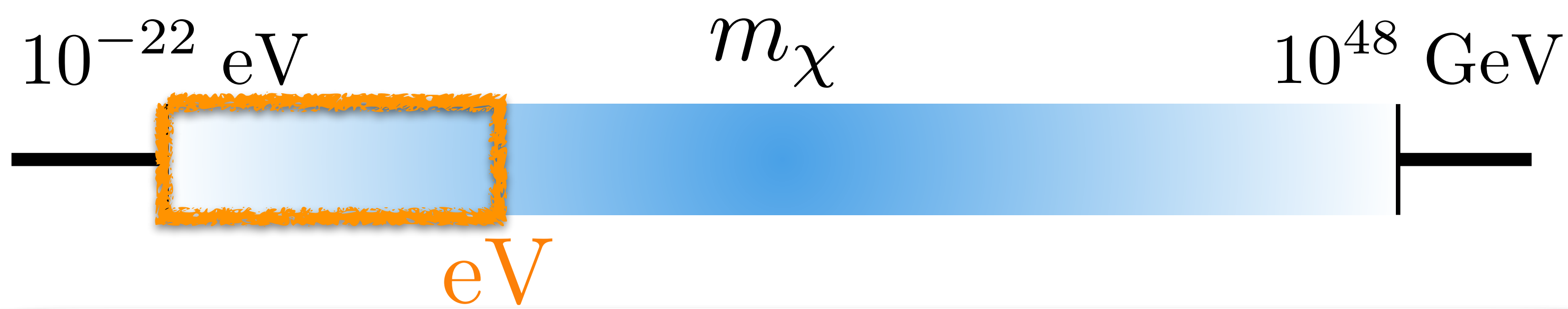
A NEW CONCEPT FOR THE DETECTION OF AXION DARK MATTER

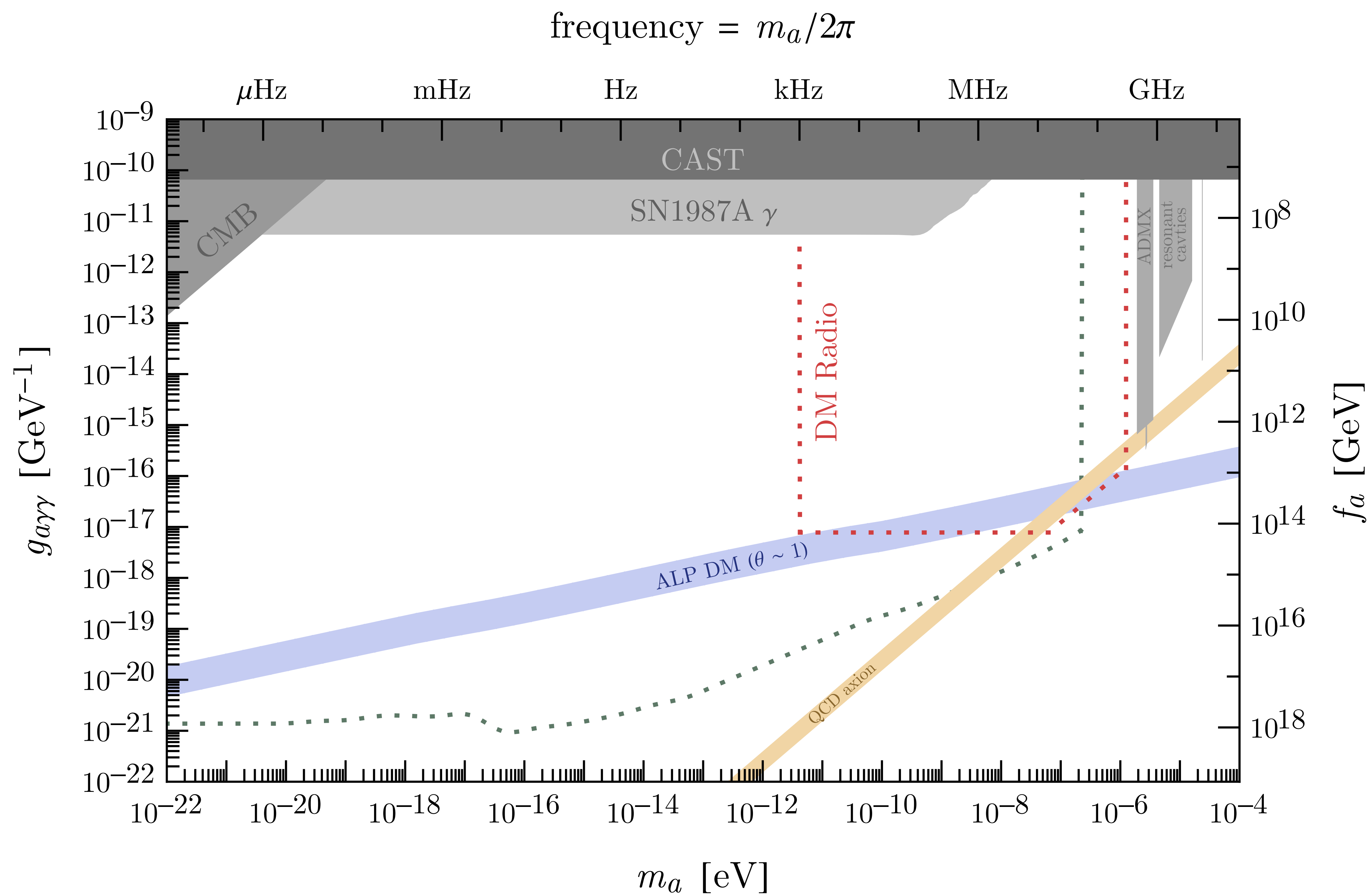
Raffaele Tito D’Agnolo - IPhT Saclay


10^{-22} eV
m_χ
10^{48} GeV
$\mathcal{O}(10^{-50})$
$\alpha_{\rm self}$
$\mathcal{O}(1)$
$\mathcal{O}(10^{-50})$
$\alpha_{\rm SM}$
$\mathcal{O}(1)$
????
PIECES!
WORLD'S
largest
puzzle!
8 BAGS
OF
PUZZLE PIECES
KING-SIZE-DOLLY
FOR TRANSPORTATION
NO
REFERENCE
ILLUSTRATION
Ravensburger Puzzle



Very good particle physics motivations:

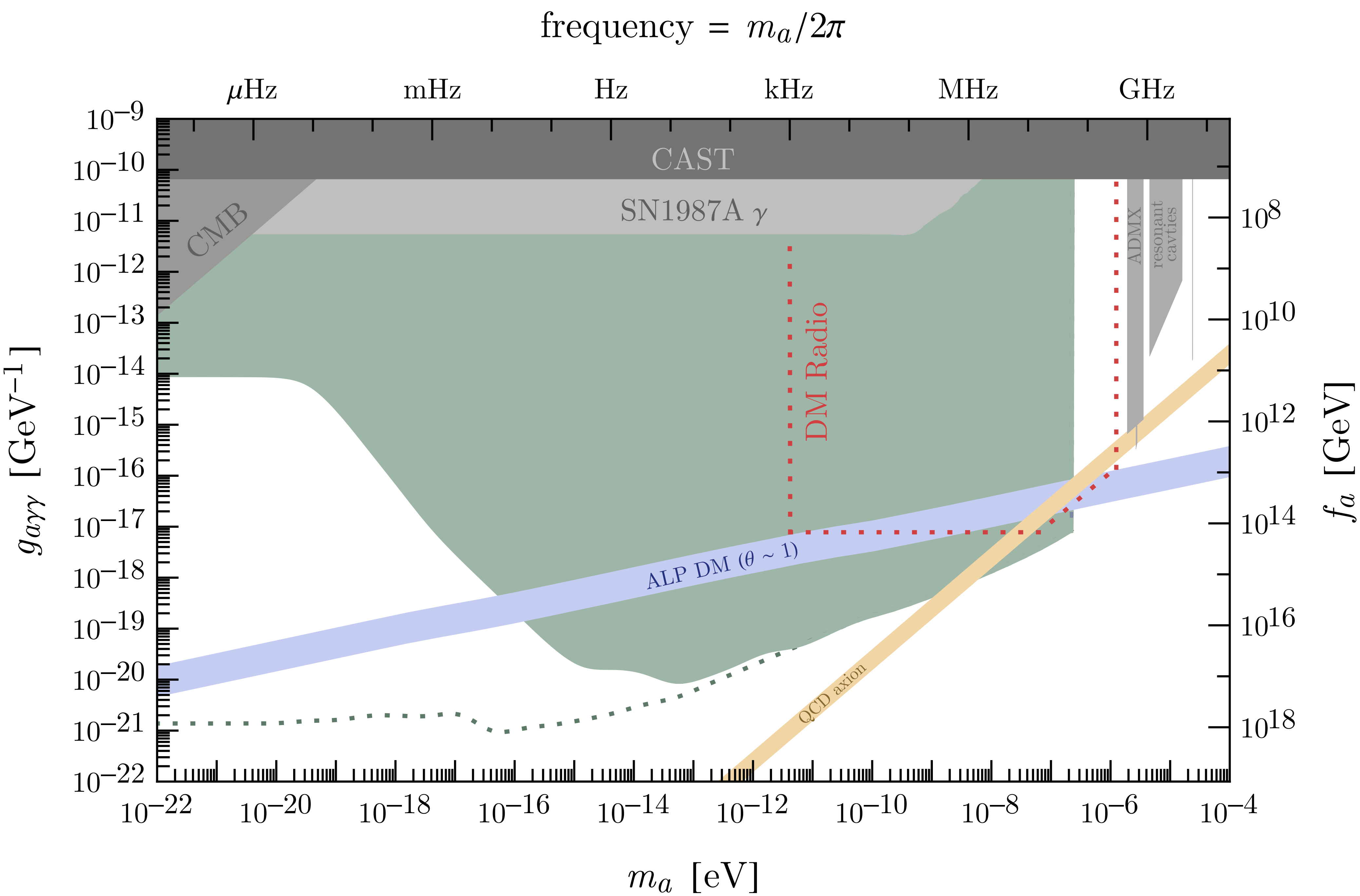
- Top-Down from String Theory
- Strong CP
- Generically predicted in a class of solutions to the Hierarchy Problem
- Simple and predictive cosmology



frequency = $m_a/2\pi$
μHz
mHz
Hz
kHz
MHz
GHz
CAST
SN1987A γ
CMB
DM Radio
ADMX
resonant cavties
ALP DM (θ ~ 1)
QCD axion
$g_{a\gamma\gamma}$ [GeV^{-1}]
f_a [GeV]
m_a [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{-22}
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}

Our new experimental concept:

Initially developed with Superconducting Radio Frequency cavity experimentalists at SLAC



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

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AXION DM IN THE LABORATORY

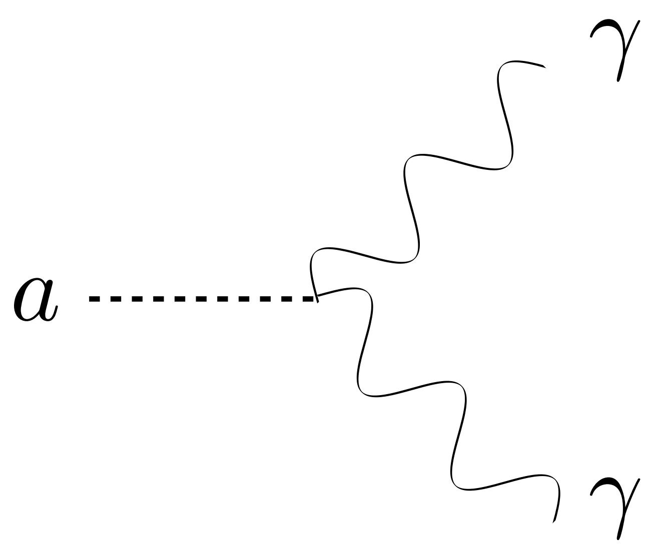
$$a(t) \simeq \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \cos(\omega_a t + \phi)$$

Frequency: $\omega_a \simeq \mathrm{GHz}\ \frac{m_a}{10^{-6}\ \mathrm{eV}}$

Coherence: $\tau_a \simeq \mathrm{ms}\ \frac{10^{-6}\ \mathrm{eV}}{m_a}$

Max Exp. Size: $\lambda_a \simeq 200\ \mathrm{m}\ \frac{10^{-6}\ \mathrm{eV}}{m_a}$

AXION DETECTION



$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + g_{a\gamma\gamma} \mathbf{B}\, \partial_t a$$

$$J_{\text{eff}}(t) \sim g_{a\gamma\gamma} B_0(t) \sqrt{\rho_{\text{DM}}} \cos m_a t$$

Cavity:

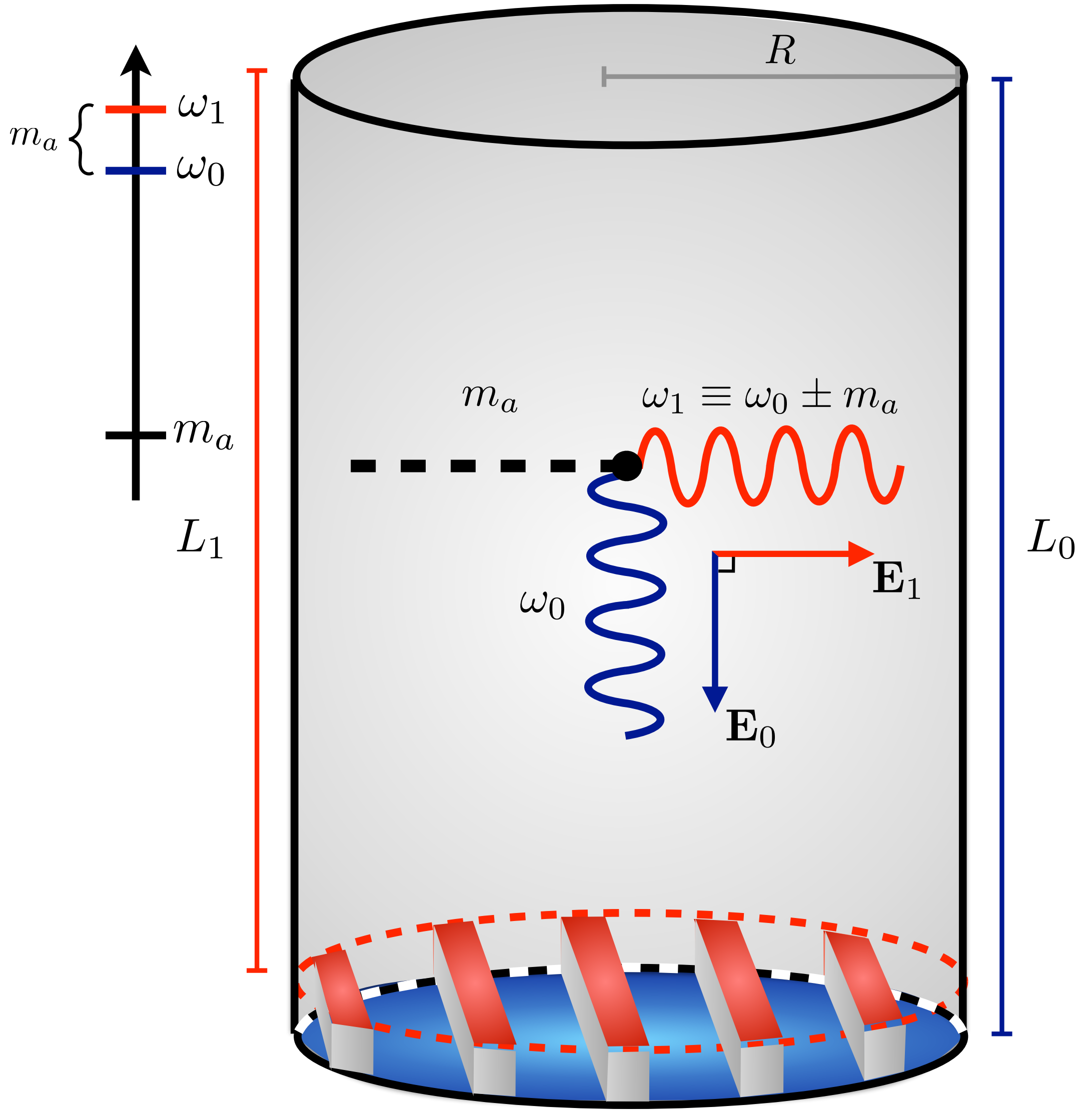
$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right)\mathbf{E}_n = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)$$

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

Problems:

Cavity size ~ $1/m_a$

Signal power decreases with axion mass



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

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

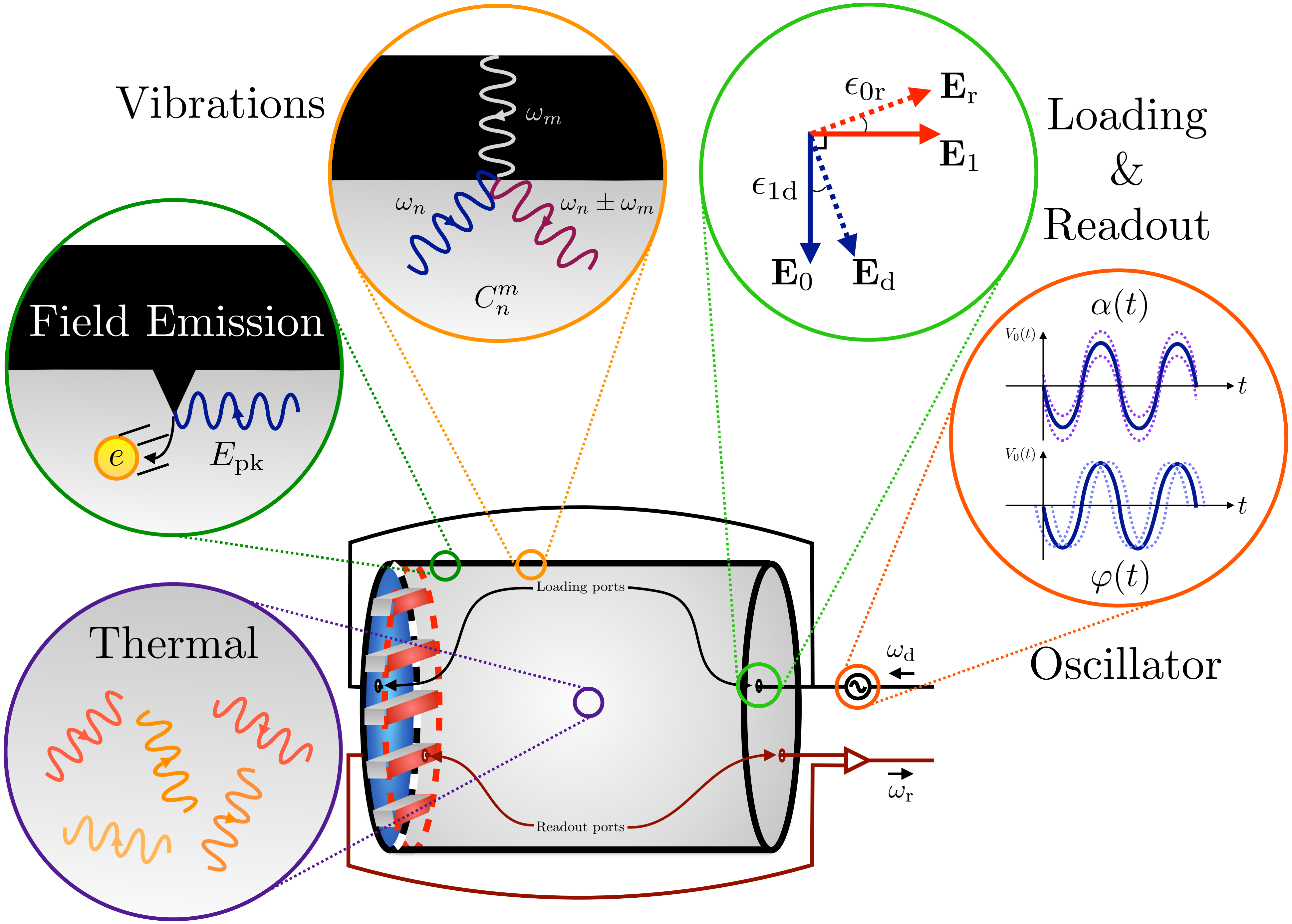
Static:

$$\mathbf{E}_1 \sim \frac{m_a g_{a\gamma\gamma}\sqrt{\rho_{\mathrm{DM}}}\mathbf{B}}{m_a^2 - \omega_1^2 + i\frac{m_a\omega}{Q_1}}$$

Oscillating:

$$\mathbf{E}_1 \sim \frac{\omega_0 g_{a\gamma\gamma}\sqrt{\rho_{\mathrm{DM}}}\mathbf{B}}{(\omega_0 + m_a)^2 - \omega_1^2 + i\frac{(\omega_0+m_a)\omega}{Q_1}}$$

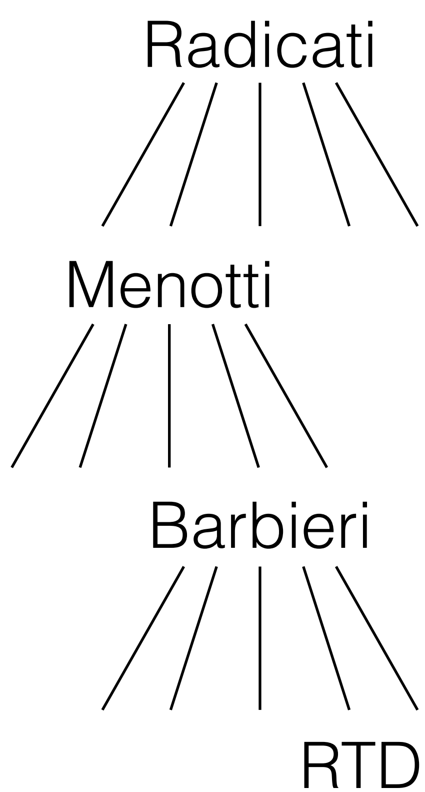
NOISE



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

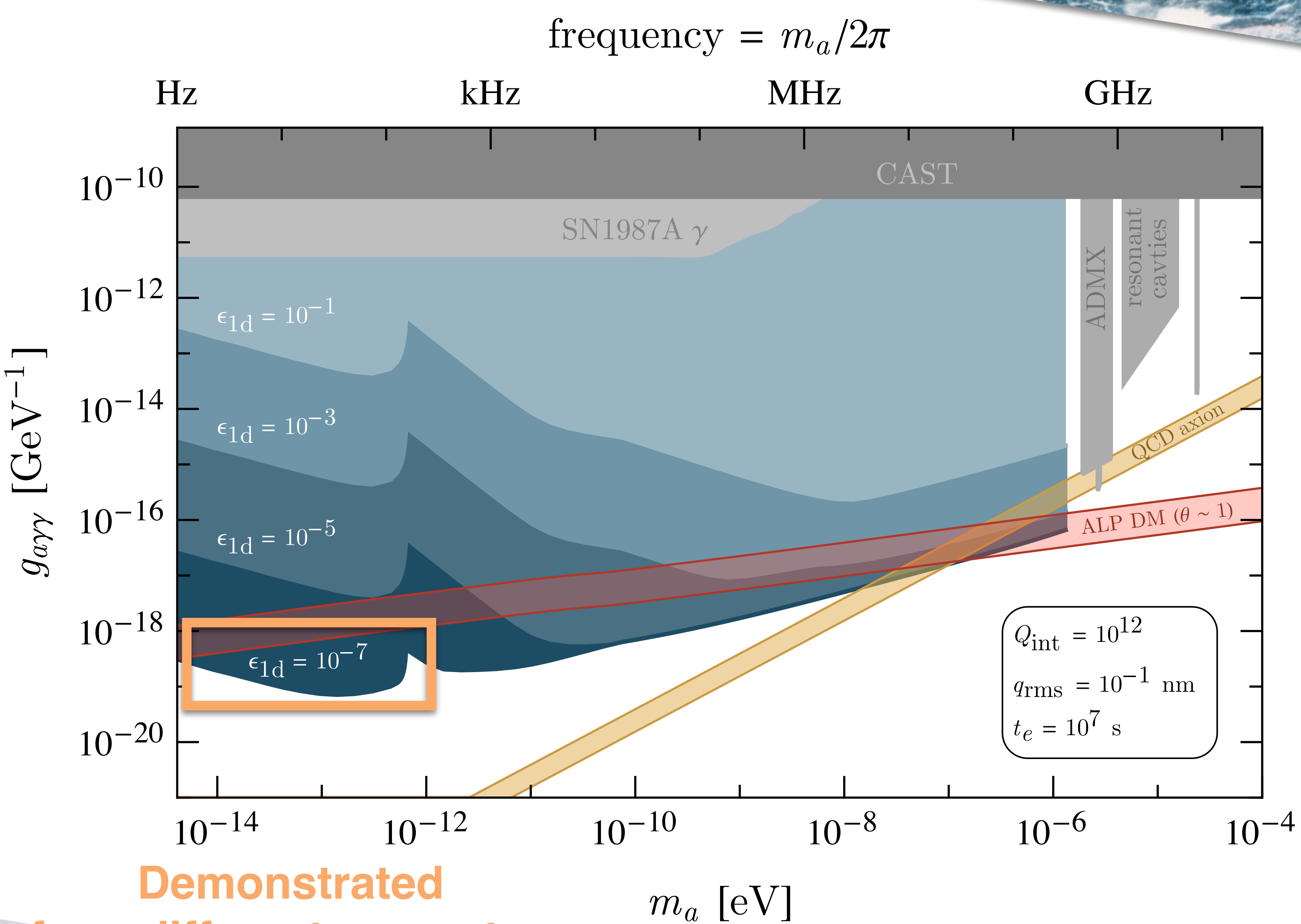
A similar cavity already exists!
Very well tested technology

