Transient Signals in Wave-like Dark Matter experiments from Black Hole formation

Based on **2408.10296** (EPJC)

in collaboration with **J. Jaeckel** (U. Heidelberg)

Arturo de Giorgi

QUP Workshop, 9th April 2025

Durham University

Where are we?

SM

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Dark Energy

Baryogenesis

BSM

New scalars

Cosmological Constant

Flavour puzzle

Hierarchy Puzzle

SM

Neutrino Masses

Higgs Potential

Strong CP

Sterile Neutrinos

Dark Matter

Dark Photons

Axions

....

(Ultra) Light DM & Periodic Signals

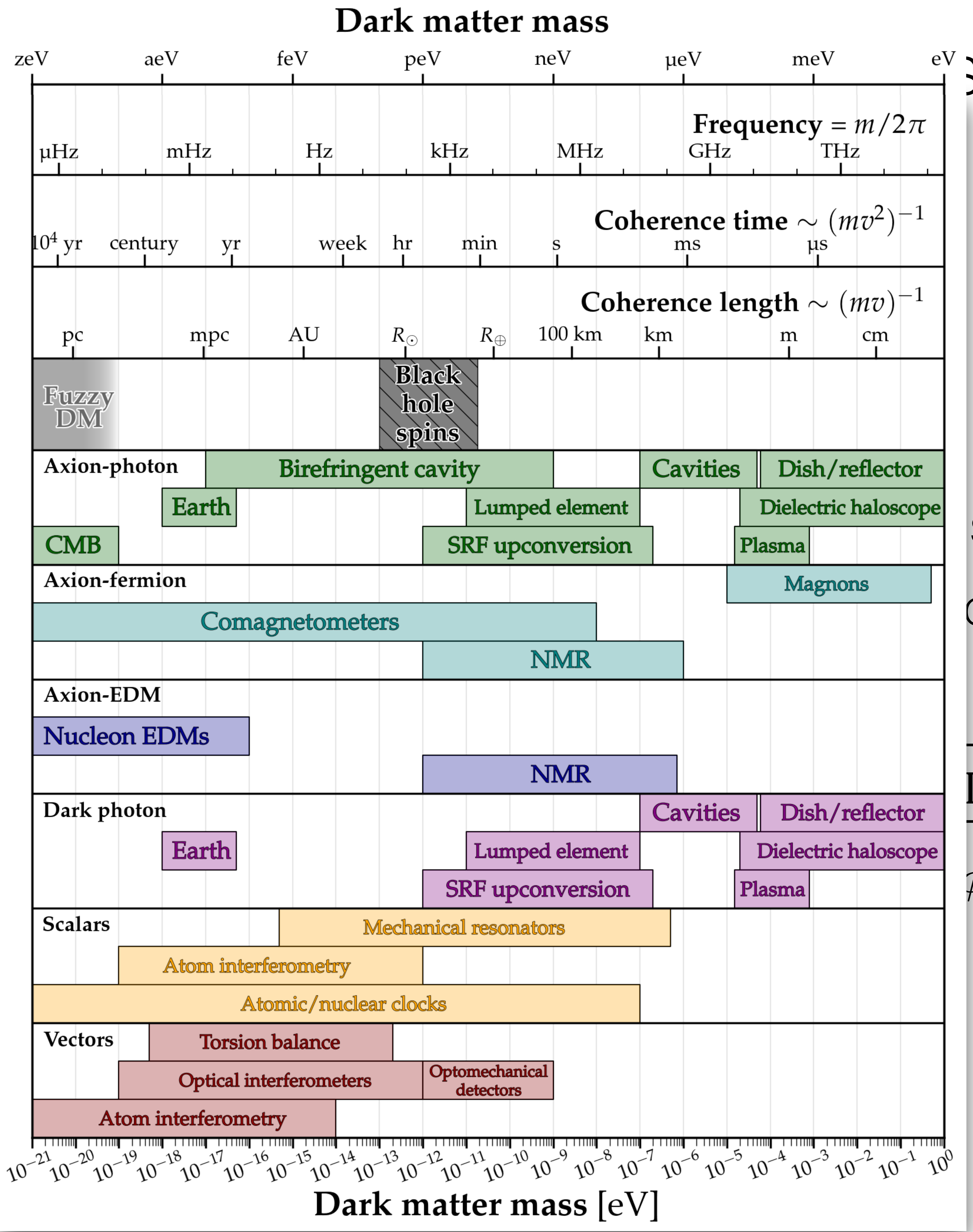
$$N_{\rm dB} \sim \frac{\rho_{\rm DM}}{m}\lambda_{\rm dB}^3 \qquad \lambda_{\rm dB} = \frac{2\pi}{mv} \qquad N_{\rm dB} \sim \left(\frac{34\,{\rm eV}}{m}\right)^4 \left(\frac{250\,{\rm km/s}}{v}\right)^3$$

For $m \lesssim 30\ {\rm eV}$ the field has **large occupation number**

⇒ it behaves as a **classical field**

$$\phi(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi}\cos(m_\phi t)$$

(Ultr s



N

$$N_{\rm dB} \sim \left(\frac{34\,{\rm eV}}{m}\right)^4 \left(\frac{250\,{\rm km/s}}{v}\right)^3$$

s **large occupation number**

a c

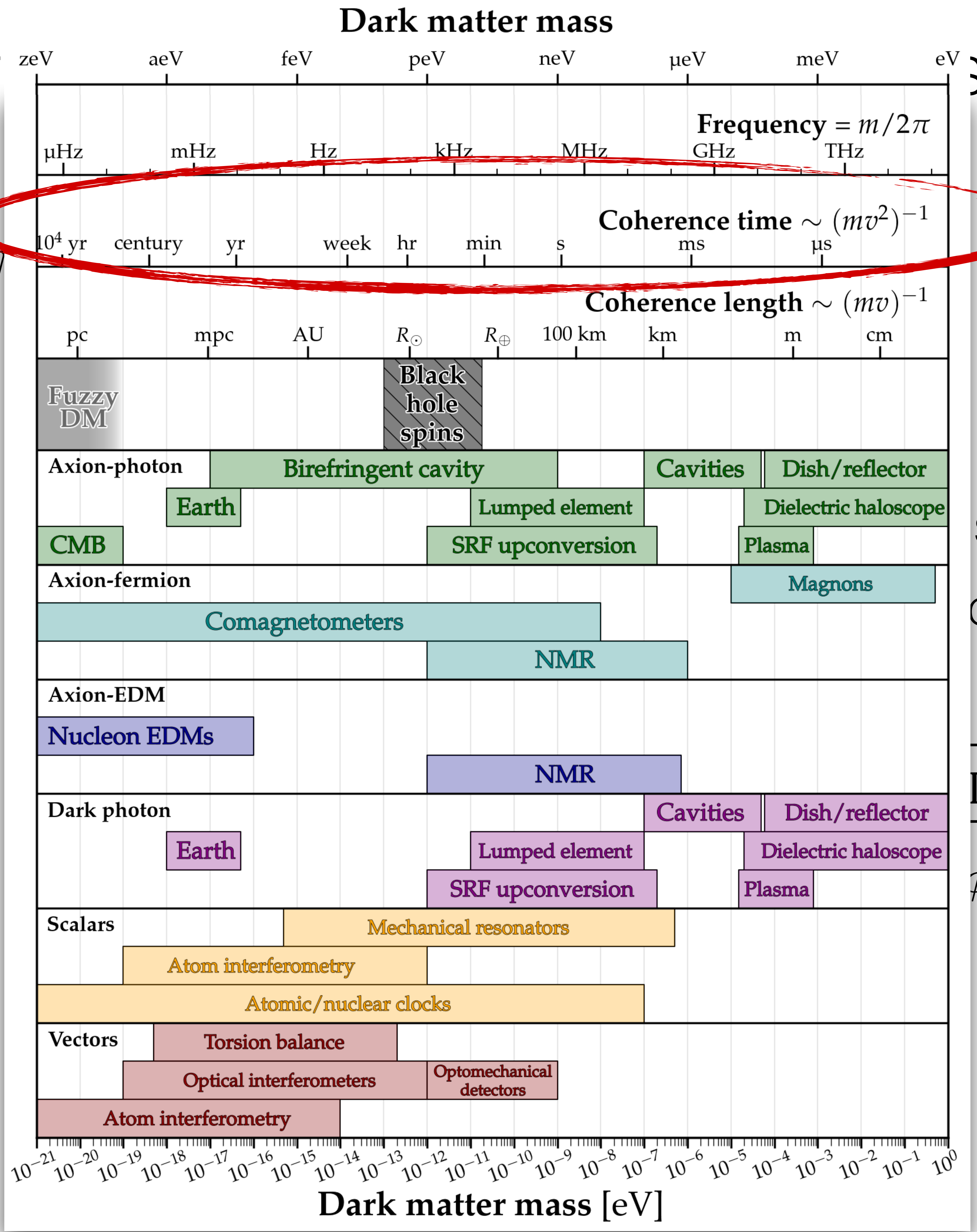
DM $\cos(m_\phi t)$

ϕ

Vast research programme!

