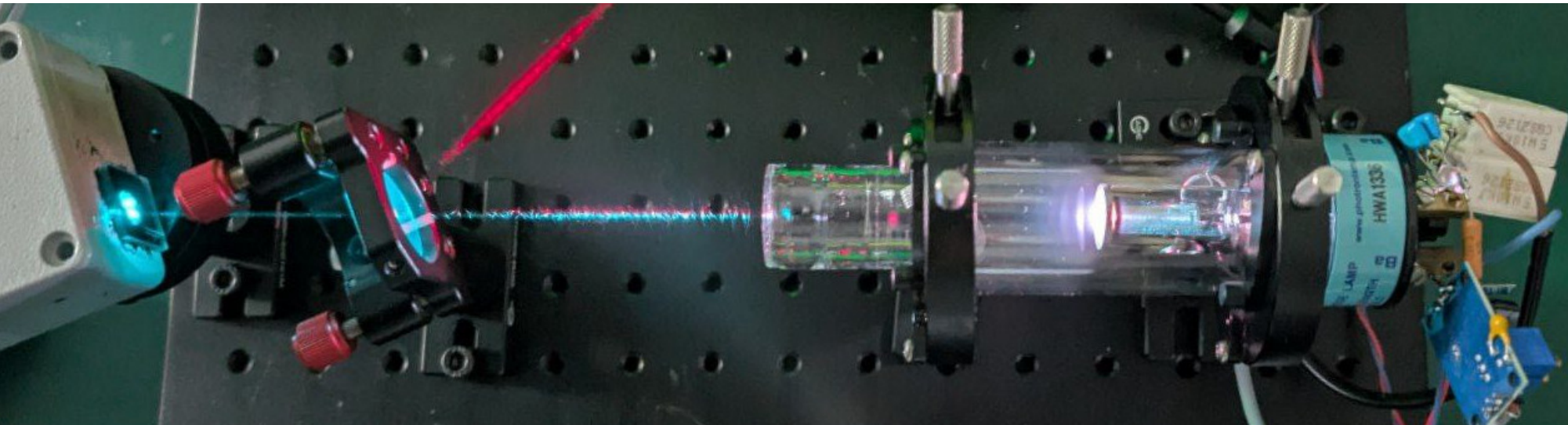
# Multichannel optogalvanic frequency stabilization of diode lasers using an audio interface

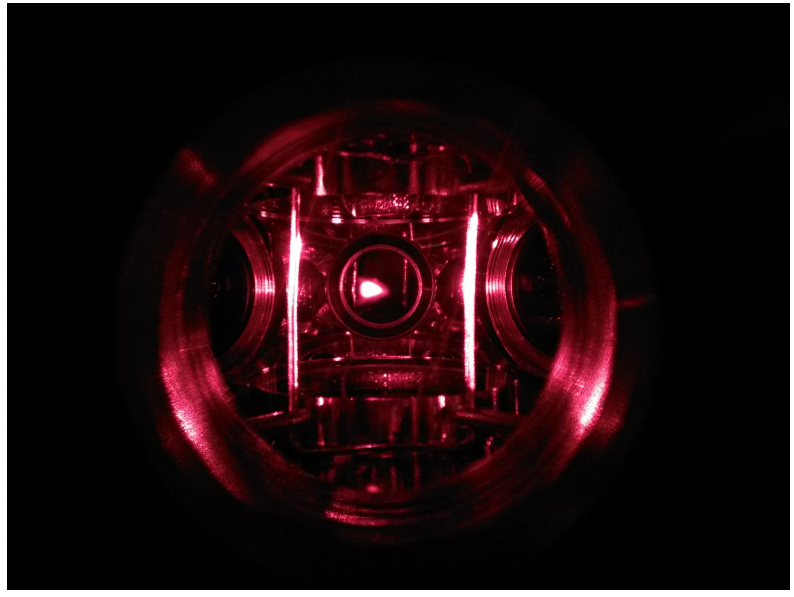
**Sébastien Bourdeauducq**

M-Labs TechTalk — October 22nd 2026



# Laser cooling

- Uses laser to reach temperatures approaching absolute zero.
- Small numbers of atoms or ions in vacuum chamber.
- Fundamental to most trapped-ion and neutral-atom quantum experiments.
- e.g. quantum gates, atomic clocks.
- Needs single-frequency light, optical frequency (hundreds THz) accurate to roughly 10MHz.



