

# Temperature Metrology at the National Institute of Standards and Technology

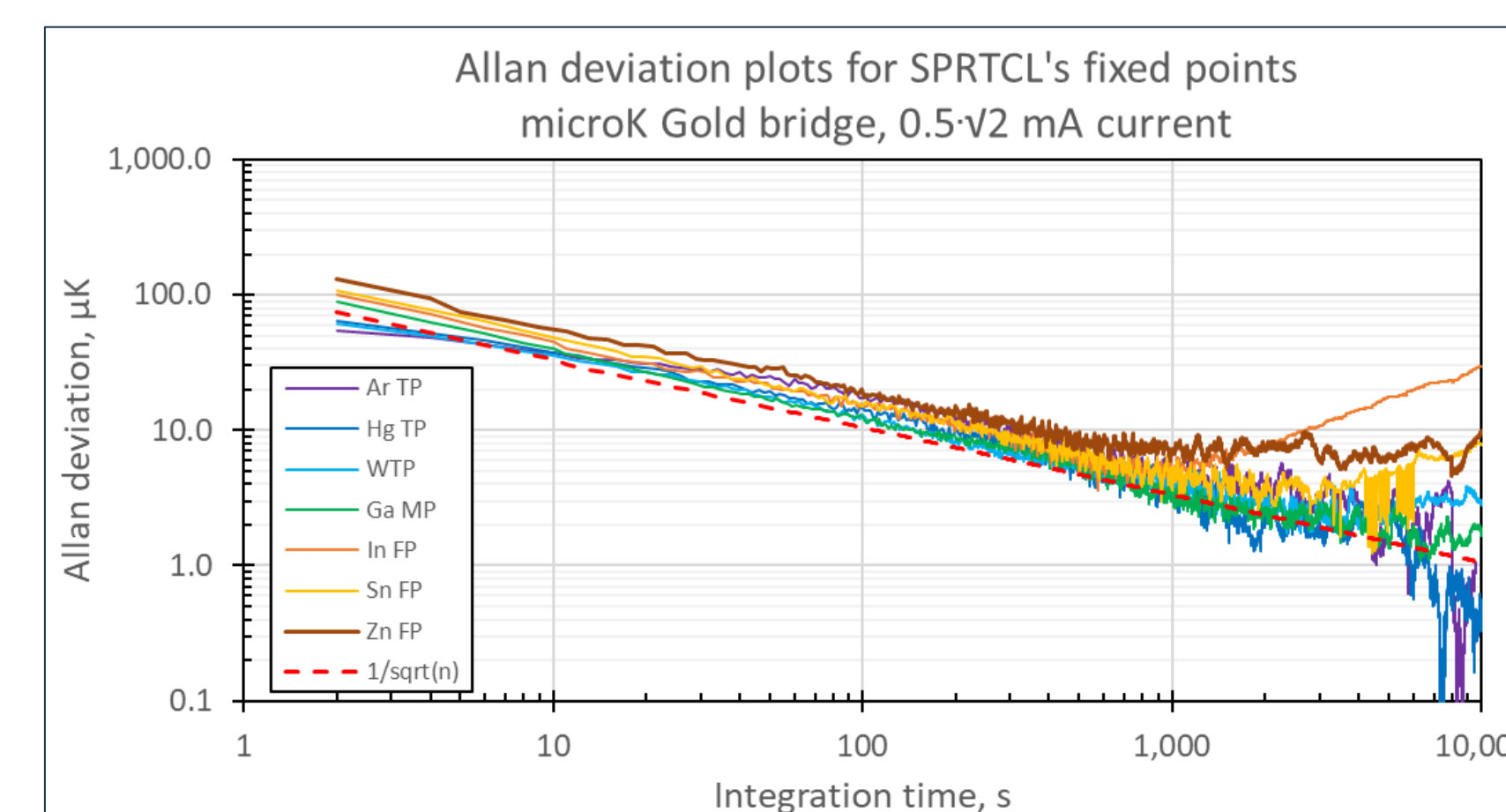
Howard W. Yoon, Wes. Tew, Richmond Wang, Klaus Quelhas,  
Steve Eckel, Daniel Barker, Nikolai N. Klimov



