Very-High Energy Steady Spectrum of Crab Nebula and Particle Acceleration

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RICAP-2016
6th Roma International Conference
on Astroparticle Physics

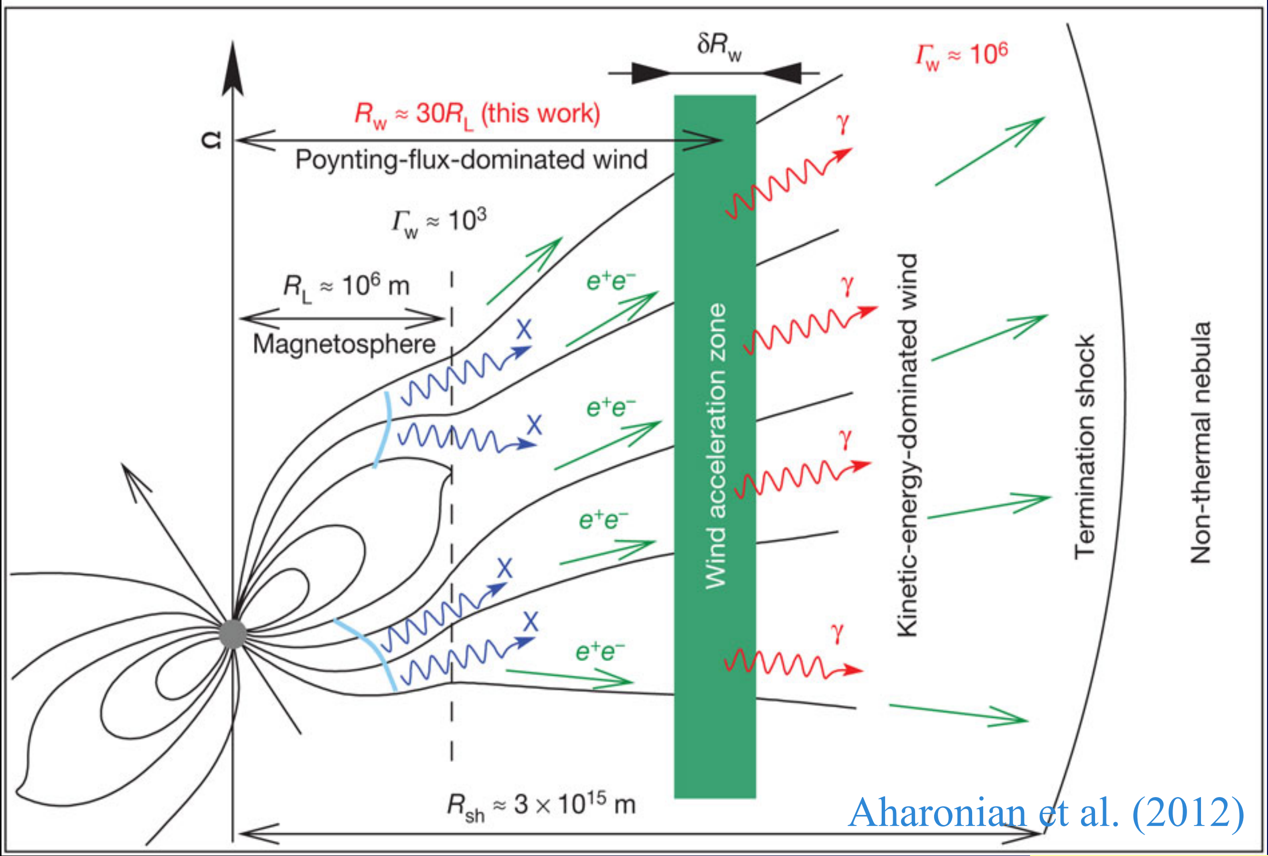
June 23rd, 2016

Outline

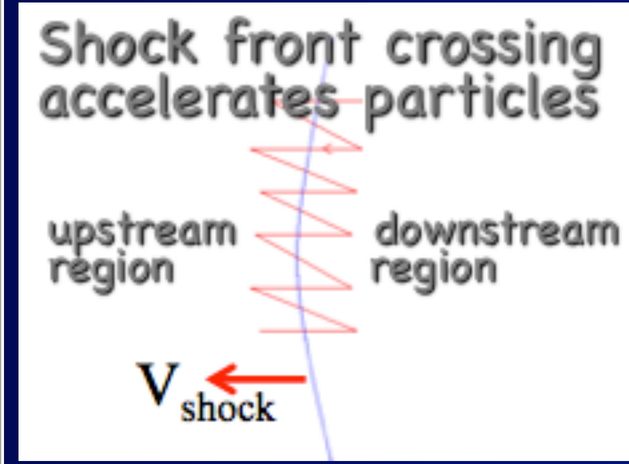
Multi-detector steady-state VHE (GeV and multi-TeV) spectrum of Crab nebula

