Optomechanical searches for invisible particles

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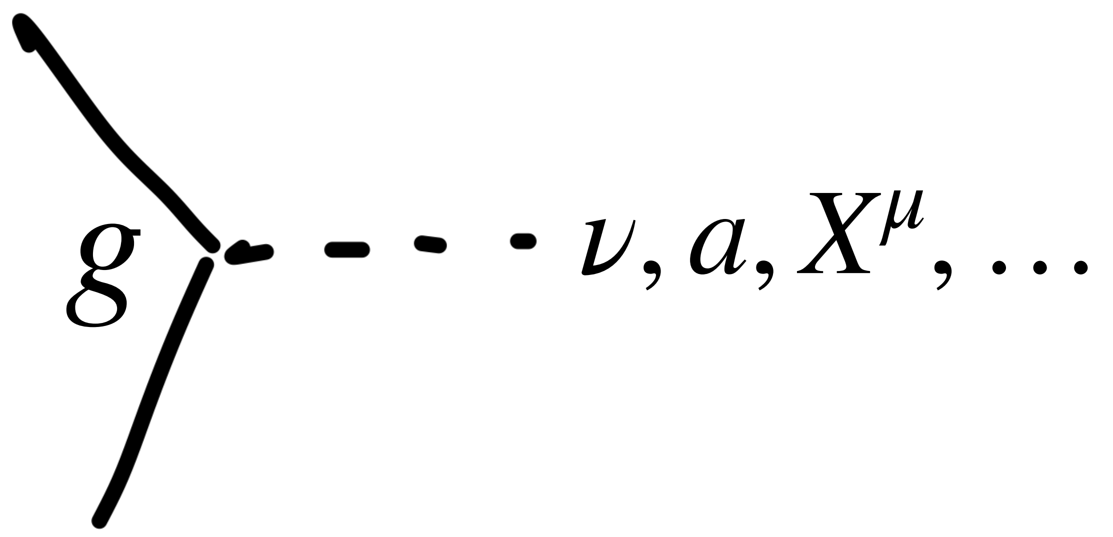
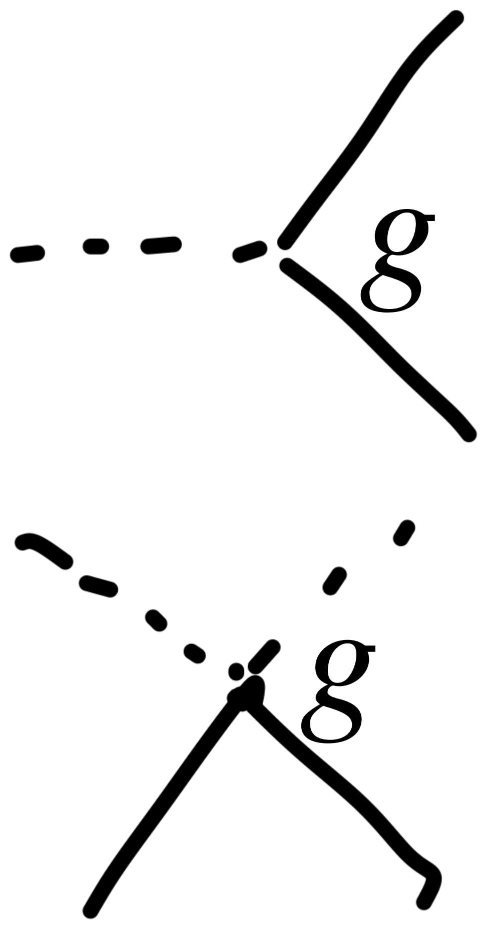
Production



Detection



$$P(\text{production \& detection}) \sim g^4$$

- Can we infer properties of particle production without scattering/ absorption?

Über die β-Strahlen des aktiven Niederschlags des Thoriums.

Von Otto v. Baeyer, Otto Hahn und Lise Meitner.

(1911)

- Check conservation laws!
- Pauli (1931): “a desperate remedy to save … the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles”
- Neutrino direct detection (1956)

$$\sigma_{\nu e} \sim G_F^2 E^2 \approx 10^{-43}\,\mathrm{cm}^2$$

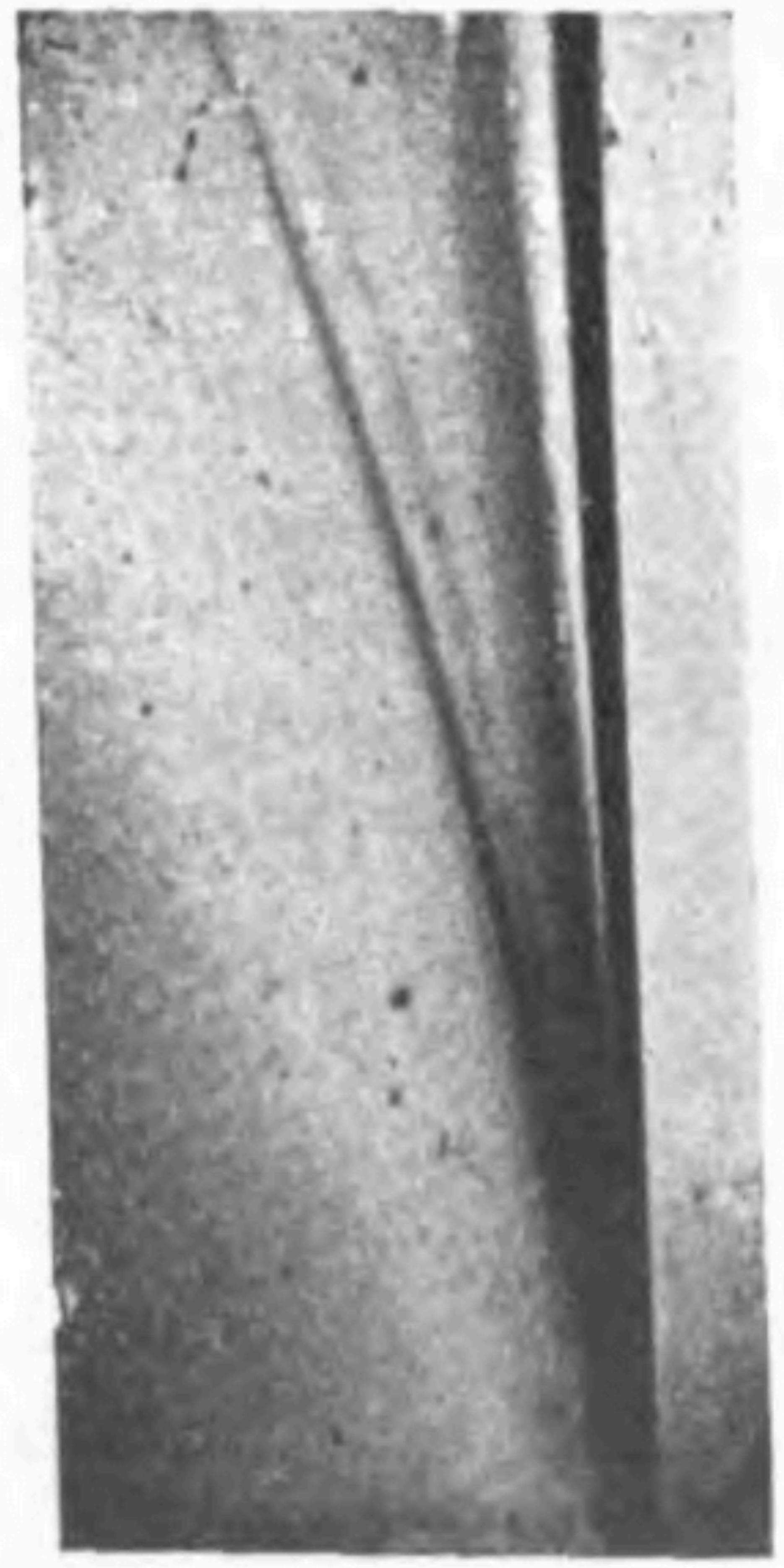
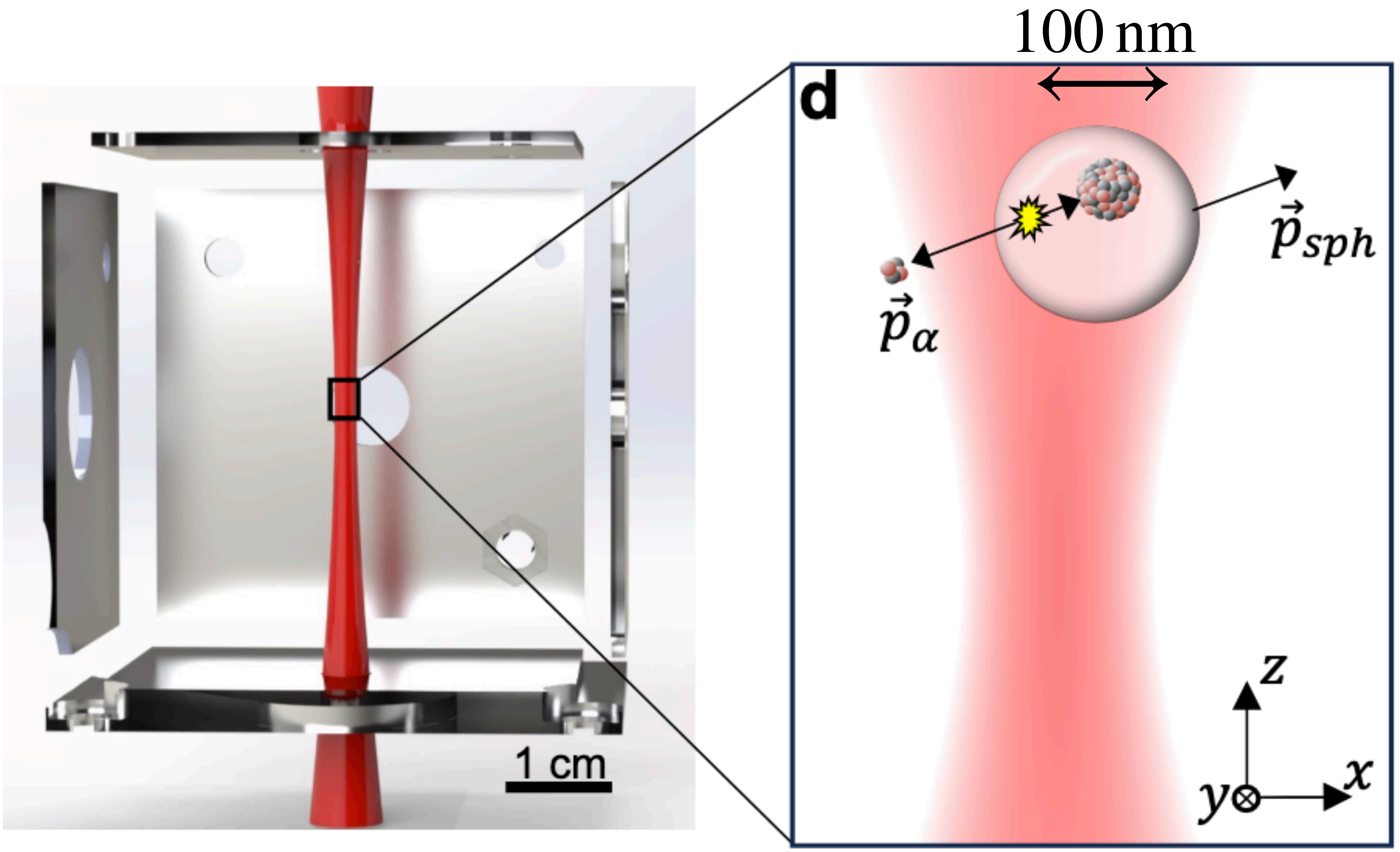


Fig. 2.

Quantum invisible particle sensor (QuIPS)



$$\mathbf{p}_\alpha = -\mathbf{p}_{\rm sph}$$

- Detect weakly coupled particles emitted in nuclear decays
- How can we minimize the quantum noise in missing momentum measurements?

LBL: Sorensen, Garcia, Denes, Rofors, R. Carney, **GM**, Beckey, Knepper, Kodroff, D. Carney
Yale: Moore, Tseng, Penny

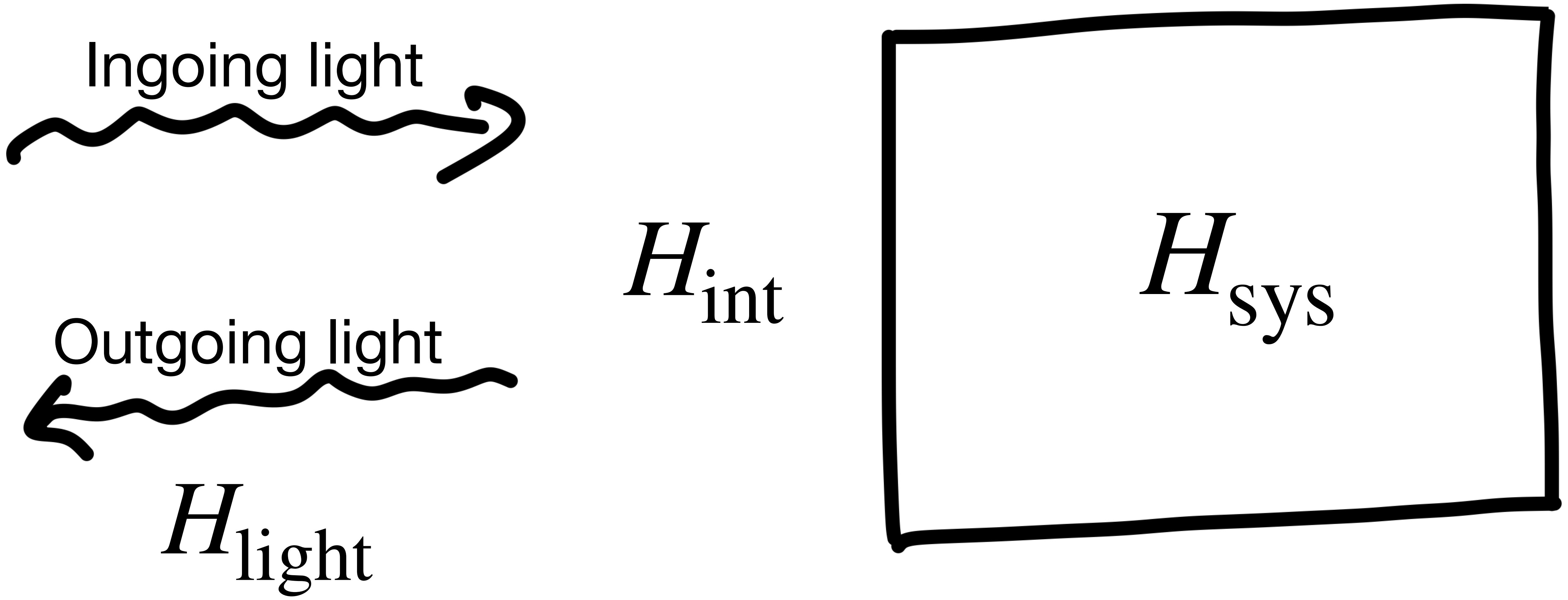
[Wang et al. 2402.13257]

Plan

1. Quantum impulse measurements
2. Testing SM β decay
3. Testing SM γ decay
4. Quantum enhanced measurements

Quantum sensing

- Weak, continuous, measurement may be viewed as a scattering problem:
    - How does the outgoing light depend on the ingoing light and the system/interaction dynamics?



