# Cosmic Relic Scattering at Gravitational Wave Detectors

**Martin Spinrath**
**National Tsing Hua University, Hsinchu, Taiwan**

**7th KAGRA International Workshop**

**Mostly based on collaborations with**
**V. Domcke [arXiv:1703.08629], C. Ting, R. Primulando [arXiv:1906.07356] and**
**C.-H. Lee, C. S. Nugroho [arXiv:2007.07908]**

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# Outline

- Introduction
- Dark Matter Scattering at GW Detectors
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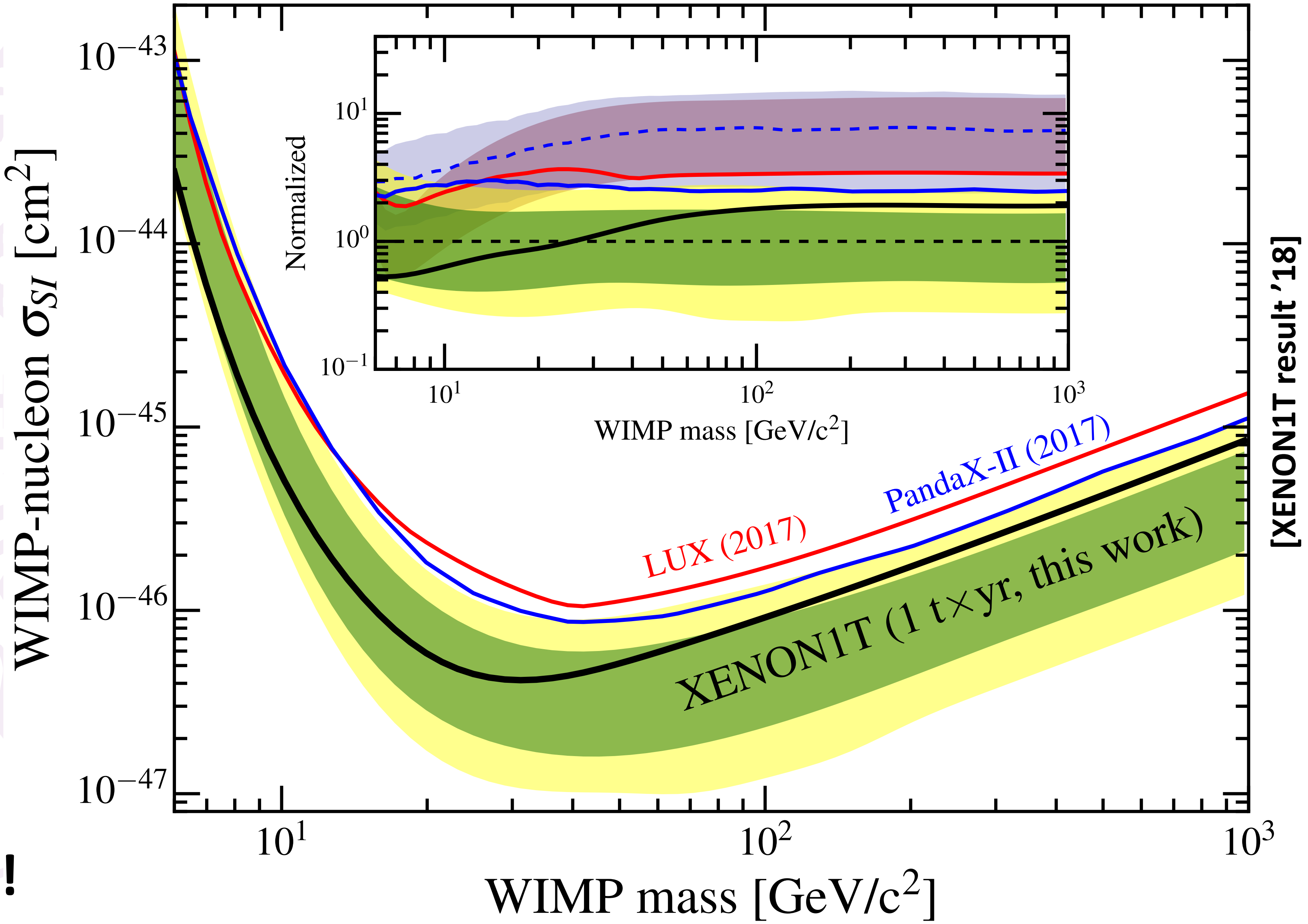
# Cosmic Relics

- Cosmic Relics are produced in the early universe and are still around today
- Examples:
  - Cosmic Microwave Background (not the focus here)
  - Cosmic Neutrino Background (no time, does not work)
  - Dark Matter (only seen gravitationally, can we see it in GW detectors?)

# WIMP Searches

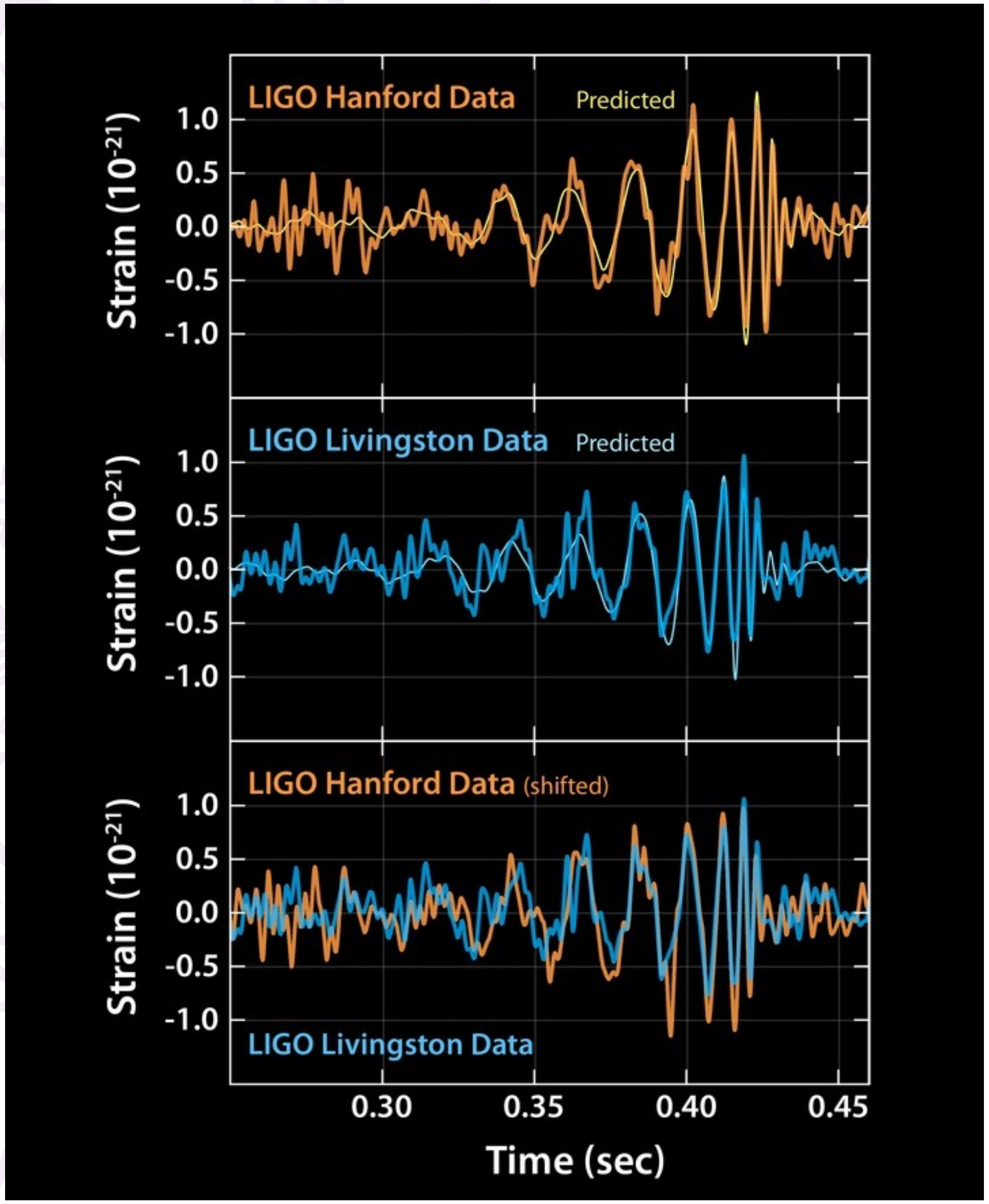


[XENON1T result '18]

**Time to think again?!**
**Light WIMPs?**

# Gravitational Wave Detectors

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



[Courtesy Caltech/MIT/LIGO Laboratory 2016]

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- Introduction
- **Dark Matter Scattering at GW Detectors**
    - **Particle Physics Approach**
    - Gravitational Wave Astronomy Approach
- Summary and Conclusions