New accurate theoretical determination of the Inverse-Compton spectrum for the joint Fermi/LAT –VHE data up to 100 TeV

Microscopic parameters of the population of energetic electrons directly connected to observations

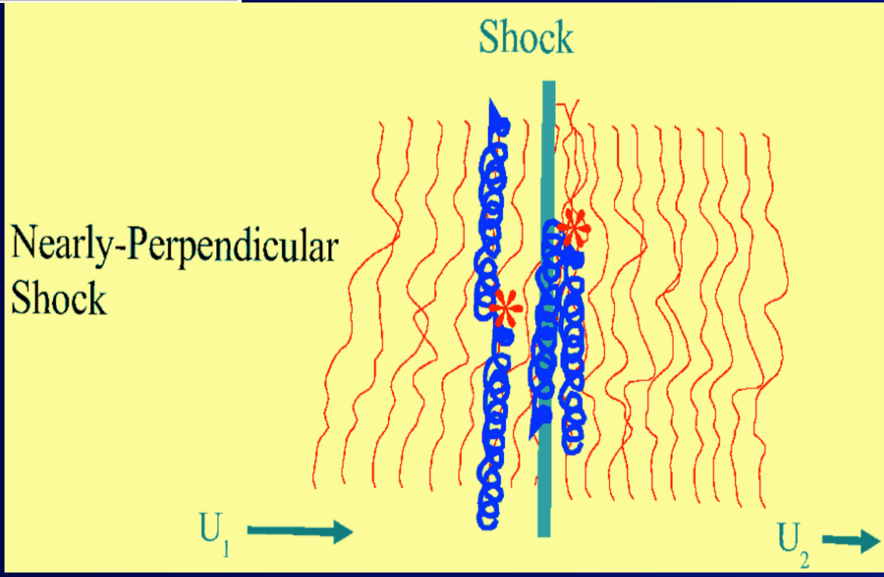


Aharonian et al. (2012)

