HIGH FREQUENCY GW BOUNDS FROM GALACTIC NEUTRON STARTS

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JCAP 12 (2024) 023

IN COLLABORATION WITH

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BENASQUE 2025

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GW SPECTRUM

02

GERTSENSHTEIN EFFECT

03

GALACTIC NEUTRON STAR

04

BOUNDS ON HFGW

GW Spectrum

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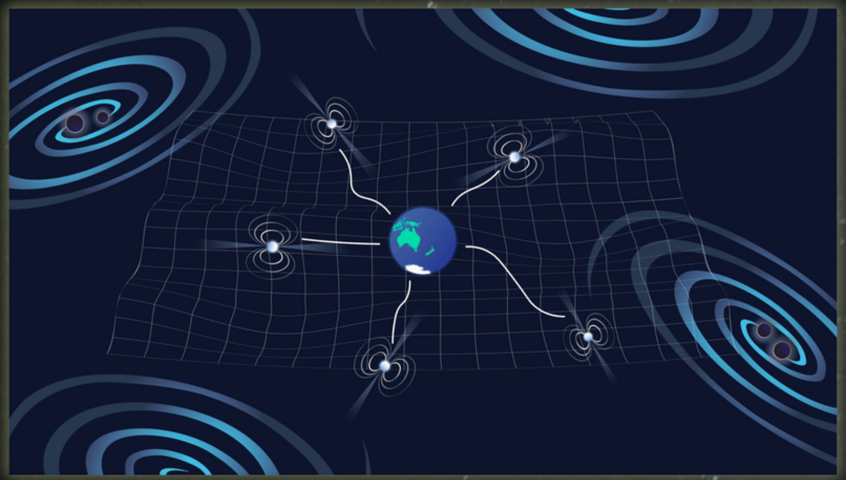
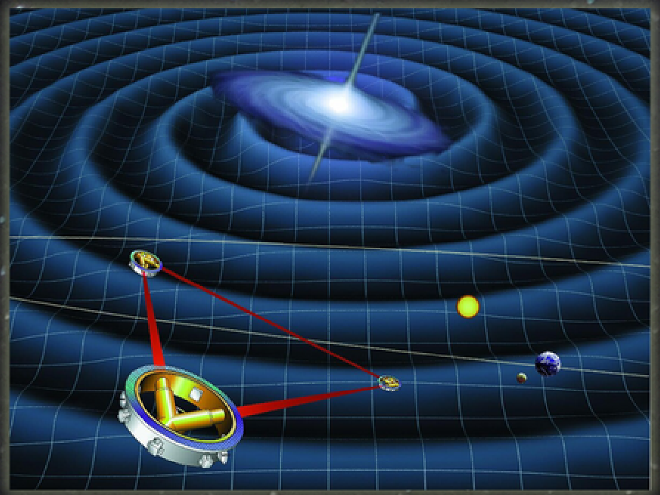
PTA

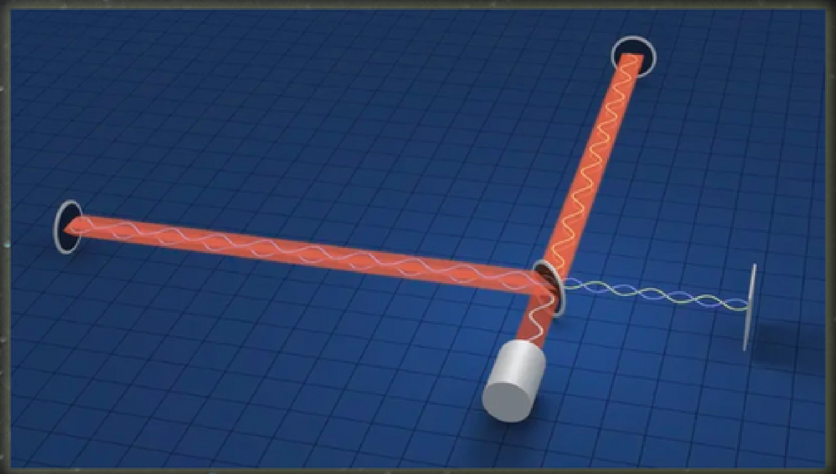


LISA



LVK

(EINSTEIN TELESCOPE)



$\sim 10^{-9}$ $\sim 10^{-3}$ $\sim 10^{2}$ frequency [Hz]

GW Spectrum

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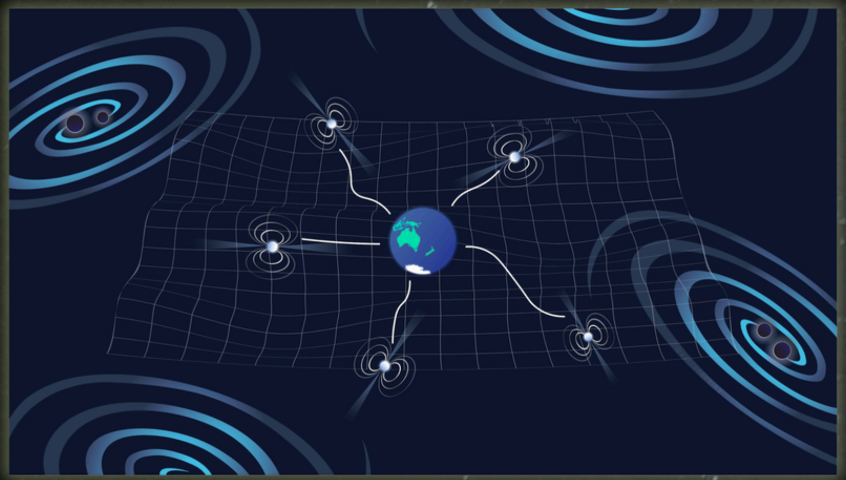
PTA



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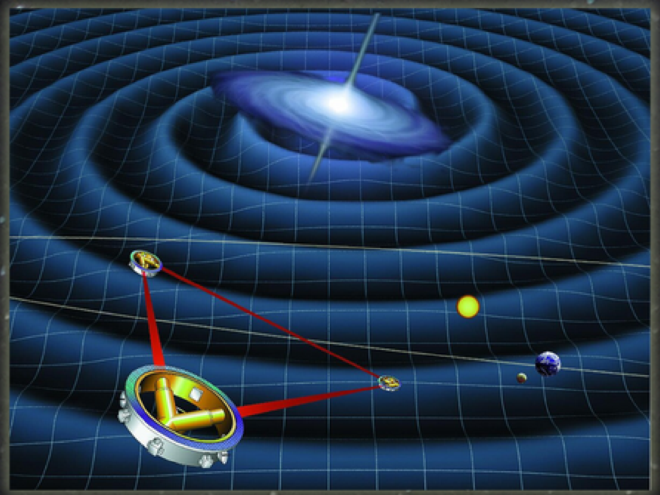

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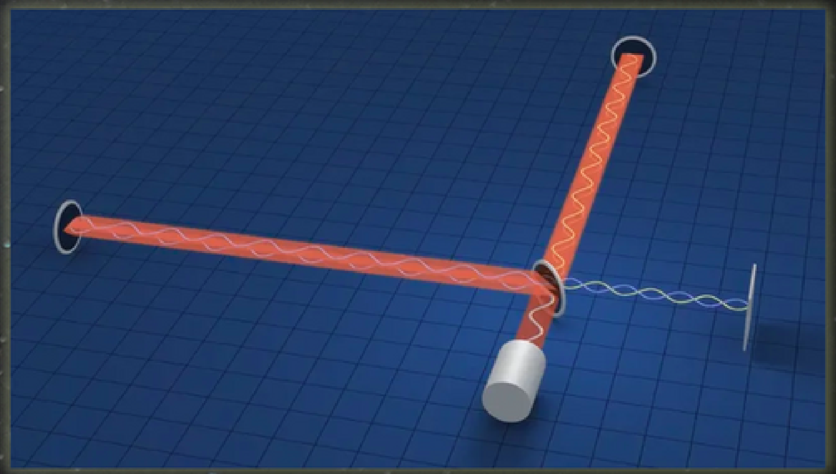

$\sim 10^{-9}$ $\sim 10^{-3}$ $\sim 10^{2}$ frequency [Hz]

Are there sources?

HFGW sources

Preheating

Grand unification
PBH evaporation

Exotic compact objects (ECOs)

Disk around supermassive BHs

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Cosmological

Astrophysical

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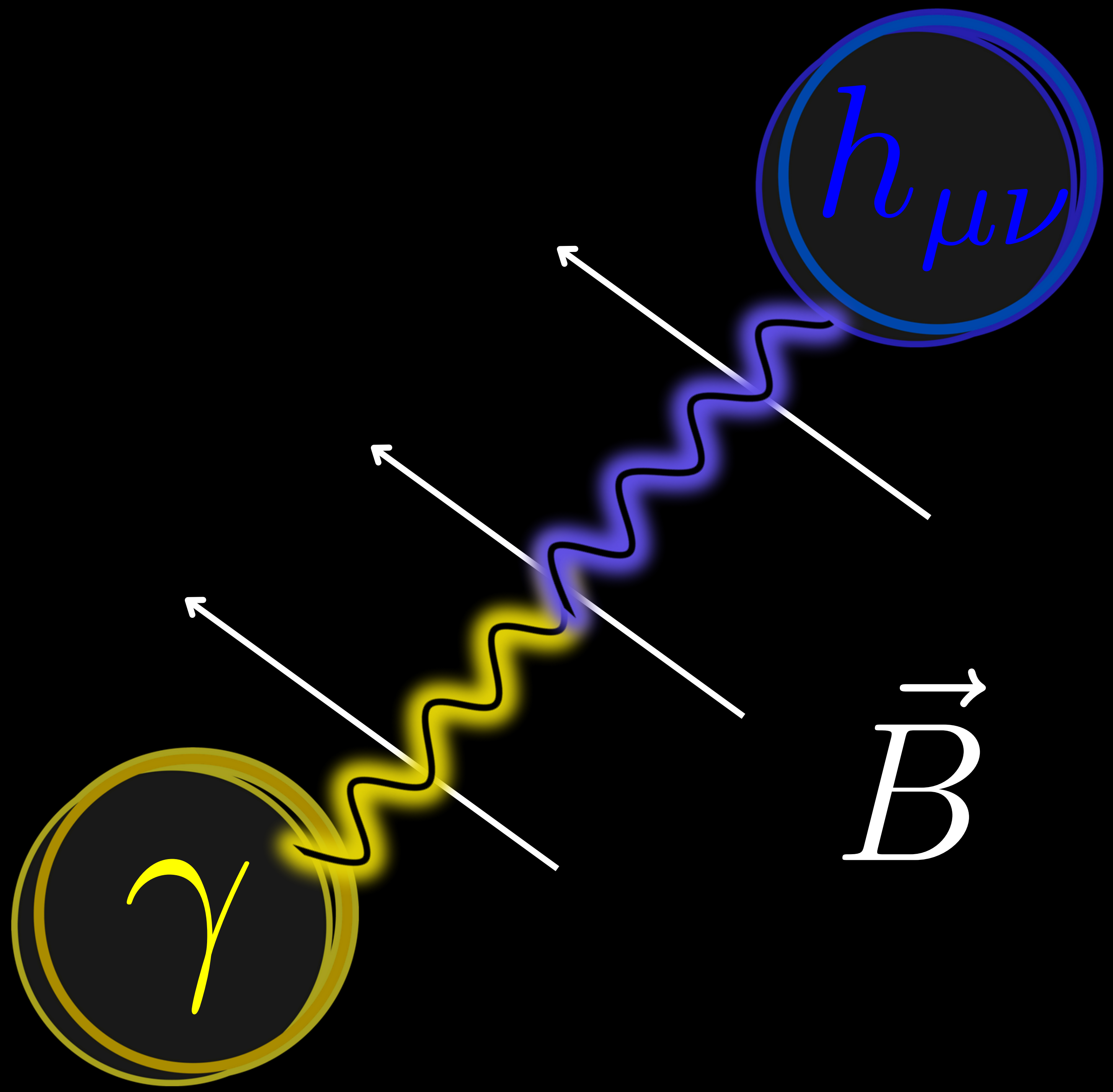
Gertsenshtein effect



Photons are converted into GW in an external magnetic field

WAVE RESONANCE OF LIGHT AND GRAVITIONAL WAVES

M. E. GERTSENSHTEĬN

Submitted to JETP editor July 29, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 113-114 (July, 1961)

M.E. Gertsenshtein JETP, 1962, Vol. 14, No. 1, p. 84
G. Raffelt and L. Stodolsky Phys.Rev.D 37 (1988) 1237
D. Boccaletti, V. De Sabbata, P. Fortini, C. Gualdi Nuovo Cim.B 70 (1970) 2, 129-146

