Dark Matter Scattering in Optomechanical Experiments

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Cosmology Frontier in Particle Physics: Astroparticle Physics and Early Universe / International Joint Workshop on the SM and Beyond
NTU & NTHU

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

Outline

- Introduction
- Dark Matter
  - Particle Physics Approach
  - Gravitational Wave Astronomy Approach
  - Wave-like Dark Matter
- Summary and Conclusions

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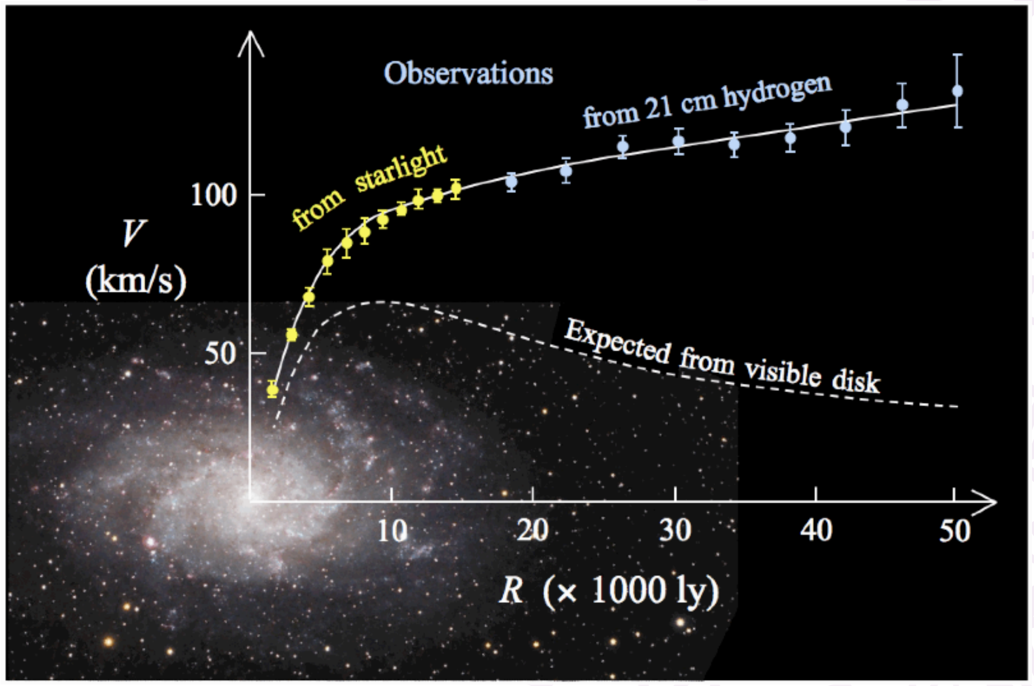
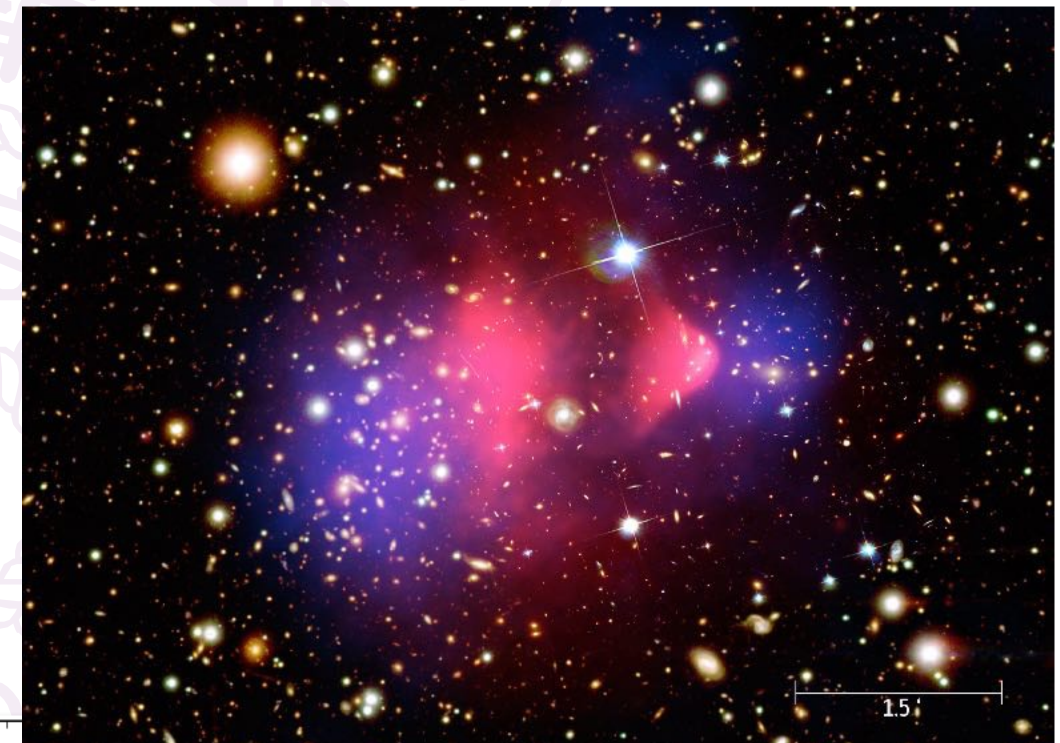
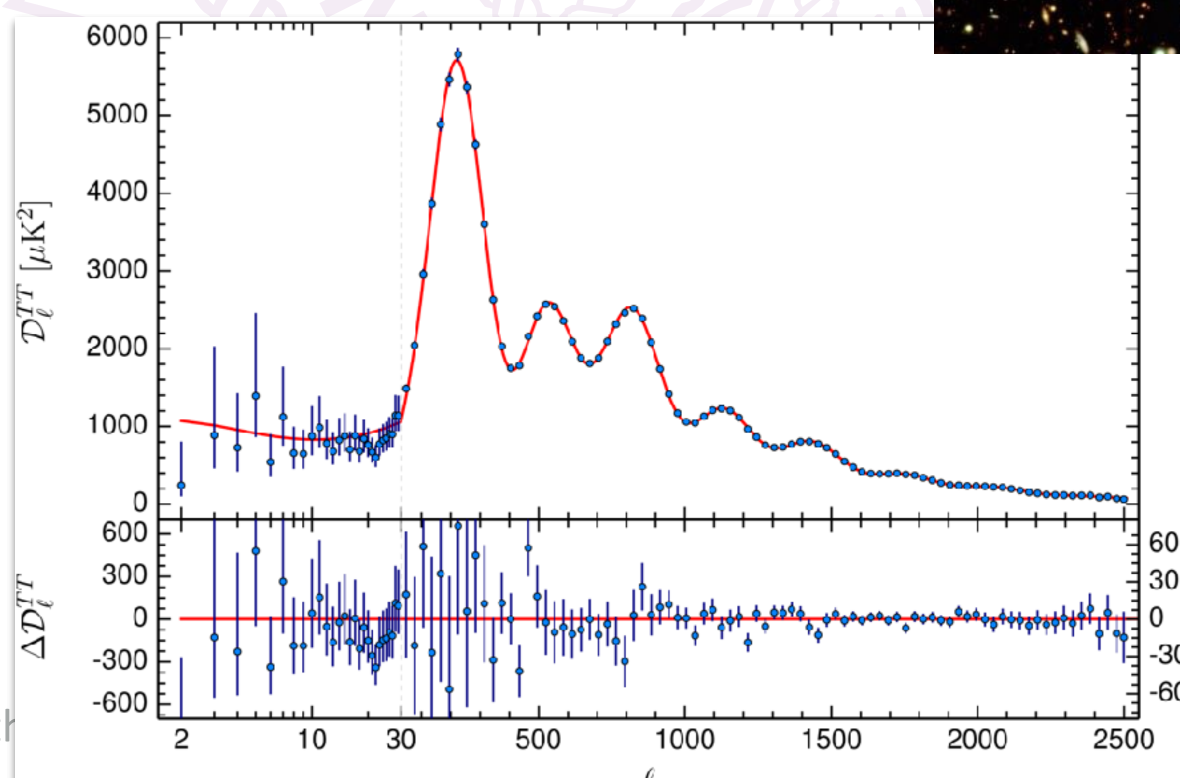
Dark Matter Evidences



[M33 rot. curve, Source: Wikipedia]

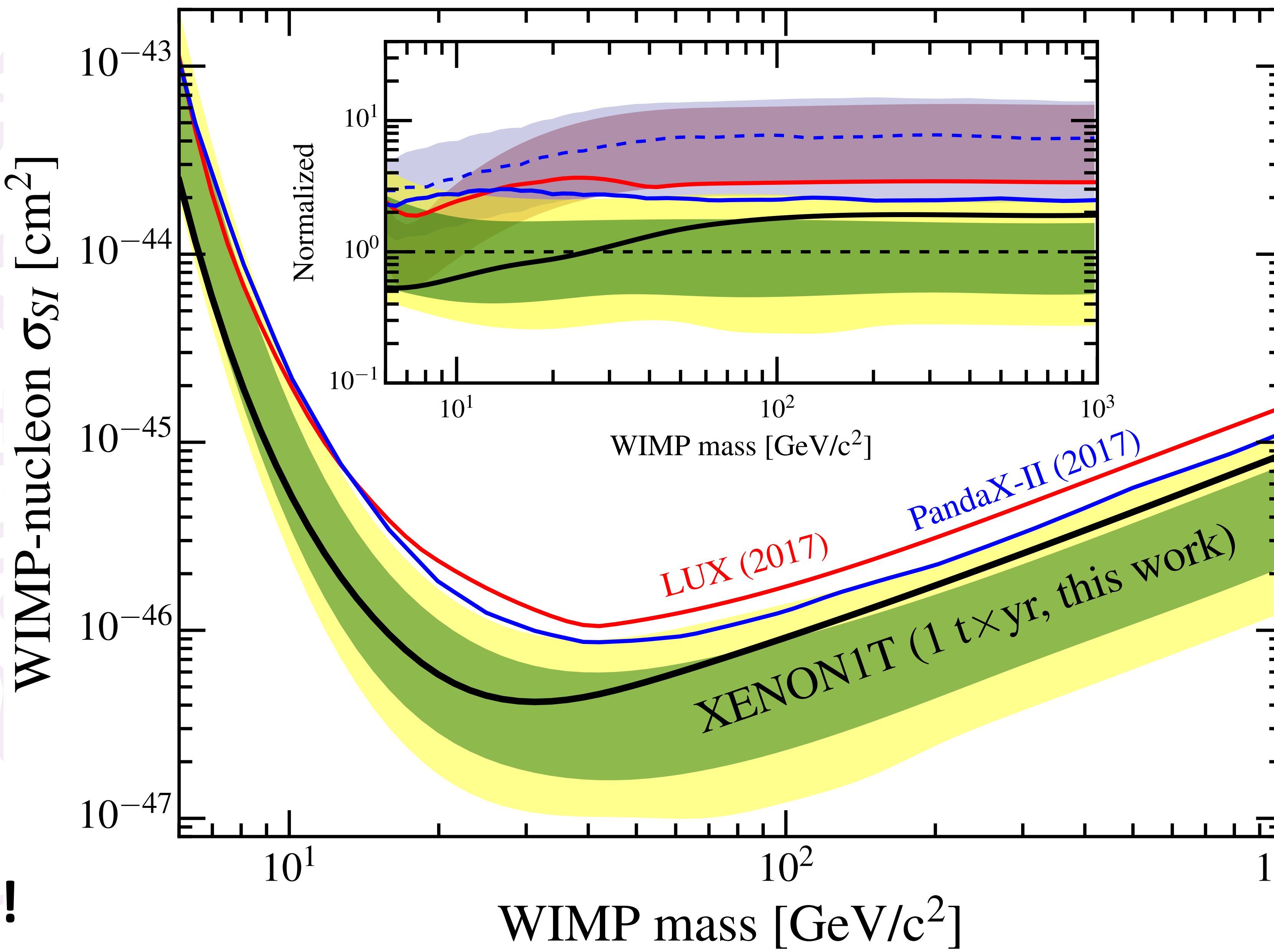
[Chandra picture of the bullet cluster]





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

WIMP Searches

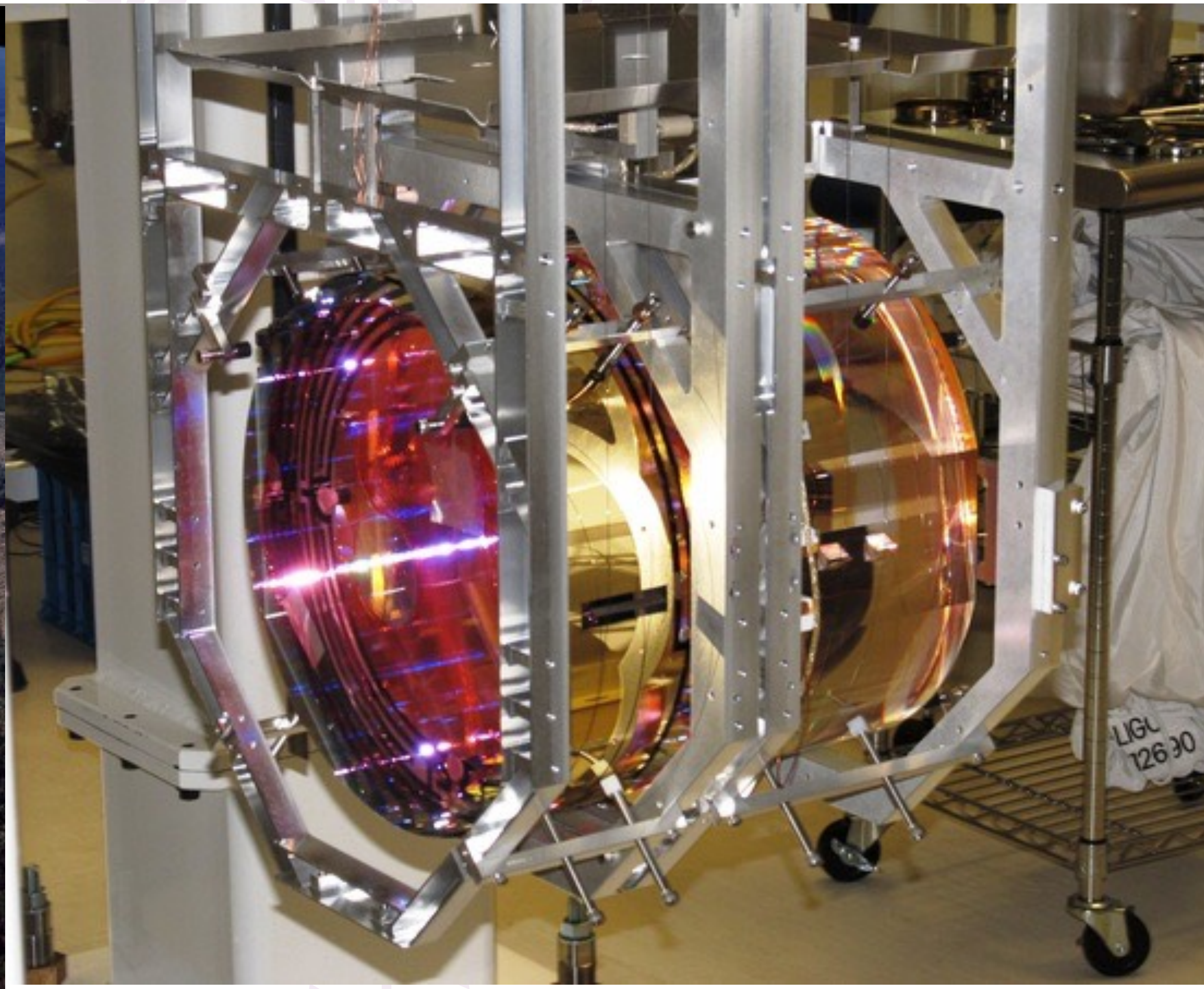


[XENON1T result '18]

Time to think again?!
Light WIMPs?

