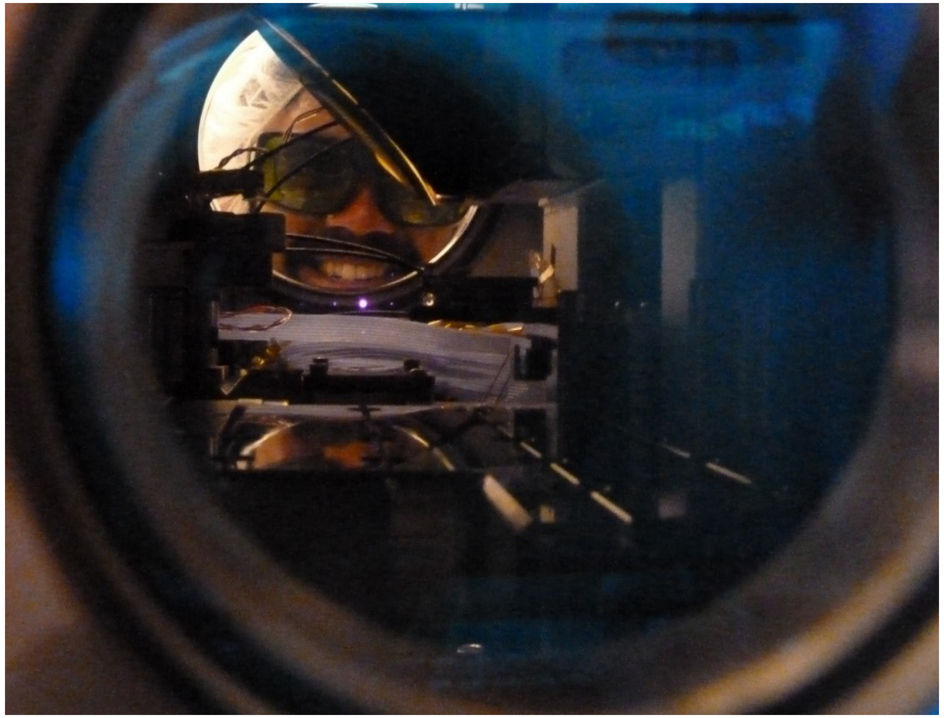
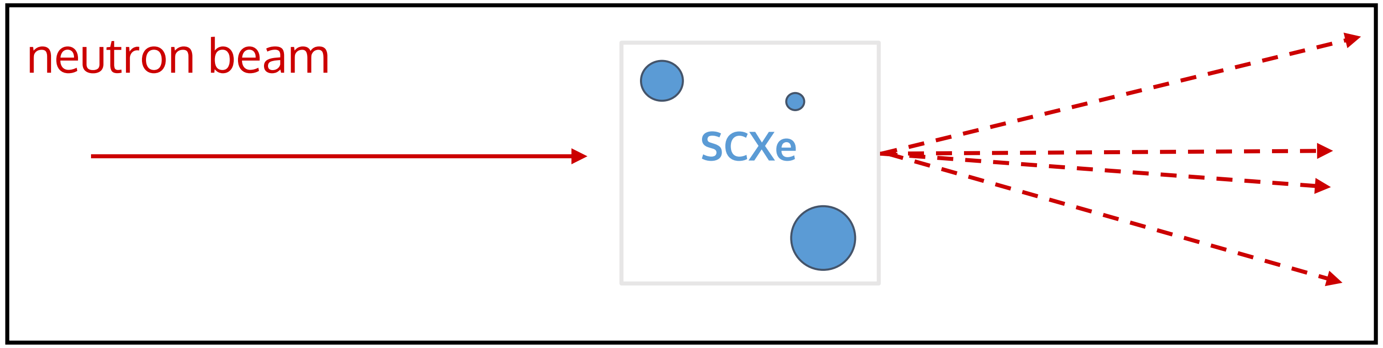
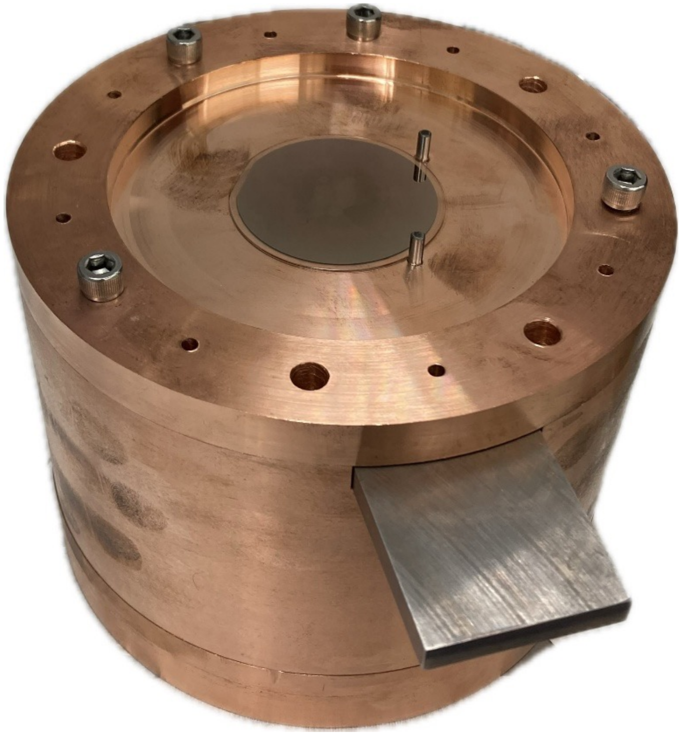
Testing Gravity at Ever Shorter Scale

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 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.

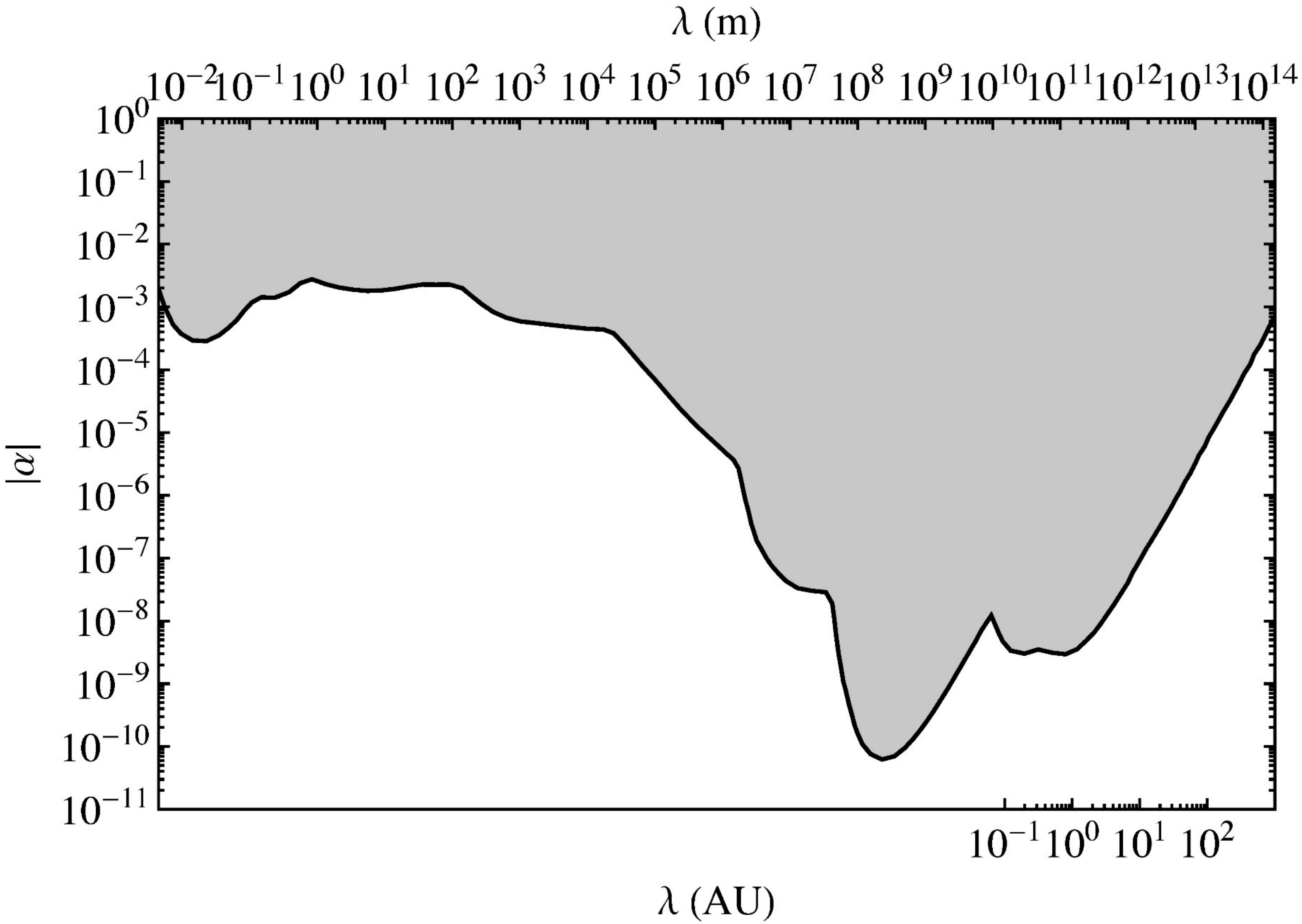
So, how well do we know that the inverse square law applies?

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

$$V(R) = G\frac{M_1M_2}{R}\left(1 + \alpha e^{-R/\lambda}\right)$$

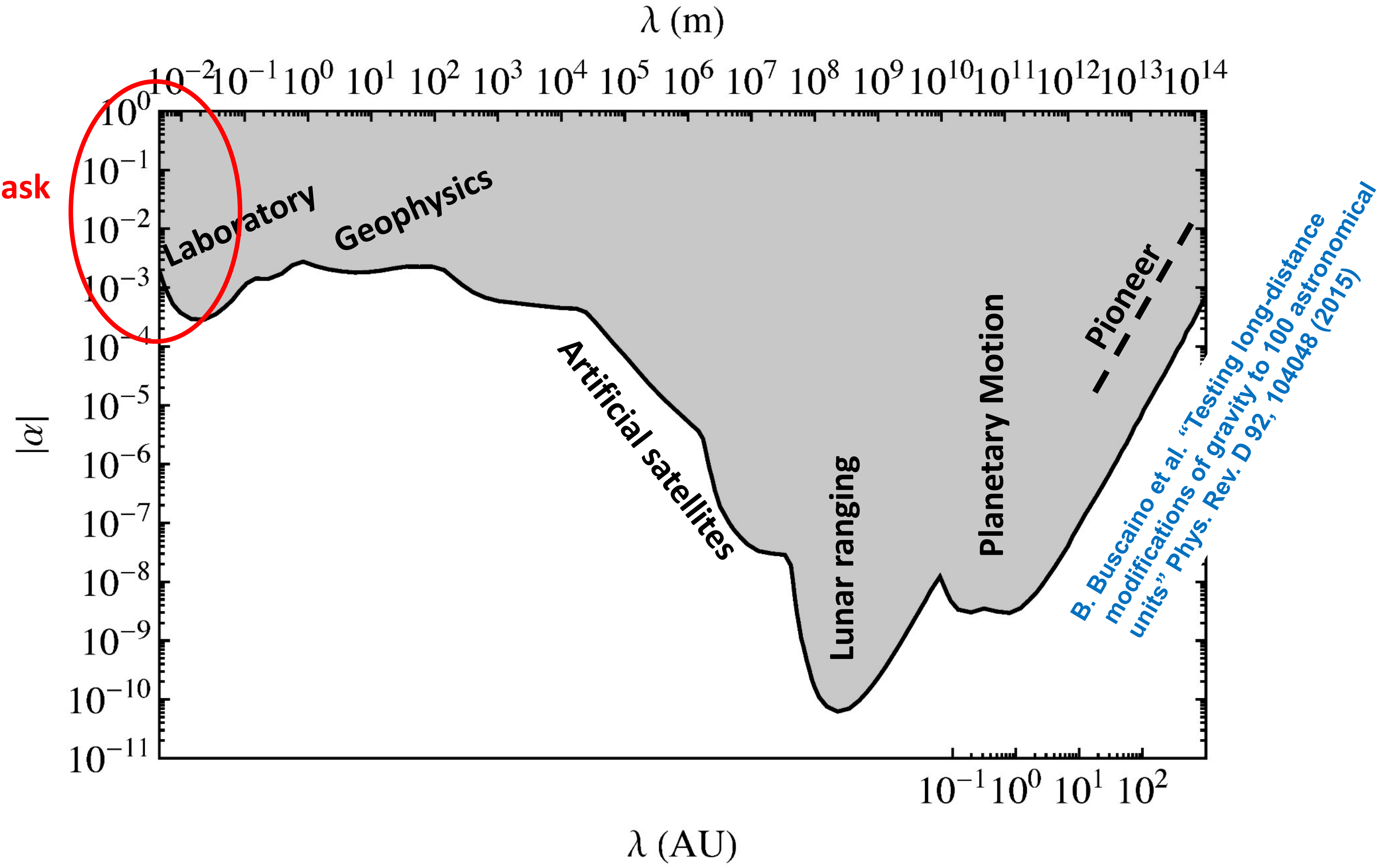
α: magnitude of the effect
λ: scale of the effect

