QUARKS-2026

Electromagnetic response to impulsive gravitational impact

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Why it might be interesting?

Experimental gravitational physics beyond LIGO:

- Another frequency range
- Another tests of General Relativity
- Another astrophysical phenomena to observe

New concepts for a gravitational experiment are currently being actively considered.

One of the most promising areas is the detection of an electromagnetic signal generated by a gravitational wave:

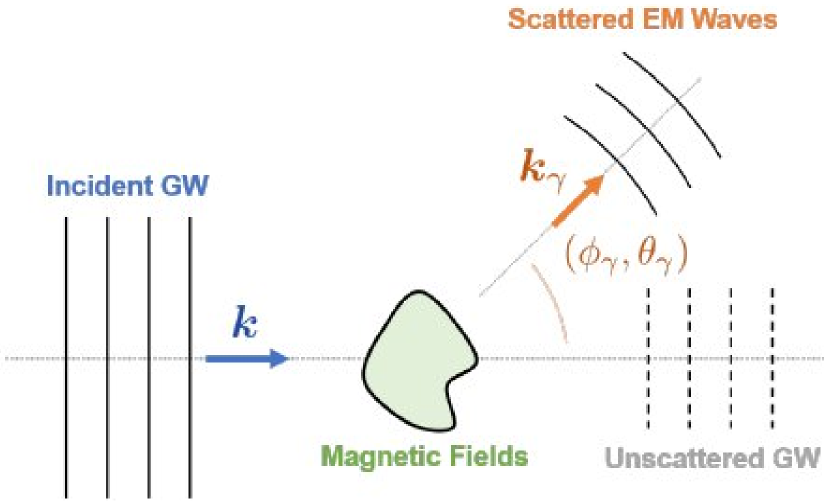
- There is already a network of radio telescopes. They can search for EM signals produced by GW to EMW conversion in various scenarios.
- Various experiments on detecting tiny EM perturbations (e.g. by axions) already exist or are being planned. They can be modified to detect perturbations due to GW-EM coupling.

However, currently only weak monochromatic GWs are considered in these scenarios!

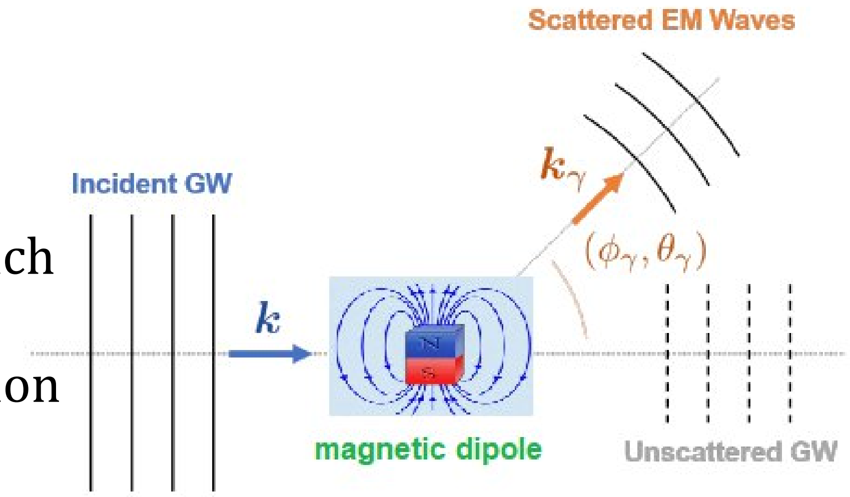
GW-EM coupling

Weak Monochromatic GW

Gertsenshtein-Zeldovich effect:

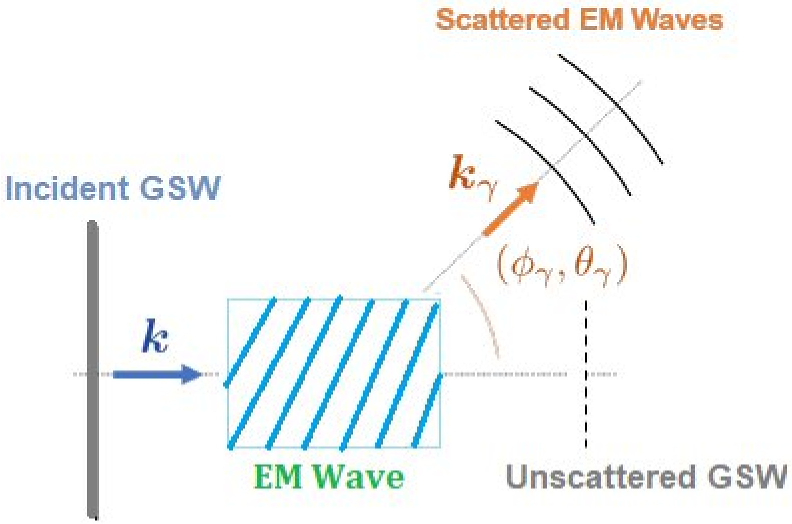


Ginsburg-Tsytovich effect
(a kind of transition scattering):

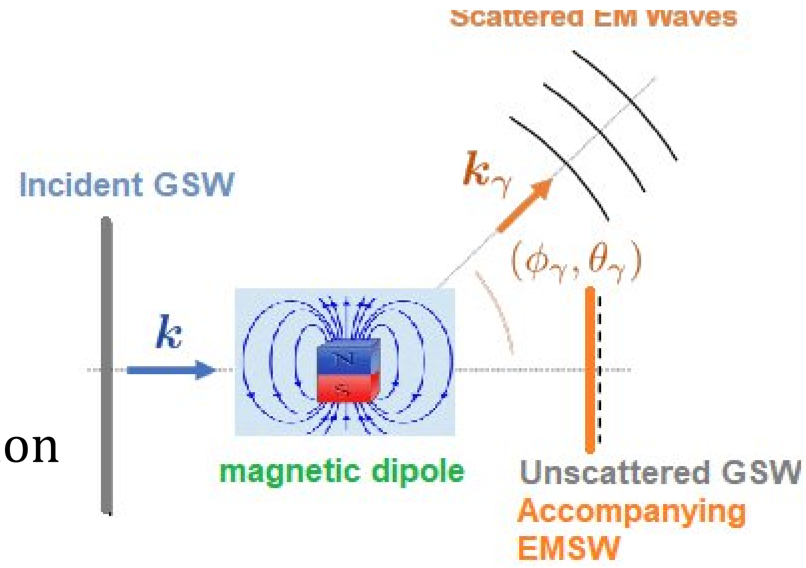


Gravitational Shock Wave (GSW)

GSW and monochromatic wave
(t'Hooft at microscopic level)



GSW and point source
(a kind of transition radiation)



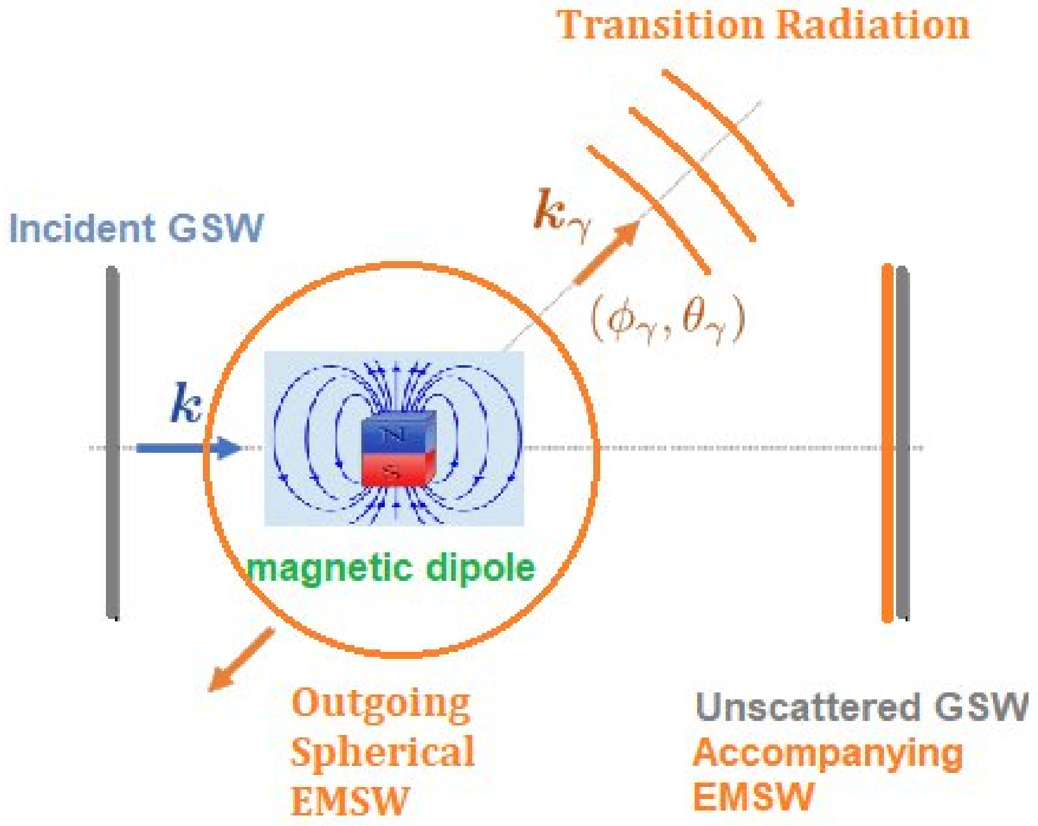
GSW interacts with EM field of point source

