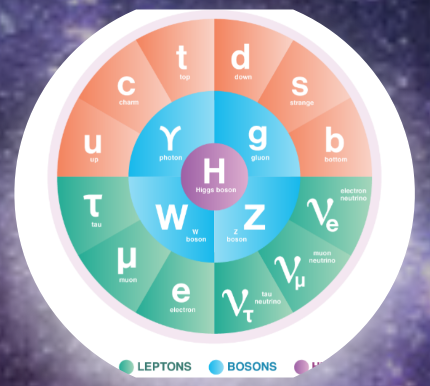
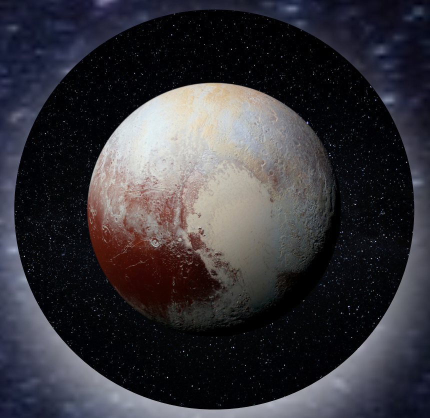
WAVES IN A BOX: RESONANT CAVITIES FOR AXION AND GW DETECTION

Raffaele Tito D'Agnolo - IPhT Saclay

DARK MATTER MASS



Person



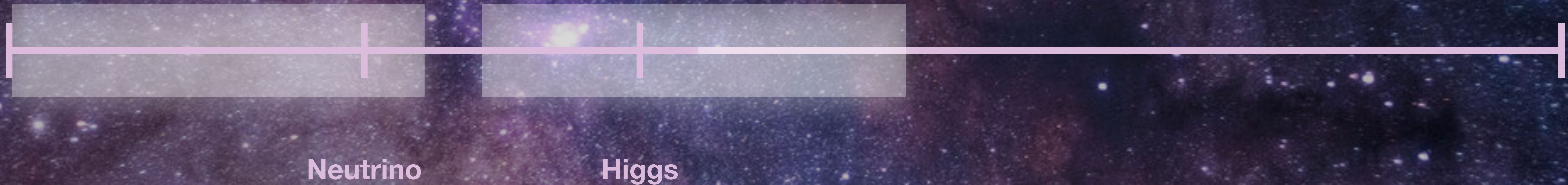
Neutrino

Higgs

Pluto


Self-coupling
50 O.M.
Mass
80 O.M.
50 O.M.
Couplings to ordinary matter

DARK MATTER MASS

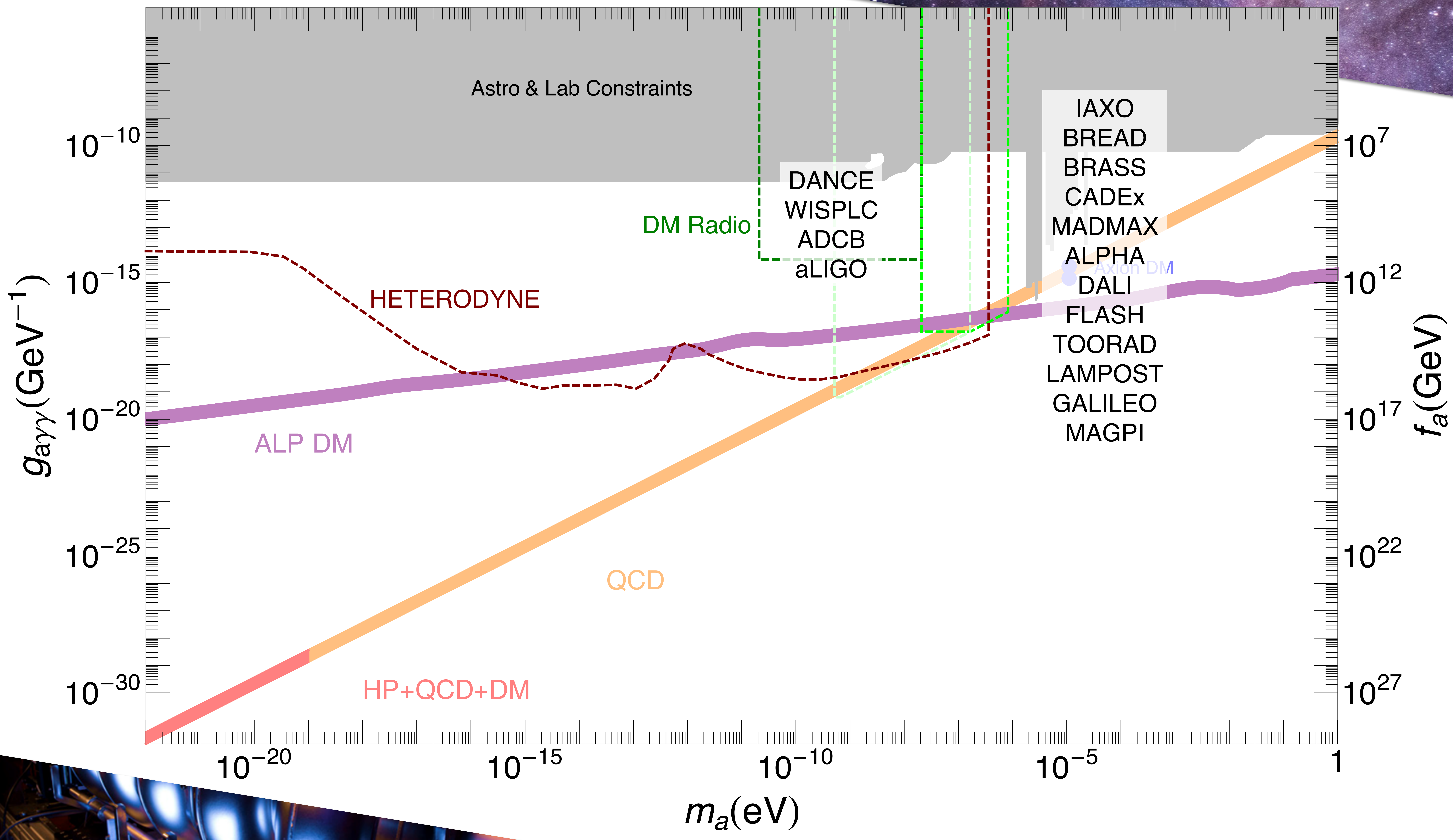


Theory Spotlight

DARK MATTER MASS

Theory Spotlight

Astro & Lab Constraints
DM Radio
HETERODYNE
Axion DM
ALP DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1



Astro & Lab Constraints
DANCE
WISPLC
ADCB
aLIGO
DM Radio
IAXO
BREAD
BRASS
CADEx
MADMAX
ALPHA
DALI
FLASH
TOORAD
LAMPOST
GALILEO
MAGPI
Axion DM
HETERODYNE
ALP DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
$f_a(\mathrm{GeV})$
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
$m_a(\mathrm{eV})$

$$\omega_g$$

ω_g
10 Hz
kHz
LIGO-VIRGO

ω_g
nHz
μHz
10 Hz
kHz
PULSAR TIMING
LIGO-VIRGO

ω_g
Largest from Astrophysics

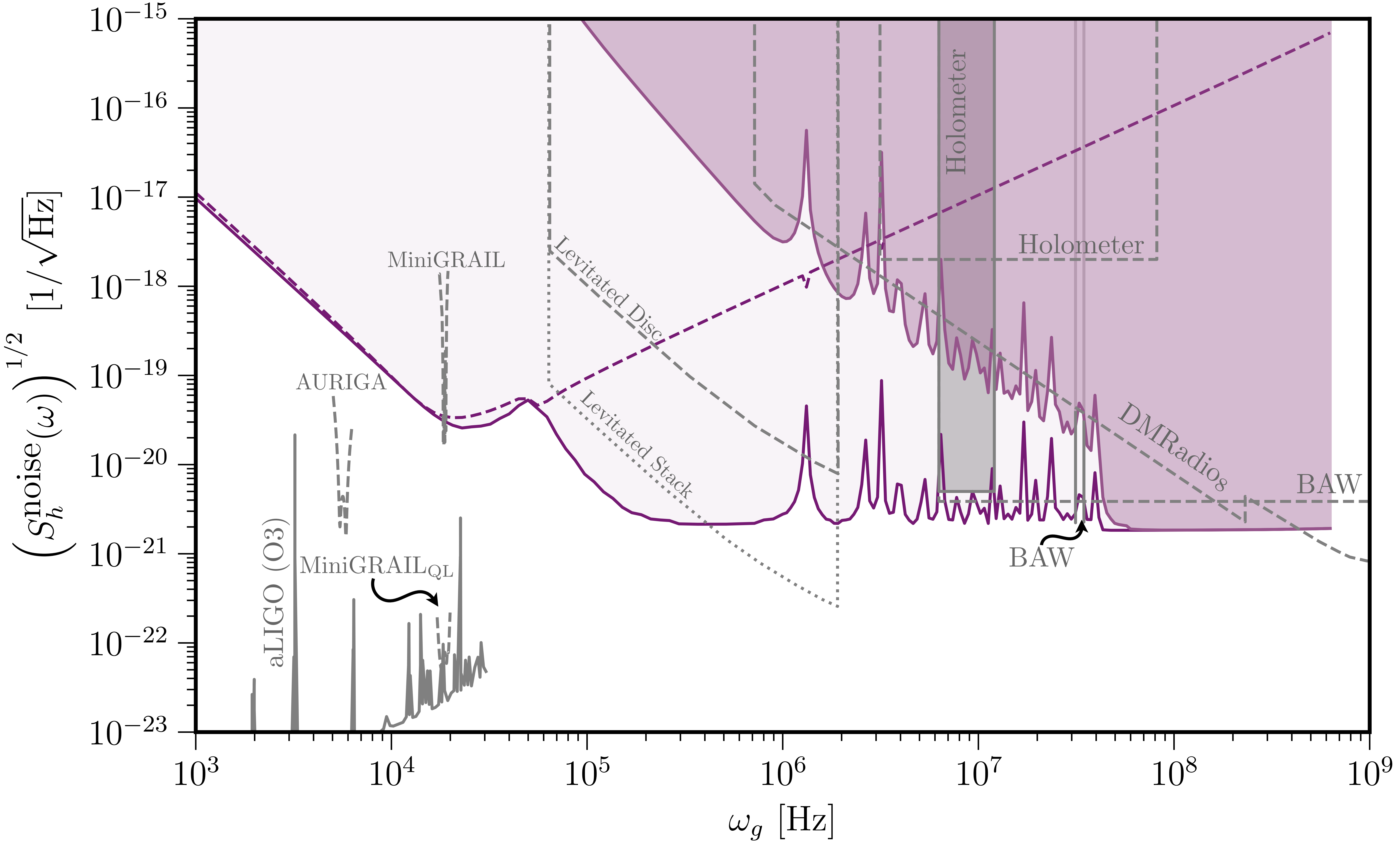
$$\omega_g$$

$$\lambda(T_*) < \frac{1}{H(T_*)}$$ Causality

$$\omega_g$$

$$\lambda(T_*) < \frac{1}{H(T_*)}$$ Causality

$$\omega_0(T_*) = \omega(T_*)\frac{a(T_*)}{a_0} \gtrsim \boxed{100\ \mathrm{MHz}}\left(\frac{T_*}{10^{15}\mathrm{GeV}}\right)\left(\frac{g_*(T_*)}{100}\right)^{1/6}$$



Berlin, Blas, D’Agnolo, Ellis, Harnik, Kahn, Schutte-Engel, Wentzel
arXiv:2303.01518

ALPS DETECTION

Dark Matter Particles in a de Broglie Volume **Today**

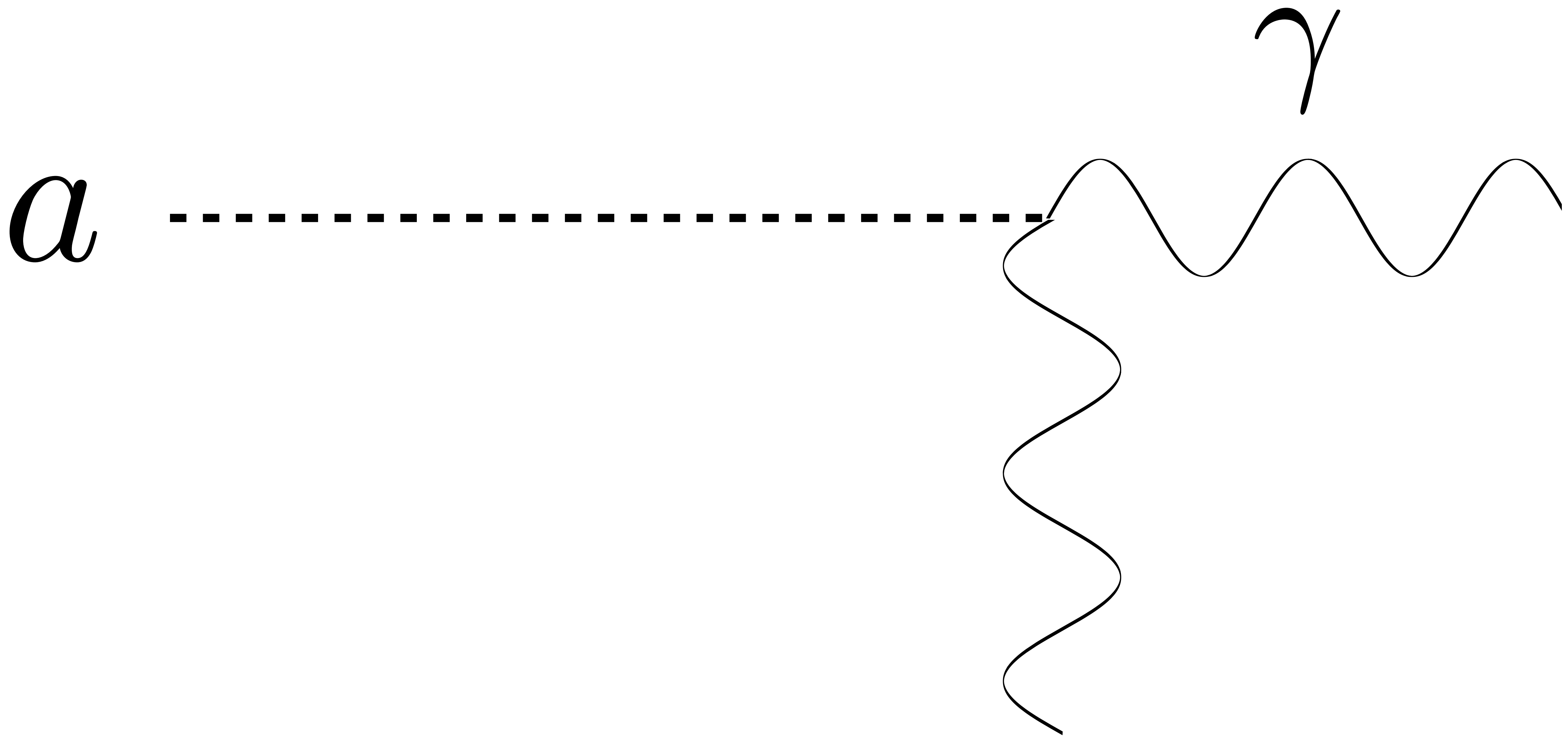
Galaxy: $$N_{\rm DM} \simeq 10^3 \left(\frac{\rm eV}{m_{\rm DM}}\right)$$

Universe: $$N_{\rm DM} \simeq 10^{-3} \left(\frac{\rm eV}{m_{\rm DM}}\right)$$

ALP DARK MATTER IN THE LAB

$$a(t) \simeq \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \cos(\omega_a t + \phi)$$

ALP DARK MATTER DETECTION



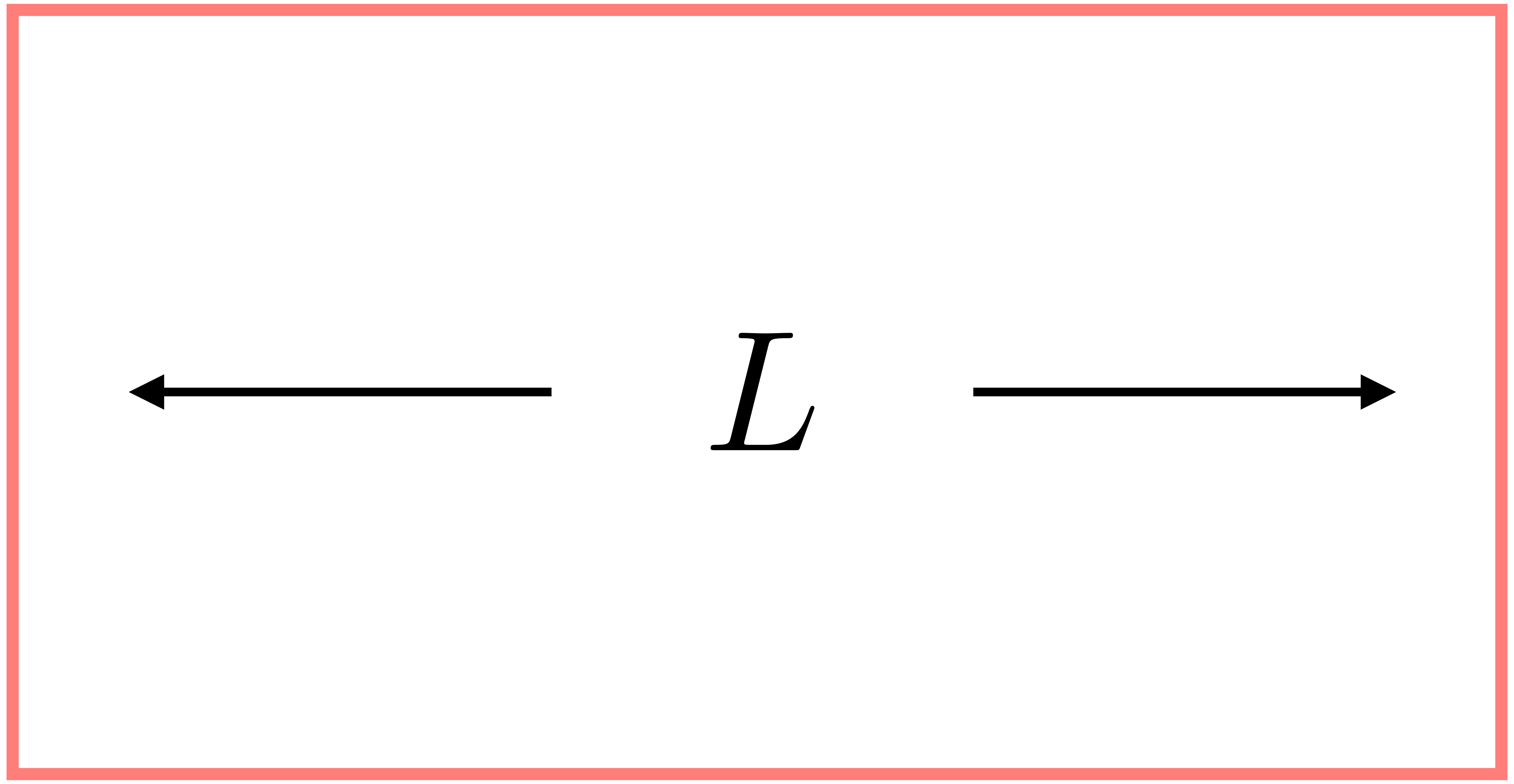
Background

$$\sim \frac{a}{f_a} E_{\rm bkg} \simeq \boxed{10^{-21} E_{\rm bkg}}$$

but you know exactly the waveform
and the signal is always there

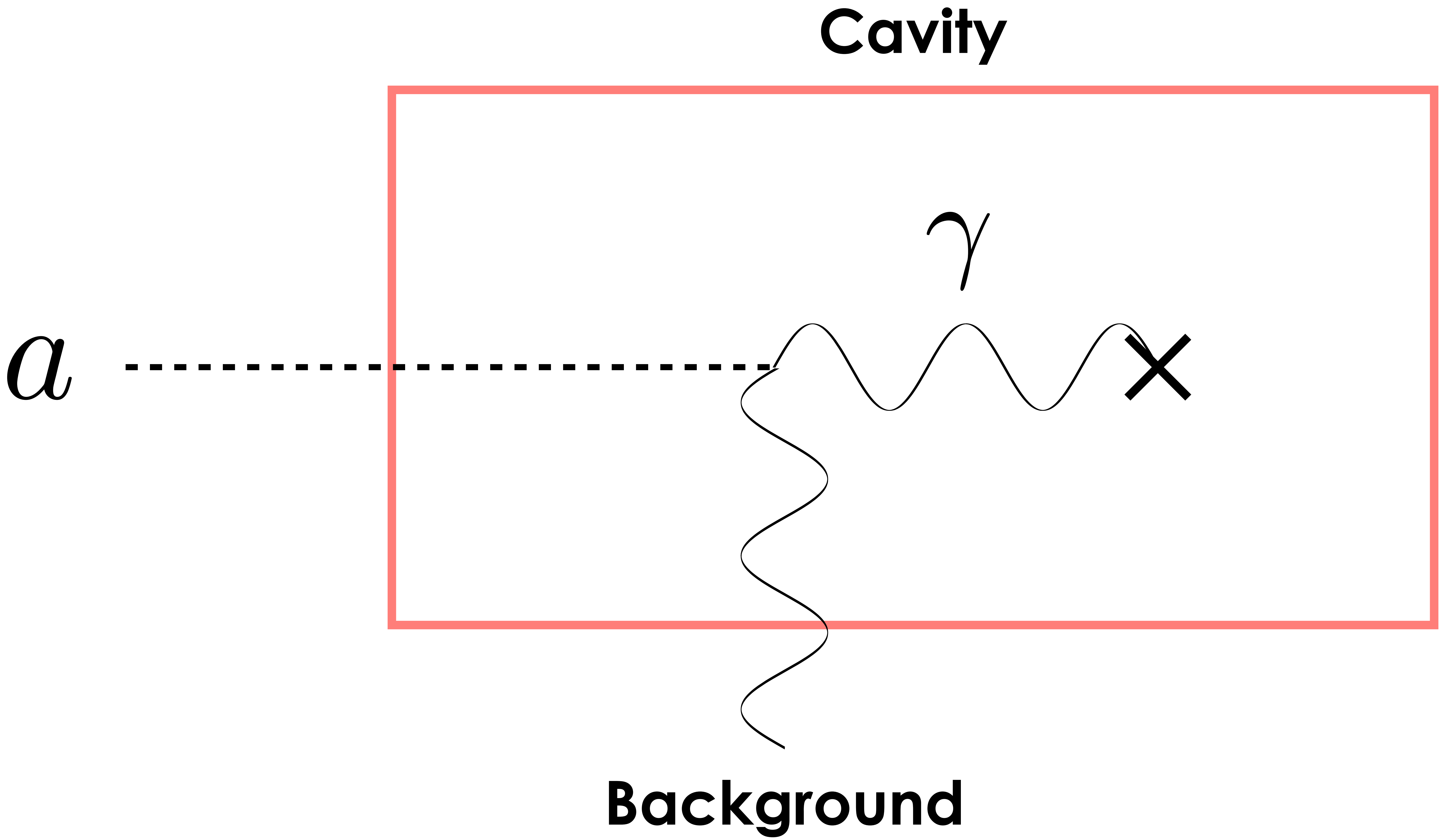
AXION DARK MATTER DETECTION

Cavity



$$m_\gamma \simeq \frac{1}{L}$$

AXION DARK MATTER DETECTION



Resonance

$$m_a \simeq \frac{1}{L}$$

Astro & Lab Constraints
Impractical
(fine control of
huge cavities)
Axion DM
QCD
HP+QCD+DM
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
$f_a(\mathrm{GeV})$
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
$m_a(\mathrm{eV})$

AXION DETECTION

Cavity:

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n} \partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma} \partial_t (\mathbf{B} \partial_t a)$$

Cavity:

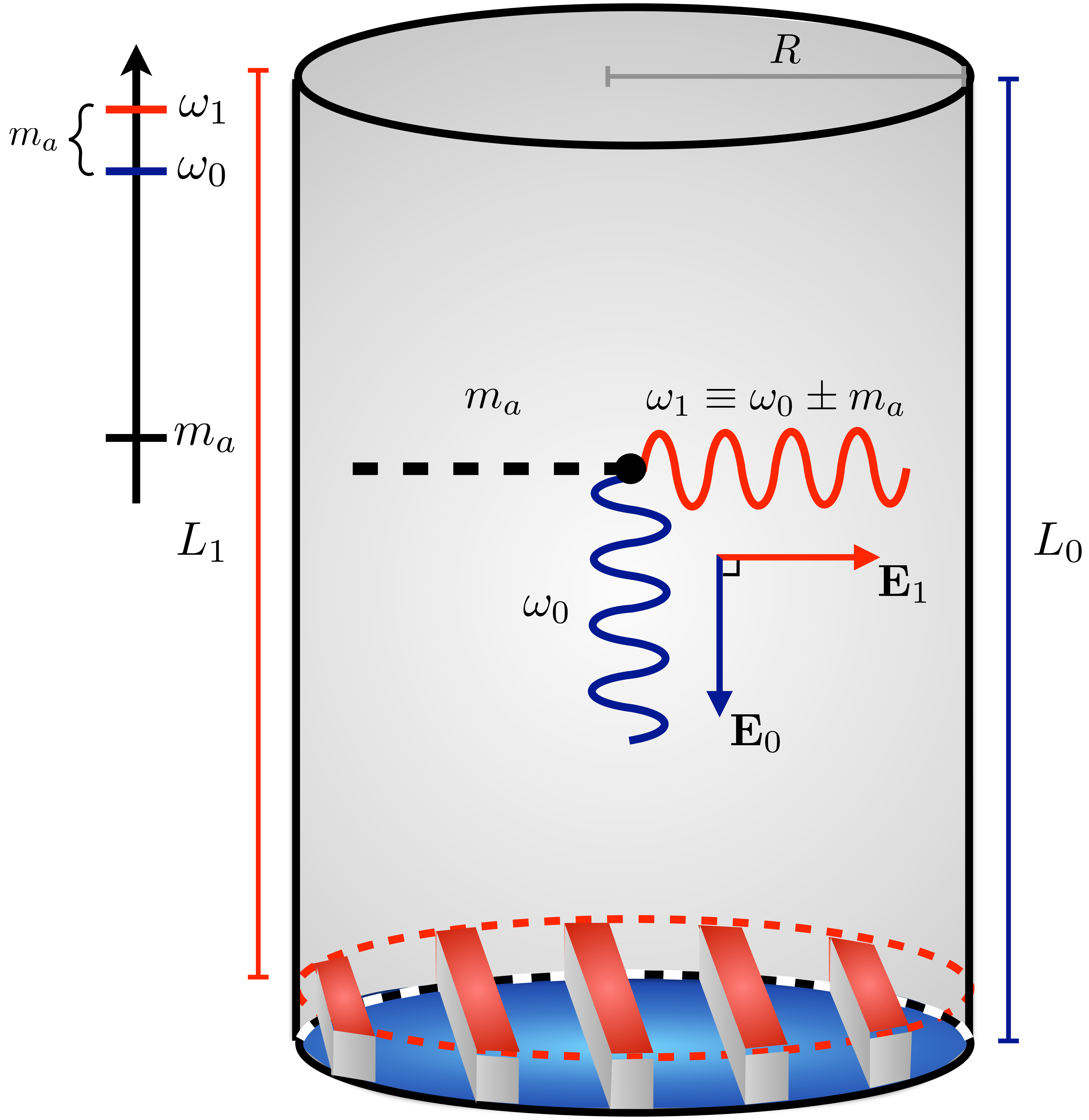
$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2 \right) \mathbf{E}_n = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)$$

$$\omega_1 \simeq m_a \qquad\qquad \partial_t(\mathbf{B}) \simeq 0$$

$$\left(\partial_t^2 + \frac{m_a}{Q_1}\partial_t + m_a^2 \right) \mathbf{E}_1 = \boxed{g_{a\gamma\gamma}\mathbf{B}\sqrt{\rho_{\mathrm{DM}}}m_a \cos m_a t}$$

HETERODYNE DETECTION

[Berlin, RTD, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou'19]