# Why Johnny can't laser-cool

*"You need this US$30,000 argon-ion laser that takes 15kW of three-phase power, and use it to pump this US$20,000 dye jet laser filled with toxic dye..."*
*"You need two ECDLs at US$35,000 each, with a US$40,000 driver, and buy a license for the locking feature. Don't forget optical isolators at US$3,000 each, they'll make your life easier."*
*"You can make the ECDLs yourself if you are on a budget. You just need to buy this rare laser diode that shows up once every five years at around US$4,000 from specialty resellers. Don't kill it with ESD or optical feedback!"*
*"We offset-lock it from a US$2,500 tellurium vapor cell held at 550C..."*
*"Use this US$50,000 Fizeau-Snyder wavemeter to determine which resonance of this US$20,000 optical cavity made of export-controlled and patented ULE® glass you are on, then use a US$5,000 AOM with driver for fine adjustment of the optical frequency..."*

# What if there was another way?

- Unlike "research-grade" hardware, telecommunication hardware has to perform.
- $200 buys you a single-frequency laser diode, tunable by at least 2nm, with 10MHz linewidth.
- $800 says your linewidth is down to 100kHz.
- All in small and rugged "butterfly" packages with fiber output.
- Cooling and repumping transitions of typical ions have natural (quantum-limited) linewidths around 5-25MHz.



Is it really that hard?

# The wavelength problem

- Telecom lasers are in the 1270-1600nm region only. No interesting transitions ☹
- Frequency conversion is difficult and/or expensive.[1]
- Visible Fabry-Perot diodes – how bad are they?

[1] Cheap DPSS pointers can be hacked for SFG, but this will be for another talk. See the PoC on 193THz.com if you're curious.

# FP diode pathologies

- Multimode: "single mode" in FP diode datasheets really means "single spatial mode". ☹ ☹
- SSM diode resonances are separated by many dozens GHz: ☺
  - Large FSR + homogeneous broadening = many diodes single-frequency just above threshold
  - Ion typically transparent to any additional frequencies
  - Beware of mode hops
  - Beware of mode partition noise
  - Beware of hysteresis
  - Easy to see and can be kept in check by diffracting collimated beam on holographic grating
- Linewidth (one mode): dozens of MHz. Not great, not terrible.

