Collision of ultra-relativistic proton with strong magnetic field

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Ref: Yuan & Shi, 2019, Phys. Letts. B, 795, 452

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I.

Method of virtual quanta

Weizsacker-Williams method of virtual quanta

Bremsstrahlung

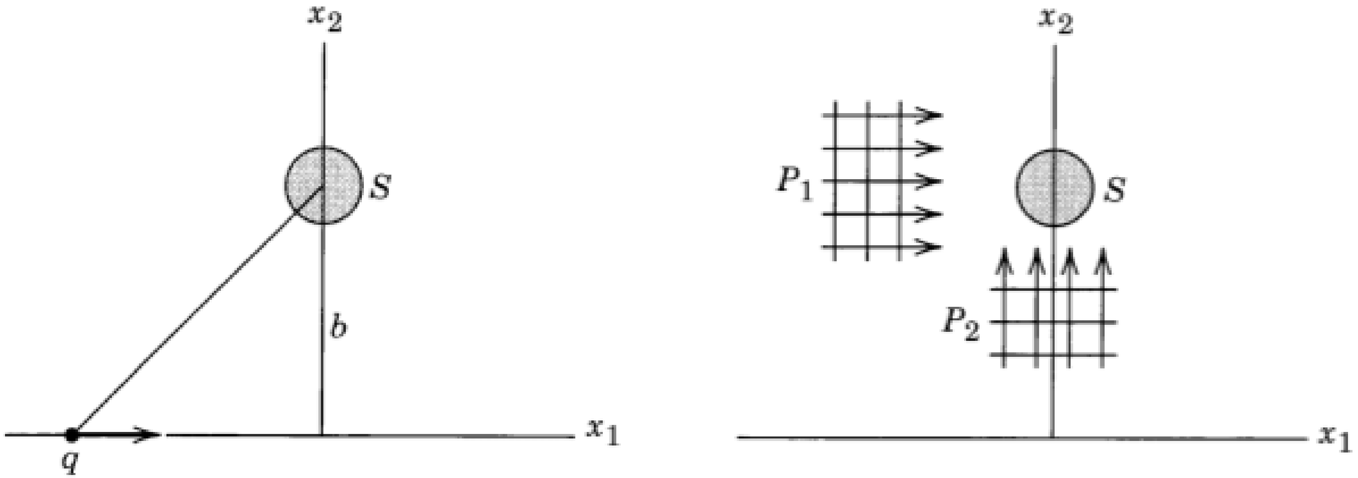
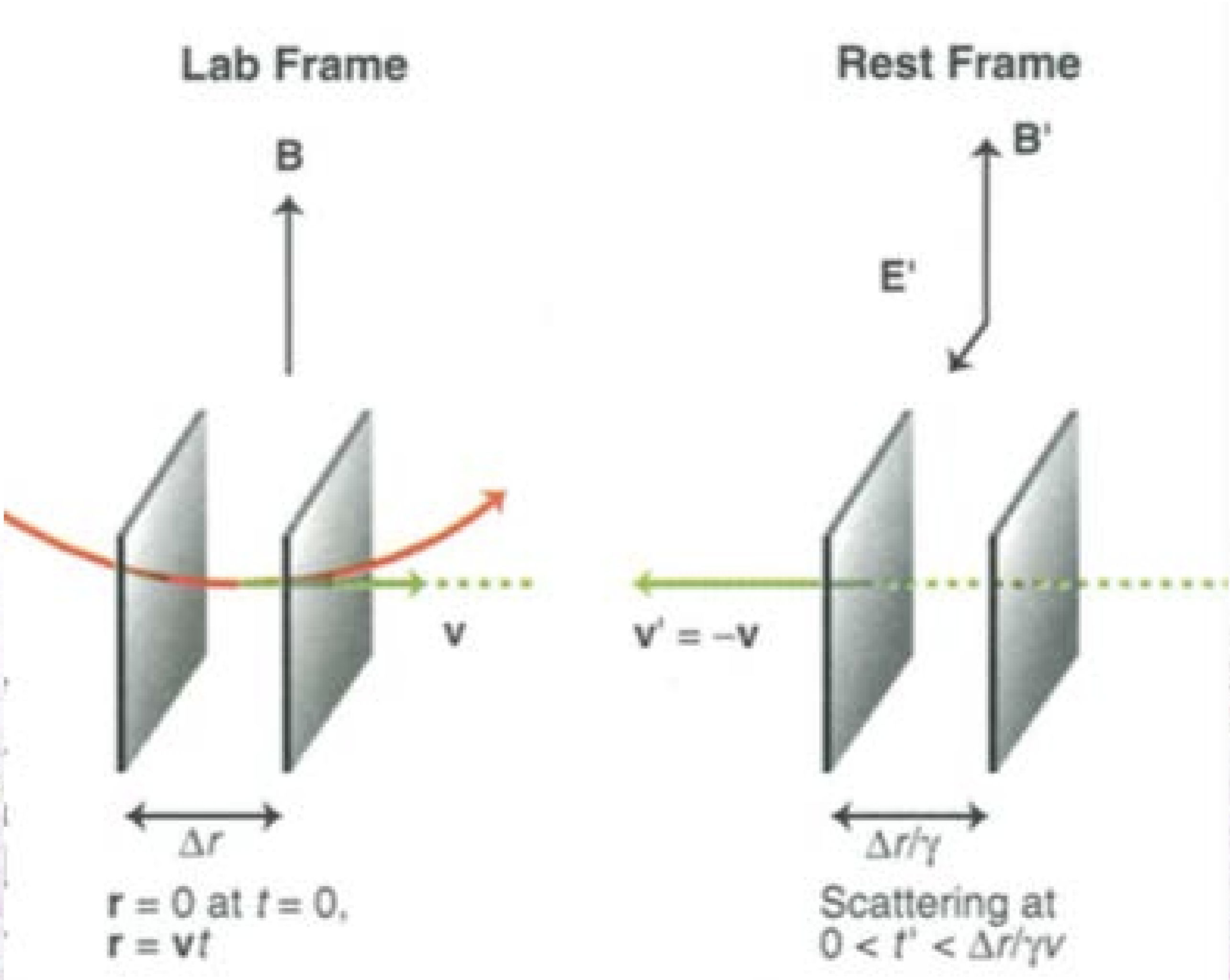


Figure 15.6 Relativistic charged particle passing the struck system S and the equivalent pulses of radiation.

