Max-Planck-Institut für Kernphysik

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Diffusive Shock Acceleration In Radiation Dominated Environments

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FIVE YEARS OF INTEGRAL

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The Problem We Are Addressing

Electron acceleration in environments where $U_{ph} \gg \frac{B^2}{8\pi}$

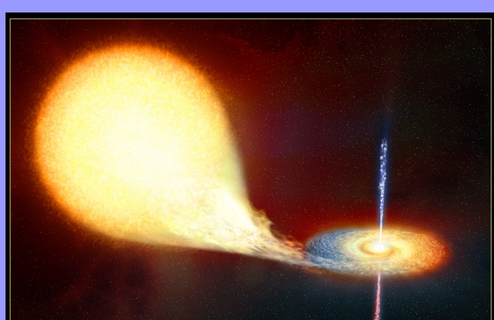
maximum energy: equilibrium between acceleration rate and loss rate.

Inverse Compton (IC) losses dominant on synchrotron.

A situation not yet studied.

Where?

Gamma-ray binaries → LS 5039 (Cesares et al., 2005)

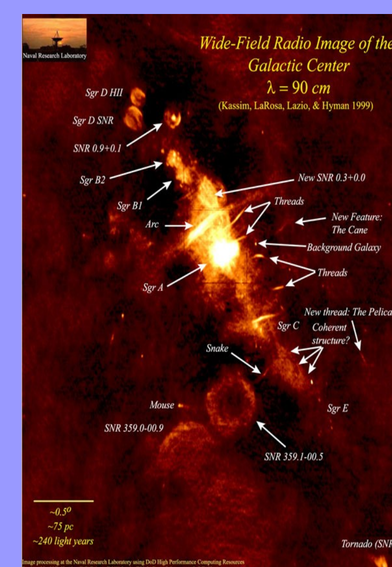


$$U_{ph} \sim 10 \div 1000 \frac{erg}{cm^3} (T \sim 38000\,K) \Longrightarrow B_{eq} \sim 50\,G$$

Galactic Centre (inner 1pc)

(Davidson et al., 1992)

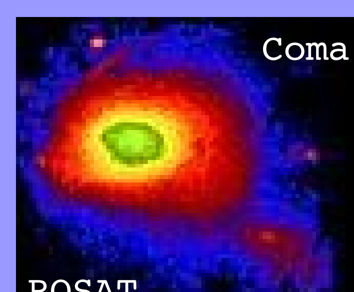
$$U_{ph} \sim 8x10^{-9} \frac{erg}{cm^3} (FIR[kT = 6x10^{-3}\,eV]) \Longrightarrow B_{eq} \sim 500\,\mu G$$



Galaxy Clusters

(Carilli & Taylor, 2002)

$$U_{ph} \sim 0.25 \frac{eV}{cm^3} (T = 2.7\,K) \Longrightarrow B_{eq} \sim 3\,\mu G$$

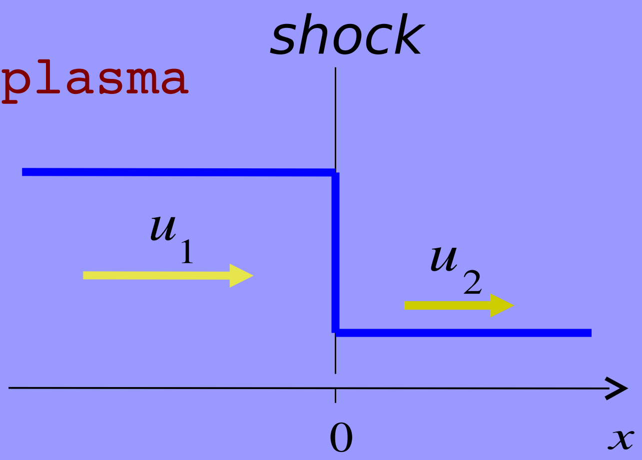


The Acceleration

(Fermi, 1949; Bell, 1978)