What do we empirically know



What do we empirically know

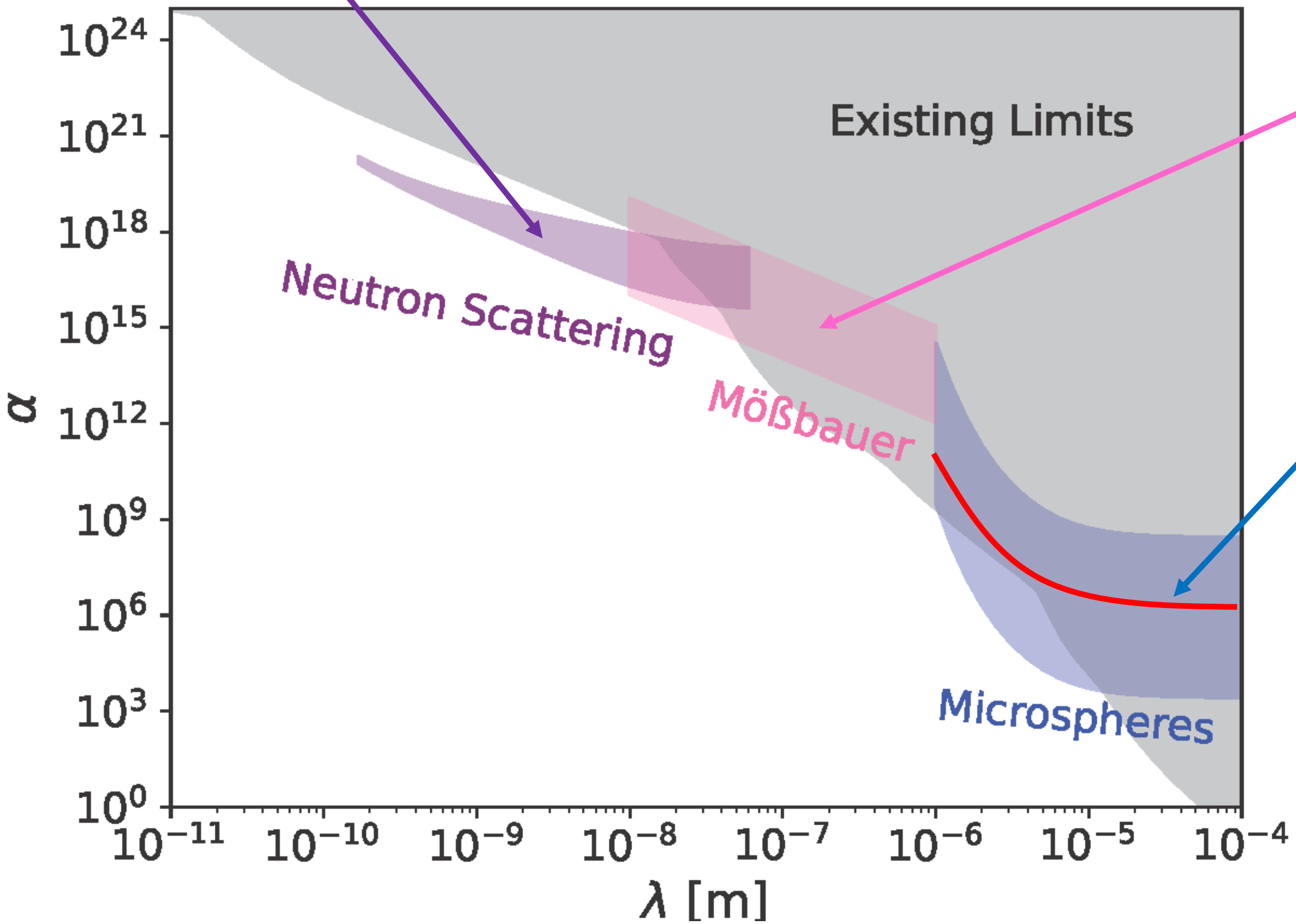
Today's primary task



B. Buscaino et al. "Testing long-distance modifications of gravity to 100 astronomical units" Phys. Rev. D 92, 104048 (2015)

Aspirations of our program (the bands are projections)

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



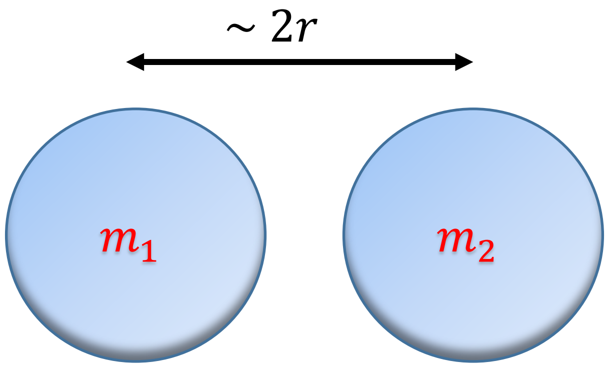
Also a motivation to “nuclear quantum optics”, with various potential applications.
GG, D.E. Kaplan, S. Rajendran, Phys Rev D 102 (2020) 115031.

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

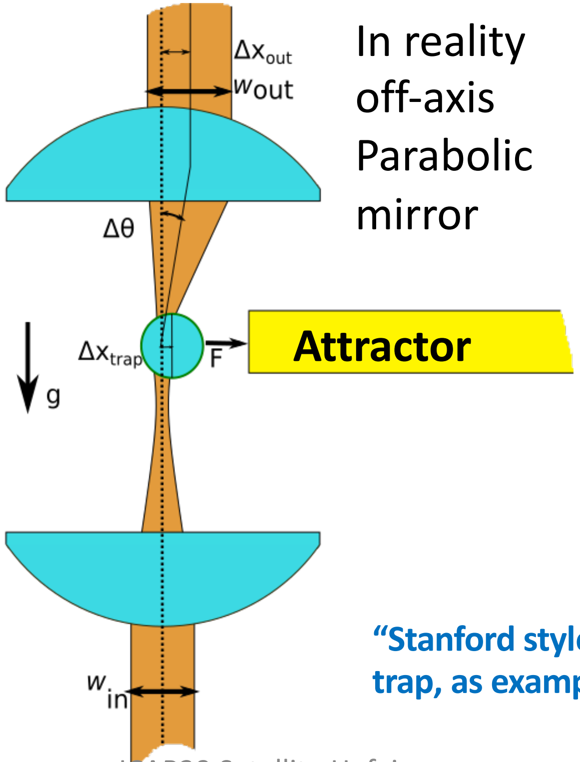
- Since $F = G\frac{M_1M_1}{R^2} = G\frac{\rho_1V_1\rho_2V_2}{R^2}$
  for atomic materials (we can’t use Neutron Stars!)
  $\rho_1 \sim \rho_2 < 20$ g/cm^3, there is no silver bullet.
  In addition, the volume $V \sim R^3$, so $F \sim G\frac{\rho^2R^6}{R^2}$
  and it is clear that measurements at short
  distance become exceedingly difficult.
- At distances <100μm even neutral matter results
  in residual E&M interaction that are a dangerous
  background for these measurements



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

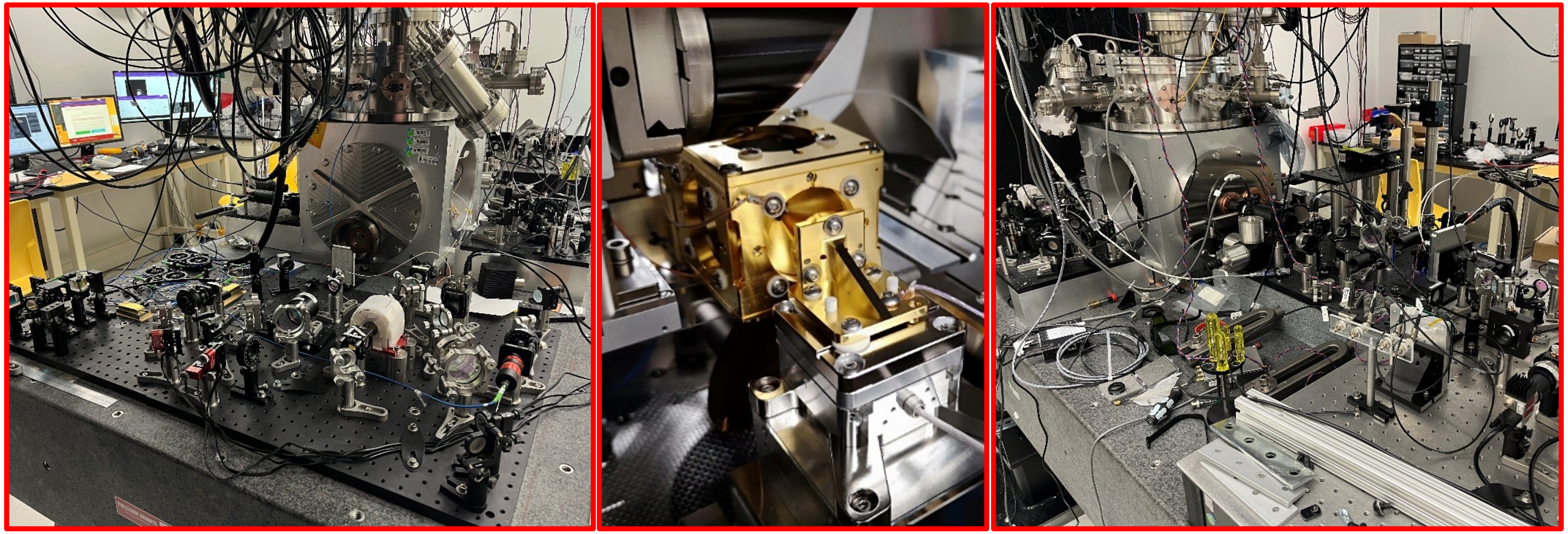
In the last 50 years, optical tweezers have developed into broad field, primarily applied to biology, in water.

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



In reality off-axis Parabolic mirror

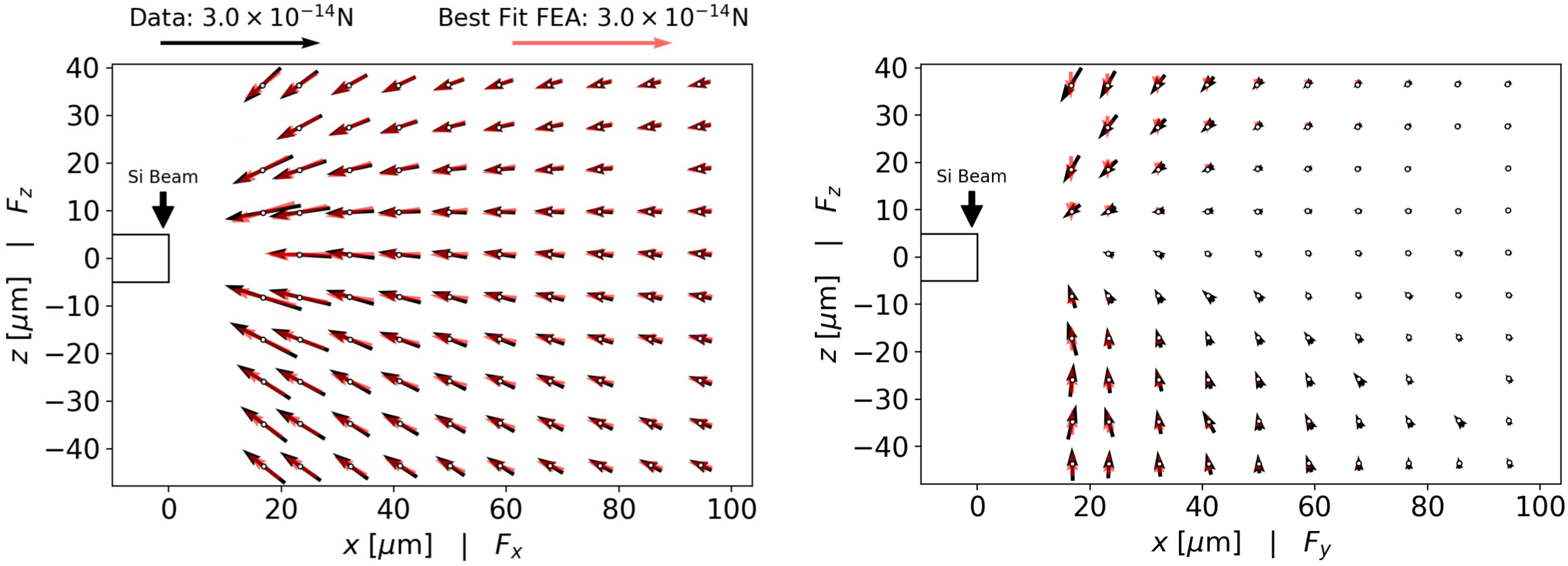
“Stanford style” trap, as example



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

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

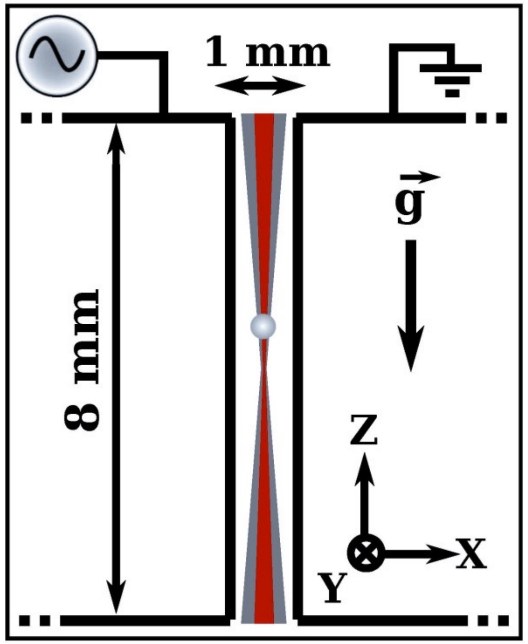
as can be shown/calibrated by measuring charged microspheres