Radicati, Pegoraro, Picasso ‘78



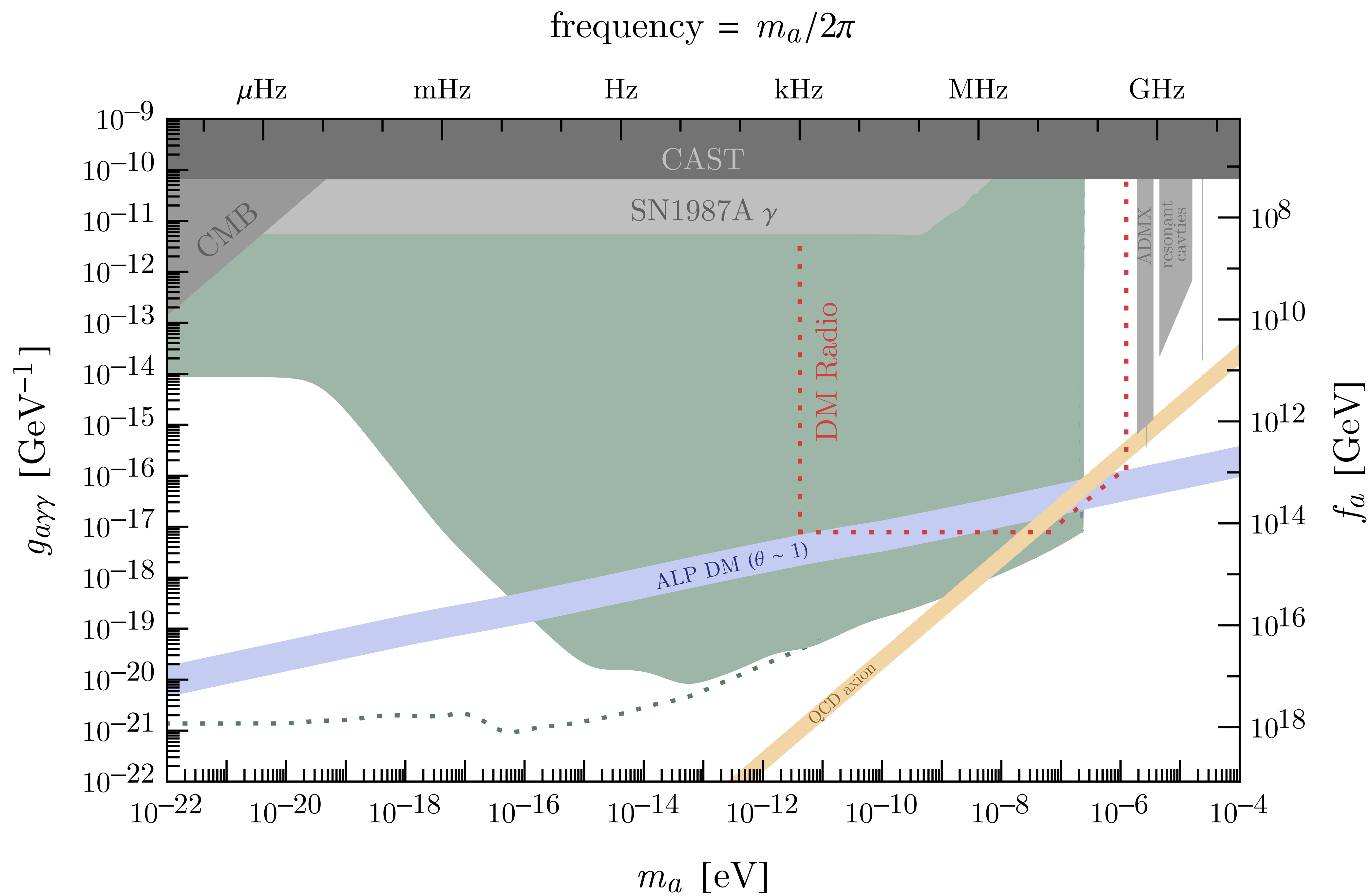
MAGO ‘05

ROBUSTNESS TO LOADING



Demonstrated for a different geometry, but same setup

Class.Quant.Grav. 20 (2003) 3505-3522, gr-qc/0502054



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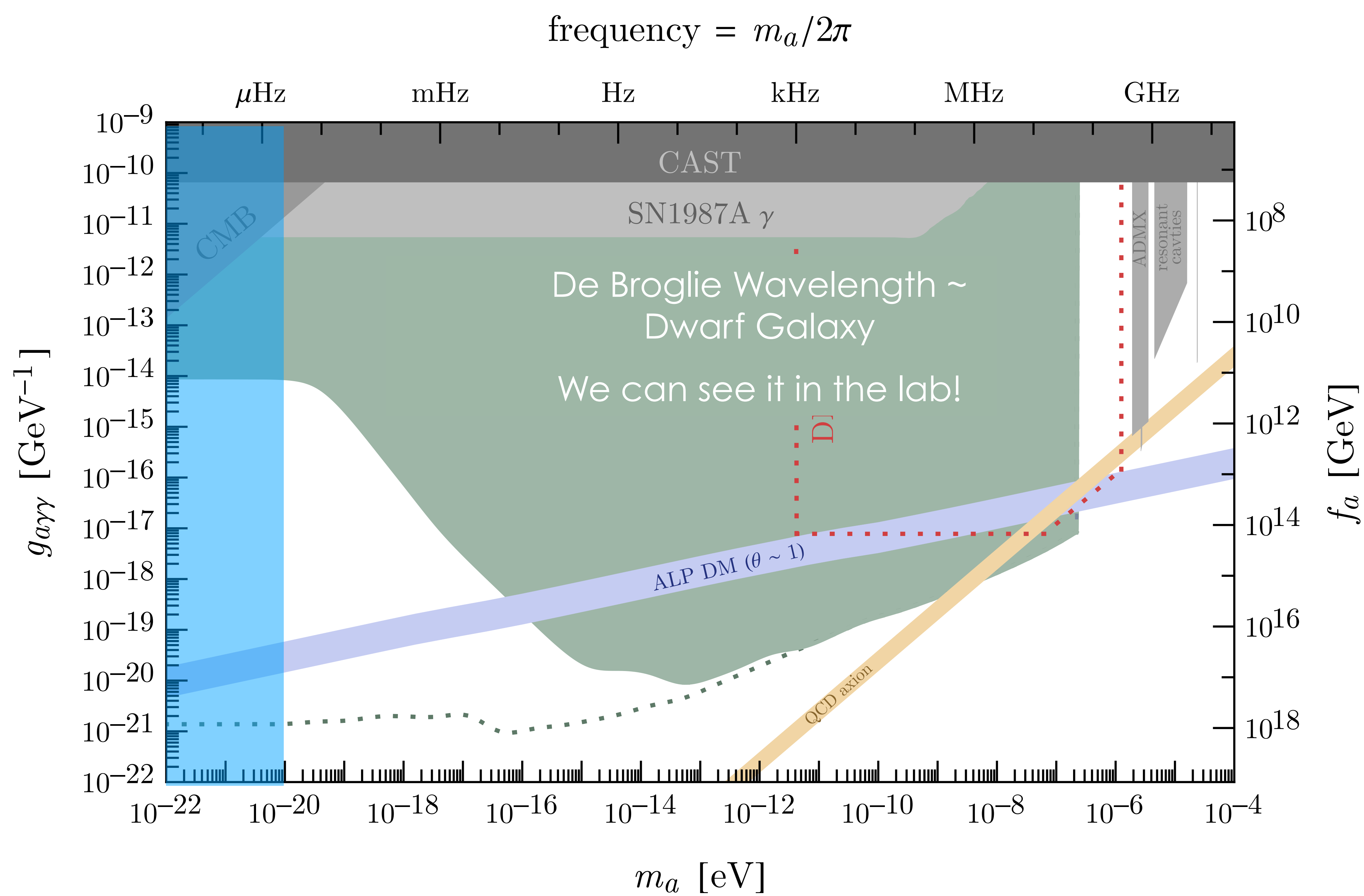
A.Berlin, **RTD**, S. Ellis, K. Zhou ‘20

BACKUP



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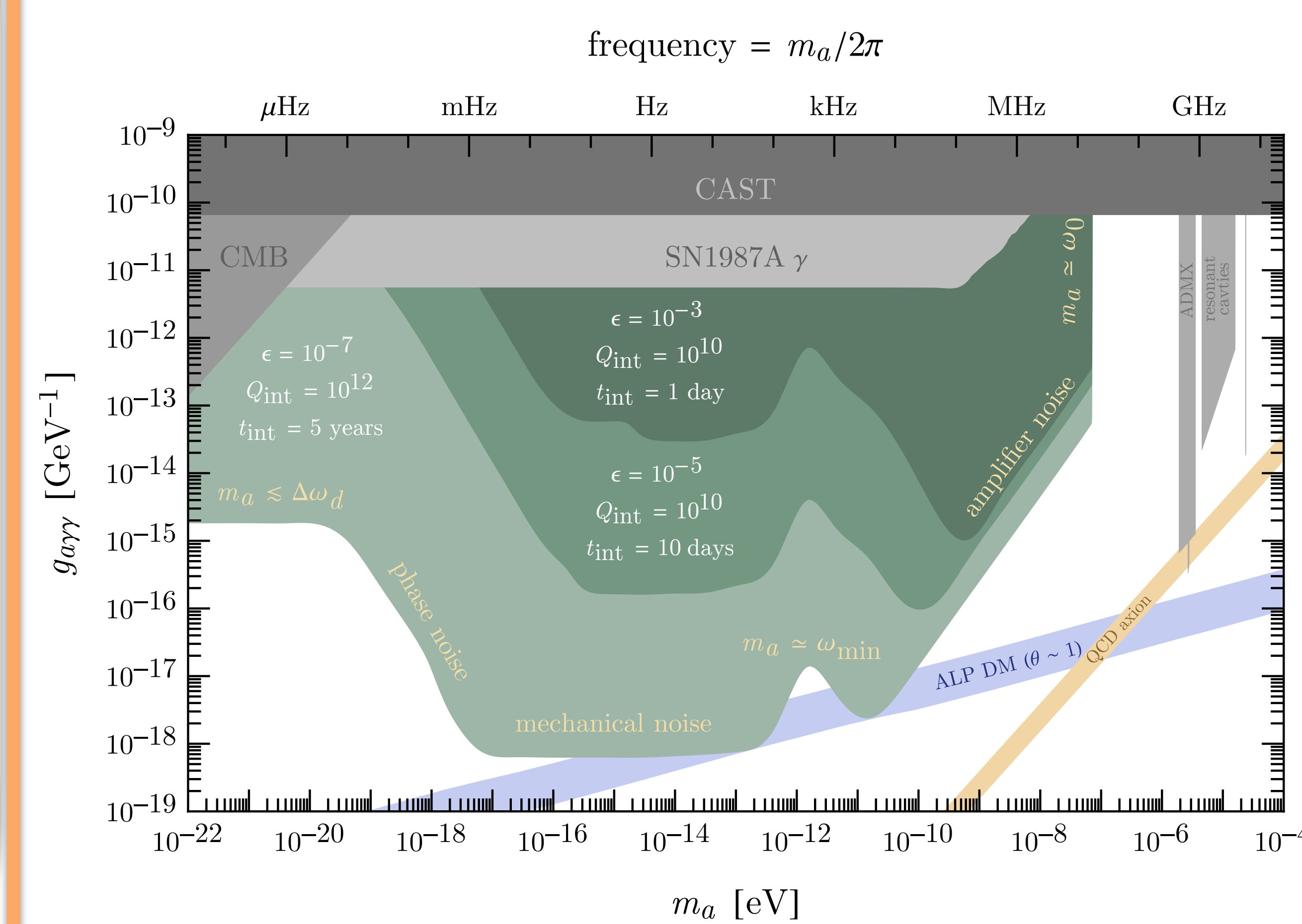
SNEAK PREVIEW

- Much shorter run time (first step of the experiment)
- Completely equivalent to resonant at the smallest masses
- No need to control finely frequency splittings

Broadband



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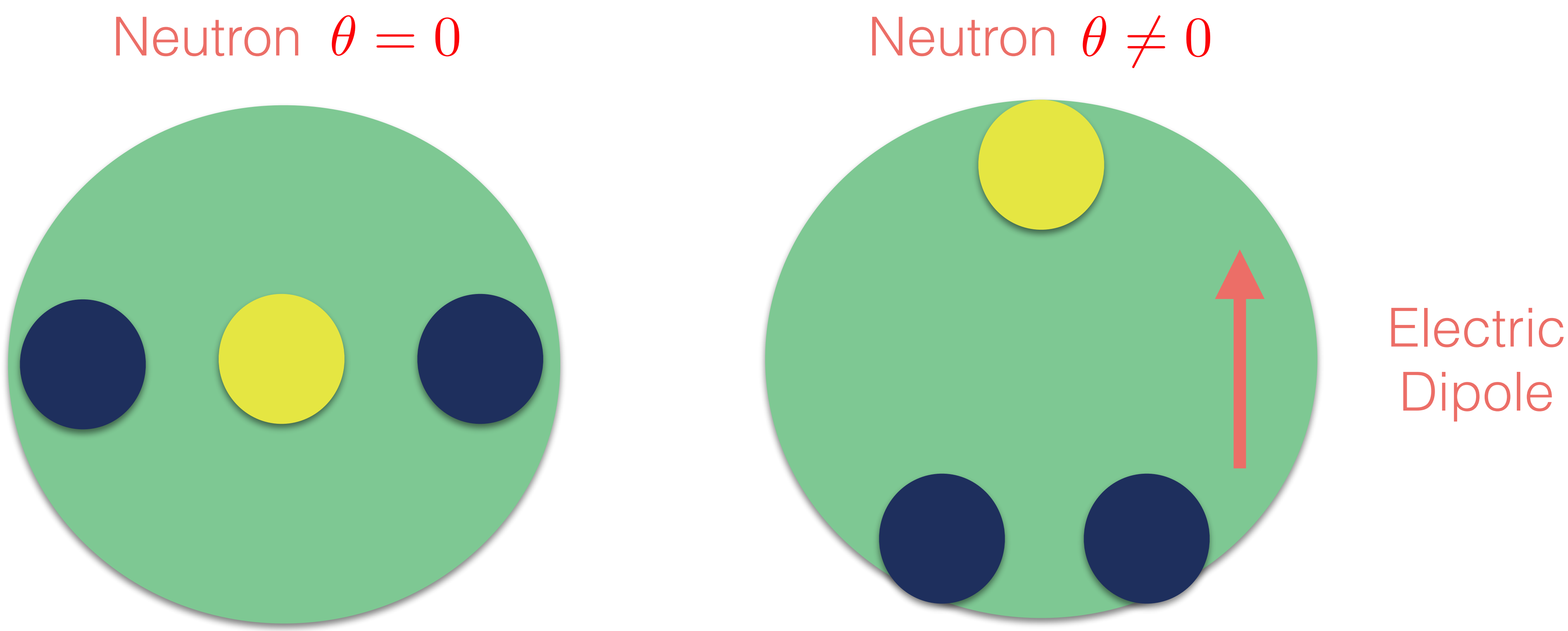
2007.15656

AXION BASICS

CP IN QCD

$$\theta G\tilde{G}$$



$|\theta| \lesssim 10^{-10}$ **Experimentally**

THE AXION FROM ABOVE

Introduce a new **global symmetry at f_a**

$$\theta G\tilde{G} \longrightarrow \left(\theta + \frac{a}{f_a}\right) G\tilde{G}$$

At the minimum

$$\langle a \rangle = -\theta f_a$$

AXION BASICS 3

QCD Phase Transition

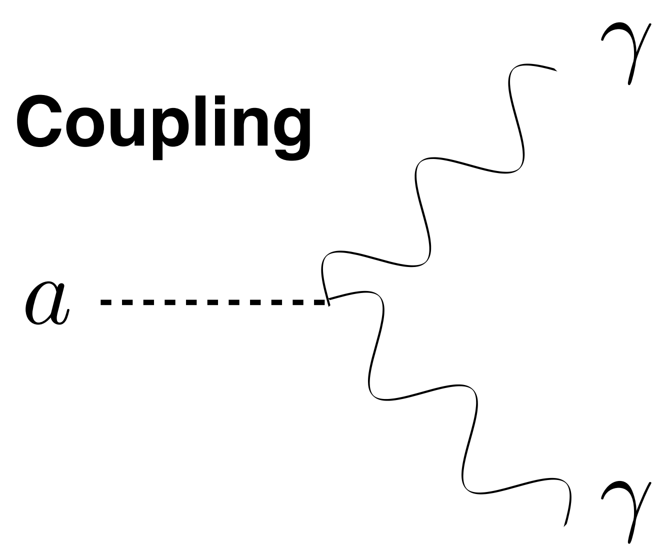
$$\frac{a}{f_a} G\tilde{G} \longrightarrow \frac{a}{f_a}\frac{\pi}{f_\pi} + \ldots$$

Mass

$$m_a \sim \frac{m_\pi^2}{f_a} \sim 10^{-2}\ \mathrm{eV}\ \frac{10^9\ \mathrm{GeV}}{f_a}$$

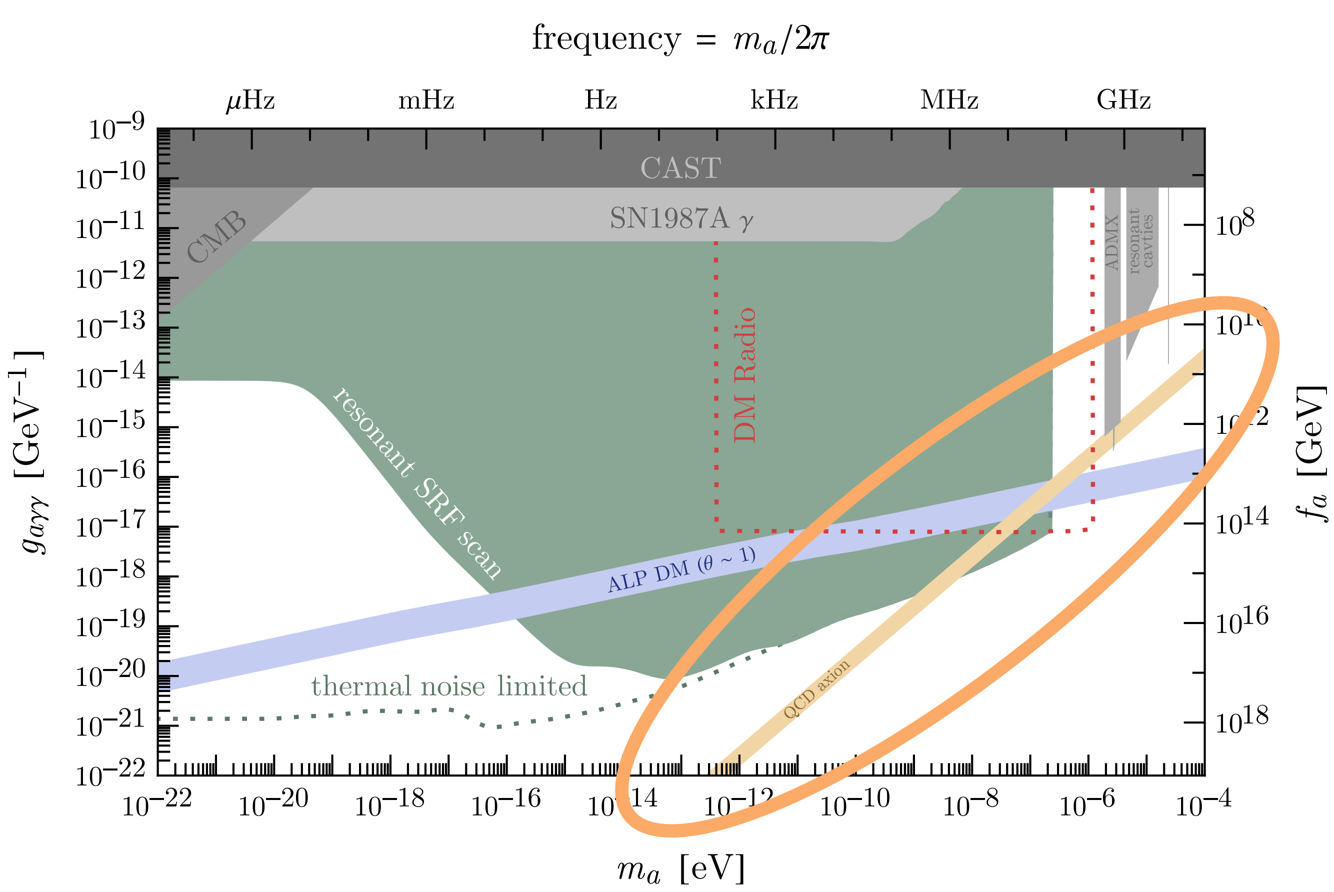
Relevant Coupling

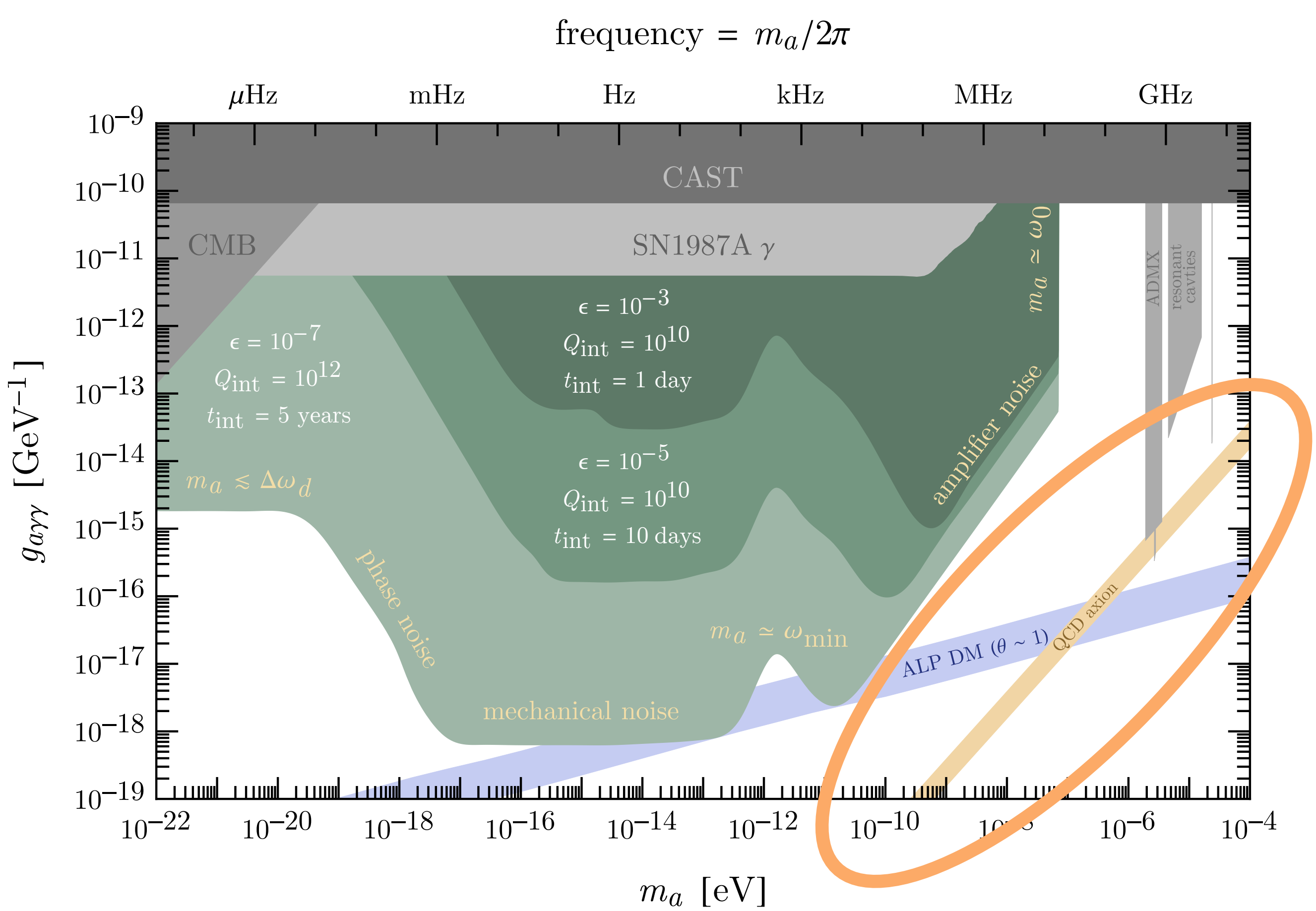
$$\frac{a}{f_a}\mathbf{E}\cdot\mathbf{B}$$