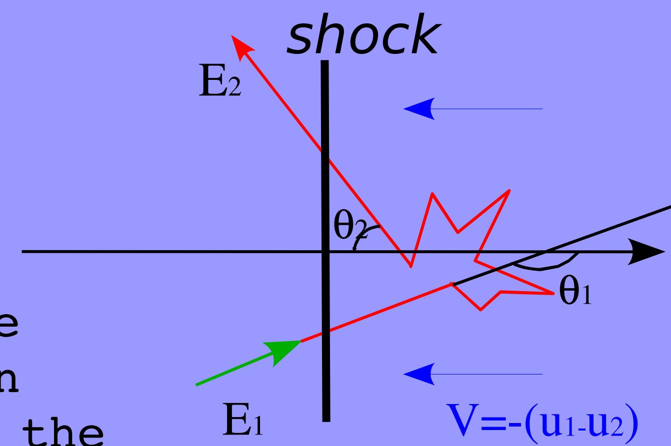
Diffusive Shock Acceleration:

bulk plasma



$$M_1 = \frac{u_1}{c_s}$$ (Mach number)

$$R = \frac{u_1}{u_2}$$ (compression ratio)



non thermal particles

Stochastic acceleration, strong non relativistic shocks:

$$\frac{dN}{dE} \propto E^{-2} \quad \Rightarrow \quad f(p) \propto p^{-4}$$

steady state distribution function at the shock position

The Acceleration

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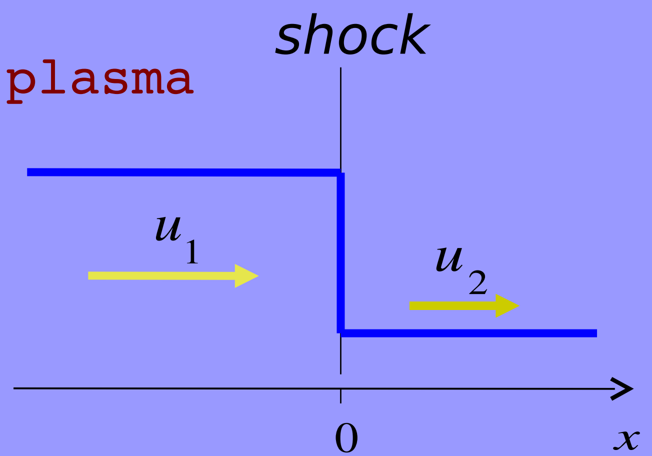

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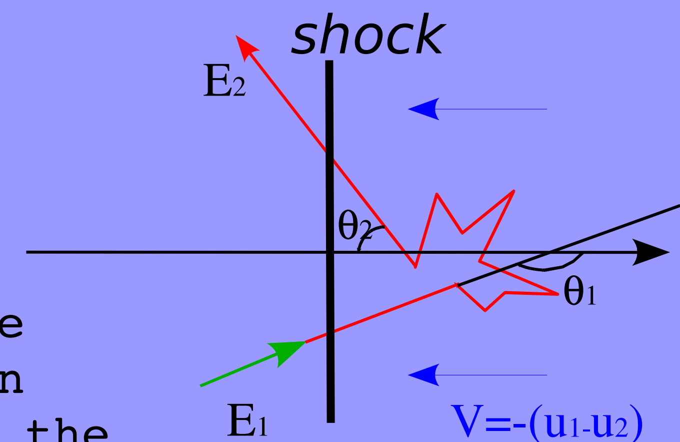


General approach: assuming the injection spectrum, typically as a power law with exponential cutoff, and introducing losses → photon spectrum.

Correct solution only if acceleration site and loss site don't coincide.

The Self-consistent Approach

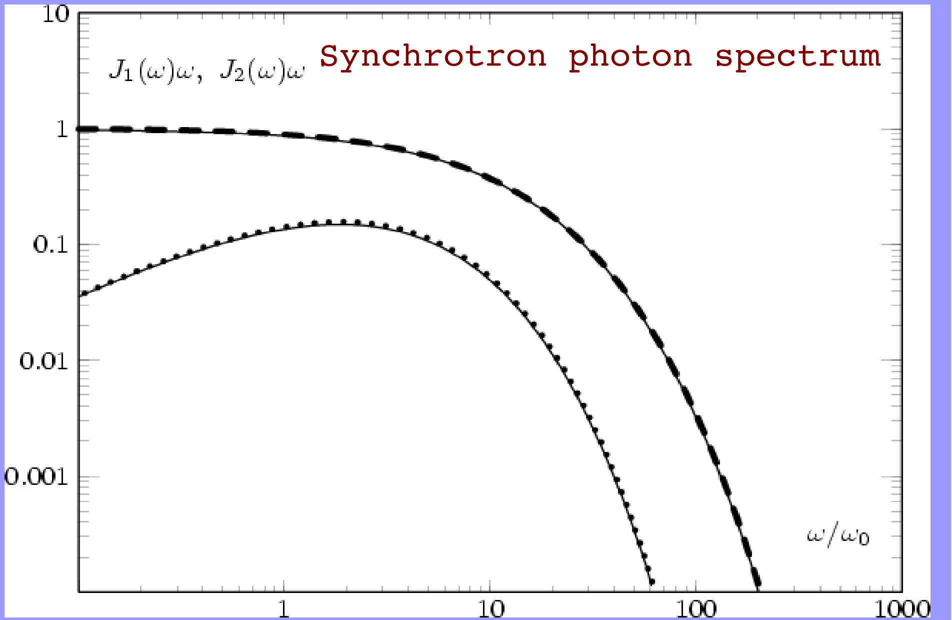
Solving the complete transport equation for electrons:

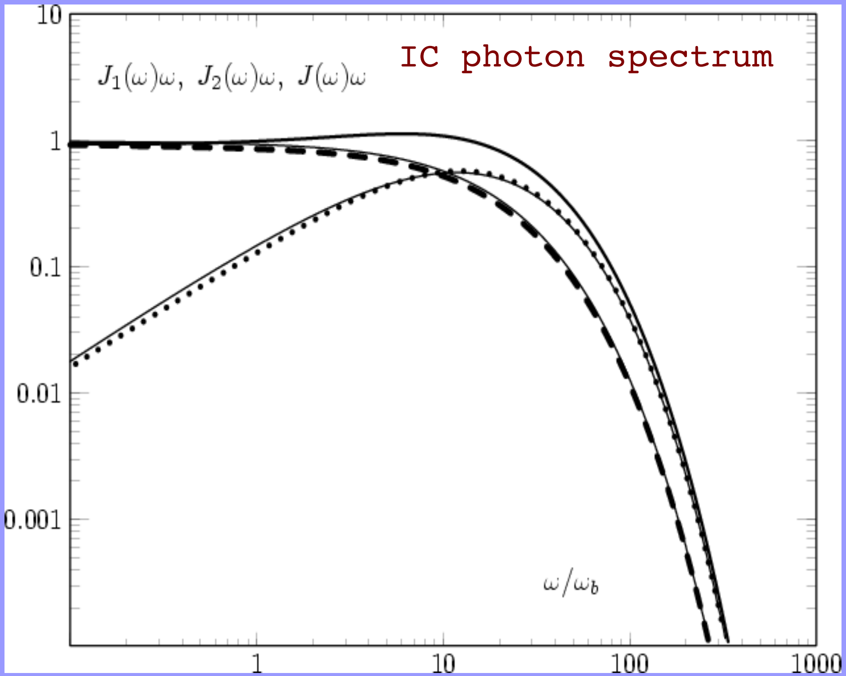
$$\frac{\partial f(x,p,t)}{\partial t}+u\frac{\partial f(x,p,t)}{\partial x}-\frac{\partial}{\partial x}\left(D\frac{\partial f(x,p,t)}{\partial x}\right)-\frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f(x,p,t)}{\partial p}+\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\dot{p}f(x,p,t)\right)=Q(x,p)$$

loss term

First step: Synchrotron losses $\propto E^2$

(Webb et al., 1984;
Heavens & Meisenheimer, 1987;
Zirakashvili & Aharonian, 2007)





Once obtained f(x,p,t) → IC photon spectrum, under the condition $U_{ph} \ll \frac{B^2}{8\pi}$.

