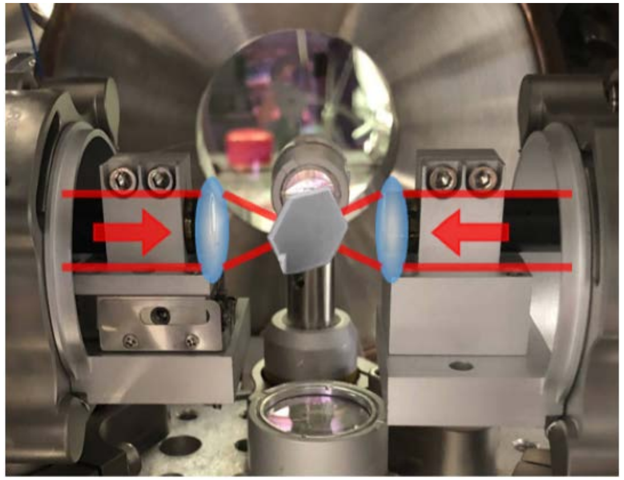
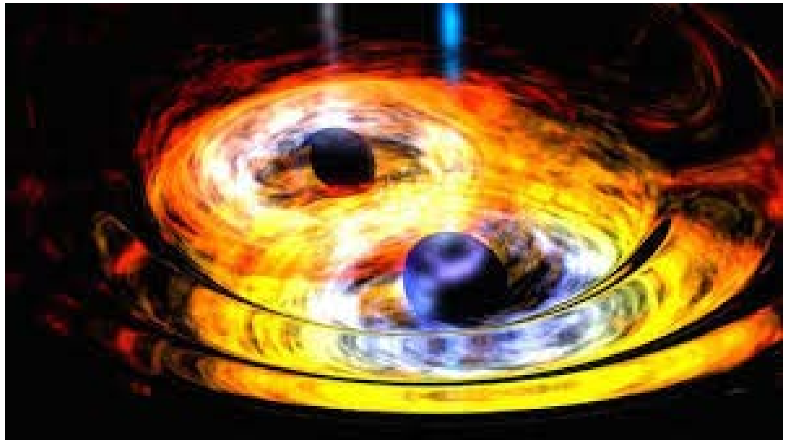
The Levitated Sensor Detector for high-frequency gravitational wave detection





A. Geraci, Northwestern University

Center for Fundamental Physics (CFP)

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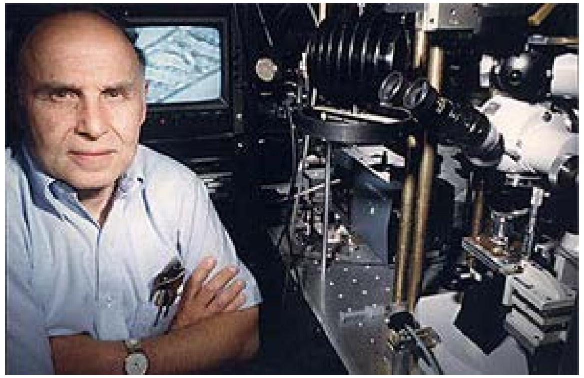
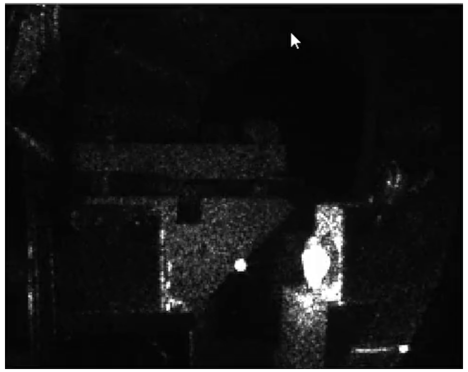
Ultra high-frequency gravitational waves: where to next? CERN Dec. 4-8, 2023

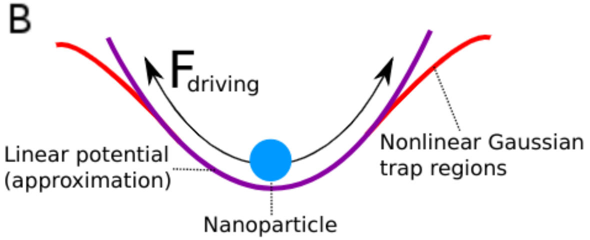
Northwestern University · NSF · Heising-Simons Foundation · Office of Naval Research Science & Technology · W.M. Keck Foundation · John Templeton Foundation · Department of Energy United States of America

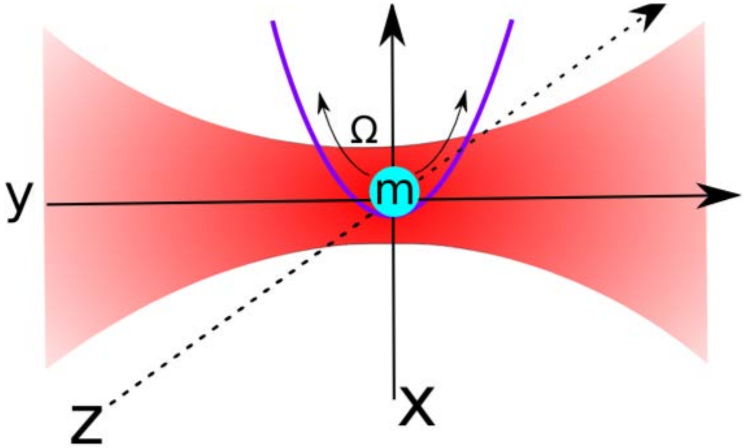
Levitated optomechanics - brief introduction

- Ashkin, Bell Labs, 1970s   Optical tweezers → biology, biophysics
- Ashkin (76) Levitation in high vacuum









1. Polarisable neutral glass particles act as high field seekers - trapped in laser focus
2. When particle is approximately spherical, acts as 3 decoupled harmonic oscillators.
3. Characteristic length scale 10’s nanometers to 10’s microns.
4. High Q factors ~ 10^12 → excellent force sensors
5. Can reduce the effective motional ‘temperature’ of such objects through feedback schemes

(Ground) state of the art:

Dynamical backaction:

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REPORT

Cooling of a levitated nanoparticle to the motional quantum ground state

Uroš Delić[1,2,*], Manuel Reisenbauer[1], Kahan Dare[1,2], David Grass[1,†], Vladan Vuletić[3], Nikolai Kiesel[1], ...
+ See all authors and affiliations

Science 21 Feb 2020:
Vol. 367, Issue 6480, pp. 892-895
DOI: 10.1126/science.aba3993

Article   Figures & Data   Info & Metrics   eLetters   PDF

A nanoparticle trapped and cooled

Cooling massive particles to the quantum ground state allows fundamental tests of quantum mechanics to be made; it would provide an experimental probe of the boundary between the classical and quantum worlds. Delić *et al.* laser-cooled an optically trapped solid-state object (a ~150-nanometer-diameter silic a nanoparticle) into its quantum ground state of motion starting from room temperature. Because the object is levitated using optical forces, the experimental configuration can be switched to free fall, thereby providing a test bed for several macroscopic quantum experiments.

Science, this issue p. 892

Measurement based cooling:

nature

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Article | Published: 14 July 2021

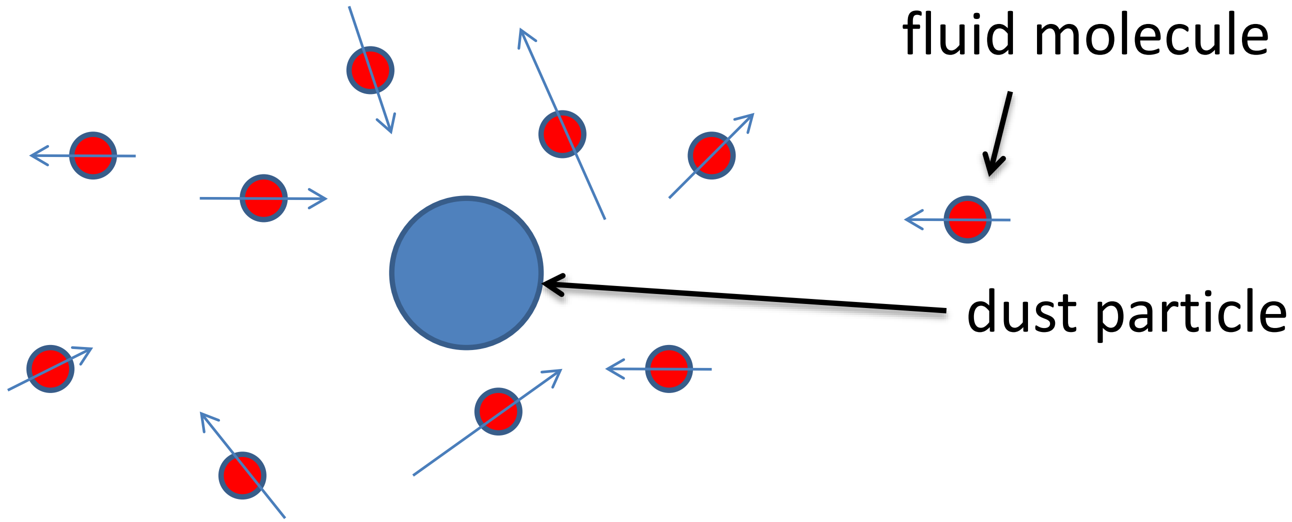
Quantum control of a nanoparticle optically levitated in cryogenic free space

Felix Tebbenjohanns, M. Luisa Mattana, Massimiliano Rossi, Martin Frimmer & Lukas Novotny

Nature **595**, 378–382 (2021) | Cite this article

Fundamental limitation: thermal noise

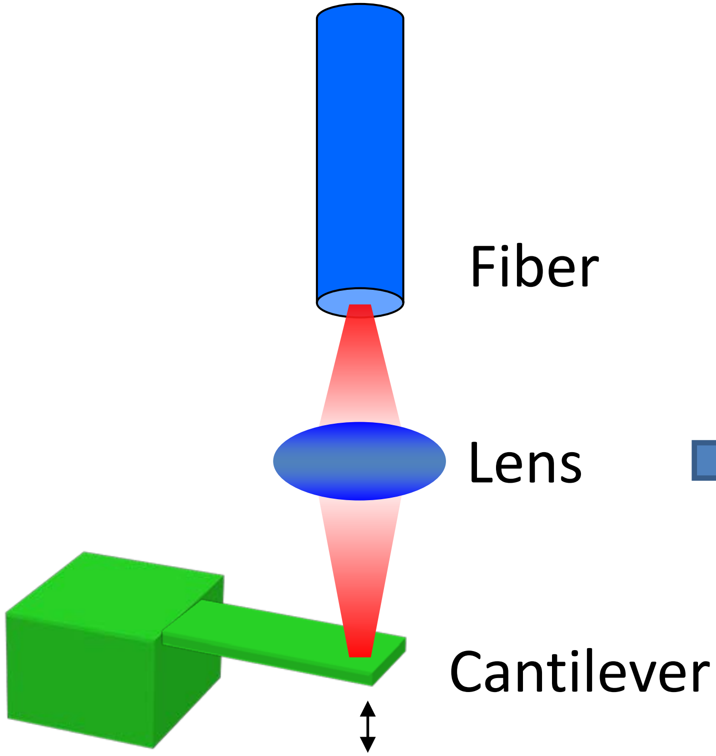
Brownian motion – random “kicks” given to particle due to thermal bath



- Random “kicks” are given to sensor due to finite T of oscillator

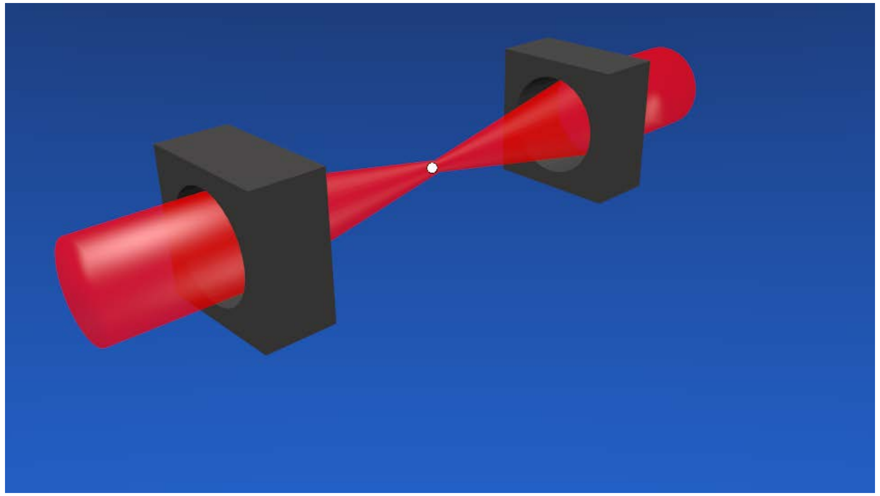
$$\frac{1}{2}k\langle x^2\rangle = \frac{1}{2}k_B T \quad \Rightarrow \quad F_{min} = \left(\frac{4kk_B Tb}{Q\omega_0}\right)^{1/2}$$

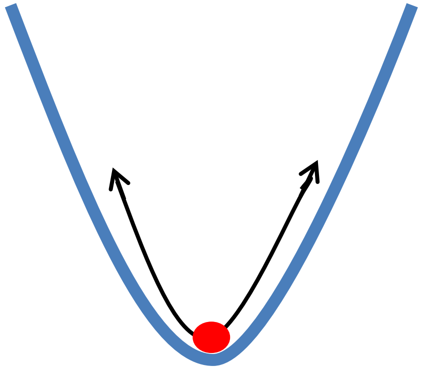
Improving sensitivity



Limitations on Q: Clamping, surface imperfections, internal materials losses

Levitate the force sensor!





