Hadronic Emission Models

Review and Outlook

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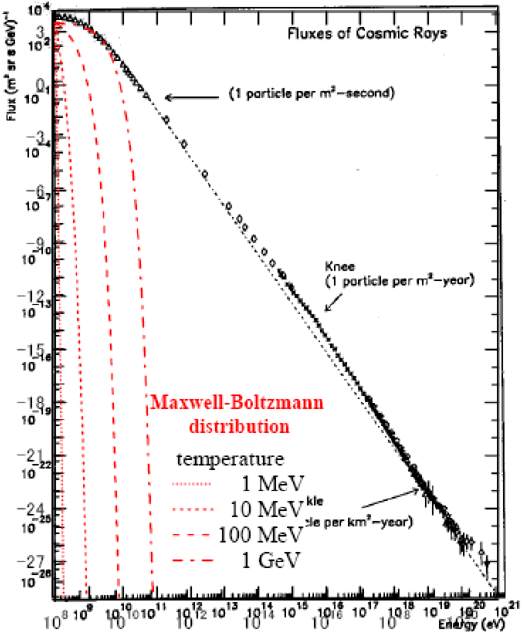
Cosmic Ray Spectrum



Cosmic Ray Spectrum

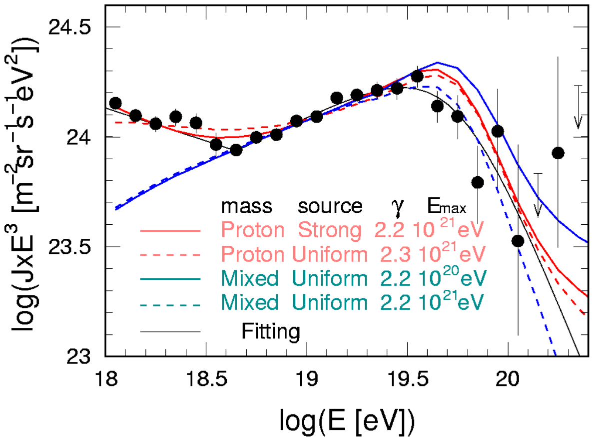


Figure: High energy end of the CR spectrum, AUGER collaboration 07

Cosmic Ray Spectrum

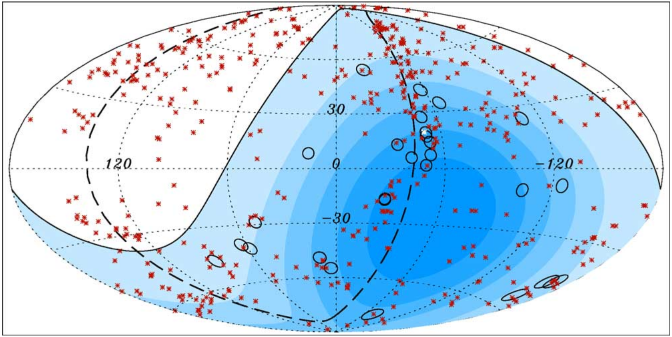


Figure: Possible association of CR events with nearby AGN, AUGER collaboration 07

AGN as CR source

- AGN are plausible CR sources
- AUGER does not contradict this

Fermi Acceleration

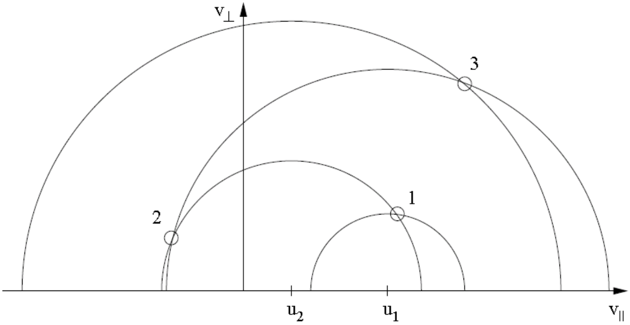


Figure: Shock acceleration

Fermi Acceleration

Multiple shock crossing leads to power law

$$\frac{dN}{d\epsilon} \propto \epsilon^{-\sigma}$$

Monte Carlo simulations for ultra-relativistic shocks ($\Gamma \rightarrow$ inf) show

