Can we detect PeV neutrinos from merging black hole binaries?

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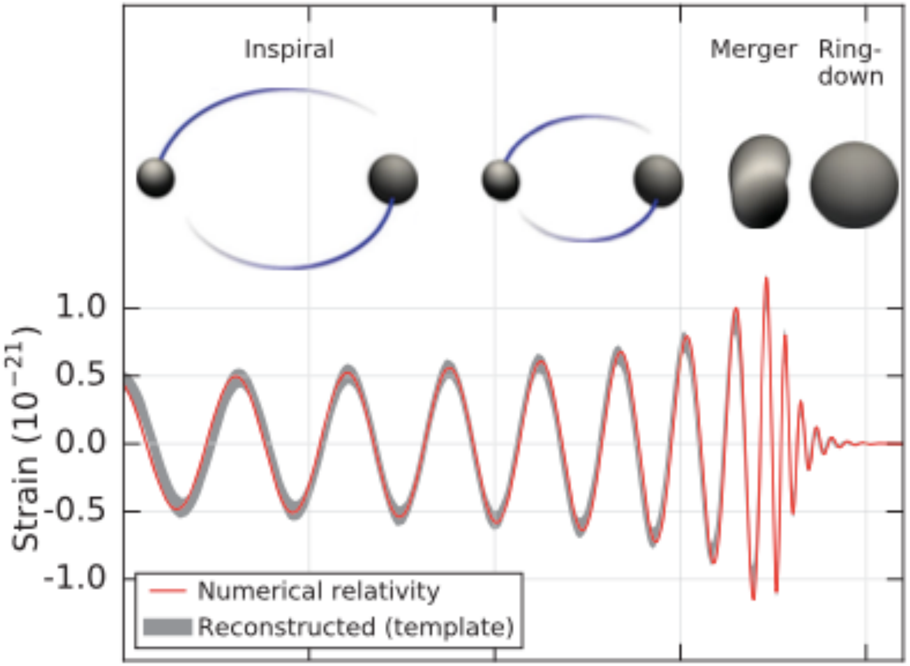
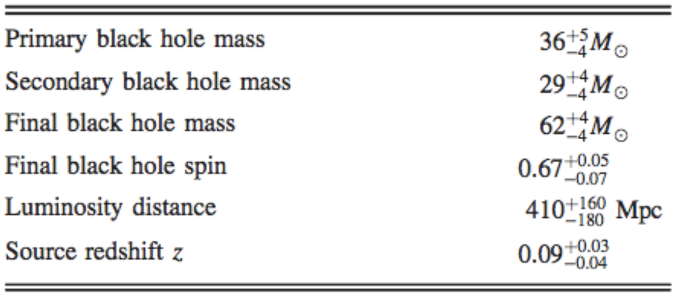
Gravitational Wave Events

