New approaches to atom interferometry

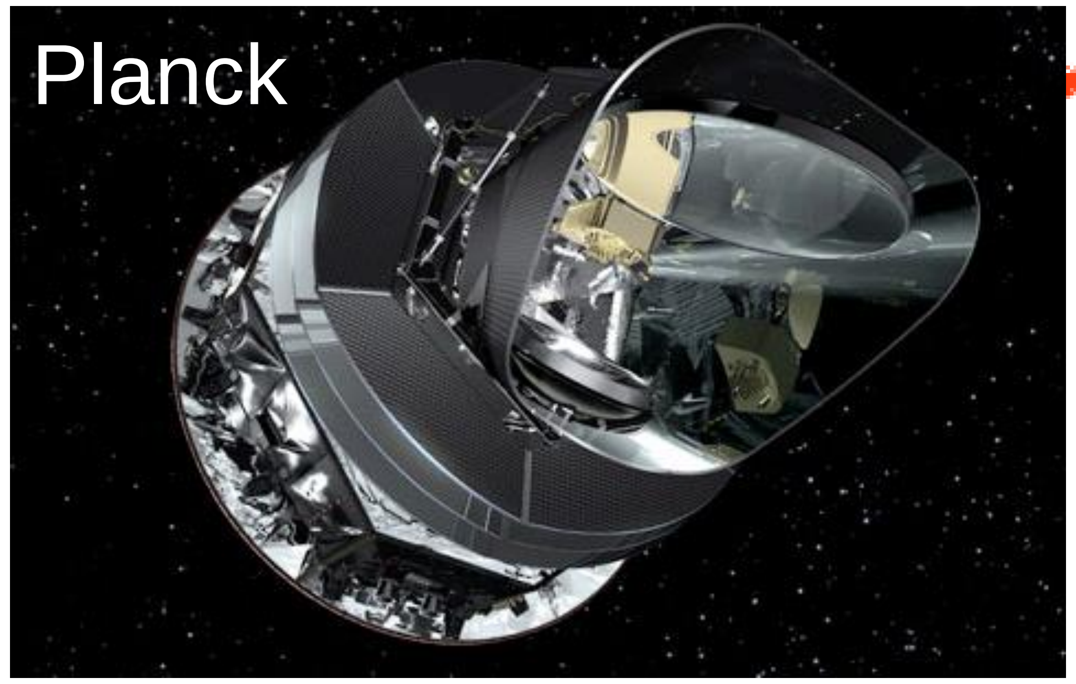
Keep the quantum state alive!

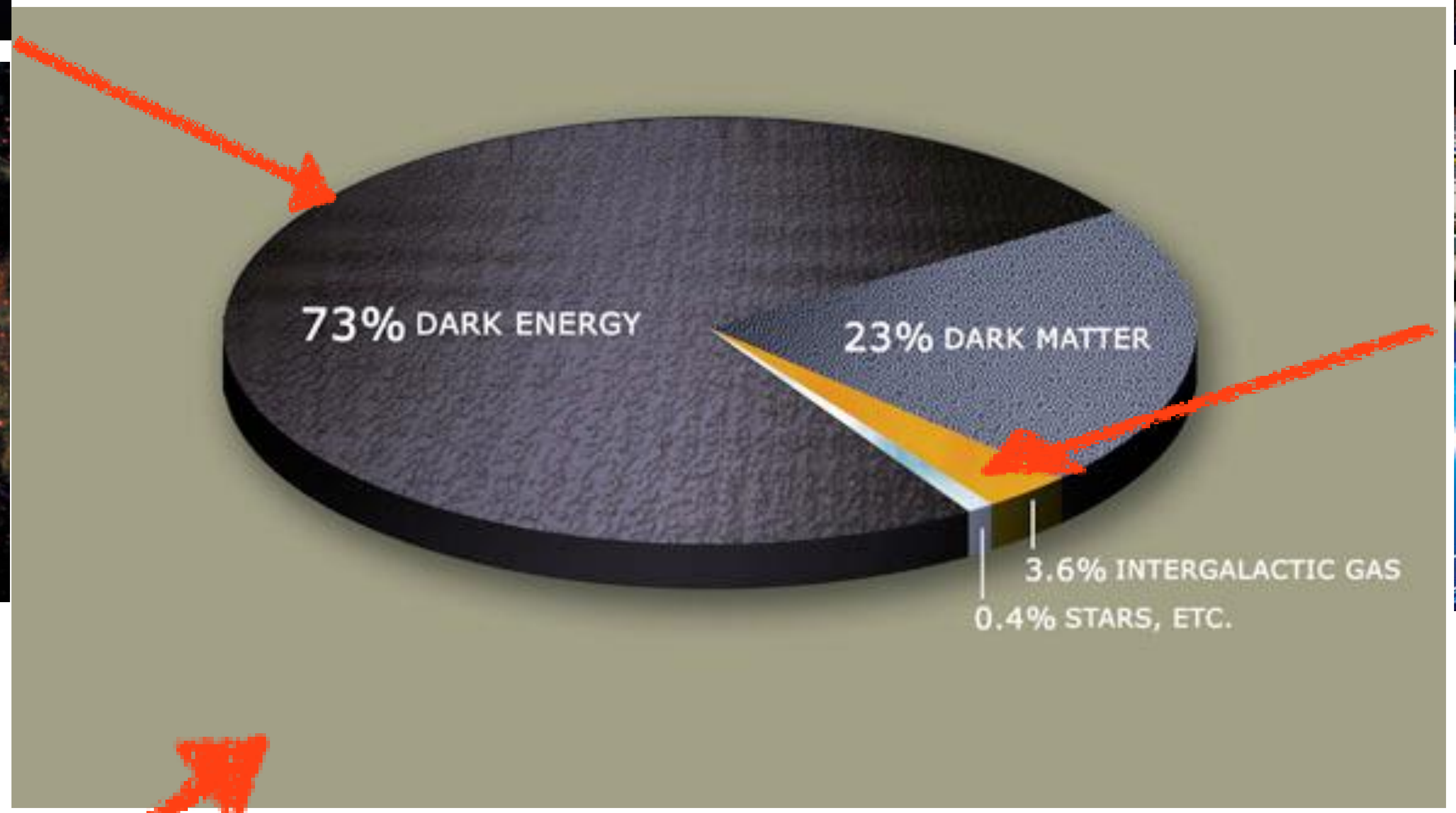
Holger Mueller, UC Berkeley

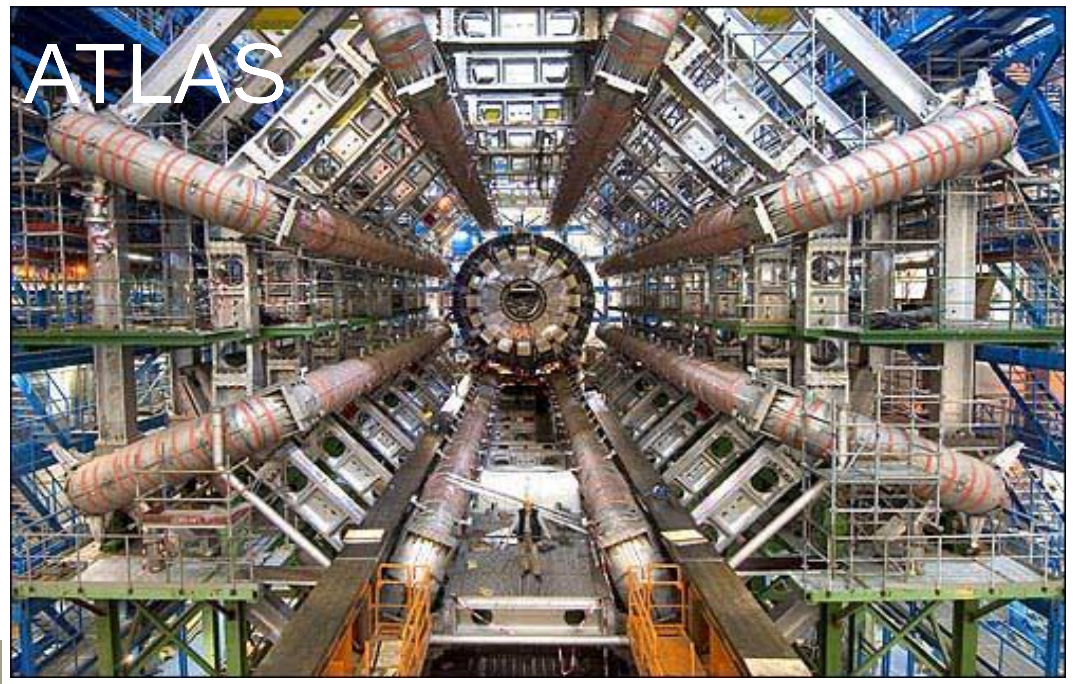
The Era of precision uncertainty

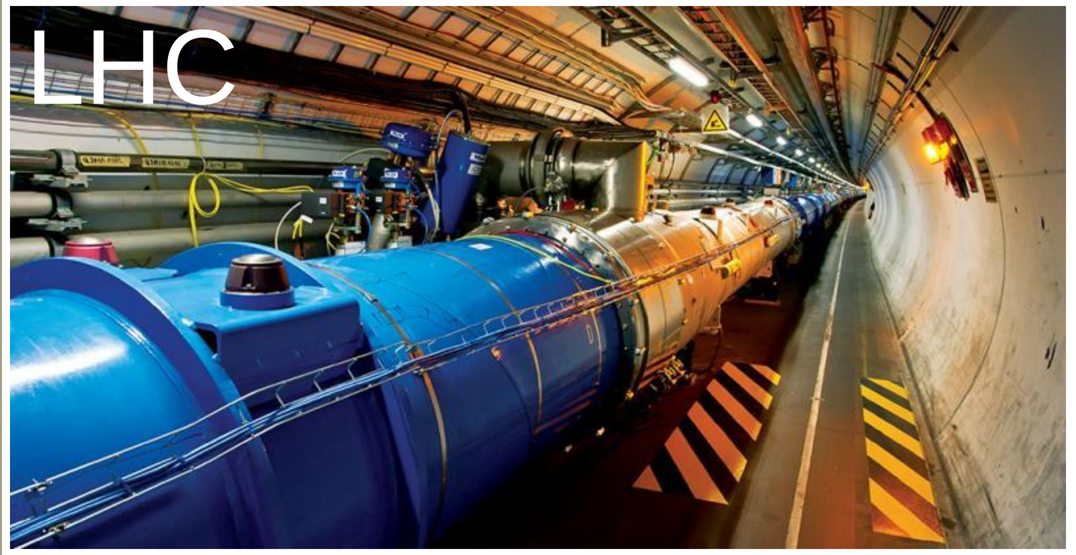
Loud and clear signals from the skies….