Gravitational Wave Detectors

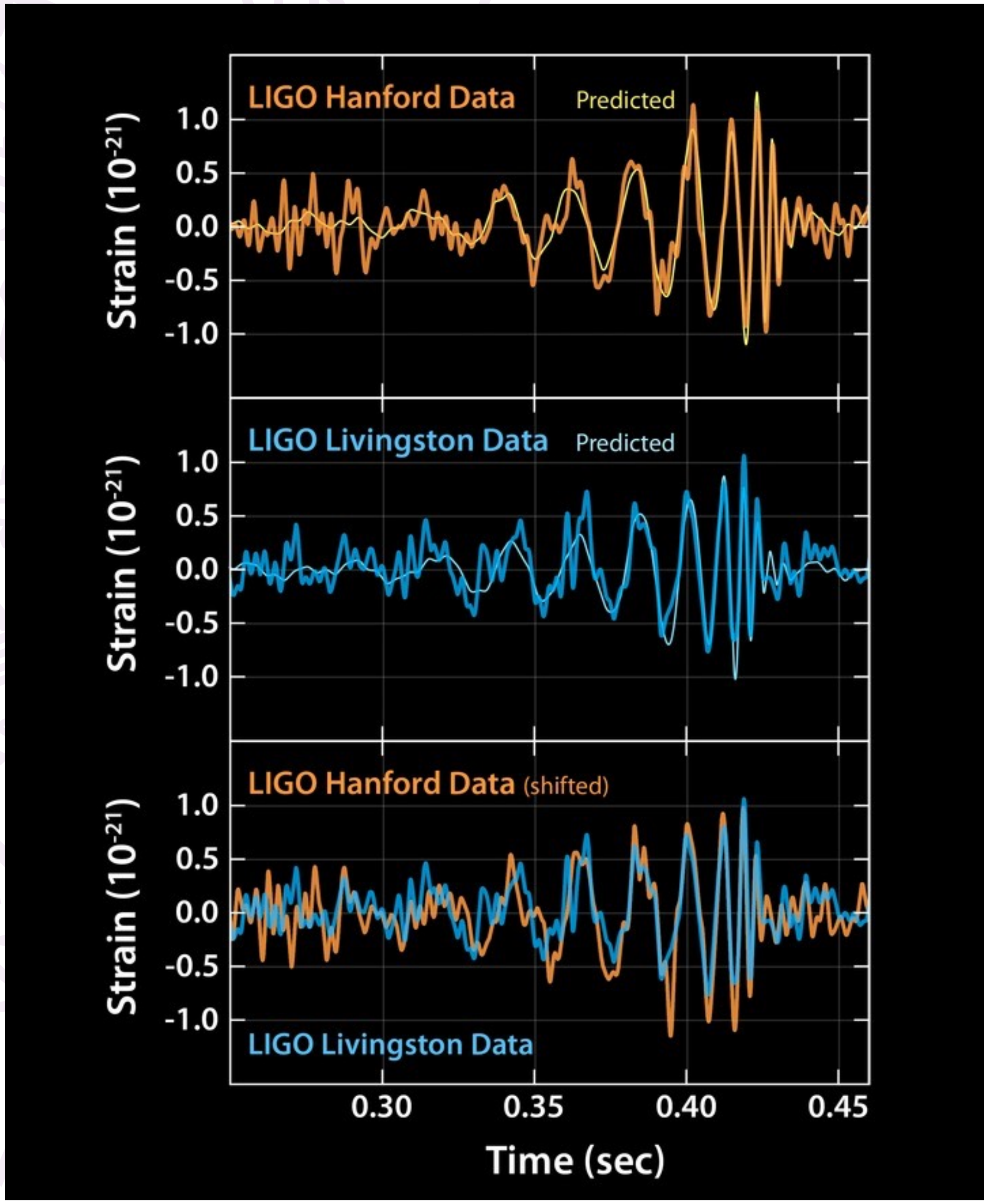
[LIGO Livingston, Courtesy Caltech/MIT/LIGO Laboratory 2016]



[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?



[Courtesy Caltech/MIT/LIGO Laboratory 2016]

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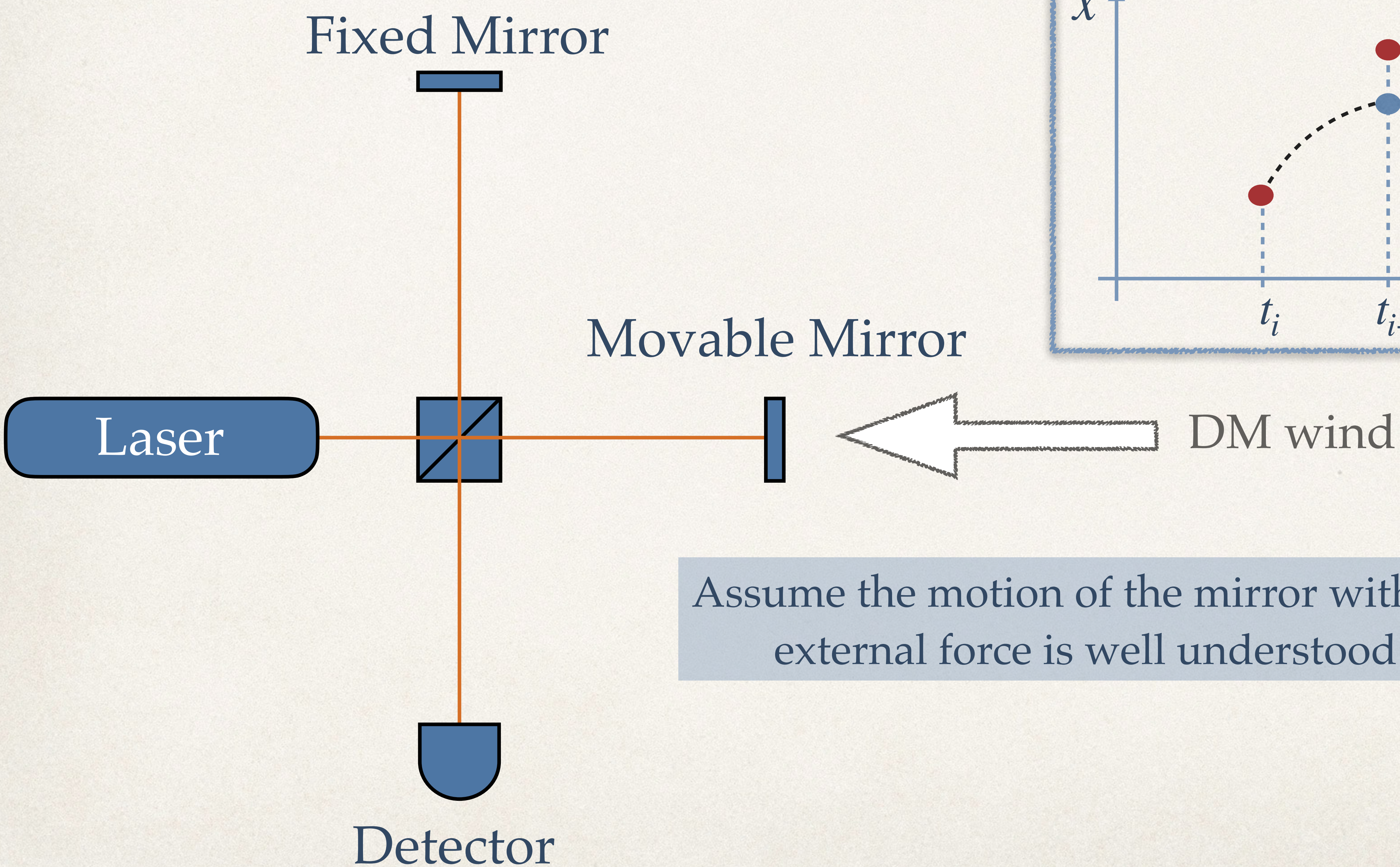
Dark Brownian Motion

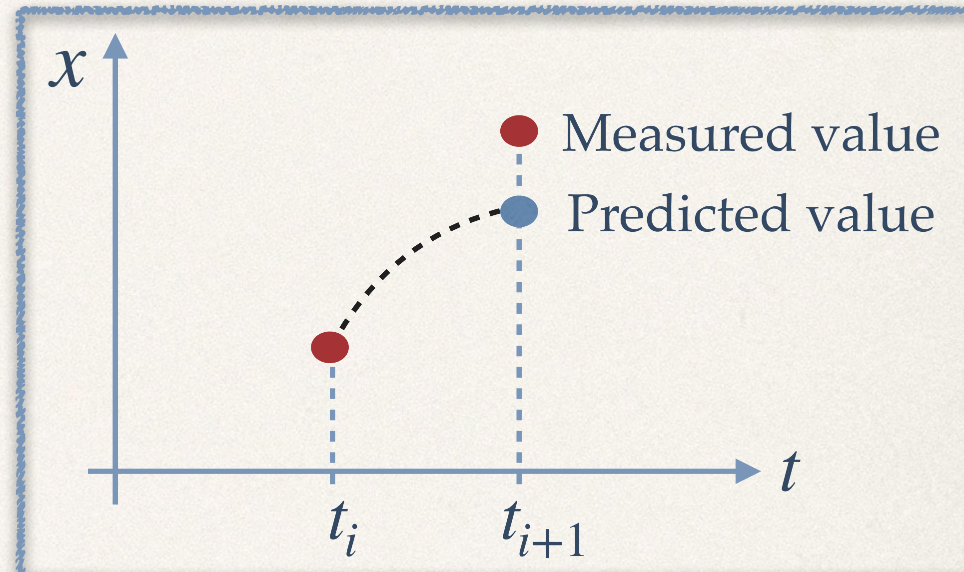
[Cheng, Primulando, MS '19]

- 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

Potential Setup

Inspired by [Valerie Domcke and Martin Spinrath, 2017]

