Project 8

Towards a radio-frequency measurement of the neutrino mass

Sebastian Böser
Gentner Kolloquium | MPIK Heidelberg | January 31st 2024

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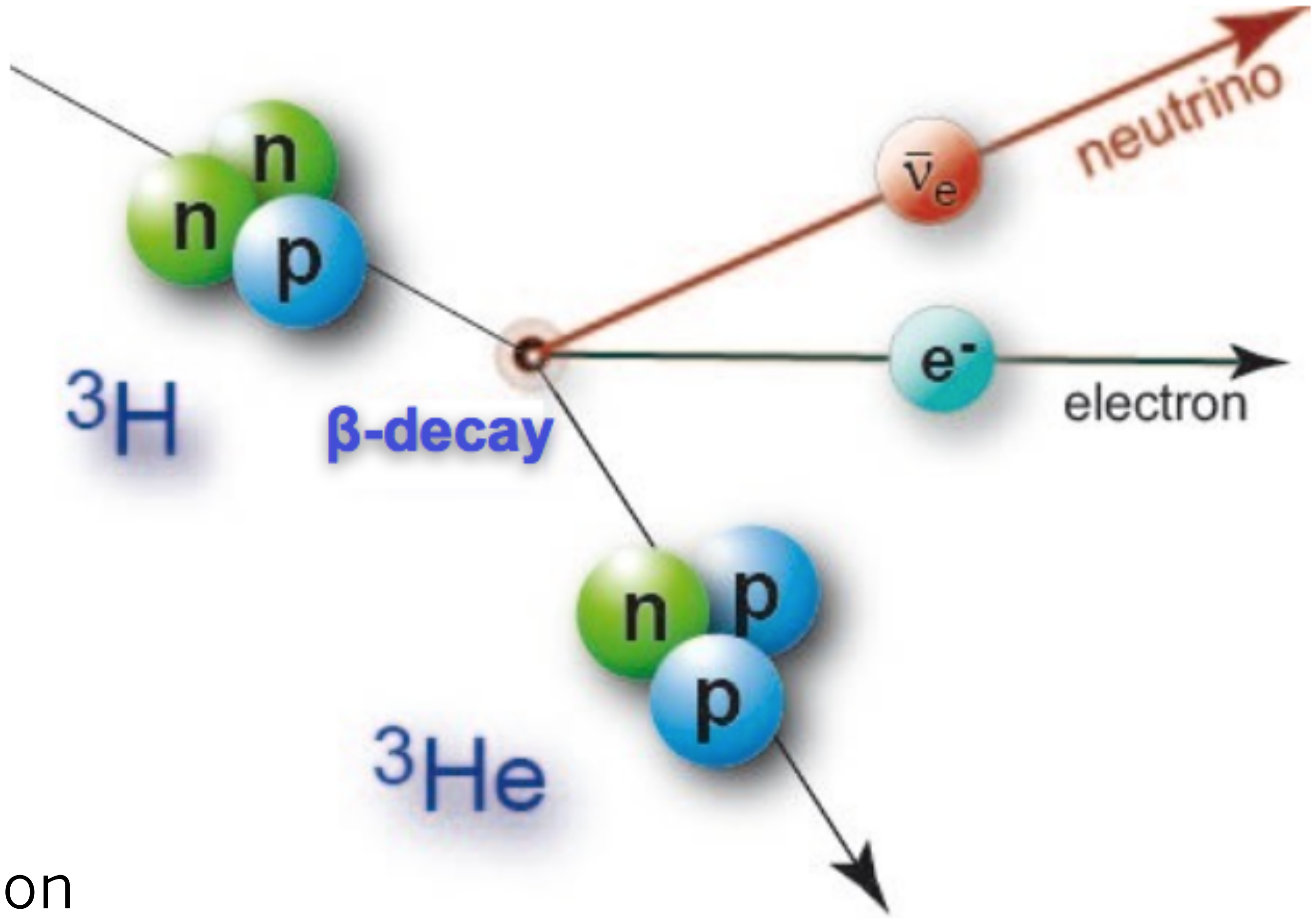
β-decay of tritium



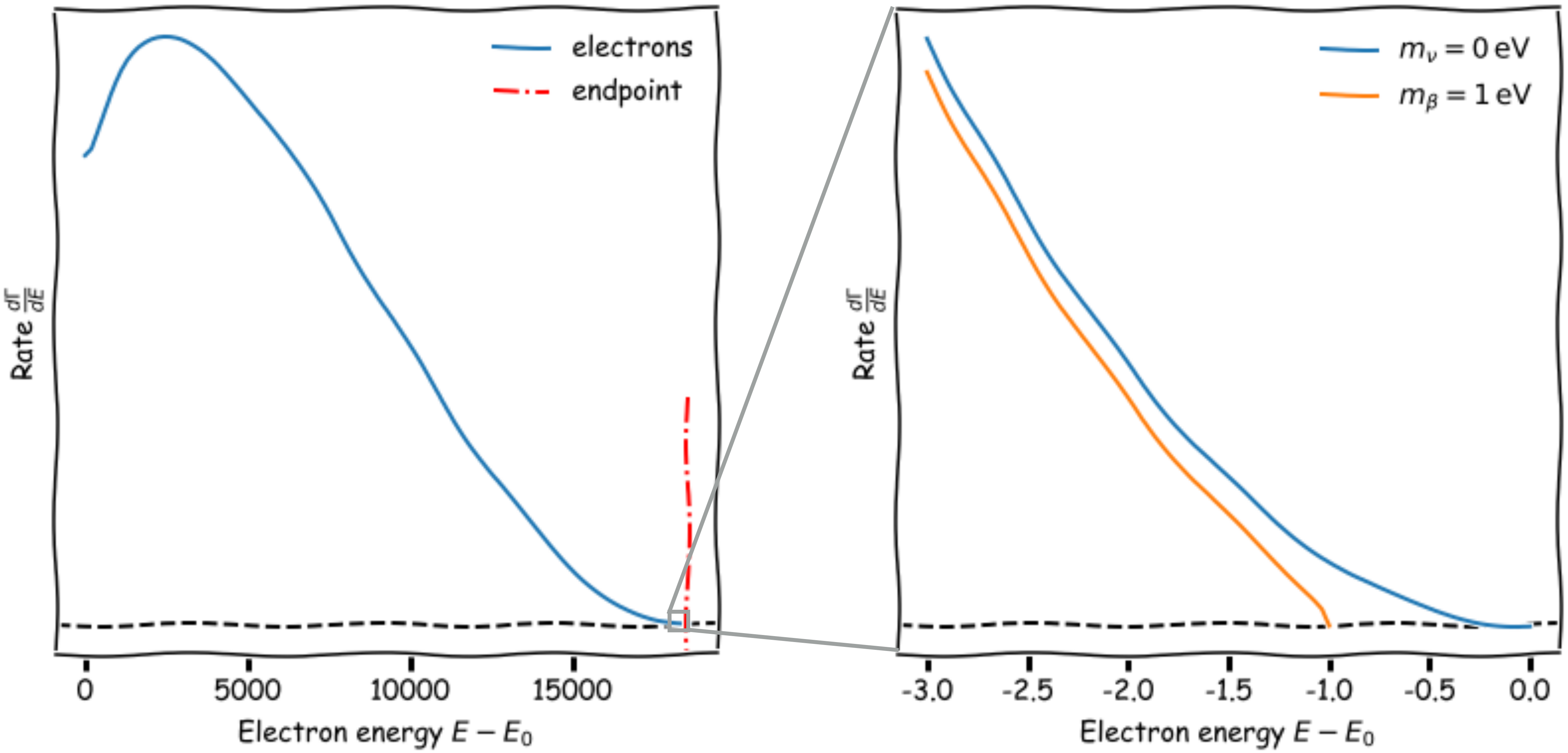
Energy conservation

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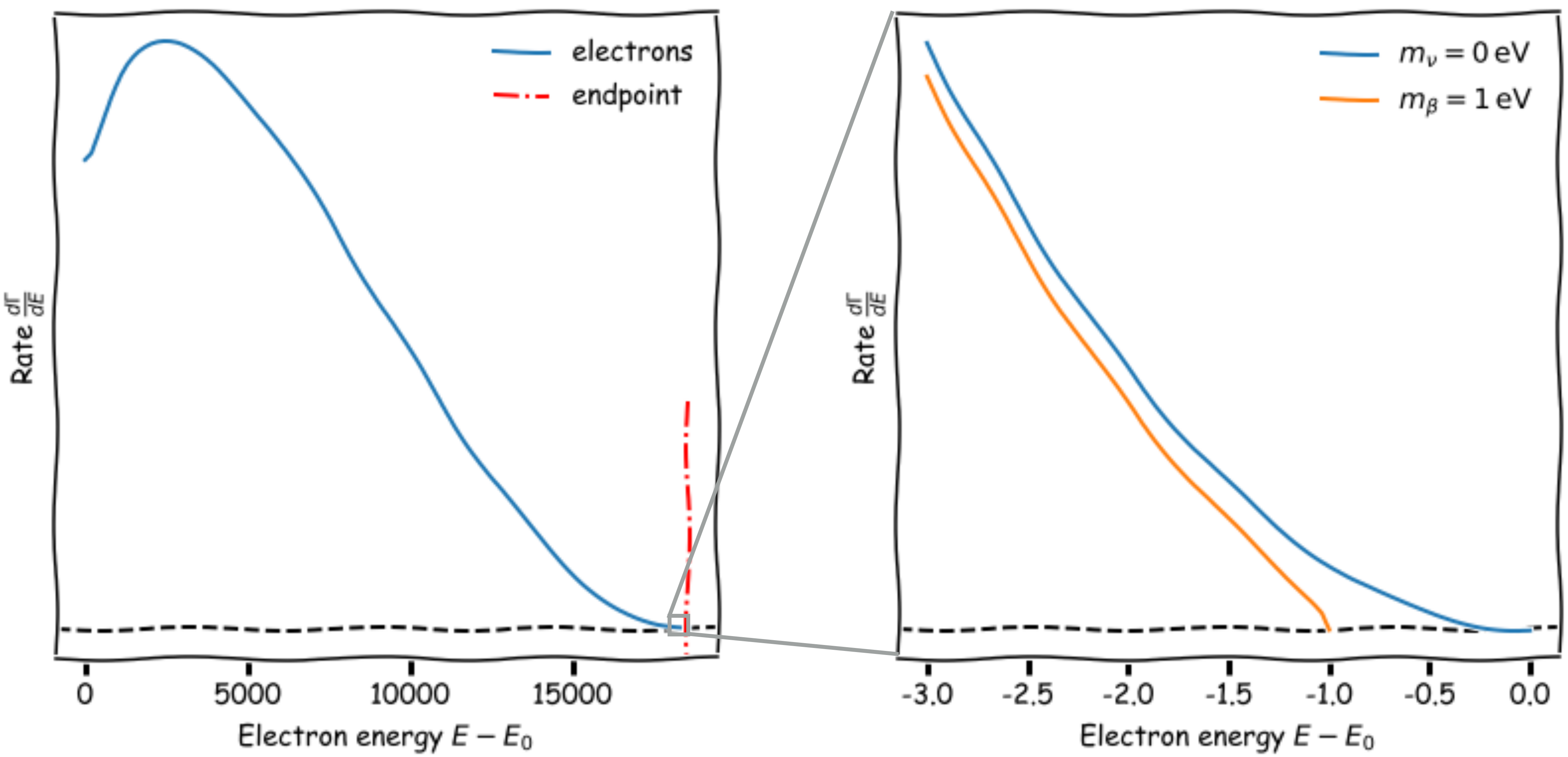

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- direct measurement of *electron* neutrino mass m_β ???

Mass of the electron neutrino ?!?

Electron neutrino

- super-position of mass eigenstates

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

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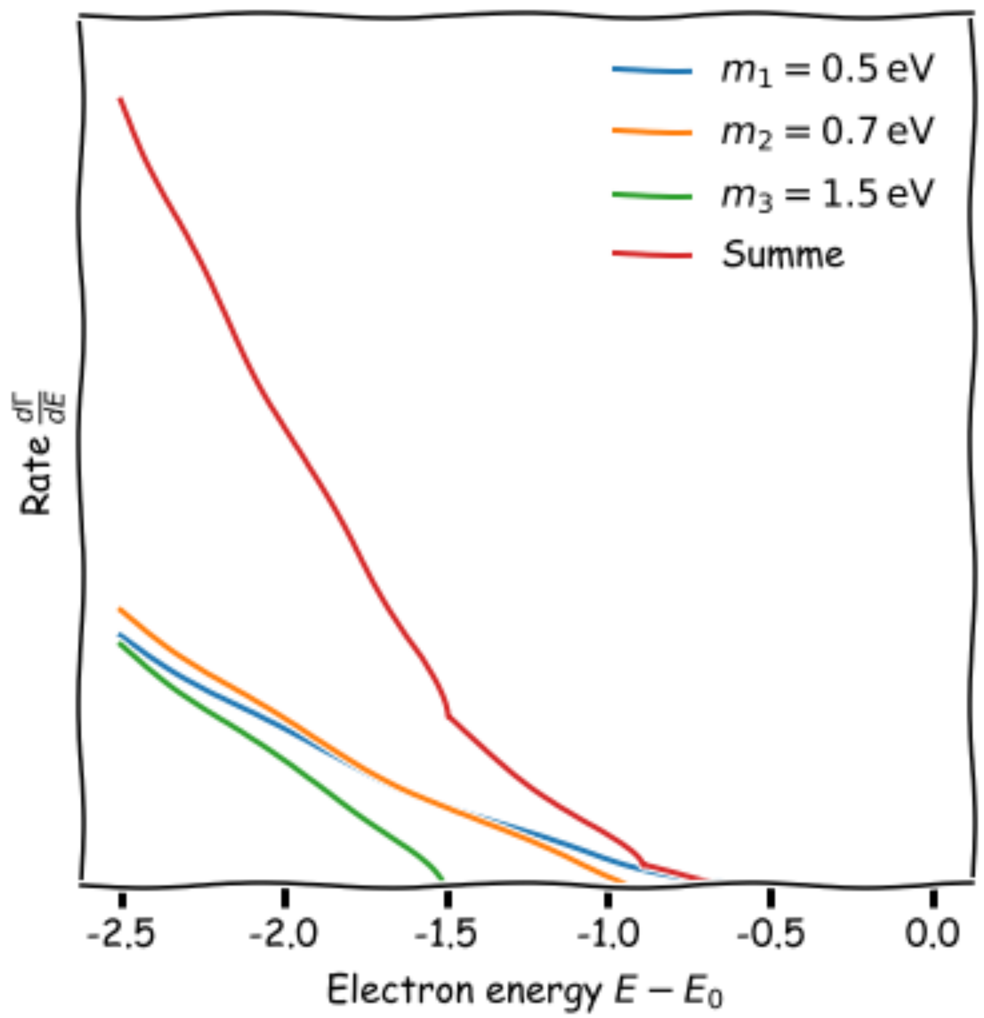
Kinematik of β-decay