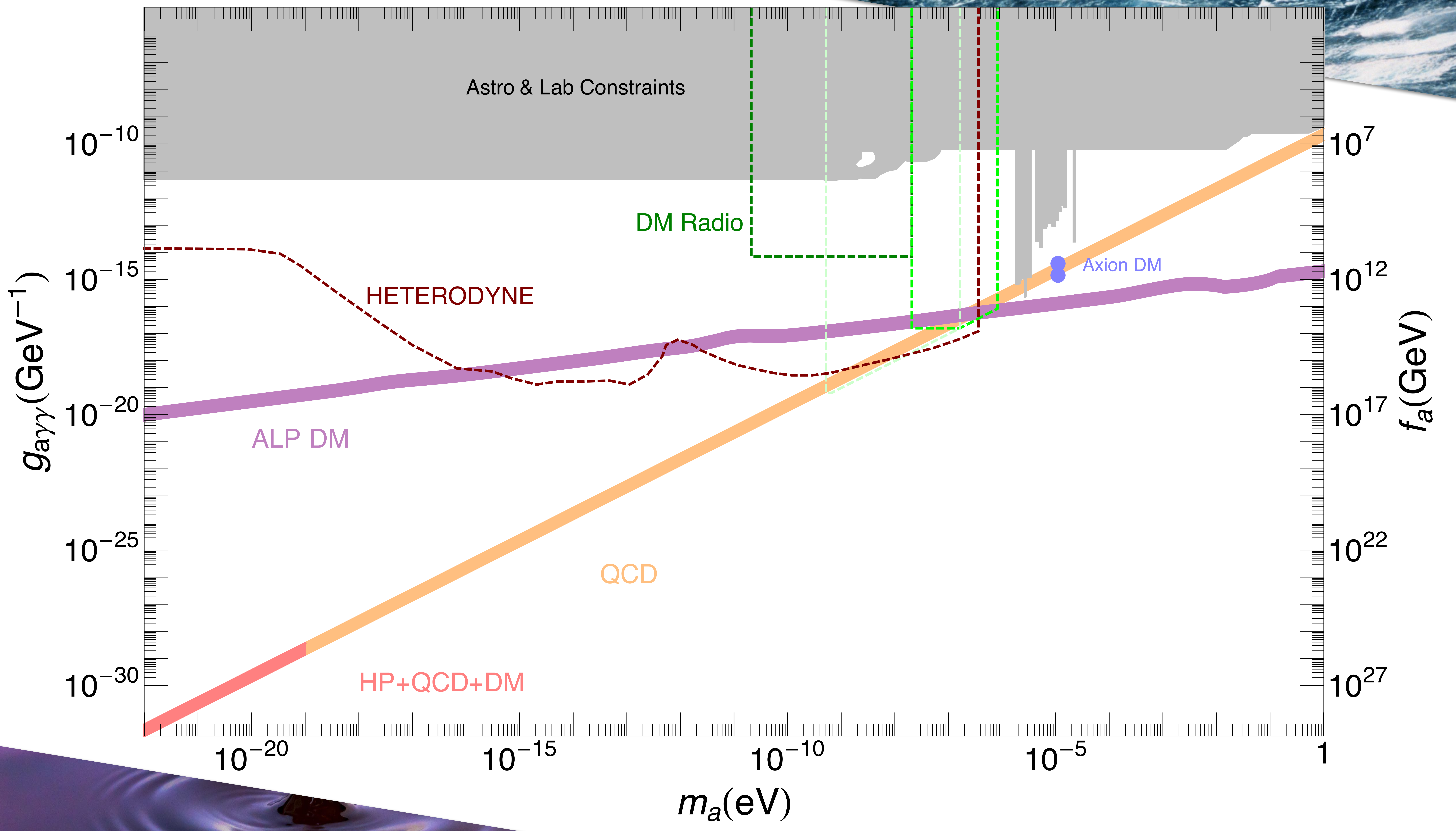
HETERODYNE DETECTION

[Berlin, RTD, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou‘19]

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2 \right) \mathbf{E}_n = \boxed{g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)}$$

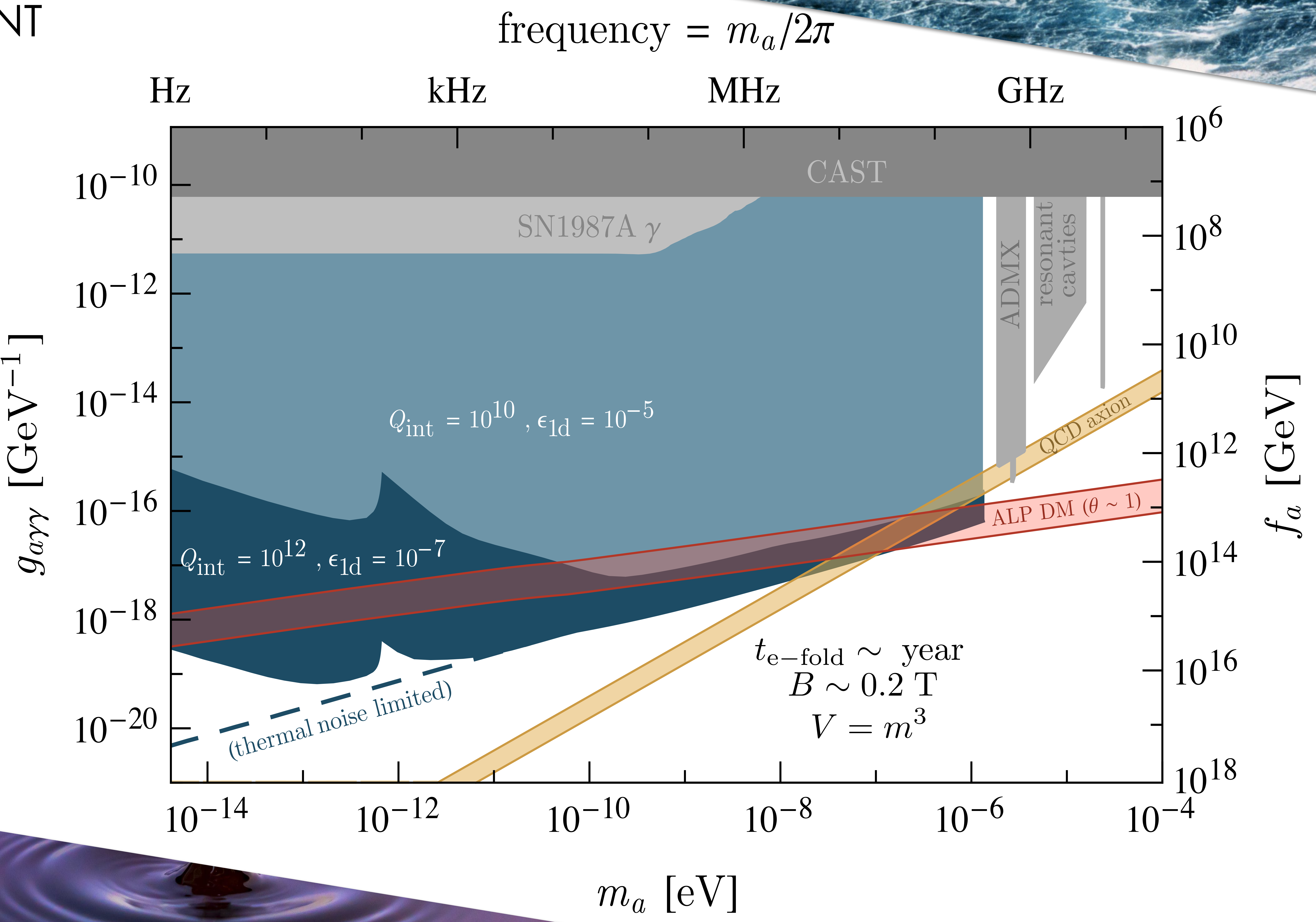
$$\boxed{\partial_t(\mathbf{B}) \simeq i\omega_0\mathbf{B} \qquad \omega_1 \simeq \omega_0 + m_a}$$

$$\boxed{\partial_t J_{\text{eff}} = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a) \propto \omega_0 m_a \gg m_a^2}$$



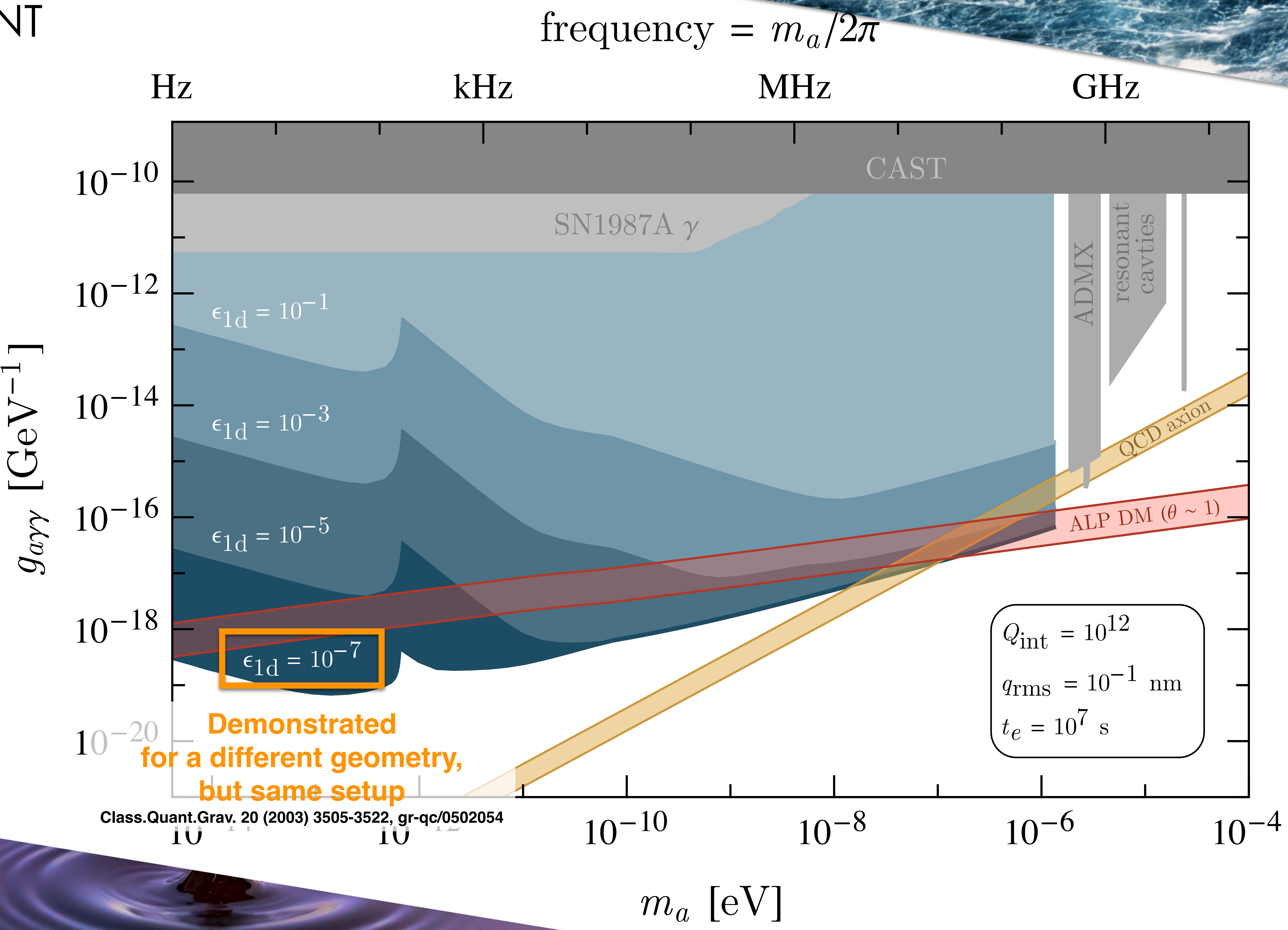
Astro & Lab Constraints
DM Radio
HETERODYNE
Axion DM
ALP DM
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

RESONANT



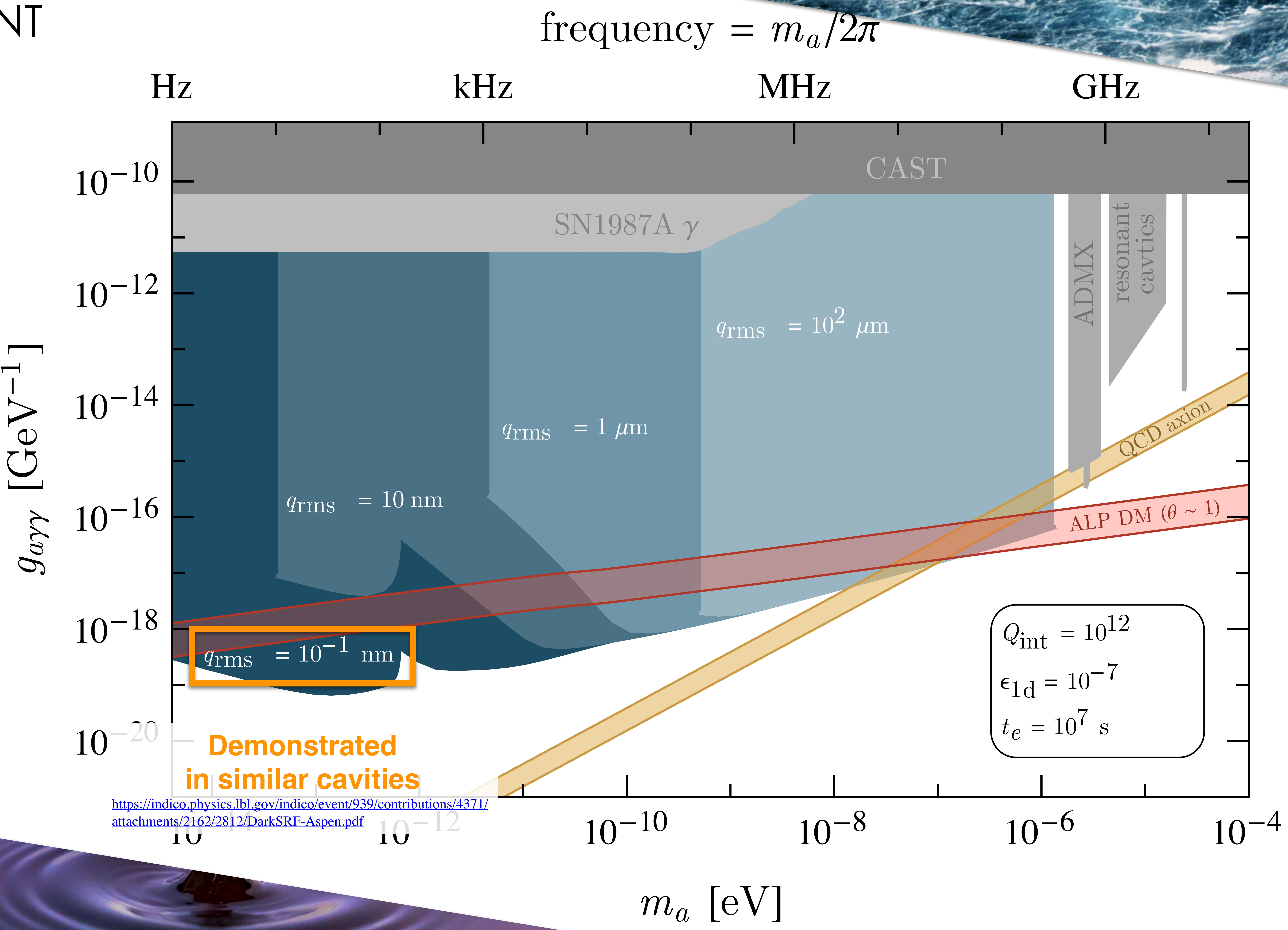
frequency = $m_a/2\pi$
Hz
kHz
MHz
GHz
CAST
SN1987A γ
ADMX
resonant cavties
$Q_{int} = 10^{10}$, $\epsilon_{1d} = 10^{-5}$
$Q_{int} = 10^{12}$, $\epsilon_{1d} = 10^{-7}$
QCD axion
ALP DM ($\theta \sim 1$)
(thermal noise limited)
$t_{e-fold} \sim$ year
$B \sim 0.2$ T
$V = m^3$
$g_{a\gamma\gamma}$ [GeV^{-1}]
f_a [GeV]
m_a [eV]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}

RESONANT



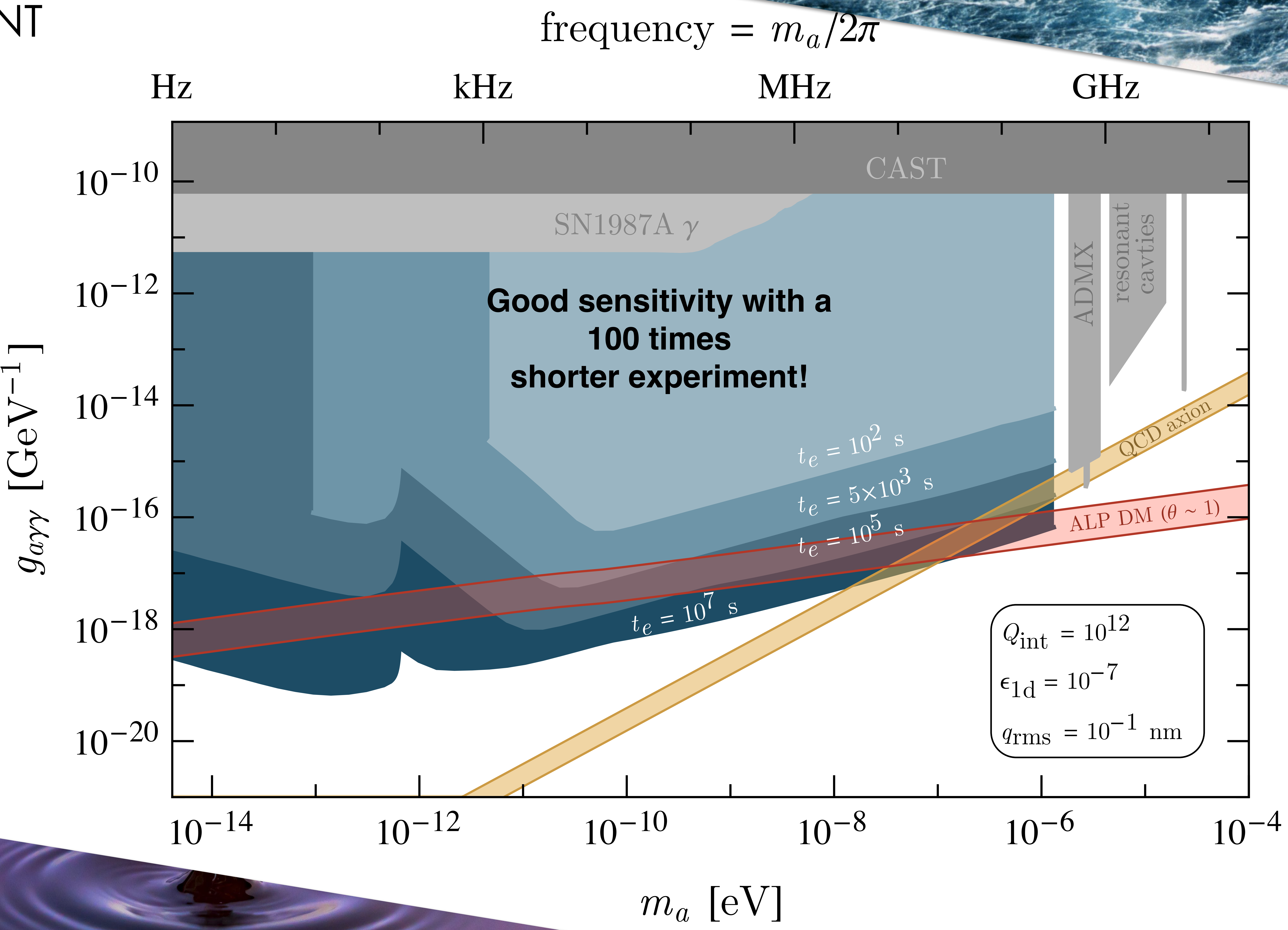
frequency = $m_a/2\pi$
Hz
kHz
MHz
GHz
CAST
SN1987A γ
ADMX
resonant cavties
$\epsilon_{1d} = 10^{-1}$
$\epsilon_{1d} = 10^{-3}$
$\epsilon_{1d} = 10^{-5}$
$\epsilon_{1d} = 10^{-7}$
QCD axion
ALP DM ($\theta \sim 1$)
$Q_{int} = 10^{12}$
$q_{rms} = 10^{-1}$ nm
$t_e = 10^{7}$ s
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
m_a [eV]
Demonstrated
for a different geometry,
but same setup
Class.Quant.Grav. 20 (2003) 3505-3522, gr-qc/0502054

RESONANT



https://indico.physics.lbl.gov/indico/event/939/contributions/4371/attachments/2162/2812/DarkSRF-Aspen.pdf

RESONANT

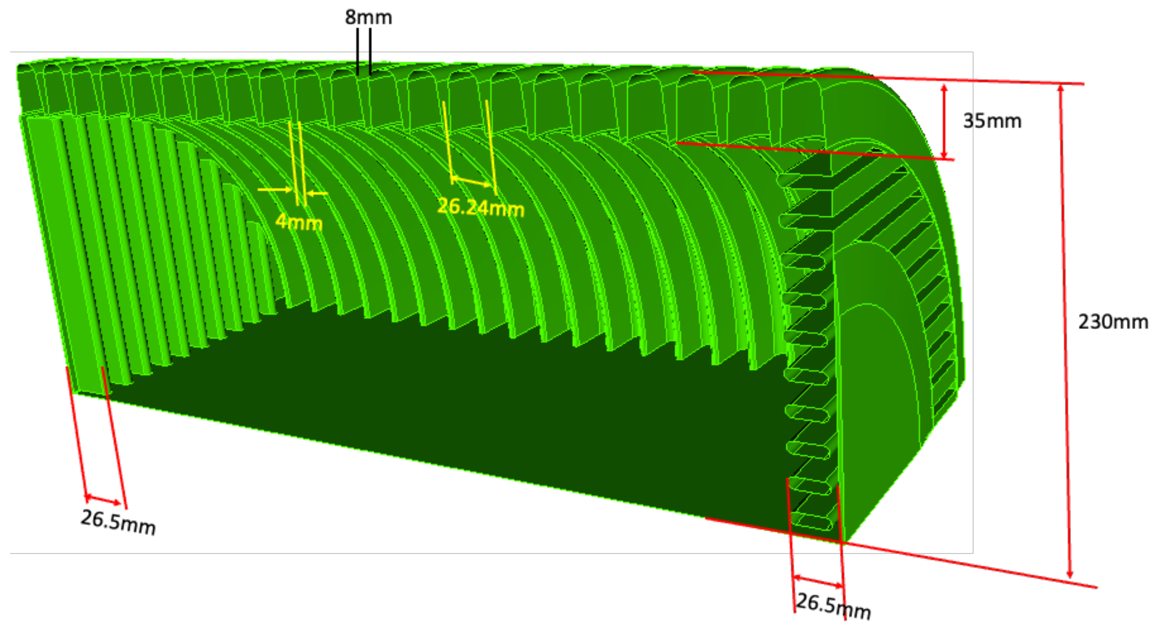


frequency = $m_a/2\pi$
Hz
kHz
MHz
GHz
CAST
SN1987A γ
ADMX
resonant cavties
Good sensitivity with a 100 times shorter experiment!
$t_e = 10^2$ s
$t_e = 5\times10^3$ s
$t_e = 10^5$ s
$t_e = 10^7$ s
QCD axion
ALP DM ($\theta \sim 1$)
$Q_{\rm int} = 10^{12}$
$\epsilon_{\rm 1d} = 10^{-7}$
$q_{\rm rms} = 10^{-1}$ nm
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
m_a [eV]

TWO PROTOTYPES [~ 1 YEAR]

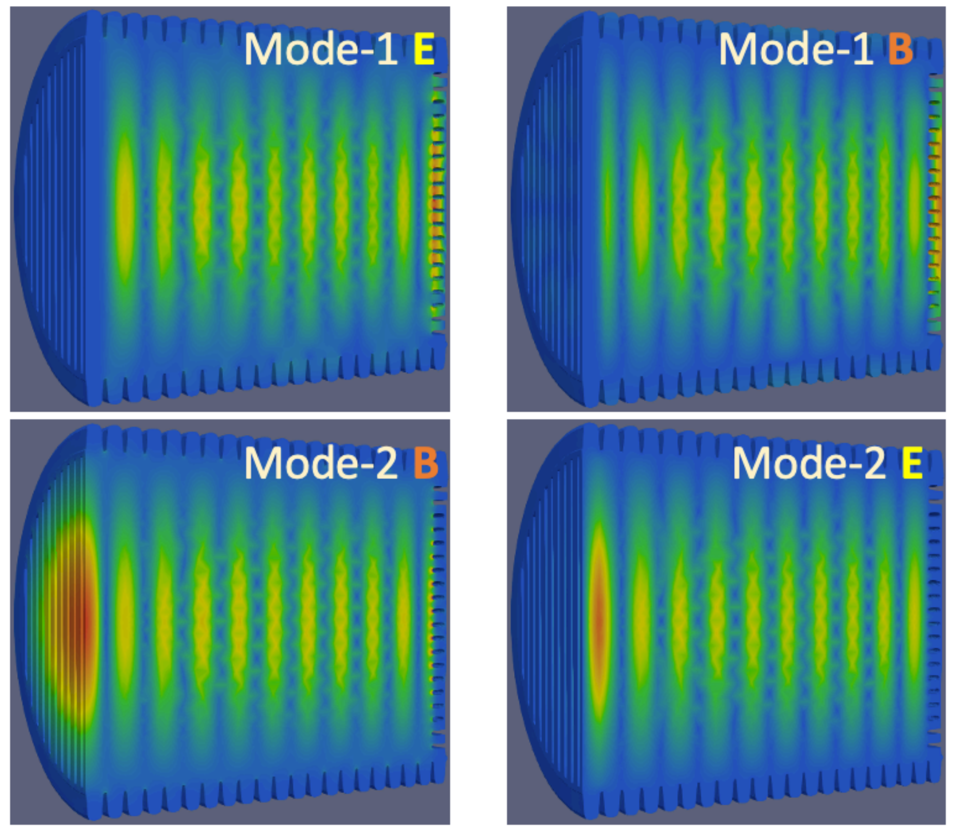
SLAC NATIONAL ACCELERATOR LABORATORY

LDRD [only internal documents]



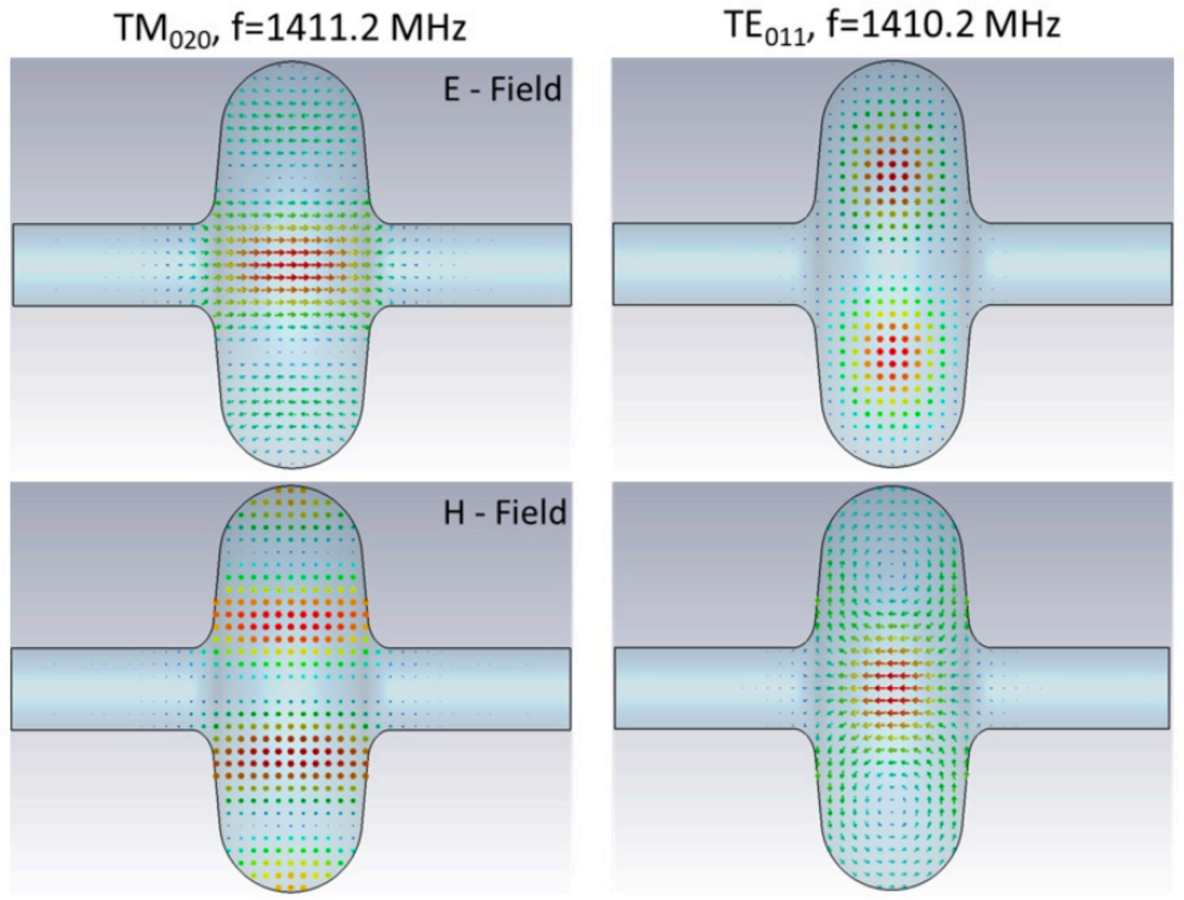
HE11
polatization-1 (E,B)

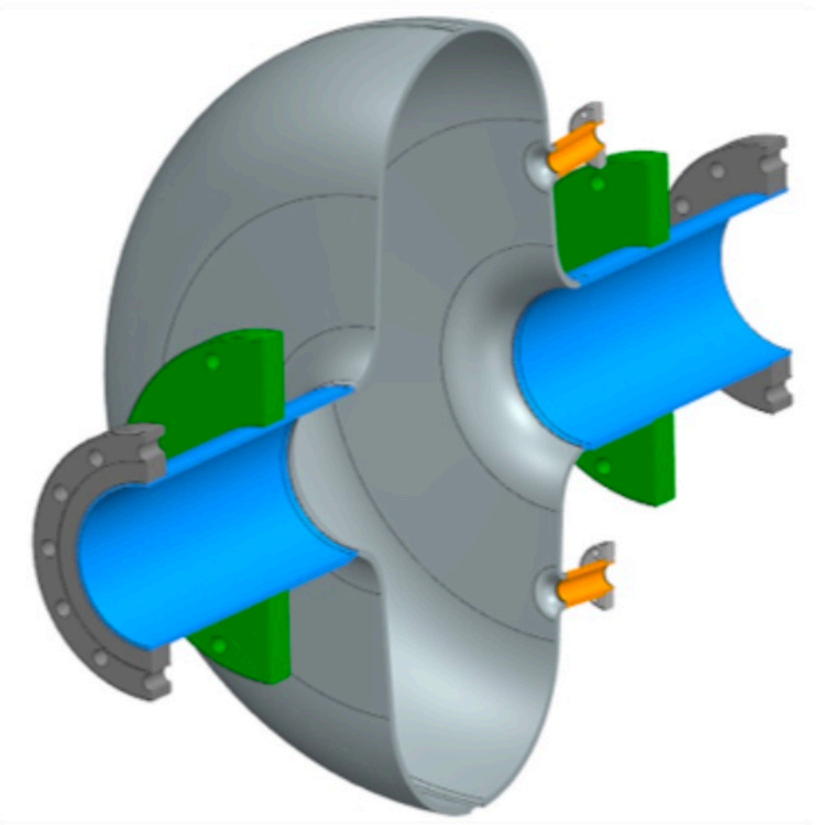
HE11
polatization-2 (B,E)