…but silence in our detectors

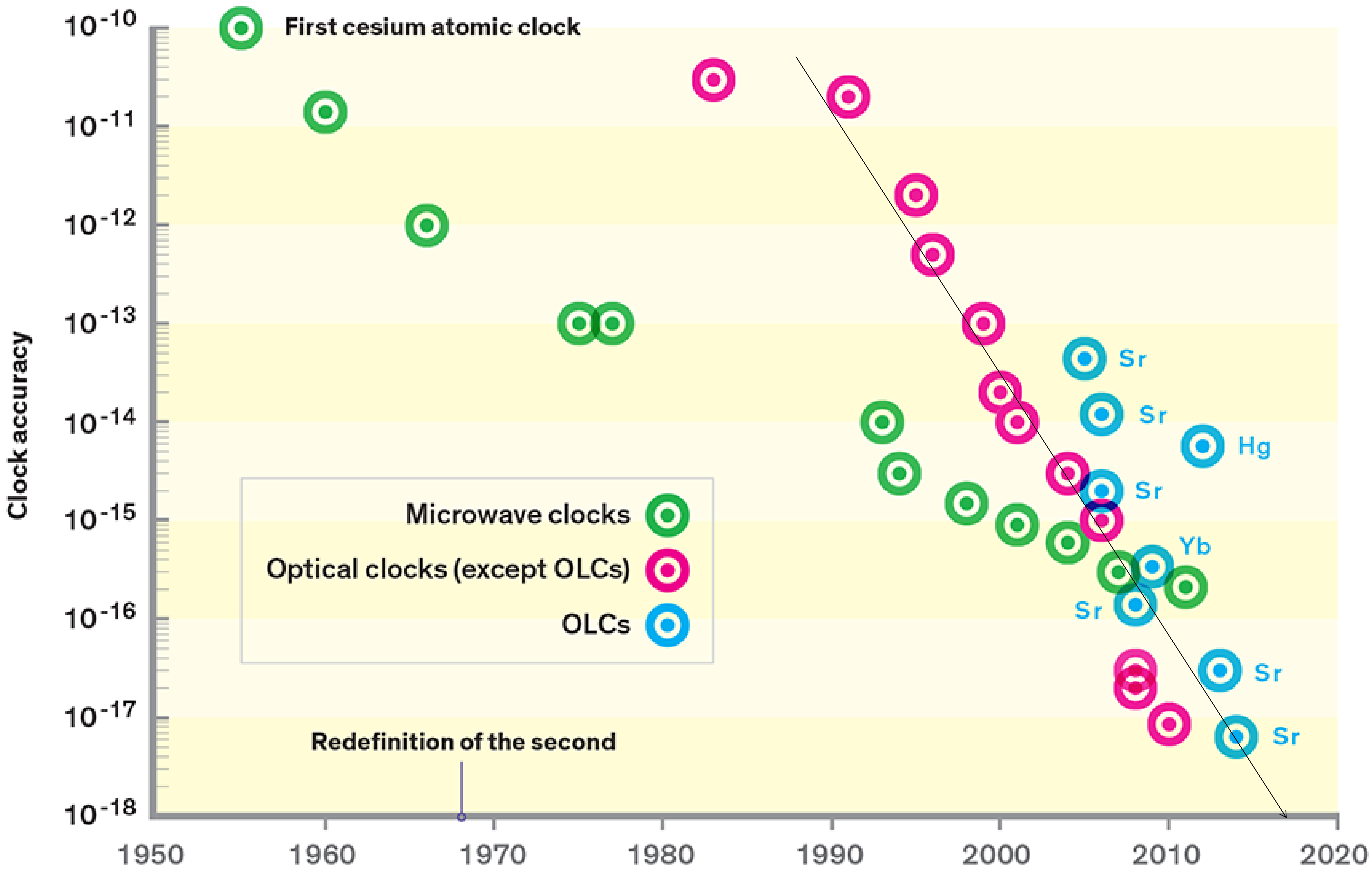






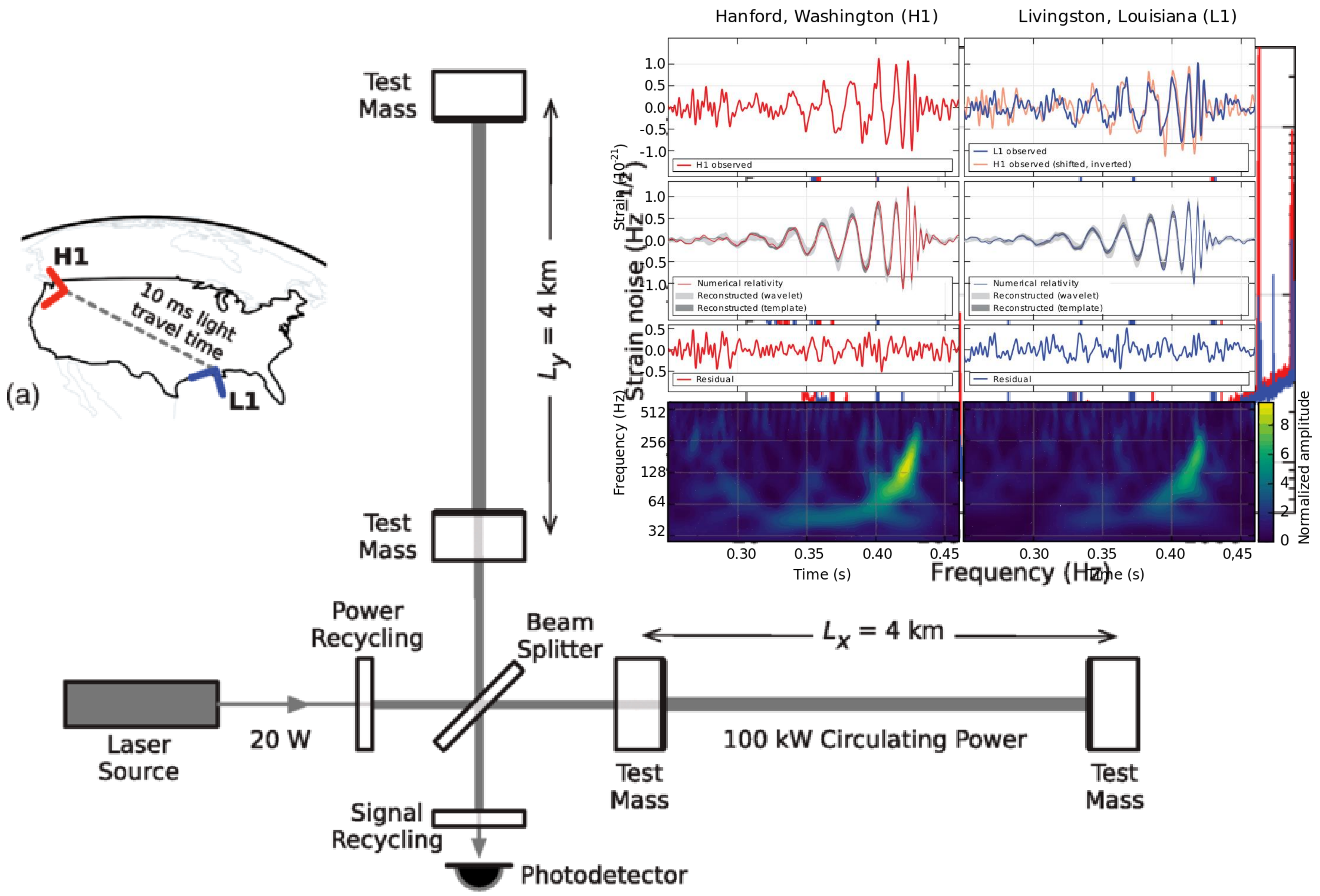


Moore’s law in atomic physics

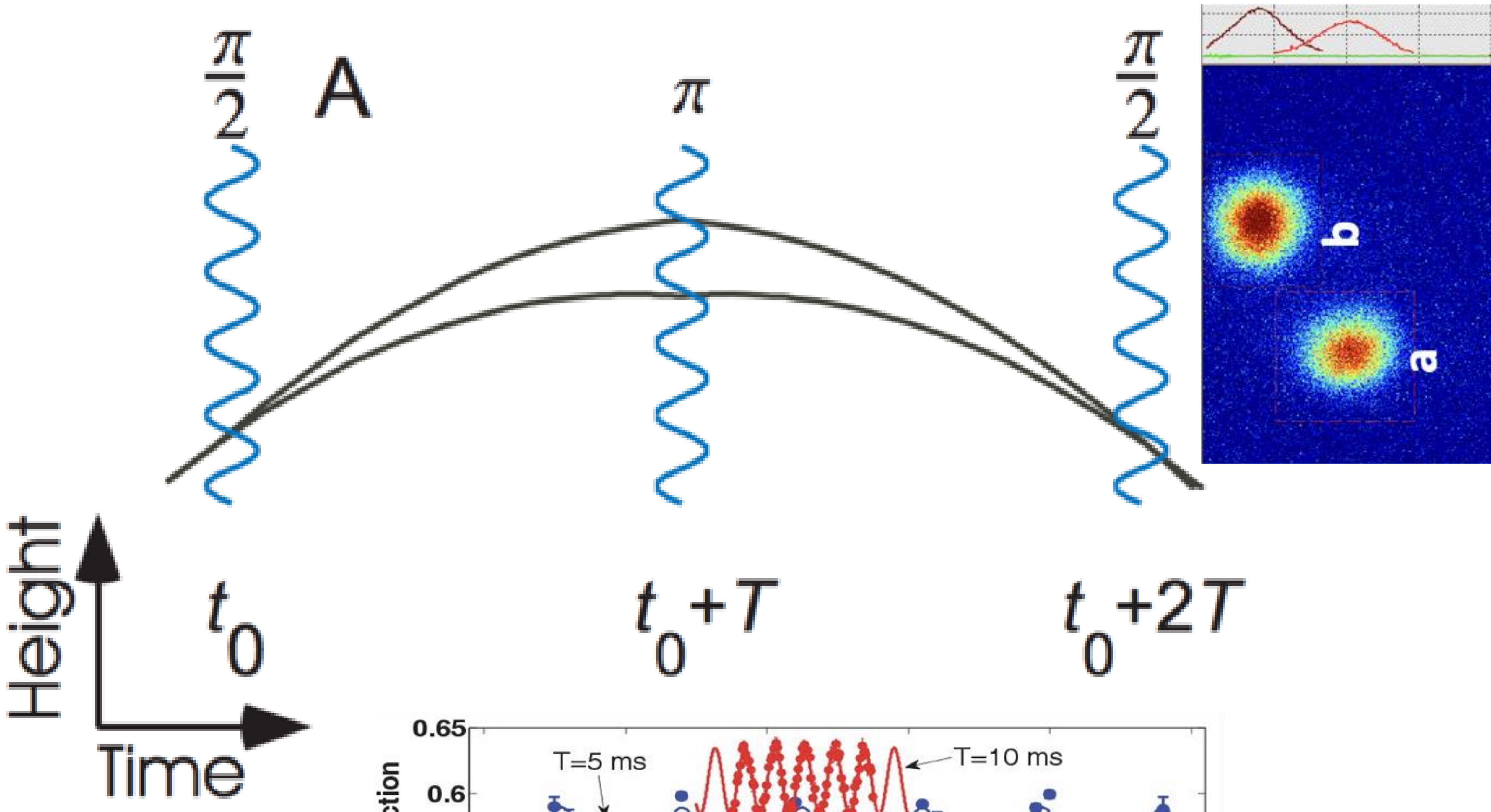


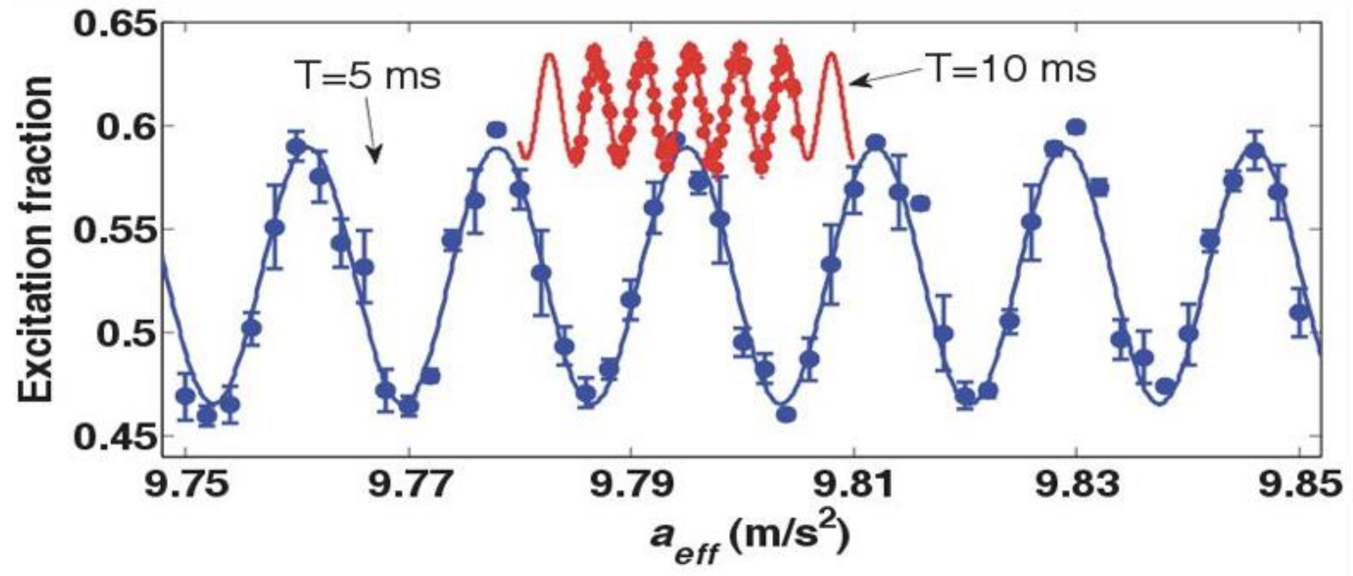
Interferometers

- Using matter to manipulate light

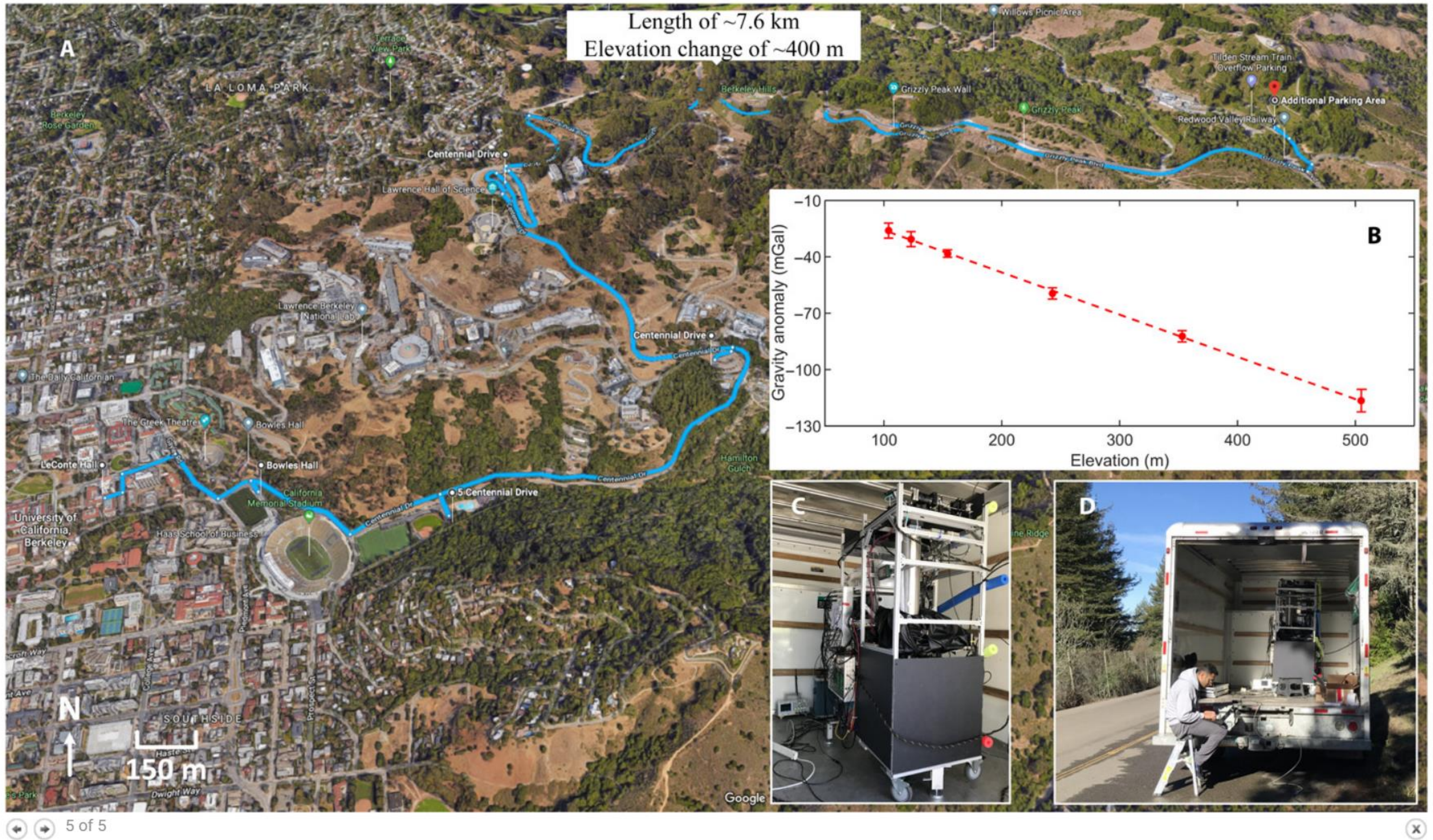


- Using light to manipulate matter





Applications: Local gravity, geophysics



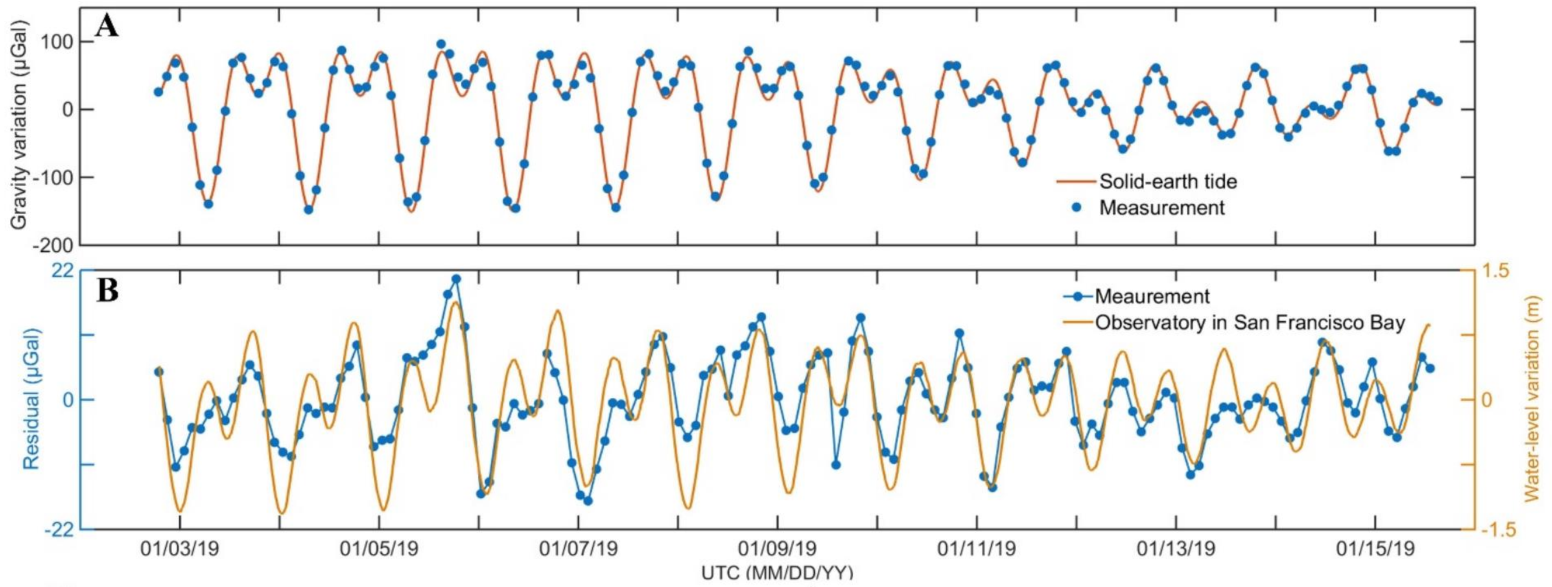


Fig. 2. Tidal gravity measurement. (**A**) Tidal gravity variation as a function of time. (**B**) Comparison between the gravity residual and the water-level variation in the San Francisco Bay. The gravity residual is the difference between the measurements and the solid-earth tide model. The water-level variation is measured by the observatory of National Oceanic and Atmospheric

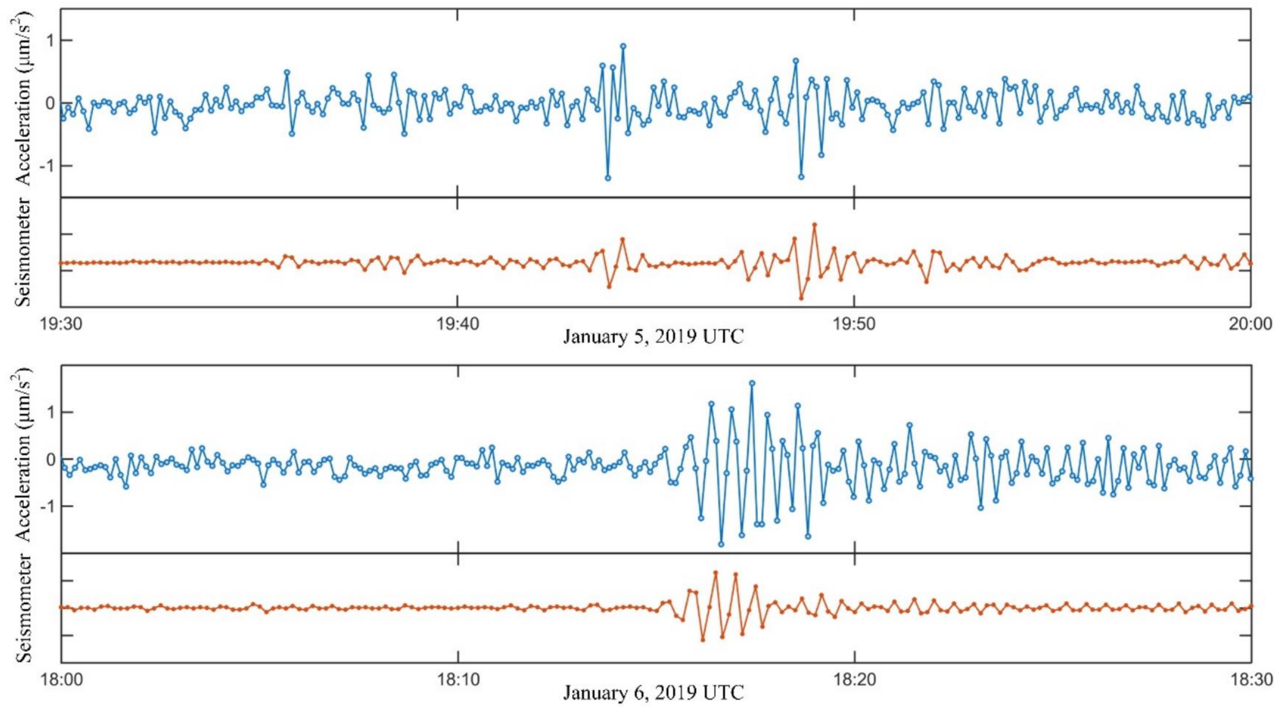
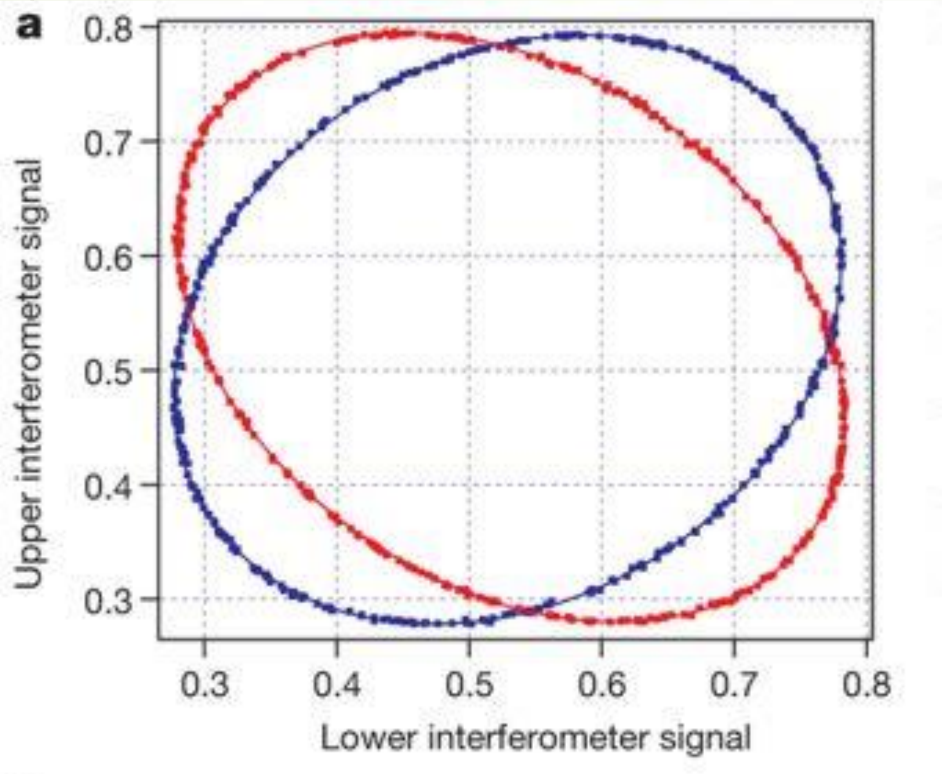
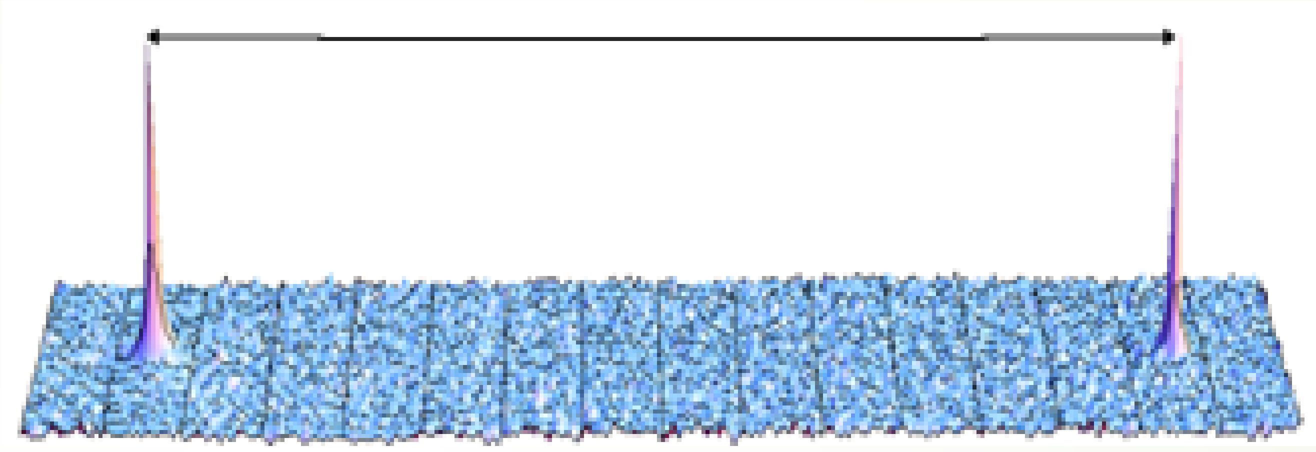


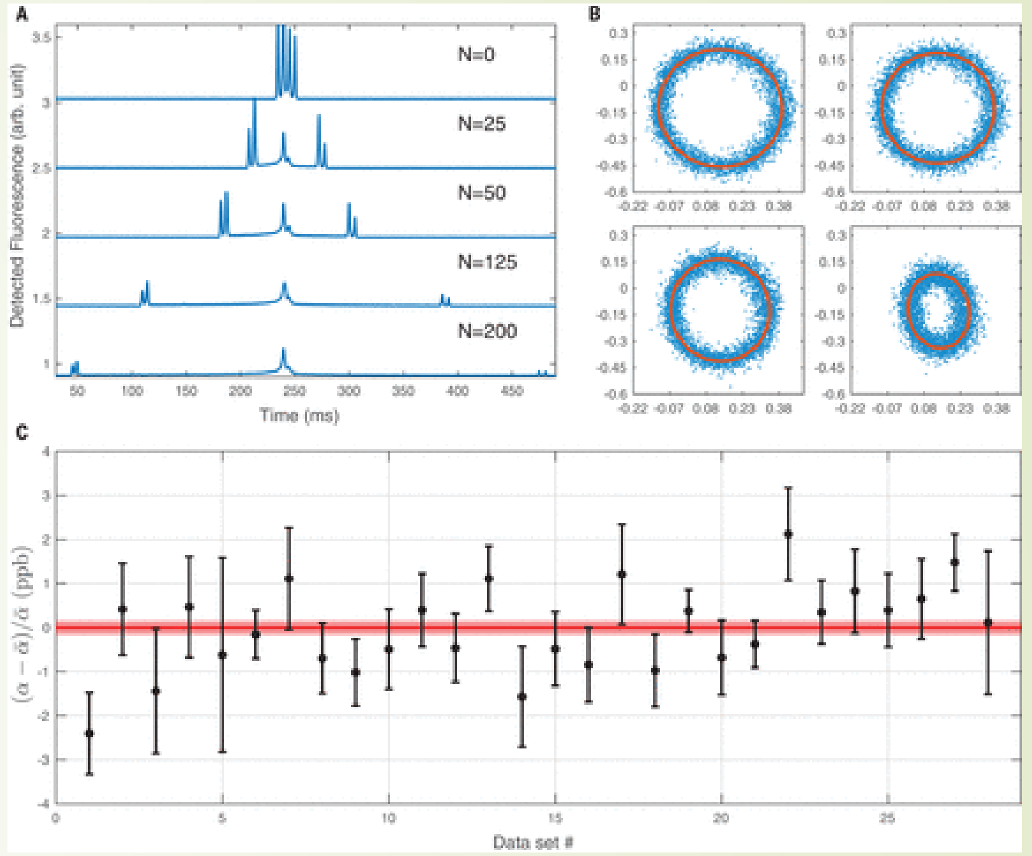
Fig. 3. Earthquake seismic waves detected in Berkeley. The atomic gravimeter measures the vertical acceleration of the seismic waves with an update rate of 0.13 Hz. The seismic signal is