[Clerk et al. RMP (2010) ; Beckey, **GM,** Carney 2311.07270]

Optomechanics

- Dielectric coupling:

$$H_{\rm int} = \int_{\rm sph} d^3\mathbf{x}\,\mathbf{P}(\mathbf{x})\cdot\mathbf{E}(\mathbf{x})$$

- Strong background laser field — linearized Hamiltonian:

$$H_{\rm int} = gxX$$

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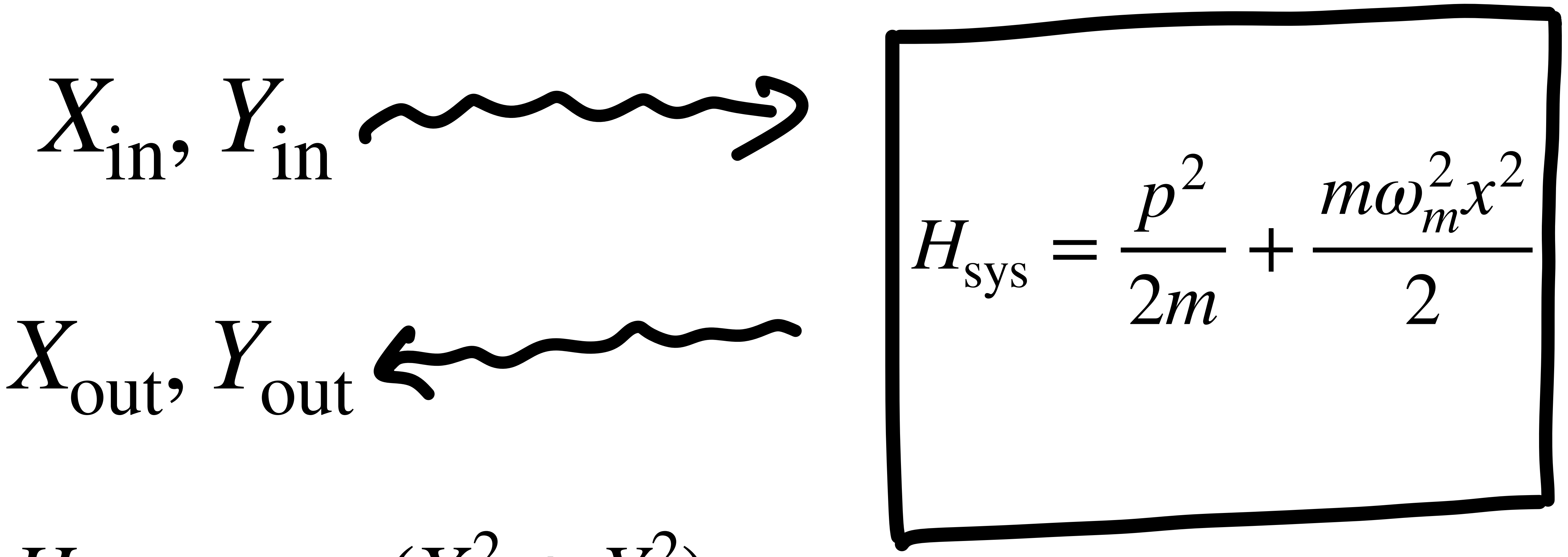


$$H_{\rm light} = \omega_0\,(X^2 + Y^2)$$

Amplitude quadrature

$$X = \frac{1}{2}\left(a + a^\dagger\right)$$

Phase quadrature

$$Y = \frac{i}{2}\left(a^\dagger - a\right)$$

[Pflanzer et al. PRA (2012); Maurer et al. PRA (2024)]

Force estimation

- Force estimated from output phase: $F_{\mathrm{E}} = \chi_{YF}^{-1}\, Y_{\mathrm{out}}$
- Uncertainty in estimator given by power spectral density PSD S_{FF}:

$$2\pi\, S_{FF}(\nu)\, \delta(\nu - \nu') = \langle F_{\mathrm{E}}(\nu) F_{\mathrm{E}}^{\dagger}(\nu') \rangle_{\mathrm{sym}}$$

- PSD has **back action** and **shot noise** contributions:

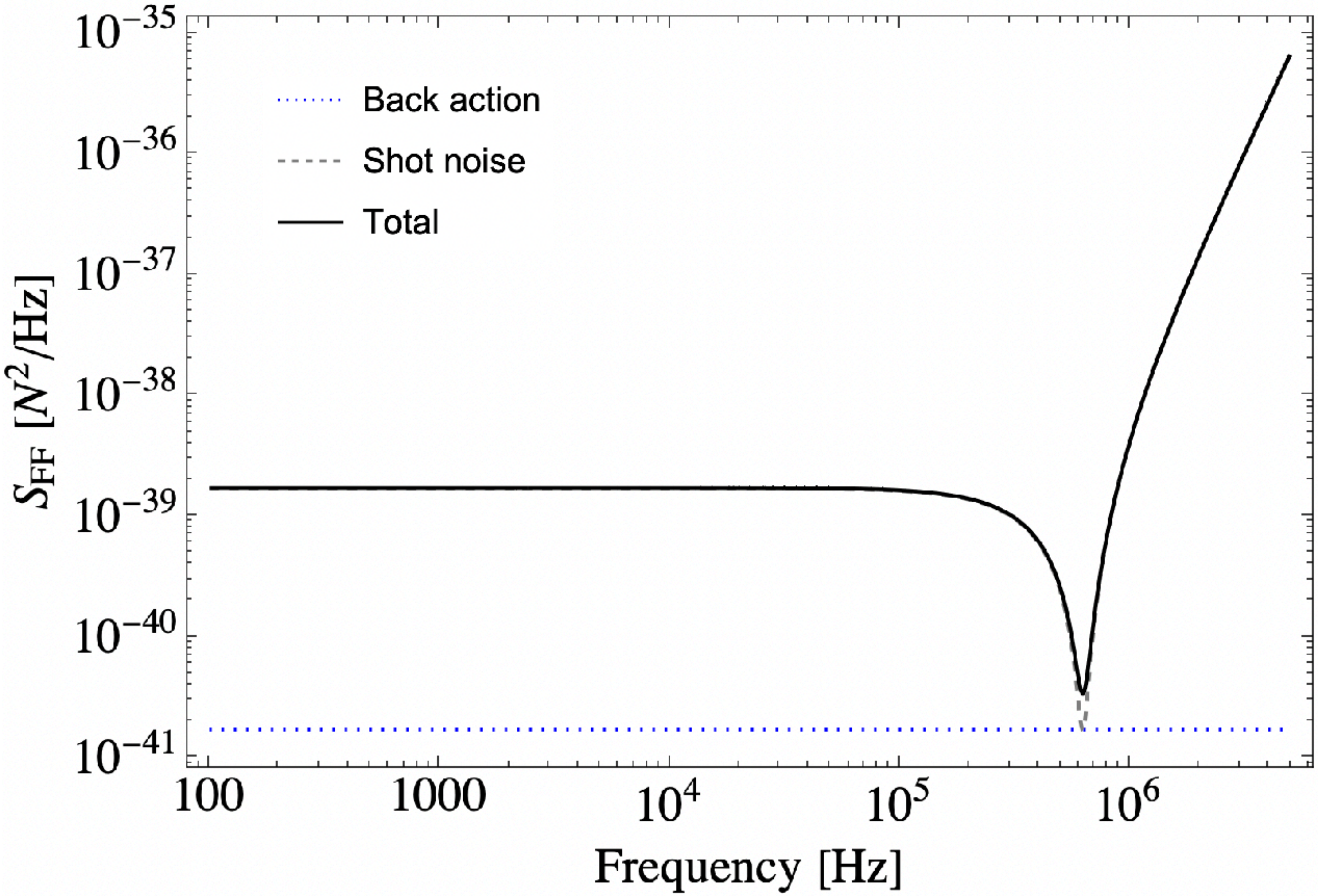
$$S_{FF}(\nu) = \frac{2P\pi}{\lambda_0} + \frac{m^2 \lambda_0 \left(\gamma^2 \nu^2 + (\nu^2 - \omega_m^2)^2 \right)}{4\pi P}$$

Scattered power P

Laser wavelength λ_0

Mechanical damping γ

Uncertainty



Signal force

$$F(t) = \Delta p \, \delta(t - t_0)$$

Impulse threshold:

$$\Delta p_{\text{th}} = \left(\int \frac{d\nu}{S_{FF}(\nu)} \right)^{-1/2}$$

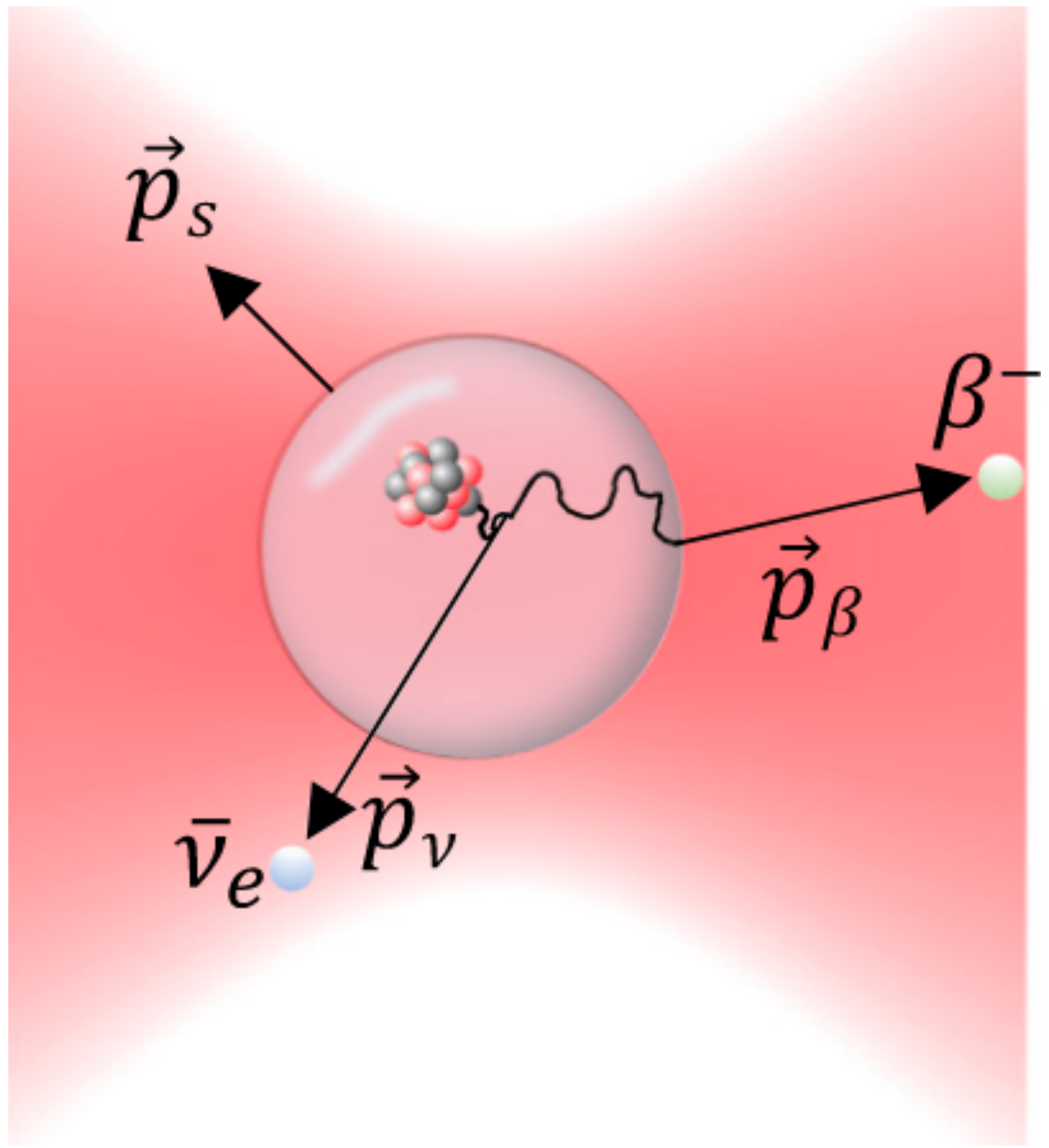
$$\approx \sqrt{m\omega_m}$$

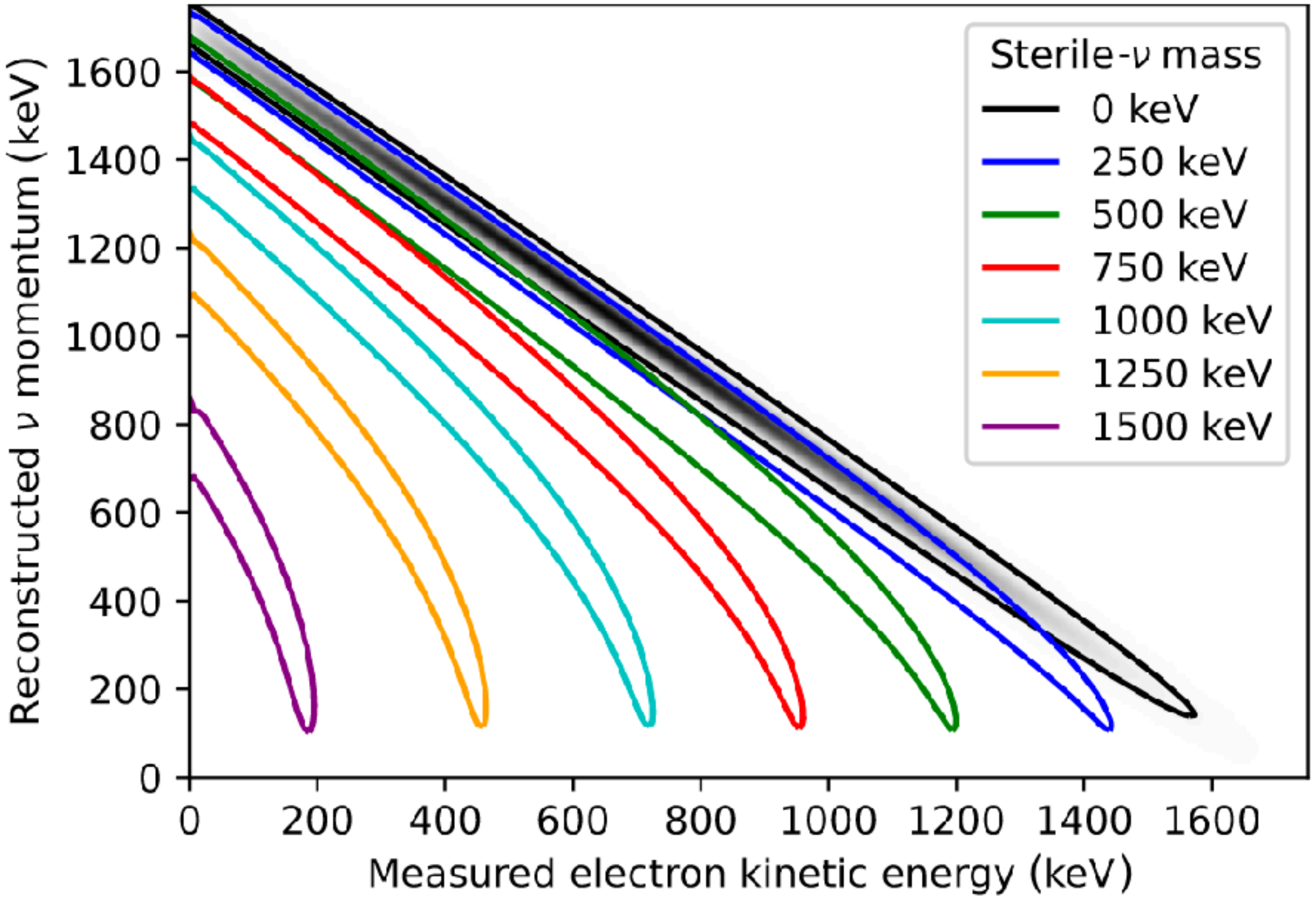
$$\approx 15\text{keV} \left(\frac{m}{\text{fg}} \frac{\omega_m}{10\text{kHz}} \right)^{1/2}$$

Physics goals

Sterile neutrinos

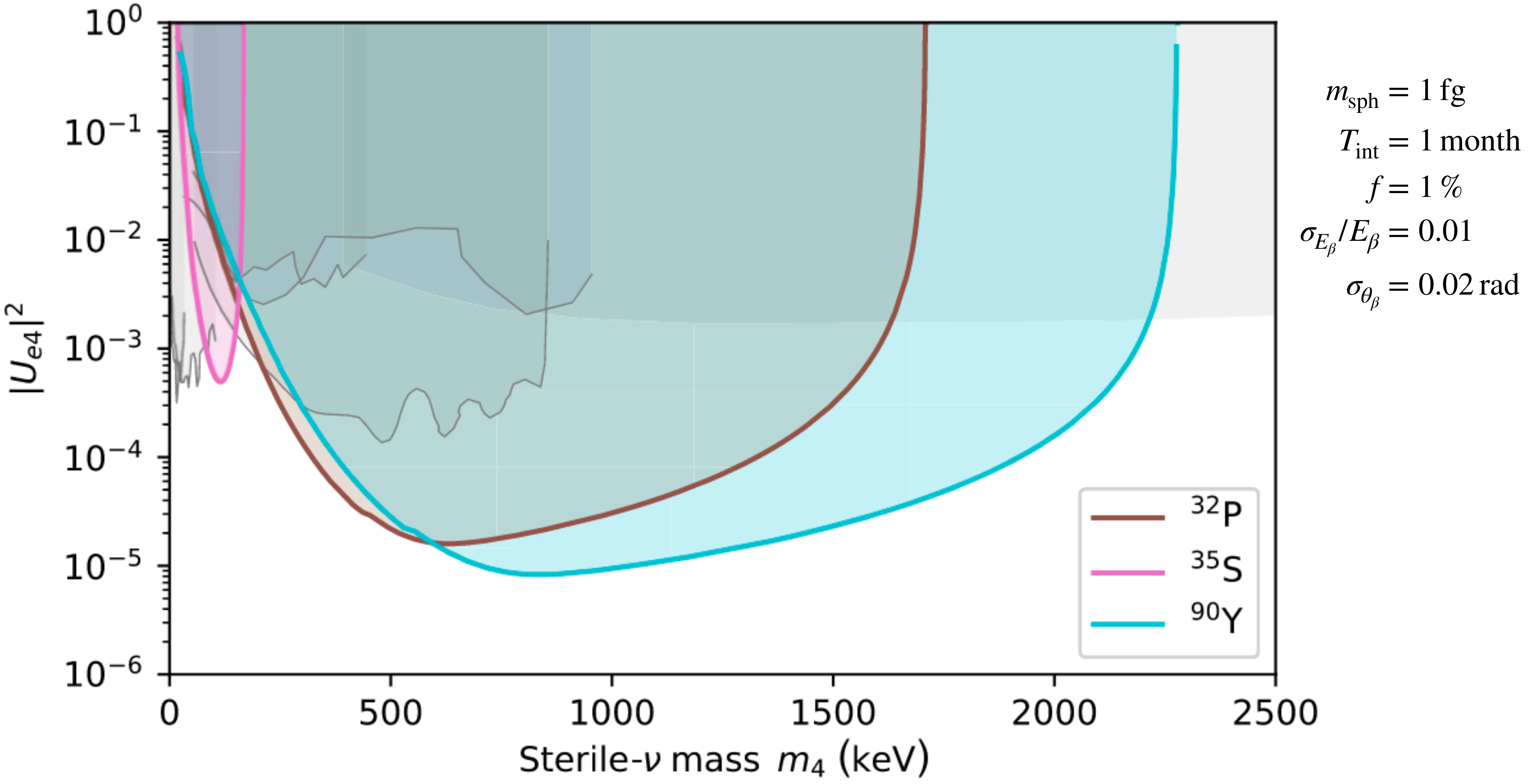
- Radioisotopes undergoing beta decay can emit heavy sterile neutrinos





$$E_\nu \approx Q - E_\beta$$

[Carney, Leach, Moore PRX Quantum (2023)]



