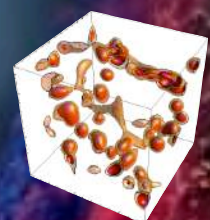
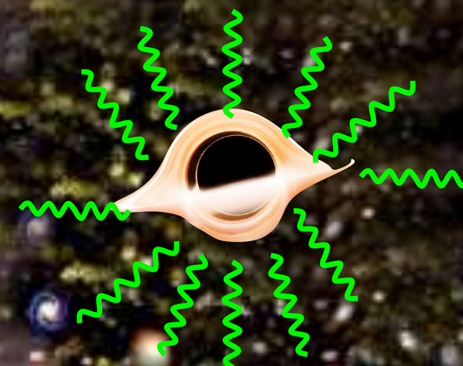
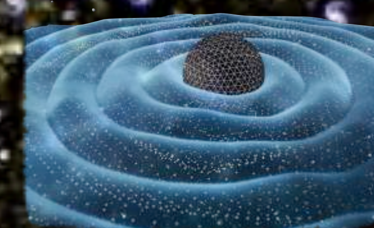
Gravitational Waves Signatures in presence of Primordial Black Holes





ϕ



Yann Mambrini, IJCLab, Université Paris-Saclay

Planck Conference, Padova

May 27th 2025

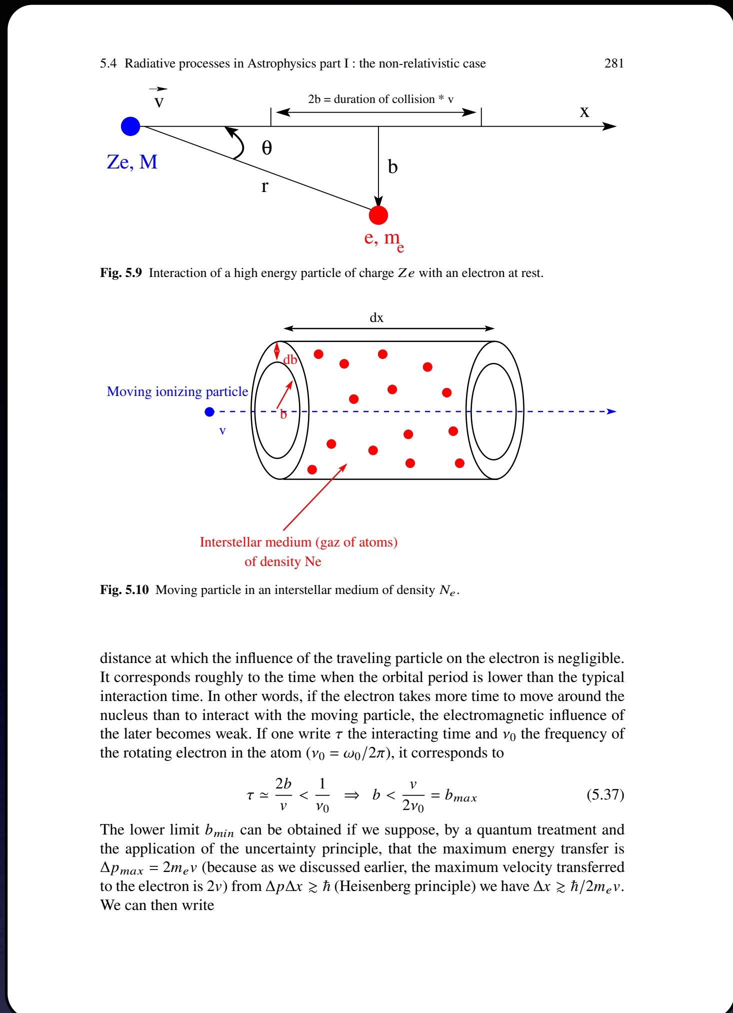

5.4 Radiative processes in Astrophysics part I : the non-relativistic case 281

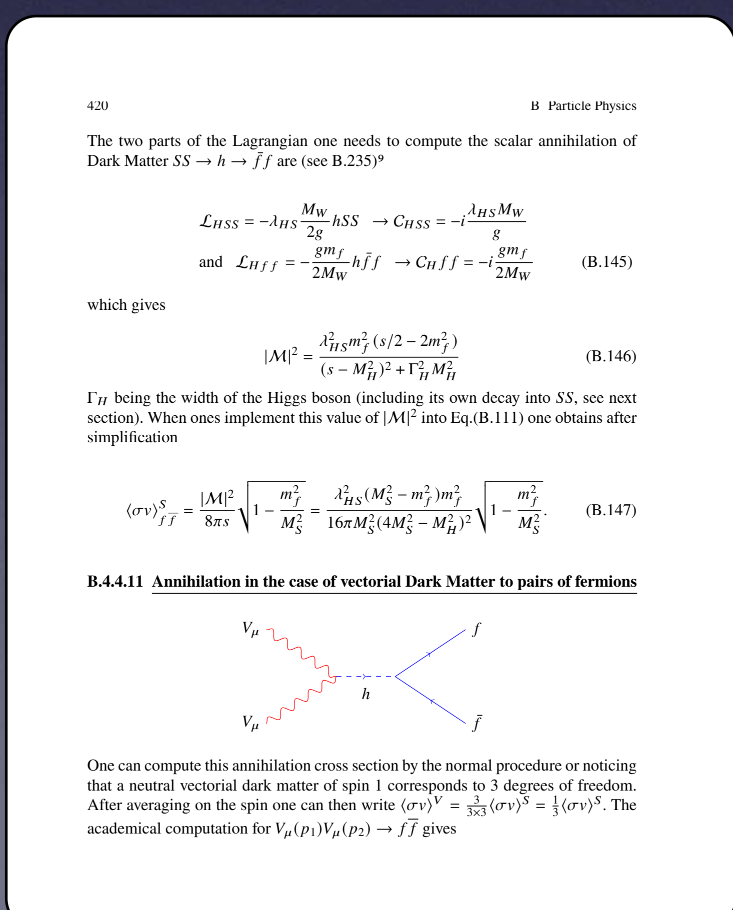
Fig. 5.9 Interaction of a high energy particle of charge Ze with an electron at rest.

Fig. 5.10 Moving particle in an interstellar medium of density N_e.

distance at which the influence of the traveling particle on the electron is negligible. It corresponds roughly to the time when the orbital period is lower than the typical interaction time. In other words, if the electron takes more time to move around the nucleus than to interact with the moving particle, the electromagnetic influence of the later becomes weak. If one write τ the interacting time and ν_0 the frequency of the rotating electron in the atom ($\nu_0 = \omega_0/2\pi$), it corresponds to

$$\tau \simeq \frac{2b}{v} < \frac{1}{\nu_0} \Rightarrow b < \frac{v}{2\nu_0} = b_{max} \quad (5.37)$$

The lower limit b_{min} can be obtained if we suppose, by a quantum treatment and the application of the uncertainty principle, that the maximum energy transfer is $\Delta p_{max} = 2m_e v$ (because as we discussed earlier, the maximum velocity transferred to the electron is $2v$) from $\Delta p \Delta x \gtrsim \hbar$ (Heisenberg principle) we have $\Delta x \gtrsim \hbar/2m_e v$. We can then write


420 B Particle Physics

The two parts of the Lagrangian one needs to compute the scalar annihilation of Dark Matter $SS \to h \to \bar{f}f$ are (see B.235)[9]

$$\mathcal{L}_{HSS} = -\lambda_{HS}\frac{M_W}{2g}hSS \;\to C_{HSS} = -i\frac{\lambda_{HS}M_W}{g}$$
$$\text{and}\quad \mathcal{L}_{Hff} = -\frac{gm_f}{2M_W}h\bar{f}f \;\to C_{H}ff = -i\frac{gm_f}{2M_W} \quad (B.145)$$

which gives

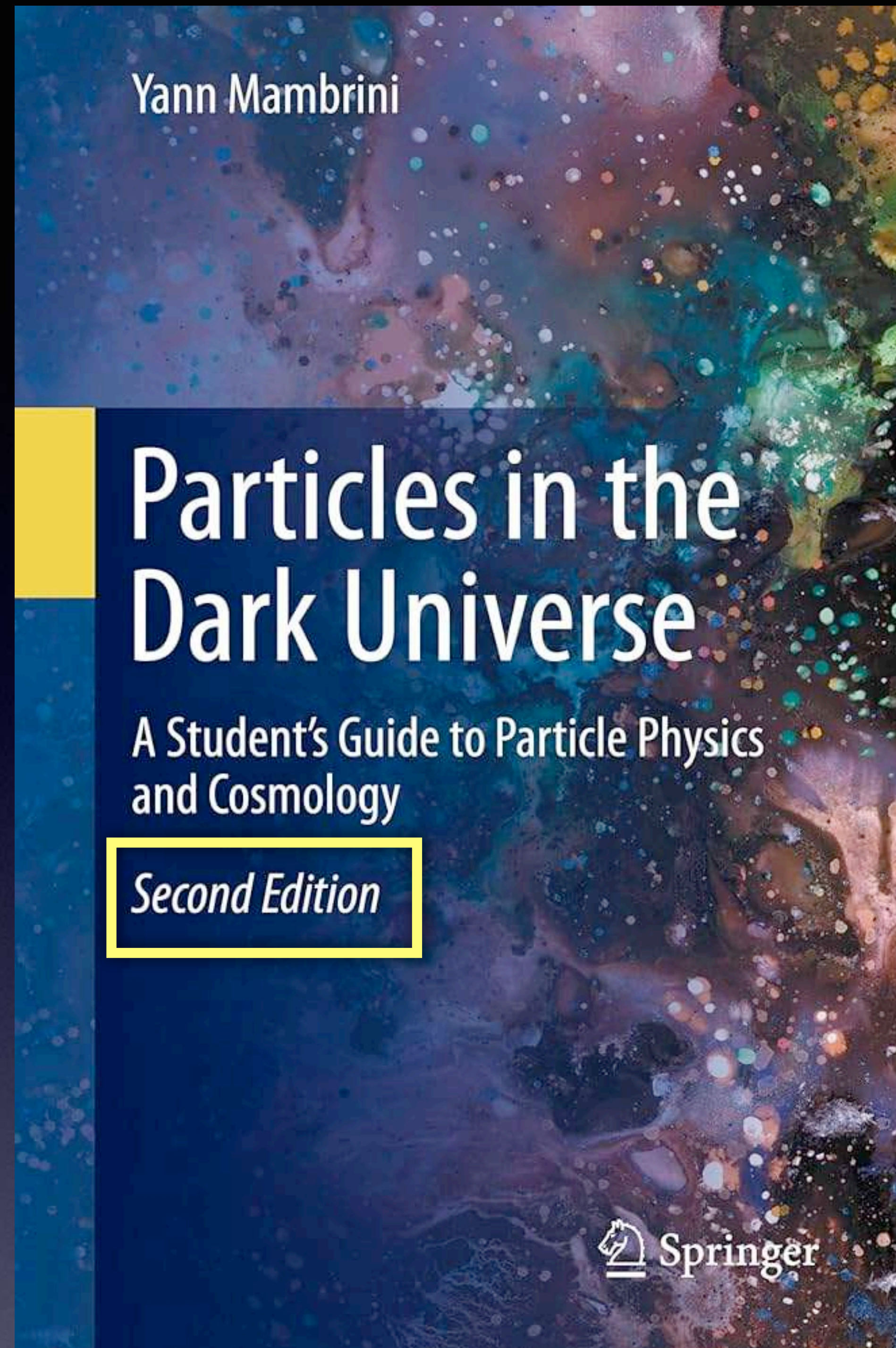
$$|\mathcal{M}|^2 = \frac{\lambda_{HS}^2 m_f^2 (s/2 - 2m_f^2)}{(s-M_H^2)^2 + \Gamma_H^2 M_H^2} \quad (B.146)$$

Γ_H being the width of the Higgs boson (including its own decay into SS, see next section). When ones implement this value of $|\mathcal{M}|^2$ into Eq.(B.111) one obtains after simplification

$$\langle\sigma v\rangle^S_{f\bar{f}} = \frac{|\mathcal{M}|^2}{8\pi s}\sqrt{1-\frac{m_f^2}{M_S^2}} = \frac{\lambda_{HS}^2(M_S^2-m_f^2)m_f^2}{16\pi M_S^2(4M_S^2-M_H^2)^2}\sqrt{1-\frac{m_f^2}{M_S^2}}. \quad (B.147)$$

B.4.4.11 Annihilation in the case of vectorial Dark Matter to pairs of fermions

One can compute this annihilation cross section by the normal procedure or noticing that a neutral vectorial dark matter of spin 1 corresponds to 3 degrees of freedom. After averaging on the spin one can then write $\langle\sigma v\rangle^V = \frac{3}{3\times3}\langle\sigma v\rangle^S = \frac{1}{3}\langle\sigma v\rangle^S$. The academical computation for $V_\mu(p_1)V_\mu(p_2) \to f\bar{f}$ gives



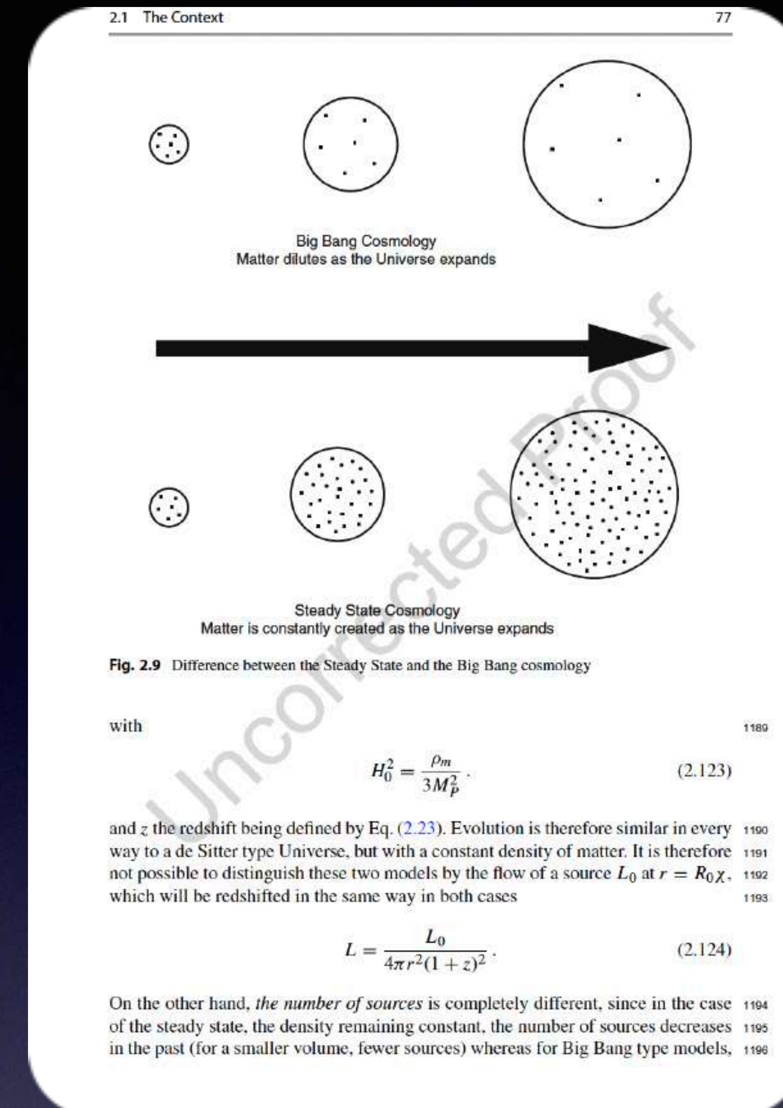

2.1 The Context 77

Fig. 2.9 Difference between the Steady State and the Big Bang cosmology

with 1189

$$H_0^2 = \frac{\rho_m}{3M_P^2}. \quad (2.123)$$

and z the redshift being defined by Eq. (2.23). Evolution is therefore similar in every 1190
way to a de Sitter type Universe, but with a constant density of matter. It is therefore 1191
not possible to distinguish these two models by the flow of a source L_0 at $r = R_0\chi$, 1192
which will be redshifted in the same way in both cases 1193

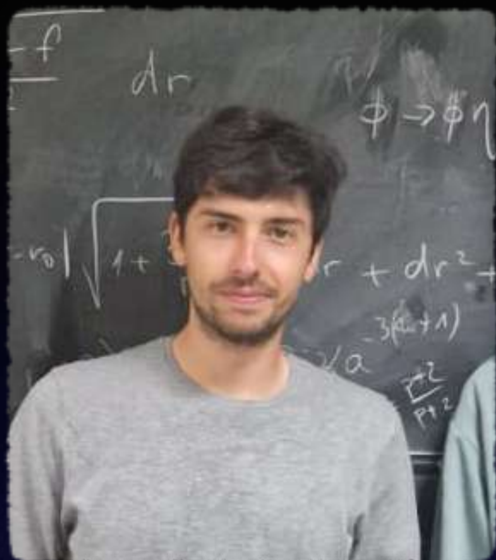
$$L = \frac{L_0}{4\pi r^2(1+z)^2}. \quad (2.124)$$

On the other hand, *the number of sources* is completely different, since in the case 1194
of the steady state, the density remaining constant, the number of sources decreases 1195
in the past (for a smaller volume, fewer sources) whereas for Big Bang type models, 1196

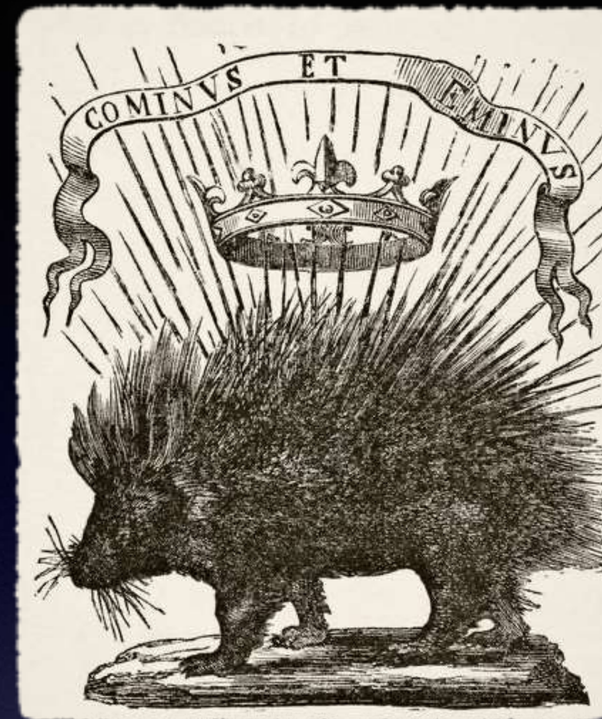
650+ pages, from inflation to dark matter detection.
2nd edition (+ PBH + unification + history of cosmological models…)
All what is needed to compute cross-sections, relic abundance,
and retrace the history of a Dark Universe.

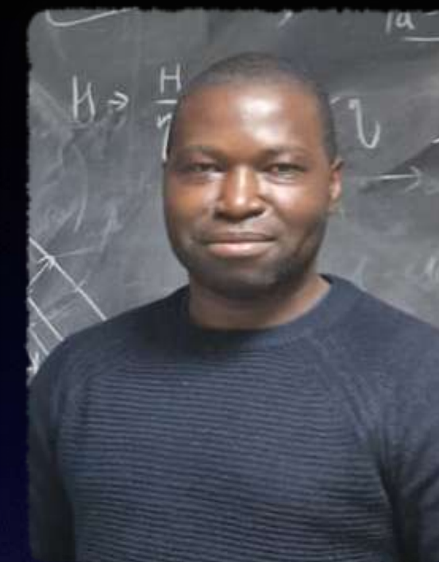
Preface and forewords by K. Olive, J. Peebles and J. Silk

students/postdocs :

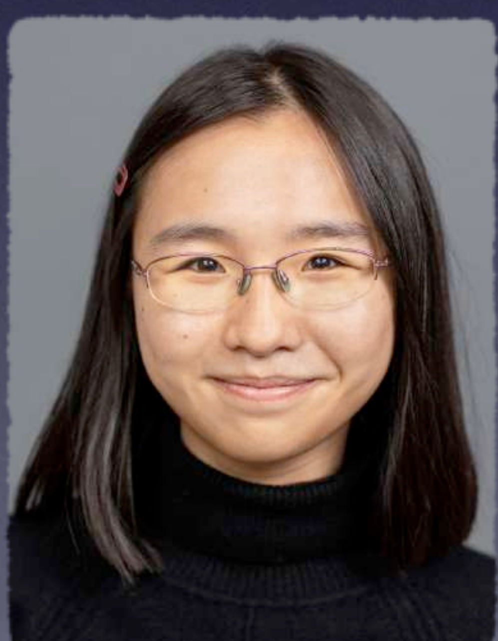


Simon Clery
(TUM, Munchen)





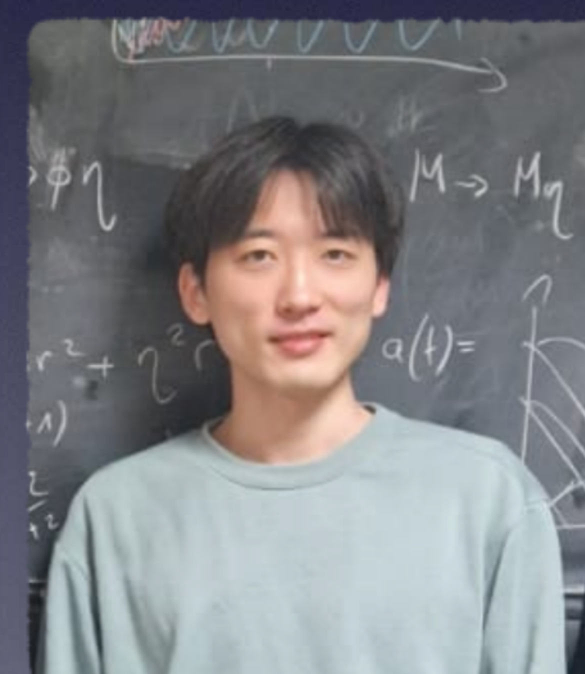
Essodjolo Kpatcha
(IJCLab, Paris-Saclay)



Wenqi Ke
(FI, Minneapolis)

Mathieu Gross
(Paris-Saclay)

Mathias Pierre
(DESY)



Jong-Hyun Yoon
(CNU, Daejon)

Based (mainly) on

M. R. Haque, E. Kpatcha, D. Maity and **Y.M.**, ``Primordial black hole versus inflaton,''
Phys. Rev. D **109** (2024) no.2, 023521 ; [arXiv:2309.06505 [hep-ph]].

M. Riajul Haque, E. Kpatcha, D. Maity and **Y.M.**, ``Primordial black hole reheating,''
Phys. Rev. D **108** (2023) no.6, 063523 ; [arXiv:2305.10518 [hep-ph]].

B. Barman, S. Jyoti Das, M. R. Haque and **Y.M.**, ``Leptogenesis, primordial gravitational waves, and PBH-induced reheating,''
[arXiv:2403.05626 [hep-ph]].

M. Gross, E. Kpatcha, **Y.M.**, M. Olea-Romacho and R. Roshan ``Gravitational Wave Production During Reheating: From the Inflaton to Primordial Black Holes'' ; [arXiv:2411.04189 [hep-ph]].

M. R. Haque, S. Maity, D. Maity and **Y.M.** ``Quantum effects on the evaporation of PBHs: contributions to dark matter,''
JCAP **07** (2024), 002 ; [arXiv:2404.16815 [hep-ph]].

And

G. Choi, M. A. G. Garcia, W. Ke, Y. Mambrini, K. A. Olive and S. Verner,
``Inflaton Production of Scalar Dark Matter through Fluctuations and Scattering,'' [arXiv:2406.06696 [hep-ph]].

M. A. G. Garcia, M. Gross, Y. Mambrini, K. A. Olive, M. Pierre and J. H. Yoon,
``Effects of fragmentation on post-inflationary reheating,'' JCAP **12** (2023), 028

Y. Mambrini and K. A. Olive, Phys. Rev. D **103** (2021) no.11, 115009 [arXiv:2102.06214]

S. Clery, Y. Mambrini, K. A. Olive and S. Verner, Phys. Rev. D **105** (2022) no.7, 075005 ; [arXiv:2112.15214]

R. T. Co, Y. Mambrini and K. A. Olive, ``Inflationary Gravitational Leptogenesis,'' ; [arXiv:2205.01689 [hep-ph]].

Gravitational wave spectrum in the presence of inflaton and primordial black holes

$$1\ \mathrm{g} \lesssim M_{BH} \lesssim 10^8\ \mathrm{g}$$

$$10^{-23}\ \mathrm{s} \lesssim t_{BH} \lesssim 1\ \mathrm{s}$$

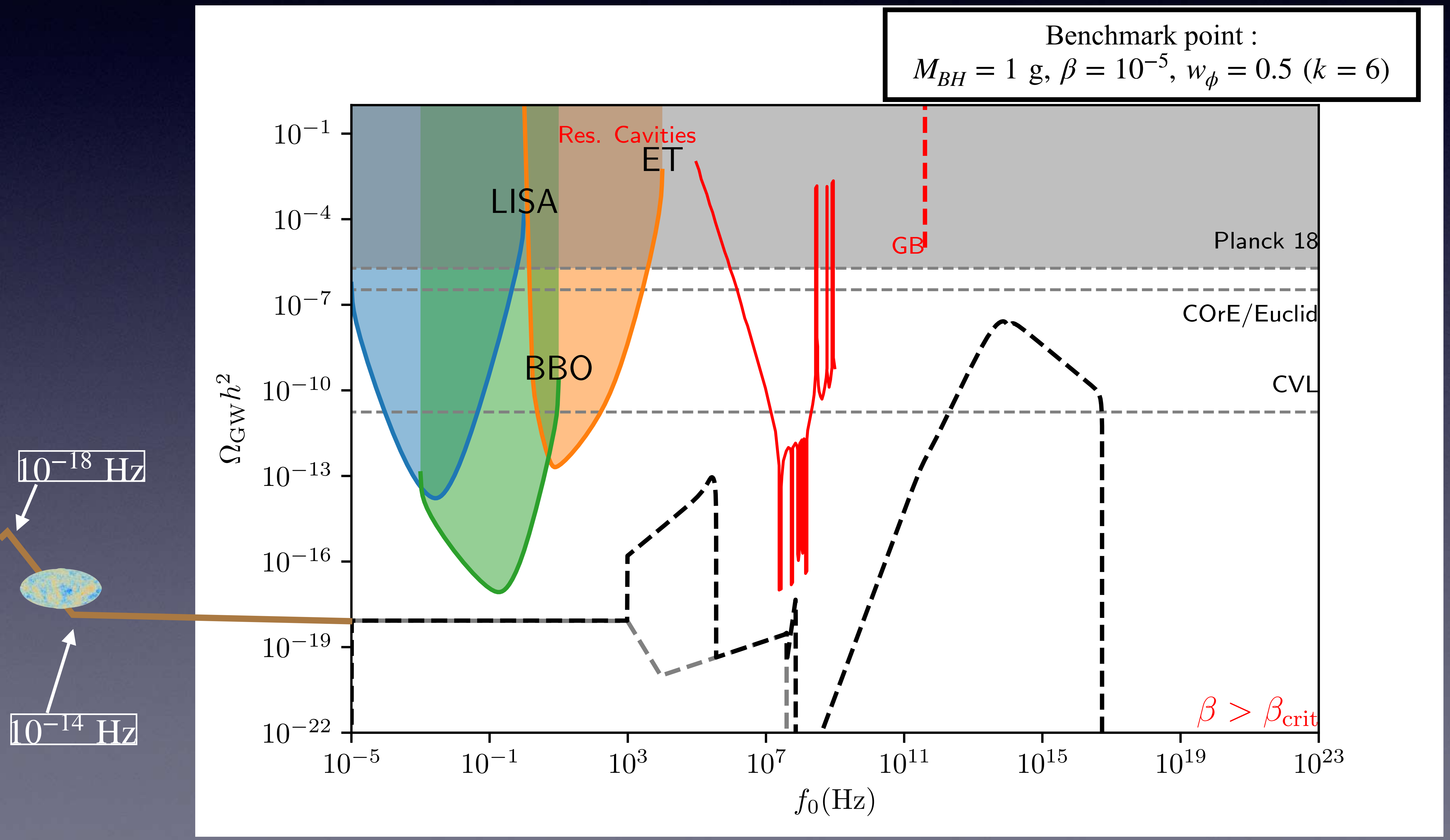
BH energy density can then dominate over inflaton energy density and lead to reheating, DM production, lepto-baryogenesis…

$$1 \text{ g} \lesssim M_{BH} \lesssim 10^8 \text{ g}$$

$$10^{-23} \text{ s} \lesssim t_{BH} \lesssim 1 \text{ s}$$

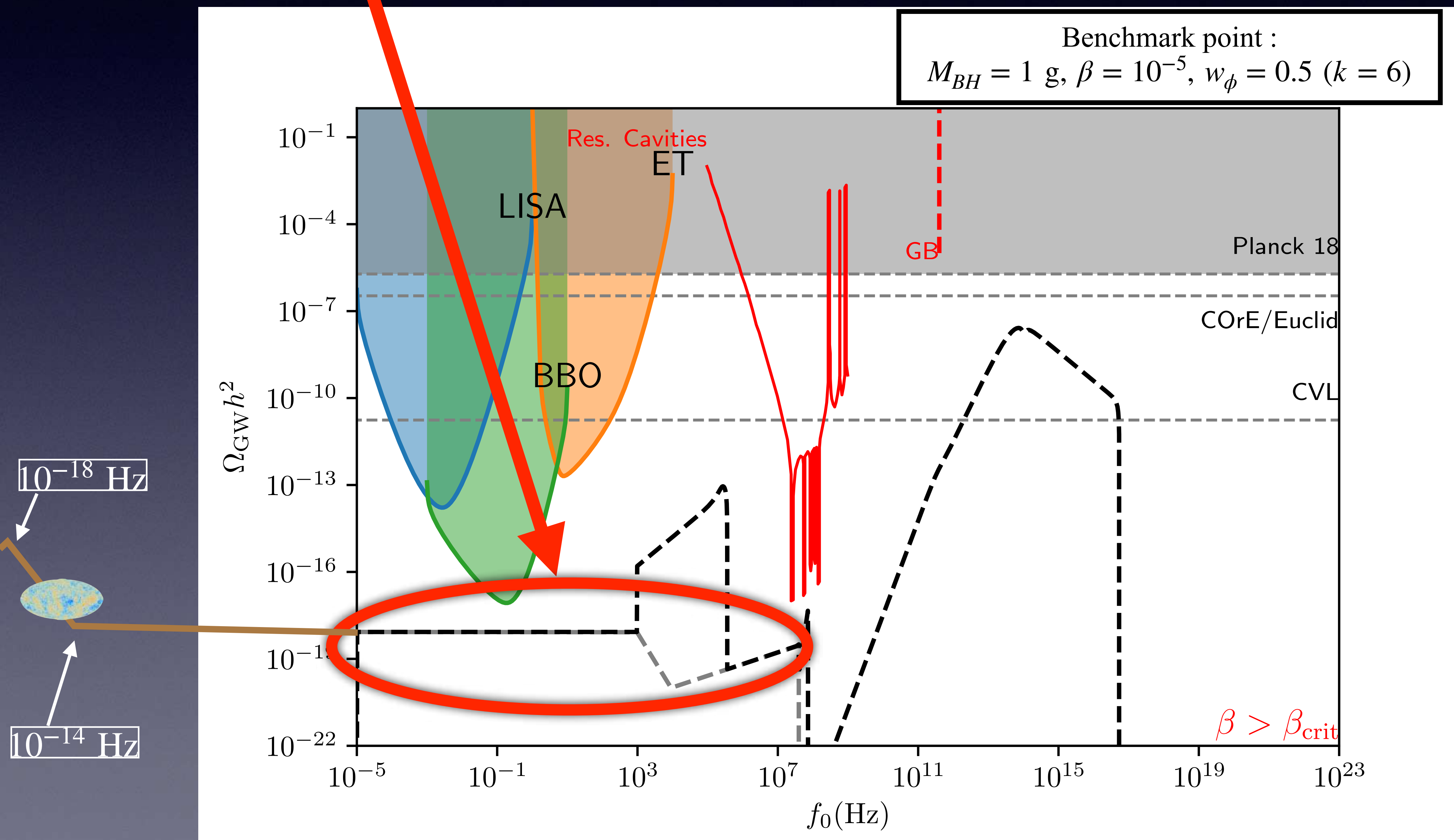
BH energy density can then dominate over inflaton energy density and lead to reheating, DM production, lepto-baryogenesis…

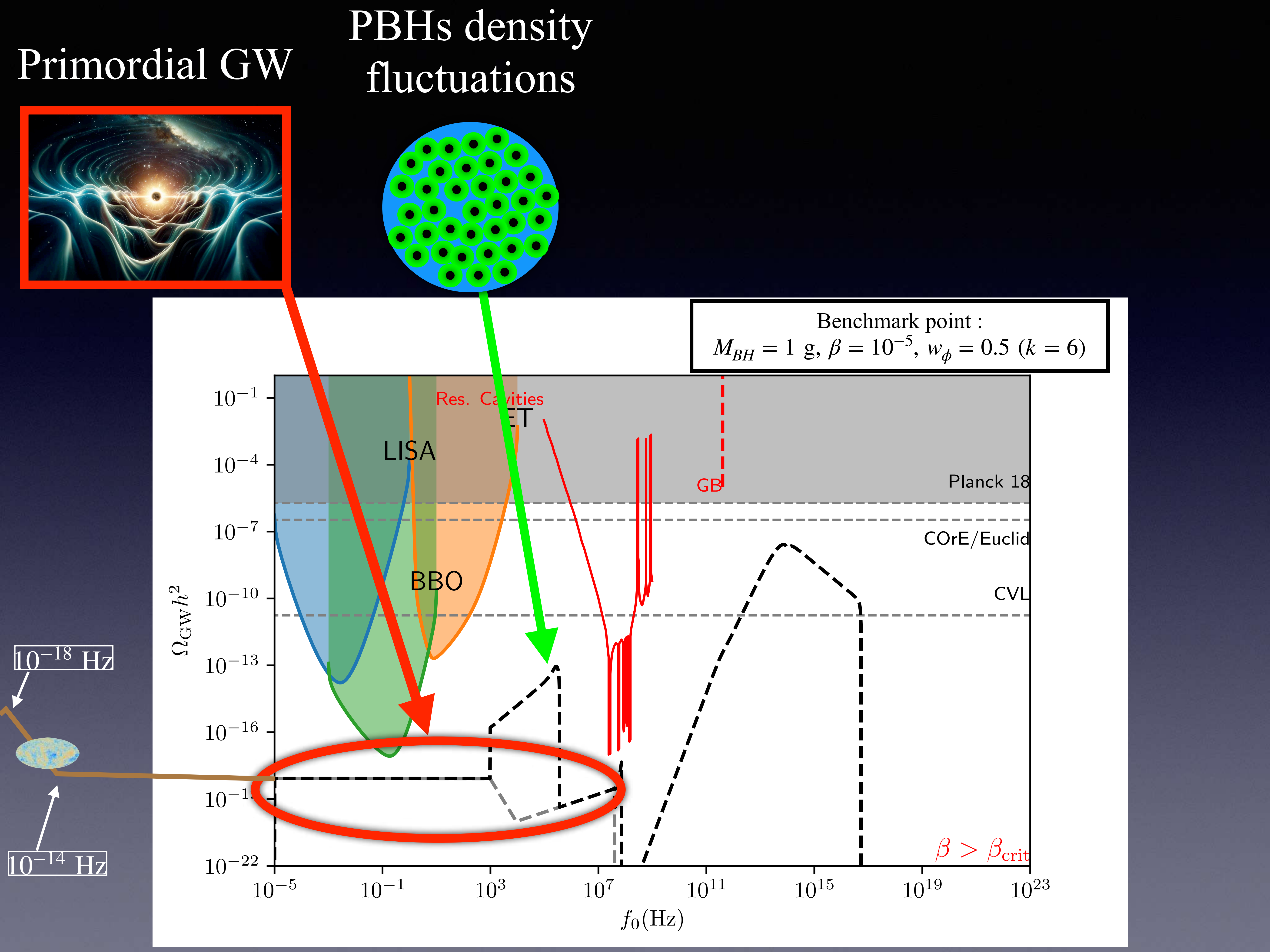
But the talk can be applied to any early matter domination era



Benchmark point :
$M_{BH} = 1$ g, $\beta = 10^{-5}$, $w_\phi = 0.5$ $(k = 6)$
Res. Cavities
ET
LISA
BBO
GB
Planck 18
COrE/Euclid
CVL
$\beta > \beta_{\rm crit}$
$\Omega_{\rm GW} h^2$
f_0(Hz)
10^{-18} Hz
10^{-14} Hz

Primordial GW





Primordial GW
PBHs density fluctuations
Benchmark point :
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Res. Cavities
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$\Omega_{\rm GW} h^2$
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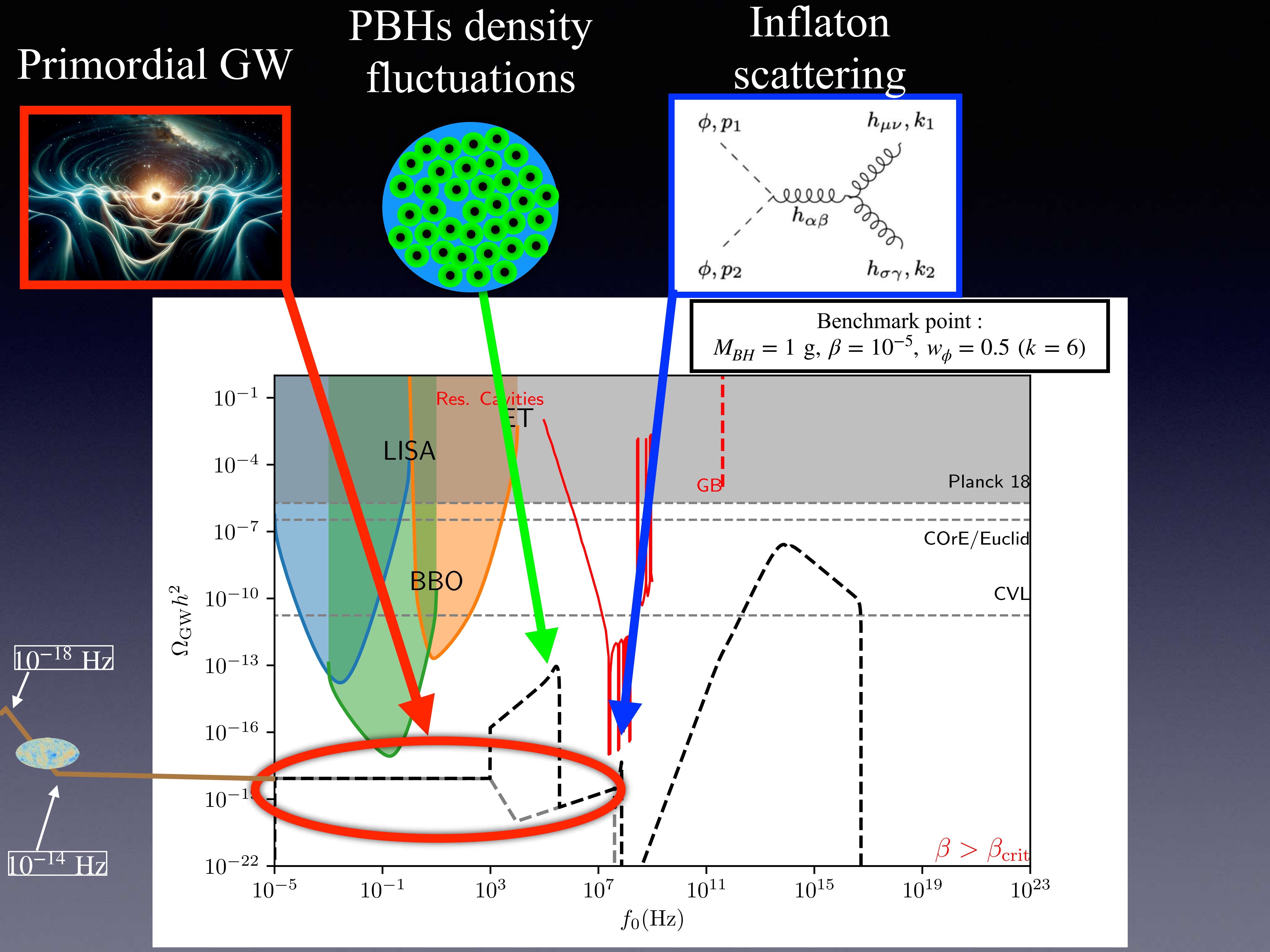
10^{-14} Hz
$\beta > \beta_{\rm crit}$
$f_0(\rm Hz)$


Primordial GW
PBHs density fluctuations
Inflaton scattering
ϕ, p_1
$h_{\mu\nu}, k_1$
$h_{\alpha\beta}$
ϕ, p_2
$h_{\sigma\gamma}, k_2$
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f_0(Hz)
10^{-18} Hz
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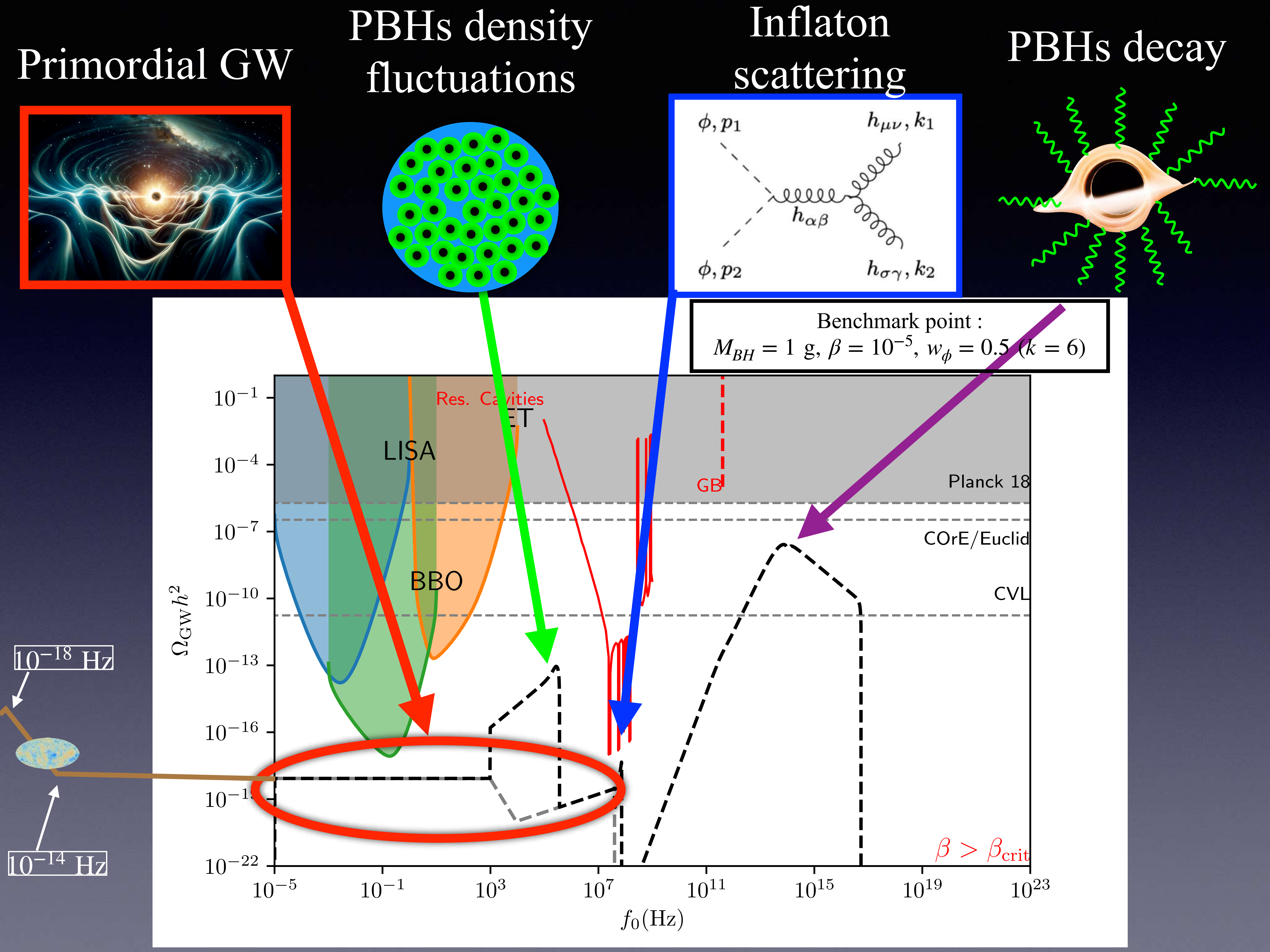
Primordial GW
PBHs density fluctuations
Inflaton scattering
PBHs decay
ϕ, p_1
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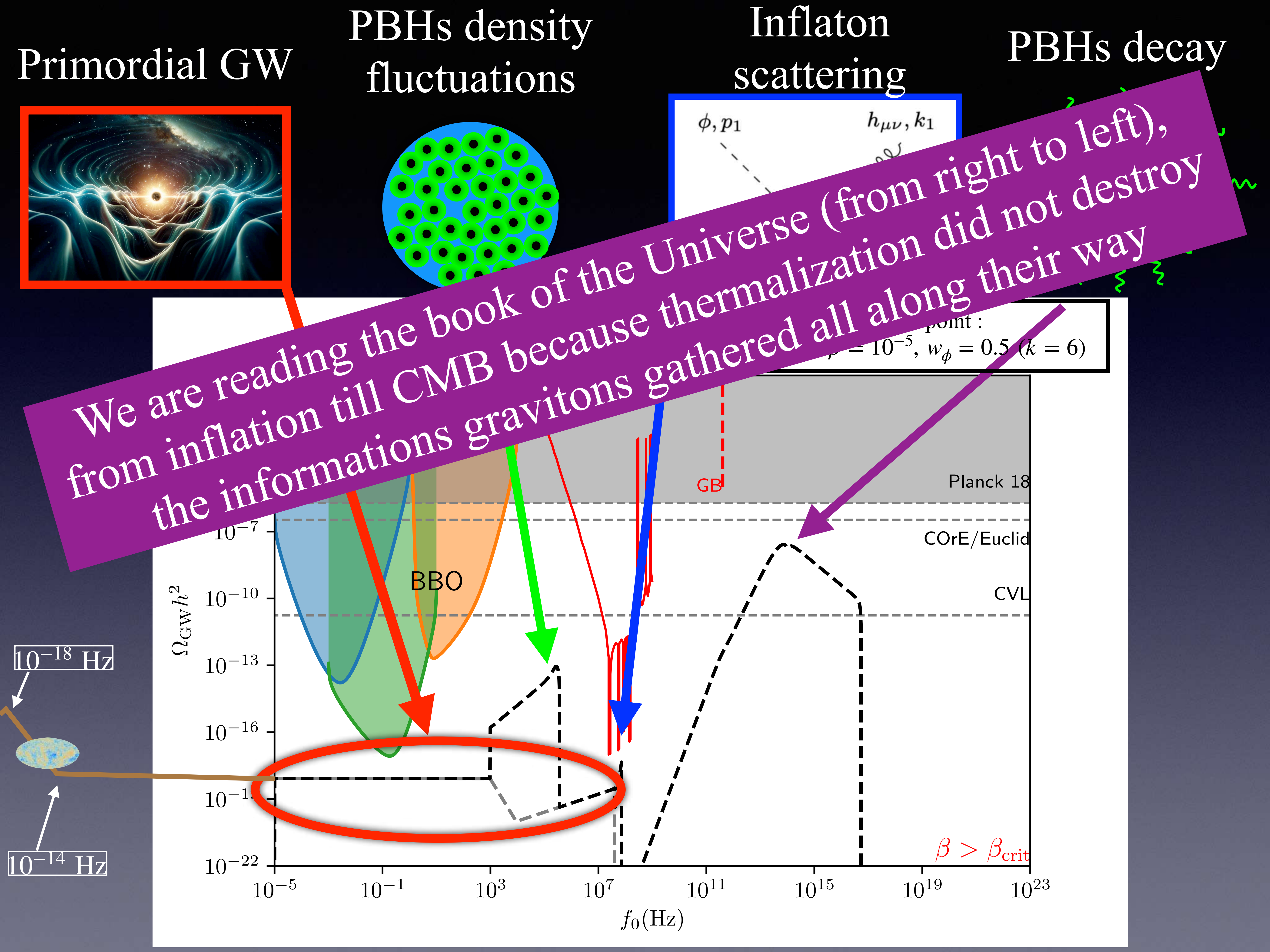

