Graviton-to -photon conversion effect in magnetized relativistic plasma

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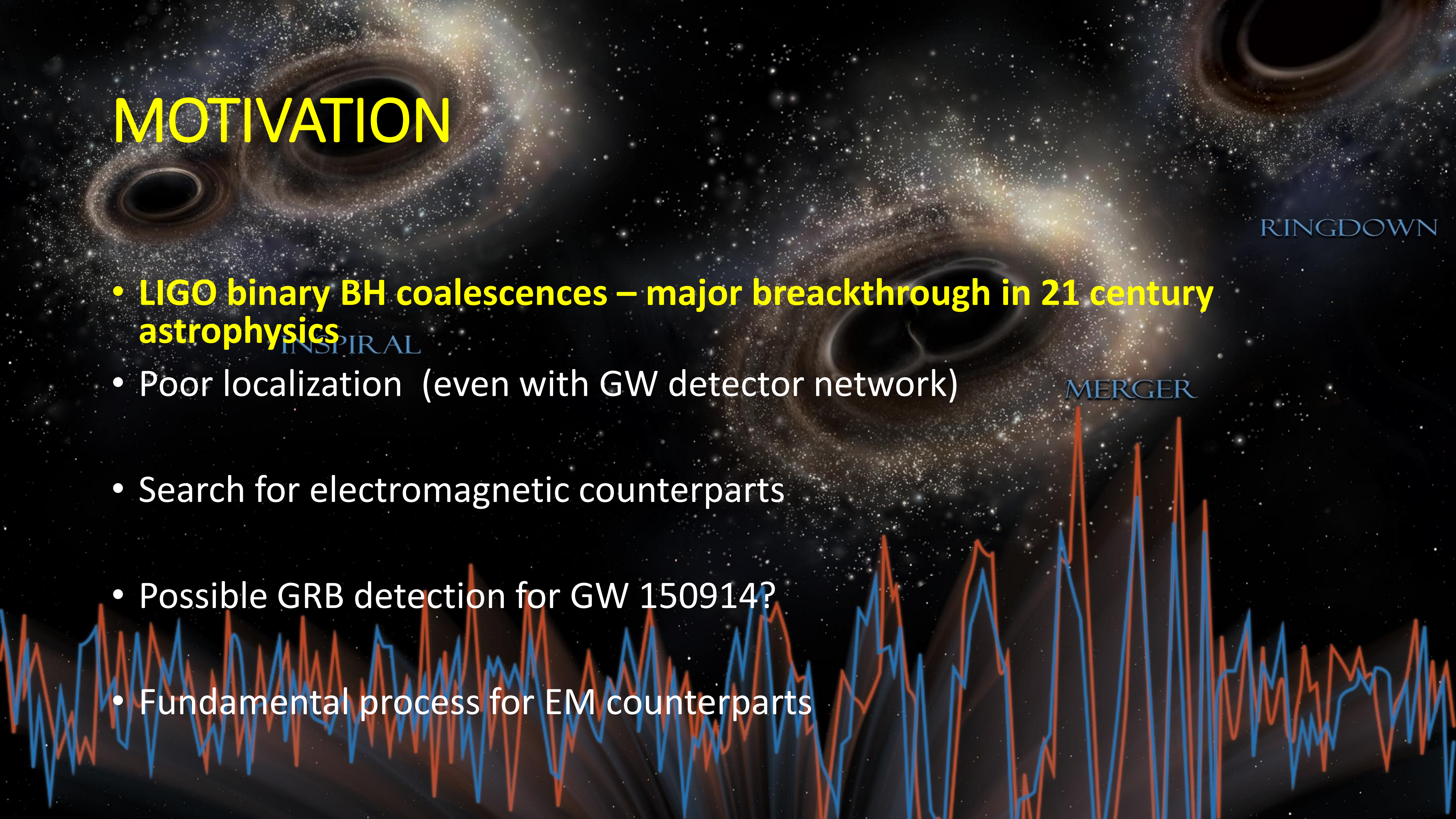
Plan

- Introduction
- Graviton-to-photon conversion
- GPh conversion in plasmas
- Application to astrophysical sources
- Conclusion

MOTIVATION

- **LIGO binary BH coalescences – major breackthrough in 21 century astrophysics**
- Poor localization (even with GW detector network)
- Search for electromagnetic counterparts
- Possible GRB detection for GW 150914?
- Fundamental process for EM counterparts



Energy release in a BH+BH coalescence:

$$E_N = (m_1 + m_2)c^2 - \frac{Gm_1 m_2}{2r}$$

$$r_{insp} \approx \frac{5G(m_1 + m_2)}{c^2} \quad \Rightarrow$$

$$\Delta E_{GW,insp} \approx \frac{1}{10}\frac{m_1 m_2}{m_1 + m_2} \approx 5\% mc^2 \sim 2.5\% Mc^2$$

$$\Delta E_{GW,total} = \Delta E_{GW,insp} + \Delta E_{GW,coal} + \Delta E_{GW,ringd} \approx 5\% Mc^2$$

$$\Delta E_{GW,total} = (M_i^{source} - M_f^{source})c^2 = 3^{+0.5}_{-0.5} M_{\odot} c^2$$

How much of this huge energy could be converted into EM radiation?