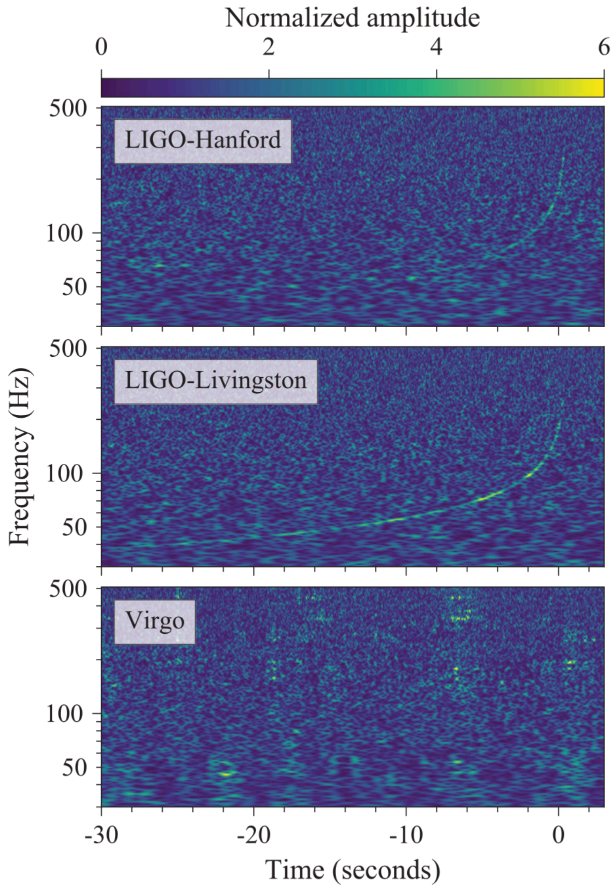
GW150914





Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

GW170817

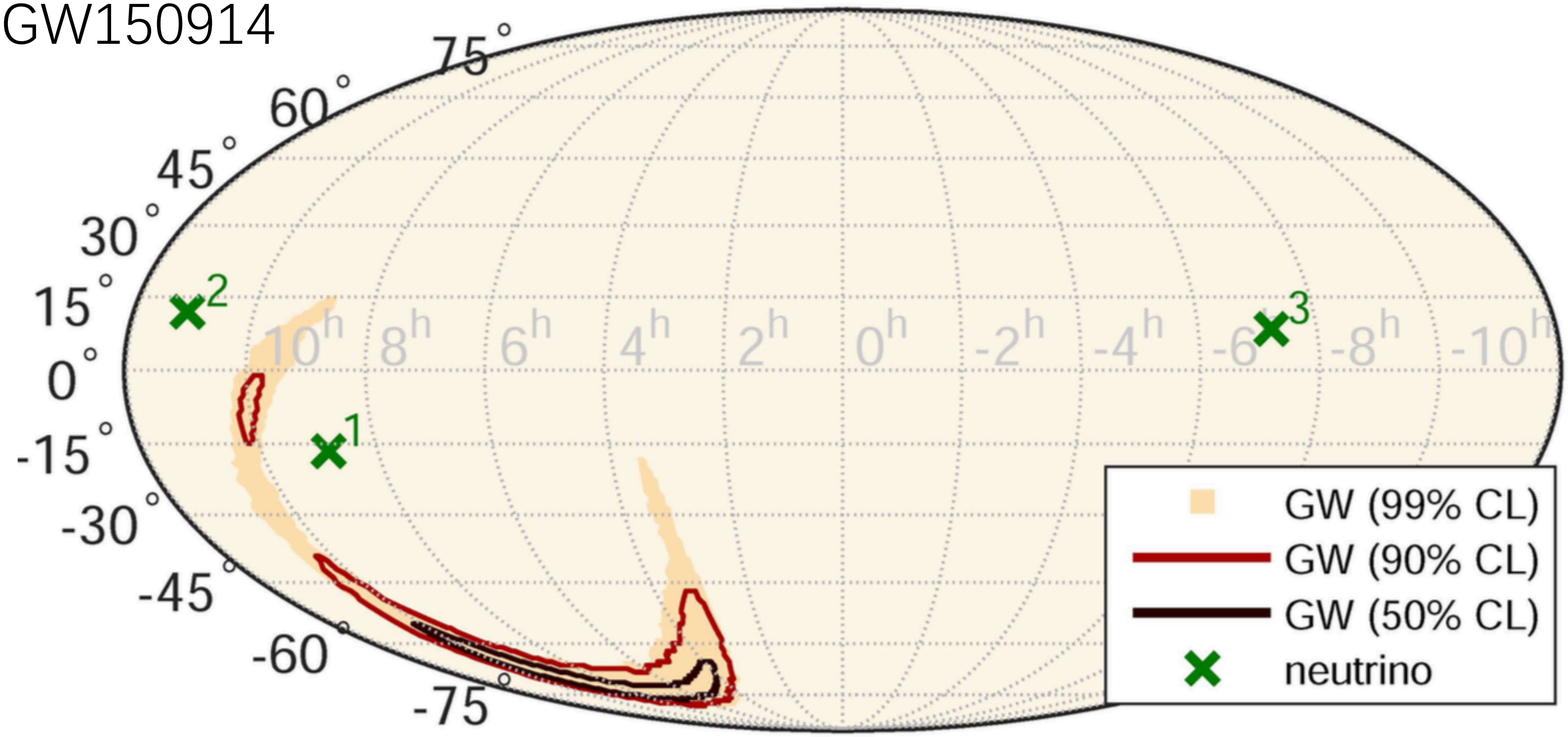


Abbott +, 2016 & 2017

and GW151012 GW151226 GW170104 GW170814 …

ANTARES and IceCube

GW150914



within ±500 s of the gravitational wave event

$$E^{\rm ul}_{\nu,\rm tot} = 5.4 \times 10^{51}\text{–}1.3 \times 10^{54}\ \rm erg$$

$$E^{\rm ul(cutoff)}_{\nu,\rm tot} = 6.6 \times 10^{51}\text{–}3.7 \times 10^{54}\ \rm erg$$

Adrián-Martínez+, 2016

pp & *pγ* Processes

$$pp \rightarrow \pi^+ \pi^- \pi^0$$

$$\pi^0 \rightarrow \gamma\, \gamma$$

$$p\,\gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} p\,\pi^0, \\ n\,\pi^+, \end{cases}$$

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \overline{\nu}_\mu \nu_\mu \\ \pi^- &\rightarrow \mu^- \overline{\nu}_\mu \rightarrow e^- \overline{\nu}_e \nu_\mu \overline{\nu}_\mu . \end{aligned}$$

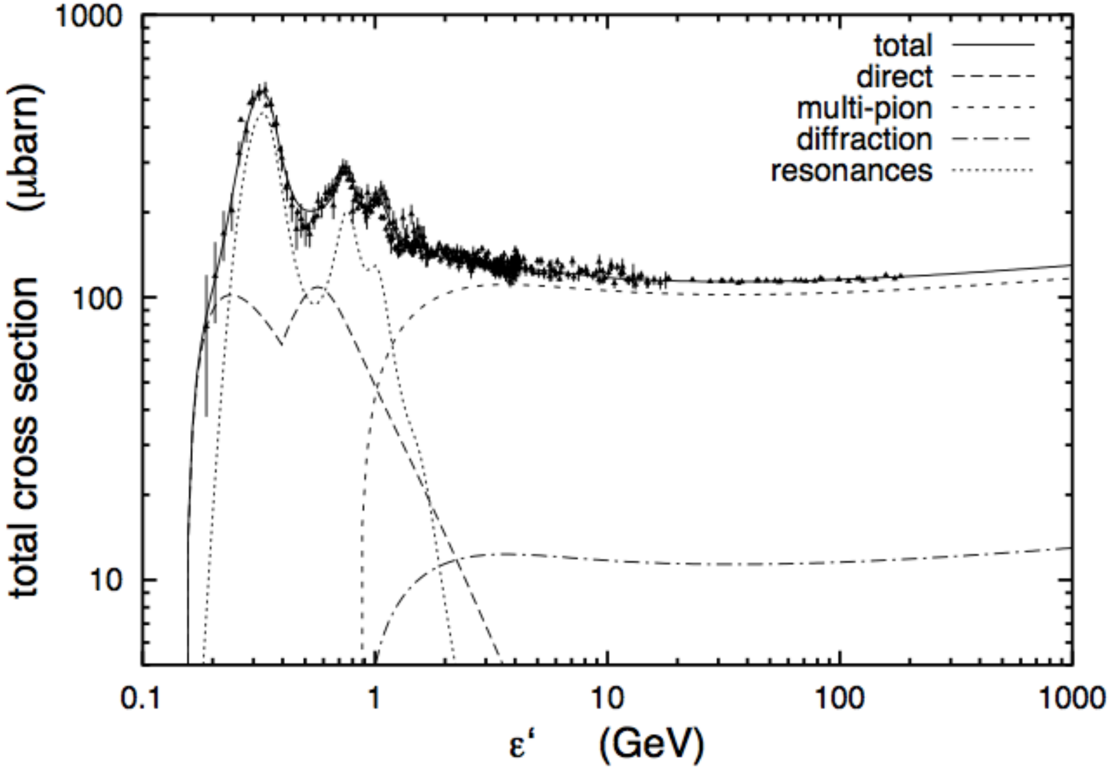


Figure 1—The total $p\gamma$ cross section, with the contributions of the baryon resonances considered in this work, the direct single-pion production, diffractive scattering, and the multipion production as a function of the photon's NRF energy (1 μbarn $= 10^{-34}$ m^2). Data are from Baldini et al.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

Mücke, 1999

pp & *pγ* Processes

Targets:
1. protons/neutrons ?
2. photons ?
3. magnetic field !