The process contains **three** phenomena:

EM Shock Wave accompanying GSW due to “jumps” of geometric quantities at GSW front (Lichnerowicz)

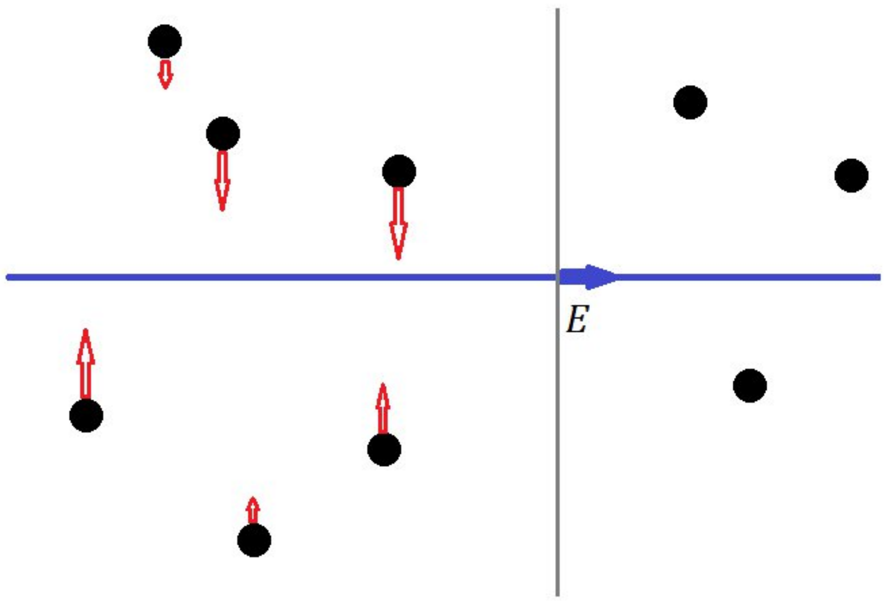
Instantaneous EM Bremsstrahlung due to change of velocity of the source behind GSW front (particle’s velocity **memory**), resulting in spherical EM Shock Wave (Barrabes, Hogan)

EM **Transition Radiation** due to the fact that the field of a source also acquires **memory** behind the GSW front