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



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Kinematik of β-decay

- energy- & momentum conservation
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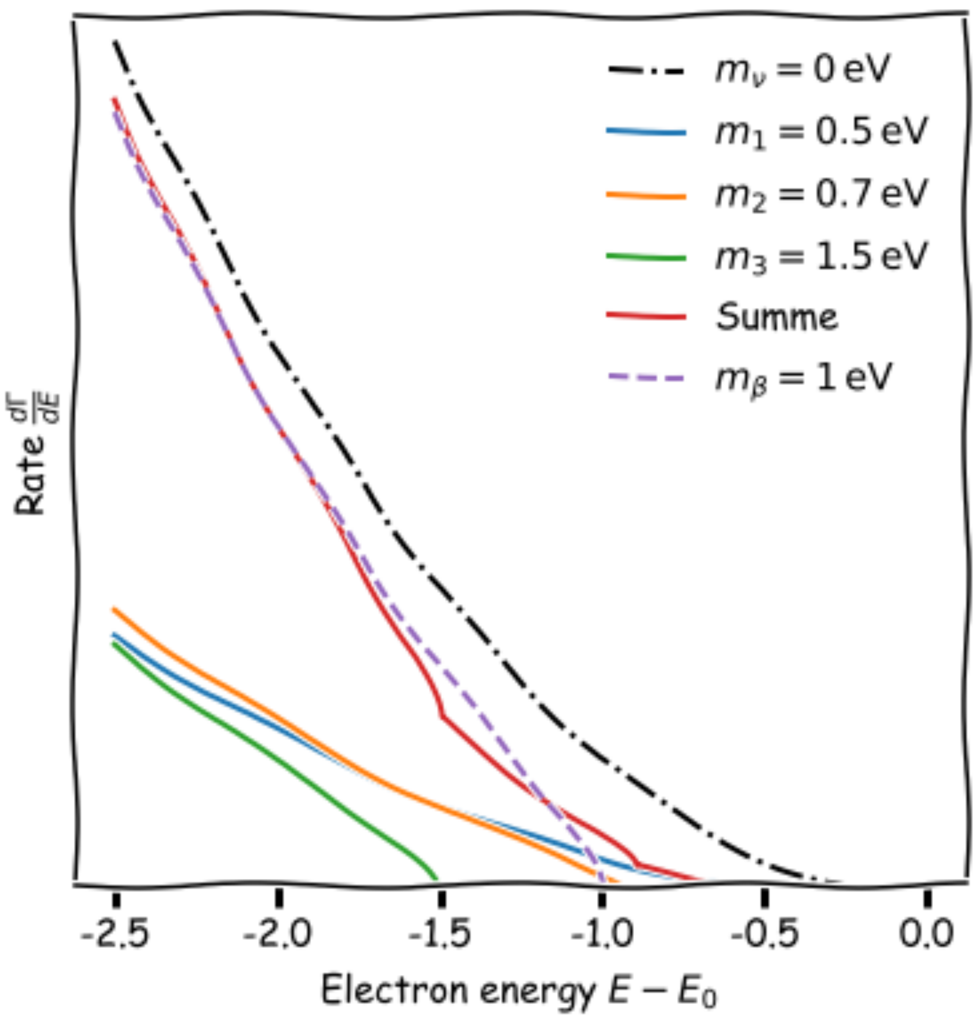
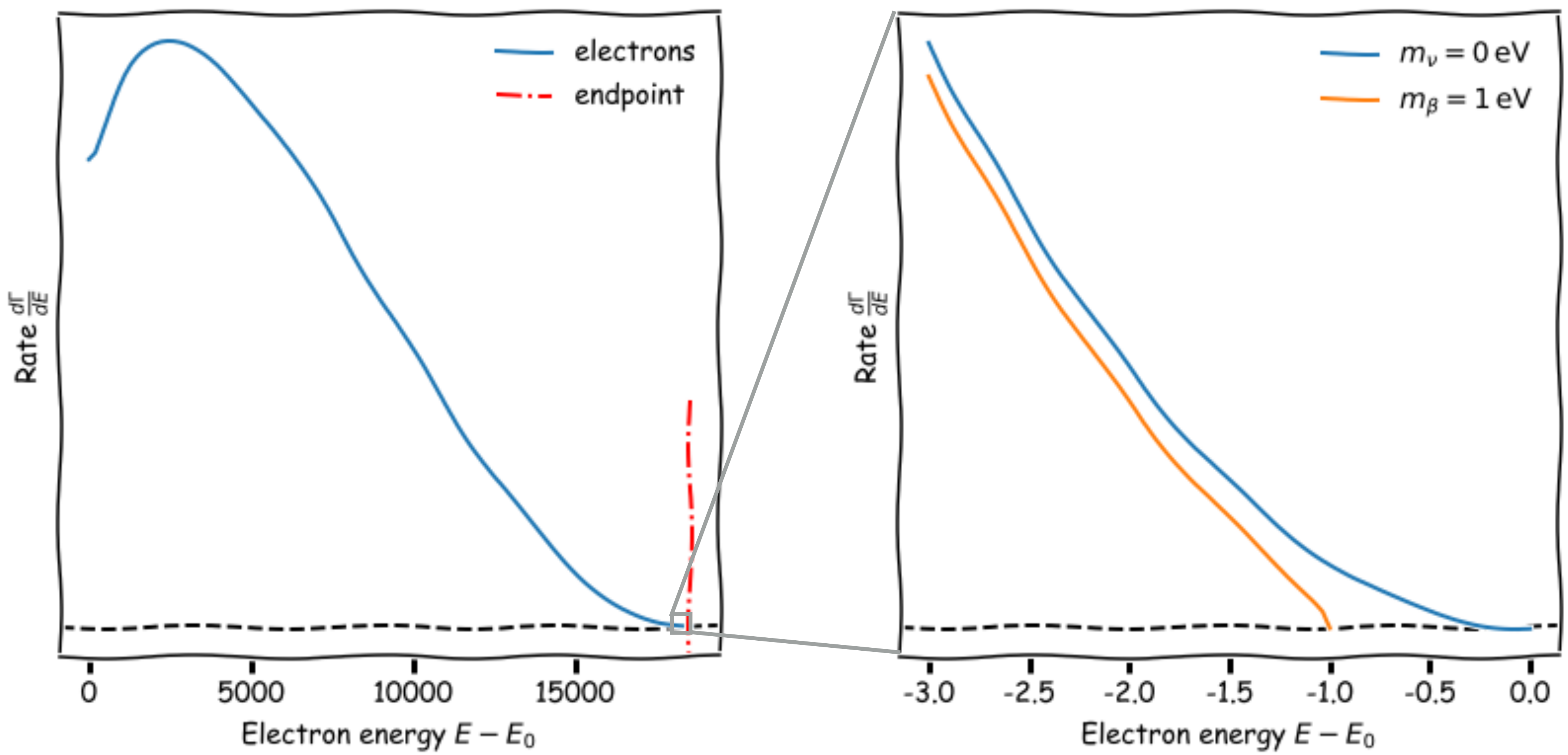
Experimental resolution

- 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: $2 \cdot 10^{-13}$

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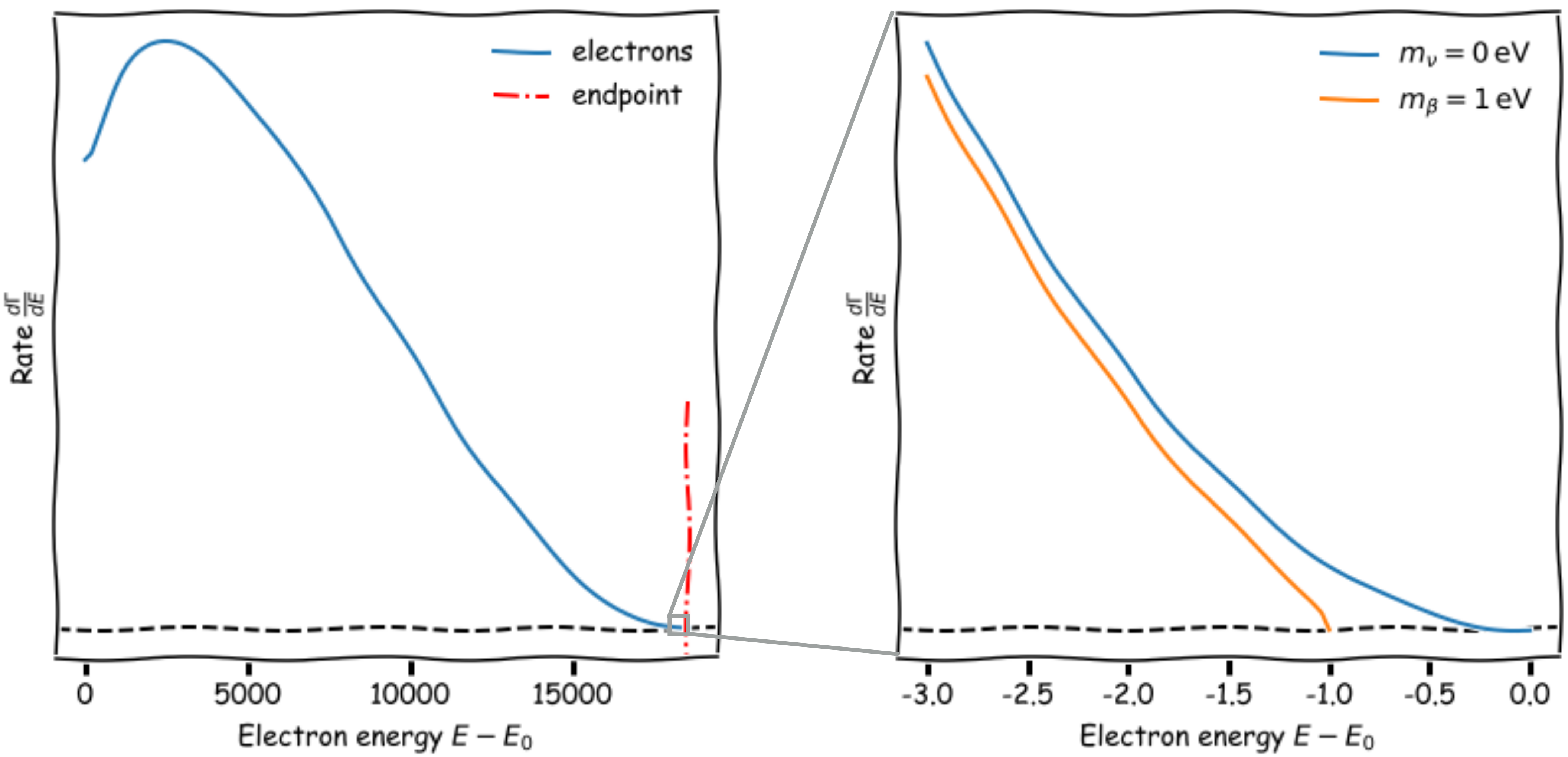

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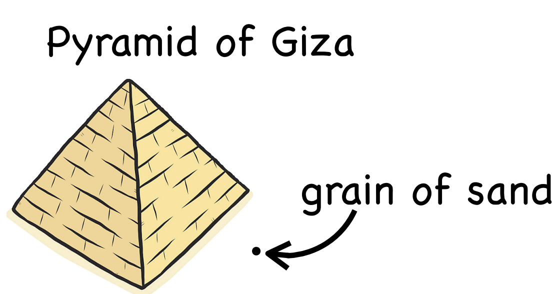