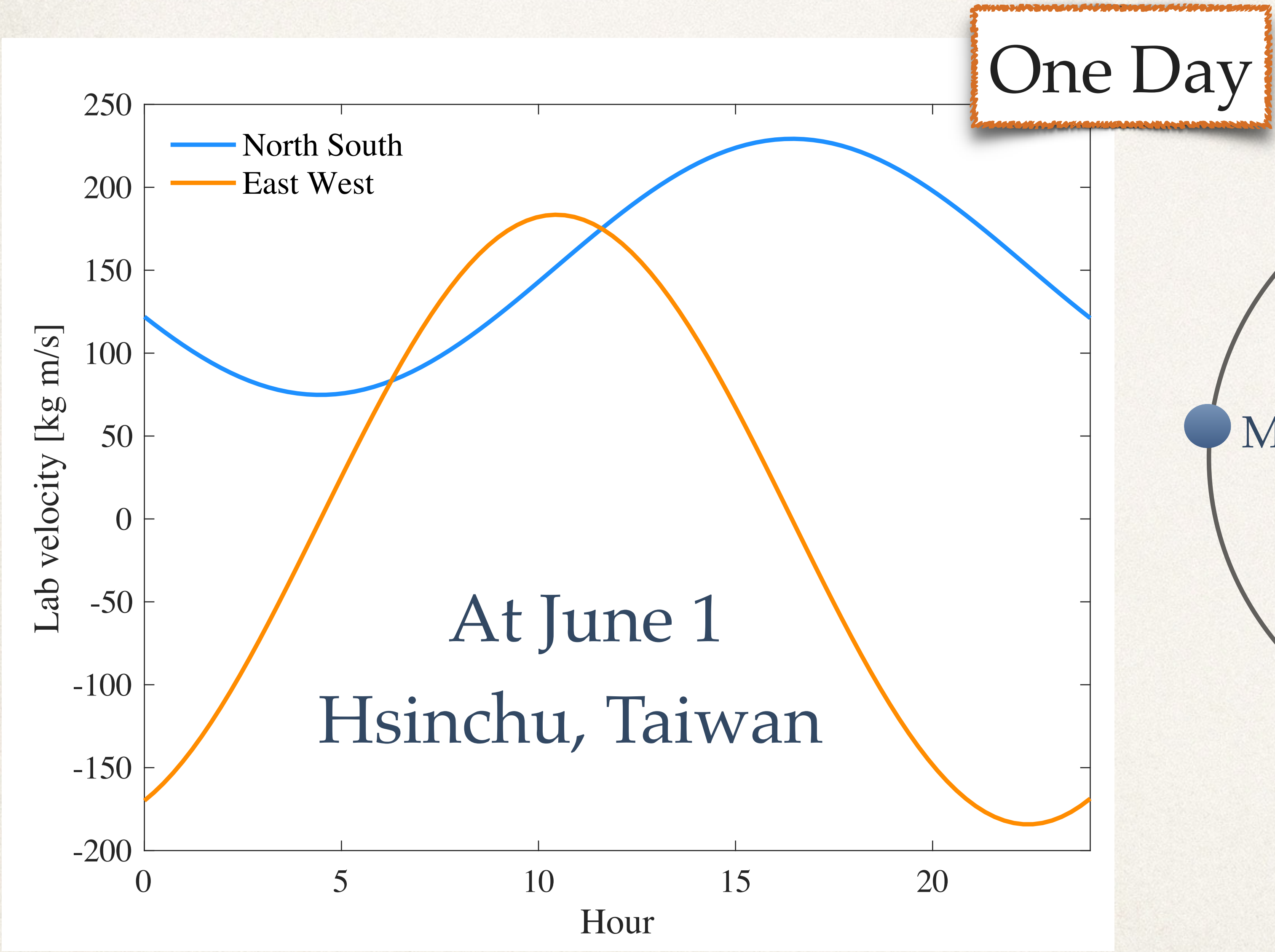


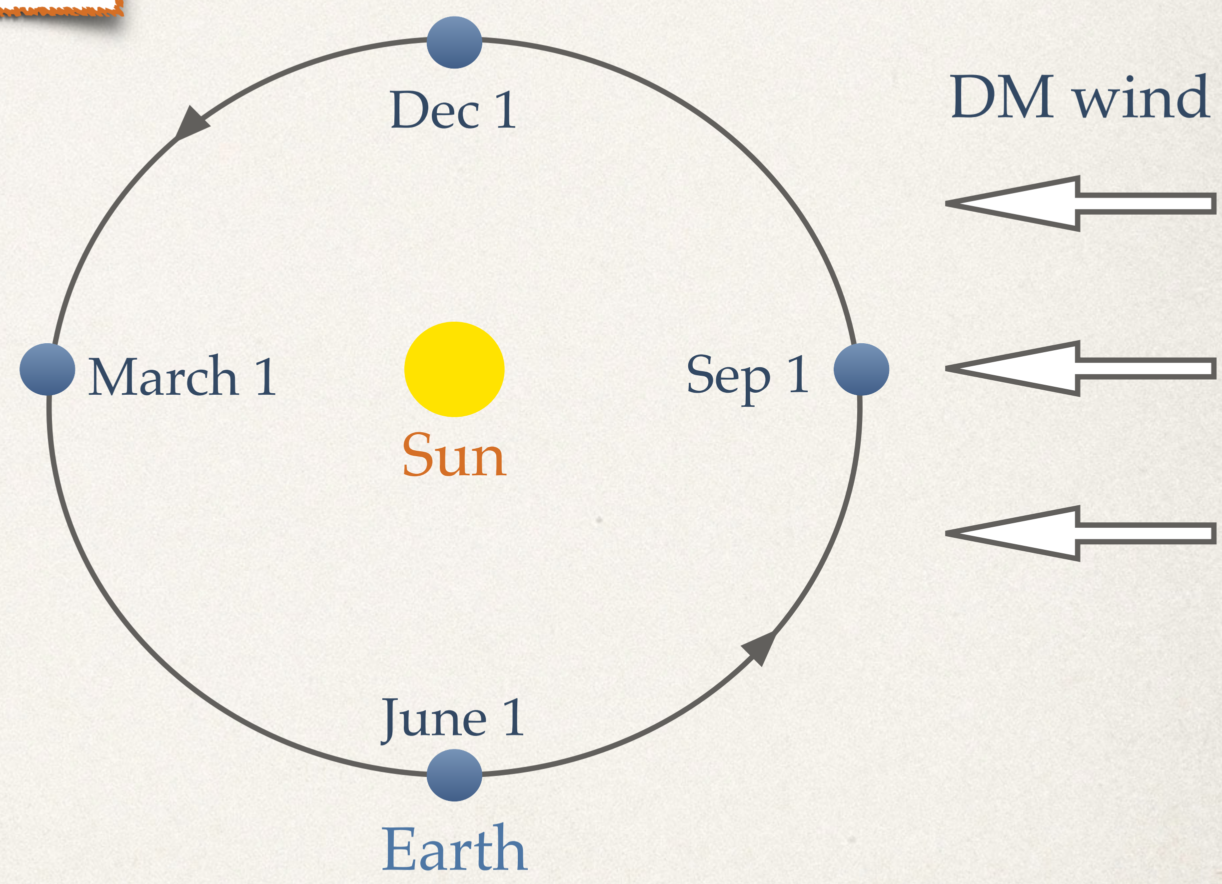


Assume the motion of the mirror without external force is well understood

[slide taken from Ting Cheng now at MPIK]

Time Dependent Lab Velocity





The Asymmetry Factor

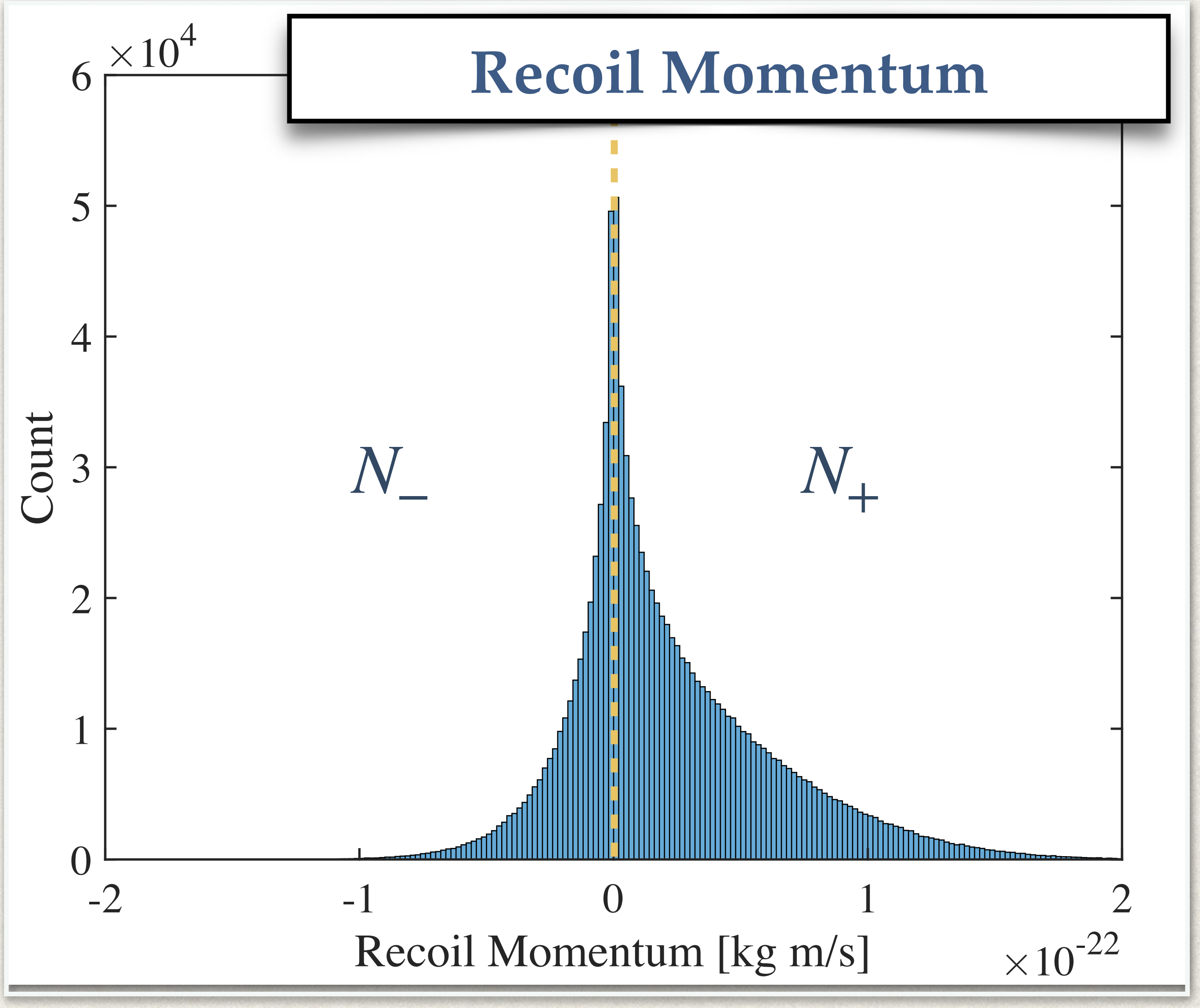
- The Asymmetry Factor :

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

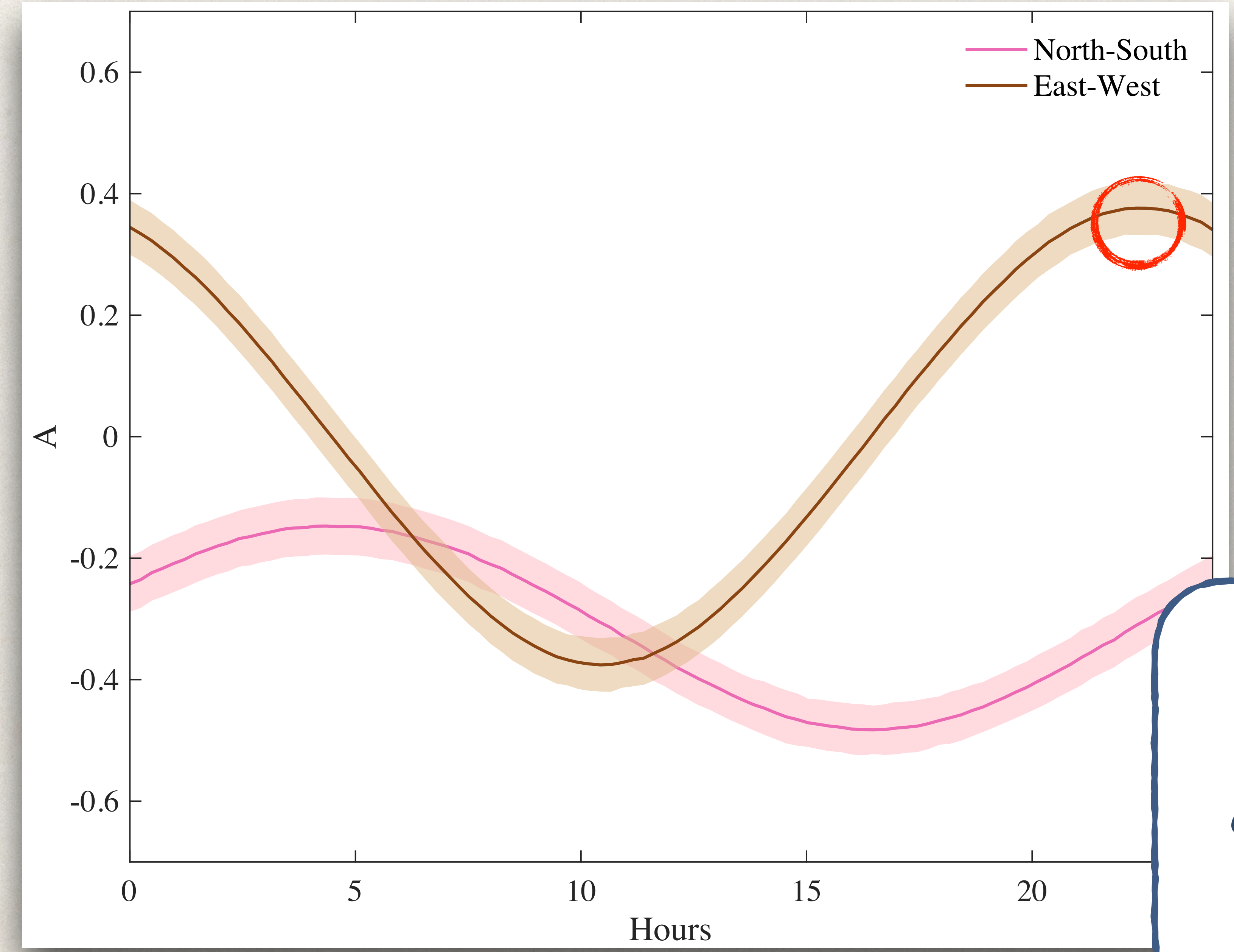
- Uncertainty of A :

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

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



Daily Modulation of A



Error Bar:

$\Delta t = 10$ min

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

$M_{DM} = 10$ MeV

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

Backgrounds

- Many potential backgrounds for our proposal
  - seismic noise, nearby traffic, radioactivity, etc.
- Two examples
  - Neutrinos
  - Hits from residual gas

Background from Neutrinos

[Cheng, Primulando, MS '19]

- Large flux of solar neutrinos which penetrate all materials and interact with matter
- For

$$\Phi_\nu \approx 6 \times 10^{10} \ 1/(\mathrm{s\ cm}^2)$$
$$\sigma_\nu \approx 10^{-44} \ \mathrm{cm}^2$$
$$M_T = 10^{-3} \ \mathrm{g\ of\ carbon}$$

- We expect O(10^{-14}) neutrino events per sec.

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

$$R_{\rm atm} = n\, A\, |v|\, f(v)$$
$$\approx 8.3 \times 10^9 \left(\frac{P}{10^{-10}\ \mathrm{mbar}} \sqrt{\frac{20\ \mathrm{K}}{T}} \frac{A}{\mathrm{mm}^2} \right) \frac{1}{\mathrm{s}}$$

Residual Gas

[Cheng, Primulando, MS '19]

- What rate could we expect for DM?

