New BSM transient signals from black hole formation

Based on **2408.10296** (EPJC), **2510.YYYYY**

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

IP3

Durham University

Arturo de Giorgi

5th AEI International Workshop

Where are we?

SM

Where are we?

Dark Energy

Baryogenesis

BSM

Cosmological Constant

Flavour puzzle

Hierarchy Puzzle

New scalars

SM

Neutrino Masses

Higgs Potential

Sterile Neutrinos

Strong CP

Dark Matter

Dark Photons

Axions

....

(Ultra) Light DM & Periodic Signals

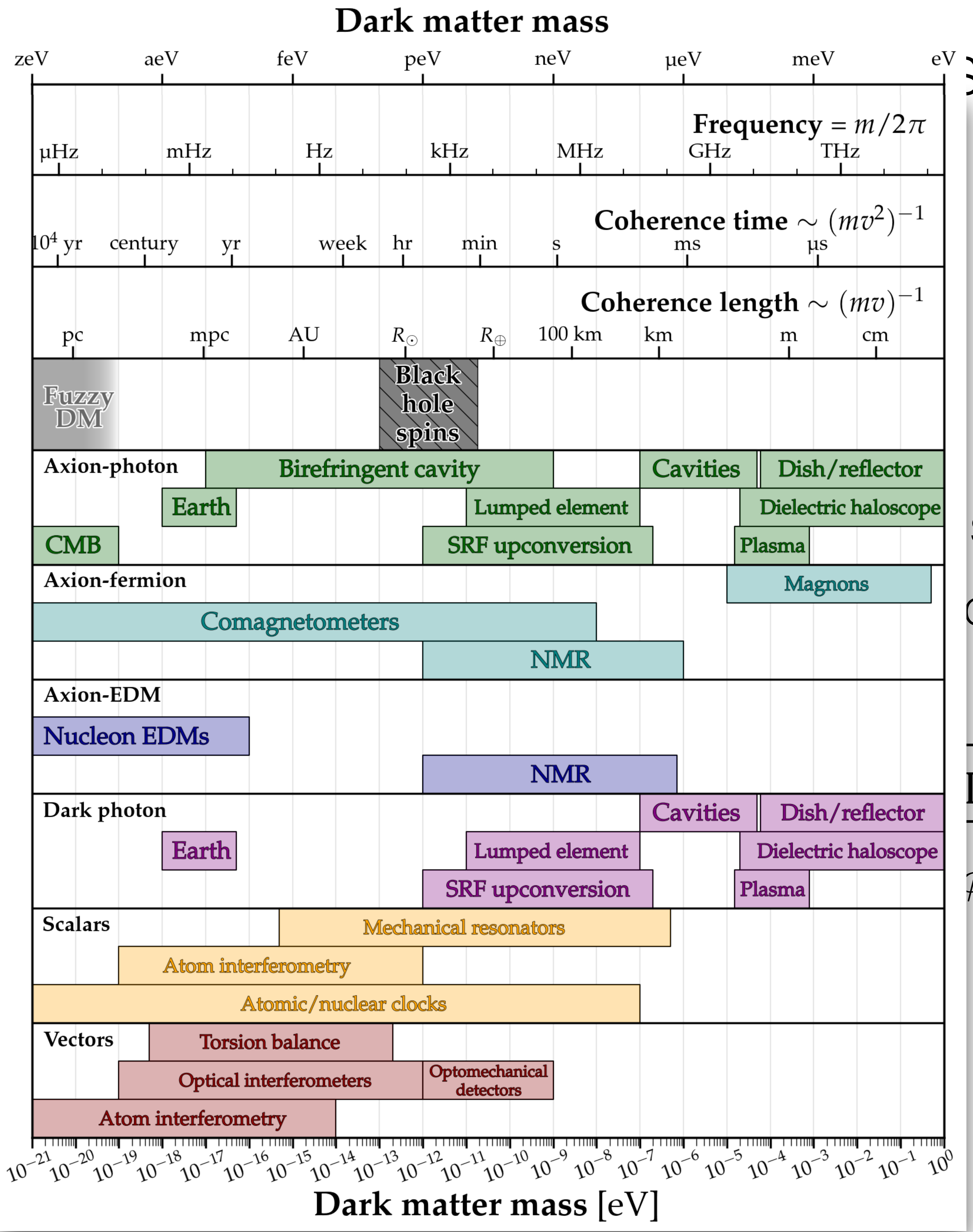
$$N_{\mathrm{dB}} \sim \frac{\rho_{\mathrm{DM}}}{m}\lambda_{\mathrm{dB}}^3 \qquad \lambda_{\mathrm{dB}} = \frac{2\pi}{mv} \qquad N_{\mathrm{dB}} \sim \left(\frac{34\,\mathrm{eV}}{m}\right)^4 \left(\frac{250\,\mathrm{km/s}}{v}\right)^3$$

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

⇒ it behaves as a **classical field**

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

(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

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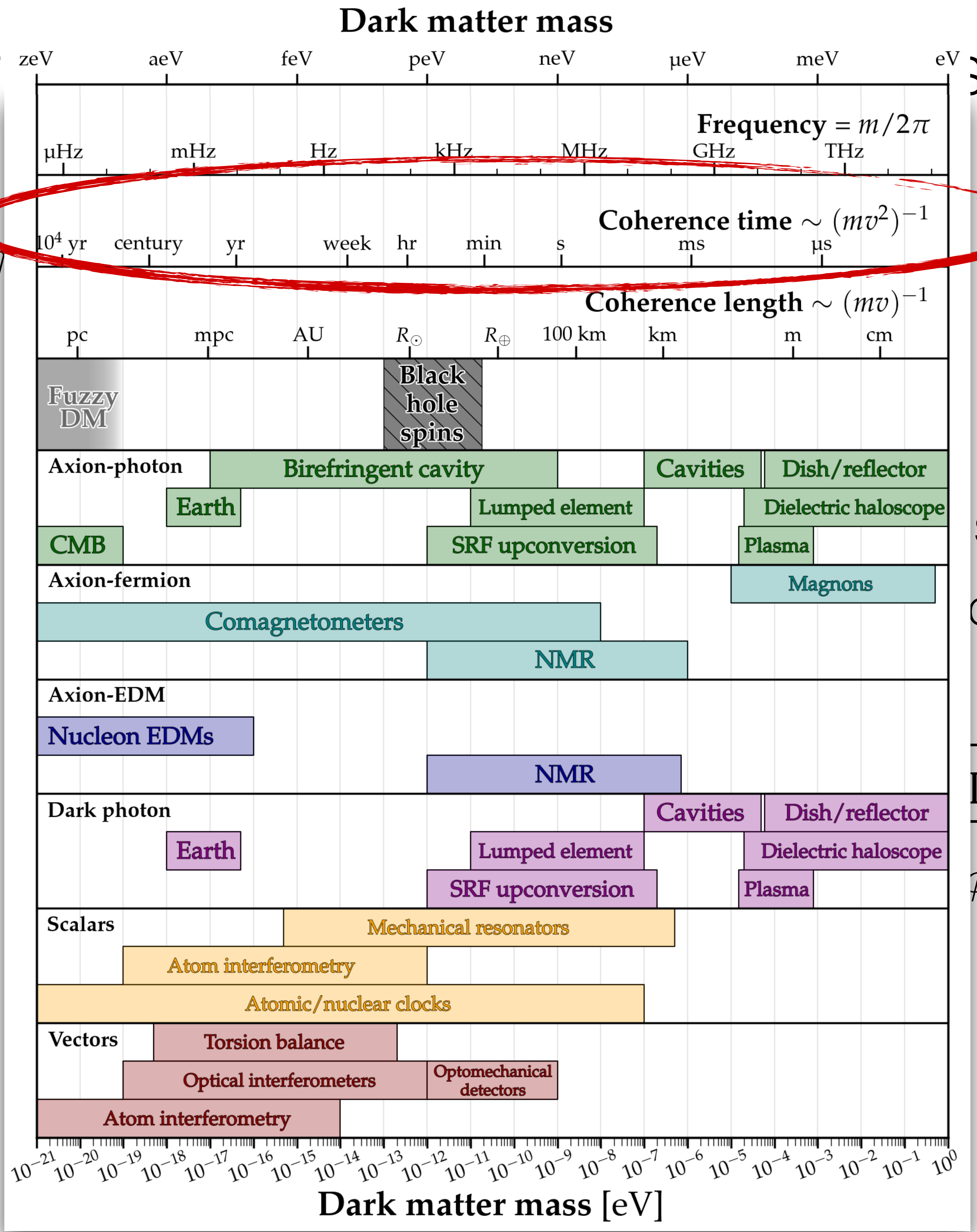

"Human" scale

N

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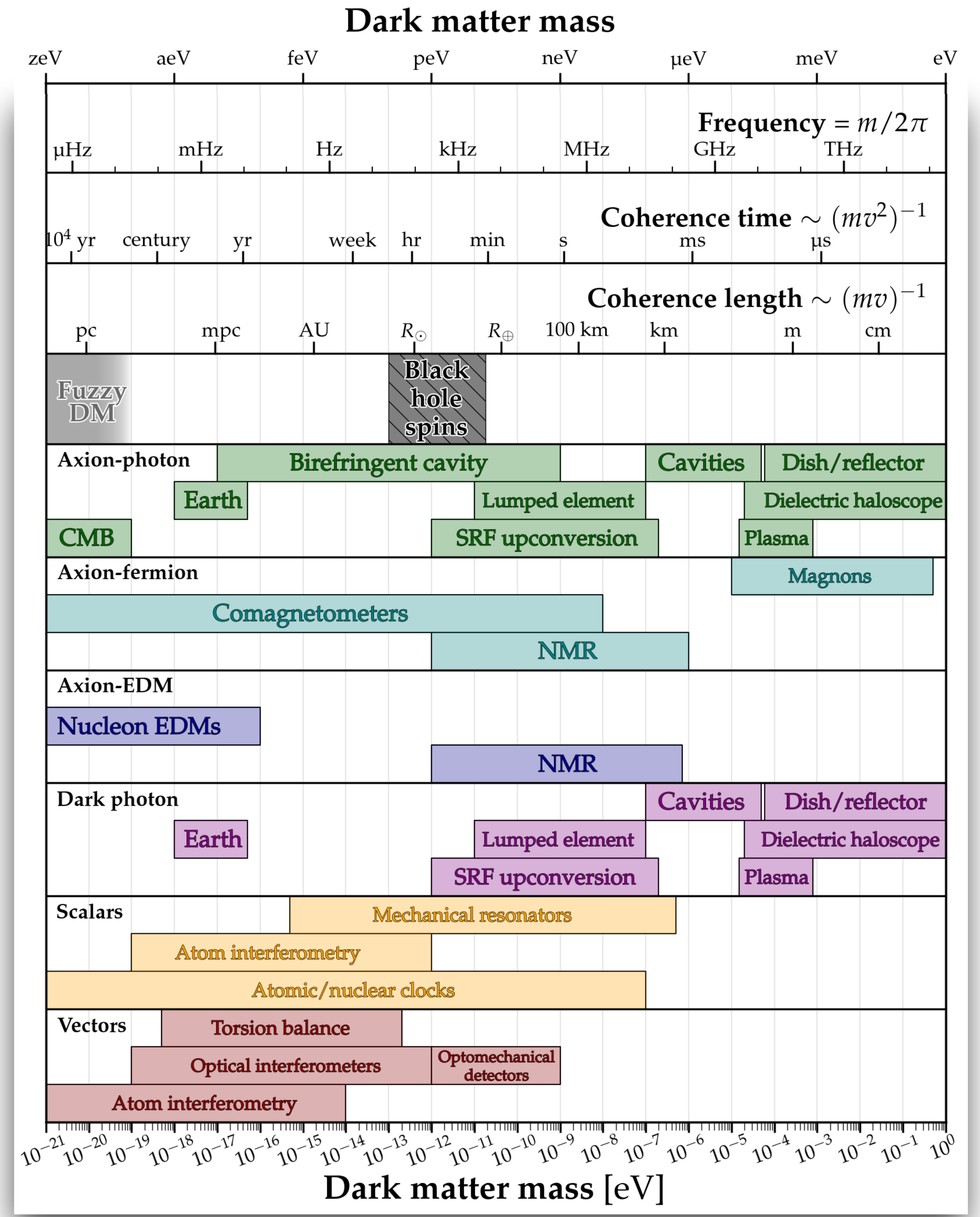
AxionLimits, C. O'Hare

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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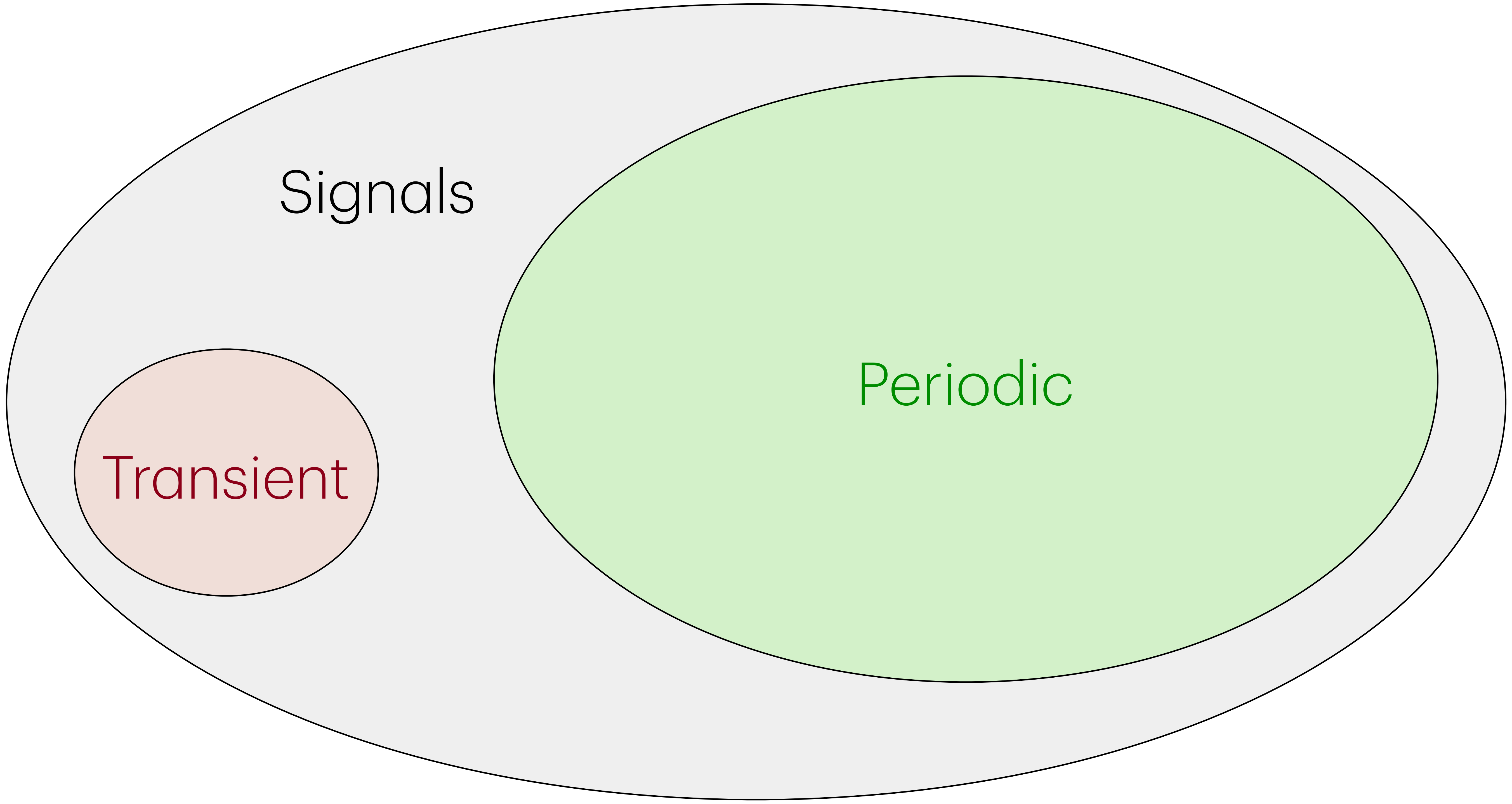
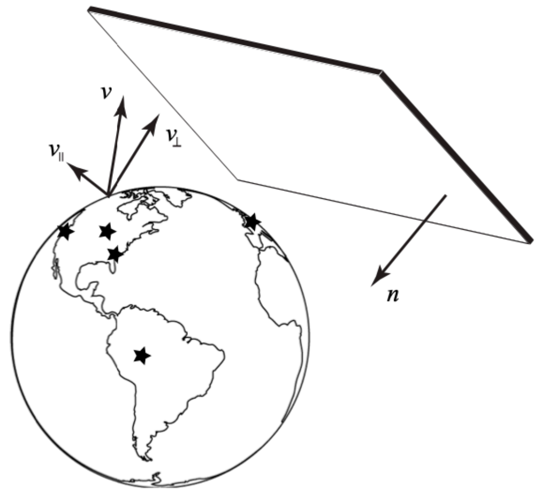
Transient Signals



