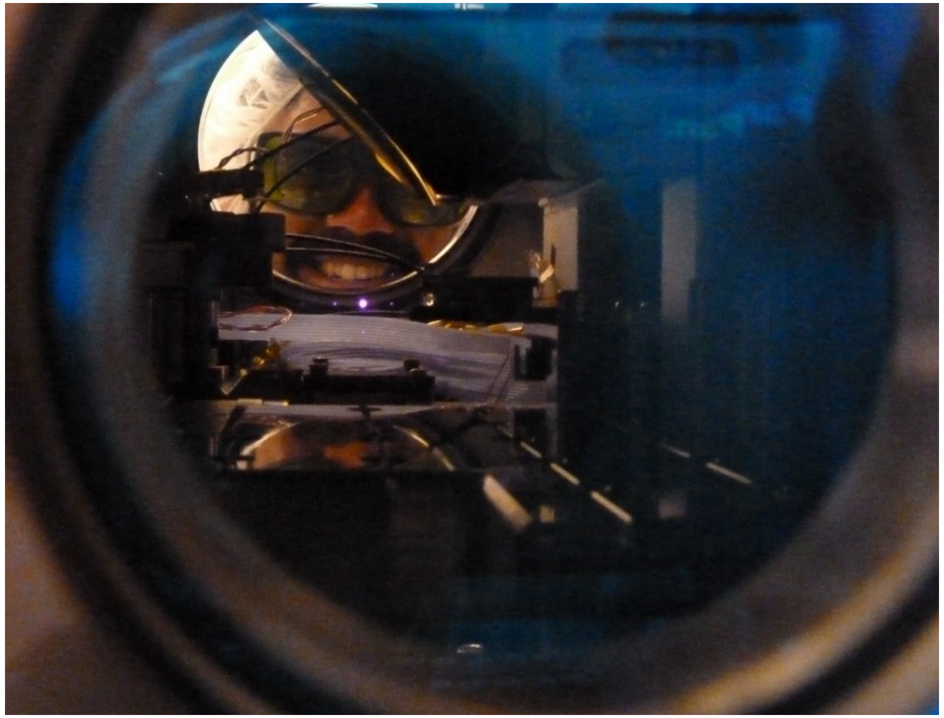
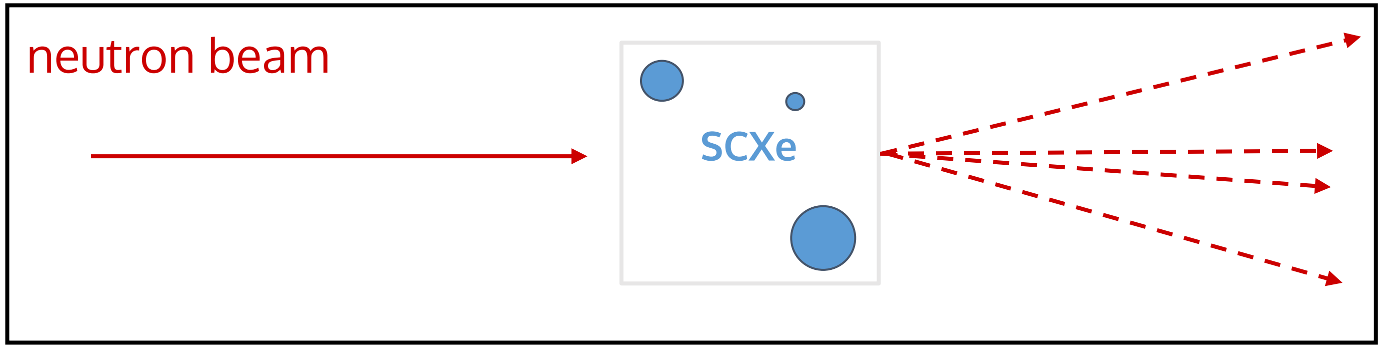
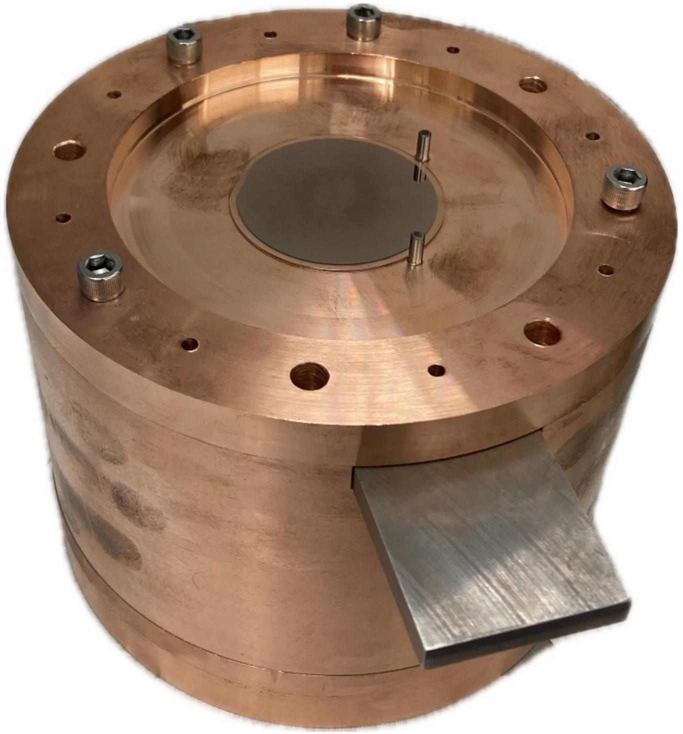
Testing Gravity at Ever Shorter Scale

a trip into exotic experimental physics







Giorgio Gratta
Physics Dept, Stanford

"My advice is to try crazy ideas and innovative experiments."

Steven Weinberg, APS News Feb 2019

The physics of Fundamental Particles and Interaction has traditionally embraced disparate techniques to crack the riddles of Nature.

Some examples

- Rutherford scattering experiments using alphas, vacuum chambers and fluorescent screens
- Stern-Gerlach experiments on spins, using magnetic field gradients
- Cosmic rays! Θ-τ puzzle. Discovery of the positron.
- Radioactive sources and the measurement of neutrino helicity
- Mössbauer spectroscopy and the first measurement of gravitational red/blue shift
- Nuclear reactors and the discovery of neutrinos
- Cyclotrons and the discovery of antiprotons
- Nuclear demagnetization cooling and the discovery of parity violation
- Accelerators and bubble chambers and the exploration of hadron physics
- Many more results from ever increasing energy accelerators and ever more complex detectors
- Colliders and W, Z, Jet physics, the Higgs
- Low background detectors and solar neutrinos
- Cosmic rays, the Sun, reactors and the discovery of neutrino oscillations

The physics of Fundamental Particles and Interaction has traditionally embraced disparate techniques to crack the riddles of Nature.

Some examples

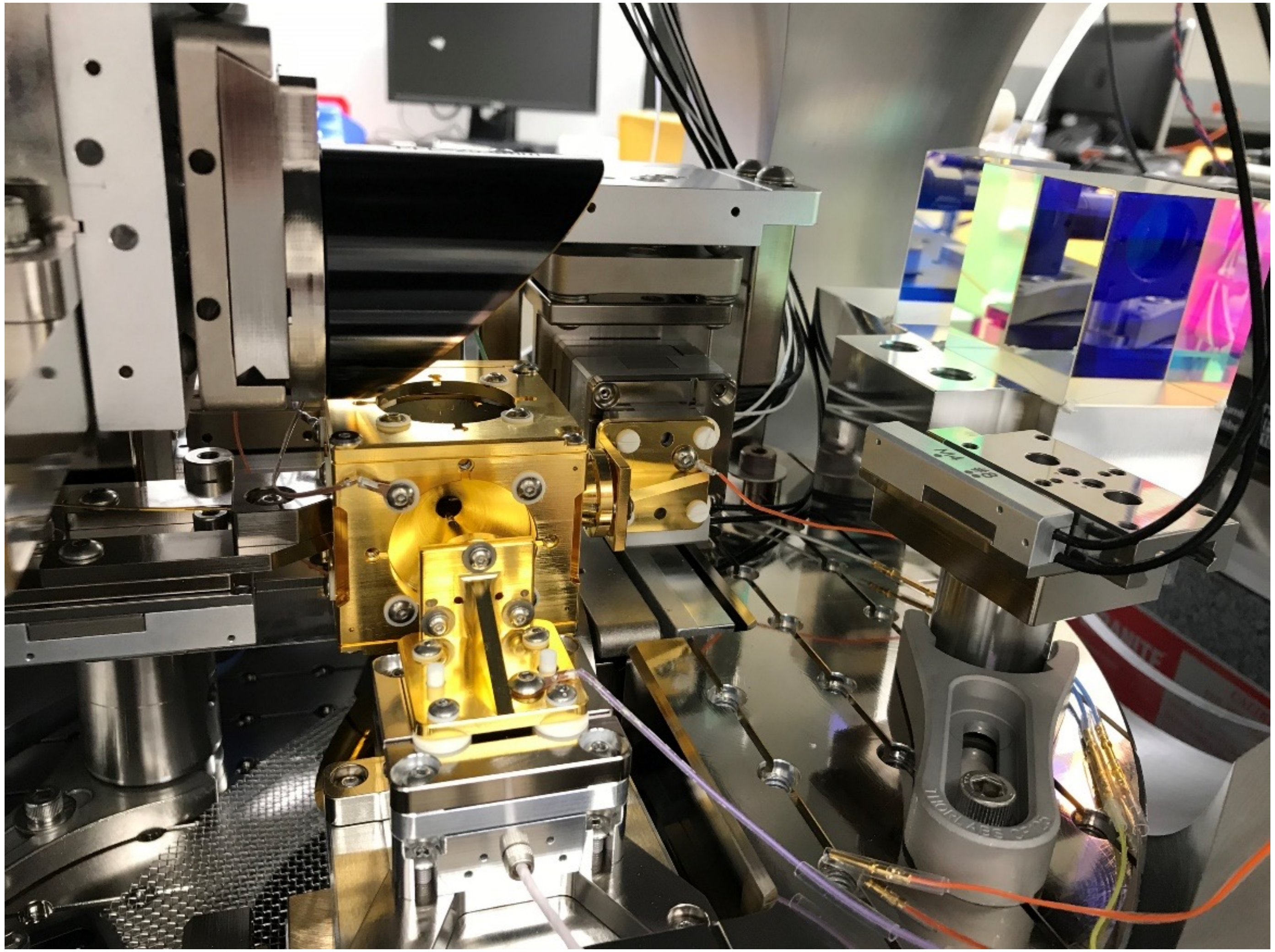
- Rutherford scattering experiments using alphas, vacuum chambers and fluorescent screens
- Stern-Gerlach experiments on spins, using magnetic field gradients
- Cosmic rays! Θ-τ puzzle. Discovery of the positron.
- Radioactive sources and the measurement of neutrino helicity
- Mössbauer spectroscopy and the first measurement of gravitational red/blue shift
- Nuclear reactors and the discovery of neutrinos
- Cyclotrons and the discovery of antiprotons
- Nuclear demagnetization cooling and the discovery of parity violation
- Accelerators and bubble chambers and the exploration of hadron physics
- Many more results from ever increasing energy accelerators and ever more complex detectors
- Colliders and W, Z, Jet physics, the Higgs
- Low background detectors and solar neutrinos
- Cosmic rays, the Sun, reactors and the discovery of neutrino oscillations

Whither the path? There is no path where no one has gone before!

Faust, Goethe, 1808

Plan

- Measuring gravity at short distance, new physics opportunities
- The physics of optically levitated dielectric microspheres
- Results in the 1 - 50μm range
- Mössbauer spectroscopy and the quest for new physics
- Status of first precision Mössbauer spectroscopy run
- (Neutron scattering experiments)



Gravity is:

- **the most evident**
- **the weakest**
- **the least well-known interaction in Nature**

Fundamental interactions	Normalized Strength	Effective Range (m)
Strong Nuclear Force	10^{38}	10^{-15}
Electromagnetic Force	10^{36}	∞
Weak Nuclear Force	10^{25}	10^{-18}
Gravity	1	∞

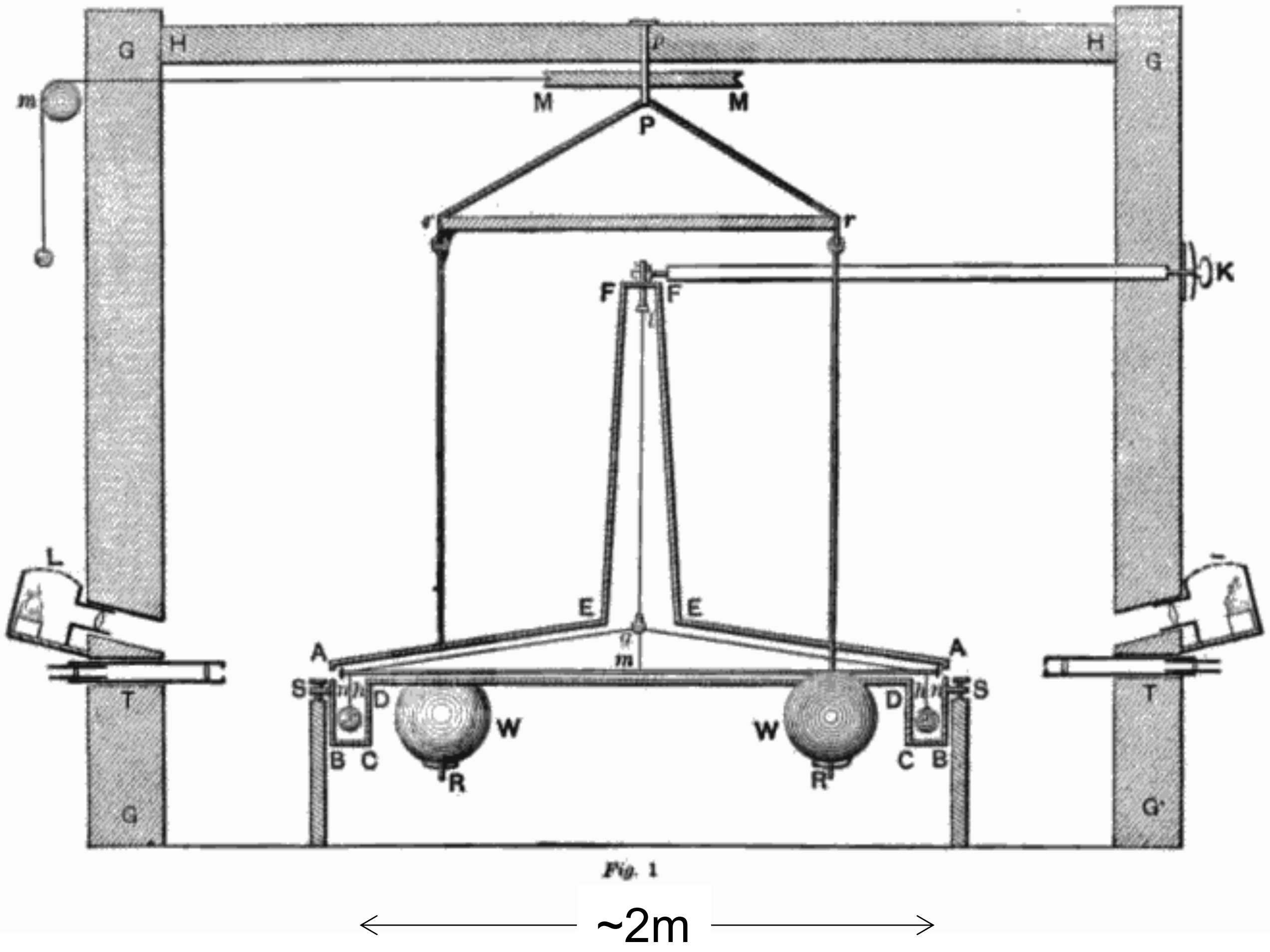
Most of the empirical features of gravity and differences in phenomenology from the other interactions can be understood in terms of the parameters above.

In addition, there is no such thing as "antigravity", so gravity cannot be shielded, which explains why this weakest force is so evident:

e.g. keeps the solar system together.

The first laboratory experiment on gravity

Apparatus by Rev. John Mitchell, used by Henry Cavendish to "Determine the Density of the Earth".

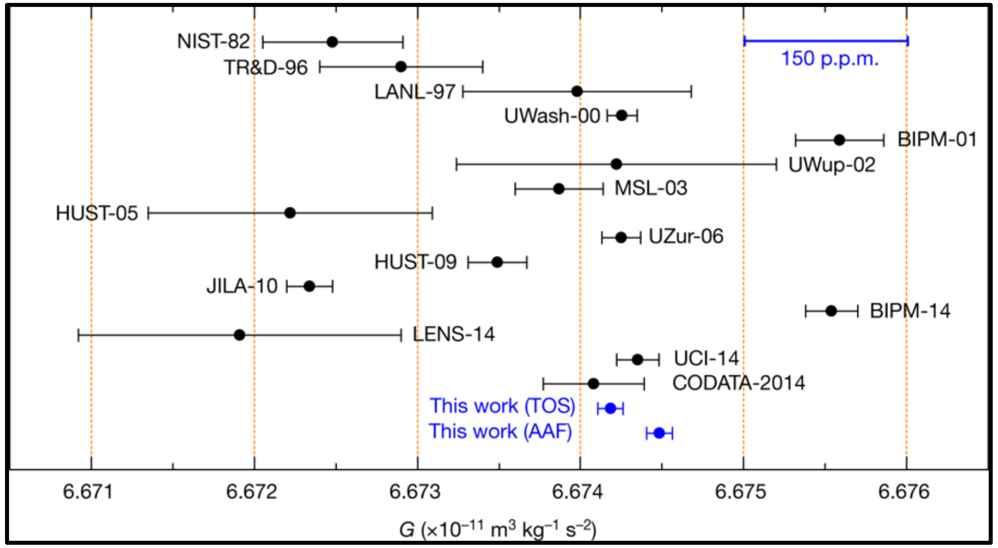


H.Cavendish, Phil. Trans. Royal Soc. London (part II) 88, p469-526 (21 Jun 1798, 228 years ago!)

Cavendish's measurement, in terms of G, gives

$$G = (6.74 \pm 0.04) \cdot 10^{-11}\, \mathrm{m^3 kg^{-1} s^{-2}} \quad \sim 0.6\%, \quad (1798)$$

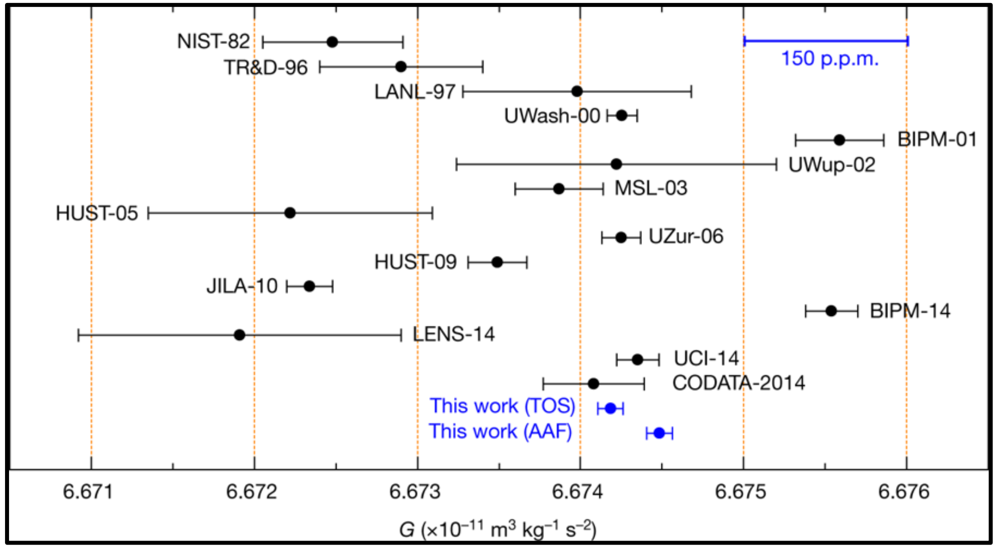
Current measurements have 11 ppm uncertainty,
but there is a few sigma disagreement between the two most recent ones (Li et al., Nature 560 (2018) 582)



At the same time we know
- **the QED coupling constant, α, to 0.23ppb**
- **the weak coupling constant, G_F, to 0.5ppm**

Cavendish's measurement, in terms of G, gives

$$G = (6.74 \pm 0.04) \cdot 10^{-11}\, \mathrm{m^3 kg^{-1} s^{-2}} \quad \sim 0.6\%, \quad (1798)$$



Current measurements have 11 ppm uncertainty,
but there is a few sigma disagreement between the two most recent ones (Li et al., Nature 560 (2018) 582)

At the same time we know
- **the QED coupling constant, α, to 0.23ppb**
- **the weak coupling constant, G_F, to 0.5ppm**

However, since we do not know how to calculate G from other quantities in physics, we do not expect to find new physics in the absolute value of G.

More interesting is to test if there are deviations from the $1/R^2$ law for gravity.

The inverse square law is generally assumed to work all the way down to the Planck length $R_P = \sqrt{\frac{G\hbar}{c^3}} = 1.6\times10^{-35}\mathrm{m}$

Of course, this is a bold assumption that requires experimental verification.

In addition, there are important theoretical reasons to suspect that deviation from $1/R^2$ may actually arise naturally and be more than just plausible.

Gravity is a notoriously rebellious interaction. Its quantum field theory is not as well established as that of other fundamental interactions.

And gravity at ordinary energies/distances is so much weaker than any of the other fundamental interactions.

Why? Are those issues related to each other?

Will the solutions of these puzzles simultaneously solve other modern puzzles in physics, such as those of Dark Matter or Dark Energy.

Anyway, one can take the point of view that exploring the law of gravity at any distance is such an important endeavor that should be carried out irrespective of theoretical prejudice.