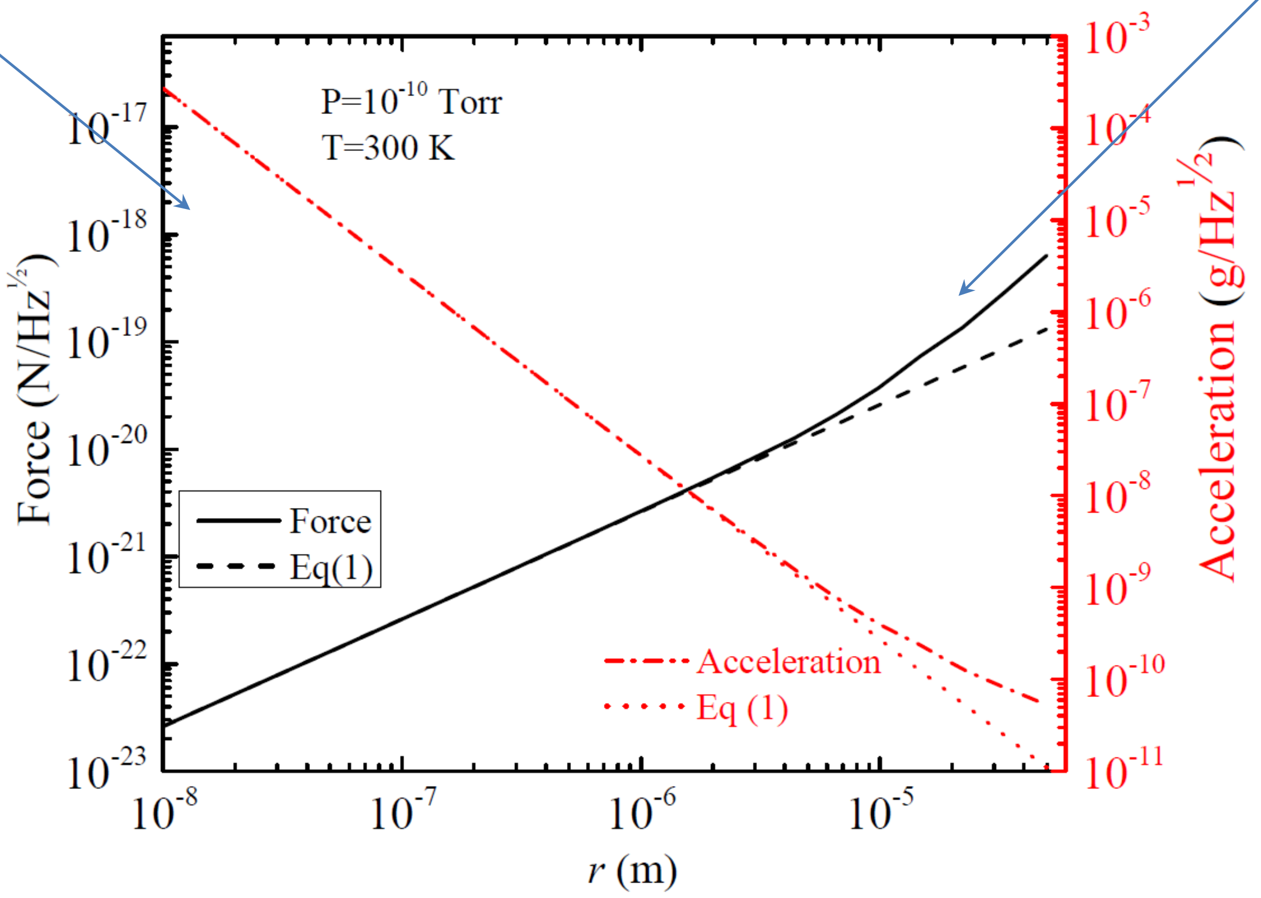
CM motion decoupled from environment – no clamping, materials losses

Projected Force sensivity

$$F_{\min} = (4k_B T \gamma m)^{1/2} \quad (1)$$

Cantilever sensors

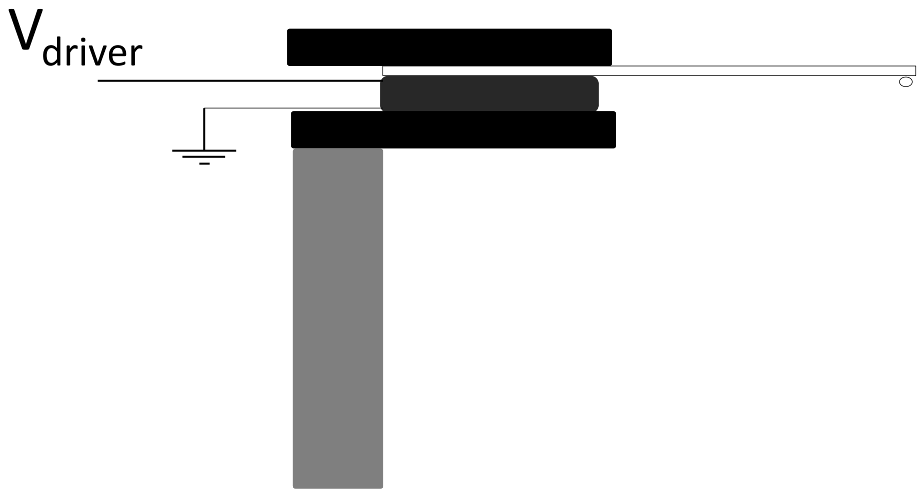
Photon recoil heating
Seen recently by
Novotny group
V. Jain et. al.,
PRL 116, 243601
(2016)

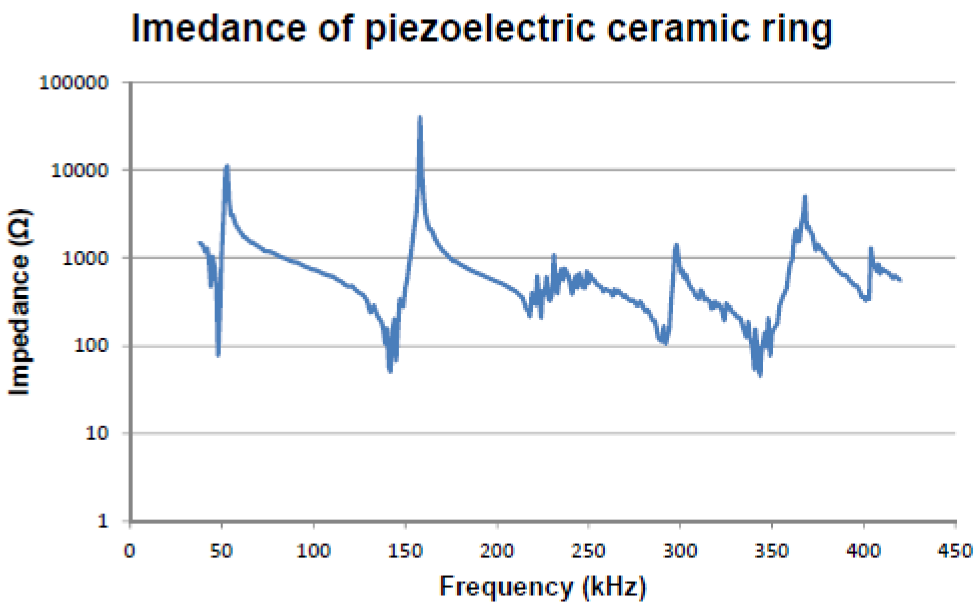


20 zN/Hz$^{1/2}$ Gieseler, Novotny, Quidant (Nature Phys. 2013)

Z. Yin, A. Geraci, T. Li, Int. J. Mod. Phys. B 27,1330018 (2013).

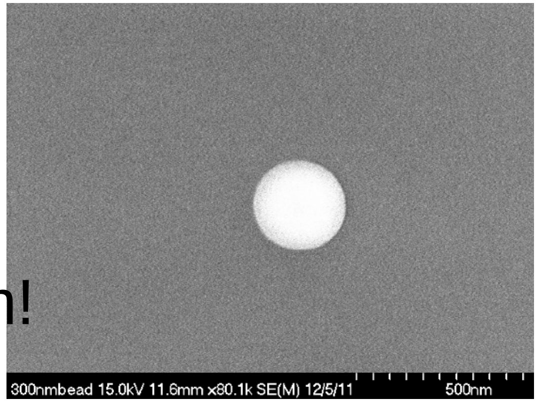
Trap loading

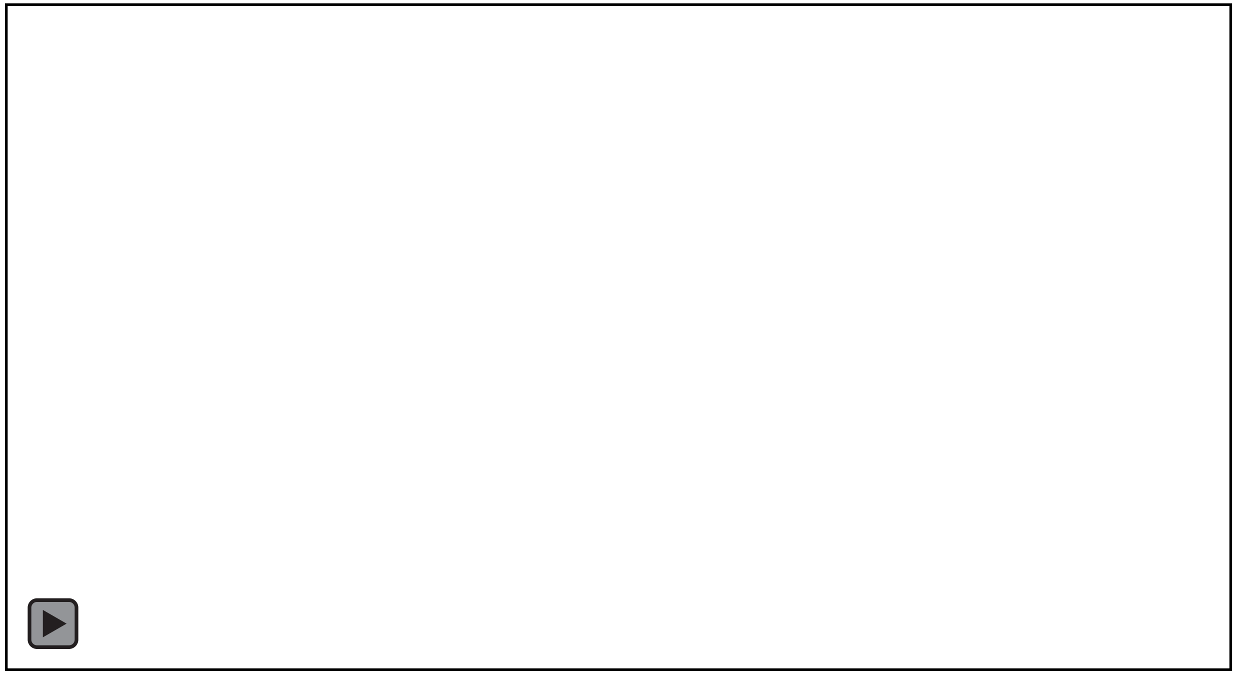




$$a \propto \frac{1}{R^2}$$

~10^7 g for R=150nm!





