Three Ideas for Quantum Sensors in Neutrino Physics

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The International Joint Workshop on the Standard Model and Beyond 2025

Mostly based on collaborations with
V. Domcke [arXiv:1703.0869], J. D. Shergold [arXiv:2411.16859]
and C. S. Nugroho [arXiv:2511.18245]

Upgrade: Some Ideas for Quantum Sensors in Neutrino & Dark Matter Physics

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Outline

- Motivation
- Neutrino Charges
- CNB and Interferometers
- Dark Matter
- Summary and Conclusions

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Fundamental Properties of Neutrinos?

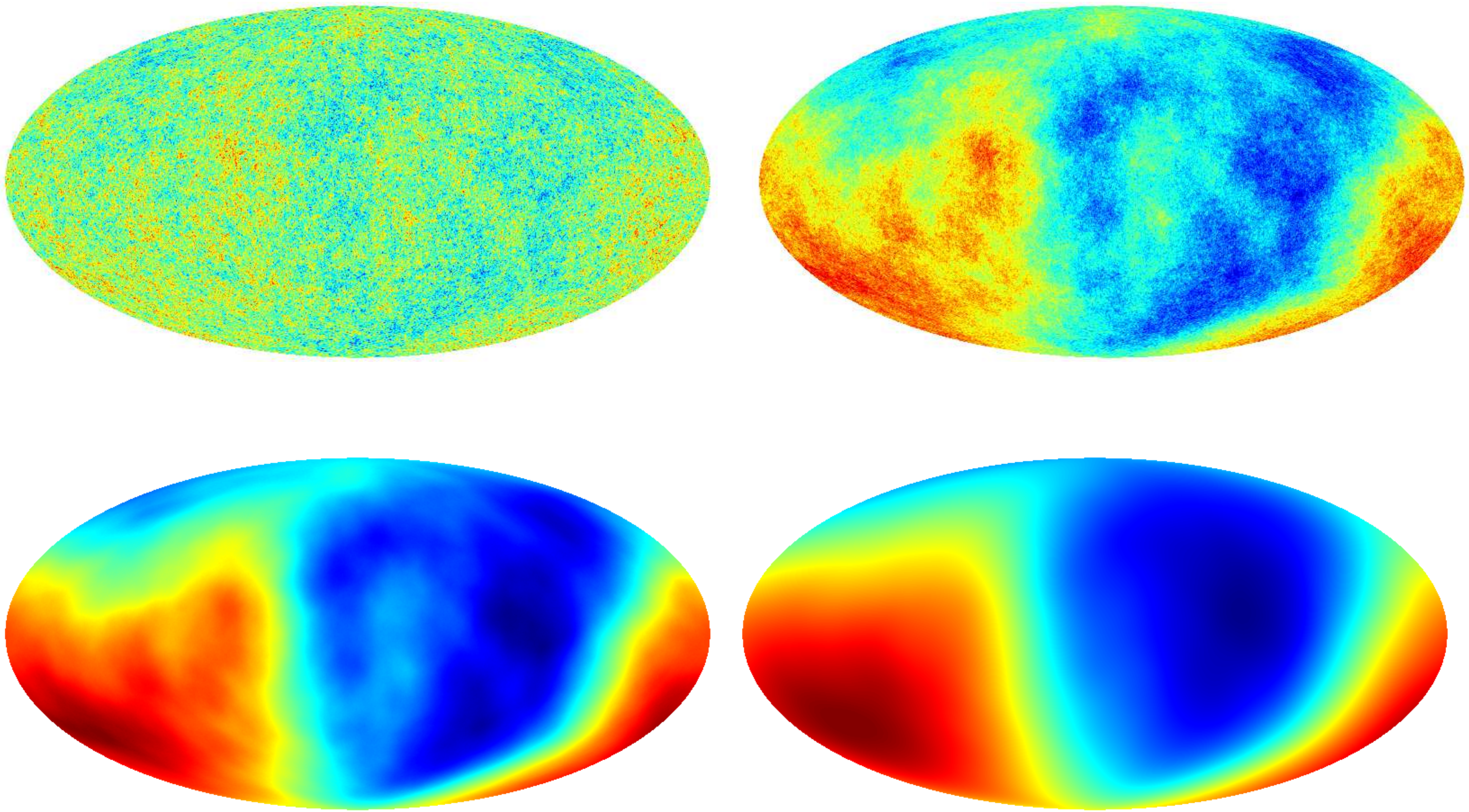
- Very light (neutrino mass < 0.1 eV)
- Come in three flavours
- Fermions
- Only interacts via W- and Z-exchange?
    - Higgs couplings? (are there proposals?)
    - Electric charge? Dipole moments?

The Cosmic Neutrino Background (CNB)

- Produced 1 s after Big Bang (CMB: 379k years)
- Number density: about 330 cm^{-3} = 6 n_0
- Temperature: 1.9 K
- Average kinetic energy: 0.5 meV
- Velocity: 10^{-3} - 1 c
- CNB neutron cross section: 10^{-27} pb (10^{-63} cm^2)
- Largest neutrino flux on Earth

The Oldest Picture of the Universe in the Future?

[Hannestad & Brandbyge ’06]



m_ν = (10^{-5} eV, 10^{-3} eV, 10^{-2} eV, 10^{-1} eV) from upper left to lower right

Quantum Sensors

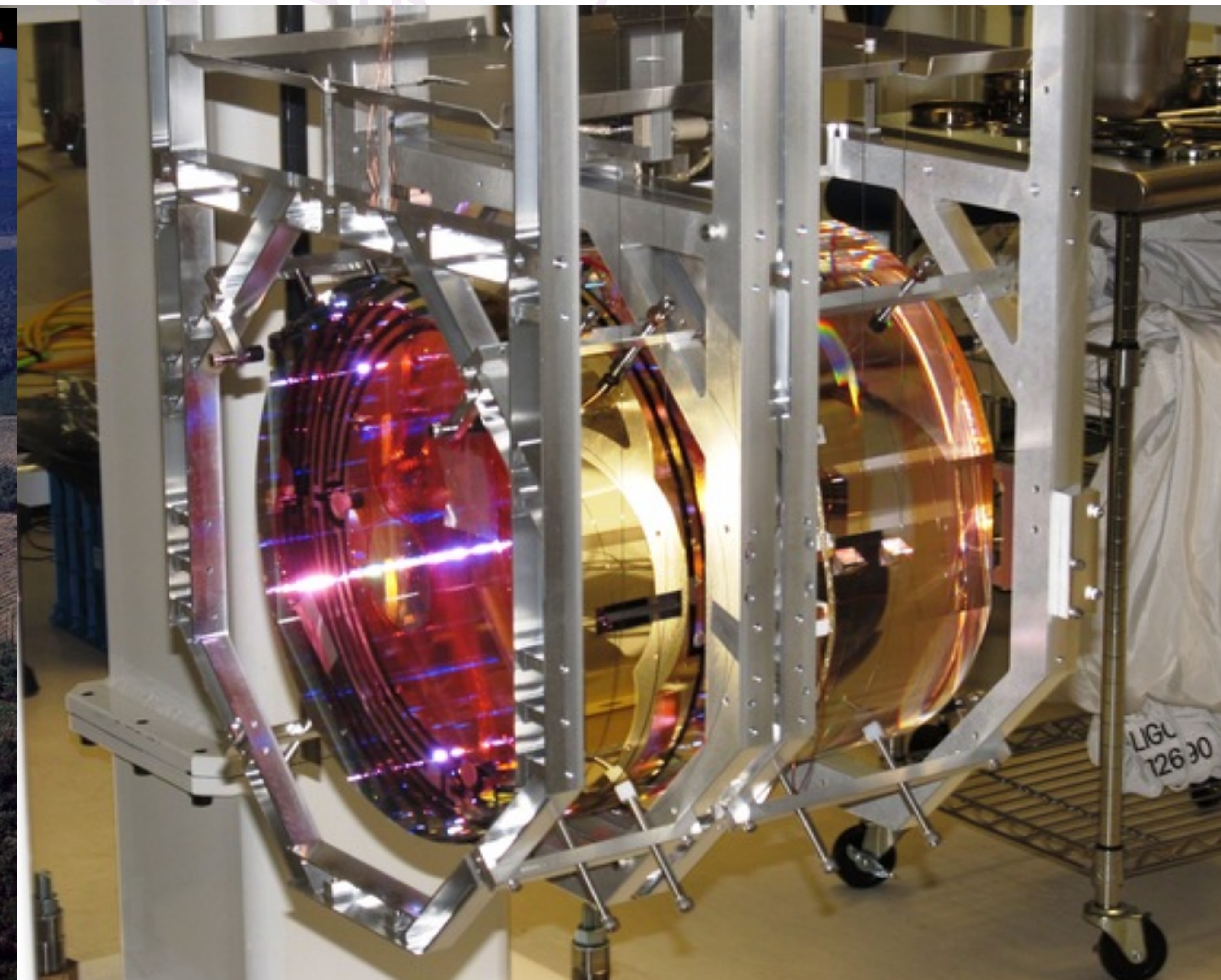
- Wikipedia's definition (accessed 29/11/25):