X. Wu, et. al., *Science Advances* 2019

Dropping atoms for high precision…







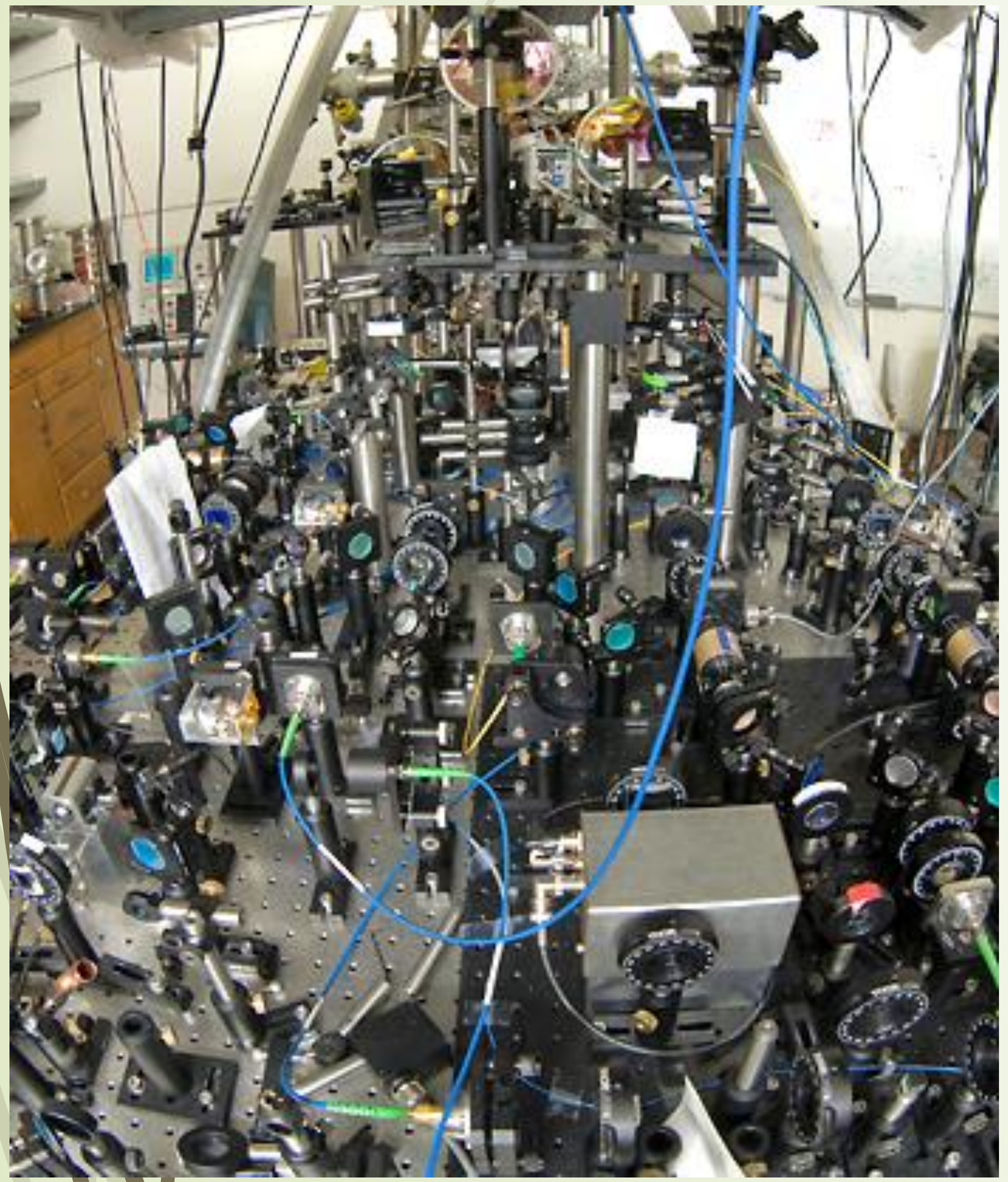
Measurement of G

Tests of GR and QM

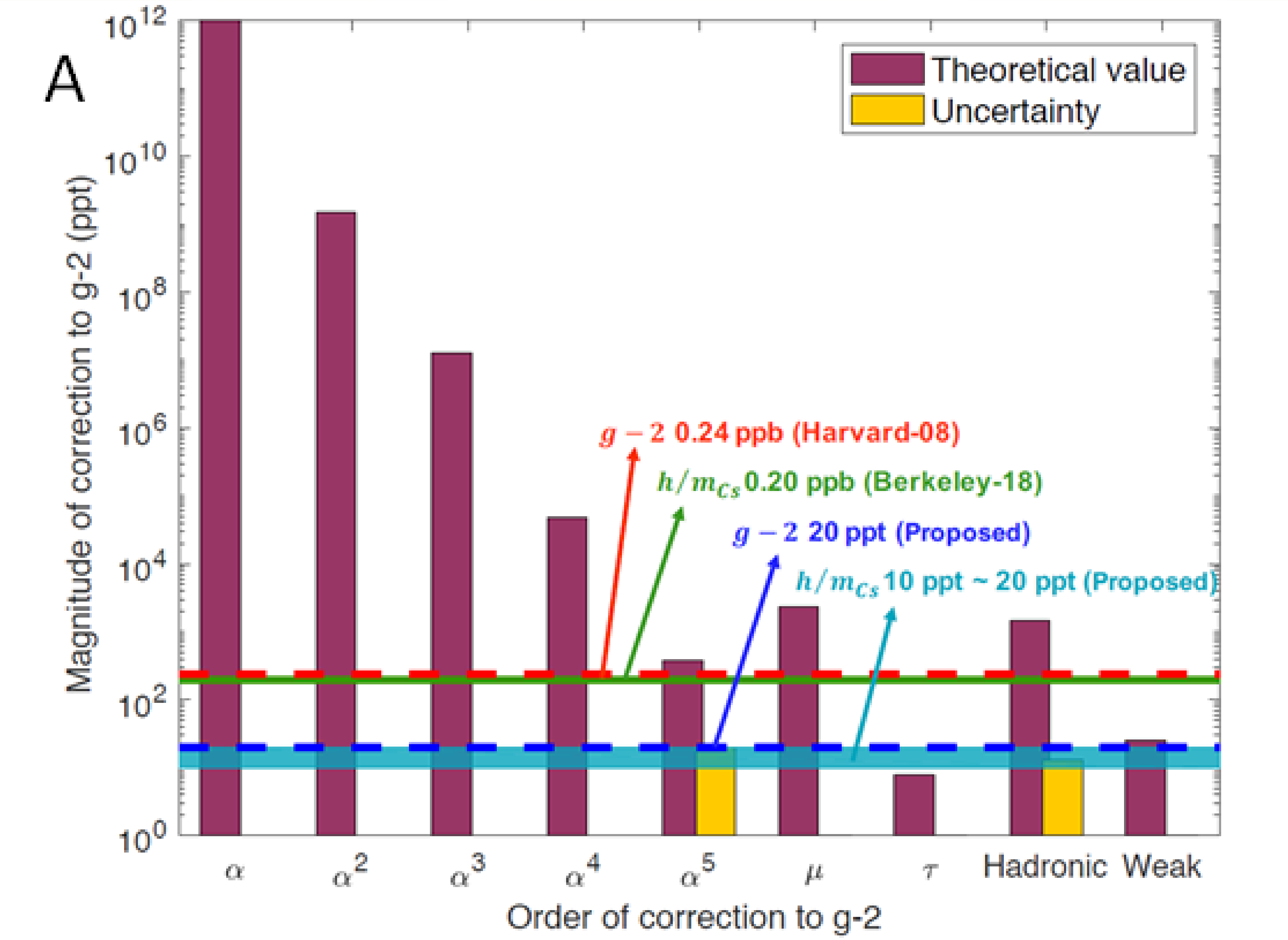
Fine-structure constant

The most precise test of the standard model

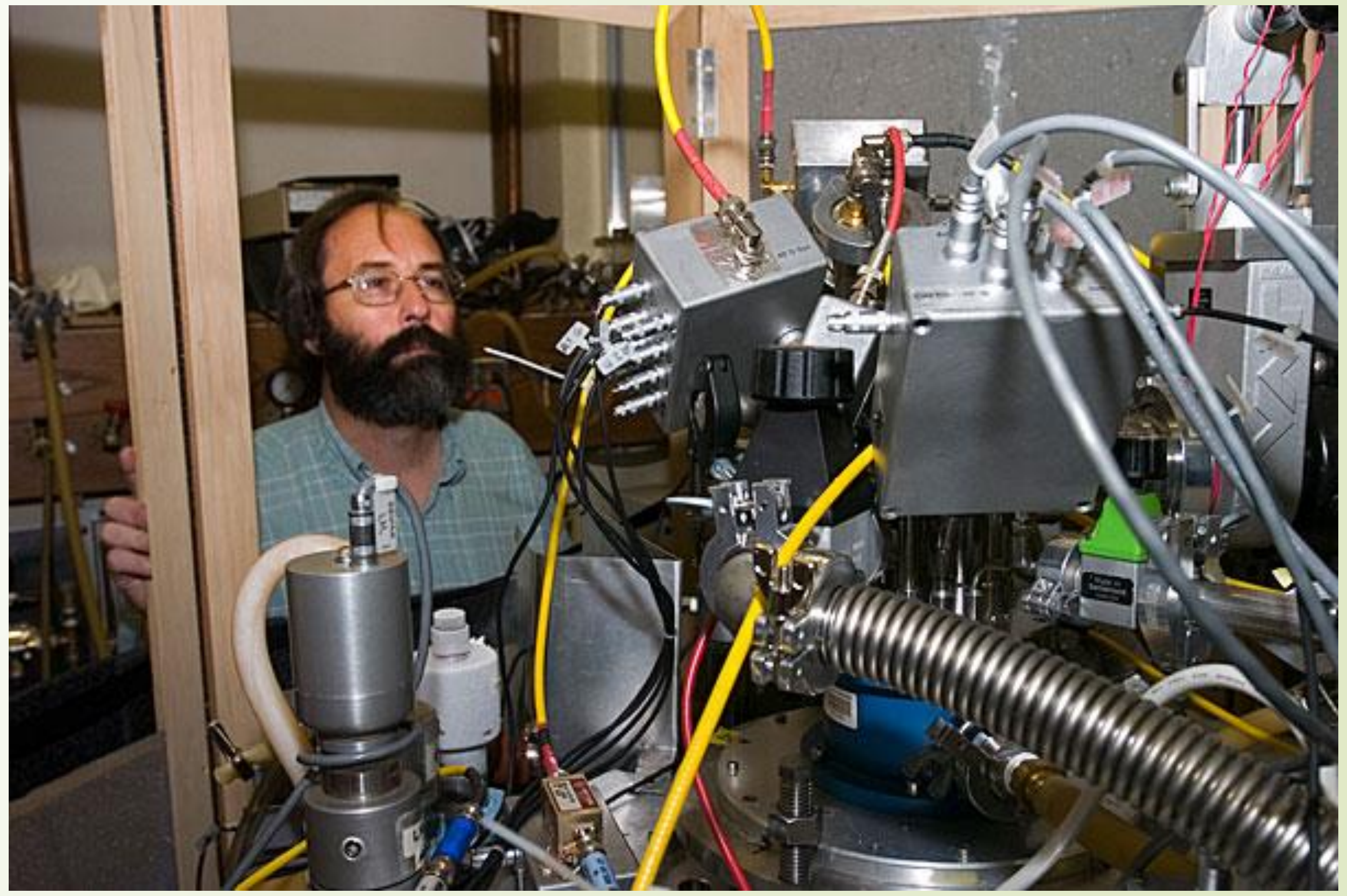
Fine structure constant



Standard Model

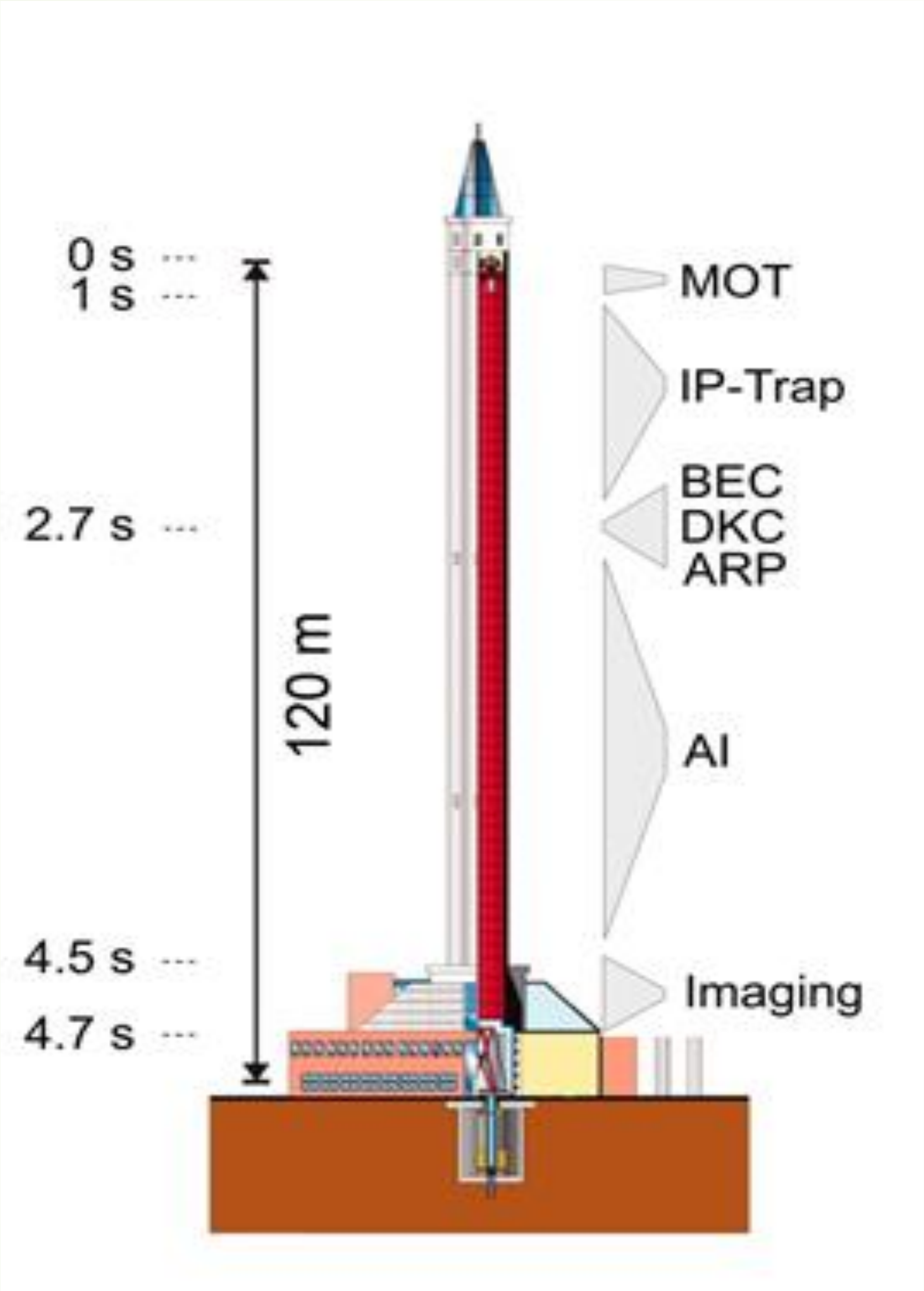


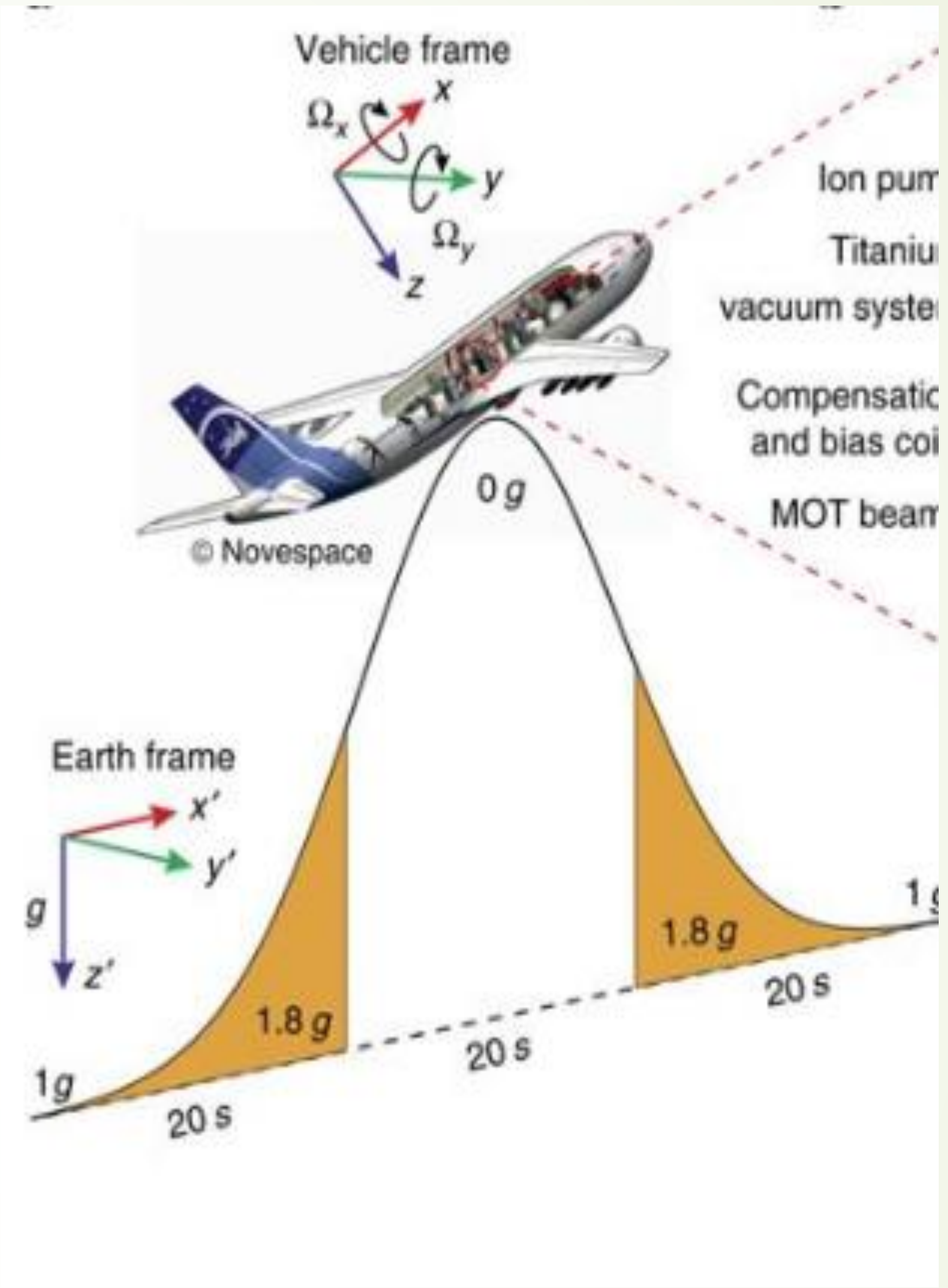
Gyromgnetic Anomaly

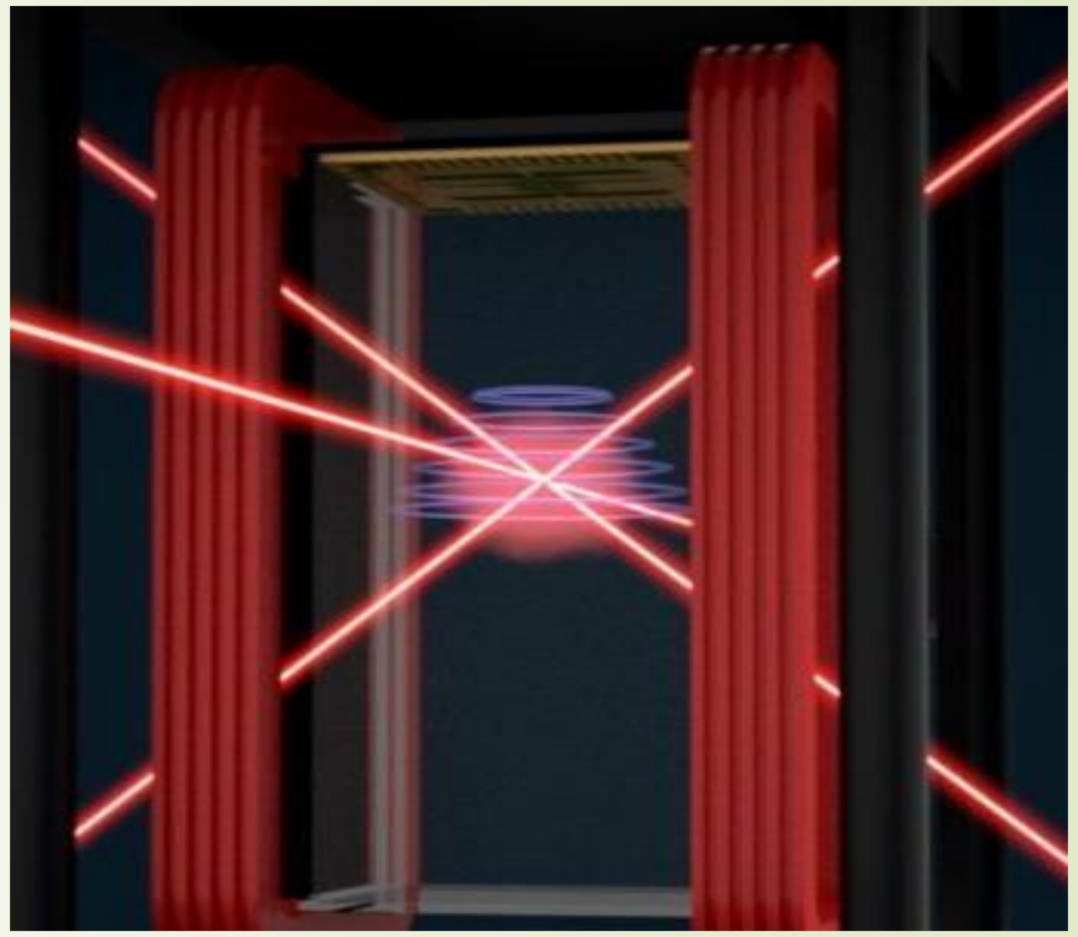


Sensitive to hypothetical particles beyond the standard model

Limitations: free-fall time

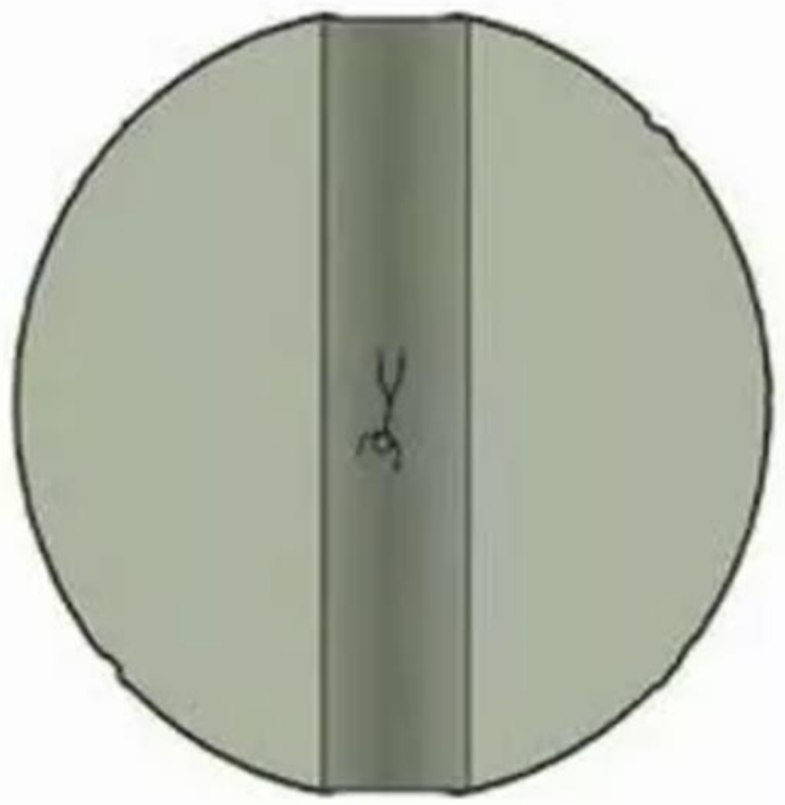






Stanford 10-m fountain	Bremen 100-m drop tower	French zero-g flights	NASA cold atom lab
2 -3 s (height)	<1 s (atom temp, vacuum, vibrations)	< 1s (atom temp, vacuum, vibrations)	<1 s (atom temp, vacuum, vibrations)

Longer coherence times

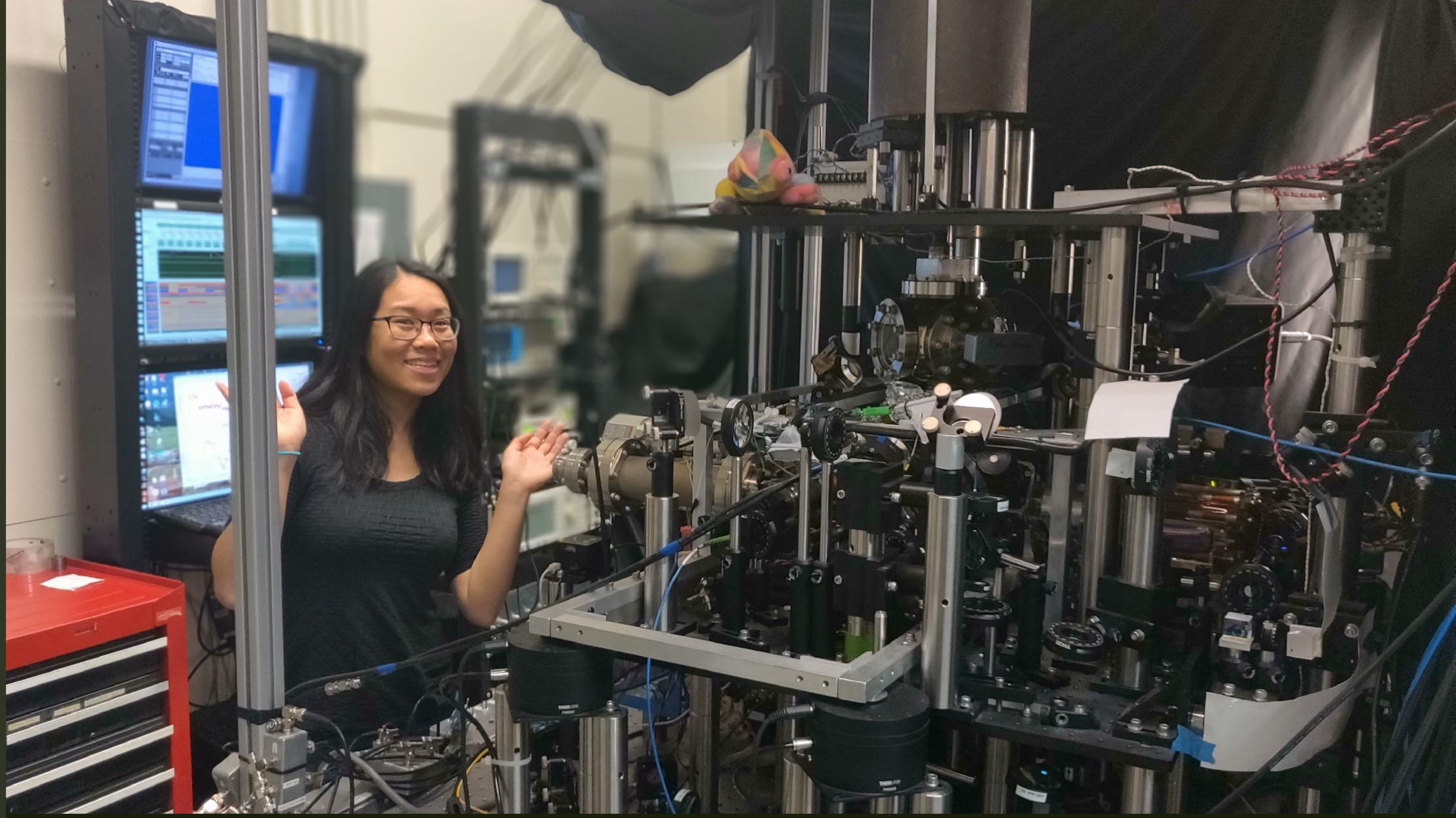


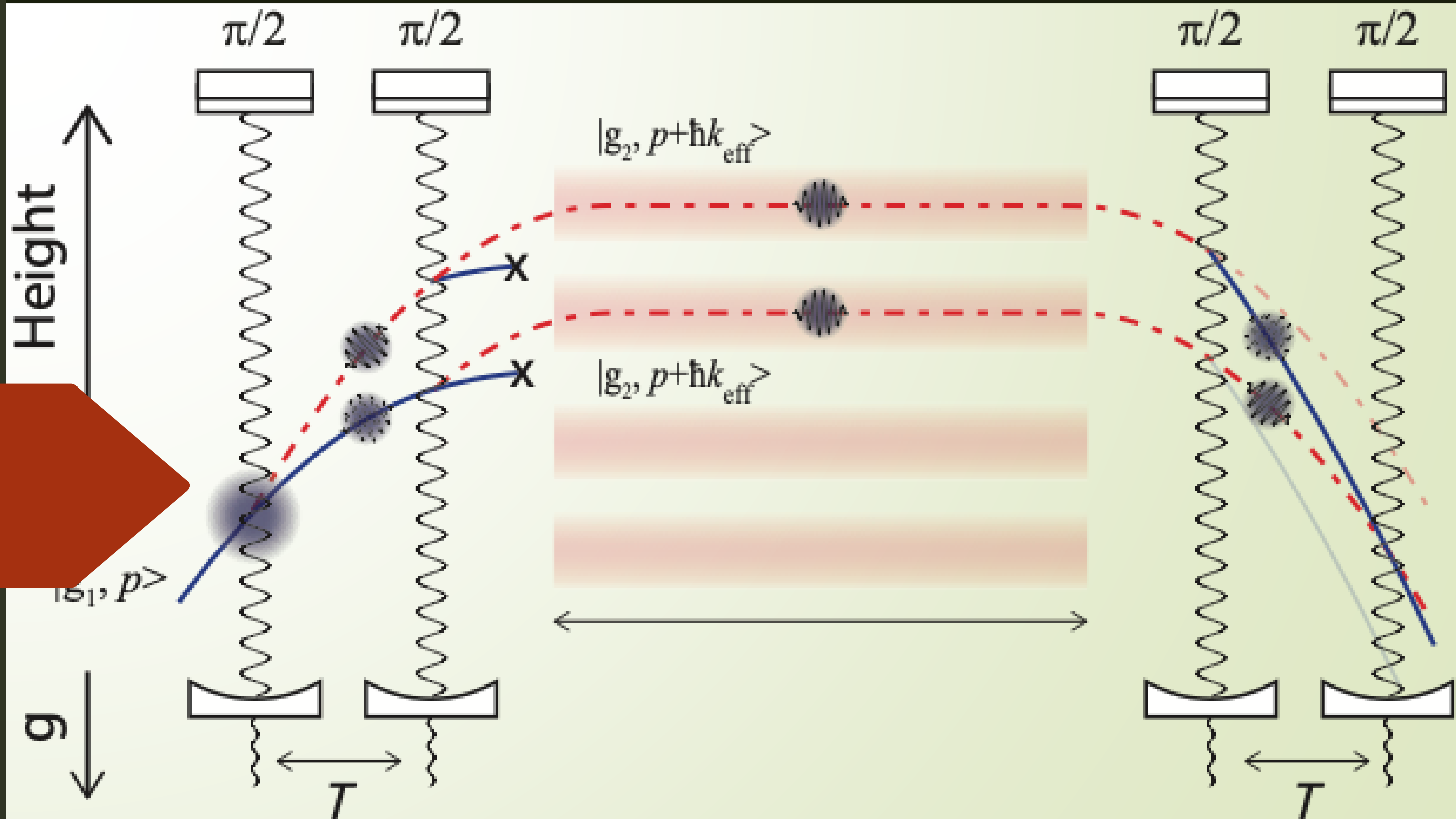
It takes at least $1/\sqrt{G\rho}$ ~ 15 minutes for locally-generated gravity to dominate in an experiment!

