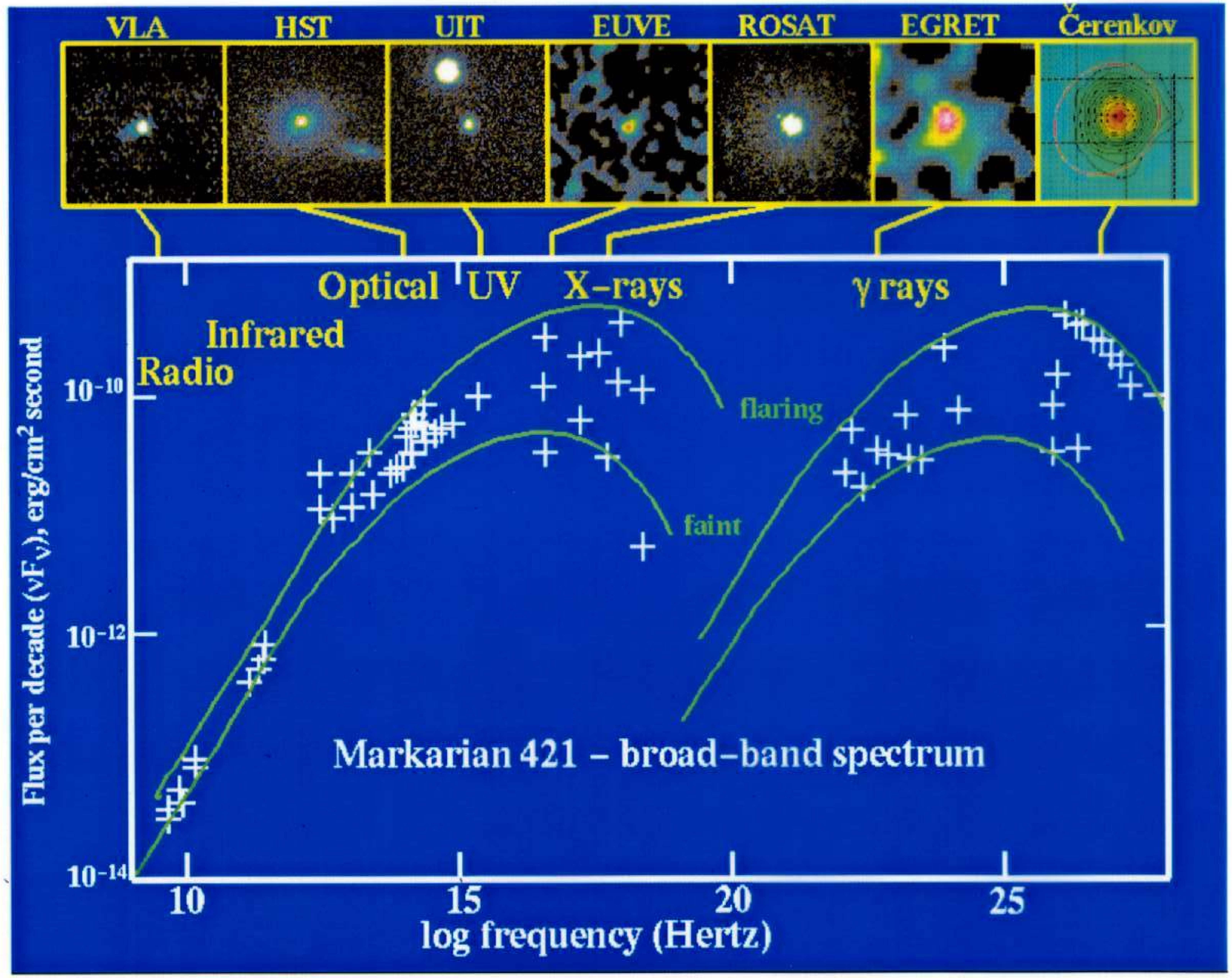
- **Maximum neutrino energy can be limited independent of model details**
  (Rachen & Mészáros, 1998, PRD)

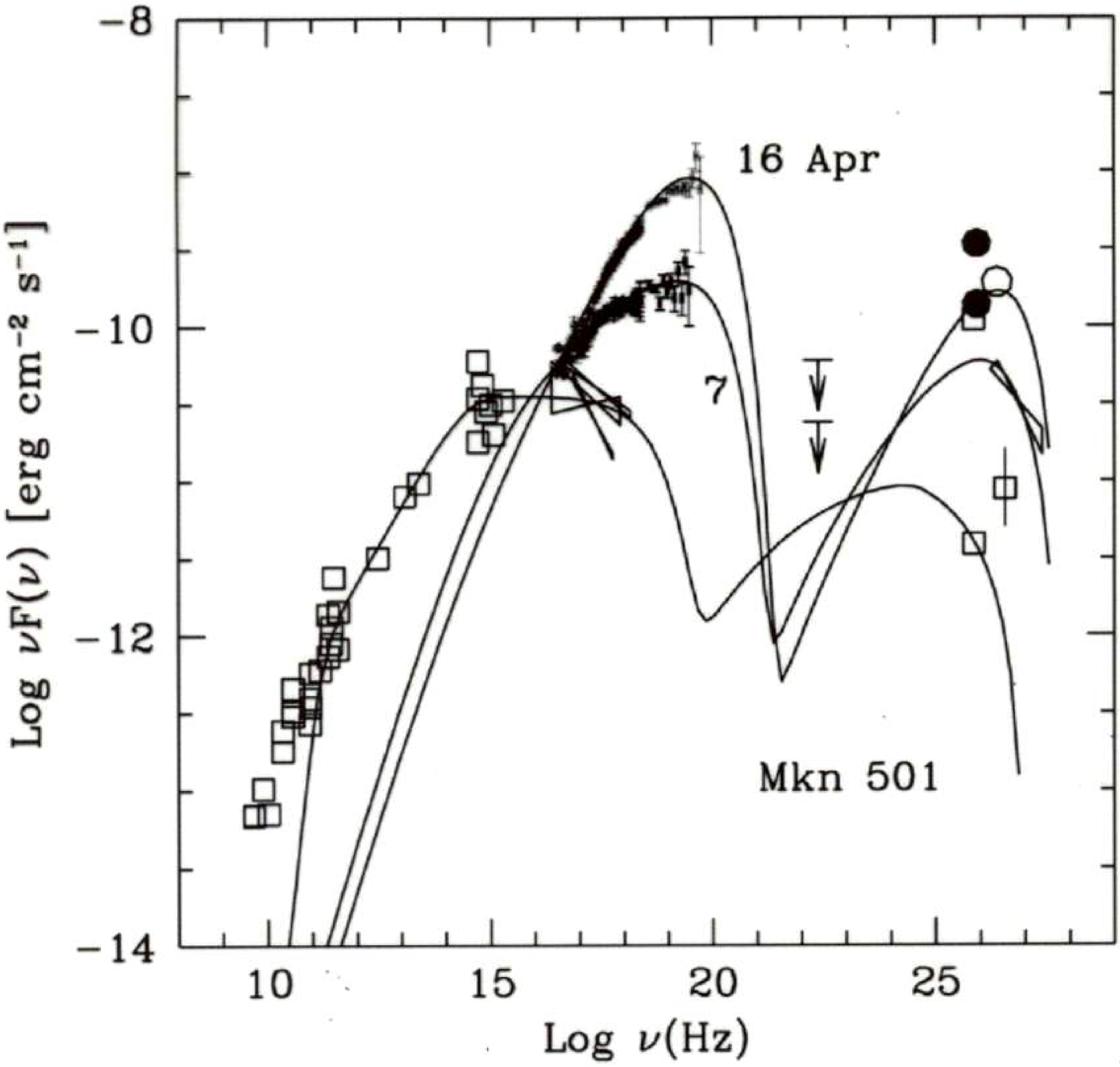
$$\boxed{E_{\nu,\text{max}} \sim 10^{19}\,\text{eV}}$$

Candidate Sources

1. TeV emitting blazars (AGN jets)
    - Motivation: TeV emission can be explained by hadronic processes
2. Gamma Ray Bursts
    - Motivation: Have been suggested as cosmic ray sources