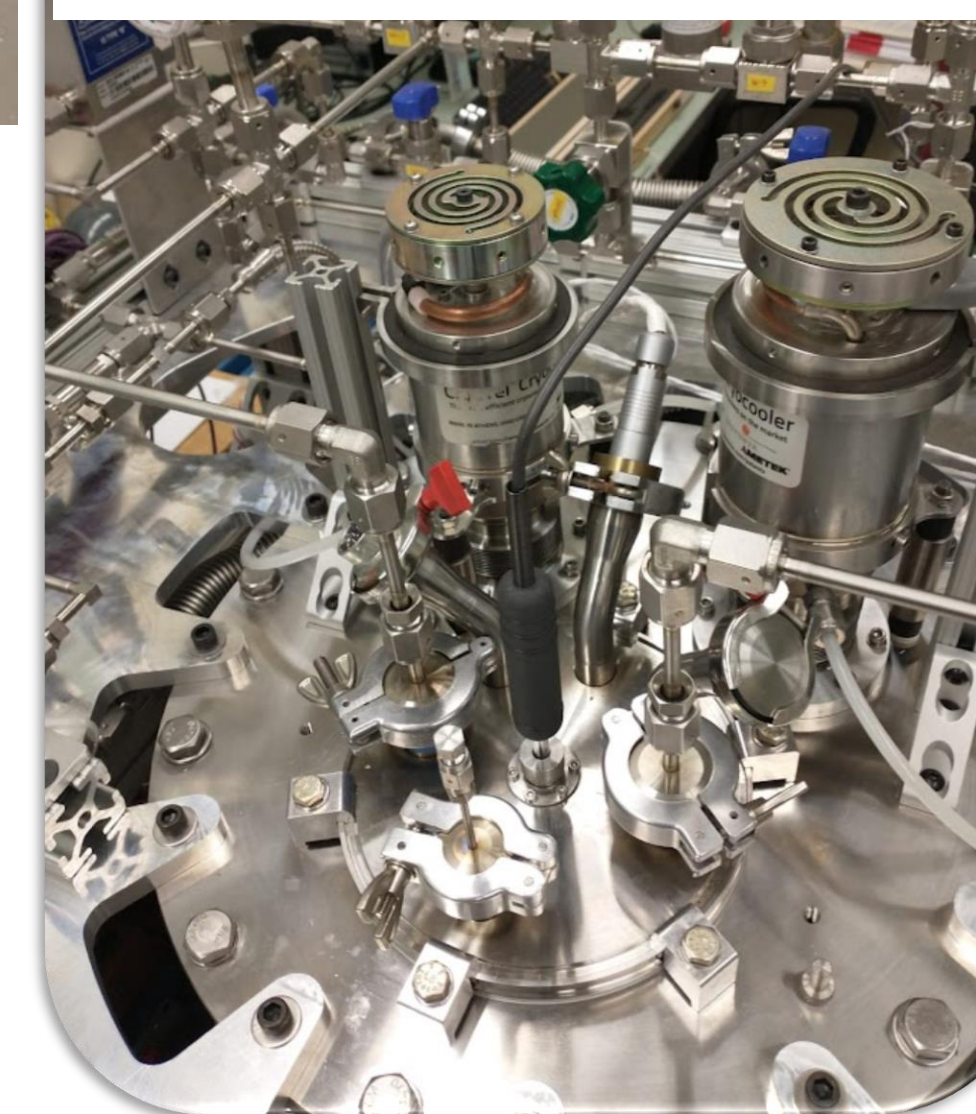
## Program objectives

- **Realize and disseminate** national measurement standards at the lowest achievable uncertainties
- **Establish and validate** international measurement equivalence via comparisons
- **Research** methods for realizations of thermodynamic temperatures