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

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

Residual Gas

[Cheng, Primulando, MS '19]

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

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

- Use LIGO resolution as naive estimate

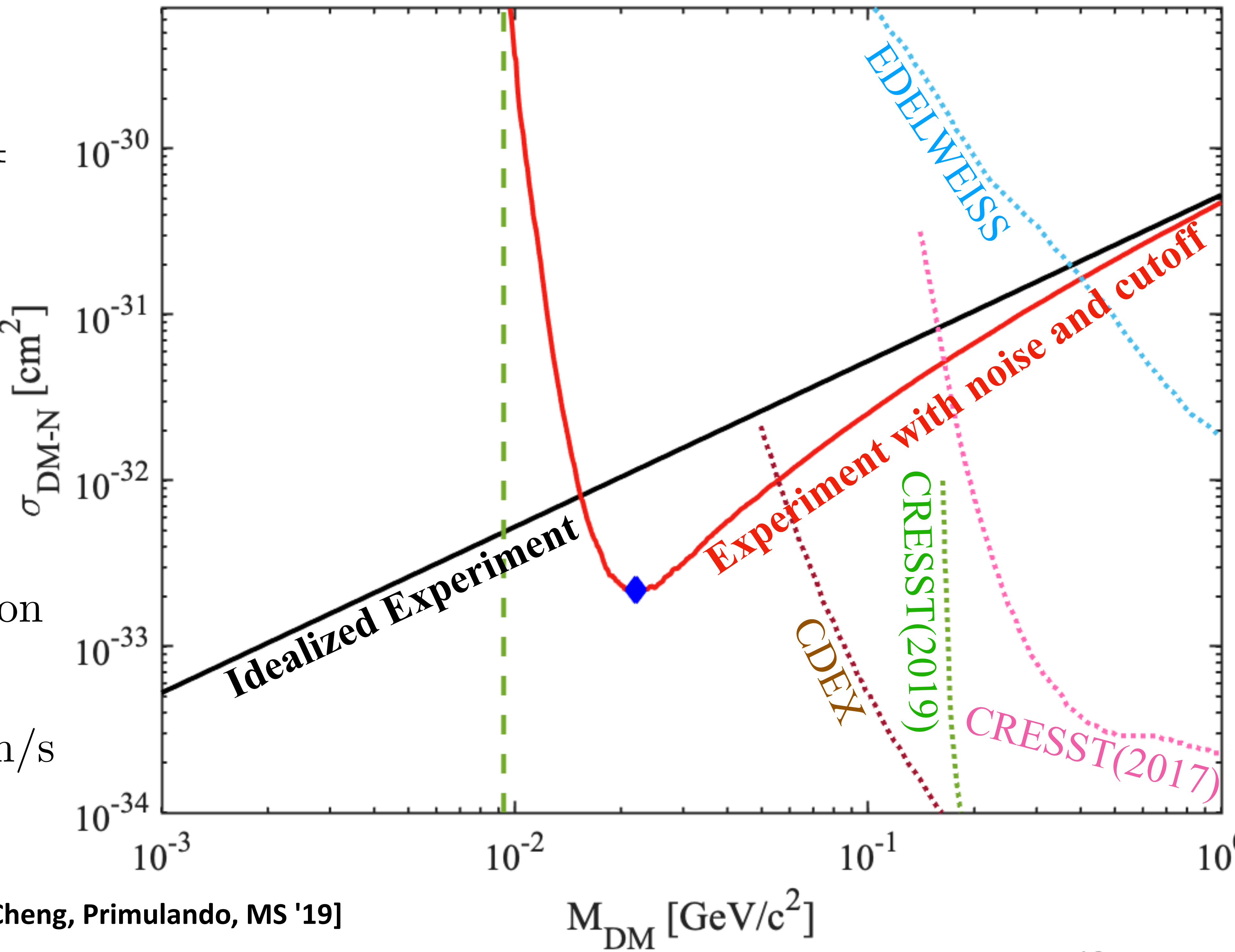
$$q_{\rm min} \equiv 2 \times 10^{-23}\ \rm kg\ m/s$$

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

Sensitivity Estimate

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

$$M_T = 10^{-3}\ \text{g of carbon}$$
$$\Delta t = 10\ \text{min}$$
$$q_{\rm min} = 2 \times 10^{-23}\ \text{kg m/s}$$



[Cheng, Primulando, MS '19]

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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

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

DM Signal

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

- Assuming DM instantaneous scattering

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

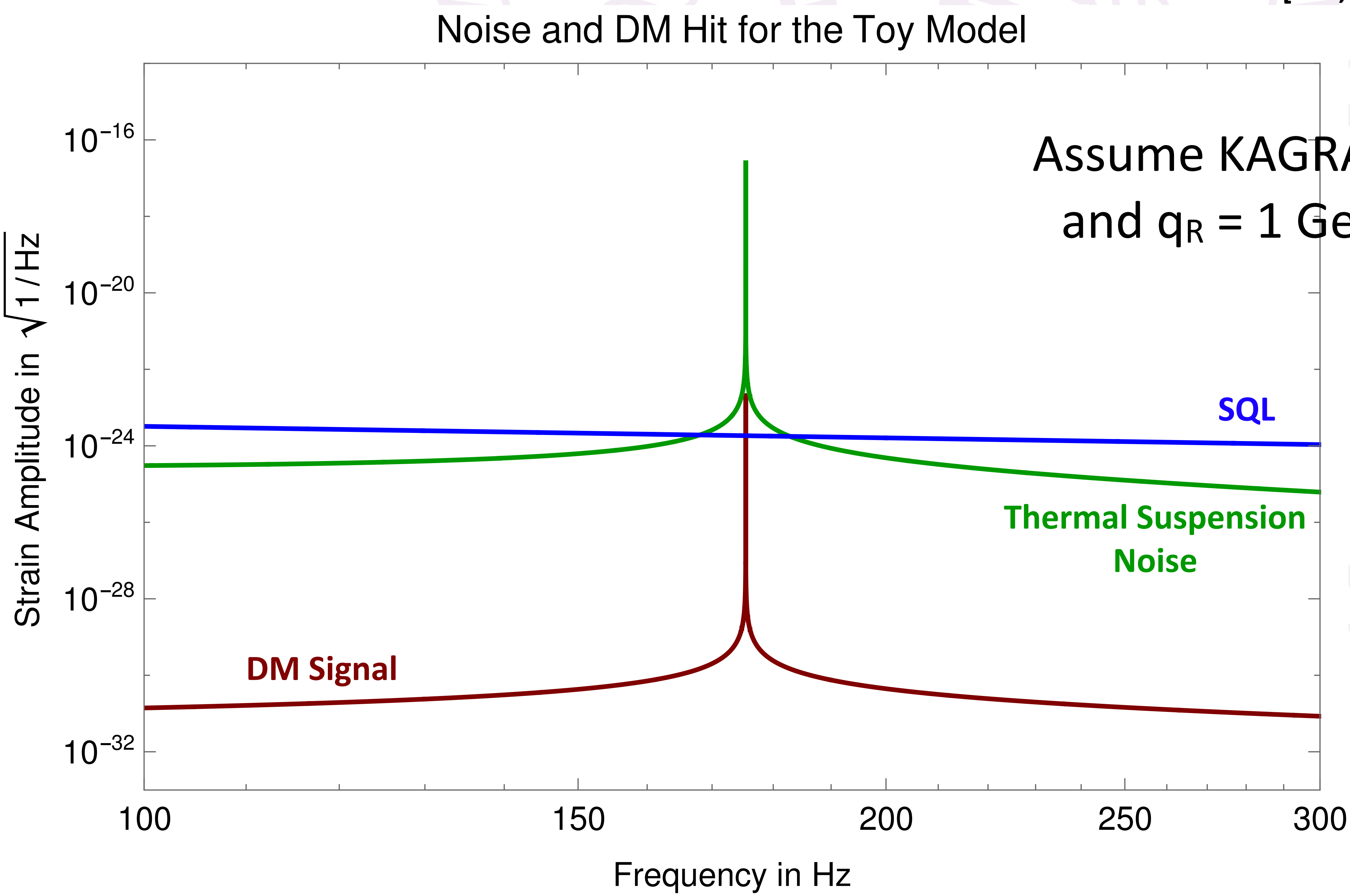
- which enters the DM strain amplitude

[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

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

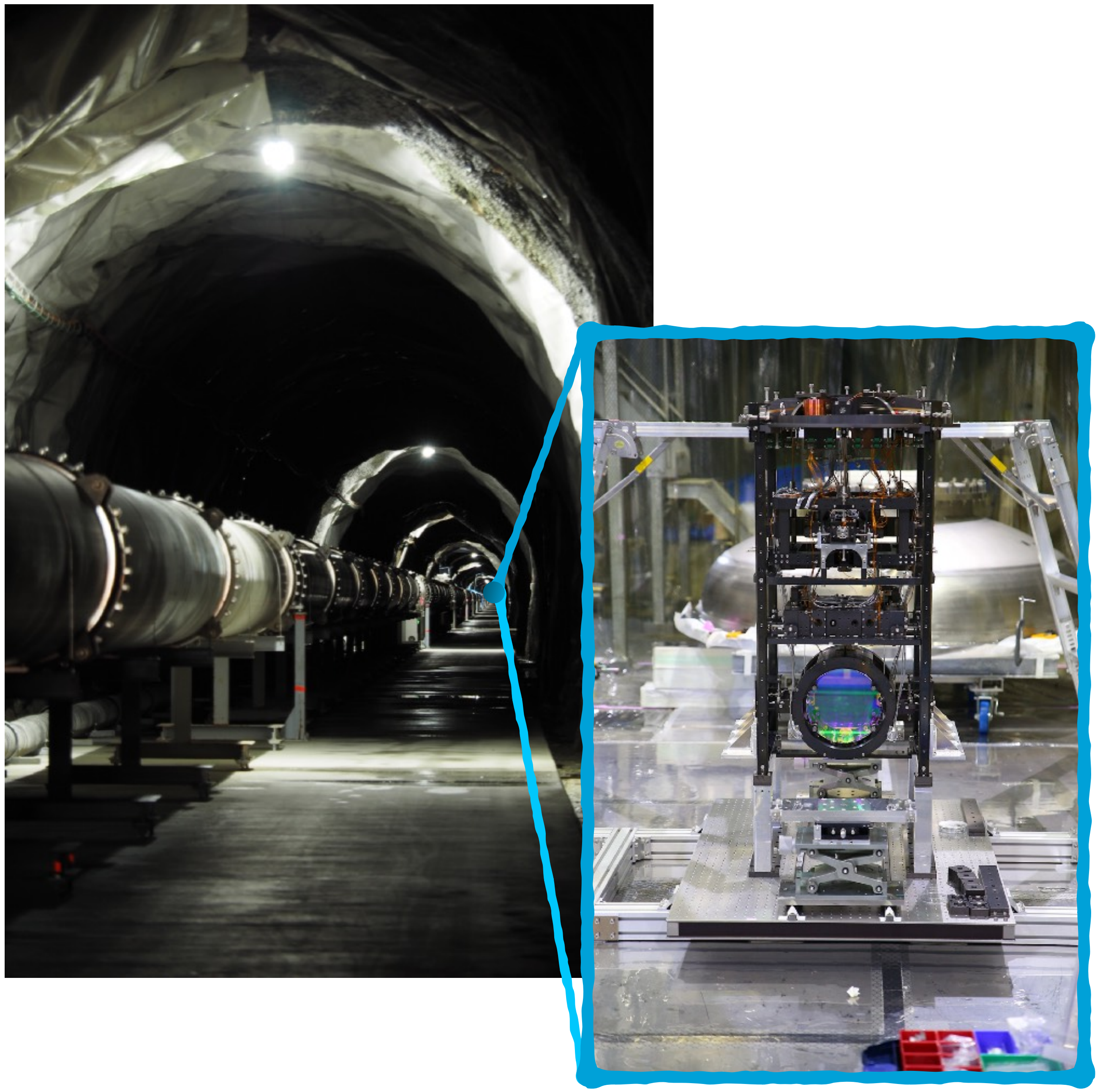
Numbers as in previous figure

- Need light, cold targets!

[slide taken from Chun-Hao Lee]

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]