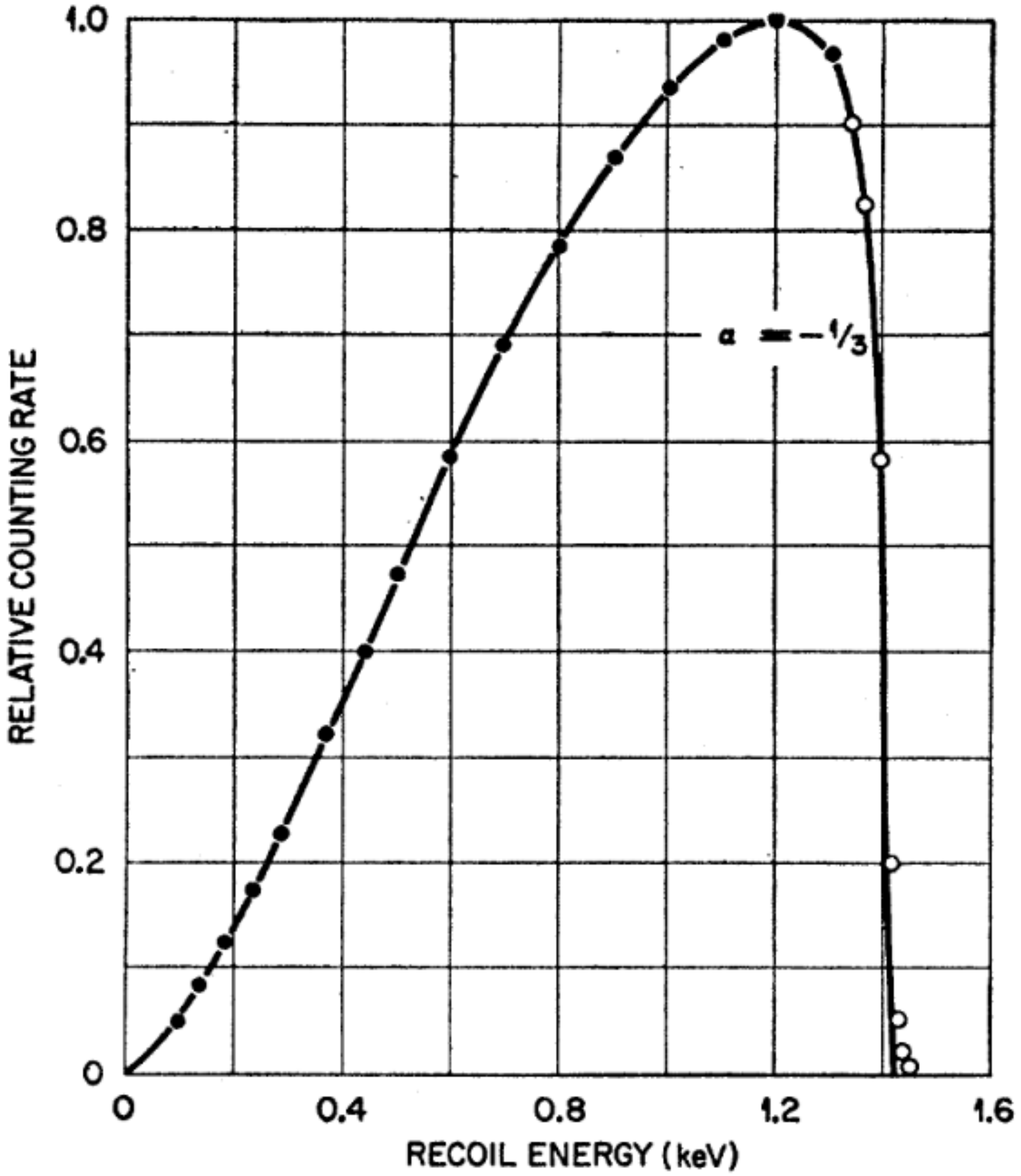
[Carney, Leach, Moore PRX Quantum (2023)]

Precision electroweak physics

- Beta decay differential distribution determined by electroweak sector of Standard Model (+ nuclear corrections)

$$\frac{d^5\Gamma}{d^2\Omega_\nu \, d^2\Omega_\beta \, dE_\beta}$$

- What can we learn by measuring more than E_β?

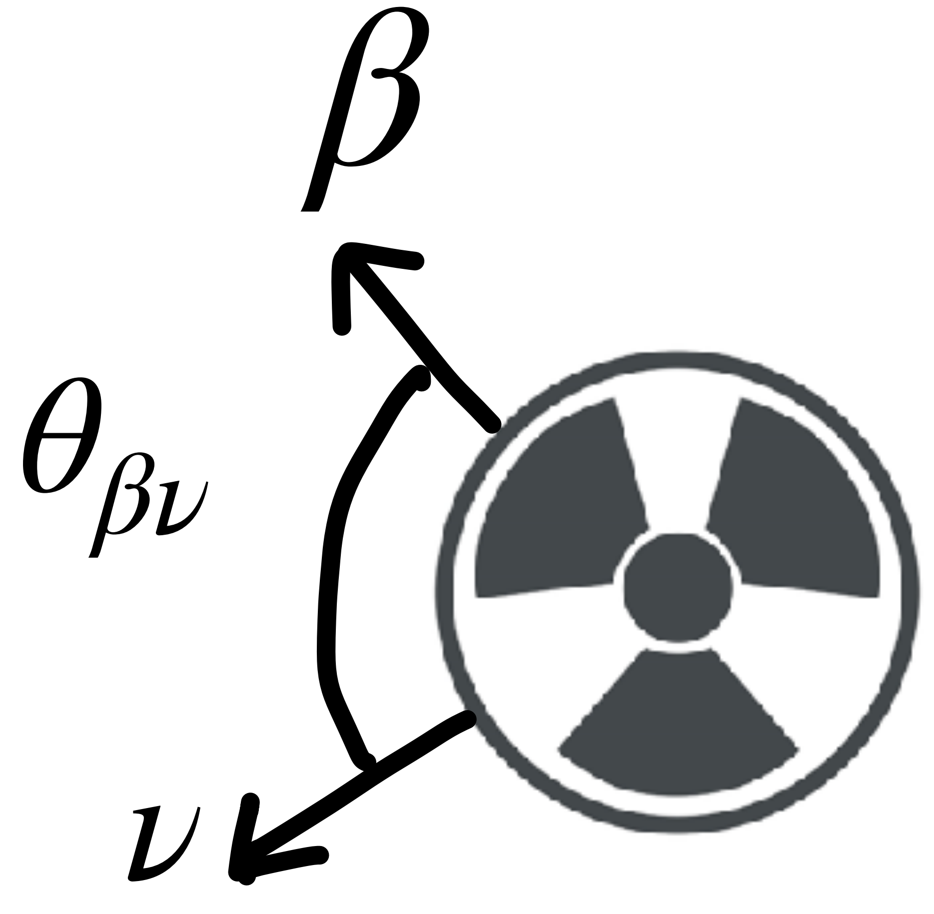


[Johnson et al Phys Rev (1963)]

Angular correlations

- For unpolarised nuclei,

$$\frac{d^2\Gamma}{dE_\beta\, d\cos\theta_{\beta\nu}} = F_0(Z, E_\beta, Q)\xi\left[1 + a_{\beta\nu}\frac{\mathbf{p}_\beta \cdot \mathbf{p}_\nu}{E_\beta E_\nu} + b\frac{m_e}{E_e}\right]$$



- Simple observable: correlation of $\beta - \nu$ angle

$$\frac{d^2\Gamma}{dE_\beta\, d\cos\theta_{\beta\nu}} = A\cos\theta_{\beta\nu} + B$$

- In SM for Gamow-Teller decays, $a_{\beta\nu} = \frac{A}{B} \cdot \frac{p_\beta}{E_\beta} = -\frac{1}{3}$

[Jackson et al. Phys Rev (1957)]

New interactions?

- The beta spectrum may be modified by additional tensor interactions

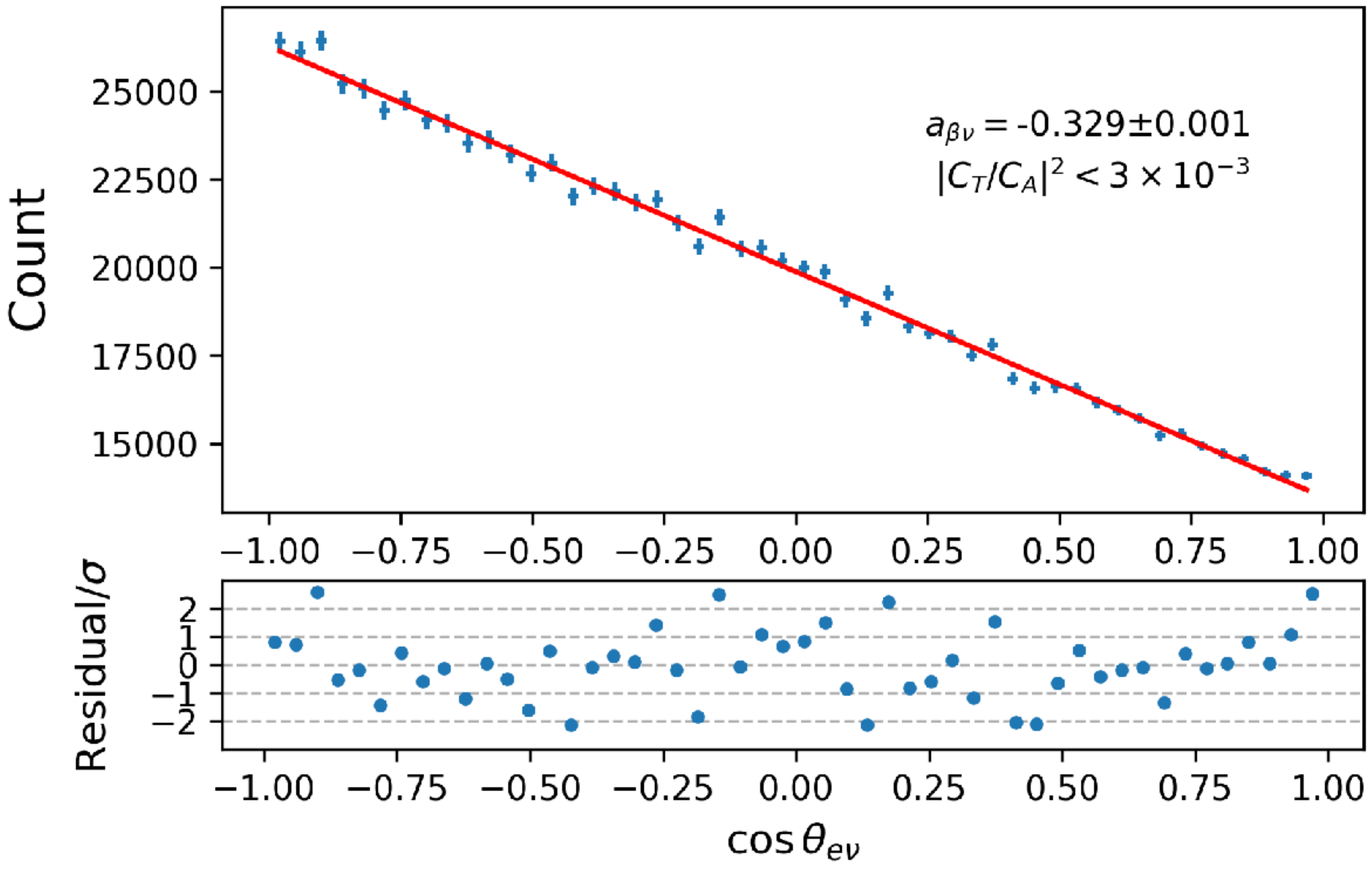
$$a_{\beta\nu} = -\frac{1}{3}\left(1 - \left|\frac{C_T}{C_A}\right|^2\right) \qquad \mathscr{L} \supset C_T\, G_F\, \bar{n}\sigma^{\mu\nu} p\, \bar{\nu}\sigma_{\mu\nu} e$$

- β-decay measurements constrain $\left|\frac{C_T}{C_A}\right|^2 \lesssim 7.6 \times 10^{-3}$ – neutron decay tension $\left|\frac{C_T}{C_A}\right|^2 \approx 4.7 \times 10^{-3}$?

- Complementary to $\mathrm{p\,p} \to \mathrm{e^+e^-} + X$ at LHC

[Burkey et al. PRL (2022); Cirigliano et al. (2013); Falkowski et al. JHEP (2021); Beck et al. PRC (2022)]

Sensitivity projection



^{66}Ni

$$m_{\rm sph} = 1\,{\rm fg}$$

$$N_{\rm decays} = 10^7$$

$$\sigma_{E_\beta}/E_\beta = 0.01$$

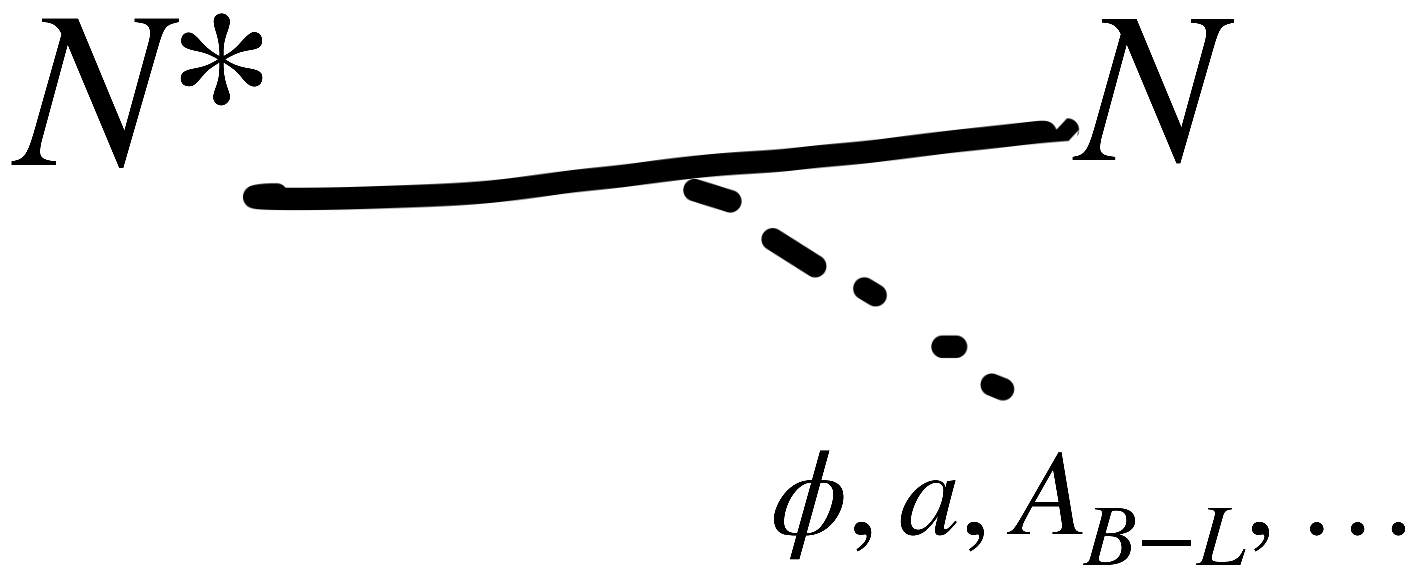
$$\sigma_{\theta_\beta} = 0.02\,{\rm rad}$$

- Sensitive to $\left|\dfrac{C_T}{C_A}\right|^2 \approx 5 \times 10^{-3}$

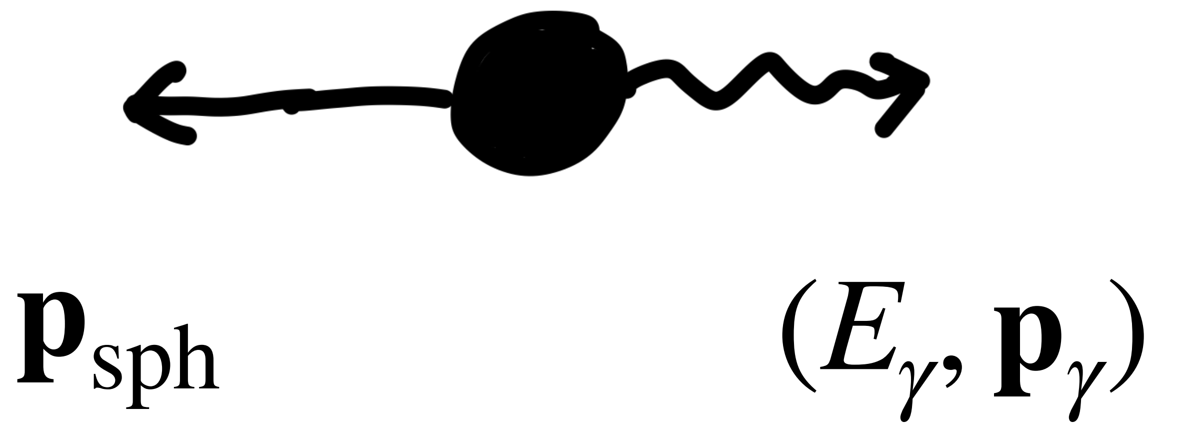
[Carney, GM, Moore, Rule 24xx.]