Graviton-to-photon conversion: a long story…

M.E. Gertsenshtein, *Wave resonance of light and gravitational waves*, *Sov. Phys. JETP* **14** (1962) 84 [*Zh. Eksp. Teor. Fiz.* 41 (1962) 113].

D. Fargion, *Prompt and delayed radio bangs at kilohertz by SN1987A: a test for gravitation-photon conversion*, *Grav. Cosmol.* 1 (1995) 301 [astro-ph/9604047] [INSPIRE].

G. Raffelt and L. Stodolsky, *Mixing of the photon with low mass particles*, *Phys. Rev.* **D 37** (1988) 1237 [INSPIRE].

A.D. Dolgov and D. Ejlli, *Conversion of relic gravitational waves into photons in cosmological magnetic fields*, *JCAP* **12** (2012) 003 [arXiv:1211.0500] [INSPIRE].

Graviton to photon conversion in magnetic field

$$(\omega^2 - k^2)h_\lambda(\boldsymbol{k}) = \kappa k A_\lambda(\boldsymbol{k})B_T\,, \qquad (1)$$

$$(\omega^2 - k^2 - m^2)A_\lambda(\boldsymbol{k}) = \kappa k h_\lambda(\boldsymbol{k})B_T\,, \qquad (2)$$

$A_\lambda(\boldsymbol{k})$ -- EM , $h_\lambda(\boldsymbol{k})$ -- GW,

$$g_{\mu\nu} = \eta_{\mu\nu} + \tilde{h}_{\mu\nu}, \quad h_j = \tilde{h}_j/\kappa \qquad (3)$$

$\kappa^2 = 16\pi G = 16\pi/m^2{}_{Pl}$

B_T -- transversal magnetic field

$$m^2 = \Omega^2 - \frac{2\alpha C\omega^2}{45\pi}\left(\frac{B}{B_c}\right)^2 \approx \Omega^2,$$

-- effective photon mass with Heisenberg-Euler correction and plasma frequency

$B_c = m_e^2/e$ - Schwinger field

$\Omega^2 = n_e e^2/m_e$ - Plasma frequency

- Eigenvalues:

$$k_1 = \pm\omega\sqrt{1+\zeta^2}, \;\; k_2 = \pm i m\sqrt{(1-\zeta^2)(1-\eta^2)},$$

$$\zeta^2 = (\kappa B)^2/m^2 \ll 1, \;\; \eta^2 = \omega^2/m^2$$

- Eigenvectors: $A_1 = \eta\zeta h_1$, Creation of photons by gravitons in magnetic field

  $h_2 = i\zeta A_2$ Creation of gravitons by photons
  Purely imaginary ➔ EM damping in plasma

- Solution A_1 means permanent creation of photons when GW passes through magnetized plasma (Dolgov, Ejili'12)

Conversion coefficient

- Eigenfunctions of system (1), (2)

$$A_j = \frac{\kappa B \omega}{\omega^2(1-\epsilon) - \Omega_e^2} h_j \approx \frac{\kappa B \omega a_e}{\Omega_e} h_j \qquad (4)$$

ε-- dielectric permeability, $a_e^2 = \frac{T_e}{e^2 n_e}$ -- Debye radius

- Take imaginary part of ε to find the GW-to-EM conversion coefficient

$$K \equiv \frac{\rho_\gamma}{\rho_{GW}} = \left(\frac{\kappa B \omega a_e}{\Omega_e}\right)^2 \qquad (5)$$

1) Non-relativistic plasma (Dolgov, Postnov ‘17)

$n_e = 0.1$ см$^{-3}$ - ISM density, $T_e = 1eV$

$a_e \approx 10^3 cm, \Omega_e = 3 \times 10^4\ rad/s, \omega = 2 \times 10^3 \mathrm{rad/s}$

$$K \approx 10^{-46} \left(\frac{\omega}{\Omega_e}\right)^2 \left(\frac{a_e}{1cm}\right)^2 \left(\frac{B}{1\ G}\right)^2 \qquad (6)$$