Fermilab

arXiv:2207.11346






GRAVITATIONAL WAVES

$$S \supset -\frac{1}{2} \int d^4x \; j^{\mu}_{\text{eff}} \, A_{\mu}$$

GW

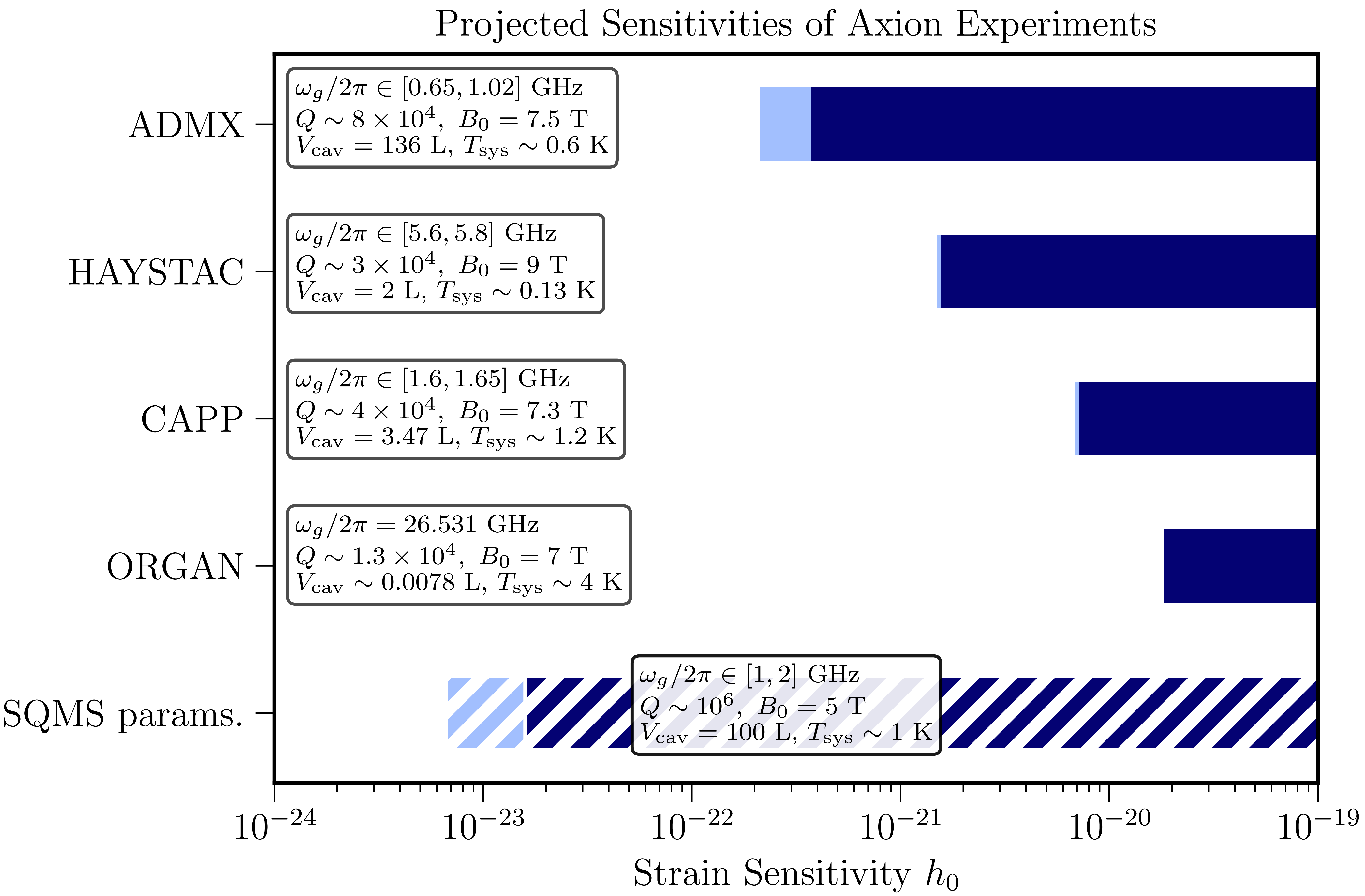
$$j^{\mu}_{\text{eff}} = \partial_{\nu} \left(\frac{1}{2} \, h \, \underline{F^{\mu\nu}} + h^{\nu}{}_{\alpha} \, \underline{F^{\alpha\mu}} - h^{\mu}{}_{\alpha} \, \underline{F^{\alpha\nu}} \right)$$

Axion

$$j^{\mu}_{\text{eff}} = \epsilon^{\mu\nu\rho\sigma} \partial_{\nu} (a \underline{F_{\rho\sigma}})$$

depends on the background field in the laboratory

GRAVITATIONAL WAVE DETECTION



Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel '21

LOWER FREQUENCIES

$$E_{\text{sig}} \sim \frac{\partial_t j_{\text{eff}}}{\omega_1^2}$$

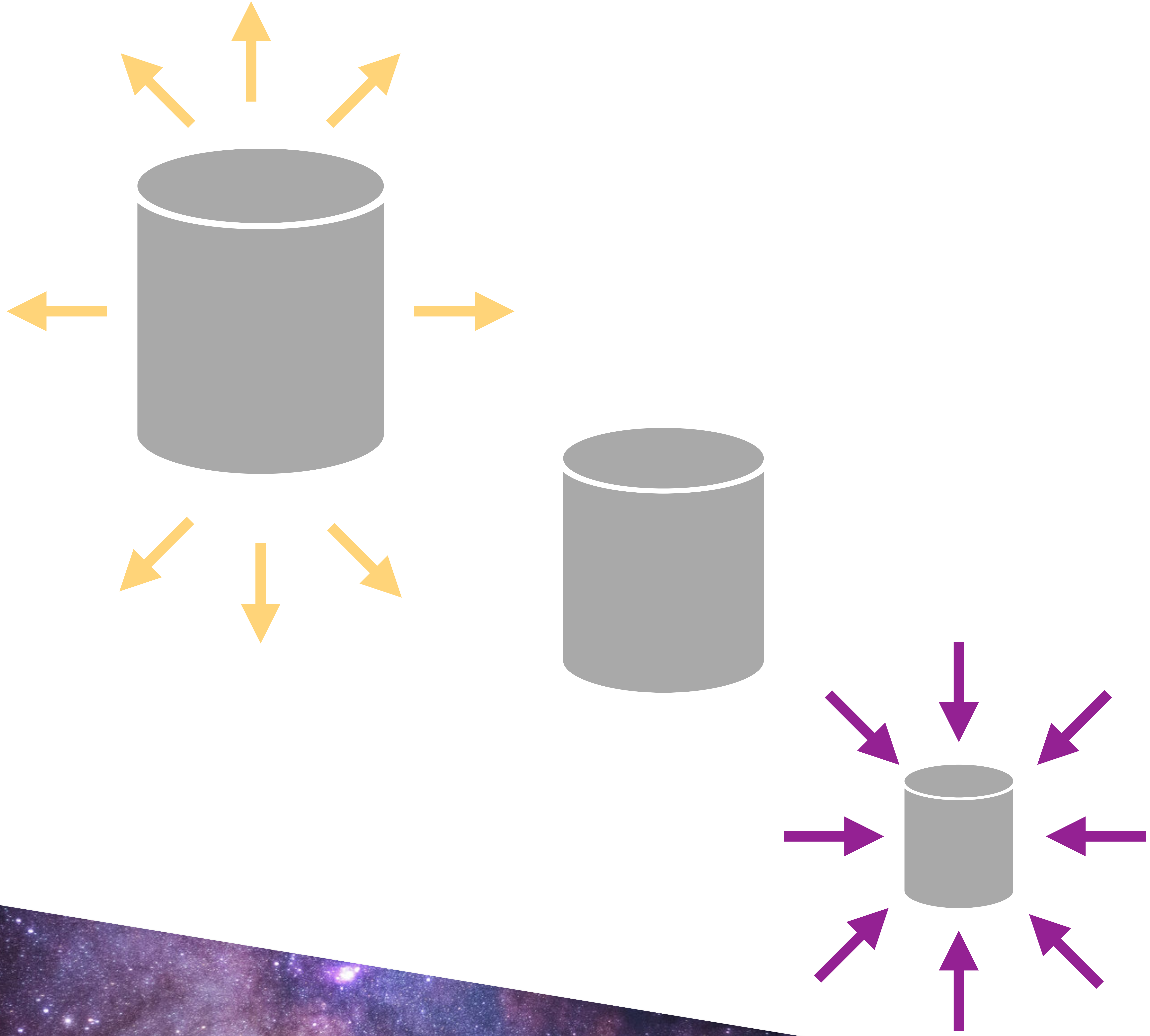
$$\partial_t j_{\text{eff}} \sim \partial_t^2 (R B_0) \sim \omega_g^2 (h B_0)(\omega_g L_{\text{cav}})^2$$

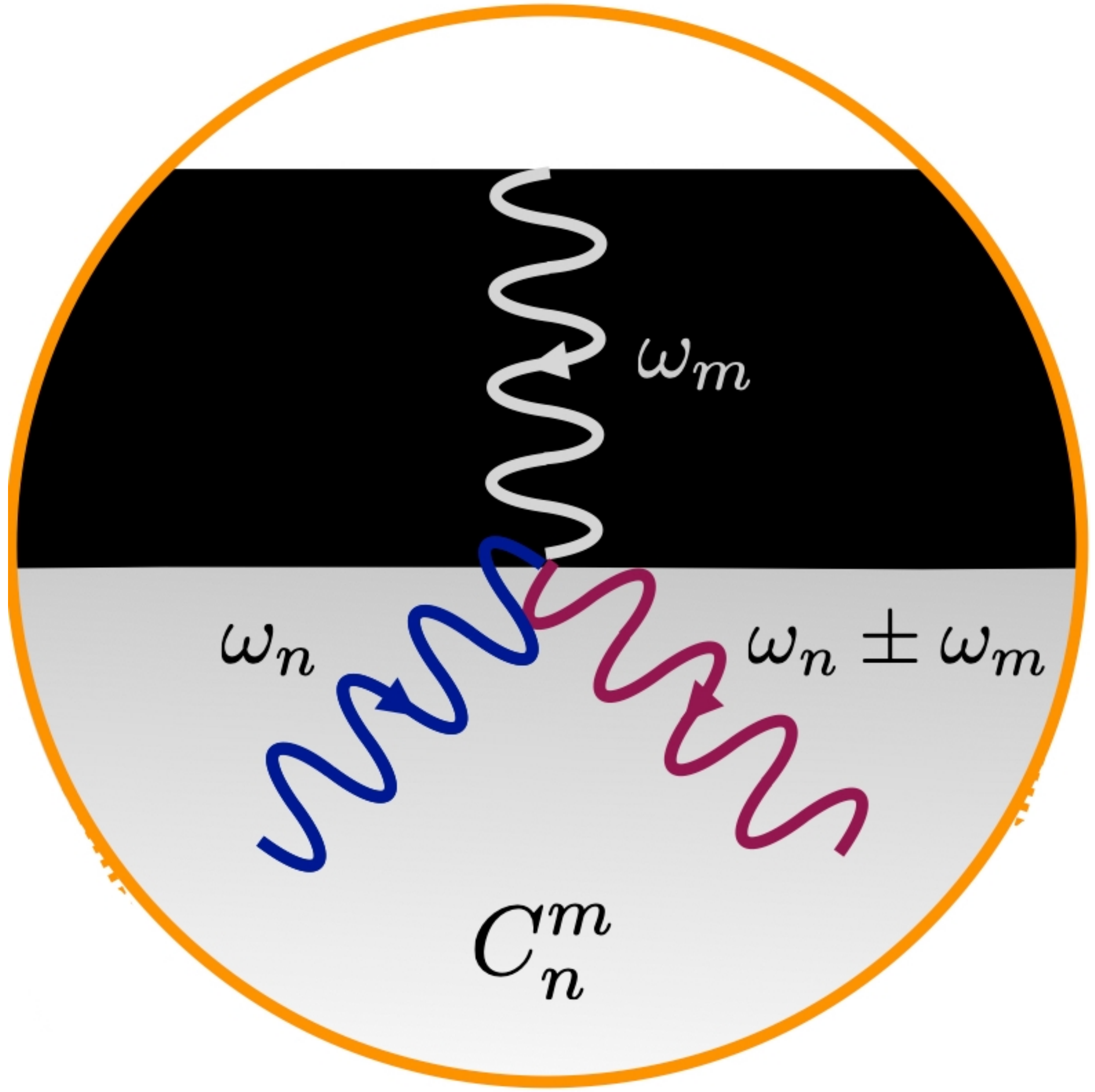
Heterodyne Detection

$$\dot{B}_0 \neq 0$$

$$\partial_t j_{\mathrm{eff}} \sim \partial_t^2 (R B_0) \sim \omega_0^2 (h B_0)(\omega_g L_{\mathrm{cav}})^2$$

Better, but not much better

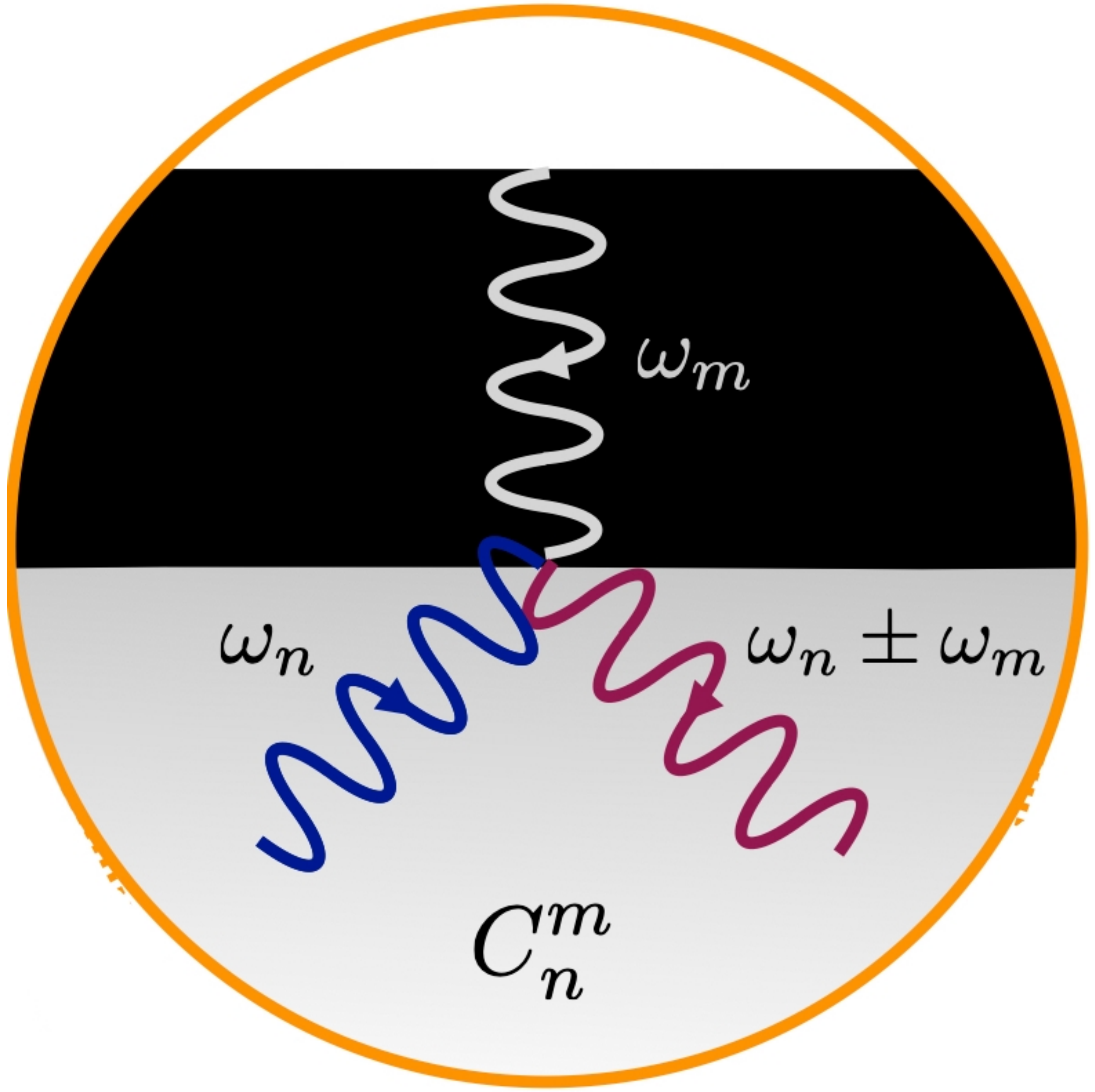



ω_m
ω_n
$\omega_n \pm \omega_m$
C_n^m

Mechanical Mode

$$\left(\partial_t^2 + \frac{\omega_m}{Q_m}\partial_t + \omega_m^2\right)\underline{u_m} = \frac{F_m}{M_{\rm cav}}$$

MECHANICAL



[Caves '78], [Radicati, Pegoraro, Picasso '78]

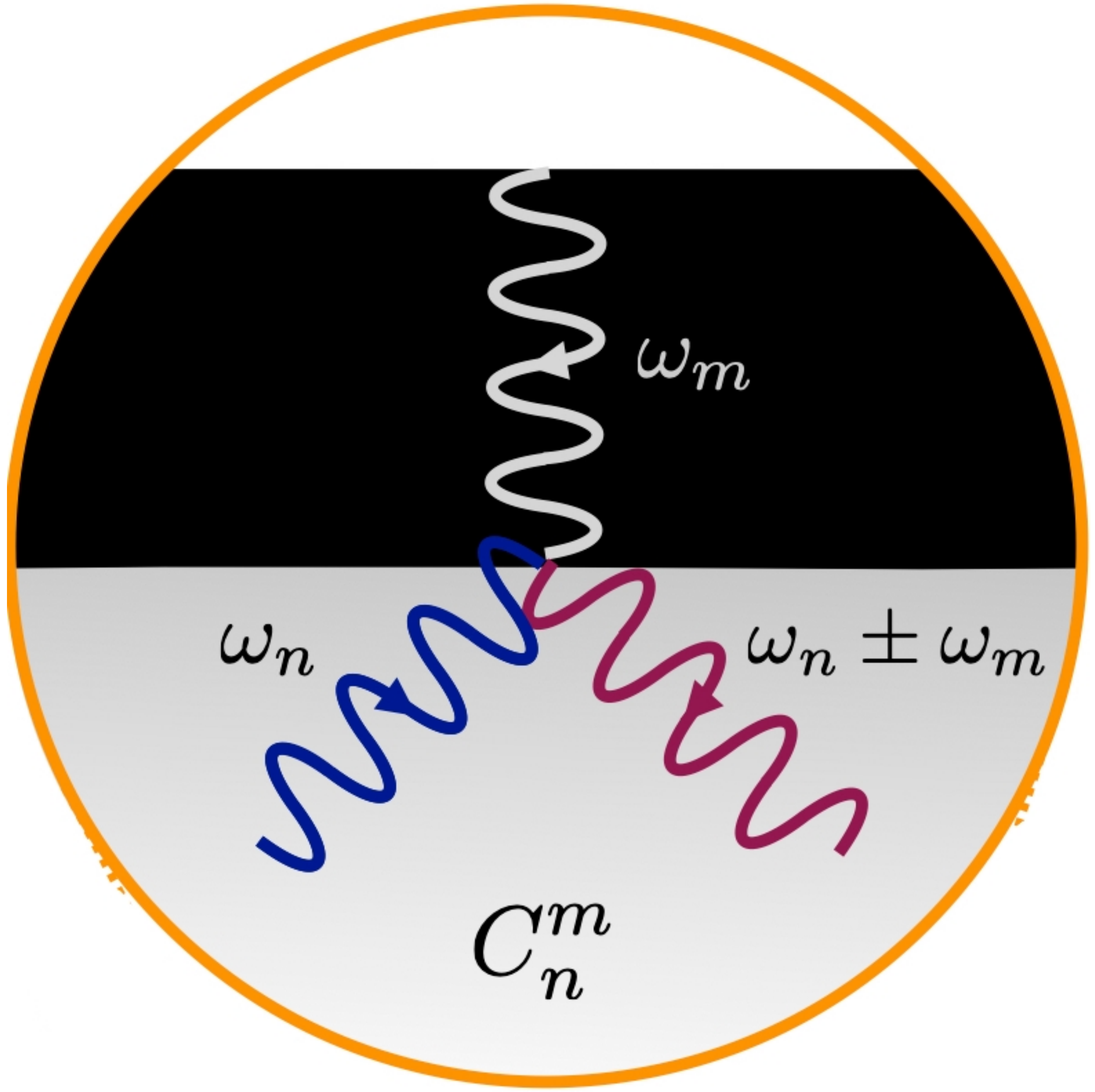
Mechanical Mode

$$\left(\partial_t^2 + \frac{\omega_m}{Q_m}\partial_t + \omega_m^2\right) \underline{u_m} = \frac{F_m}{M_{\rm cav}}$$

$$\omega_g \simeq \omega_m$$

$$u_m \simeq Q_m \, h \, L_{\rm cav}$$

MECHANICAL



[Caves '78], [Radicati, Pegoraro, Picasso '78]

HETERODYNE READOUT

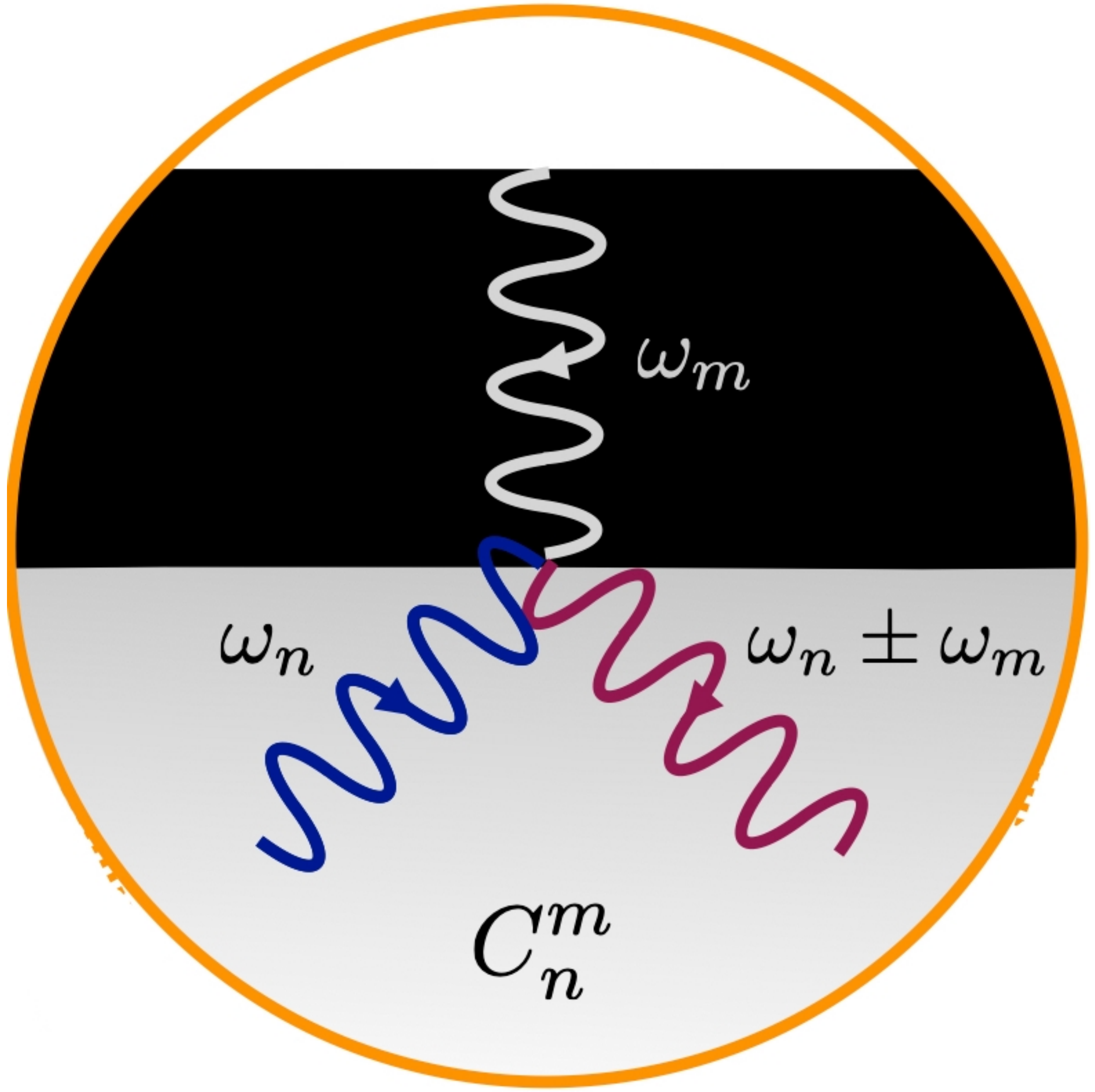
MECHANICAL

On resonance

$$E_{\rm sig} \sim Q_m Q_1 (h B_0)$$

Below resonance

$$E_{\rm sig} \sim Q_1 (h B_0) \frac{\omega_g^2}{(\omega_m^{\rm min})^2}$$

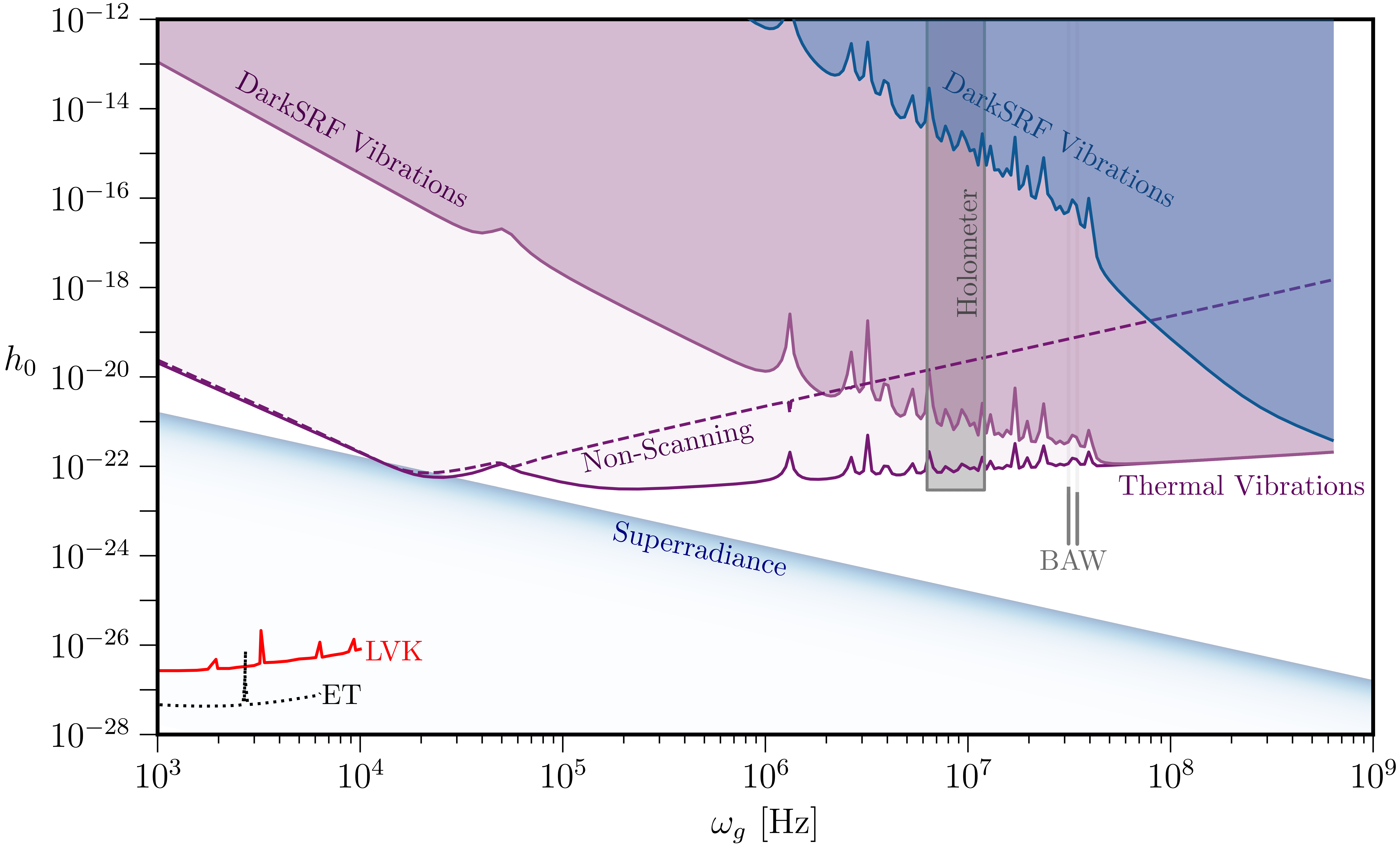


[Caves '78], [Radicati, Pegoraro, Picasso '78]

MECHANICAL VS ELECTROMAGNETIC RESONANCE

$$\omega_m \simeq \frac{c_s}{L} \ll \omega_{\rm em} \simeq \frac{c}{L}$$

MONOCHROMATIC SIGNAL



Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel,Wentzel '23
arXiv:2303.01518