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

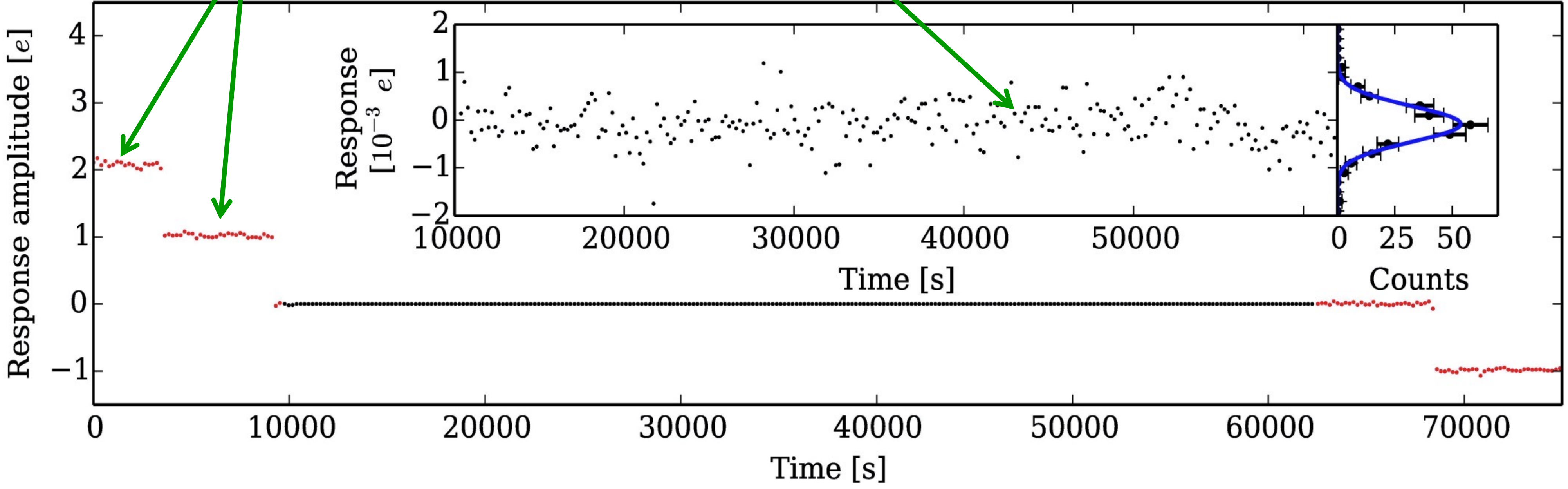
Similar results in G.Winstone et al., Phys. Rev. A 98 (2018) 053831

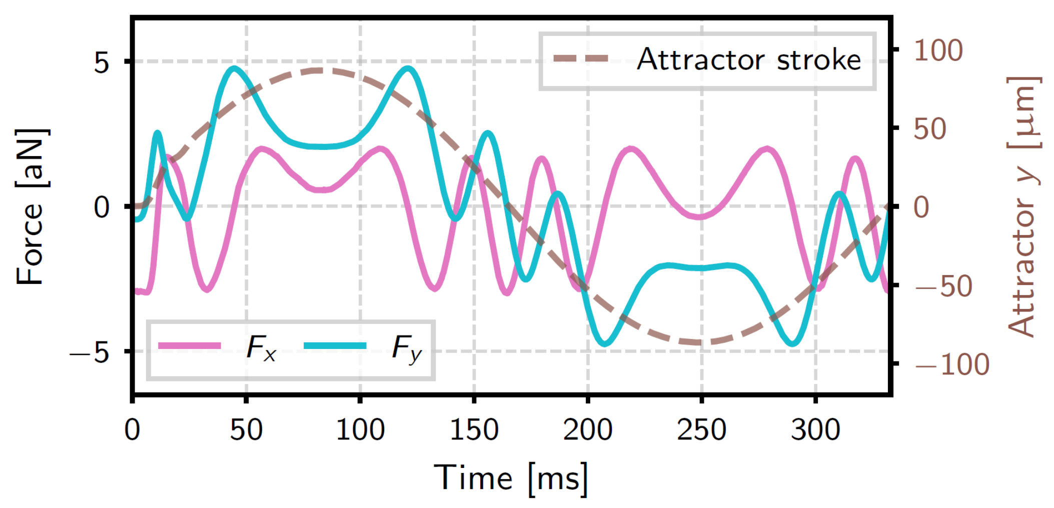
The possibility of setting the charge of the microsphere at leisure, opens the opportunity to search for very small charges (<<1milli-e^-) or, more interestingly, search for deviations from neutrality of matter.



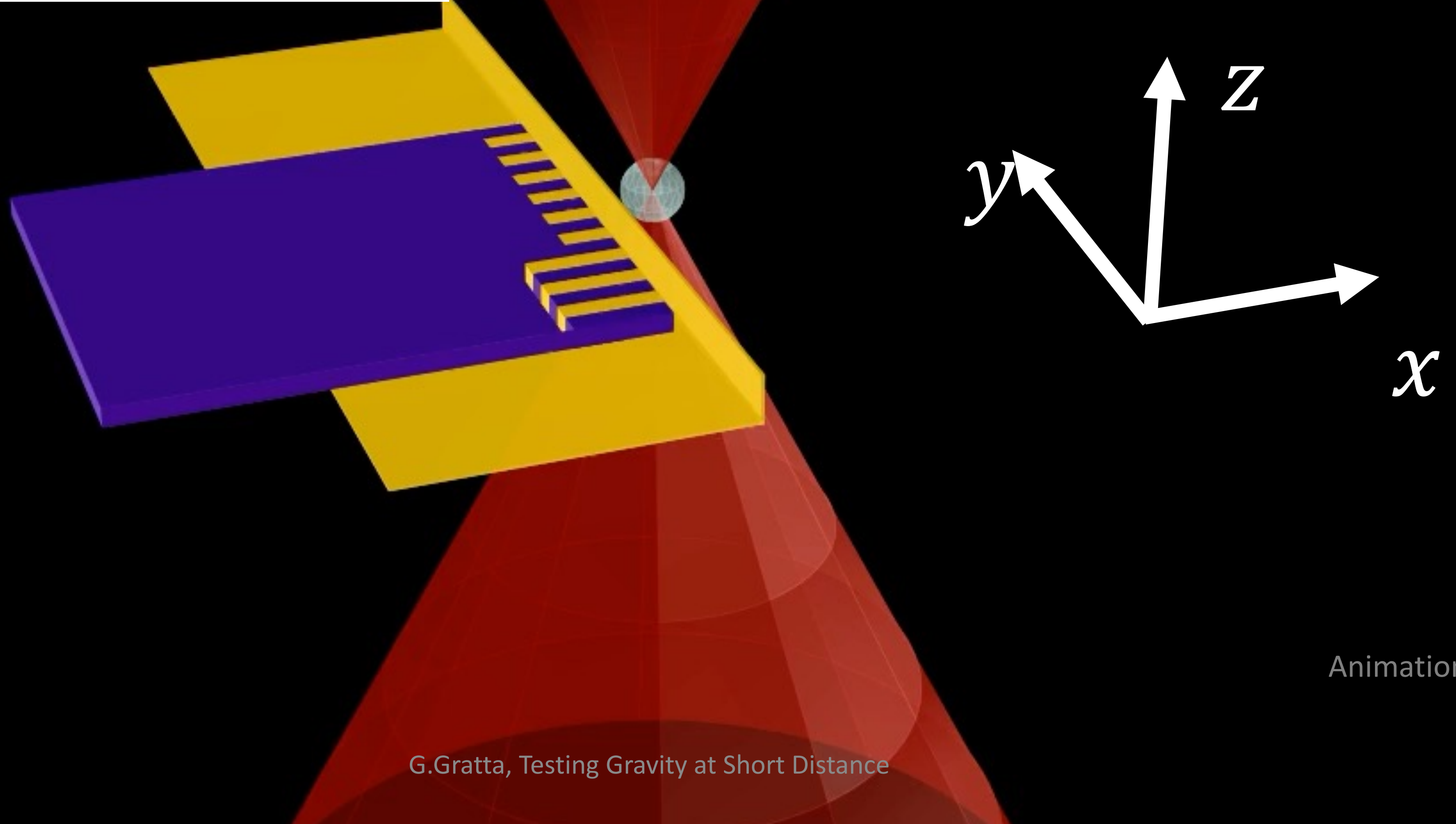
Quantized charge

"0 charge" with increased 500 V RF amplitude.





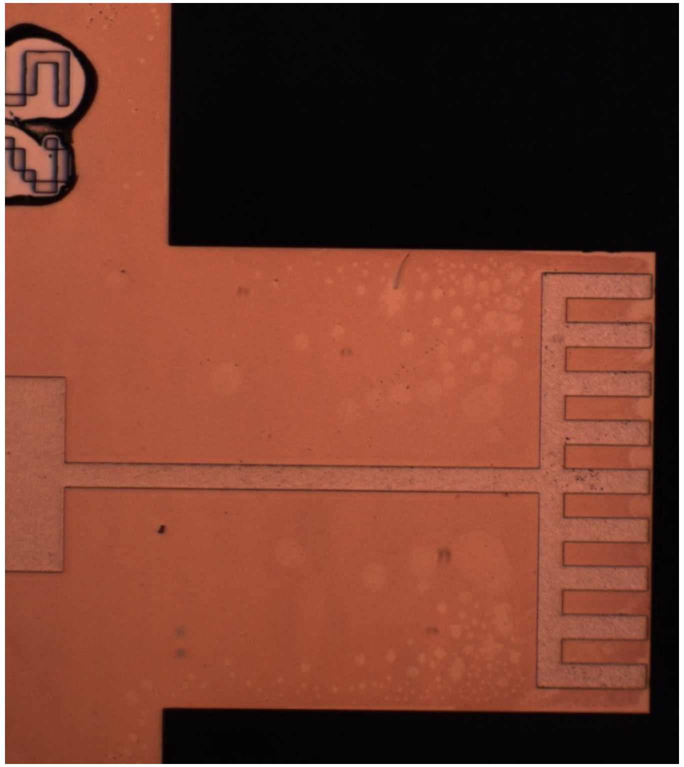
*Microsphere motion greatly exaggerated



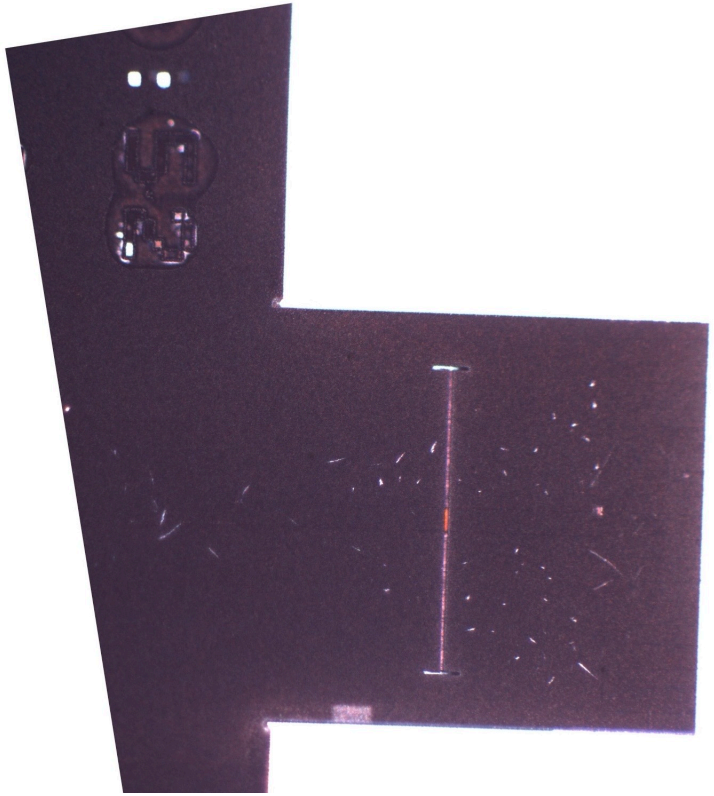
Animation by G. Venugopalan

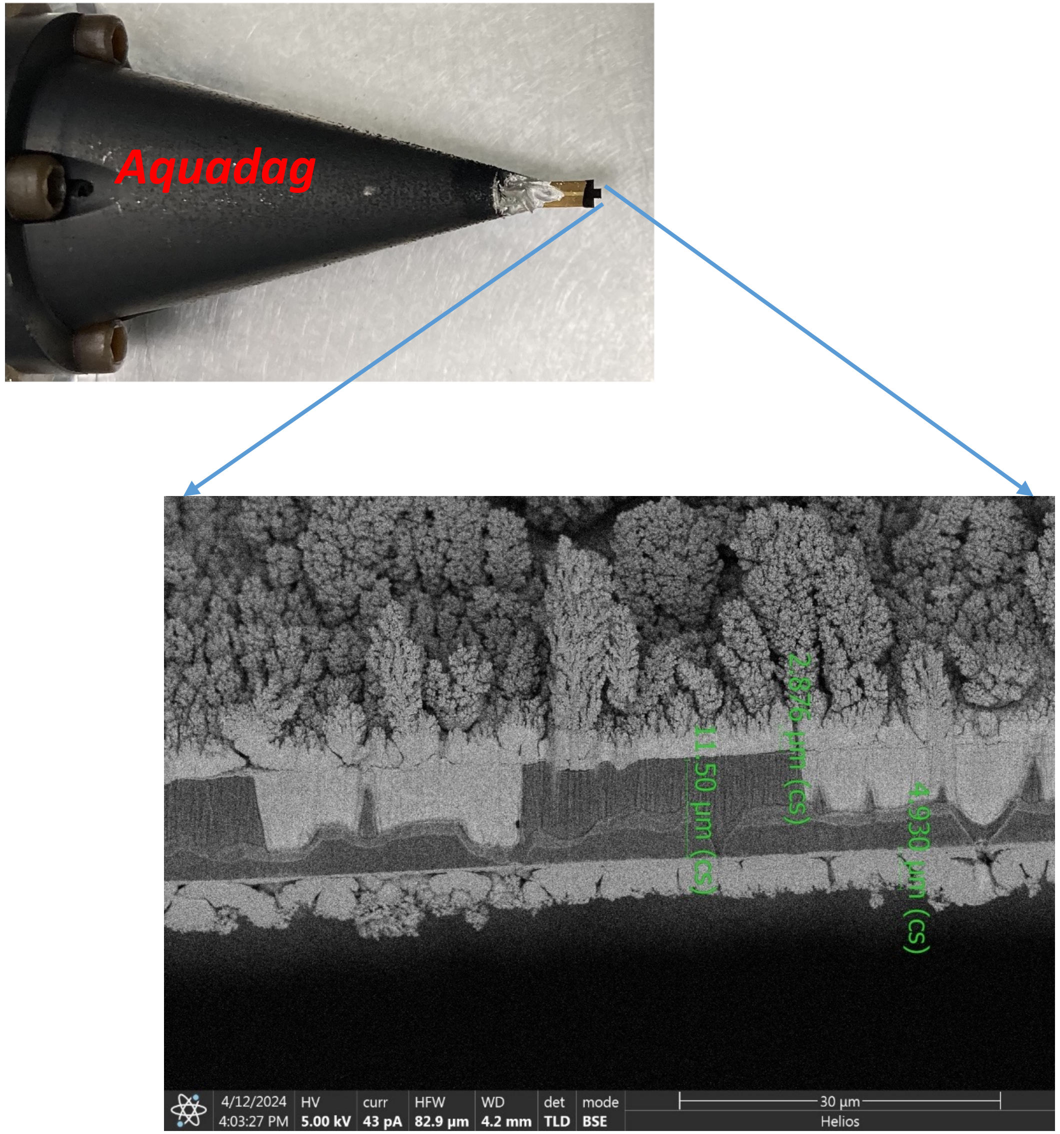
Electroplating "Platinum Black"

