Detect Axions with Mössbauer Effect

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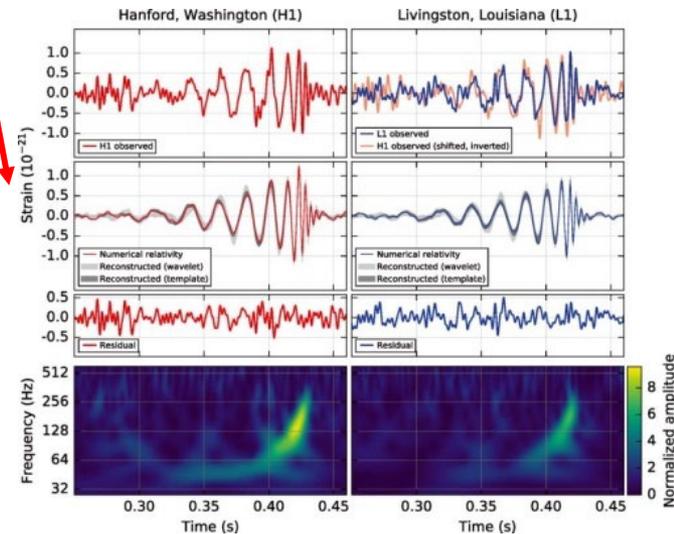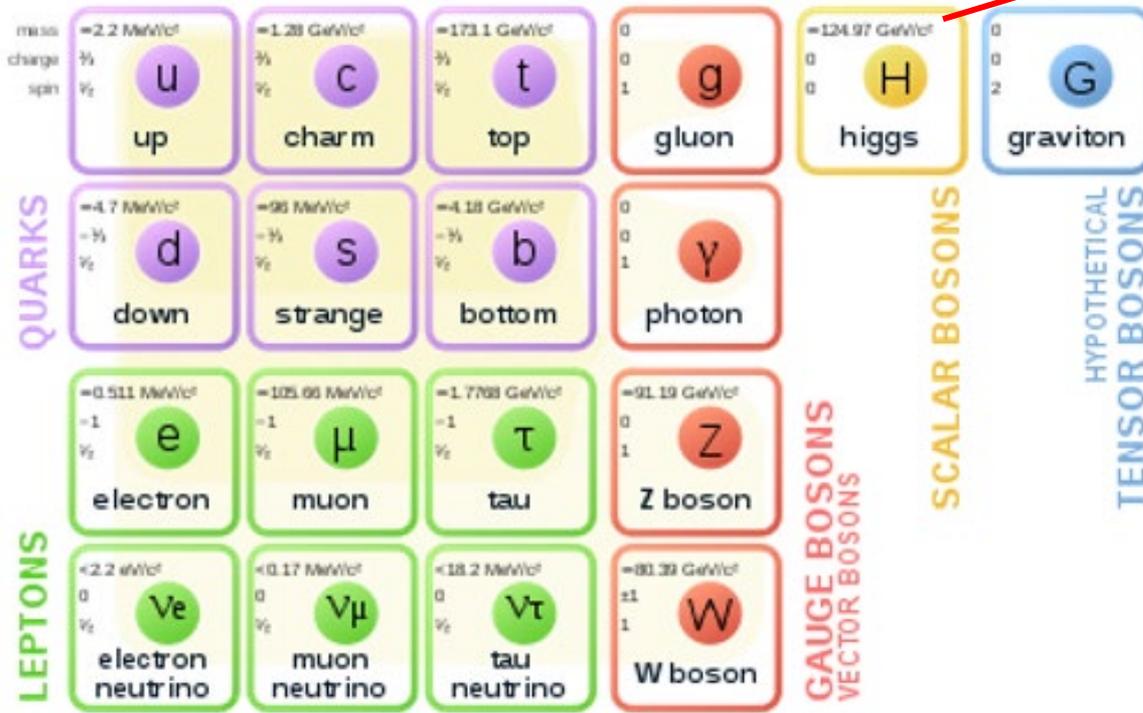HKUST

Current Status of Particle Physics:

+ anything else?