Magnetic field:
super Eddington accretion disk sourced by tidal disruption of asteroids or planets

B ~ 10^{11} G
Lasting time scale ~ day

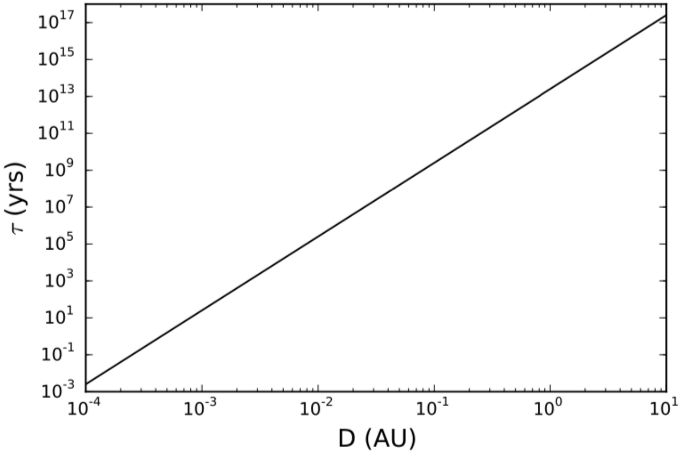


Fig. 2. The coalescence time needed for two SmBHs in the GW150914 event as a function of the binary orbital radius.

Zhang+, 2016
Kotera+, 2016

pB Process

Fermi-Weizsacker-Williams (FWW) Method of Virtual Quanta

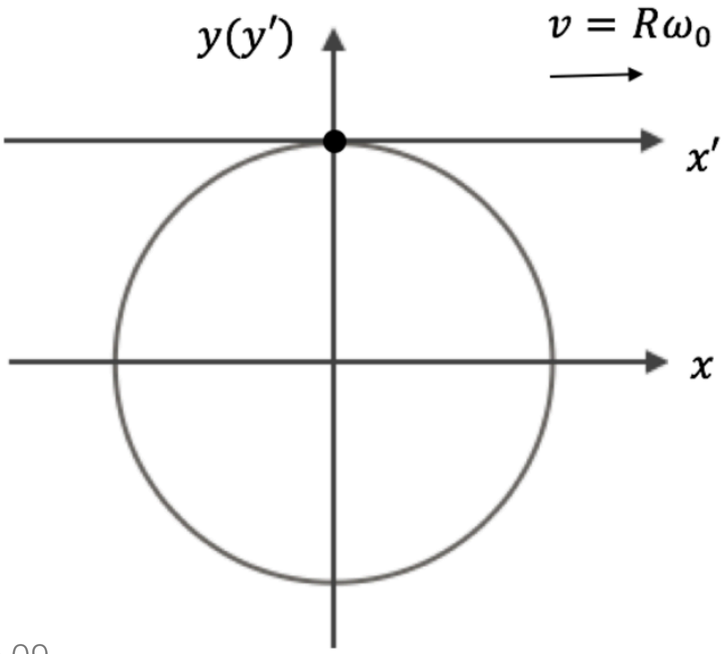
A proton moves in a static magnetic field directed along the z-axis in the laboratory frame Σ.

In the particle instantaneous rest frame Σ′

$$E' = \gamma B(\frac{v_y}{c},\ \ -\frac{v_x}{c},\ \ 0);$$

$$B' = \gamma B(0,\ \ 0,\ \ 1)$$

A equivalent electromagnetic field in –**v** direction



pB Process

Fermi-Weizsacker-Williams (FWW) Method of Virtual Quanta

A proton moves in a static axial magnetic field directed along the z-axis in the laboratory frame Σ.

In the particle instantaneous rest frame Σ'

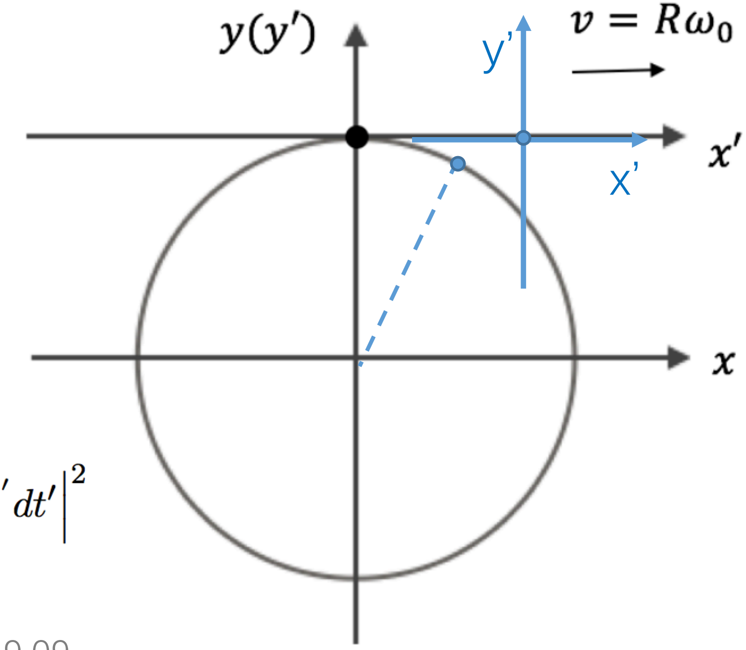
$$E' = \gamma B(\frac{v_y}{c},\ -\frac{v_x}{c},\ 0);$$