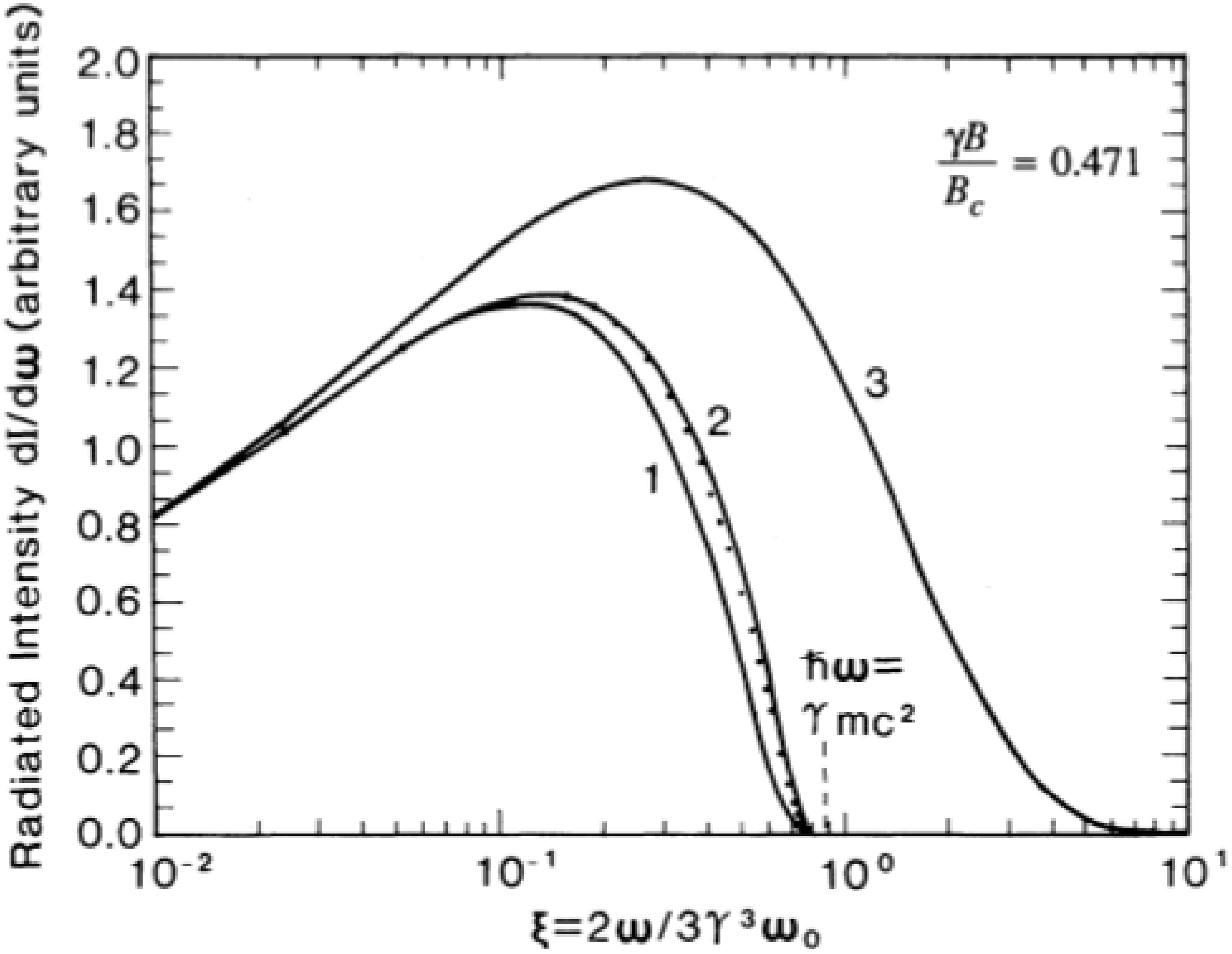
Jackson, J.D. 1976

Unification of Synchrotron Radiation and Inverse Compton Scattering



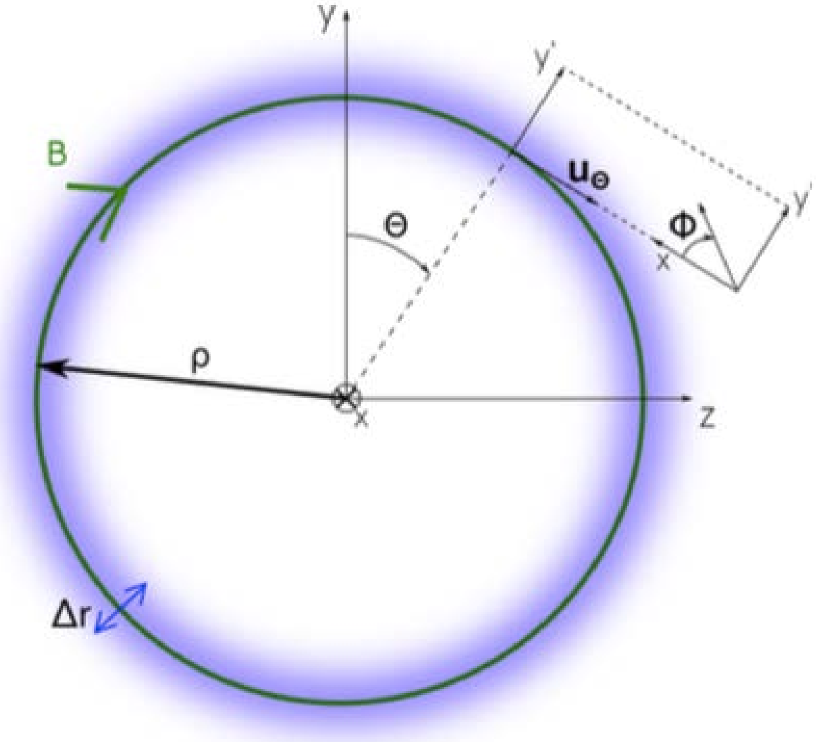
Lewin, Barber, & Chen 1995, Science

Synchrotron Radiation: an Inverse Compton Effect



Lieu & Axford 1993

Synchro-Curvature radidation

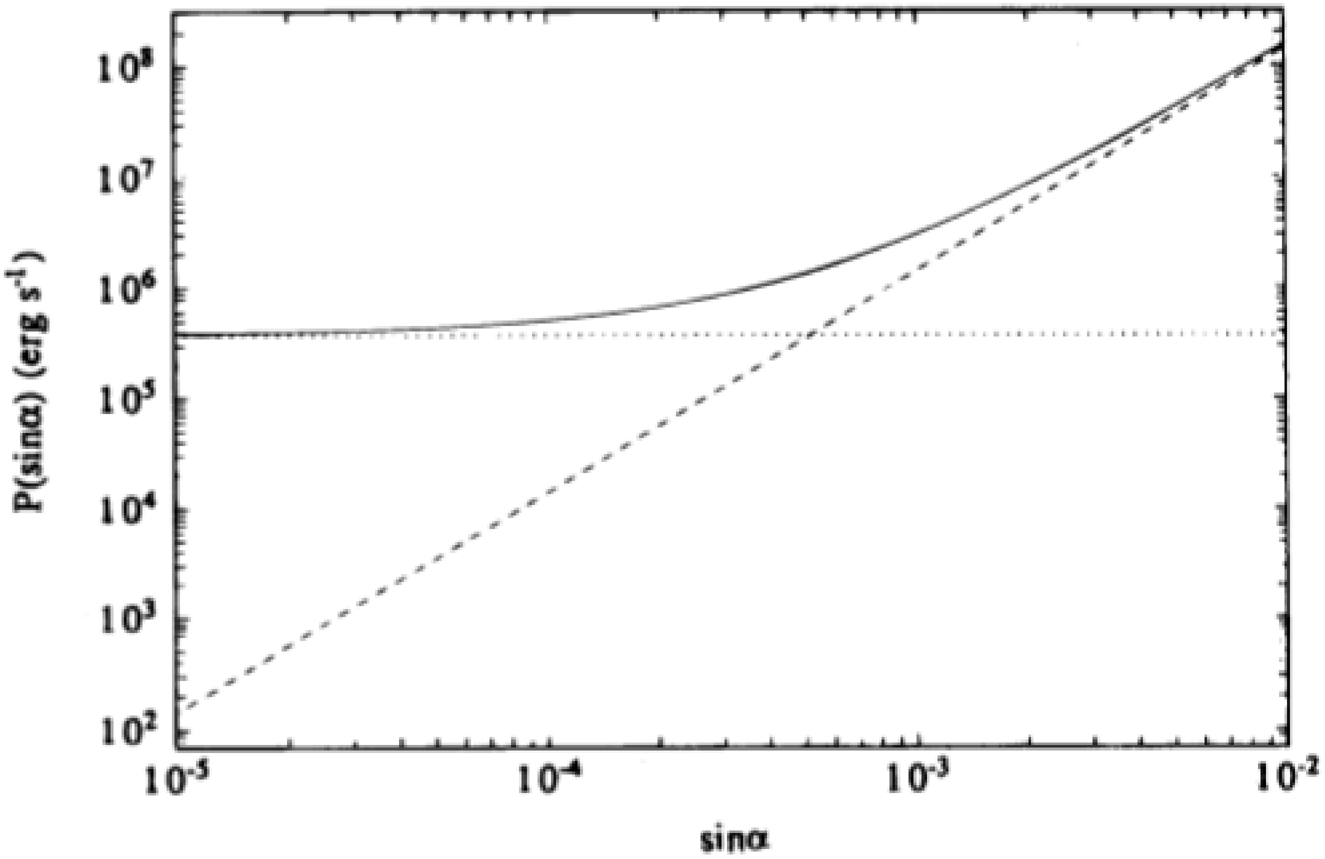


$$\frac{dP}{d\omega}=\frac{dP_{\parallel}}{d\omega}+\frac{dP_{\perp}}{d\omega}$$

$$=-\frac{\sqrt{3}e^2\gamma\omega}{4\pi r_c^*\,\omega_c}\left\{\left[\int_{\omega/\omega_c}^{\infty}K_{5/3}(y)dy-K_{2/3}\left(\frac{\omega}{\omega_c}\right)\right]+\frac{[(r_B+\rho)\Omega_0^2+r_B\,\omega_B^2]^2}{c^4Q_2^2}\left[\int_{\omega/\omega_c}^{\infty}+K_{5/3}(y)dy+K_{2/3}\left(\frac{\omega}{\omega_c}\right)\right]\right\},$$

