On the inner engine of the high-energy (GeV) emission of gamma-ray bursts

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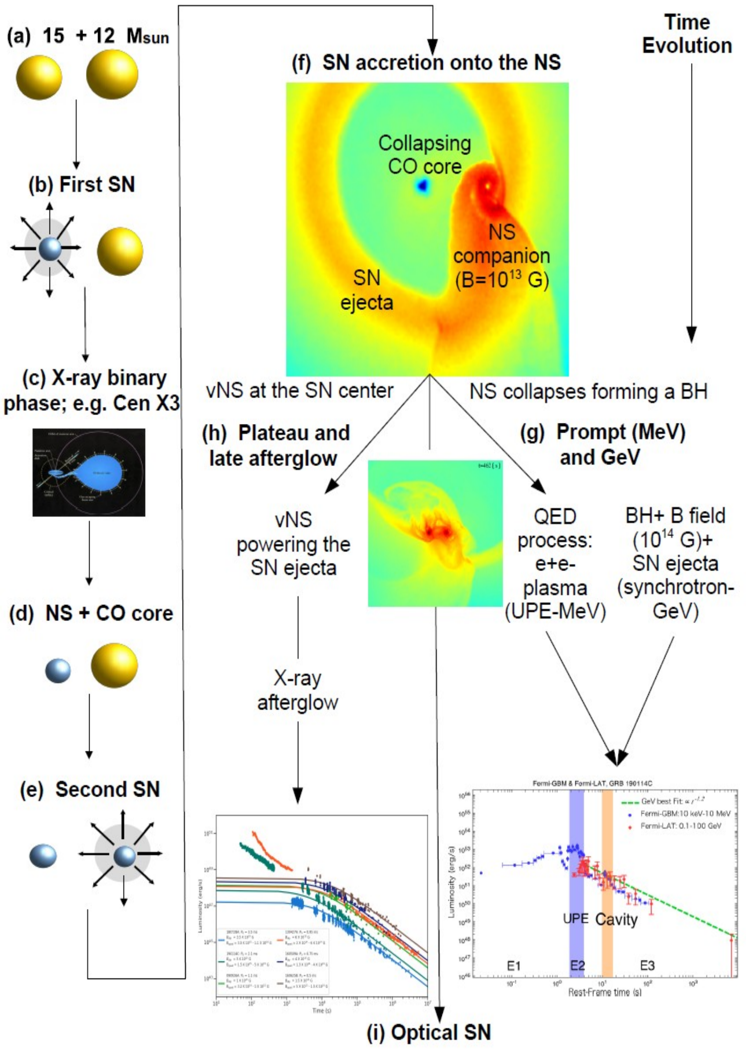
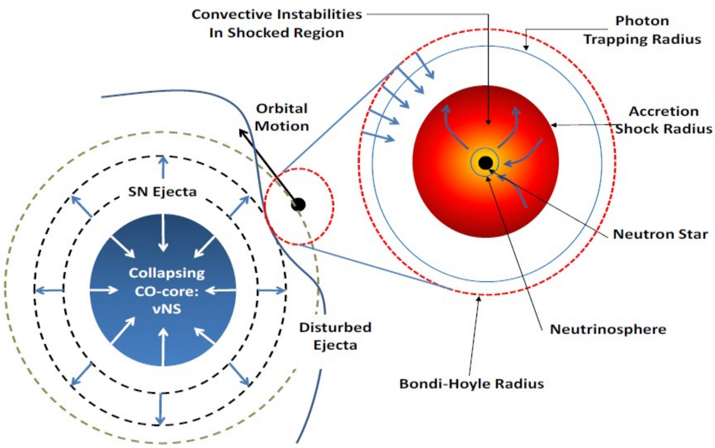