When IC Losses Dominate

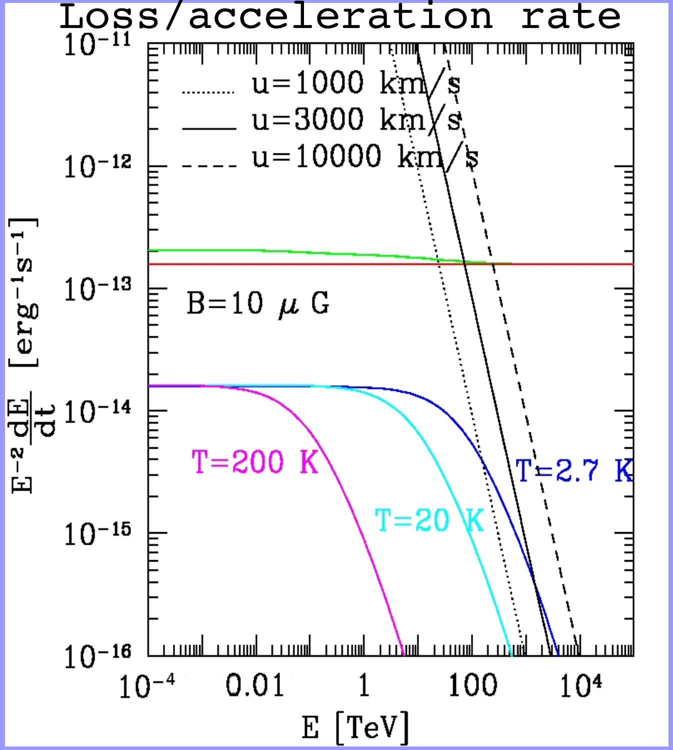
IC losses at low energies: Thomson scattering $\propto E^2$.

But IC cross section decreases at high energies!

Observed X-ray non-thermal emission in SNR $\rightarrow$ TeV electrons (e.g. Bamba et al., 2003).

Klein-Nishina (KN) regime: $\frac{\epsilon E_e}{(m_e c^2)^2} > 1$ $\begin{cases} \text{CMB photons:} & E_e \sim 500\,TeV \\ \text{Optical photons:} & E_e \sim 50\,GeV \end{cases}$

EXAMPLE: SN explosion



InterStellar Medium:

(Moskalenko et al., 2006)

$$U_{CMB} \sim 0.25 \frac{eV}{cm^3}; \quad U_{FIR} \sim 0.25 \frac{eV}{cm^3}; \quad U_{OPT/NIR} \sim 0.25 \frac{eV}{cm^3}$$

$$\frac{B^2}{8\pi} \geqslant U_{ph}$$

Negligible contribution of the IC

BUT...

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- CMB photons: $E_e \sim 500\, TeV$
- Optical photons: $E_e \sim 50\, GeV$

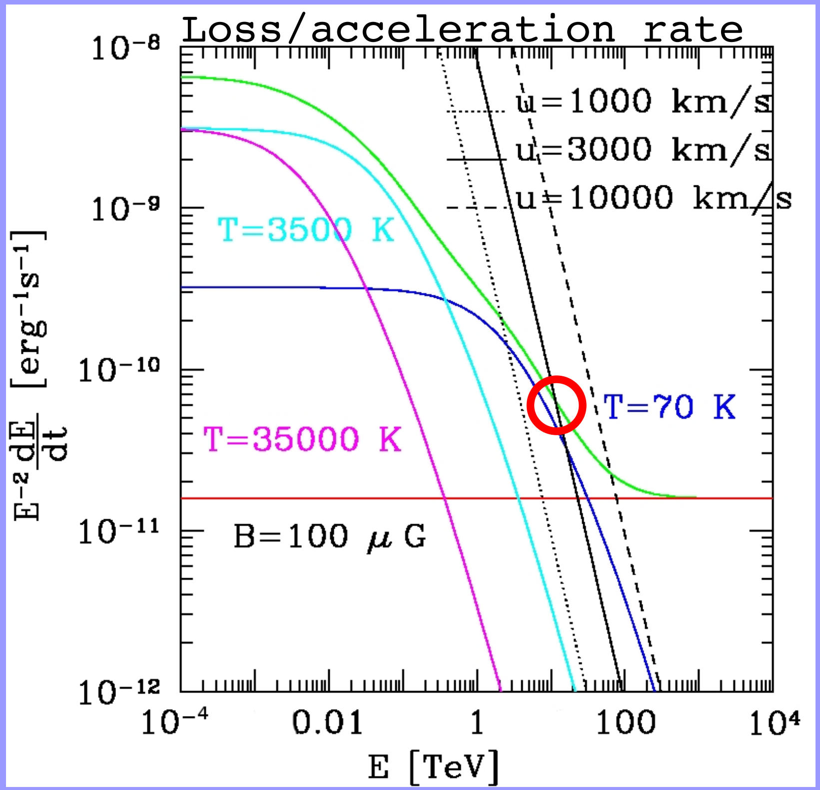
EXAMPLE: SN explosion

Galactic Centre (inner 1pc):

(Davidson et al., 1992)

$$U_{FIR} \sim 5000 \frac{eV}{cm^3};\ U_{NIR} \sim 5\times10^4 \frac{eV}{cm^3};\ U_{UV/OPT} \sim 5\times10^4 \frac{eV}{cm^3};$$

$B \sim 100\, \mu G$ (Hinton&Aharonian, 2007)



We expect a significant modification of the spectra.