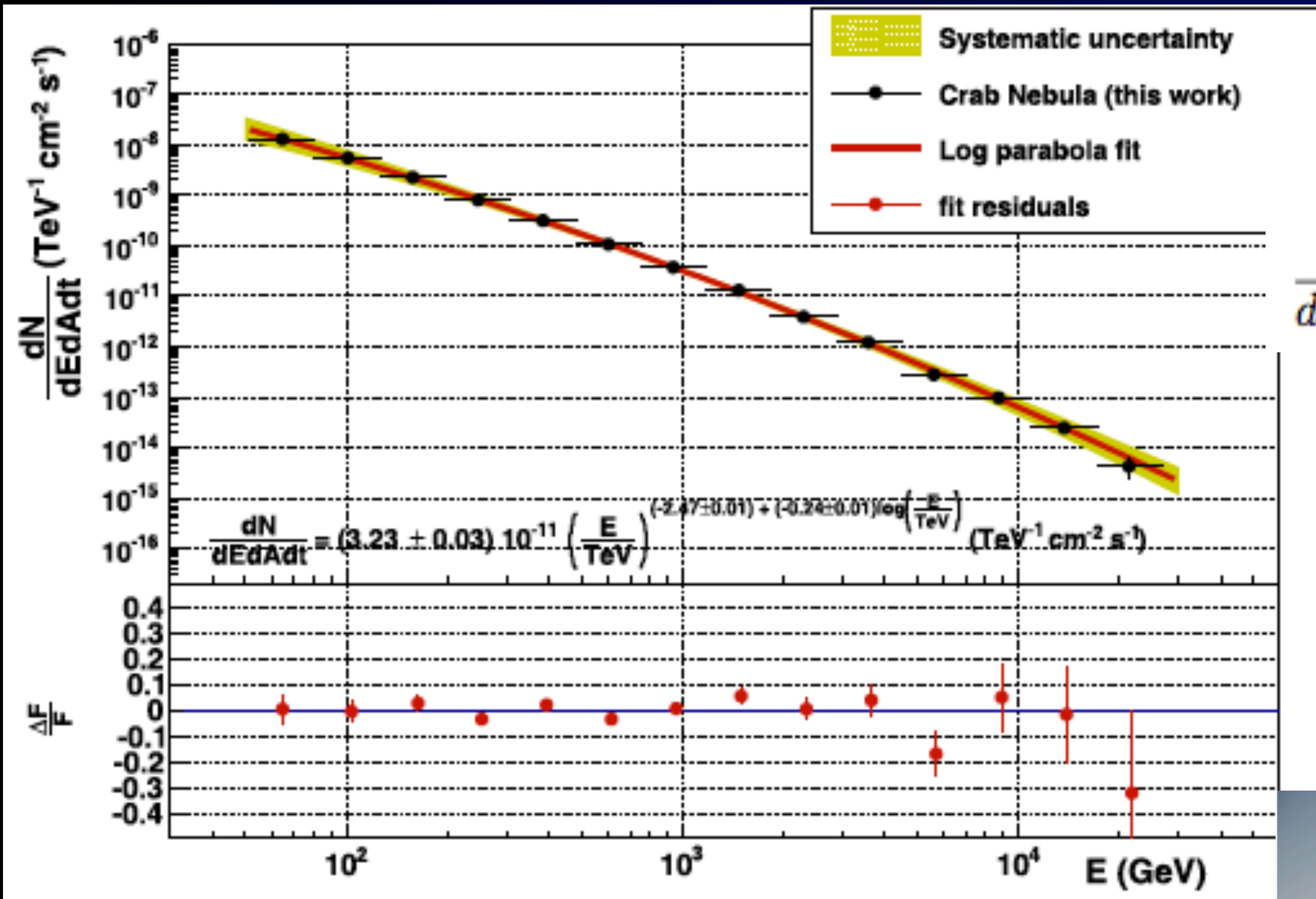


TS is a large-scale quasi-perpendicular shock

Relativistic e^+e^- advected in the magnetized wind are accelerated at termination shock (Aarons & Tavani 1994) or through shock-driven reconnection