Binary driven hypernova physical processes

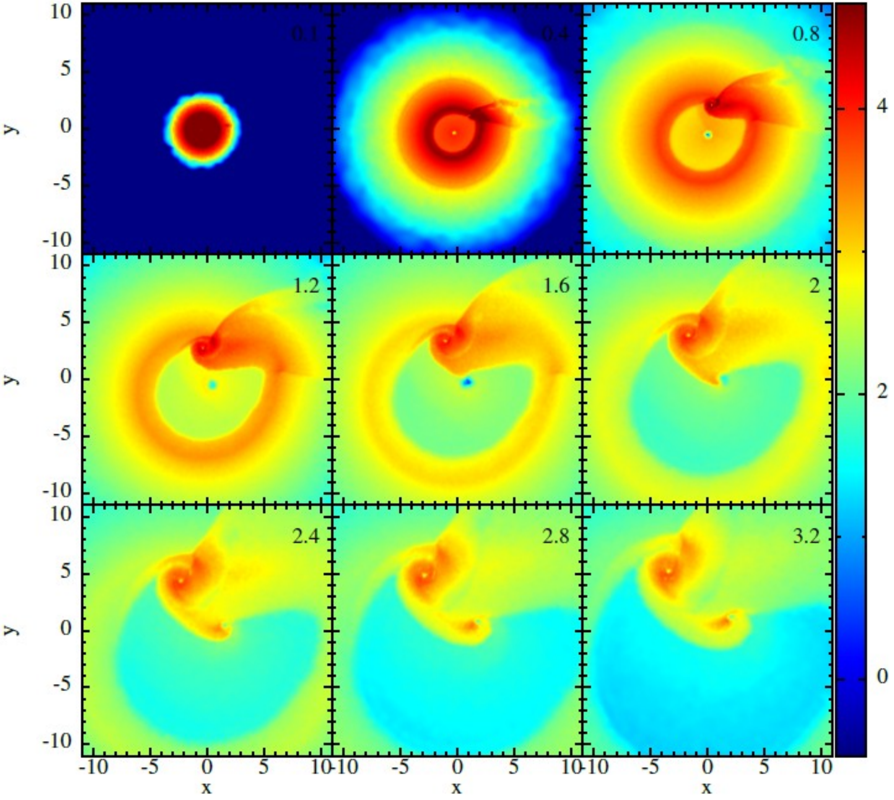
BdHN component/phenomena	GRB observable				
	X-ray precursor	Prompt (MeV)	GeV-TeV emission	X-ray flares early afterglow	X-ray plateau and late afterglow
SN breakout[a]	⊗				
Hypercritical accretion onto the NS[b]	⊗				
e^+e^- from BH formation: transparency in low baryon load region[c]		⊗			
Inner engine: newborn BH + *B*-field+SN ejecta[d]			⊗		
e^+e^- from BH formation: transparency in high baryon load region (SN ejecta)[e]				⊗	
Synchrotron emission by νNS injected particles on SN ejecta[f]					⊗
νNS pulsar-like emission[f]					⊗

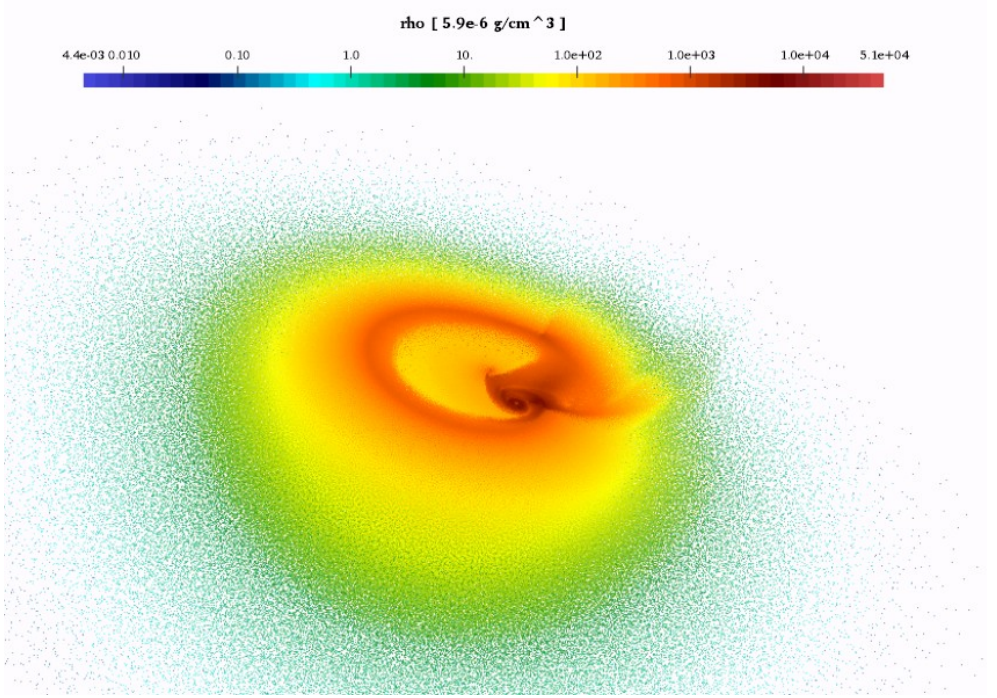
Theoretical treatment:

Rueda & Ruffini, ApJL (2012)
Fryer, Rueda, Ruffini, ApJL (20
Becerra, et al. ApJ (2015)
Fryer, et al. PRL (2015)
Becerra, et al. ApJ (2016)
Cipolletta, et al., PRD (2017)
Becerra, et al.ApJ (2018)
Becerra, et al. ApJ (2019)
Wang, et al., ApJ (2019)
Ruffini, et al., ApJ (2020)
Rueda, et al., ApJ (2020)
Rueda & Ruffini, EPJC (2020)