Before plating



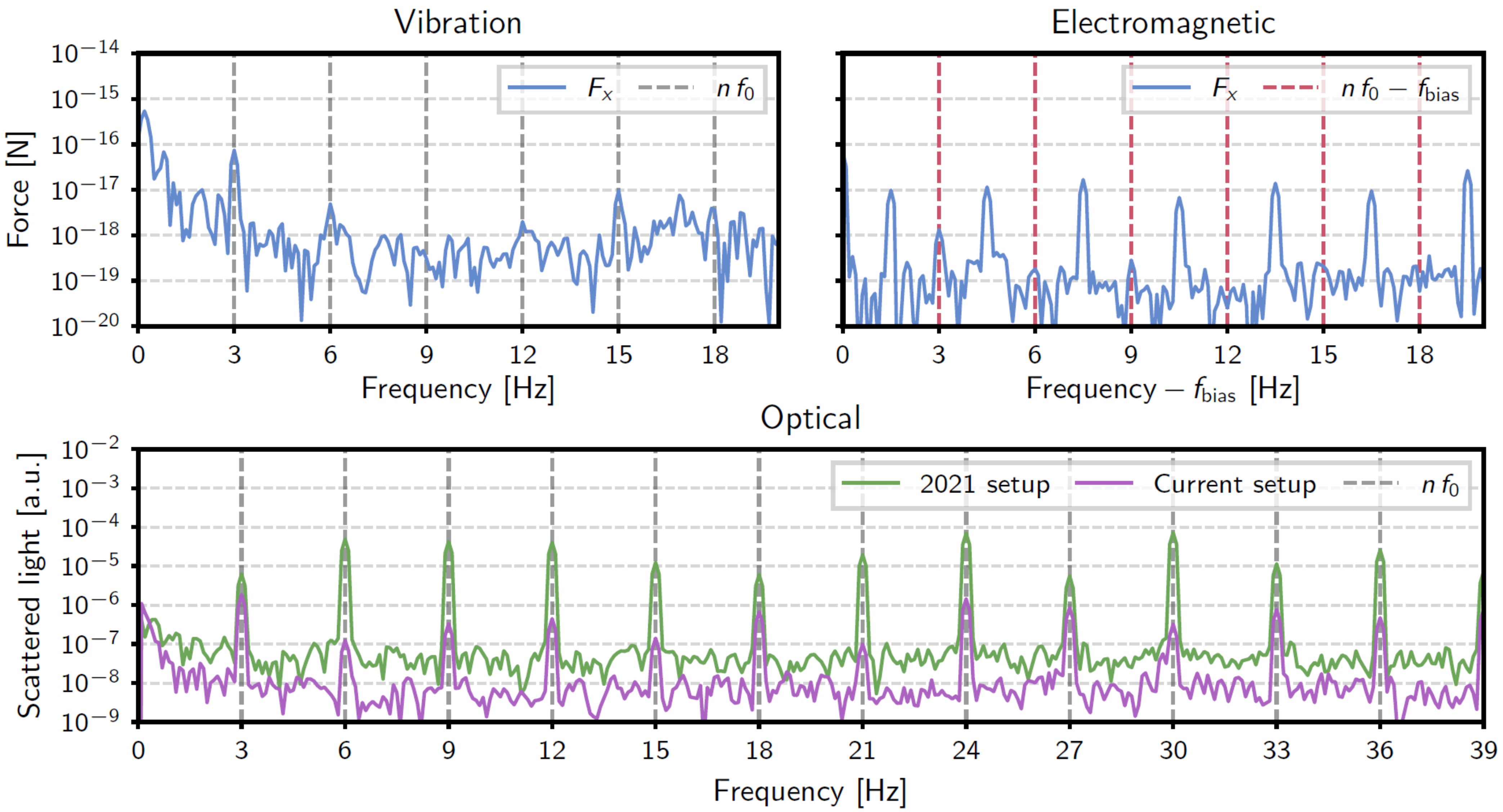
After plating,
longer exposure



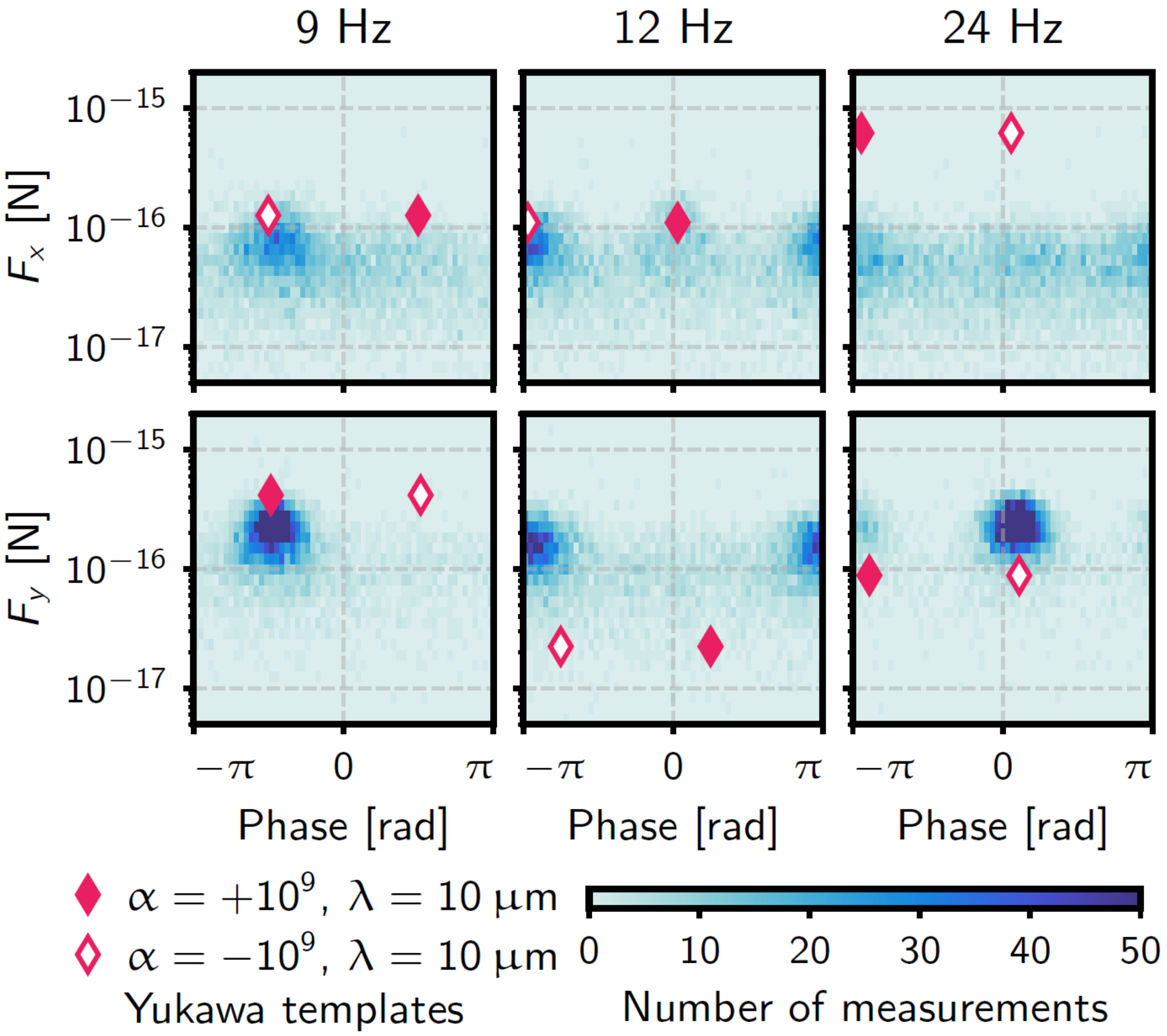


Backgrounds are still the most serious limitation to the sensitivity,

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

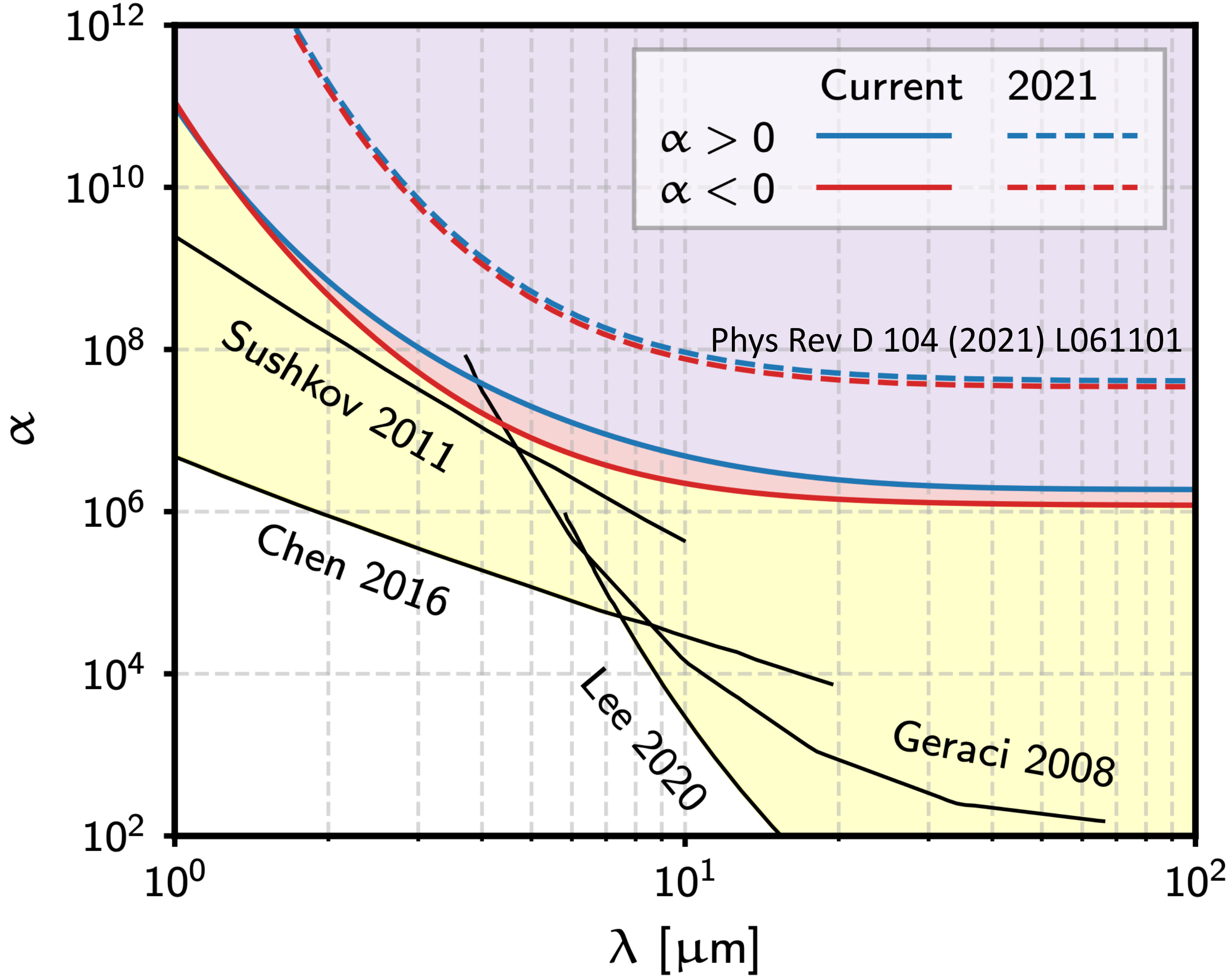


The force measurement in 2 coordinates (eventually 3), its phase, and the use of the six harmonics with the most power better constrains the measurement.



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
See also Poster by C. Brandenstein at this meeting.