# Dark Brownian Motion

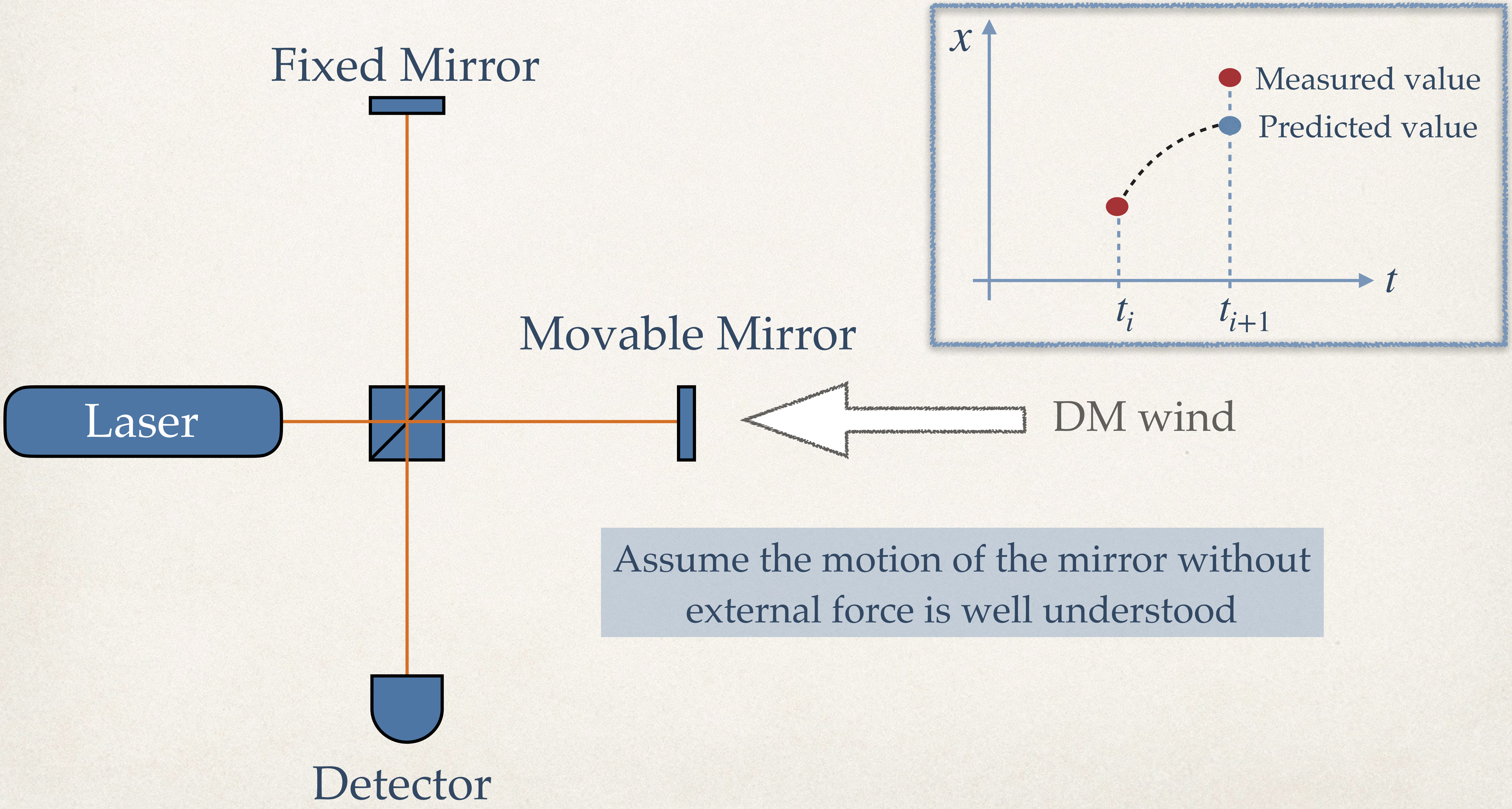
[Cheng, Primulando, MS '19]

- 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

**[slide taken from Ting Cheng now at MPIK]**

# The Asymmetry Factor

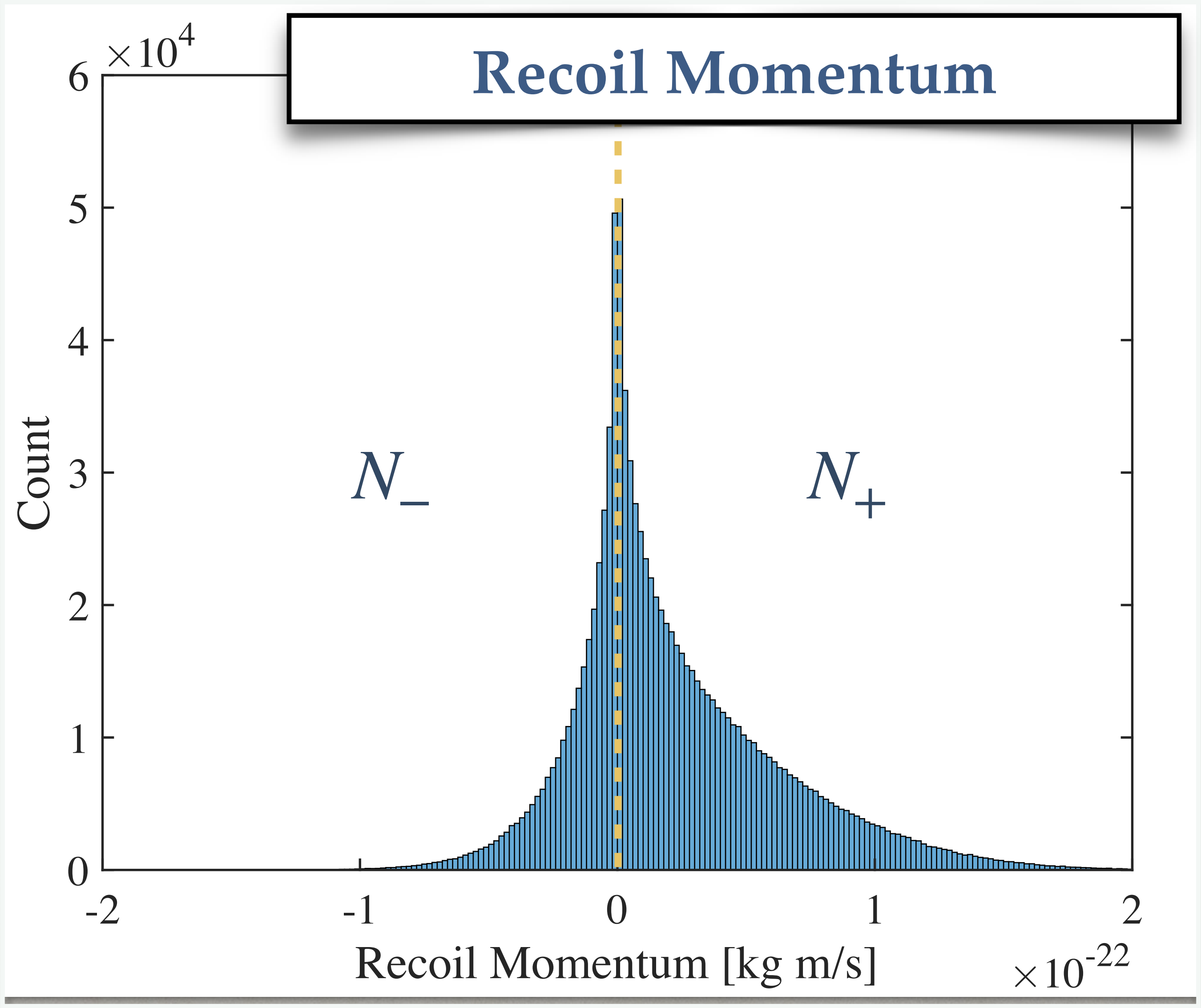
- The Asymmetry Factor :

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

- Uncertainty of A :

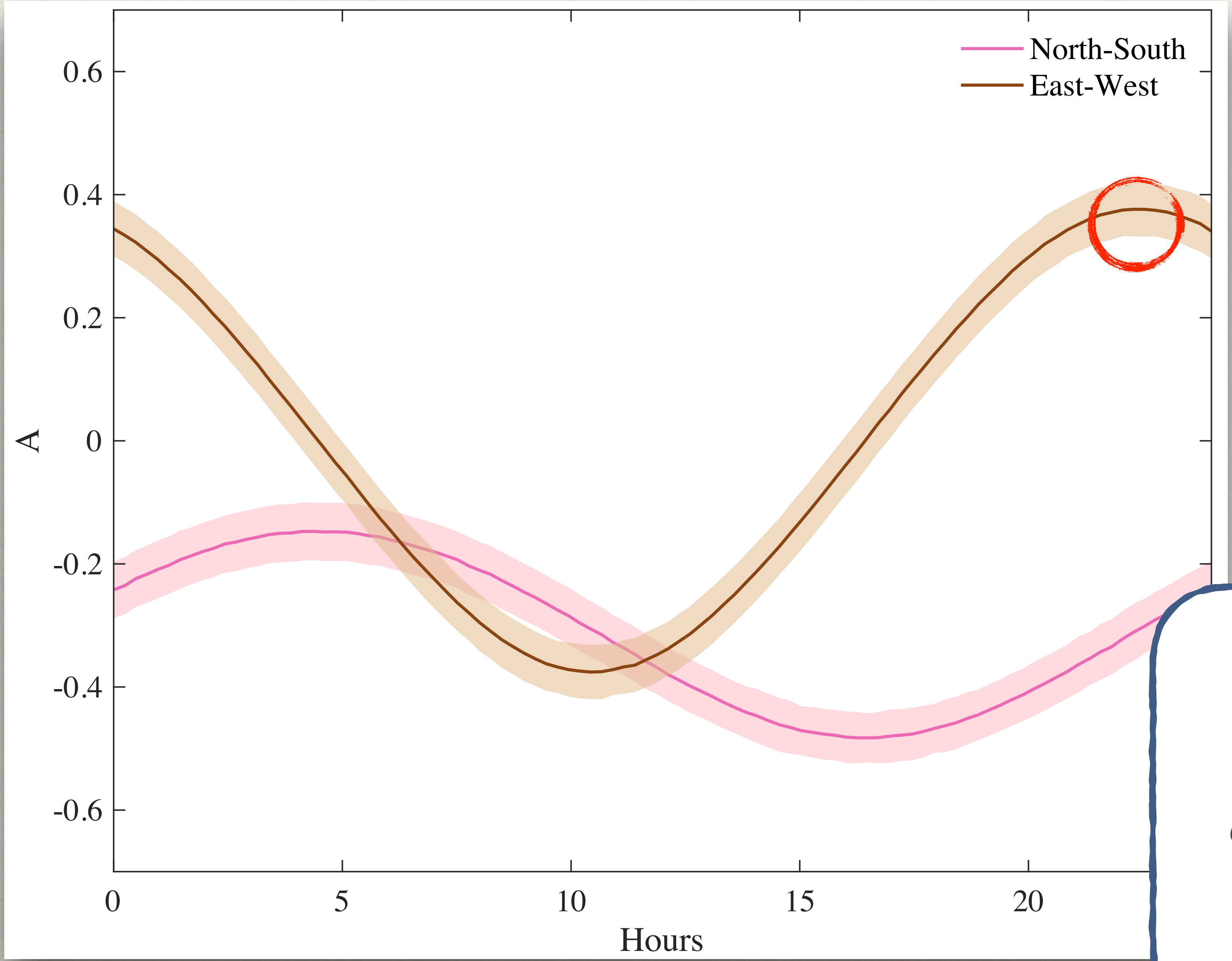
$$\sigma_A = \frac{2}{\sqrt{N}} \sqrt{p_+ p_-}$$