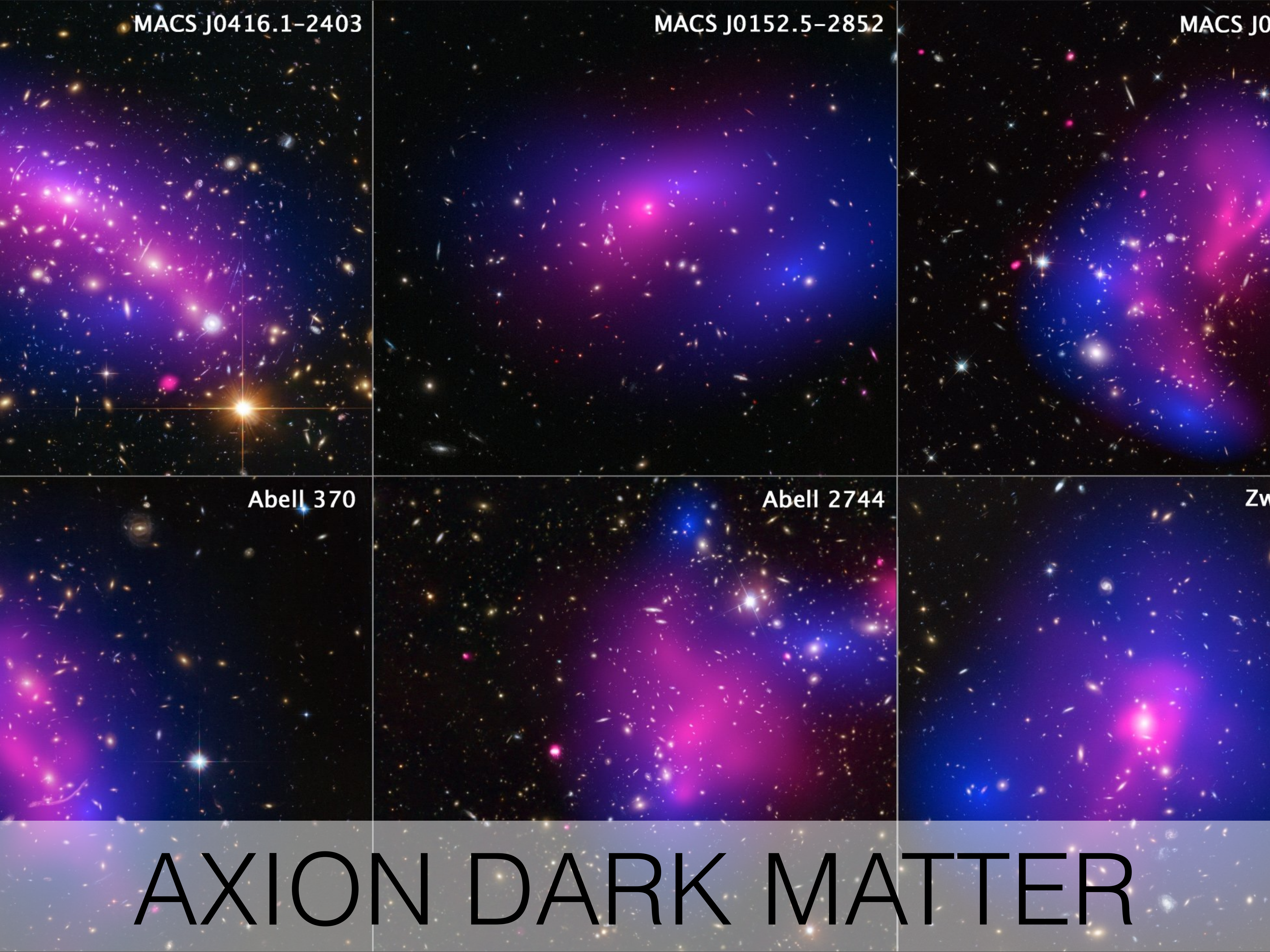


SNEAK PREVIEW: QCD AXION

Relevant to QCD Theta Angle







AXION DARK MATTER

MISALIGNMENT PRODUCTION

PQ breaking before inflation
(for simplicity)

$$T \gg \Lambda_{\rm QCD}$$

$$V(a) = 0$$

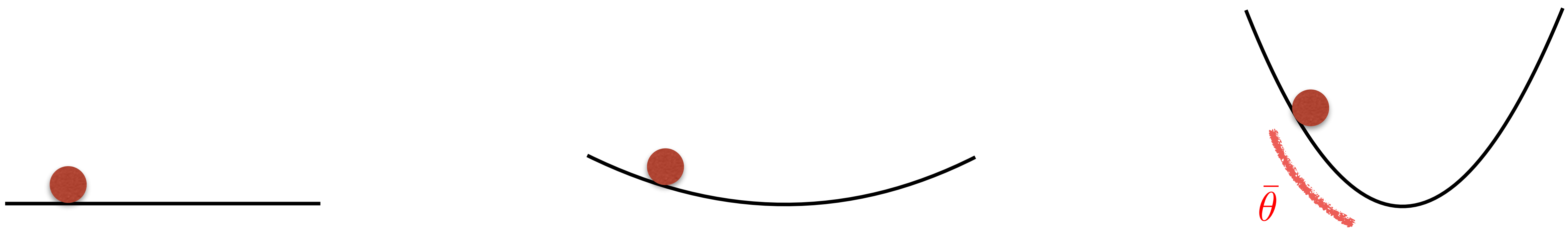
MISALIGNMENT PRODUCTION

PQ breaking before inflation
(for simplicity)

$$m_a(T) \approx 0.1 m_a \left(\frac{\Lambda_{\text{QCD}}}{T} \right)^4$$

MISALIGNMENT PRODUCTION

PQ breaking before inflation
(for simplicity)



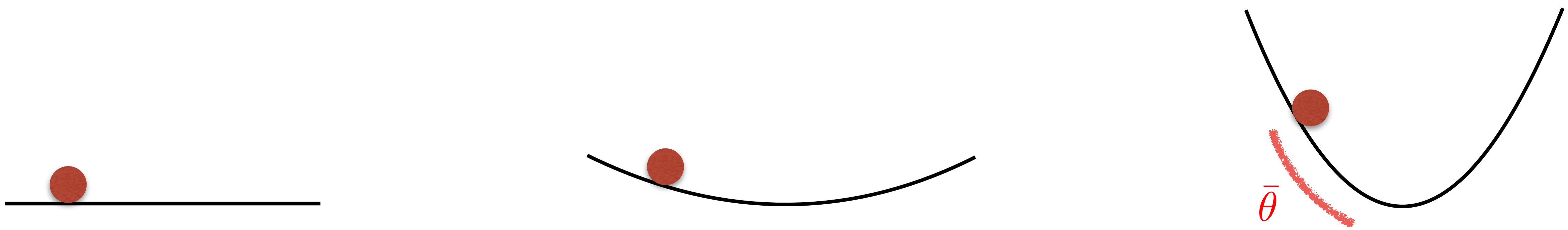
$$\rho_a = \frac{m_a^2 f_a^2 \bar{\theta}^2}{2}$$

MISALIGNMENT PRODUCTION

Huge occupation number in a De Broglie volume (+ coherent state)

=

classical field

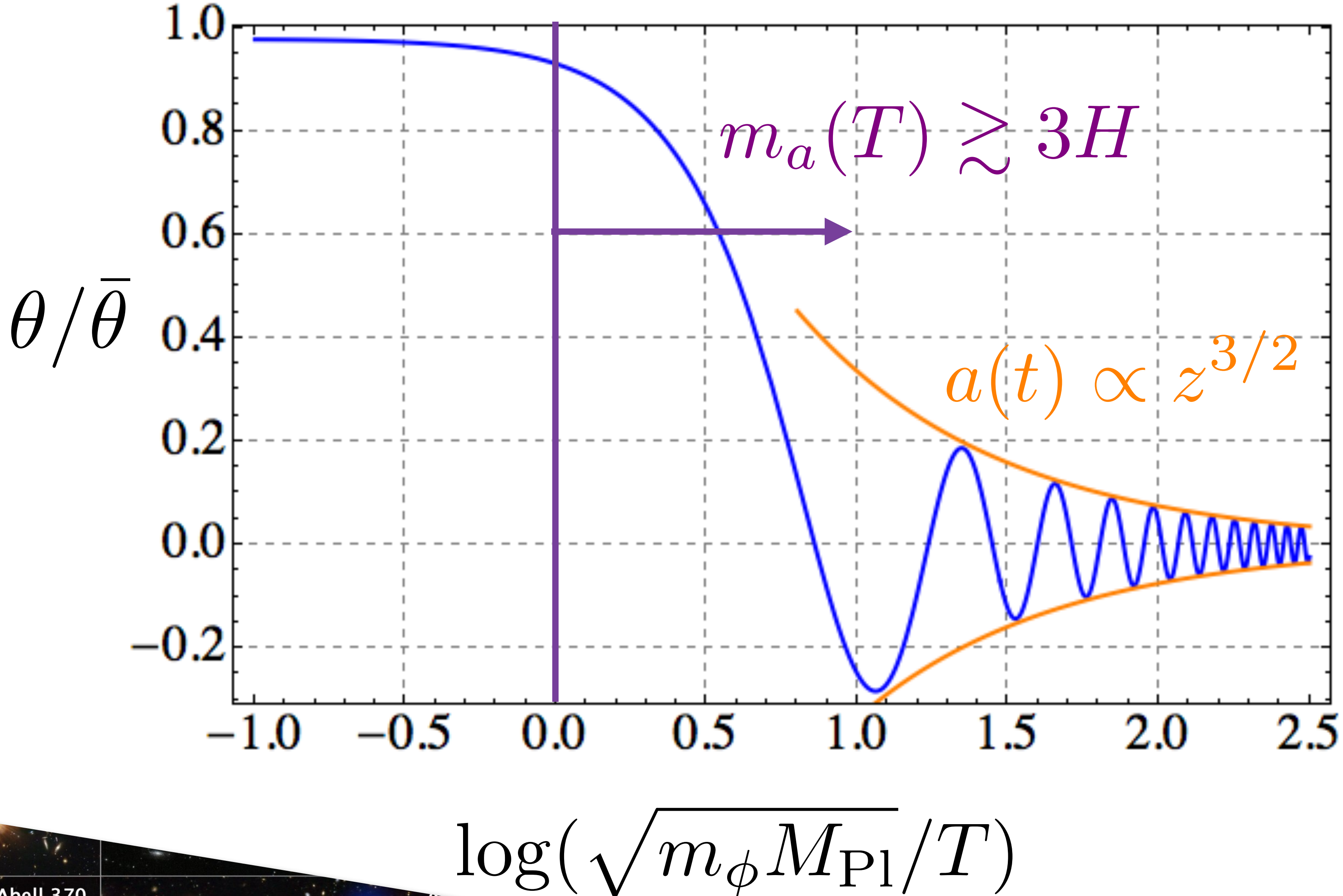


$$\theta \equiv a/f_a$$

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

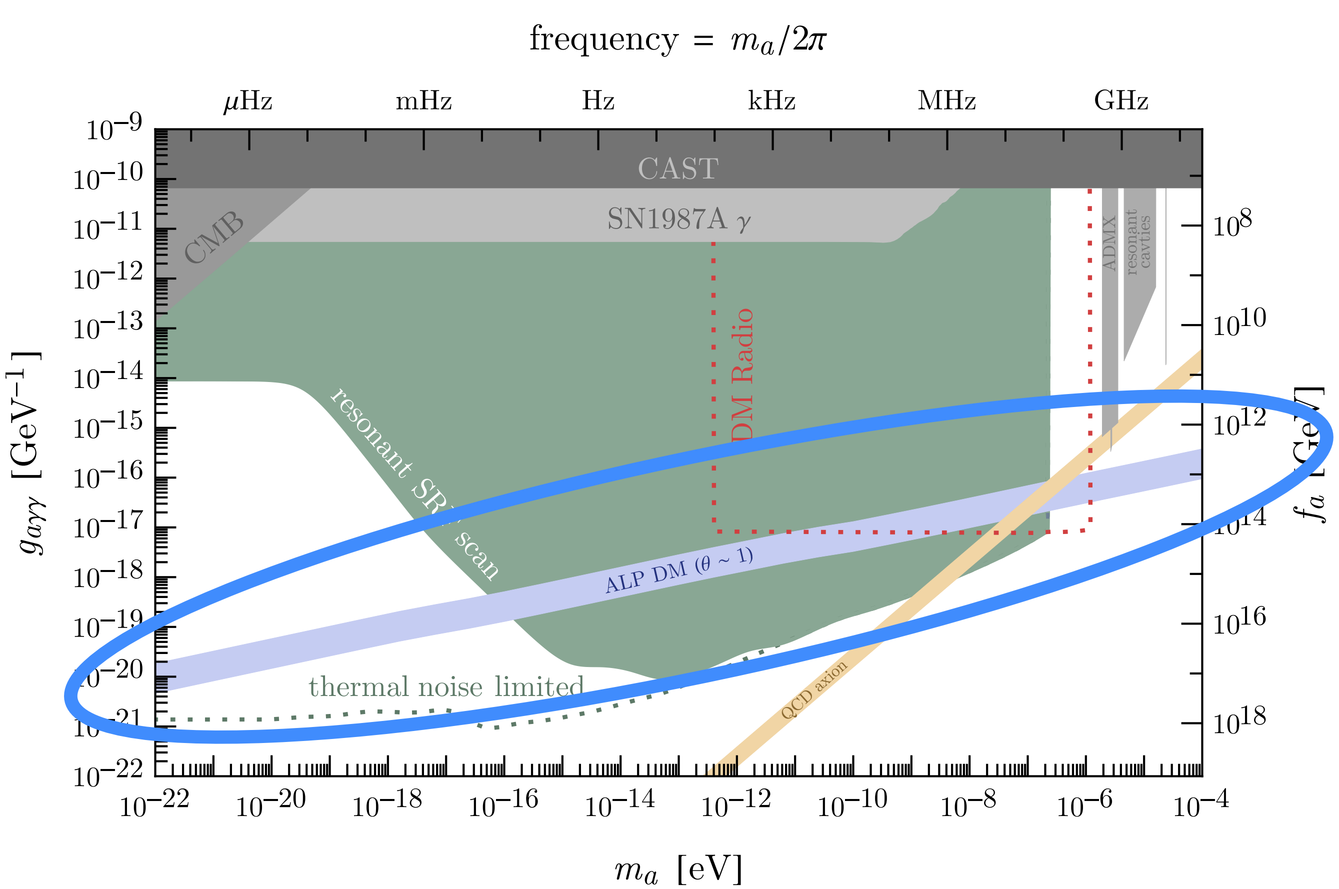
AXION COSMOLOGY

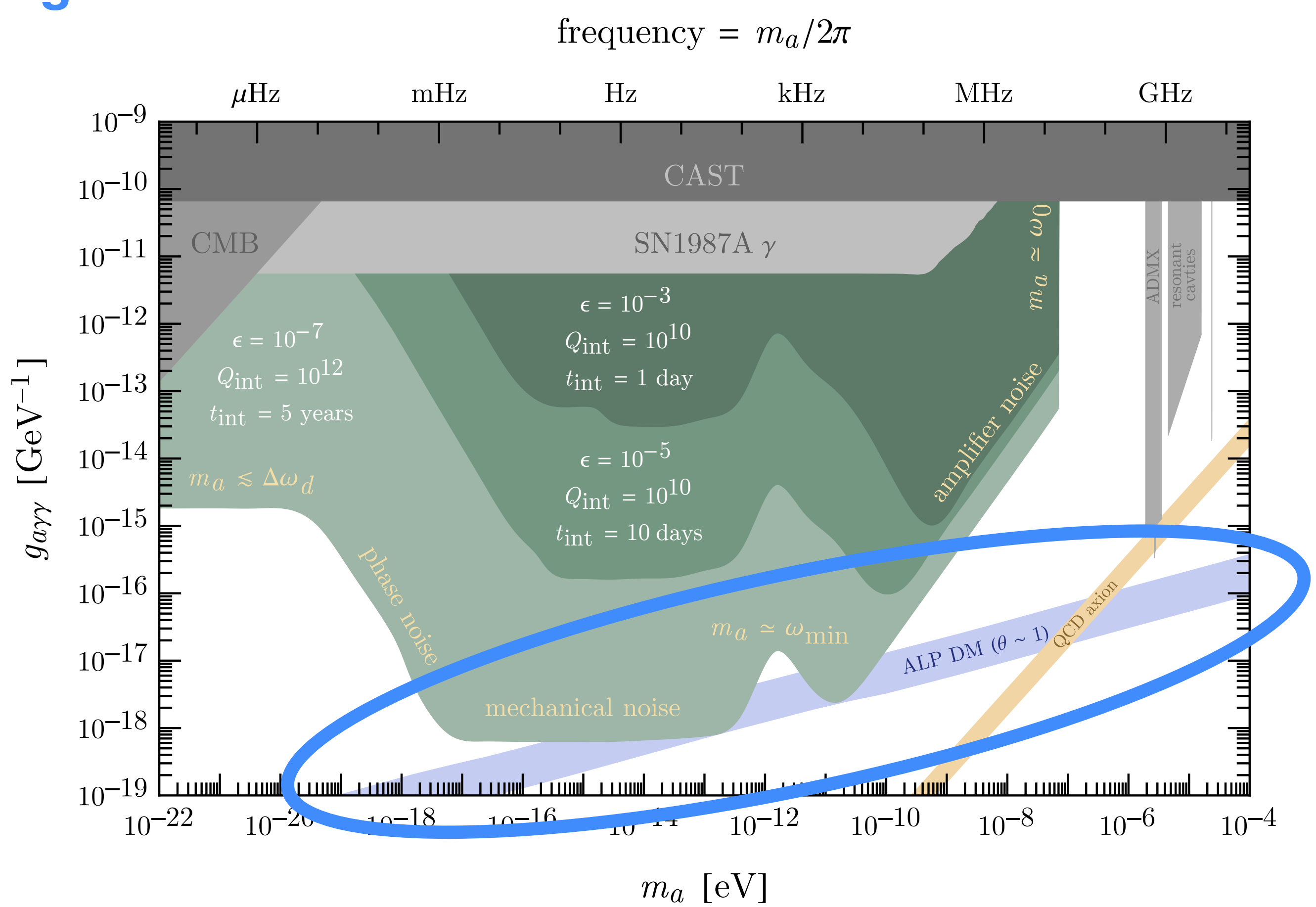
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$



SNEAK PREVIEW: SIMPLEST ALP

"Simplest ALP"
T-independent mass
Natural misalignment





N.B. Many ways to populate the rest of the parameter space
Agrawal, Marques-Tavares, Xue '17
Graham, Scherlis '18
Marques-Tavares, Mao '18

AXION DARK MATTER DETECTION

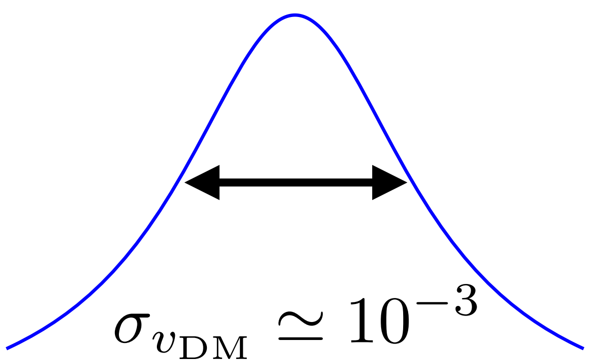
AXION DM IN THE LABORATORY

Produced Colder than the SM (even if not via misalignment)

$$E_a \approx m_a$$

It acquires a **small velocity dispersion** from virialization **in the Milky Way**

$$E_a \simeq m_a \left(1 + \frac{v_{\rm DM}^2}{2}\right)$$

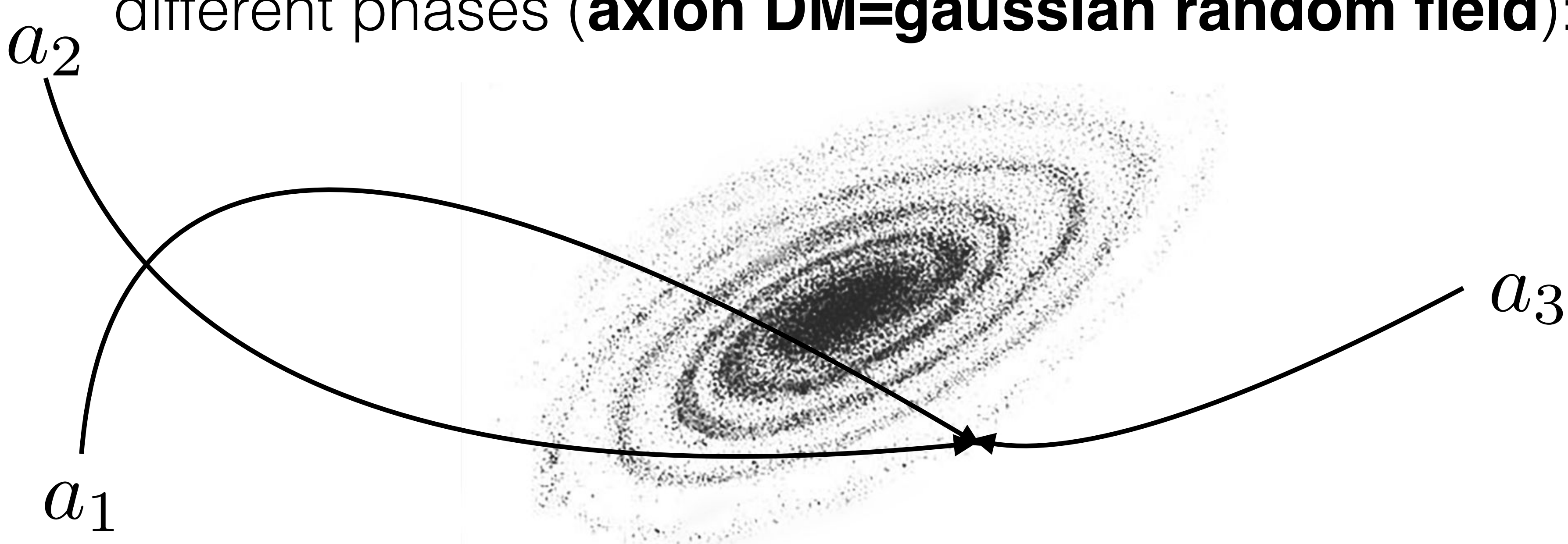


Lots of axions in each frequency bin that we can resolve (even more in a De Broglie volume):

$$\Delta N_a \simeq \frac{\rho_{\rm DM} V}{m_a^2 t_{\rm int} v_{\rm DM}^2} \simeq 10^{24} \left(\frac{10^{-14}\ {\rm eV}}{m_a}\right)^2 \left(\frac{\rm year}{t_{\rm int}}\right) \left(\frac{V}{{\rm m}^3}\right)$$

AXION DM IN THE LABORATORY

In each experimental bin we are summing over a multitude of plane waves with different phases (**axion DM=gaussian random field**):



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

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

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

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

AXION DM IN THE LABORATORY

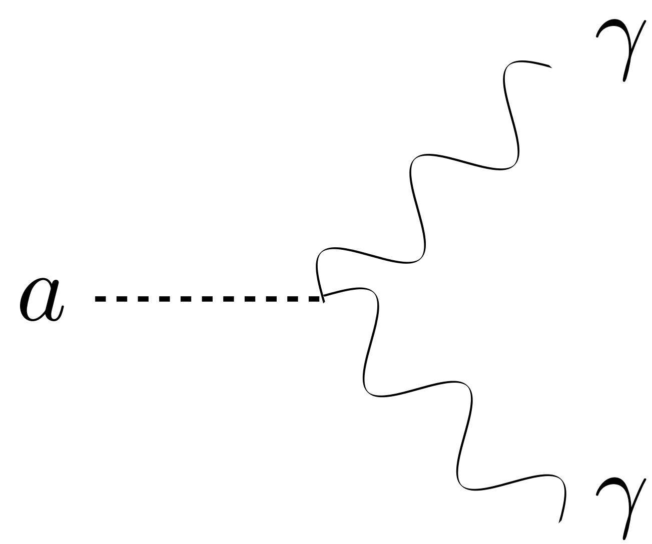
$$a(t) \simeq \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \cos(\omega_a t + \phi)$$

Frequency: $\omega_a \simeq \text{GHz}\ \frac{m_a}{10^{-6}\ \text{eV}}$

Coherence: $\tau_a \simeq \text{ms}\ \frac{10^{-6}\ \text{eV}}{m_a}$

Max Exp. Size: $\lambda_a \simeq 200\ \text{m}\ \frac{10^{-6}\ \text{eV}}{m_a}$

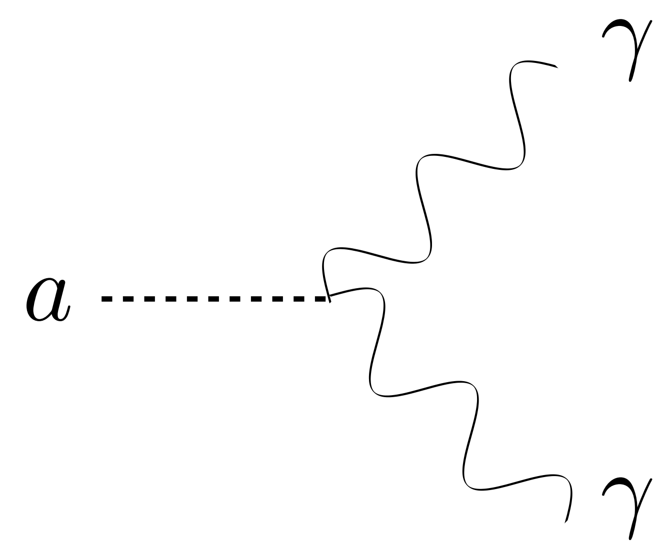
AXION DETECTION



$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + \underline{g_{a\gamma\gamma} \mathbf{B} \, \partial_t a}$$

$$\boxed{J_{\text{eff}}(t) \sim g_{a\gamma\gamma} B_0(t) \sqrt{\rho_{\text{DM}}} \cos m_a t}$$