Maximum possible effect during BH-BH coalescence in ISM:

$B^2/(8\pi) = \epsilon_B \rho$ $\quad T = \epsilon_T m_e$ $\quad a_e^2 \sim \epsilon_T (m_e m_p)/(4\pi\alpha\rho) = \epsilon_T/\Omega^2$

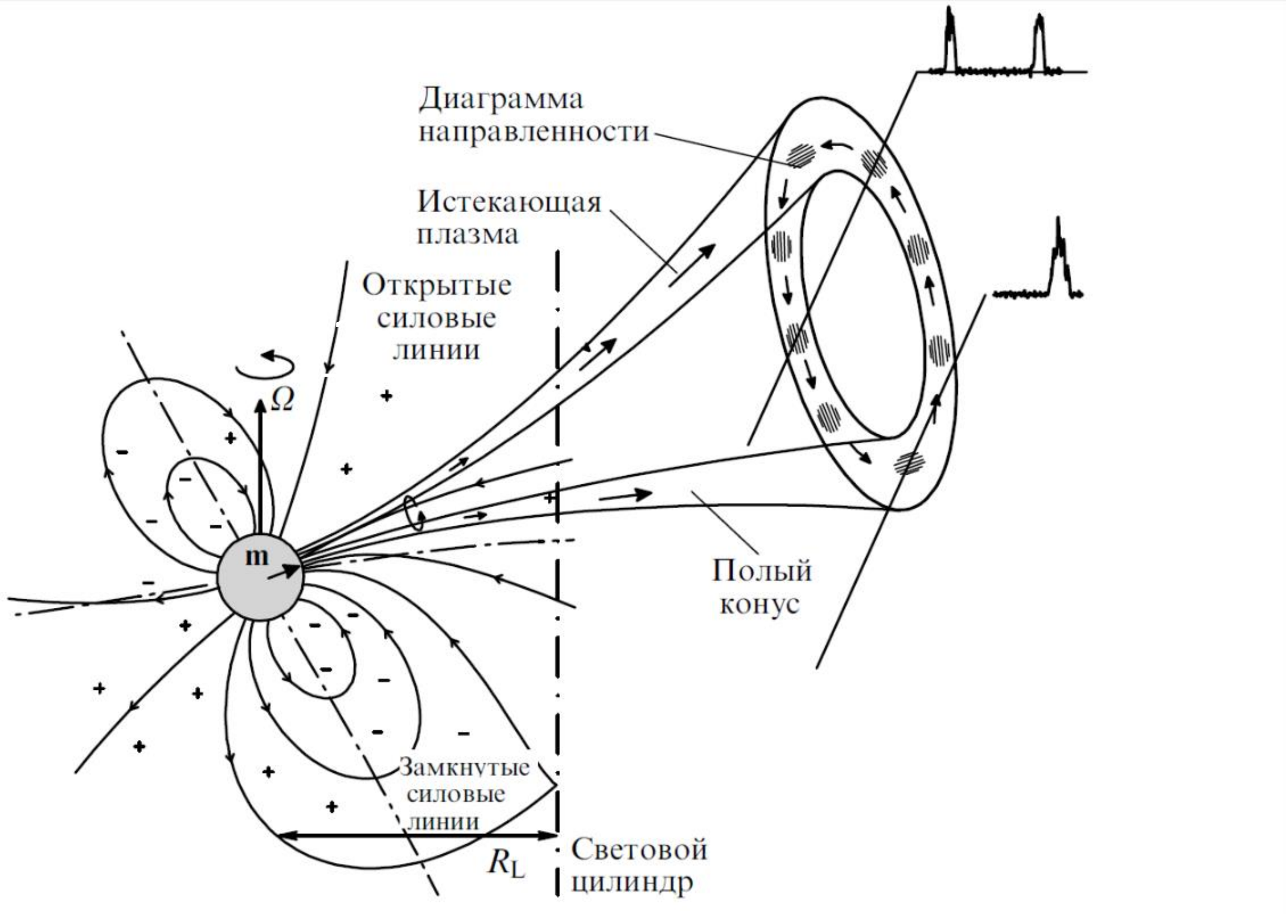
$$K \le \epsilon_B \epsilon_T \frac{32\pi}{\alpha} \left(\frac{\omega}{\Omega}\right)^2 \left(\frac{m_e}{m_p}\right) \left(\frac{m_p}{m_{\mathrm{Pl}}}\right)^2 \sim 10^{-37} \epsilon_B \epsilon_T \ll 1$$

$$\left(\frac{\omega}{\Omega}\right)^2 \simeq \frac{1}{2} \left(\frac{m_{\mathrm{Pl}}}{M}\right)^2 \frac{m_{\mathrm{Pl}}^2 (m_p m_e)}{4\pi\alpha\rho} \approx \left(\frac{3M_\odot}{M}\right)^2 \left(\frac{\rho}{10^{-24} \mathrm{g\,cm}^3}\right)^{-1}$$

