Project 8: A frequency based approach to measure the neutrino mass

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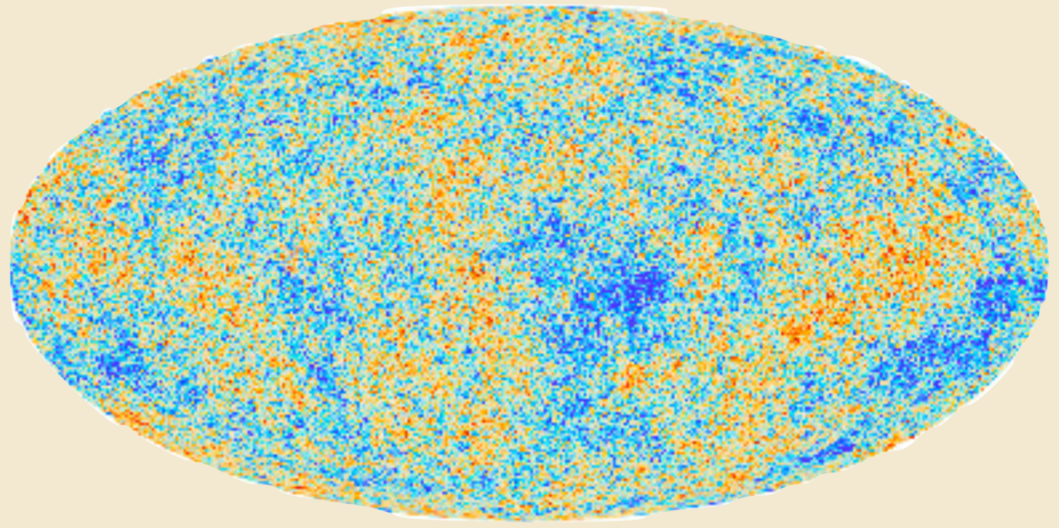
International School of Nuclear Physics
39th Course
Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics
Erice-Sicily
September 16-24, 2017

UNIVERSITY *of* WASHINGTON

Where to look for neutrino masses

M.C. Gonzalez-Garcia, K. Valerius and others

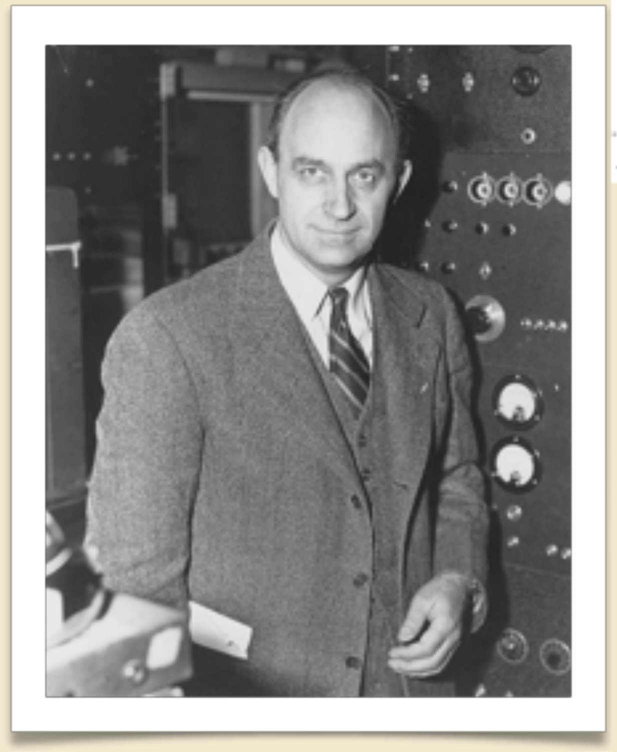
Three different combination of eigen masses



Tool	*Cosmology CMB + BAO + LSS*
Observable	$\sum m_\nu = \sum_{i=1}^{3} m_i$
Present best limit	*0.15 - 1 eV*
Potential reach	*20-50 meV*
Model dependence	*Multi-parameter cosmological model*

Anti-electron neutrino mass and tritium beta decay spectrum

Finite neutrino mass modifies the decay electron spectrum!



PHYSIQUE NUCLÉAIRE. — *Possibilité d'émission de particules neutres de masse intrinsèque nulle dans les radioactivités β.* Note de M. FRANCIS PERRIN, présentée par M. Jean Perrin.

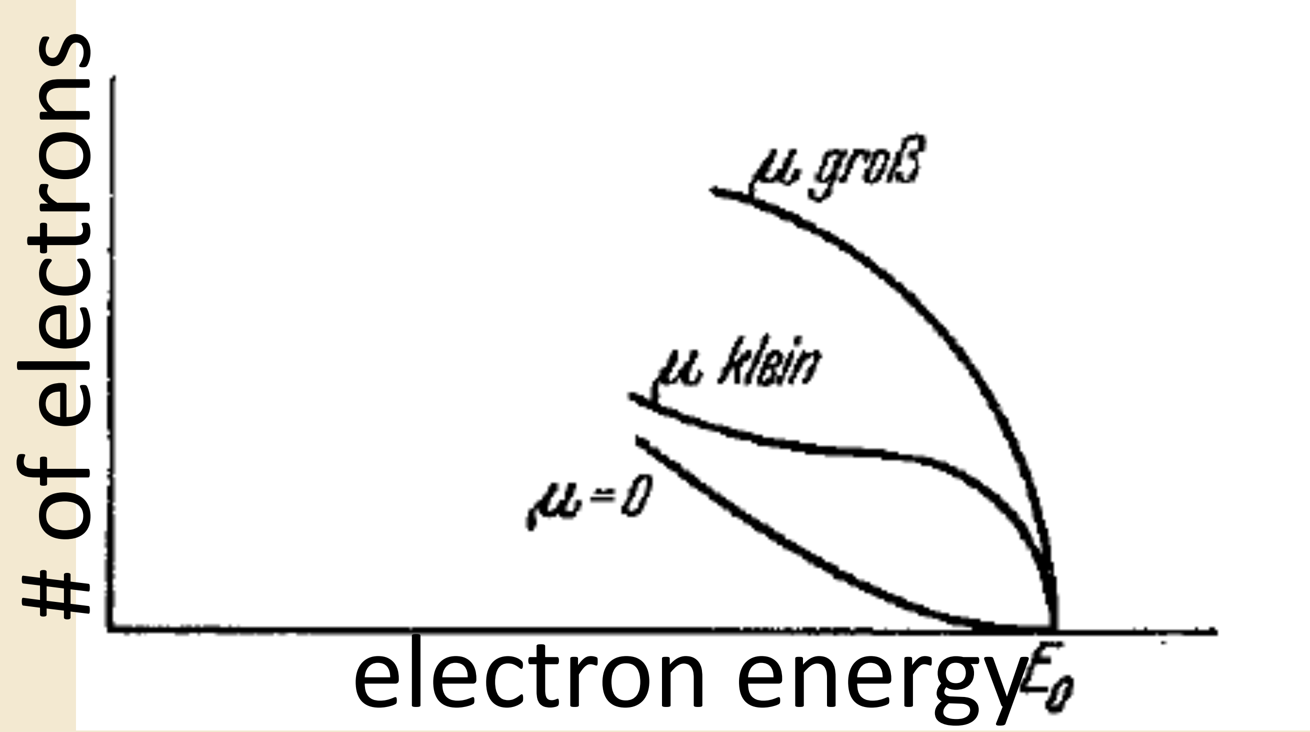
SÉANCE DU 18 DÉCEMBRE 1933.

Versuch einer Theorie der β-Strahlen. I[1]).

Von E. Fermi in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

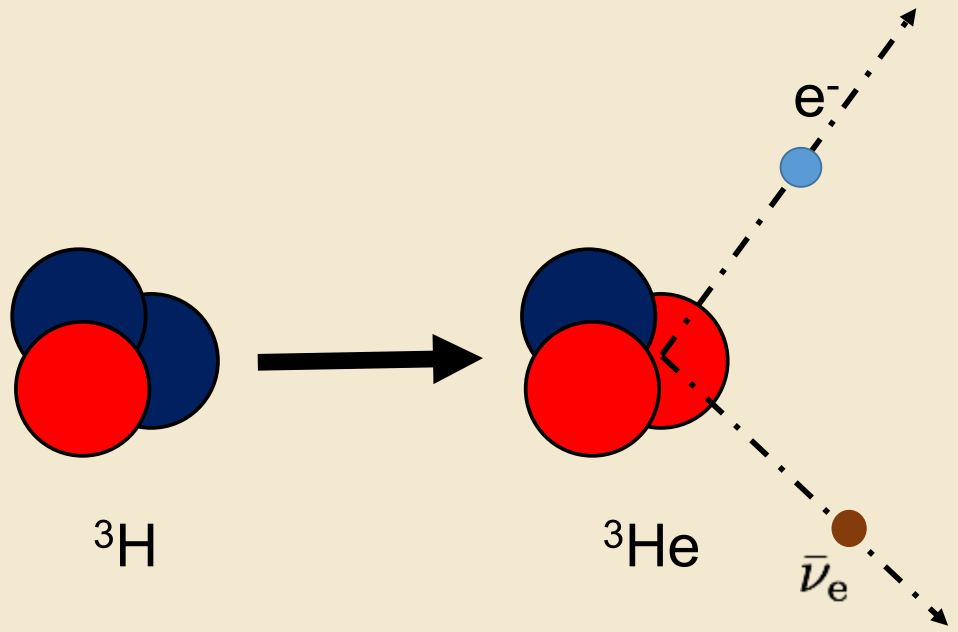
Zeitschrift für Physik, Vol. 88, p. 161



Any new final state can modify the decay spectrum! Sterile neutrinos!?

Idealized situation:

1. Super-allowed β^--decay of ***isolated*** atom
2. Single neutrino mass state



nuclear matrix element for T

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{nuc}|^2 \, p\cdot(E+m_e)\cdot(E_0-E)\cdot\sqrt{(E_0-E)^2 - m^2(\nu_e)}$$

constants

purely kinematic variables

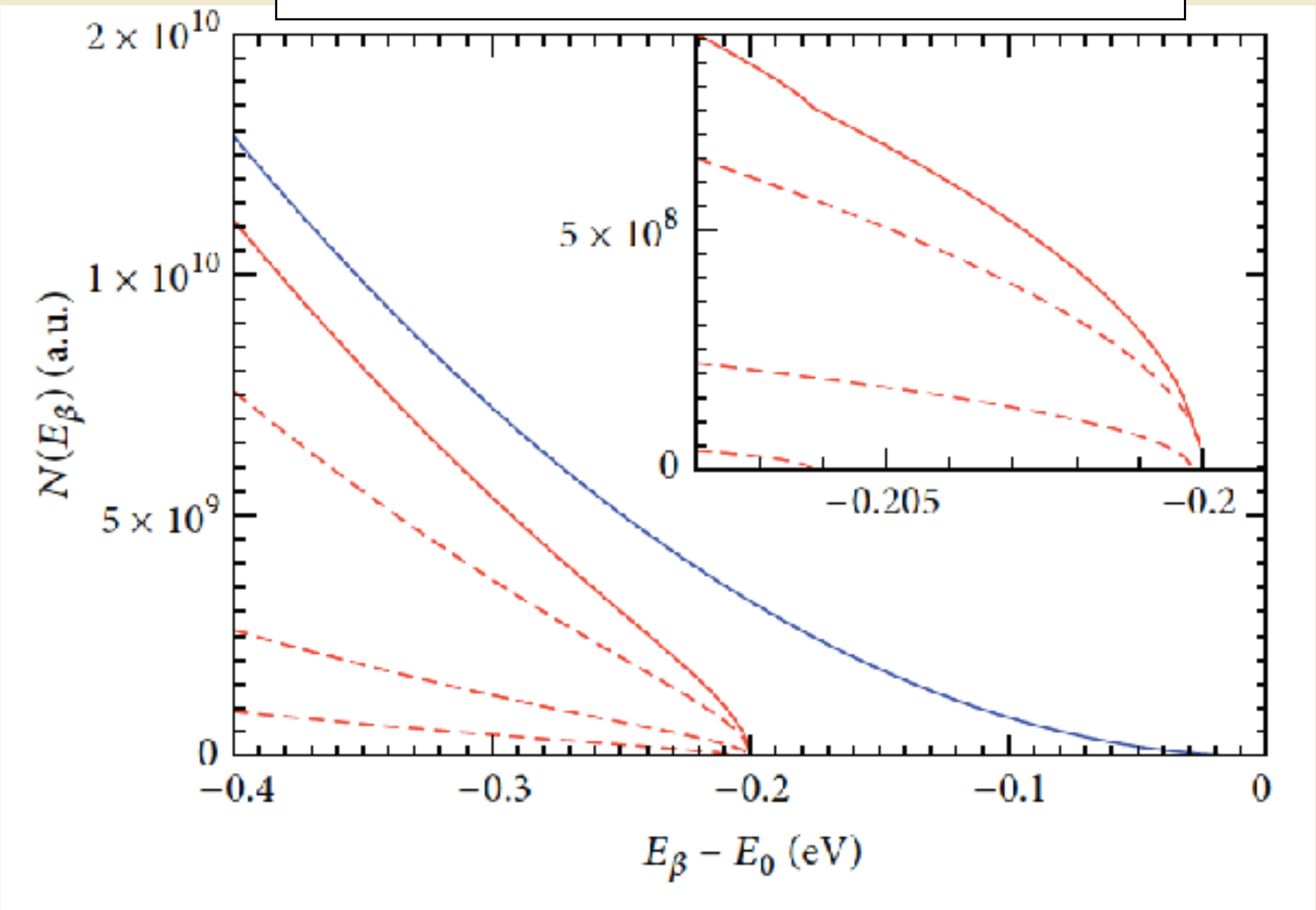
β⁻-decay electron spectrum

With neutrino mixing and nuclear recoil for T_{nuc}:

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{nuc}|^2 F(Z, E_e) p_e E_e \sum_i |U_{ei}|^2 (E_{max} - E_e) \times \sqrt{(E_{max} - E_e)^2 - m_{\nu i}^2} \cdot \Theta(E_{max} - E_e - m_{\nu i})$$

$$m(\nu_e) = \sqrt{\sum_i |U_{e,i}|^2 m_i^2} \qquad BR \approx \left(\frac{\delta E}{E_0}\right)^3$$

For T: m_β=0.0 eV m_β=0.2 eV



Nucciotti, Advances in High Energy Physics, Vol. 2016, 9153024

Tritium
$Q(T_A)$ = 18.59201(7) keV
Super allowed transition
$T_{1/2}$ = 12.32 y
BR (1eV) = 2 x 10^{-13}

^{187}Re
Q= 2.4667(15) keV
Unique first forbidden decay
$T_{1/2}$ = 4 x 10^{10} y
BR (1eV) = 7 x 10^{-11}

Experimentally disfavored

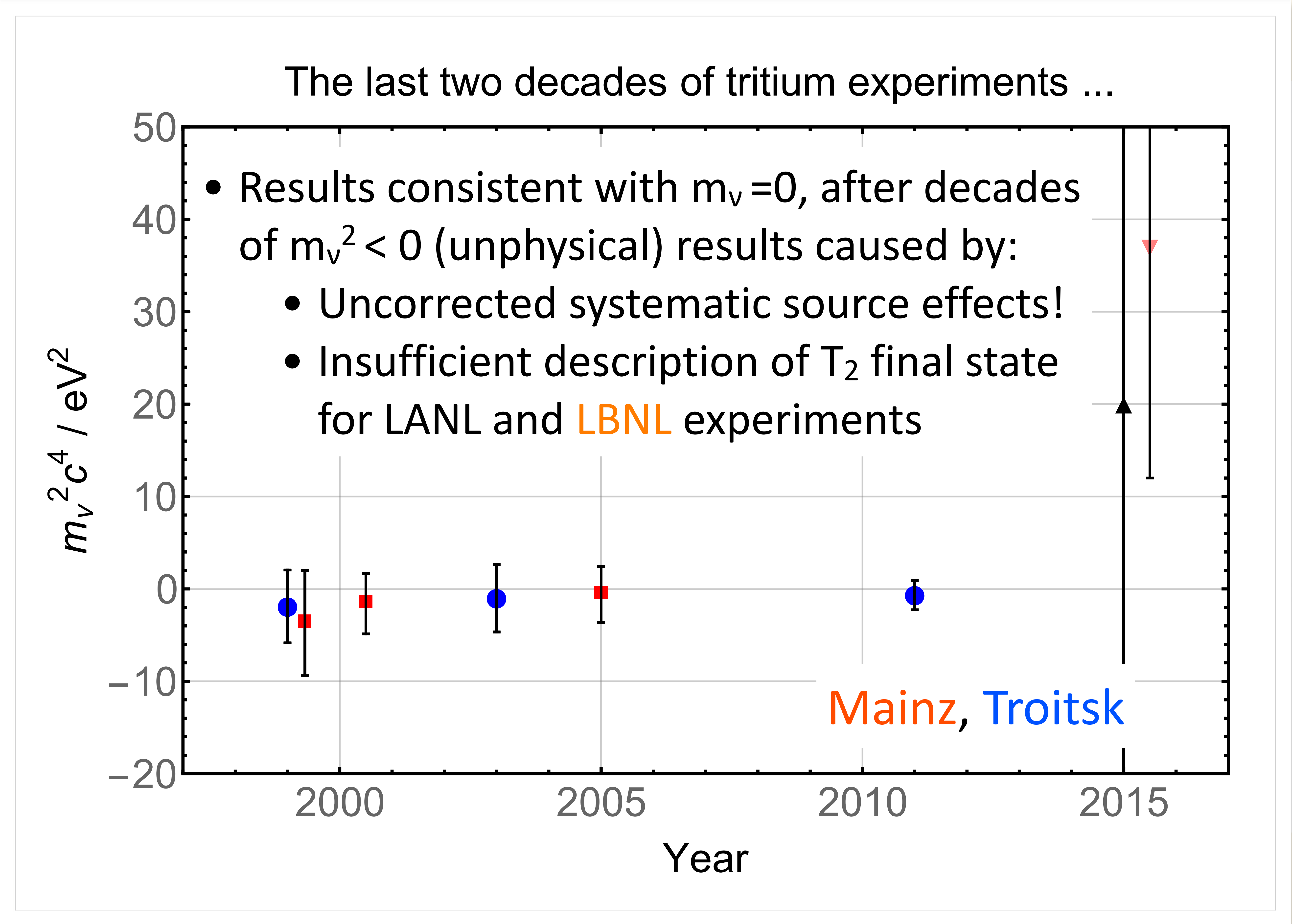
^{115}In to ^{115}Sn*
Q = 0.173(12) keV
Only 1.2x10^{-6} of the 498 keV decay to ground state

