Dark Matter Searches in Gravitational Wave Detectors

Martin Spinrath (史馬丁)
National Tsing Hua University, Taiwan &
National Center for Theoretical Sciences, Taiwan

3rd International Joint Workshop on the Standard Model and Beyond
and 11th KIAS Workshop on Particle Physics and Cosmology
Jeju Island, Korea

Mostly based on collaborations with
C.-H. Lee, C. S. Nugroho [arXiv:2007.07908] and
C.-H. Lee, R. Primulando [arXiv:2208.06232]

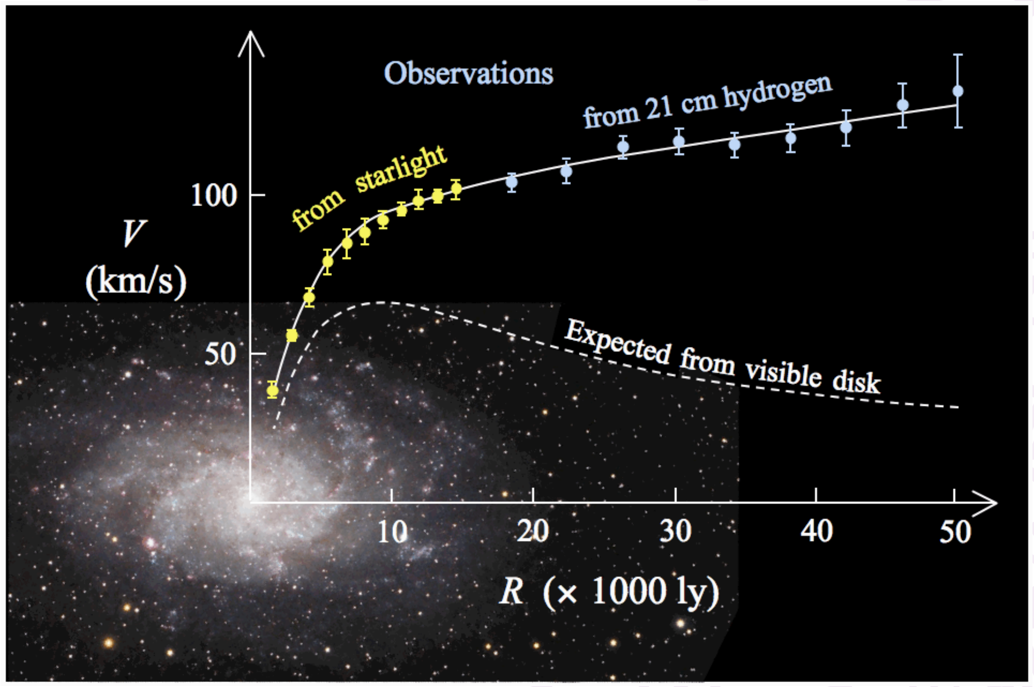
Outline

- Motivation
- Dark Matter in KAGRA
- Summary and Conclusions

Outline

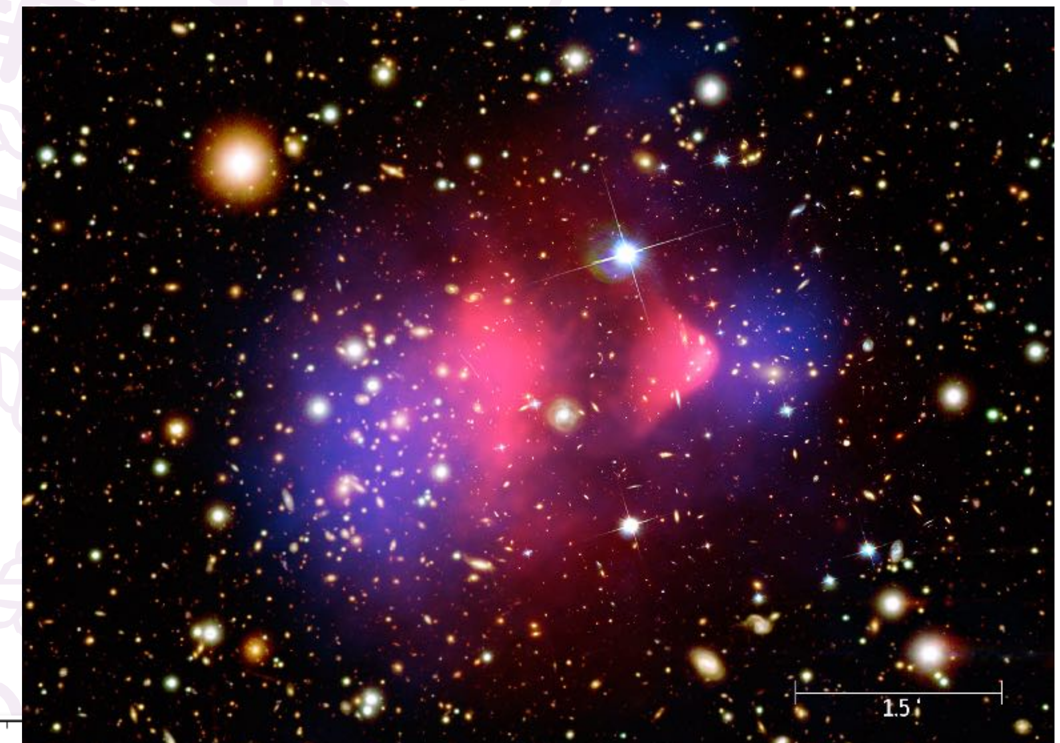
- **Motivation**
- Dark Matter in KAGRA
  - Introduction
  - Particle Dark Matter
  - Heavy Dark Matter
- Summary and Conclusions

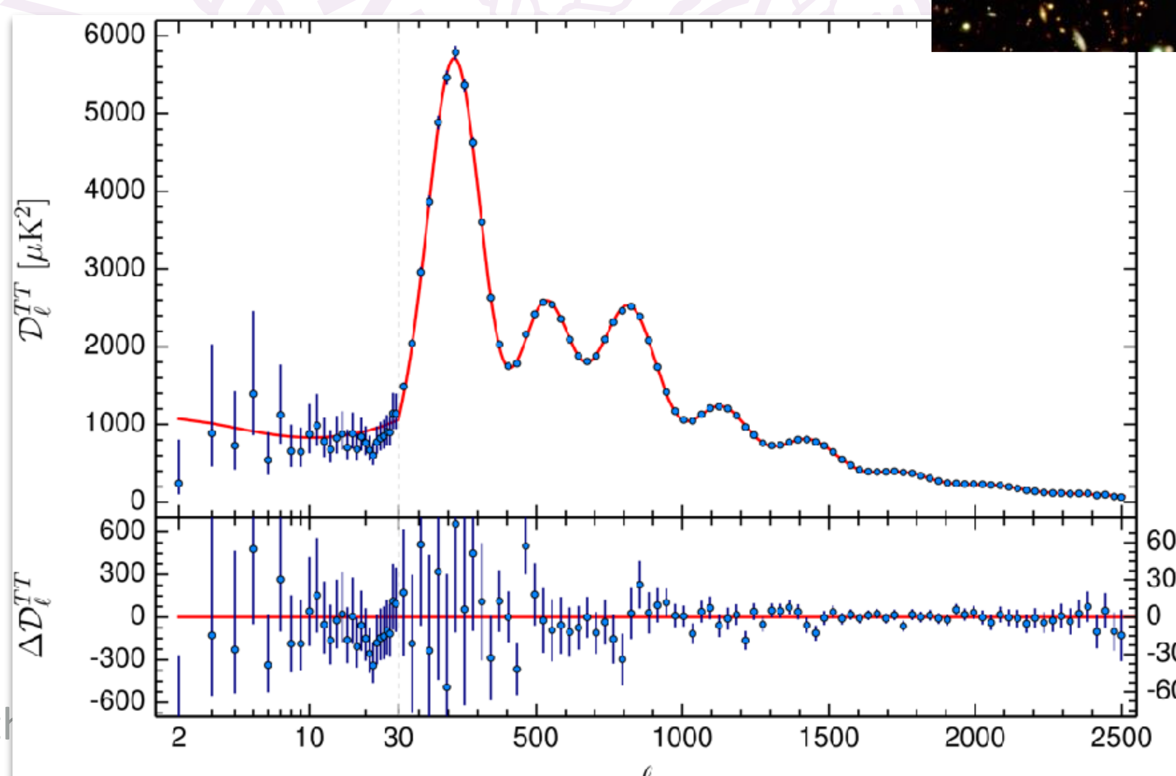
Dark Matter Evidences



[M33 rot. curve, Source: Wikipedia]

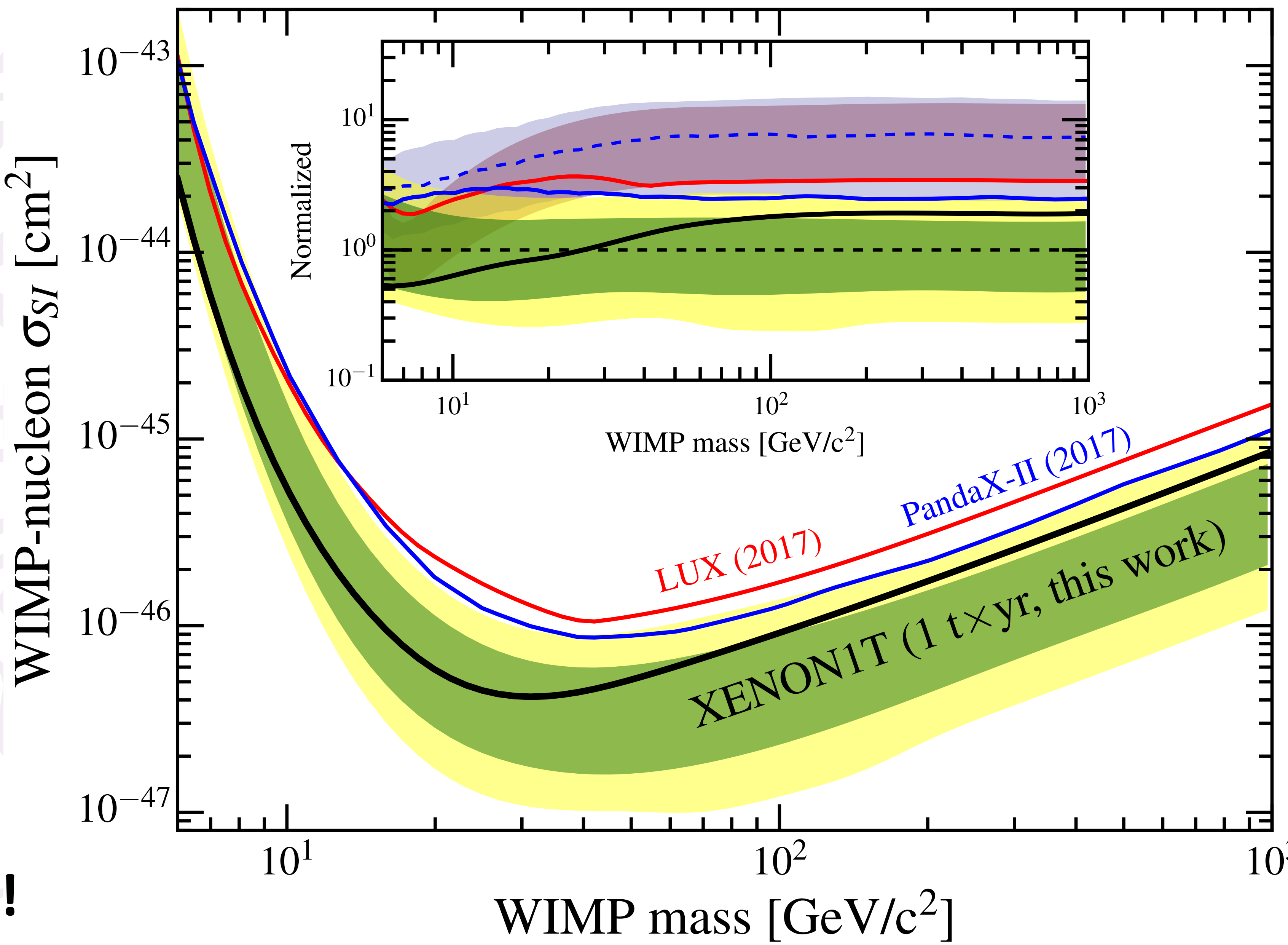
[Chandra picture of the bullet cluster]