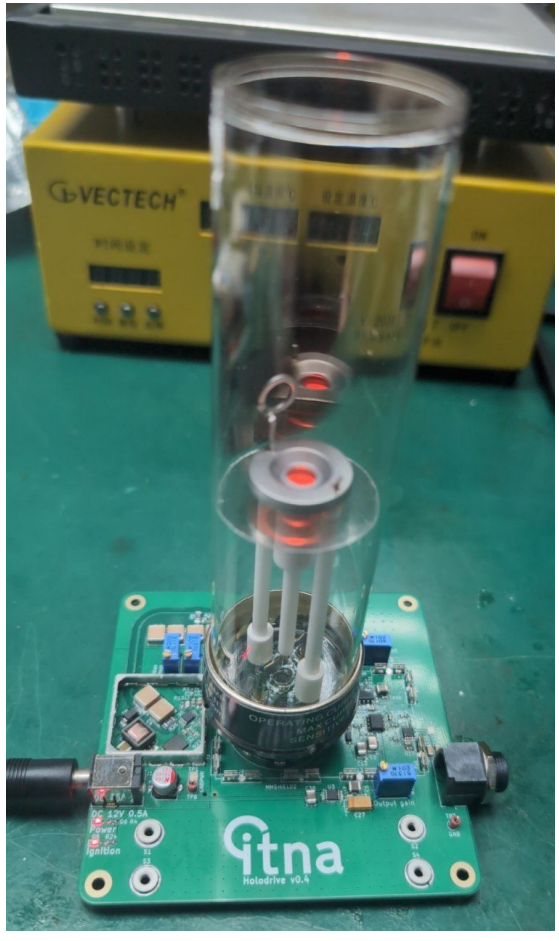
# Optogalvanic stabilization

- Main problem: keeping laser optical frequency at a setpoint within spectral line of interest.
- Using the ionized species as reference:[2] hollow cathode discharges produce large numbers of ions with "brute forcing" of all quantum states. $50 off Taobao.
- Hollow cathode lamp (HCL) spectral lines often sufficiently far apart that inexpensive grating spectrometer can resolve them. NIST ASD gives you the exact wavelengths.
- Optogalvanic effect: when the laser drives a transition in the HCL plasma, the plasma impedance varies by a small amount.
- But plasma discharge is noisy.

[2] Neutrals in MOTs need hundreds of mW of single-frequency laser power, which cannot be done with free-running FP diodes. This is why we focus on ions.

# The Holodrive

Low-noise optogalvanic front-end for hollow cathode lamps




`https://git.m-labs.hk/ITNA/holodrive`

# Lock-in amplifier to the rescue

- Most noise is at DC (1/f).
- Solution: Modulate the laser then look for an optogalvanic signal in a narrow band around the modulation.
- Since modulation is known, bandwidth and noise can be reduced indefinitely, at the expense of response time.

# The DSP lock-in amplifier

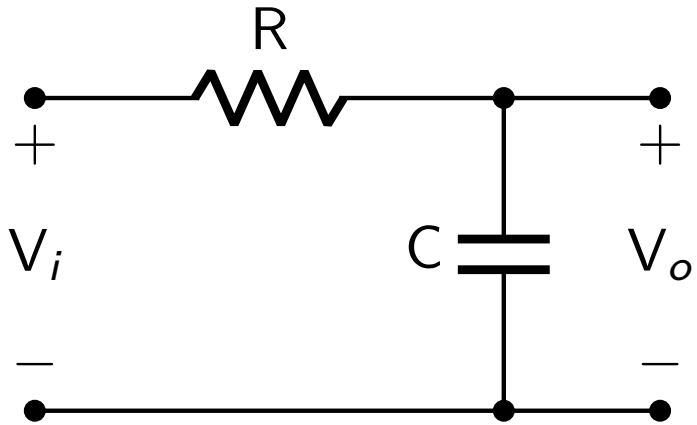
$i(t)$: (real) input signal, $\mathscr{L}()$: low-pass filter, $\omega$: angular frequency of modulation/demodulation

$$
\begin{aligned}
&\mathscr{L}(i(t) \cdot e^{-i\omega t}) \\
&= \mathscr{L}(A_i cos(\omega t + \phi_i) \cdot e^{-i\omega t}) \\
&= \mathscr{L}(A_i \frac{e^{i(\omega t+\phi_i)} + e^{-i(\omega t+\phi_i)}}{2} \cdot e^{-i\omega t}) \\
&= \frac{A_i}{2} \mathscr{L}(e^{i\phi_i} + e^{-i(2\omega t+\phi_i)}) \\
&\approx \frac{A_i}{2} e^{i\phi_i}
\end{aligned}
$$

Both magnitude $A_i$ and phase $\phi_i$ at the carrier are extracted, and other frequencies (noise) are rejected.