## NIST ITS-90 Calibration Lab

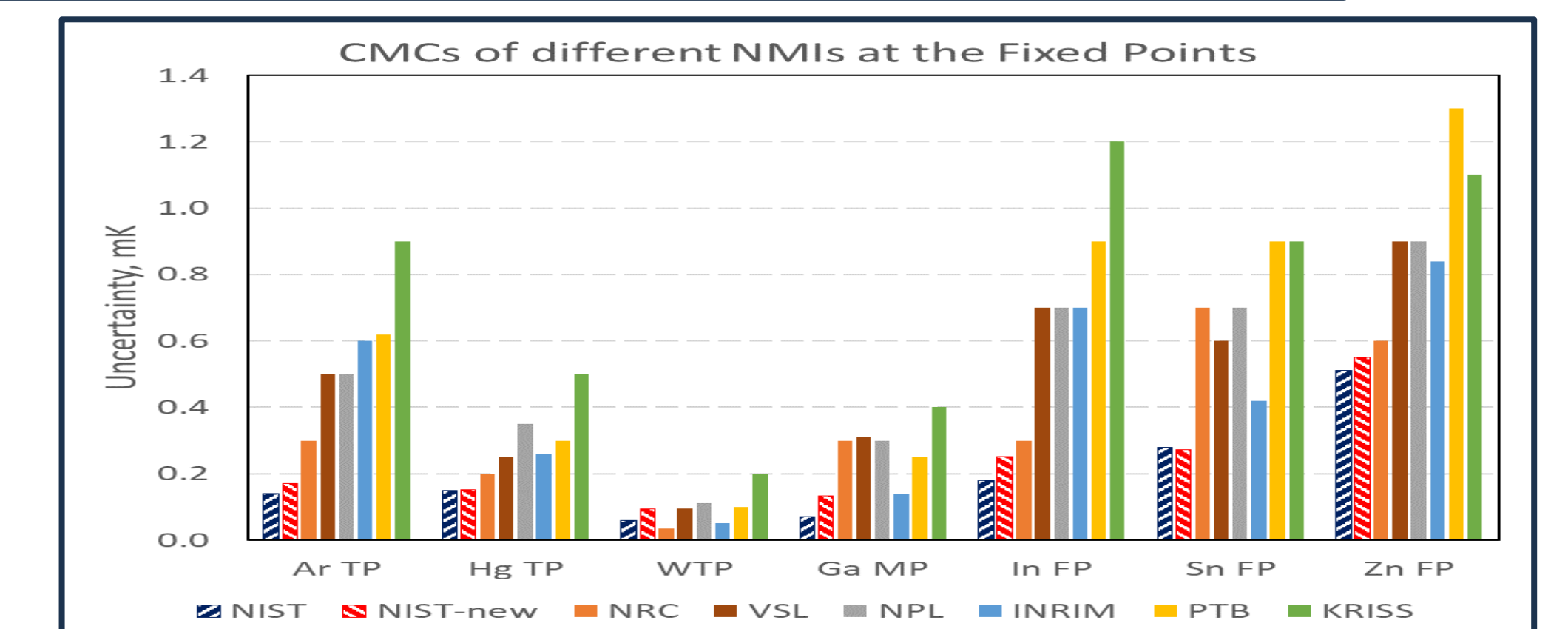


## NIST-built Ar point



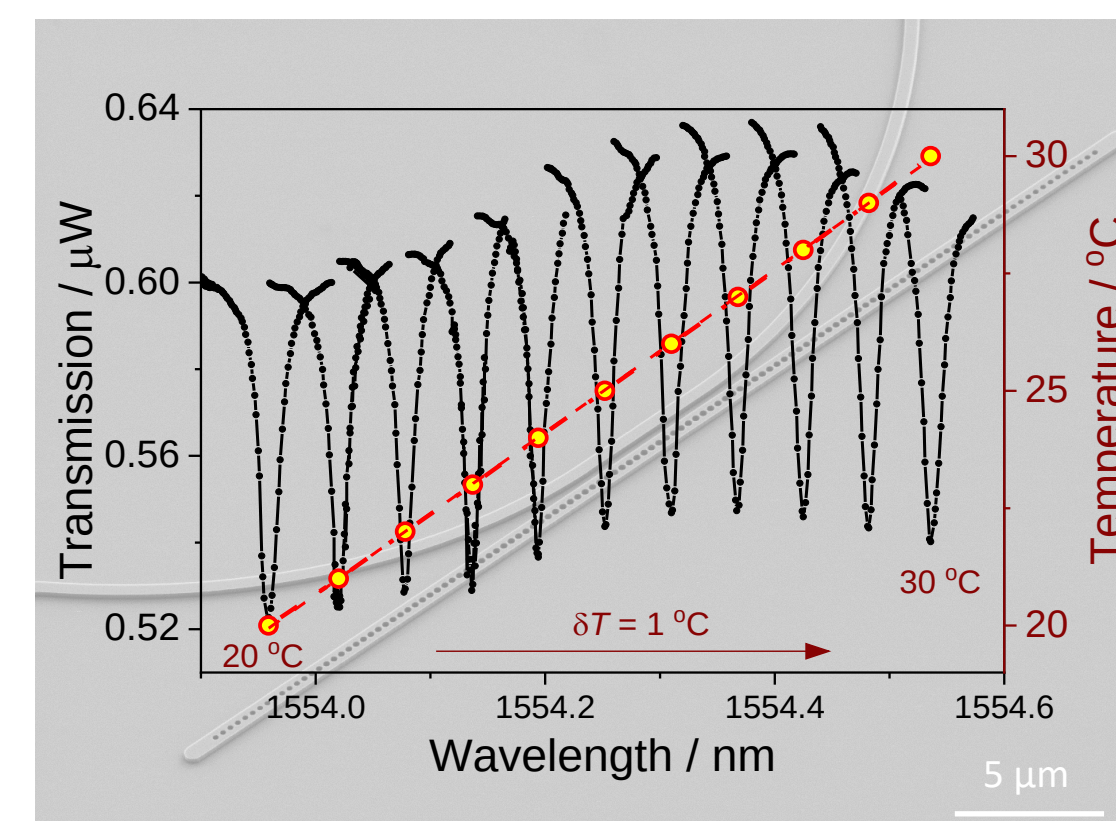
## NIST ITS-90 realization uncertainties

