Project 8

Towards a radio-frequency measurement of the neutrino mass

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KSETA plenary workshop | Durbach | September 28th 2021

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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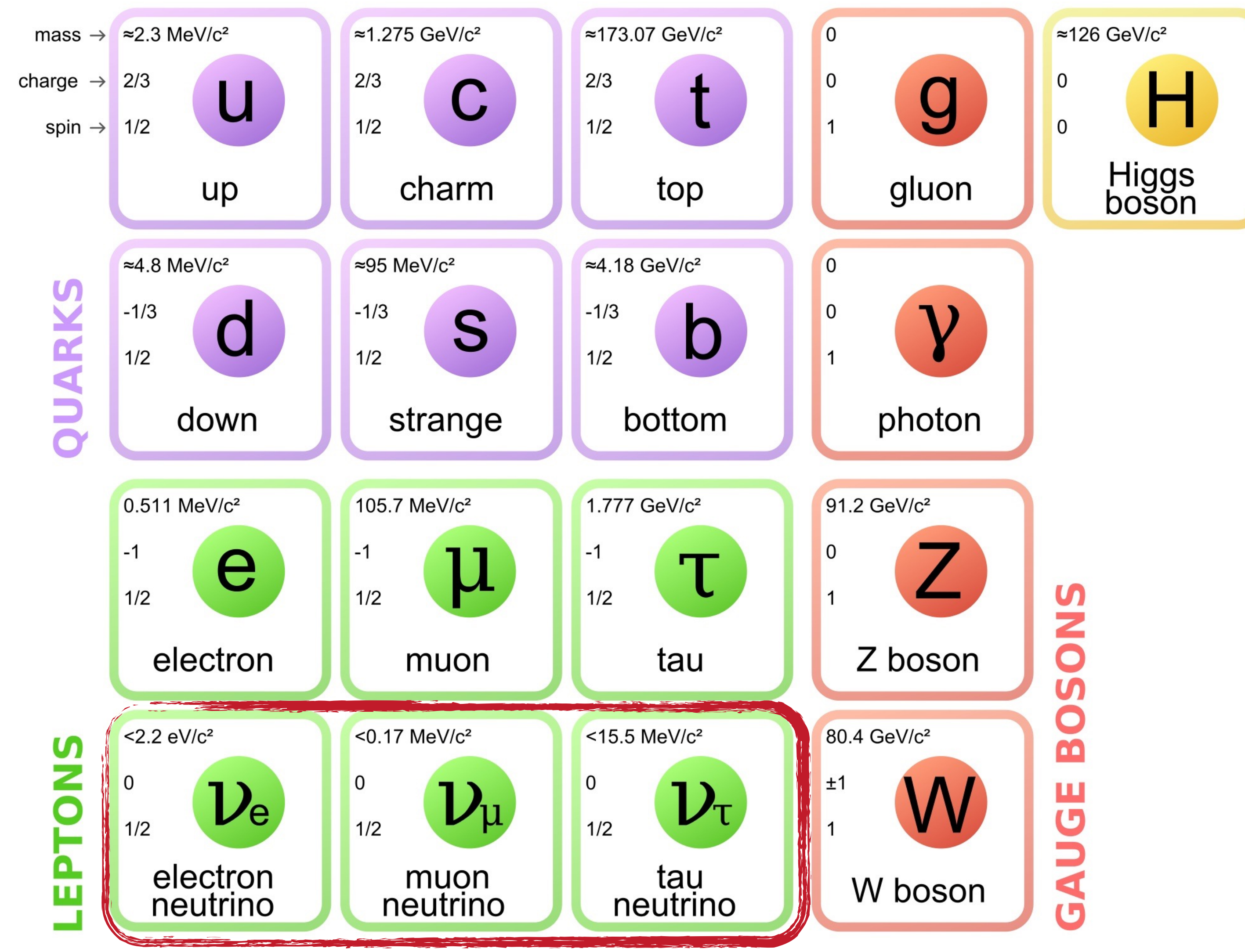
Neutrinos in the standard model

Fact sheet

- only fermions
  without charge
- interact only with
  weak force
  - very low event rates
- neutrinos are **left-handed**
  - Goldhaber experiment
- massless...?
  - neutrino oscillations!
    → $\Delta m^2 > 0$



T. Kajita A.B. McDonald

Nobel price 2015

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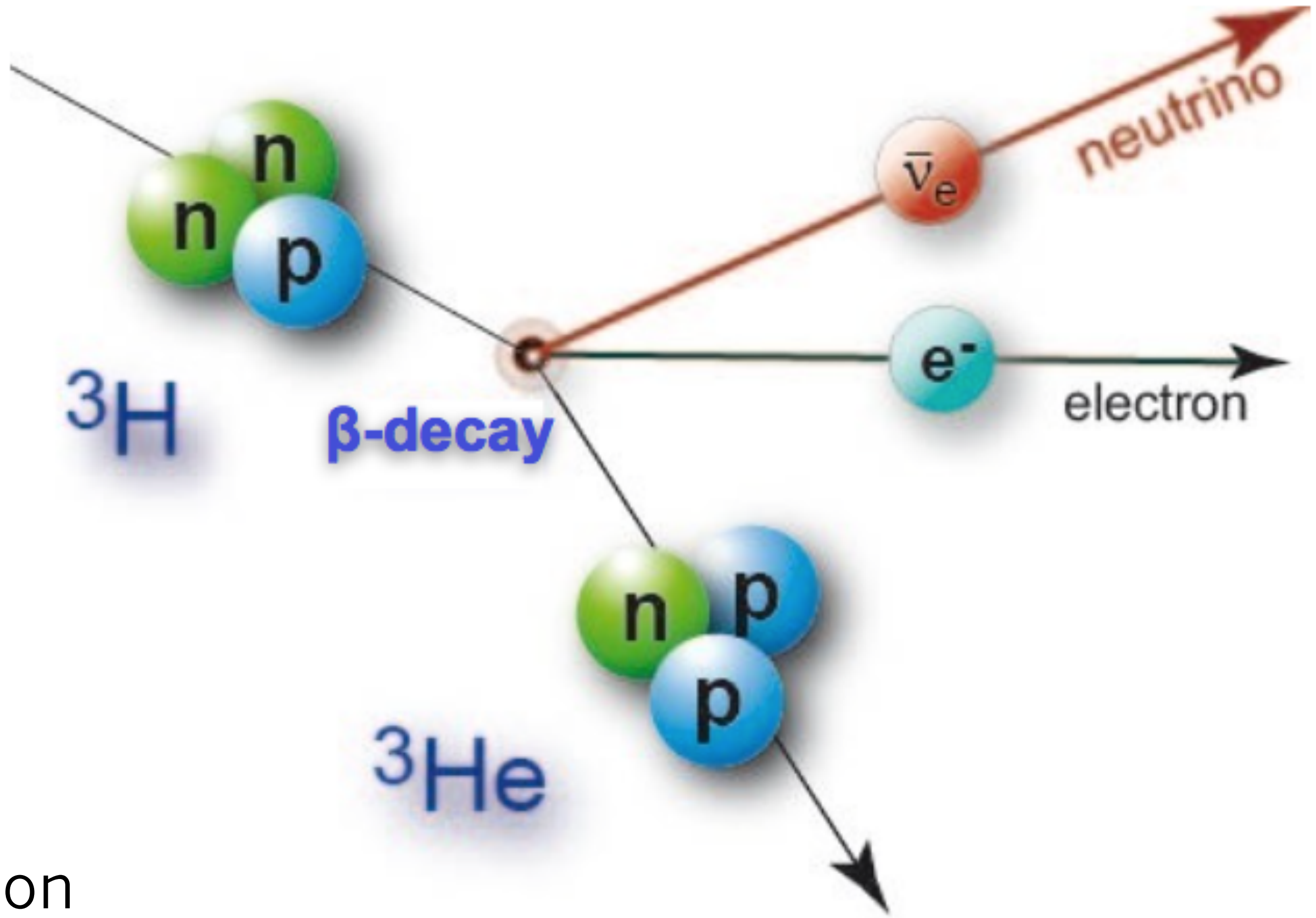
β-decay of tritium



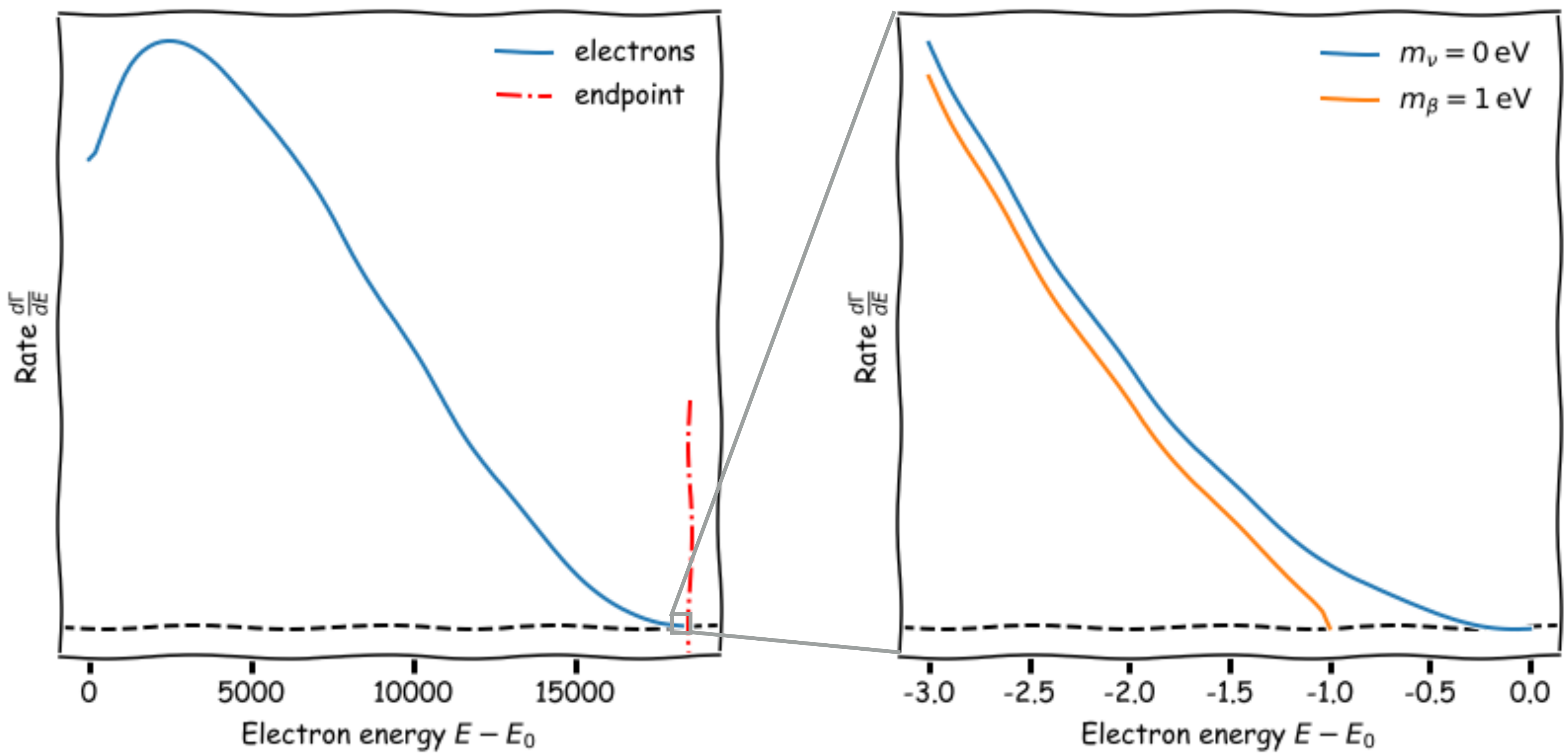
Energy conservation

- sum of rest masses and kinetic energy
  - initial mass of ^{3}H nucleus

Momentum conservation

- electron energy maximal when neutrino at rest
  - $p_\nu = 0 \rightarrow$ solve for m_ν

Tritium β-spectrum



End-point of spectrum depends on neutrino mass

$$\frac{dN}{dE} \sim F(Z,E)p_e(E+m_e)\sqrt{(E-E_0)^2 - m_\beta^2)}$$

- direct measurement of *electron* neutrino mass m_β ???

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Mass of the electron neutrino ?!?

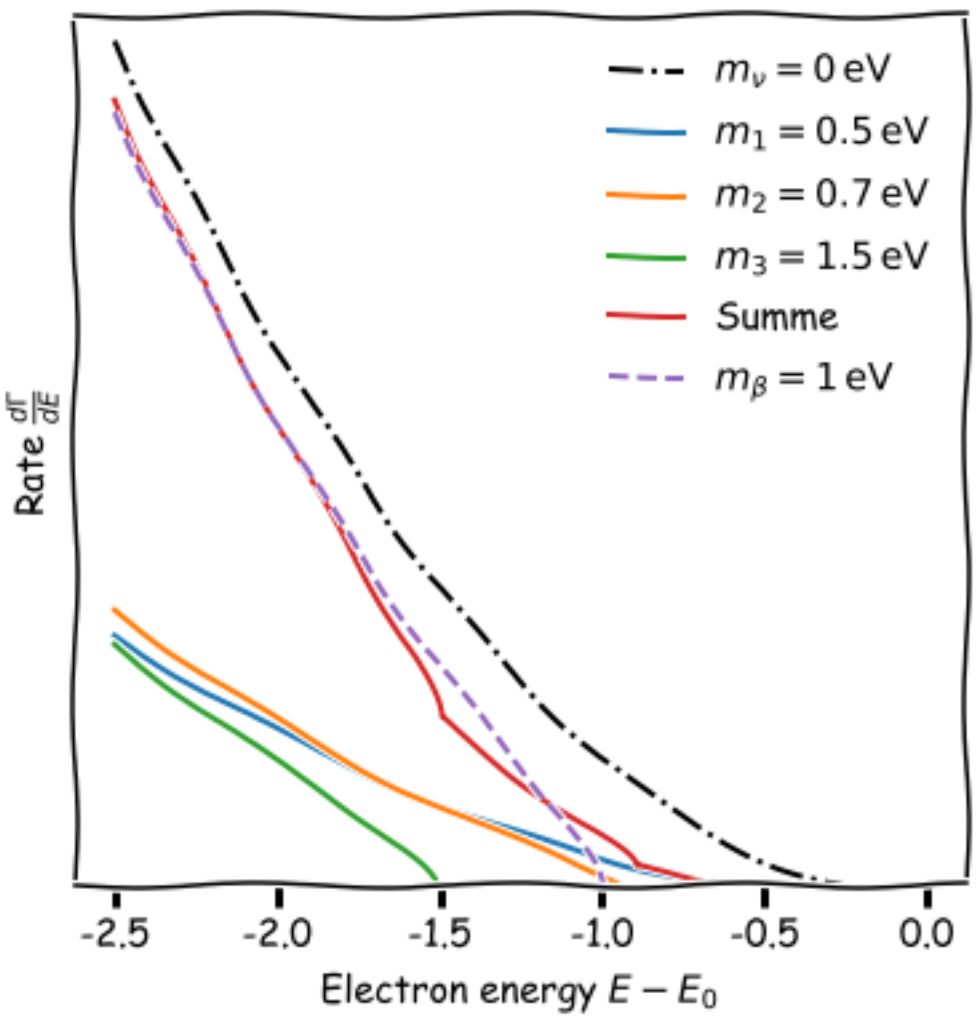
Electron neutrino

- super-position of mass eigenstates

$$|\nu_e\rangle = \sum_i^{n_\nu} U_{ei}|\nu_i\rangle$$

Kinematik of β-decay

- energy- & momentum conservation
  - only apply to mass eigenstates
  - kinks in the spectrum

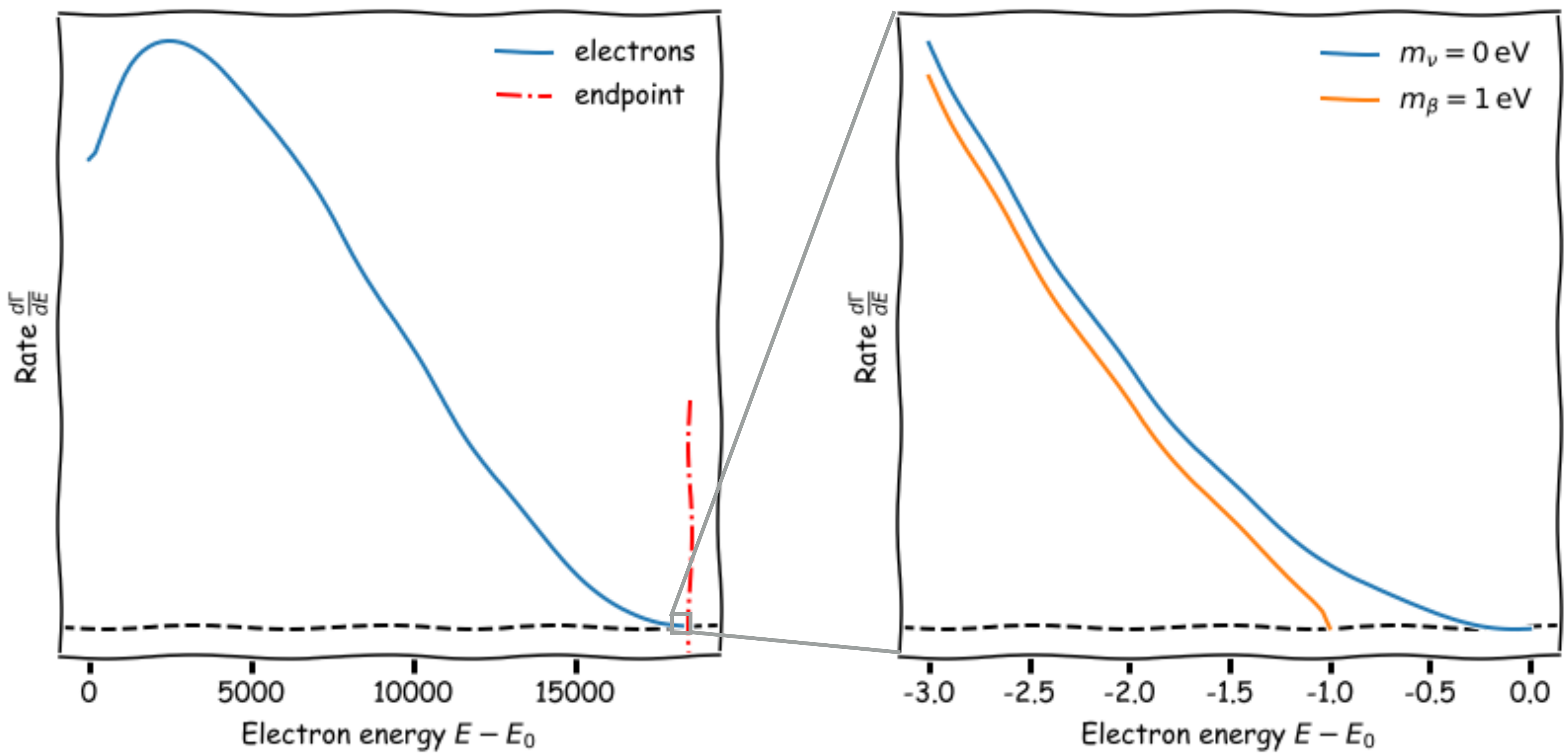


Experimental resolution

- not sufficient
  - define effective neutrino mass

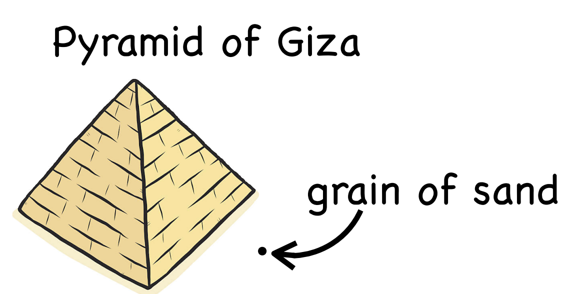
$$m_\beta^2 = \sum_i^{n_\nu} \left|U_{ei}{}^2\right| m_i^2$$

β-decay experiment



Fraction of electrons im range of interest

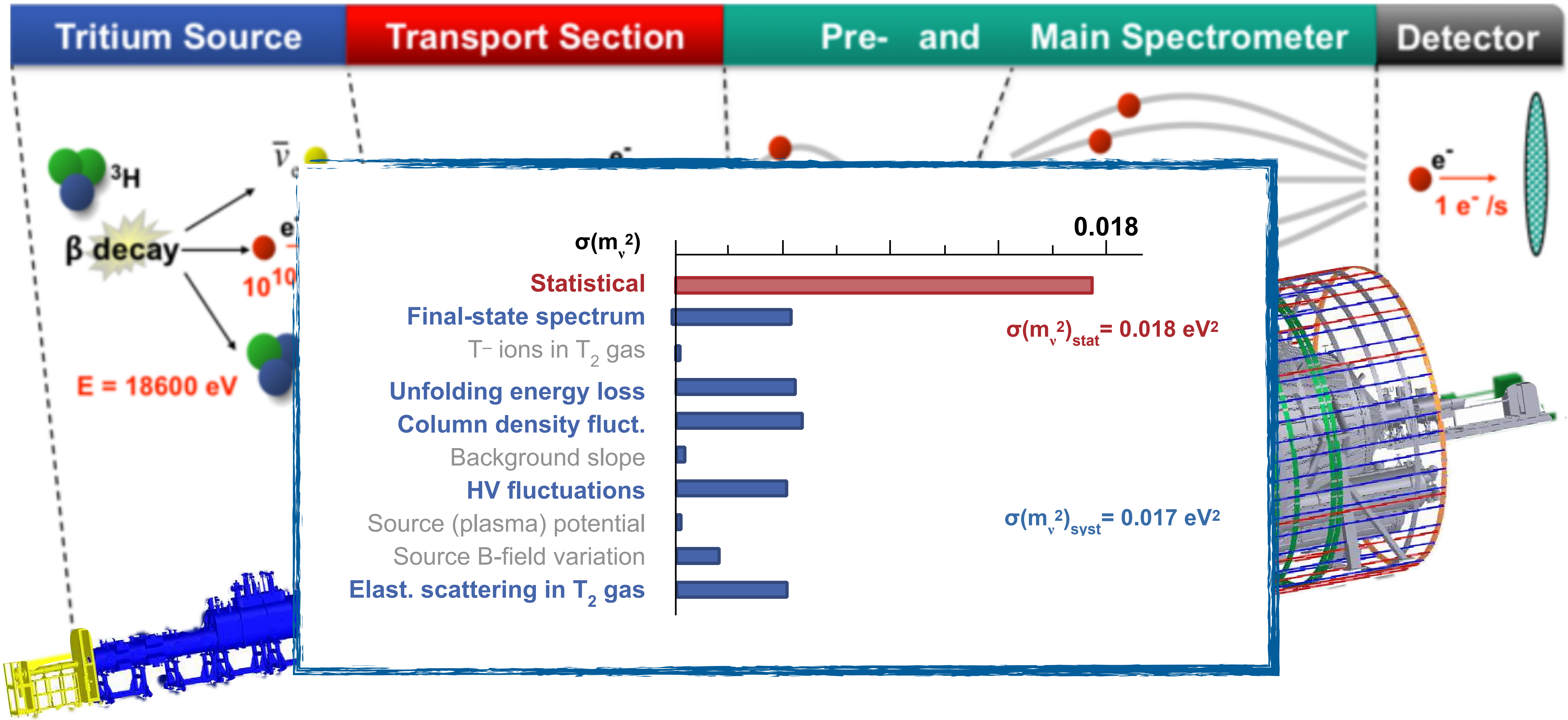
- last 10eV: $2 \cdot 10^{-10}$
- last 1eV: $2 \cdot 10^{-13}$



Experimental requirements

- extremely high statistics
- very good energy resolution

State of the art — KATRIN



Key components

- windowless gaseous tritium source (T_2) → statistic
- MAC-E spectrometer (10m diameter!) → resolution

Alternative approach

Electron in B-field

- cyclotron radiation

$$f_c = \frac{1}{2\pi}\frac{eB}{m_e}$$

First-order relativistic correction

$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}}$$

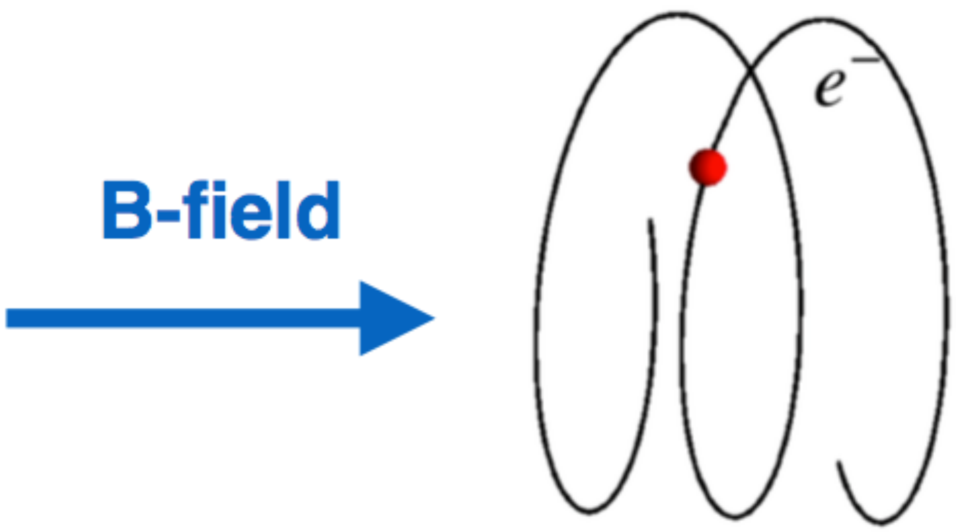
- ▸ energy measurement!

Energy resolution $\Delta E/E \sim \Delta f/f$

- ΔE/E ~ 0.1eV / 18.6 keV = 5ppm → easy!