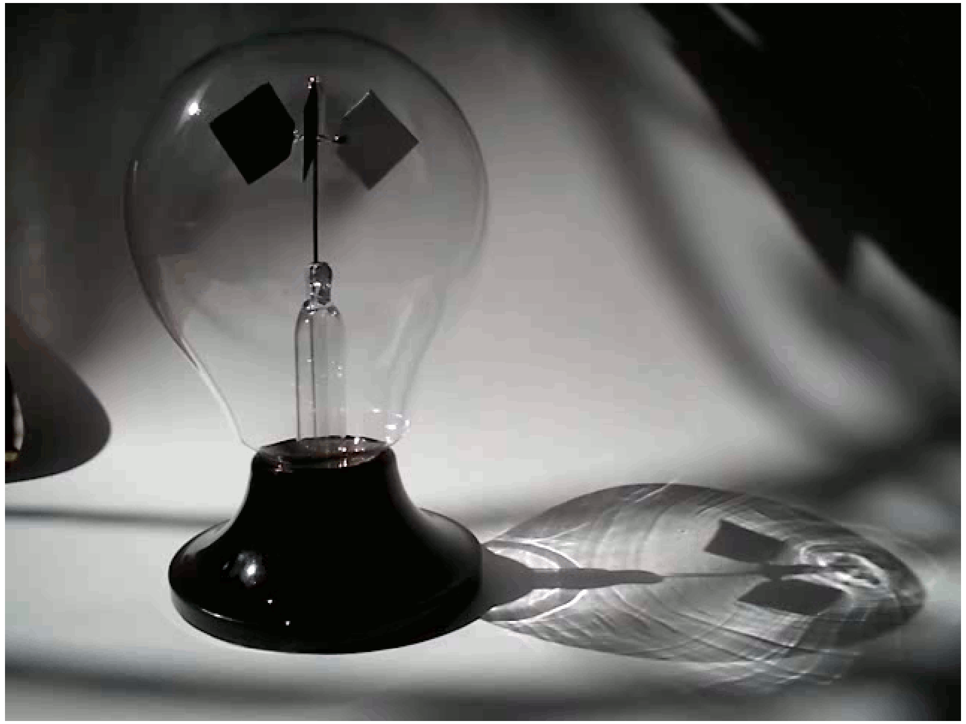
Weisman etl.al, Review of Scientific Instruments **93**, 115115 (2022)

Trapping instabilities

- **Radiometric forces**

Trap instabilities arise from uneven heating of the sphere surface

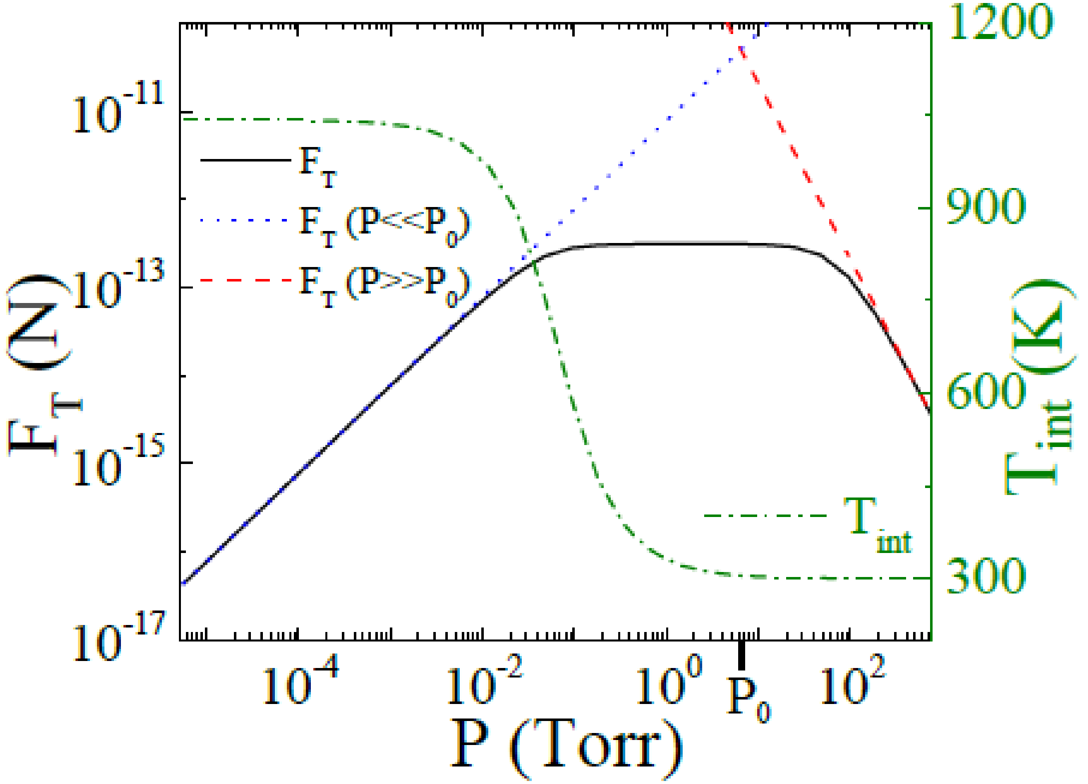
Important when mean free path ~ object size

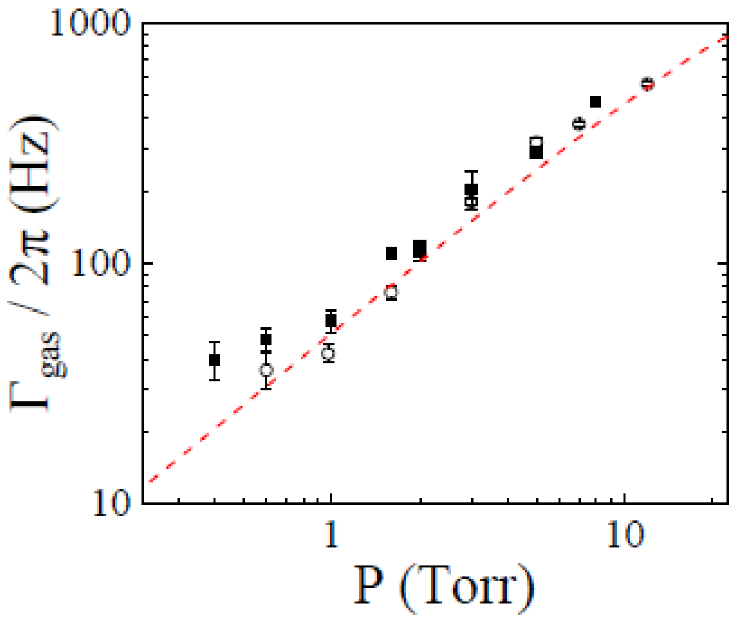


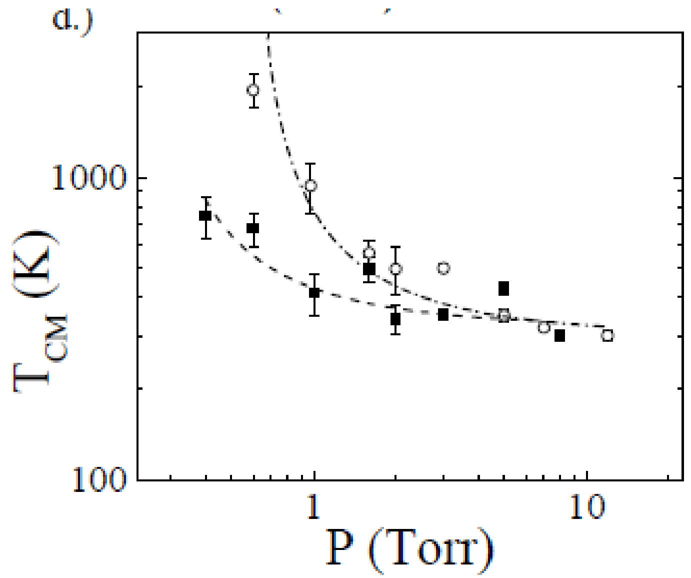
Crooke's Radiometer

Radiometric forces

$$F_T = -\frac{\pi r^2 \eta \sqrt{\frac{\alpha R_g}{MT}}\Gamma_i}{\frac{P}{P_0} + \frac{P_0}{P}}$$







1% temp gradient across surface

R=1.5 μm, I=2 x 10^9 W/m^2

Ranjit et.al., PRA 91, 051805(R) (2015).

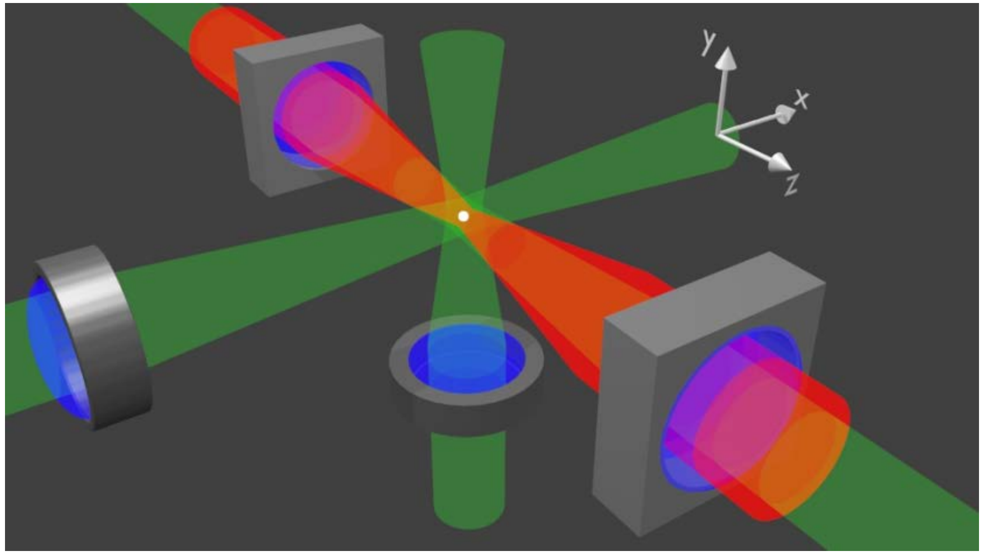
Heating rate > gas damping rate

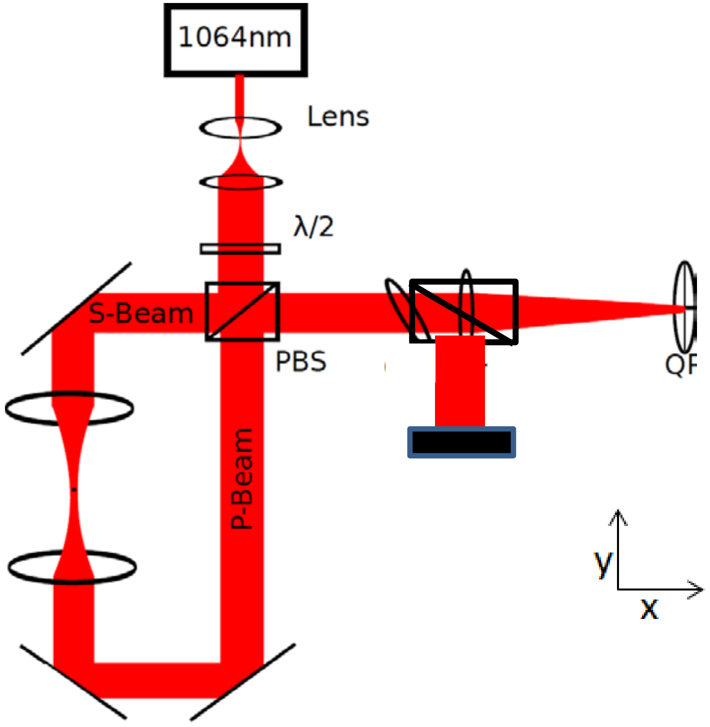
→ Particle loss → Need feedback!