Gamma decays

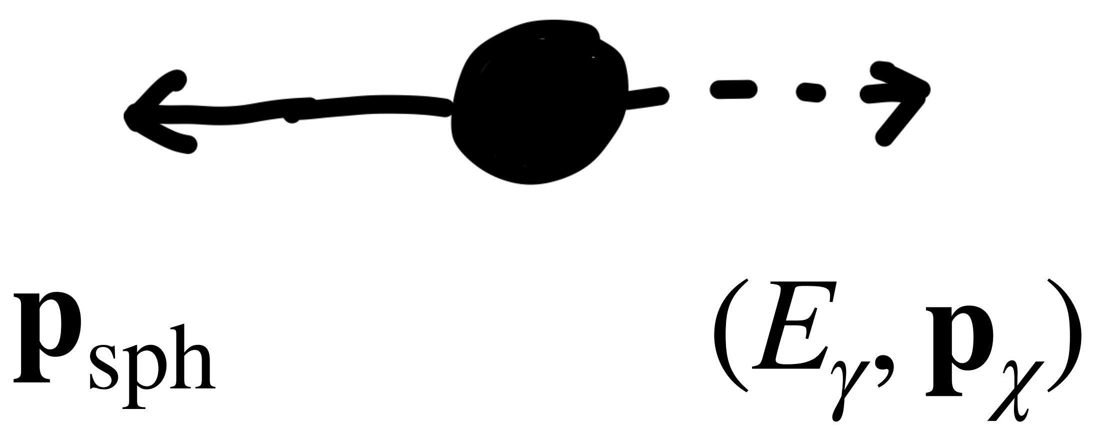
- Excited nuclear states can de-excite by emitting a photon
- Or, may emit a **massive**, invisible state



Photon emission



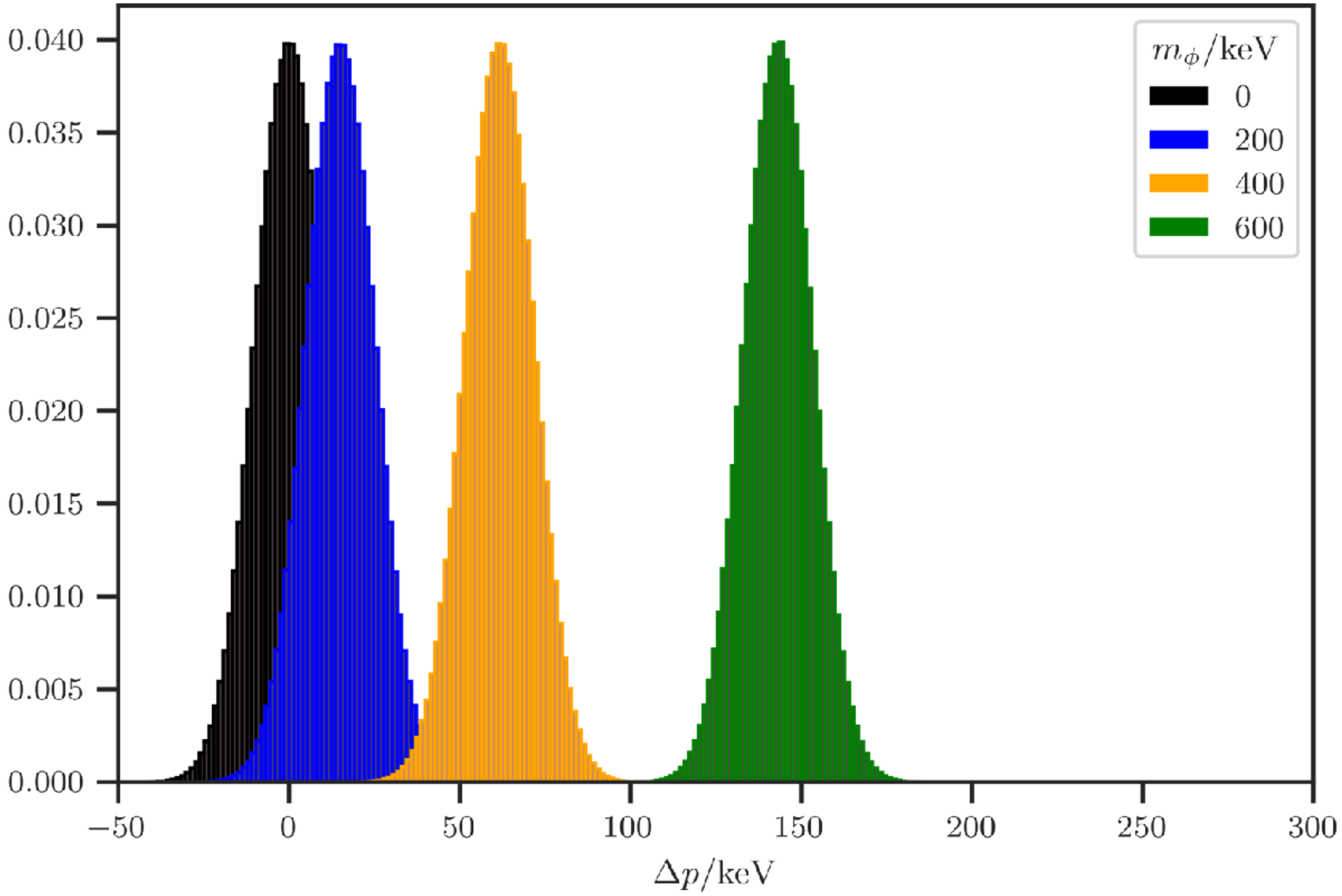
Invisible emission



$$\Delta p = \mathbf{p}_\gamma - \mathbf{p}_\chi = E_\gamma(1 - v_\chi)$$

[Weinberg PRL (1978); Treiman, Wilczek PLB (1978); …; Benato et al. (2019); Dent et al. (2022); Carney, **GM**, Moore 24xx]

Missing momentum



Nuclear batteries

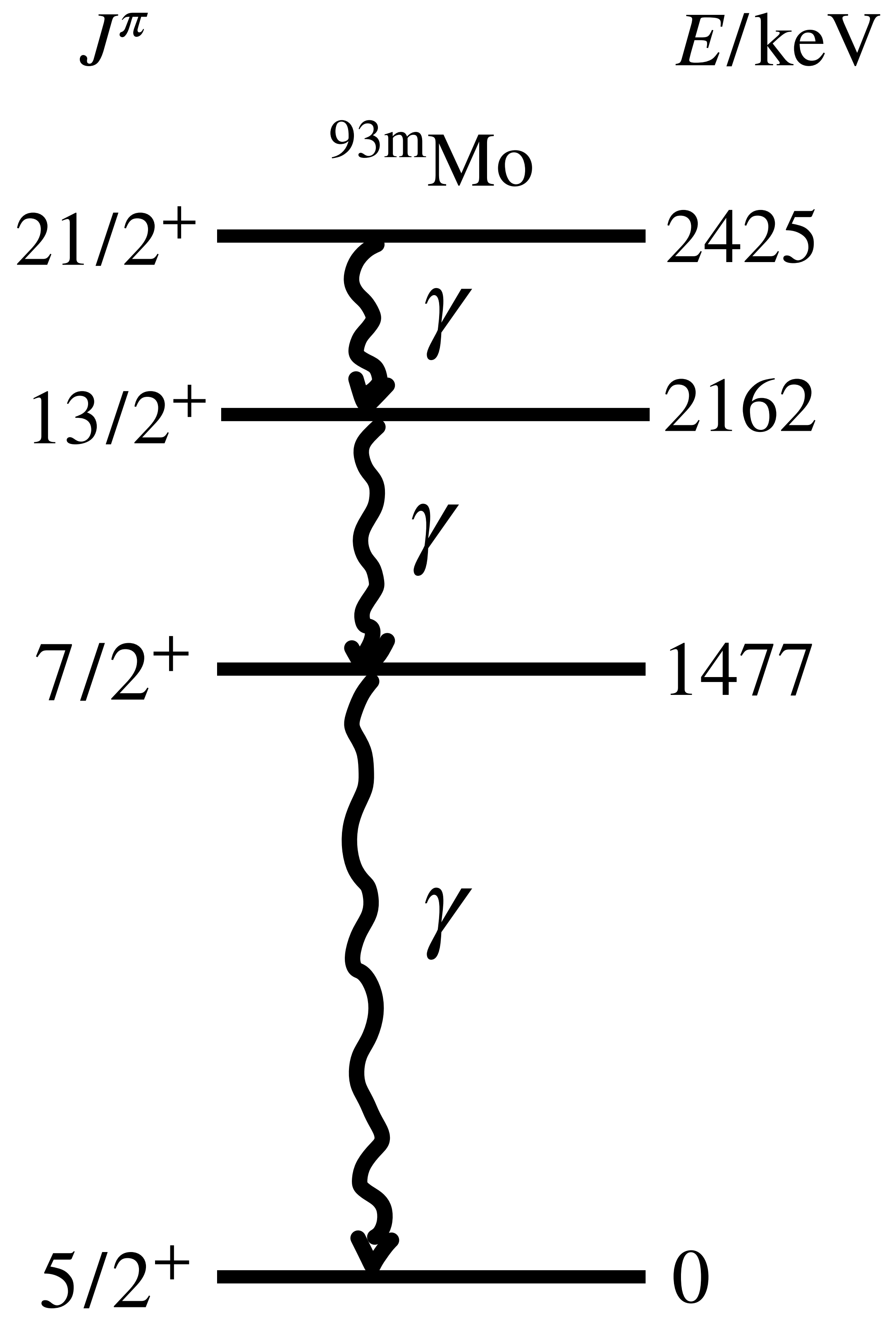
- Metastable excited nuclear isomers: long lifetimes (seconds - years)

- Isomer transition initiates prompt gamma cascade

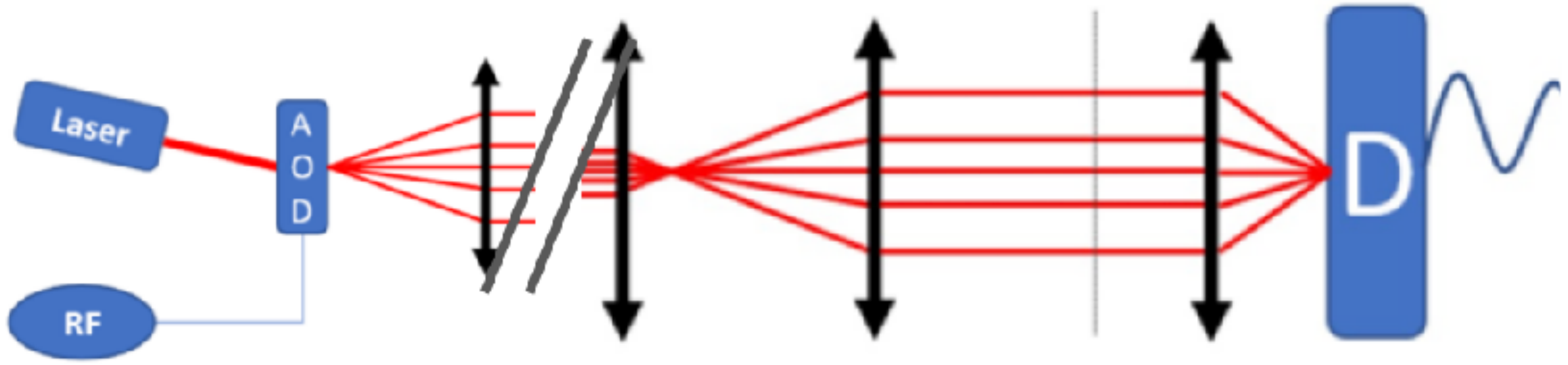
- Aim to constrain branching ratio to invisible states, e.g.

$$\mathscr{L}_{\text{int}} = g_\phi \phi \bar{N} N$$

$$\mathrm{BR}_\phi(E\ell) \approx \frac{1}{2}\left(\frac{g_\phi}{e}\right)^2 v_\phi^{2\ell+1}, \quad l > 0$$

