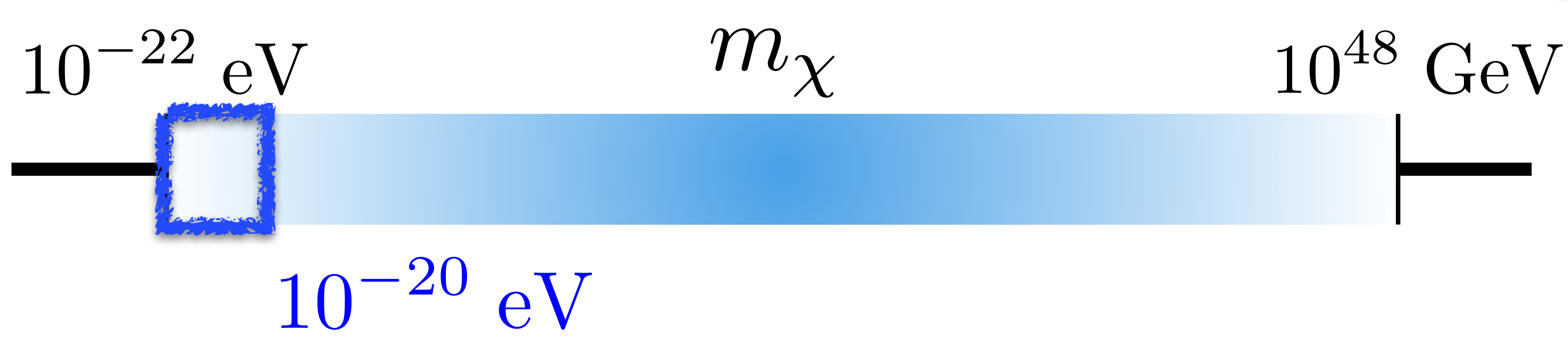
A NEW CONCEPT FOR THE DETECTION OF AXION DARK MATTER

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



Hu, Barkana, Gruzinov '00
Hui, Ostriker, Tremaine, Witten '17

$$\lambda \sim 1/mv \sim \text{kpc}$$

Consistent with CMB

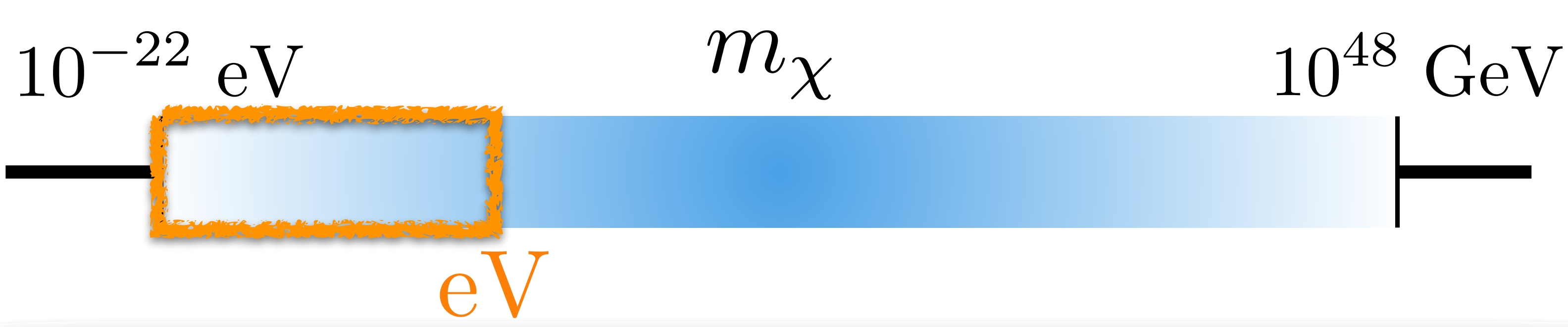
Reduced population of halos smaller than

$$10^{10}\, M_\odot \left(\frac{10^{-22}\ \text{eV}}{m}\right)^{4/3}$$

Central core in galactic halos

but more detailed analyses show tension

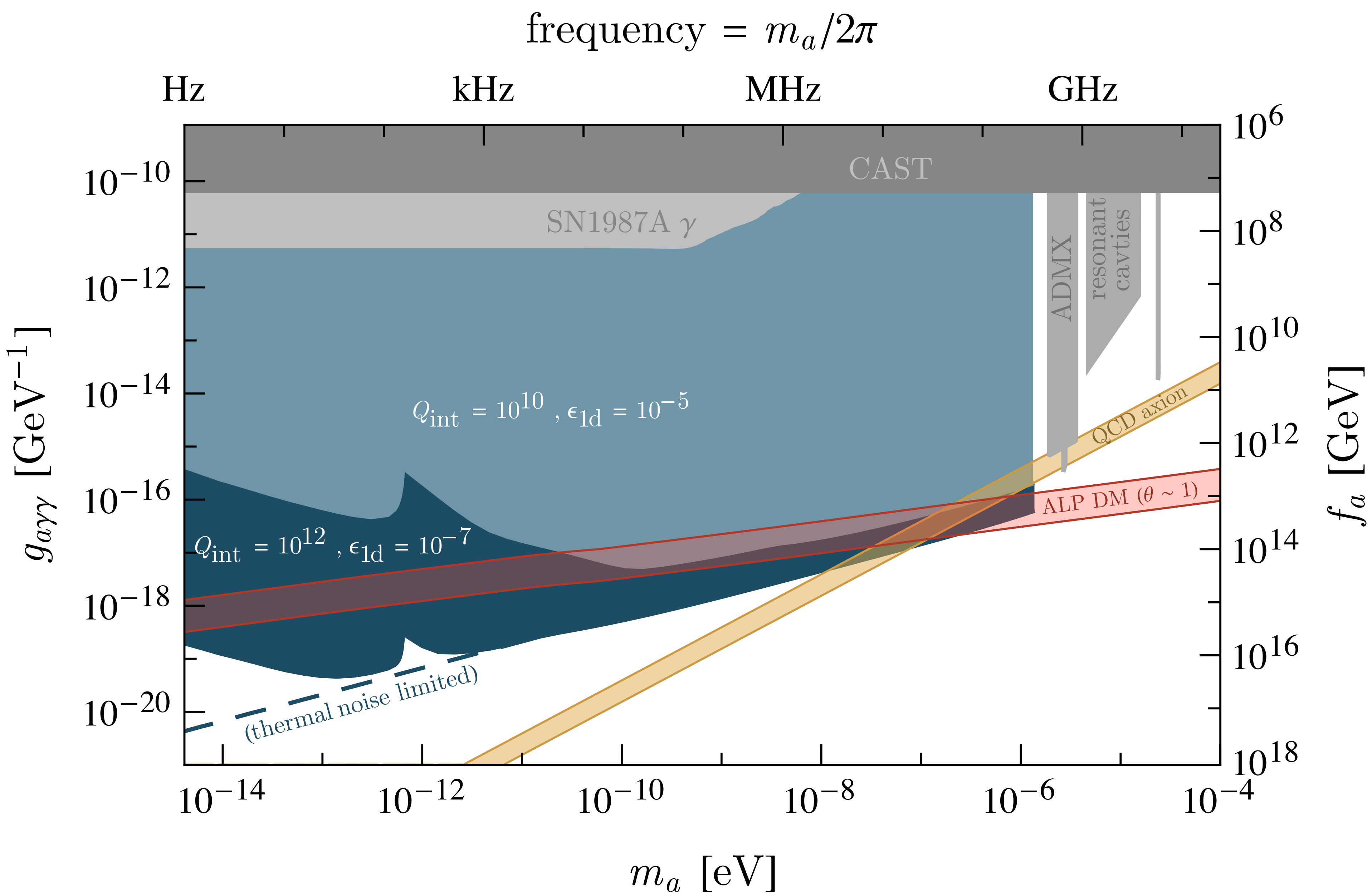
Bar, Blas, Blum, Sybiriakov '18
Safarzadeh, Spergel '19



Very good particle physics motivations:

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

SNEAK PREVIEW

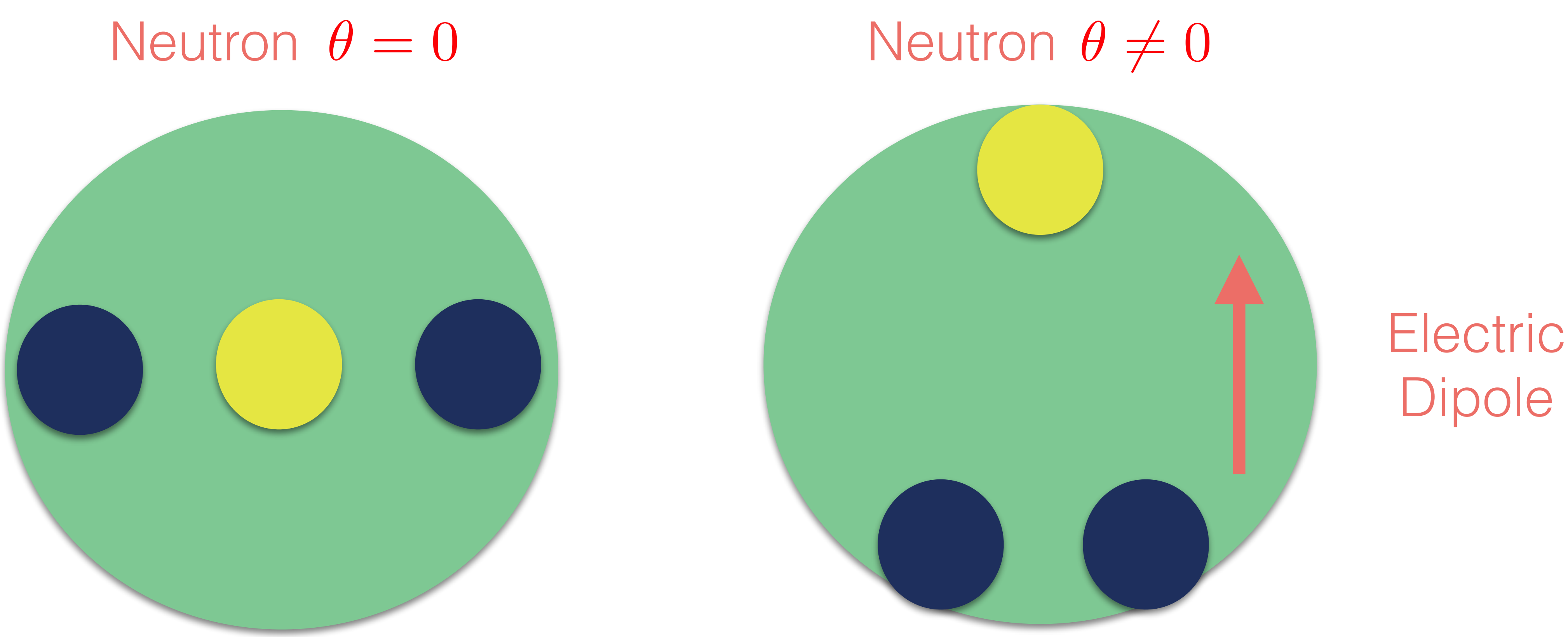


$$t_{\rm e-fold} \sim \text{ year} \quad B \sim 0.2 \text{ T} \quad V = m^3$$

AXION BASICS

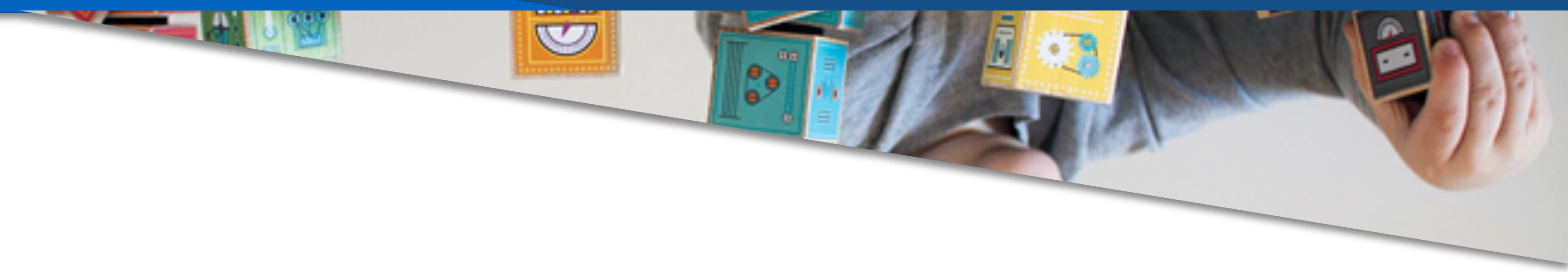
CP IN QCD

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



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

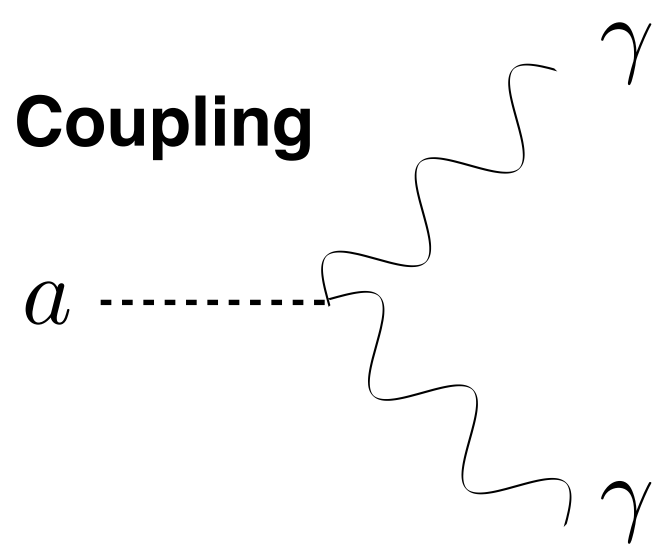
$$\frac{a}{f_a} G\tilde{G} \longrightarrow \frac{a}{f_a}\frac{\pi}{f_\pi} + \ldots$$

Mass

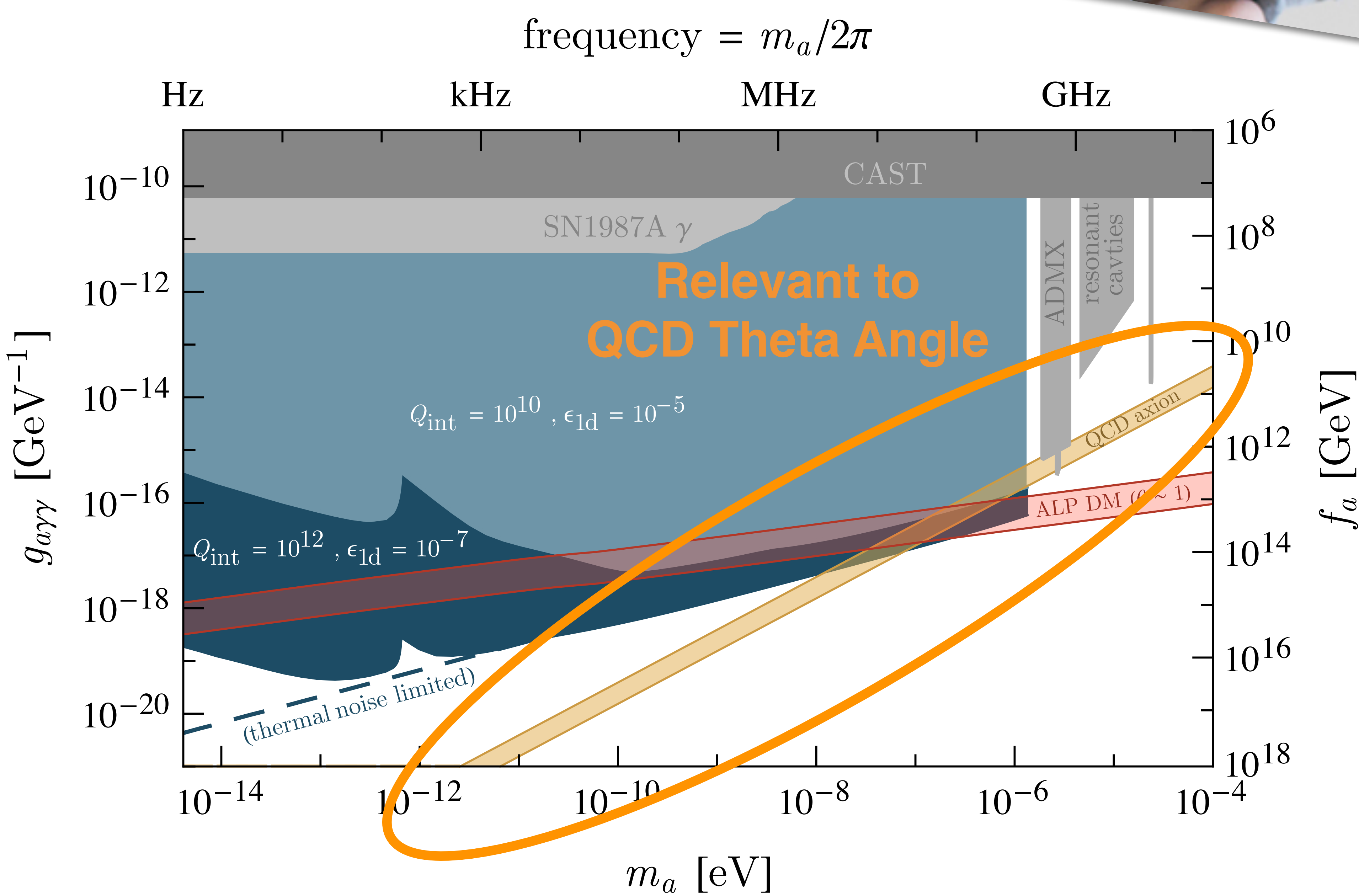
$$m_a \sim \frac{m_\pi^2}{f_a} \sim 10^{-2}\ \mathrm{eV}\ \frac{10^9\ \mathrm{GeV}}{f_a}$$