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

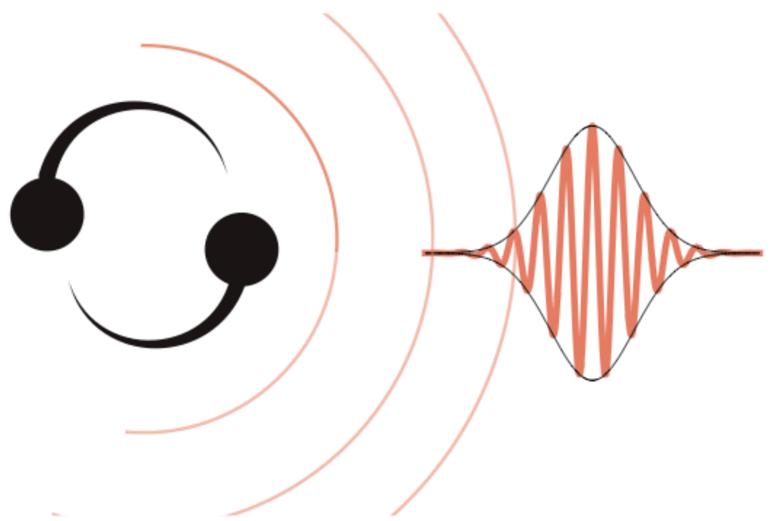
Passage of a domain wall

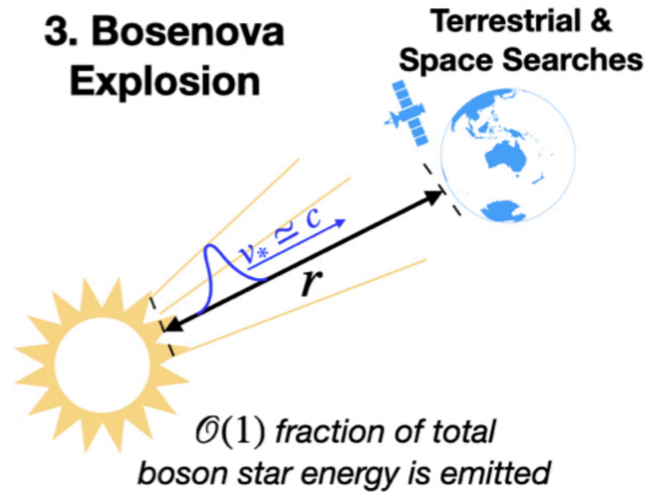
"How do you know if you ran through a wall?"
M. Pospelov et al. (1205.6260)



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

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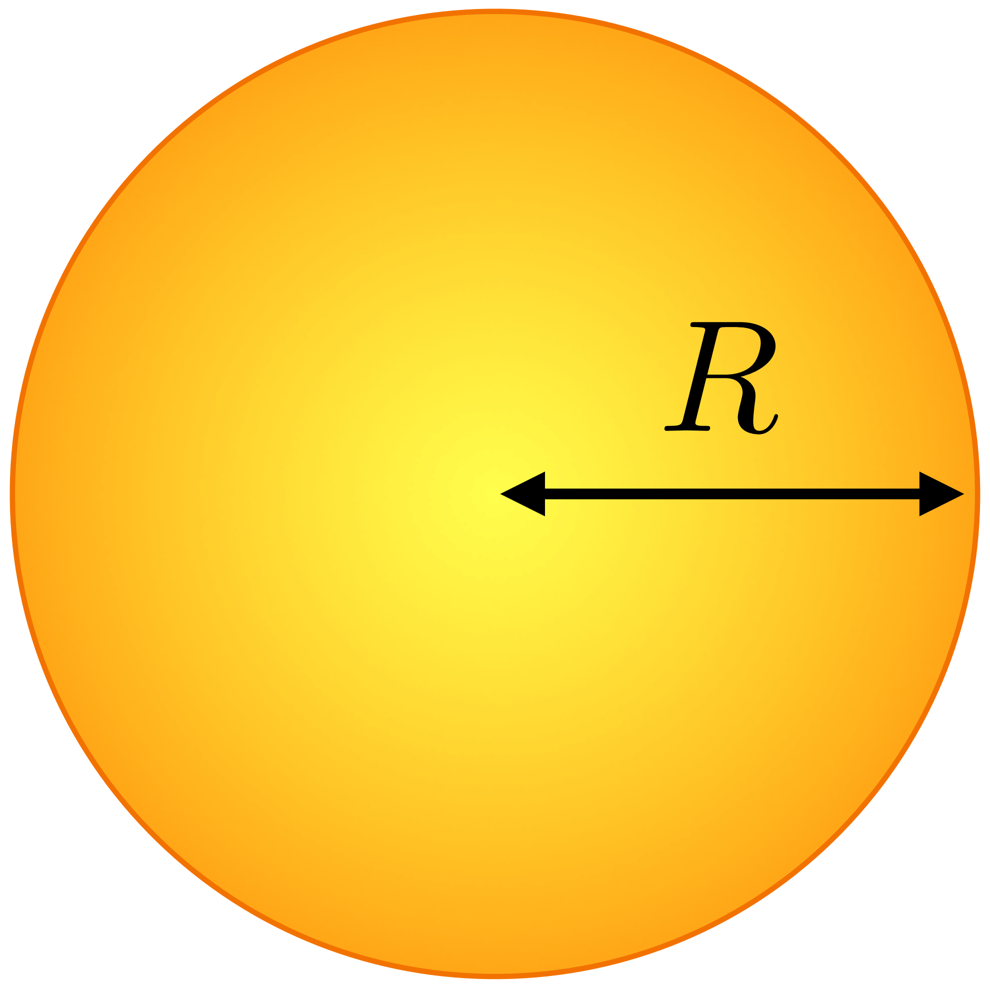
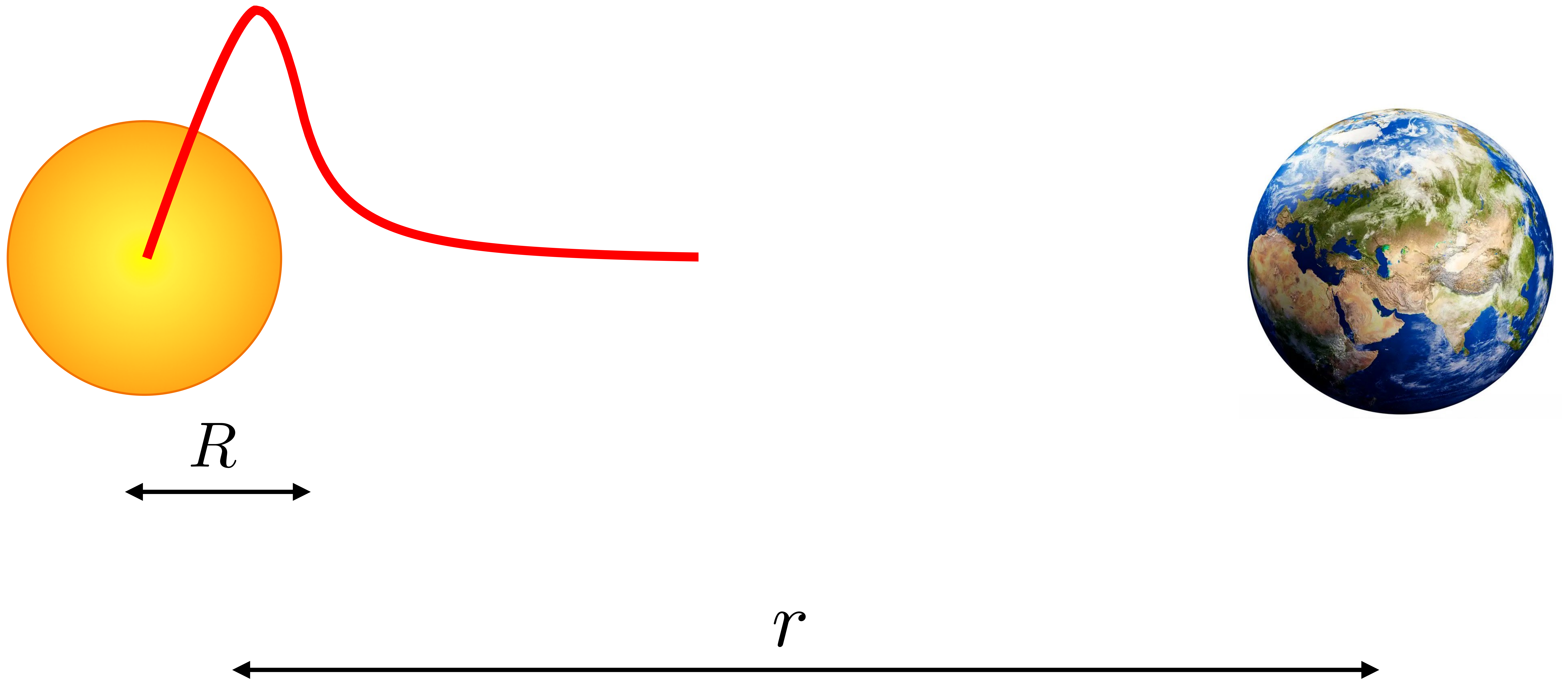


New Mechanism

Transient Signal from BH Formation



*not in scale

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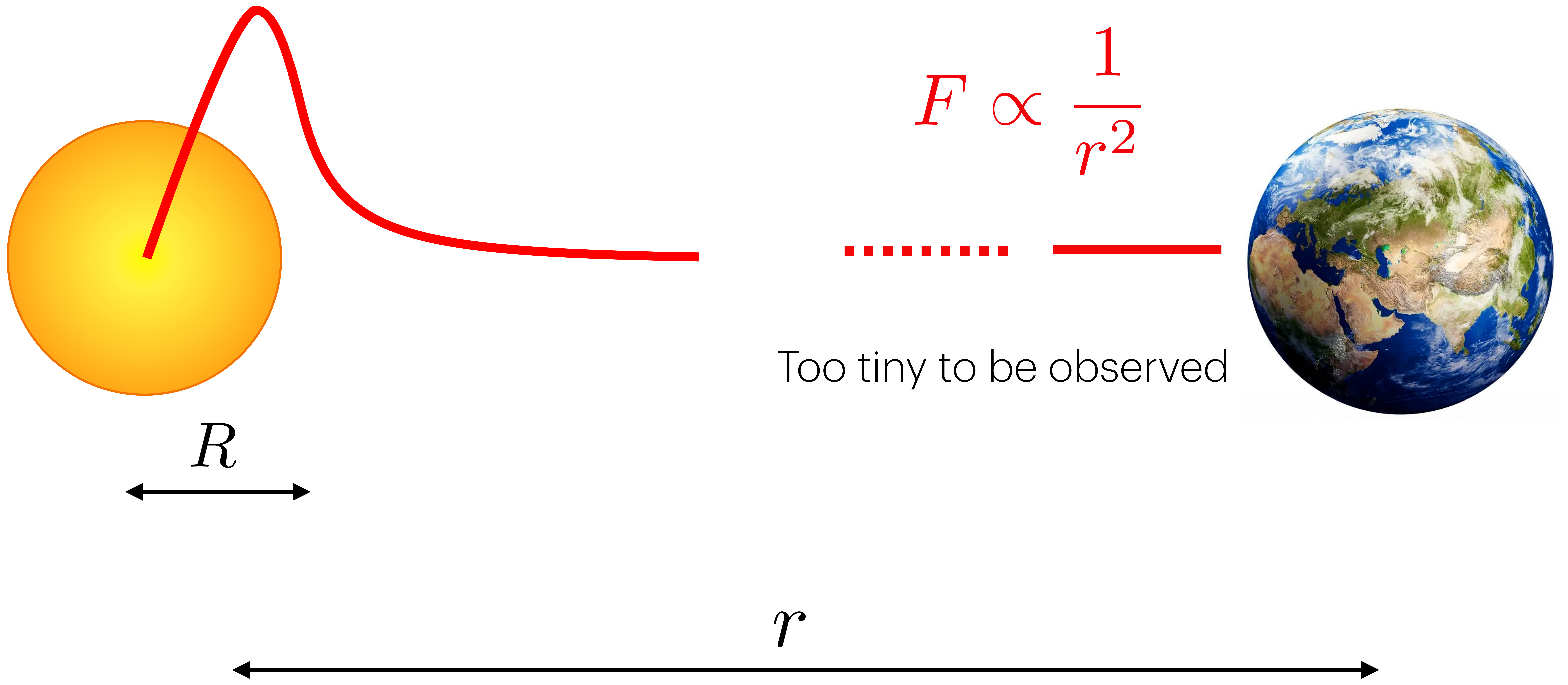