in the stripe wind (Petri & Lyubarsky 2007)



MAGIC differential flux



Photon VHE spectrum:

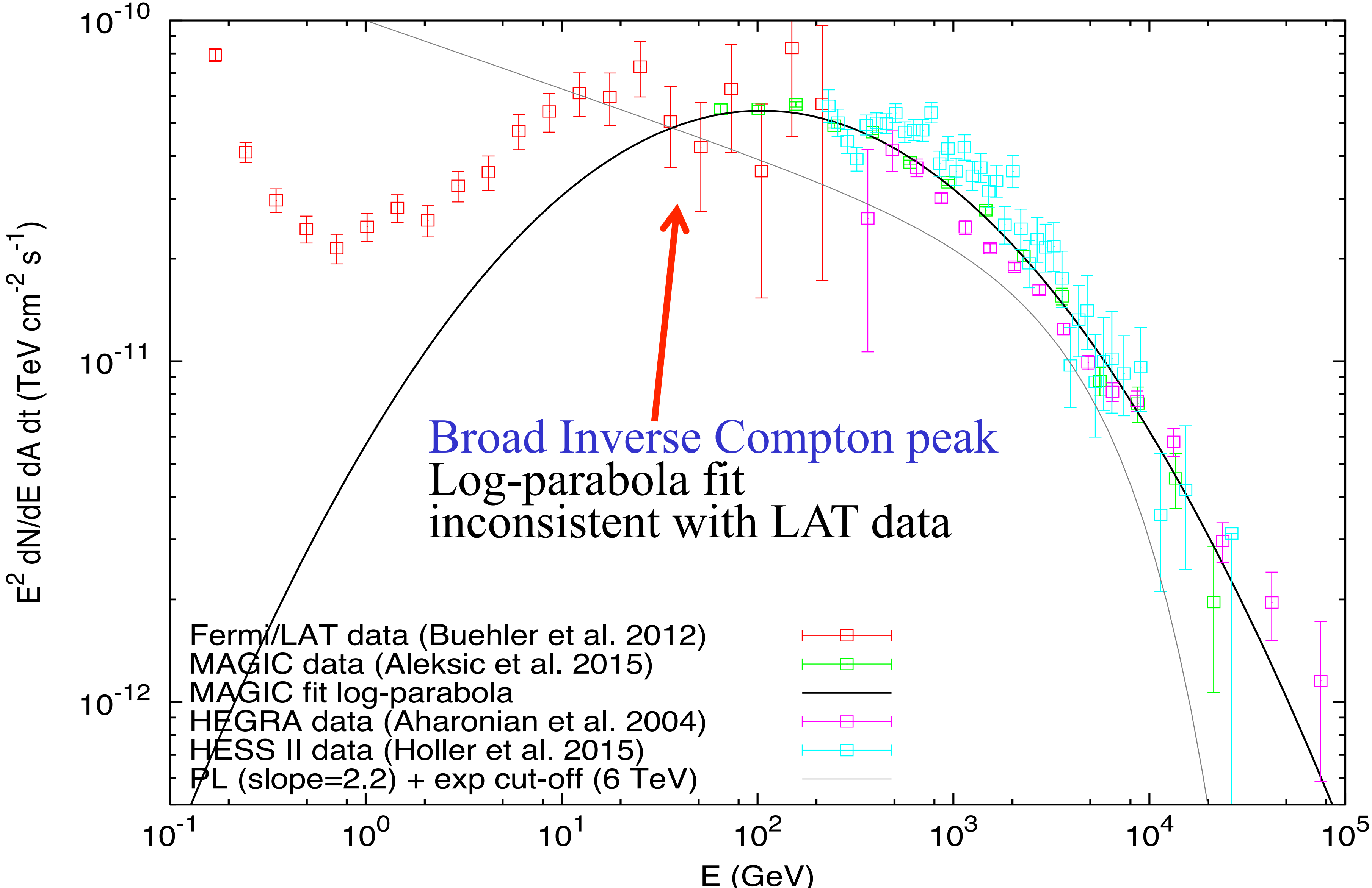
$$\frac{dN}{dEdAdt} \propto \left(\frac{E}{E_0}\right)^{[\alpha+\beta\cdot\log(E/E_0)]}$$