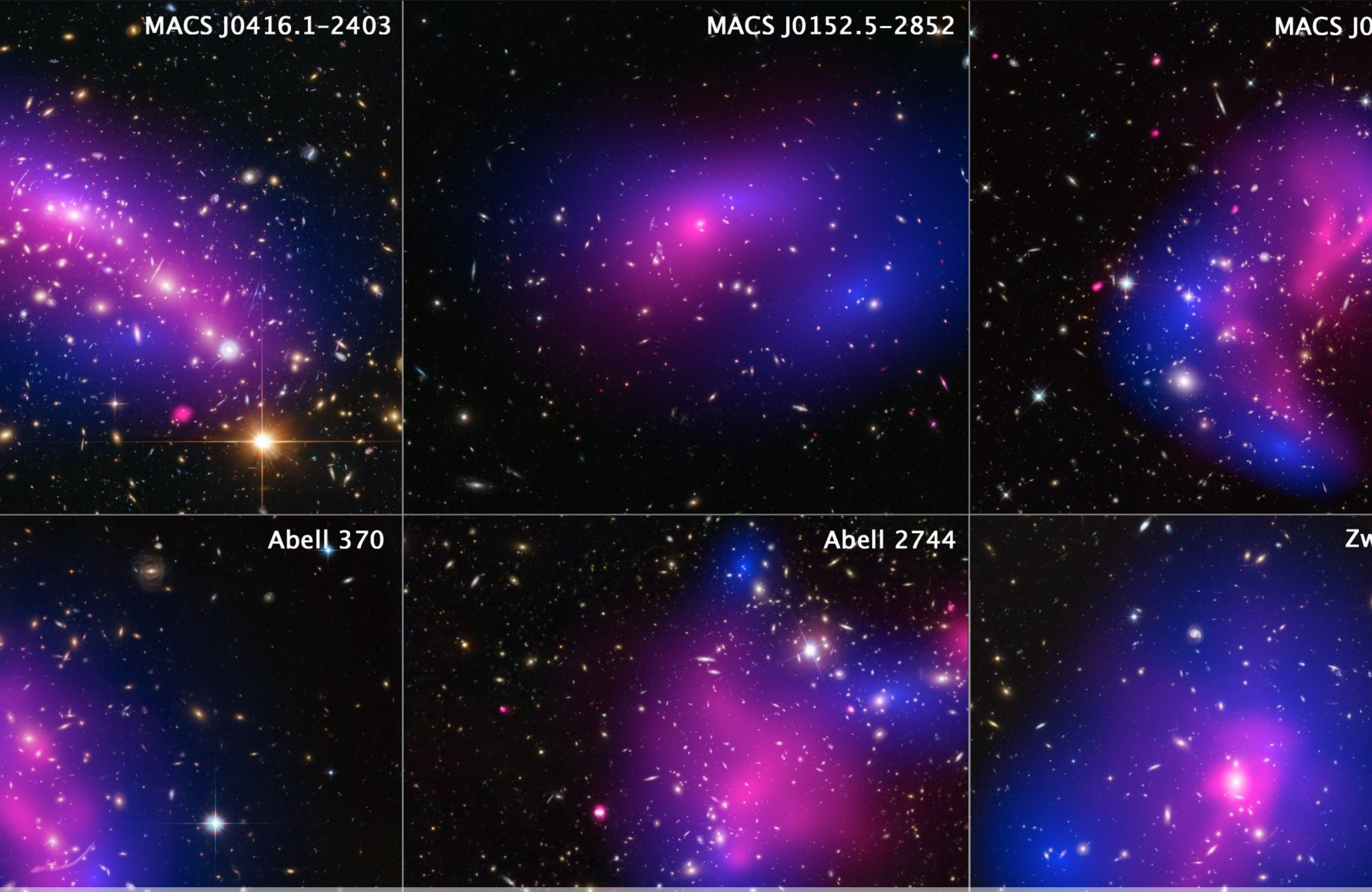
Relevant Coupling

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



SNEAK PREVIEW: QCD AXION





AXION DARK MATTER

MISALIGNMENT PRODUCTION

PQ breaking before inflation

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

$$V(a) = 0$$

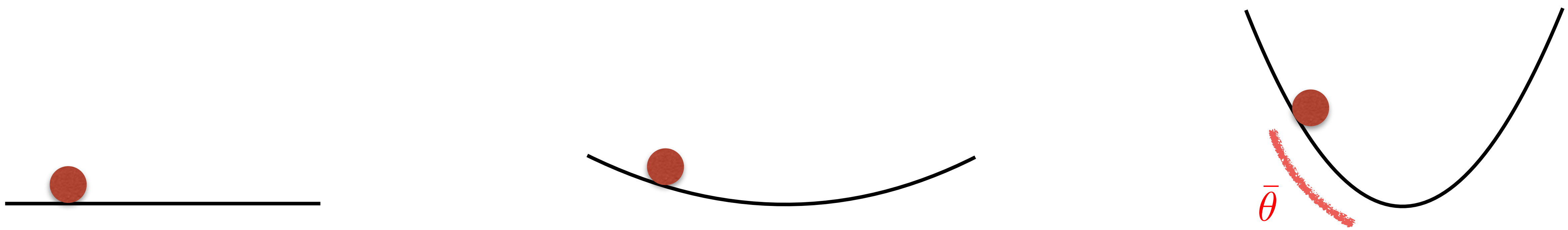
MISALIGNMENT PRODUCTION

PQ breaking before inflation

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

MISALIGNMENT PRODUCTION

PQ breaking before inflation



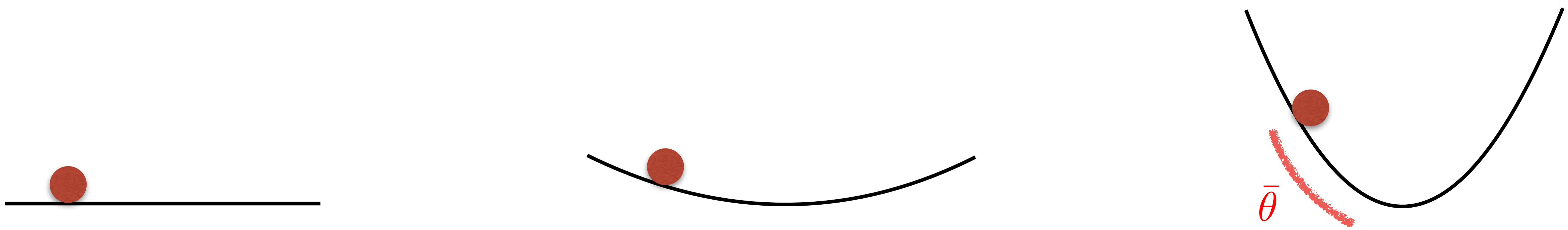
$$\rho_a = \frac{m_a^2 f_a^2 \bar{\theta}^2}{2}$$

MISALIGNMENT PRODUCTION

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

=

classical field

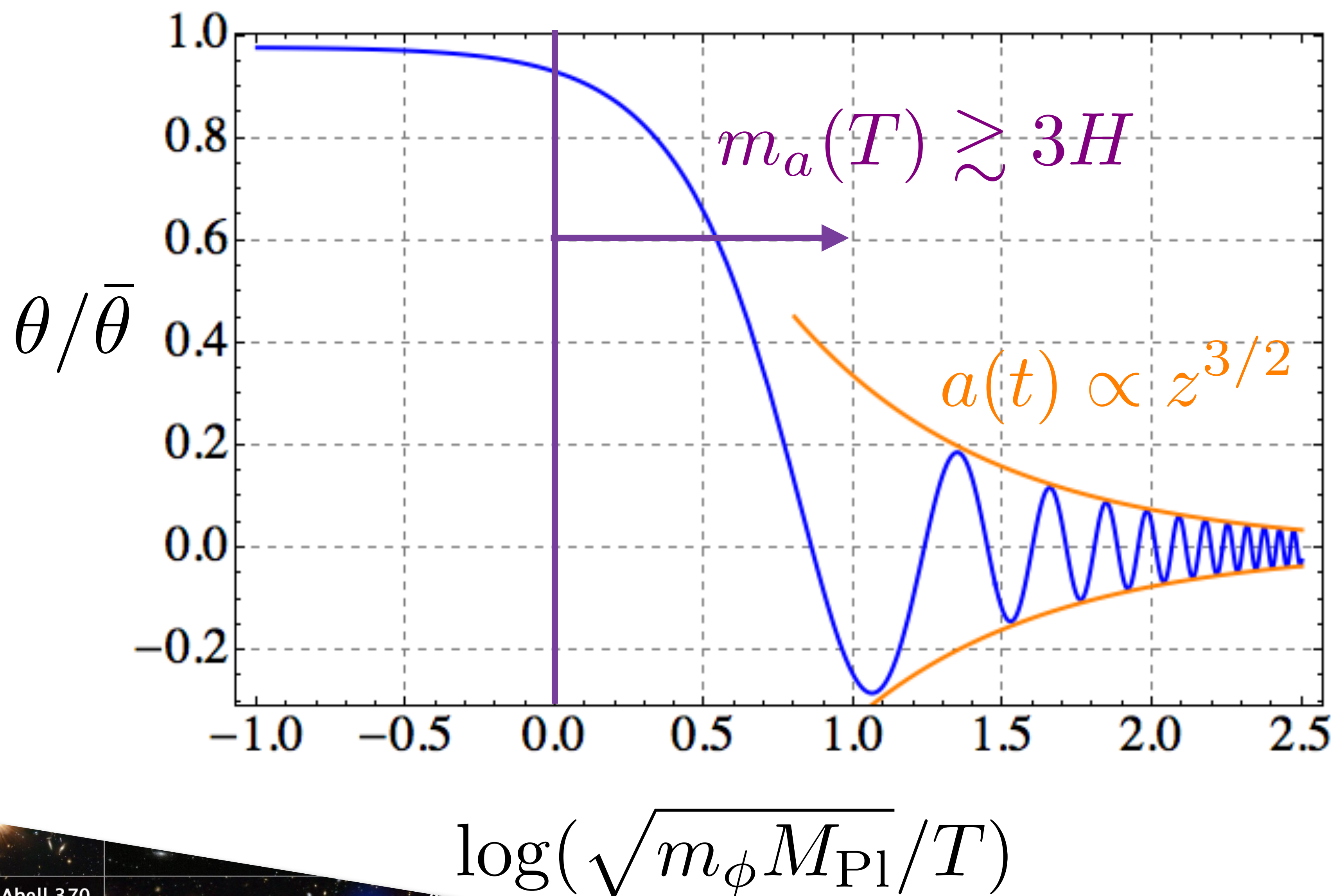


$$\theta \equiv a/f_a$$

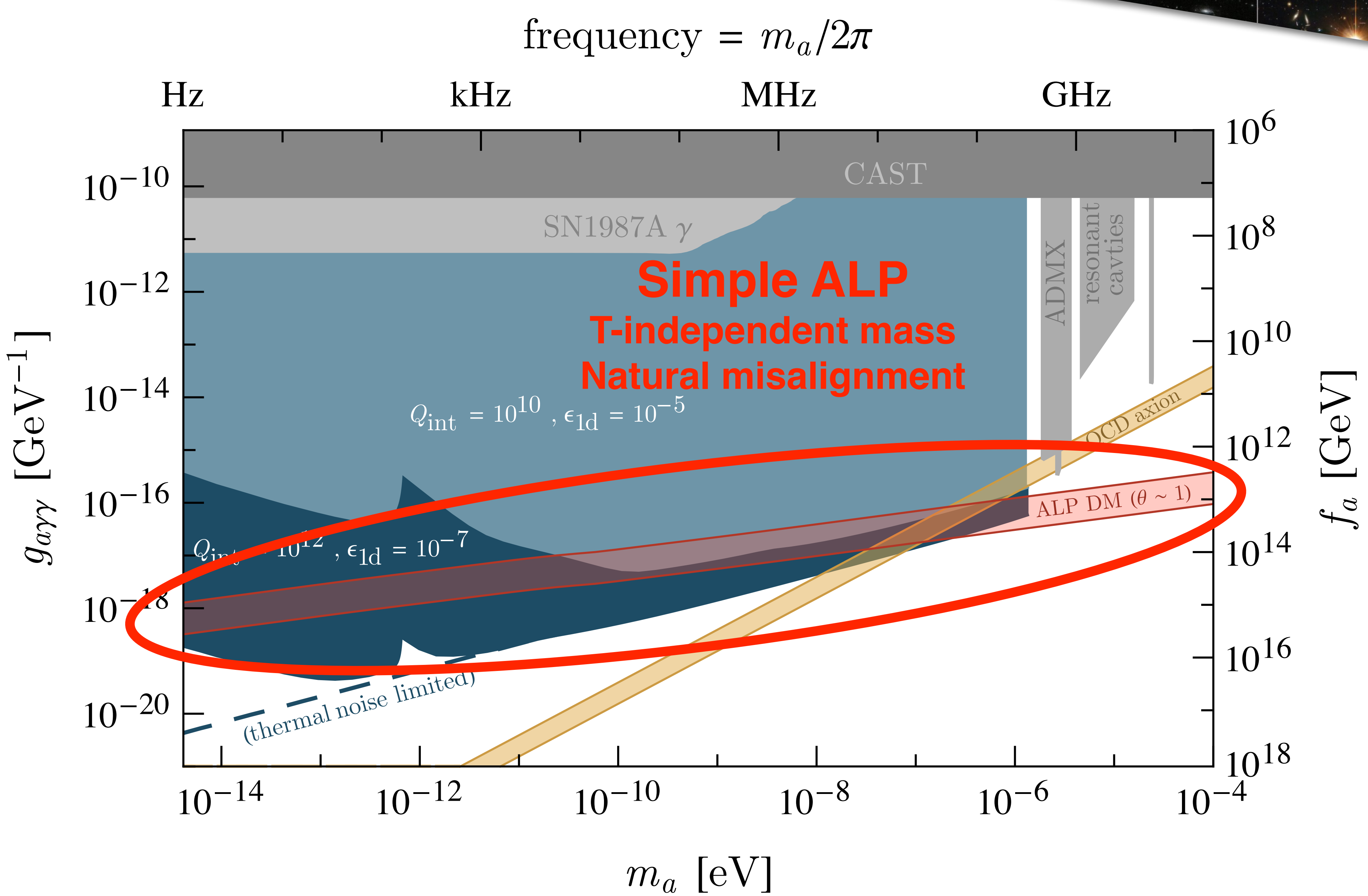
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

AXION COSMOLOGY

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



SNEAK PREVIEW: SIMPLEST ALP



AXION COSMOLOGY IN THE GALAXY

Rough Picture at Production (modulo $\delta\rho$)

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

Different axions take different paths
to reach our galactic potential well where they virialize:

$$\tau_a \sim 1/m_a \langle v_{\rm DM}^2 \rangle \sim Q_a/m_a \sim 10^6/m_a$$

$$\lambda_a \sim 1/m_a \sqrt{\langle v_{\rm DM}^2 \rangle} \sim 10^3/m_a$$

AXION COSMOLOGY IN THE GALAXY 2

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

$$dN_v = \frac{\rho_{\rm DM}}{m_a} V f(v) dv \simeq 10^{15} \left(\frac{10^{-6}\ {\rm eV}}{m_a}\right)^2 \left(\frac{\rm year}{t_{\rm int}}\right) \left(\frac{V}{\rm m^3}\right)$$

So in each bin we are summing over a multitude of plane waves with different phases:

$$a(t) \propto \sum_v {\rm Re}\left[e^{i\omega_v t} \sum_{i=1}^{n_v} e^{i\phi_i} \right]$$

CL Theorem : Gaussian Random Field

$$\langle a(t) \rangle = 0 \qquad \langle |a(t)|^2 \rangle = \frac{\rho_{\rm DM}}{m_a^2}$$

AXION DARK MATTER DETECTION

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

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 $\langle n(\omega) \rangle = 0 \quad \langle n(\omega) n(\omega') \rangle = \delta(\omega - \omega') S_n(\omega)$

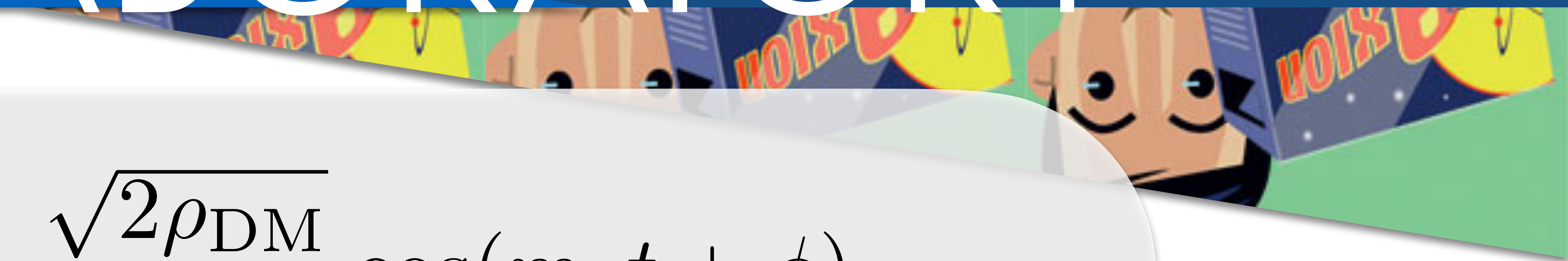
Likelihood:

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

Only the average 2-point function matters.

