Dark Matter Scattering in Optomechanical Experiments

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16th PATRAS Workshop on Axions, WIMPs and WISPs

Mostly based on collaborations with
C. Ting, R. Primulando [arXiv:1906.07356] and C.-H. Lee, C. S. Nugroho [arXiv:2007.07908]

Outline

- Introduction
- Particle Physics Approach
- Gravitational Wave Astronomy Approach
- Summary and Conclusions

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- **Introduction**
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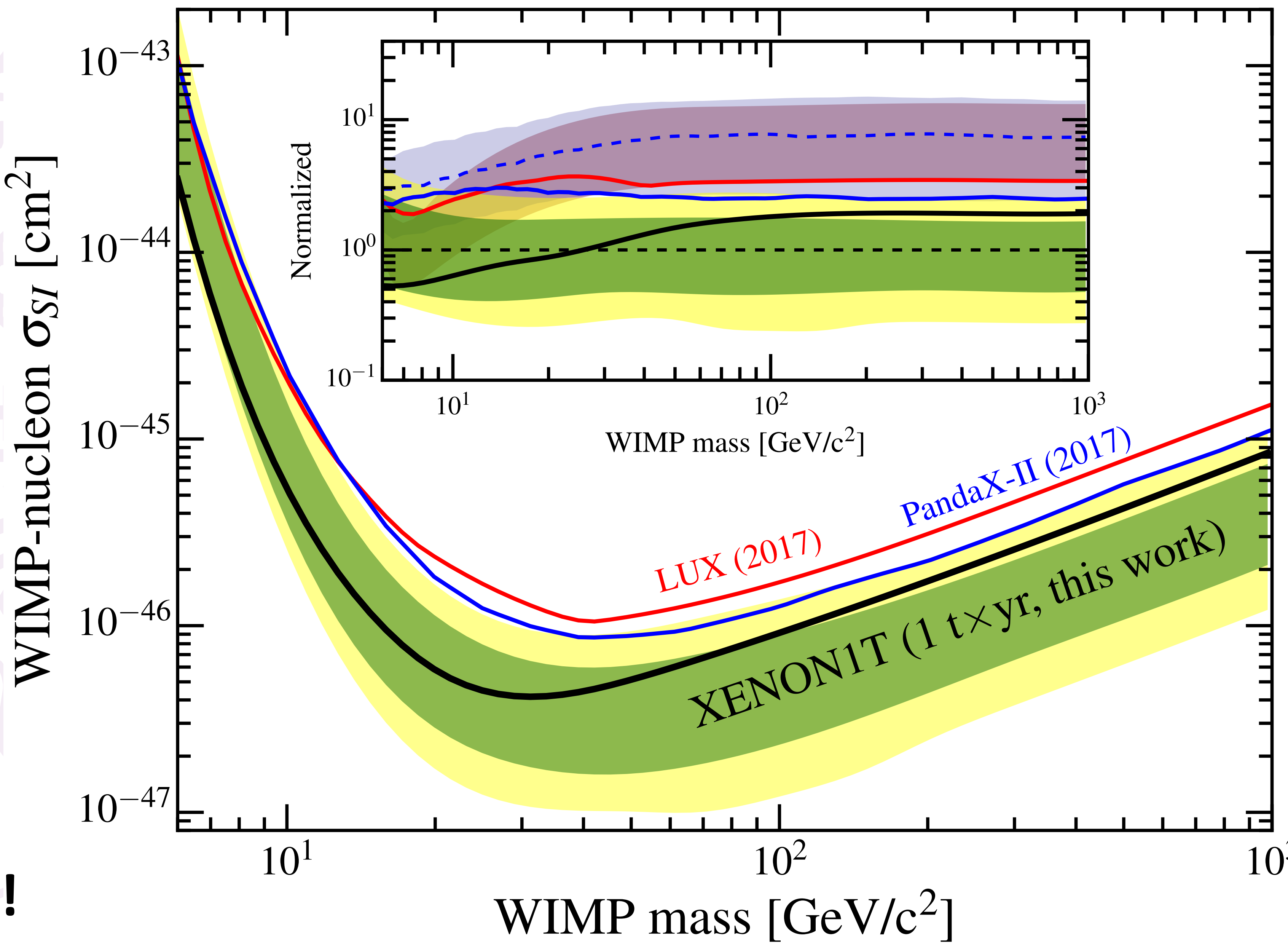
WIMP Searches