AxionLimits, C. O'Hare

(Ultr… s



"Human" scale

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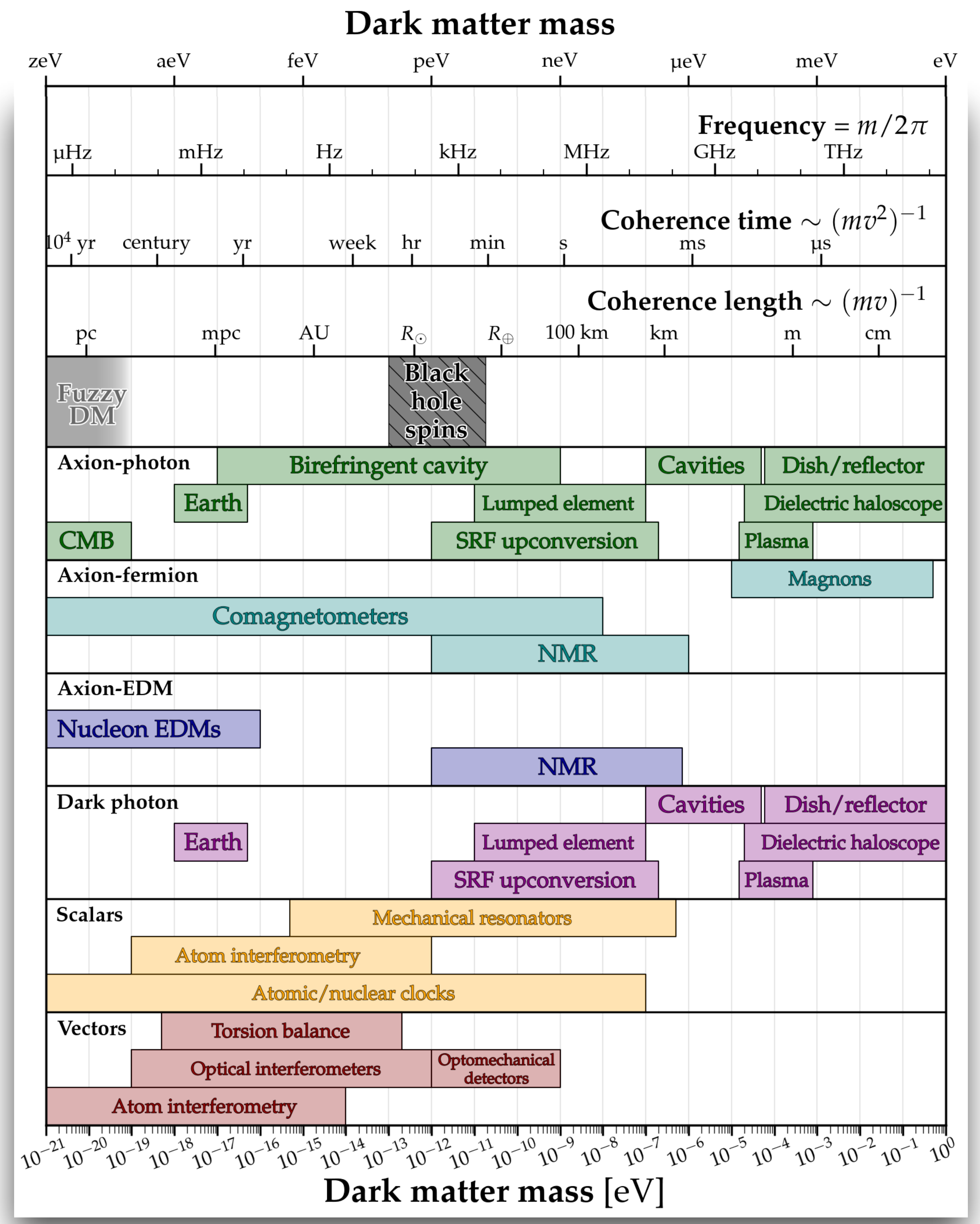
AxionLimits, C. O'Hare

Different signal for New Physics?



What if the **local** DM density is **small**?

Or what if DM is made of **several subcomponents**?

What if an ultra light scalar exists, but it is **not DM**?

...

The infamous "**why not**"?

AxionLimits, C. O'Hare

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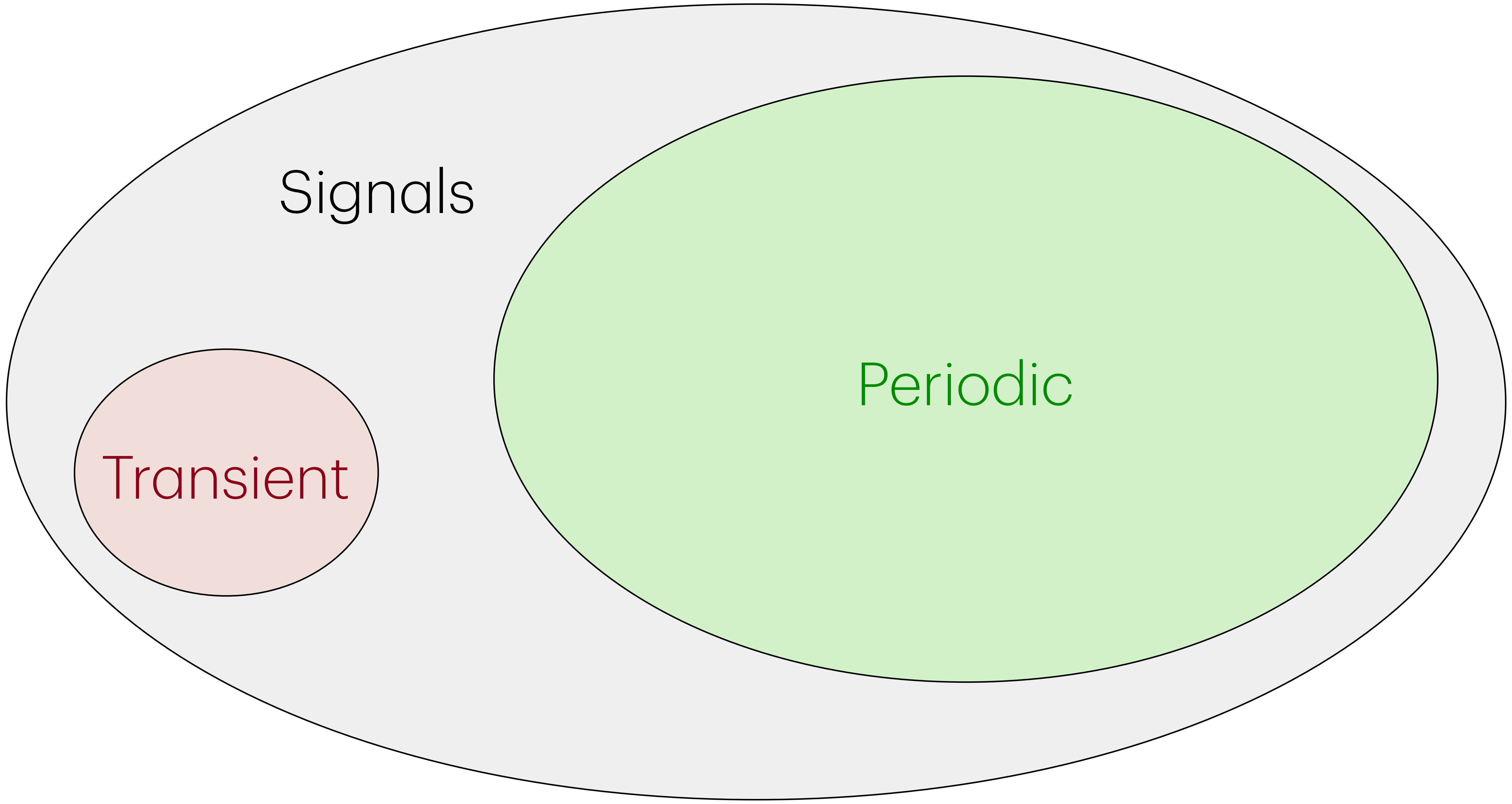
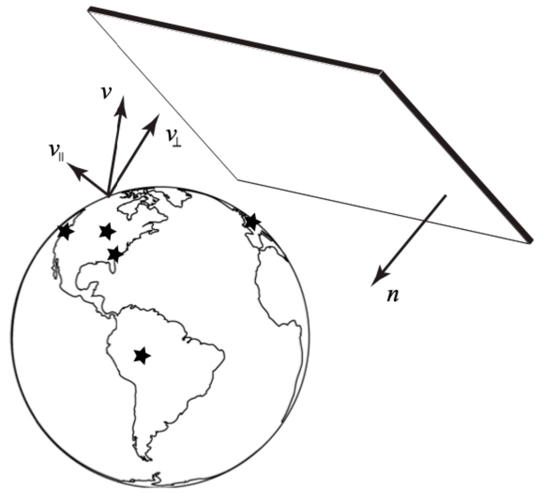
Transient Signals

Some interesting studies in the literature:
(non-exhaustive list)