A ‘deterministic’ axion gives the same result (see next slide)

AXION COSMOLOGY IN THE LABORATORY

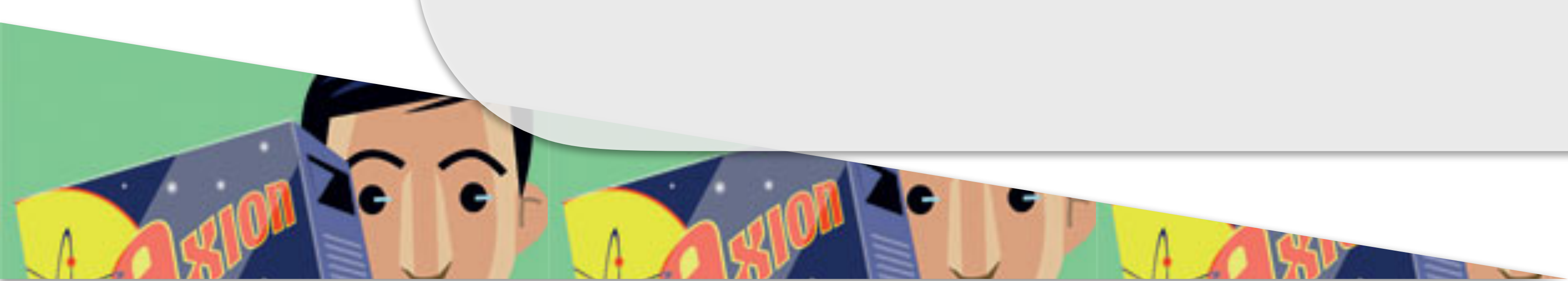


$$a(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \cos(m_a t + \phi)$$

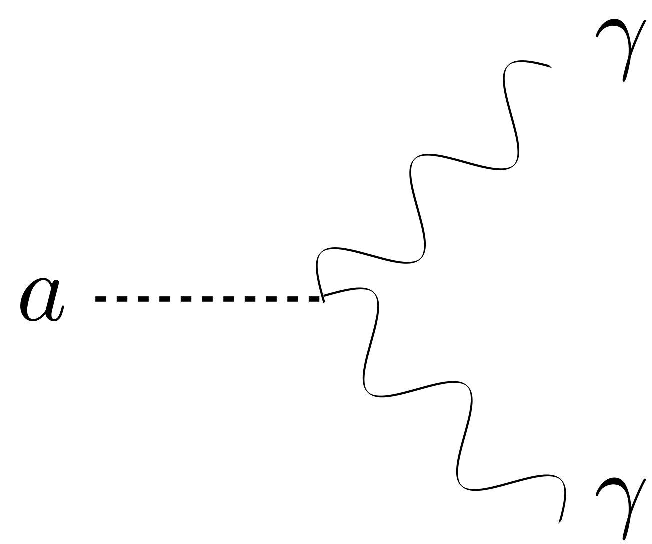
Frequency: $\omega_a \simeq \text{GHz}\ \frac{m_a}{10^{-6}\ \text{eV}}$

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

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



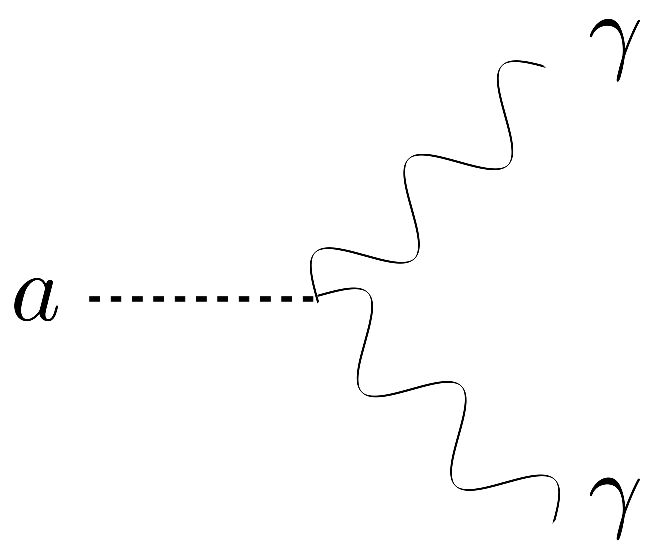
AXION DETECTION



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

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

AXION DETECTION



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

$10^4\ {\rm A/cm^2}$	$10^7\ {\rm A/cm^2}$	$10^8\ {\rm A/cm^2}$
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

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

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

AXION DETECTION

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

Cavity:

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

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

AXION DETECTION

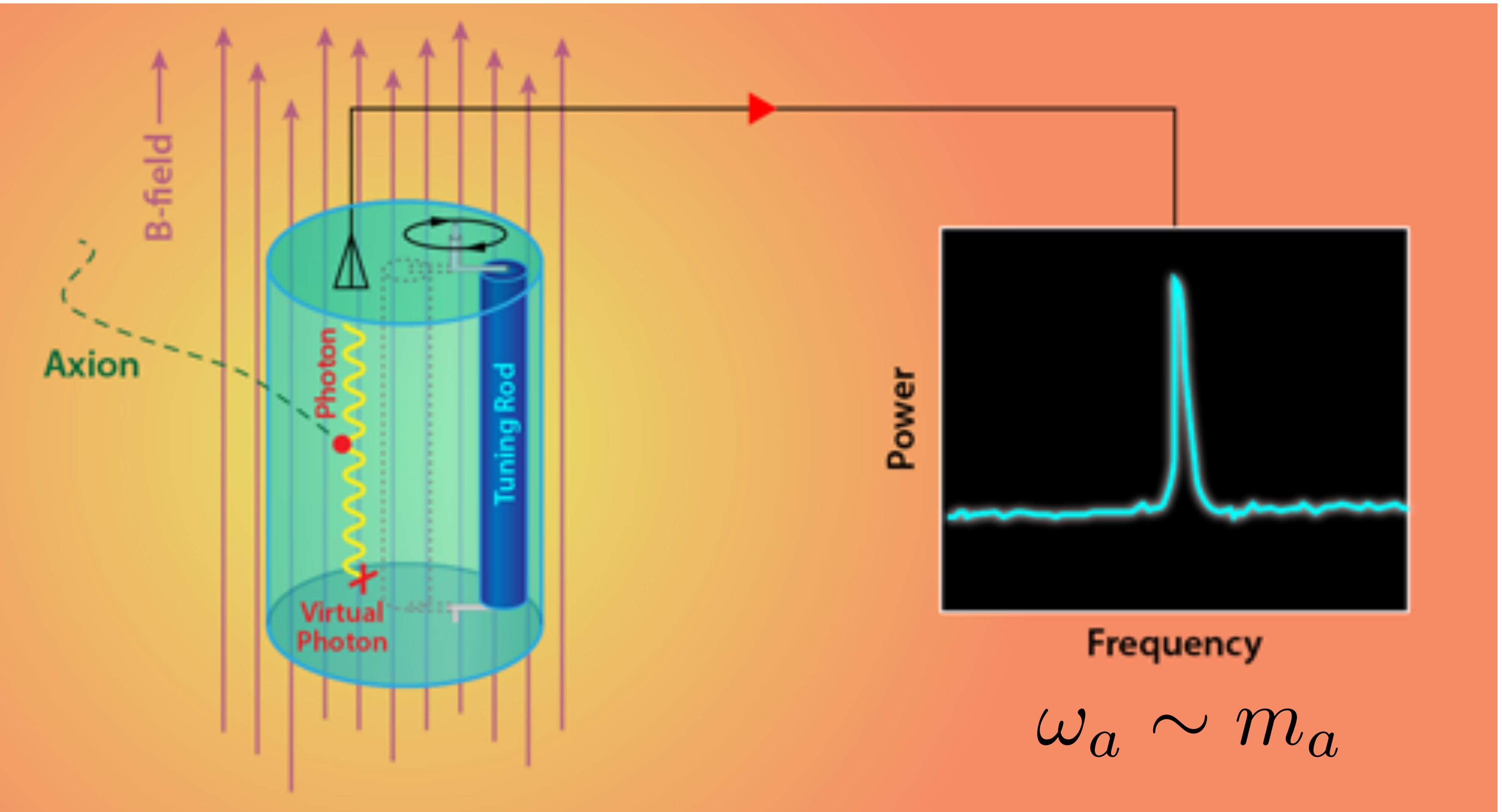
$$\left(\partial_t^2 + \frac{m_a}{Q_1}\partial_t + m_a^2\right)\mathbf{E}_1 \sim m_a \cos m_a t$$

Resonant for many cycles

$$Q_a \sim 10^6$$

Ideal for

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



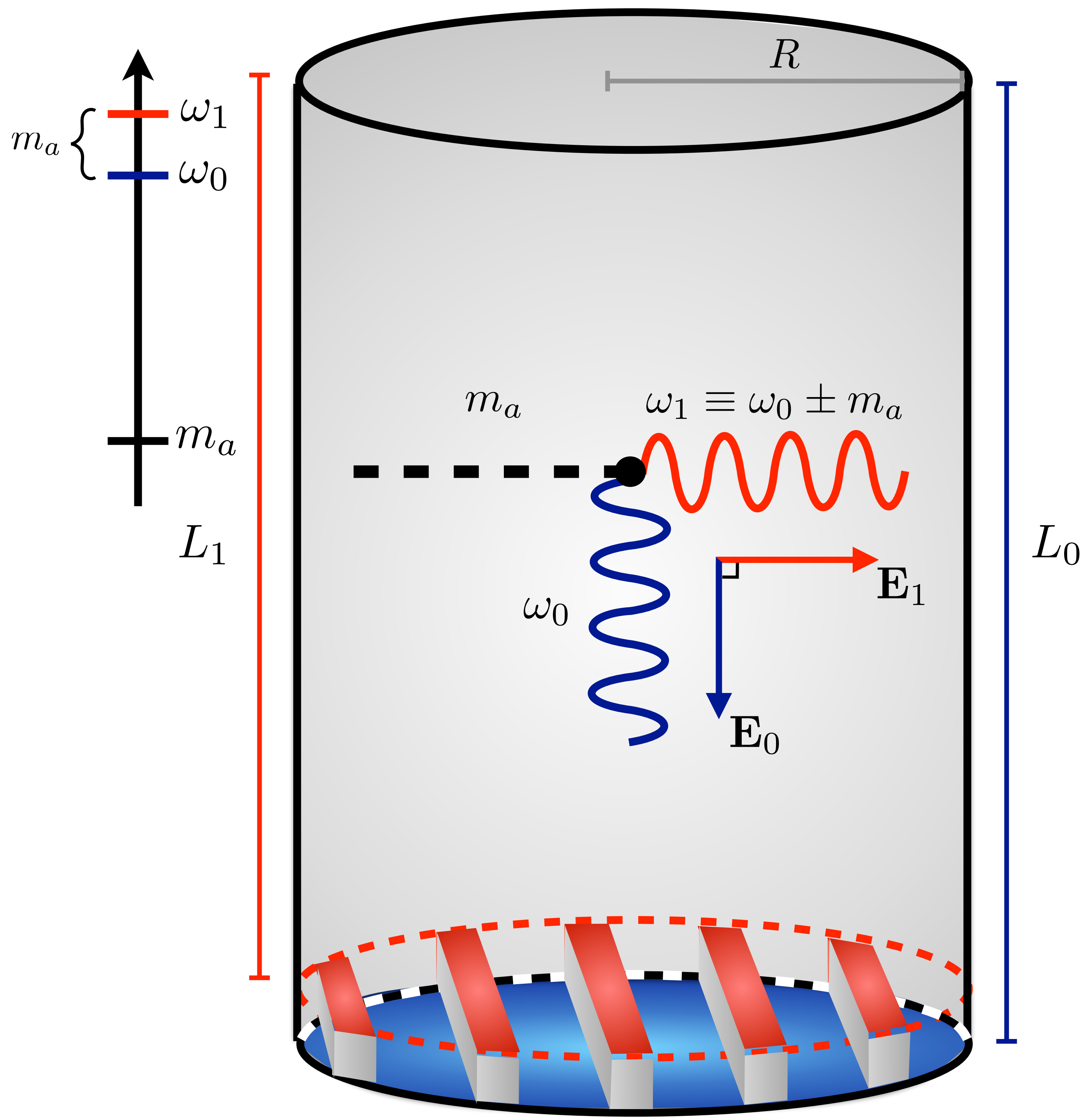
$$\omega_a \sim m_a$$

Problems:

1. **Cavity size** ~ (axion mass)^-1

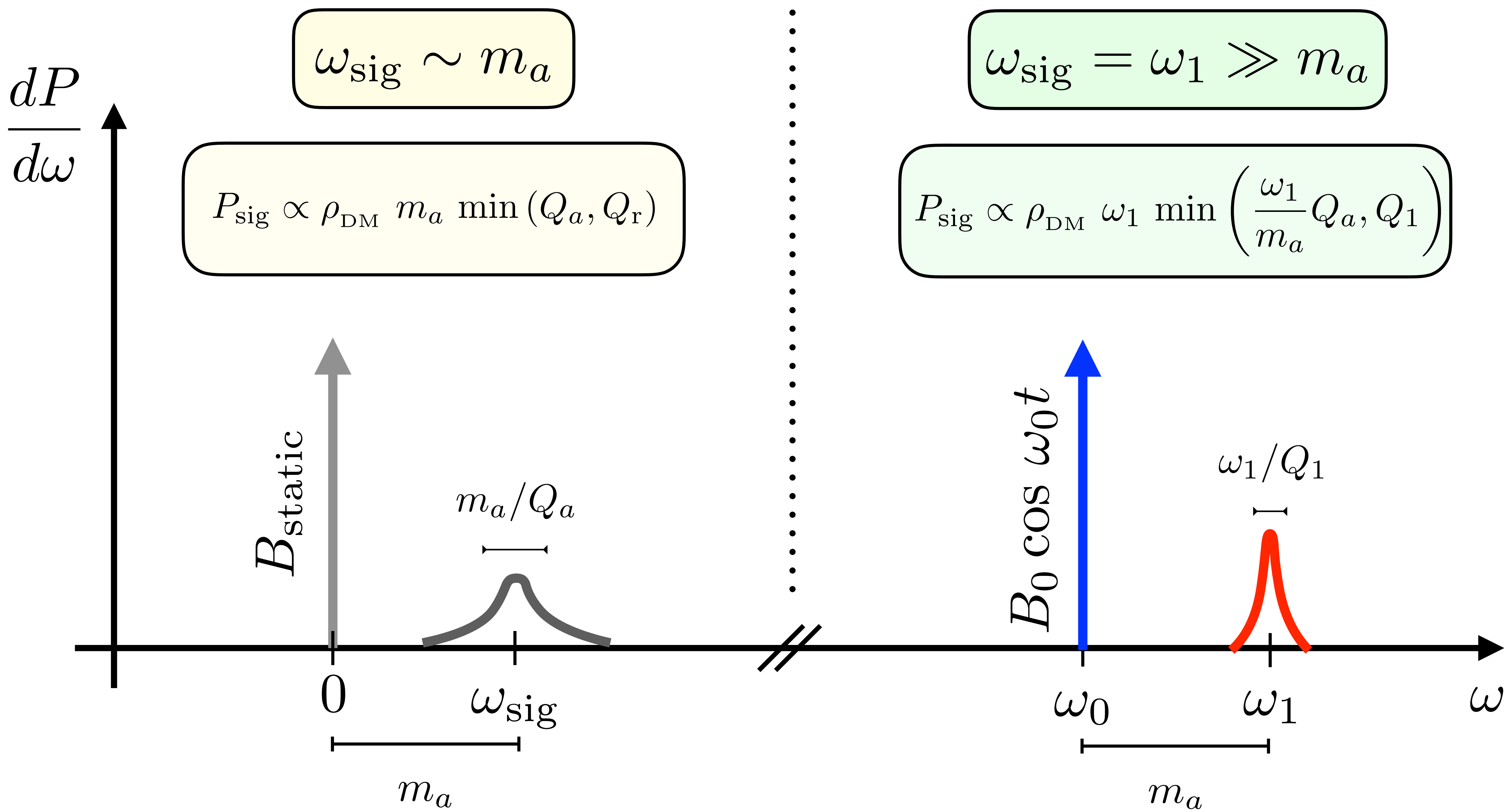
2. **Signal power** decreases with axion mass