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



**[slide taken from Ting Cheng now at MPIK]**

# Daily Modulation of A



[T.C., M. Spinrath, R. Primulando 2019]

Error Bar:

$\Delta t = 10$ min

$\sigma_{DM-N} = 10^{-31}$ $\mathrm{cm}^2$

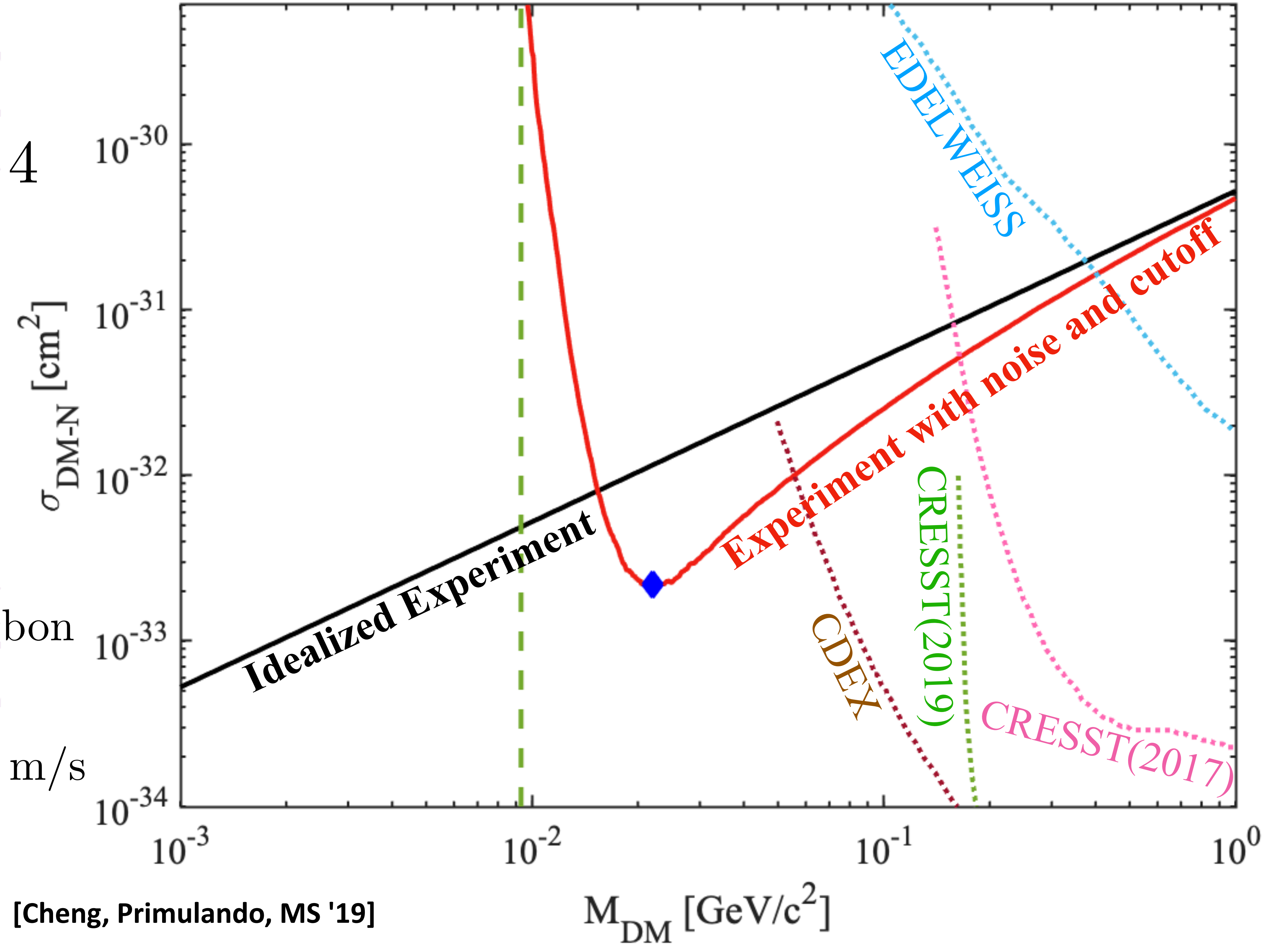
$M_{DM} = 10$ MeV

# Backgrounds

- Small neutrino cross section and target mass
  - Negligible O($10^{-14}$) neutrino events per sec
- Residual gas
  - Naively, many O($10^{9}$) events/sec
  - After momentum cutoff O($10^{-9}$) events/sec (irrelevant in KAGRA)
- Seismic noise, nearby traffic, radioactivity, ... setup dependent

# Sensitivity Estimate

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



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

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

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

**[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]

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

- We neglect here some noise components

# Toy Model: DM Signal I

**[Lee, Nugroho, MS '20; Tsuchida *et al.* '19]**

- The DM signal is easier to model for a real eq.

$$m\,\ddot{x}_r + 2\,m\,\omega_r\,\xi\,\dot{x}_r + m\,\omega_r^2\left(1+\xi^2\right)x_r = \frac{q_R}{L}\,\delta(t)$$

- That has the solution

$$x_{\rm DM}(t) = \theta(t)\frac{q_R}{m\,\omega_r\,L}\exp\left(-\omega_r\,\xi\,t\right)\sin(\omega_r\,t)$$

- And we will need

$$|\tilde{x}_{\rm DM}(\omega)|^2 = \frac{q_R^2}{m^2\,L^2}\,\frac{1}{\left(\omega^2-\omega_r^2(1-\xi^2)\right)^2+4\,\omega_r^4\,\xi^2}$$

# Toy Model: DM Signal II

**[Lee, Nugroho, MS '20; Tsuchida *et al.* '19]**

- After matching the real and complex equation

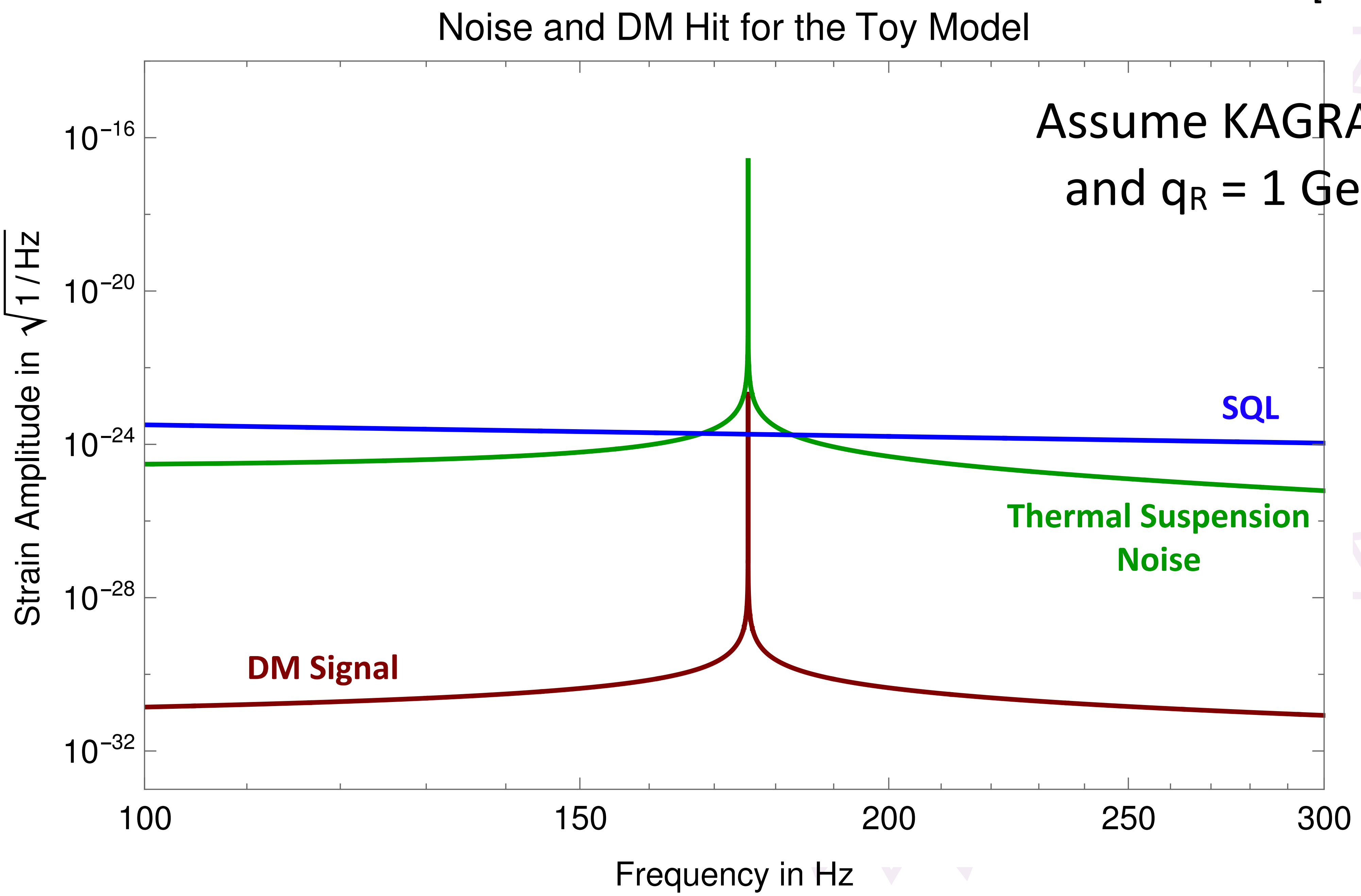
$$|\tilde{x}_{\mathrm{DM}}(\omega)|^2 = \frac{q_R^2}{m^2\,L^2}\,\frac{1}{(\omega^2-\omega_c^2)^2+\omega_c^4\phi^2}$$