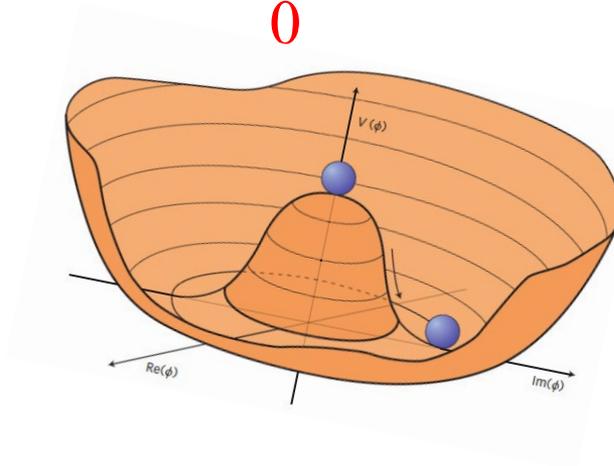# Left-over problems:

- The identity of dark matter

- Gauge hierarchy problem

- Strong CP problem

- The identity of inflaton field

- Baryogenesis

- Cosmological constant

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Left-over problems:

- The identity of dark matter $\longrightarrow$ misalignment mechanism

- Gauge hierarchy problem $\longrightarrow$ relaxion

- Strong CP problem $\longrightarrow$ QCD axion

- The identity of inflaton field
- Baryogenesis   can be related to axion
- Cosmological constant

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QCD axion direct detection

$$(\theta - \arg \det \mathrm{M_q})\frac{\alpha_s}{8\pi}\mathrm{G}\tilde{\mathrm{G}}$$

0

The introduction of axion sets the average value of $\bar{\theta}$ to zero.

Axion DM leads to a time dependent $\bar{\theta}$.

$$a(t, \vec{x}) \approx \frac{\sqrt{2\rho_{\mathrm{DM,local}}}}{m_a} \sin\left(\omega_a t - \vec{p}\cdot\vec{x}\right)$$

Chiral Lagrangian

Axion affects the nucleon and mesons through Chiral Lagrangian.

lead to pion-axion mixing

$$U = e^{i\pi^a \tau^a / f_\pi} \qquad U_0 = \begin{pmatrix} e^{i\phi_u} & 0 \\ 0 & e^{i\phi_d} \end{pmatrix}$$

$$\begin{aligned}
u &\to e^{i\phi_u} u \\
d &\to e^{i\phi_d} d, \\
\phi_u + \phi_d &= \theta
\end{aligned}$$

$$(\theta - \arg \det \mathrm{M_q}) \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\mathcal{L} = -\frac{1}{4} f_\pi^2 \mathrm{Tr}[\partial_\mu U \partial^\mu U^\dagger] + B_0 \mathrm{Tr}[(MU_0)U + (MU_0)^\dagger U^\dagger]$$

$$- c_1 \bar{N}((MU_0)P_L + (MU_0)^\dagger P_R)N \implies \text{change nucleon mass}$$

$$- c_2 \bar{N}(U^\dagger (MU_0)^\dagger U^\dagger P_L + U(MU_0)U P_R)N$$

change nucleon-pion interactions

$$c_+ \frac{m_u m_d \sin\theta}{f_\pi [m_u^2 + m_d^2 + 2m_u m_d \cos\theta]^{1/2}} \qquad c_+ \frac{m_u m_d \sin\theta}{f_\pi [m_u^2 + m_d^2 + 2m_u m_d \cos\theta]^{1/2}}$$