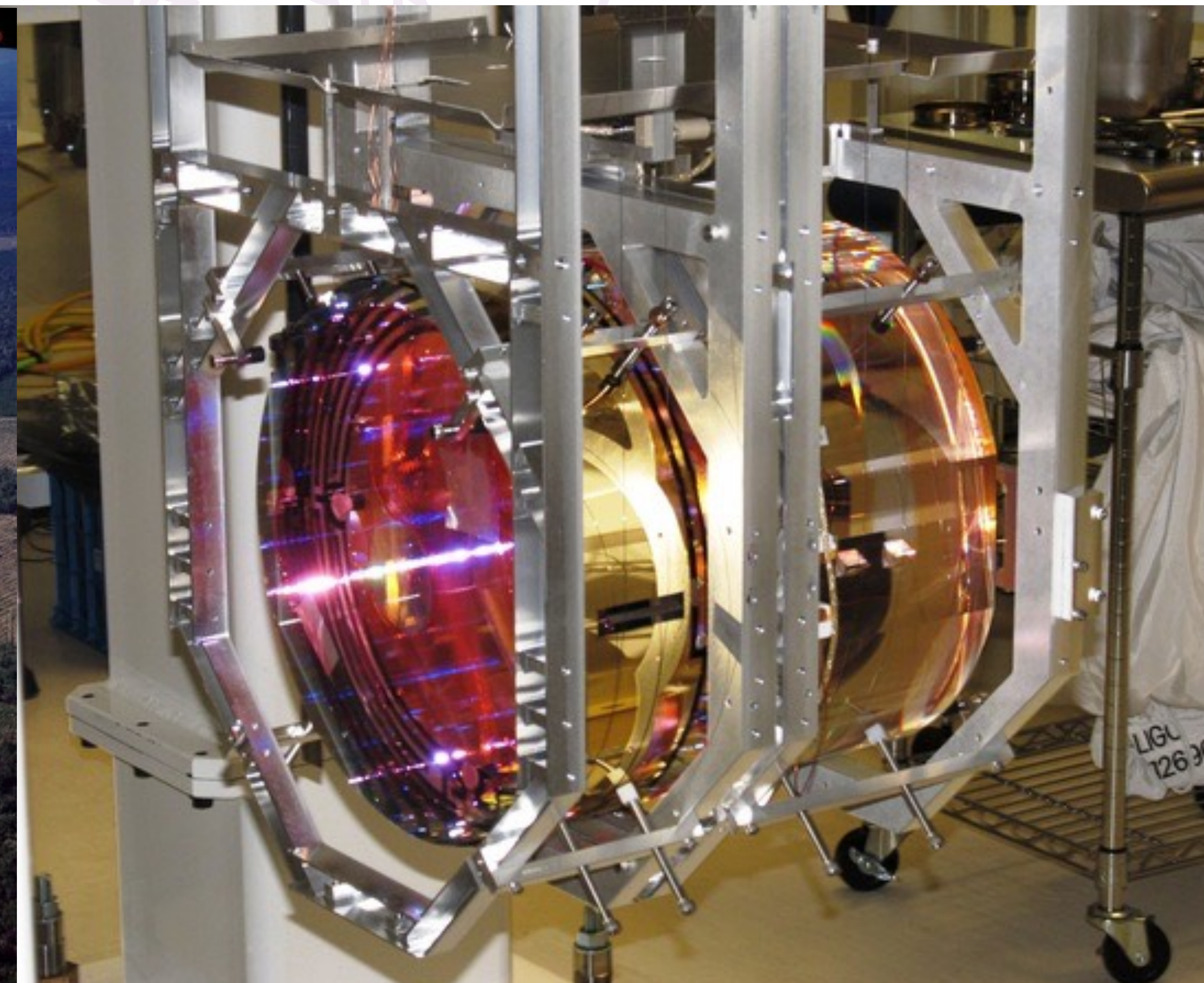


[XENON1T result '18]

Time to think again?!
Light WIMPs?

Gravitational Wave Detectors

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

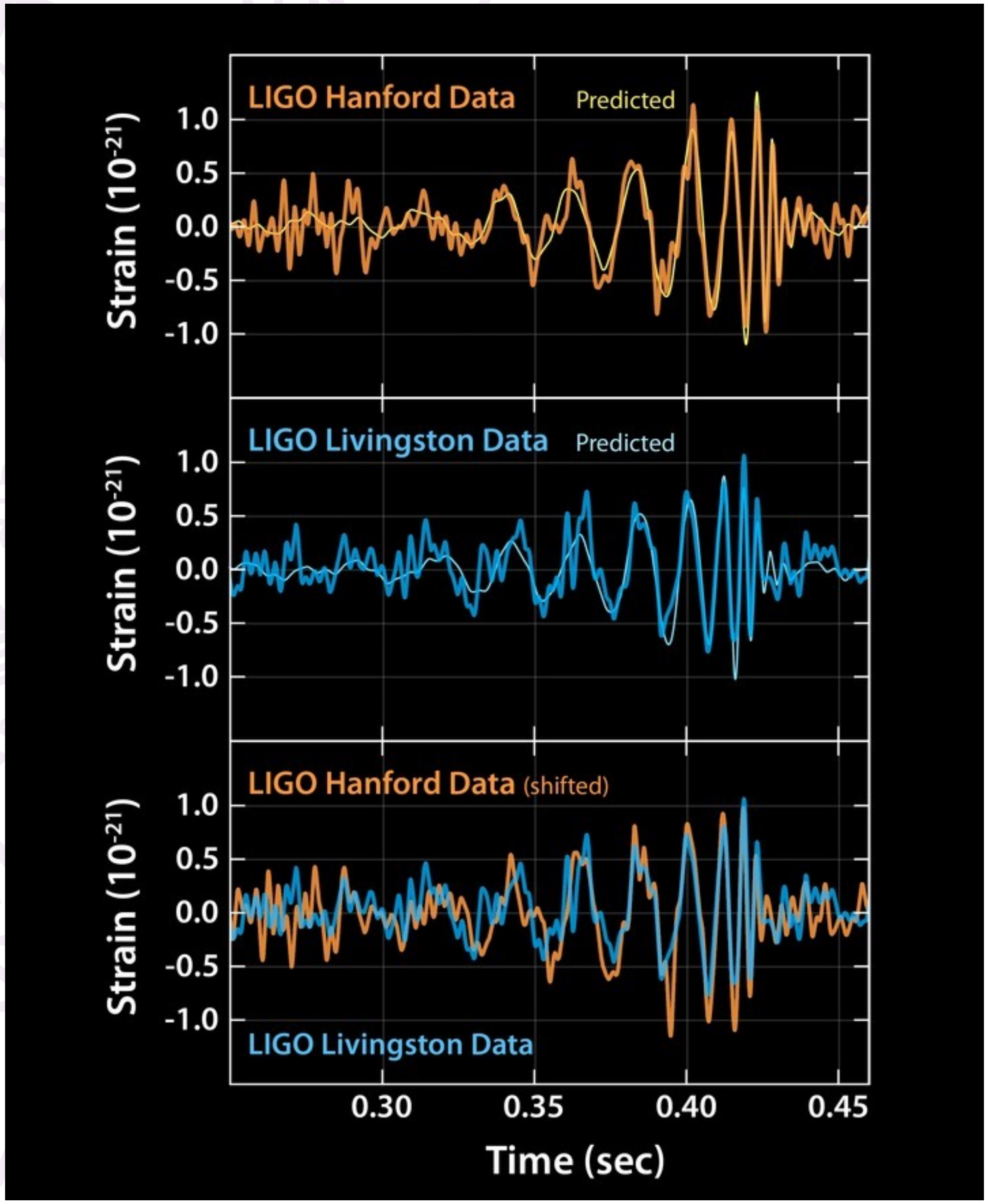


[LIGO test mass, Courtesy Caltech/MIT/LIGO Laboratory 2016]

Gravitational Wave Detectors

- Decade long R&D efforts
- Impressive sensitivities
- Impressive results
- Nobelprize 2017
- Other uses for this technology?