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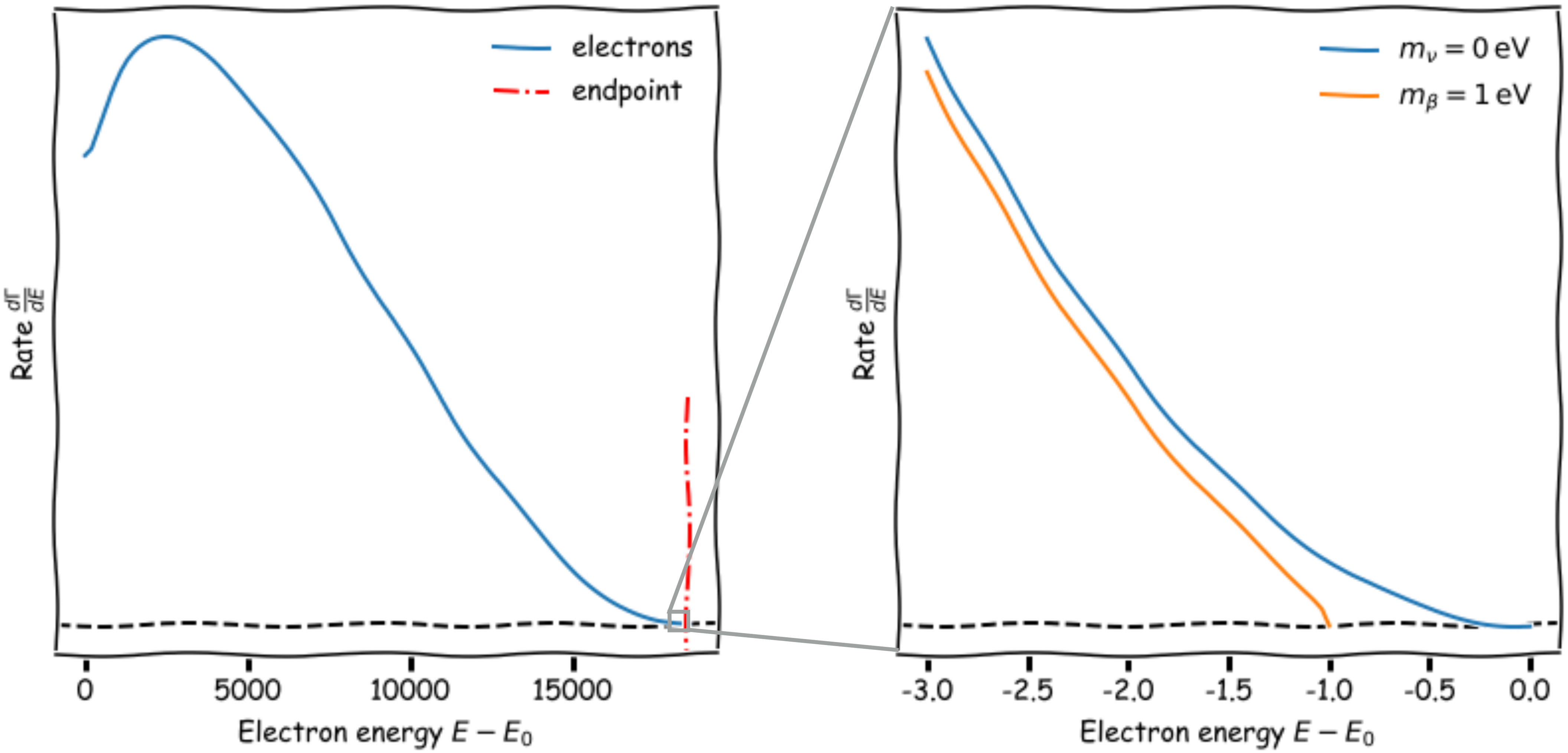

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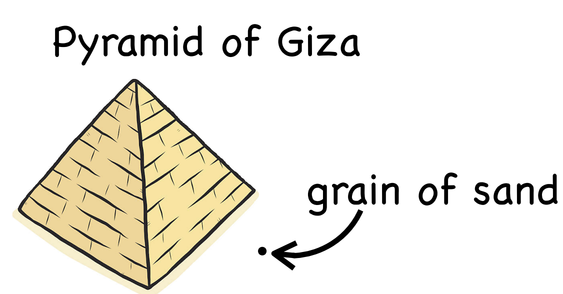

Experimental requirements

- extremely high statistics
- very good energy resolution

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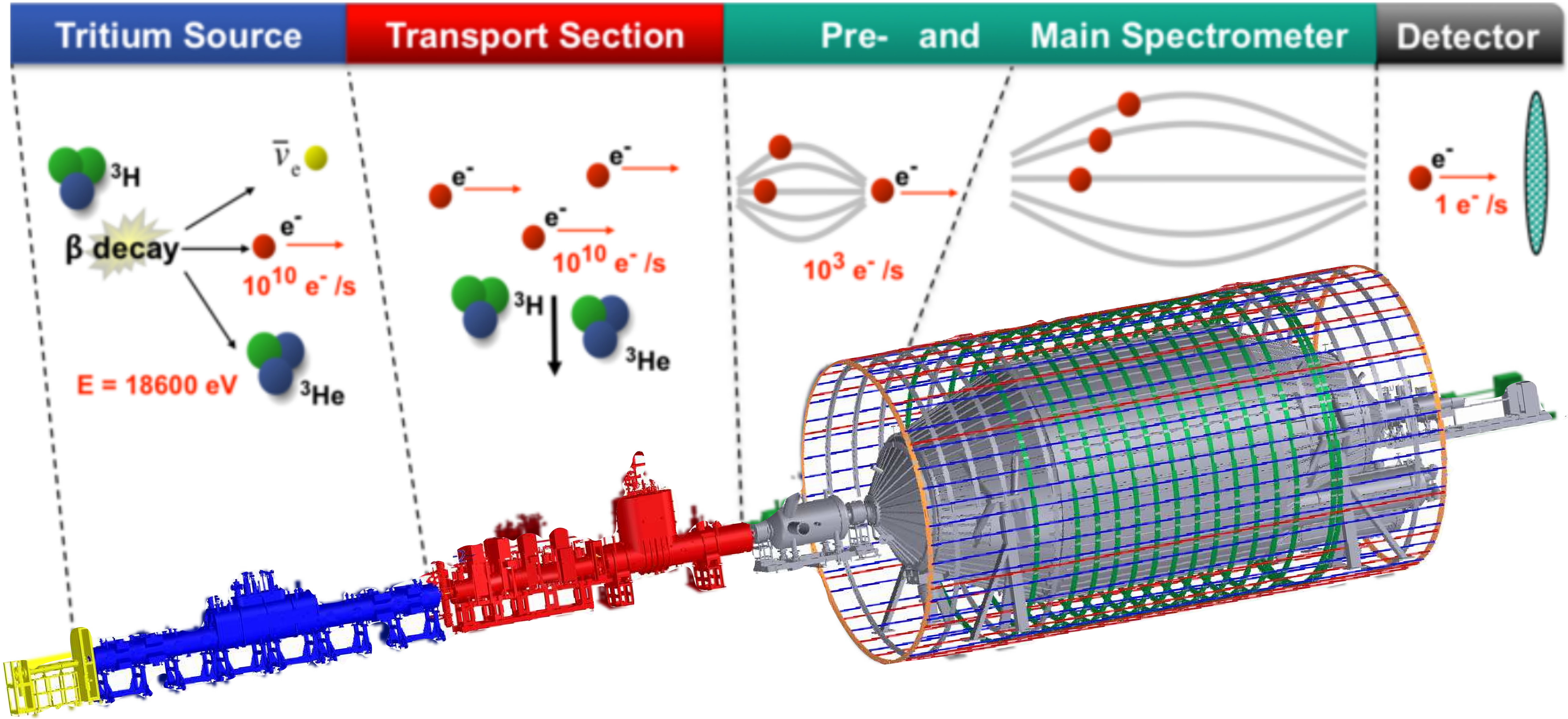
State of the art — KATRIN



Key components

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

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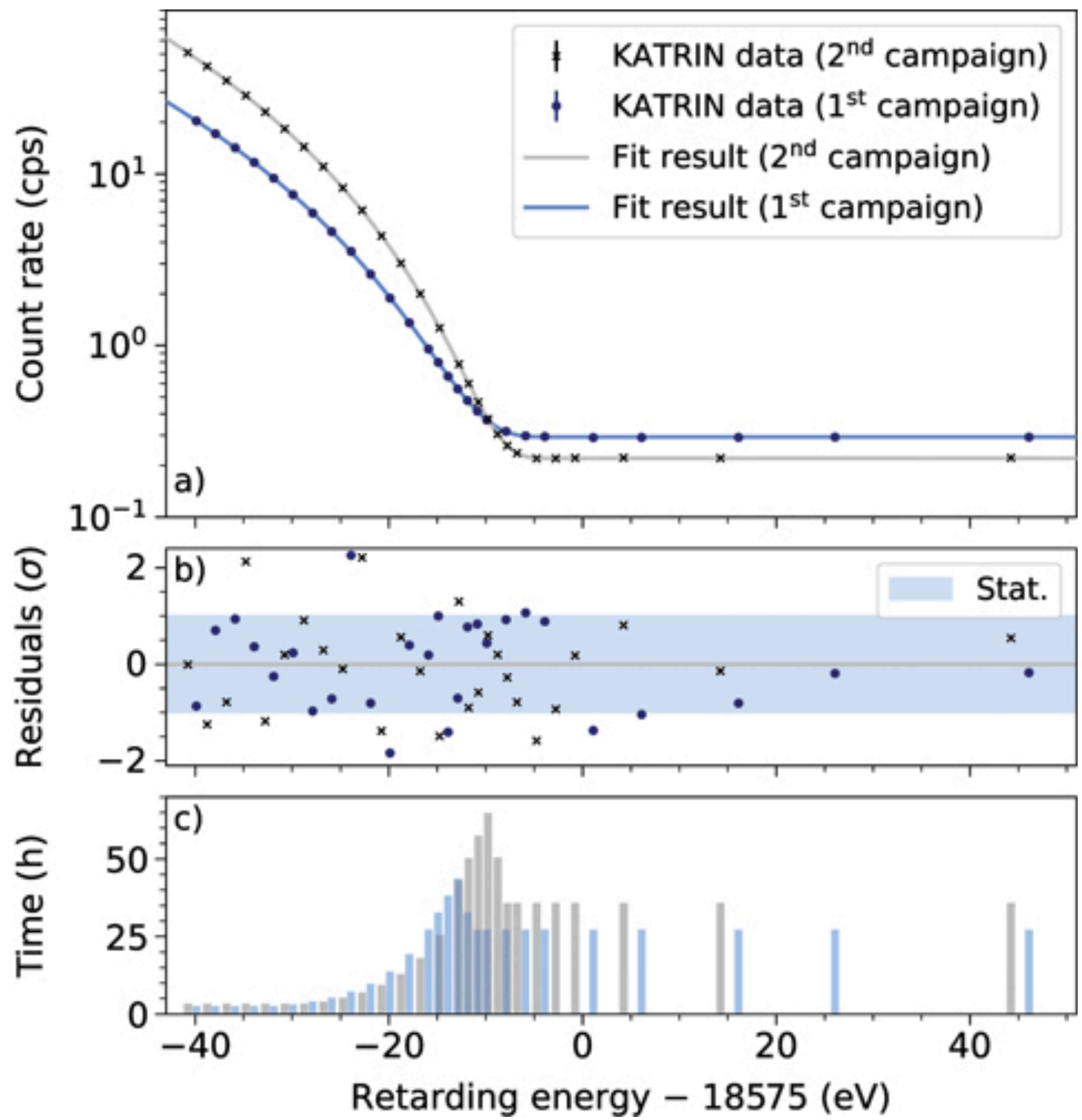
Status — KATRIN limit

Current world-best limit

- Combination of
  1st & 2nd campaign results
  - $\boxed{m_\beta < 0.8\text{ eV (90\% CL)}}$
- Results from 1st-5th campaign
  - expected soon
  - sensitivity to
    $m_\beta \lesssim 0.5$ eV (90% CL)

Future

- Expected sensitivity
  - $m_\beta \lesssim 0.3$ eV (90% CL)
- Limited by
  - statistics ~ scales with $N^{-\frac{1}{4}}$
  - **systematics**
  - **backgrounds**

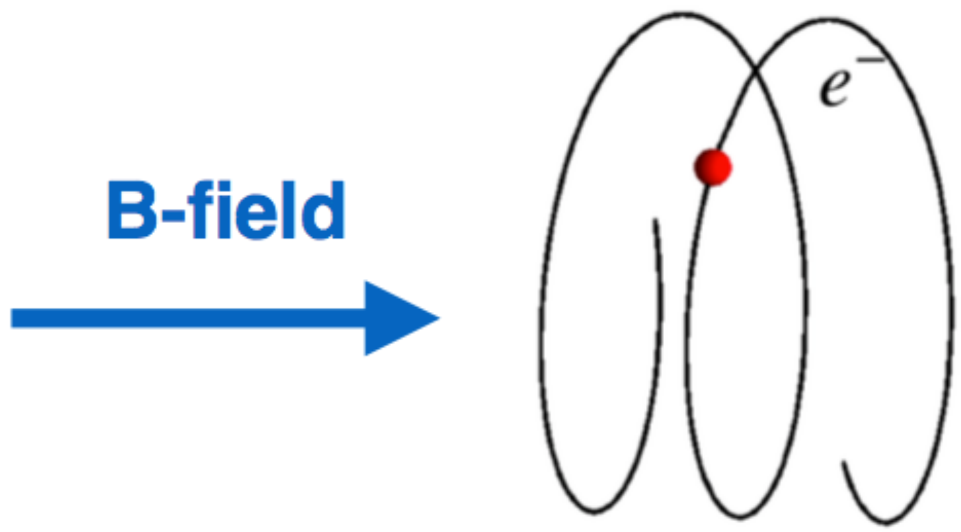


Alternative approach

Electron in B-field

- cyclotron radiation

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



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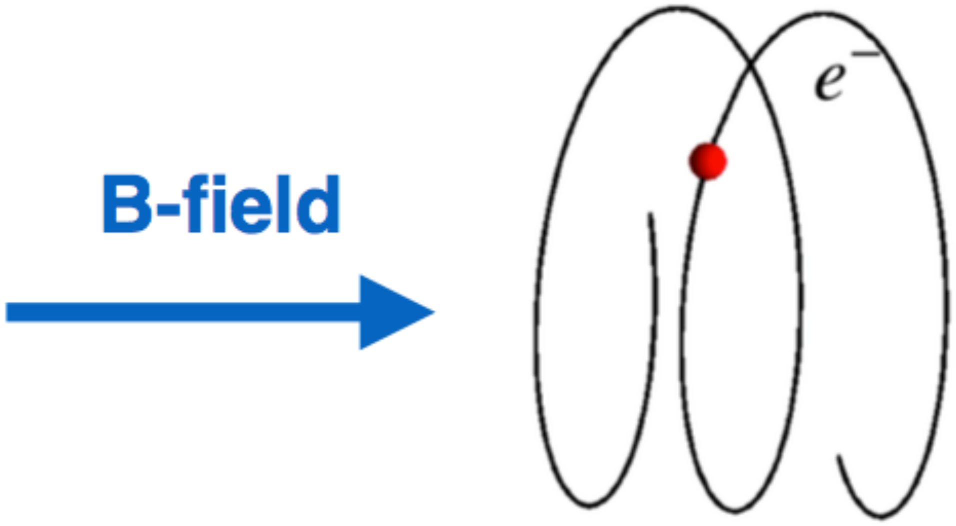
First-order relativistic correction

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

- ▸ energy measurement!