n p π n p

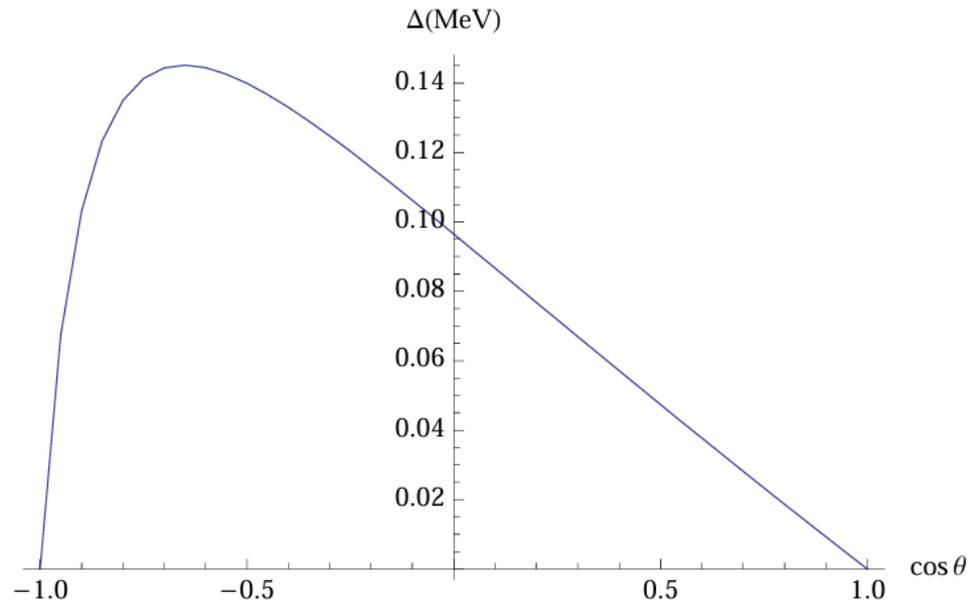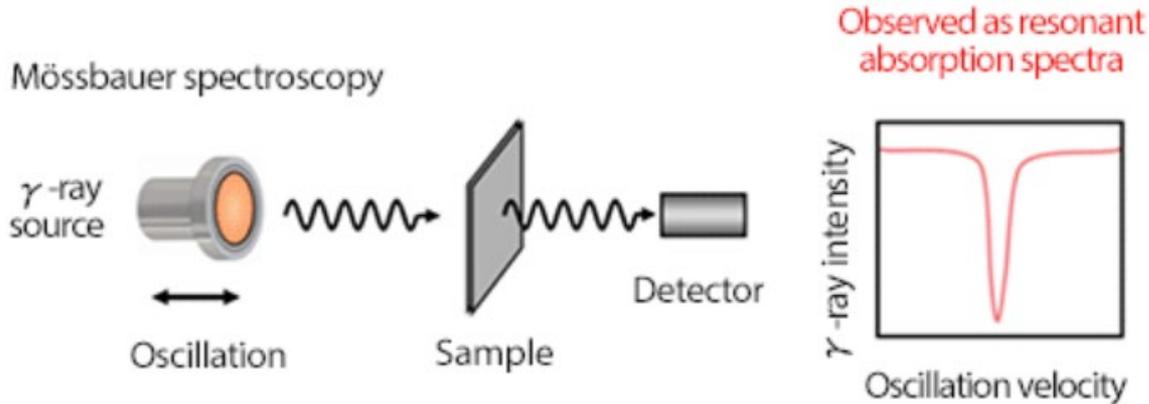# Simple example

Figure 2: *Shift in the deuteron binding energy as a function of* $\cos\theta$

Mossbauer Effect

Mössbauer spectroscopy

Observed as resonant absorption spectra

γ-ray source

Oscillation

Sample

Detector

γ-ray intensity

Oscillation velocity

Ag-109 isotope
lifetime ~ 57s, f ~ 88 keV

$$\frac{\delta f}{f} \sim 10^{-22}$$ Extremely narrow

It is very challenging to measure the natural linewidth experimentally.

So far, the best measurement has achieved 7 times of the nature width.

$$\frac{\delta f}{f} = g\,\Delta Z$$

μm

If axion leads to the change of nucleon-pion coupling, it will change the energy splits.

RDFT calculations

modified by axion

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi$$

$$- \frac{1}{2}\alpha_S(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_V(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)$$

$$- \frac{1}{2}\alpha_{TV}(\bar{\psi}\vec{\tau}\gamma_\mu\psi)(\bar{\psi}\vec{\tau}\gamma^\mu\psi)$$

$$- \frac{1}{3}\beta_S(\bar{\psi}\psi)^3 - \frac{1}{4}\gamma_S(\bar{\psi}\psi)^4 - \frac{1}{4}\gamma_V[(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)]^2$$

$$- \frac{1}{2}\delta_S\partial_\nu(\bar{\psi}\psi)\partial^\nu(\bar{\psi}\psi) - \frac{1}{2}\delta_V\partial_\nu(\bar{\psi}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\gamma^\mu\psi)$$

$$- \frac{1}{2}\delta_{TV}\partial_\nu(\bar{\psi}\vec{\tau}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\vec{\tau}\gamma^\mu\psi)$$

$$- \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - e\frac{1-\tau_3}{2}\bar{\psi}\gamma^\mu\psi A_\mu.$$