# A simple DSP low-pass filter

First-order analog RC low-pass filter with bandwidth $\frac{1}{2\pi RC}$:




Its time-domain behavior is determined by the differential equation:

$$\frac{dV_o(t)}{dt} = \frac{1}{RC}(V_i(t) - V_o(t))$$

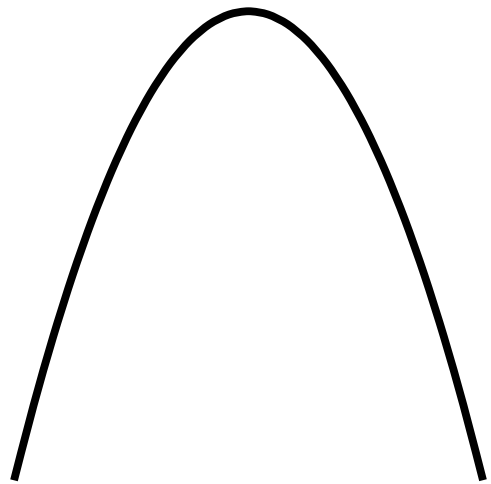
Similar behavior is easy to implement in a DSP:

$$V_o(n+1) = V_o(n) + k(V_i(n) - V_o(n))$$

Just cascade the equation for a higher-order filter (steeper rolloff).

# Lock-in optogalvanic spectroscopy

- Many experiments use chopper wheel as modulator.
- But with a diode laser, one can do better!
- Use optical frequency dependence on current ("chirp").
- Spectral line converts FM to AM.
- Phase tells you which side of the line you are.
- Allows locking the laser to the top of the line.