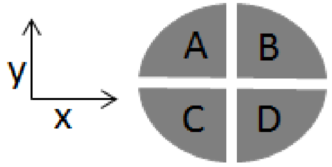
3D feedback cooling of a nanosphere

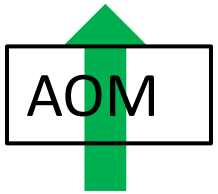
Needed to stabilize the particle, damp and cool it

Mitigate photon recoil heating

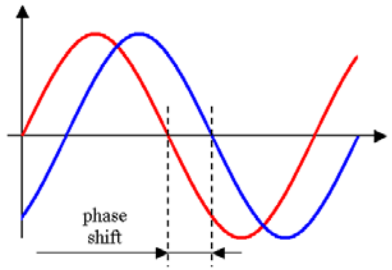








780 nm



$x(t)$

$v_x(t)$

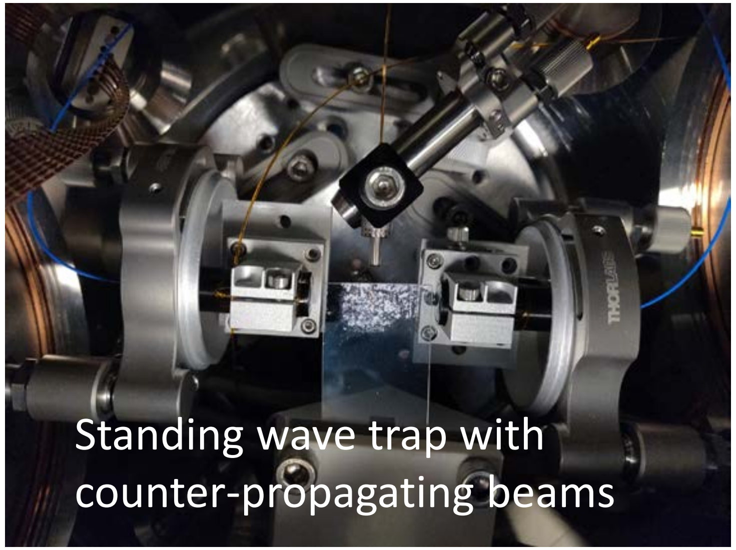
$$F_{\min} = \sqrt{\frac{4kK_B TB}{\omega_0 Q}}$$

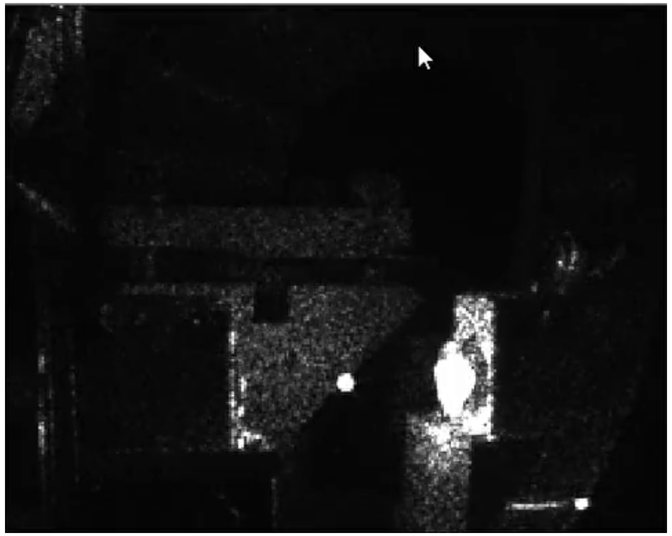
$$Q_{eff} = \frac{Q_0 \Gamma_0}{\Gamma_0 + \Gamma_{cool}}$$

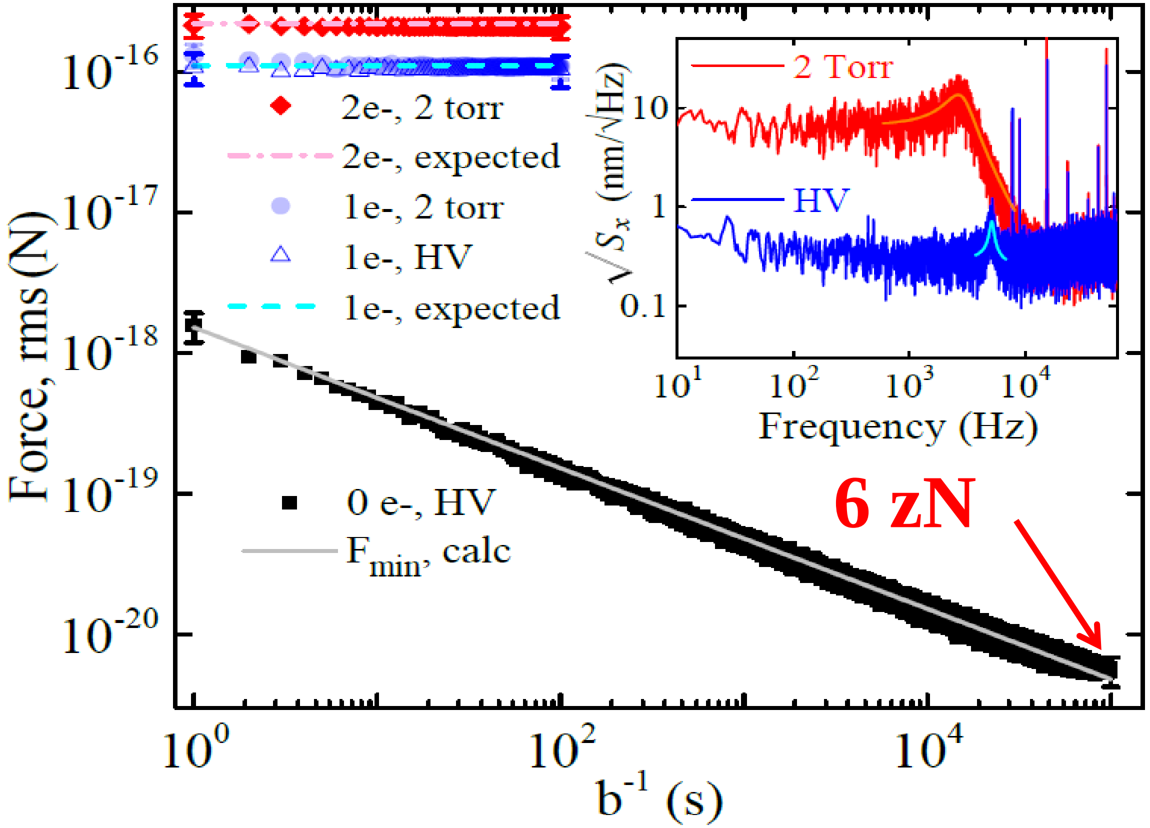
$$T_{eff} = \frac{T_0 \Gamma_0}{\Gamma_0 + \Gamma_{cool}}$$

Ranjit et.al., PRA 91, 051805(R) (2015).

Calibrated zN force sensitivity



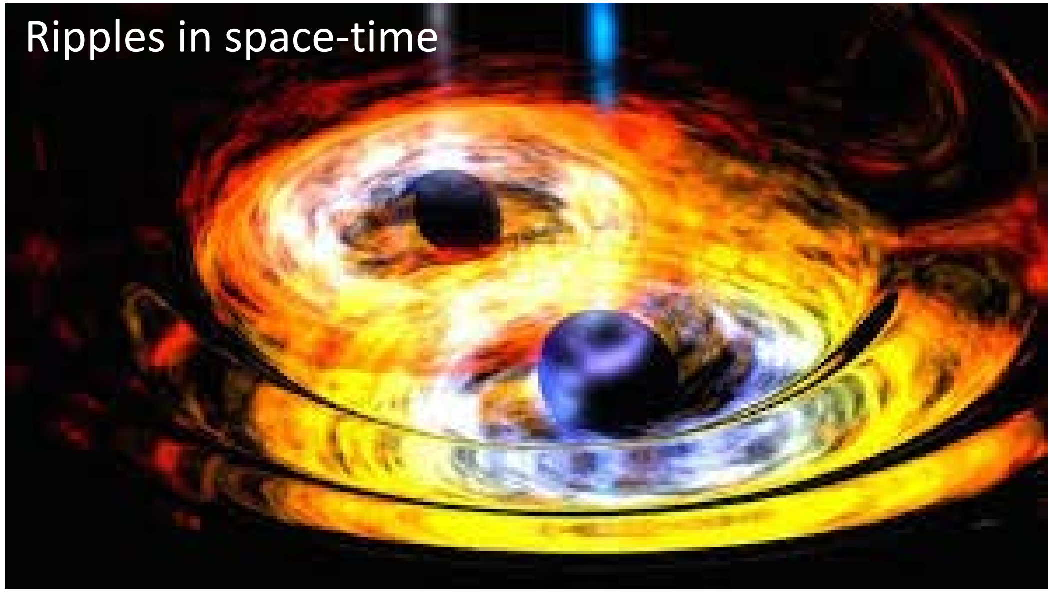




zeptonewton sensitivity in a standing wave trap w/ 3-D laser feedback cooling –

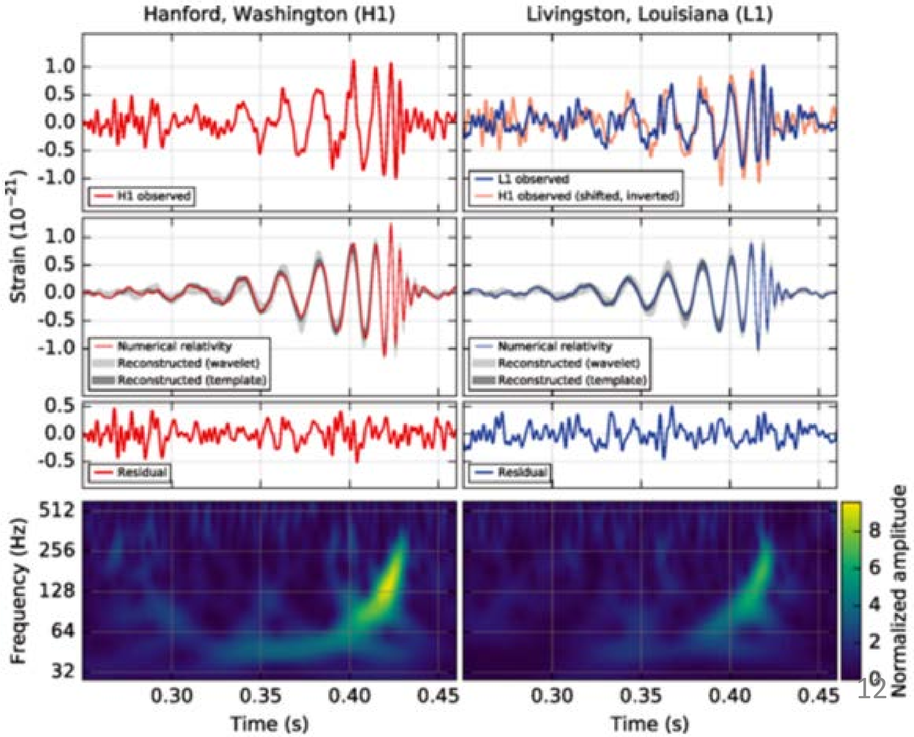
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016)

Gravitational waves



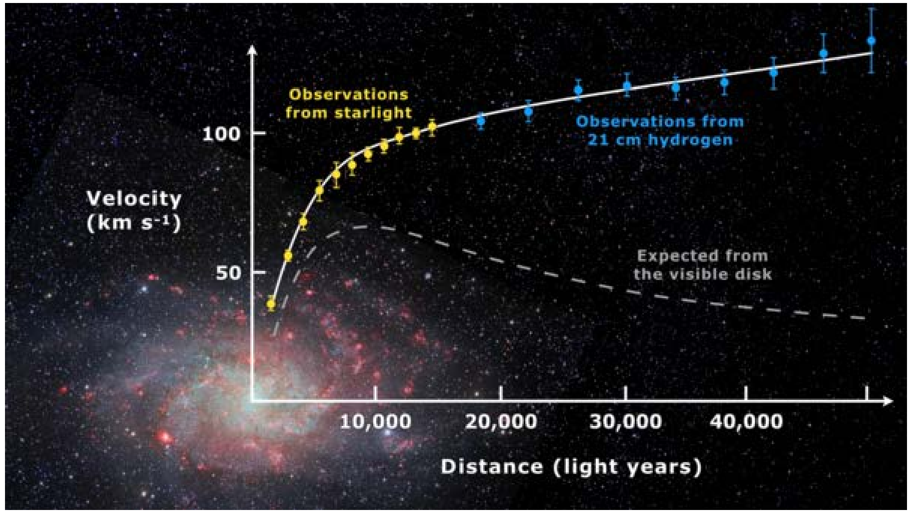
- One of last predictions of GR to be tested
- Discovered by LIGO Sep 2015 !!
- Sources:
  - Inspirals of astrophysical objects
  - Inflation, Phase transitions, etc.