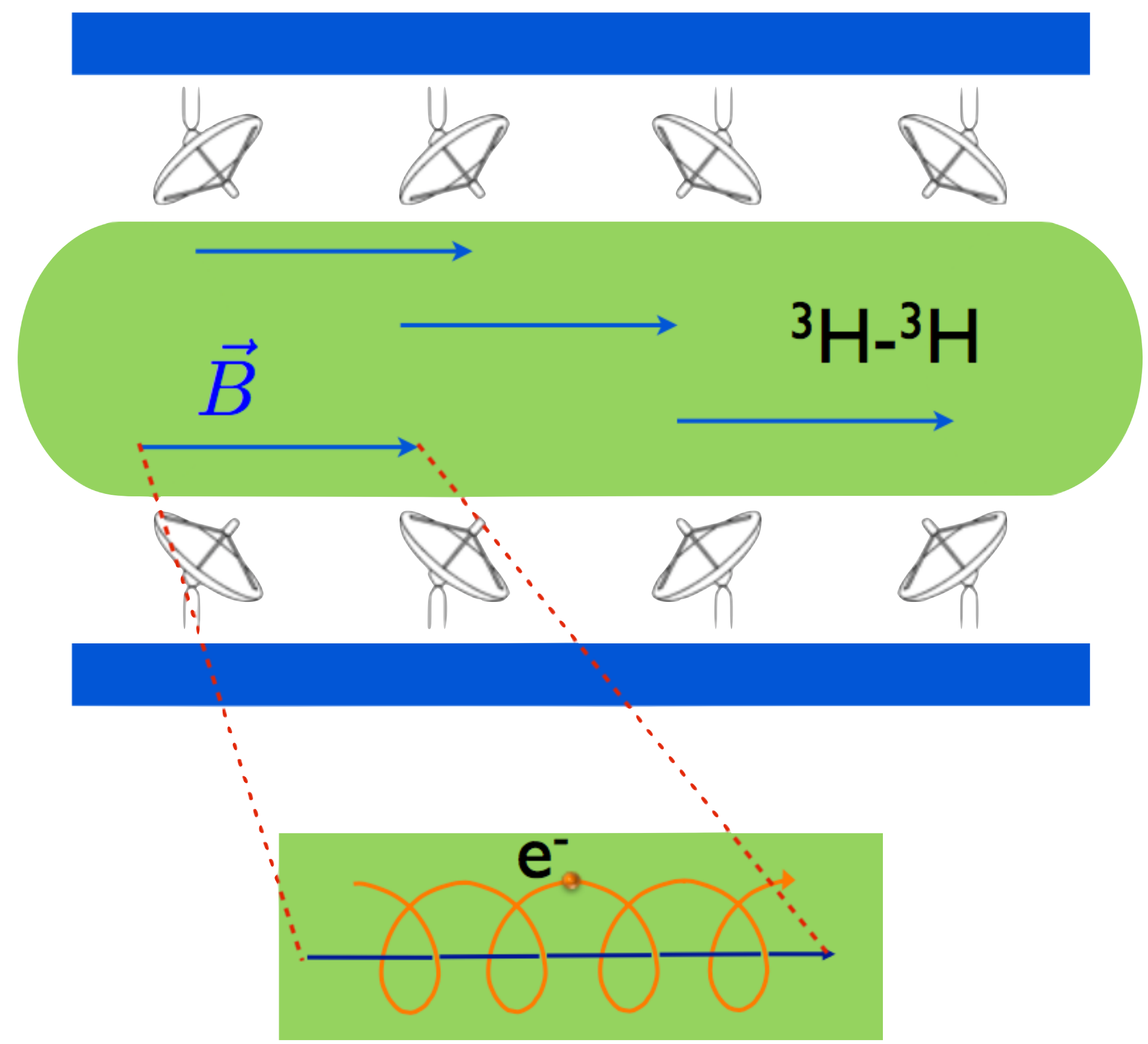
Frequency resolution $\Delta f \sim 1/\Delta t$

- Δt = 20µs → 1400m @ 18keV → hard!
  - ▸ store in magnetic trap



"Never measure anything but frequency" — A. L. Schawlow

Experiment



B. Monreal and J. Formaggio, Phys. Rev D80:051301

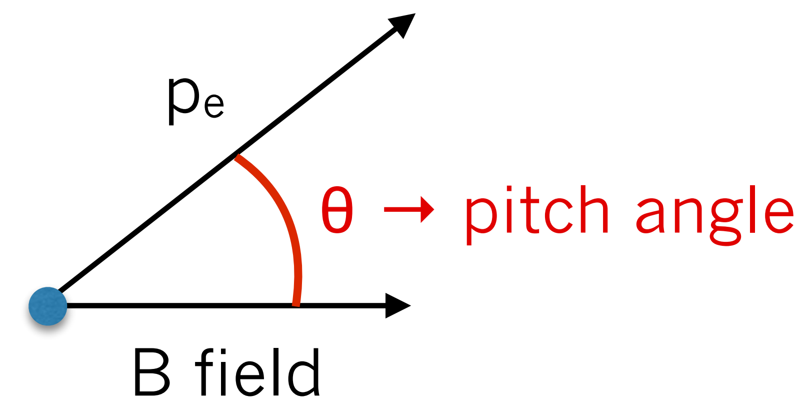
Idea

- fill volume with ^3H gas
- add magnetic field
  - decay electrons orbit around field lines
- add antennae
- measure cyclotron radiation
  - electron spectrum

Radiated power

Larmor formula

$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2}{3}\frac{q^4 B^2}{m_e^2}(\gamma^2-1)\sin^2\theta$$

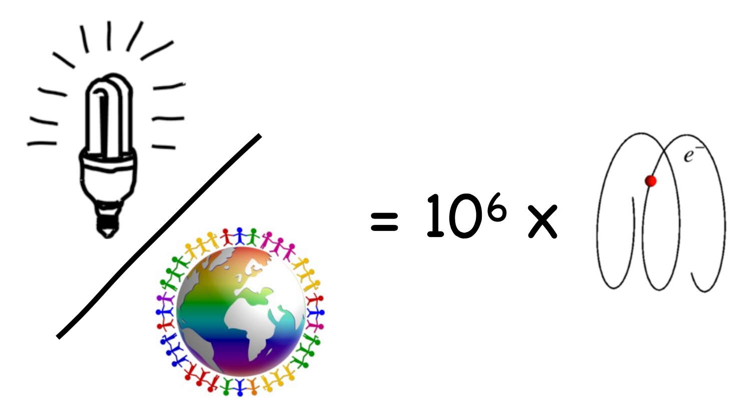


Radiated power

- 1.1 fW for 18 keV electrons at 90°
- 1.7 fW for 30.4 keV electron at 90°

Comparison

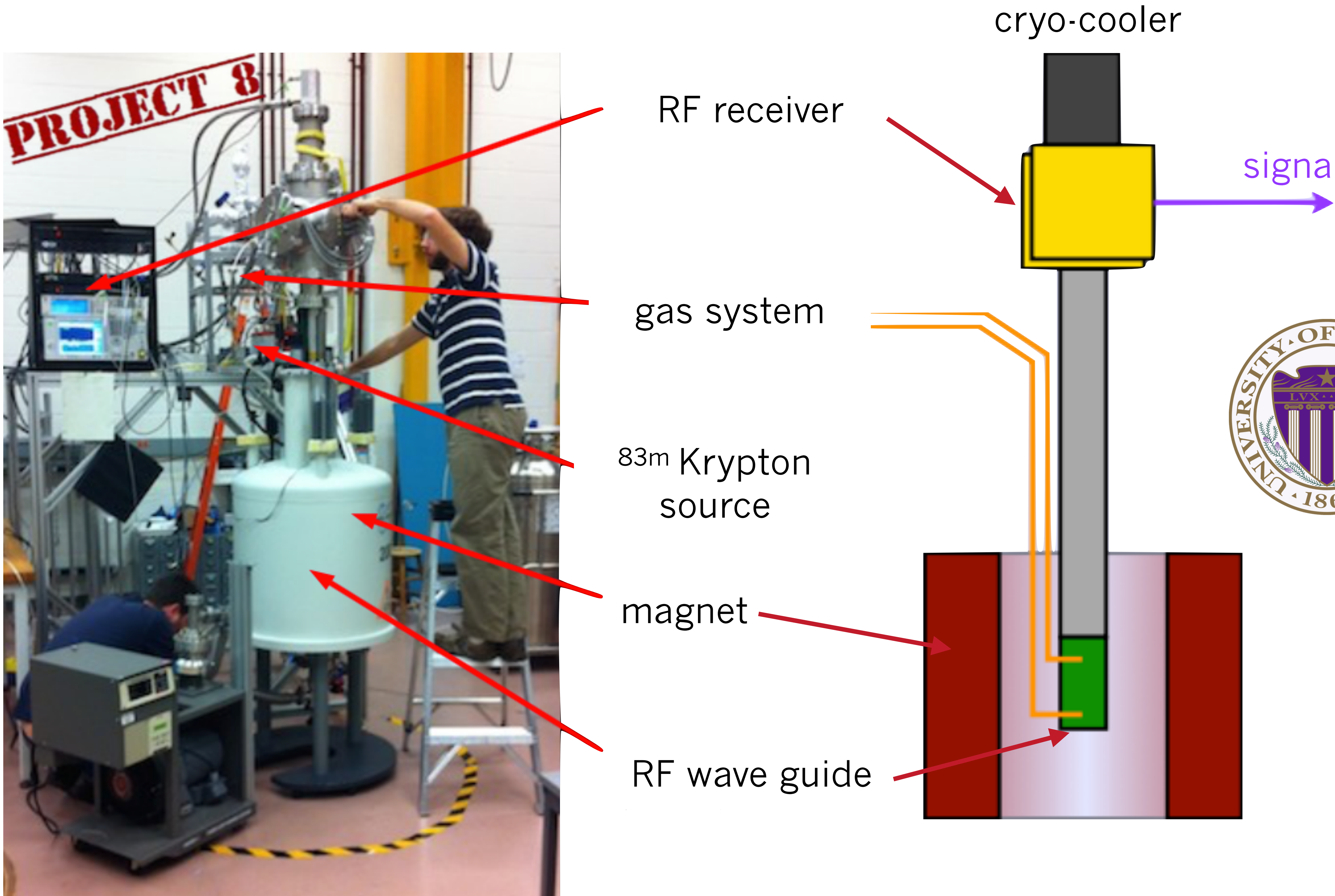
- 10W energy saving light bulb by world population
  - 10^6 larger power per person



Consequences

- need very low-noise detection system
- see mostly electrons at very large *pitch angle θ*

Project 8 prototype



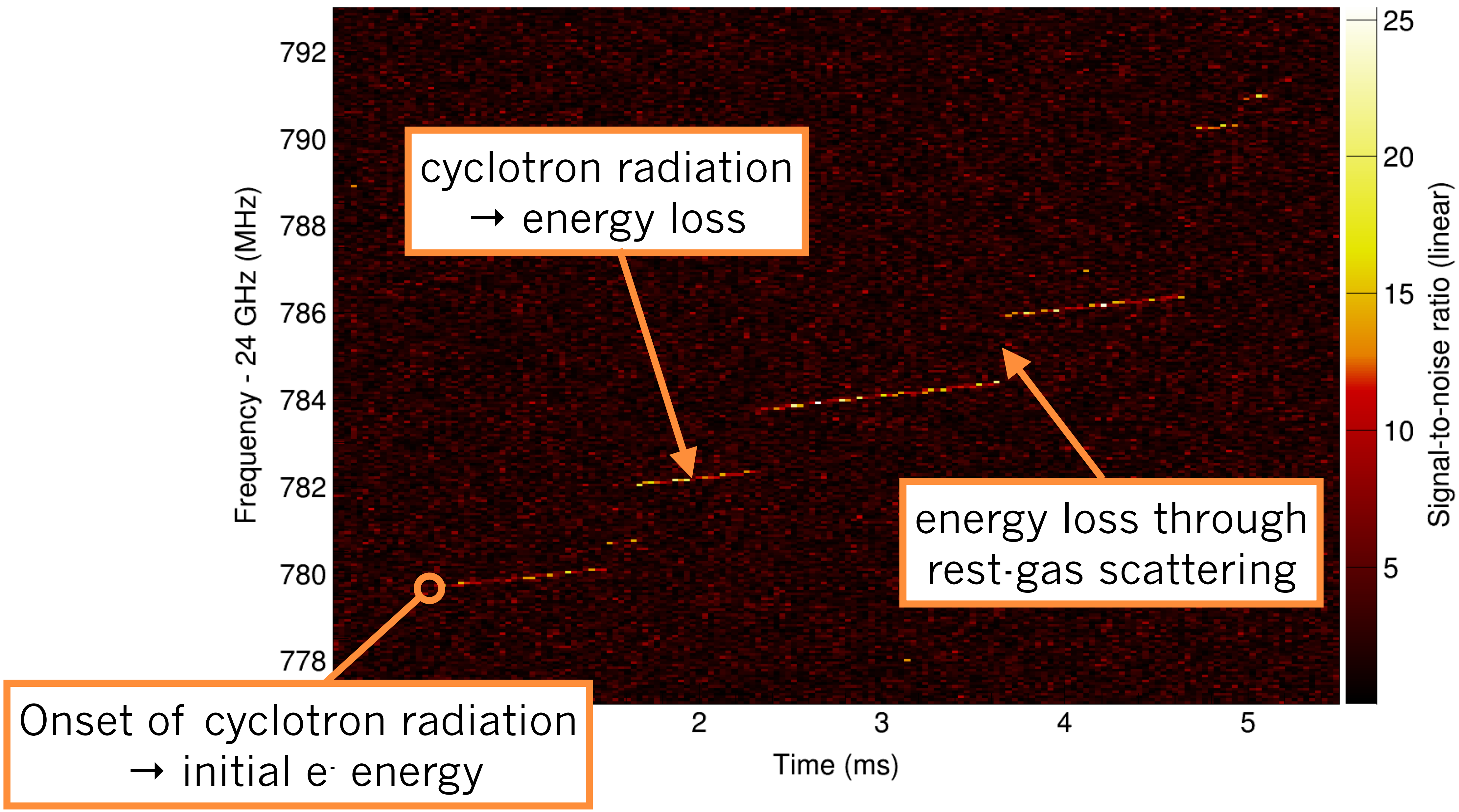
Measured signal

Begin of data-taking on 06.06.2014

- first signal → captured electron

$$f_\gamma = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}}$$

PhysRevLett.114.162501 (2015)



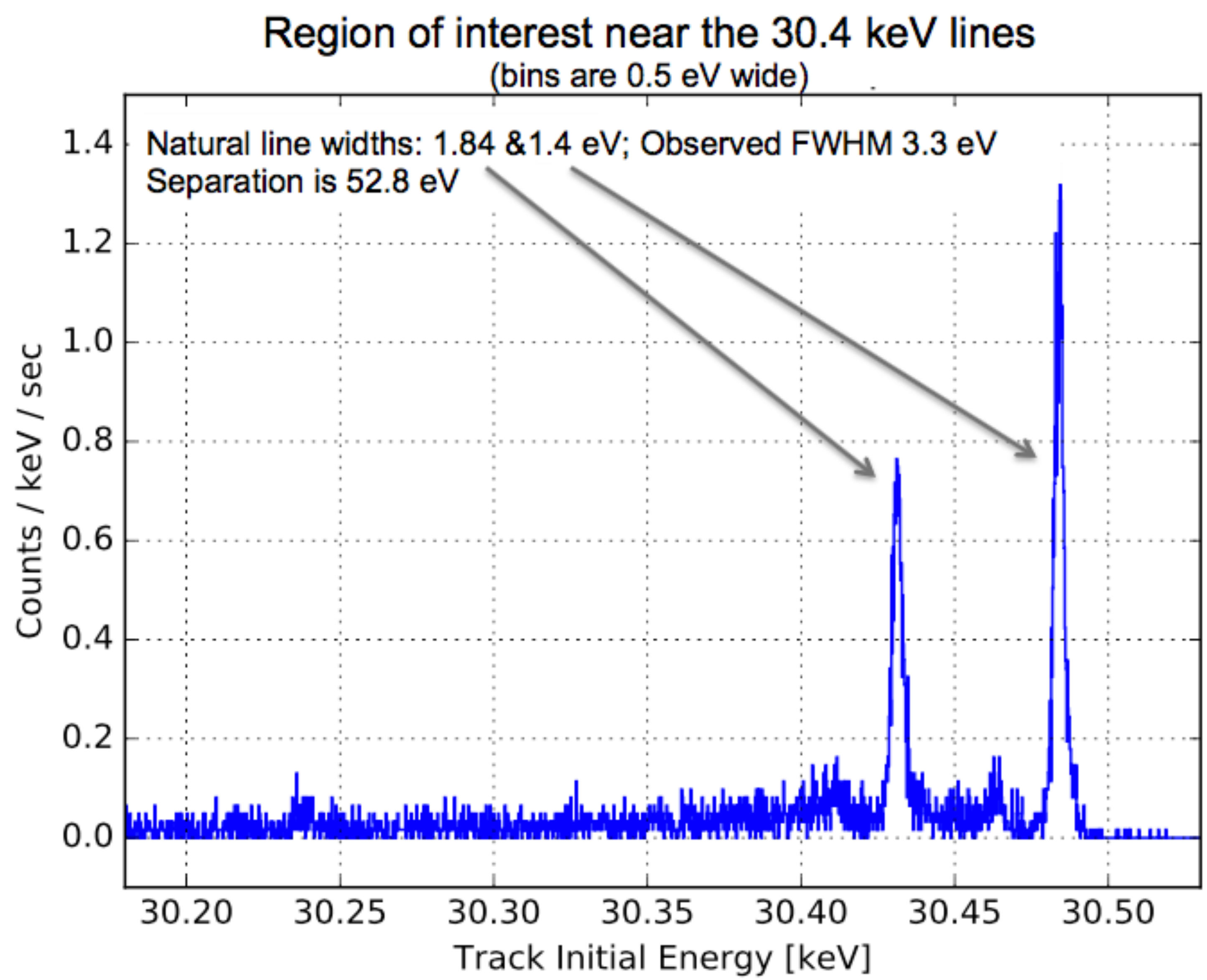
Phase I: results

Improved Phase I setup

- more homogeneous B-field
- reduced sensor noise
- improved temperature stability

Achieved resolutions

- σ(E) = 3.3eV @ 30.4keV
- σ(E) = 5.1eV @ 17.8keV



P8 Collaboration, J. Phys. G 44 (5) 2017

▸ new measurement method established

CRES — *Cyclotron Radiation Emission Spectroscopy*

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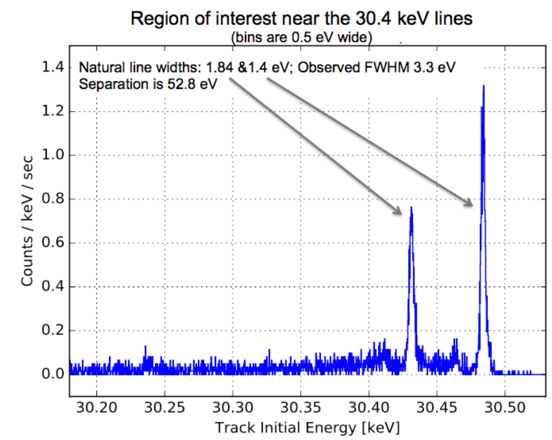
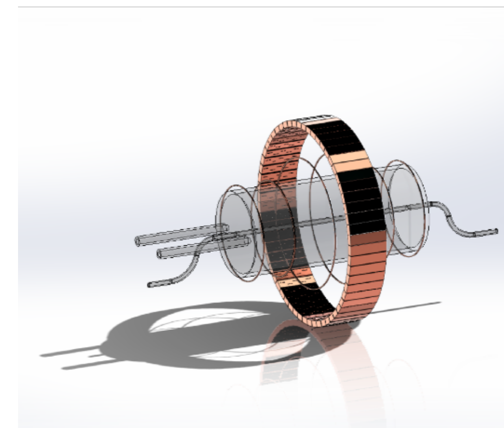
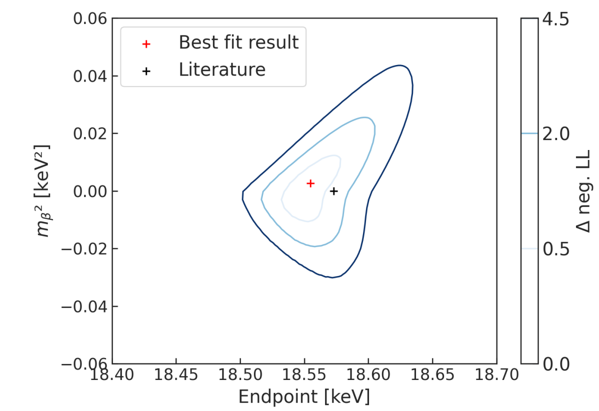
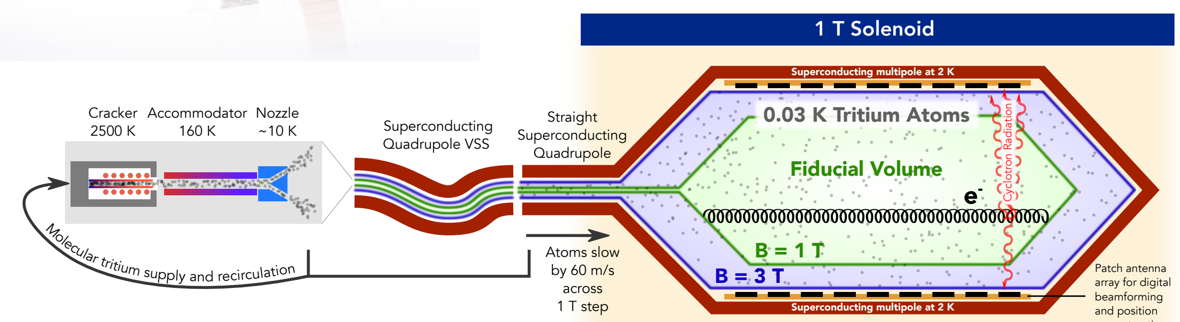
Project Plan (and talk outline)

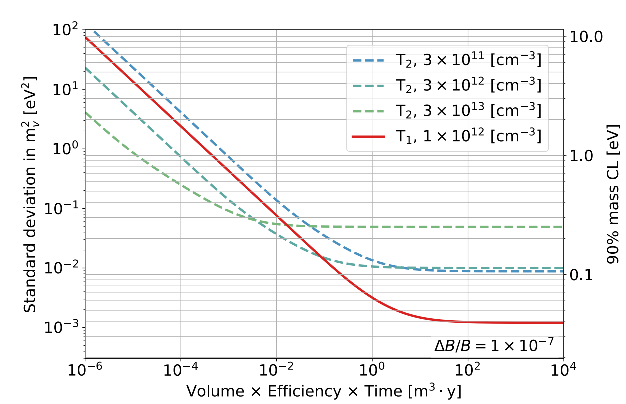
- **Phase I**
  - demonstrate CRES technique ✓
- **Phase II**
  - first Tritium spectrum with CRES (✓)
- **Phase III**
  - Go bigger!
    demonstrate CRES in free space
  - Go atomic!
    demonstrate atomic tritium trapping
- **Phase IV**
  - full apparatus, reaching
    $m_\beta < 0.04$ eV sensitivity



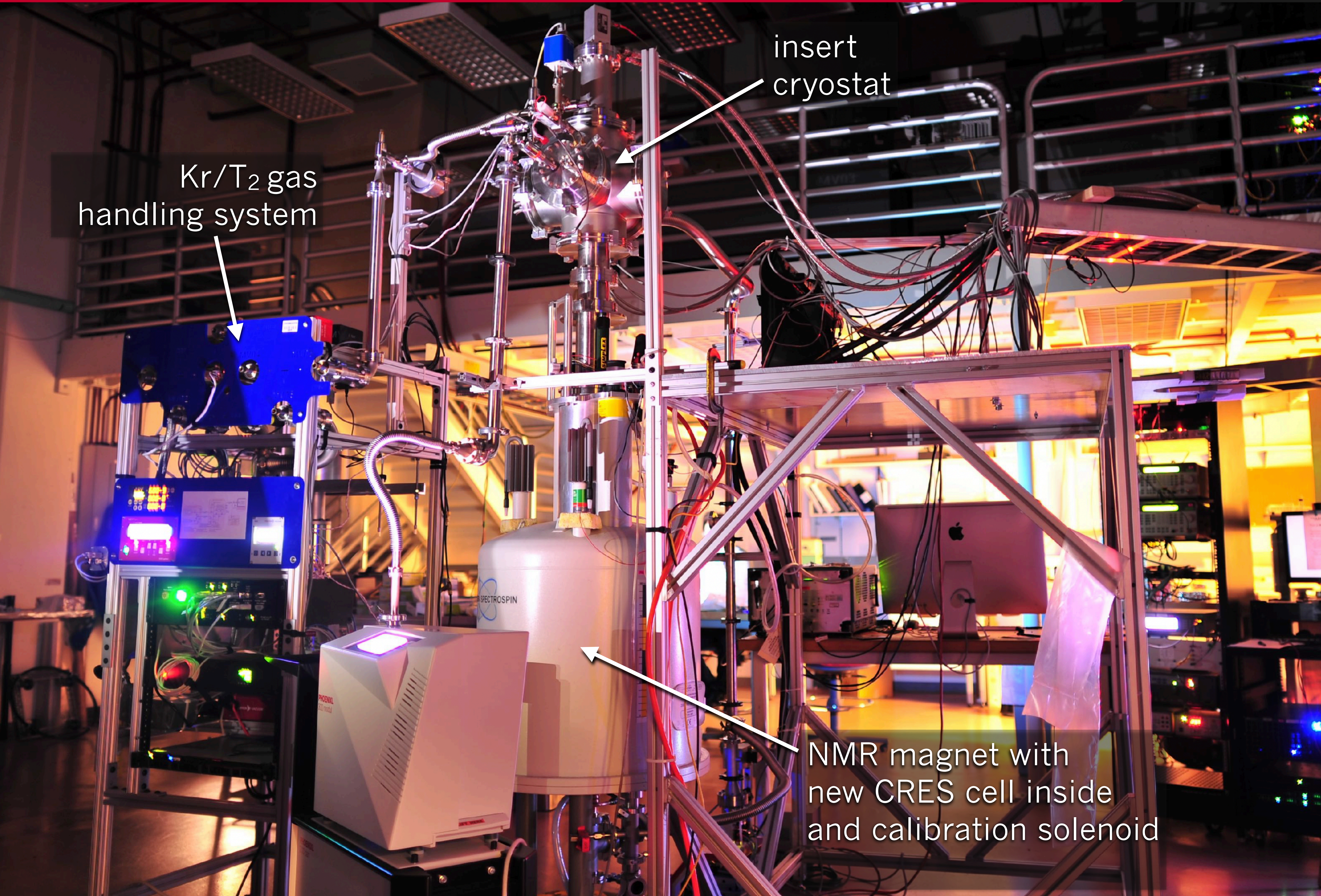








Phase II setup



Phase II: ^{83m}Kr data

Krypton data taking

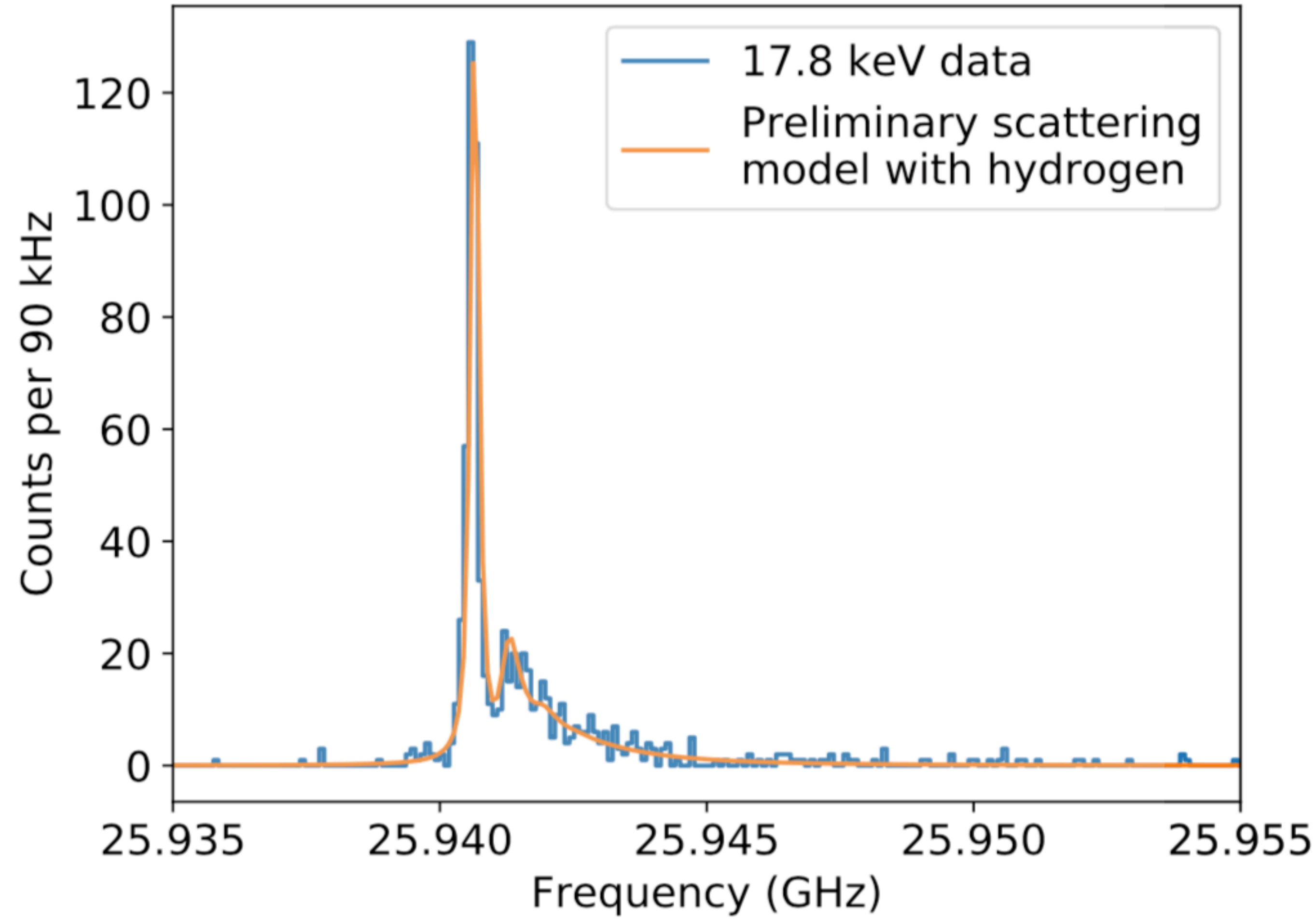
- shallow traps
  - only retain large pitch angles → low rate
  - little variation in B field within trap → good energy resolution

Electron scattering

- before detection
  - low-energy (high-frequency) tail in spectrum

Hydrogen scattering model

- 4eV FWHM Voigt profile
- 2.84eV line width in ^{83m}Kr
  - detector resolution surpasses intrinsic line width



Phase II: T_2 data

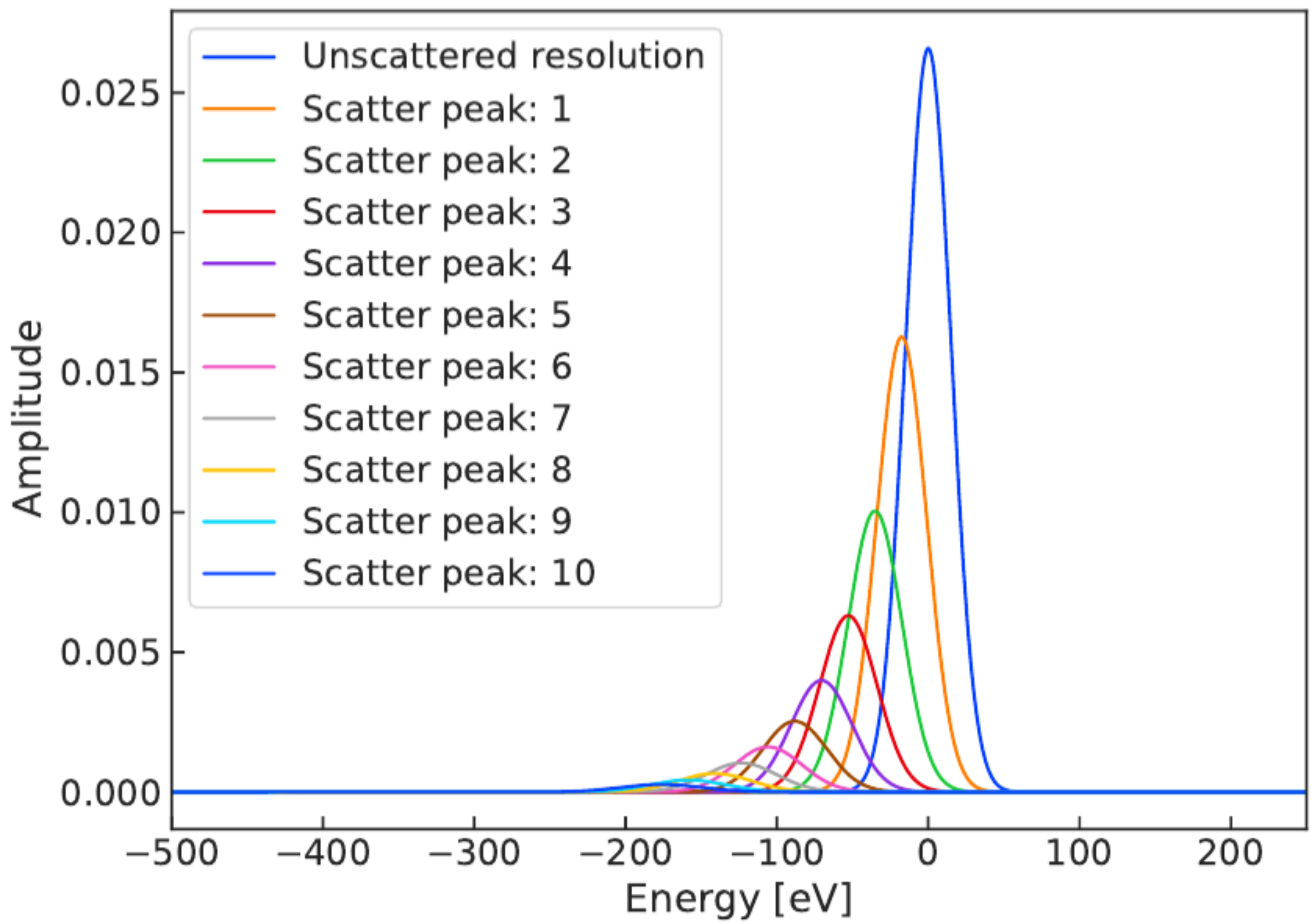
Tritium data taking

- $6 \cdot 10^4$ longer half-life → dramatically decreased rate
  - increasing pressure

Tritium configuration

- optimized configuration for best endpoint sensitivity with ~100 days of data
- use deeper trap
  - better statistics
  - worse energy resolution $\sigma(E) = 1.5$ eV → 12.0 eV
- lineshape still well described by model (gas composition!)