$$B' = \gamma B(0,\ 0,\ 1)$$

A equivalent electromagnetic Field in –**v** direction

The Poynting flux S(ω) of the equivalent incident radiation

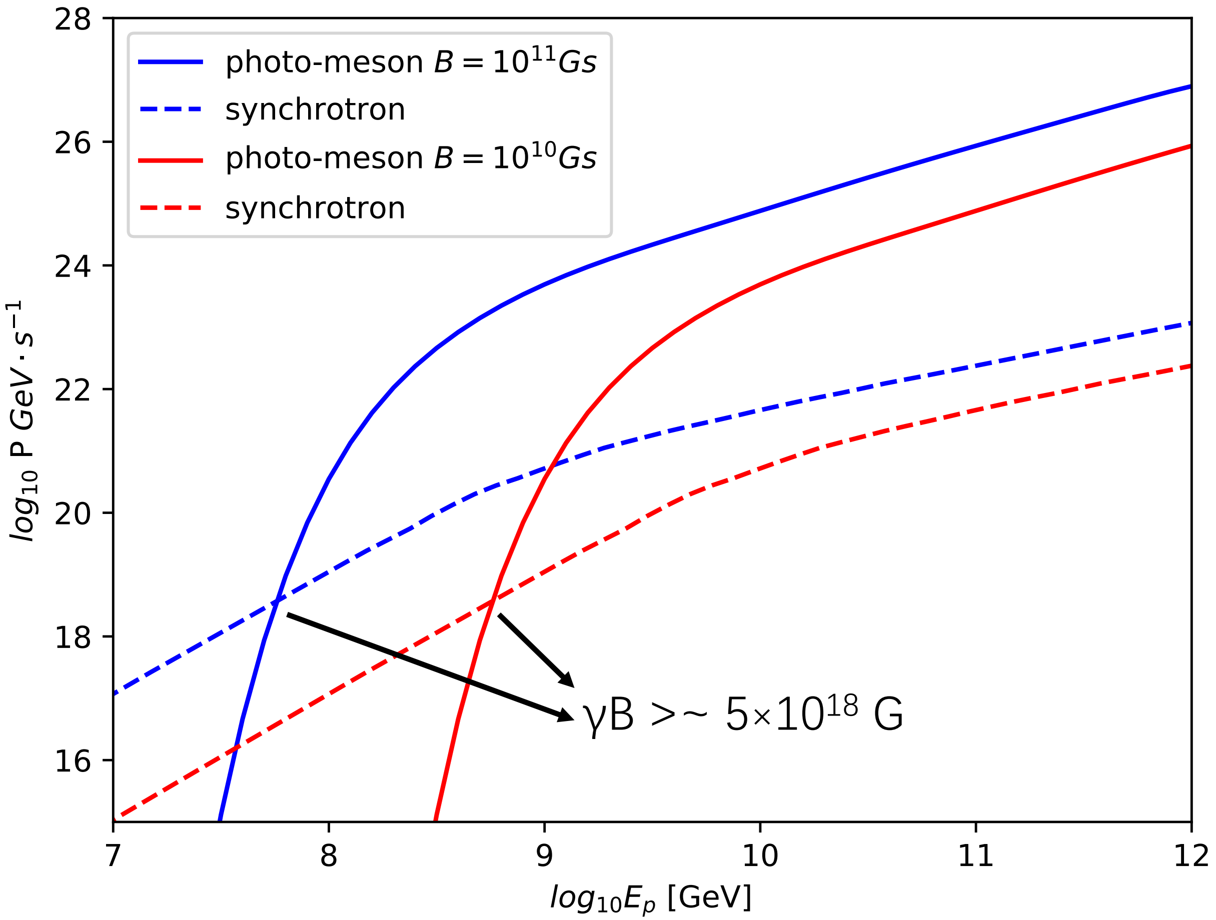
$$S'(\omega') = c\left|\frac{1}{2\pi}\int_{-T}^{T} E' e^{i\omega' t'} dt'\right|^2 = c(\frac{\omega' m}{2\pi e})^2 \left|\int_{-T}^{T} v'_\perp(t') e^{i\omega' t'} dt'\right|^2$$



pB Process

The energy loss rate of protons

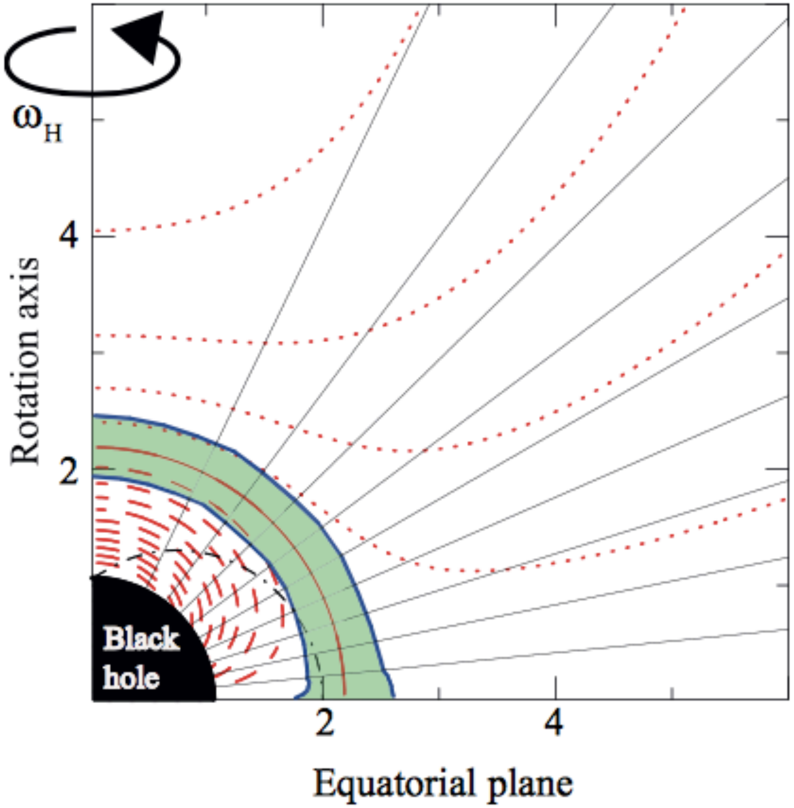
Yuan & Shi, 2019

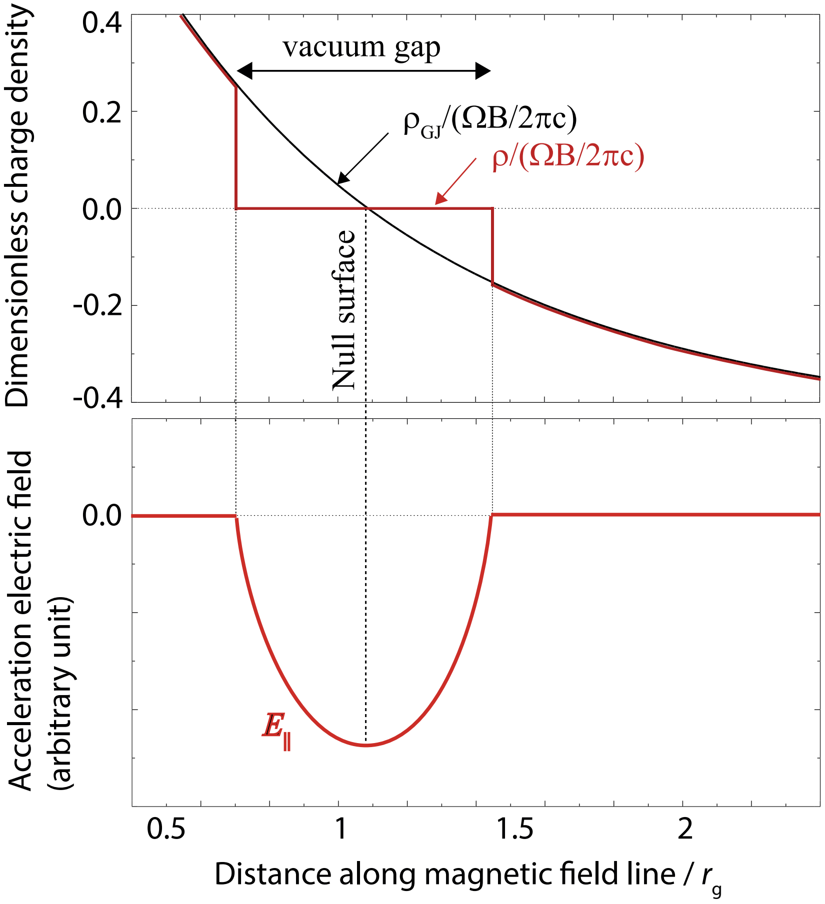


Newly-formed BH after merger

Gap Acceleration of Protons

Kerr BH: frame dragging $\Omega_F = 0.3\omega_H \quad R_{null} = 2.1R_H$





Hirotani, Pu, 2016

Newly-formed BH after merger

Gap Acceleration of Protons

Gap height

$$\lambda_{\gamma\gamma} = \frac{1}{\sigma_{\gamma\gamma} n_{\rm ph}} \sim R_{\rm g,100} \left(\frac{n_{\rm ph}}{10^{20} {\rm cm}^{-3}} \right)^{-1}$$