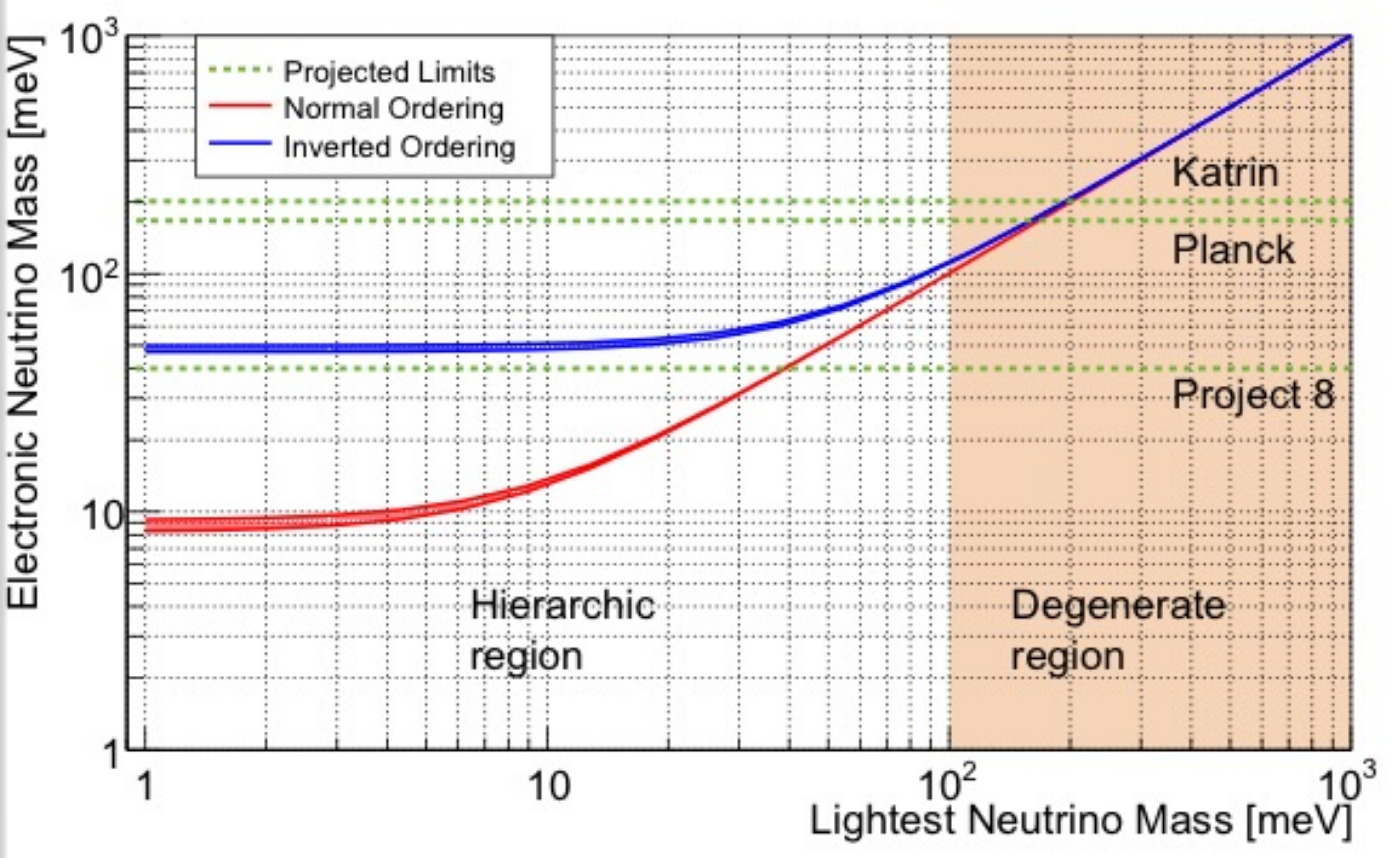
No experimental scheme devised!

For ^{163}Ho EC experiments:
L. Gastaldo,
A. Faessler,
T. Kieck

Limits on anti-electron neutrino mass from tritium decay

Tritium has been the “workhorse” for decades, but … :





KATRIN: The largest MAC-E filter ever built

Magnetic **A**diabatic **C**ollimation with **E**lectrostatic filter
A. Picard et al., Nucl. Instr. Meth. B 63 (1992)

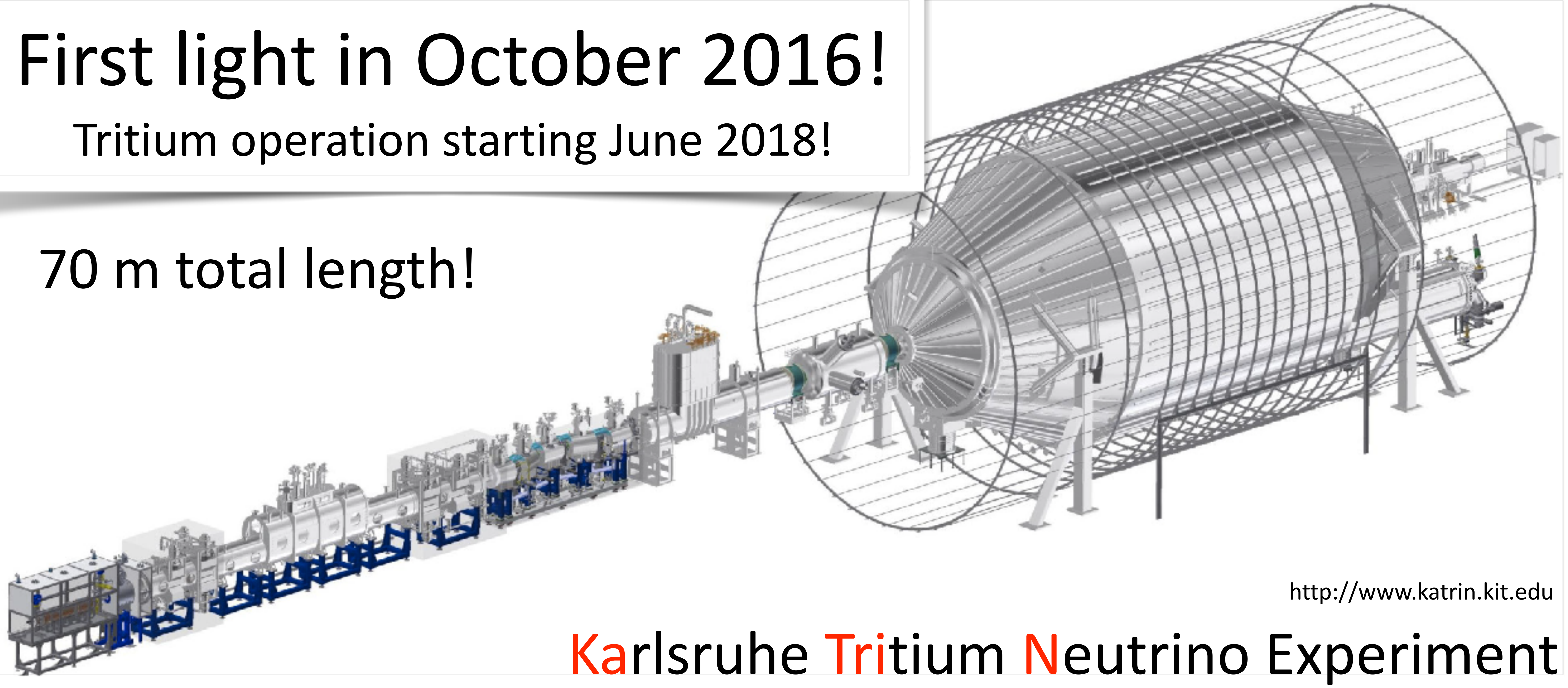
$$\mu = \frac{E_\perp}{B} = \text{const.} \qquad \frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}$$

Retarding electric field:
Count decay e^- above threshold!

Experimental challenges:
- Highest source luminosity
- Highest energy resolution
- Control of inelastic scattering rate
- Safe tritium handling

First light in October 2016!
Tritium operation starting June 2018!

70 m total length!

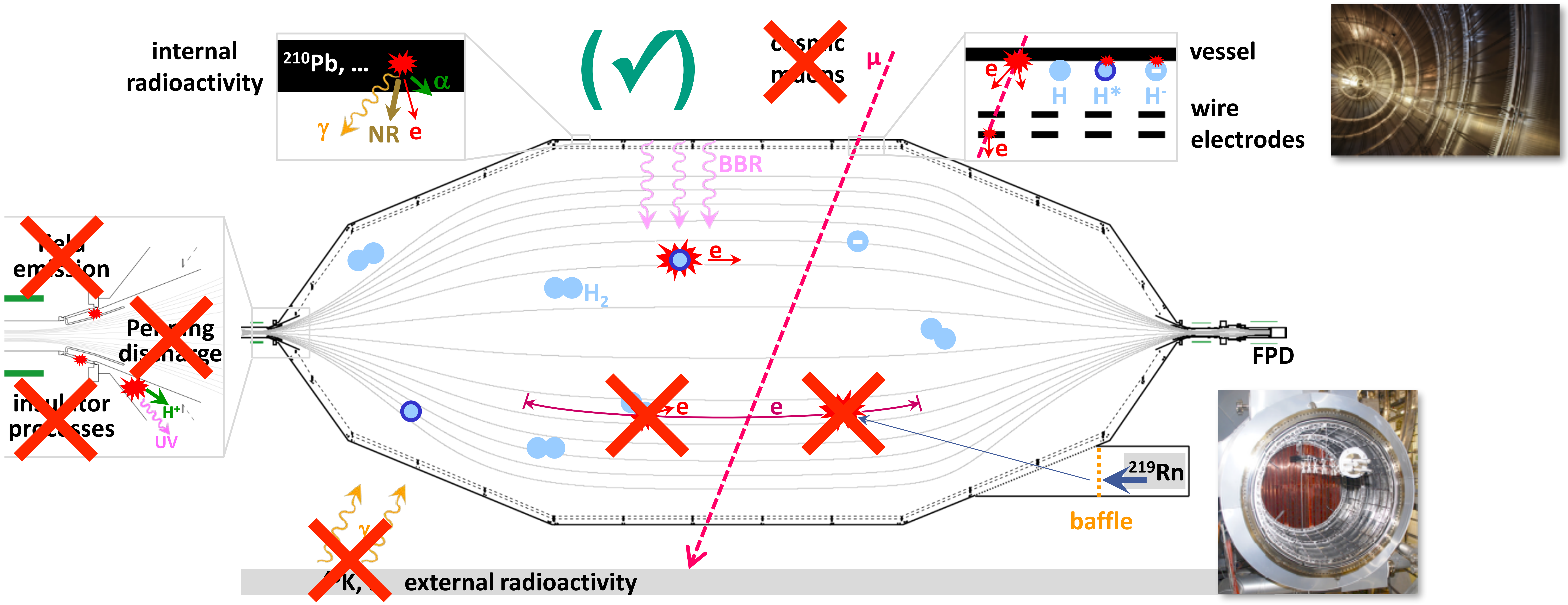


http://www.katrin.kit.edu

Karlsruhe Tritium Neutrino Experiment

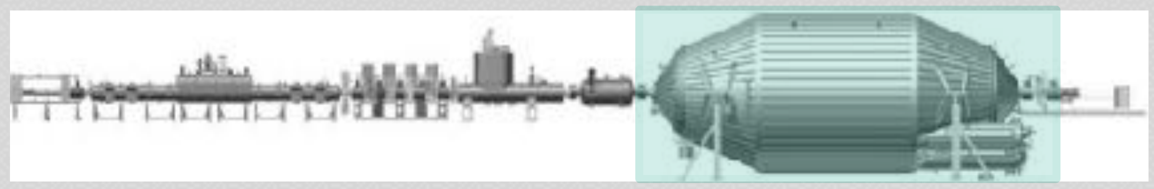
KATRIN talks: K. Valerius, G. Drexlin, H. Seitz-Moskaliuk, S. Mirz, …

Backgrounds in KATRIN



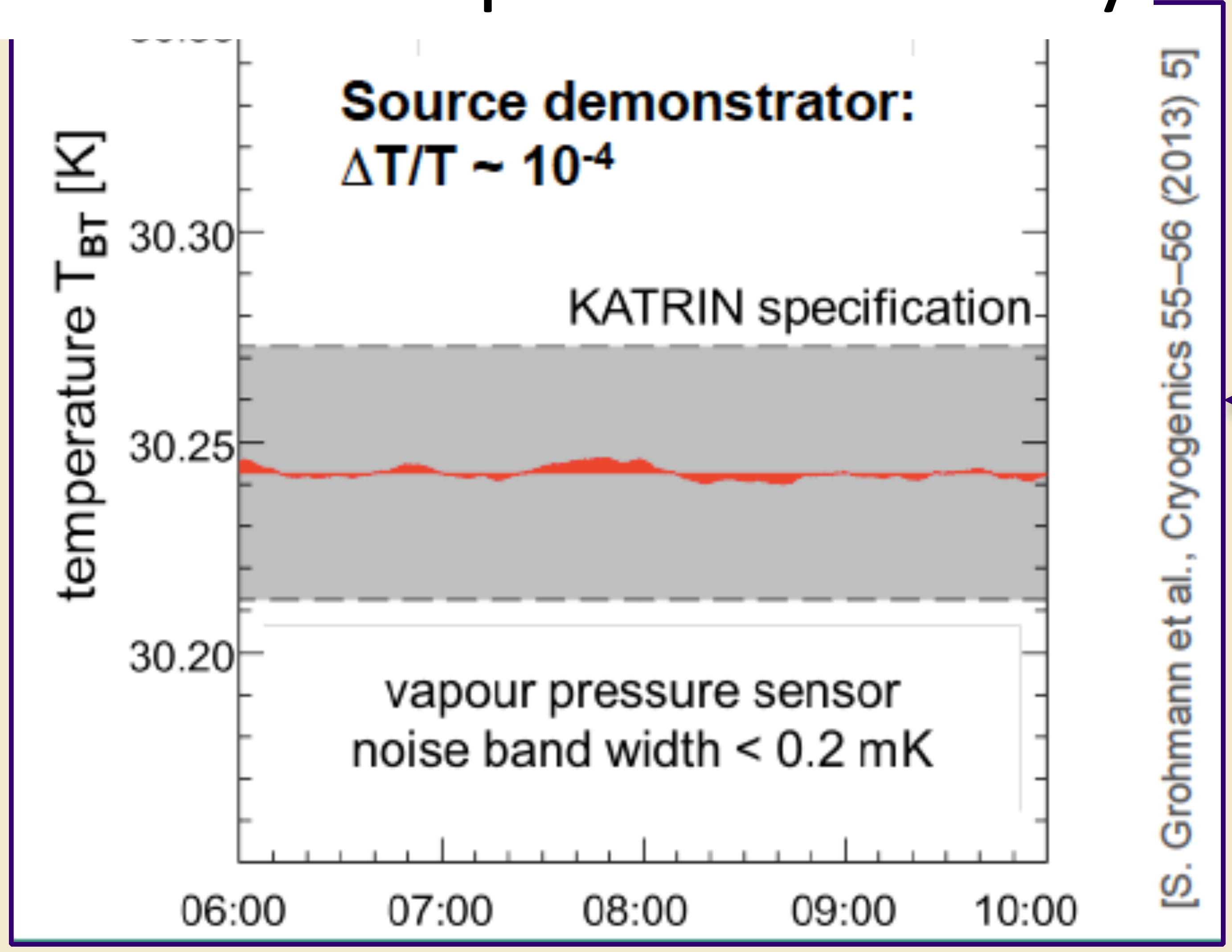
- **8 sources of background investigated and understood**
- **7 out of 8 avoided or actively eliminated by**
  - fine-shaping of special electrodes
  - inner electrode (wire grids on neg. potential)
  - symmetric magnetic fields
  - cold traps (LN_2-cooled baffles to remove ^{219}Rn)

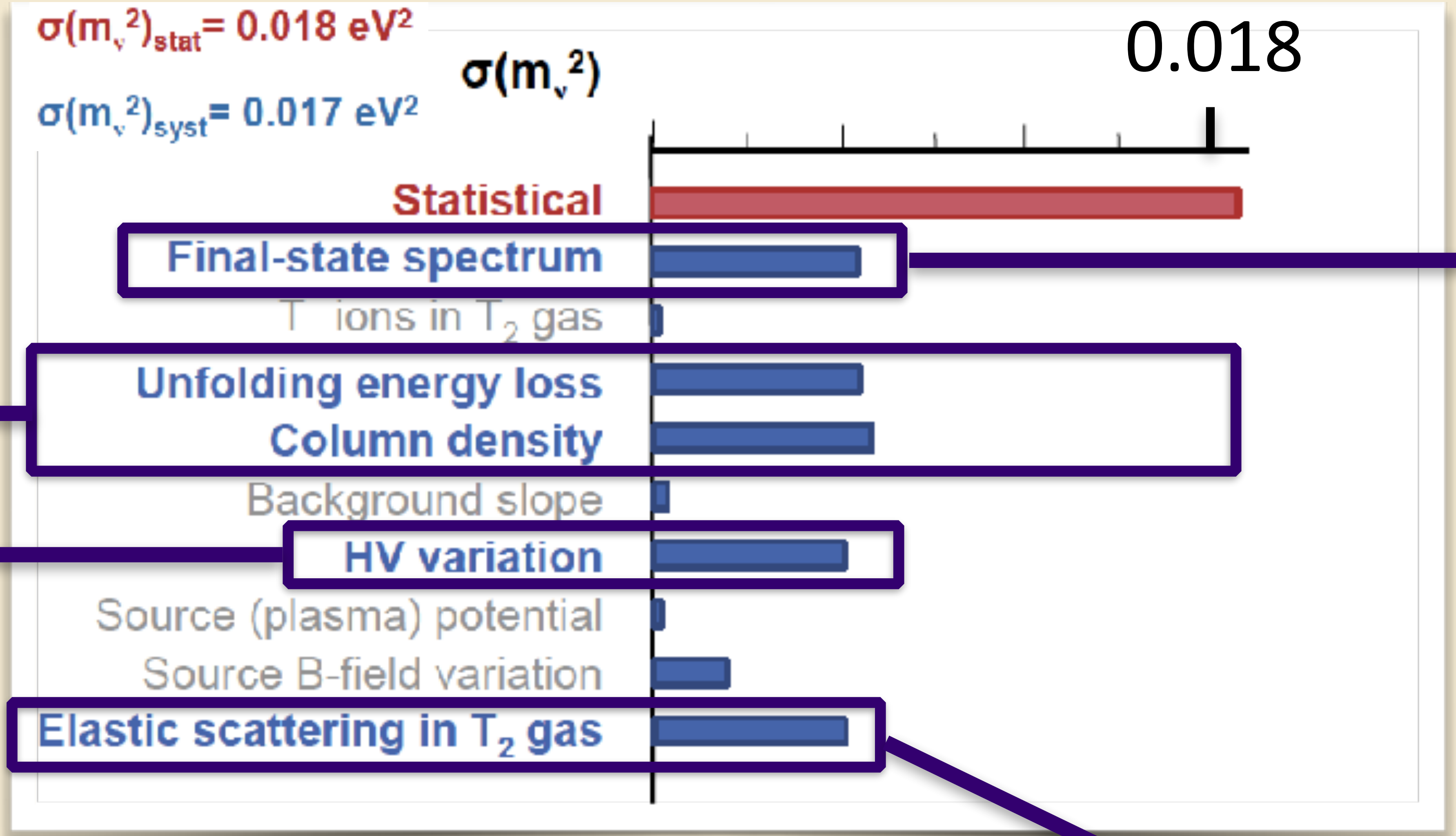
- **1 out of 8 remaining:**
  ^{210}Pb on spectrometer walls (thermal ionisation of neutral H* atoms)
- Countermeasures:
  - extensive bake-out (done)
  - irradiation by strong UV source (ongoing investigation)