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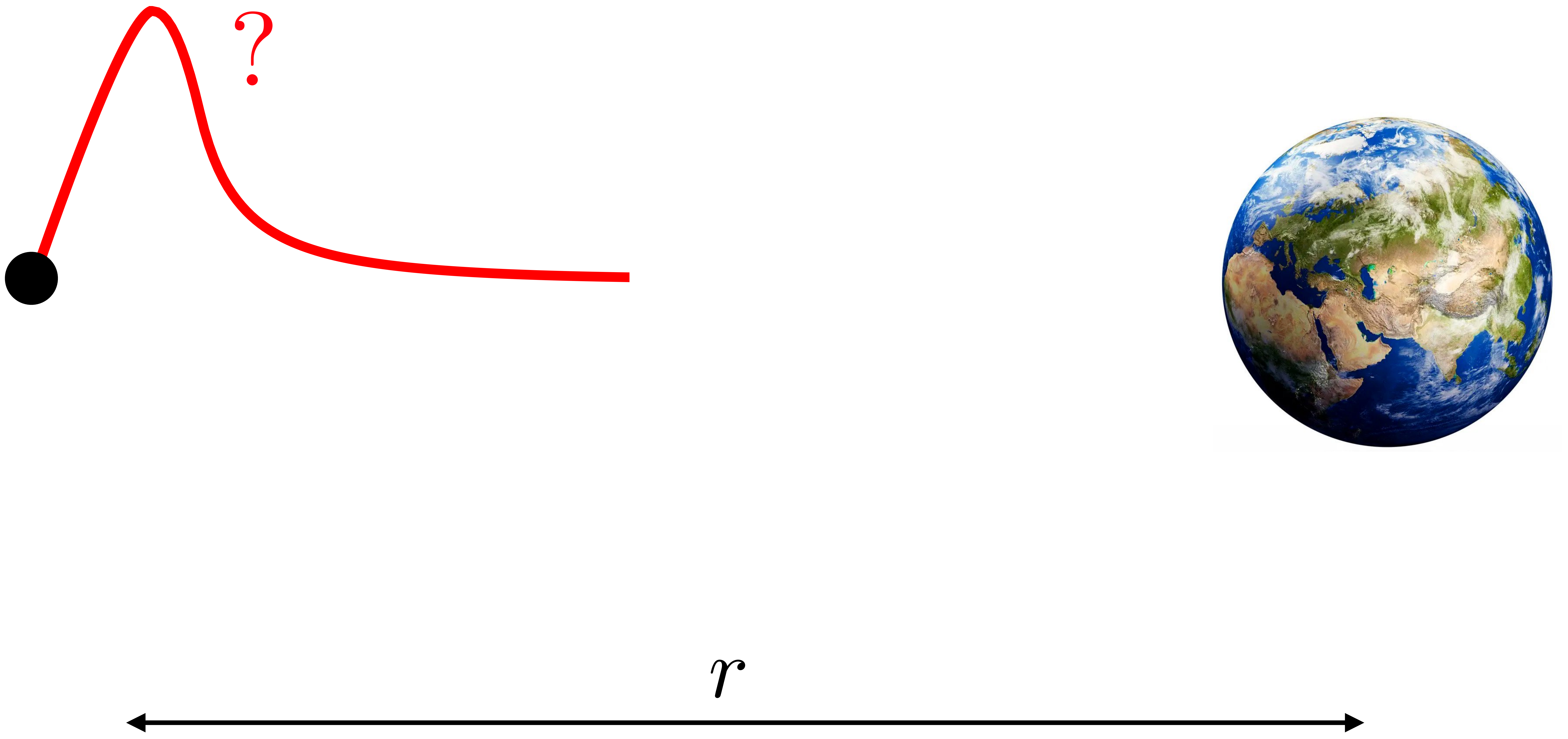

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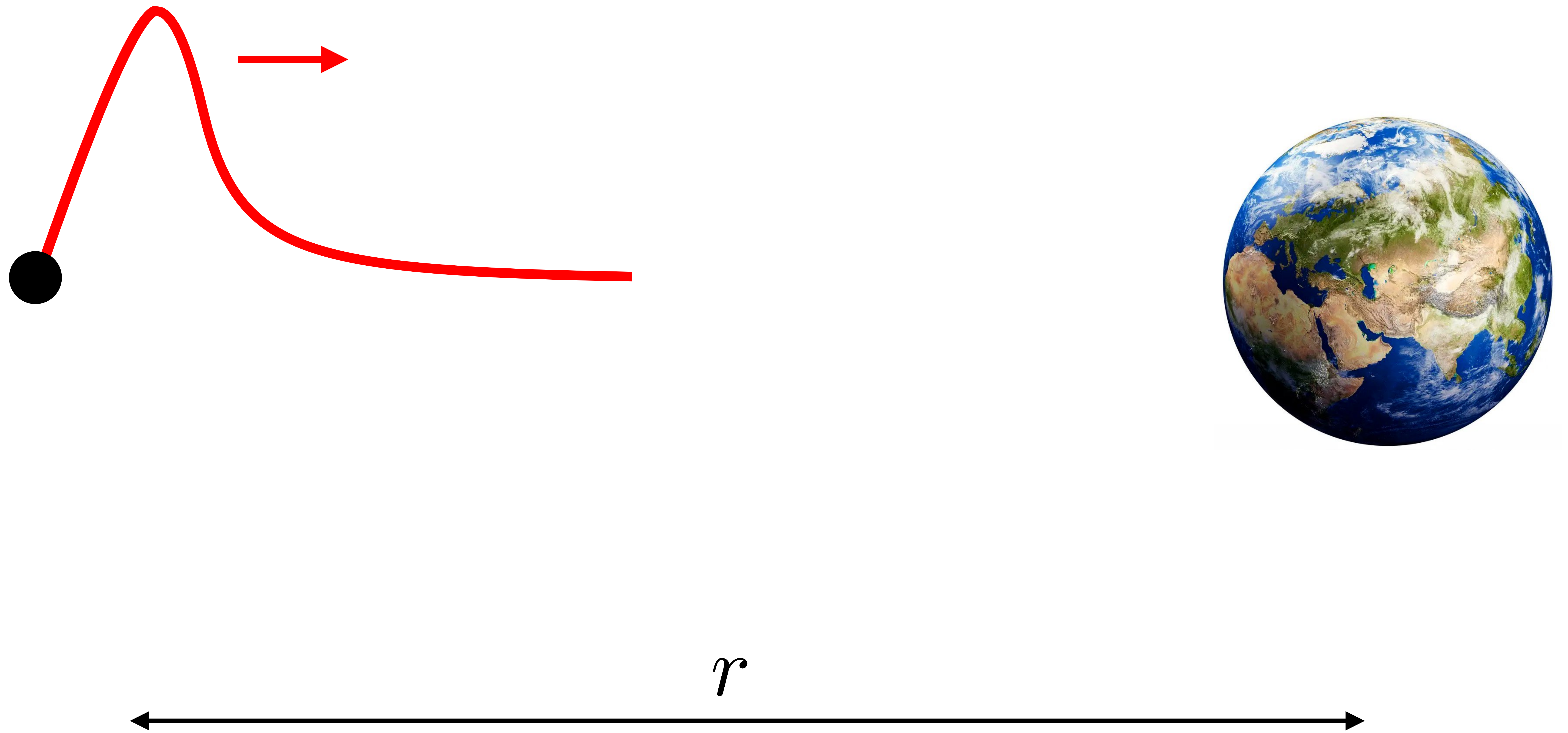
Transient Signal from BH Formation



*not in scale

$\mathrm{ly} \sim 10^{13}\ \mathrm{Km}$

Transient Signal from BH Formation

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

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

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

r

*not in scale

Mass-Dilution Effect

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

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typical velocity

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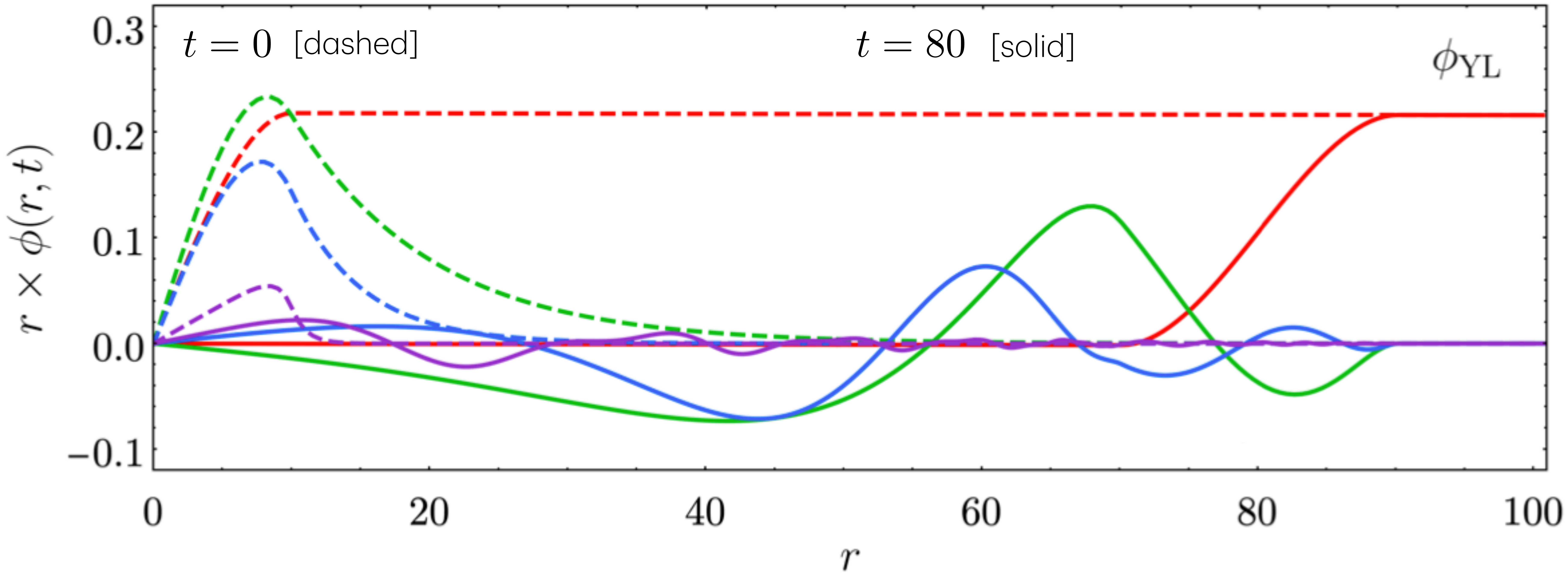


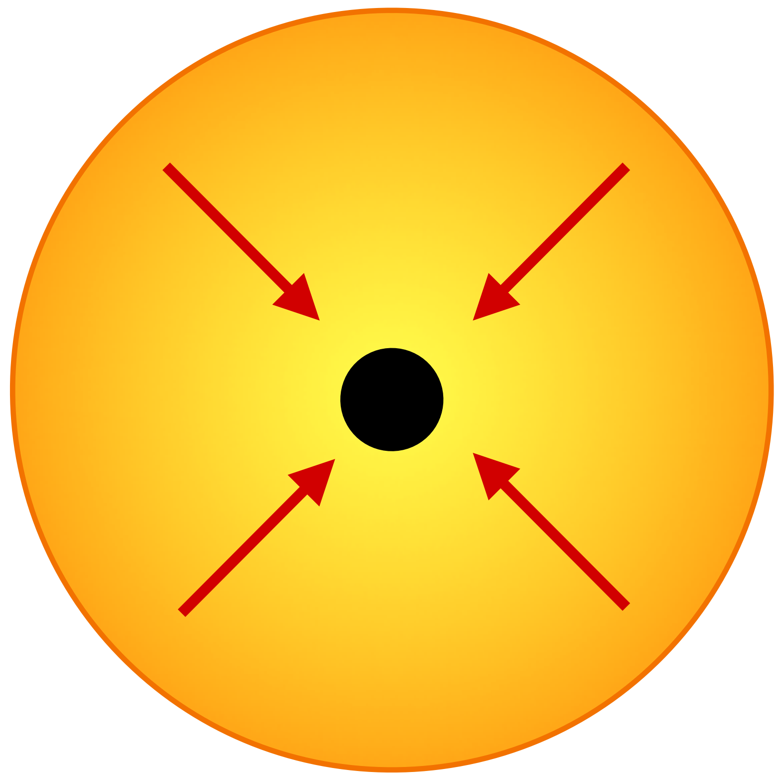
$m_\phi = 0$ (**red**)
$m_\phi = 0.1$ (**green**)
$m_\phi = 0.2$ (**blue**)
$m_\phi = 1$ (**purple**)

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

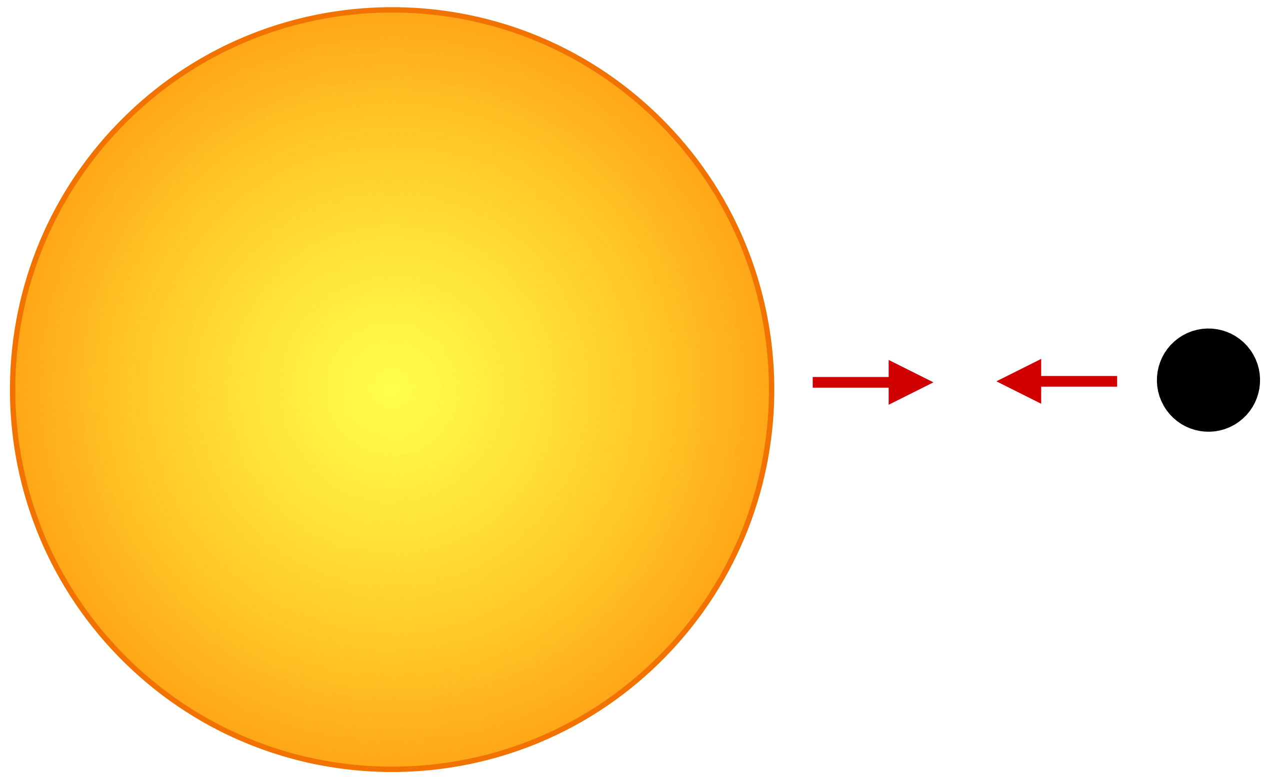
[natural units]
$c = \hbar = 1$

Sources

Accretion



Merger



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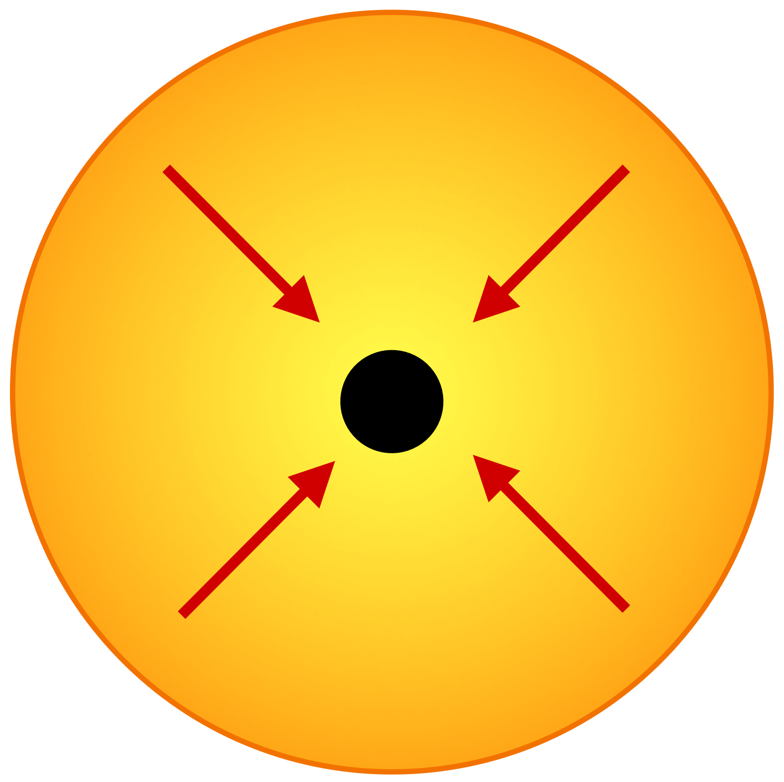