"Nuclei are well-protected affairs"

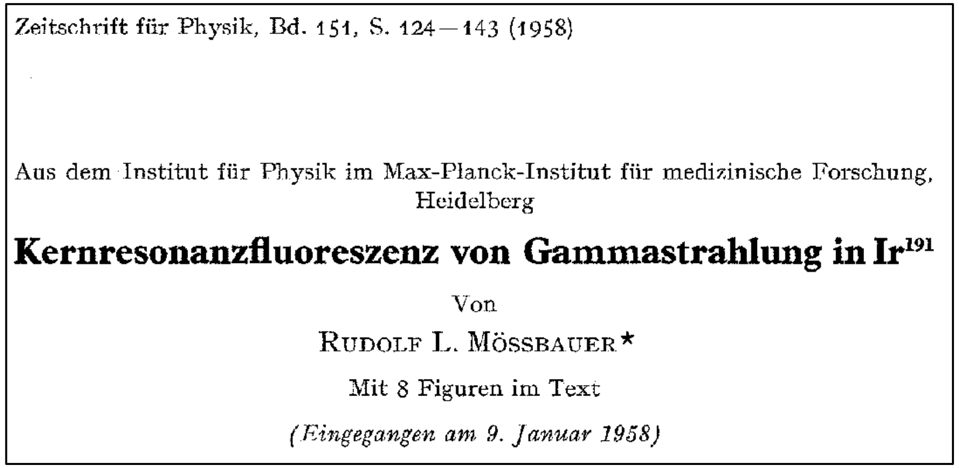
They have electric charge, but that is screened by the electron cloud and so has little coupling to external E&M disturbances.

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

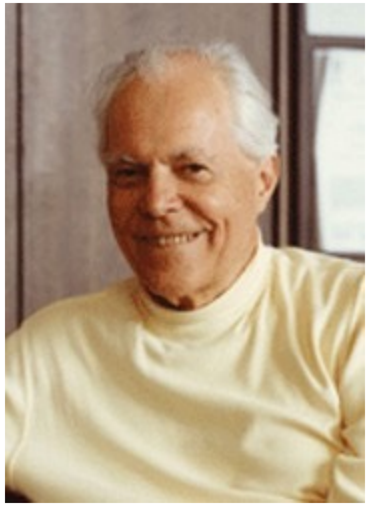
Kernresonanzfluoreszenz von Gammastrahlung in Ir^{191}

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

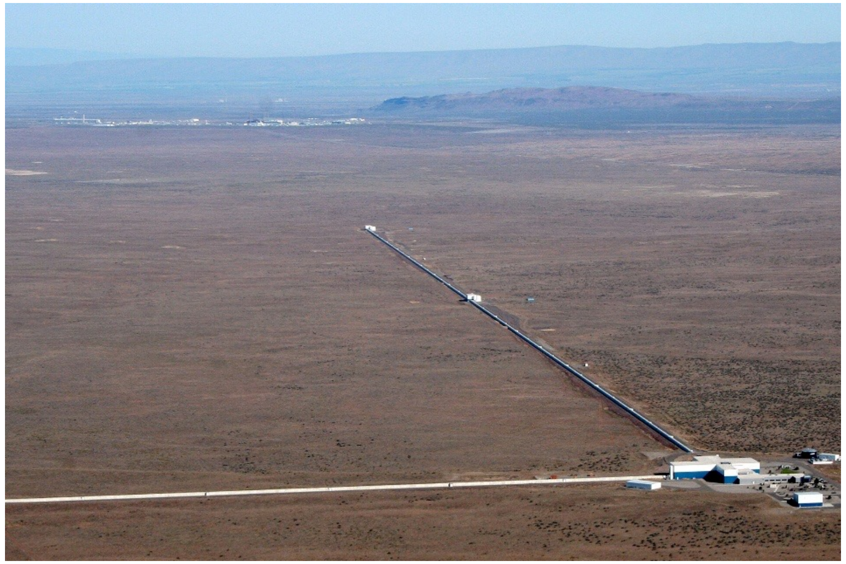
Somewhat disconcertingly, Mössbauer spectroscopy was then ``appropriated'' by Chemists!

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

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

In some cases, the natural line width is directly accessible

	Nuclide	E (eV)	$T_{1/2}$	Γ (eV)	Γ/E
Used mainly in chemistry	$^{57}_{26}$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}
Essentially unexplored	$^{45}_{21}$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}



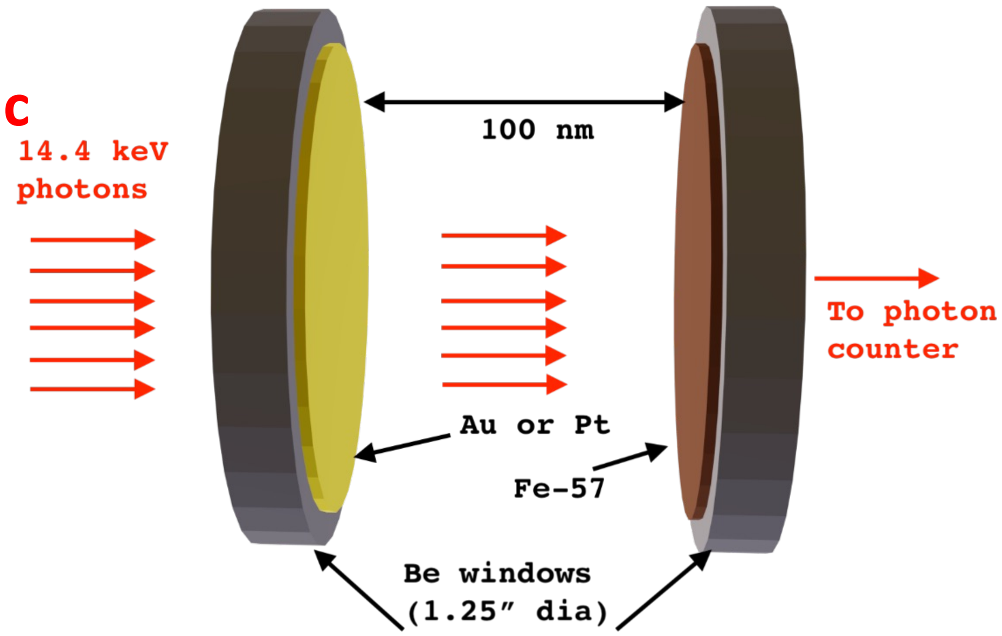
For reference, aLIGO strain sensitivity:
$\delta l/l \sim 10^{-23}/\sqrt{\mathrm{Hz}}$

Principle of the experiment

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 are not sensing a force but the effect of the field on a bound (nuclear) state*:*
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*

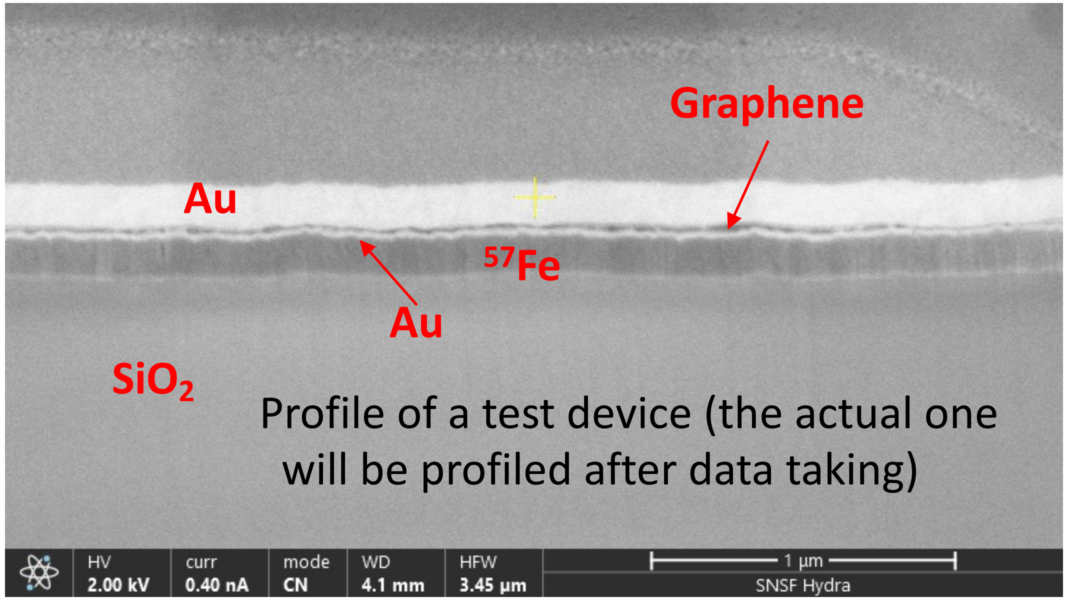
200 µm SiO_2 wafer substrate

400nm ^{57}Fe film

20nm Au capping film

5-layer graphene Decoupling/buffer film

200nm Au “attractor” film



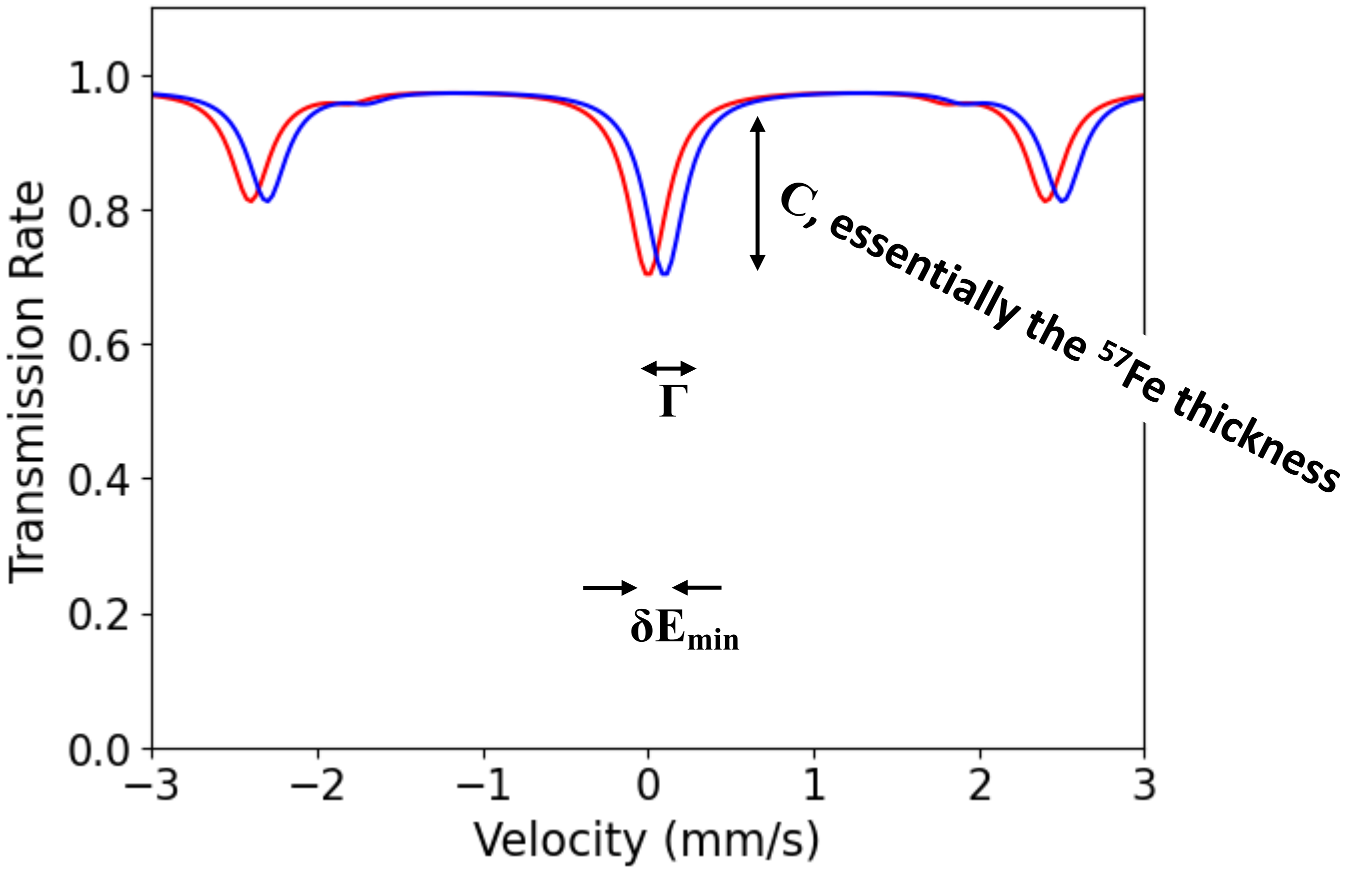
Profile of a test device (the actual one will be profiled after data taking)

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)