Primordial GW
PBHs density fluctuations
Inflaton scattering
PBHs decay
We are reading the book of the Universe (from right to left), from inflation till CMB because thermalization did not destroy the informations gravitons gathered all along their way
ϕ, p_1
$h_{\mu\nu}, k_1$
Planck 18
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$\beta > \beta_{\rm crit}$
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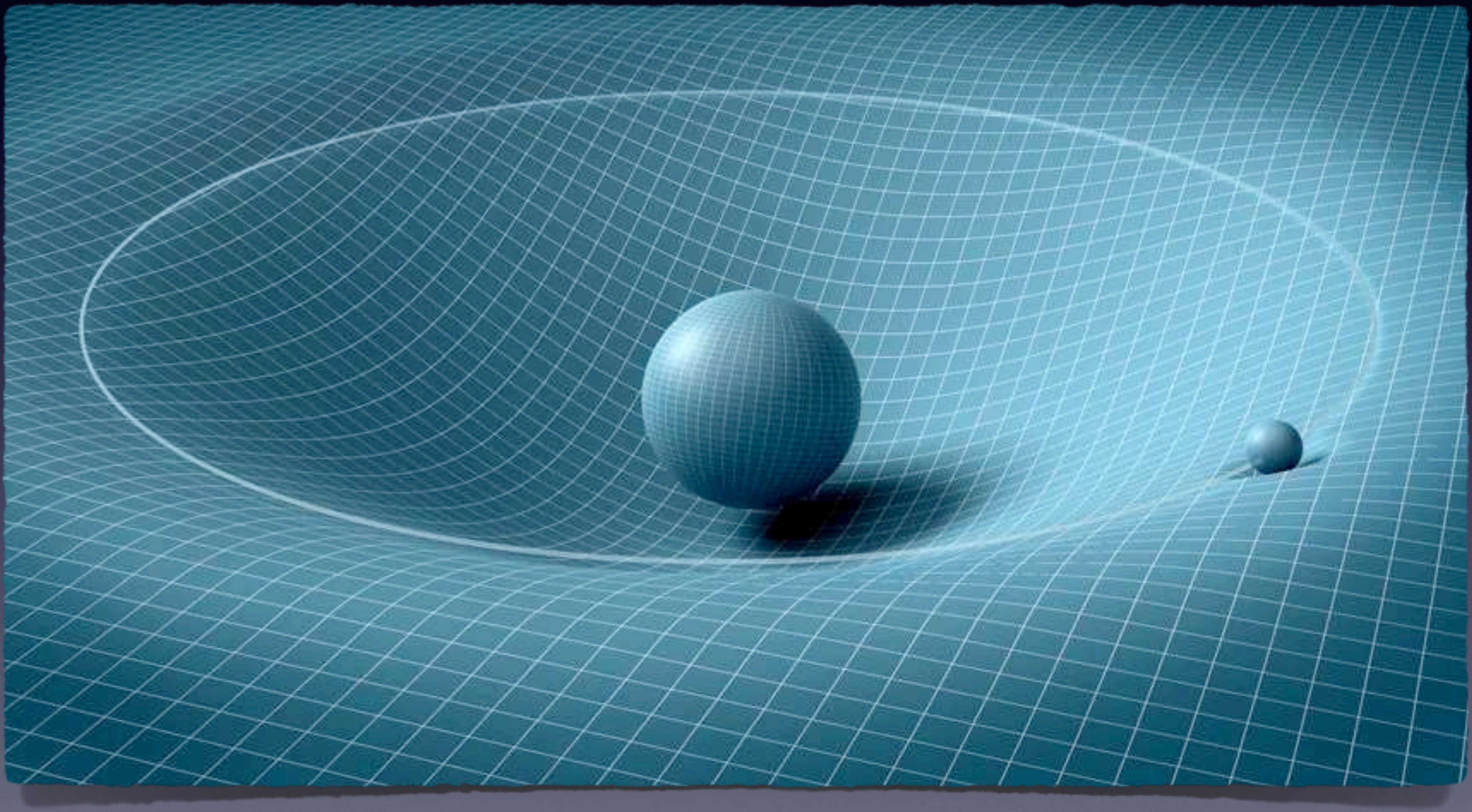
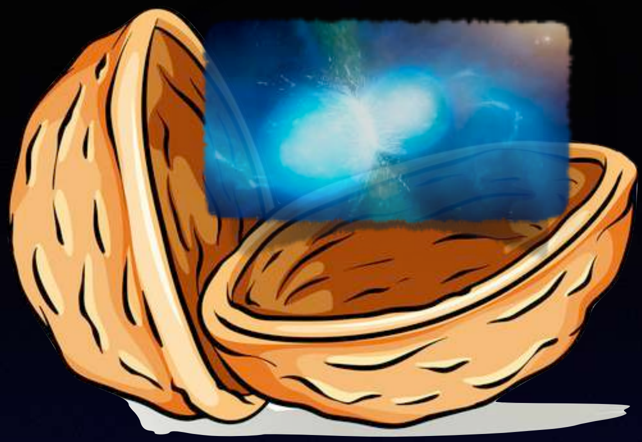
f_0(Hz)
10^{-18} Hz
10^{-14} Hz

I) Much ado about gravity

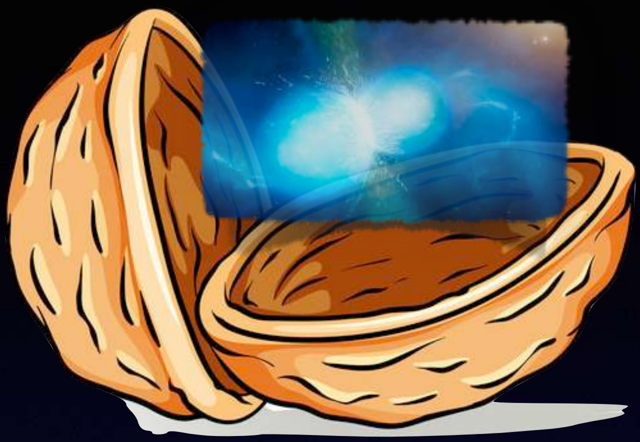
When horizon(s) source the matter



Gravitational production in a nutshell

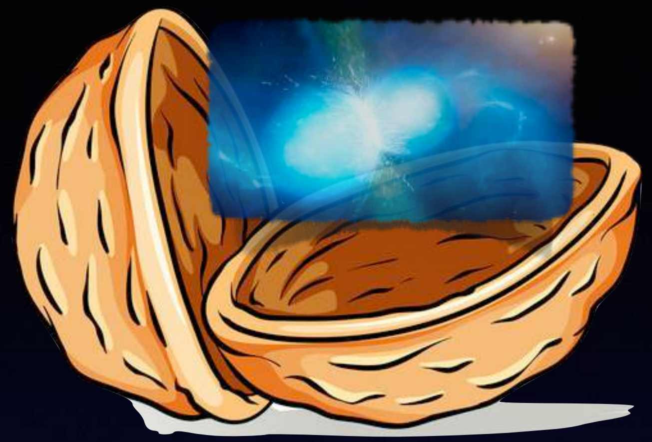


Gravitational production in a nutshell



$$G_{\mu\nu} = \frac{1}{M_P^2} T_{\mu\nu} = \frac{1}{M_P^2} \times \frac{1}{2} \langle \rho_\chi \rangle \, g_{\mu\nu}$$

Gravitational production in a nutshell



$$G_{\mu\nu} = \frac{1}{M_P^2} T_{\mu\nu} = \frac{1}{M_P^2} \times \frac{1}{2}\langle \rho_\chi \rangle\, g_{\mu\nu}$$

$$\Rightarrow \quad \langle \rho_\chi \rangle \sim \mathscr{R}\, M_P^2 \sim H^2 M_P^2$$

Gravitational production in a nutshell

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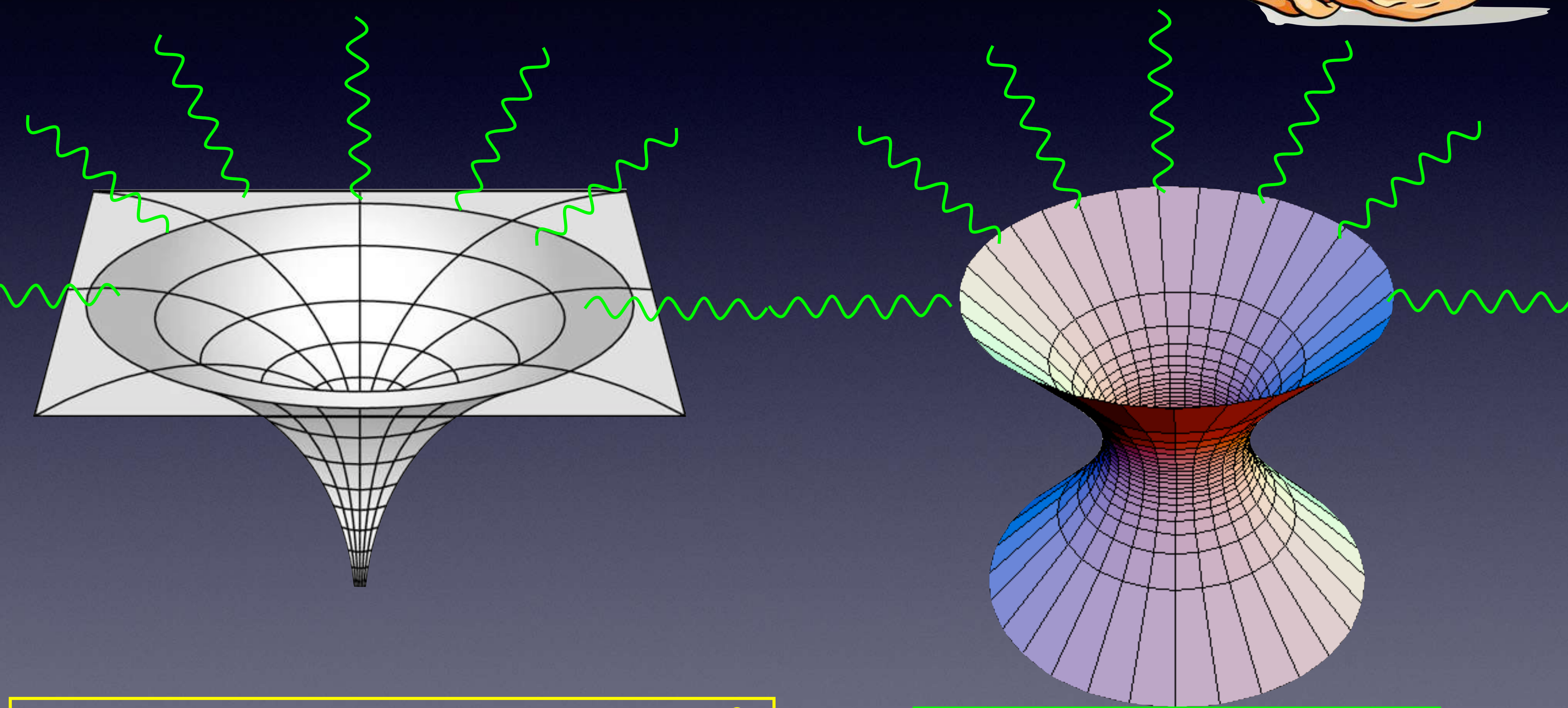

Schwarzschild horizon, $T \sim \frac{1}{R_S} = \frac{M_P^2}{M_{BH}}$

De Sitter horizon, $T = \frac{H_{dS}}{2\pi}$

Gravitational production in a nutshell

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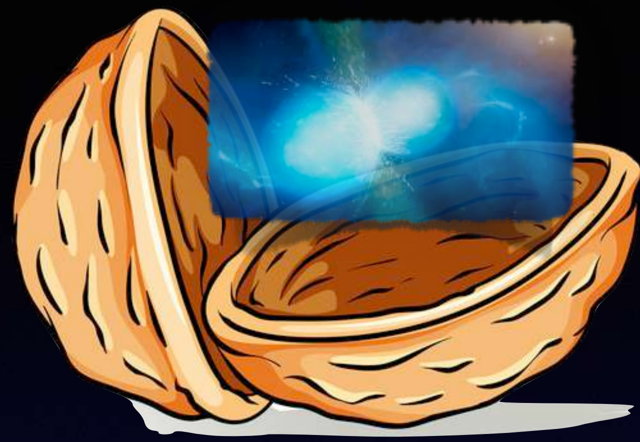
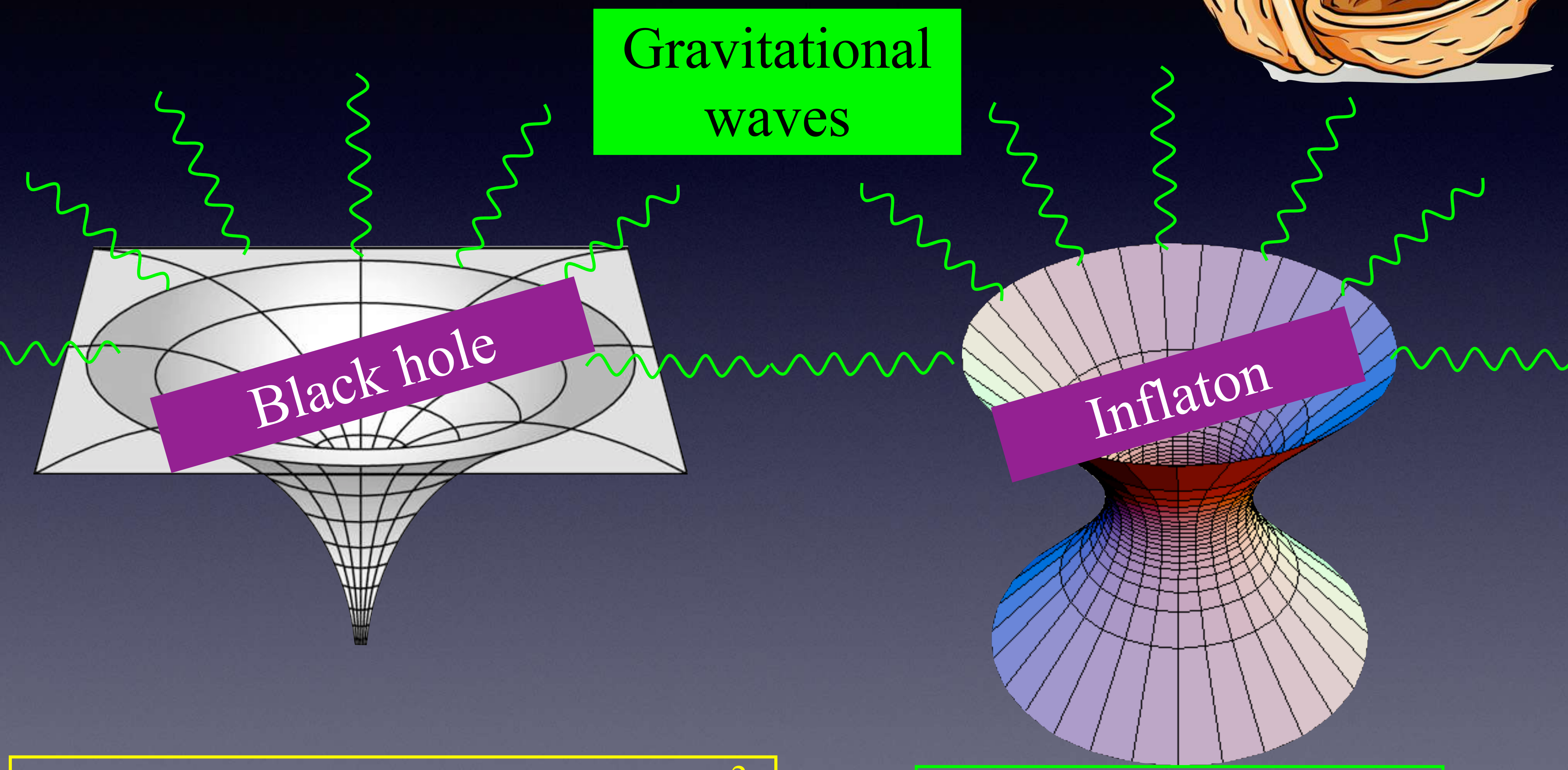
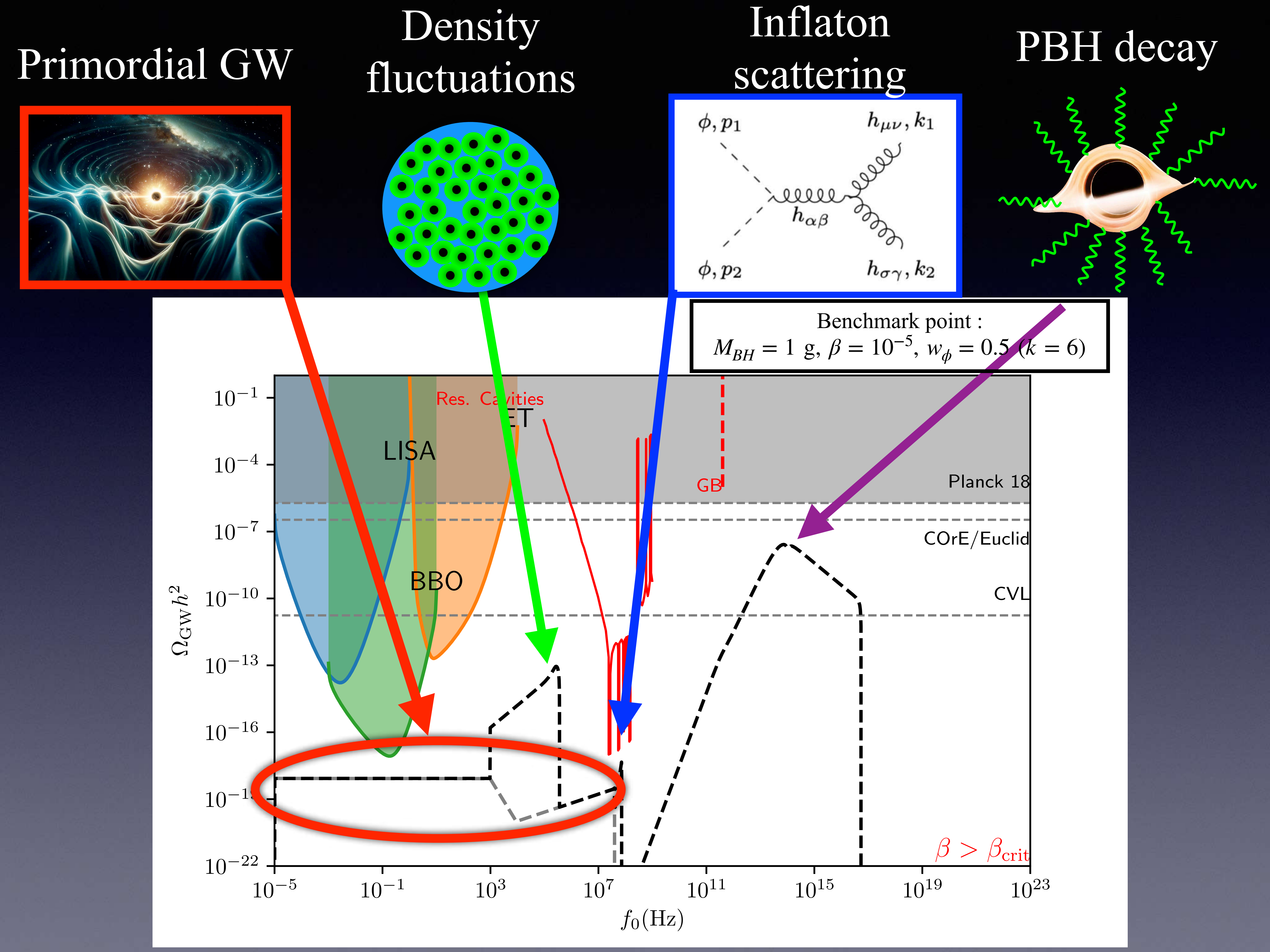




Schwarzschild horizon, $T \sim \frac{1}{R_S} = \frac{M_P^2}{M_{BH}}$

De Sitter horizon, $T = \frac{H_{dS}}{2\pi}$

All the rest is just poetry…



Primordial GW
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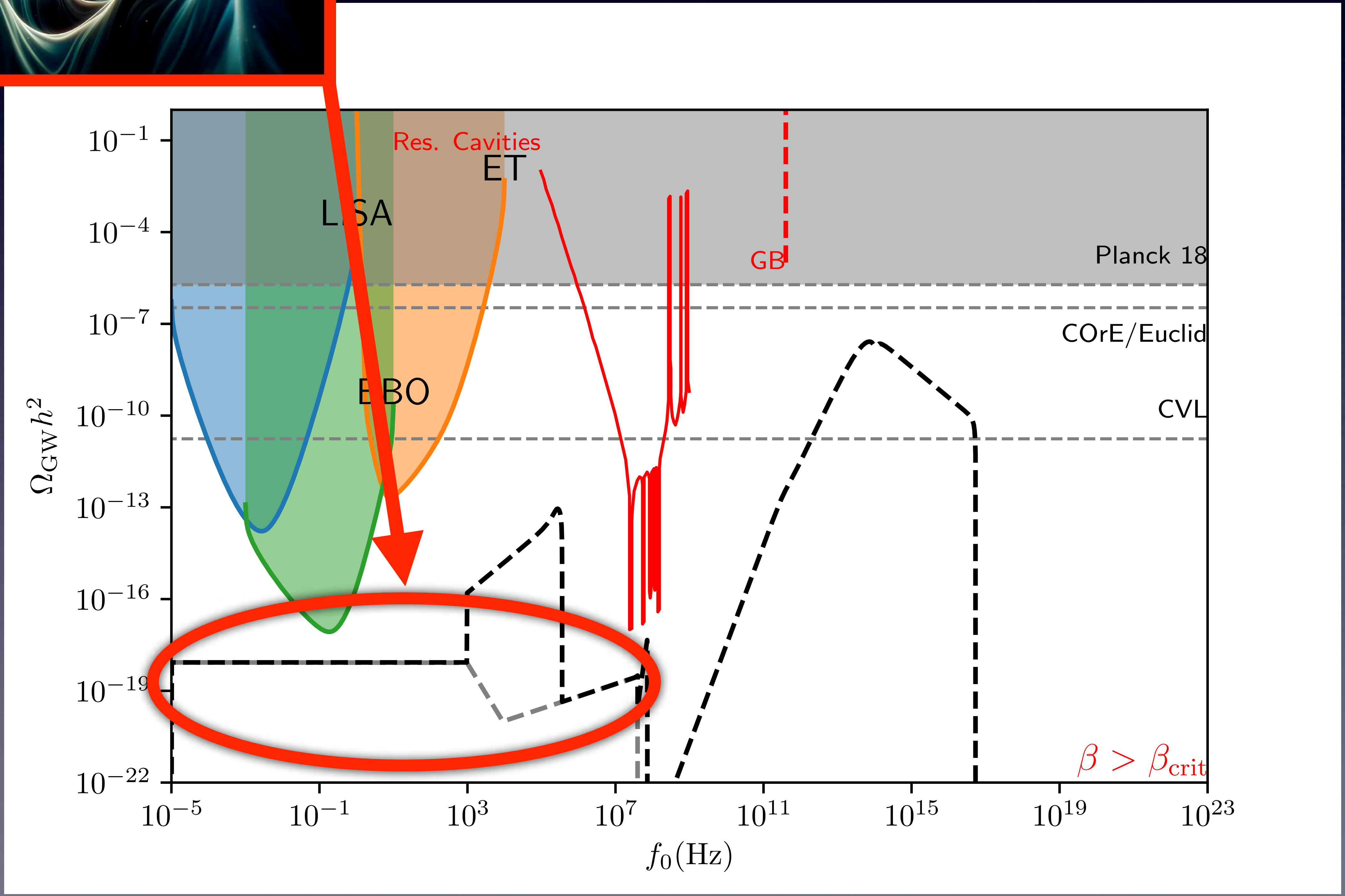
f_0(Hz)

Primordial GW

Primordial GW

Mathieu Gross



Primordial GW : a primer

In the case of a scalar field, $\chi = \int \frac{d^3k}{a(2\pi)^3}[\chi_k(\tau)e^{-ikx}a_k^\dagger + \chi_k(\tau)^\dagger e^{ikx}a_k]$

within the gravitational background, the equation of motion for $\chi_k(\tau)$ (τ being the *conformal* time) is

$$\chi_k'' + (k^2 - \frac{a''}{a})\chi_k = 0 \quad \Rightarrow \quad \chi_k'' + (k^2 - \frac{2}{\tau^2})\chi_k = 0,\ a = -\frac{1}{H\tau},$$

whose solution is $\chi_k(a) \sim \frac{e^{-ik\tau}}{a\sqrt{2k}}\left(1 + i\frac{H}{\frac{k}{a}}\right).$

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Needs acceleration (Schwarzschild or de Sitter)

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Needs acceleration (Schwarzschild or de Sitter)

whose solution is $\chi_k(a) \sim \frac{e^{-ik\tau}}{a\sqrt{2k}}\left(1 + i\frac{H}{\frac{k}{a}}\right).$

One then has on super horizon scale ($\frac{k}{a} \ll H$),

$$|\chi_k(\tau)|^2 \sim \frac{H^2}{2k^3} \quad \Rightarrow \quad \delta\chi^2 = |\chi_k|^2 d^3k = |\chi_k|^2 \frac{k^3}{2\pi^2}\frac{dk}{k} = \left(\frac{H}{2\pi}\right)^2 d\ln k$$

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We then obtain $\dfrac{d\rho_\chi}{d\ln k} = \dfrac{\nabla^2 |\delta\chi|^2}{d\ln k} = k^2 \left(\dfrac{H}{2\pi}\right)^2$

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The treatment for the graviton is the same, considering it as ~ two massless degrees of freedom. We then obtain

$$\Omega_{GW} = \frac{\frac{d\rho_{GW}}{d\ln k}}{\rho_{tot}} = \frac{k^2 H_{\rm end}^2}{12\pi^2 M_P^2 H^2} = \frac{1}{12\pi^2}\left(\frac{H_{\rm end}}{M_P}\right)^2 \frac{k^2}{H^2}$$

$$|\chi_k(\tau)|^2 \sim \frac{H^2}{2k^3} \quad \Rightarrow \quad \delta\chi^2 = |\chi_k|^2 d^3k = |\chi_k|^2 \frac{k^3}{2\pi^2}\frac{dk}{k} = \left(\frac{H}{2\pi}\right)^2 d\ln k$$

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At horizon crossing, $k = H \quad \Rightarrow \quad \dfrac{d\rho_{GW}}{d\ln k} = \dfrac{1}{12\pi^2}\left(\dfrac{H_{\rm end}}{M_P}\right)^2 \rho_{tot} \simeq 10^{-14}\rho_{tot}$

PGW are modes which *exited the horizon* during inflation :

$$\chi_k(a) \sim \frac{e^{-ik\tau}}{a\sqrt{2k}}\left(1 + i\frac{H}{\frac{k}{a}}\right)$$

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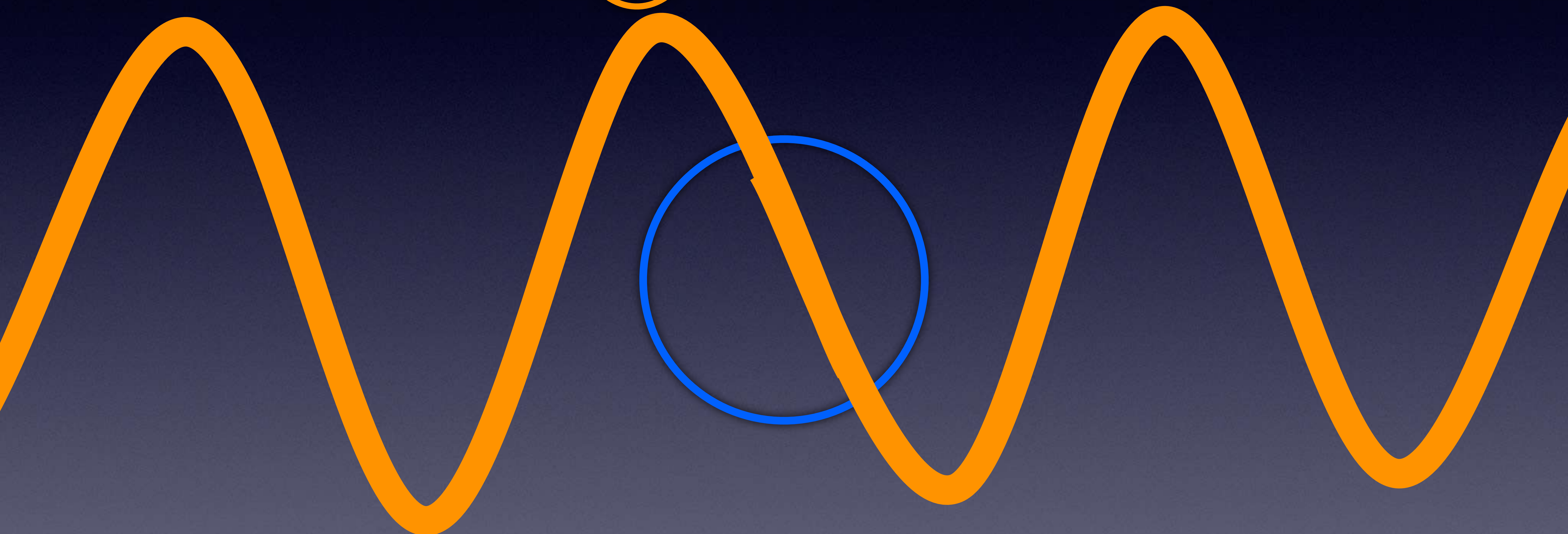

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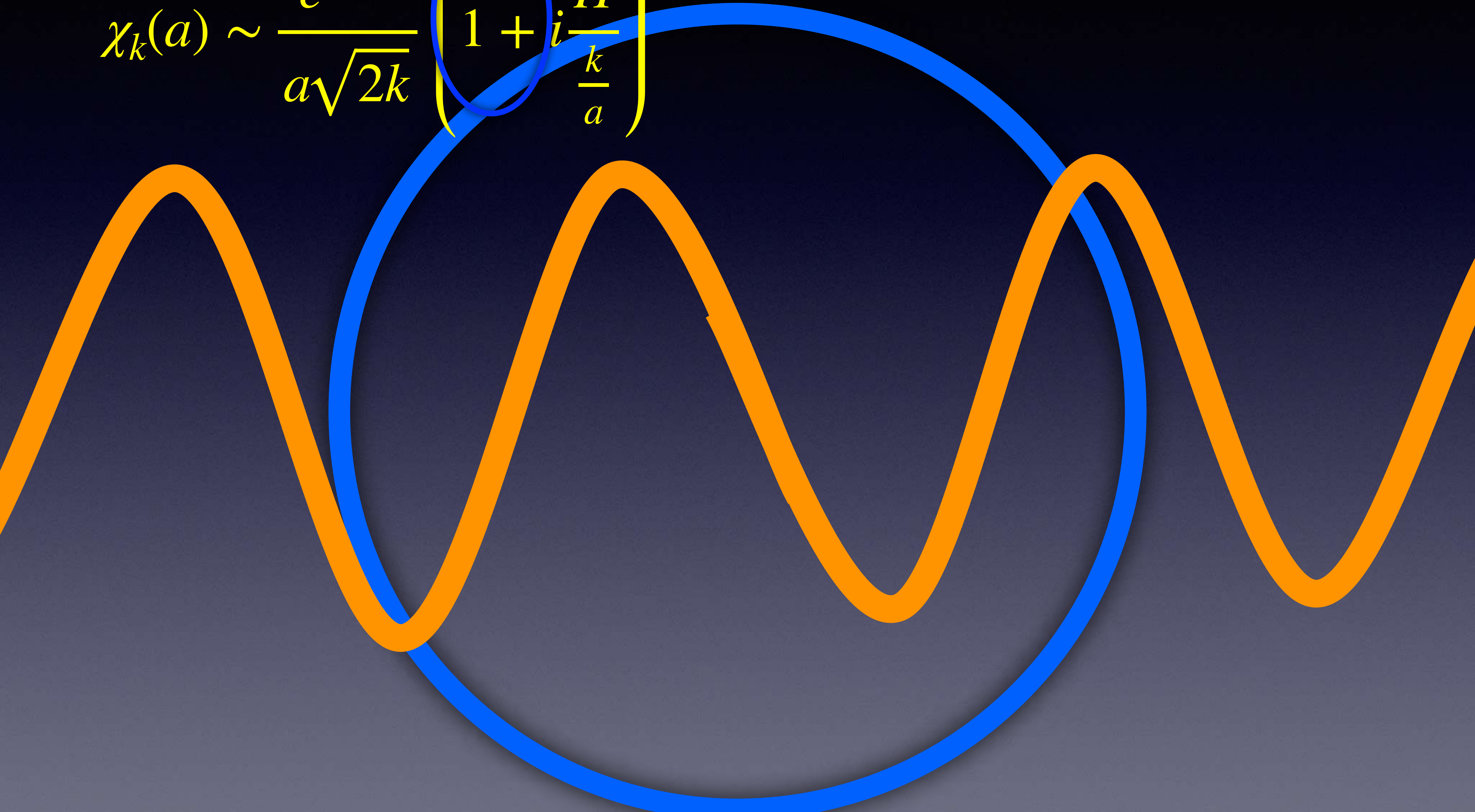

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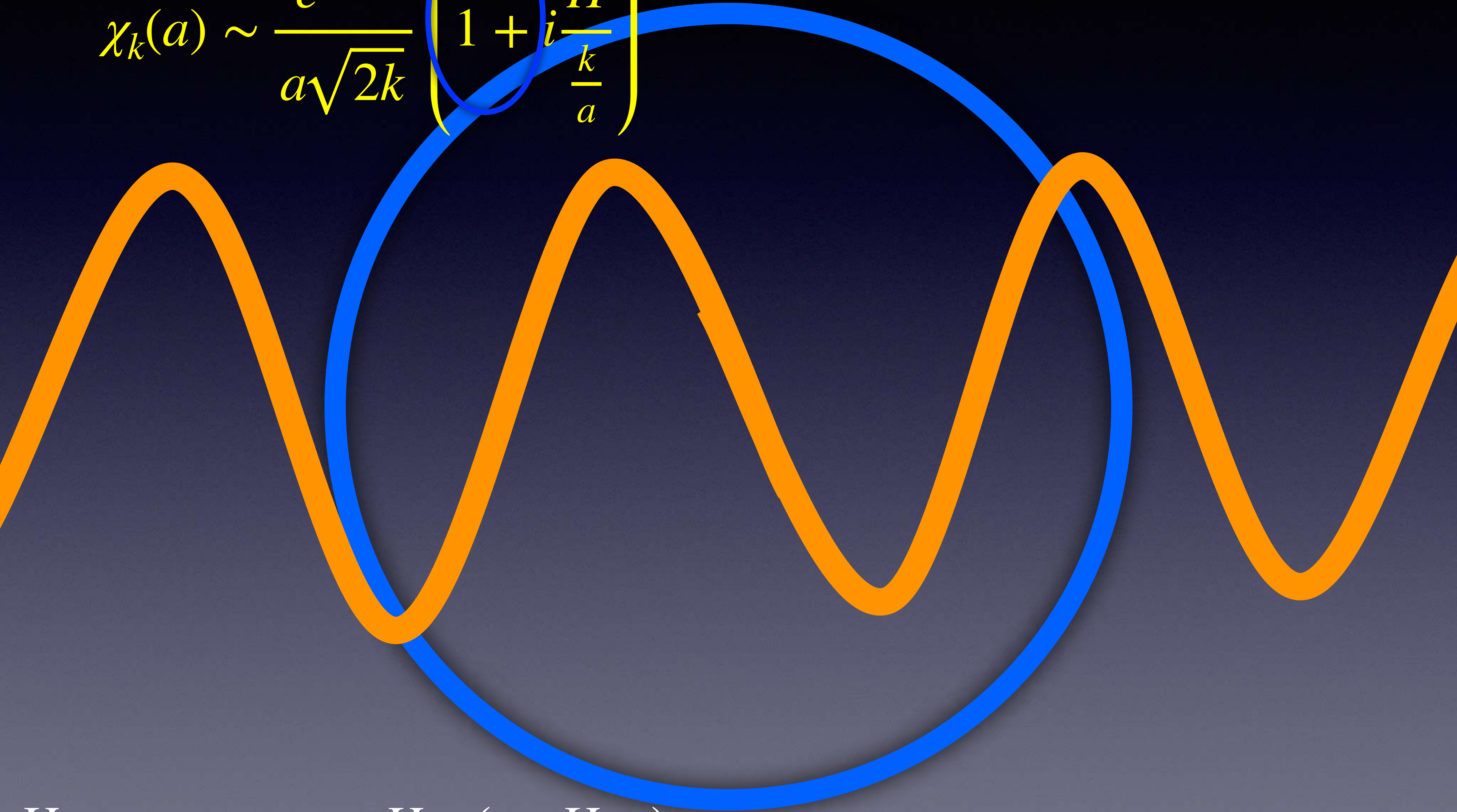

$H_{horizon\ crossing} = H_{hc}\ (< H_{\mathrm{end}})$ Frozen fluctuations → oscillating particles

Primordial GW with PBH and ϕ

$a < a_{\rm hc}$

$a = a_{\rm hc}$

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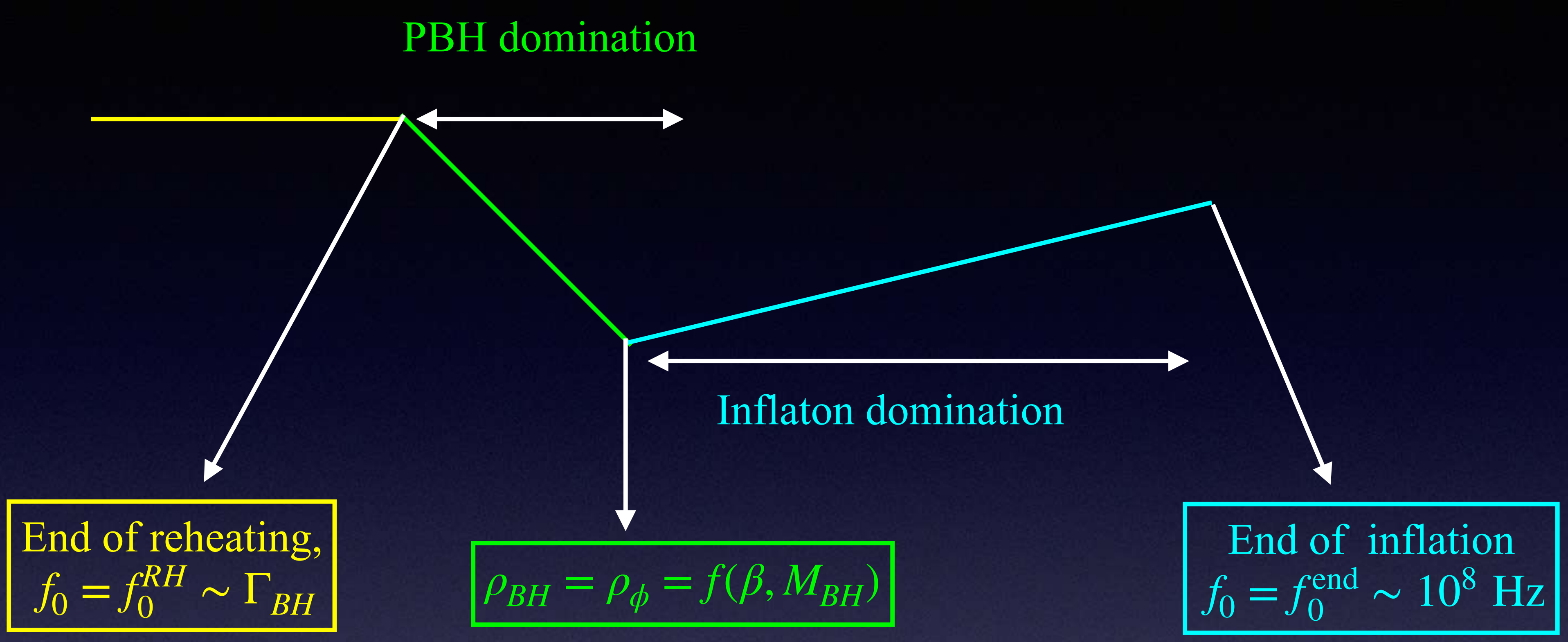
Inflaton domination ($w_\phi = \frac{1}{2}$, $V(\phi) \sim \phi^6$)