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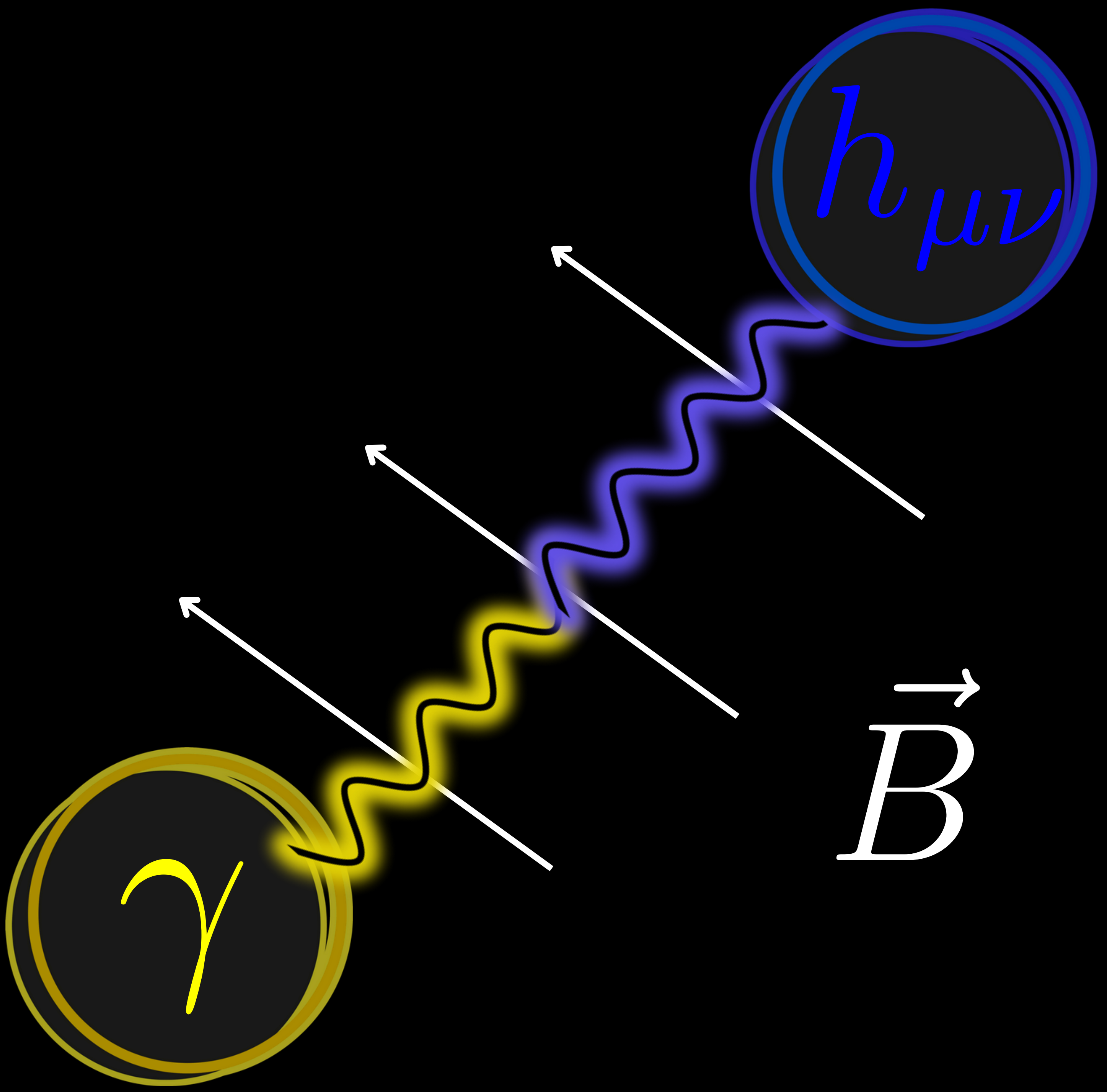
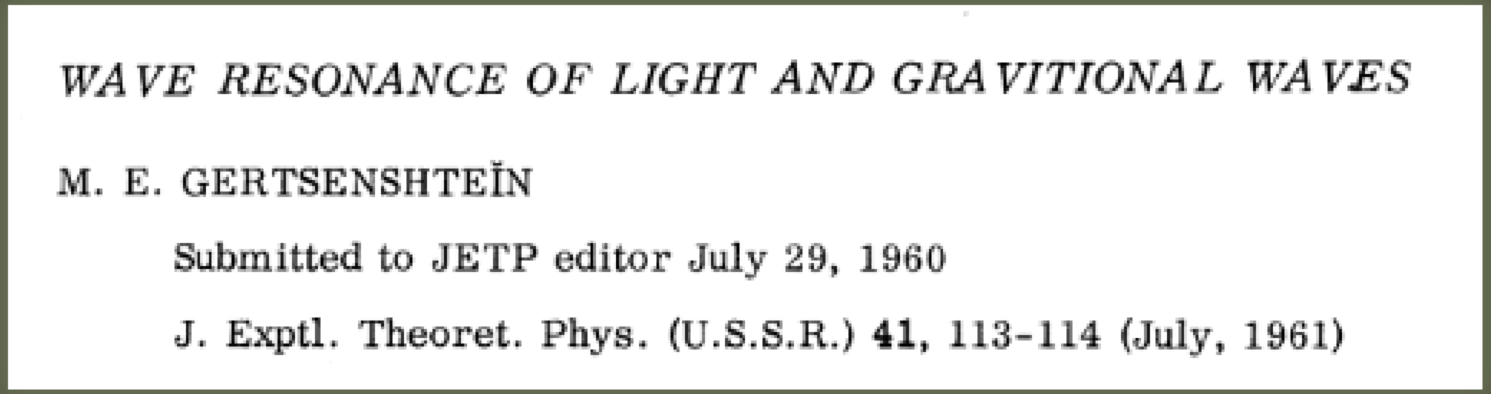
Gertsenshtein effect



The inverse Gertsenshtein process: GW are converted into photons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How Gertsenshtein finshed his paper

From general relativity follows also the possibility of the inverse conversion of gravitational waves into light waves, but this problem is hardly of interest.

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Gertsenshtein effect

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LOL

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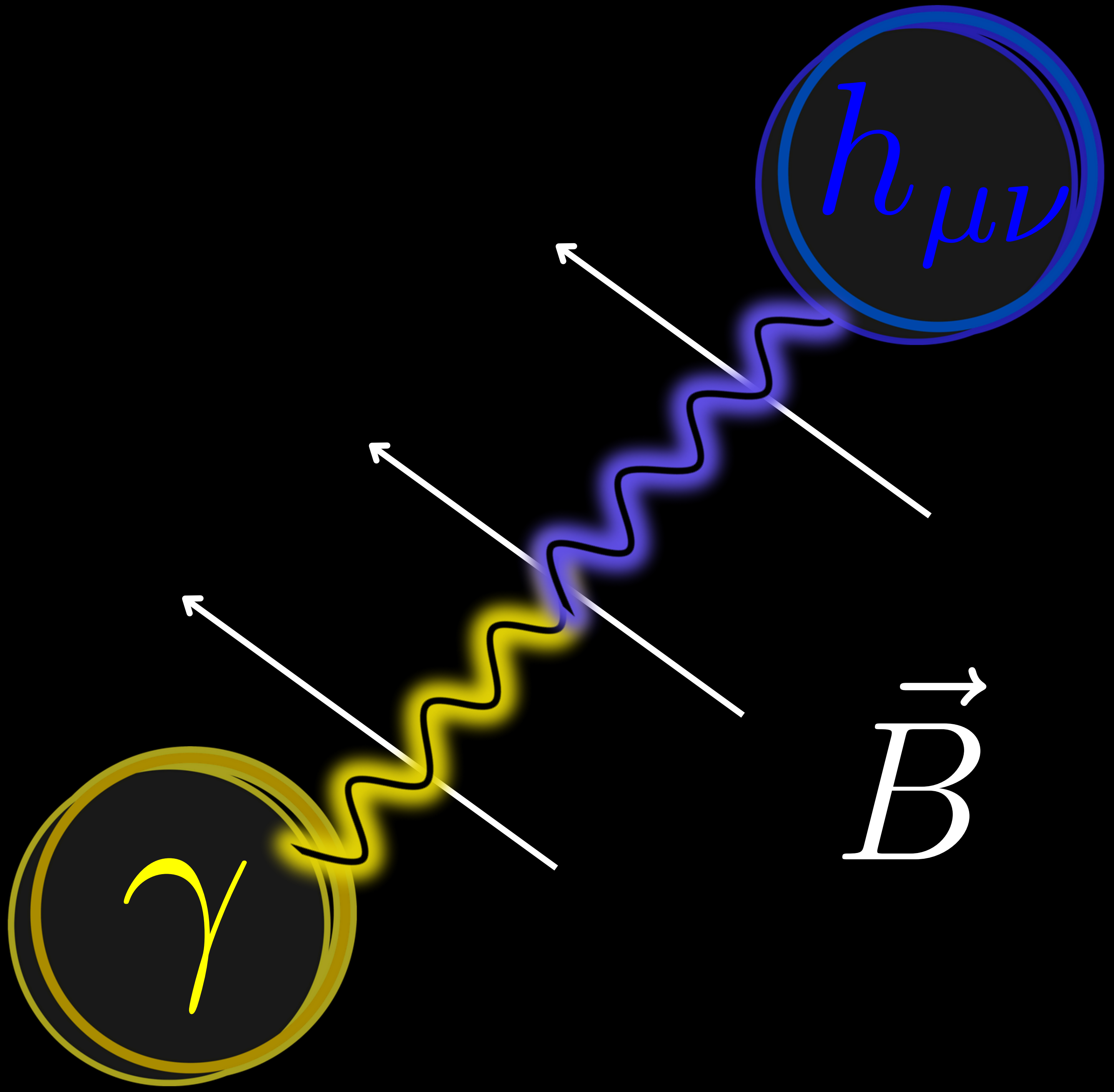
Gertsenshtein effect



How does it work?

Everything couples to gravity

$$S \supset \int d^4x \sqrt{-g}\, \mathcal{L}_{\mathrm{EM}}$$

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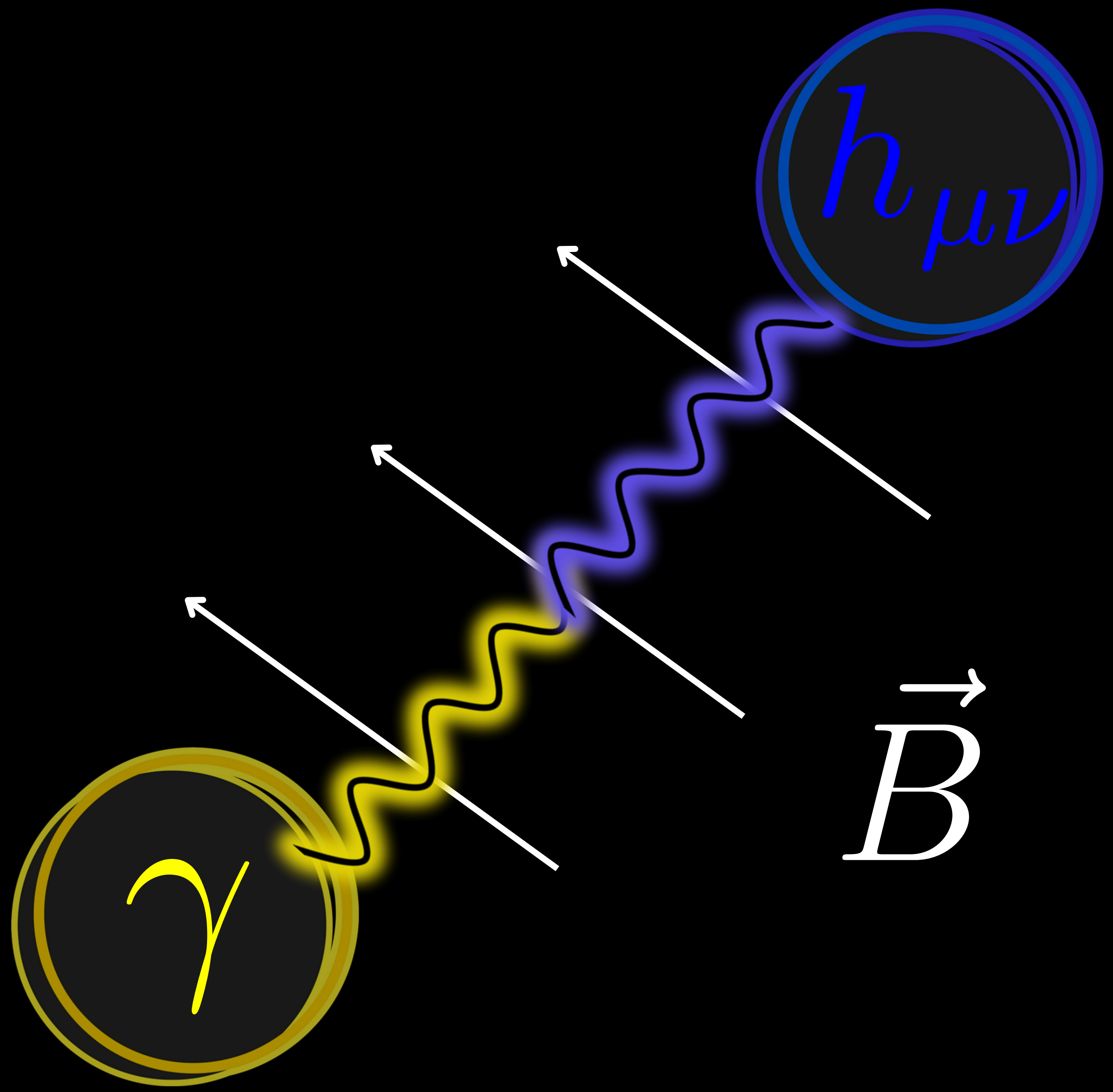