"Within quantum technology, a **quantum sensor** utilizes quantum mechanical phenomena, such as quantum superposition, quantum entanglement, and quantum squeezing, to measure things."

- Here we will consider
  - Superconducting Quantum Interference Devices (SQUIDs)
  - Spin Exchange Relaxation-Free (SERF) magnetometers
  - Laser and matter interferometers

Famous Example: Gravitational Wave Detectors

[LIGO Livingston, Courtesy Caltech/MIT/LIGO Laboratory 2016]



[LIGO test mass, Courtesy Caltech/MIT/LIGO Laboratory 2016]

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What if neutrinos have charge?

- Lots of interesting phenomena
  [Reviews: Giunti, Studenikin '14; Giunti, Kouzakov, Li, Studenikin '24, ...]
- Well-known: Moving charges create B-field

$$\vec{B}_\nu = \frac{q_\nu e}{4\pi\epsilon_0 c} \frac{\gamma_\nu |\vec{\beta}_\nu| R_\perp \hat{e}_\phi}{\left(R_\perp^2 + \gamma_\nu^2 R_\parallel^2\right)^{\frac{3}{2}}},$$

[Shergold, MS '24]

- Just take lots of neutrinos (a beam) and put in a sensitive magnetometer

Prospects?

[Shergold, MS '24]

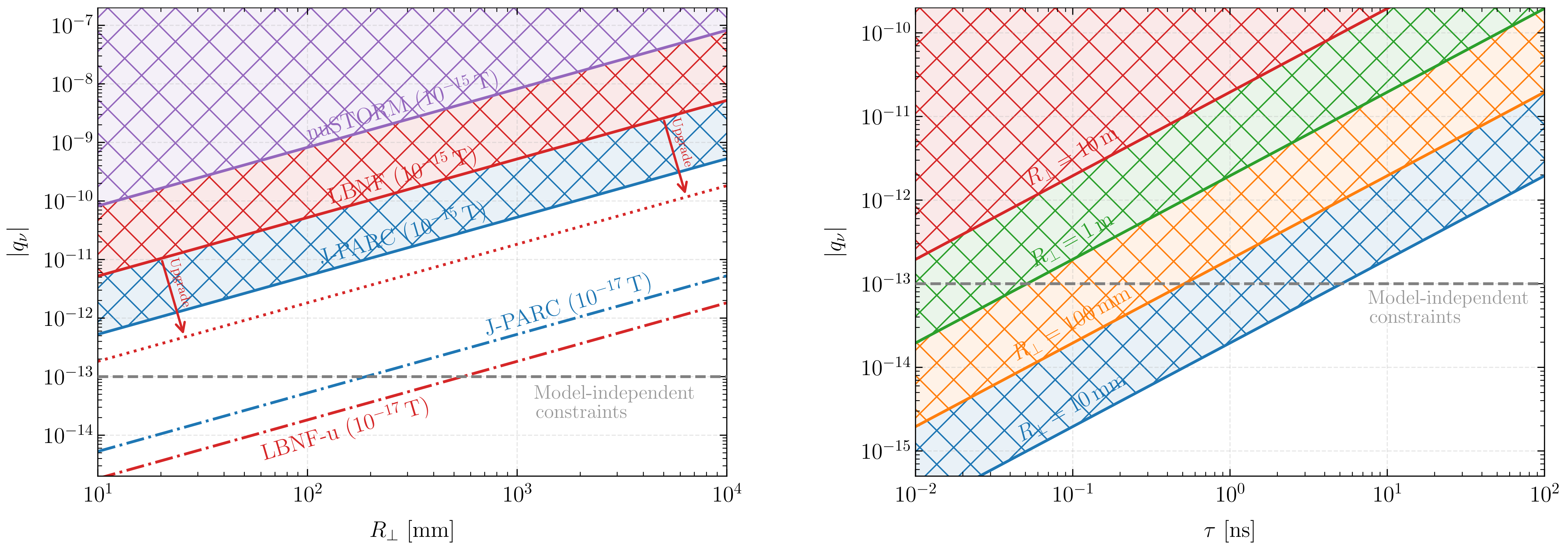

FIG. 1. Sensitivity to the neutrino charge for left panel: the most promising existing and upcoming neutrino experiments, cf. Table I, and right panel: a toy experiment with variable bunch size, but otherwise the same beam parameters as J-PARC. In both panels, the solid lines assume a magnetometer with sensitivity comparable to existing SQUIDs, $B_{\rm ref} \simeq 10^{-15}$ T, while the dot-dashed lines assume sensitivity to $B_{\rm ref} \simeq 10^{-17}$ T, akin to a SERF magnetometer. The horizontal dashed line represents the current, most stringent, model-independent laboratory bounds on the individual flavor-diagonal charges, $|q_{\nu_\alpha}| \lesssim 10^{-13}$ [10–12].