$$\sigma \rightarrow 2.2$$

Fermi Acceleration

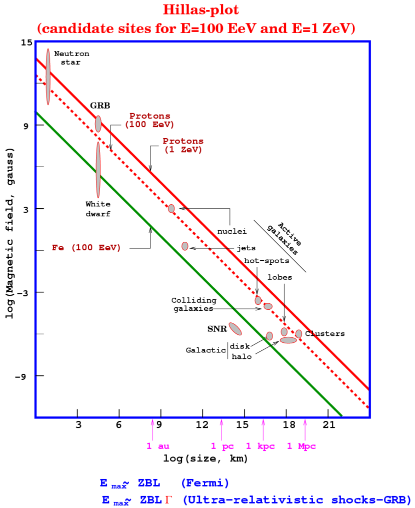


Figure: Hillas plot: Particle gyroradius has to be confined in the source

Fermi Acceleration

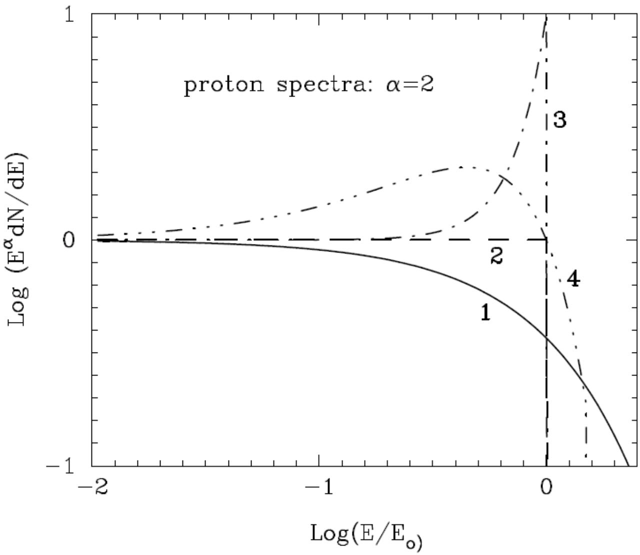


Figure: Possible pile-up spectra (Aharonian 2002)

Synchrotron radiation

Power emitted by synchrotron process

$$P_\nu(\nu,\gamma) = \sqrt{3}\frac{e^3 B \sin\theta}{mc^2} F\left(\frac{\nu}{\nu_c}\right)$$

using the modified Bessel-function

$$F\left(\frac{\nu}{\nu_c}\right) = \frac{\nu}{\nu_c}\int_{\frac{\nu}{\nu_c}}^{\infty} K_{\frac{5}{3}}(\xi)d\xi$$

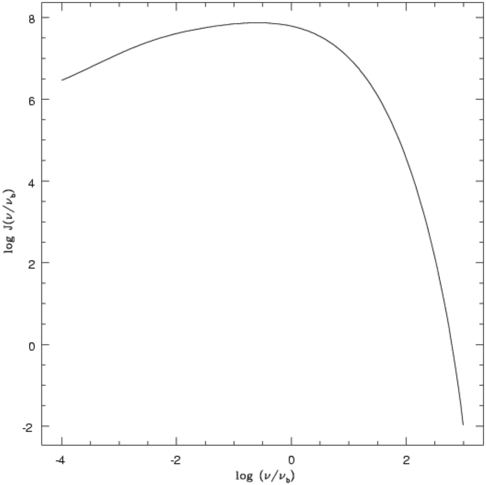
Synchrotron radiation

Changes for protons

With $\chi = m_p/m_e$ and $E_p = E_e$

Larmor-frequency	$\nu_p = \chi^{-1}\nu_e$
Energy loss	$dE_p/dt = \chi^{-4} dE_e/dt$
Characteristic frequency	$\nu_{cp} = \chi^{-3}\nu_{ce}$