RDFT Results

Dominant terms

Channels	$1/2^-$ (MeV)	$7/2^+$ (MeV)	ΔE (MeV)
E_{α_S}	-17623.997	-17510.543	+112.997
E_{α_V}	+13065.872	+12992.183	-73.689
$E_{\alpha_{TV}}$	+19.427	+19.152	-0.273
E_{β_S}	+2539.210	+2510.932	-28.278
E_{γ_S}	-870.667	-857.668	+12.998
E_{γ_V}	-100.616	-99.473	+1.143
E_{δ_S}	+46.431	+44.635	-1.796
E_{δ_V}	+197.220	+189.950	-7.269
$E_{\delta_{TV}}$	+2.166	+2.121	-0.045
E_{kin}	+1477.263	+1461.798	-15.465
E_{cou}	+334.000	+334.475	+0.475
E_{pair}	-8.908	-10.347	-1.439
E_{cm}	-6.673	-6.516	+0.158
E_{tot}	-928.814	-929.298	-0.483

Axion Correction

$$\eta_S(\theta_a) = \frac{\alpha_S(\theta_a)}{\alpha_S(\theta_a = 0)}, \quad \eta_V(\theta_a) = \frac{\alpha_V(\theta_a)}{\alpha_V(\theta_a = 0)}$$
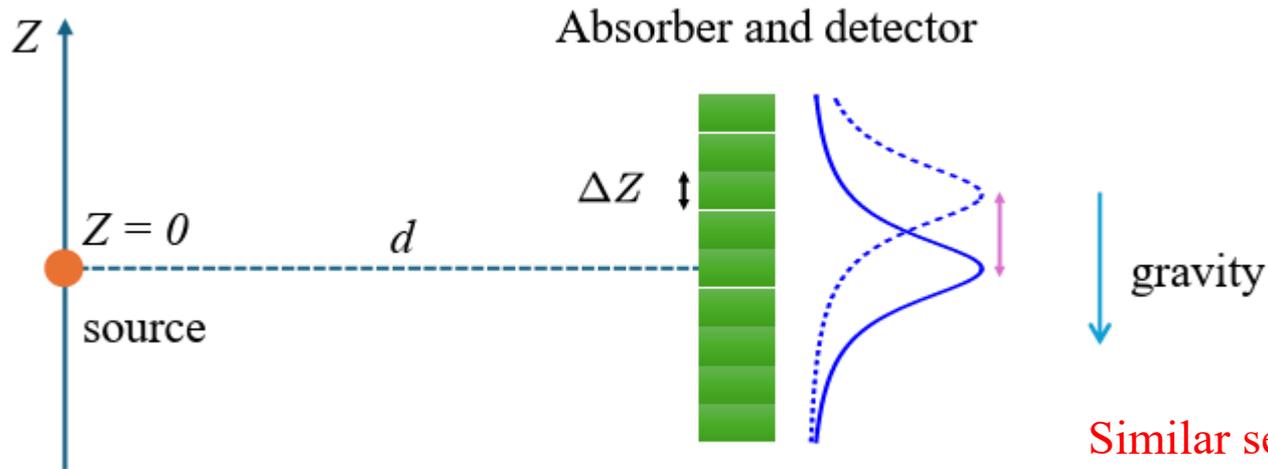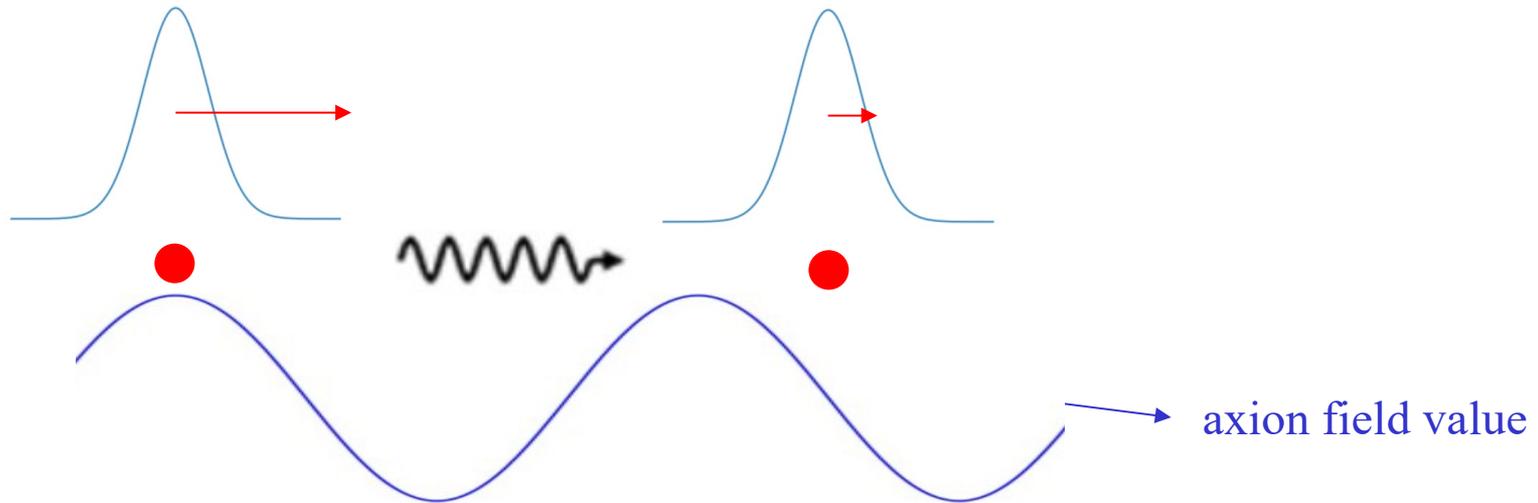
The scalar interaction part as example