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102 (2016).



Dark Matter

- Zwicky detected its influence on cluster motions in the mid-1930s, Rubin detected it in galaxy rotation curves in the 1960s
- Its nature and origin is one of the most vexing problems in physics and astronomy
- One of strongest hints of physics beyond the Standard Model



Galactic Rotation Curves: much more gravity than from ordinary matter

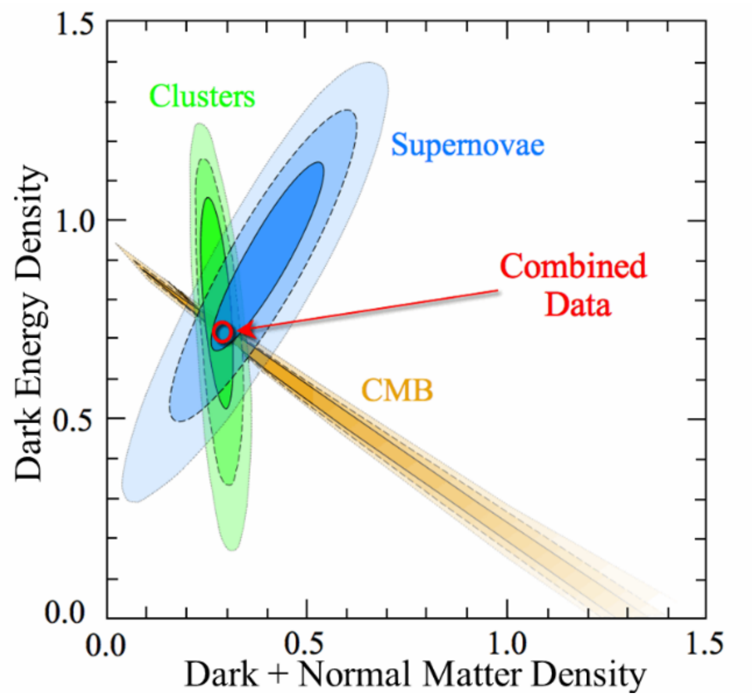
Gravitational Lensing: "Bullet" cluster – separation of lensing from visible matter

Also: Structure formation, Cosmic Microwave background, …

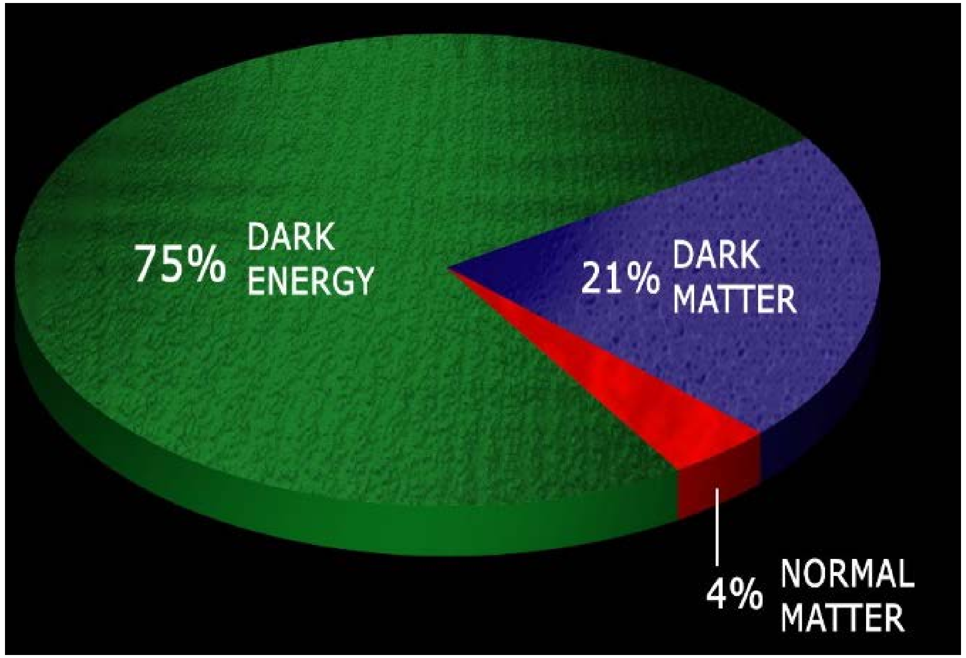
Corbelli, E.; Salucci, P. (2000), *Monthly Notices of the Royal Astronomical Society*. **311** (2): 441–447

The Dark Sector

- New particles, fields, and forces may be lurking undetected because of their extremely weak coupling to ordinary matter
- ~95% of the energy content of our universe is unknown to us!

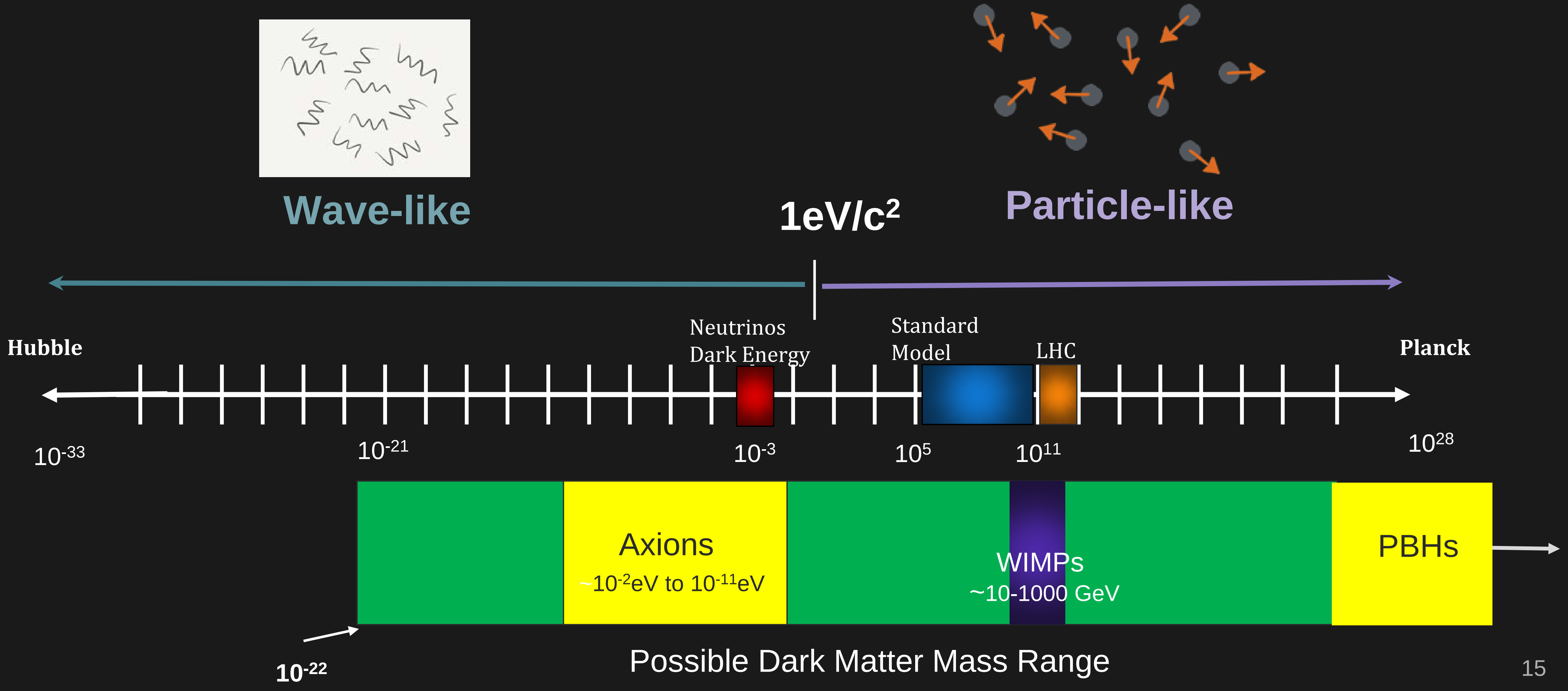


Evidence supporting a universe of dark matter and energy. Image: Kowalski *et al,* Astrophys. J. **686,** 794 (2008).



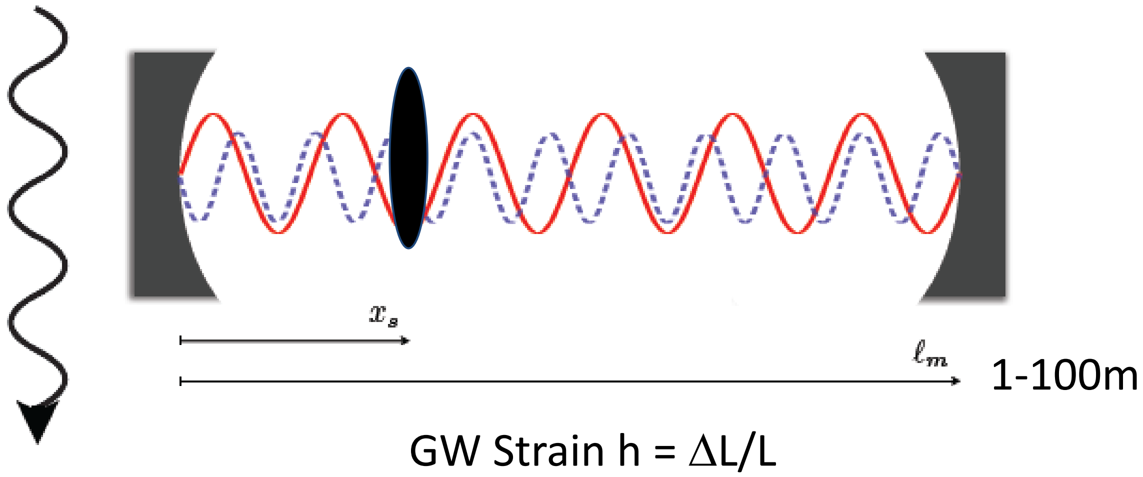
Our best estimate for composition of universe. Image credit: ADMX

Dark Matter



Possible Dark Matter Mass Range

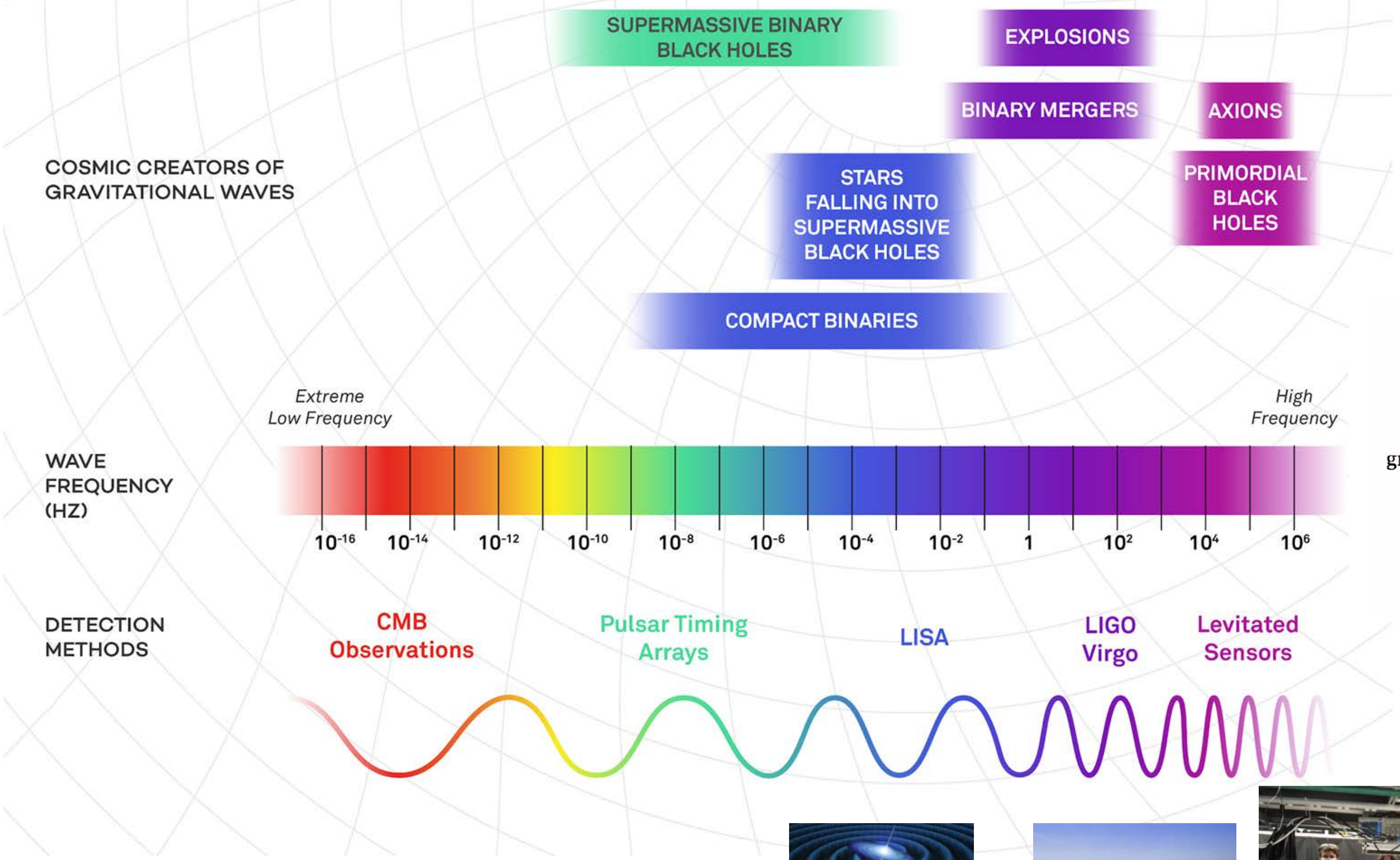
Novel gravitational wave detector for > 10 kHz