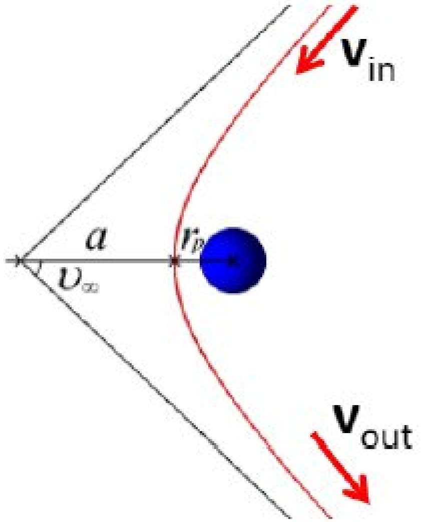


Gravitational Memory Effect

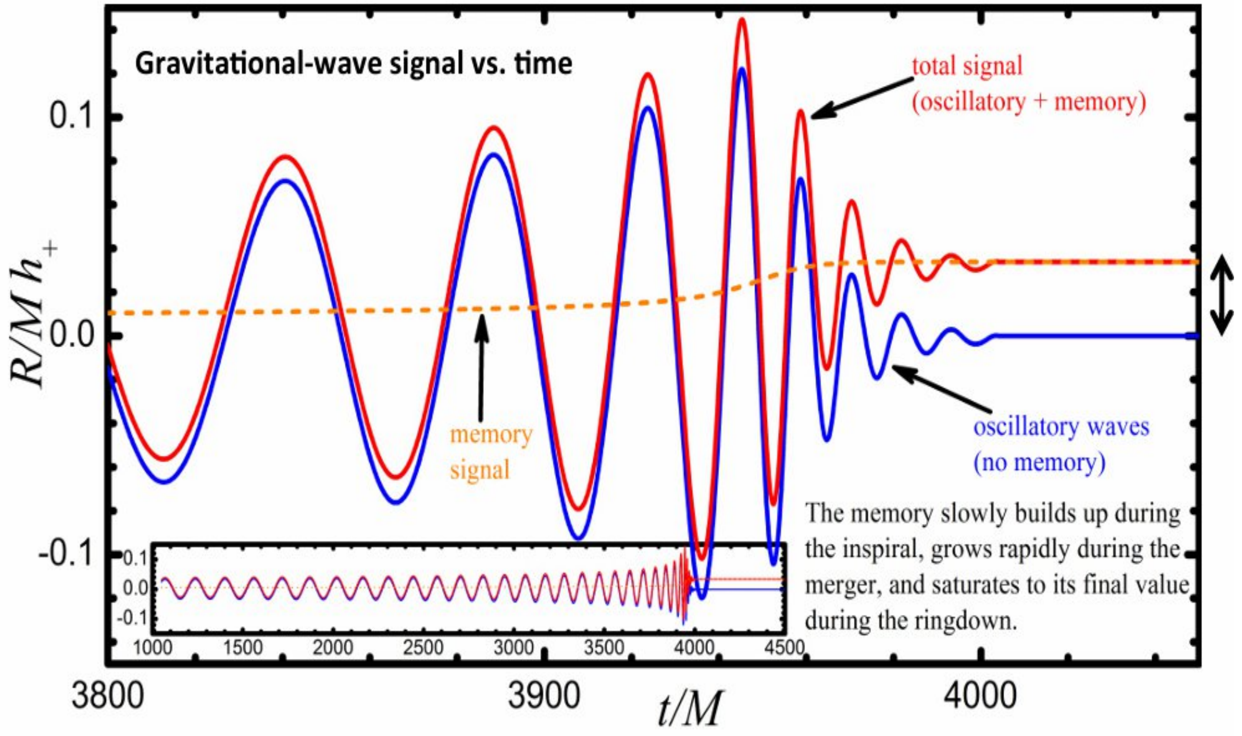
Recoil effect when GSW (e.g. generated by ultrarelativistic object with energy E) passes through the system of test particles: *velocity memory* of test particles



Coordinate memory due to hyperbolic flyby (Zeldovich, Polnarev, Braginsky, Christodoulou)



Search for coordinate memory in LIGO



GSW-EM interaction in terms of memory: the geometry

Let $\mathcal{N}$ be a smooth hypersurface - the front of GSW, $l_\mu = \partial_\mu \mathcal{N}$, $du = l_\mu dx^\mu$. $\mathcal{N}$ is located at $u = 0.$

Let $(l, n, m, \bar{m})$ be a double null tetrade, so that $m \cdot \bar{m} = -l \cdot n = 1$.

The scalar product is given by the smooth background metric: $\tilde{g}^{\mu\nu} = -l^\mu n^\nu - n^\mu l^\nu + m^\mu \bar{m}^\nu + \bar{m}^\mu m^\nu$.

The full metric (background + shock wave) is $g_{\mu\nu} = \tilde{g}_{\mu\nu} + \chi(u) f(x) l_\mu l_\nu$, $\partial_l f = 0$.

l^μ is geodesic and null for both metrics.