EXISTING PROTOTYPE

MAGO ‘05

R. Ballantini, A. Chincarini, S. Cuneo, G. Gemme,* R. Parodi, A. Podest`a, and R. Vaccarone

INFN and Universita` degli Studi di Genova, Genova, Italy

Ph. Bernard, S. Calatroni, E. Chiaveri, and R. Losito

CERN, Geneva, Switzerland

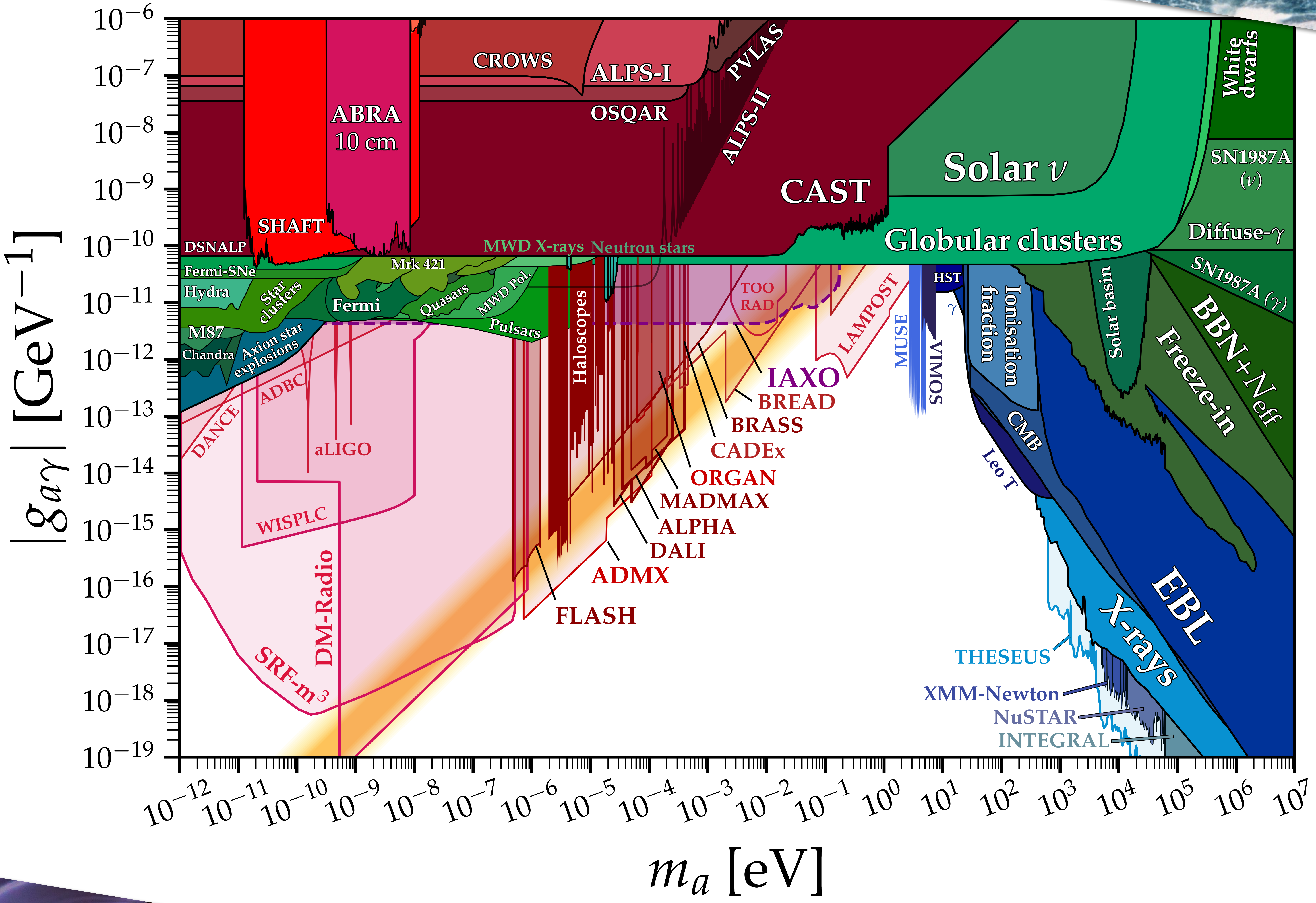
R.P. Croce, V. Galdi, V. Pierro, and I.M. Pinto

INFN, Napoli, and Universita` degli Studi del Sannio, Benevento, Italy

E. Picasso

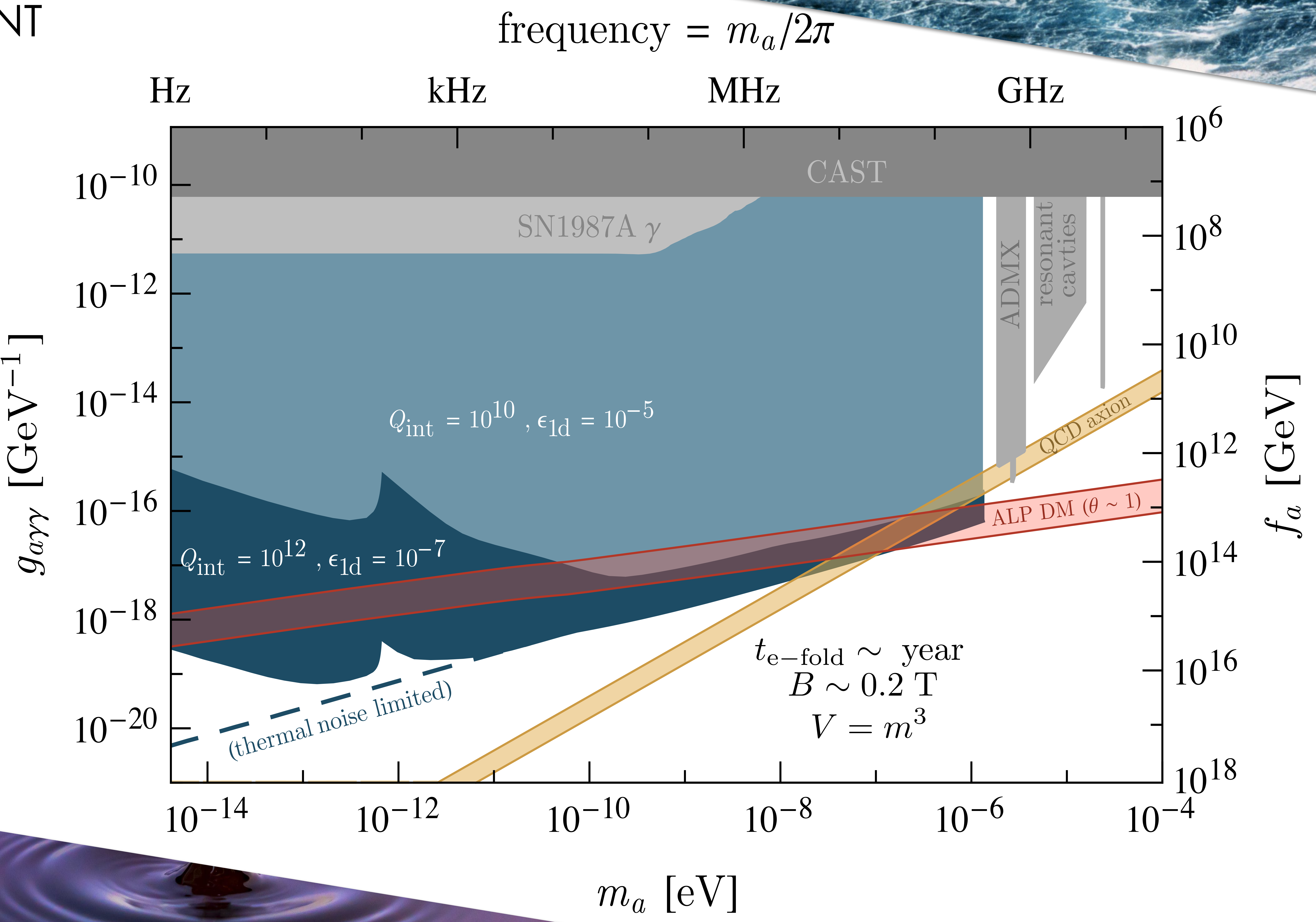
INFN and Scuola Normale Superiore, Pisa, Italy and CERN, Geneva, Switzerland

BACKUP



$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
OSQAR
PVLAS
ALPS-II
ABRA 10 cm
SHAFT
CAST
Solar ν
Globular clusters
White dwarfs
SN1987A (ν)
Diffuse-γ
SN1987A (γ)
DSNALP
MWD X-rays
Neutron stars
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
Quasars
MWD Pol.
Pulsars
M87
Chandra
Axion star explosions
Haloscopes
TOO RAD
LAMPOST
IAXO
BREAD
BRASS
CADEx
ORGAN
MADMAX
ALPHA
DALI
ADMX
FLASH
DANCE
ADBC
aLIGO
WISPLC
DM-Radio
SRF-m^3
MUSE
VIMOS
HST
Ionisation fraction
CMB
Leo T
Solar basin
BBN+N_{eff}
Freeze-in
EBL
X-rays
THESEUS
XMM-Newton
NuSTAR
INTEGRAL

RESONANT


frequency = $m_a/2\pi$
Hz
kHz
MHz
GHz
CAST
SN1987A γ
ADMX
resonant cavties
$Q_{\rm int} = 10^{10}$, $\epsilon_{\rm 1d} = 10^{-5}$
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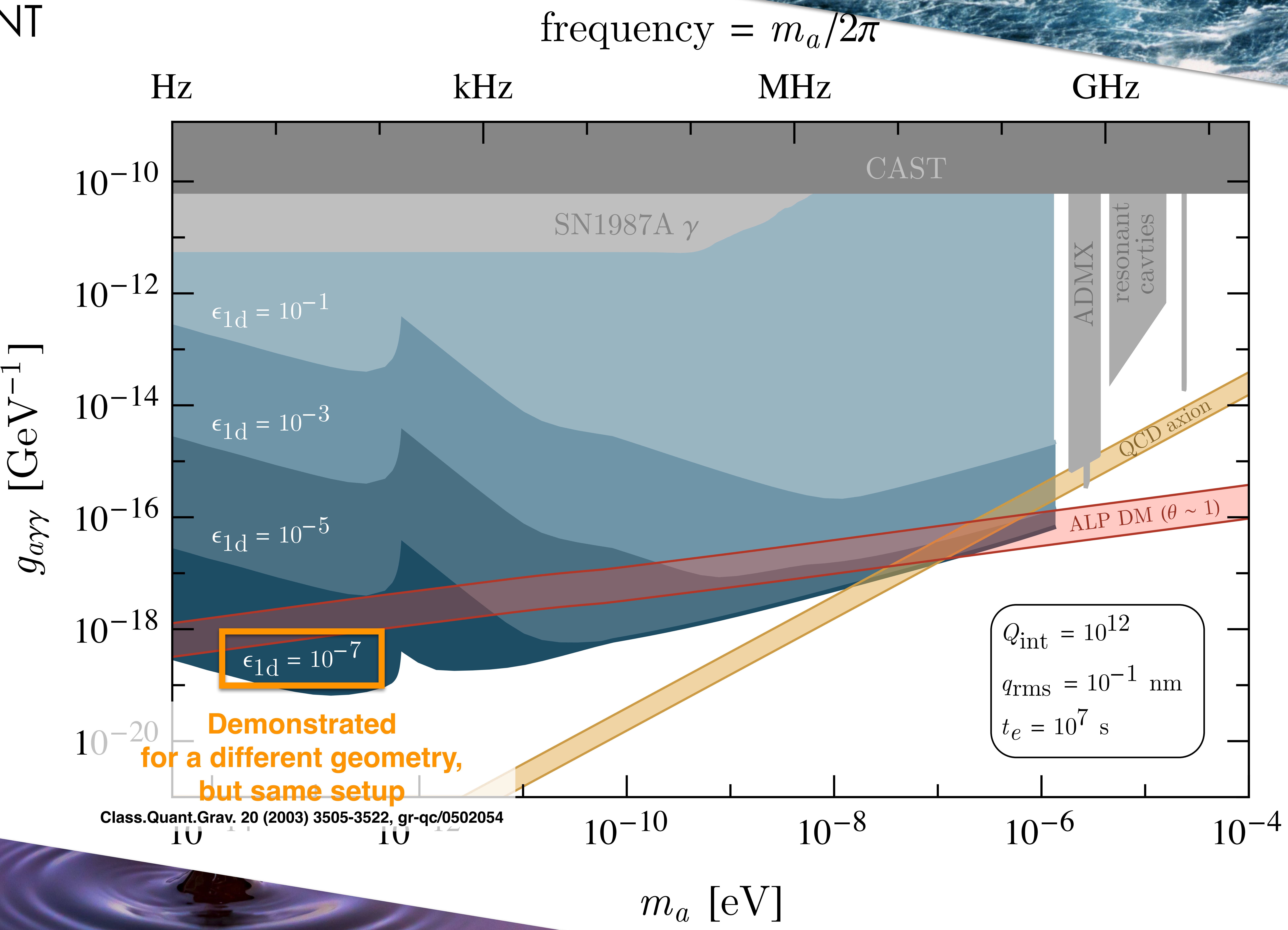
$V = m^3$
$g_{a\gamma\gamma}$ [GeV^{-1}]
f_a [GeV]
m_a [eV]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}

RESONANT



frequency = $m_a/2\pi$
Hz
kHz
MHz
GHz
CAST
SN1987A γ
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resonant cavties
$\epsilon_{1d} = 10^{-1}$
$\epsilon_{1d} = 10^{-3}$
$\epsilon_{1d} = 10^{-5}$
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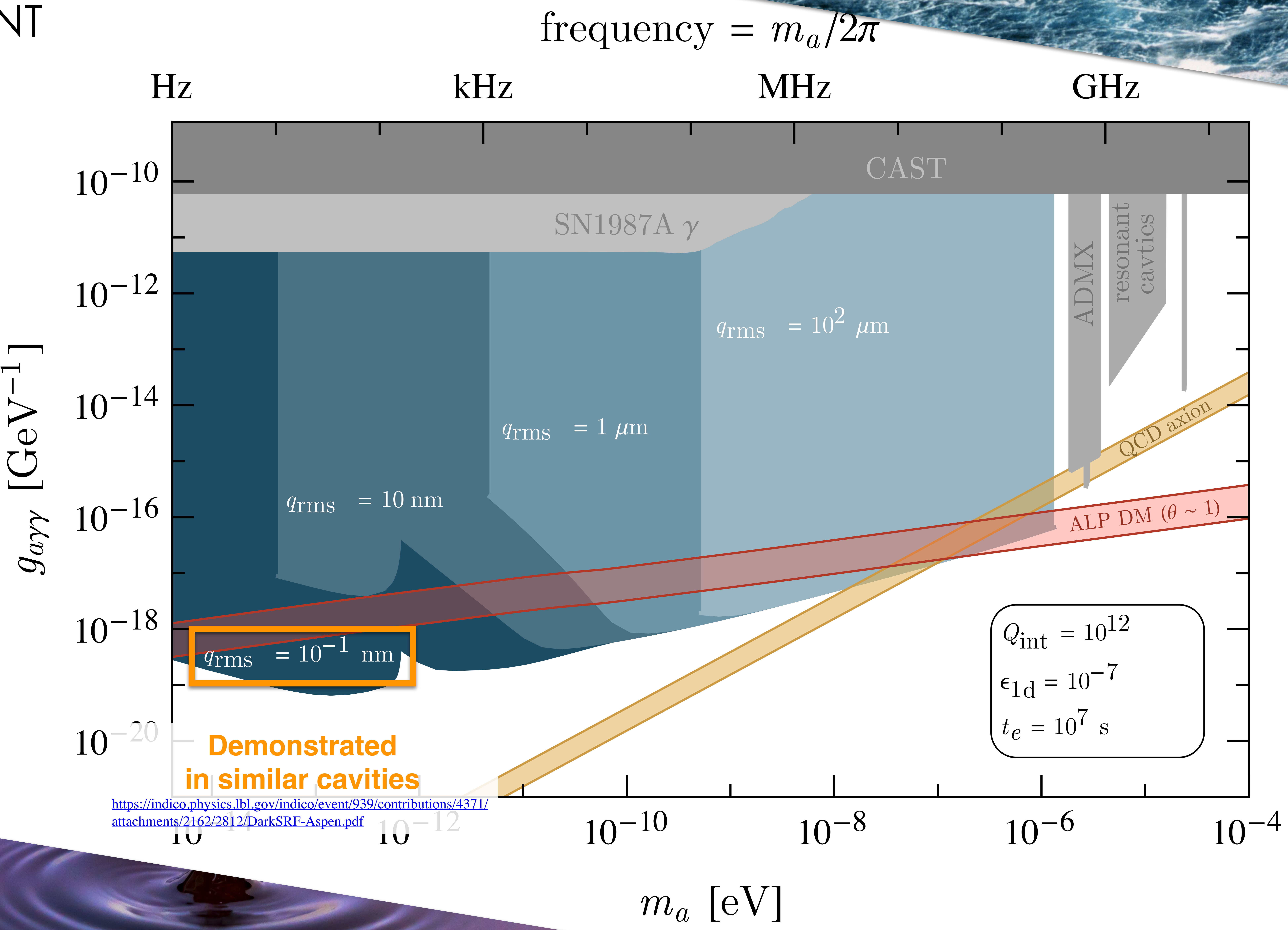
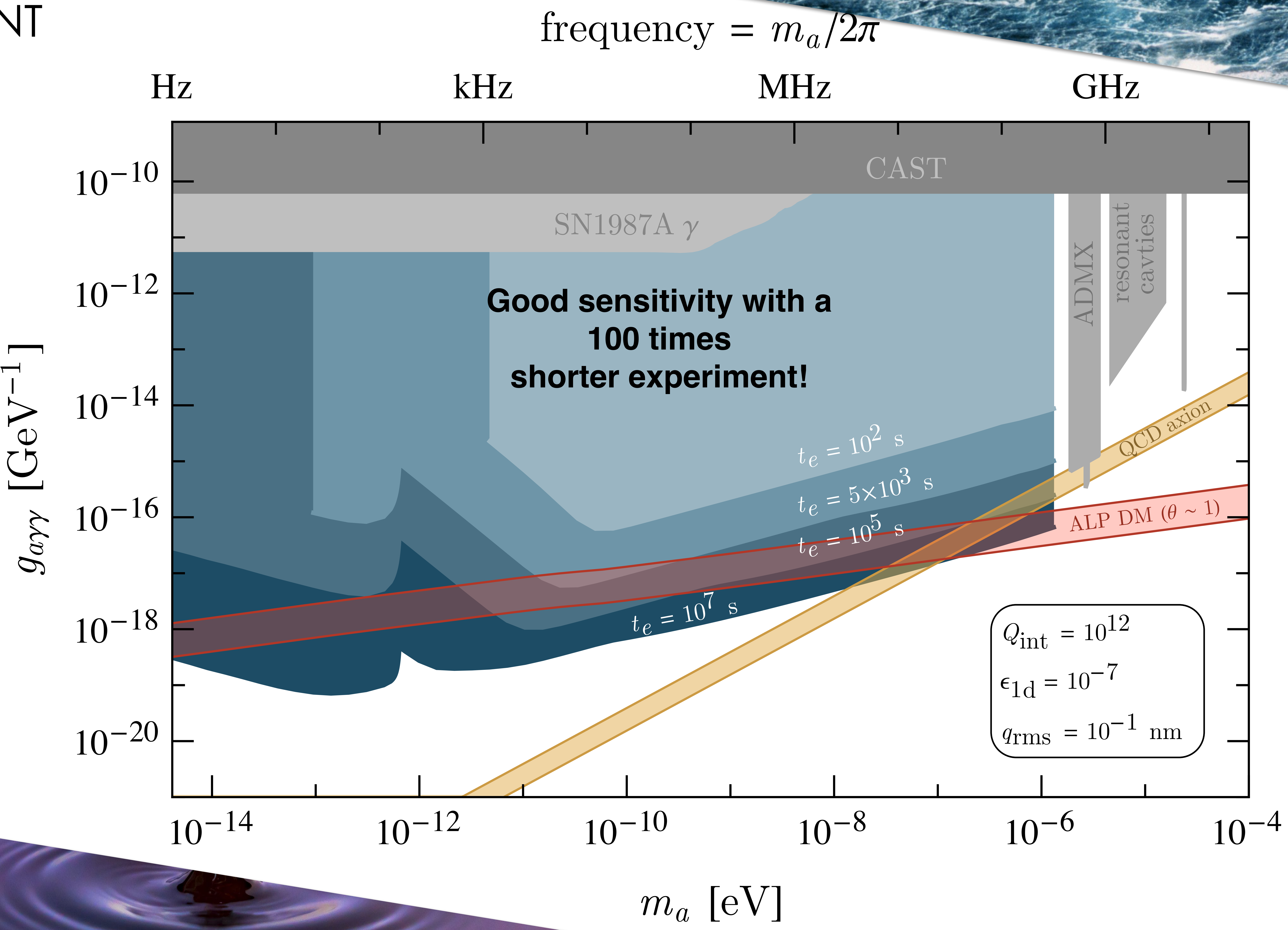
Demonstrated
for a different geometry,
but same setup
Class.Quant.Grav. 20 (2003) 3505-3522, gr-qc/0502054
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
m_a [eV]

RESONANT



https://indico.physics.lbl.gov/indico/event/939/contributions/4371/attachments/2162/2812/DarkSRF-Aspen.pdf

RESONANT



frequency = $m_a/2\pi$
Hz
kHz
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SN1987A γ
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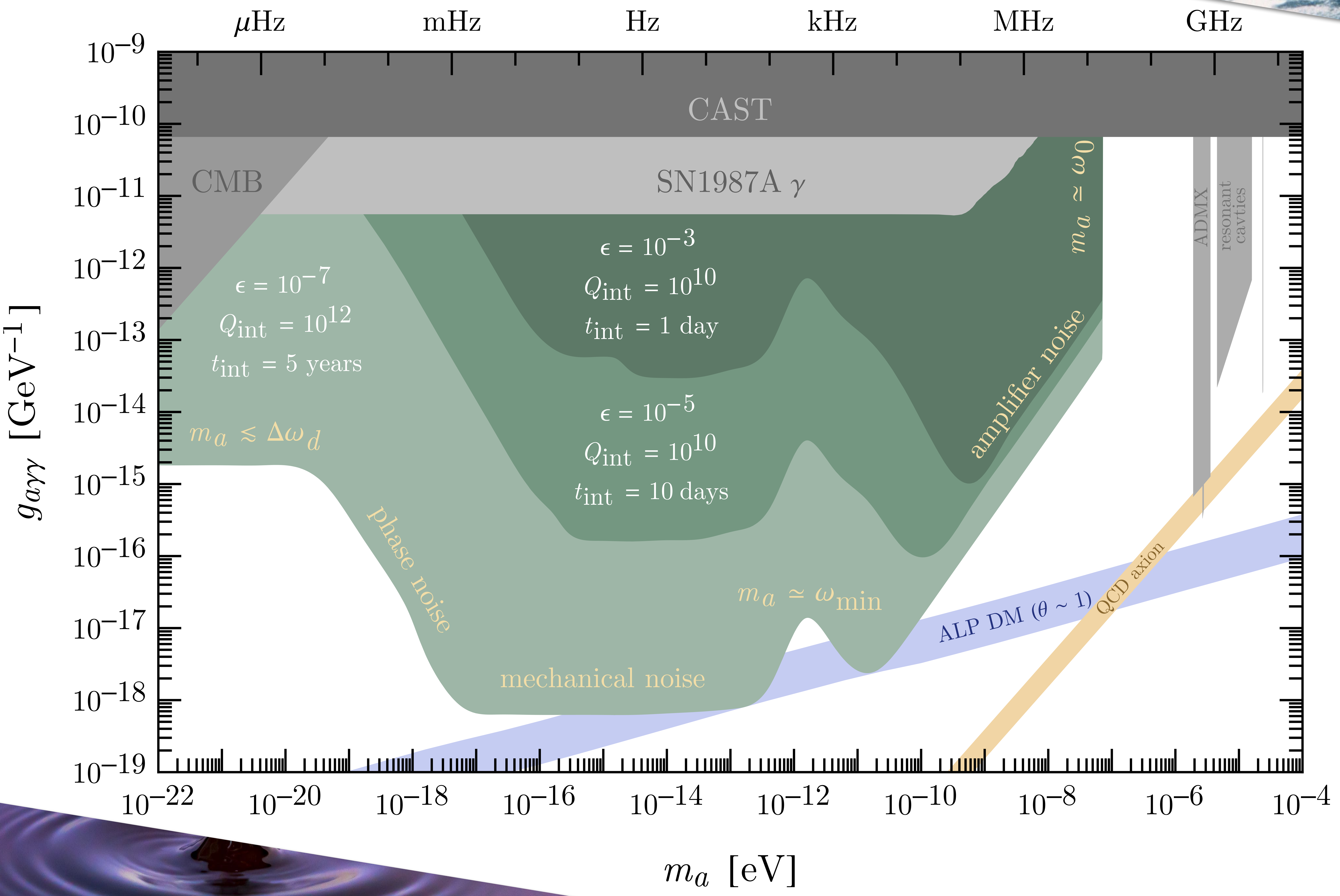
resonant cavties
Good sensitivity with a 100 times shorter experiment!
$t_e = 10^2$ s
$t_e = 5\times10^3$ s
$t_e = 10^5$ s
$t_e = 10^7$ s
QCD axion
ALP DM ($\theta \sim 1$)
$Q_{\rm int} = 10^{12}$
$\epsilon_{\rm 1d} = 10^{-7}$
$q_{\rm rms} = 10^{-1}$ nm
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
m_a [eV]

A.Berlin, RTD, S. Ellis, K. Zhou 2007.15656



Proper Detector Frame (PDF) Vs **Transverse Traceless (TT) Frame**

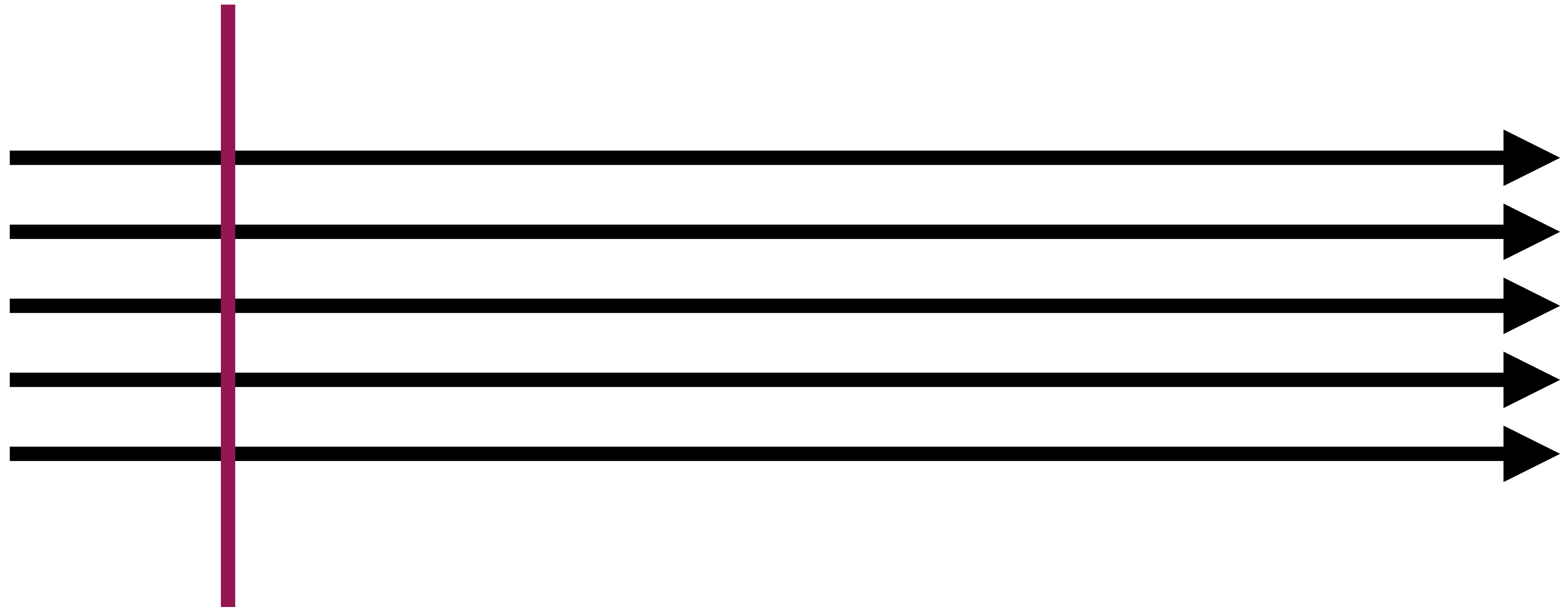
(Fermi Normal Coordinates)

proper detector frame = laboratory

$$(t, x, y, z)$$

probe wire

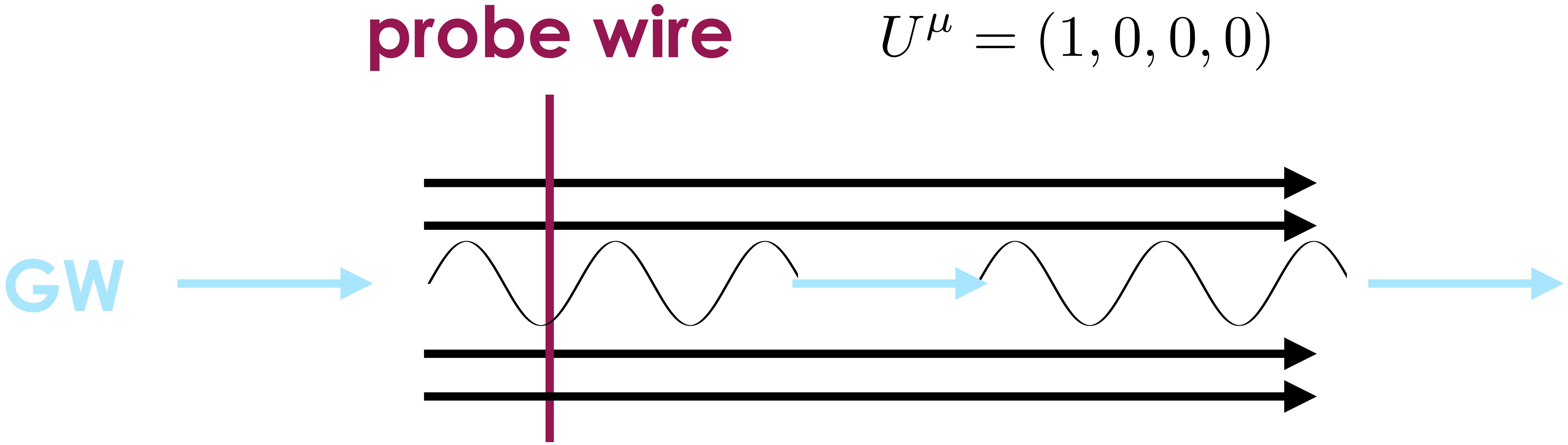
$$U^\mu = (1, 0, 0, 0)$$



$$\mathbf{B} = B_0 \hat{z}$$

proper detector frame = laboratory

$$(t, x, y, z)$$



$$U^\mu = (1, 0, 0, 0)$$

proper detector frame = laboratory

$$(t, x, y, z)$$

GW $\longrightarrow$ $\hat{z}$

$$h_{00} = -\omega_g^2 \, h_{ab}^{\mathrm{TT}} \, x^a \, x^b \left[-\frac{i}{\omega_g z} + \frac{1 - e^{-i\omega_g z}}{(\omega_g z)^2} \right]$$

$$h_{ij} = \omega_g^2 \left[\left(\delta_{iz} \, h_{ja}^{\mathrm{TT}} + \delta_{jz} \, h_{ia}^{\mathrm{TT}} \right) z \, x^a - h_{ij}^{\mathrm{TT}} \, z^2 - \delta_{iz} \, \delta_{jz} \, h_{ab}^{\mathrm{TT}} \, x^a \, x^b \right] \left[-\frac{1 + e^{-i\omega_g z}}{(\omega_g z)^2} - 2i \, \frac{1 - e^{-i\omega_g z}}{(\omega_g z)^3} \right]$$

$$h_{0i} = -\omega_g^2 \left(h_{ia}^{\mathrm{TT}} \, z \, x^a - \delta_{iz} \, h_{ab}^{\mathrm{TT}} \, x^a \, x^b \right) \left[-\frac{i}{2 \, \omega_g z} - \frac{e^{-i\omega_g z}}{(\omega_g z)^2} - i \, \frac{1 - e^{-i\omega_g z}}{(\omega_g z)^3} \right]$$