^{83m}Kr peak

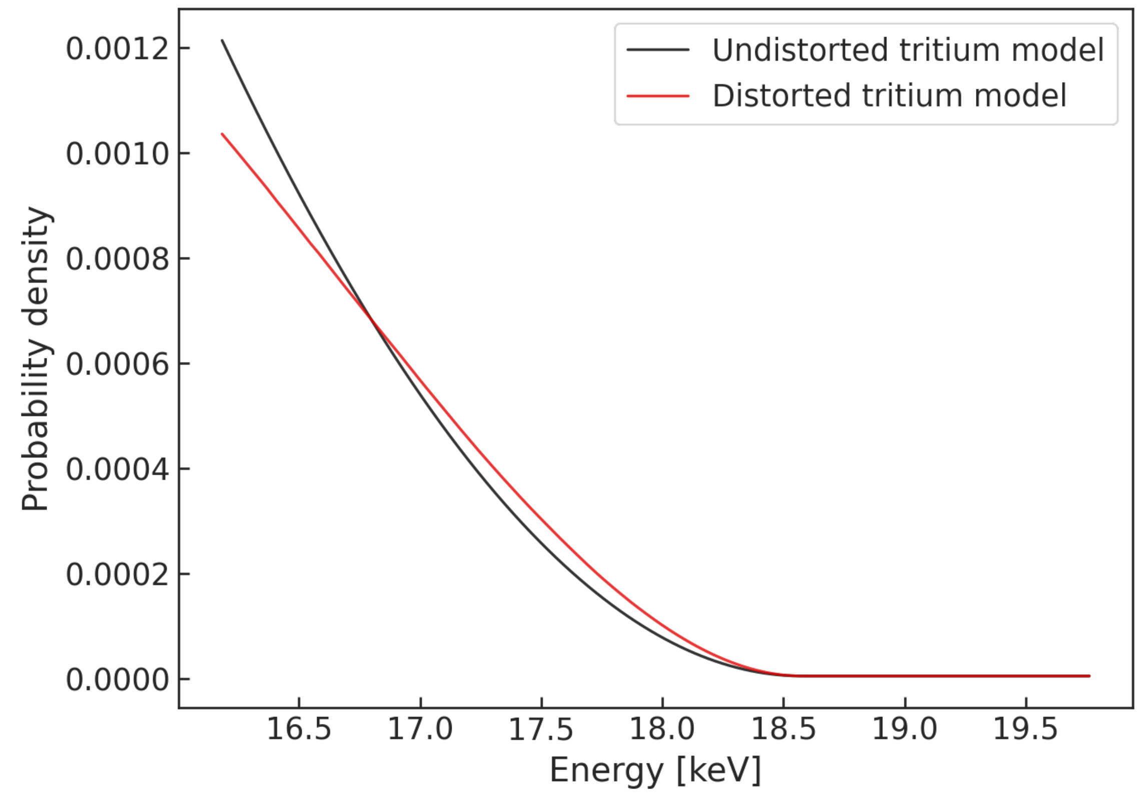


Detection efficiency

Emitted cyclotron power

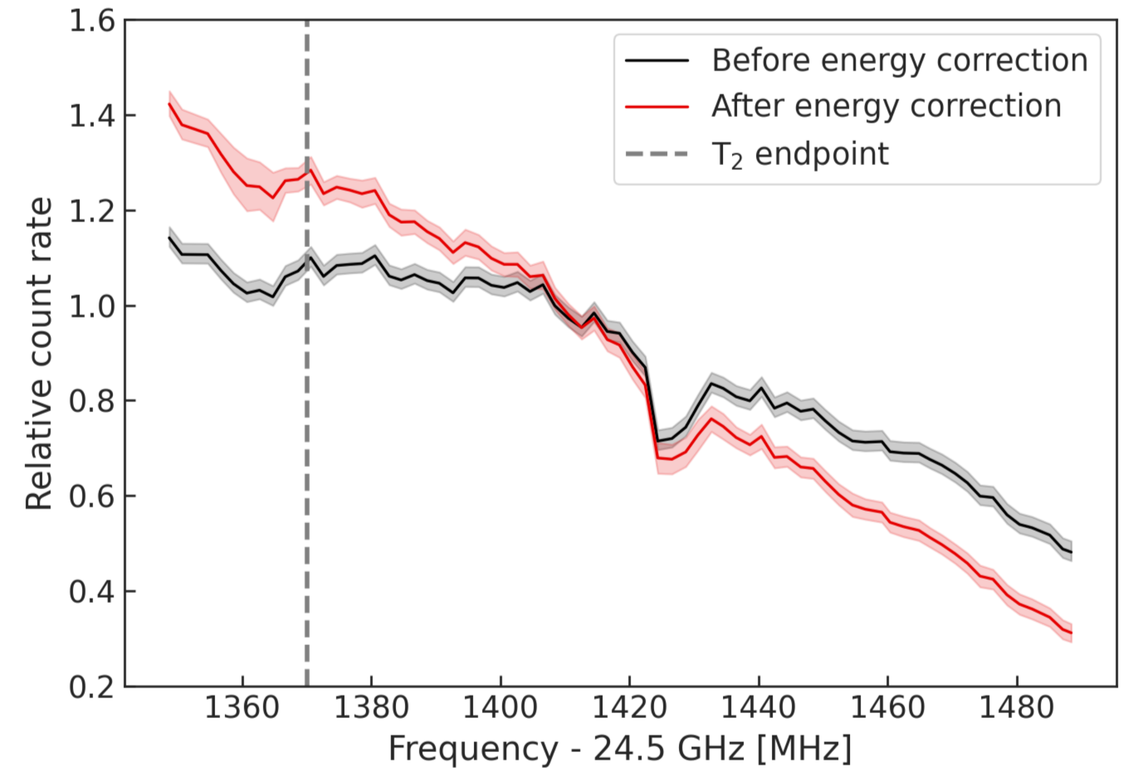
$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2}{3}\frac{q^4B^2}{m_e^2}(\gamma^2-1)\sin^2\theta$$

- detection probability is energy (→ frequency) dependent!
- distorted spectrum
  - impacts neutrino mass analysis



Additional effects

- frequency (→ energy) dependent effects of waveguide
- frequency (→ energy) dependent receiver and amplification chain
  - **need calibration over ROI!**



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Phase II: Solenoid calibration

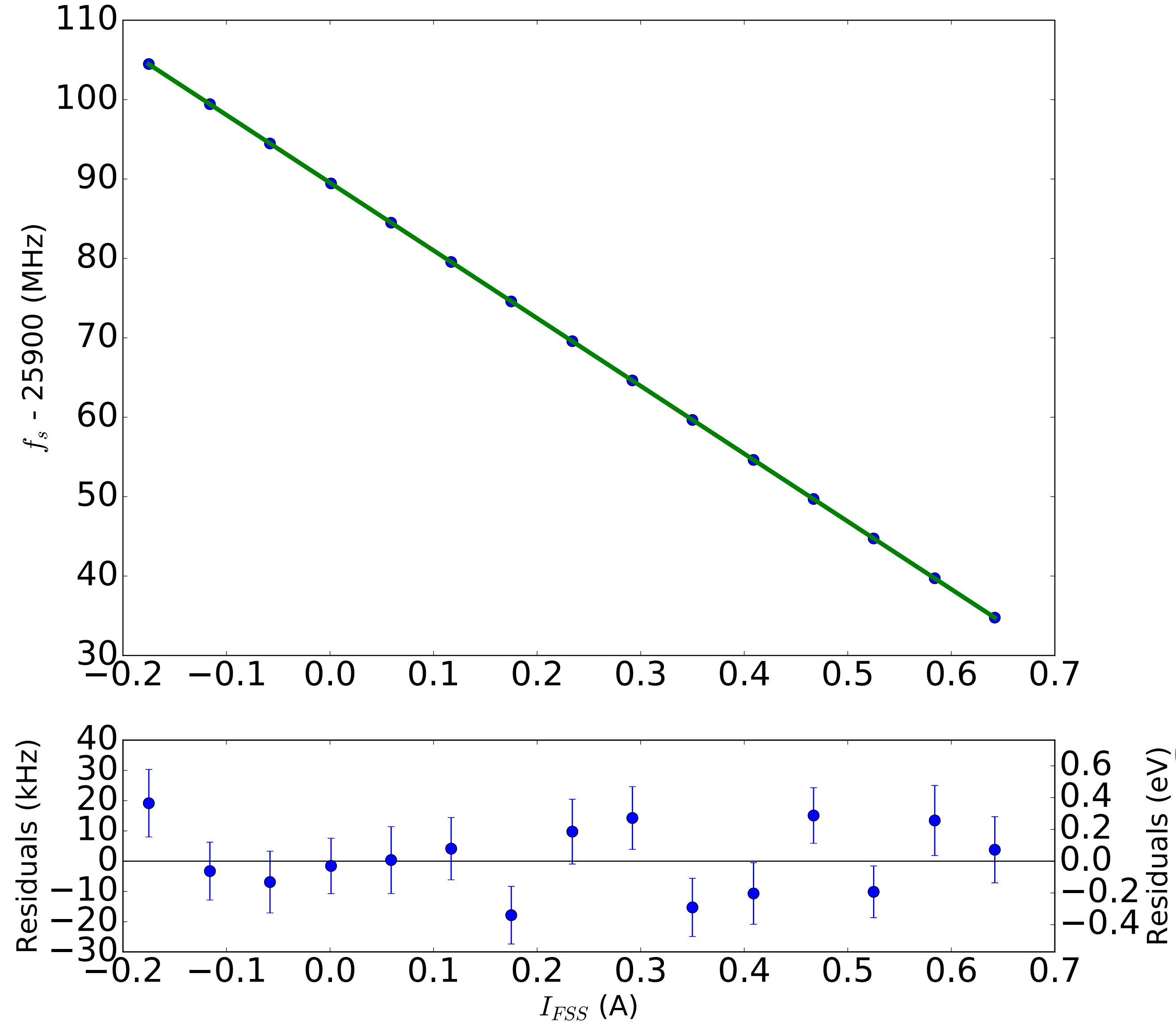
Cyclotron frequency

$$f_c = \frac{1}{2\pi}\frac{eB}{m_e}$$

- linear dependence on absolute B-field

Calibration

- cannot easily ramp NMR magnet
  - installed **field-shifting solenoid** inside NMR bore
  - shift background field and thus cyclotron frequency
- shifted 17.8 keV line of ^{83m}Kr
  - range of 70MHz (~1.5 keV)
  - linearity demonstrated within ~0.010MHz (~0.0002eV)



Analysis validation with pseudo data

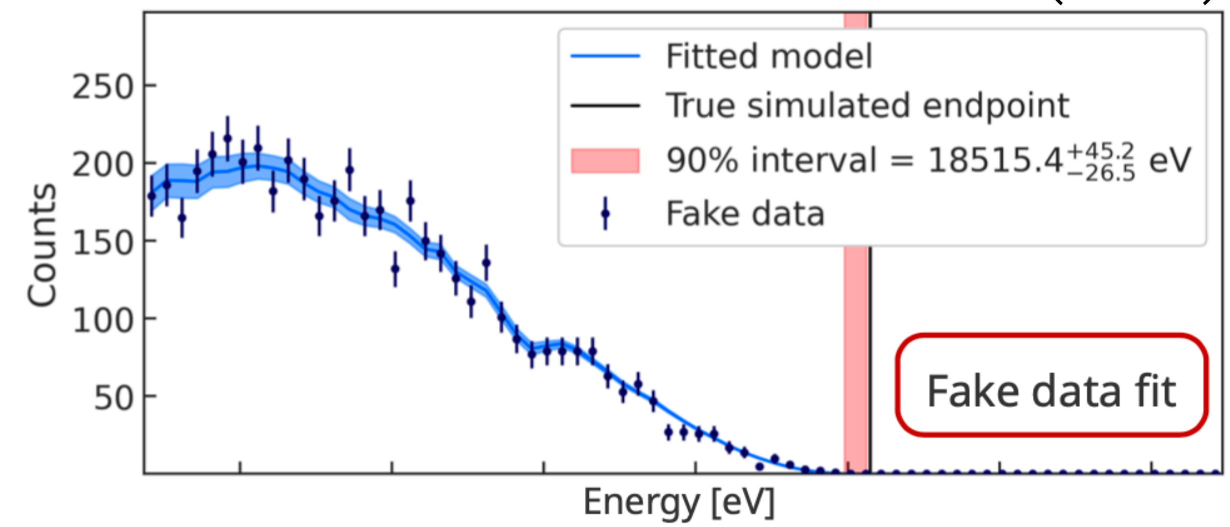
Data generation model

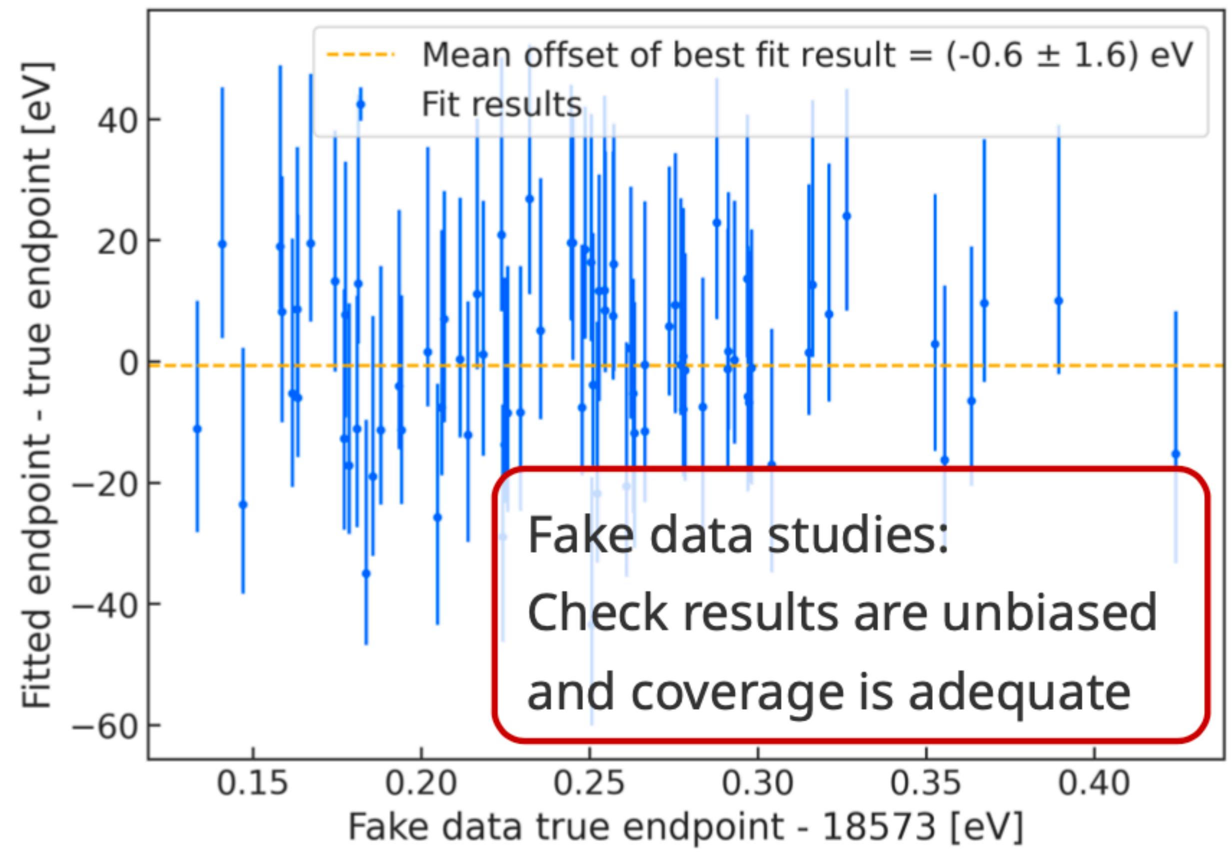
- tritium spectral model
- efficiency vs energy (frequency)
- resolution effects from
  - detector response
  - scattering (gas composition)
  - molecular excitations

Analysis approach

- Frequentist analysis MLE with Monte Carlo uncertainty propagation
- Bayesian analysis with priors for systematic uncertainties

C. Claessens (Mainz)





T2 analysis results

Analysis methods

- Frequentist analysis
- Bayesian analysis
  - good agreement!

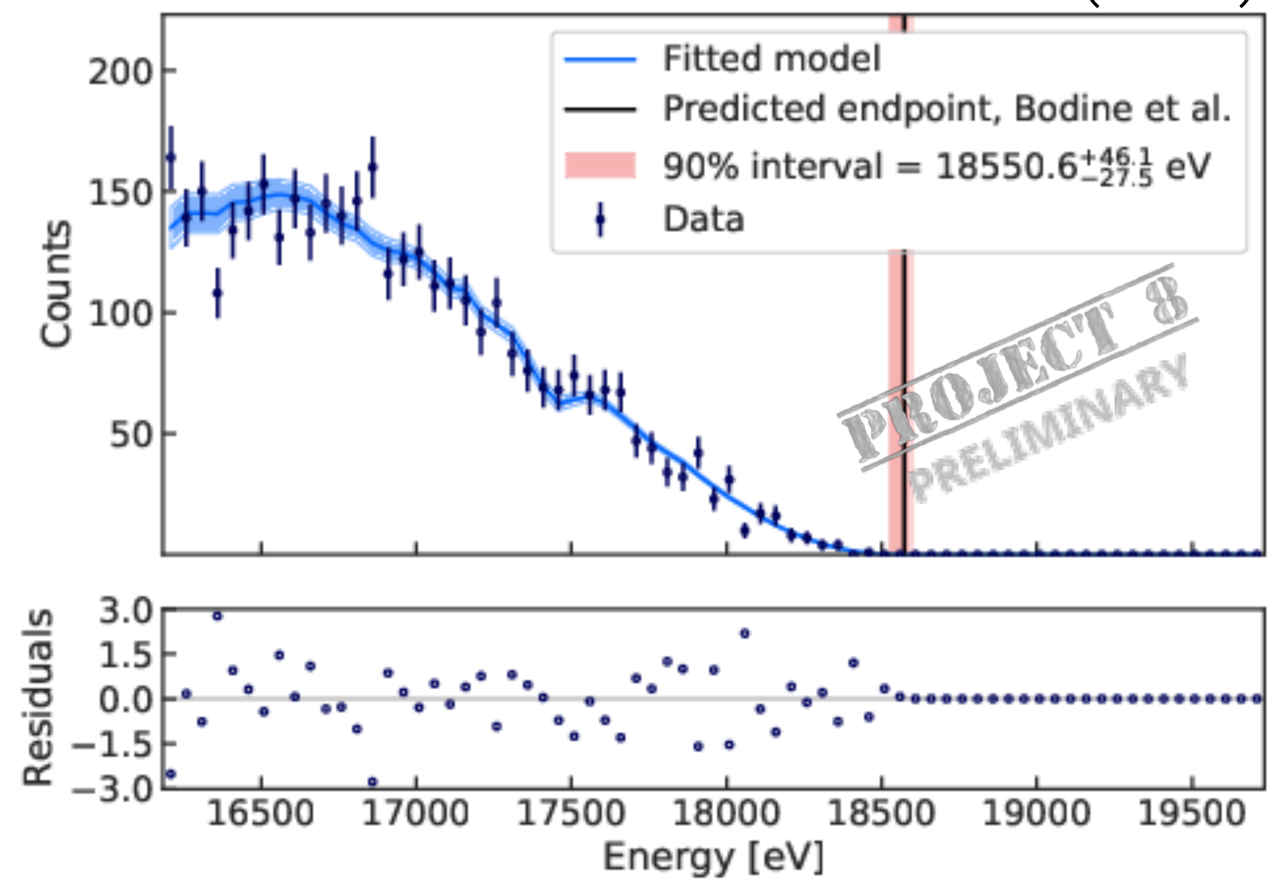
Analysis results

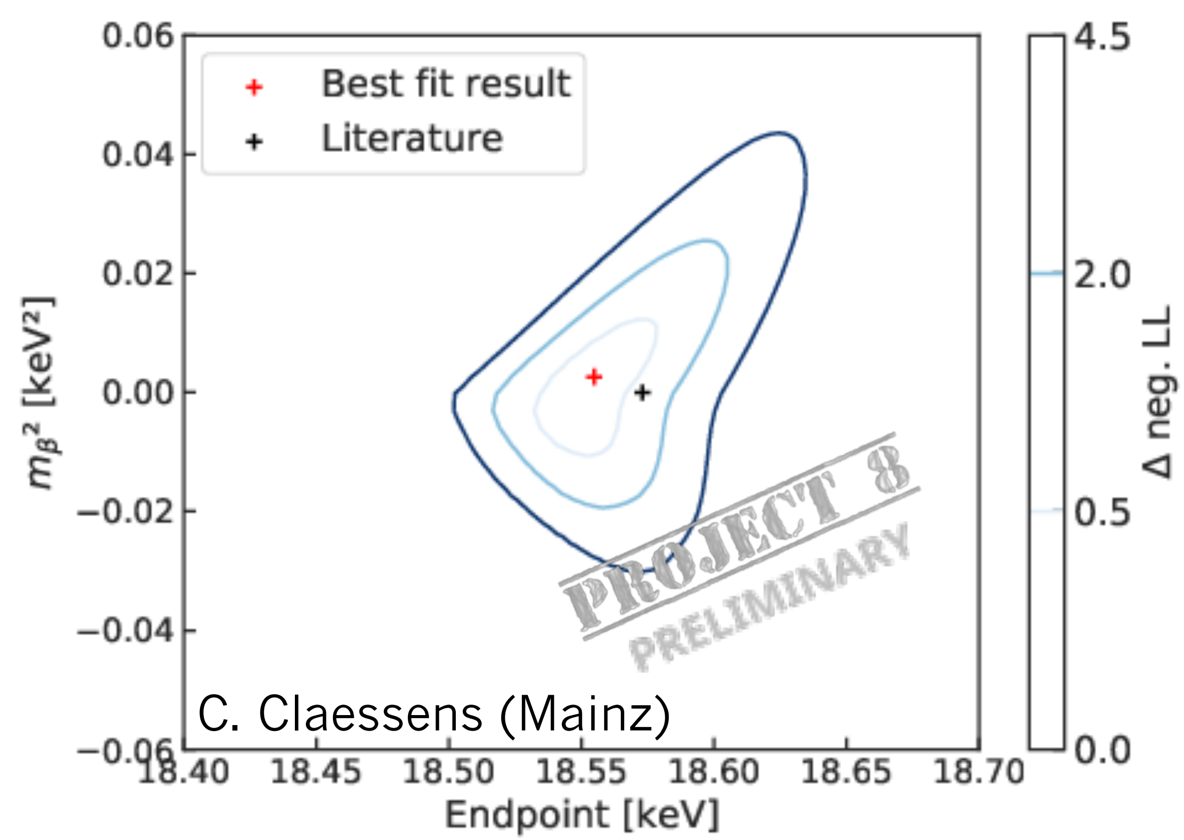
- T_2 endpoint (90% CL)
  - $E_0 = 18550.6^{+46.1}_{-27.5}$ eV
- Background rate (90% CL)
  - $R \leq 3 \cdot 10^{-10}$ $eV^{-1}s^{-1}$
- Neutrino mass (90% CL)
  - $m_\beta \leq 185$ eV/c^2

Analysis is being finalized

- publication pending

C. Claessens (Mainz)





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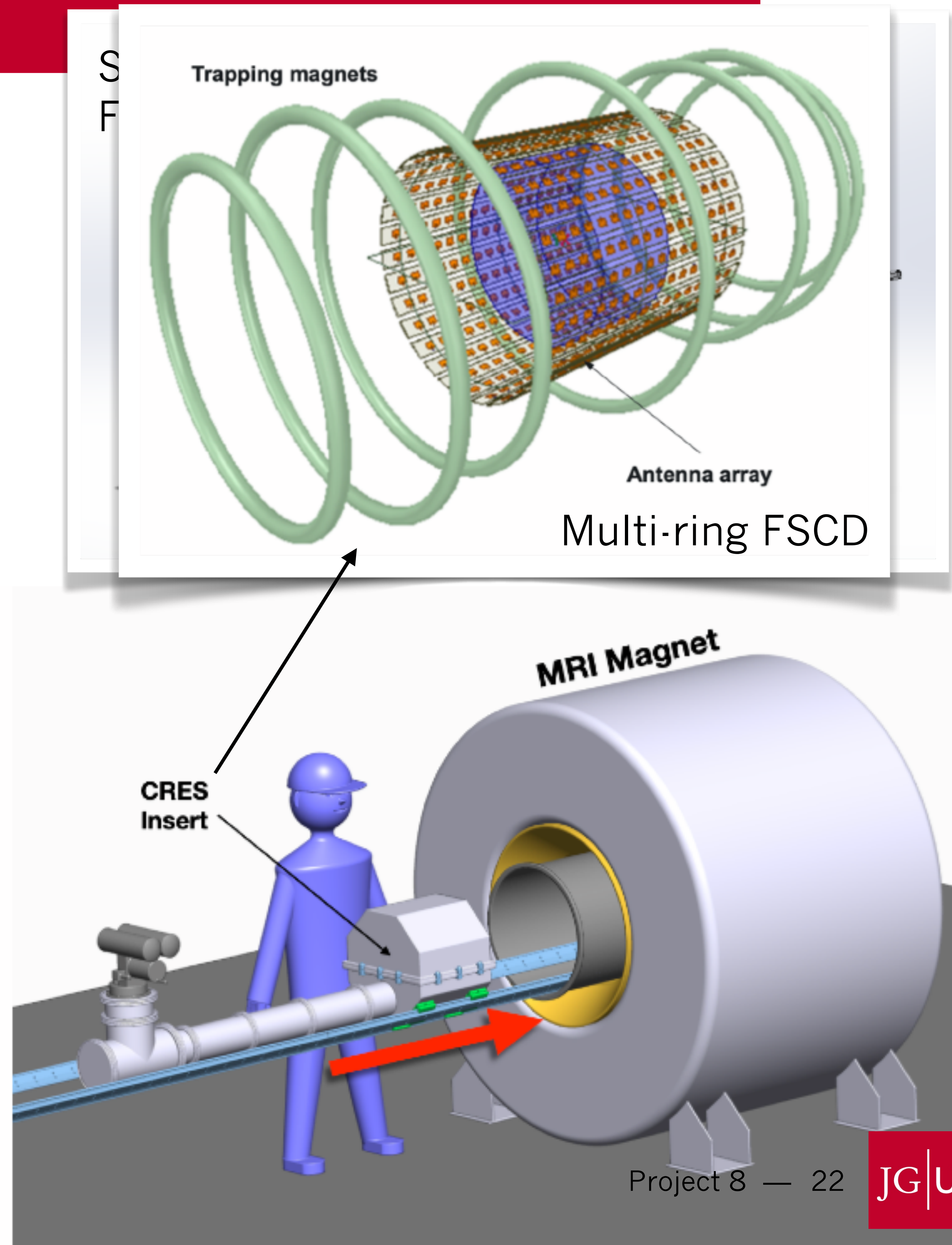
Phase III concept



Phase II design

- volume limited by waveguide dimensions
  - “free-space” CRES demonstrator (*FSCD*)

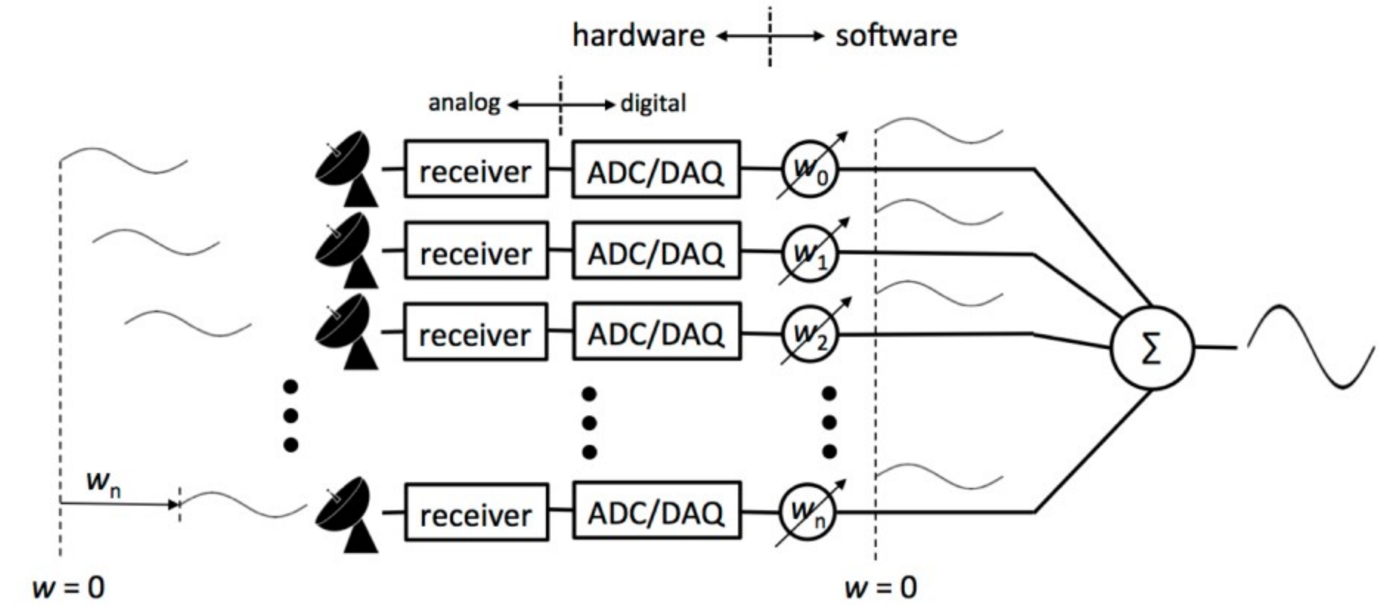
Characteristics

- 1T MRI magnet
- T_2 in fused silica cylinder
  - density $3 \cdot 10^{12}$ cm^{-3}
- long bathtub trap
  - 10-100cm^3 effective volume
- read out by **phased antenna array**