Everything couples to gravity

$$S \supset \int d^4x \sqrt{-g}\, \mathcal{L}_{\rm EM}$$

Linearising gravity

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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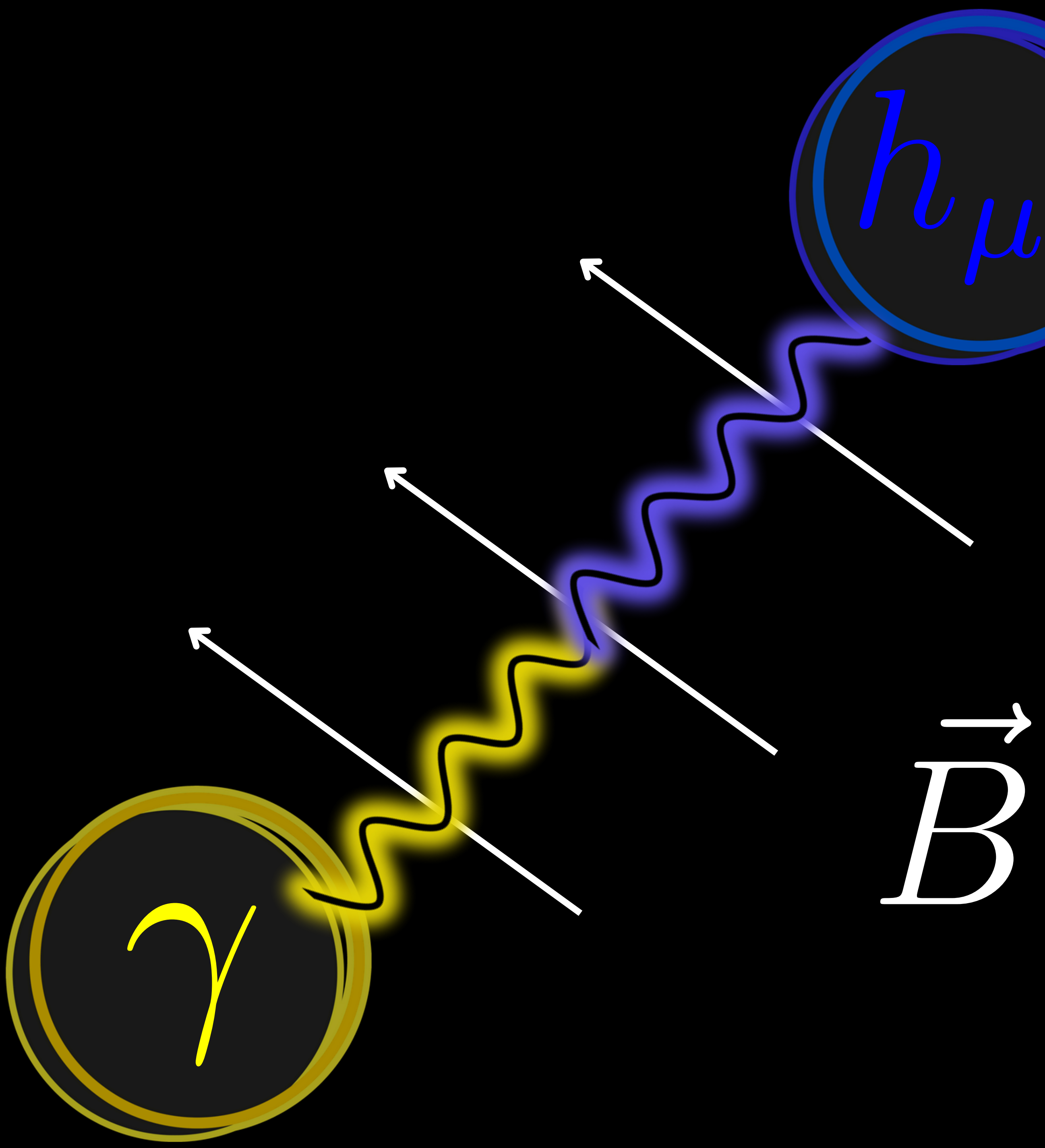
Gertsenshtein effect



Everything couples to gravity

$$S \supset \int d^4x \sqrt{-g}\, \mathcal{L}_{\rm EM}$$

Linearising gravity

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

EoM for the GW

$$\Box h_{\mu\nu} \sim \frac{1}{M_{pl}^2} T_{\mu\nu}^{em}$$

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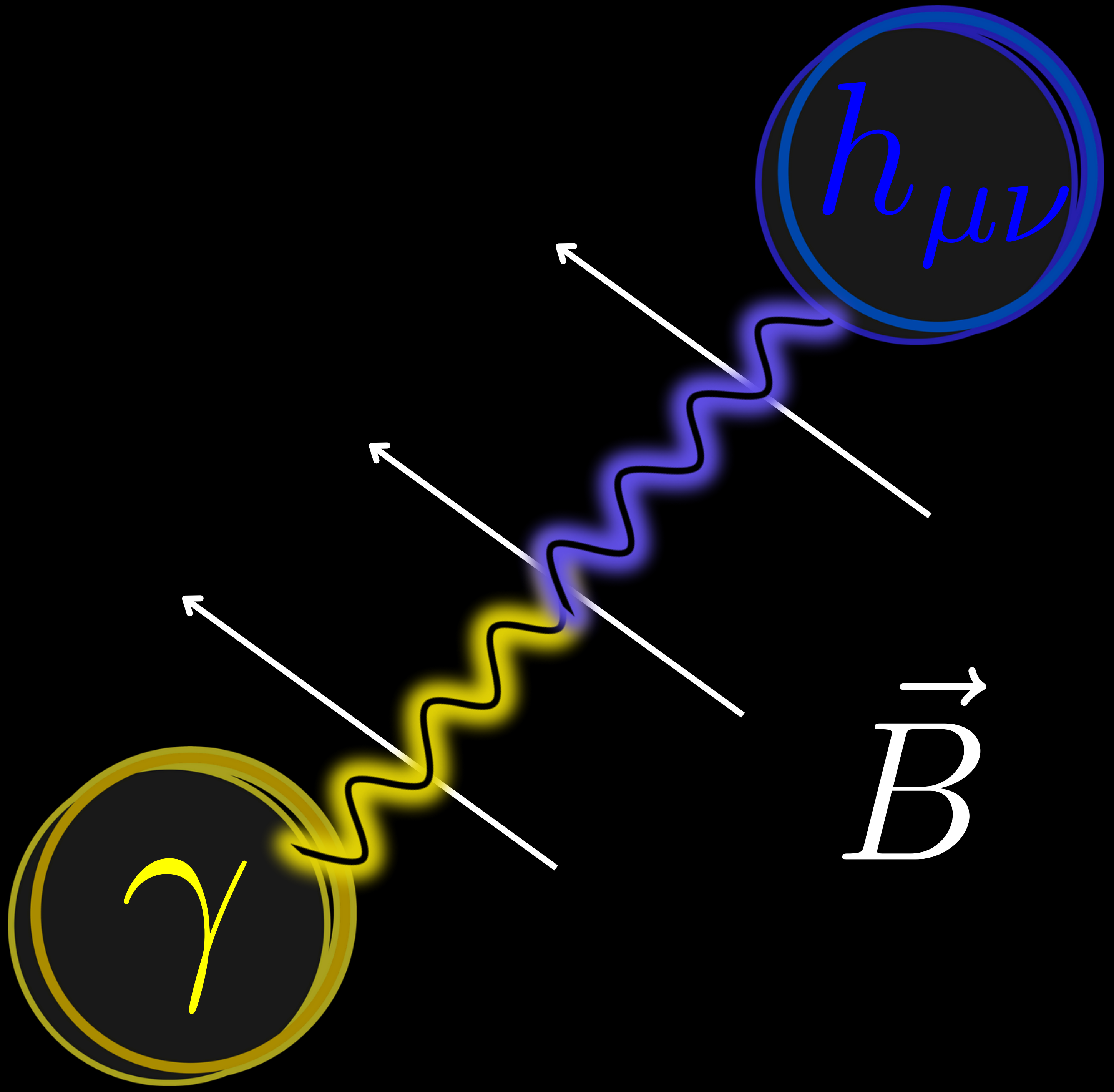
Gertsenshtein effect



Energy momentum tensor

$$T^{\mu\nu} = F^{\mu\alpha}F^{\nu}{}_{\alpha} - \frac{1}{4}g^{\mu\nu}F^{\alpha\beta}F_{\alpha\beta}$$

with

$$F_{\mu\nu} = F^{0}_{\mu\nu} + f_{\mu\nu}$$

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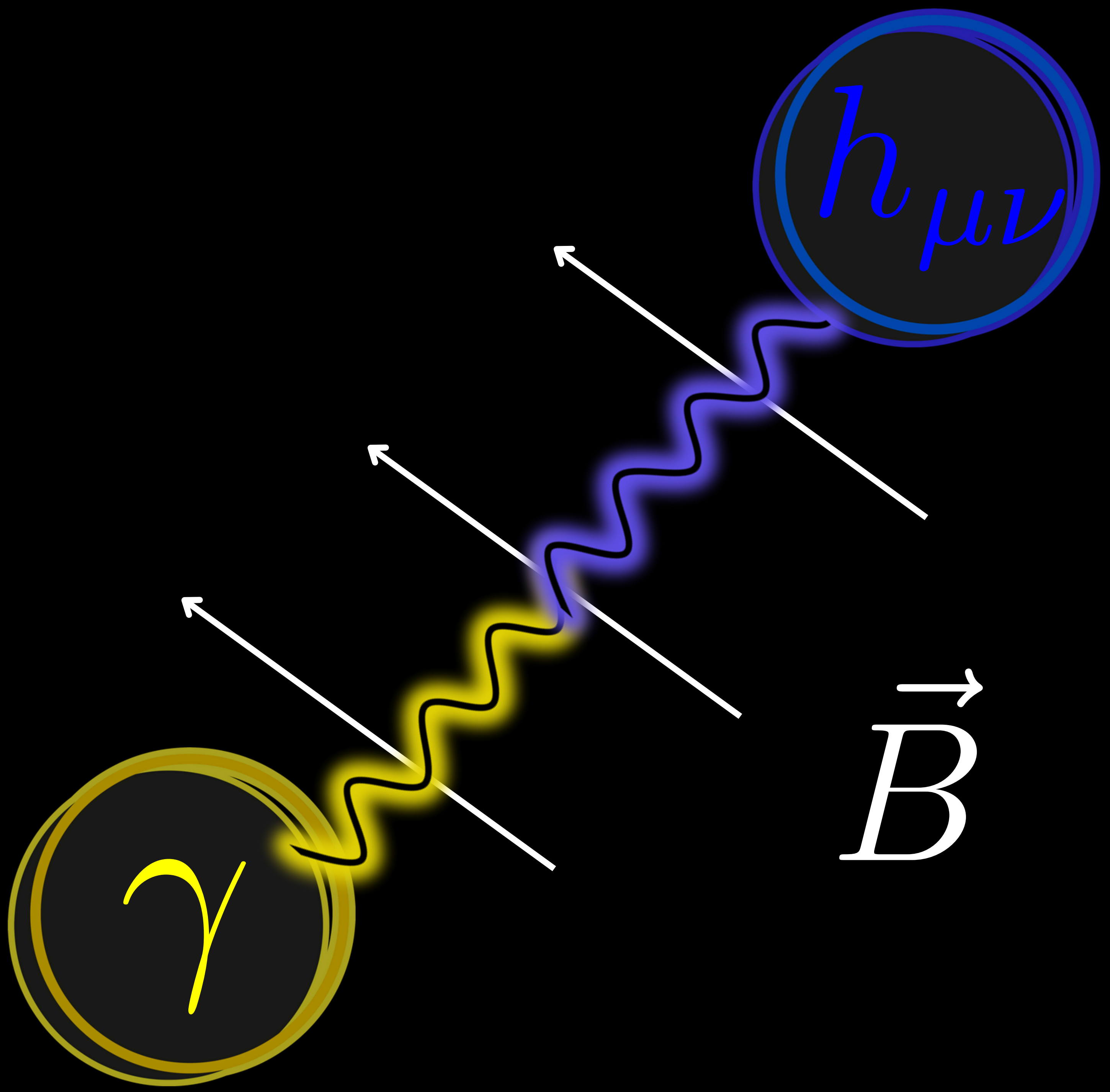
Gertsenshtein effect



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with

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One example of the terms

$$T_{xy} = F^{0x}{}_{\lambda}f^{y\lambda} + f^x_{\lambda}F^{0y\lambda}$$

$$h_\times \longleftrightarrow T_{xy} \sim B^{ext} \cdot B^{wave}$$

(EM wave moving in the z direction)