- The DM strain amplitude **[Moore, Cole, Berry '14]**

$$h_{\mathrm{DM}}(\omega) = \sqrt{\frac{2\,\omega}{\pi}}\,|\tilde{x}_{\mathrm{DM}}(\omega)|$$

# Toy Model: Strain Amplitudes

**[Lee, Nugroho, MS '20]**



Assume KAGRA-like parameters and $q_R$ = 1 GeV/$c^2$ 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

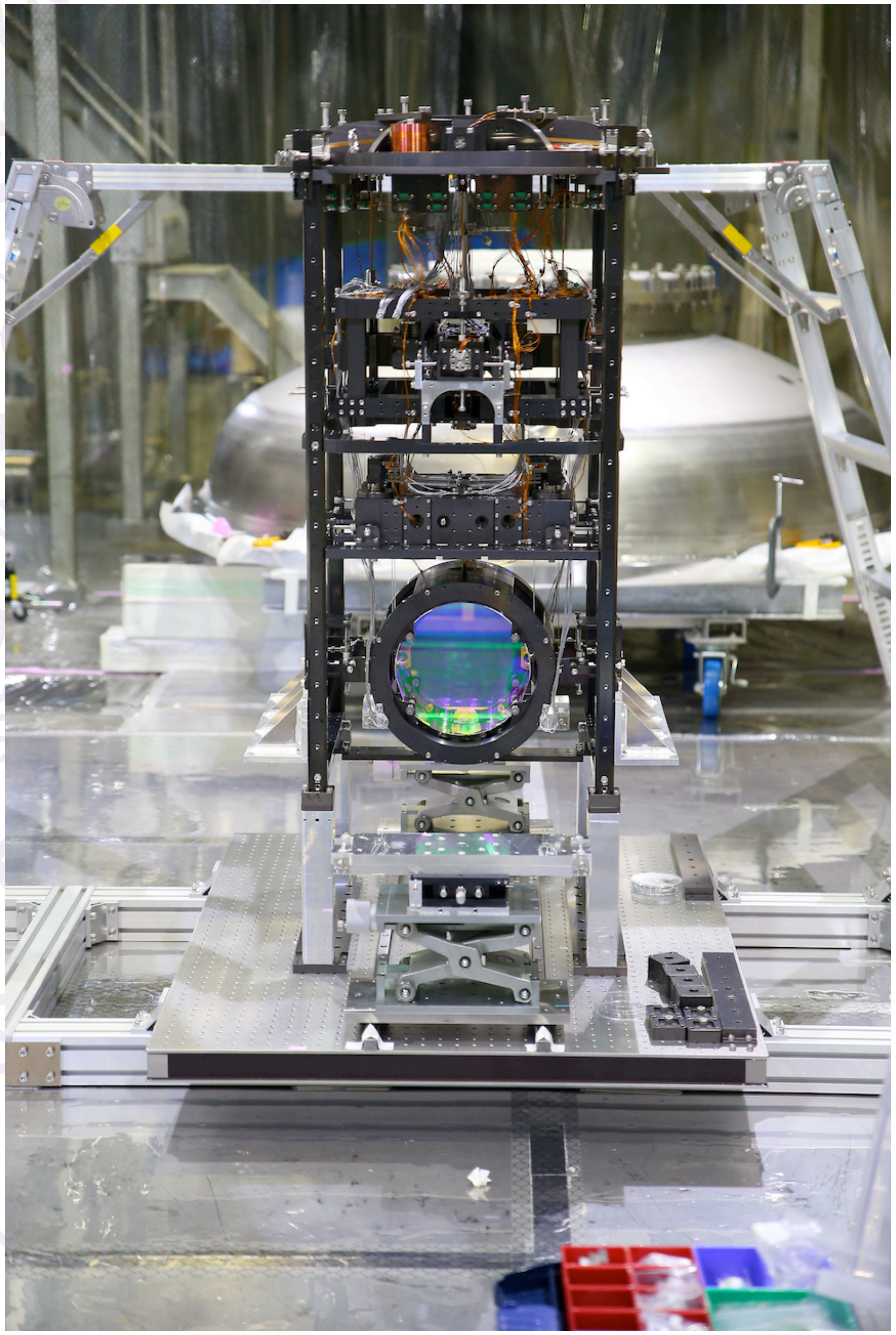
$$\varrho_{\mathrm{th}}^2 = \frac{1}{2\pi} \frac{q_R^2}{m\, k_B\, T} = \frac{1}{2\pi} \frac{E_R}{E_{\mathrm{th}}} \underset{\uparrow}{=} 4.09 \times 10^{-24}$$

**Numbers as in previous figure**

- Need light, cold targets!

# KAGRA

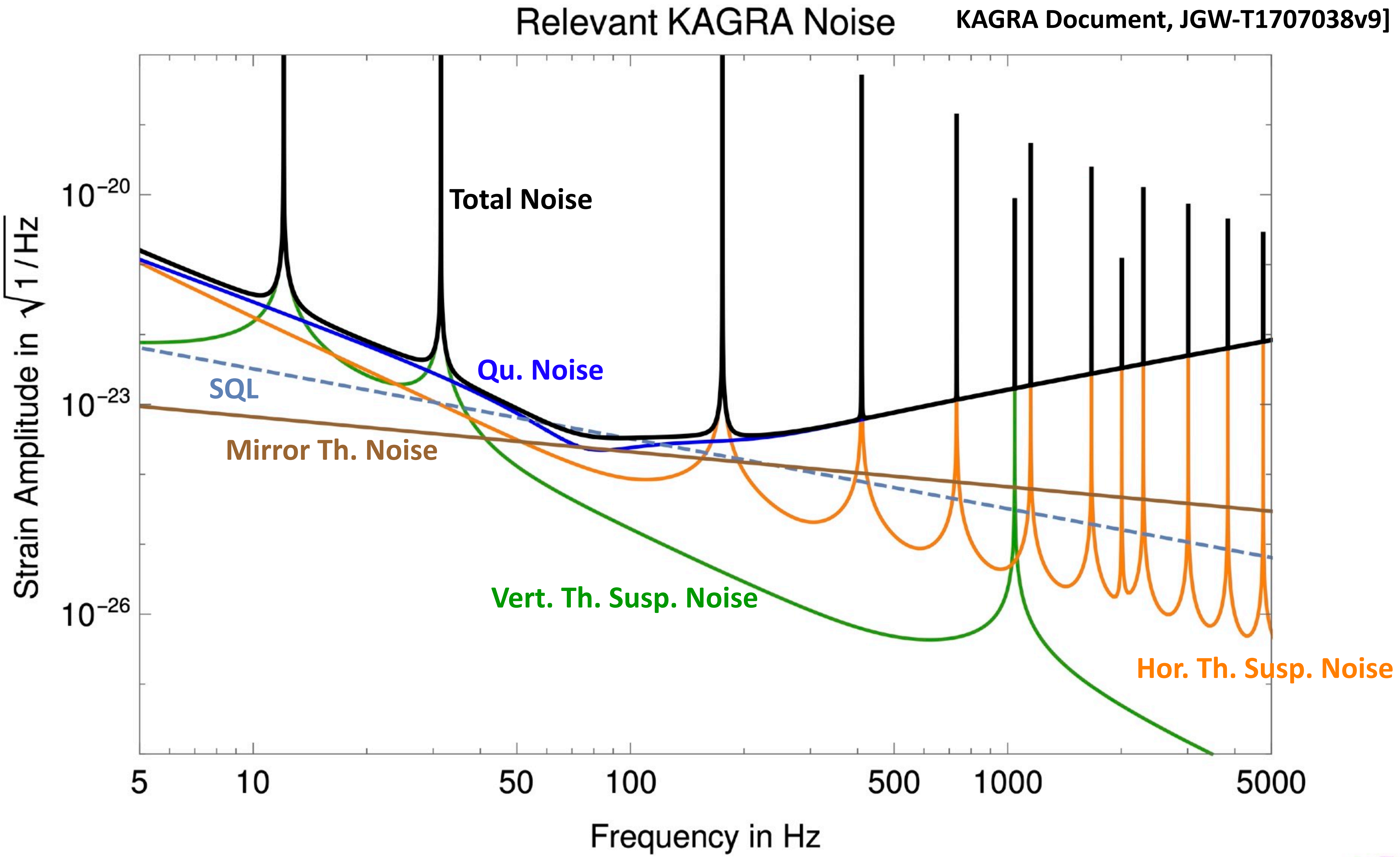
- KAGRA is a new gravitational wave detector in Japan
- Advantage: Cryogenic (T about 20 K)
- The mirror is a pendulum on springs on a pendulum (3 x coupled, damped harmonic oscillators)
- Equations of motion have matrix form