Phase III: readout and beamforming

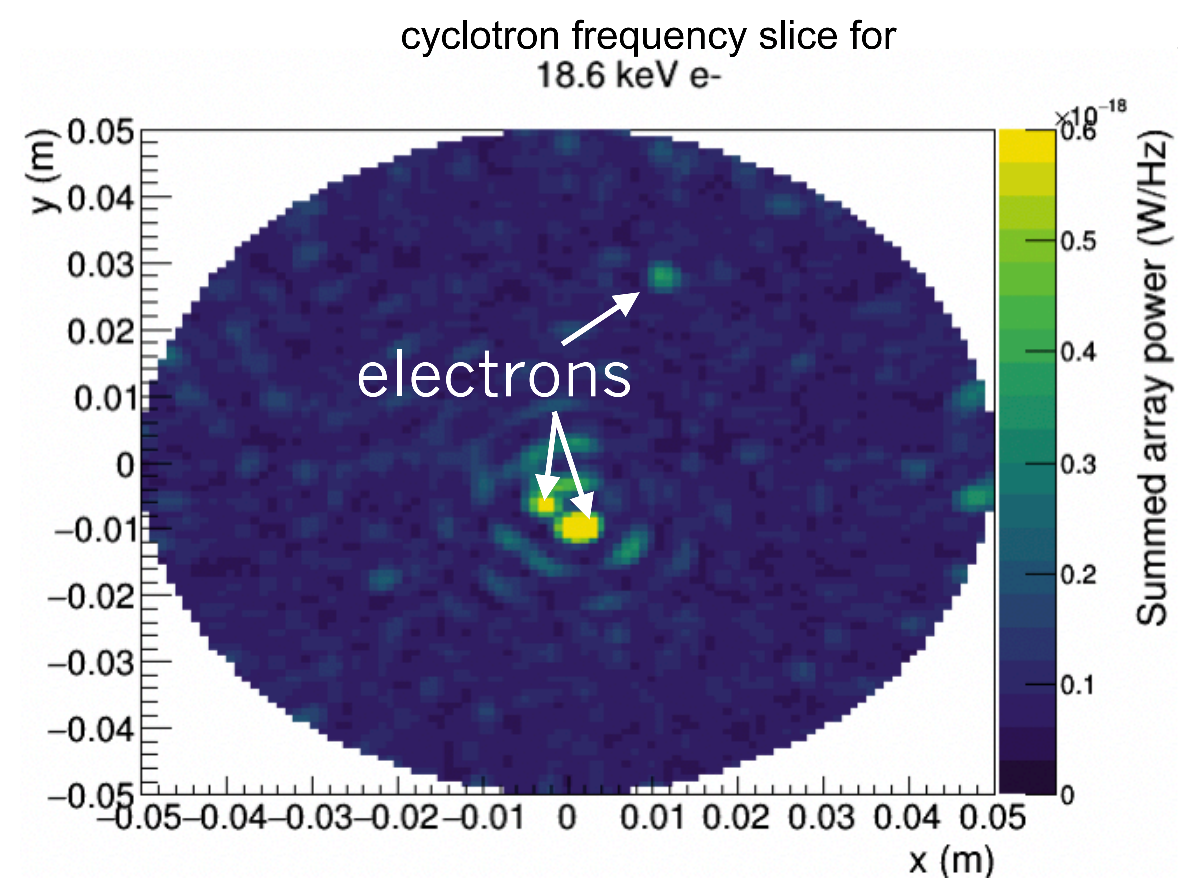
Cyclotron radiation

- distributed over **many channels**
  - individual channel has too low SNR for trigger



Real-time digital beam-forming

- construction focus by applying individual phase delays to signals in each frequency slice



Challenges

- high data rate and bandwidth
- large cross-section → many focal points
- side lobes → fake events
- eventually: simultaneous electrons
- **low signal power**

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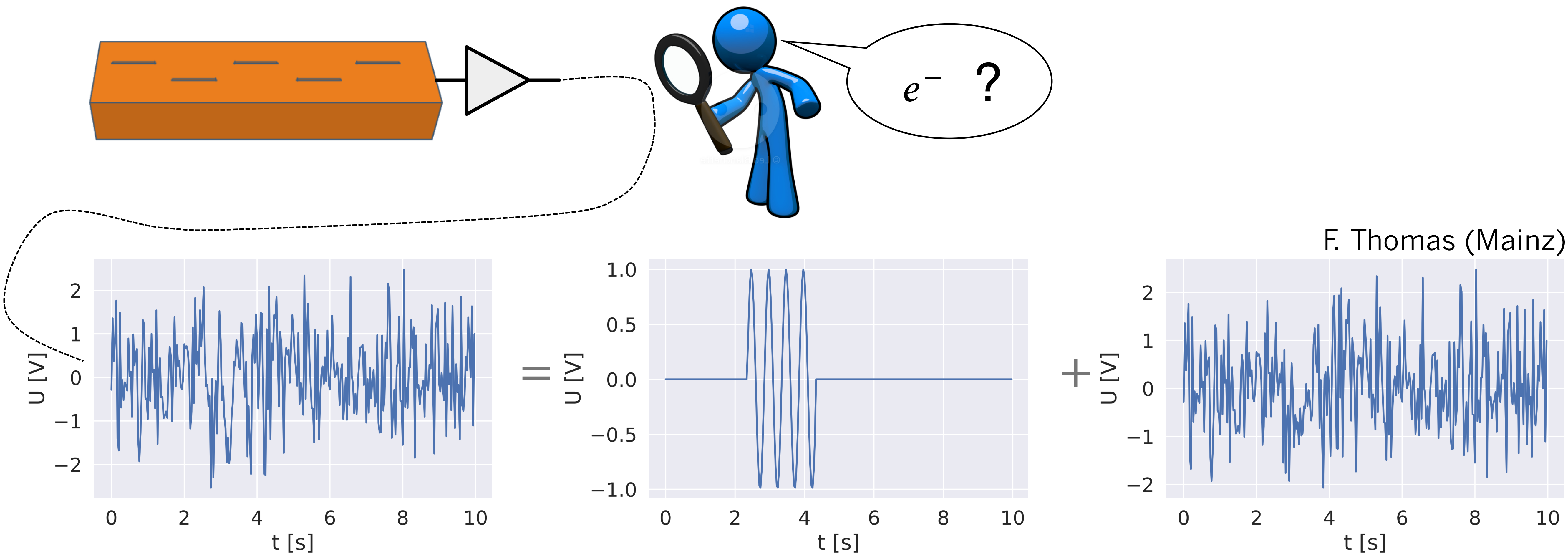
Recovering the signal

The challenge:



Voltage timeseries x
(toy data)

Signal s

Noise n

Matched filtering

Mathematical method

$$y_i = (s \star x)_i = \sum_k s_k^* \, x_{i+k}$$

- equivalent to *cross-correlation*
- returns **physical power** of signal
- proven to be **ideal algorithm** for Gaussian noise

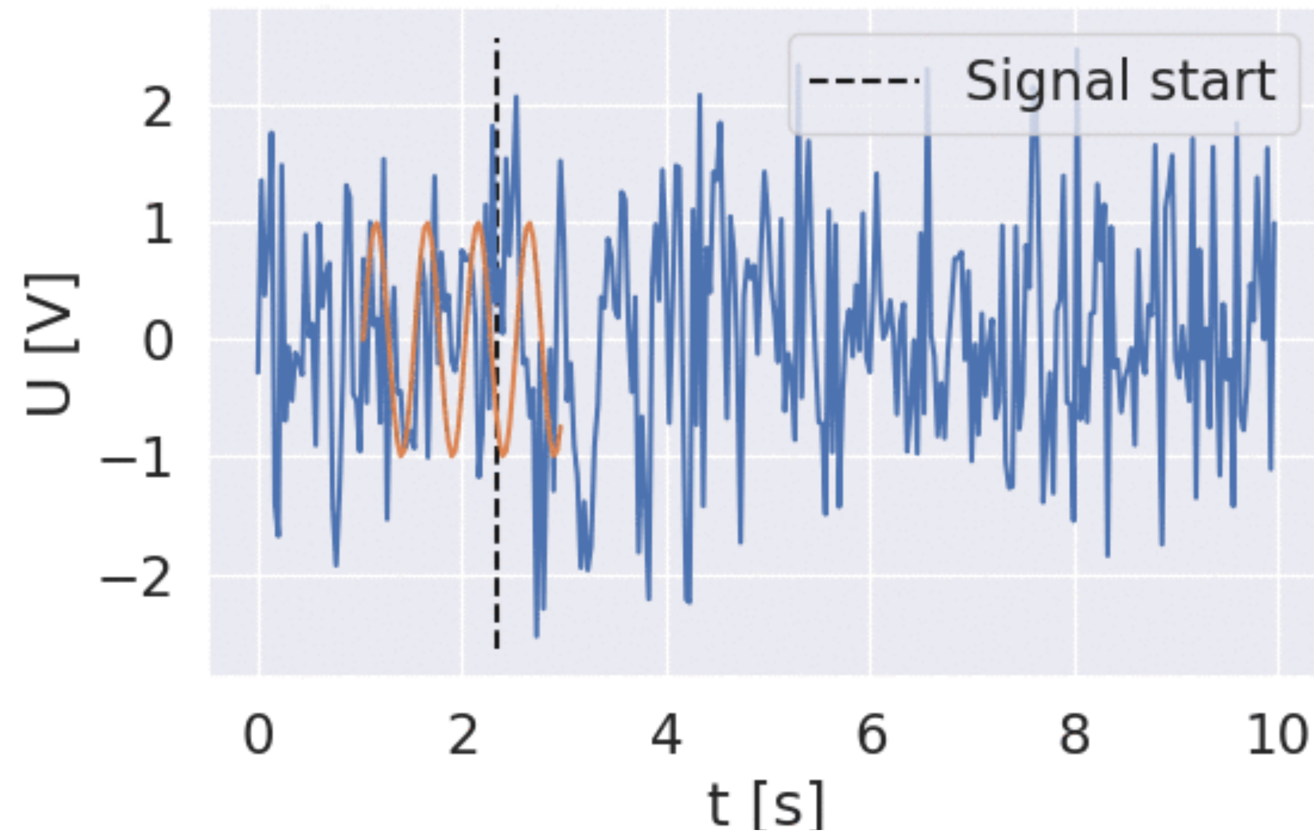
Discrete Fourier transform

- matched filter with sine waves

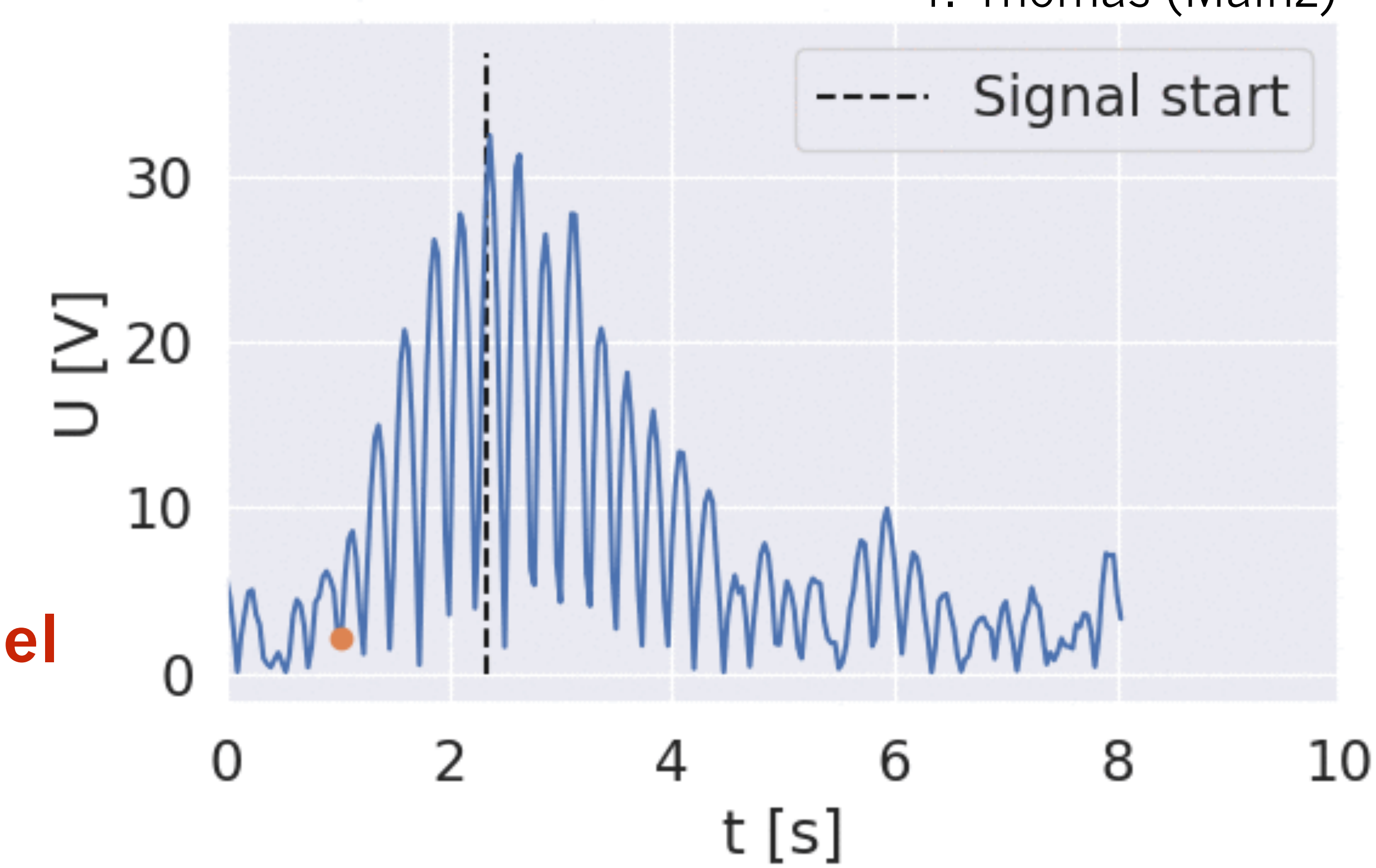
Many antennas

- sum over all channels with appropriate phase delays

Need accurate per channel signal model



F. Thomas (Mainz)



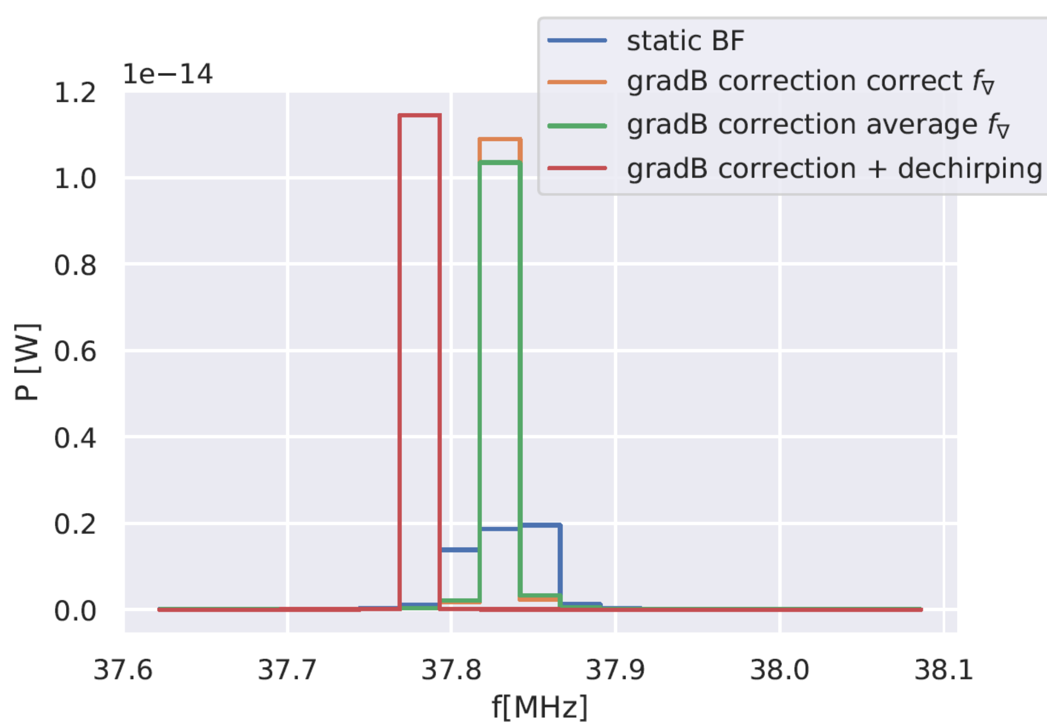
Improving the signal model

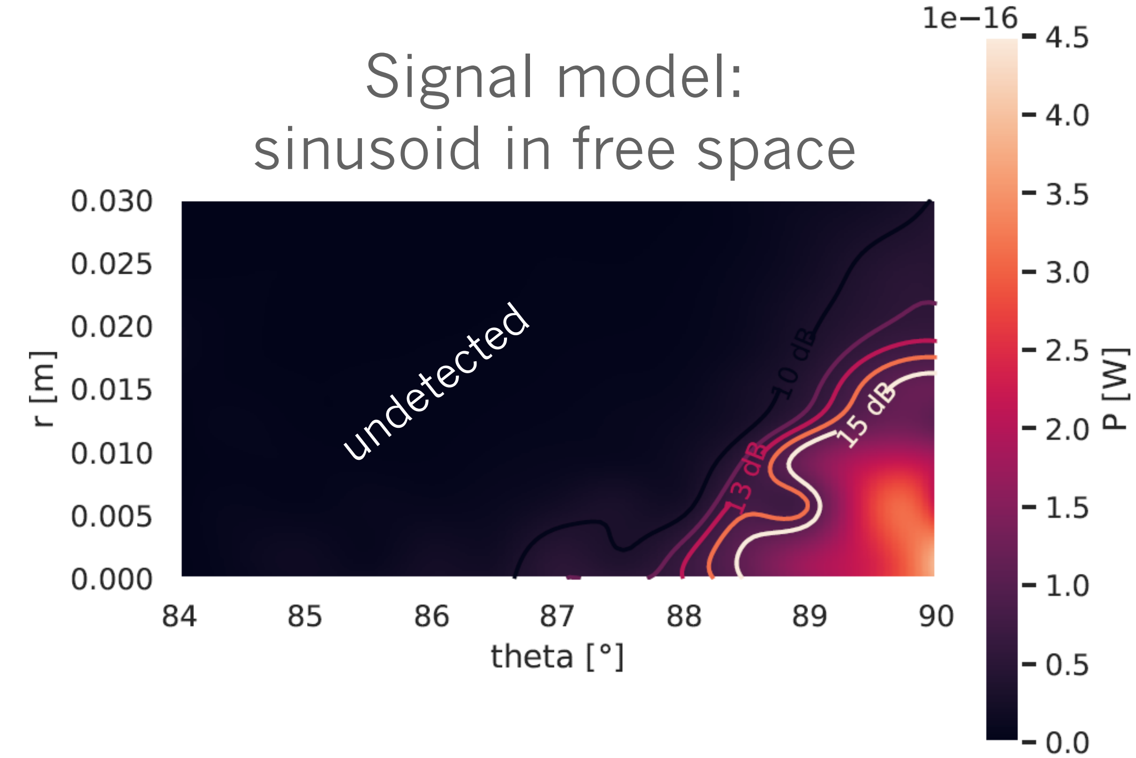
grad B · motion

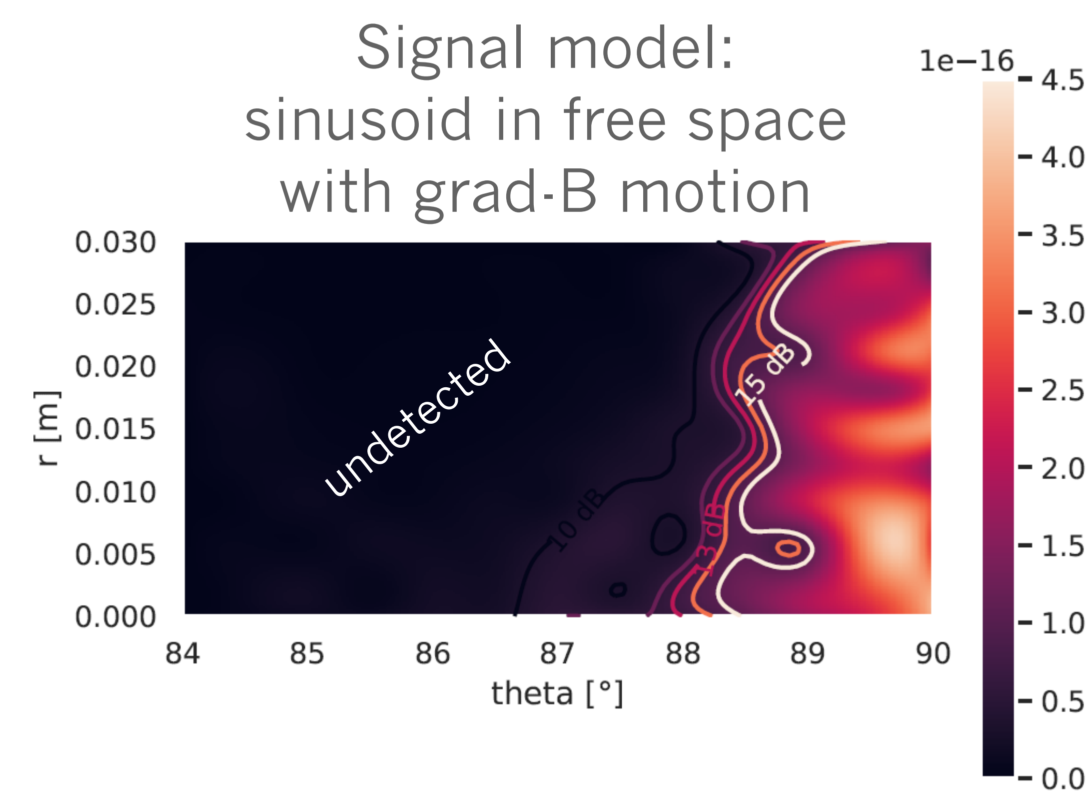
- background field not homogeneous
  - electron centroid moves in $\vec{B}\times\vec{\nabla}|B|$ direction

Simulation example

- Single electron θ=90°, r=2cm







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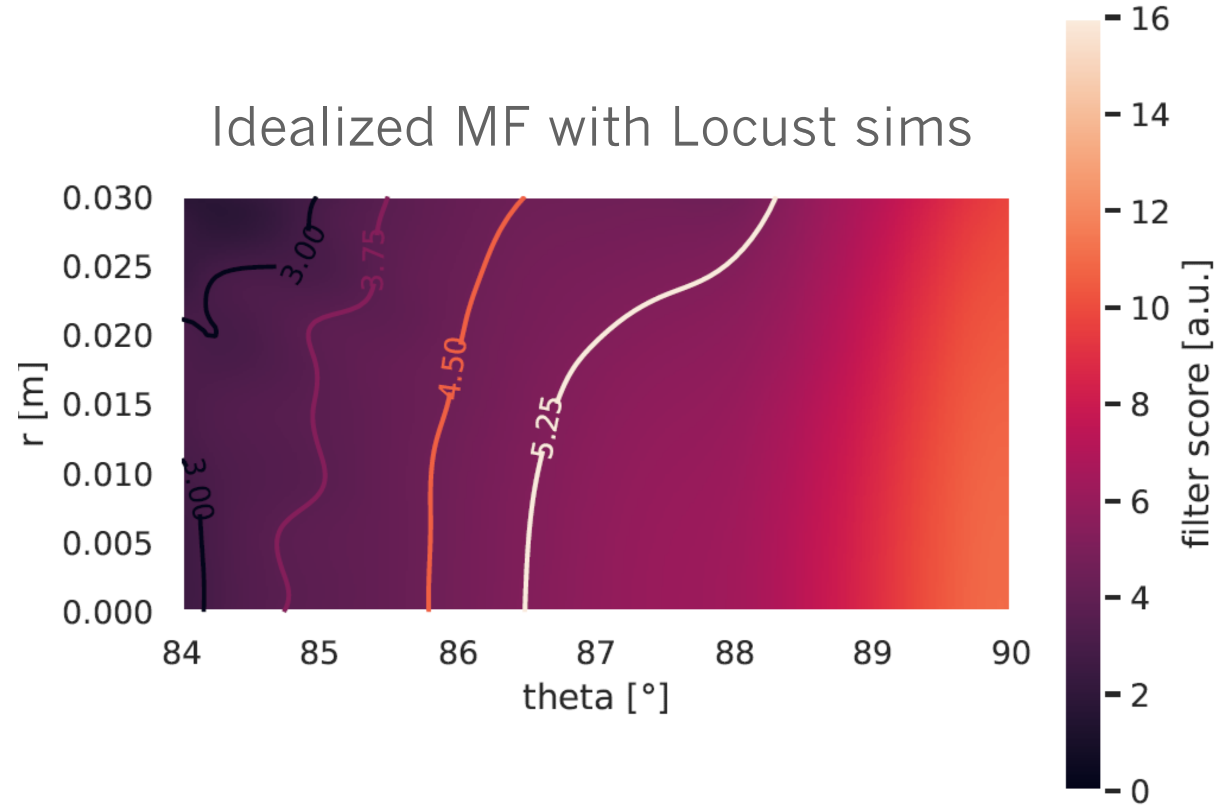
Signal vs. background

Ideal signal model

- full simulation of electron signal
  - detailed electron tracking (Kassiopeia)
  - detailed antenna response (Locust)
- takes ~1.5hrs per event