[https://wiki.cosmos.esa.int/planckpla2015/images/2/2f/A15_TT.png]

WIMP Searches



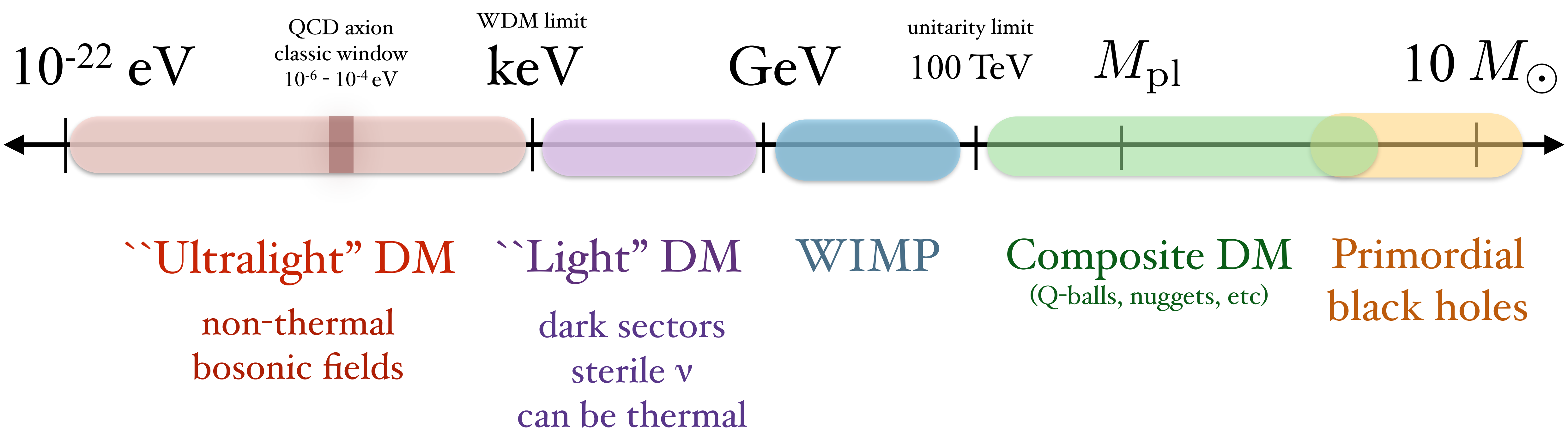
[XENON1T result '18]

Time to think again?!
Light DM? Heavy DM?

Dark Matter: The Challenge

Mass scale of dark matter

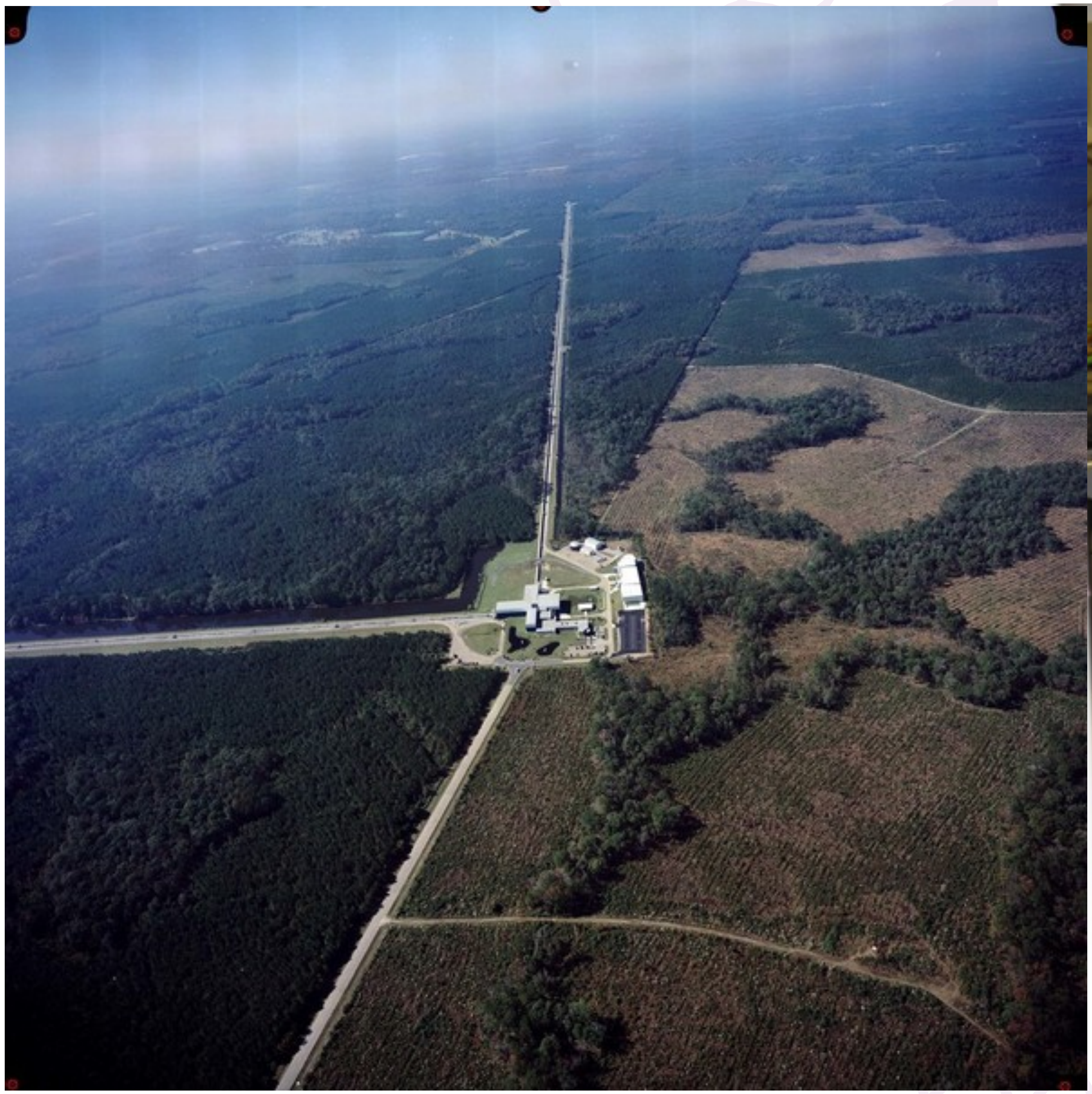
(not to scale)



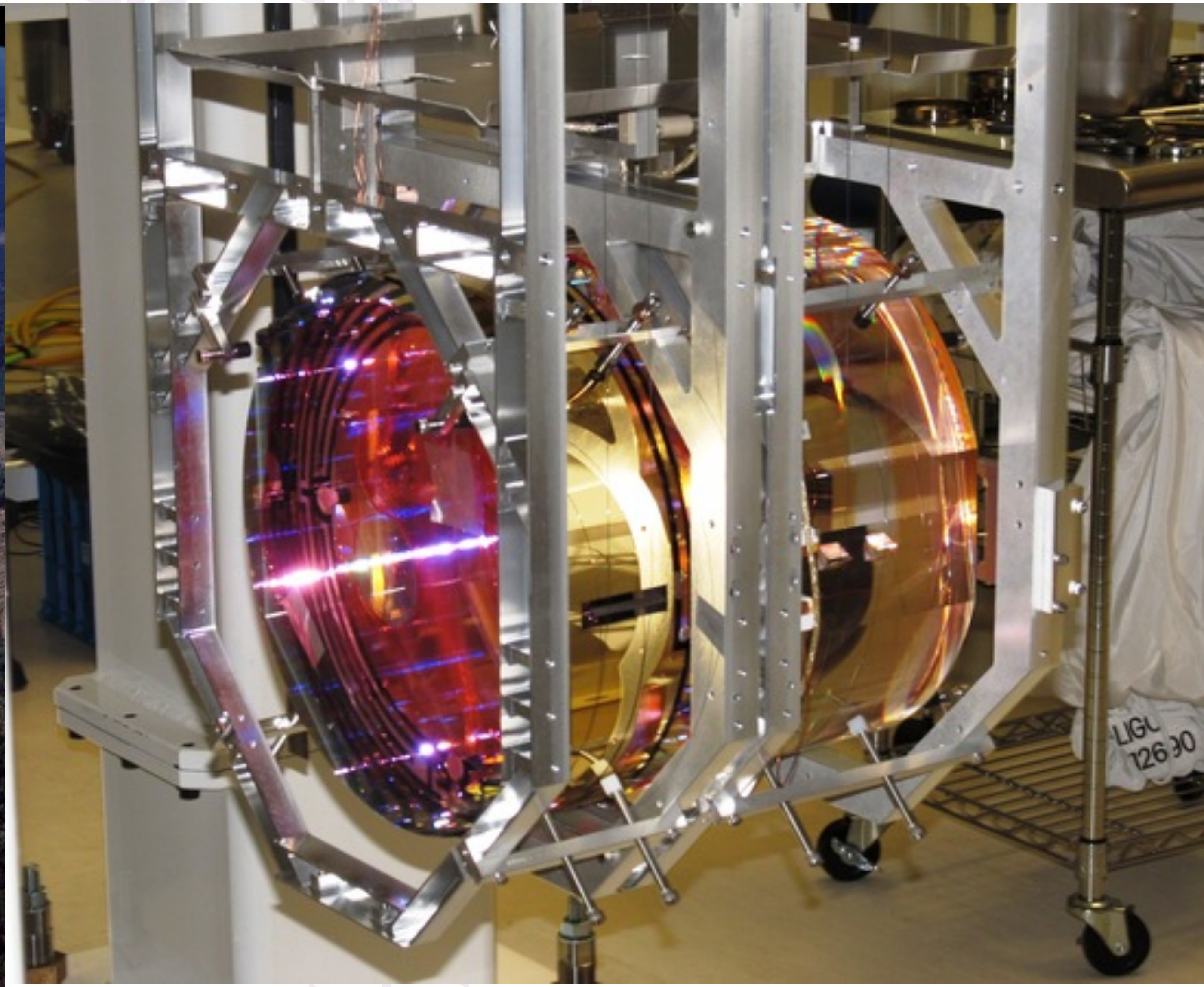
[Taken from Lin 2019 TASI lecture]