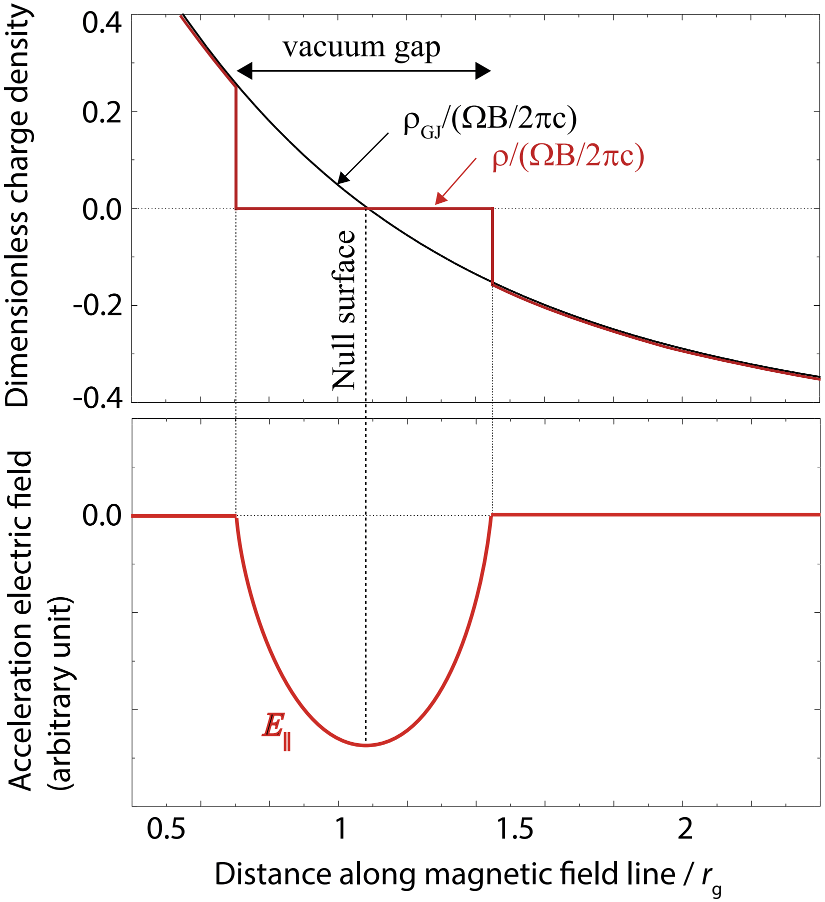
Accretion disk dynamo: voltage drop

$$\Delta V \sim 4.4 \times 10^{20} B_{11} M_{100} \left(\frac{h}{R_{\rm g}} \right)^{2} \ {\rm V}$$

The gap acceleration luminosity

$$\begin{aligned} L_{\rm acc} &= n_{\rm GJ} P_{\rm acc} \\ &\approx 6 \times 10^{46} {\rm erg\ s}^{-1} M_{100}^{2} B_{11}^{2} \left(\frac{h}{R_{\rm g}} \right)^{3} \end{aligned}$$

~ same order of magnitude as the BZ mechanism



UHE Neutrino energy and flux

Neutrino energy

$$E_\nu = f_{p\to\nu} E_{p,\max} \approx 20 \text{ EeV} \qquad f_{p\to\nu} \approx 0.2 \times \frac{1}{4} = 0.05$$

For GW150914

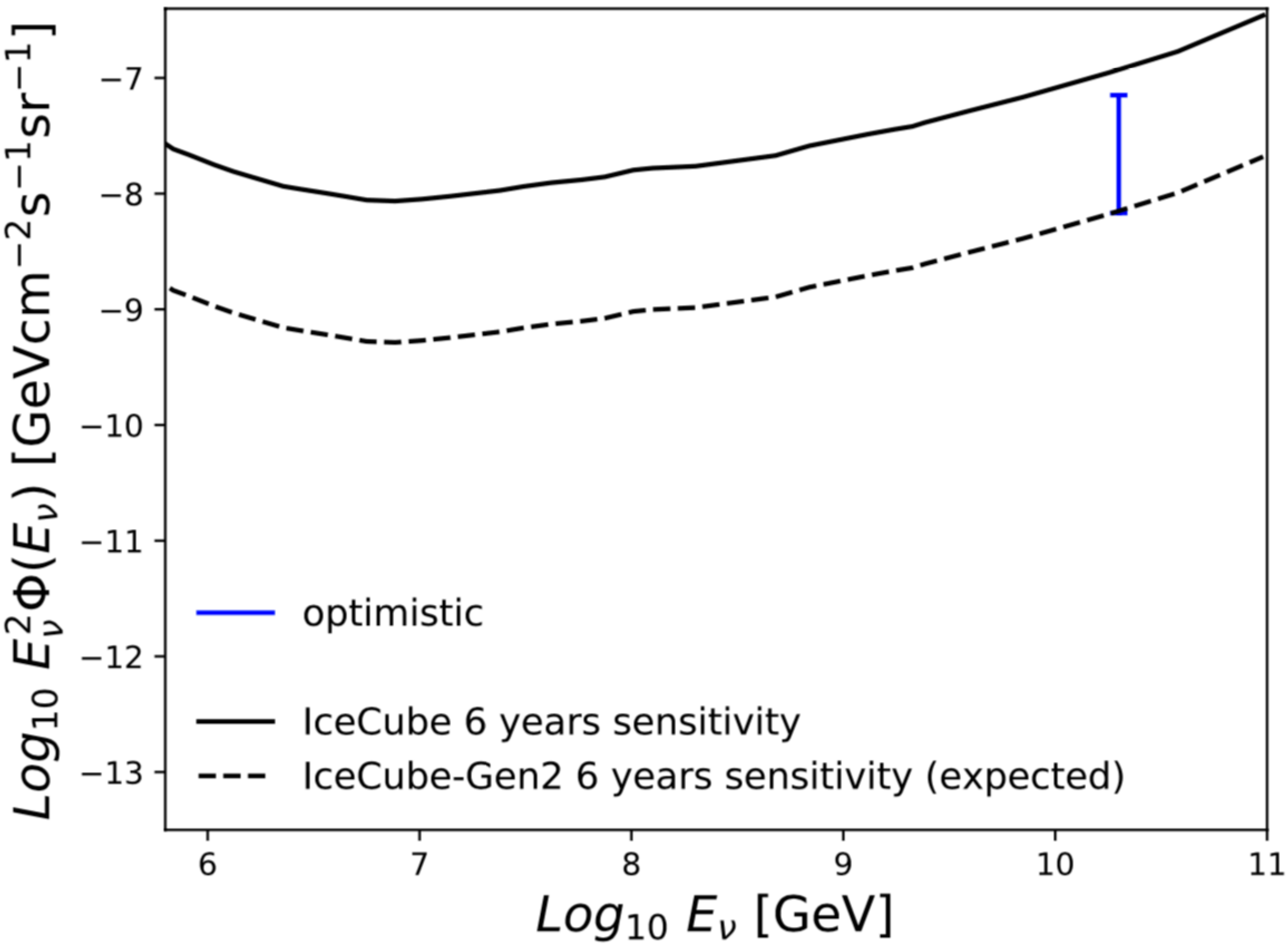
$$\begin{aligned} E_\nu^2 \Phi_\nu &\sim f_{\gamma\pi} f_\nu f_z \frac{L_{\rm acc}}{4\pi D_{\rm s}^2} \\ &\sim 3.4 \times 10^{-7} \text{ GeV cm}^{-2}\text{ s}^{-1}\, f_\nu f_z \left(\frac{L_{\rm acc}}{10^{46.5}\text{ erg s}^{-1}} \right) \left(\frac{D_{\rm s}}{430\text{ Mpc}} \right)^{-2} \end{aligned}$$