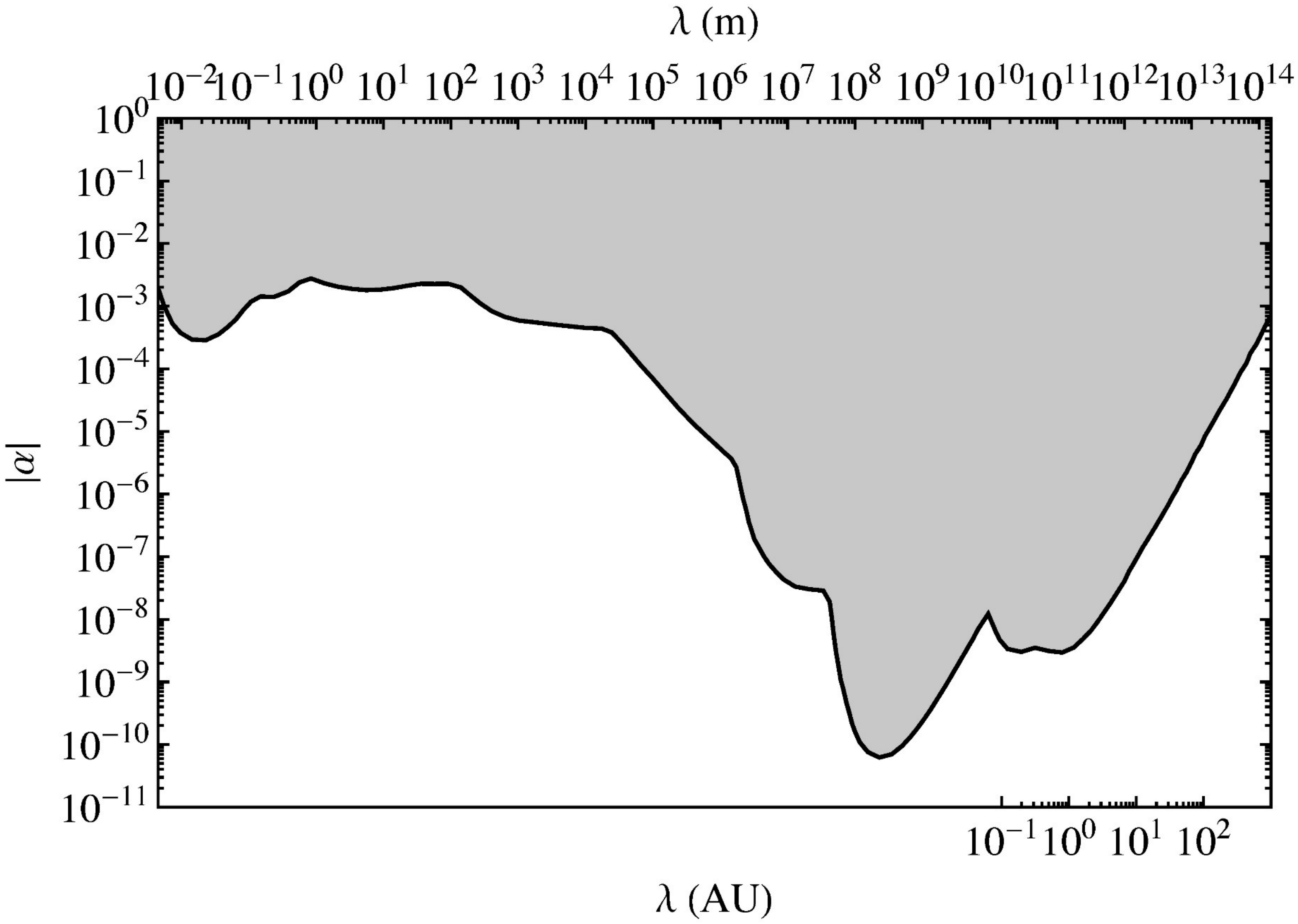
So, how well do we know that the inverse square law applies?

It is customary to express potential deviations from the $1/R^2$ law by modifying the potential with a Yukawa term, obtaining:

$$V(R) = G\frac{M_1 M_2}{R}\left(1 + \alpha e^{-R/\lambda}\right)$$

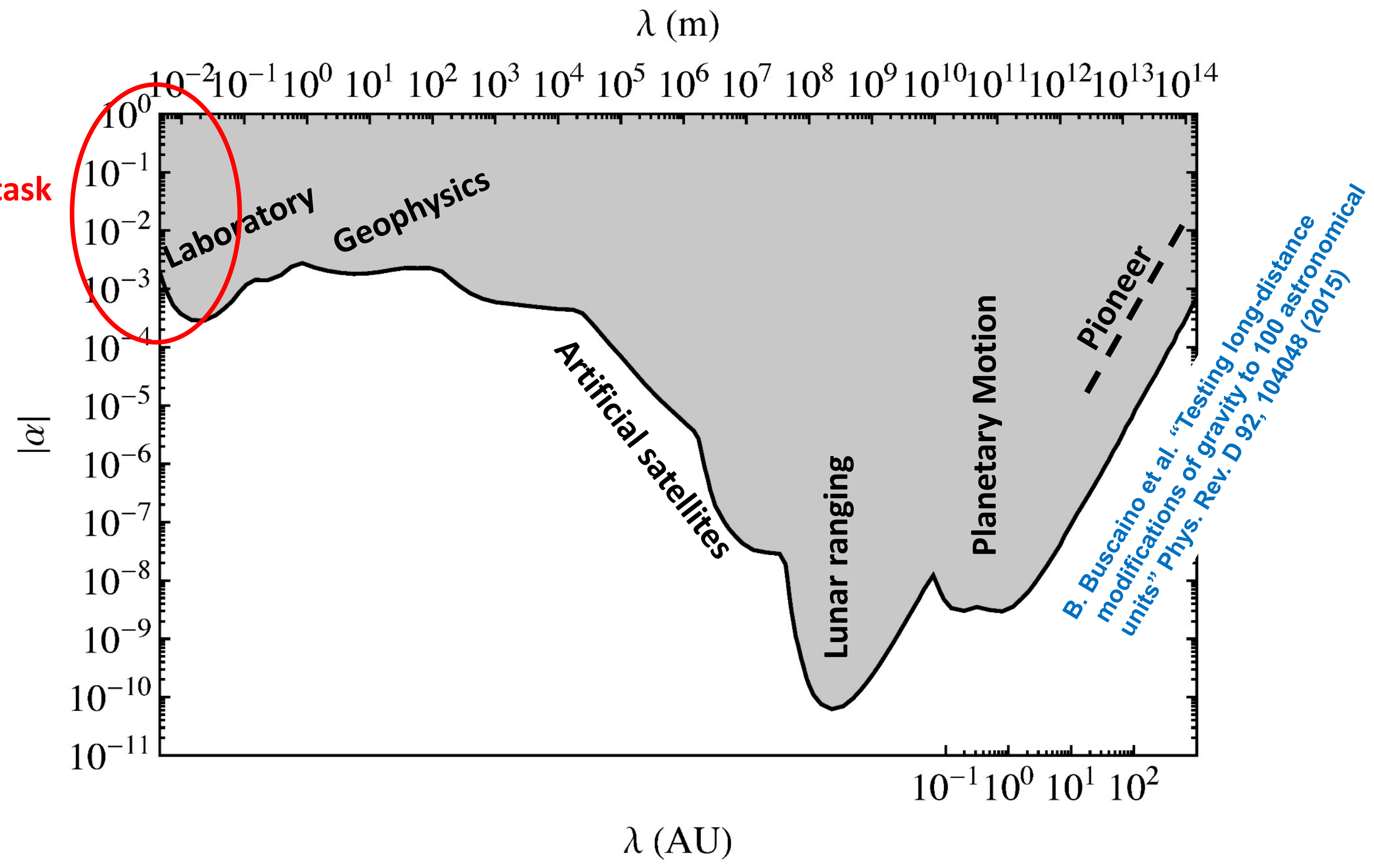
α: magnitude of the effect
λ: scale of the effect

What do we empirically know



What do we empirically know

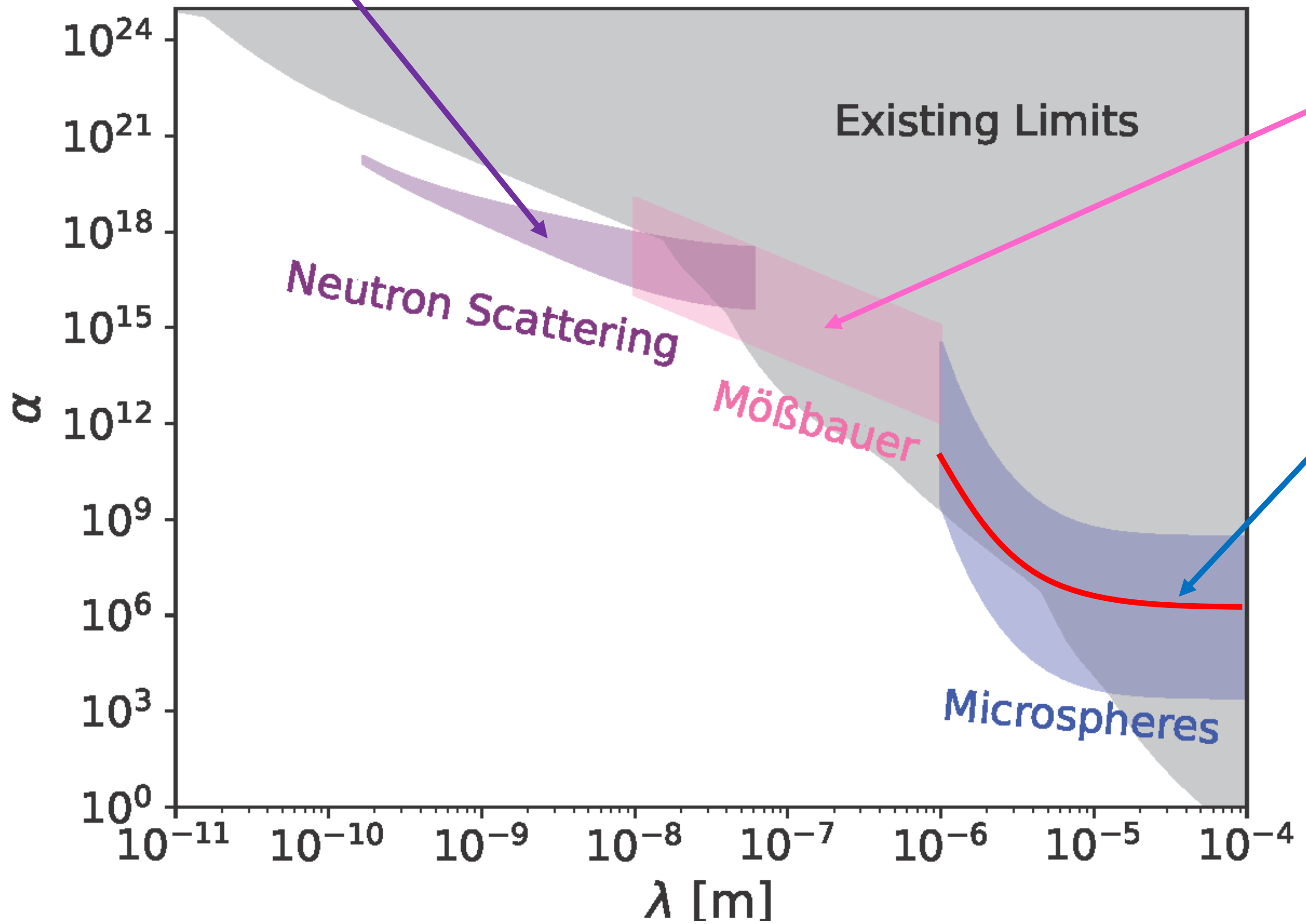
Today's primary task



Aspirations of our program (the bands are projections)

Z.Bogorad, P.W.Graham, GG,
Phys Rev D 108 (2023) 055005

Also a motivation to "nuclear quantum optics", with various potential applications.
GG, D.E. Kaplan, S. Rajendran, Phys Rev D 102 (2020) 115031.

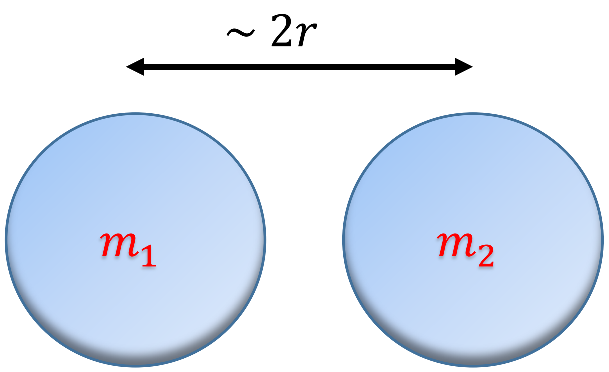


Recent result:
G.Venugopalan et al., Nature Sci Rep 16 (2026) 5180
Also, application to neutrality of matter, inertial sensing, quantum S&T

It is also desirable to have some overlap between techniques, *convenient in case of a discovery.*

Experimental challenges

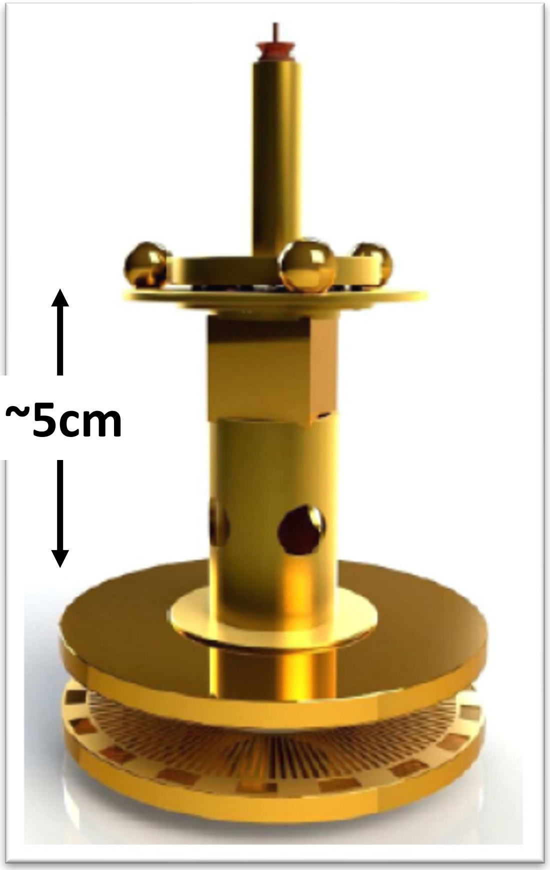
- Since $F = G\frac{M_1 M_1}{R^2} = G\frac{\rho_1 V_1 \rho_2 V_2}{R^2}$
  for atomic materials (we can't use Neutron Stars!)
  $\rho_1 \sim \rho_2 < 20$ g/cm^3, there is no silver bullet.
  In addition, the volume $V \sim R^3$, so $F \sim G\frac{\rho^2 R^6}{R^2}$
  and it is clear that measurements at short distance become exceedingly difficult.
- At distances <100μm even neutral matter results in residual E&M interaction that are a dangerous background for these measurements



$r \sim 10\mu m \;\rightarrow F_N \sim 10^{-21} N$

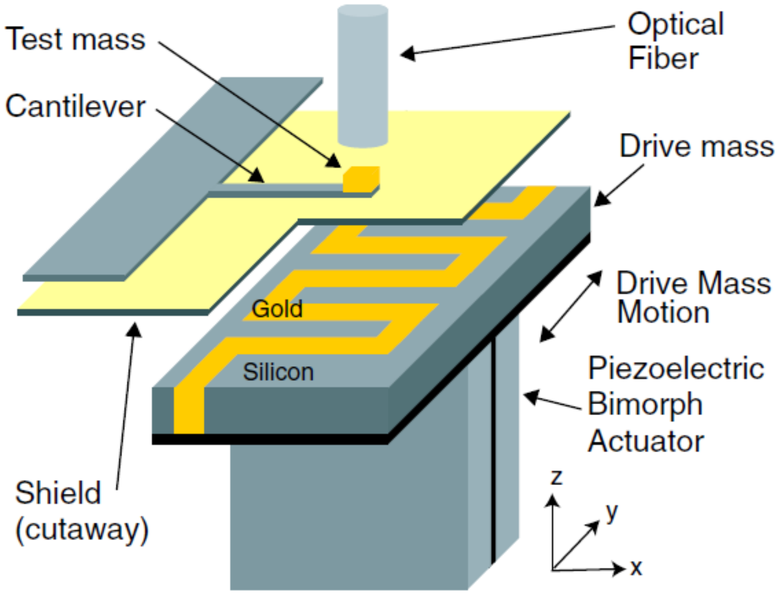
Most inverse-square law measurements are/have been done with wonderfully sophisticated versions of Cavendish's setup.

As distances become shorter, this approach becomes clumsy and substantial efforts have to do with "artificial" issues (e.g. how to machine a 5 cm diameter disk flat to μm level…).



Sketch of the EotWash apparatus from the University of Washington in Seattle
Phys. Rev. Lett. 124, 101101 (2020)

In recent times, some new measurements have been made using AFM techniques (but, still, these use mechanical springs)



Sketch of the custom cryogenic AFM apparatus from Kapitulnik's group at Stanford
J.Chiaverini *et al.*, PRL 90 (2003) 151101

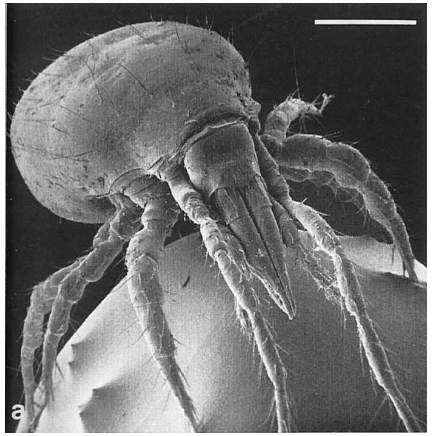
Given the small strength of gravity we need to measure really small forces

Some orders of magnitude of more or less familiar forces (weighs)

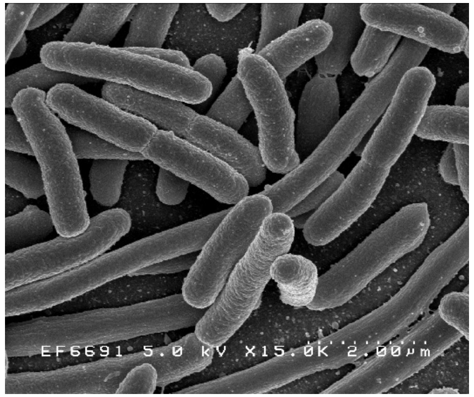
A bathroom scale resolves ~1 *N*

100 kg ~ 1kN

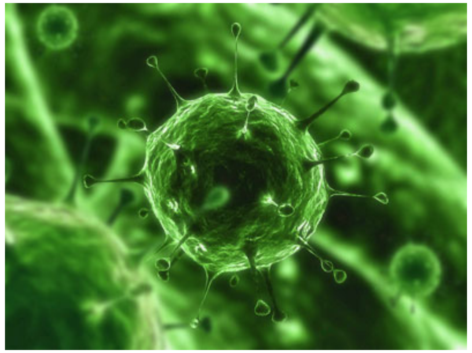
A dust mite 10^{-7} N



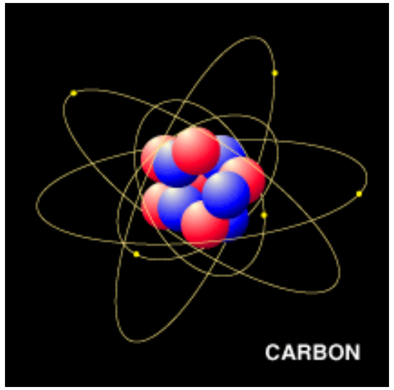
E. coli 10^{-14} N



Virus 10^{-19} N



Carbon atom 10^{-25} N

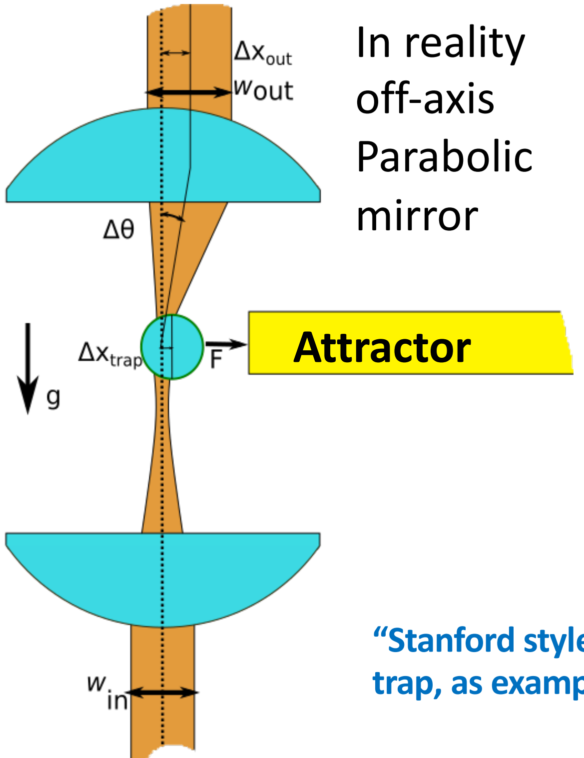


Conventional AFM measures 10^{-12} N

Specialized, cryogenic setups can result in ~10^{-16} N/√Hz noise floors

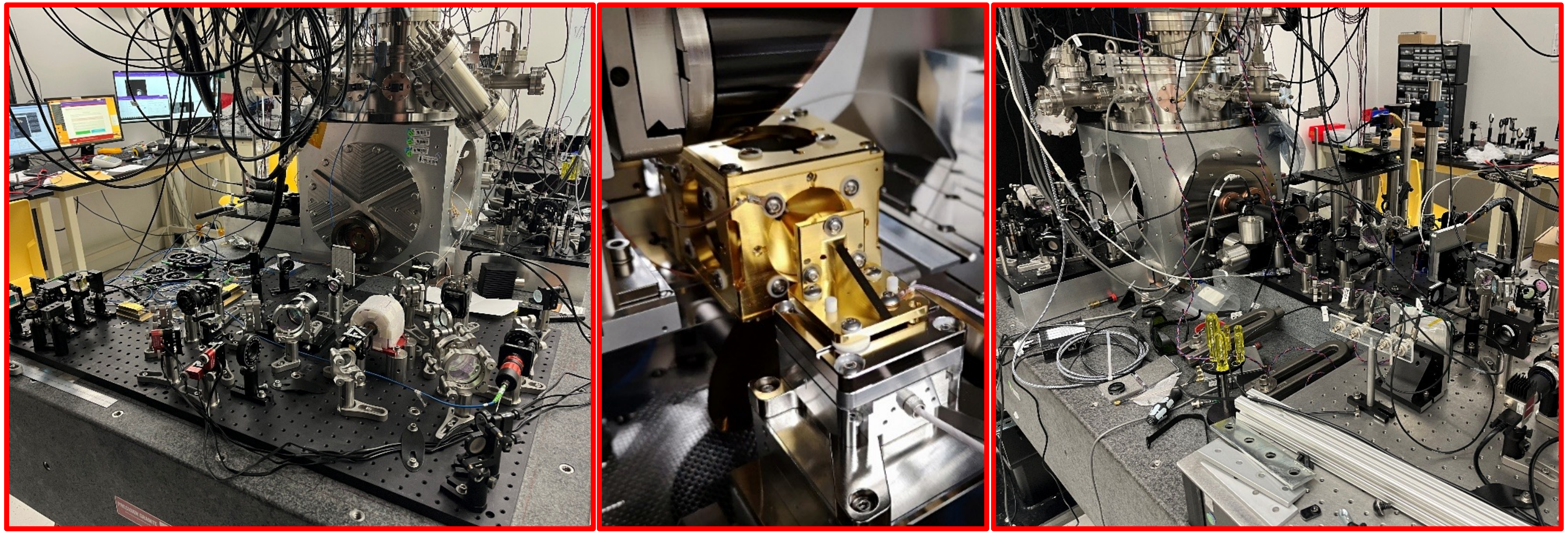
In the last 50 years, optical tweezers have developed into broad field, primarily applied to biology, in water.