Current systematic limitations of a MAC-E filter

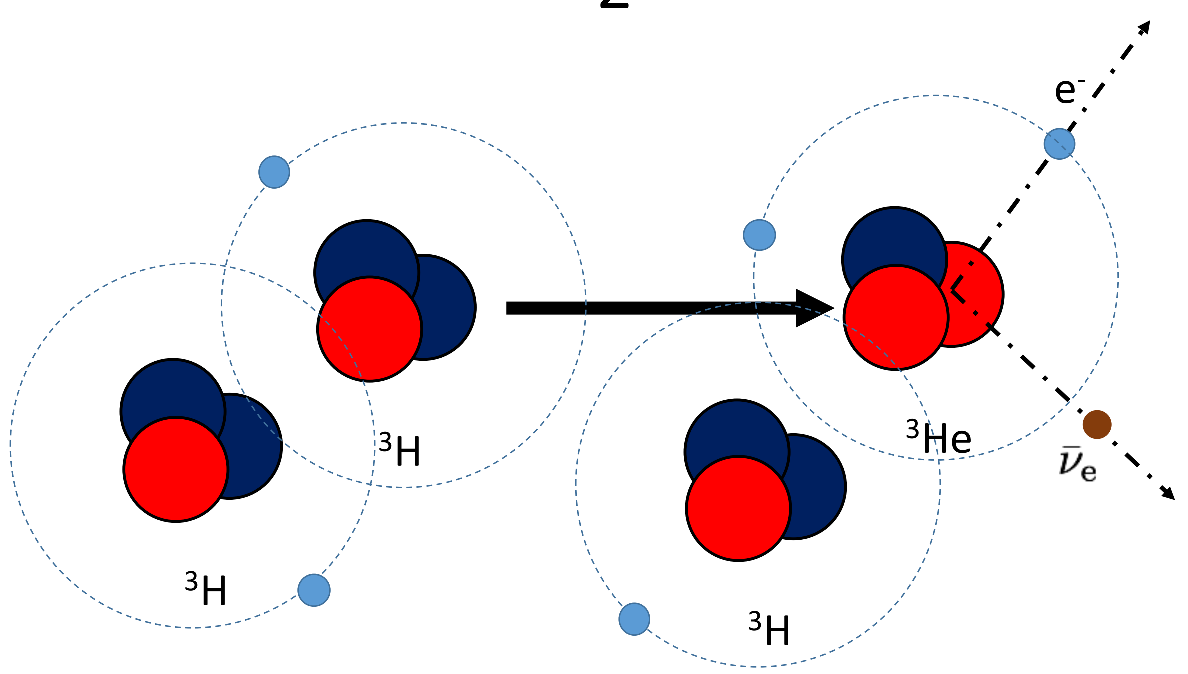
Excellent temperature stability

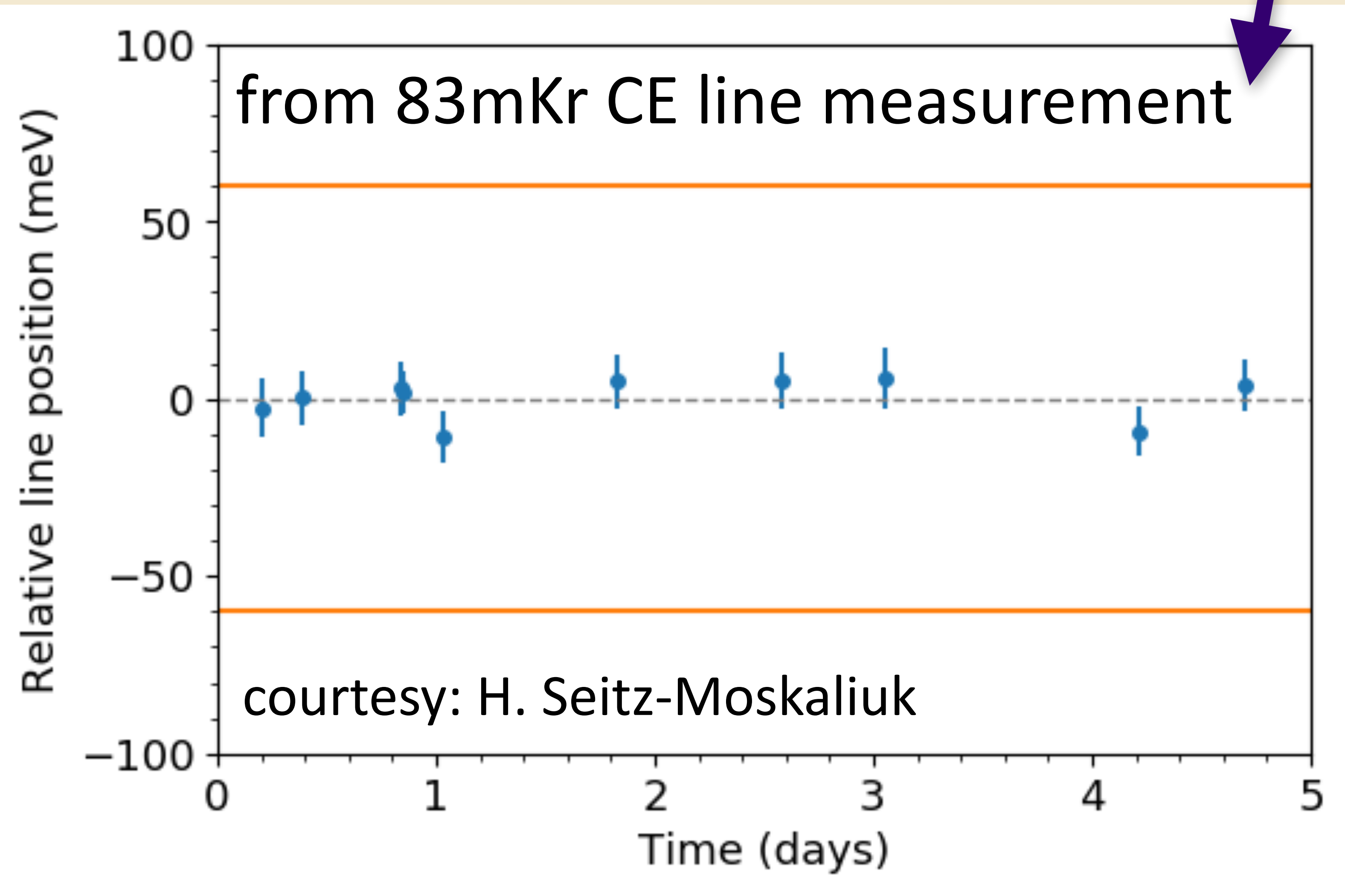




Kathrin Valerius, HEPHY Colloquium, Vienna, Jan 2016

Irreducible excitation of ro-vibrational initial and final states of T_2 molecule.



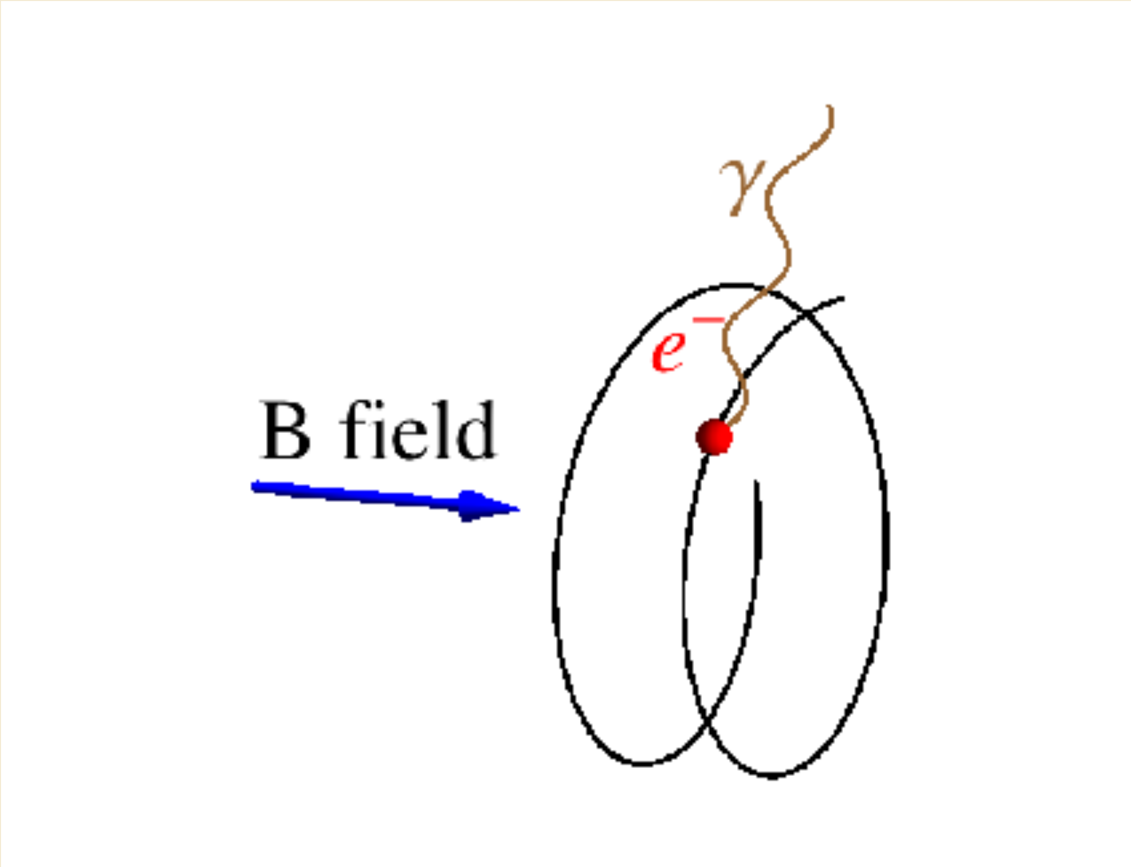


Big challenge for new techniques:

- Development of orthogonal set of systematic effects!
- Different classes of bkgds!
- Statistics!

1. e^- energy loss
2. e^- can be scattered into angular acceptance cone of the MAC-E filter

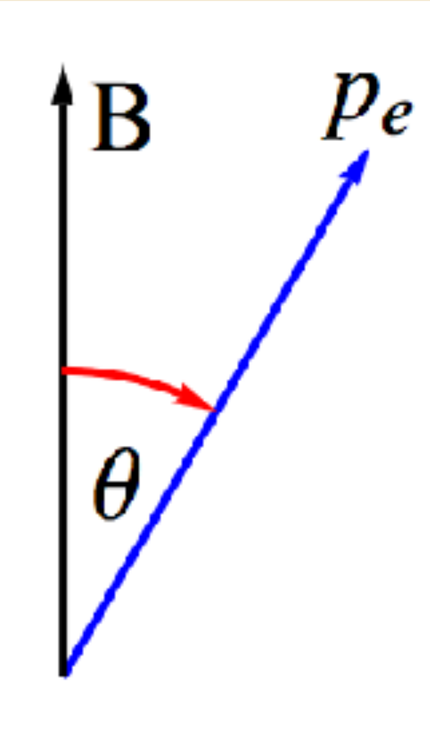
Project 8: Cyclotron radiation emission spectroscopy of T_2

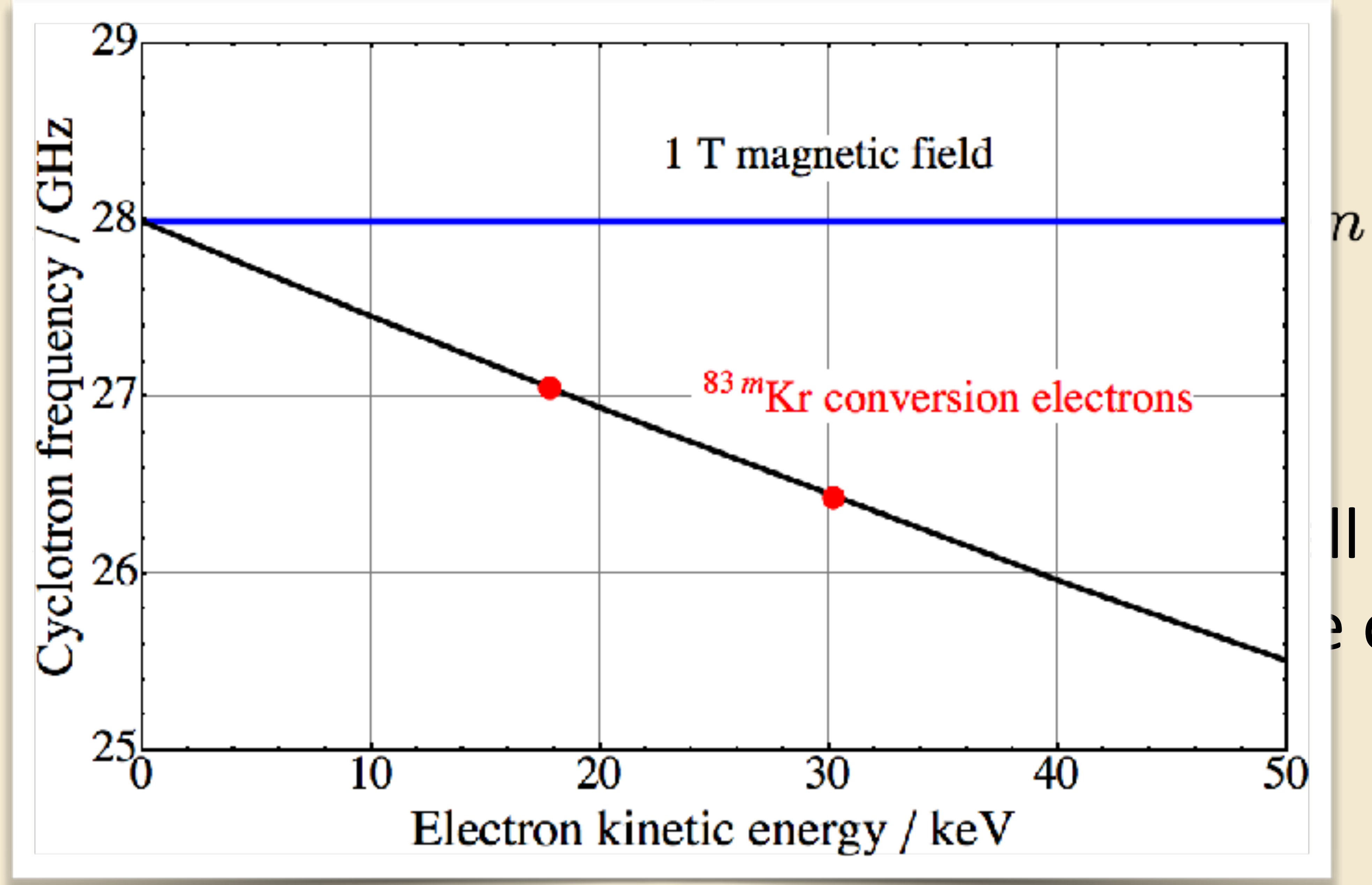


Novel approach: J. Formaggio and B. Monreal, Phys. Rev D 80:051301 (2009)

- Cyclotron radiation from single electrons
- Source transparent to microwave radiation
- No e- transport from source to detector
- Highly precise frequency measurement

$$f_\mathrm{c} = \frac{f_{\mathrm{c},0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_\mathrm{e} + E_\mathrm{kin}/c^2}$$