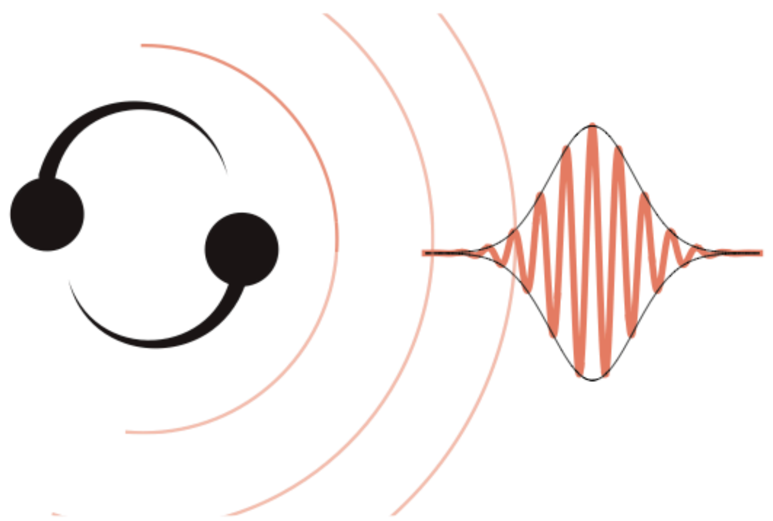
Passage of a domain wall

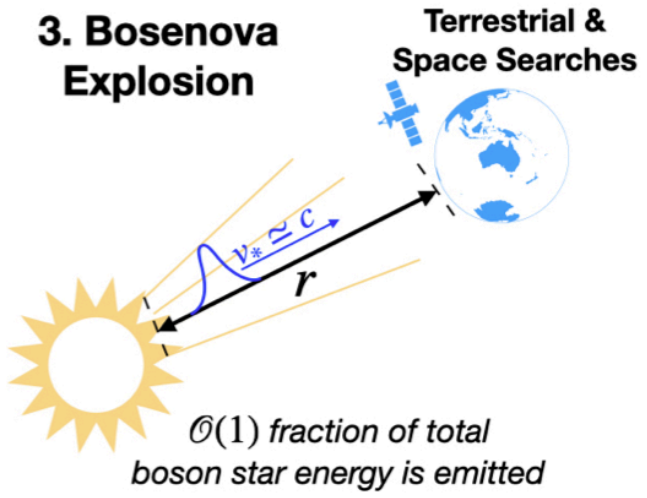
"How do you know if you ran through a wall?"
M. Pospelov et al. (1205.6260)



Binary mergers

"Quantum sensor networks as exotic field telescopes for multi-messenger astronomy"
C. Dailey et al. (2002.04352)



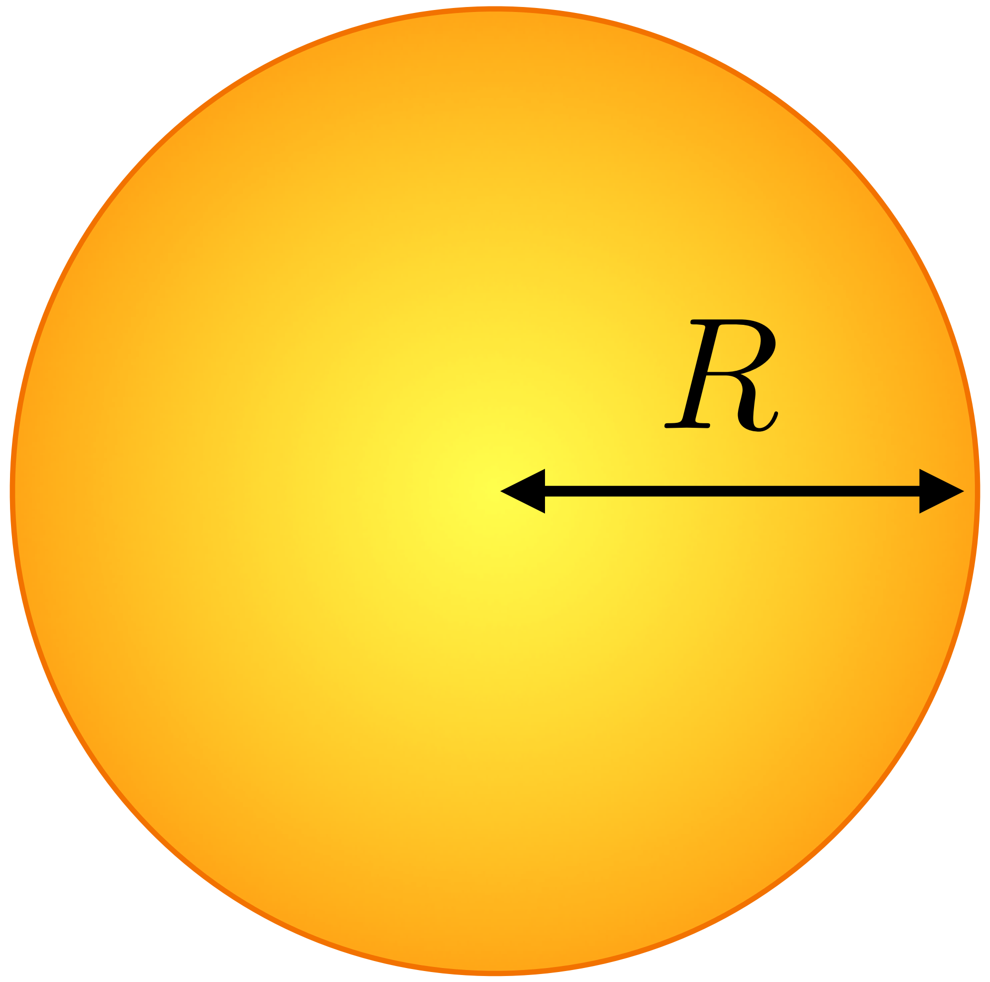


Bosenova

"Detection of Bosenovae with Quantum Sensors on Earth and in Space?"
J. Arakawa, V. Takhistov et al. (2306.16468)

Transient Signal from BH Formation

New process!



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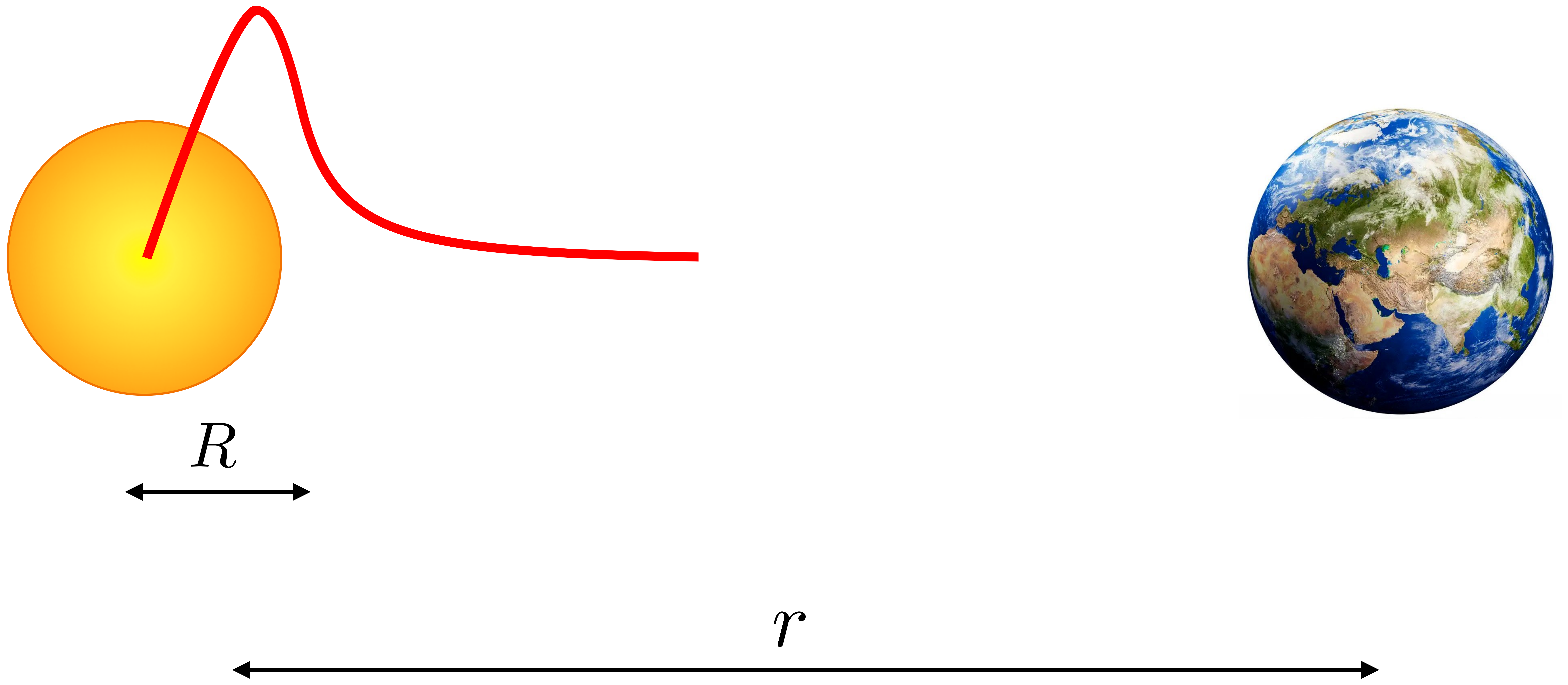

