Radiative Processes in High-Energy Astrophysics

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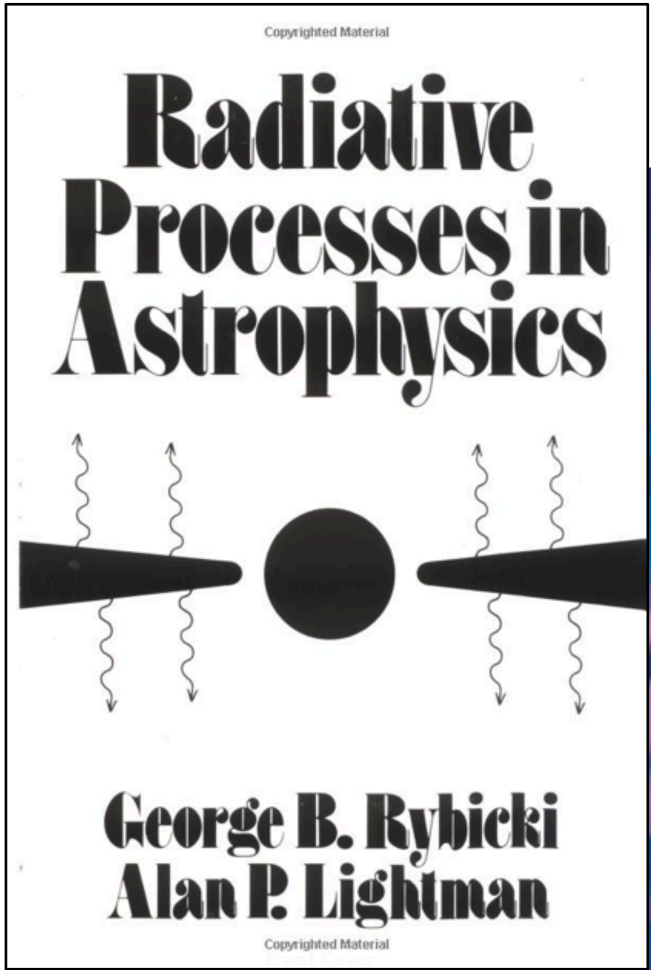
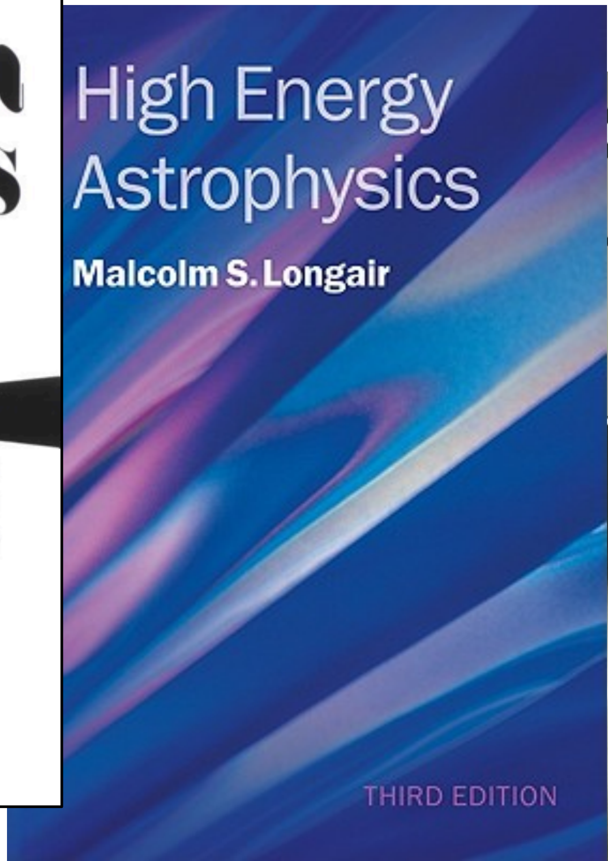
Outline

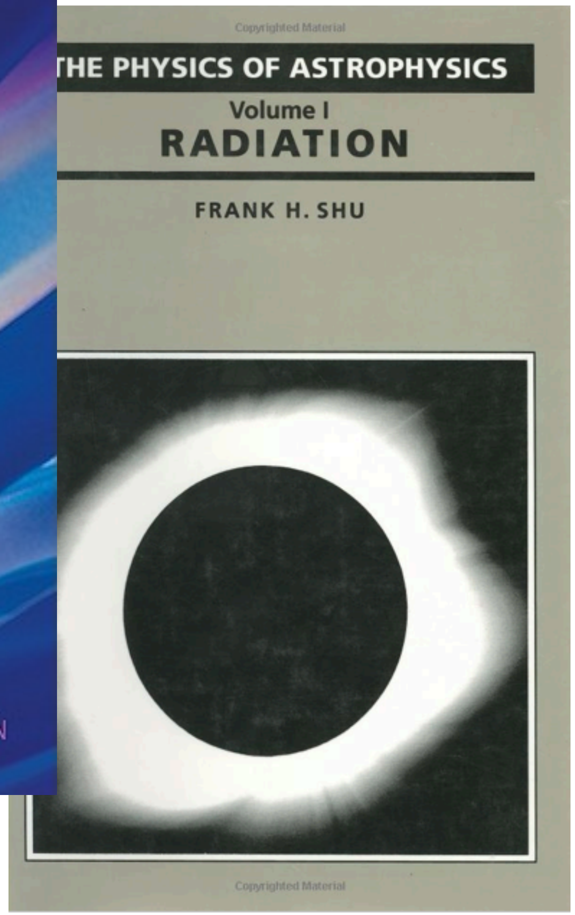
A very basic introduction to the selected radiative processes which are of the main importance in high-energy astrophysics

- Basic definitions and concepts
- Synchrotron Emission
- Inverse-Compton Emission
- Thermal Bremsstrahlung
- Proton-Proton Interactions
- Photo-Meson Production
- Photon-Photon Annihilation

I. Basic Definitions and Concepts







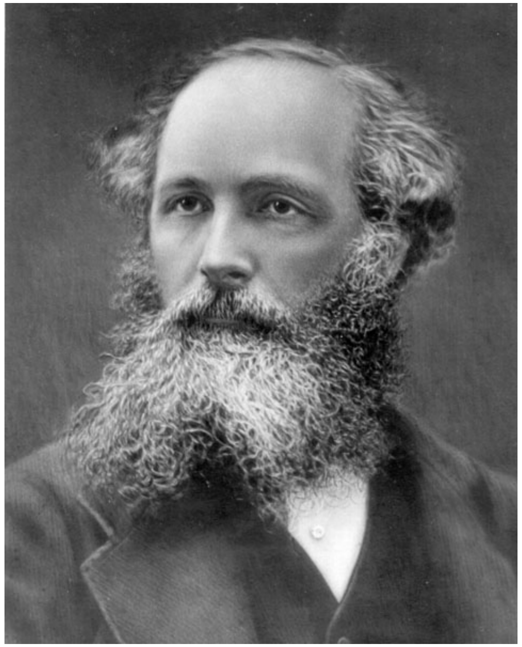
I. Maxwell Equations

$$\vec{\nabla} \times \vec{B} = \frac{1}{c}\frac{\partial}{\partial t}\vec{E} \tag{1}$$

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial}{\partial t}\vec{B} \tag{2}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{3}$$

$$\vec{\nabla} \cdot \vec{E} = 0 \tag{4}$$



$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \vec{\nabla}^2\right)\vec{E} = 0 \quad \text{and} \quad \left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \vec{\nabla}^2\right)\vec{B} = 0 \tag{5}$$

$$\vec{E} = \sum_{\pm} \vec{E}_{\pm}(\zeta \pm ct) \quad \text{and} \quad \vec{B} = \sum_{\pm} \vec{B}_{\pm}(\zeta \pm ct) \tag{6}$$

Propagation of EM signal in vacuum is described by the Maxwell equations (1-4). EF and MF satisfy the homogeneous wave equation (5); general solutions (6) consist of plane waves propagating at the speed of light *c* .

I. Electromagnetic Waves

Fourier decomposition

$$\vec{E}\,(\vec{r},t) = \frac{1}{(2\pi)^3}\int d^3k\ \hat{e}(\vec{k})\ \exp\left[i\left(\vec{k}\cdot\vec{r} - \omega\,t\right)\right] \qquad (7)$$

$$\vec{B}\,(\vec{r},t) = \frac{1}{(2\pi)^3}\int d^3k\ \underbrace{\hat{b}(\vec{k})\ \exp\left[i\left(\vec{k}\cdot\vec{r} - \omega\,t\right)\right]}_{\text{monochromatic plane wave}} \qquad (8)$$

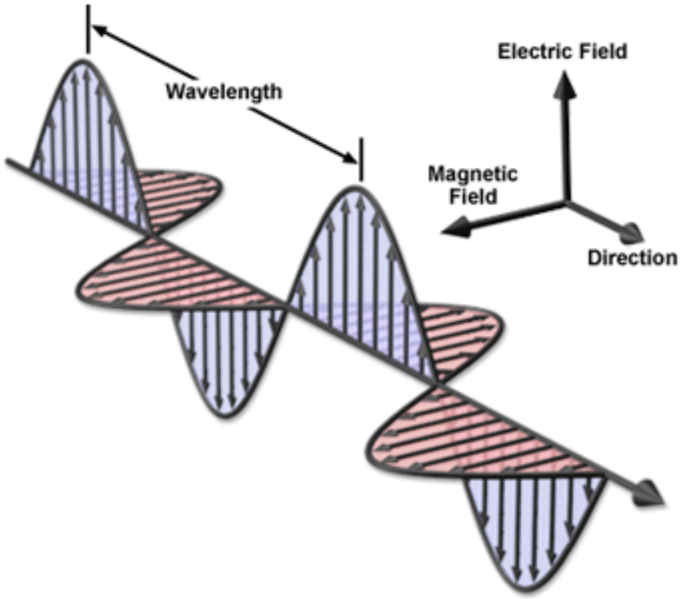
$$v_{\rm ph} \equiv \omega/k = c$$
$$v_{\rm g} \equiv \partial\omega/\partial k = c$$

$$\hat{k}\times\hat{e} = \hat{b}$$
$$\hat{k}\times\hat{b} = -\hat{e}$$
$$\hat{k}\cdot\hat{e} = 0$$
$$\hat{k}\cdot\hat{b} = 0$$

$$\vec{F}_{\rm M} \propto \vec{E}\times\vec{B}$$

where $\hat{k} \equiv \vec{k}/k$

Electromagnetic Wave



Waves with frequency ω travelling in the direction given by the wave vector k with the phase and group velocities equal c; electric and magnetic vectors are both transverse to the direction of wave propagation, perpendicular to each other, and equal in magnitude; the associated Poynting flux points along k.