AXION DETECTION



$$J_{\text{eff}} \sim 10^{-15}\ \text{A/cm}^2 \left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \text{GeV}^{-1}}\right)\left(\frac{B_0}{4\ \text{T}}\right)$$

$10^4\ \text{A/cm}^2$	$10^7\ \text{A/cm}^2$	$10^8\ \text{A/cm}^2$
Flashlamp	**Copper**	**Graphene**

AXION DETECTION

$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + g_{a\gamma\gamma} \mathbf{B}\, \partial_t a$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

Cavity:

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

AXION DETECTION

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

AXION DETECTION

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

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

AXION DETECTION

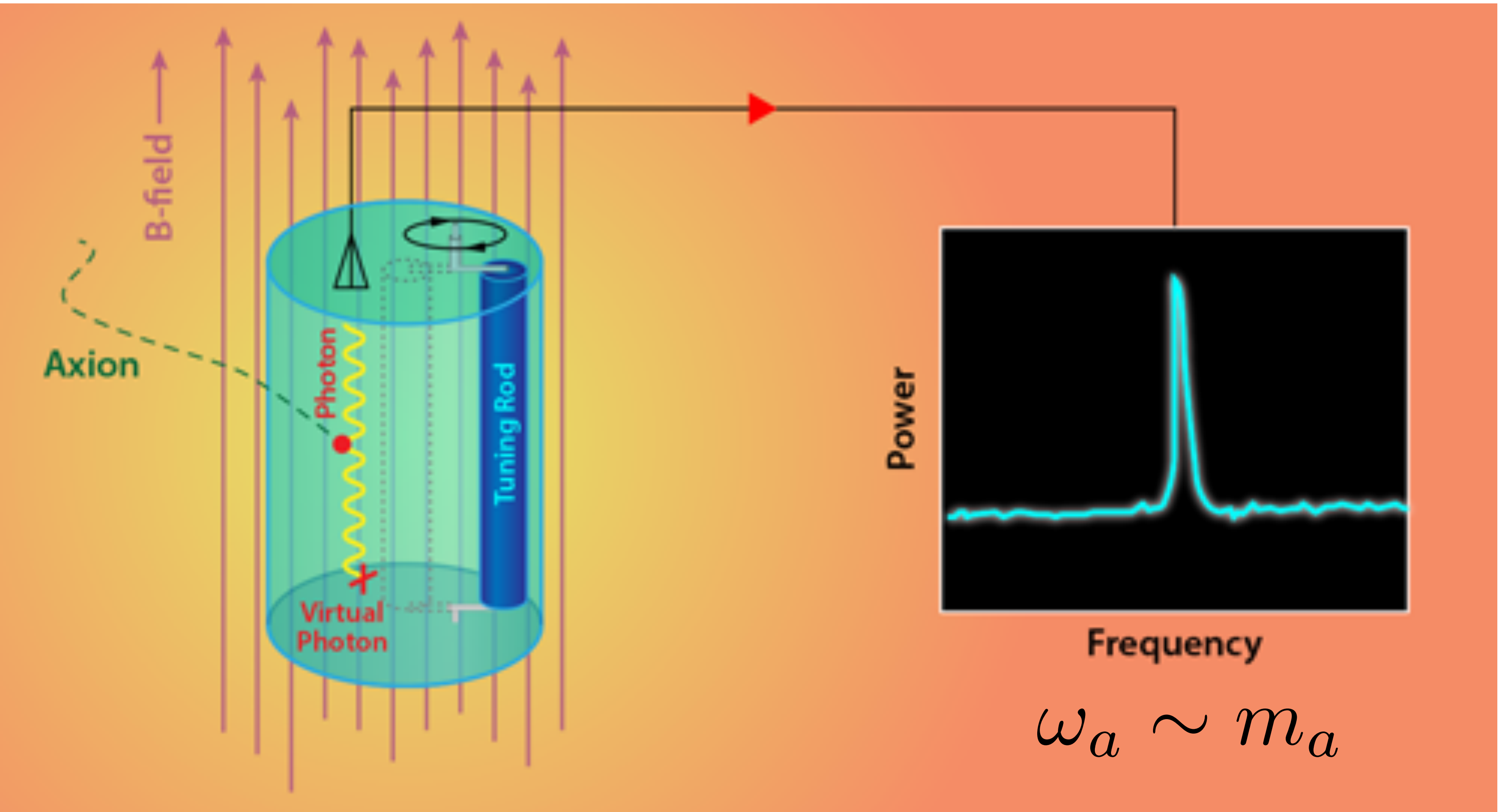
$$\left(\partial_t^2 + \frac{m_a}{Q_1}\partial_t + m_a^2\right)\mathbf{E}_1 \sim m_a \cos m_a t$$

Resonant for many cycles

$$Q_a \sim 10^6$$

Ideal for

$$m_a \sim \text{GHz} \sim 10^{-6}\ \text{eV}$$

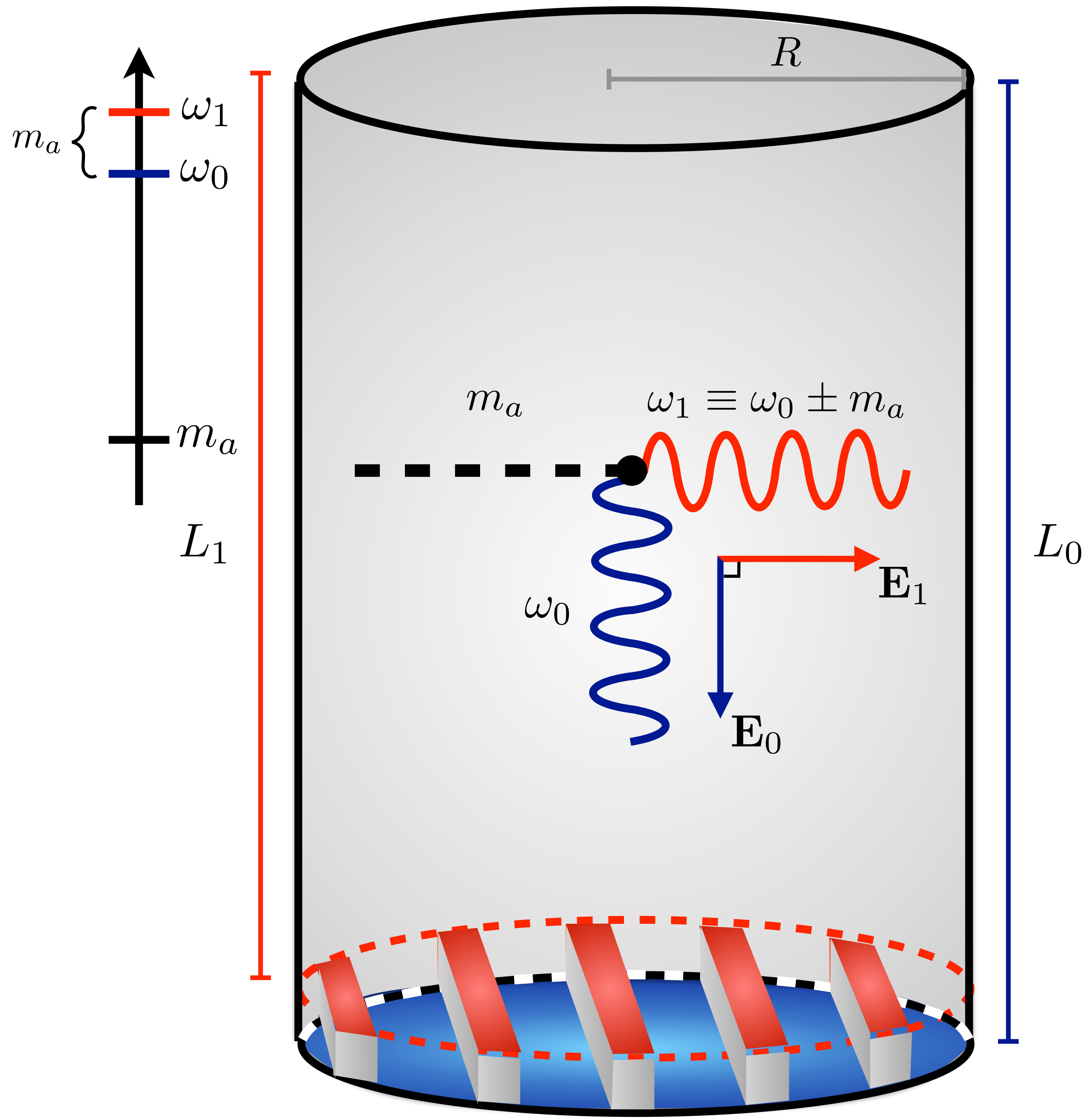


$$\omega_a \sim m_a$$

Problems:

1. **Cavity size** ~ (axion mass)^-1
2. **Signal power** decreases with axion mass

LOW MASS AXION DETECTION



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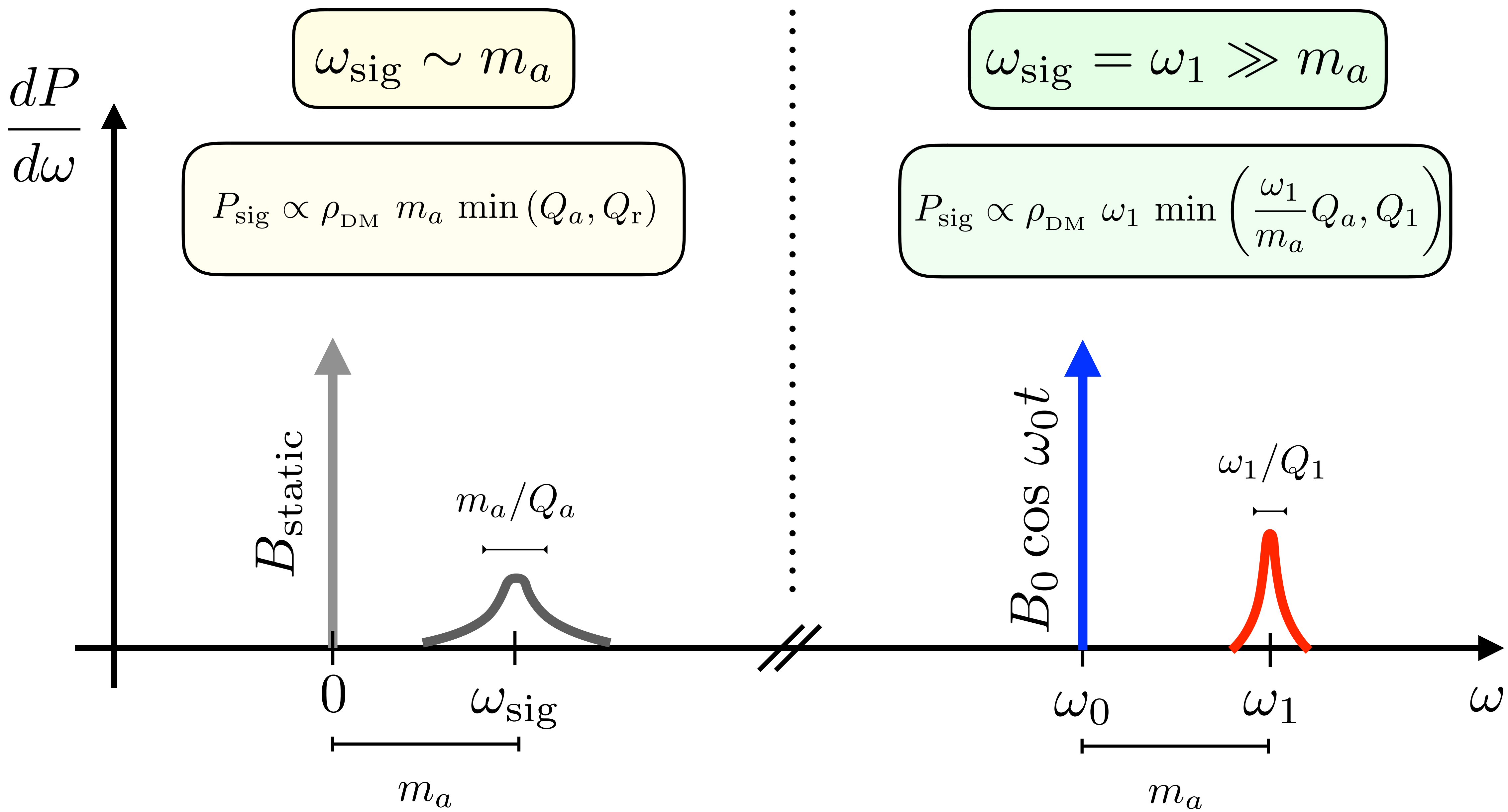
LOW MASS AXION DETECTION



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OUR ANCESTORS HUNTING FOR GWs

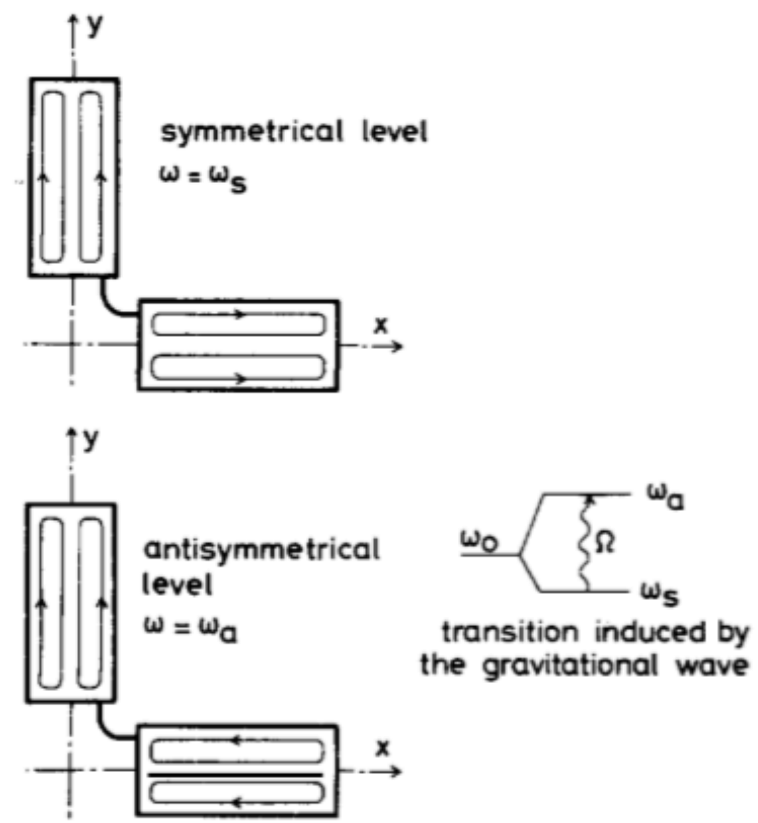
With a different geometry,
viable also for gravitational waves!
Radicati, Pegoraro, Picasso '78

Radicati

Menotti

Barbieri

RTD



MAGO '05

OUR ANCESTORS HUNTING FOR GWs

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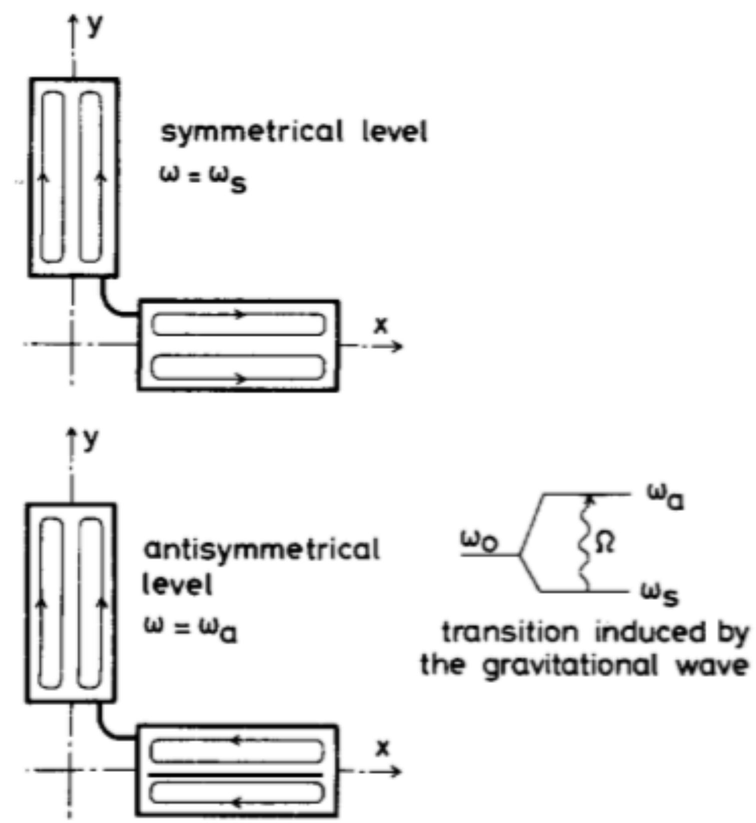

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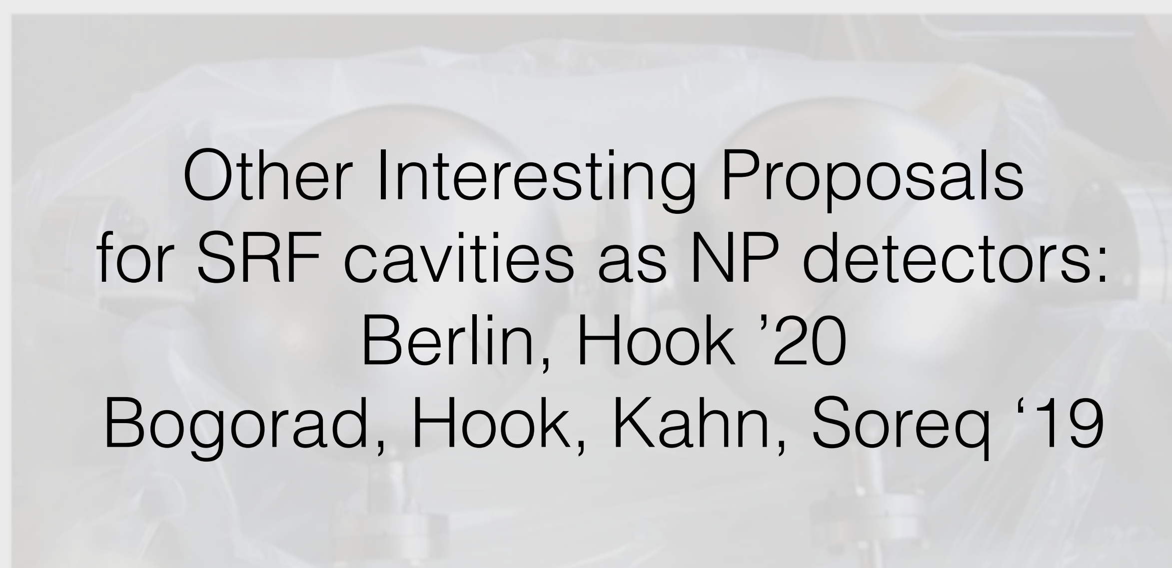
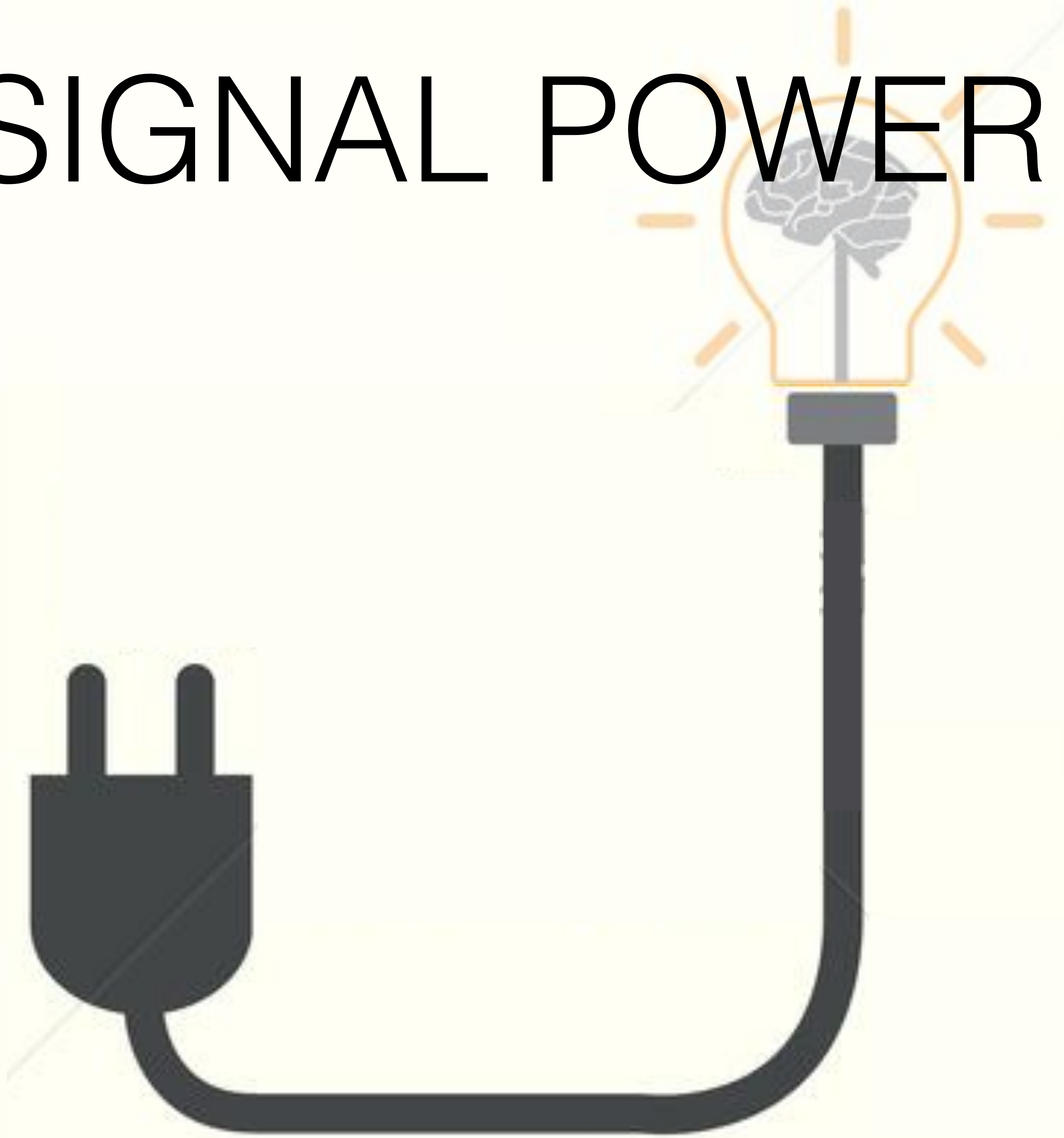
MAGO '05



SIGNAL POWER



SIGNAL POWER AT LOW MASSES

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

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

Static:

$$\mathbf{E}_1 \sim \frac{m_a g_{a\gamma\gamma}\sqrt{\rho_{\mathrm{DM}}}\mathbf{B}}{m_a^2 - \omega_1^2 + i\frac{m_a \omega}{Q_1}}$$

Oscillating:

$$\mathbf{E}_1 \sim \frac{\omega_0 g_{a\gamma\gamma}\sqrt{\rho_{\mathrm{DM}}}\mathbf{B}}{(\omega_0 + m_a)^2 - \omega_1^2 + i\frac{(\omega_0+m_a)\omega}{Q_1}}$$

SIGNAL POWER AT LOW MASSES

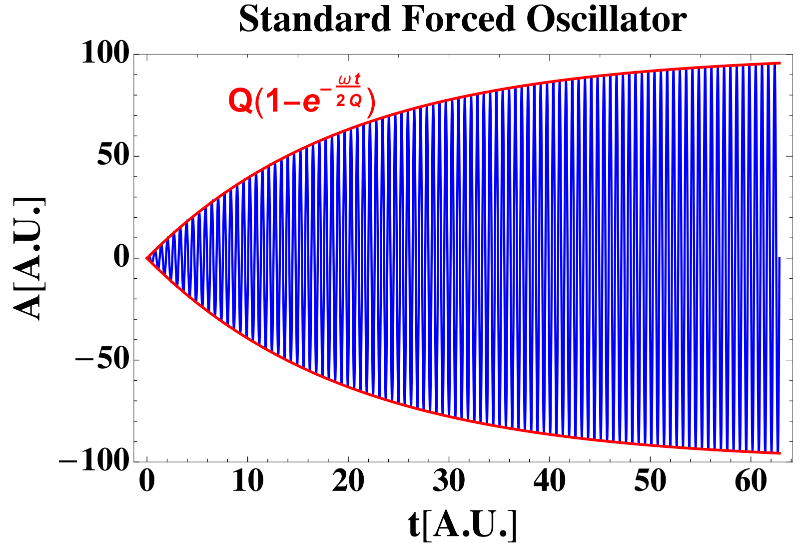
Power = Energy/Time

Time

$$\min[\tau_a, \tau_r] = \min\left[\frac{Q_a}{m_a}, \frac{Q_1}{\omega_1}\right]$$

$$t = \tau_a = \frac{Q_a}{m_a}$$ **Axion stops being monochromatic**

$$t = \tau_r = \frac{Q_1}{\omega_1}$$ **Steady State**



SIGNAL POWER AT LOW MASSES

Power = Energy/Time

Energy

$$\omega_1^2 B_a^2 V \min\left[\frac{Q_a^2}{m_a^2}, \frac{Q_1^2}{\omega_1^2}\right]$$