[Photo courtesy: KAGRA Observatory, ICRR, The University of Tokyo (c) Rohan Mehra, provided via ICRR, Univ. of Tokyo]

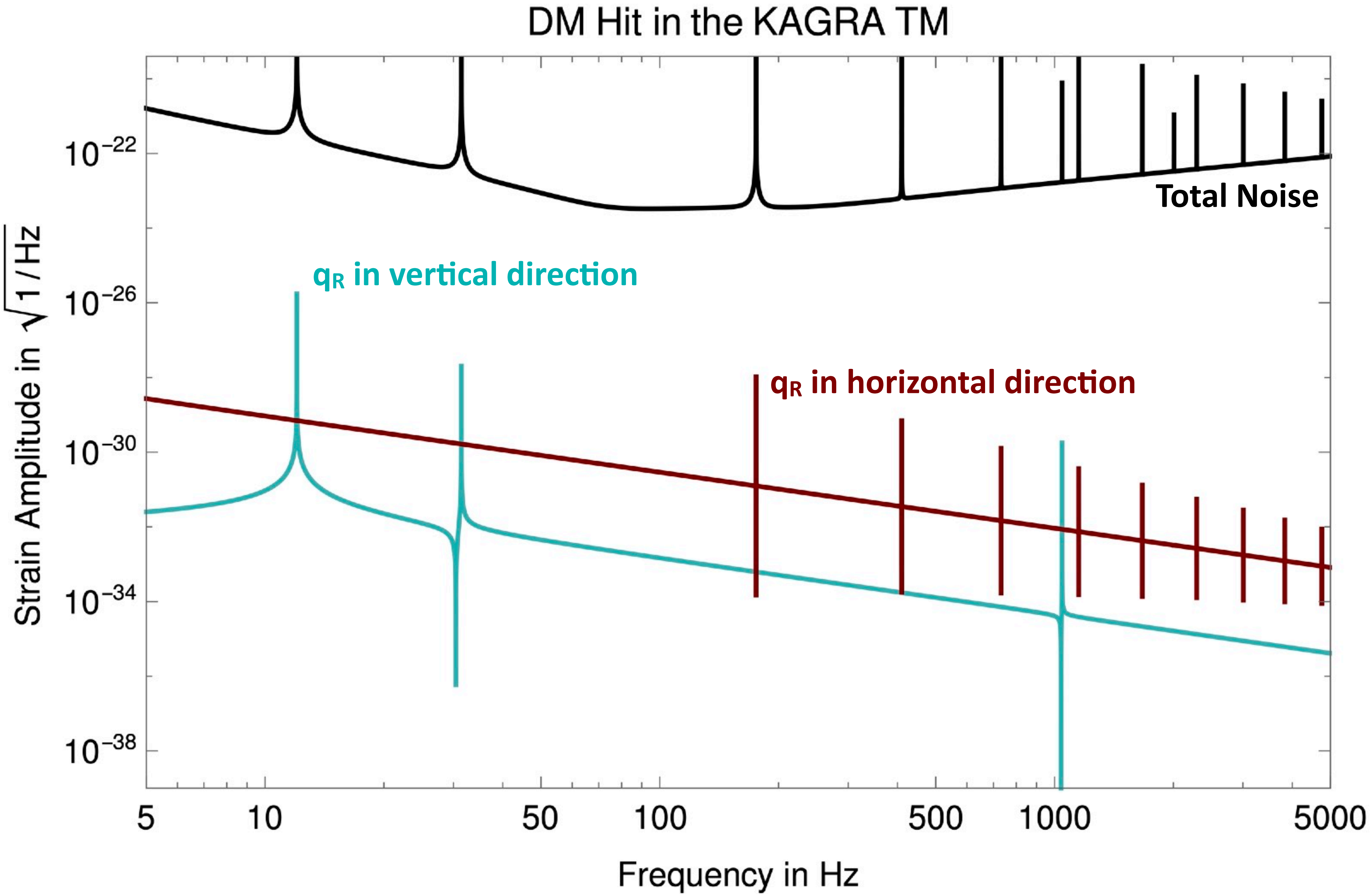
# KAGRA Noise

[Fig. from Lee, Nugroho, MS '20 based on KAGRA Document, JGW-T1707038v9]



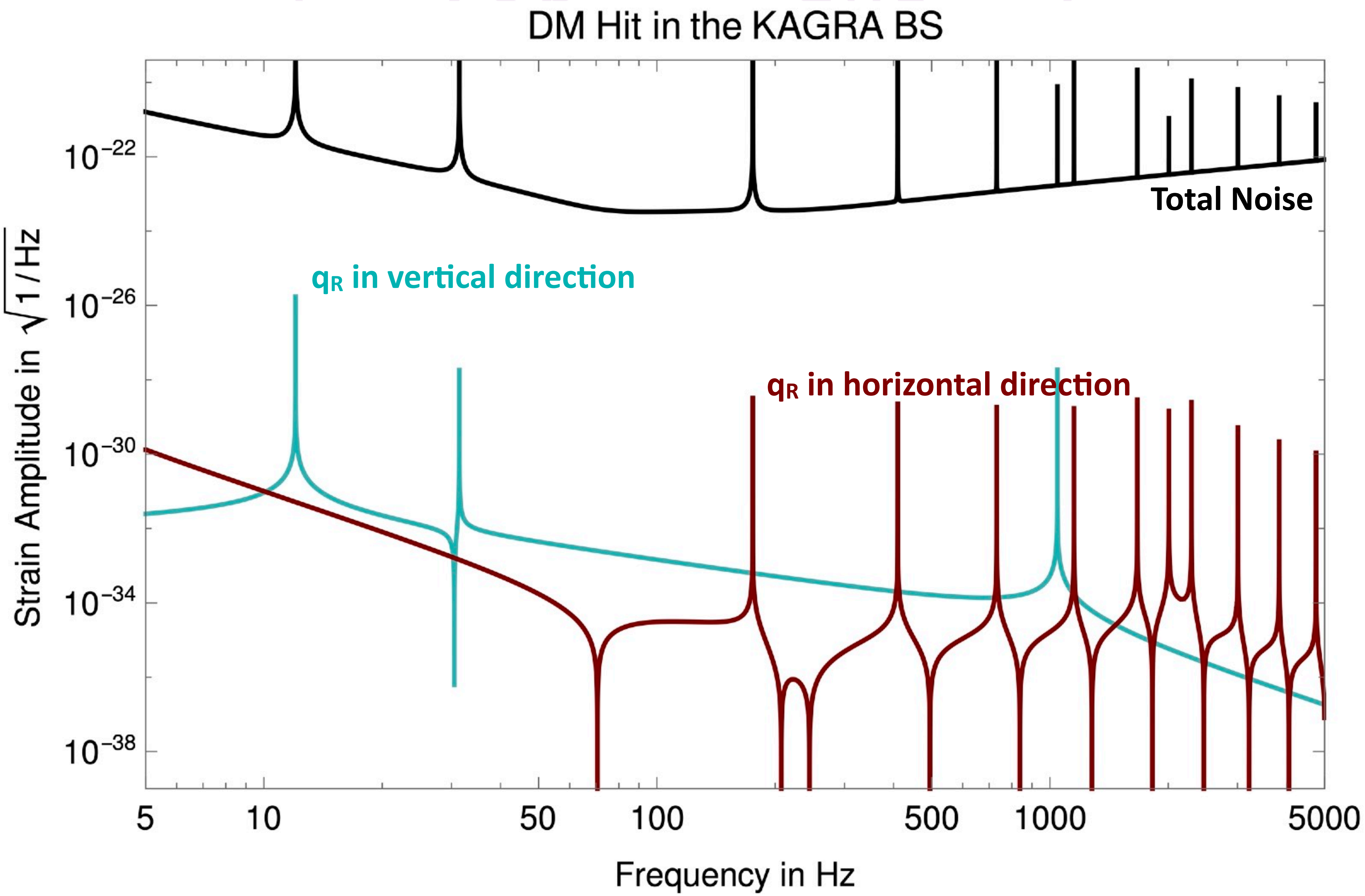
# DM Signal at KAGRA

[Lee, Nugroho, MS '20]