*not in scale

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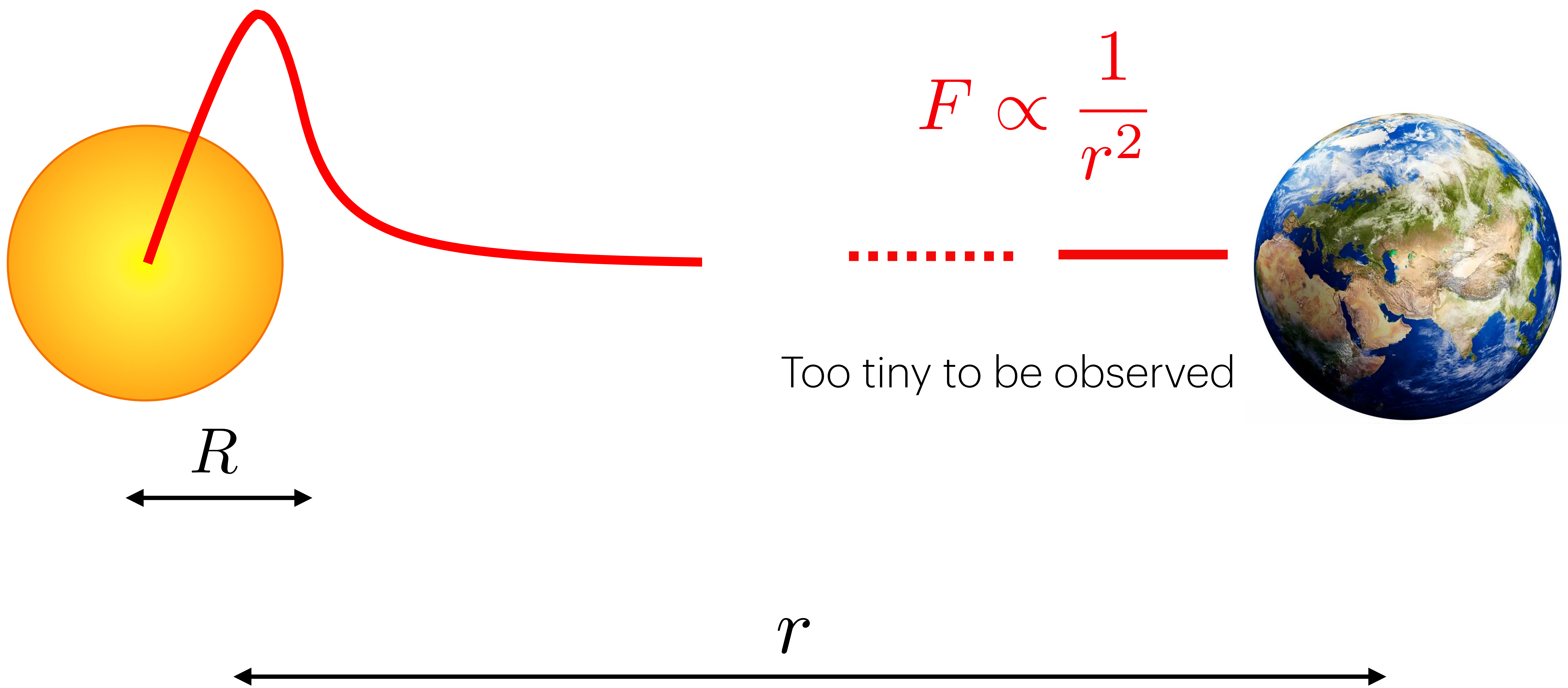

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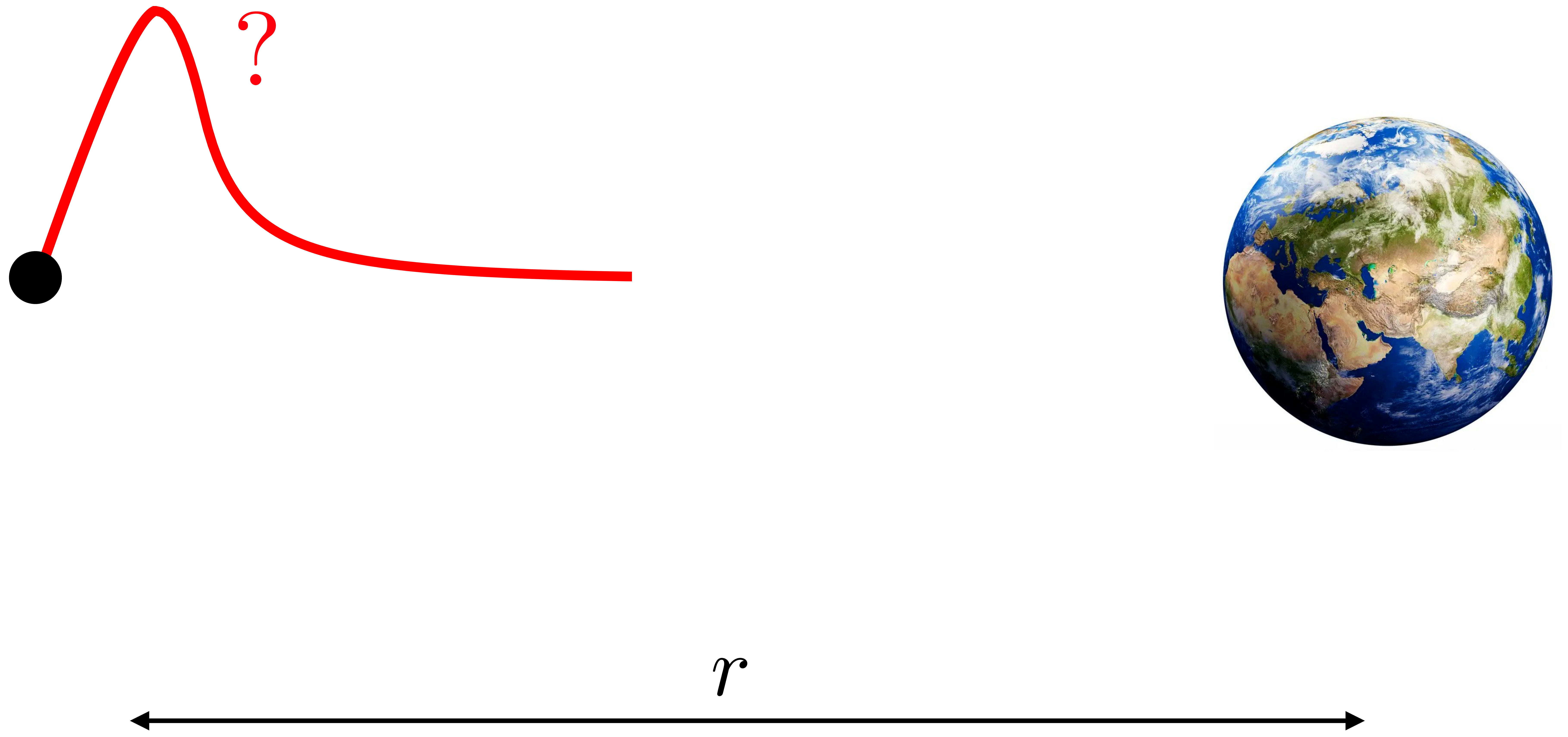

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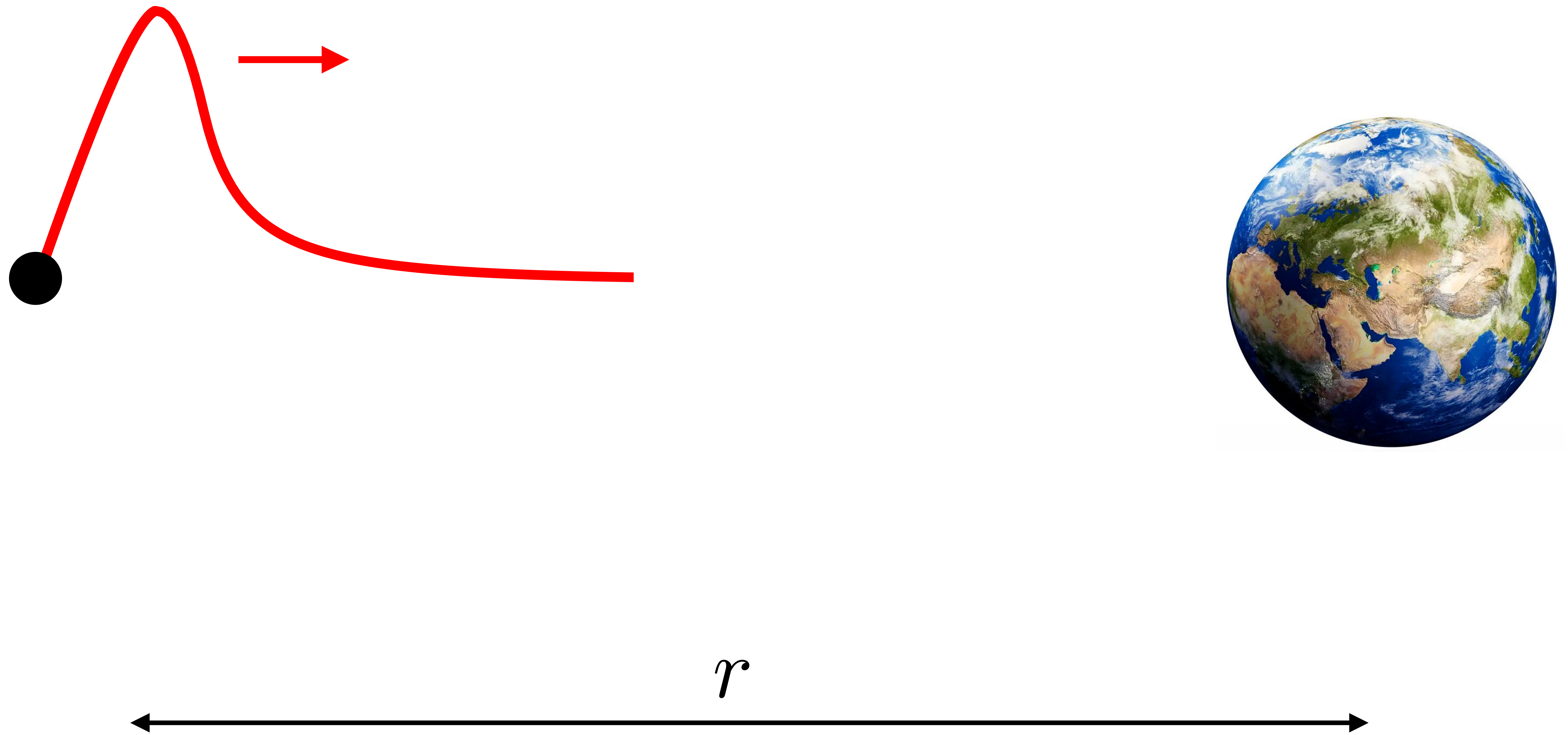

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Transient Signal from BH Formation

New process!

$$F \propto \frac{1}{rR}$$

$\frac{r}{R}$ enhancement!