I. Basic Definitions

monochromatic specific intensity: the amount of radiant energy *dE* which crosses in time *dt* the area *dA* normal to a given direction, within a solid angle *dΩ*

$$I_\nu = \frac{dE}{dA\, d\Omega\, d\nu\, dt} \tag{9}$$

monochromatic energy flux

$$S_\nu = \oint I_\nu \, d\Omega \tag{10}$$

monochromatic emission coefficient (emissivity): the energy *dE* emitted per unit time *dt* per unit solid angle *dΩ* per unit volume of the emitting matter *dV*

$$j_\nu = \frac{dE}{dV\, d\Omega\, d\nu\, dt} \tag{11}$$

optical depth τ of the medium through which the radiation is propagating, absorption coefficient α and cross section σ

$$\tau_\nu(L) = \int_0^L n_{\rm ab}(\ell)\, \sigma_\nu \, d\ell \equiv \int_0^L \alpha_\nu(\ell)\, d\ell \tag{12}$$

I. Radiative Transfer

$$\left(\frac{d}{d\tau_\nu} + 1\right) I_\nu = \frac{j_\nu}{\alpha_\nu} \tag{13}$$

$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)}\, \frac{j_\nu}{\alpha_\nu}\, d\tau'_\nu \tag{14}$$

Radiative transfer theory describes electromagnetic radiation propagating along straight lines from the source to the observer

$$I_\nu(0) \neq 0\ ,\ j_\nu = 0\ ,\ \alpha_\nu = 0 \quad \rightarrow \quad I_\nu(L) = I_\nu(0) \tag{15}$$

$$I_\nu(0) \neq 0\ ,\ j_\nu = 0\ ,\ \alpha_\nu \neq 0 \quad \rightarrow \quad I_\nu(L) = I_\nu(0)\, e^{-\tau_\nu(L)} \tag{16}$$

$$I_\nu(0) = 0\ ,\ j_\nu \neq 0\ ,\ \alpha_\nu = 0 \quad \rightarrow \quad I_\nu(L) = \int_0^L j_\nu(\ell)\, d\ell \tag{17}$$

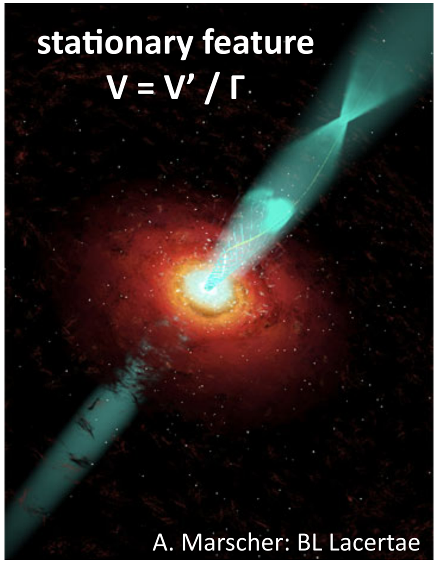
$$I_\nu(0) = 0\ ,\ j_\nu = const\ ,\ \alpha_\nu = const\ \rightarrow\ I_\nu(L) = \frac{j_\nu}{\alpha_\nu}\left[1 - e^{-\alpha_\nu L}\right] \tag{18}$$

I. Relativistic Beaming

viewing angle $$\vec{\beta} \cdot \hat{k} = \beta \cos\theta \tag{19}$$

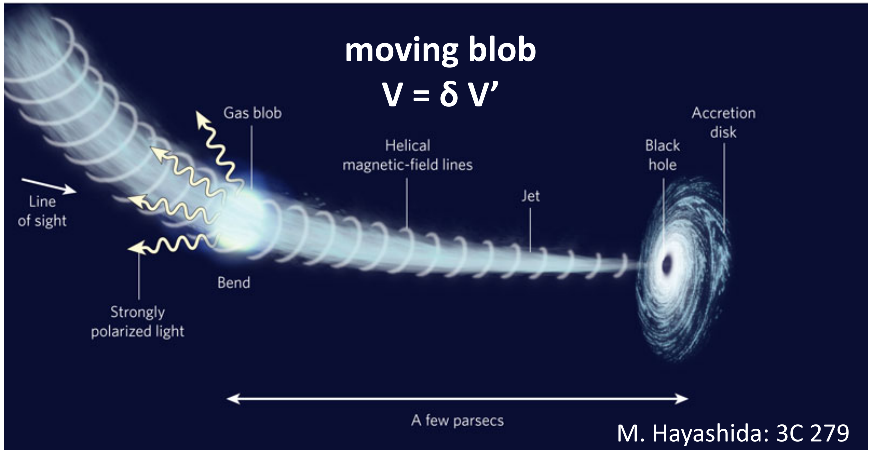
Doppler factor $$\delta \equiv \frac{1}{\Gamma\,(1 - \beta \cos\theta)} \tag{20}$$

Lorentz factor $$\Gamma \equiv \frac{1}{\sqrt{1 - \beta^2}} \tag{21}$$



$$\nu = \delta\,\nu' \tag{22}$$

$$\frac{I_\nu}{\nu^3} = \mathrm{inv} \quad \rightarrow \quad I_\nu = \delta^3\, I'_{\nu'} \tag{23}$$



$$j_\nu = \delta^2\, j'_{\nu'}$$
$$\alpha_\nu = \delta^{-1}\, \alpha'_{\nu'}$$
$$d\Omega = \delta^{-2}\, d\Omega'$$
$$\cos\theta = (\cos\theta' + \beta)/(1 + \beta\, \cos\theta')$$
$$dV = dV'/\Gamma \quad \text{or} \quad dV = \delta\, dV'$$

I. Transformations

$\delta \to \delta/(1+z)$
$I \equiv \int I_\nu \, d\nu$, etc.

$$I = \left(\frac{\delta}{1+z}\right)^4 I' \quad \text{and} \quad I' = \int j' \, ds' \tag{24}$$

$$d\Omega = dA \, d_\theta^{-2} = dA \, (1+z)^4 \, d_L^{-2} \tag{25}$$

$$dV' = dA' \, ds' = dA \, ds' \tag{26}$$

$$S = \int I \, d\Omega = \delta^4 \, d_L^{-2} \int I' \, dA = \delta^4 \, d_L^{-2} \int j' \, dV' \tag{27}$$

$$L' \equiv \oint \frac{\partial L'}{\partial \Omega'} \, d\Omega' \quad \text{with} \quad \frac{\partial L'}{\partial \Omega'} \equiv \frac{L'}{4\pi} \equiv \int j' \, dV' \tag{28}$$

$$L_{\rm iso} \equiv 4\pi \, d_L^2 \, S = \delta^4 \, L' \tag{29}$$

$$L_{\rm em} \equiv \oint \frac{L_{\rm iso}}{4\pi} \, d\Omega \simeq \Gamma^2 \, L' \tag{30}$$

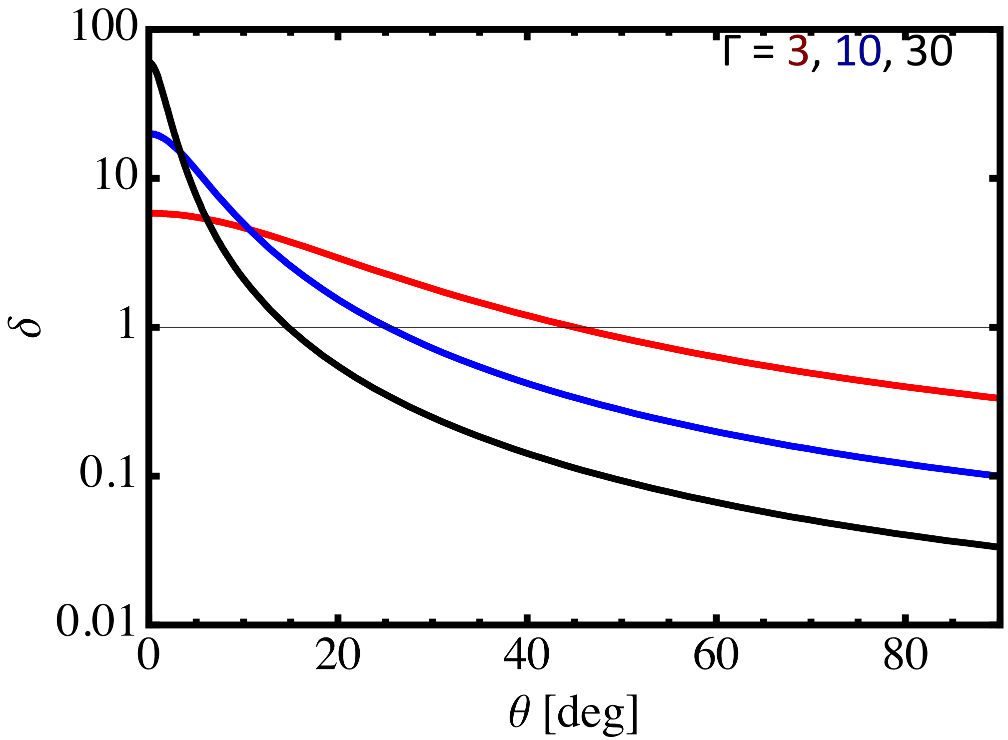
I. Summary

$\delta = 1 / \Gamma (1 - \beta \cos\theta)$

$\delta \approx \Gamma$ for $\theta \leq 1/\Gamma$

Assuming that the emission is isotropic in the source rest frame:

- Observed frequency $\nu = \delta \nu' / (1+z)$
- Intrinsic luminosity $L' = 4\pi j' V'$
- Observed energy flux $S = \delta^4 L' / 4\pi d_L^2$
- "Isotropic" luminosity $L_{iso} = \delta^4 L'$
- Total emitted power $L_{em} = \Gamma^2 L'$

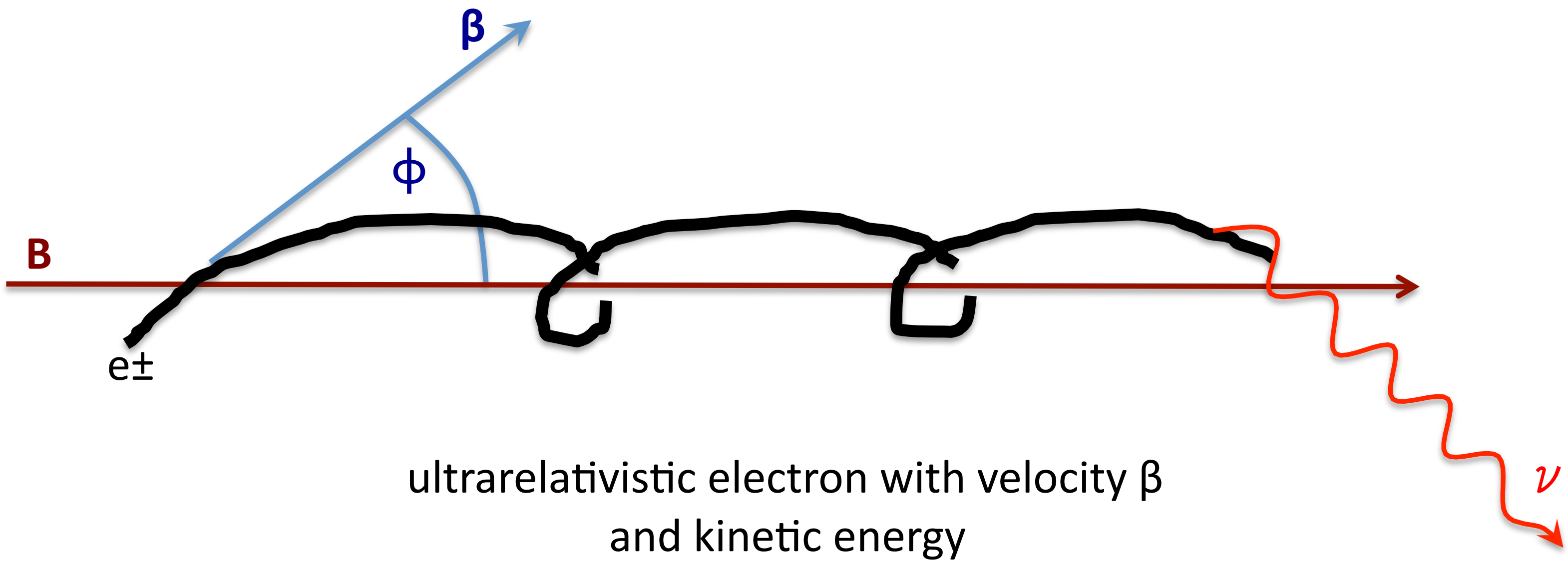


for $\delta = 1$ and $L'_{\nu'} \propto \nu'^{-\alpha}$

$$S_\nu = L_\nu / 4\pi d_L^2 = (1+z)\, L'_{\nu'}/4\pi d_L^2 = (1+z)^{1-\alpha}\, L'_\nu/4\pi d_L^2$$

$$[\nu S_\nu] = [\nu L_\nu]/4\pi d_L^2 = [\nu' L'_{\nu'}]/4\pi d_L^2 = (1+z)^{1-\alpha}[\nu L'_\nu]/4\pi d_L^2$$