Microspheres optically trapped in vacuum make superb force sensors. **No mechanical springs!**



In reality off-axis Parabolic mirror

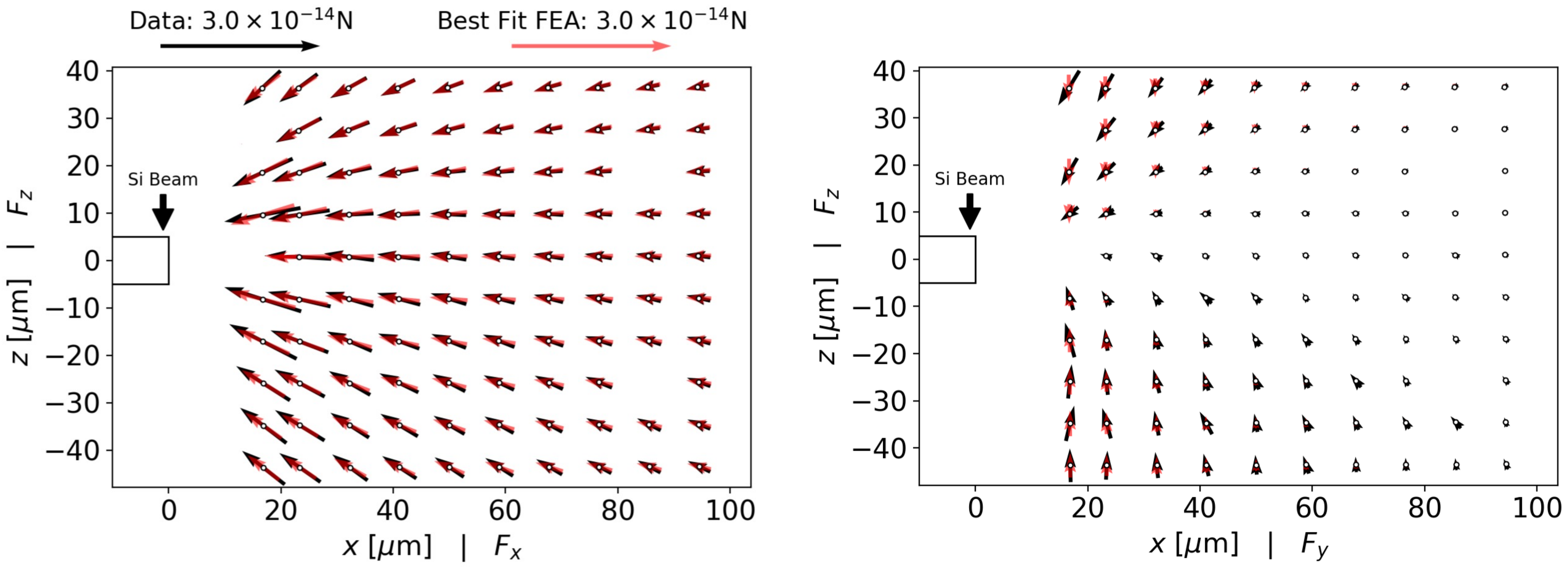
"Stanford style" trap, as example



Rev. Sci. Instrum. 91, 083201 (2020)

The trapped microsphere (5-10μm diameter) is an excellent force sensor, with full 3D, vector field mapping capability

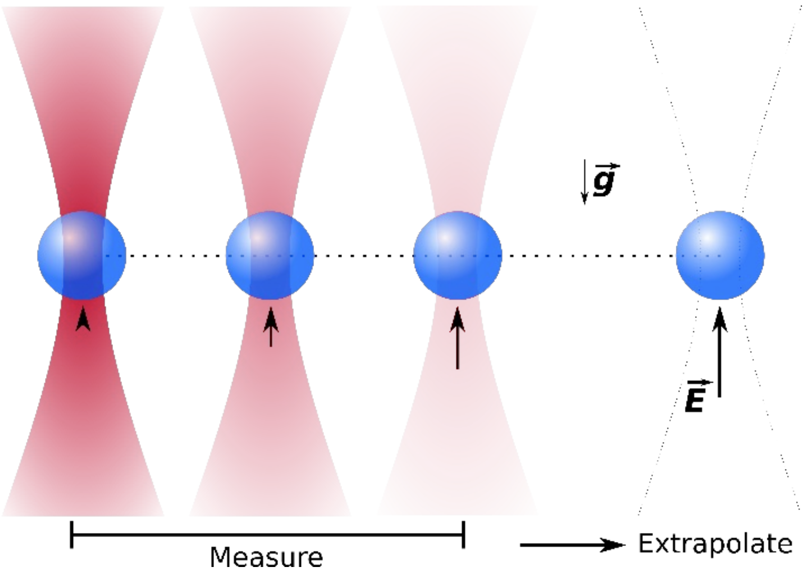
as can be shown/calibrated by measuring charged microspheres

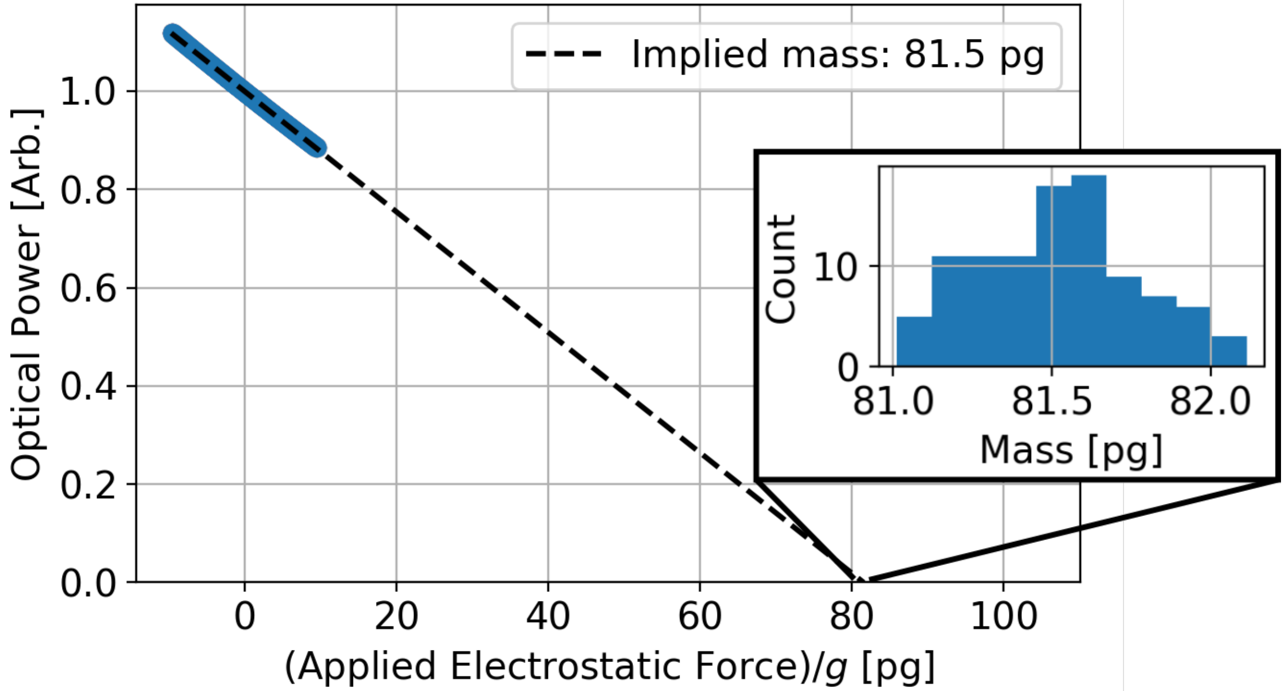


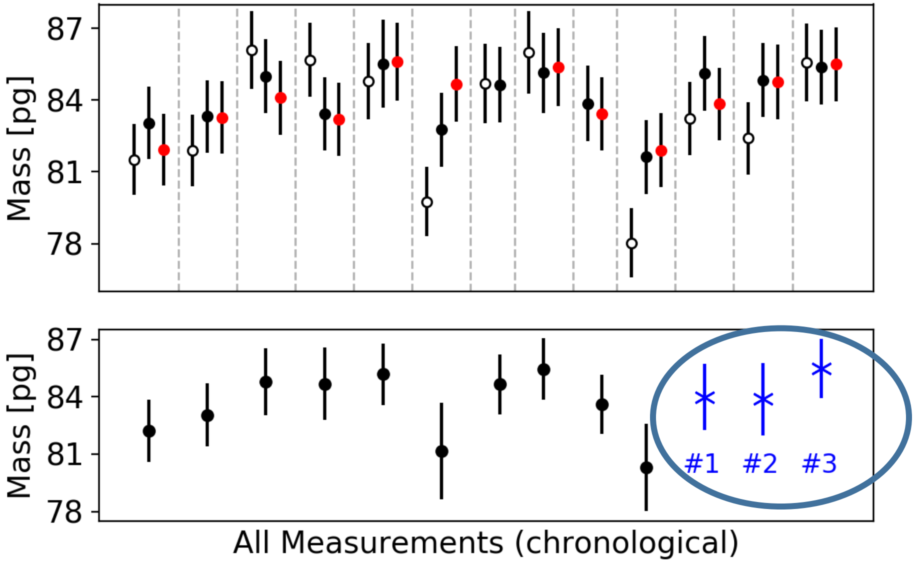
C.Blakemore et al., Phys. Rev. A 99 (2019) 023816

Similar results in G.Winstone et al., Phys. Rev. A 98 (2018) 053831

Precision measurement of microsphere mass and density







This technique only requires the knowledge/measurement of the relative power needed to compensate for a certain electrostatic force. Ie, it only needs the linearity of a photodiode.

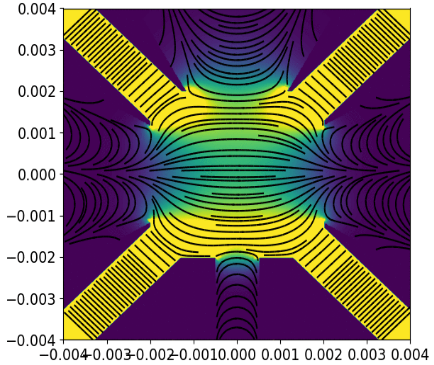
These three microspheres are then individually recovered and their diameter measured offline in an SEM

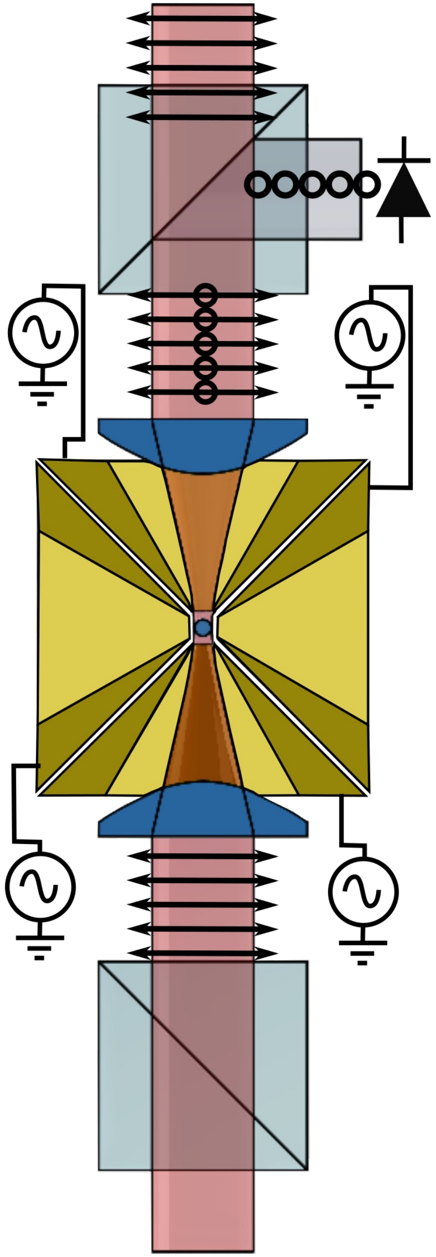
C.Blakemore et al., Phys. Rev. Appl. 12 (2019) 024037

Spinning trapped microspheres

Since microspheres have a electric dipole moments, a torque can be applied by a rotating external electric field.

A.Rider et al. Phys Rev A 99 (2019) 041802(R)
C.P.Blakemore et al. Phys Rev A 106 (2022) 023503



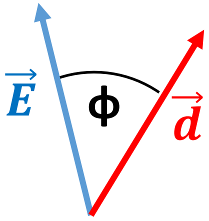


Application in vacuum sensing,

C. Blakemore at al, J. Vac. Sci. Technol. B 38, 024201 (2020)

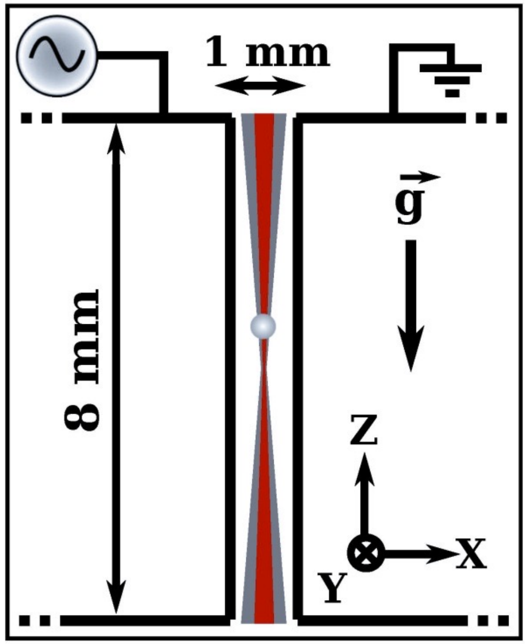
navigation,

and microsphere stabilization (lower noise).



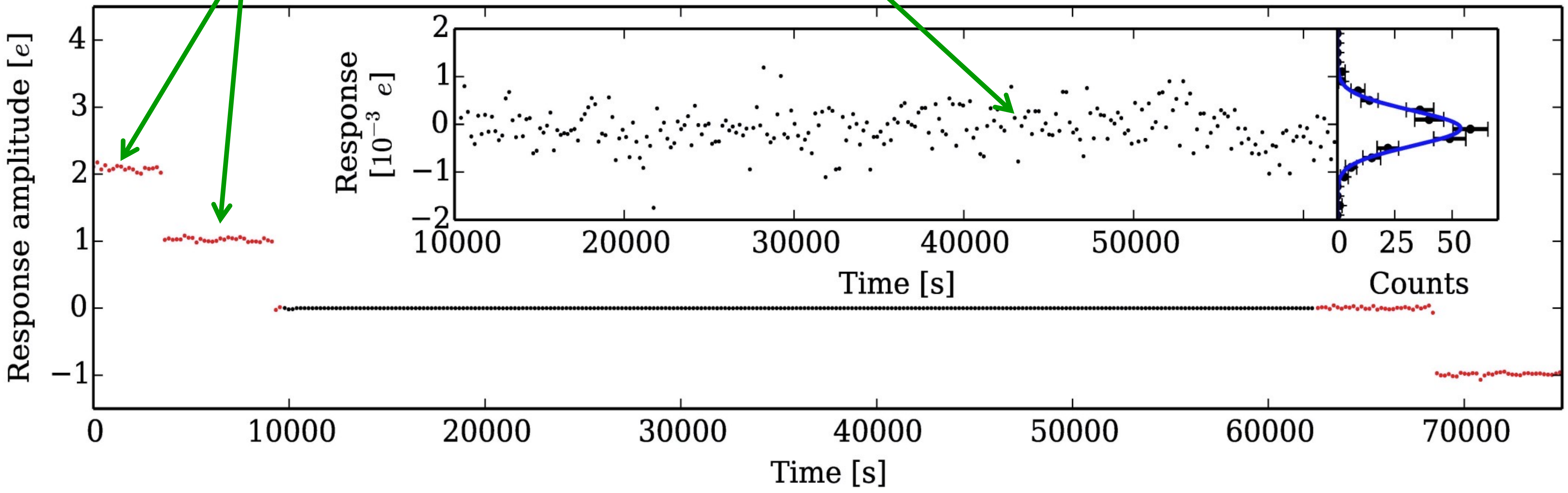
But the dipole moment also couples to E-field gradients which can be minimized but not entirely eliminated.

The possibility of setting the charge of the microsphere at leisure, opens the opportunity to search for very small charges (<<1milli-e^-) or, more interestingly, search for deviations from neutrality of matter.

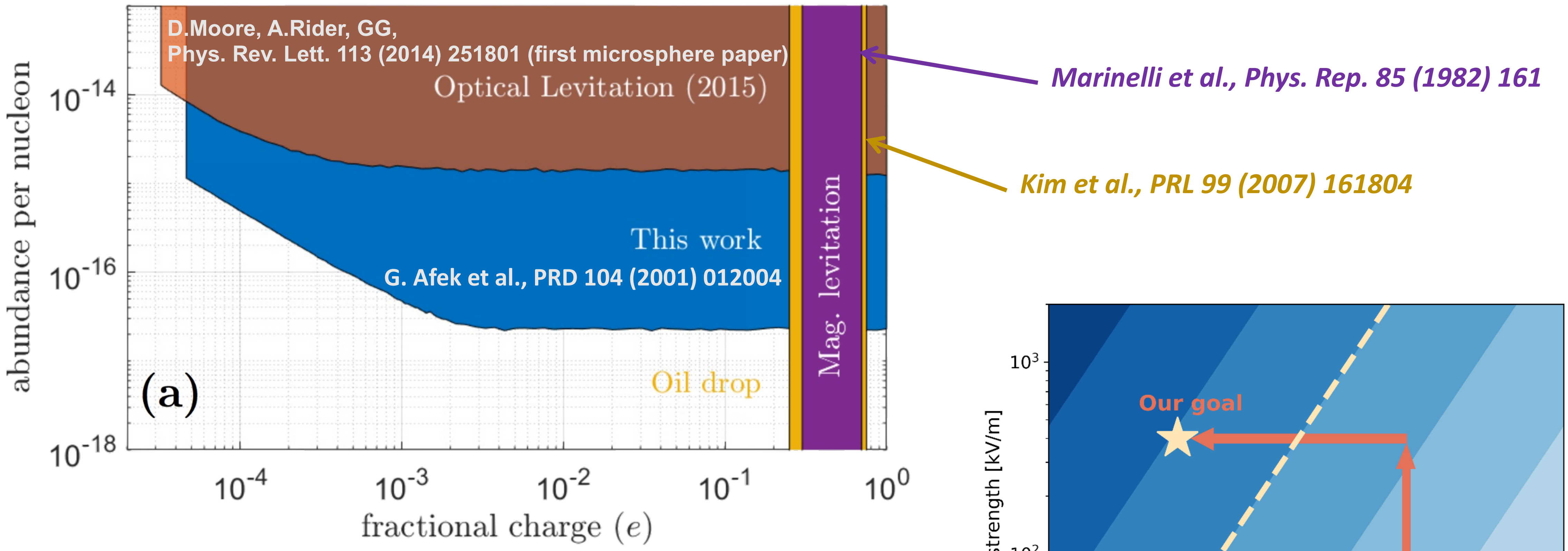


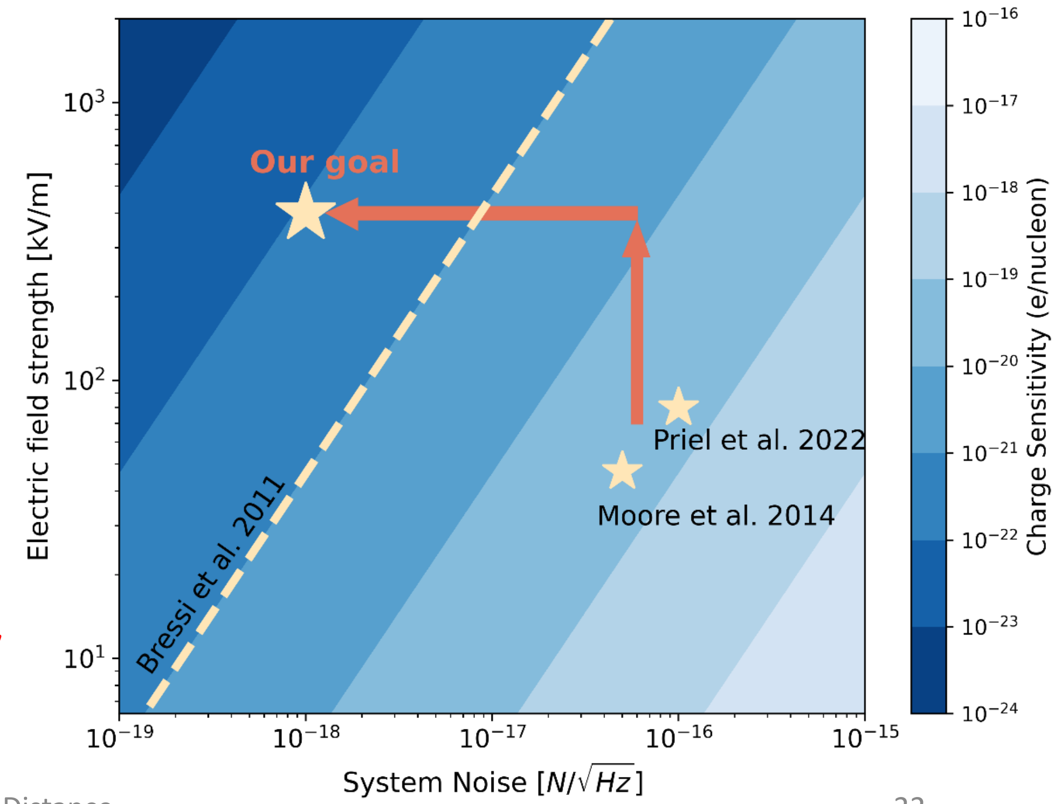
Quantized charge

"0 charge" with increased 500 V RF amplitude.