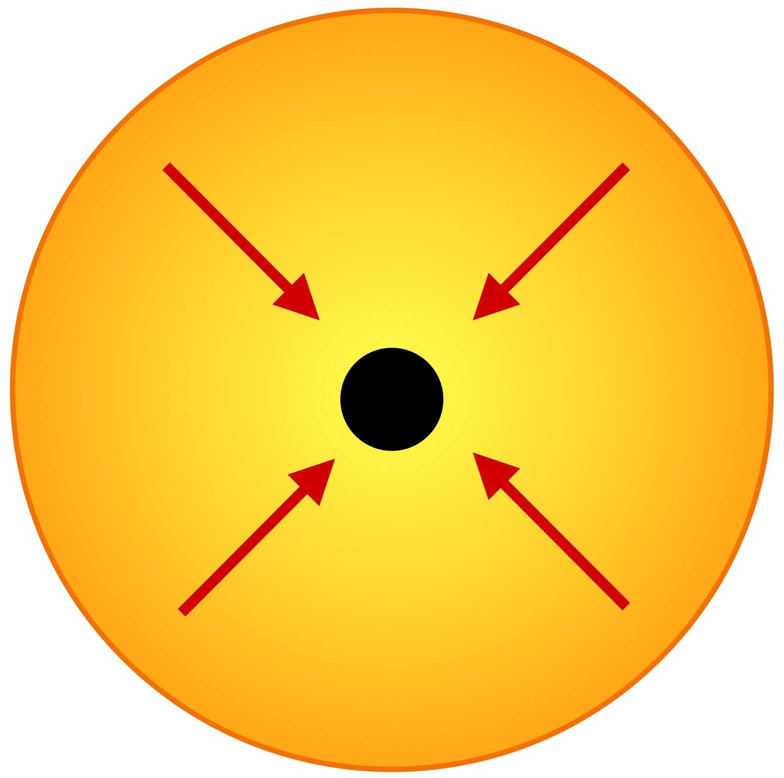
$m_\phi \lesssim \frac{1}{r}$ avoid signal dilution!

r

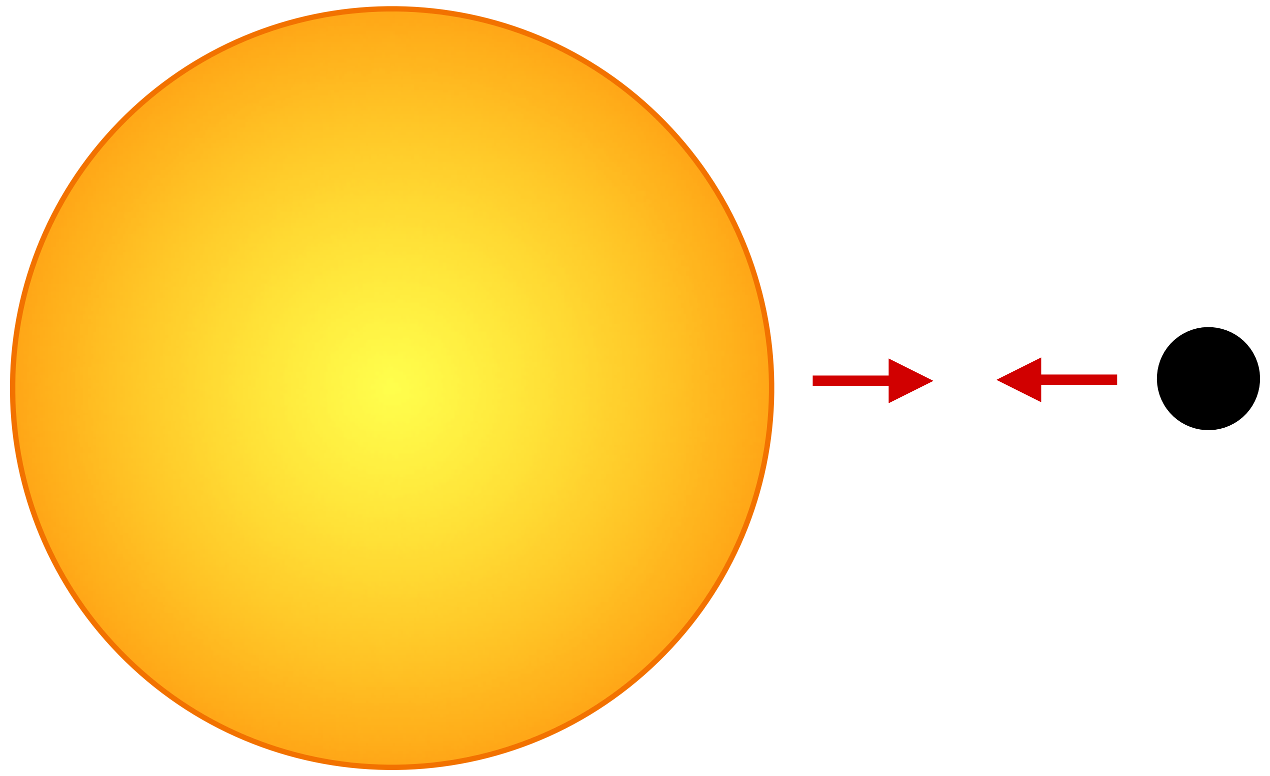
*not in scale

Sources

Collapse



Merger



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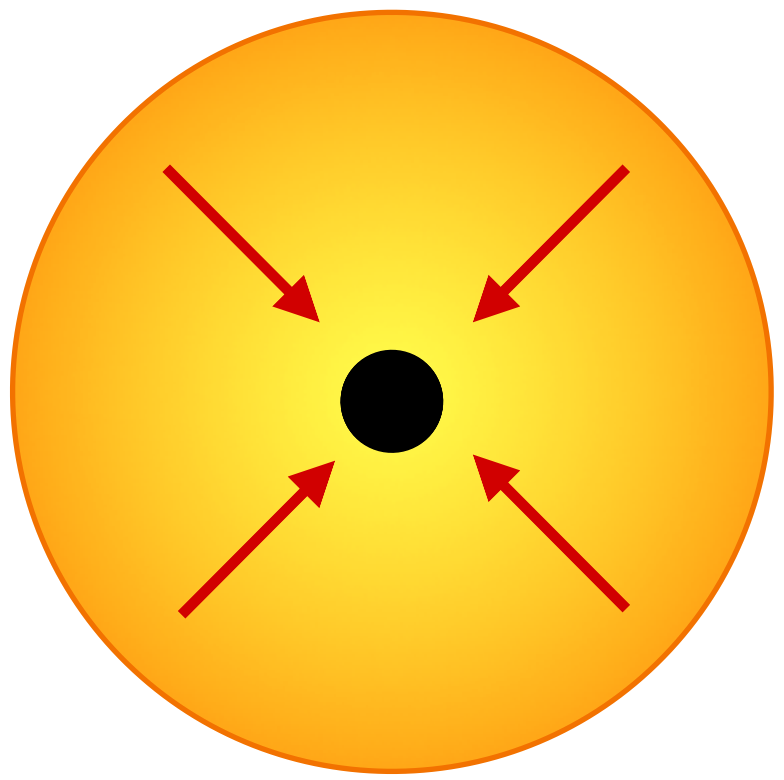