One common effect: gravitational force

Gravitational Wave Detectors



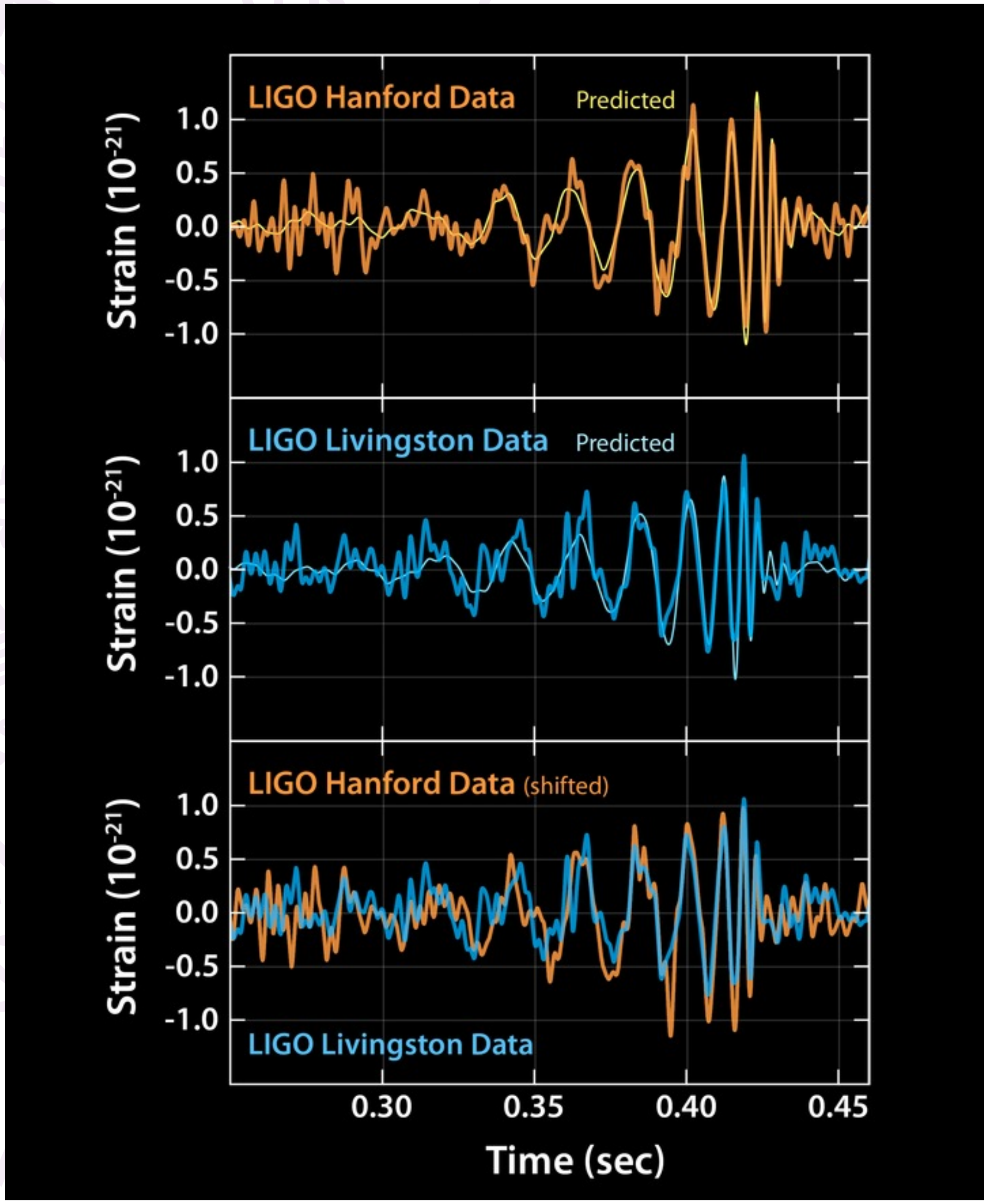
[LIGO Livingston, Courtesy Caltech/MIT/LIGO Laboratory 2016]



[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?



[Courtesy Caltech/MIT/LIGO Laboratory 2016]

Similar Talks in this Workshop

- Xing-Yu Yang "Sources for Pulsar Timing Array Observations" on Monday
- Asuka Ito "Gravitational Wave Search through Electromagnetic Telescopes"
- Yong Tang "Probing Ultralight Dark Matter with Space-based Gravitational-Wave Interferometers" earlier today
- Huaike Go "Some Recent Developments on BSM Probes with Gravitational Waves" on Friday
- ...?

Outline

- Motivation
- **Dark Matter in KAGRA**
  - **Introduction**
  - Particle Dark Matter
  - Heavy Dark Matter
- Summary and Conclusions

Damped Harmonic Oscillator

[Lee, Nugroho, MS '20]

- KAGRA uses complex spring constants

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

$$\omega_c^2 \equiv k_c/m$$

- 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 neglected some noise components here)

Noise

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

- Thermal noise from fluctuation-dissipation theorem

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

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

- Standard Quantum Limit

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

- The noise strain amplitude is

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

Two DM Forces (we considered)

- Short-range force, instantaneous scattering

$$\vec{F}_{\mathrm{DM}} = \vec{q}_R \delta(t - t_0)$$

[Lee, Nugroho, MS '20]

- Long-range force, continuous scattering

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

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

Outline

- Motivation
- **Dark Matter in KAGRA**
  - Introduction
  - **Particle Dark Matter**
  - Heavy Dark Matter
- Summary and Conclusions

DM Signal (Short-Range Force)

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

- Assuming DM instantaneous scattering

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

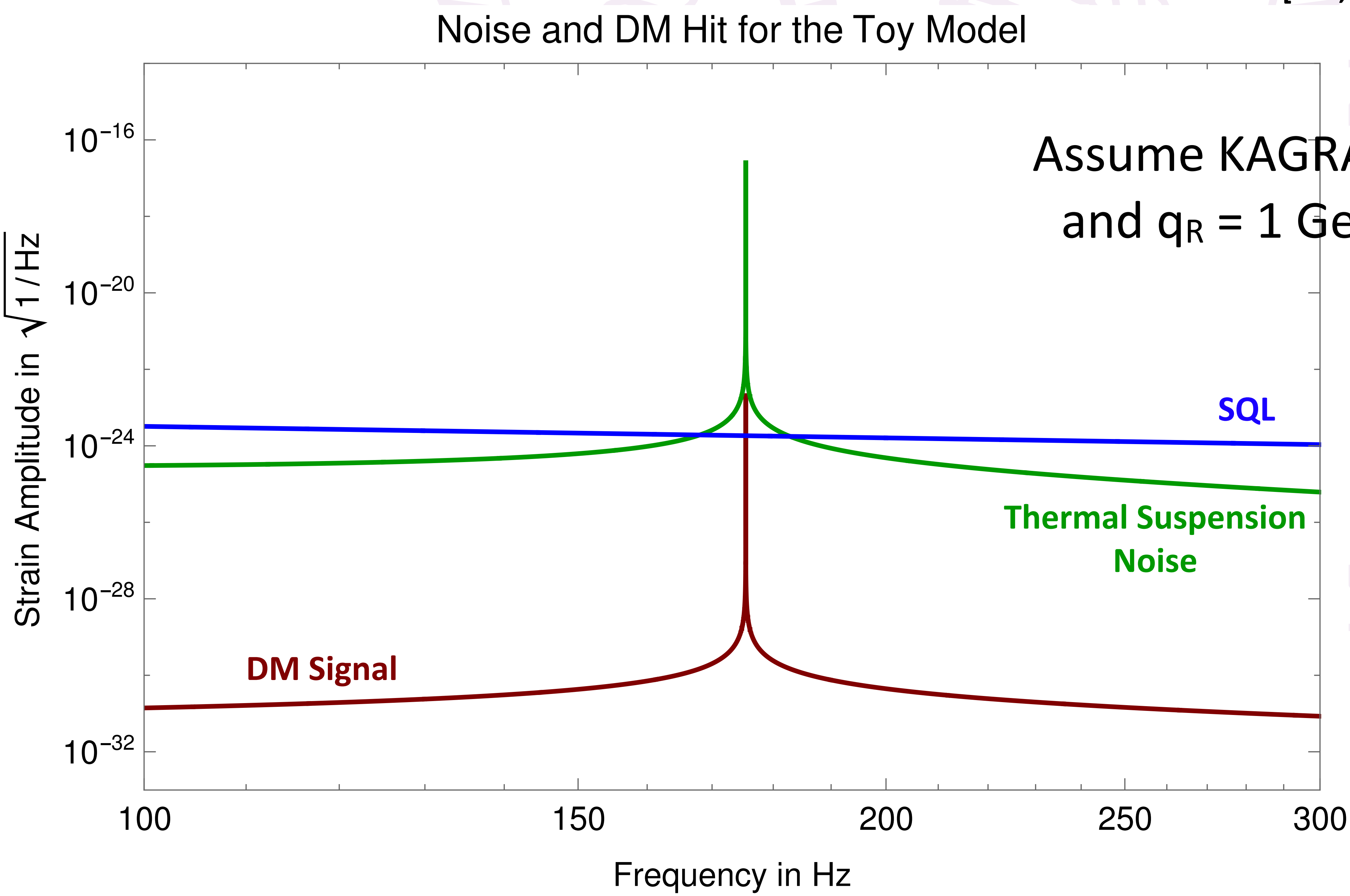
- which enters the DM strain amplitude

[Moore, Cole, Berry '14]

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

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

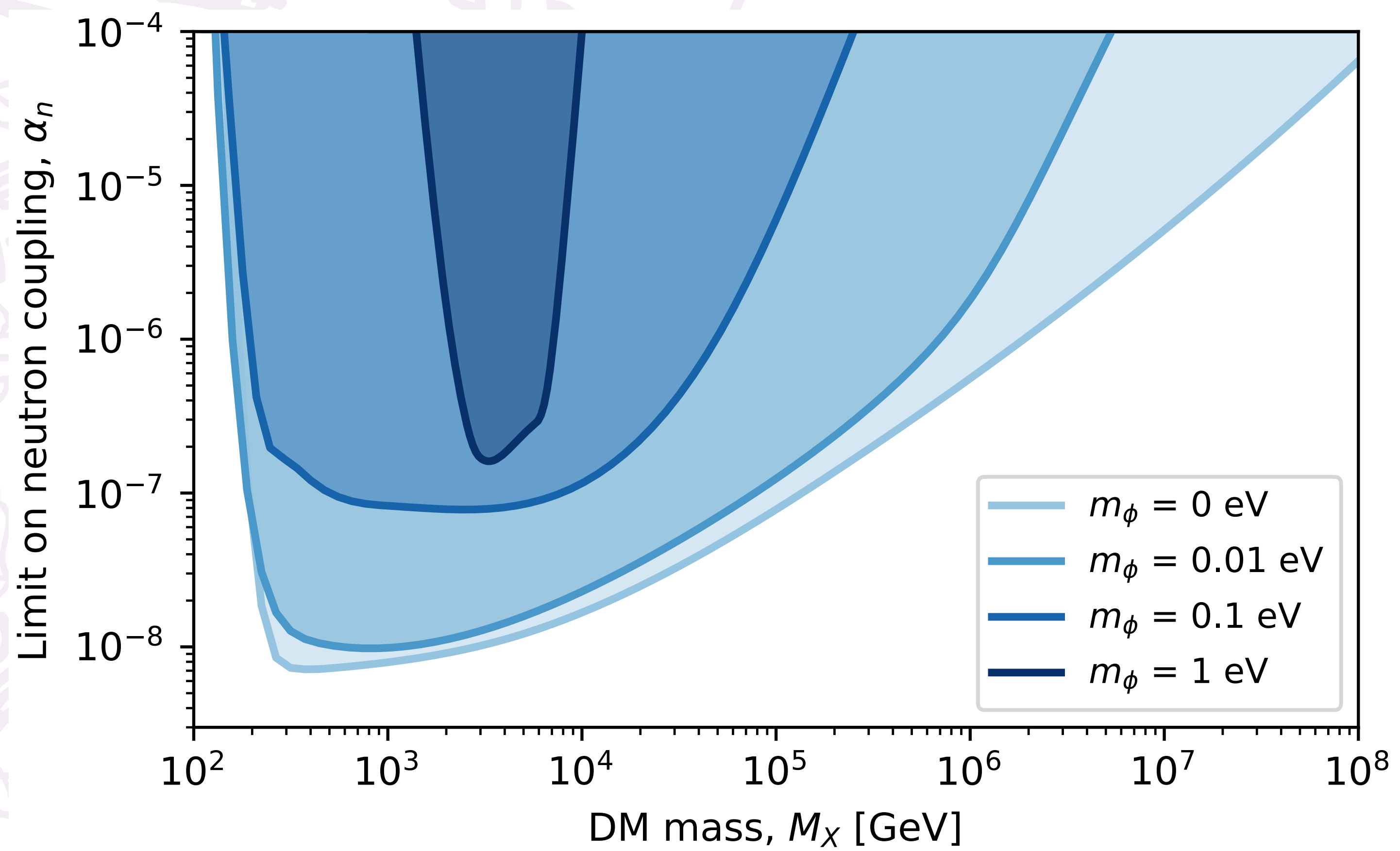
$$\varrho_{\mathrm{th}}^2 = \frac{1}{2\pi} \frac{q_R^2}{m\, k_B\, T} = \frac{1}{2\pi} \frac{E_R}{E_{\mathrm{th}}} = 4.09 \times 10^{-24}$$

Numbers as in previous figure

- Need light, cold targets!