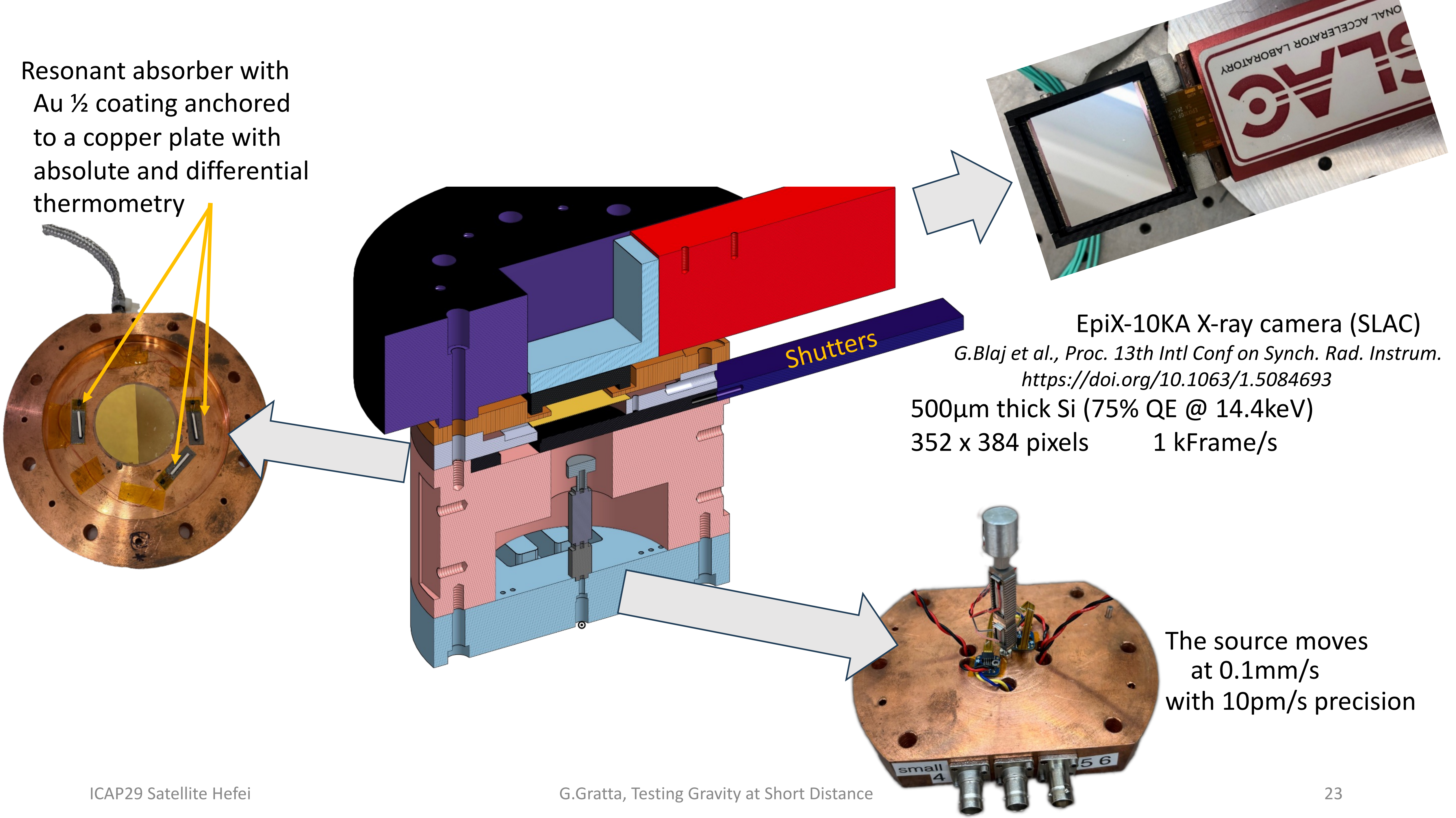
** The Pound & Rebka initial (final) experiment had a 8.4 x 10^{-12} eV (3.5 x 10^{-12} eV) sensitivity*

Known systematics: δE = 10^{-15} eV is equivalent to:

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

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.

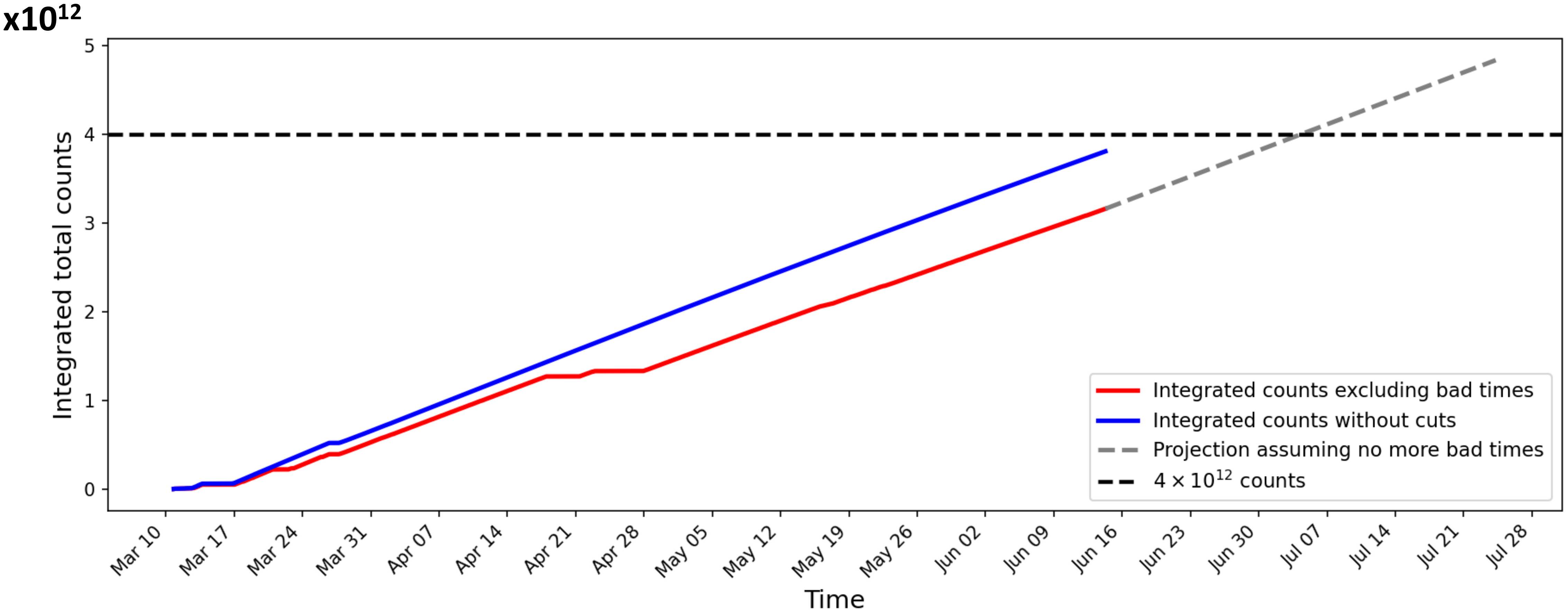
https://doi.org/10.1063/1.5084693

500µm thick Si (75% QE @ 14.4keV)

352 x 384 pixels 1 kFrame/s

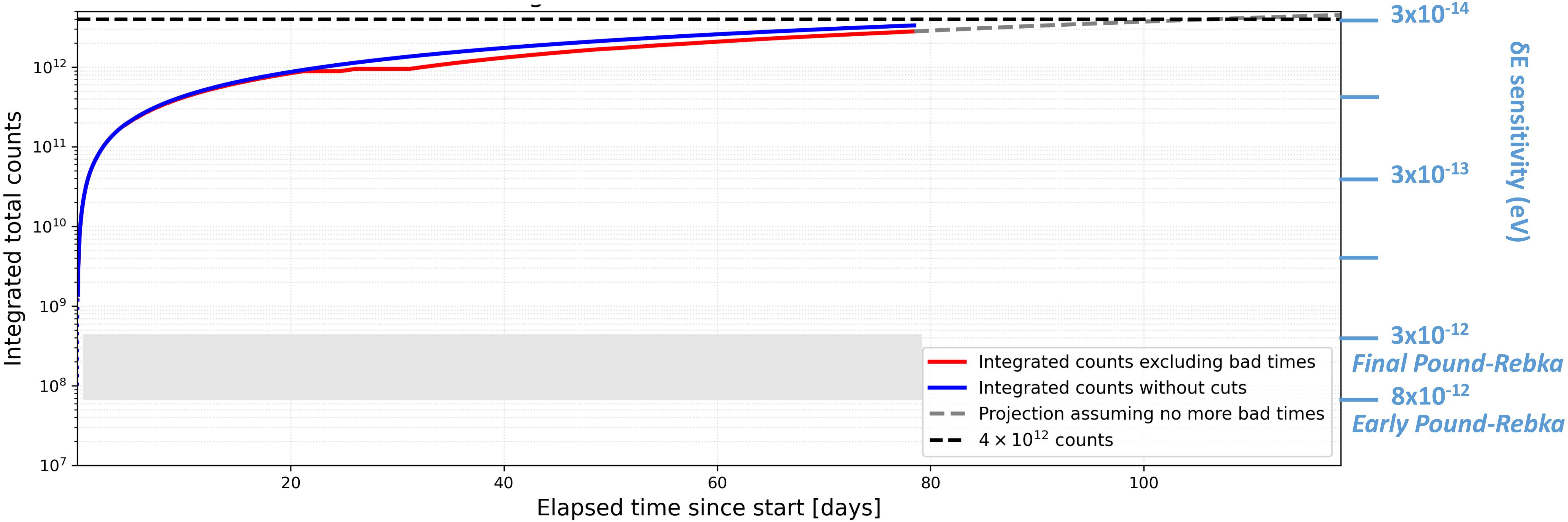
The source moves at 0.1mm/s with 10pm/s precision

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



Probably the most sensitive Mössbauer experiment ever done!

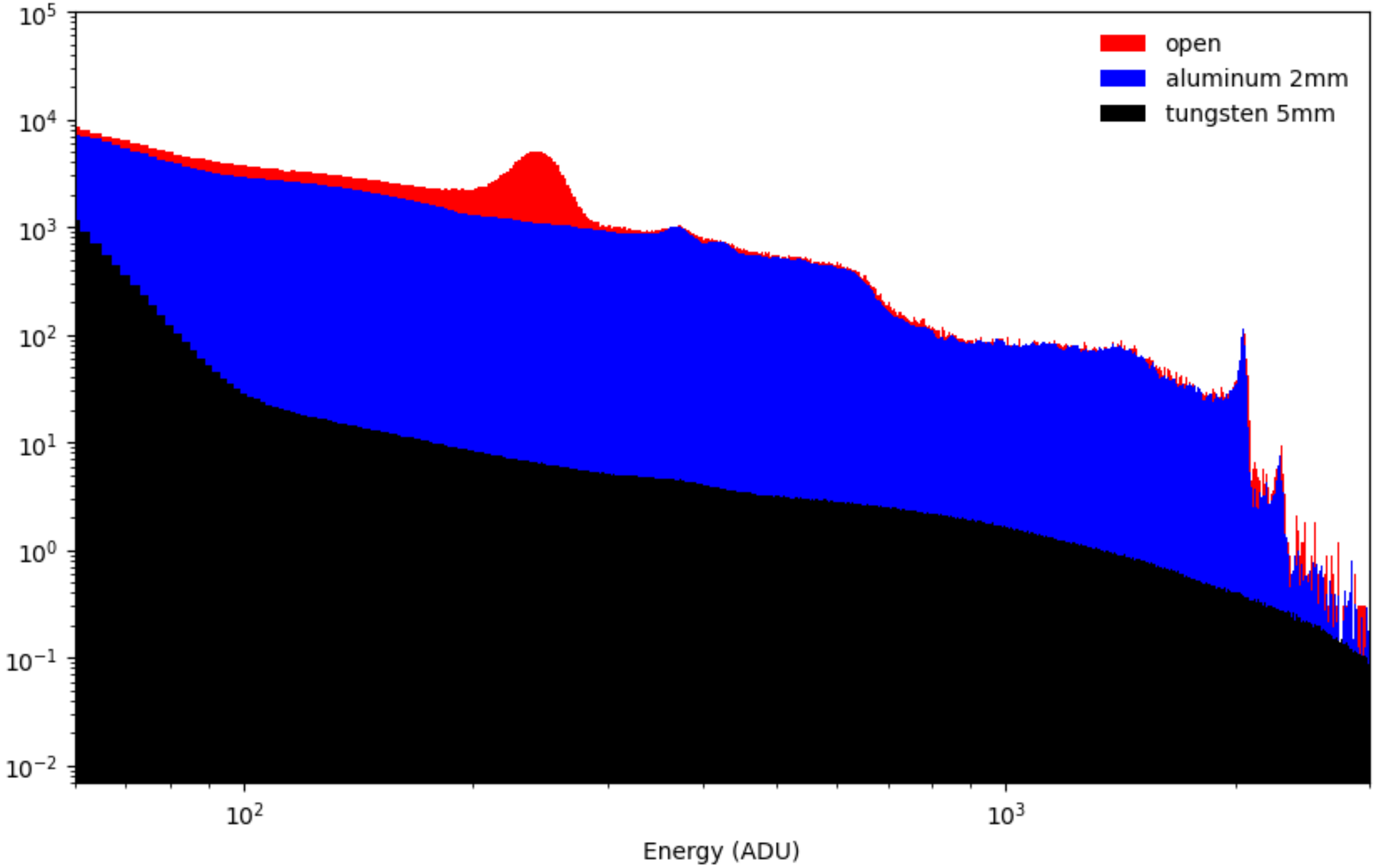
…and we are likely to be the first imaging Mössbauer experiment