LOW MASS AXION DETECTION



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

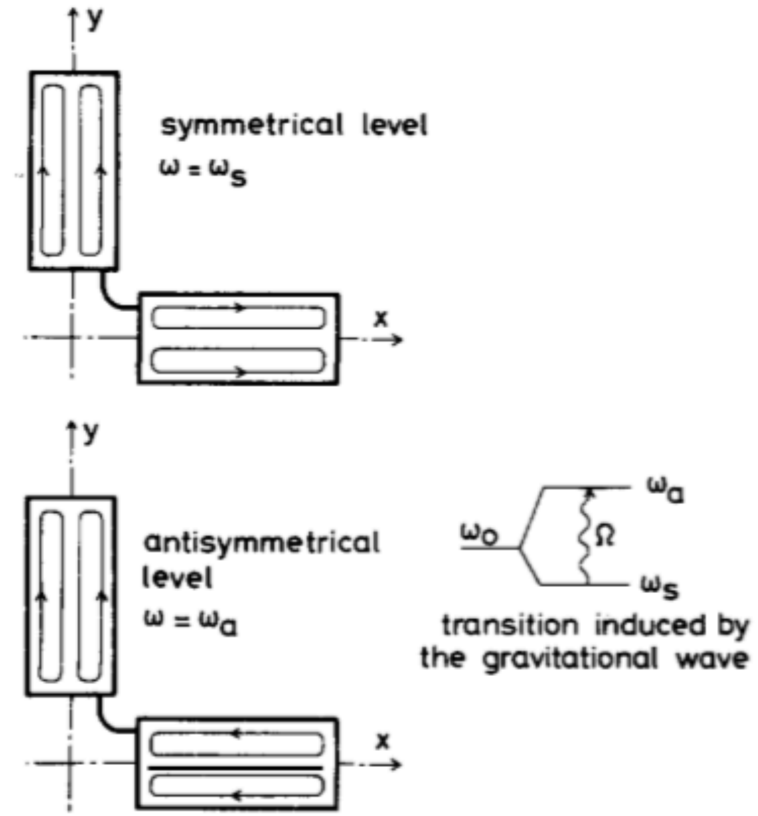
LOW MASS AXION DETECTION



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

OUR ANCESTORS HUNTING FOR GWs

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



Radicati

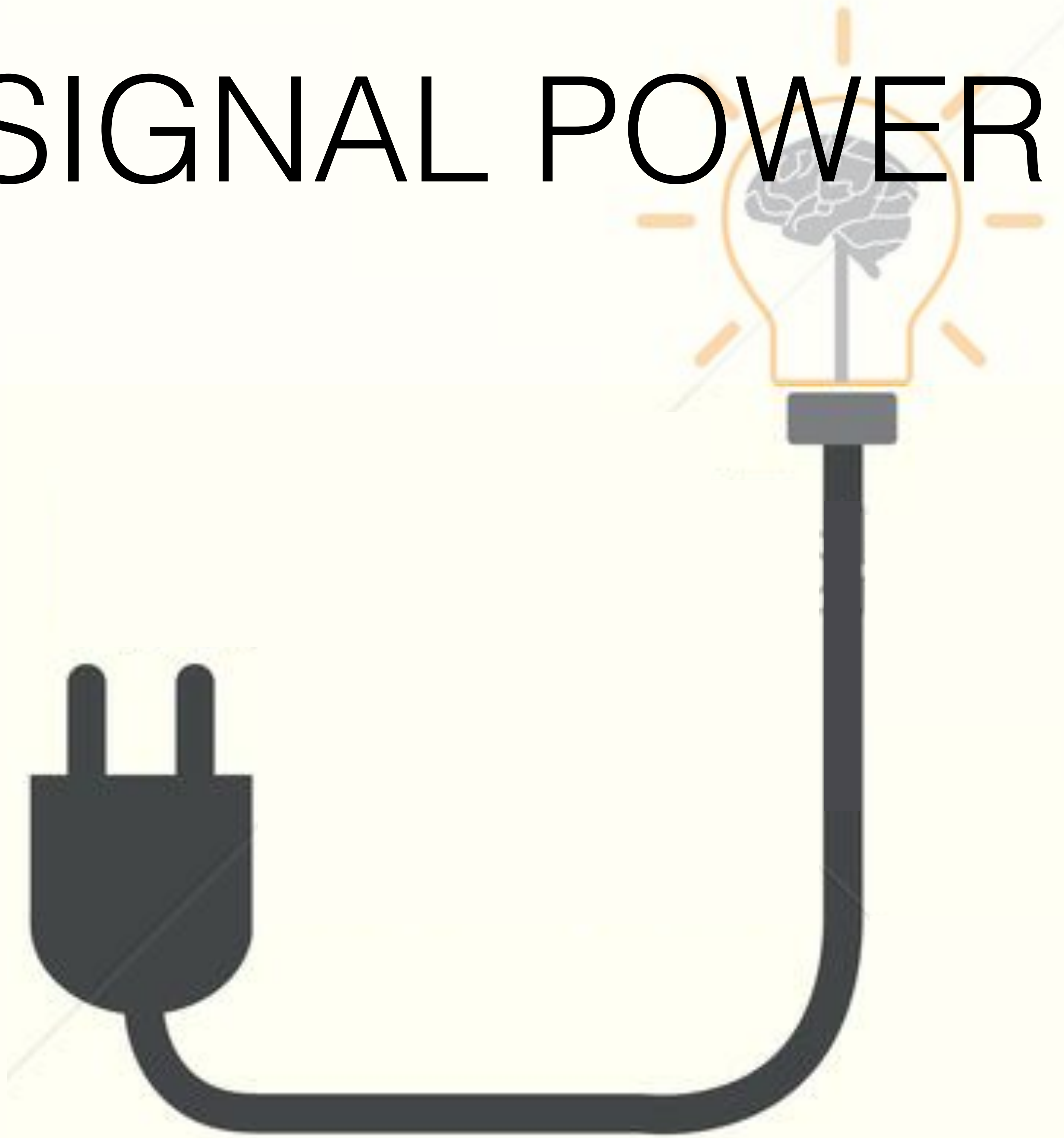
Menotti

Barbieri

RTD

MAGO '05

SIGNAL POWER



SIGNAL POWER AT LOW MASSES

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

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

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

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:

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

Oscillating:

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

SIGNAL POWER AT LOW MASSES

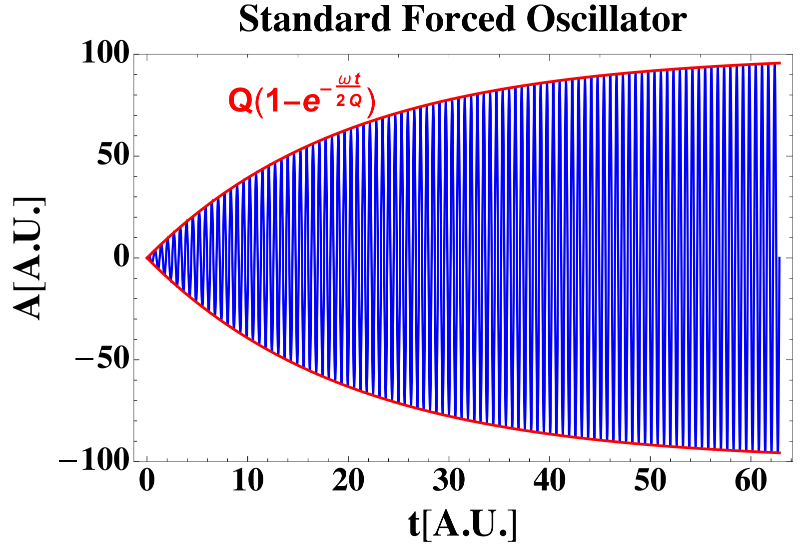
Power = Energy/Time

Time

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

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

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



SIGNAL POWER AT LOW MASSES

Power = Energy/Time

Energy

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

Time

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

Static: $\omega_1 \simeq m_a$

$$P \simeq m_a B_a^2 V \min\left[Q_a, Q\right]$$

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

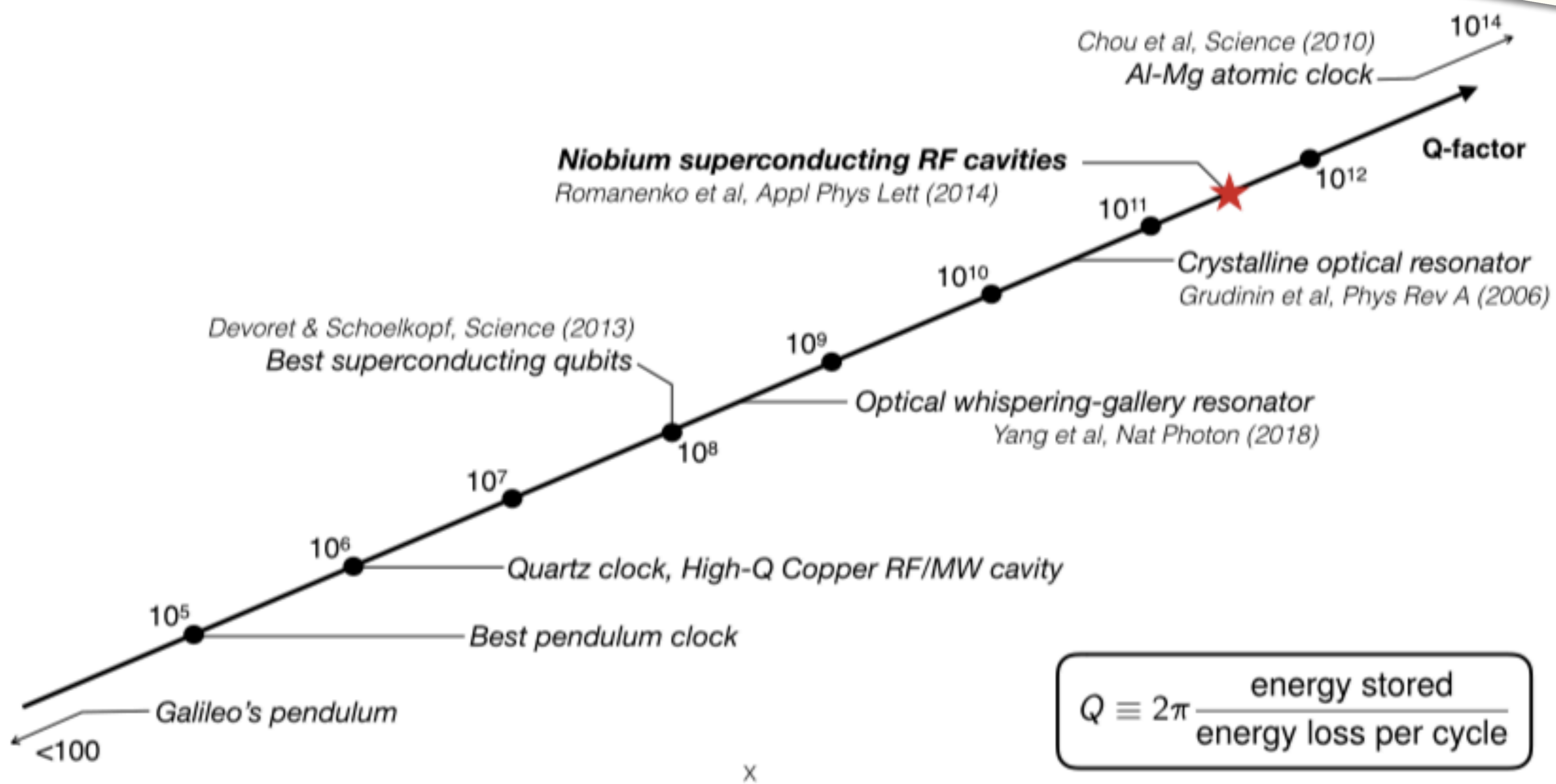
$$\min\left[\tau_a, \tau_r\right] = \min\left[\frac{Q_a}{m_a}, \frac{Q}{\omega_1}\right]$$

Oscillating: $\omega_1 > m_a$

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

Great advantage of high-Q resonators at low m_a

SUPERCONDUCTING RADIOFREQUENCY CAVITIES

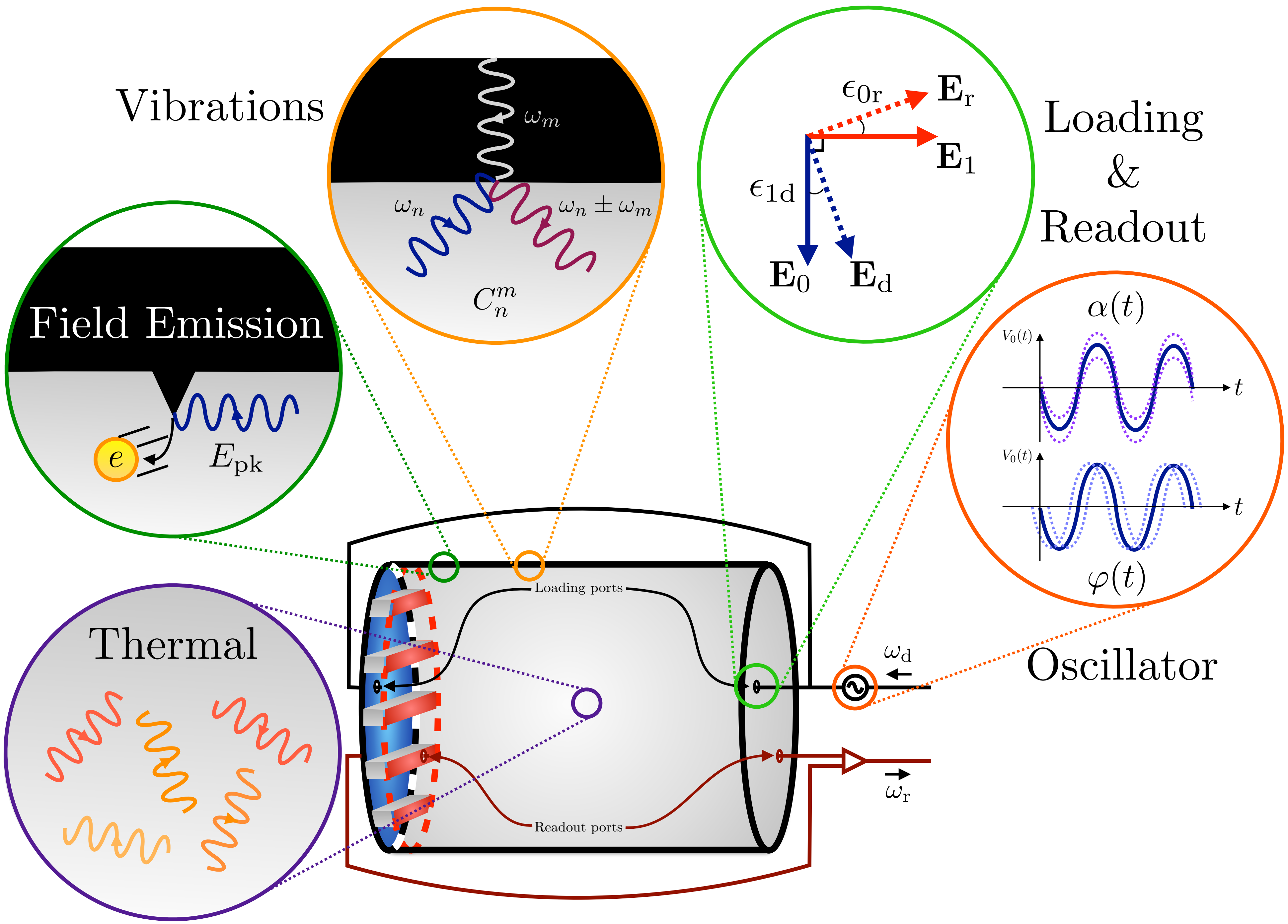


From Anna Grassellino, Fermilab

NOISE AND SENSITIVITY

NOISE



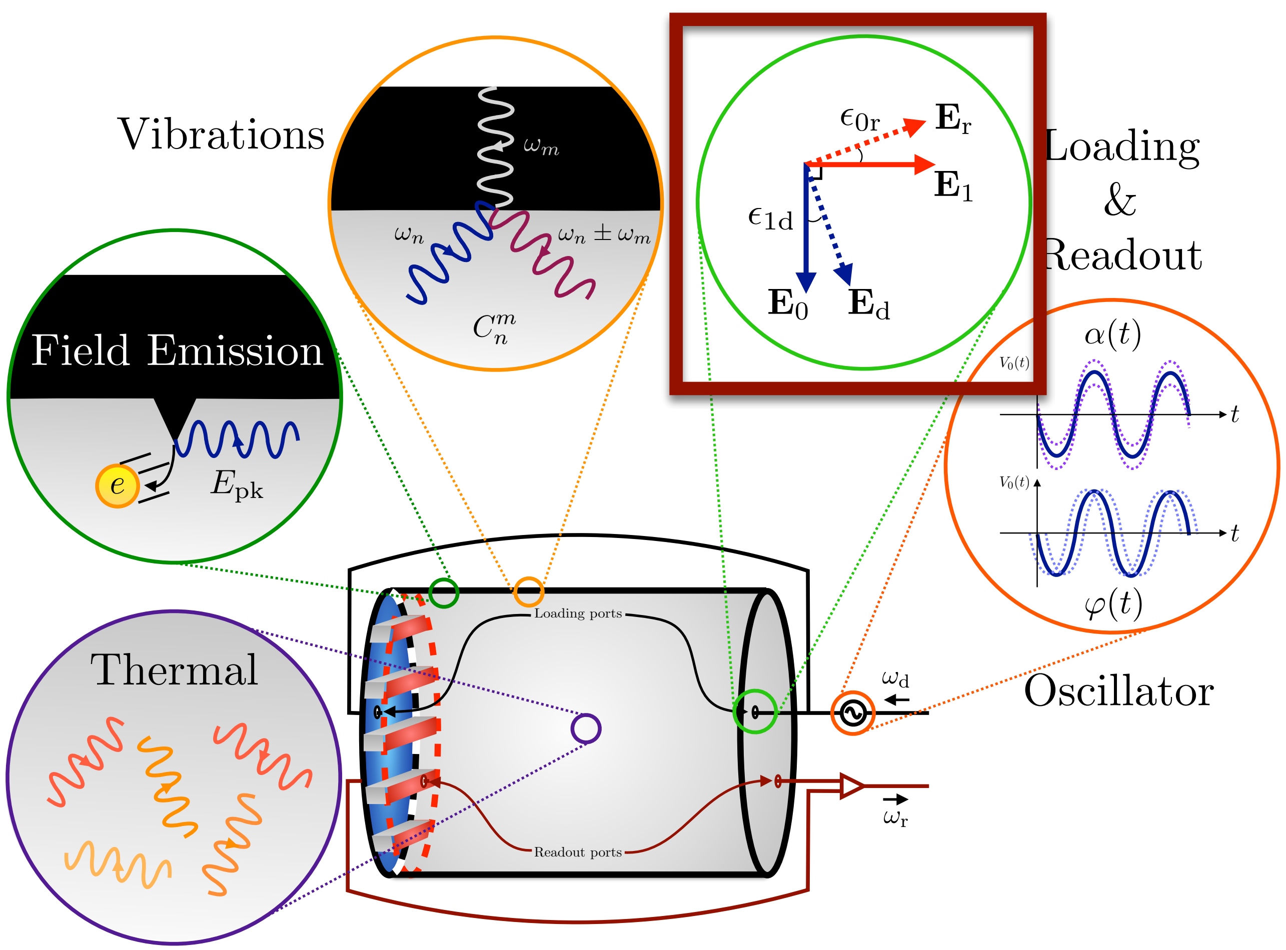
Vibrations
ω_m
ω_n
$\omega_n \pm \omega_m$
C_n^m
$\epsilon_{0\mathrm{r}}$
$\mathbf{E}_\mathrm{r}$
$\mathbf{E}_1$
$\epsilon_{1\mathrm{d}}$
$\mathbf{E}_0$
$\mathbf{E}_\mathrm{d}$
Loading & Readout
Field Emission
e
E_pk
$\alpha(t)$
$V_0(t)$
t
$\varphi(t)$
Thermal
Loading ports
Readout ports
ω_d
ω_r
Oscillator