- E.g., gravitational harmonic oscillator

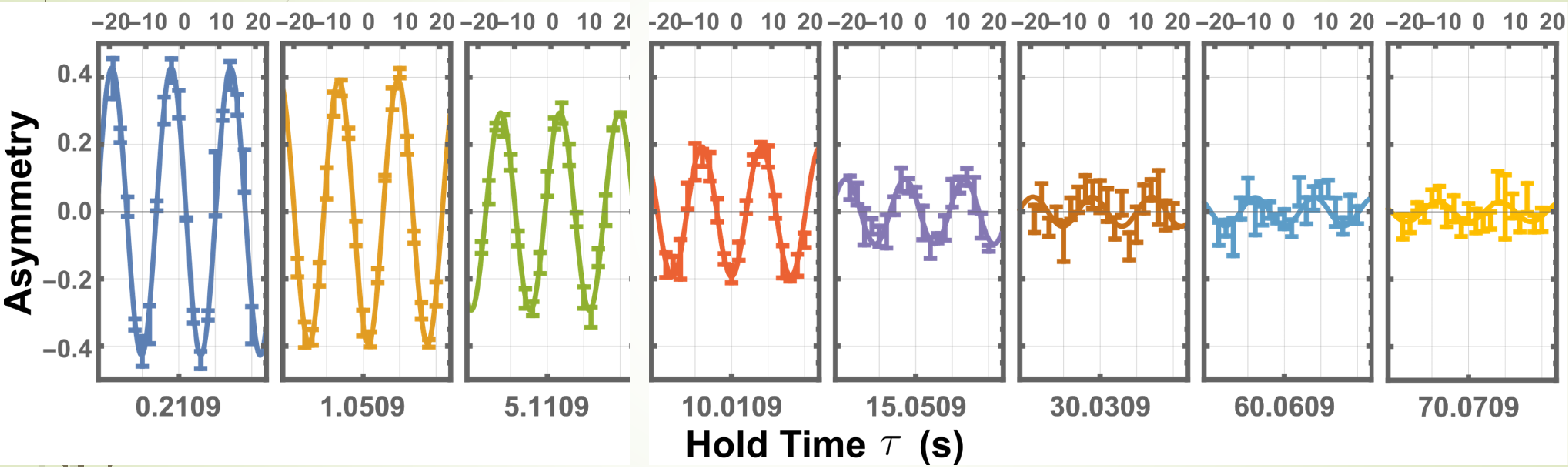
Minimum time scale on which quantum aspects of gravity can be expected to be noticeable

Lattice interferometer

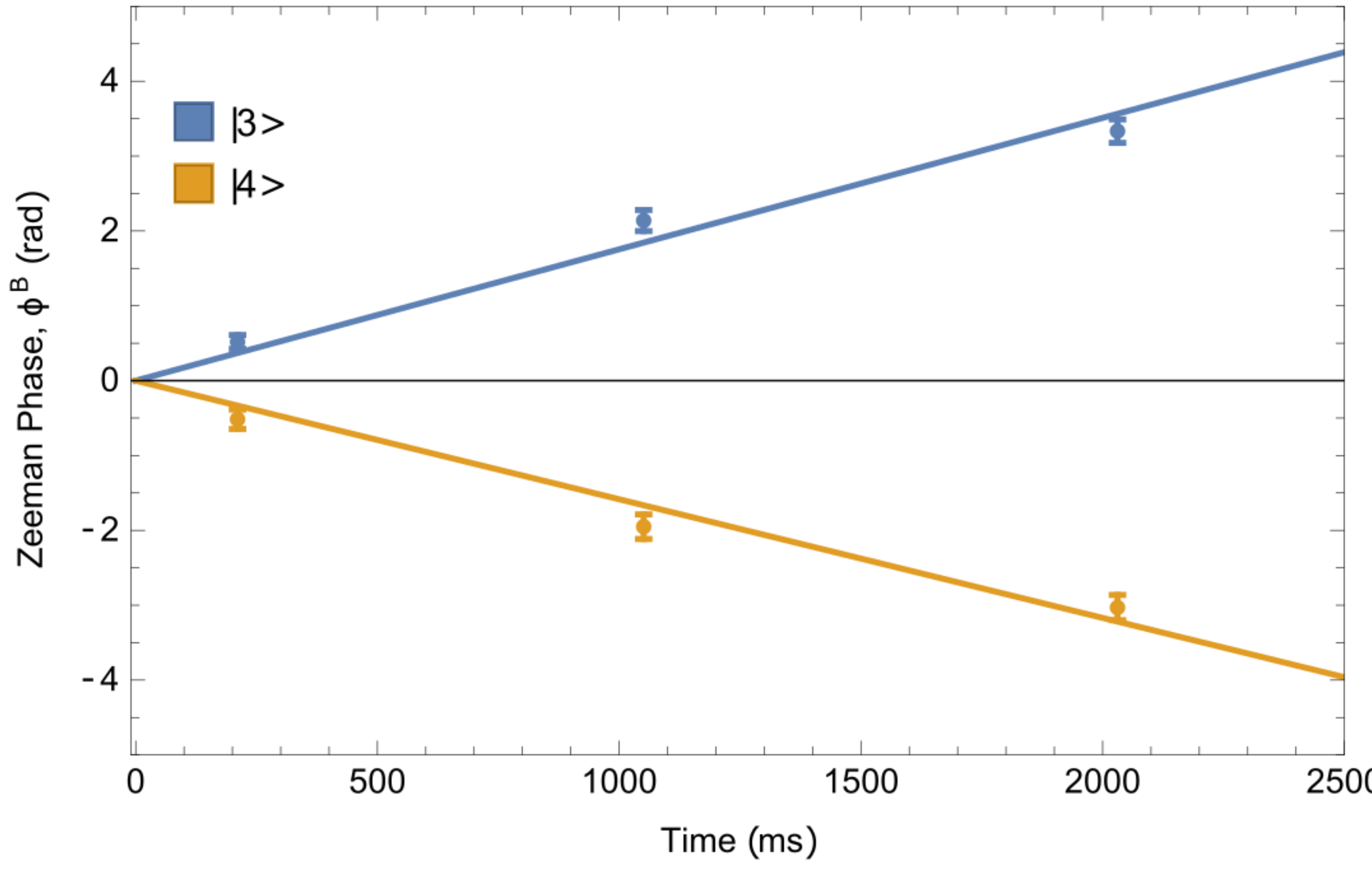


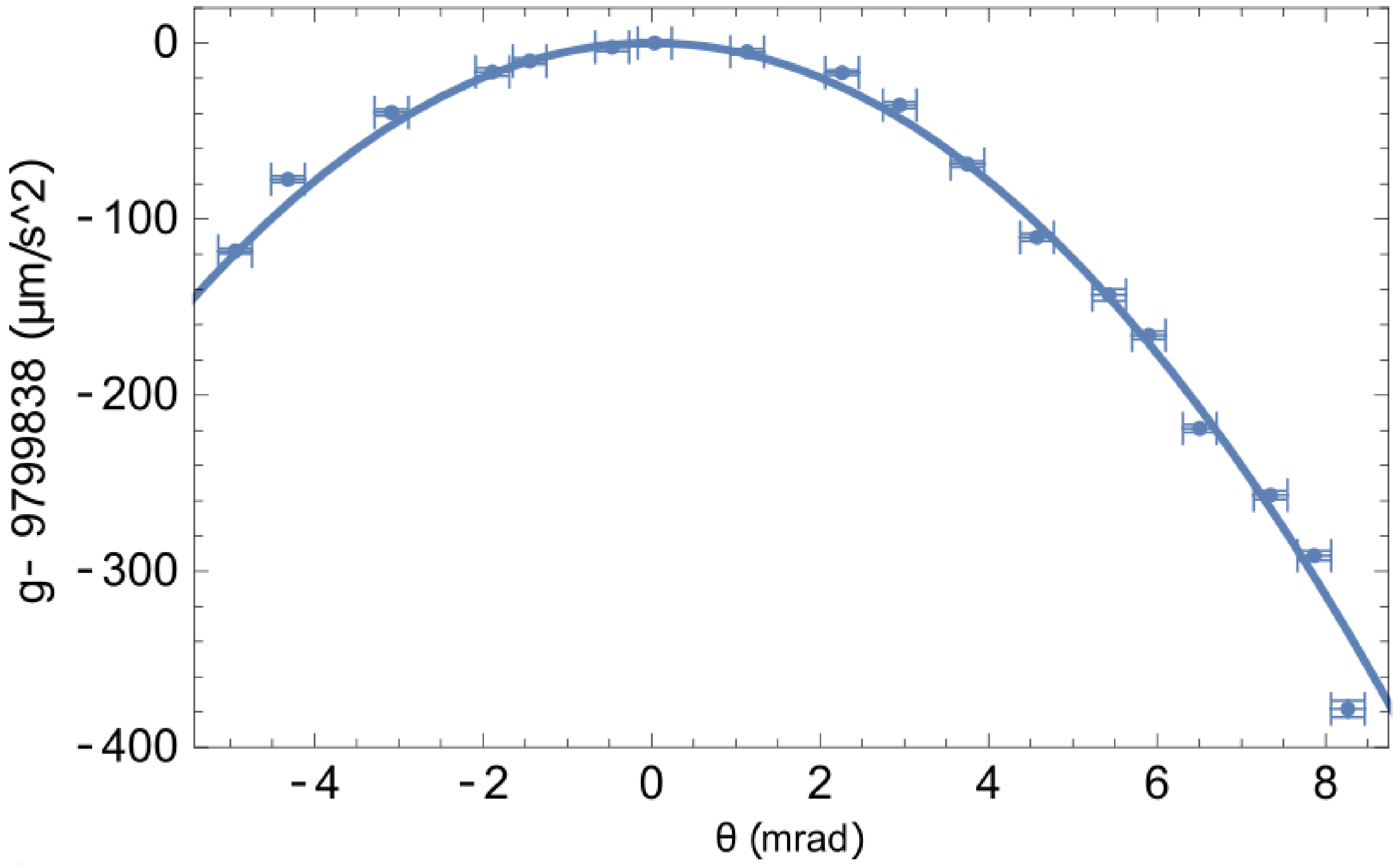


Longer coherences



Probing gravity by holding atoms for 20 seconds. Xu et al., Science **366**, 745-749 (2019)
Minute-scale gravimetry using a coherent atomic spatial superposition, Panda et al., Nature Physics 20, 1234 (2024)

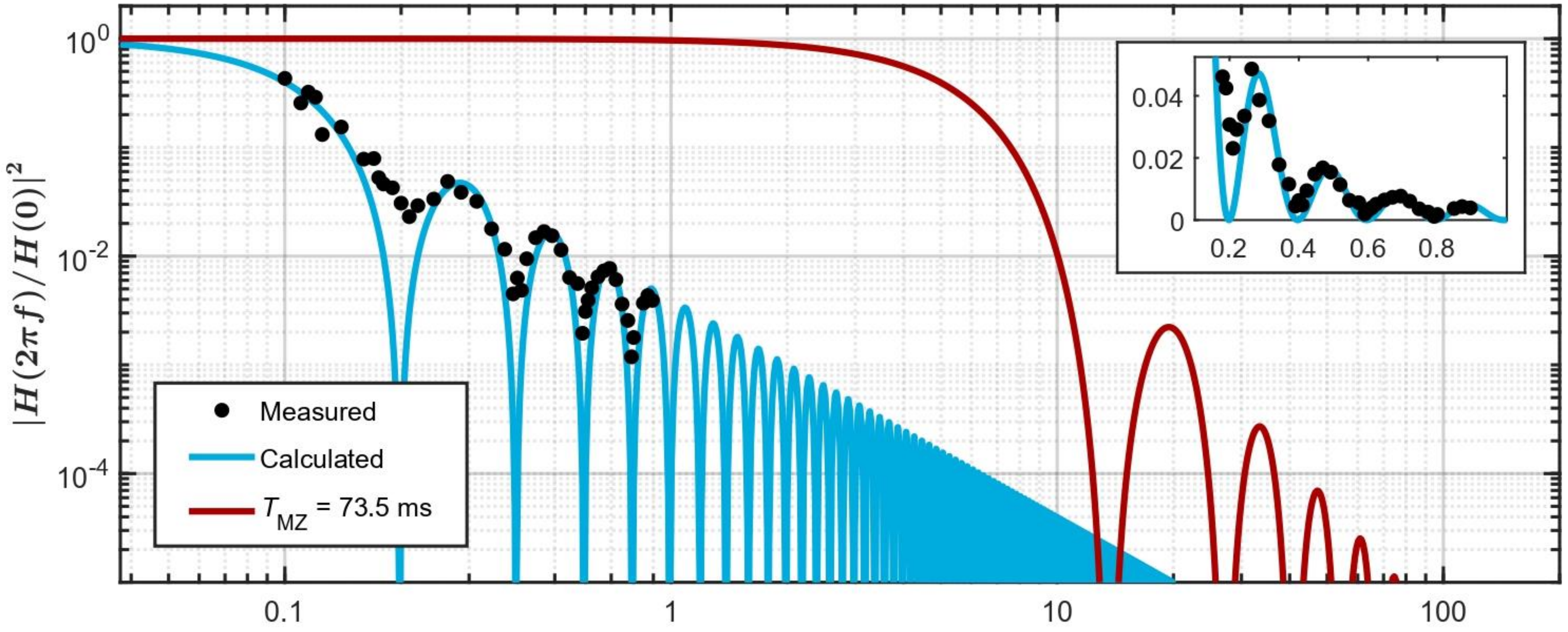




Operation under strong B-field…

…tilt o…

Suppression of vibrational noise, immune to tilt



immune against vibration, no vibration isolation required

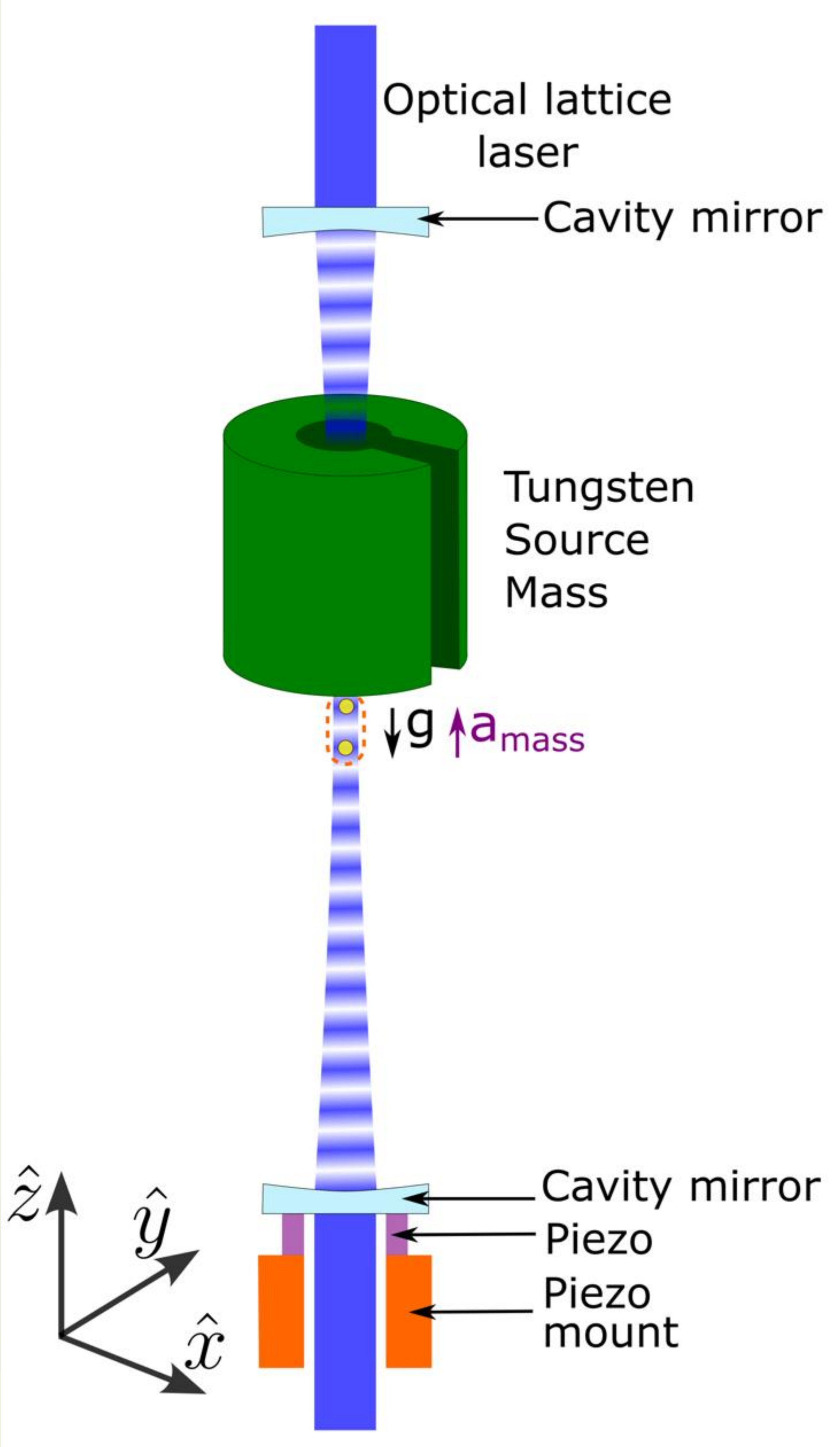
Atomic gravimeter robust to environmental effects, *Appl. Phys. Lett. 123*, 064001 (2023)

But what about systematics….?

Test case: measuring the gravity of a small mass

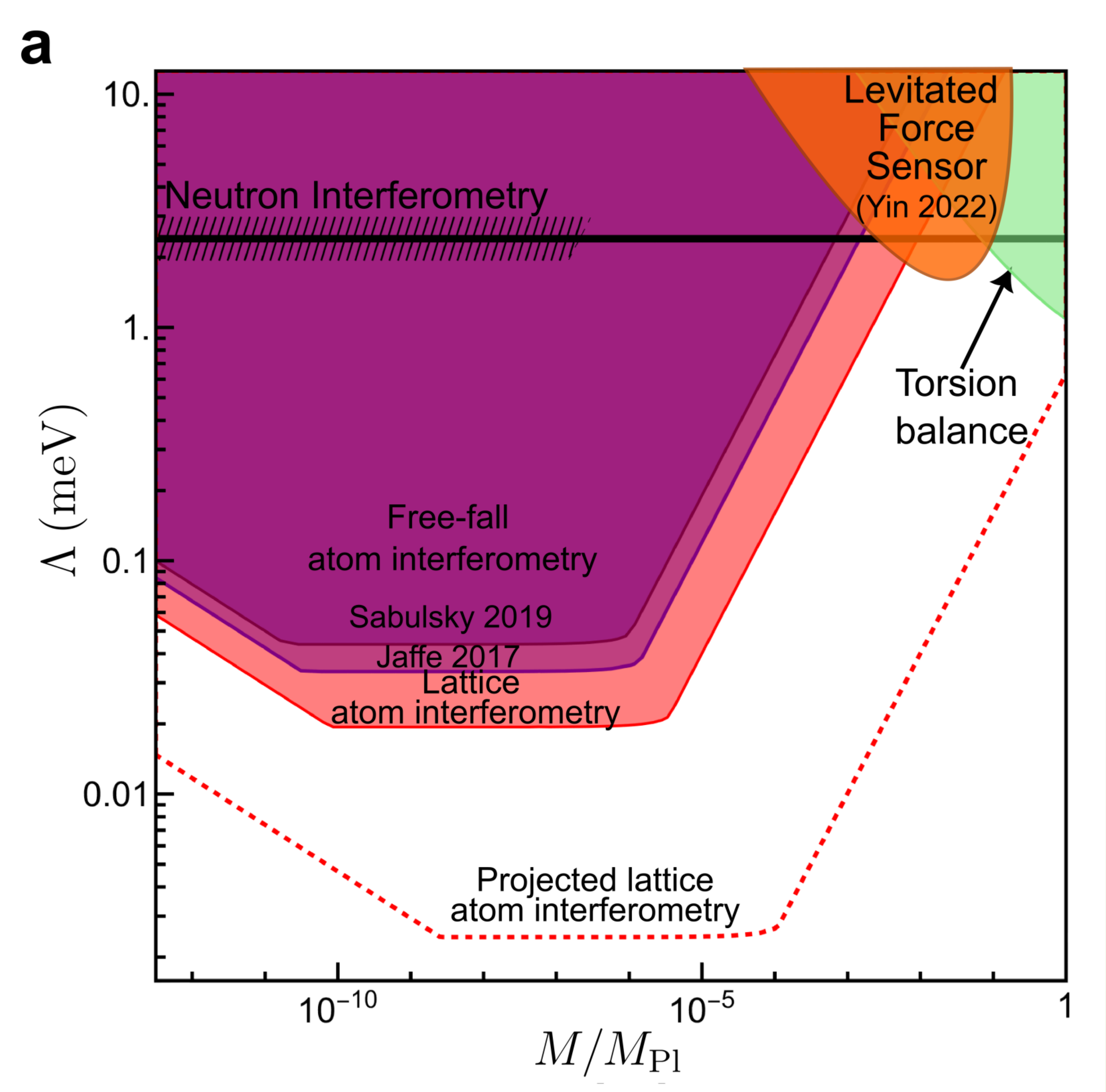
- Light shift
- Lattice imperfections
- Toggle mass nearby ($\tilde{\mathcal{M}} = 1$) and far-away ($\tilde{\mathcal{M}} = 0$).
- Atoms above ($\tilde{\mathcal{E}} = +1$) and below source mass ($\tilde{\mathcal{E}} = +1$).