Synchrotron radiation



Pair Production

Interaction

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

with absorption

$$\frac{d\tau_{abs}}{dx} = \pi r_0^2 C \left(\frac{m^2 c^4}{E} \right)^{1-\alpha} \int s_0^{-\alpha+2} \phi(s) ds$$

Pair Production

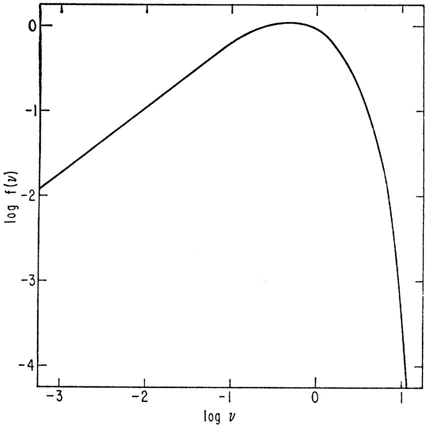


Figure: Cross section for pair creation (Gould & Schreder 1967)

Photo-Hadron interaction

Principal interactions

π^0 cascade

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

$\pi^\pm$ cascade

$p + \gamma \rightarrow n + \pi^+$

Bethe-Heitler process

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

Photo-Hadron interaction

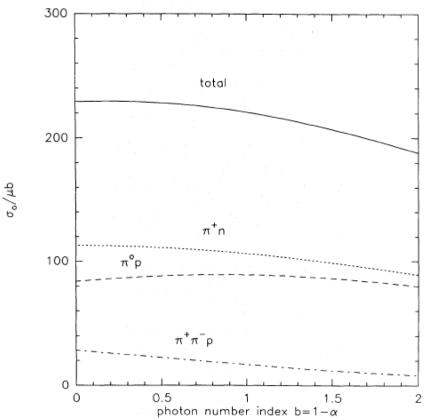


Figure: Cross section for different meson productions (Mannheim & Biermann 1989)

p-p-Interactions

Principal interactions

$$
\begin{aligned}
p + p &\rightarrow p + p + a(\pi^+ + \pi^-) + b\pi^0 \\
p + p &\rightarrow p + n + \pi^+ + a(\pi^+ + \pi^-) + b\pi^0 \\
p + p &\rightarrow n + n + 2\pi^+ + a(\pi^+ + \pi^-) + b\pi^0
\end{aligned}
$$

p-p-Interactions

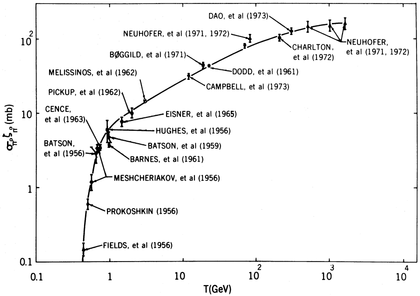


Figure: Cross sections for π^0 production in p-p-interaction(Stecker 1973)