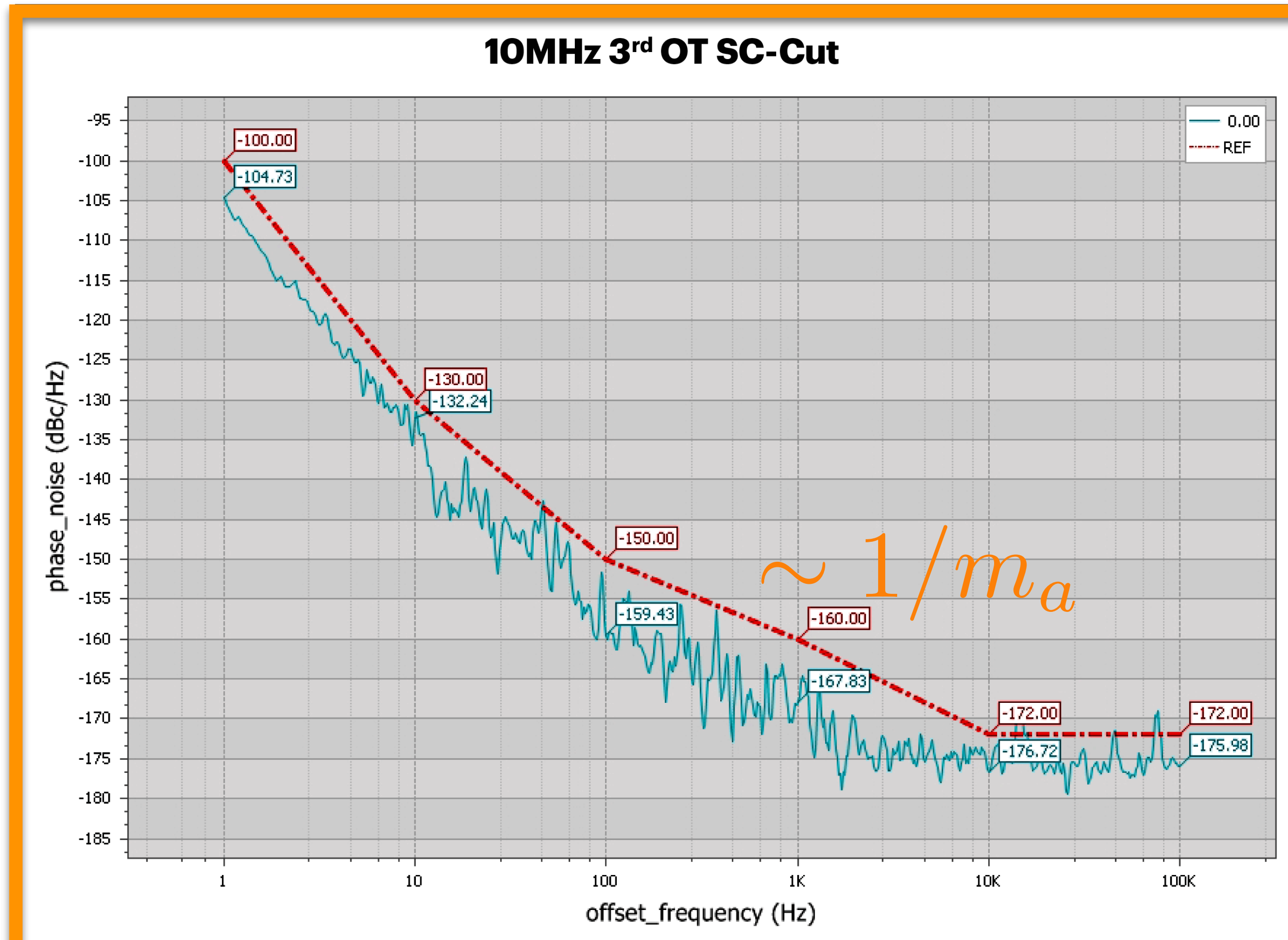
OSCILLATOR NOISE

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

$\sim 1/m_a$

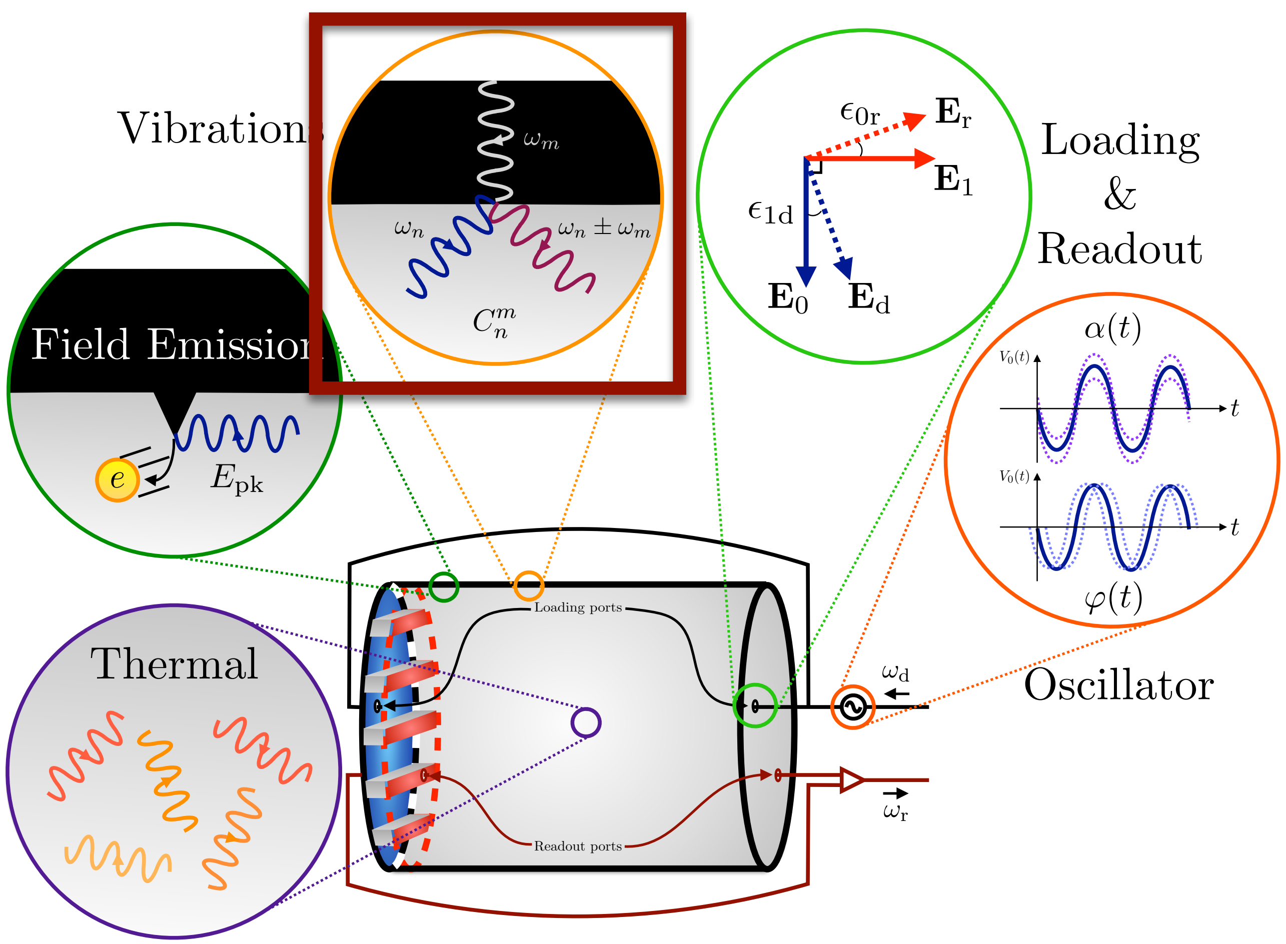
Cavity Response





VIBRATIONAL NOISE

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



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

$$\sim 1/m_a^4$$

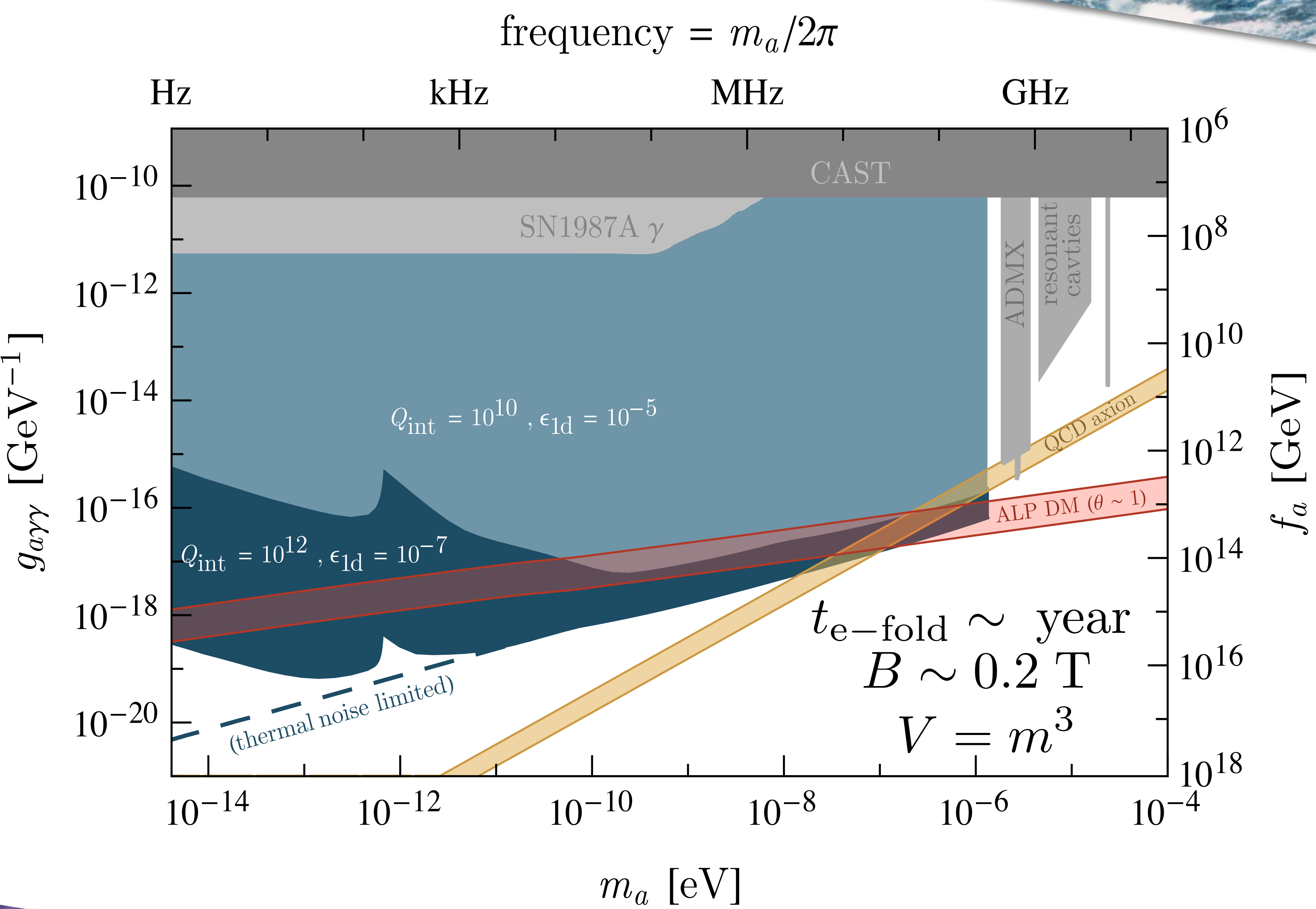
Off Resonance

$$\sim 1/m_a^2$$

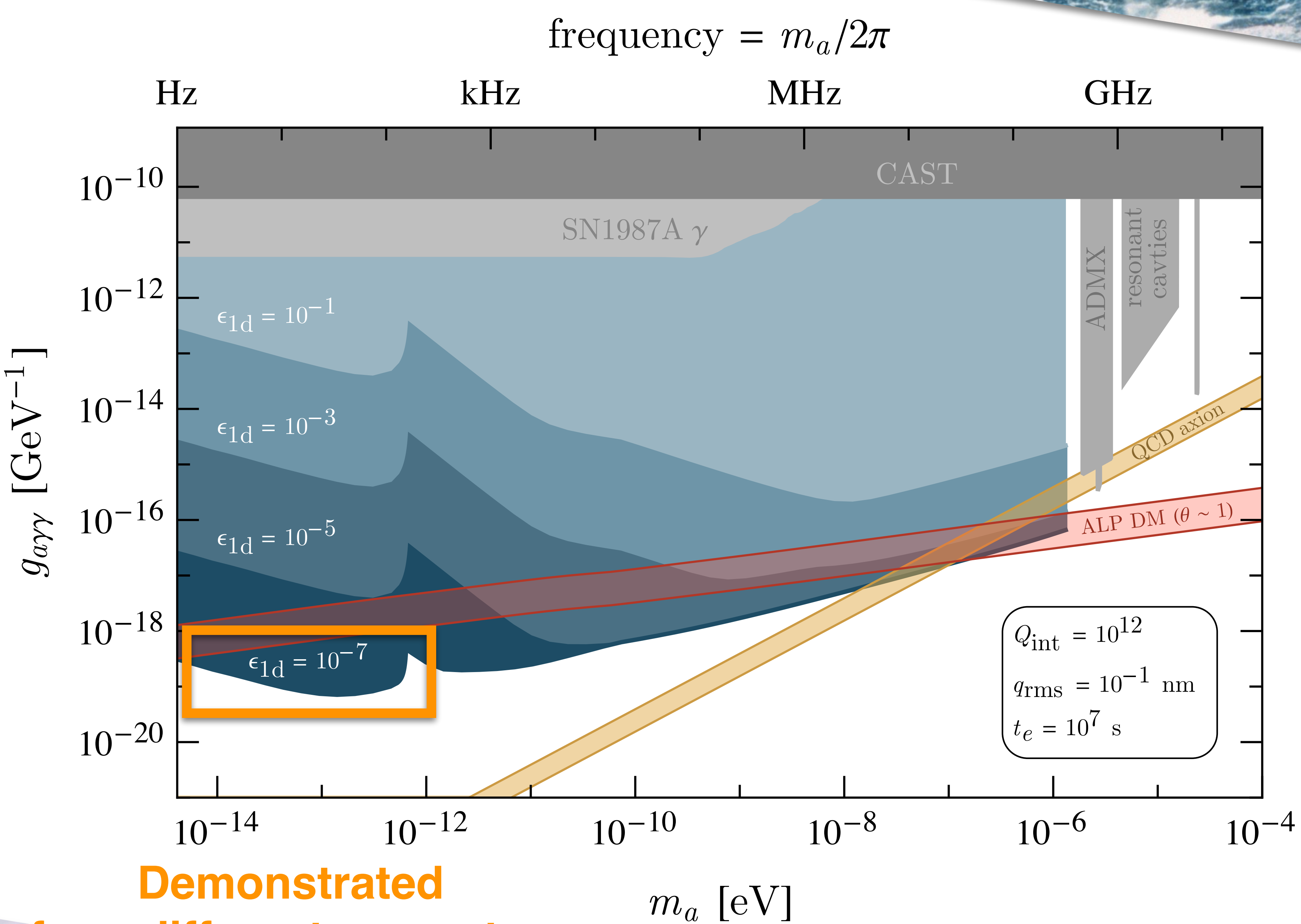
$$\omega_m^{\rm min} \simeq {\rm kHz}$$

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

SENSITIVITY



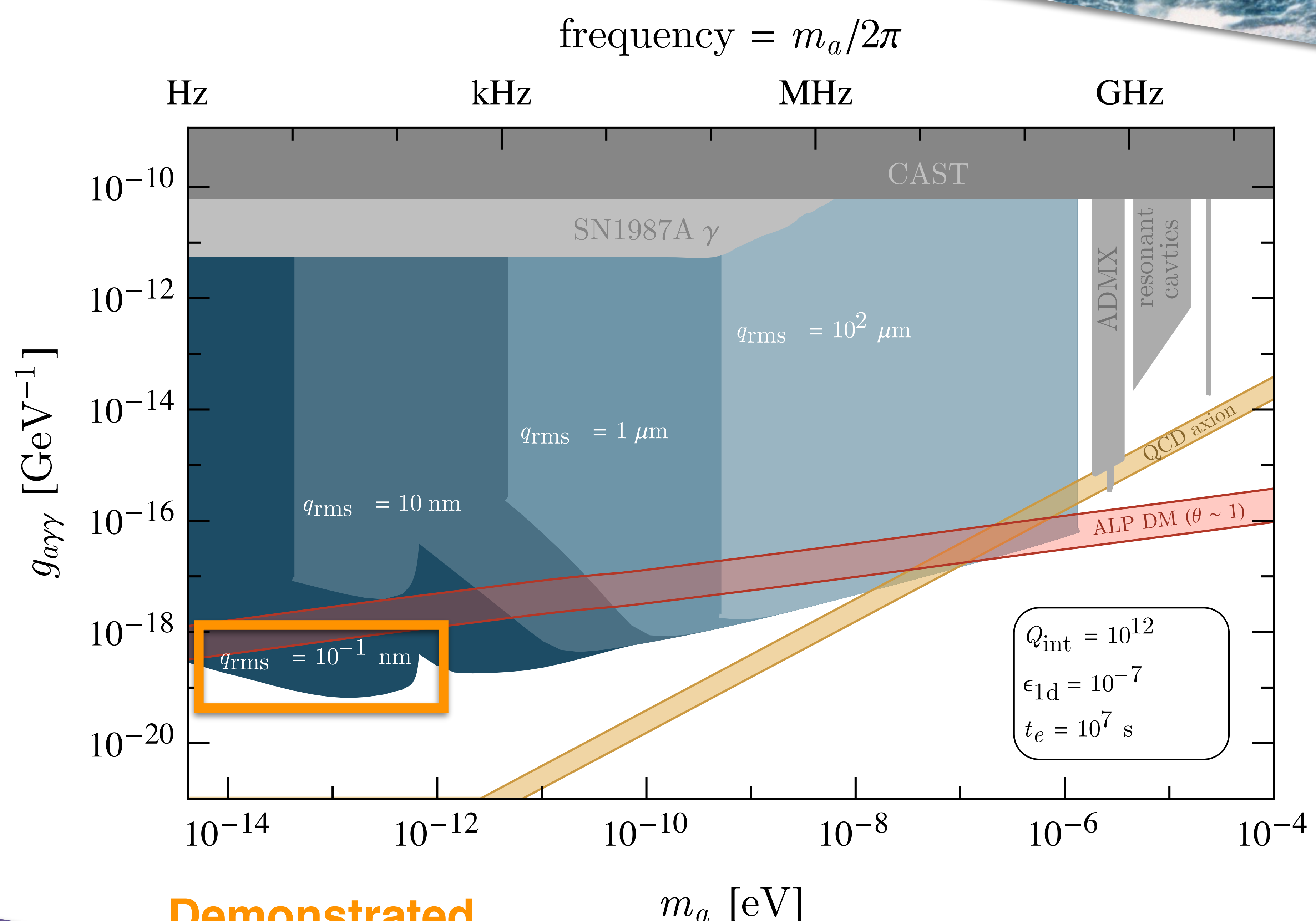
ROBUSTNESS TO LOADING



Demonstrated for a different geometry, but same setup