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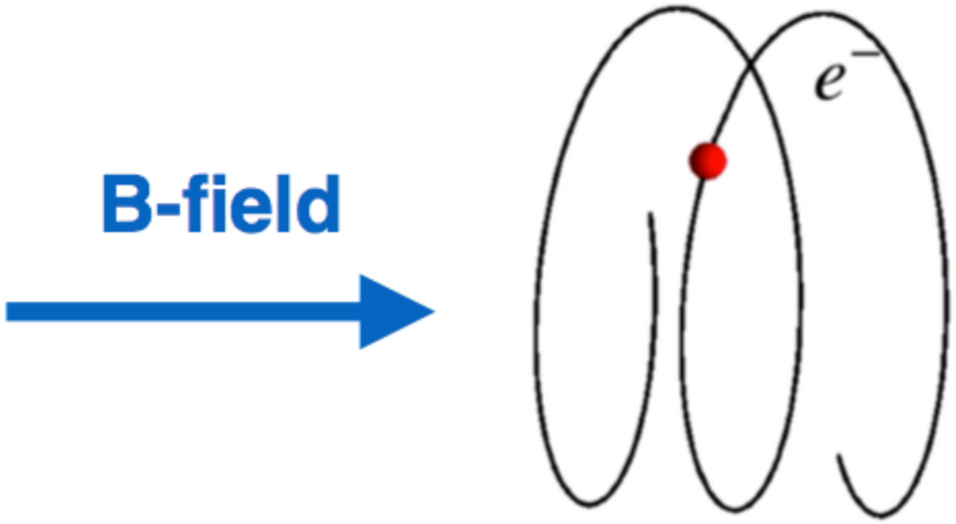
Energy resolution $\Delta E/E \sim \Delta f/f$

- $\Delta E/E \sim 0.1\text{eV} / 18.6\text{ keV} = 5\text{ppm}$ → easy!



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

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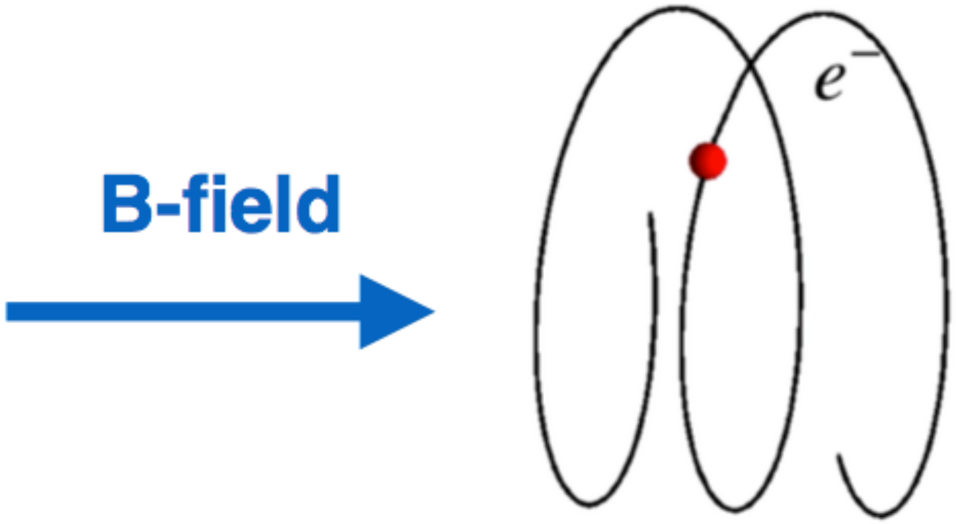
- ▸ energy measurement!

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



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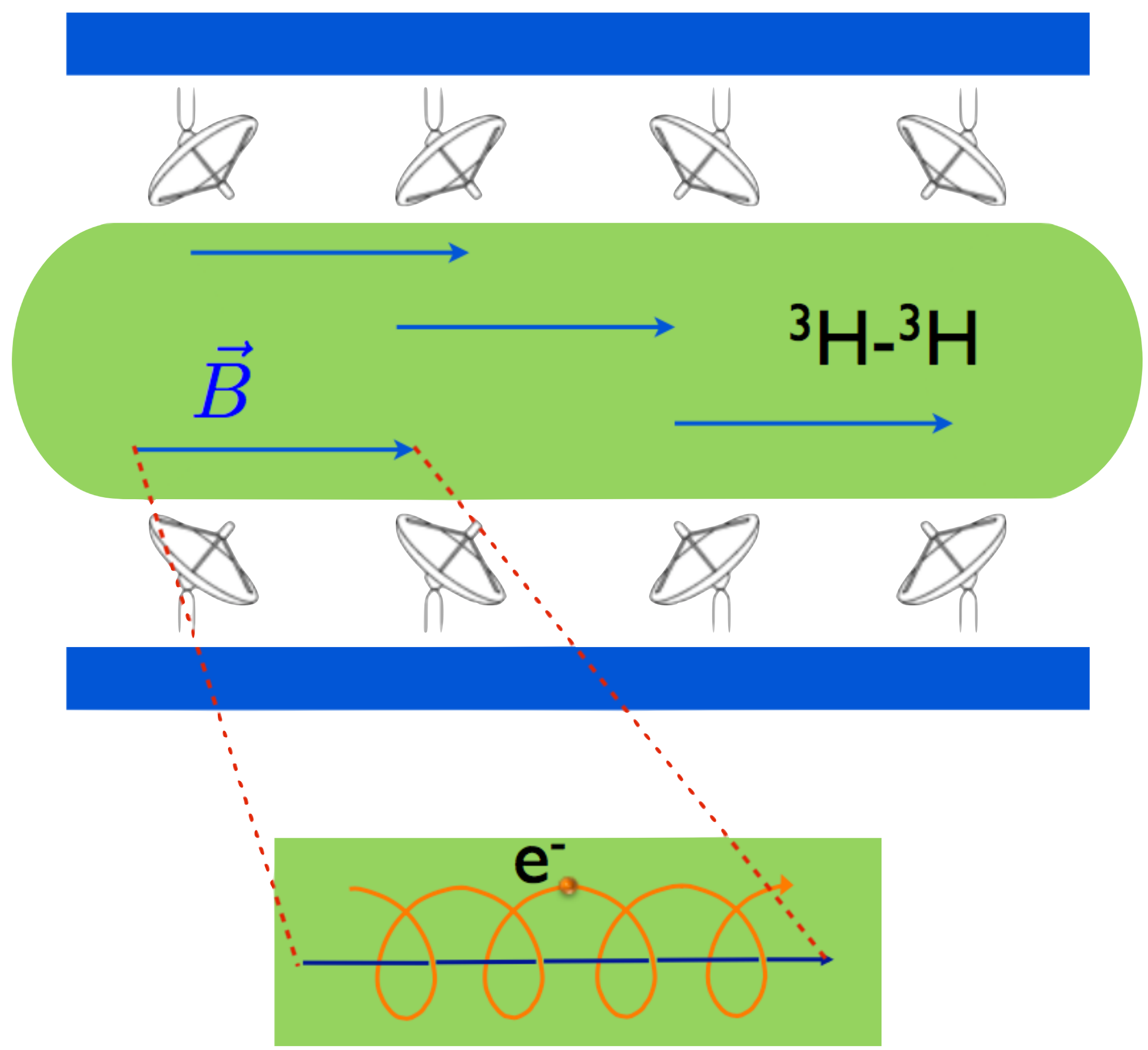
Experiment

Idea

- fill volume with tritium atom gas
- add magnetic field
  - decay electrons orbit around field lines
- measure cyclotron radiation
  - electron spectrum

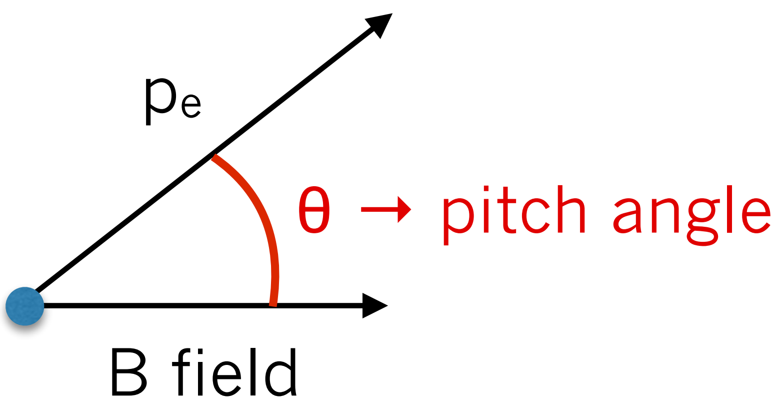


B. Monreal and J. Formaggio, Phys. Rev D80:051301

Radiated power

Larmor formula

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



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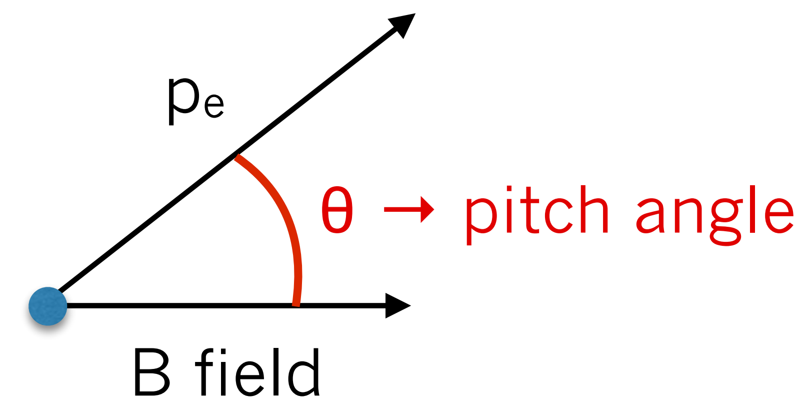

Radiated power

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

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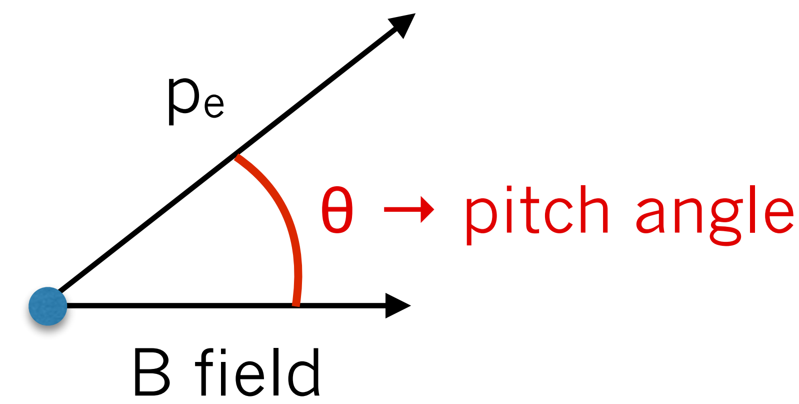

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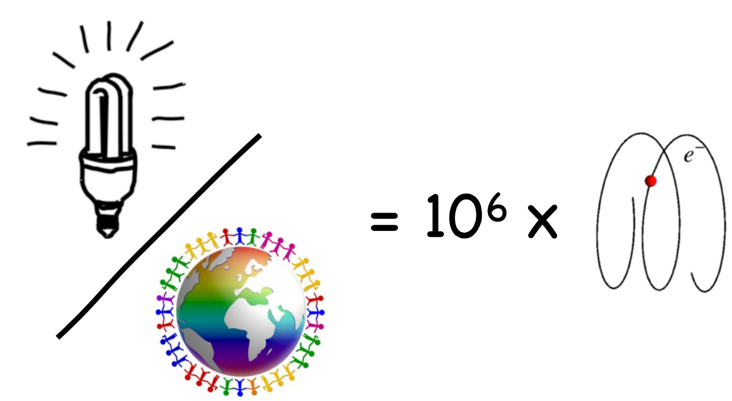
Comparison

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



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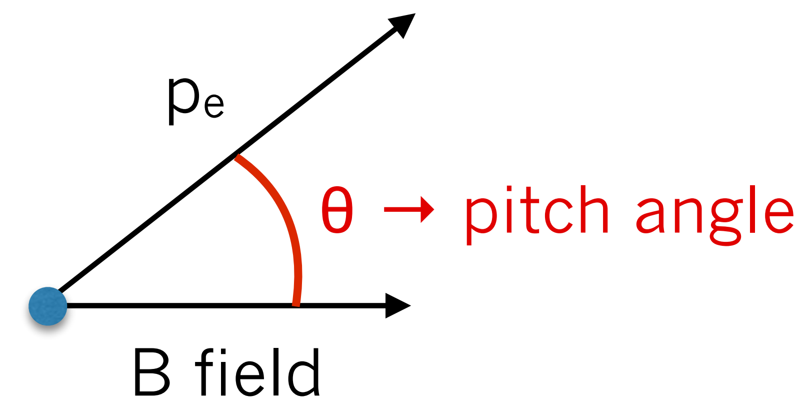