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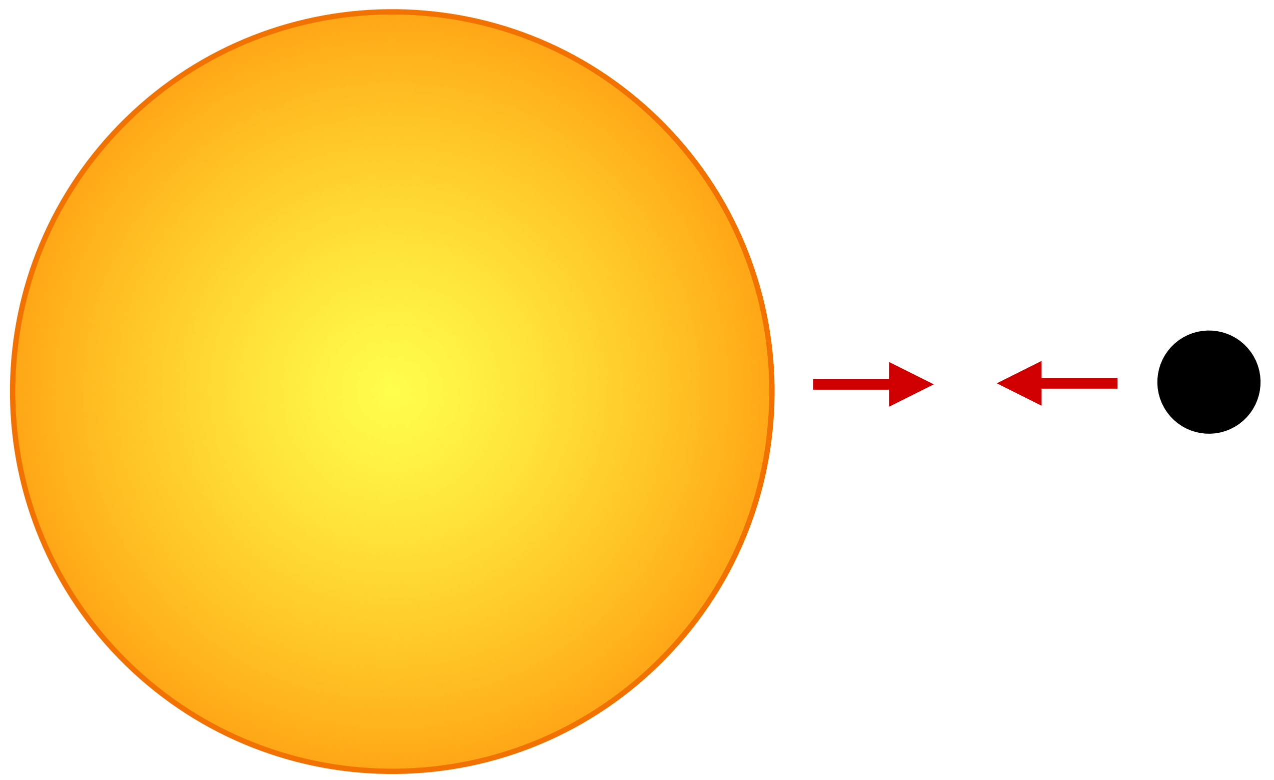

$$f_{\mathrm{SN1987A}} \approx 2 \times 10^{-3}\mathrm{Hz}\,,$$

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

$$R_s \equiv 2GM \qquad R_s^{\mathrm{sun}} \approx 2.95\ \mathrm{Km}$$

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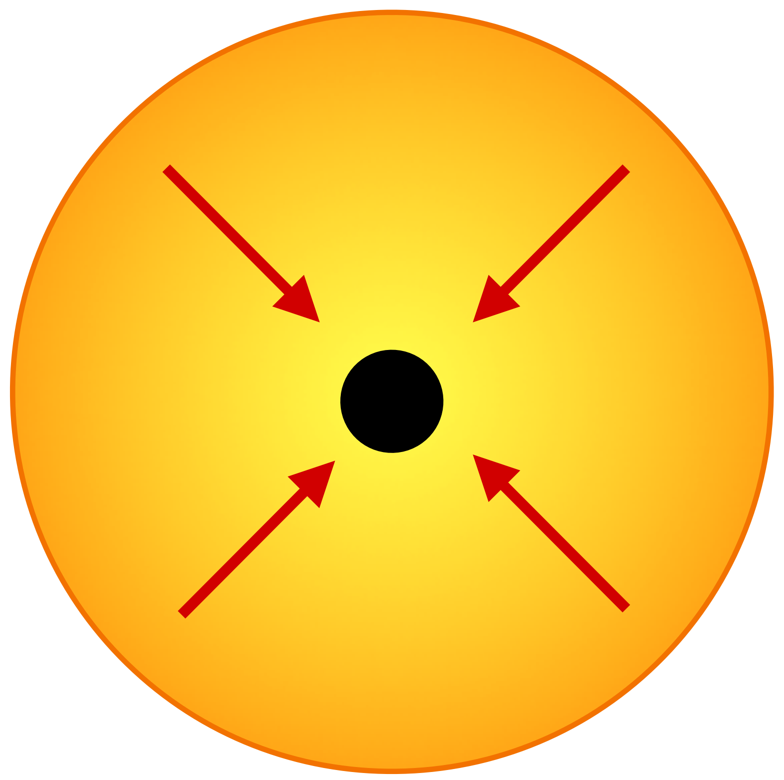

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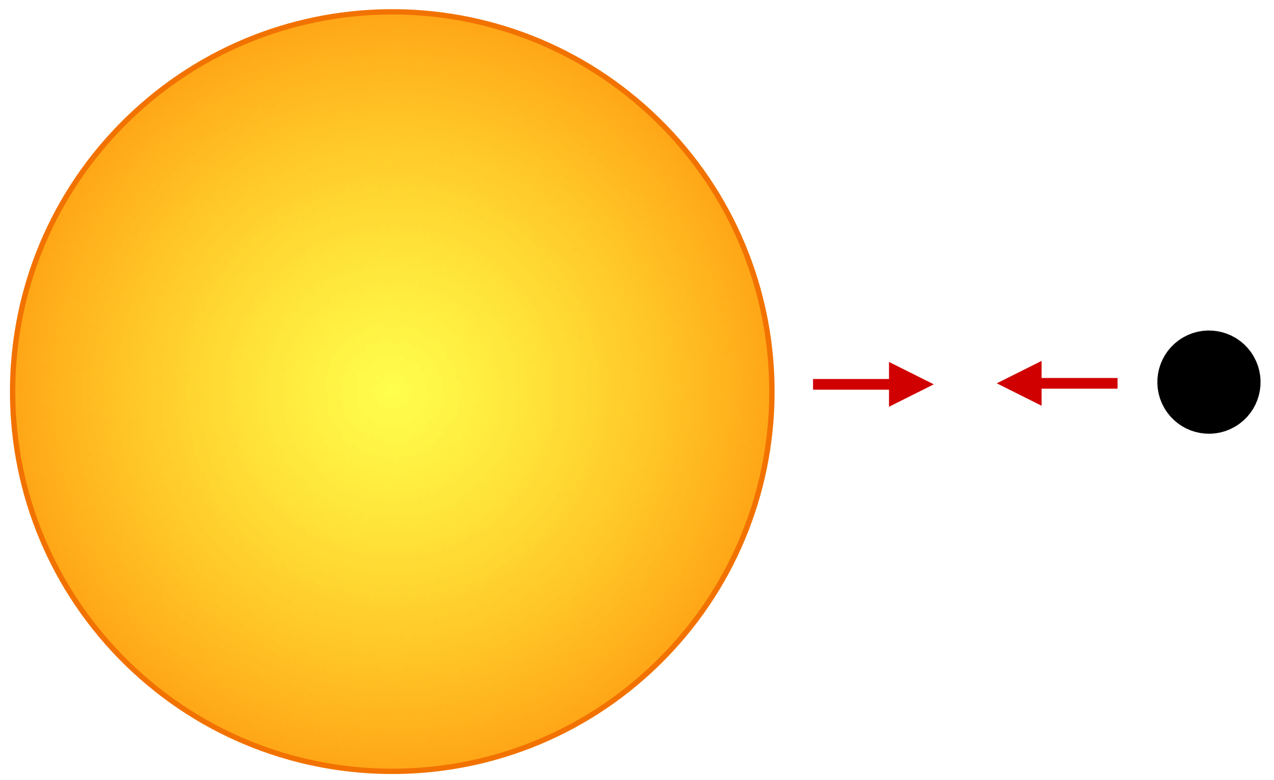

Very different frequencies

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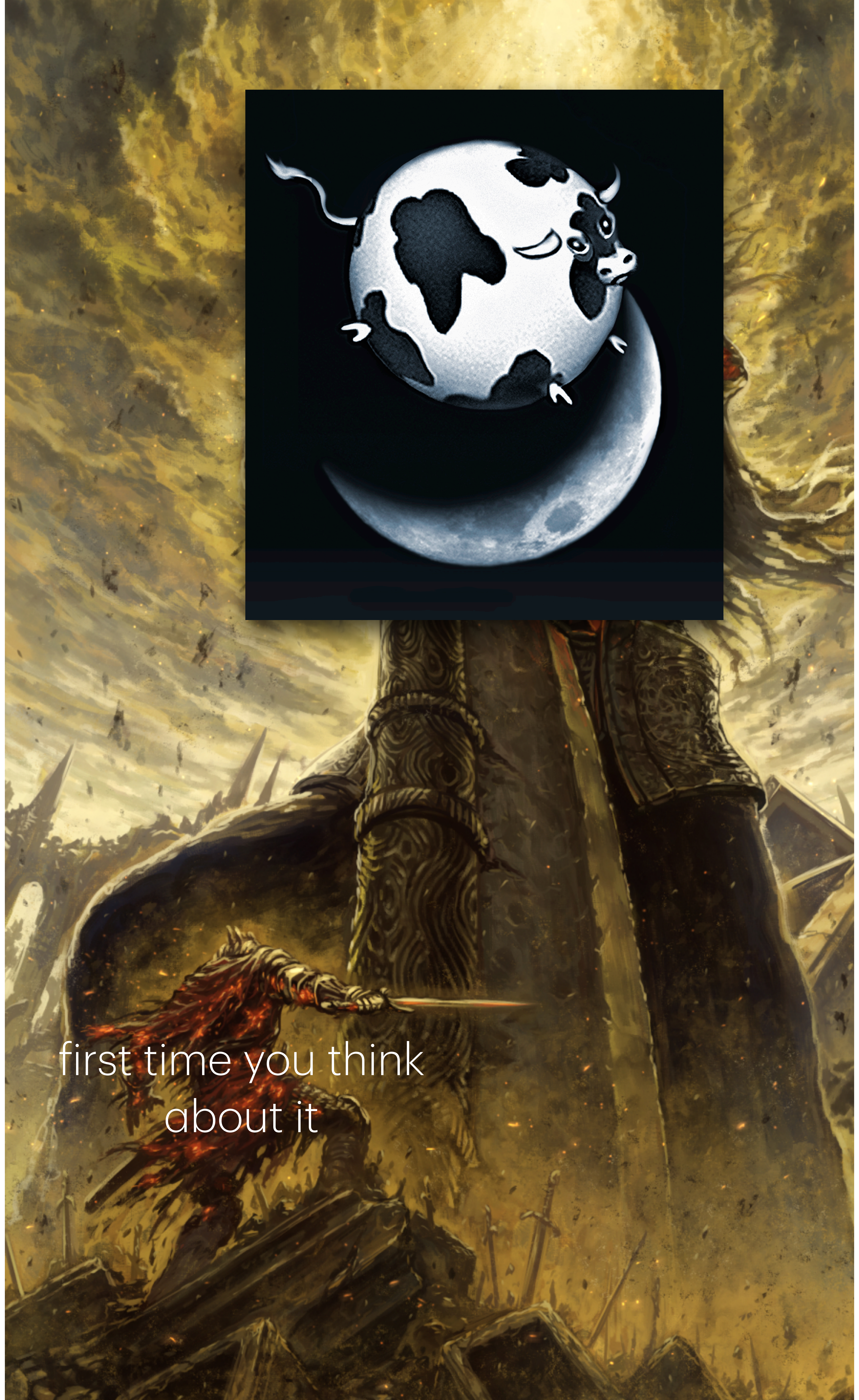

“spherical cow”

Where to start?

Ultra-simplified approach:

1. BH formation is **istantaneous**
2. **Neglect** BH **remnant** effects

“spherical cow”

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]

Couplings

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

We considered some case studies:

> *Interferometer: LISA Pathfinder*
> *Torsion Pendulum*
> [2310.06017, 2109.08822]
>
> *Optical Magnetometry: GNOME*
> [2305.01785]
>
> *Haloscope: DMRadio-m^3*
> [2204.13781]