Detective distance: <~ 5 Mpc from an isotropic neutrino source

Diffuse Neutrino Flux

$$\begin{aligned} E_\nu^2 \Phi_\nu &\sim \frac{D_{\rm H}}{4\pi} f_{\gamma\pi} f_\nu f_z t L_{\rm acc} \rho_0 \\ &\sim 6.8 \times 10^{-9} - 7.1 \times 10^{-8} \text{ GeV cm}^{-2}\text{ s}^{-1} \\ &\quad f_\nu f_z \left(\frac{L_{\rm acc}}{10^{46.5}\text{ erg s}^{-1}} \right), \end{aligned}$$

UHE Neutrino energy and flux



UHE Neutrino energy and flux

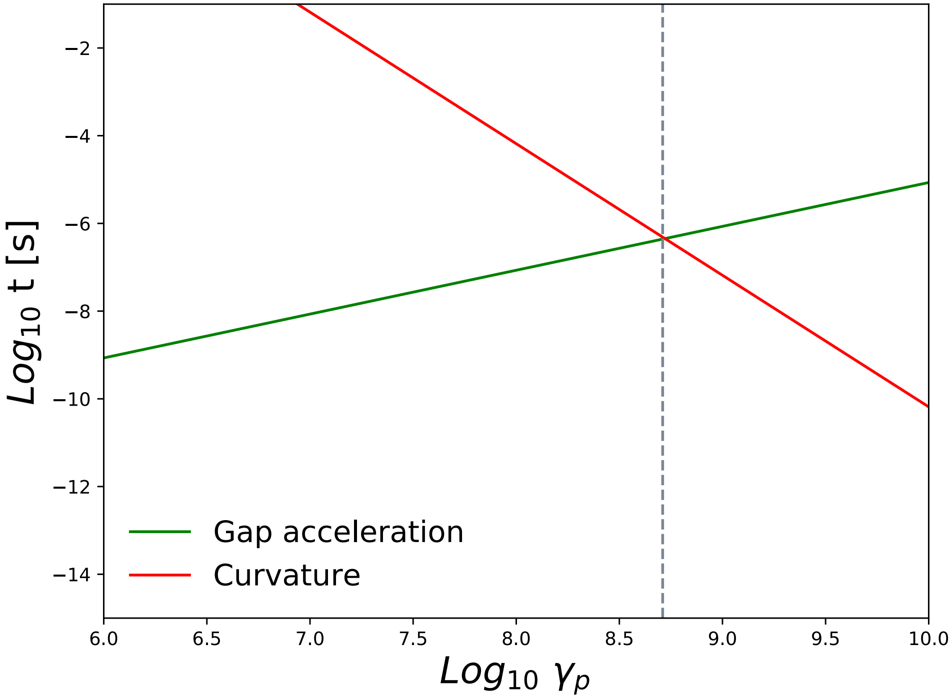
Levinson 2000

Curvature radiation $P_{\rm cur} = \frac{2}{3}\frac{Z^2 e^2 c \gamma_p^4}{r_{\rm c}^2} \sim 2.1 \times 10^9 \ {\rm erg\ s^{-1}\ M_{100}^{-2}} \left(\frac{\gamma_{\rm p}}{10^8}\right)^4 \left(\frac{\rm r_c}{\rm R_g}\right)^{-2}$