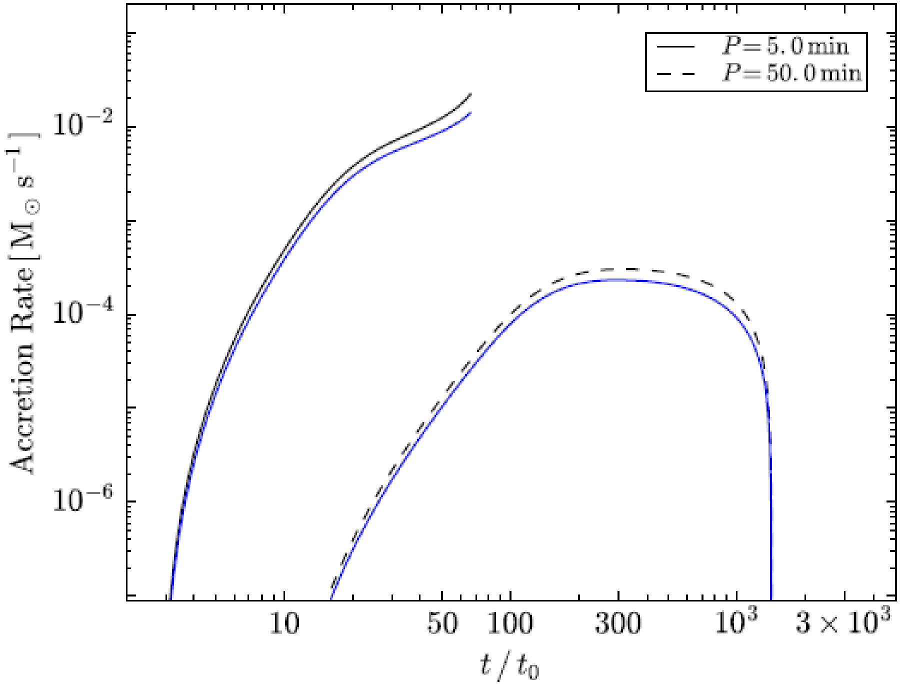
3D SPH simulations of BdHNe

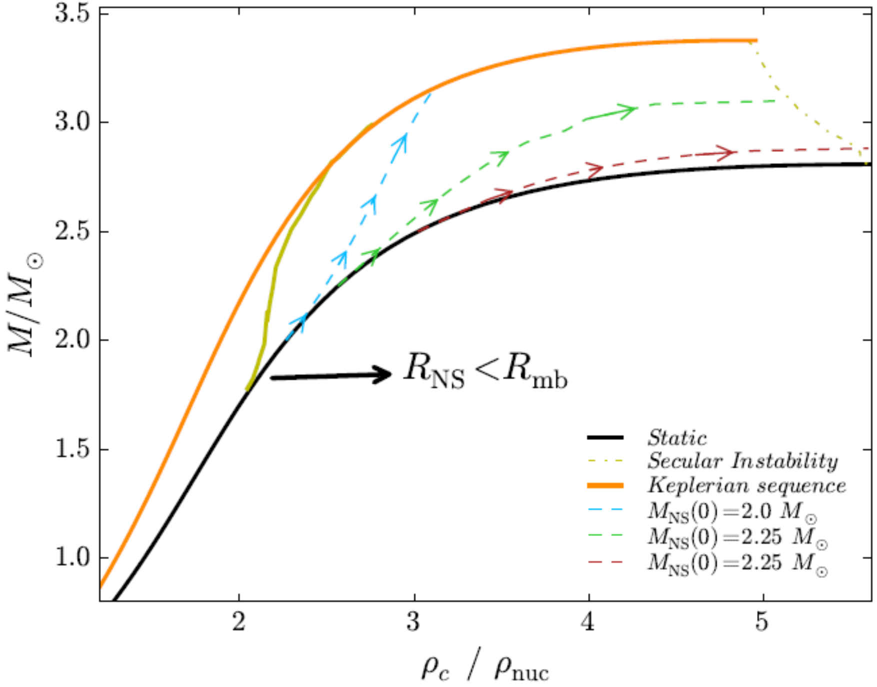




Becerra, Ellinger, Fryer, Rueda, Ruffini; ApJ 871, 14 (2019); arXiv:1803.04356

NS evolution to the BH formation point





Becerra, Cipolletta, Fryer, Rueda, Ruffini, ApJ 2015; arXiv: 1505.07580
ApJ 2016; arXiv:1606.02523
Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD (2017)