II. Synchrotron Emission



ultrarelativistic electron with velocity β
and kinetic energy

$$E_e = \gamma\, m_e c^2 \quad >> \quad m_e c^2$$

gyrating along the magnetic field *B*
with pitch angle ϕ

II. Single Electron

gyrofrequency ω_B

$$\omega_{\rm B} = \frac{eB}{\gamma\, m_{\rm e} c} \tag{31}$$

radius of gyration projected on a plane normal to B and the Larmor radius r_L

$$r_{\rm B} = \frac{c}{\omega_{\rm B}}\, \sin\phi \equiv r_{\rm L}\, \sin\phi \tag{32}$$

total synchrotron power radiated by a single electron

$$P_{\rm syn}(\phi) = \frac{1}{4\pi}\, \sigma_{\rm T}\, c\, \gamma^2\, B^2\, \sin^2\phi \tag{33}$$

$$P_{\rm syn} \equiv \frac{1}{2}\int_0^{\pi} P_{\rm syn}(\phi)\, \sin\phi\, d\phi = \frac{1}{6\pi}\, \sigma_{\rm T}\, c\, \gamma^2\, B^2 \tag{34}$$

lifetime of the synchrotron-radiating electron (synchrotron cooling timescale)

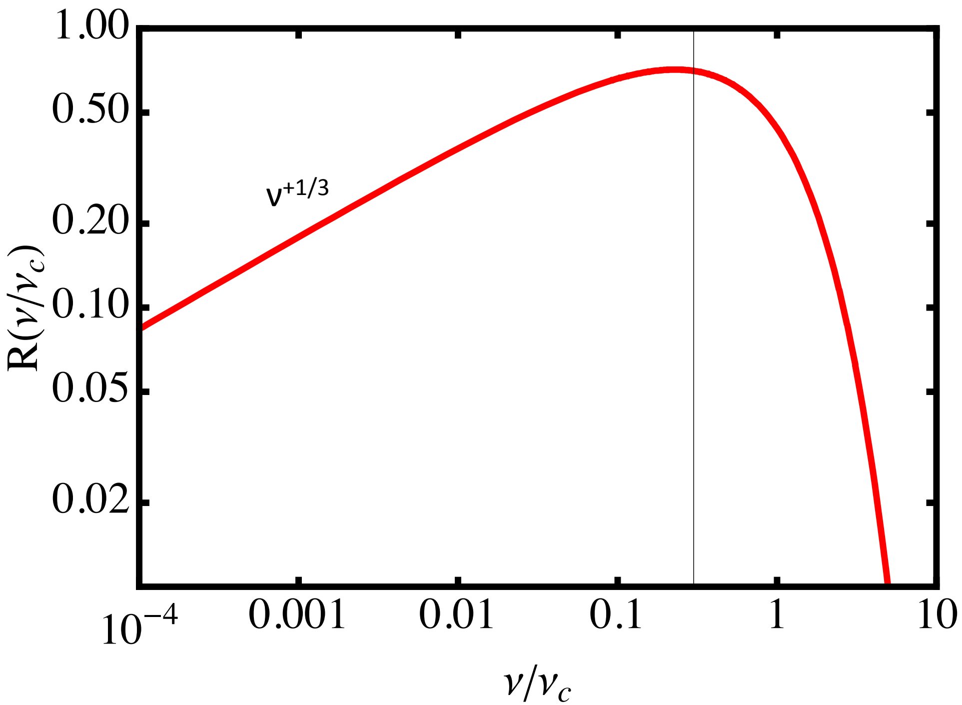
$$\tau_{\rm syn} \equiv \frac{\gamma\, m_{\rm e} c^2}{P_{\rm syn}} = \frac{6\pi\, m_{\rm e} c}{\sigma_{\rm T}\, \gamma\, B^2} \tag{35}$$

II. Spectral Distribution

$$P_{\rm syn}(\nu) = \frac{\sqrt{3}\, e^3 B}{m_{\rm e} c^2} \times \mathcal{R}\left(\frac{\nu}{\nu_{\rm c}}\right) \tag{36}$$

$$\nu_{\rm c} \equiv \frac{3\, eB}{4\pi\, m_{\rm e} c}\, \gamma^2 \tag{37}$$

$$\mathcal{R}(x) \equiv \frac{x^2}{2} K_{4/3}\left(\frac{x}{2}\right) K_{1/3}\left(\frac{x}{2}\right) - 0.3\, \frac{x^3}{2} \left[K^2_{4/3}\left(\frac{x}{2}\right) - K^2_{1/3}\left(\frac{x}{2}\right)\right] \tag{38}$$



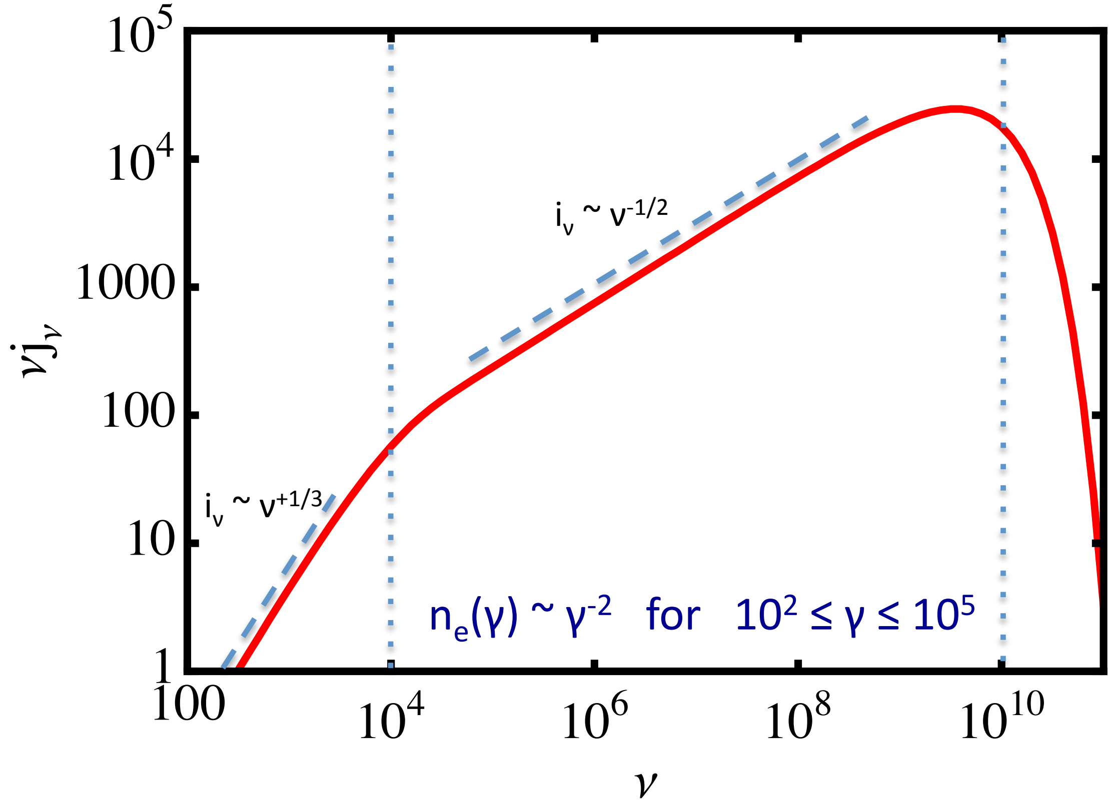
characteristic synchrotron frequency
$\nu_c \approx 4\ (B/\mu G)\ \gamma^2$ [Hz]

$R(\nu) \sim \nu^{+1/3}$ for $\nu < \nu_c$
but sometimes we approximate
$R(\nu) \sim \delta(\nu - \nu_c)$

II. Ensemble of Electrons

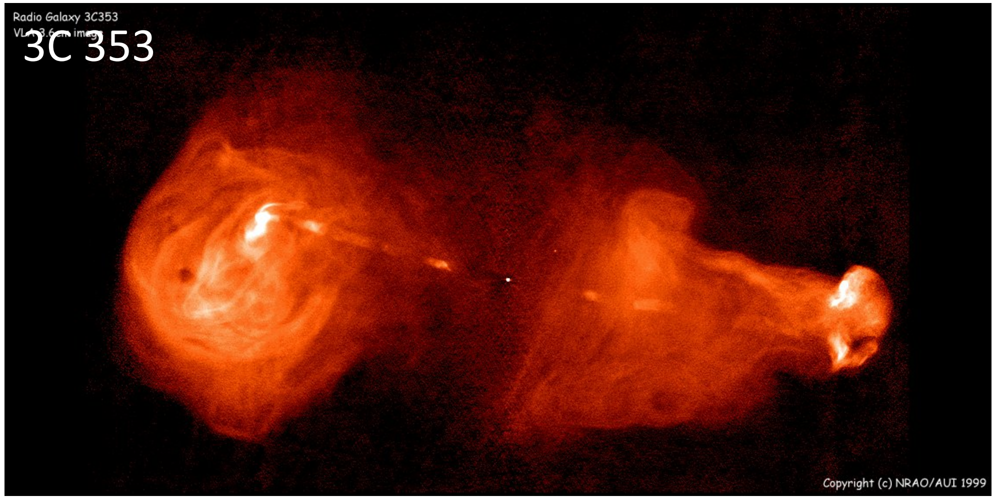
$$j_\nu = \frac{1}{4\pi}\int P_{\rm syn}(\nu)\, n_{\rm e}(\gamma)\, d\gamma \qquad (39)$$

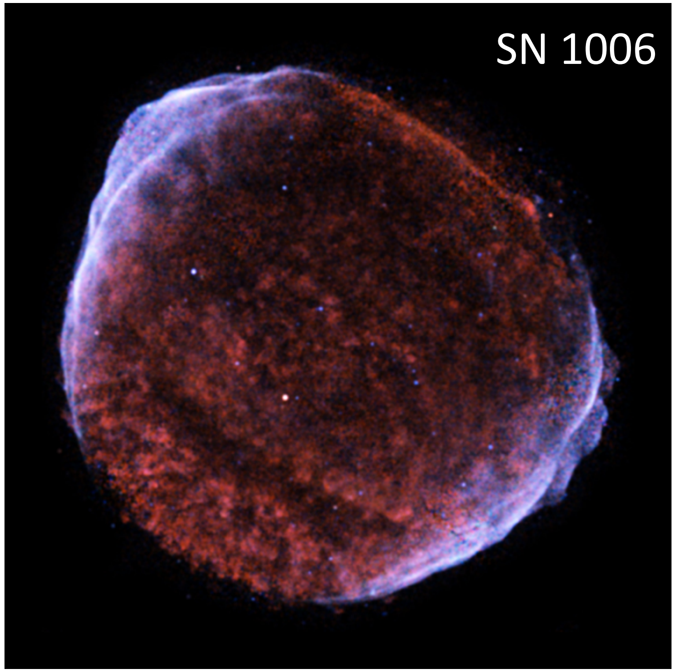
$$\begin{array}{llll} \text{if} & n_{\rm e}(\gamma) \propto \gamma^{-p} & \text{for} & \gamma_{\rm min} \le \gamma \le \gamma_{\rm max} \\ \text{then} & j_\nu \propto \nu^{-(p-1)/2} & \text{for} & \nu_{\rm c}\gamma^2_{\rm min} \ll \nu \ll \nu_{\rm c}\gamma^2_{\rm max} \end{array} \qquad (40)$$



II. Summary

- Synchrotron cooling timescale $\tau_{syn} \sim 1 / \gamma B^2$
- Emitted synchrotron power $P_{syn} \sim \gamma^2 B^2$
- Characteristic synchrotron frequency $\nu \approx 4 (B/\mu G) \gamma^2$ [Hz]
- Synchrotron spectral index ($S_\nu \sim \nu^{-\alpha}$) $\alpha = (p-1)/2 > -1/3$
- For a power-law electron energy distribution, synchrotron continuum is a power-law within only limited frequency range; electron breaks and cut-offs result in smoothly curved synchrotron spectra!