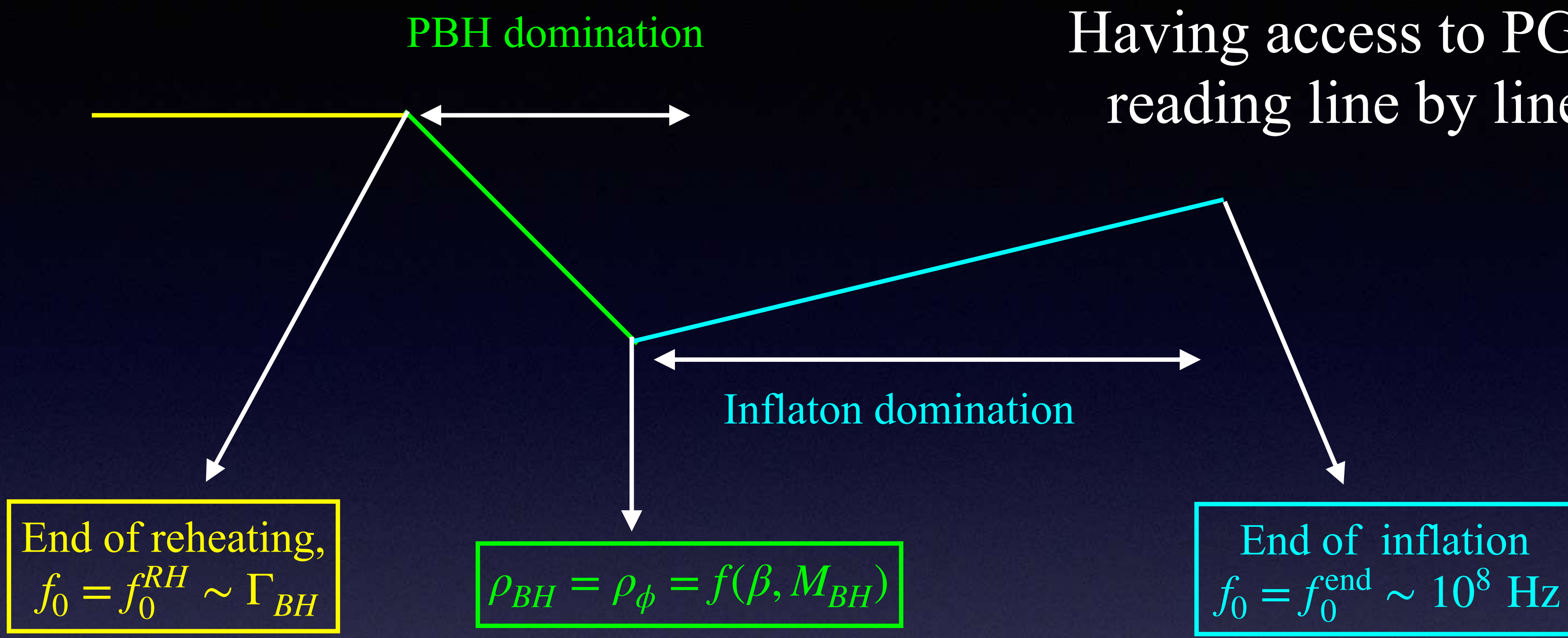
$$\Omega_{GW} \sim 10^{-18}\left(\frac{f_0}{10^5\ {\rm Hz}}\right)^{\frac{2}{5}}$$

Primordial GW with PBH and ϕ



Primordial GW with PBH and ϕ

Having access to PGW spectrum is literally reading line by line the pre-BBN history



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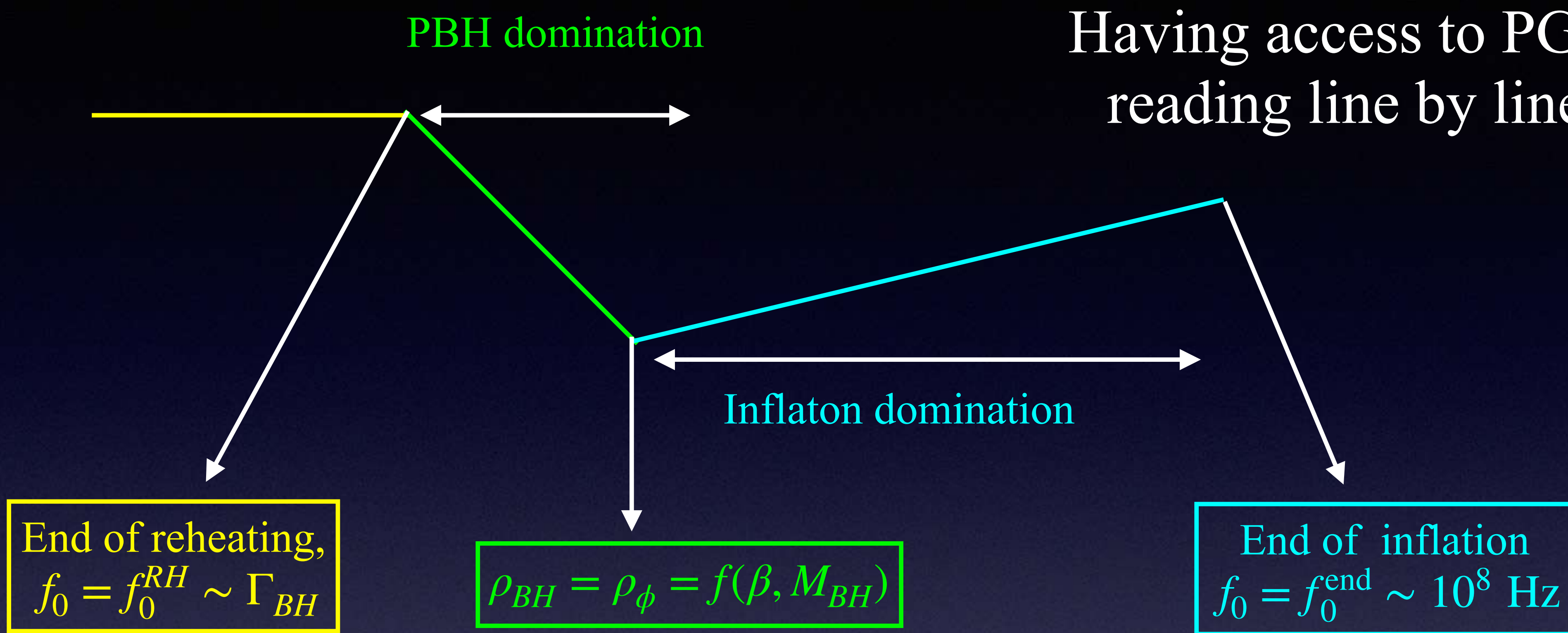
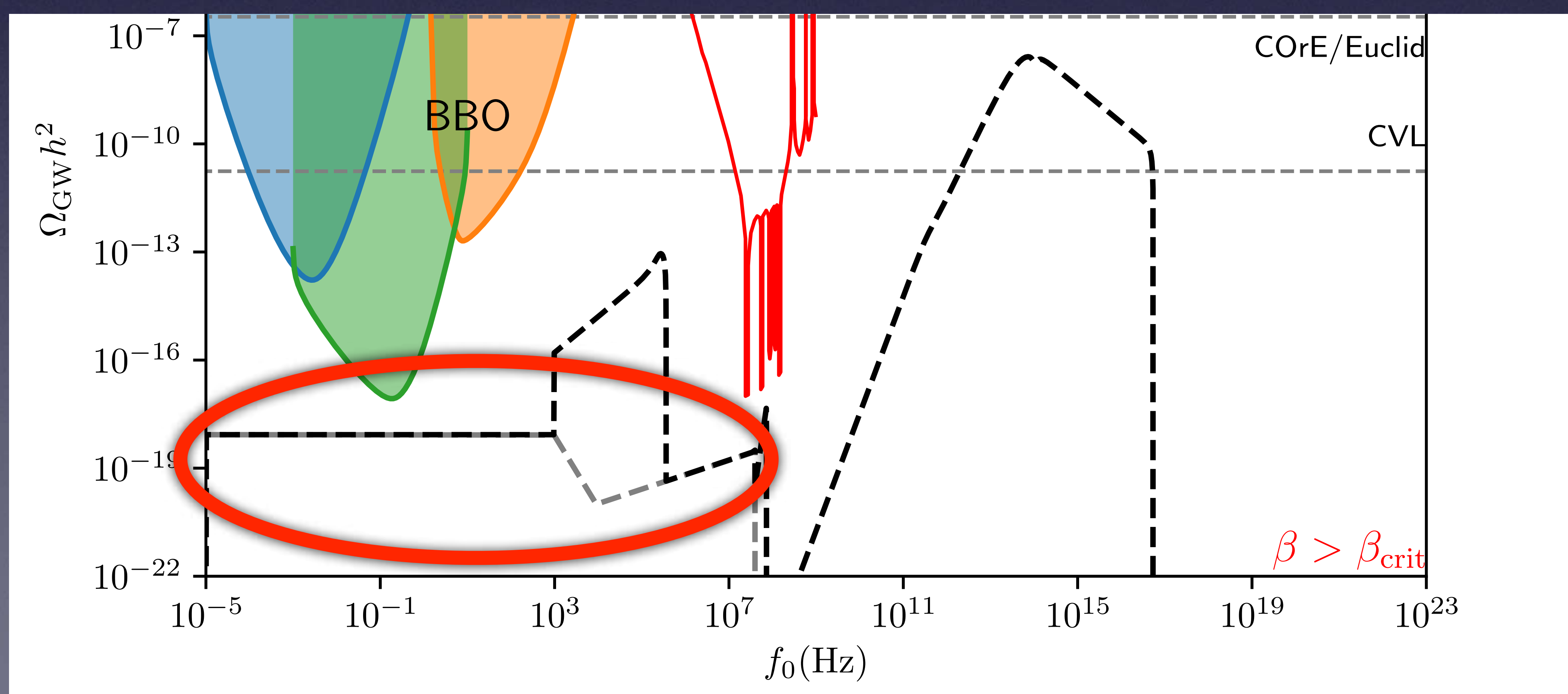
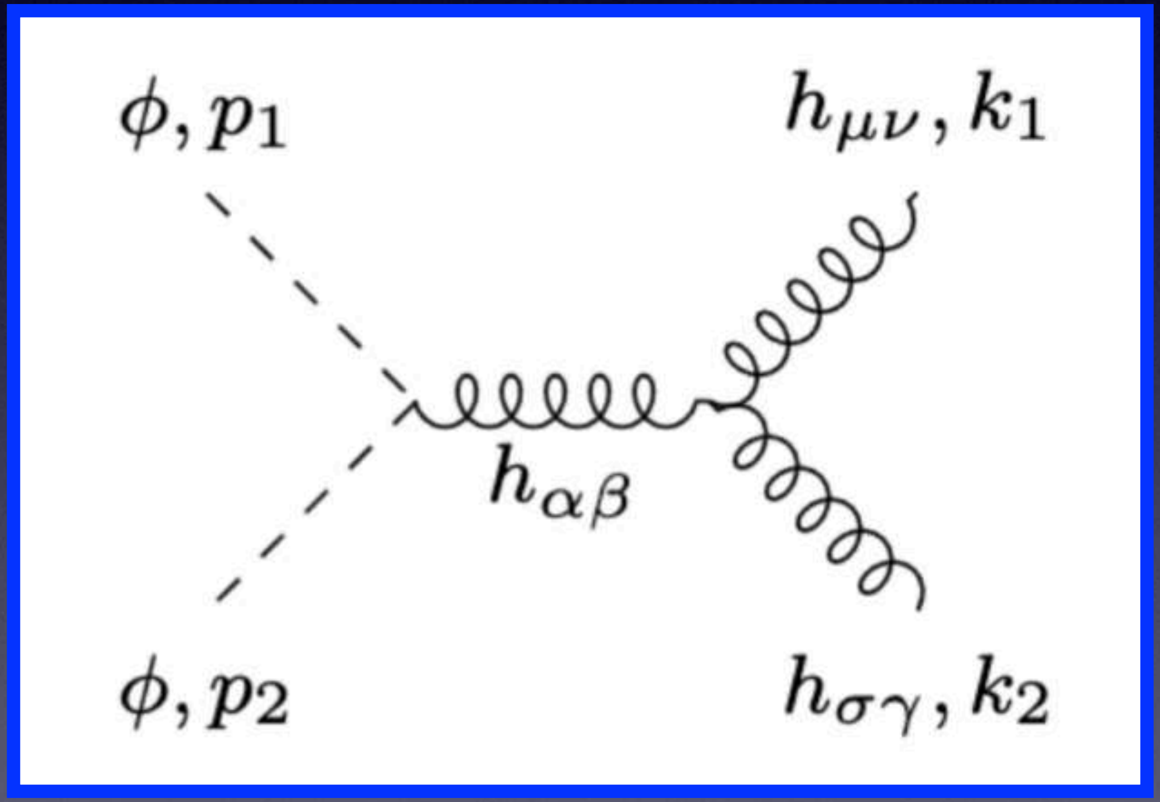




GW from inflaton scattering



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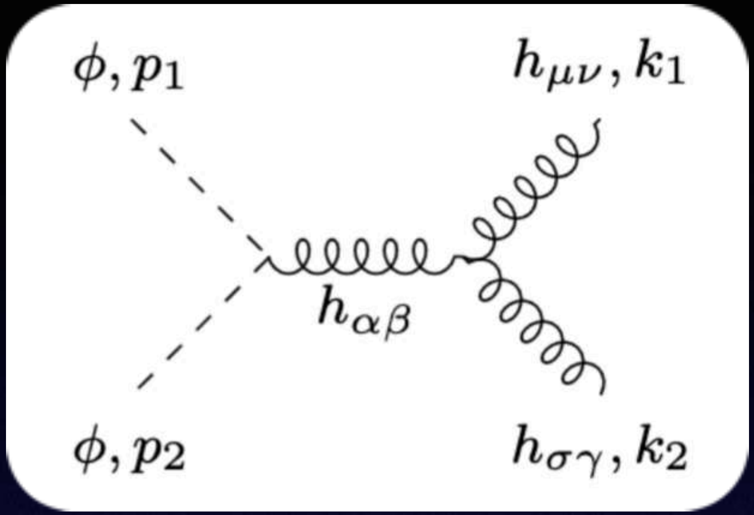

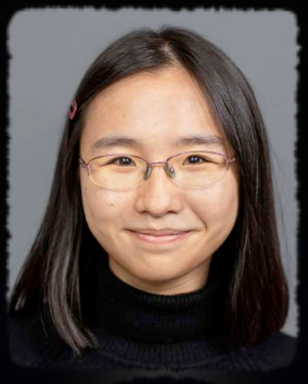

Gyonju Choi

Wenqi Ke

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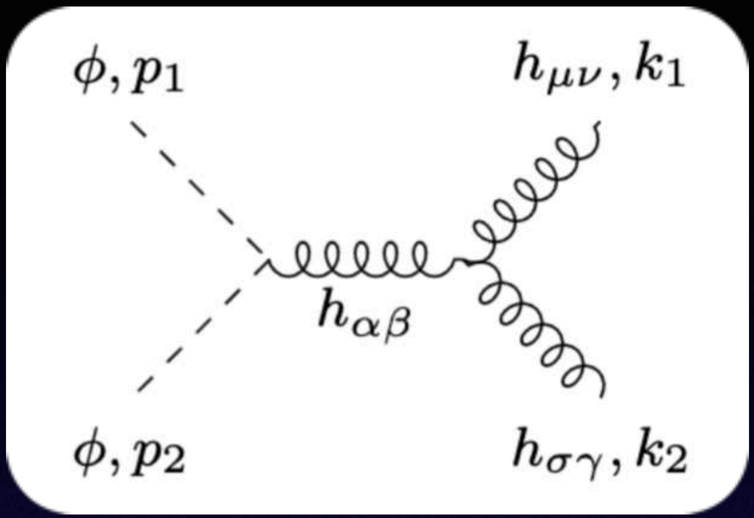

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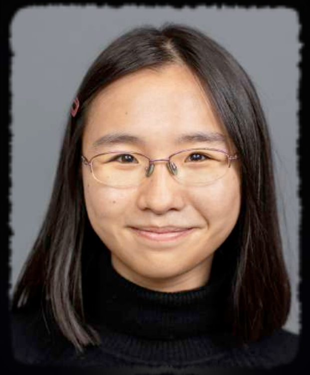

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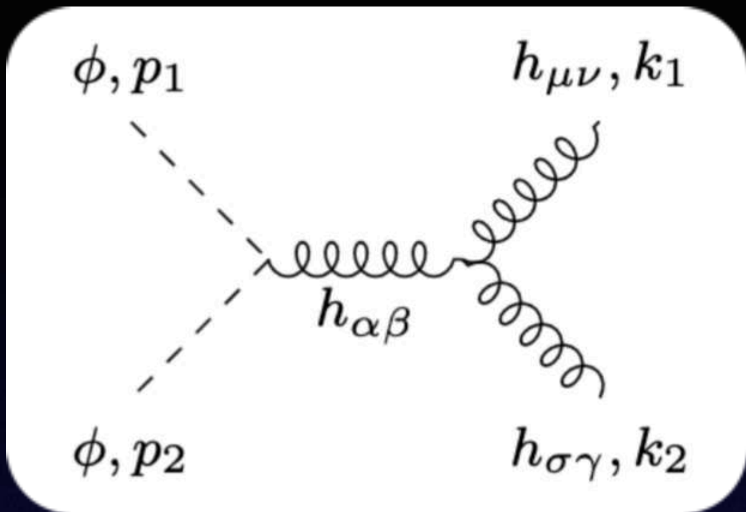

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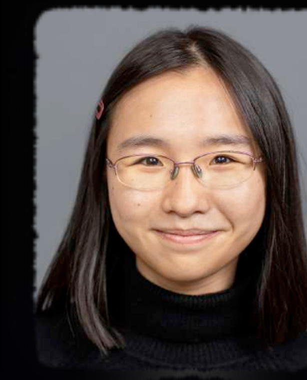

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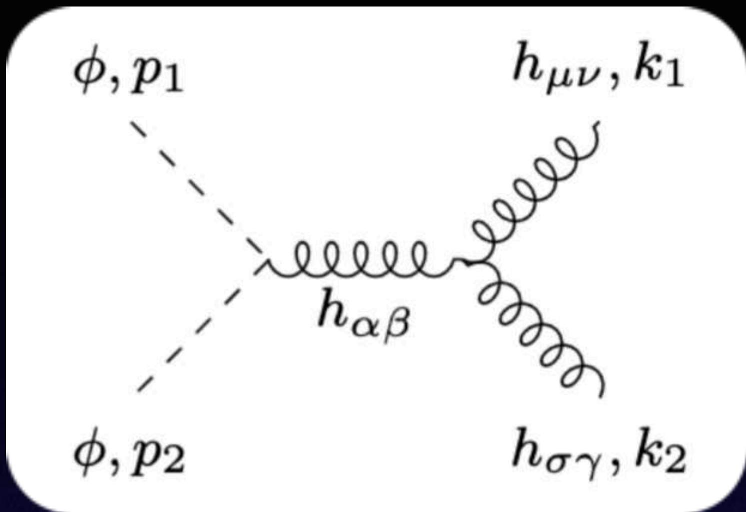

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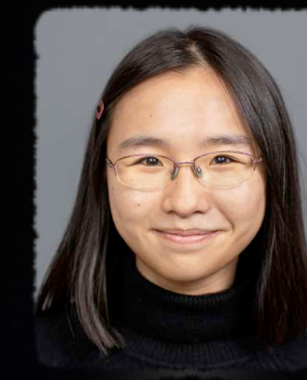

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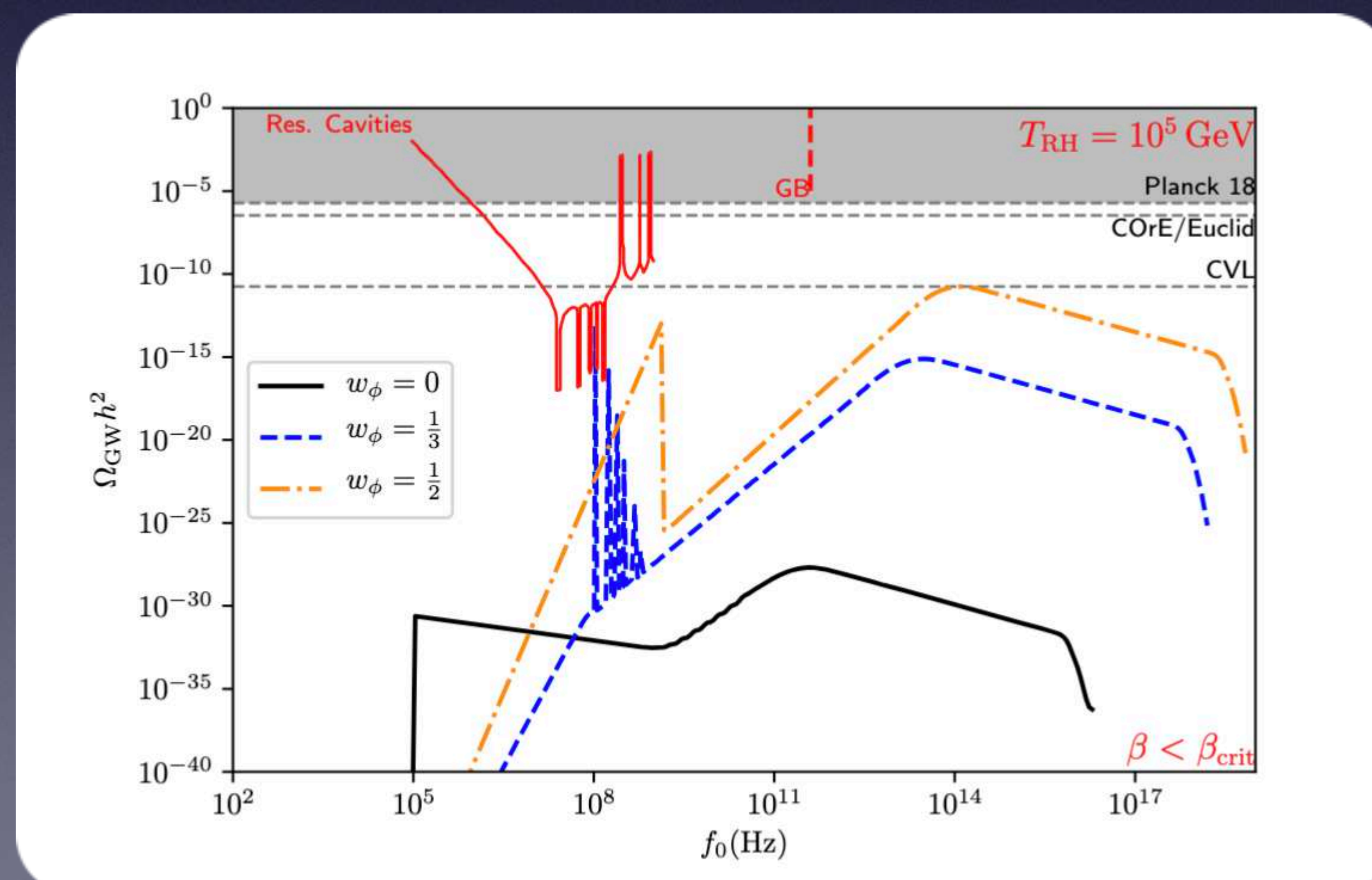

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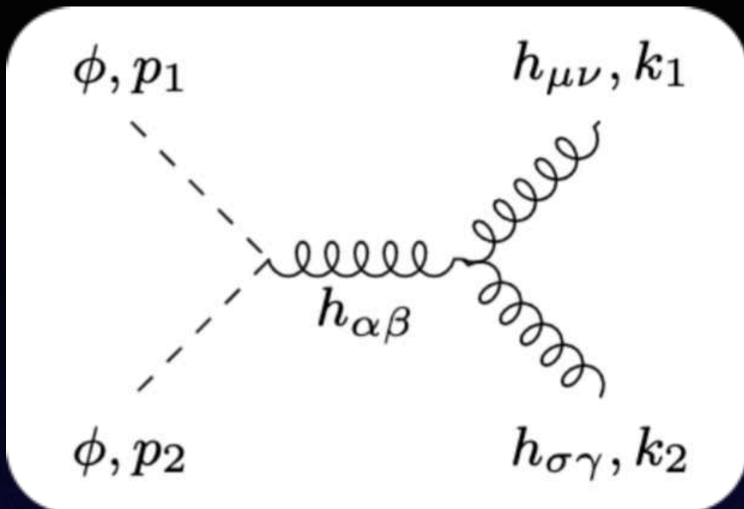

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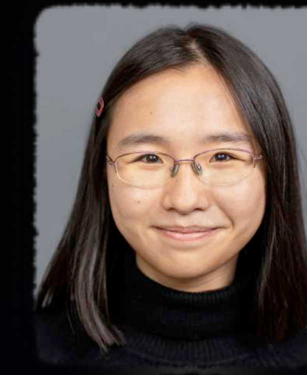

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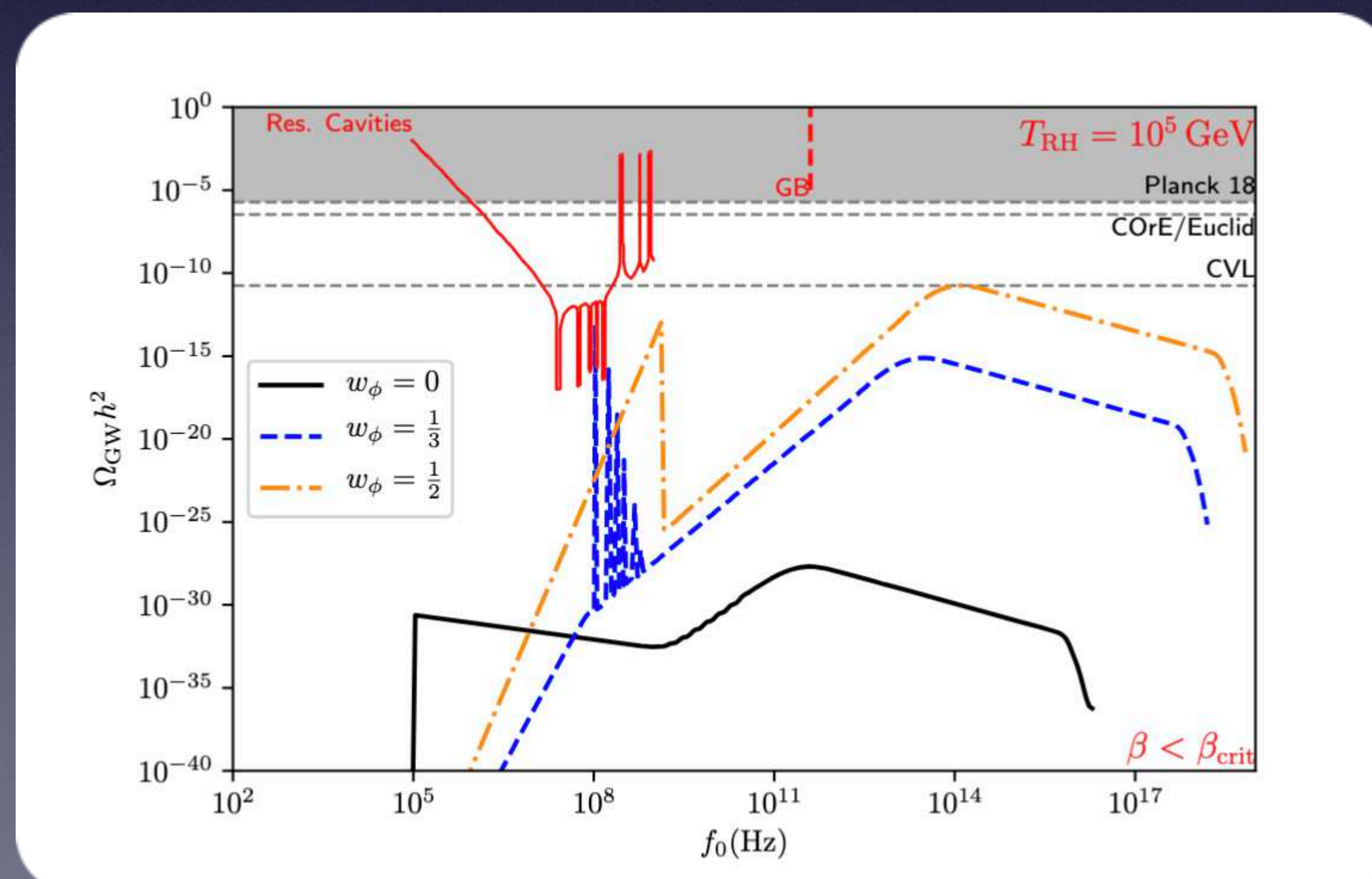
The PBHs would influence the spectrum from

$$\rho_{RH} = \alpha T_{RH}^4 = \frac{4}{3}\Gamma_{BH}^2 M_P^2$$



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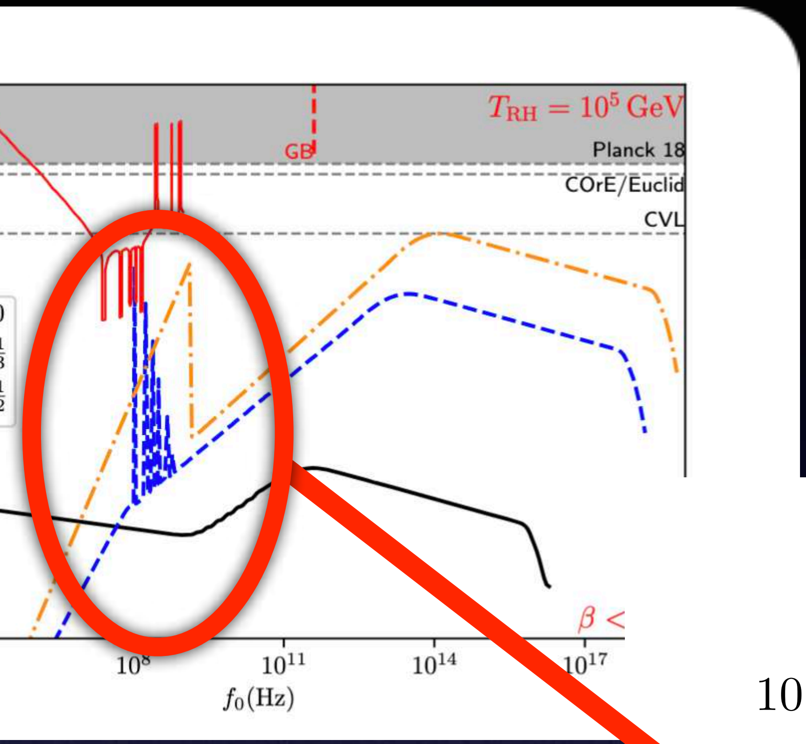

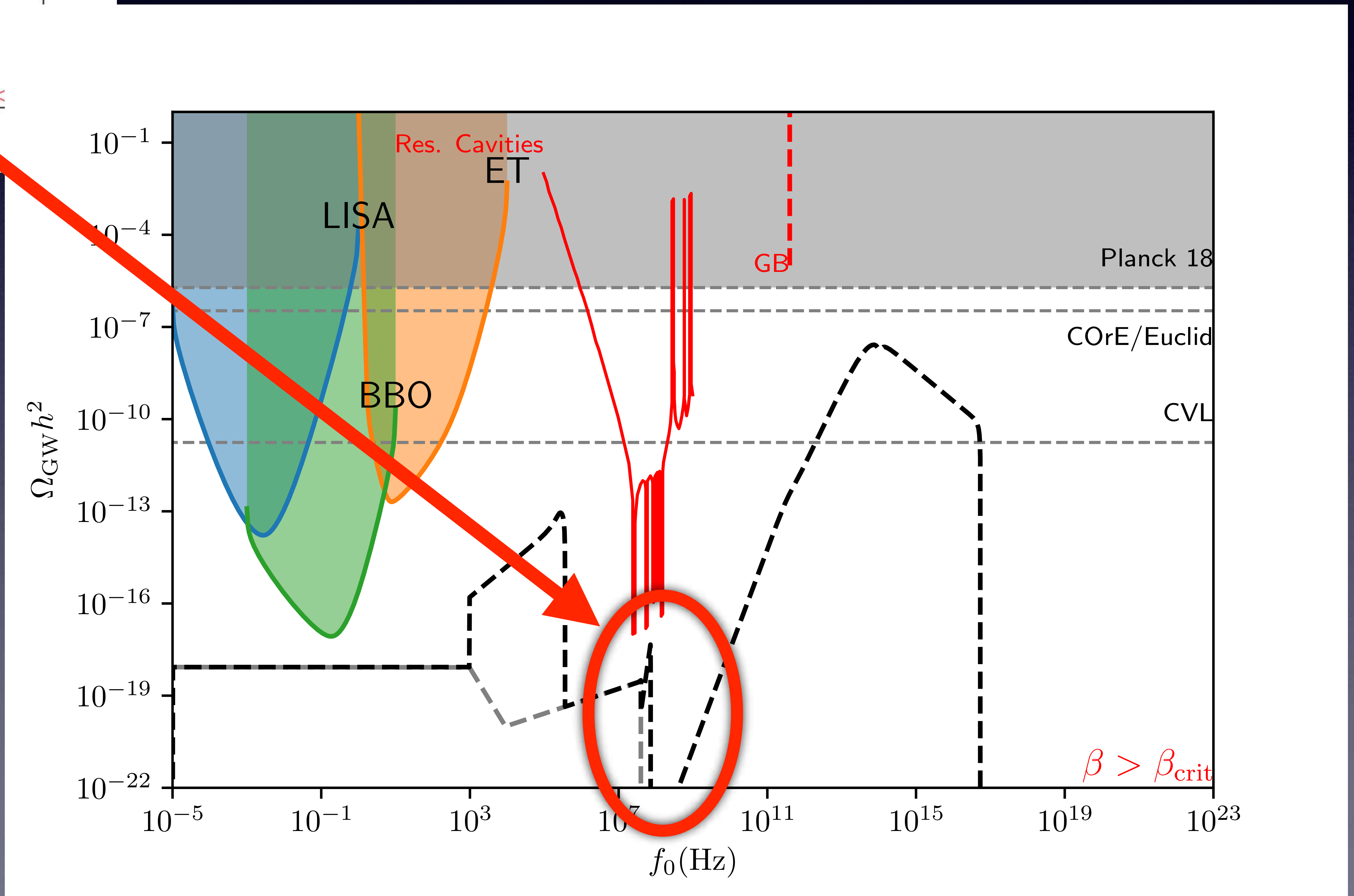

Aparté : the Boltzmann-Bogoliubov fight

Simon Clery

The Bogoliubov approach

$$\chi(\eta, \vec{x}) = \int \frac{d^3\vec{k}}{(2\pi)^{3/2} a} X_{\vec{k}}(\eta)\, e^{i\vec{k}.\vec{x}},$$

$$X''_{\vec{k}} + \underbrace{\left[k^2 + a^2 m_\chi^2 + \frac{a^2 R}{6}\right]}_{\omega_k^2} X_{\vec{k}} = 0$$

ω_k^2

can be negative if the

Ricci $R = -6\frac{a''}{a^3}$ is negative

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$$n_k = |\beta_{\vec{k}}|^2 = \frac{1}{2\omega_k}|\omega_k X_{\vec{k}} - i X'_{\vec{k}}|^2$$

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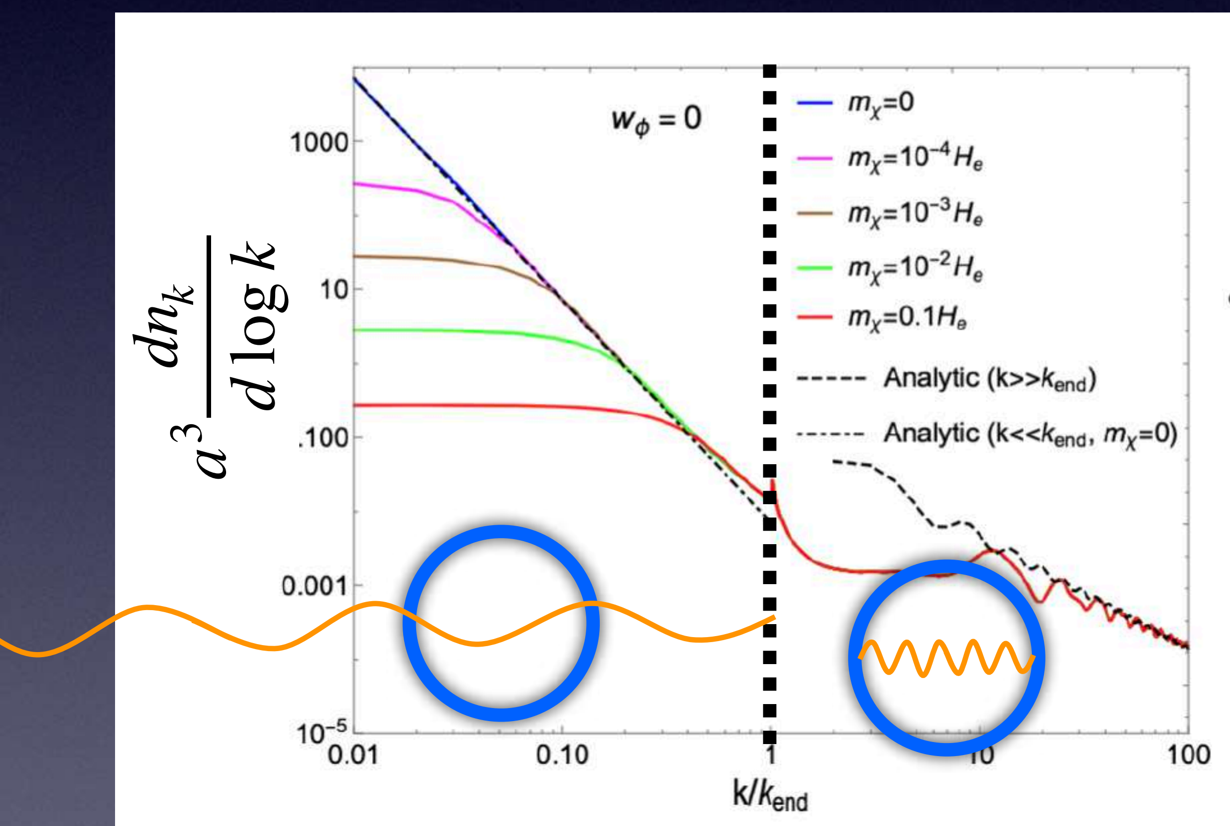

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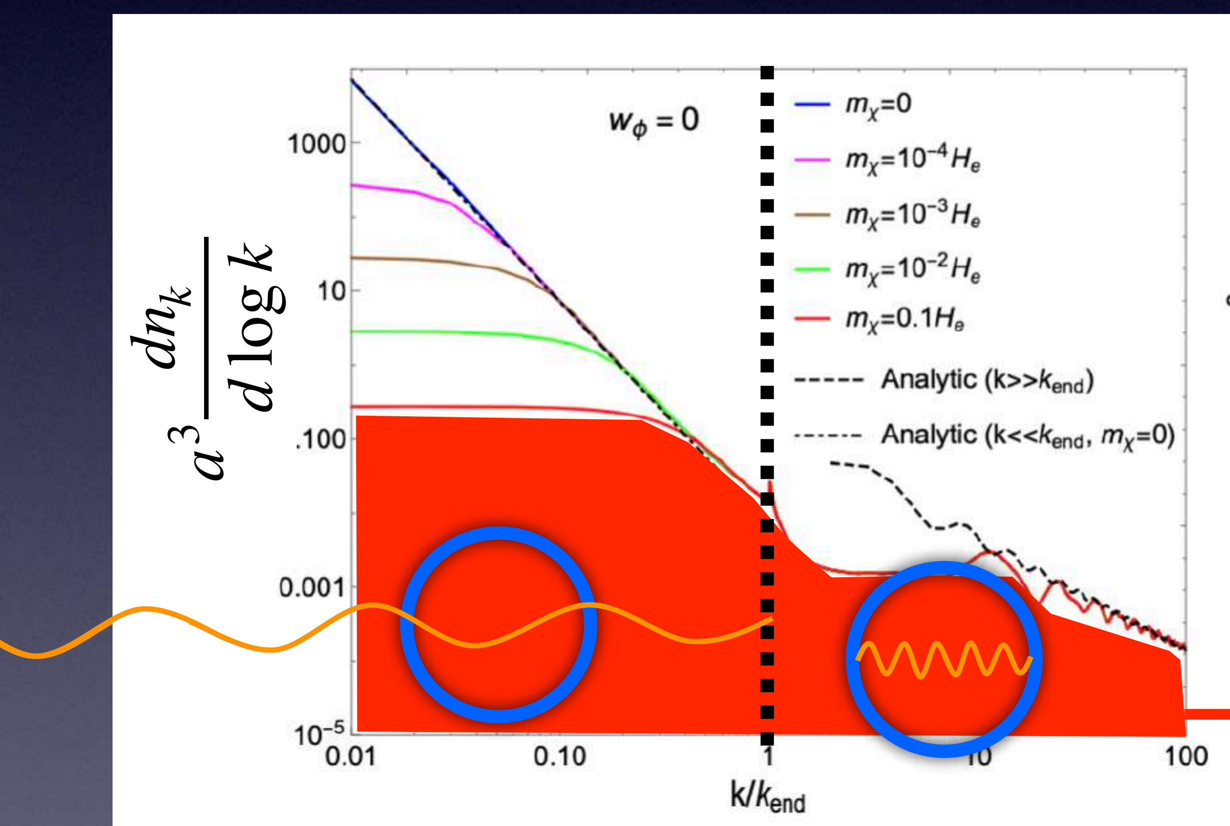

$$\rho \sim T_{dS}^4 \sim \frac{H^4}{16\pi^4}$$

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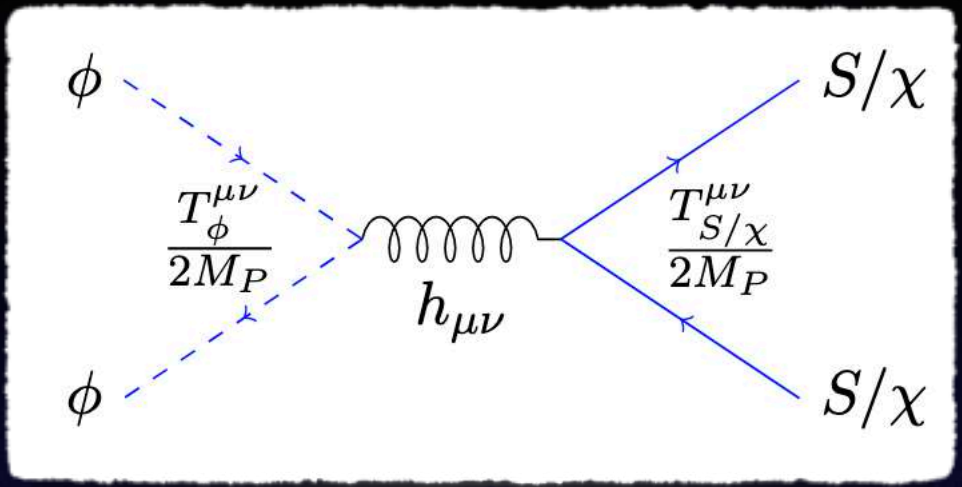
The Boltzmann approach



Boltzmann would have calculated the number density, solving the equation

$$\frac{dn_\chi}{dt} + 3H(t)\, n_\chi = R(t)$$

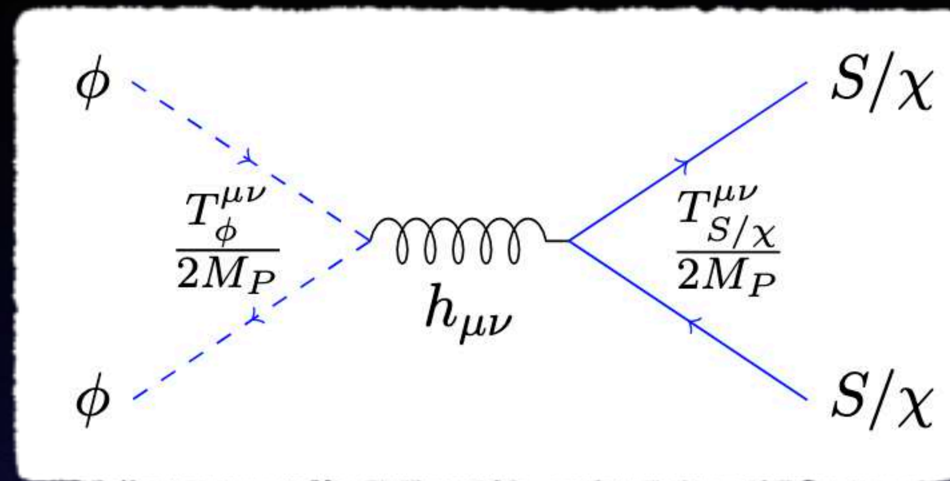
with

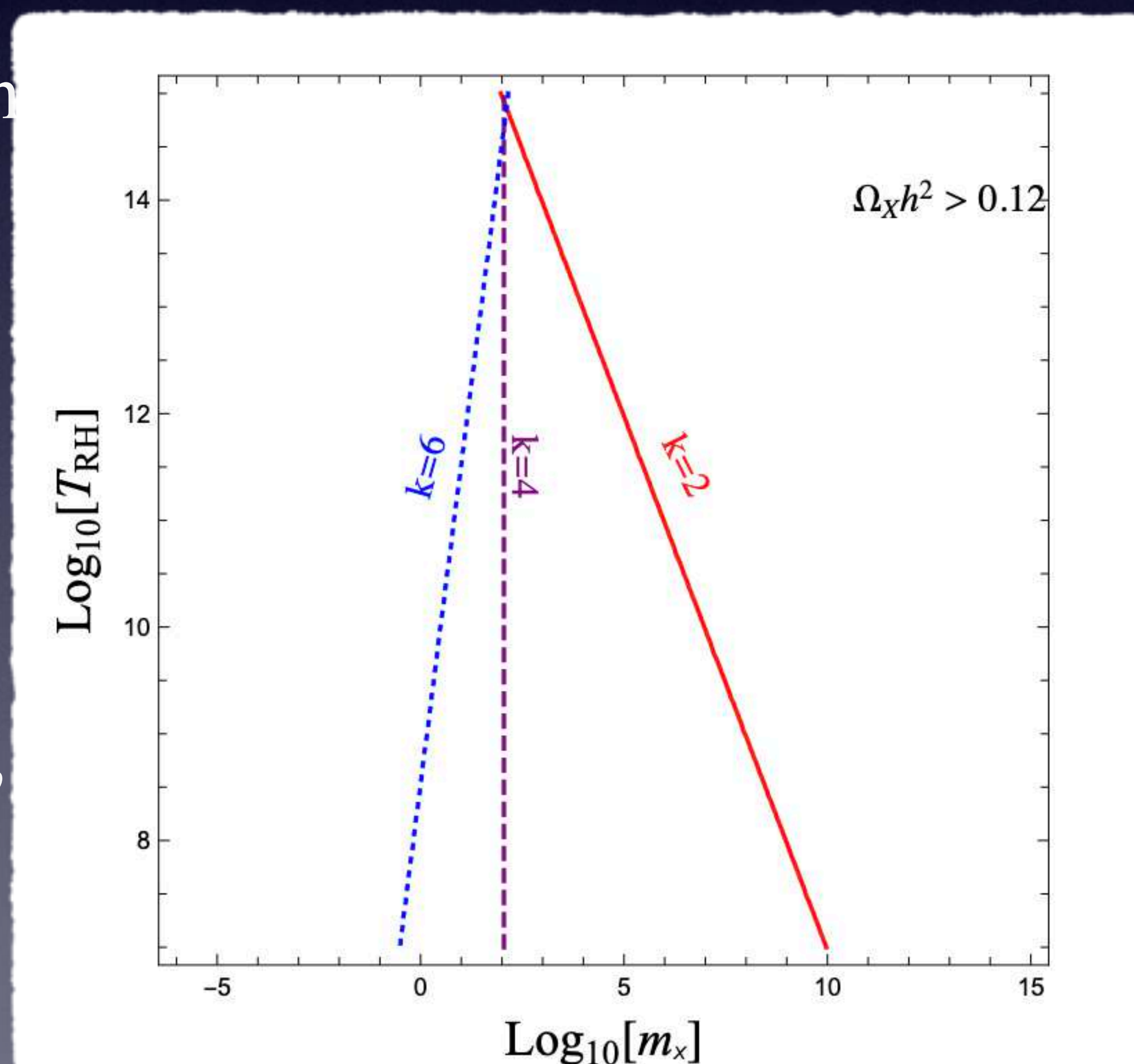
$$R(t) \sim n_\phi^2 \times \sigma_{\phi\phi\to\chi\chi}\, v \sim \left(\frac{\rho_\phi}{m_\phi}\right)^2 \times \frac{|\mathscr{M}_{\phi\phi\to\chi\chi}|^2}{8\pi m_\phi^2},$$