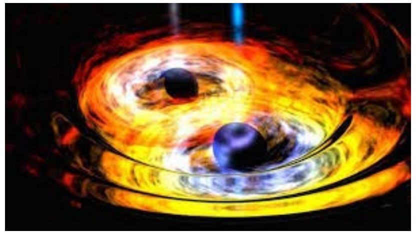
- Laser intensity changed to match trap frequency to GW frequency
- For a 10m cavity, $h \sim 10^{-22}$ Hz $^{-1/2}$ at high frequency (100kHz)
- Limited by thermal noise in sensor (not laser shot noise) → much better at high frequency!

A. Arvanitaki and AG, Phys. Rev. Lett. 110, 071105 (2013), Aggarwal et. al., Phys. Rev. Lett. **128**, 111101 (2022).

Frequency landscape for gravitational waves

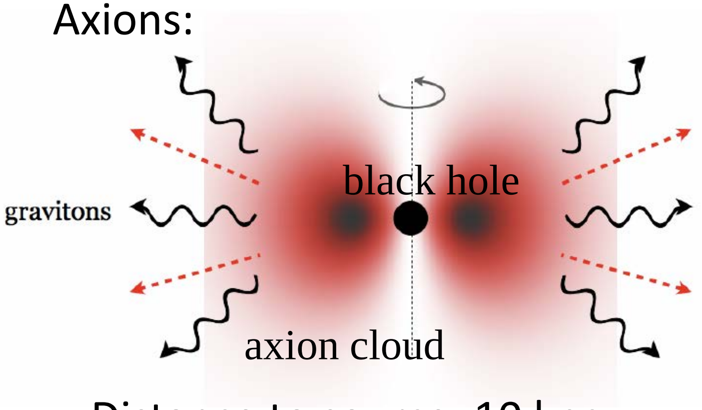


PBHs:

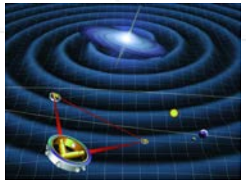


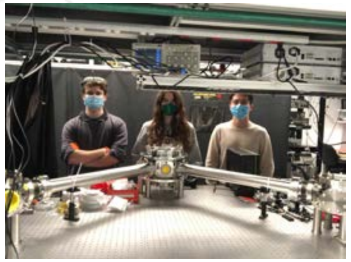
Distance to source: 1 kpc (within our galaxy)

Axions:

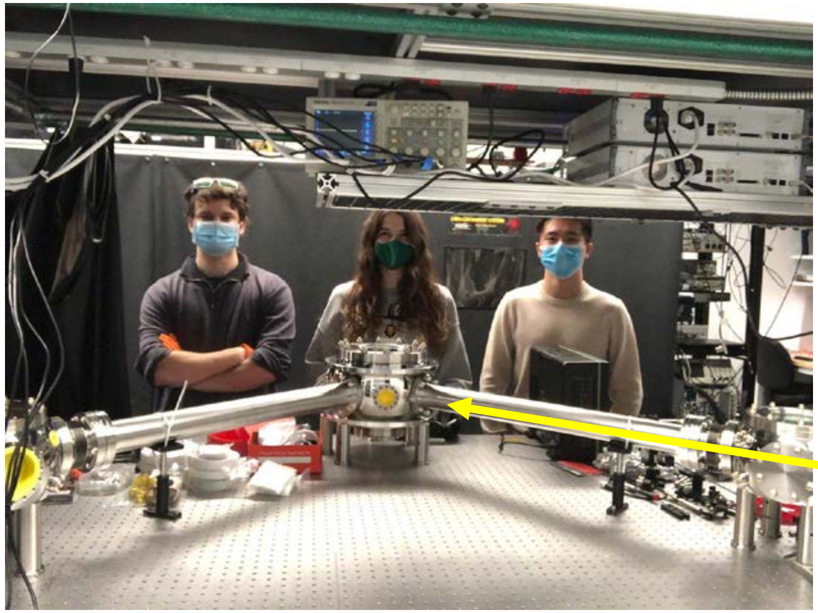


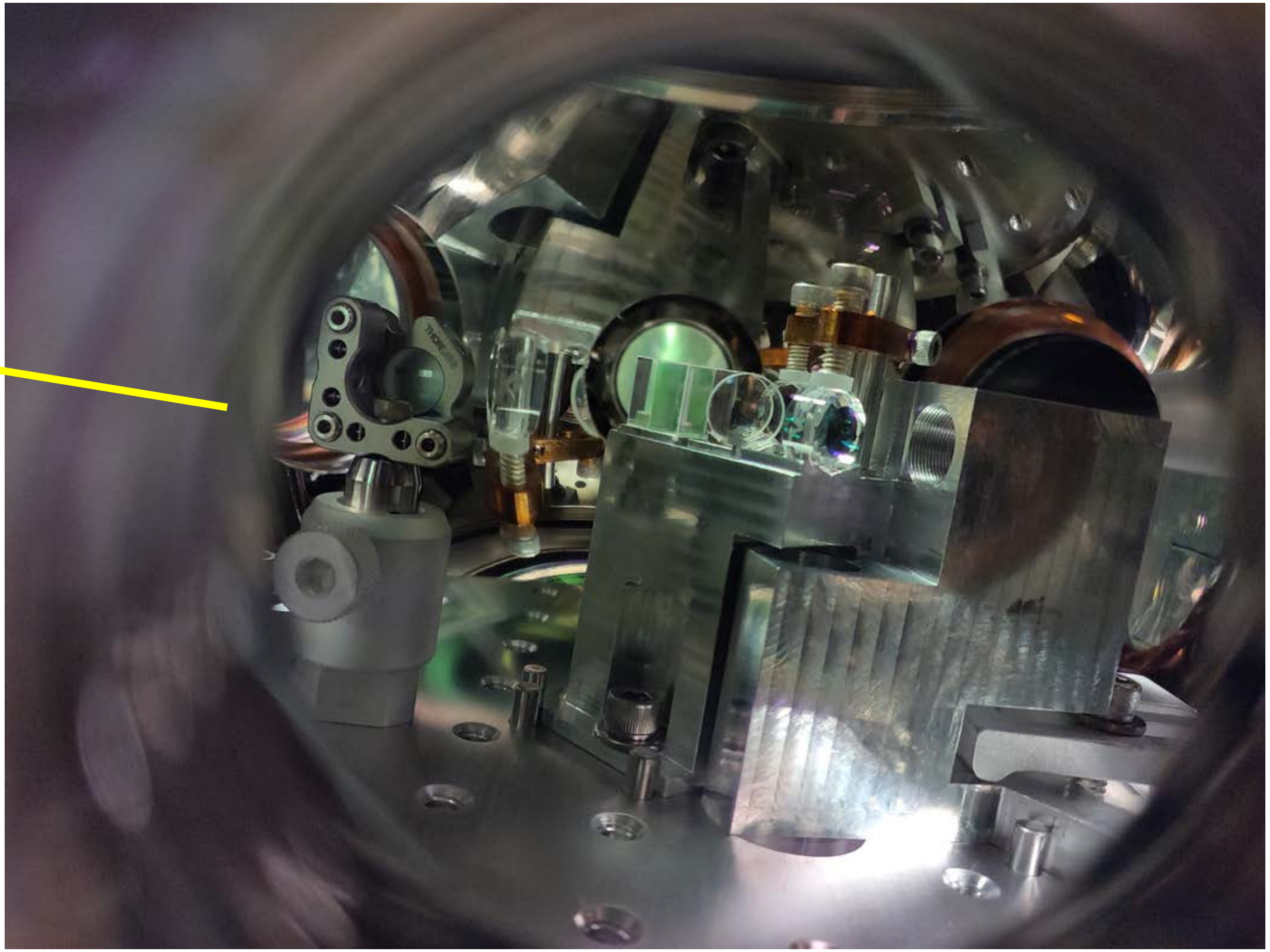
Distance to source: 10 kpc (within our galaxy)





1-meter Levitated Sensor Detector (LSD) prototype



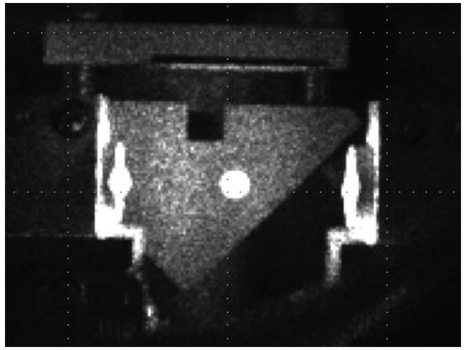


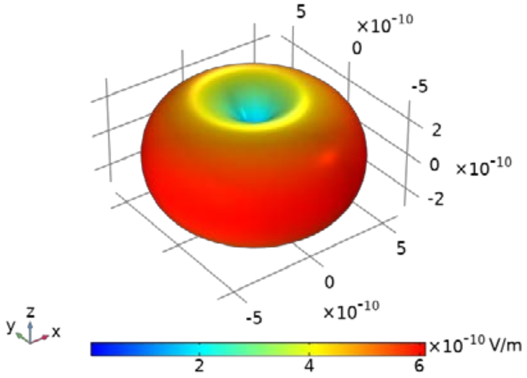
The LSD Collaboration -- Experiment: AG(PI), Nancy Aggarwal (co-I), Geroge Winstone (PD), Shelby Klomp (G), Aaron Wang (G), Peter J. Pauzauskie (UW), Greg Felsted (UW, G) Theory: Jacob Sprague (G), Shane Larson (co-I), Vicky Kalogera (co-I)

Levitated object optimization: disc/plate vs sphere

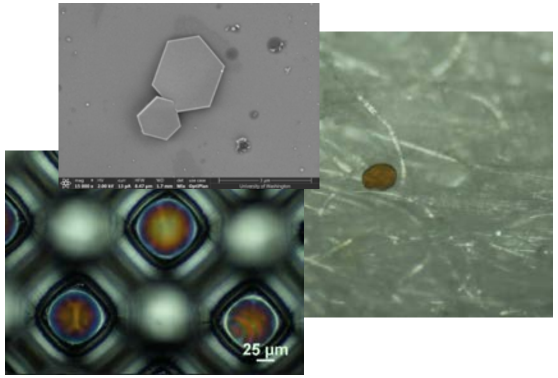
Ideal sensor: high mass, high frequency, low photon recoil