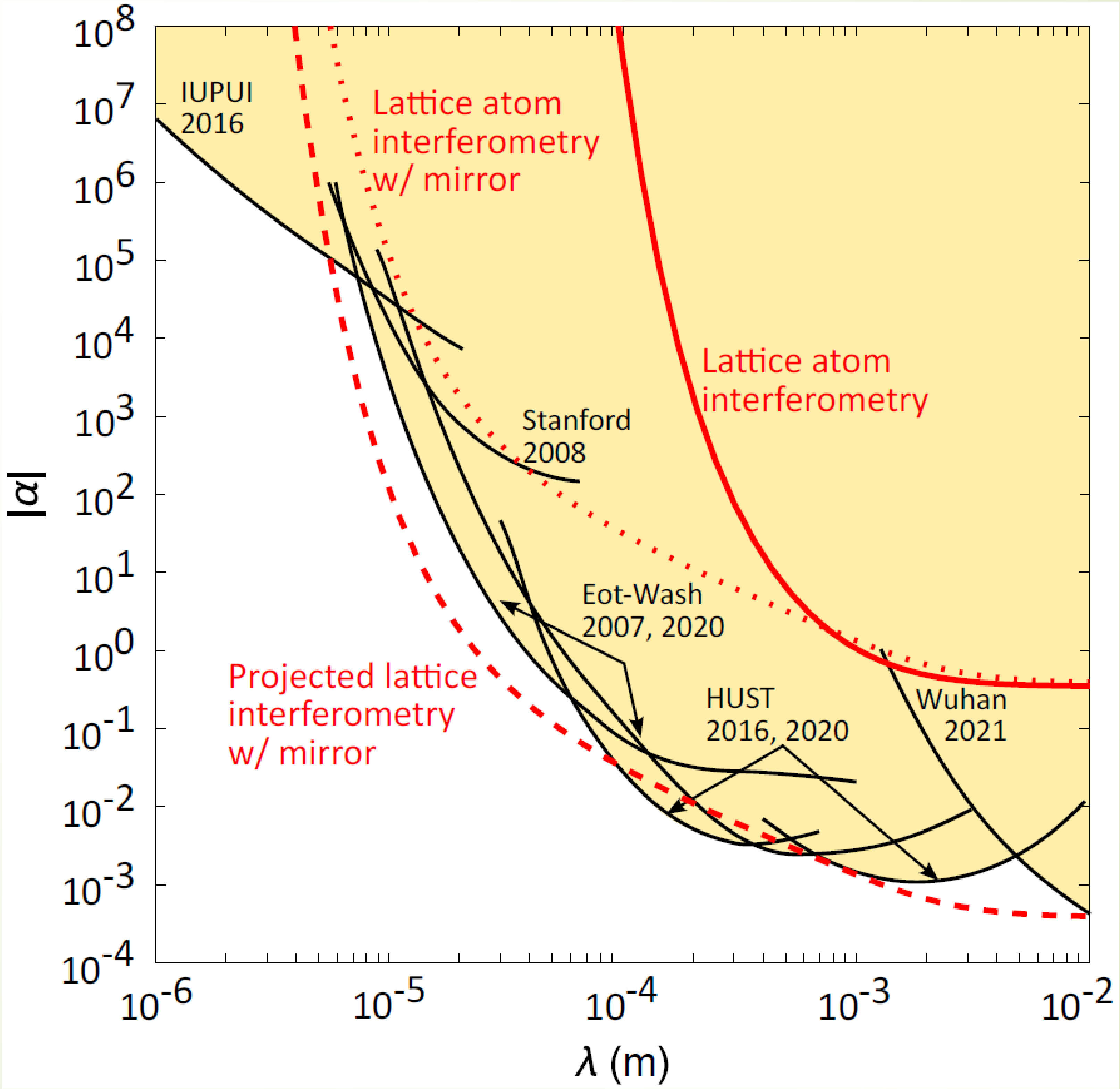
$$\boxed{a_{\text{mass}} = [a(1,1) - a(1,-1) - a(0,1) + a(0,-1)]/2}$$



… 6 x as sensitive as atomic fountain

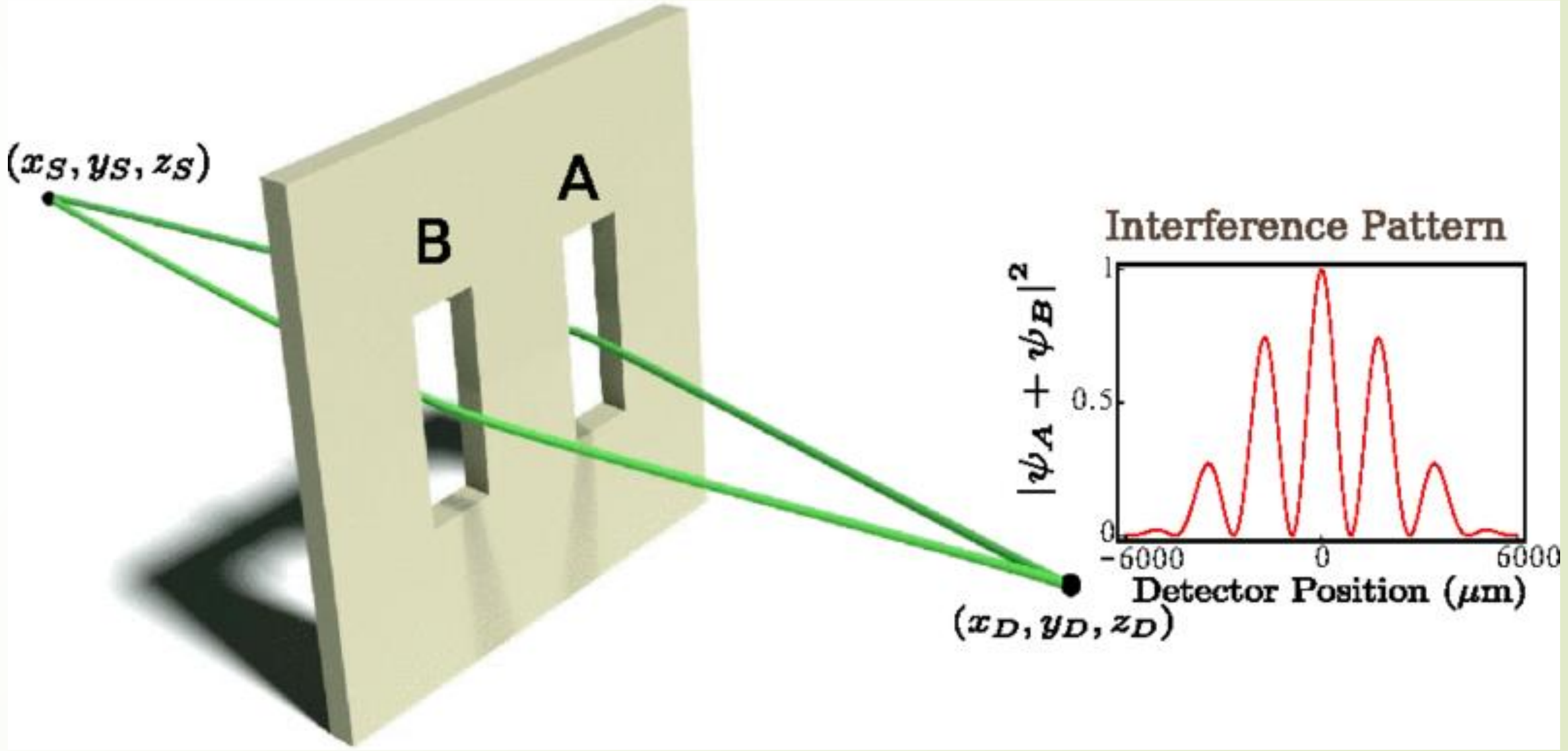
- $a_{\text{mass}} = 33.3 \pm 5.6_{\text{stat}} \pm 2.7_{\text{syst}} \text{nm/s}^2$
- Rules out screened (chameleon) forces

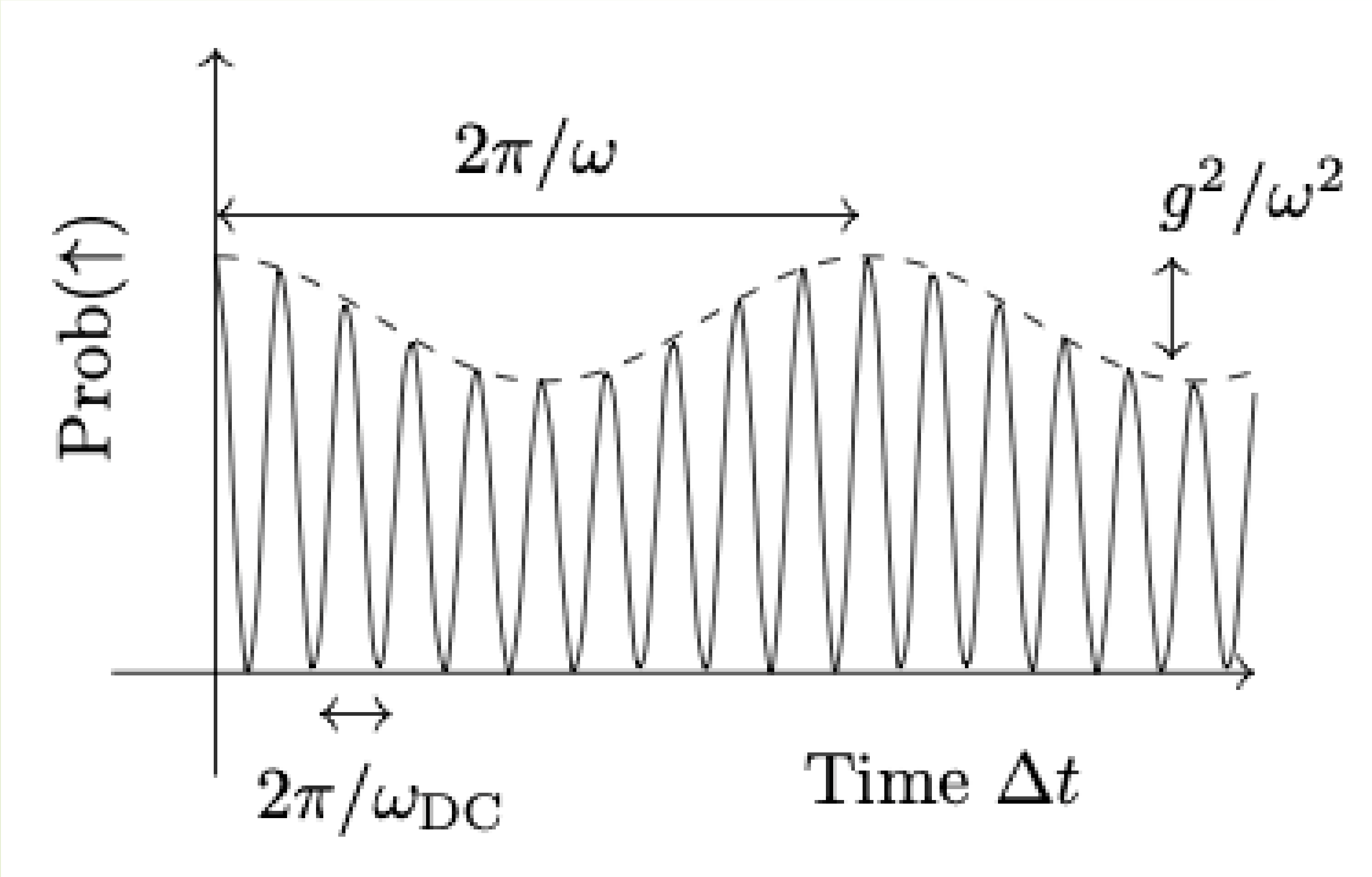




Feynman, 1957: what is a superposition of space-times?

- Spatial superposition of mass => superposition of gravitational fields.
- Surprisingly testable… collapse and revival of atomic interference fringes
- …signal scales with T^2 or T^4.



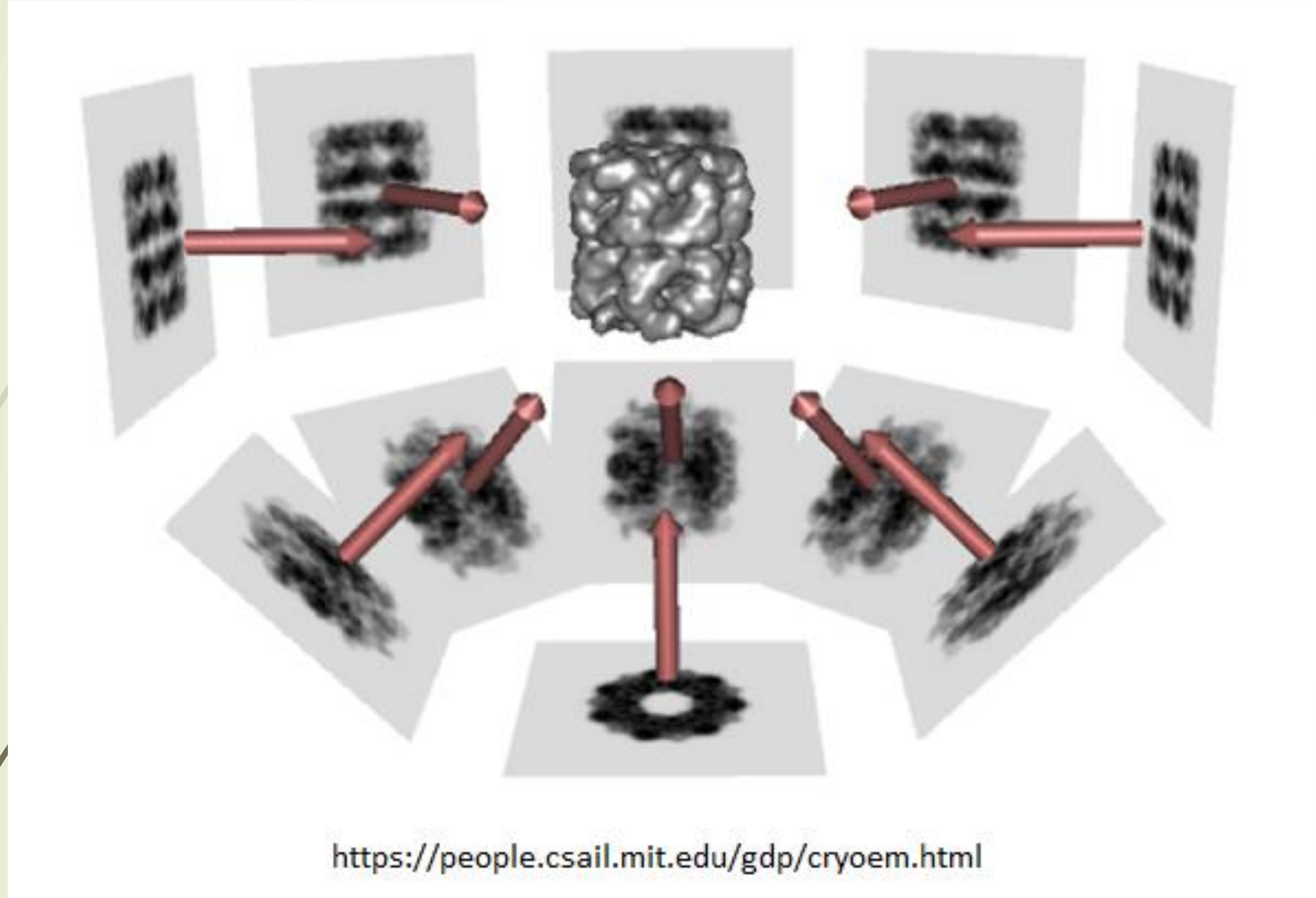


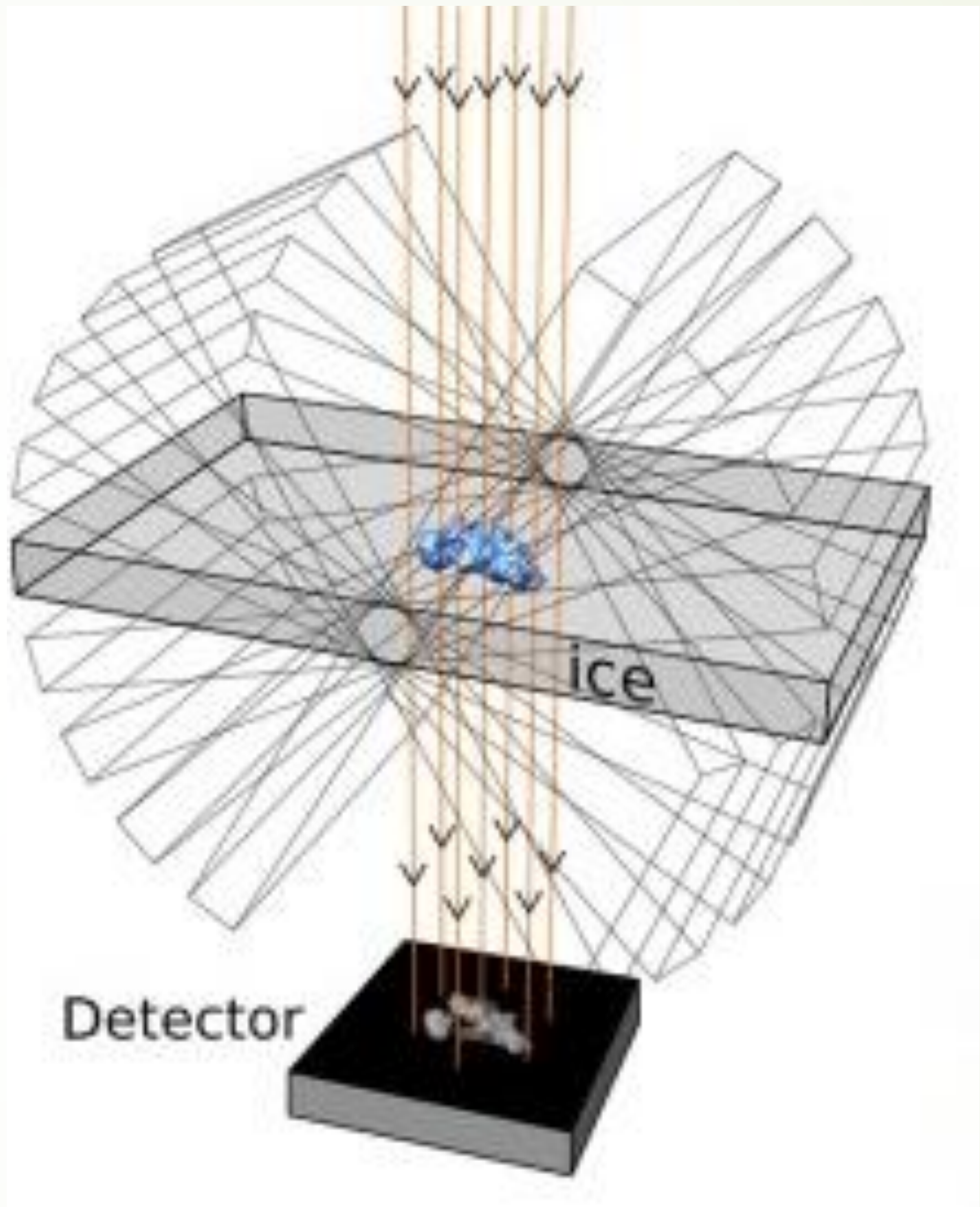
Carney, Muller, Taylor PRXQ 2021

Laser phase plate in cryo-electron microscopy

Extract all the information that is carried on the electron beam

Single-particle cryo-EM is growing quickly, as we know very well…





Koning et al., Ann. Anatom. (2018); ThermoFisher

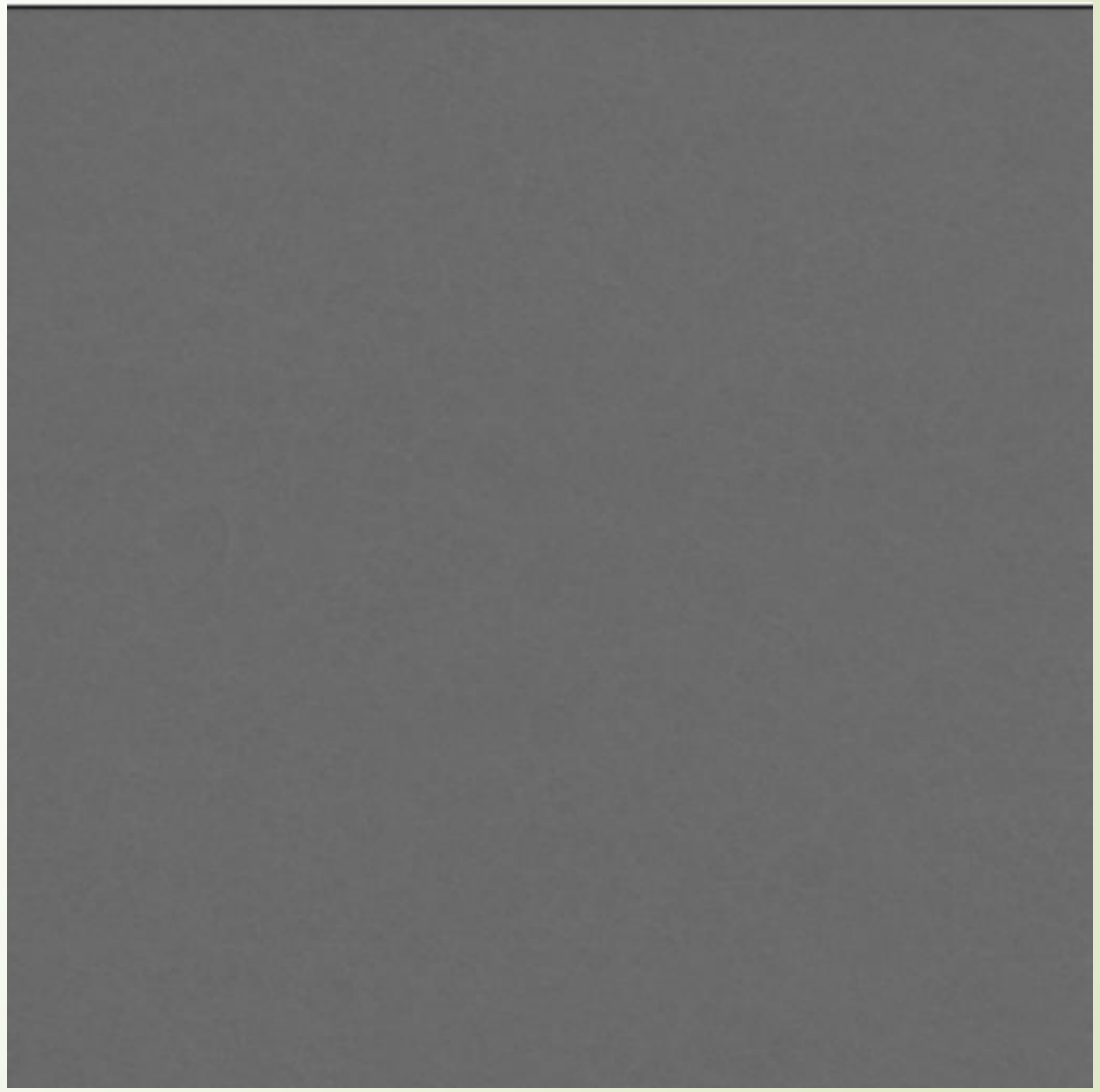
…and we want cryo-ET to grow equally well very soon!

What's so hard about that?

- Radiation damage
  - ~10 e-/Å^2 significantly alter structure
  - ~100 e-/Å^2 cause bubbles, etc.