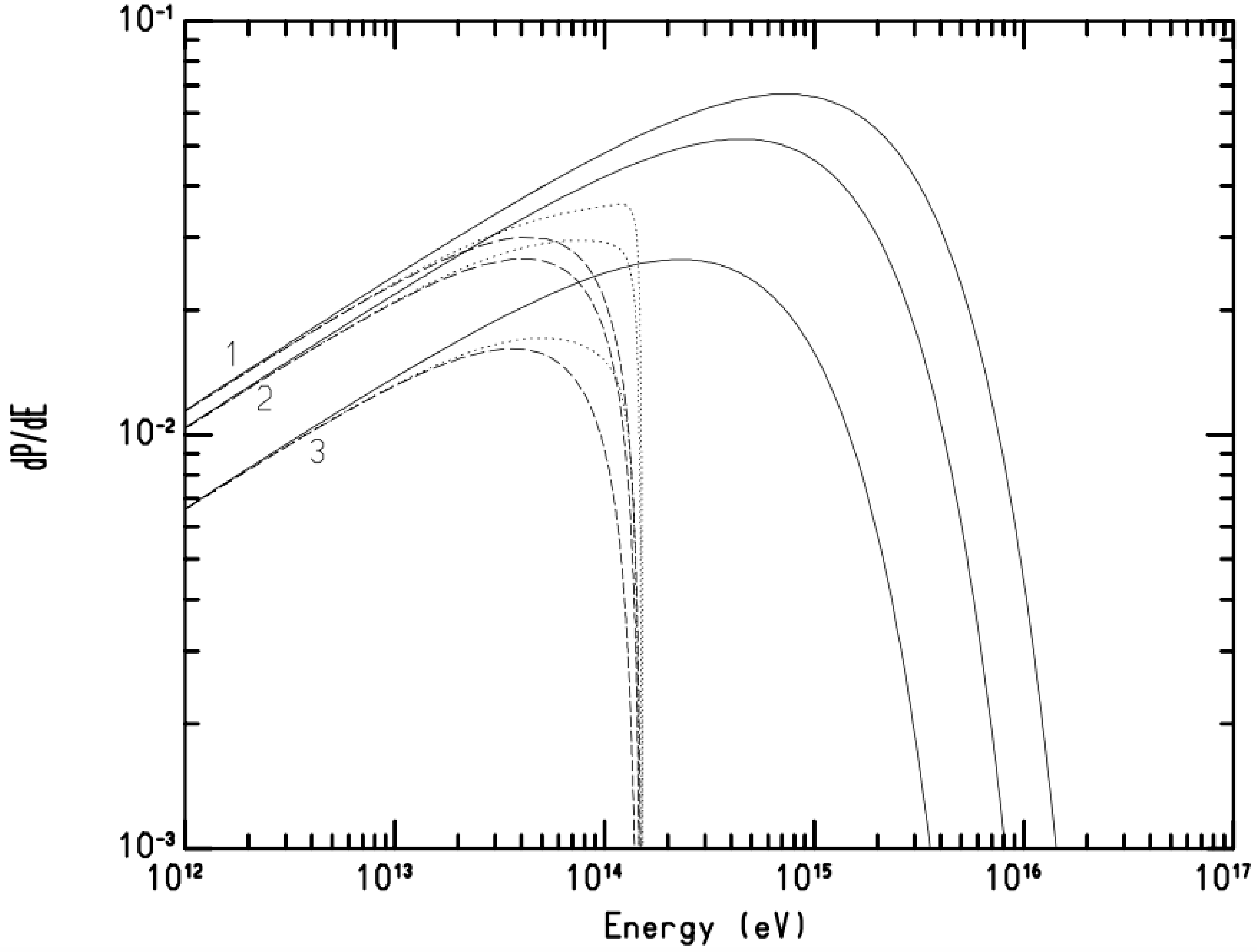
Zhang & Cheng, 1995; Cheng & Zhang, 1995

Synchro-Curvature radiation



Zhang & Cheng, 1995; Cheng & Zhang, 1995

Quantum Synchro-Curvature radiation



Yuan & Zhang, 1997; Zhang & Yuan 1998

II.

Proton magnetic field (PB) process

Pion production via proton
Syn. radiation in strong magnetic fields

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

$$\mathcal{L} = \frac{i f_\pi}{m_\pi} \psi \gamma_5 \gamma_\mu \tau_a \psi \partial^\mu \phi_a,$$

Maruyama, et al., 2015, Phys. Rev. D 91 123007

Photo-hadronic Processes

$$p + \gamma \overset{\Delta(1232)}{\longrightarrow} p' + \pi \,. \qquad \gamma + p \overset{\Delta,N}{\rightarrow} \Delta' + \pi \,, \quad \Delta' \rightarrow p' + \pi'$$

$$\gamma + p \overset{\Delta,N}{\rightarrow} \rho + p' \,, \quad \rho \rightarrow \pi + \pi' \,.$$