(Similar motivation to the talks from Jun'ya Kume, Sander Vermeulen and Doris Todorović)



[Courtesy Caltech/MIT/LIGO Laboratory 2016]

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Dark Brownian Motion

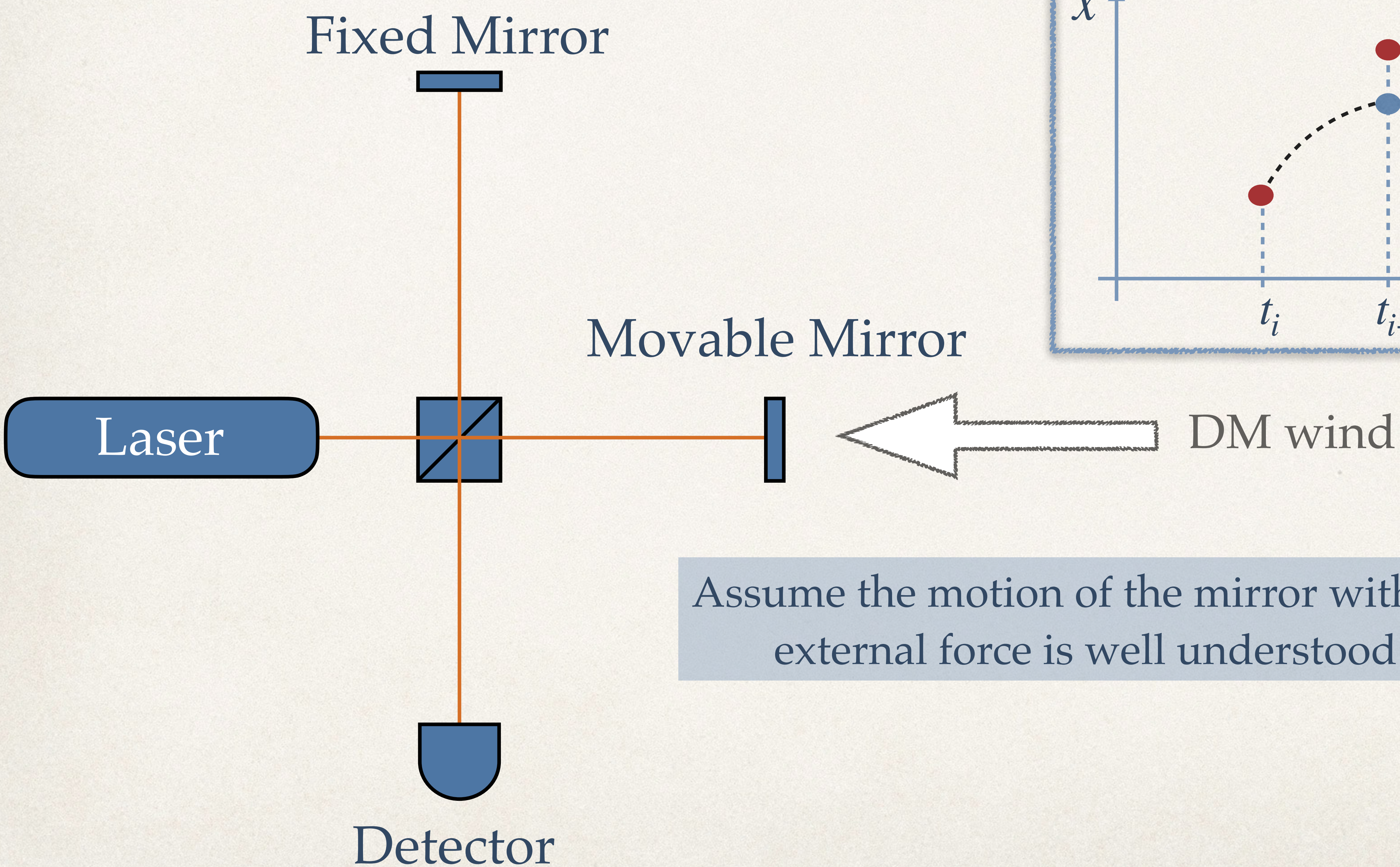
[Cheng, Primulando, MS '19]

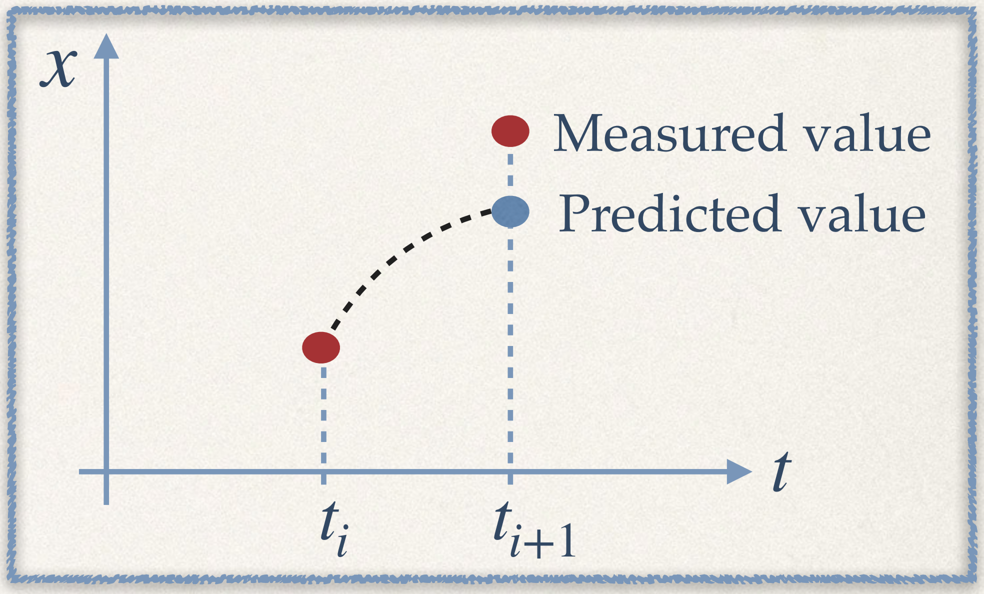
- Any target mass in a bath of DM
- DM scatterings induce Brownian Motion
- Measure the position of a light target mass with high precision
- Look for time-dependent asymmetries