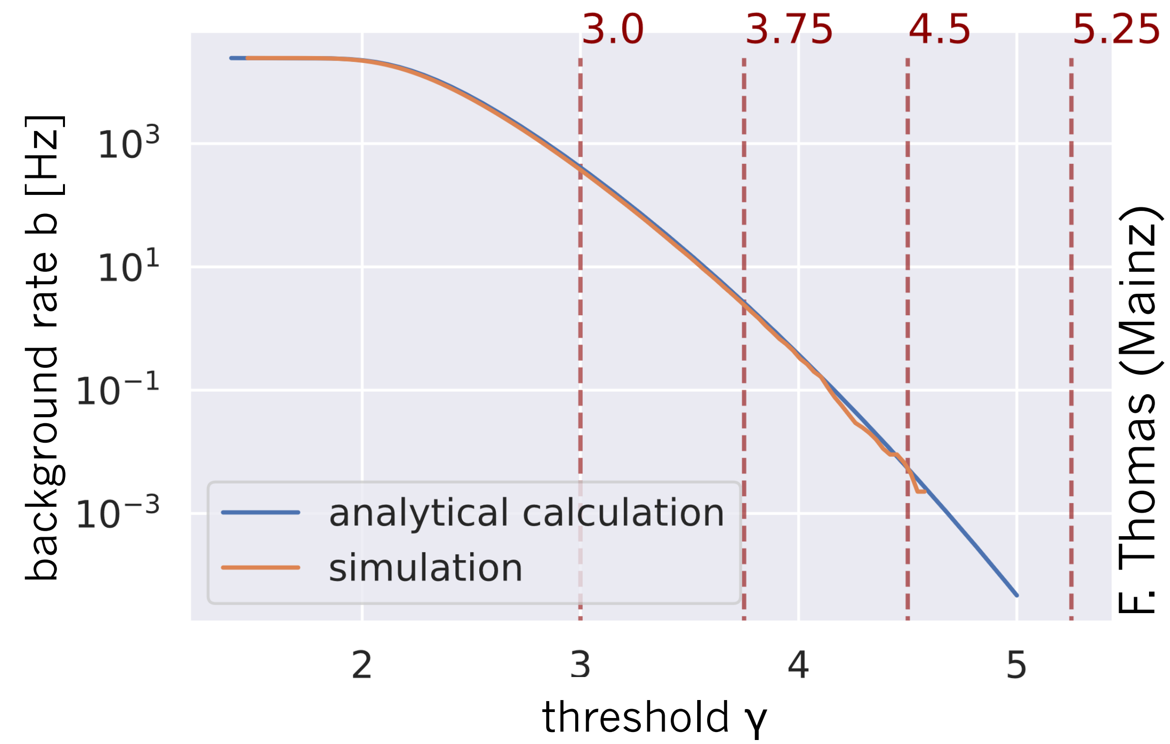


Thermal noise

- assume white spectrum
- temperature T=10K

Threshold γ

- determines background rate *b*
- determines effective volume V_{eff}



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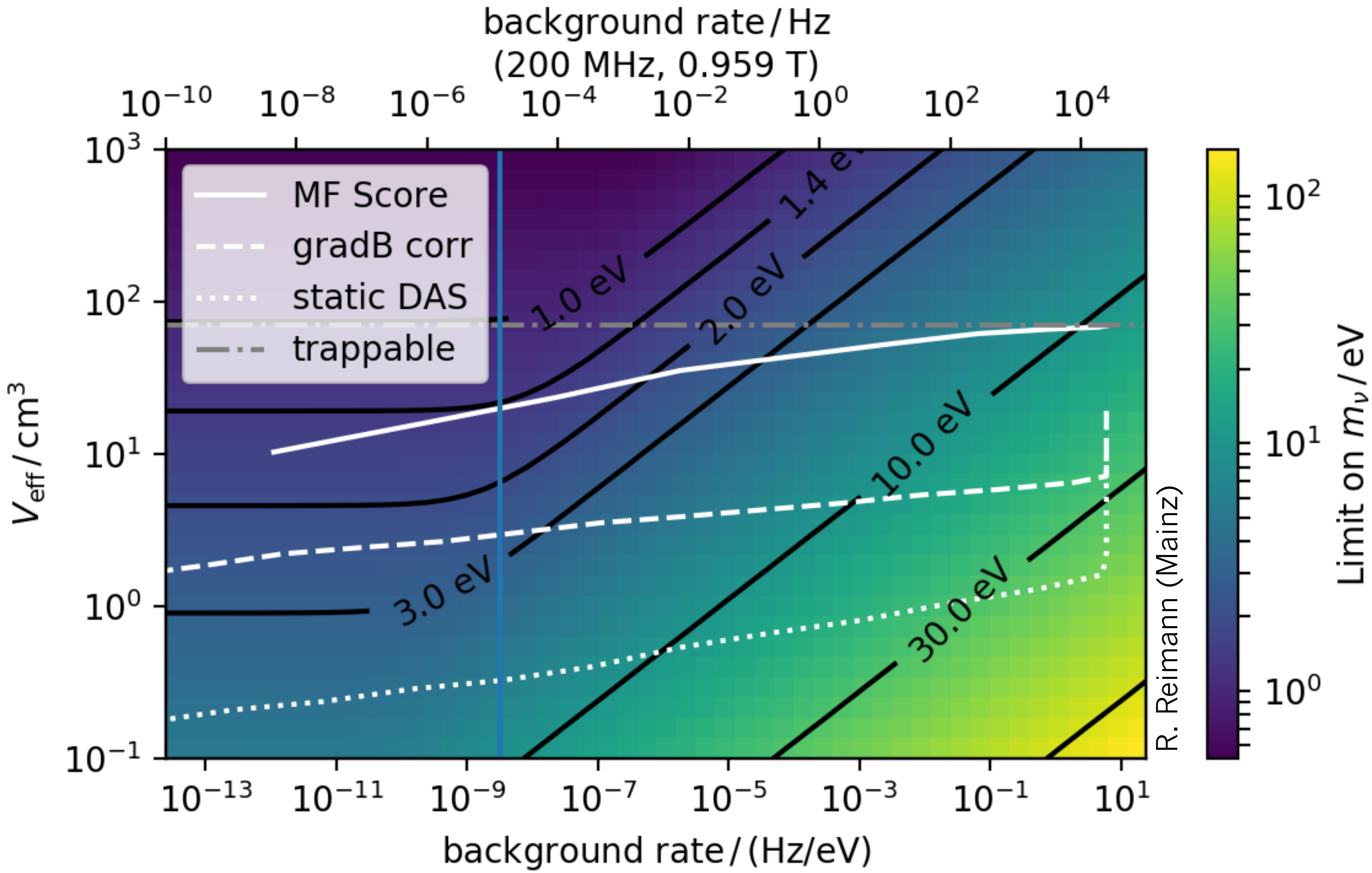
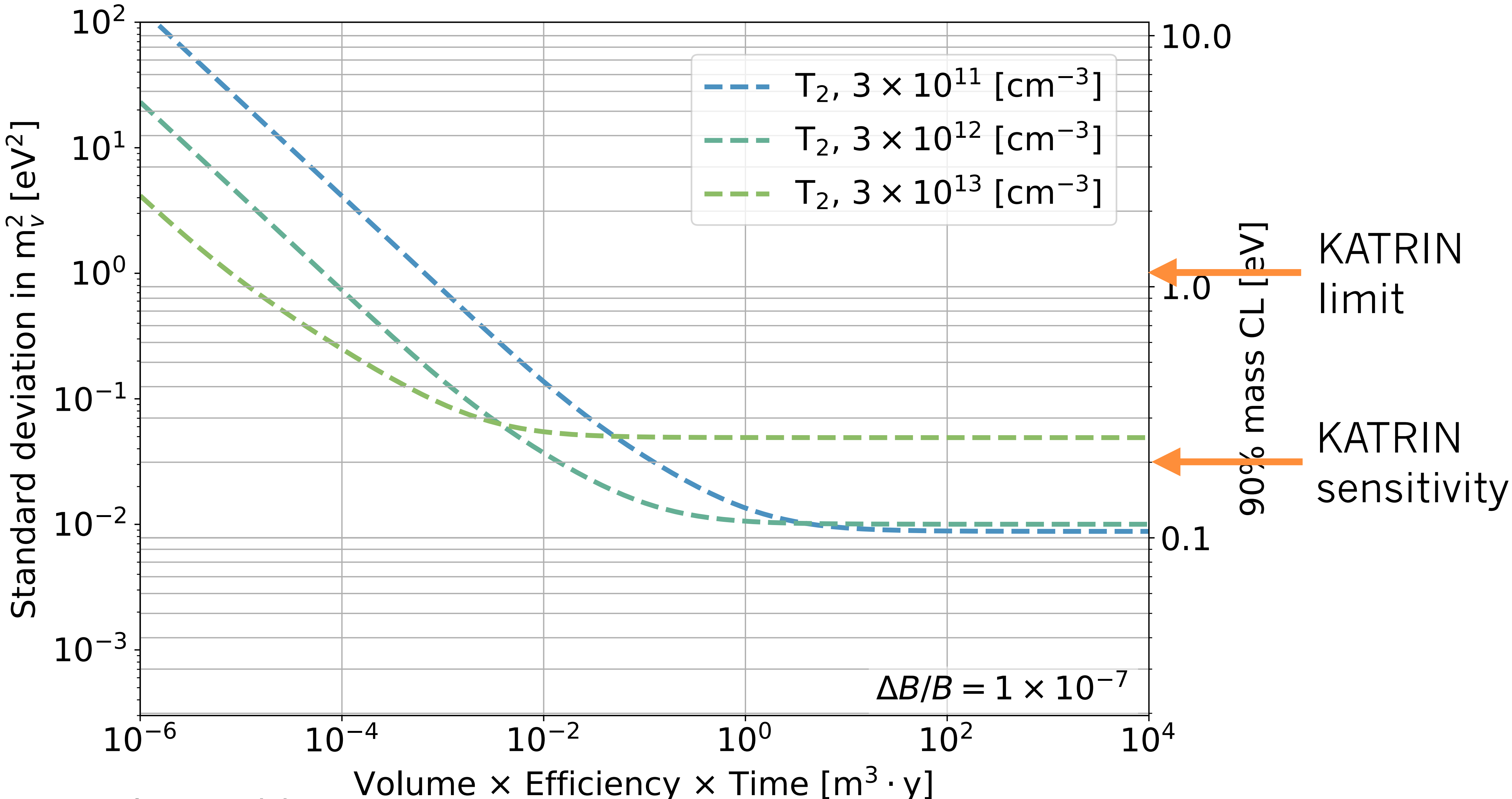
Sensitivity vs backround



Need very fast and very accurate signal simulation!

Potential for neutrino mass?



Sensitivity limited by

- density of tritium gas → rest gas interactions
- molecular excitations in T_2
  - ▸ need **atomic tritium**

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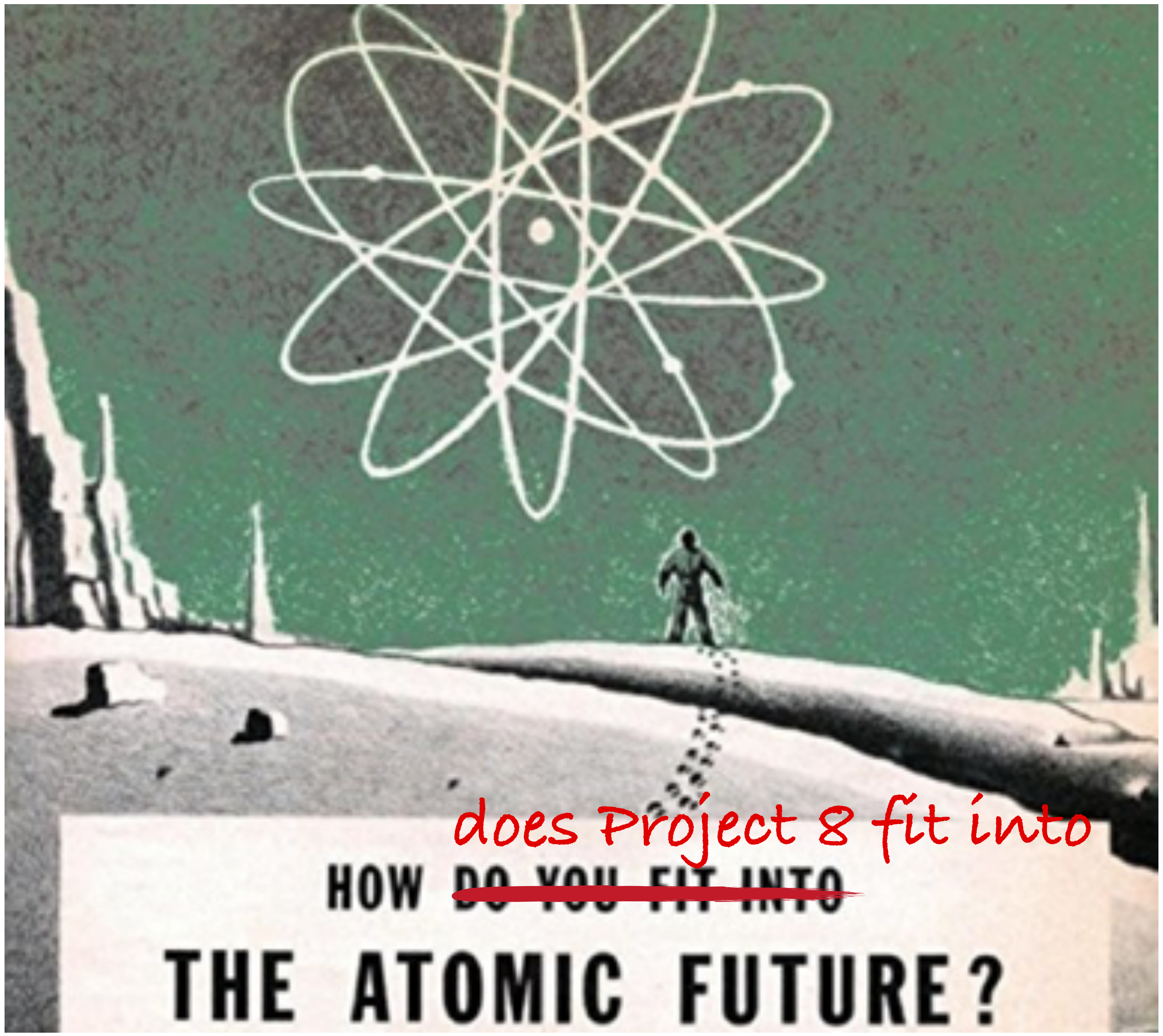
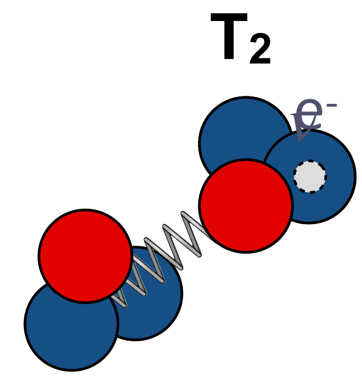
Molecular tritium limitations





Molecular excitations
in ^{3}He daughter molecule

- blur tritium endpoint
  - fundamental limit to measurement of ν-mass

Need atomic tritium
for **ultimate** experiment!

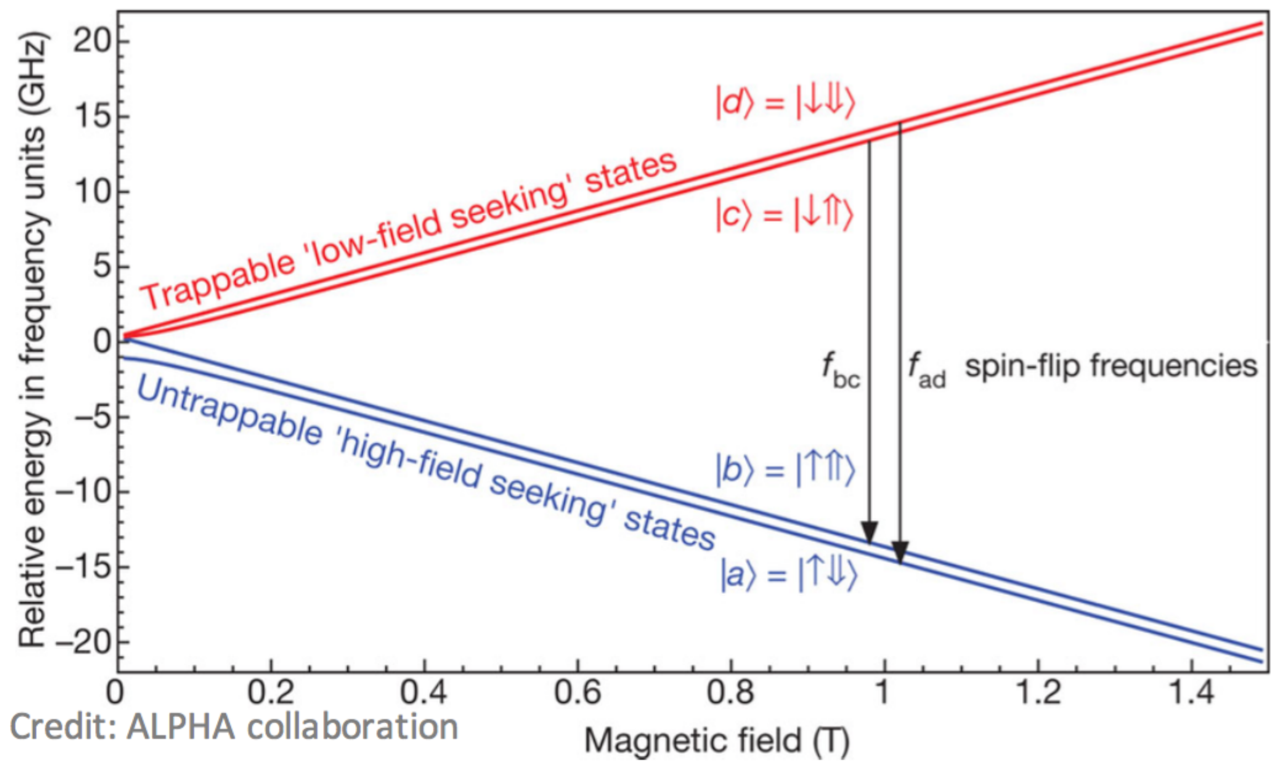
Magnetic guiding of neutral atoms

Dissociation of T_2

- heat to 2400K → easy!

Storage of atomic T

- recombination catalyzed by walls
  → difficult!
- H,D and T have unpaired e^-
  - non-zero magnetic moment μ
  - tend to (anti-)align with B-field if change is adiabatic



Credit: ALPHA collaboration

Potential energy

- $\Delta E = -\vec{\mu}\cdot\vec{B}$

→ follow field minimum

Can trap neutral atoms in magnetic minimum!

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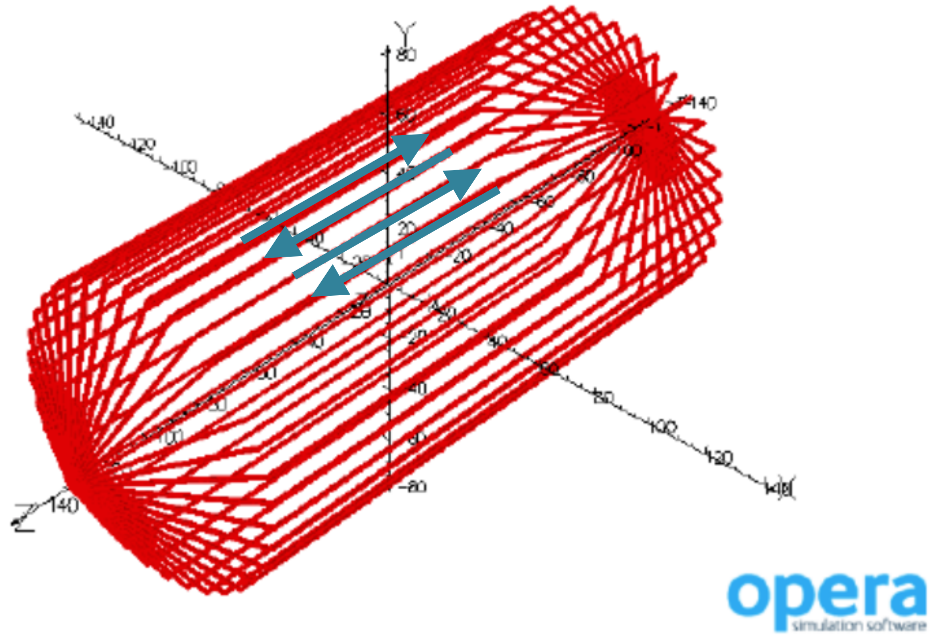
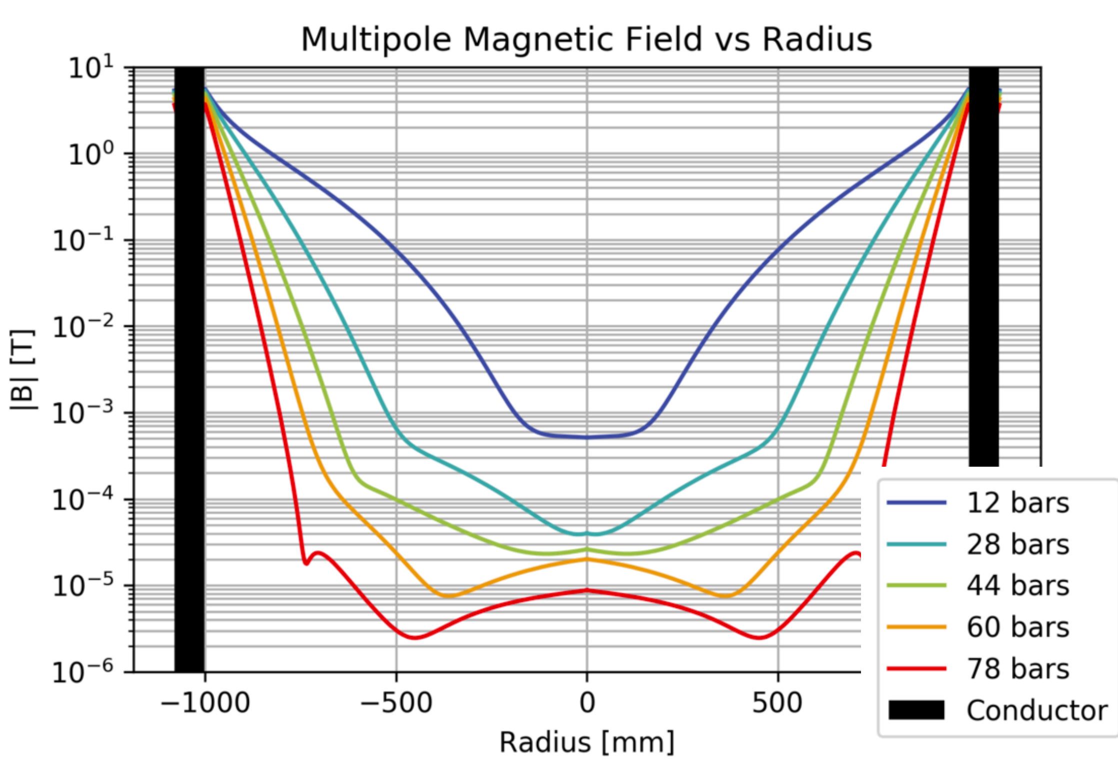
Atom trapping





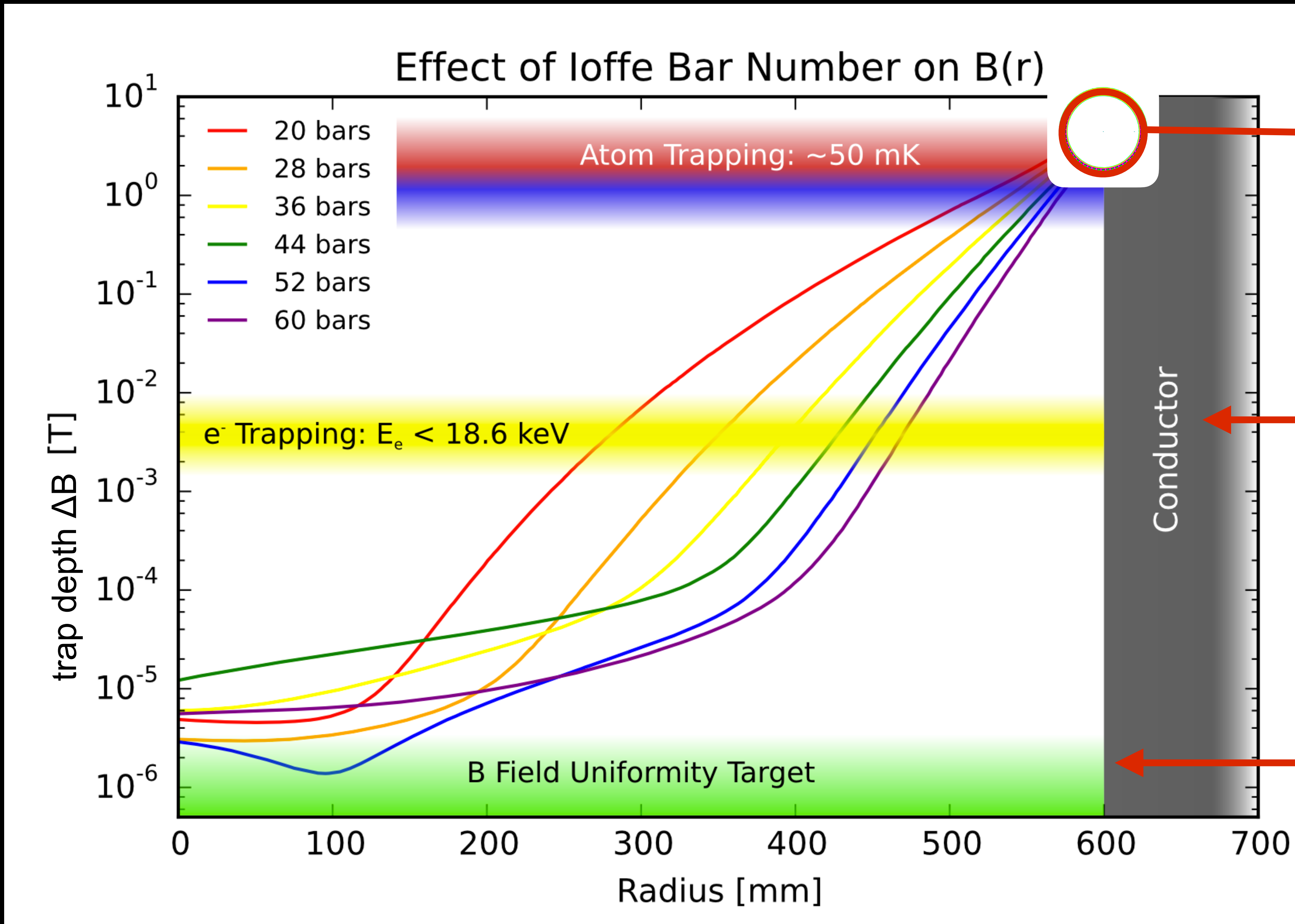
Studying Ioffe-Pritchard trap

- similar to UCN and anti-hydrogen traps (ALPHA)
- plausible field step
  - $\Delta B = 2T$
- limit thermal loss fraction
  - $\varepsilon_{loss} = 10^{-10}$
- maximum allowed temperature
  - T_{max} = **30mK**

Challenges

- cooling from 2400K to sub-Kelvin level
- keep high T/T_2 purity
  - molecular T_2 not trapped!
- field uniformity in central region

Phase IV: trap challenges



Conductor + structure size

↕

effective volume

↕

target uniformity level

A. Lindman (Mainz)

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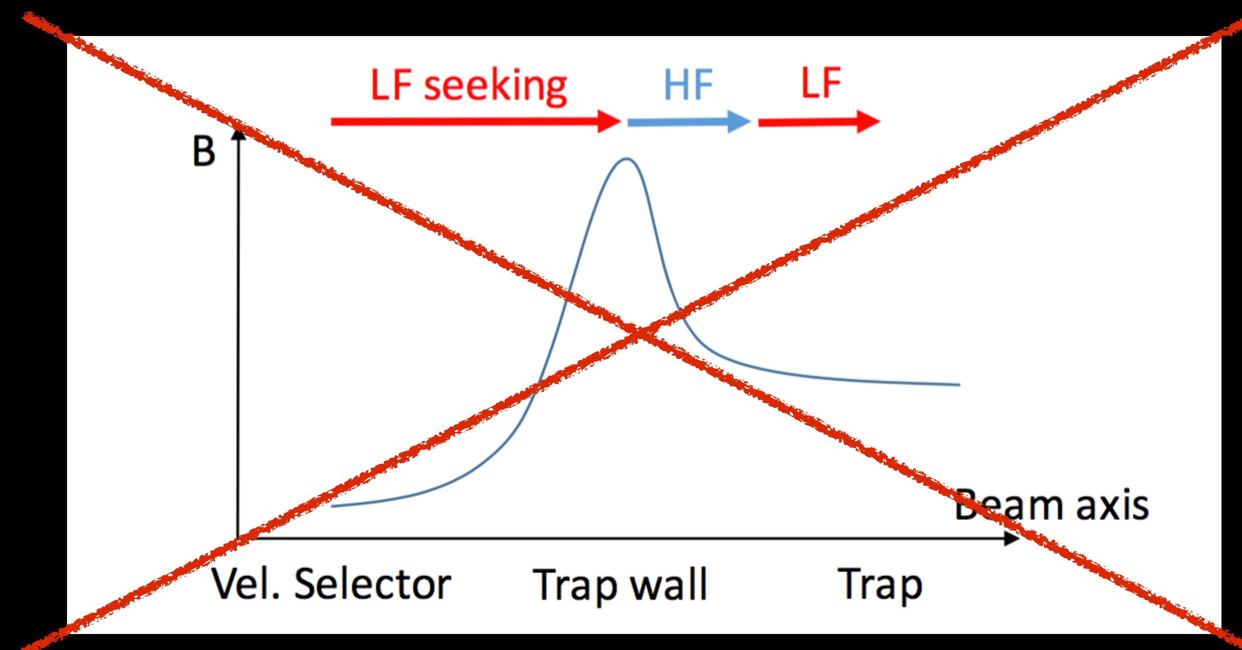
How to fill the trap?

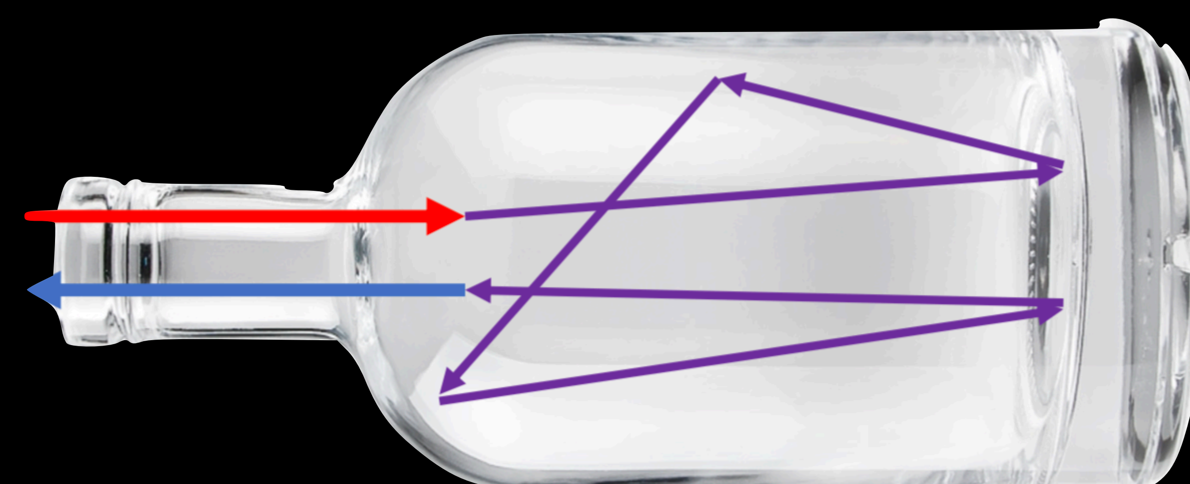
Spin-flip loading ?