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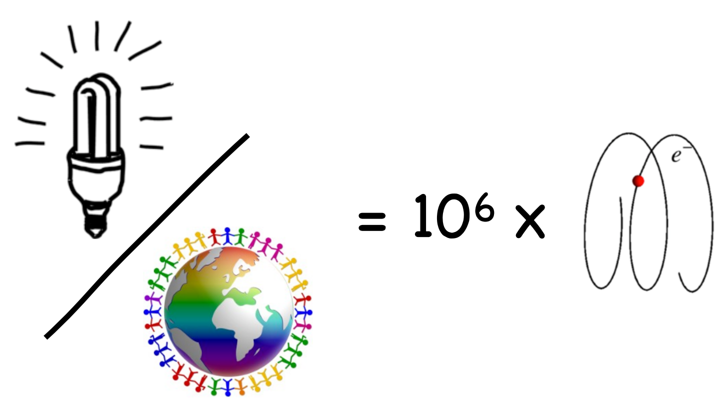
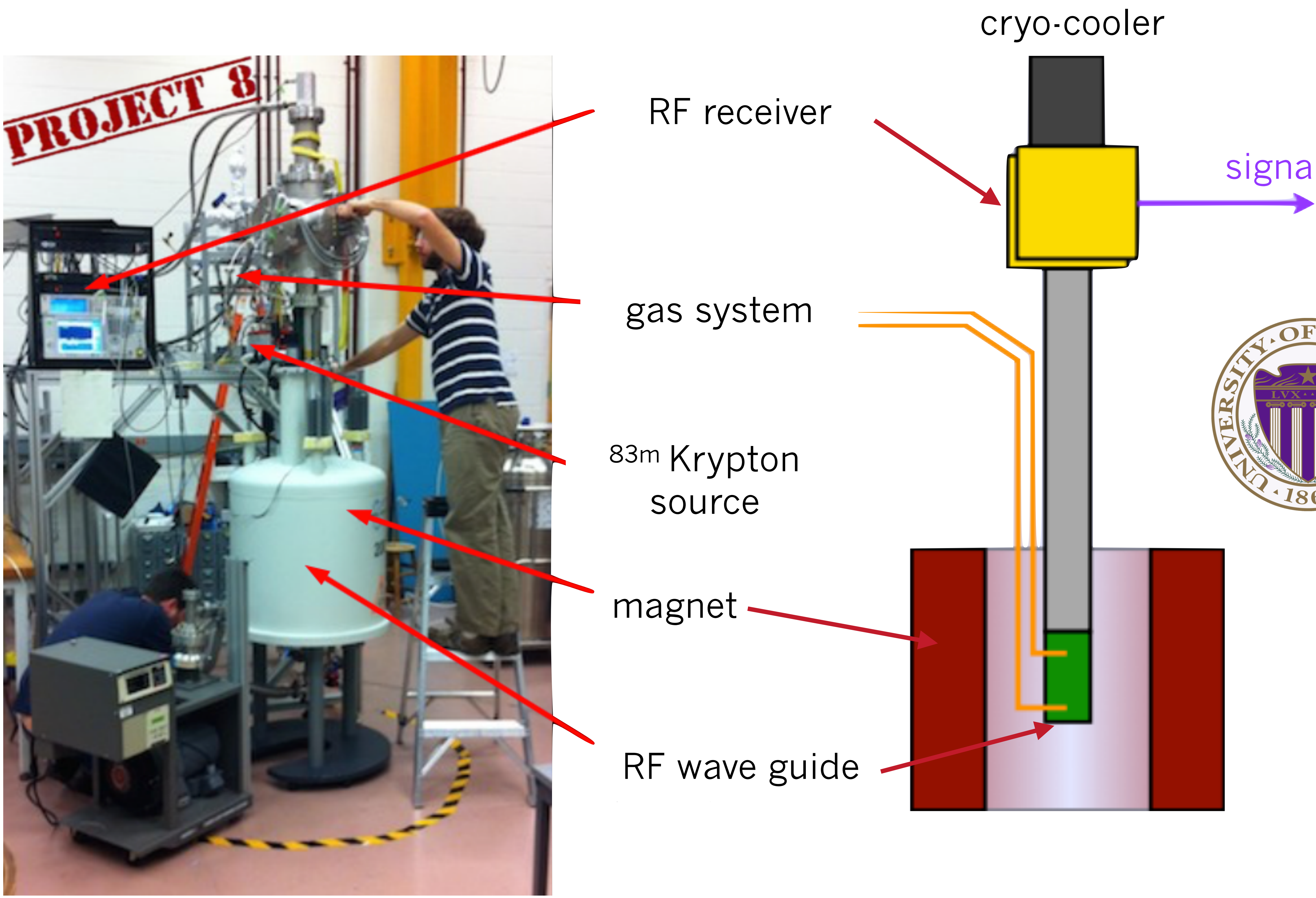


Consequences

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

Phase I: apparatus

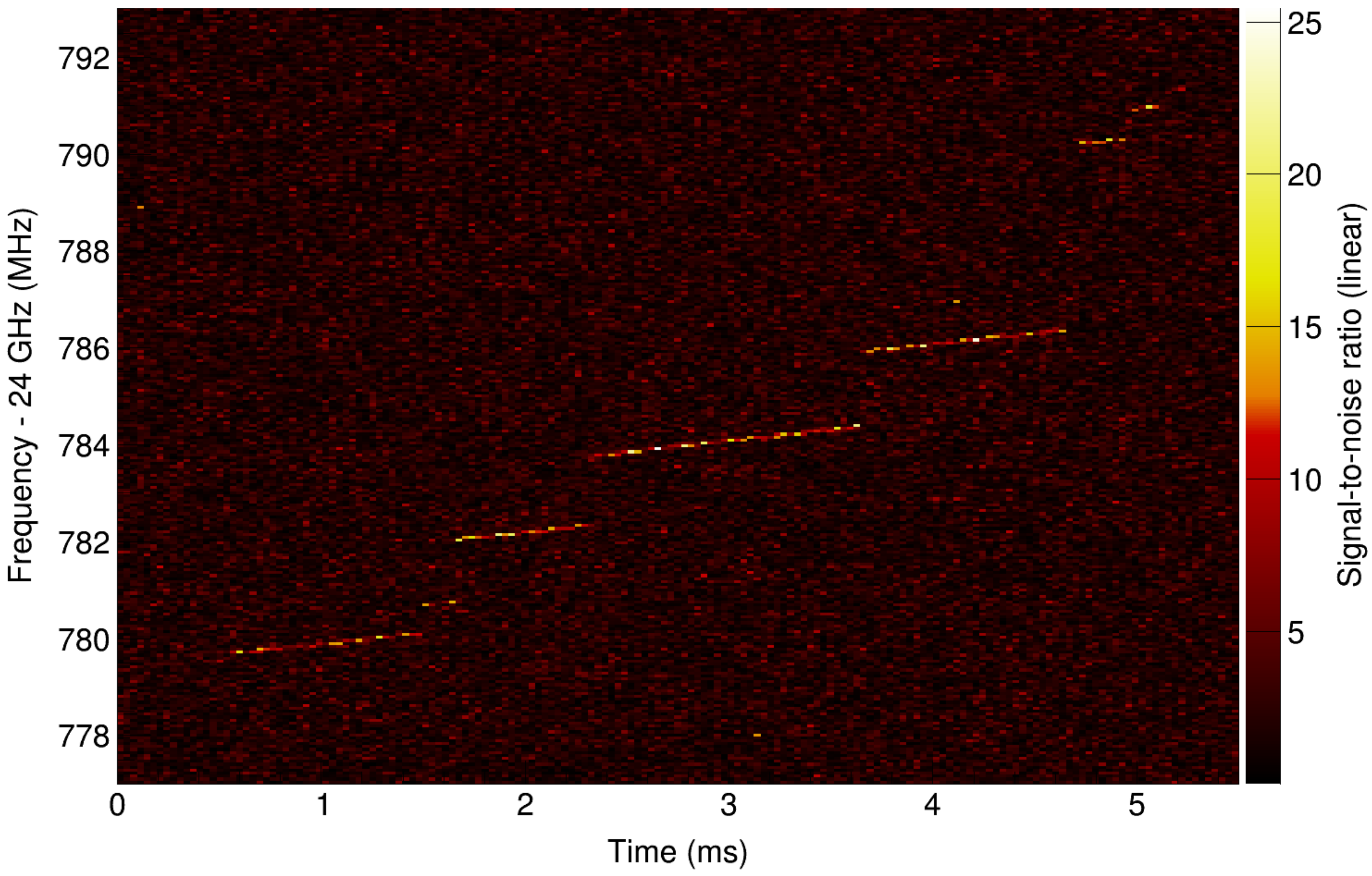


Measured signal

Begin of data-taking on 06.06.2014

- first signal → captured electron

PhysRevLett.114.162501 (2015)



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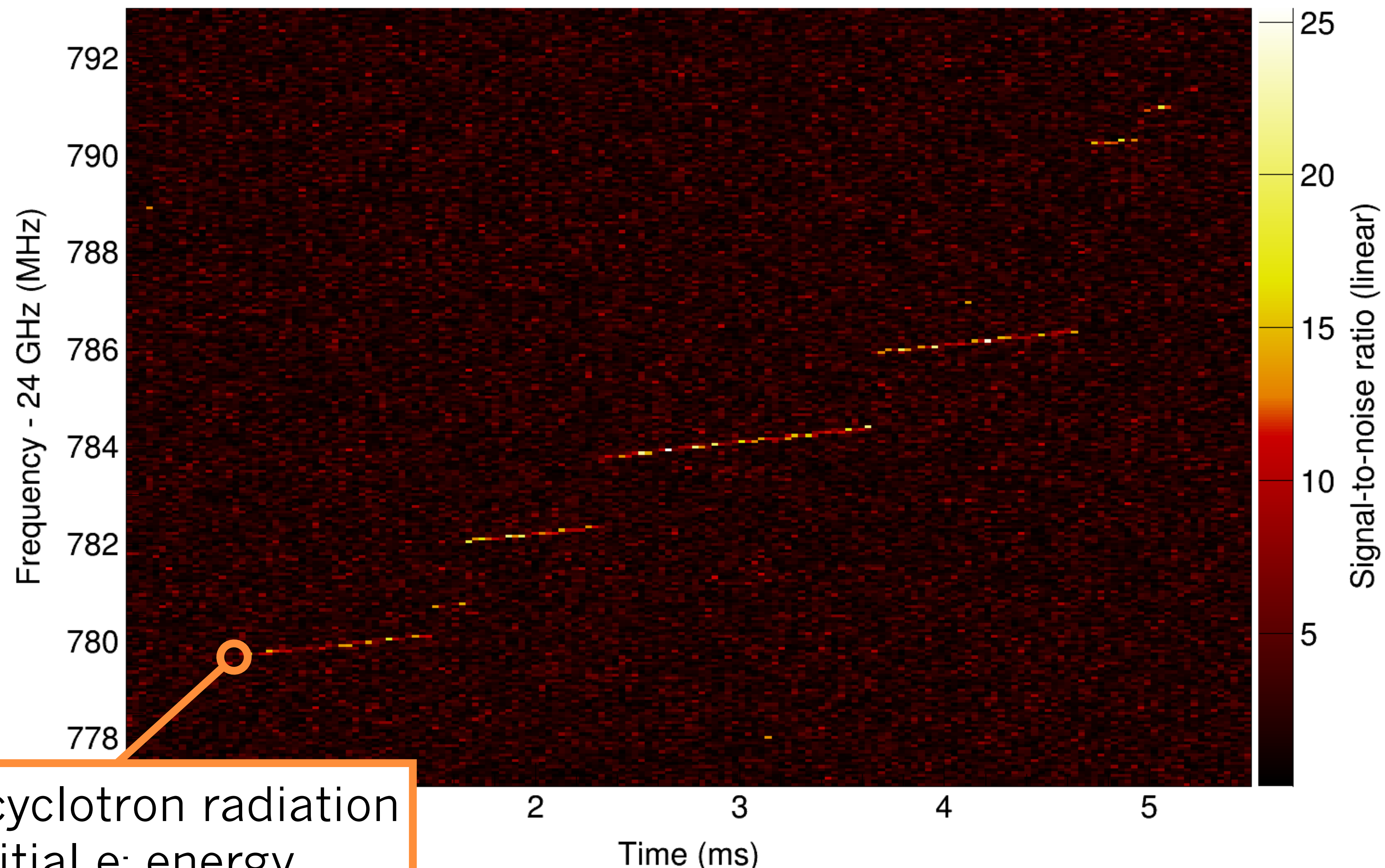