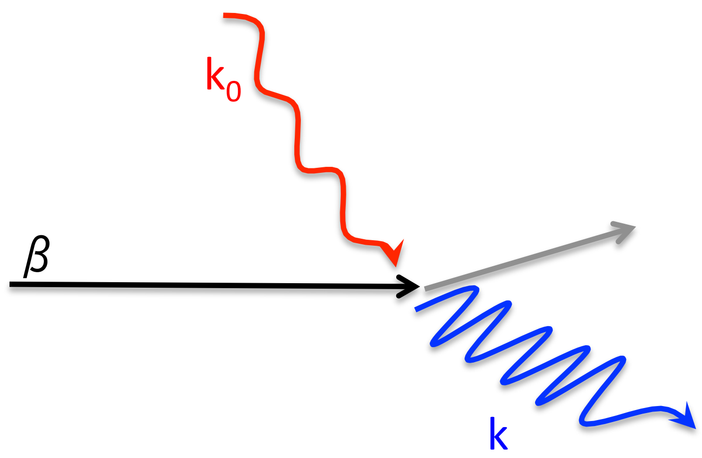


Radio synchrotron emission of AGN jets and lobes
X-ray synchrotron emission of SNRs

III. Inverse-Compton Emission

ultrarelativistic electron with velocity $\vec{\beta}$ and energy $E_e = \gamma m_e c^2 \gg m_e c^2$
incident (target) photon with wave vector $\vec{k}_0$ and energy $\varepsilon_0 \equiv \epsilon_0 \, m_e c^2$
scattered photon with wave vector $\vec{k}$ and energy $\varepsilon \equiv \epsilon \, m_e c^2$

$\psi_0 \equiv \cos^{-1} \eta_0$ — angle between $\vec{k}_0$ and $\vec{\beta}$
$\psi \equiv \cos^{-1} \eta$ — angle between $\vec{k}$ and $\vec{\beta}$
$\chi \equiv \cos^{-1} \kappa$ — angle between $\vec{k}_0$ and $\vec{k}$



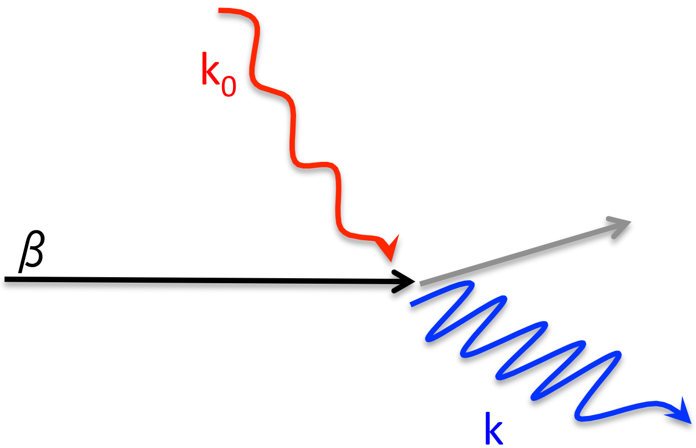
III. Kinematics

transformation to the ERF
$$\epsilon'_0 = \gamma\, \epsilon_0\, (1 - \beta\, \eta_0) \tag{41}$$

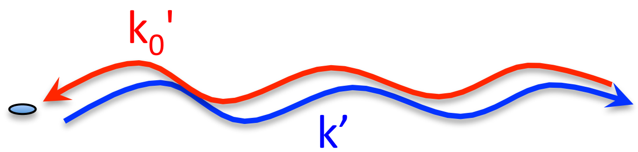
scattering (4-momentum conservation)
$$\epsilon' = \frac{\epsilon'_0}{1 + \epsilon'_0\, (1 - \kappa')} \tag{42}$$

transformation back to the PRF
$$\epsilon = \gamma\, \epsilon'\, (1 + \beta\, \eta') \tag{43}$$

for $\epsilon'_0 < 1$ one has $\epsilon' \approx \epsilon'_0$ (elastic scattering)
for $\beta \approx 1$ one has $\eta'_0 \approx -1$, $\eta' = -\kappa'$ and $\eta \approx 1$ ('head-on approximation')



PRF



ERF

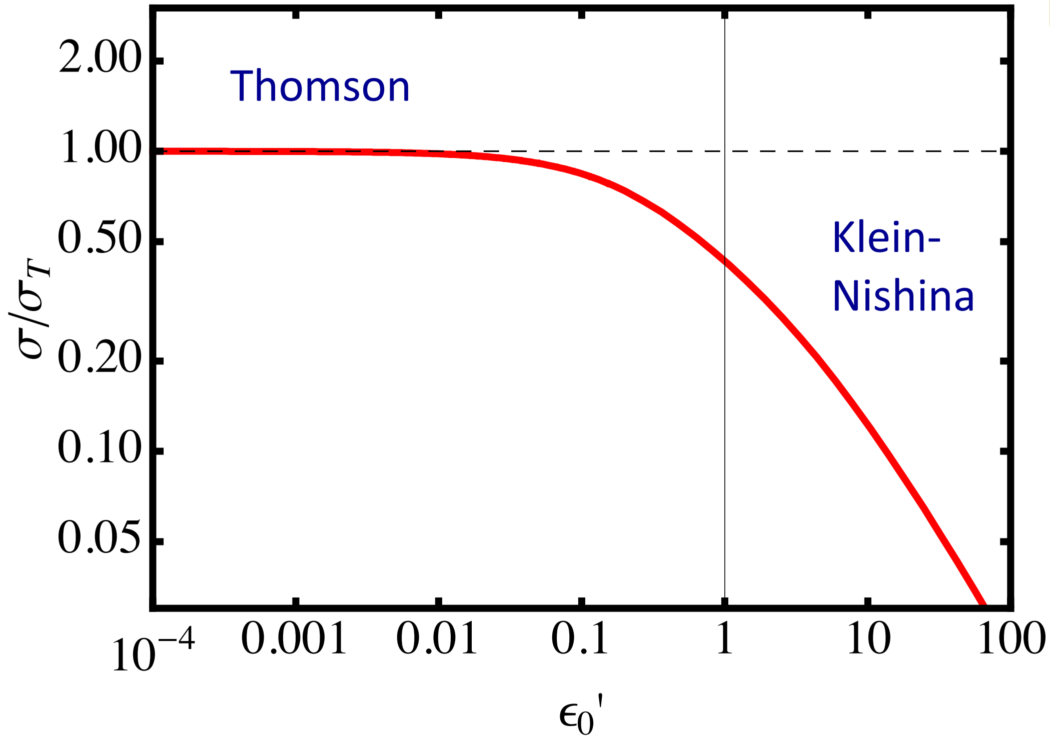
III. Thomson and KN Regimes

$$\frac{d^2\sigma}{d\Omega'\,d\epsilon'} = \frac{3\sigma_{\rm T}}{16\pi}\left(\frac{\epsilon'}{\epsilon'_0}\right)^2\left(\frac{\epsilon'_0}{\epsilon'}+\frac{\epsilon'}{\epsilon'_0}-(1-\kappa'^2)\right)\times\delta\left[\epsilon'-\frac{\epsilon'_0}{1+\epsilon'_0\,(1-\kappa')}\right] \quad (44)$$

$$\sigma \equiv \oint d\Omega' \int d\epsilon' \, \frac{d^2\sigma}{d\Omega'\,d\epsilon'} =$$

$$= \frac{3\sigma_{\rm T}}{8\epsilon'_0}\left[\left(1-\frac{2}{\epsilon'_0}-\frac{2}{\epsilon'^2_0}\right)\ln(1+2\epsilon'_0)+\frac{1}{2}+\frac{4}{\epsilon'_0}-\frac{1}{2\,(1+2\epsilon'_0)^2}\right] \approx$$

$$\approx \begin{cases} \sigma_{\rm T} & \text{for} \quad \epsilon'_0 \ll 1 \\ \frac{3\sigma_{\rm T}}{8\epsilon'_0}\ln(2\,e^{1/2}\,\epsilon'_0) & \text{for} \quad \epsilon'_0 \gg 1 \end{cases} \quad (45)$$



Klein-Nishina suppression is often modeled as a sharp cut-off

III. Isotropic Electron Distribution

$$P_{\rm ic}(\nu) = c\,h\,\epsilon \int d\epsilon_0 \oint d\Omega_0 \oint d\Omega_{\rm e}\,(1-\beta\,\eta_0)\,n(\epsilon_0,\Omega_0)\,\frac{d^2\sigma}{d\Omega\,d\epsilon} \tag{46}$$

$$\tau_{\rm ic} \equiv \frac{\gamma\,m_{\rm e}c^2}{\int d\nu\,P_{\rm ic}(\nu)} \tag{47}$$

$$j_\nu = \frac{1}{4\pi}\int P_{\rm ic}(\nu)\,n_{\rm e}(\gamma)\,d\gamma \tag{48}$$

for $n(\epsilon_0,\Omega_0) = n(\epsilon_0)/4\pi$

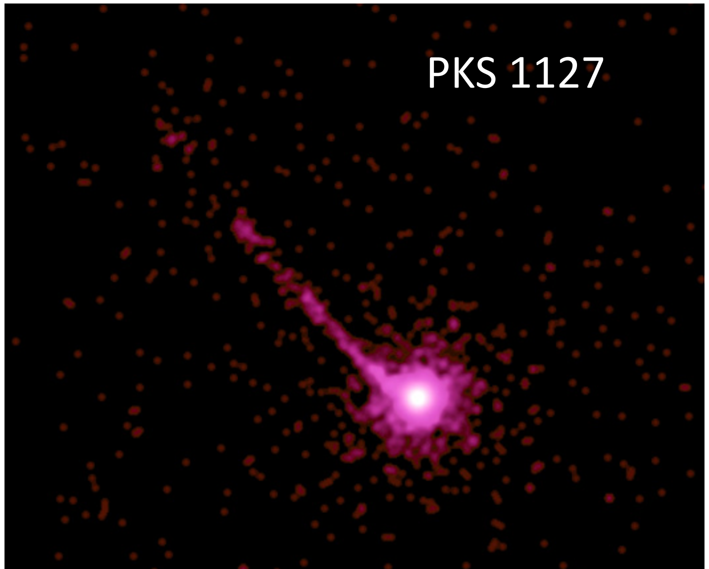
$$j_\nu = \frac{3\,c\,h^2\,\sigma_{\rm T}\,\nu}{16\pi\,m_{\rm e}c^2}\int d\epsilon_0 \int d\gamma\,n(\epsilon_0)\,n_{\rm e}(\gamma)\,\frac{f(\epsilon,\epsilon_0,\gamma)}{\gamma^2\,\epsilon_0} \tag{49}$$