|                                | Dist. | Ar TP ✓ | Hg TP ✓ | WTP ✓   | Ga MP ✓ | In FP ✓ | Sn FP ✓ | Zn FP ✓ |
|--------------------------------|-------|---------|---------|---------|---------|---------|---------|---------|
| Bridge repeatability           | N     | 0.009   | 0.009   | 0.010   | 0.010   | 0.010   | 0.010   | 0.011   |
| Bridge non-linearity           | N     | 0.018   | 0.019   | 0.019   | 0.019   | 0.020   | 0.021   | 0.022   |
| AC Quadrature                  | N     | -       | -       | -       | -       | -       | -       | -       |
| Standard resistor              | R     | 0.009   | 0.009   | 0.009   | 0.009   | 0.009   | 0.009   | 0.009   |
| Phase transition repeatability | N     | 0.038   | 0.033   | 0.032   | 0.028   | 0.039   | 0.046   | 0.082   |
| Cell-to-cell reproducibility   | R     | x       | 0.032   | 0.010   | 0.004   | 0.016   | 0.031   | 0.135   |
| Chemical impurities            | N     | 0.049   | 0.01    | 0.01    | 0.01    | 0.07    | 0.06    | 0.17    |
| Hydrostatic head               | R     | 0.030   | 0.020   | 0.004   | 0.003   | 0.010   | 0.006   | 0.008   |
| Self-heating                   | N     | 0.016   | 0.012   | 0.011   | 0.011   | 0.021   | 0.024   | 0.025   |
| Heat flux                      | N     | 0.03    | 0.029   | 0.015   | 0.009   | 0.032   | 0.034   | 0.037   |
| gas pressure                   | 0     | 0       | 0       | 0       | 0       | 0.019   | 0.013   | 0.016   |
| Slope of plateau               | R     | 0.028   | 0.011   | -       | 0.008   | 0.023   | 0.015   | 0.023   |
| Isotopic composition           | -     | -       | -       | 0.006   | -       | -       | -       | -       |
| WTP propagation                | N     | 0.009   | 0.039   | -       | 0.052   | 0.079   | 0.095   | 0.136   |
| # of realizations              | uc    | 27      | 16      | a lot   | 11      | 14      | 17      | 14      |
| Reference                      | uc    | 0.085   | 0.076   | 0.047   | 0.067   | 0.126   | 0.136   | 0.276   |
|                                | Pond  | set     | Hg 99-2 | Ga 98-3 | In 96-2 | Sn 22-1 |         |         |
|                                | U     | 0.17    | 0.15    | 0.09    | 0.13    | 0.25    | 0.27    | 0.55    |
|                                |       | 0.14    | 0.15    | 0.06    | 0.07    | 0.18    | 0.28    | 0.51    |