$$\eta_S = -0.4\,\frac{m_\pi^2(\theta_a)}{m_\pi^2(\theta_a = 0)} + 1.4 \simeq 1 + 0.044\,\theta_a^2$$

Total correction

$$
\begin{aligned}
&\Delta E_S(\theta_a) - \Delta E_S(0) \\
=&[E_S^{\text{Ex.}}(\theta_a) - E_S^{\text{G.s.}}(\theta_a)] - [E_S^{\text{Ex.}}(0) - E_S^{\text{G.s.}}(0)] \\
\simeq&[\eta_S(\theta_a) - \eta_S(0)][E_S^{\text{Ex.}}(0) - E_S^{\text{G.s.}}(0)] \\
\simeq&0.044\,\theta_a^2 \times 113\text{MeV} \\
=&5.0\,\theta_a^2\text{MeV}.
\end{aligned}
$$

Experiment Setup

axion field value

Absorber and detector

Z

$Z = 0$

d

ΔZ

source

gravity

$$\delta E_{\text{bind}}(d) = \Delta E_{\text{bind}}(t + d, \vec{d}) - \Delta E_{\text{bind}}(t, 0)$$

Similar setup has been proposed to search for gravitational wave.
Sci. Bull. 69, 2795 (2024)

Systematic and Statistical Uncertainties

$$N_{\text{det}} = R_s \, \text{Br} \, \delta T \frac{(2\pi d)\boxed{\Delta Z}}{4\pi d^2}$$

A too narrow detector leads to a very large statistical error.