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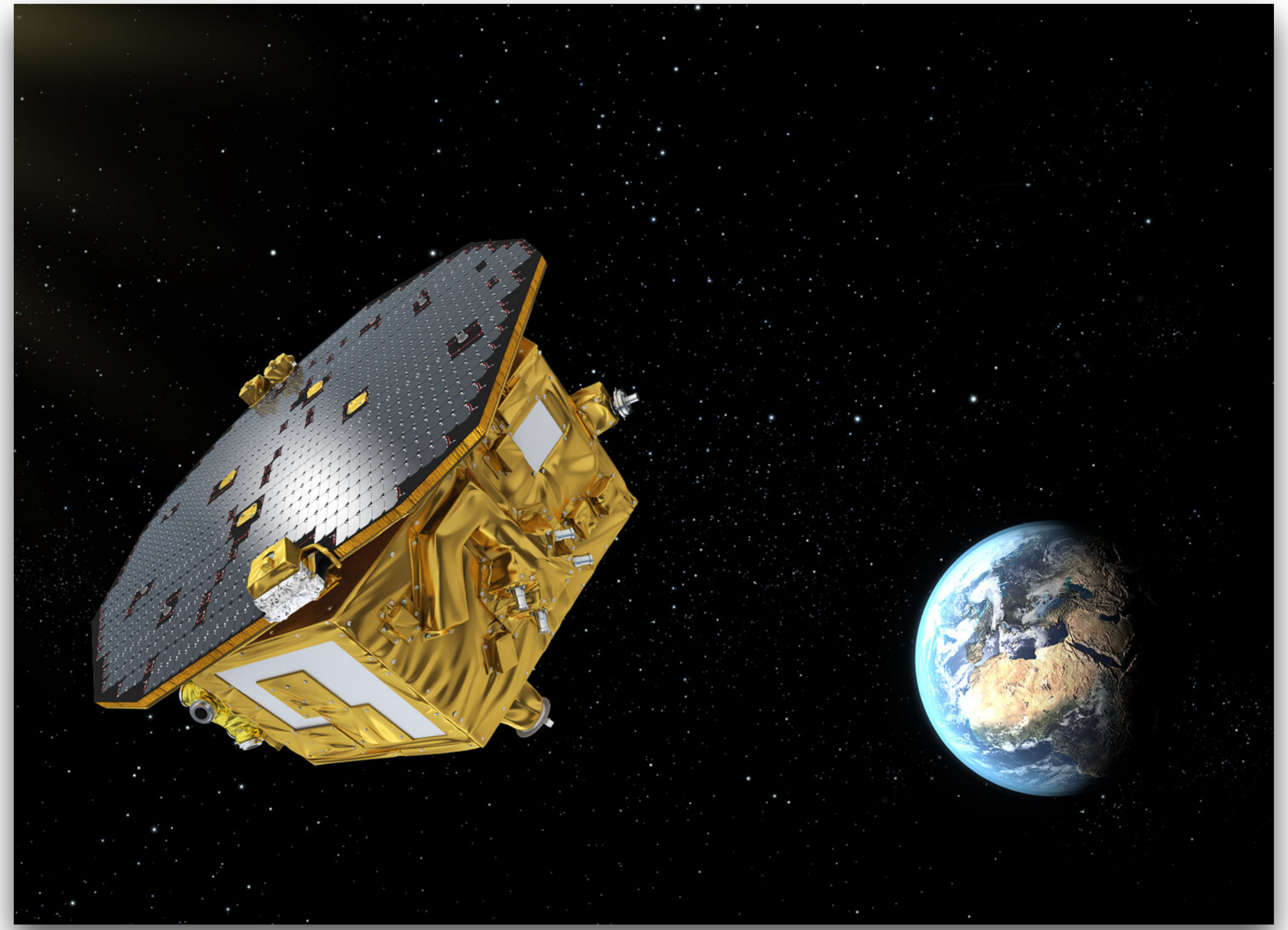
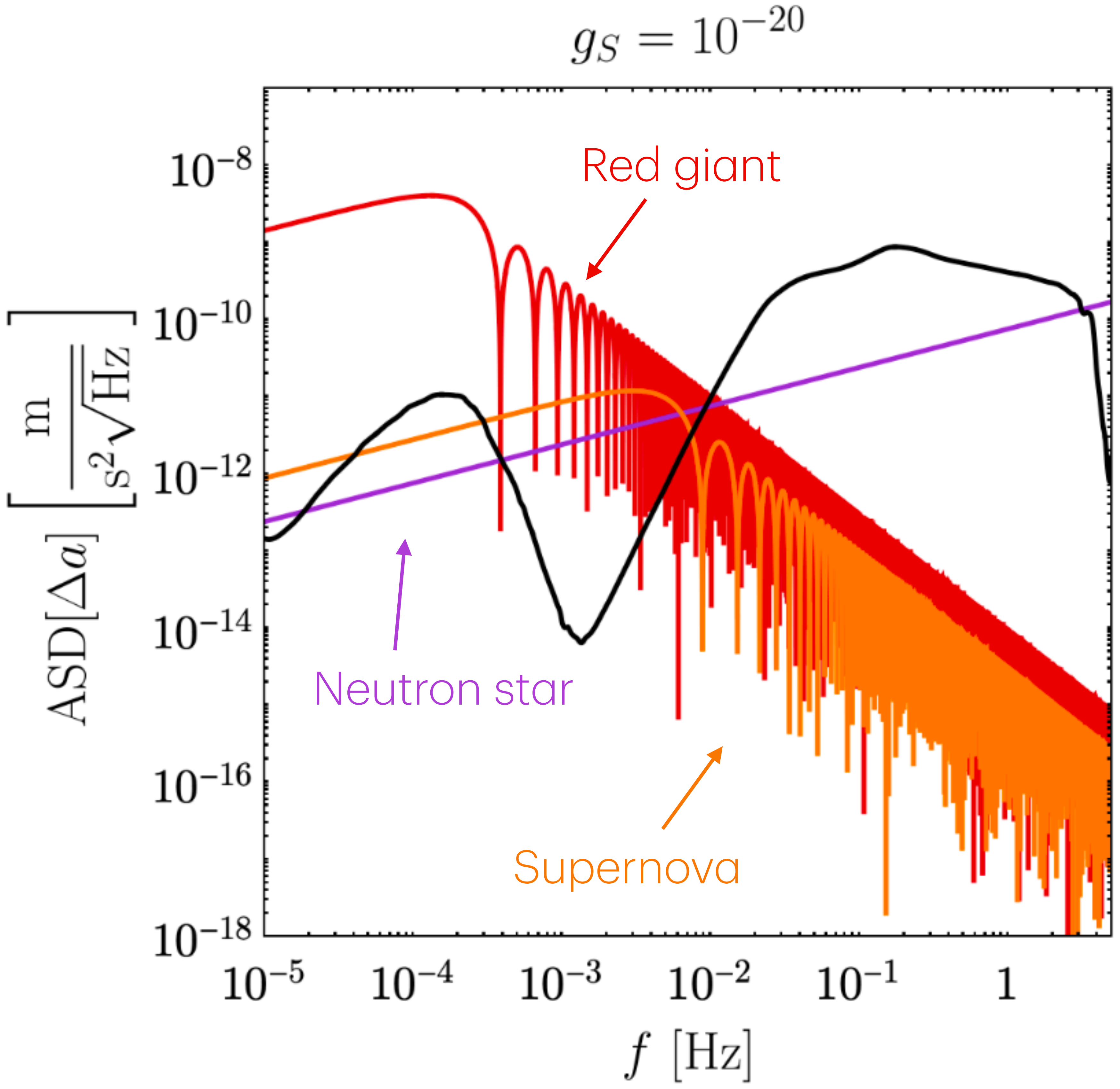


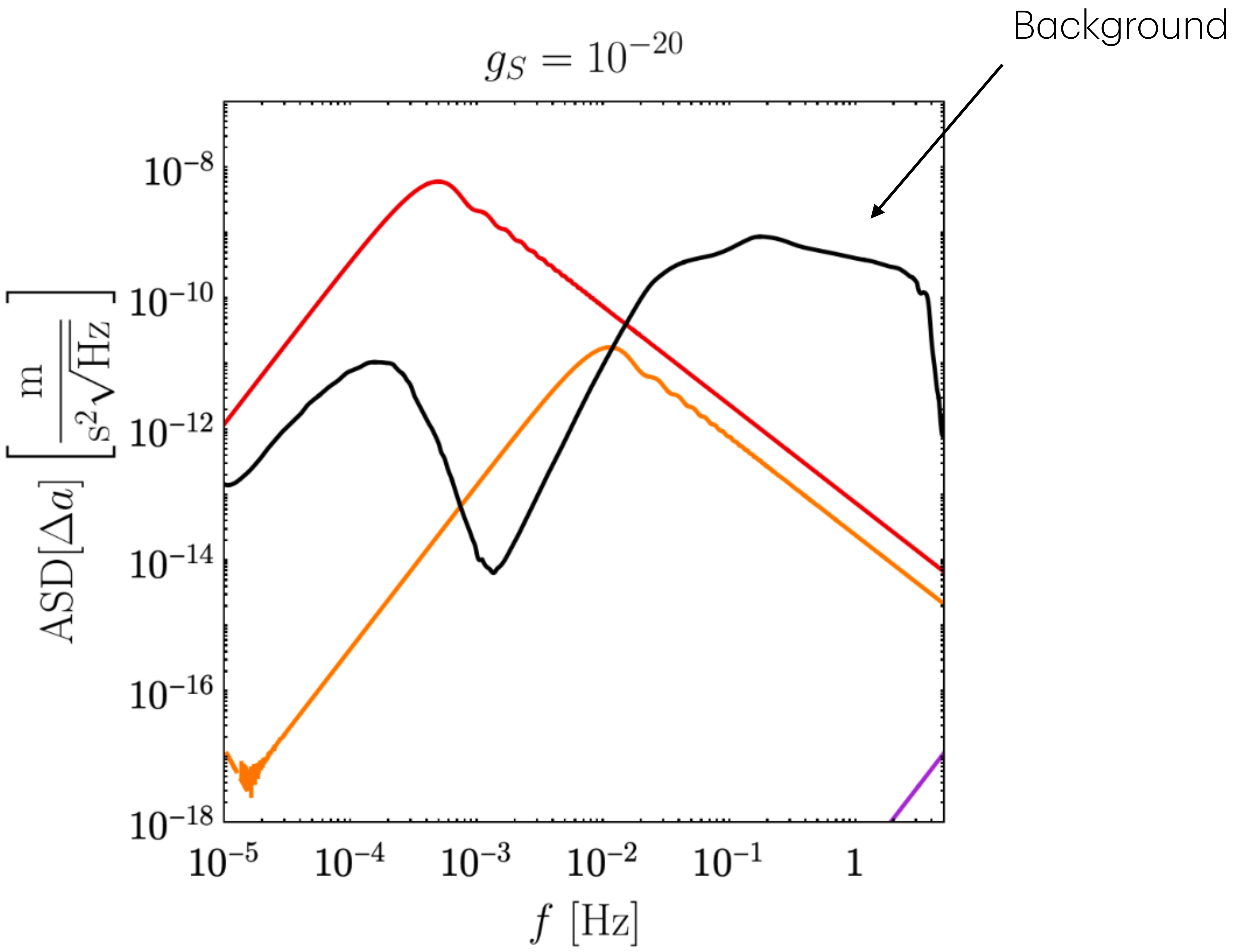
Credit: ESA

Signal VS Noise

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



(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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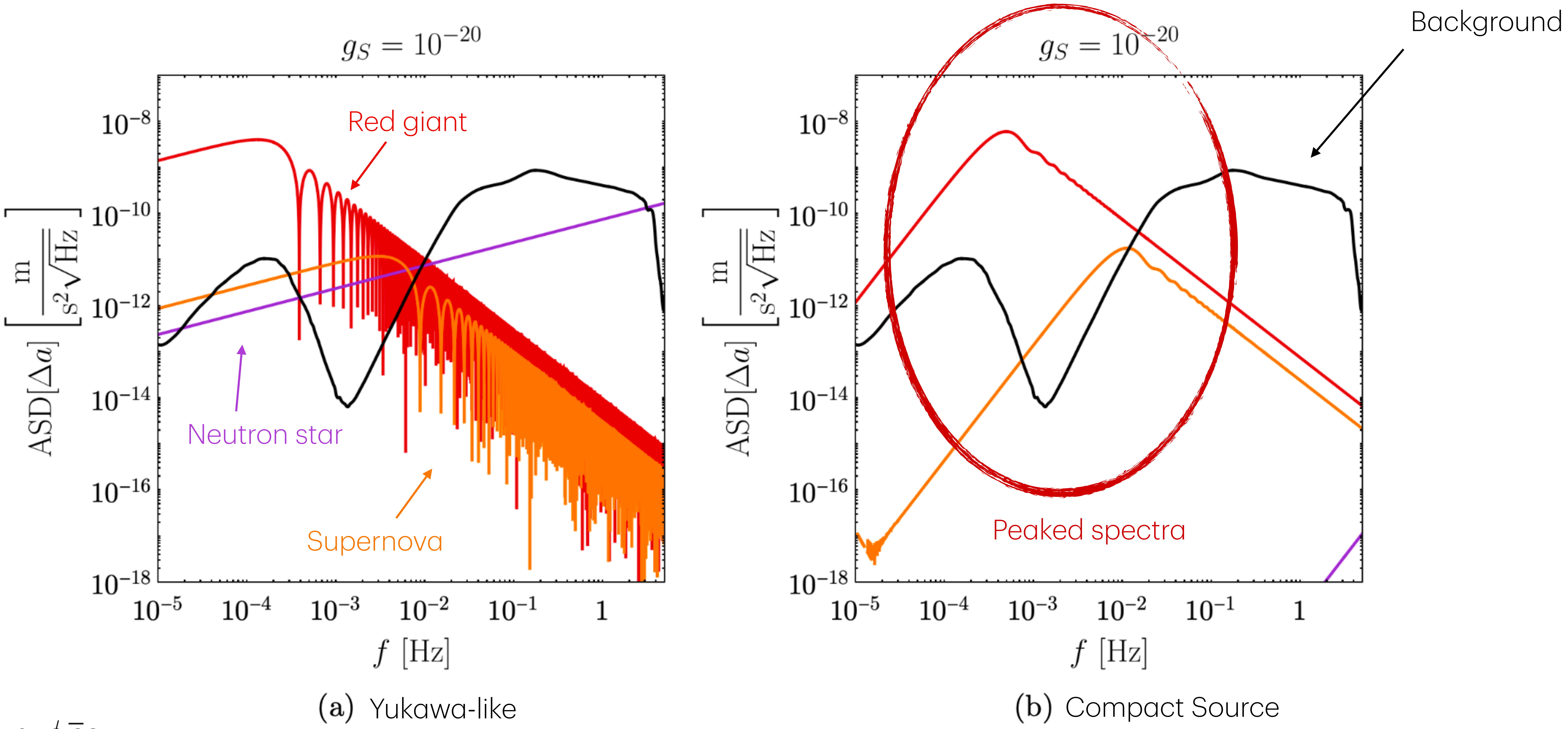
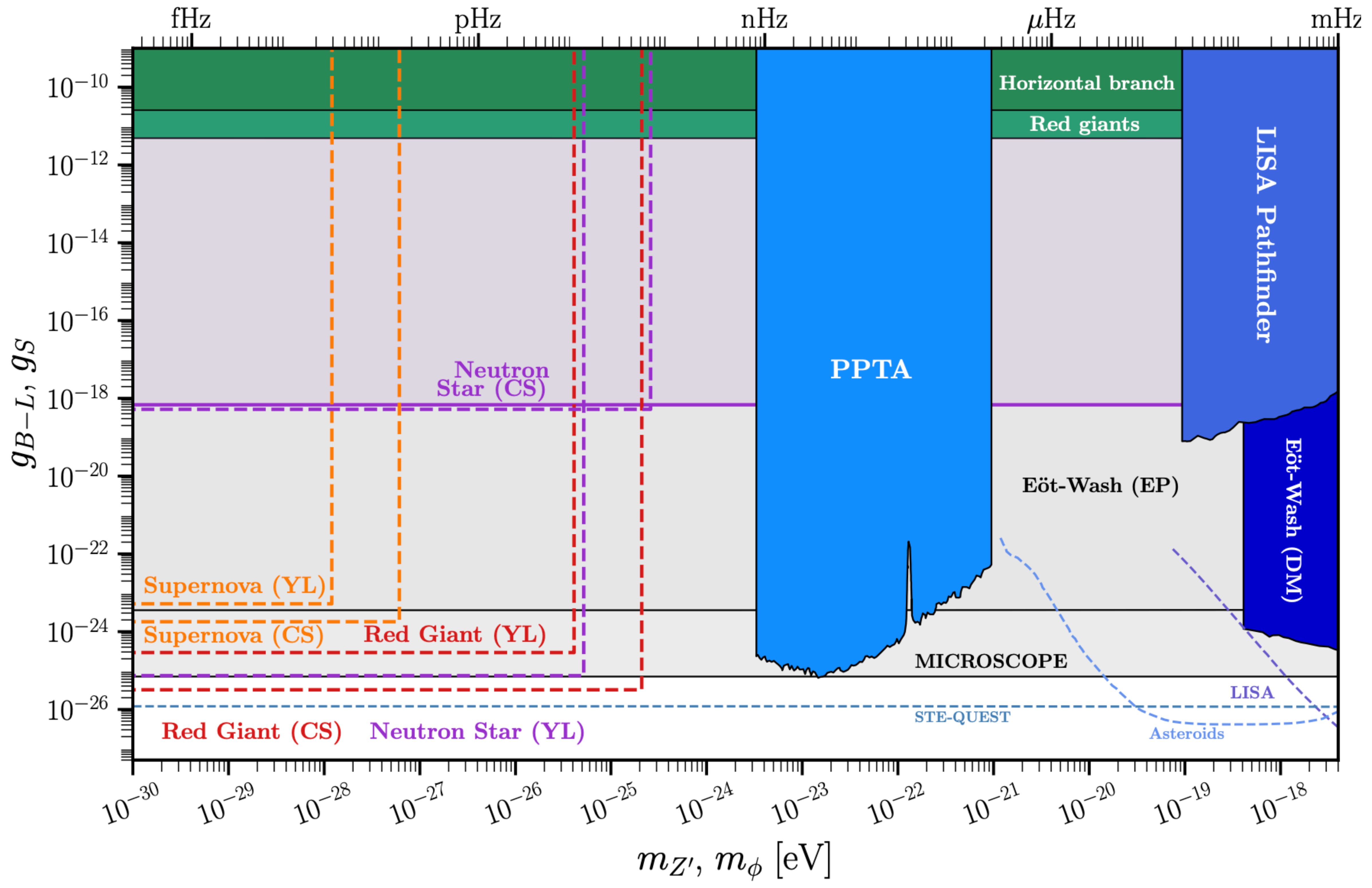