“Papetrou-Wald” solution: magnetic field around a Kerr black hole

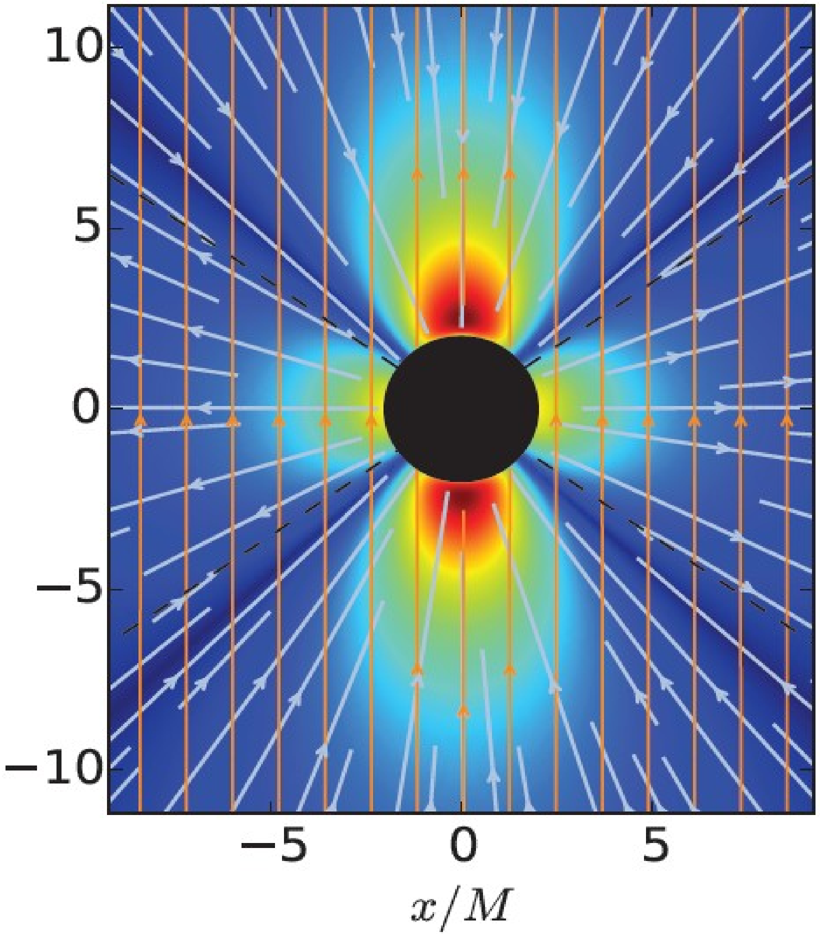
$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right)dt^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2 + \frac{A}{\Sigma}\sin^2\theta d\phi^2 - \frac{4aMr\sin^2\theta}{\Sigma}dtd\phi,$$

$$E_{\hat{r}} = \frac{B_0 aM}{\Sigma^2 A^{1/2}}\left[2r^2\sin^2\theta\Sigma - (r^2+a^2)(r^2 - a^2\cos^2\theta)(1+\cos^2\theta)\right],$$

$$E_{\hat{\theta}} = B_0 aM\frac{\Delta^{1/2}}{\Sigma^2 A^{1/2}}2ra^2\sin\theta\cos\theta(1+\cos^2\theta),$$

$$B_{\hat{r}} = \frac{B_0\cos\theta}{\Sigma^2 A^{1/2}}\left\{(r^2+a^2)\Sigma^2 - 2Mra^2[2r^2\cos^2\theta + a^2(1+\cos^4\theta)]\right\},$$

$$B_{\hat{\theta}} = -\frac{\Delta^{1/2}}{\Sigma^2 A^{1/2}}B_0\sin\theta[Ma^2(r^2 - a^2\cos^2\theta)(1+\cos^2\theta) + r\Sigma^2].$$



Ruffini, et al., ApJ (2019)
Rueda, Ruffini, et al.; in preparation (2020)

The “blackholic quantum” of energy

$$\mathscr{E} = \hbar\, \Omega_{\rm eff}, \quad \Omega_{\rm eff} \equiv 4 \left(\frac{m_{\rm Pl}}{m_n}\right)^8 \left(\frac{\hat{a}}{\hat{M}}\right) \left(\frac{B_0^2}{\rho_{\rm Pl}}\right) \Omega_+$$

$$\varepsilon_e = \hbar\, \omega_p, \quad \omega_p \equiv \frac{4\,G}{c^4} \left(\frac{m_{\rm Pl}}{m_n}\right)^4 e\, B_0\, \Omega_+$$