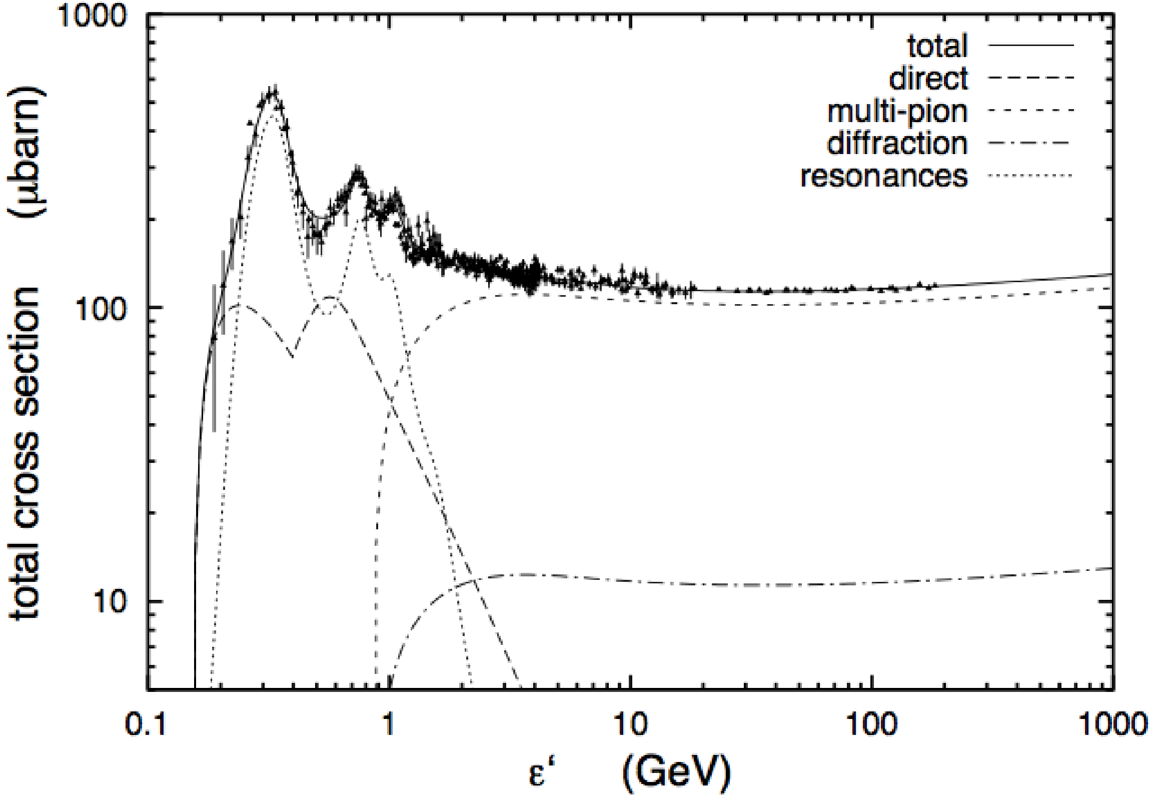


Figure 1—The total $p\gamma$ cross section, with the contributions of the baryon resonances considered in this work, the direct single-pion production, diffractive scattering, and the multipion production as a function of the photon's NRF energy (1 μbarn = 10^{-34} m^2). Data are from Baldini et al. (1988).

Mücke, 1999

Semi-quantitative analysis

$$P_{\rm syn} \simeq \sigma_{\rm T}^{p} S' \simeq \frac{2\gamma^{2} e^{4} B^{2}}{3 m_{p}^{2} c^{3}} \simeq \sigma_{\rm T}^{p} c \gamma_{p}^{2} U_{\rm B},$$

$$P_{pB} \simeq \sigma_{\rm res} S' = \sigma_{\rm res} c \gamma_{p}^{2} U_{\rm B}.$$

$$\sigma_T \simeq 0.2\ \mu barn$$

$$\sigma_{res} \simeq 200\ \mu barn\ (0.2 GeV < E_\gamma < 0.5)$$

Yuan & Shi, 2019, Phys. Letts. B, 795, 452

Semi-quantitative analysis

$$0.2\ \mathrm{GeV} < \hbar\omega_c' = \frac{\gamma_p \hbar e B}{m_p c} < 0.5\ \mathrm{GeV},$$

$$0.2 B_{\mathrm{c}}^{p} < \gamma_p B < 0.5 B_{\mathrm{c}}^{p}.$$

$$B_{\mathrm{c}}^{p} = m_p^2 c^3 / (\hbar e) = 1.5 \times 10^{20}\ \mathrm{G}$$

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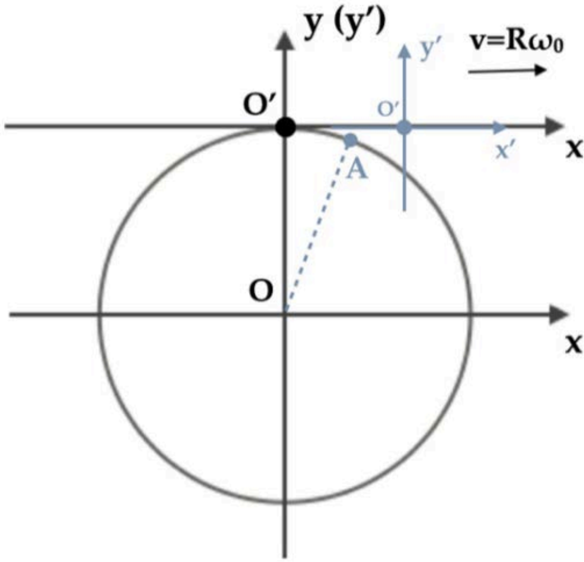
Proton magnetic field (PB) process

$$S'(\omega') = c\left|\frac{1}{2\pi}\int_{-\infty}^{\infty} E' e^{i\omega' t'} dt'\right|^2$$

$$= c\left(\frac{\omega' m_p}{2\pi e}\right)^2 \left|\int_{-\infty}^{\infty} v'_\perp(t') e^{i\omega' t'} dt'\right|^2 .$$



$$S'(\omega') = \frac{2m_p^2 c^3}{3\pi^2 e^2}\left(\frac{\omega'}{\omega_0 \gamma_p^2}\right)^2 \left[K_{1/3}^2(\xi) + 2K_{2/3}^2(\xi)\right].$$

$$\xi = \frac{2\sqrt{2}\omega'}{3\gamma_p^2 \omega_0}.$$

Yuan & Shi, 2019, Phys. Letts. B, 795, 452

Proton magnetic field (PB) process

Power spectrum of the virtual photons,

$$\frac{d^2 P'}{d\epsilon_{\rm r}' dA'} = \frac{m_p c^2 \gamma_p B}{3\pi^3 e\hbar}\left(\frac{\omega'}{\omega_0 \gamma_p^2}\right)^2 \left[K_{1/3}^2(\xi) + 2K_{2/3}^2(\xi)\right]$$

$$\simeq 4.7 \times 10^{51}\ \mathrm{cm^{-2}\,s^{-1}} \left(\frac{\gamma_p B}{B_c^p}\right)^{-1} \left(\frac{\epsilon_{\rm r}'}{m_p c^2}\right)^2$$

$$\left[K_{1/3}^2(\xi) + 2K_{2/3}^2(\xi)\right]$$

$$\frac{d^2 P'}{d\epsilon_{\rm r}' dA'} \sim \frac{(\gamma_p B)^2 c}{4\pi^2 \hbar \omega'_{\rm peak}},$$