[slide taken from Ting Cheng now at MPIK]

Potential Setup

Inspired by [Valerie Domcke and Martin Spinrath, 2017]





Assume the motion of the mirror without external force is well understood

The Asymmetry Factor

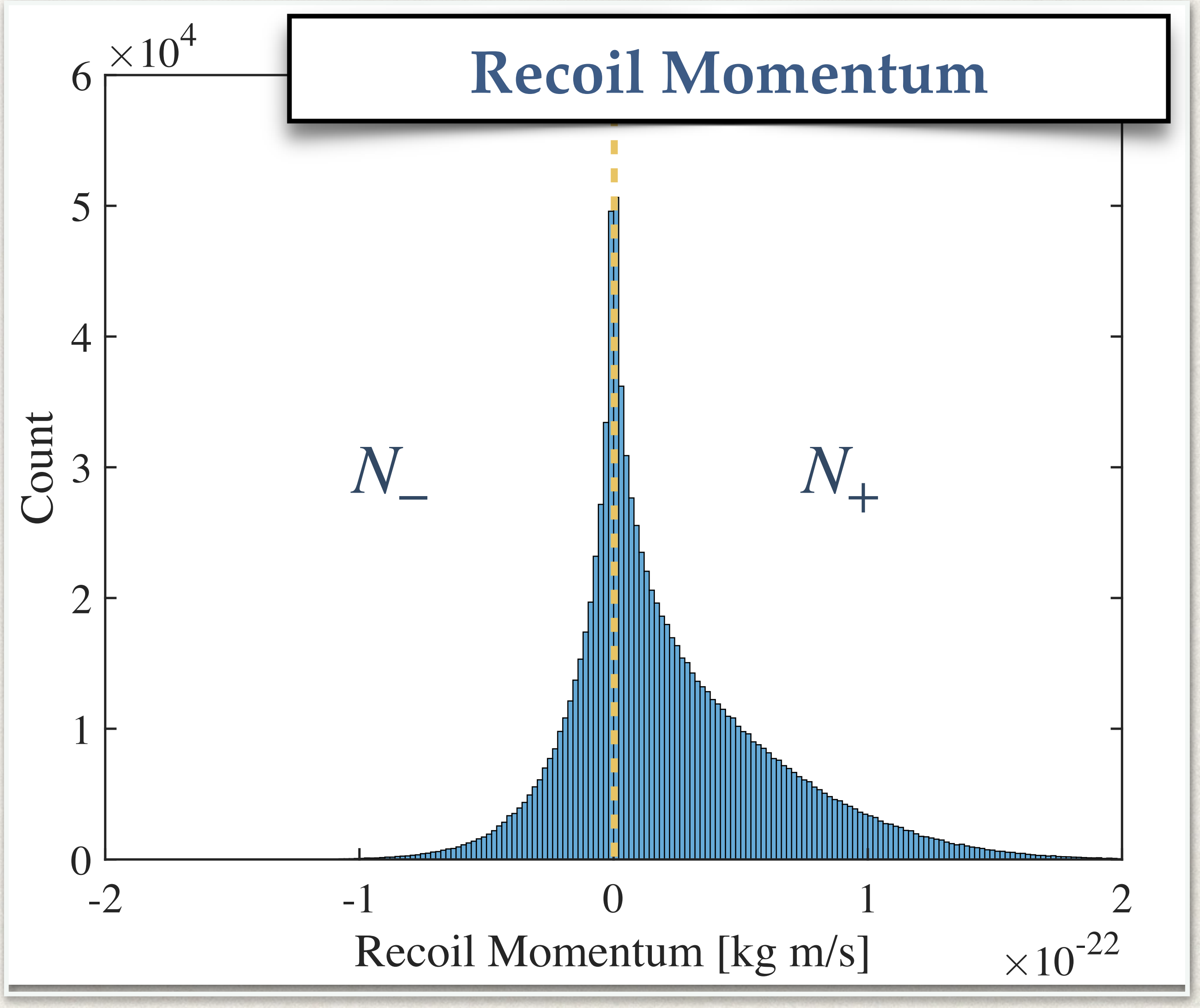
- The Asymmetry Factor :

$$A = \frac{N_+ - N_-}{N_+ + N_-} = p_+ - p_-$$

- Uncertainty of A :

$$\sigma_A = \frac{2}{\sqrt{N}}\sqrt{p_+ p_-}$$

$A, p_\pm$ are independent of DM mass



Backgrounds

- Many potential backgrounds for our proposal
  - seismic noise, nearby traffic, radioactivity, etc.
- In the paper we discuss two examples
  - Neutrinos (negligible $O(10^{-14})$ events per sec)
  - Hits from residual gas (after momentum cutoff $O(10^{-9})$ events per sec)

