SS433 as a natural laboratory for astrophysical neutrinos

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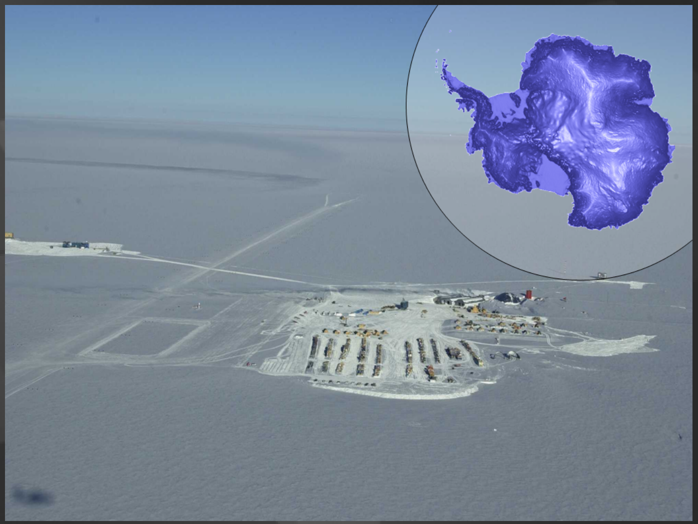
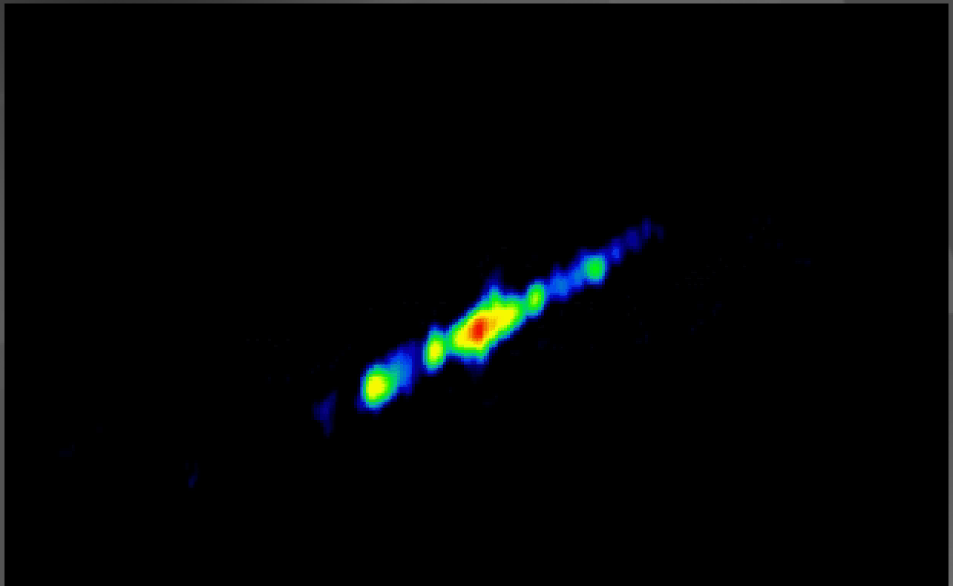
Outline

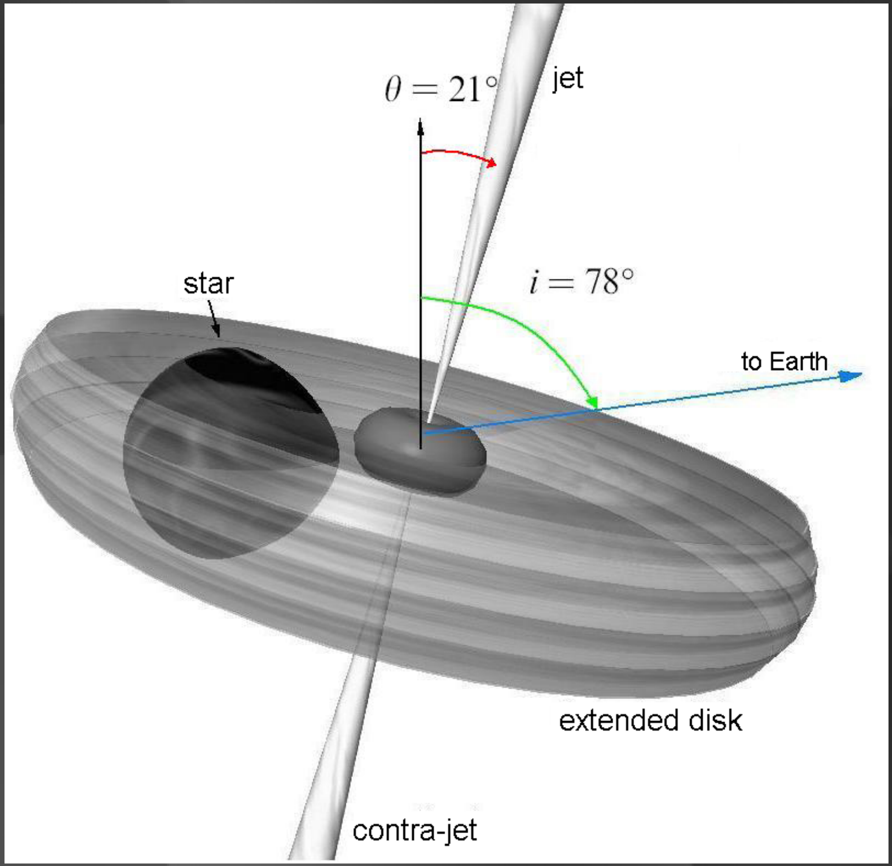
- Overview of SS433
- HE processes in the jets
  - Protons and Electrons: shock-accelerated
  - pp and pγ interactions: produce pions
  - pions interact and decay giving leptons and γ-rays
- Neutrino flux
- Absorption of γ-rays
  - γγ and γN interactions
- Gamma-ray flux
- Discussion



SS433: a precessing microquasar with heavy jets

- Microquasar: normal star + compact object with jets
- Jets with high kinetic power: $L_k=10^{39}$erg/s
- Fe lines from detected from jets (Migliari et al. 2002)
- Jets and extended disk wind in precession (P_{prec}=162 d)
- Potential neutrino source (Eichler 1980, Learned &

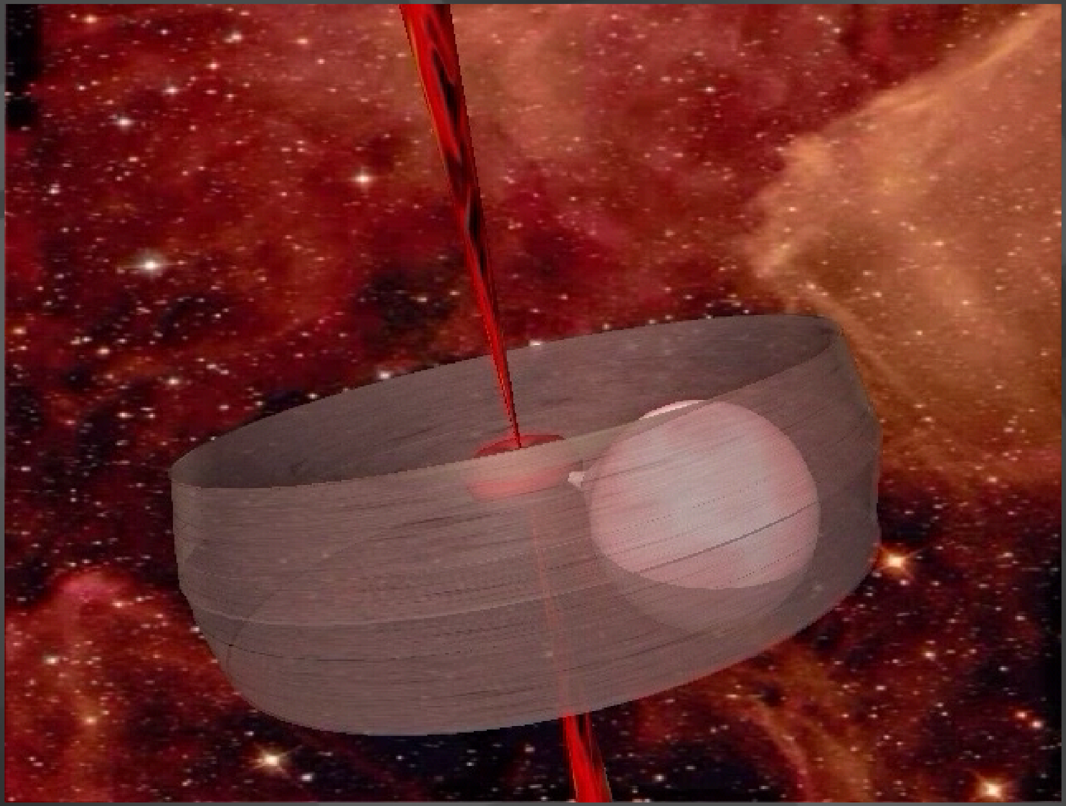




VLBA

Overview of SS433:

a cartoon…

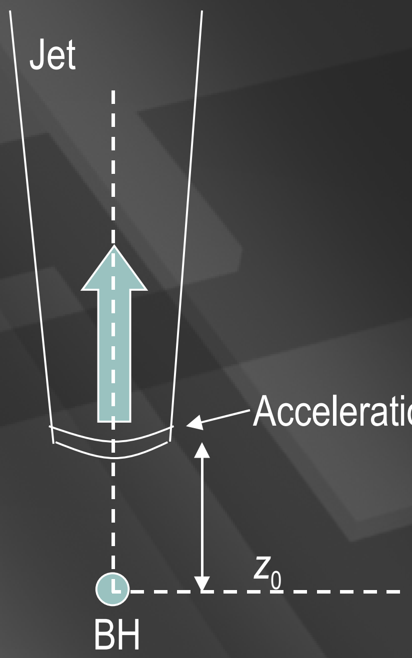


Parameters of the model for SS433

Parameter	Value
L_k: jet kinetic power	10^{39}erg s^{-1}
$\dot{m}_{\rm j}$: mass loss rate in the jet	$\sim 5 \times 10^{-7} M_{\odot}{\rm yr}^{-1}$
$M_{\rm bh}$: Black Hole mass	$5M_{\odot}$
$M_{\star}$: mass of the donor star	$17M_{\odot}$
$R_{\star}$: radius of the donor star	$32R_{\odot}$
a: orbital separation	$\sim 65.5R_{\odot}$
z_0: jet's launching point	$50R_g = 3.6 \times 10^8$cm
$z_{\rm acc}$: jet's acceleration point	3.5×10^9cm
$\Delta z_{\rm acc}$: size of acceleration region	3.5×10^8cm
$\beta_{\rm b}$: bulk jet velocity in units of c	0.26
ξ: jet half-opening angle	0.6°
$i_{\rm j}$: angle between LOS and orbital axis	78°
θ: angle between the jet and orbital axis	21°