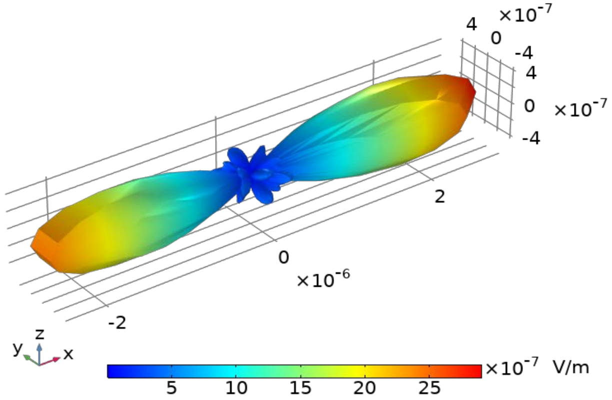
SiO2 spheres





SiO2 disks & NaYF hexagons



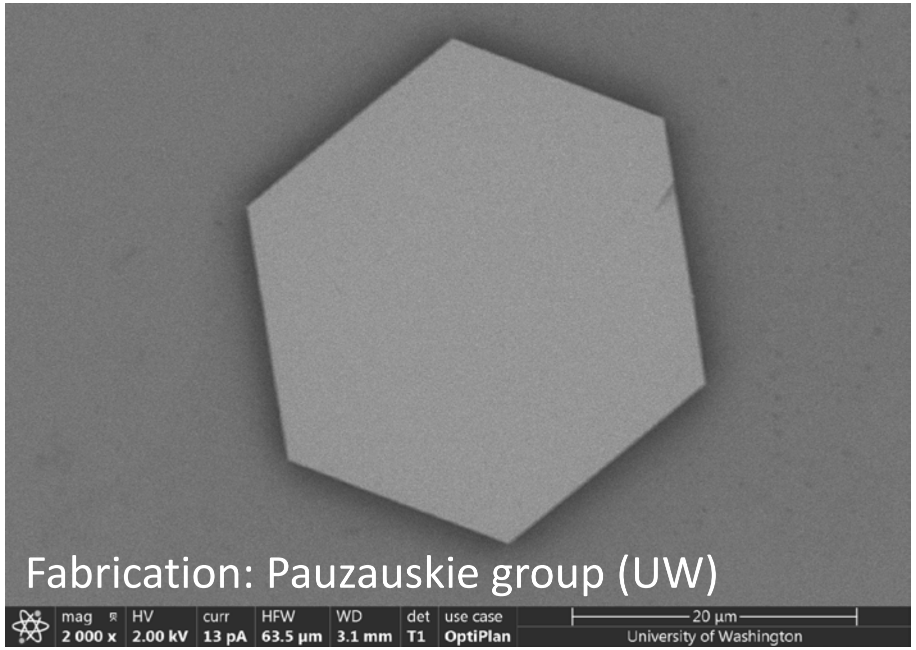


- High-index end caps with low-index spacer
- Increased mass and internal reflections

- Less isotropic scattering reduces photon recoil noise

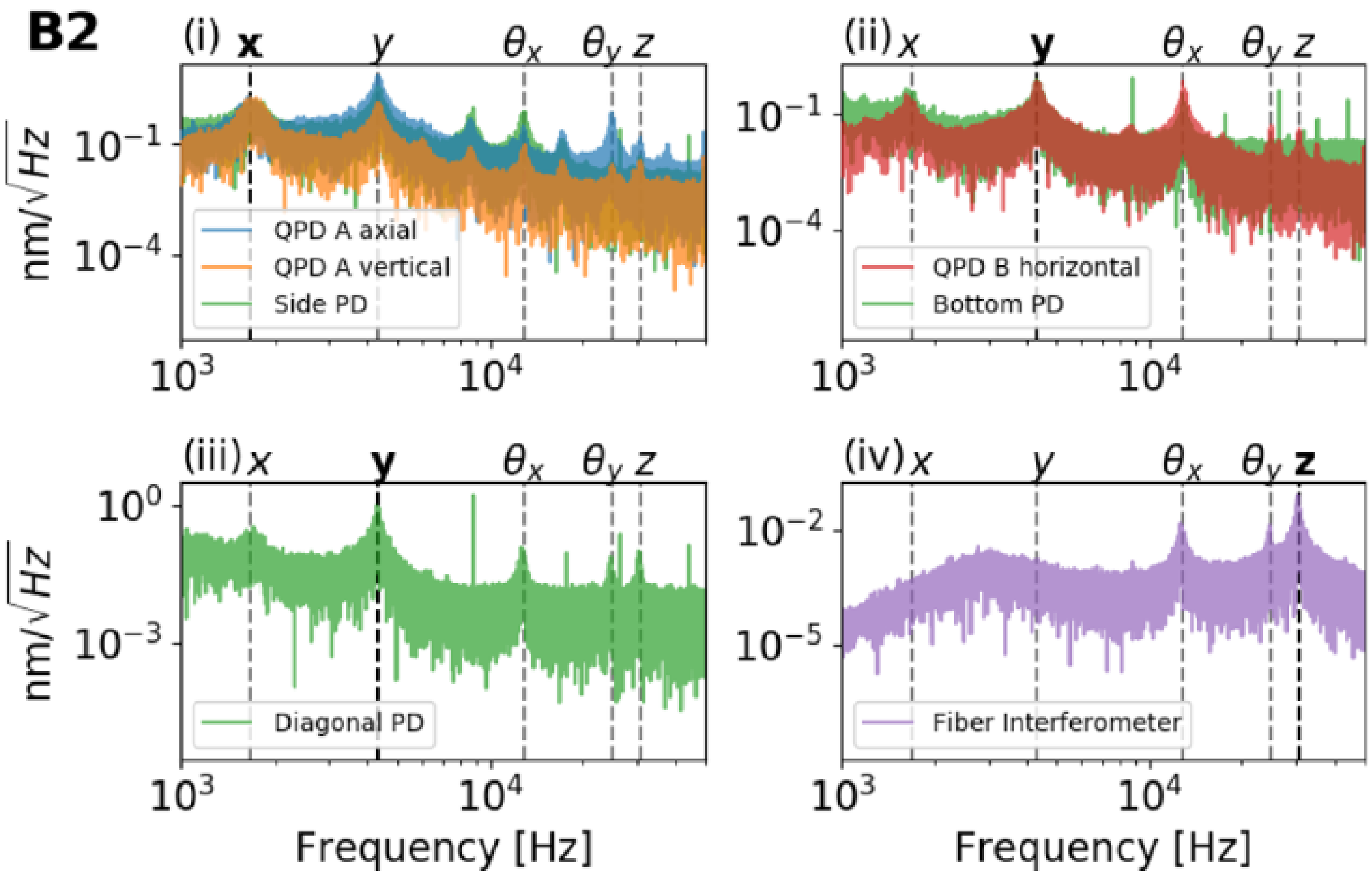
Aggarwal et. al., Phys. Rev. Lett. **128**, 111101 (2022).

Optical trapping of NaYF hexagonal prisms



Hexagonal plate "stands up" with normal vector to face along the axis of the standing wave trap

Axial frequency (z-) highest due to intensity gradient along optical lattice



G. Winstone et.al., Phys. Rev. Lett. **129**, 053604 (2022)

Figure of merit η for GW detection

$$h_{\text{limit}} = \frac{4}{\omega_0^2 L}\sqrt{\frac{k_B T_{\text{CM}}\gamma_g b}{M}\left[1+\frac{\gamma_{\text{sc}}}{N_i\gamma_g}\right]}H(\omega_0)$$

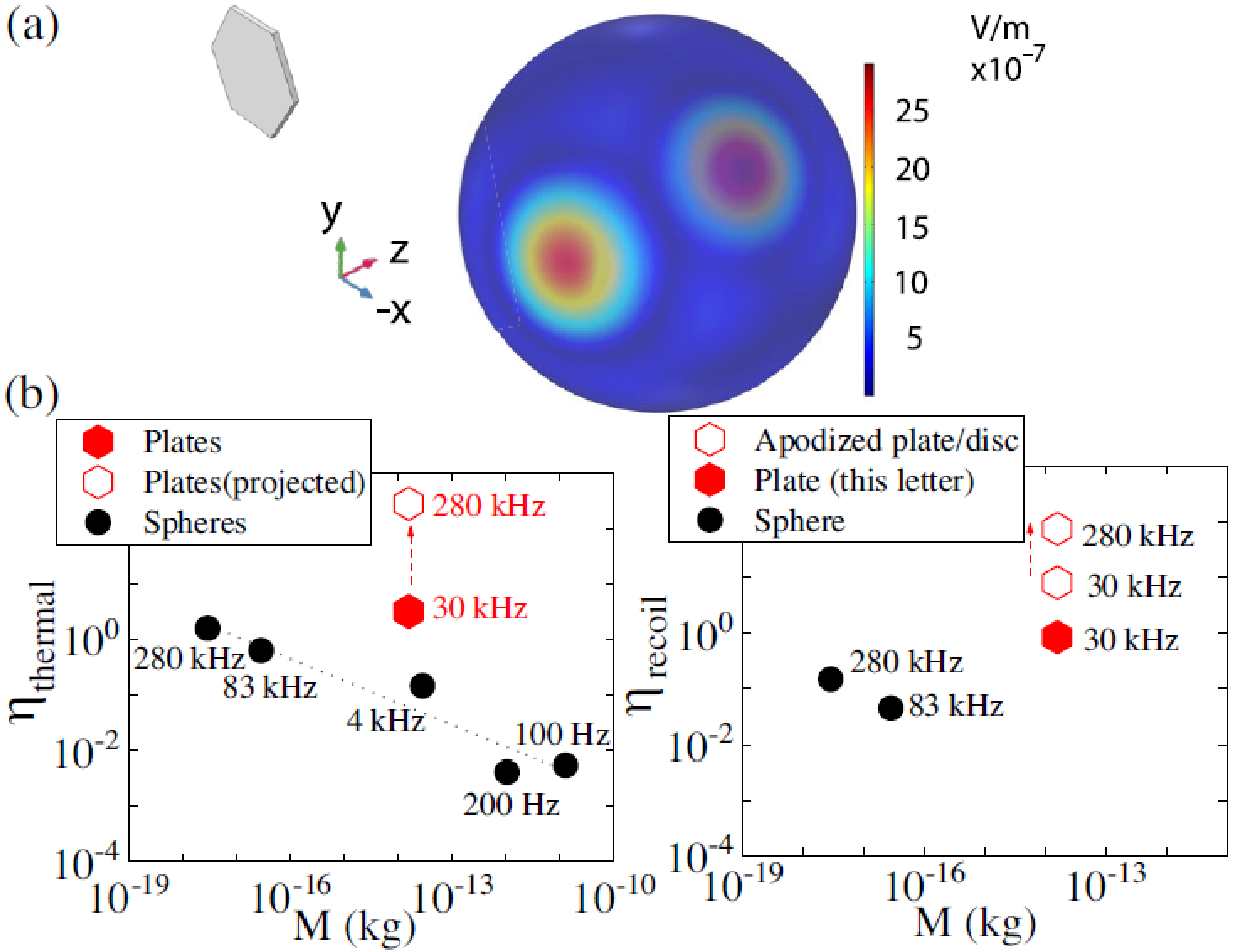
Ideal sensor: high mass, high frequency, low photon recoil