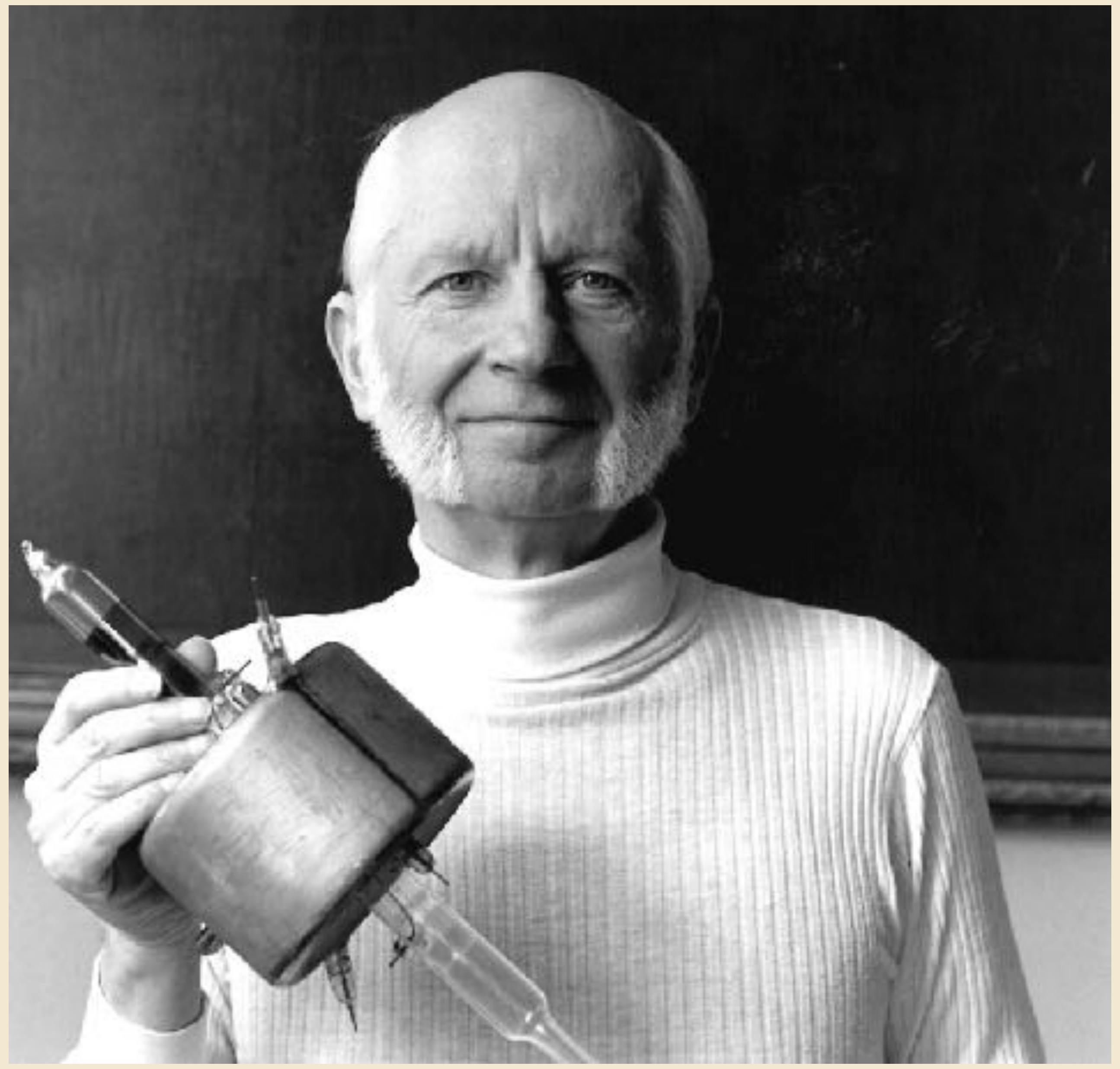
$nc^2)\sin^2\theta$

ll but readily detectable with

e of the art detectors

Hans Dehmelt

9.9.1922- 7.3.2017



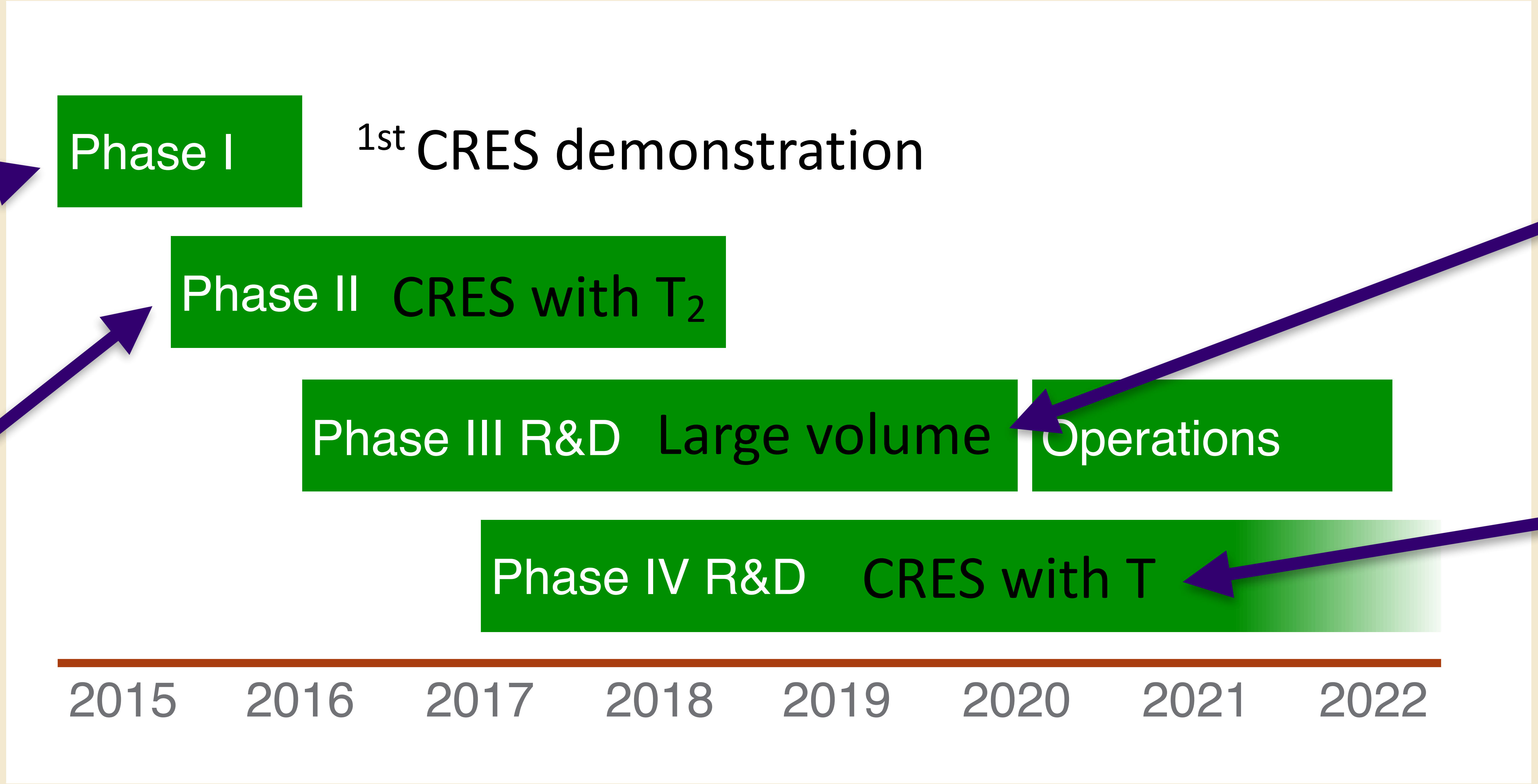
Project 8: A four phases approach

Every aspect of the new technology has to be demonstrated before we can design an atomic tritium experiment!

Phase I
CRES in a waveguide with ^{83m}Kr

Phase II
CRES in a waveguide with T_2 gas

C. Claessens
Signal reconstruction
Thursday, 18:55 - 19:15



Phase III
Large volume
CRES with T_2 gas

Phase IV
Large volume
CRES with T gas

S. Böser
Thursday, 16:35 - 17:00

Frequency and energy resolution of CRES

Energy resolution vs. frequency resolution

$$\frac{\Delta E_{\mathrm{kin}}}{E_{\mathrm{kin}}} = \left(1 + \frac{m_{\mathrm{e}}c^2}{E_{\mathrm{kin}}}\right)\frac{\Delta\nu_{\mathrm{c}}}{\nu_{\mathrm{c}}}$$

≈ 28 for 18.6 keV electron

$$\Delta E_{\mathrm{kin}} \approx 0.2\,\mathrm{eV} \rightarrow \frac{\Delta\nu_{\mathrm{c}}}{\nu_{\mathrm{c}}} \approx 4 \times 10^{-7}$$

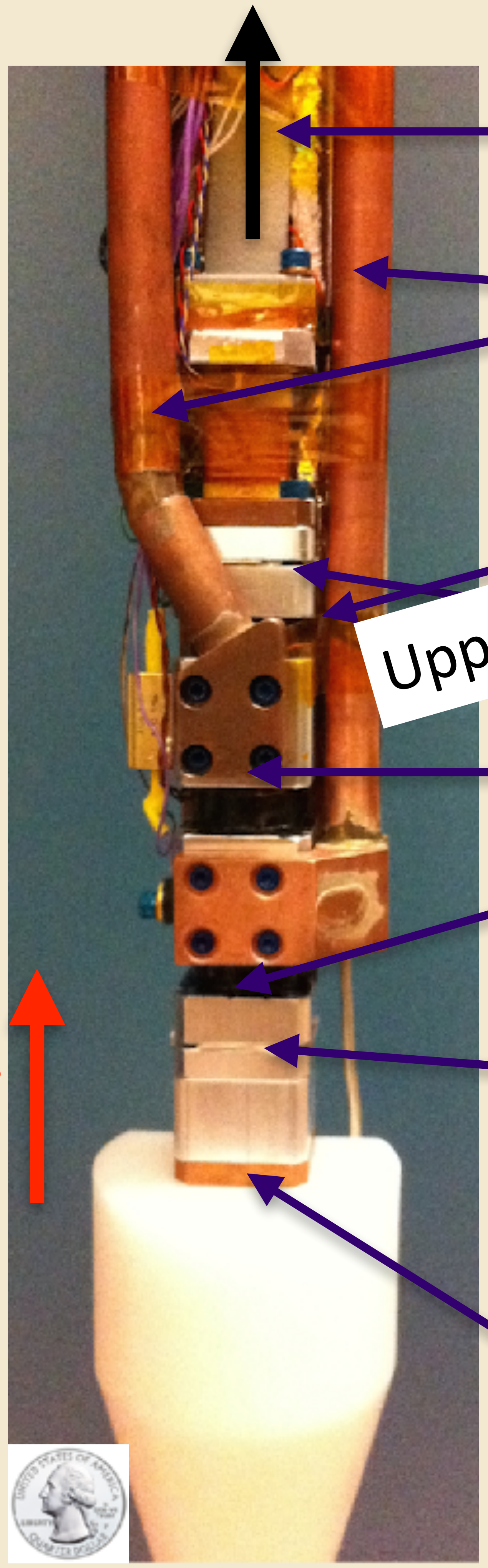
$$\nu_{\mathrm{c}} \approx 27\,\mathrm{GHz} \rightarrow \Delta\nu_{\mathrm{c}} \approx 11\,\mathrm{kHz}$$

Frequency resolution vs. observation time

$$\Delta\nu_{\mathrm{c}} \times t_{\mathrm{obs}} \geq \frac{1}{2\pi} \rightarrow t_{\mathrm{obs}} \geq 14\,\mu\mathrm{s}$$

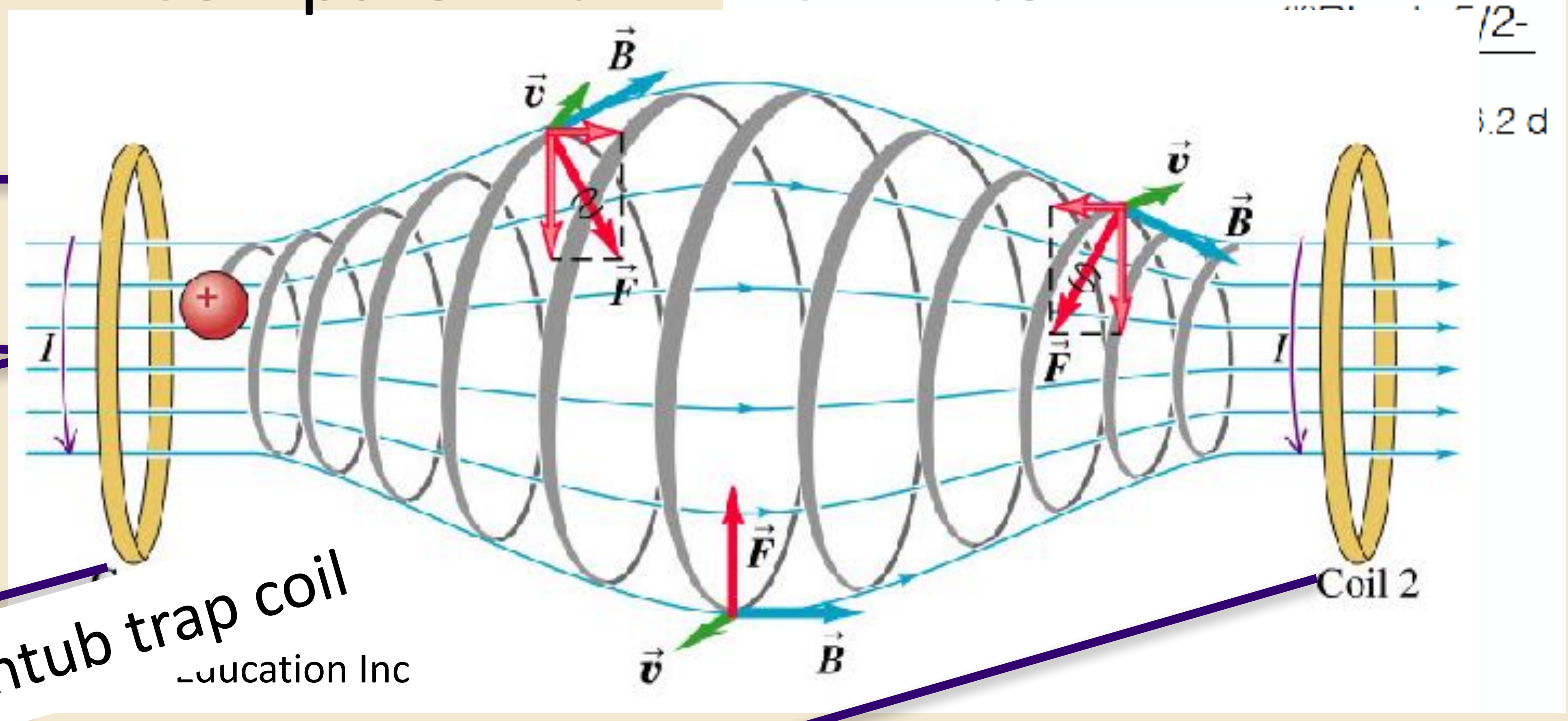
→ Need for a magnetic (no work) trap!

To cryogenic amplifier



1T

Compare with MAC-E filter in KATRIN!



Upper bathtub trap coil

Indium gasket

Gas volume

Lower bathtub trap coil

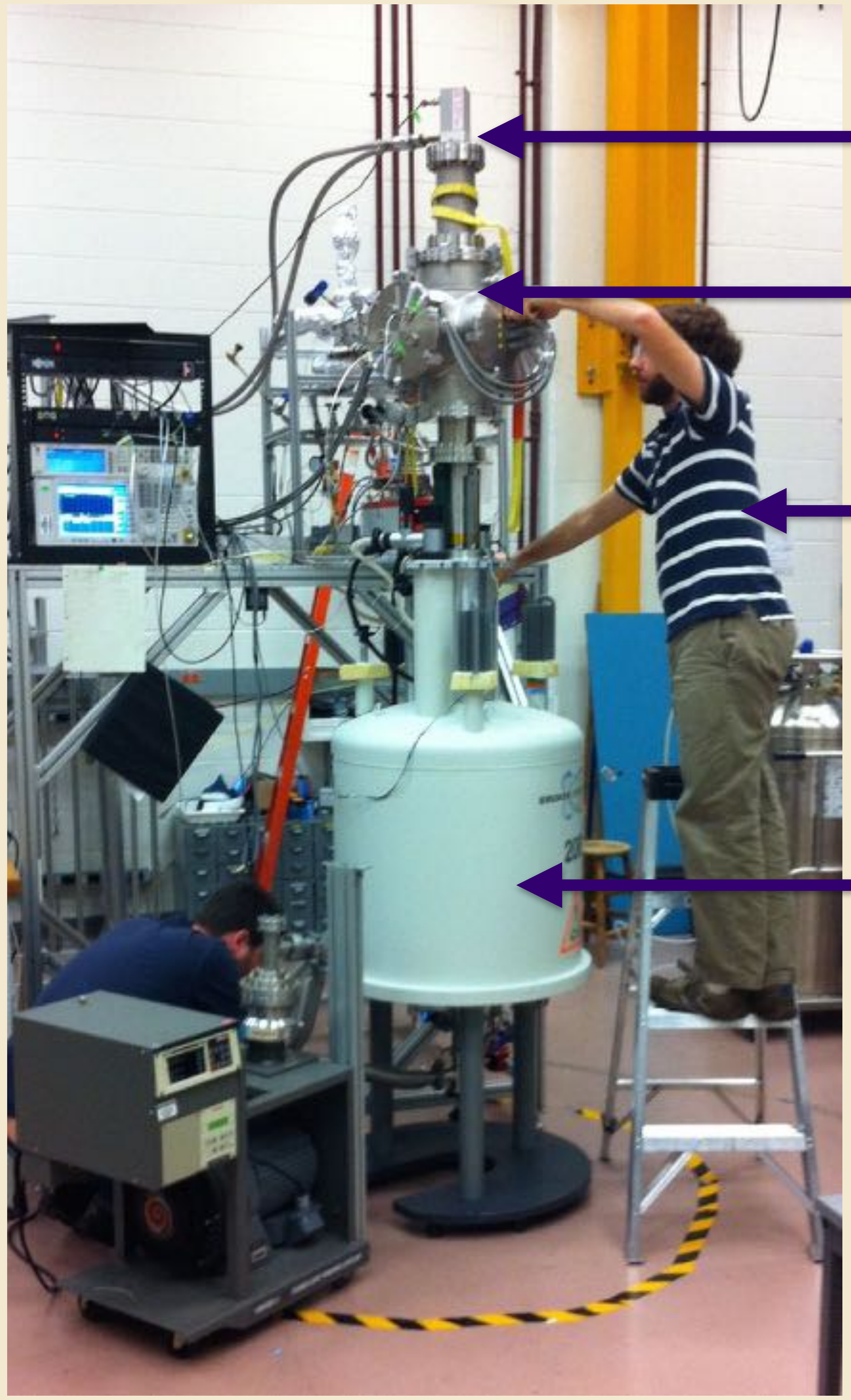
$$\sin\theta_{\mathrm{min}} = \sqrt{\frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}}$$