2) Relativistic lepton plasma: the case of BH+NS coalescences

$$R_l = \frac{c}{\omega_{NS}} - light\ cylinder$$

ω_{NS} – pulsar spin frequency



Relativistic plasma creation in pulsars

Dielectric permeability of collisional plasma

- $\epsilon_T - 1 = -\frac{1}{(ka_e)^2} - \frac{1}{(ka_i)^2} + i\sqrt{\frac{\pi}{2}}\frac{\Omega_e^2}{\omega k a_e}$ (9)
- $\epsilon_T^R - 1 = \frac{2\pi e^2 n_e}{\omega(\omega+i\nu)}\left\{1 + \left[\frac{(\omega+i\nu)^2}{k^2} - 1\right]\left(1 - \frac{\omega+i\nu}{2k}\ln\frac{\omega+i\nu+k}{\omega+i\nu-k}\right)\right\}$ (15)
- $Im\ \epsilon_T^R = \frac{3}{4}\frac{\Omega_{rel}^3}{\omega^4}\left(\Omega_{rel}\ Arg\left(1 - \frac{2i\omega}{\Omega_{rel}}\right) + 2\omega\left(1 - \frac{1}{2}\ln\frac{\Omega_{rel}^2+4\omega^2}{\Omega_{rel}^2}\right)\right)$ (16)

(If $\frac{2\omega}{\Omega_{rel}} \ll 1$)

Insert imaginary part of dielectric permeability of relativistic plasma (16) into Eq. (4):

$$A_j \approx \frac{\kappa B\omega}{\omega^2\left(\frac{\Omega_{rel}}{\omega}\right)-\Omega_{rel}^2} h_j = \frac{\kappa B\omega}{\Omega_{rel}^2\left(\frac{\omega}{\Omega_{rel}}-1\right)} h_j \approx \frac{\kappa B\omega}{\Omega_{rel}^2} h_j \qquad \left(\frac{2\omega}{\Omega_{rel}} \ll 1\right).$$

Relativistic vs non-relativistic plasma

$$K_{nr} = \left(\frac{\kappa B \omega a_e}{\Omega_e}\right)^2$$

$$K_{ur} = \left(\frac{\kappa B \omega}{\Omega_{rel}^2}\right)^2$$

Transition to non-relativistic case: $\gamma \to 1$

$$\frac{\kappa B \omega}{\Omega_{rel}^2} = \frac{\kappa B \omega}{\Omega_{rel}\,\Omega_{rel}} = \kappa B \omega \left(\frac{T_e}{n_e e^2}\right)^{\frac{1}{2}} \left(\frac{T_e}{n_e e^2}\right)^{\frac{1}{2}} = \kappa B \omega \left(\frac{\gamma m_e}{n_e e^2}\right)^{\frac{1}{2}} \left(\frac{T_e}{n_e e^2}\right)^{\frac{1}{2}} = \frac{\kappa B \omega a_e}{\Omega_e}$$

Conversion coefficient in relativistic plasma

$B = \frac{B_0 R_0^3}{{R_l}^3} \approx 1\ G \left(\frac{P}{1s}\right)^{-3} \left(\frac{B_0}{10^{12} G}\right)$ – magnetic field at the l. c. *(wave-zone)*

$n_{e\ rel} = \lambda n_{GJ}$, λ – plasma multiplicity,

n_{GJ}=(ΩB)/2πe – Goldreich-Julian density

$$K_{rel} = \left(\frac{\kappa B \omega}{\Omega_{rel}^2}\right)^2 \approx 10^{-35} \left(\frac{\omega}{100\ rad/s}\right)^2 \left(\frac{P}{1\ s}\right)^2 \left(\frac{\lambda}{10^5}\right)^{-2} \left(\frac{\gamma}{10^5}\right)^2 \quad (8)$$