Rueda & Ruffini; EPJC 80, 300 (2020); arXiv:1907.08066

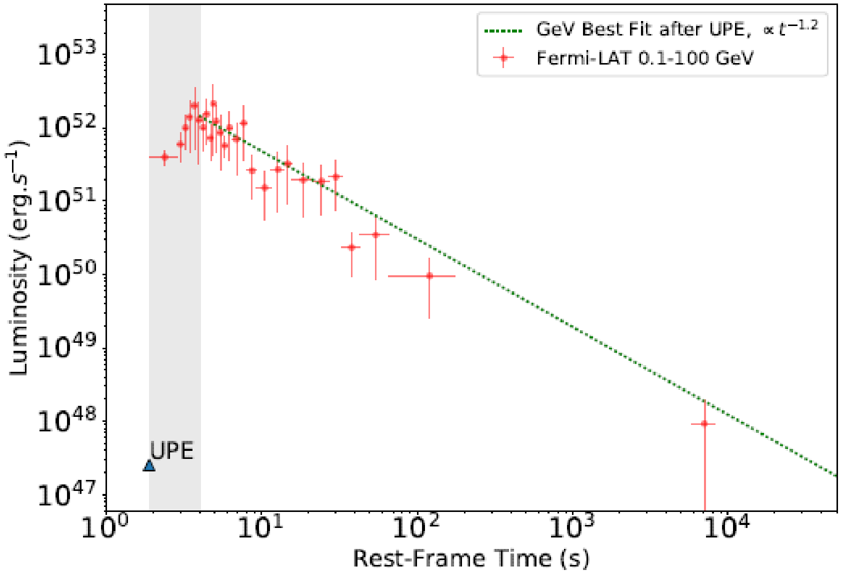
There are no losses along the BH rotation axis

ultrahigh-energy cosmic rays (UHECRs)

Table 1 *Inner engine* astrophysical quantities for GRBs and AGN. The power reported in the last row is the one to accelerate ultrahigh-energy particles, i.e. $\dot{\mathscr{E}} = \mathscr{E}/\tau_{\rm el}$. In both cases the parameters (mass, spin and magnetic field) have been fixed to explain the observed high-energy ($\gtrsim$ GeV) luminosity

	GRB (130427-like)	AGN (M87*-like)
$\tau_{\rm el}$	2.21×10^{-5} s	0.49 day
ε_e (eV)	1.68×10^{18}	1.19×10^{19}
$\mathscr{E}$ (erg)	4.73×10^{36}	5.19×10^{47}
$\dot{\mathscr{E}}$ (erg/s)	2.21×10^{41}	1.22×10^{43}

Off-axis radiation: high-energy (GeV) emission



Inner engine parameters (M, J, B) can be obtained from:

(i) GeV energy budget from BH
(ii) Mechanism: synchrotron radiation by accelerated electrons
(iii) Transparency of high-energy photons (>0.1 GeV) to magnetic pair production

Moradi, Rueda, Ruffini, Wang; submitted (2020); arXiv:1911.07552

An approximate solution of the electron synchrotron emission in the PW EM field:

Ruffini, Rueda, Moradi, et al., ApJ 886, 82 (2019); arXiv:1812.00354

$$m_e c^2 \frac{d\gamma}{dt} = e\frac{1}{2}\alpha B_0\, c - \frac{2}{3} e^4 \frac{B_0^2 \sin^2\langle\chi\rangle}{m_e^2 c^3}\gamma^2,$$

$$\gamma_{\rm max} = \frac{1}{2}\left[\frac{3}{e^2/(\hbar c)}\frac{\alpha}{\beta \sin^2\langle\chi\rangle}\right]^{1/2}$$

$$t_c = \frac{\hbar}{m_e c^2}\frac{3}{\sin\langle\chi\rangle}\left(\frac{e^2}{\hbar c}\alpha\,\beta^3\right)^{-1/2}$$

$$\begin{aligned}\epsilon_\gamma &= \frac{3e\hbar}{2m_e\, c} B_0 \sin\langle\chi\rangle\, \gamma_{\rm max}^2 = \frac{9}{8}\frac{m_e c^2}{e^2/\hbar c}\frac{\alpha}{\sin\langle\chi\rangle} \\ &\approx \frac{78.76}{\sin\langle\chi\rangle}\alpha \text{ MeV}.\end{aligned}$$

$$\frac{Du^{\hat{a}}}{d\tau} = \dot{u}^{\hat{a}} + \omega_{\hat{c}}{}^{\hat{a}}{}_{\hat{b}} u^{\hat{b}} u^{\hat{c}} = \frac{q}{m} F^{\hat{a}}{}_{\hat{b}} u^{\hat{b}} - \mathcal{F}^{\hat{a}}$$