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The Idea

[Domcke, MS '17]

- Pendulum in neutrino wind

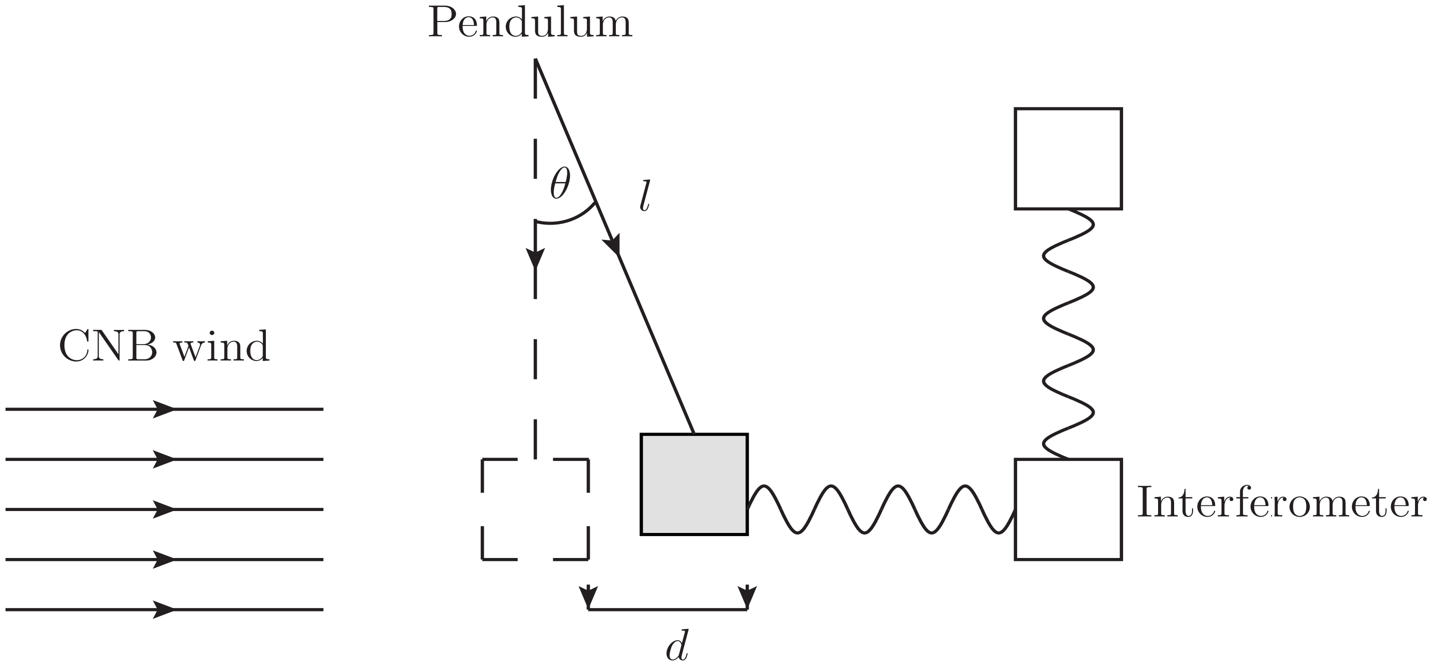
$$a_\nu \gtrsim \frac{g}{l} d$$

- LIGO-like interferometers

$$a_\nu \gtrsim 10^{-16} \mathrm{cm/s}^2$$

- Einstein telescope maybe

$$a_\nu \gtrsim 3 \cdot 10^{-18} \mathrm{cm/s}^2$$



[For more general particle physics applications, see Englert, Hild, Spannowsky '17]

Theory: Scattering

[Domcke, MS ’17; see also Duda *et al.* '01, ..., Opher '74]

- The basic formula

$$a_{G_F^2} = \Phi_\nu \frac{N_{AV}}{A\, m_{AV}} N_c \, \sigma_{\nu-A} \, \langle \Delta p \rangle$$

- Incoming flux: Φ_ν
- #nuclei in 1 g test material: $N_{AV}/(A m_A V)$
- Neutrino-nucleus cross-section: $\sigma_{\nu-A}$
- Coherence factor: N_c
- Average momentum transfer: $\langle \Delta p \rangle$

Theory: Scattering

[Domcke, MS '17; see also Duda *et al.* '01, ..., Opher '74]

- Results for three kinematical cases:

$$a_{G_F^2} = \frac{n_\nu}{2\,\bar{n}_\nu} \begin{cases} 3 \cdot 10^{-33}\,\mathrm{cm/s^2} & \text{for (R)} \\ 5 \cdot 10^{-31}\,(m_\nu/0.1\ \mathrm{eV}/c^2)\,\mathrm{cm/s^2} & \text{for (NR-NC)} \\ 2 \cdot 10^{-27}\,(10^{-3}/\beta_{\mathrm{vir}})\,\mathrm{cm/s^2} & \text{for (NR-C)} \end{cases}$$

(There is also an acceleration from the Stodolsky effect which is smaller than NR-C)

- Compare to experimental sensitivity:

$$a_\nu \gtrsim 10^{-16}\mathrm{cm/s^2}$$

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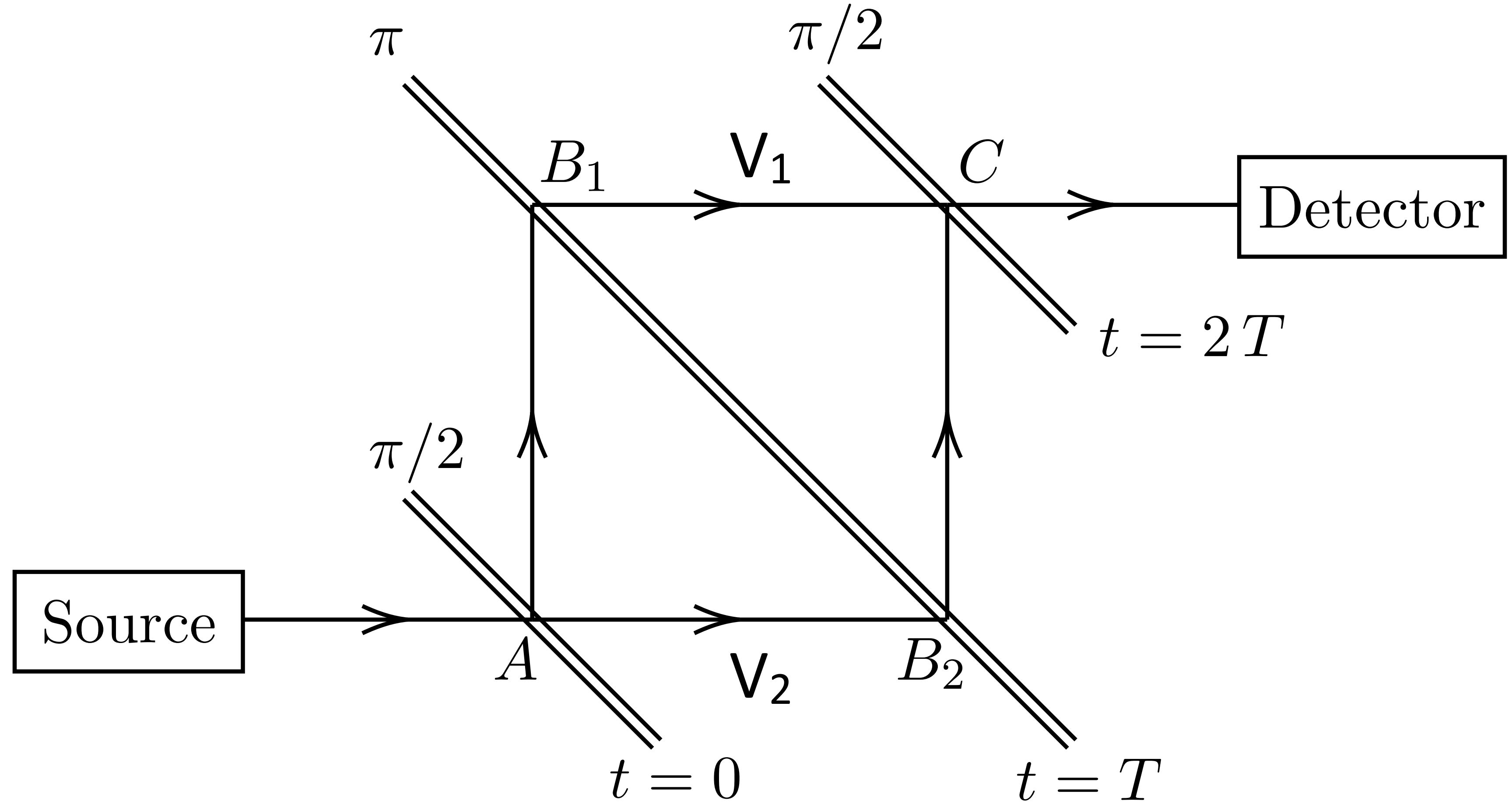
Why Matter Interferometers?