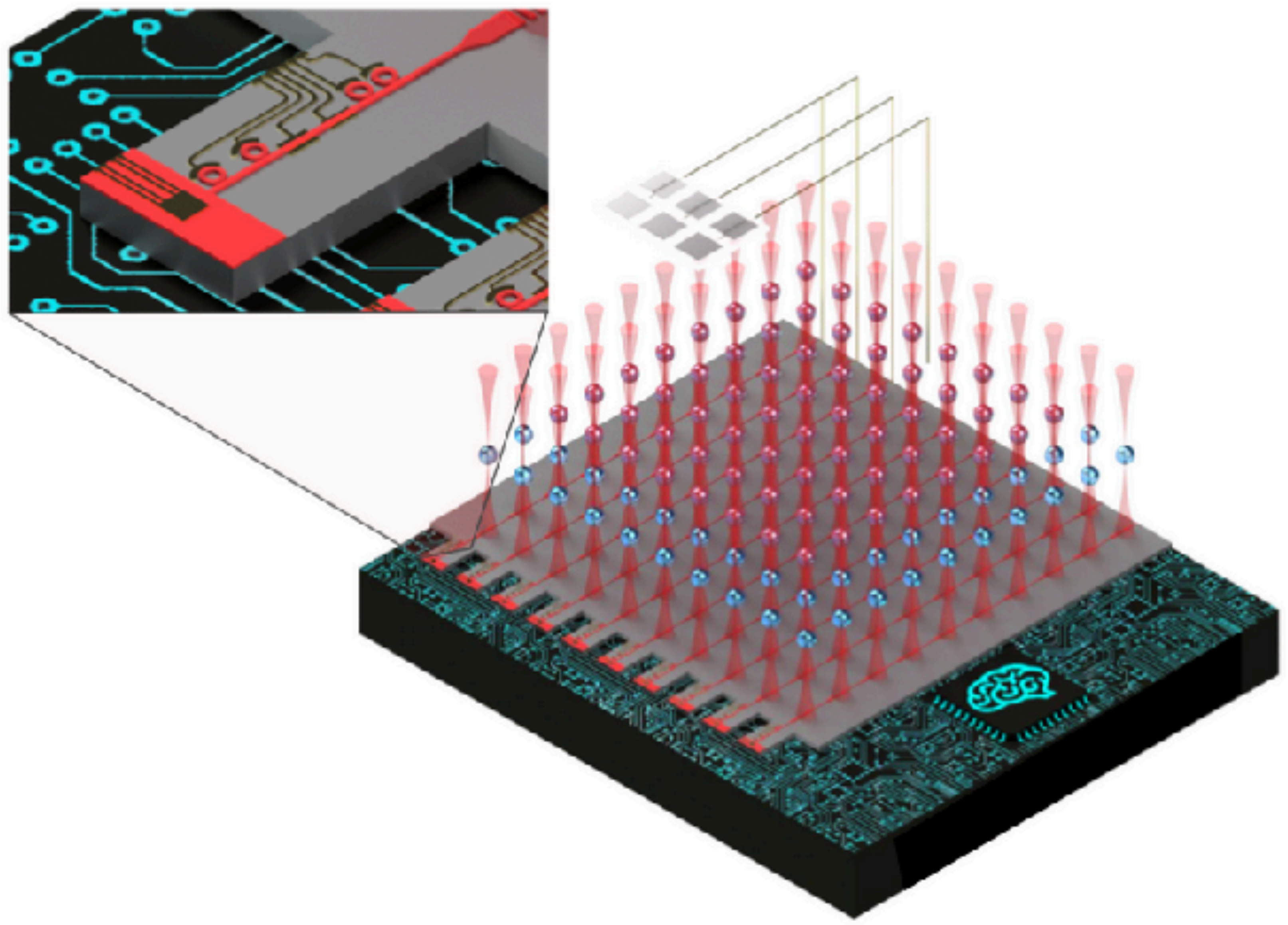


Sphere arrays

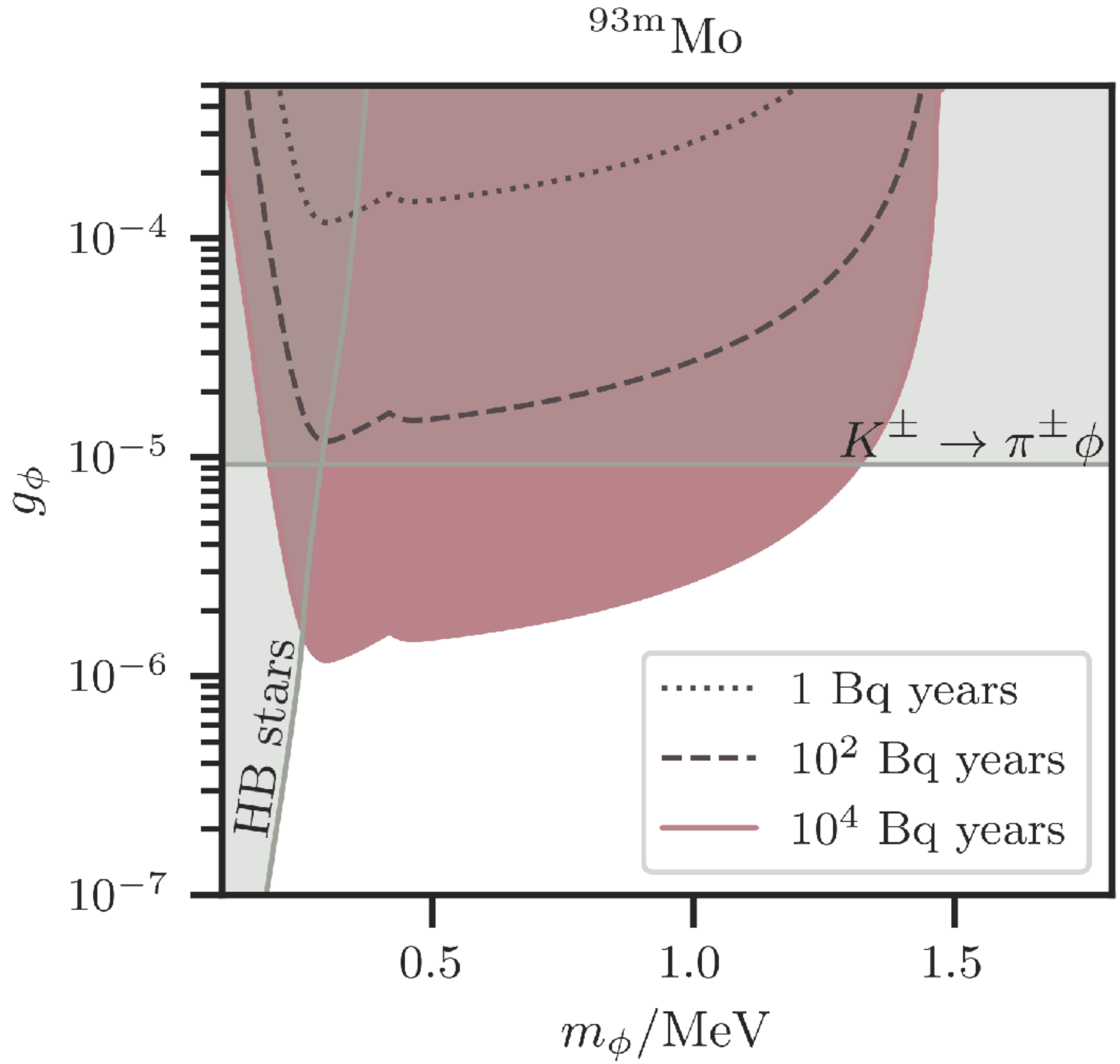


- Using beam splitters, can currently levitate + readout 100s of spheres

- Aim to scale this up to 100x100 sphere array

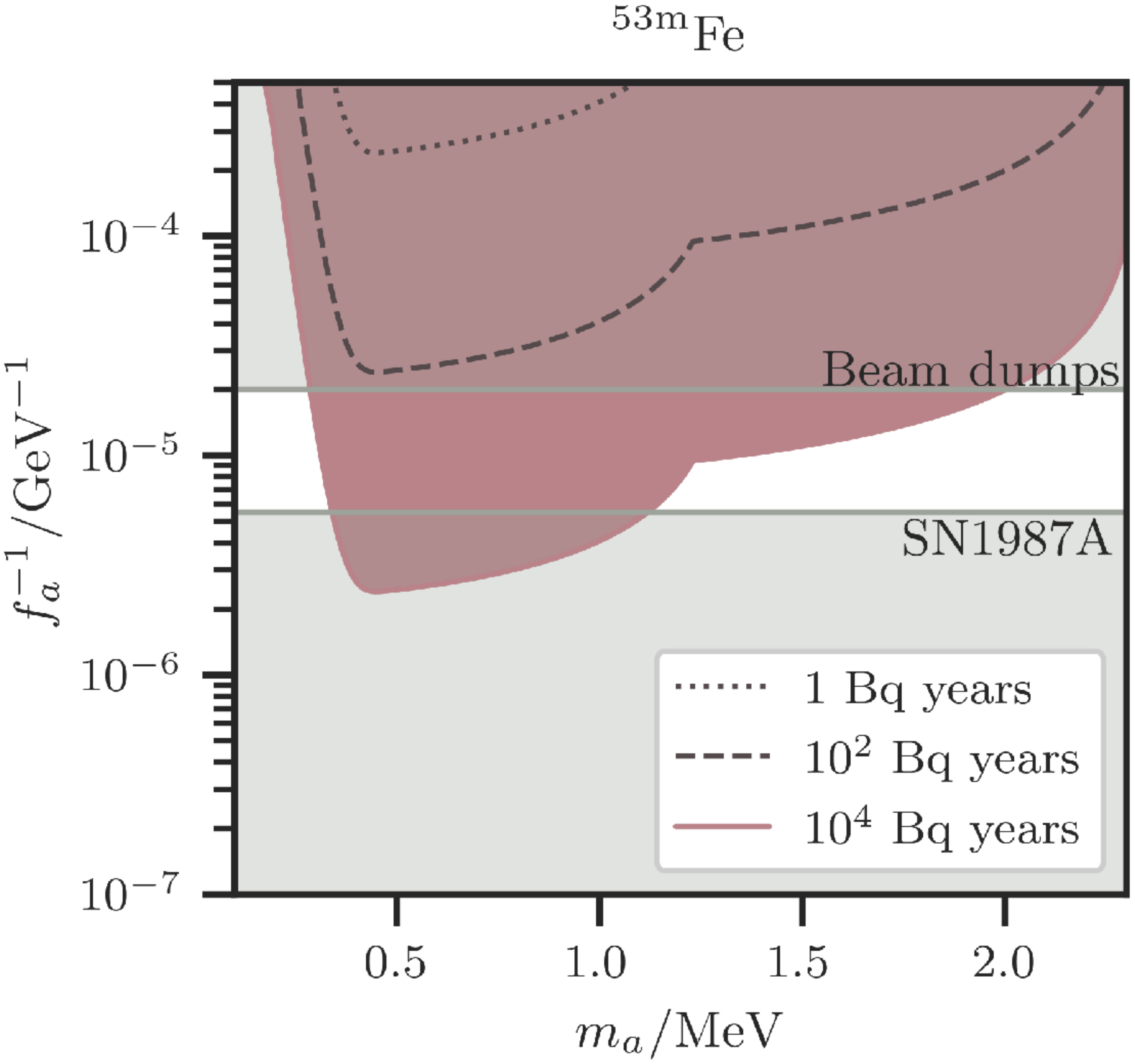


[D. Moore]



$m_{\mathrm{sph}} = 1$ fg
$\sigma_{E_\gamma}/E_\gamma = 0.01$
$\sigma_{\theta_\gamma} = 0.01$ rad

[Carney, Moore, **GM** 24xx.]



$$\mathscr{L}_{\text{int}} = \frac{1}{f_a}\partial_\mu a\,\bar{N}\gamma^\mu\gamma^5 N$$

Summary of BSM searches

- Reconstruction of $\mathbf{p}_\nu$ by measuring $\mathbf{p}_{\rm sph}$ and $\mathbf{p}_\beta$ allows:

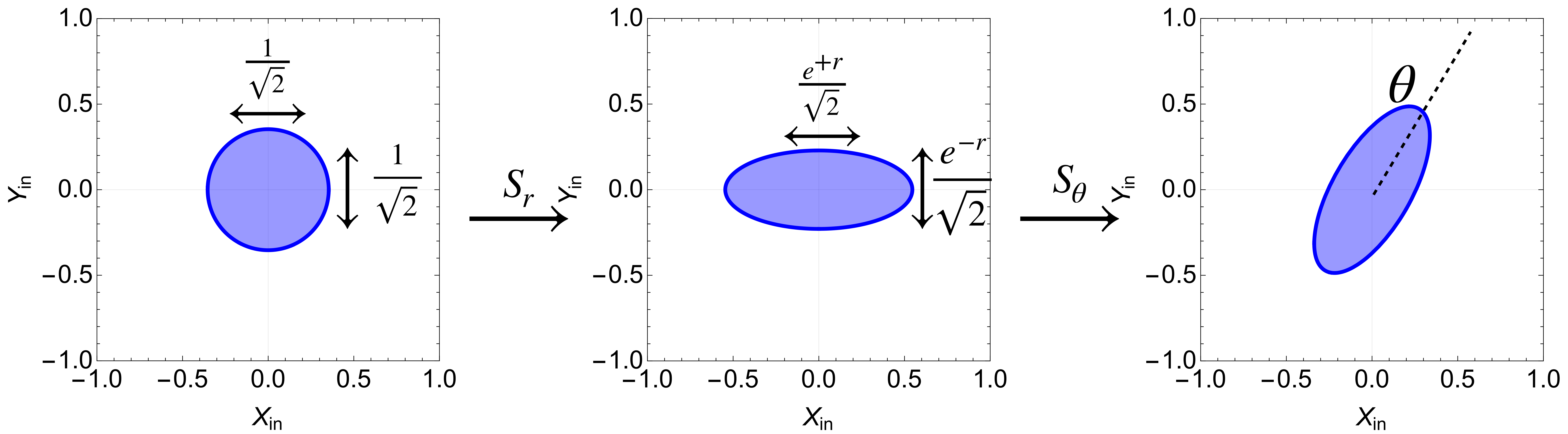
    1. Searches for heavy neutrino ν_4 mixing with ν_e;

    2. Searches for modifications to $a_{\beta\nu}$ parameter of β-spectrum.

- Infer $\mathbf{p}_\gamma$ to search for heavy states emitted in γ-decay

Squeezing

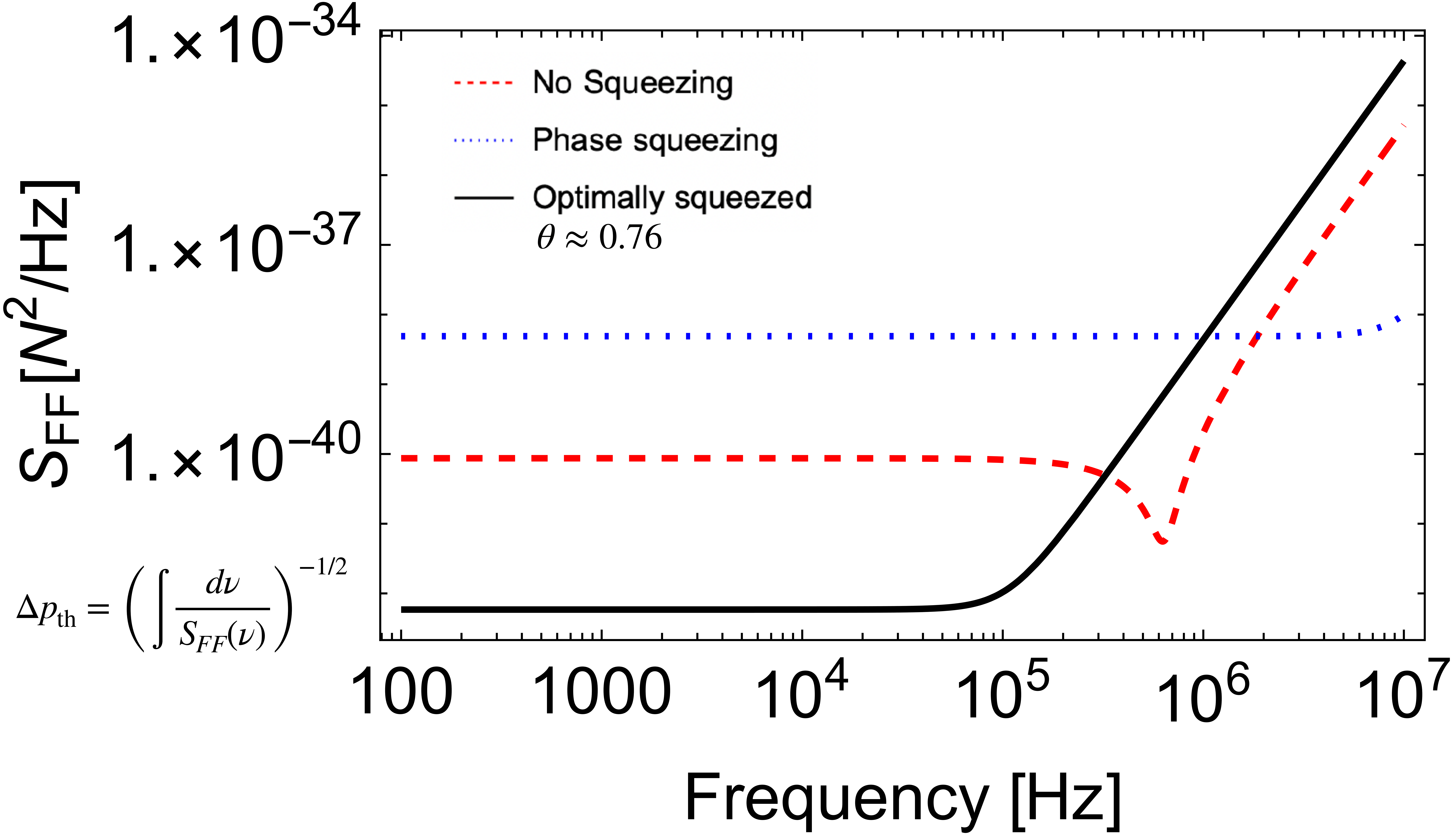
- Transform incoming light: $\begin{pmatrix} a_{\text{in}} \\ a_{\text{in}}^{\dagger} \end{pmatrix} \rightarrow U \begin{pmatrix} a_{\text{in}} \\ a_{\text{in}}^{\dagger} \end{pmatrix} U^{\dagger}$, with $U = S_{\theta} \underset{}{\overset{\mathrm{SU}(1,1)}{\overset{\Cap}{S_r}}}$.