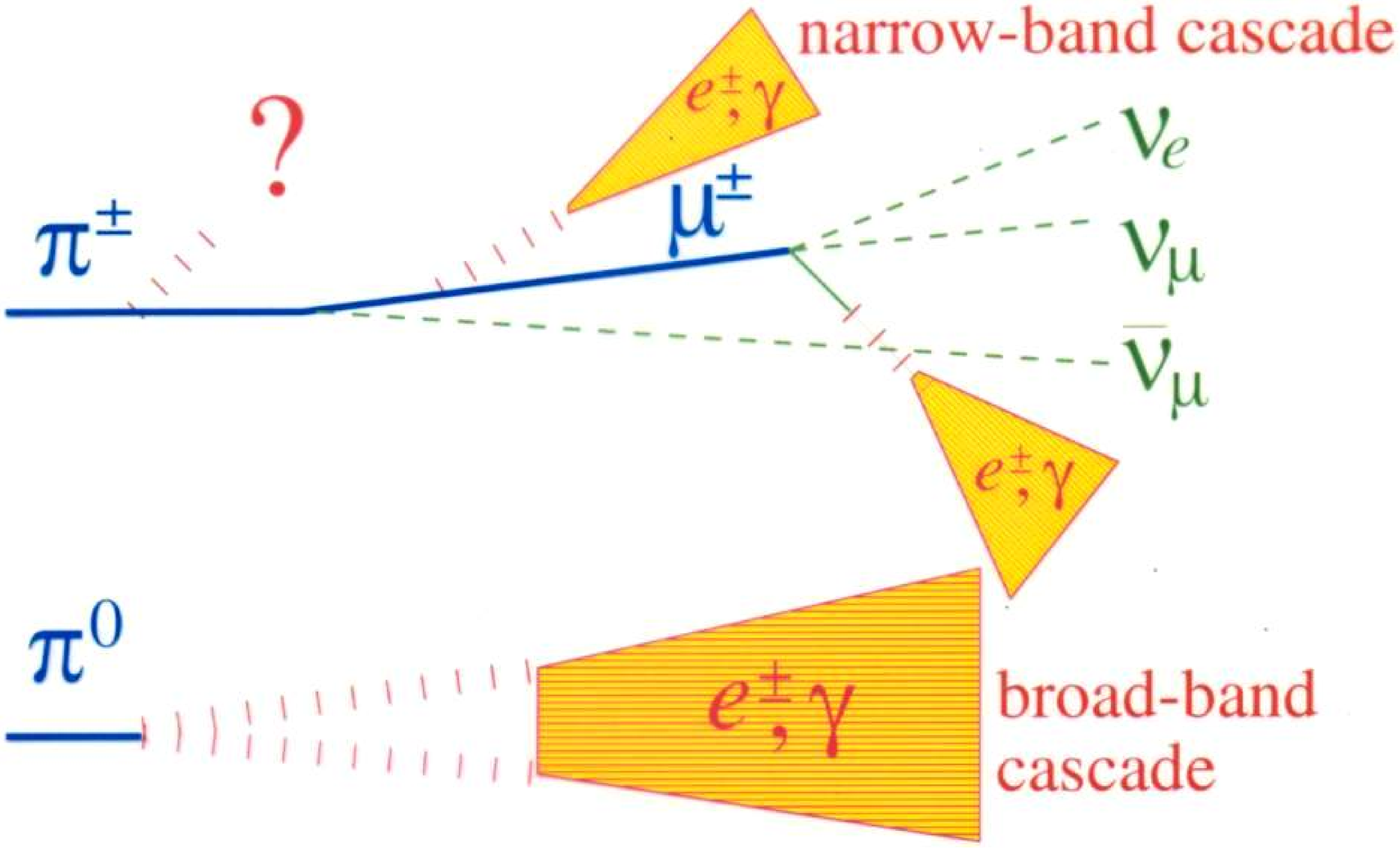
Both source types are strongly variable


VLA
HST
UIT
EUVE
ROSAT
EGRET
Čerenkov
Radio
Infrared
Optical
UV
X-rays
γ rays
flaring
faint
Markarian 421 – broad-band spectrum
Flux per decade (νF_ν), erg/cm^2 second
10^{-10}
10^{-12}
10^{-14}
10
15
20
25
log frequency (Hertz)



- Beppo-SAX > keV synchrotron spectrum too hard for primary acceleration process
- Can be explained as second generation of narrow band cascade

Neutrinos and γ-rays

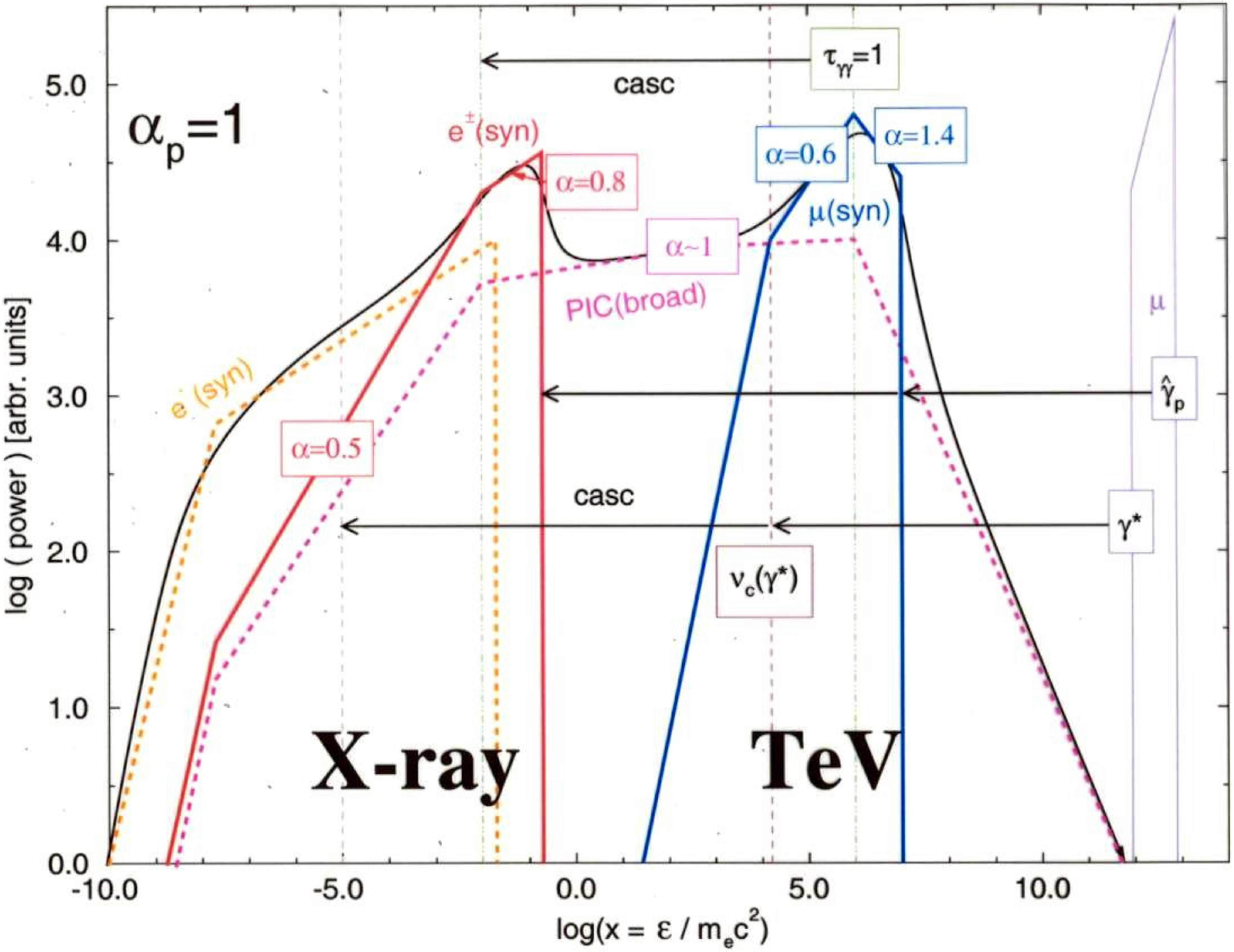


- Neutrino and γ-ray production are strictly related by iso-symmetry

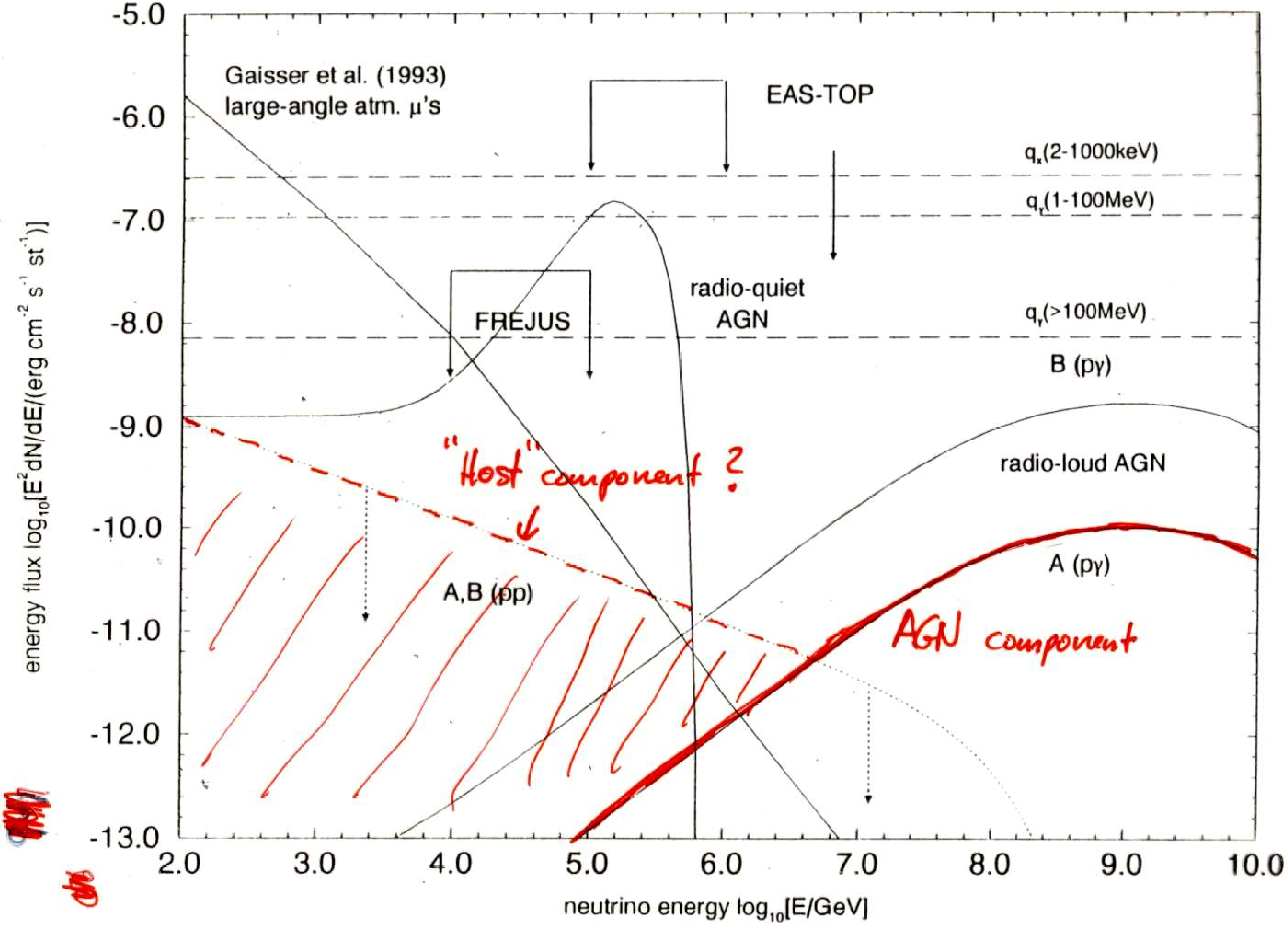
- Secondary particle cooling (synchrotron, adiabatic) can modify neutrino spectra