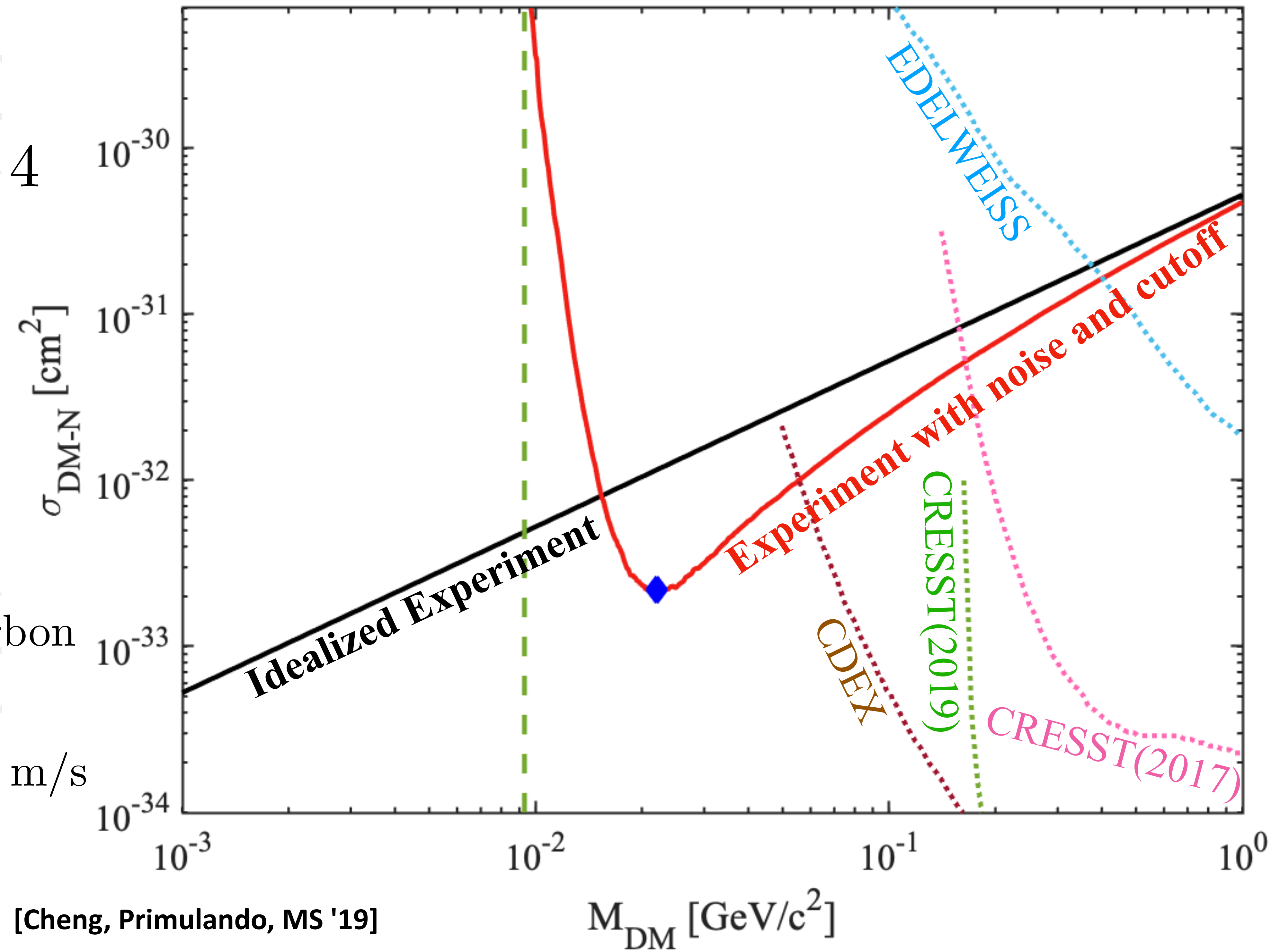
Sensitivity Estimate

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

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

$\Delta t = 10$ min

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



[Cheng, Primulando, MS '19]

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Toy Model: Damped Harmonic Oscillator

[Lee, Nugroho, MS '20]

- We want to study a simple toy model first

$$m\,\ddot{x}_c + k_c\,(1 + \mathrm{i}\,\phi)\,x_c = \frac{F_{\mathrm{ext},c}}{L}$$

- The experimental output

[Moore, Cole, Berry '14]