ρ_ϕ obtained from the Friedmann equation

$$H^2 = \frac{\rho_\phi^2}{3M_P^2}$$

The Boltzmann approach



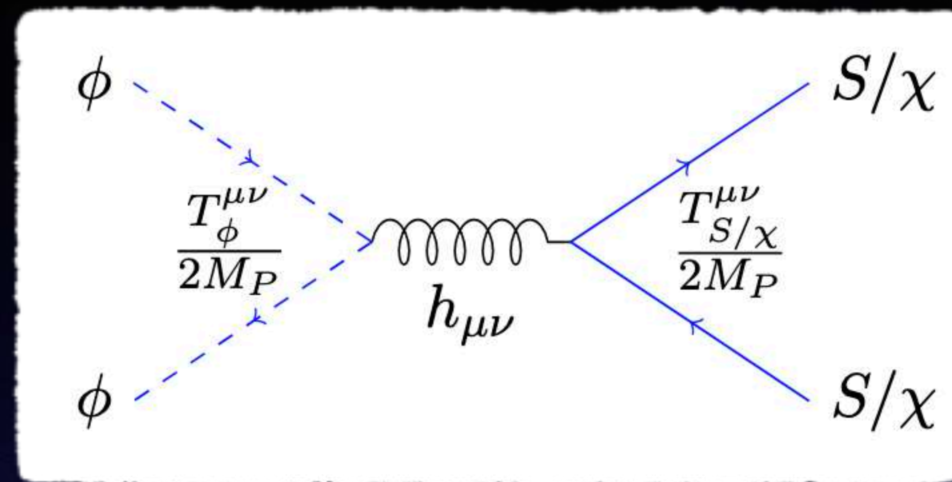


Boltzmann would h … olving the equation

$R(t) \sim$ … $\frac{\ldots_{\to\chi\chi}|^2}{\ldots m_\phi^2}$,

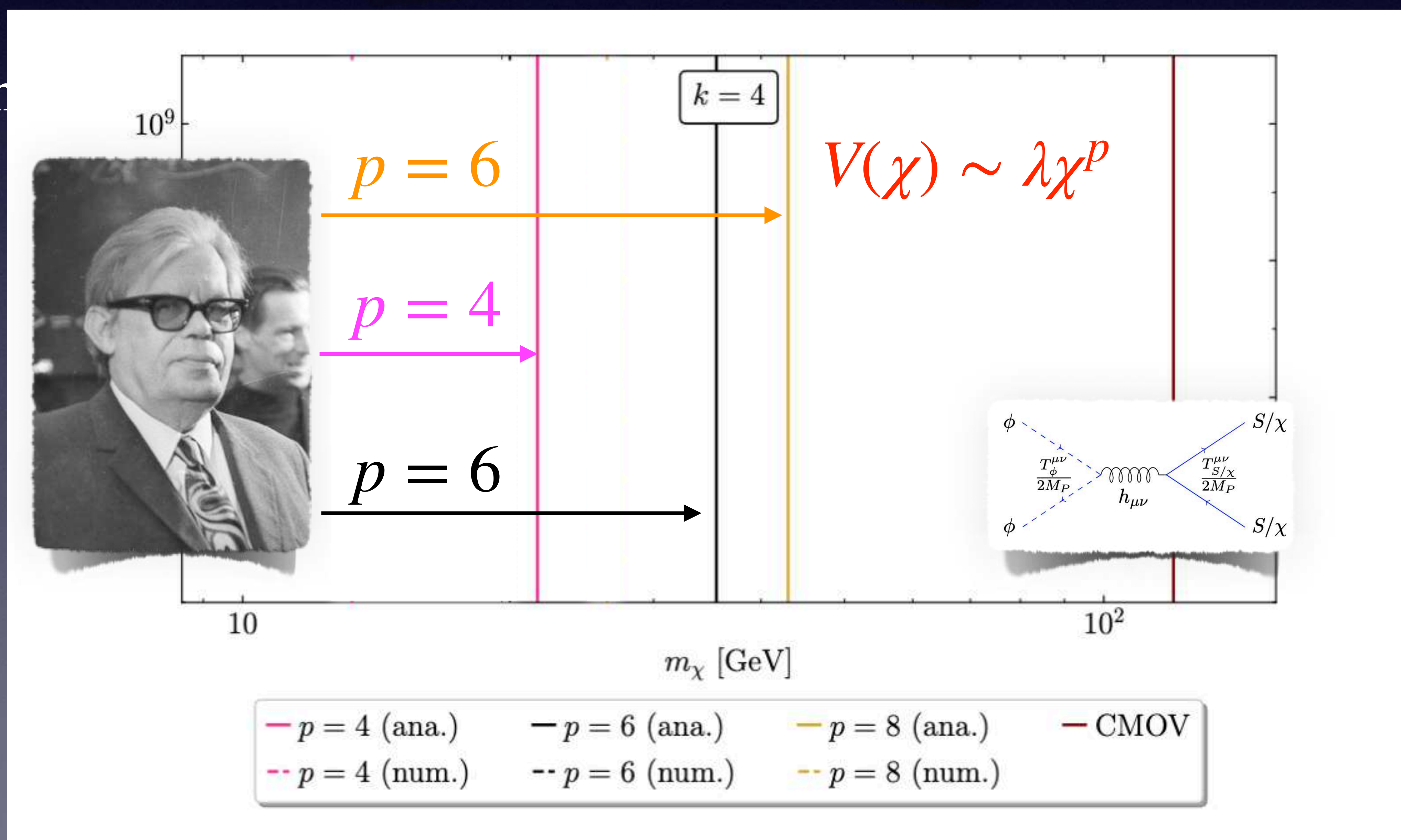
ρ_ϕ … on

The Boltzmann approach



Boltzman

uation



The Boltzmann approach

Boltz

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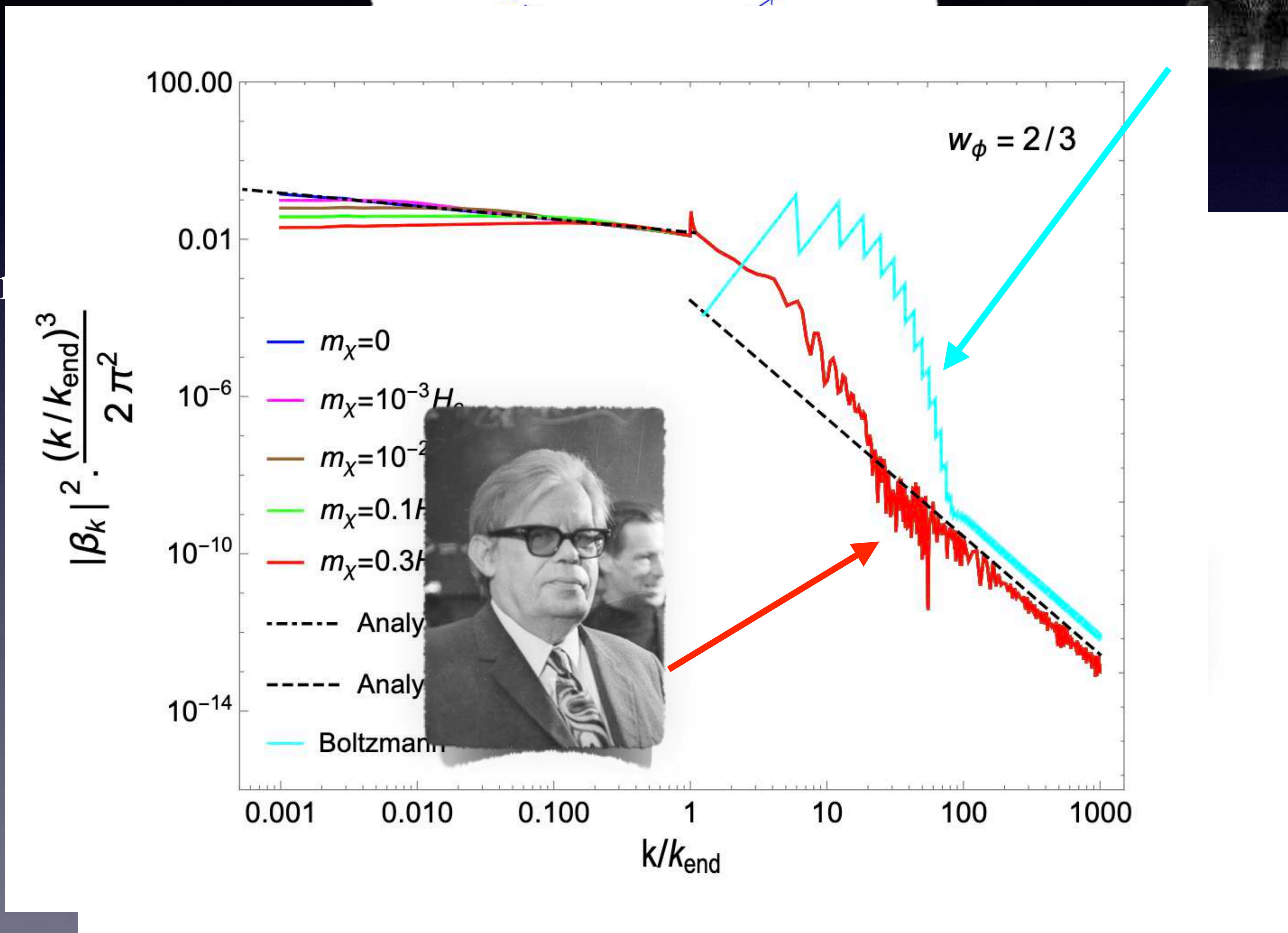

Equivalence for modes *inside* the horizon

⇔

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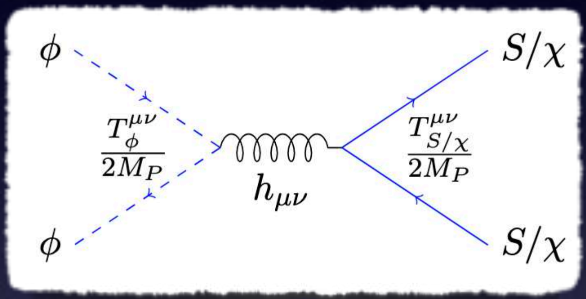
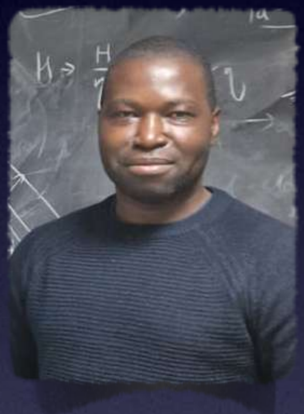
⇔



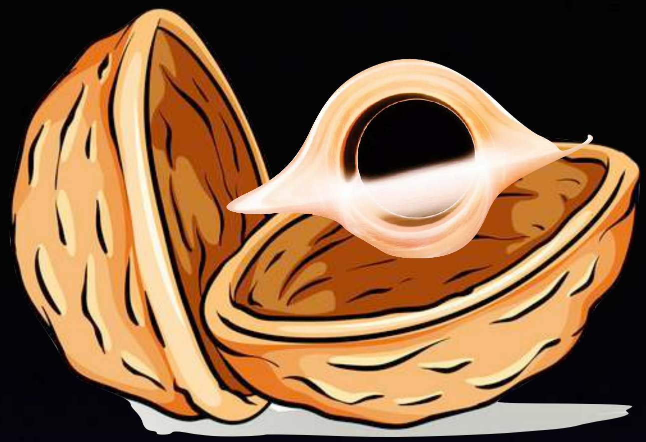
Primordial Black Holes as *source* of GW

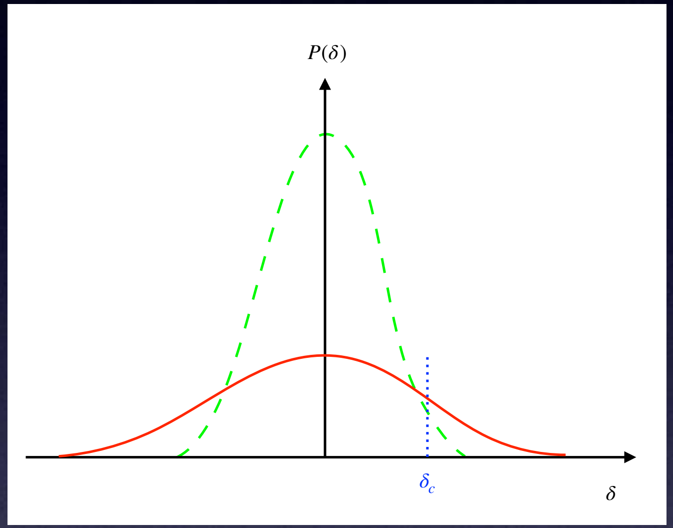
Mathieu Gross



Donald Kpatcha

PBH in a nutshell

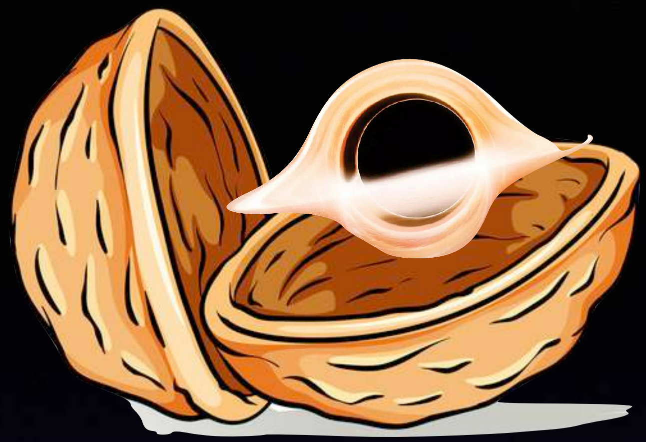


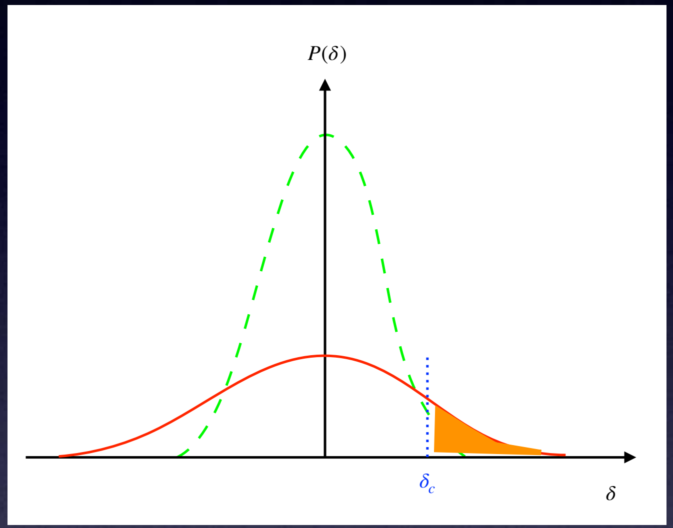


A Black hole can be formed in regions where there is an over density

$$\frac{\delta\rho}{\rho} \gtrsim \delta_c, \text{ with } \delta_c \simeq 1.$$

PBH in a nutshell





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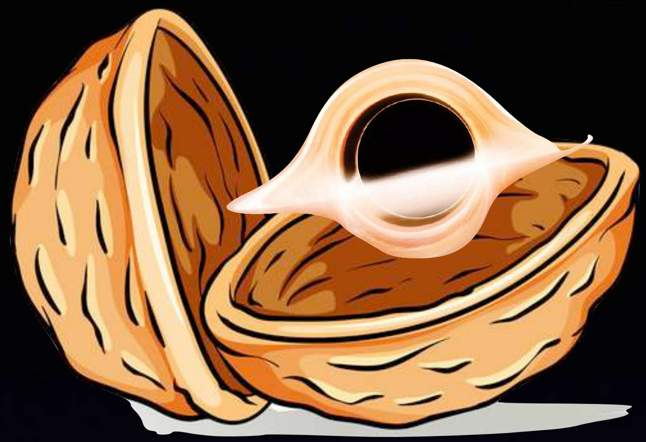
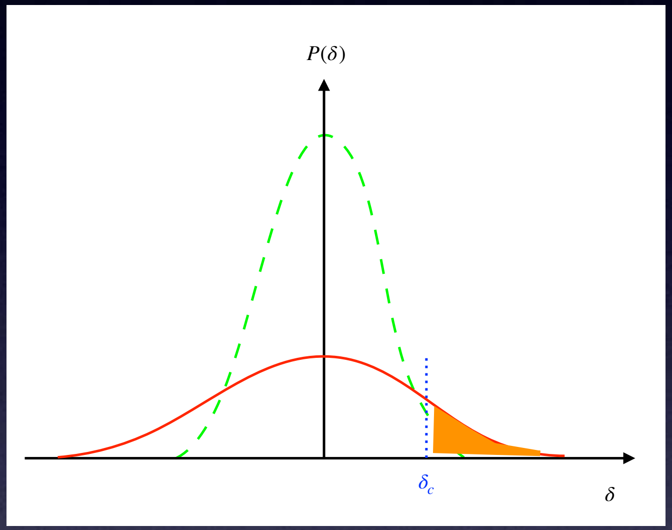
The fraction

$$\beta = \frac{\rho_{\rm BH}}{\rho_{tot}} \sim \int_{\delta_c}^{\infty} P(\delta) d\delta$$

PBH in a nutshell





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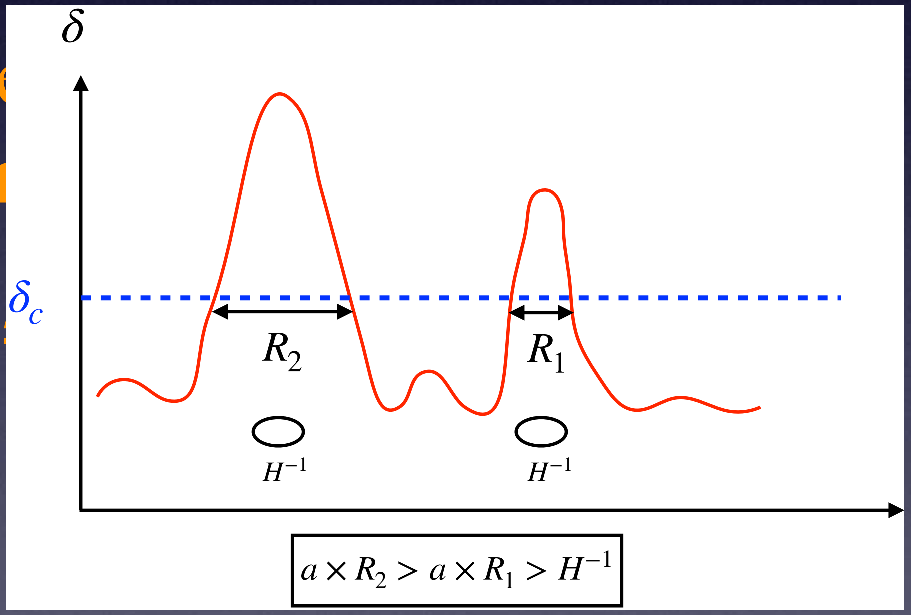

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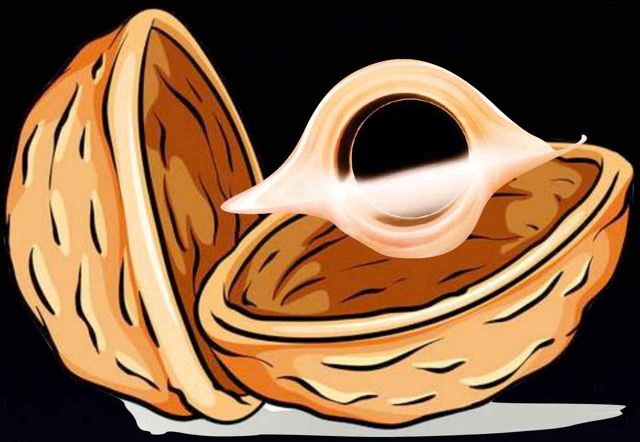
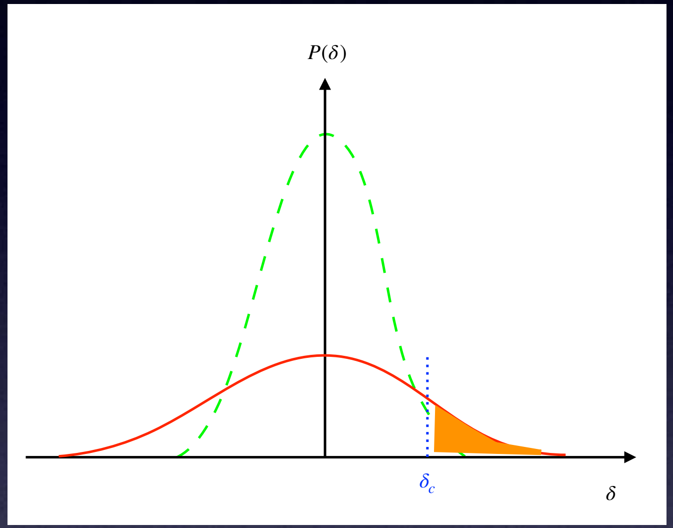
PBH in a nutshell





A Black hole can be forme

where there is an over

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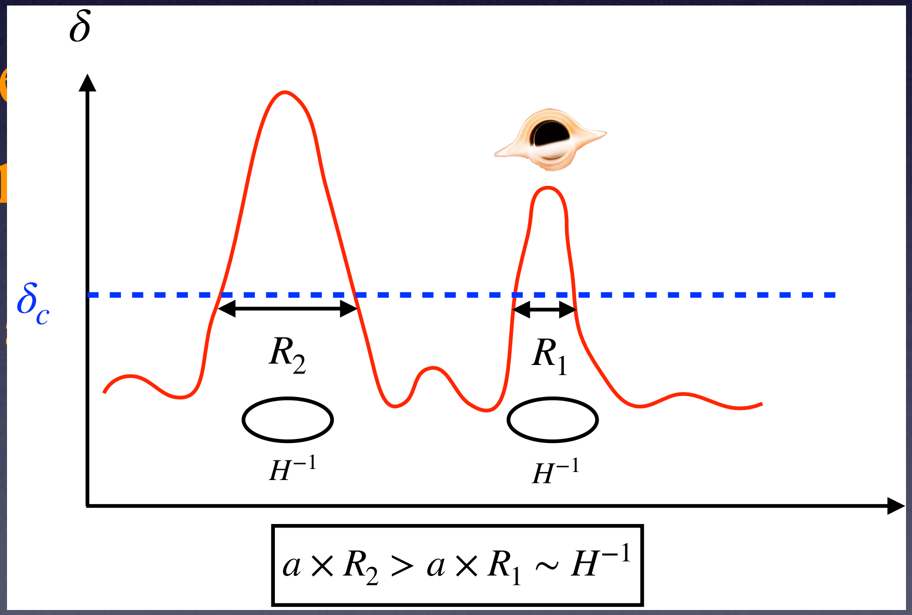

The fraction

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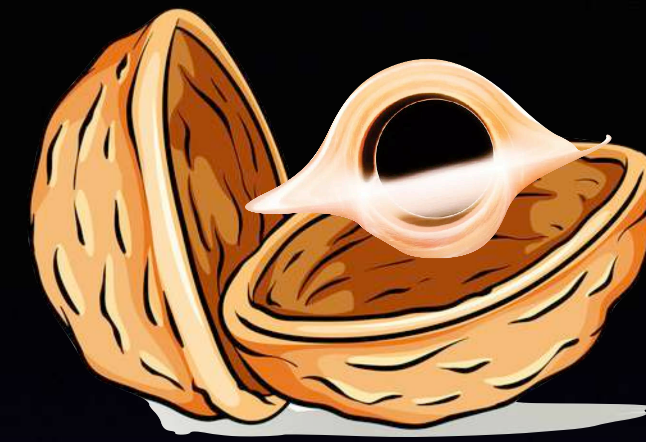

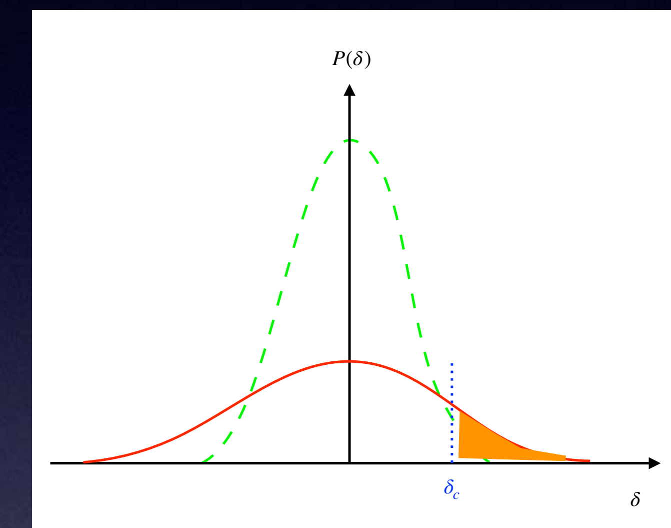

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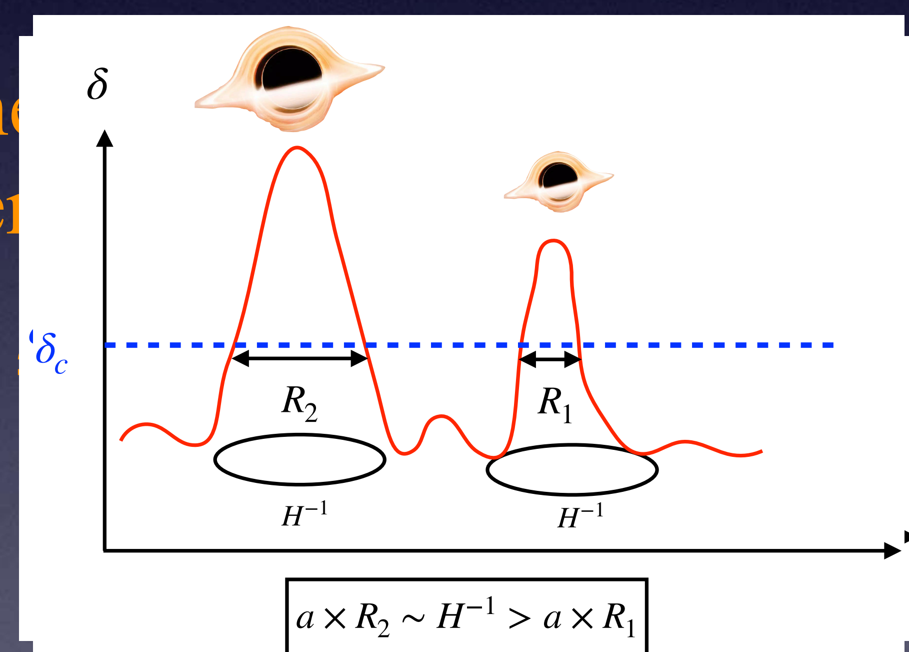

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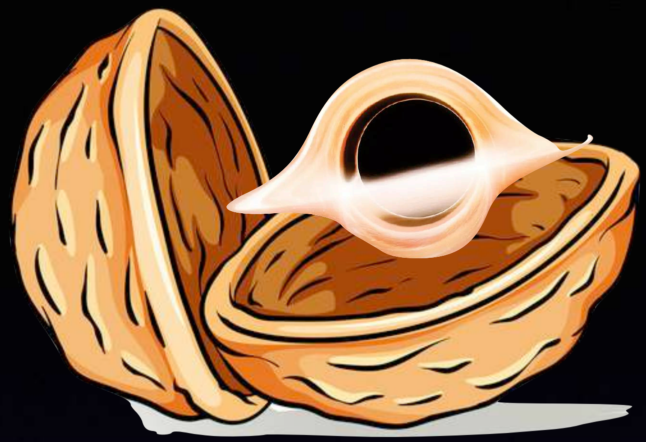

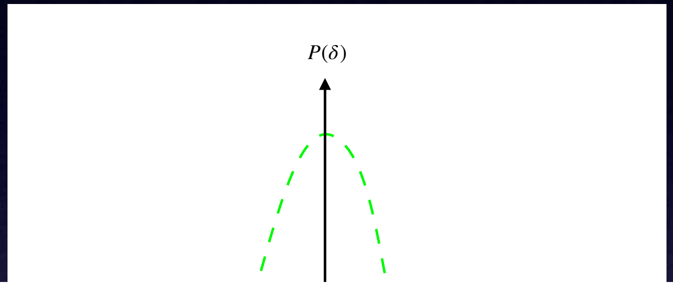

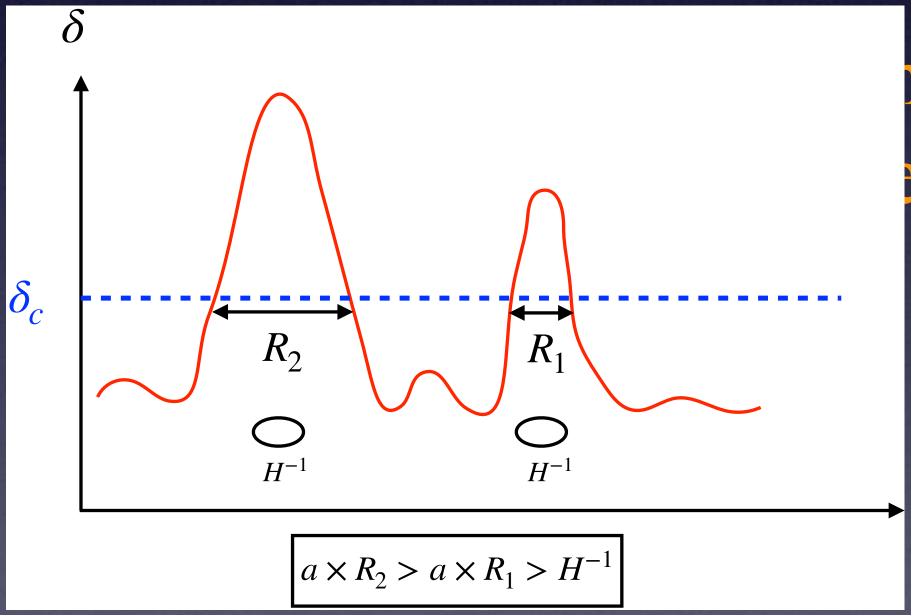

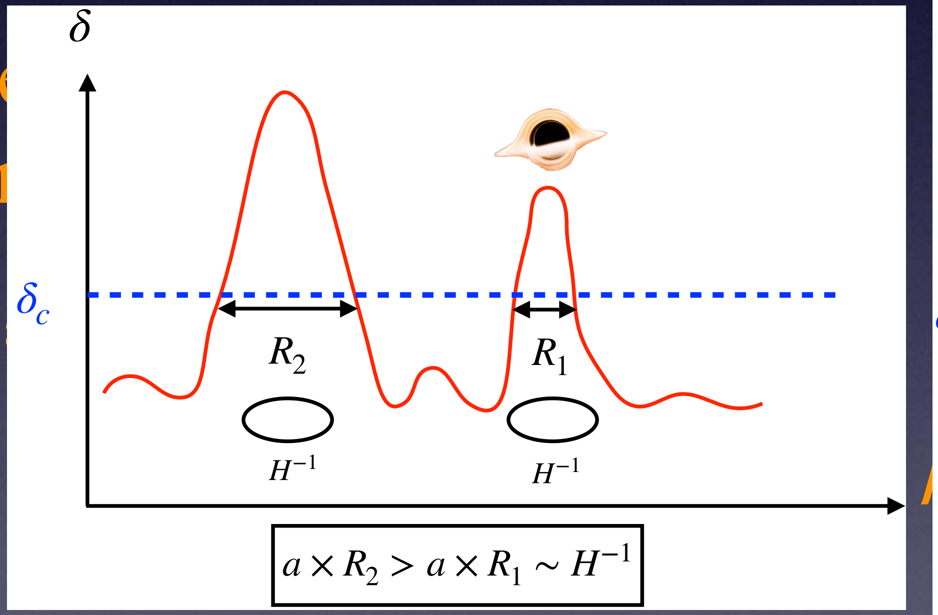

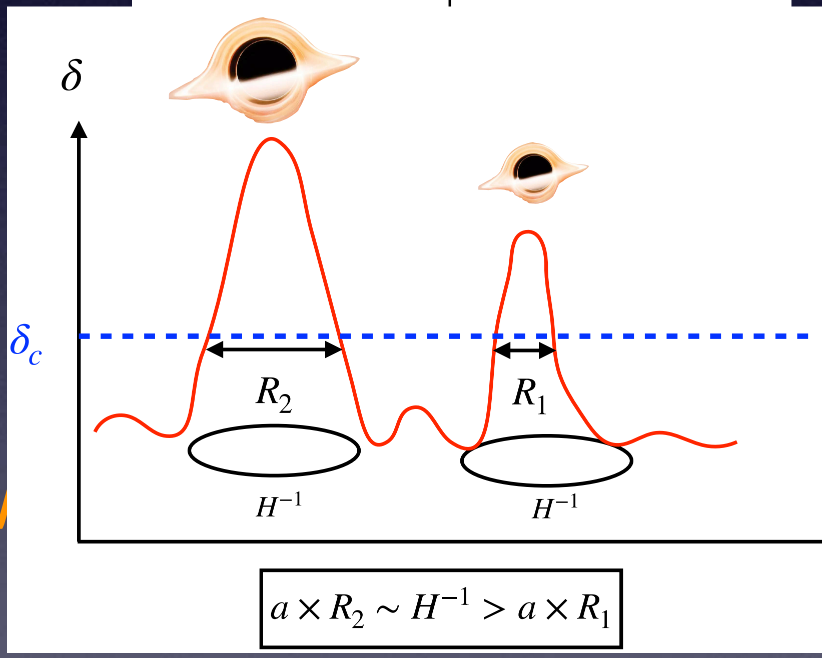

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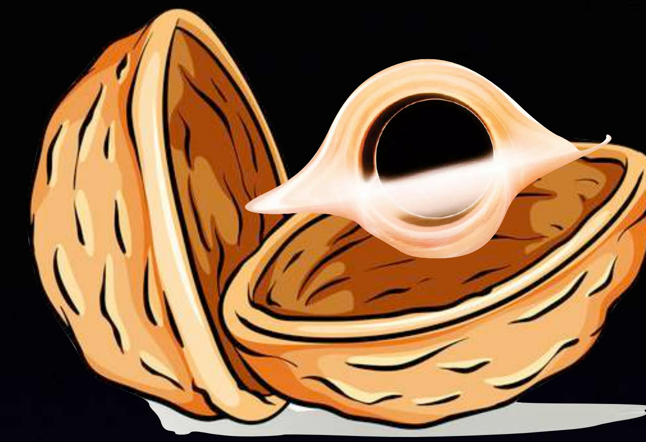

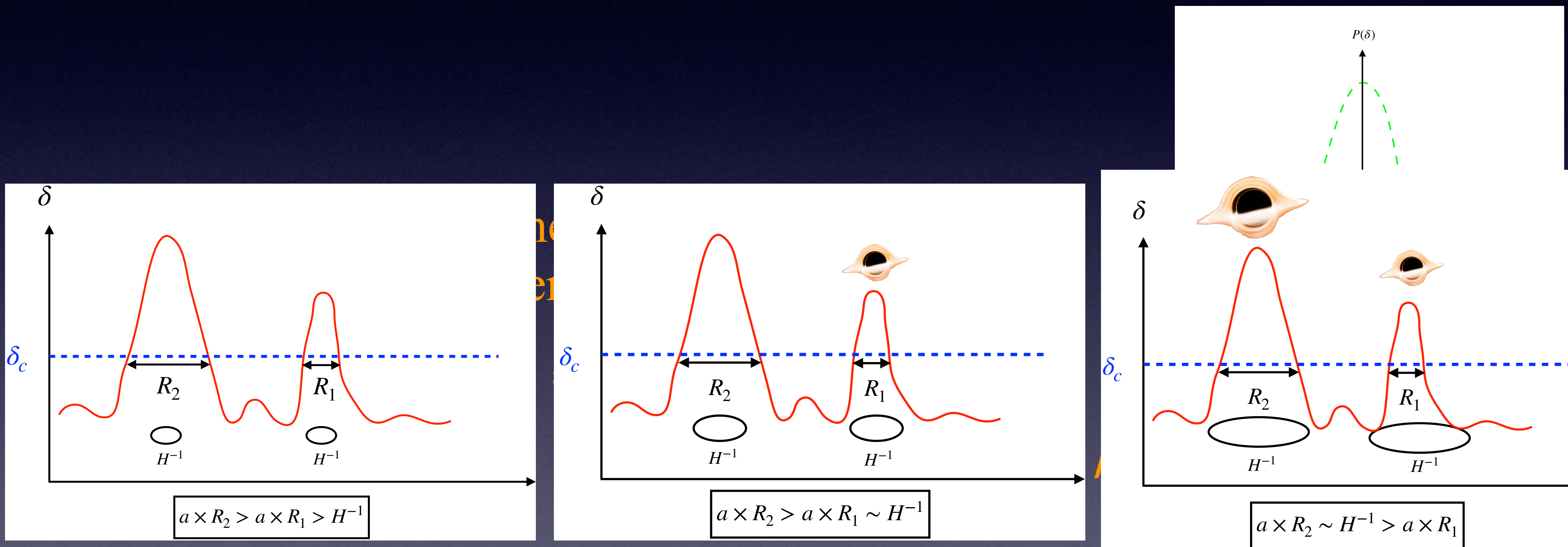

The mass in the horizon is : $M_{\rm BH} \sim \frac{4\pi}{3}(cH^{-1})^3\rho = 8\pi t M_P^2$

$$M_{\rm BH} \sim 3.6 \times 1\ {\rm g}\left(\frac{\rm t}{10^{-38}\ {\rm s}}\right) = 10^{16}\ {\rm g}\left(\frac{\rm t}{10^{-23}\ {\rm s}}\right) = {\rm M}_\odot\left(\frac{\rm t}{10^{-6}\ {\rm s}}\right)$$

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PBHs are unstable : Hawking radiation

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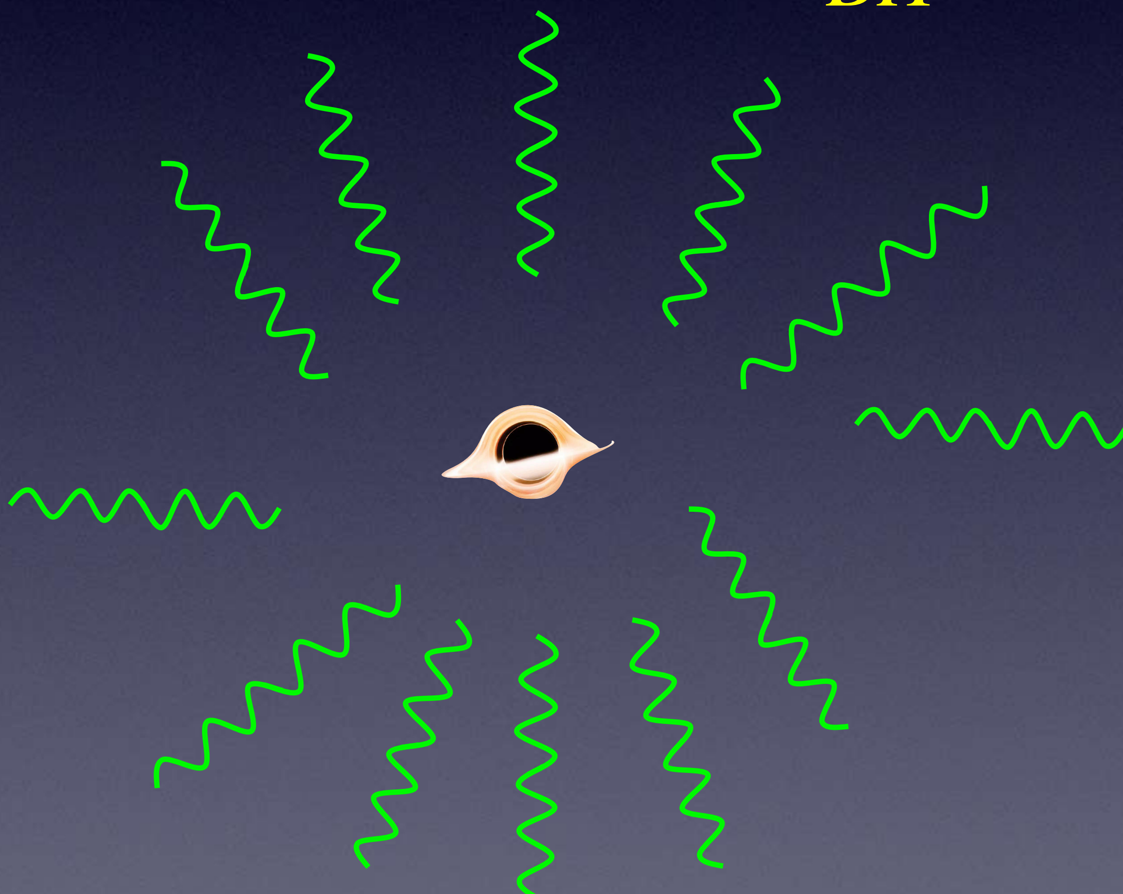

$$\frac{dM_{\rm BH}}{dt} = - \frac{g_* \pi}{480} \frac{M_P^4}{M_{\rm BH}^2}$$

Black Hole lifetime : $\tau_{\rm BH} = \frac{M_{\rm BH}^3}{M_P^4} \simeq 10^{17} \text{s} \left(\frac{\text{M}_{\rm BH}}{10^{15} \text{g}} \right)^3$