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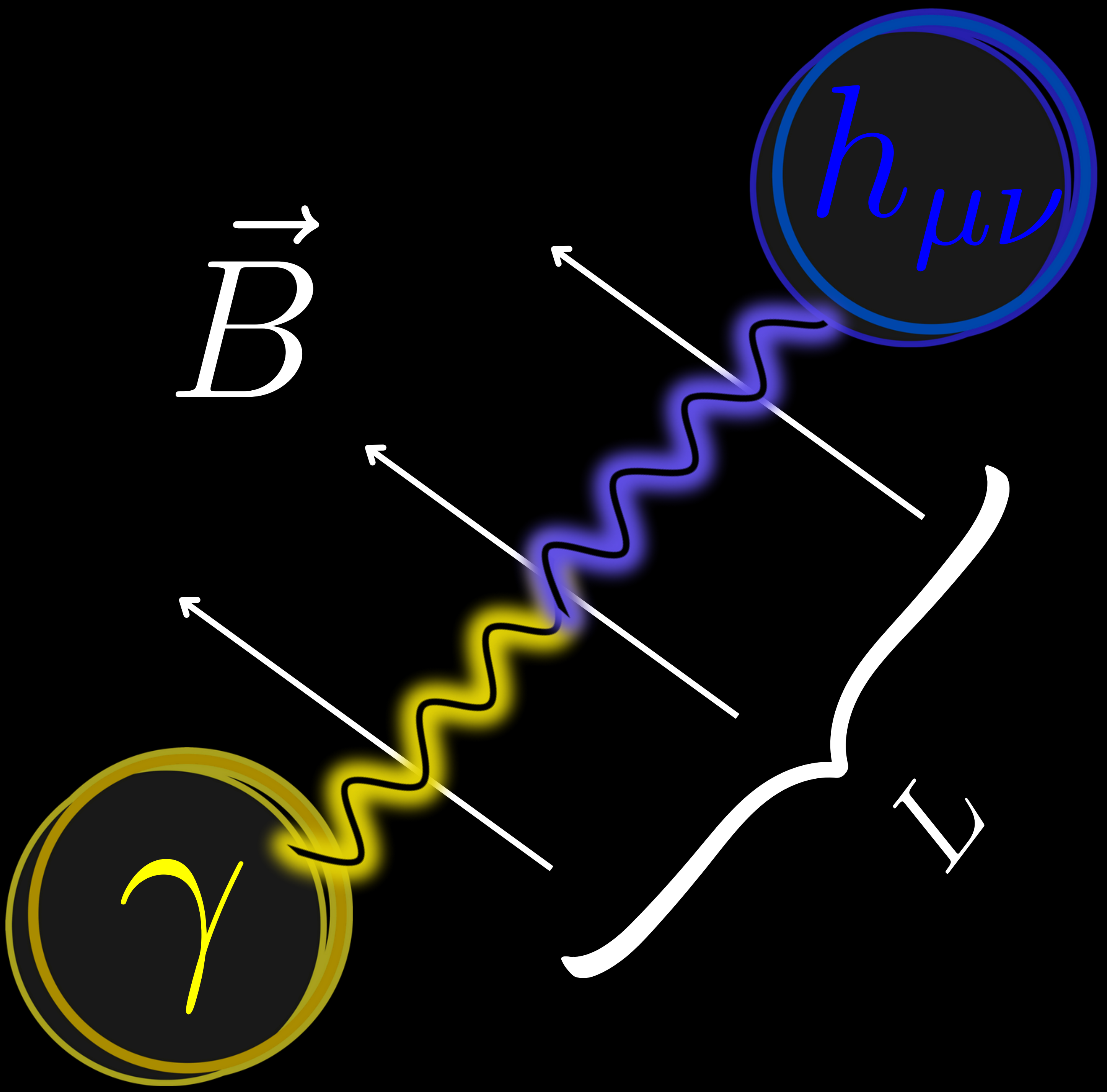
Gertsenshtein effect



$$T_{xy} \sim B^{ext} \cdot B^{wave}$$

Approximating as plane waves

$$B^{wave} = E_* e^{i(kz-\omega t)}$$

Solving the Green function (in the region where there is a magnetic field) we obtain the strain

$$h \propto \frac{B^{ext} E_*}{M_{pl}^2 \omega^2} \times L$$

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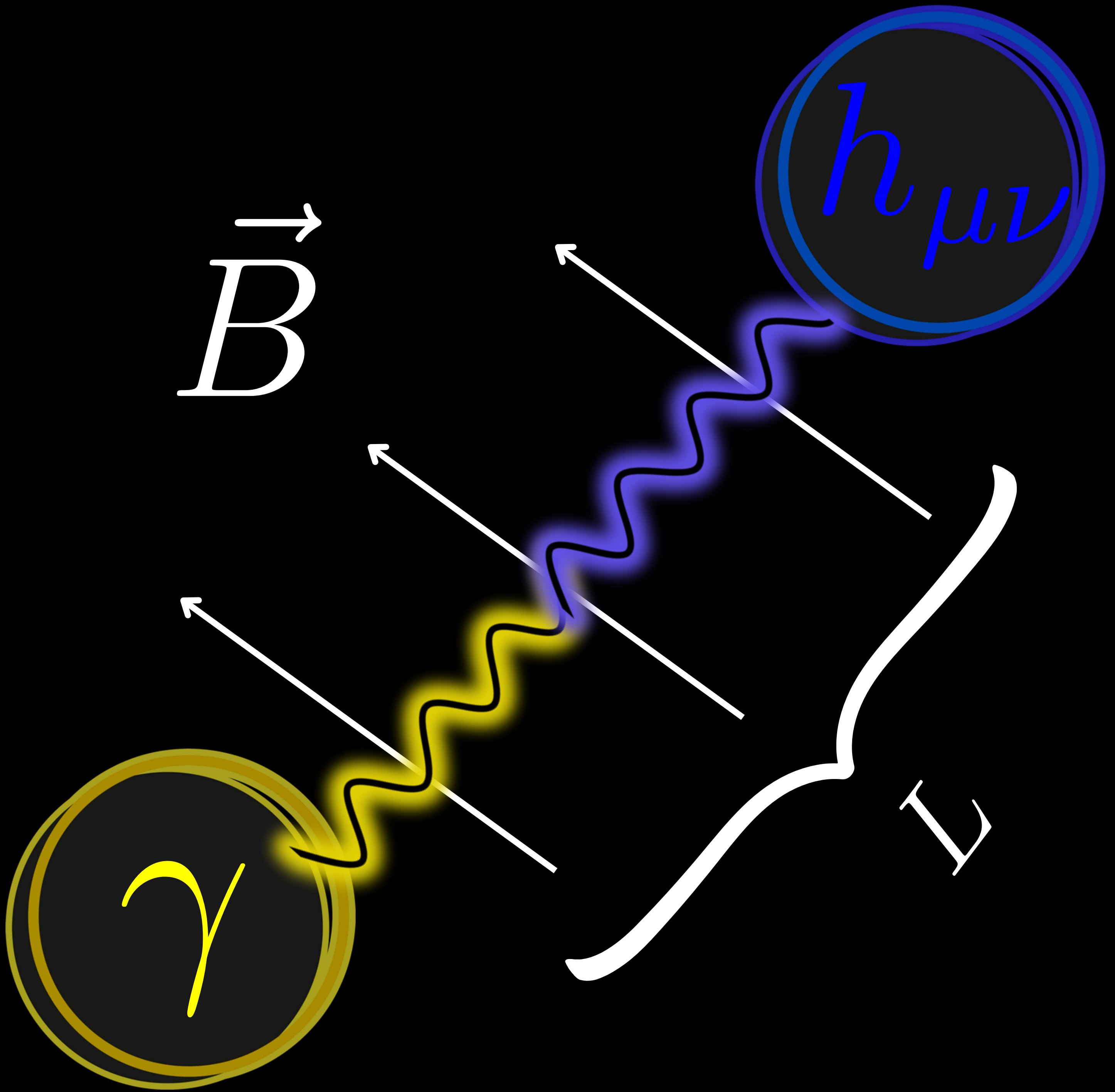
Gertsenshtein effect



The strain is

$$h \propto \frac{B^{ext} E_*}{M_{pl}^2 \omega^2} \times L$$

Conversion probability

$$P = \frac{\text{GW flux}}{\text{EM flux}}$$

$$\text{GW flux} \propto M_{pl}^2 \omega^2 h^2 \qquad \text{EM flux} \propto E_*^2$$

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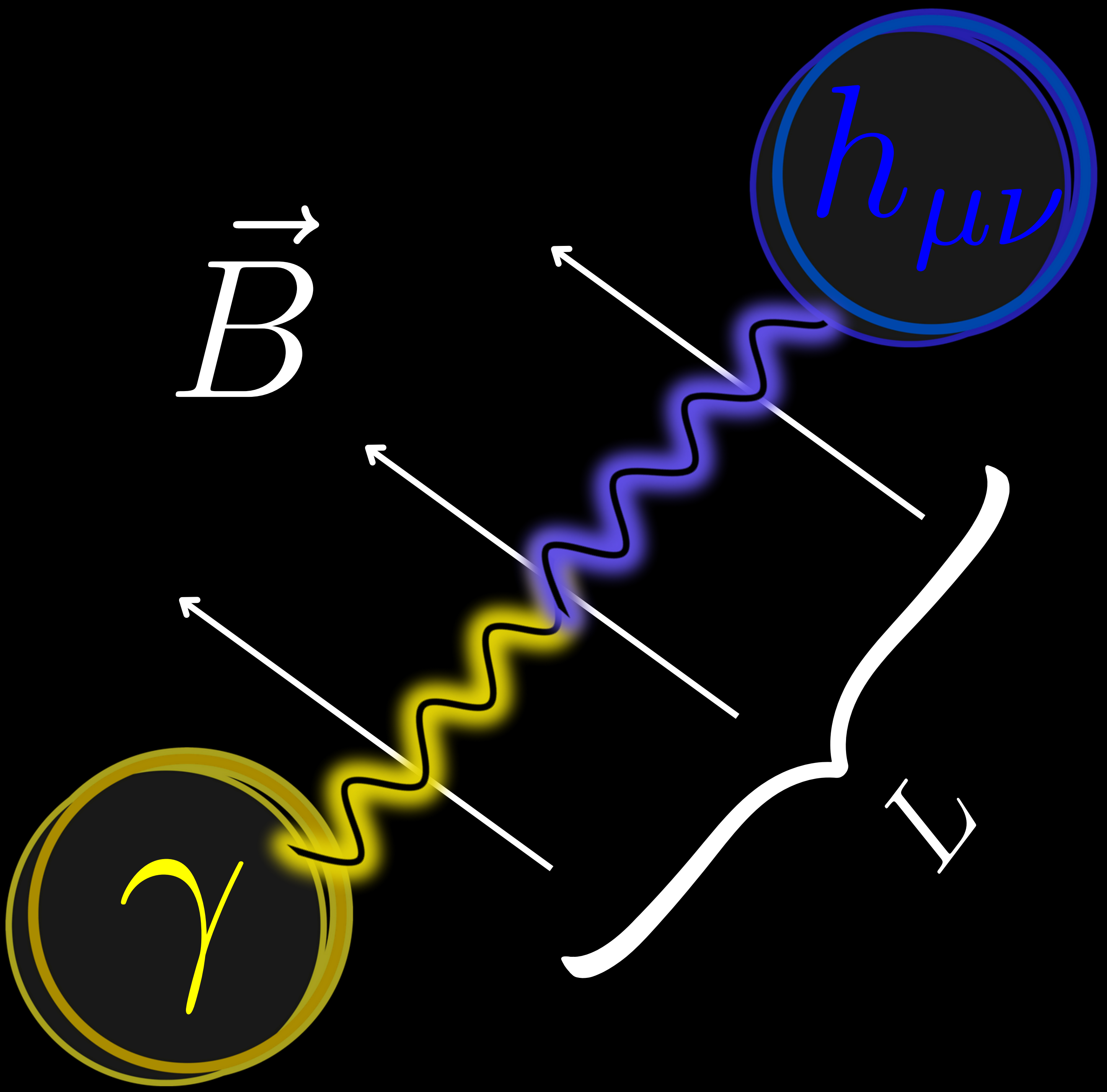

Conversion probability

$$P = \frac{\text{GW flux}}{\text{EM flux}}$$

$$P_{h\to\gamma} \sim \frac{B^2 L^2}{M_p^2}$$

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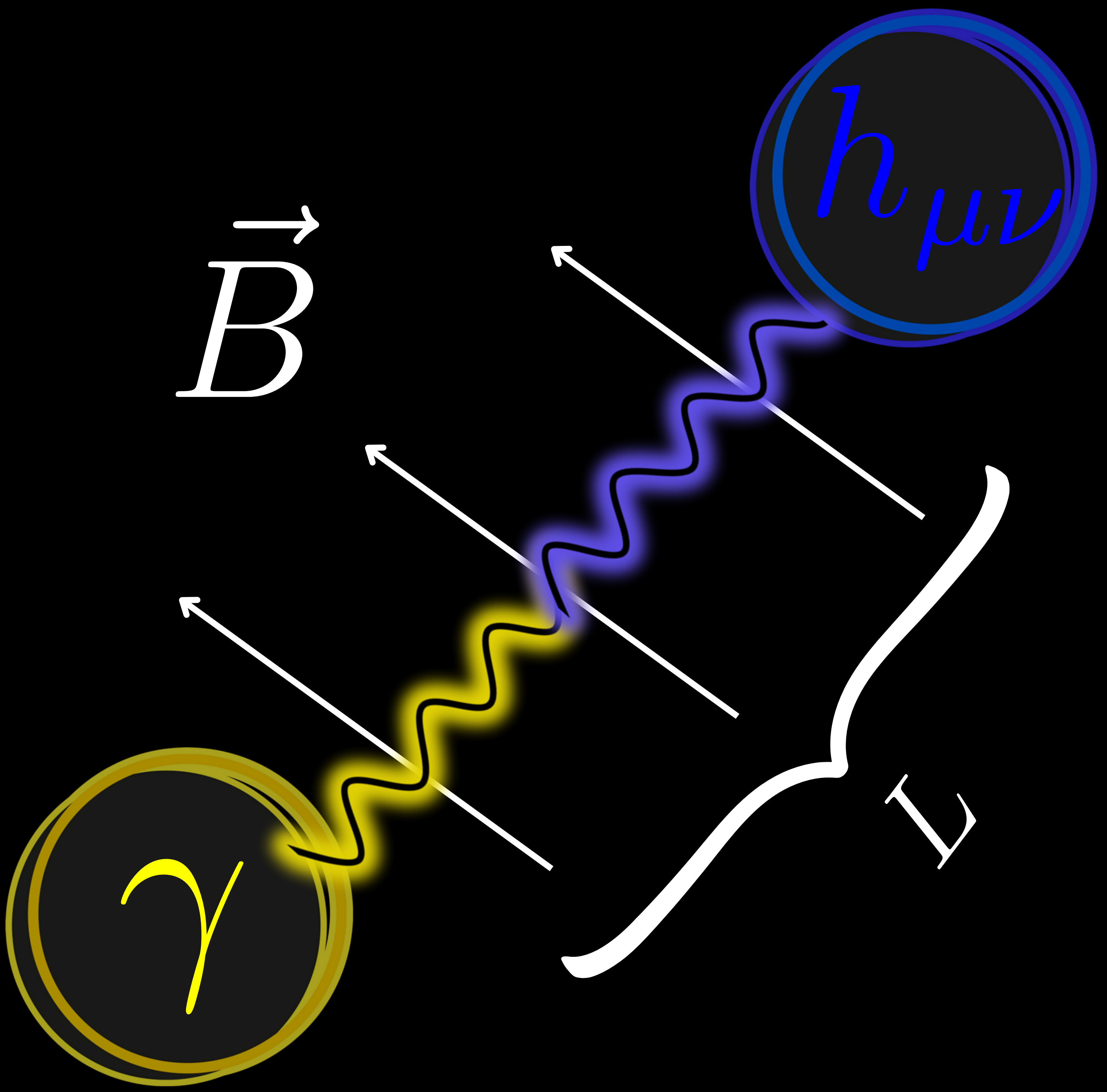
Gertsenshtein effect