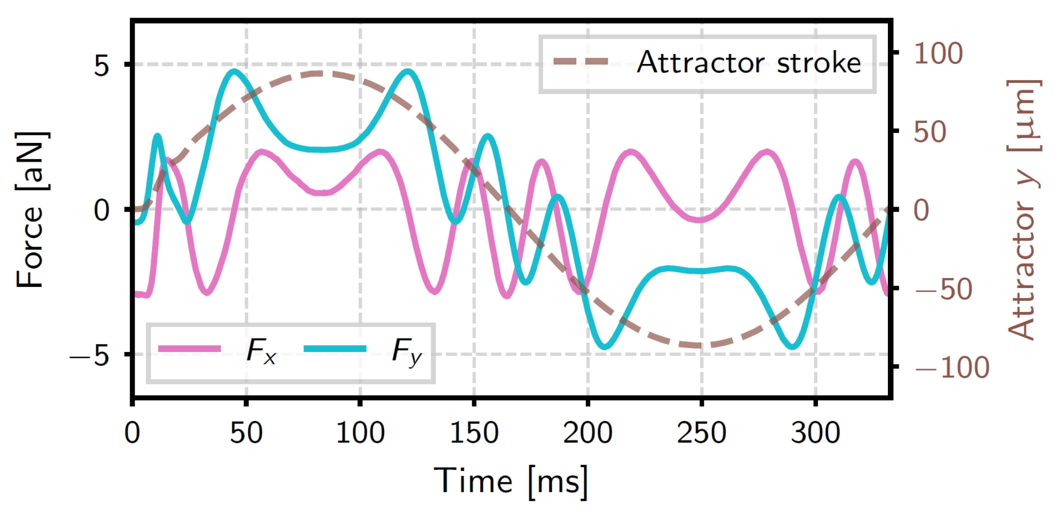


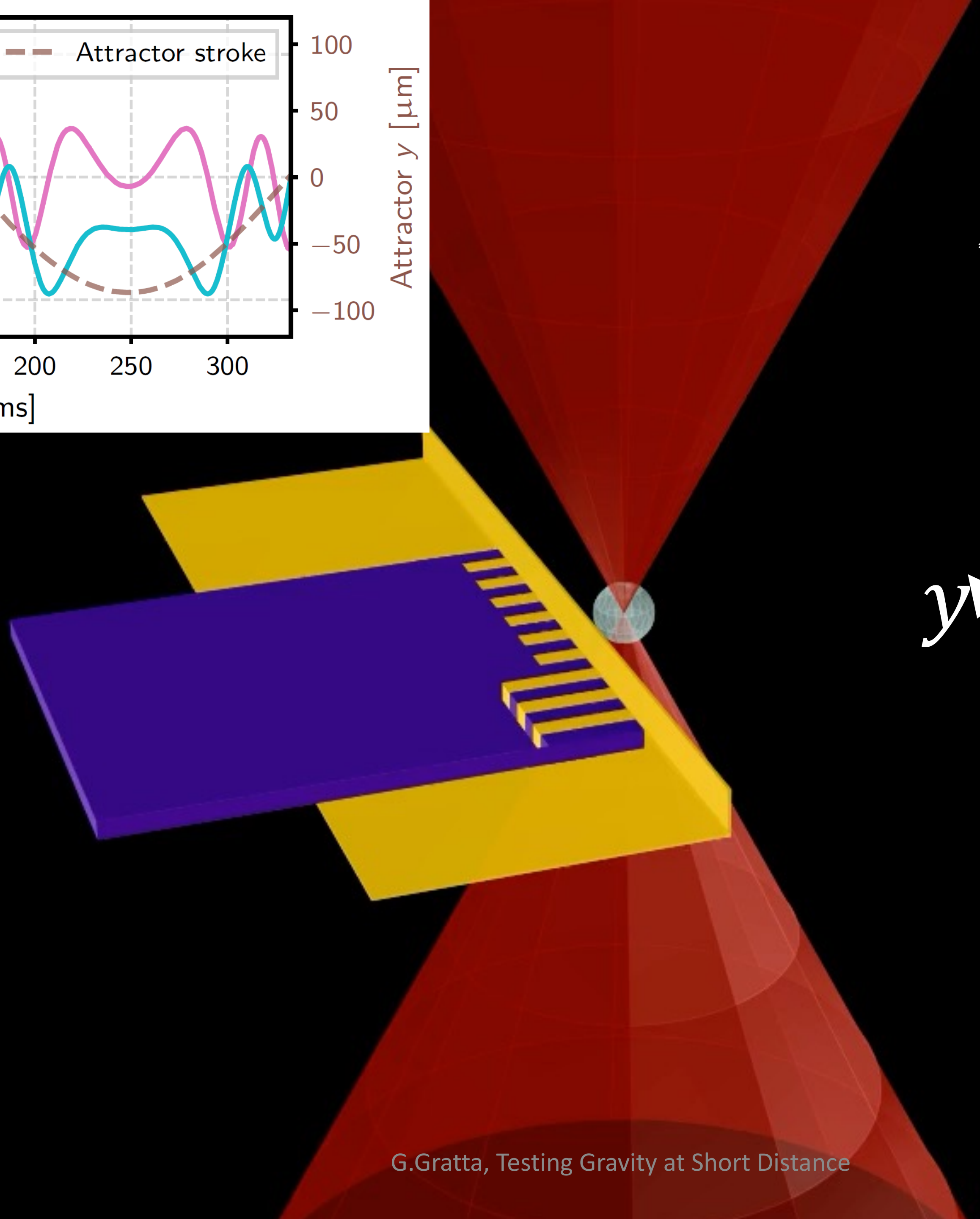
Existing millicharge or neutrality limits

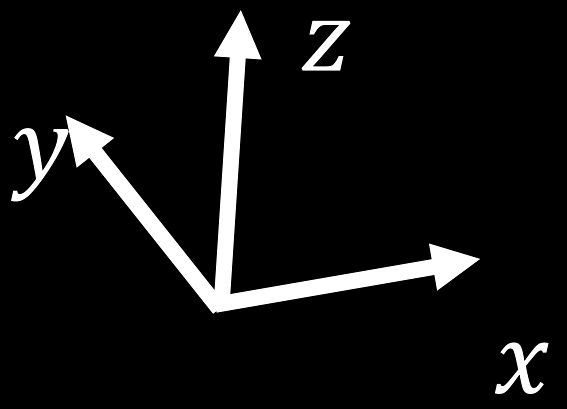




and expected sensitivity



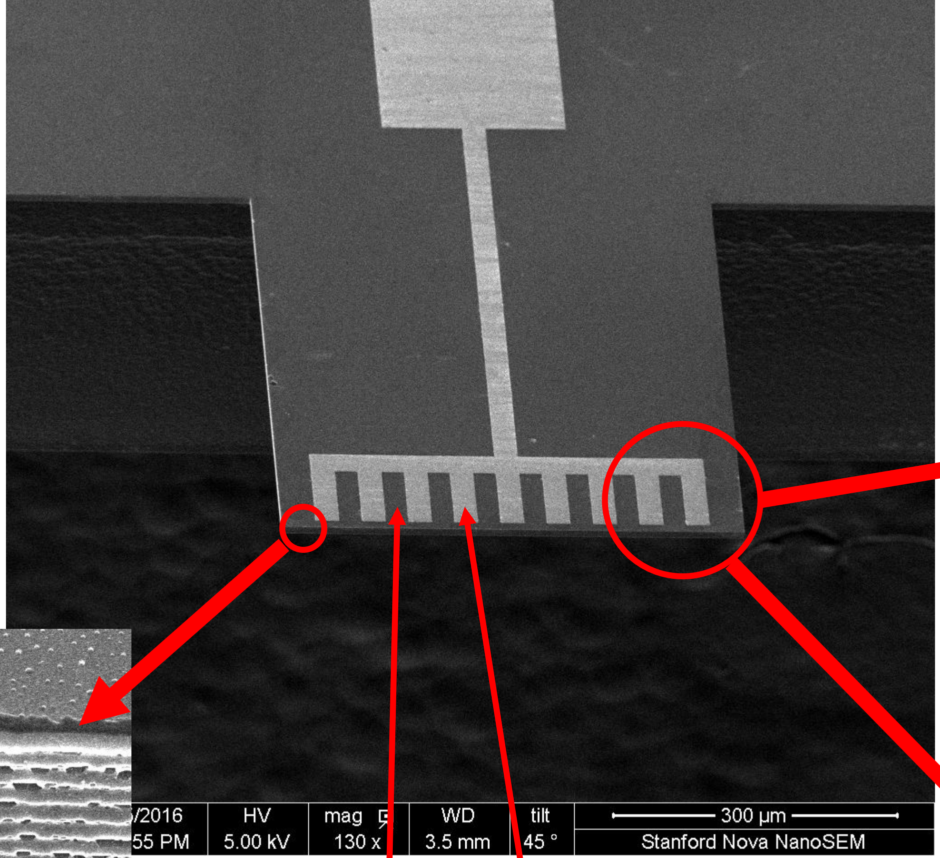




*Microsphere motion greatly exaggerated

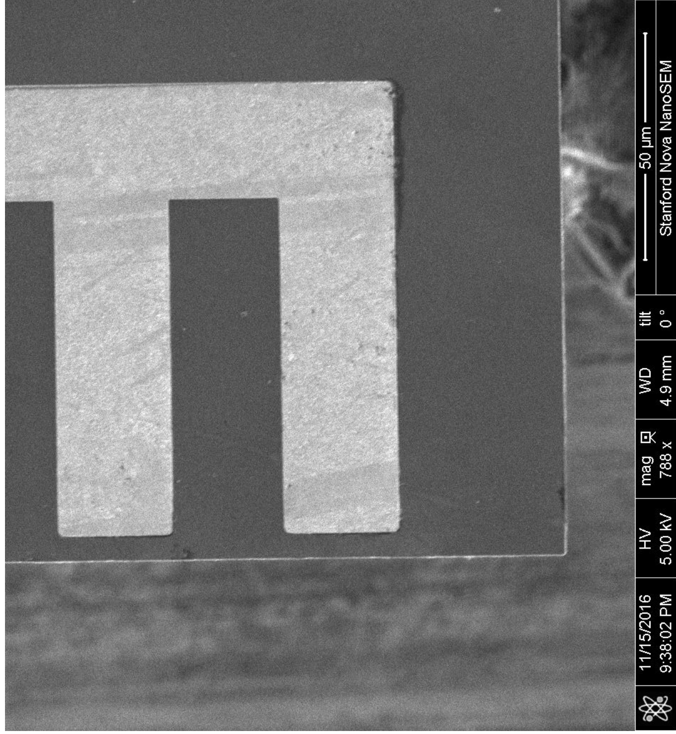
Animation by G. Venugopalan

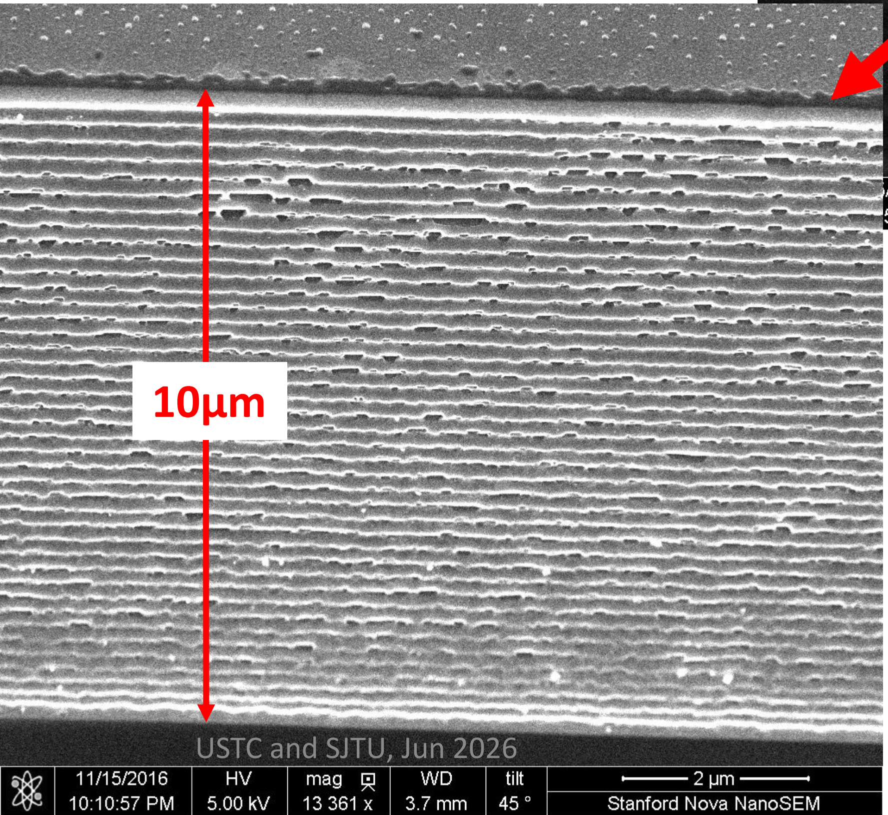
First generation attractor set, here shown before Au coating

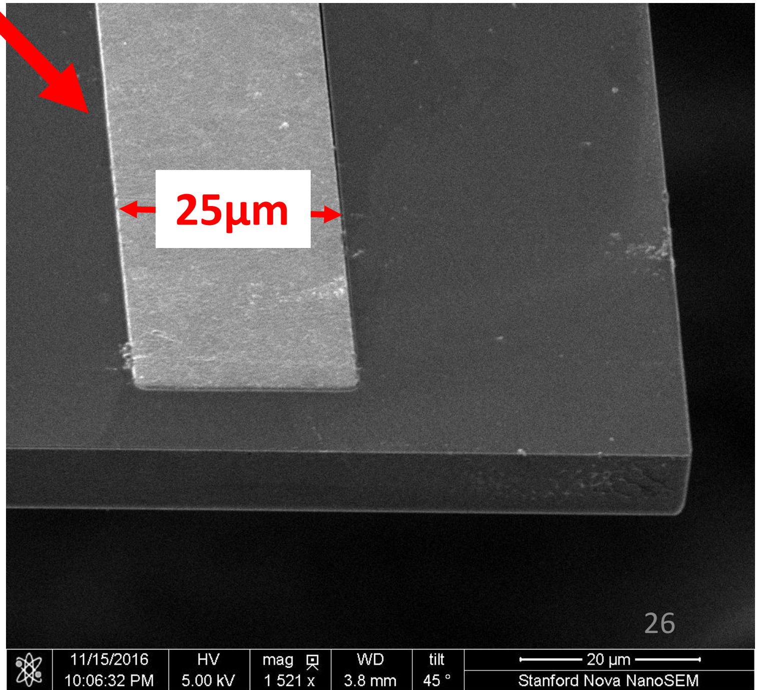


Si

Au

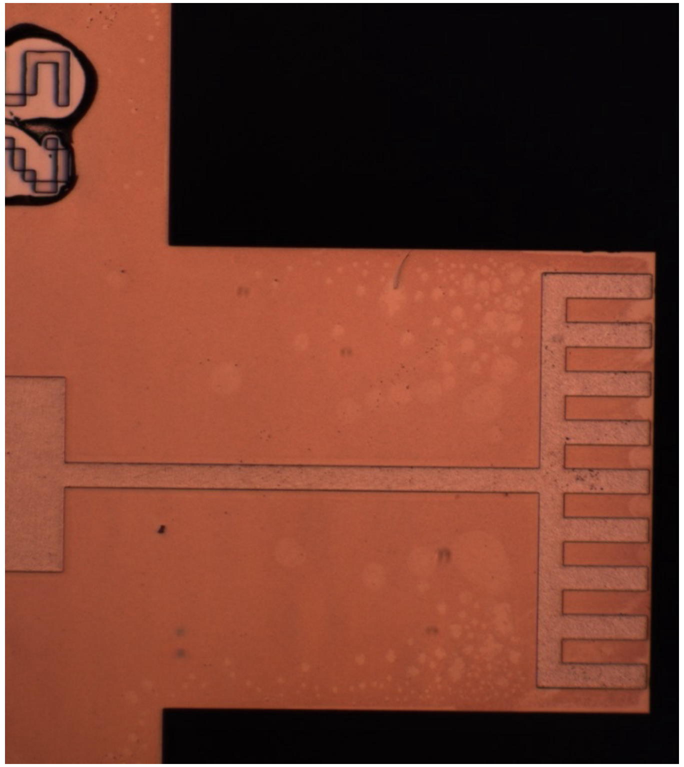




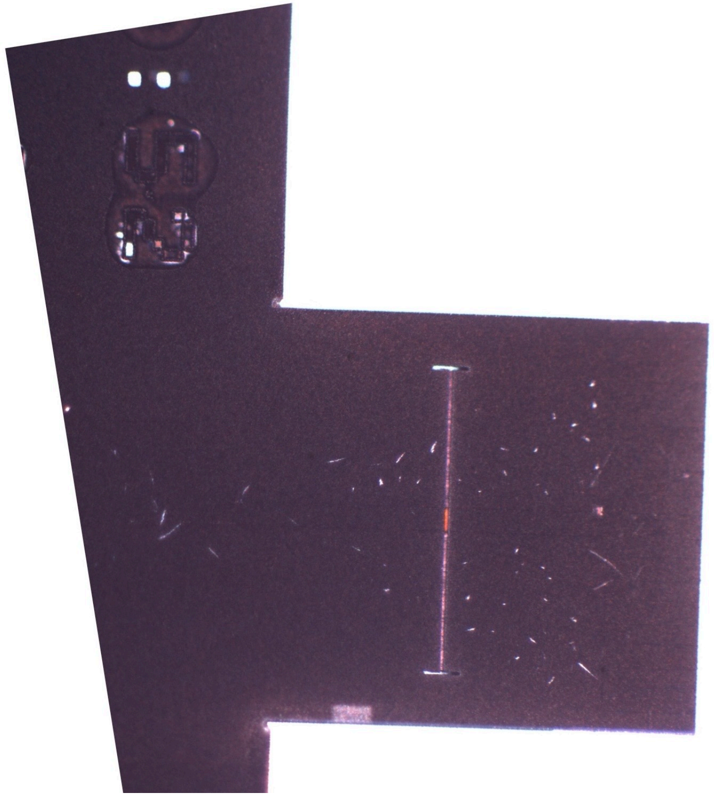


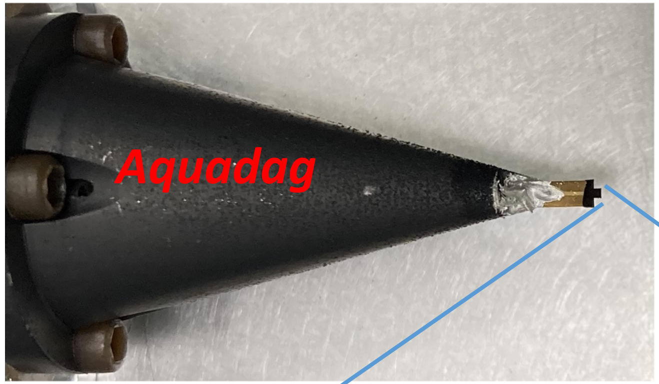
Electroplating "Platinum Black"