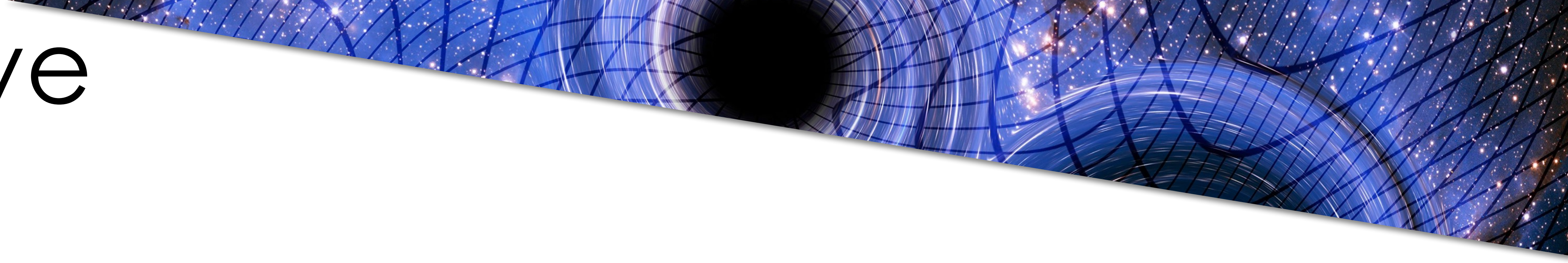
TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

GW $\longrightarrow$ $\hat{z}$

$$h_{00}^{\mathrm{TT}} = h_{0i}^{\mathrm{TT}} = 0$$

$$h_{ij}^{\mathrm{TT}} = e^{i\omega_g(t-z)} \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

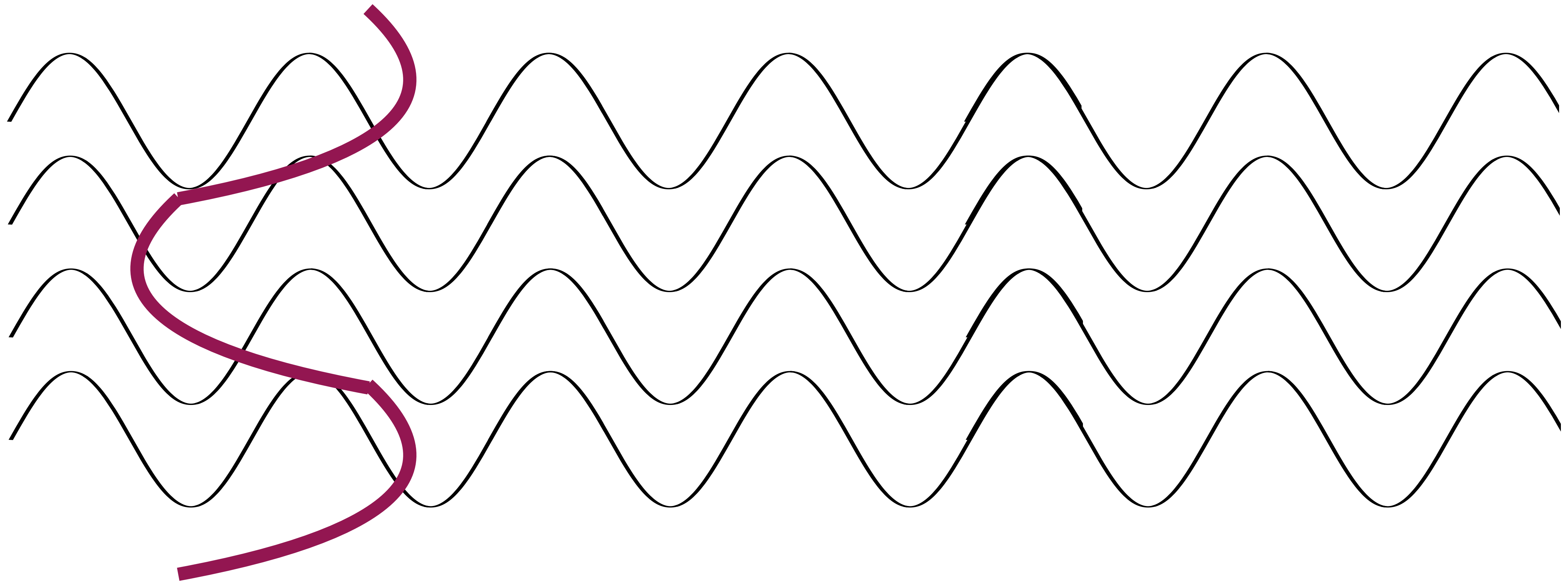
$$t_{\mathrm{TT}} \simeq t - \frac{i}{4}\omega_g\,(x^2 - y^2)\,h_+\,e^{i\omega_g t} \quad , \quad x_{\mathrm{TT}} \simeq x - \frac{1}{2}x\,(1 - i\omega_g z)\,h_+\,e^{i\omega_g t}$$

$$y_{\mathrm{TT}} \simeq y + \frac{1}{2}y\,(1 - i\omega_g z)\,h_+\,e^{i\omega_g t} \quad , \quad z_{\mathrm{TT}} \simeq z - \frac{i}{4}\omega_g\,(x^2 - y^2)\,h_+\,e^{i\omega_g t}$$

TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

probe wire



$$\mathbf{B} = B_0 \hat{z} + \frac{i}{2}(h_+ B_0) e^{i\omega_g t}(\omega_g x, -\omega_g y, 0) + \mathcal{O}(h^2)$$

TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

$$\mathbf{B} = B_0 \hat{z}$$

Theorem: $j^{\mu}_{\mathrm{eff},\mathrm{TT}} = 0$

TT gauge = comoving with the wave

$$(t_{\mathrm{TT}}, x_{\mathrm{TT}}, y_{\mathrm{TT}}, z_{\mathrm{TT}})$$

Wrong Conclusion

Theorem: $j^{\mu}_{\mathrm{eff,TT}} = 0$	→	No signal

Surprisingly common mistake in the literature
(confusion between TT frame and laboratory frame)

TT gauge = comoving with the wave

$$(t_{\rm TT}, x_{\rm TT}, y_{\rm TT}, z_{\rm TT})$$

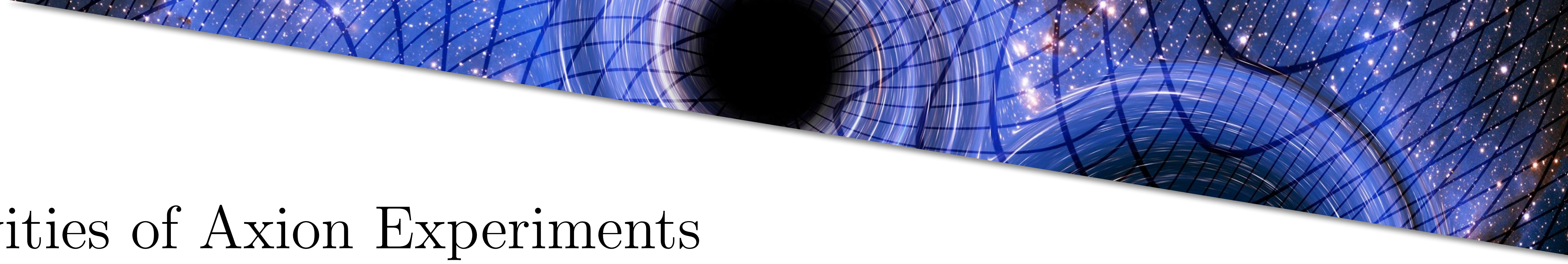
Wrong Conclusion

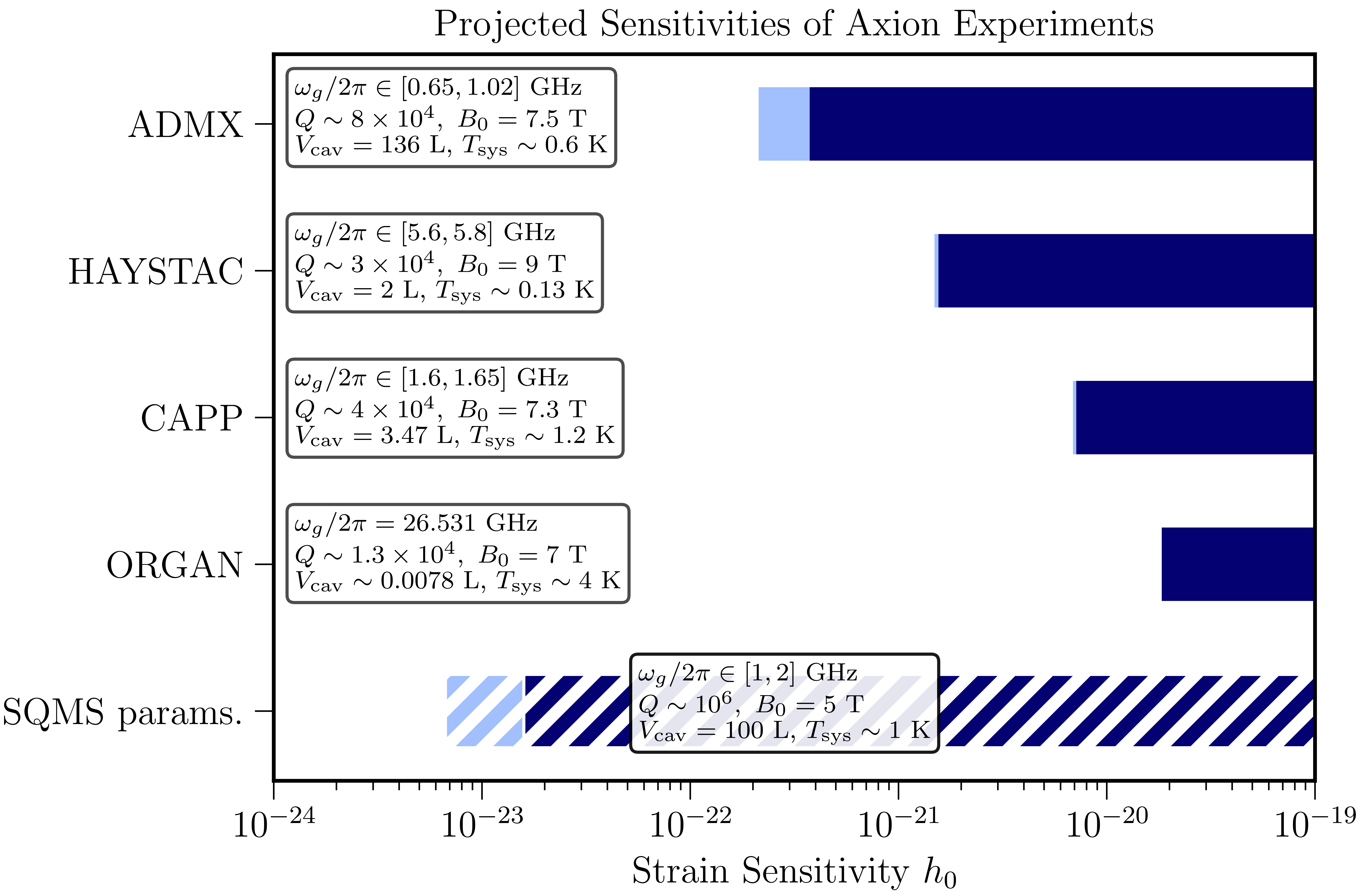
Theorem: $j^{\mu}_{\rm eff, TT} = 0$ → No signal

Doubly Wrong:

1. Impossible to prepare a uniform B-field in the TT frame
2. Even if you could do it, there would still be a signal (wire moving)

GRAVITATIONAL WAVE DETECTION





Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel '21

SUPERRADIANCE

$$\omega_g \simeq 2m_a \simeq \mathrm{GHz}\ \left(\frac{10^{-4} M_\odot}{M_{\mathrm{BH}}}\right)$$

$$h = 10^{-24}\ \left(\frac{\Delta a_*}{0.1}\right) \left(\frac{1\,\mathrm{kpc}}{D}\right) \left(\frac{M_b}{10^{-1}\,M_\odot}\right) \left(\frac{\alpha}{0.2}\right)^7$$

Signal from:[Arvanitaki, Geraci '12]

PRIMORDIAL BHs

$$\frac{N_{\rm cycles}}{Q} \simeq \left(\frac{\rm GHz}{f_g}\right)^{5/3} \left(\frac{10^{-9} M_\odot}{m_{\rm PBH}}\right)^{5/3}$$

$$Q = 10^6$$

$$h \simeq 10^{-26} \left(\frac{1{\rm pc}}{D}\right) \left(\frac{m_{\rm PBH}}{10^{-9} M_\odot}\right)^{5/3} \left(\frac{\omega_g}{\rm GHz}\right)^{2/3}$$

If they are DM and are all in binaries (1 year)

$$D \simeq 10^{-3}\ {\rm pc}$$

If they are DM

$$D \simeq 10\ {\rm pc} \left(\frac{m_{\rm PBH}}{10^{-9} M_\odot}\right)$$

POWER FROM THE SUN

Power

$$\frac{dP}{dE} \sim \text{const.}$$

$$\frac{d\Gamma}{dE} \sim \frac{1}{E}$$

Number of gravitons

Signal from:[Weinberg ‘65]

POWER FROM THE SUN

$$\Gamma \sim \exp[B \log(E/\Lambda)], \quad B \ll 1$$

Signal from:[Weinberg ‘65]

POWER FROM THE SUN

Signal

$$P_{\text{tot}} \simeq 6 \times 10^{14}\ \frac{\text{erg}}{\text{s}} \simeq 10^{11}\ \text{eV}^2$$

Total emitted power (in gravitons)

$$P_{\text{exp}} \simeq 10^{-12}\ \text{eV}^2$$

Power reaching a m-sized experiment on Earth (in gravitons)

Signal from:[Weinberg ‘65]

POWER FROM THE SUN

Signal

$$P_{\rm tot} \simeq 6 \times 10^{14}\ \frac{\rm erg}{\rm s} \simeq 10^{11}\ {\rm eV}^2$$

Total emitted power (in gravitons)

$$P_{\rm exp} \simeq 10^{-12}\ {\rm eV}^2$$

Power reaching a m-sized experiment on Earth (in gravitons)

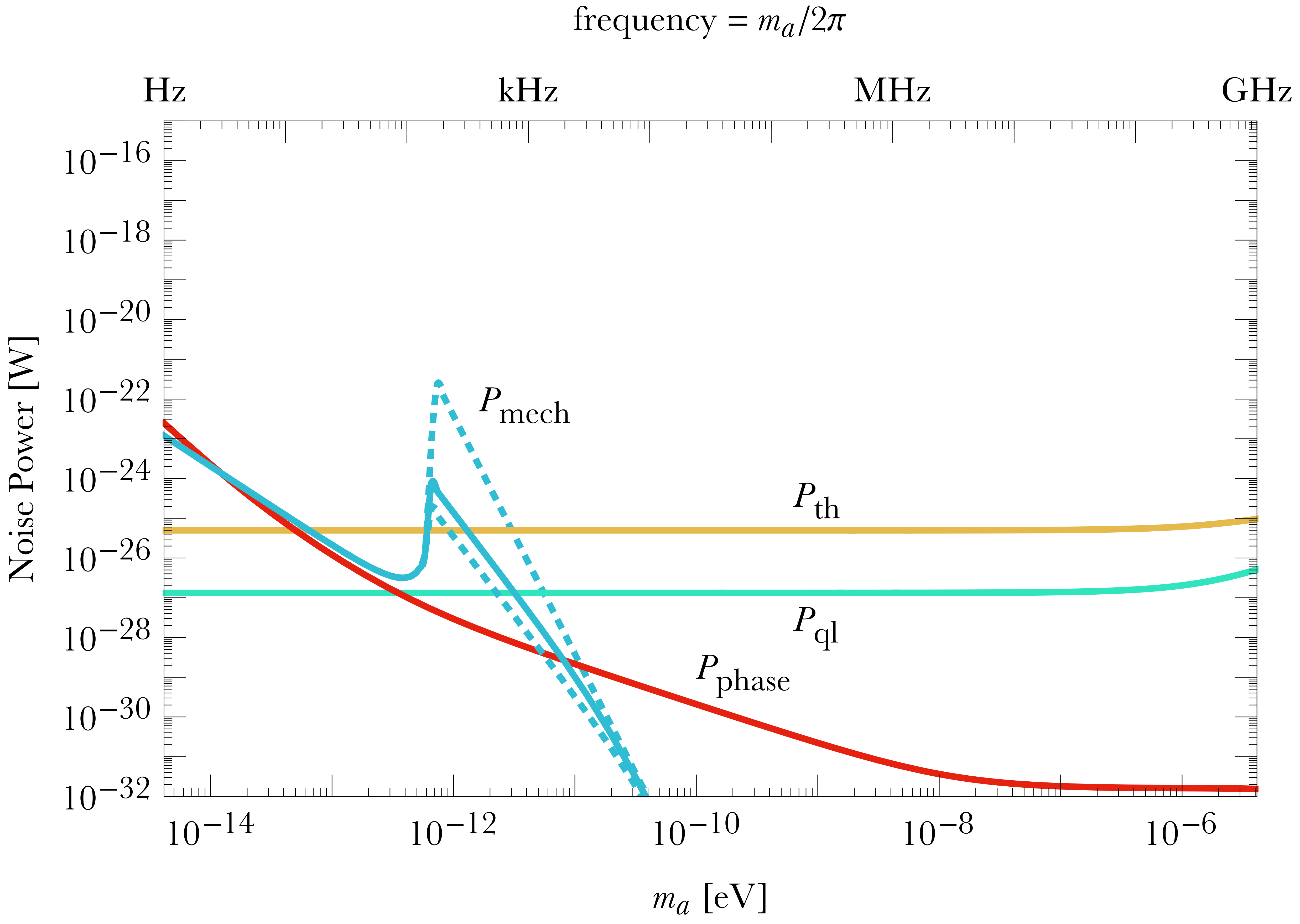
Noise

$$P_{\rm th} \simeq T\Delta\omega \simeq {\rm eV}^2 \left(\frac{T}{\rm K}\right)$$

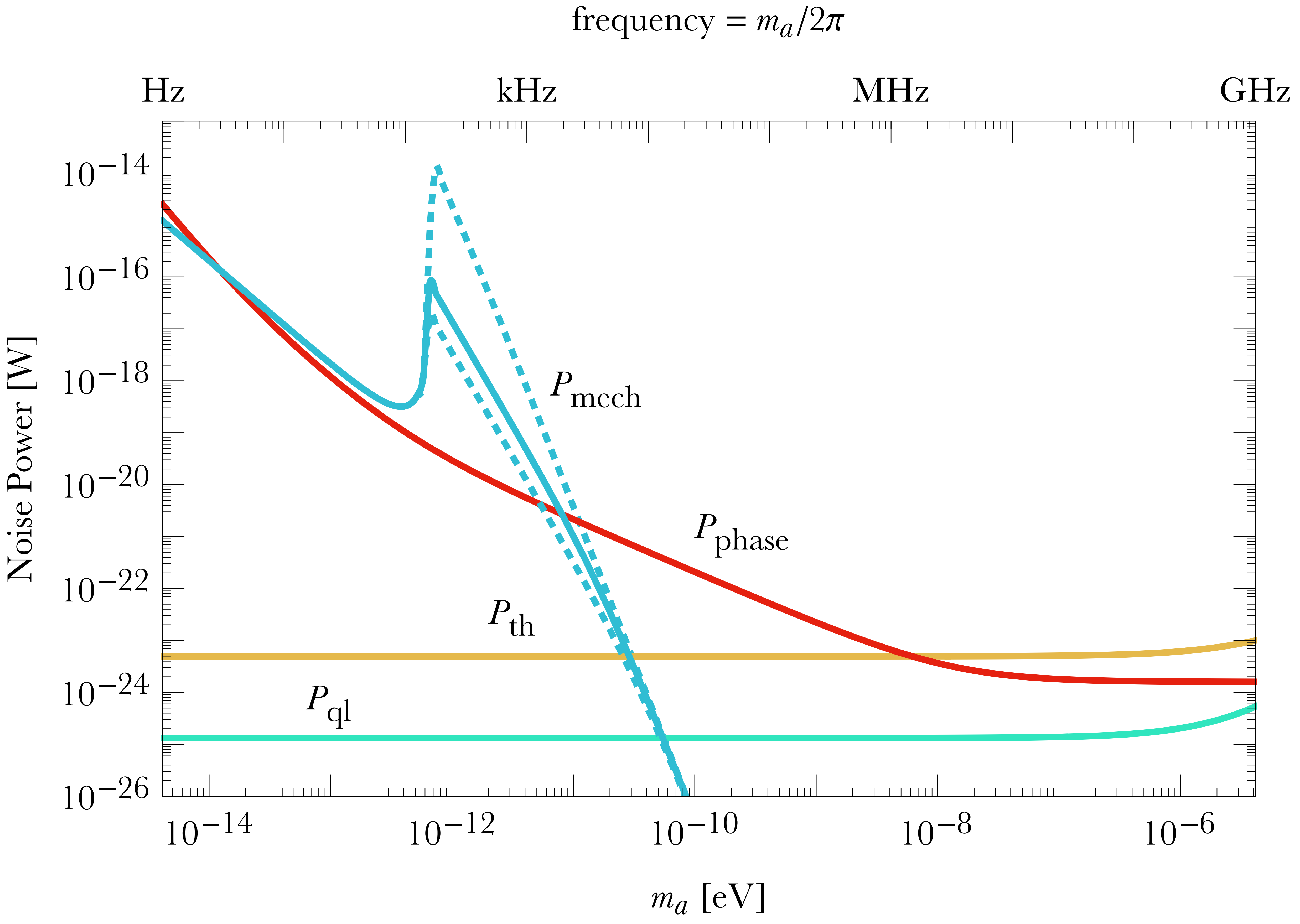
Thermal Noise in the bandwidth of the signal (in photons)

Signal from:[Weinberg '65]

NOISE PSDs

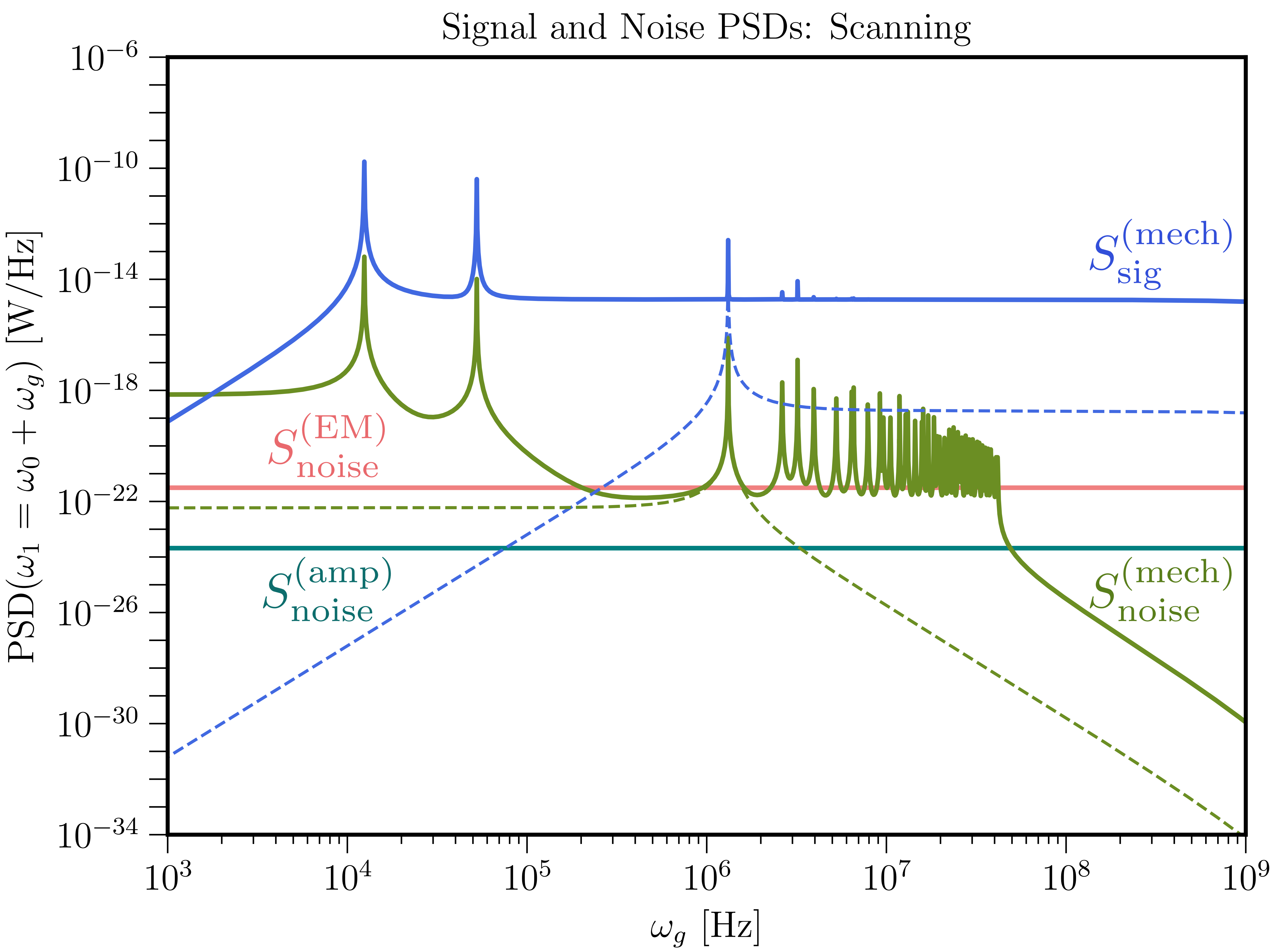


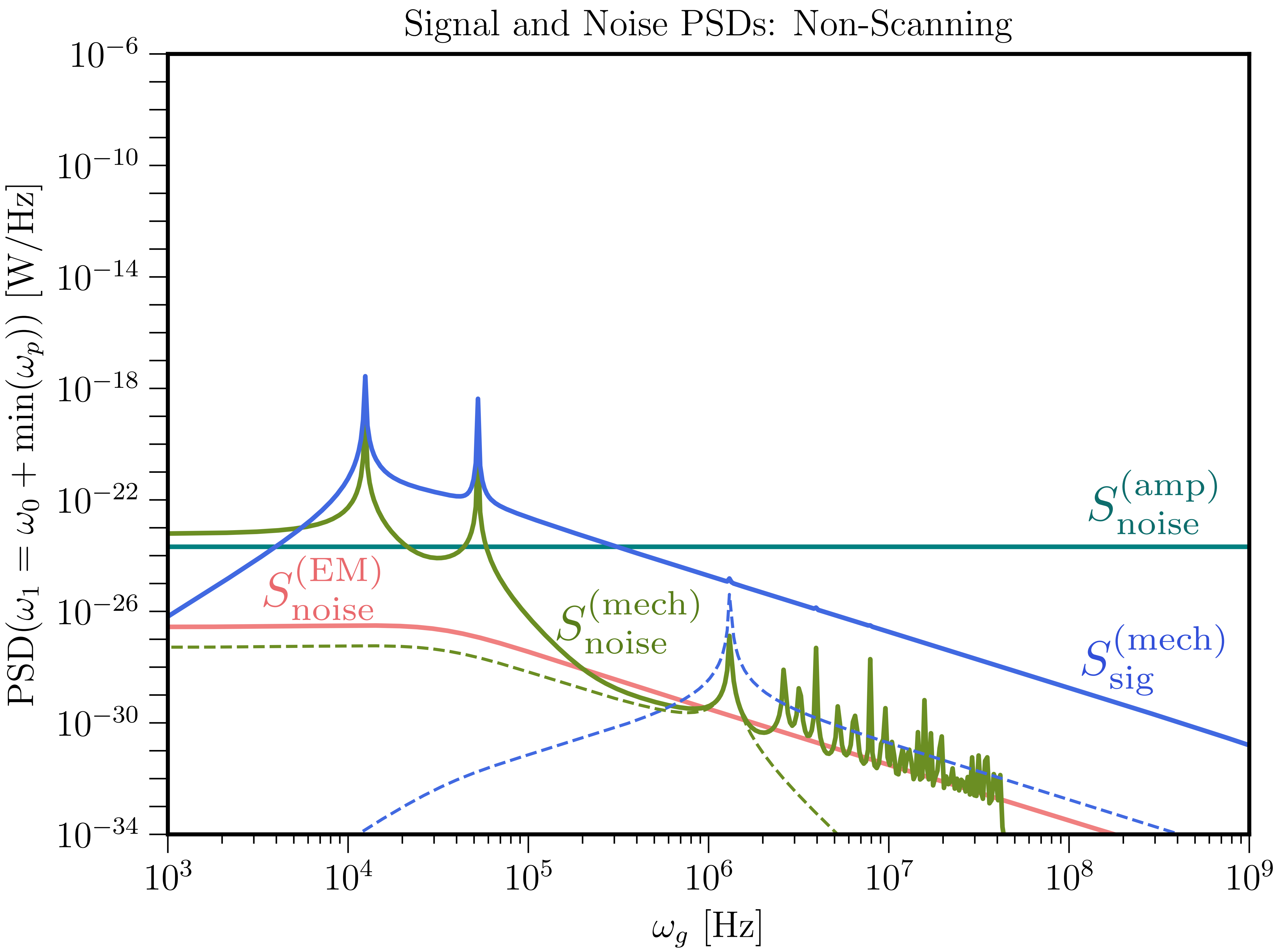
$$\epsilon_{1d} = 10^{-7}, \quad Q = 10^{12}$$