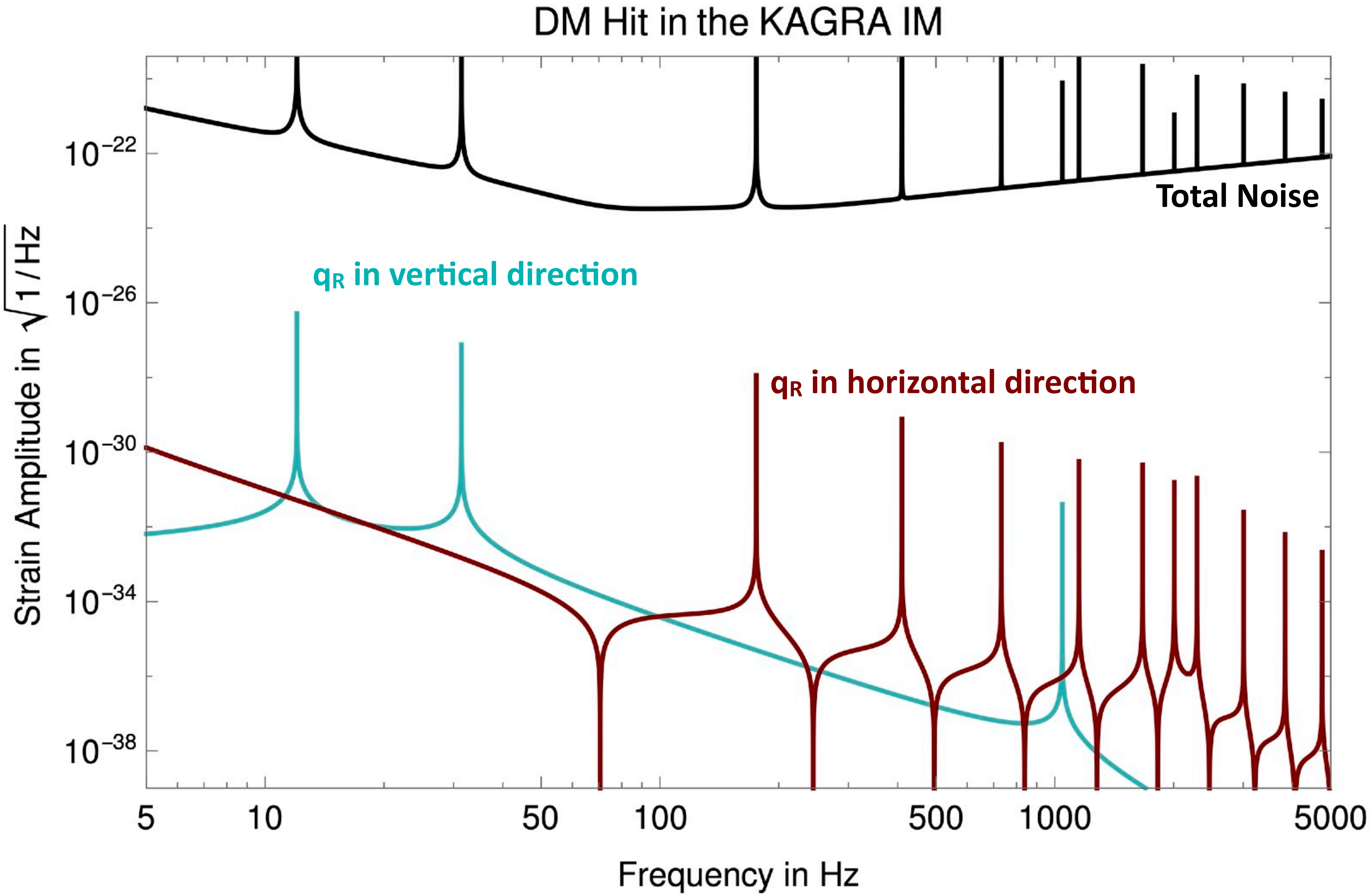
# DM Signal at KAGRA

**[Lee, Nugroho, MS '20]**



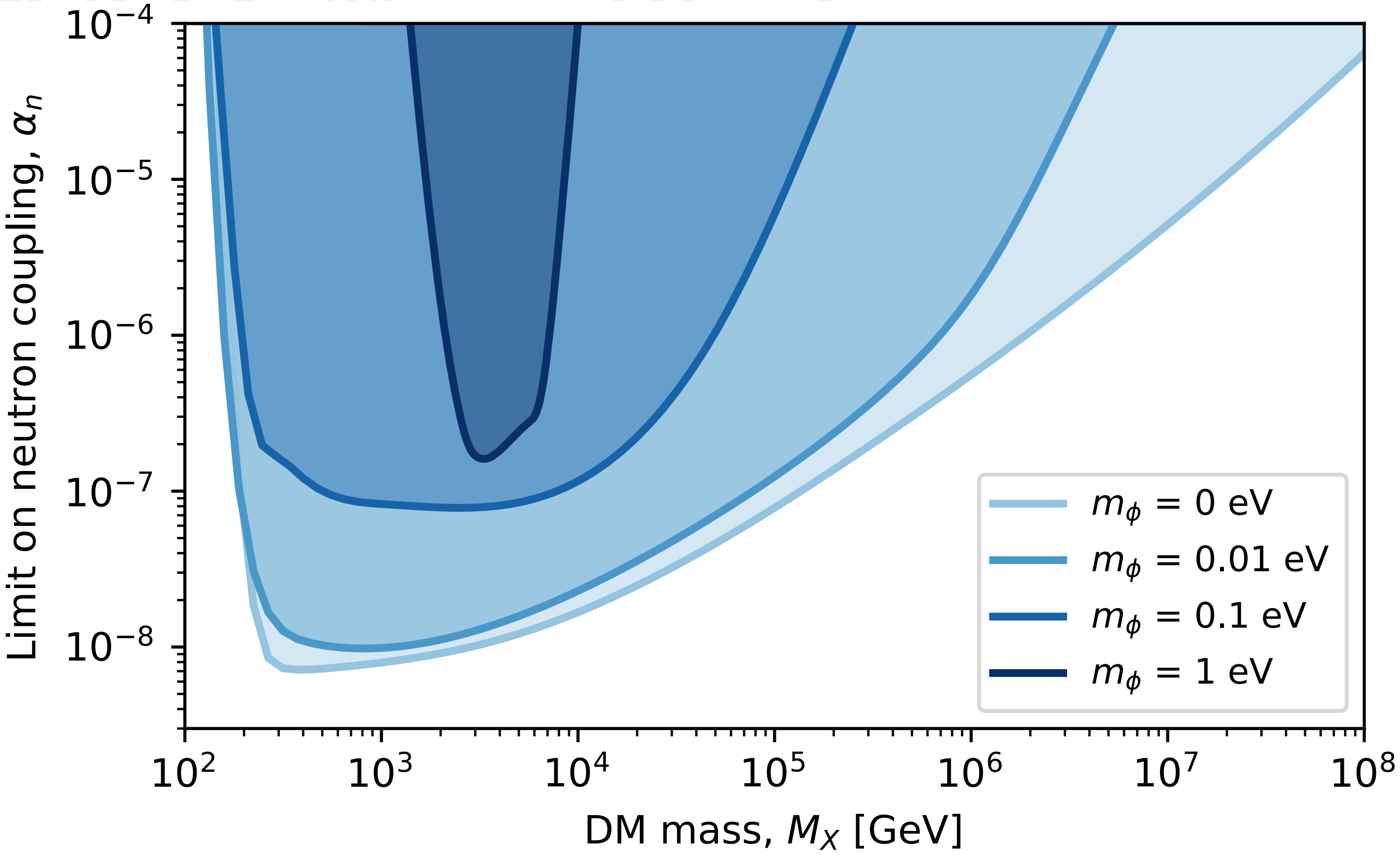
# DM Signal at KAGRA

[Lee, Nugroho, MS '20]



# Other technology

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



**[Monteiro *et al.* '20]**

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# Summary and Conclusions

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

# Me & My Group

- Since 2018 Assistant Professor at National Tsing Hua University in Taiwan
- Background in Theoretical Particle Physics
    - Neutrino physics, Grand Unification, Supersymmetry, ...
- Group:
    - currently 1 PhD student
    - Expect at least 1 more master student next year

# My Plans & Motivation

- Recently also interested in particle cosmology
  - Cosmic Relics
  - Cosmic Phase Transitions
- Interests about KAGRA
  - Theoretical modeling of potential signals
  - Generalising sensitivity curves for non-wave signals

# Backup

# Residual Gas

**[Cheng, Primulando, MS '19]**

- Gravitational wave detectors have ultra high vacua in their chambers
- We can estimate the hit rate from residual gas

$$R_{\text{atm}} = n\,A\,|v|\,f(v)$$

$$\approx 8.3 \times 10^9 \left( \frac{P}{10^{-10}\ \text{mbar}} \sqrt{\frac{20\ \text{K}}{T}} \frac{A}{\text{mm}^2} \right) \frac{1}{\text{s}}$$

# Residual Gas

[Cheng, Primulando, MS '19]

- What rate could we expect for DM?

$$R_{\rm DM} = (Z+N)^2\,\sigma_{{\rm DM}-N}\,\frac{M_T}{M_{\rm mol}}\,\frac{\rho_{\rm DM}}{M_{\rm DM}}\,\bar{v}_{\rm DM}$$
$$= 0.37\left(\frac{Z+N}{12}\,\frac{\sigma_{{\rm DM}-N}}{10^{-31}\,{\rm cm}^2}\,\frac{M_T}{10^{-3}\,{\rm g}}\,\frac{\rho_{\rm DM}}{0.3\,{\rm GeV/cm}^3}\,\frac{20\,{\rm MeV}}{M_{\rm DM}}\,\frac{\bar{v}_{\rm DM}}{341\,{\rm km/s}}\right)\frac{1}{\rm s}$$

- Can we cut on the background?
  - Yes! Cut on minimum recoil momentum

# Residual Gas

[Cheng, Primulando, MS '19]

- No air flow: $\langle q_{\mathrm{atm}} \rangle$
- The width of the recoil momentum is

$$\sigma_{q_{\mathrm{atm}}} \approx 2.5 \times 10^{-24} \left( \frac{P}{10^{-10}\ \mathrm{mbar}} \frac{A}{\mathrm{mm}^2} \frac{\delta t}{0.1\ \mathrm{ns}} \sqrt{\frac{T}{20\ \mathrm{K}}} \right)^{1/2} \frac{\mathrm{kg\ m}}{\mathrm{s}}$$