Onset of cyclotron radiation
→ initial e⁻ energy

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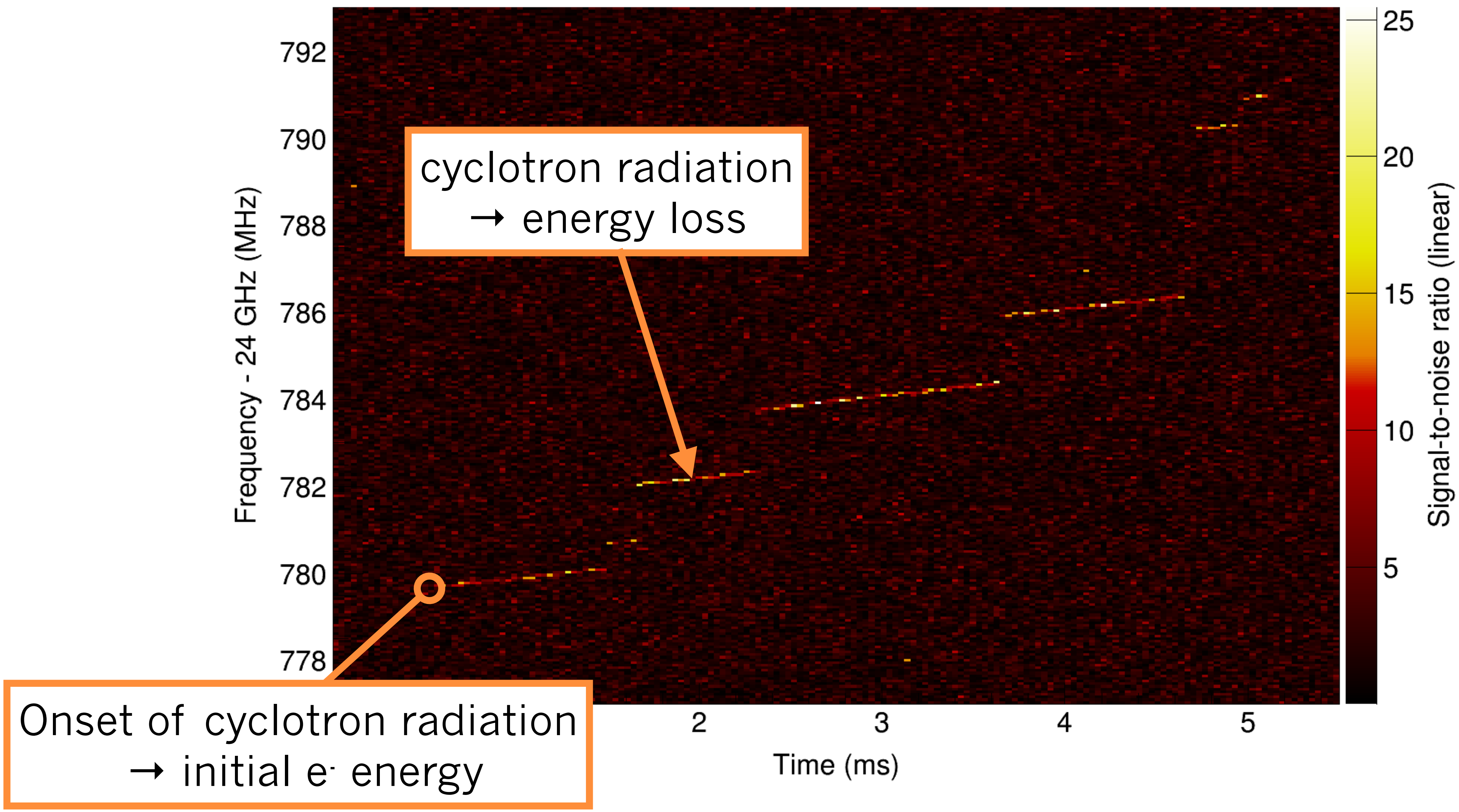

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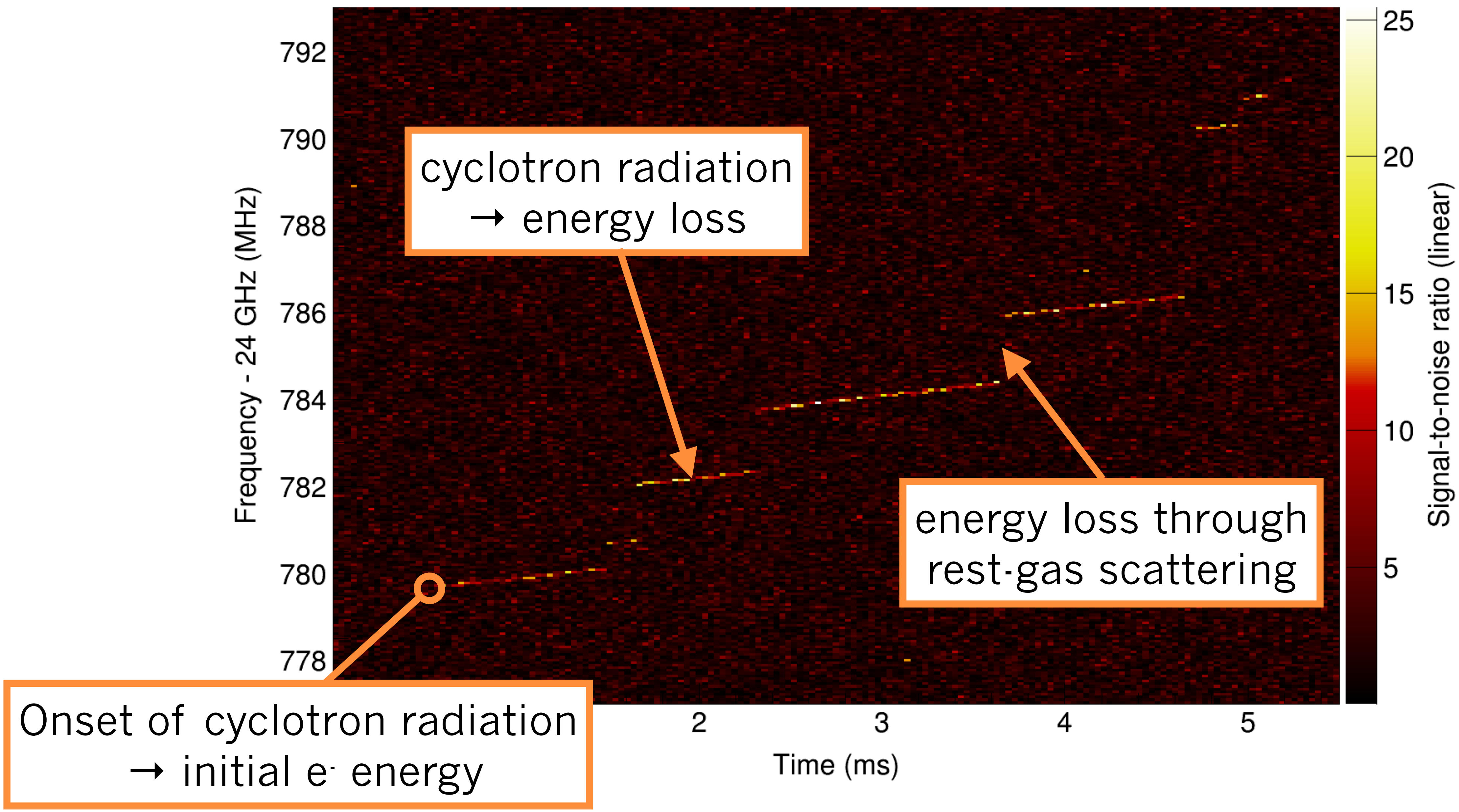


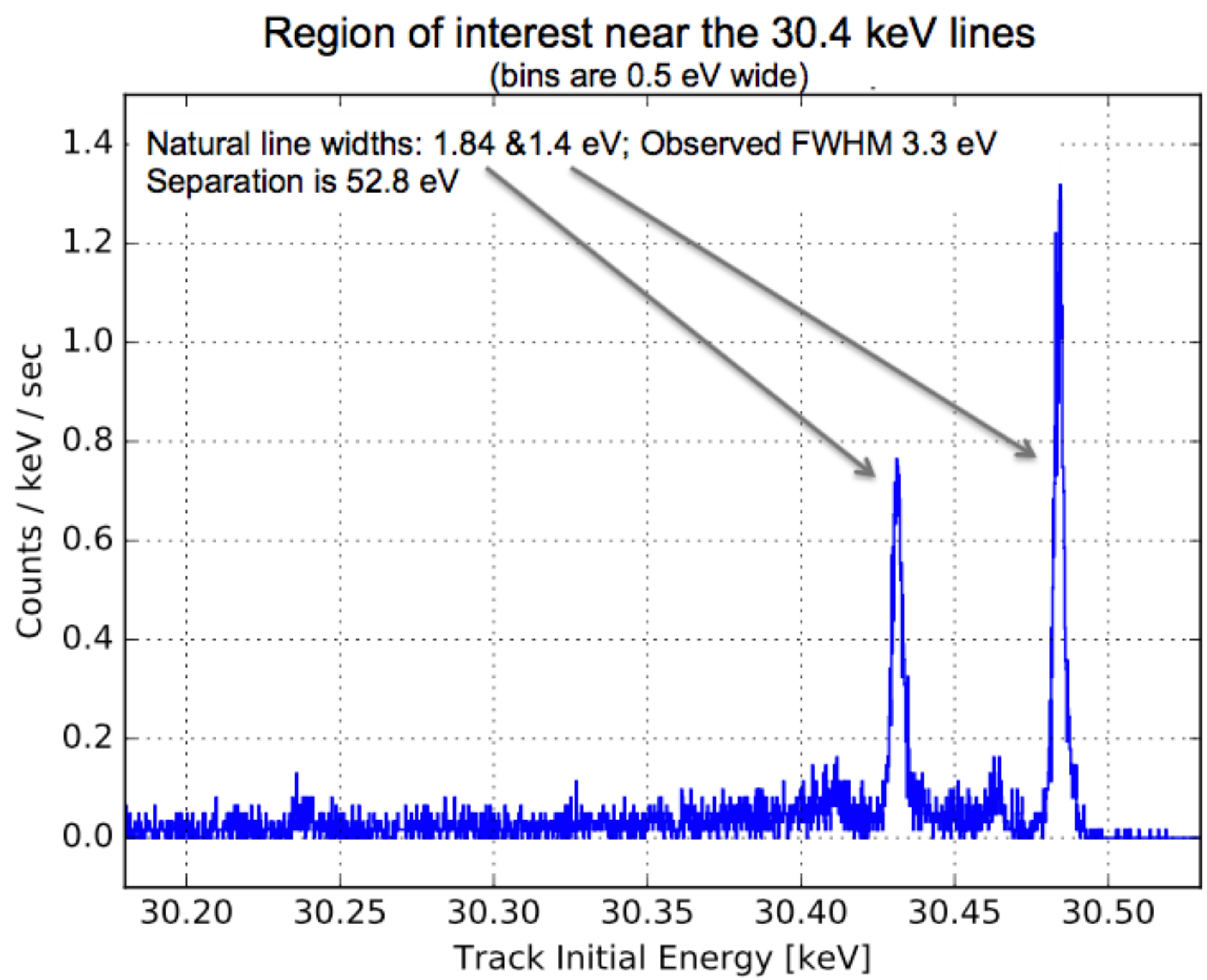
Phase I: results

Improved Phase I setup

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

Achieved resolutions

- $\sigma(E) = 3.3\text{eV}$ @ 30.4keV
- $\sigma(E) = 5.1\text{eV}$ @ 17.8keV



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

▸ new measurement method established

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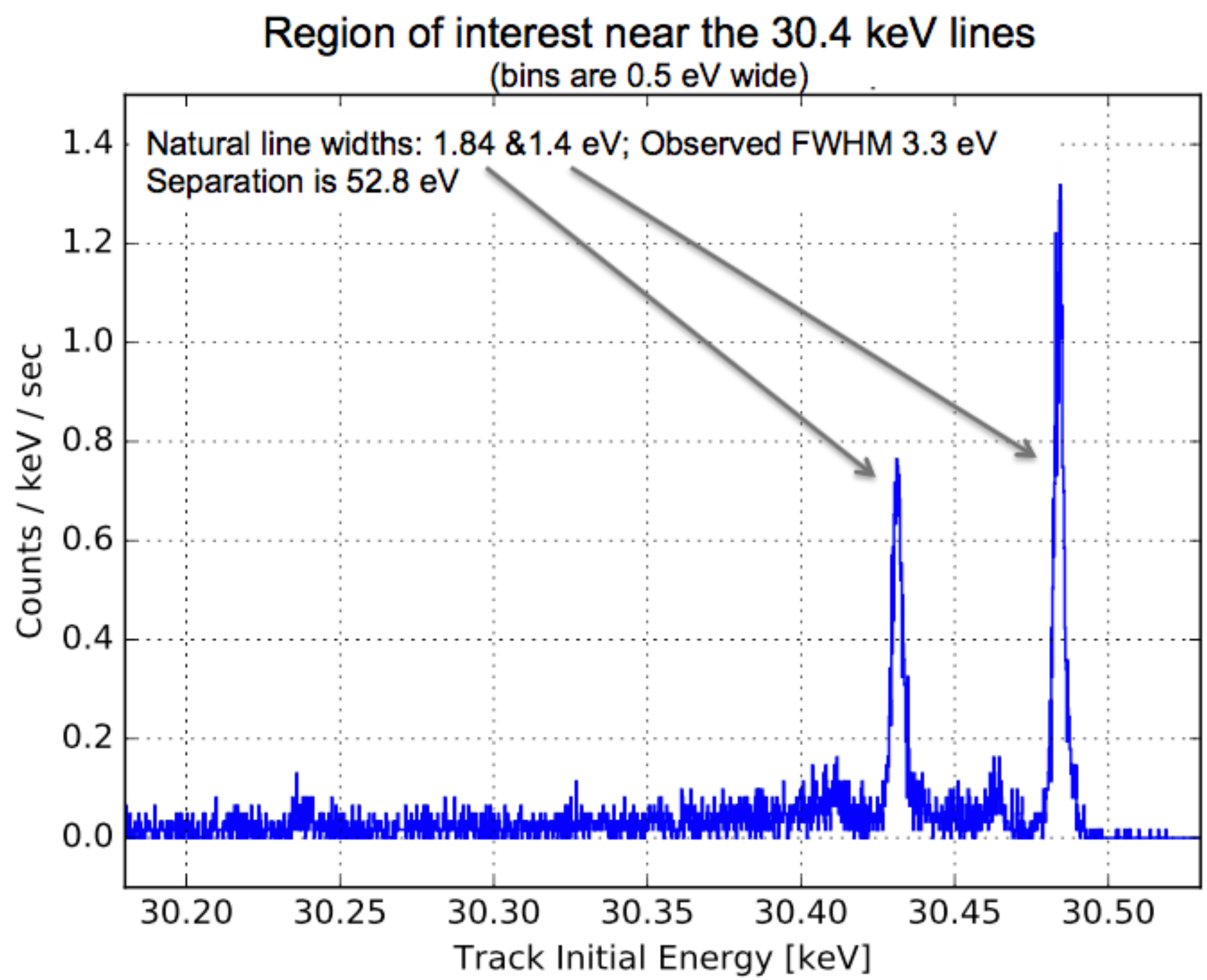