[Nugroho, MS '25]

- Advantage in talk by Vincent Gene L. Otero:
  - Neutrinos interact directly with light in interferometer
- But what if they have no charge?
  - Neutral neutrinos interact with matter
- Try matter interferometers!

Matter Interferometers



[Figure taken from Nugroho, MS '25 where you can also find more references about matter interferometers]

Key formula for measured phase difference

$$\Delta\Phi = -\frac{1}{\hbar}\oint V(\vec{x})\,\mathrm{d}\,t = \frac{1}{\hbar}(V_2 - V_1)\,T$$

What is the physics?

- The Hamiltonian coupling neutrinos to a matter fermion ψ_T

$$\mathcal{H}(x) = \frac{G_F}{\sqrt{2}} \sum_{i,j} \bar{\nu}_i \gamma_\mu (1-\gamma_5) \nu_j \, \bar{\psi}_T \gamma^\mu (V_{ij} - A_{ij}\gamma_5) \psi_T$$

- Effective potential can be written as

$$V_\nu = \phi_\nu(\vec{r})$$ ← scalar potential [Wolfenstein '78; Mikheyev, Smirnov '86]

$$- \vec{\mu}_T \cdot \vec{B}_\nu(\vec{r}) - \sum_{k,s_k} \vec{\mu}_k \cdot \vec{B}_T(\vec{r})$$ ← pseudo B-fields [potential for Stodolsky '75]

$$- \sum_{k,s_k} I_k(\vec{r}) \, \vec{\mu}_k \cdot \vec{\mu}_T$$ ← spin-spin interaction [potential for Stodolsky '75]

Some First Estimates

- Necessary: Lepton asymmetry Δ_ν (< 35)

[Domcke *et al.* '25]

- For a non-relativistic Dirac neutrino species coupling to a single neutron

$$\phi^D_{\nu,NR} \approx \frac{G_F}{\sqrt{2}} \frac{\Delta_\nu}{\mathrm{cm}^3} V_{11} \approx -3.18 \times 10^{-38} \Delta_\nu \ \mathrm{eV} \ ,$$

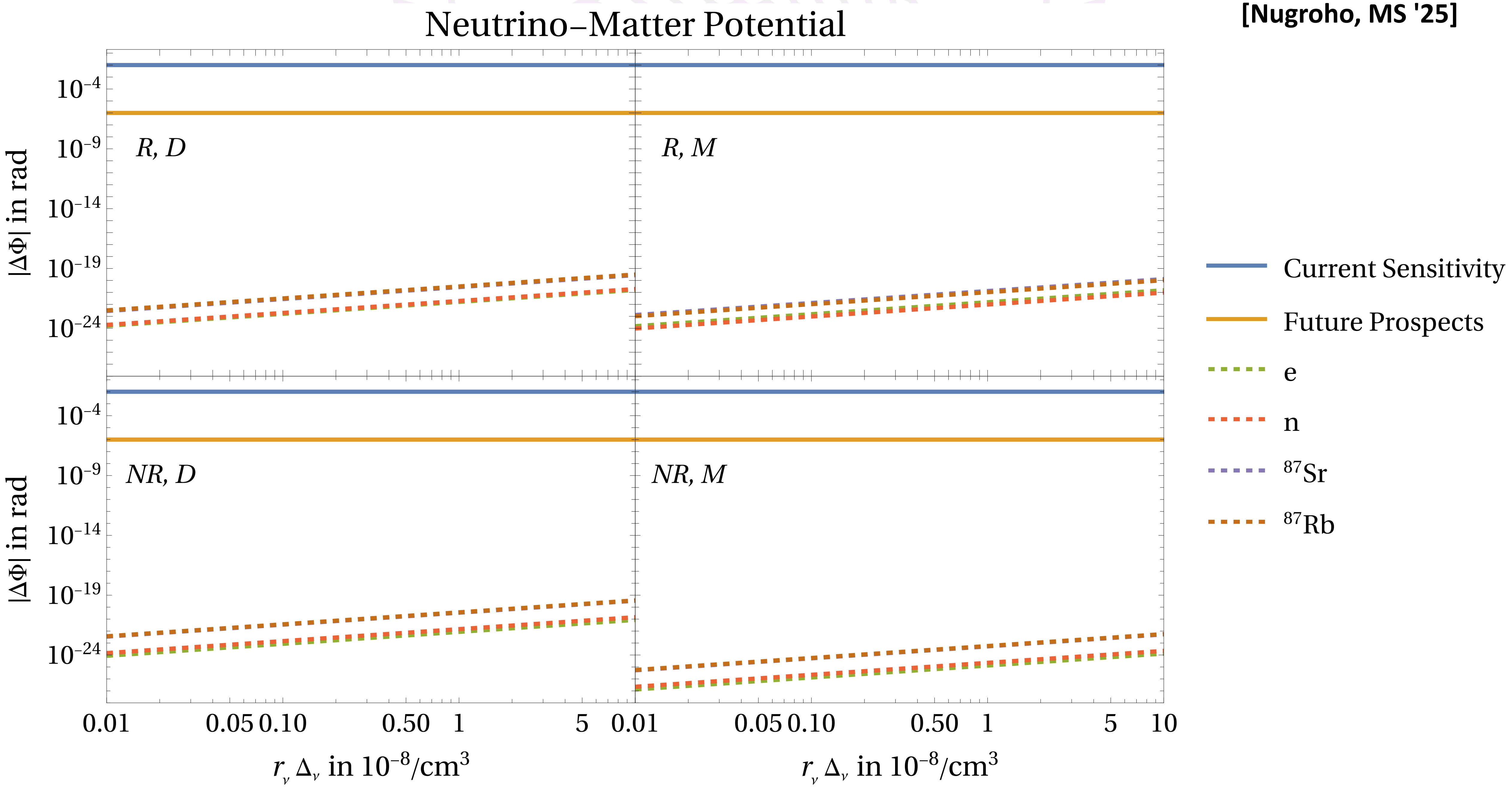
$$|\vec{B}^D_{\nu,NR}| \approx \frac{G_F}{\sqrt{2}} \frac{1}{|\vec{\mu}_n|} \frac{|\Delta_\nu|}{\mathrm{cm}^3} A_{11} \approx 5.27 \times 10^{-31} |\Delta_\nu| \ \mathrm{T} \ ,$$

$$|I^D_{k,NR}| \approx \frac{G_F}{\sqrt{2}} \frac{1}{|\vec{\mu}_k||\vec{\mu}_n|} \frac{|\Delta_\nu|}{\mathrm{cm}^3} A_{11} \approx 5.27 \times 10^{-31} \frac{|\Delta_\nu|}{|\vec{\mu}_k|} \ \mathrm{T}$$