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KAGRA

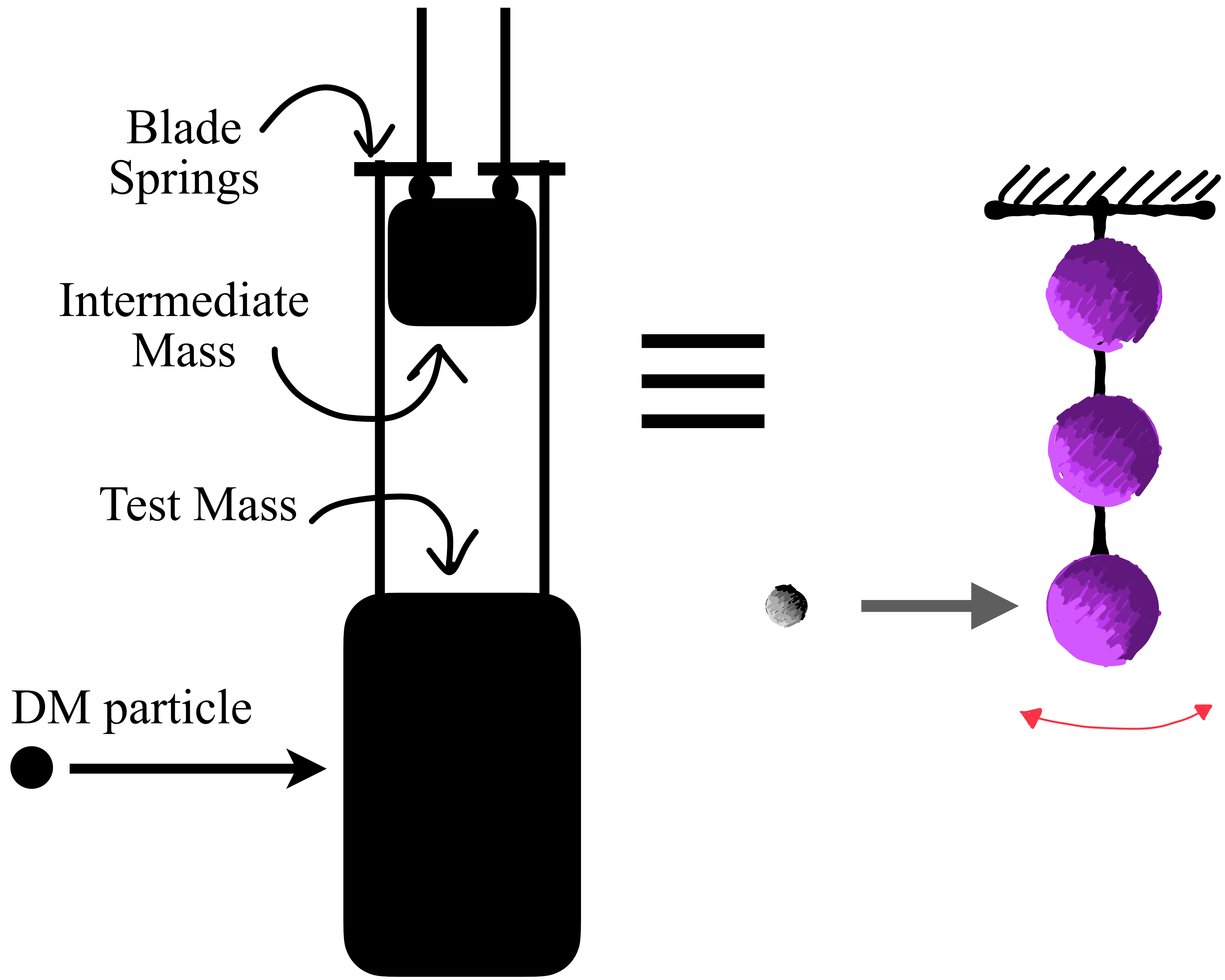
- An equation of motion in matrix form

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

Masses of the components, a 3x3 matrix

Complex spring constants of the components, a 3x3 matrix

External DM force

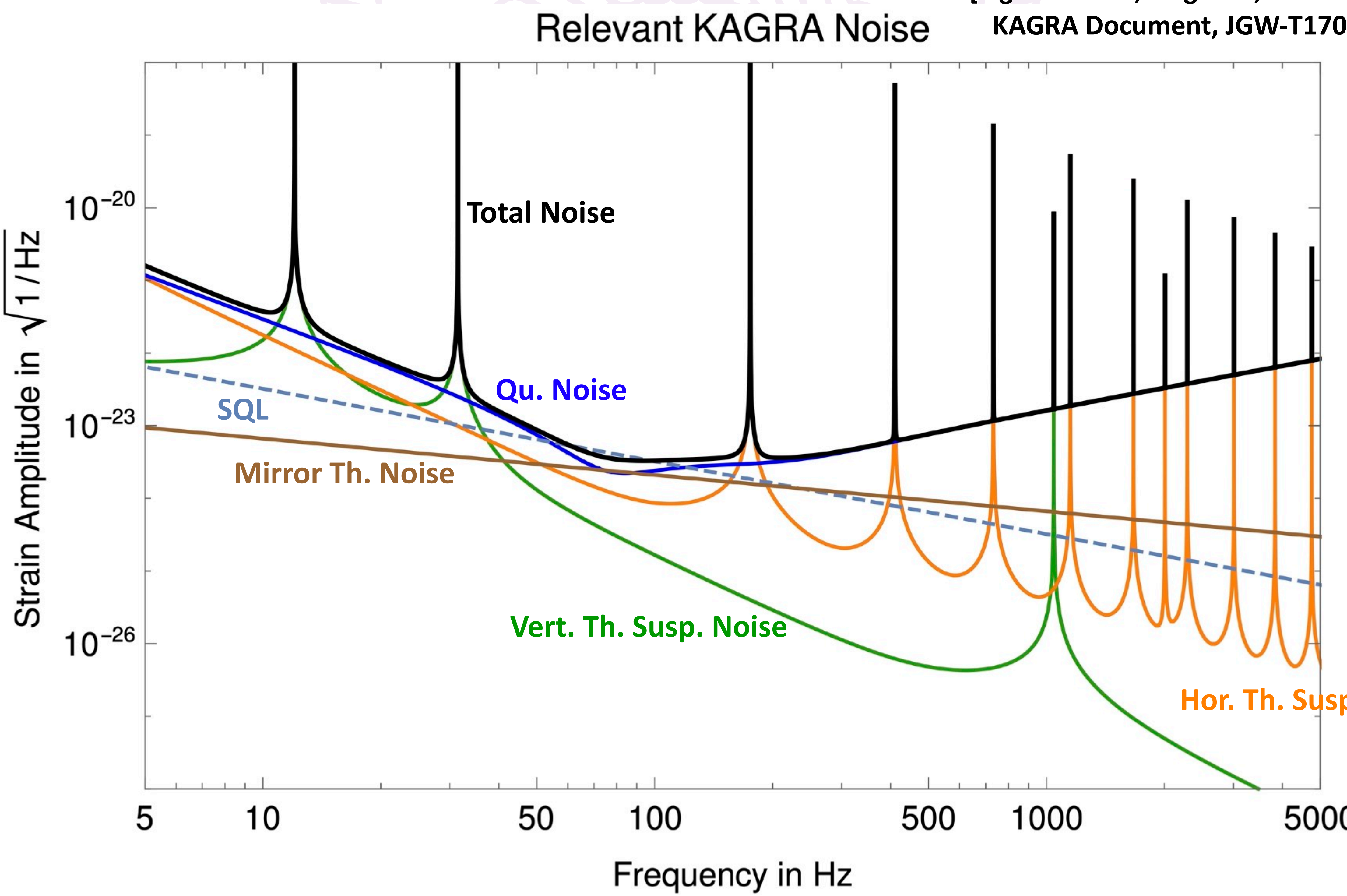


- Two sets of equations
  - For DM hits in vertical and horizontal direction, respectively

[KAGRA Document, JGW-T1707038v9]

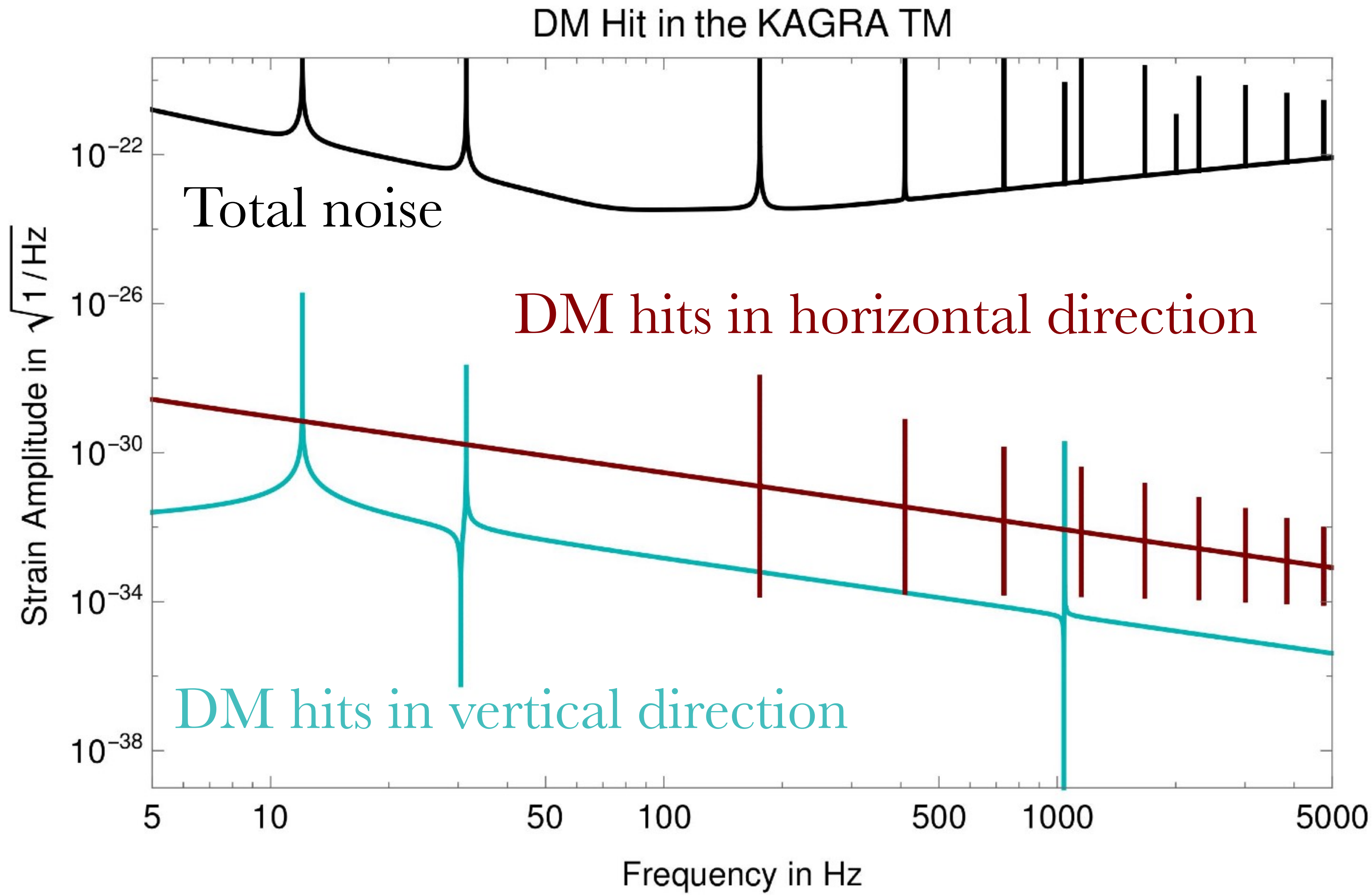
KAGRA Noise

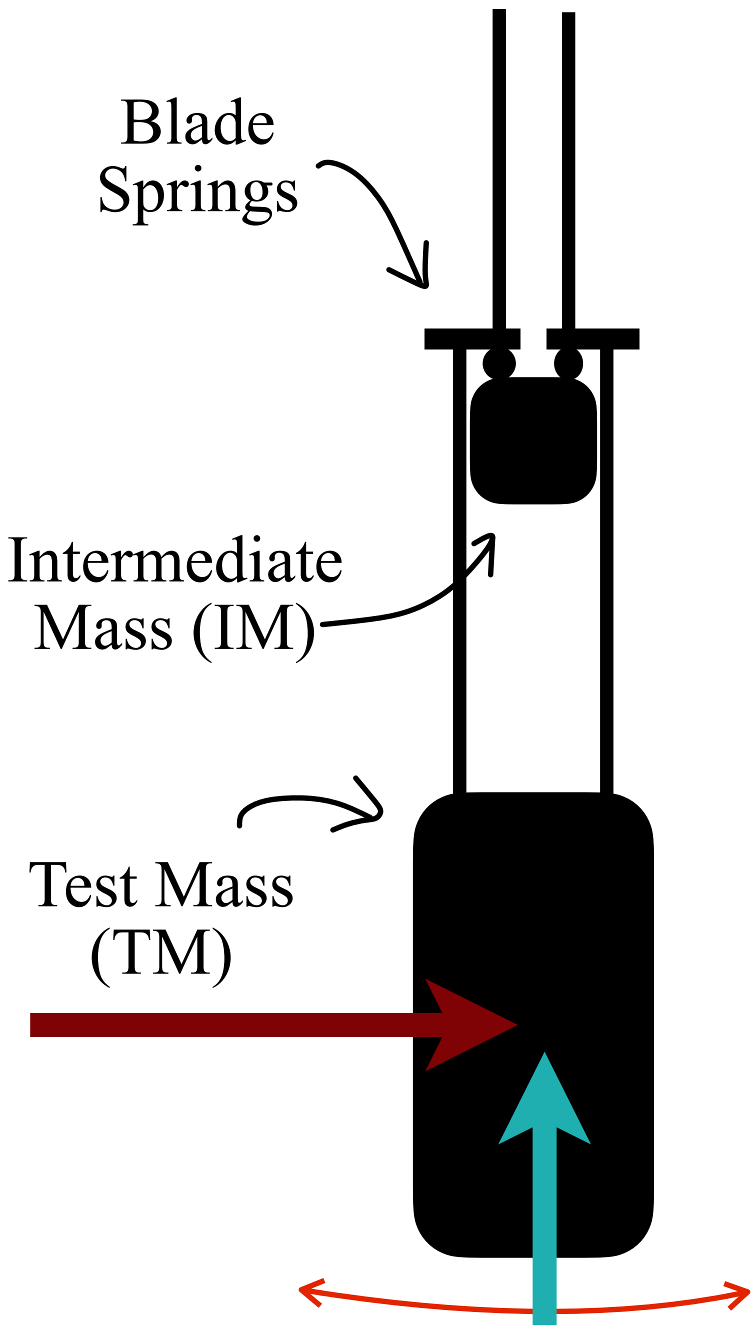
[Fig. from Lee, Nugroho, MS '20 based on KAGRA Document, JGW-T1707038v9]