Log-parabola

Aleksic et al. 2015 (2009-11 data)

Most likely explanation:
E>1 GeV photons Inverse Compton up-scattering off the relativistic e^- within the nebula (target photons from dust or CMB or synchrotron self-Compton)

Multi-detector VHE differential flux

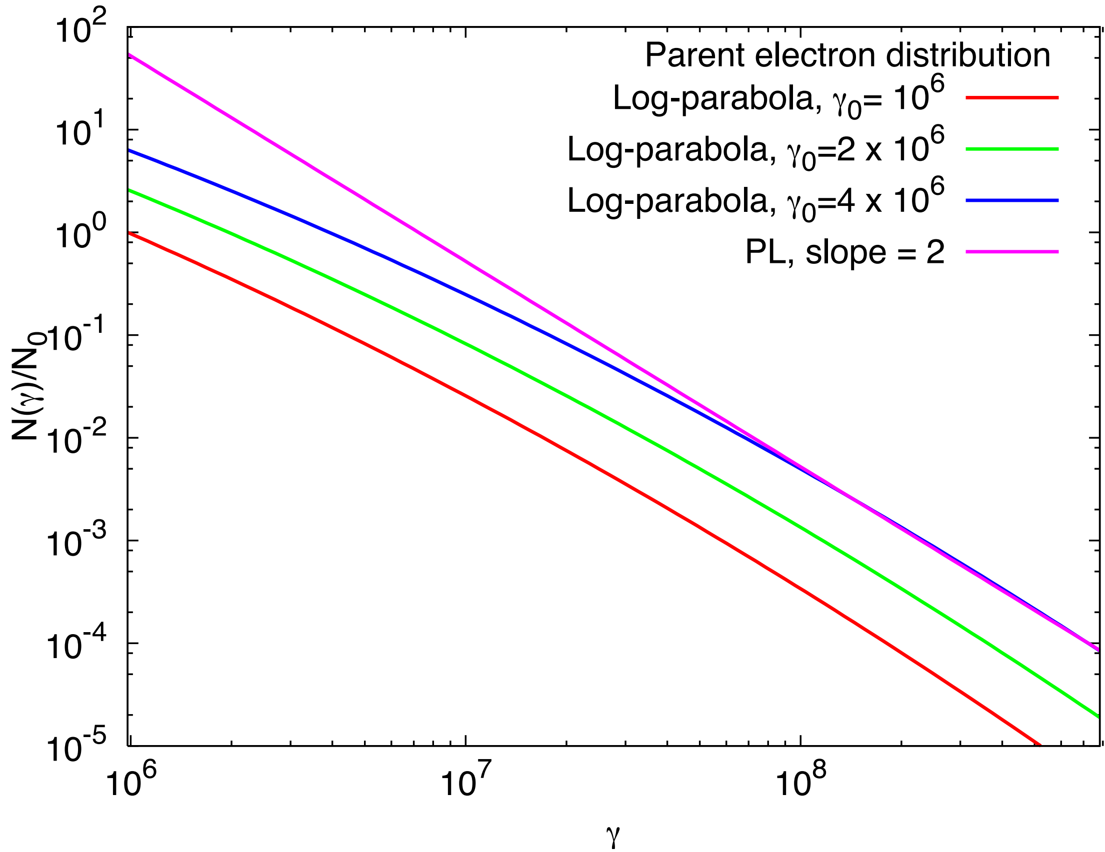


Blazars' X-ray non-thermal synchrotron spectrum are well fit by log-parabola.
Such spectrum originates from log-parabola energetic electrons spectrum (Massaro et al. 2004).
What about VHE?

Microscopic assumptions

VHE-emitting electrons accelerated by the nebula TS have a log-parabola distribution, not power-law as expected from standard diffusive acceleration model for shocks

$$N(\gamma) = N_0(\gamma/\gamma_0)^{-[s-1+r\log(\gamma/\gamma_0)]}$$



Key assumptions on the IC power

Monochromatic target photon field up-scattering off energetic electrons

Extreme Klein-Nishima limit $\frac{4\varepsilon_0\gamma}{m_e c^2} \gg 1$ ε_0 : energy of photon target

New VHE steady spectrum I

$$\frac{dN}{d\varepsilon dA dt}(\varepsilon) = \left[1 + \left(-s + 1 - 2r\log(\varepsilon/\bar{\varepsilon}_0)\right) \cdot \left(\ln\frac{4\varepsilon_0\varepsilon}{(m_e c^2)^2} - \frac{11}{6}\right)\right]$$

Peak width

$$\times \quad \mathcal{A}(\varepsilon_0, \bar{\varepsilon}_0)(\varepsilon/\bar{\varepsilon}_0)^{-[s+r\cdot\log(\varepsilon/\bar{\varepsilon}_0)]}$$