[Nugroho, MS '25]

Neutrino-Matter Potential

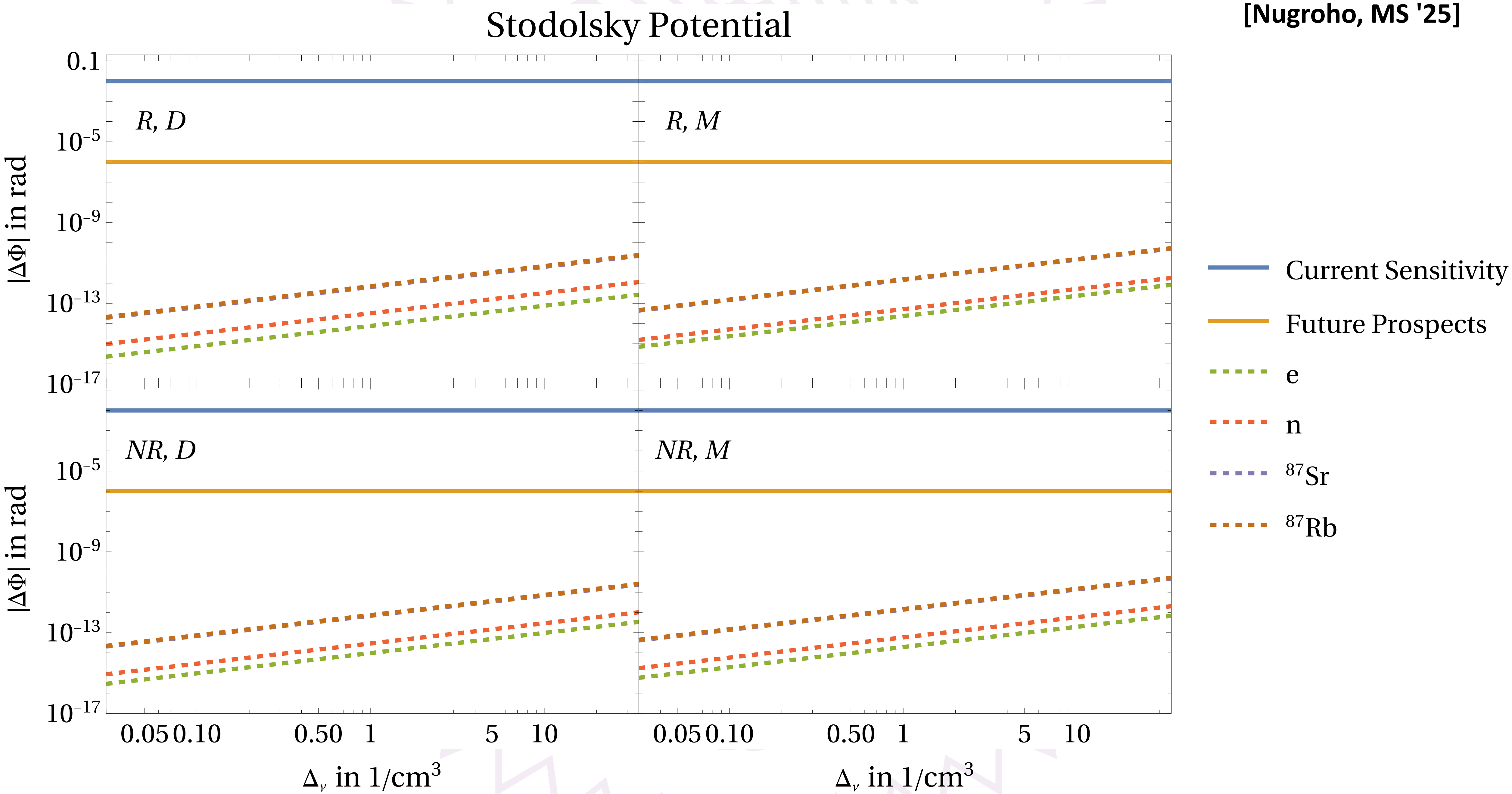
[Nugroho, MS '25]



(r_ν represents the density gradient due to diffraction, see the talk from Vincent Gene L. Otero)

Stodolsky Potential

[Nugroho, MS '25]



(much larger than the neutrino-matter potential but still difficult)

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Dark Matter induced Brownian Motion

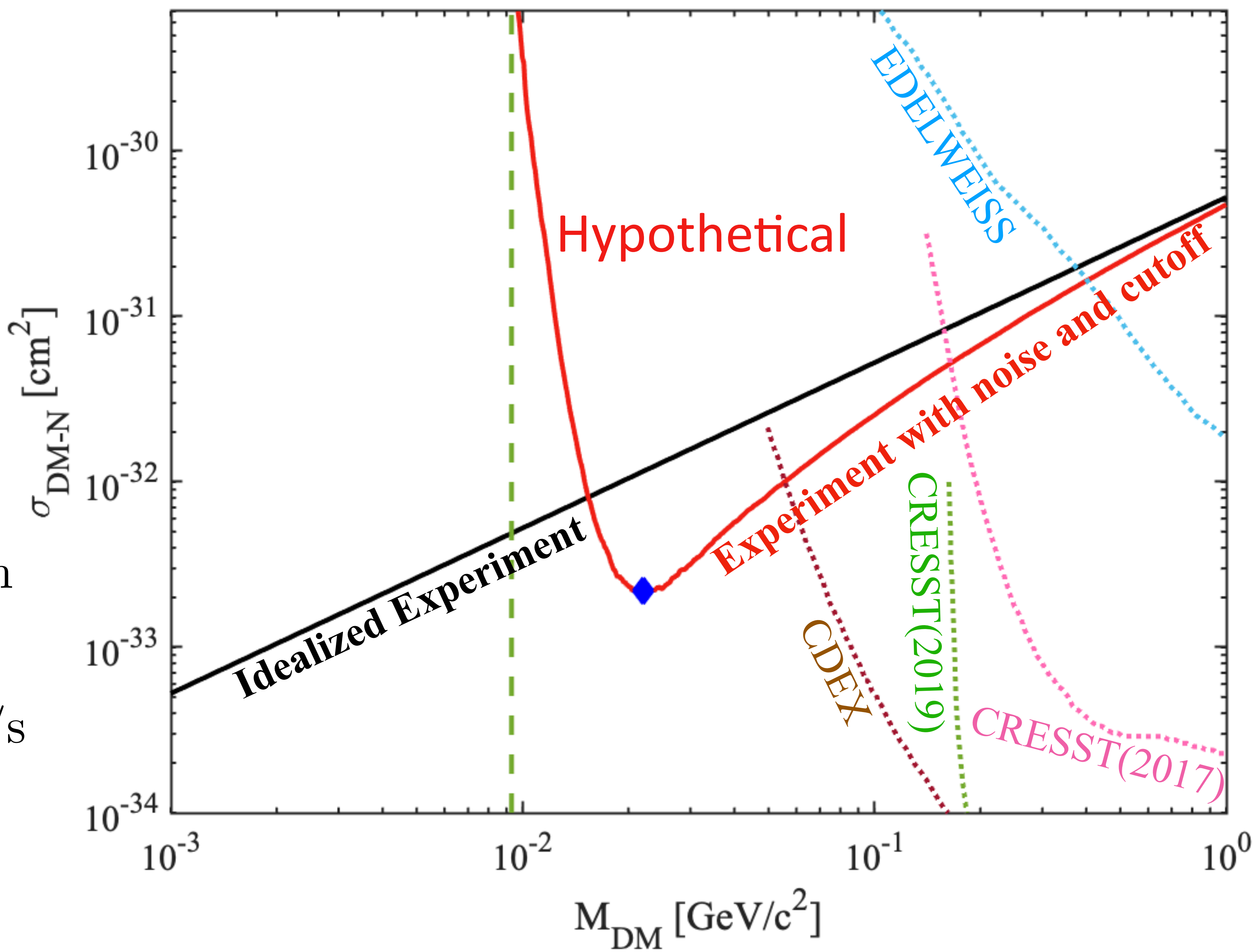
[Cheng, Primulando, MS '19]