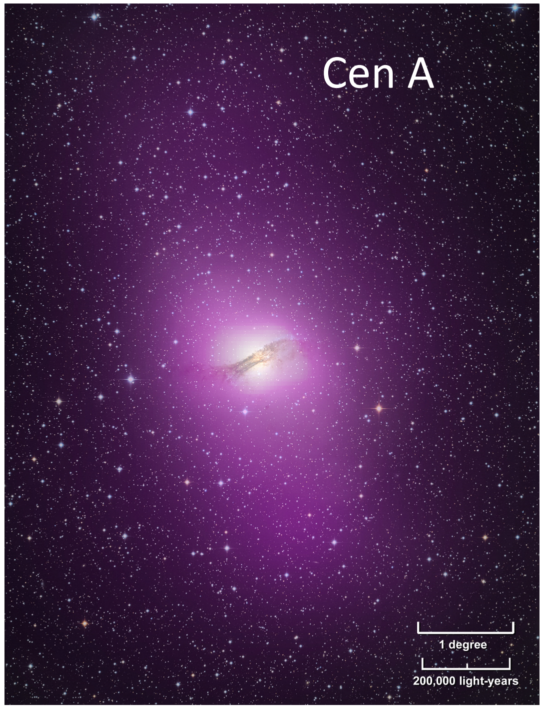
$$f(\epsilon,\epsilon_0,\gamma) = 2q\,\ln q + q + 1 - 2q^2 + \frac{(Q\,q)^2\,(1-q)}{2\,(1+Qq)} \tag{50}$$

where $Q \equiv 4\epsilon_0\gamma$, $q \equiv \epsilon/4\epsilon_0\gamma\,(\gamma-\epsilon)$ and $1/4\gamma^2 \leq q \leq 1$

III. Summary

- IC/TR cooling timescale $\tau_{ic} \sim 1 / \gamma U_0$
- Emitted IC/TR power $P_{ic} \sim \gamma^2 U_0$
- Characteristic IC/TR energy $\varepsilon \approx \varepsilon_0 \gamma^2$
- IC/TR spectral index ($S_\nu \sim \nu^{-\alpha}$) $\alpha = (p-1)/2 > -1$
- For a power-law electron energy distribution, IC continuum is a power-law within only limited frequency range; electron breaks and cut-offs, as well as KN effects, result in smoothly curved IC spectra!



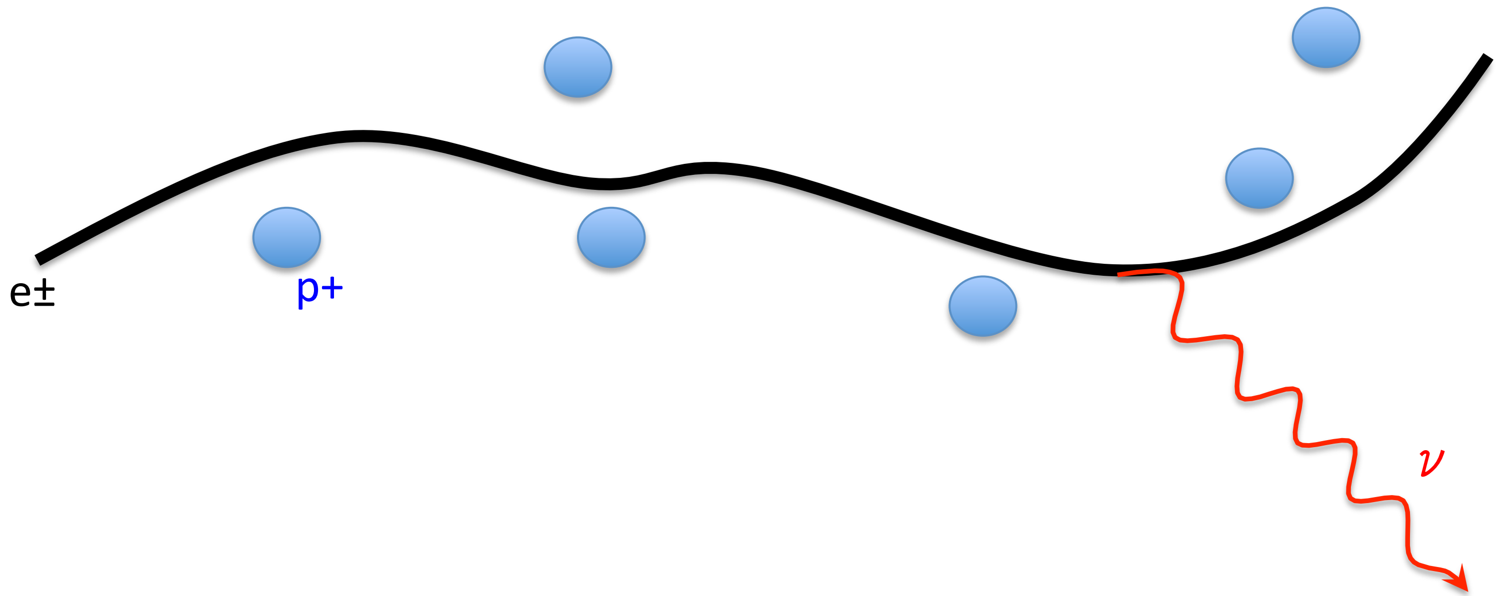


X-ray IC emission of AGN jets
γ-ray IC emission of AGN lobes

IV. Thermal Bremsstrahlung

Electron-ion bremsstrahlung ("free-free emission"):
radiation of the thermal electrons accelerated in the Coulomb field of thermal ions

$$n_{\rm th}(v)\,dv = 4\pi\,n_{\rm g}\,v^2\,\left(\frac{m_{\rm e}}{2\pi\,kT}\right)^{3/2}\,e^{m_{\rm e}v^2/2kT}\,dv \qquad (51)$$

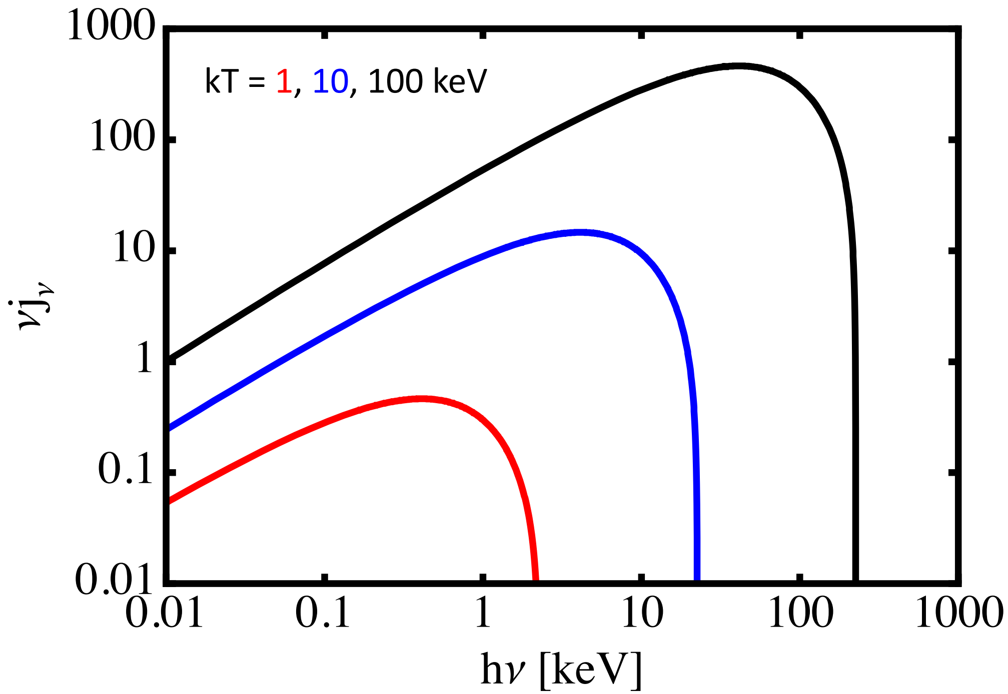


IV. Free-Free Emissivity

$$P_{\rm ff}(\nu) = \frac{32\, e^6}{\sqrt{3} m_{\rm e} c^3} \left(\frac{2\pi}{3k m_{\rm e}}\right)^{1/2} n_{\rm g}^2\, T^{-1/2}\, e^{-h\nu/kT} \, \ln\left[2.25\, \frac{kT}{h\nu}\right] \qquad (52)$$

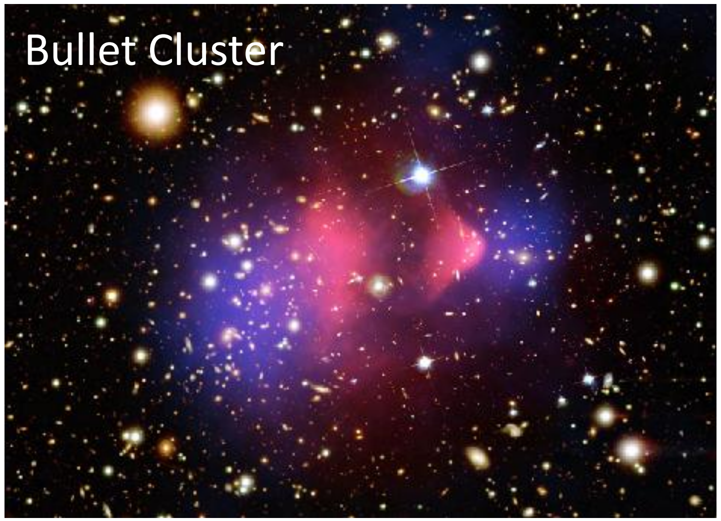
$$j_\nu = \frac{1}{4\pi} P_{\rm ff}(\nu) \qquad (53)$$

Detection of the thermal bremsstrahlung emission enables to diagnose thermal plasma (density and temperature) in astrophysical sources of high-energy radiation.