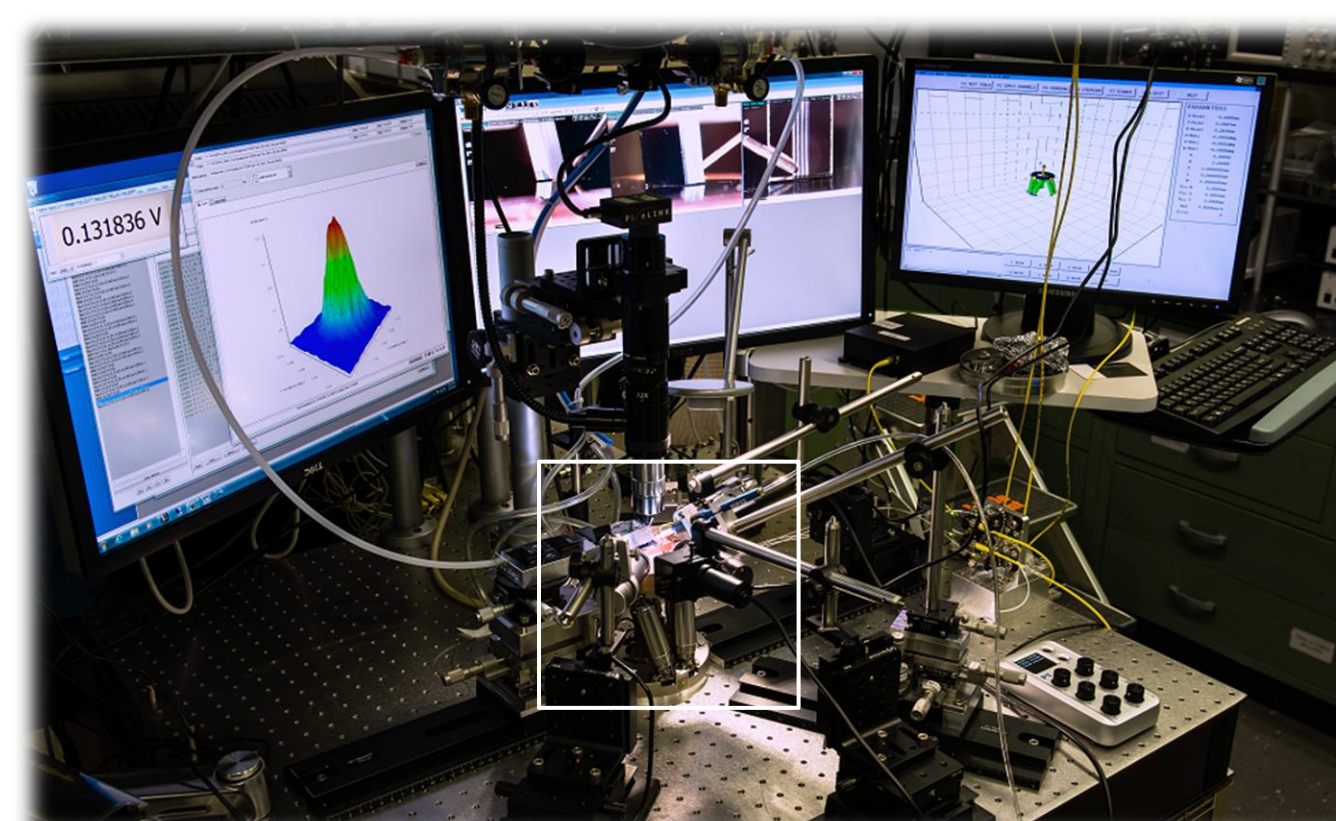


## Sensitive Photonic Thermometer (Spot)

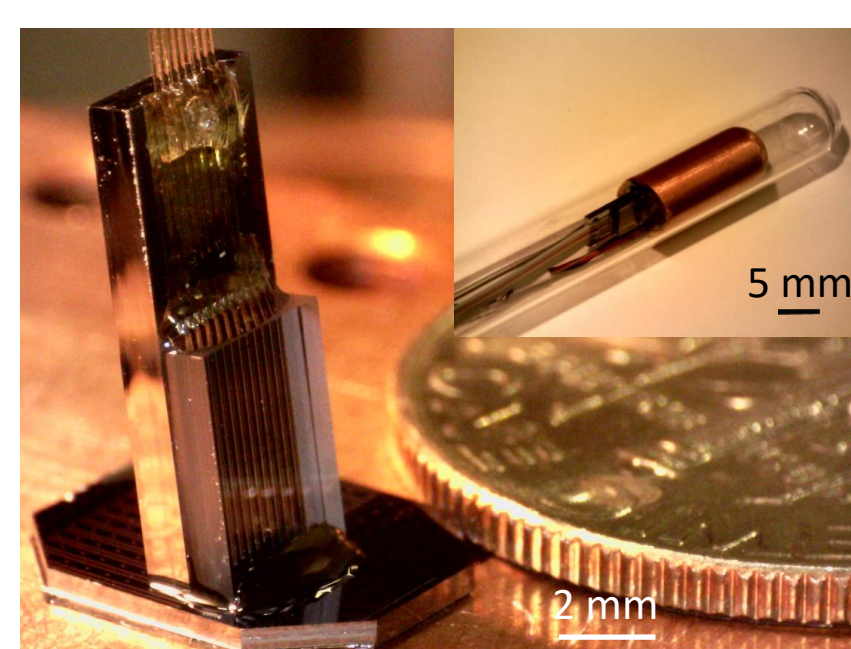
### Temperature response



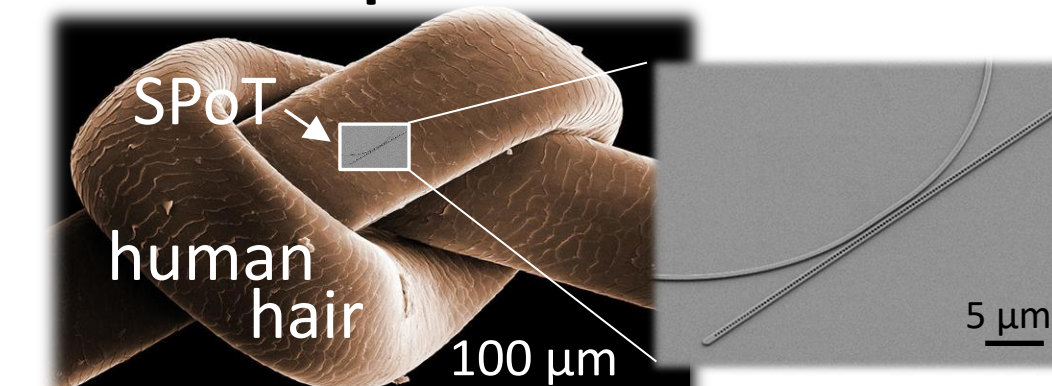
### Photonic packaging setup



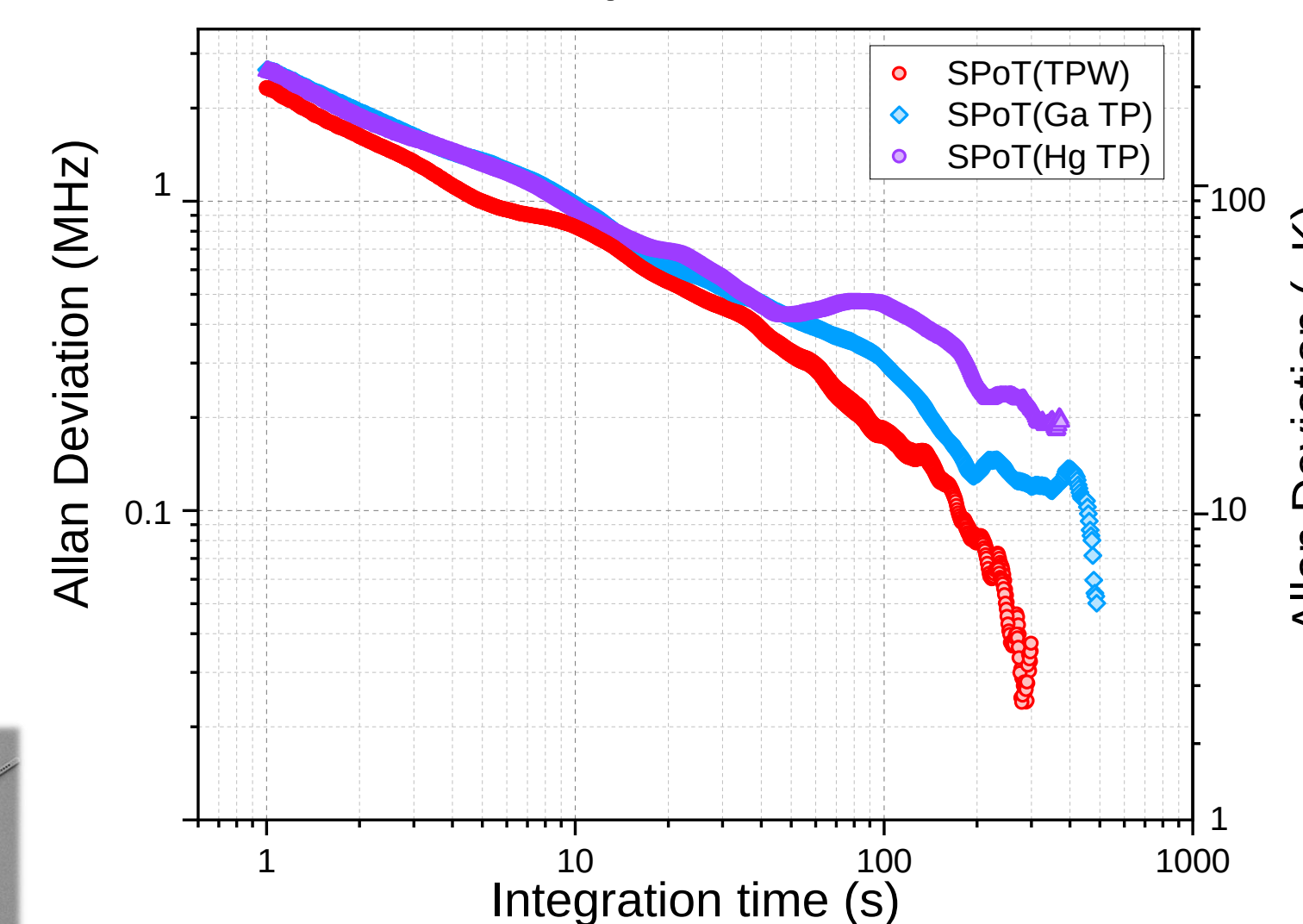