$$\frac{\langle A \rangle^2}{\sigma_A^2 + \sigma_{\rm bkg}^2} = 4$$

$$M_T = 10^{-3} \text{ g of carbon}$$

$$\Delta t = 10 \text{ min}$$

$$q_{\rm min} = 2 \times 10^{-23} \text{ kg m/s}$$



DM Signal at KAGRA? (Long-Range Force & Heavy DM)

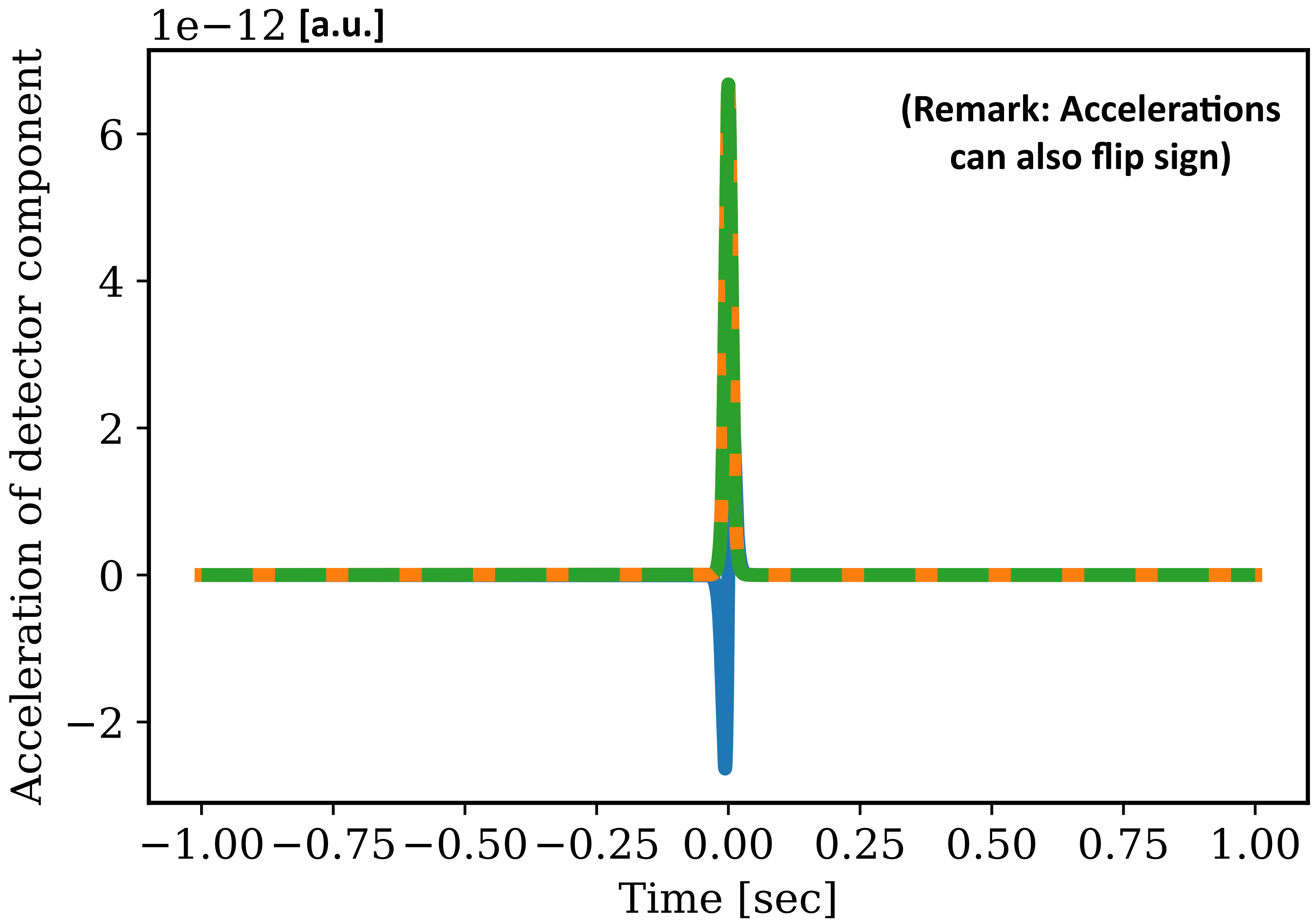
[Hall, Callister, Frolov, Müller, Pospelov, Adhikari '16; Lee, Primulando, MS '22]

- Long-Range force, continuous scattering

$$\vec{F}_{\mathrm{DM}} = \vec{\nabla}\left(M_T M_{\mathrm{DM}} \frac{G_{\mathrm{N}}}{|\vec{x}_T - \vec{x}_{\mathrm{DM}}|} \left(1 + (-1)^s \, \delta_{\mathrm{SM}} \delta_{\mathrm{DM}} \exp(-|\vec{x}_T - \vec{x}_{\mathrm{DM}}|/\lambda)\right)\right)$$

- We consider λ to be similar to the arm length
- Need to consider all mirrors simultaneously