Conversion probabiliity

$$P_{h\to\gamma} \sim \frac{B^2 L^2}{M_p^2}$$

	L	B
Galactic Setting	↑ kpc	nG ↓
Neutron Stars	↓ 100 - 1000 km	TG ↑

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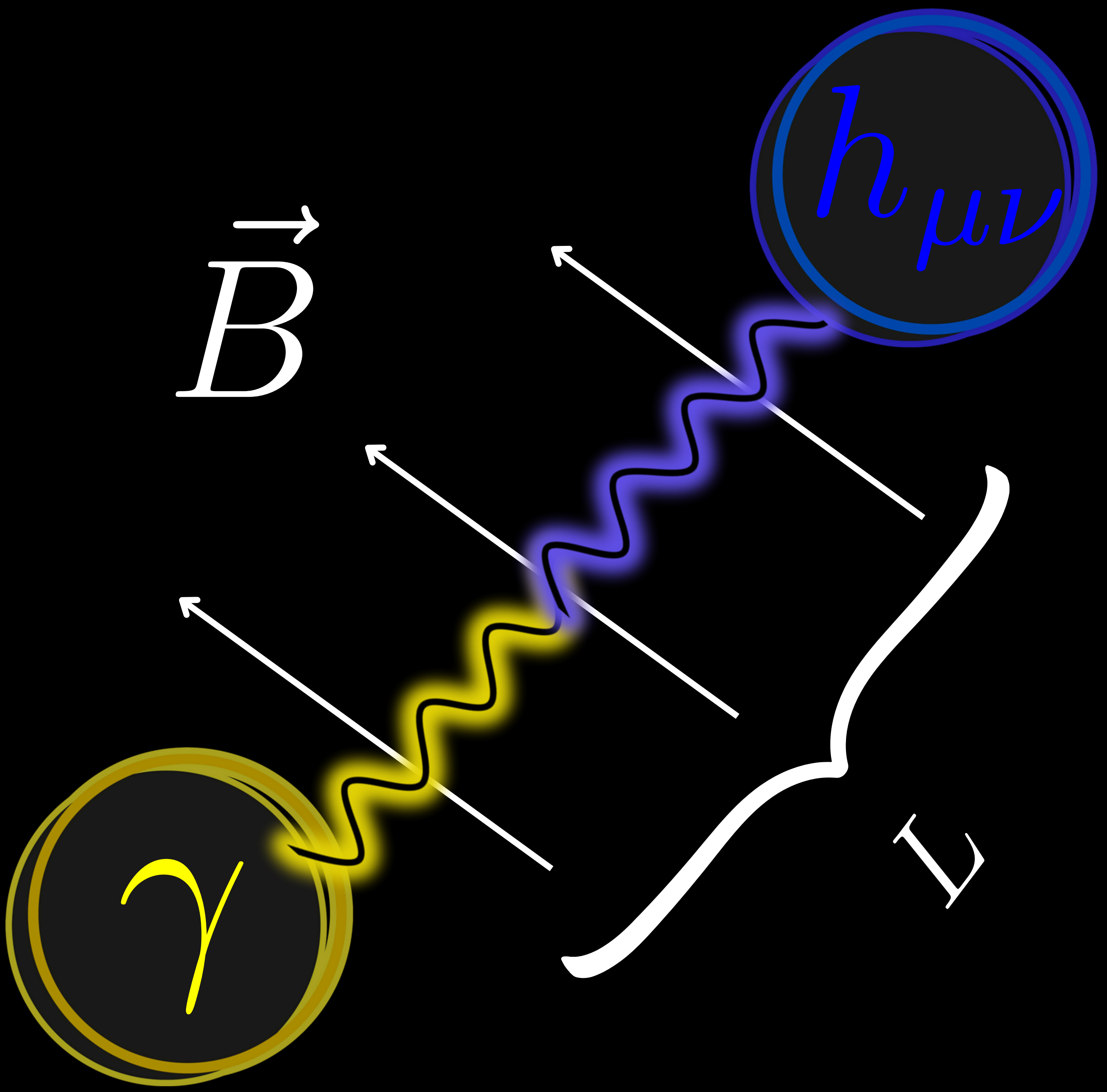
Gertsenshtein effect



Conversion probabiliity

$$P_{h\to\gamma} \sim \frac{B^2 L^2}{M_p^2}$$

	L		B	
Galactic Setting	↑	kpc	nG	↓
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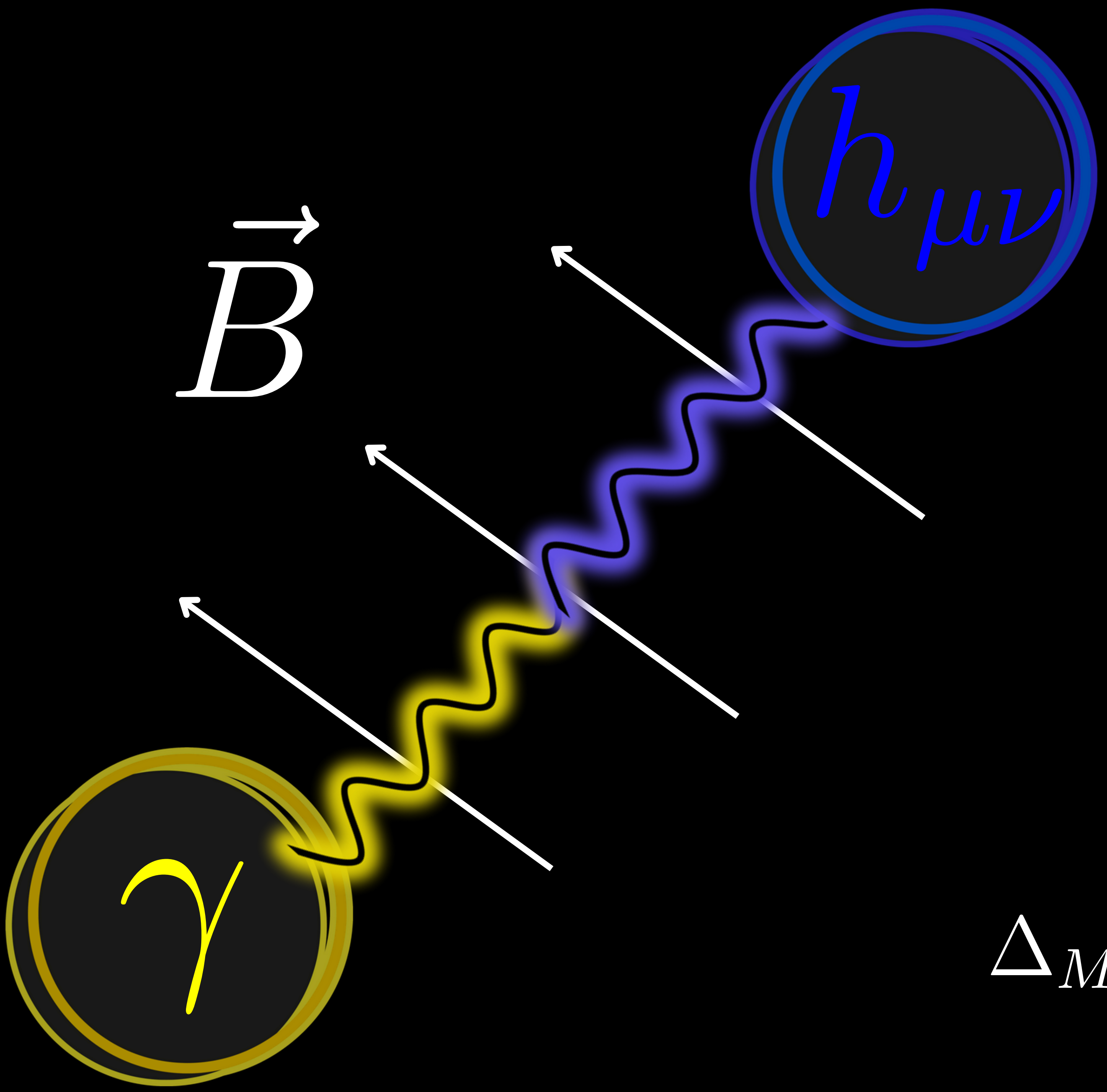

Conversion probabiliity

$$P_{\parallel(\perp)}(f) = \left| \int_{\ell_0}^{\ell_1} \mathrm{d}\ell \, \Delta_{\mathrm{M}}(\ell) \exp\left\{ -i \int_{\ell_0}^{\ell} \mathrm{d}\ell' \, \Delta_{\parallel(\perp)}(\ell') \right\} \right|^2$$

Effective photon mass:

- QED vacuum effects
- Plasma effects

$$\Delta_M \propto \kappa B_t^{ext}$$

$$\kappa = (16\pi G)^{1/2}$$

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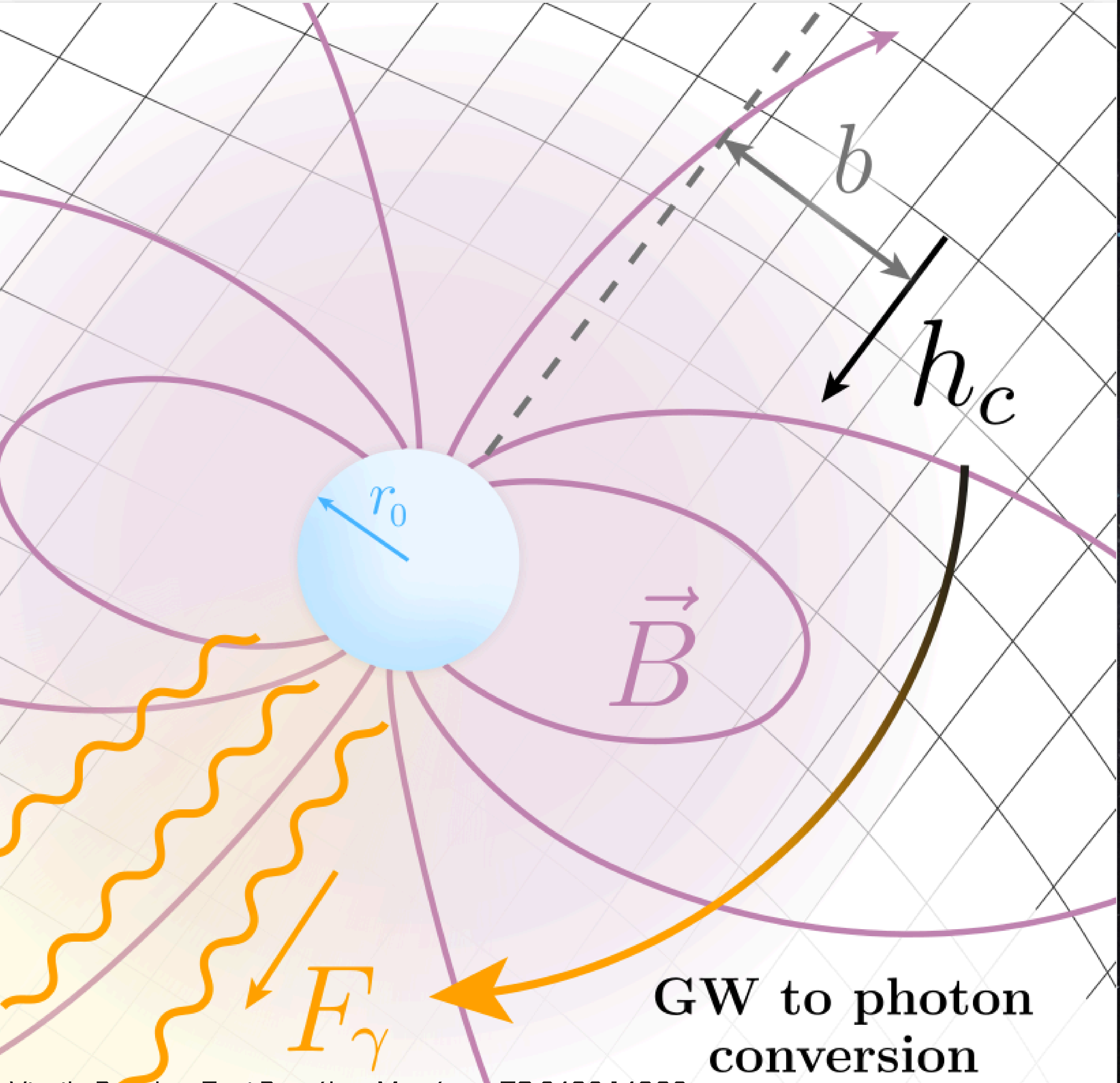