KAGRA

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

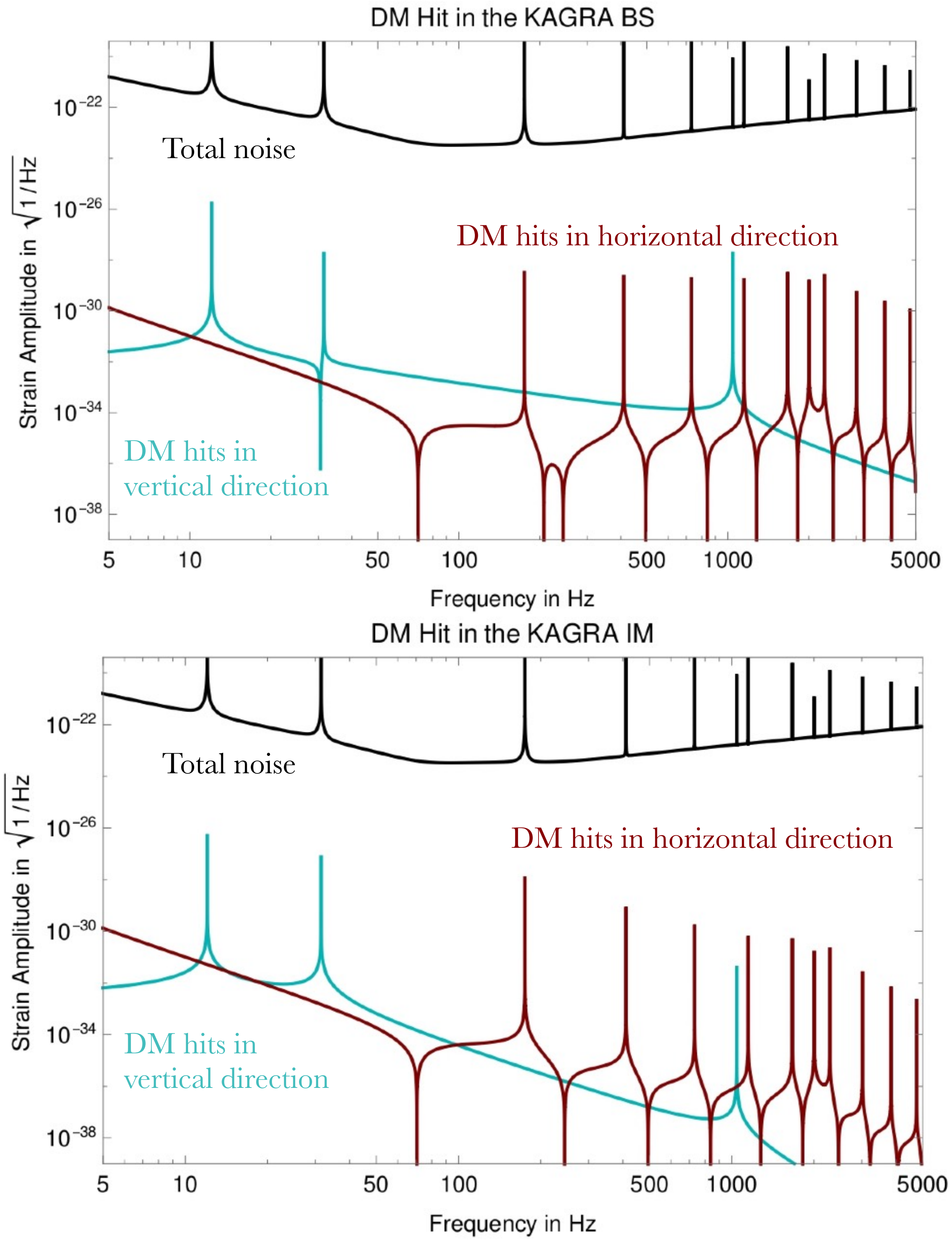




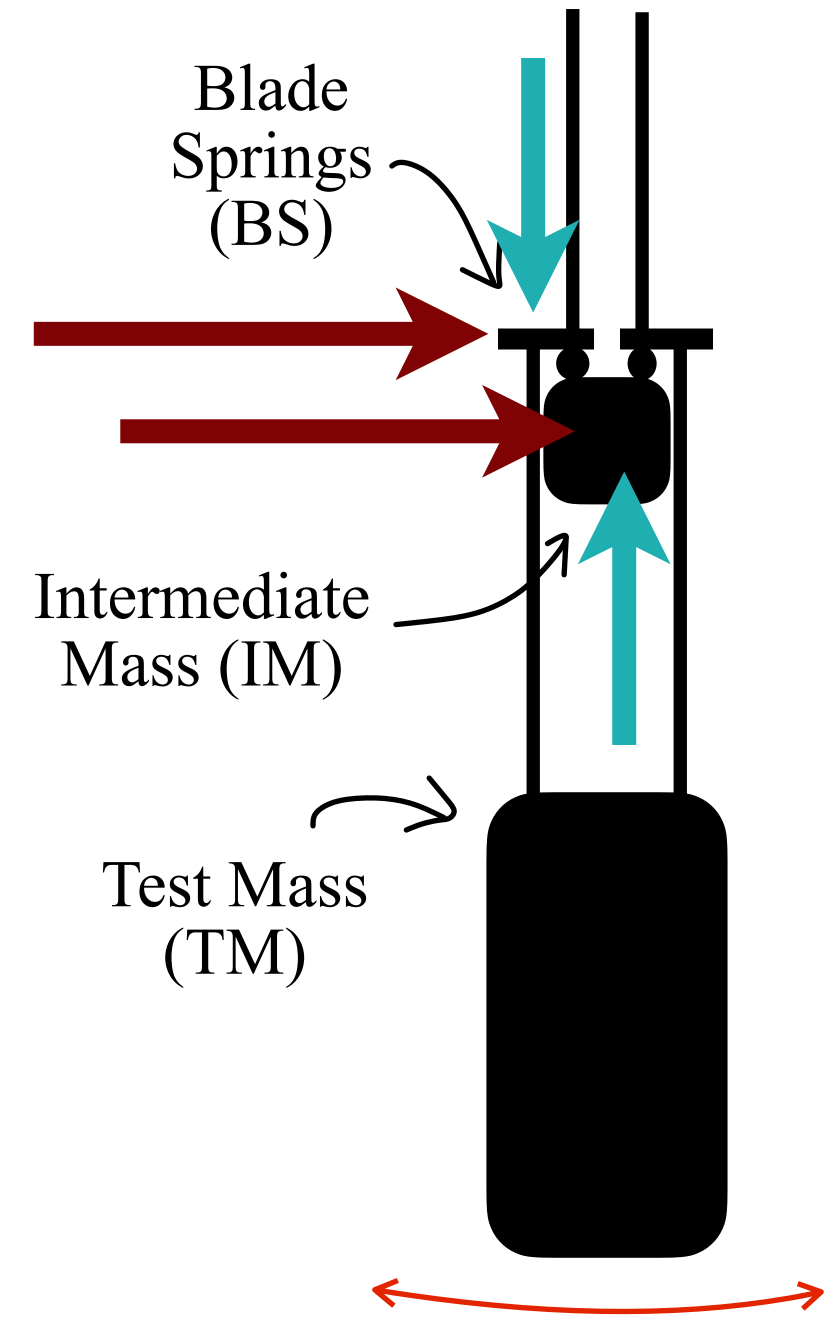
[C. H. Lee, C. S. Nugroho and M. Spinrath, EPJ C 80, no. 12, 1125 (2020)]

[slide taken from Chun-Hao Lee]

KAGRA



- q_R = 1 GeV/c² x 220 km/s



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

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]

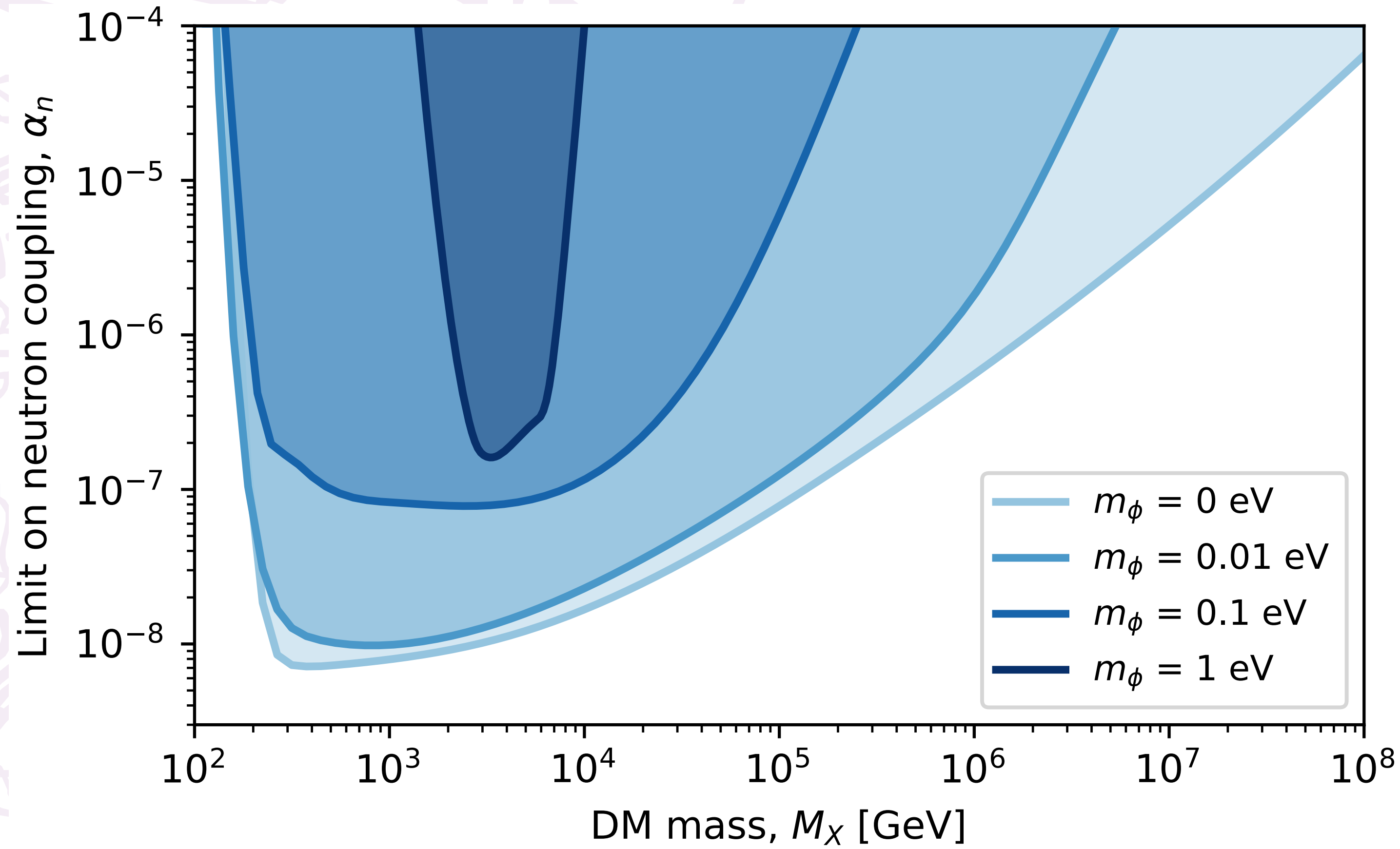
- Expected strain amplitude

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

[Lee, Nugroho, MS '20]

Other technology

- 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 arXiv:2008.06074]

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Little (Incomplete) Overview

- $M_{DM} < 1$ MeV: quantum decoherence **[Riedel '12; Riedel, Yavin '16]**
- $M_{DM} < 10^{-4}$ eV: Sound of DM **[Arvanitaki, Dimopoulos, van Tilburg '16; AURIGA '16]**
- $M_{DM} < 10^{-11}$ eV: Variation of fundamental constants **[Stadnik, Flambaum '14; '15; Grote, Stadnik '19]**
- $10\ M_{\odot} < M_{DM} < 10^5\ M_{\odot}$: GW lensing **[Jung, Shin '17]**
- $M_{DM} < 10^{-11}$ eV: Dark Photons **[Pierce, Riles, Zhao '18]**
- $M_{DM} < 10^{-10}$ eV: Mirror oscillations **[Morisaki, Suyama '18]**

Ultralight DM

- Large occupation number ➙ acts like a classical field
- Motivated by string moduli fields
- Lagrangian

$$\mathcal{L}_\phi = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2$$

$$\mathcal{L}_{\phi-\mathrm{SM}} = \kappa\phi\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

[Morisaki, Suyama ’18]

Motion of Optical Instruments

[Morisaki, Suyama ’18]

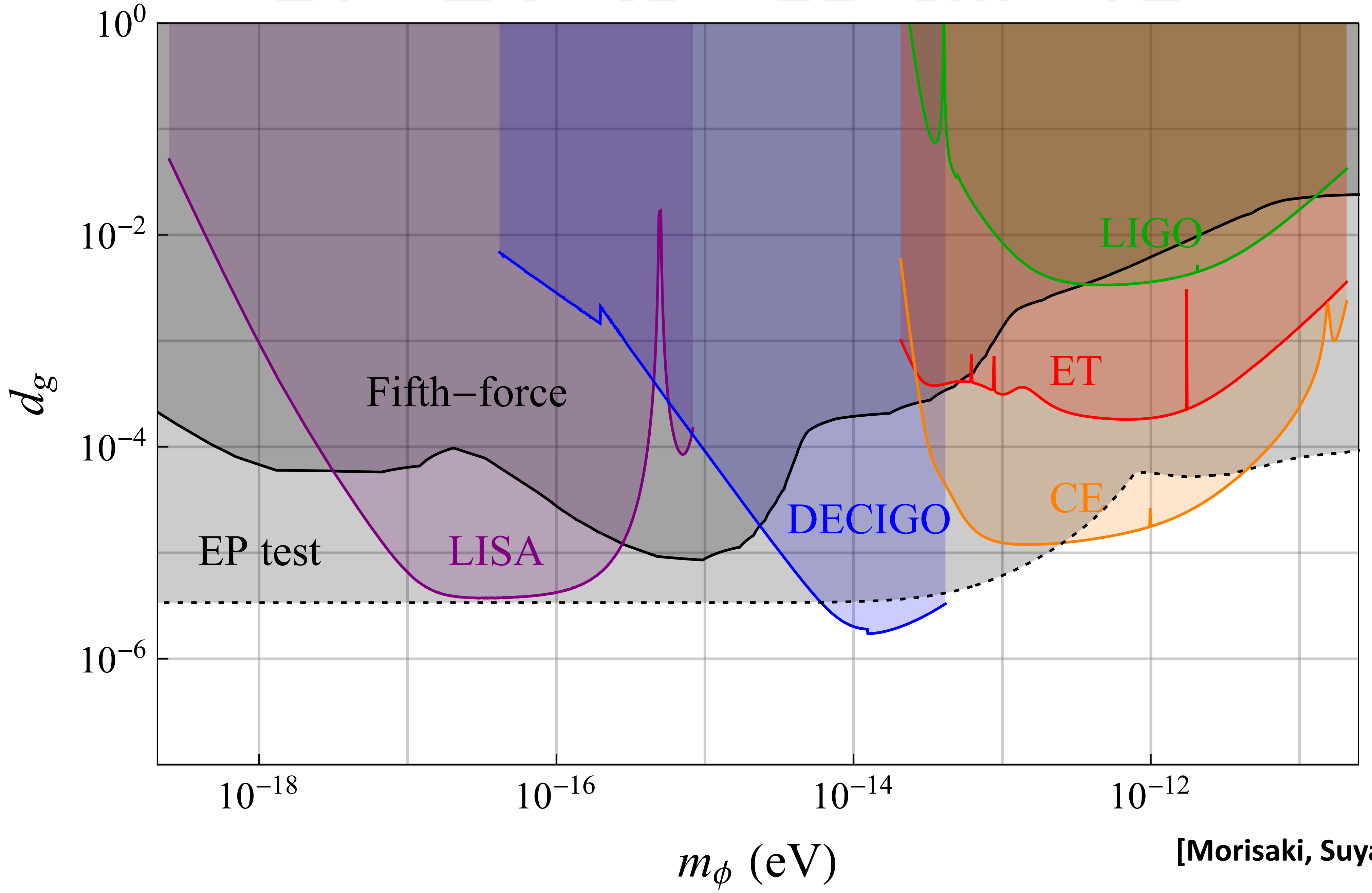
- The DM wave pushes optical instruments
- Assuming plane DM waves

$$x^i \simeq d_g^* \kappa \phi_{\vec{k}} \frac{k^i}{m_\phi^2} \sin(\omega_k t - \vec{k} \cdot \vec{x}_0 + \theta_{\vec{k}}) + \text{const.}$$

- where

$$\omega_k \sim m_\phi,\ \Delta\omega_k \sim m_\phi v_{\text{DM}}^2 \text{ and } |\vec{k}| \lesssim m_\phi v_{\text{DM}} \sim 10^{-3}\, m_\phi$$

Prospects in this Setup



[Morisaki, Suyama '18]

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Summary and Conclusions

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

Backup

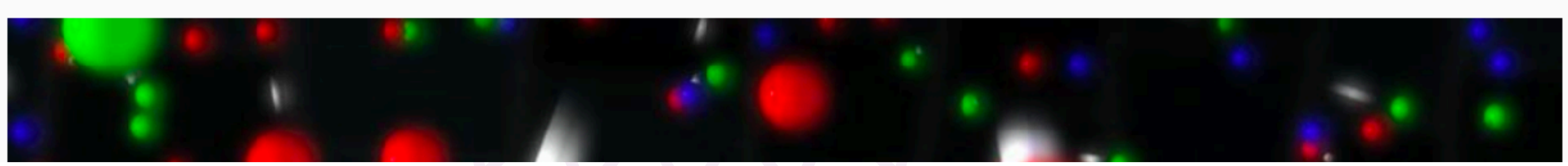
Didn't we already find it?