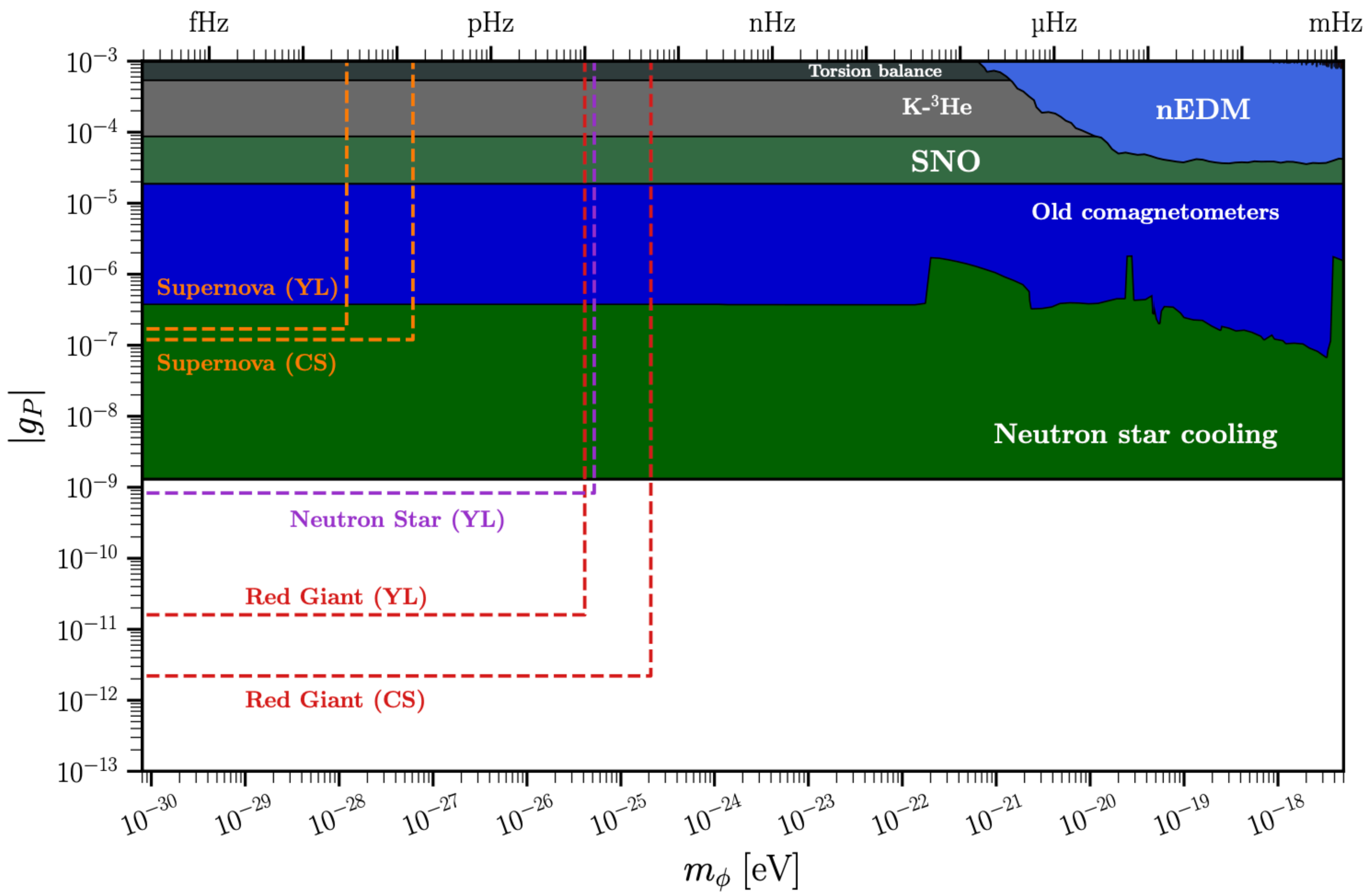
$\mathcal{L} \subset -g_S \phi \overline{N} N + g_S \phi \bar{e} e$

Sensitivities comparable to current bounds

Scalar



Pseudo-scalar



(similarly for photons)

Caveats and Improvements

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

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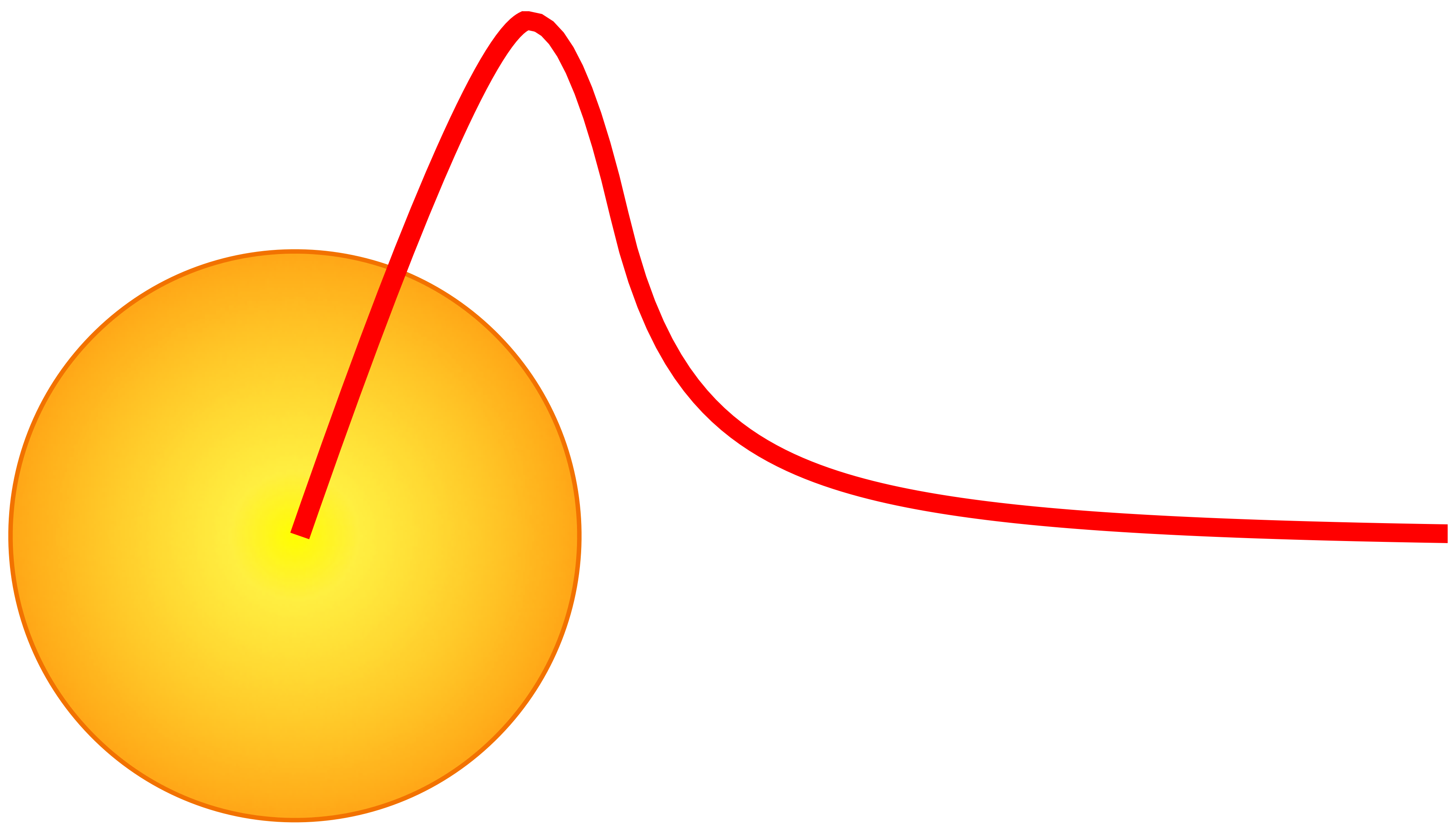
Work in progress (**2510.YYYYY**)

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

—

How much energy is left?

Crude estimate:



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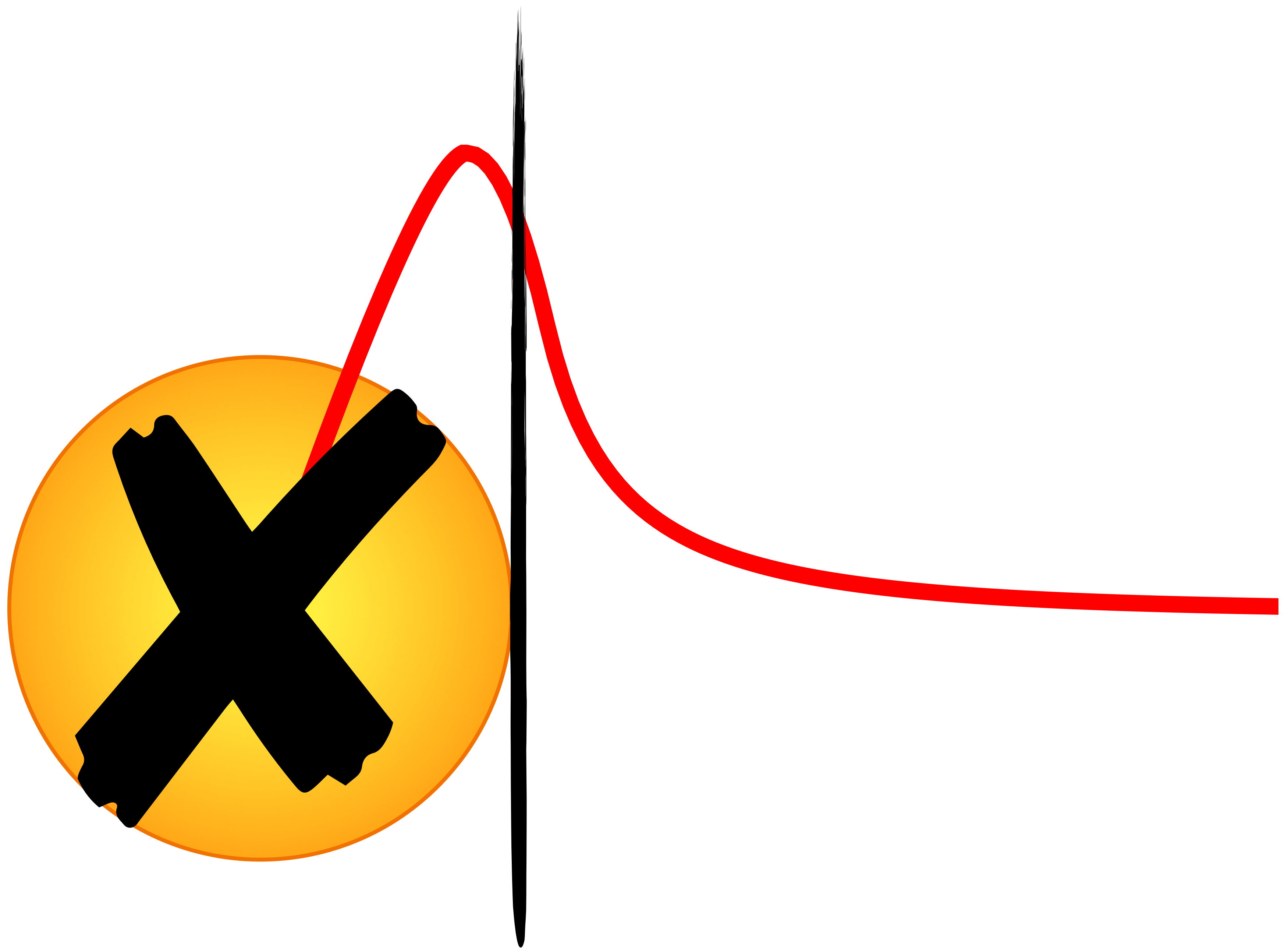

$$\times \frac{1}{2}$$

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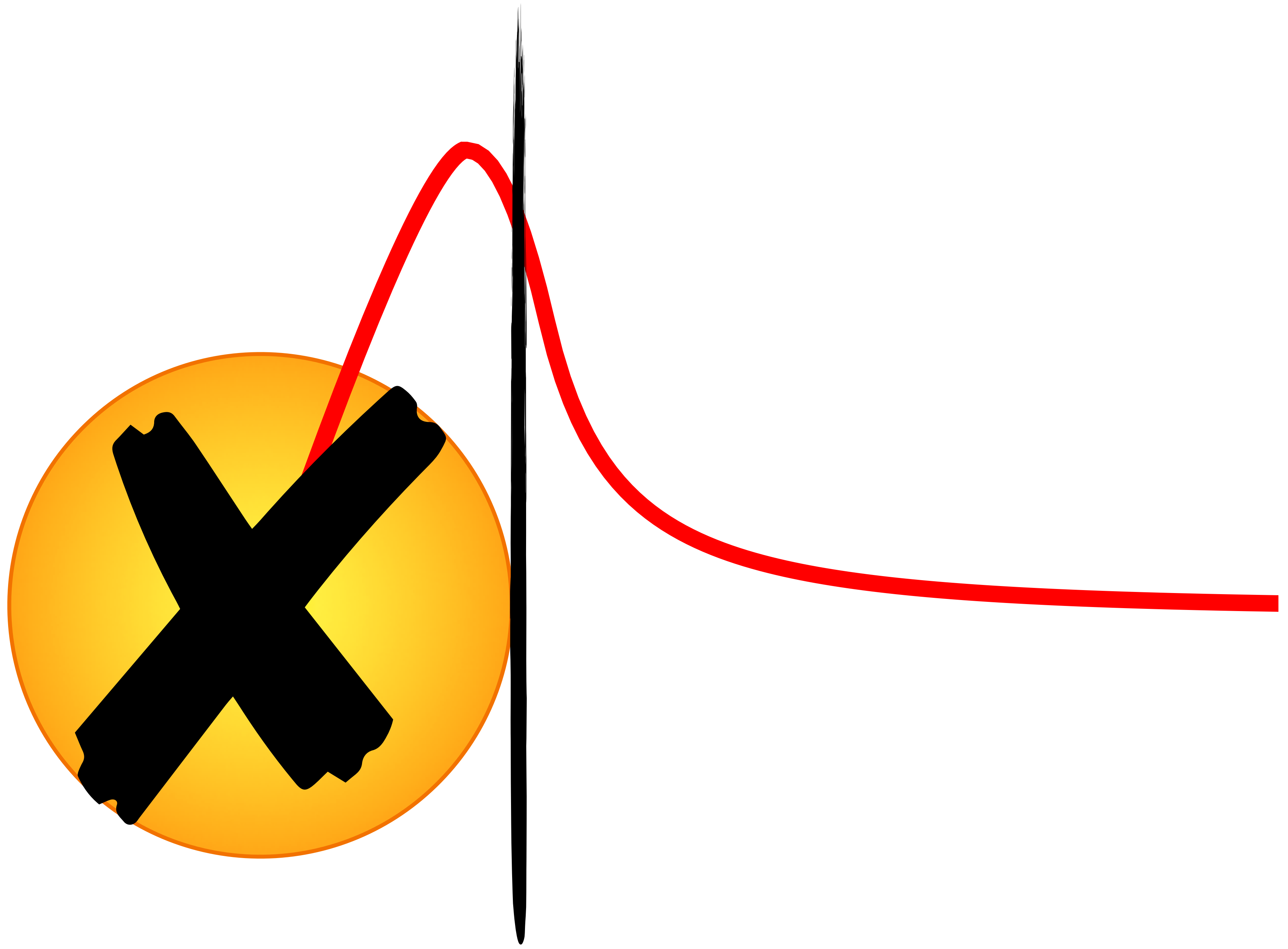

$$\times \frac{1}{2}$$

$$g_{\max} \to g_{\max} \times \sqrt{\frac{12R}{5R_s}} \approx 0.9\, g_{\max} \times \sqrt{\left(\frac{R}{10\,\mathrm{Km}}\right)\left(\frac{10\, M_{\odot}}{M}\right)}$$

almost *no impact* for *Neutron Stars* - huge impact on larger objects

Let us *improve* the calculation

~~Ultra-~~**simplified** approach:

1. BH formation is **istantaneous**
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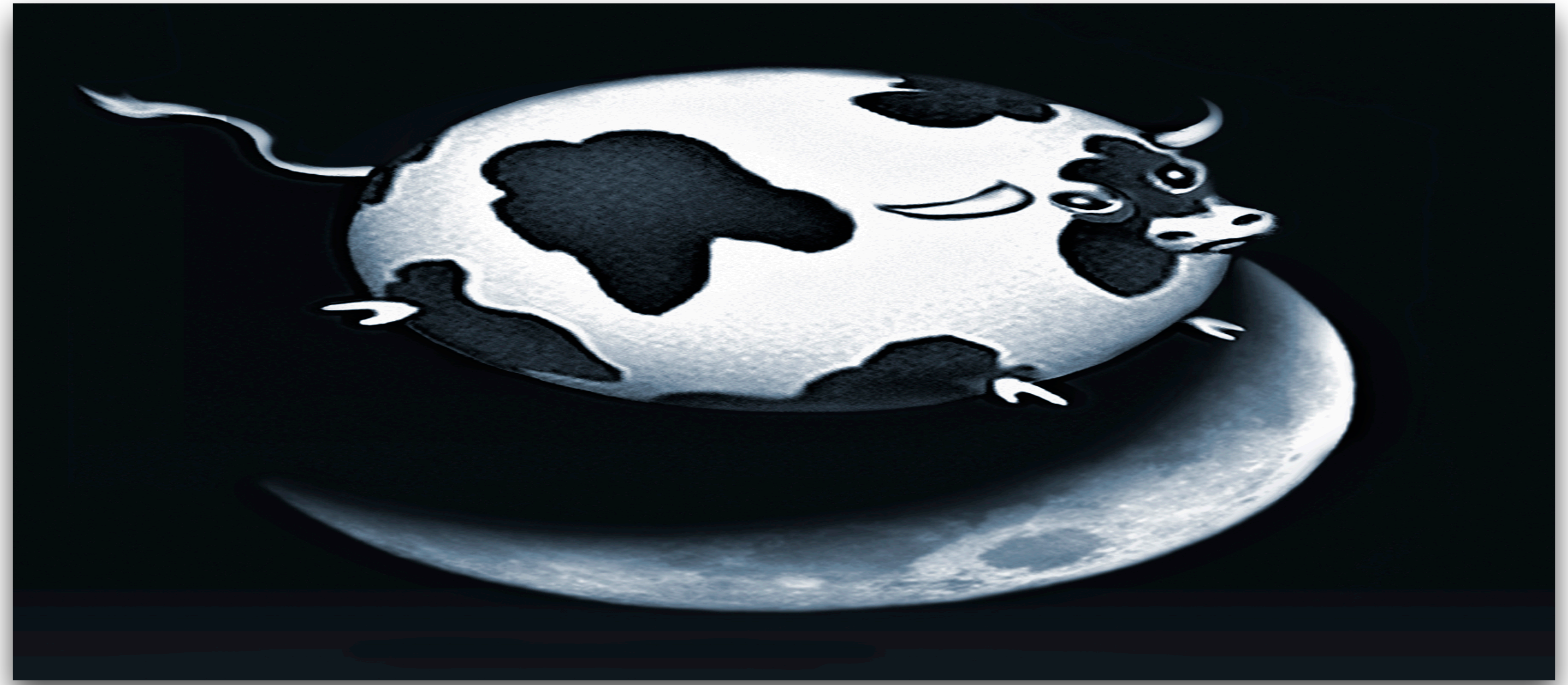

"spherical cow" → "ellipsoidal cow"

Wave-equation in BH Background

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2 \, , \qquad f(r) = 1 - \frac{r_H}{r}$$

As always in GR, the choice of coordinates is fundamental!

"Tortoise Coordinates"

$$x = r + r_H \log\left|1 - \frac{r_H}{r}\right|$$

horizon:

$$r \to r_H \Rightarrow x \to -\infty$$

$$\phi(r,t) = e^{-i\omega t}\frac{\psi(r)}{r}$$

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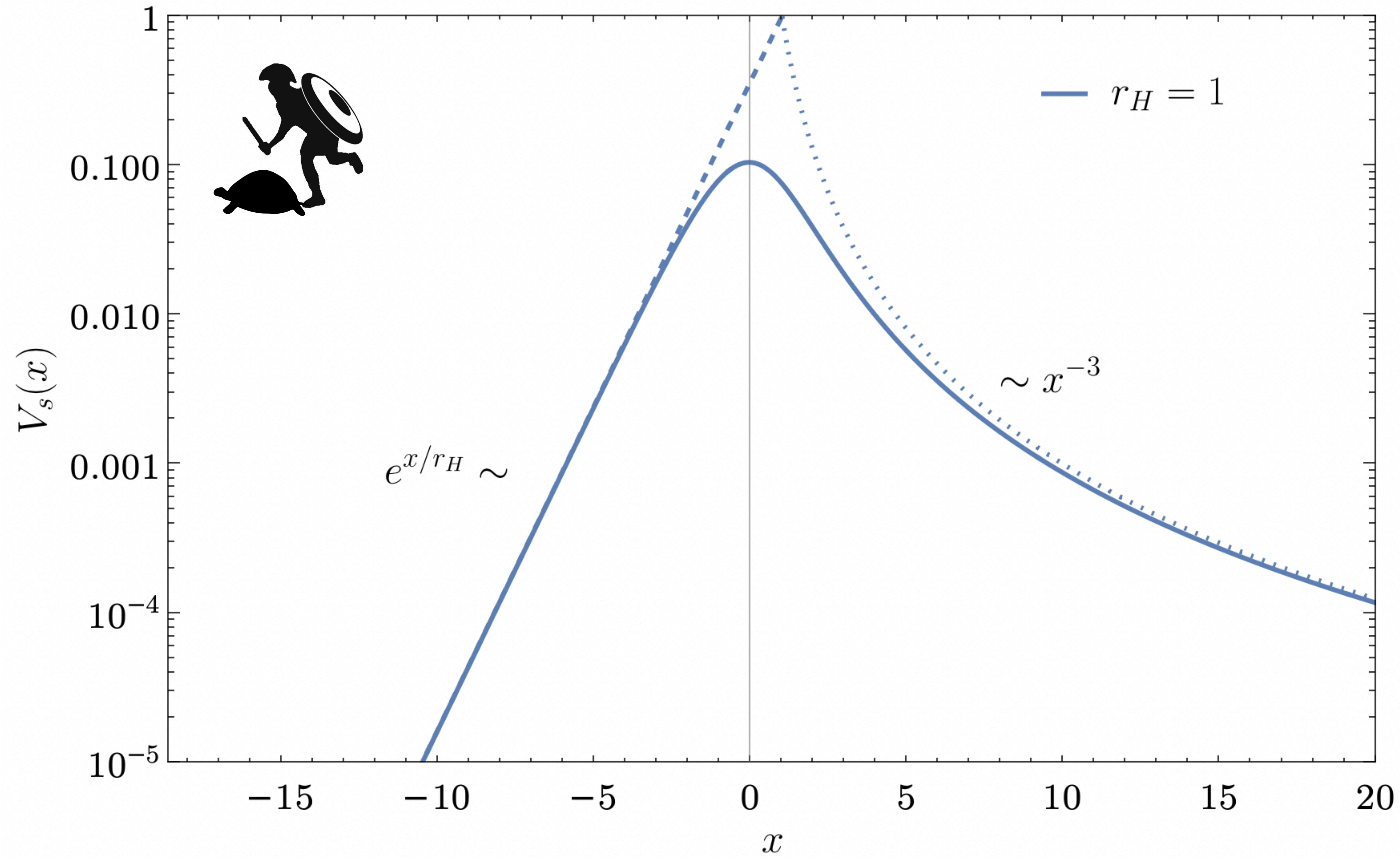
$$-\frac{d^2\psi(x)}{dx^2} + \left(V_s(x) - \omega^2\right)\psi(x) = 0$$

Schröedinger-like equation

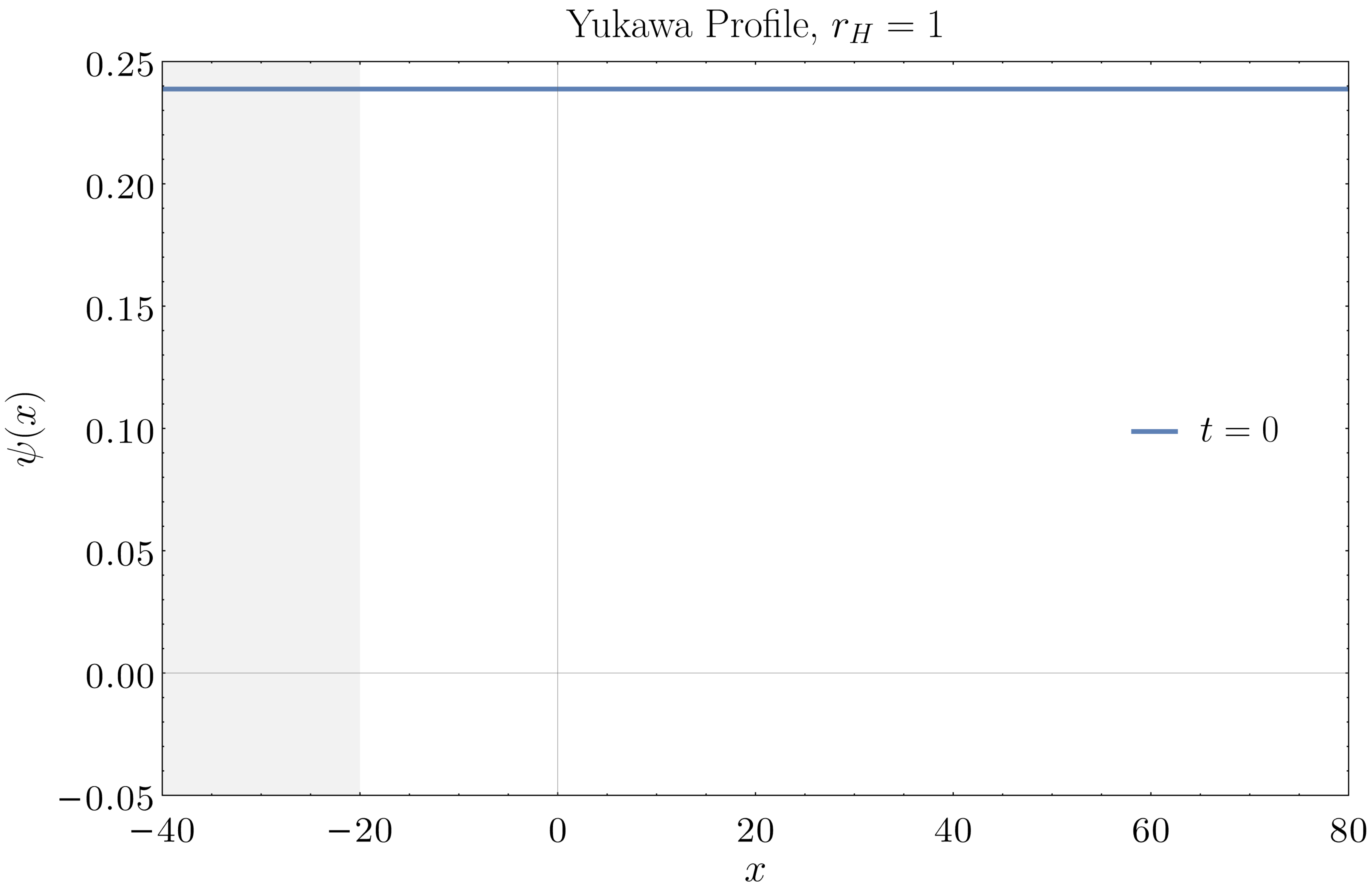
$$\phi(r,t) = e^{-i\omega t}\frac{\psi(r)}{r}$$

BH Potential



Shape Distorsion

PRELIMINARY



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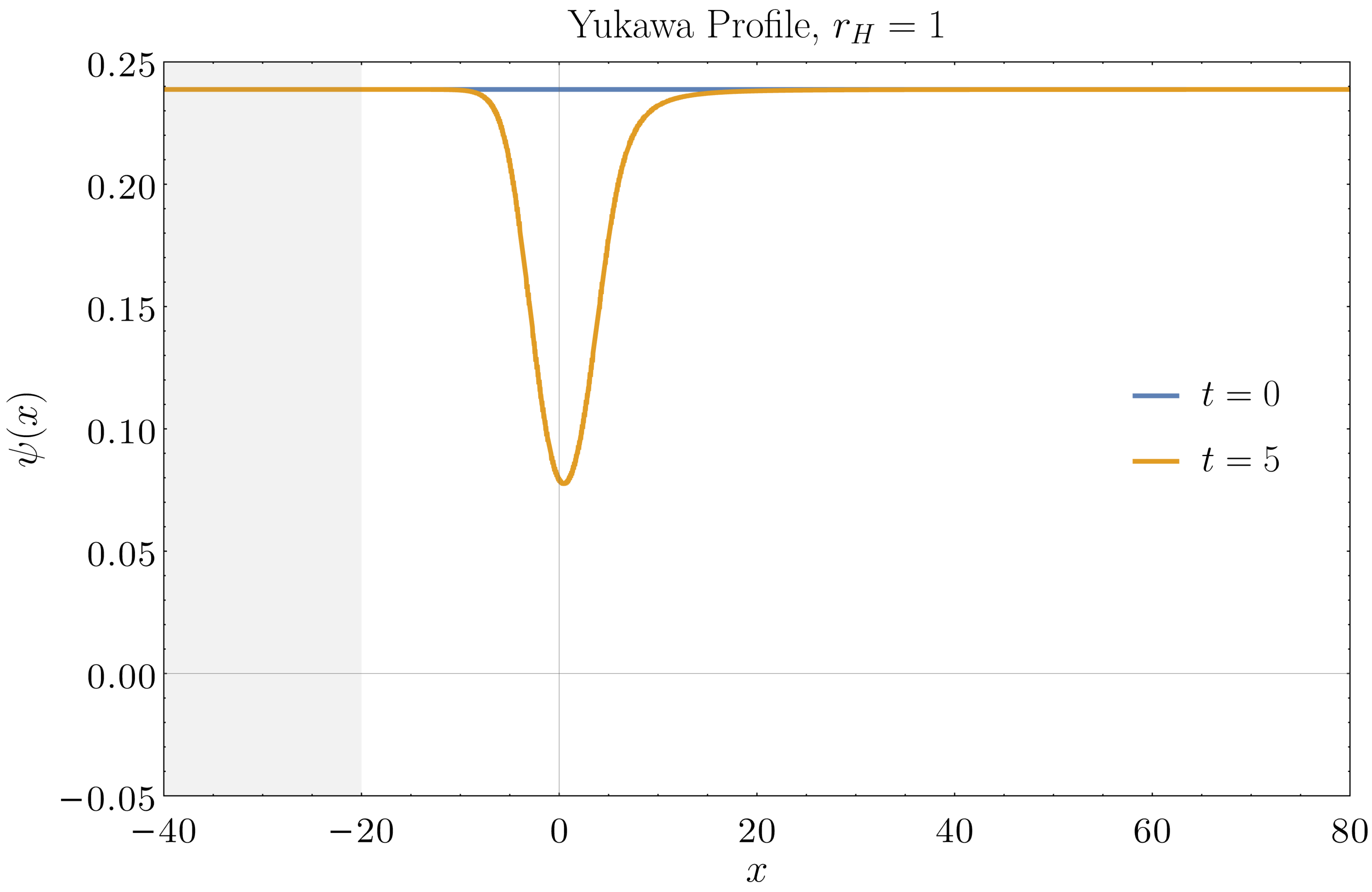