Thermal noise dominated

$$\eta_{\text{thermal}} \equiv \omega_0^2\sqrt{M\rho l}$$

Photon recoil noise dominated

$$\eta_{\text{recoil}} = \omega_0^{3/2}\sqrt{M/\gamma_{sc}}$$

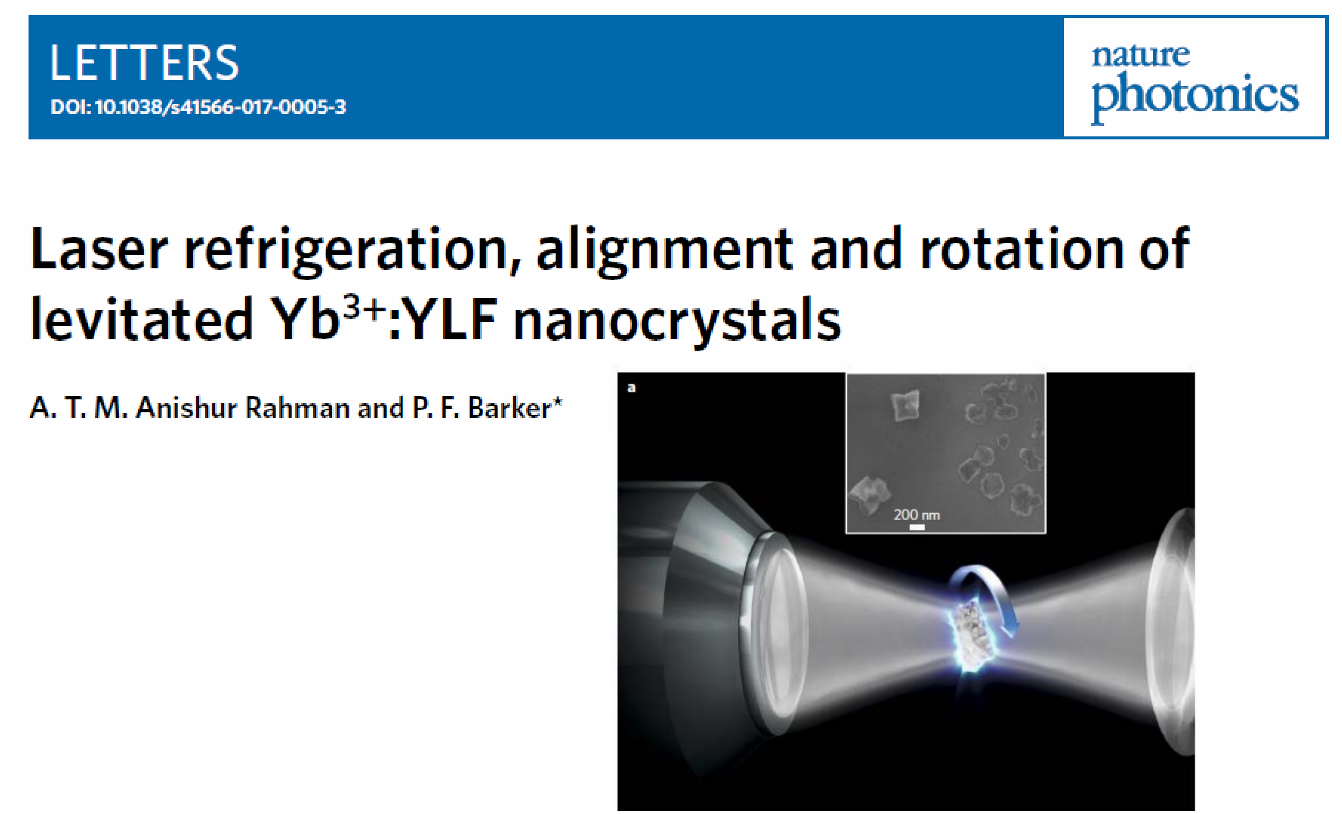


G. Winstone et.al., Phys. Rev. Lett. **129**, 053604 (2022)

Future goal: Laser refrigeration of NaYF material

- Particles could withstand higher intensities

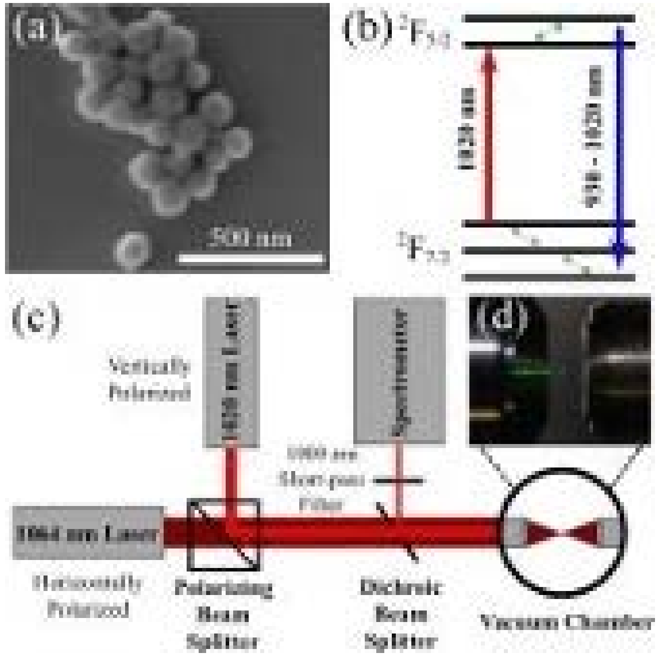
→ Pathway for MHz trapping frequencies → high bandwidth accelerometers and gravitational wave detectors


LETTERS
DOI: 10.1038/s41566-017-0005-3
nature photonics

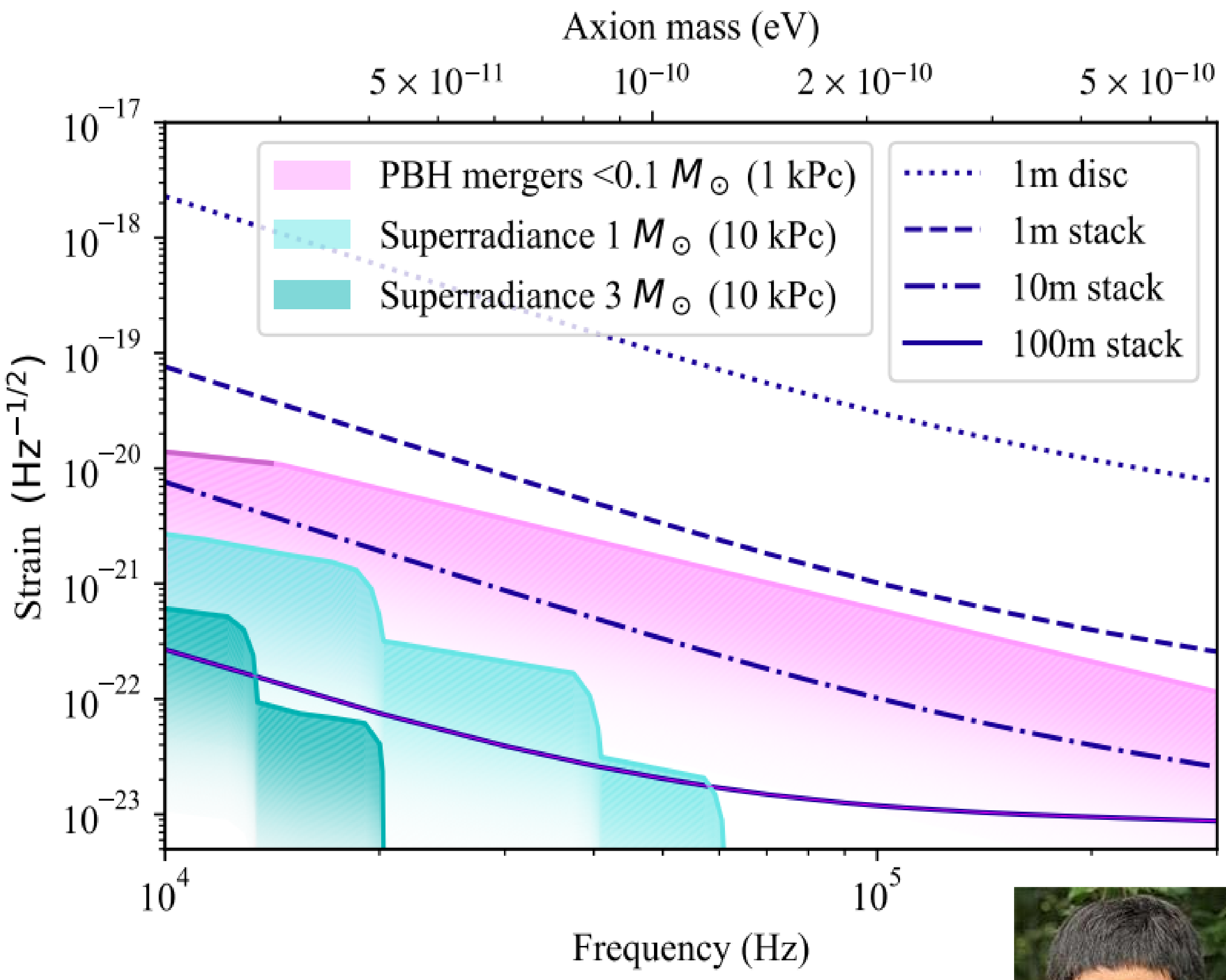
Laser refrigeration, alignment and rotation of levitated Yb^{3+}:YLF nanocrystals

A. T. M. Anishur Rahman and P. F. Barker*

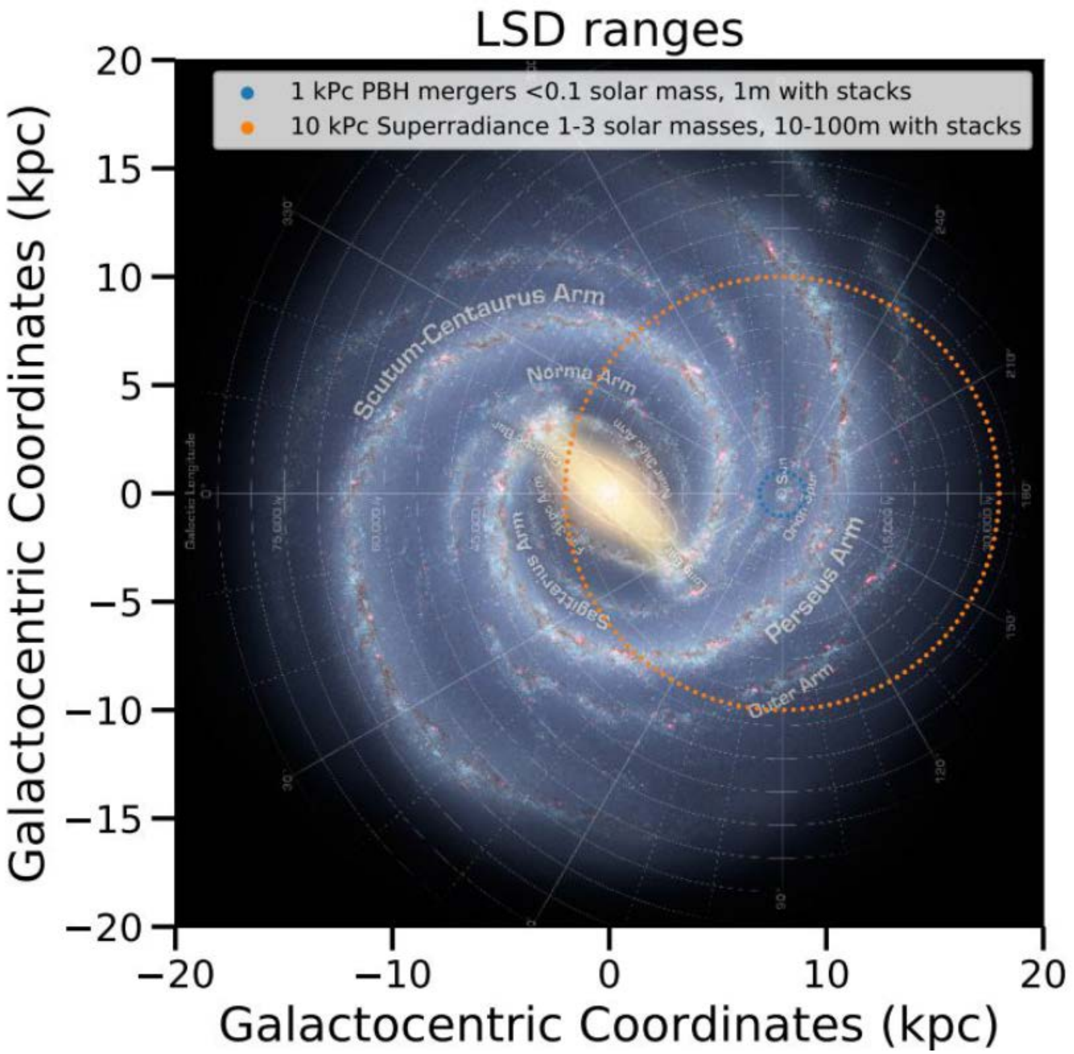
Danika R. Luntz-Martin, R. Greg Felsted, Siamak Dadras, Peter J. Pauzauskie, and A. Nick Vamivakas, "Laser refrigeration of optically levitated sodium yttrium fluoride nanocrystals," Opt. Lett. **46**, 3797-3800 (2021)



Search Range for the Levitated Sensor Detector (LSD)



Source modeling: Next talk by Jacob Sprague:



[Aggarwal et. al., Phys. Rev. Lett. **128**, 111101 (2022)].

Summary

- Calibrated zeptonewton force sensing with optically levitated nanospheres

  → new approach for high frequency gravitational waves

  Geometric methods to mitigate recoil heating, improve sensitivity

  Materials allow solid-state cooling→ higher frequency detectors
- Source modeling in process - PBHs, BH superradiance (axions, vector bosons)
- Future outlook: network of detectors planned: GOLDEN (Gravitational wave Observatory Levitated DEtector Network (UC Davis – N. Aggarwal, University College London – P. Barker, others?)

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