source radiation intensity

branching ratio of the 88 keV photon

A competition:

       the systematic uncertainty
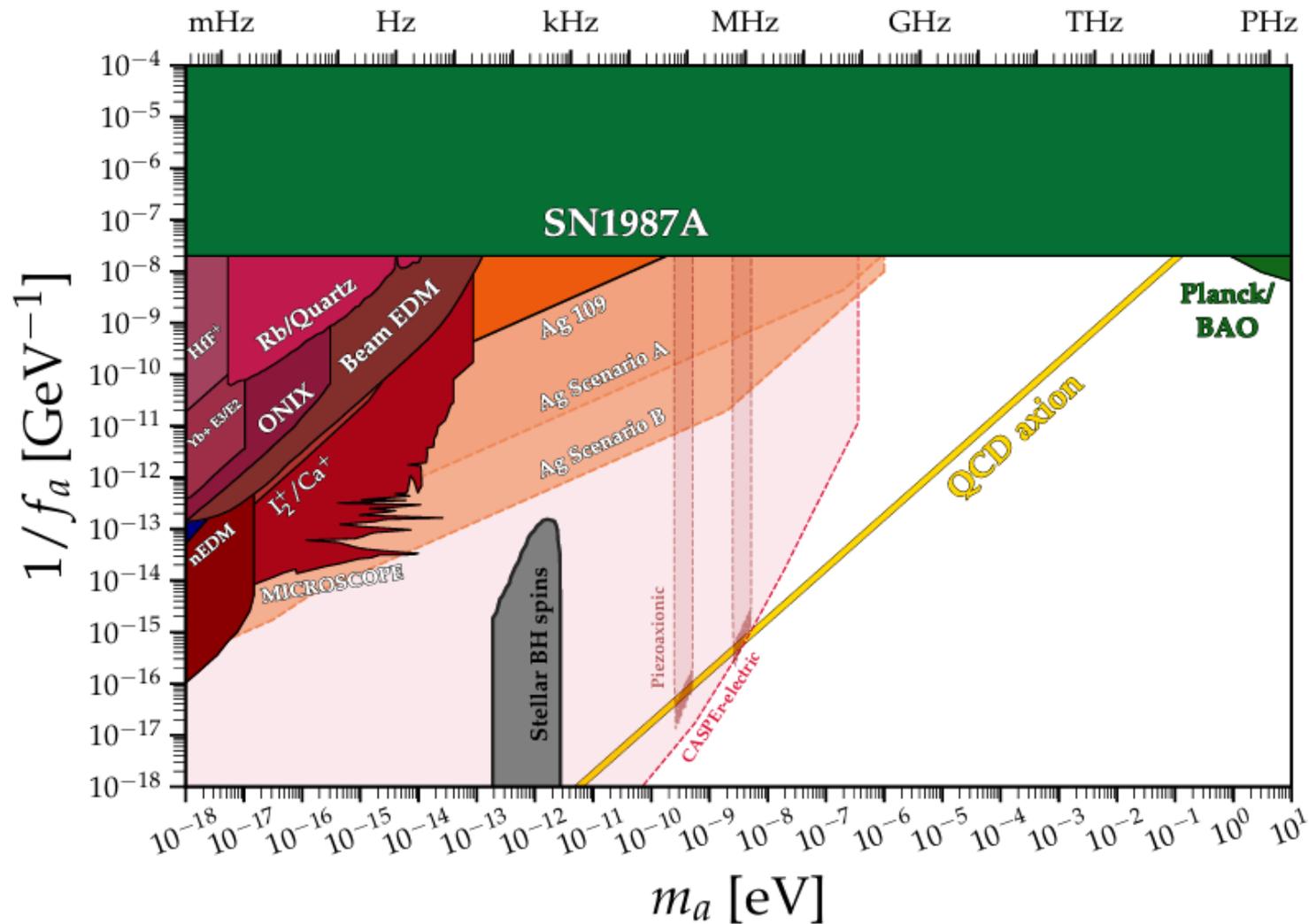   worse with a larger detector width