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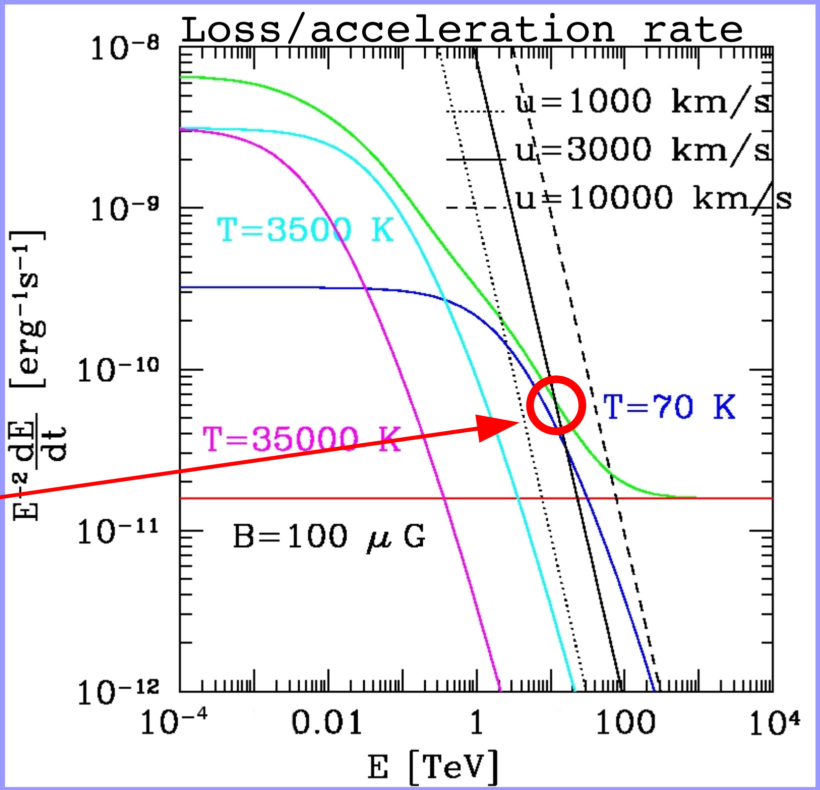
Depending on B and the shock velocity u synchrotron emission from soft to hard X-rays.

$E^* \sim 10$ TeV

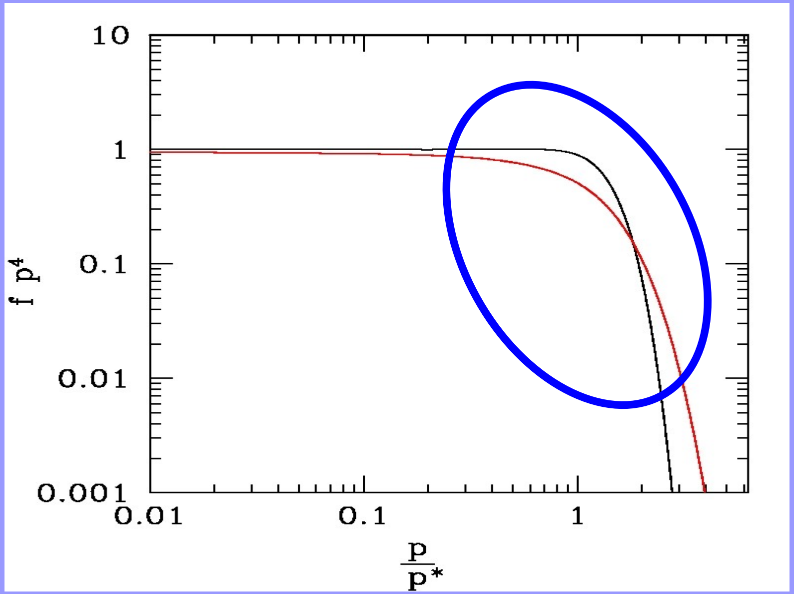
$\epsilon_\gamma \sim 1$ keV



Results: The Electron Spectum

(Vannoni, Gabici&Aharonian, to be submitted)

One realistic case: SNR in the inner Galactic Centre.