- Muon-synchrotron cooling: observable γ-ray signature?

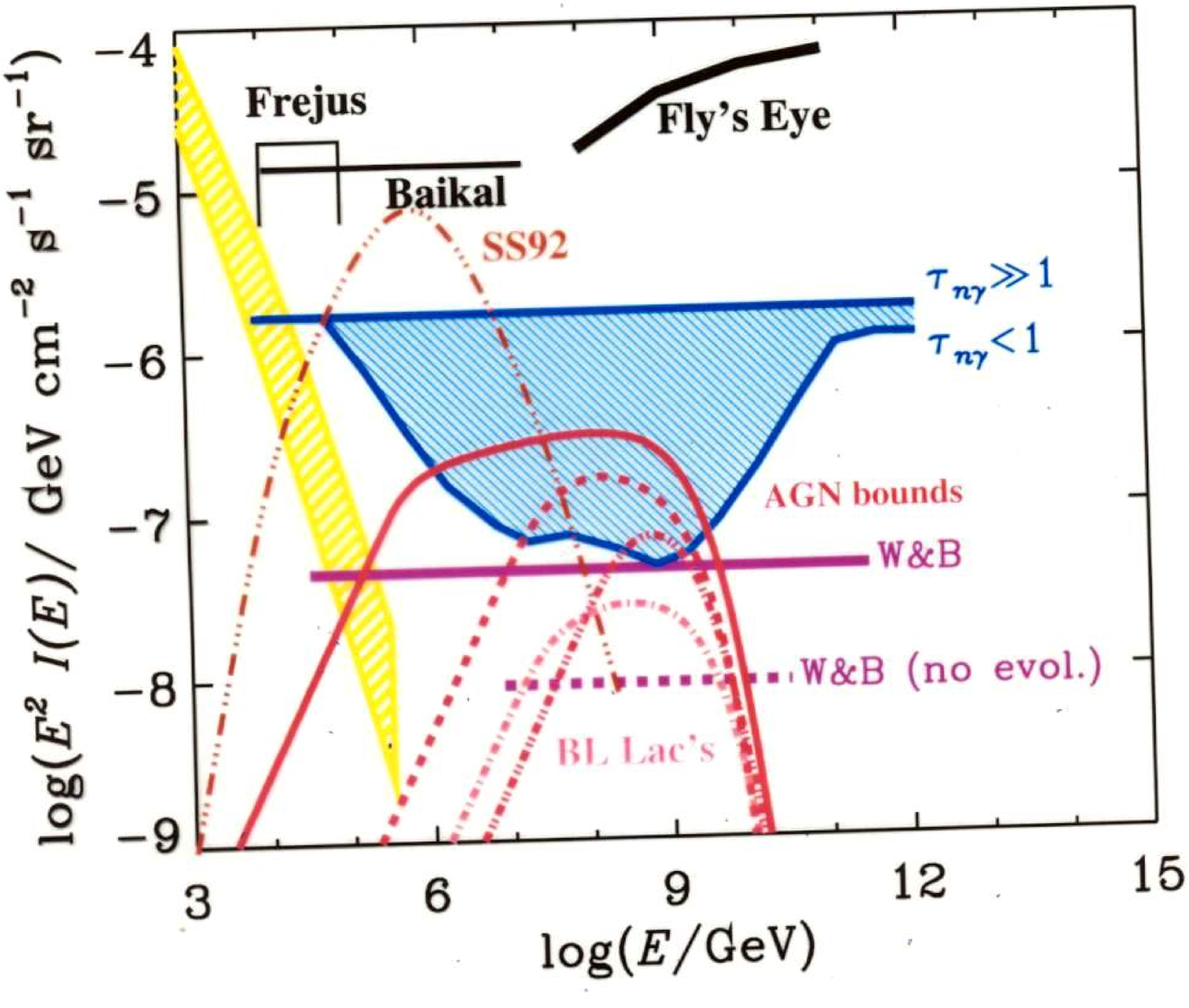
Muon induced (narrow) cascade (schematic)



K. Mannheim/Astroparticle Physics 3 (1995) 295–302



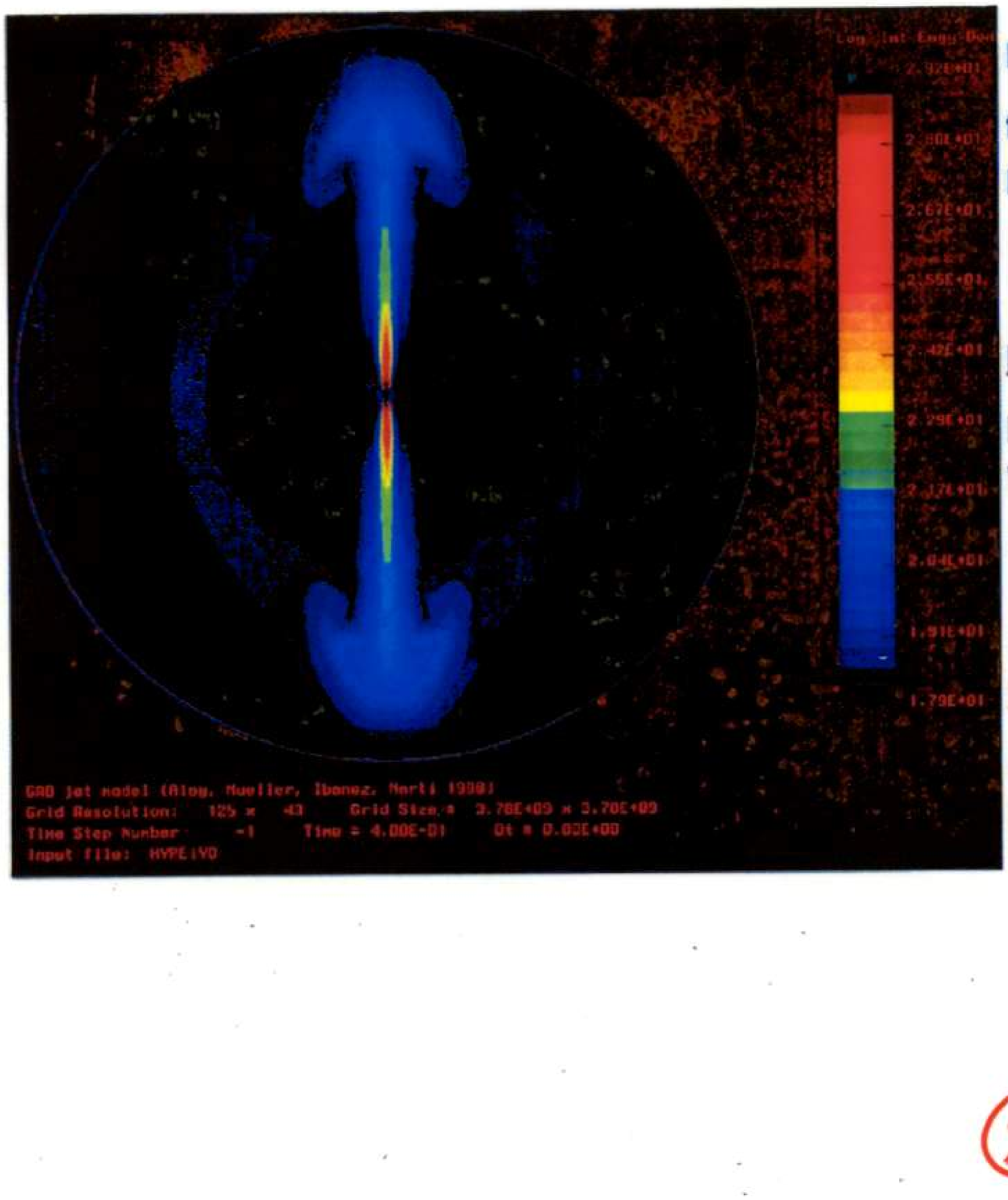
Diffuse AGN neutrino bound



VHE ν-fluxes predicted from hadronic AGN models are yet (!) consistent with observational constraints

Gamma Ray Bursts ...