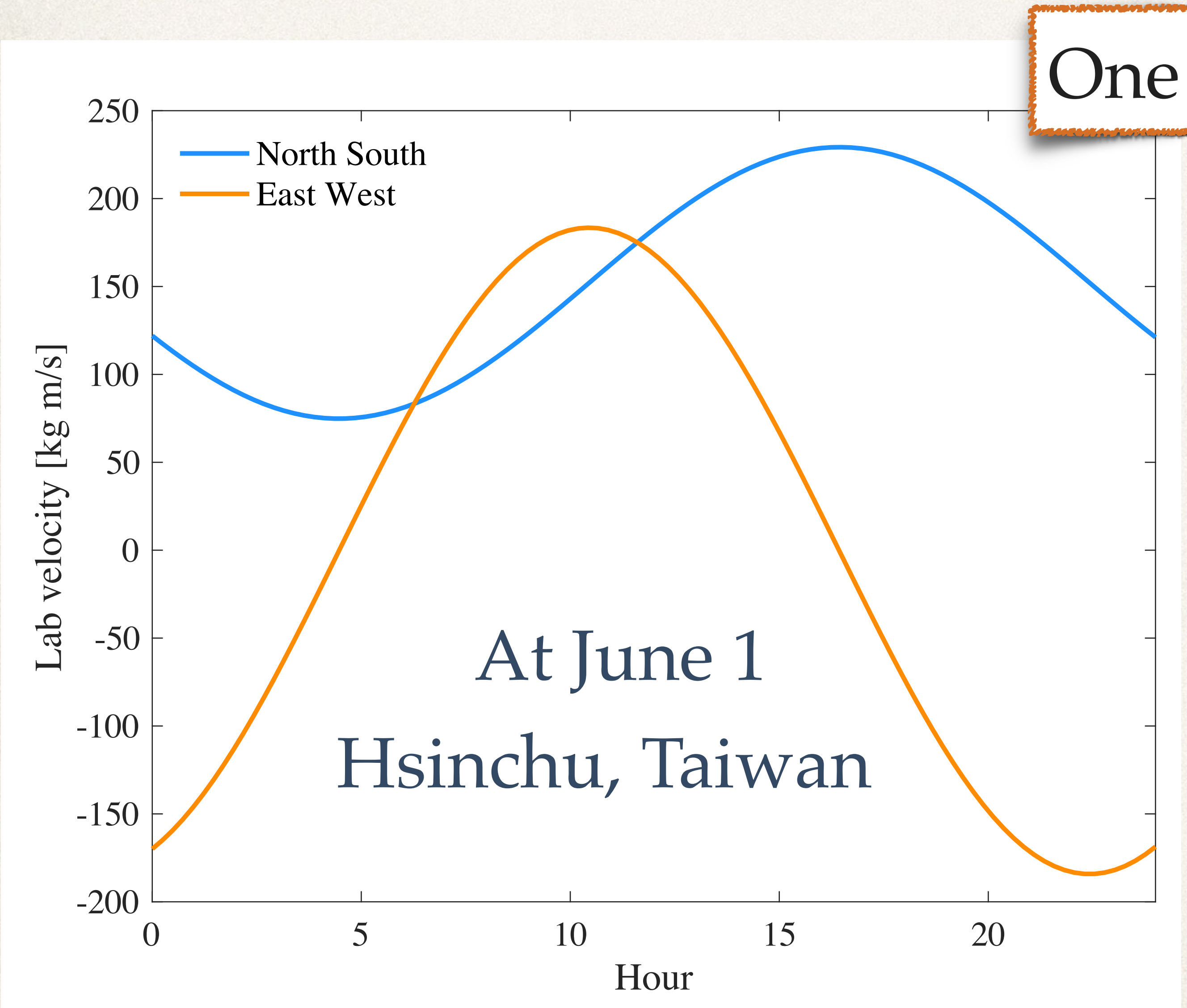
- Use LIGO resolution as naive estimate

$$q_{\mathrm{min}} \equiv 2 \times 10^{-23}\ \mathrm{kg\ m/s} \approx 3.7 \times 10^{-5}\ \mathrm{GeV/c}$$

- Remaining gas hit rate $R_{\mathrm{atm}}^{\mathrm{cut}} \approx 5 \times 10^{-6}\ \mathrm{Hz}$

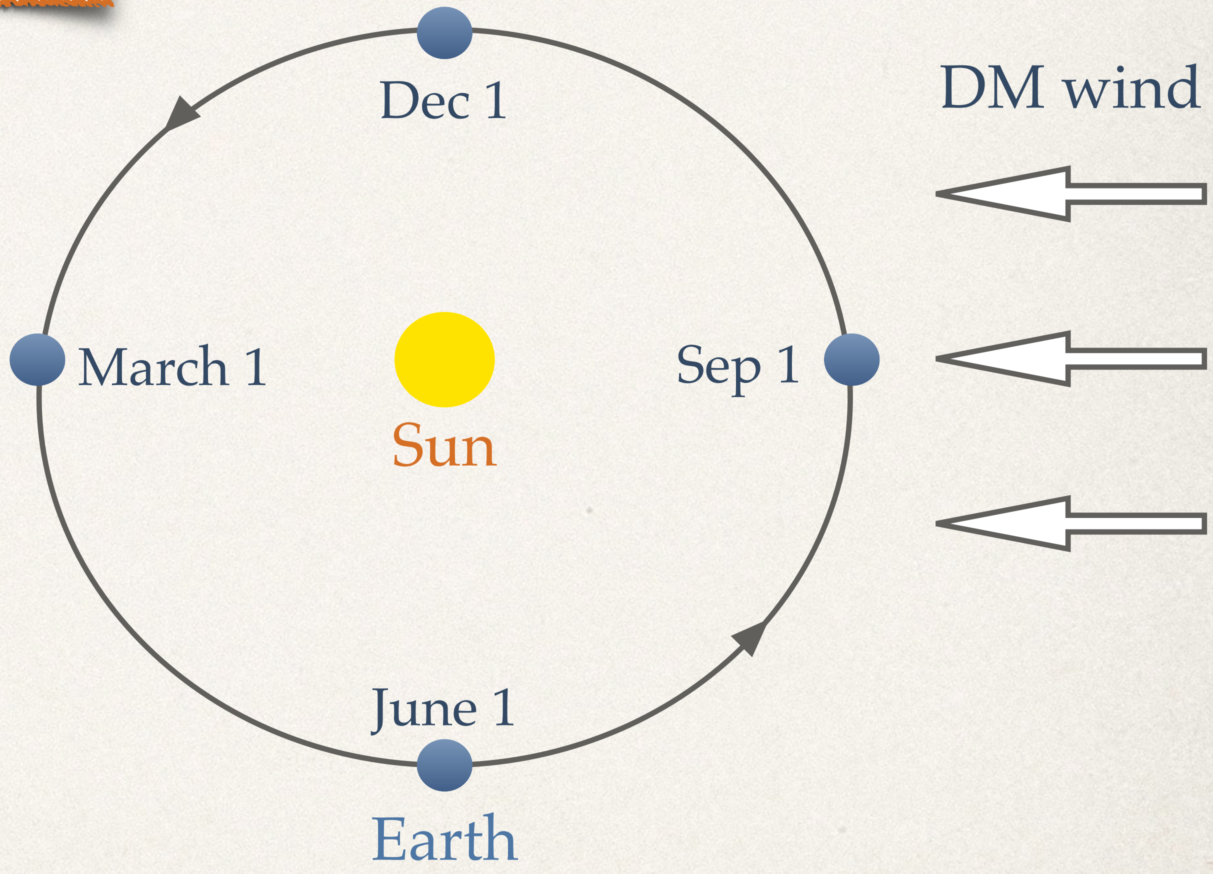
[slide taken from Ting Cheng now at MPIK]