- Flip atom spin at trap edge
  - Carry atoms over potential wall (+ energy loss)
- But: stimulated emission
  - will lose trapped atoms



Cornucopia* loading

- Blow cold atoms into trap
  → accept loss through entrance hole
- required input flux for 1cm hole @ 50mK
  - $5 \cdot 10^{12}$ atoms/sec



S. Böser, Mainz

* horn of plenty

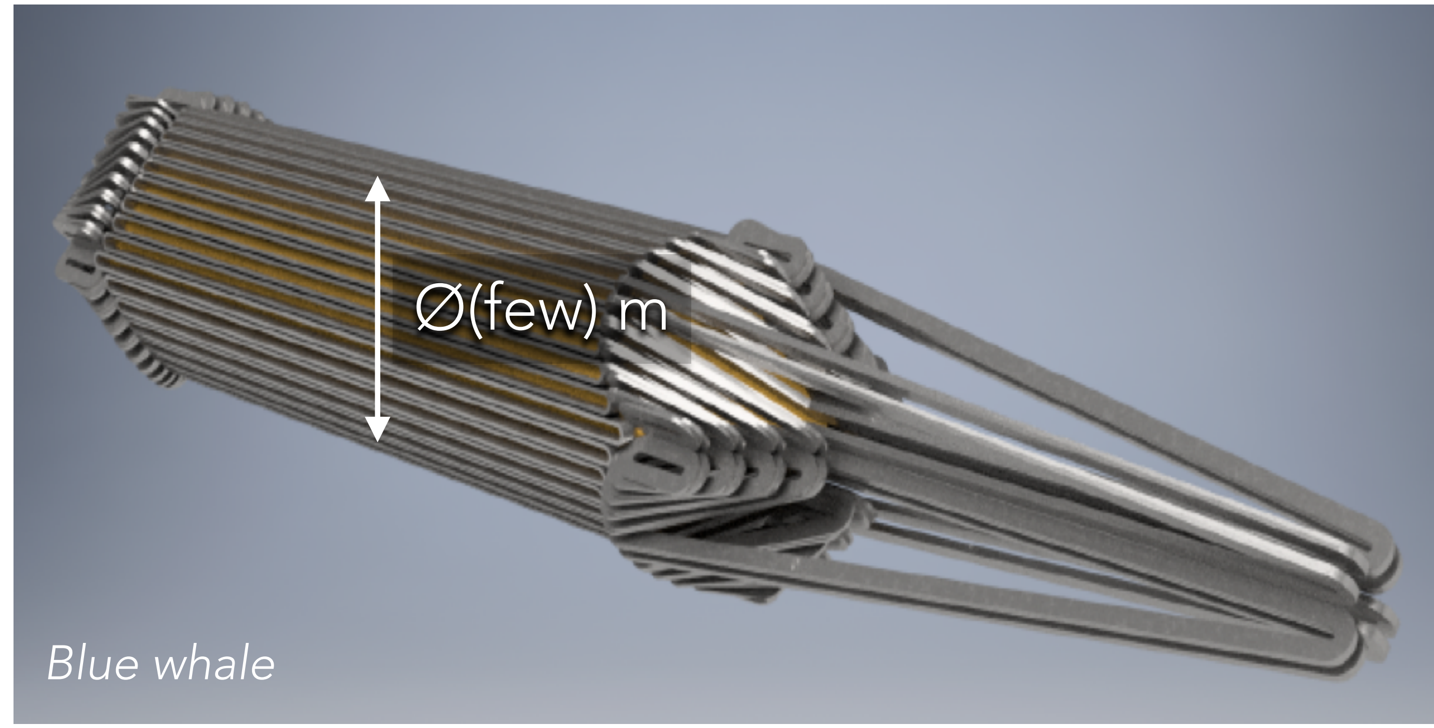
JGU

Project8 — Phase IV: first designs

Design challenges

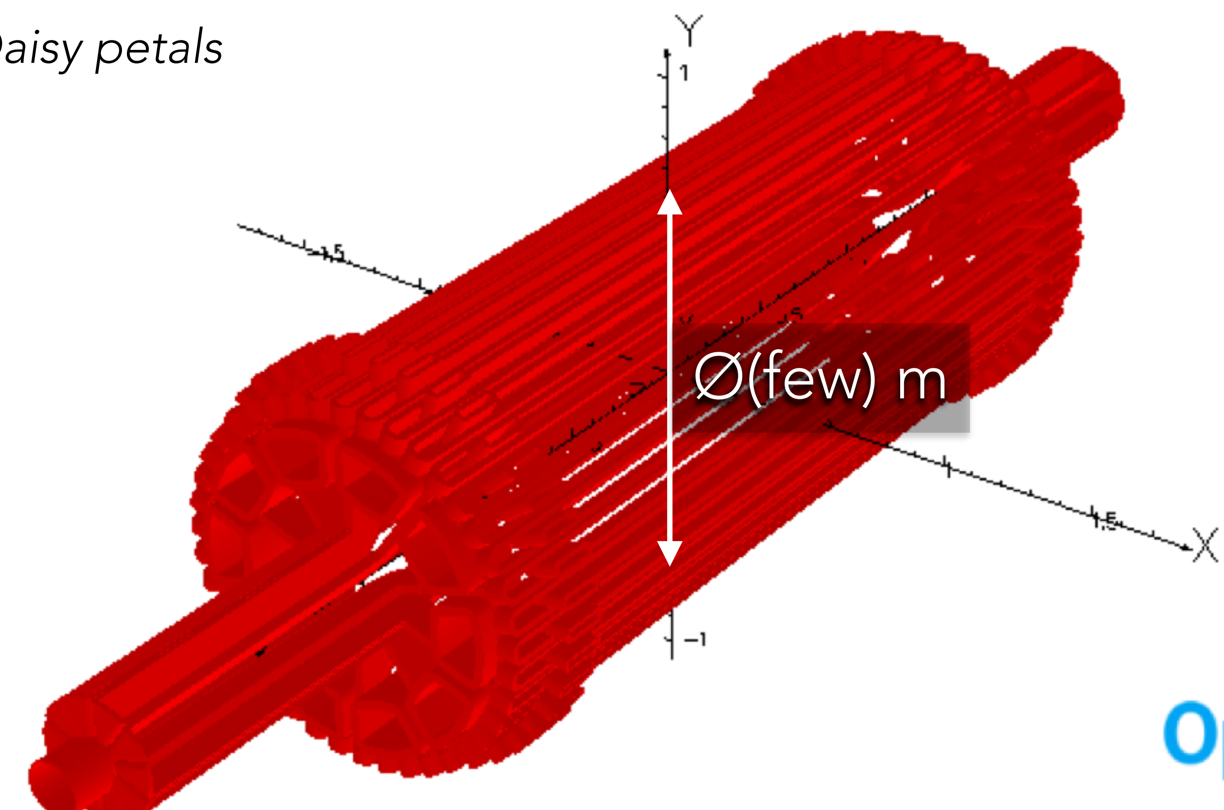
- keep 2T magnetic contours outside all structures
- provide very large trap volume (m^3)
- provide very homogenous fiducial volume (m^3)
- manufacturing and operation stability
- compatible with antenna array for read-out of CRES signal

Final design still some way out!



Blue whale

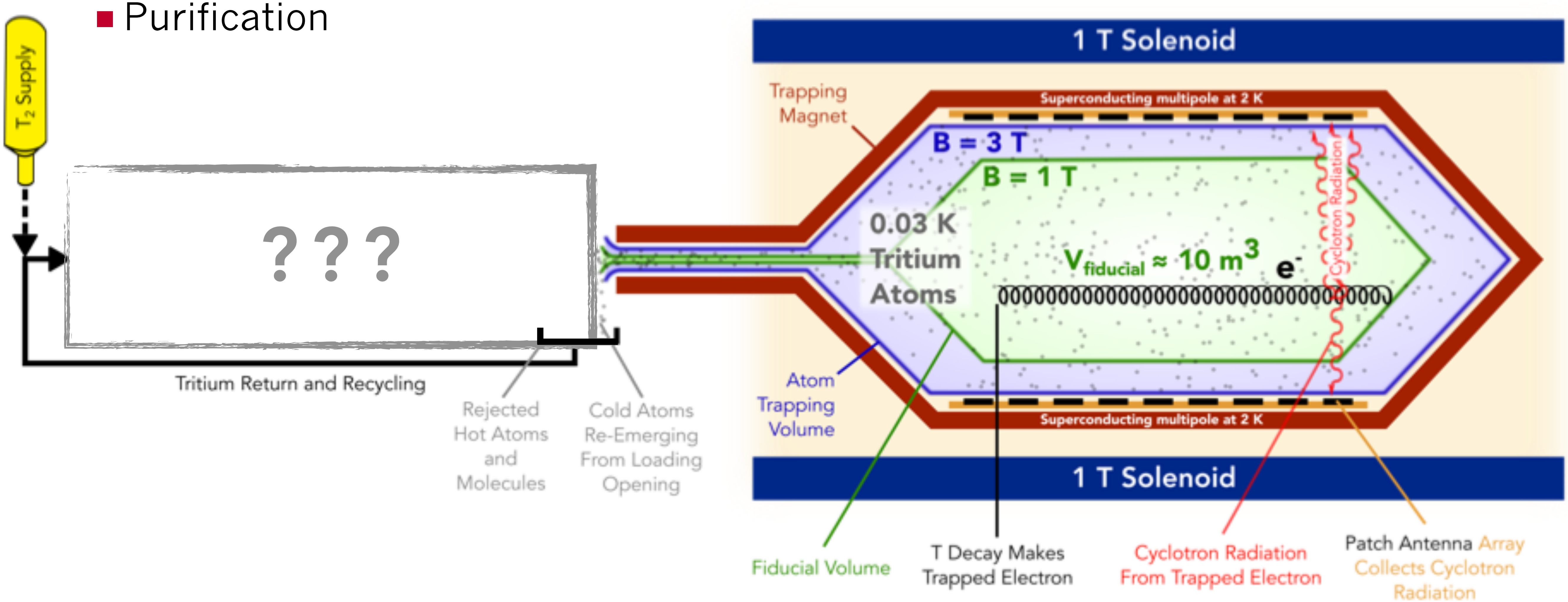
Daisy petals



Phase IV: Conceptual design

Atomic T source

- Dissociation
- Cooling
- Purification



T_2 dissociation schemes

Microwave dissociation @ 151MHz

- well tested for hydrogen
- chemical reaction with glass
  - not feasible with tritium!

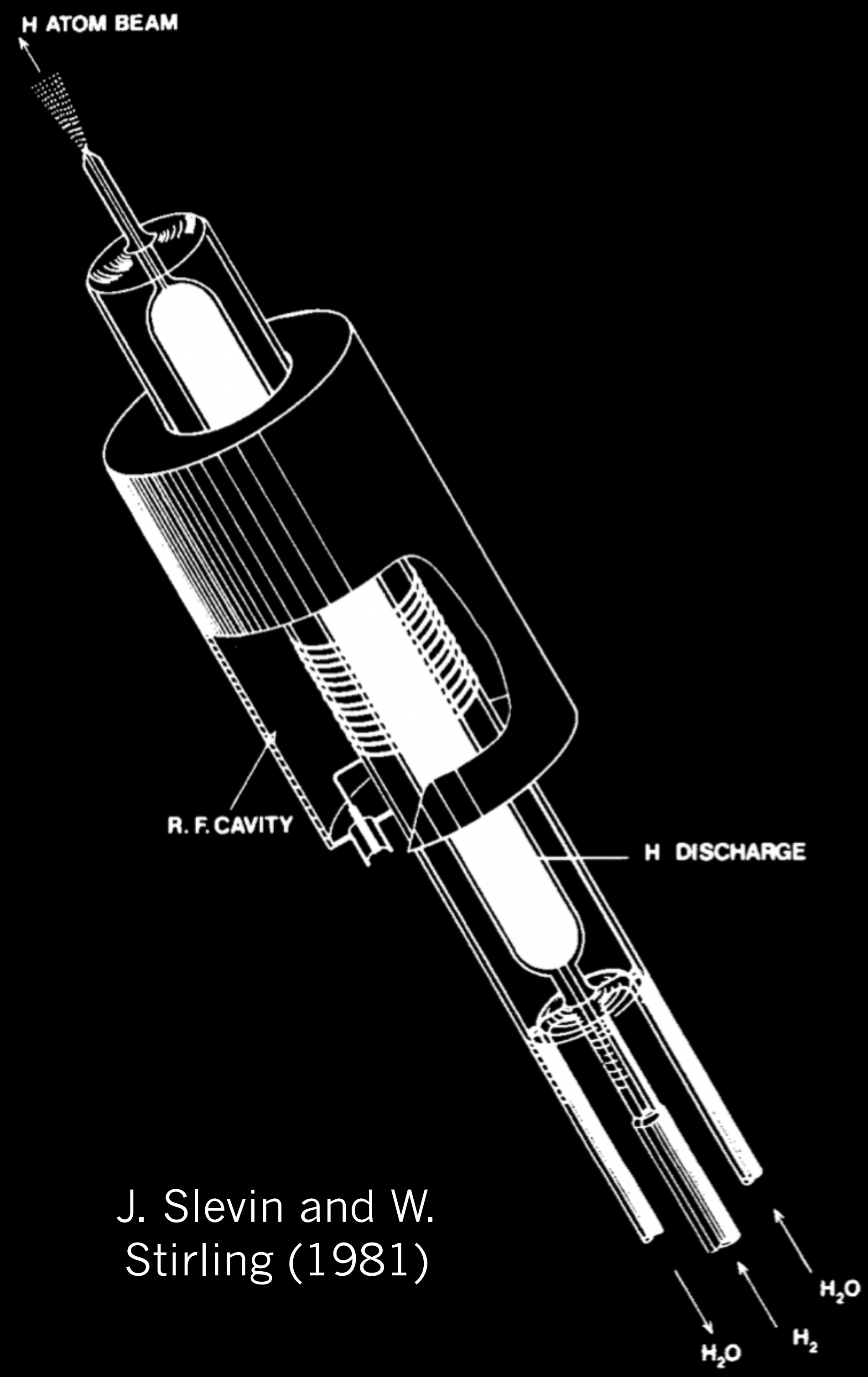
Laser dissociation

- dissociation energy 4.52eV
  - wavelength < 274nm
- required laser power ~ kW!

Coulomb explosion

- difficult to re-neutralize

...



J. Slevin and W. Stirling (1981)

PRISMA

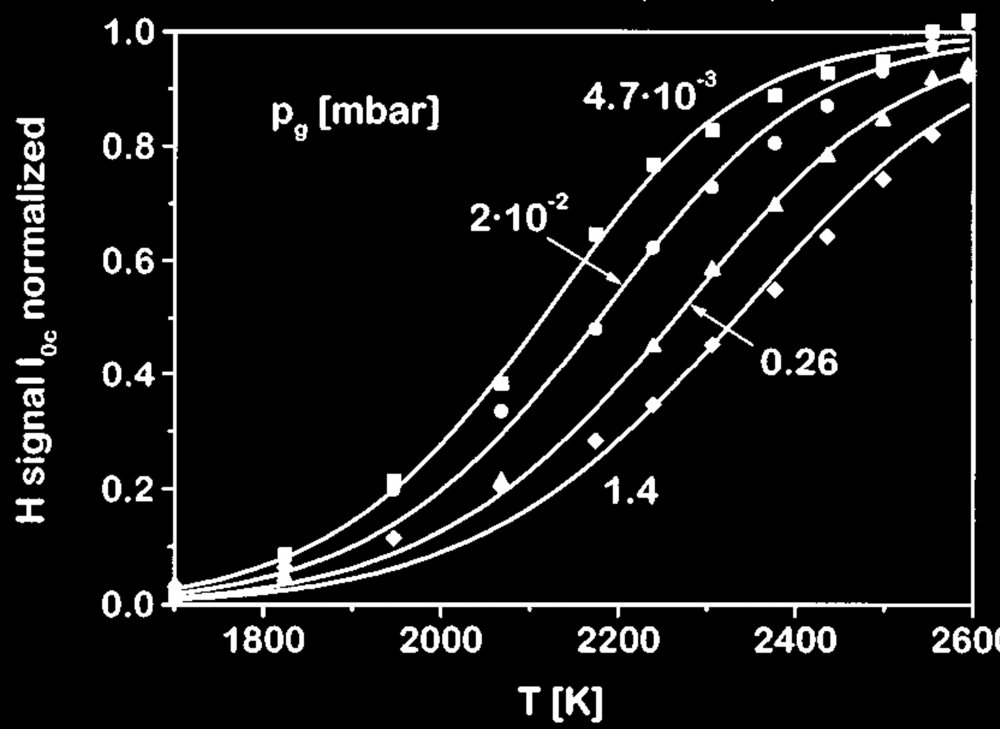
JG|U

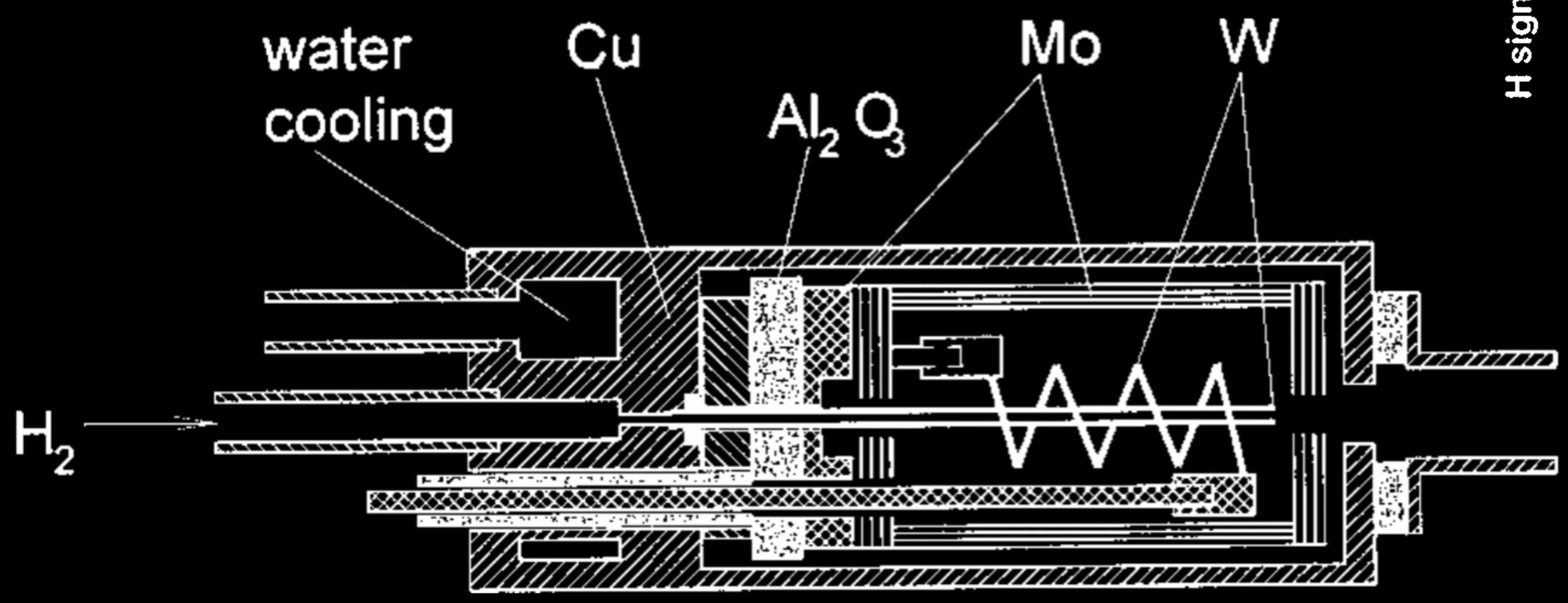
Thermal Dissociator

Hot tungsten tube heated to 2500K

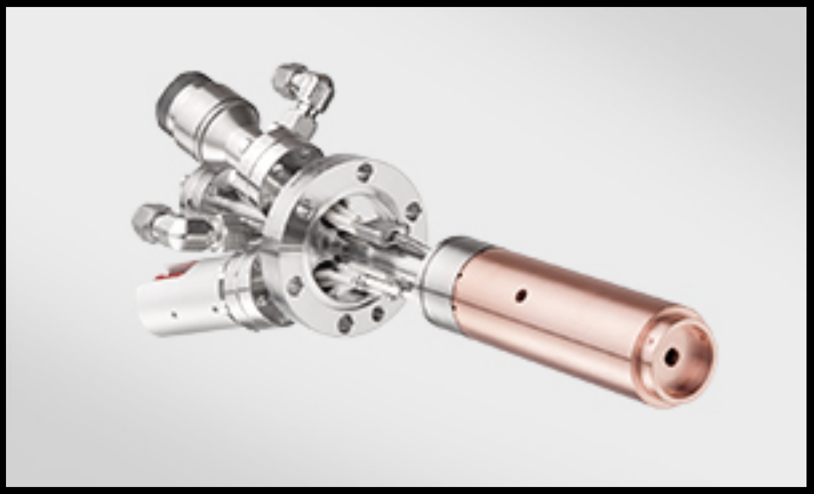
- radiatively or
- by electron bombardment
  - commercial devices available

Tscherisch (1999)





K.G. Tschersich and V. von Bonin (1998)



HABS hydrogen cracker

Cooling atomic hydrogen

Hydrogen recombination

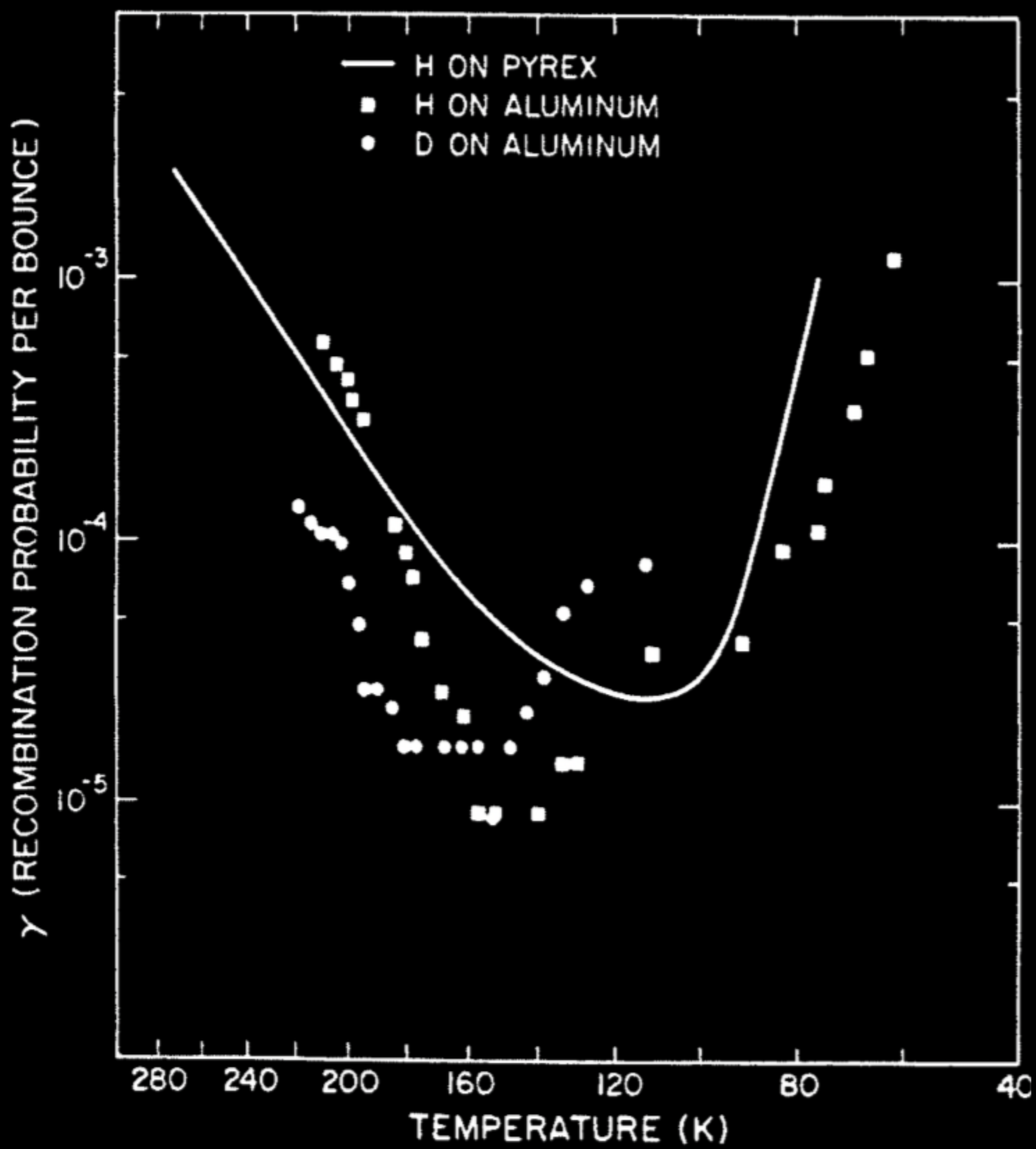
- two-body gas interactions
  - small cross-sections
- wall interactions
  - long *sticking* time
  - dominates recombination

Probability depends on

- temperature
- material
- hydrogen isotope

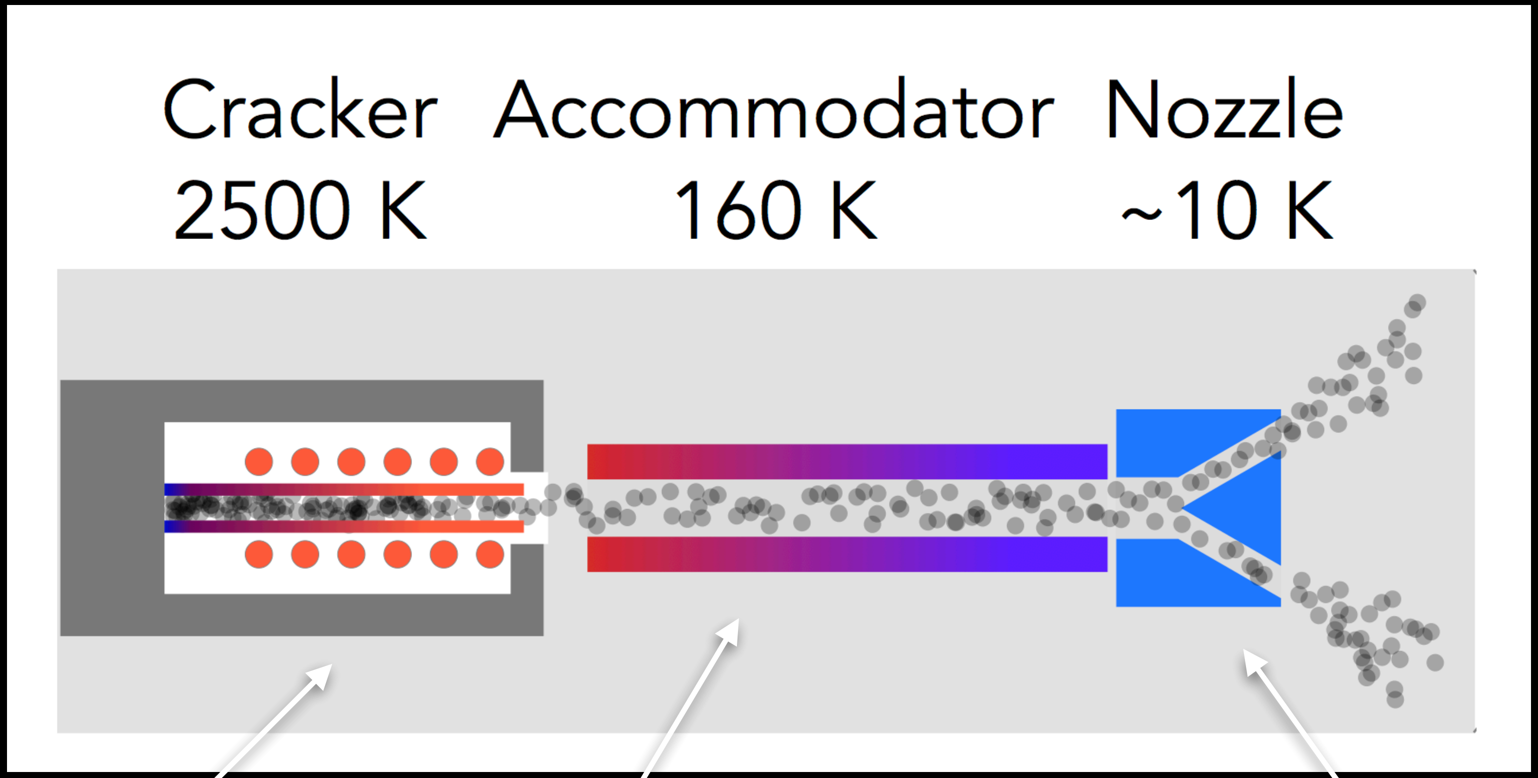
Superfluid He containment

- does not work for tritium!