### Fiber-coupled SPoT chip



### SPoT compared to a human hair

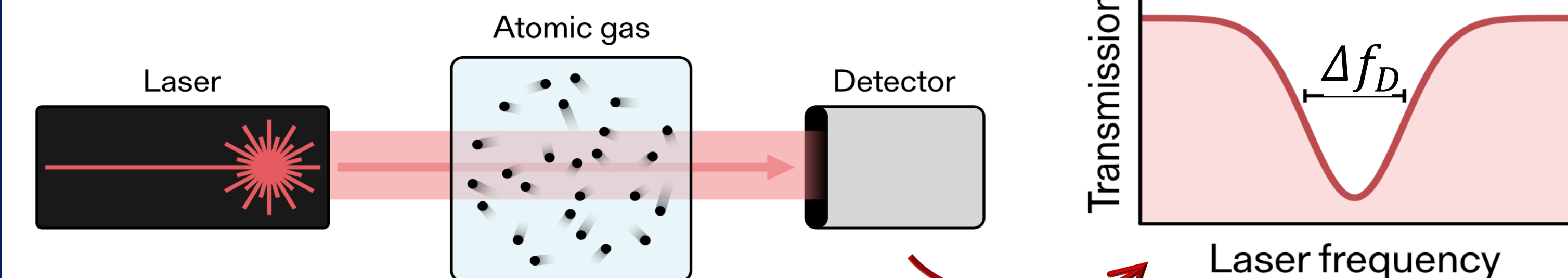


### Sub-10 μK resolution



## Fast Doppler Thermometers

Measure transmission of light through an atomic gas:



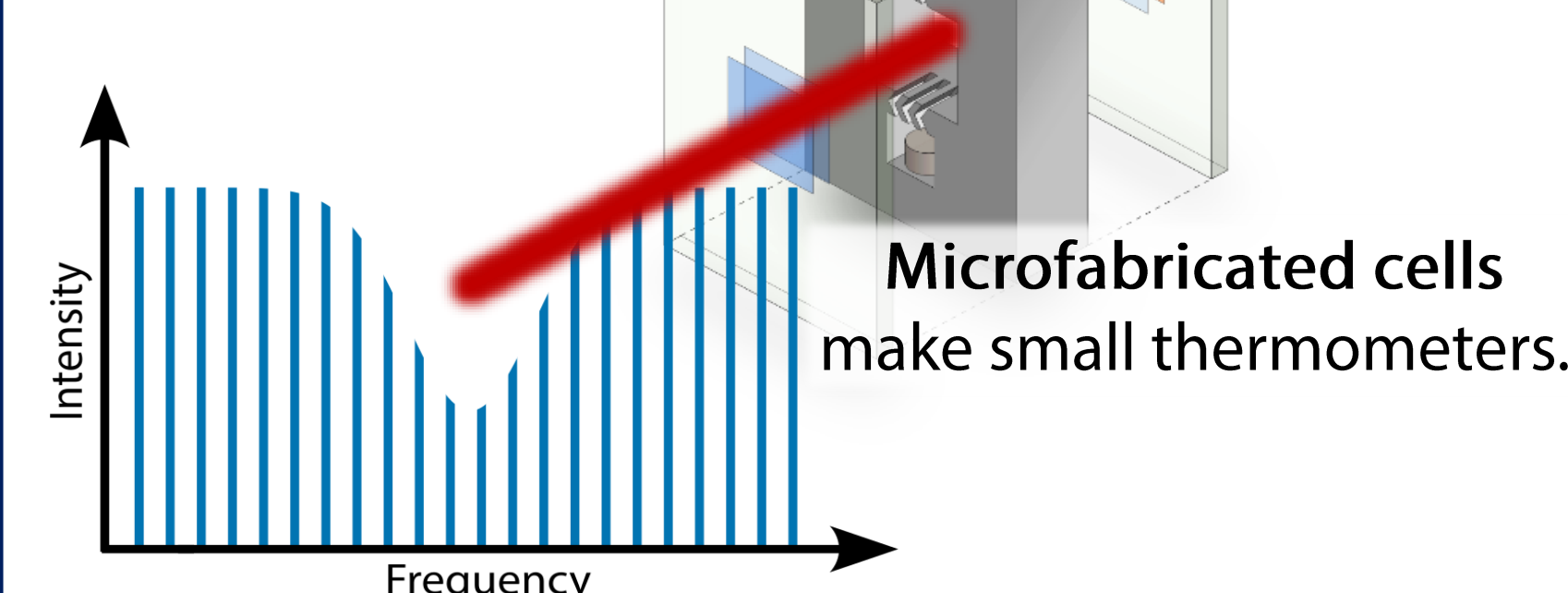
Measured Doppler width gives:

$$T = \frac{c^2}{k_B} \frac{m}{f_0^2} \Delta f_D^2$$

- using
- SI defining constants
  - Immutable gas properties

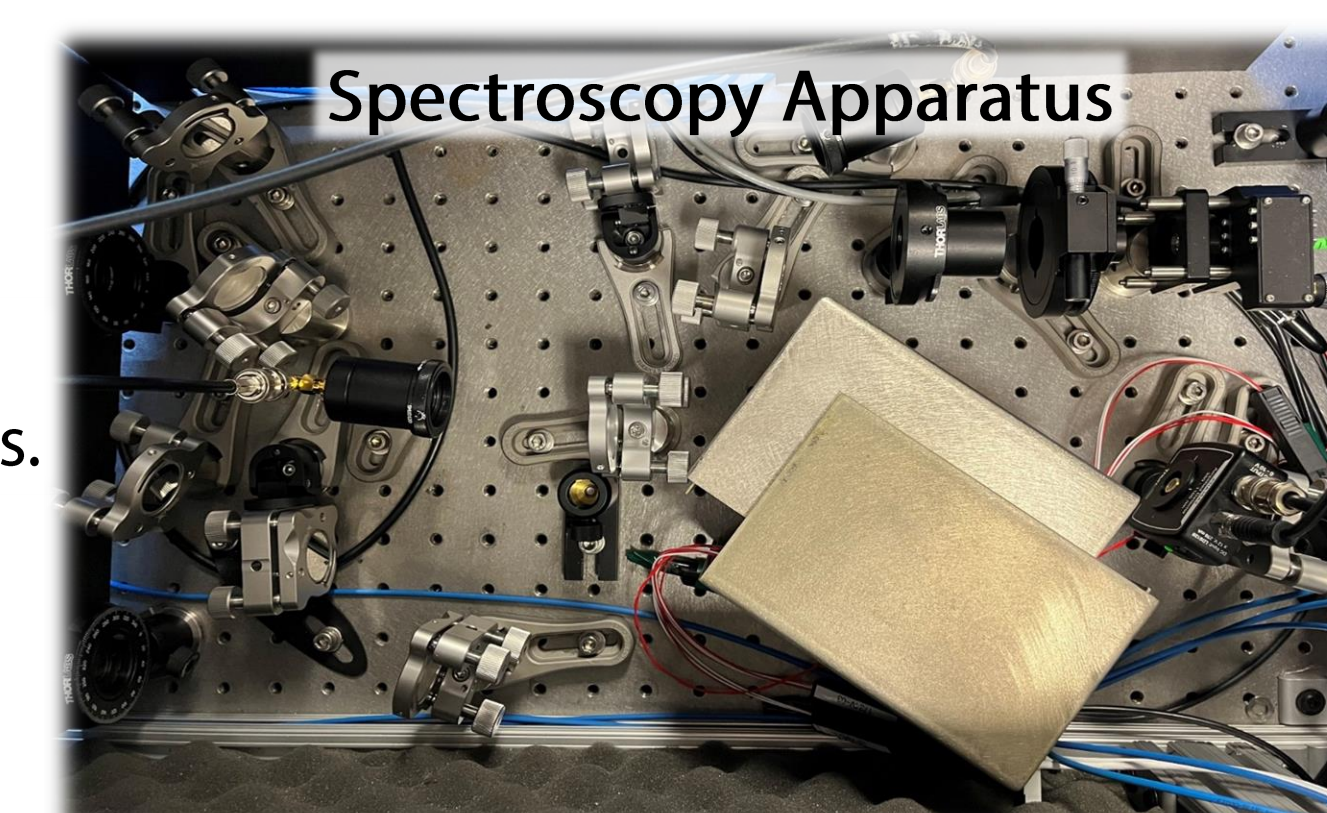


Deployable Doppler Thermometer

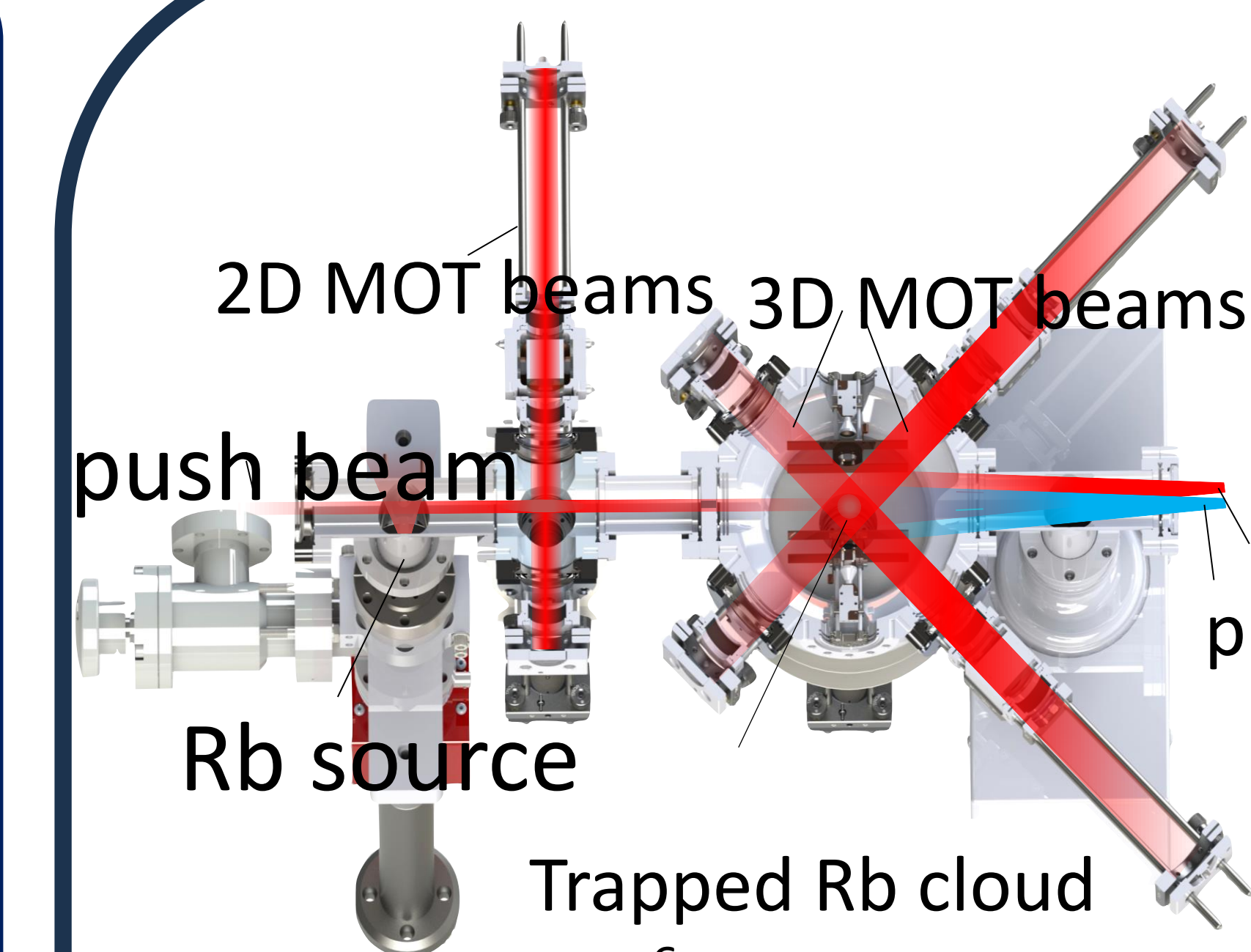


Microfabricated cells make small thermometers.

Electro-optic combs parallelize readout.



## Atom-based Thermometry



Trapped Rb cloud  
~10<sup>6</sup> atoms at 0.5 mK