GW generated by PBH

1) from direct decay

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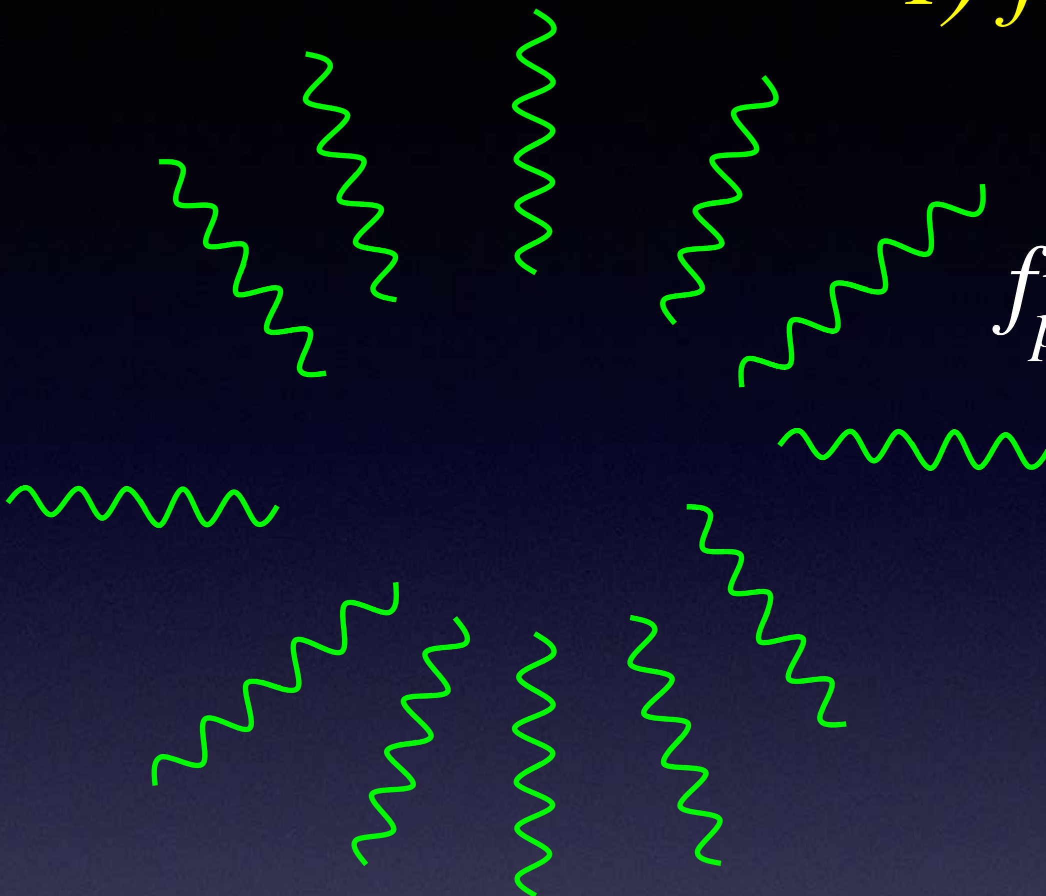

$$f_{peak}^{PBH} \sim T_{BH}\frac{a_{RH}}{a_0} \sim T_{BH}\frac{T_0}{T_{RH}} \sim \frac{T_{BH}T_0}{\sqrt{\Gamma_{BH}M_P}}$$

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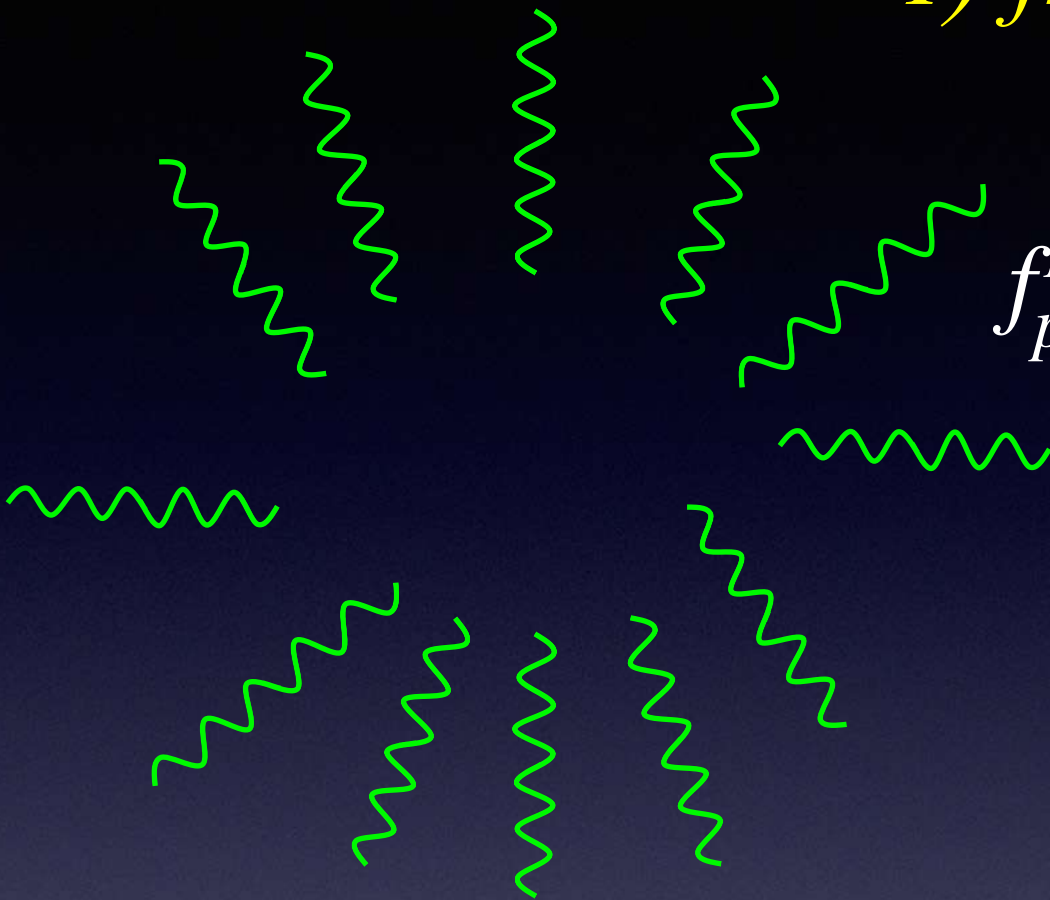

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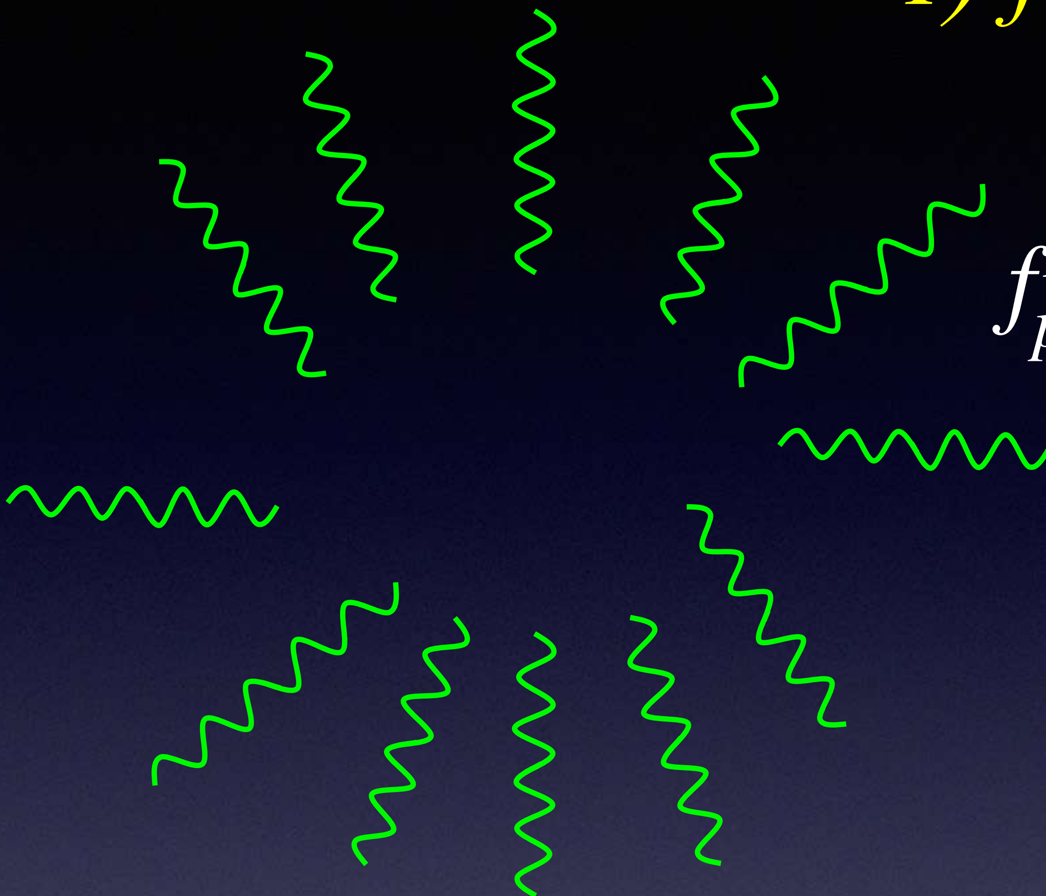

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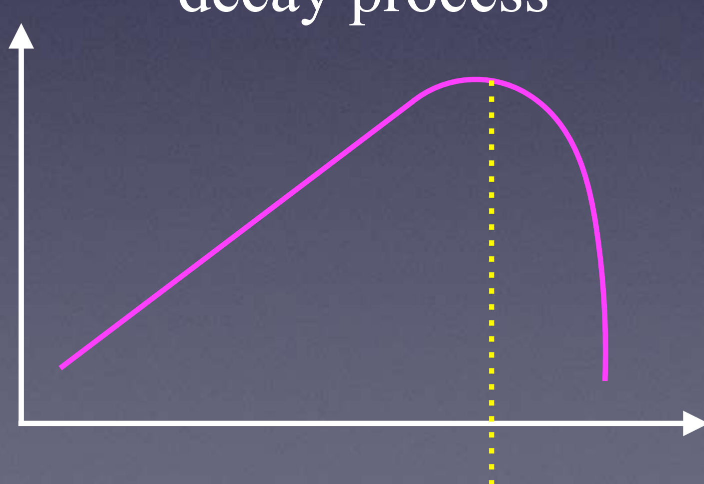

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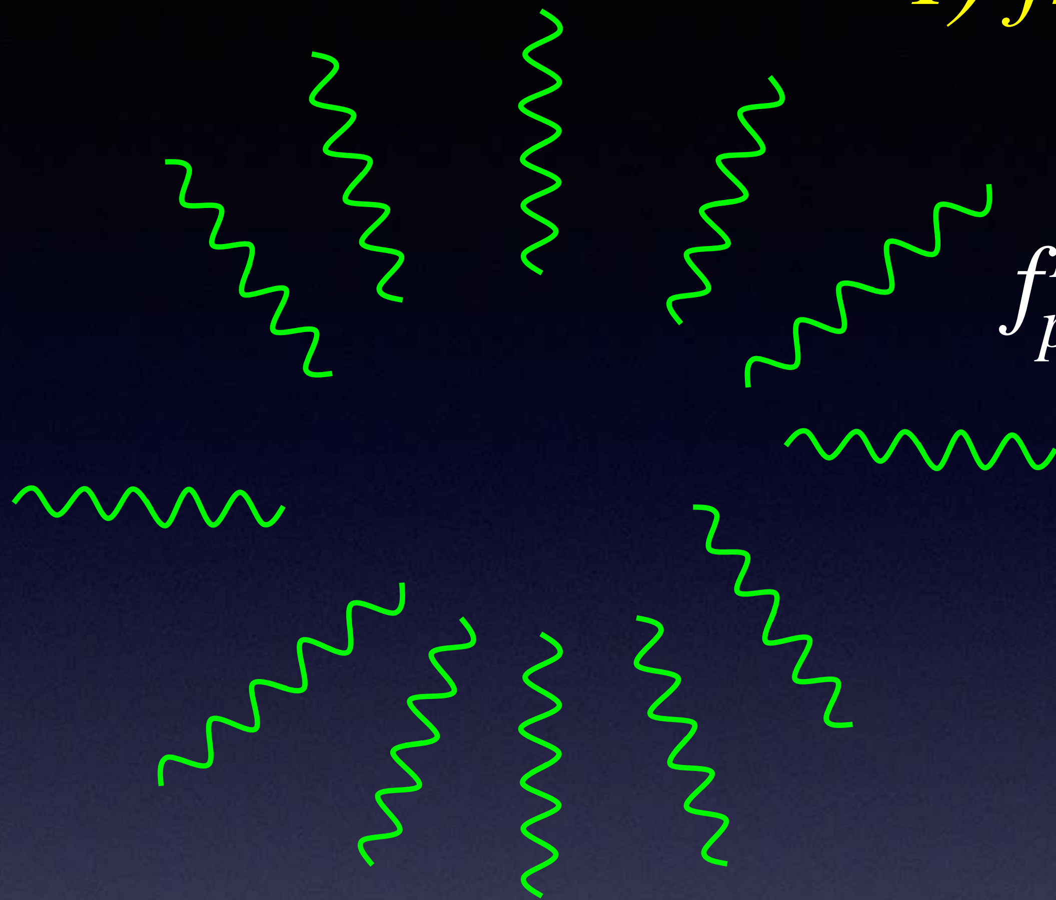

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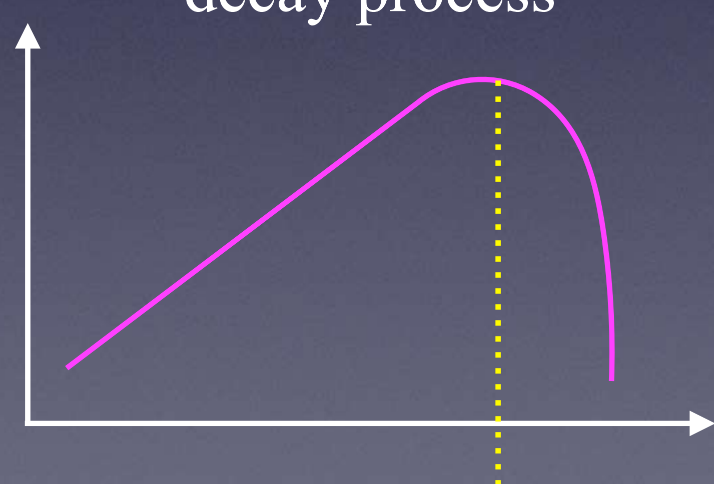

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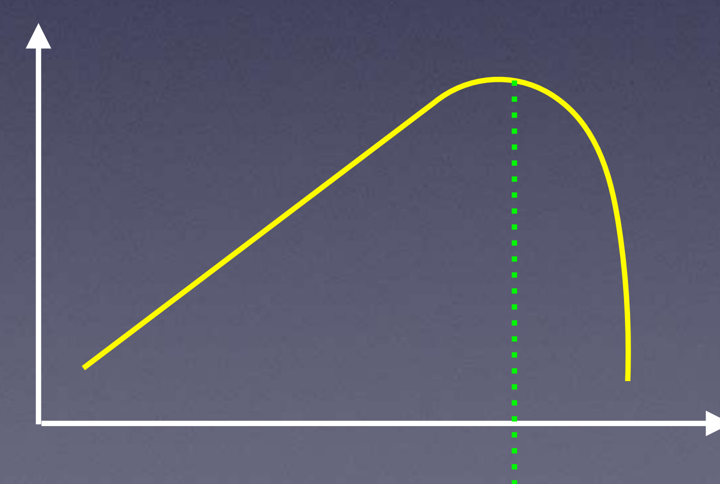
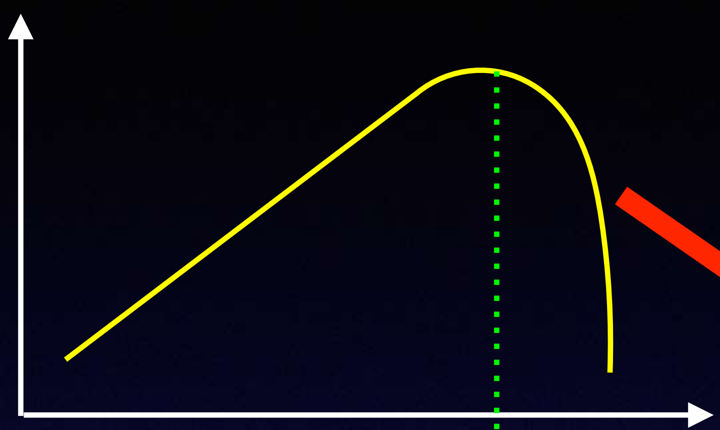


$$f_0^{BH} \sim 10^{13}\sqrt{\frac{M_{BH}}{1\ \text{g}}}\ \text{Hz}$$

GW generated by PBH

1) from direct decay

Nowadays



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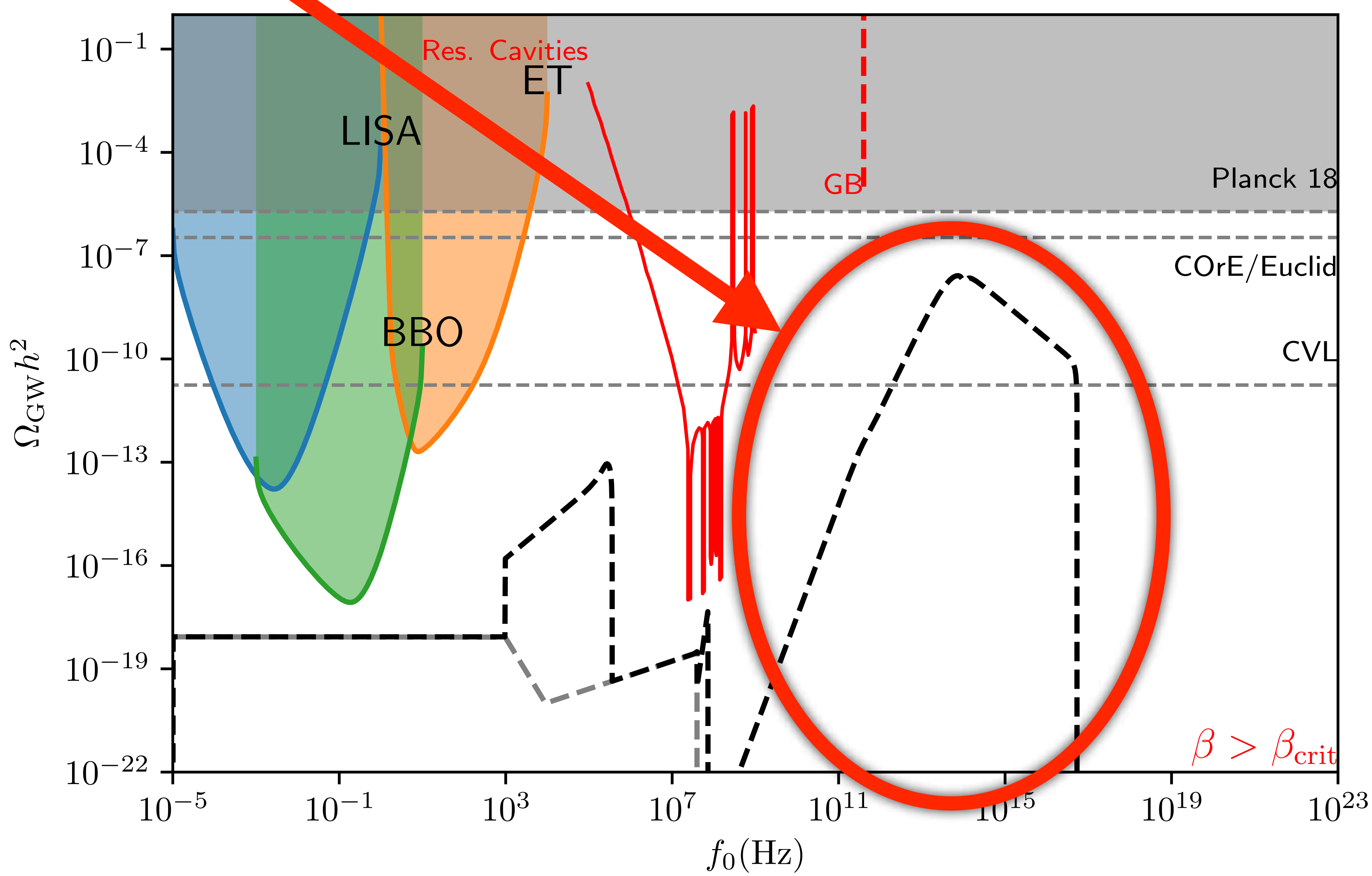
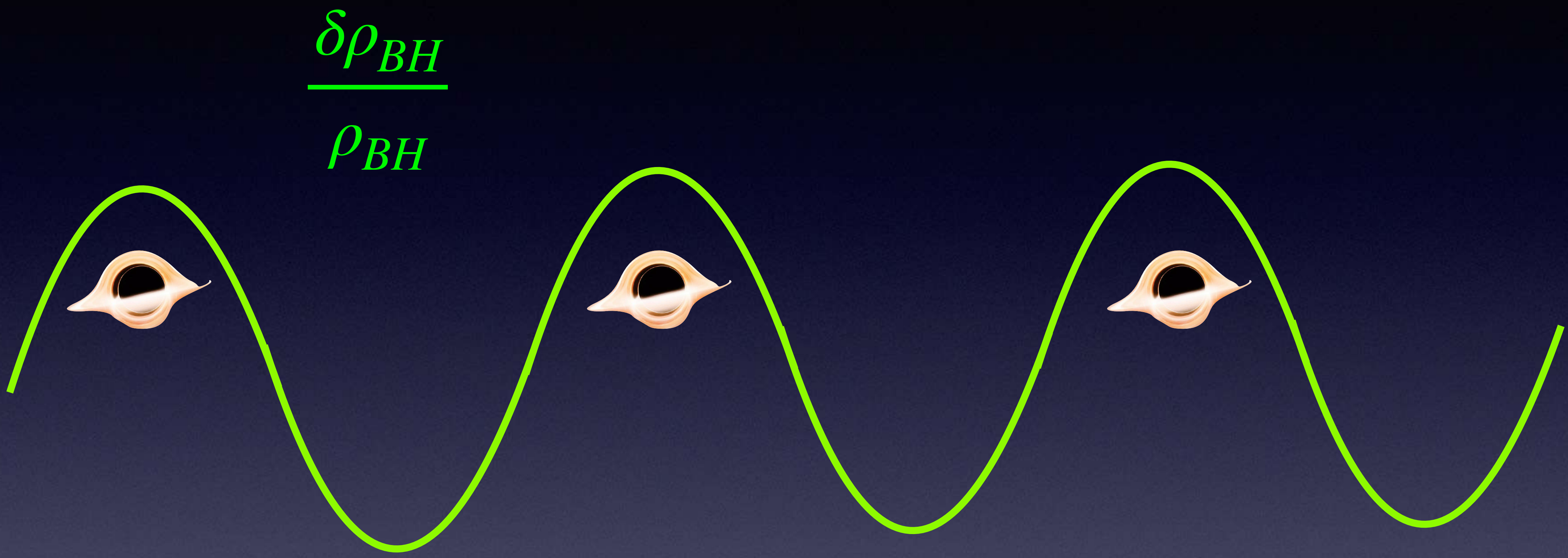
Taking into account grey-body factor, finite lifetime, exact evolution of $M_{BH}(t)$, using *BlackHawk* software



GW generated by PBH

2) from density fluctuations



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2 steps :

1) Poisson equation transfers *density* fluctuations $\frac{\delta\rho_{BH}}{\rho_{BH}}$ into *potential* (scalar) Φ-fluctuations (isocurvature → curvature) :

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$$\nabla^2 \Phi = \frac{\delta\rho_{BH}}{2M_P^2}, \quad \delta\rho_{BH} = \rho_{BH} - \bar{\rho}_{BH}$$

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$$ds^2 = (1 - 2\Phi)dt^2 - a^2(1 + 2\Phi + h_{ij})\, dx^i dx^j$$

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$$h''_{ij} + 2Hh'_{ij} + \Delta h_{ij} = S_{ij} = \partial_i\Phi\partial_j\Phi + \ldots$$

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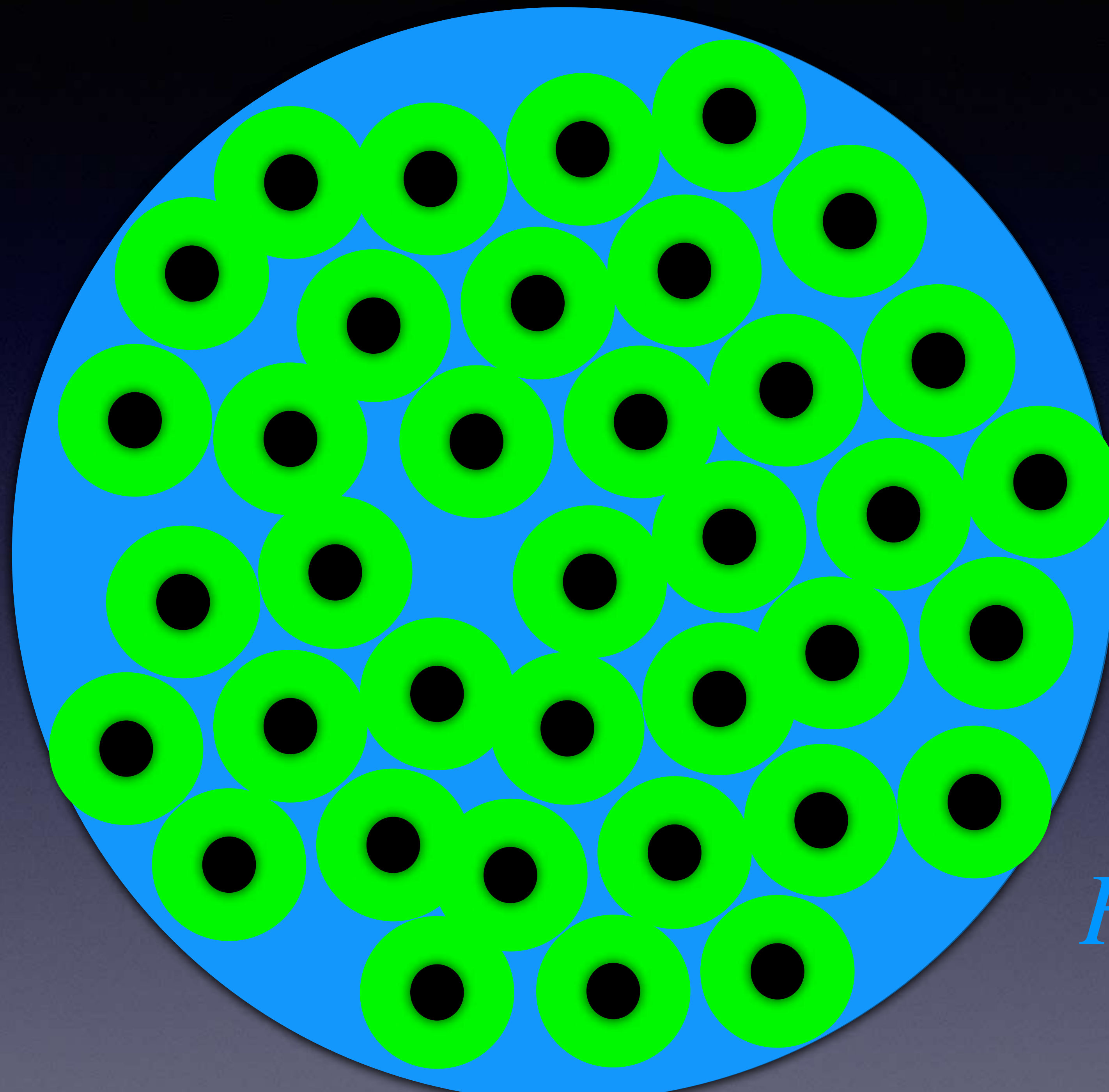
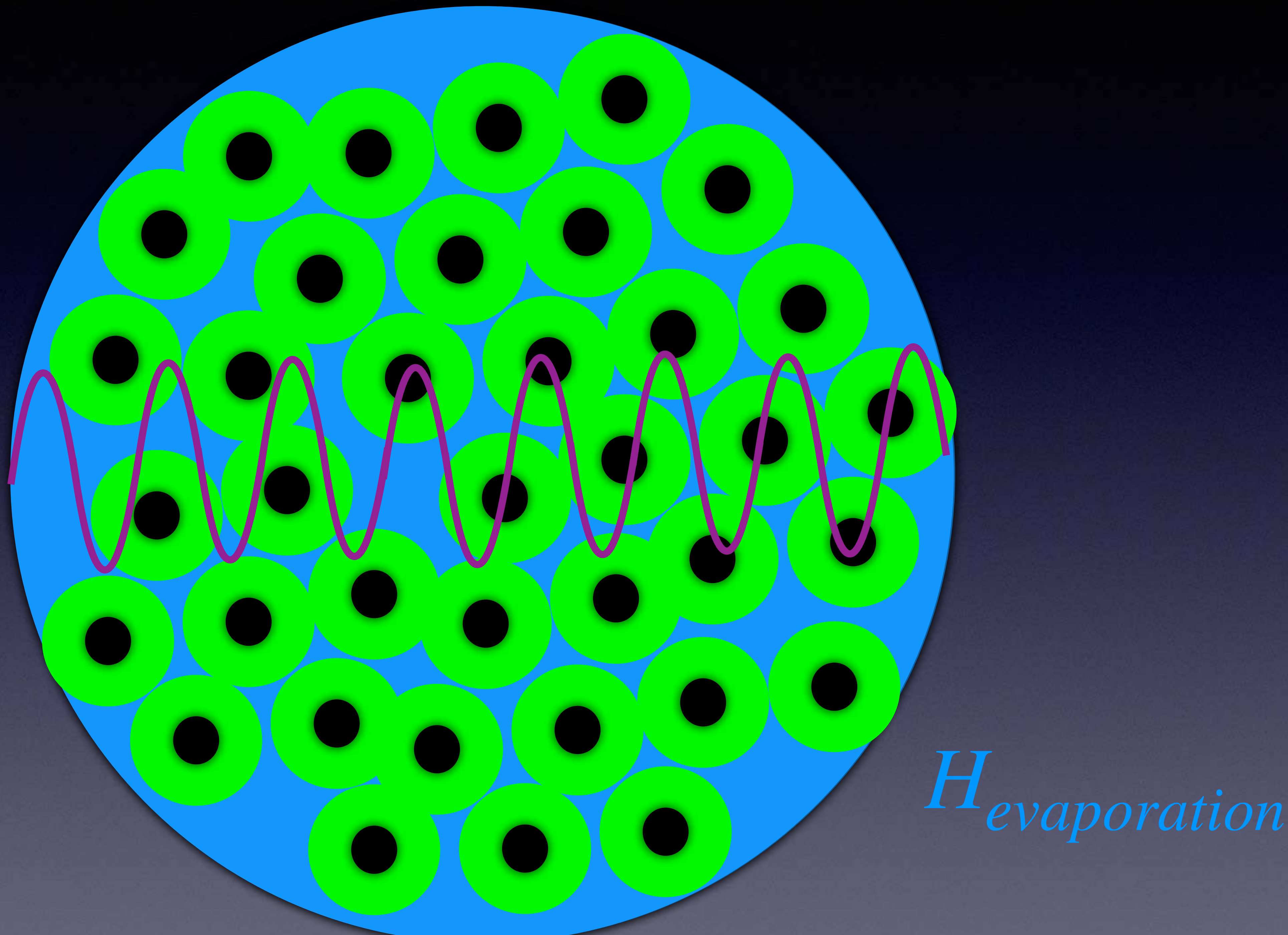
Computation of transfer functions $\mathcal{T}_{ij}$

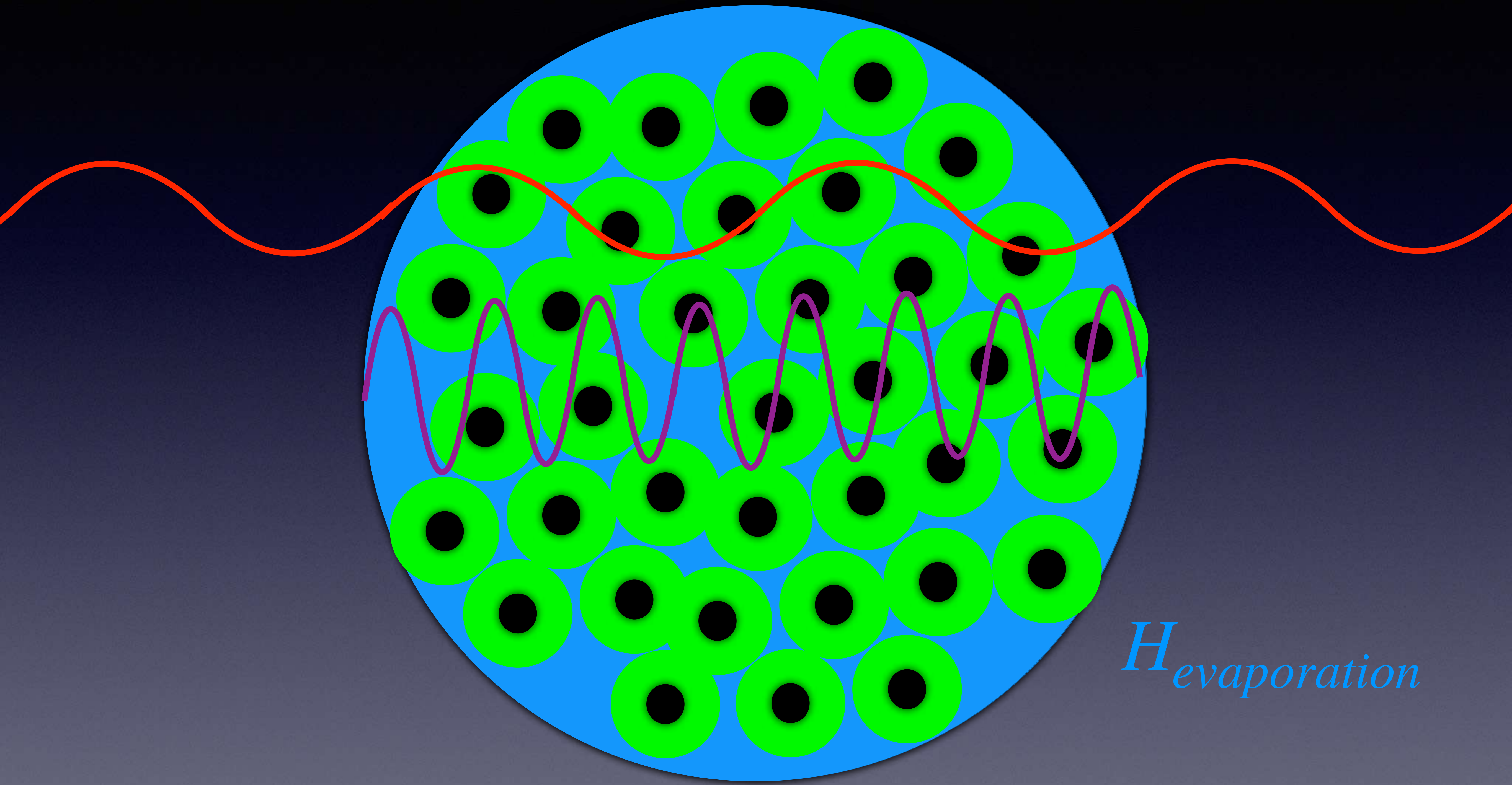


$H_{evaporation}$



Minimum wavelength (maximum frequency) corresponds to the distance between 2 black holes

Maximum wavelength corresponds to the size of the horizon at evaporation time



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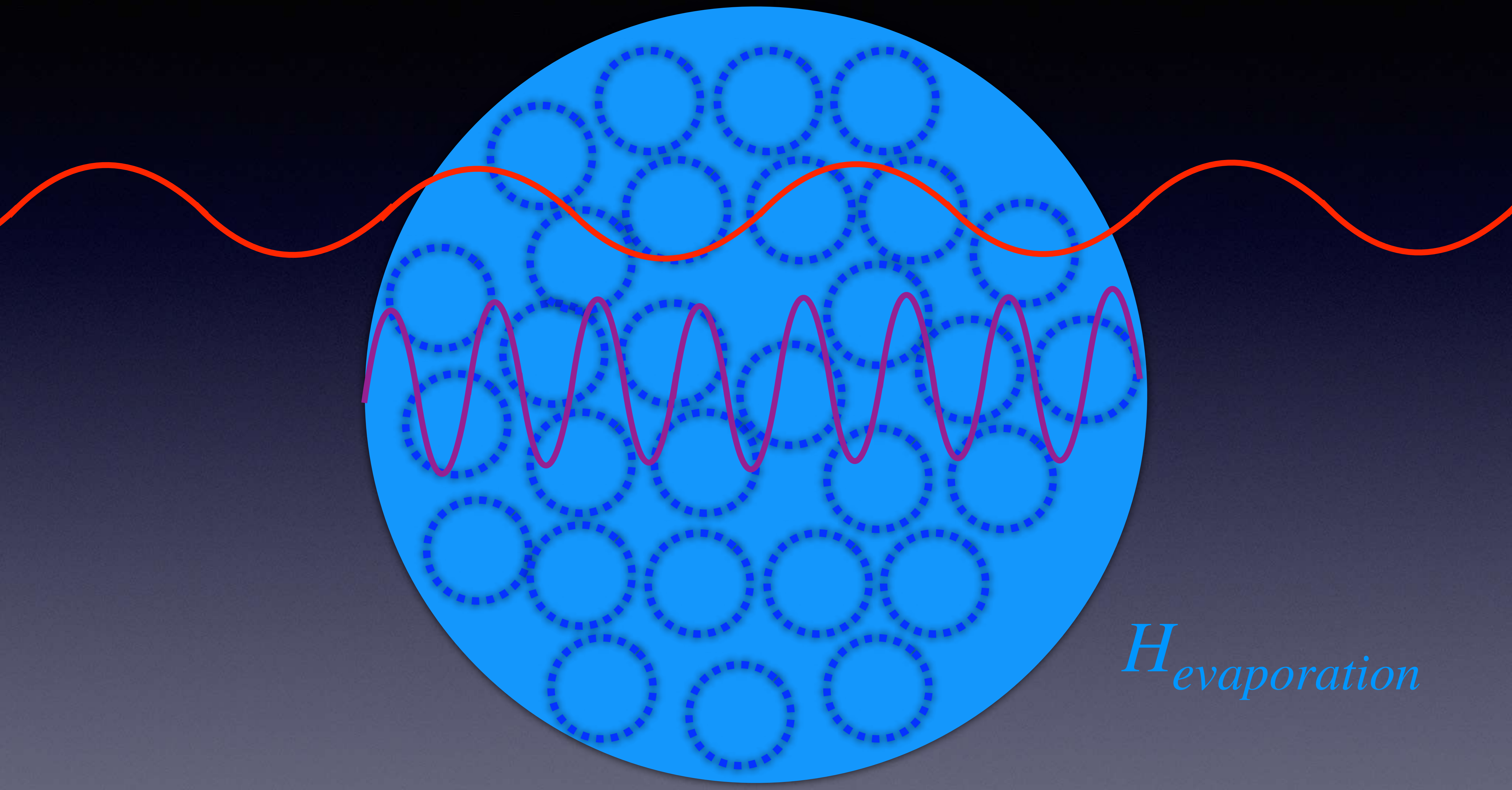

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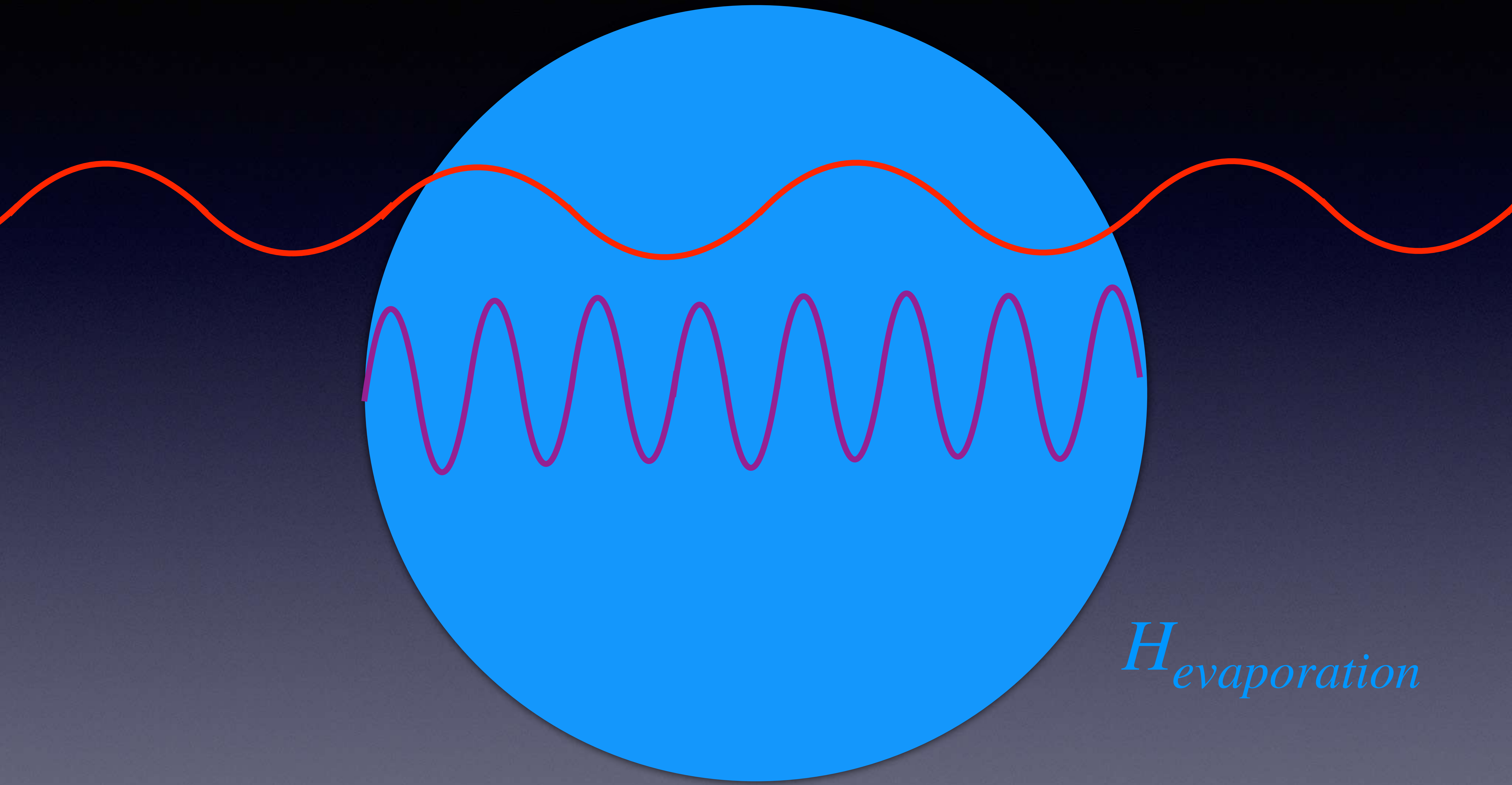

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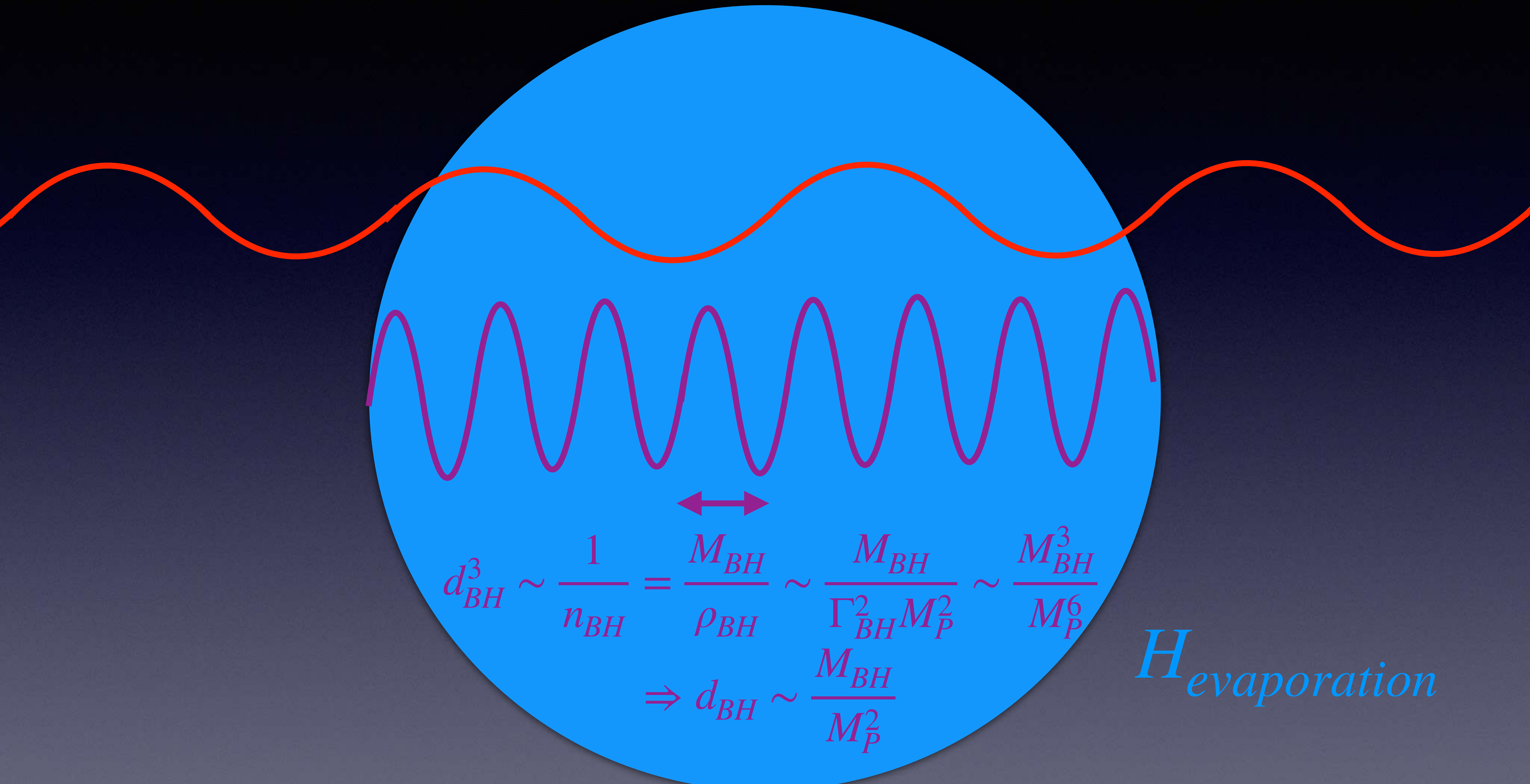

$$d_{BH}^3 \sim \frac{1}{n_{BH}} = \frac{M_{BH}}{\rho_{BH}} \sim \frac{M_{BH}}{\Gamma_{BH}^2 M_P^2} \sim \frac{M_{BH}^3}{M_P^6}$$