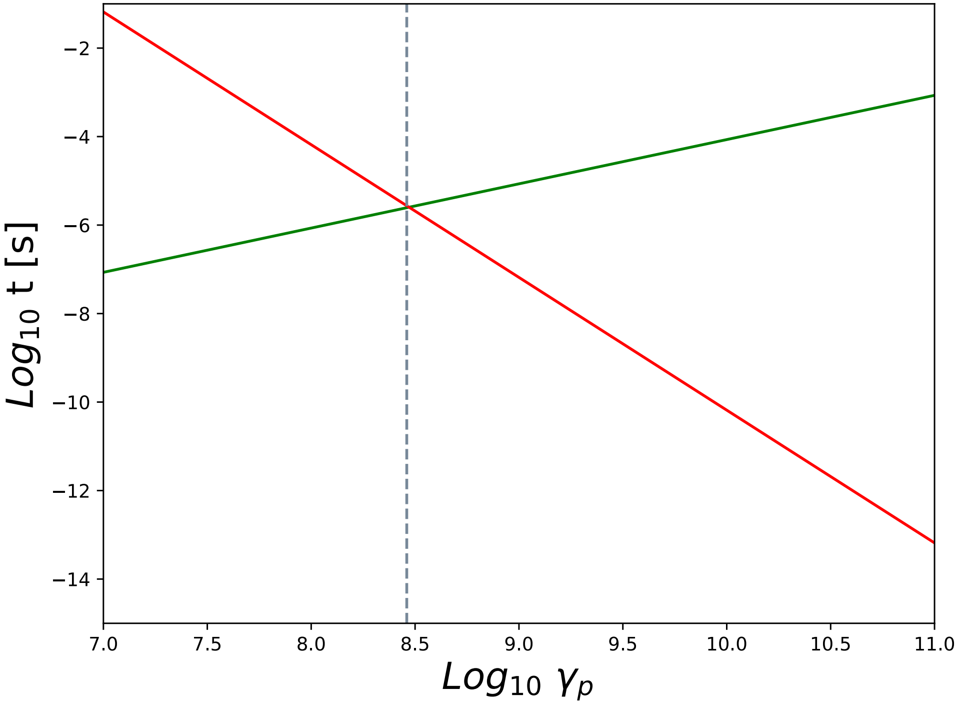
When acceleration rate equals curvature radiation, the maximum proton energy

$$E_{p,\rm max} \sim 4.8 \times 10^{17}\ {\rm eV}\ B_{11}^{1/4} M_{100}^{1/2} (hR_{\rm c}^2/R_g^3)^{1/4}$$

Lorentz facto $\gamma_p \approx 5{\times}10^8$.



B = 10^{11} G



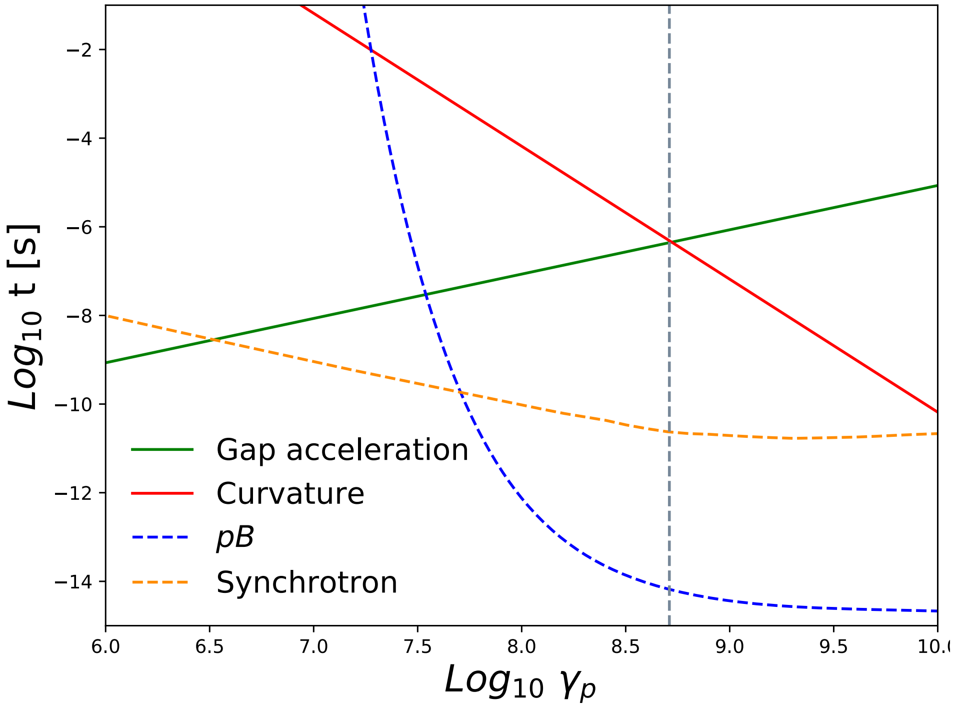
B = 10^{10} G

UHE Neutrino energy and flux

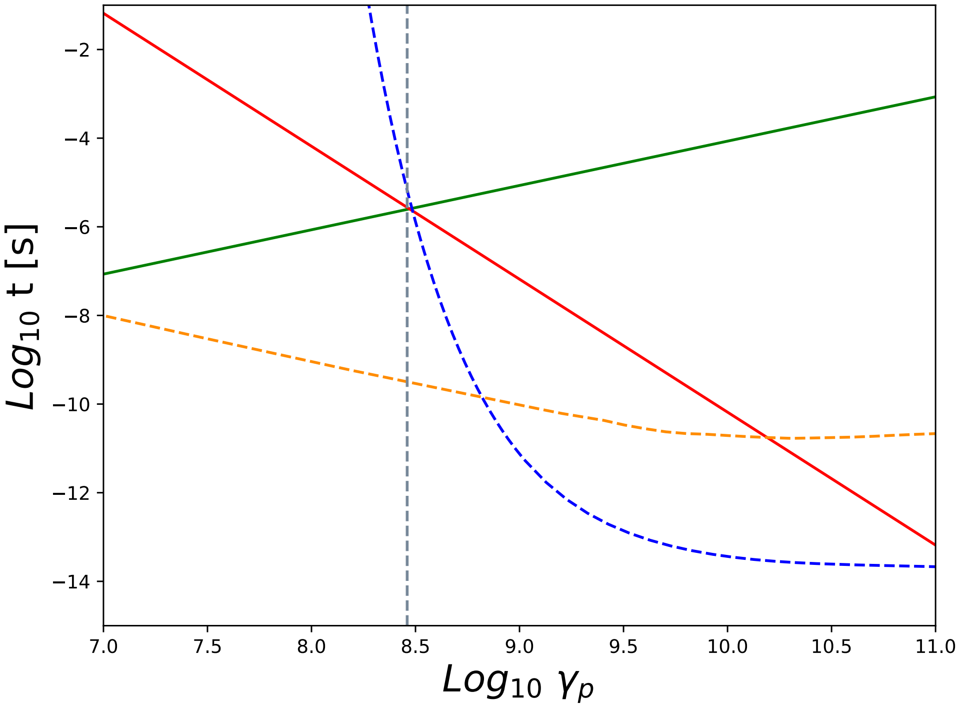
Neutrino energy $E_{\nu,\mathrm{cur}} \approx 20\ \mathrm{PeV}$

Transmitted fraction $\eta_p = E_{p,\mathrm{max}}/(e\Delta V) \approx 10^{-3}$

The total proton luminosity $L_p = \eta_p L_{\mathrm{acc}} \sim 10^{43.5}\ \mathrm{erg\ s^{-1}}$