Proton magnetic field (PB) process

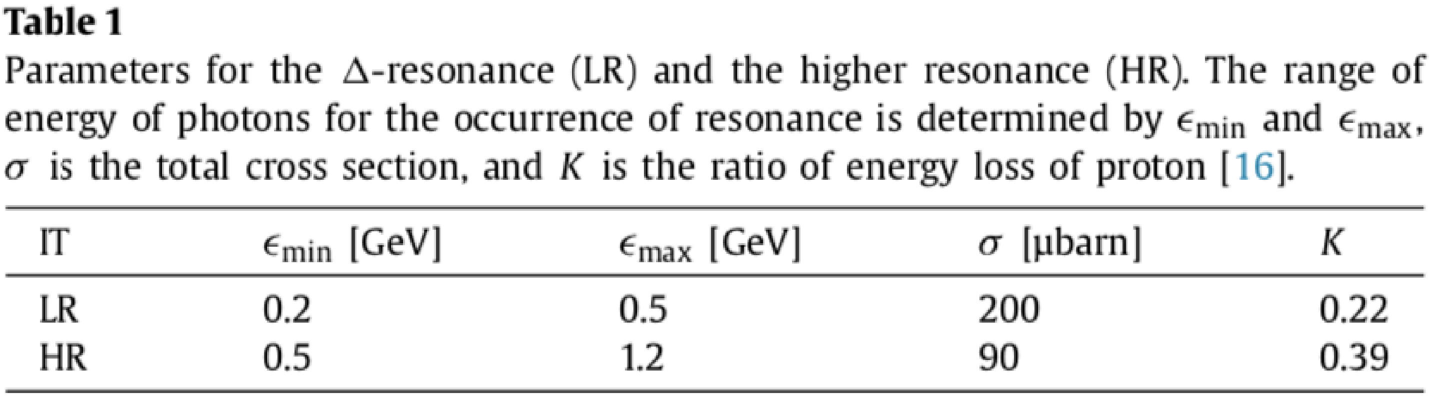


Table 1

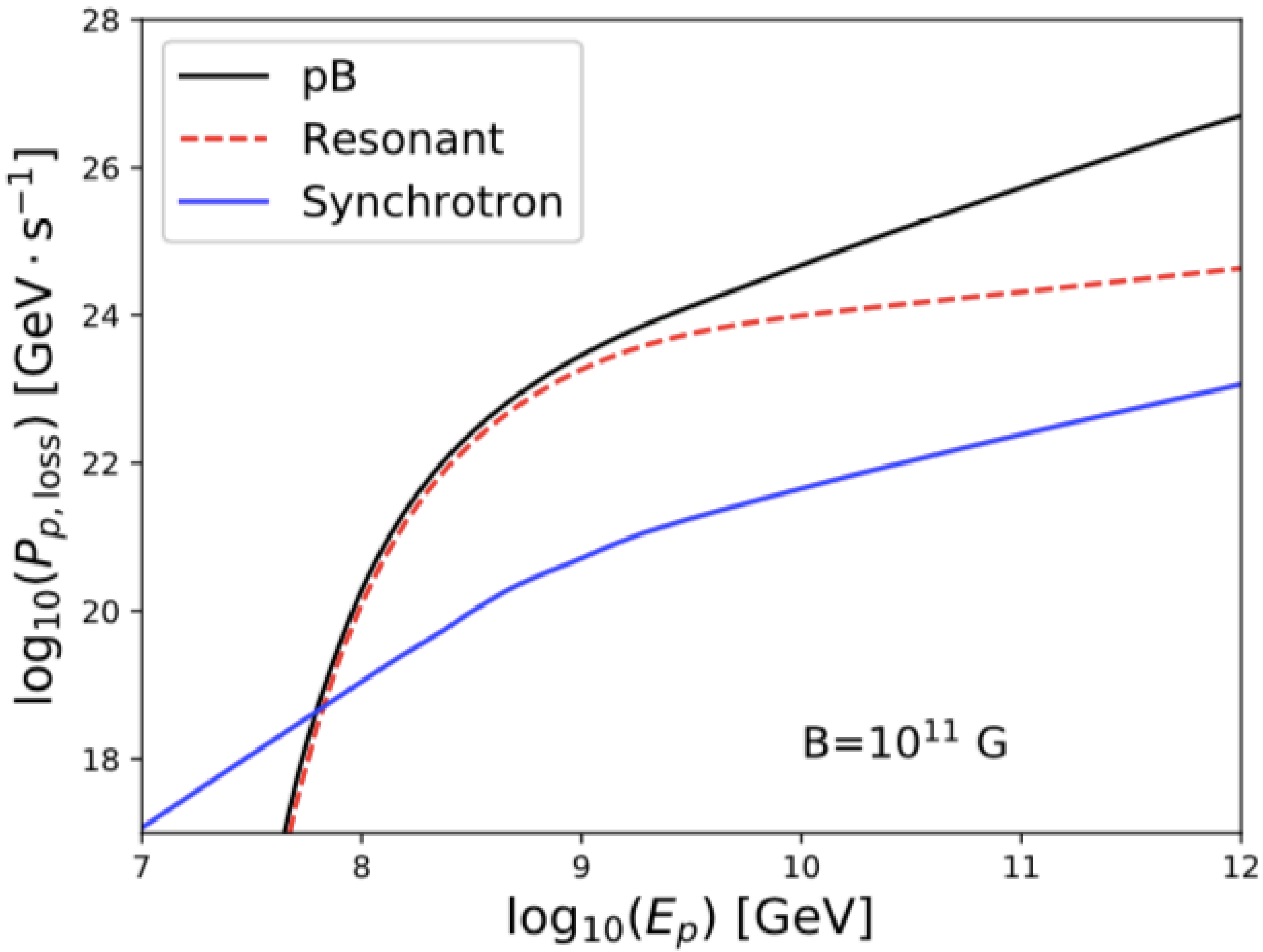
Parameters for the Δ-resonance (LR) and the higher resonance (HR). The range of energy of photons for the occurrence of resonance is determined by $\epsilon_{\rm min}$ and $\epsilon_{\rm max}$, σ is the total cross section, and K is the ratio of energy loss of proton [16].