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

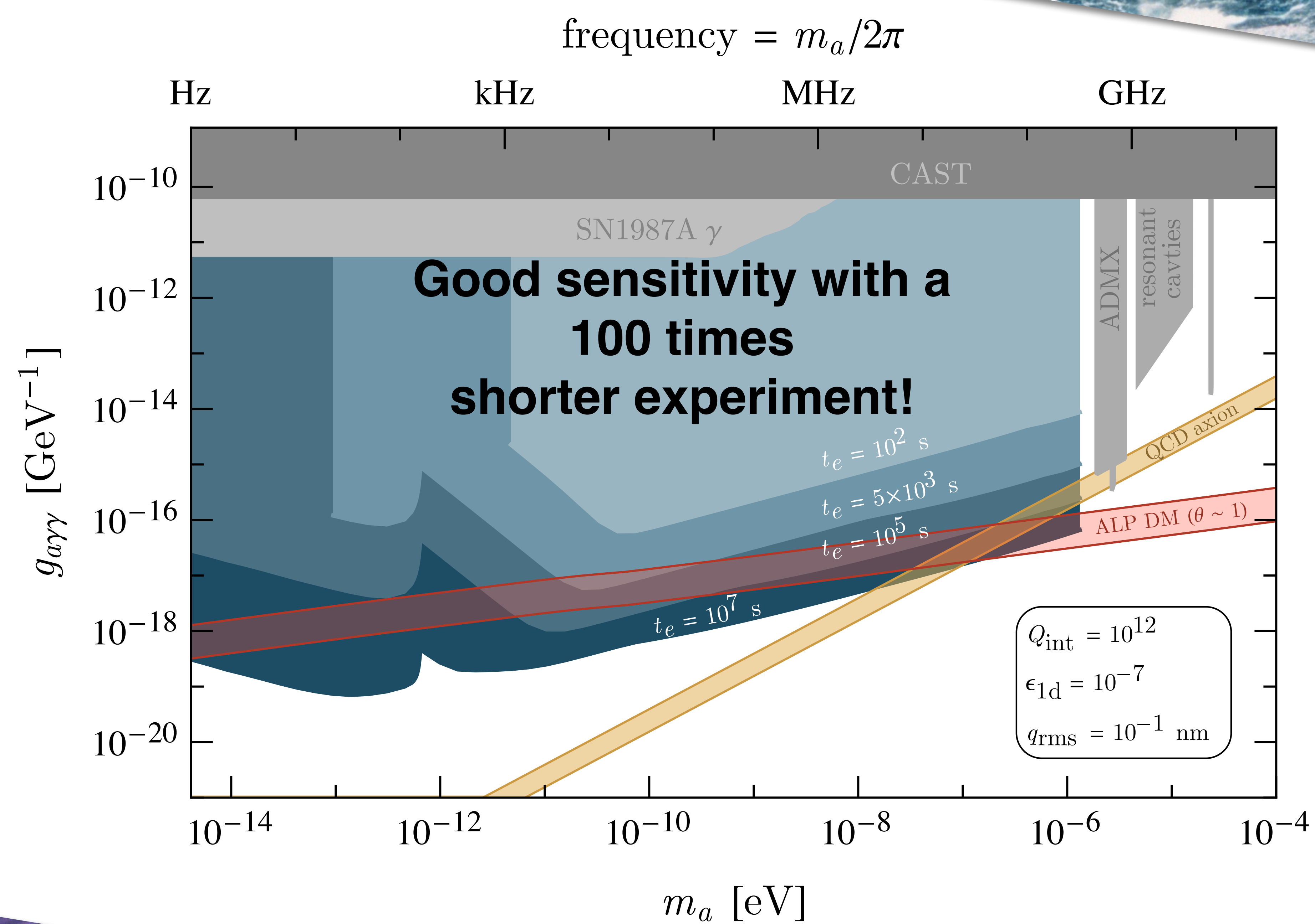
ROBUSTNESS TO ATTENUATION OF VIBRATIONS



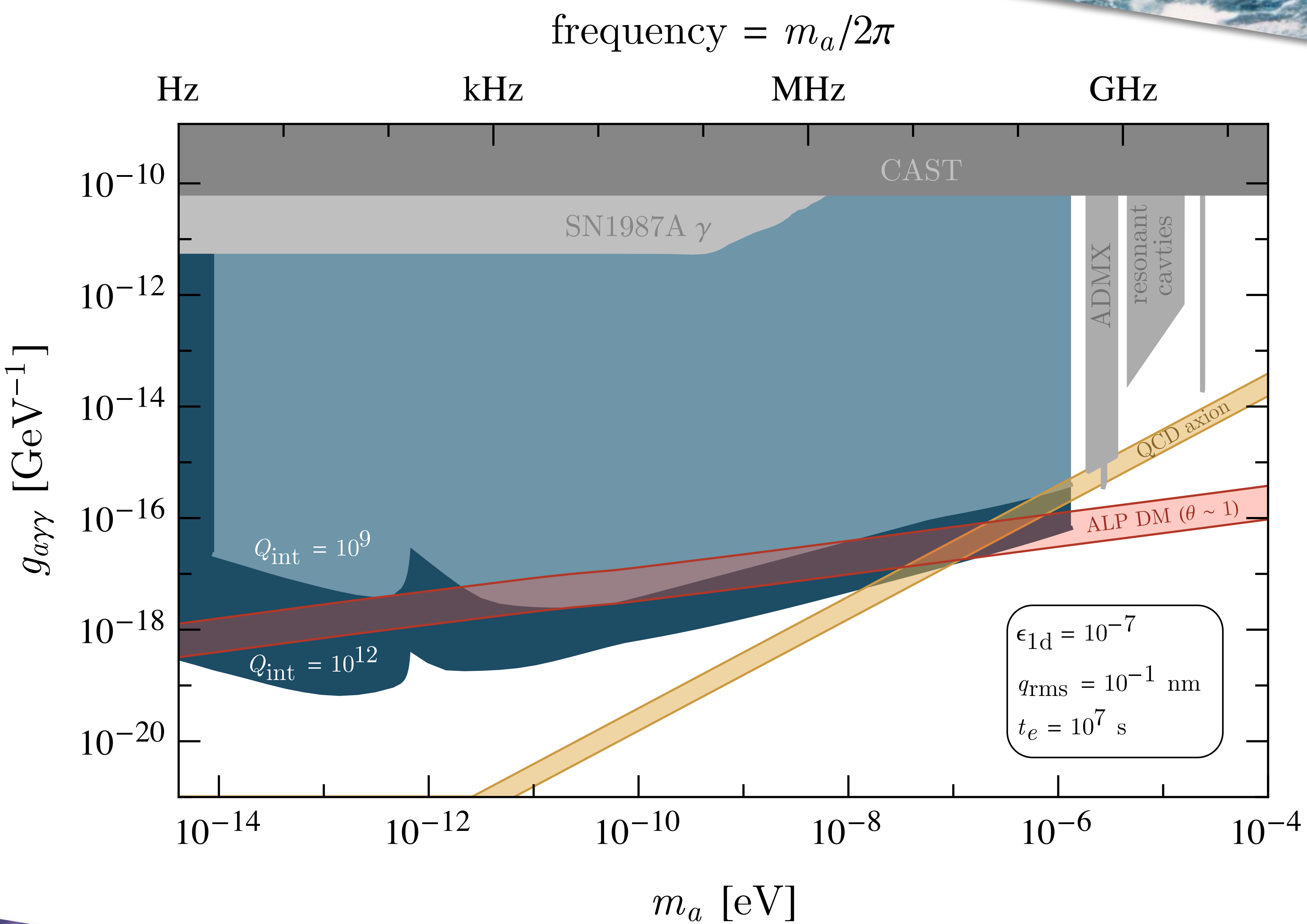
Demonstrated in similar cavities

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

INTEGRATION TIME

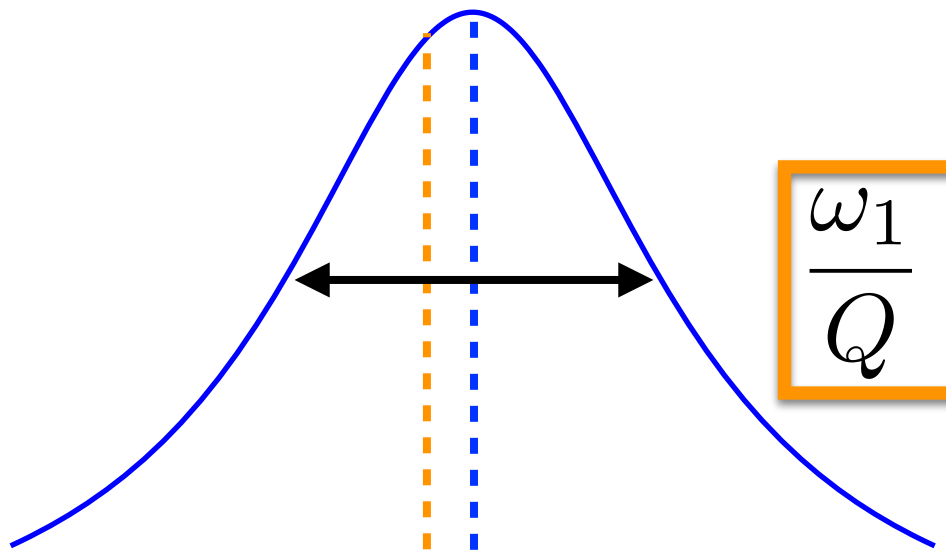


THE POWER OF Q



BROADBAND APPROACH

$$\omega_1 = \omega_0 + m_a$$

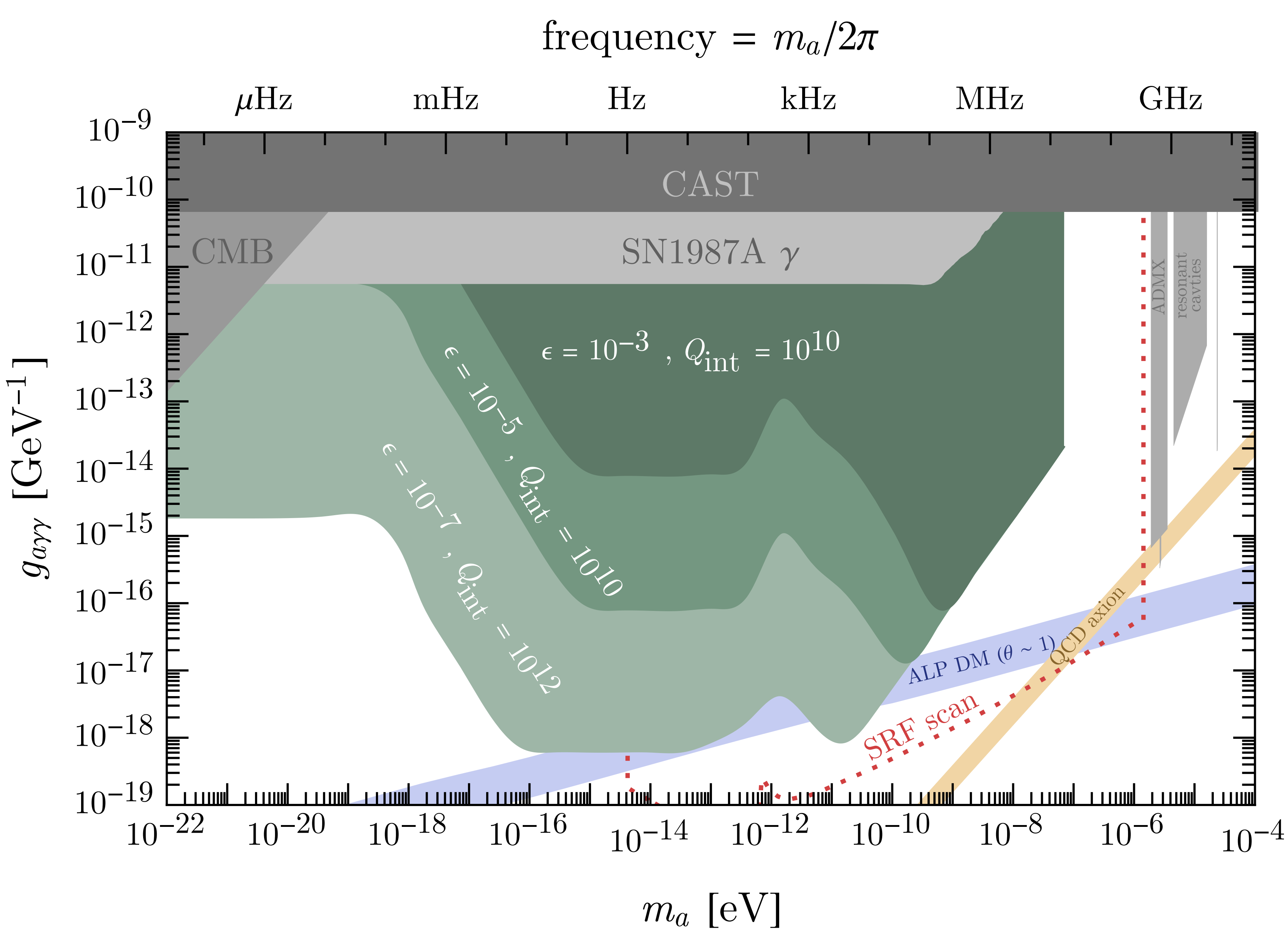


$$\frac{\omega_1}{Q} \gg m_a, \omega_1 - \omega_0$$

$$\mathbf{E}_1 \propto \frac{1}{(\omega_0 \pm m_a)^2 - \omega_1^2 + i\frac{\omega_1(\omega_0 \pm m_a)}{Q}} \propto Q$$

BROADBAND APPROACH

PRELIMINARY!