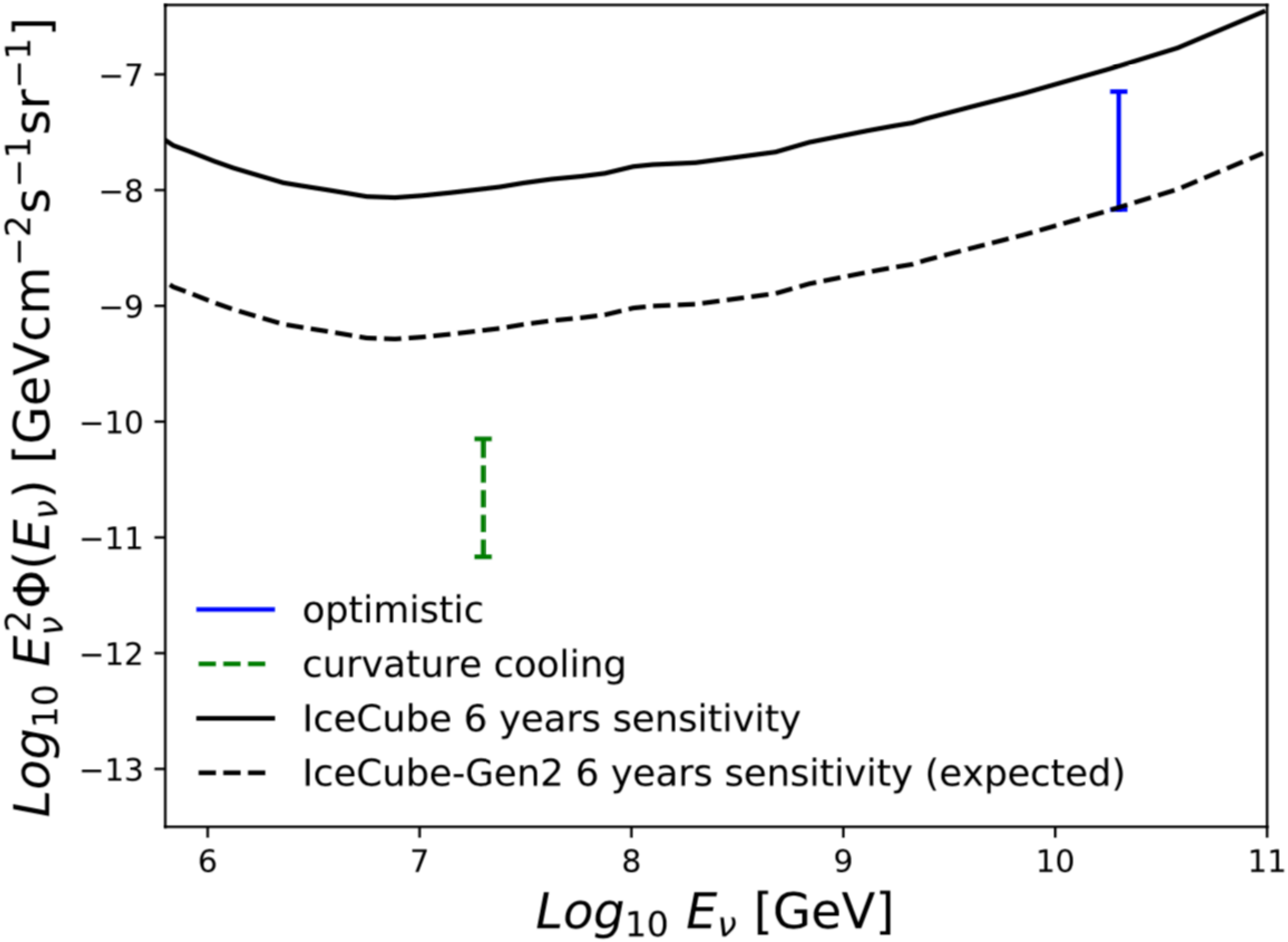


B = 10^{11} G



B = 10^{10} G

UHE Neutrino energy and flux



Discussion

Fermi GBM: 3σ-level of transient signal of luminosity ~ 10^{49} erg s^{-1}

Coincidence?

B ~ 5 × 10^{12} G

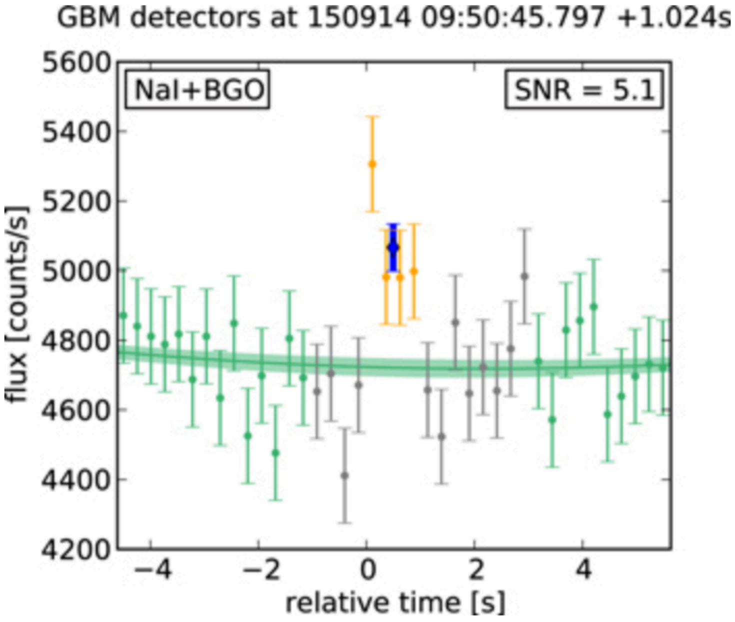
Transmitted fraction $\eta_{p,12} \sim 10^{-4}$

The total proton luminosity $\sim 10^{45}\ \mathrm{erg\ s^{-1}}$

Neutrino energy ~ 35 PeV

One individual source:
distance <~ 50 Mpc

The diffuse neutrino luminosity:
a detectable fraction of IceCube-Gen2



Connaughton +, 2016

Summary

1. Black hole binary mergers: low density of protons and photons

2. *pB* process:
   unusual target: strong magnetic field

$$g^2/e^2 \sim 10^3\text{, threshold } \gamma B >\sim 5\times10^{18}\text{ G}$$

3. Optimistic case: 20 EeV, <~ 5 Mpc, diffuse flux detectable by IceCube-Gen2
   With curvature cooling: 20 PeV, <~ 0.5 Mpc

4. Unique neutrino and photon spectrum

Thanks for listening!
Suggestions and comments are welcome.