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Neutron Stars

Typical values

$$T \sim \mathcal{O}(0.1 - 1)\ \mathrm{s}$$

$$r_0 \sim 10\ \mathrm{km}$$

$$B_0 \sim 10^{13}\ \mathrm{G}$$

$$B = \sqrt{\frac{2}{3}} B_0 \left(\frac{r}{r_0}\right)^{-3}$$

b: impact parameter

F: photon flux

h: strain

Neutron Stars in our Galaxy

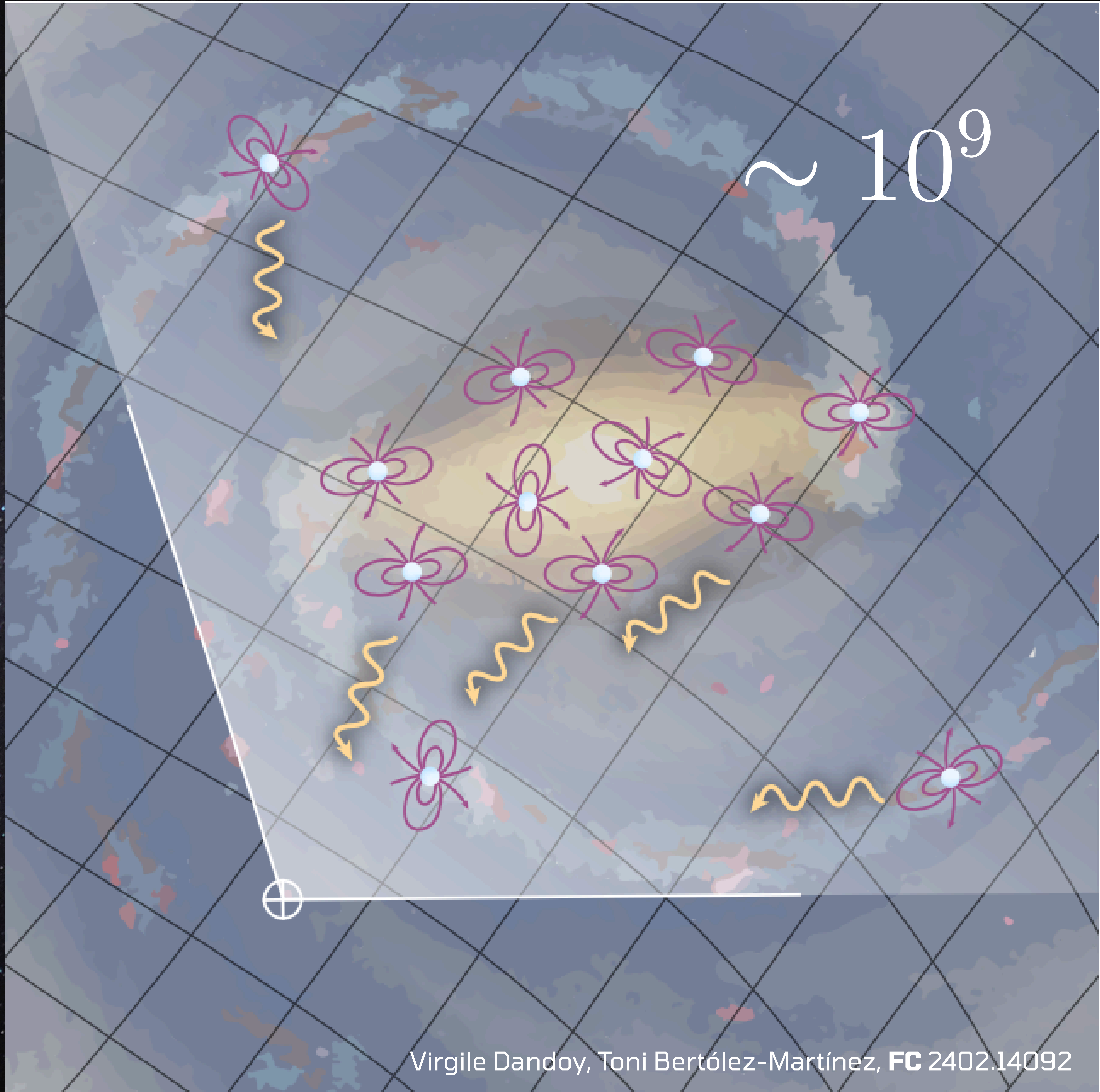
Neutron stars distribution

$$n(\vec{r})$$

Of these some are active and some are dead stars

Distributions

$$P_{act}(B_0, T) \quad P_{dead}(B_0, T)$$



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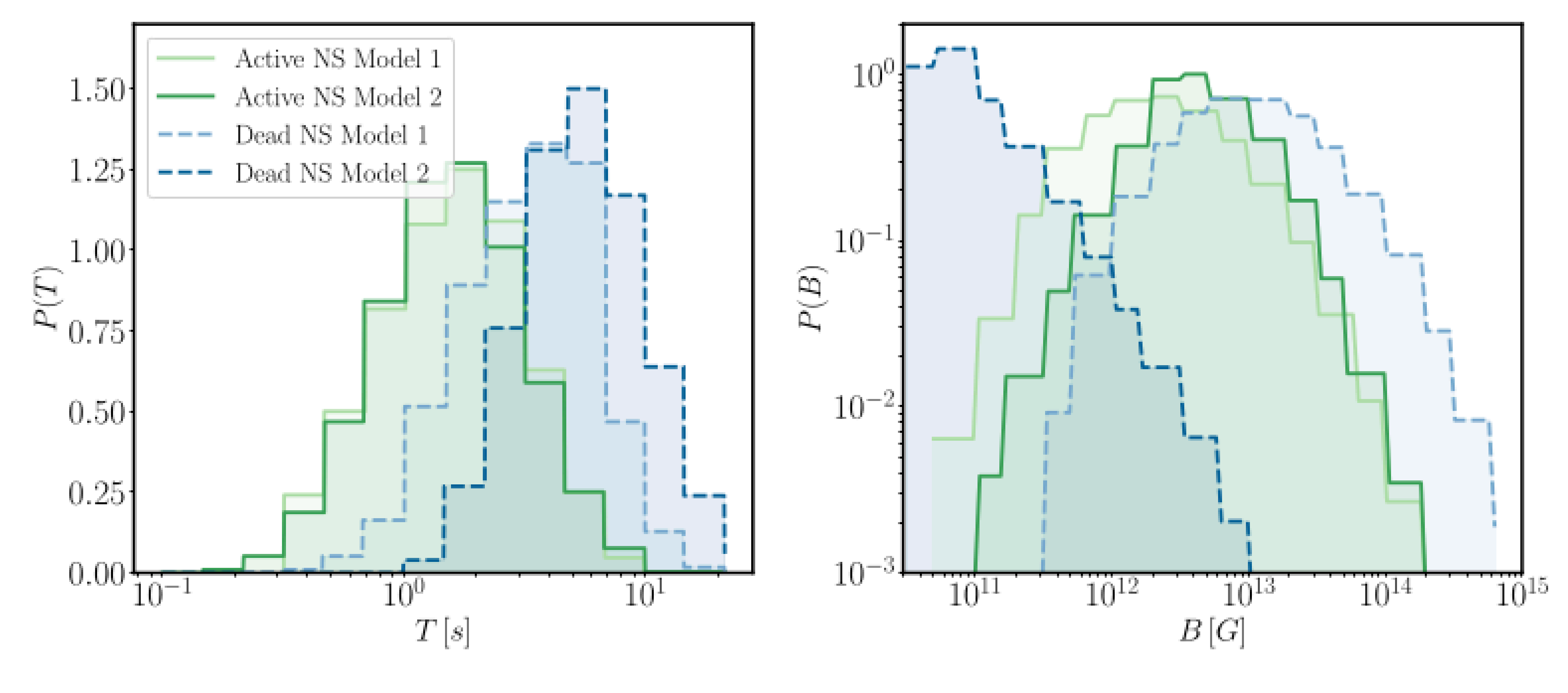
Neutron Stars in our Galaxy

$P_{act}(B_0, T)$ green $P_{dead}(B_0, T)$ blue

Today's distribution



Model 1:Constant B
Model 2: Decaying B

(Different model for the NS evolution fit the data, we use constant and decaying magnetic field)

S.B. Popov, J.A. Pons, J.A. Miralles, P.A. Boldin, B. Posselt 0910.2190
C.-A. Faucher-Giguere, V. M. Kaspi astro-ph/0512585
Benjamin R. Safdi, Zhiquan Sun, Alexander Y. Chen 1811.01020