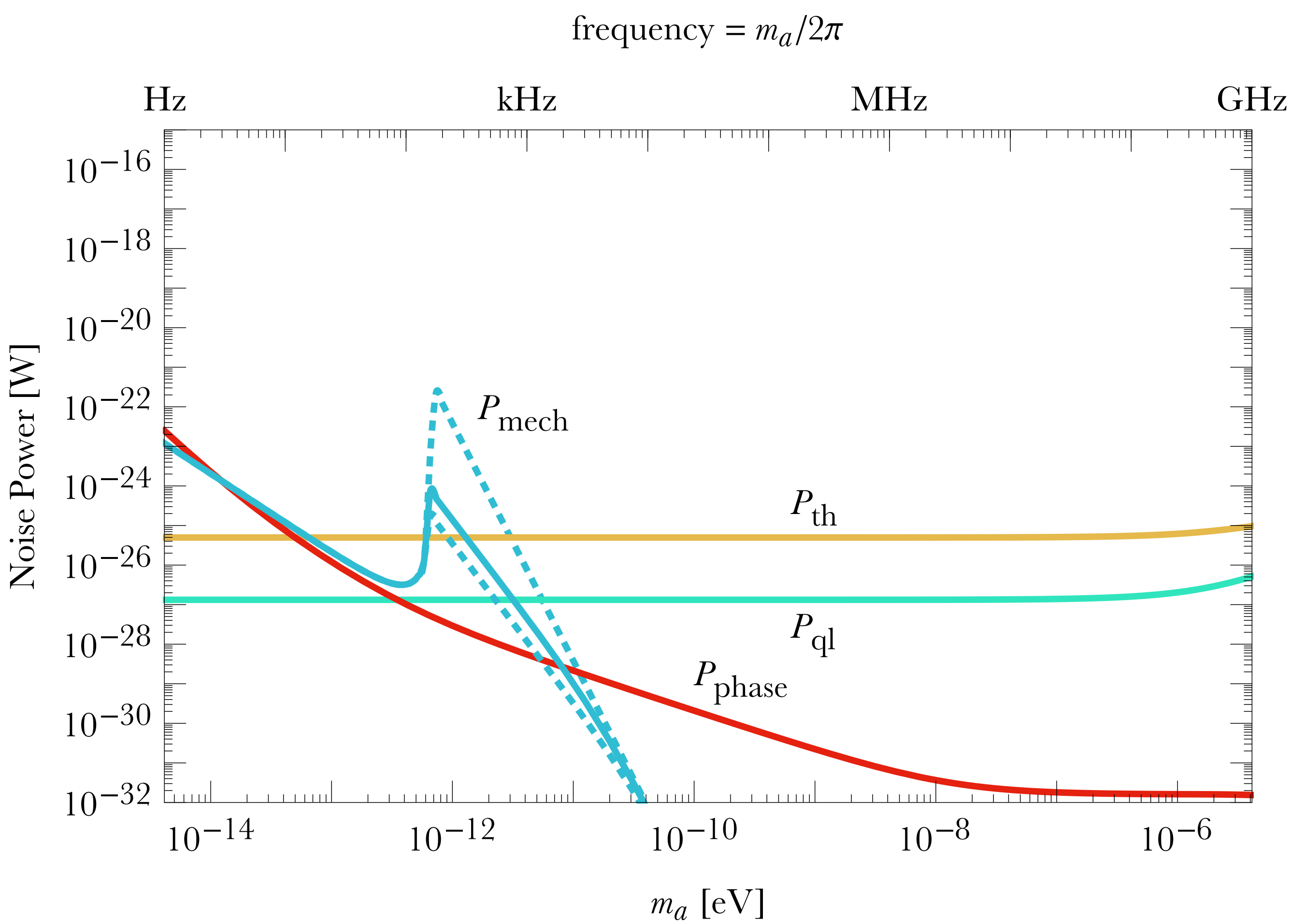
$$t_{int} \sim 5 \text{ years} \quad B \sim 0.2 \text{ T} \quad V = \text{m}^3$$

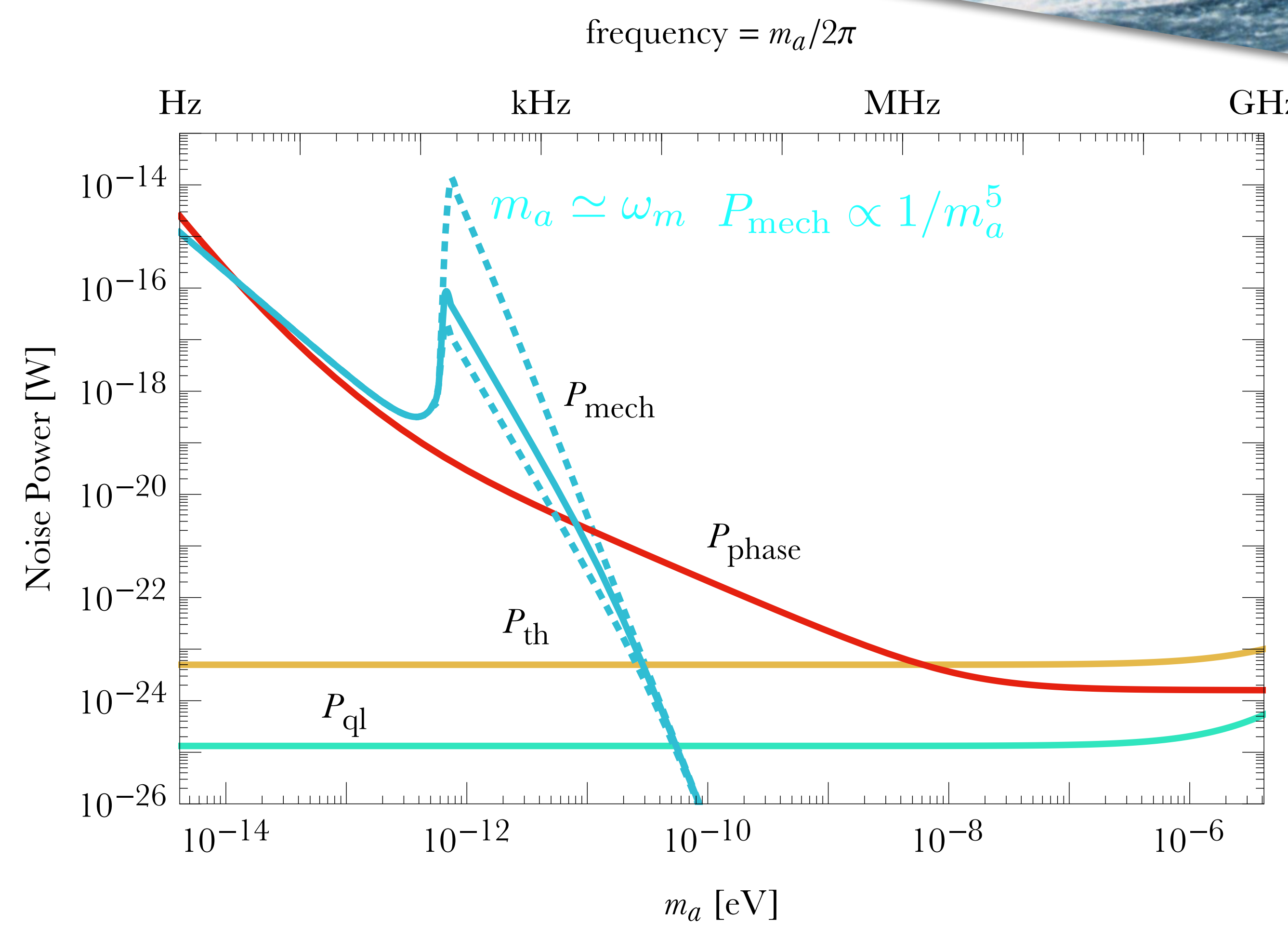
CONCLUSION

- 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

NOISE



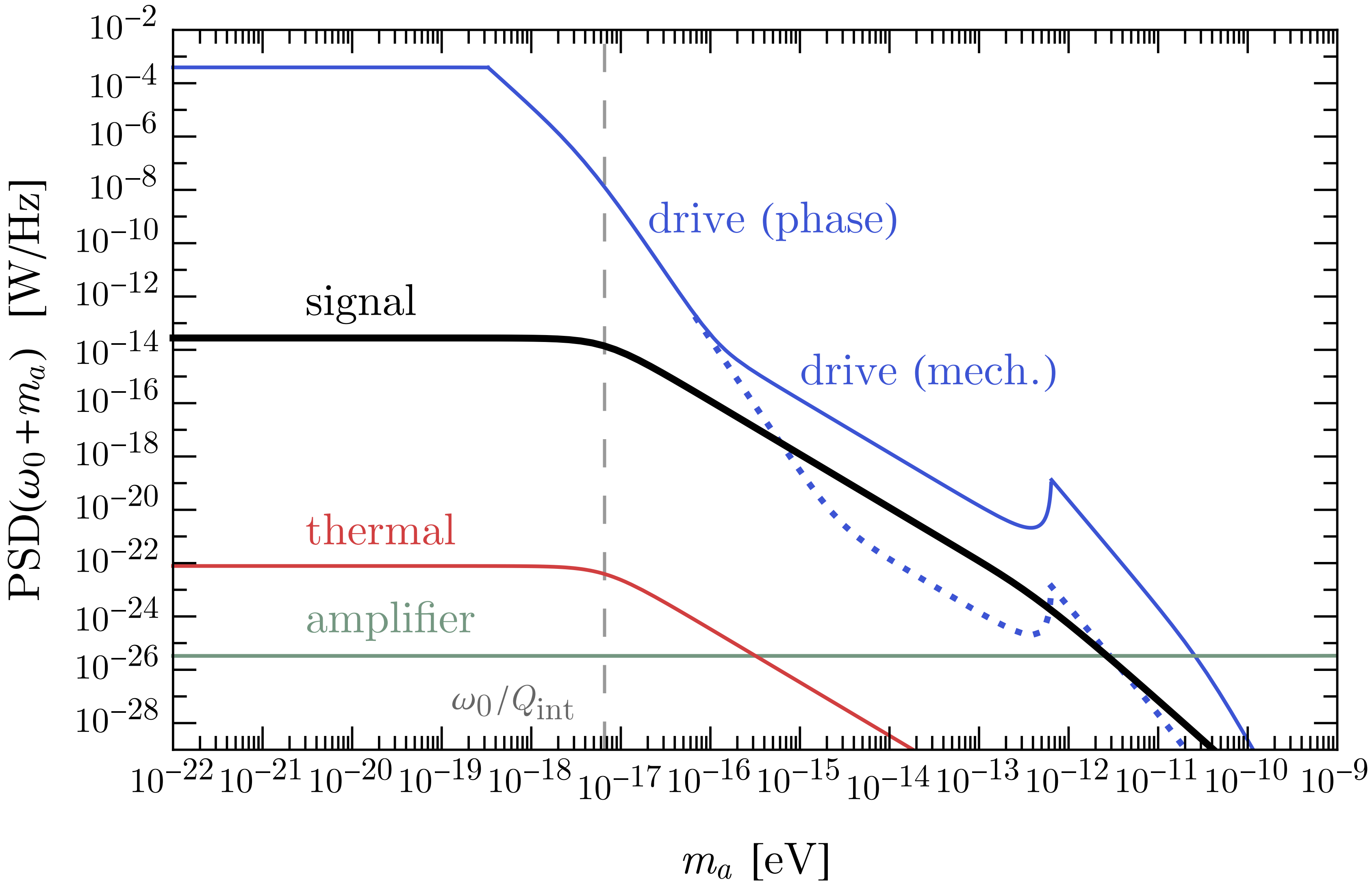


$\epsilon_{1d} = 10^{-7}, \quad Q = 10^{12}$

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

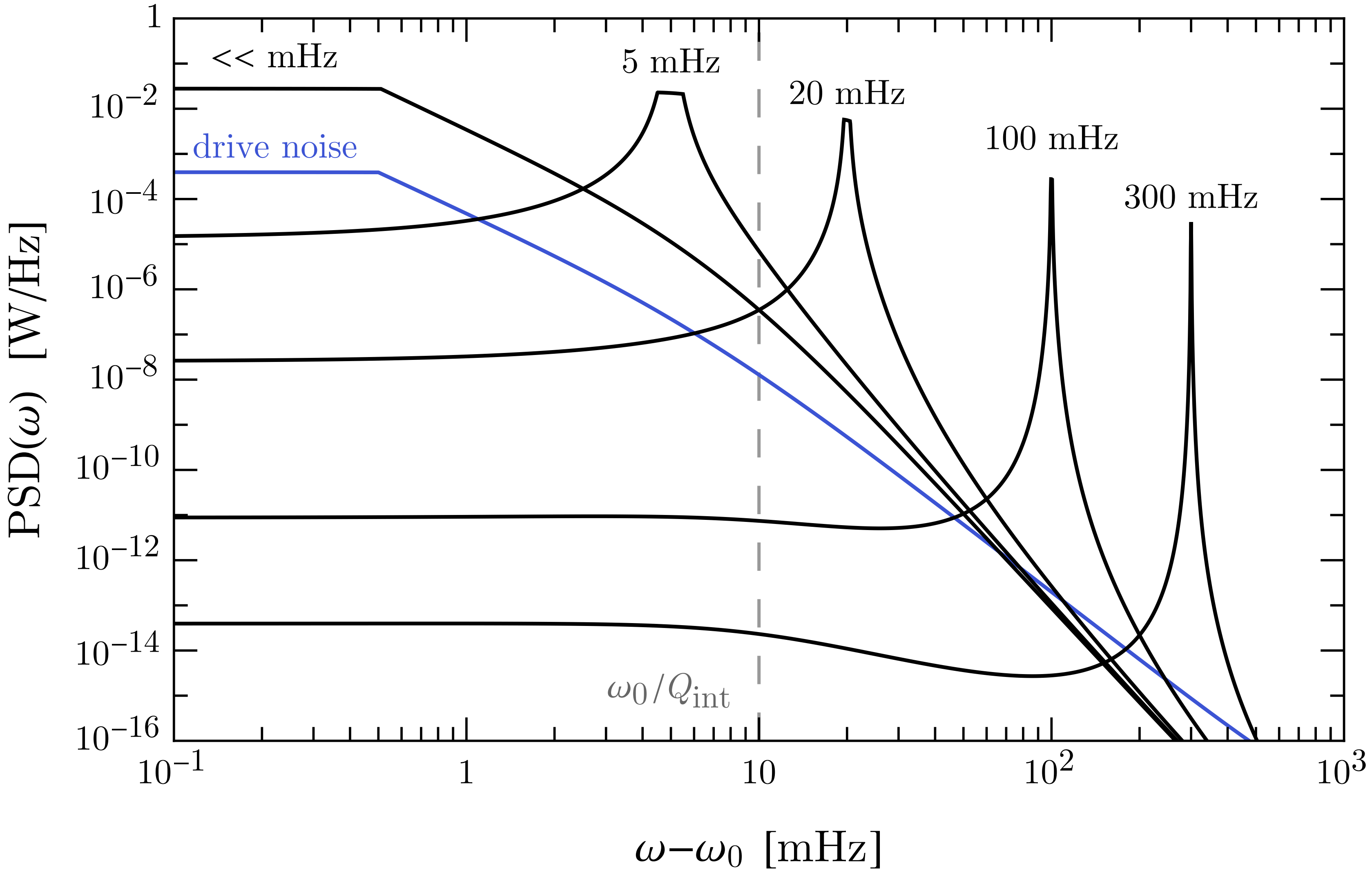
BROADBAND APPROACH

PRELIMINARY!



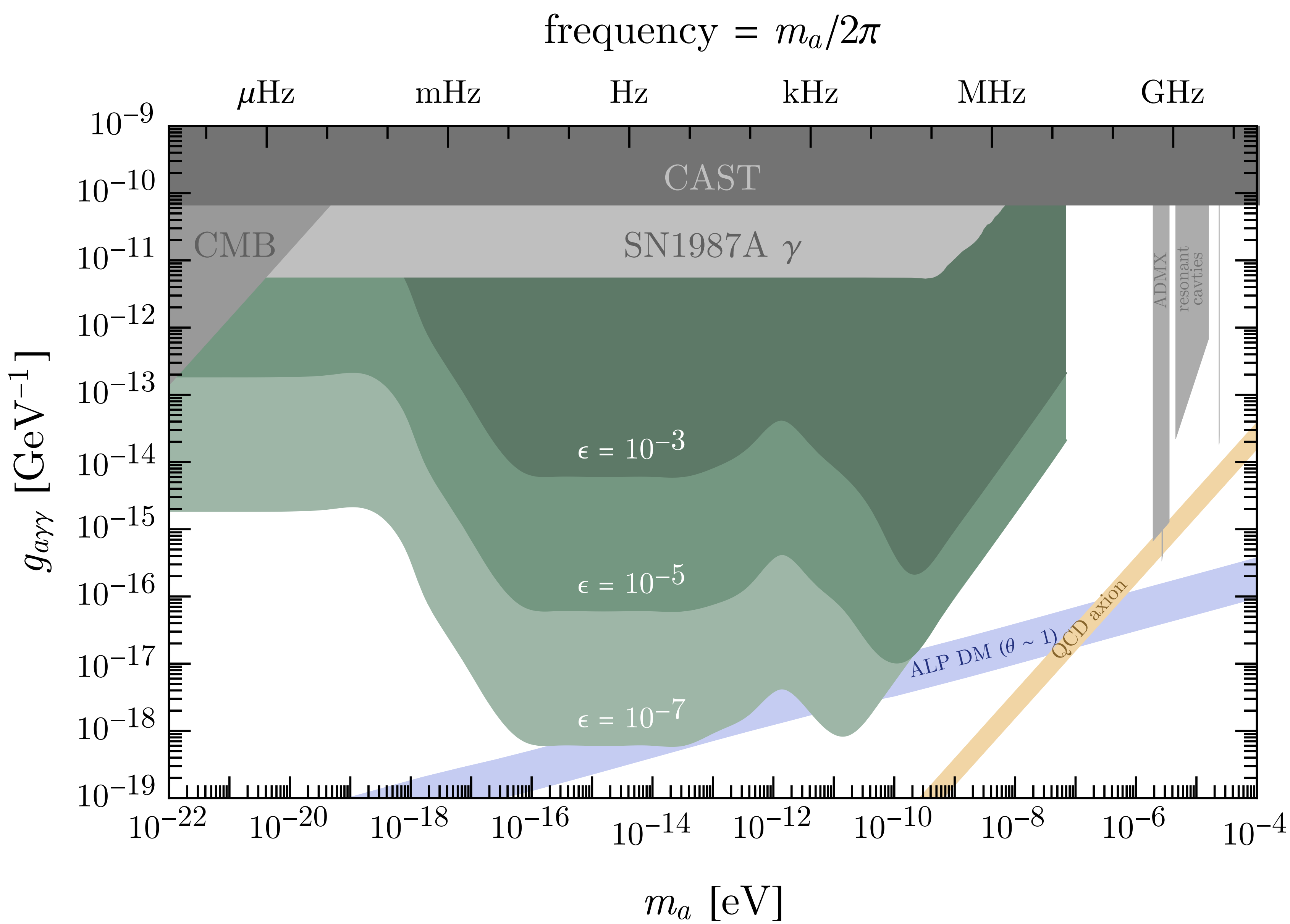
BROADBAND APPROACH

PRELIMINARY!