$$\epsilon_{1d} = 10^{-5}, \quad Q = 10^{10}$$

NOISE PSDs GWs





MADMAX and LAMPOST

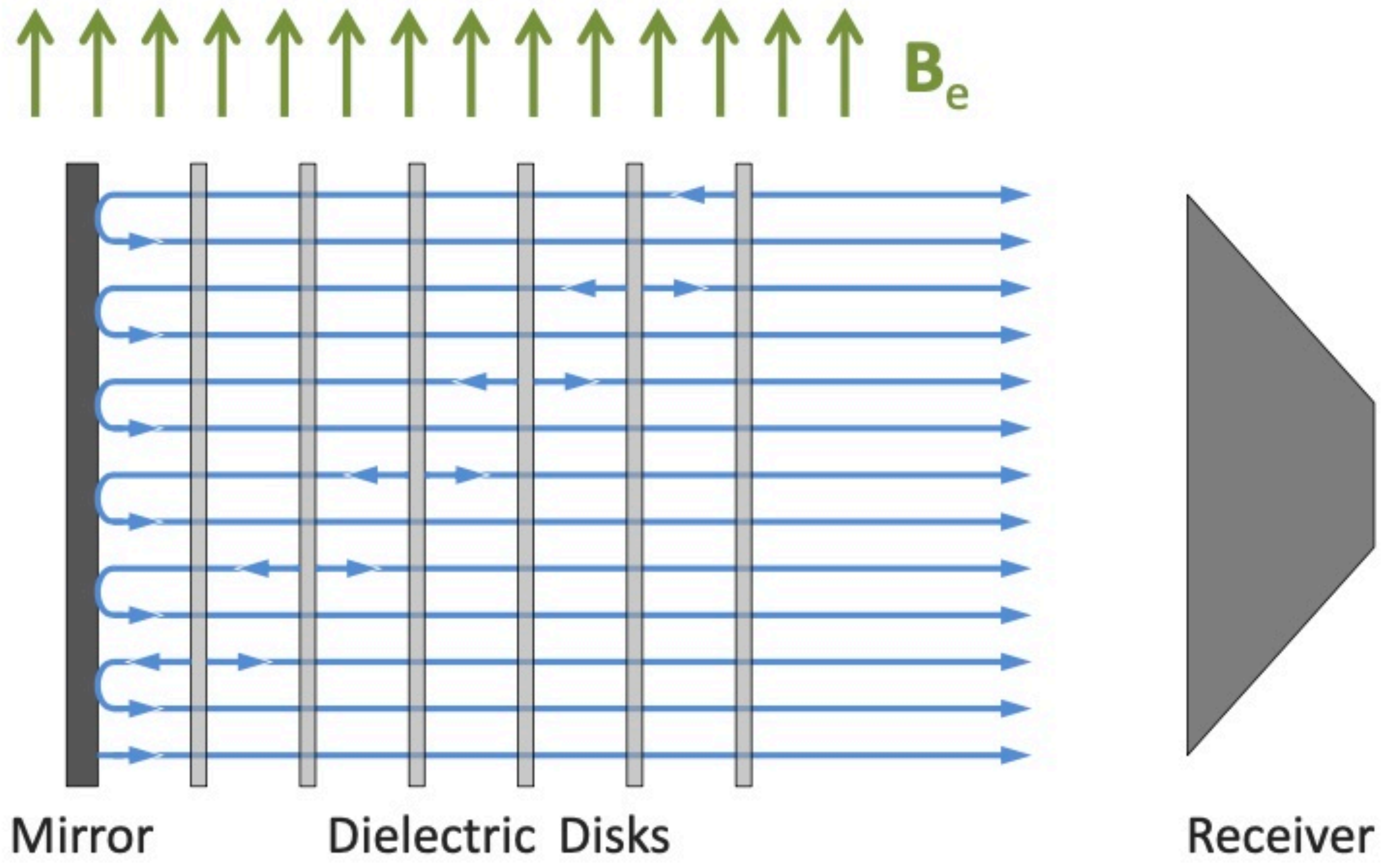
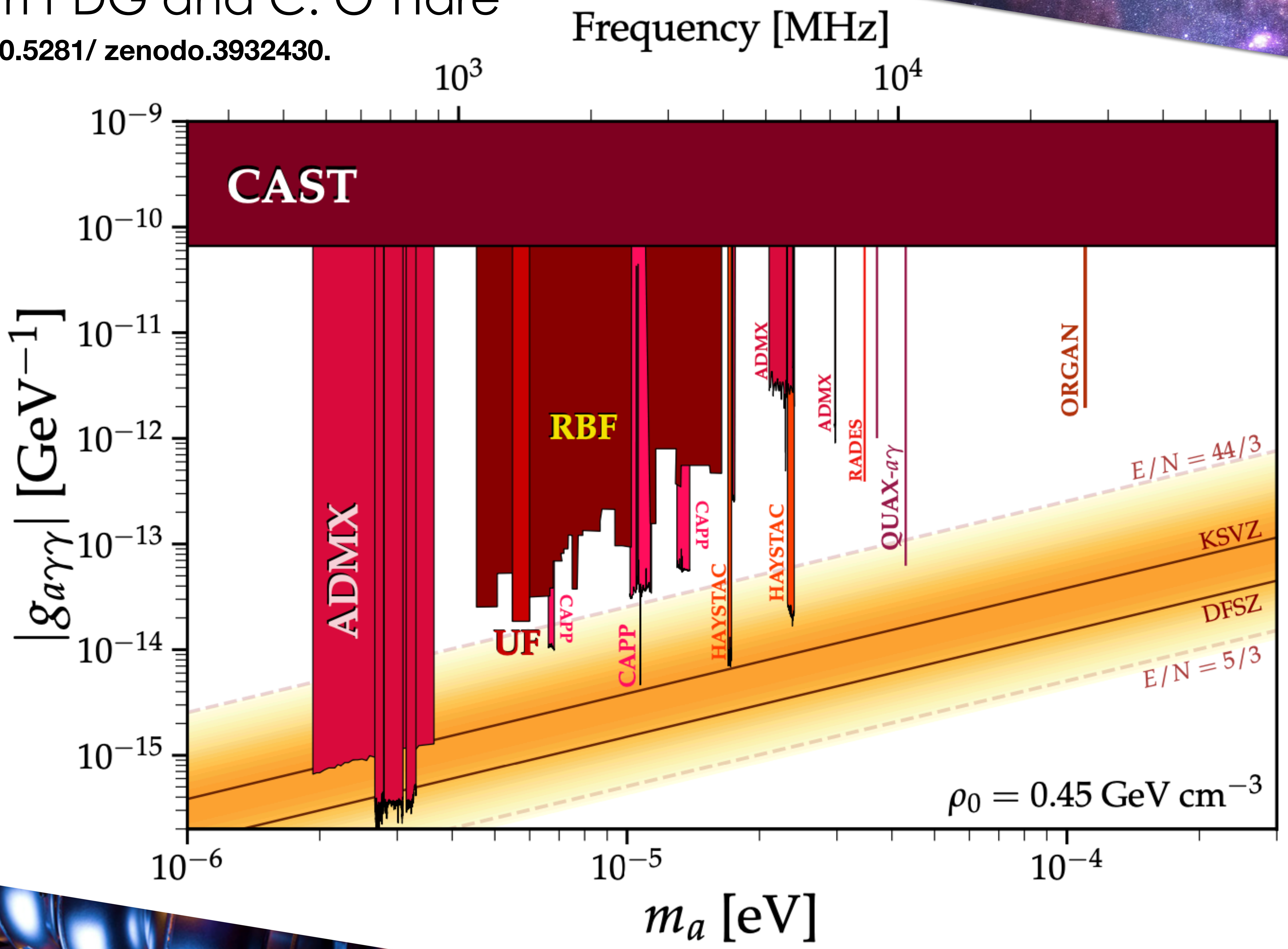
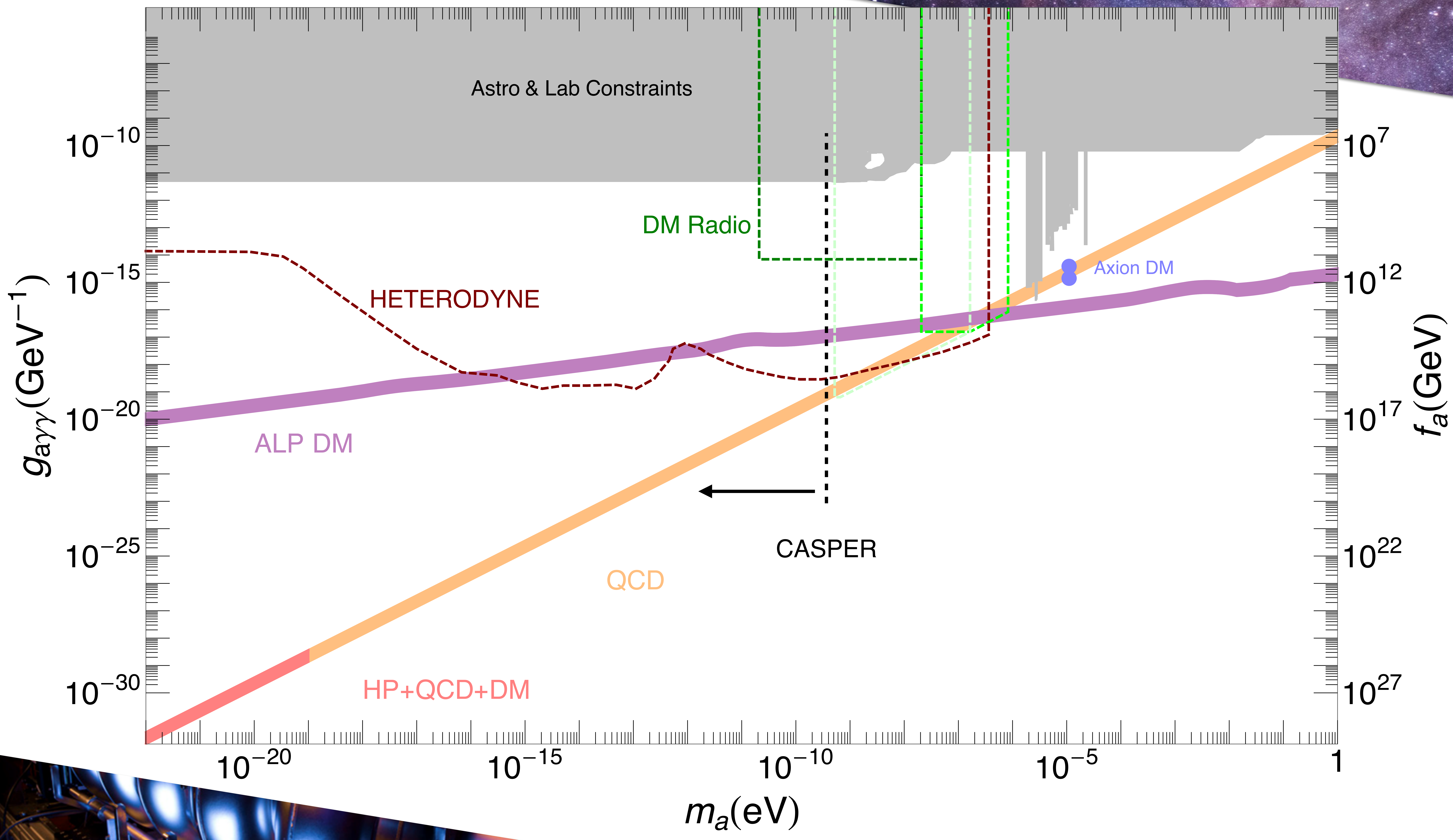


Figure from PDG and C. O'Hare

https://doi.org/10.5281/ zenodo.3932430.

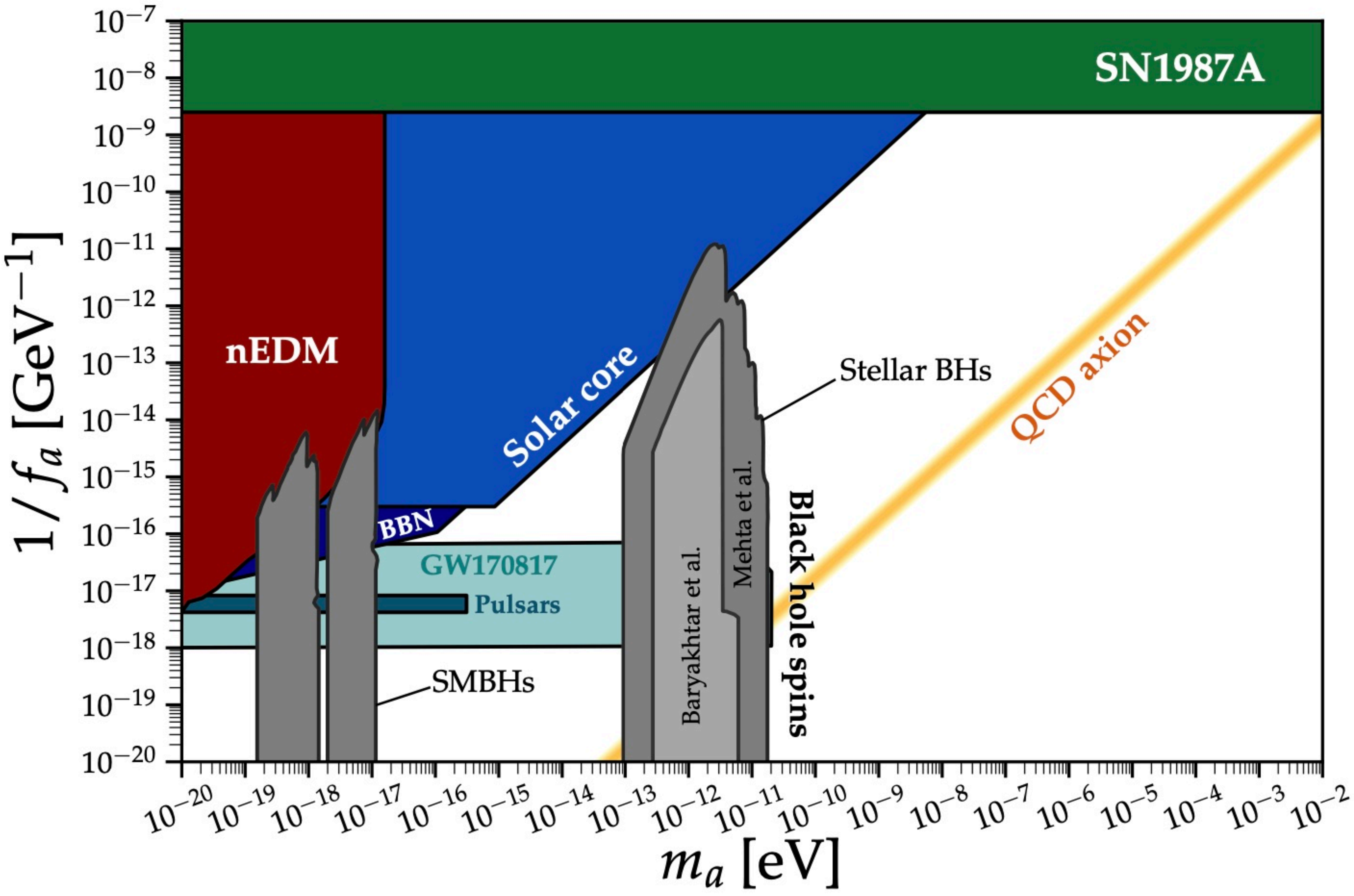




Astro & Lab Constraints
DM Radio
HETERODYNE
Axion DM
ALP DM
CASPER
QCD
HP+QCD+DM
$g_{a\gamma\gamma}(\mathrm{GeV}^{-1})$
$f_a(\mathrm{GeV})$
$m_a(\mathrm{eV})$
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{7}
10^{12}
10^{17}
10^{22}
10^{27}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1

Figure from PDG and C. O'Hare

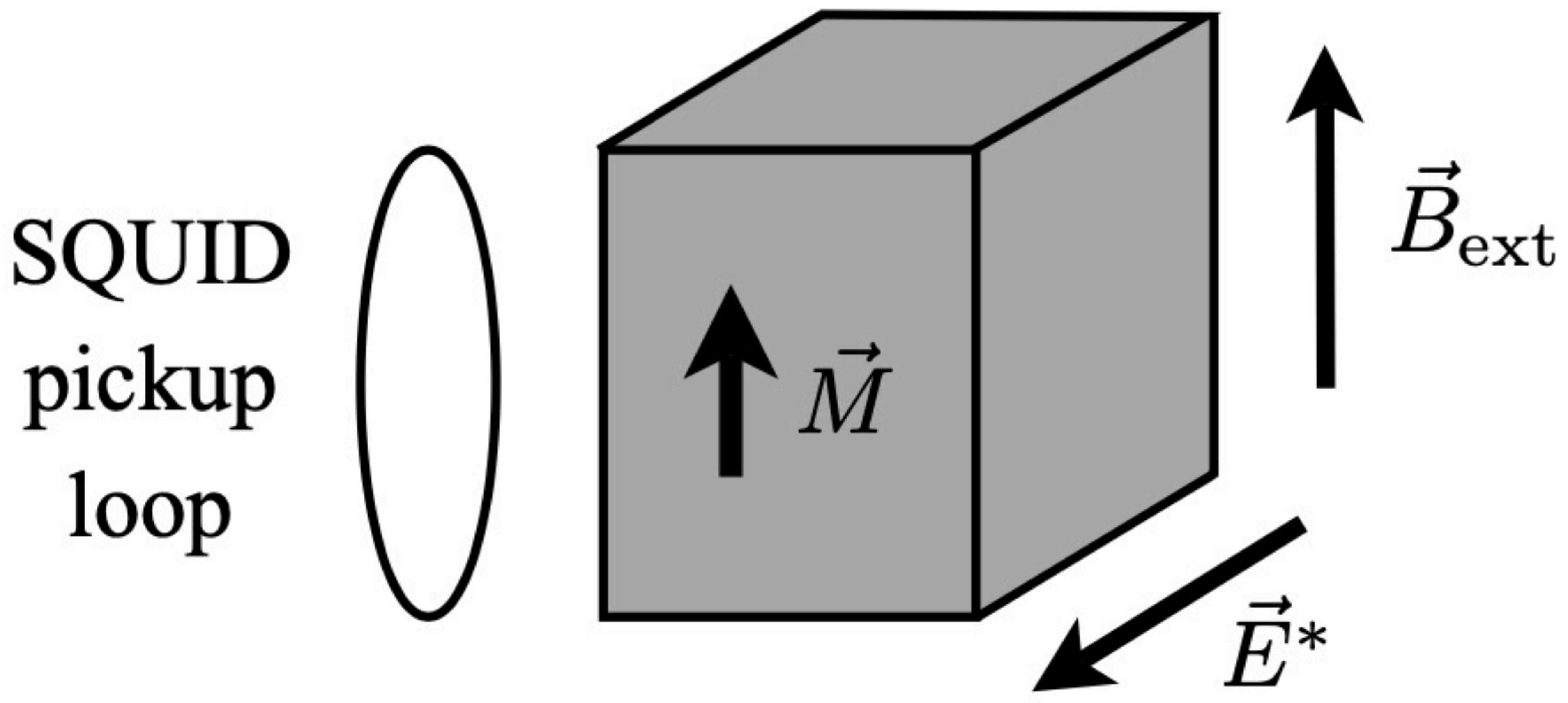
https://doi.org/10.5281/ zenodo.3932430.



Valid for QCD Axion!

CASPER

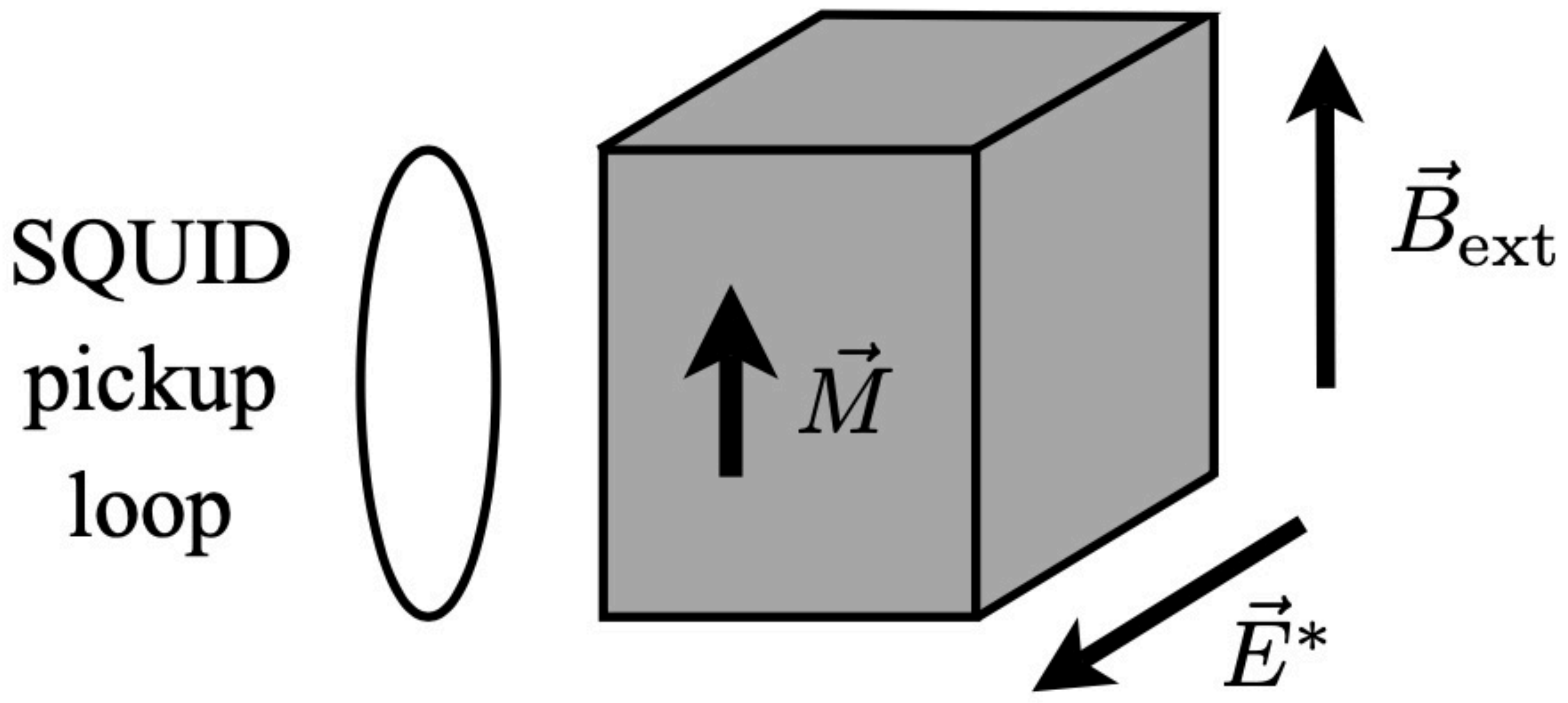
$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$



Without the axion you have a magnetisation component precessing around B (Larmor frequency)

CASPER

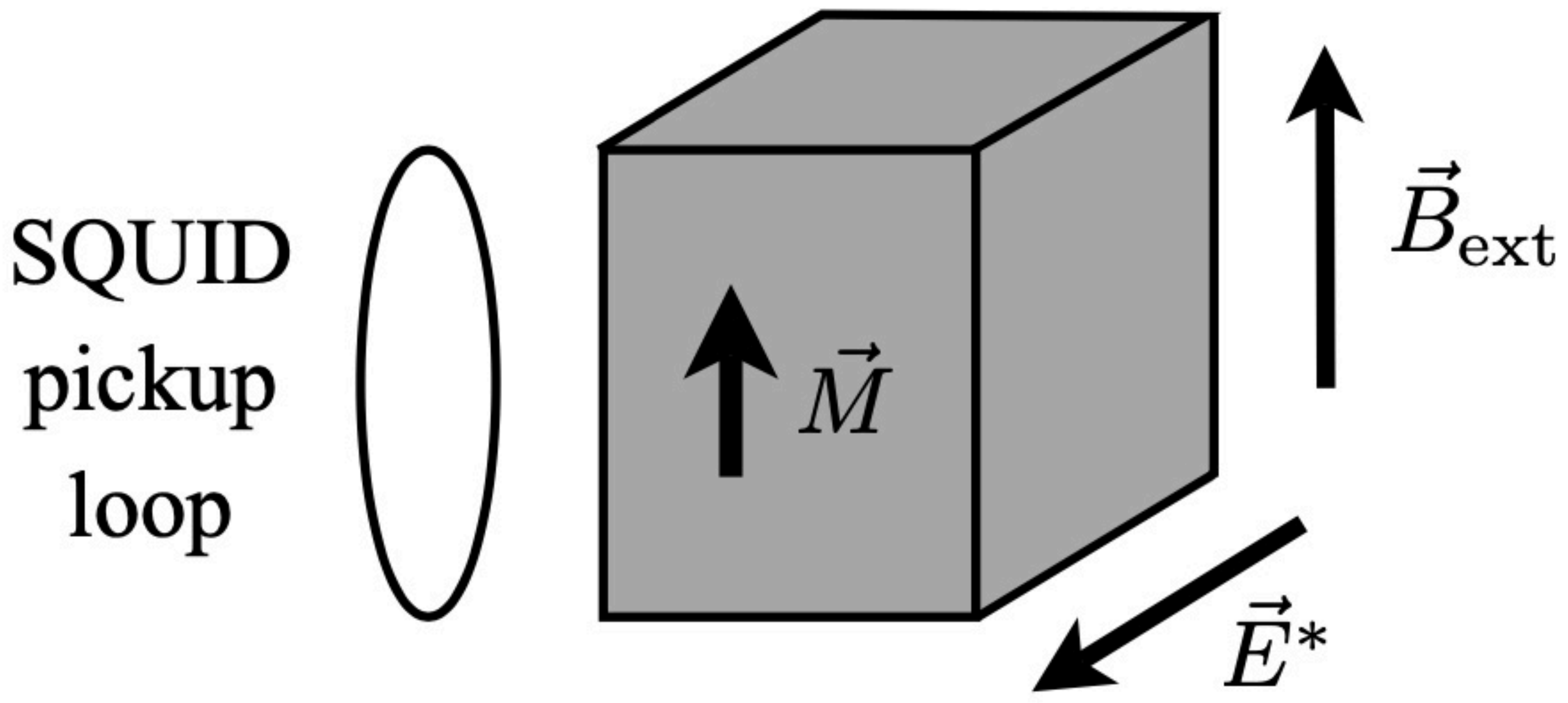
$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$



$$M(t) \approx np\mu E^* \epsilon_S d_n \frac{\sin\left[\left(\frac{2\mu B_{\text{ext}} - m_a c^2}{\hbar}\right) t\right]}{\frac{2\mu B_{\text{ext}} - m_a c^2}{\hbar}} \sin\left(2\mu B_{\text{ext}} t\right)$$