Photon flux

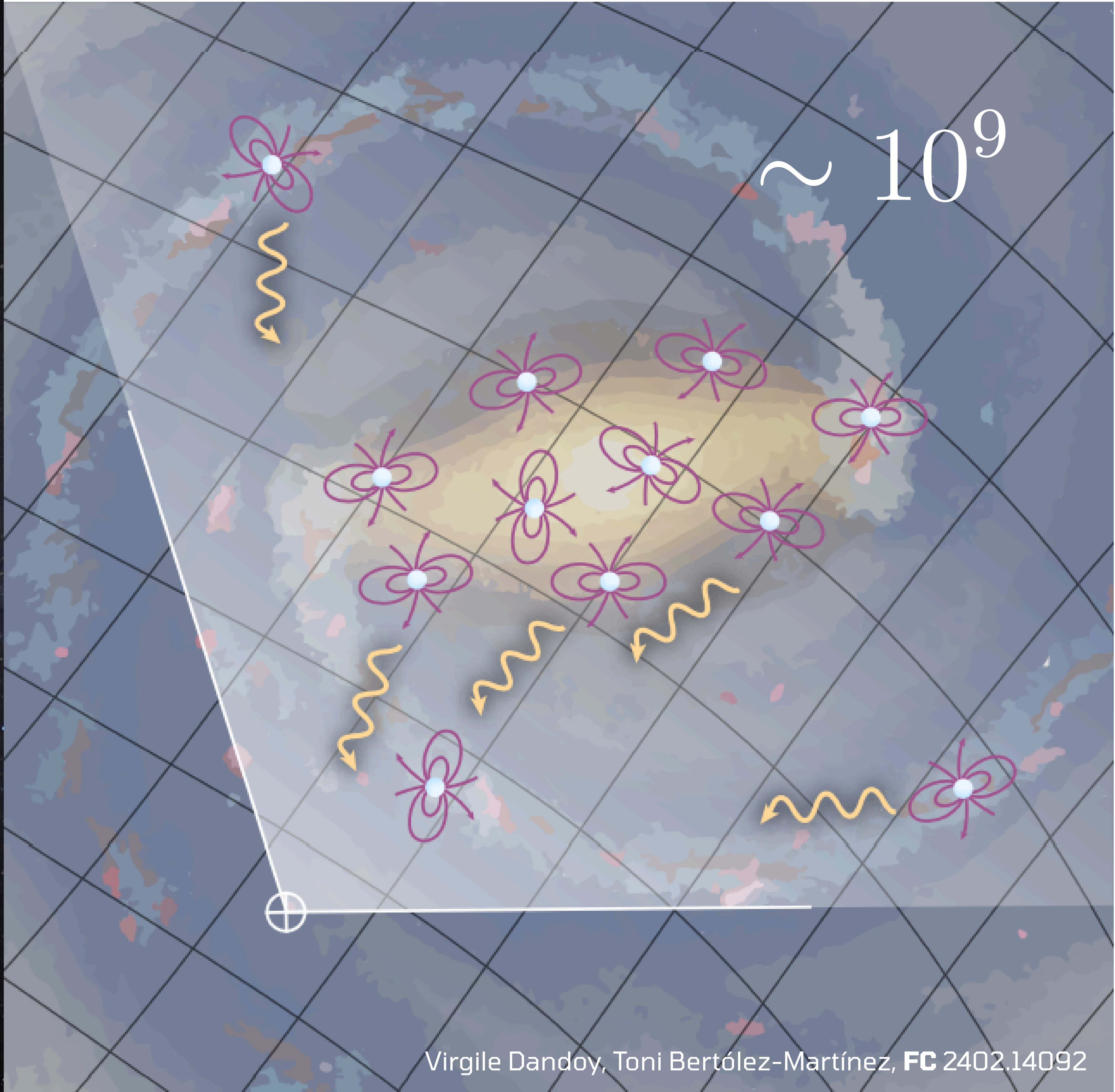
Given a GW background

$$f \quad h_c$$

$$\downarrow$$

$$\frac{\partial F_\gamma^{gal}}{\partial f}(f, h_c)$$

Same frequency as GW background



Photon flux

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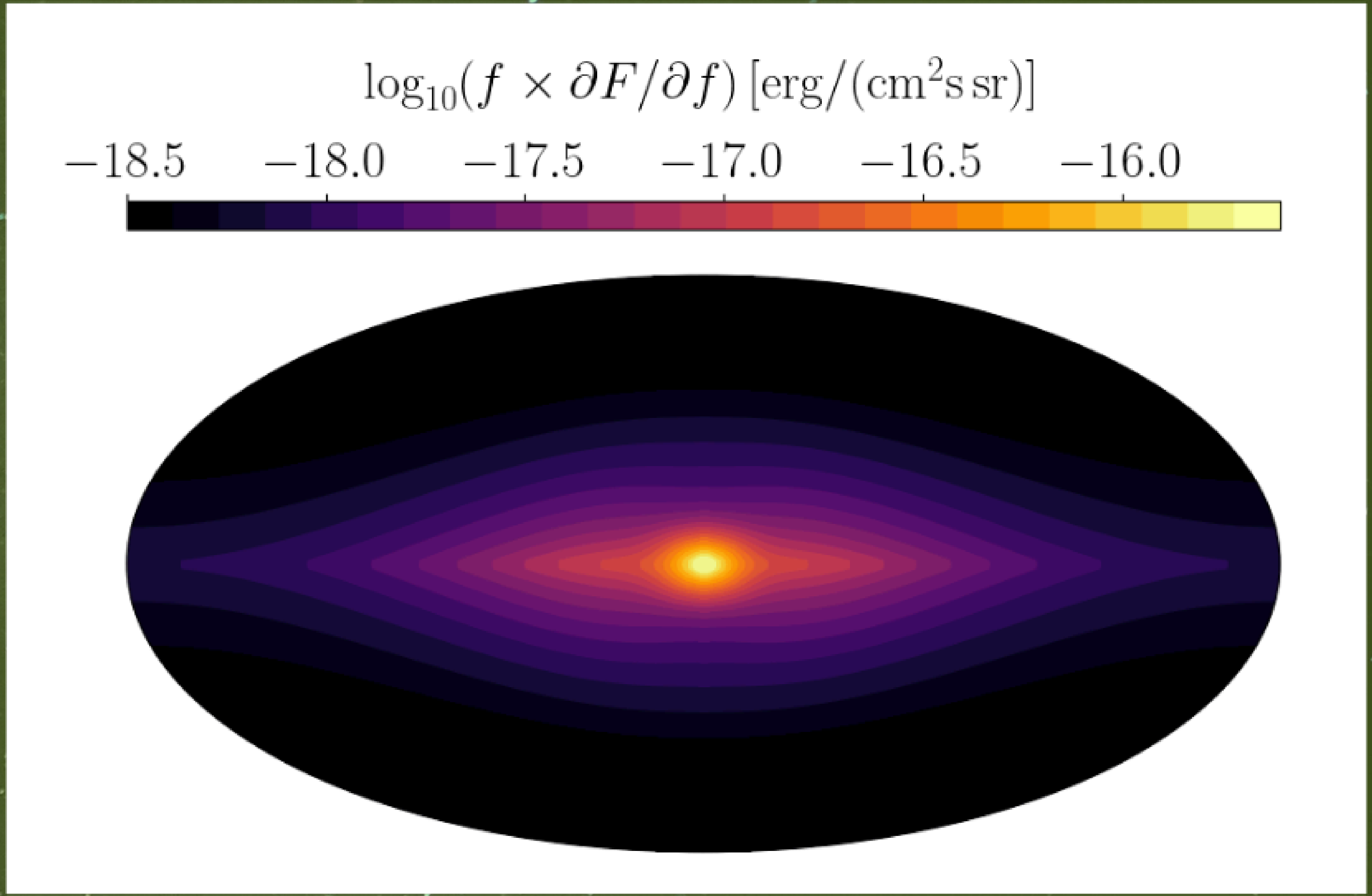
Given a GW background

$$f \quad h_c$$

↓

$$\frac{\partial F_\gamma^{gal}}{\partial f}(f, h_c)$$



$$f = 10^{15}\ \mathrm{Hz} \quad h_c = 10^{-25}$$

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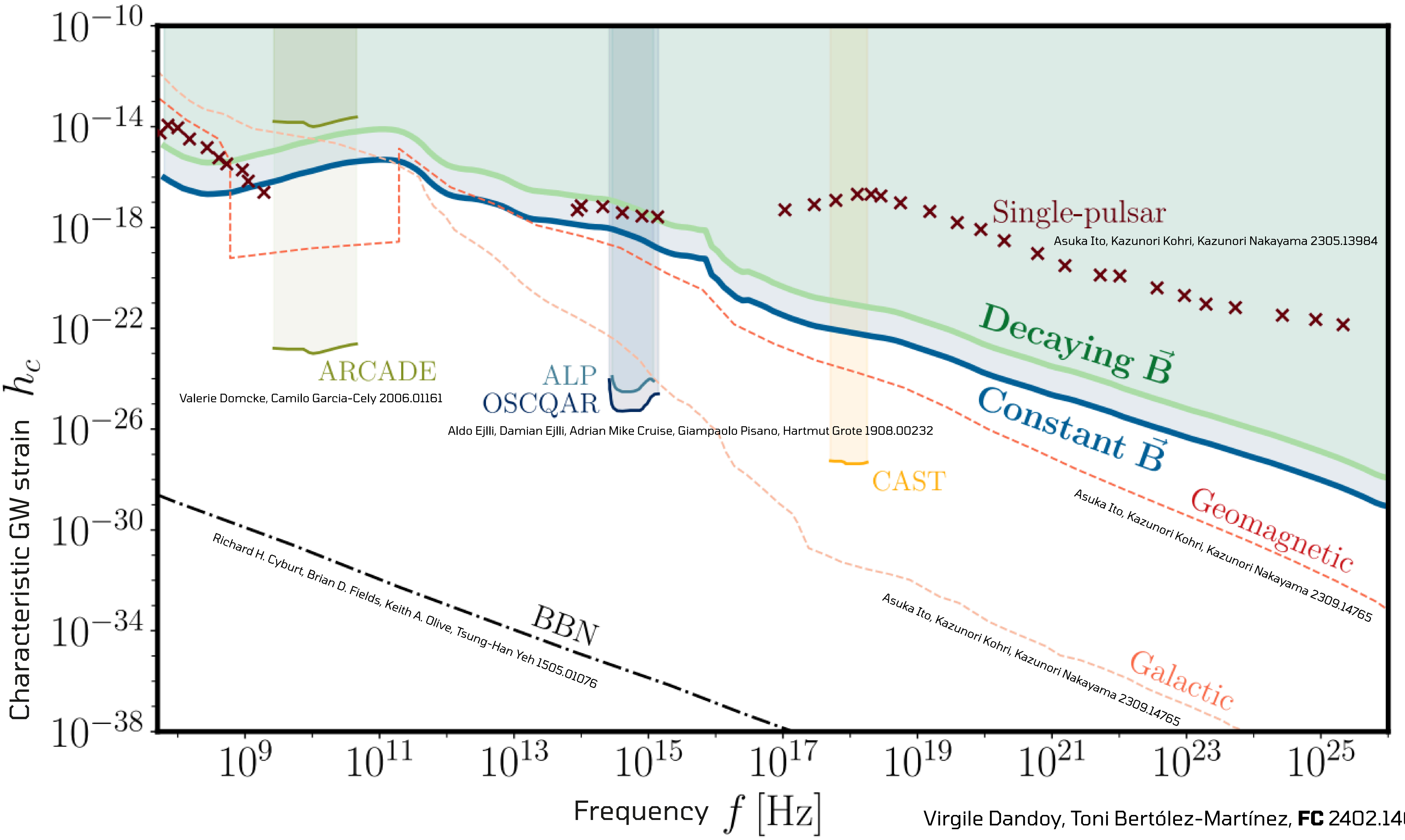

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THANK YOU!

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4.4 Summary of Sources

Table 1: Summary of late universe sources. We distinguish between coherent and stochastic sources by reporting the strain $h(f)$ or characteristic strain $h_{c,\mathrm{sto}}$, respectively. See Section 4.1 for details on these expressions and the assumptions made.

Source	**Typical frequency**	**Amplitude**
Neutron star mergers	$\lesssim (1-5)\,\mathrm{kHz}$	$h(f) \lesssim 10^{-26}\,\mathrm{sec}$
Phase transitions in neutron star mergers	$\simeq 0.6\,\mathrm{MHz} \times \left(\frac{0.1}{v_w}\right)\left(\frac{1\,\mathrm{ms}}{\tau}\right)$	$h_{c,\mathrm{sto}} \simeq 1.5 \times 10^{-24} v_f^2 \left(\frac{100\,\mathrm{Mpc}}{D}\right)$
Disk around supermassive BHs	$\simeq 3.3 \times 10^{19}\,\mathrm{Hz}$	$h_{c,\mathrm{sto}} \lesssim 3 \times 10^{-44}$
Sun	$\simeq 10^{14}\,\mathrm{Hz}$	$h_{c,\mathrm{sto}} \lesssim 3 \times 10^{-42}$
Primordial BH mergers	$\lesssim \frac{4400}{(m_1+m_2)}\mathrm{Hz}$	$h(f) \approx 10^{-31}\,\mathrm{sec}\left(\frac{\mathrm{kpc}}{D}\right)\left(\frac{m_{\mathrm{PBH}}}{10^{-5}M_\odot}\right)^{5/6}\left(\frac{f}{\mathrm{GHz}}\right)^{-7/6}$
Primordial BH mergers: SGWB	$\lesssim \frac{4400}{(m_1+m_2)}\mathrm{Hz}$	$h_{c,\mathrm{sto}} \approx 5 \times 10^{-31}\left(\frac{f_{\mathrm{ISCO}}}{\mathrm{GHz}}\right)^{-1.07}$
Primordial BH mergers: memory	$\lesssim \frac{4400}{(m_1+m_2)}\mathrm{Hz}$	$h(f) \approx 5 \times 10^{-25}\,\mathrm{sec}\left(\frac{f_{\mathrm{ISCO}}}{f}\right)\left(\frac{m_{\mathrm{PBH}}}{10^{-5}M_\odot}\right)\left(\frac{\mathrm{kpc}}{D}\right)$
Primordial BH hyperbolic encounters	$\simeq 0.5\,\mathrm{GHz}\left(\frac{10^{-5}M_\odot}{m_{\mathrm{PBH}}}\right)\left(\frac{R_S}{r_p}\right)^{3/2}$	$h(f) \approx 10^{-24}\,\mathrm{sec}\left(\frac{f}{\mathrm{GHz}}\right)^{2/3}\left(\frac{m_{\mathrm{PBH}}}{10^{-5}M_\odot}\right)^{5/3}\left(\frac{\mathrm{Mpc}}{D}\right)$
Exotic compact objects	$\lesssim C^{3/2}\left(\frac{6 \times 10^{-3}\,\mathrm{M}_\odot}{M}\right)\mathrm{MHz}$	$h(f) \approx 10^{-31}\,\mathrm{sec}\left(\frac{f}{\mathrm{GHz}}\right)^{-7/6}\left(\frac{m_{\mathrm{PBH}}}{10^{-5}M_\odot}\right)^{5/6}\left(\frac{\mathrm{kpc}}{D}\right)$
Superradiance: annihilation	$\simeq 5\,\mathrm{MHz}\left(\frac{\mu}{10^{-8}\,\mathrm{eV}}\right)$	$h_S(f) \approx 5 \times 10^{-30}\,\mathrm{sec}\left(\frac{m_{\mathrm{PBH}}}{10^{-5}M_\odot}\right)\left(\frac{\mathrm{kpc}}{D}\right)$ $h_{V,T}(f) \approx 10^{-26}\,\mathrm{sec}\left(\frac{m_{\mathrm{PBH}}}{10^{-5}M_\odot}\right)\left(\frac{\mathrm{kpc}}{D}\right)$
Superradiance: nonlinear effects	$\simeq 5\,\mathrm{MHz}\left(\frac{\mu}{10^{-8}\,\mathrm{eV}}\right)$	$h(f) \approx 10^{-27}\,\mathrm{sec}\left(\frac{m_{\mathrm{PBH}}}{10^{-5}M_\odot}\right)\left(\frac{\mathrm{kpc}}{D}\right)$

Table 2: Summary of stochastic sources. For the conversion between energy density $\Omega_{\rm GW}$ and characteristic strain, see Eqs. (9) and (12). The amplitudes reported are maximum values: for all the details on how to obtain these expressions, the dependence on the parameters of the models and the assumptions behind them, see the corresponding sections above.