P8 Collaboration, J. Phys. G 44 (5) 2017

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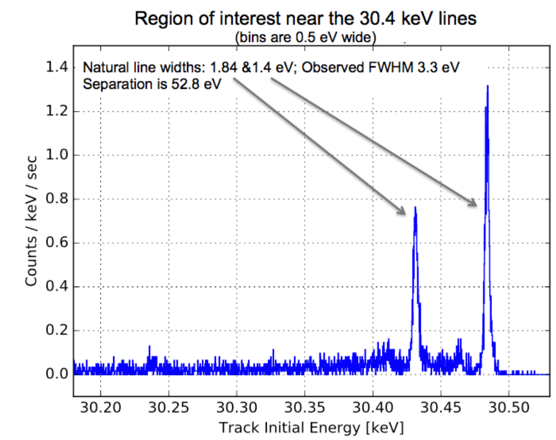
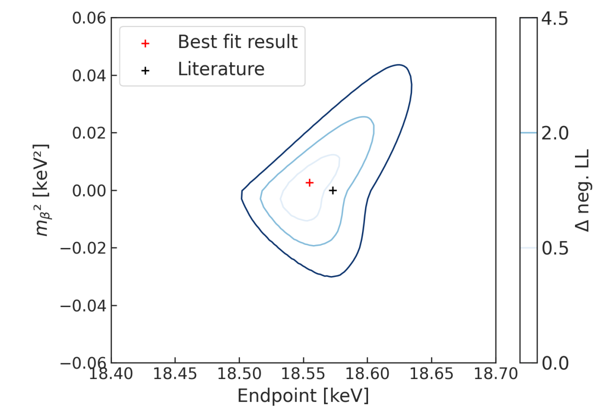
CRES — *Cyclotron Radiation Emission Spectroscopy*

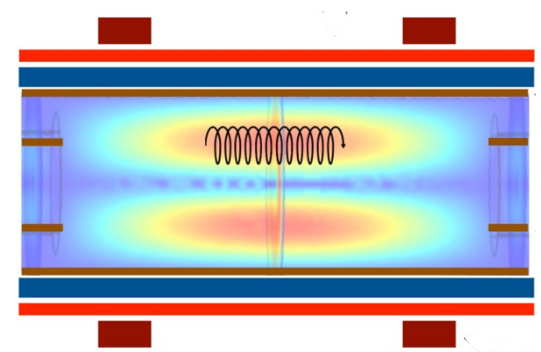
Project Plan (and talk outline)

- **Phase I**
  - demonstrate CRES technique ✓

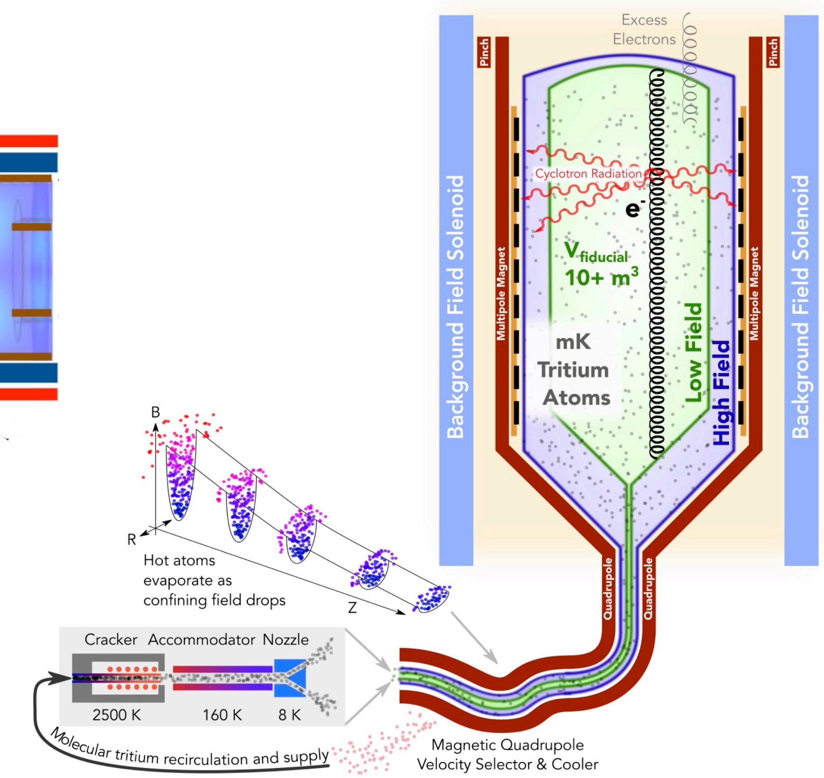




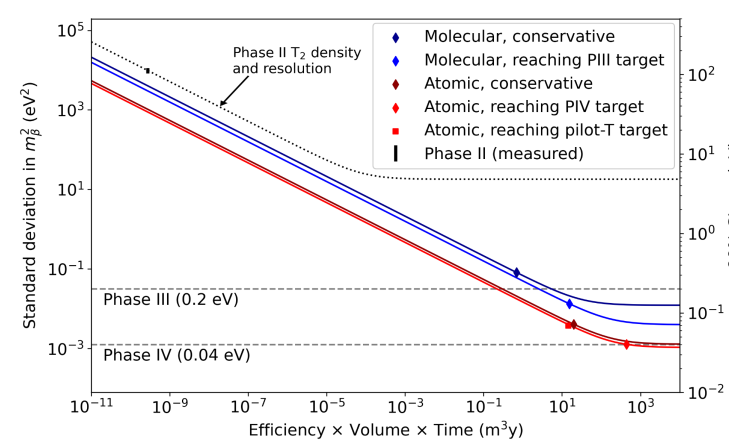
- **Phase II**
  - first Tritium spectrum with CRES



- **Phase III**
  - Go bigger!
    demonstrate large cavity
  - Go atomic!
    demonstrate atomic tritium trapping



- **Phase IV**
  - full apparatus, reaching
    $m_\beta < 0.04$ eV sensitivity



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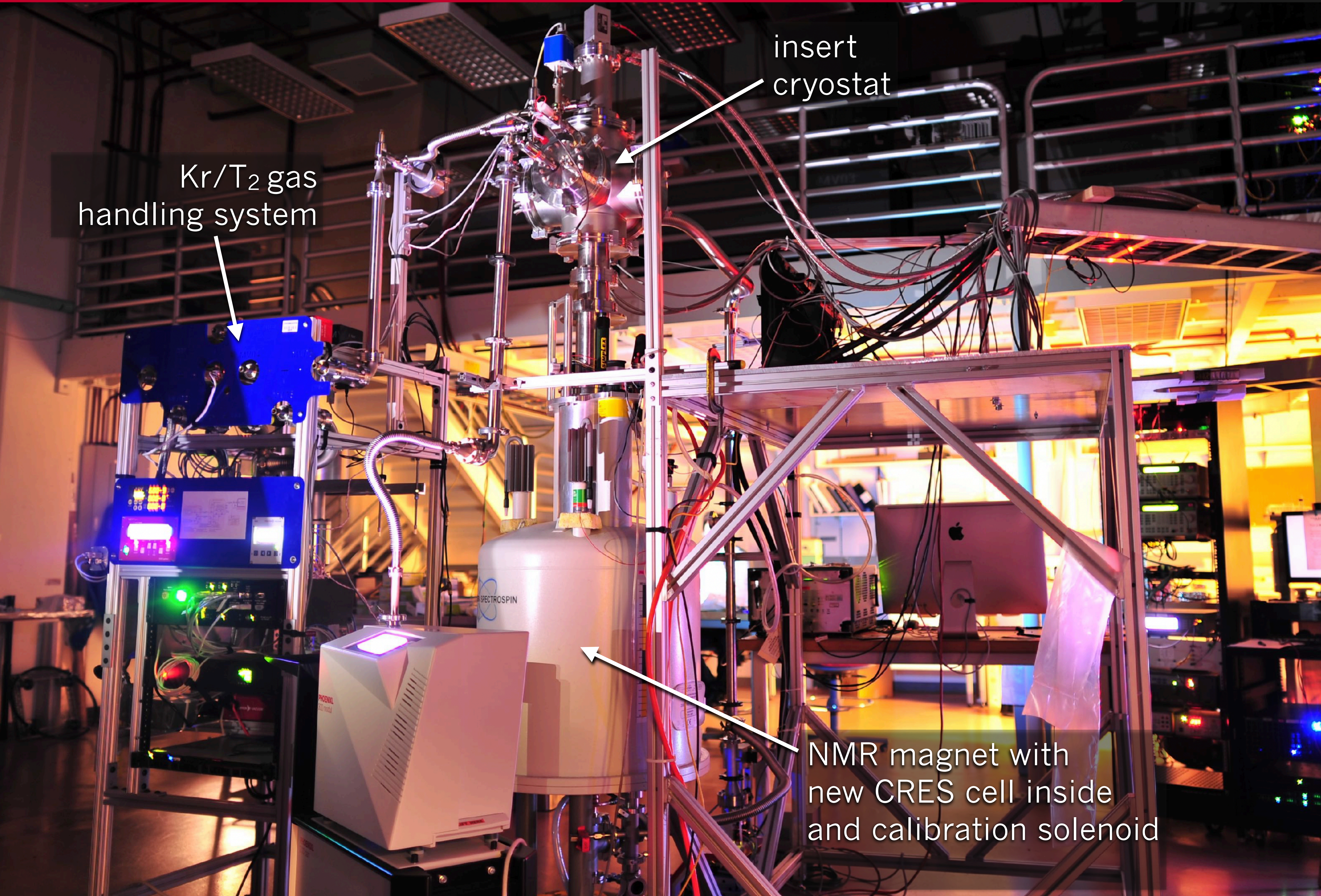
Phase II setup



Phase II: ^{83m}Kr data

Krypton data taking

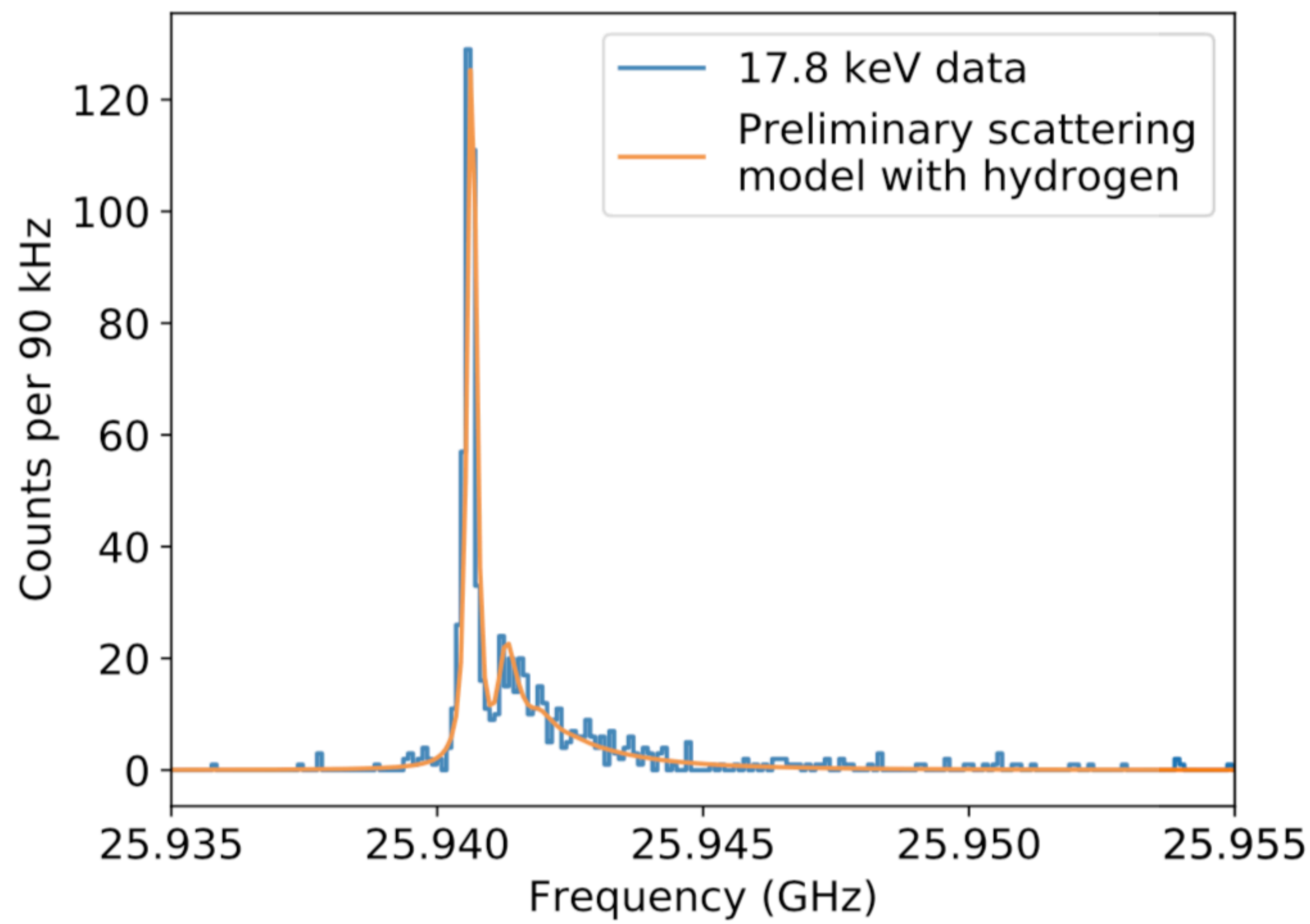
- shallow traps
  - only retain large pitch angles → low rate
  - little variation in B field within trap → good energy resolution