Relativistic particles in the jets

- One-zone approximation (e.g. Khangulyan et al. 2007)
- Magnetic Field: $$\frac{B^2}{8\pi} = \rho_k^{(\mathrm{exp})} \ll \rho_k^{(\mathrm{bulk})}$$
- Shock acceleration of electrons and protons



Rate: $$\frac{1}{E_p}\frac{dE_p}{dt} = t_{\mathrm{acc}}^{-1} = \eta \frac{ceB}{E_p}$$

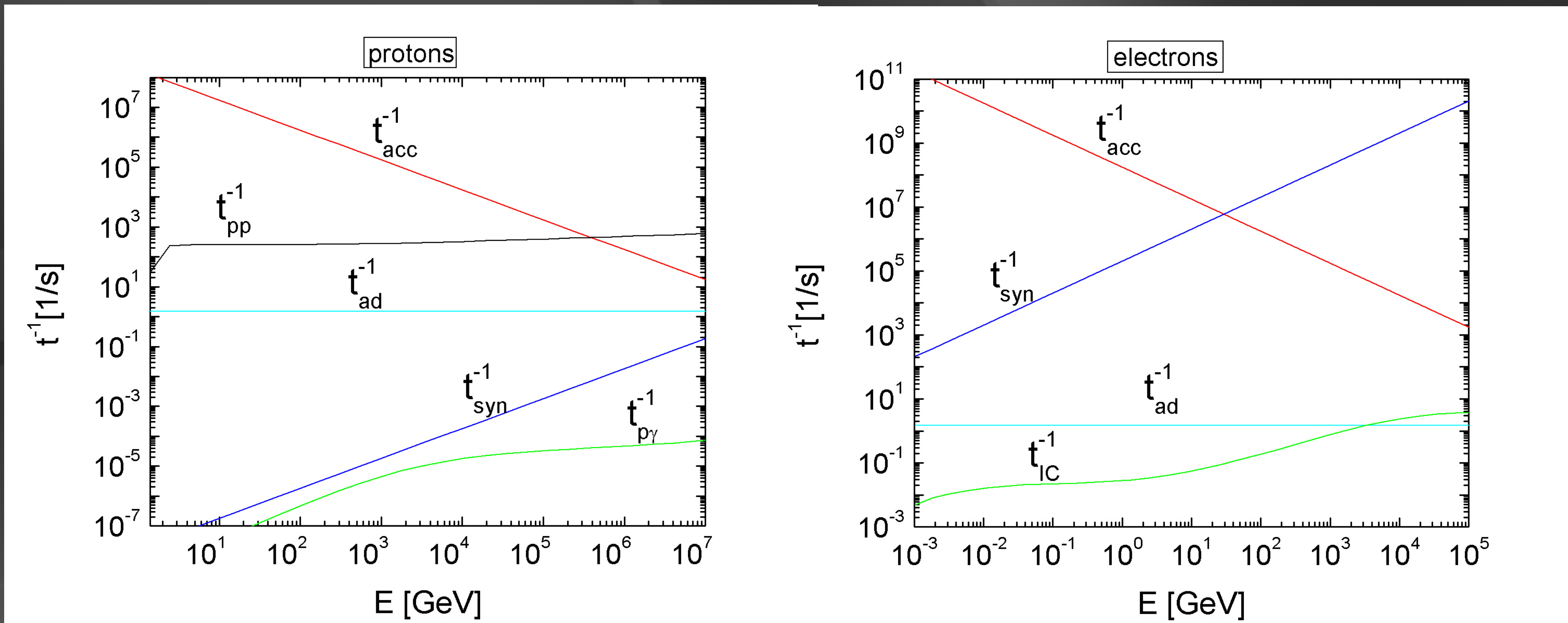
Injection function: $Q'(E') \propto E'^{-\alpha}$ (GeV^{-1} cm^{-3} s^{-1} sr^{-1})

Power in relativistic particles: $$L_{e,p} = \int_V d^3r \int_{E_{e,p}^{(\mathrm{min})}}^{E_{e,p}^{(\mathrm{max})}} dE_{e,p} E_{e,p} Q_{e,p}(E_{e,p}, z)$$

Is a fraction q_{rel} of kinetic power $L_{\mathrm{rel}} = q_{\mathrm{rel}} L_{\mathrm{k}} = L_p + L_e$ and $L_p = a\ L_e$

MQ SS433 - HE processes in the jets:

Particle interaction rates



Proton energy loss:

$$b_p(E) = -\frac{dE}{dt} = -E\left[t^{-1}_{\rm syn} + t^{-1}_{\rm ad} + t^{-1}_{pp}\right]$$

Electron energy loss:

$$b_e(E) = -\frac{dE}{dt} = -E\left[t^{-1}_{\rm syn} + t^{-1}_{\rm ad}\right]$$

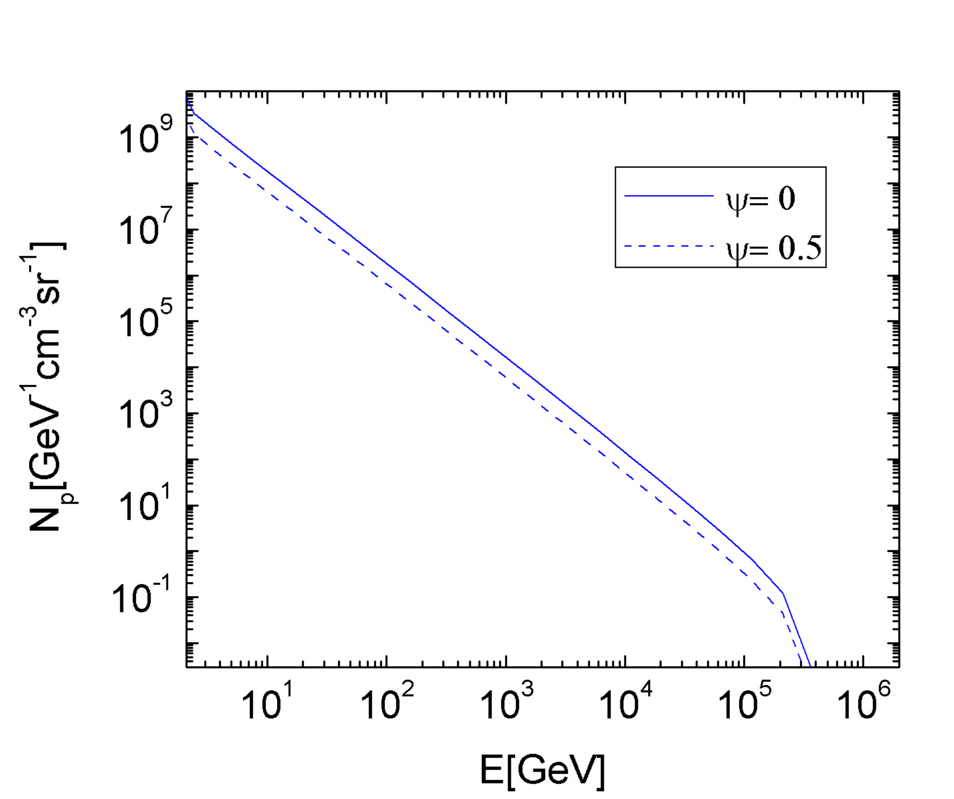
Distributions of primary particles

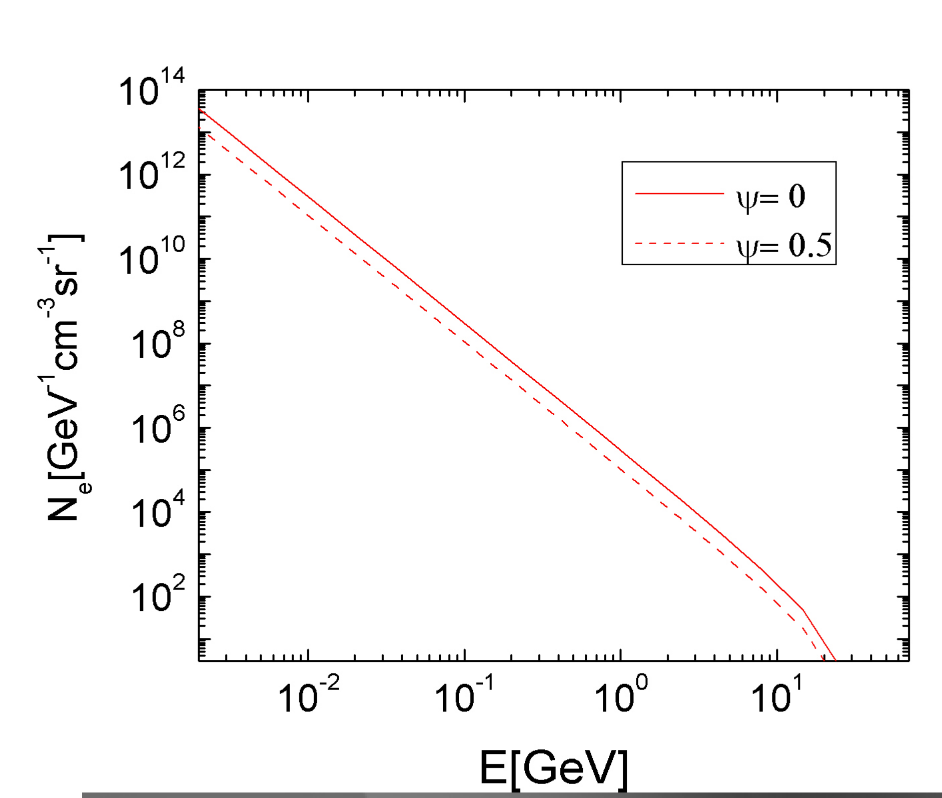
- Balance equation

$$\frac{\partial N(E,z)b(E,z)}{\partial E} + t_{\rm esc}^{-1}(z)\, N(E,z) = Q(E,z)$$

$$N(E,z) = \frac{1}{|b(E)|}\int_E^{E^{(\rm max)}} dE' Q(E',z) \exp\left\{-t_{\rm esc}^{-1}(z)\, \tau(E,E')\right\}$$

$$\tau(E,E') = \int_E^{E'} \frac{dE''}{|b(E'')|}$$





Secondary pions and muons

- Balance equation

$$\frac{\partial\left[b(E,z)N(E,z)\right]}{\partial E} + t^{-1}_{\{\pi,\mu\}}(E,z)N(E,z) = Q(E,z)$$

$$t^{-1}_{\{\pi,\mu\}}(E,z) = t^{-1}_{\rm dec}(E) + t^{-1}_{\rm esc}(z)$$

$$p + p \longrightarrow p + p + a\pi_0 + b(\pi^+ + \pi^-)$$

$$p + \gamma \to \Delta^+$$

$$\Delta^+ \to p + \pi^0$$

$$\Delta^+ \to n + \pi^+$$

- Injection functions:

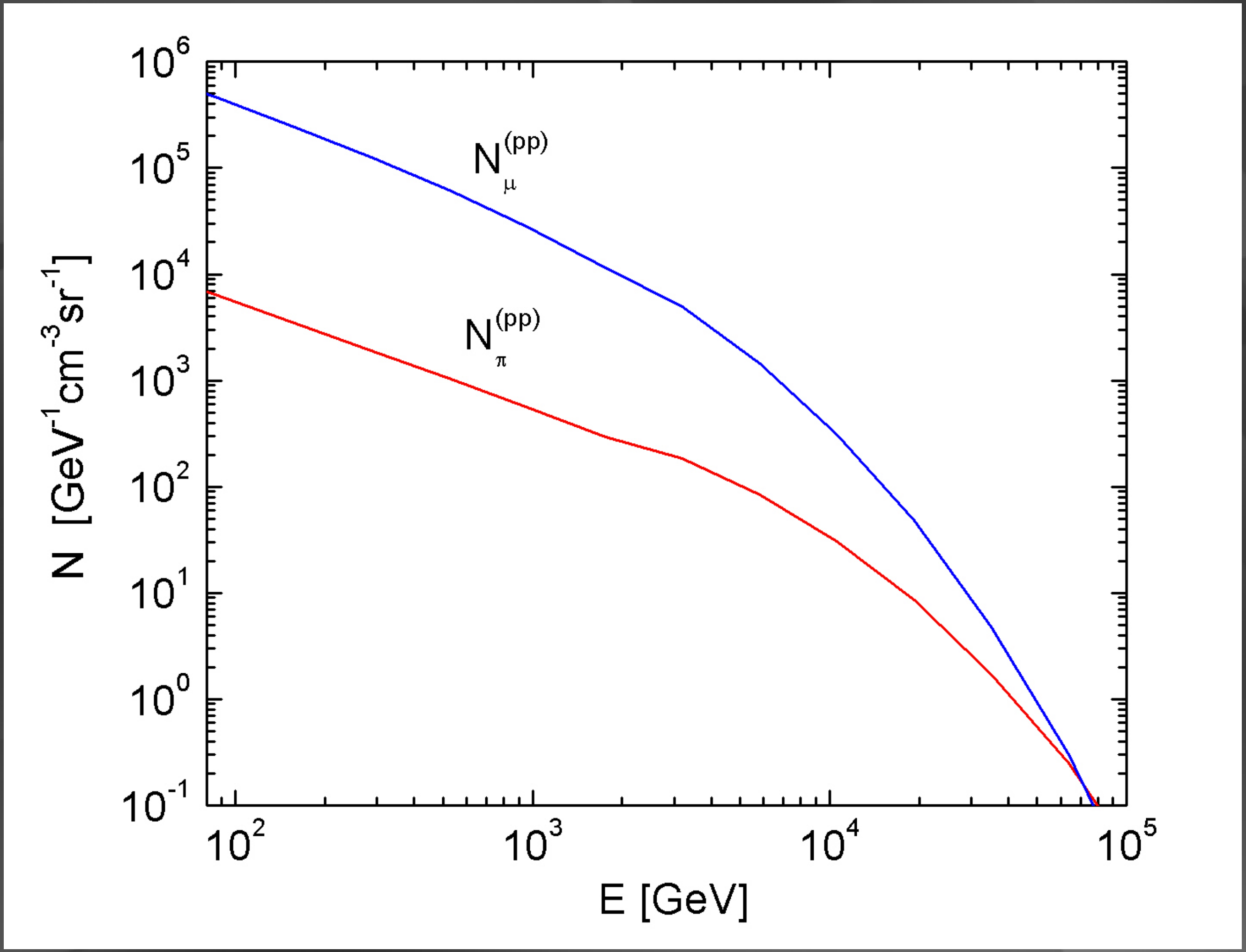
$$Q^{(pp)}_\pi(E) = n_{\rm c}\, c \int_{\frac{E}{E_p^{(\rm max)}}}^{1} \frac{dx}{x} N_p\left(\frac{E}{x}\right) F^{(pp)}_\pi\left(x, \frac{E}{x}\right) \sigma^{(\rm inel)}_{pp}\left(\frac{E}{x}\right)$$

SIBYLL code (Kelner et al. 2006)

$$Q^{(p\gamma)}_\pi(E) = \int_E^{E_p^{(\rm max)}} dE_p N_p(E_p)\, \omega_{p\gamma}(E_p) n_\pi(E_p) \delta(E_\pi - 0.2E_p)$$

SOPHIA code (Atoyan & Dermer 2003, see also Kelner et al. 2008)

Charged pions and muon distributions



Gamma-ray and neutrino emission

γ 's:

$$Q_\gamma^{(pp)}(E_\gamma) = n_c c \int_{E_\gamma}^{E_p^{(\max)}} dE_p N_p(E_p) \sigma_{pp}(E_p) F_\gamma(E_\gamma; E_p)$$

(Kelner et al. 2006)

$$Q_\gamma^{(p\gamma)}(E_\gamma) = 2 \int dE_\pi Q_{\pi^0} \delta(E_\gamma - 0.5E_\pi)$$

$\pi^0 \to \gamma\gamma$

(Atoyan & Dermer 2003)

Differential γ-ray flux at Earth [cm^{-2} s^{-1} GeV^{-1}]

$$\frac{d\Phi_\gamma(E)}{dE} = Q_\gamma(E)\Delta V \frac{d\Omega}{dA} \exp\left[-\tau_\gamma(E)\right] = Q_\gamma(E)\frac{\Delta V}{d^2} \exp\left[-\tau_\gamma(E)\right]$$

Attenuation effect

ν 's: From $N_\pi(E)$, $N_\mu(E)$ → $Q_{\nu_\alpha}(E)$

$$\pi^- \to \mu^- \bar{\nu}_\mu \to e^- \nu_\mu \bar{\nu}_e \bar{\nu}_\mu$$
$$\pi^+ \to \mu^+ \nu_\mu \to e^+ \bar{\nu}_\mu \nu_e \nu_\mu$$

Kinematics of decays (e.g. Lipari et al 2008)

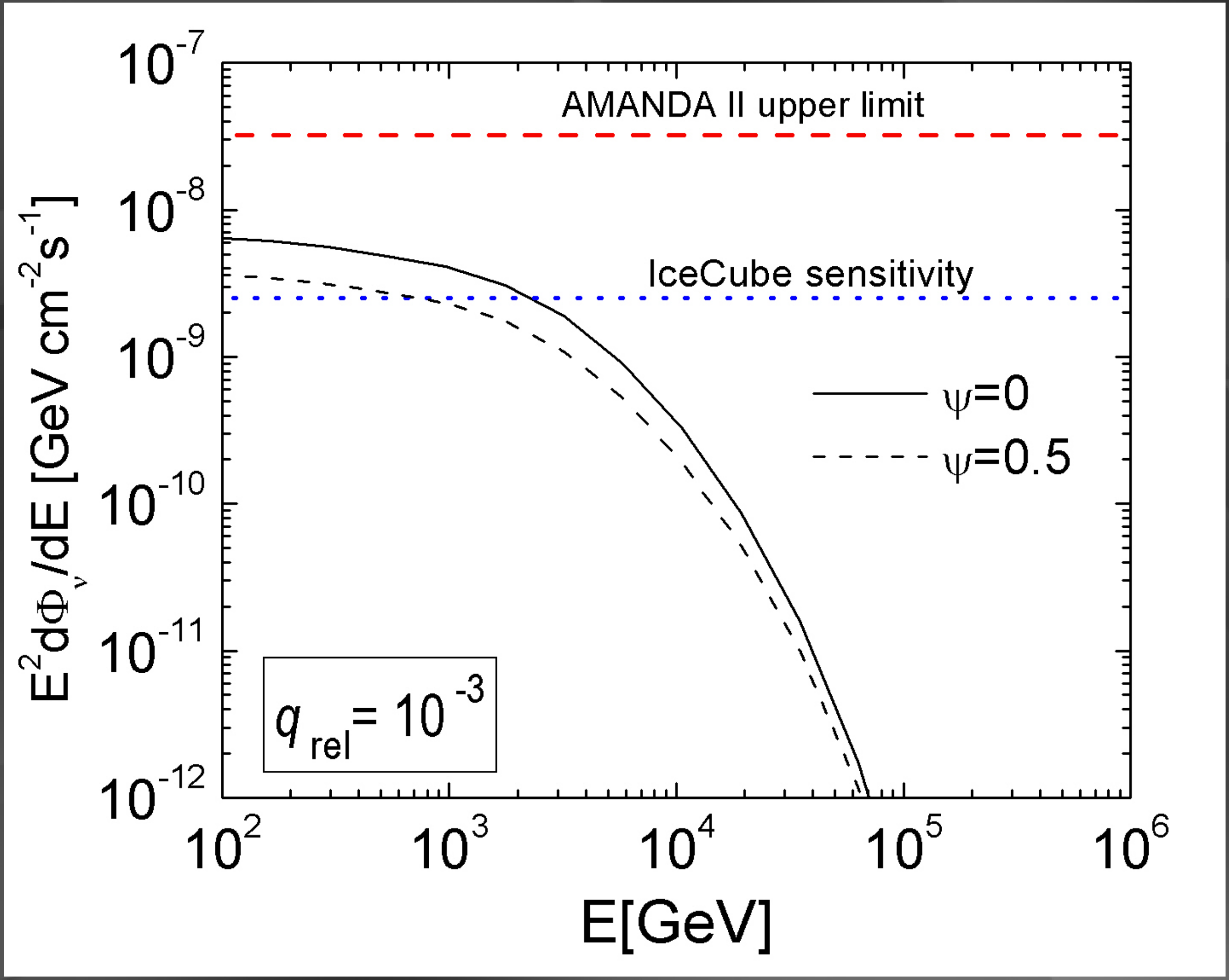
Differential ν_α flux at Earth [cm^{-2} s^{-1} GeV^{-1}]