Lower Kapton window

Indium gasket

WR42 waveguide short

Phase I: A table top demonstrator experiment



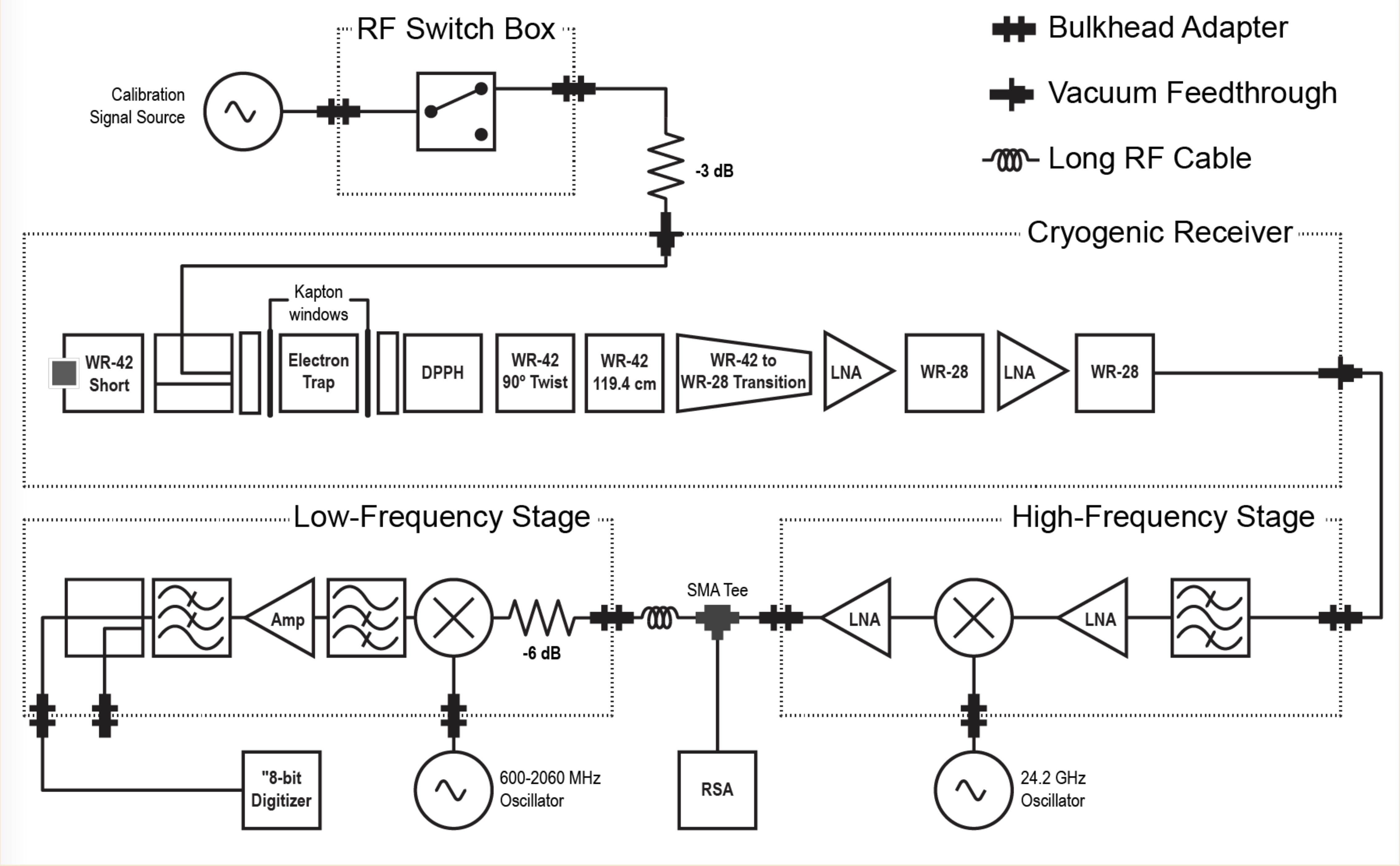
30 K cold head

Low noise cryogenic amplifiers

Ben LaRoque

NMR magnet

Double stage superheterodyne receiver chain:
25.2 GHz ⟶ 1 GHz



The first light in the detector from a single electron

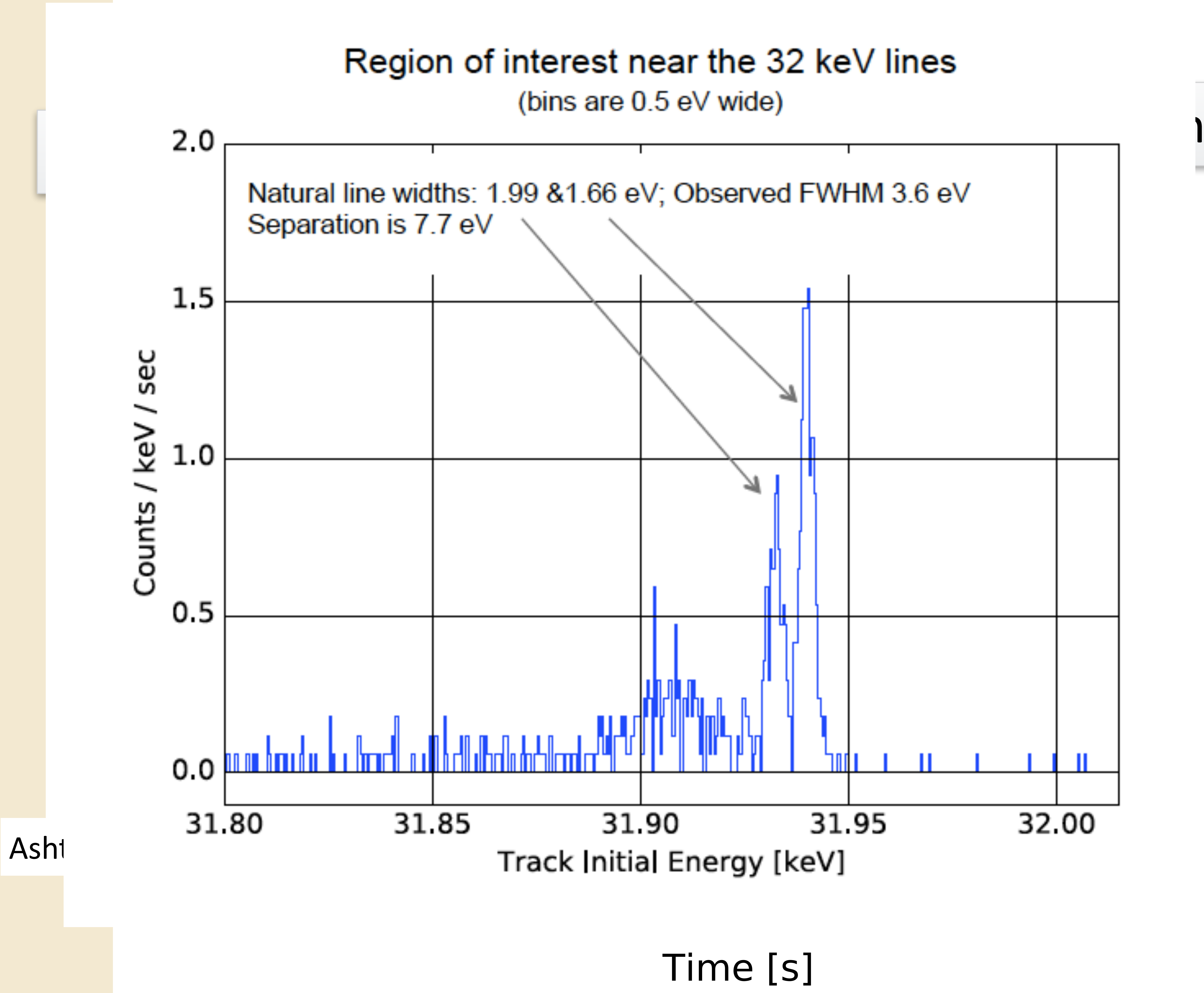
Digitize output of a super-heterodyne mixing stage

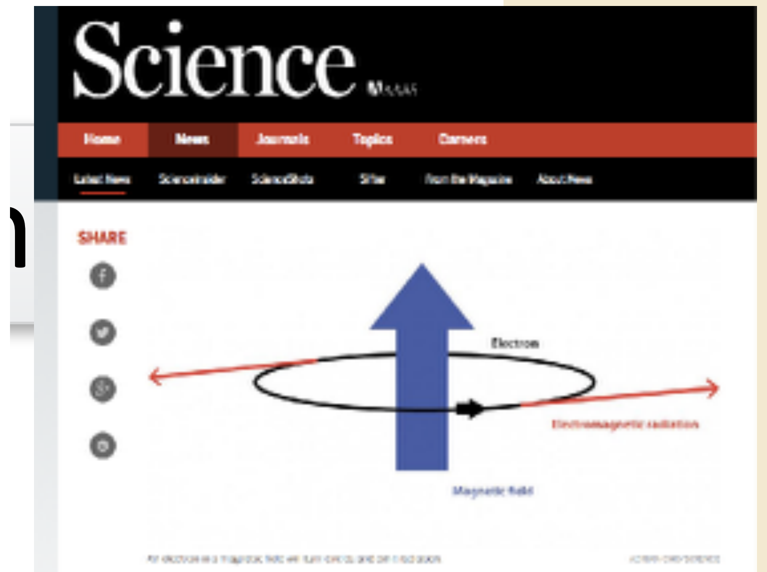
↓

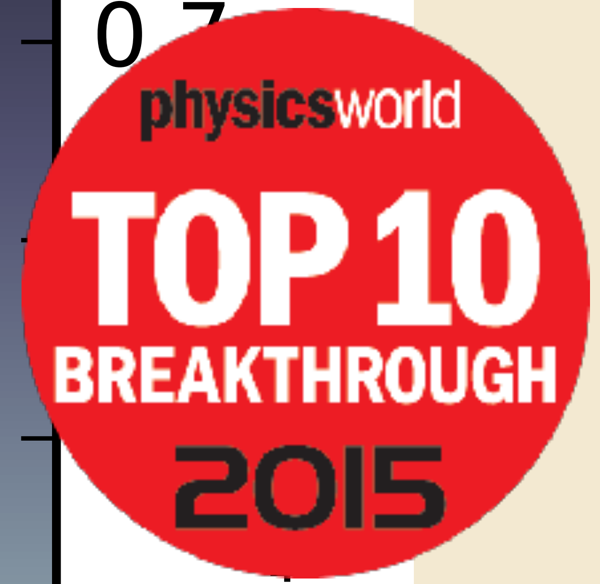
Fourier transform short time slices

↓

Plot power vs. frequency as function of time

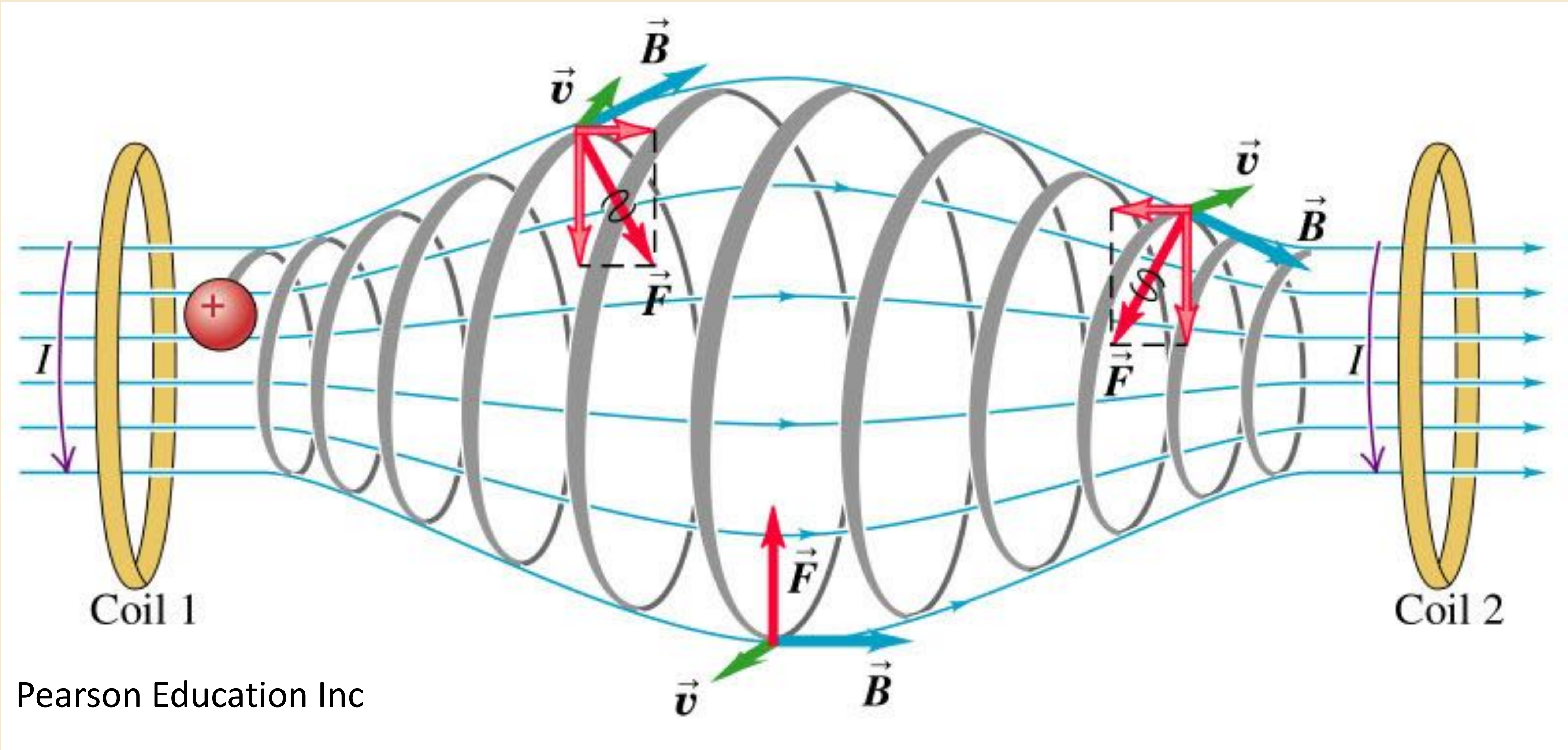




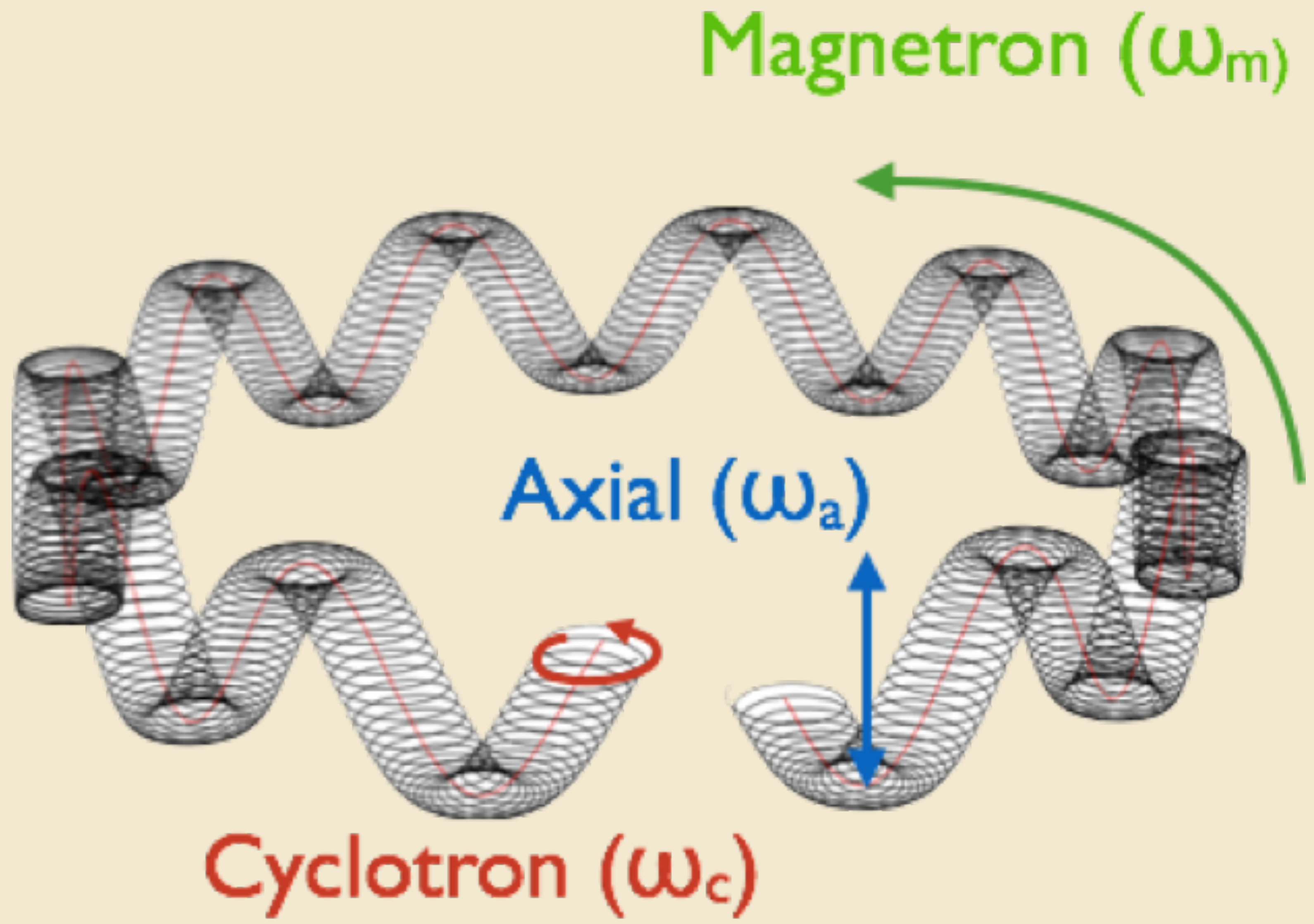


Rich frequency spectrum of raw CRES signal

e^- confinement in magnetic bottle:
→ Non-trivial e^- motion



Similarity to Penning trap with three separated eigenmotions



http://wswww.physik.uni-mainz.de/werth/g_fak/penning.htm

Signal model predicts frequency side bands due to B-modulation and Doppler-effect!

Rich frequency spectrum of CRES signals

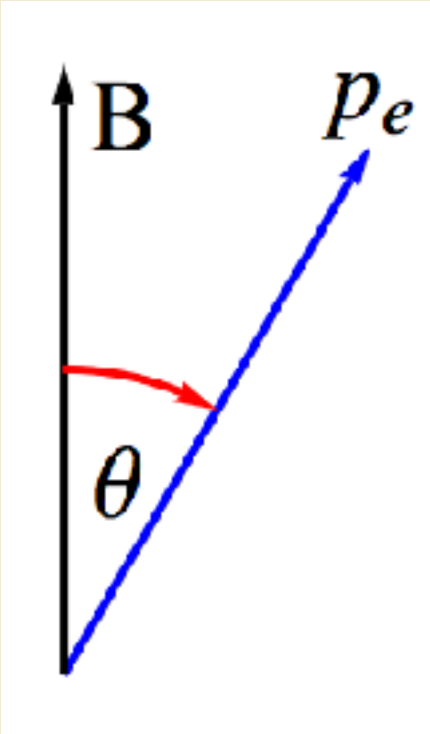
Phase I:
Non-uniform microwave background!