D. A. Knapp et al., AIP conference proceedings (1984)
Wood and H. Wise, J. Chem. Phys. 66, 1049, (1962)

Cooling tritium atoms



Cracker
95% purity

Accommodator
(liquid nitrogen)

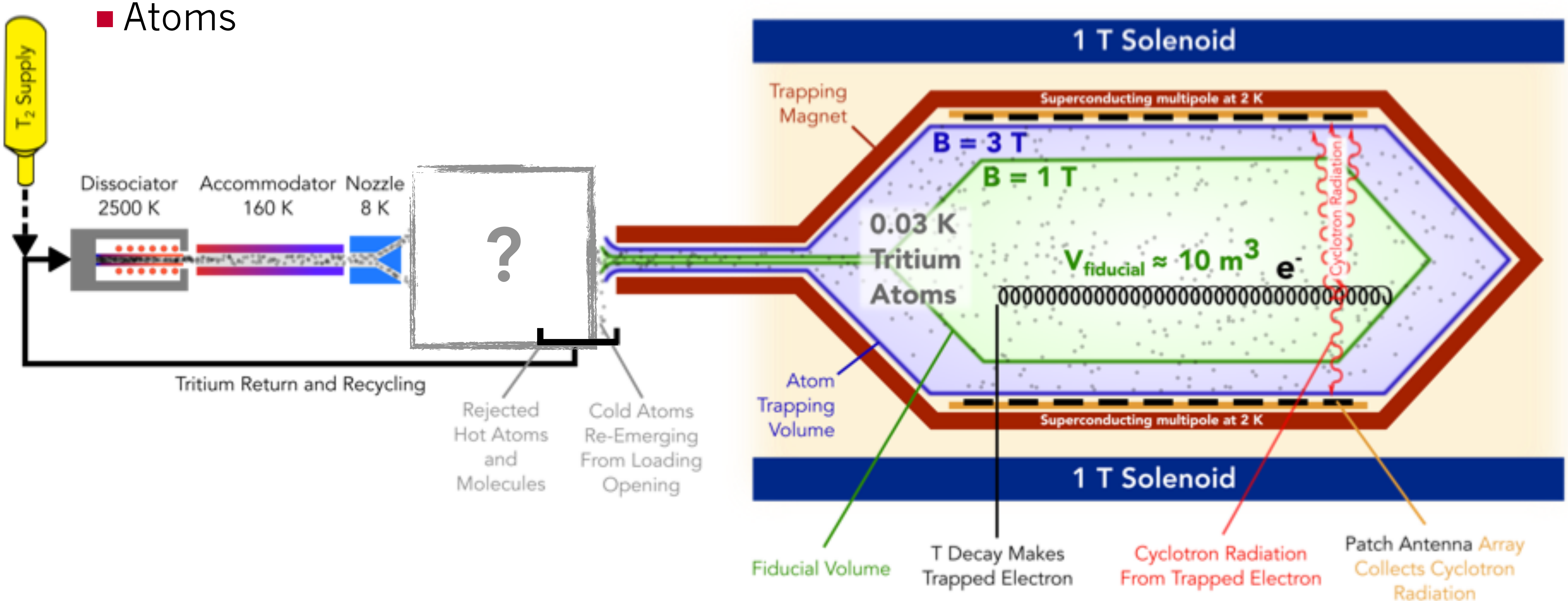
Final nozzle

- design for few bounces
- freeze-out 30K
  → periodic purging

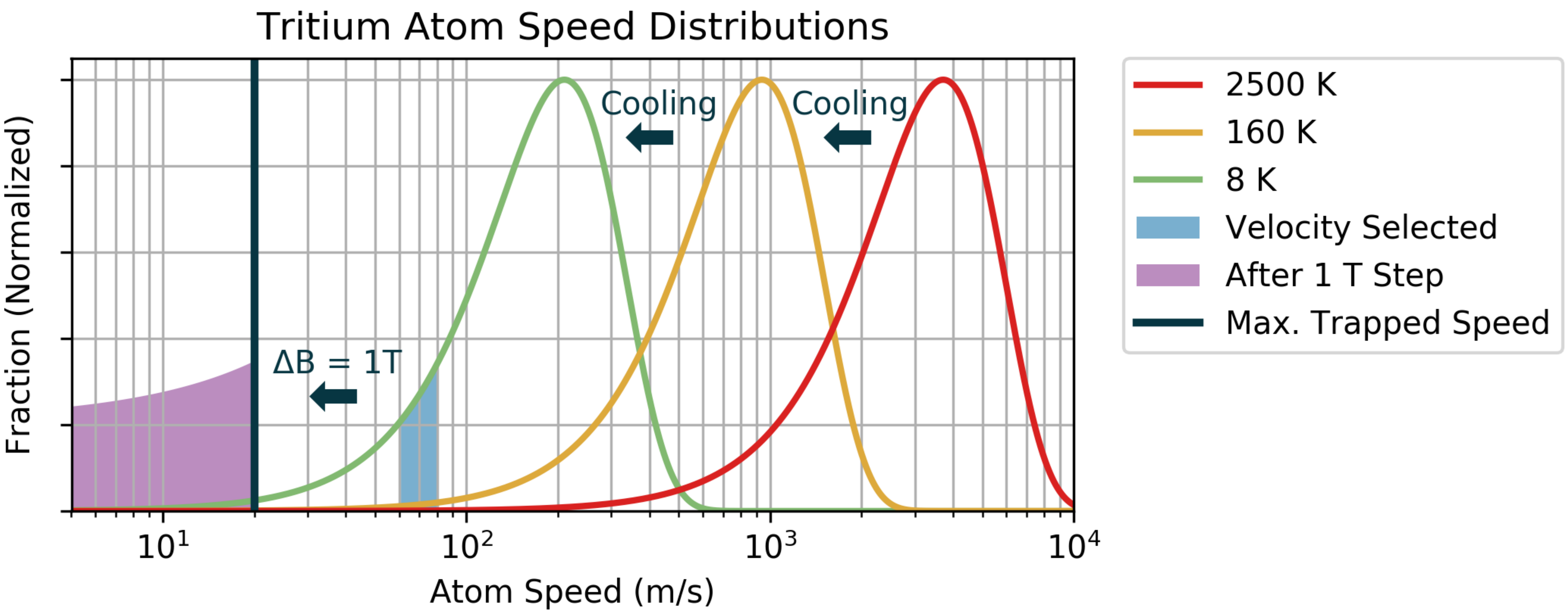
Conceptual design II

Selector for

- Velocity
- State
- Atoms



Cooling tritium atoms



Magnetic field step into solenoid

- energy loss for trapped low-field seekers

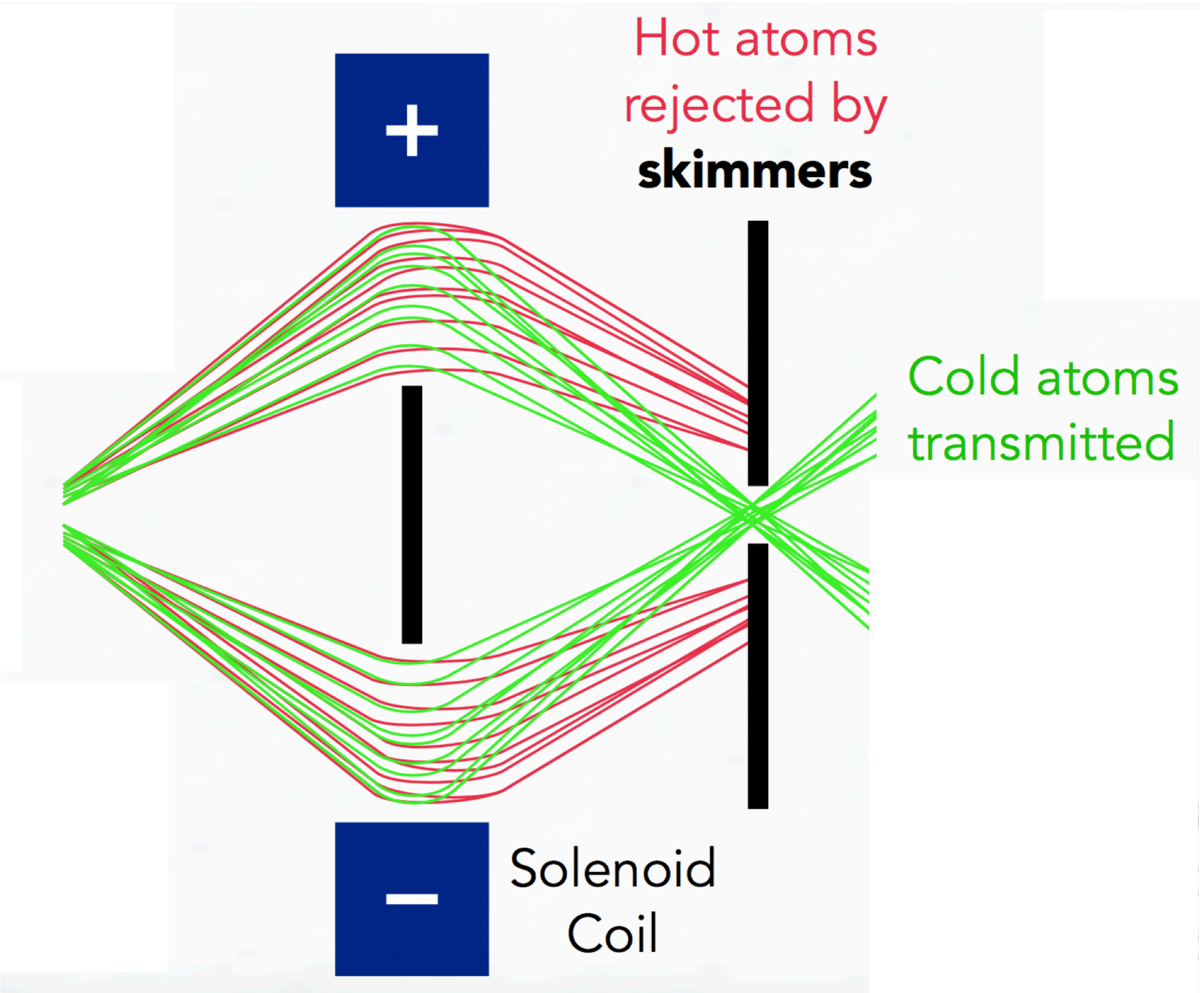
Selection of “*cold*” velocity slice

- need 10^{19} atoms/sec at the source!

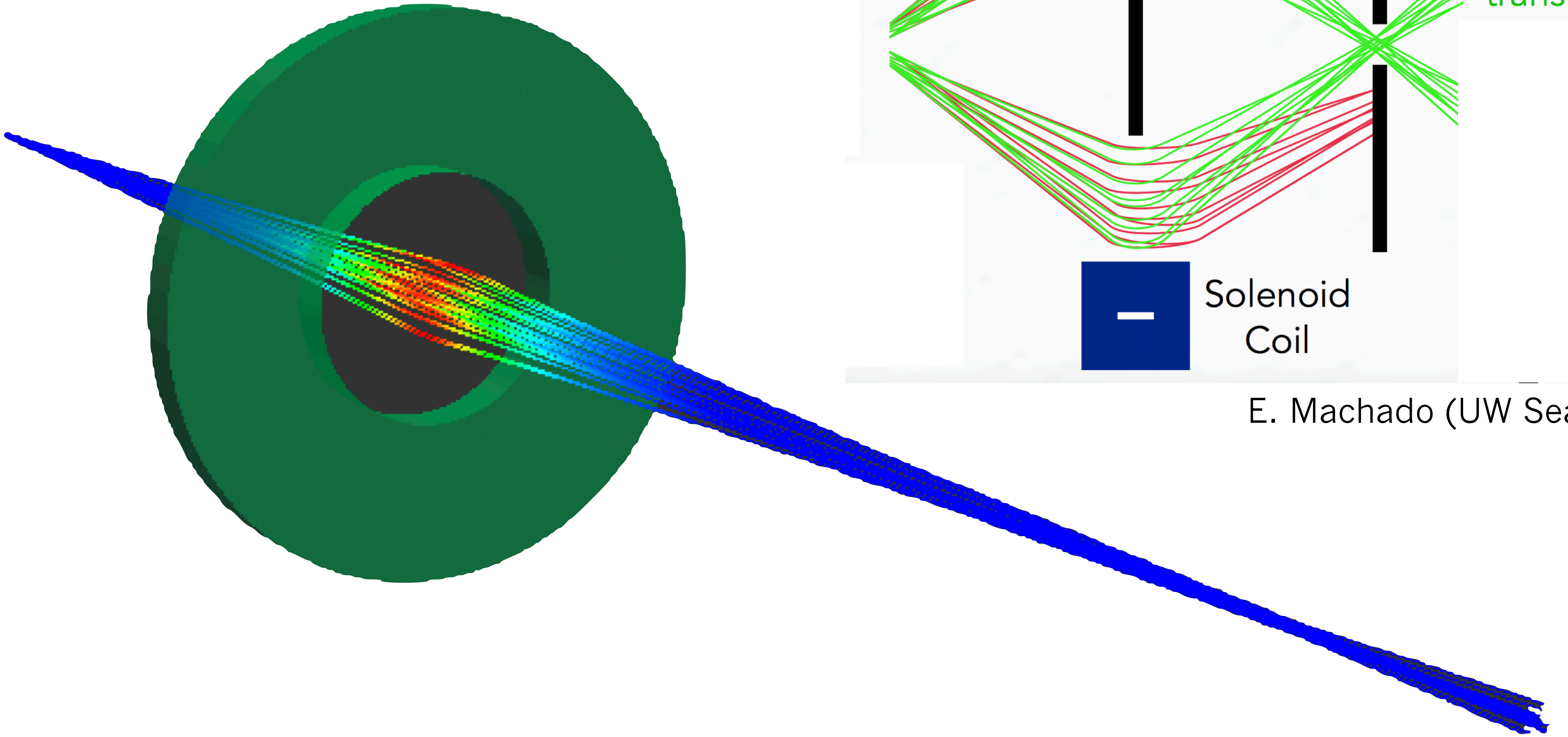
Velocity and State selector I

Magnetic moment μ
→ can build thin lens for atomic T

- cold atoms focused on inlet
- hot atoms rejected by skimmers



E. Machado (UW Seattle)



PRISMA

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Velocity and State Selectors II

Only atomic T guided magnetically

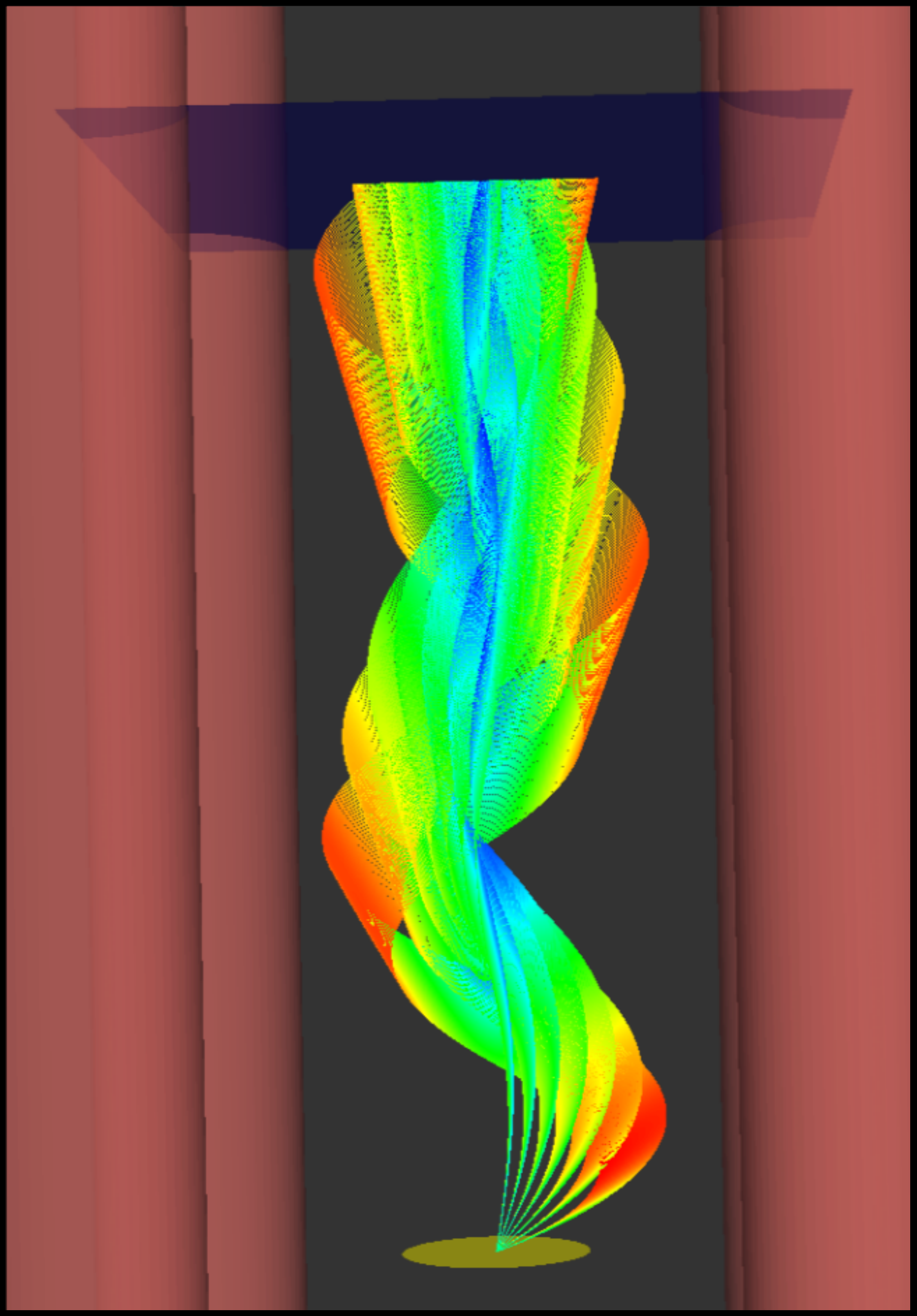
- (bend) quadrupole with skimmers

Tune acceptance for

- $T_{out} = \mathcal{O}(50mK)$
- T_2 contammination < 10^{-5}
  - efficiency $\varepsilon_{cold} \sim 25\%$-$100\%$

Initial design study

- works best if atoms are injected at angle w.r.t. tube axis

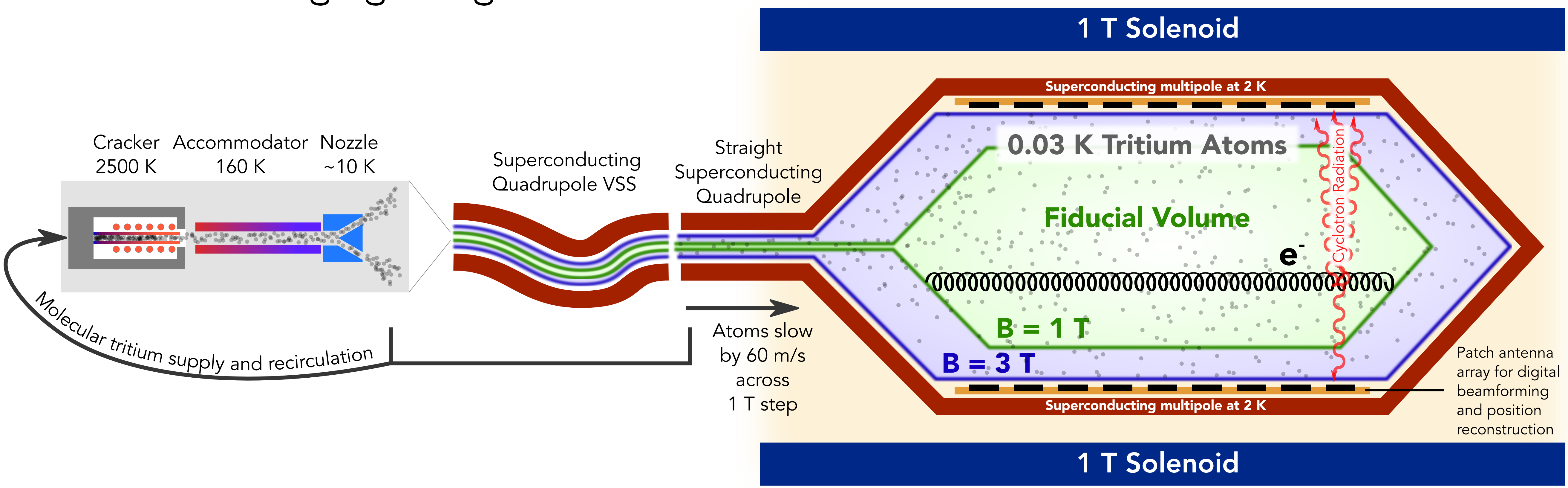


A. Etienney, INP Grenoble & U. Mainz

Phase IV: Conceptual design

Requirements

- $10 m^3$ fiducial volume at 10^{12} cm^{-3} atomic T density
  - challenging design



Early research focused on

- generation of a sufficiently **intense** and **cold** T_2 beam
- conceptual design for magnetic trapping

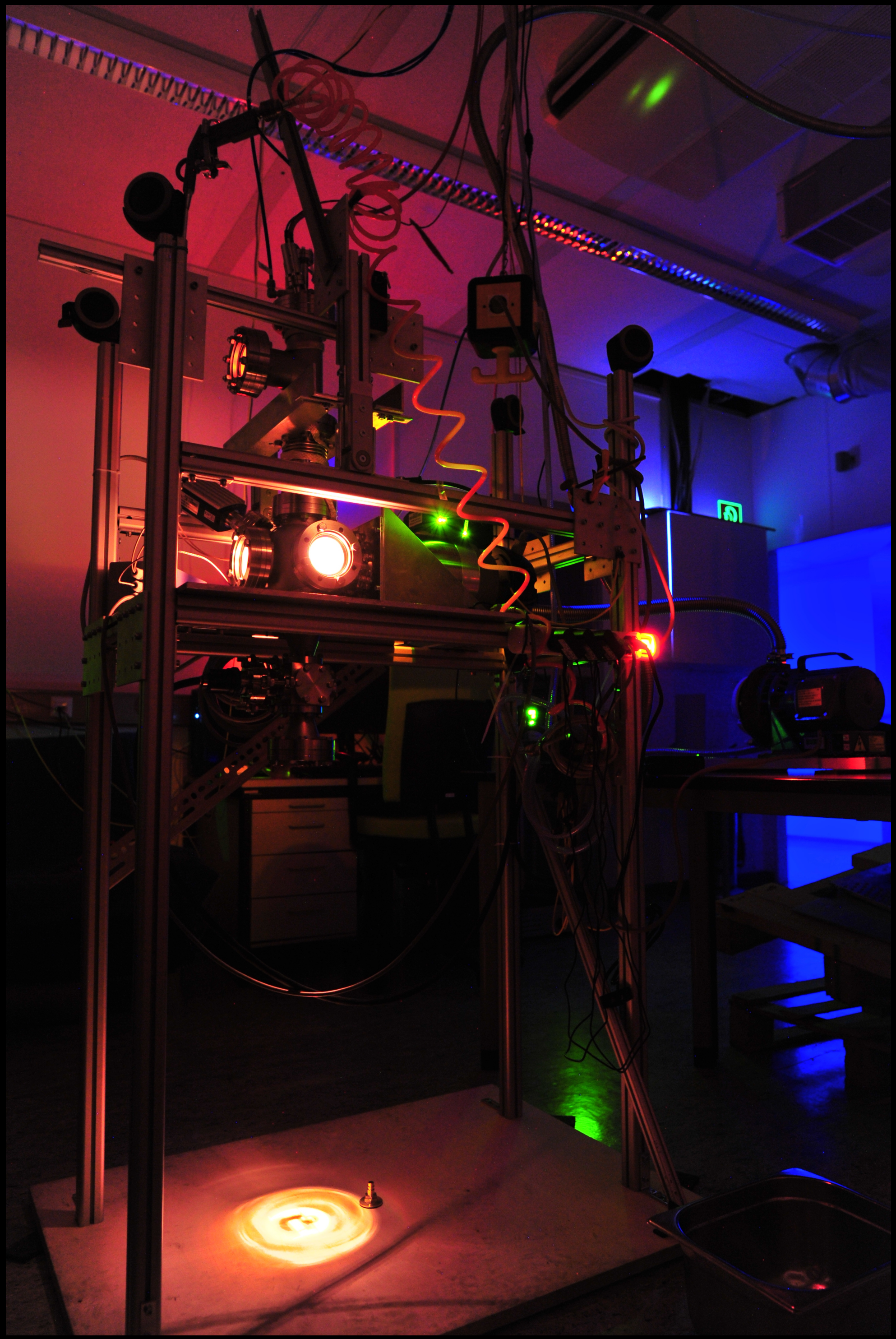
Atomic H-isotope teststand

Goals

- Verify conceptual designs
  - → Flow
  - → Temperature
  - → Purity

Approach

- Start with thermal cracker
  - establish atomic signal
  - start with H_2 and D_2



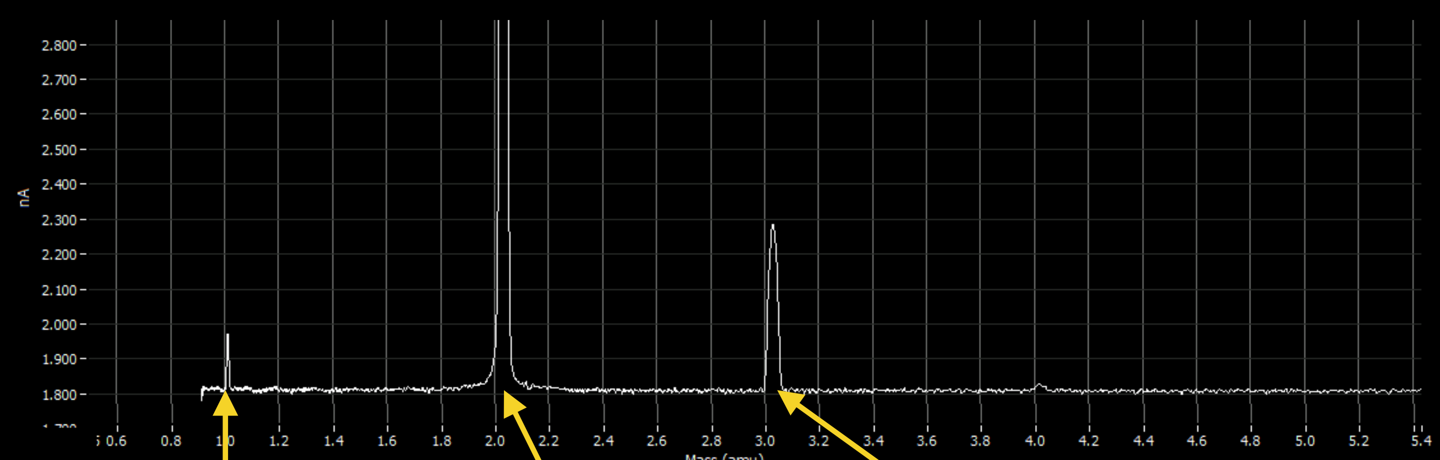
Mainz atomic source

Goals

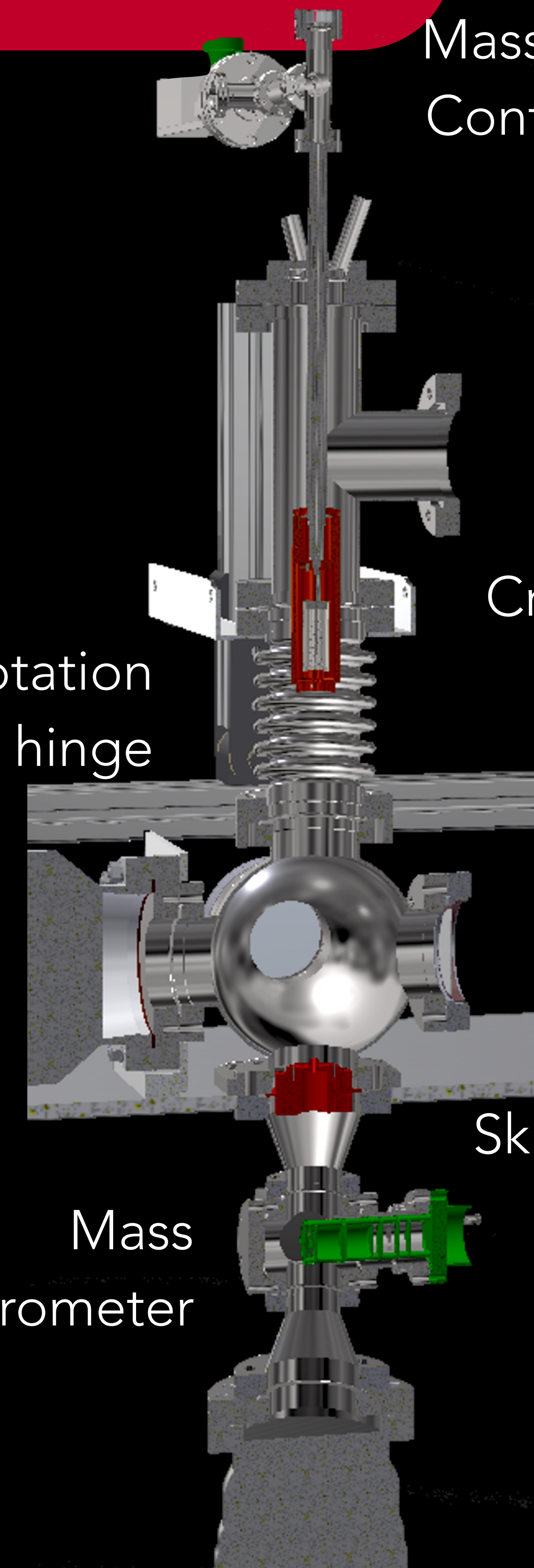
- Test commercial cracker
  - → spec'ed to 10^{17} atoms/sec
  - → can this be exceeded?
- Beam profile
  - → important for quadrupole injection scheme