Time

$$\min[\tau_a, \tau_r] = \min\left[\frac{Q_a}{m_a}, \frac{Q_1}{\omega_1}\right]$$

Static: $\omega_1 \simeq m_a$

$$P \simeq m_a B_a^2 V \min[Q_a, Q_1]$$

Naively no reason to build resonators with Q > 10^6

SIGNAL POWER AT LOW MASSES

Power = Energy/Time

Energy

$$\omega_1^2 B_a^2 V \min\left[\frac{Q_a^2}{m_a^2}, \frac{Q^2}{\omega_1^2}\right]$$

Time

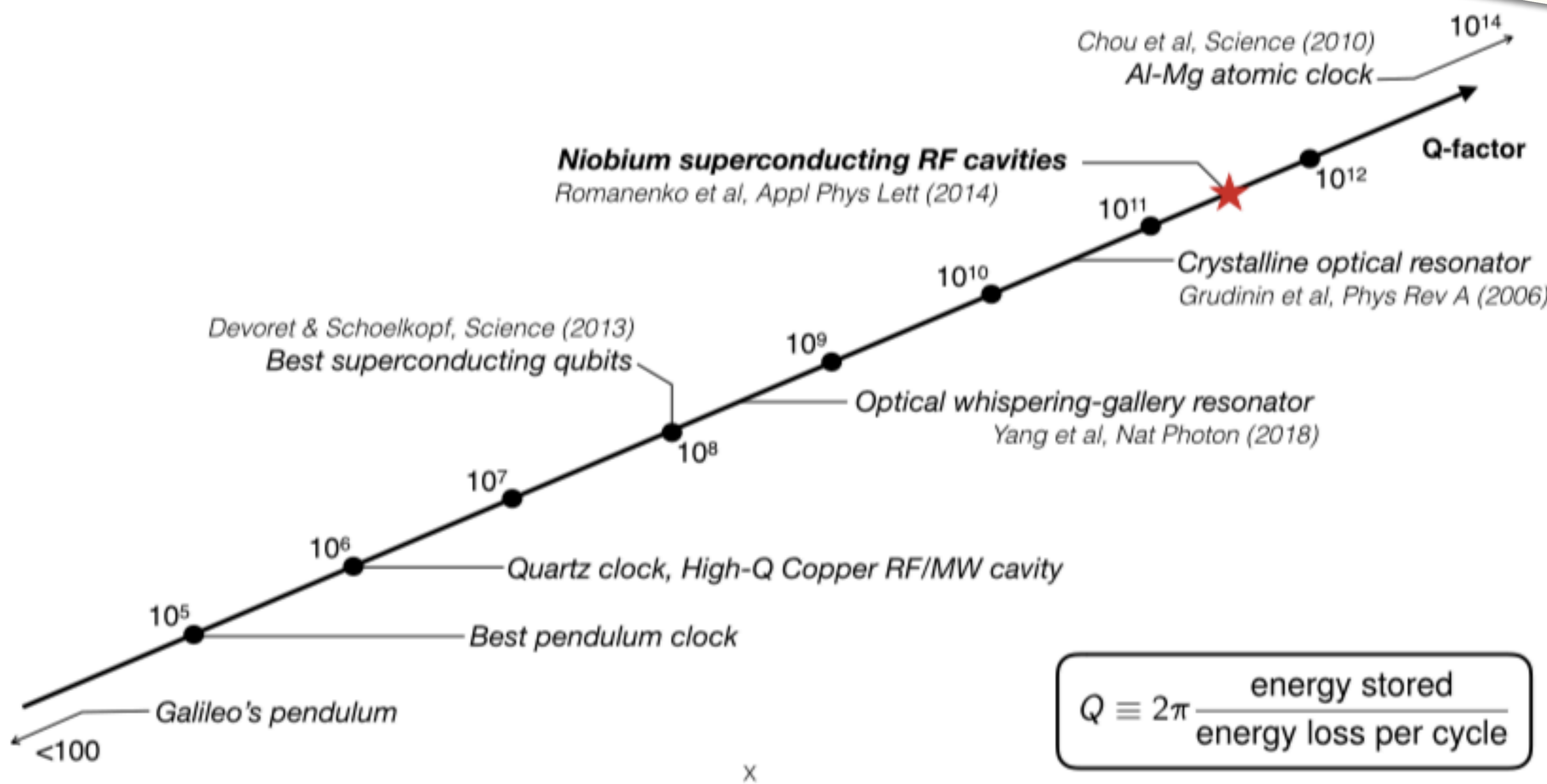
$$\min[\tau_a, \tau_r] = \min\left[\frac{Q_a}{m_a}, \frac{Q_1}{\omega_1}\right]$$

Oscillating: $\omega_1 > m_a$

$$P \simeq \omega_1 B_a^2 V \min[Q_a(\omega_1/m_a), Q_1]$$

Great advantage of high-Q resonators at low m_a

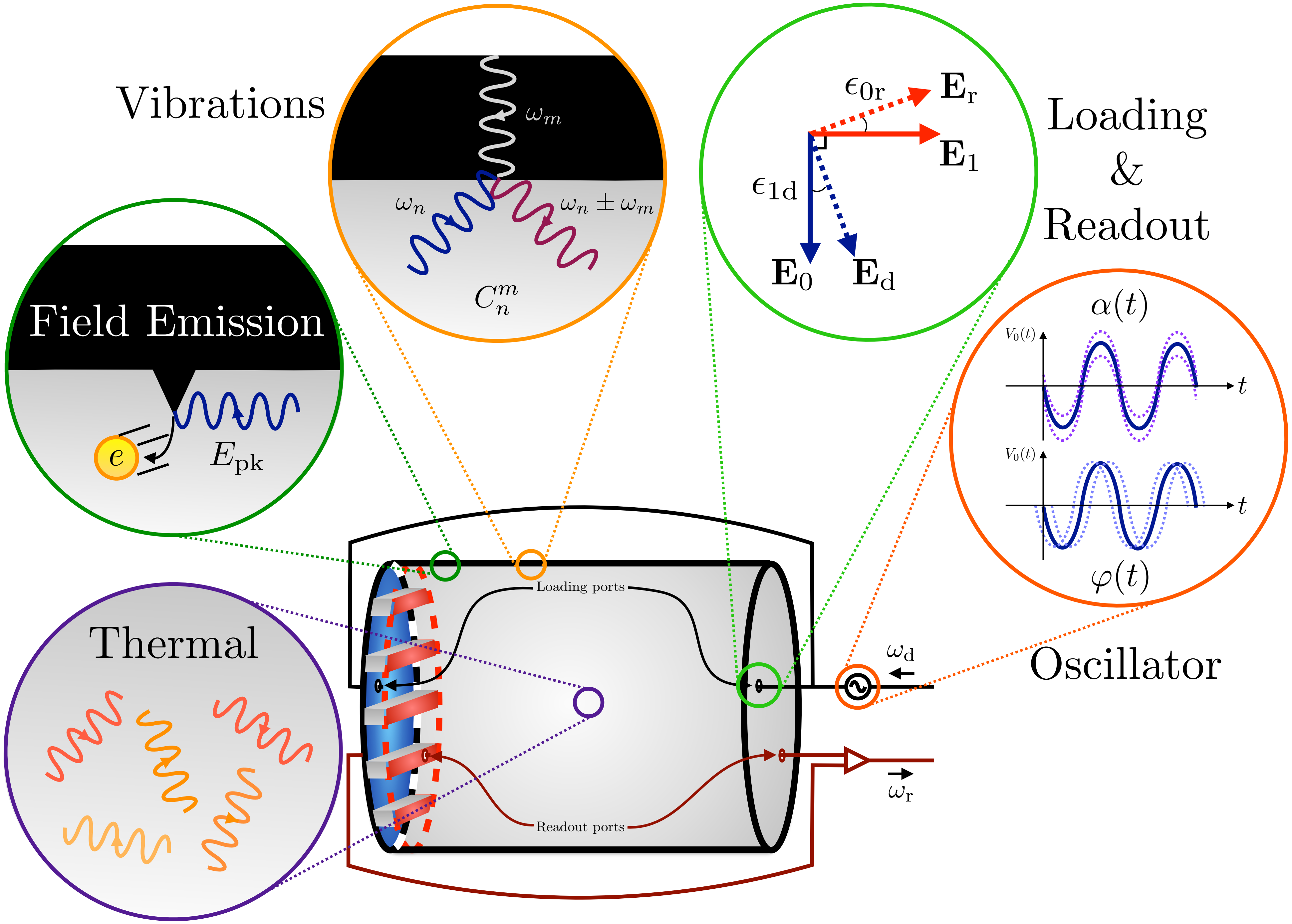
SUPERCONDUCTING RADIOFREQUENCY CAVITIES



From Anna Grassellino, Fermilab

NOISE AND SENSITIVITY

NOISE



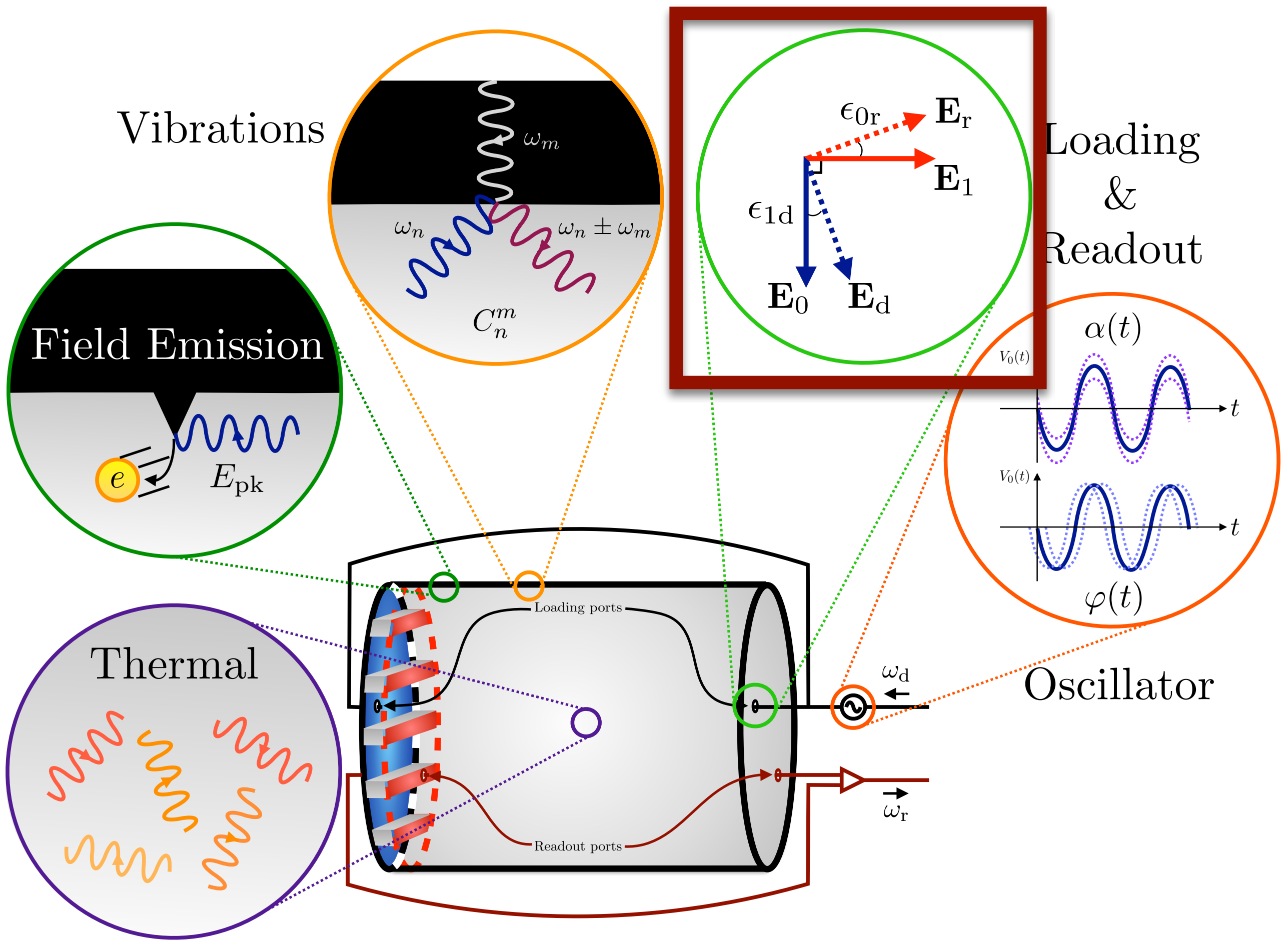
Vibrations
ω_m
ω_n
$\omega_n \pm \omega_m$
C_n^m
$\epsilon_{0\mathrm{r}}$
$\mathbf{E}_\mathrm{r}$
$\mathbf{E}_1$
$\epsilon_{1\mathrm{d}}$
$\mathbf{E}_0$
$\mathbf{E}_\mathrm{d}$
Loading & Readout
Field Emission
e
E_pk
$\alpha(t)$
$V_0(t)$
t
$\varphi(t)$
Thermal
Loading ports
Readout ports
ω_d
ω_r
Oscillator

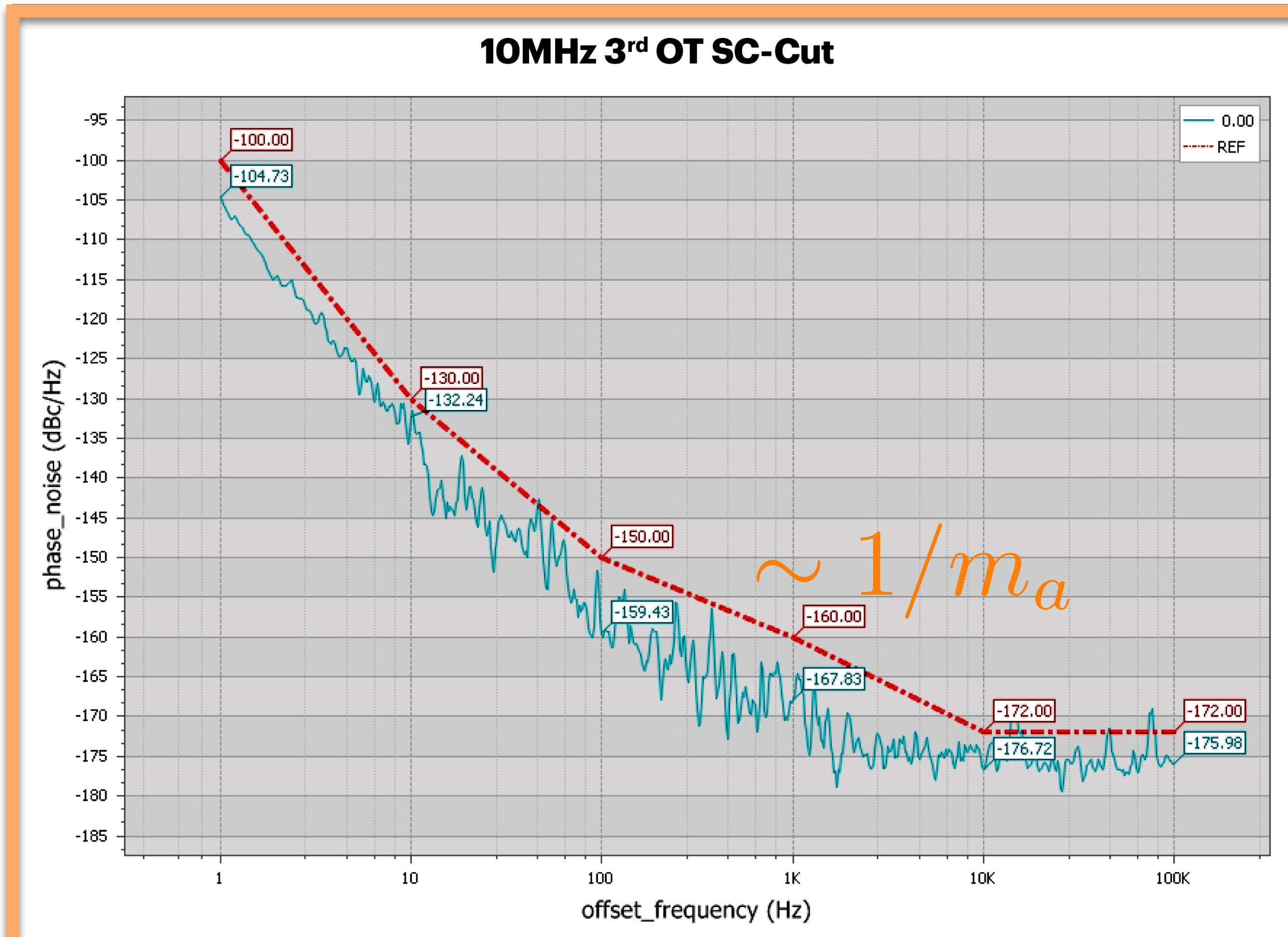
OSCILLATOR NOISE

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

$\sim 1/m_a$

Cavity Response

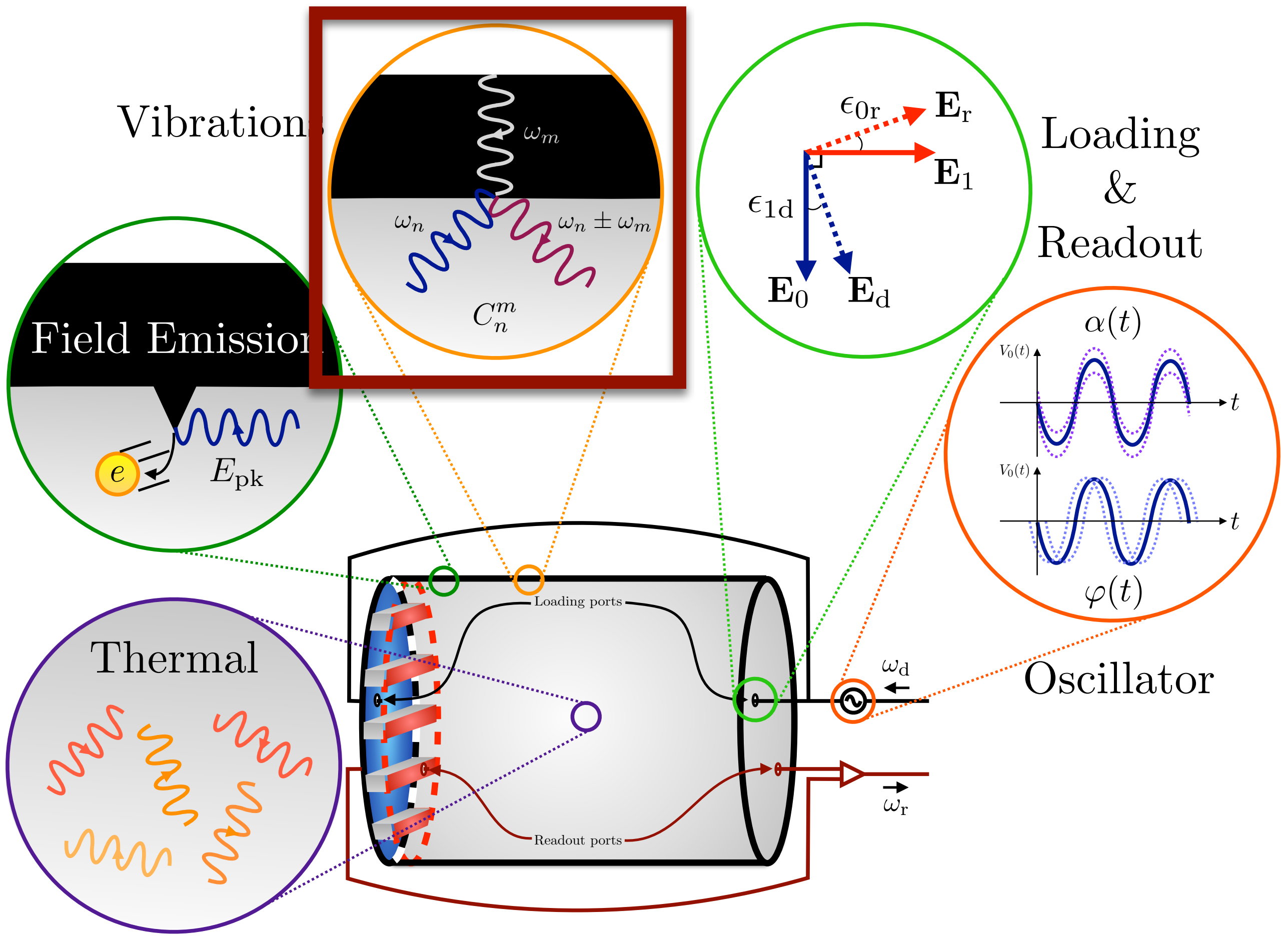




$\sim 1/m_a$

VIBRATIONAL NOISE

$$S_{\text{mech}}(\omega) = \sum_{n=0,1} S^{(n)}_{\text{mech}}(\omega) \simeq \frac{\epsilon_{1d}^2}{4}\frac{\omega_0}{Q_0} P_{\text{in}} \sum_{n=0,1} \frac{\left(S_{q_m}(\omega-\omega_0)/V^{2/3}\right)(\omega_n/Q_n)\,\omega_n^4\,\omega^2}{\left[(\omega^2-\omega_n^2)^2+(\omega\,\omega_n/Q_n)^2\right]\left[(\omega_0^2-\omega_n^2)^2+(\omega_0\,\omega_n/Q_n)^2\right]}$$



Wall Displacement

$$S_{q_m}(\omega) \simeq \frac{1}{M^2}\frac{S_{f_m}(\omega)}{(\omega^2-\omega_m^2)^2+(\omega_m\omega/Q_m)^2}$$

On Resonance

$$\sim 1/m_a^4$$

Off Resonance

$$\sim 1/m_a^2$$

$$\omega_m^{\text{min}} \simeq \text{kHz}$$

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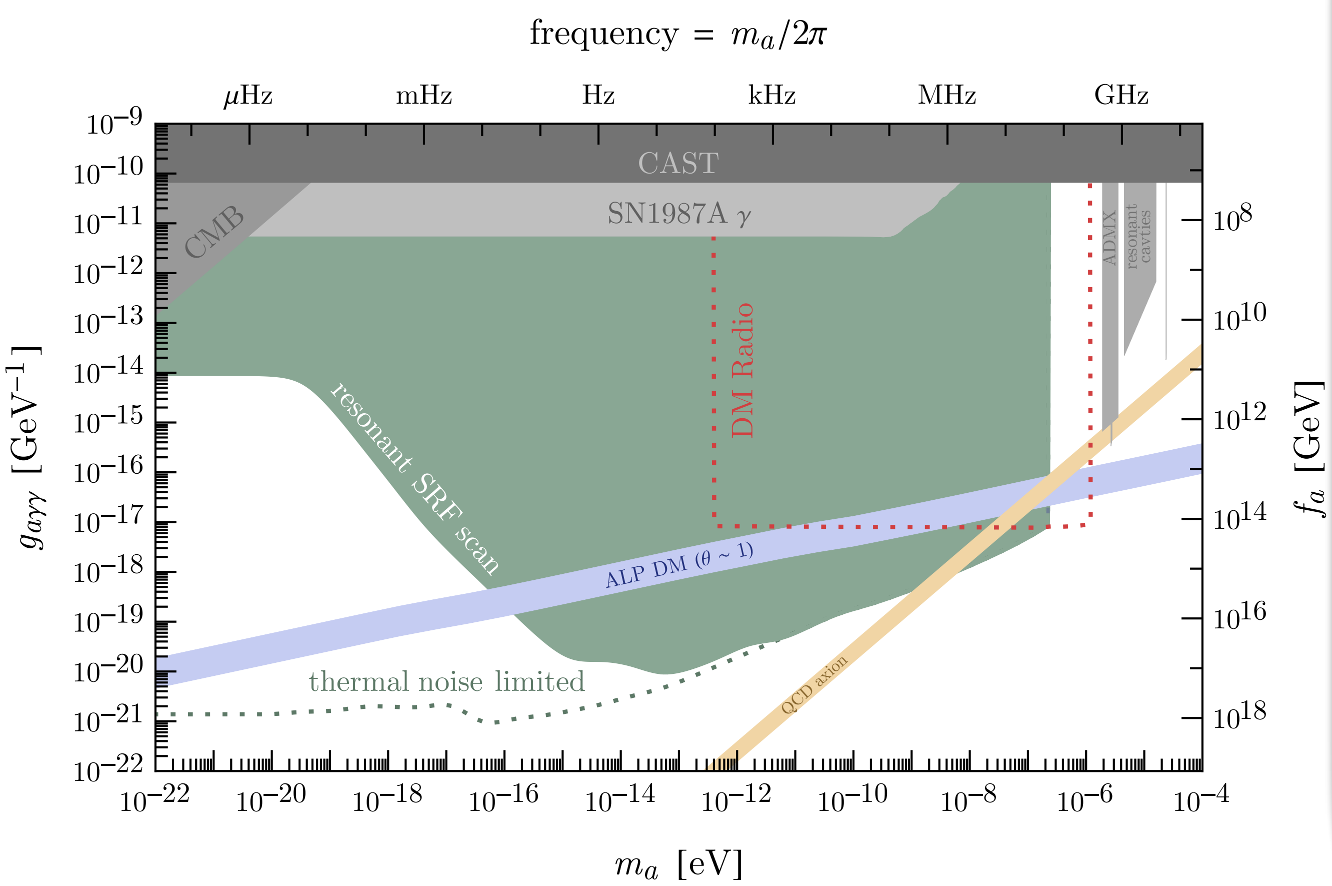
RESONANT VS BROADBAND