Electron spectrum at the shock surface (arbitrary normalization).

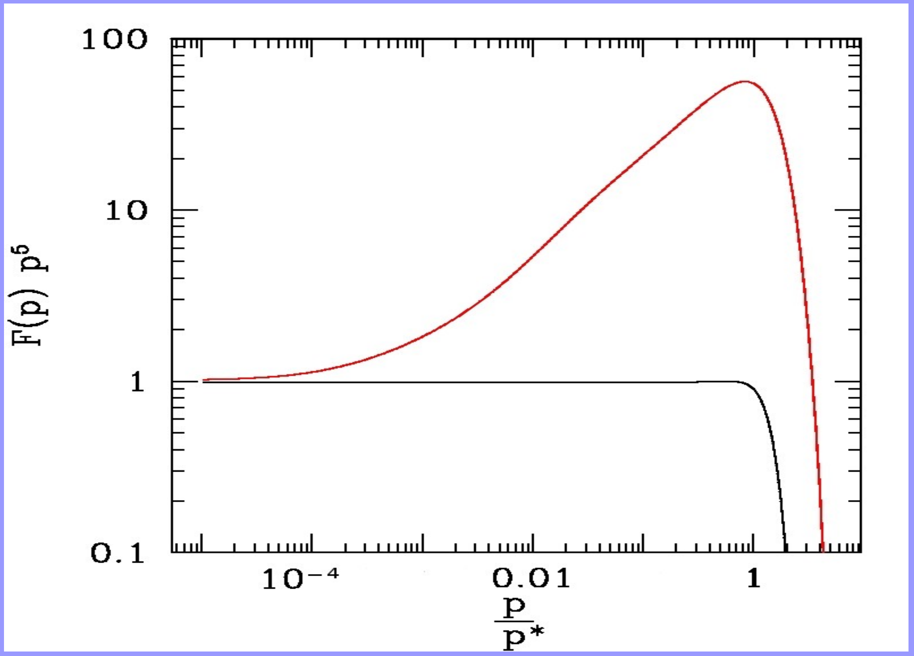
In the IC (KN) loss dominated regime (red curve):

- broader cutoff region
- shallower cutoff shape

Electron spectrum integrated over the up + down-stream regions.

Hardening due to the KN effect, pile up around the cutoff energy up to a factor ~100 compared to pure synchrotron losses.

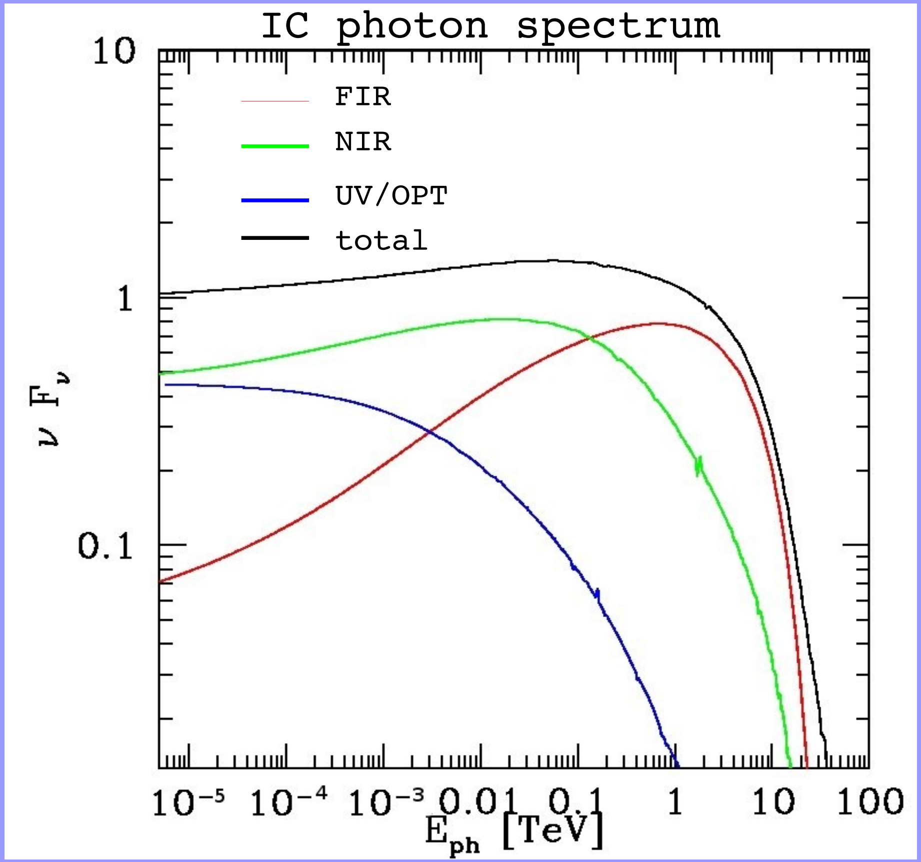
(watch out for the normalization!)