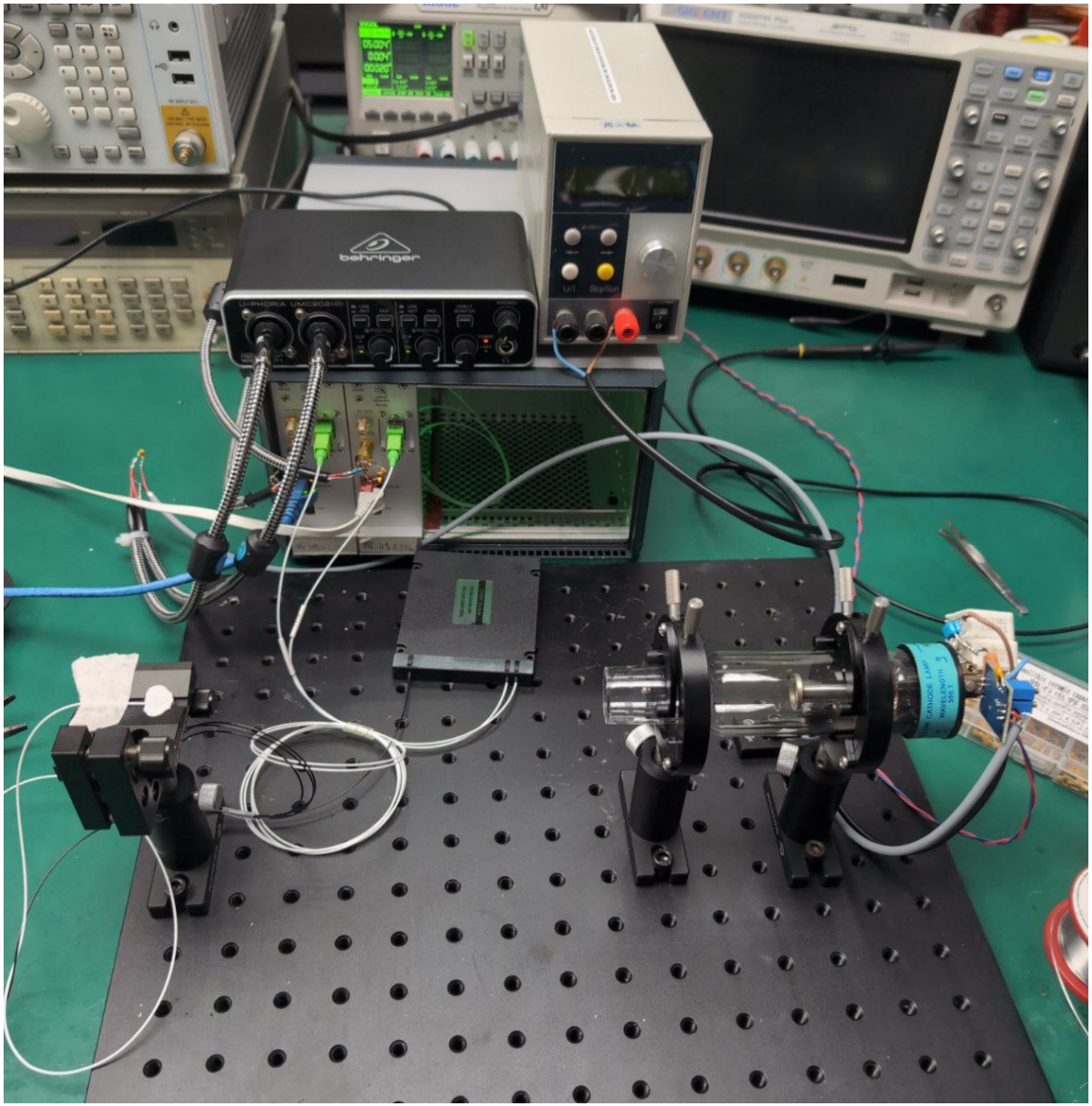
# Soundlocker

- Cheap DAC/ADC: USB audio interface (Behringer UMC202HD, 2x192kHz 24-bit) with USB isolator.
- Lesser soundcards might work, motherboard audio quality varies greatly (but always inferior to UMC202HD in my tests).
- Software written in C++ with ImGui and OpenBSD sndio.
- DDS to modulate laser, DSP lock-in as above, GUI for setup and testing, control loop.
- Open source – `https://git.m-labs.hk/ITNA/sndlock`



# Lanthanum III test

Transitions aligned to CWDM grid (1390nm/1410nm), hyperfine structure.