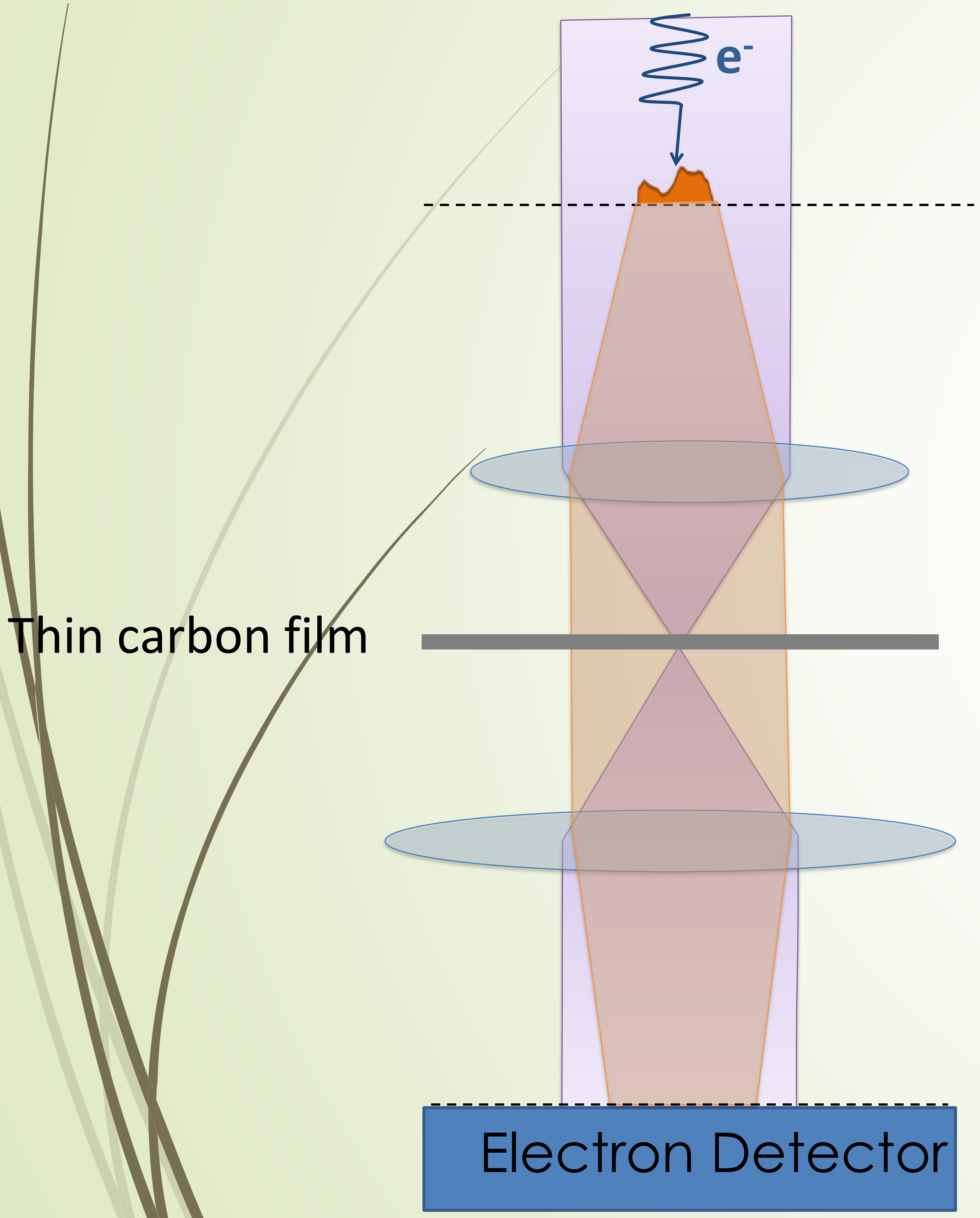
=> Very low SNR <0.1

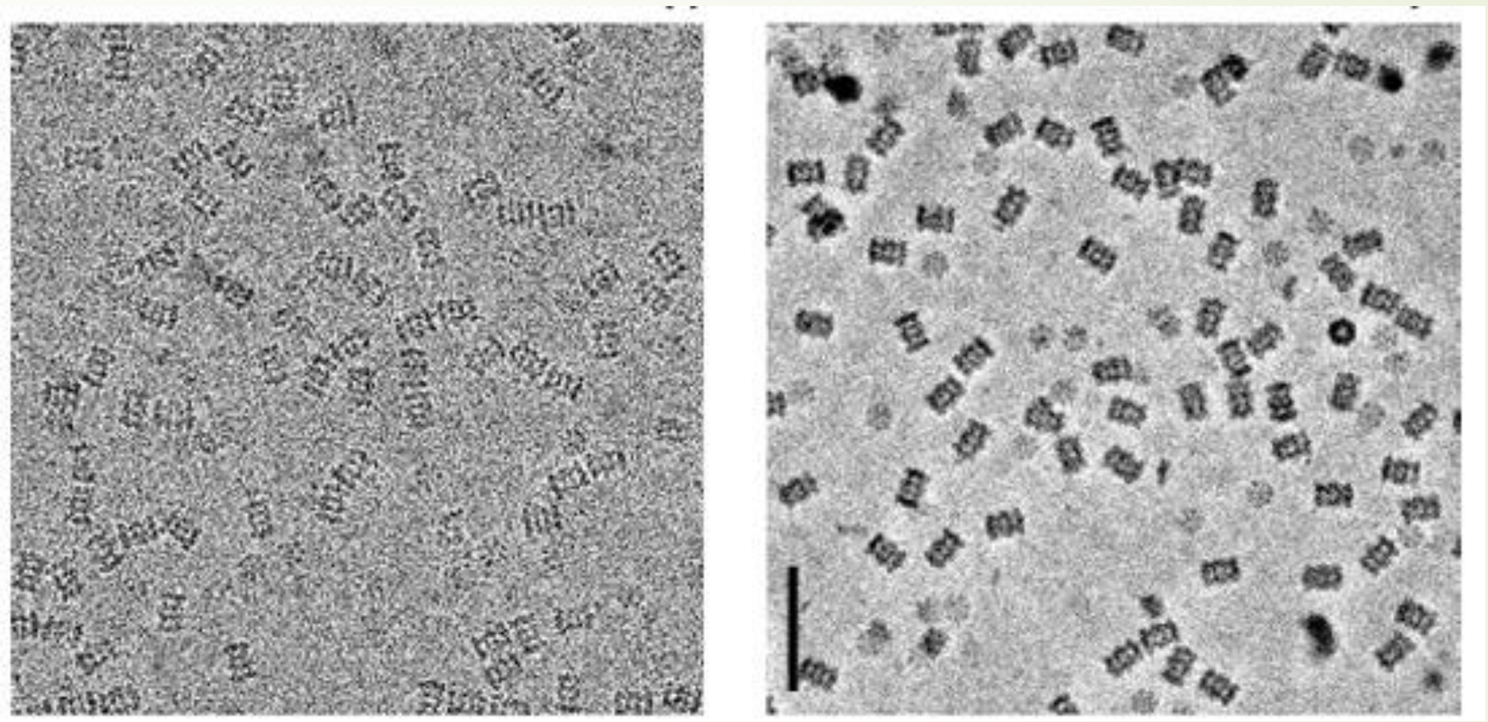
  - Need to average 10,000s of particles,100s-1,000s should suffice
  - Tomography extremely difficult



Raw image example

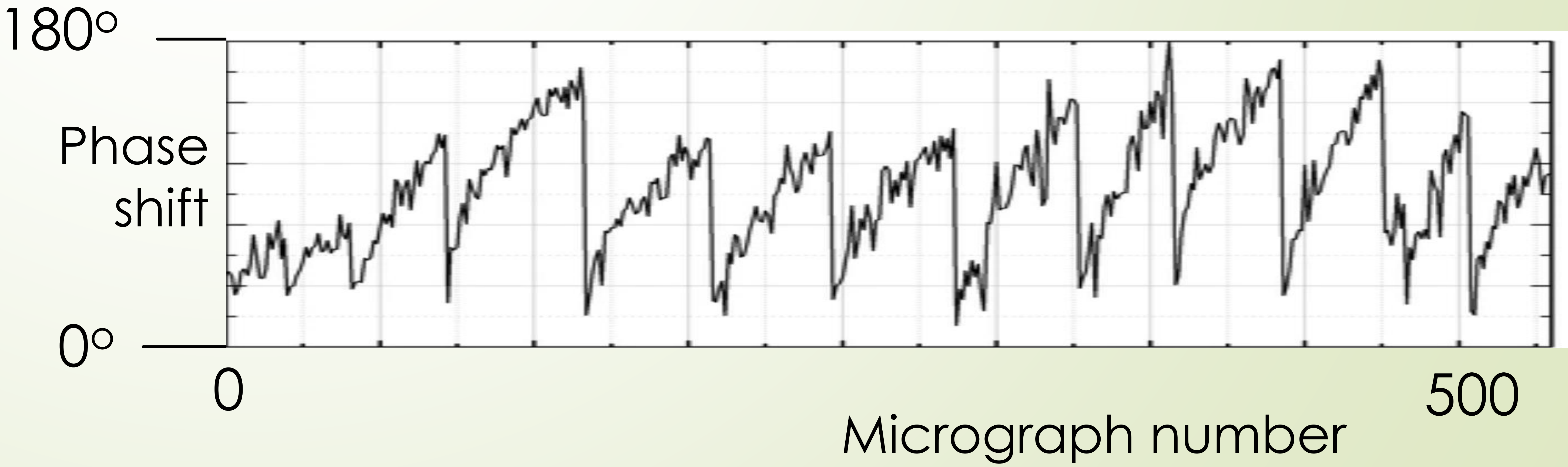
(Volta) phase contrast is elegant, but…



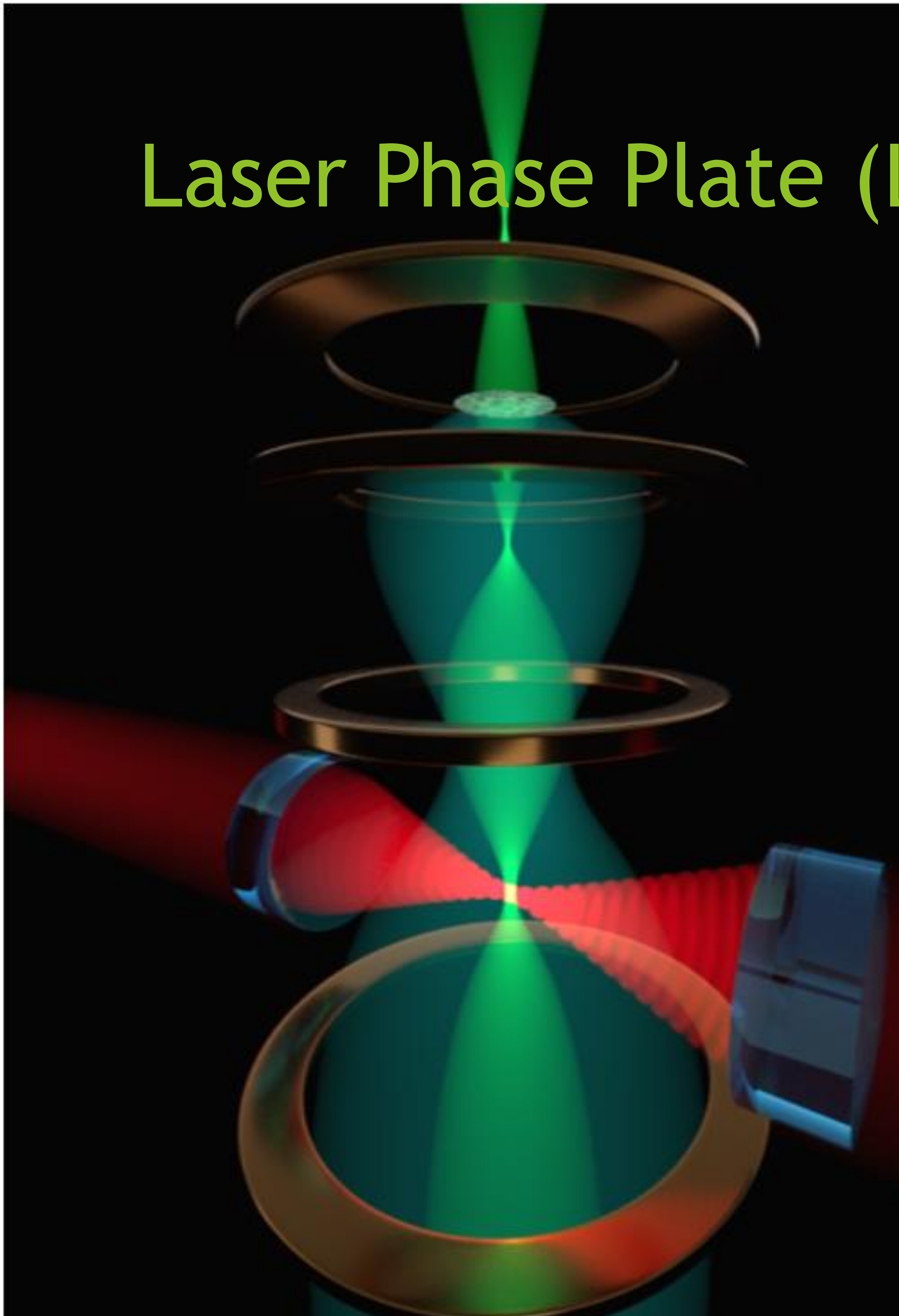


Danev et al., *eLife 6:e23006*, 2017.

- …effect is not well-controlled
- …few labs have successfully tried it



Laser Phase Plate (LPP)



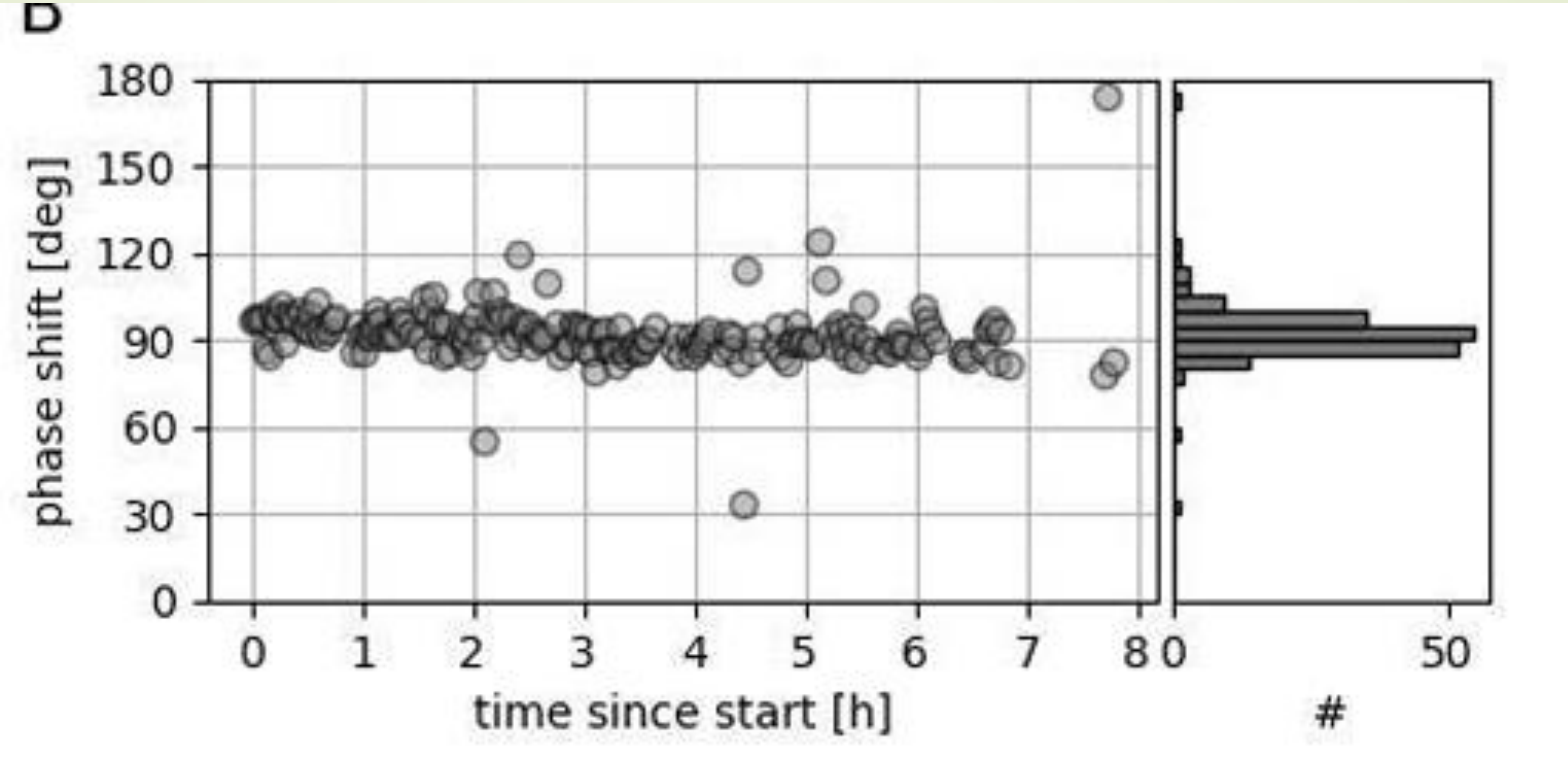
- Phase shift through ponderomotive potential