# Time Dependent Lab Velocity

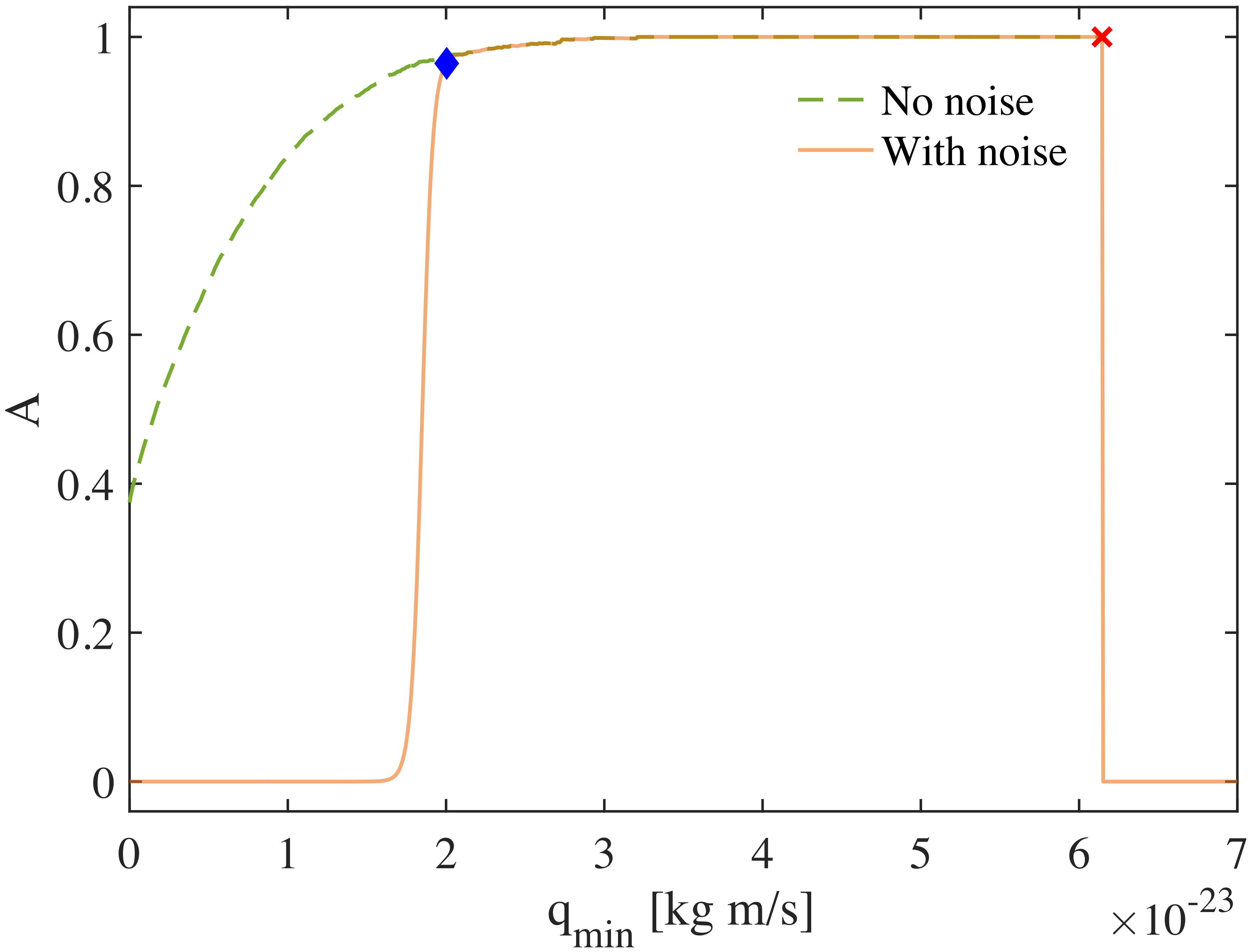


One Day

At June 1
Hsinchu, Taiwan



# Dependence of A on $q_{min}$



[Cheng, Primulando, MS '19]

# Toy Model: Noise

[Saulson '90; Gonzales, Saulson '94;
Thorne '87]

- Thermal noise from fluctuation-dissipation theorem

[Callen, Welton '51;
Callen, Greene '55]

$$S_{\mathrm{th}}(\omega) = \frac{4\,k_B\,T}{L^2\,\omega^2}\Re[Y(\omega)] = \frac{4\,k_B\,T}{L^2}\frac{\phi\,\omega_c^2/(m\,\omega)}{(\omega^2-\omega_c^2)^2+\omega_c^4\phi^2}$$

- Standard Quantum Limit

$$S_{\mathrm{qu}} = \frac{8\,\hbar}{m\,\omega^2\,L^2}$$

- The noise strain amplitude is

$$h_n = \sqrt{h_{\mathrm{th}}^2 + h_{\mathrm{qu}}^2} = \sqrt{S_{\mathrm{th}} + S_{\mathrm{qu}}}$$

# Toy Model: Coefficient Matching

**[Lee, Nugroho, MS '20]**

- KAGRA provides complex spring constants
- DM modeled with real coefficients
- Match oscillation frequency and damping

$$\omega_r = \omega_c \left(1+\phi^2\right)^{1/4} \cos\left(\frac{1}{2}\arctan\phi\right) \approx \omega_c \left(1+\frac{\phi^2}{8}\right)$$

$$\xi = \tan\left(\frac{1}{2}\arctan\phi\right) \approx \frac{\phi}{2}\left(1-\frac{\phi^2}{4}\right)$$

# Equations of Motion

**[Lee, Nugroho, MS '20 based on KAGRA Document, JGW-T1707038v9]**

- The equations of motion take a 3x3 matrix form

$$\left( M \frac{\mathrm{d}^2}{\mathrm{d}\,t^2} + K_v \right) \vec{x}_v(t) = \frac{\vec{F}_{\mathrm{ext},v}(t)}{L}$$

- KAGRA can see vertical and horizontal modes
  - two sets of equations

# DM Signal

[Lee, Nugroho, MS '20]

- We only need the Fourier transform of the displacement

$$\vec{\tilde{x}}_v(t) = \left(-M\omega^2 + K_v\right)^{-1} \frac{\vec{\tilde{F}}_{\mathrm{ext},v}(t)}{L}$$

- We can then study the effect of the test mass for a hit in different components and directions

# Space-Based Experiments

- LISA target sensitivity (0.1 mHz < *f* < 1 Hz)

$$\sqrt{S_{\Delta g}} \leq 3\sqrt{2}\ \mathrm{fm\ s}^{-2}/\sqrt{\mathrm{Hz}} \times \sqrt{1 + (f/8\ \mathrm{mHz})^4}$$

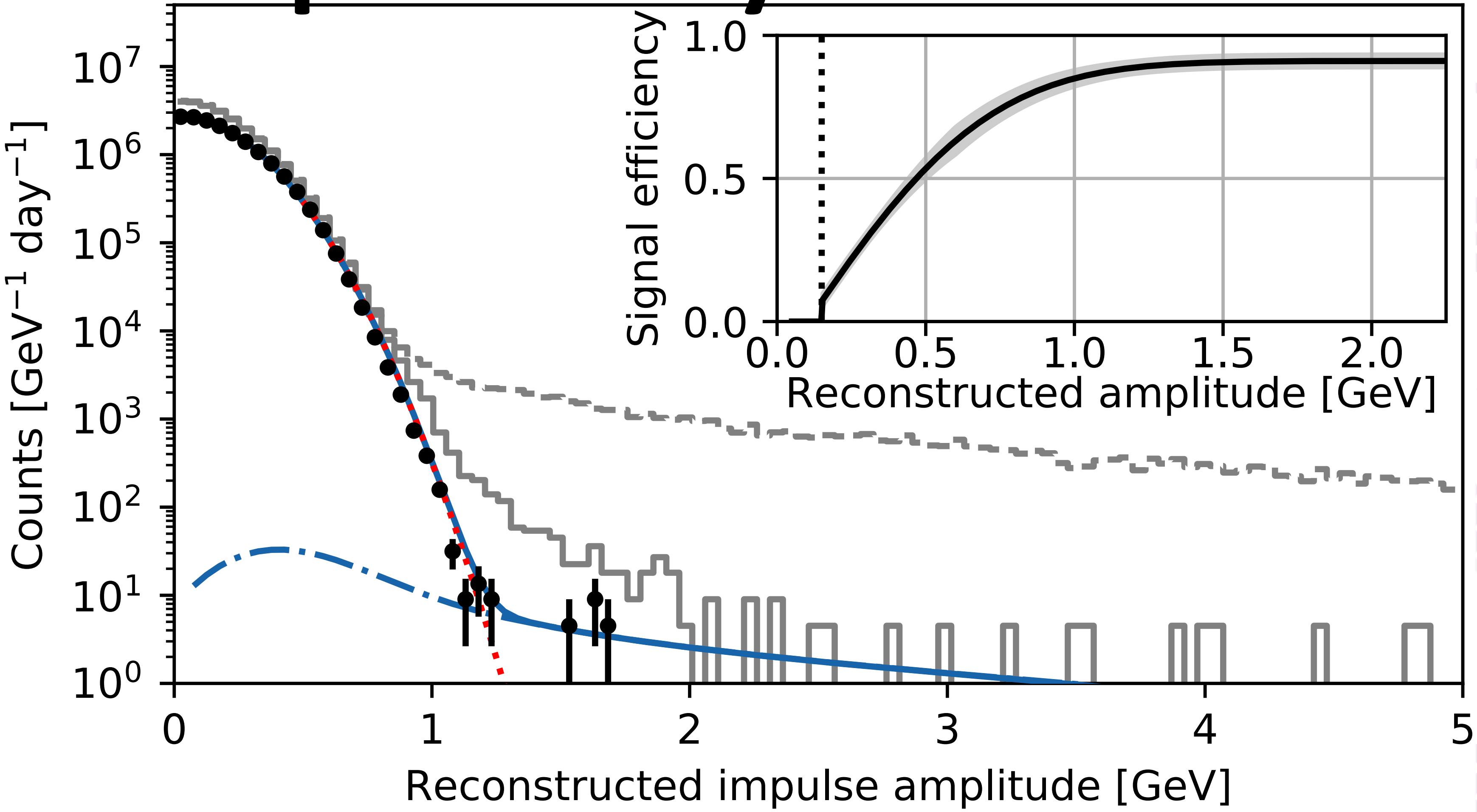
**[LISA Pathfinder '16]**

- Expected strain amplitude

$$\sqrt{S_{\Delta g,\mathrm{DM}}} \sim 4.1 \times 10^{-7} \sqrt{\frac{f}{\mathrm{Hz}}}\ \ \mathrm{fm\ s}^{-2}/\sqrt{\mathrm{Hz}}$$

**[Lee, Nugroho, MS '20]**

# Optically Levitated Devices



**[Monteiro *et al.* '20]**

FIG. 2. Measured rate of reconstructed impulses after all cuts (black points), compared to the spectrum with only live-time selections applied (gray, solid) and with no cuts applied (gray, dashed). The Gaussian background (red, dotted), DM signal (blue, dot-dashed), and sum of background and signal (blue, solid) are also shown at the 95% CL upper limit, $\alpha_n = 8.5 \times 10^{-8}$, for $M_X = 5 \times 10^3$ GeV, $m_\phi = 0.1$ eV, and $f_X = 1$. (Inset) Overall signal efficiency versus amplitude (black) and estimated error (gray band) above the analysis threshold, $q_{\rm thr} = 0.15$ GeV (dotted).