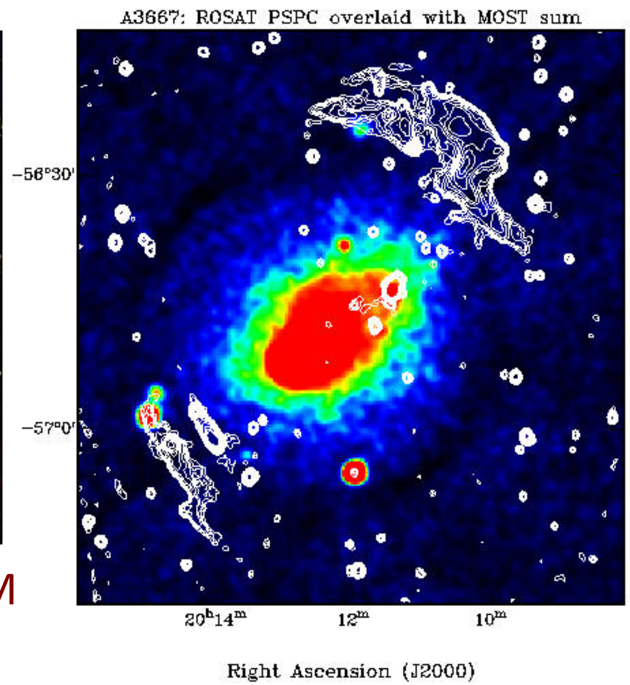


IV. Summary

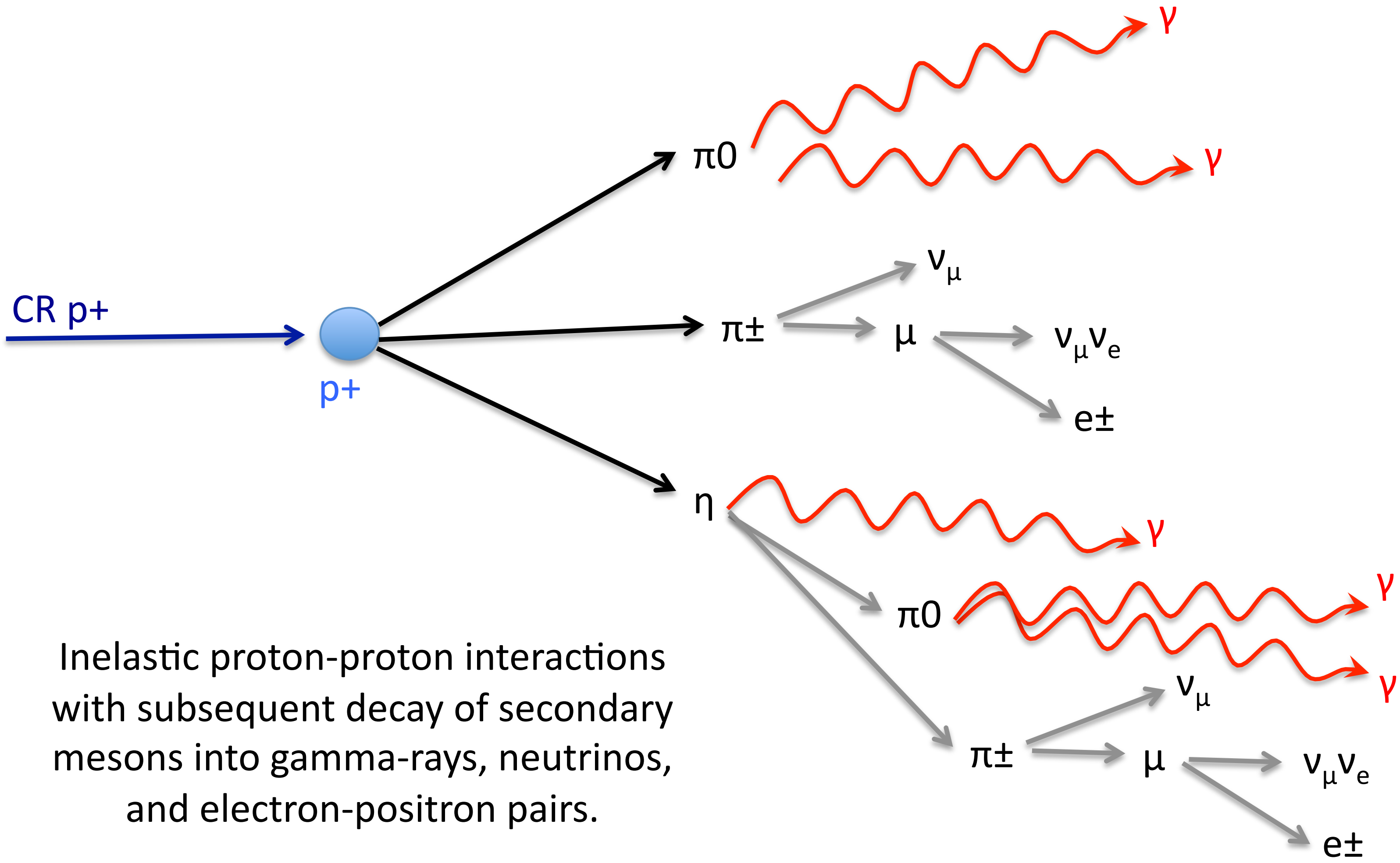
- Bremsstrahlung cooling timescale $\tau_{ic} \sim 1 / n_g$
- Emitted bremsstrahlung power $P_{ic} \sim T^{1/2} n_g^2$
- Critical (maximum) photon energy $\varepsilon_{cr} \approx kT$
- Bremsstrahlung spectral index ($S_\nu \sim \nu^{-\alpha}$) $\alpha \approx 0$
- Thermal and non-thermal bremsstrahlung may compete with the IC process within the MeV/GeV photon energy range in the case of the systems characterized by high density of thermal gas (starbursts, SNRs)



X-ray bremsstrahlung emission of ICM



V. Proton-Proton Interactions

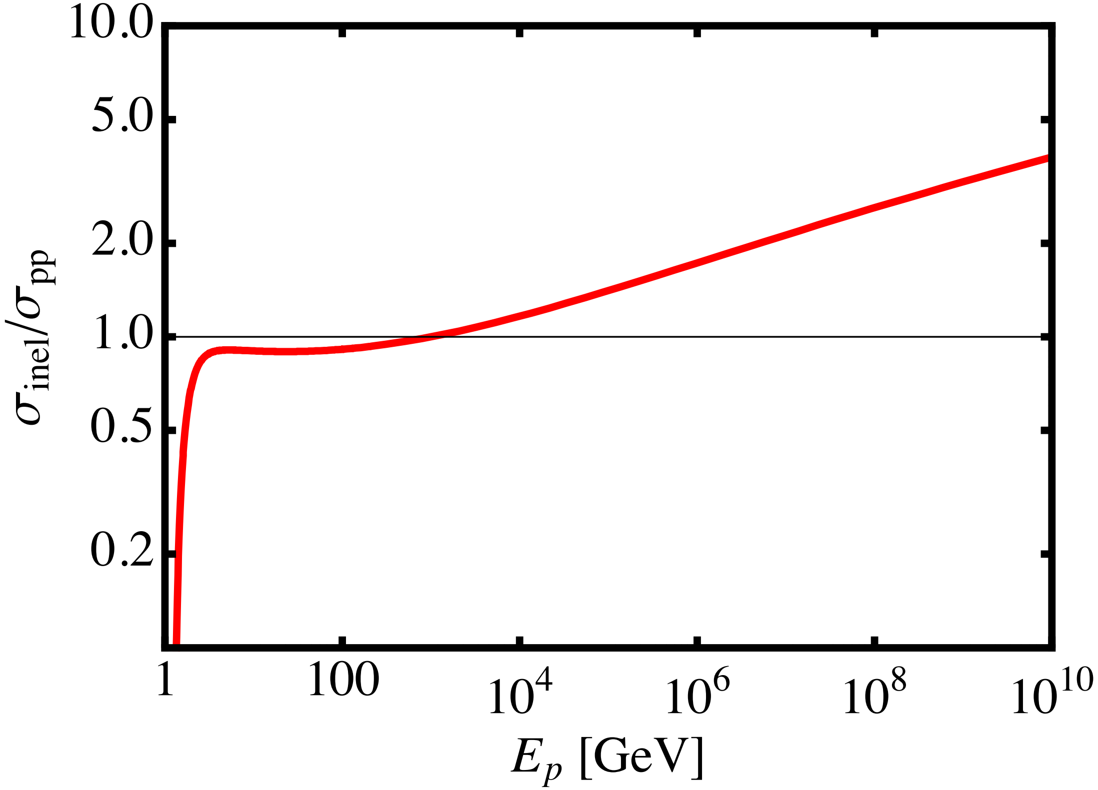


Inelastic proton-proton interactions with subsequent decay of secondary mesons into gamma-rays, neutrinos, and electron-positron pairs.

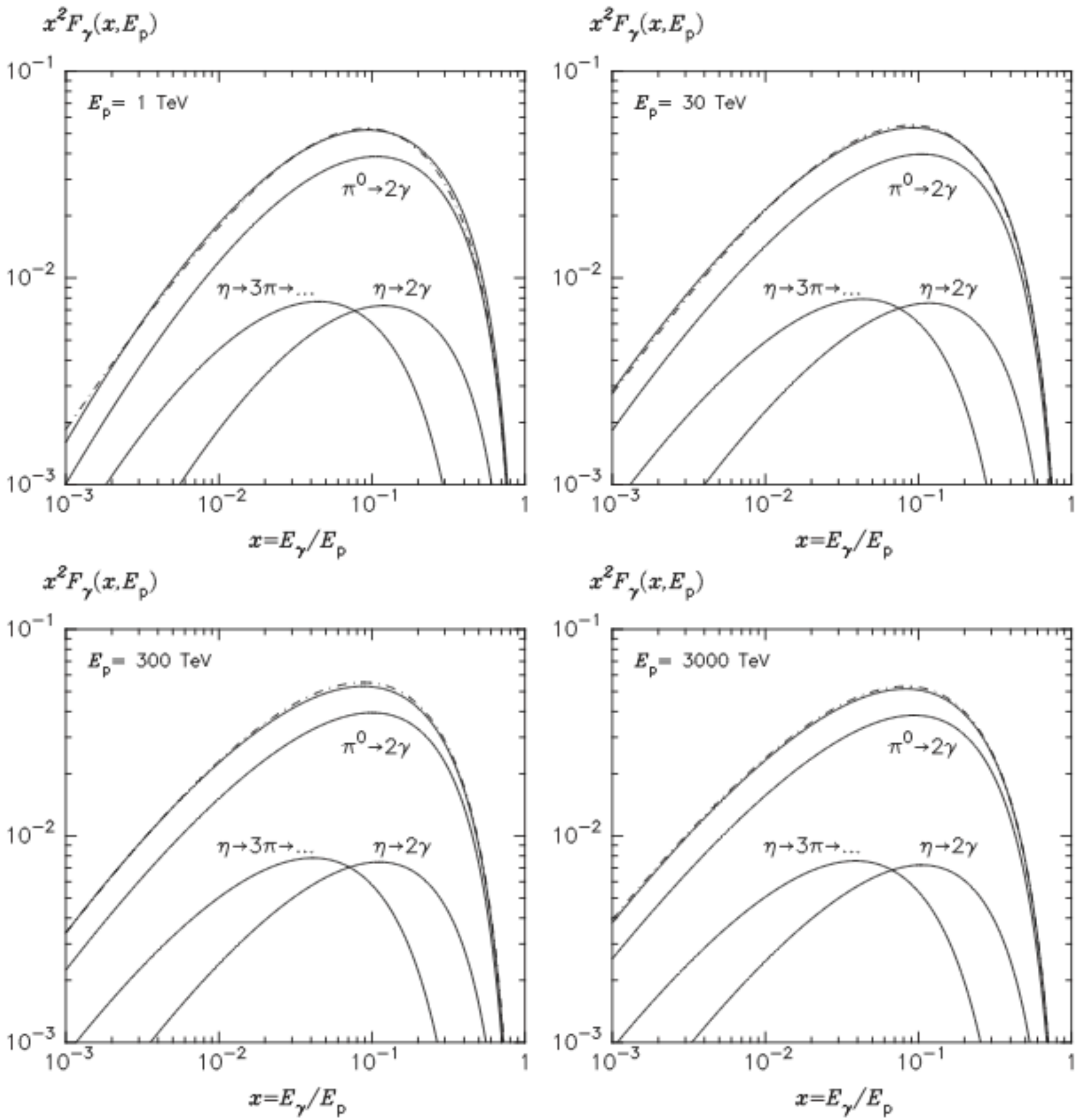
V. Inelastic Cross Section

$$\frac{\sigma_{\rm inel}(E_p)}{\sigma_{pp}} \simeq \left[1 + 0.055\,\ln\left(\frac{E_p}{\rm TeV}\right) + 0.007\,\ln^2\left(\frac{E_p}{\rm TeV}\right)\right] \times \left[1 - \left(\frac{E_{\rm th}}{E_p}\right)^4\right]^2 \tag{54}$$

$$\sigma_{pp} = 34.3\,{\rm mb} \quad \text{and} \quad E_{\rm th} = m_p c^2 + 2m_\pi c^2 + m_\pi^2 c^2/2m_p \simeq 1.22\,{\rm GeV} \tag{55}$$