       the statistical uncertainty
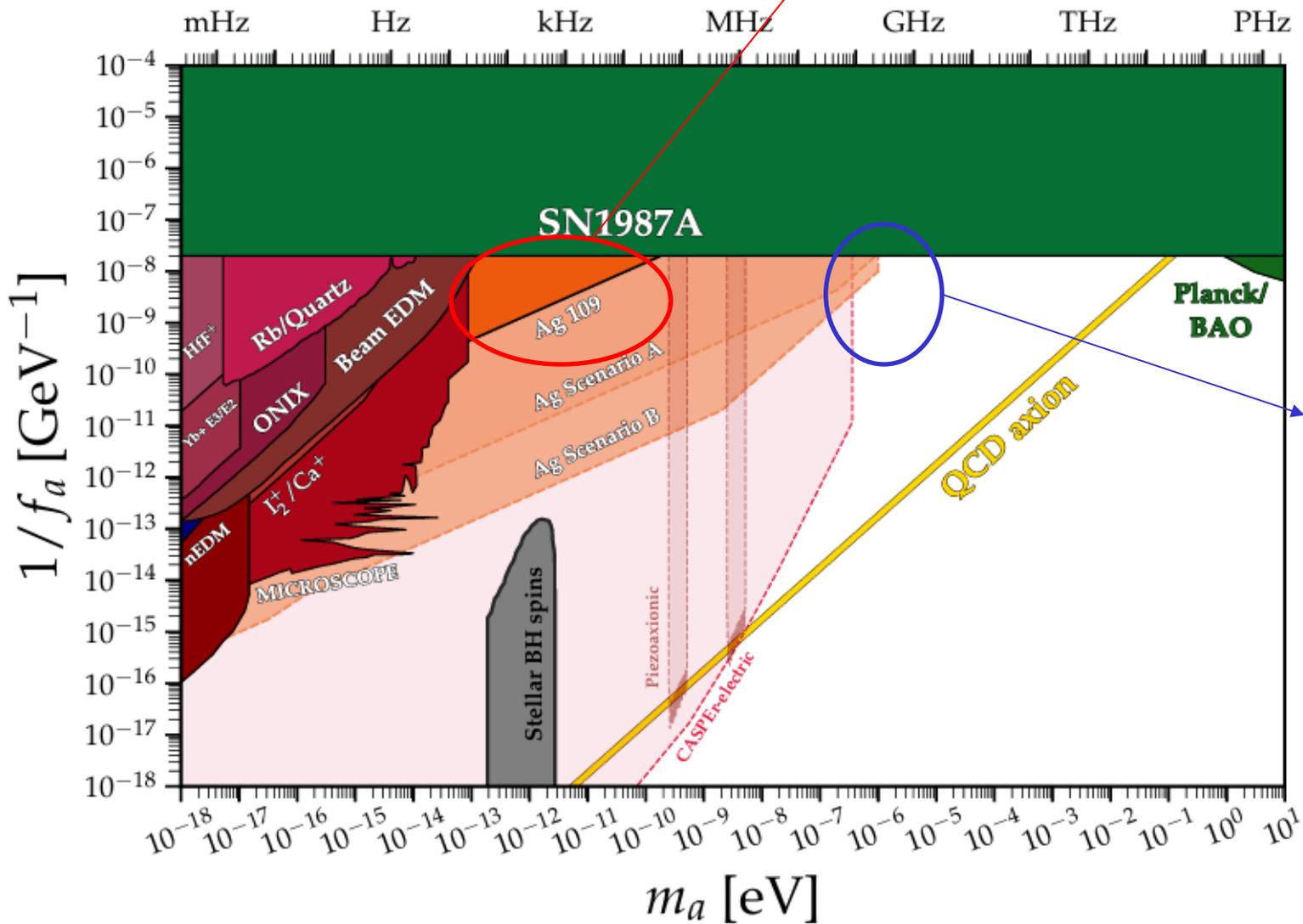   better with a larger detector width

A smart data analysis strategy is introduced to balance these two competing aspects.

Sensitivity

	$g(g_\oplus)$	d(m)	ΔZ	ϵf_S	$m_{a,\max}$(eV)	R_s(Ci)
A	1	1	10μm	0.04	10^{-6}	1
B	10^{-4}	100	1 dm	0.04	10^{-6}	10

Sensitivity

Ruled out by current width measurement.
Jetp Lett. 90, 499–503 (2009)

Detector time resolution determines the frequency upper limit.

Conclusion

- QCD axion dark matter leads to time-dependent nuclear binding energy.

- This can be tested using Mossbauer Spectroscopy.

- Ag-109 has an ultra-intrinsic fractional width of 10^{-22}, perfect for this purpose.

- Current width measurement has already imposed interesting constraints.

- A large parameter space can be probed in the future