$$\frac{d\Phi_{\nu_\alpha}(E)}{dE} = \frac{\Delta V}{d^2} \sum_{\nu_\beta} P_{\nu_\beta \to \nu_\alpha} Q_{\nu_\beta}(E) \exp\left[-\tau_\nu(E)\right]$$

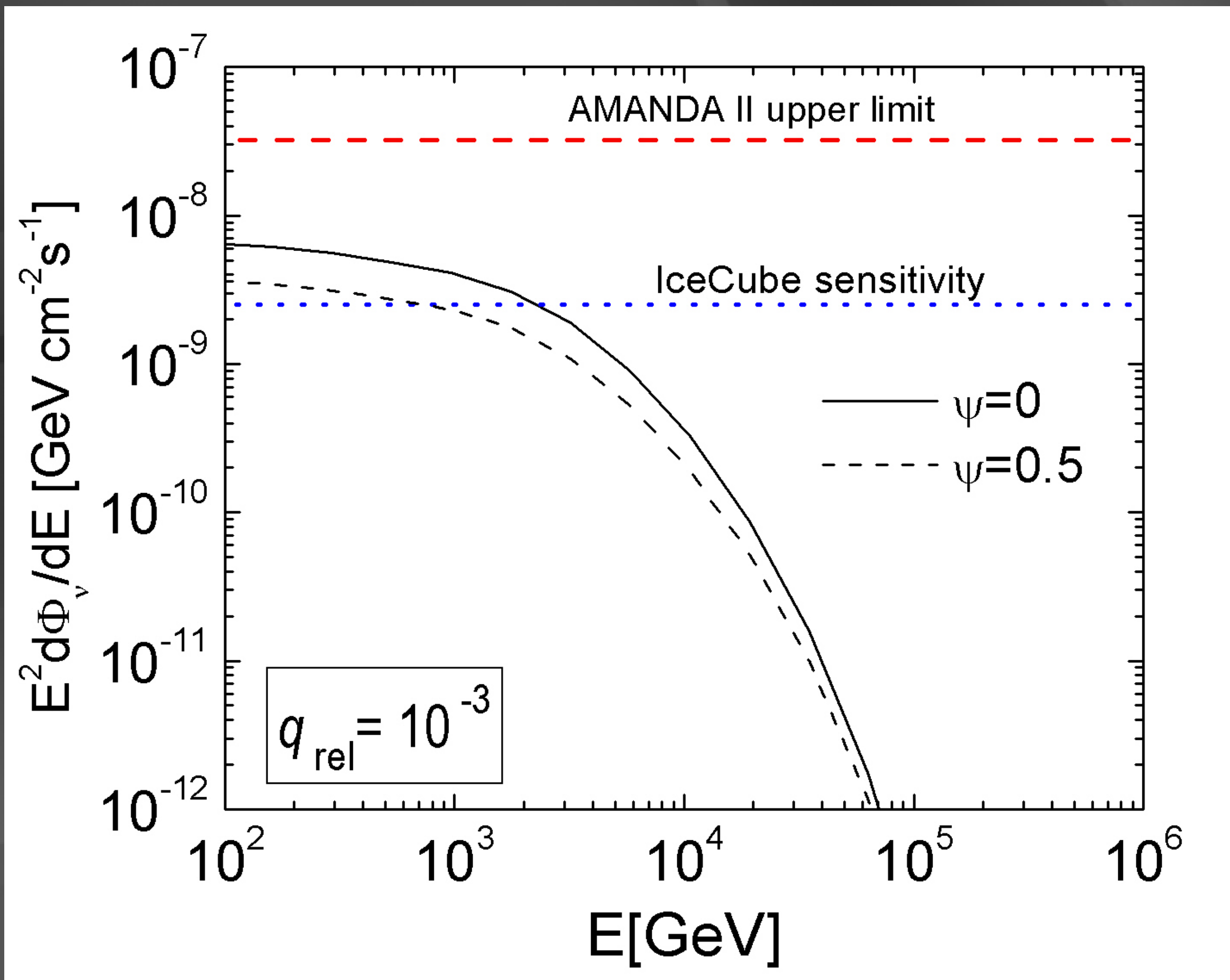
ν-Oscillation effect

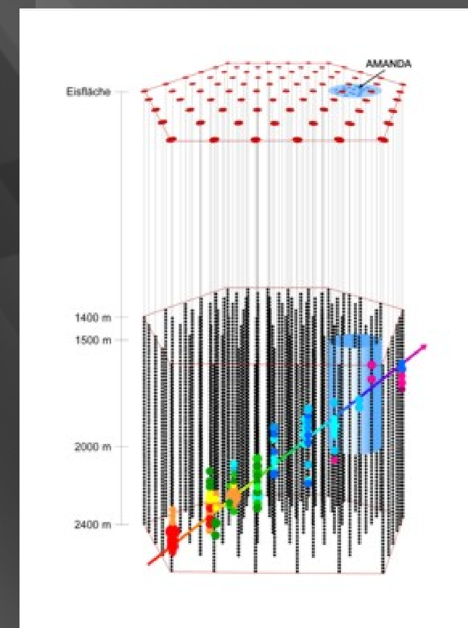
Attenuation effect

Differential Neutrino flux at Earth



Integrated neutrino flux





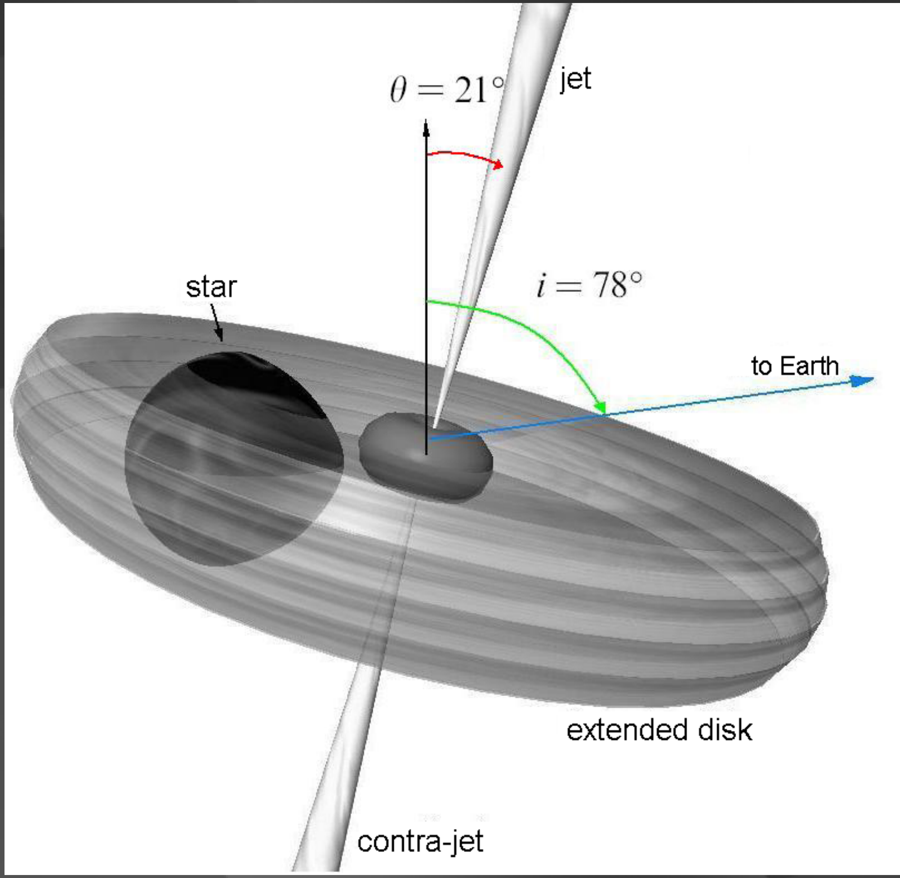
Here, $q_{rel}= 10^{-3}$

Gamma-ray absorption in MQs

- γ-rays can be absorbed by:

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

$$\gamma N \rightarrow \pi^i N$$
$$\gamma N \rightarrow N e^+ e^-$$



- Optical depth

$$\frac{dI_\gamma}{dl} = -\frac{I_\gamma}{\lambda_\gamma}$$

$$d\tau = dl/\lambda_\gamma$$

Differential optical depth

$$I_\gamma(E) = I_\gamma^{(0)}(E)\exp\left[-\tau(E)\right]$$

Absorption due to γγ interactions

- Differential optical depth (Gould & Schreder 1967)

$$d\tau_{\gamma\gamma} = (1 - \hat{e}_\gamma \cdot \hat{e}_{\rm ph}) n_{\rm ph} \sigma_{\gamma\gamma} \; d\rho_\gamma \; dE \; d\cos\theta' \; d\phi'$$

- Target photons from the star:

$$n_\star(E) = \frac{2E^2}{(h\ c)^3 (e^{E/kT_\star} - 1)} ({\rm ph\ cm^{-3} erg^{-1} sr^{-1}})$$