Forbes Billionaires Innovation Leadership Money Consumer Industry Lifestyle Fe

21,761 views | Feb 28, 2019, 02:00am

Earliest Signal Ever: Scientists Find Relic Neutrinos From 1 Second After The Big Bang

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.



[https://www.forbes.com/sites/startswithabang/2019/02/28/earliest-signal-ever-scientists-find-relic-neutrinos-from-1-second-after-the-big-bang/#50b3e913d99c]

Didn't we already find it?

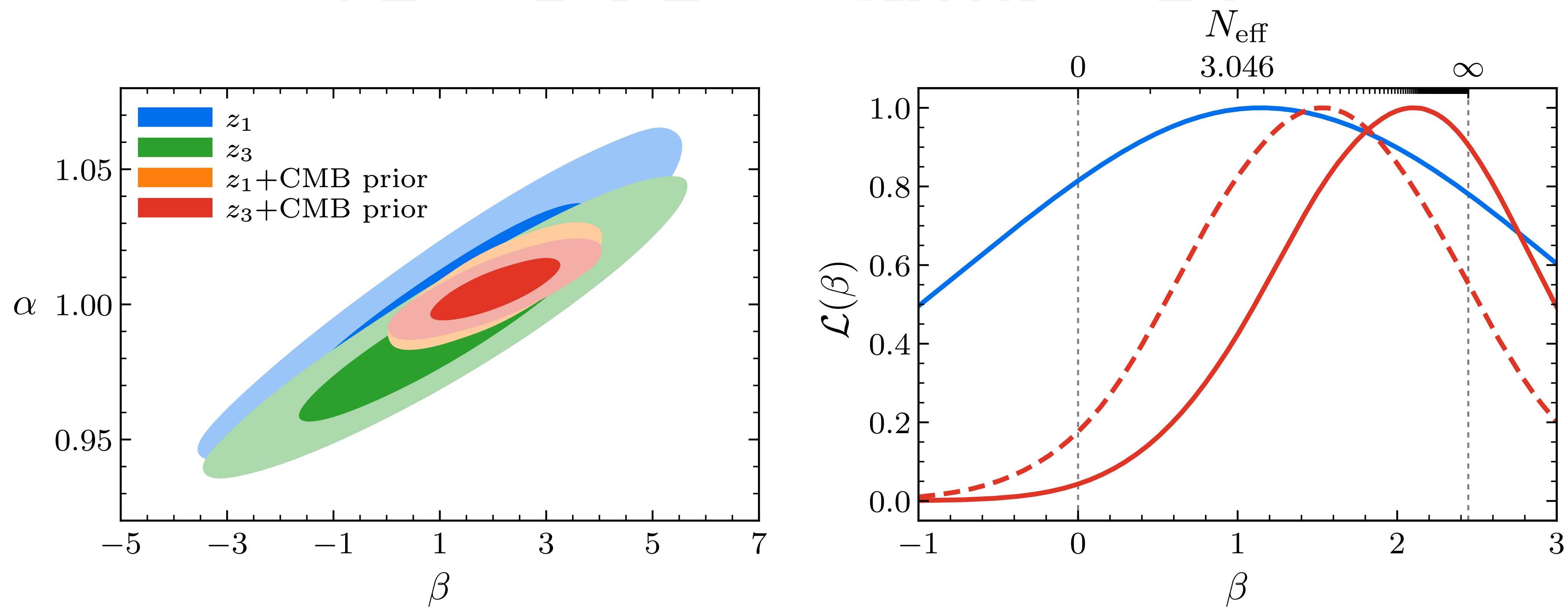


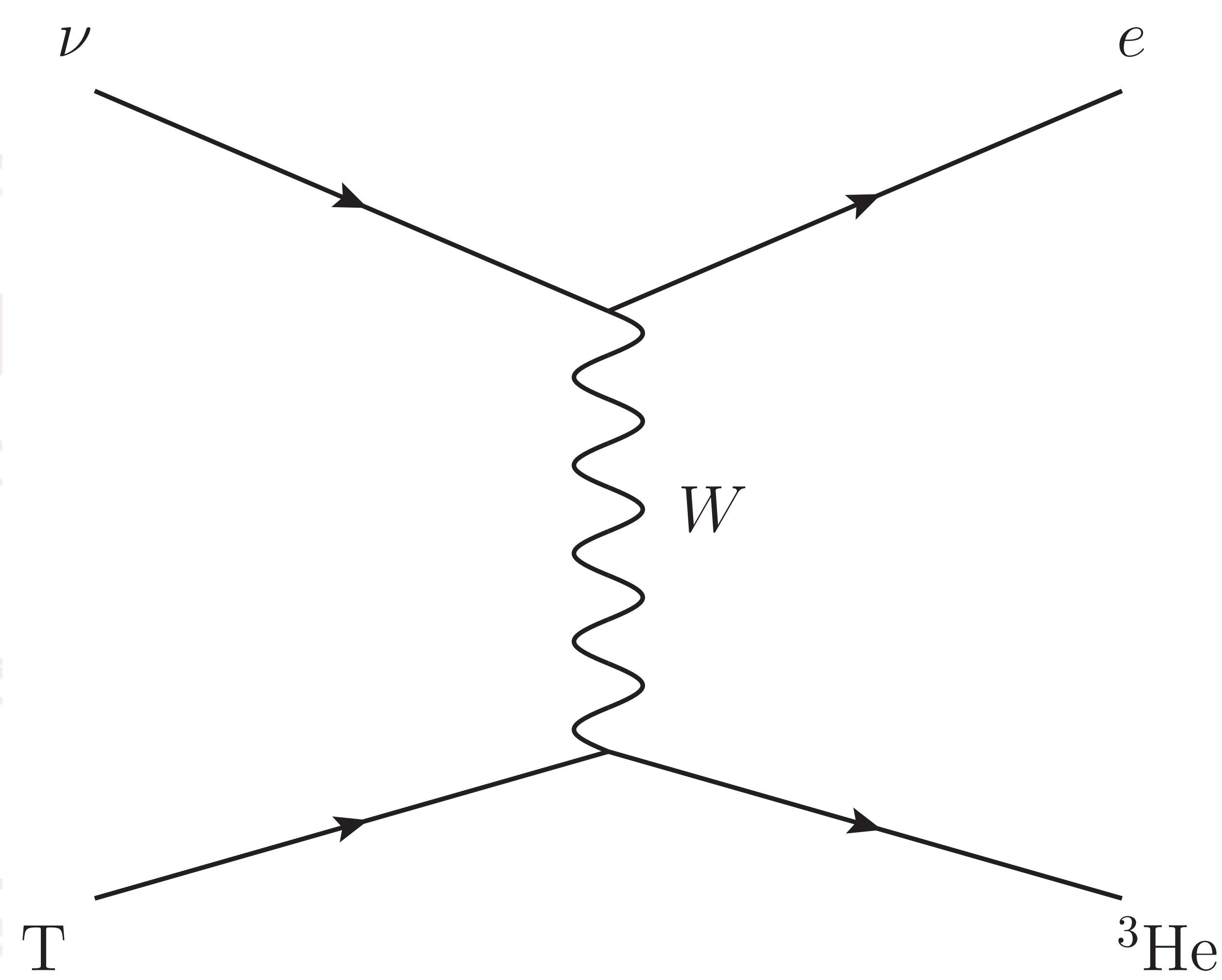
Figure 3: *Left:* Contours showing 1σ and 2σ exclusions in the α-β plane for the two redshift bins z_1 and z_3, both from the BAO data alone and after imposing a CMB prior on α. *Right:* One-dimensional likelihood of β without (blue) and with (red) the α-prior for the combined redshift bins. The dashed line is the result after marginalizing over the lensing amplitude A_L.

[Baumann, Beutler, Flauger, Green, Slosar, Vargas-Magaña, Wallisch, Yèche '18 (Nature Physics '19)]

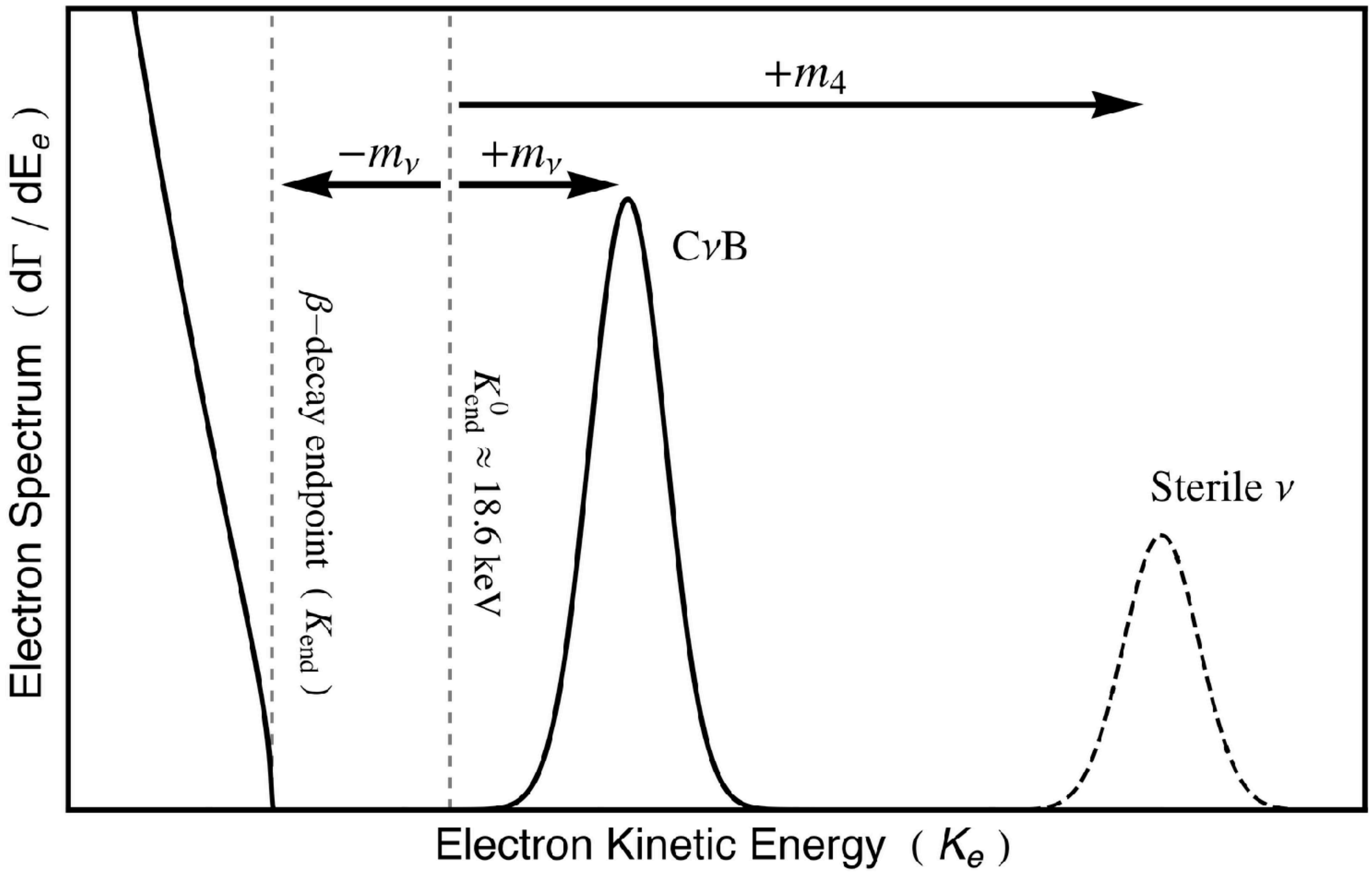
Inverse Beta Decay

- Lots of Neutrinos around
- Radioactive nuclei, e.g. tritium
- Wait for a neutrino capture
- Goes back to Weinberg

[Weinberg '62]



Energy Spectrum



[Long, Lunardini, Sabancilar ’14]

Numbers

[PTOLEMY '13;
Long, Lunardini, Sabancilar '14]

- Number of tritium target nuclei: 2 x 10^{25} (100 g)
- Rate for Dirac particles (no right-helical neutrinos today):

$$\Gamma^{\mathrm{D}}_{\mathrm{CNB}} = \bar{\sigma}\, c\, n_0\, N_T \approx 4.06 \ \mathrm{yr}^{-1}$$

- Rate for Majorana particles (both helicities equally present):

$$\Gamma^{\mathrm{M}}_{\mathrm{CNB}} = 2\,\Gamma^{\mathrm{D}}_{\mathrm{CNB}} \approx 8.12 \ \mathrm{yr}^{-1}$$

- Background rate within 0.1 eV of endpoint: 2 Hz

Current Status

[PTOLEMY '18]

PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

E. Baracchini[3], M.G. Betti[11], M. Biasotti[5], A. Boscá[16], F. Calle[16], J. Carabe-Lopez[14], G. Cavoto[10,11], C. Chang[22,23], A.G. Cocco[7], A.P. Colijn[13], J. Conrad[18], N. D'Ambrosio[2], P.F. de Salas[17], M. Faverzani[6], A. Ferella[18], E. Ferri[6], P. Garcia-Abia[14], G. Garcia Gomez-Tejedor[15], S. Gariazzo[17], F. Gatti[5], C. Gentile[25], A. Giachero[6], J. Gudmundsson[18], Y. Hochberg[1], Y. Kahn[26], M. Lisanti[26], C. Mancini-Terracciano[10], G. Mangano[7], L.E. Marcucci[9], C. Mariani[11], J. Martínez[16], G. Mazzitelli[4], M. Messina[20], A. Molinero-Vela[14], E. Monticone[12], A. Nucciotti[6], F. Pandolfi[10], S. Pastor[17], J. Pedrós[16], C. Pérez de los Heros[19], O. Pisanti[7,8], A. Polosa[10,11], A. Puiu[6], M. Rajteri[12], R. Santorelli[14], K. Schaeffner[3], C.G. Tully[26], Y. Raitses[25], N. Rossi[10], F. Zhao[26], K.M. Zurek[21,22]

Submitted to the LNGS Scientific Committee on March 19$^{\text{th}}$, 2018

Abstract

We propose to achieve the proof-of-principle of the PTOLEMY project to directly detect the Cosmic Neutrino Background (CNB). Each of the technological challenges described in [1, 2] will be targeted and hopefully solved by the use of the latest experimental developments and profiting from the low background environment provided by the LNGS underground site. The

Didn't we already find it?