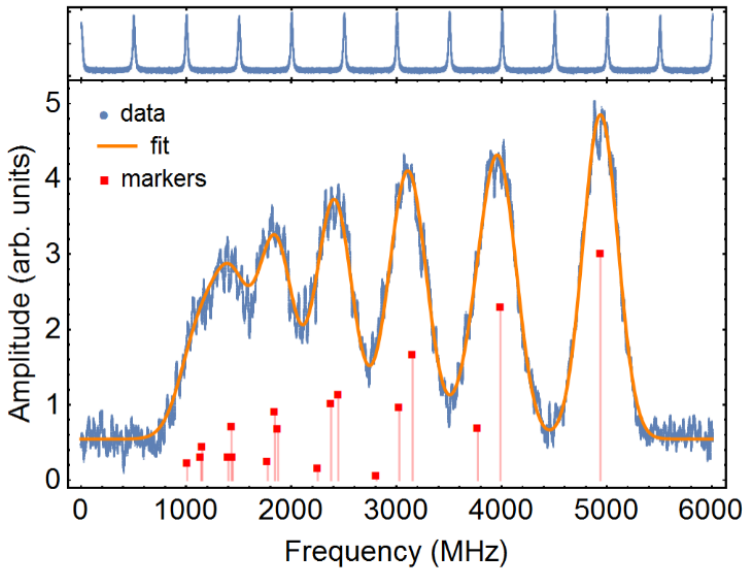


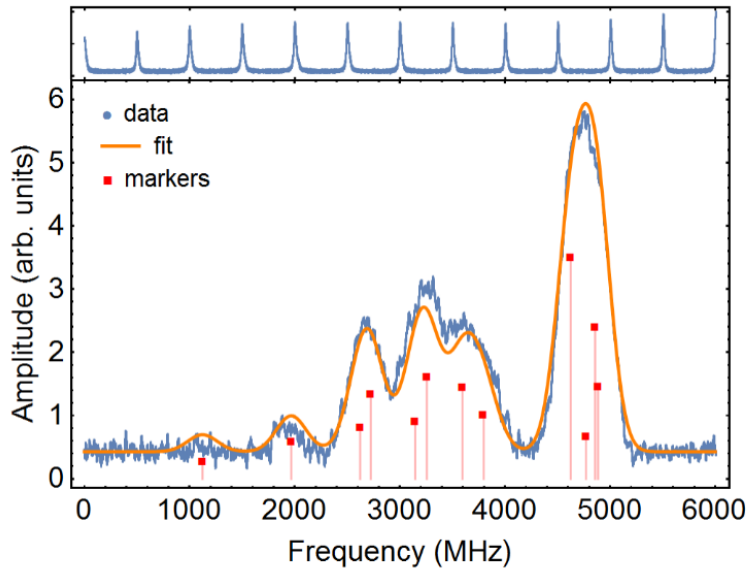
# Lanthanum III test




Soundlocker on $100 UMC202HD, 2x$200 telecom diodes
9mW laser power, single pass.

# Lanthanum III test



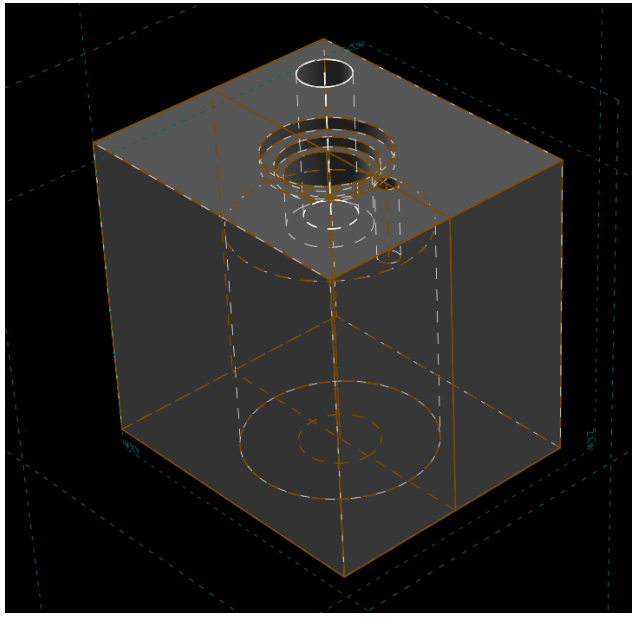

Olmschenk (2018):
traditional lock-in ($6,500 SRS?), $$$$$ ECDL+BOA
60/50mW laser power, 5/10 passes.
(Shape is different due to AM with chopper vs. FM and magnitude plot)

# Why not a lanthanum ion trap?

- Narrow natural linewidths (kHz): low photon scattering rate.
- 1400nm is completely invisible.
- 1400nm cameras are very expensive and generally awful.
- Complicated hyperfine structure requiring many lasers.
- Barium looks better: no hfs, lots of scattering, near peak eye sensitivity, well-studied.