The "shock" is described by $\chi(u) \to \delta(u)$, $\chi^{(1)}(u) \to \theta(u)$, $\chi^{(2)}(u) \to u\theta(u)$, $\ldots,$

The "directions" reflecting the GSW geometry: $D = l \cdot \tilde{\nabla}$, $\delta = m \cdot \tilde{\nabla}$, $\bar{\delta} = \bar{m} \cdot \tilde{\nabla}$, (along GSW) $\Delta = n \cdot \tilde{\nabla}$. (across GSW)

Spin coefficients describe the geometry of background and the front of GSW: flat background, Ricci-flat background, flat GSW front, spherical or cylindrical GSW front or any.

$$\kappa = -m \cdot Dl \ , \quad \rho = -m \cdot \bar{\delta} l \ , \quad \sigma = -m \cdot \delta l \ , \quad \tau = -m \cdot \Delta l \ ,$$

$$\pi = \bar{m} \cdot Dn \ , \quad \lambda = \bar{m} \cdot \bar{\delta} n \ , \quad \mu = \bar{m} \cdot \delta n \ , \quad \nu = \bar{m} \cdot \Delta n \ ,$$

$$\varepsilon = \frac{1}{2}(n \cdot Dl - \bar{m} \cdot Dm) \ , \quad \alpha = -\frac{1}{2}(n \cdot \bar{\delta} l - \bar{m} \cdot \bar{\delta} m) \ ,$$

$$\beta = -\frac{1}{2}(n \cdot \delta l - \bar{m} \cdot \delta m) \ , \quad \gamma = -\frac{1}{2}(n \cdot \Delta l - \bar{m} \cdot \Delta m) \ .$$

GSW-EM interaction in terms of memory: the equations of motion

Outside the source, the electromagnetic field satisfies the equations

$$g^{\alpha\mu}\nabla_\alpha F_{\mu\nu} = 0 \ , \quad \partial_{(\alpha}F_{\mu\nu)} = 0 \ .$$

The GSW contribution can be rewritten as an effective current:

$$\tilde{\nabla}^\mu F_{\mu\nu} = j_\nu \ , \quad \partial_{(\alpha}F_{\mu\nu)} = 0 \ ,$$
$$j_\nu = \chi\left(f(D-2\rho)F_{l\nu} - 2\Re\left[F_{lm}\bar{\delta}(f l_\nu)\right]\right) .$$

The effective current is conserved due to $0 = \tilde{\nabla}^\nu\tilde{\nabla}^\mu F_{\mu\nu} = \tilde{\nabla}^\nu j_\nu$, then $(D-2\rho)j_n + 2\Re\left[(\bar{\delta}+\pi-2\alpha)j_m\right] = 0$

Let us introduce EM NP scalars: $\Phi_0 = F_{lm} \ , \quad \Phi_1 = \frac{1}{2}(F_{ln} + F_{\bar{m}m}) \ , \quad \Phi_2 = F_{\bar{m}n} \ .$

The Maxwell equations are:

$$(D-2\rho)\Phi_1 - (\bar{\delta}+\pi-2\alpha)\Phi_0 = 0 \ ,$$
$$(\Delta+2\mu)\Phi_1 - (\delta+2\beta-\tau)\Phi_2 - \nu\Phi_0 = -\chi\Re\left(\bar{\delta}(f\Phi_0) + (\pi-\alpha+\bar{\beta})f\Phi_0\right) \ ,$$
$$(D-\rho+2\varepsilon)\Phi_2 - (\bar{\delta}+2\pi)\Phi_1 + \lambda\Phi_0 = \frac{1}{2}\chi f D\bar{\Phi}_0 \ ,$$
$$(\Delta-2\gamma+\mu)\Phi_0 - (\delta-2\tau)\Phi_1 - \sigma\Phi_2 = -\frac{1}{2}\chi f D\Phi_0 \ .$$

The l.h.s is standard for Maxwell equations in NP formalism,
the r.h.s. is the effective current due to GSW-EM interaction.

GSW-EM interaction in terms of memory: the solution

Near the GSW front we can look for a solution in the form of an expansion

$$\Phi_I = \tilde{\Phi}_I + \Phi_I^{(0)}\chi(u) + \Phi_I^{(1)}\chi^{(1)}(u) + O(\chi^{(2)}(u)), \quad I = 0..2.$$

Unperturbed — EMSW — EM Memory

Let's substitute the ansatz into the equations.