Mass spectrography

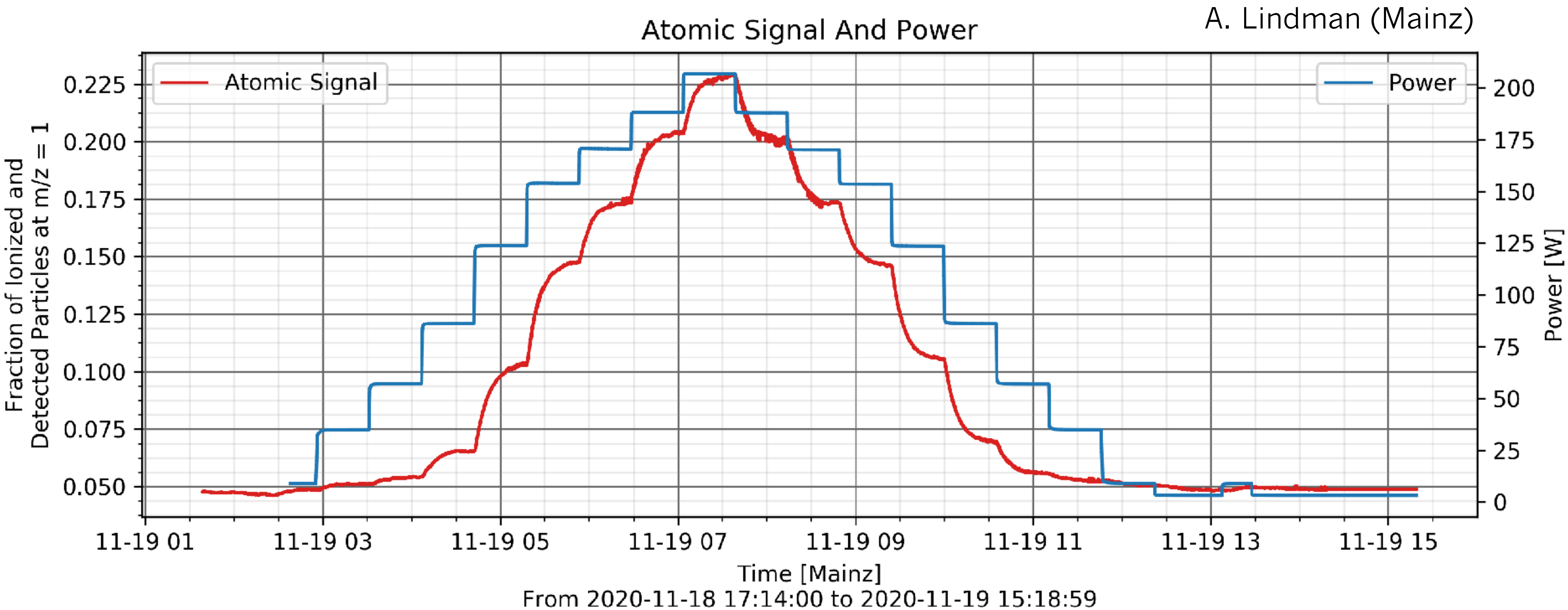
- Auto-resonant ion trap-based mass spectrometer



mass = 1 → H_1 mass = 2 → H_2 / D mass = 3 → HD

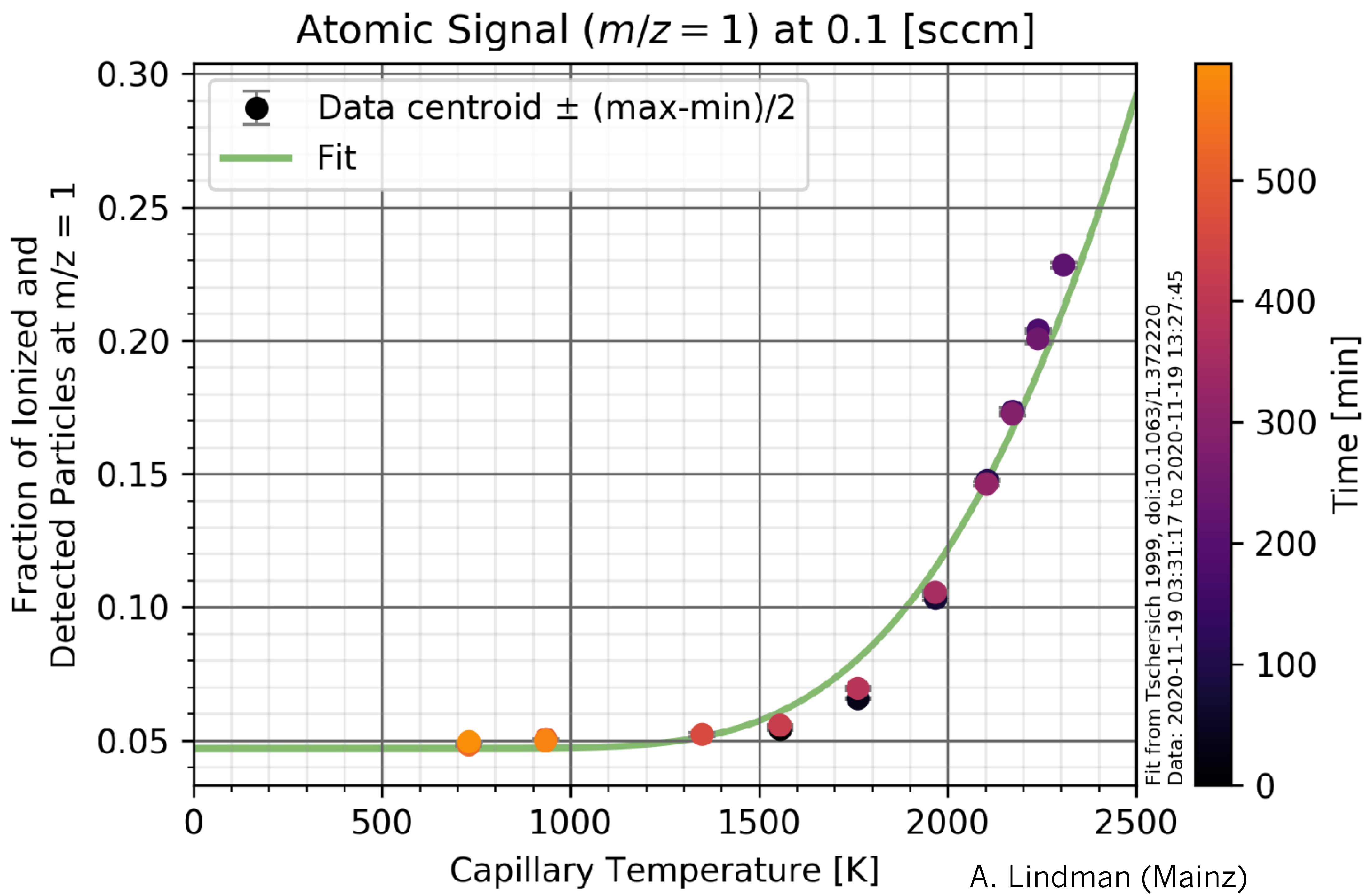


Mainz atomic source results



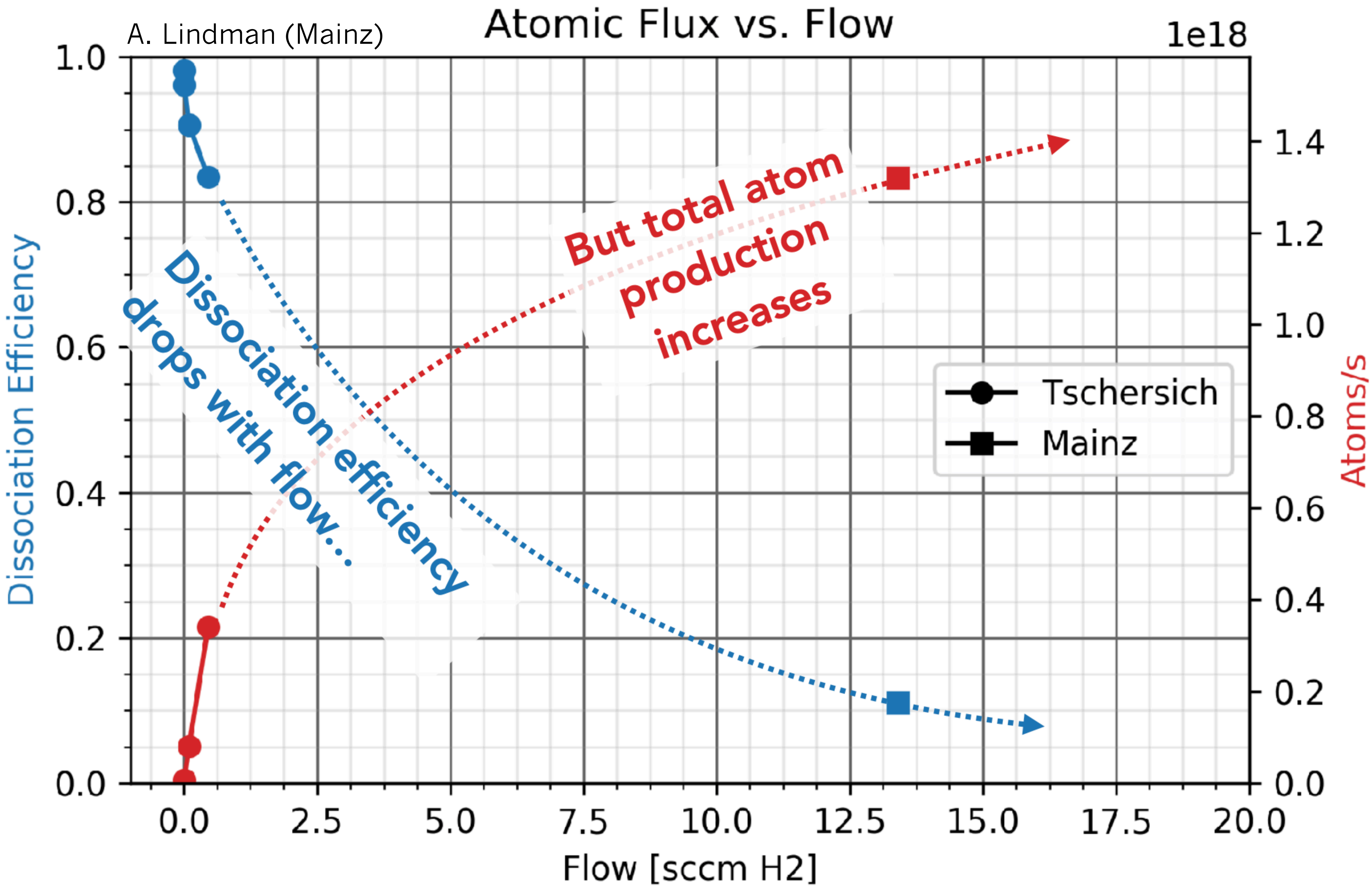
First atomic hydrogen beam!

Mainz atomic source results



A. Lindman (Mainz)

Mainz atomic source results



Monitoring beam quality: wire detector

Working principle

- Heat flow [W/m] … into H2 on wire:

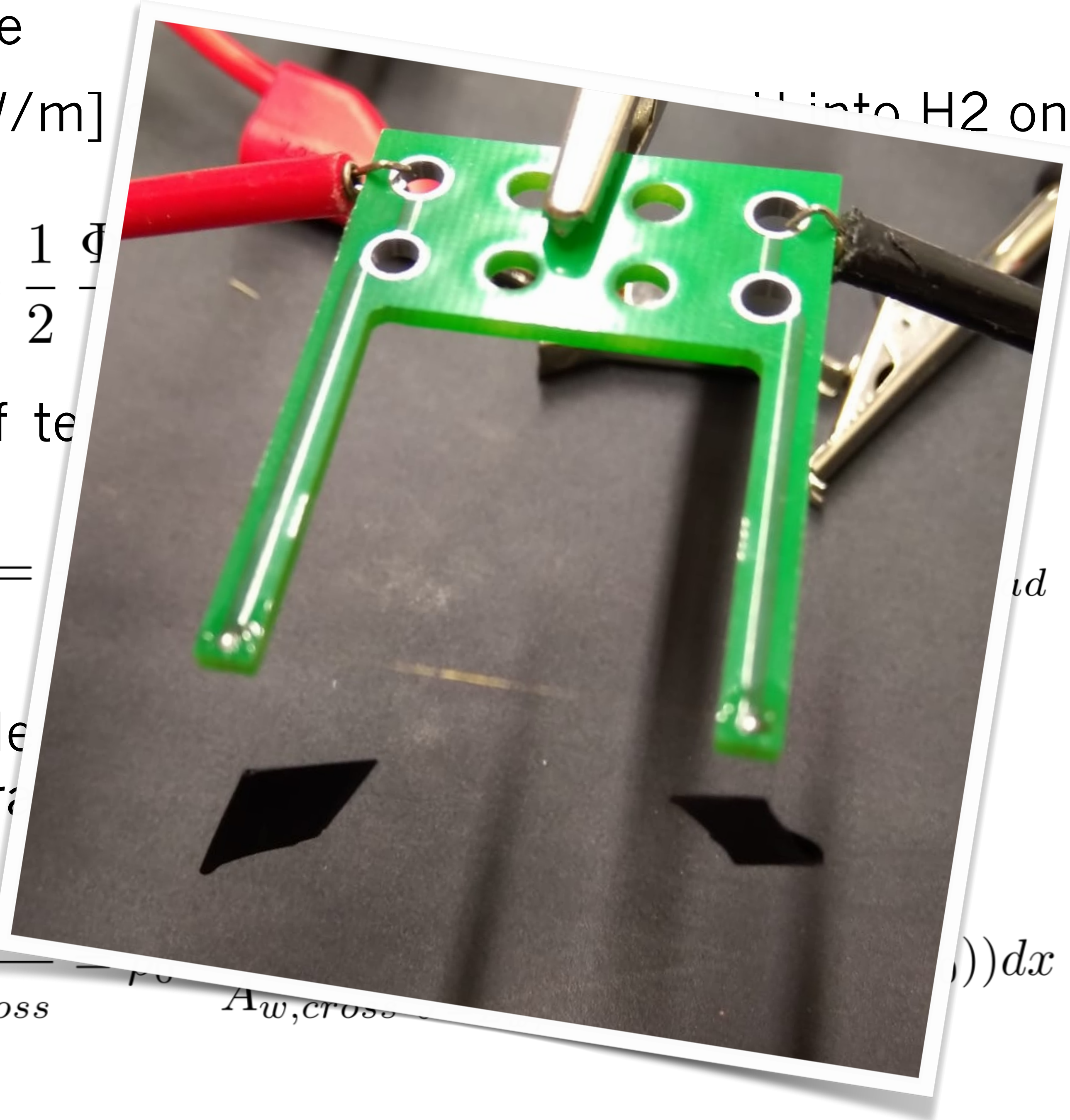
$$F_{beam}(x) = \frac{1}{2} \Phi \ldots$$

- Simulation of te…

$$F_{conduction} = \ldots$$

- Resistance Me… for Tempera…

$$R = \rho \cdot \frac{L_w}{A_{w,cross}} = \rho \ldots \frac{\ldots}{A_{w,cross}} \ldots))dx \quad \propto T$$



Recombination
H -> H_2
≈ 4.75 eV

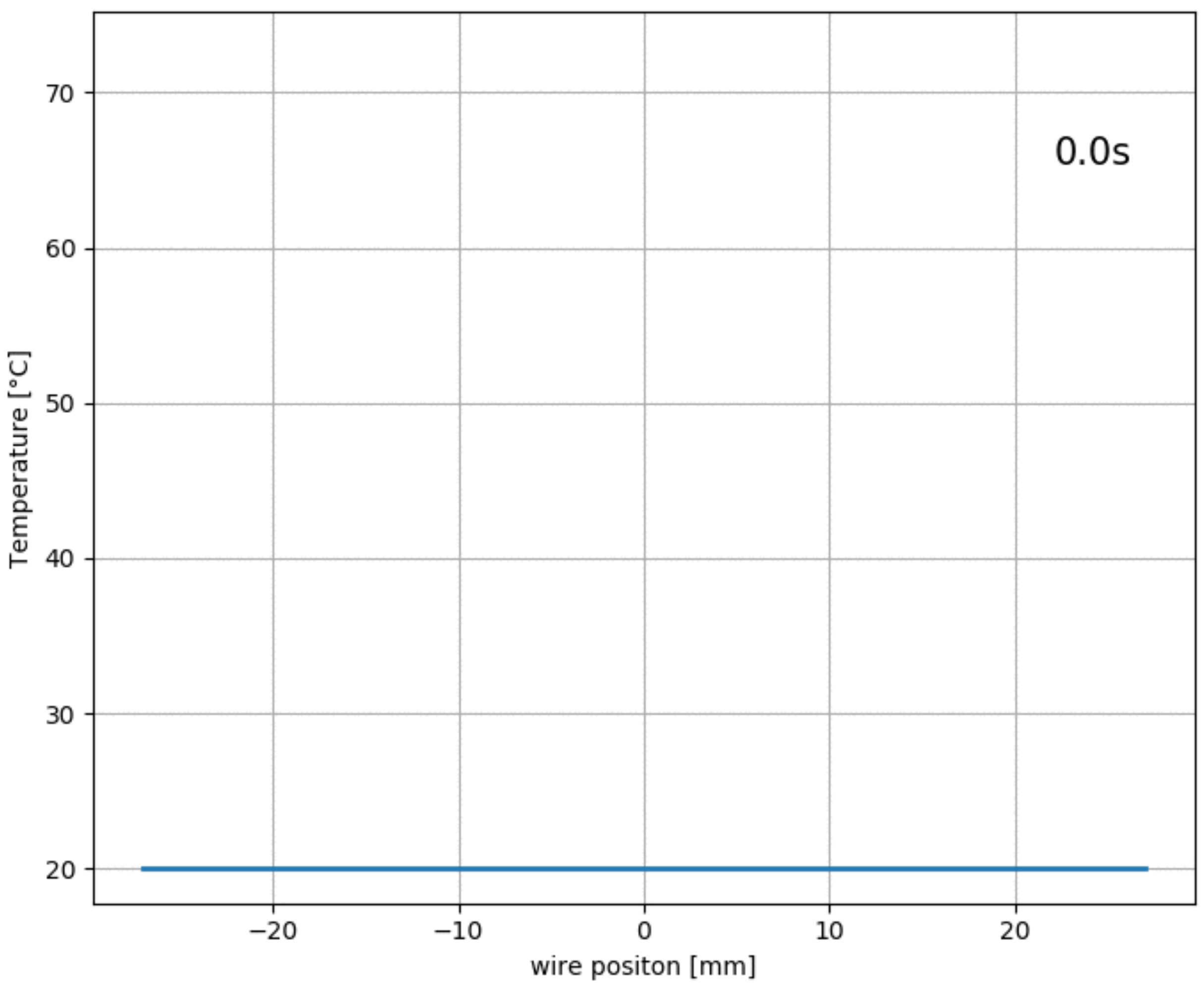
↓

Wire heats up

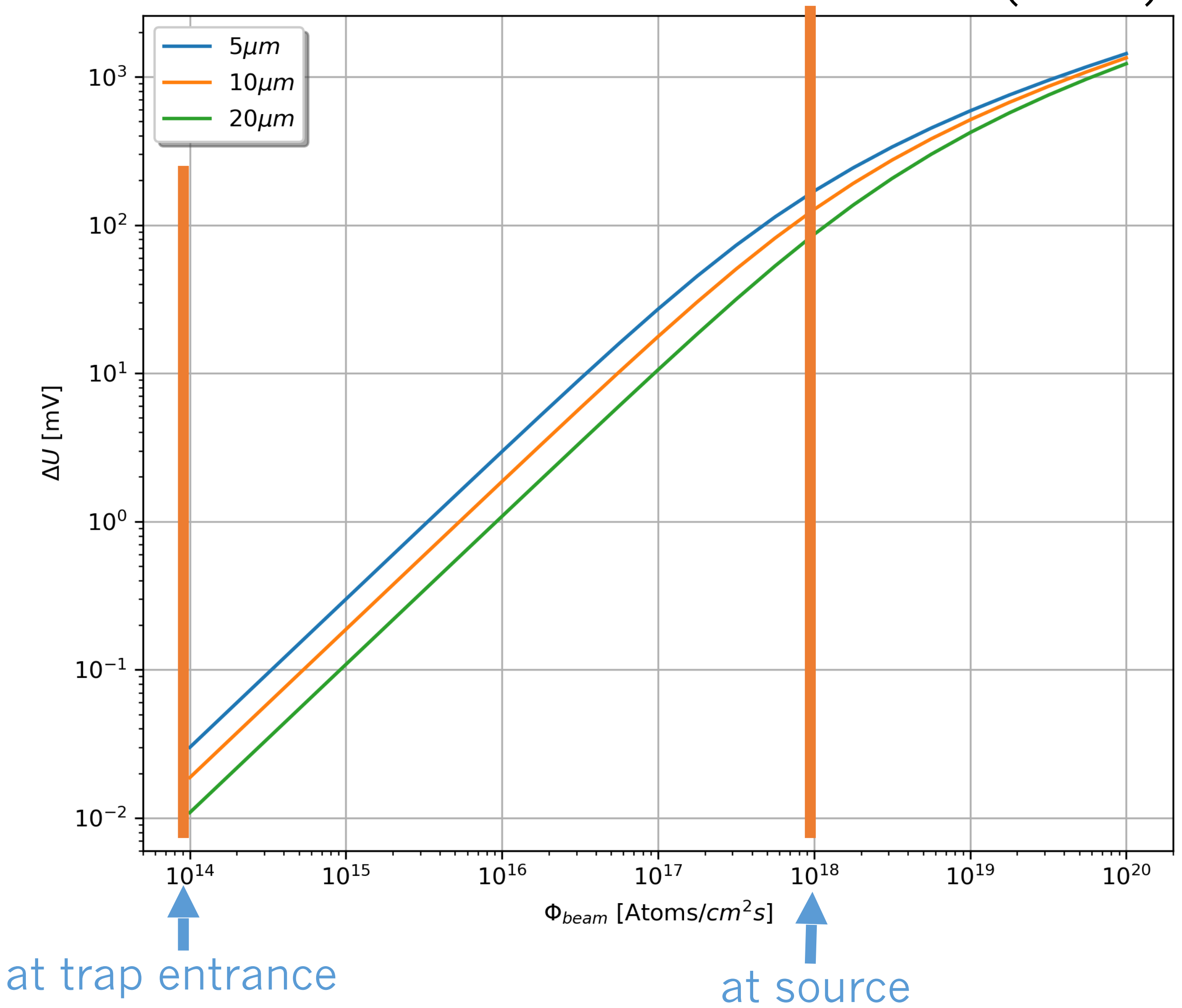
↓

Higher resistance

Temperatures and heat flow simulation



Ch. Matthé (Mainz)



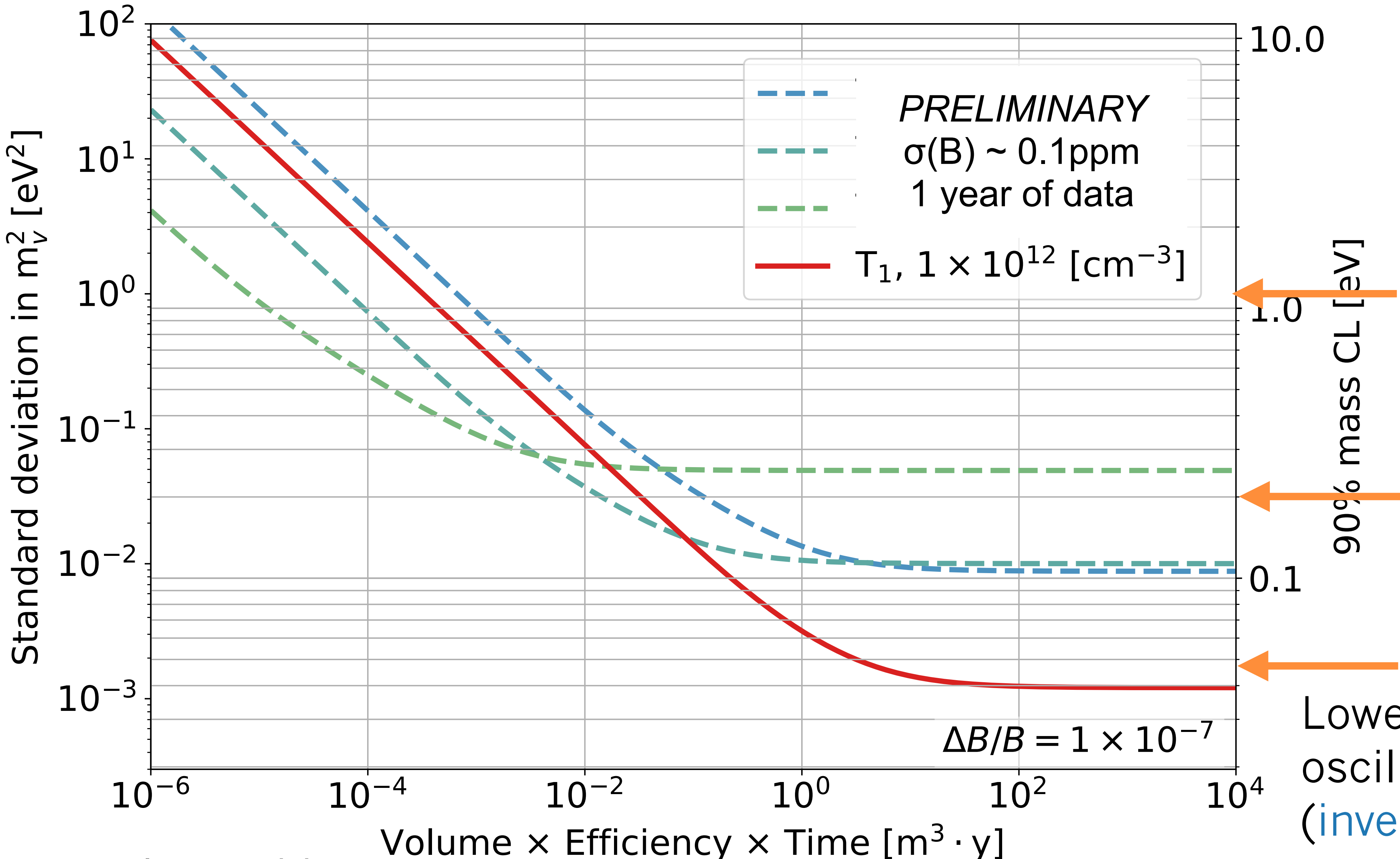
Numerical finite-element simulation

- 10 μm tungsten wire
- 1mA base current
- 10^{17} Atoms/s recombination flux

Sensitivity

- covers full experimental range
- mostly linear
  (T^4 radiative loss at high fluxes)

Potential for neutrino mass!



KATRIN limit

KATRIN sensitivity

Lower limit from oscillations (inverted ordering)

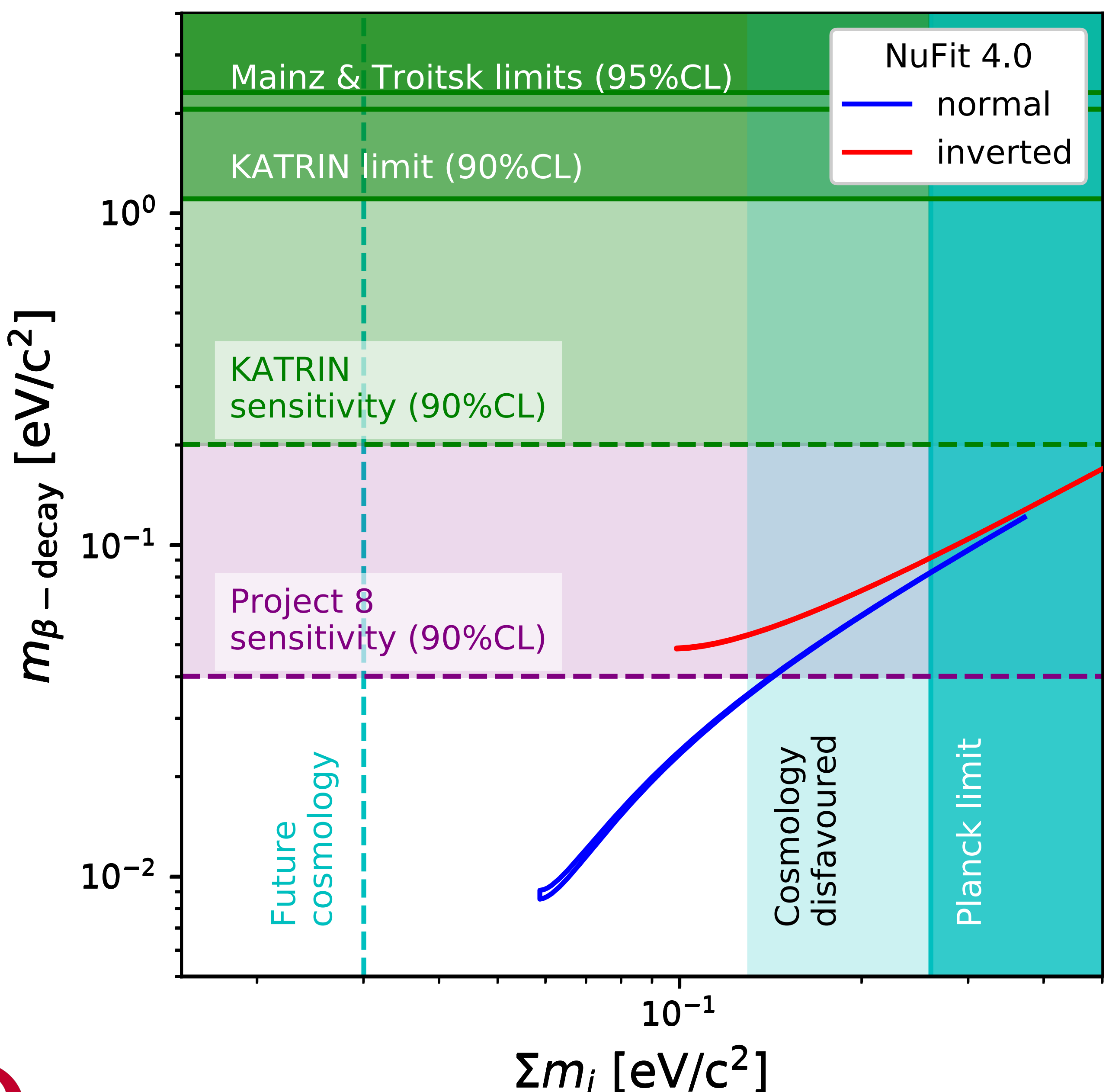
Sensitivity limited by

- density of tritium gas → rest gas interactions
- molecular excitations in T_2 → **atomic tritium**
- magnetic field homogeneity

Comparison of methods

Measuring neutrino masses

- approaches are complementary



$$\Delta m^2 = m_2^2 - m_1^2$$

Oscillation experiments

$$M = \sum_i^{n_\nu} m_i$$

Cosmological measurements

$$m_{\beta\beta}^2 = \left| \sum_i^{n_\nu} U_{ei}^2 m_i \right|^2$$

0νββ decay experiments

$$m_\beta^2 = \sum_i^{n_\nu} \left| U_{ei}^2 \right| m_i^2$$

β-decay experiments

Project 8 collaboration

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Thank you!