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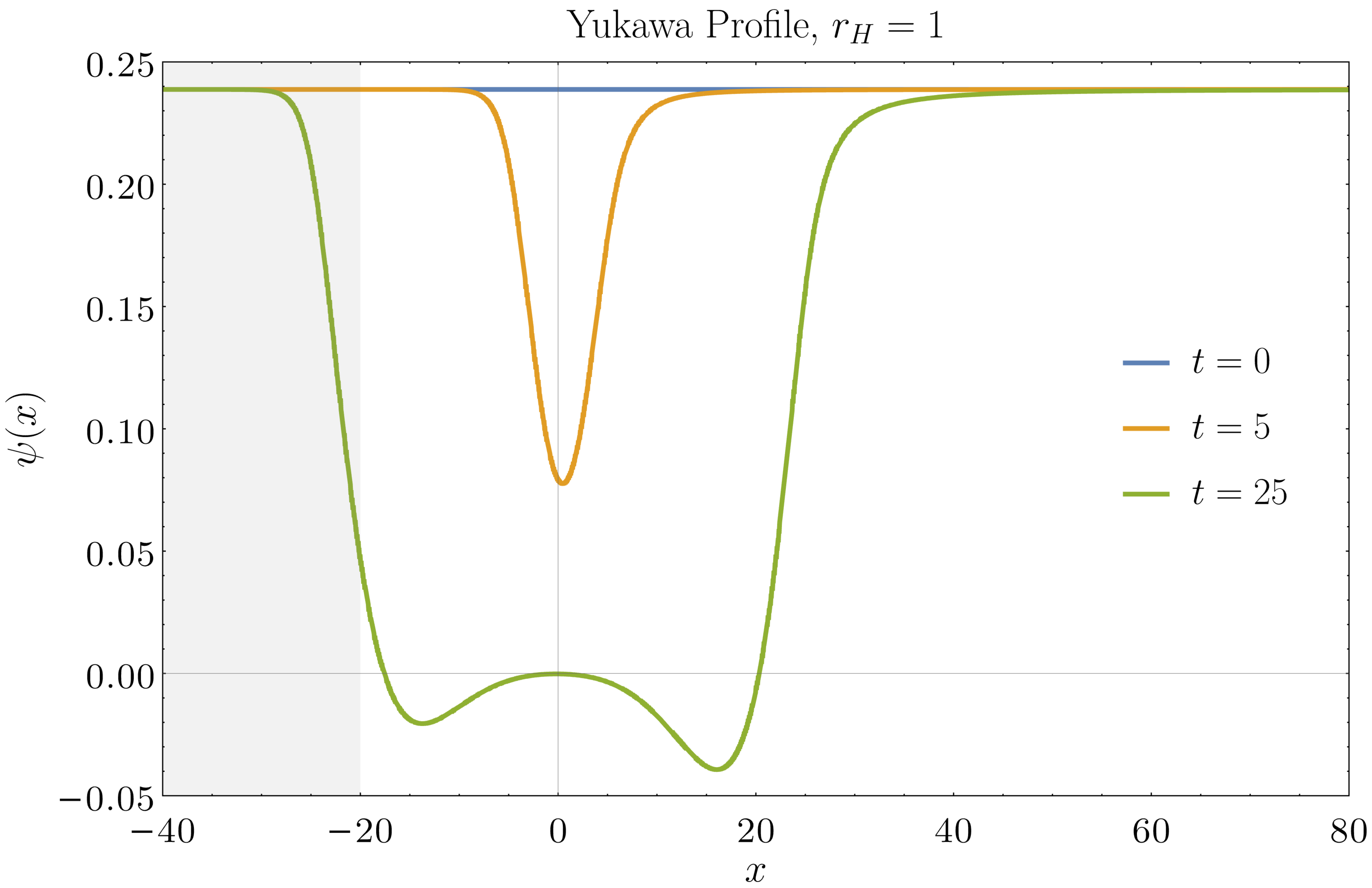

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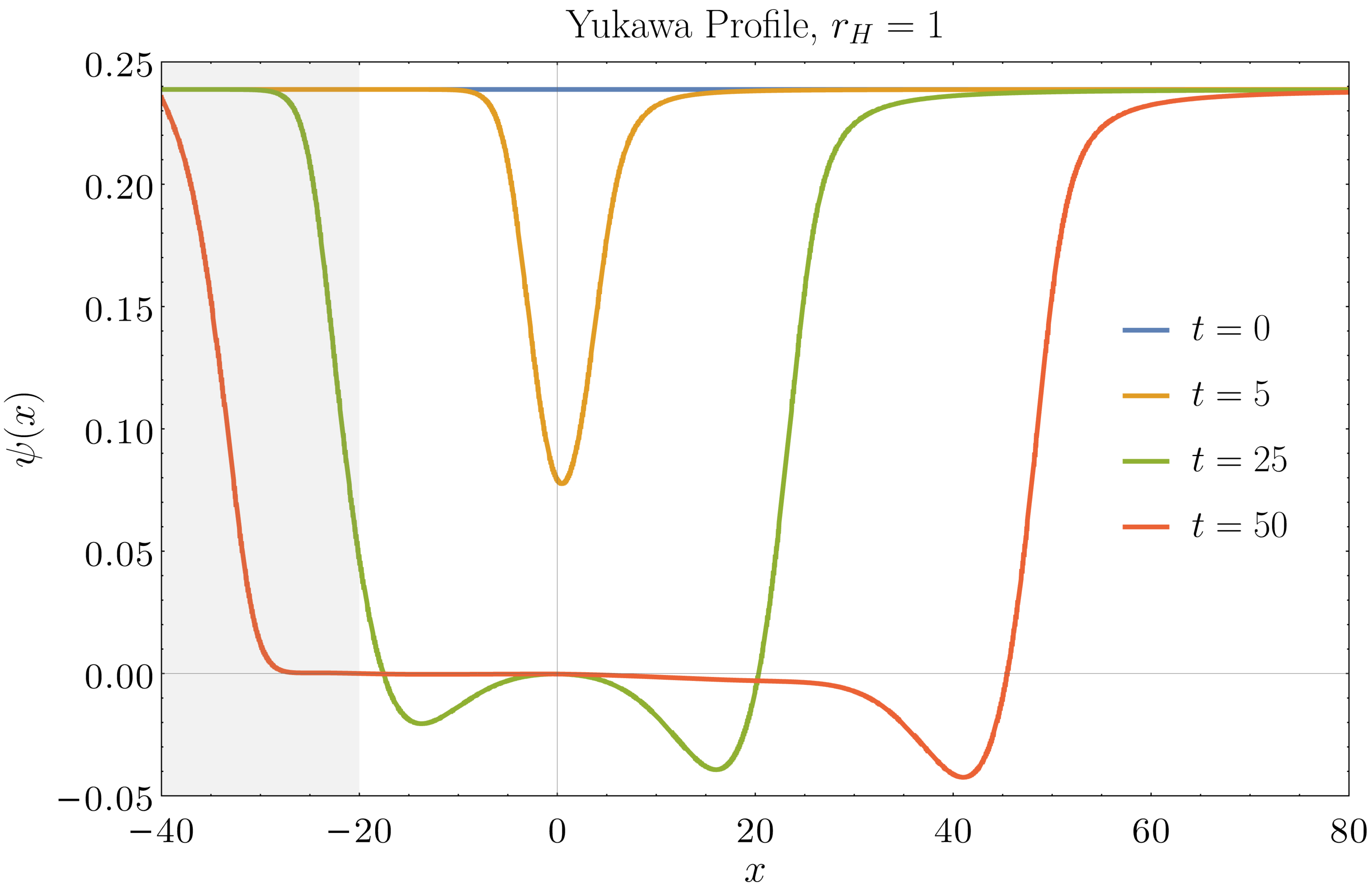

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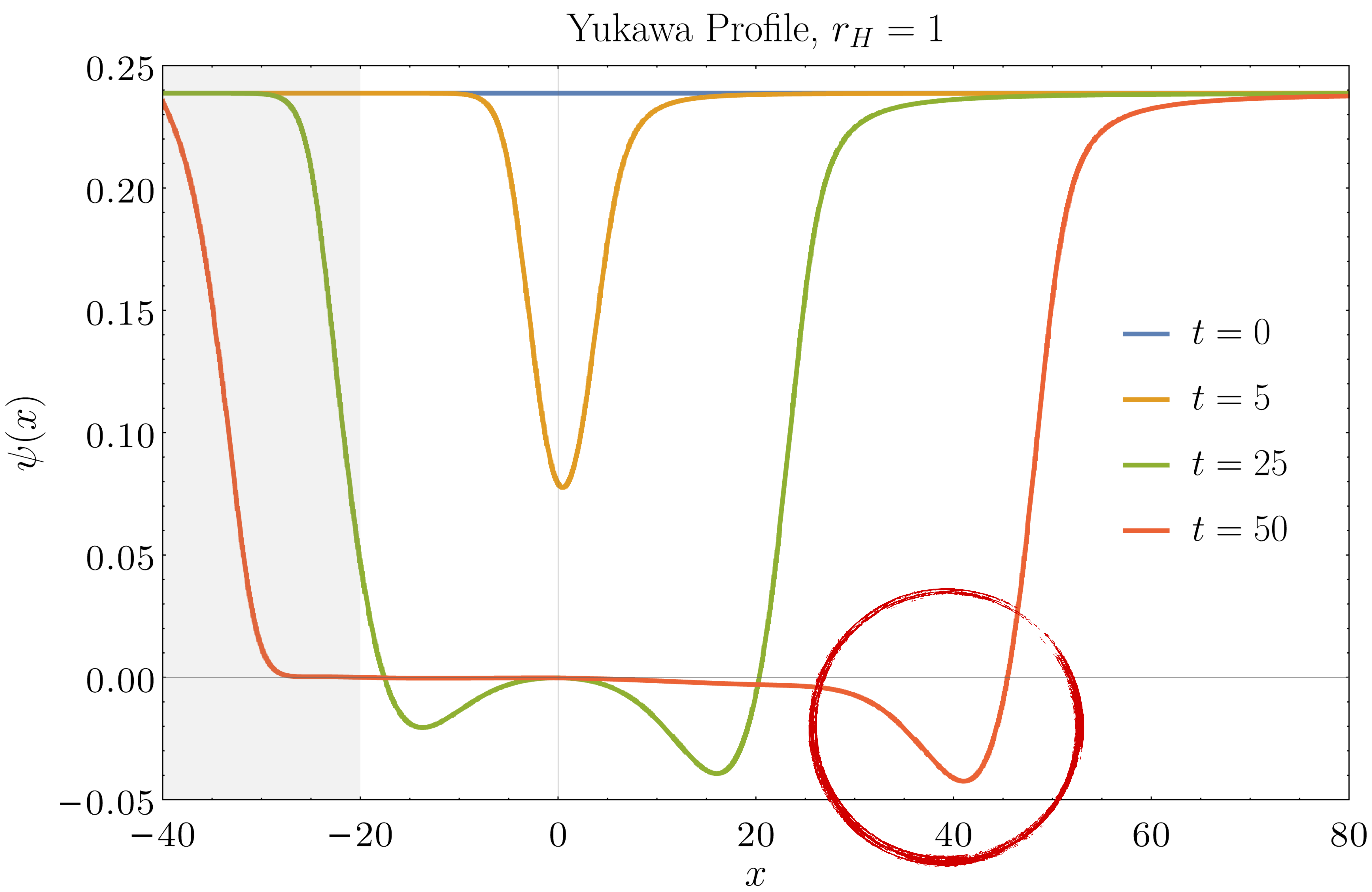

New feature! ~ reflection on the barrier

Summary and future directions

Searches for **periodic** and **transient** signals are **complementary**

$\Rightarrow$ need to characterise **most-likely frequency ranges**

New mechanism: BSM transients from **BH formation**

Frequency^{-1} **~ size of the source** - Neutron Star: **kHz range**

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New mechanism: BSM transients from **BH formation**

Frequency^{-1} **~ size of the source** - Neutron Star: **kHz range**

Better characterisation of the signal?
In progress and out soon!

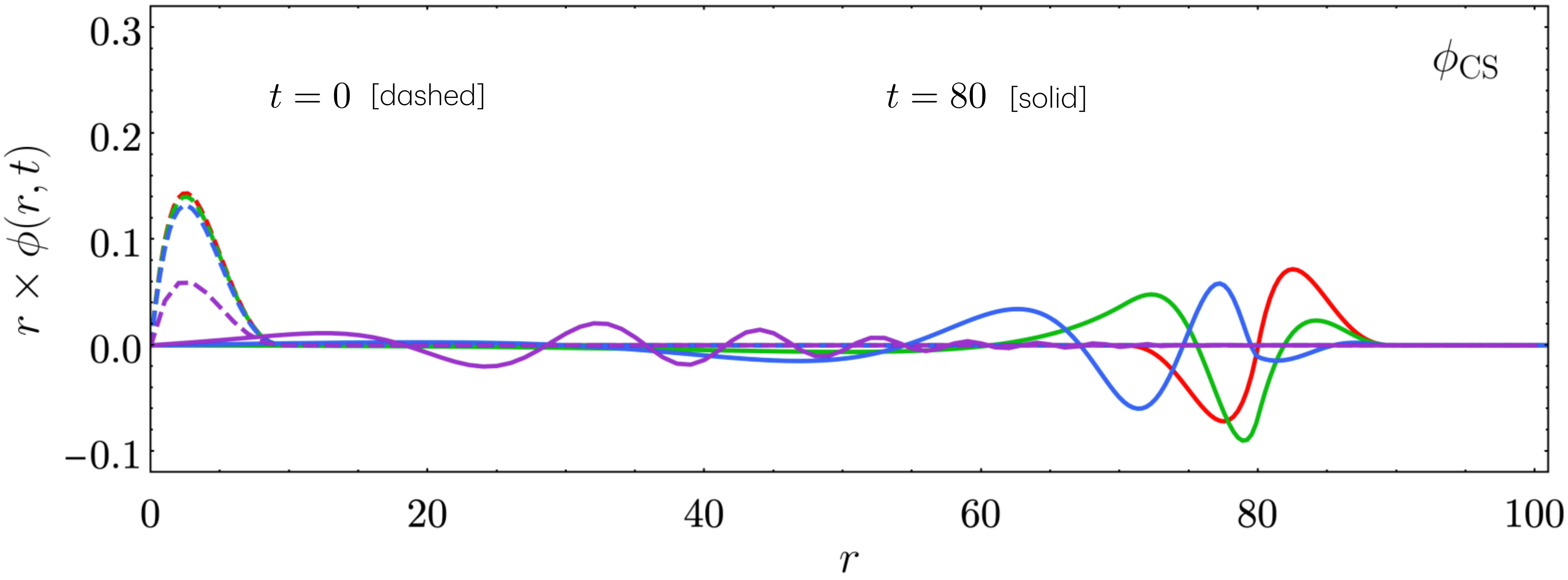
Work in progress (**2510.YYYYY**)

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

2408.10296 (EPJC)
2510.YYYYY

Thanks

Compact Field Propagation



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