Pitch angle correction

In a harmonic magnetic trap (B ~ z^2) the measured microwave frequency depends on the electron pitch angle:

magnetic field at trap bottom

pitch angle ≅ 90˚



$$\omega_\gamma = \frac{eB}{m + E_{\text{kin}}}\left(1 + \frac{\cot^2\theta}{2}\right)$$

measured microwave frequency

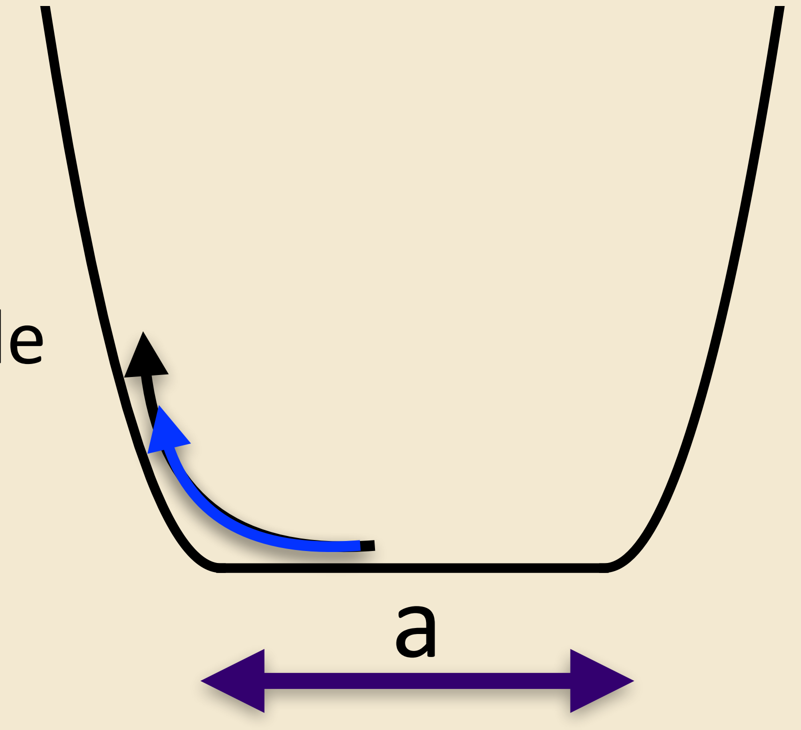
kinetic energy

More details: see talk C. Claessens

Approximate model of the bathtub trap

smaller pitch angle

larger pitch angle



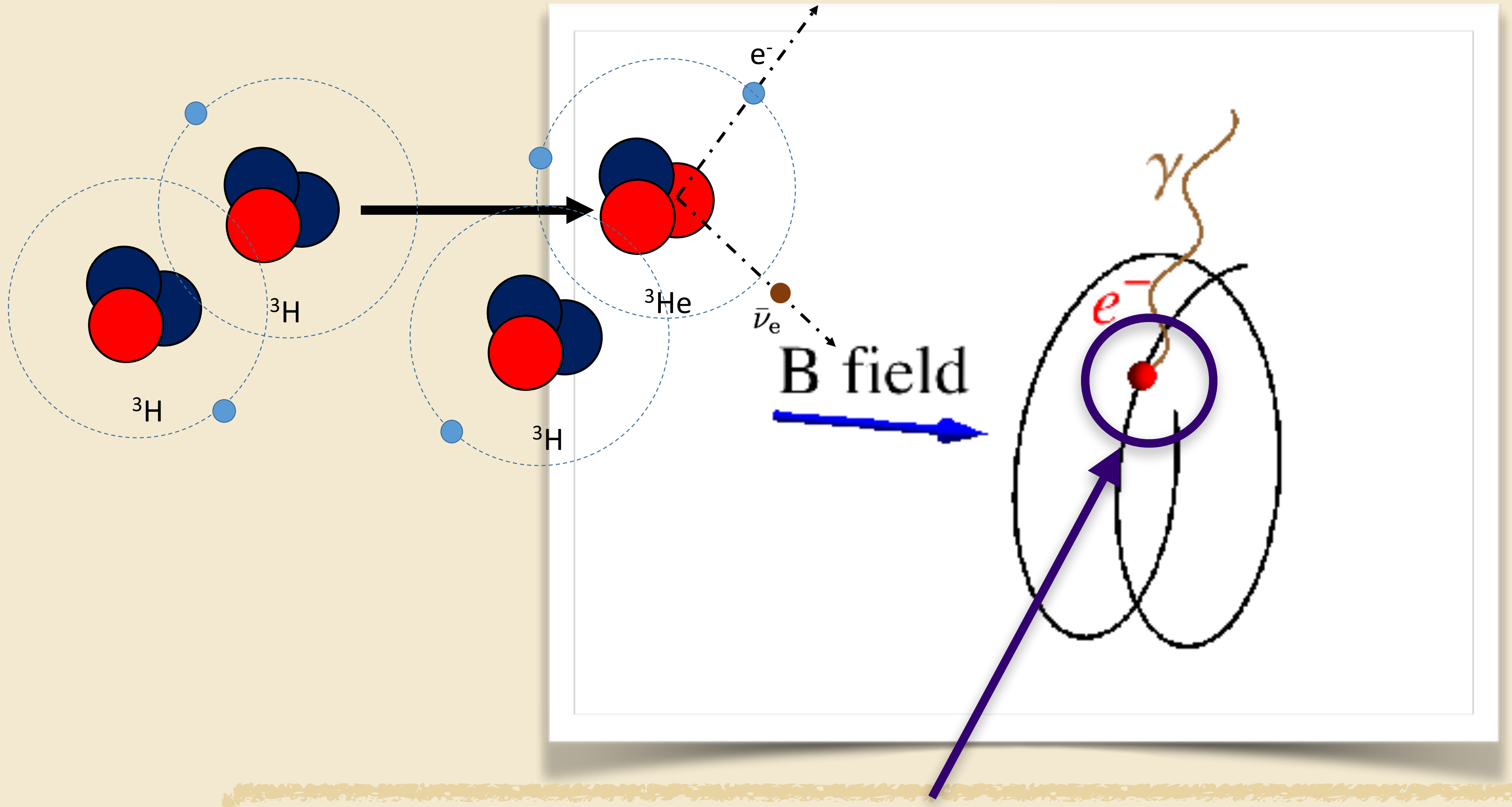
harmonic trap walls

flat bottom of bathtub trap

Approximate expression for axial frequency

$$\omega_{\text{a}} \propto v\left(\frac{a}{\sin\theta} + \frac{4\sin\theta}{m\cos^2\theta}\right)^{-1}$$

Project 8 Phase II: A combined T_2 and ^{83m}Kr source



$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

Source of T_2 decay electrons:

- Safe handling of T_2 gas
- Temperature range: ≅ 80-300 K
- Fine T_2 pressure regulation
- 10^{-9}-10^{-5} torr operation pressure
- Gas composition measurements

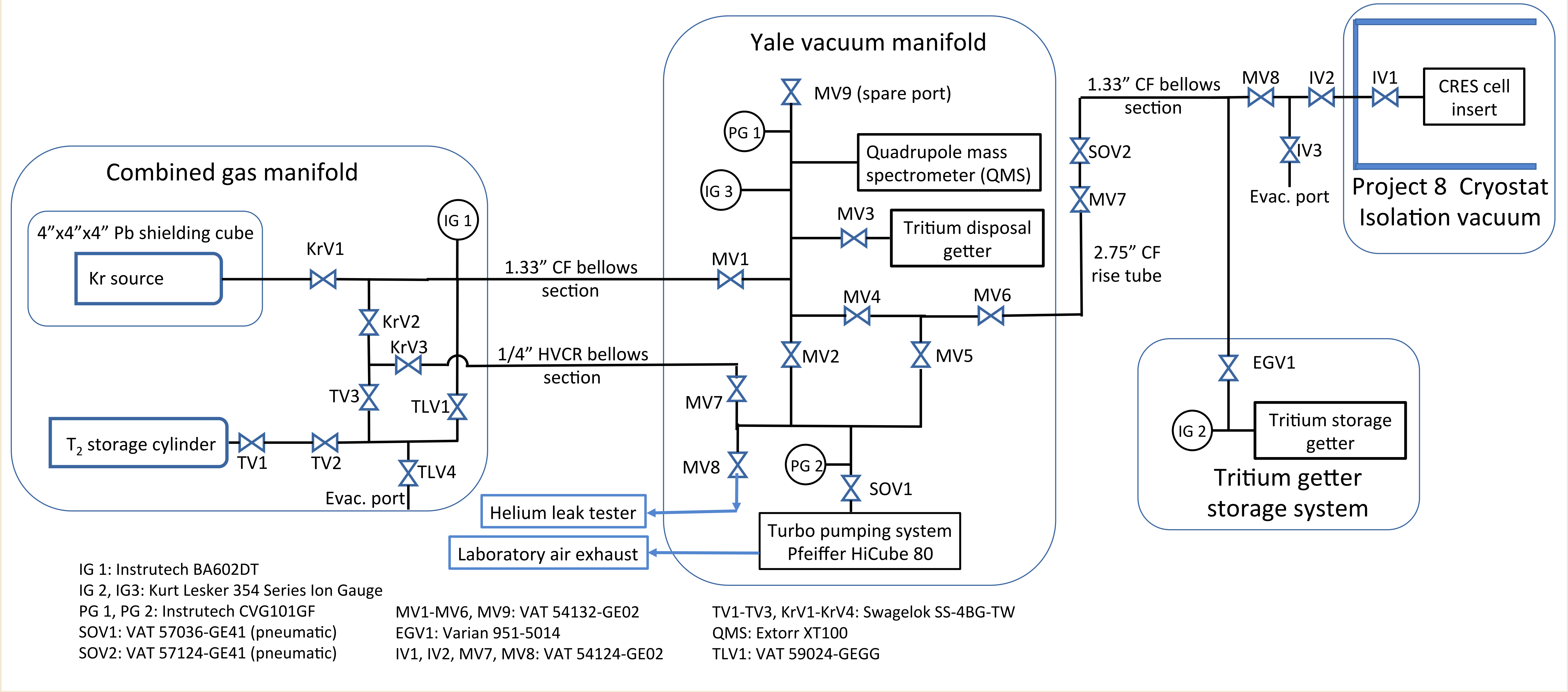
Source of ^{83m}Kr conversion electrons:

- ^{83m}Kr CE energies well known
- Matching CE energy range 9 - 32 keV
- B field long term stability
- ^{83m}Kr goes where T_2 goes (co-magnetometer)

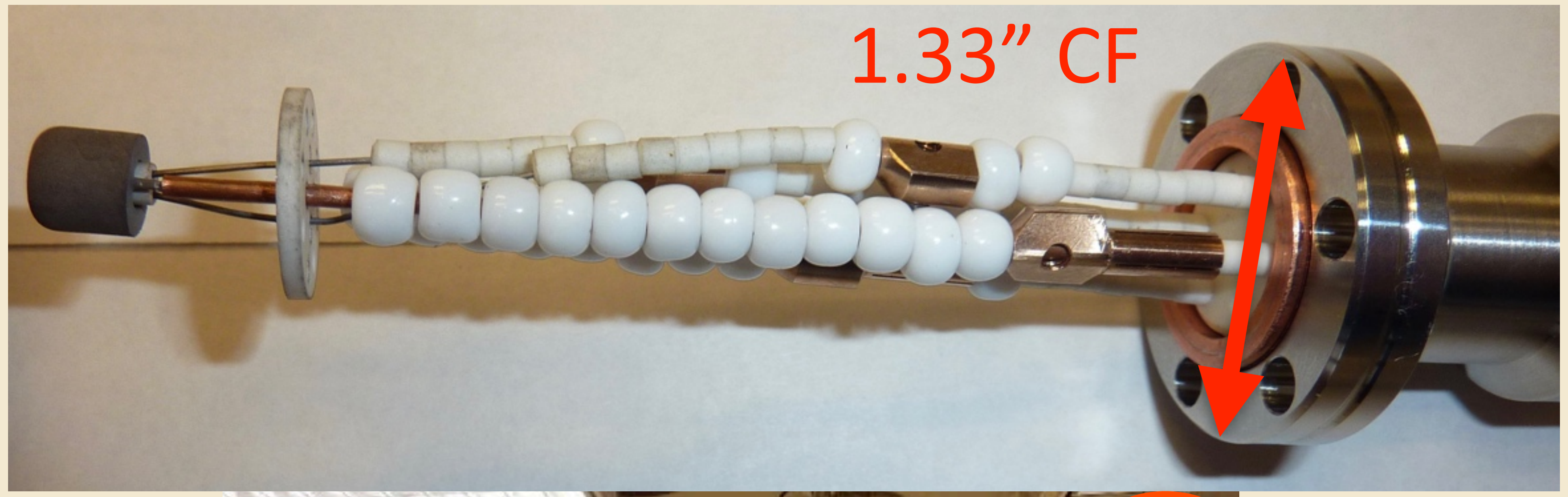
Tritium storage in metal getter

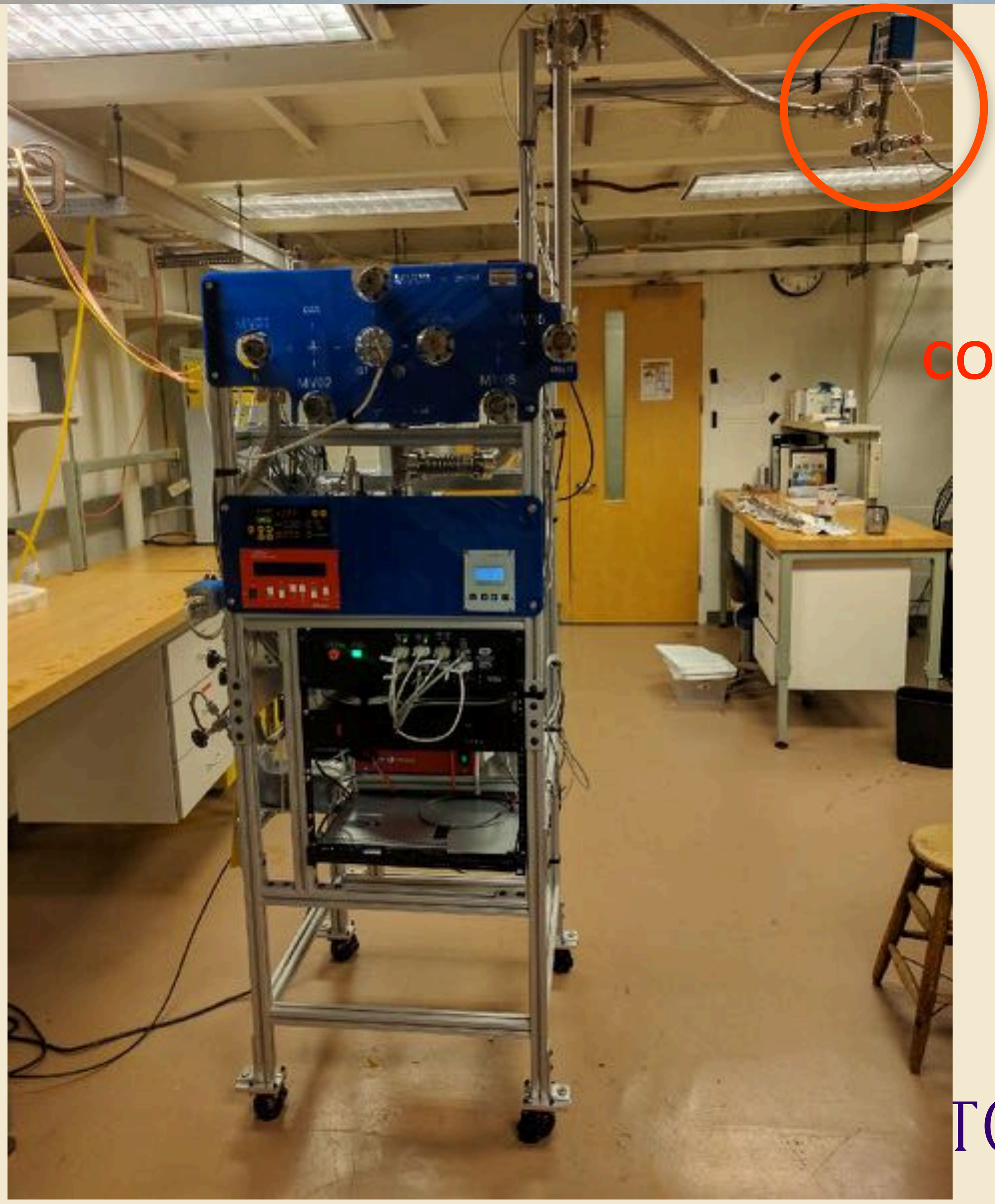
Successfully tested the loading and release of D_2 from a SAES St172 getter sample (together with KIT):

- Continuous pumping of H_2, CO, CO_2, H_2O, CH_4
- Simple pressure regulation
- Expect similar behavior for T_2
- Recapture T_2 at room temperature



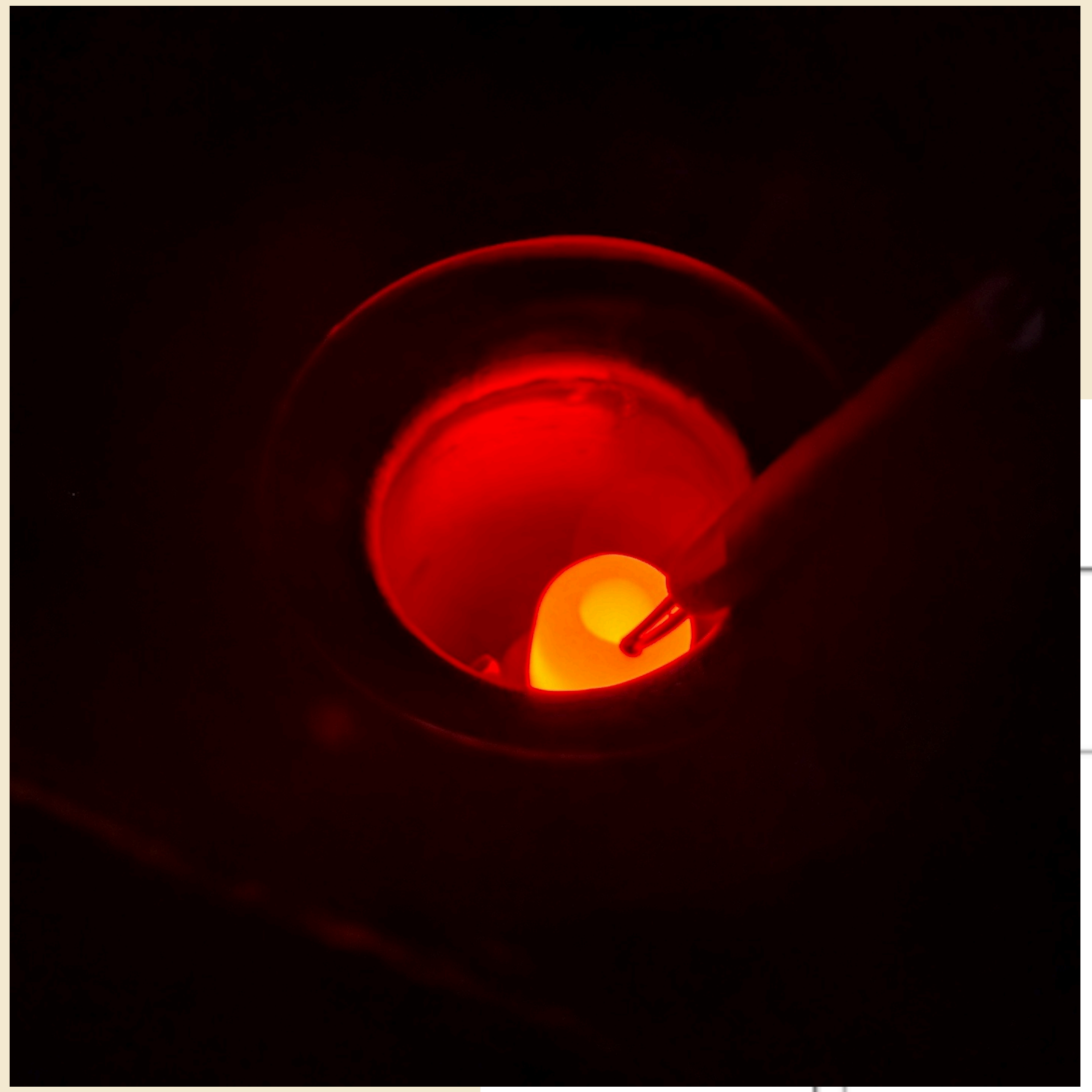
Compact T_2 reservoir built and commissioned @ UW