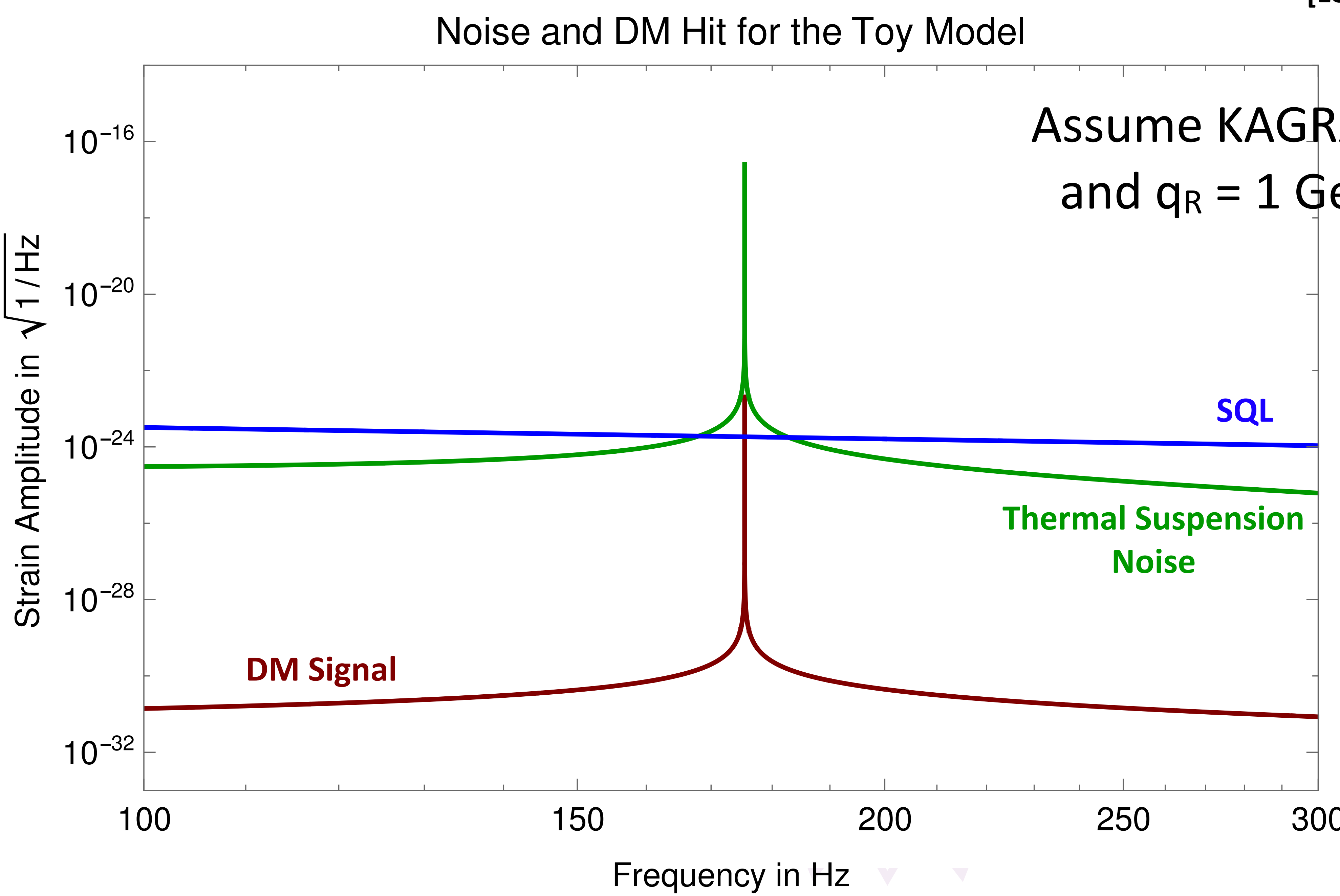
$$x_{\mathrm{tot},c}(t) = \underbrace{x_{\mathrm{th},c}(t)}_{\text{Suspension Thermal Noise}} + \underbrace{x_{\mathrm{qu},c}(t)}_{\text{Quantum Noise}} + \underbrace{x_{\mathrm{DM},c}(t)}_{\text{DM Signal}}$$

- We neglect here some noise components

Toy Model: Strain Amplitudes

[Lee, Nugroho, MS '20]

Assume KAGRA-like parameters and q_R = 1 GeV/c² x 220 km/s



Signal-to-Noise Ratio

[Lee, Nugroho, MS '20; Moore, Cole, Berry '14]

- The optimal SNR is given by

$$\varrho^2 = \int_{f_{\min}}^{f_{\max}} \mathrm{d}\, f \, \frac{4\, |\tilde{x}_{\mathrm{DM}}(2\,\pi\, f)|^2}{S_n(2\,\pi\, f)}$$

- Near the peak (FWHM) neglect quantum noise

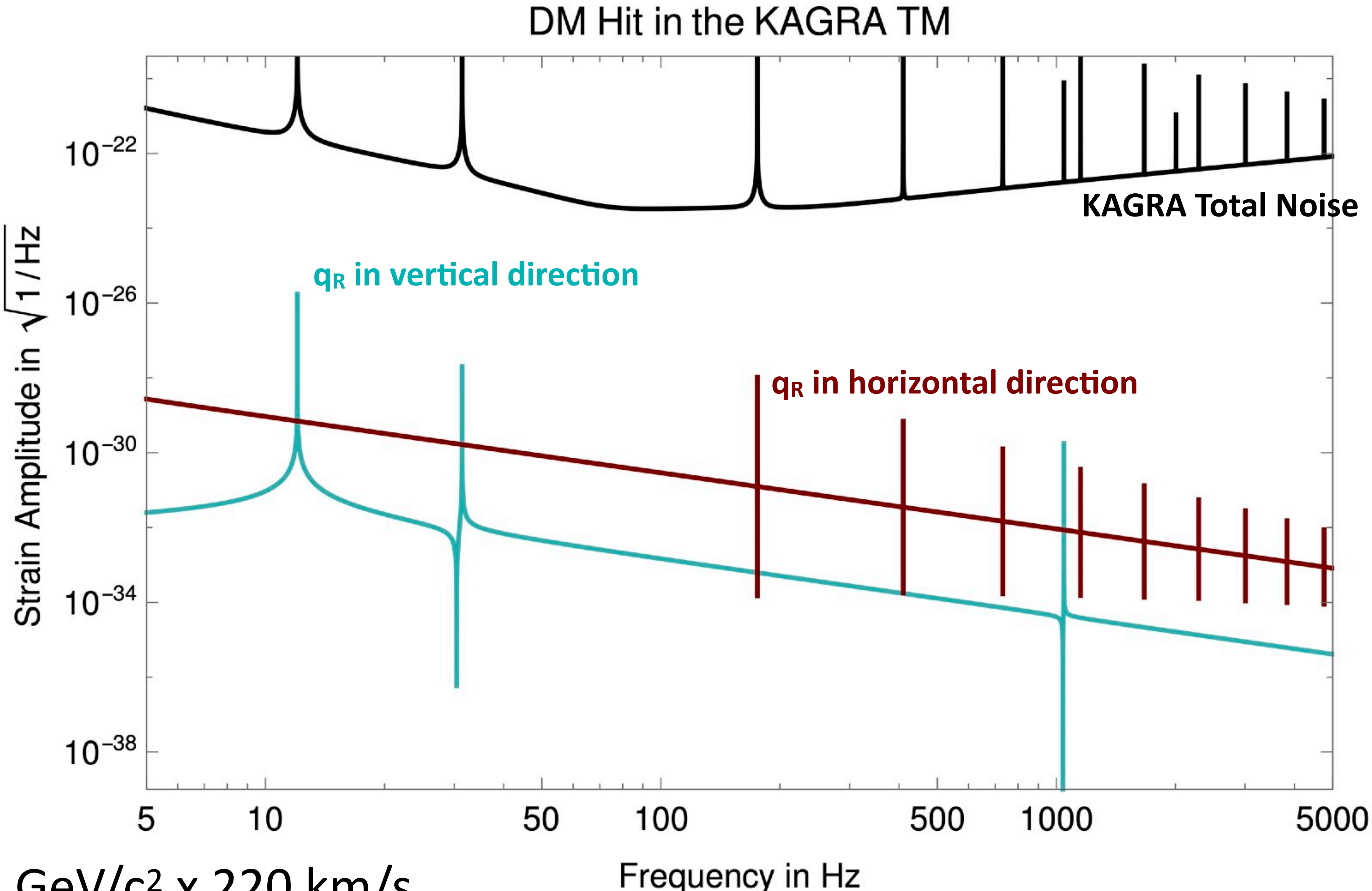
$$\varrho_{\mathrm{th}}^2 = \frac{1}{2\pi} \frac{q_R^2}{m\, k_B\, T} = \frac{1}{2\pi} \frac{E_R}{E_{\mathrm{th}}} = 4.09 \times 10^{-24}$$