- No charging
- No radiation damage
- Well-controlled

- Need 75 kW focused to 8 μm for 300 keV beam

…but needed relay optics triples Cc currently

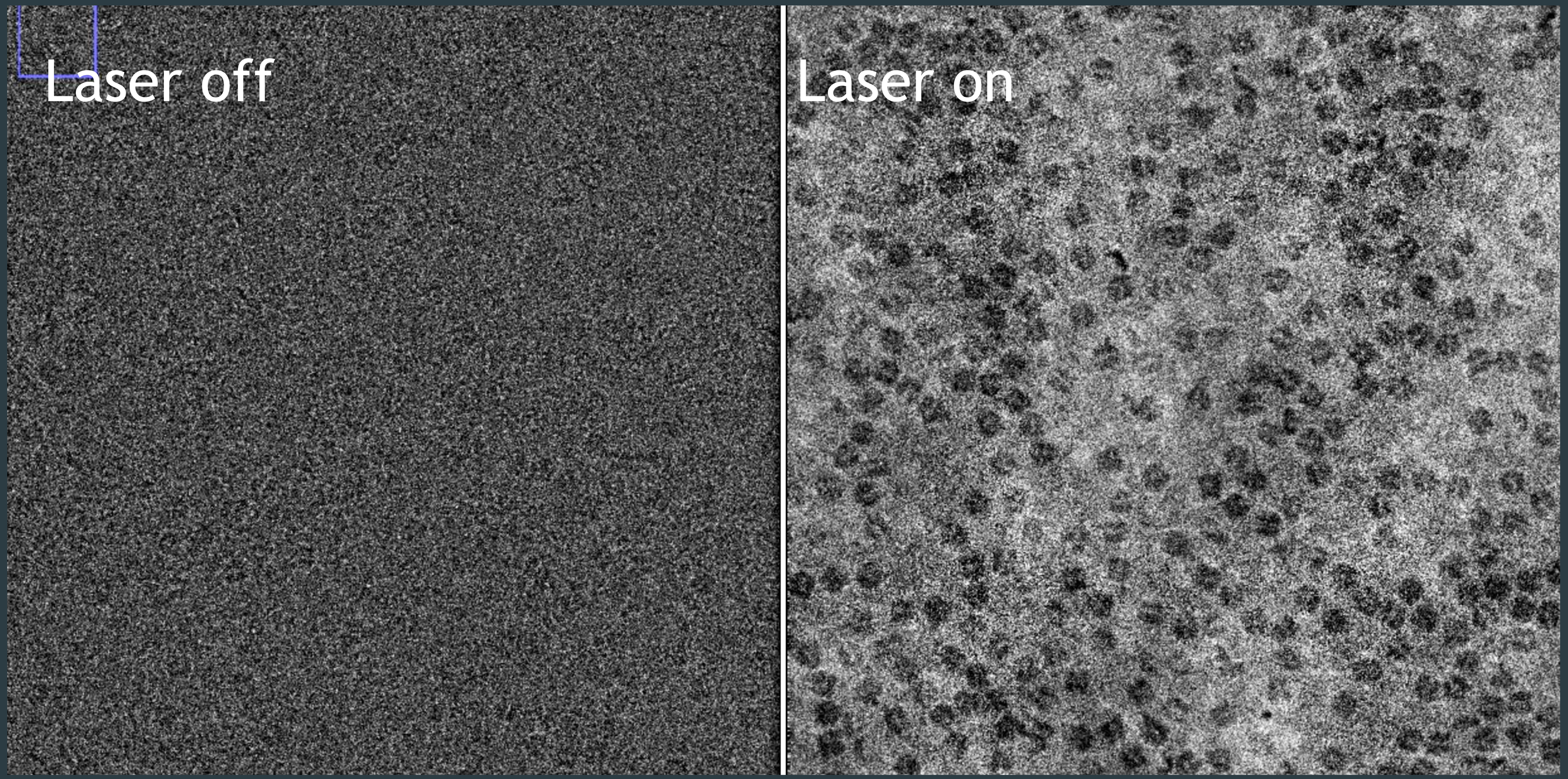

0.78
3.41



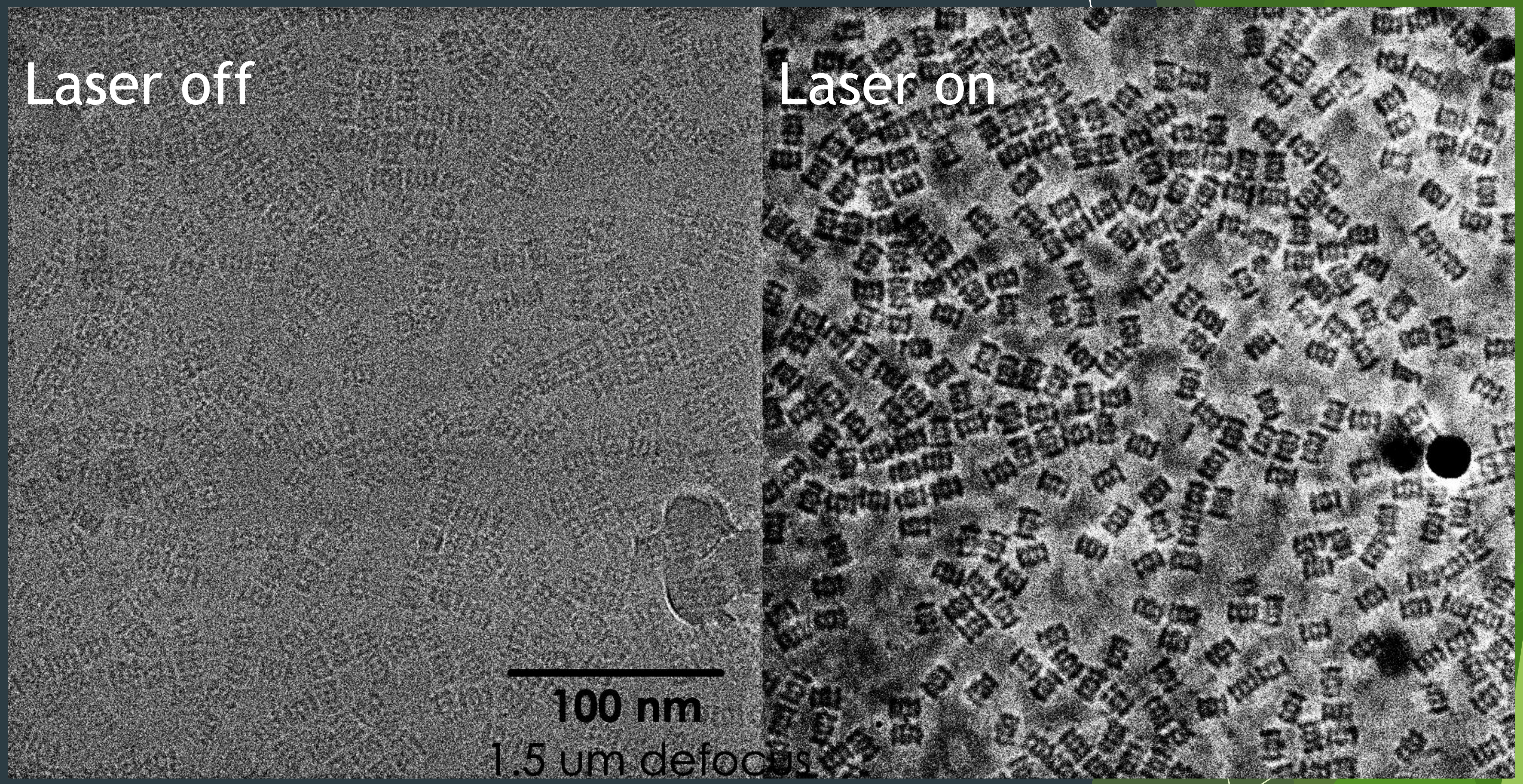
Phase shift is stable

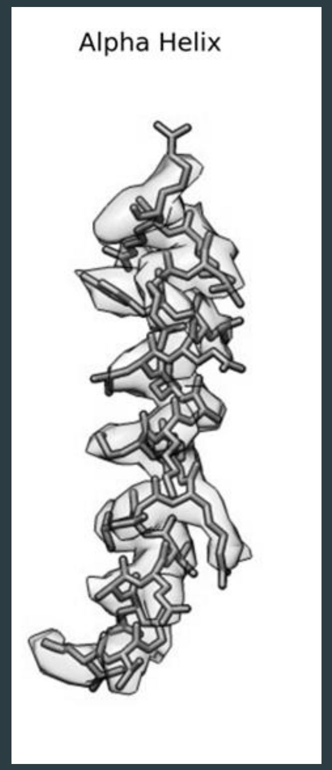
Single-particle cryo-EM with the LPP

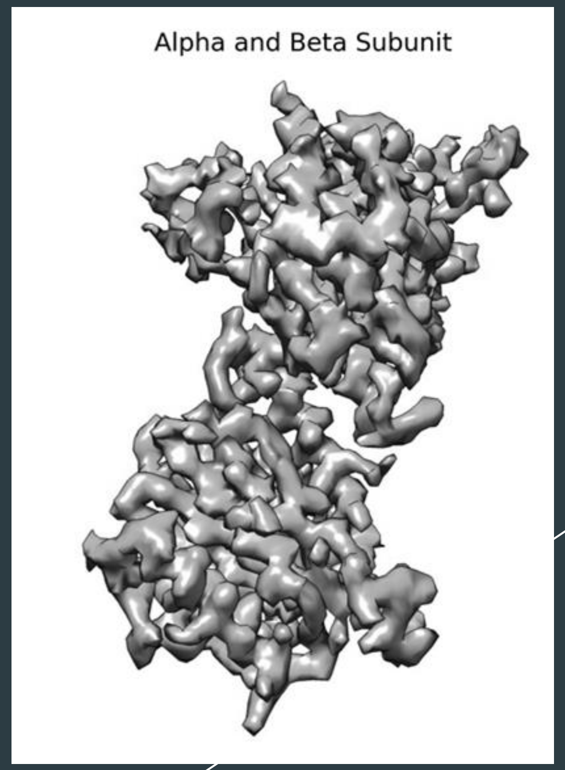
Rubisco



20S proteasome



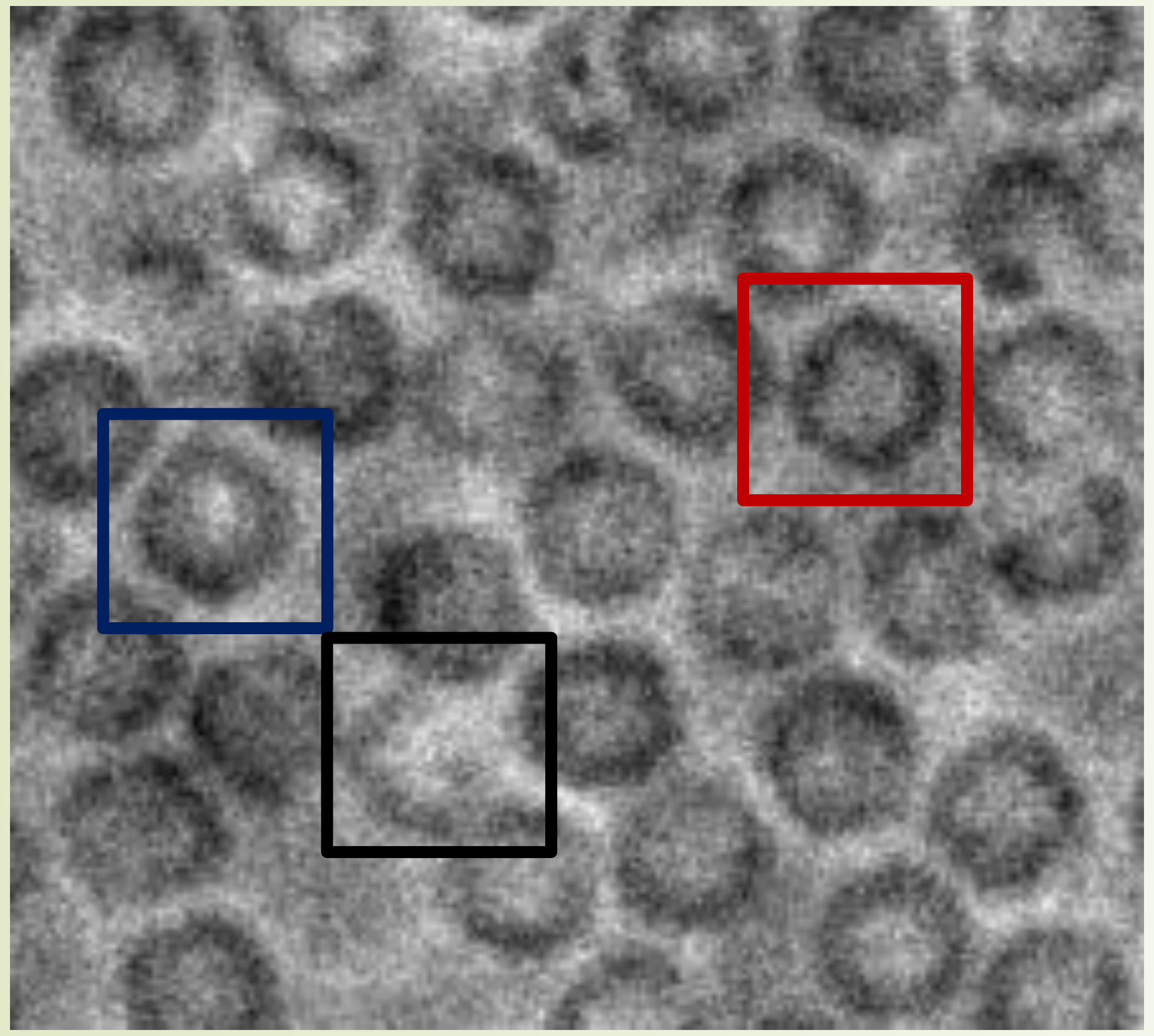




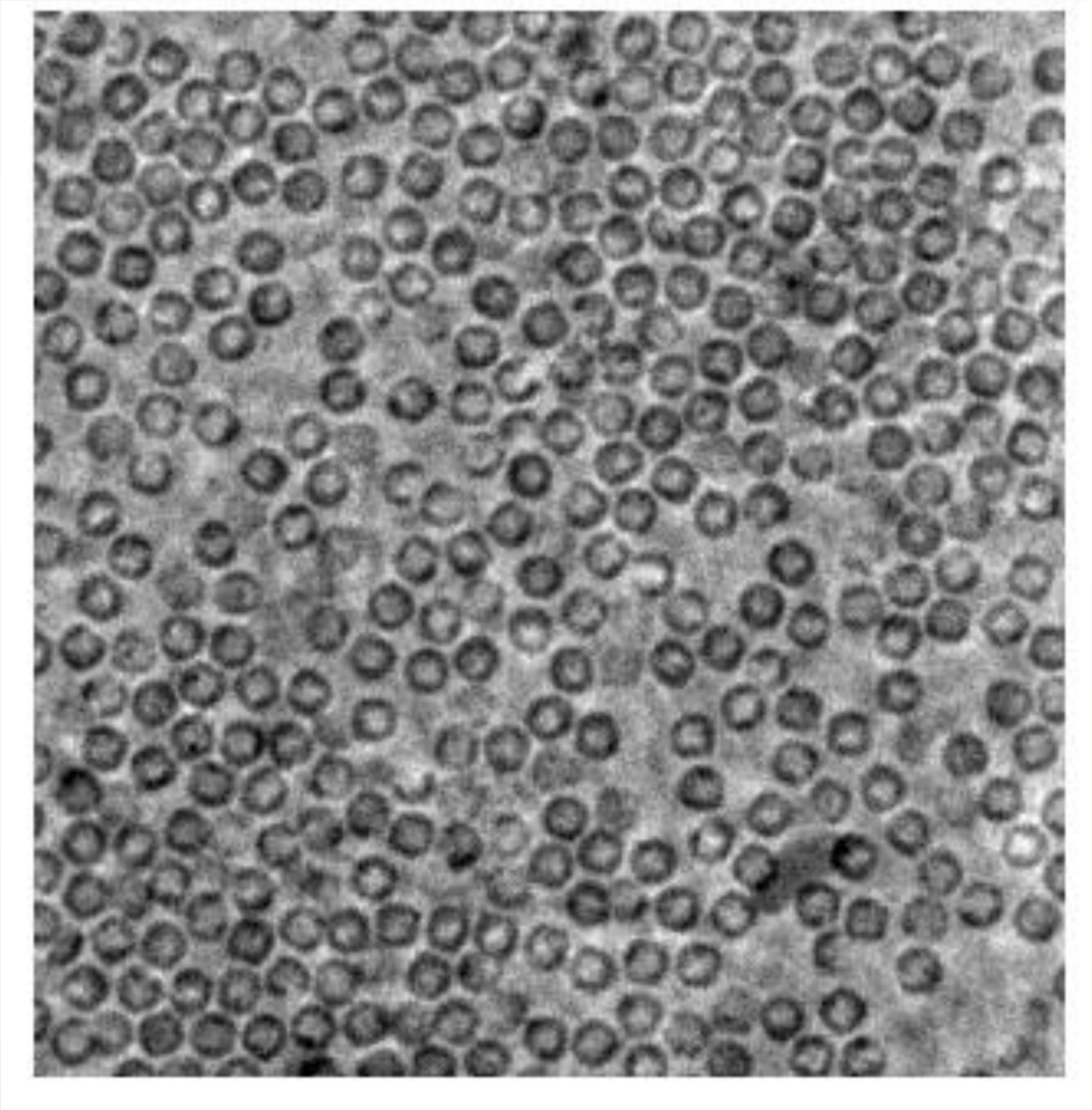
Thanks to Yifan Cheng!

Carter Turnbaugh, et al., [Rev. Scientific Instrum. 92, 053005 (2021)]

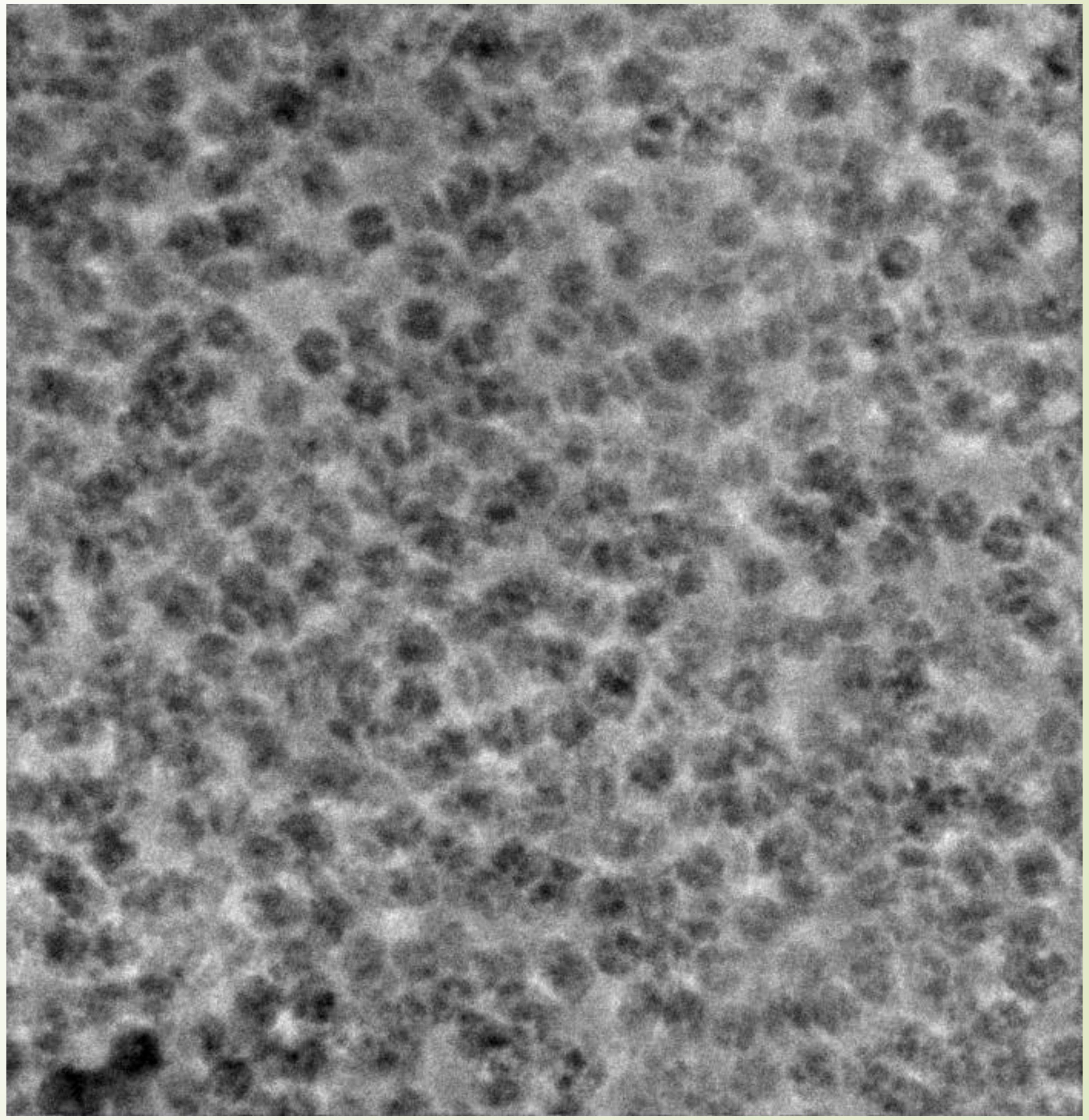
LPP reveals unexpected particle-to-particle variations…



Light center ("ring")
Dark center ("disc")
Incomplete rings ("Gs")



ApoF

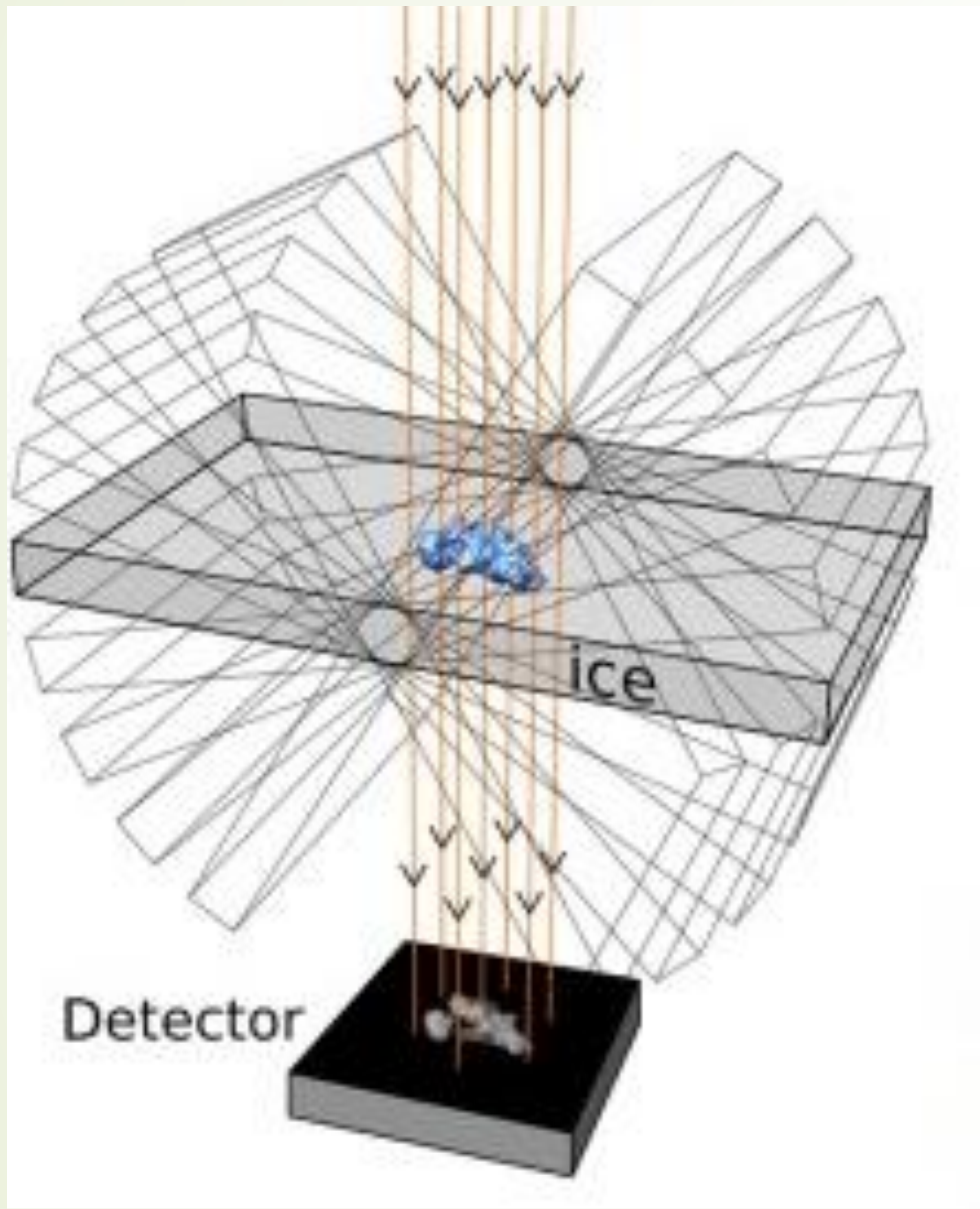


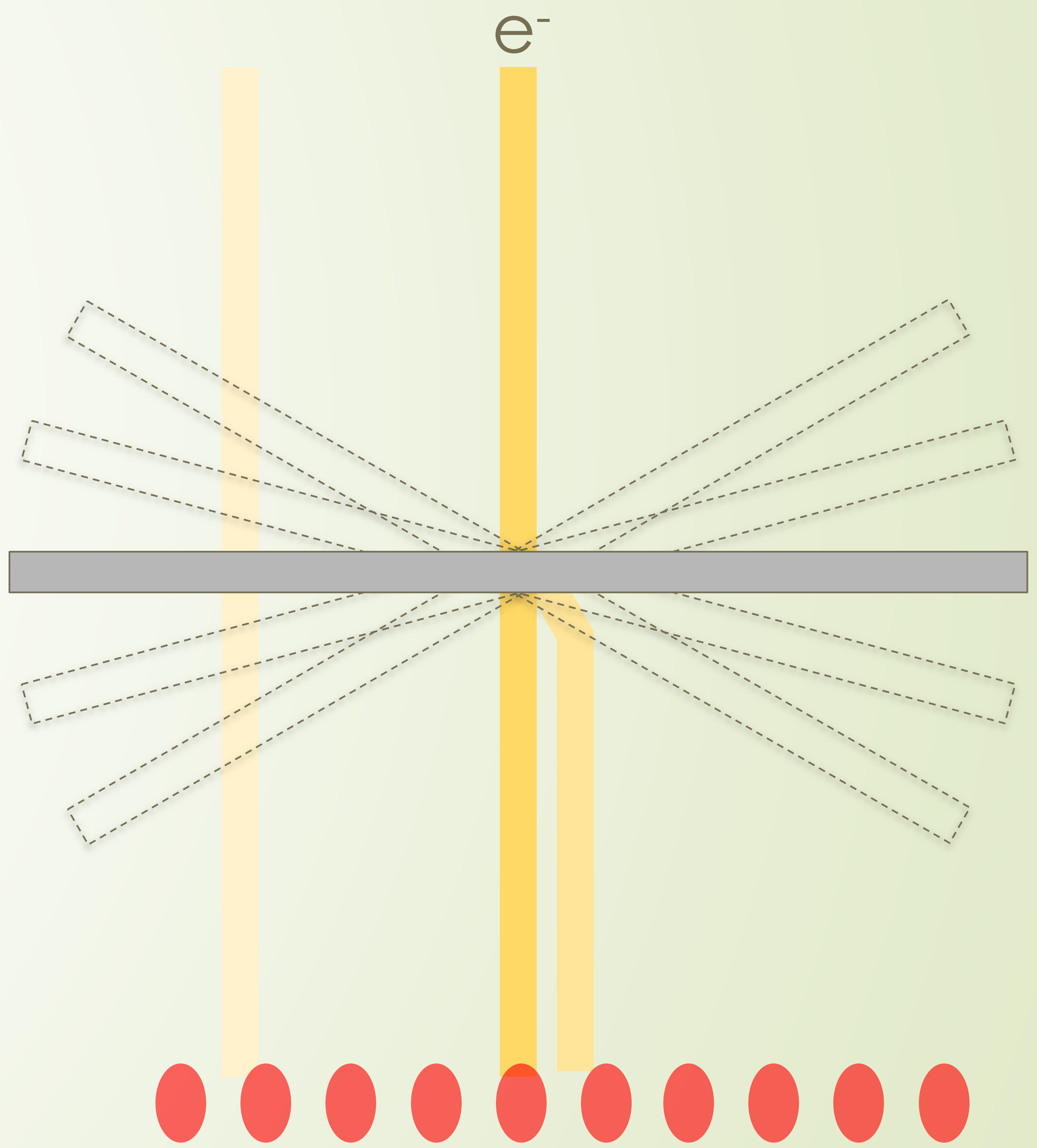
Rubisco

…making structural heterogeneity much more visible

- See structural variation between *individual* particles (rather than class average)
- AI can be trained to do this in large datasets
- Doing so on a large scale may open new areas in cell & structural biology

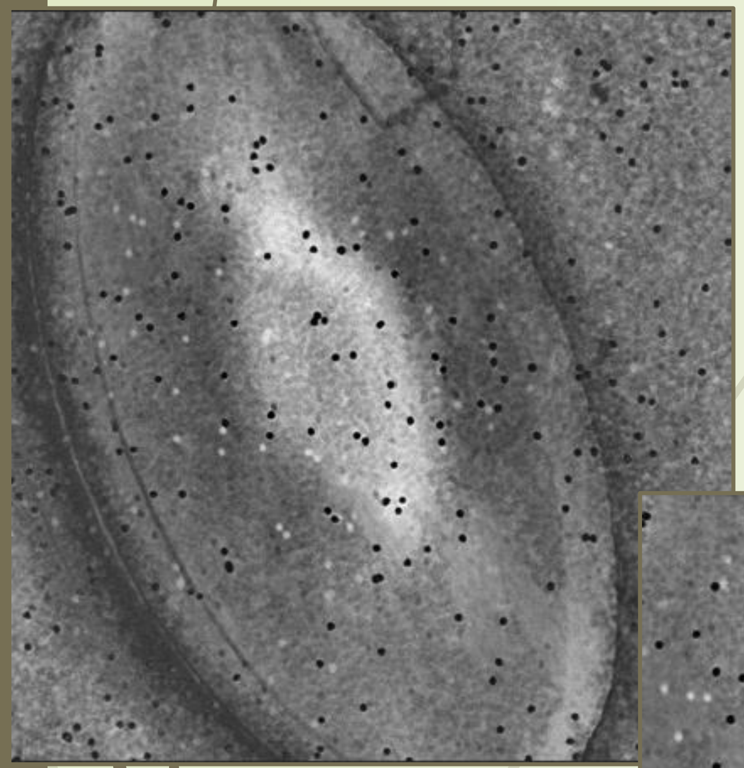
Tomography is the next frontier….



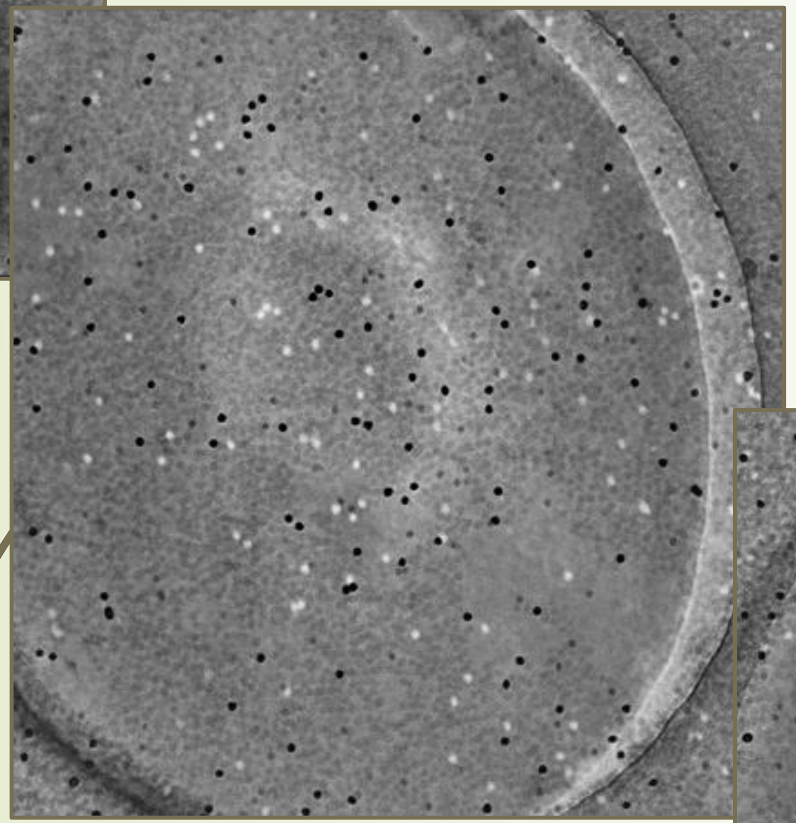


…but can we align the electron beam to the laser at each tilt angle?