The Future?!

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

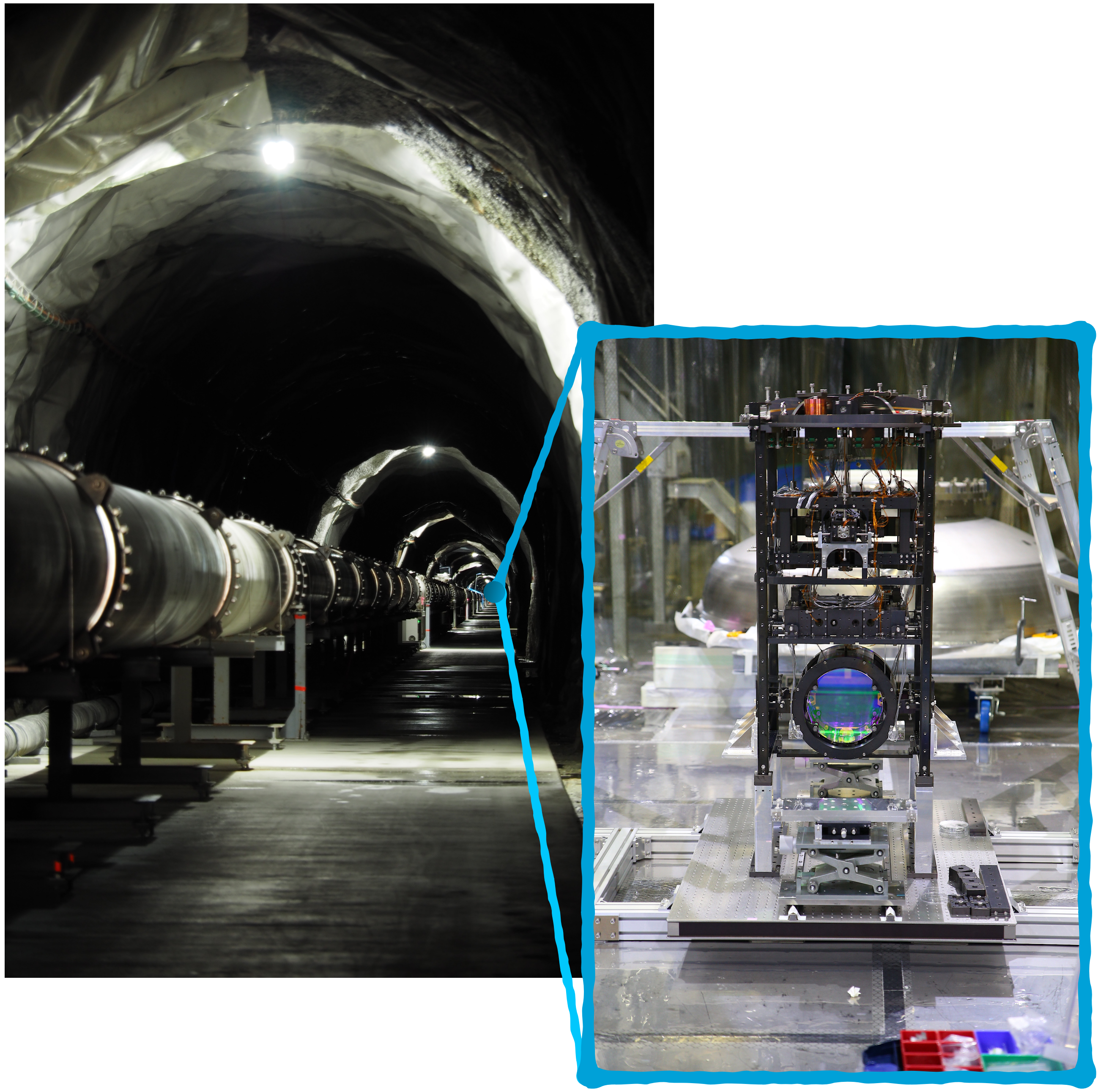


[Monteiro *et al.* '20]

[for an overview DM searches using Mechanical Quantum Sensing, see, e.g., arXiv:2008.06074]

KAGRA

- A cryogenic (T ~ 20 K) interferometer located in Kamioka, Japan
- A new GW detector with two 3 km baseline arms arranged in an "L" shape
- Started running on 25th February 2020



[KAGRA , Courtesy KAGRA Observatory, ICRR, The University of Tokyo]

[slide taken from Chun-Hao Lee]