BROADBAND APPROACH

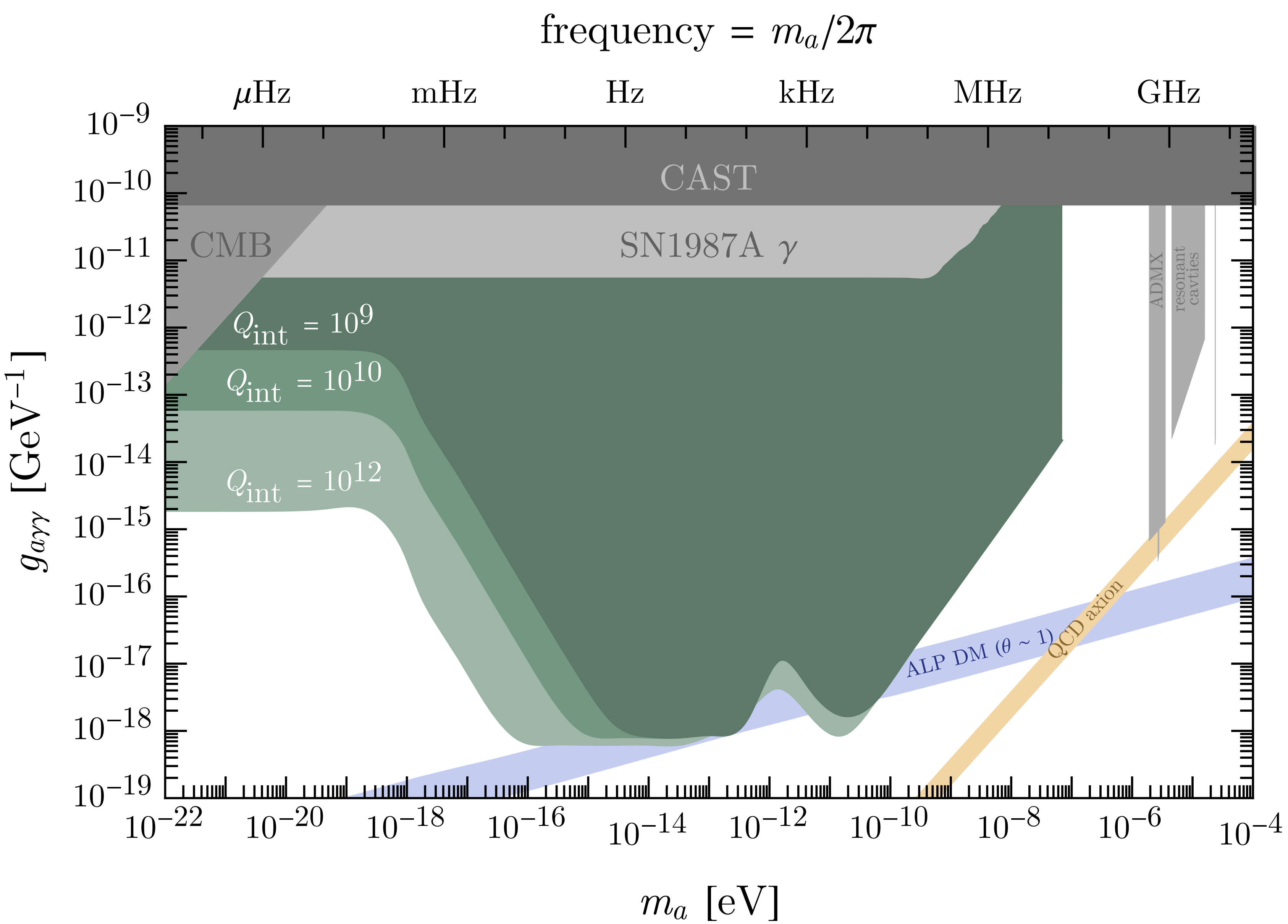
PRELIMINARY!



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

BROADBAND APPROACH

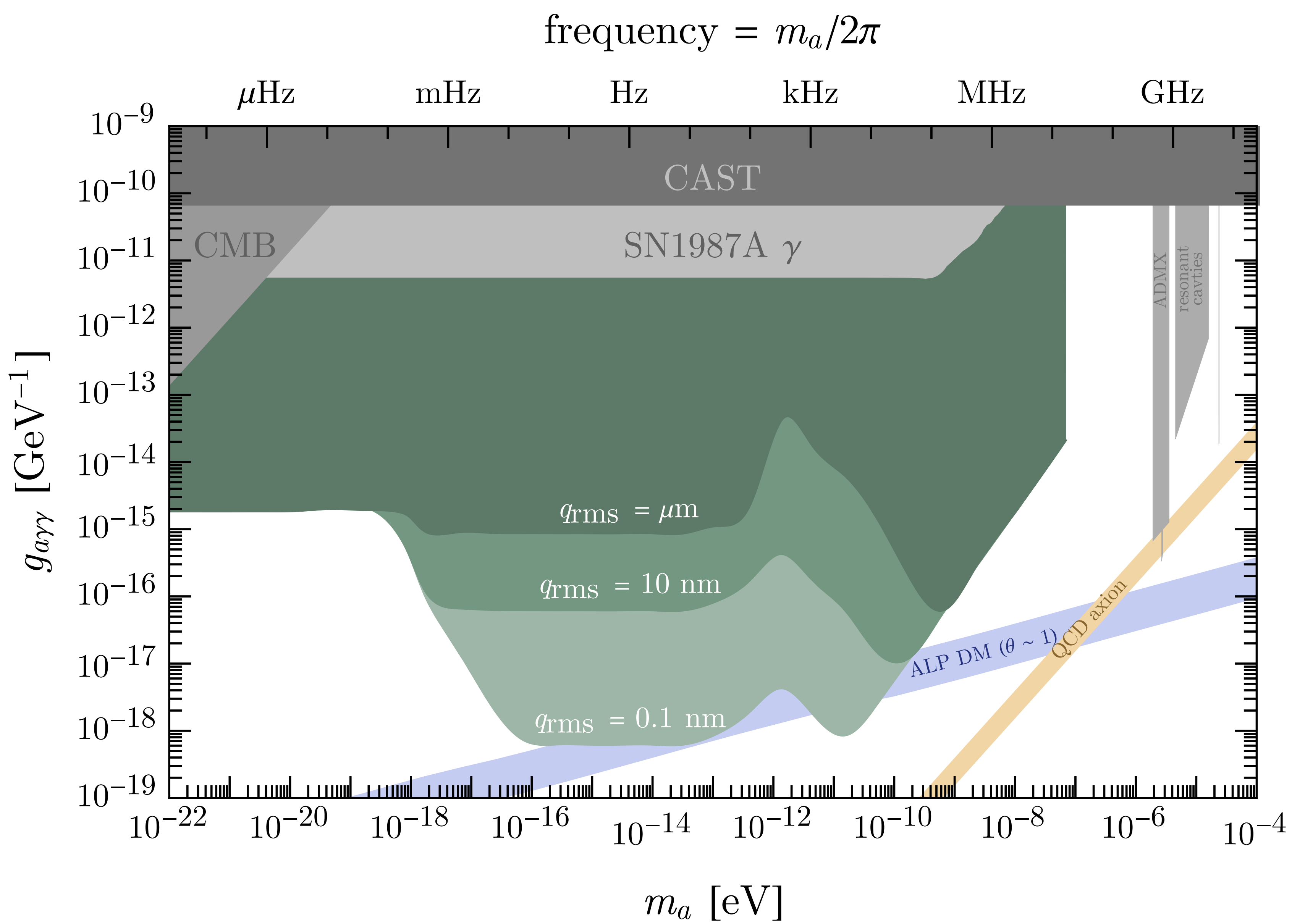
PRELIMINARY!



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

BROADBAND APPROACH

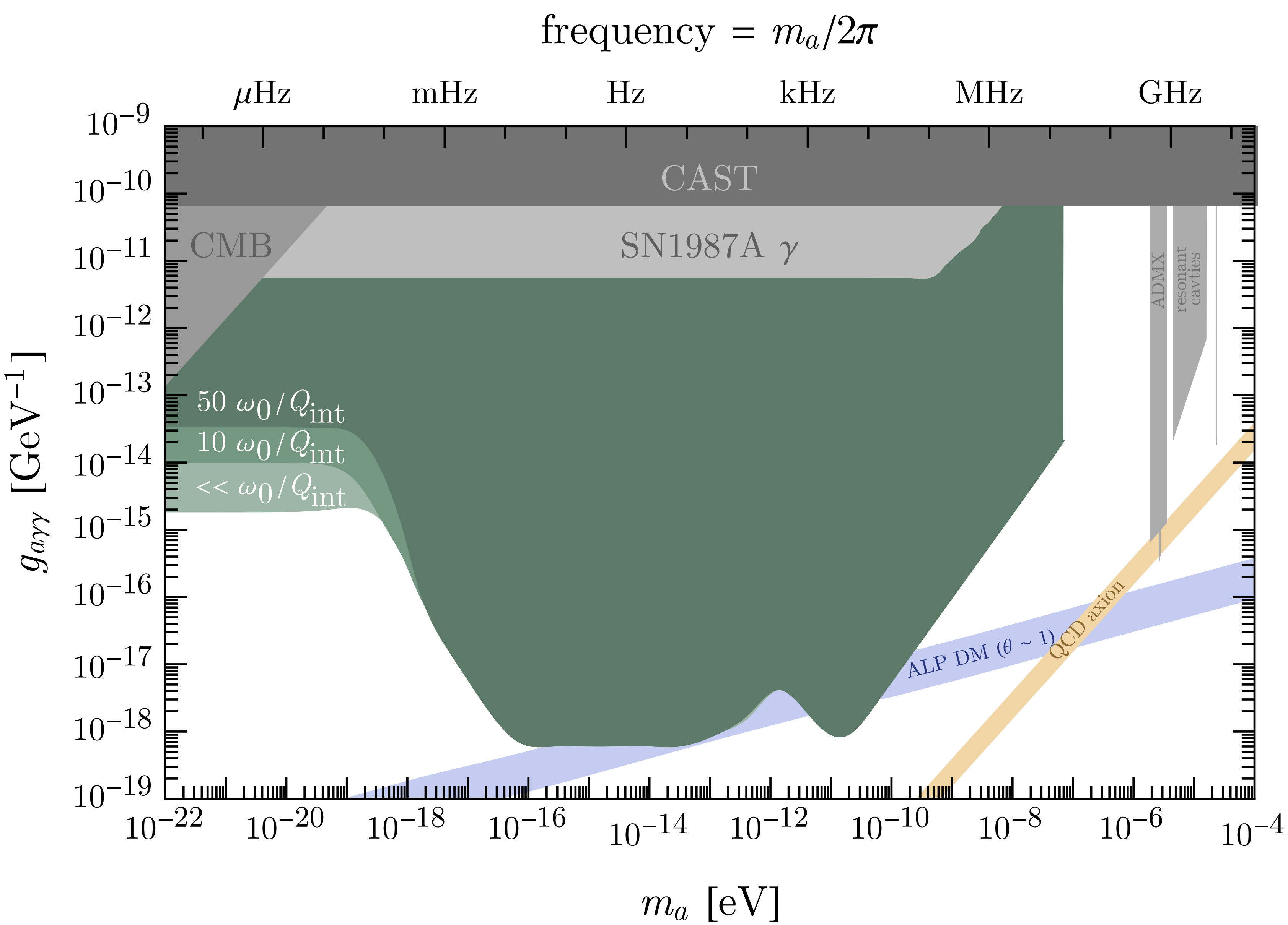
PRELIMINARY!



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

BROADBAND APPROACH

PRELIMINARY!



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

OVERCOUPLING

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

Quantum noise floor (amplifier)

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

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

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

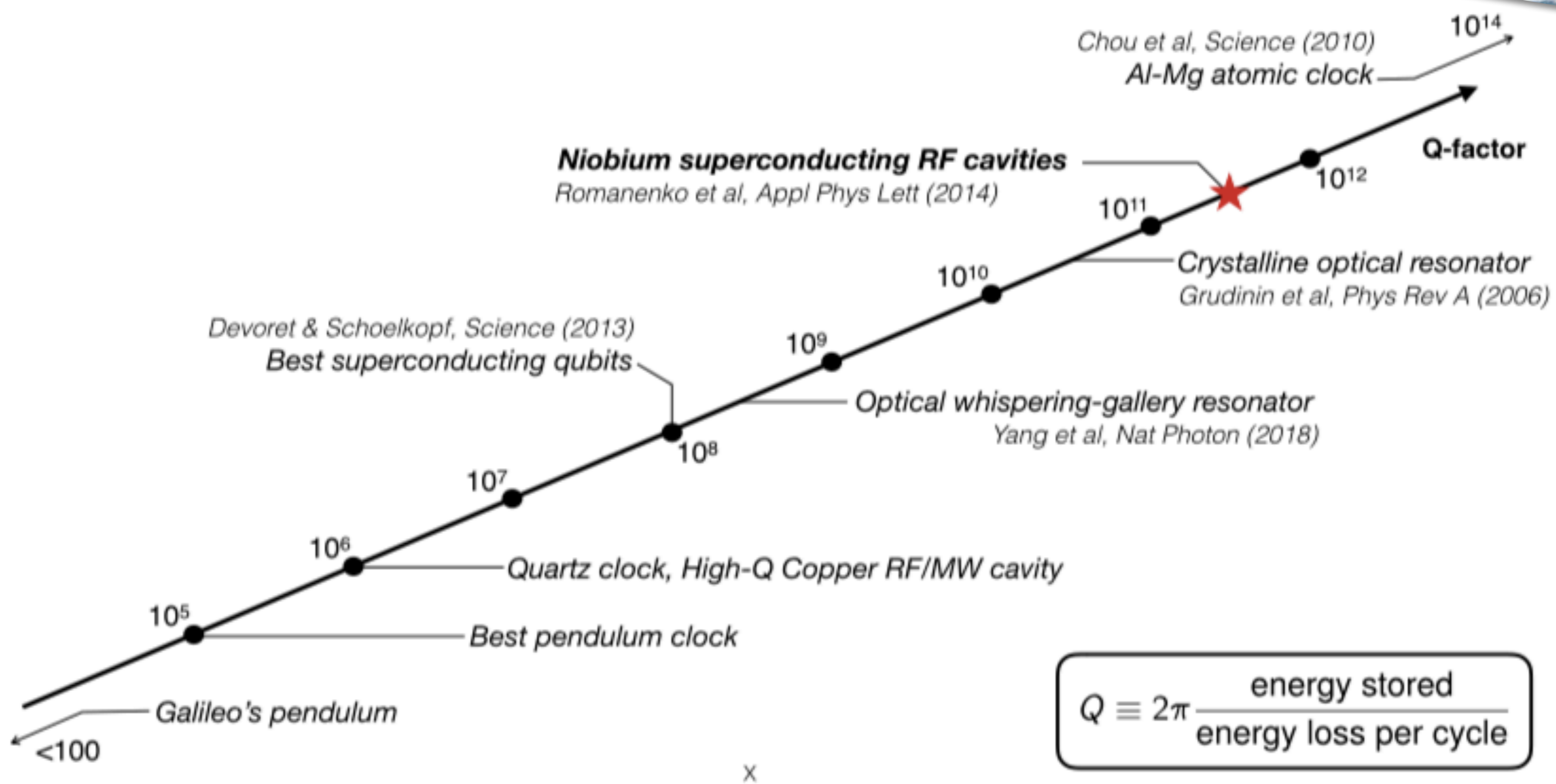
$$\min\left[\tau_a, \tau_r\right] = \min\left[\frac{Q_a}{m_a}, \frac{Q}{\omega_1}\right]$$

Ratio: Oscillating/Static

$$\frac{P_{\rm osc}}{P_{\rm stat}} \sim \left(\frac{0.2\ \mathrm{T}}{4\ \mathrm{T}}\right)^2 \times \begin{cases} (Q_1/Q_a)^2\,\dfrac{(\omega_1/Q_1)}{(m_a/Q_a)} & \dfrac{m_a}{Q_a} \ll \dfrac{\omega_1}{Q_1} \\ (\omega_1/m_a)^2 & \dfrac{m_a}{Q_a} \gg \dfrac{\omega_1}{Q_1} \end{cases}$$

Great advantages of our setup at low m_a

SUPERCONDUCTING RADIOFREQUENCY CAVITIES



From Anna Grassellino, Fermilab