"Typical" Acceleration on Detector Components



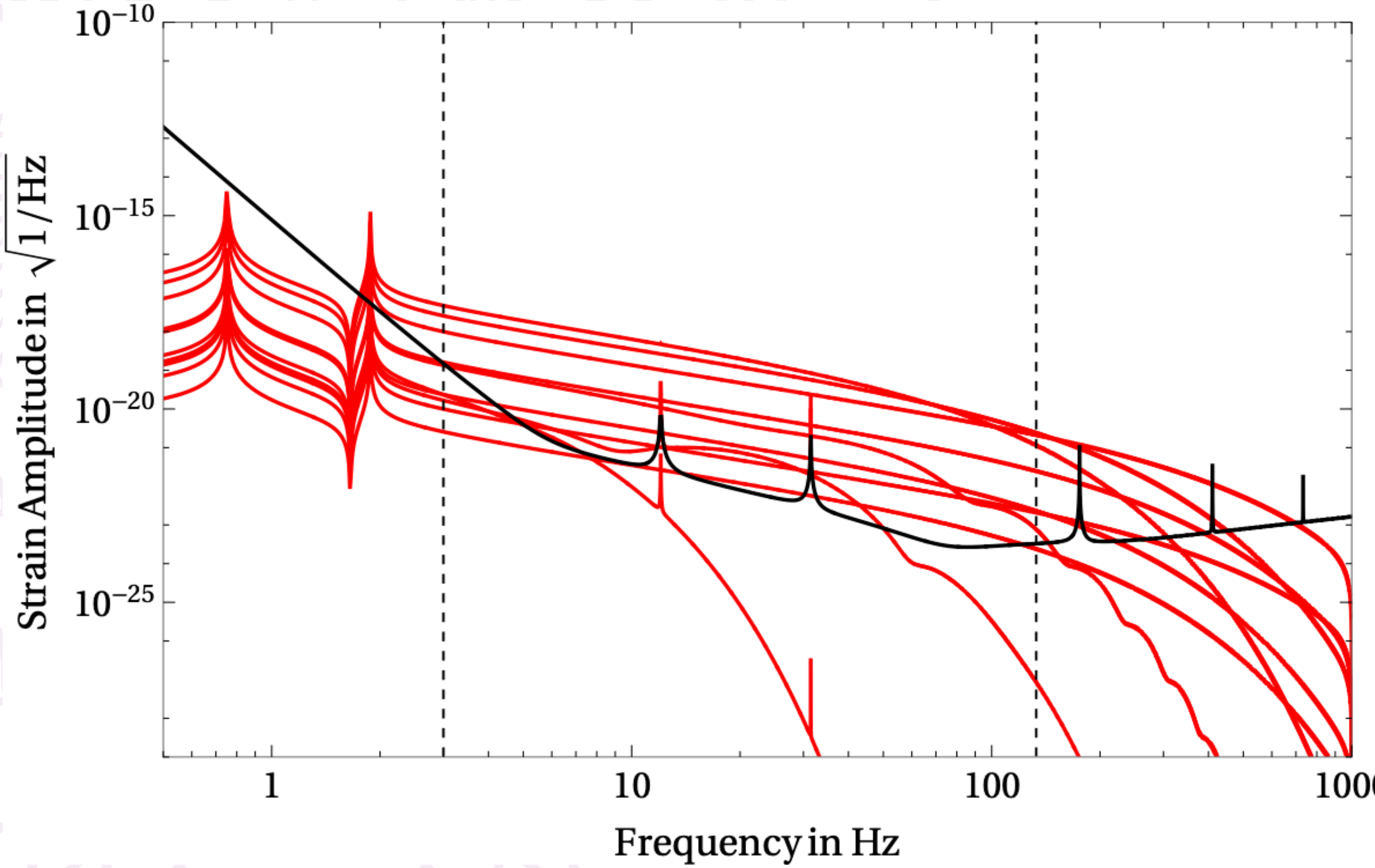
How to define the SNR frequency range?

[Lee, Primulando, MS '22]

Trade-off:
Larger range, larger SNR
Larger range, more costly

Compromise
3 - 133 Hz

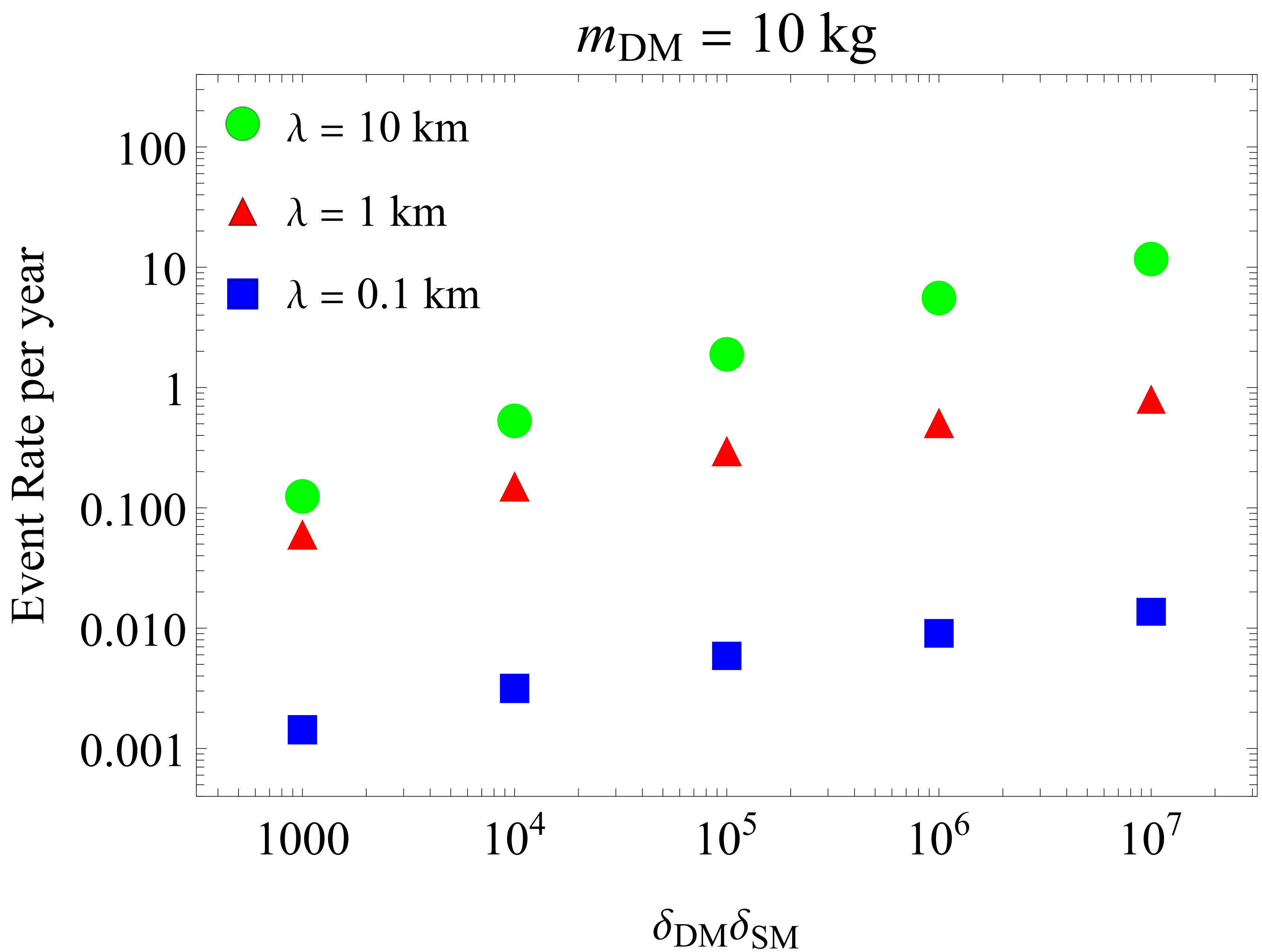
Larger frequencies less important to find ρ > 1



A selection of possible DM signals.