Results: The Photon Spectrum

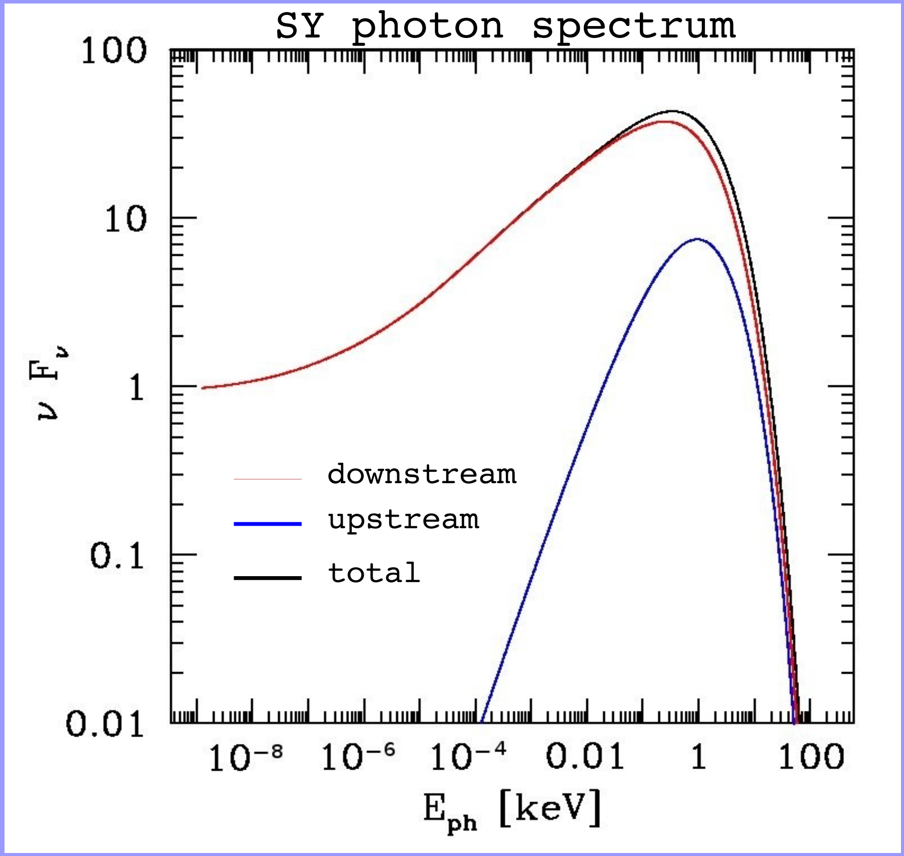
(Vannoni, Gabici&Aharonian, to be submitted)

Change in the electron spectrum → features in the photon spectra.



KN cross-section modifies both the electron and the photon spectrum in opposite directions.

Almost perfect compensation



The bump in the electron distribution is reproduced in the synchrotron spectrum.

Pile up at keV energies

Outlook

- Electron accelerators embedded in a strong radiation field: IC can become the dominant loss channel.

- Klein-Nishina effects can set in, significantly affecting the particle spectrum (pile up at the cutoff).

- Impact on the radiation (Synchrotron and IC).

  ➡ Most significant feature in the synchrotron spectrum.

Specific sources (work in progress):

SNR in the Galactic Centre: (depending on values of B and shock velocity)
electrons cutoff energy
~1÷100 TeV
synchrotron pile up in the UV/X-rays
~few eV÷100 keV

More (still to explore):

Microquasar: multi keV synchrotron from electrons in the jet (may require relativistic DSA).
Galaxy Clusters: if IC on the CMB is the dominant channel we expect features in keV synchrotron photons.