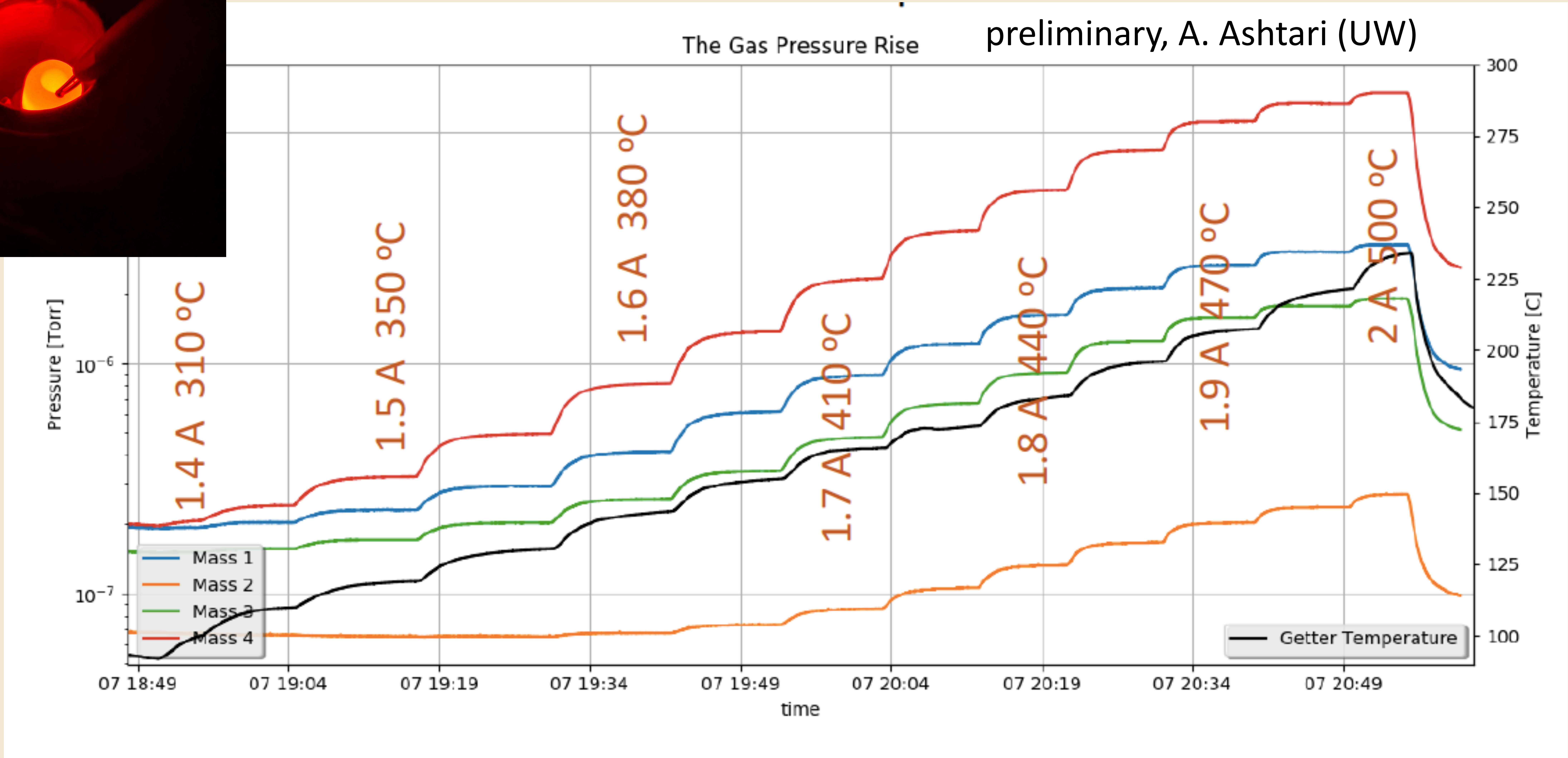




Getter compartment

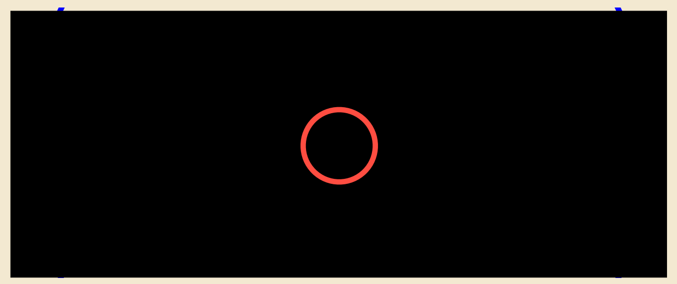
Tritium storage in metal getter





Project 8 Phase II: T_2 compatible CRES cell

Phase I: WR42



0.170” (4.3 mm)

0.420” (10.7 mm)

Technical challenges for a T_2 compatible CRES cell

1. Transport circularly polarized radiation.
2. Larger volume!
3. Low-loss microwave guide!
4. No ferromagnetic construction material.
5. Hermetic confinement of T_2 gas
6. Low loss microwave transparent windows
7. Cryogenic operation
8. Matched thermal expansion coefficients

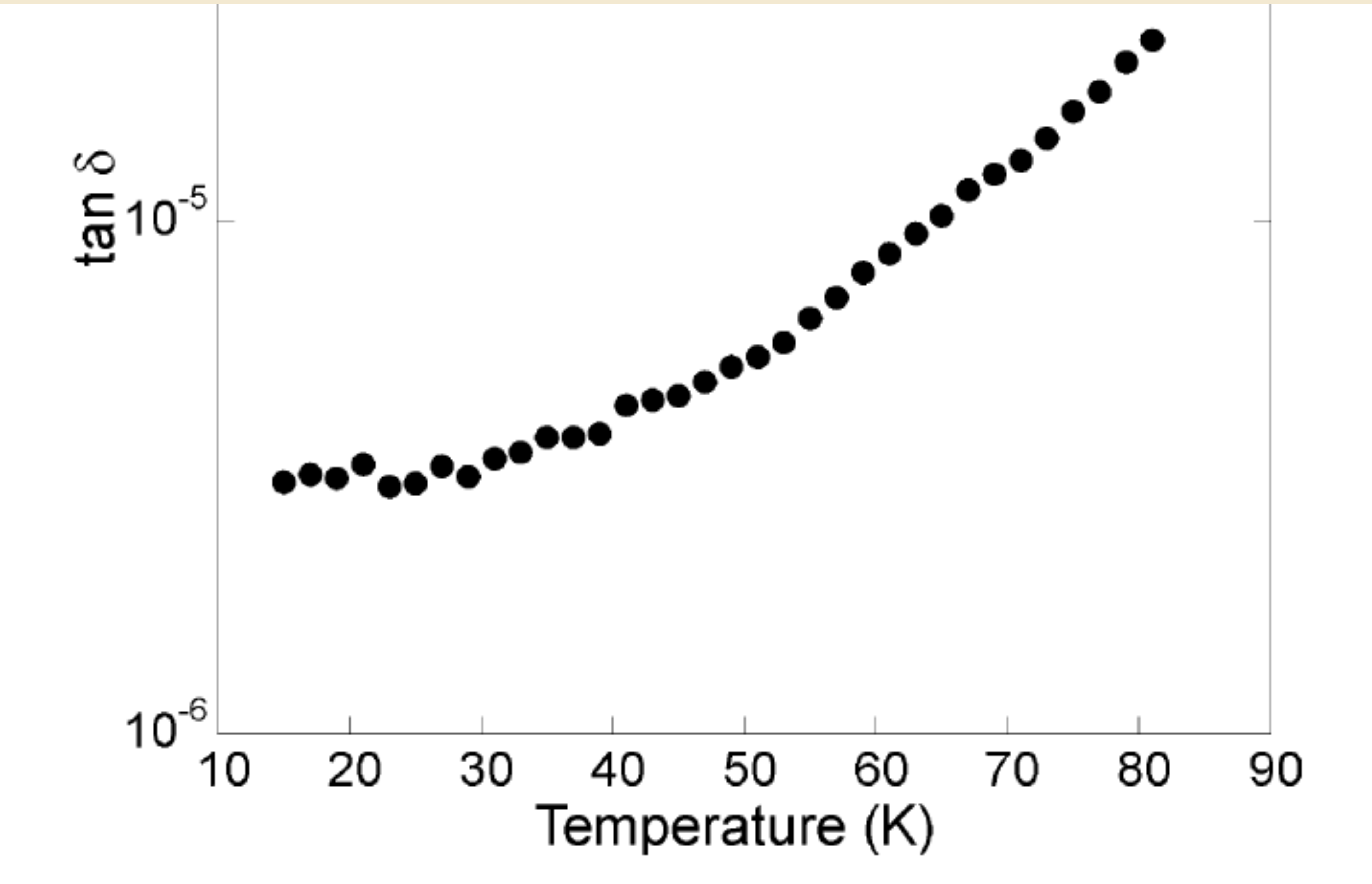
Oxygen-free high-conductivity copper

No organic (kapton) window materials!

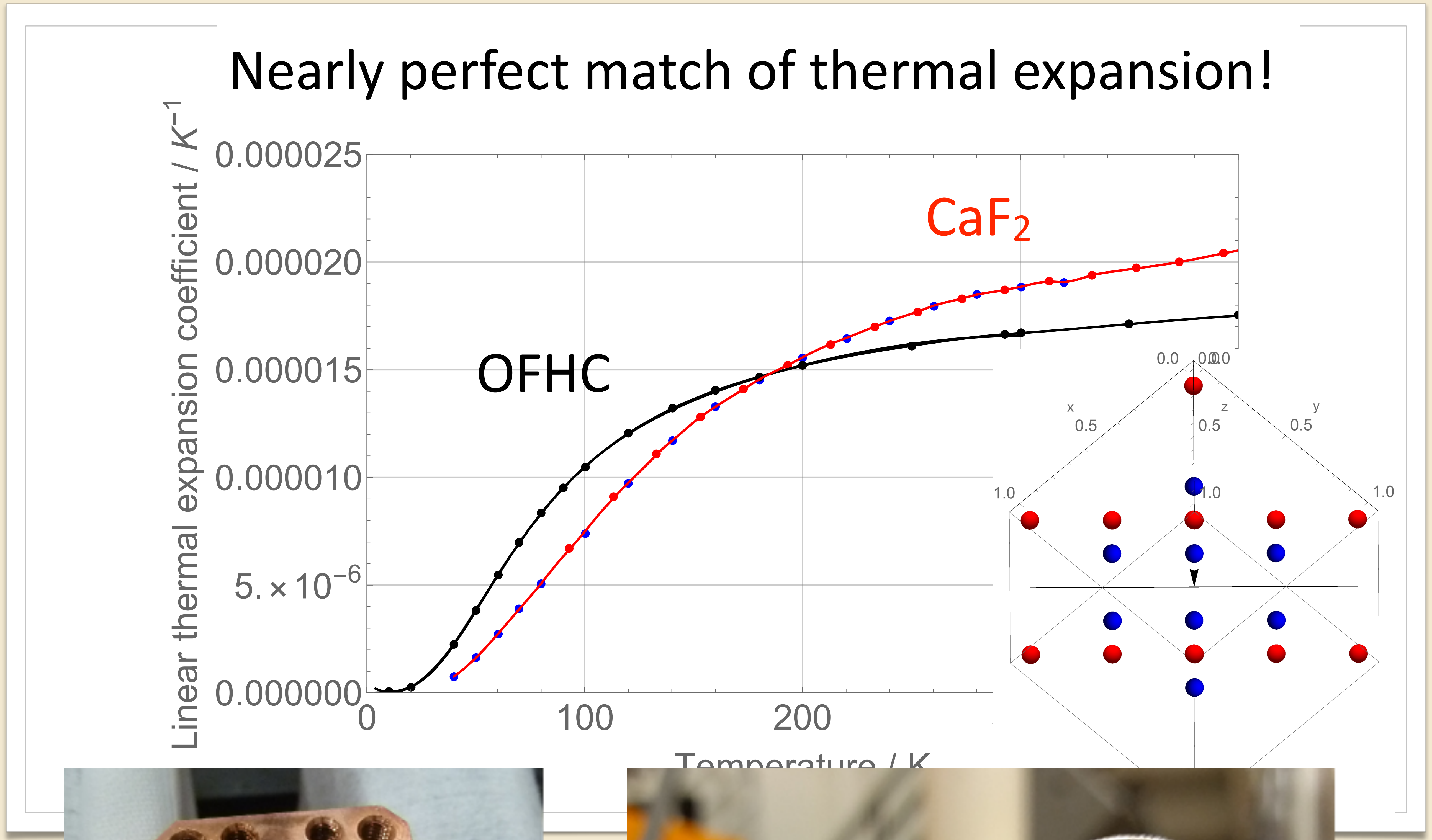
Calcium difluoride windows, indium sealed

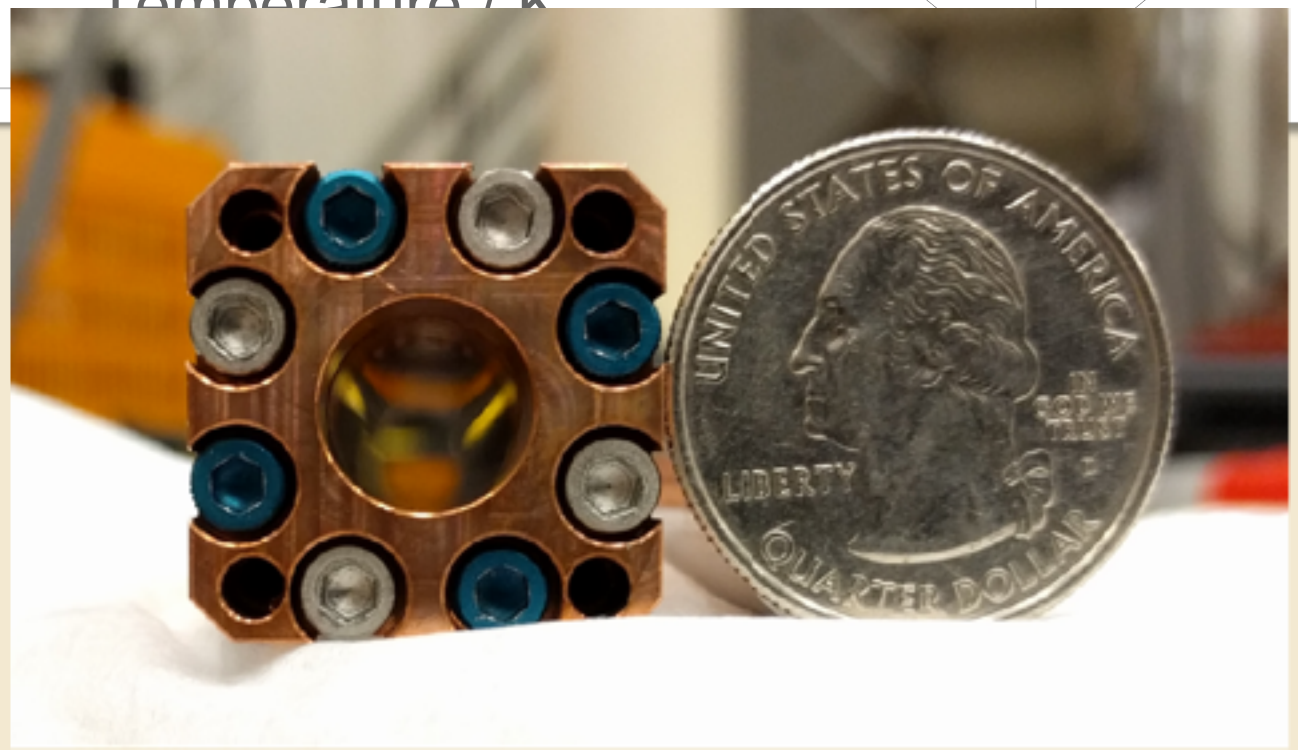
CaF_2 windows are ideal but very brittle!