KAGRA

- An equation of motion in matrix form

$$M_T \ddot{\vec{x}} + K\vec{x} = \frac{\vec{F}_{\mathrm{DM}}}{L}$$

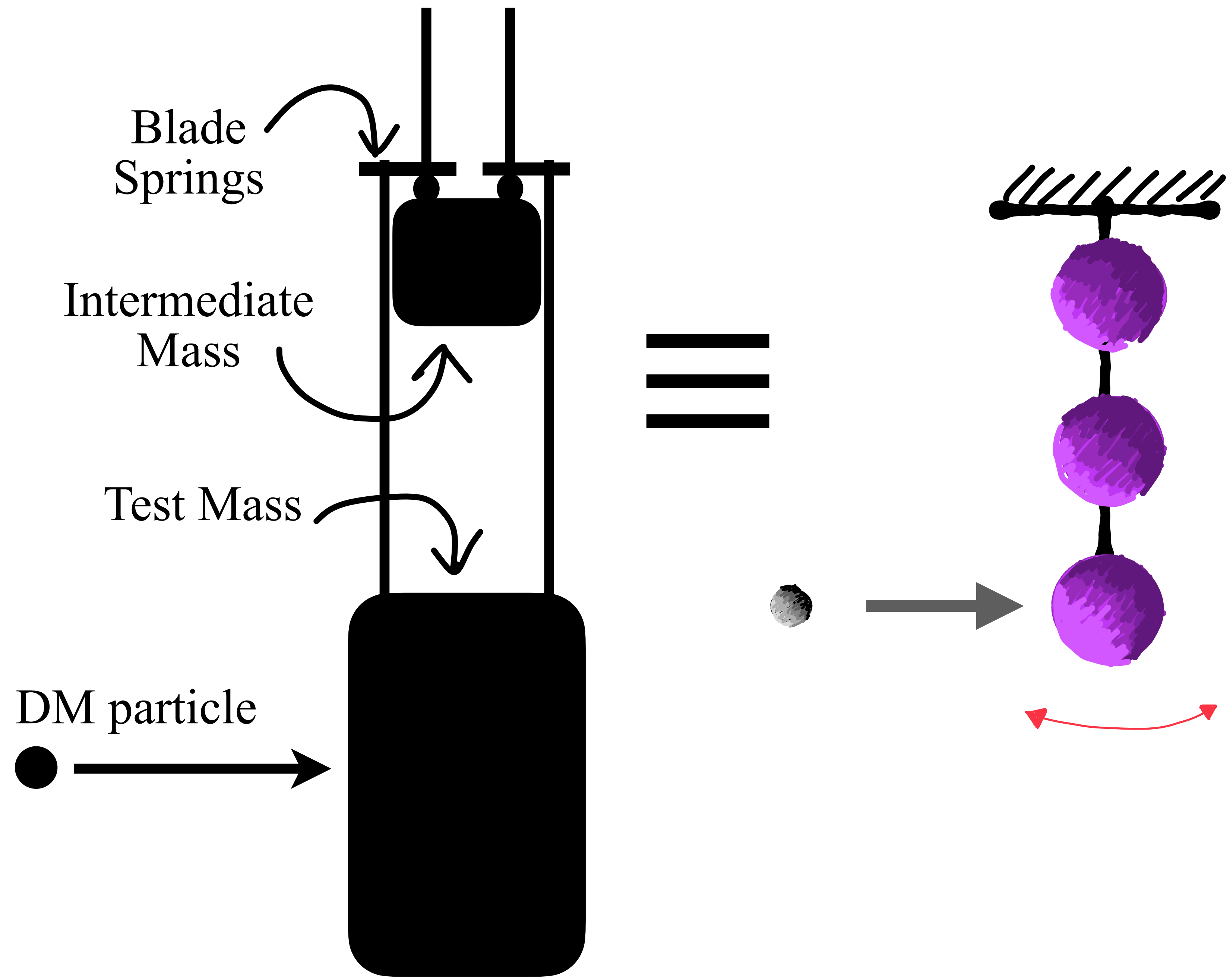
Masses of the components, a 3x3 matrix

Complex spring constants of the components, a 3x3 matrix

External DM force

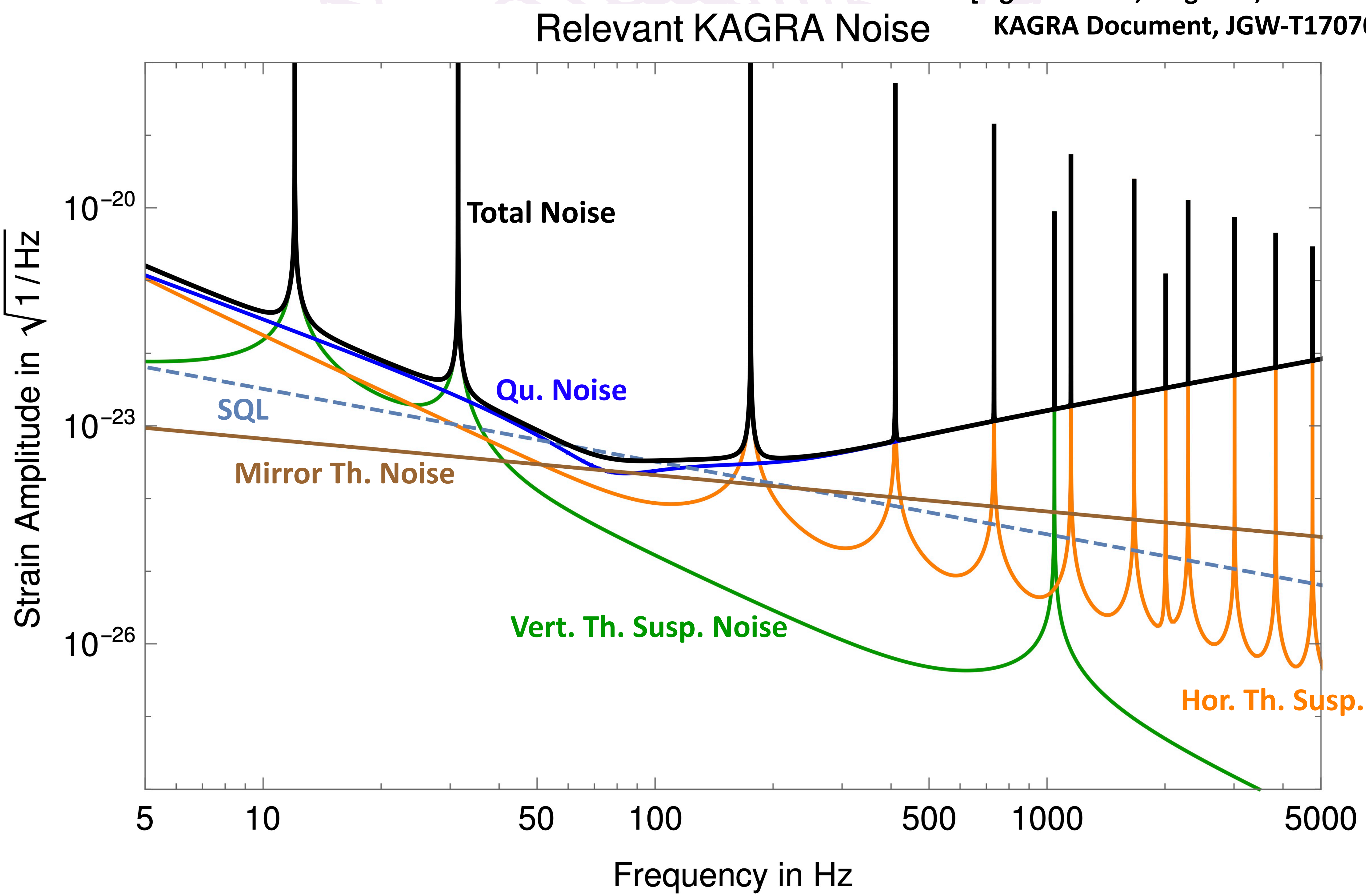
- Two sets of equations
  - For DM hits in vertical and horizontal direction, respectively

[KAGRA Document, JGW-T1707038v9]



KAGRA Noise

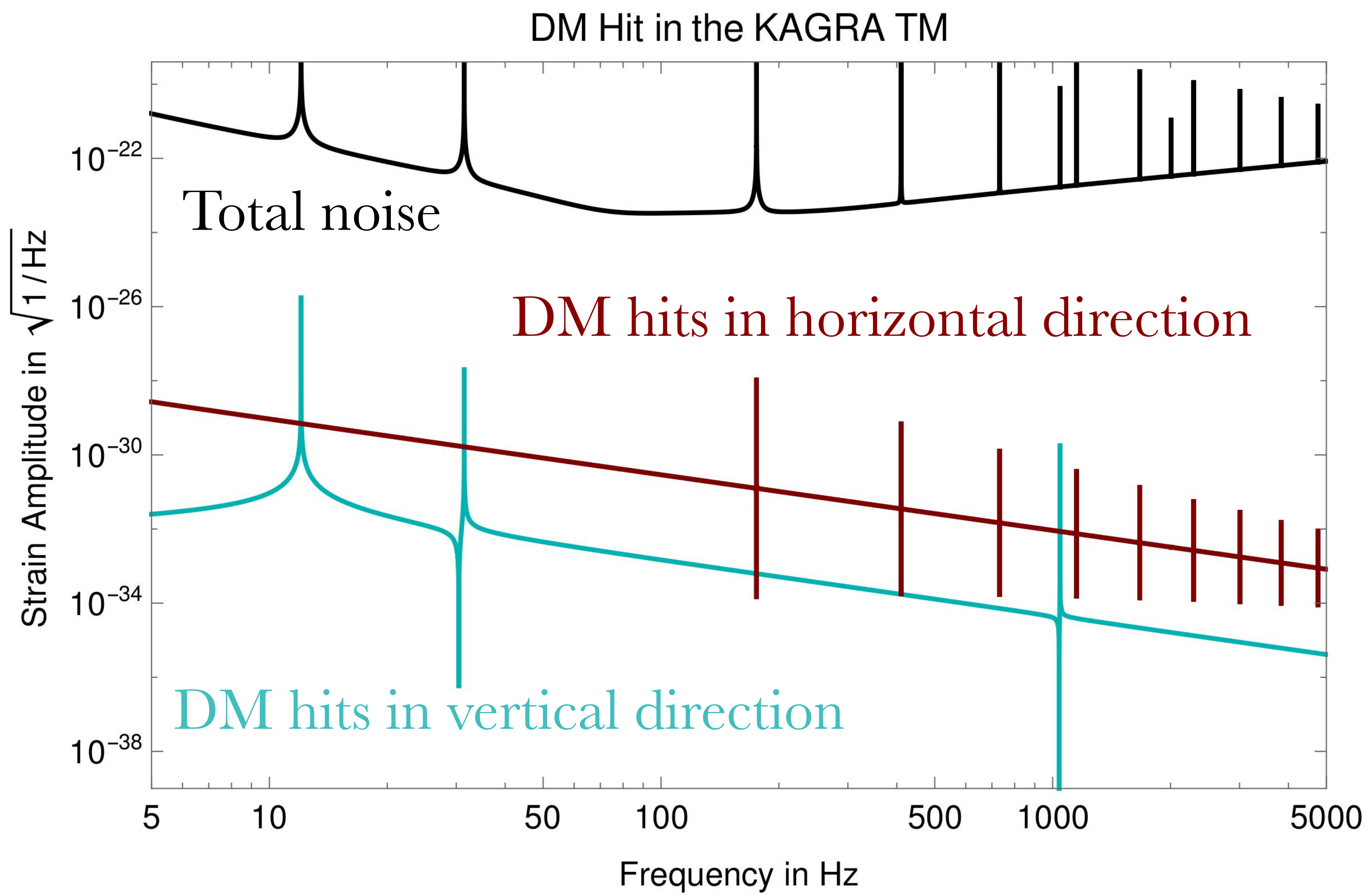
[Fig. from Lee, Nugroho, MS '20 based on KAGRA Document, JGW-T1707038v9]

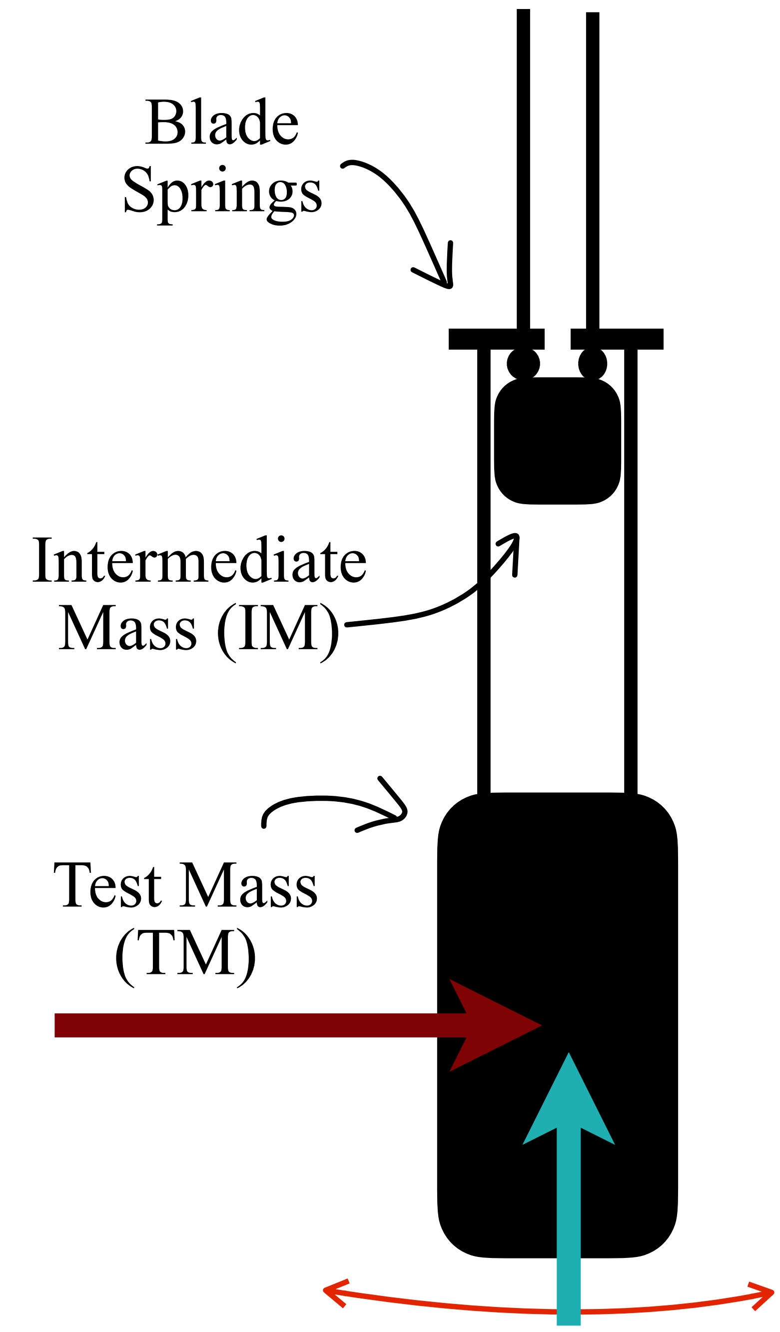


[slide taken from Chun-Hao Lee]

KAGRA

- $q_R = 1\ \mathrm{GeV}/c^2 \times 220\ \mathrm{km/s}$





[C. H. Lee, C. S. Nugroho and M. Spinrath, EPJ C 80, no. 12, 1125 (2020)]

Outline

- Motivation
- **Dark Matter in KAGRA**
  - Introduction
  - Particle Dark Matter
  - **Heavy Dark Matter**
- Summary and Conclusions

DM Signal (Long-Range Force)