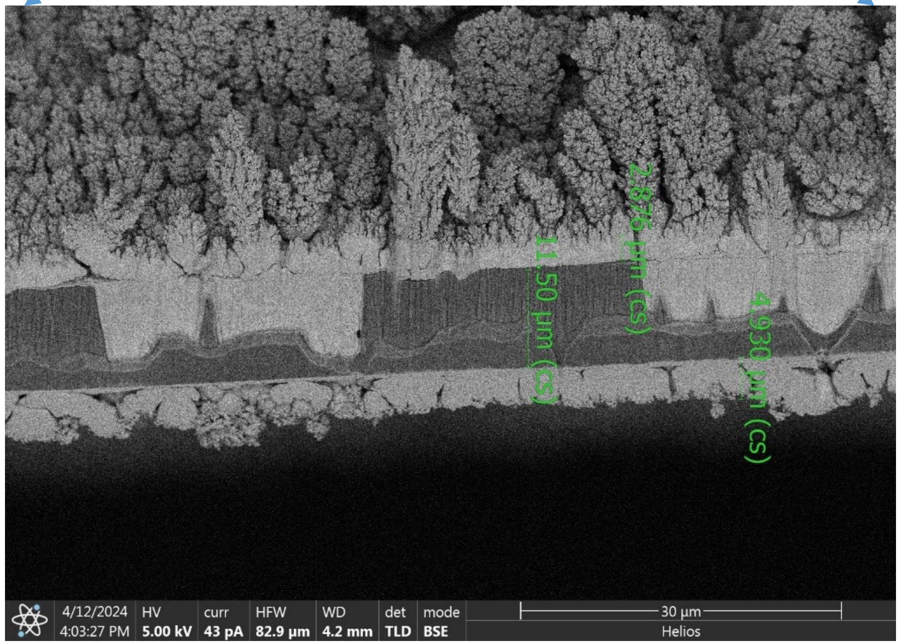
Before plating



After plating,
longer exposure

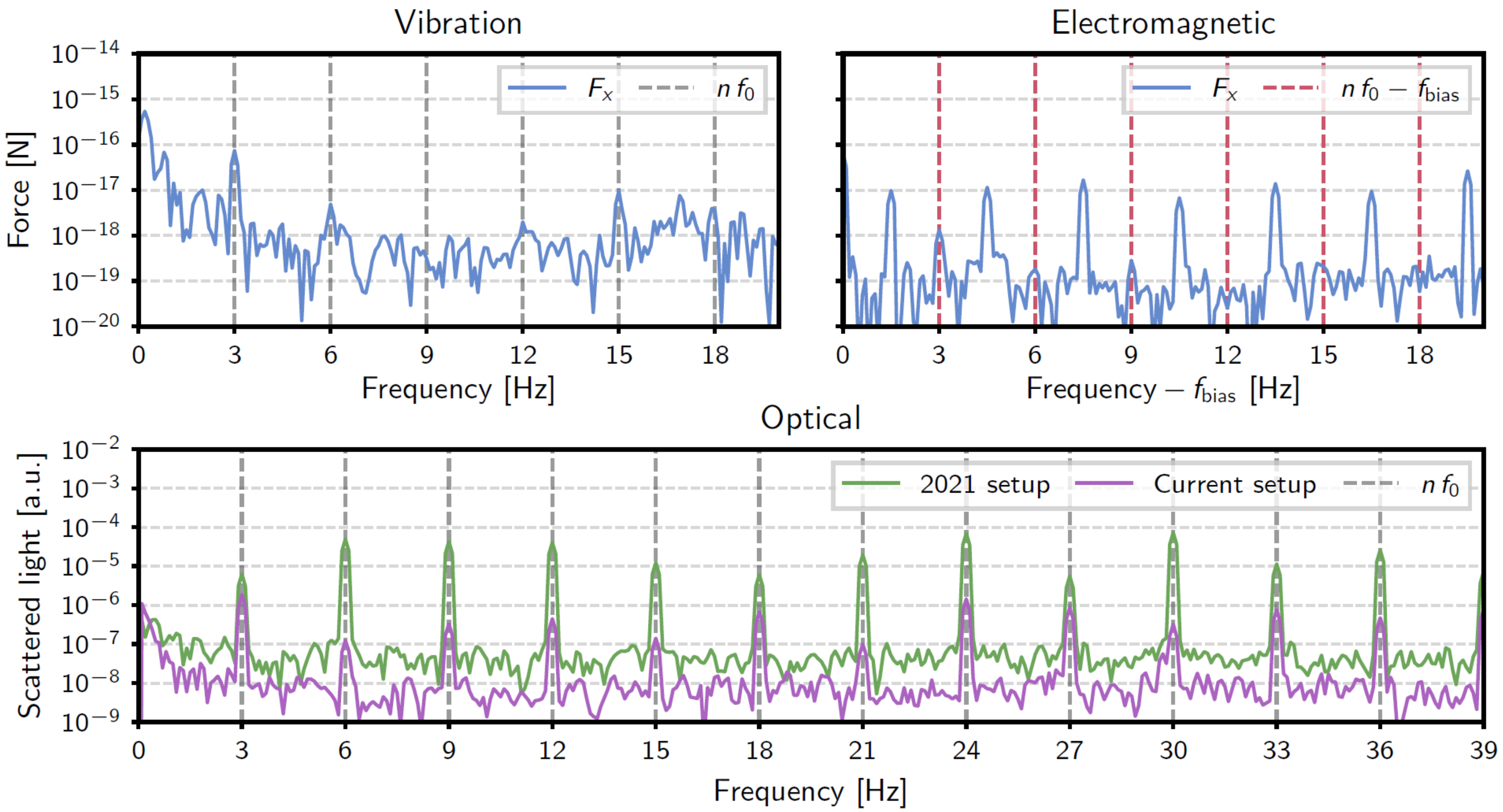




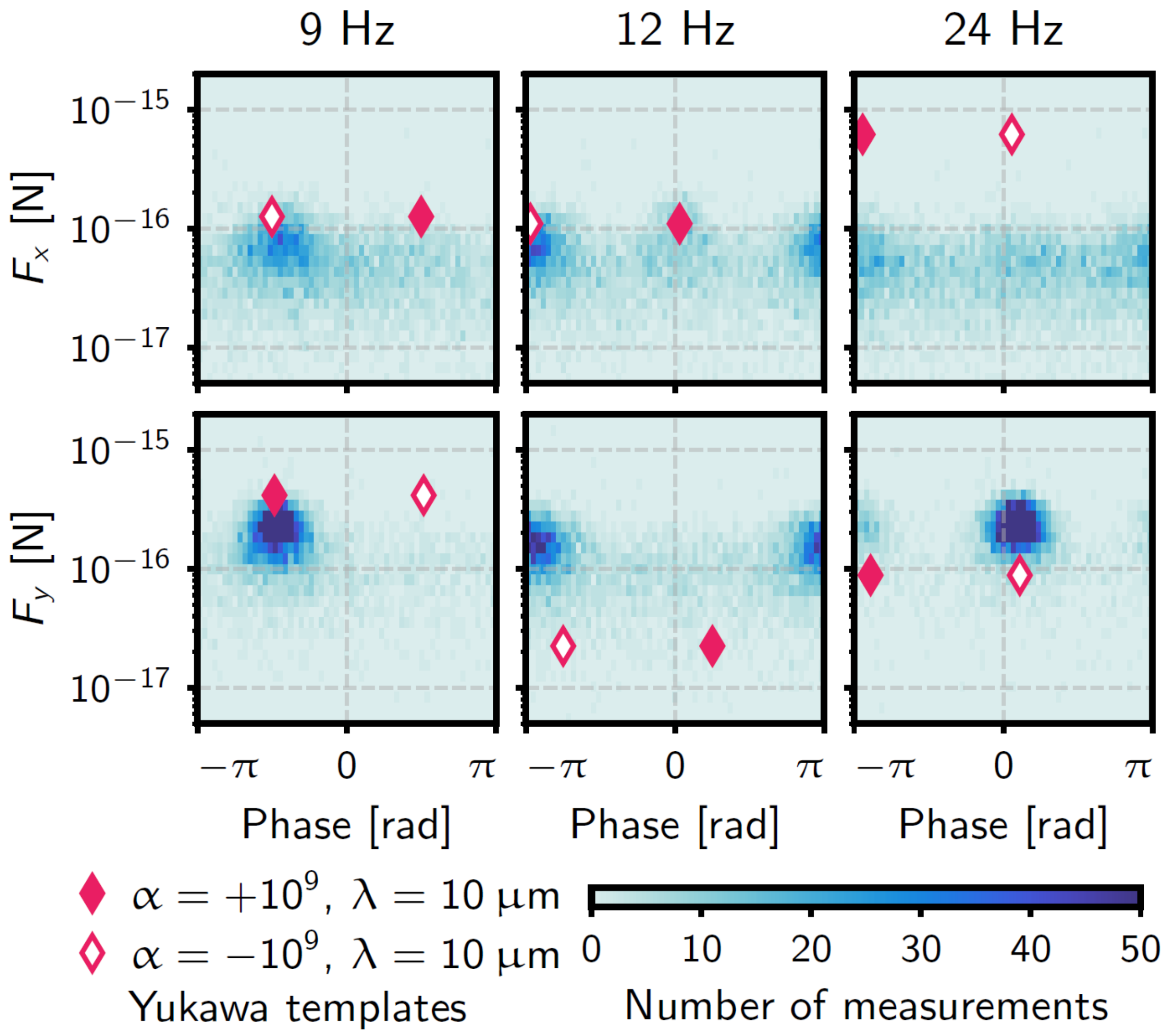


Backgrounds are still the most serious limitation to the sensitivity,

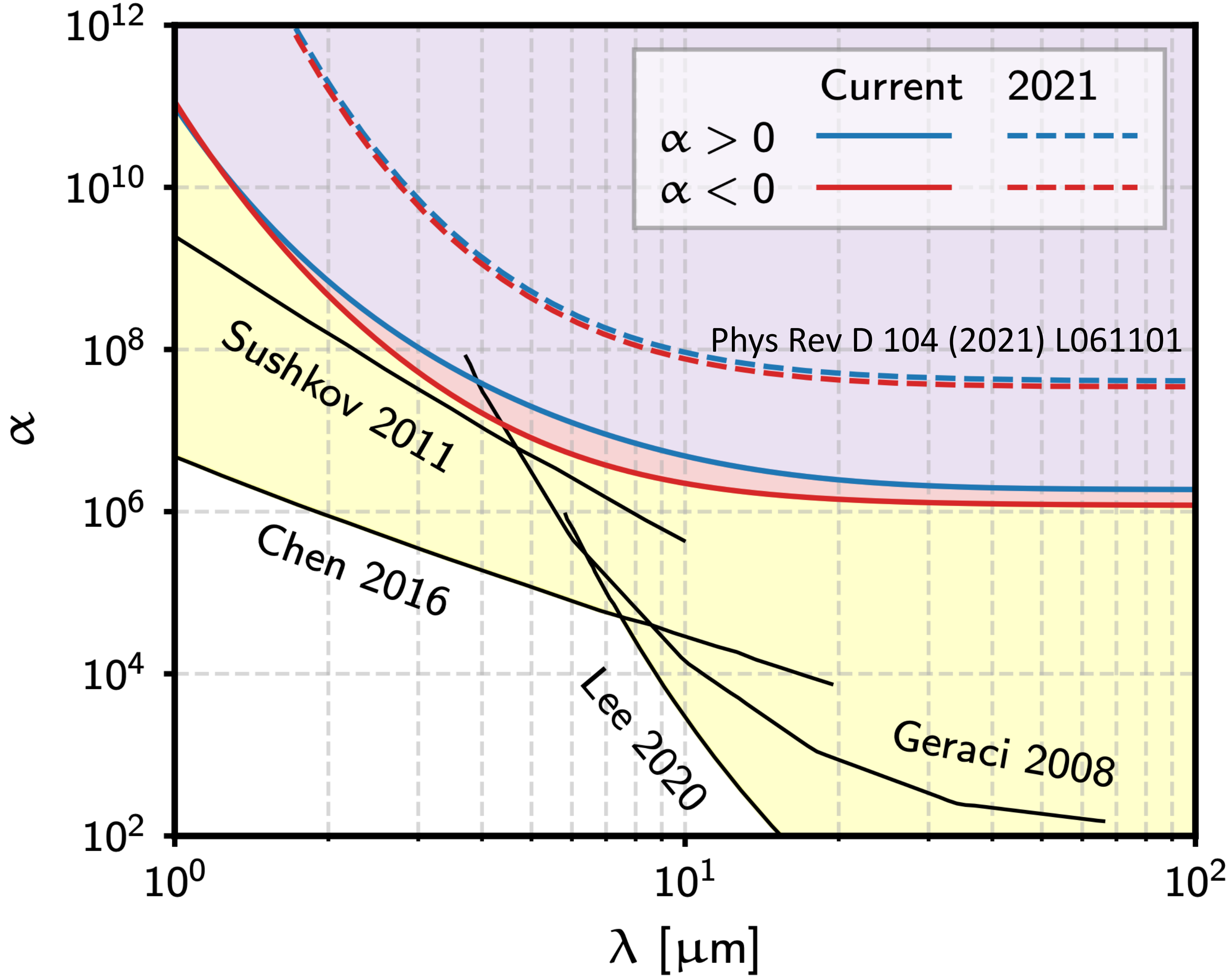
but the dominant optical one was reduced by ~2 orders of magnitude



The force measurement in 2 coordinates (eventually 3), its phase, and the use of the six harmonics with the most power better constrains the measurement.



Result



G.Venugopalan et al., Nature Sci Rep 16 (2026) 5180

- Limit is set using profile-likelihood approach
- Better understanding and reduction of background:
  ➔ 100x improvement
- Setting limit on positive and negative coupling constants
- First measurement of the force *vector*
- Sensitivity still limited by diffuse light backgrounds (and, more is likely lurking under that)
- Working on more background abating techniques
  ➔ Most notably a 100pixel, fast, hi res photodetector

Now I want to describe a different technique, using nuclei (as opposed to atoms) as force sensors

GG, D.E. Kaplan, S. Rajendran, Phys Rev D 102 (2020) 115031.

"Nuclei are well-protected affairs"

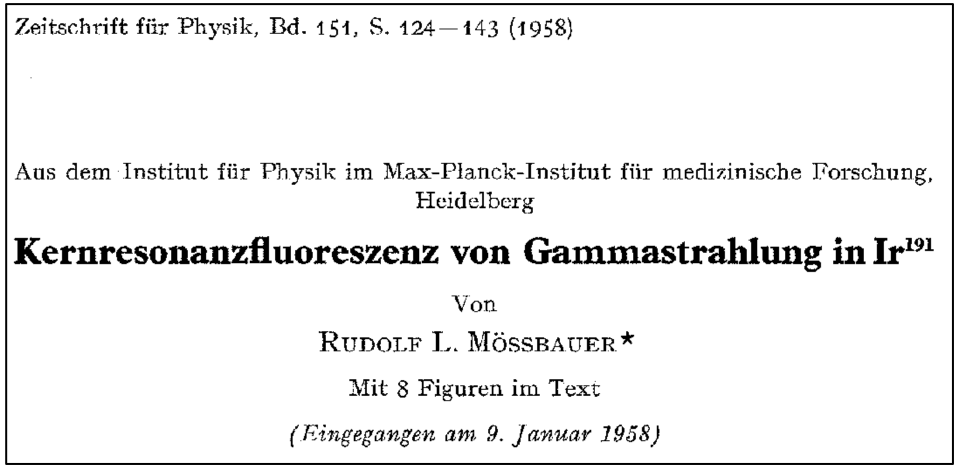
They have electric charge, but that is screened by the electron cloud and so has little coupling to external E&M disturbances.

In addition, nuclear level shifts due to E&M coupling, occurs through coupling to multipole (mainly dipole) moments and these are suppressed by the size of the nucleus.

And, this is further suppressed, in the case of unpolarized nuclei, by $\sqrt{N}$, when looking for the shift of a spectroscopy line that is measured by N events.

→ Can nuclear (gamma) spectroscopy used to investigate new forces?

Glen Rebka at the basement station



Zeitschrift für Physik, Bd. 151, S. 124—143 (1958)

Aus dem Institut für Physik im Max-Planck-Institut für medizinische Forschung, Heidelberg

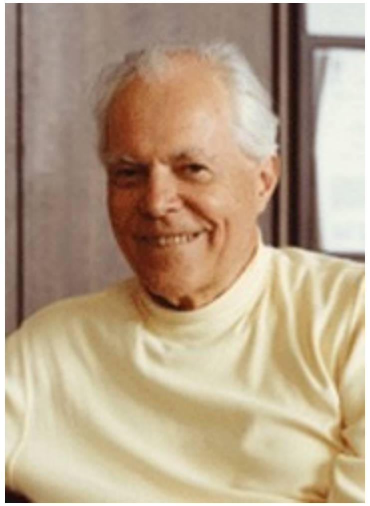
Kernresonanzfluoreszenz von Gammastrahlung in Ir^{191}

Von

RUDOLF L. MÖSSBAUER*

Mit 8 Figuren im Text

(Eingegangen am 9. Januar 1958)



Source: Pontifical Academy of Sciences

Mössbauer spectroscopy was used in an elegant experiment to detect, for the first time, gravitational red/blue shift of photons.

Pound & Rebka Physical Review Letters. 4 (1960) 337

Somewhat disconcertingly, Mössbauer spectroscopy was then ``appropriated'' by Chemists!

→ *It's time to reclaim it back for fundamental physics!*

Incidentally ^{229}Th clock transition is a special case of this.

Recoils in atomic and nuclear spectroscopy

In atomic physics, we are used to the fact that a photon emitted by an atom can be re-absorbed by another atom of the same species:

The fact that this works is kind of accidental, because the emitted photon is somewhat red shifted by the recoil of the emitting atom and, for the same reason, it needs to be a bit blue shifted to excite the absorbing one.

Quantitatively the energy of the emitted photon is: $E_\gamma = \Delta E\left(1 - \frac{\Delta E}{2Mc^2}\right)$

And, to be absorbed the energy has to be $E_\gamma = \Delta E\left(1 + \frac{\Delta E}{2Mc^2}\right)$

where ΔE is the energy difference between the two states and M is the mass of the atom.

This only works if the relative linewidth $\frac{\Gamma}{E_\gamma} > \frac{\Delta E}{Mc^2}$

Atomic physics example:

Natural linewidth for Na D_1 line: $\tau = 16\text{ns}$, $\delta\nu = 10\text{MHz}$ and $\frac{\Gamma}{E_\gamma} = \frac{\delta\nu}{\nu} = 2 \cdot 10^{-8}$

$$\frac{\Delta E}{Mc^2} = \frac{2.1eV}{23 \cdot 1GeV} \cong 10^{-10}$$

so $\frac{\Gamma}{E_\gamma} > \frac{\Delta E}{Mc^2}$ (in reality this is even better because the line is broadened by collisions and thermal motion --which is the reason why state of the art clocks use cooled atoms and atomic fountains)

Nuclear physics examples:

Natural linewidth for ^{152}Sm ~900 keV transition: $T_{1/2} = 28$fs, $\frac{\Gamma}{E_\gamma} = \frac{1.6 \cdot 10^{-2}}{9 \cdot 10^5} = 1.7 \cdot 10^{-8}$

$$\frac{\Delta E}{Mc^2} = \frac{9 \cdot 10^5 eV}{152 \cdot 10^9 eV} \cong 6 \cdot 10^{-6}$$

Now $\frac{\Gamma}{E_\gamma} < \frac{\Delta E}{Mc^2}$ and the photons emitted by a piece of Sm cannot be resonantly absorbed by another piece of Sm.

(you may remember that this issue was used in the experiment to measure the helicity of the neutrino, exactly by requiring that a previous recoil would boost the Sm nucleus and make the resonant absorption possible)

In other words, the recoil moves the lines soooo far apart that there is no hope to see resonant absorption.

Note, incidentally, that the very long half-lives actually observed in nuclear physics occur because:
"nuclei are protected affairs"!

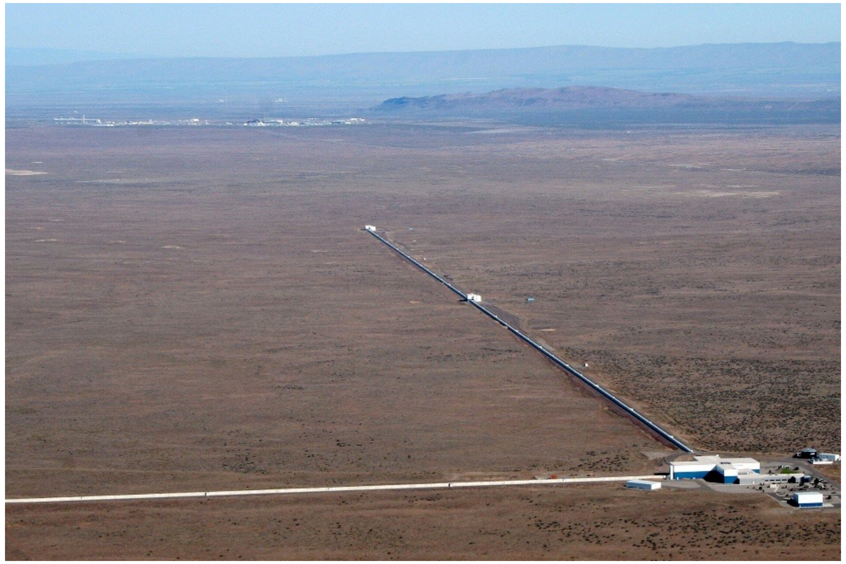
But, under special conditions (low γ energy and a stiff lattice), the entire lattice recoils rigidly, so that M above is way larger than the mass of a nucleus.

In some cases, the natural line width is directly accessible

Nuclide	E (eV)	$T_{1/2}$	Γ (eV)	Γ/E
$^{57}_{26}$Fe	14,413	98.3 ns	4.7×10^{-9}	6.4×10^{-13}
$^{73}_{32}$Ge	13,328	2.92 μs	1.6×10^{-10}	1.2×10^{-14}
$^{181}_{73}$Ta	6,237	6.05 μs	7.5×10^{-11}	1.2×10^{-14}
$^{67}_{30}$Zn	93,300	9.07 μs	5.0×10^{-11}	5.4×10^{-16}
$^{45}_{21}$Sc	12,400	318 ms	1.4×10^{-15}	1.13×10^{-19}
$^{107}_{47}$Ag	93,125	44.3 s	1.03×10^{-17}	1.1×10^{-22}
$^{103}_{45}$Rh	39,753	56.1 min	1.36×10^{-19}	3.4×10^{-24}
$^{189}_{76}$Os	30,814	5.8 hr	2.2×10^{-20}	7.0×10^{-25}

Used mainly in chemistry (first four rows)

Essentially unexplored (last four rows)

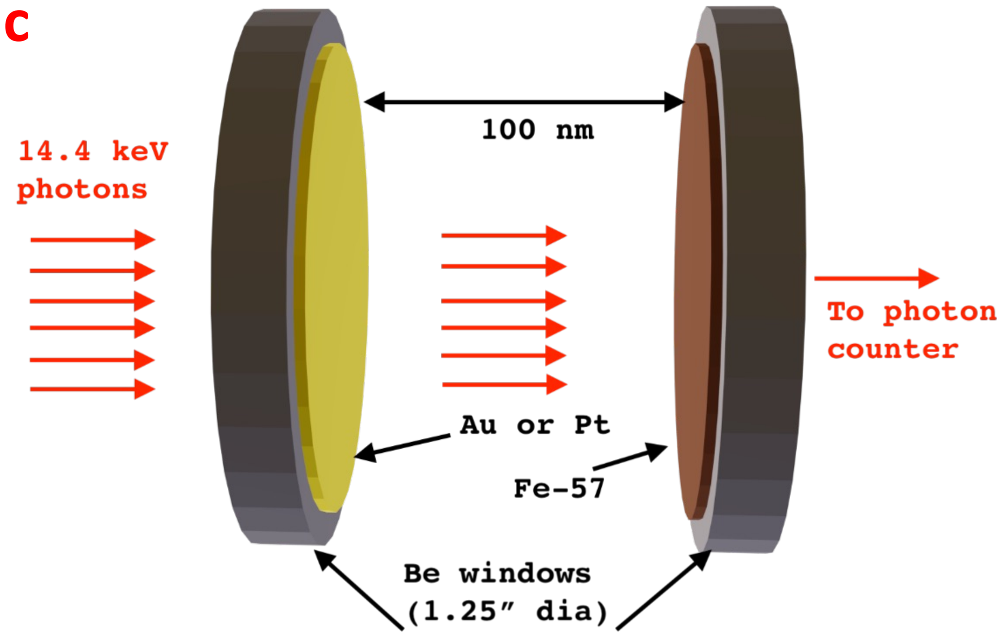


For reference, aLIGO strain sensitivity:
$\delta l/l \sim 10^{-23}/\sqrt{Hz}$

The new, hypothetical interaction, perturbs the isomeric state, slightly changing the position of the line.

By design, the experiment is insensitive to vector interactions, highly suppressing EM backgrounds.