... signatures of stellar black hole creation?



Log Int. Energ

t = 0.4 s

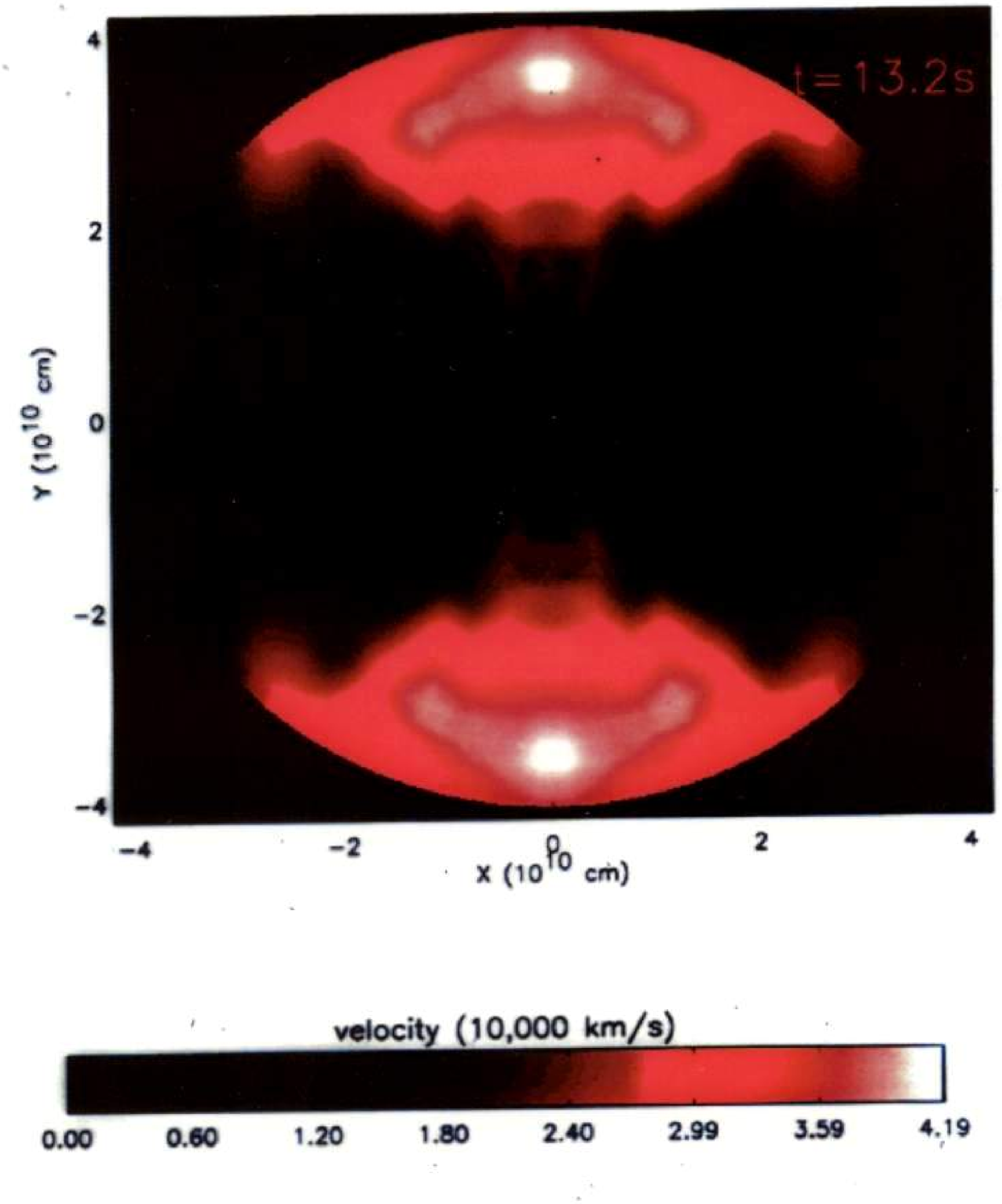
R = 1.9×10^9 cm

<u>Initial model</u>

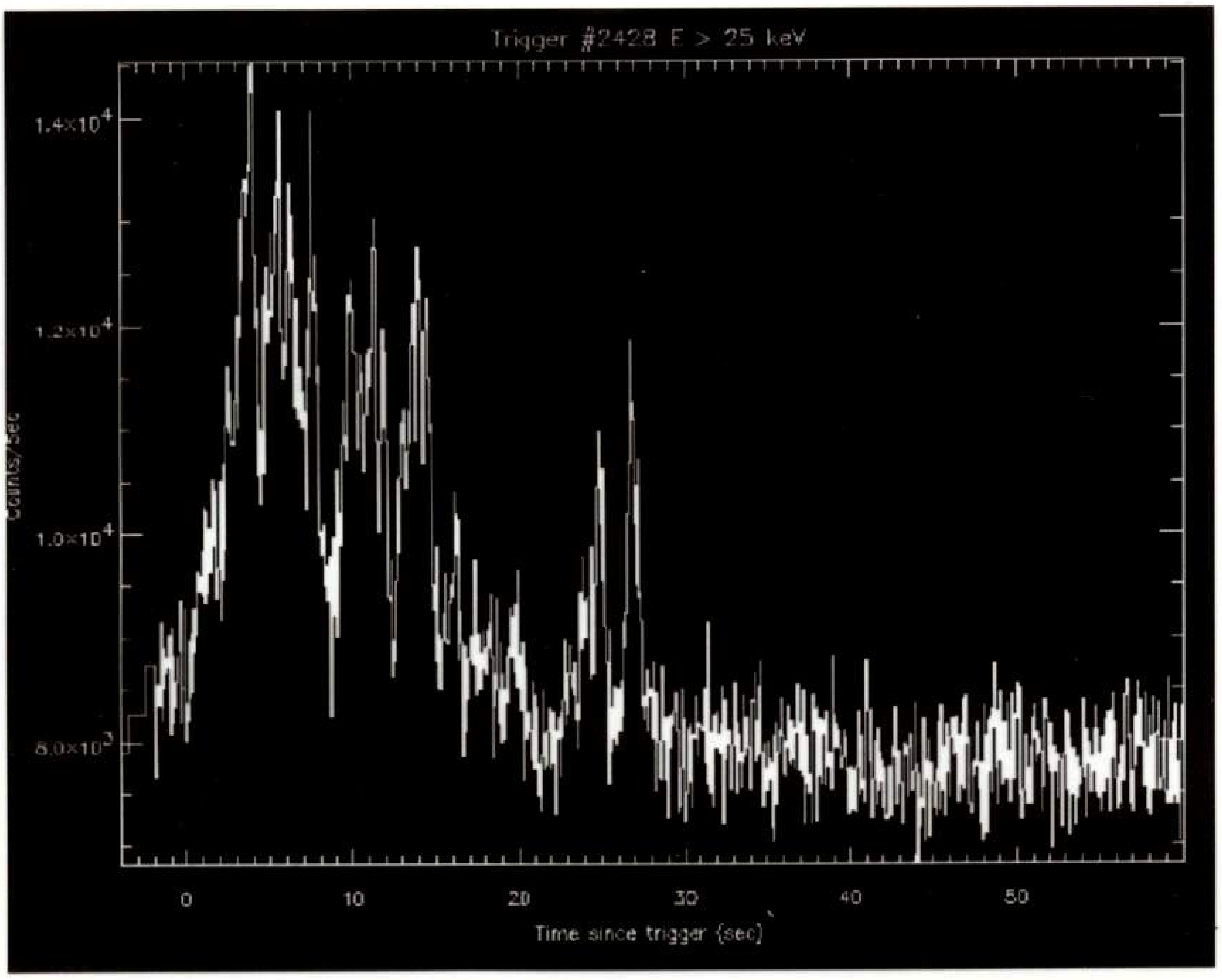
**MacFadyen &
Woosley '98**

SR-simulation

**Aloy, M üller,
Ibañez, Martí '**


t=13.2s
4
2
0
-2
-4
Y (10^{10} cm)
-4
-2
0
2
4
X (10^{10} cm)
velocity (10,000 km/s)
0.00
0.60
1.20
1.80
2.40
2.99
3.59
4.19