Numbers as in previous figure

- Need light, cold targets!

DM Signal at KAGRA

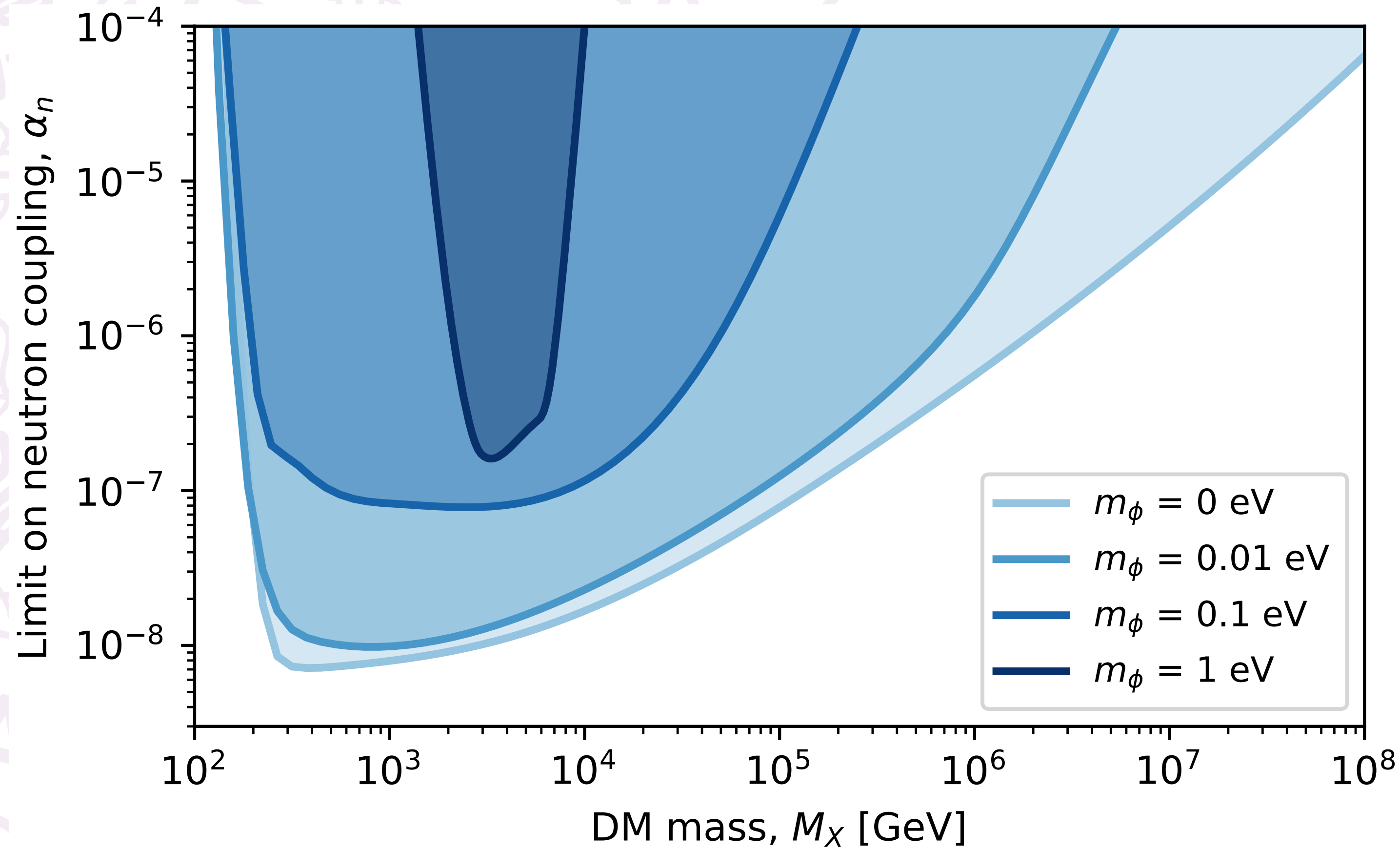
[Lee, Nugroho, MS '20]



q_R = 1 GeV/c^2 x 220 km/s

Current Reality

- Optically levitated mass
- Target mass 1 ng
- Temperature 200 µK
- Several days exposure
- Experimental threshold 0.15 GeV



[Monteiro *et al.* '20]