Note that we search for the new interaction by measuring the effect of the field on a bound state, *and not by sensing a force: this is a rather new concept of measurement.*

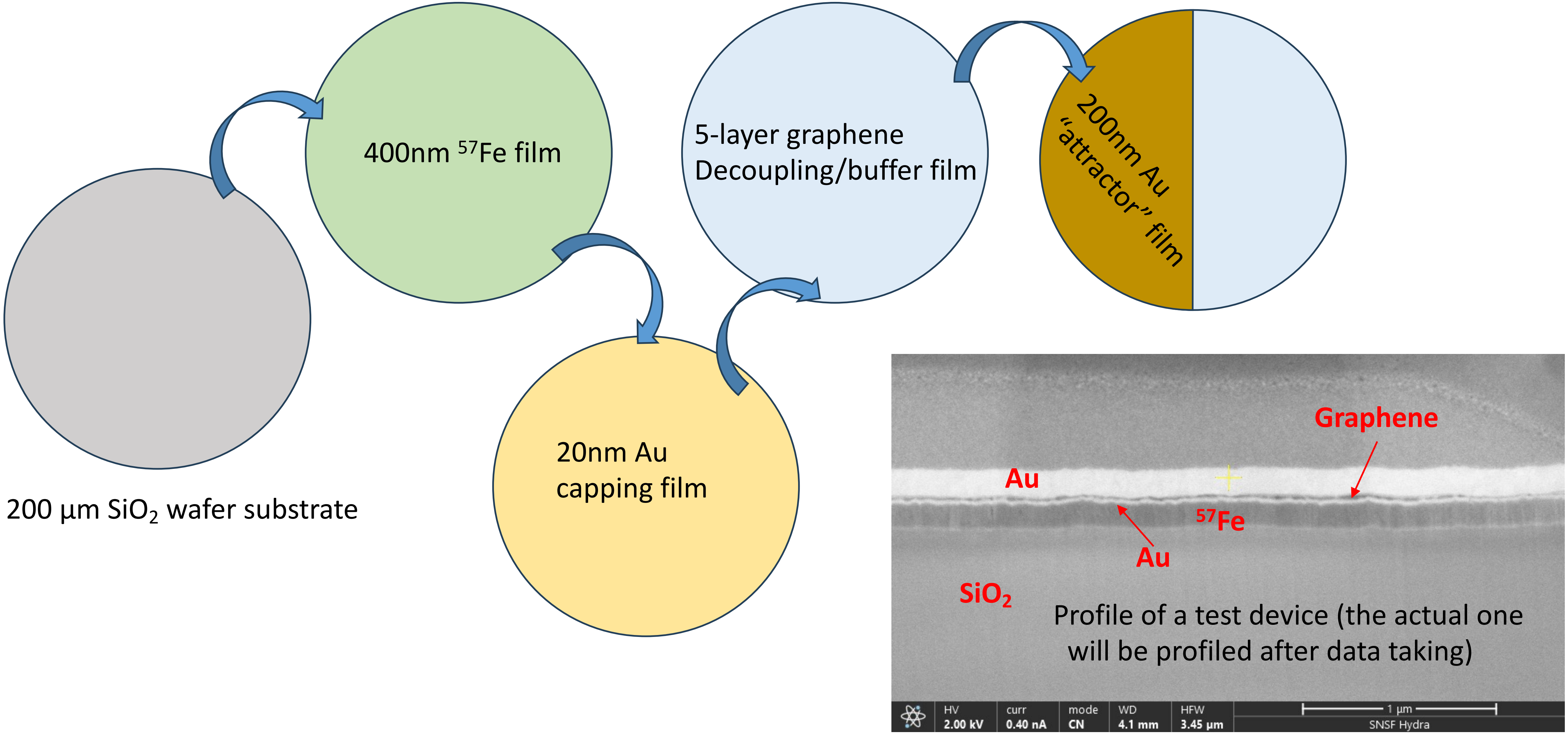


Unfortunately, there is nuclear physics between a measured effect and the line shift potentially observed by an experiment.

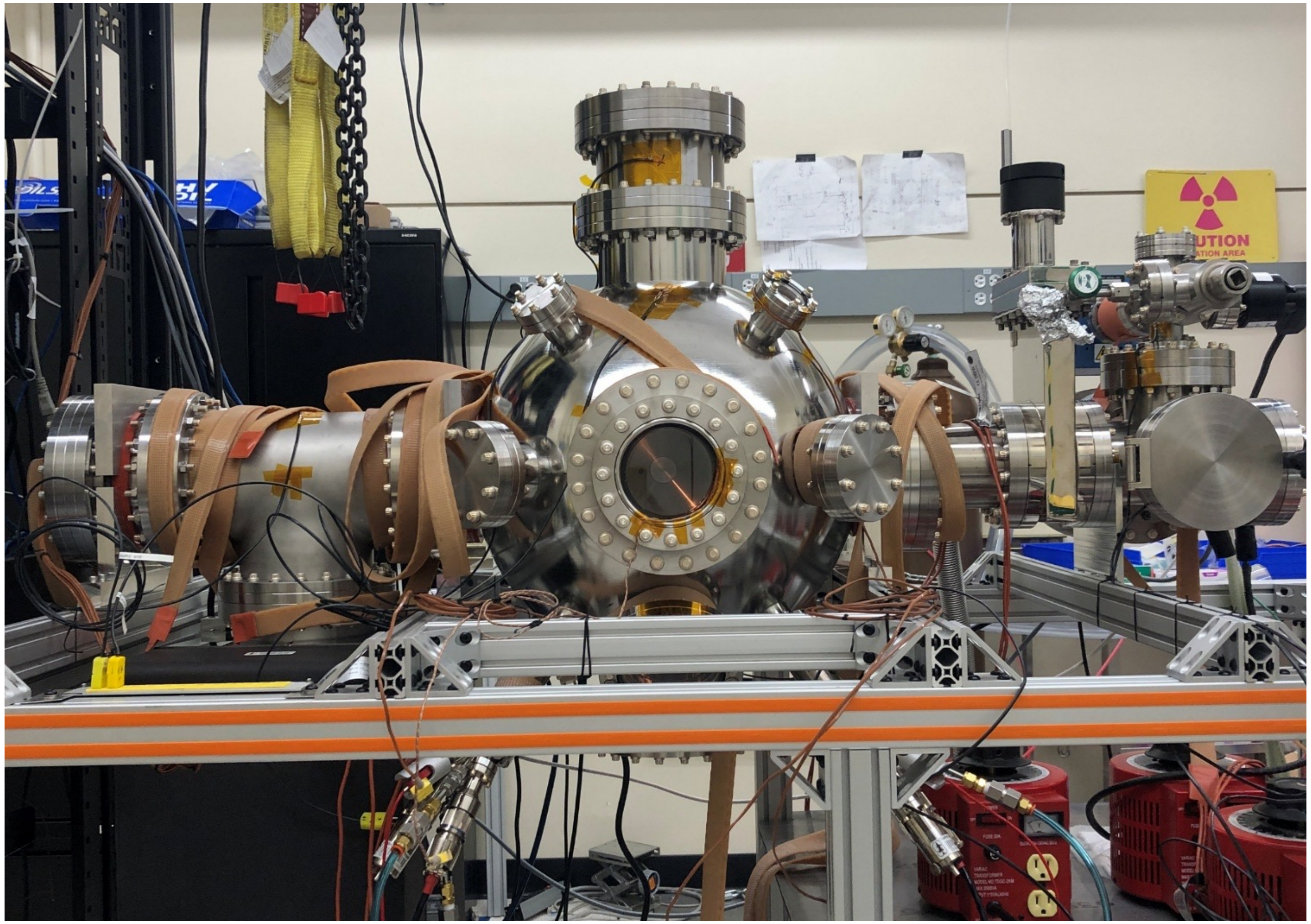
Yet, a line shift, as long as real, is a discovery, irrespective of the nuclear physics.

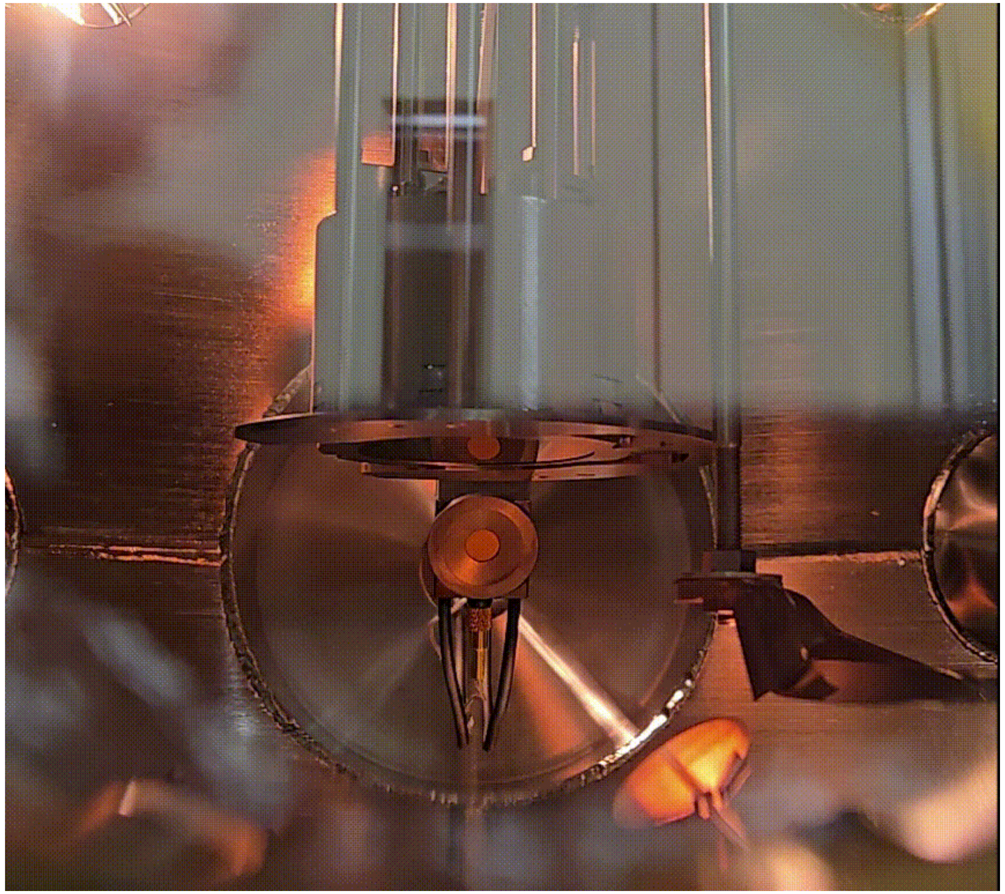
…reminds me of neutrinoless double beta decay!

A first experiment with ^{57}Fe: *Integrated resonant absorber and attractor sourcing the new interaction*



Dedicated evaporators to produce stress-free films



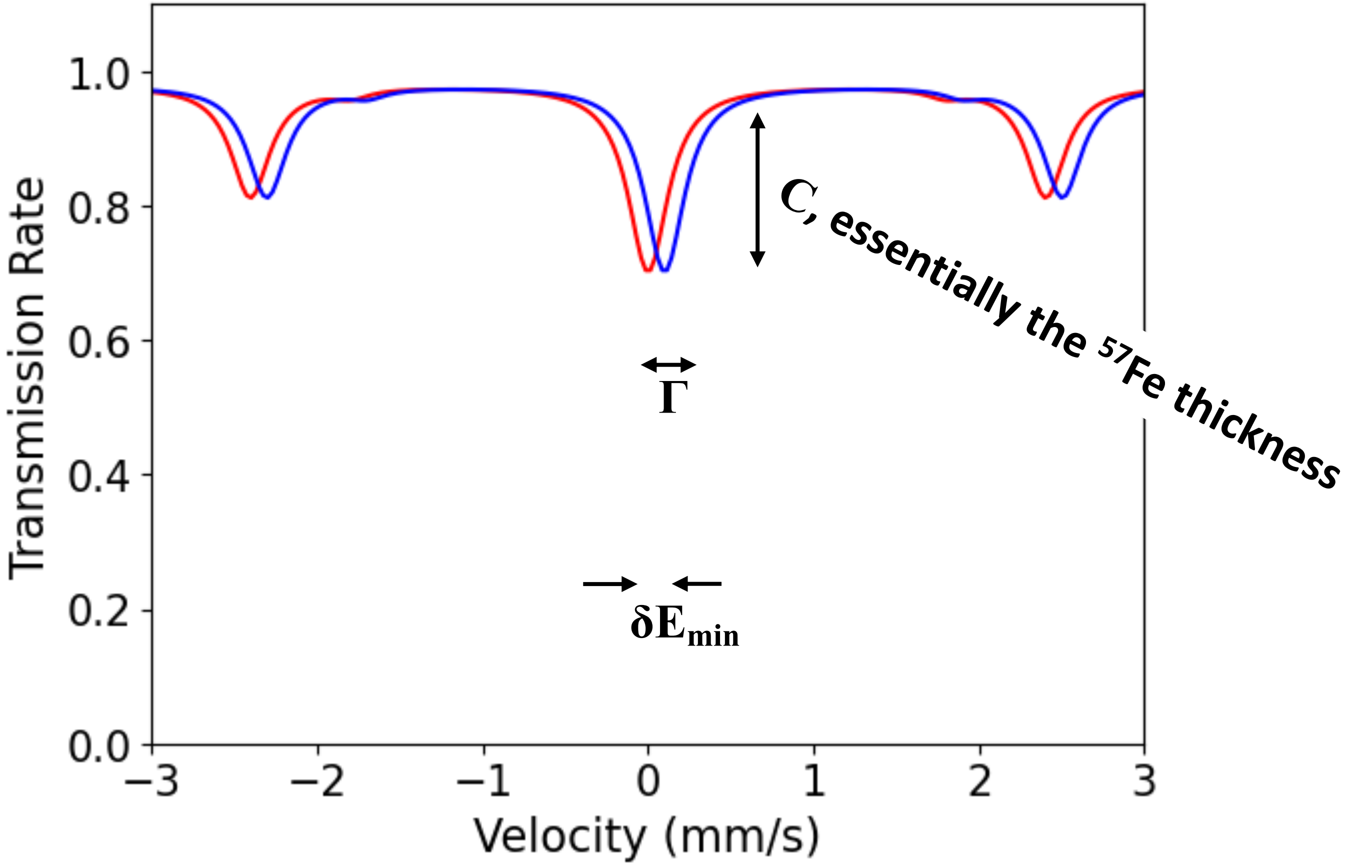


The sensitivity to an energy shift depends on the linewidth (Γ), the contrast (C), and the counting statistics (n)

$$\delta E_{min} = \frac{T(v_0)}{2\sqrt{n}} \left|\frac{dT}{dv}\right|_{v_0}^{-1} \sim \frac{T(v_0)\,\Gamma}{2\sqrt{n}C}$$

We are initially shooting for
δE_{min} = 3 x 10^{-14} eV*

➔Γ = 0.28 mm/s = 1.3x10^{-8} eV
C = 0.18
n = 2x10^{12} on each side
(100 days @ 2.5 x 10^5 evts/s)



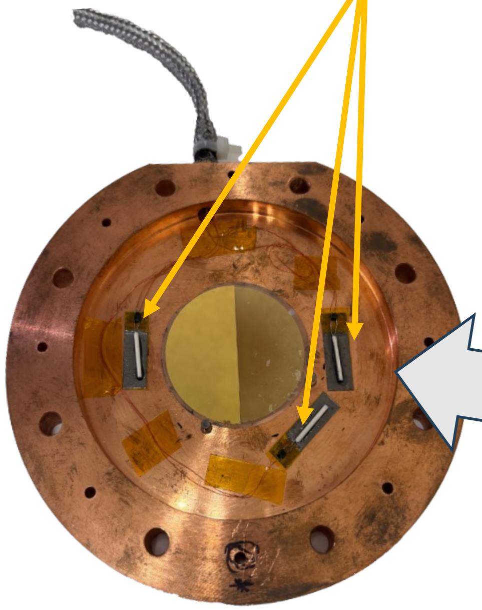
** The Pound & Rebka initial (final) experiment had a 8.4 x 10^{-12} eV (3.5 x 10^{-12} eV) sensitivity*

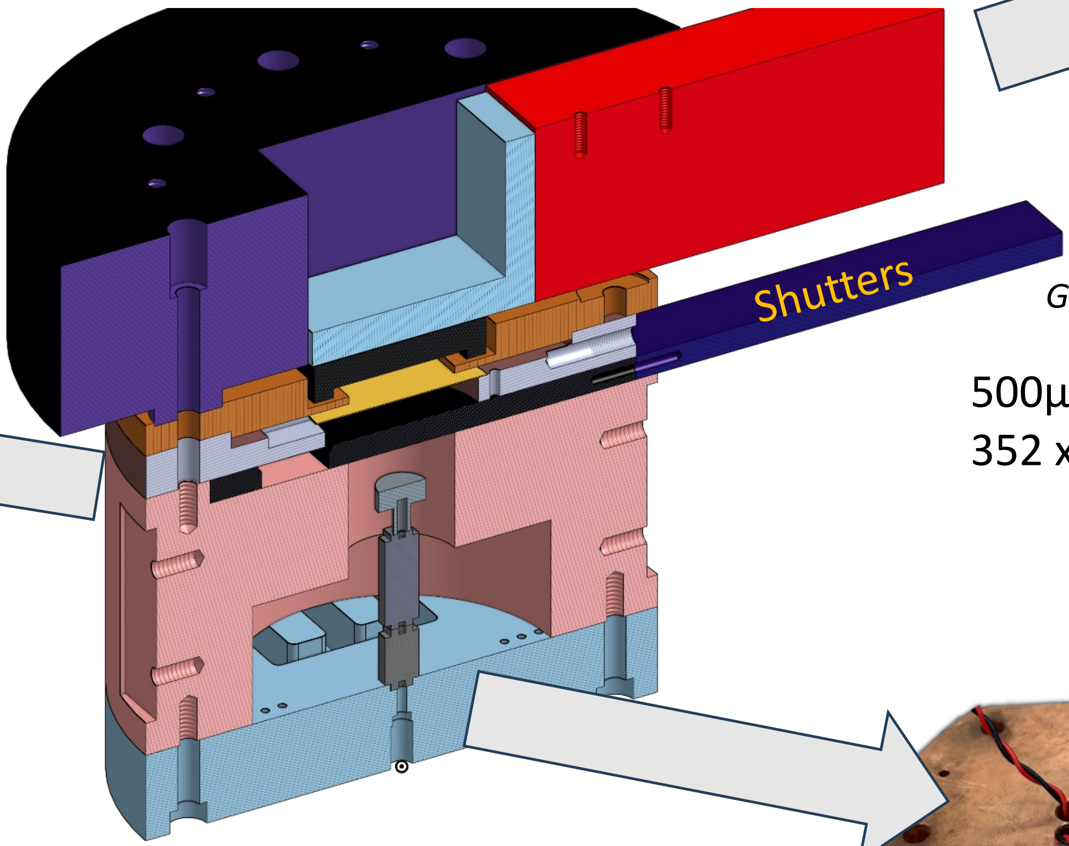
Known systematics: $\delta E = 10^{-15}$ eV is equivalent to:

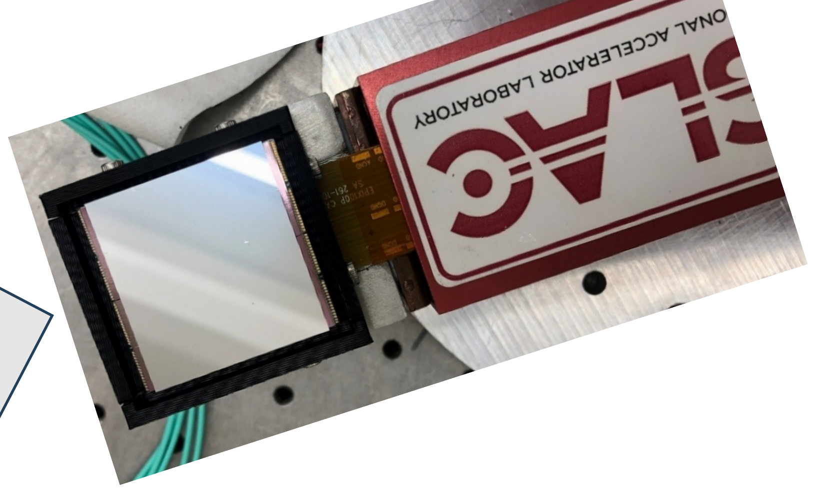
• **Temperature**	$\Delta E \sim 10^{-11} \left(\frac{T}{300K}\right)^3 \ eV/K$	$0.1\ mK$
• **Casimir**	$\Delta E \sim 3 \cdot 10^{-15} \left(\frac{10\ nm}{d}\right)^4 \ eV$	$20\ nm$
• **Magnetic**	$\Delta E \ll 10^{-8}\ eV/T$	$50\ nT$
• **Pressure**	$\Delta E \sim 10^{-10}\ eV/GPa$	$10\ \mathrm{k}Pa$

Across the size of absorber (~5cm diameter)

Resonant absorber with Au ½ coating anchored to a copper plate with absolute and differential thermometry





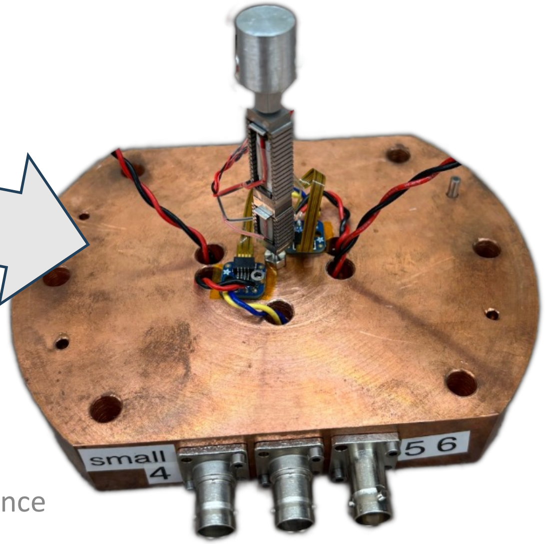


EpiX-10KA X-ray camera (SLAC)

G.Blaj et al., Proc. 13th Intl Conf on Synch. Rad. Instrum.
https://doi.org/10.1063/1.5084693