Pion decay

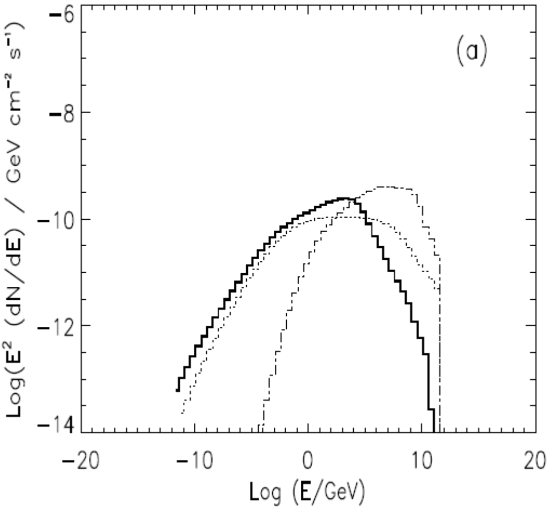


Figure: Decay spectrum of π^0

Pion decay

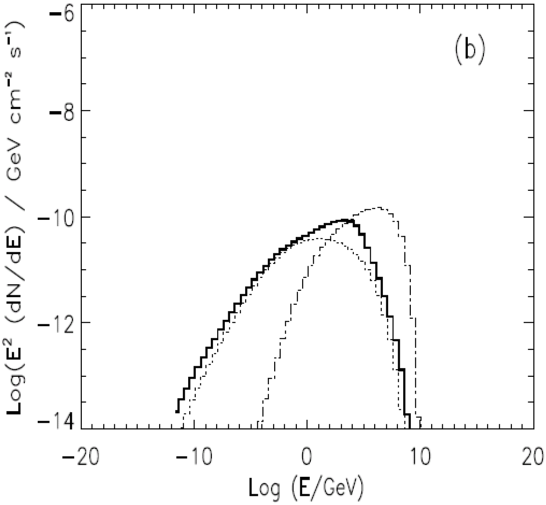


Figure: Synchrotron spectrum for electrons from $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$

Classes of models

Three basic models

Proton-Synchrotron

Photo-Hadron

Proton-Proton

Proton-Initiated Cascade

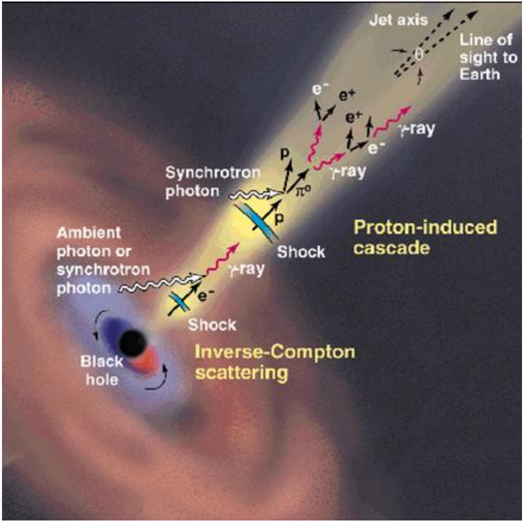


Figure: Cascade model (Mannheim 1993)

Proton-Initiated Cascade

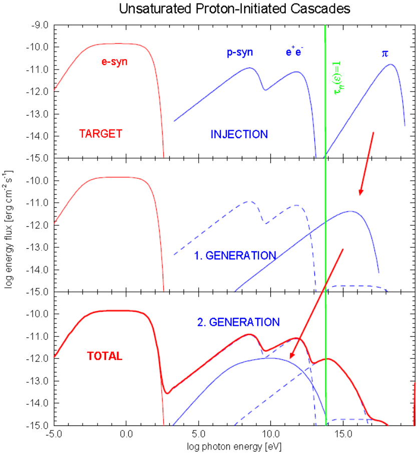


Figure: Sketch of the cascade (Mannheim 1995)

Proton-Initiated Cascade

Idea of the model

- Electrons and protons co-accelerated
- Protons produce Pions and synchrotron
- π-decay emission in optical thick regime
- e^+e^- cascade through synchrotron emission