log-parabola

$$\bar{\varepsilon}_0 = m_e c^2 \gamma_0$$

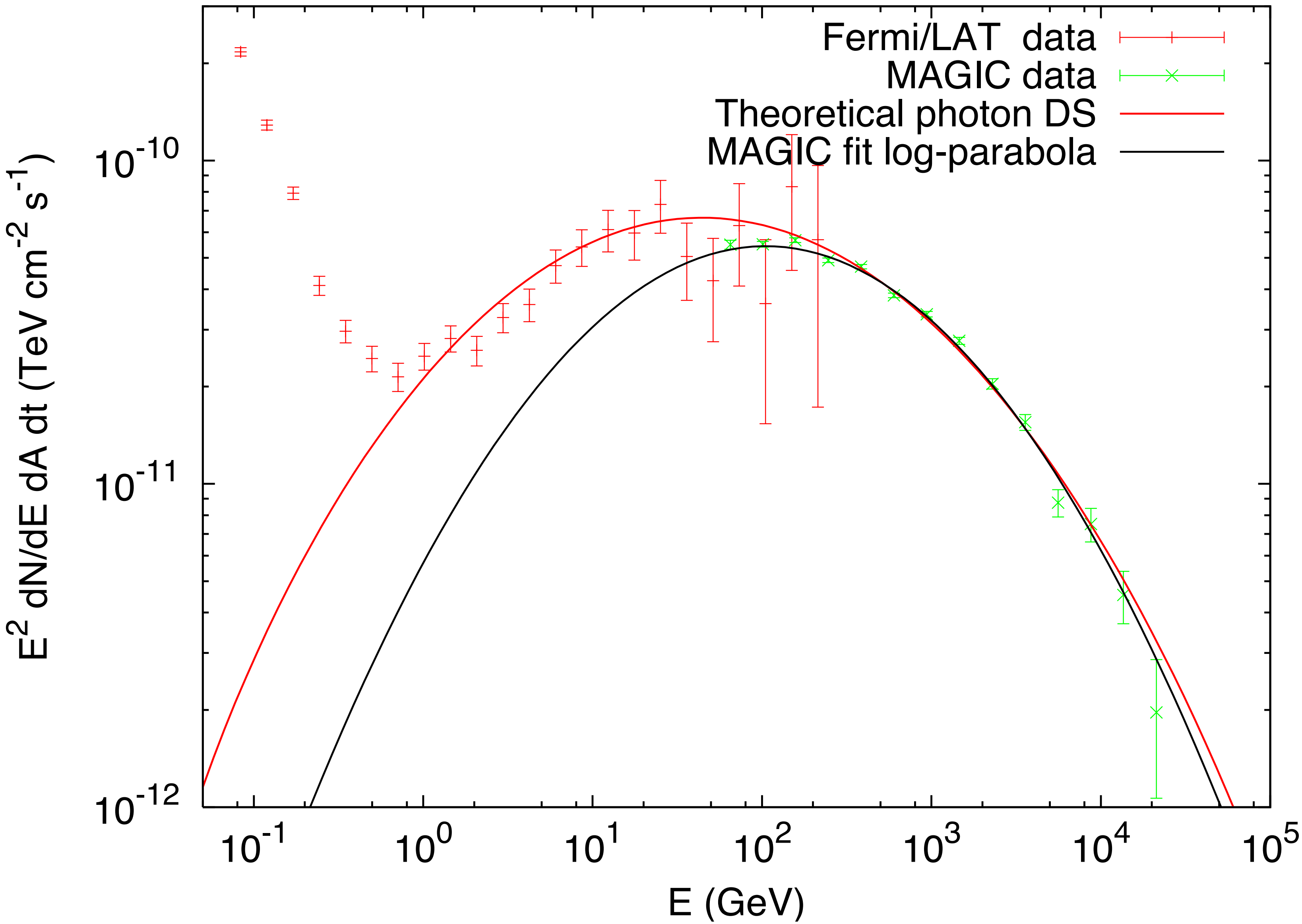
The new VHE steady-state spectrum is a standard log-parabola with a pre-factor governing the width of the IC peak

s=2.42 (2.47±0.01), r = 0.15 (0.24±0.01), $\bar{\varepsilon}_0$ = 982 GeV

Folded with mono-chromatic assumption for the IC characteristic photon energy: $h\nu_{IC} = m_e c^2 \gamma$

In extreme Klein-Nishima limit, the photon acquires a sizeable fraction of the electron energy. CMB ruled out (Synchrotron self-Compton ->).