CASPER

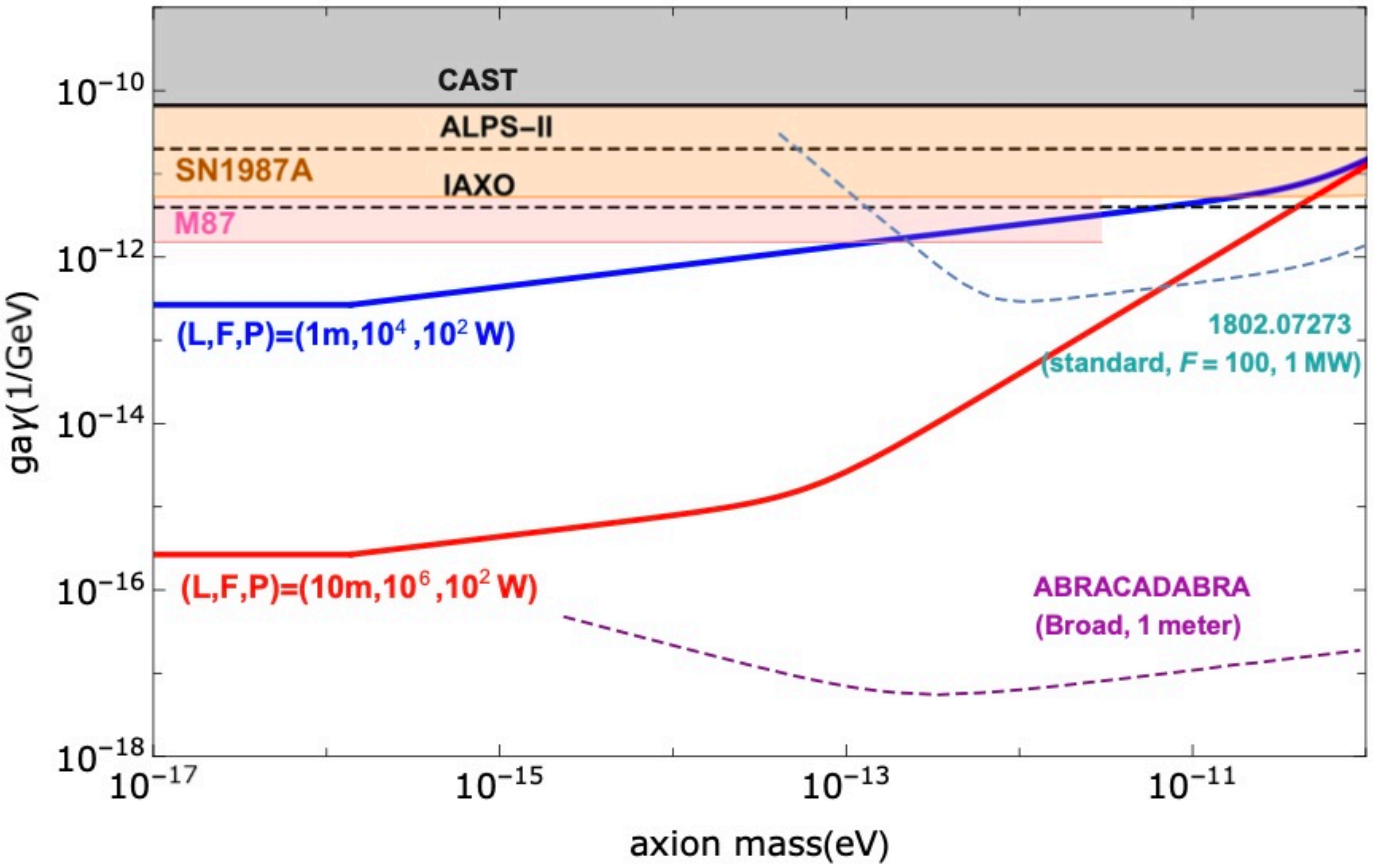
$$H \simeq \frac{a}{m_N f_a} \vec{\sigma} \cdot \vec{E}$$



	n	E^*	p	T_2	Max. B_{ext}
Phase 1	$10^{22}\ \frac{1}{\text{cm}^3}$	$3 \times 10^8\ \frac{\text{V}}{\text{cm}}$	10^{-3}	1 ms	10 T
Phase 2	$10^{22}\ \frac{1}{\text{cm}^3}$	$3 \times 10^8\ \frac{\text{V}}{\text{cm}}$	1	1 s	20 T

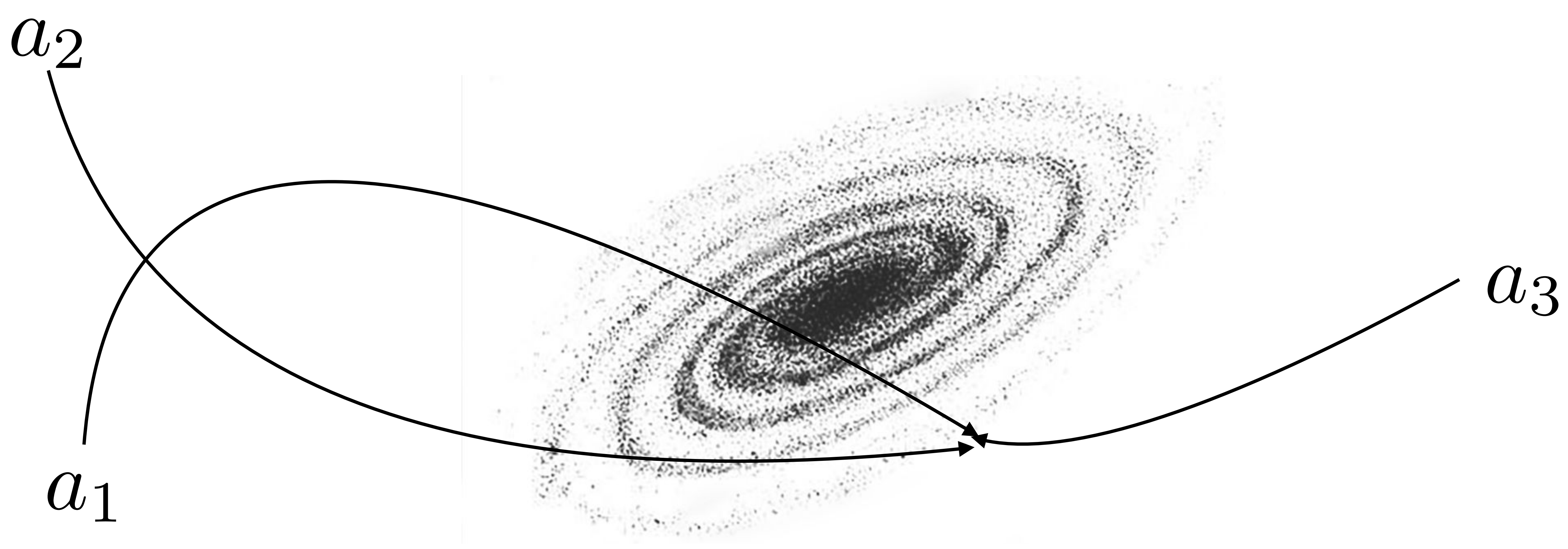
DANCE

Obata, Fujita, Michimura, '18

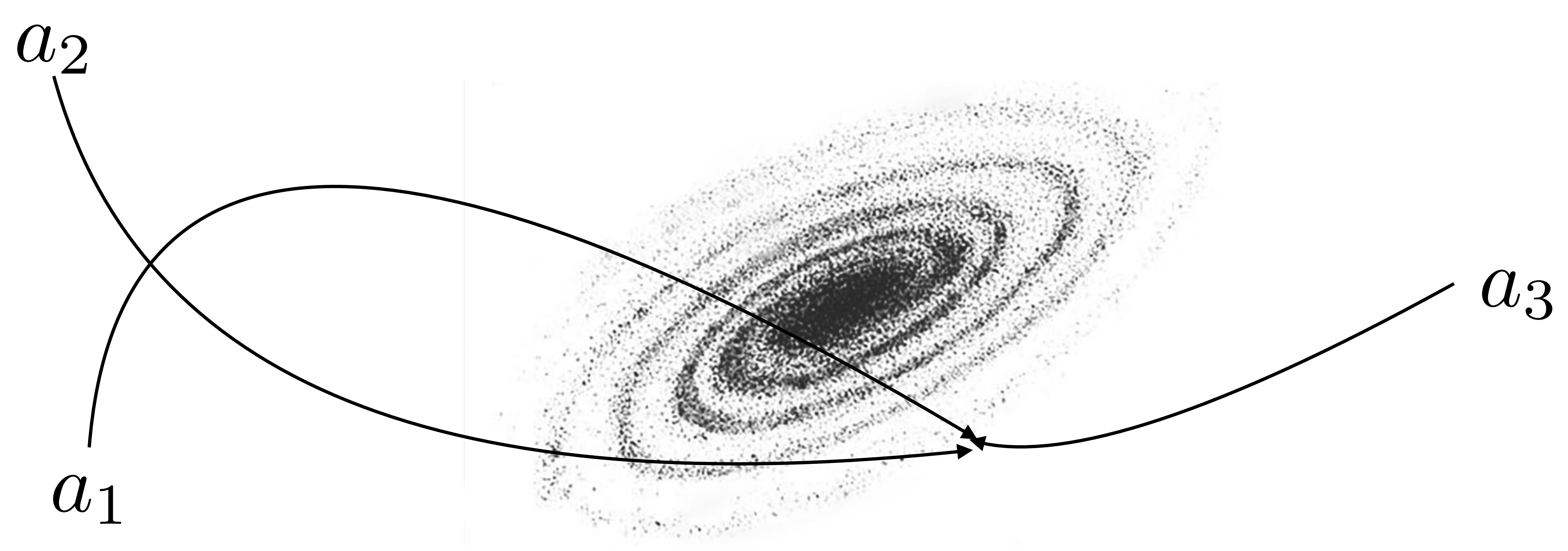


ALP DARK MATTER IN THE LAB

In each experimental bin we are summing over a multitude of plane waves with different phases



In each experimental bin we are summing over a multitude of plane waves with different phases



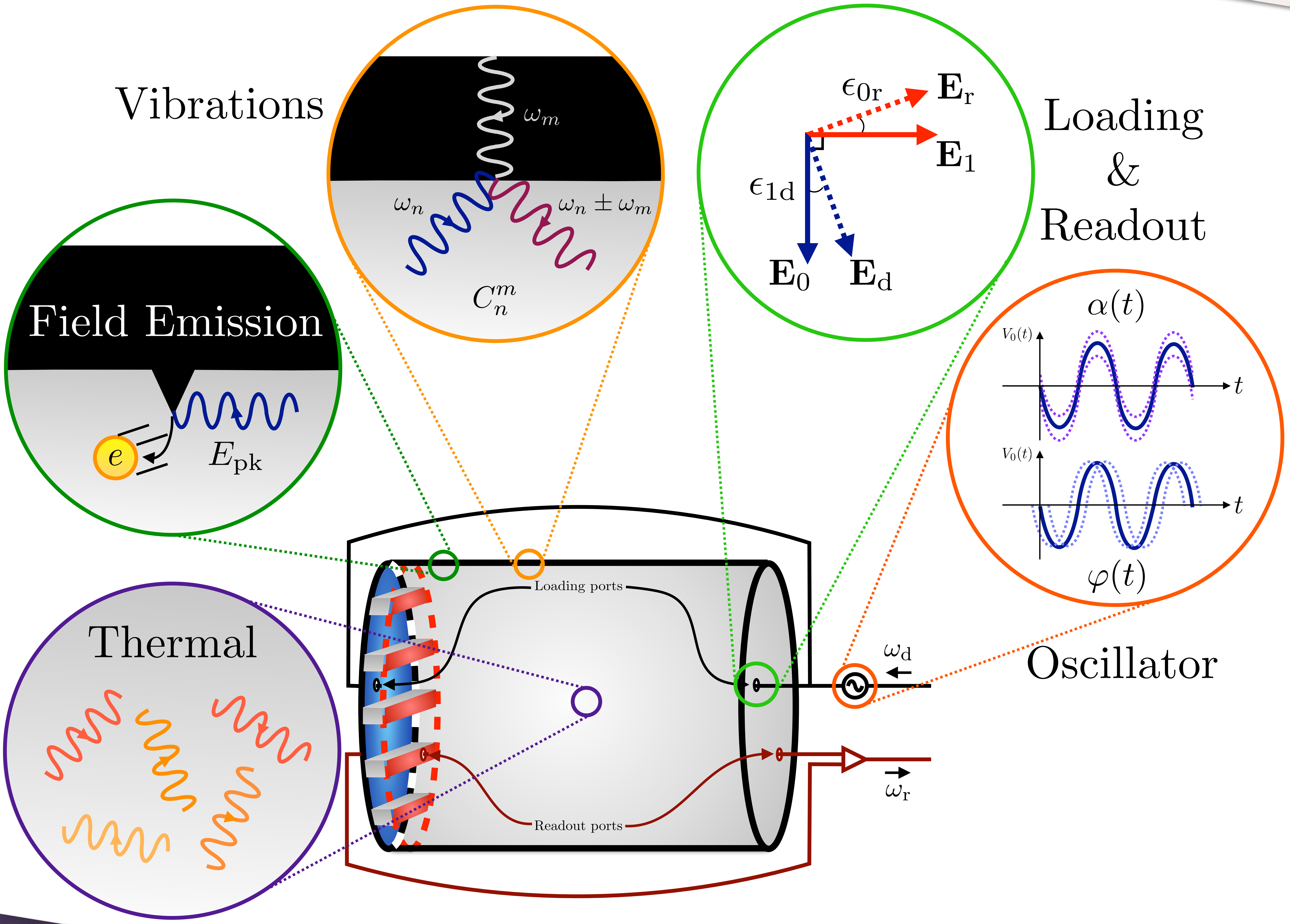
$$a(t) = a_0 \left[\cos\left(m_a \left(1 + \frac{v_1^2}{2}\right) t + \phi_1 \right) + \cos\left(m_a \left(1 + \frac{v_2^2}{2}\right) t + \phi_2 \right) + ... \right]$$

$$\simeq a_0 \cos(m_a t + \phi) \left[\cos(\delta\omega_a t + \phi') + ...\right]$$

$$\delta\omega_a \simeq \frac{1}{m_a \langle v_{\rm DM}^2 \rangle} \simeq \frac{10^6}{m_a}$$

Effectively: very **slow modulation of** an approximately **monochromatic field**

ULTRALIGHT AXION-LIKE DARK MATTER


Vibrations
ω_m
ω_n
$\omega_n \pm \omega_m$
C_n^m
ϵ_{0r}
$\mathbf{E}_r$
$\mathbf{E}_1$
ϵ_{1d}
$\mathbf{E}_0$
$\mathbf{E}_d$
Loading
&
Readout
Field Emission
e
E_{pk}
$\alpha(t)$
$V_0(t)$
t
$\varphi(t)$
Oscillator
Thermal
Loading ports
Readout ports
ω_d
ω_r

LEAKAGE NOISE

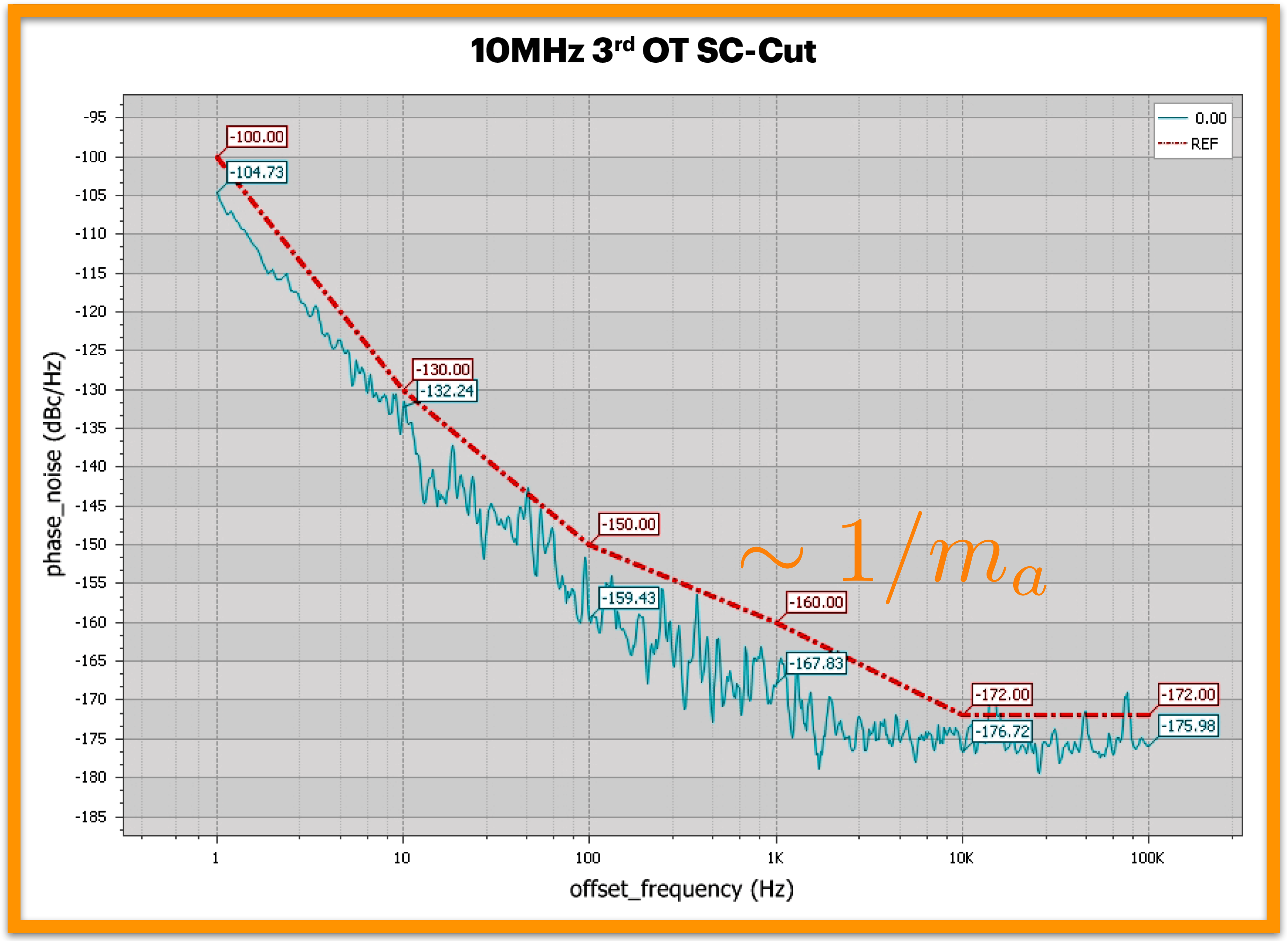
$$S_{\rm phase}(\omega) \simeq \frac{1}{2}\,\epsilon_{\rm 1d}^2\, S_\phi(\omega-\omega_0)\,\boxed{\frac{(\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2+(\omega\,\omega_1/Q_1)^2}}\,\frac{\omega_0 Q_1}{\omega_0 Q_0}\,P_{\rm in}$$

Cavity Response

LEAKAGE NOISE

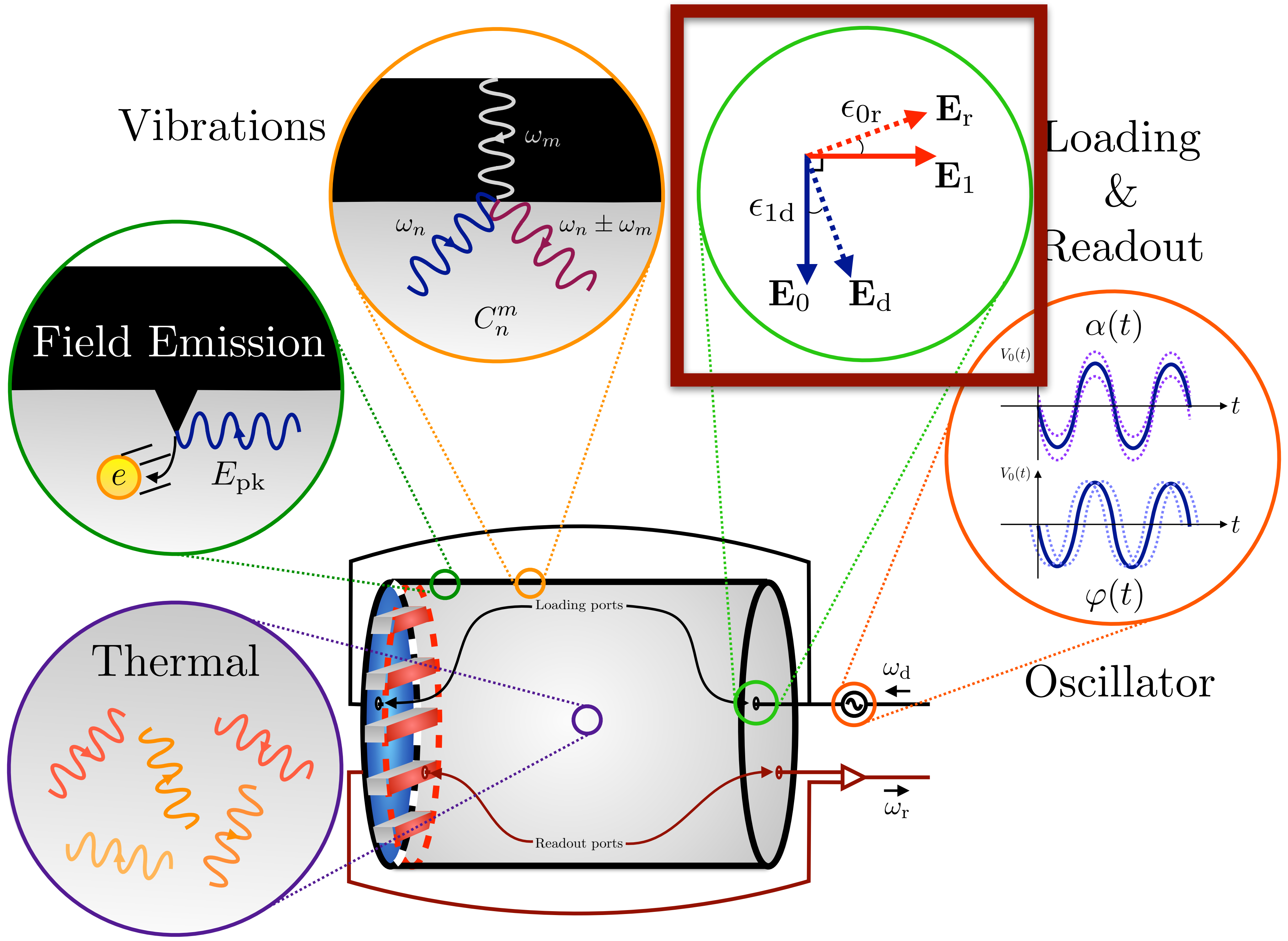
$$S_{\text{phase}}(\omega) \simeq \frac{1}{2}\,\epsilon_{1\text{d}}^2\, \boxed{S_\phi(\omega-\omega_0)}\, \frac{(\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2+(\omega\,\omega_1/Q_1)^2}\, \frac{\omega_0 Q_1}{\omega_0 Q_0}\, P_{\text{in}}$$

$\sim 1/m_a$



LEAKAGE NOISE

$$S_{\rm phase}(\omega) \simeq \frac{1}{2}\,\boxed{\epsilon_{\rm 1d}^2}\,S_\phi(\omega-\omega_0)\,\frac{(\omega\,\omega_1/Q_1)^2}{(\omega^2-\omega_1^2)^2+(\omega\,\omega_1/Q_1)^2}\,\frac{\omega_0 Q_1}{\omega_0 Q_0}\,P_{\rm in}$$

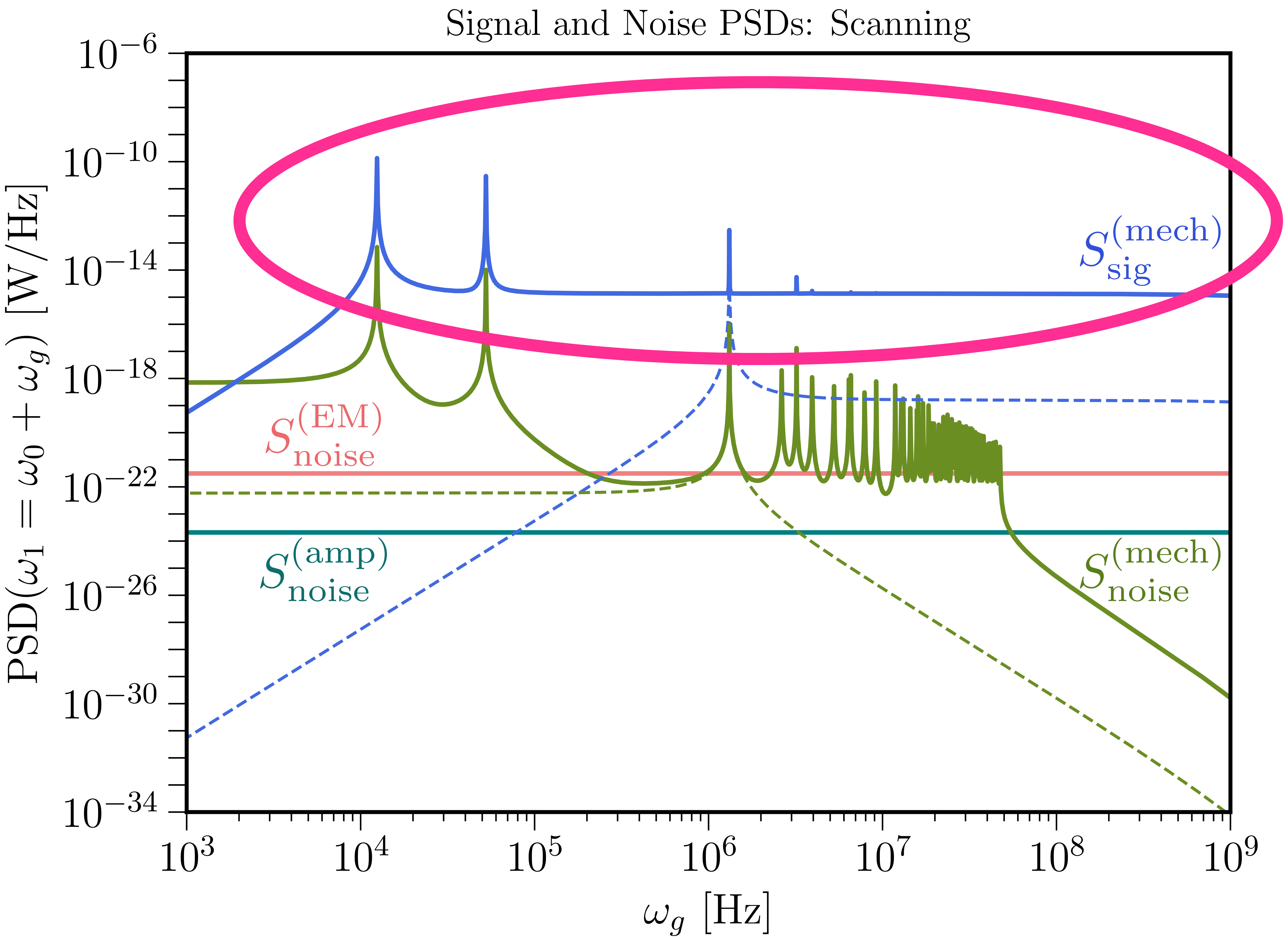


From MAGO
and other similar cavities

NOISE

Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel,Wentzel '23
arXiv:2303.01518