V. Gamma-Ray Production

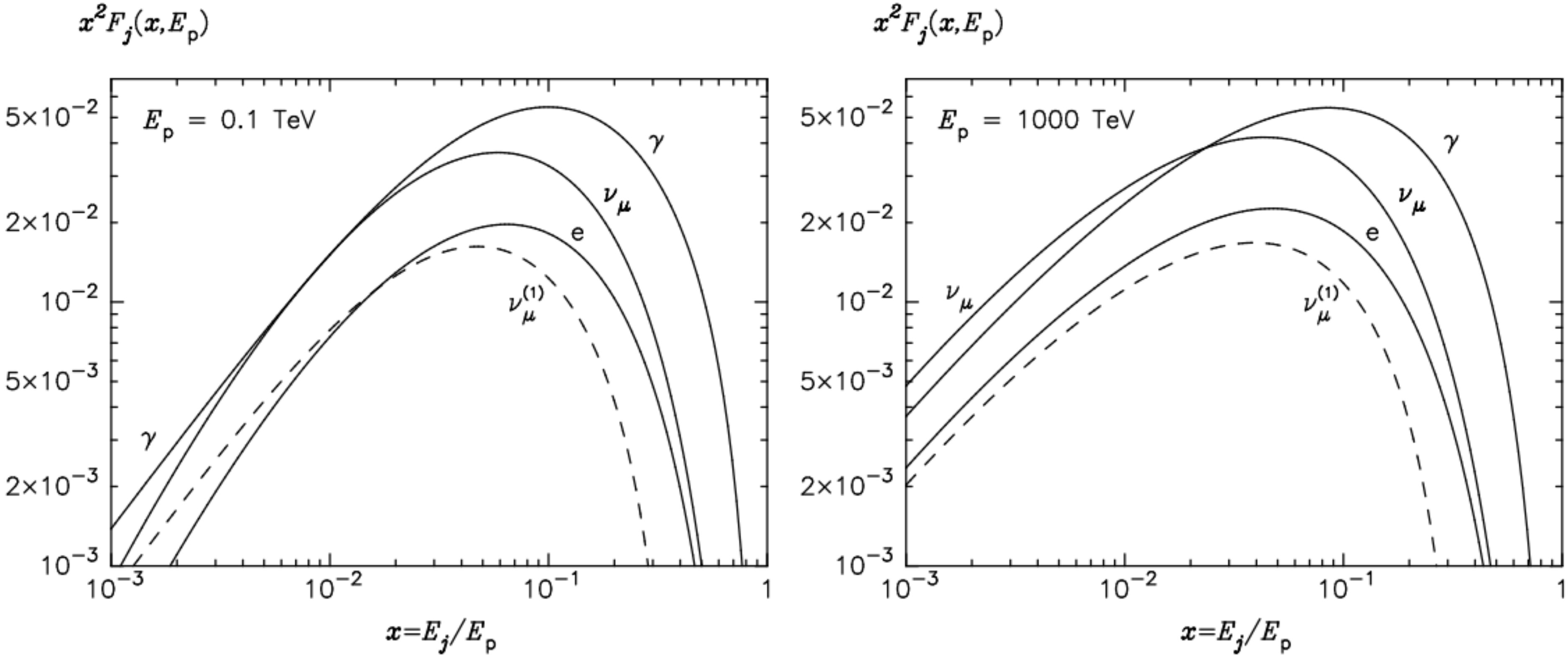


~6 gamma-rays with energies

$\varepsilon_\gamma \approx 0.1\ E_p$

per *pp* collision are produced (plots from Kelner et al. 2006)

V. Secondary Particles



(from Kelner et al. 2006)

V. Broad-Band Spectra

"delta-approximation"

$$\dot{n}_\gamma(\varepsilon_\gamma) = 2\int_{E_{\rm min}} \frac{q_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2 c^4}}\, dE_\pi \tag{56}$$

$$q_\pi(E_\pi) \simeq 5.9\, c\, n_{\rm g} \times J_p\left(m_p c^2 + 5.9\, E_\pi\right) \times \sigma_{\rm inel}\left(m_p c^2 + 5.9 E_\pi\right) \tag{57}$$

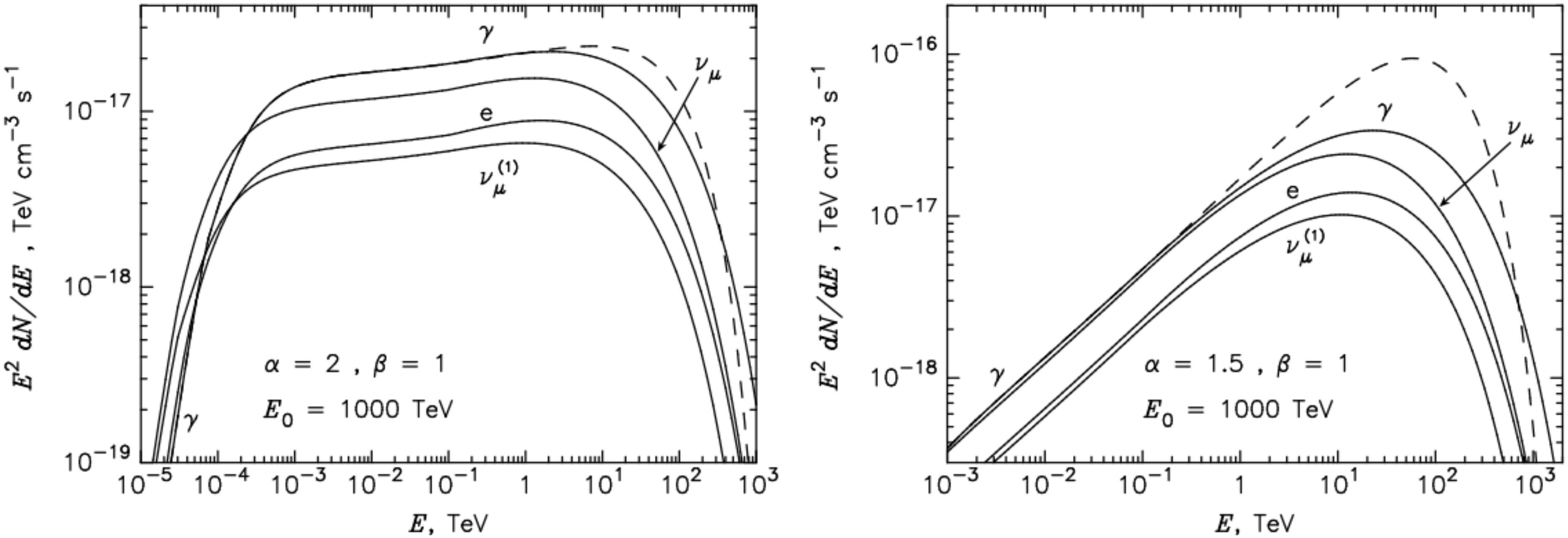
$$E_{\rm min} = \varepsilon_\gamma + \frac{m_\pi^2 c^4}{4\varepsilon_\gamma} \quad \text{and} \quad m_\pi c^2 = 135\,{\rm MeV} \tag{58}$$

$$j_\varepsilon = \frac{\varepsilon_\gamma}{4\pi}\, \dot{n}_\gamma(\varepsilon_\gamma) \tag{59}$$

Energy spectra of secondary particles closely follow energy spectrum of CR protons

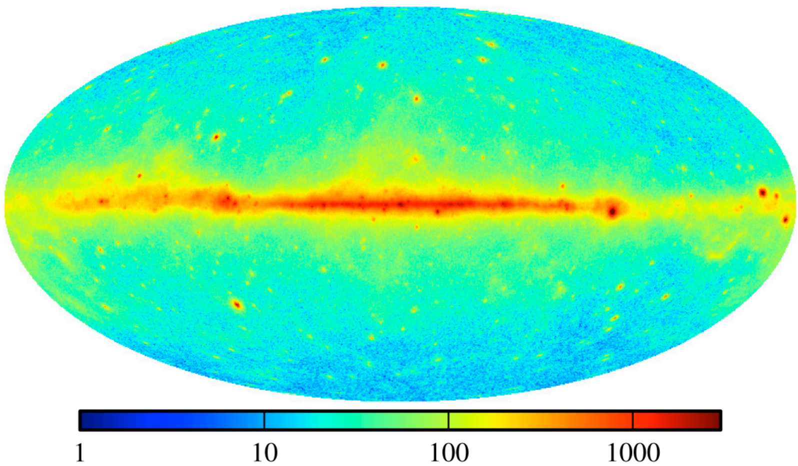
$J_p(E_p) \sim E_p^{-\alpha} \exp[-(E_p/E_0)^\beta]$

(from Kelner et al. 2006)



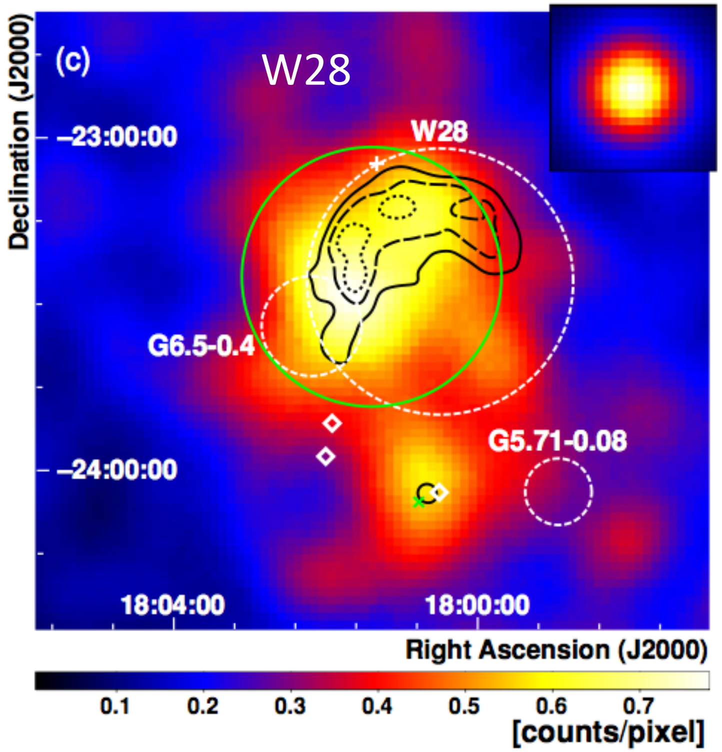
V. Summary

- PP interaction timescale $\tau_{pp} \sim 1 / n_g$
- Energies of produced γ-rays $\varepsilon_\gamma \approx 0.1\ E_p$
- γ-ray photon index ($dN_\gamma/d\varepsilon_\gamma \sim \varepsilon^{-\Gamma}$) $\Gamma_\gamma = \alpha_\gamma + 1 \approx \alpha_p$
- Low-energy cutoff in γ-ray spectra around 130 MeV expected!
- Production of γ-rays always accompanied by the production of neutrinos and secondary e± pairs.