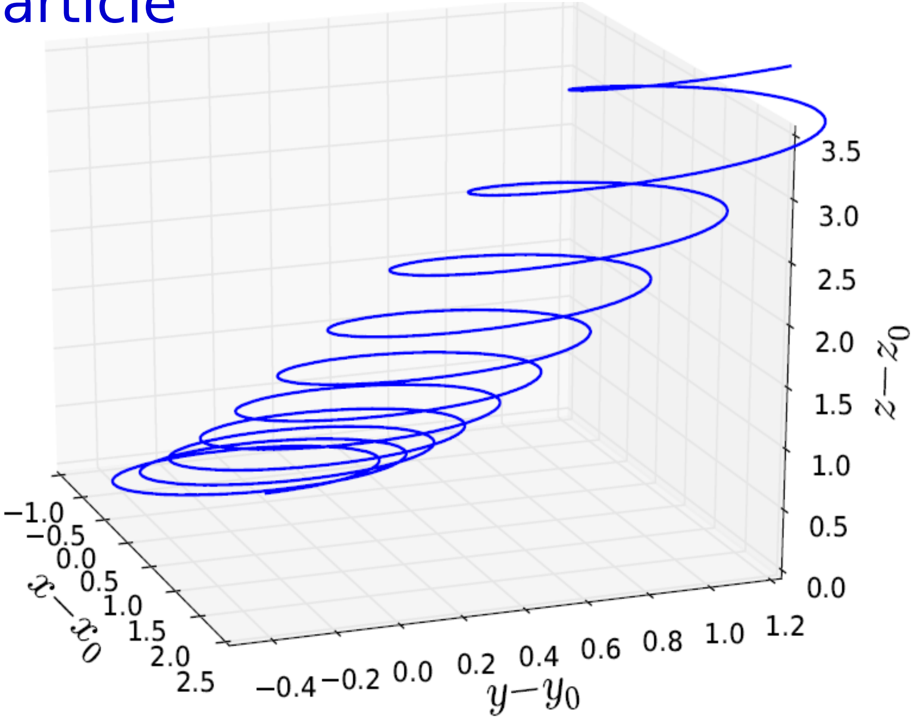
$$\mathcal{P} \equiv \frac{2}{3}\left(\frac{q}{m}\right)^2 q^2 \hat{\gamma}^3 \left[(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B})^2 - (\boldsymbol{v}\cdot\boldsymbol{E})^2\right].$$

$$\mathcal{F}^{\hat{a}} = \frac{2}{3}\left(\frac{q}{m}\right)^2 \frac{q^2}{m}\left(F_{\hat{c}\hat{d}} F^{\hat{d}}{}_{\hat{e}} u^{\hat{c}} u^{\hat{e}}\right) u^{\hat{a}} + \frac{2}{3}\left(\frac{q}{m}\right)^2 \frac{q^2}{m} F^{\hat{a}}{}_{\hat{b}} F^{\hat{b}}{}_{\hat{c}} u^{\hat{c}} + \frac{2}{3}\left(\frac{q}{m}\right)^2 q \frac{DF^{\hat{a}}{}_{\hat{b}}}{dx^{\hat{c}}} u^{\hat{b}} u^{\hat{c}} \approx \frac{2}{3}\left(\frac{q}{m}\right)^2 \frac{q^2}{m}\left(F_{\hat{c}\hat{d}} F^{\hat{d}}{}_{\hat{e}} u^{\hat{c}} u^{\hat{e}}\right) u^{\hat{a}} = -\frac{\mathcal{P}}{m} v^{\hat{a}}$$