Resonant



$t_{\mathrm{e-fold}} \sim$ year $\quad B \sim 0.2$ T $\quad V = m^3$

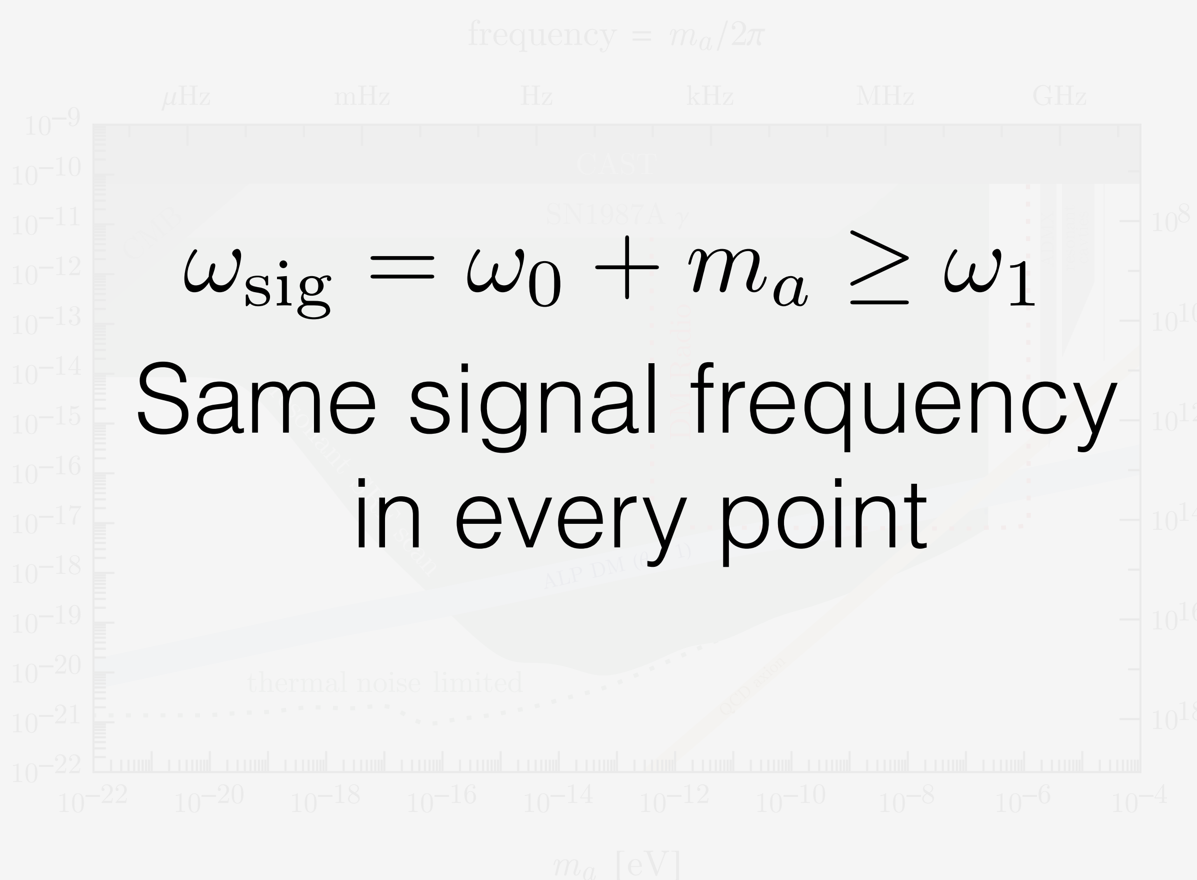
Broadband

$$\omega_{\mathrm{sig}} = \omega_1 = \omega_0 + m_a$$

Different signal frequency in every point

RESONANT VS BROADBAND

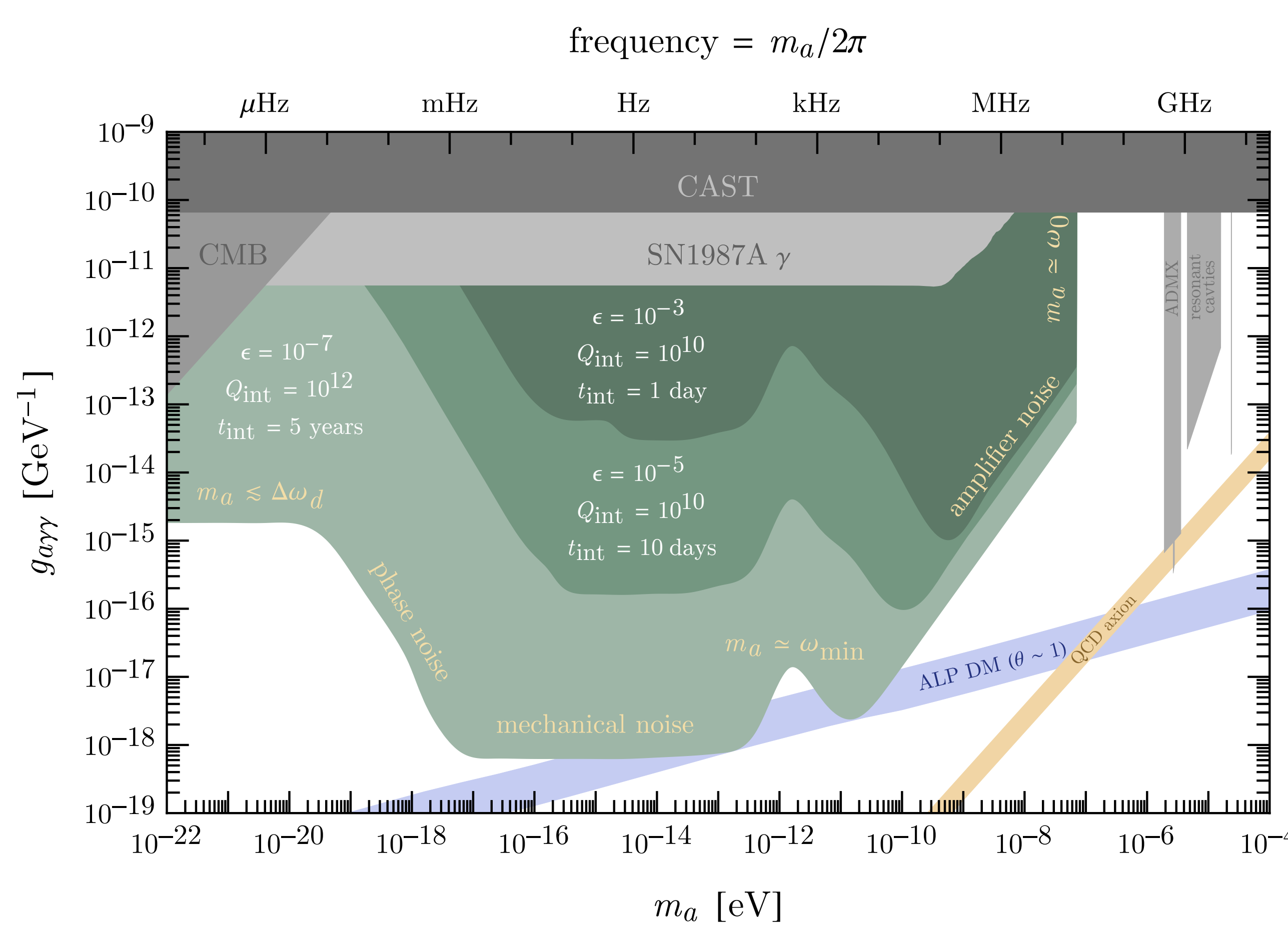
Resonant



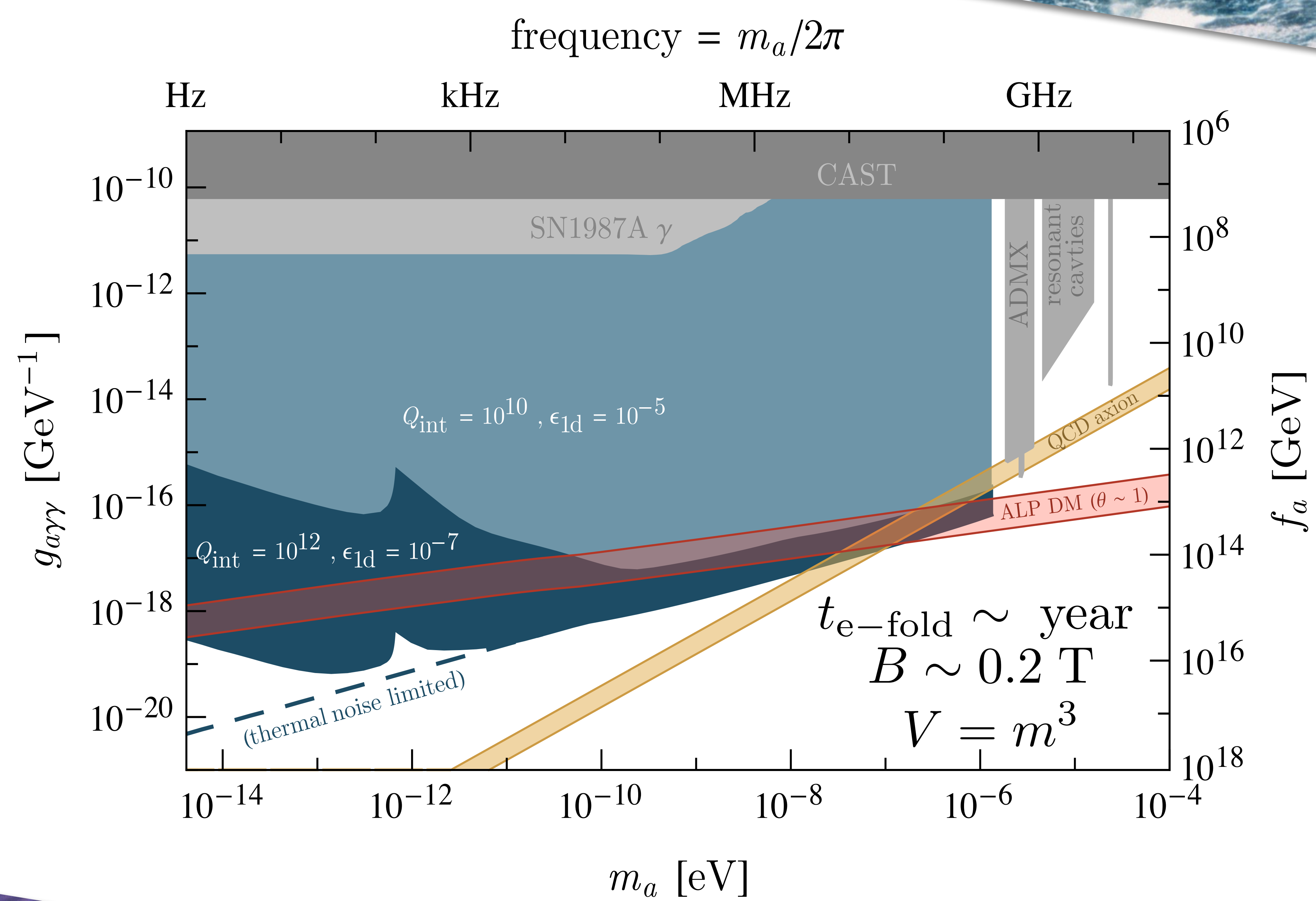
$$\omega_{\text{sig}} = \omega_0 + m_a \geq \omega_1$$

Same signal frequency in every point

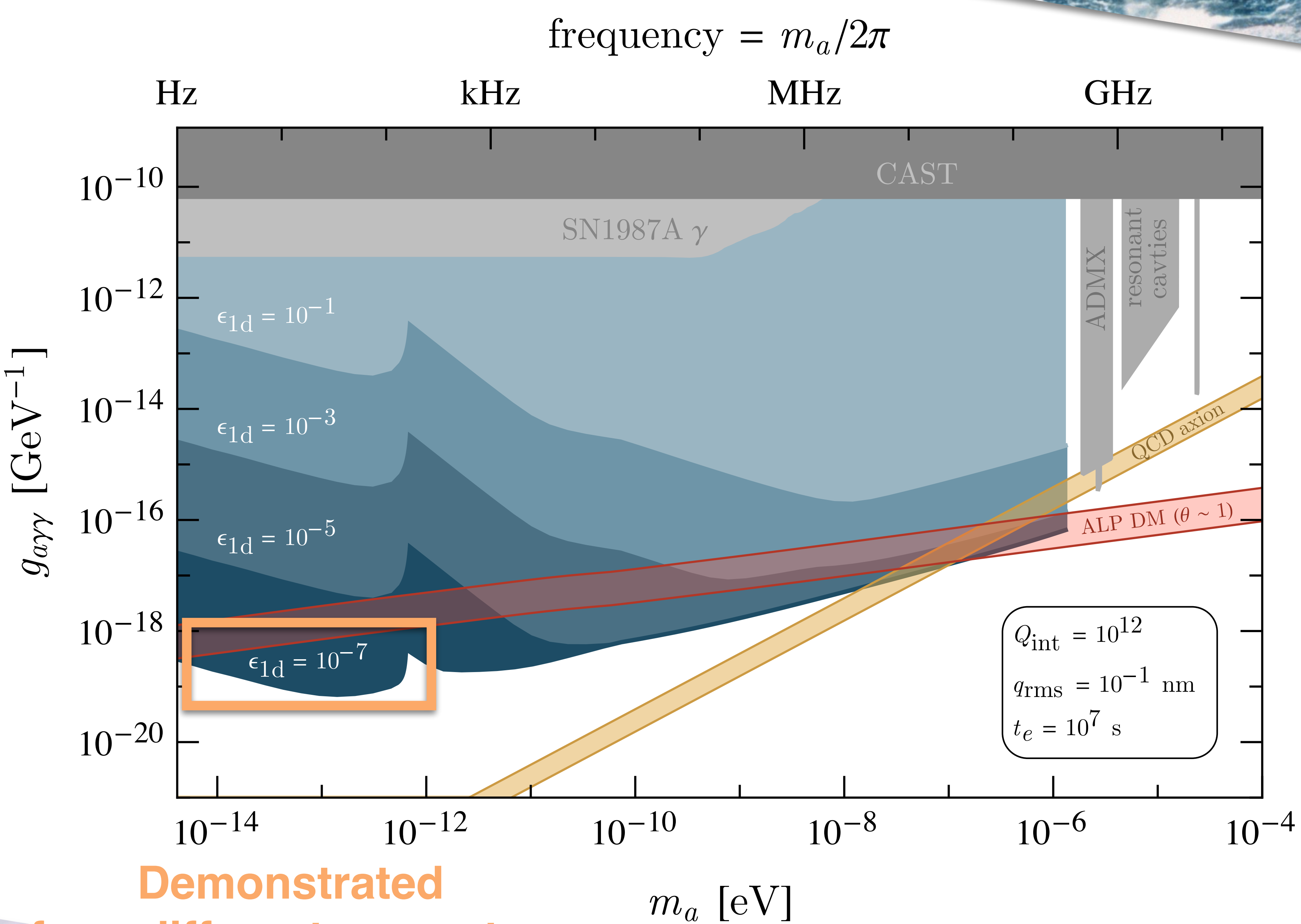
Broadband



SENSITIVITY (RESONANT)



ROBUSTNESS TO LOADING



Demonstrated for a different geometry, but same setup

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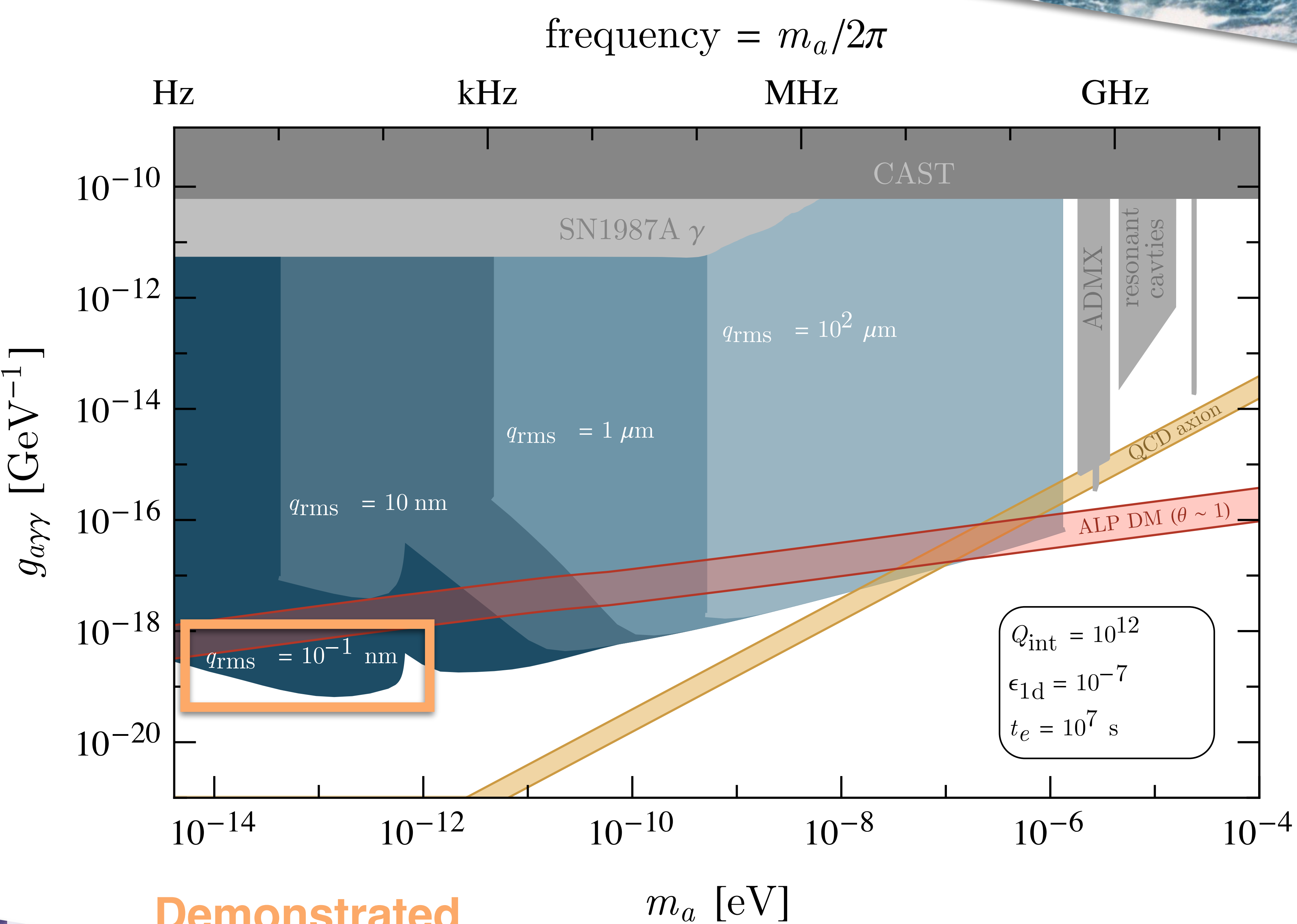
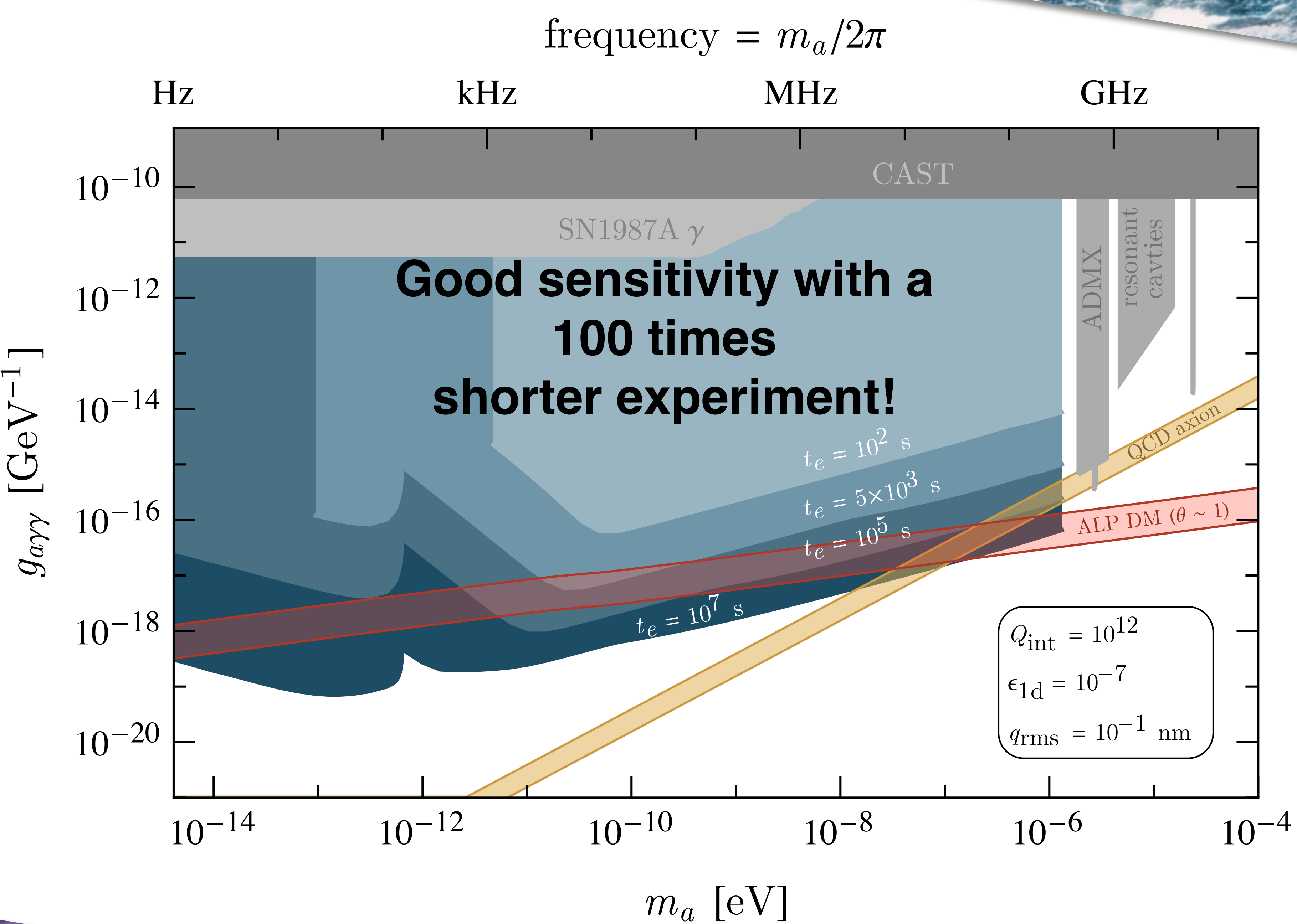
ROBUSTNESS TO ATTENUATION OF VIBRATIONS