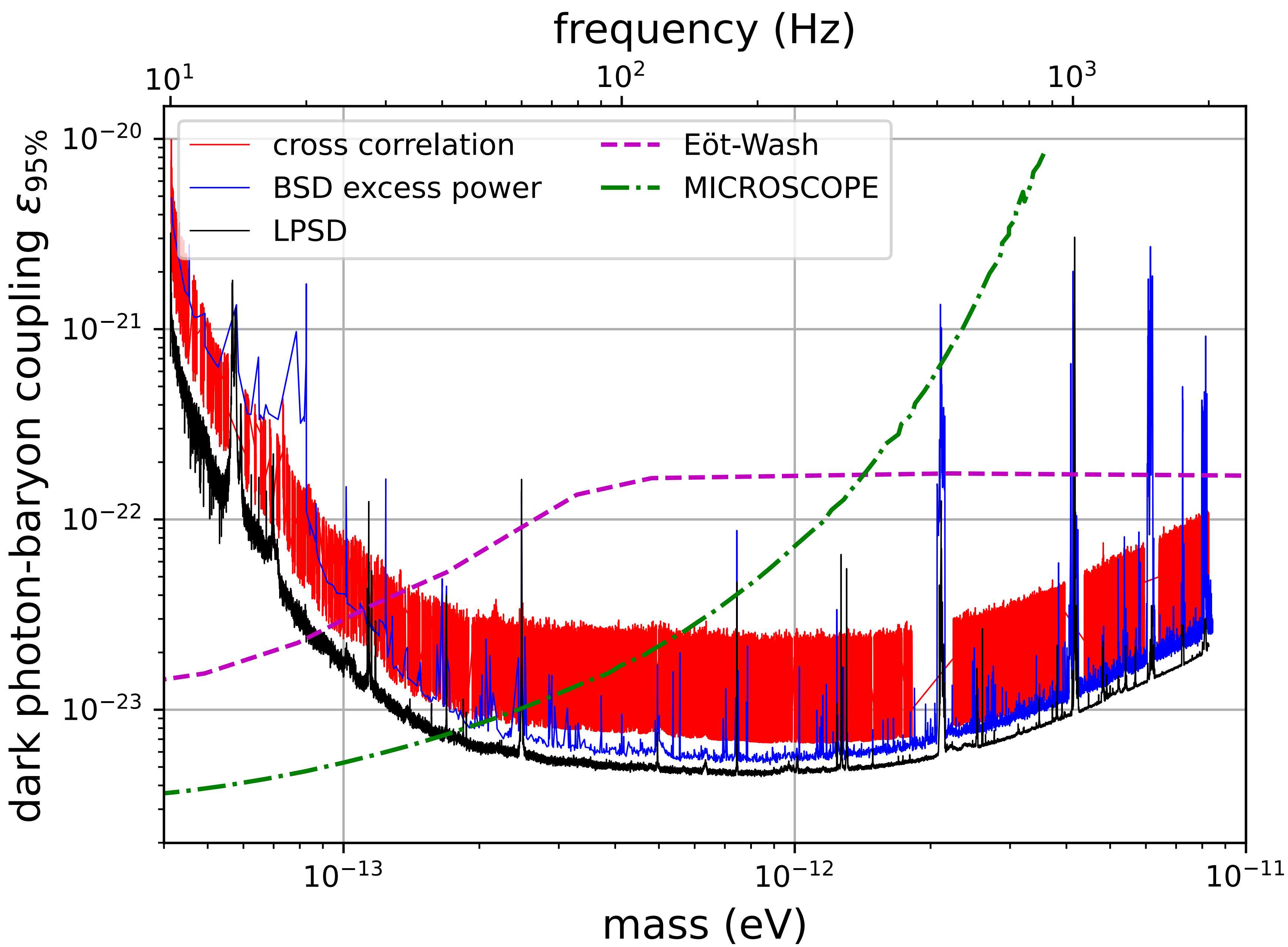
Macroscopic DM at KAGRA

[Lee, Primulando, MS '22]



SNR > 1

Example LVK Result

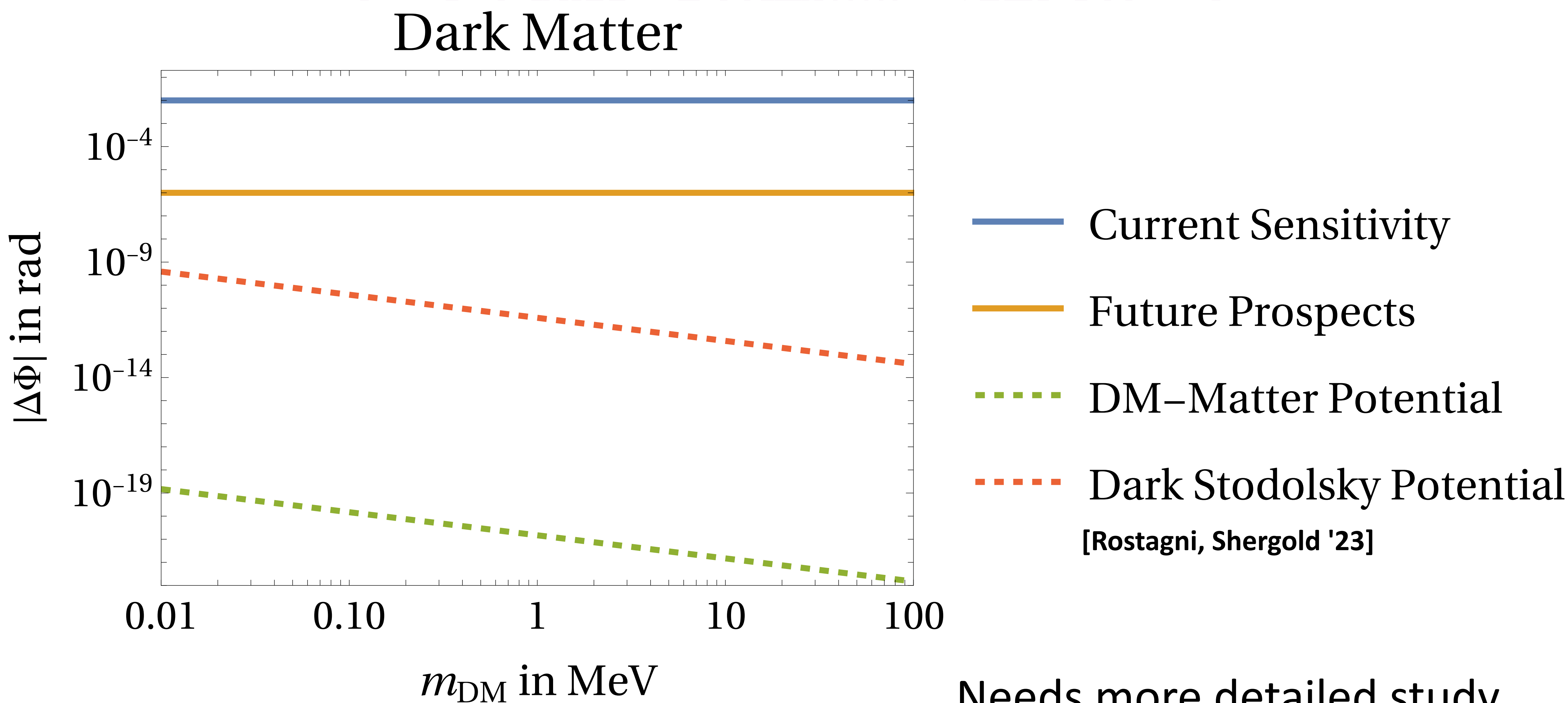


(b) Dark photons

[taken from LIGO, Virgo, KAGRA '25, arXiv:2510.27022]

Dark Matter at Matter Interferometers

[Nugroho, MS '25; also see, e.g., Du *et al.* '22, Badurina *et al.* '25, Arvanitake *et al.* '16, ...]



[Rostagni, Shergold '23]

Needs more detailed study

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Summary and Conclusions

- Quantum Sensors are exciting
  - Even for particle physicists!
- Can probe neutrino charges in a model-independent way
- It is difficult to see the CNB in interferometers
  - Other proposals necessary (PTOLEMY?)
- Dark Matter has more promising prospects