Gamma Ray Burst lightcurve

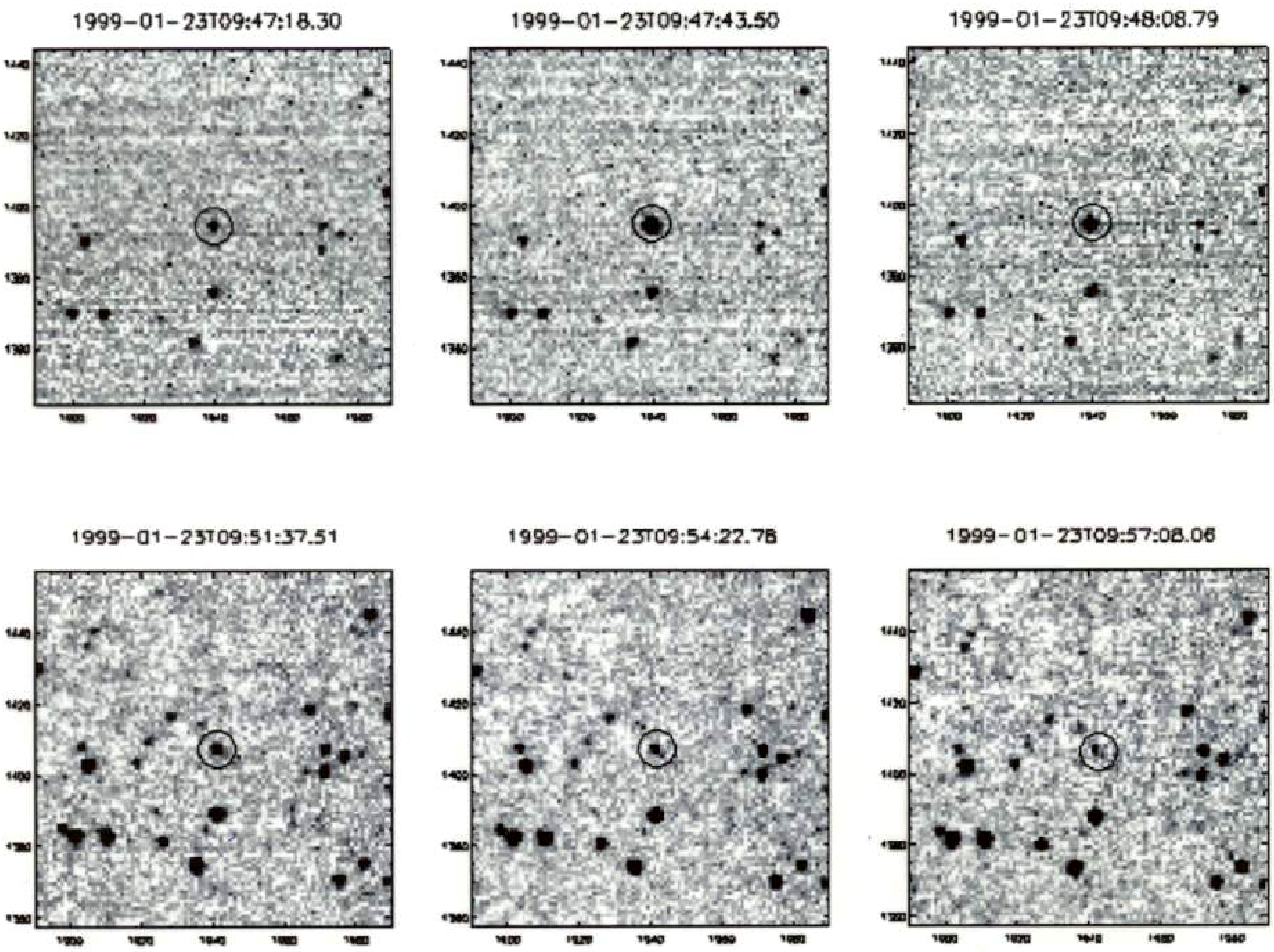


- **Duration of gamma emission:** $\sim 1{-}30$ **seconds**

- **Most power in GRBs is emitted in** $\sim 0.1\,\mathrm{s}$ **flares**

GRB 990123

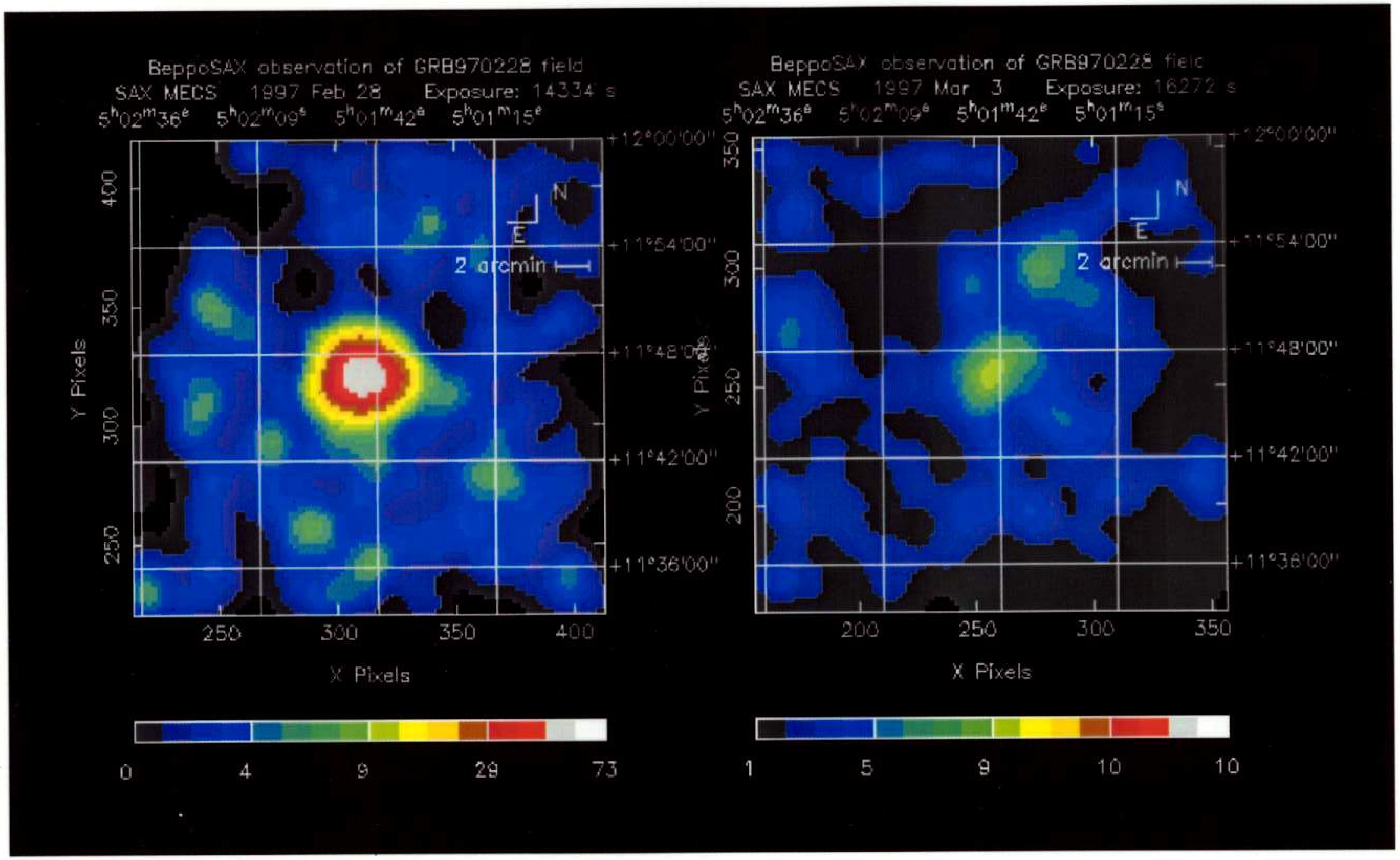
“most energetic event since the big bang”



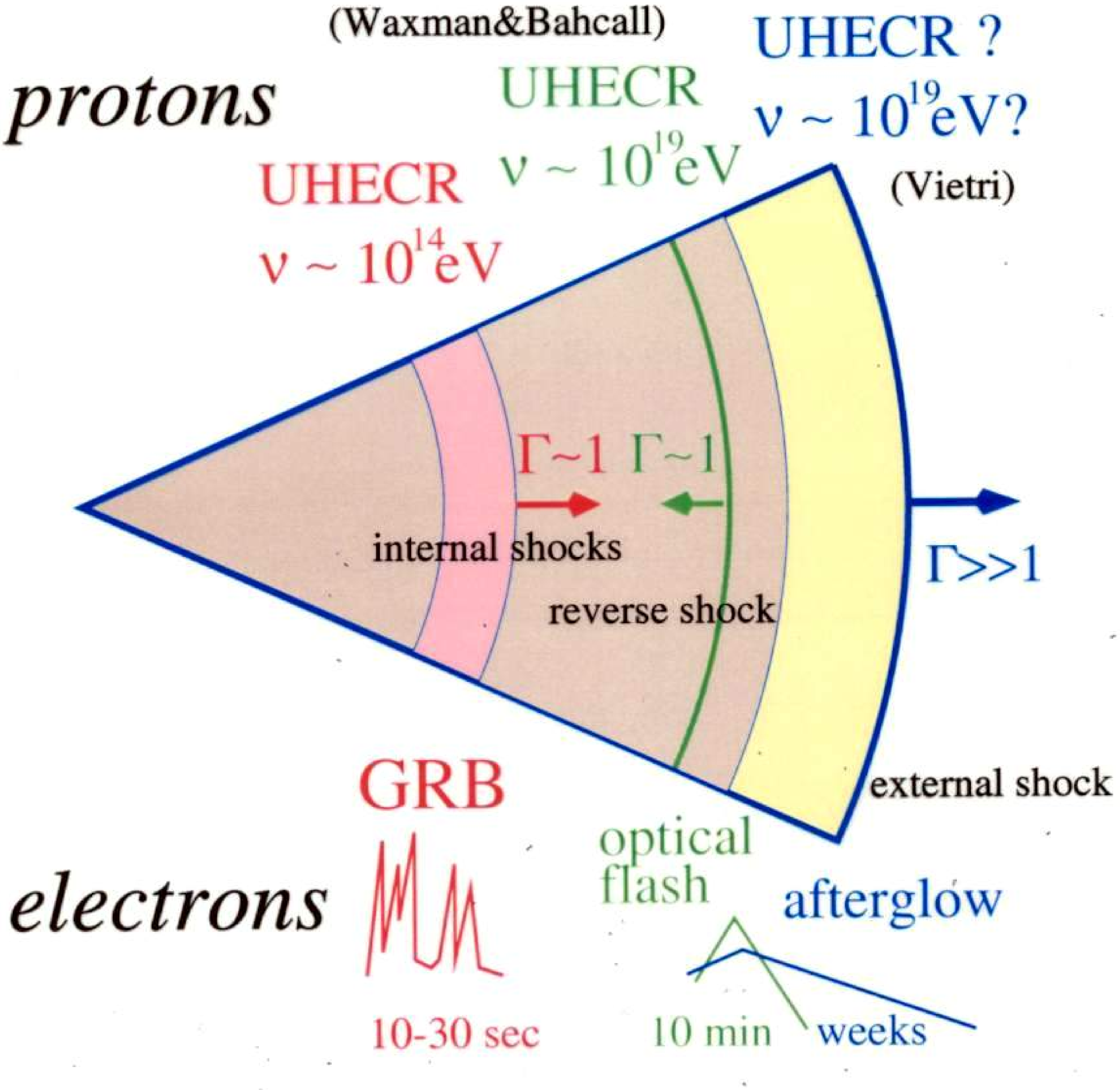
1999-01-23T09:47:18.30
1999-01-23T09:47:43.50
1999-01-23T09:48:08.79
1999-01-23T09:51:37.51
1999-01-23T09:54:22.78
1999-01-23T09:57:08.06