[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

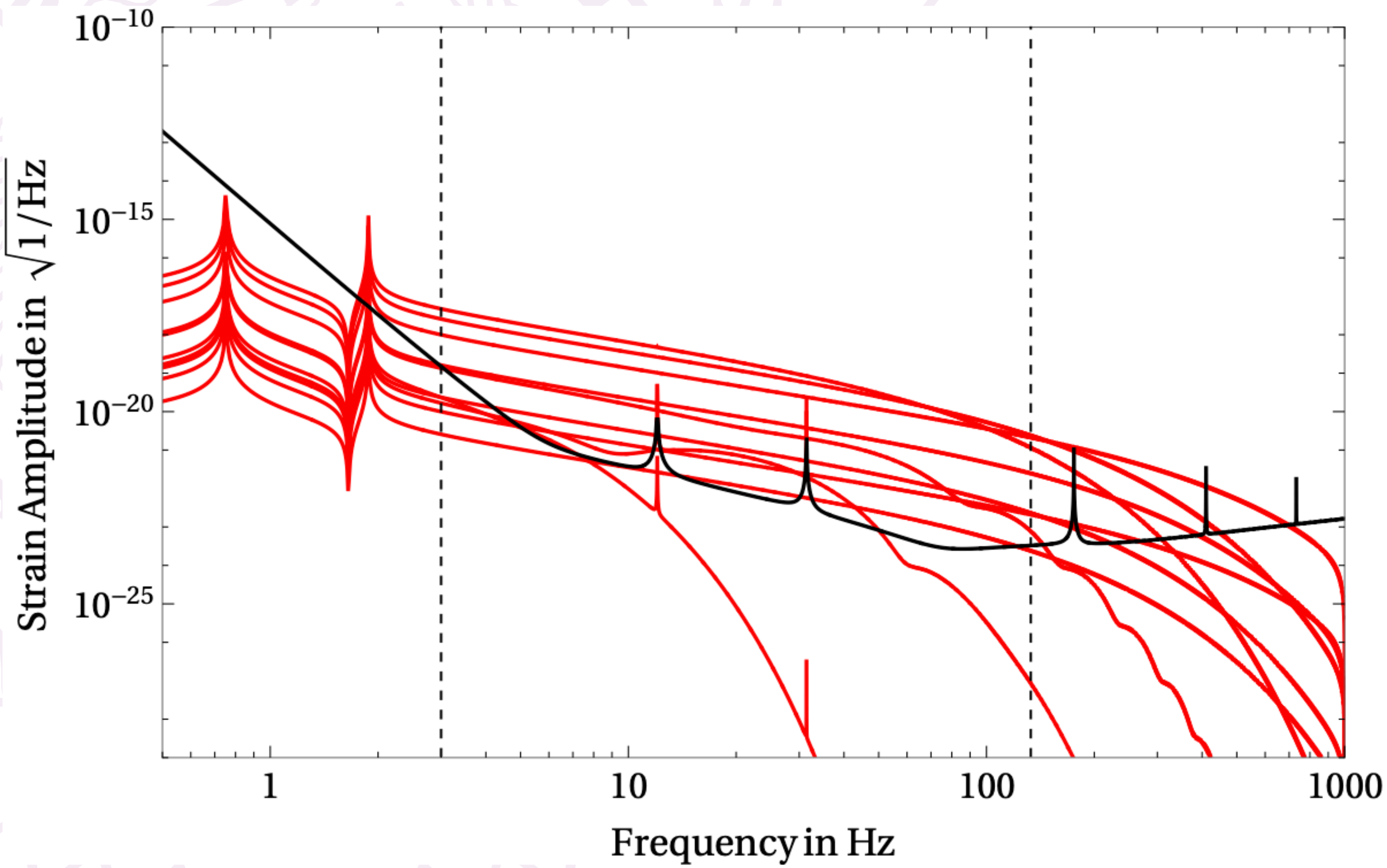
How to define the SNR frequency range?

[Lee, Primulando, MS '22]

Trade-off:
Wider range
- larger SNR ρ
- numerically costly

Compromise
3 - 133 Hz

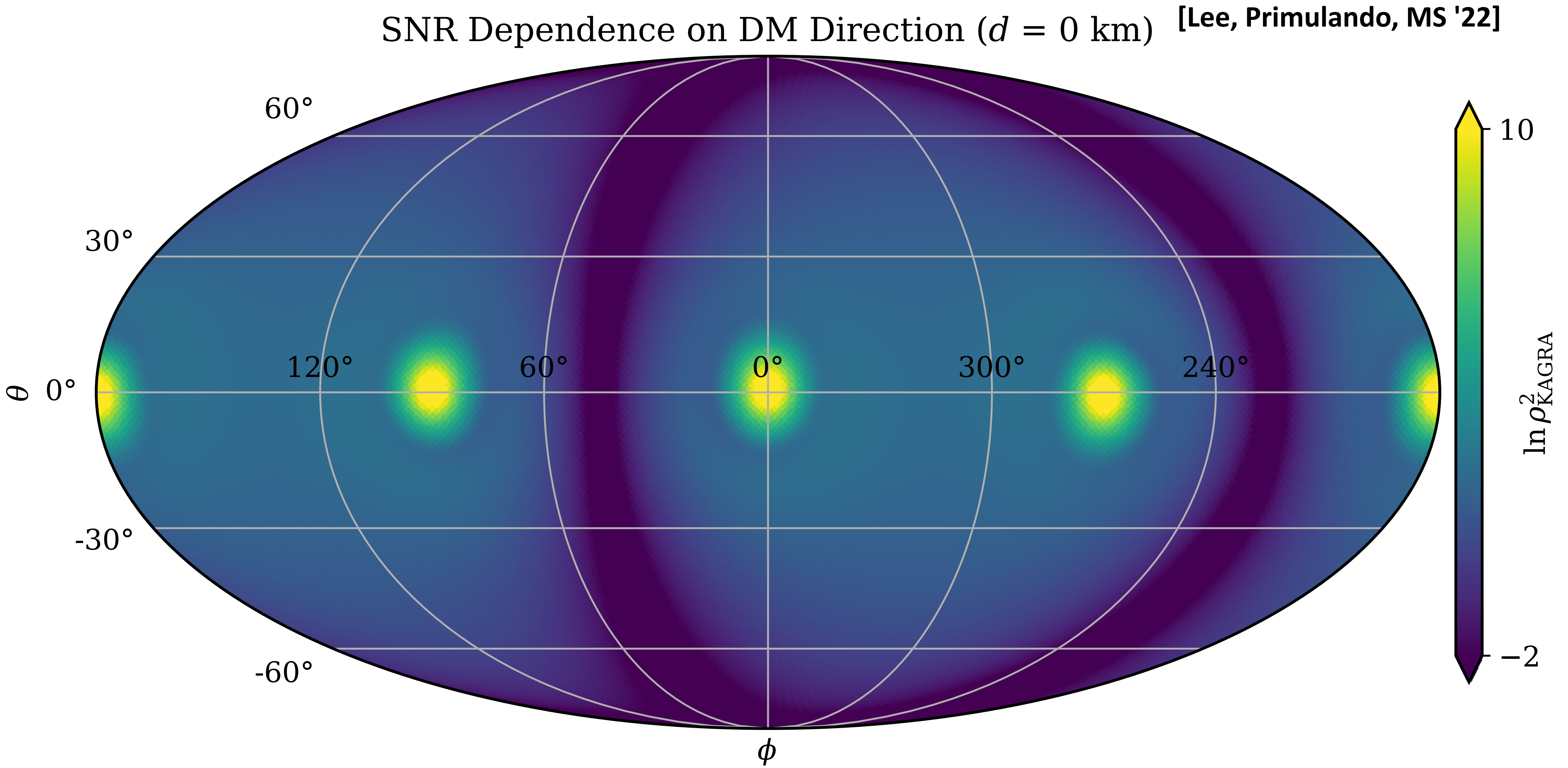
Larger frequencies less important to find ρ > 1



A selection of possible DM signals.

Directional Signal Dependence

[Lee, Primulando, MS '22]



$M_{\mathrm{DM}} = 10$ kg $\quad \vec{x}_{0,\mathrm{DM}} = (0,0,0)$ km $\quad \vec{v}_{\mathrm{DM}} = 220(\cos\phi\cos\theta, \sin\phi\cos\theta, \sin\theta)$ km/s $\quad \lambda = 1$ km $\quad \delta_{\mathrm{DM}}\delta_{\mathrm{SM}} = 10$

Event Rate Estimate

[Lee, Primulando, MS '22]

- Define a large sphere
- Estimate the number of DM objects passing through it
- Multiply with fraction of events with SNR > threshold

$$
\begin{aligned}
p(\rho_{\mathrm{th}}^2) &= \int_{\rho_{\mathrm{th}}^2}^{\infty} g(\rho^2)\, \mathrm{d}\,\rho^2 \\
&= \frac{1}{\mathcal{N}_p} \int f_v(\vec{v}_{\mathrm{DM}})\, f_x(\vec{x}_{0,\mathrm{DM}})\, \theta(\rho_{\mathrm{KAGRA}}^2(\vec{v}_{\mathrm{DM}}, \vec{x}_{0,\mathrm{DM}}) - \rho_{\mathrm{th}}^2)\, \mathrm{d}^3\, \vec{v}_{\mathrm{DM}}\, \mathrm{d}^3\, \vec{x}_{0,\mathrm{DM}}
\end{aligned}
$$

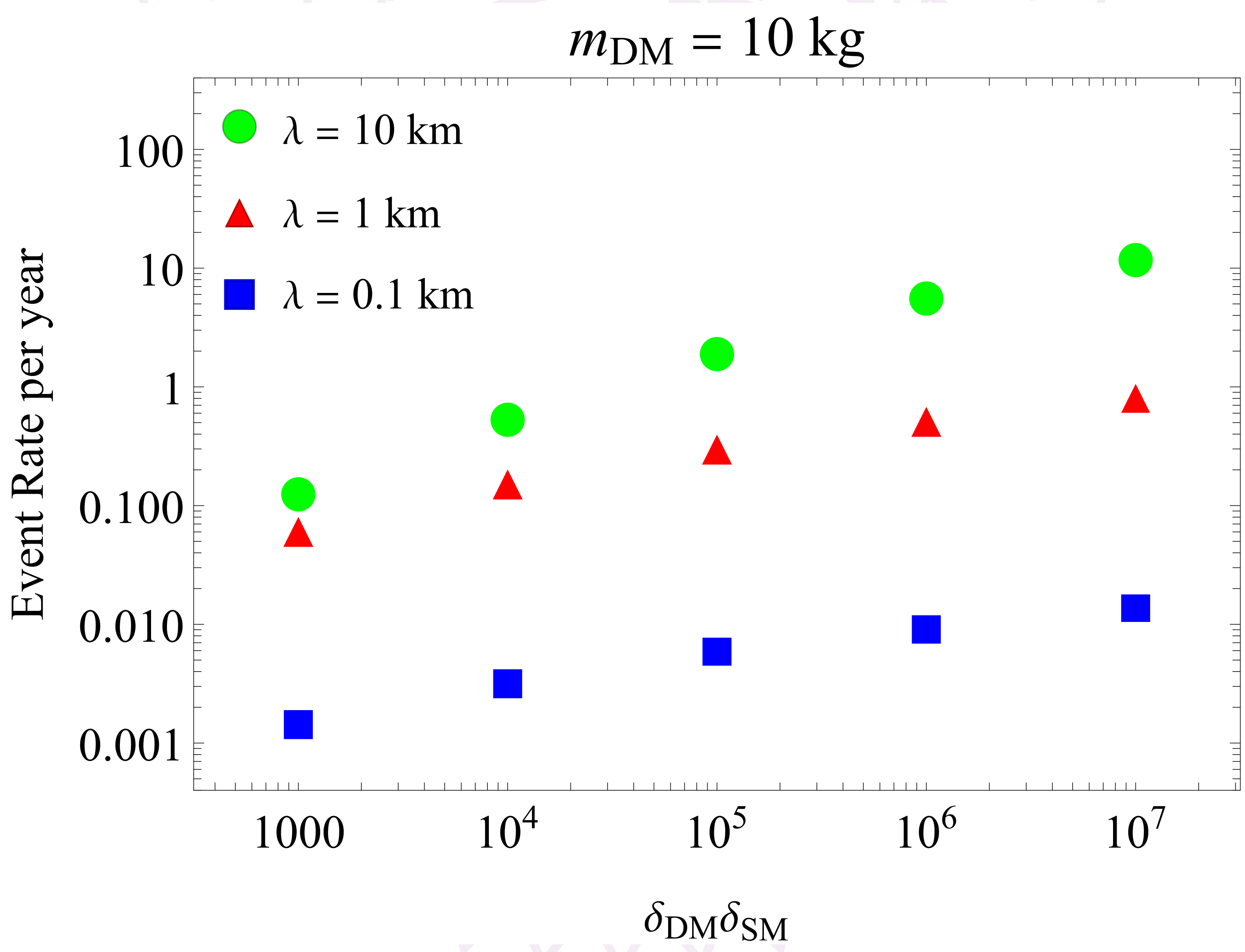
Assumptions

[Lee, Primulando, MS '22]

- Standard Halo Model for DM velocity distribution
- Flat distribution for DM initial position

Expected Event Rate

[Lee, Primulando, MS '22]



Outline

- Motivation
- Dark Matter in KAGRA
- **Summary and Conclusions**

Summary and Conclusions

- DM might be different than expected
- Looking for mechanical forces is the safest bet
- Impressive new technologies
  - Macroscopic objects at the quantum limit
- Can we use them to find "exotic" DM?
  - Maybe.