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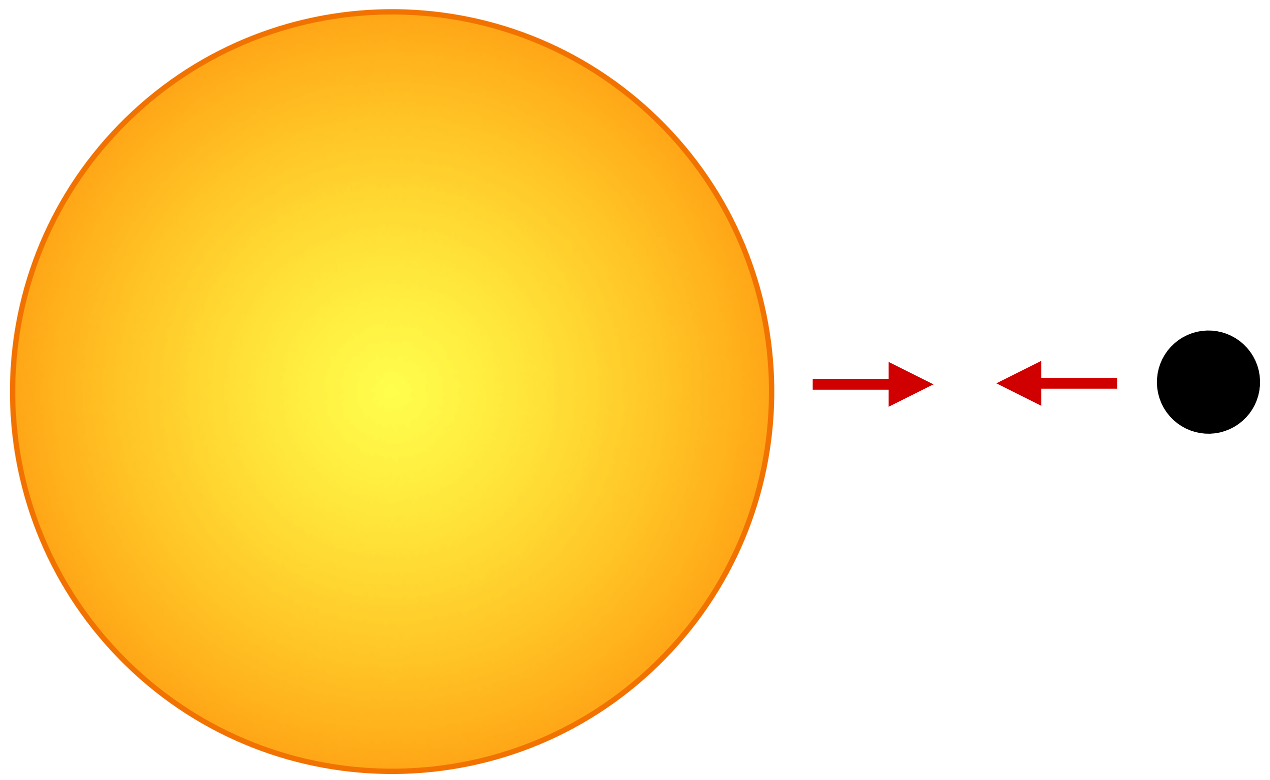

$f_{\mathrm{SN1987A}} \approx 2 \times 10^{-3}\mathrm{Hz}\,,$

Most famous supernova

$f_{\mathrm{Betelgeuse}} \approx 9 \times 10^{-5}\mathrm{Hz}\,,$

Red-giant, SN candidate

$f_{\mathrm{NS}} \approx 5 \times 10^{3}\mathrm{Hz}$

Closest Neutron Star

Name	Type	M $[M_\odot]$	r [ly]	R
SN1987A	Supernova	20	170×10^3	$35\,R_\odot \approx 2.4 \times 10^7$ Km
Betelgeuse	Red Giant	18	500	$800\,R_\odot$
RX J1856.5-3754	Neutron Star	0.9	400	10 Km

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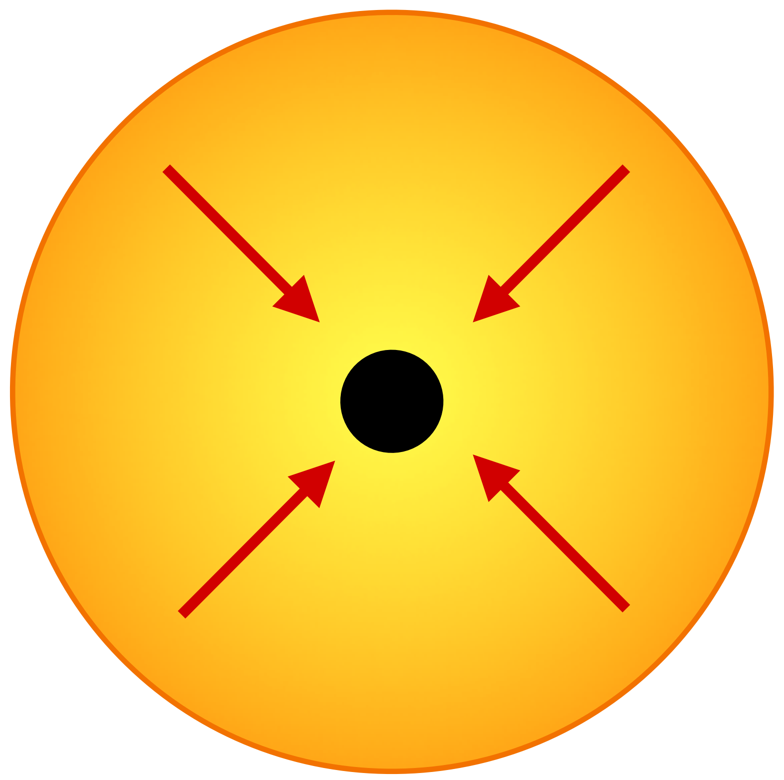

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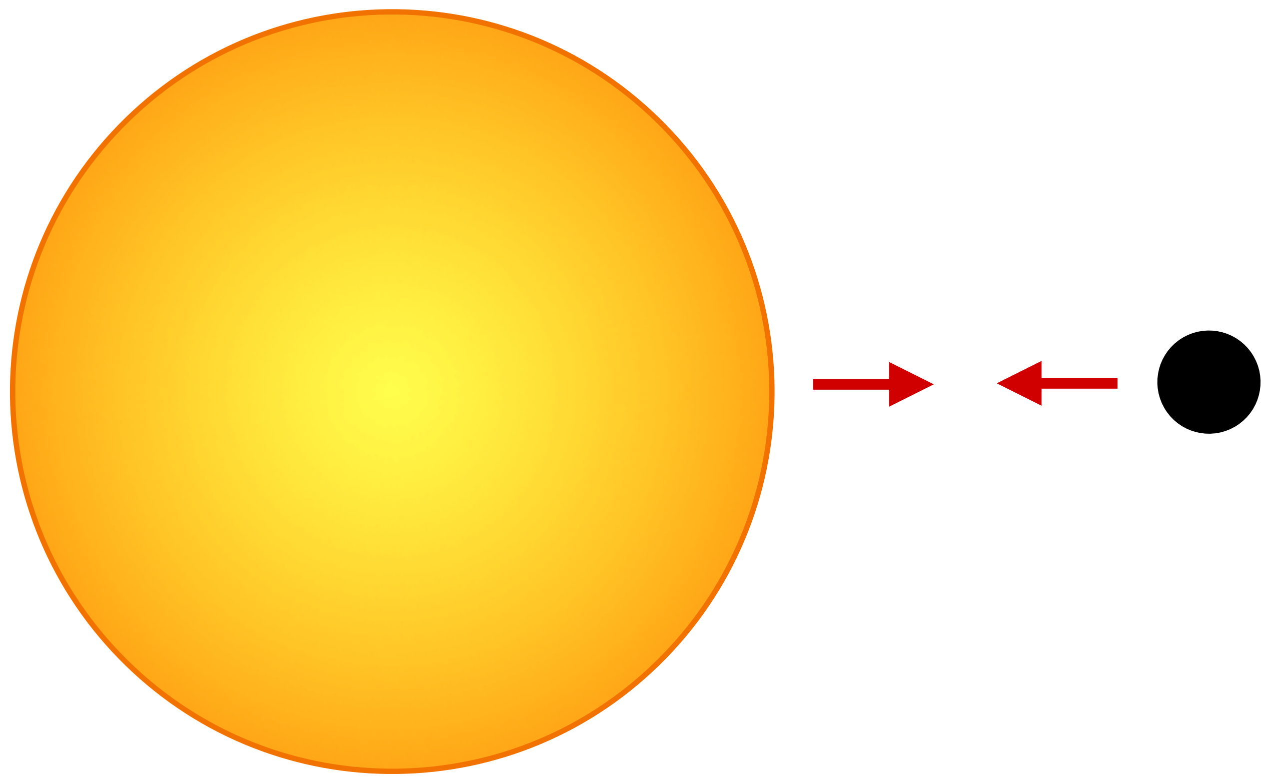

Very different frequencies

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Initial Field Configuration

1) **Yukawa-type** source

$$\mathcal{L}_{\text{source}} = \sum_{\psi} g_{\phi\psi\psi}\phi\bar{\psi}\psi \equiv \phi J(x)$$

$$J(x) = g_{\text{YL}}\frac{3}{4\pi R^3}\Theta(-t)\Theta(R-r)$$

$$\phi_{\text{YL}}(r \le R) = \frac{g_{\text{YL}}}{8\pi R}\left(3 - \frac{r^2}{R^2}\right)$$

$$\phi_{\text{YL}}(r \ge R) = \frac{g_{\text{YL}}}{4\pi r}\,.$$

2) What if the field had some tiny **self-interactions**? *"Compact Source"*

$$\phi_{\text{CS}}(x) = \begin{cases} \phi_{\text{CS}}(r) & r \le R\,, \\ 0 & \text{otherwise} \end{cases}$$

Example:

$$\phi_{\text{CS}}(r) = \sqrt{\frac{35|E|R}{6\pi}}\frac{(R-r)^3}{R^4}$$

[fixed energy E]

Signal VS Noise

$$\tilde{h}(\omega) \equiv \int_{-\infty}^{\infty} \mathrm{d}t\, h(t) e^{-i\omega t} \qquad \mathrm{ASD}[h](f) \equiv \sqrt{f}|\tilde{h}(f)|$$