Proton-Initiated Cascade

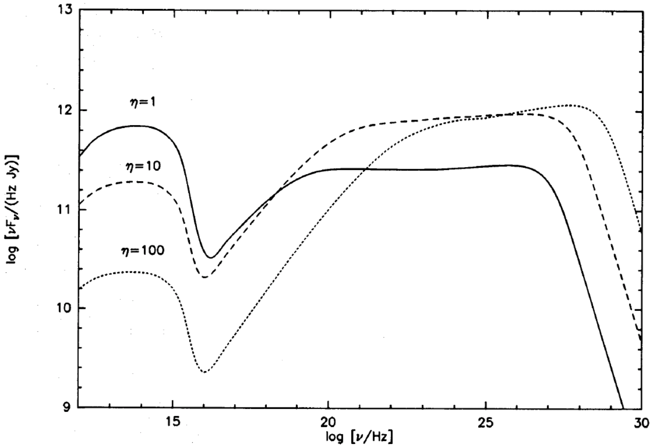


Figure: Proton-initiated cascade model for 3C279

Proton-Initiated Cascade

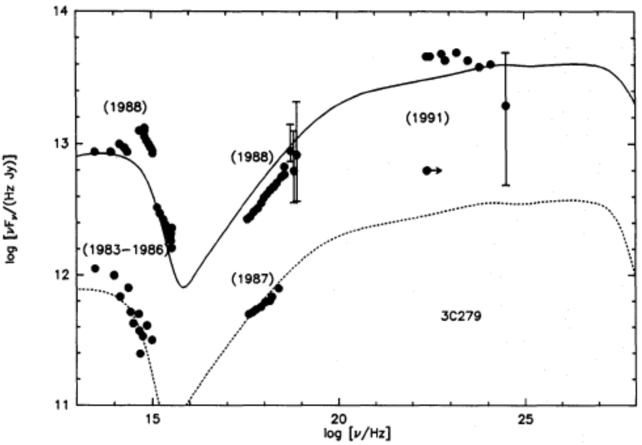


Figure: Cosmic Ray Spectrum

Proton-Synchrotron, Aharonian

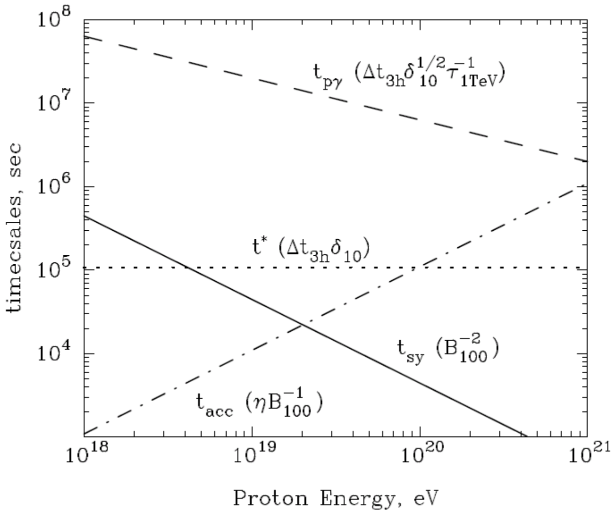


Figure: Loss time scales assuming $B = 100$ G (Aharonian 2002)

Proton-Synchrotron, Aharonian

- Loss timescale compared to dynamical timescale
- Short timescales require very high magnetic field for proton synchrotron
- $p - \gamma$ processes with far-infrared neglected
- requires ultra-high energy protons
- no attached neutrino emission

Proton-Synchrotron, Aharonian

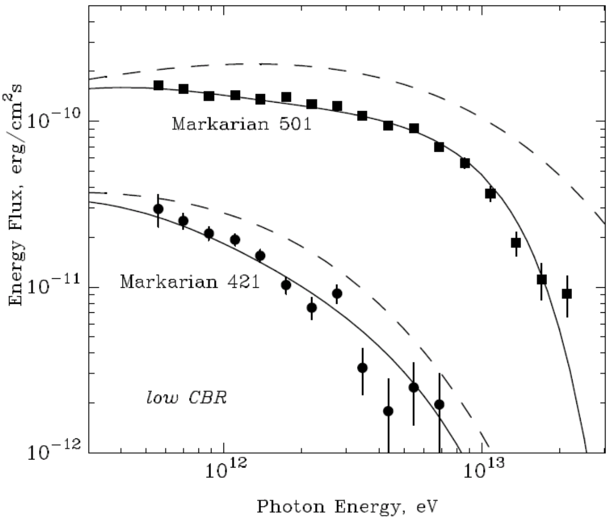


Figure: Cosmic Ray Spectrum

Proton-Synchrotron, Mücke

Alternative model

Different approach from Mücke& Protheroe (1999)