Source	Frequency Range	Amplitude $\Omega_{\rm GW}(f)$	Characteristic Strain $h_{c,\rm sto}$
Inflation: vacuum amplitude	flat in the range $(10^{-16} - 10^{8})$ Hz	$\lesssim 10^{-16}$	$\lesssim 10^{-32}\left(\frac{\rm MHz}{f}\right)$
Inflation: extra-species	$(10^{5} - 10^{8})$ Hz	$\lesssim 10^{-10}$	$\lesssim 10^{-29}\left(\frac{\rm MHz}{f}\right)$
Inflation: broken spatial reparametrization	Blue in the range $(10^{-16} - 10^{8})$ Hz	$\lesssim 10^{-10}$	$\lesssim 10^{-29}\left(\frac{\rm MHz}{f}\right)$
Inflation: secondary GW production	Flat or bump	$\lesssim 10^{-8}$	$\lesssim 10^{-28}\left(\frac{\rm MHz}{f}\right)$
Preheating	$(10^{6} - 10^{9})$ Hz	$\lesssim 10^{-10}$	$\lesssim 10^{-29}\left(\frac{\rm MHz}{f}\right)$
Oscillons	$(10^{6} - 10^{9})$ Hz	$\lesssim 10^{-10}$	$\lesssim 10^{-29}\left(\frac{\rm MHz}{f}\right)$
Cosmic gravitational microwave background	$f_{\rm peak} \sim (10 - 100)$ GHz	$\Omega_{\rm GW}(f_{\rm peak}) \lesssim 10^{-6}$	$h_c(f_{\rm peak}) \lesssim 10^{-31}\left(\frac{\rm MHz}{f}\right)$
Phase transitions	$\lesssim 10^{9}$ Hz	$\lesssim 10^{-8}$	$\lesssim 10^{-28}\left(\frac{\rm MHz}{f}\right)$
Defects	Scale invariant	$\Omega_{\rm rad,0}\,\frac{v^4}{M_{\rm Pl}^4}\,F_U$	$10^{-26}\,\frac{v^4}{M_{\rm Pl}^4}\,F_U\left(\frac{\rm MHz}{f}\right)$
Gauge textures	$\sim 10^{11}\,\frac{v}{M_{\rm Pl}}$ Hz	$\lesssim 10^{-4}\,\frac{v^4}{{M_{\rm Pl}}^4}$	$\lesssim 10^{-26}\,\frac{v^4}{M_{\rm Pl}^4}\left(\frac{\rm MHz}{f}\right)$
Grand unification primordial BH evaporation	$(10^{18} - 10^{15})$ Hz	$\lesssim 10^{-8}$	$\lesssim 10^{-28}\left(\frac{\rm MHz}{f}\right)$

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Radial trajectory

$$P_{0,\|(\perp)}(f) = 2\left|\int_{r_0}^{R} \mathrm{d}r\, \Delta_{\mathrm{M}}(r) \exp\left\{-i\int_{r_0}^{r} \mathrm{d}r'\, \Delta_{\|(\perp)}\left(r'\right)\right\}\right|^2 ,$$

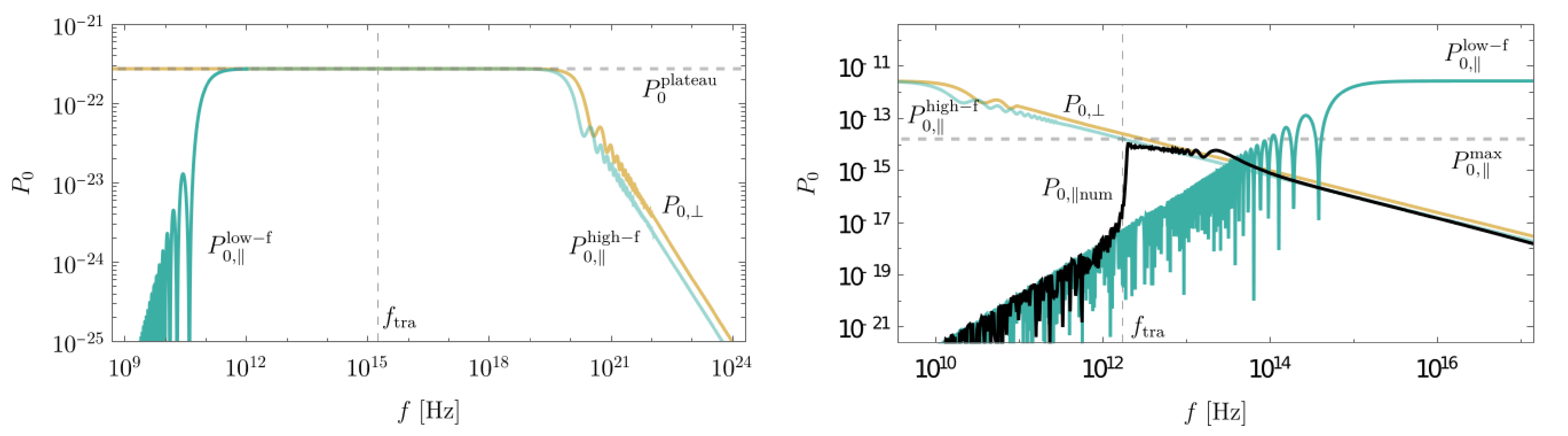
Generalised trajectory

$$P_{\|(\perp)}(f, b) = 2\left|\int_{y_{\min}}^{y_{\max}} \mathrm{d}y\, \Delta_{\mathrm{M}}(y) \exp\left\{-i\int_{y_{\min}}^{y} \mathrm{d}y'\, \Delta_{\|(\perp)}\left(y'\right)\right\}\right|^2 .$$

Radial trajectory

$$P_{0,\|(\perp)}(f) = 2\left|\int_{r_0}^{R} \mathrm{d}r\, \Delta_{\mathrm{M}}(r) \exp\left\{-i\int_{r_0}^{r} \mathrm{d}r'\, \Delta_{\|(\perp)}\left(r'\right)\right\}\right|^2$$

Conversion probability as a function of the frequency for an NS with B0 = 10^8 Gauss, T = 0.1 s, and r0 = 10 km (left) and for B0 = 10^13 Gauss, T = 1 s, and r0 = 10 km (right)



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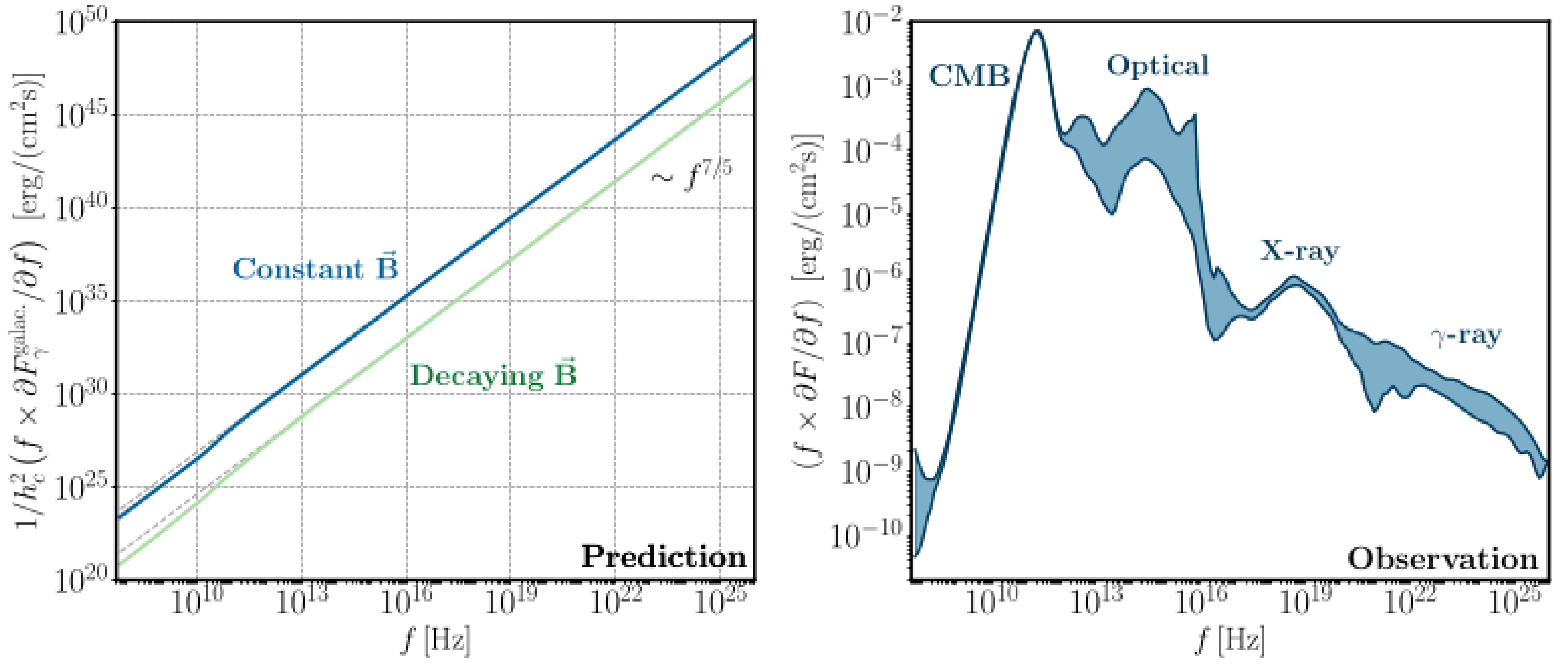


Figure 4: *Left*: Predicted frequency spectrum of the total induced flux $\partial F_\gamma^{\text{galac.}}/\partial f$, normalized by $1/h_c^2$. Blue and green lines show the results for a NS model with constant and decaying $\vec{B}$, respectively. We set $r_0 = 10\,\text{km}$. *Right*: Frequency spectrum measured on Earth, adapted from Ref. [59]. The thick band corresponds to the 95% confidence interval. Data allows to put a bound on h_c at each frequency.

The photon flux from this SGWB conversion must be compared to observations of the all-sky integrated flux.

In the right panel we show the latter after the substraction of all galactic sources which are known and accounted for.

Then, the flux can not be brighter than this flux, otherwise it would be in conflict with current observations

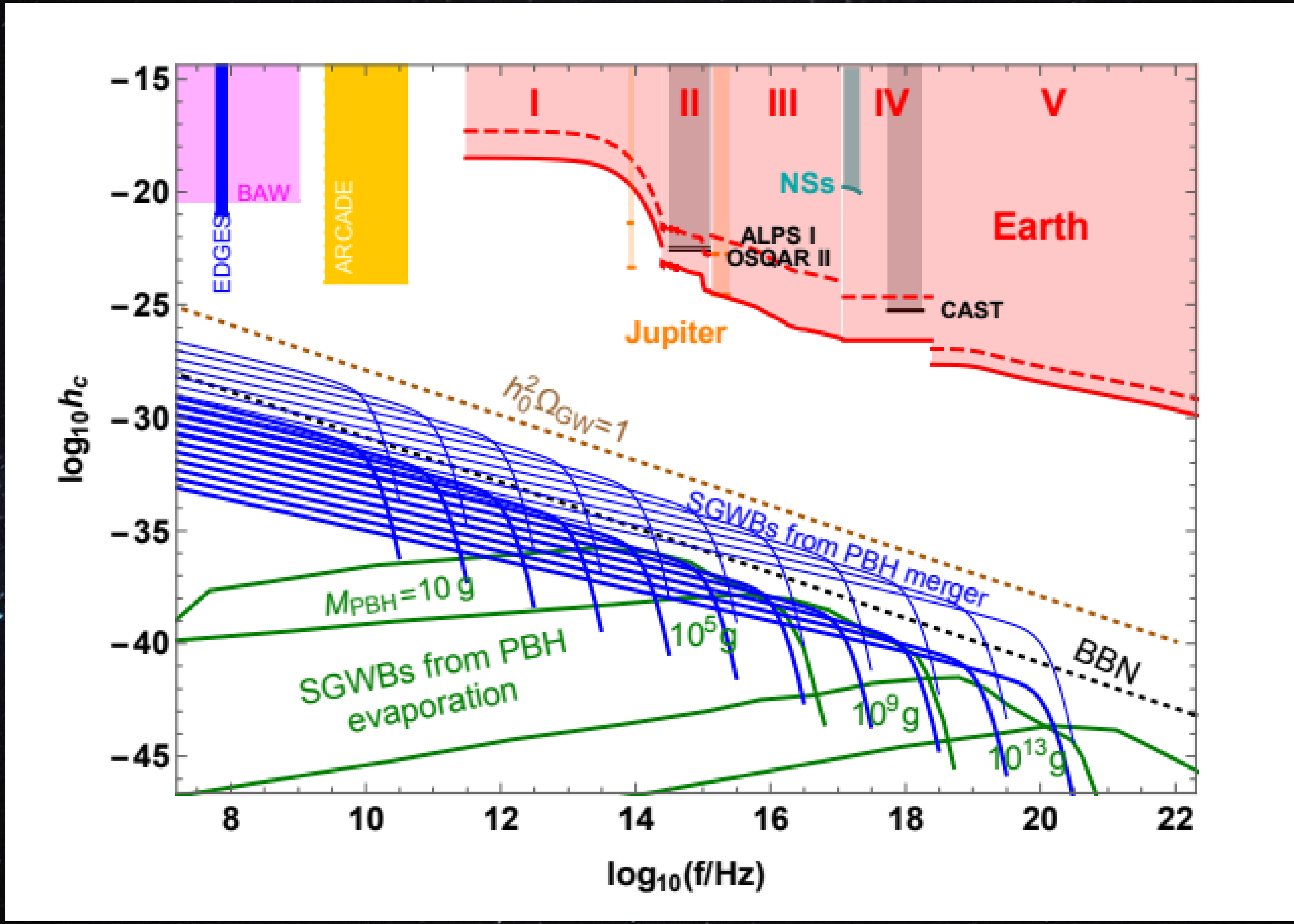
Flux from one neutron star

$$\frac{\partial F_\gamma}{\partial f} = \pi^2 M_{\rm pl}^2 f h_c^2 \left[\left(\frac{b_{c,\parallel}(f, B_0)}{r} \right)^2 P_{0,\parallel}(f) + \left(\frac{b_{c,\perp}(f, B_0)}{r} \right)^2 P_{0,\perp}(f) \right]$$

Total flux, integrating over distribution of galaxies

$$\frac{\partial F_\gamma^{\rm galac.}}{\partial f}(f, h_c) = \int \mathrm{d}^3\boldsymbol{r}\, n_{\rm ns}(\boldsymbol{r}) \int \mathrm{d}B_0\, \mathrm{d}T \Big(0.004 \times P_{\rm act.}(B_0, T) + 0.996 \times P_{\rm dead}(B_0, T) \Big) \frac{\partial F_\gamma}{\partial f}(B_0, T, \boldsymbol{r}, f, h_c).$$

Virgile Dandoy, Toni Bertólez-Martínez, **FC** 2402.14092



I
II
III
IV
V
BAW
EDGES
ARCADE
NSs
Earth
ALPS I
OSQAR II
CAST
Jupiter
$h_0^2\Omega_{GW}=1$
SGWBs from PBH merger
BBN
$M_{PBH}=10$ g
10^5g
10^9g
10^{13}g
SGWBs from PBH evaporation
$\log_{10}h_c$
$\log_{10}$(f/Hz)

2305.01832