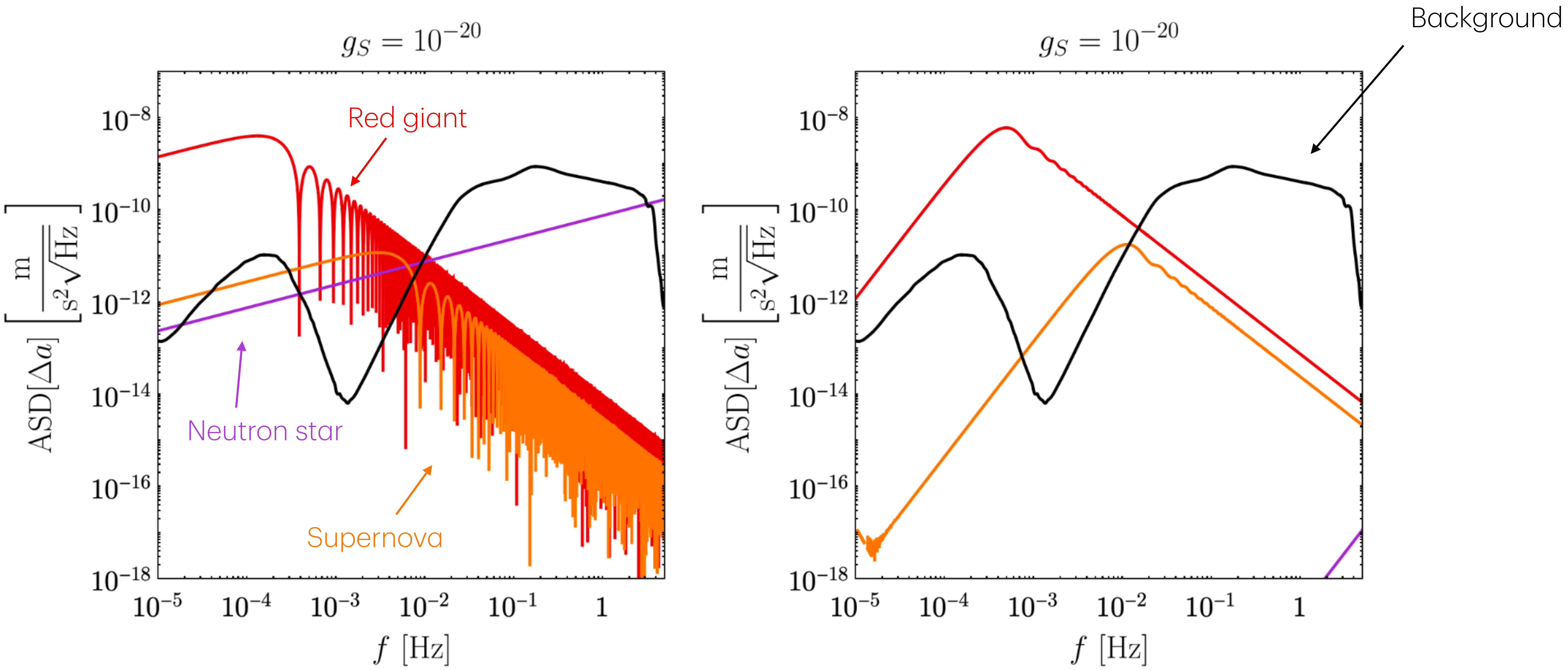
We considered some case studies:

Interferometer: LISA Pathfinder

Torsion Pendulum

Optical Magnetometry: GNOME

DMRadio-m3



(a) Yukawa-like

(b) Compact Source

$$\mathcal{L} \subset -g_S \phi \overline{N} N + g_S \phi \bar{e} e$$

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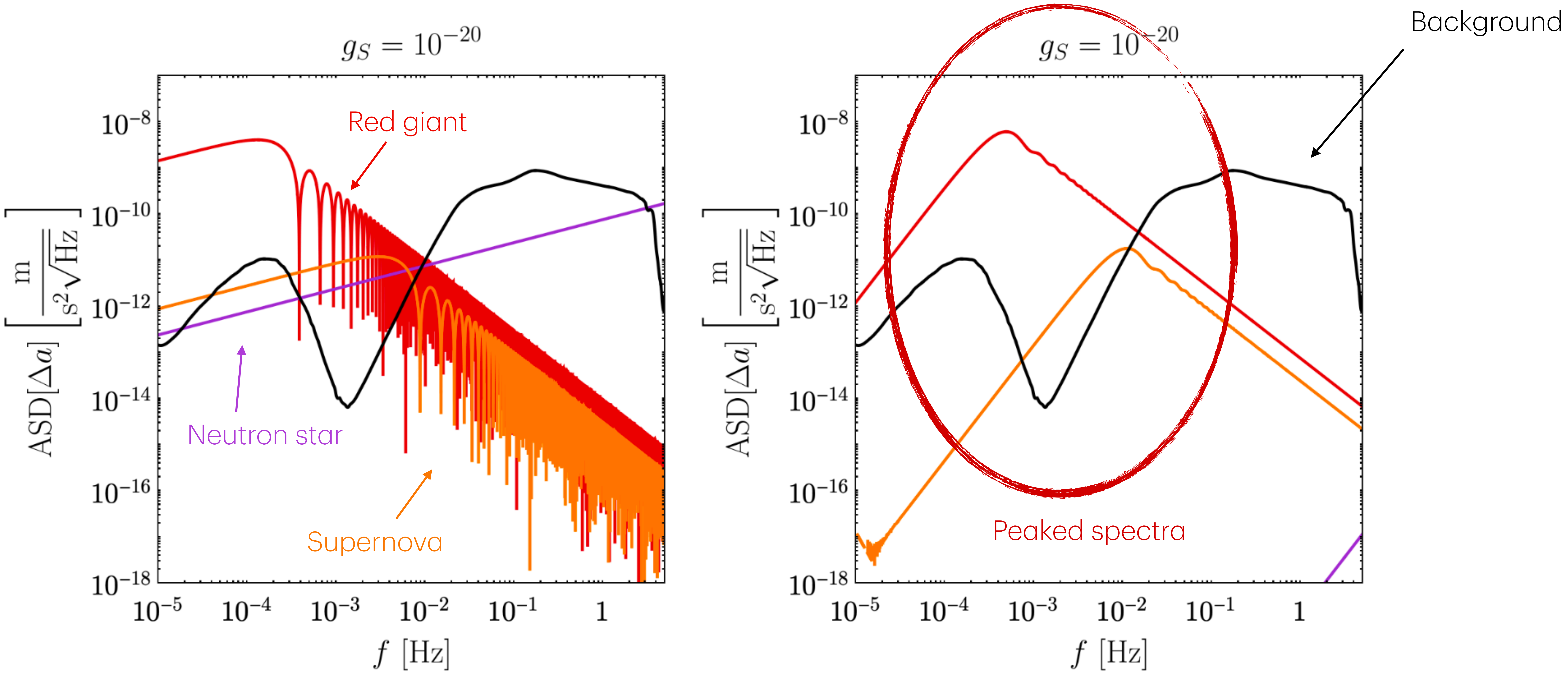

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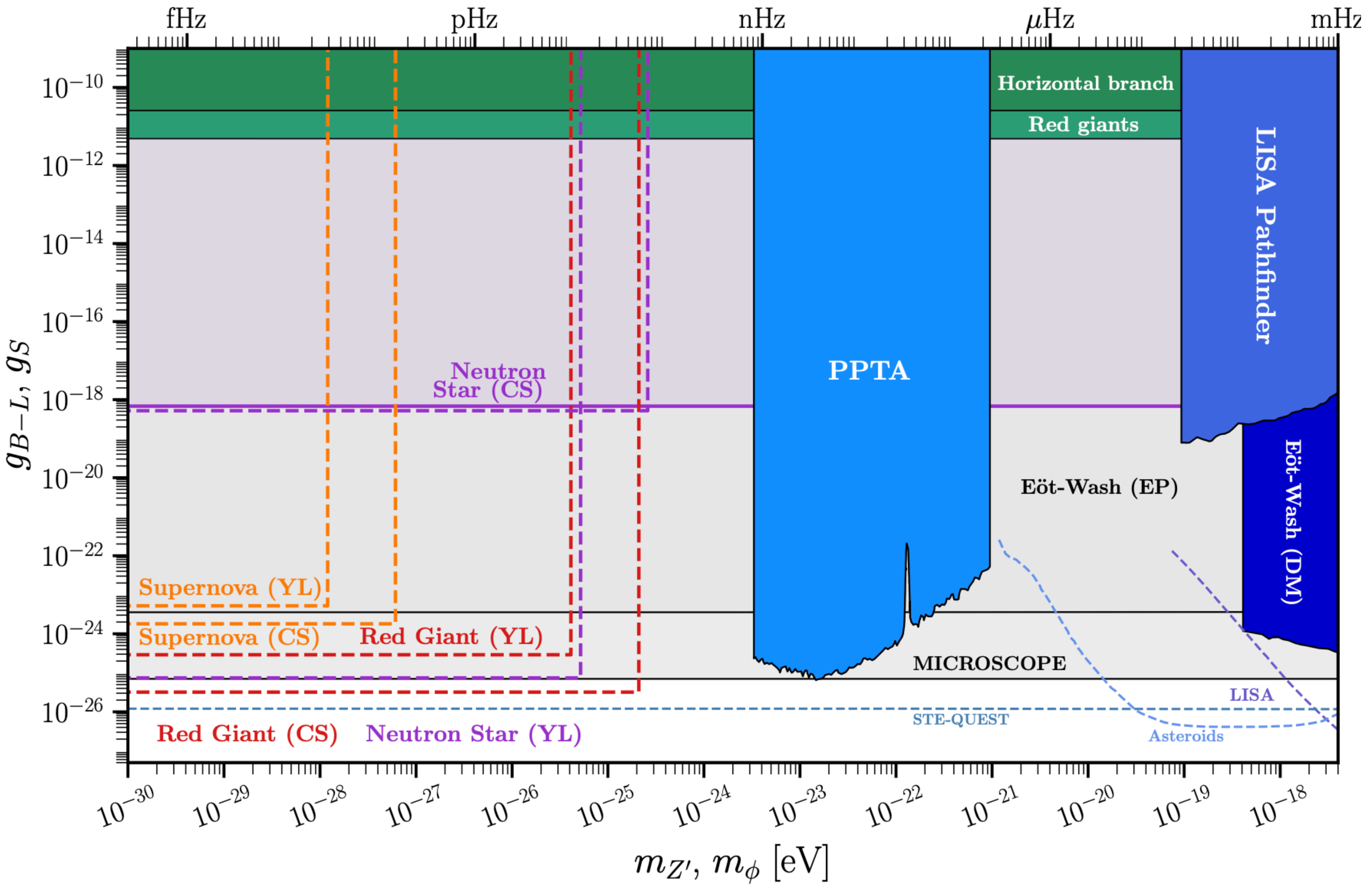
(b) Compact Source