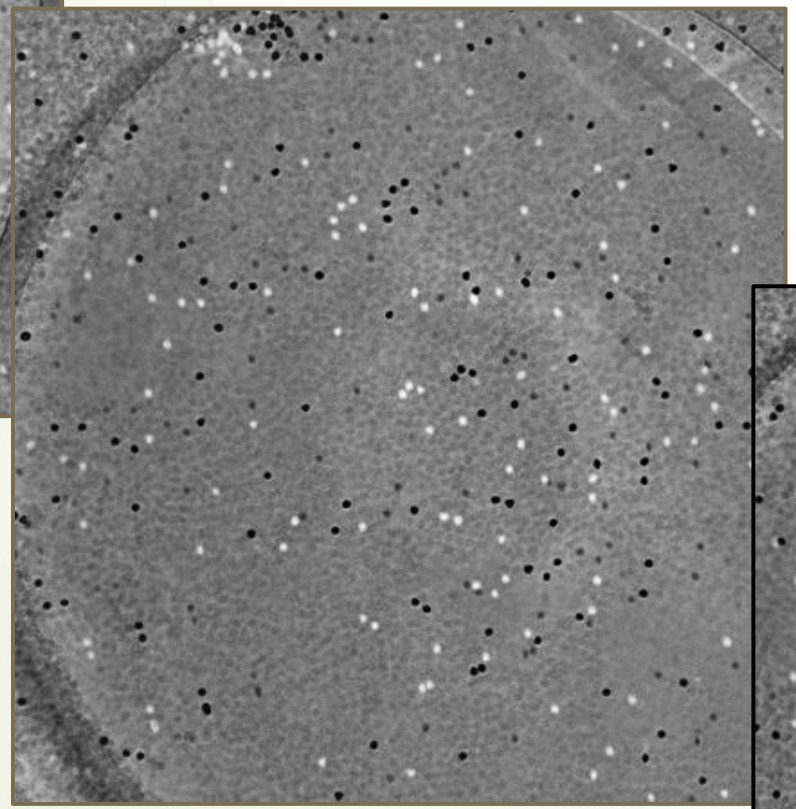
Rubisco on quantifoil grids, uncoated
-57° to 57° in 3° increments
-24° to 24° symmetric
2e-/ tilt angle



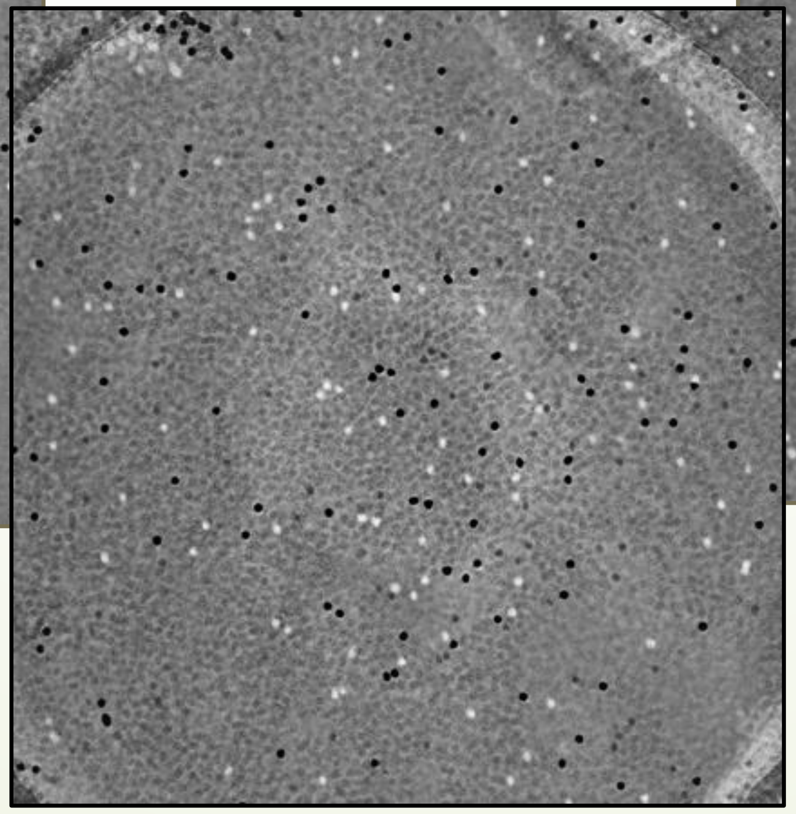
-57°



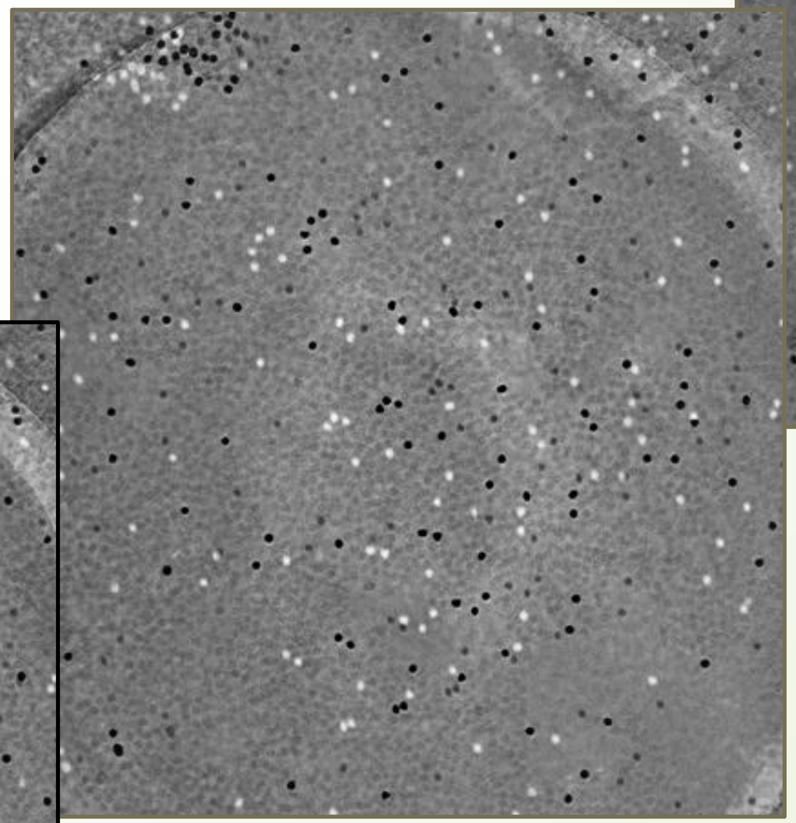
-32°



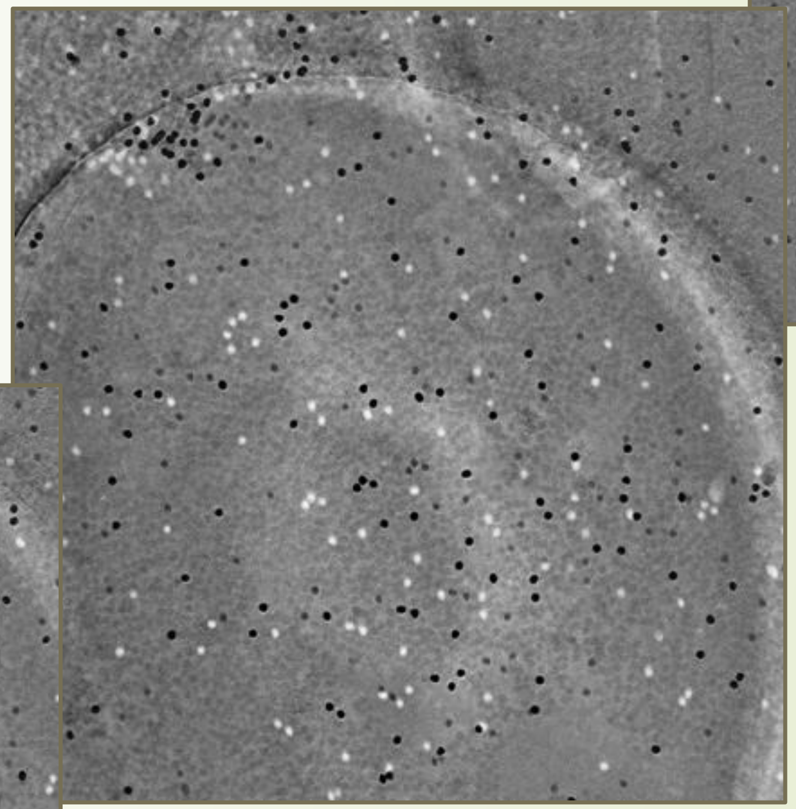
-15°



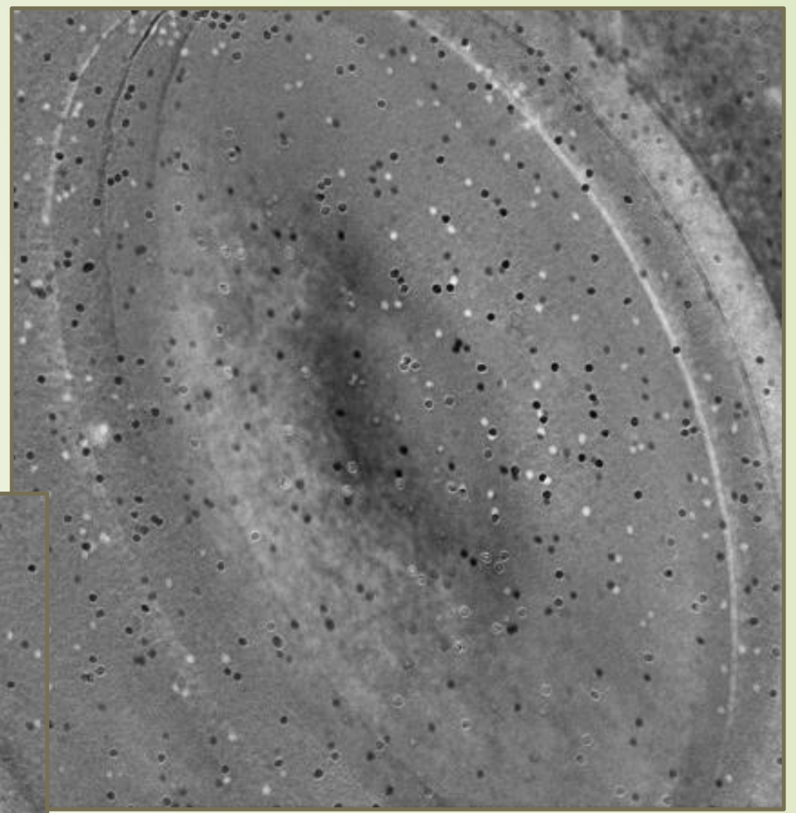
0°



+15°

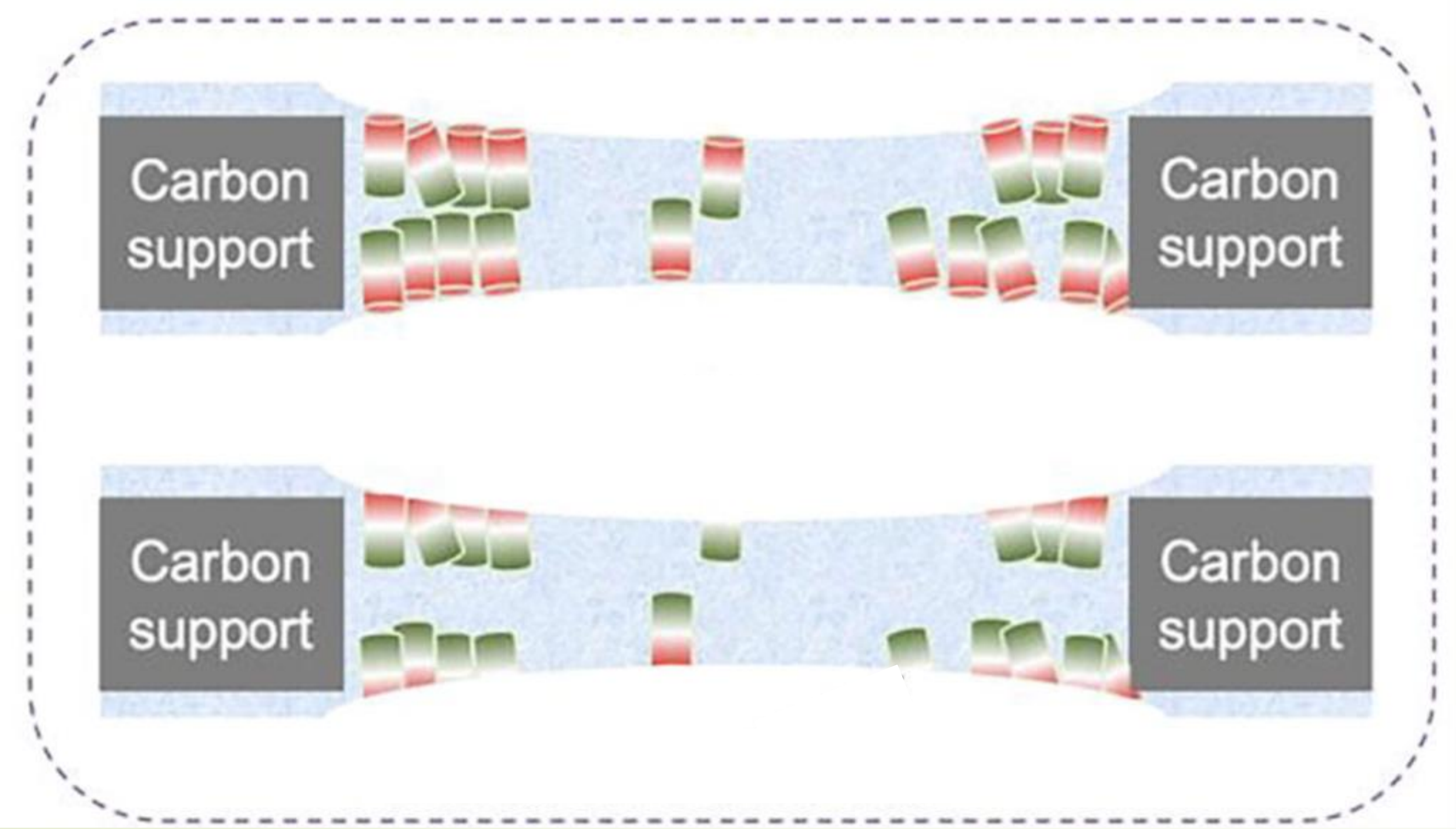


+32°



+57°

Tomogram (laser on) z-slices 0 to 84 nm



Hongwei Wang's talk
Journal of molecular biology 435, 9, 167926 (2023)

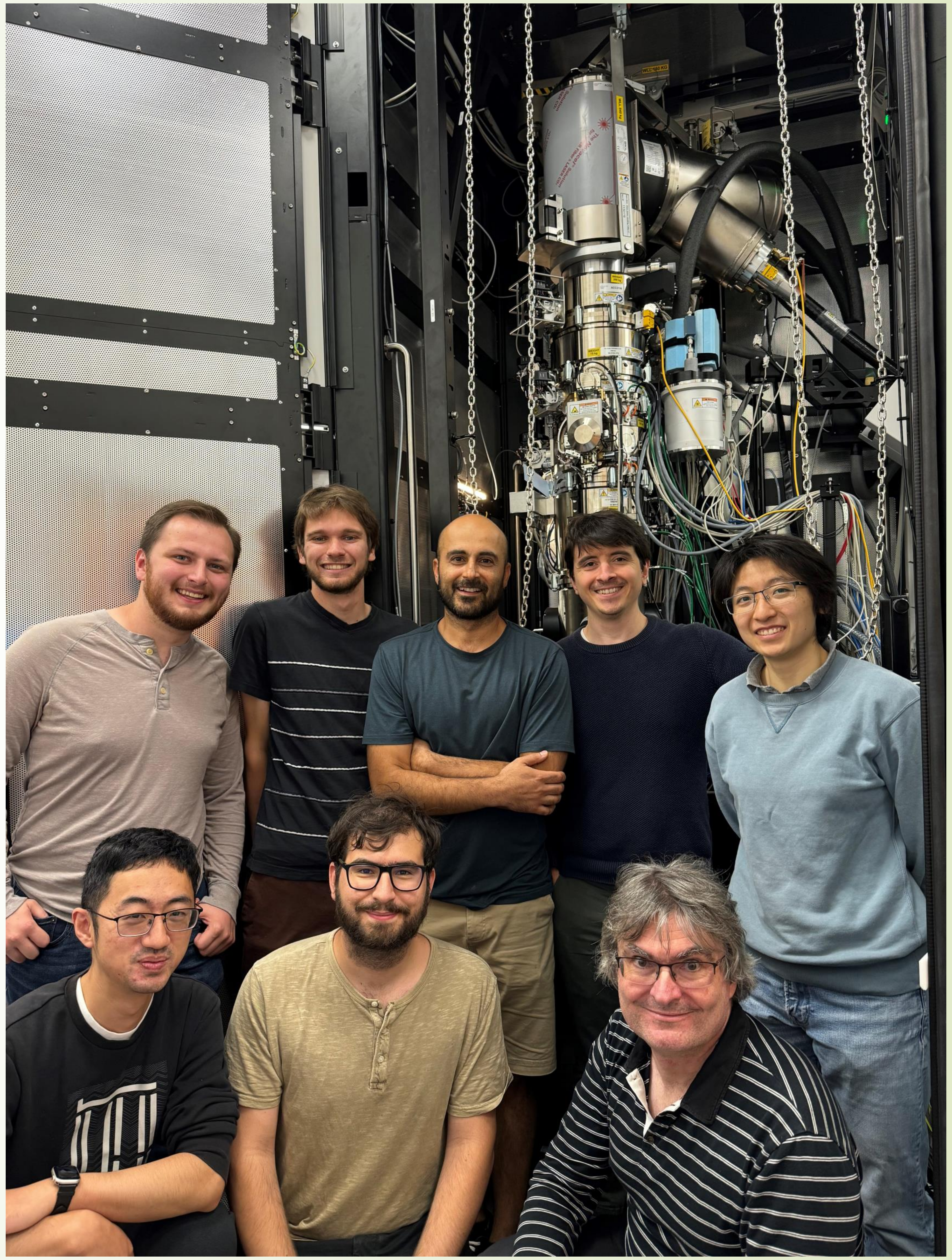
We expect much better results with the new microscope

First images in Fall 2024 (projected)

- 1 Å resolution instead of 3 Å
- Cs- correction
- Long effective focal length
- High throughput

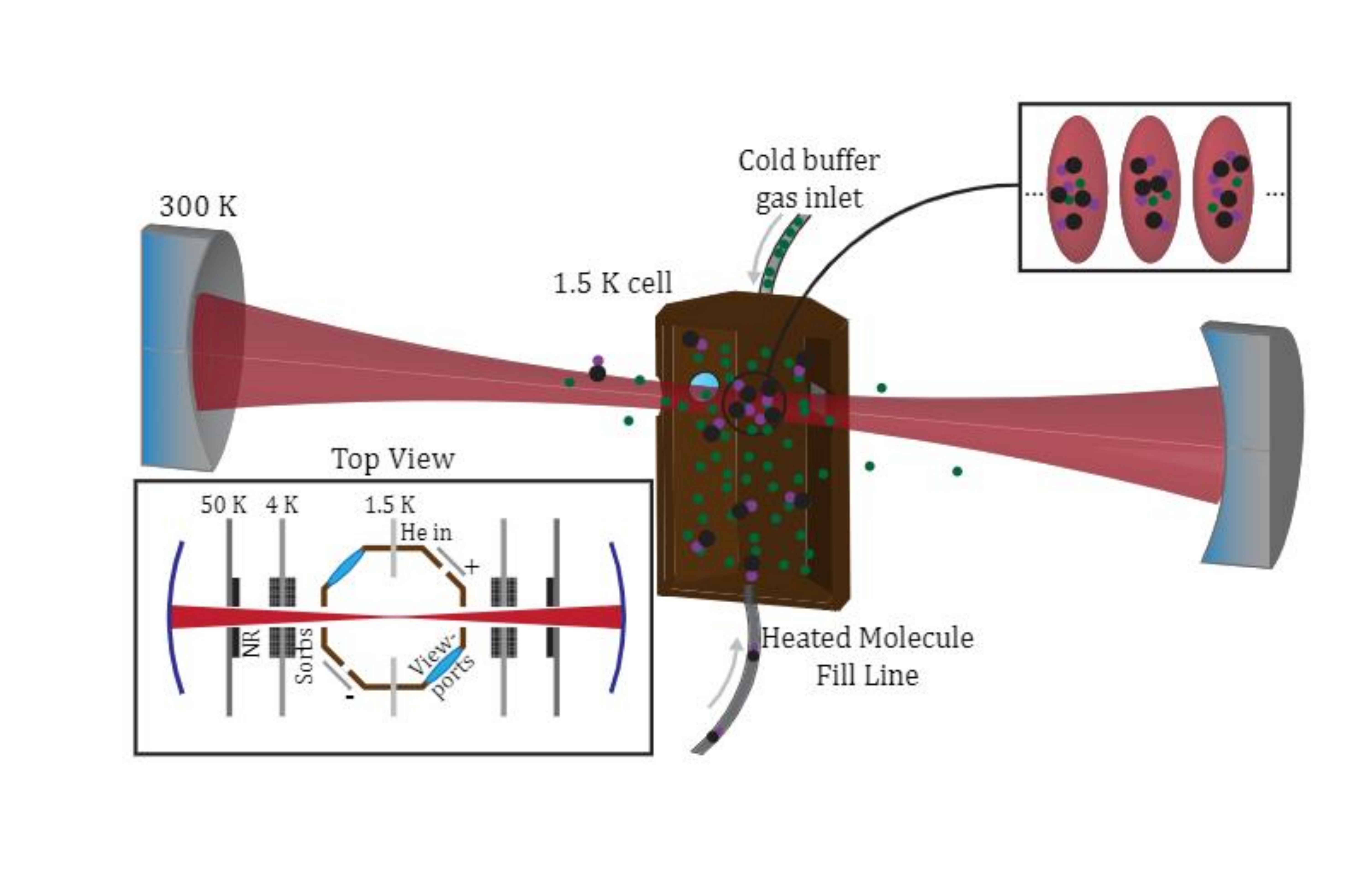
Getting ready for applications

- Nearly 100% of the information that is carried by the electron beam is finally accessible.
- Hope to see images in 2024
- Working with CZII on XLPP & outfitting their microscope
- Working with TFS to transfer the technology



- Alpha: Jack Roth, Madeline Bernstein, Andrew Christensen, & Yuno Iwasaki
- Lattice interferometer: Prabudhya Bhattacharyya, James Egelhoff, Garrett Louie, Cristian D. Panda, & Matthew J. Tao
- TEM & cavities: Jessie Zhang, Petar Petrov, Jeremy Axelrod, Hang Chen, Ian Hicklin, Jonathan Remis, & Robert M. Glaeser

Bringing it all back home: universal dipole trap



- Insensitive to internal state, energy level structure, and magnetic properties.
- Helium buffer gas at 1.5 K
- 10-20K trap depth
- Studied loading dynamics, loss rates
- Potentially new possibilities in molecular spectroscopy, cold chemical reactions, precision measurement