Coherent state

Phase squeezed

General squeezed



No Squeezing
Phase squeezing
Optimally squeezed
$\theta \approx 0.76$
$1.\times 10^{-34}$
$1.\times 10^{-37}$
$1.\times 10^{-40}$
$S_{FF}[N^2/Hz]$
$\Delta p_{\rm th} = \left(\int \frac{d\nu}{S_{FF}(\nu)} \right)^{-1/2}$
100
1000
10^4
10^5
10^6
10^7
Frequency [Hz]

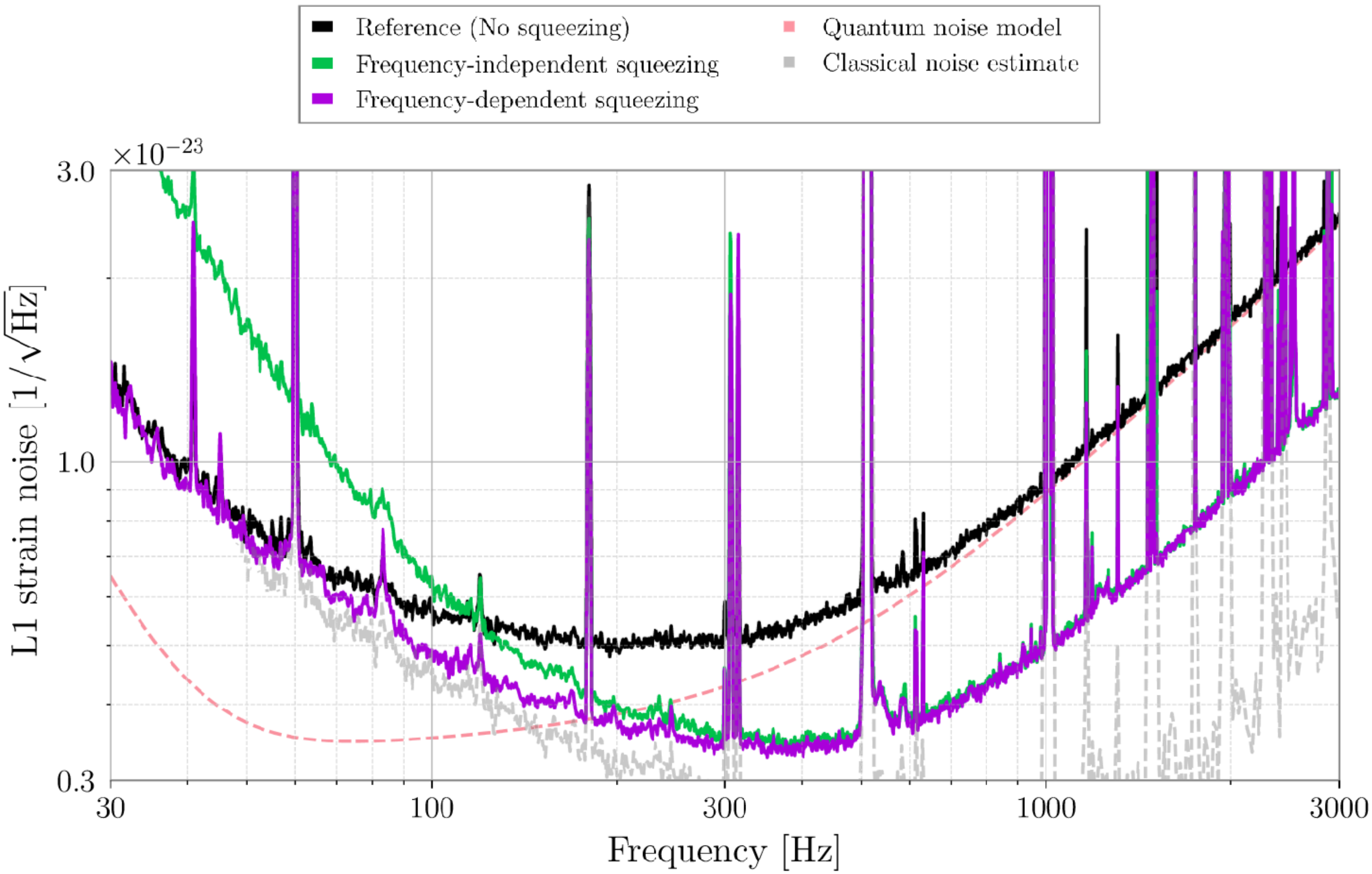
Frequency-dependent squeezing

- Squeezing angle may be frequency-dependent $S(r, \theta(\nu))$
- Cavities introduce phase shifts $\alpha_i(\nu) = \arctan(\frac{\nu - \omega_i}{\omega_i} + \nu/\gamma_i)$
- Use a sequence of cavities to tune $\theta(\nu)$ to minimise noise:

$$\tan \theta_*(\nu) = \frac{2\mathrm{Re}\, \chi_{YX}\chi_{YY}^*}{\chi_{YX}{}^2 - \chi_{YY}{}^2}$$

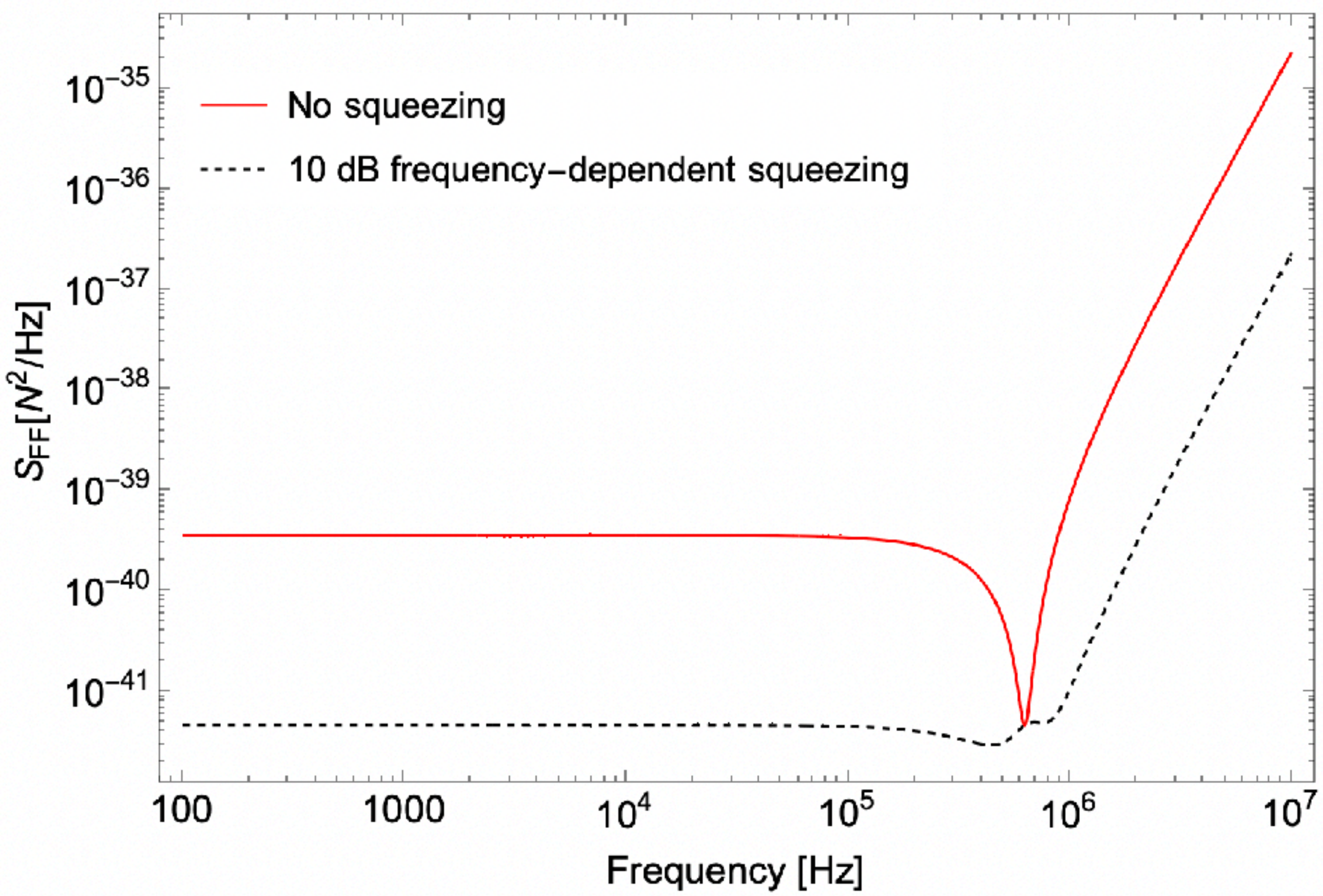
$$S_{FF}(r, \theta_*) \approx e^{-2r} S_{FF}(r = 0)$$

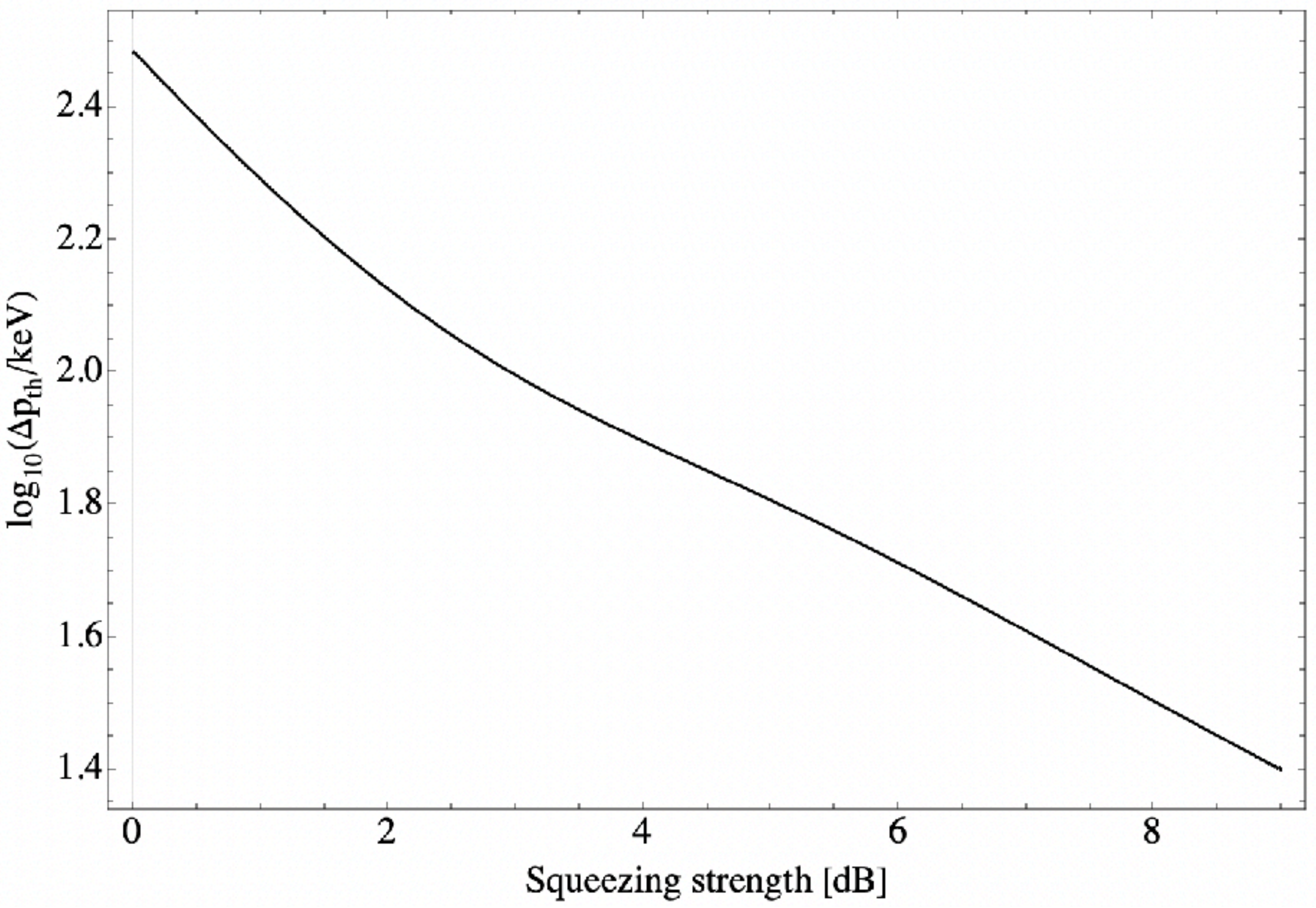
[Unruh PRD (1979); Kimble et al. PRD (2001); Ghosh et al. 2211.14460; Beckey, Carney, **GM** 24xx]

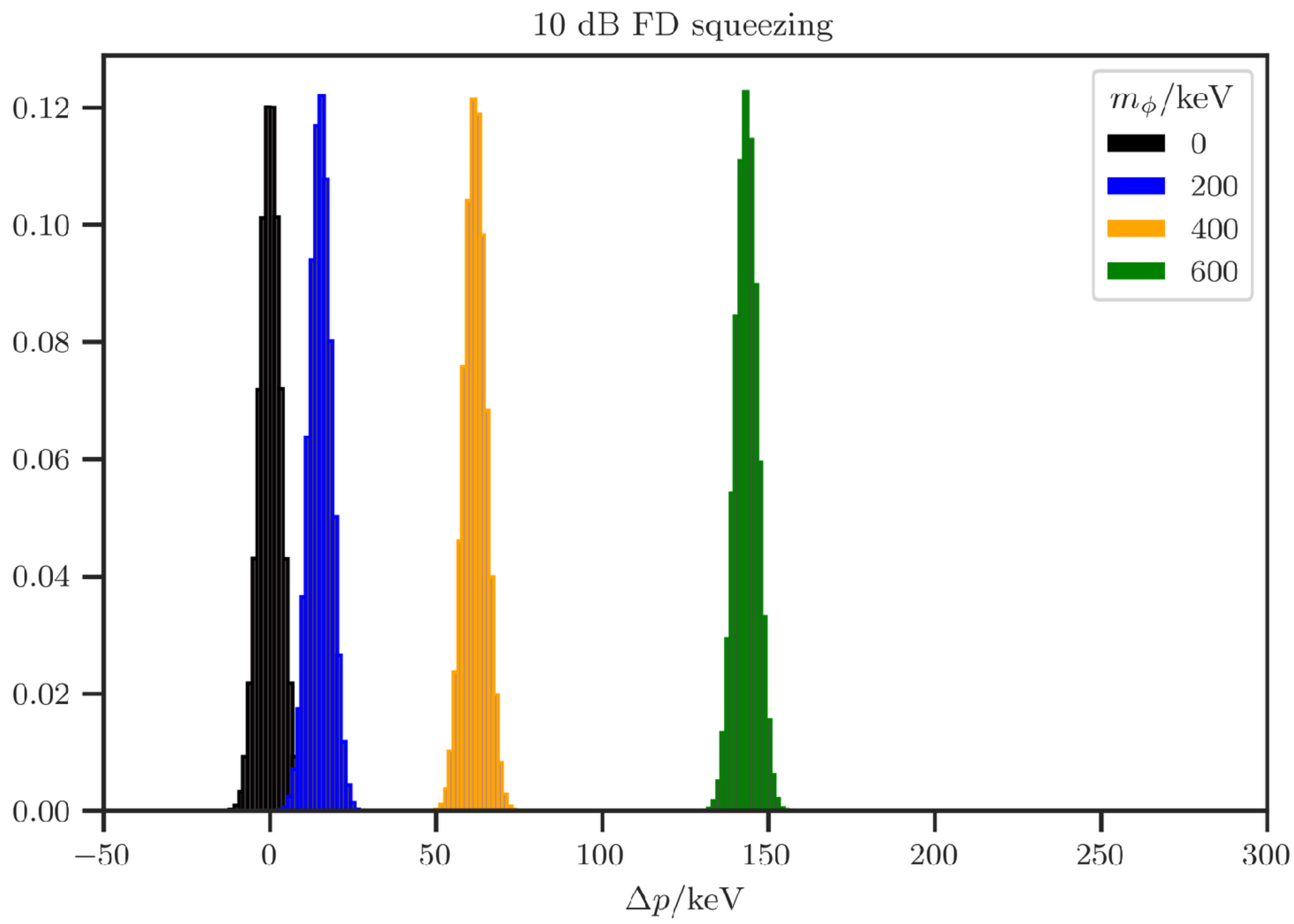


[Ganapathy et al., PRX Quantum (2023)]

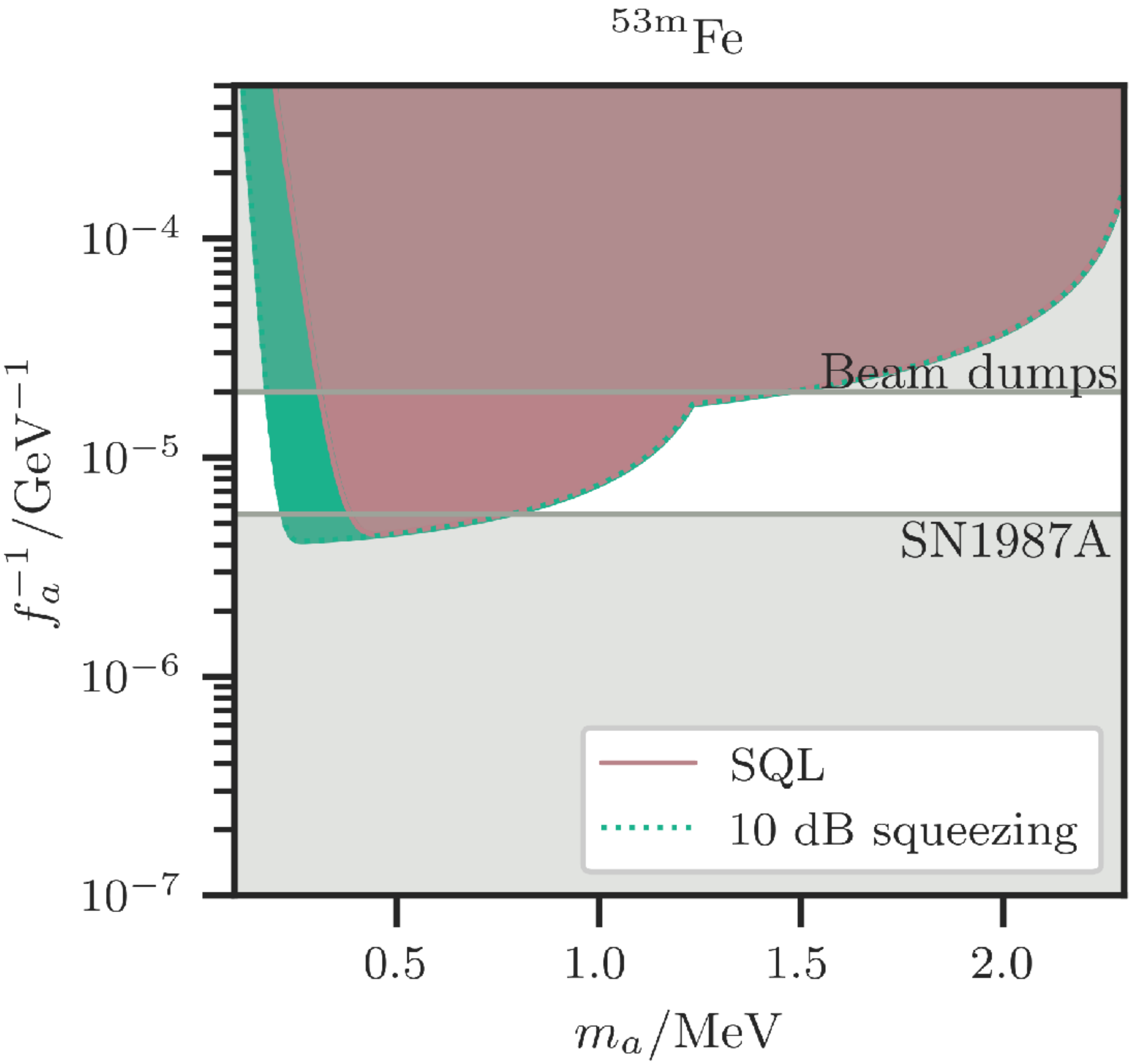
Impulse sensitivity







10 dB FD squeezing
m_ϕ/keV
0
200
400
600
0.00
0.02
0.04
0.06
0.08
0.10
0.12
−50
0
50
100
150
200
250
300
Δp/keV