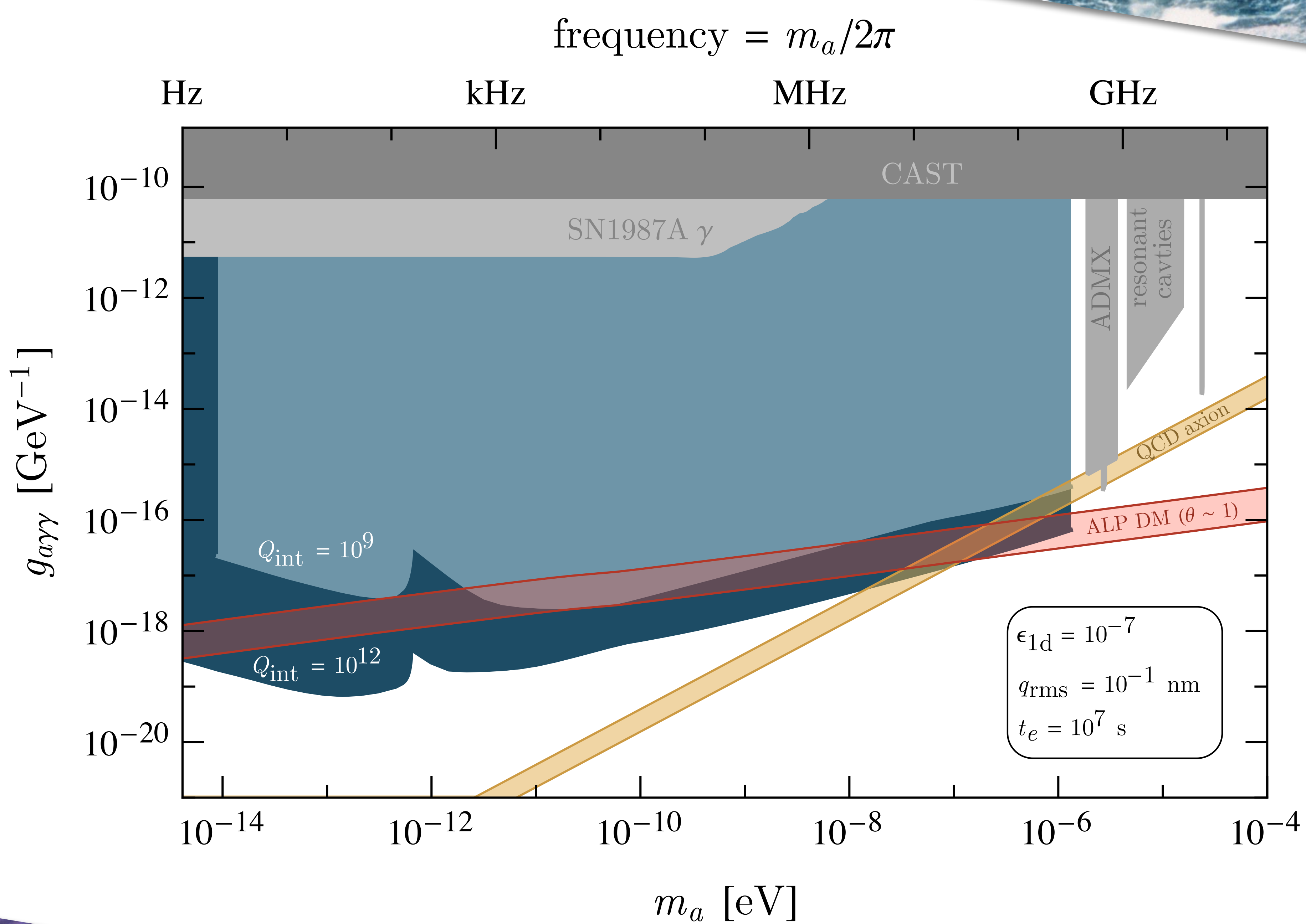
Demonstrated in similar cavities

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

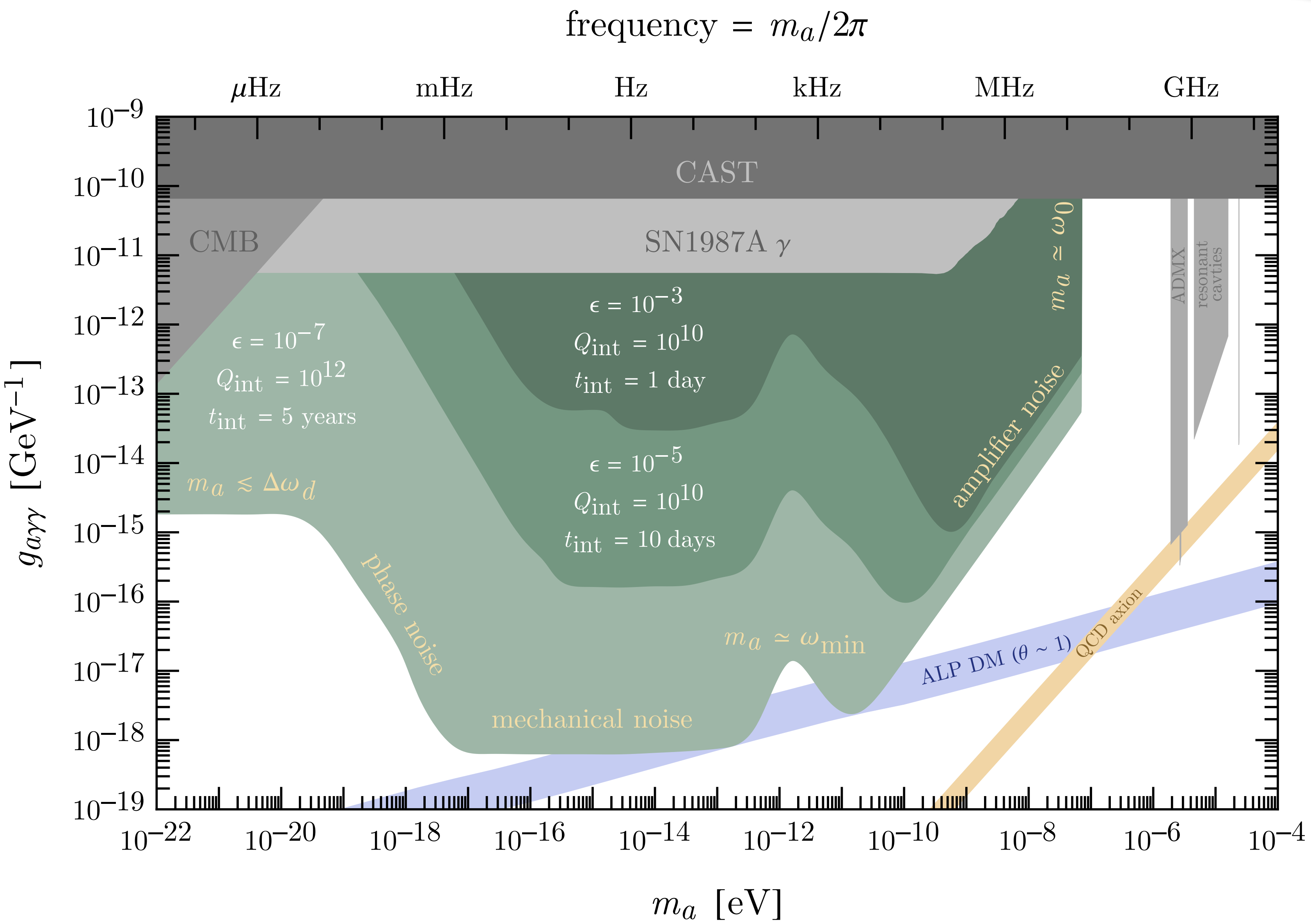
INTEGRATION TIME



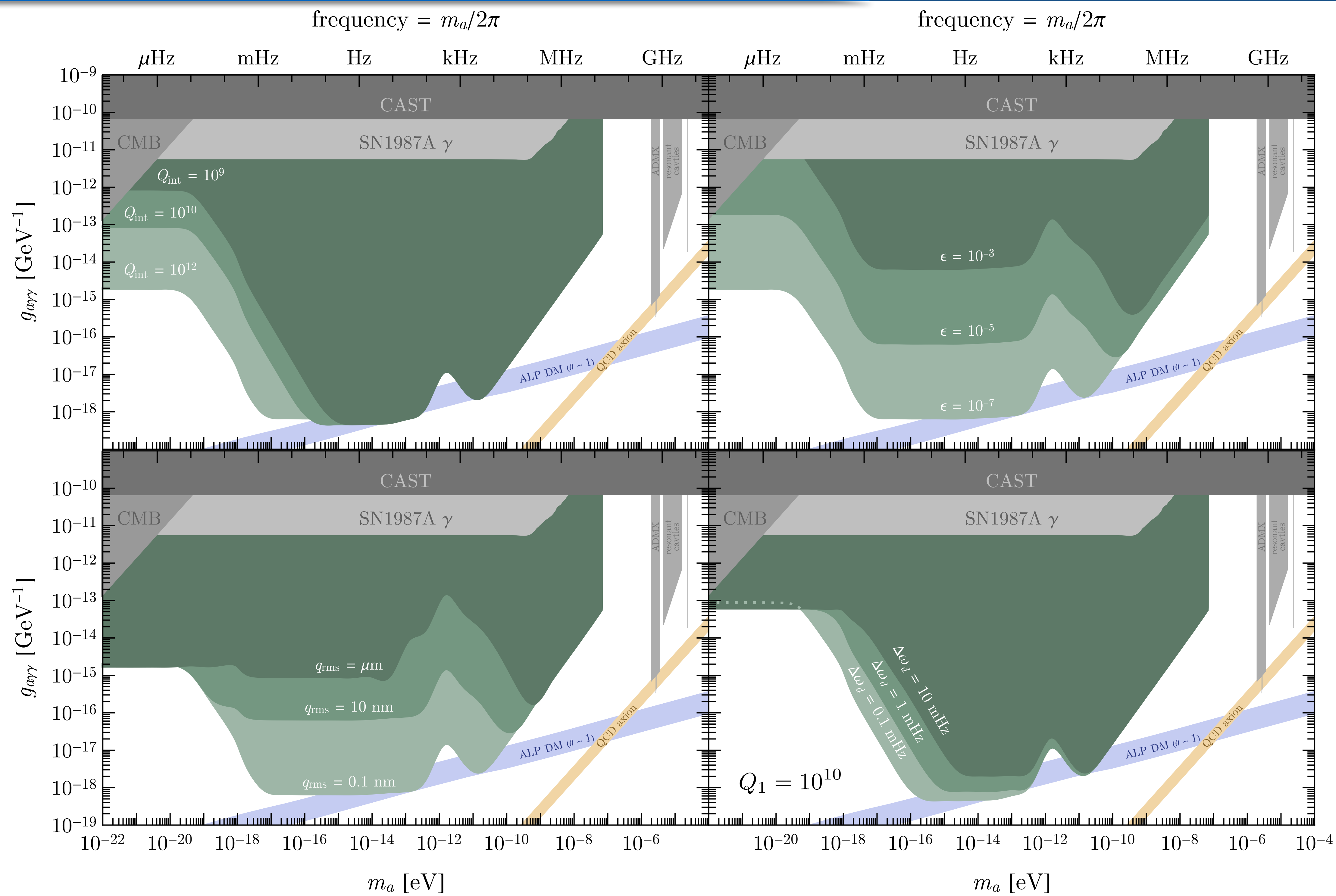
THE POWER OF Q



SENSITIVITY (BROADBAND)



ROBUSTNESS TO EXPERIMENTAL DETAILS (BROADBAND)



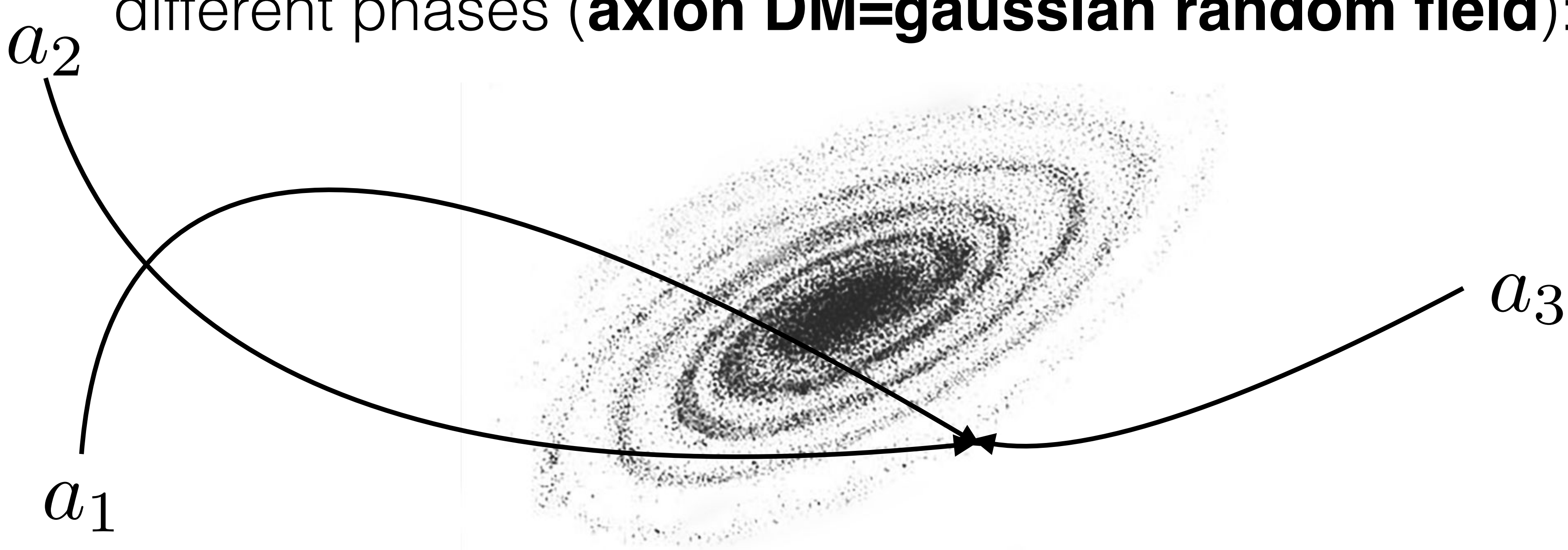
CONCLUSION

- Light Dark Matter candidates behaving as a classical field are appealing theoretically (strong CP problem, Higgs mass, generically expected from string theory), maybe as appealing as WIMPs were in the past
- We are just starting to explore them experimentally (in this talk **new concept for axion dark matter detection**)

BACKUP

AXION DM IN THE LABORATORY

In each experimental bin we are summing over a multitude of plane waves with different phases (**axion DM=gaussian random field**):



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

$$t_{\rm int} \gg \frac{1}{\delta\omega_a} \gg \frac{1}{m_a} \rightarrow a_0 = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}$$ ϕ **Irrelevant**

$$\frac{1}{\delta\omega_a} \gtrsim t_{\rm int} \gg \frac{1}{m_a} \rightarrow a_0 < \frac{\sqrt{2\rho_{\rm DM}}}{m_a}$$ ϕ **Irrelevant**

STATISTICS INTERLUDE

Time: Gaussian Random Field

$$\langle a(t+\tau)a(t'+\tau)\rangle = \langle a(t)a(t')\rangle$$

Mean $\langle a(t)\rangle = 0$

Variance $\langle |a(t)|^2\rangle = \dfrac{\rho_{\rm DM}}{m_a^2}$

Frequency: Gaussian Random Field

Mean $\langle a(\omega)\rangle = 0$

Variance $\langle a(\omega)a^*(\omega')\rangle = \delta(\omega-\omega')S_a(\omega)$

STATISTICS INTERLUDE

Data: $d(\omega) = n(\omega) + s(\omega) \quad s(\omega) \sim a(\omega)$

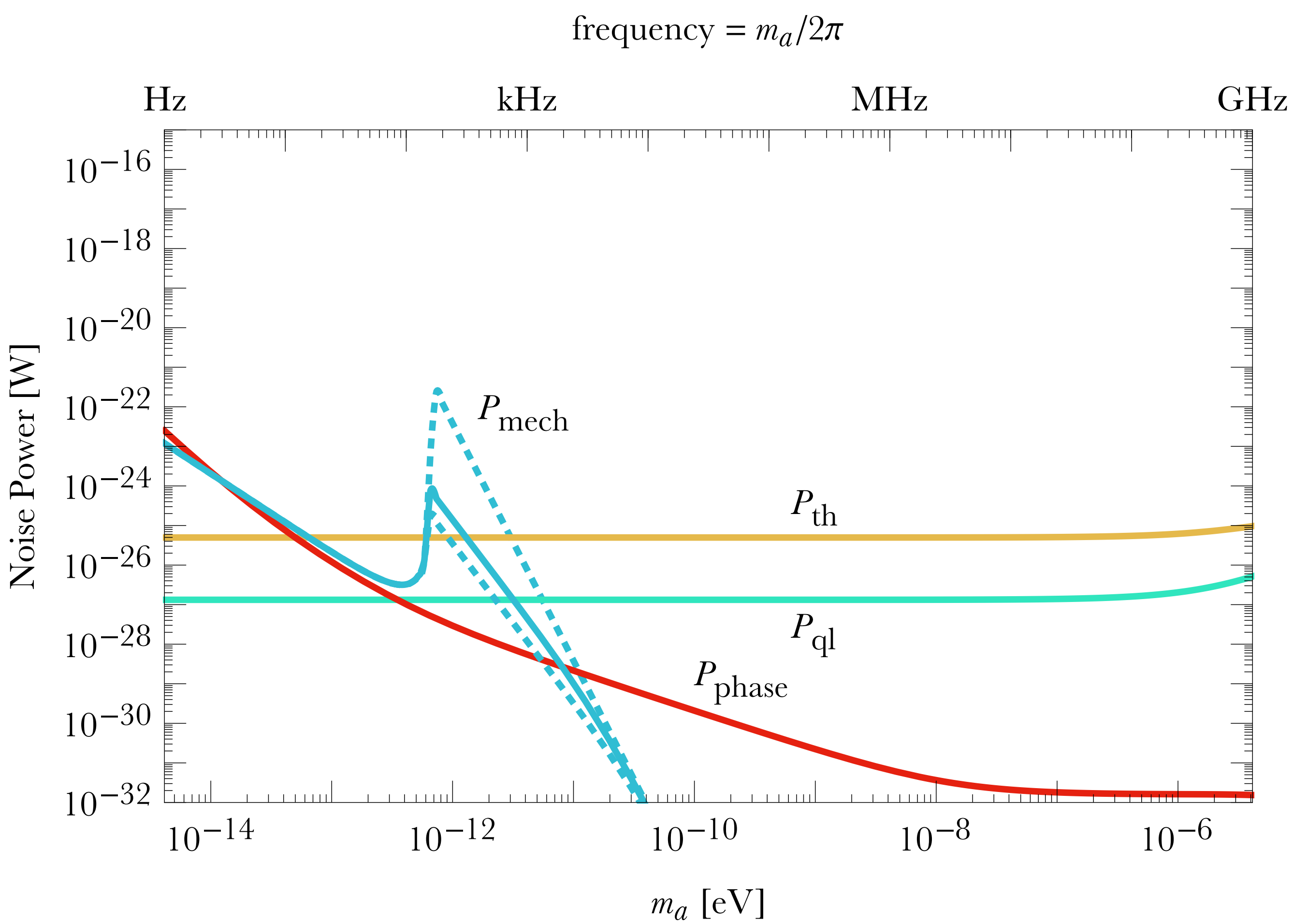
Noise: Gaussian Colored $\langle n(\omega) \rangle = 0 \quad \langle n(\omega) n(\omega') \rangle = \delta(\omega - \omega') S_n(\omega)$

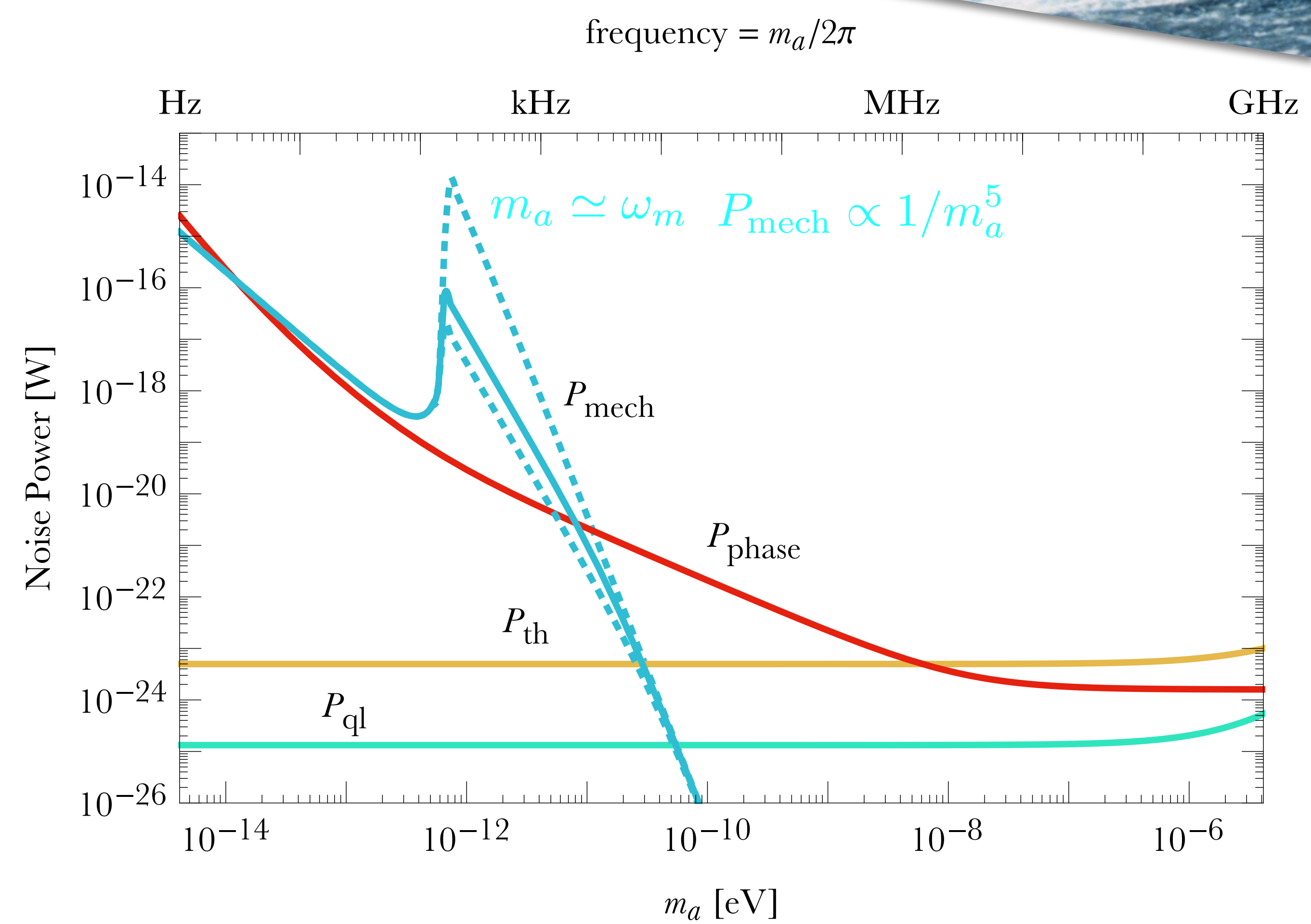
Likelihood:

$$L[d(\omega)] = \frac{1}{Z} e^{-\int d\omega \boxed{\frac{d(\omega) d^*(\omega)}{S_n(\omega) + S_{\mathrm{sig}}(\omega)}}}$$

Only the average 2-point function matters.
A ‘deterministic’ axion gives the same result (see next slide)

NOISE (RESONANT)