- Fully modeled cascade
- Co-acceleration of *e* and *p*
- includes *p*-, μ- and *e*-synchrotron
- includes neutrino-emission

Proton-Synchrotron, Mücke

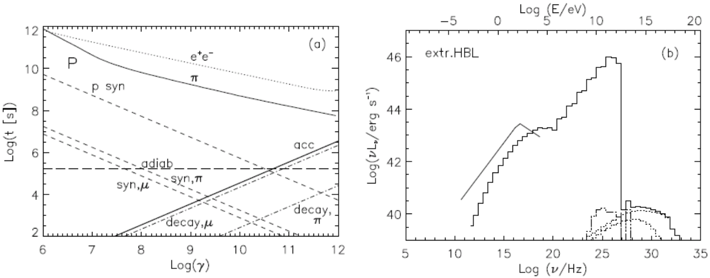


Figure: Extreme HBL parameters: $B = 30$ G, $L_{jet} = 5 \times 10^{45}$ erg/s, $\nu L_{max,syn} = 10^{43.4}$ erg/s, $u_{phot} = 10^9$ eV/cm^3, p synchrotron cascade (dashed line), μ synchrotron cascade (dashed-triple dot), π^0 cascade (upper dotted line) and $\pi^{\pm}$-cascade (lower dotted line) (Mücke & Protheroe 2002)

Proton-Synchrotron, Mücke

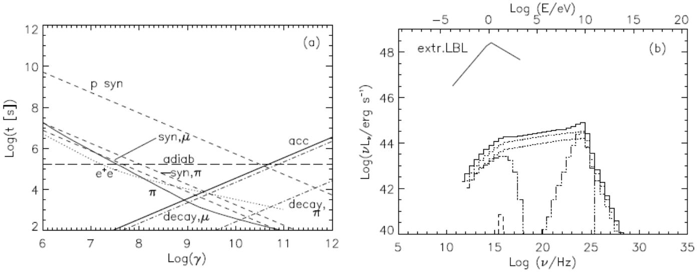


Figure: Extreme LBL parameters: $B = 30$ G, $L_{jet} = 5 \times 10^{45}$ erg/s, $\nu L_{max,syn} = 10^{48.4}$ erg/s, $u_{phot} = 10^{14}$ eV/cm^3, p synchrotron cascade (dashed line), μ synchrotron cascade (dashed-triple dot), π^0 cascade (upper dotted line) and $\pi^{\pm}$-cascade (lower dotted line) (Mücke & Protheroe 2002)