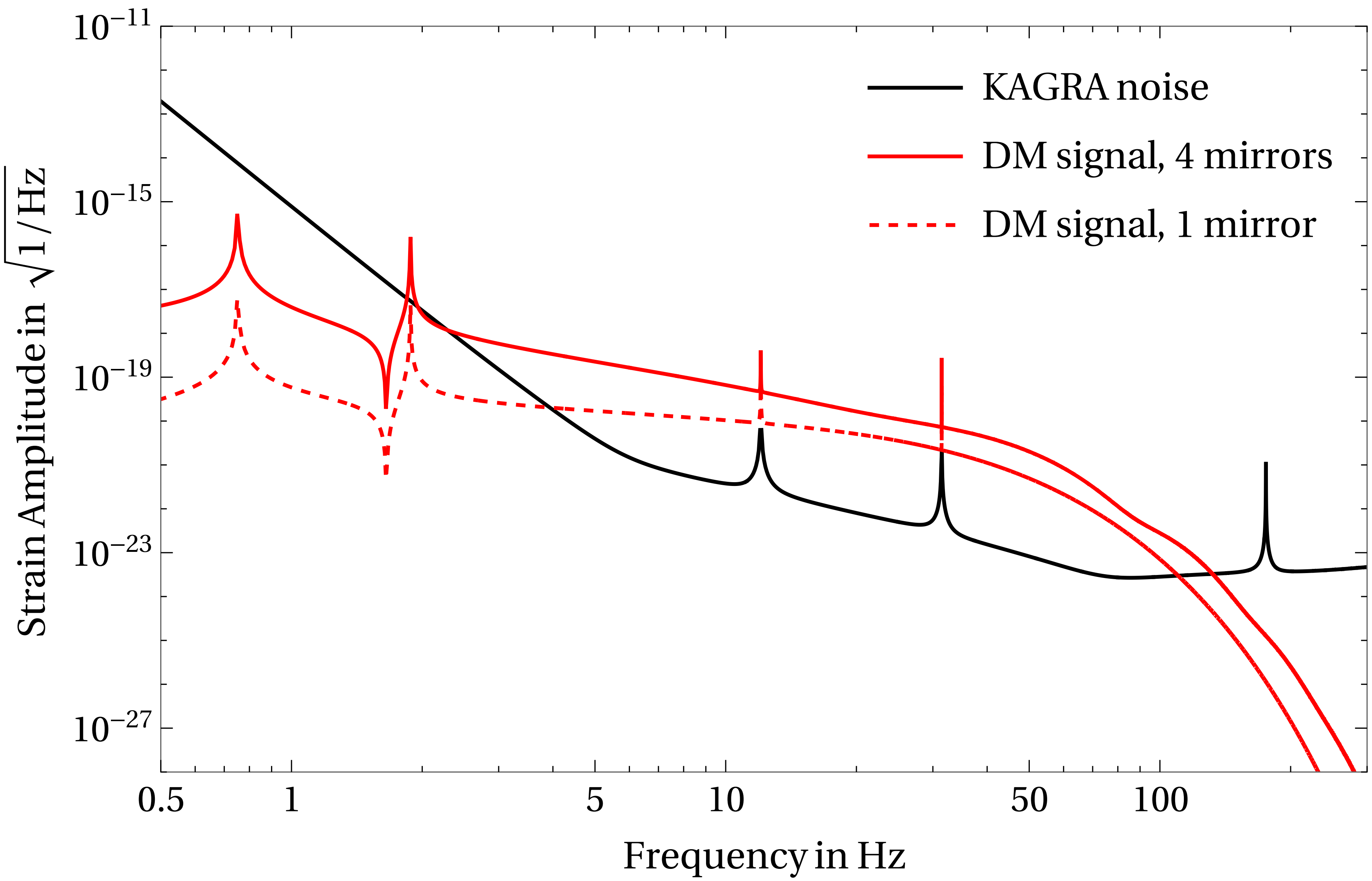
Backup

Comparison

$$M_{\mathrm{DM}} = 10\ \mathrm{kg}$$
$$\vec{x}_{0,\mathrm{DM}} = (0,2,2)\ \mathrm{km}$$
$$\vec{v}_{\mathrm{DM}} = (220,0,0)\ \mathrm{km/s}$$
$$\lambda = 1\ \mathrm{km}$$
$$\delta_{\mathrm{DM}}\delta_{\mathrm{SM}} = 5\times 10^5$$

(We treated the DM velocity to be constant)

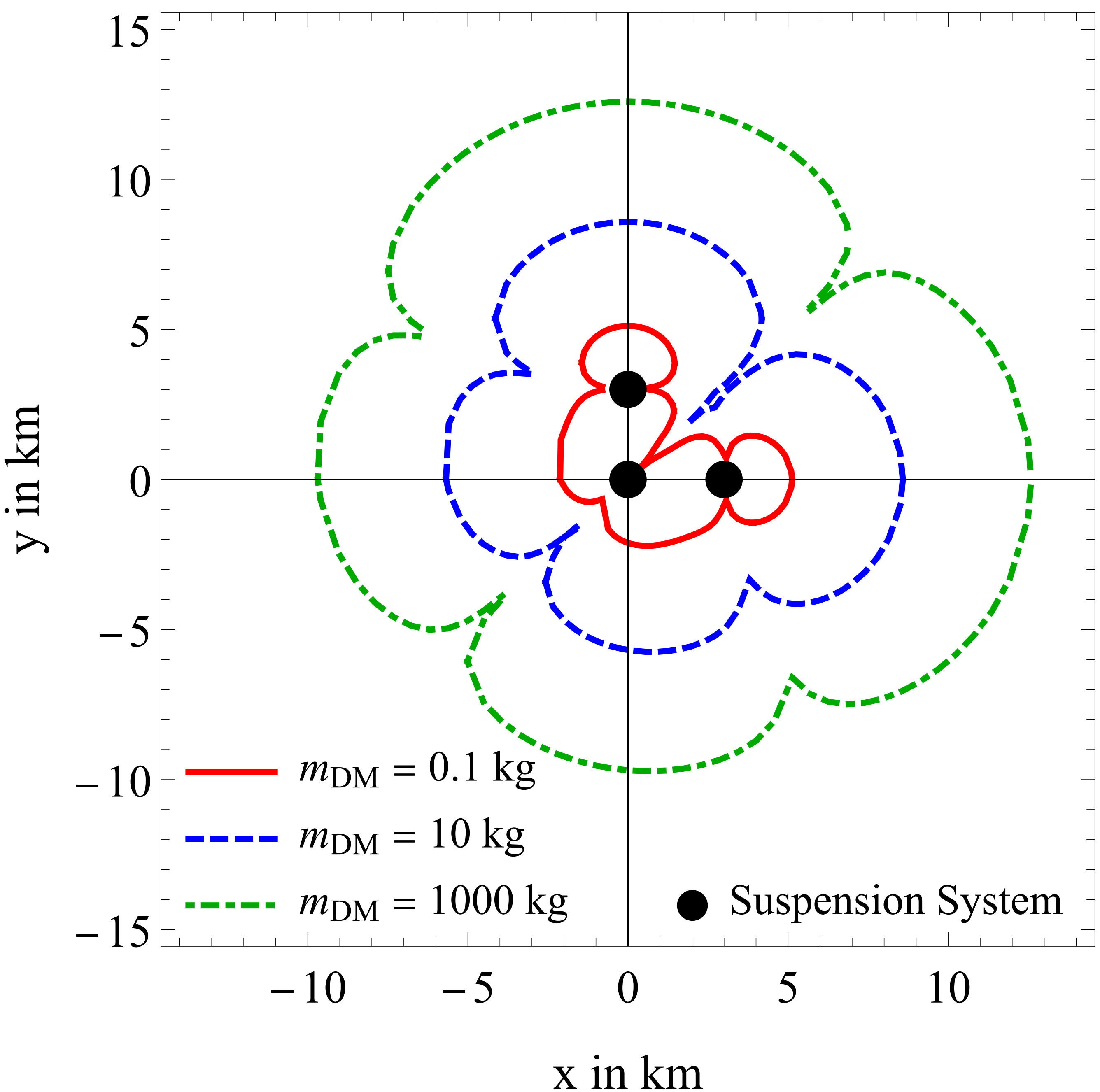
[Lee, Primulando, MS '22]



Parameter Dependence

[Lee, Primulando, MS '22]

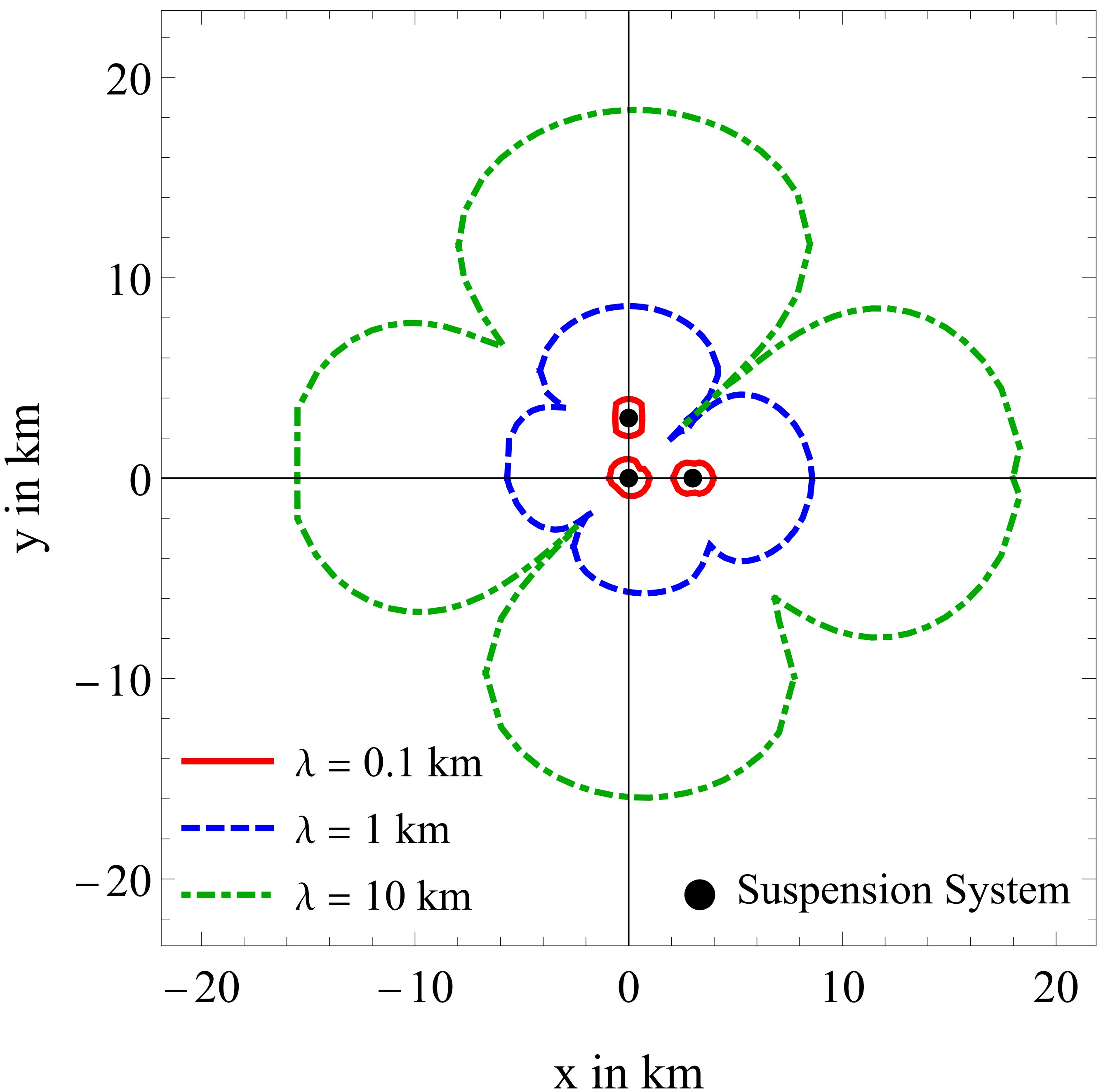
- Cut through interferometer plane
- DM velocity: 220 km/s in z-direction
- λ = 1 km, $\delta_{SM}\,\delta_{DM} = 10^5$
- Inside the contours: SNR > 1