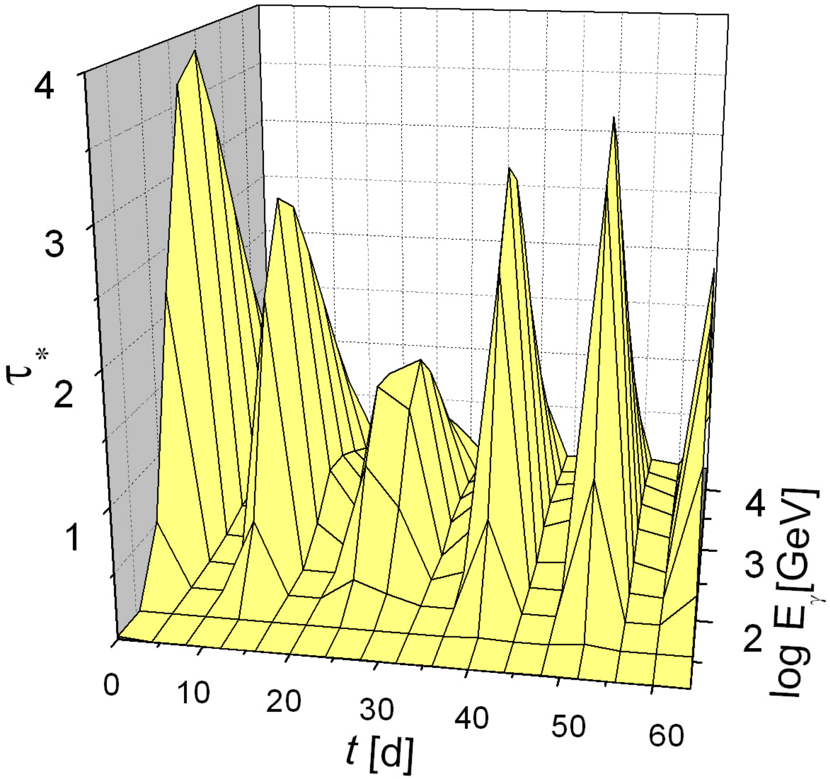
with T_*=8500 K for SS433

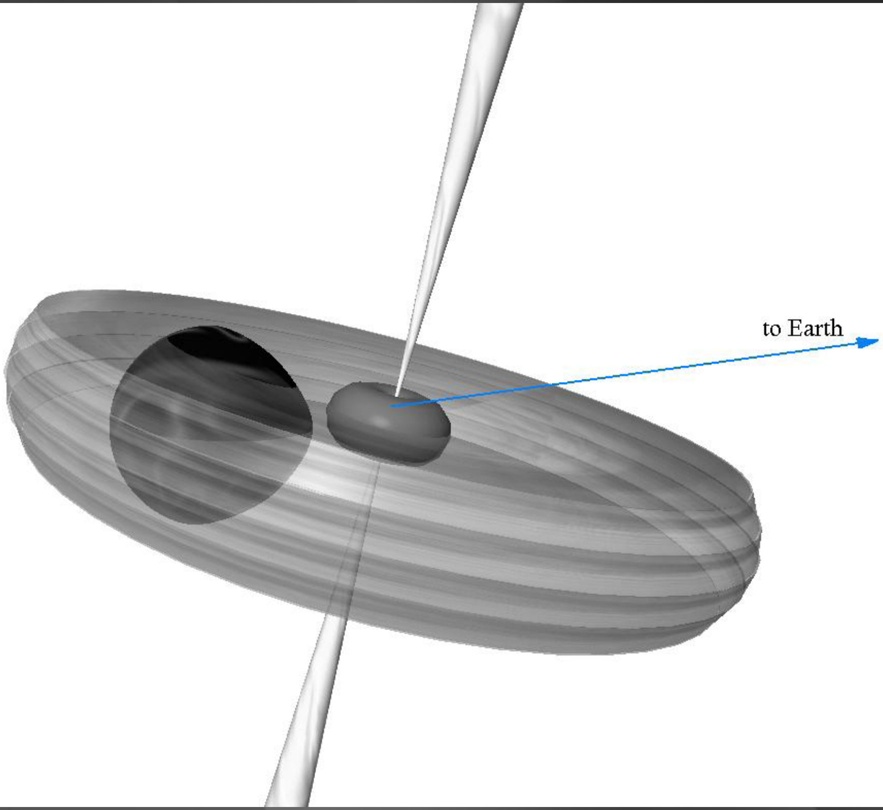
- Target photons from the extended disk
    - UV emission: Black body with T= 21000 K, (10^3 Å < λ < 10^4 Å)
      R_{UV} = 33 R_* (Gies et al. 2002)
    - IR emission: $n_{\rm ph}(E) \propto E^{0.6}$, (2μm < λ <12 μm)
      R_{IR}= 50 R_* (Fuchs et al. 2005)

Gamma-ray absorption in SS433:

γγ absorption

Starlight contribution

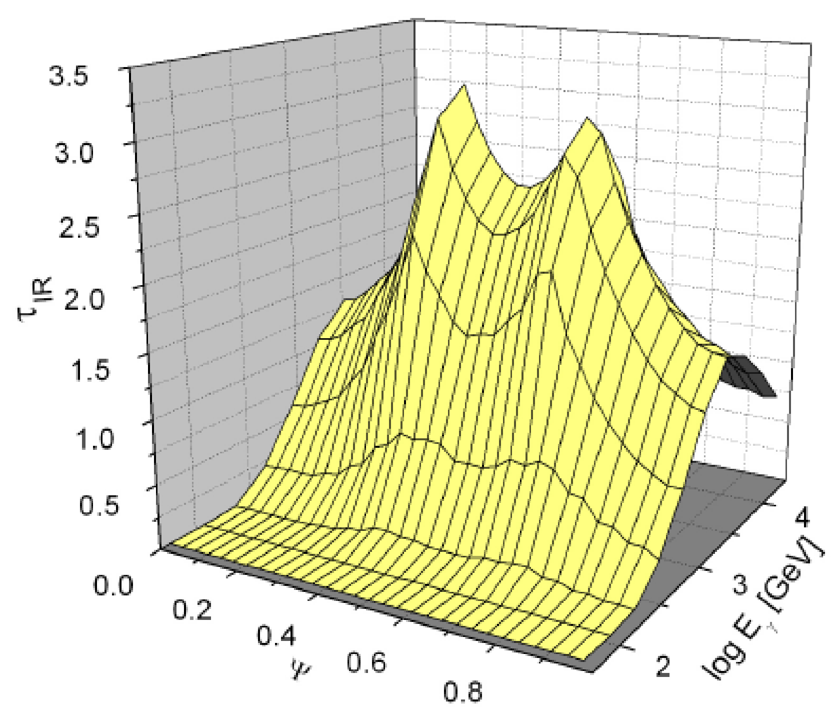




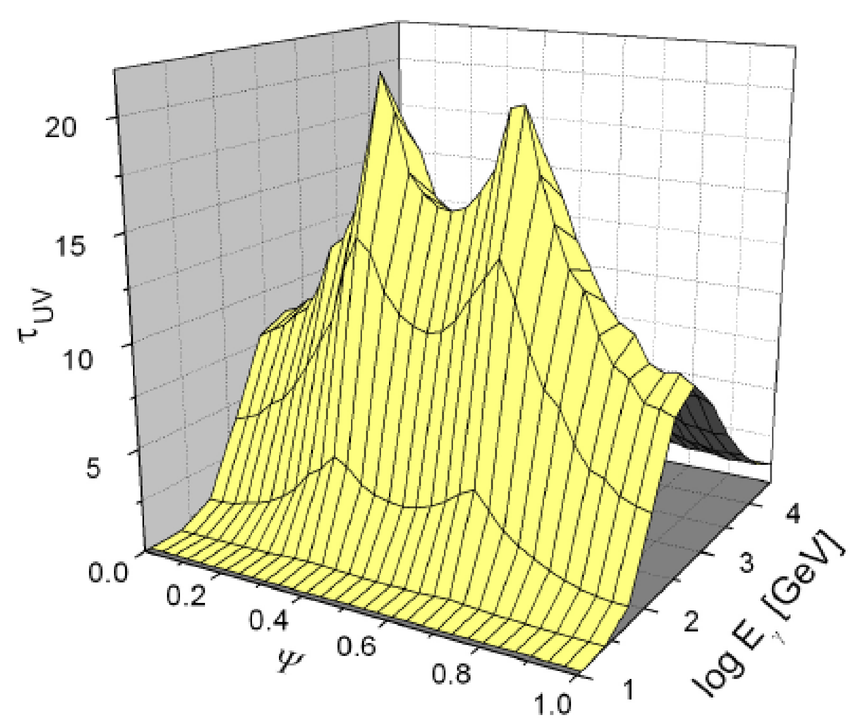
Gamma-ray absorption in SS433:

γγ absorption

Contribution due to IR emission



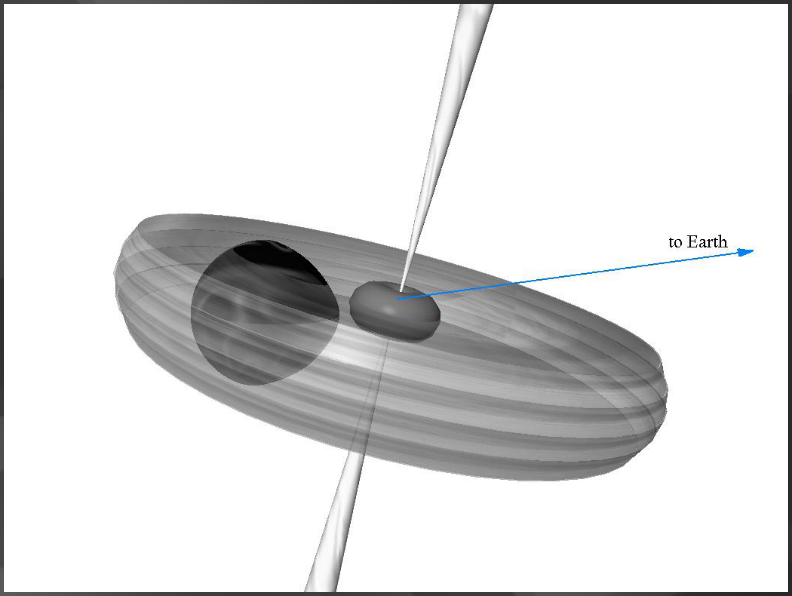
Contribution due to UV emission



Absorption due to γ*N* interactions

- Optical depth

$$\tau_{\gamma N}(\vec{z}_{\rm j}) = \int_0^\infty d\rho_\gamma \sigma_{\gamma N} \frac{(\rho_\star + \rho_{\rm w})}{m_p}$$