IT	$\epsilon_{\rm min}$ [GeV]	$\epsilon_{\rm max}$ [GeV]	σ [μbarn]	K
LR	0.2	0.5	200	0.22
HR	0.5	1.2	90	0.39

$$P_{\rm p,loss}(E_p) = \sum_{\rm IT} \left[K^{\rm IT} E_p \Gamma^{\rm IT}(E_p) \right],$$

$$\Gamma^{\rm IT}(E_p, B) = \gamma_p^{-1} \int_{\epsilon_{\rm min}^{\rm IT}}^{\epsilon_{\rm max}^{\rm IT}} \epsilon_{\rm r}^{-1} \frac{d^2 P'}{d\epsilon_{\rm r}' dA'}(\epsilon_{\rm r}, \gamma_p, B) \sigma^{\rm IT}(\epsilon_{\rm r}) d\epsilon_{\rm r},$$

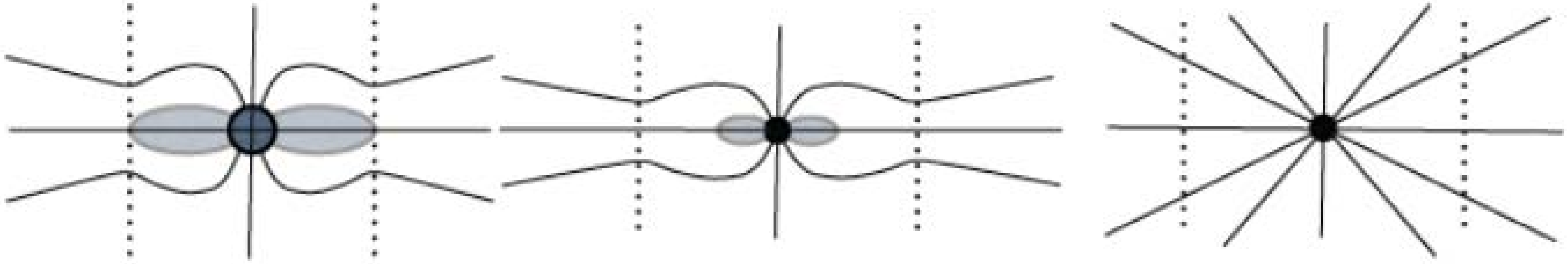
Proton magnetic field (PB) process



III.

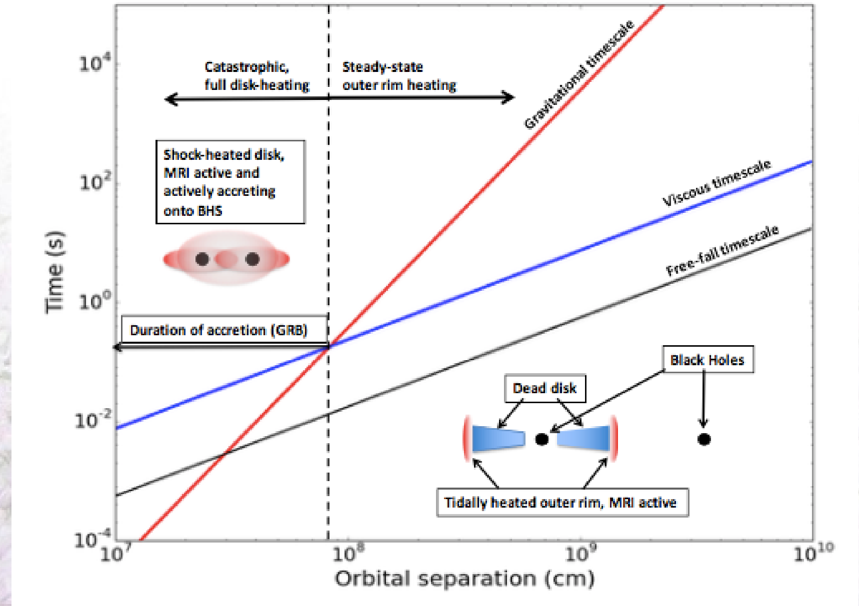
PeV neutrinos from merging black hole binaries?

Magnetic fields around a BH



$$B \sim 1.5 \times 10^6\ G\ M_{100}^{-1/2} \eta_E^{1/2} \left(\frac{R}{R_g}\right)^{-1},$$