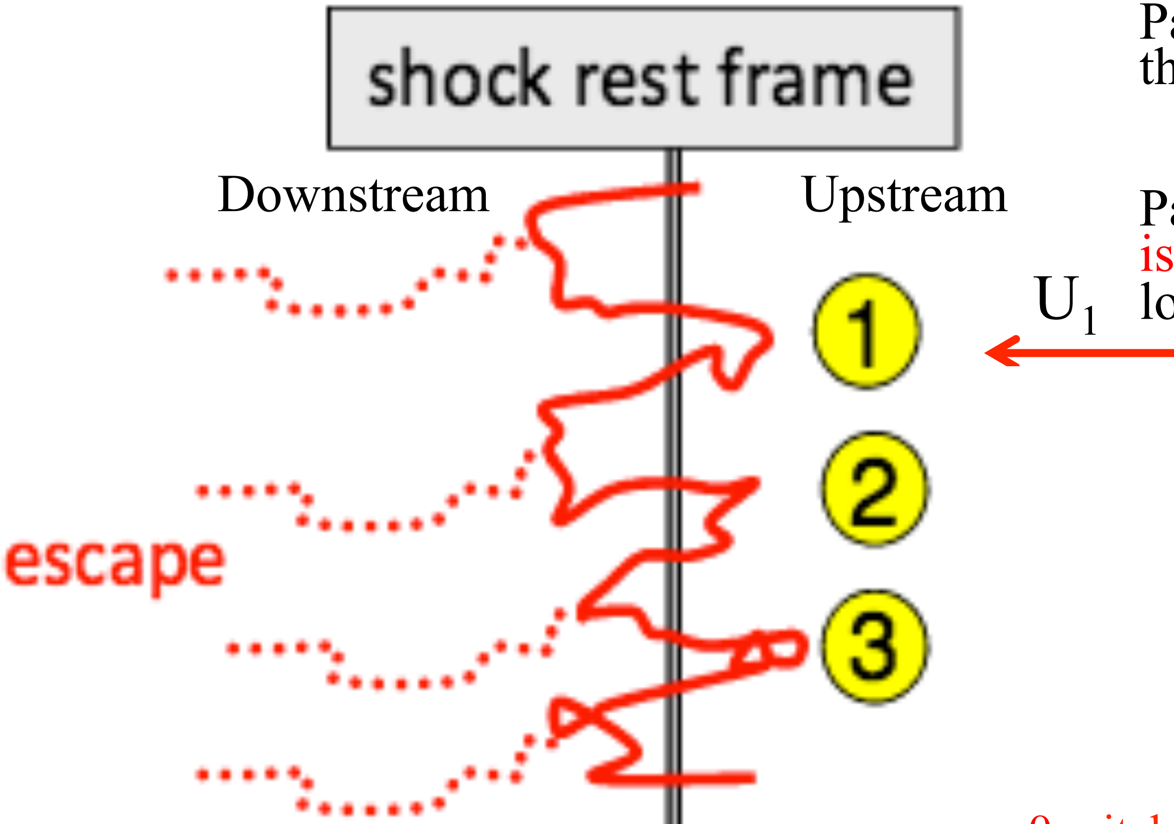
New VHE steady spectrum II



Natural joint explanation of LAT + VHE data: IC off far-infrared pool

Microscopic interpretation

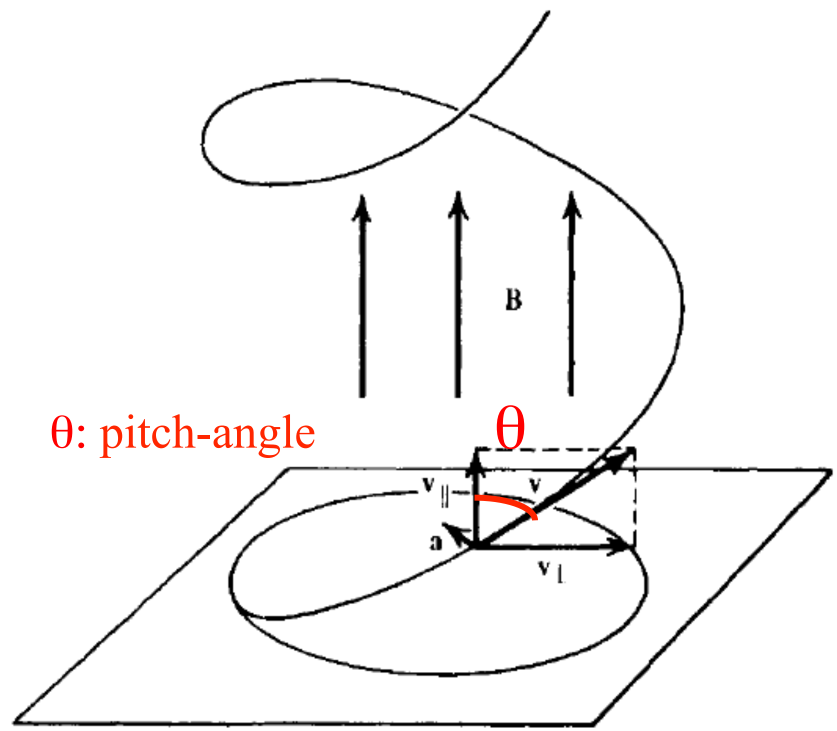
One back-step to standard model of Diffusive Shock Acceleration



Particle speed much greater than the shock speed ($v >> U_1$)

↓

Particle distribution nearly isotropic in pitch-angle, in the local plasma frames



Standard Model of Diffusive Shock Acceleration

1) Probability of remaining in the acceleration region independent of particle energy γ (only for highest energies)