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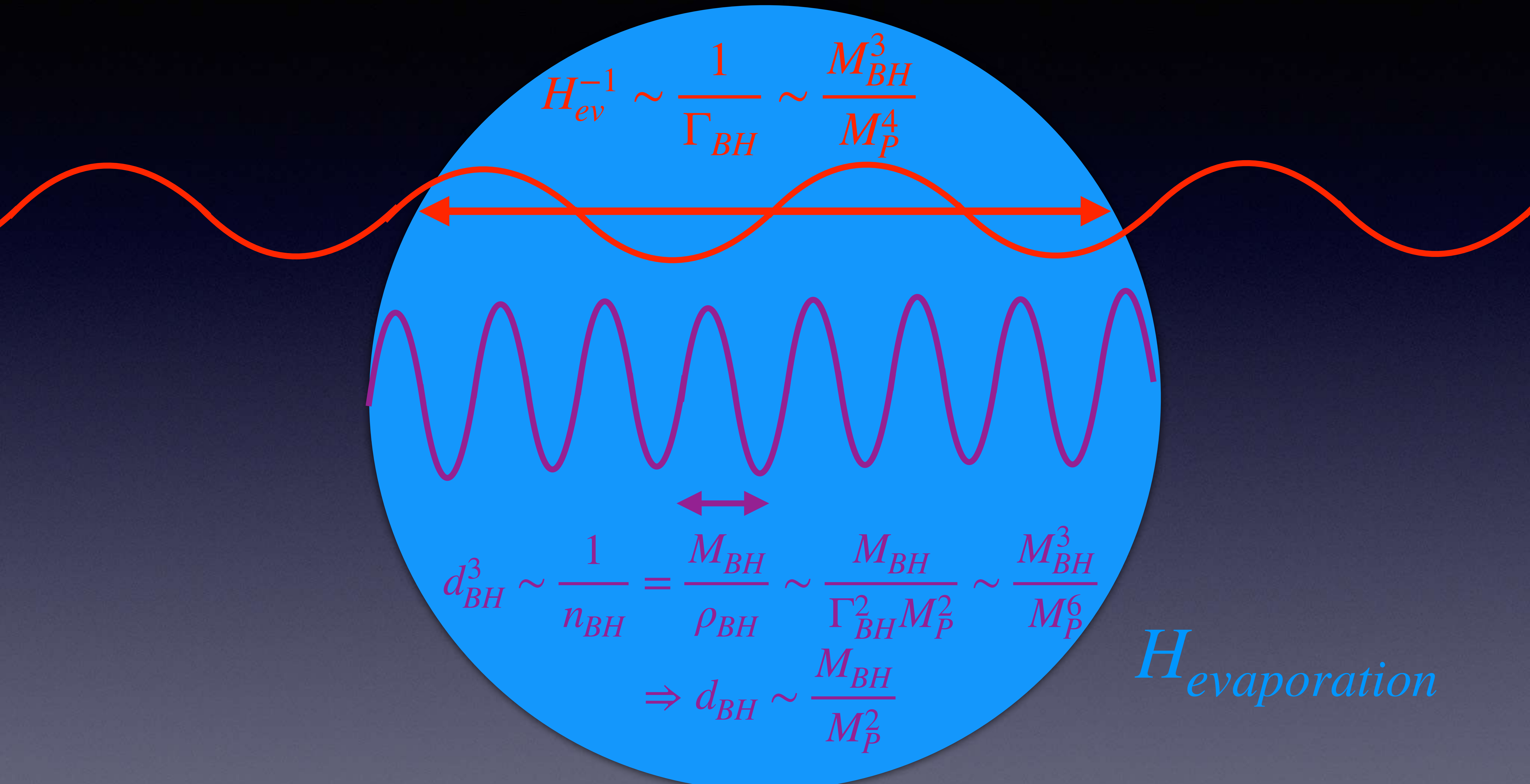

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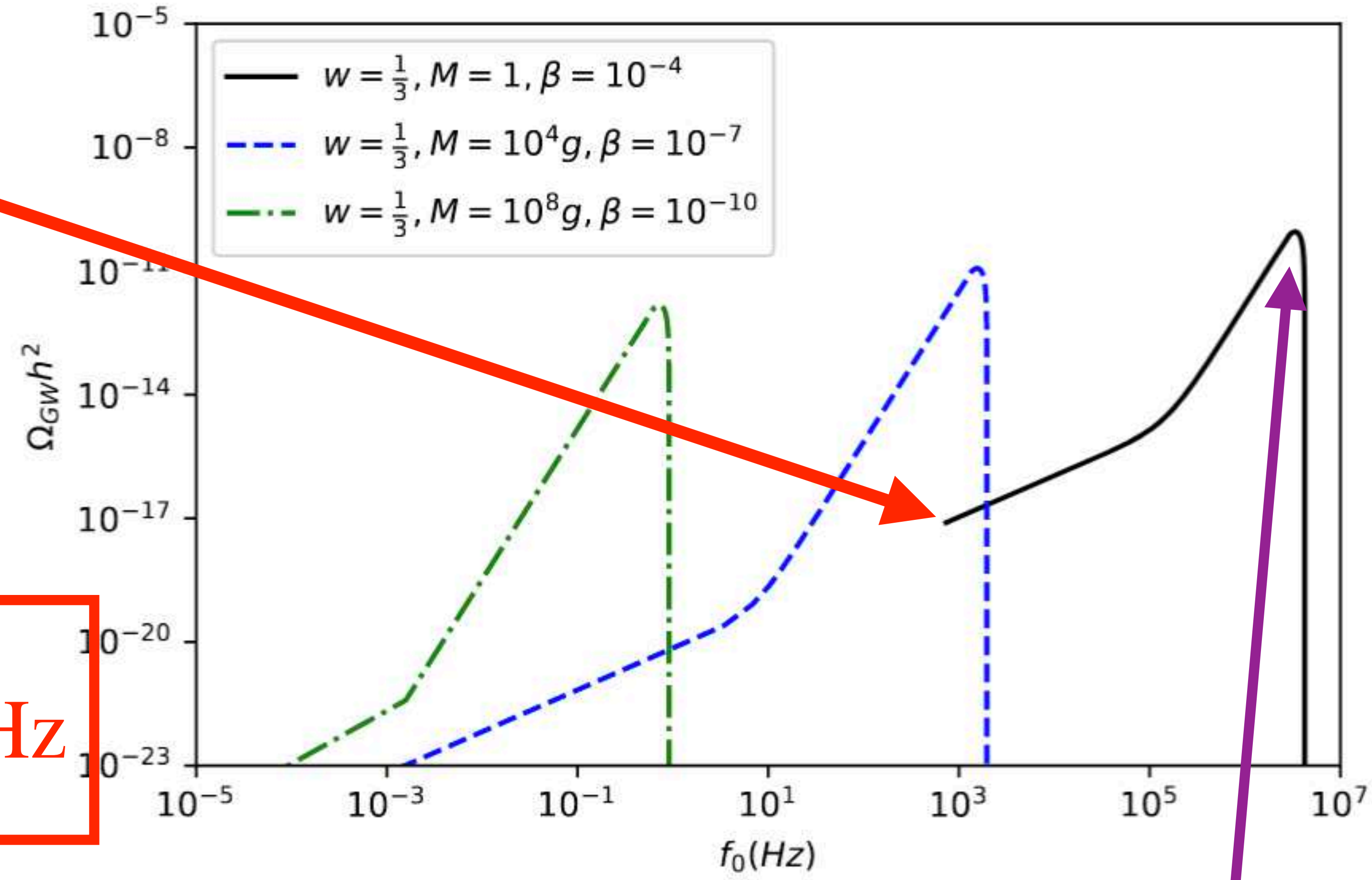
Minimum wavelength (maximum frequency) corresponds to the distance between 2 black holes

Horizon at evaporation

$$H_{ev}^{-1} \sim \frac{1}{\Gamma_{BH}} \sim \frac{M_{BH}^3}{M_P^4}$$

$$f_0^{ev} \simeq 1.4 \times 10^3 \left(\frac{1\ \mathrm{g}}{M_{BH}}\right)^{\frac{3}{2}}\ \mathrm{Hz}$$

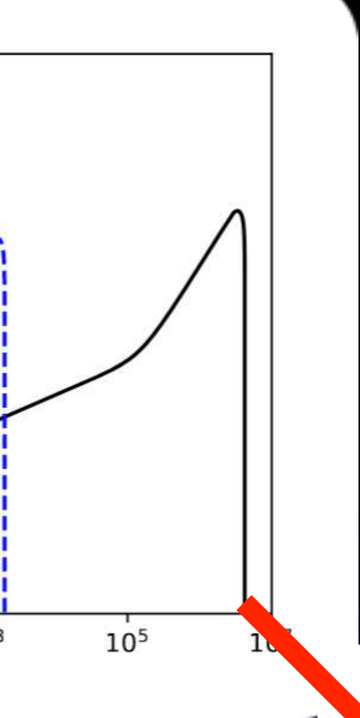


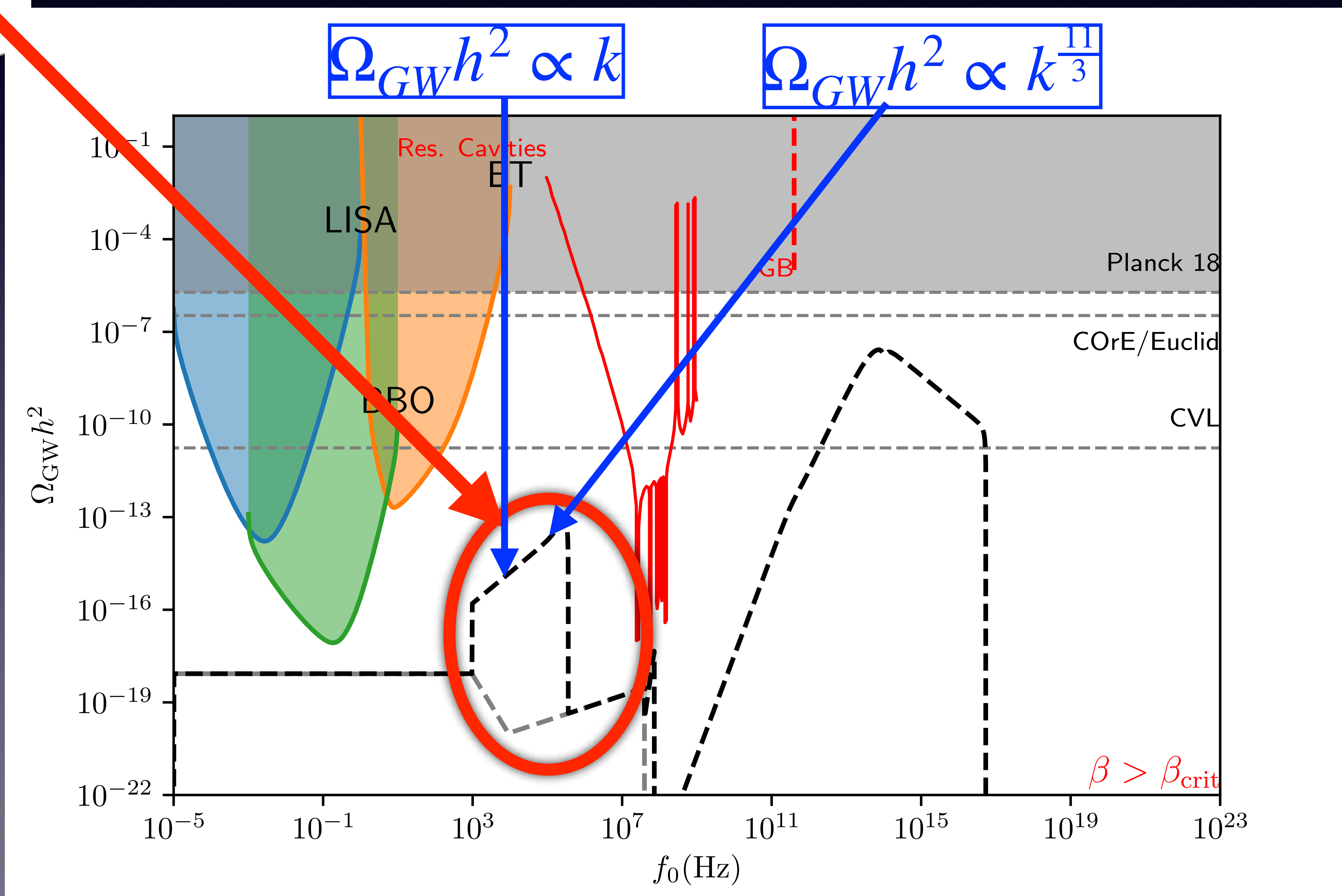
Distance between PBH

$$d_{BH}^3 \sim \frac{1}{n_{BH}} = \frac{M_{BH}}{\rho_{BH}} \sim \frac{M_{BH}}{\Gamma_{BH}^2 M_P^2} \sim \frac{M_{BH}^3}{M_P^6}$$

$$\Rightarrow d_{BH} \sim \frac{M_{BH}}{M_P^2}$$

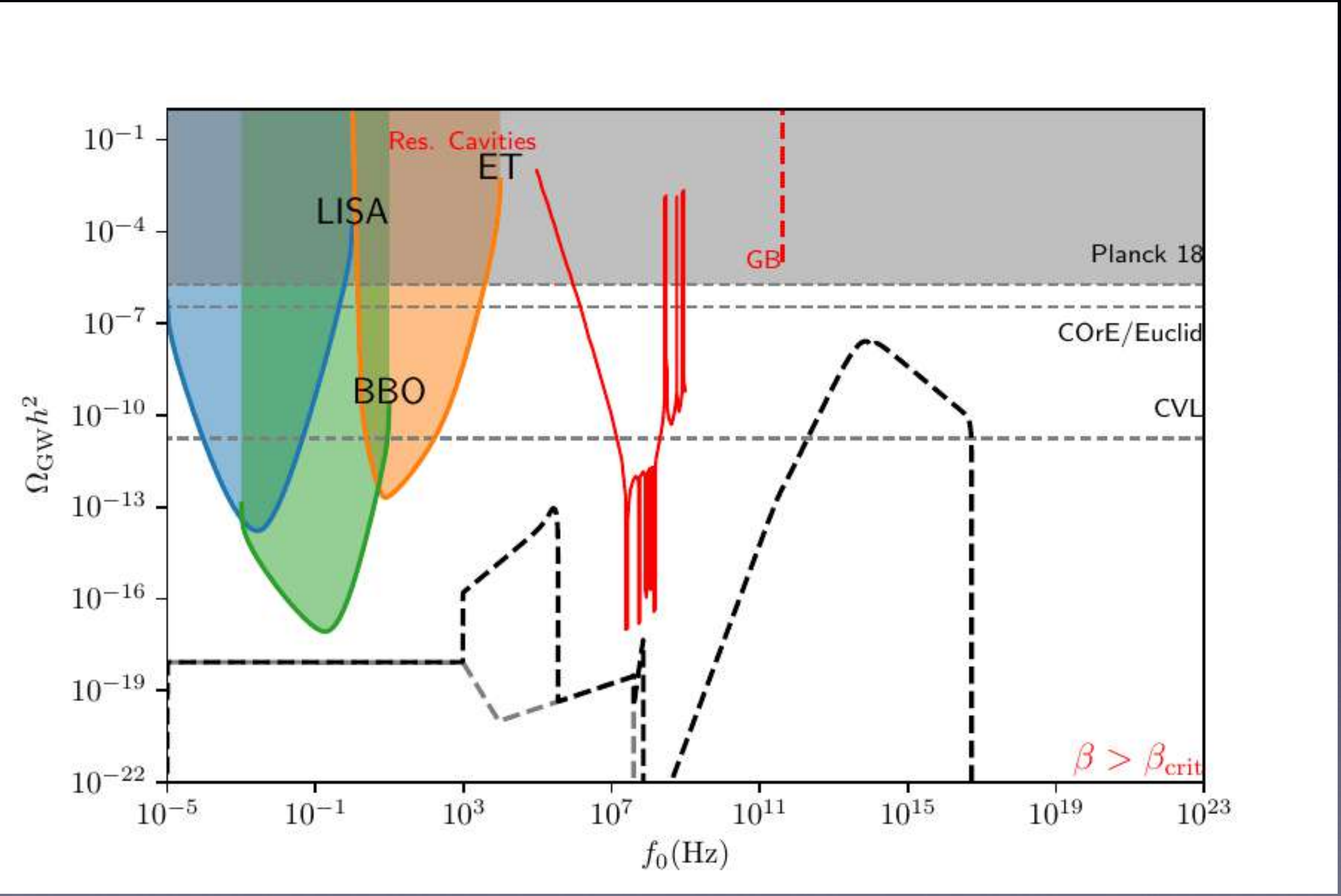
$$f_0^{BH} \simeq 3.7 \times 10^6 \left(\frac{1\ \mathrm{g}}{M_{BH}}\right)^{\frac{5}{6}}\ \mathrm{Hz}$$


10^5


$\Omega_{GW}h^2 \propto k$
$\Omega_{GW}h^2 \propto k^{\frac{11}{3}}$
Res. Cavities
ET
LISA
GB
Planck 18
COrE/Euclid
DBO
CVL
$\beta > \beta_{\rm crit}$
$\Omega_{\rm GW}h^2$
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-5}
10^{-1}
10^{3}
10^{7}
10^{11}
10^{15}
10^{19}
10^{23}
$f_0(\rm Hz)$

For other PBH masses?

From 1 g to 10^8 g



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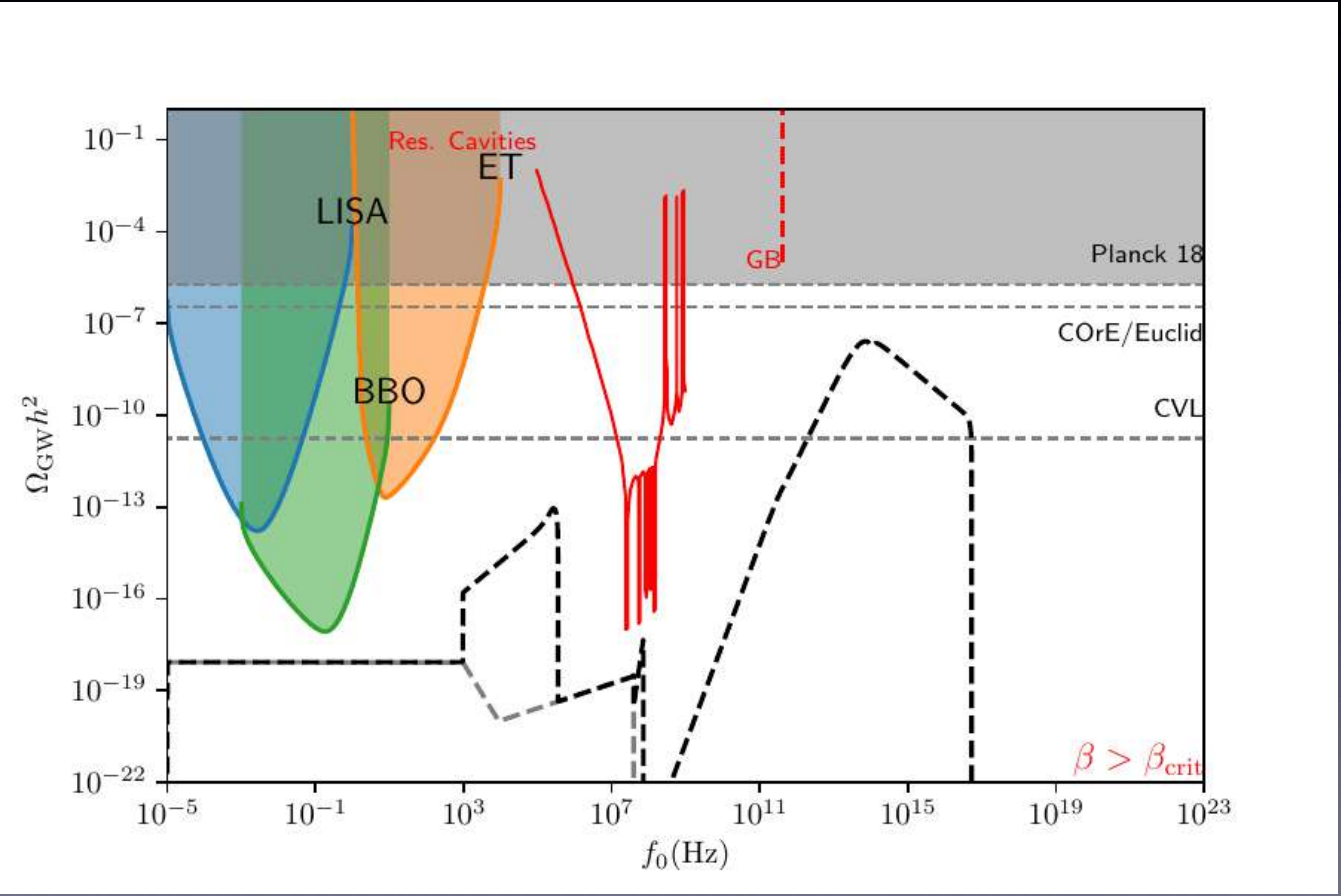
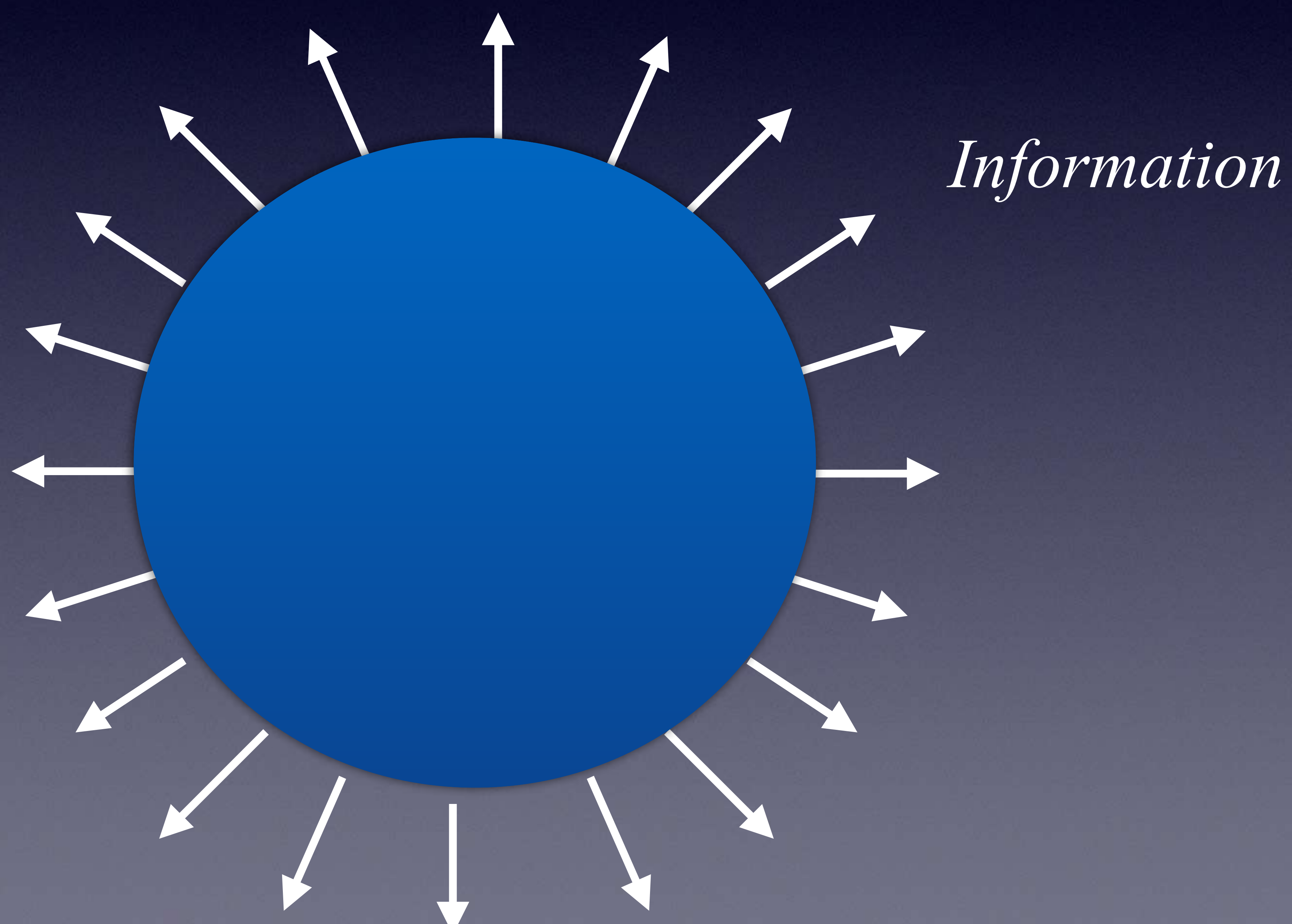


Memory burdening (P)BH

In a system of high storage capacity,
the information stored in the system tends to backreact
to resist to the porcess of information lost



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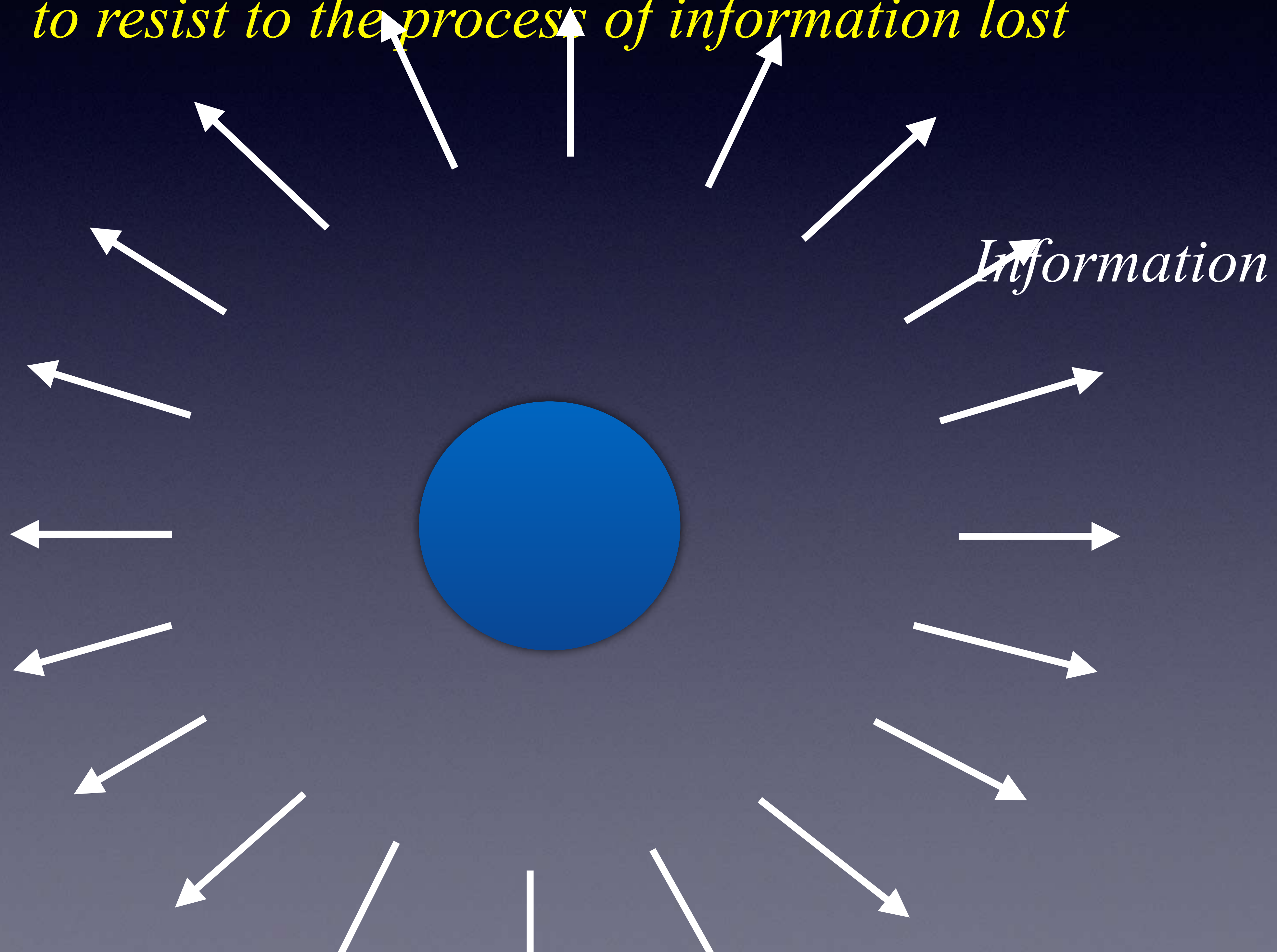

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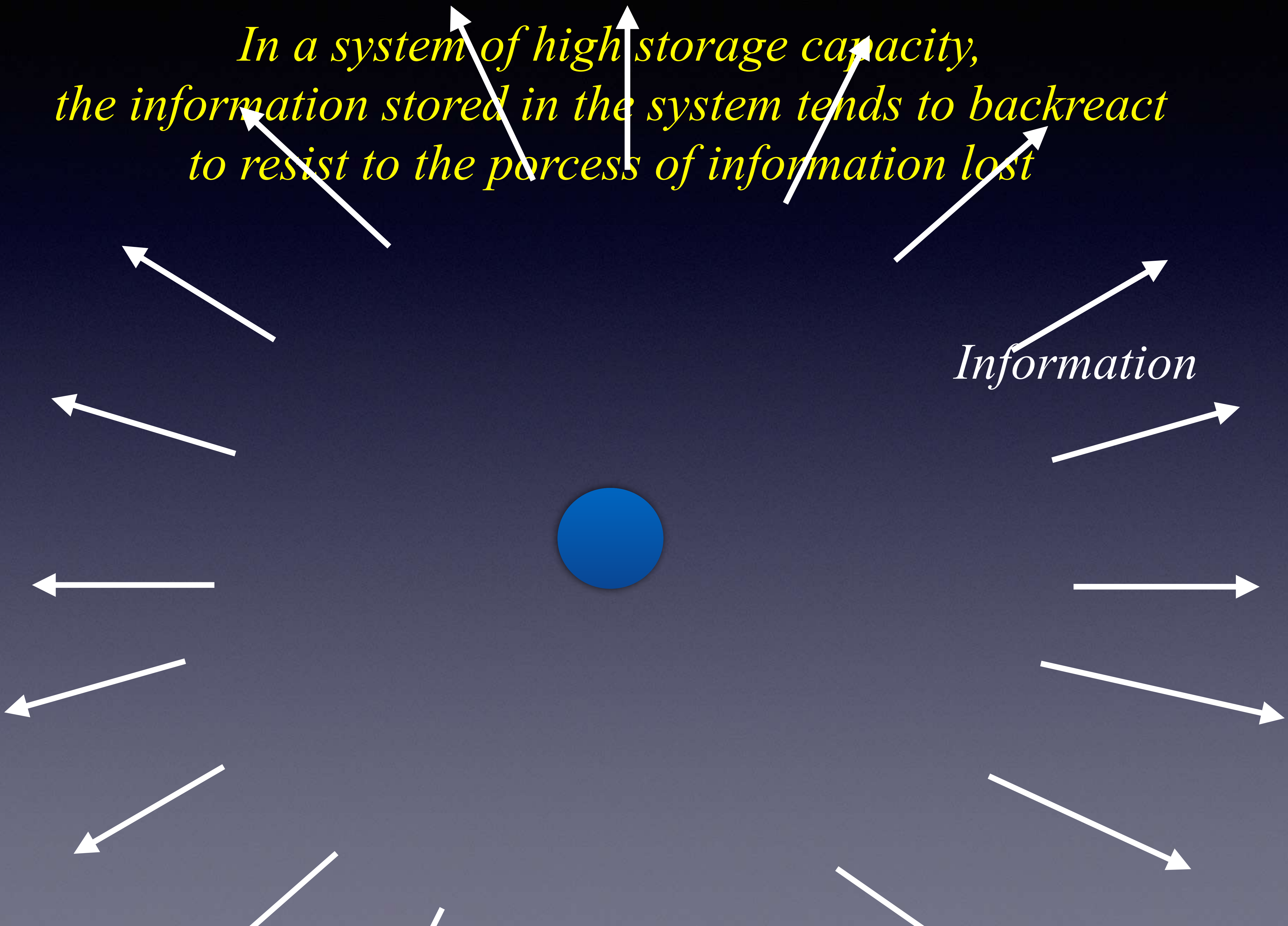

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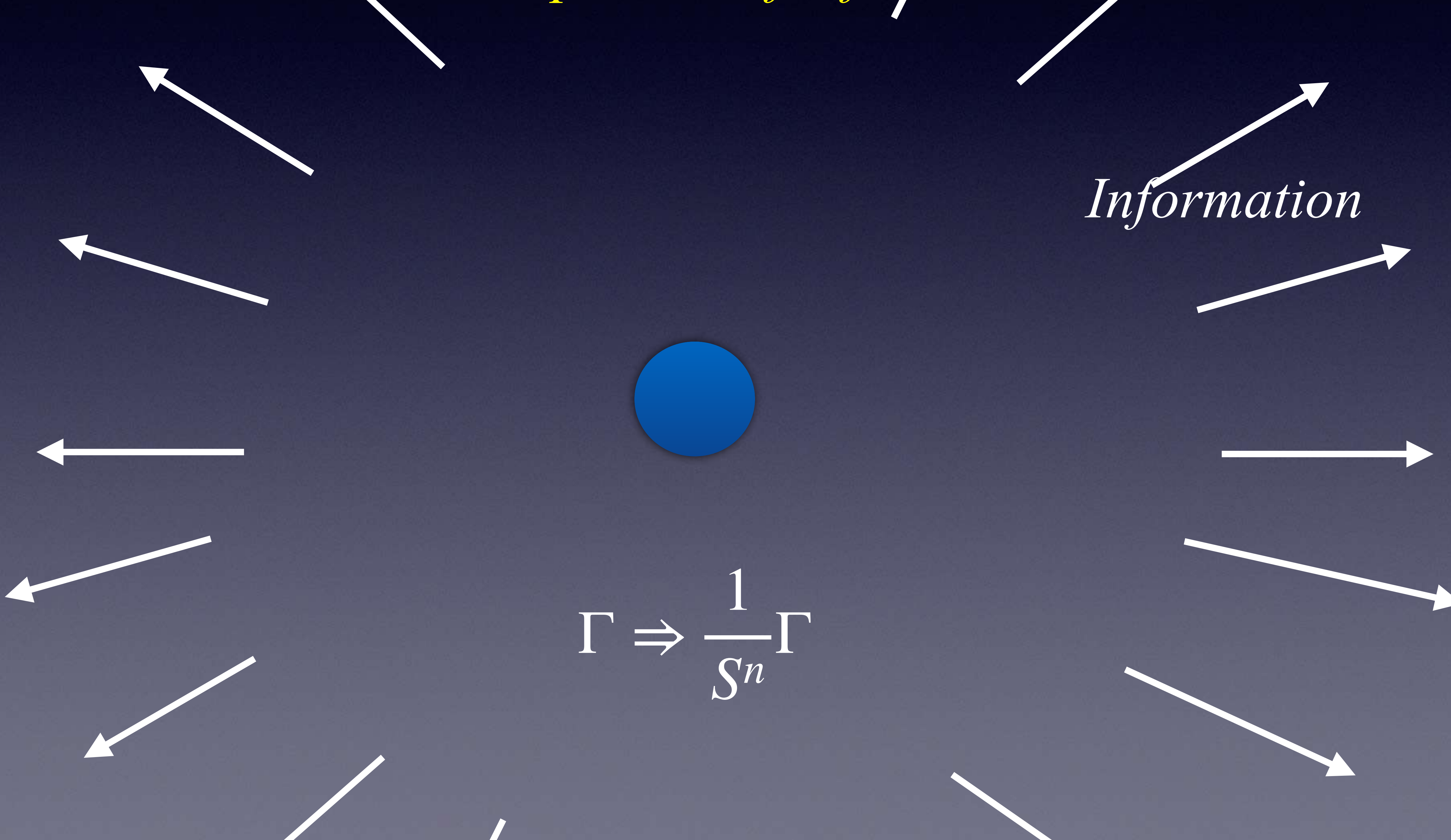

$$\Gamma \Rightarrow \frac{1}{S^n}\Gamma$$

Memory burdening (P)BH

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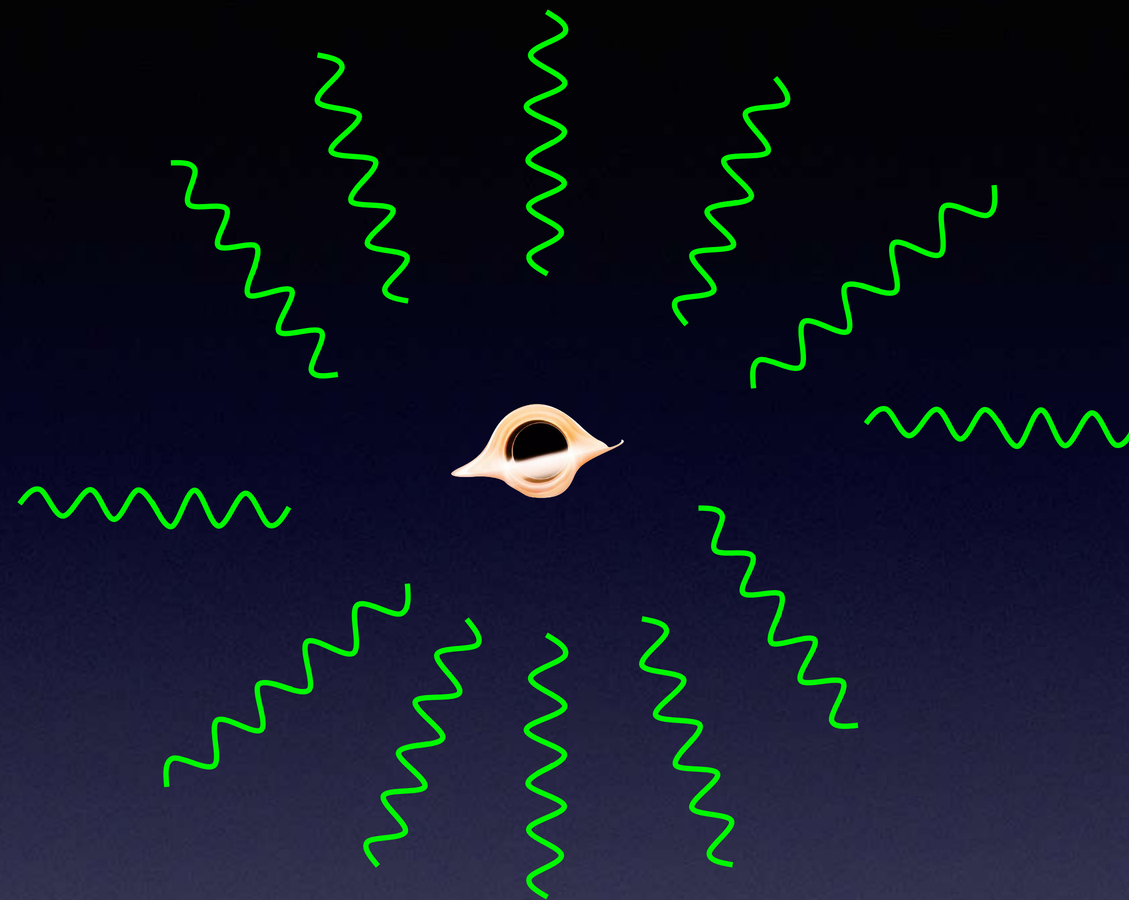

$$\Gamma_{BH}^{sem.clas.} \Rightarrow \frac{1}{S^n}\Gamma_{BH}^{sem.class.} \sim \frac{M_P^{2n+3}}{M_{BH}^{2n+2}}$$

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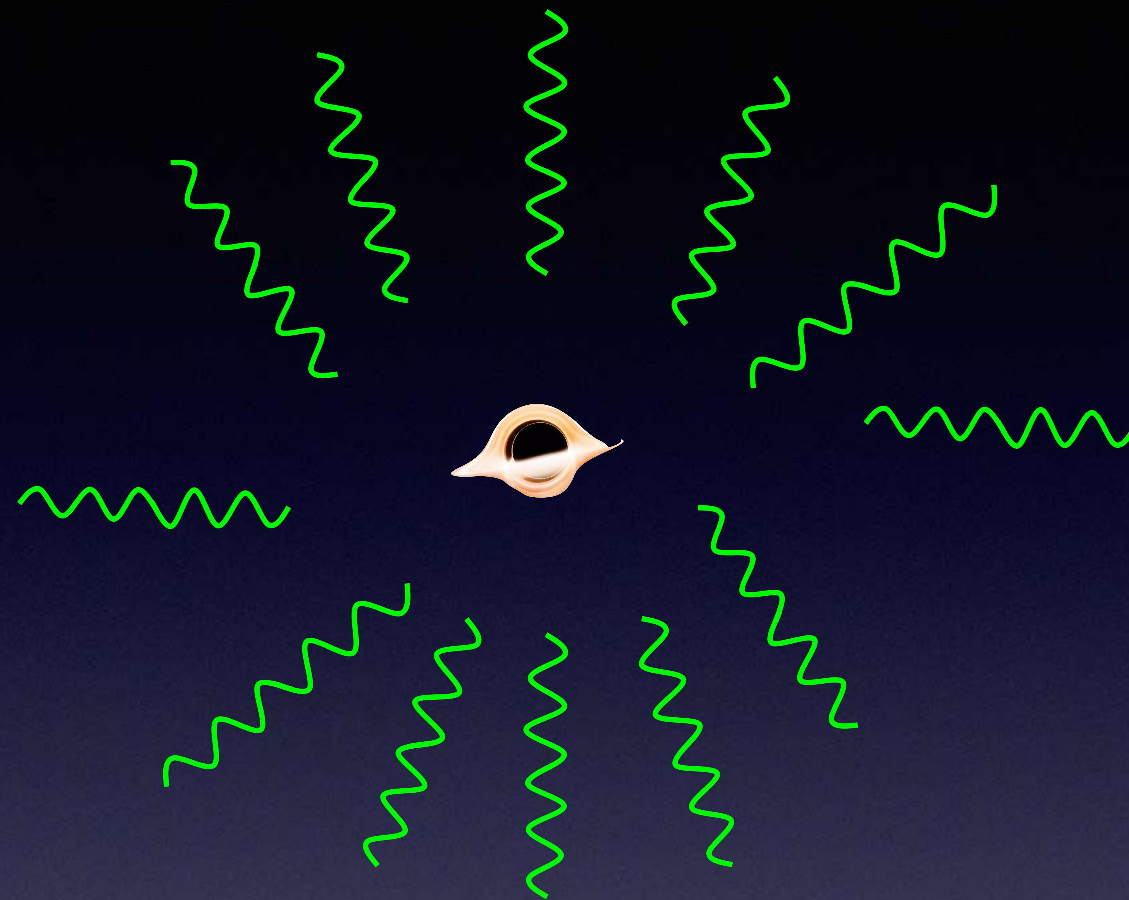