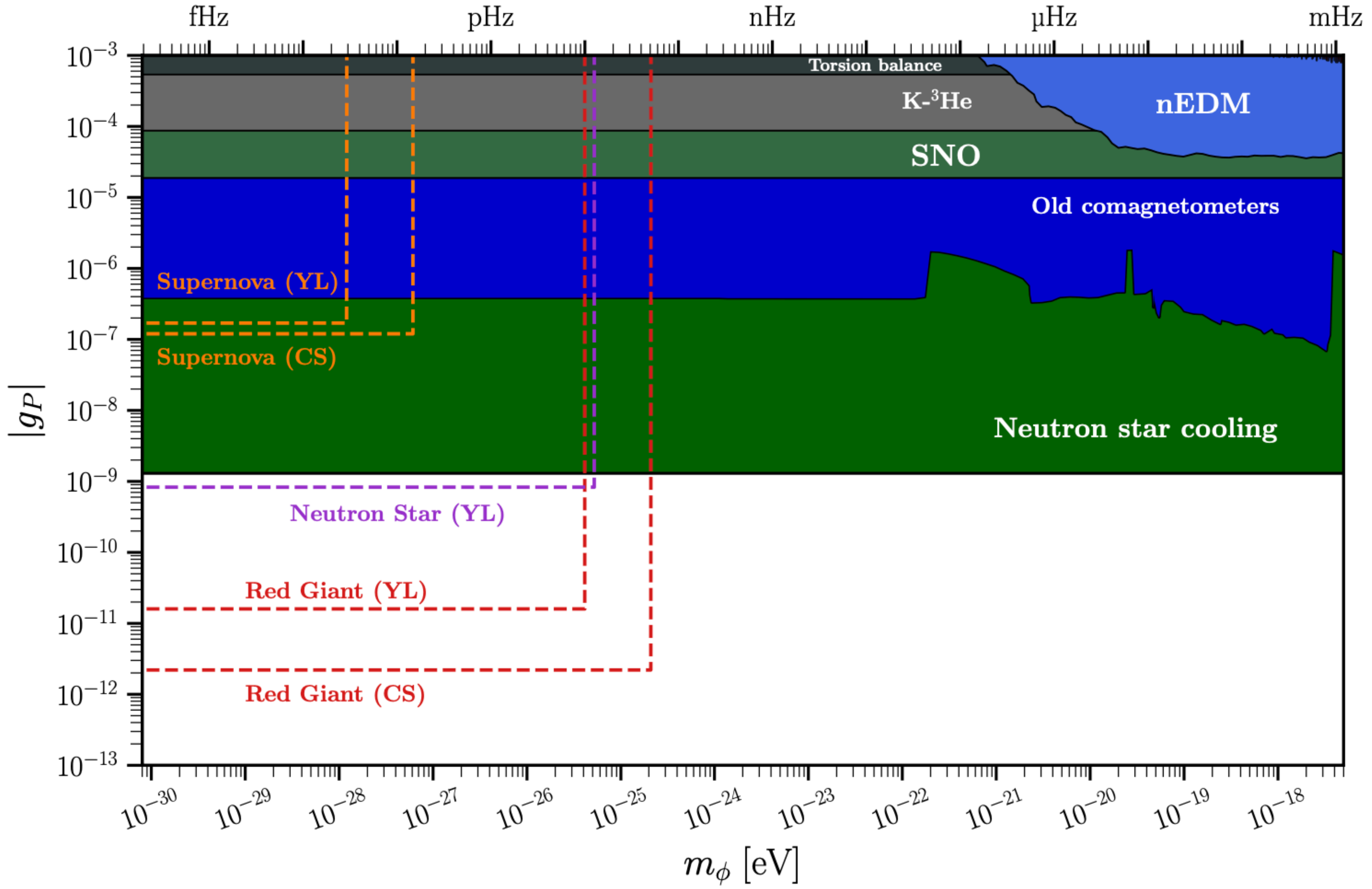
$\mathcal{L} \subset -g_S\phi\overline{N}N + g_S\phi\bar{e}e$

Results

Scalar



Pseudo-scalar



(similarly for photons)

$$\mathcal{L} \subset -g_S\phi\,\overline{N}N - g_S\phi\,\bar{e}e - g_P\phi\,\overline{N}i\gamma_5 N - \frac{g_\gamma}{4}\phi F^{\mu\nu}\widetilde{F}_{\mu\nu}$$

Caveats and Improvements

1. The BH does not form **istantaneously**
2. The BH **remnant** will affect the signal

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1. The BH does not f… **ntaneously**

Stay tuned!

2. The BH **remnant** will affect the signal

—

Work in progress

with **J. Jaeckel** (U. Heidelberg) and **Y. Garcia del Castillo** (New South Wales U.)

—

Thanks

Mass-Dilution Effect

If **massive**, different Fourier **modes** propagate at a **different speed** $\Rightarrow$ **dilution**

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If **massive**, different Fourier **modes** propagate at a **different speed** ⇒ **dilution**

$$\Delta v_{\rm typ}\, r \lesssim R \quad \oplus \quad \Delta v_{\rm typ} \sim \frac{m_\phi}{\omega_{\rm typ}} \sim m_\phi R \quad \Rightarrow \quad m_\phi \lesssim \frac{1}{r}$$

typical velocity

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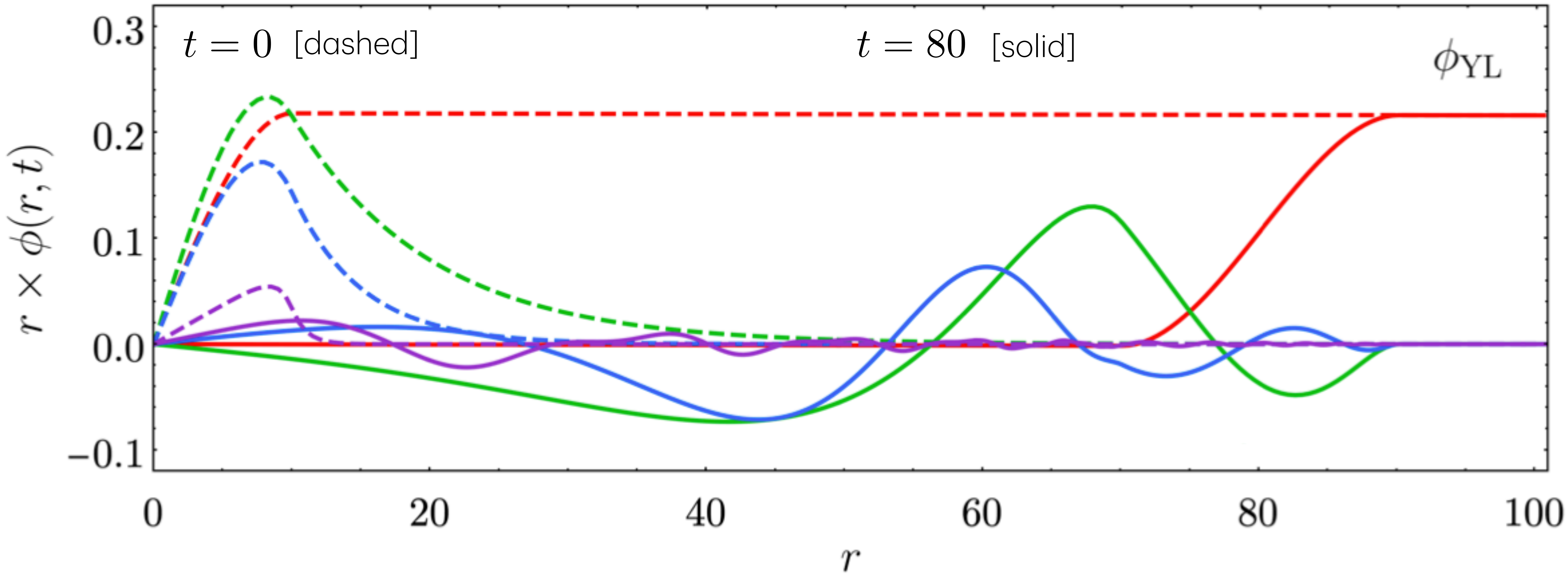
typical velocity



$m_\phi = 0$ (**red**)
$m_\phi = 0.1$ (**green**)
$m_\phi = 0.2$ (**blue**)
$m_\phi = 1$ (**purple**)

$$\phi(r,0) = \frac{e^{-m_\phi r}}{4\pi r}$$

[natural units]
$c = \hbar = 1$