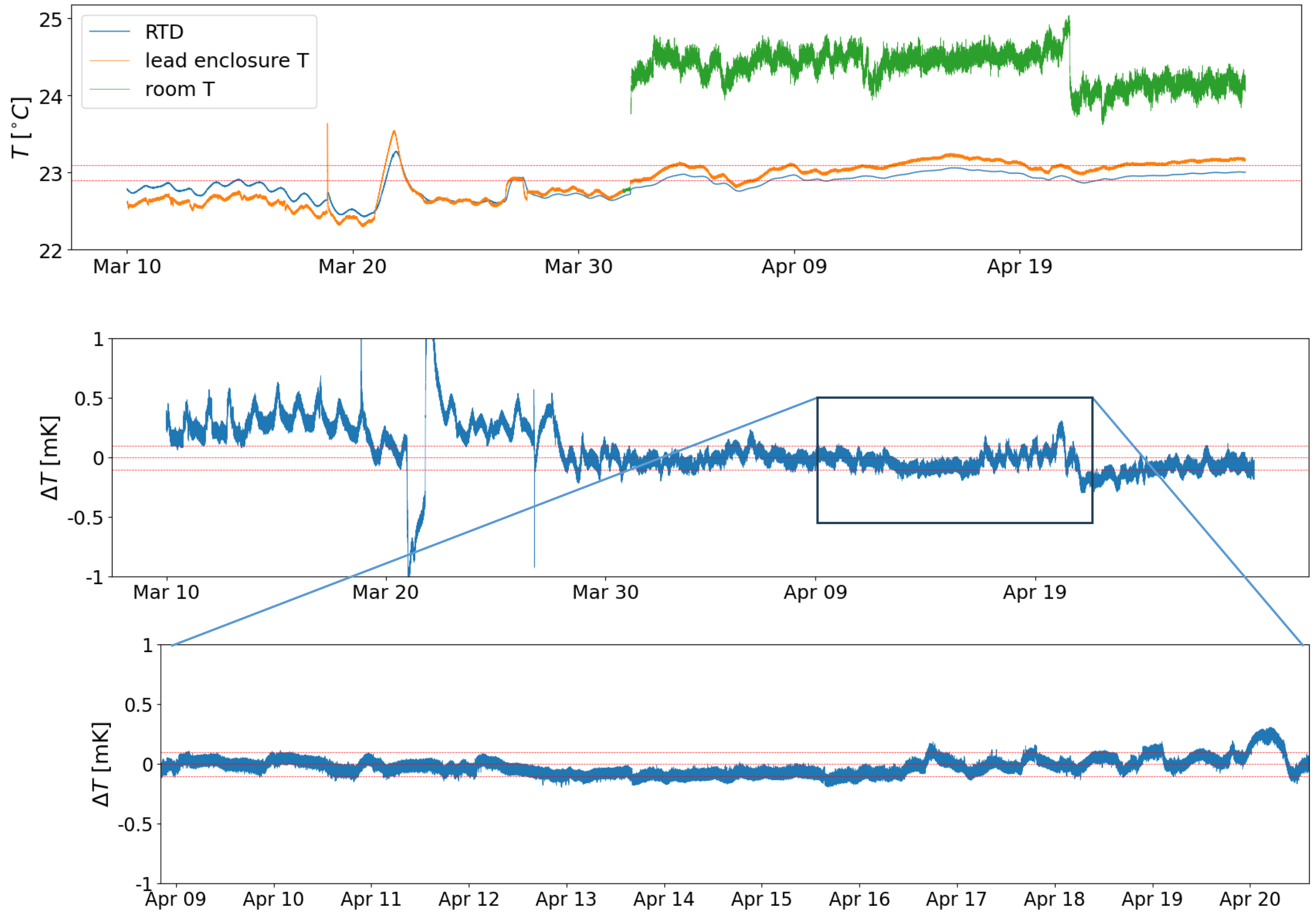
500µm thick Si (75% QE @ 14.4keV)

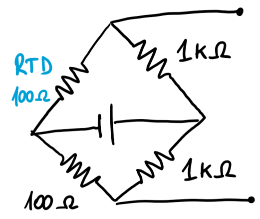
352 x 384 pixels   1 kFrame/s

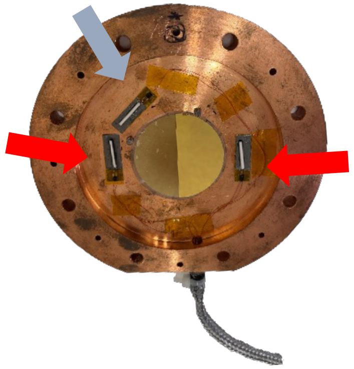


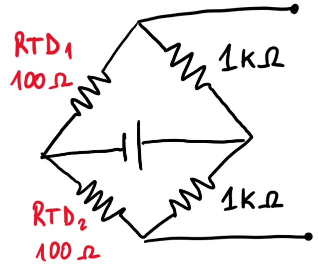
The source moves at 0.1mm/s with 10pm/s precision

Most challenging constraint: temperature. Our system appears to be good (between the two sides of the absorber) to 0.2 mK.

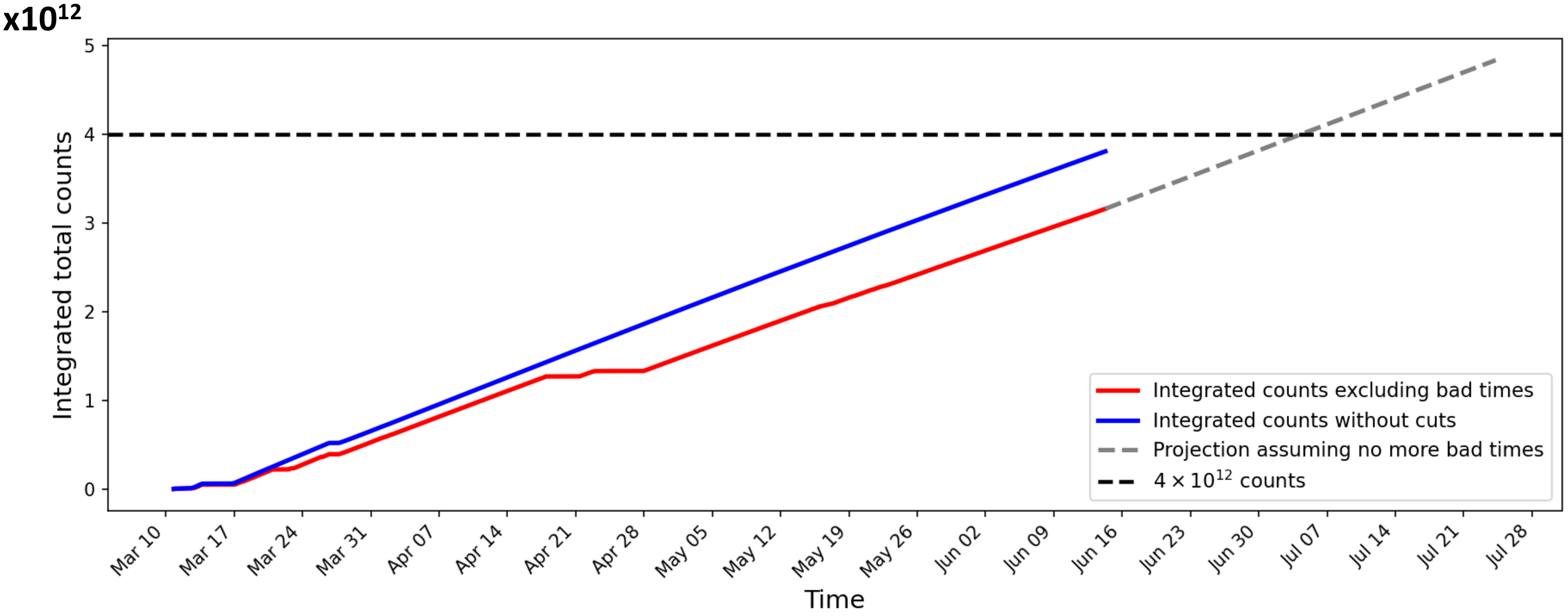




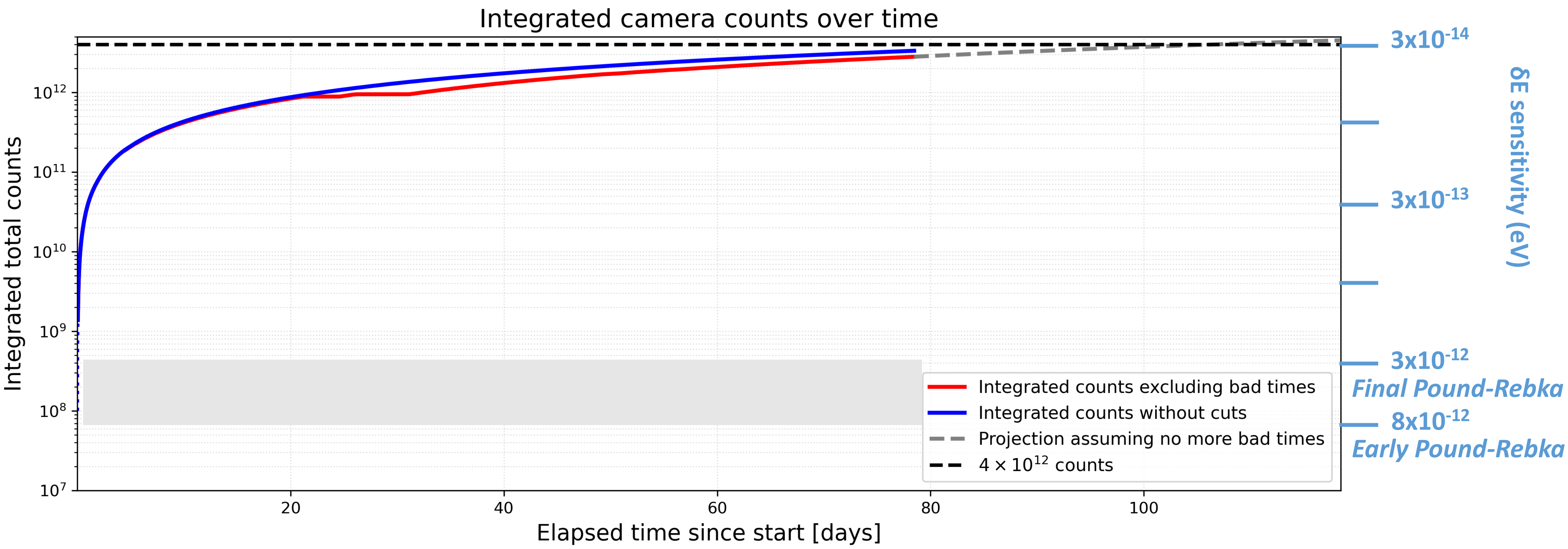




We already have ~100 days of data on disk, using a ~30mCi ^{57}Co source.



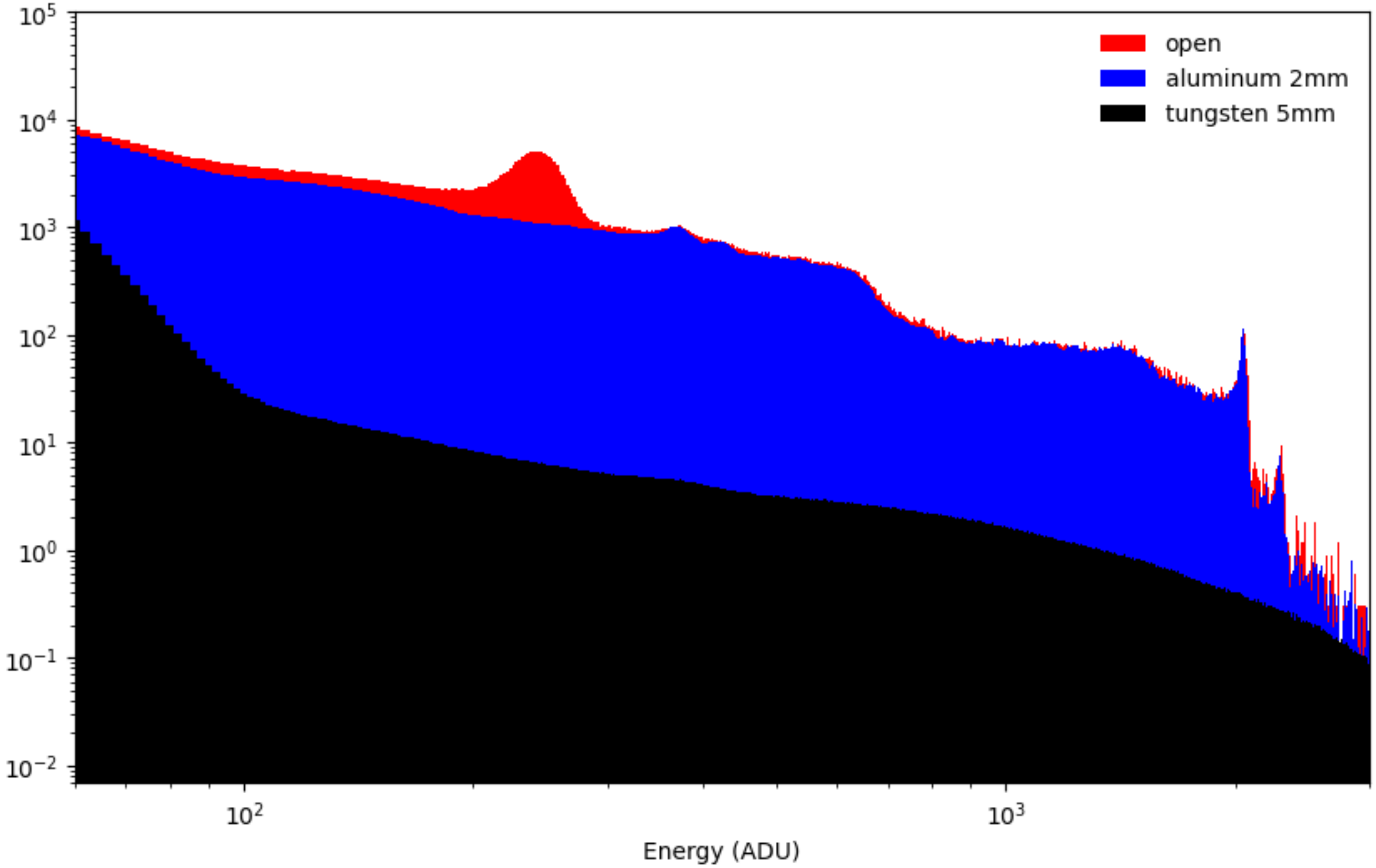
Probably the most sensitive Mössbauer experiment ever done!



1) **Being compact makes it easier**
2) **Being compact means a large solid angle, which makes is harder**

… as we will see in a minute

Single pixel energy spectrum with different shutter configurations for 1 day of data



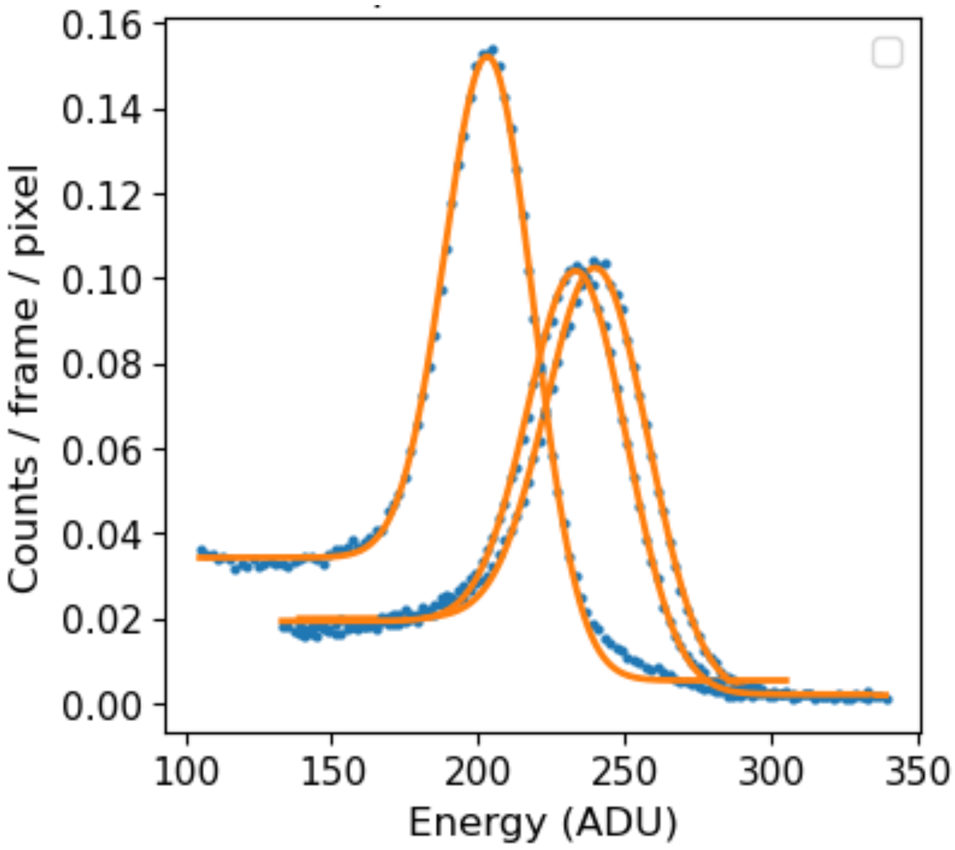
Closing the tungsten shutter eliminates all signals other than electronic noise and generic radioactive/cosmic ray background.

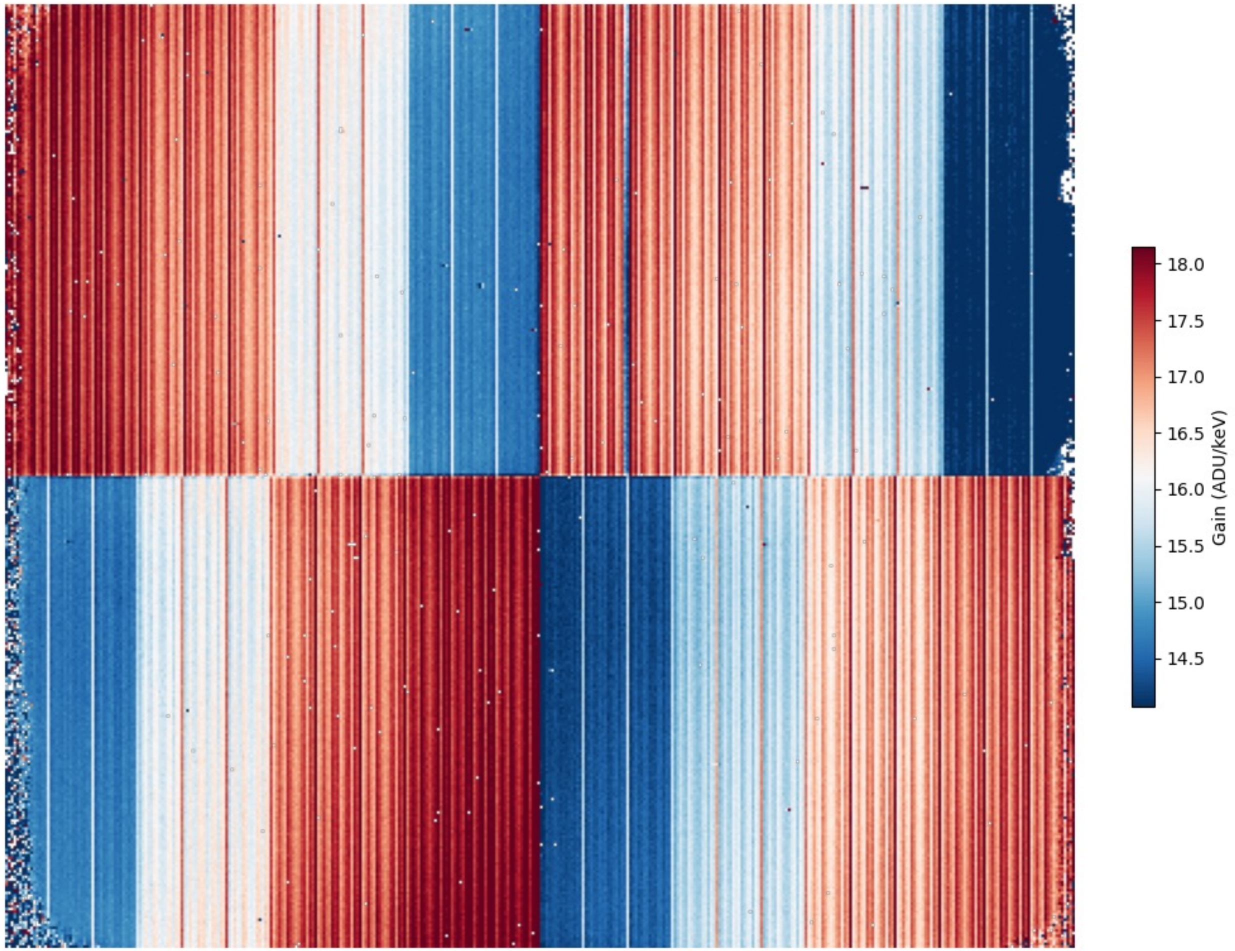
An aluminum shutter removes 99.2% of the 14.4keV gammas, but transmits 92% of the 122.1keV gammas.

With no shutters the 14.4keV peak is clearly visible with a rate of ~5 evt s^{-1} $pixel^{-1}$ or ~0.7 Mevt s^{-1} for the entire camera.

The rate on the camera is higher because of the other lines.