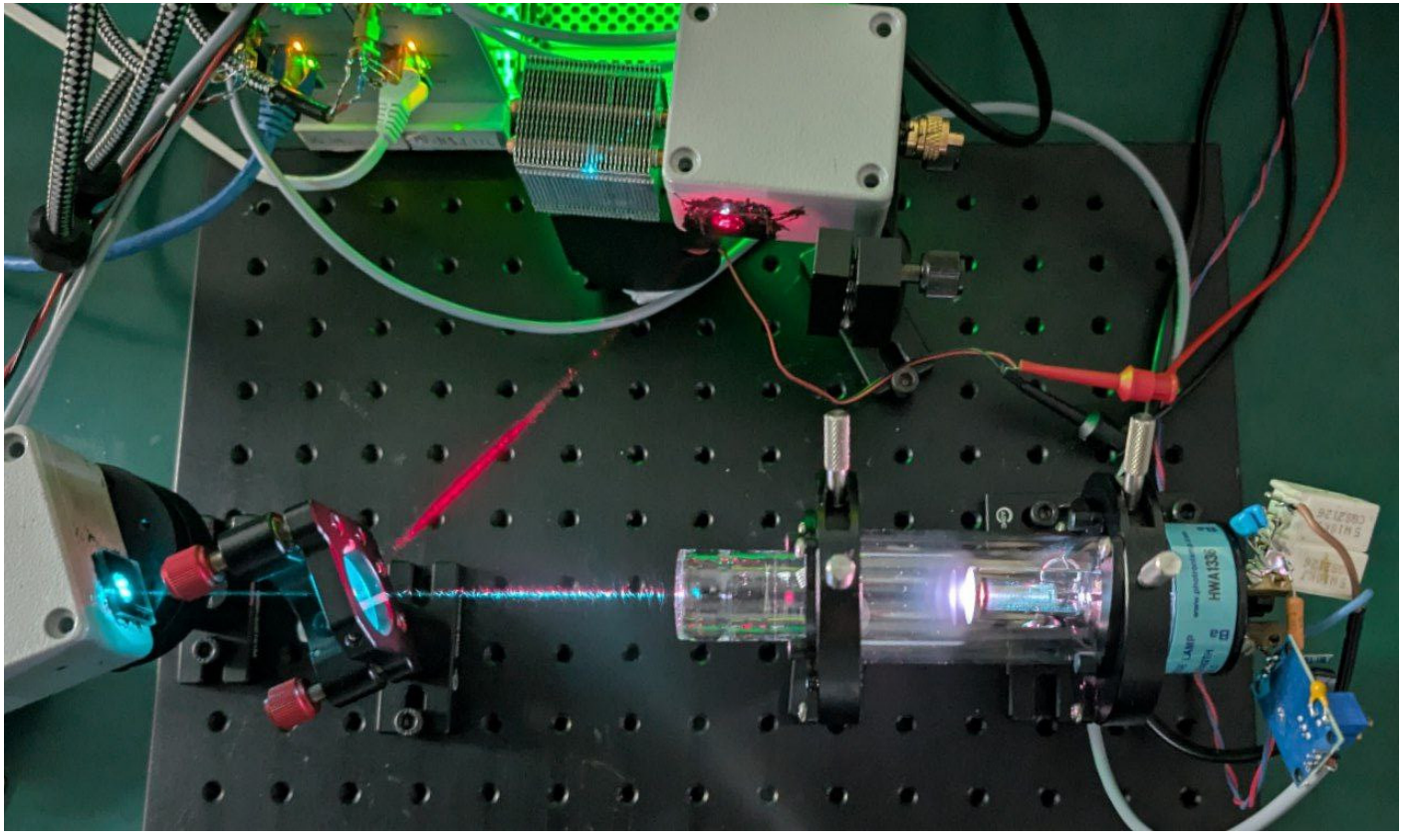
# Building simple tunable diode lasers

- SHARP wavelength-selected diode for 493nm, DVD writer diode for 650nm.
- Machined copper mount (PCBWay), diode soldered with indium/tin, collimator, venting hole, TEC, thermistor.
- Into airtight enclosure.
- Two ways to avoid condensation on cold diode:
  - silica gel, DHT22 sensor for monitoring.
  - vacuum (from air conditioning service gear), open light bulb as Pirani gauge: better thermal insulation, but less forgiving.



# Locking to Barium II

- 493nm and 650nm beams combined on dichroic mirror.
- Orthogonal modulation frequencies from stereo channels ☺
- RAM and photoelectric effect at 493nm adds constant signal, simply subtracted.
- Both lasers locked to single lamp with TEC feedback!



# What comes next

- Using harmonics to improve SNR and lock accuracy.
- Chop the beam, only modulate blocked (avoid ion heating).
- Building the world's cheapest laser-cooled ion trap!