Accompanying EMSW from the equation on $\mathcal{N}$:

$$\Phi_0^{(0)} = \Phi_1^{(0)} = 0\ ,$$
$$(D - \rho + 2\varepsilon)\Phi_2^{(0)} = \frac{1}{2} f D\bar{\tilde{\Phi}}_0\ .$$

EM memory from the system of equations on $\mathcal{N}$:

$$\Phi_0^{(1)} = \frac{1}{2} f D\tilde{\Phi}_0 - \sigma\Phi_2^{(0)}\ ,$$
$$(D - 2\rho)\Phi_1^{(1)} = (\bar{\delta} + \pi - 2\alpha)\Phi_0^{(1)}\ ,$$
$$(D - \rho + 2\varepsilon)\Phi_2^{(1)} = (\bar{\delta} + 2\pi)\Phi_1^{(1)} - \lambda\Phi_0^{(1)}$$

The flat case

Let the background be flat and the GSW be plain-fronted (spin coefficients vanish, formulas become simpler). Then $\mathcal{N}$ is a Cauchy surface, and one can solve the Cauchy problem to find the EM field perturbation behind the GSW front, the $\mathcal{M}^+$ region of spacetime. The Cauchy data is the EM memory.

$$\Phi_I = \tilde{\Phi}_I + \breve{\Phi}_I , \quad I = 0..2 , \quad x \in \mathcal{M}^+ ,$$

$\tilde{\Phi}_I$ — Unperturbed; $\breve{\Phi}_I$ — Perturbation

The characteristic Cauchy problem:

$$\Box \breve{\Phi}_0 = 0 , \quad x \in \mathcal{M}^+ ,$$
$$\breve{\Phi}_0 = \frac{1}{2} f D \tilde{\Phi}_0 , \quad x \in \mathcal{N} .$$

Plus the condition of a sufficiently rapid decrease of the field at spatial infinity (fulfilled for point sources).

The remaining components of the Maxwell tensor can be found from $D\breve{\Phi}_1 = \bar{\delta}\breve{\Phi}_0 , \quad DD\breve{\Phi}_2 = \bar{\delta}\bar{\delta}\breve{\Phi}_0 .$

Same formulas for those who don't like NP formalism:

$$\Box \hat{F}_{vi} = 0 , \quad u > 0 ,$$
$$\hat{F}_{vi} = \partial_v (f \bar{F}_{vi}) , \quad u = 0 .$$

$$\hat{F}_{uv} = -\frac{1}{2} \int_{-\infty}^{v} \partial_i \hat{F}_{vi} \, dv' , \quad \hat{F}_{ui} = \int_{-\infty}^{v} \left(\partial_u \hat{F}_{vi} + \partial_i \hat{F}_{uv} \right) dv' , \quad \hat{F}_{ij} = \int_{-\infty}^{v} \left(\partial_i \hat{F}_{vj} - \partial_j \hat{F}_{vi} \right) dv' .$$