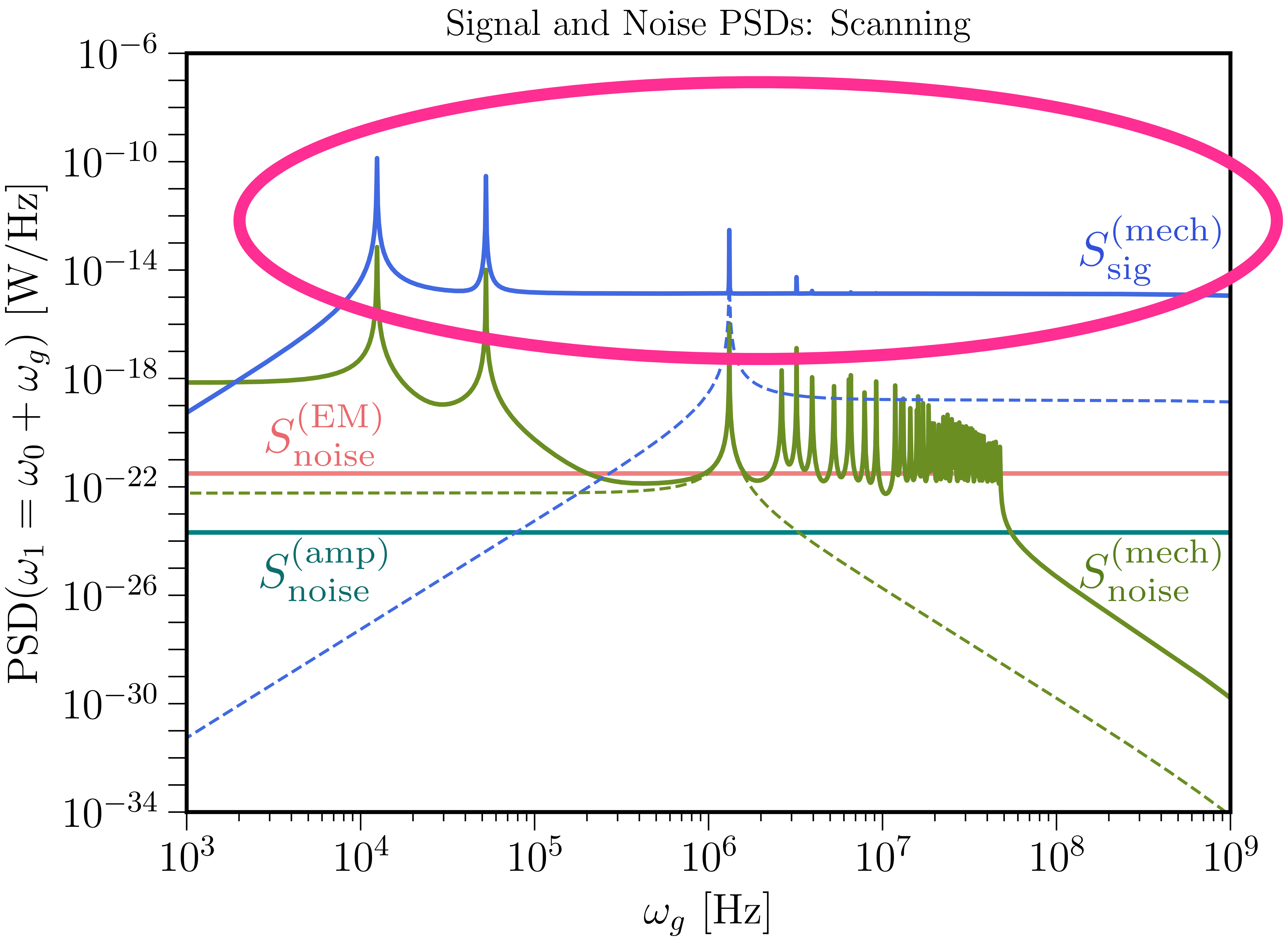
RESONANT



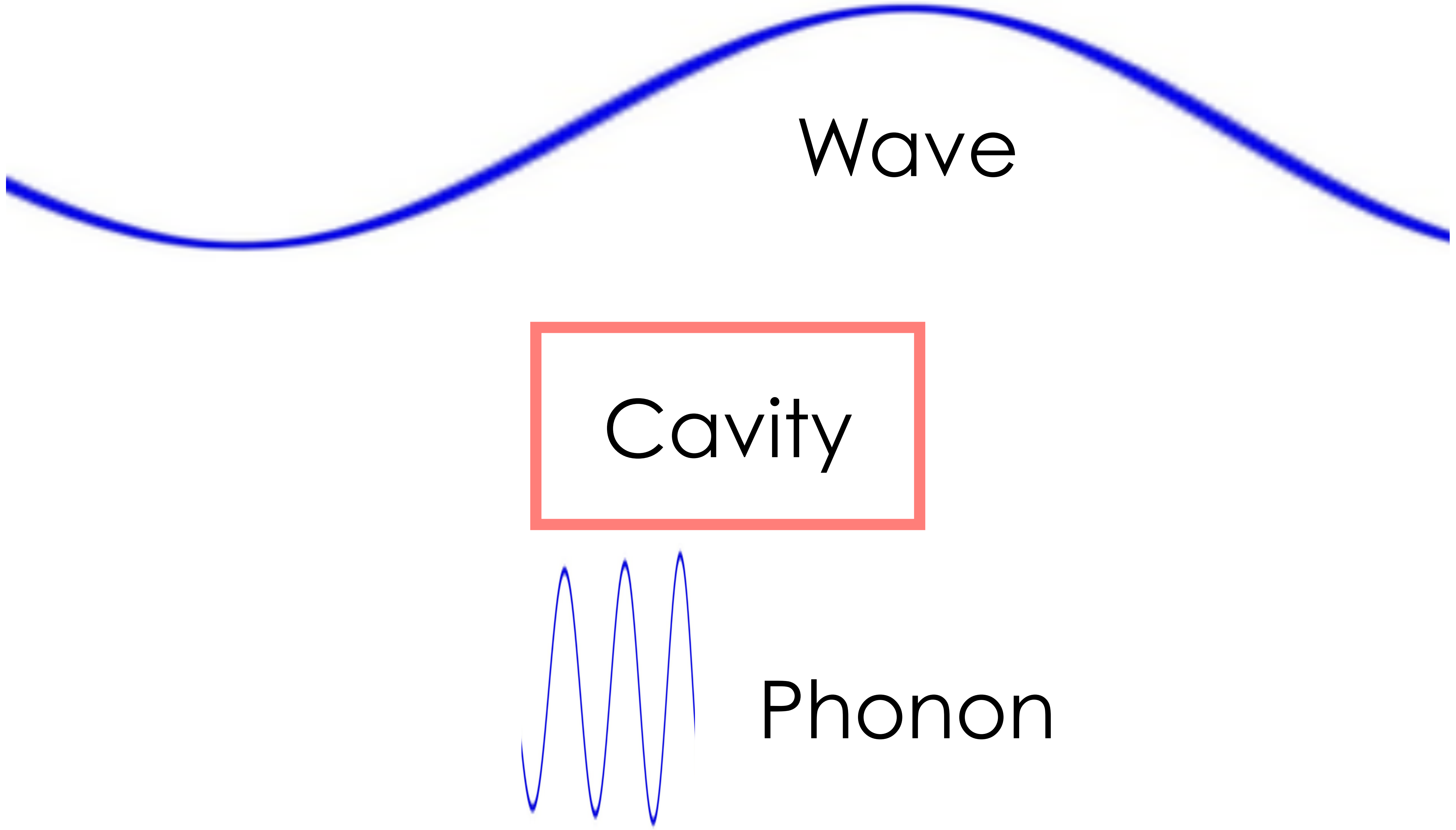
SIGNAL DOMINATED BY THE FIRST FEW MECHANICAL RESONANCES

Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel,Wentzel '23
arXiv:2303.01518

RESONANT

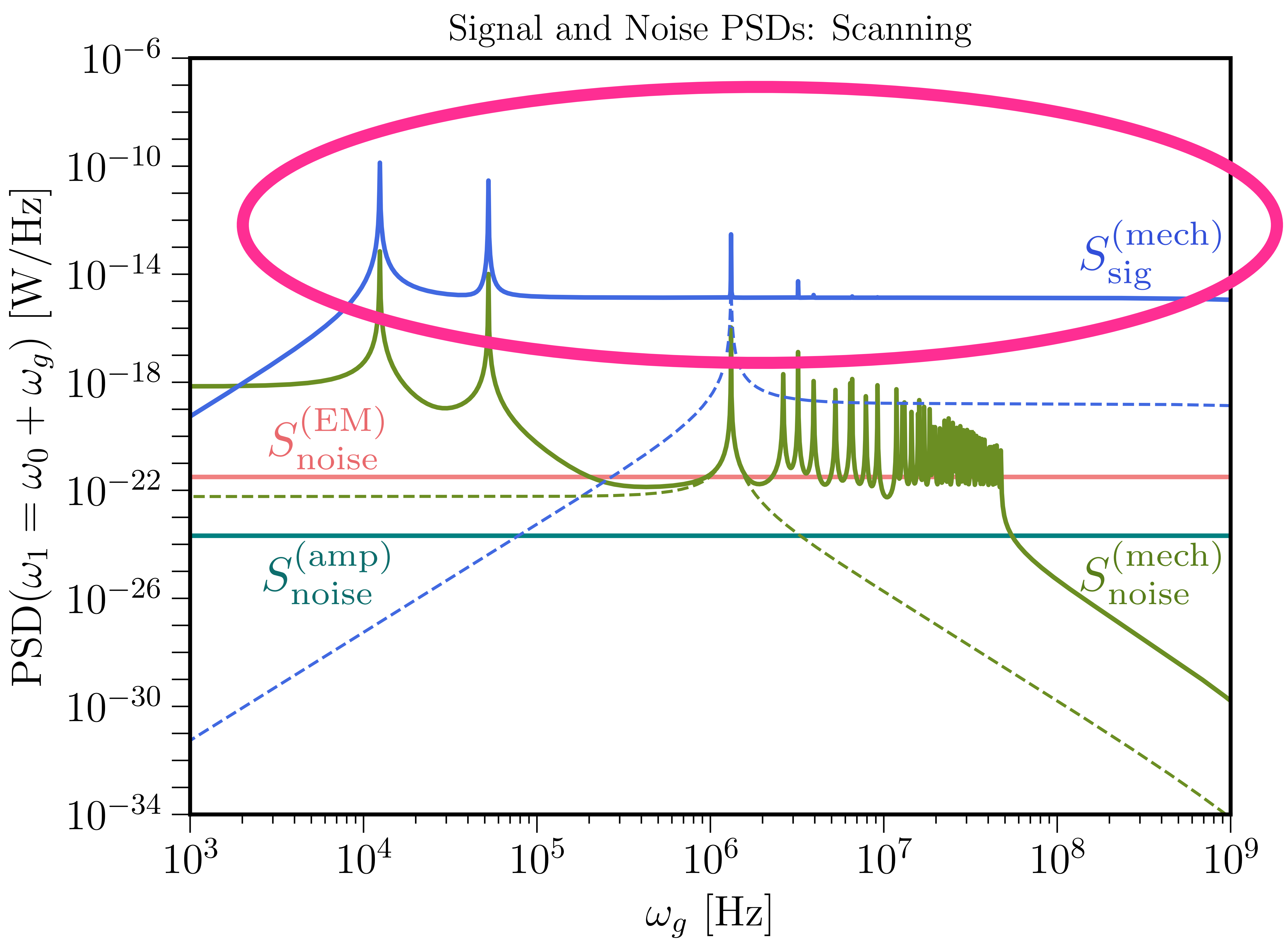


SIGNAL DOMINATED BY THE FIRST FEW MECHANICAL RESONANCES



Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel,Wentzel '23
arXiv:2303.01518

RESONANT



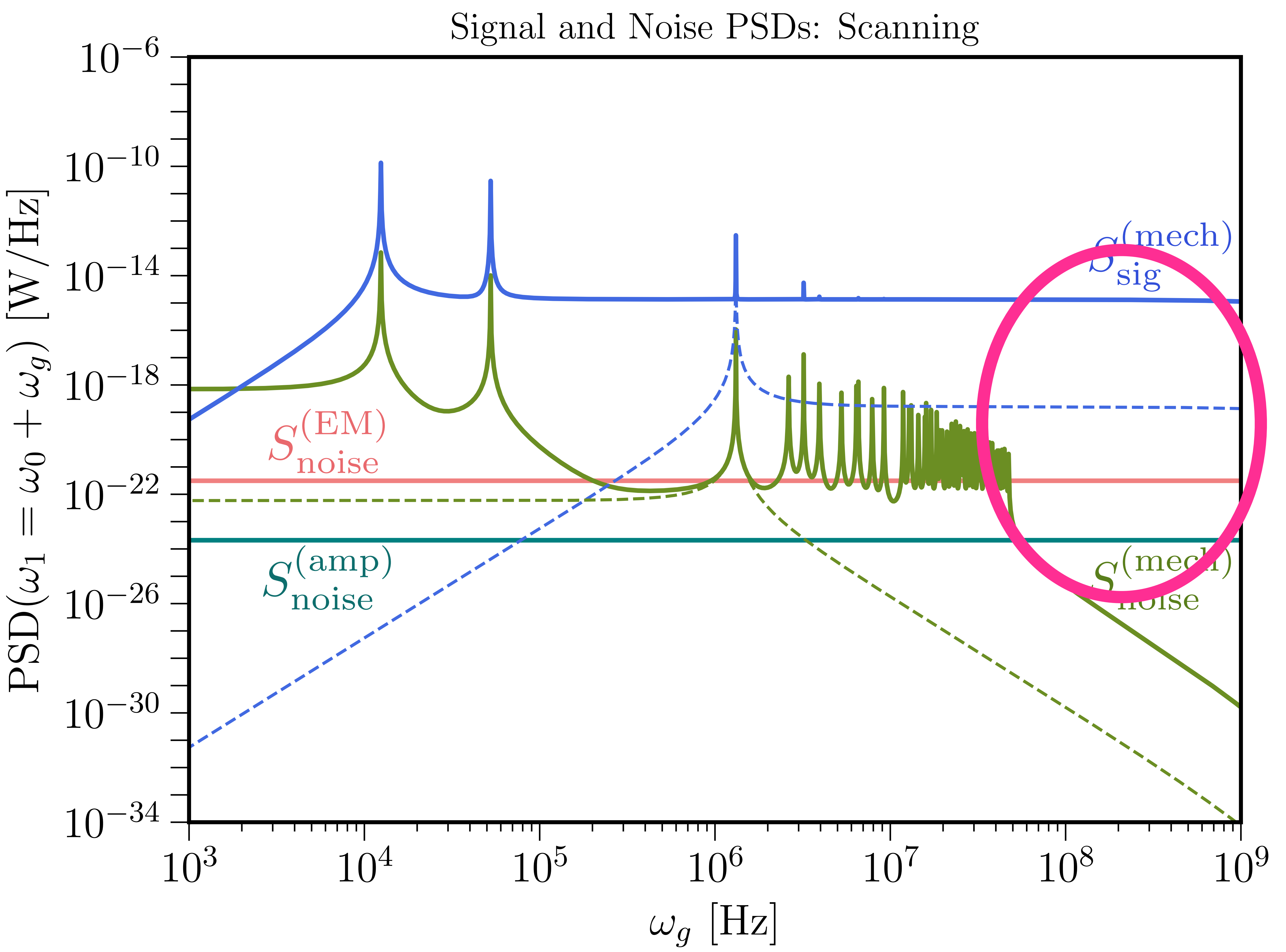
SIGNAL DOMINATED BY THE FIRST FEW MECHANICAL RESONANCES

$$\eta^g_{\mathrm{mech}} \sim \frac{1}{\omega_m^2}$$

$$Q_m \sim \frac{1}{\omega_m}$$

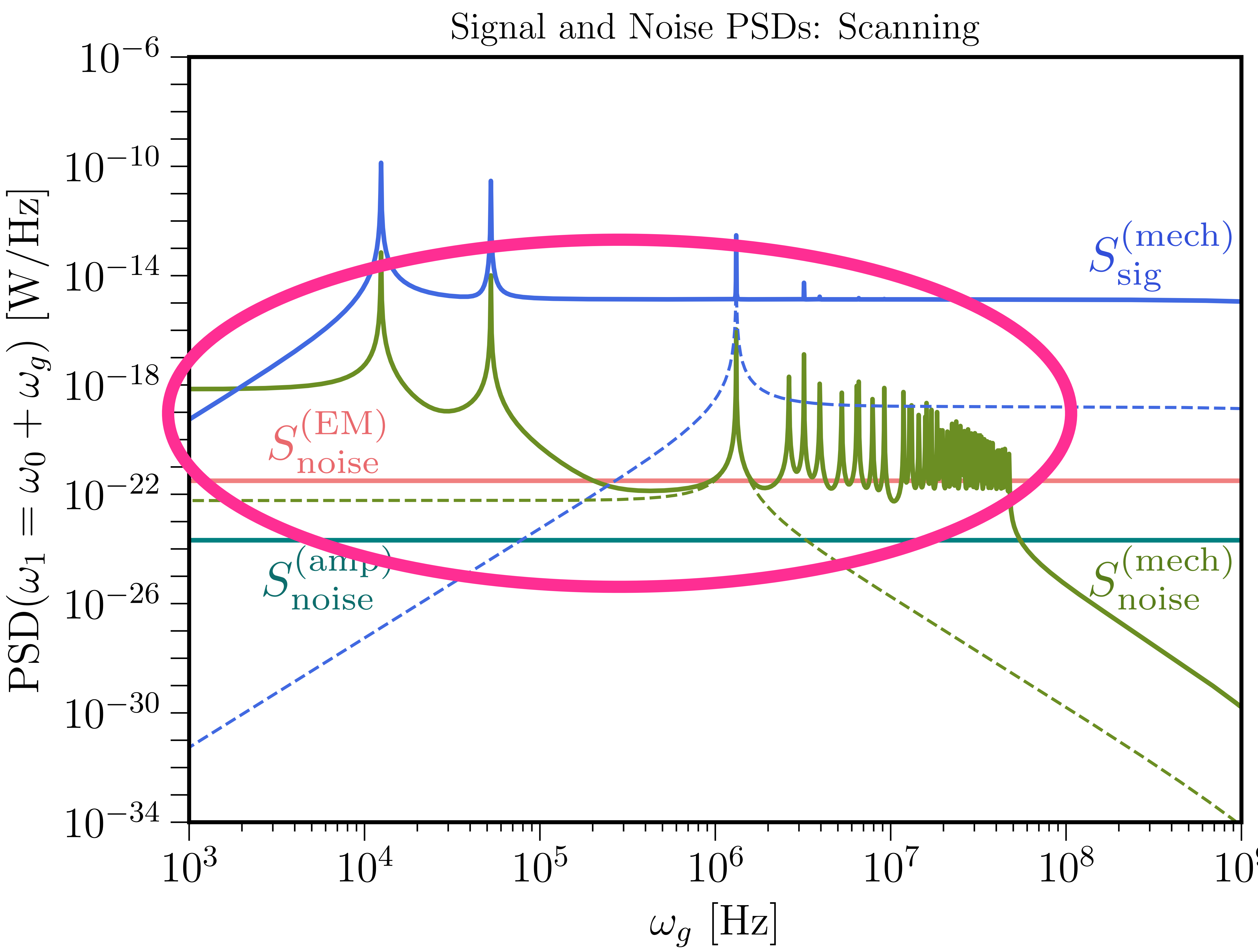
Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel,Wentzel '23
arXiv:2303.01518

RESONANT



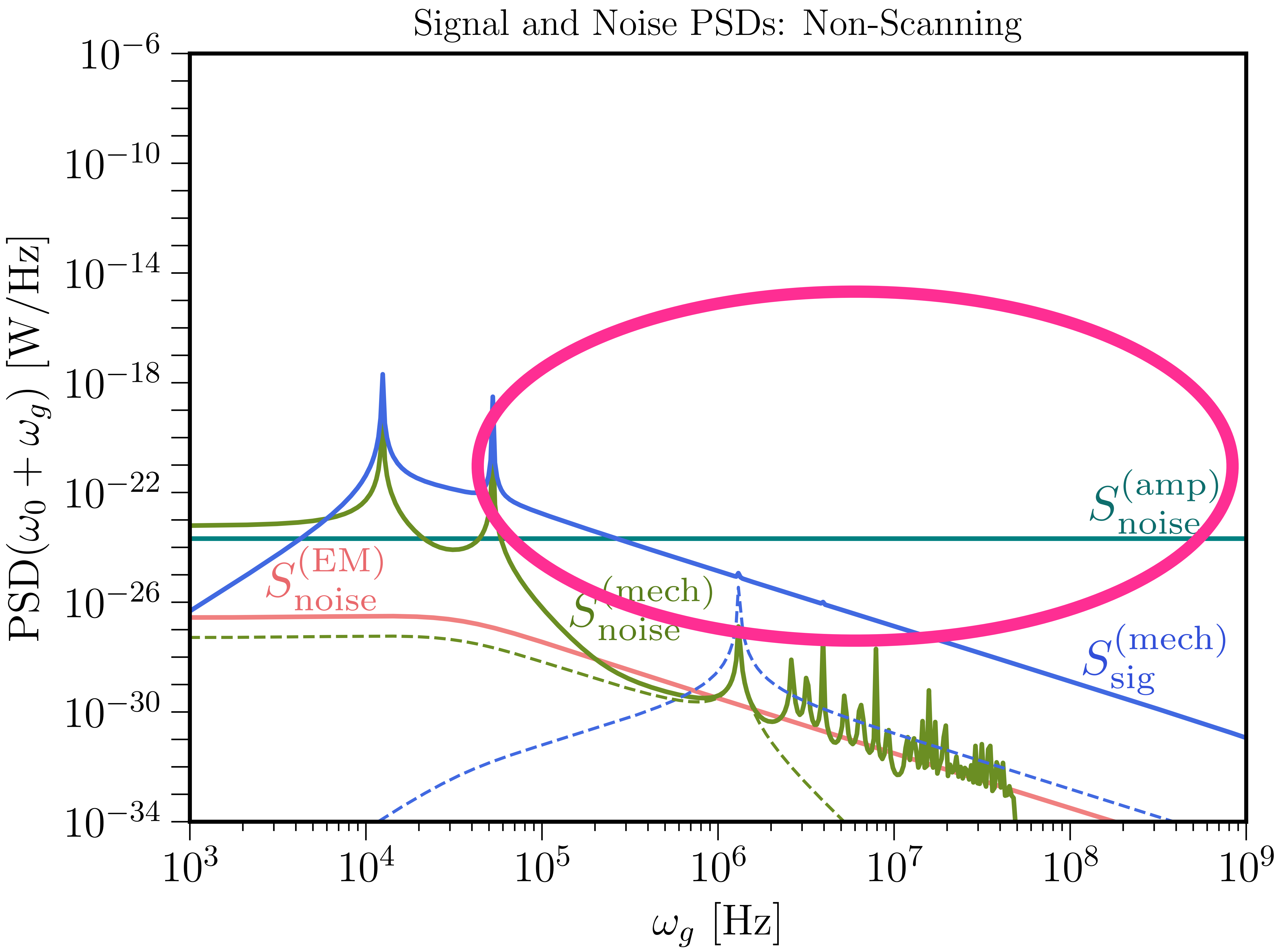
$$\mathrm{SNR}_{\mathrm{EM\ noise}} \simeq \frac{1}{64}\sqrt{\frac{\pi\, t_{\mathrm{int}}}{2\,\Delta\omega_{\mathrm{osc}}}}\; Q_{\mathrm{int}}^2\, |\eta_{\mathrm{mech}}^{g}|^2\, |\eta_{\mathrm{mech}}^{\mathrm{EM}}|^2\, \frac{P_{\mathrm{in}}}{T}\, h_0^2$$

RESONANT



$$\mathrm{SNR}_{\mathrm{mech\ noise}} \simeq \frac{1}{4}\sqrt{\frac{\pi^3\, t_{\mathrm{int}}}{2\,\Delta\omega_{\mathrm{osc}}}}\ |\eta^{g}_{\mathrm{mech}}(\omega_p^{\mathrm{sig}})|^2\ \frac{|\eta^{\mathrm{EM}}_{\mathrm{mech}}(\omega_p^{\mathrm{sig}})|^2}{|\eta^{\mathrm{EM}}_{\mathrm{mech}}(\omega_p^{\mathrm{noise}})|^2}\ \frac{M_{\mathrm{cav}}^2\, V_{\mathrm{cav}}^{2/3}}{S_{F_p}(\omega_g)}\ h_0^2\,\omega_g^4$$

BROADBAND



$$\mathrm{SNR}_{\mathrm{amp\ noise}}^{(\mathrm{broadband})} \simeq \frac{1}{64} \sqrt{\frac{\pi\, t_{\mathrm{int}}}{2\,\Delta\omega_{\mathrm{osc}}}}\ \frac{Q_{\mathrm{int}}}{Q_{\mathrm{cpl}}}\, |\eta_{\mathrm{mech}}^{g}|^2\, |\eta_{\mathrm{mech}}^{\mathrm{EM}}|^2\ \frac{P_{\mathrm{in}}}{T}\, h_0^2\, \frac{\omega_0}{\omega_g^2}$$

GRAVITATIONAL WAVES SOURCES

GRAVITATIONAL WAVE SIGNALS

THEORY	**EXPERIMENT**
Primordial	Noise-like
PHASE TRANSITIONS, INFLATION, …	Frequency spectrum

GRAVITATIONAL WAVE SIGNALS

THEORY	EXPERIMENT
Primordial	Noise-like
PHASE TRANSITIONS, INFLATION, …	Frequency spectrum

$$\rho_{GW}(\omega) \sim h^2 \omega^4$$

$$\frac{\rho_{GW}}{\rho_0} \lesssim 10^{-5}$$

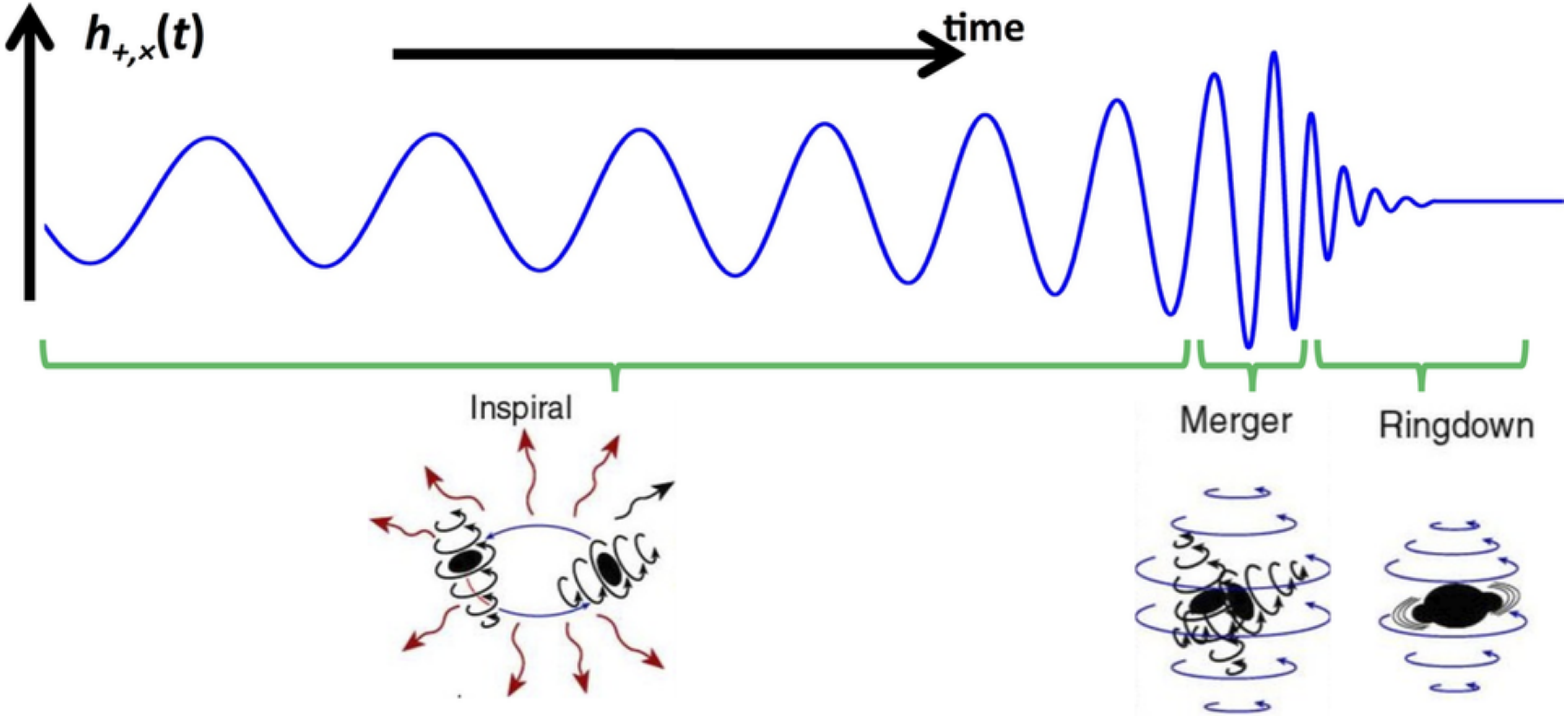
GRAVITATIONAL WAVE SIGNALS

THEORY	CAVITY EXPERIMENT
Primordial PHASE TRANSITIONS, INFLATION, …	$$\frac{\rho_{GW}}{\rho_0} \gg 1$$

GRAVITATIONAL WAVE SIGNALS

THEORY	**CAVITY EXPERIMENT**
Primordial PHASE TRANSITIONS, INFLATION, …	$\frac{\rho_{GW}}{\rho_0} \gg 1$
Primordial, but generated Tody PRIMORDIAL BHs, SUPERRADIANCE	

MERGERS



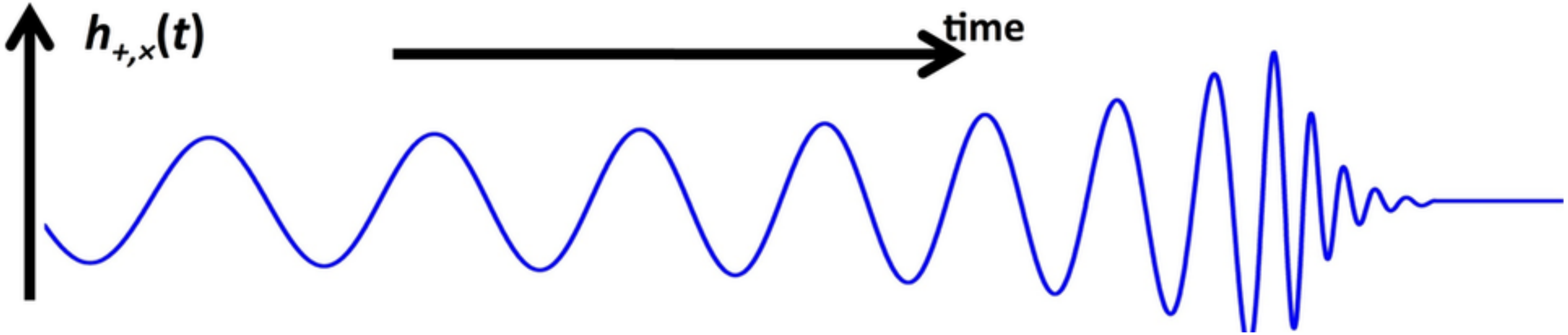
Stolen from the web

Rule of Thumb

$$\omega \sim \frac{c}{\text{size}}$$

$$h \sim \text{mass} \sim \text{size}$$

MERGERS



$$h_0 \sim 10^{-29} \times \left(\frac{1\ \mathrm{pc}}{D}\right)\left(\frac{M_b}{10^{-11}\ M_\odot}\right)^{5/3}\left(\frac{\omega_g}{1\ \mathrm{GHz}}\right)^{2/3}$$

GRAVITATIONAL WAVE SIGNALS

THEORY	CAVITY EXPERIMENT
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Primordial, but generated Tody PRIMORDIAL BHs, SUPERRADIANCE	$$h_{\rm cav}/h_{\rm sig} \gtrsim 10^5$$

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Astrophysical BHs, NEUTRON STARS, …	$\omega \lesssim 10\ \text{kHz}$ (roughly)