- observable with a binocular …

  …**but 10 billion light-years away**


BeppoSAX observation of GRB970228 field
SAX MECS 1997 Feb 28 Exposure: 14334 s
$5^h02^m36^s$ $5^h02^m09^s$ $5^h01^m42^s$ $5^h01^m15^s$
+12°00'00"
+11°54'00"
+11°48'00"
+11°42'00"
+11°36'00"
N
E
2 arcmin
Y Pixels
400
350
300
250
X Pixels
250
300
350
400
0
4
9
29
73
BeppoSAX observation of GRB970228 field
SAX MECS 1997 Mar 3 Exposure: 16272 s
$5^h02^m36^s$ $5^h02^m09^s$ $5^h01^m42^s$ $5^h01^m15^s$
+12°00'00"
+11°54'00"
+11°48'00"
+11°42'00"
+11°36'00"
N
E
2 arcmin
Y Pixels
350
300
250
200
X Pixels
200
250
300
350
1
5
9
10
10

The fireball model



(Waxman&Bahcall)

UHECR ?
$\nu \sim 10^{19}$eV?
(Vietri)

protons

UHECR
$\nu \sim 10^{19}$eV

UHECR
$\nu \sim 10^{14}$eV

$\Gamma \sim 1$ $\Gamma \sim 1$

internal shocks

reverse shock

$\Gamma >> 1$

external shock

GRB

optical flash