Proton-Synchrotron, Mücke

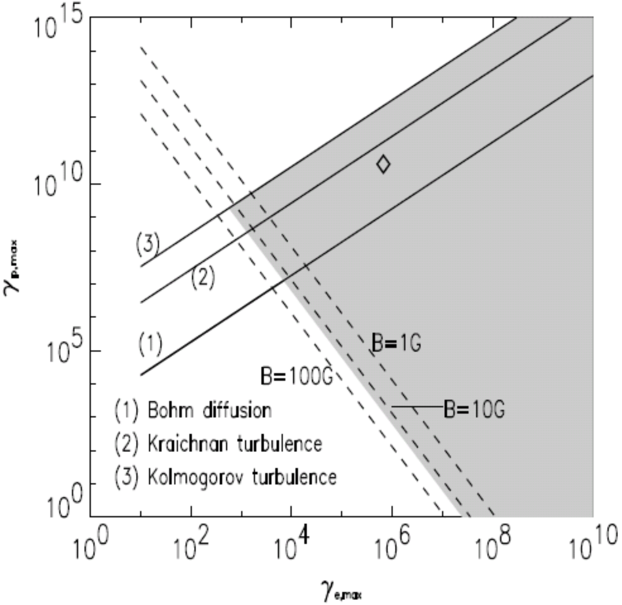


Figure: Allowed turbulence parameters for the co-acceleration

Proton-Synchrotron, Mücke

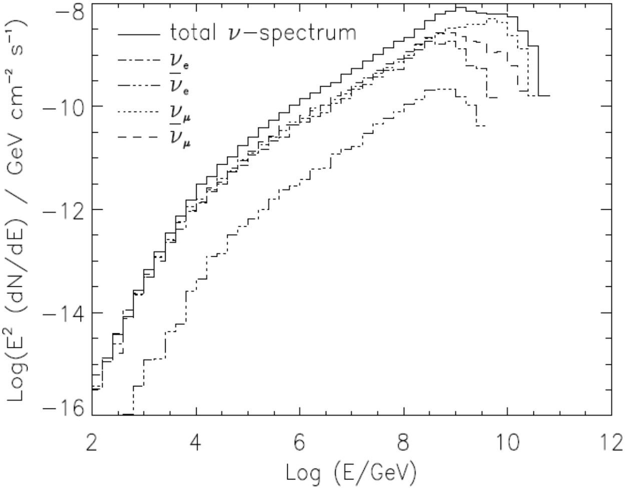


Figure: Associated neutrion emission for the case of Mkn 501

Proton-Synchrotron, Mücke

HBL

- Assumption: Low target photon density
- Little photo-meson production
- Major contribution: Proton synchrotron in high energy hump
- Direct electron synchrotron in low energy hump
- Requires high acceleration efficiency

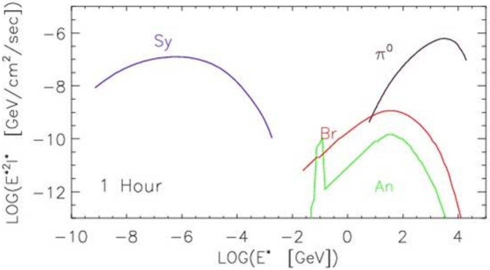
LBL

- High target photon density
- Lower maximum energy (low acceleration efficiency)
- High energy hump from p and μ synchrotron

Proton-Proton-collider

p-p-interactions

- May play role when additional density is inferred



Outlook

- Models so far are either leptonic or hadronic. We are missing mixed models
- All models are equilibrium solutions. Variability is inferred only via time scales

Outlook

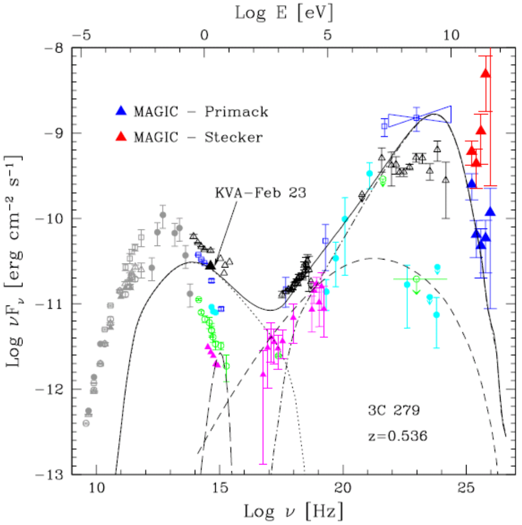


Figure: The spectrum of 3C279, an interesting candidate for mixed models

Conclusion

- A number of hadronic alternatives to SSC/EC exist
- Main processes are p-synchrotron emission of cascading via π, μ and e
- Different regimes of validity
- Neutrinos can give a hint which model is correct
- Model development has to be pushed forwsrd