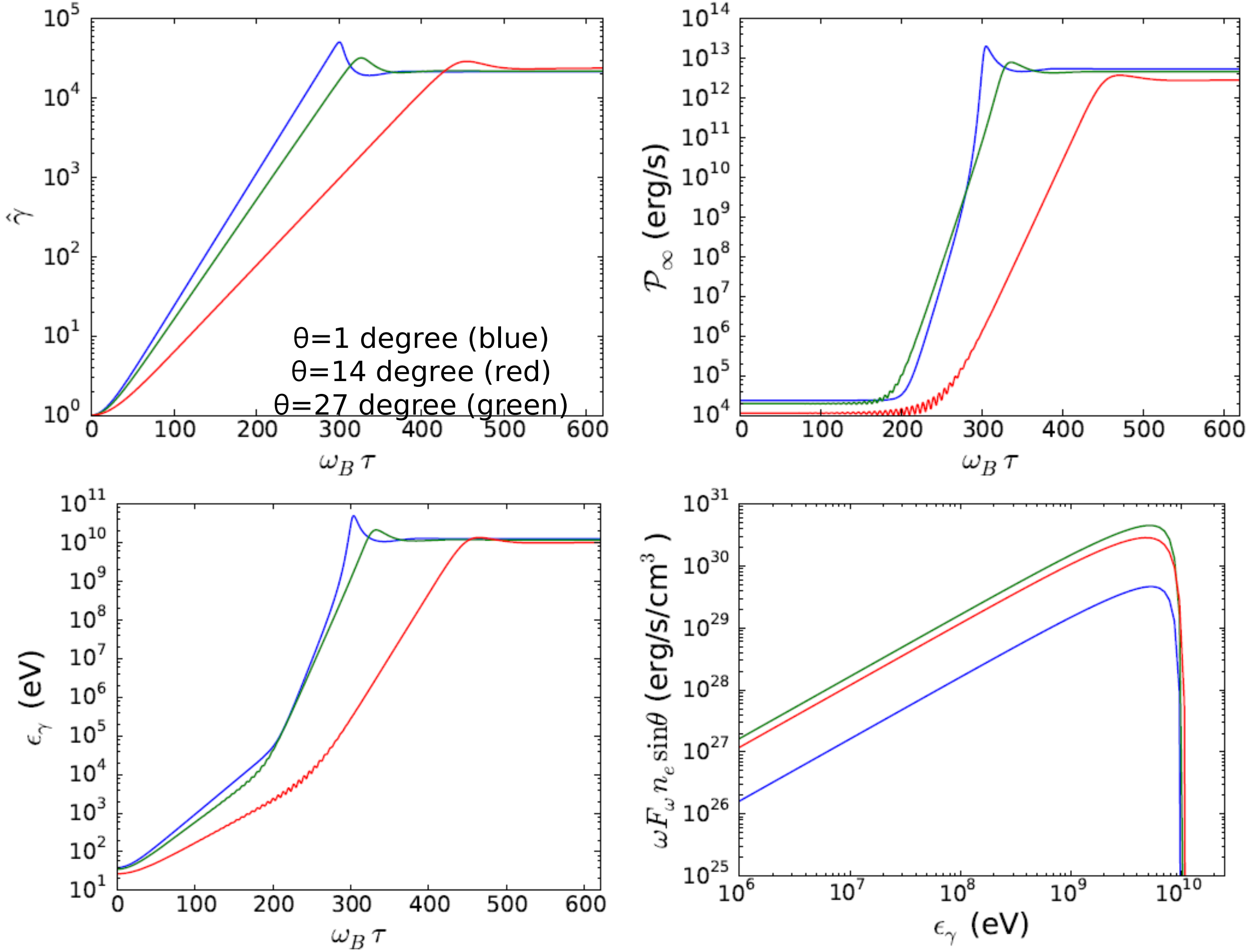
Motion of a charged, accelerated particle in the PW solution

$$\dot{\hat{\gamma}} = -\frac{e}{m} E^{\hat{r}} v^{\hat{r}} \hat{\gamma} - \frac{\mathcal{P}}{m} + \left[\frac{M}{r^2\sqrt{1-2M/r}} - \frac{6Ma\sin\theta}{r^3} v^{\hat{\theta}}\right] \hat{\gamma} v^{\hat{r}},$$

$$\begin{aligned}
\dot{v}^{\hat{i}} = &-\frac{e}{m}\left[(E^{\hat{r}} - v^{\hat{\phi}} B^{\hat{\theta}})\delta^{\hat{i}}{}_{\hat{r}} + v^{\hat{\phi}} B^{\hat{r}} \delta^{\hat{i}}{}_{\hat{\theta}} + (v^{\hat{r}} B^{\hat{\theta}} - v^{\hat{\theta}} B^{\hat{r}})\delta^{\hat{i}}{}_{\hat{\phi}} - E^{\hat{r}} v^{\hat{r}} v^{\hat{i}}\right] \\
&- \frac{\mathcal{P}}{m\hat{\gamma}} v^{\hat{i}} - \left(\frac{M}{r^2\sqrt{1-2M/r}} - \frac{6Ma\sin\theta}{r^3} v^{\hat{\theta}}\right)\hat{\gamma} v^{\hat{r}} v^{\hat{i}} \\
&- \left[\frac{6Ma\sin\theta}{r^3} v^{\hat{\phi}} + \frac{M (v^{\hat{\theta}})^2}{r^2(1-2M/r)^{5/2}} + \frac{\sqrt{1-2M/r}}{r}(v^{\hat{\phi}})^2\right]\hat{\gamma}\,\delta^{\hat{i}}{}_{\hat{r}} \\
&+ \left[\frac{M}{r^2(1-2M/r)^{5/2}} v^{\hat{r}} v^{\hat{\theta}} - \frac{\cos\theta}{r\sin\theta}(v^{\hat{\phi}})^2\right]\hat{\gamma}\,\delta^{\hat{i}}{}_{\hat{\theta}} \\
&- \left[\frac{6Ma\sin\theta}{r^3} v^{\hat{r}} - \frac{\sqrt{1-2M/r}}{r} v^{\hat{r}} v^{\hat{\phi}} - \frac{\cos\theta}{r\sin\theta} v^{\hat{\theta}} v^{\hat{\phi}}\right]\hat{\gamma}\,\delta^{\hat{i}}{}_{\hat{\phi}}.
\end{aligned}$$