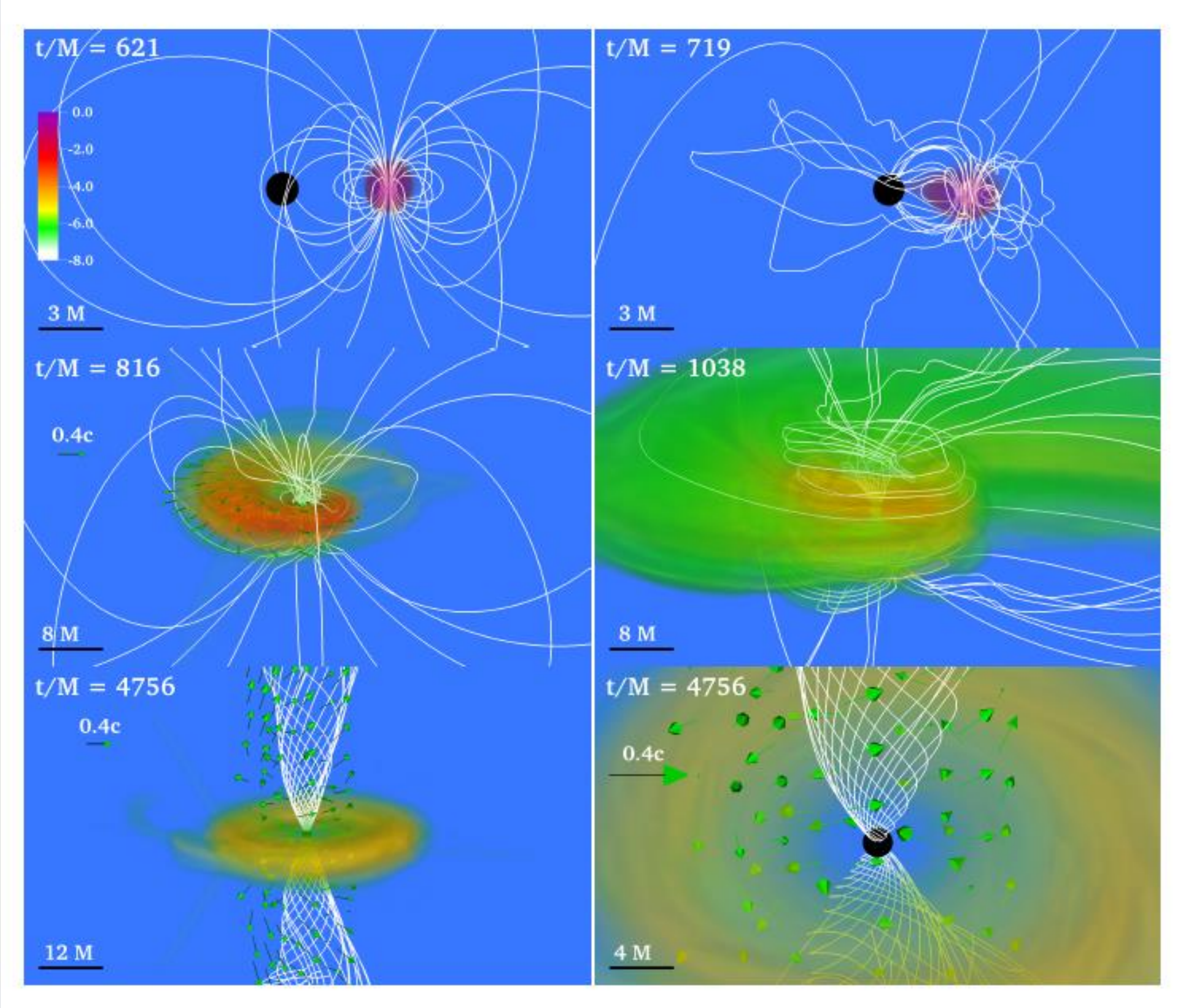
Importantly, the NS magnetic field cancels out!

Relativistic vs non-relativistic case

- $K \approx 10^{-46} \left(\frac{\omega}{\Omega_e}\right)^2 \left(\frac{a_e}{cm}\right)^2 \left(\frac{B}{1\ G}\right)^2$
- $K_{rel} \approx 410^{-34} \left(\frac{f_{GW}}{100\ Hz}\right)^2 \left(\frac{P}{1\ s}\right)^2 \left(\frac{\lambda}{10^5}\right)^{-2} \left(\frac{\gamma}{10^5}\right)^2$

Astrophysical prospects

- NS+BH coalescences are awaited
- GW to EM conversion in the wave zone of a pulsar+ BH coalescence is rather small
- In the strong-field zone, the conversion could be much higher: jet launching during coalescences is anticipated with the MRI field enhancement up to 10^{15} G (arXiv:1810.08618)



Conclusions

- Graviton to photon conversion effect in a magnetized relativistic plasma is studied
- General formula for the effect applicable to the wave zone in a PSR+BH coalescence is obtained
- The effect can be amplified in the case of early jet launching (before the NS is fully disrupted and accretion disc is formed)
- Low-density relativistic plasma density before the coalescence → EM precursors to short GRBs?