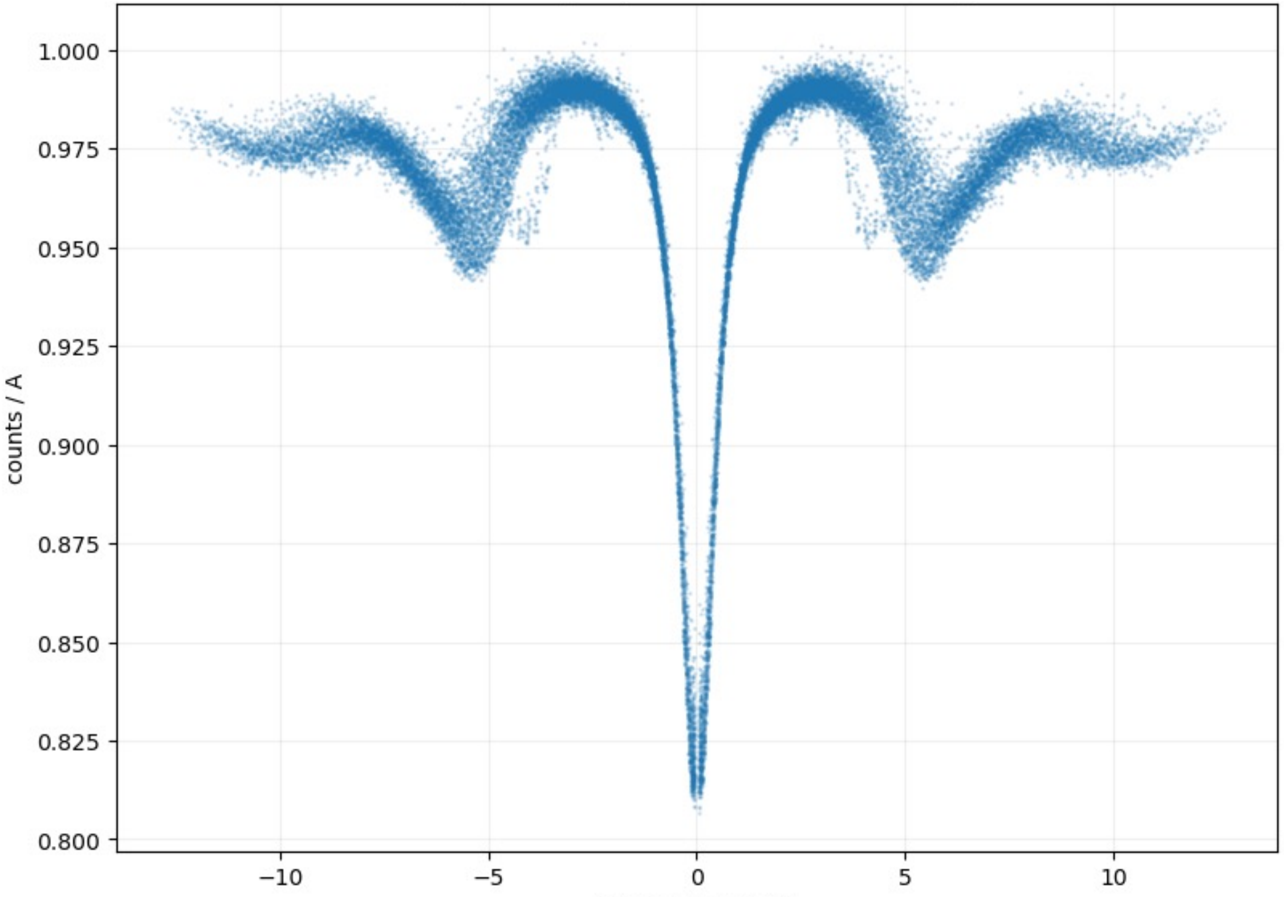
The 14.4keV line as recorded by 3 random pixels.
Note that the energy calibration depends on the pixel and the rate on the position on the camera.





Gain map for the camera. Note the 4 quadrants and the readout where each column has one ADC.

Now a broader velocity scan for the entire camera:
250 velocities, 5 min each, 20 hr data total @ $5x10^5$ ev/s



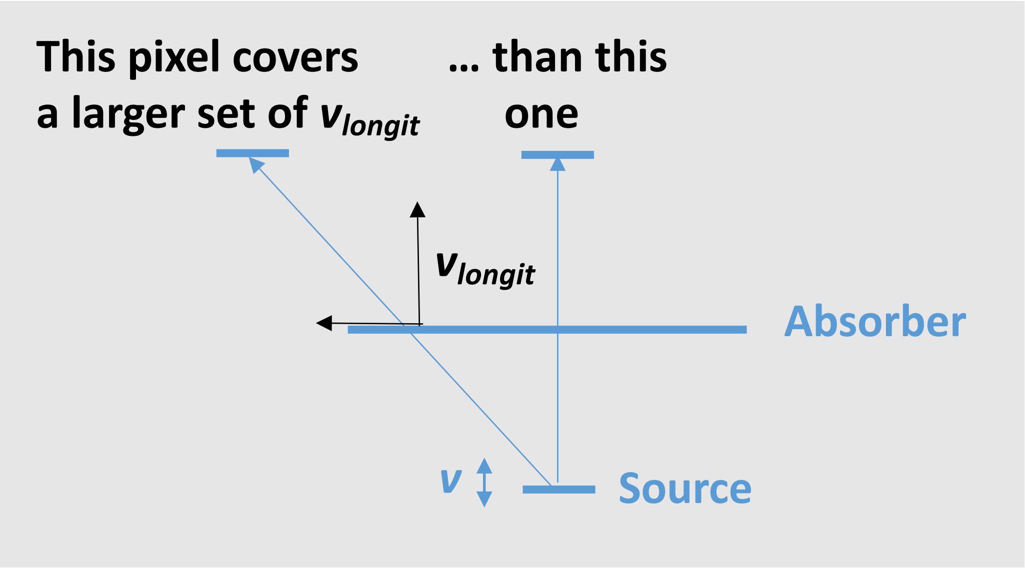
Energy or velocity in units of Γ

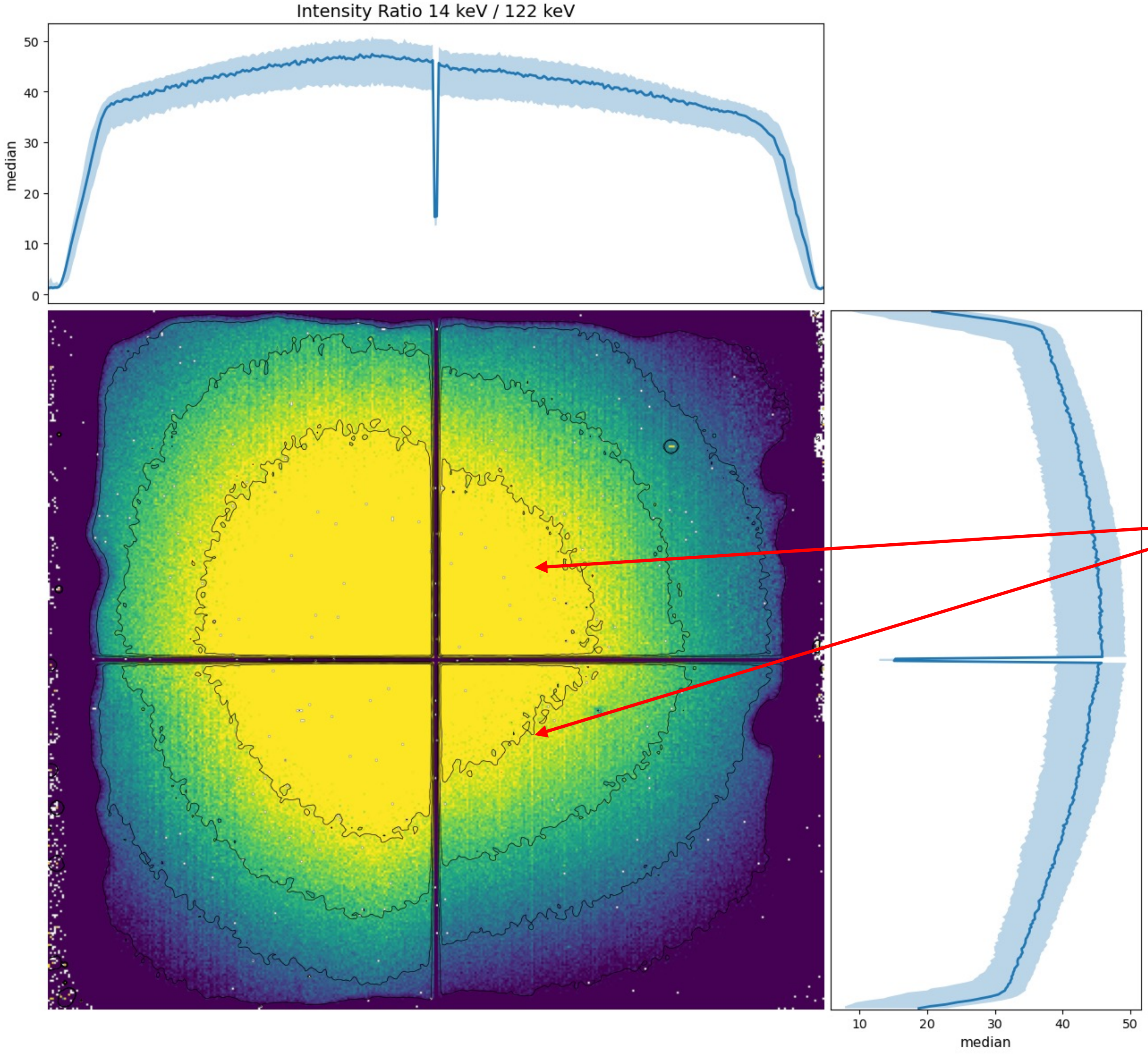
This data is used for calibration and to check that things are well-understood.

The “science data” only covers the central line.

The side-lines are asymmetric, as the longitudinal component the velocity depends on the velocity.

In addition, they are “fuzzy” because pixels at different azimuthal angles cover different ranges of (longitudinal) velocity.





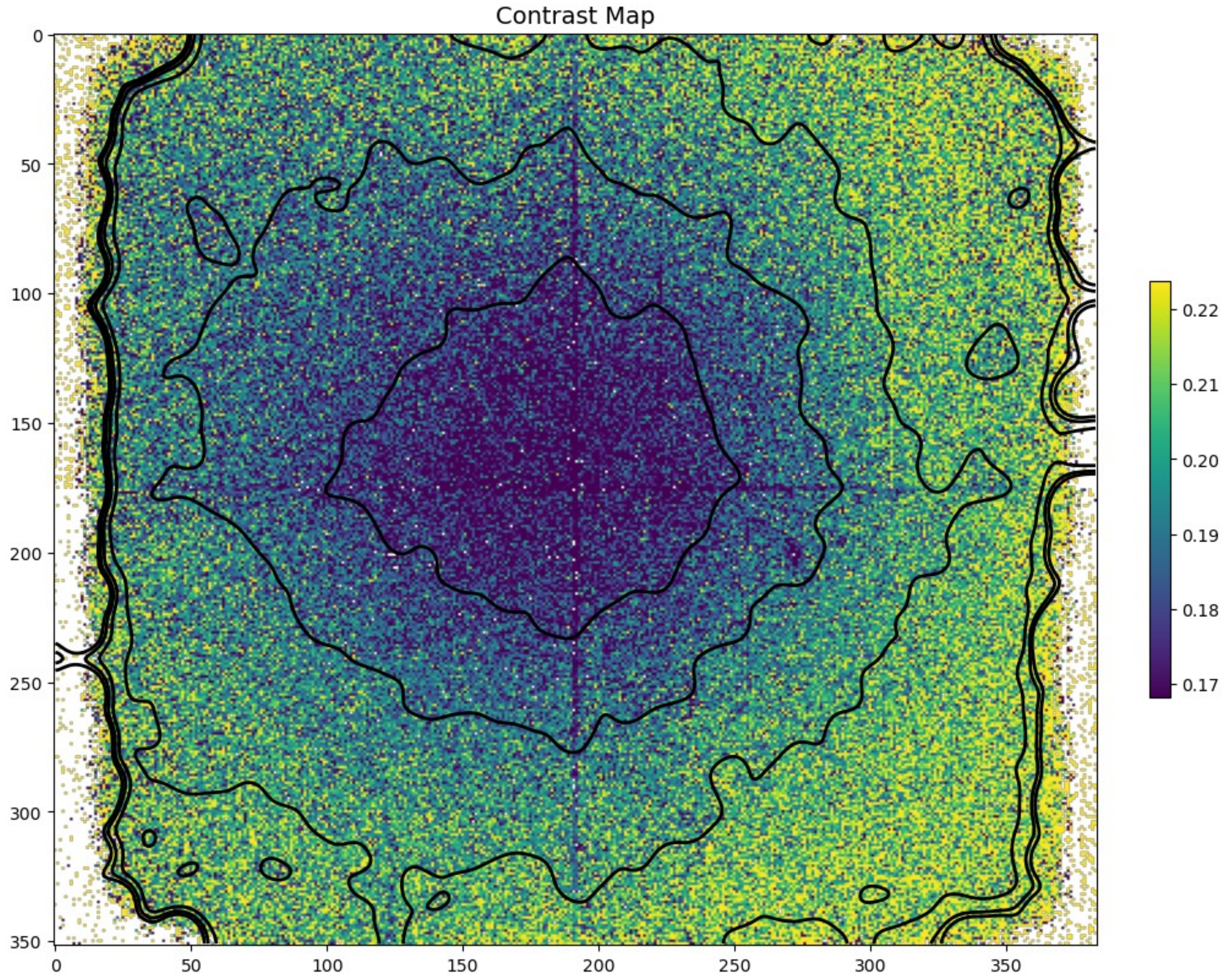
1 day at ~0.5 Mcts/s (for 14.4 keV events)

Note that the source is not perfectly centered over the camera.

Since the 122.1 keV go thru the Au with little losses, the 14.4/122.1 ratio readily shows where the Au is.

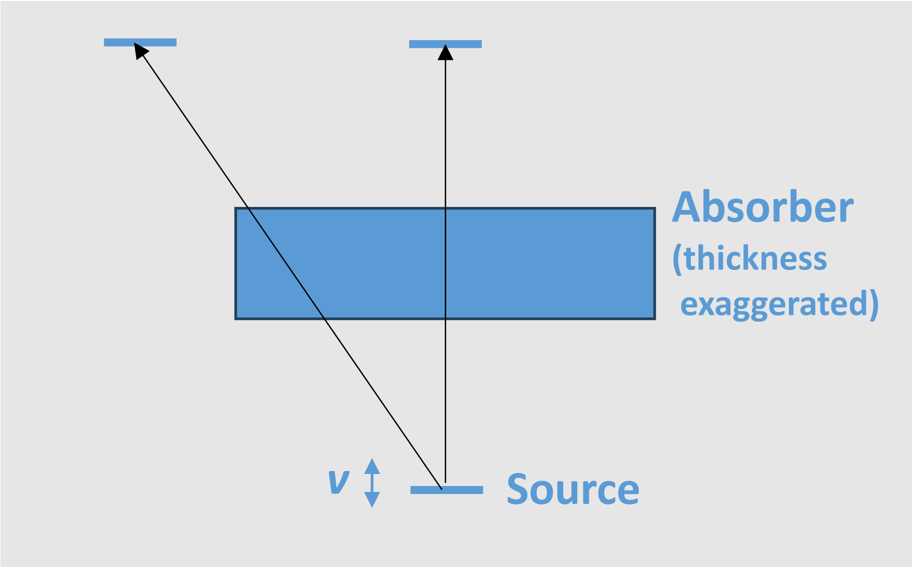
One may ask: why don't you show a Geant simulation of this. Answer: because Geant does not have a Mössbauer package.
We are fixing this now.

Resonant absorption contrast map



The contrast only depends on the ^{57}Fe thickness,

so, it increases at large angles because the slant depth increases with the azimuthal angle.



Next on the Mössbauer front

A Geant Mössbauer package is in preparation

New experiment with a 100 mCi source (3x statistics, we may change the absorber/attractor parameters)

Developing a natural linewidth ^{181}Ta source –should be ~150x narrower, although no one has ever gotten close to the natural width.

Rather tricky:

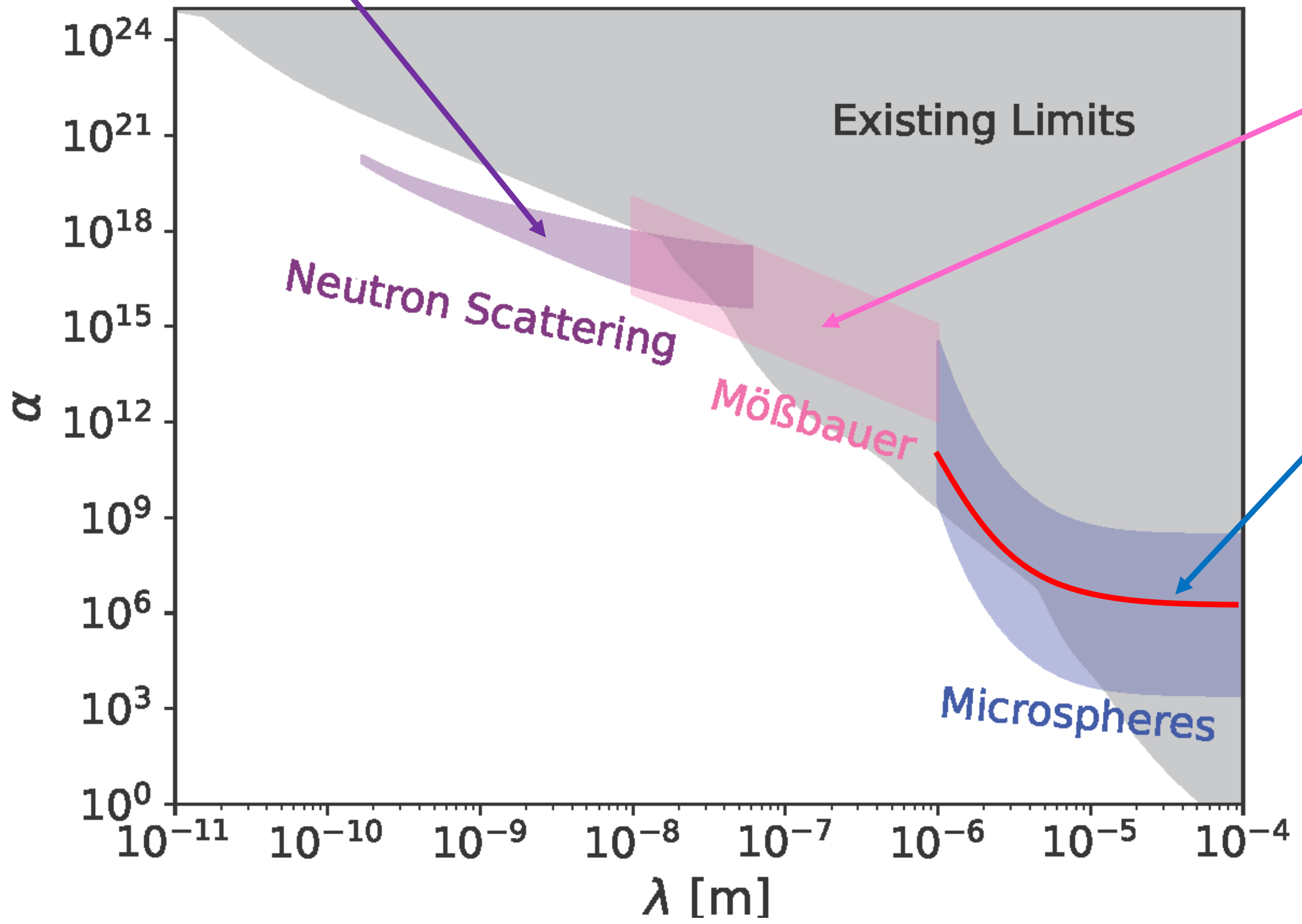
- procure enriched ^{180}W
- produce a ^{180}W film on MgO substrate
- neutron activate to ^{181}W in a reactor
- absorber is a ^{181}Ta on a Be substrate

Internal conversion is larger for Ta (than for Fe) and, in addition, there is a velocity shift between source and absorber.

Aspirations of our program (the bands are projections)

Z.Bogorad, P.W.Graham, GG, Phys Rev D 108 (2023) 055005
First data set collected in May at the ANSTO reactor in Sydney.

Also a motivation to "nuclear quantum optics", with various potential applications.
GG, D.E. Kaplan, S. Rajendran, Phys Rev D 102 (2020) 115031.



Recent result:
G.Venugopalan et al., Nature Sci Rep 16 (2026) 5180
Also, application to neutrality of matter, inertial sensing, quantum S&T

It is also desirable to have some overlap between techniques, *convenient in case of a discovery.*

Finally, a note of caution

This field is not unlike exploring a jungle.

Particle physicists are used to:

- Backgrounds that are "perfectly" simulated by GEANT *et al.*

- Many measurements dominated by statistical errors which are easy to compute (and at times "overcomputed")

- A very mature field expecting a very high-quality standard for results

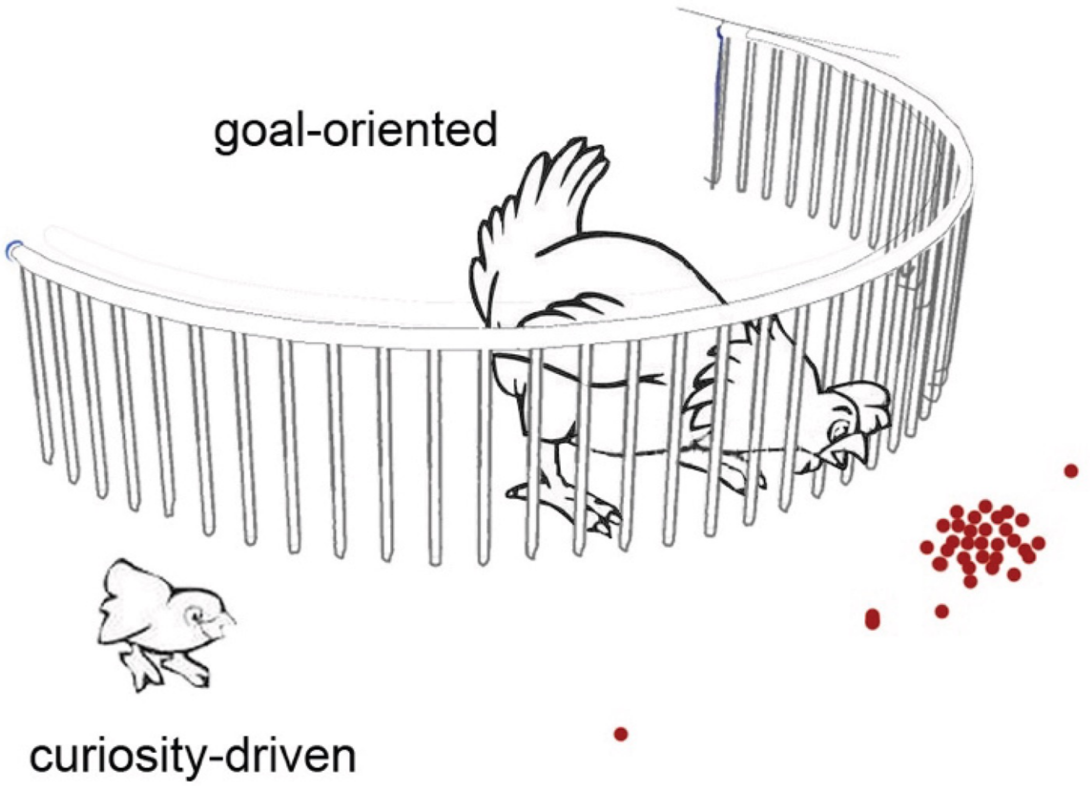
The jungle works differently, and experiments tend to be dominated by systematics, some of which are difficult to quantify. Some experiments may have dubious discovery potential, at least in the pioneering phase.

But discoveries change fields.

When I started in low energy neutrino physics "low background" was a rather qualitative term. Now we have "perfect" simulations, like in colliders.

So, we should keep in mind that some redundancy is healthy.

Conclusion



Cartoon by Ted Hänsch

The current cast