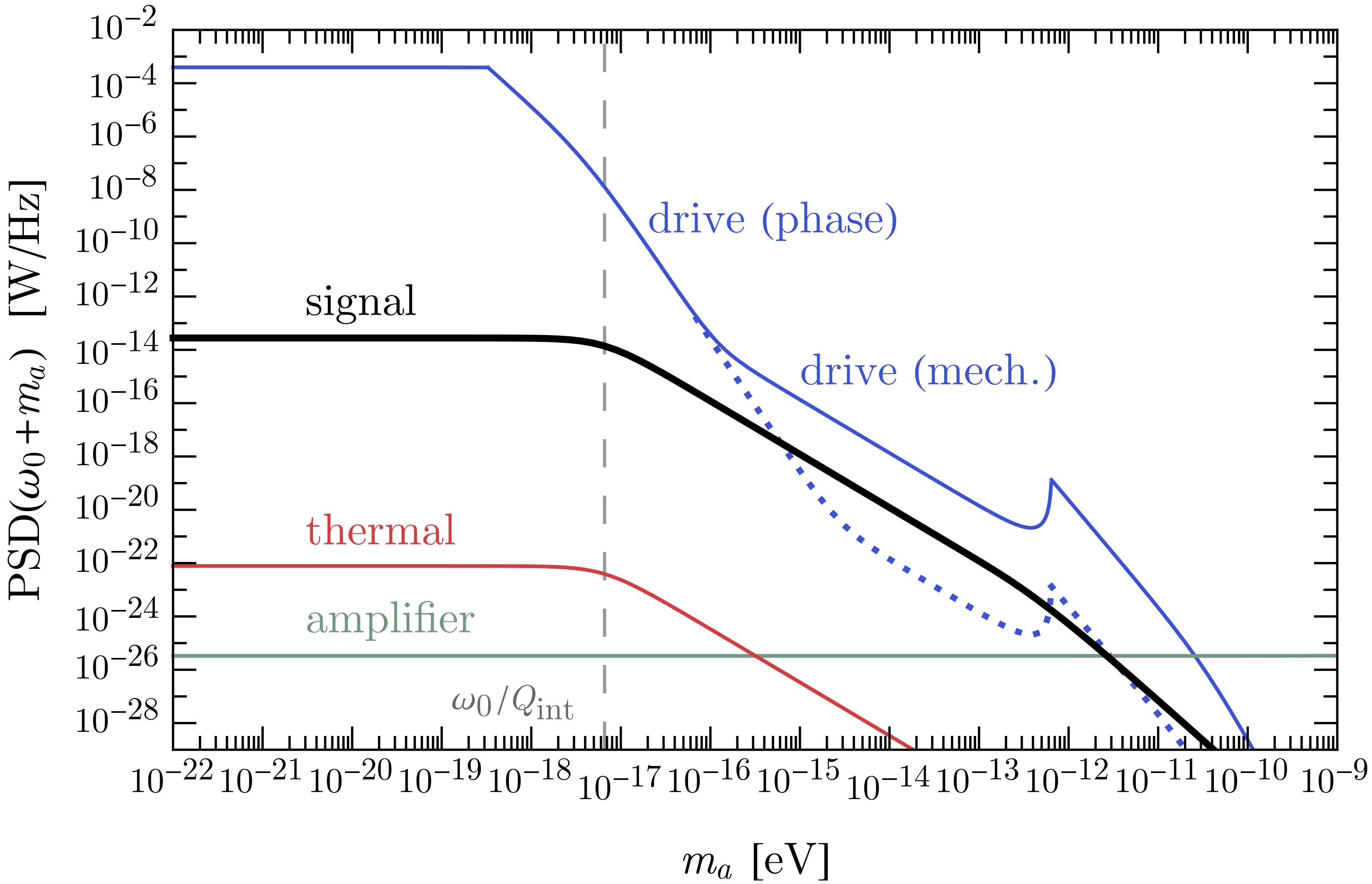


$\epsilon_{1d} = 10^{-7}, \quad Q = 10^{12}$

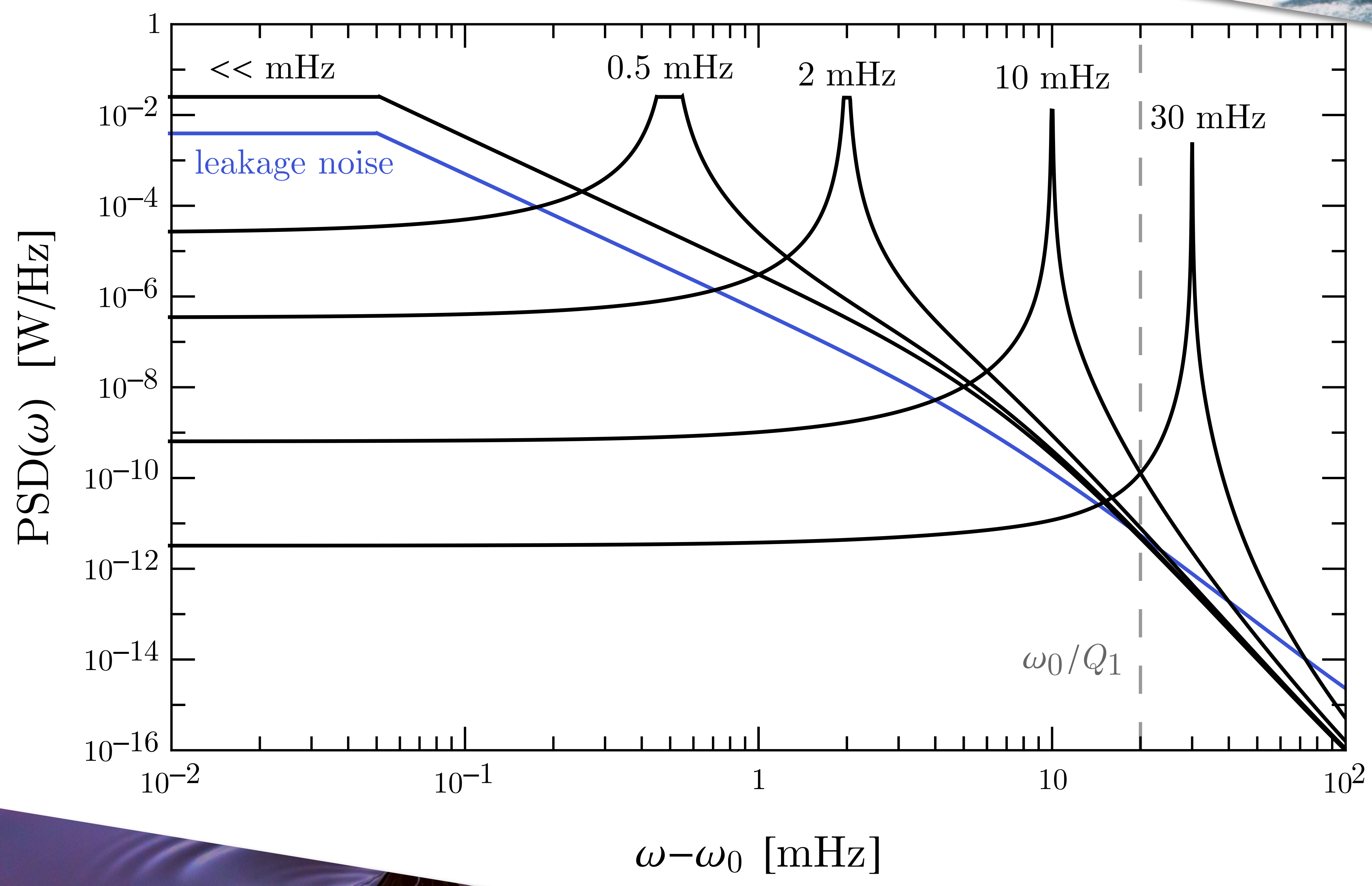
$\epsilon_{1d} = 10^{-5}, \quad Q = 10^{10}$

NOISE (BROADBAND)

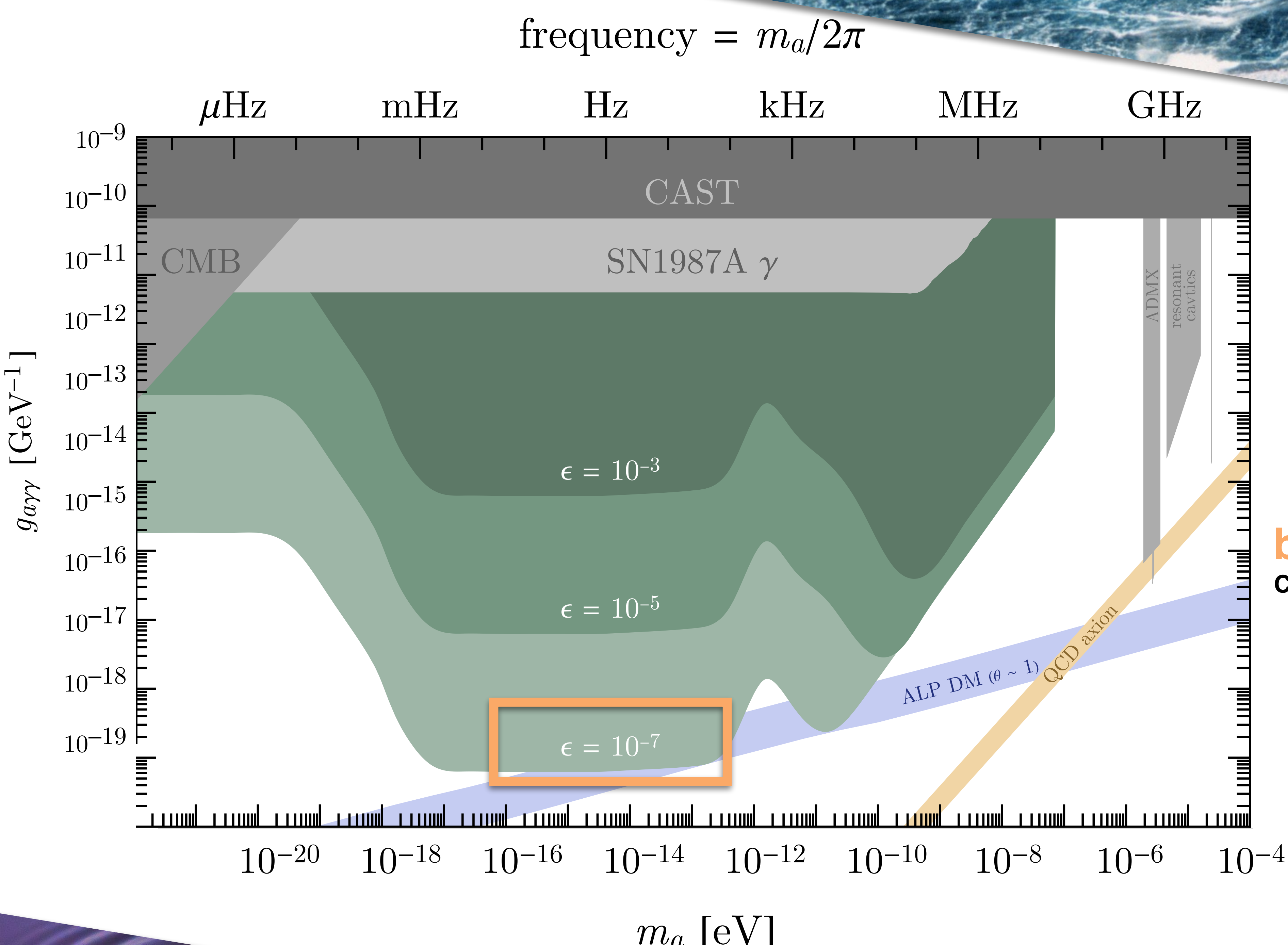
PRELIMINARY!



MASS REACH (BROADBAND)



ROBUSTNESS TO LOADING



Demonstrated for a different geometry, but same setup

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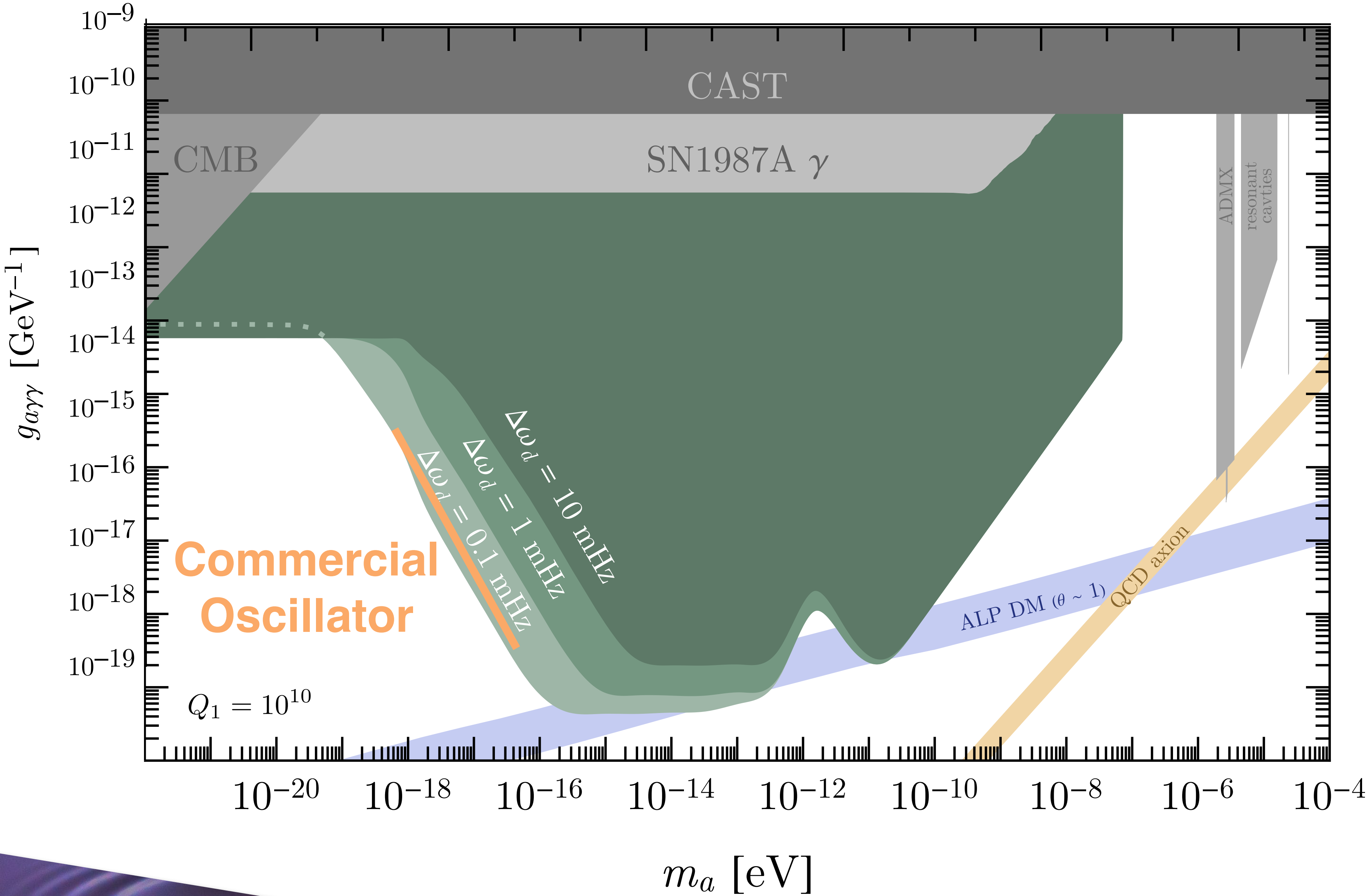
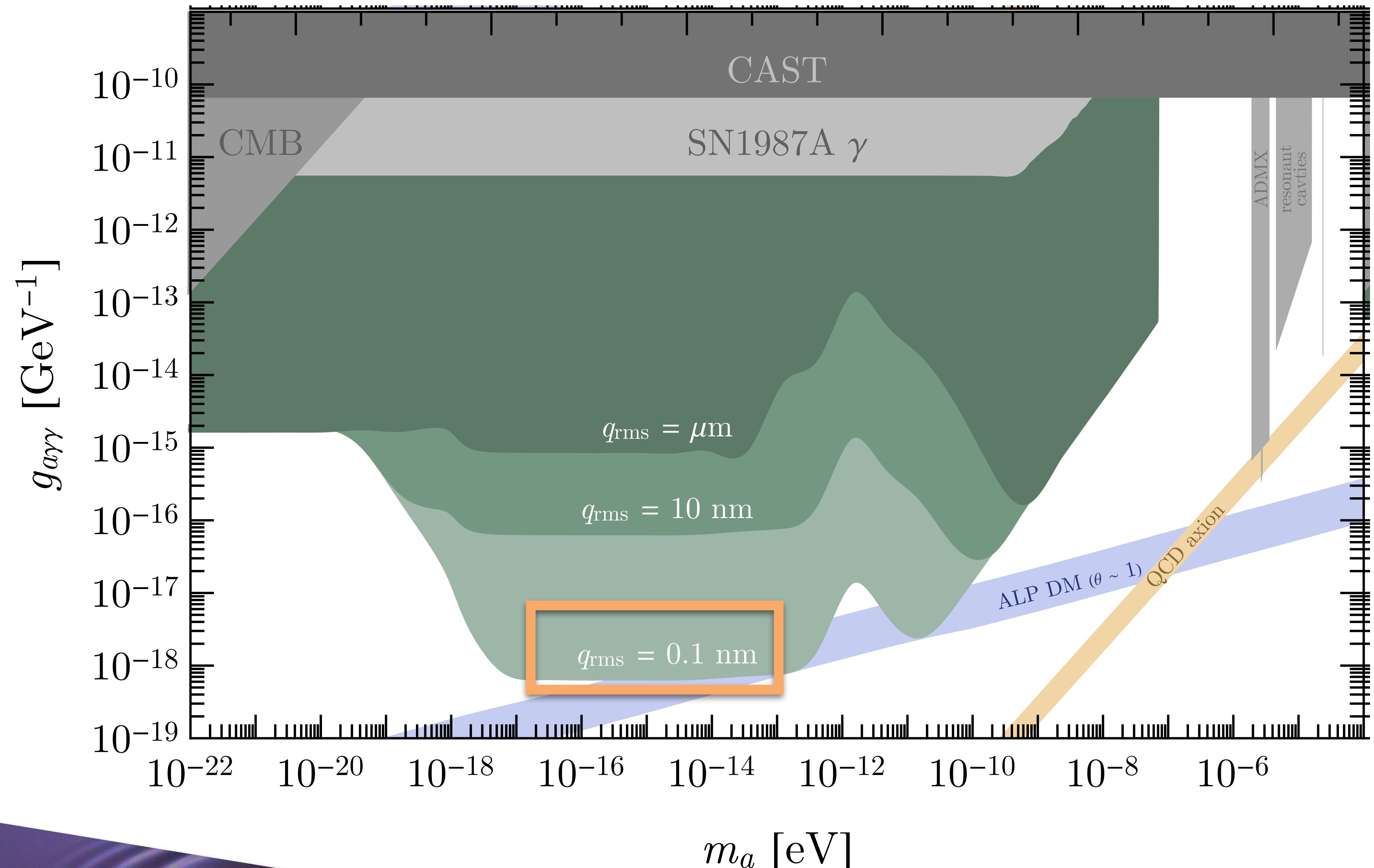
ROBUSTNESS TO LOW FREQUENCY NOISE



ROBUSTNESS TO ATTENUATION OF VIBRATIONS

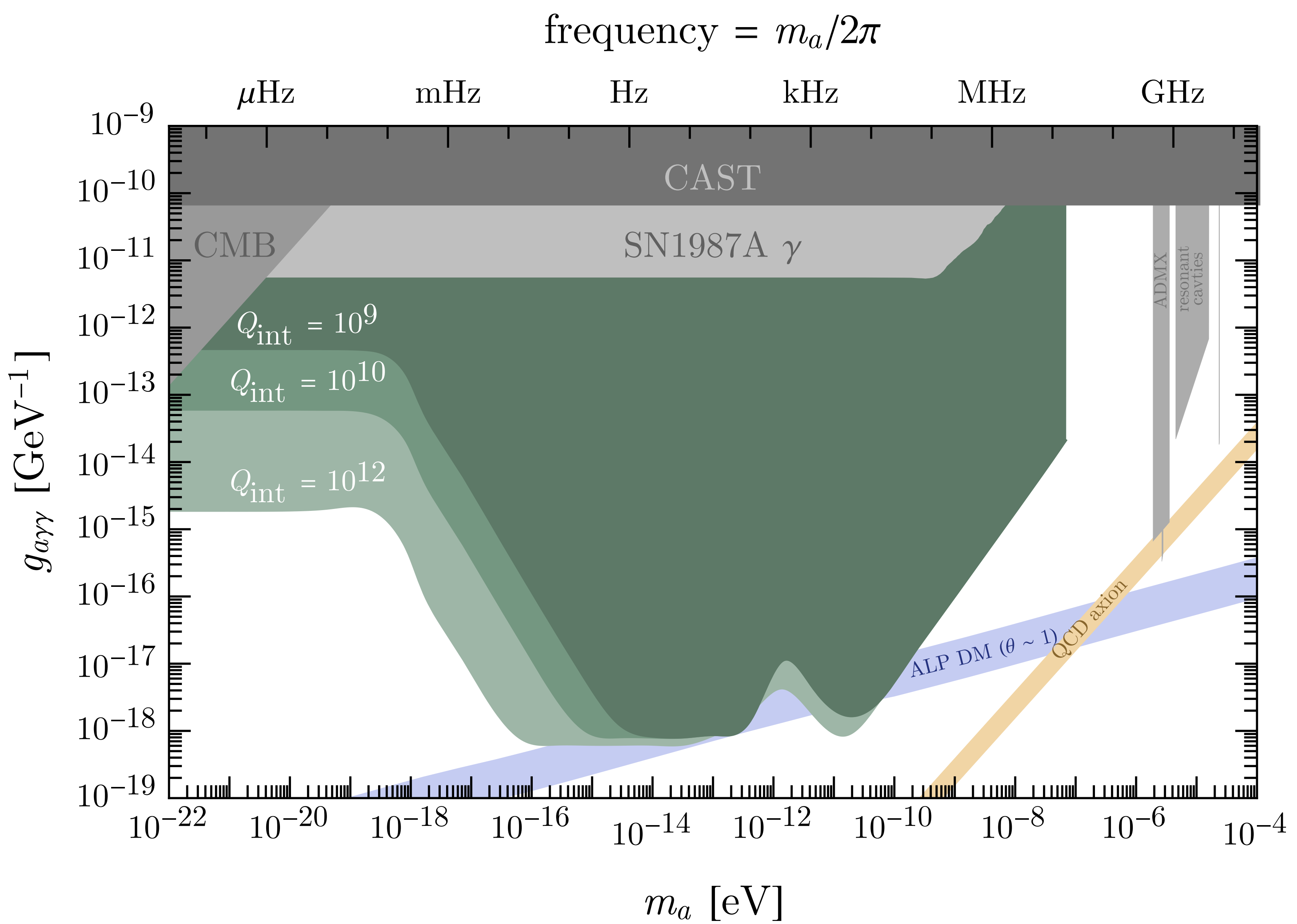


Demonstrated in similar cavities

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

BROADBAND APPROACH

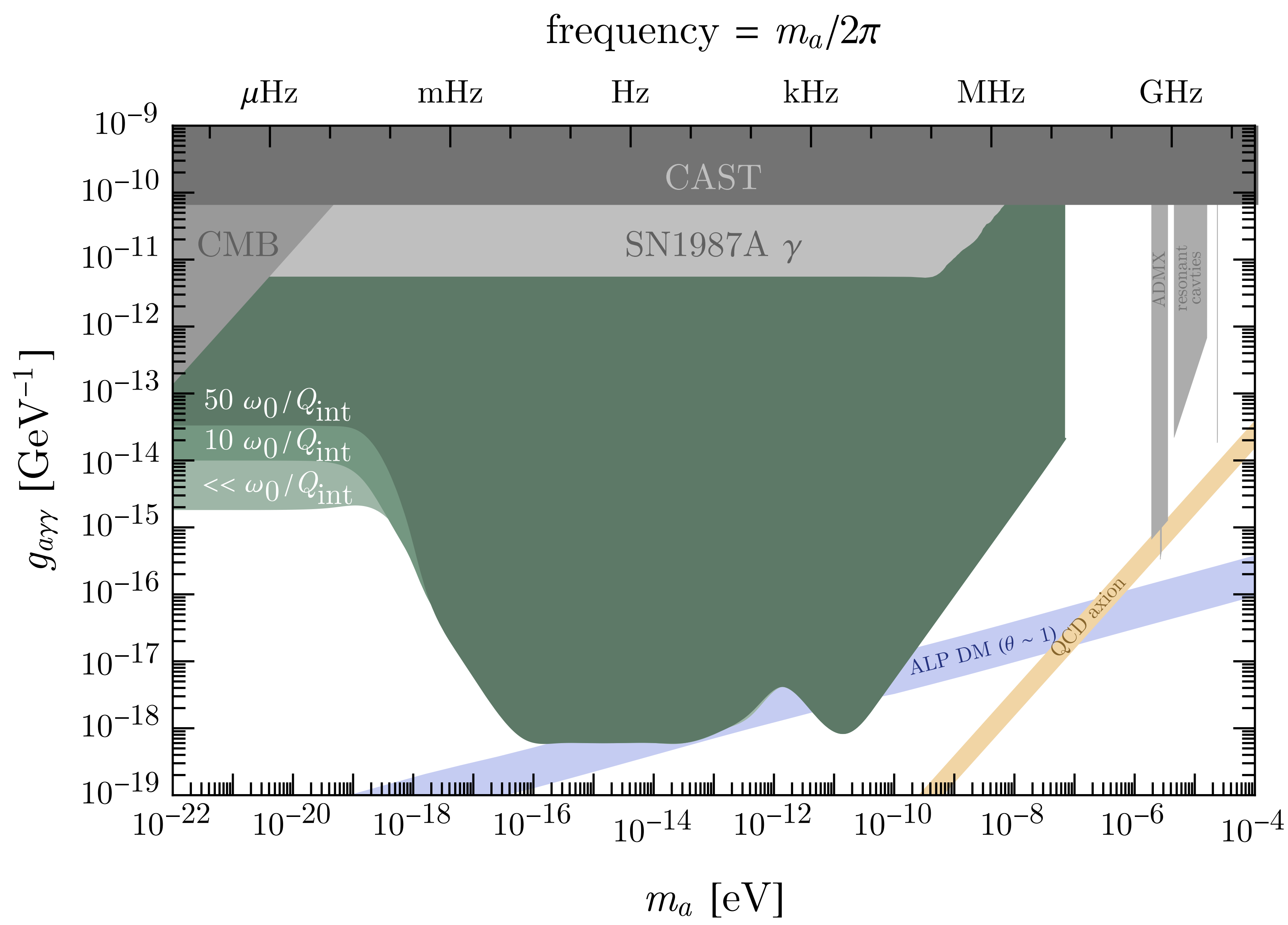
PRELIMINARY!



$$t_{\rm int} \sim 5 \text{ years} \quad B \sim 0.2 \text{ T} \quad V = \text{m}^3$$

BROADBAND APPROACH

PRELIMINARY!



$$t_{\text{int}} \sim 5 \text{ years} \quad B \sim 0.2 \text{ T} \quad V = \text{m}^3$$

OVERCOUPLING

$$S_{\text{sig}}(\omega) \to \frac{Q_1}{Q_{\text{cpl}}} S_{\text{sig}}(\omega)$$

Quantum noise floor (amplifier)

$$S_{\text{noise}}(\omega) = \boxed{S_{\text{ql}}(\omega)} + \frac{Q_1}{Q_{\text{cpl}}} \left(S_{\text{th}}(\omega) + S_{\text{phase}}(\omega) + S^{(1)}_{\text{mech}}(\omega) \right) + \frac{Q_0}{Q_{\text{cpl}}} S^{(0)}_{\text{mech}}(\omega)$$

Overcoupling preserves the SNR in each frequency bin, but allows for bigger scan steps