^{53m}Fe
10^{-4}
10^{-5}
10^{-6}
10^{-7}
f_a^{-1}/GeV^{-1}
Beam dumps
SN1987A
SQL
10 dB squeezing
0.5
1.0
1.5
2.0
m_a/MeV

Conclusions

- Quantum-limited impulse measurements enable measurement of nuclear recoils
- Sensitive to sub-MeV dark state emissions in beta and gamma decay, as well as electroweak precision tests
- Quantum-enhanced techniques decrease noise, allowing access to lighter masses

Thank you

Backup slides

Quantum light

- Some notation:
  - Hermitian photon operators:

Amplitude quadrature $X_{\mathbf{p}} = \frac{1}{2}(a_{\mathbf{p}} + a_{\mathbf{p}}^{\dagger})$

Phase quadrature $Y_{\mathbf{p}} = \frac{i}{2}(a_{\mathbf{p}}^{\dagger} - a_{\mathbf{p}})$

$$[X_{\mathbf{p}}, Y_{\mathbf{q}}] = i\delta_{\mathbf{p},\mathbf{q}}$$

$$\begin{aligned} A_\mu(\mathbf{x}) &= \sum_{\mathbf{p},r} \epsilon^*_{r,\mu}(\mathbf{p}) u^*_{\mathbf{p}}(\mathbf{x}) a_{\mathbf{p},r} + \mathrm{h.c.} \\ &= \sum_{\mathbf{p},r} \mathrm{Re}\Big[\epsilon_{r,\mu}(\mathbf{p}) u_{\mathbf{p}}(\mathbf{x})\Big] X_{\mathbf{p}} + \mathrm{Im}\Big[\epsilon_{r,\mu}(\mathbf{p}) u_{\mathbf{p}}(\mathbf{x})\Big] Y_{\mathbf{p}} \end{aligned}$$

Input-output relations

- For quadratic dynamics, the input and output are linearly related:

$$Y_{\text{out}} = Y_{\text{in}} + \sqrt{\kappa} x$$

Measurement rate κ

- We may integrate out the mechanical d.o.f to find

$$Y_{\text{out}} = \chi_{YX} X_{\text{in}} + \chi_{YY} Y_{\text{in}} + \chi_{YF} F_{\text{in}}$$

Susceptibilities χ_{ij}

Input force F_{in}

- Construct an estimator for the force:

$$F = \chi_{YF}^{-1} Y_{\text{out}}$$

Unbiased:
$\langle F \rangle = \langle F_{\text{in}} \rangle$

Quantum uncertainties

- What about higher-point statistics? For Gaussian processes, all encoded in power spectral density (PSD) S_{FF}:

$$2\pi S_{FF}(\nu)\delta(\nu - \nu') = \langle F(\nu)F^{\dagger}(\nu')\rangle$$

$$S_{FF} = \chi_{YF}^{\ -2} \sum_{ij=X,Y} \chi^{*}_{Yi}\chi_{Yj}S_{ij} + S^{\text{in}}_{FF}$$

"Intrinsic uncertainty" from input force fluctuations

"Measurement-related" uncertainty

- The uncertainty in the estimator of the force has additional contributions from the uncertainty in the input light

Standard quantum limit

- In coherent, classical state, $S_{XX} = S_{YY} = \frac{1}{2}$ & $S_{XY} = 0$

$$\chi_{YF}\ ^{2} S_{FF} = \frac{1}{2}\ \chi_{YX}\ ^{2} + \frac{1}{2}\ \chi_{YY}\ ^{2}$$

Back action **Shot noise**

$$S_{FF}(\nu) = \frac{P\pi}{\lambda_0} + \frac{m^2\lambda_0\left(\gamma^2\nu^2 + (\nu^2 - \omega_m^2)^2\right)}{4\pi P}$$

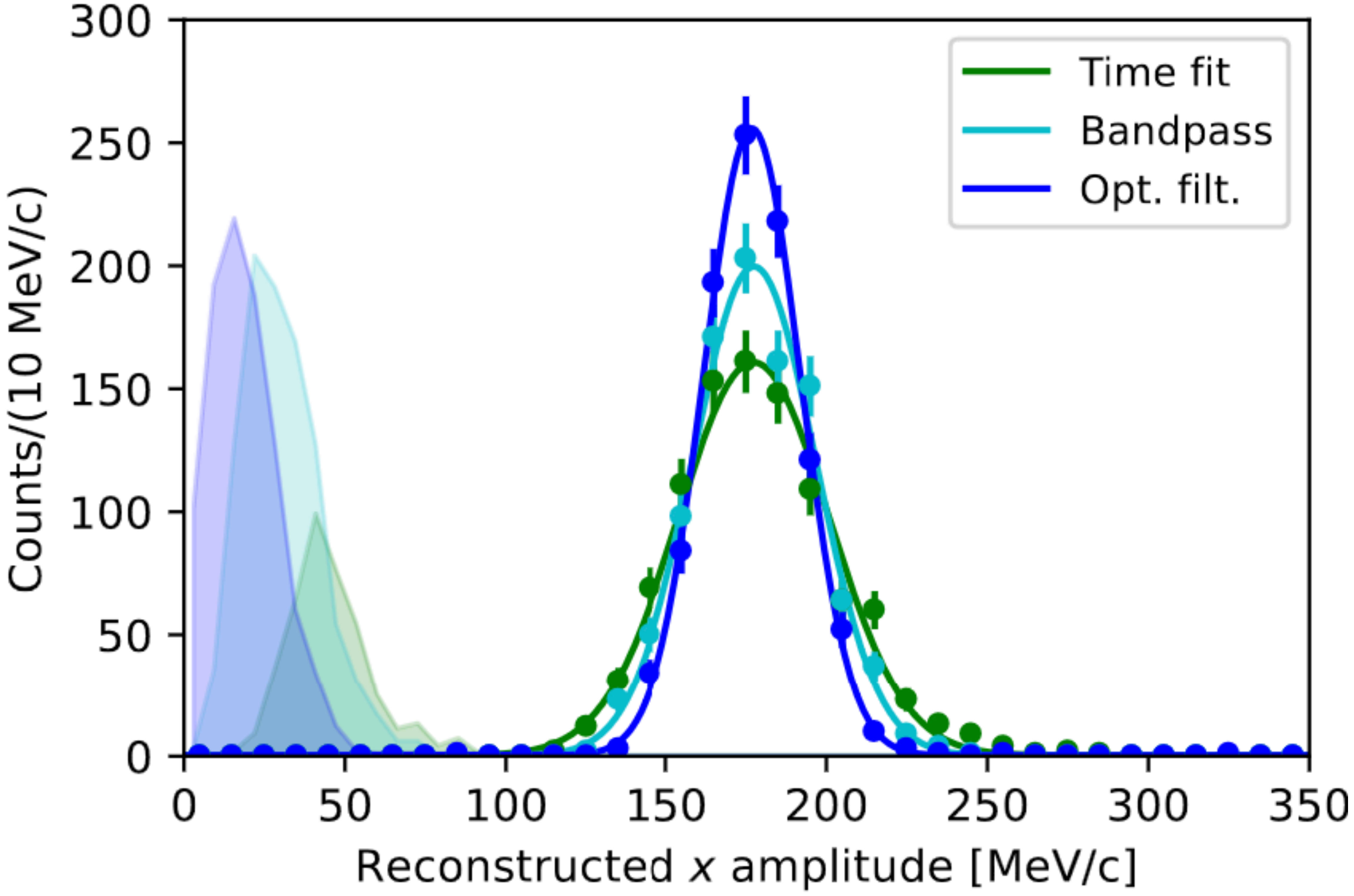
$$S_{FF}(0) \overset{\text{SQL}}{\approx} m\omega_m^2$$

Scattered power P,
Wavelength λ_0,
Mechanical damping γ

- What does this mean for our impulse measurements?

Optimal filtering

- We are looking for an impulse kick $F_{\text{in}}(t, t_0) = \Delta p\, \delta(t - t_0)$
- How do we maximize the SNR?
  - Optimal filtering: $$F_f(t) = \int d\nu\, e^{i\nu(t-t_0)} F(\nu) \cdot f(\nu)$$
  - Filter $f(\nu) = 2\pi \Delta p \dfrac{1}{S_{FF}(\nu)}$



[2402.13257]

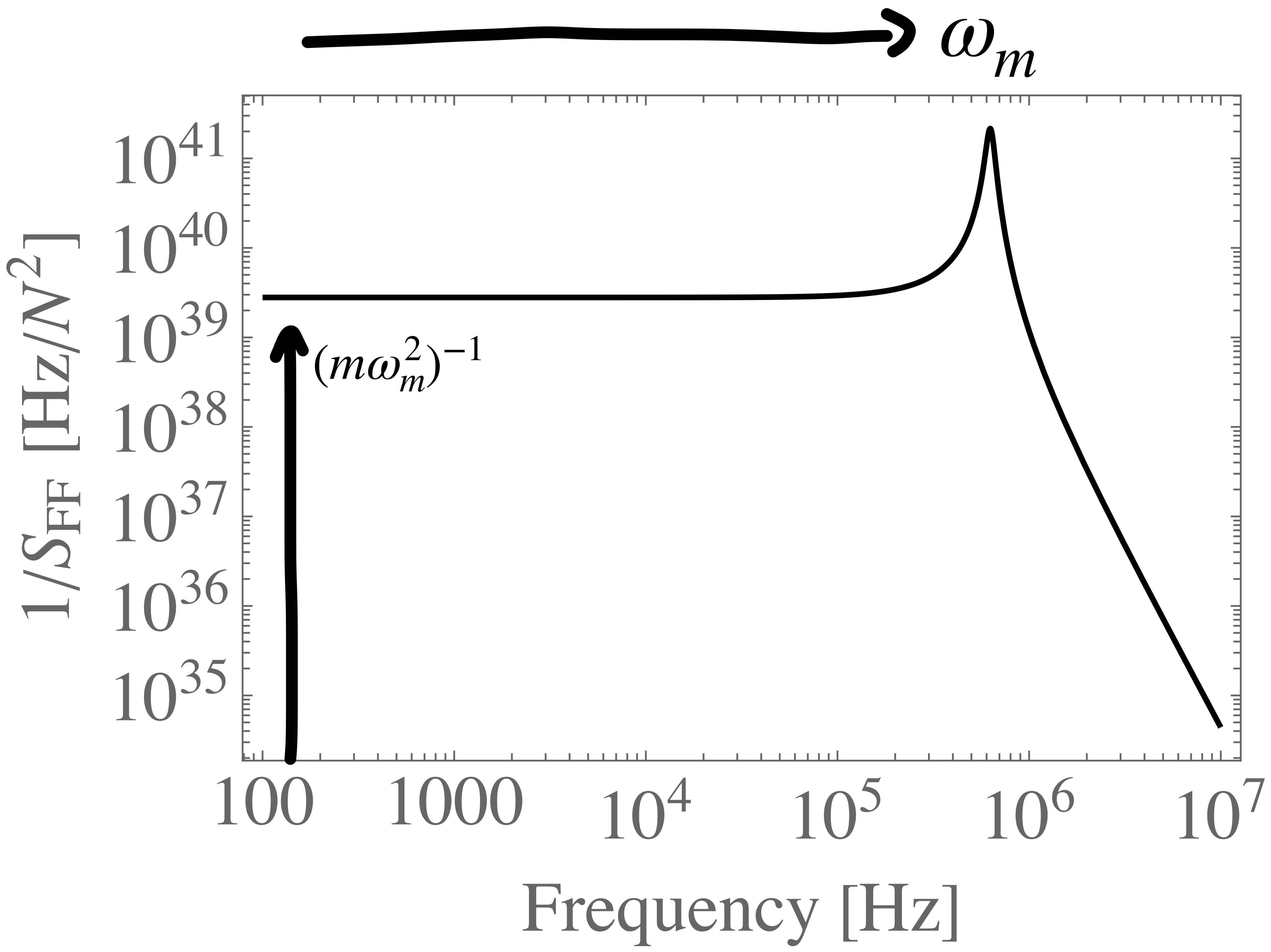
Momentum uncertainty

- Optimal SNR:

$$\mathrm{SNR}_* = \Delta p \left(\int \frac{d\nu}{S_{FF}(\nu)} \right)^{1/2}$$

$$\mathrm{SNR}_* > 1$$

$$\implies \Delta p > \left(\int \frac{d\nu}{S_{FF}(\nu)} \right)^{-1/2} \equiv \Delta p_{\mathrm{th}}$$

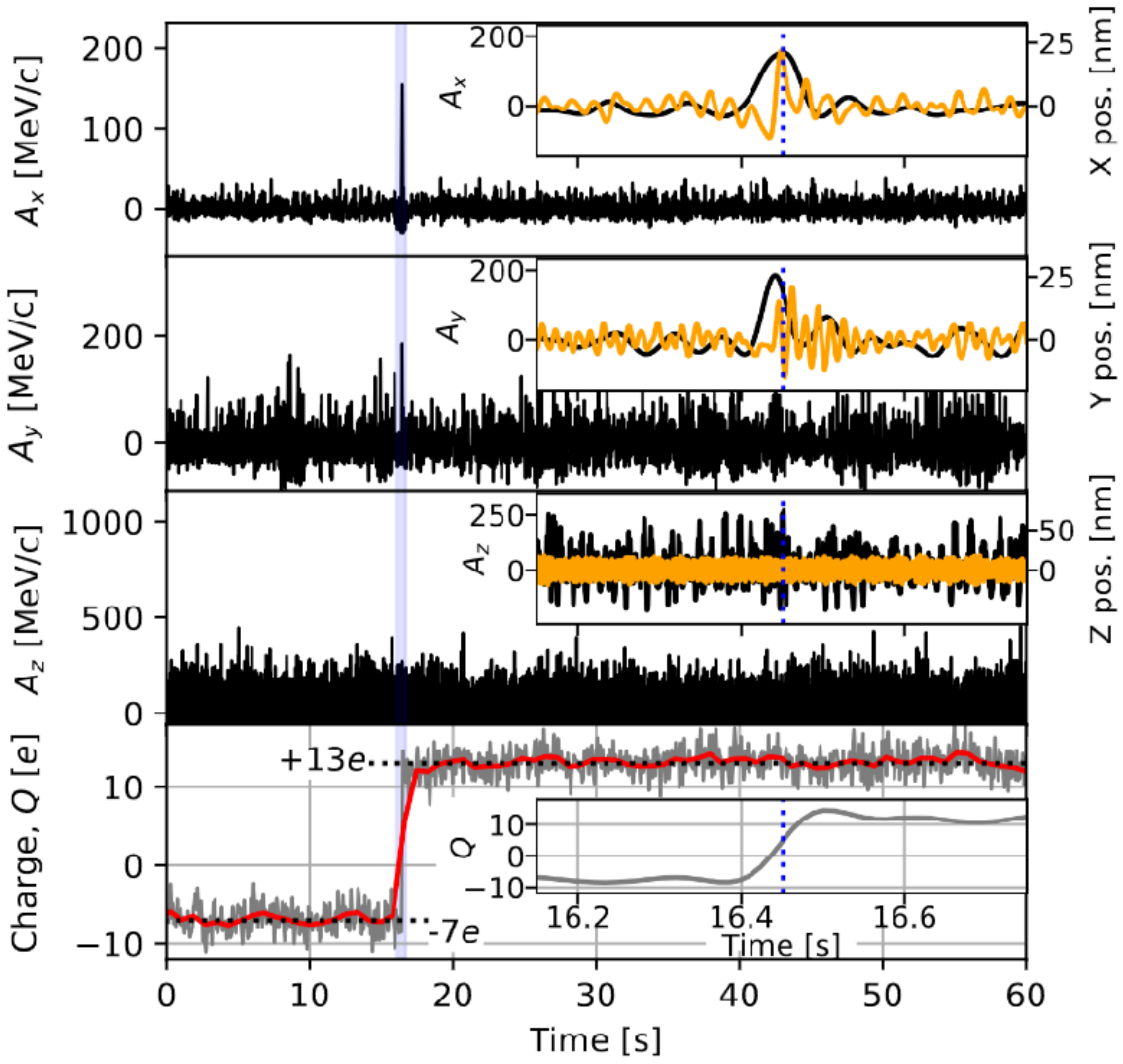


- For sensing at SQL, $\Delta p_{\mathrm{th}} \approx \sqrt{m\omega_m}$

$$\approx 15\mathrm{keV} \left(\frac{m\omega_m}{1\mathrm{fg} \times 10\mathrm{kHz}} \right)^{1/2}$$

Charge change

- Veto on charge state of sphere to remove backgrounds



[Wang et al. 2402.13257]

Squeezing

Squeezing operator: $S(r,\theta) = \exp\left(\frac{r}{2}(e^{-i\theta}a^2 - e^{i\theta}a^{\dagger 2})\right)$

$$S_{ij} \to \quad \begin{aligned} S_{XX} &= \frac{1}{2}\left(\cosh 2r - \cos\theta \sinh 2r\right) \\ S_{YY} &= \frac{1}{2}\left(\cosh 2r + \cos\theta \sinh 2r\right) \\ S_{XX} &= -\frac{1}{2}\sinh 2r \sin\theta \end{aligned}$$

How can we generate this dynamically?
Non-linear crystals

$$H = \omega a^\dagger a + 2\omega b^\dagger b + i\chi^{(2)}(a^2 b^\dagger - a^{\dagger 2} b)$$

Pump $b \to \beta e^{2i\omega t} + b$:

$$\begin{aligned} U_I(t) &= \exp iH_I t \\ &= \exp\left(\chi^{(2)}\, t(\beta^* a^2 - \beta a^{\dagger 2})\right) \end{aligned}$$

Nuclear physics I

Nuclear EFT may be treated as an expansion in powers of nucleon momentum.