Lyutikov +, 2017

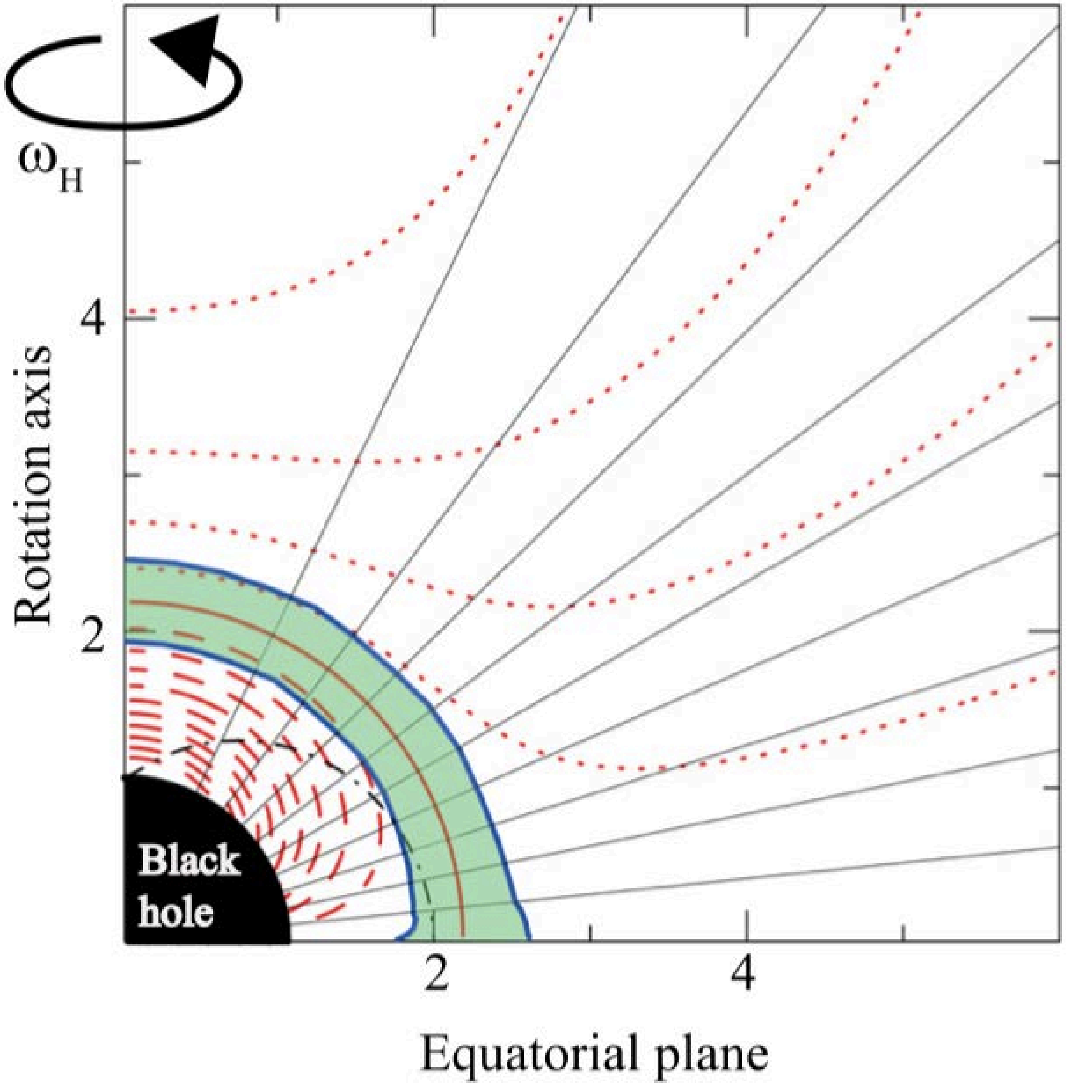


P ~ 1–10 s

B ~ 10^{10} G.

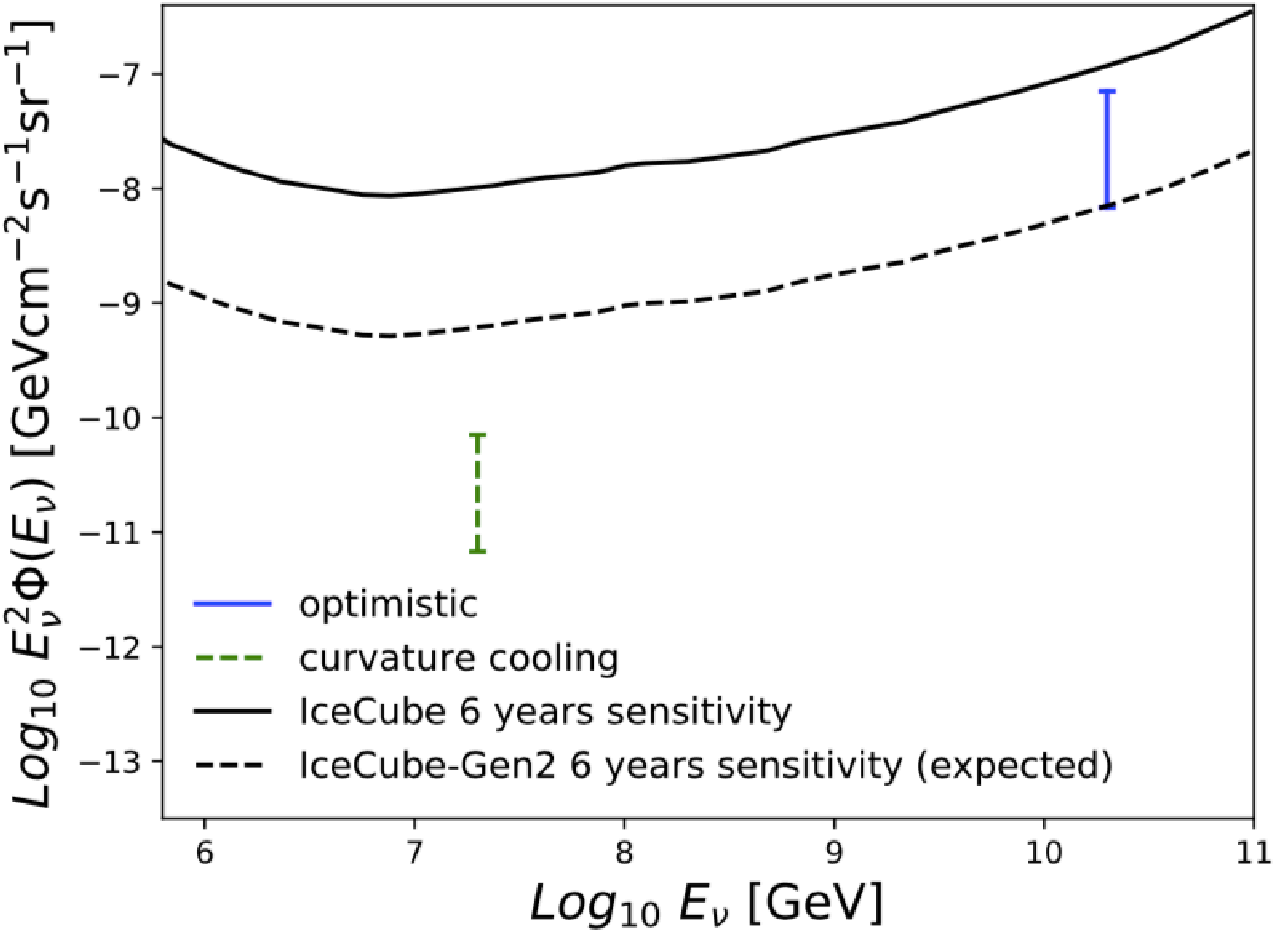
Perna +, 2016

Acceleration Gap



Hirotani & Pu, 2016, ApJ

Diffuse flux of ultra-high energy neutrinos from the binary BH merging event.



Shi & Yuan, 2019, submitted

Some discussions

Advantages:

- Natural targets
- Neutrino emission
- EM courterpart

Uncertainties:

- Strength of magnetic filed
- the optical depth of neutrinos (lager than other sources, eg. AGNs, TDEs)

Thanks！

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