CaF_2 window material:
+ Low loss tangent (low absorption loss)
+ Isotropic crystal properties
+ Small dielectric constant (low reflections)
- Very soft and brittle

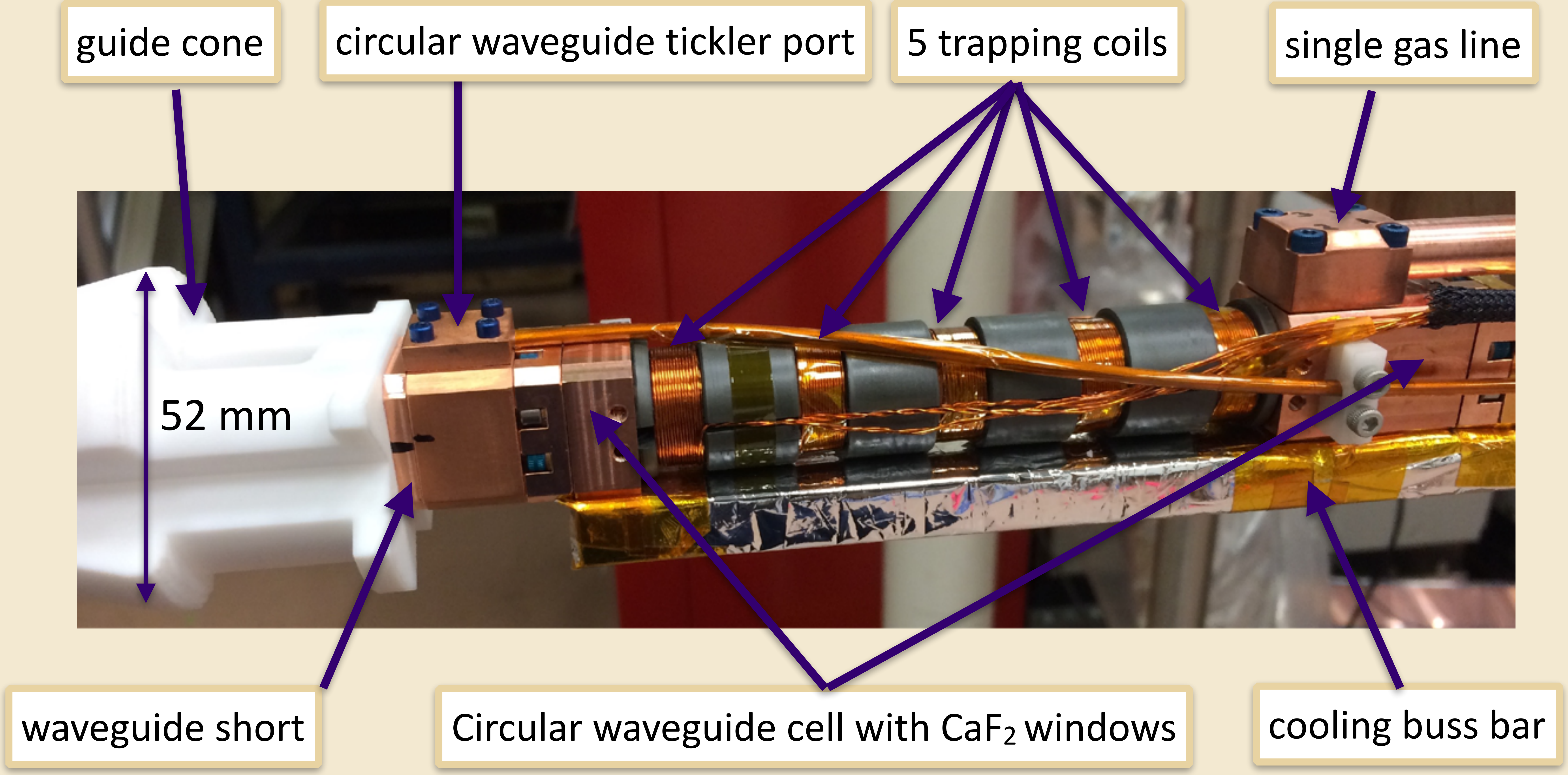


M. Jacob et al., J. of the Europ. Ceramic Society 23 (2003); 2617





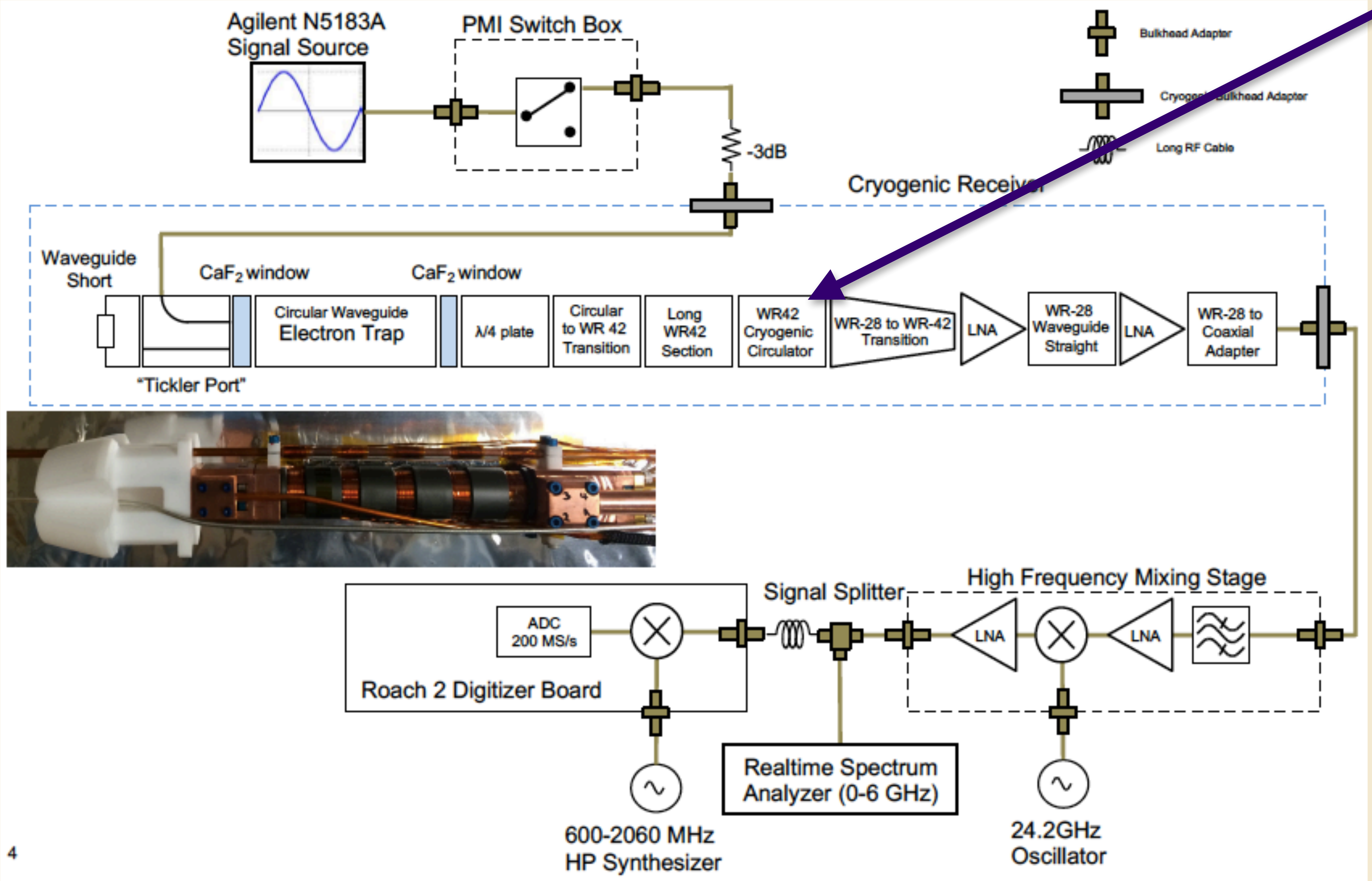
The Phase IIa CRES cell before installation



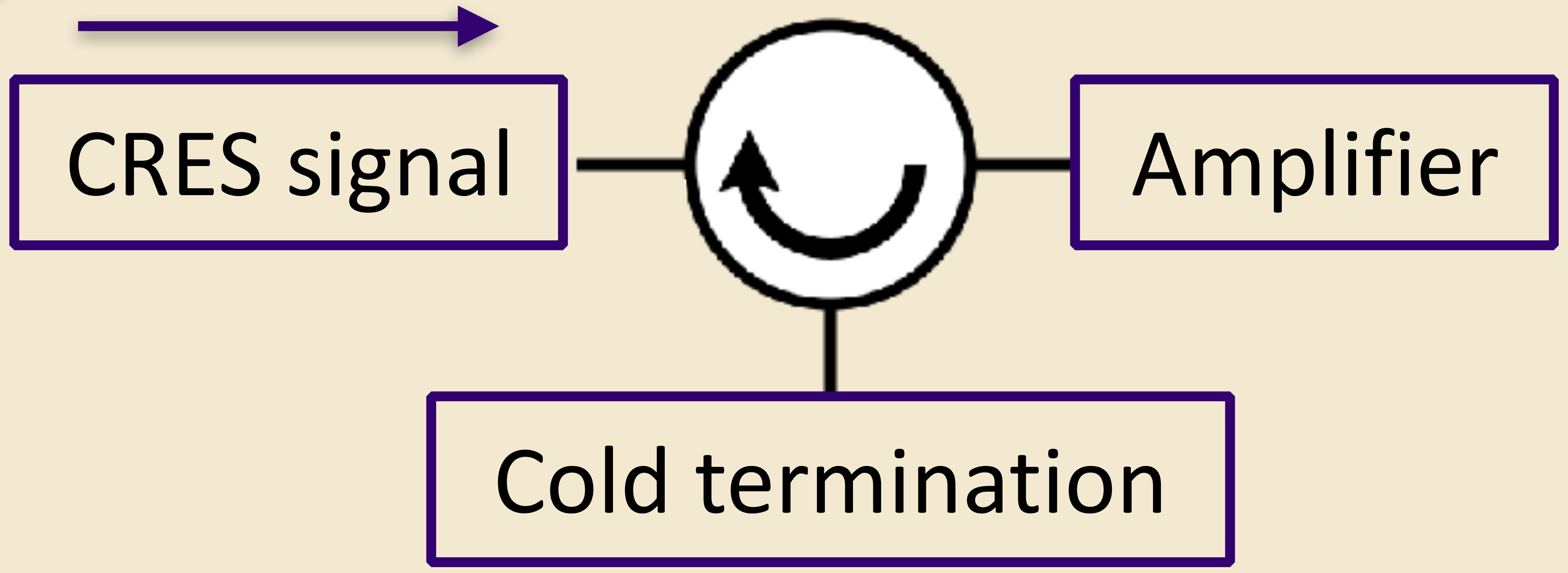
Successful CRES cell operation:
- Commissioning with ^{83m}Kr
- 50-300 K cell temperature

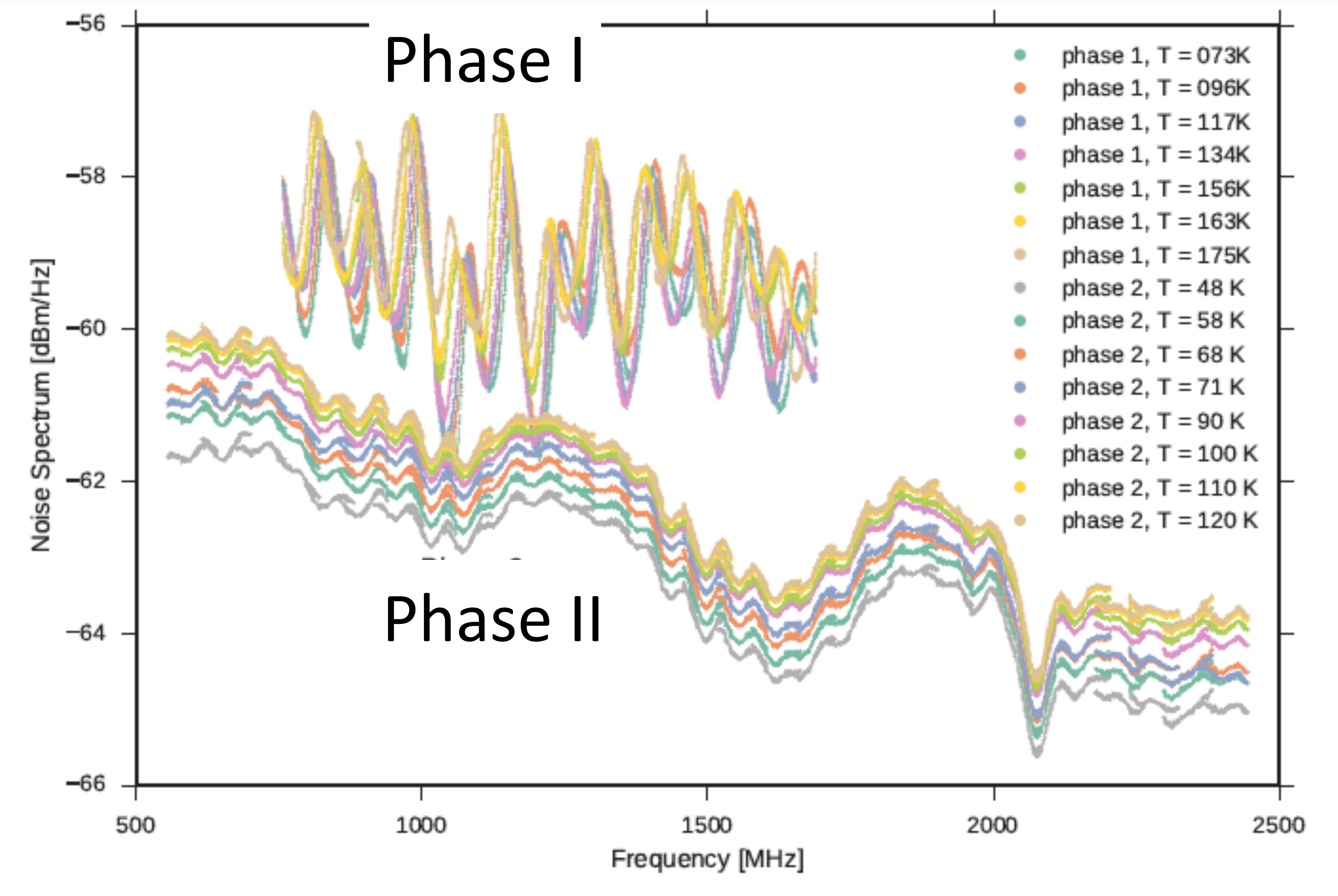
To be used with T_2 gas after late fall 2017!

Upgraded microwave infrastructure



Cryogenic circulator





Typical CRES signals live

17.8 keV electrons, realtime x20

lower energy ⇨

Video removed for web version

ongoing commissioning with ^{83m}Kr

DAQ Phase II upgrade and the path towards Phase III

Multichannel, scalable DAQ system update for Phase II based on ROACH:

- **R**econfigurable **O**pen **A**rchitecture **C**omputing **H**ardware
- Widely used in radioastronomy
- Based on Xilinx Virtex 5 FPGA
- Project 8 is currently commissioning a 3 channel version

see C. Claessens (Thursday)

ROACH

Increase T_2 gas volume for Phase III:
larger magnetic field volume,
free space antenna array

see S. Boeser's talk (Thursday)

Summary

Project 8:

- Phase I: 1st direct observation of cyclotron radiation from a single electron
- Phase I: Successfully measured ^{83m}Kr spectrum using CRES
- Phase II: Operation of a T_2 compatible CRES cell initially with ^{83m}Kr
  Combined T_2 and ^{83m}Kr gas system built and operation approved
  First T_2 CRES measurement later this fall
- Phase III+IV: R&D program concurrent with Phase II

Thank you!

Acknowledgments

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Case Western Reserve University
Sebastian Böser, Christine Claessens, Alec Lindman
Johannes Gutenberg Universität, Mainz
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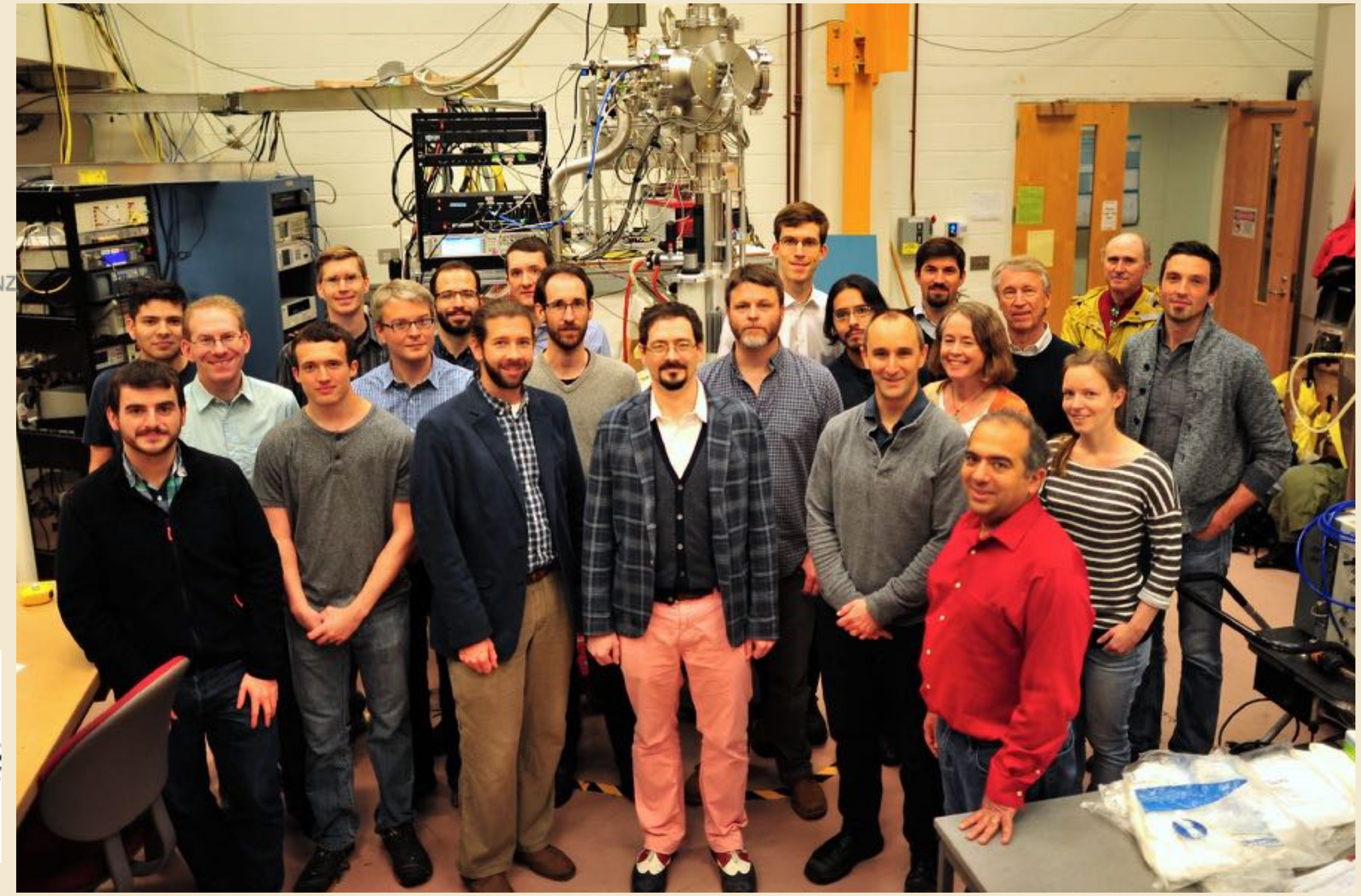

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