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



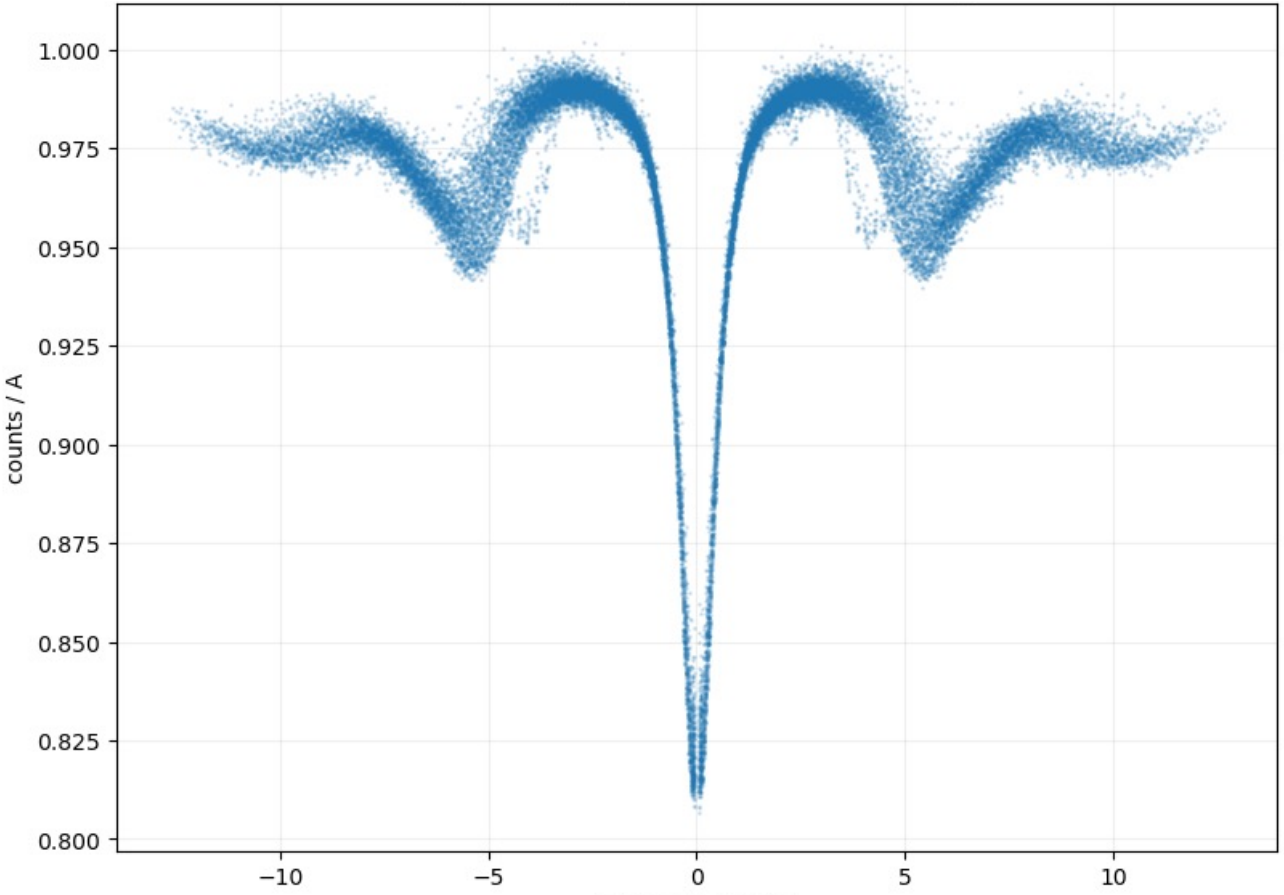
Closing the tungsten shutter eliminates all signals other than electronic noise and generic radioactive/cosmic ray background.

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.

Now a broader velocity scan for the entire camera:
250 velocities, 5 min each, 20 hr data total @ 5×10^5 ev/s



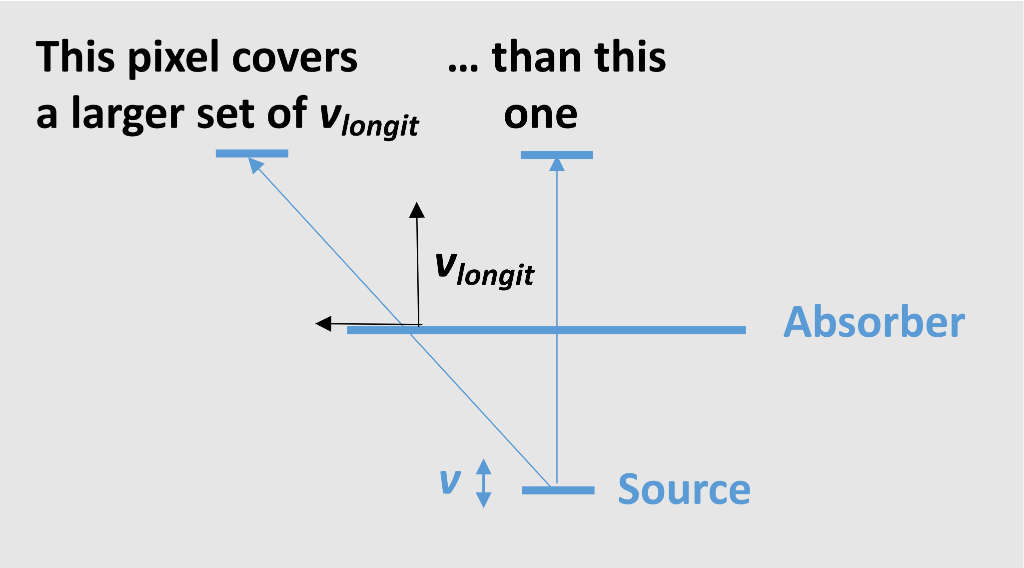
Energy or velocity in units of Γ

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.



This pixel covers a larger set of v_{longit}

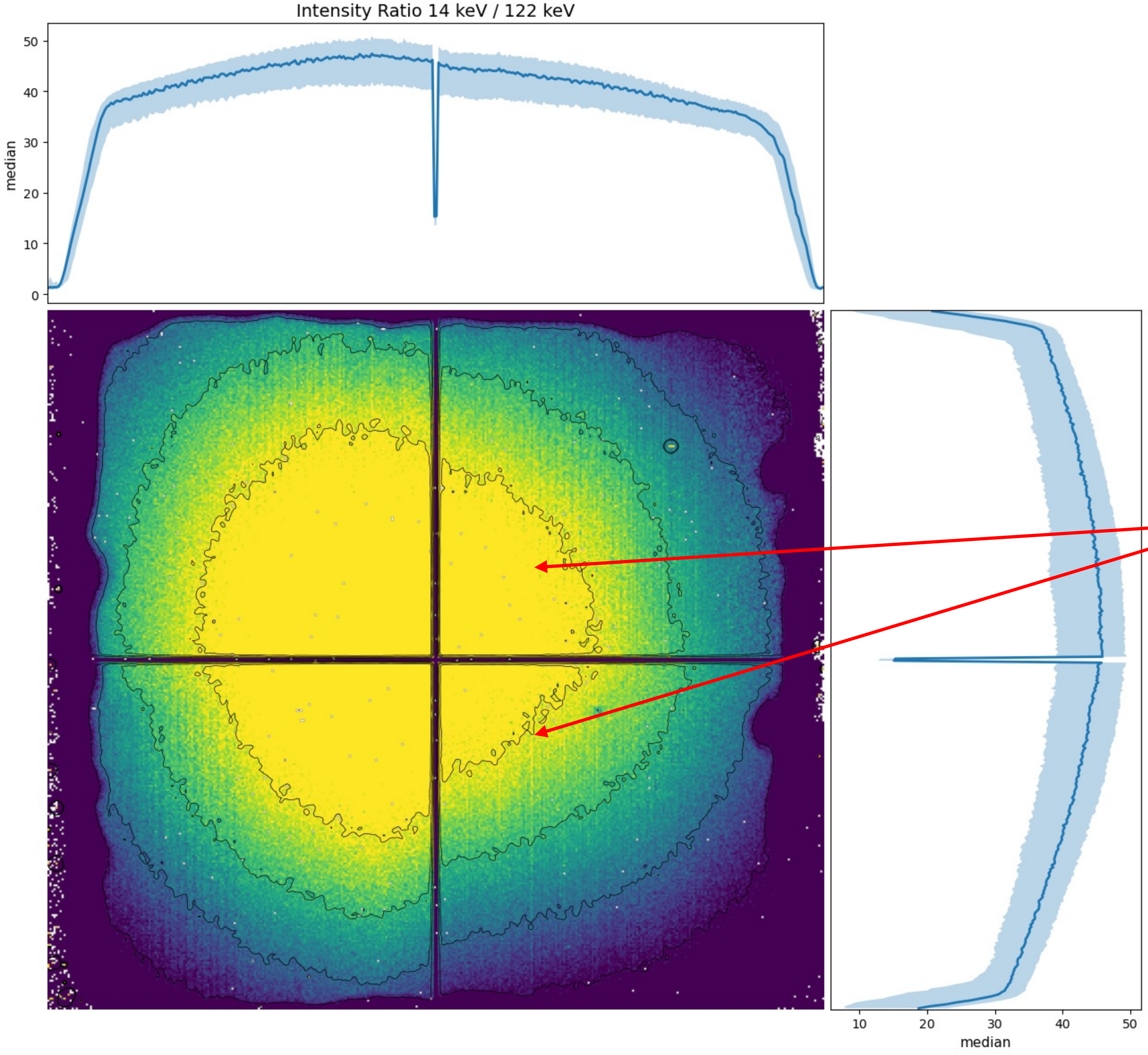
… than this one

v_{longit}

Absorber

v

Source



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

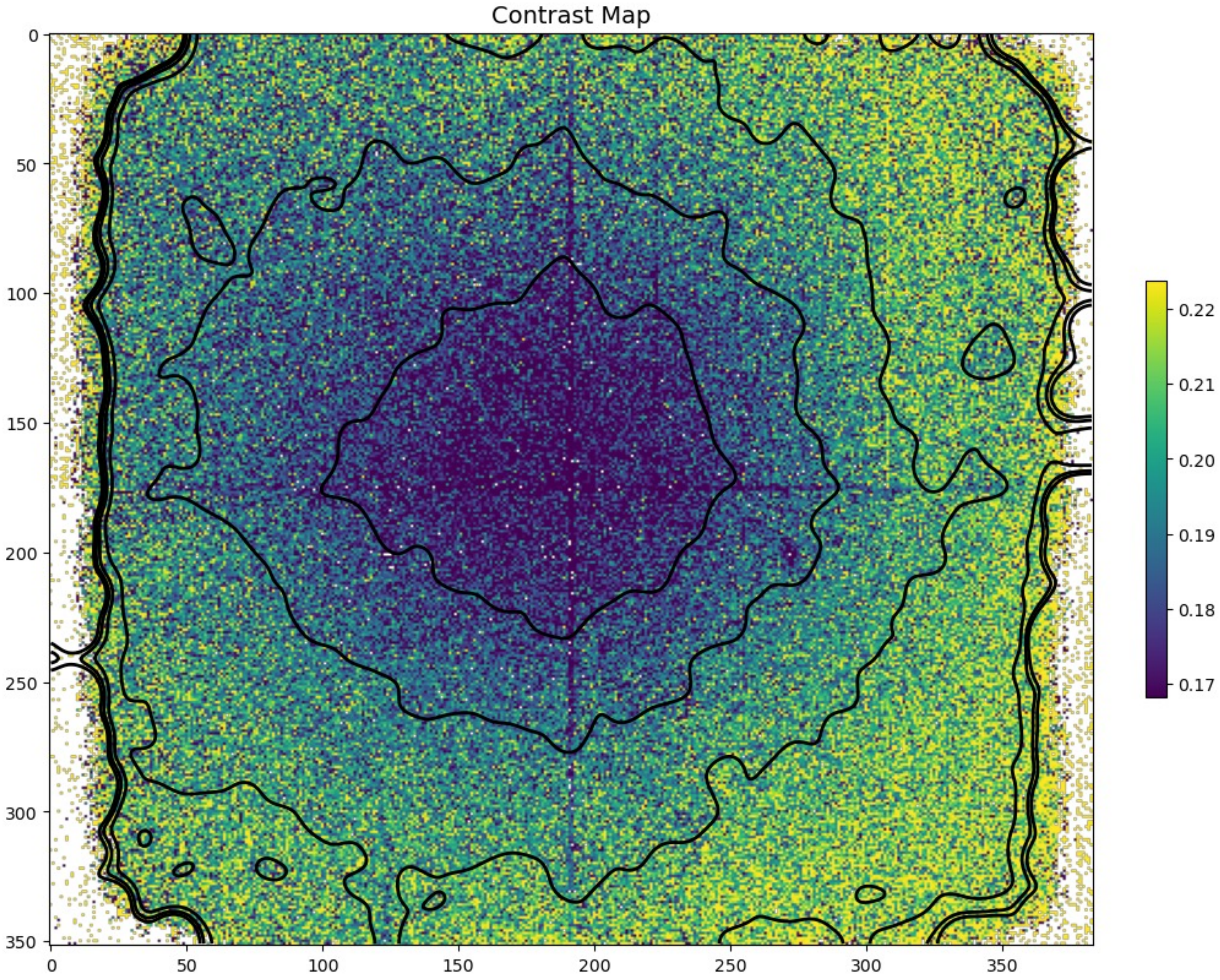
Note that the source is not perfectly centered over the camera.

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.

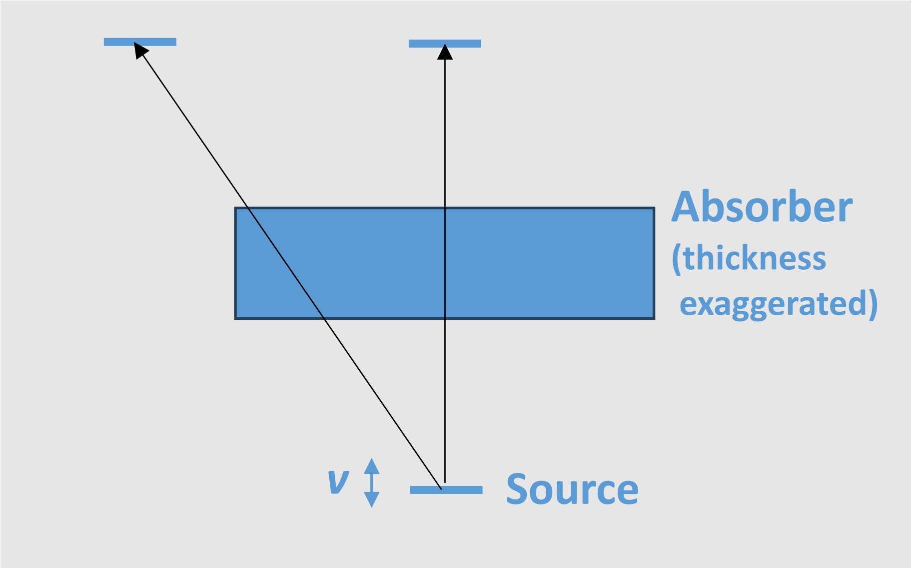
We are fixing this now.