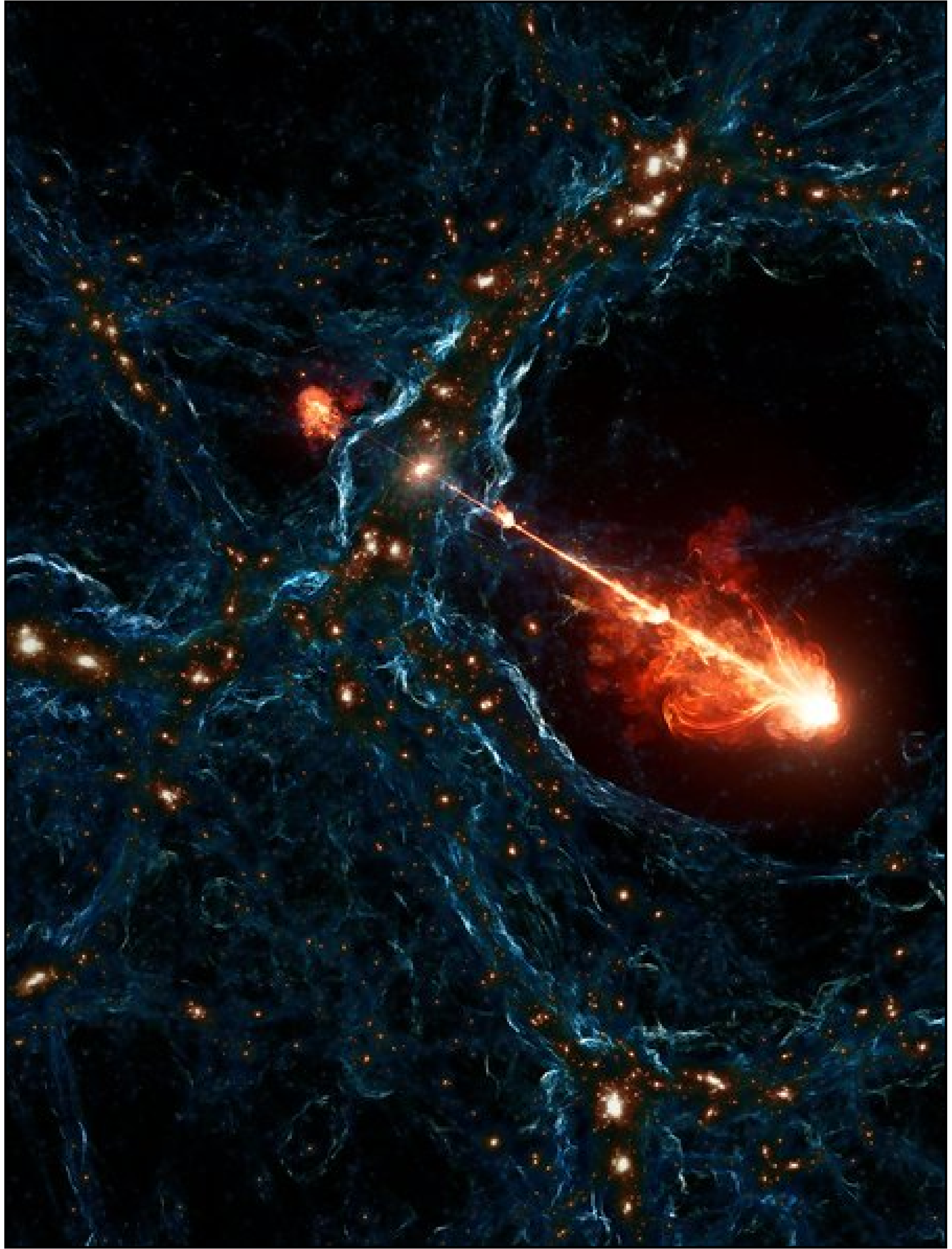
Applications

GSW sources:

- Ultrarelativistic objects space (e.g. jets from supermassive black holes)
- Ultrareltivistic objects in laboratory (e.g. femtosecond laser pulses, beams of particles)
- Early Universe...

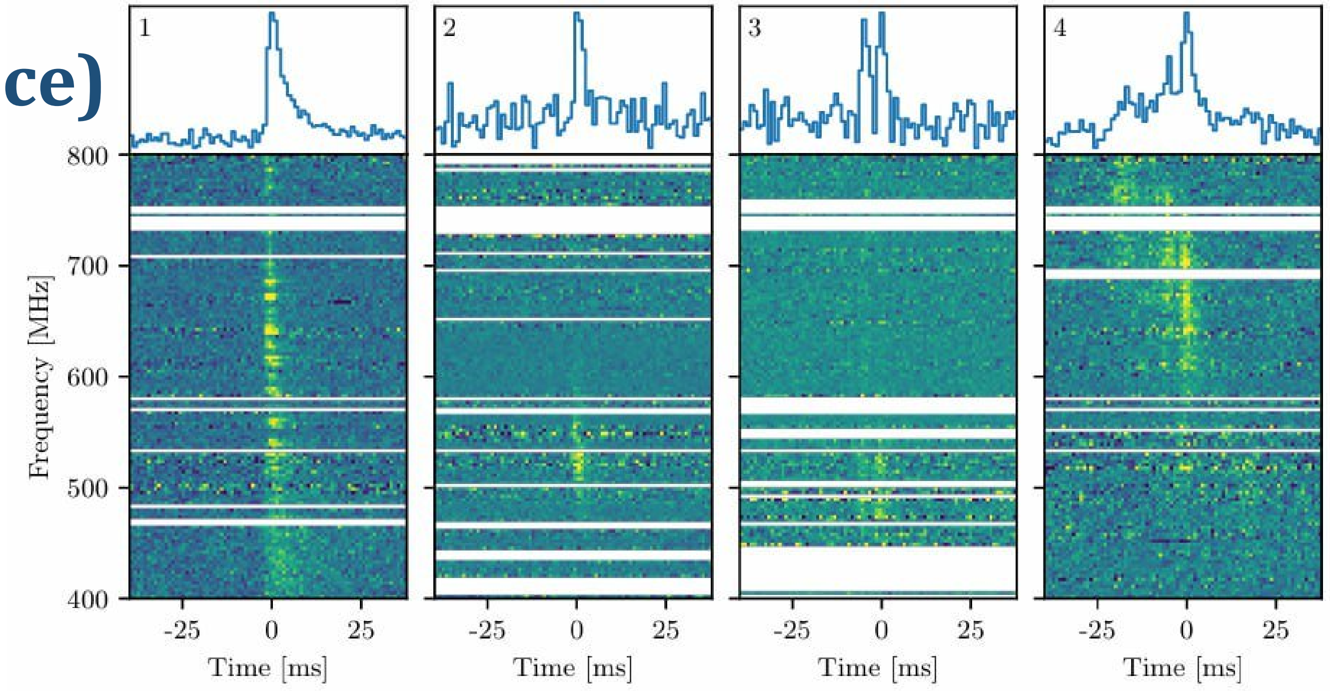
EM sources:

- In Cosmos (pulsars, magnetars, accretion discs)
- Laboratory magnetic field sources



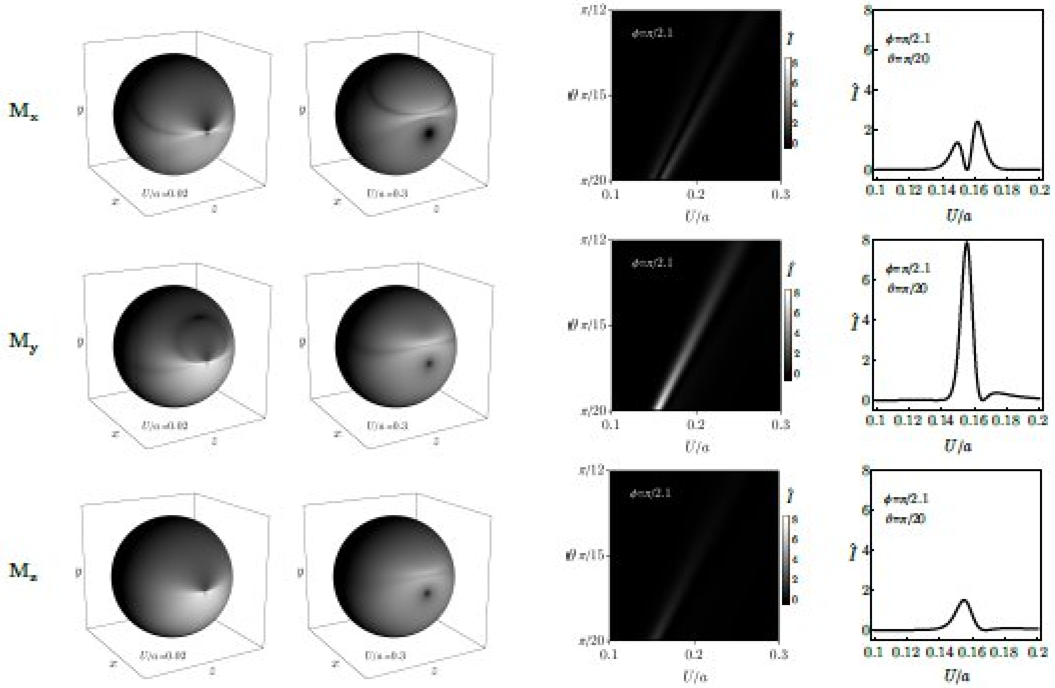
Fast Radio Bursts (come from space)

- frequencies of the order of hundreds of MHz;
- duration of the order of a millisecond;
- may have a non-trivial time profile with sub-peaks;
- irregular repetitions are possible;
- assuming an isotropic burst, the energy is up to 10^{35} J;
- many sources have been identified as magnetars



If FRB occurs as a result of an EM response to an impulsive gravitational impact:

- the source should be a magnetar (the strongest EM source);
- duration is the time for light to cross the near-magnetosphere region, about millisecond;
- the time profile depends on the dipole and quadrupole moments;
- the burst is significantly anisotropic, which resolves the issue of the energy source for repeating bursts.



Summary

A new type of GW-EM coupling is considered: **Transition Radiation on GSW**.

> *If the boundary between two media (with different permittivity/permeability) moves towards the EM source, transition radiation occurs due to the reconfiguration of the EM field at the boundary.*

Gravitaional Shockwave is a boundary between two spacetime regions which moves toward the EM source. Transition radiation occurs due to the reconfiguration of the EM field at the GSW front.

There are various scenarios where ultra-relativistic objects may perturb electromagnetic fields. It is possible that some of these phenomena are potentially observable.

Thank you for your attention!