Rueda, Ruffini, et al.; in preparation (2020)



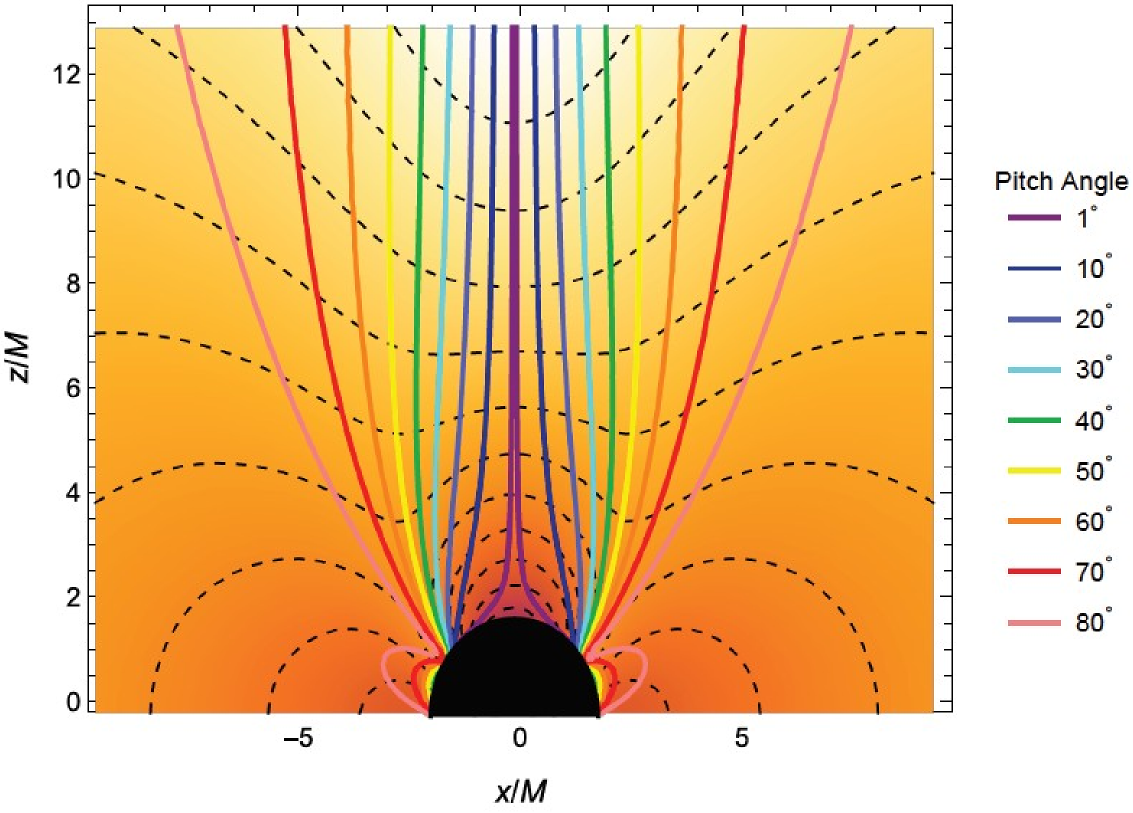
Electron accelerated from different positions near the BH:

M=4 Msun, a/M = 0.3, B = 10^{11} G

r~4M and different polar angles θ

Rueda, Ruffini, et al.; in preparation (2020)

Discussion and Conclusions



Picture taken from:
Moradi, Rueda, Ruffini, Wang; submitted (2020); arXiv:1911.07552

(i) There is ***no bulk expansion motion*** (no deceleration, so no degadration of the peak-energy of the spectrum is expected)

(ii) Electrons radiate in the >~***GeV regime*** during their acceleration

(iii) The GeV energetics is paid by the ***BH extractable energy***

(iv) The high-energy emission is produced by ***synchrotron radiation***

(v) The system is ***transparent to GeV*** photons

(vi) The GeV emission is radiated from e- with appropriate pitch angles and those occur ***within 60 degrees from the BH rotation axis***: a crucial result for the morphology of the BdHN I