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.

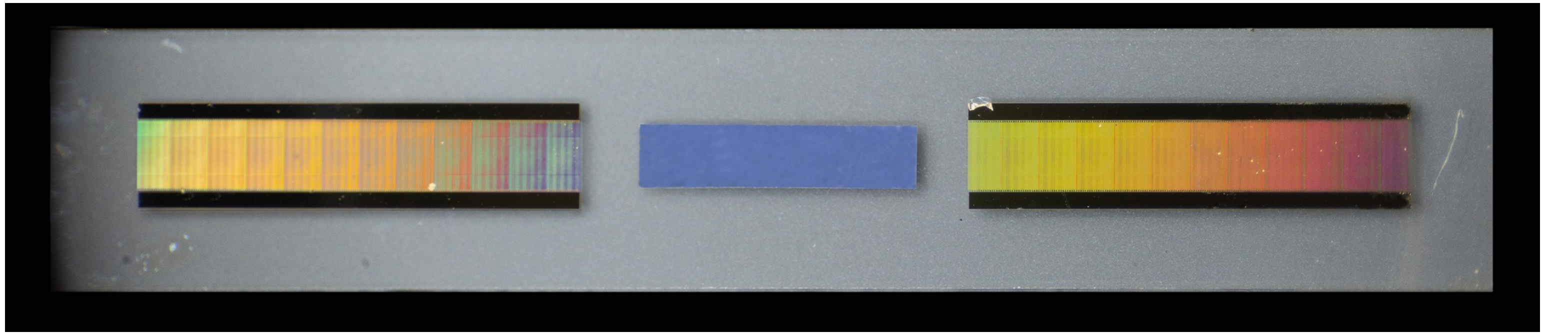
Rather tricky:

- 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

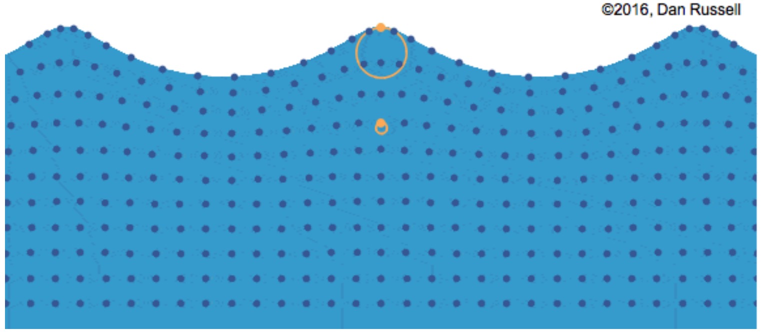
Internal conversion is larger for Ta (than for Fe) and, in addition, there is a velocity shift between source and absorber.

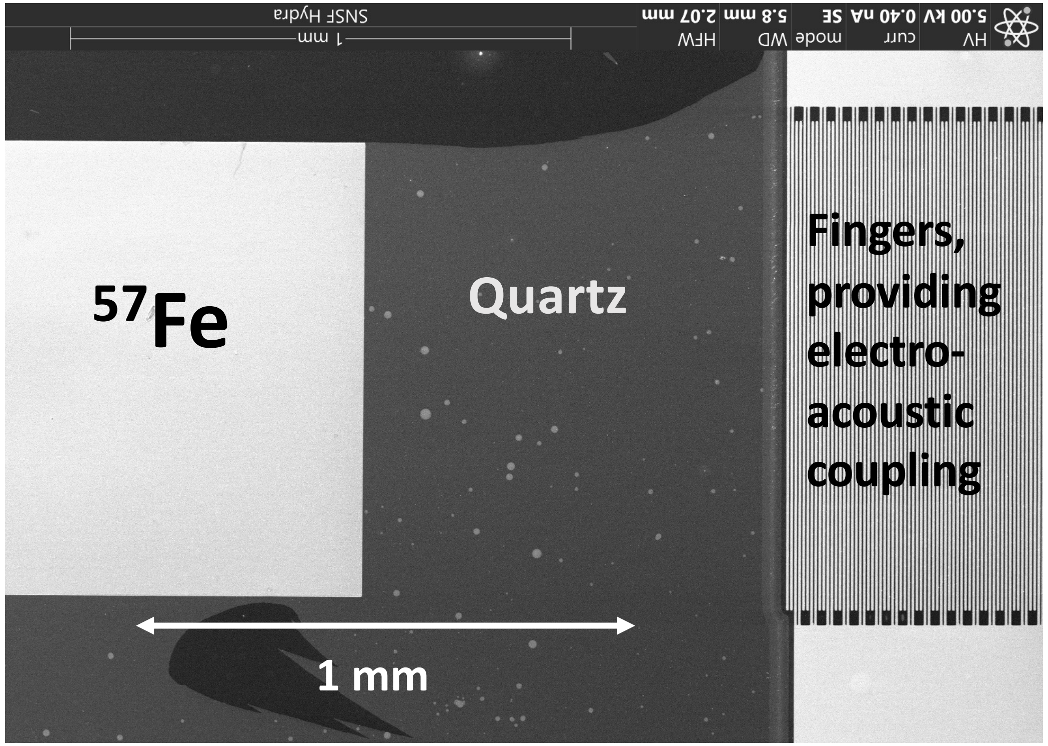
Fun side-project: a γ-ray AOM

Nazeeri et al. PRL 136 18 (2026)



The resonant absorber is now deposited over a region of quartz where a surface acoustic wave propagates.


©2016, Dan Russell

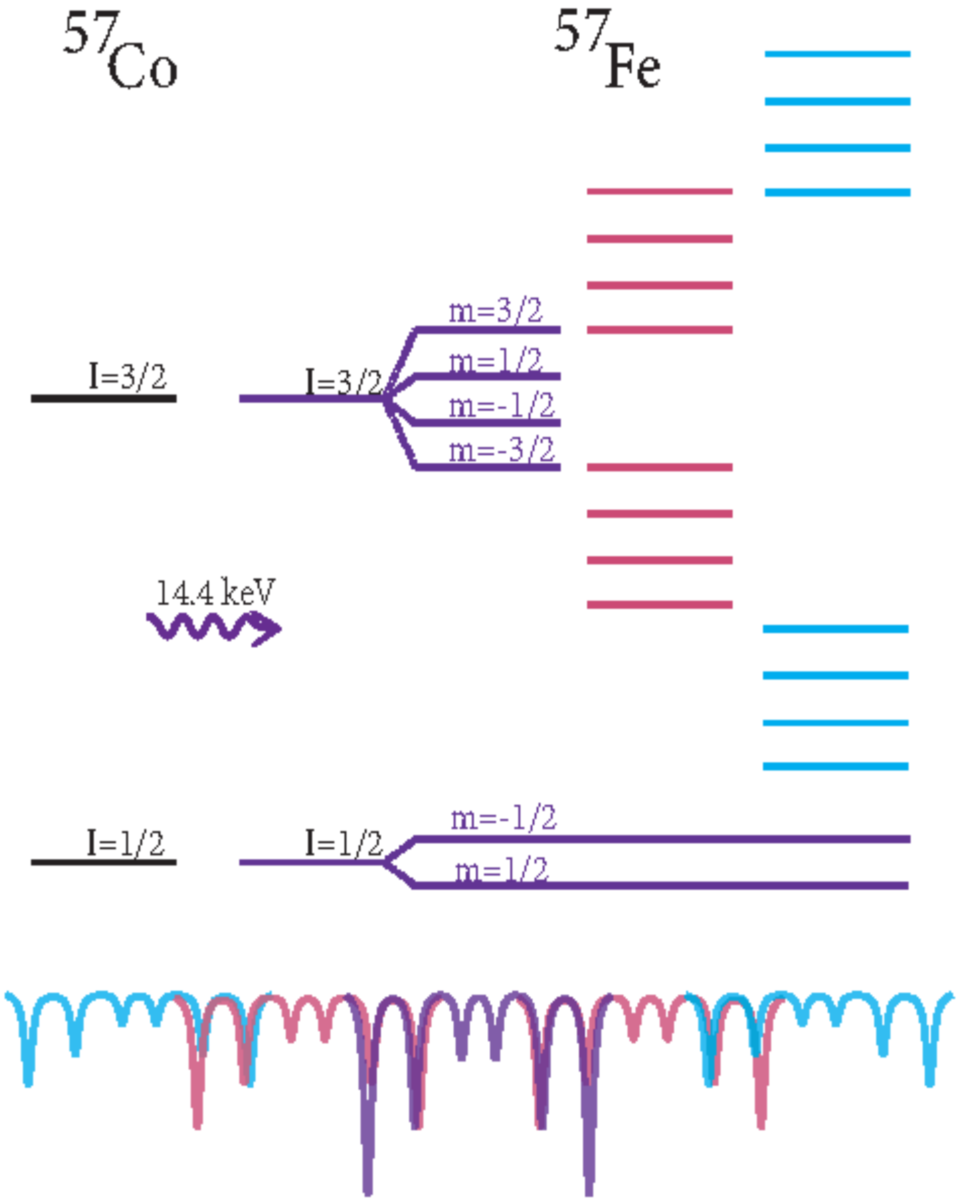


Expected effect

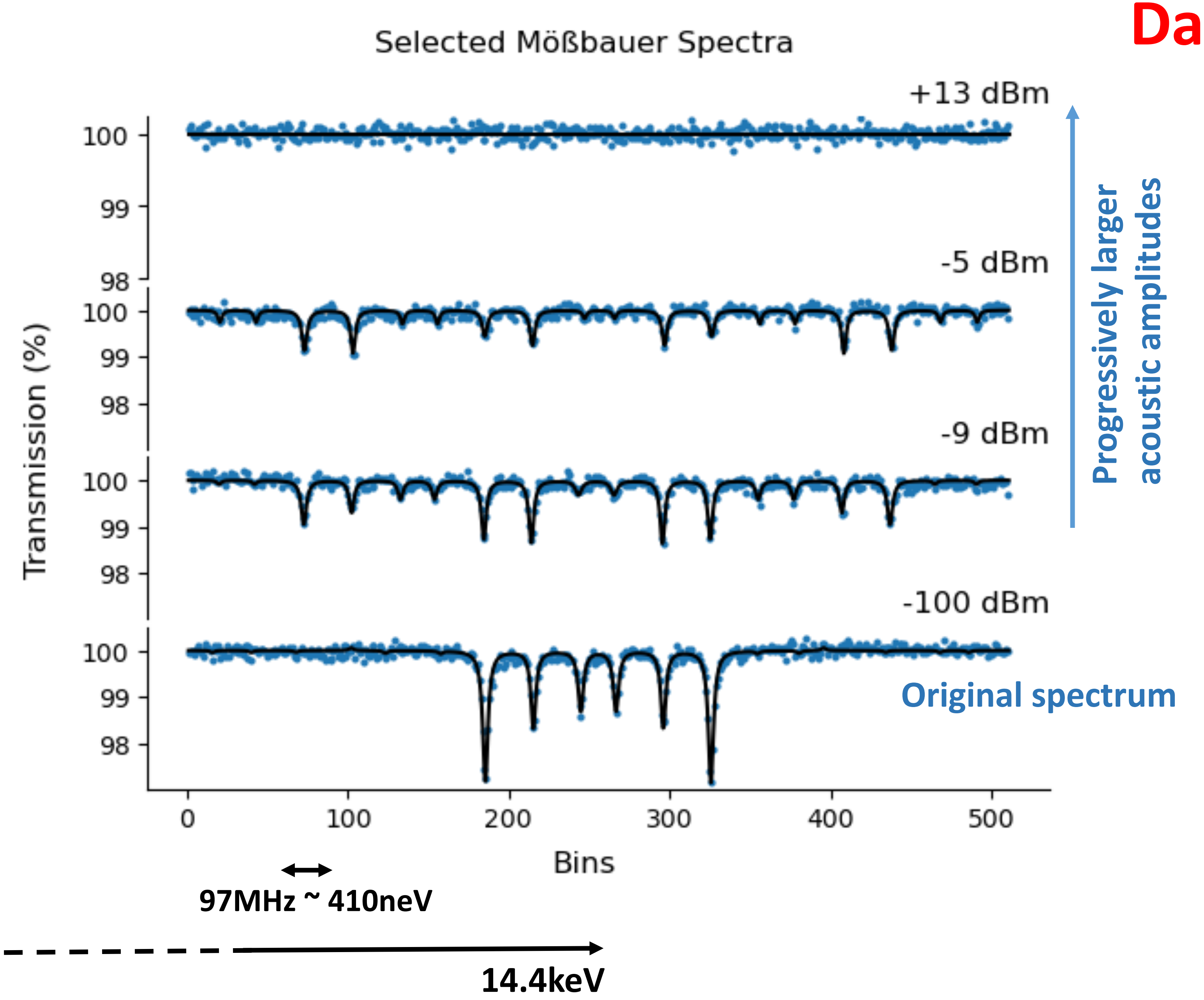
Like in an AOM, phonons in the quartz transfer energy to the γ-rays, producing higher order modes.

This is happening in the regime where $\tau_{SAW} \sim 10\text{ns} < \tau_{Fe\text{-}57} \sim T_{1/2}/\sqrt{2} \sim 70\text{ns}$

In our device, the acoustic frequency, 97 MHz, is almost exactly the same as the energy difference between different m states, producing various degeneracies.



Data



Note that the integral of counts is constant in the different spectra.

As the acoustic amplitude increases, a larger fraction of the integral is contributed by sidebands away from the center.

Note that at max amplitude, the counts are all in far away sidebands (out of range for the spectrometer).

Concluding, the current cast

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