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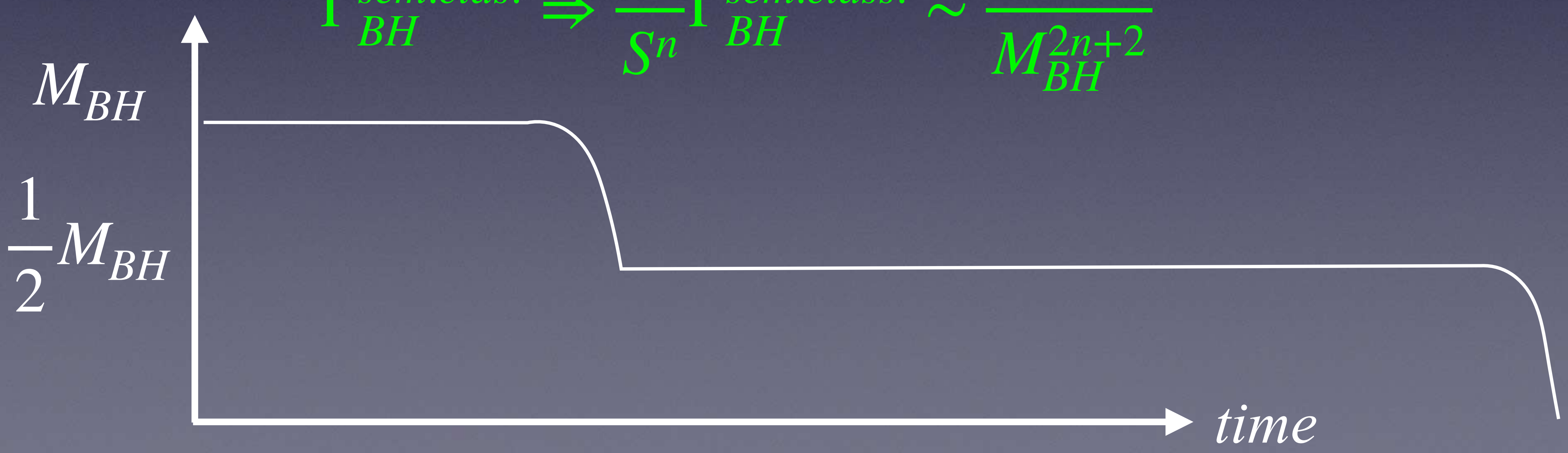
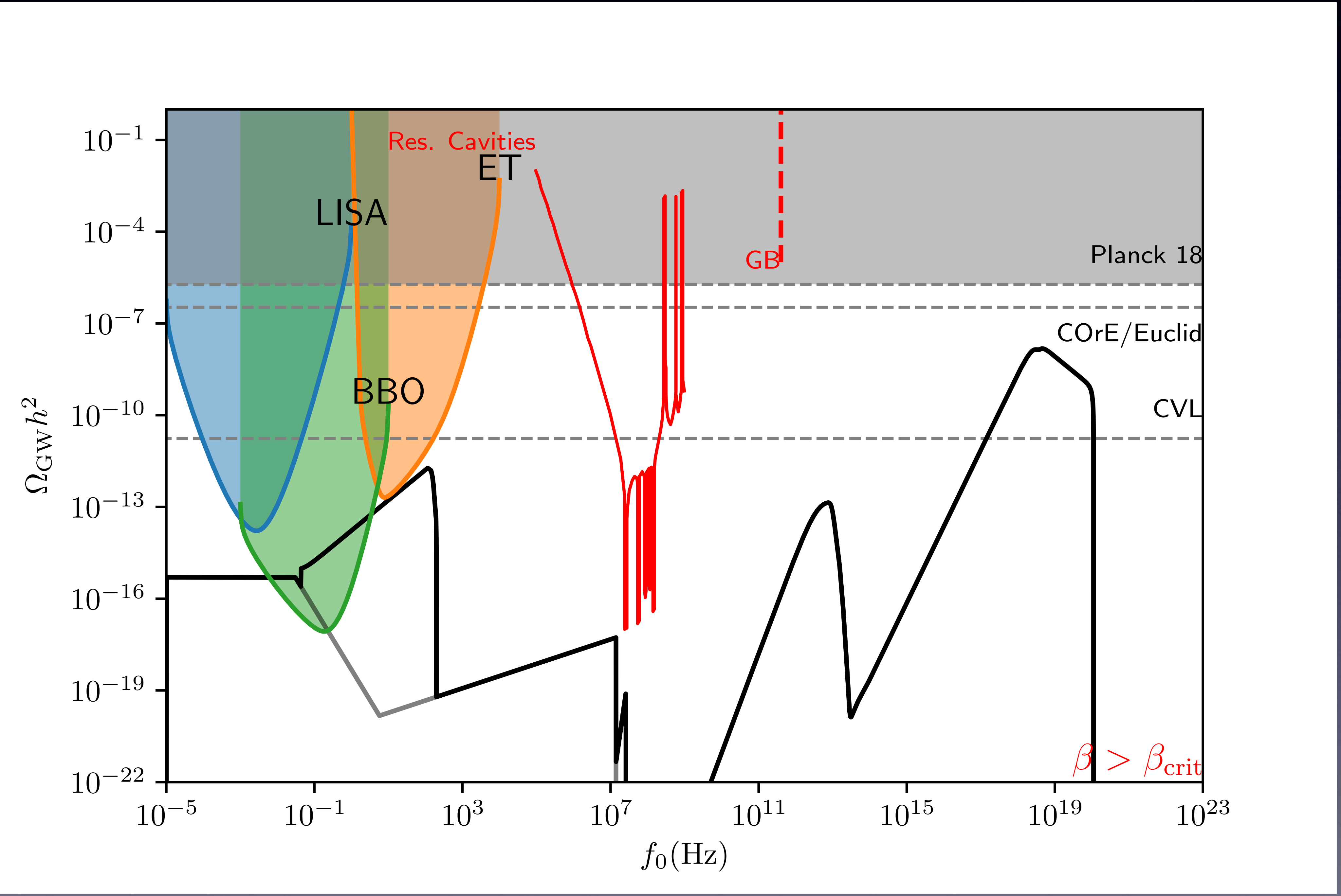


Memory burdening the PBH



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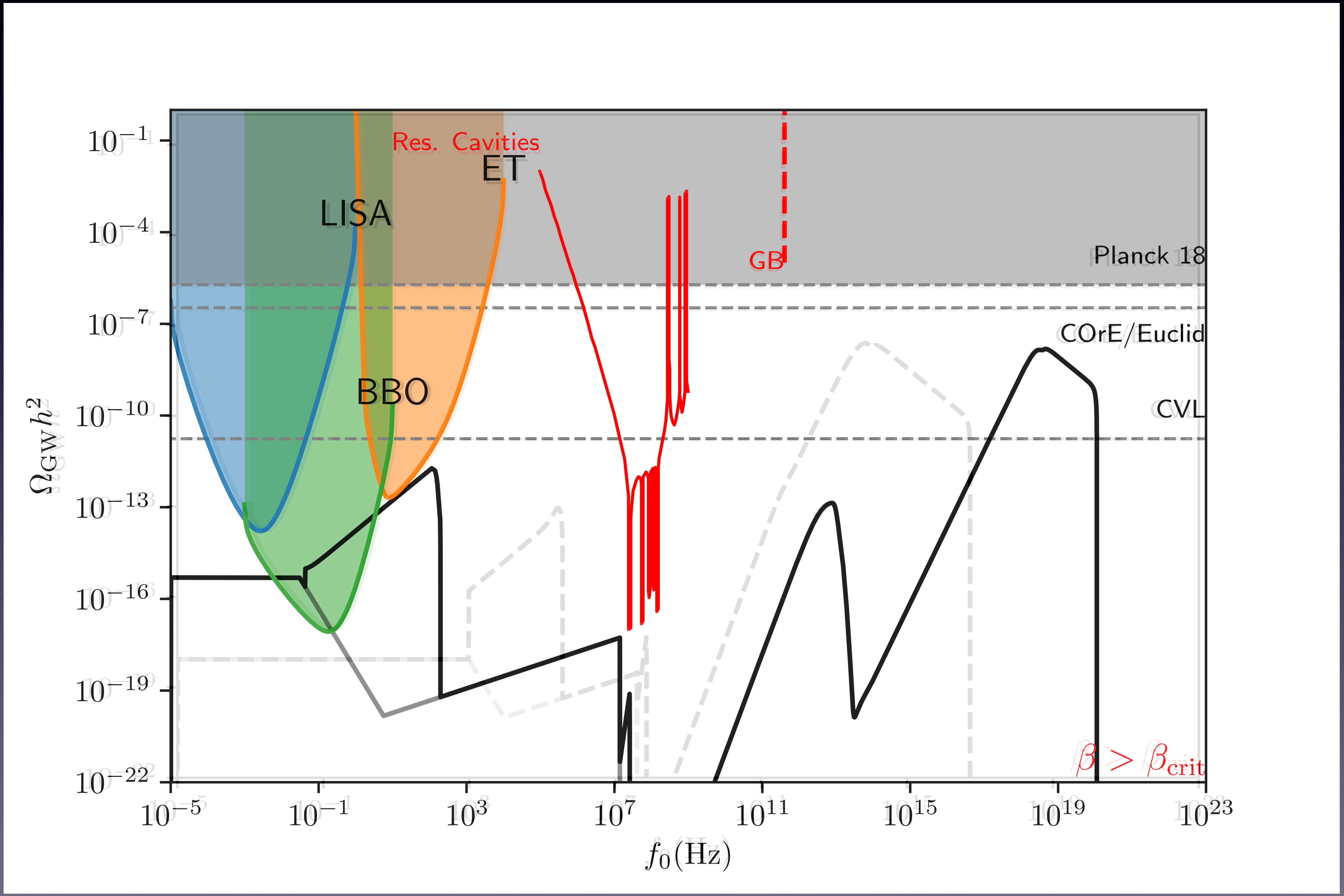
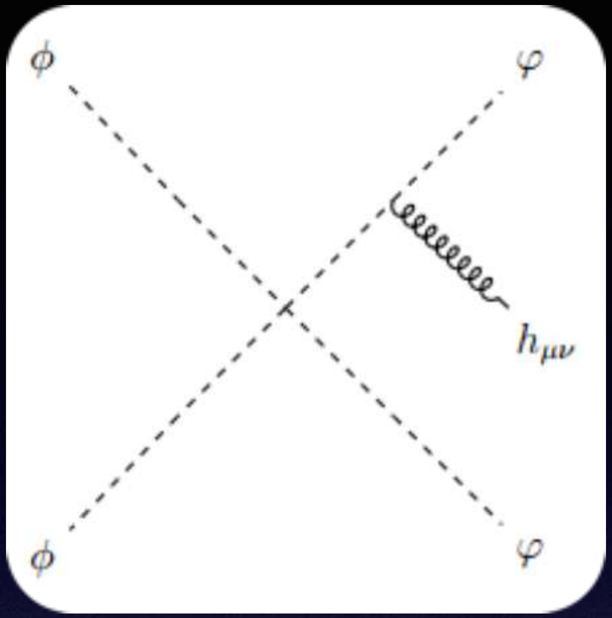


Graviton bremsstrahlung



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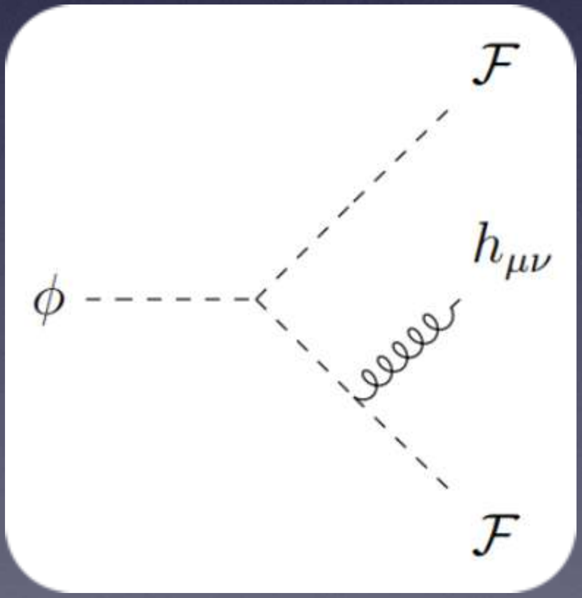

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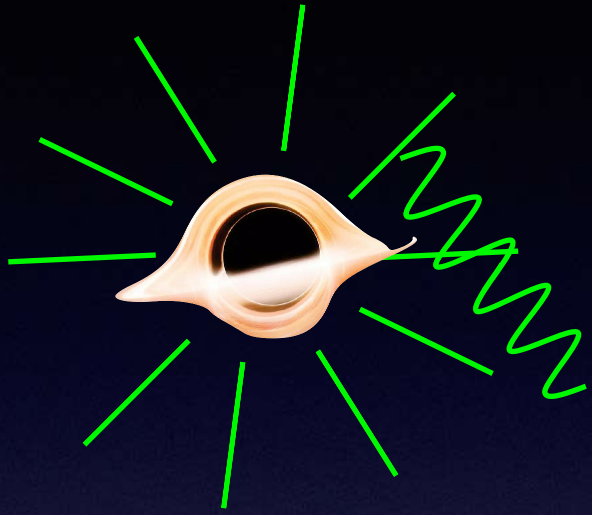

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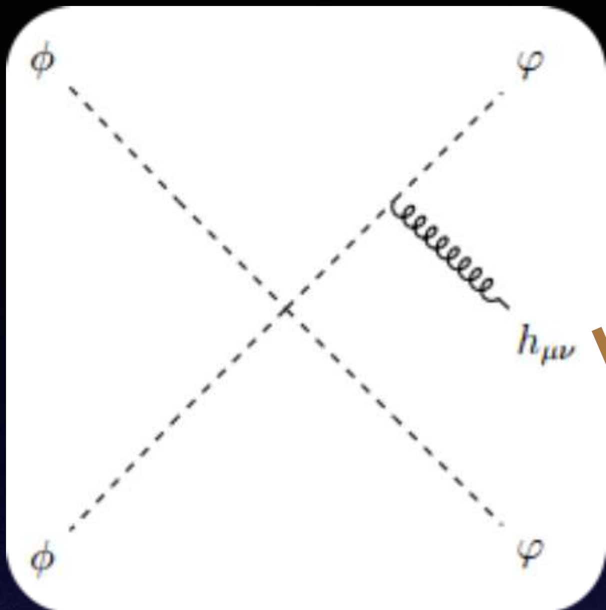

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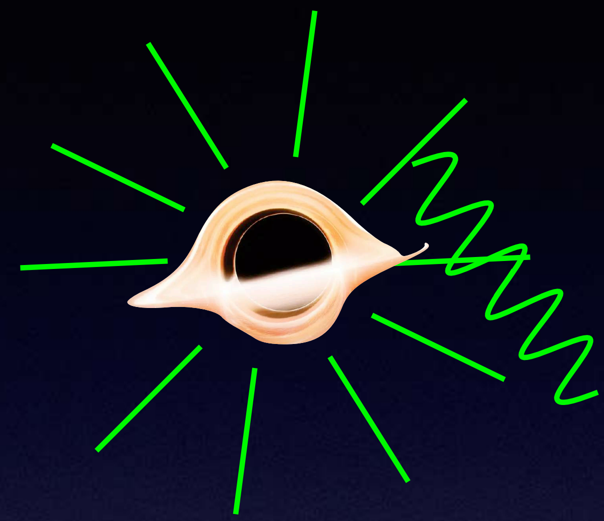

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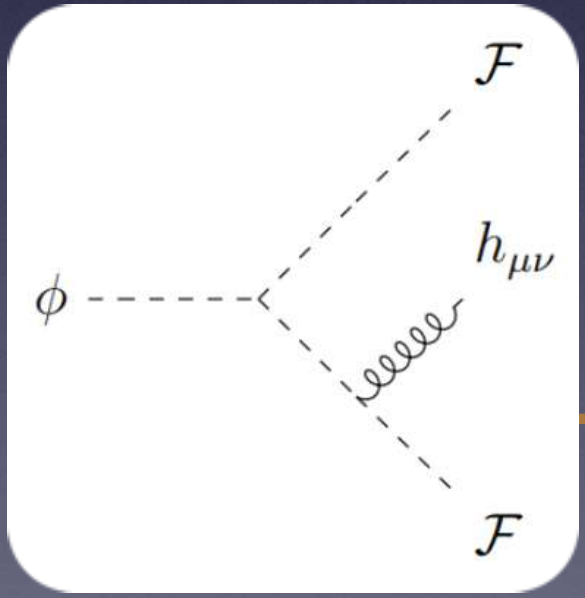

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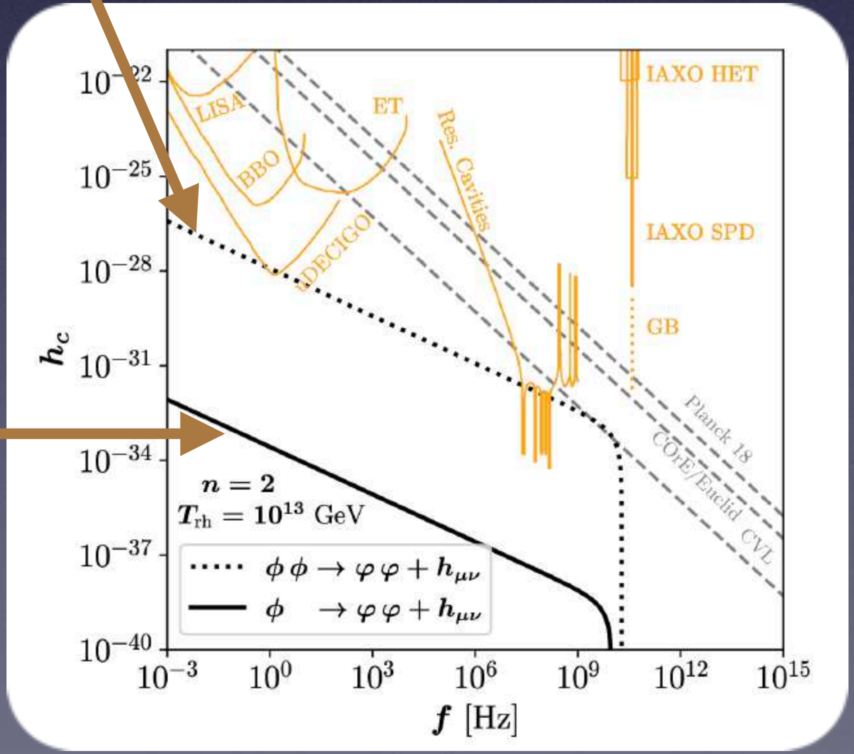

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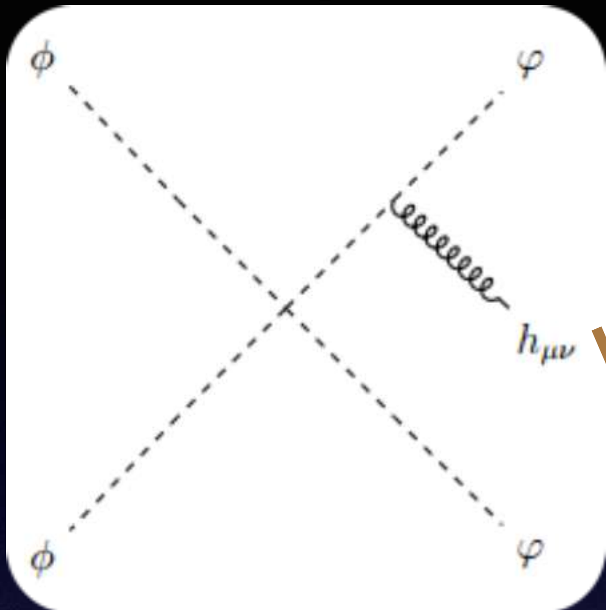

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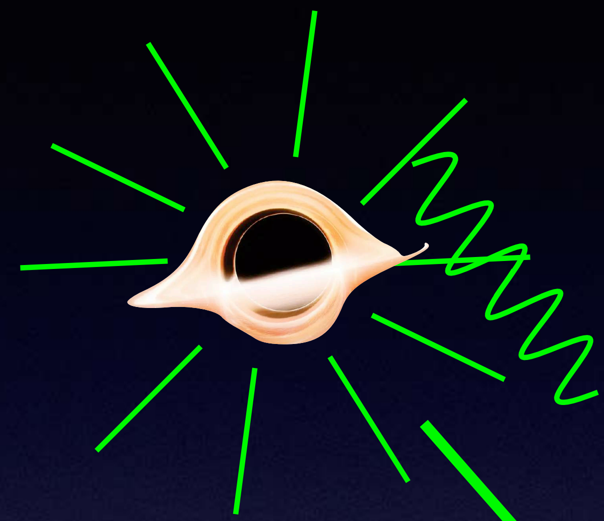

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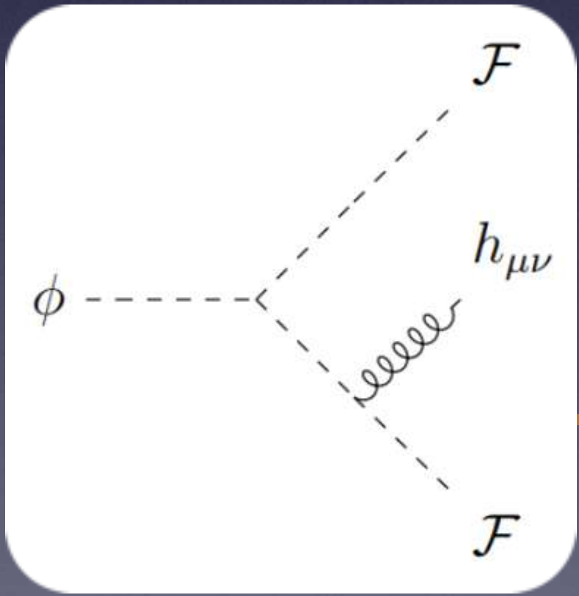

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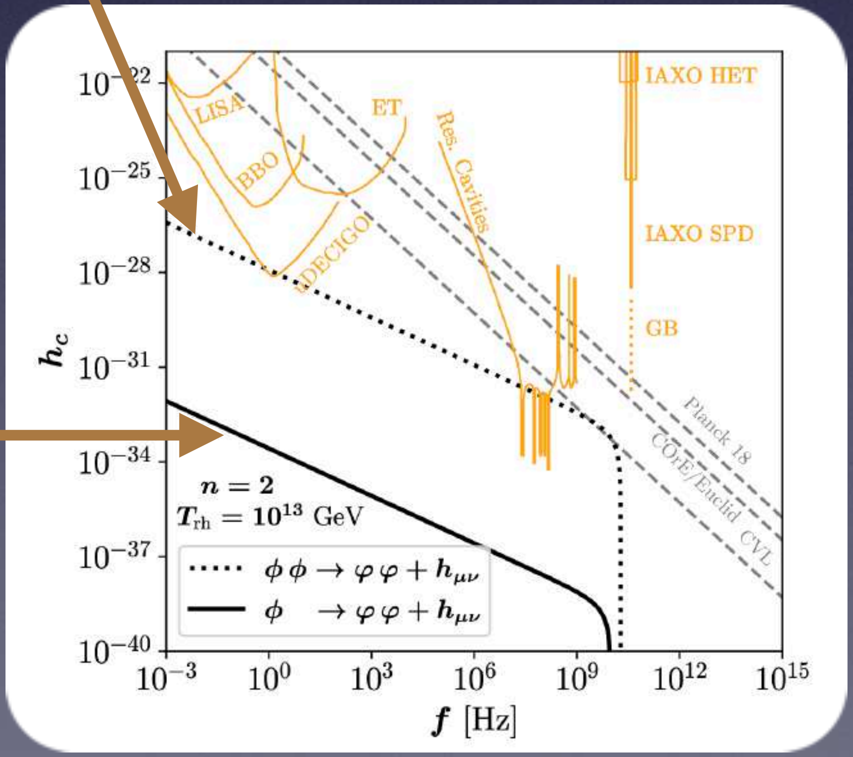
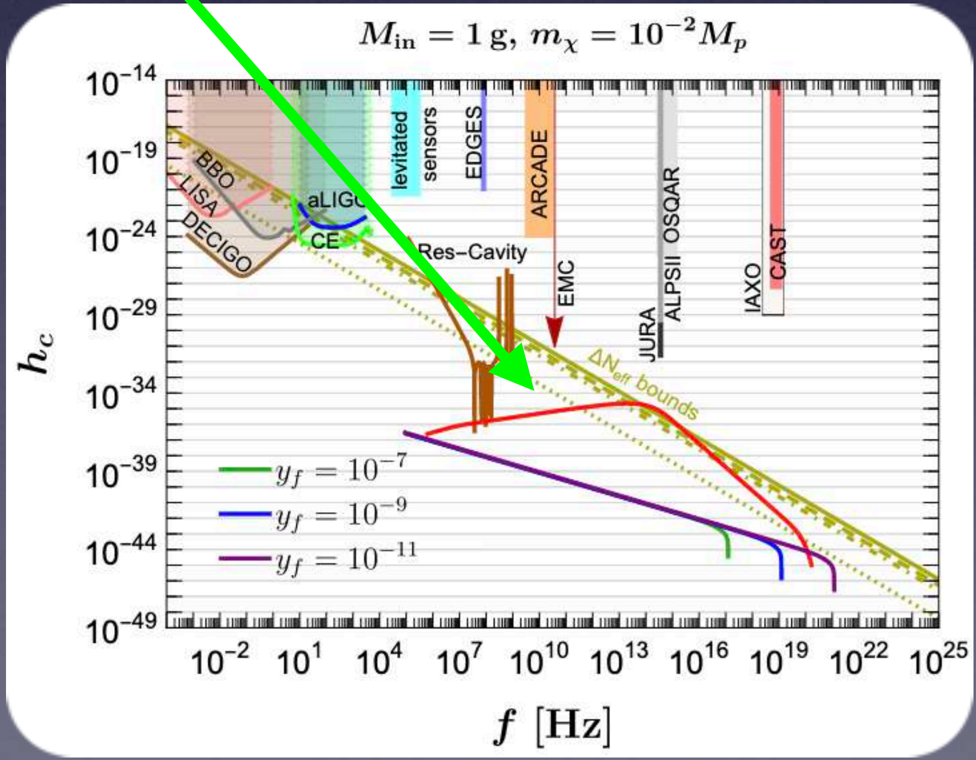
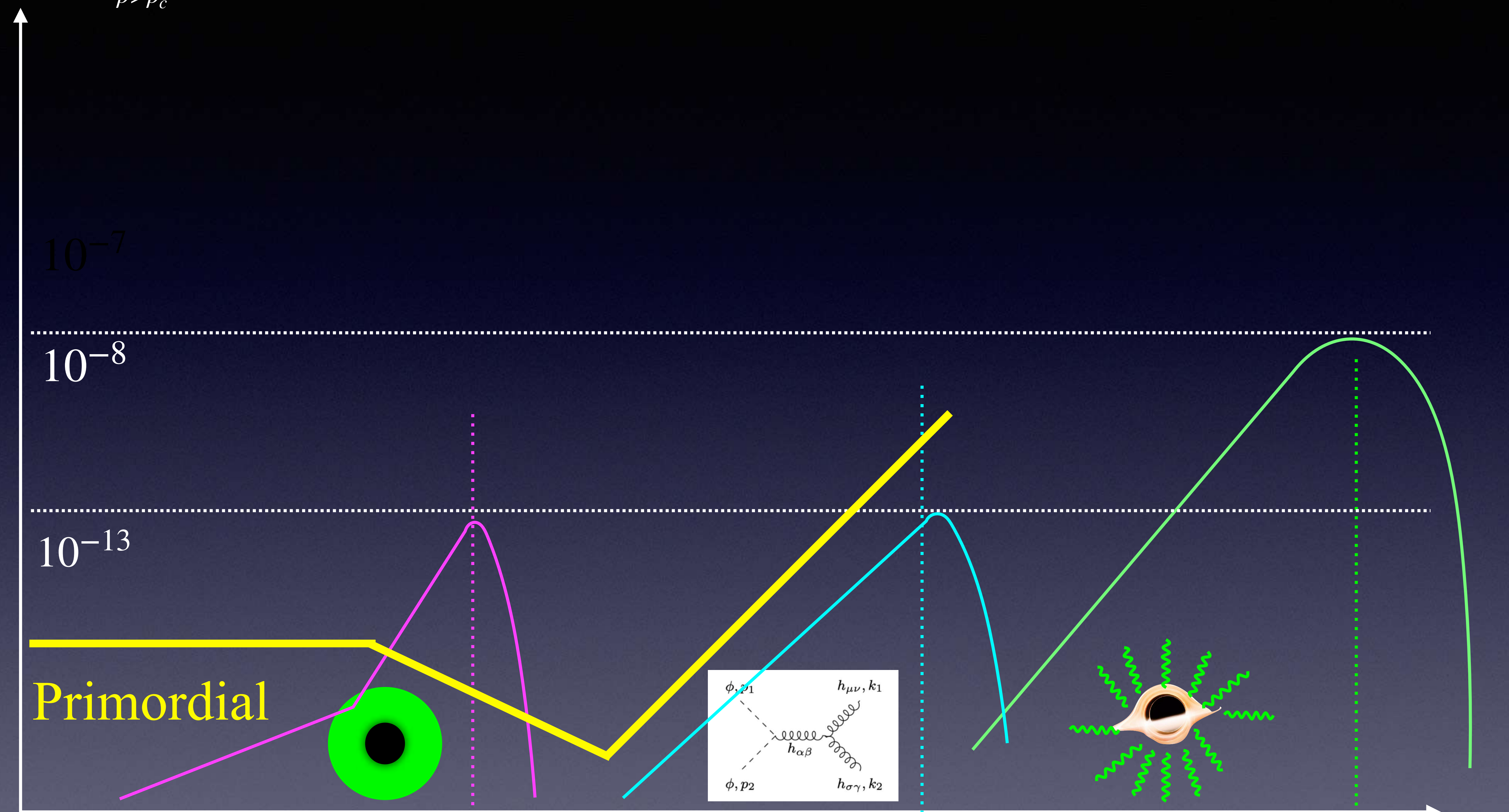




Conclusion : PGW spectrum summary

$\left.\frac{d\Omega_{GW}^{BH}}{d\ln k_0}\right|_{\beta>\beta_c}$



$f_0^{\phi} \sim 10^3 \left(\frac{10^4\ \mathrm{g}}{M_{BH}}\right)^{\frac{5}{6}}$ Hz

$f_0^{\phi} \sim 10^9 \left(\frac{10^{10}}{T_{RH}}\right)^{\frac{5k-2}{6k}}$ Hz

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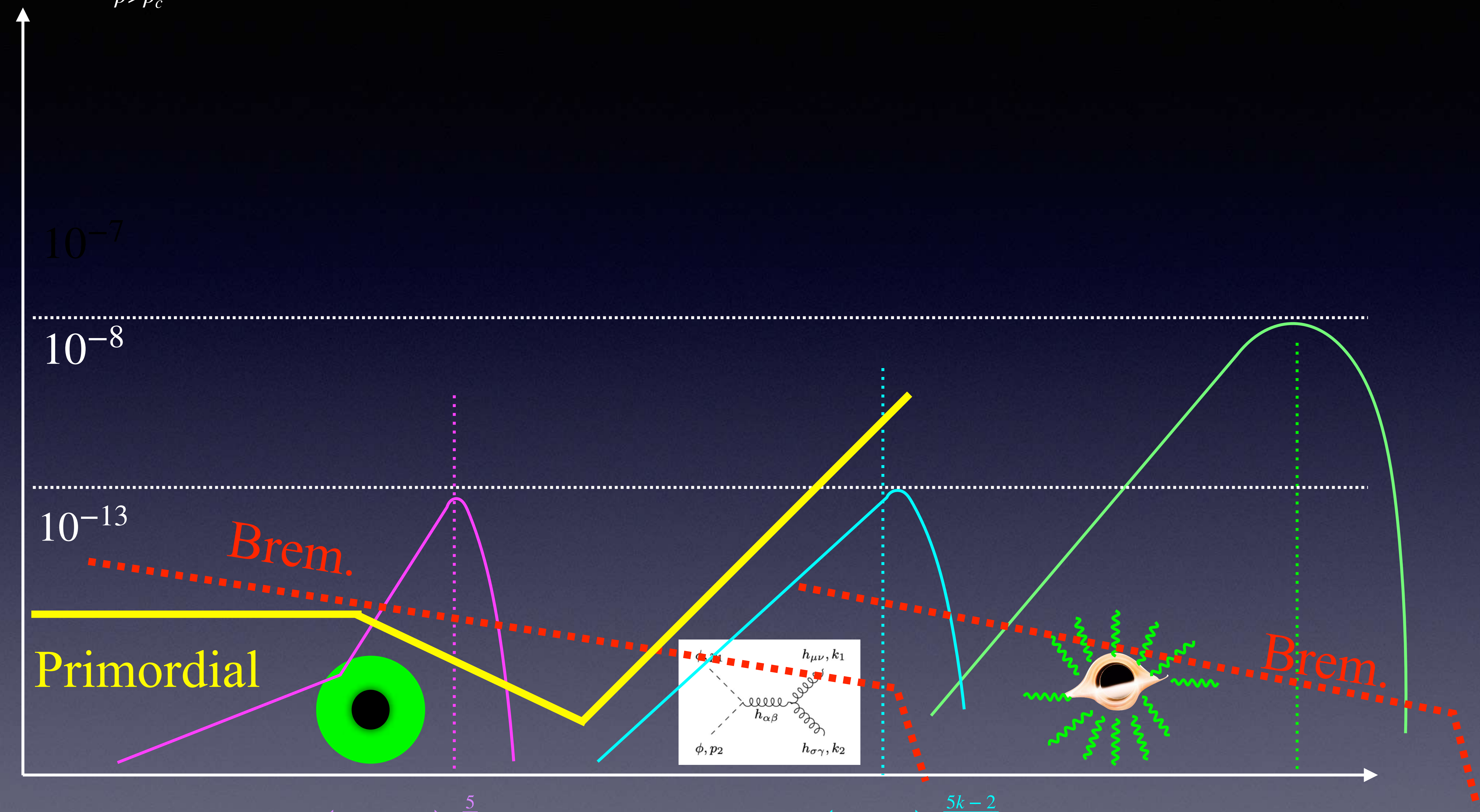

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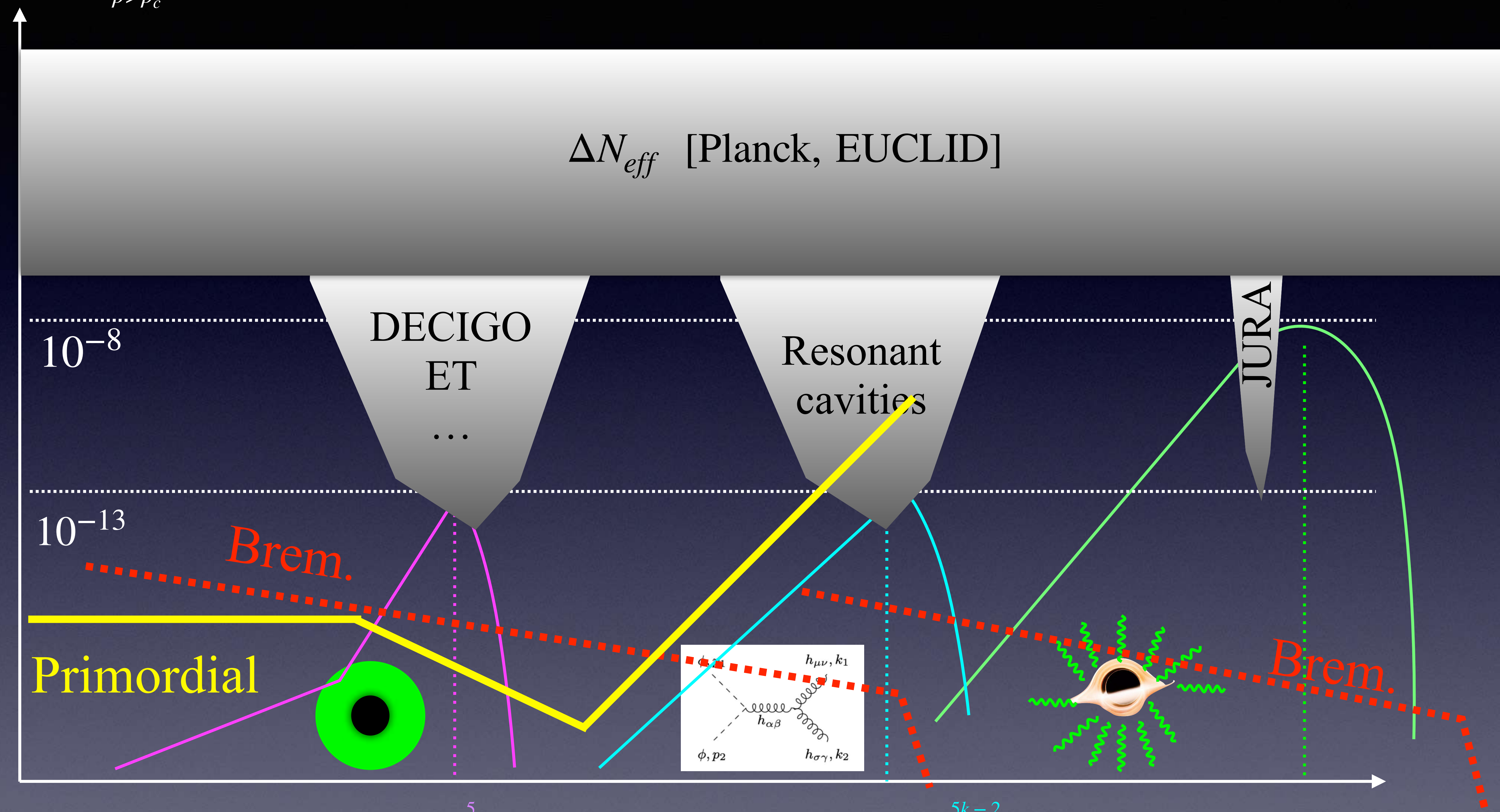

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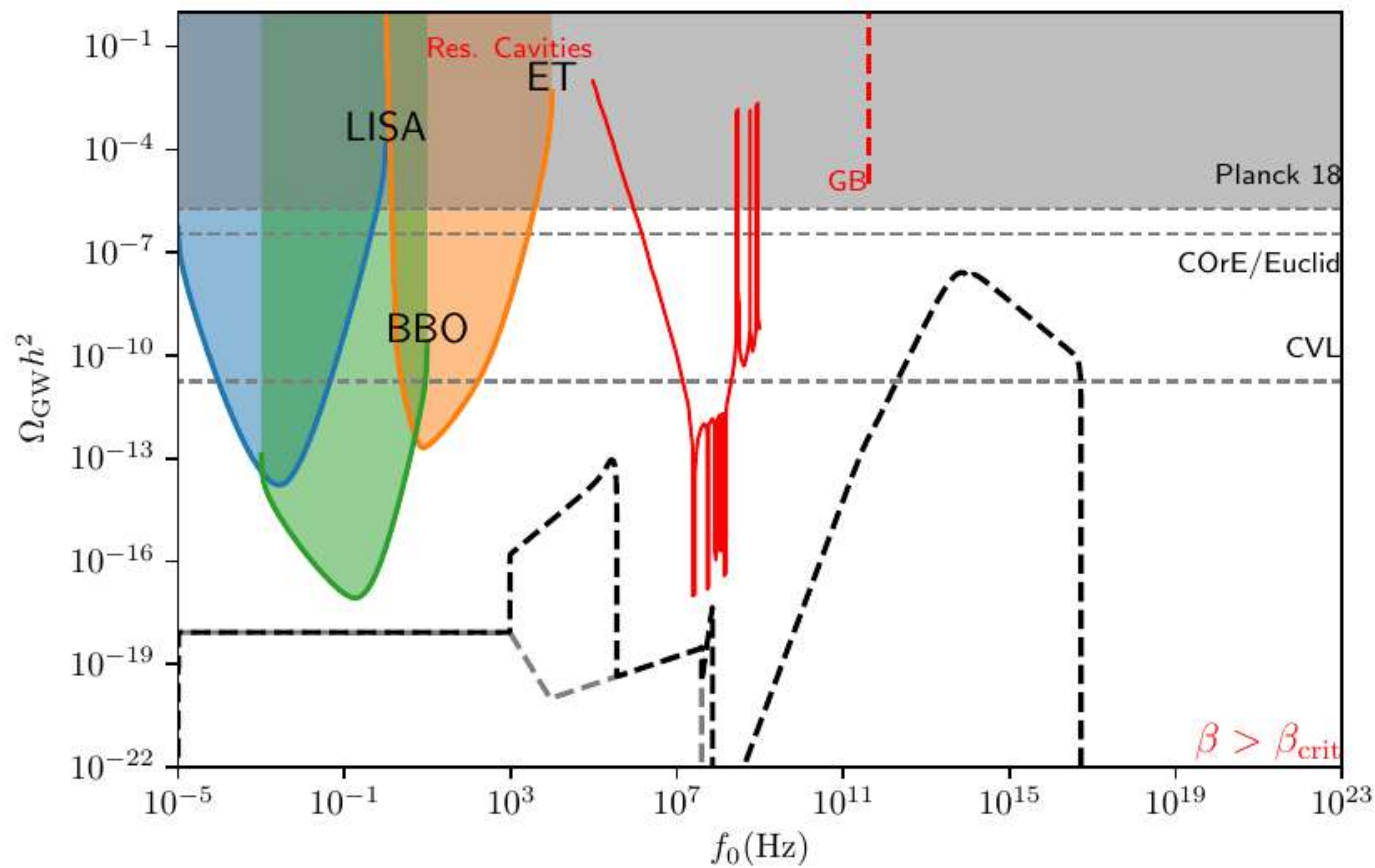
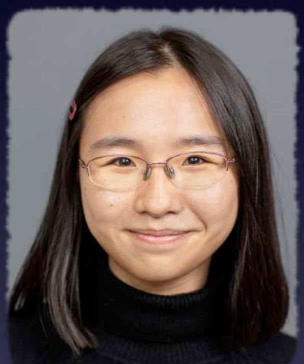
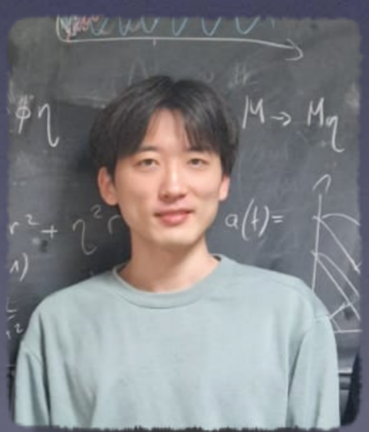


Thank you!

Mathieu Gross



Wenqi Ke



Jong-Hyun Yoon

Simon Clery

Gyonju Choi

$$ds^2 = \left(1 - \frac{R_S}{r} - \frac{\Lambda}{3}r^2\right) dt^2 - \frac{dr^2}{1 - \frac{R_S}{r} - \frac{\Lambda}{3}r^2}$$

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Two horizons, the Schwarzschild one

$$r = R_S = \frac{M_{BH}}{4\pi\ M_P^2} \quad \Rightarrow ds^2 = d\tau^2 - e^{2\frac{\rho}{R_S}} d\rho^2 \quad \Rightarrow \quad H_S = 4\pi \frac{M_P^2}{M_{BH}}$$

and the de Sitter one

$$r = \sqrt{\frac{3}{\Lambda}} \quad \Rightarrow \quad ds^2 = d\tau^2 - e^{2\sqrt{\frac{\Lambda}{3}}\tau} d\rho^2 \quad \Rightarrow \quad H_\Lambda = \sqrt{\frac{\Lambda}{3}}$$

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$\phi = \int \alpha_\omega \, e^{i\omega\tau} + \beta_\omega \, e^{-i\omega\tau}$ followed by a Bogoliubov transformation

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$$|\beta_\omega|^2 \ : \ 0 \ \rightarrow \ \frac{1}{e^{\frac{2\pi\omega}{H}} - 1} \quad \text{which implies} \quad T_H = \frac{H}{2\pi} = \begin{cases} \frac{M_P^2}{M_{BH}} \\ \frac{H_\Lambda}{2\pi} \end{cases}$$

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The vacuum state of a field depends on the motion of the observer

or

The number of particles is observer dependent.

$$T_H = \frac{H}{2\pi} = \begin{cases} \frac{M_P^2}{M_{BH}} \\ \frac{H_\Lambda}{2\pi} \end{cases} \Rightarrow \quad \rho_\chi \sim \begin{cases} n_{BH} \times T_{BH} \\ \frac{3H_\Lambda^4}{16\pi^2} \end{cases}$$

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A second remark about the new concept of proper vibration is, that it is not always invariantly determined by the form of the universe. The separation of time from the spatial coordinates may succeed in a number of different space-time-frames. For De Sitters universe I know three of them. Besides which P. O. Müller (l.c.) has redently give tions, there is an expanding form with infinite form with finite R *). A proper vibration of one f form into a proper vibration of the other frame, variables is destroyed by the transformation.

For all I have found hithertoo I would conclude, that the alarming phenomena (i.e. pair production and reflexion of light in space) are not connected with the *velocity* of expansion, but would probably be caused by *accelerated* expansion. They may play an important part in the critical periods of cosmology, when expansion changes to contraction or vice-versa.