afterglow

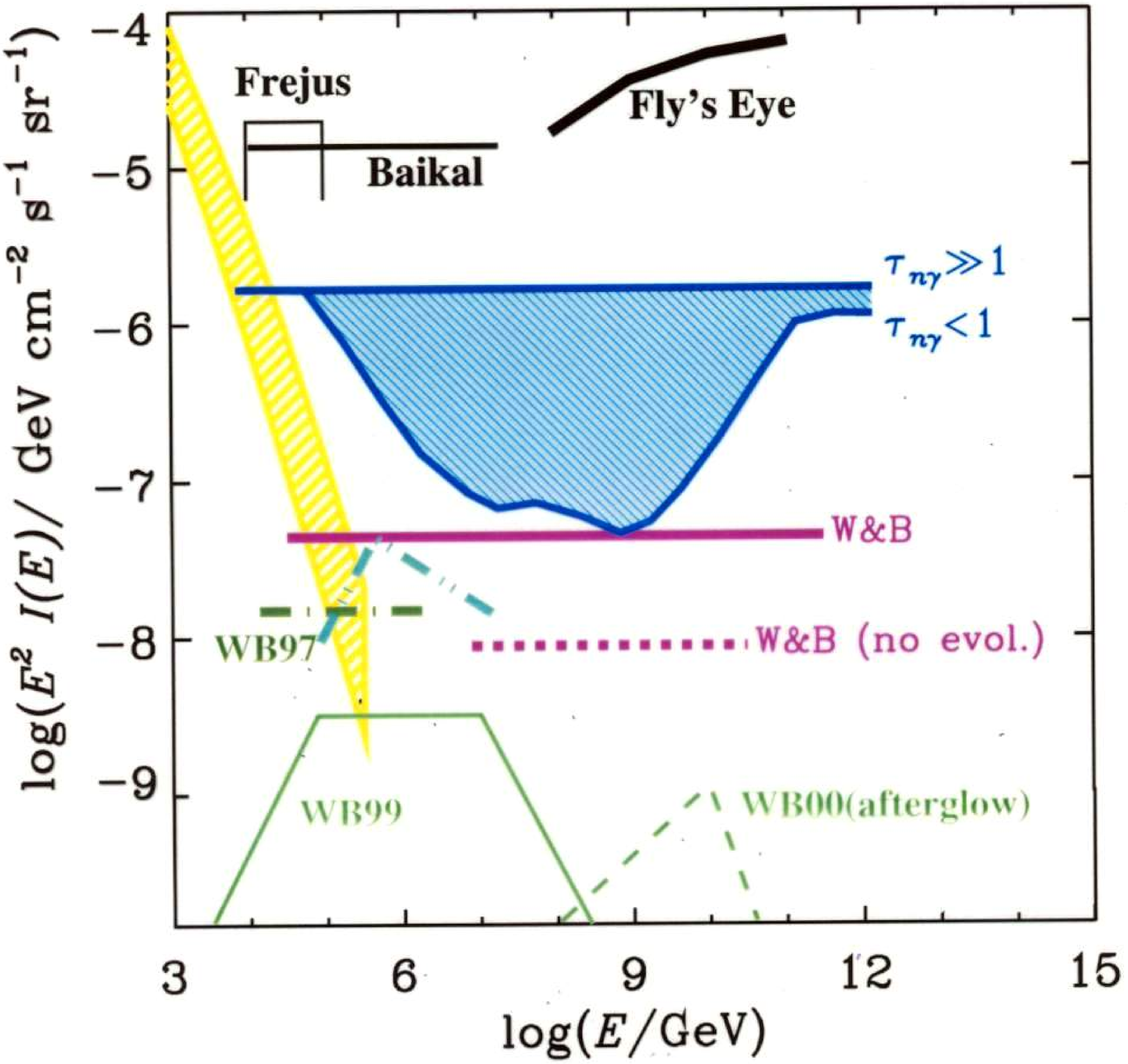
electrons

10-30 sec

10 min

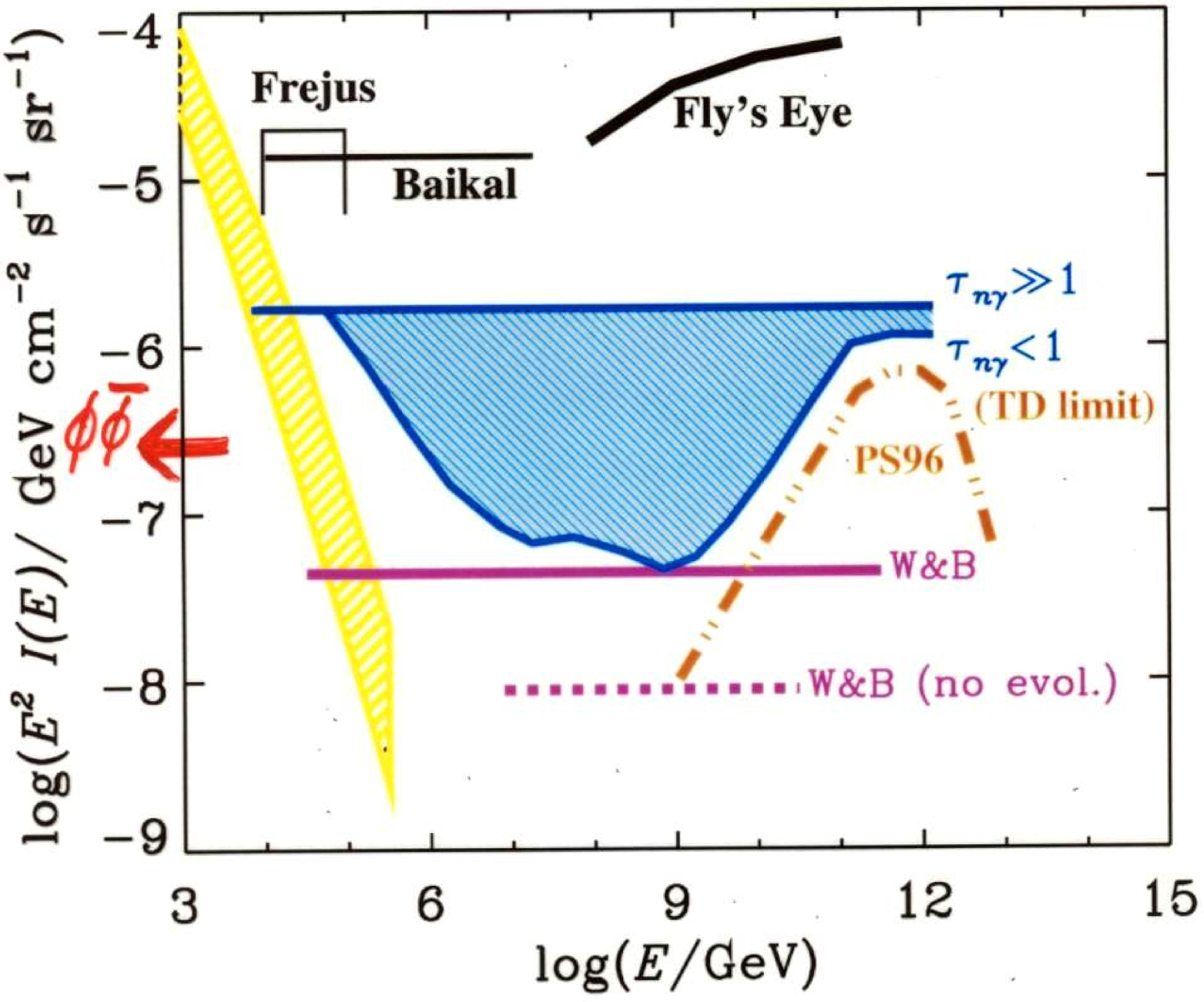
weeks

GRB neutrino fluxes



If GRB produce UHECR, neutrino flux should be on level with WB bound!

Non-acceleration scenarios



TD models bound by EGRB, not by UHECR — but predictions are compatible with UHECR bound for accelerator sources!

Neutrino oscillations

- extragalactic: $\frac{\delta m^2 L}{E} \gg 1$

  $\Rightarrow \boxed{P_{osc} \simeq \frac{1}{2} \sin^2 2\theta}$

- no disappearance !

- ν_τ - appearance likely

  $\Rightarrow$ enhanced detection probability

- ν_e - appearance ? ($\nu_\mu \to \nu_e$)
  - for $E_\nu > 10^{15}$ eV
  - from GRB & AGN cores
  - if $\sin^2 2\theta \sim 0.1$ ← ?

ν_τ detection by showers vs. muon tracks

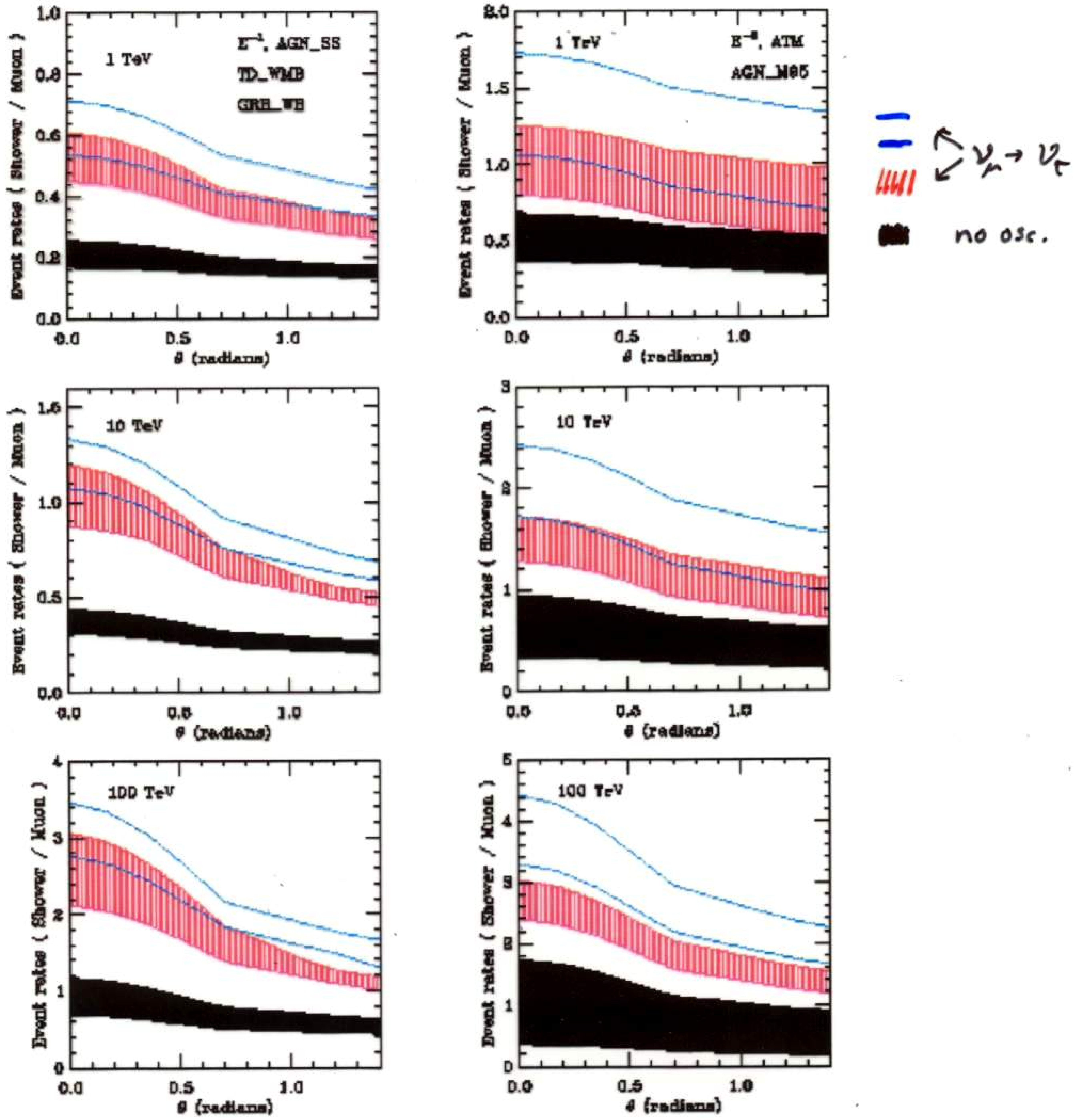
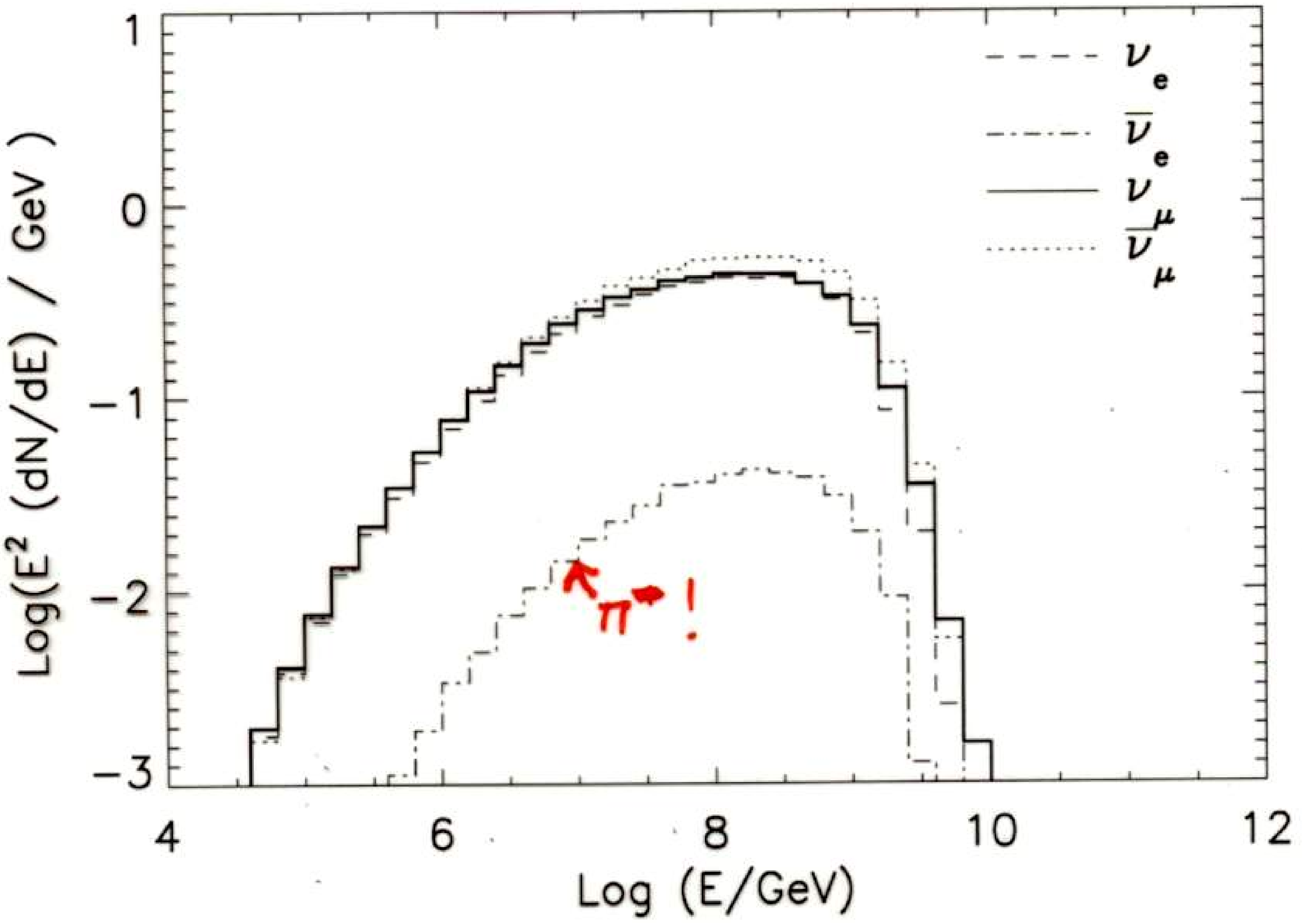