- In 2018 >95% confidence from BAO+CMB data
- Already in 2015 strong evidence from CMB:

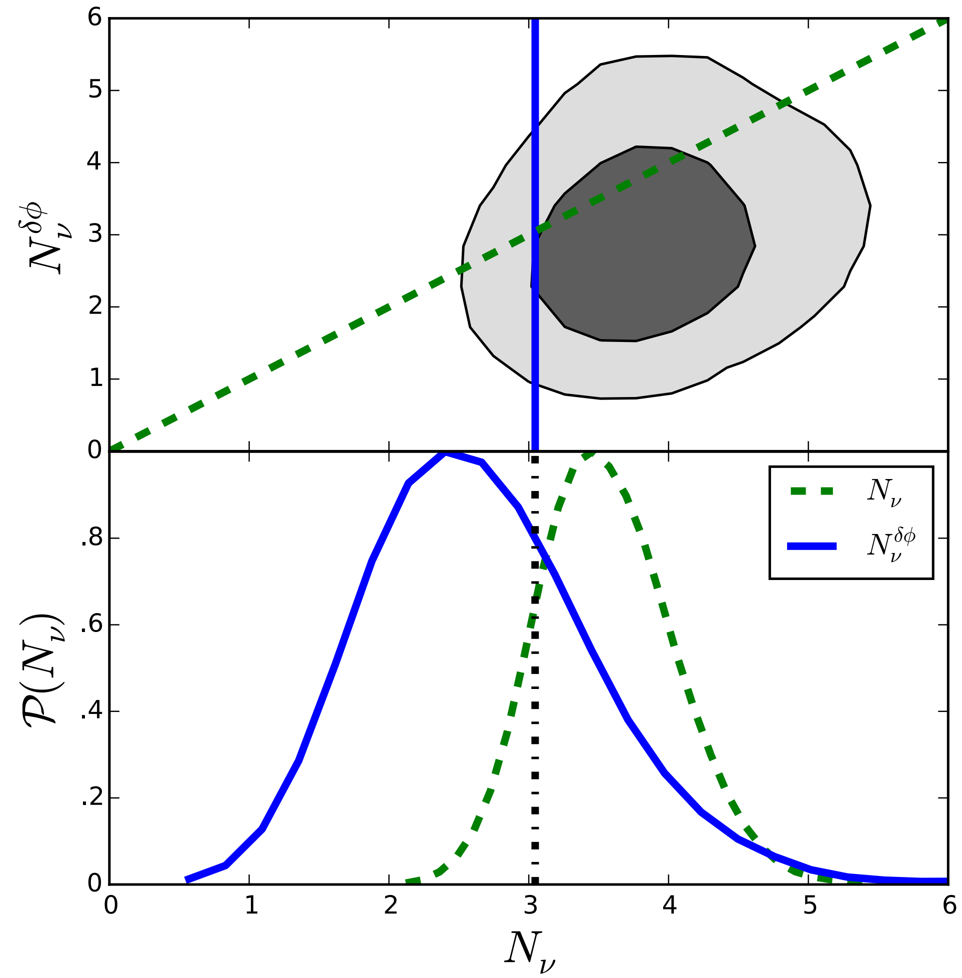


FIG. 3: **Top**: 2D constraints on the jointly varying ΛCDM+N_ν+$N_\nu^{\delta\phi}$ parameter space. The constraints on N_ν (damping) and $N_\nu^{\delta\phi}$ (phase shift) are essentially orthogonal. **Bottom**: Constraints from March 2013 *Planck* temperature power spectrum measurements on the number of neutrino species from (1) *blue/solid:* varying $N_\nu^{\delta\phi}$ while holding N_ν fixed at three and (2) *green/dashed:* varying along the physical direction $N_\nu = N_\nu^{\delta\phi}$. The constraints assume a Gaussian τ prior of mean $\mu = 0.085$ and width $\sigma = 0.015$.

[Follin, Knox, Millea, Pan '15]

Theory: Magnetic Torque

[Domcke, MS ’17; see also Duda *et al.* '01, ..., Stodolsky '75]

- Neutrino background splits electron energy levels (spin effect → magnetic effect)

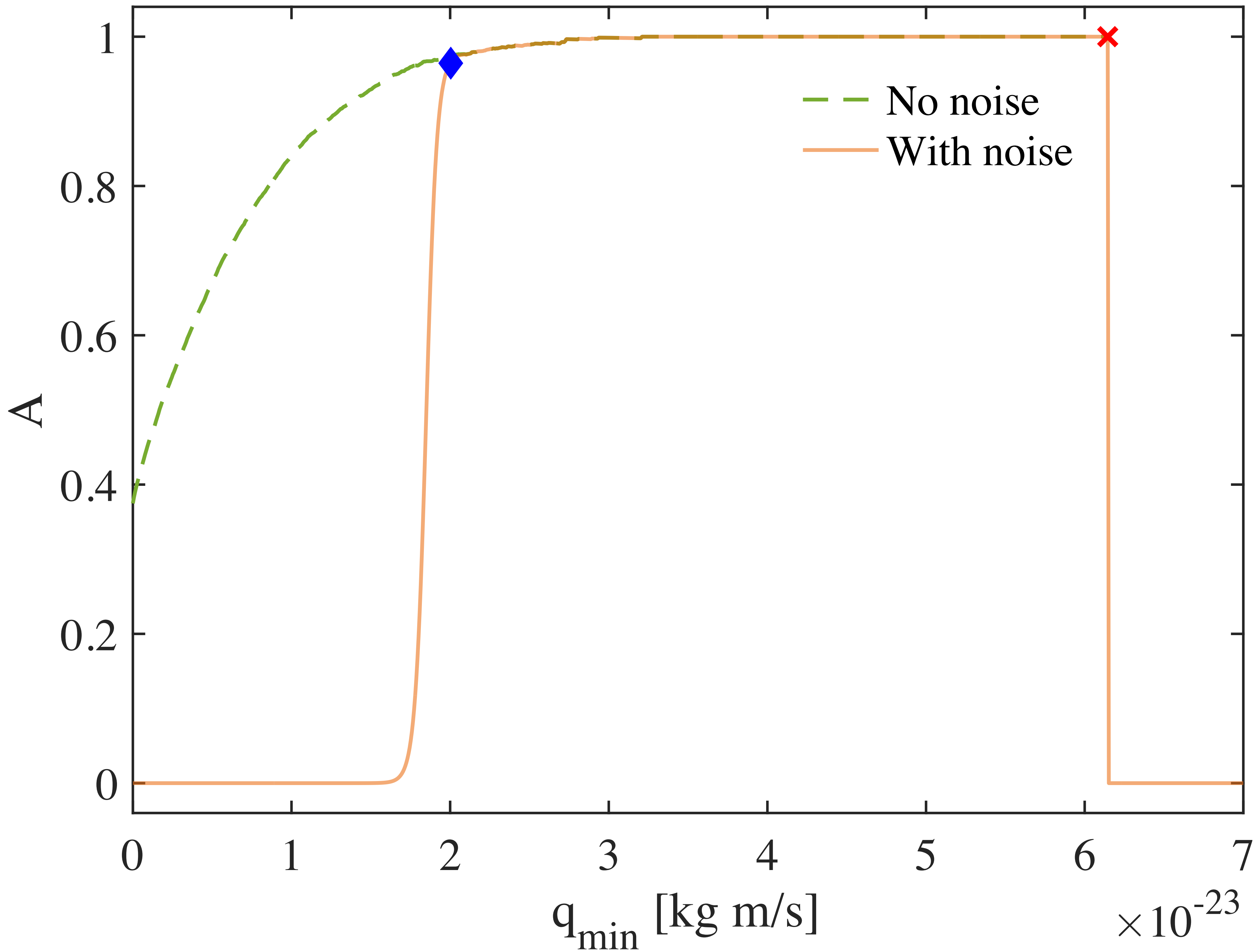
$$a^R_{G_F} = \frac{N_{AV}}{A\, m_{AV}} \frac{2\sqrt{2}}{\pi} G_F\, \beta_\oplus^{\mathrm{CMB}} \frac{\gamma}{R} \sum_{\alpha=e,\mu,\tau} (n_{\nu_\alpha} - n_{\bar{\nu}_\alpha})\, g_A^\alpha$$

- For one flavour

$$a^R_{G_F} \approx 4 \cdot 10^{-29} \frac{n_{\bar{\nu}_\mu} - n_{\nu_\mu}}{2\, \bar{n}_\nu} \,\mathrm{cm/s}^2$$

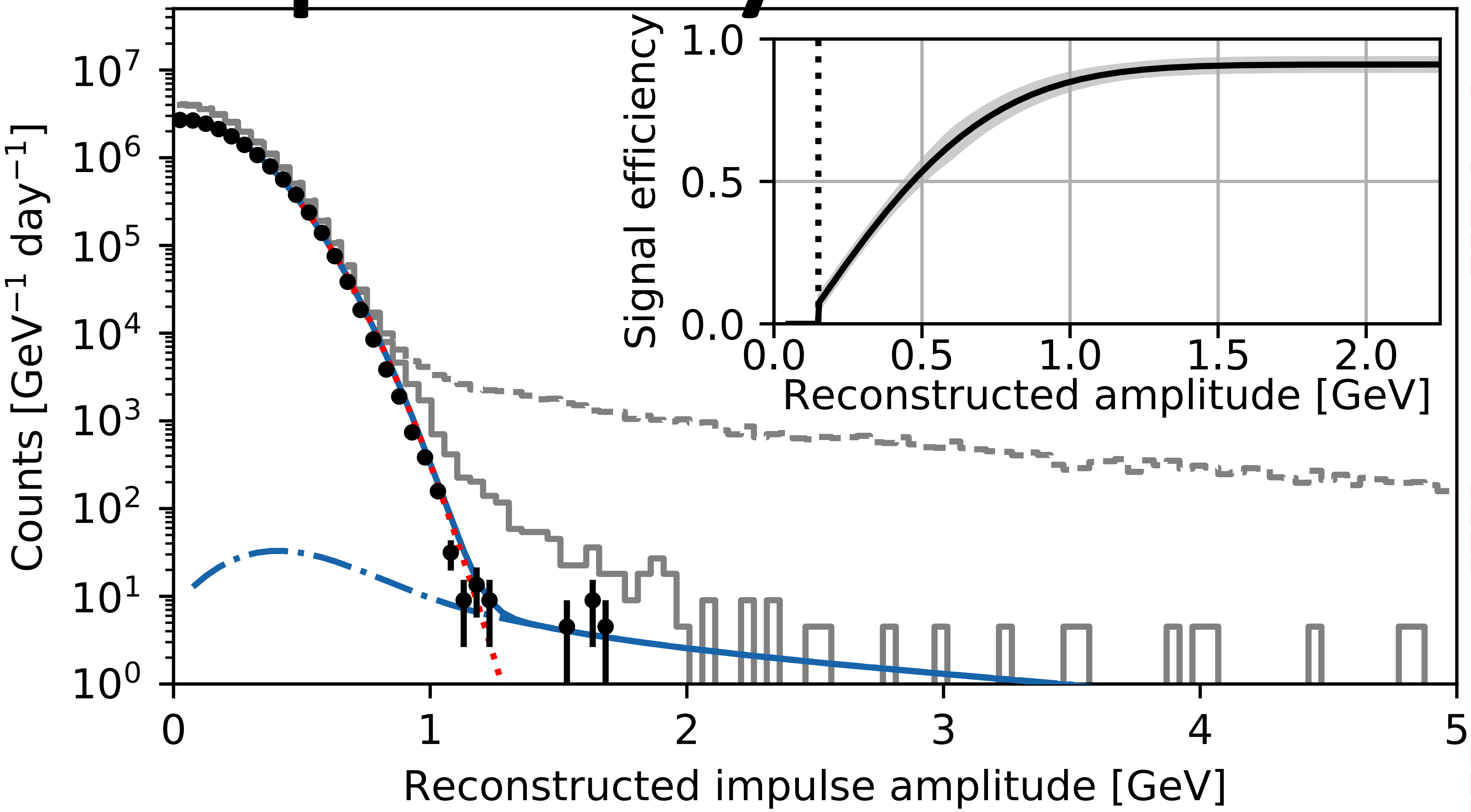
- Caveats:
  - Experimentally difficult (magnetic effect)
  - Needs lepton asymmetry

Dependence of A on q_{min}



[Cheng, Primulando, MS '19]

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).