Parameter Dependence

[Lee, Primulando, MS '22]

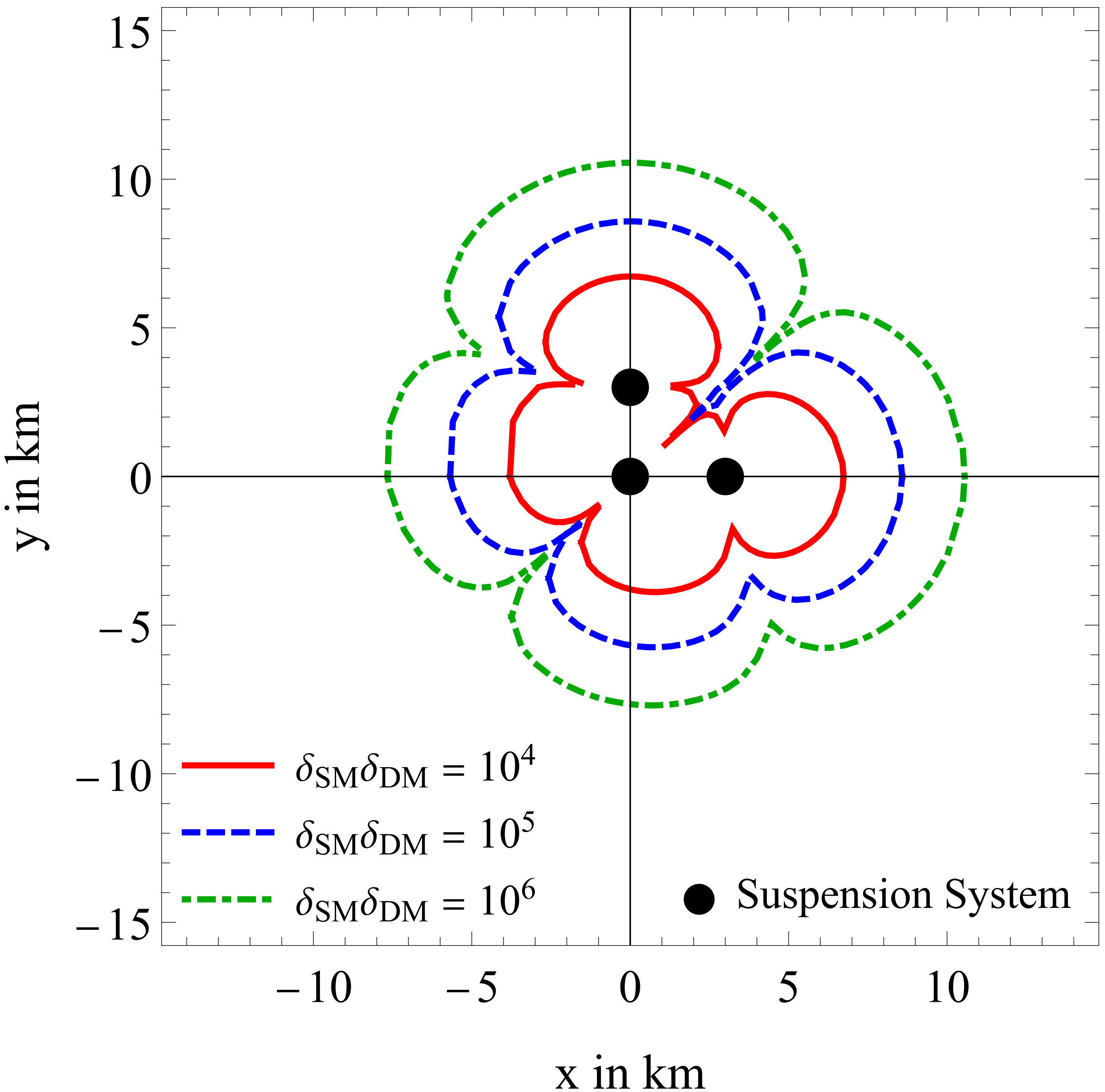
- Cut through interferometer plane
- DM velocity: 220 km/s in *z*-direction
- m_{DM} = 10 kg, $\delta_{SM}\,\delta_{DM} = 10^5$
- Inside the contours: SNR > 1



Parameter Dependence

[Lee, Primulando, MS '22]

- Cut through interferometer plane
- DM velocity: 220 km/s in *z*-direction
- λ = 1 km, m_{DM} = 10 kg
- Inside the contours: SNR > 1



Expected Event Rate

[Lee, Primulando, MS '22]

- Find fraction of events with SNR > threshold

$$p(\rho_{\rm th}^2) = \int_{\rho_{\rm th}^2}^{\infty} g(\rho^2)\ {\rm d}\,\rho^2$$
$$= \frac{1}{\mathcal{N}_p} \int f_v(\vec{v}_{\rm DM})\, f_x(\vec{x}_{0,{\rm DM}})\, \theta(\rho^2_{\rm KAGRA}(\vec{v}_{\rm DM}, \vec{x}_{0,{\rm DM}}) - \rho^2_{\rm th})\ {\rm d}^3\,\vec{v}_{\rm DM}\ {\rm d}^3\,\vec{x}_{0,{\rm DM}}$$

- Assumptions
  - Standard Halo Model for DM velocity distribution
  - Flat distribution for DM initial position

Expected Event Rate

[Lee, Primulando, MS '22]

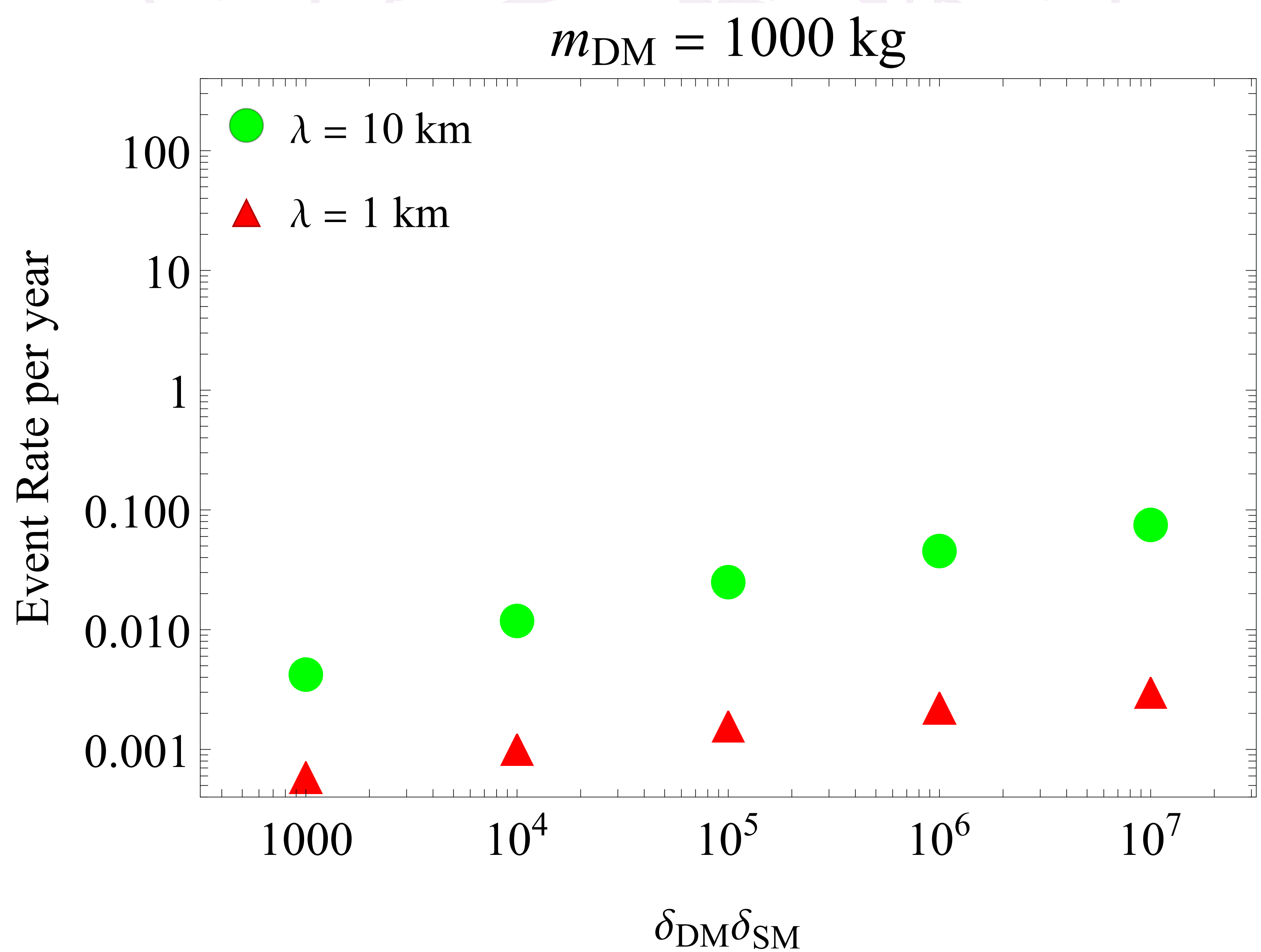
- Numerical challenge since SNR cannot be inverted
- The observable event rate is then given by

$$R_{\mathrm{obs}} = p(1)\, R_{\mathrm{total}}$$
$$= \frac{p(1)}{2} \int |\vec{\Phi}_{\mathrm{DM}} \cdot \vec{S}| f_v(\vec{v}_{\mathrm{DM}})\, \mathrm{d}^2\, \vec{S}\, \mathrm{d}^3\, \vec{v}_{\mathrm{DM}}$$

where R_{total} counts the DM particles going through a sphere with a sufficiently large radius

Expected Event Rate

[Lee, Primulando, MS '22]



Expected Event Rate

[Lee, Primulando, MS '22]