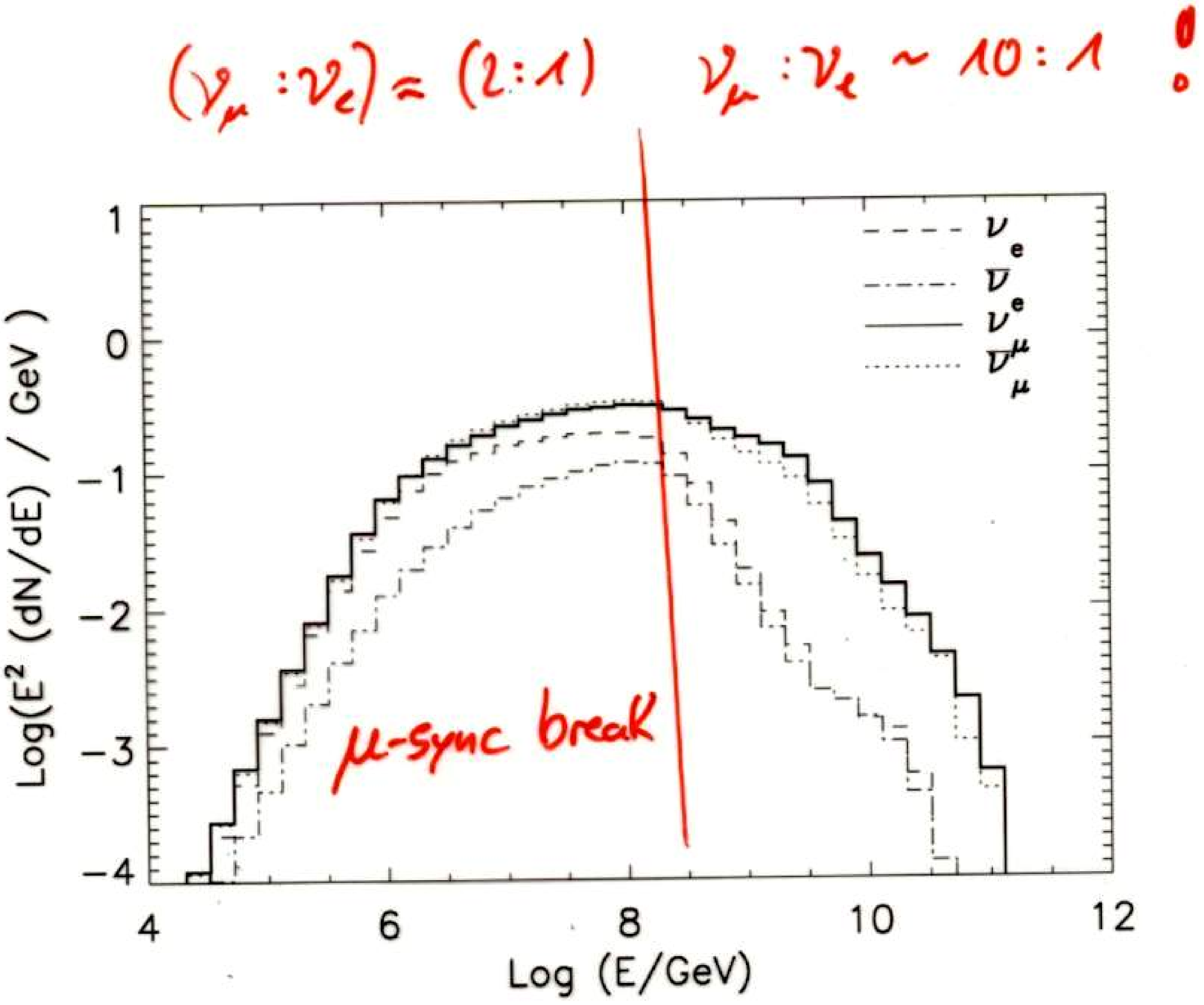
FIG. 2. Ratio of shower event rates to muon event rates

Iyer-Dutta, Reno & Sarcevic, 2001

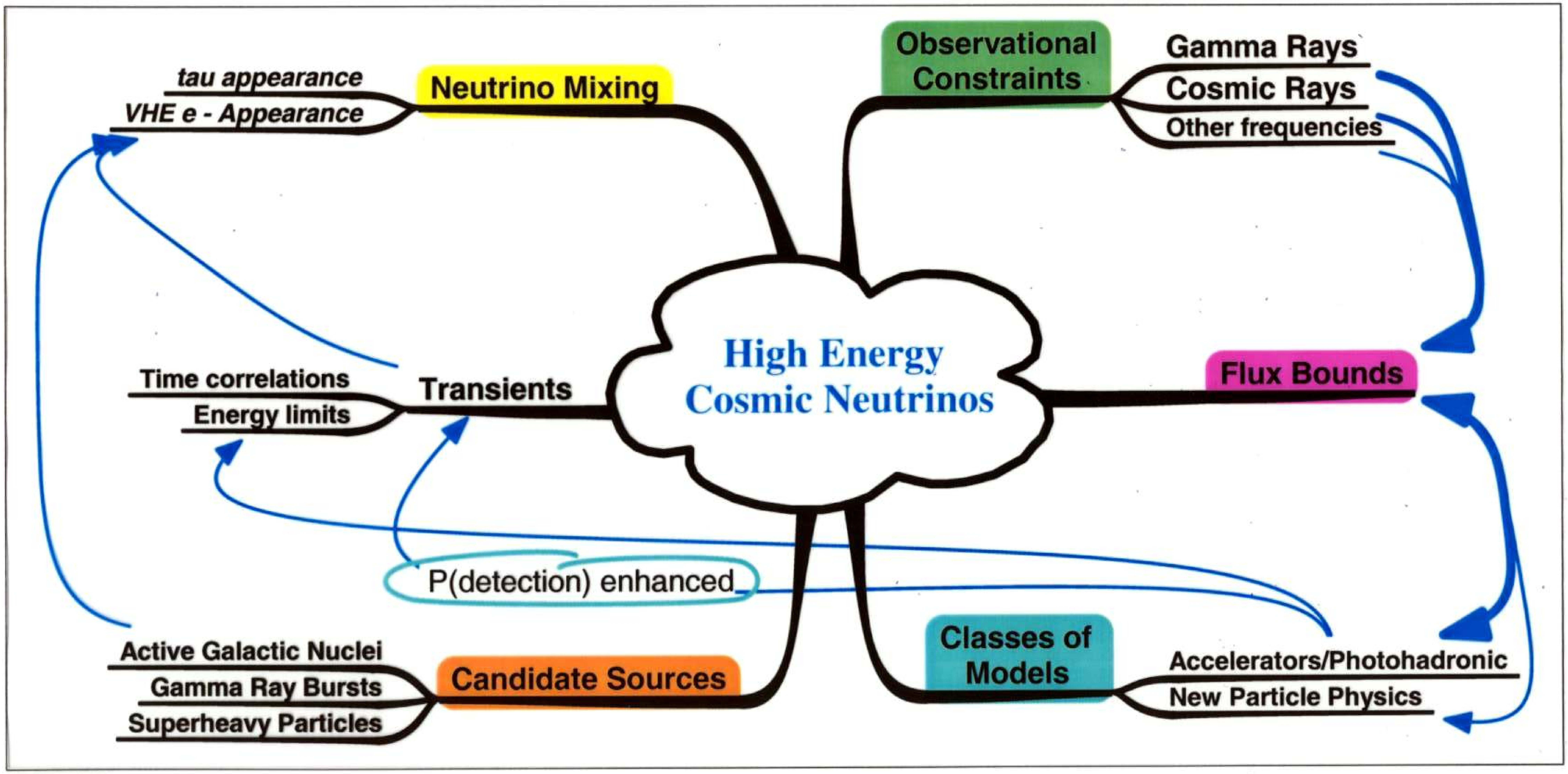
$(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) \approx 2 : 1$



Neutrino spectrum from blazar flare with $T = 10^4\,$s, obtained with SOPHIA



Neutrino spectrum from GRB flare with $T = 1\,\mathrm{s}$, obtained with SOPHIA



High Energy Cosmic Neutrinos

- **Neutrino Mixing**
  - *tau appearance*
  - *VHE e - Appearance*
- **Observational Constraints**
  - Gamma Rays
  - Cosmic Rays
  - Other frequencies
- **Flux Bounds**
- **Transients**
  - Time correlations
  - Energy limits
- **Candidate Sources**
  - Active Galactic Nuclei
  - Gamma Ray Bursts
  - Superheavy Particles
- **Classes of Models**
  - Accelerators/Photohadronic
  - New Particle Physics

P(detection) enhanced

? - 15/06/2001