Recoil corrections goes as either

$$\frac{Q}{m_{\mathrm{N}}} \approx 5 \times 10^{-4} \frac{Q}{0.5\,\mathrm{MeV}},$$

or as $(QR_{\mathrm{nuc}})^2 \approx 10^{-4} \left(\frac{A}{100}\right)^{2/3} \left(\frac{Q}{0.5\,\mathrm{MeV}}\right)^2$:

We may ignore higher-order derivative operators.

[Parity invariance of EM/strong force implies $\mathbf{q} \cdot \langle \mathbf{R}_{\mathrm{N}} \rangle \approx 0$, where $\mathbf{R}_{\mathrm{N}}$ is nuclear centre-of-mass coordinate]

Nuclear physics II

The renormalisation of the vector and axial currents generically causes ambiguities even at leading order in recoil expansion:

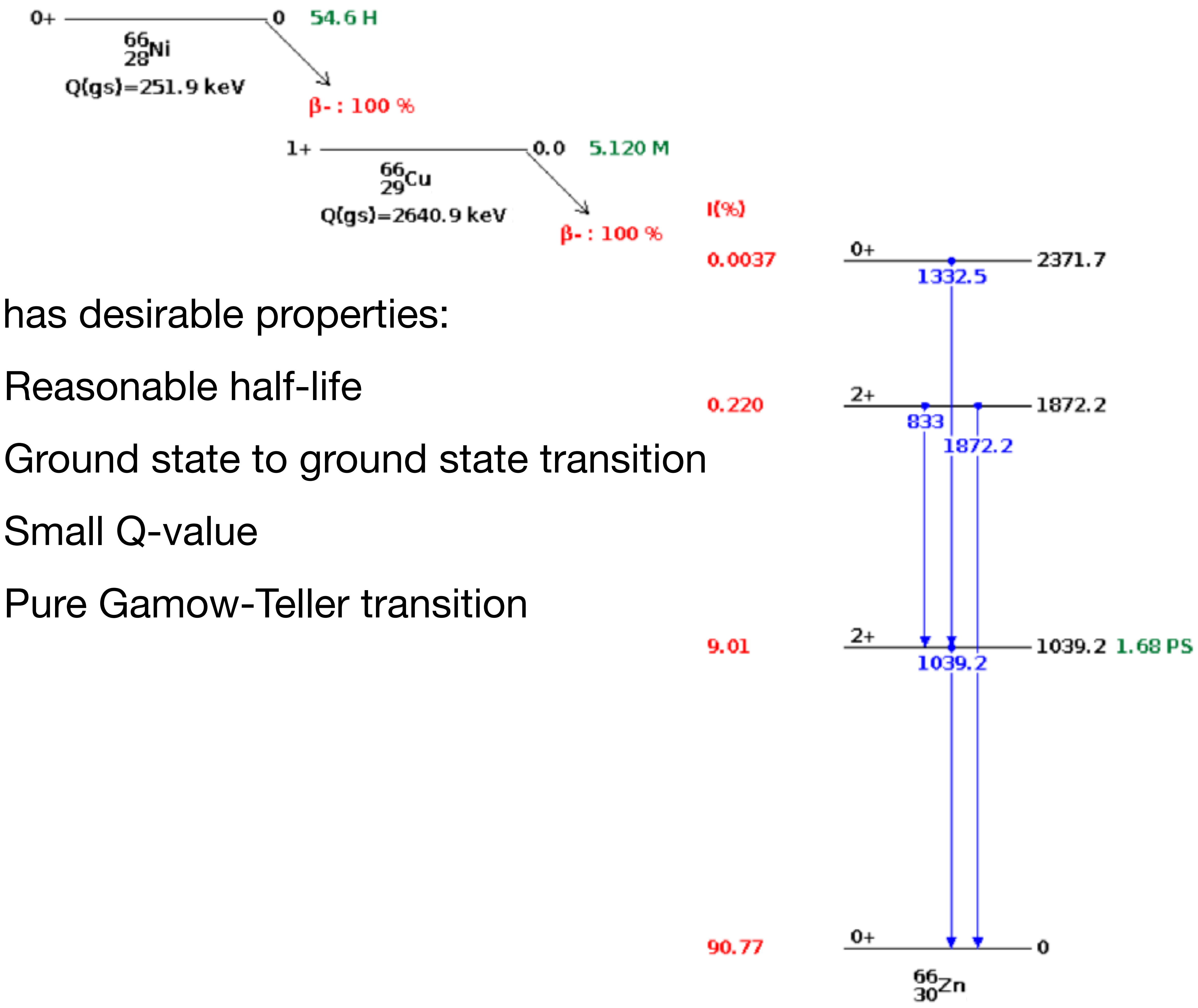
$$L^{\mu}\langle f \quad V_{\mu} \quad i\rangle = a(q)^2 \frac{P \cdot \ell}{M + M'}$$

$$L^{\mu}\langle f \quad A_{\mu} \quad i\rangle = c(q)^2 \frac{P^{\mu} \ell^{\nu} C_{\mu\nu}}{M + M'}$$

The form factors $a(q^2)$ and $c(q^2)$ are incalculable for larger nuclei.

For pure Gamow-Teller transitions
$(J_i = 1\,, J_f = 0, \pi_i \cdot \pi_f = 1)$, $a(q^2) = 0$. Approximate $c(q^2) \approx c(0)$,
which only affects total rate/normalisation — cancels in differential observable.

Nickel-66



- Ni-66 has desirable properties:
    1. Reasonable half-life
    2. Ground state to ground state transition
    3. Small Q-value
    4. Pure Gamow-Teller transition

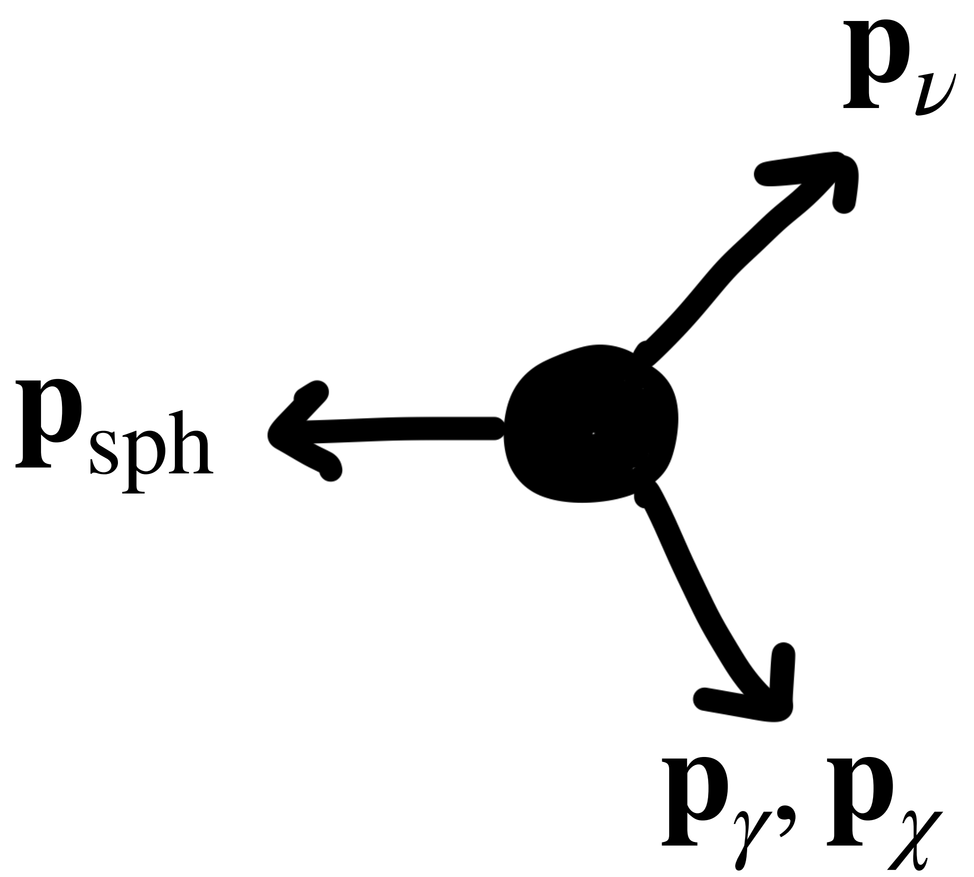
- BUT, child is unstable: need to differentiate decays
    - Transitions have very different Q-values

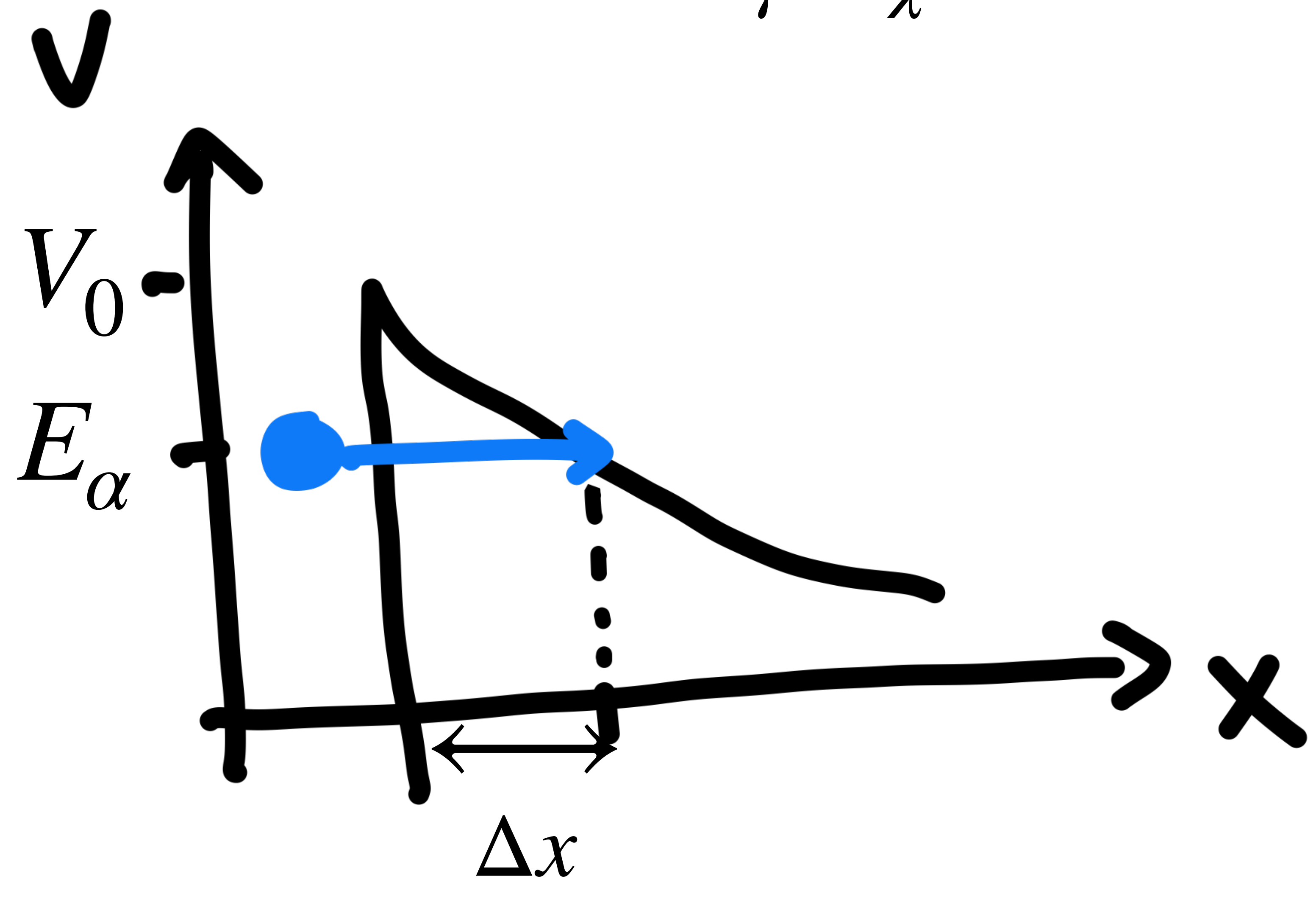
What gamma decays?

- Most gamma decays follow beta decay/ electron capture. The neutrino momentum is degenerate with invisible BSM momentum

- Alpha decay is predominantly to child ground state

$$P \sim \exp\left(-2\sqrt{m_\alpha(V_0 - E_\alpha)} \cdot \Delta x\right)$$

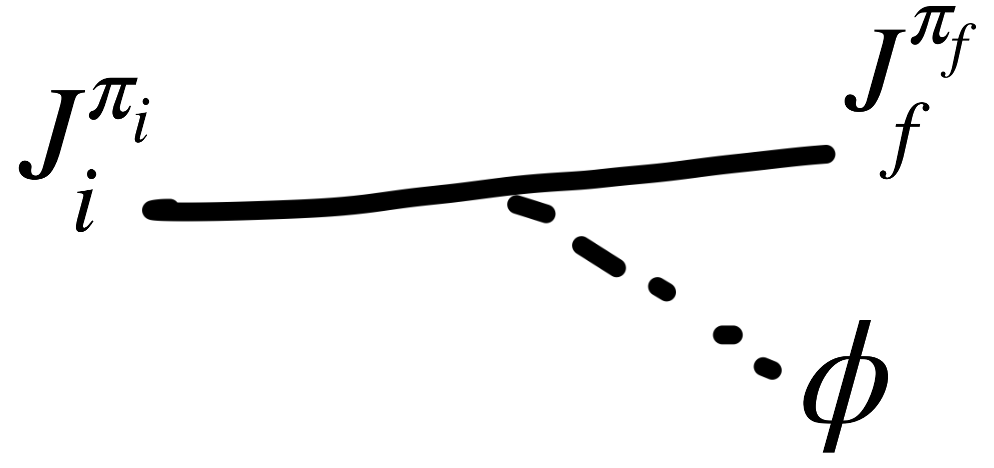




Dark state emission

e.g. Nucleon-coupled scalar

$H_{\rm int} = g_\phi \phi \bar{N} N$



$$\mathscr{M} \sim \langle i; 0 \ \ \mathscr{H}_{\rm int} \ \ f; \mathbf{k}_\phi \rangle$$

$$\sim g_\phi \langle i \ \ e^{i\mathbf{k}_\phi \cdot \mathbf{x}} \ \ f \rangle \cdot \langle 0 \ \ \phi \ \ \mathbf{k}_\phi \rangle$$

$$kr \approx 1\,\mathrm{MeV} \times 5\,\mathrm{fm} \approx 0.03$$

Initial and final nuclear states are labelled by their angular momentum and parity $\ J^\pi \rangle$.

In multipole expansion, transitions come in two types:

$$E\ell : \Delta J = \ell, \pi_i \cdot \pi_f = (-1)^\ell$$ **Scalars**

$$M\ell : \Delta J = \ell, \pi_i \cdot \pi_f = (-1)^{\ell+1}$$ **Pseudoscalars**

Branching ratios

- Aim to constrain branching ratio to invisible states:

$$\mathrm{BR}(J_i^{\pi_i} \to J_j^{\pi_f} + \chi) = \frac{\Gamma(J_i^{\pi_i} \to J_j^{\pi_f} + \chi)}{\Gamma_{\mathrm{tot}}}$$

- Depends on selection rules of transition, as well as particle properties. e.g. scalar emission:

$$\mathrm{BR}_\phi(E\ell) \approx \frac{1}{2}\left(\frac{g_\phi}{e}\right)^2 v_\phi^{2\ell+1}, \quad l > 0$$