+

2) Isotropy in the pitch-angle in the local plasma frame

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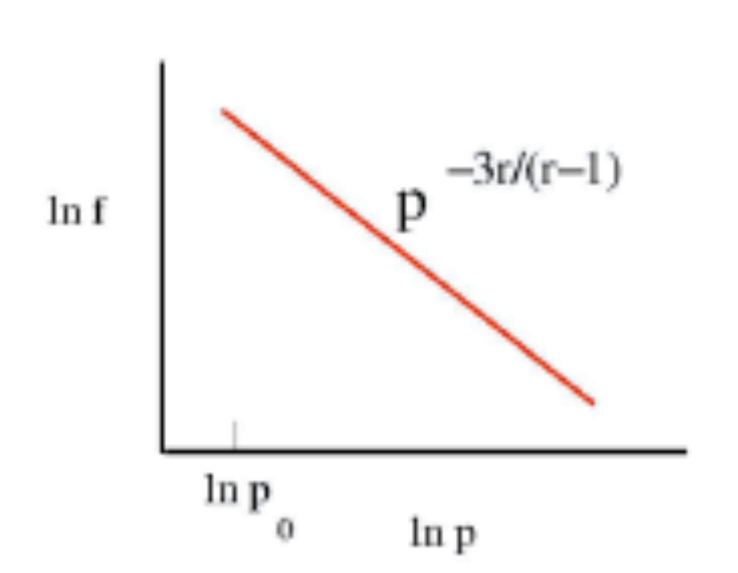
Time-asymptotic (steady-state) solution to transport equation for 1-dimensional shock

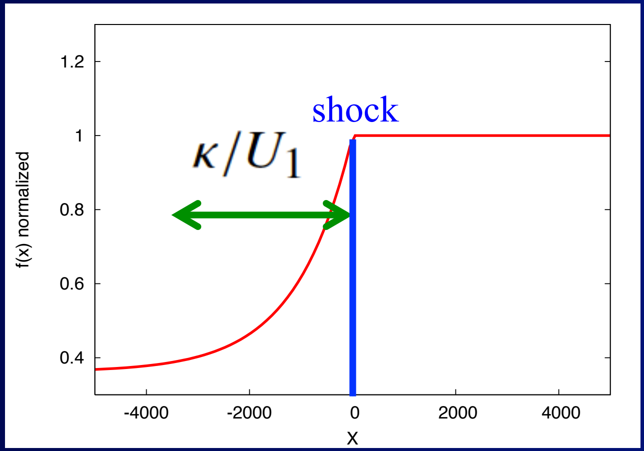
The spectrum is a power-law in momentum depending only on the shock compression ratio (if back-reaction of energetic particles is neglected)



Crab nebula termination shock

In the mildly relativistic TS ($U_1 \sim 0.2c$) of the Crab nebula, the condition $v \gg U_1$ still applies

1) Probability of remaining in the acceleration region decreasing with energy: $P(\gamma) \sim \gamma^{-q}$



$\kappa/U_1 \sim \kappa_\perp/U_1$ at TS

30 TeV electrons in B_0=140 μG have Larmor radius $m_e c^2\gamma/eB_0$= 0.00034 pc comparable with diffusion length κ/U_1

+

2) Weakly isotropic in pitch-angle ($U_1 \sim 0.2c$ and $\gamma \sim 10^6$)

$$N(\gamma) = N_0(\gamma/\gamma_0)^{-[s-1+r\log(\gamma/\gamma_0)]}$$

Connection observations to microscopic parameters: $\beta \simeq -r = q/2\log(1+\Delta p/p)$

$$q = 2rU_1/c \rightarrow q = 0.06$$

Small energy dependence
Qualitative agreement with previous estimates
(Lemoine & Pelletier 2003)

Summary & Conclusion

Natural reproduction of the joint Fermi/LAT and VHE spectrum down to ~ 1 GeV, including the broad IC peak at ~200 GeV by using a new theoretical derivation of log-parabola spectrum

Microscopic: Probability for TeV electrons of remaining in the acceleration region at mildly relativistic shock weakly decreasing on energy; thus, the distribution in momentum of emitting particles is not a power-law

Determination of the synchrotron self-Compton spectra underway (e^- with $\gamma < 10^8$ in a B =140 μG emit synchrotron up to 25 keV)

Back-up slides

New VHE steady spectrum I

$$\frac{dN}{d\varepsilon dA dt}(\varepsilon) = \left[1 + (-s + 1 - 2r\log(\varepsilon/\bar{\varepsilon}_0)) \cdot \left(\ln\frac{4\varepsilon_0\varepsilon}{(m_e c^2)^2} - \frac{11}{6}\right)\right]$$

$$\times \quad \mathcal{A}(\varepsilon_0, \bar{\varepsilon}_0)(\varepsilon/\bar{\varepsilon}_0)^{-[s + r\cdot\log(\varepsilon/\bar{\varepsilon}_0)]}$$

Pre-factor: peak width

log-parabola

$$\bar{\varepsilon}_0 = m_e c^2 \gamma_0$$