Lots of R&D

Physical device	Mass	Frequency	Temp.	Quantum limit	Sensitivity, e.g. acceleration, strain, force...
Resonant acoustic wave:					
BAW/Weber bar [41]	1000 kg	1 kHz	4 K		$h_s \sim 10^{-21}/\sqrt{\mathrm{Hz}}$
HBAR/phonon counting [76]	50 μg	10 GHz	10 mK	single phonon	$\sigma_E \sim 30\ \mu$eV $h_s \sim 10^{-15}/\sqrt{\mathrm{Hz}}$ ($h_s \sim 10^{-9}/\sqrt{\mathrm{Hz}}$broadbandbelowres)
superfluid helium cavities [52]	1 ng	300 MHz	50 mK	single phonon	$\sigma_E \sim 1\ \mu$eV
Resonant and below-resonance detectors:					
cantilever optomechanical accelerometer [77]	25 mg	10 kHz	300 K		$\sqrt{S_a} \sim 3\times10^{-9}$ g/$\sqrt{\mathrm{Hz}}$ ($\sqrt{S_a} \sim 10^{-7}$ g/$\sqrt{\mathrm{Hz}}$ broadband below res)
SiN-suspended test mass accelerometer [78, 79]	10 mg	10 kHz	300 K		$\sqrt{S_a} \sim 10^{-7}$ g/$\sqrt{\mathrm{Hz}}$ ($\sqrt{S_a} \sim 10^{-6}$ g/$\sqrt{\mathrm{Hz}}$ broadband below res)
membrane optomechanics [80–86]	10 ng	1.5 MHz	100 mK	at SQL	$\sqrt{S_a} \sim 10^{-7}$g/$\sqrt{\mathrm{Hz}}$ $\sqrt{S_f} \sim 10^{-17}$ N/$\sqrt{\mathrm{Hz}}$
crystalline cantilever for force sensing [87]	0.2 ng	1 kHz	200 mK		$\sqrt{S_a} \sim 3\times10^{-7}$g/$\sqrt{\mathrm{Hz}}$ $\sqrt{S_f} \sim 10^{-18}$ N/$\sqrt{\mathrm{Hz}}$
Pendula above resonance:					
LIGO mirror [88]	10 kg	10 Hz – 10 kHz	300 K	SN limited above 100 Hz	$\sqrt{S_a} \sim 4\times10^{-15}$ g/$\sqrt{\mathrm{Hz}}$ at 100 Hz $\sqrt{S_x} \sim 10^{-19}$ m/$\sqrt{\mathrm{Hz}}$
suspended mg mirror [89–91]	1 mg	1 – 10 kHz	300 K	factor of 20 in displacement from (off-resonant) SQL	$\sqrt{S_a} \sim 7\times10^{-11}$ g/$\sqrt{\mathrm{Hz}}$ at 600 Hz $\sqrt{S_x} \sim 5\times10^{-17}$ m/$\sqrt{\mathrm{Hz}}$
crystalline cantilever [92]	50 ng	10 – 100 kHz	300 K	at (off-resonant) SQL	$\sqrt{S_a} \sim 2\times10^{-7}$ g/$\sqrt{\mathrm{Hz}}$ at 20 kHz $\sqrt{S_x} \sim 10^{-16}$ m/$\sqrt{\mathrm{Hz}}$
Levitated and free-fall systems:					
LISA pathfinder [93]	15 kg	1 – 30 mHz	300 K		$\sqrt{S_a} \sim 10^{-15}$ g/$\sqrt{\mathrm{Hz}}$
mm magnetically-levitated sphere [94]	4 mg	20 Hz	5 K		$\sqrt{S_a} \sim 2\times10^{-7}$ g/$\sqrt{\mathrm{Hz}}$ $\sqrt{S_f} \sim 8\times10^{-12}$ N/$\sqrt{\mathrm{Hz}}$
sub-mm magnetically-levitated sphere [95]	0.25 μg	1–20 Hz	laser cool to $<$ 9 K		$\sqrt{S_a} \sim 10^{-7}$ g/$\sqrt{\mathrm{Hz}}$ $\sqrt{S_f} \sim 2\times10^{-16}$ N/$\sqrt{\mathrm{Hz}}$
optically trapped microsphere [96]	1 ng	10 – 100 Hz	laser cool to 50 μK	factor of 100 in displacement from (off-resonant) SQL	$\sqrt{S_a} \sim 10^{-7}$ g/$\sqrt{\mathrm{Hz}}$ $\sqrt{S_f} \sim 10^{-18}$ N/$\sqrt{\mathrm{Hz}}$
optically trapped nanosphere [97, 98] (rotational [99])	3 fg	300 kHz	laser cool to 12 μK	ground state	$\sqrt{S_a} \sim 7\times10^{-4}$ g/$\sqrt{\mathrm{Hz}}$ $\sqrt{S_f} \sim 2\times10^{-20}$ N/$\sqrt{\mathrm{Hz}}$ $\sqrt{S_\tau} \sim 10^{-27}$ Nm/$\sqrt{\mathrm{Hz}}$
trapped ion crystal [18]	10^{-6} fg	1 MHz			$\sqrt{S_a} \sim 50$ g/$\sqrt{\mathrm{Hz}}$ $\sqrt{S_f} \sim 4\times10^{-22}$ N/$\sqrt{\mathrm{Hz}}$

TABLE I. Examples of currently-available mechanical sensors. Sensitivities for continuous sensing are represented by the relevant noise power spectral densities (e.g. S_a is the acceleration noise power), or threshold (σ_E is the single-phonon detection threshold). Here we summarize solid-state mechanical detectors, although atom interferometers can be characterized by similar metrics.

White paper:
"Mechanical Quantum Sensing in the Search for Dark Matter"
[arXiv:2008.06074]

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Summary and Conclusions

- Gravitational Wave Astronomy has just begun
- Impressive new technologies
- Can we use them to find DM?
  - Maybe.
- We need more research

A bit of Advertisement

The Future is DARK Workshop

29th of June - 1st of July

Free registration

- Neutrinos
- Dark Matter
- Gravitational Waves