Cross section $\sigma_{\gamma N}(E) = \sigma_{\gamma N}^{(e)}(E) + \sigma_{\gamma N}^{(\pi)}(E)$

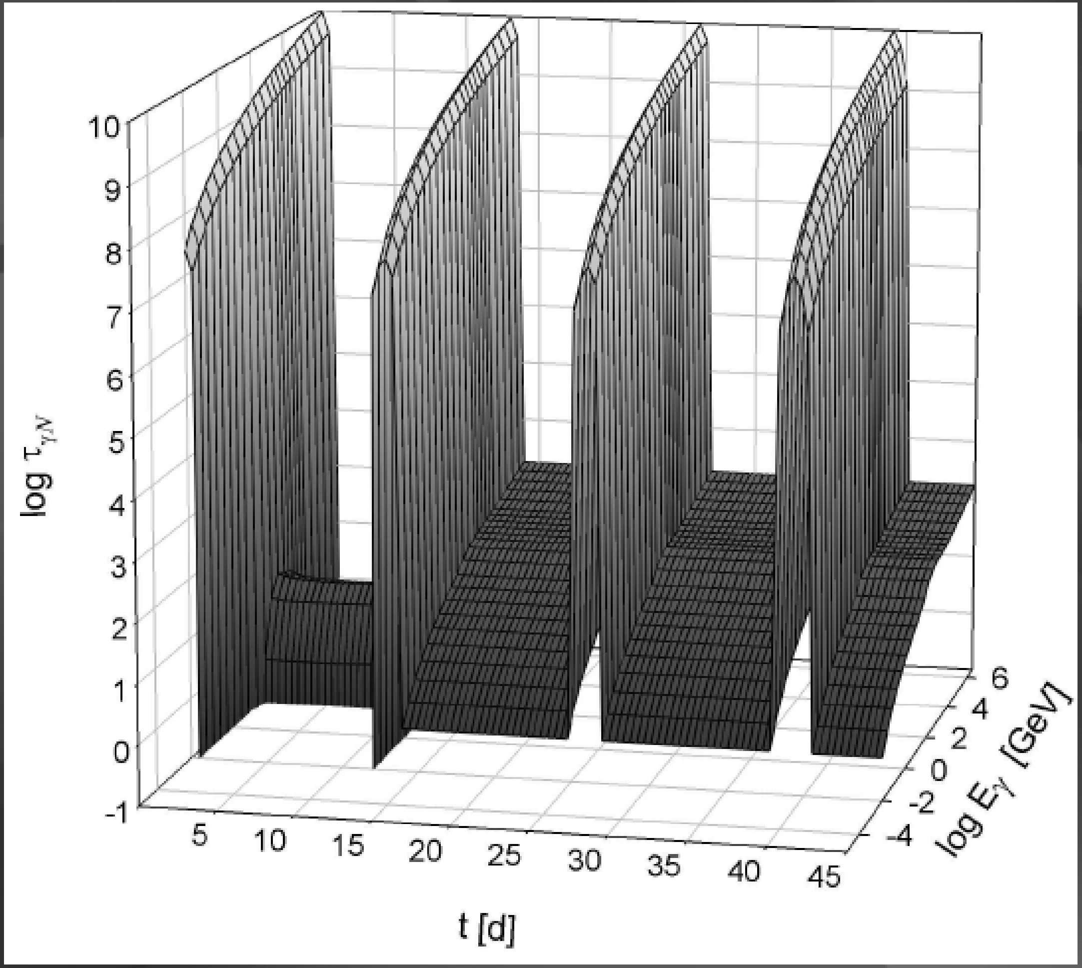
$\gamma N \rightarrow N e^+ e^-$ $\gamma N \rightarrow \pi^i N$

Density of the star: $\rho_\star(r) = \frac{M_\star}{4\pi R_\star r^2}\Theta(r - R_\star)$

Densidad of the extended disk: $\rho_{\rm w}(r_\gamma, \theta_Z) = \frac{\dot{M}_{\rm w}}{v_{\rm w}\Delta\Omega r_\gamma^2}$

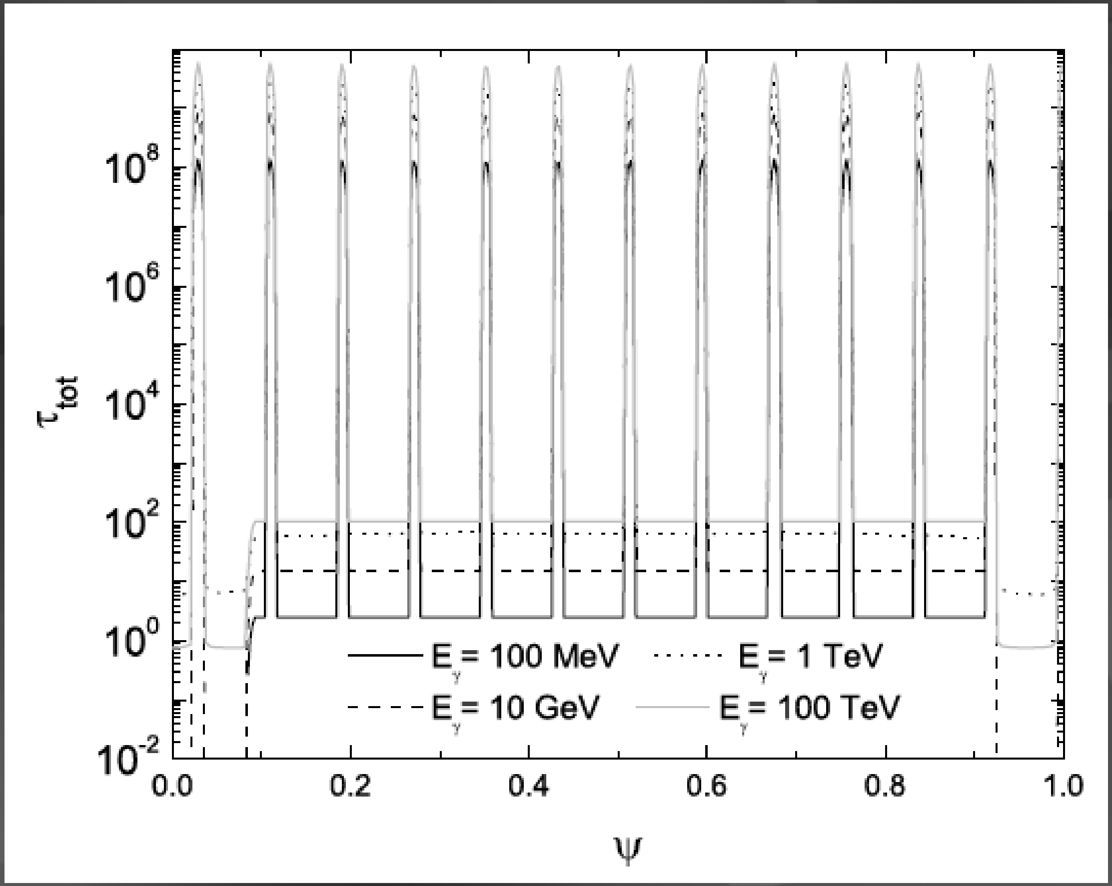
Gamma-ray absorption in SS433:

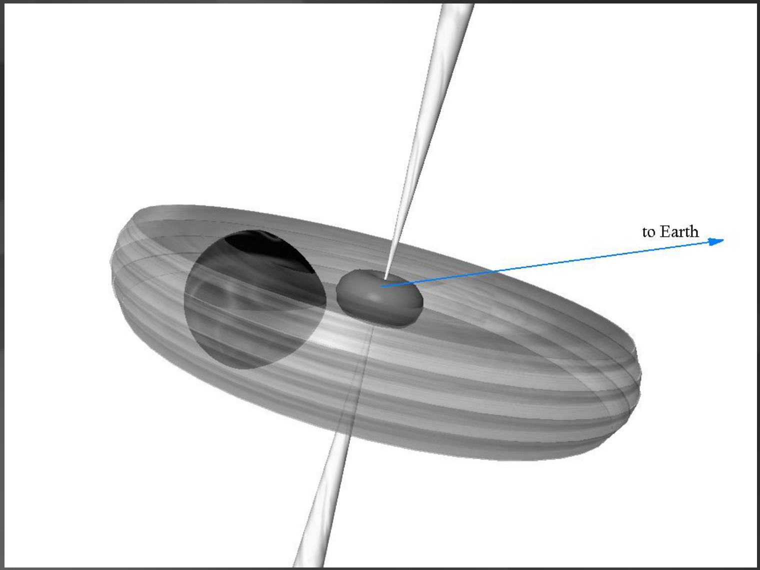
γ*N* optical depth



Gamma-ray absorption in SS433:

Total optical depth



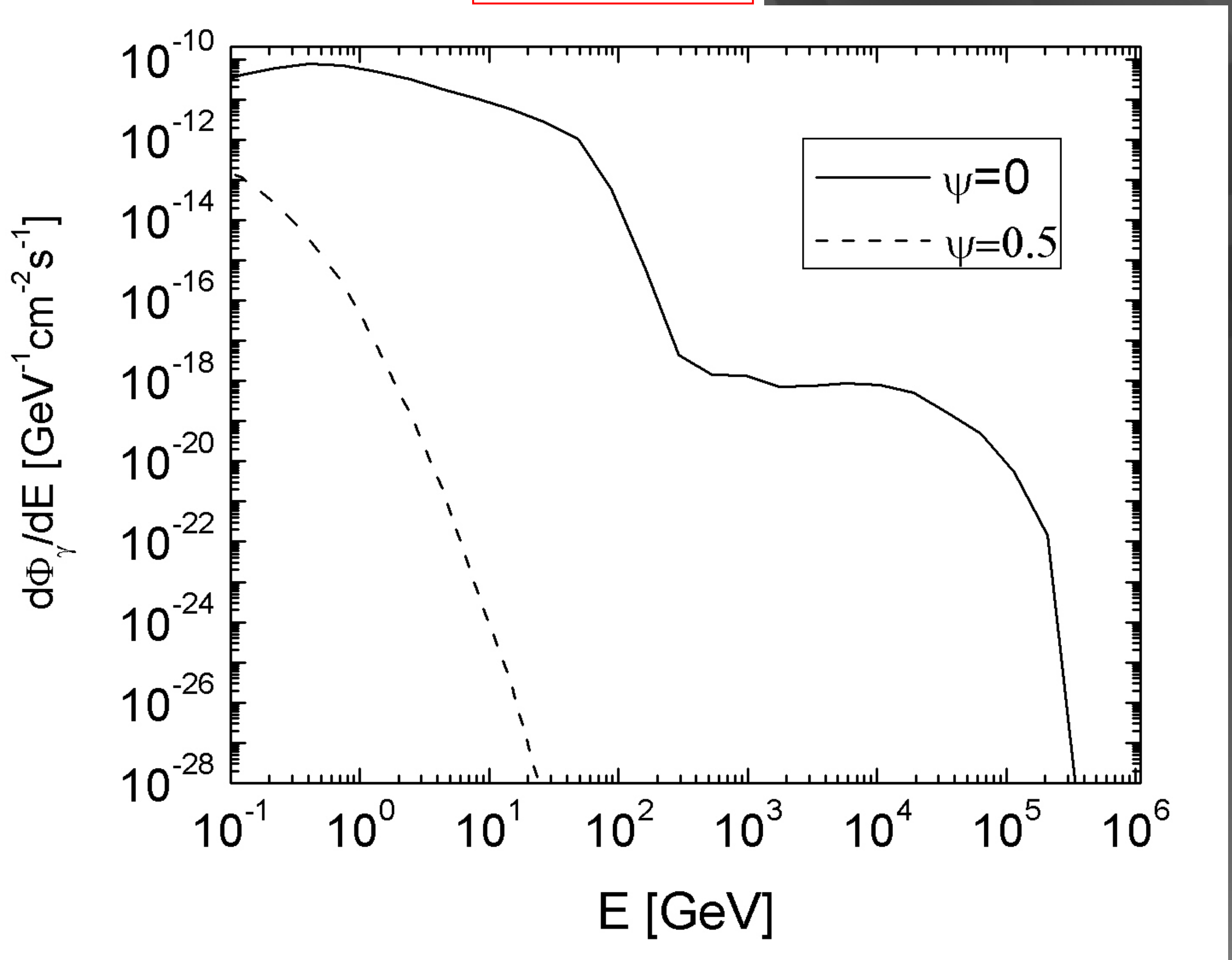


For γ-rays originated at jet base

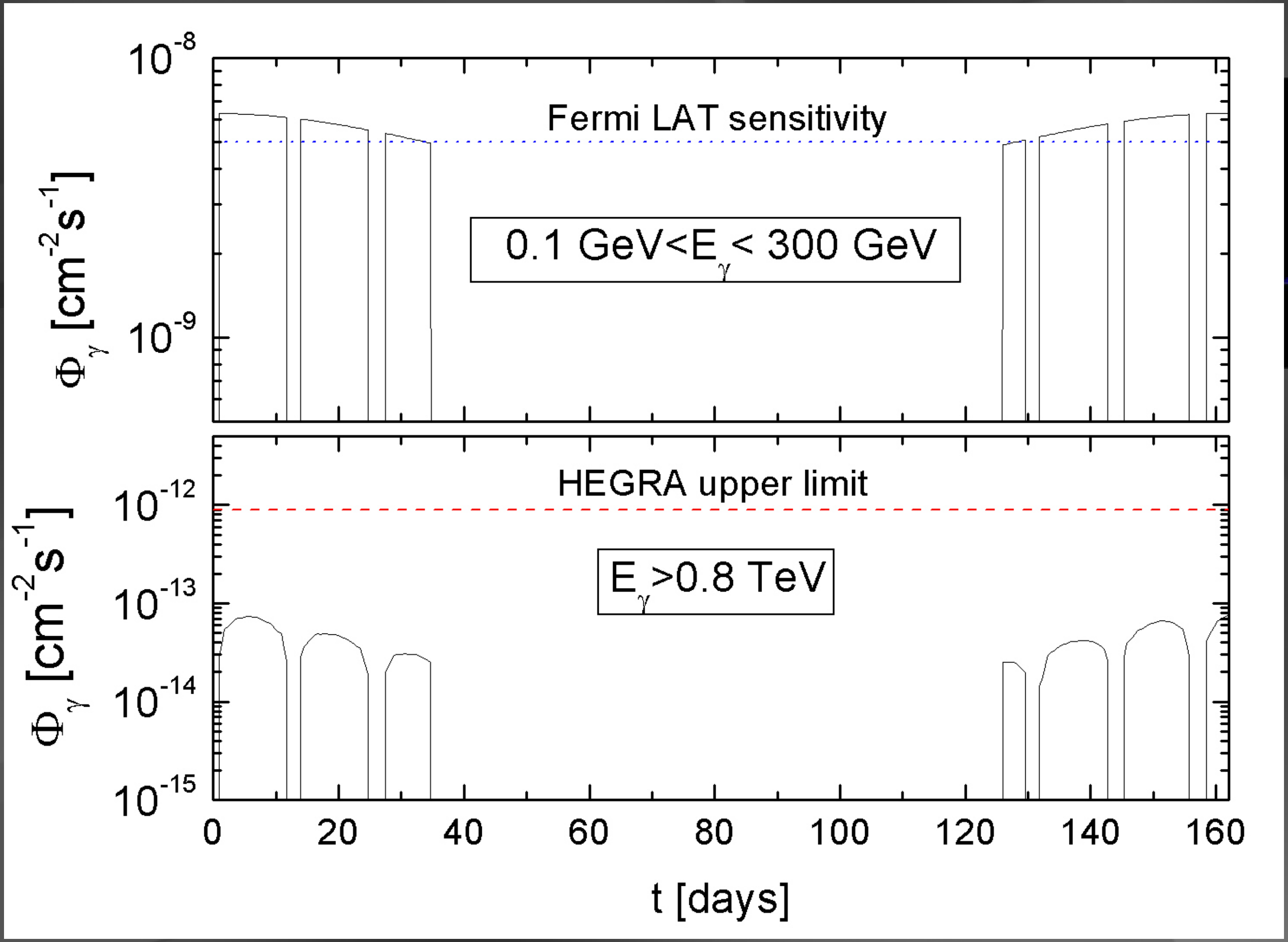
Gamma-ray absorption in SS433:

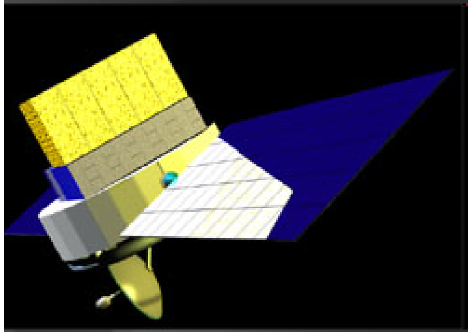
Effects on a gamma signal

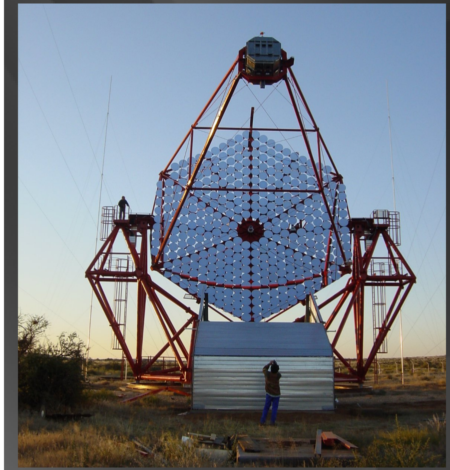
$$\frac{d\Phi_\gamma(E)}{dE} = Q_\gamma(E)\frac{\Delta V}{d^2}\exp\left[-\tau_\gamma(E)\right]$$