Diffuse GeV emission of the Galaxy

GeV emission of middle-age SNRs



VI. Photo-Meson Production

$$\tau_{pp} \simeq [c \times \sigma_{pp} \times n_g]^{-1} \tag{60}$$

$$\sigma_{pp} = 34.3\,\mathrm{mb} \tag{61}$$

$$\tau_{p\gamma} \simeq [c \times \langle \sigma_{p\gamma} K_{p\gamma} \rangle \times n_0^\star]^{-1} \tag{62}$$

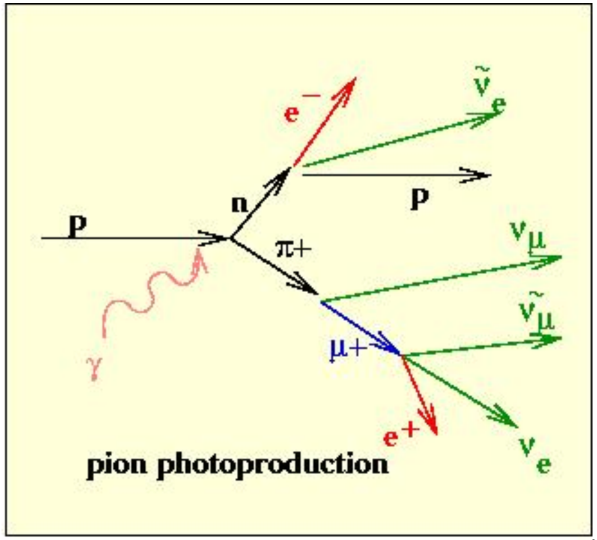
$$\langle \sigma_{p\gamma} K_{p\gamma} \rangle \simeq 0.07\,\mathrm{mb} \tag{63}$$

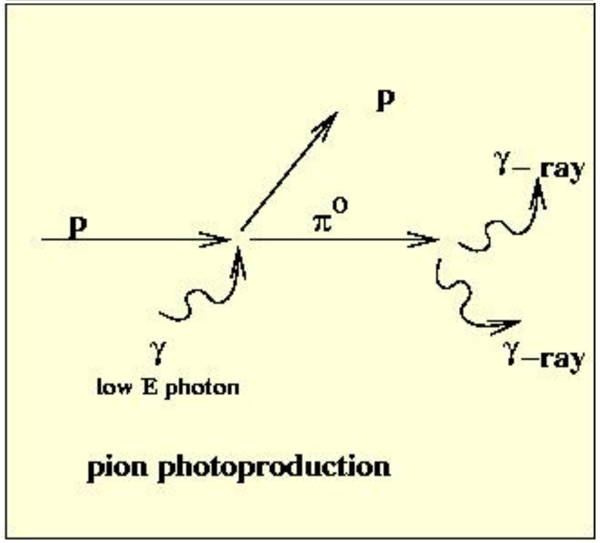
$$n_0^\star = \int_{\varepsilon_{th}} d\varepsilon_0\, n_0(\varepsilon_0) \tag{64}$$

$$\varepsilon_{th}(E_p) = \frac{m_\pi c^2}{E_p / m_p c^2} \tag{65}$$

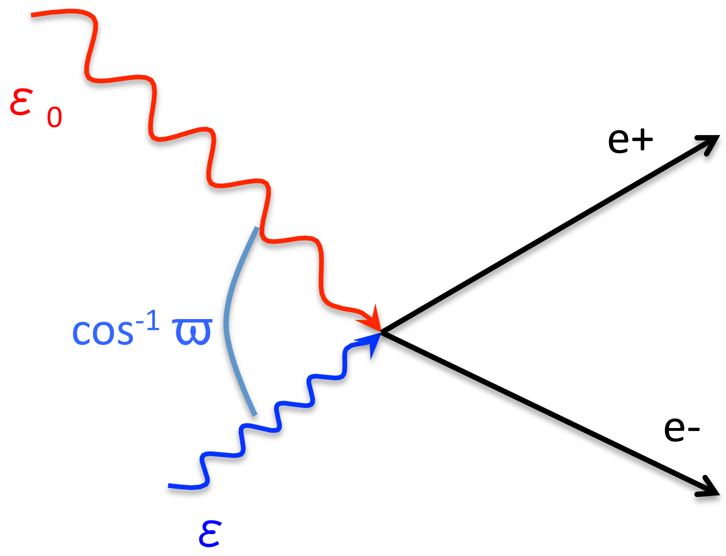
number density of target photons

product of photo-meson cross section and inelasticy parameter averaged over the resonant energy range





VII. Photon-Photon Annihilation



$$\varepsilon \times \varepsilon_0 > (m_e c^2)^2$$

VII. Energy “Resonance”

$$\sigma_{\gamma\gamma} = \frac{3\sigma_T}{16}(1-b^2)\left[(3-b^4)\ln\left(\frac{1+b}{1-b}\right) - 2b(2-b^2)\right] \quad (66)$$

$$b \equiv \left(1 - \frac{2}{\epsilon\,\epsilon_0\,(1-\varpi)}\right)^{1/2} \quad (67)$$

velocity of the created e± in the center-of-momentum frame

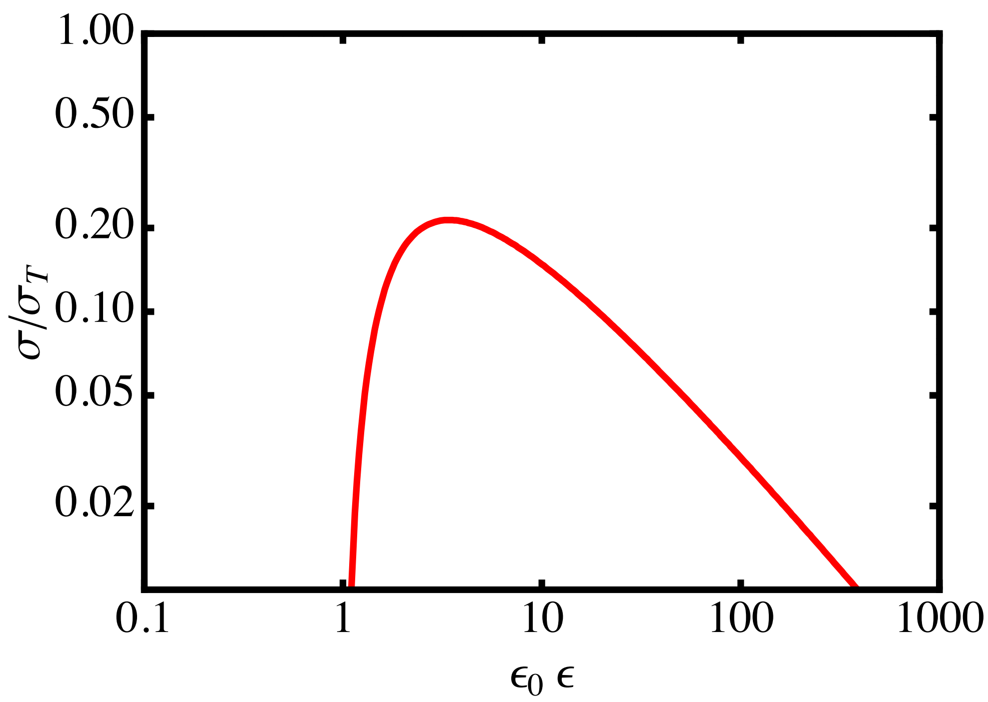
$$\langle\sigma_{\gamma\gamma}\rangle \equiv \frac{1}{2}\int_{-1}^{1-(2/\epsilon\epsilon_0)} d\varpi\,(1-\varpi)\,\sigma_{\rm pp} \approx \quad (68)$$

$$\approx 0.65\,\sigma_T\,\frac{(\epsilon\epsilon_0)^2-1}{(\epsilon\epsilon_0)^3}\ln(\epsilon\epsilon_0)\,H[\epsilon\epsilon_0-1] \sim \frac{2}{3}\sigma_T\,\delta(\epsilon\epsilon_0-2)$$

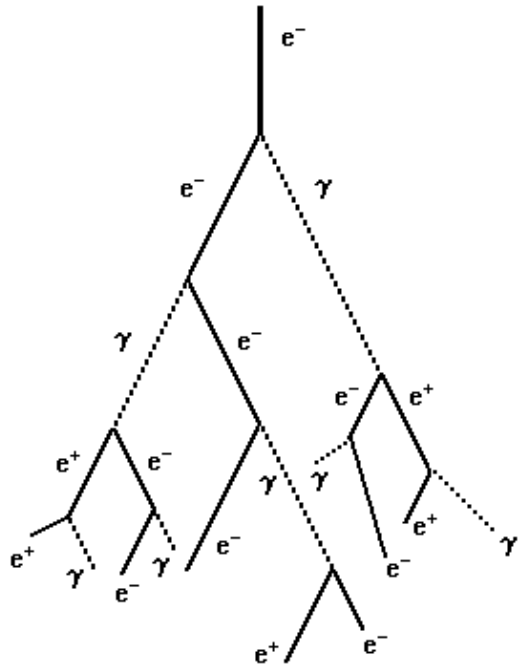
Optical depth:

$$\tau_{\gamma\gamma} = \int_0^L d\ell \int_{1/\epsilon_0}^{\infty} d\epsilon_0\, n_0(\epsilon_0)\,\langle\sigma_{\gamma\gamma}\rangle \quad (69)$$

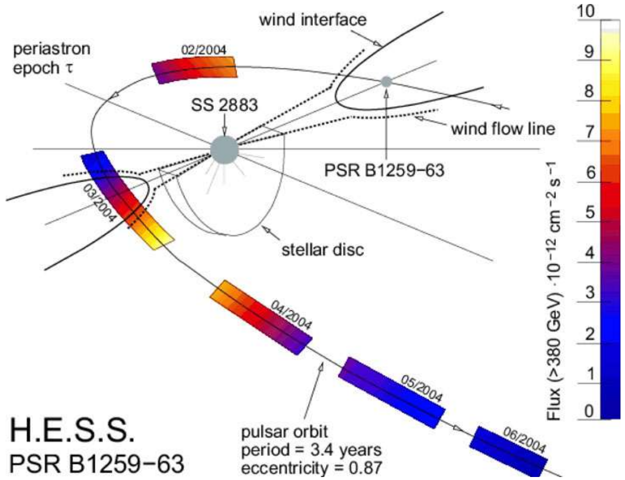
$$\rightarrow \quad \tau_{\gamma\gamma\,(\epsilon=2/\epsilon_0)} \sim \frac{1}{3}\sigma_T\,L\,n_0 \quad (70)$$



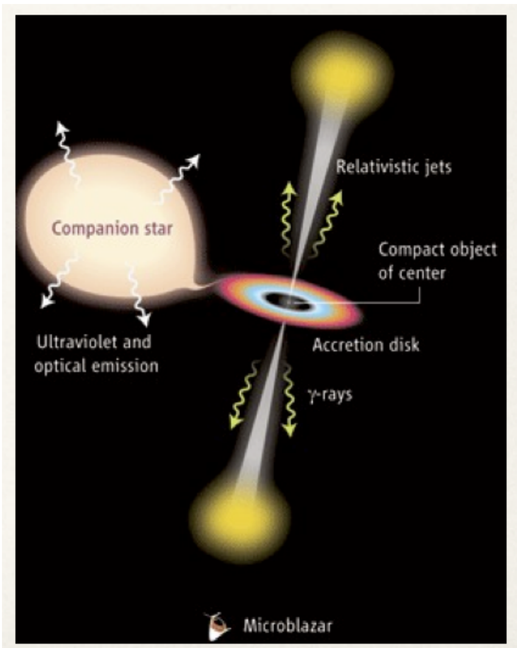
VII. Summary



- Energy "resonance" $\varepsilon_0\, \varepsilon \sim 2\, (m_e\, c^2)^2$, so that the 0.1 GeV – 10 TeV γ-rays are absorbed most efficiently by X-ray – infrared photons
- Generation of secondary ultrarelativistic pairs $E_{e\pm} \approx \varepsilon/2 \;>>\; m_e\, c^2$
- The absorbed power is not lost, but reprocessed to lower-frequencies (via synchrotron and IC cooling of secondary pairs).
- Development of linear and isotropic cascades.
- Absorption may lead to formation of breaks and cut-offs in γ-ray spectra of astrophysical sources.



GeV/TeV emission of Gamma-ray Binaries



Credit: Mirabel Science, 2012, 335, 175