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"The proper vibrations of the expanding universe,"
PHYSICA, vol. 6, no. 7–12, pp. 899–912, 1939

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v_1 v_2 v_3

$V_{walkway} < v_1, v_2, v_3$

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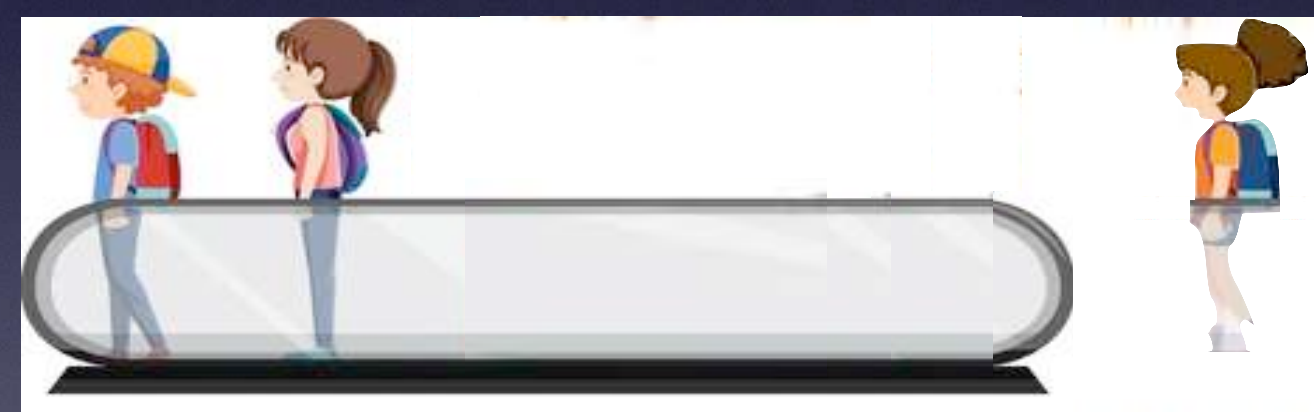

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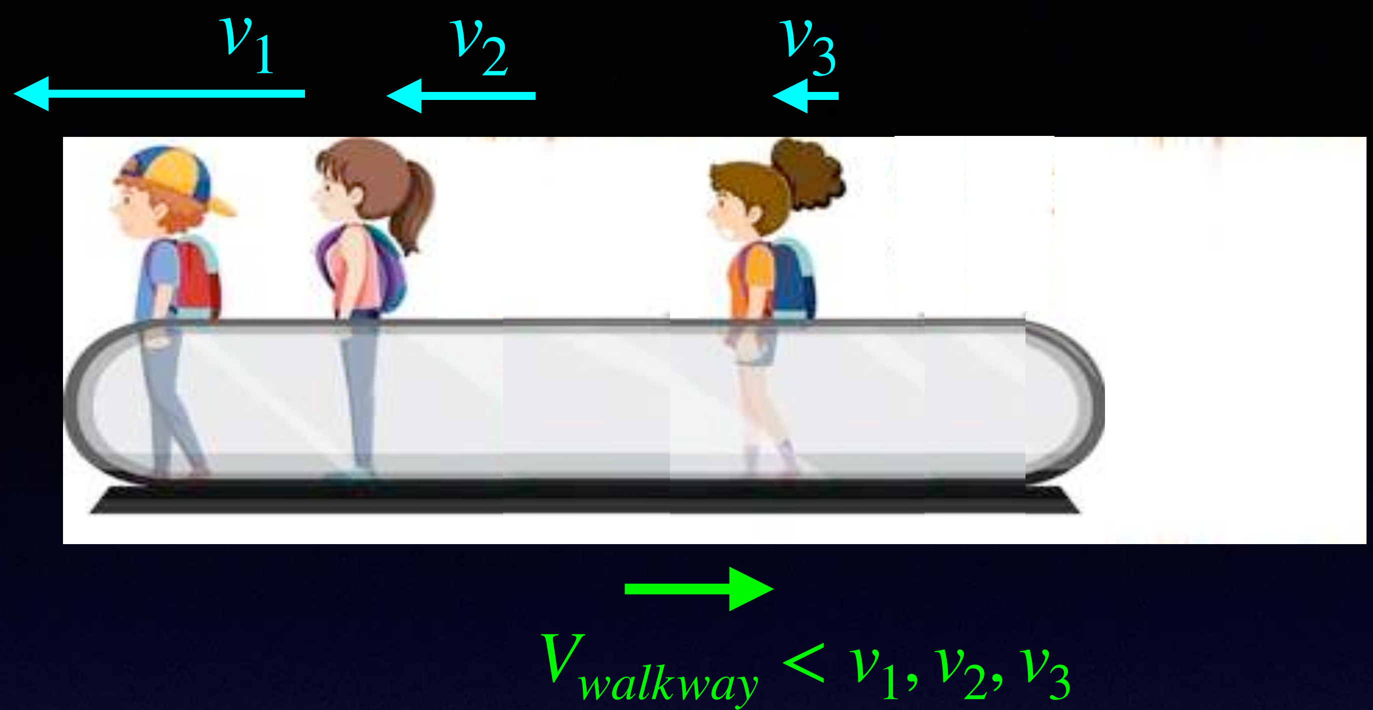

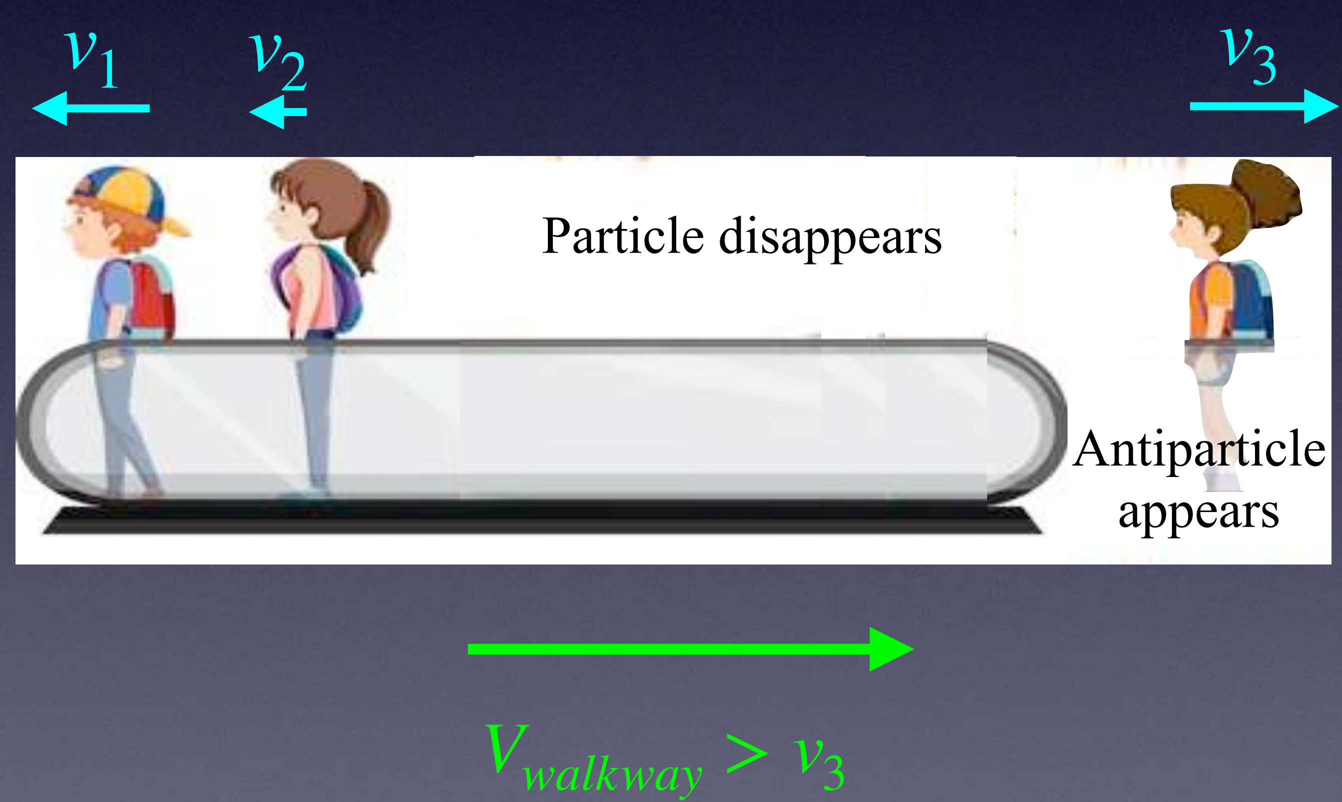

THE PROPER VIBRATIONS OF THE EXPANDING UNIVERSE 903

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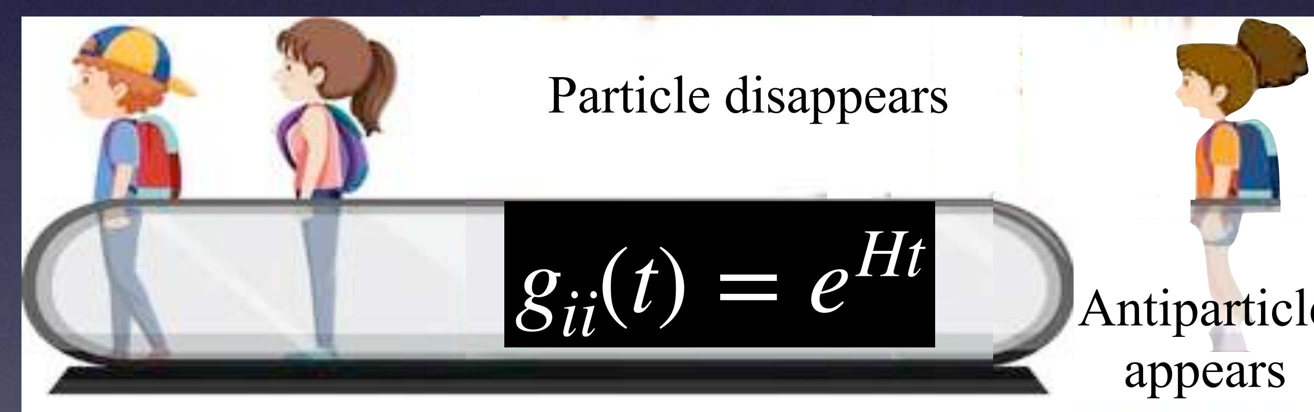
Positive frequencies
$a_\omega^\dagger e^{-i\omega t}$

v_1 v_2 v_3

$V_{walkway} < v_1, v_2, v_3$

Pos. + neg. frequencies
$\sim a_\omega^\dagger e^{-i\omega t} + \beta\, b_\omega^\dagger e^{+i\omega t}$

v_1 v_2 v_3



$V_{walkway} > v_3$

$$T_H = \frac{H}{2\pi} = \begin{cases} \frac{M_P^2}{M_{BH}} \\ \frac{H_\Lambda}{2\pi} \end{cases} \Rightarrow \quad \rho_\chi \sim \begin{cases} n_{BH} \times T_{BH} \\ \frac{3H_\Lambda^4}{16\pi^2} \end{cases}$$

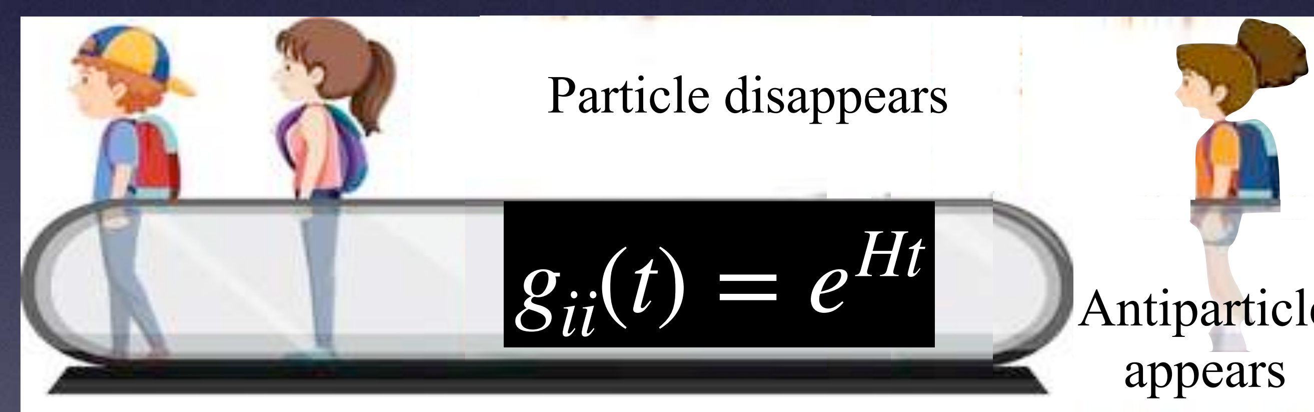
Positive frequencies
$a_\omega^\dagger e^{-i\omega t}$

v_1 v_2 v_3

$V_{walkway} < v_1, v_2, v_3$

Pos. + neg. frequencies
$\sim a_\omega^\dagger e^{-i\omega t} + \beta\, b_\omega^\dagger e^{+i\omega t}$

v_1 v_2 v_3



$V_{walkway} > v_3$

$e^{2\pi i \nu t}$ will re-assume (or approximately re-assume) the form $Ae^{2\pi i \nu' t}$ — and *not* $Ae^{2\pi i \nu' t} + Be^{-2\pi i \nu' t}$ — whenever $R(t)$, after an intermediate period of arbitrary variation, returns to constancy (or to approximate constancy). I can see no reason whatsoever for $f(t)$ to behave rigorously in this way, and indeed I do not think it does. There will thus be a mutual adulteration of positive and negative frequency terms in the course of time, giving rise to what in the introduction I called „the alarming phenomena". They are certainly very slight, though, in two cases, viz. 1) when R varies slowly 2) when it is a linear function of time (see the following sections).

A second remark about the new concept of proper vibration is, that it is not always invariantly determined by the form of the universe. The separation of time from the spatial coordinates may succeed in a number of different space-time-frames. For De Sitters universe I know three of them. Besides which P. O. Müller (l.c.) has redently give tions, there is an expanding form with infinite form with finite R *). A proper vibration of one f form into a proper vibration of the other frame, f variables is destroyed by the transformation.

For all I have found hithertoo I would conclude, that the alarming phenomena (i.e. pair production and reflexion of light in space) are not connected with the *velocity* of expansion, but would probably be caused by *accelerated* expansion. They may play an important part in the critical periods of cosmology, when expansion changes to contraction or vice-versa.

E. Schrödinger,
"The proper vibrations of the expanding universe,"
PHYSICA, vol. 6, no. 7–12, pp. 899–912, 1939

See also Schwinger effect (1951),
Unruh effect (1976)
Bunch, Davies, Ford and Parker works…

Early history of gravitational production

- 1939 : in *The Proper Vibrations of the Expanding Universe*, Schrodinger propose to treat his equation in a de Sitter metric

The expansion of the Universe can mix positive- and negative-frequency mode solutions of the wave equation. He calls it « mutual adulteration », and considered it as an « alarming phenomena » of « outstanding importance », which can produce matter « merely by the expansion of the Universe ».

- 1965 : Parker's thesis

« ... gravitational production seems inescapable if one accepts quantum field theory and general relativity »

- 1971 : Zeldovich + Starobinsky

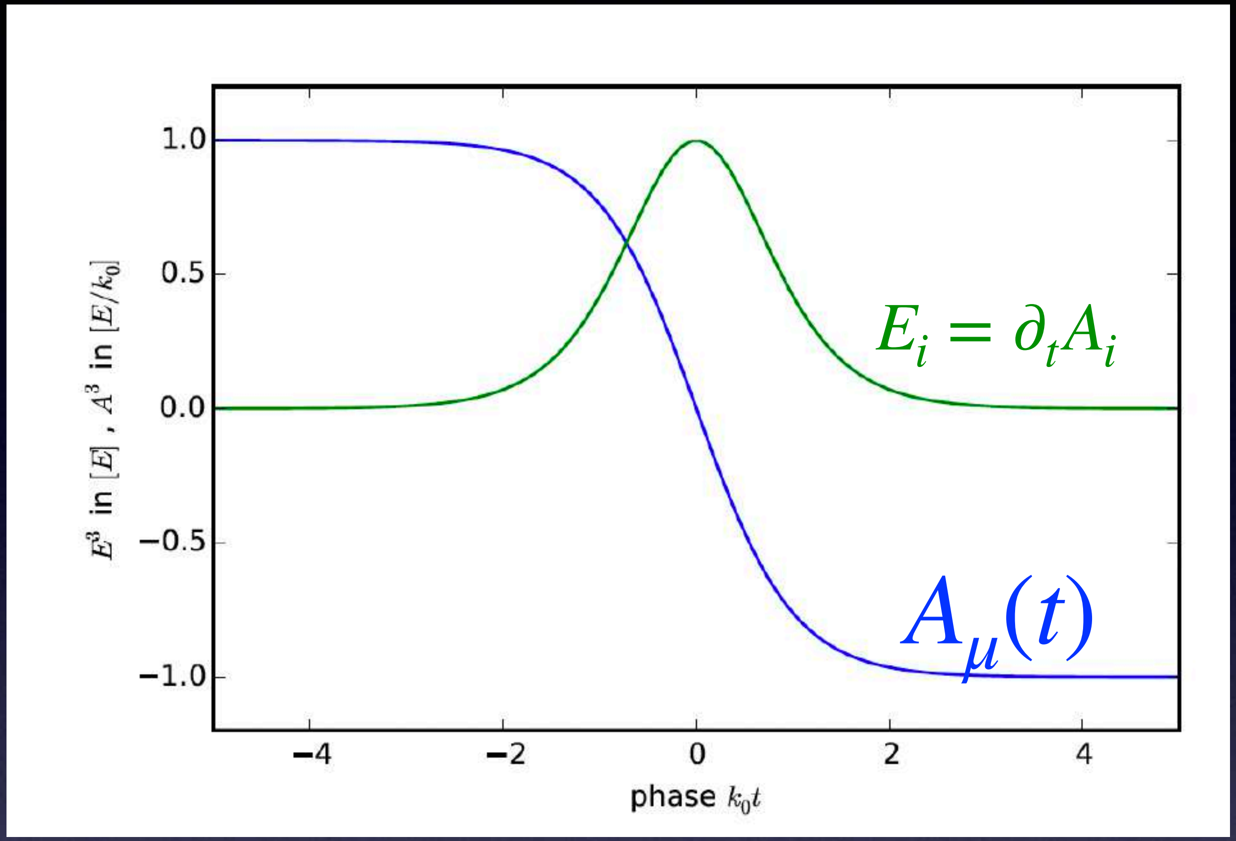
Gravitational poduction to render the Universe homogeneous (due to the homogeneity of the curvature)

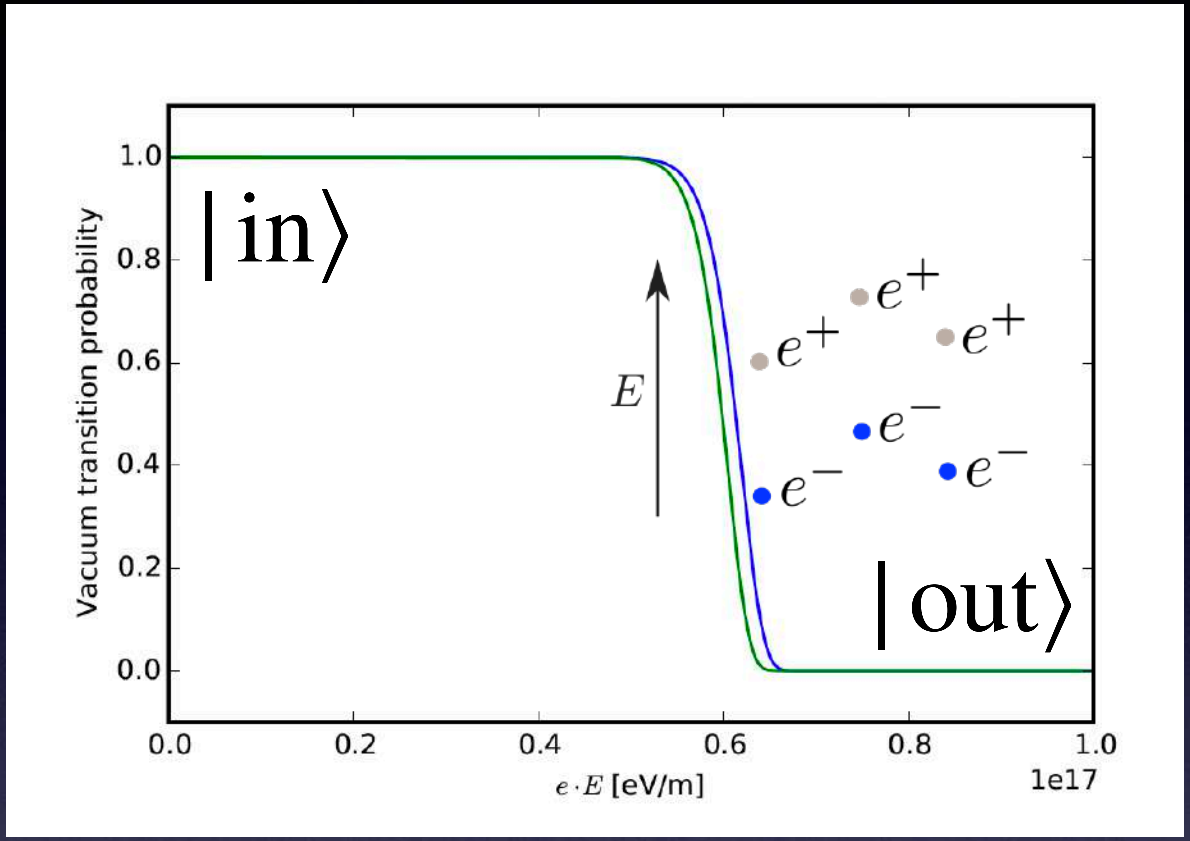
- 1981 : Mukhanov, Chibisov

Quantum fluctuations in the inflaton field leads to predictions for density perturbations explaining anisotropies of the CMB

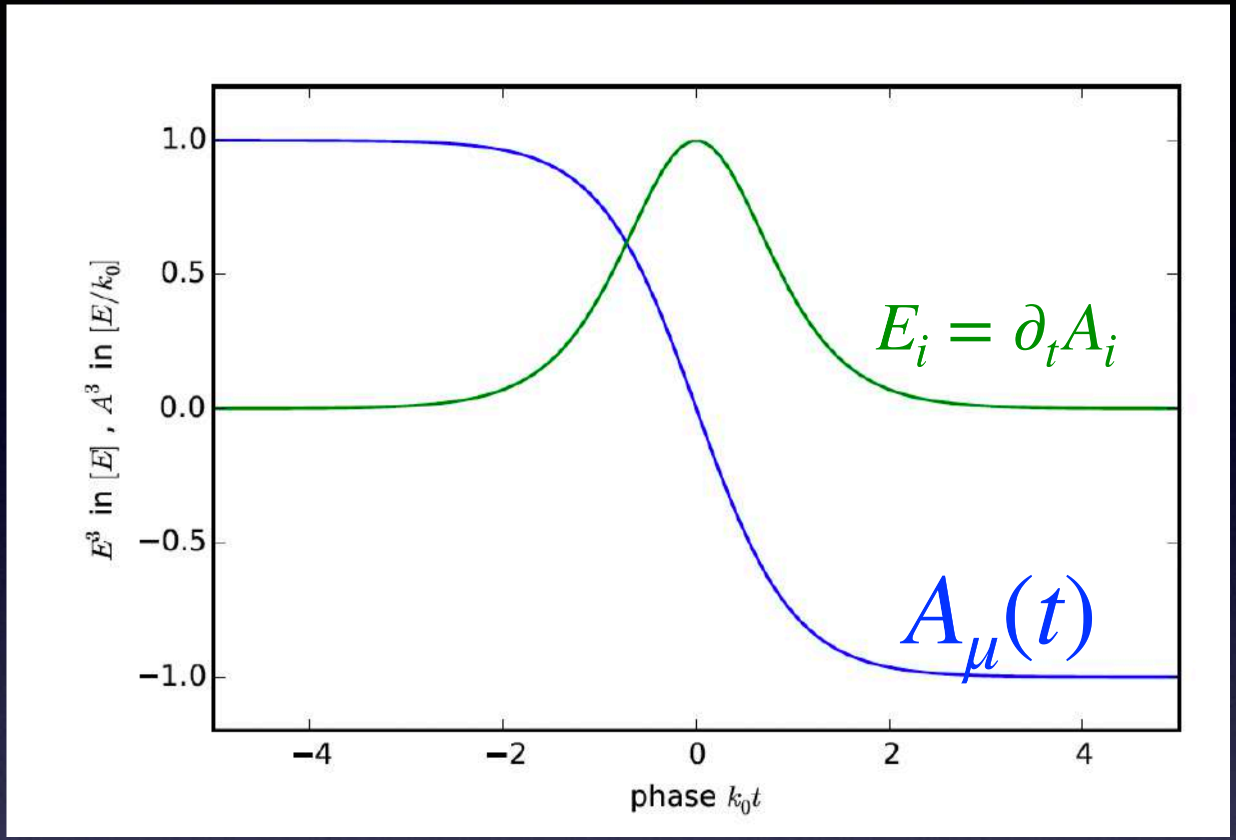
- 1987 : Ford *Applying GP to reheating, lepto and dark matter (axion) production*

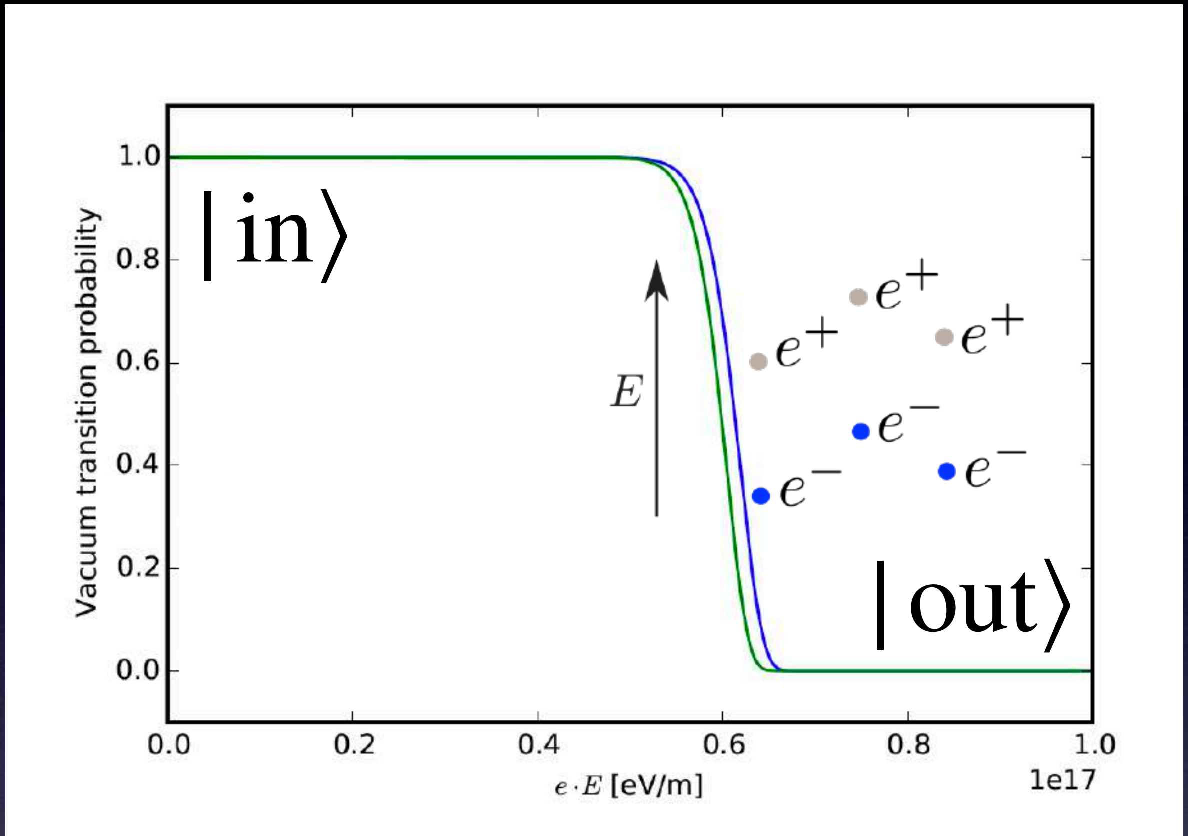
The Schwinger effect





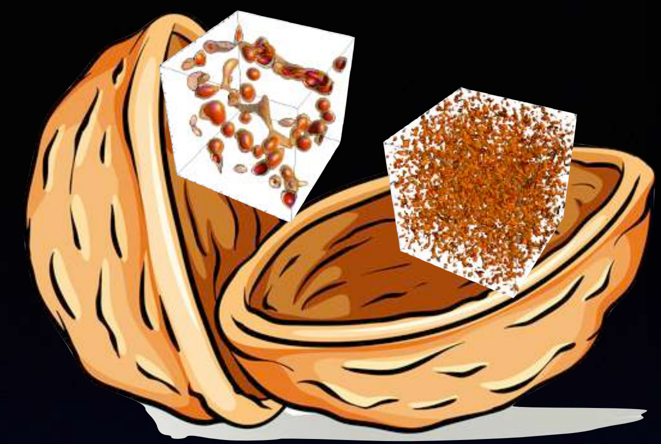
The Schwinger effect

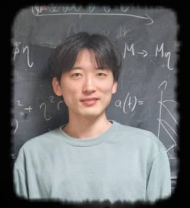




$\mathcal{L} \supset S(t)\, \chi^\dagger \chi$ $S(t) = \phi(t), A_\mu(t), g_{\mu,\nu}(t)$	Schwinger effect	Unruh effect	Hawking radiation	de Sitter temperature
Mean number	$e^{-\frac{m}{T_S}}$	$\frac{1}{e^{\frac{E}{T_U}} \pm 1}$	$\frac{1}{e^{\frac{E}{T_{BH}}} \pm 1}$	$\frac{1}{e^{\frac{E}{T_{HG}}} \pm 1}$
Temperature	$T_S = \frac{1}{2\pi}\frac{qE}{m}$	$T_U = \frac{a}{2\pi}$	$T_{BH} = \frac{M_P^2}{8\pi M_{BH}}$	$T_{dS} = \frac{H_{dS}}{2\pi}$

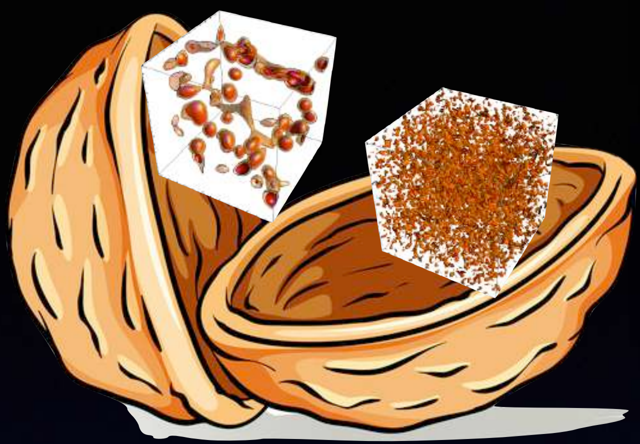
Reheating in a nutshell

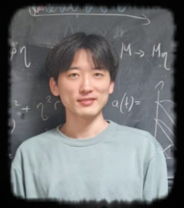




$$\phi$$

Reheating in a nutshell



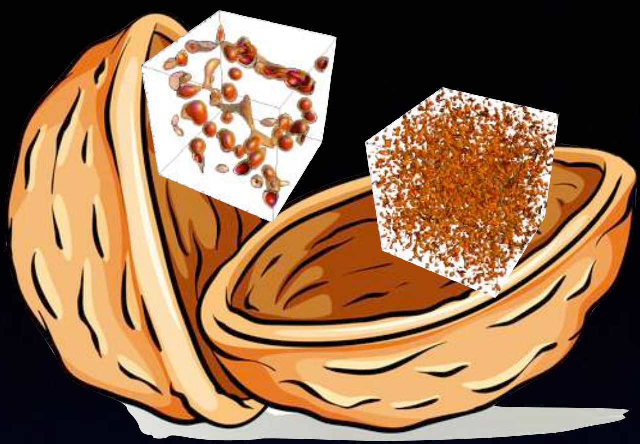


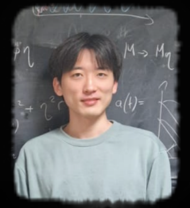
Reheating : /ˌriːˈhiːtɪŋ/ *noun*

Process of transfer of energy from a de Sitter space to radiation through the oscillations of a *classical homogeneous* field (the inflaton)

ϕ

Reheating in a nutshell





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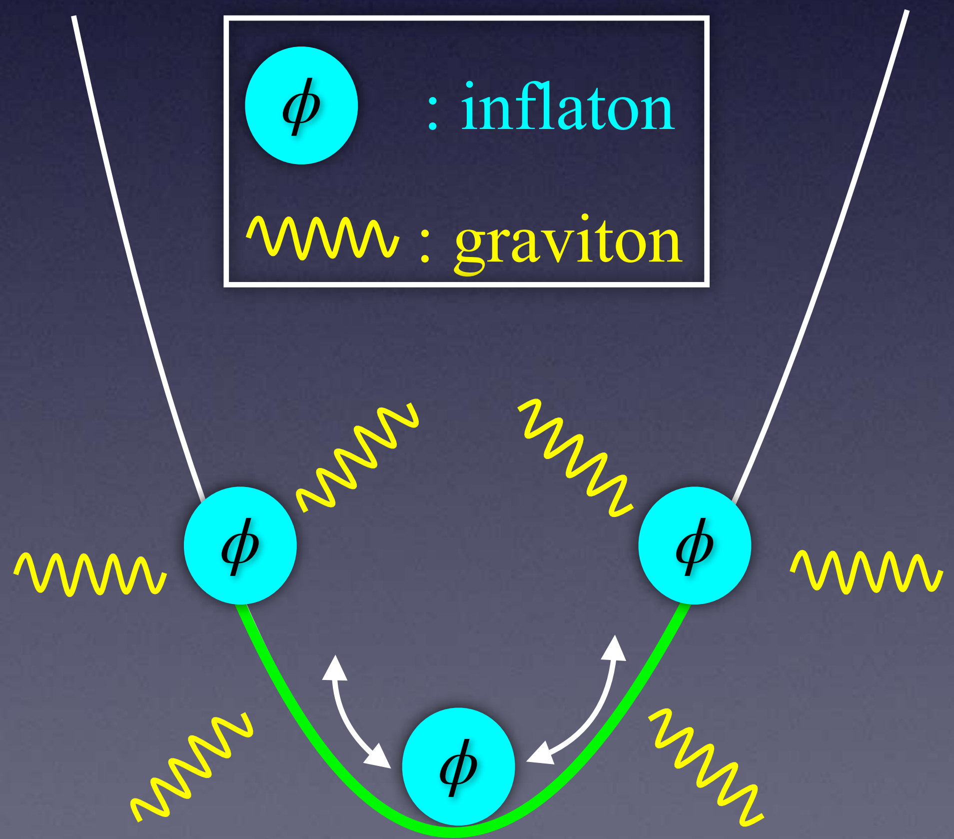
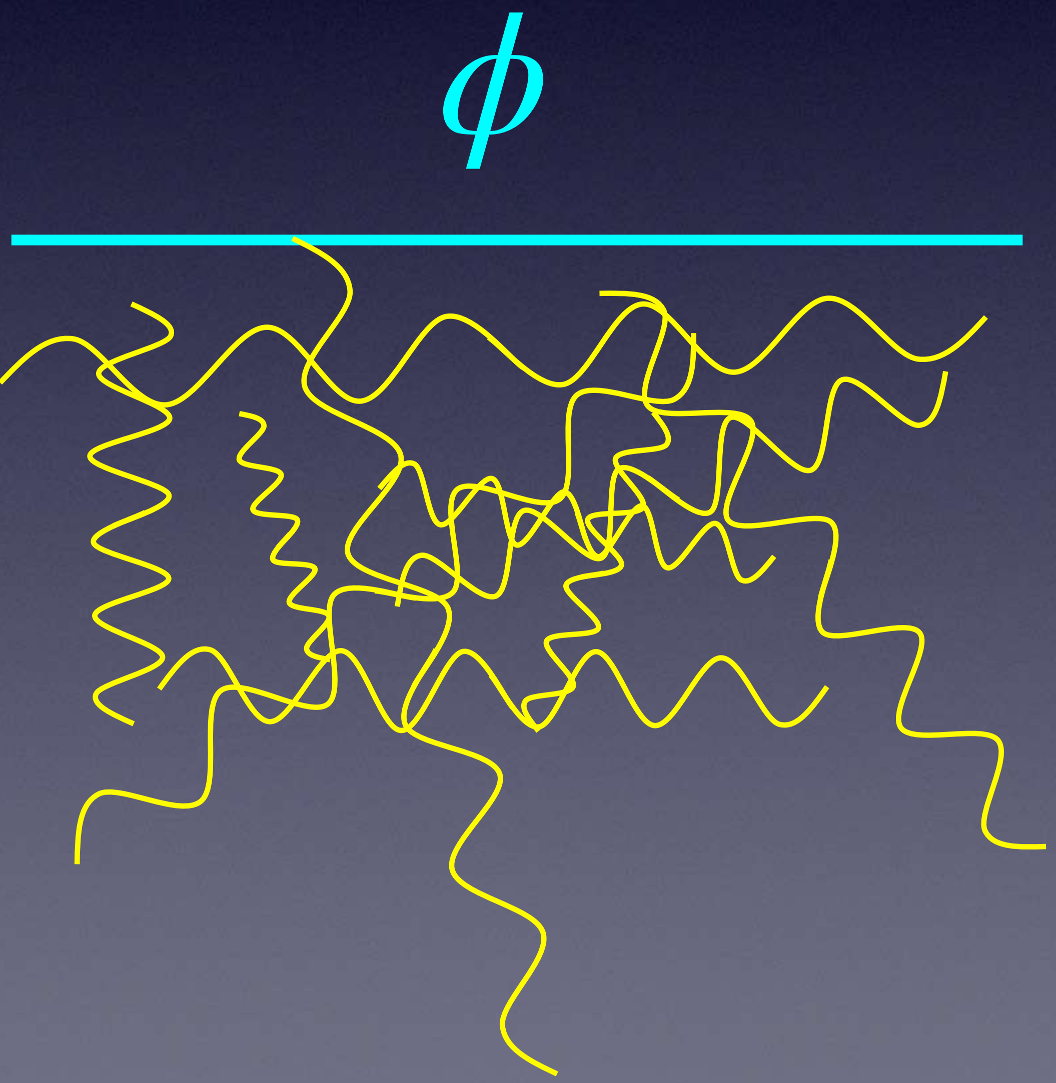
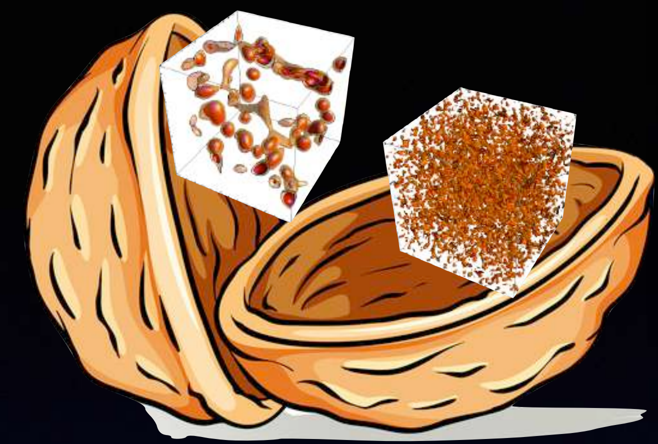
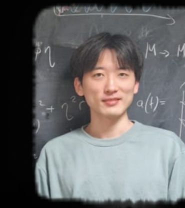




Reheating in a nutshell





$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$

$$\rho_\phi = \frac{1}{2}\dot{\phi} + V(\phi)$$

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\frac{d\rho_{GW}}{dt} + 4H\rho_{GW} = +\Gamma_\phi \rho_\phi$$

Reheating in a nutshell

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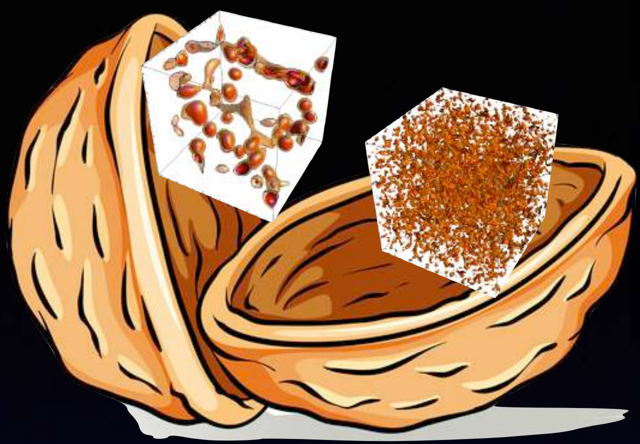
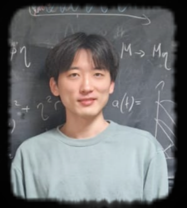
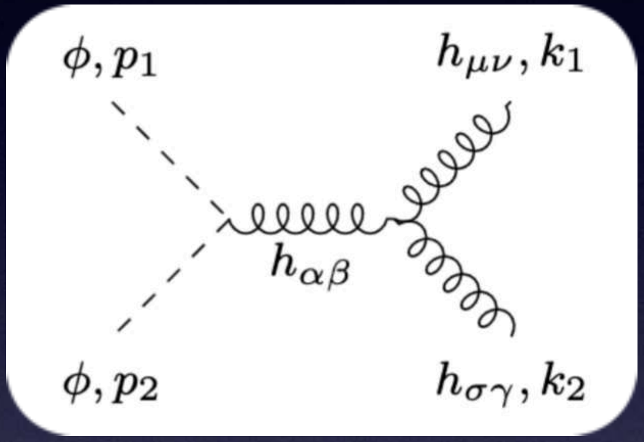
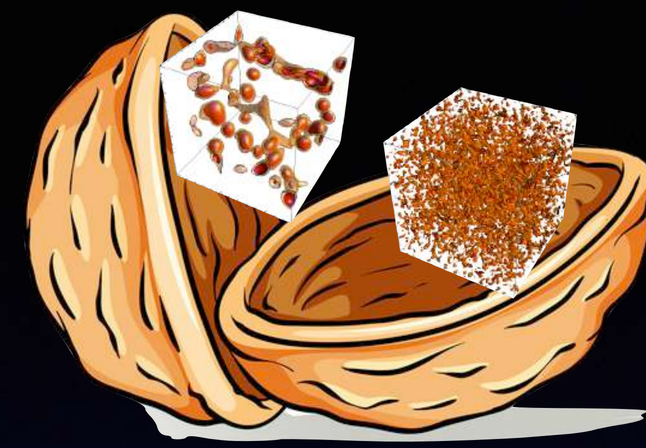


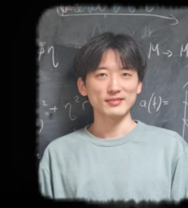




Feynman approach

Reheating in a nutshell





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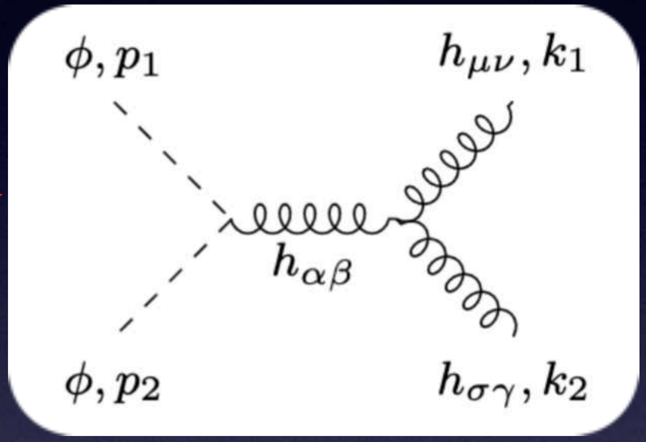
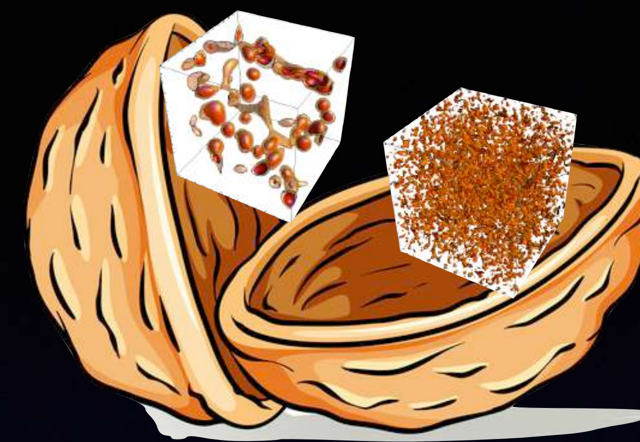
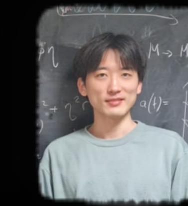


Feynman approach

Bogoliubov approach : this corresponds to the mode which *never exited the horizon* during inflation

Reheating in a nutshell





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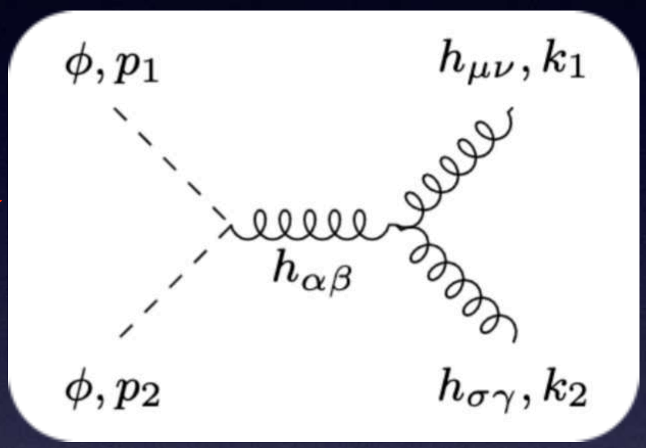

Feynman approach

Bogoliubov approach : this corresponds to the mode which *never exited the horizon* during inflation

IR PGW (bogo) :

UV PGW (⇔ Feynman)