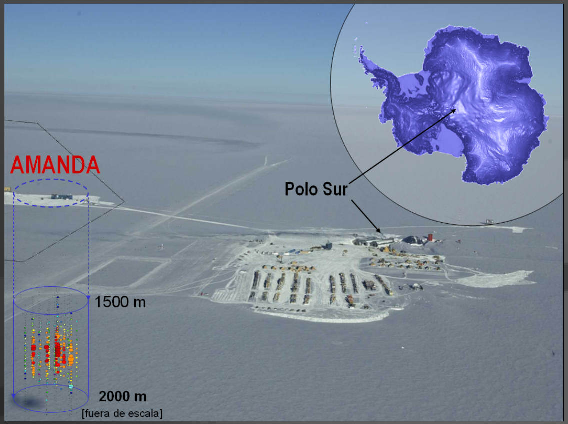
Integrated gamma-ray fluxes

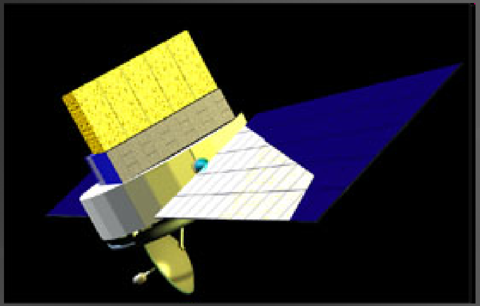


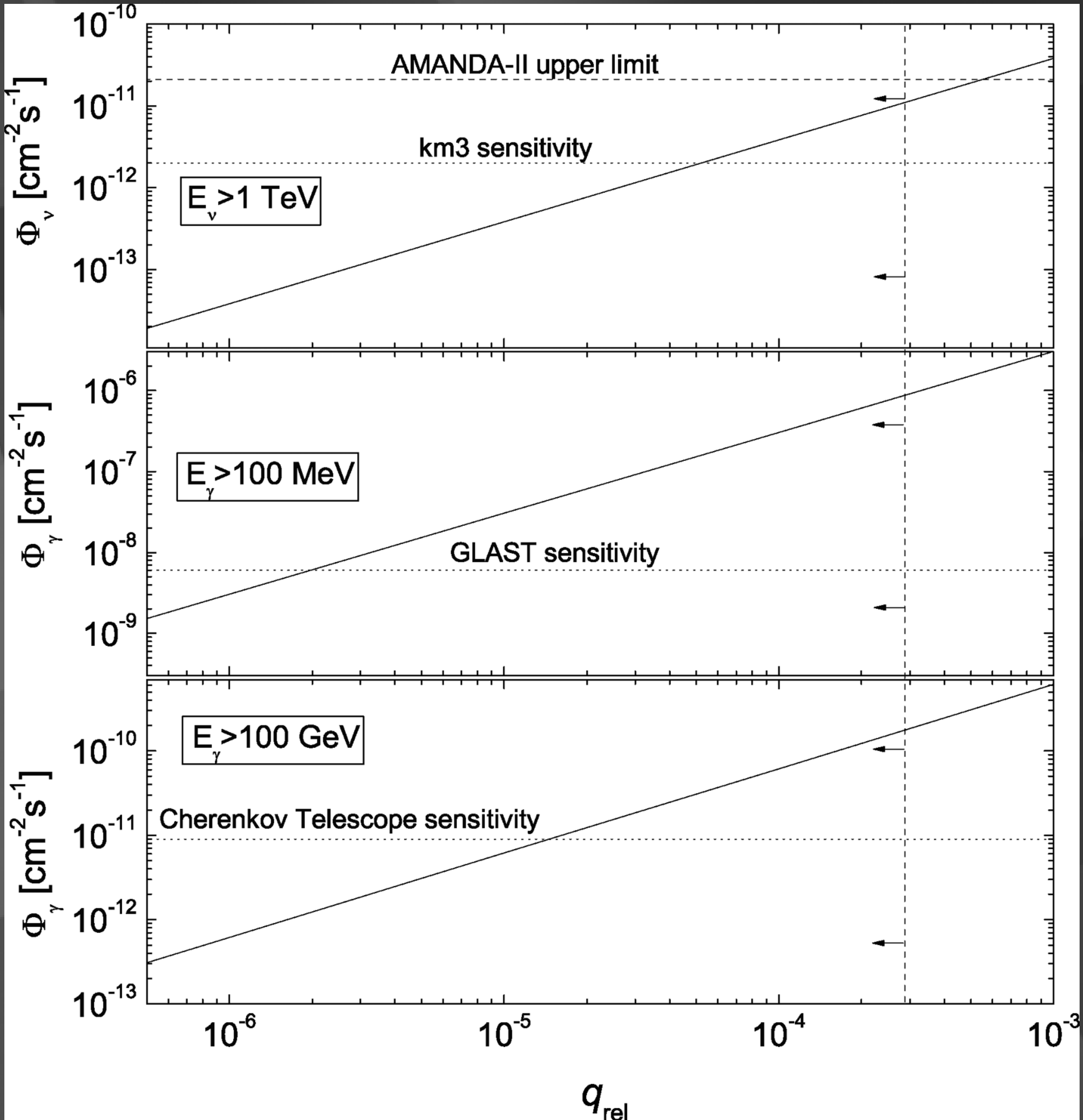




Average fluxes as a function of $q_{rel}=L_{rel}/L_k$







An example:

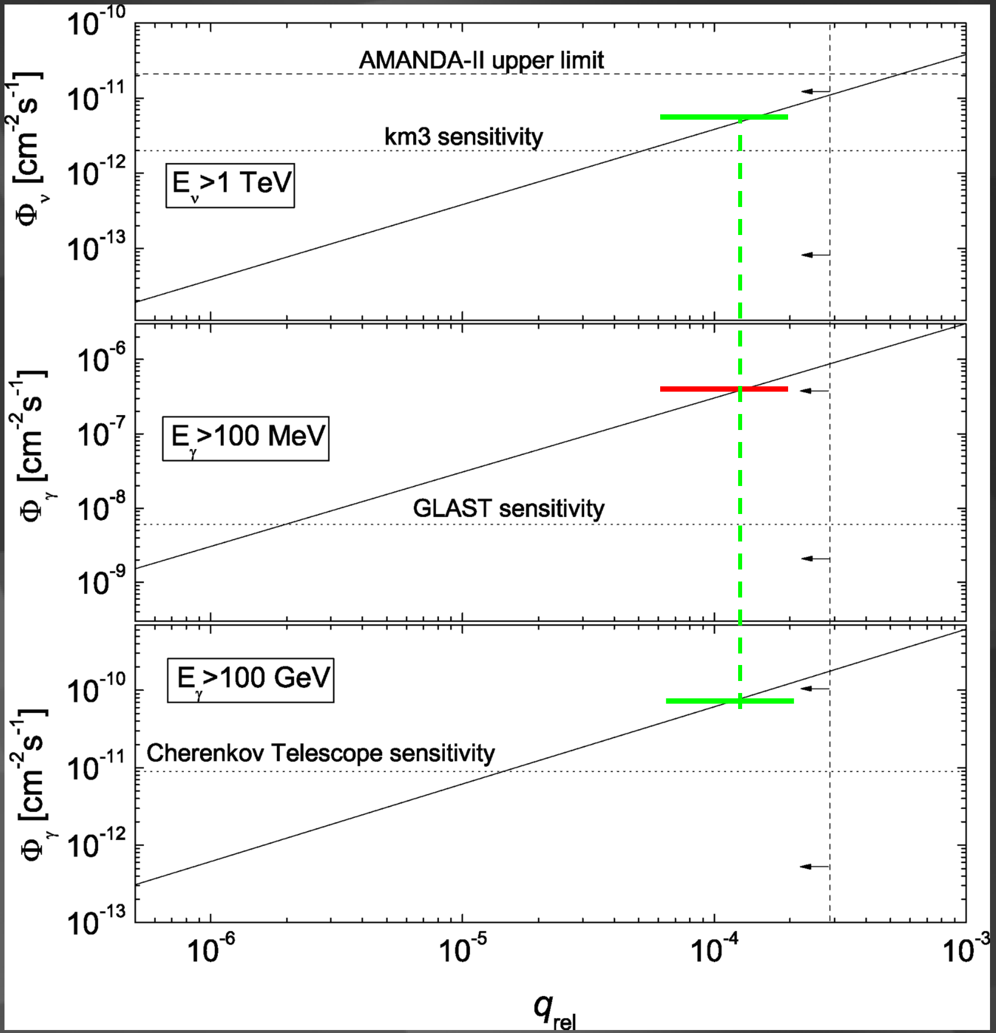
Suppose that Fermi Lat detects a signal which implies detection with Cherenkov telescopes and neutrino detection

a) Less neutrinos than expected. Possible reason: More gamma rays from leptonic origin

b) More neutrinos than expected. Possible reason: γ-ray absorption overestimated

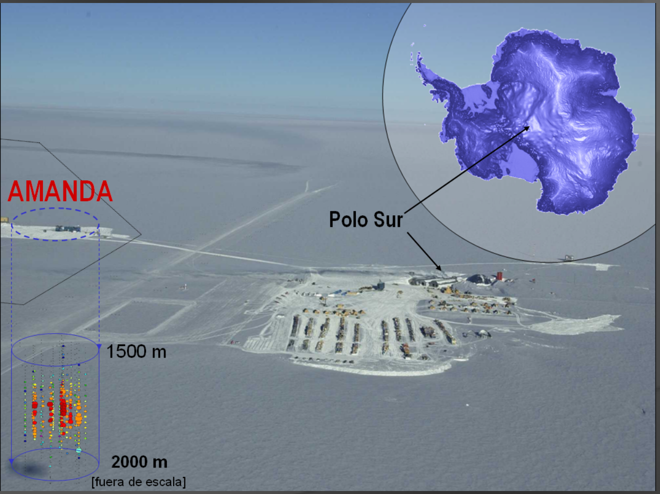
c) Less (more) VHE gamma than expected. Possible reason: absorption under(over)estimated.

(work in progress)



Final comments

- Main conclusion: the consistency of the model will be tested with future neutrino and gamma-ray observations.
- Several parameters such as the magnetic field in the jet, the opening angle, and the power in relativistic particles are to be adjusted.
- Model should explain both gamma-ray observations at different energies and VHE neutrinos.
- A more realistic treatment is necessary: e.g. leave one-zone approximation.

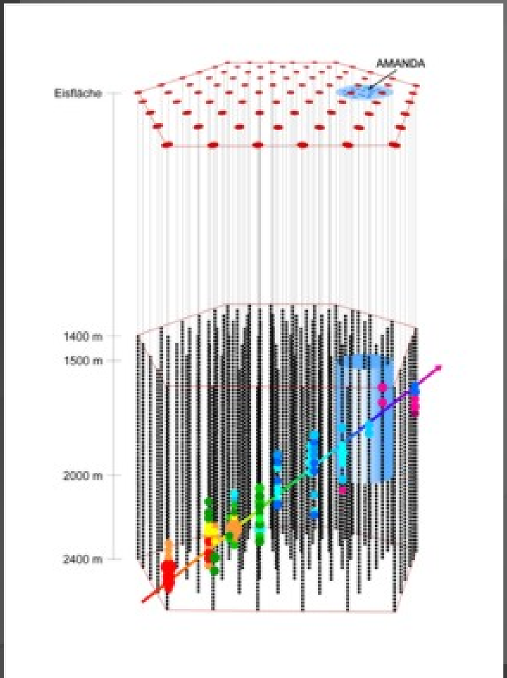


Future work

Consider a more complete transport equation:

$$\frac{\partial N(E,z,t)}{\partial t} + \frac{\partial}{\partial E}\left[N(E,z,t)\frac{\partial E}{\partial t}\right] + \frac{\partial N(E,z,t)}{\partial z} = Q(E,t)\delta(z - z_{\mathrm{acc}})$$

Apply model to other jet systems such as AGNs and GRBs



Some useful references

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Thank you!!