Electron scattering

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

Hydrogen scattering model

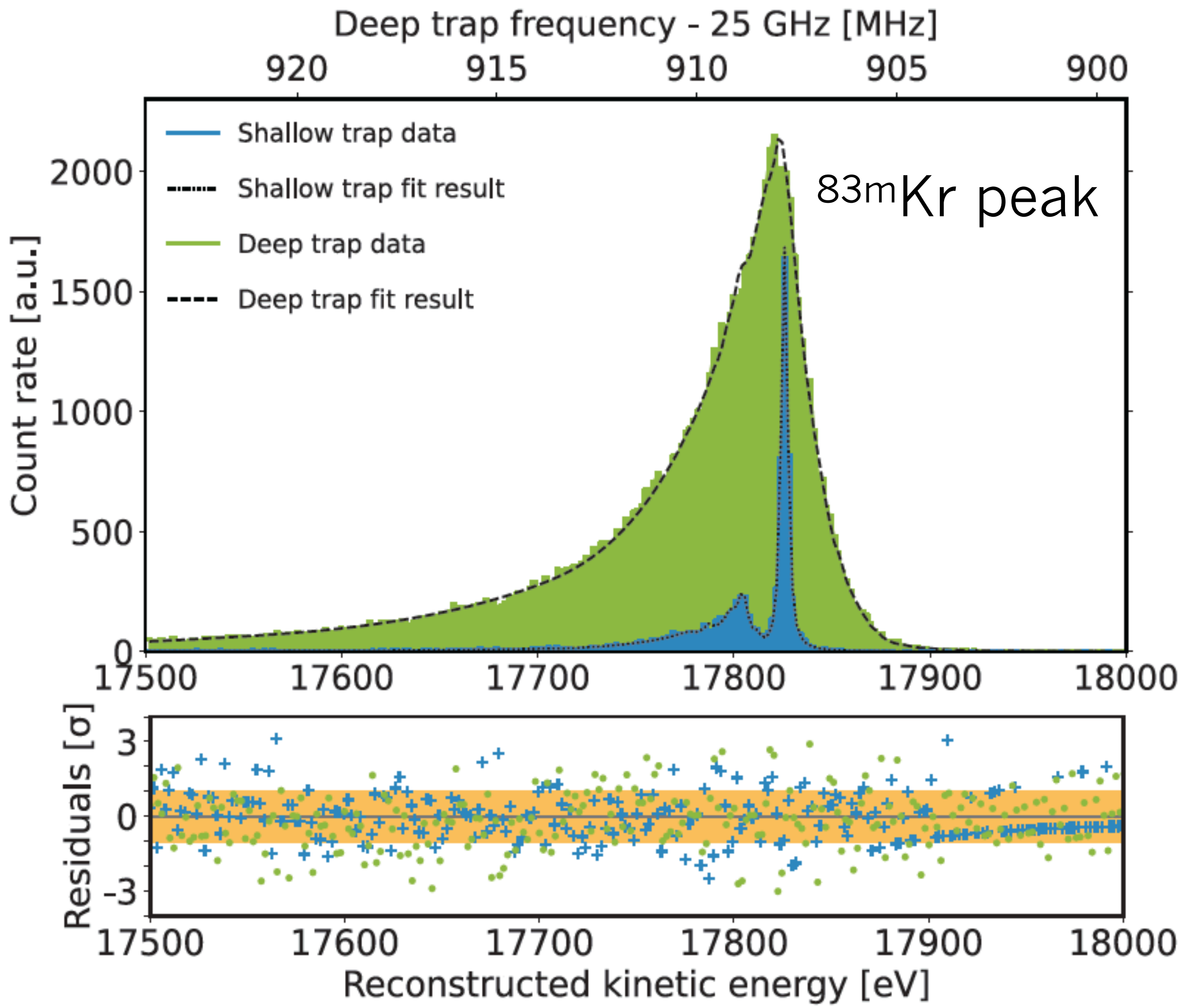
- 4eV FWHM Voigt profile
- 2.84eV line width in ^{83m}Kr
  - detector resolution surpasses intrinsic line width



Phase II: T_2 data

Tritium data taking

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



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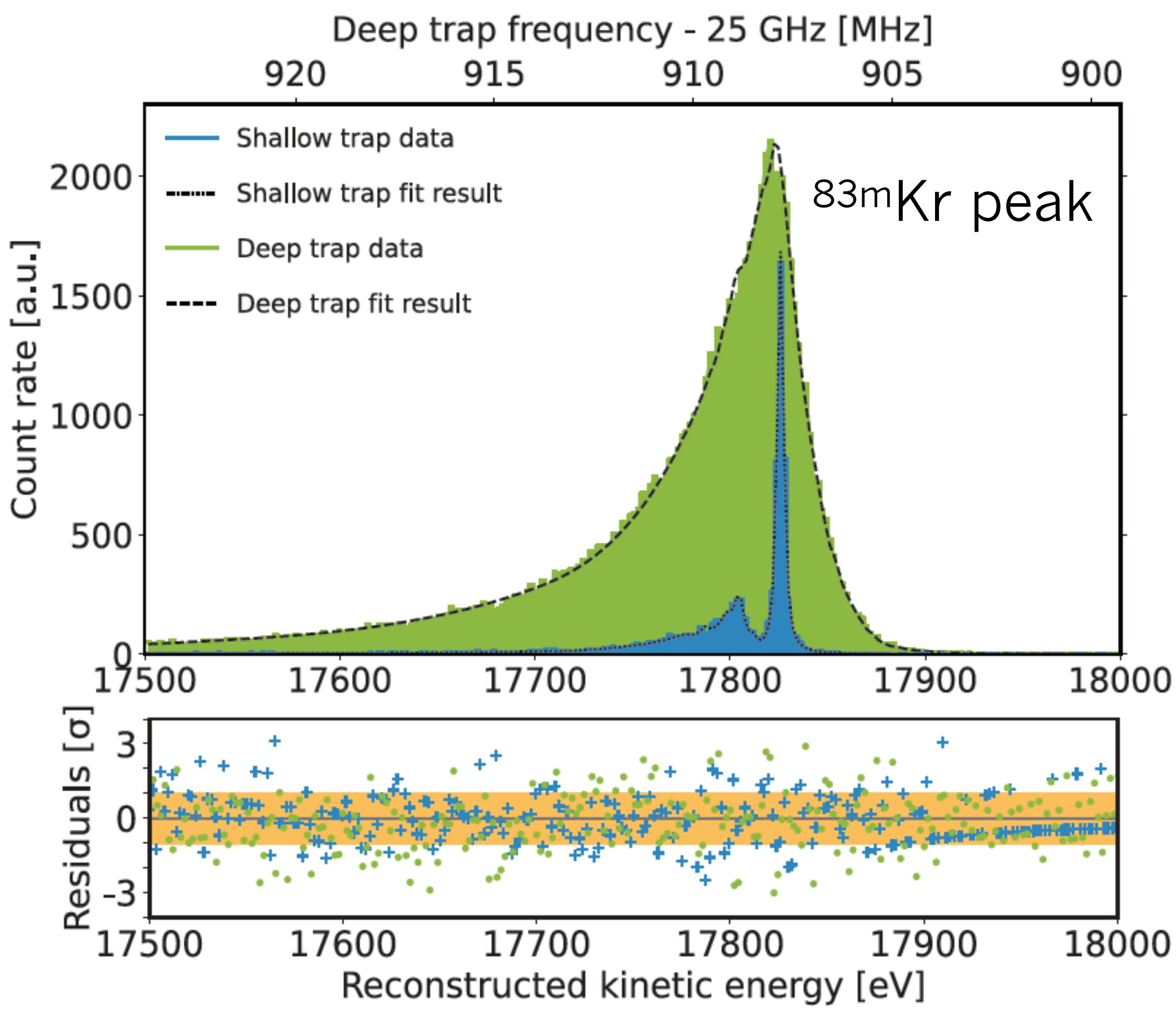
Tritium configuration

- 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!)



Detection efficiency

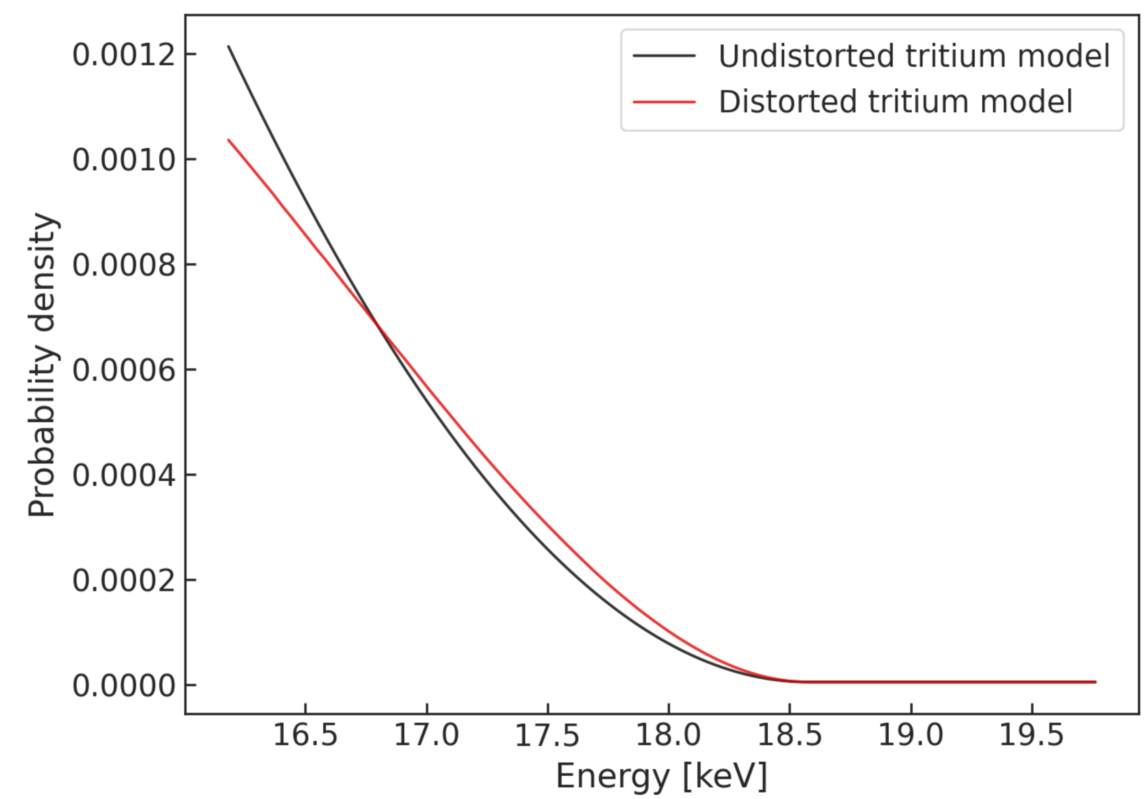
Emitted cyclotron power

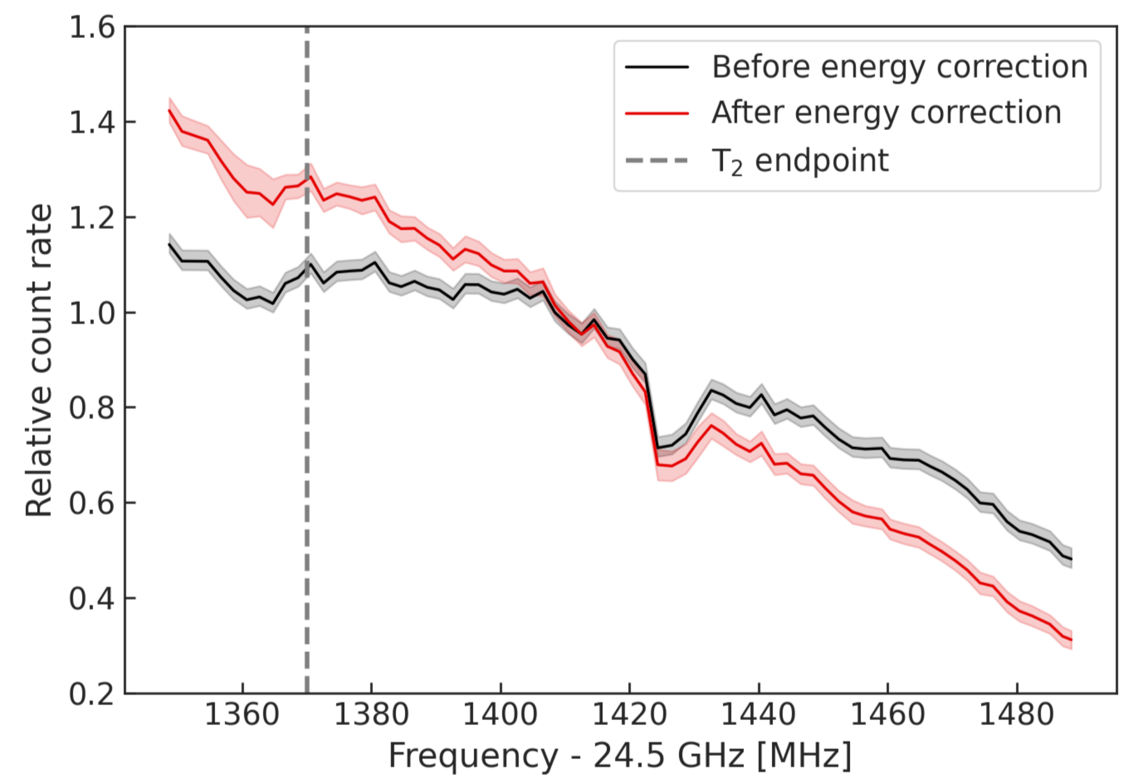
$$P(\gamma, \theta) = \frac{1}{4\pi\varepsilon_0} \frac{2}{3} \frac{q^4 B^2}{m_e^2} (\gamma^2 - 1) \sin^2 \theta$$

- 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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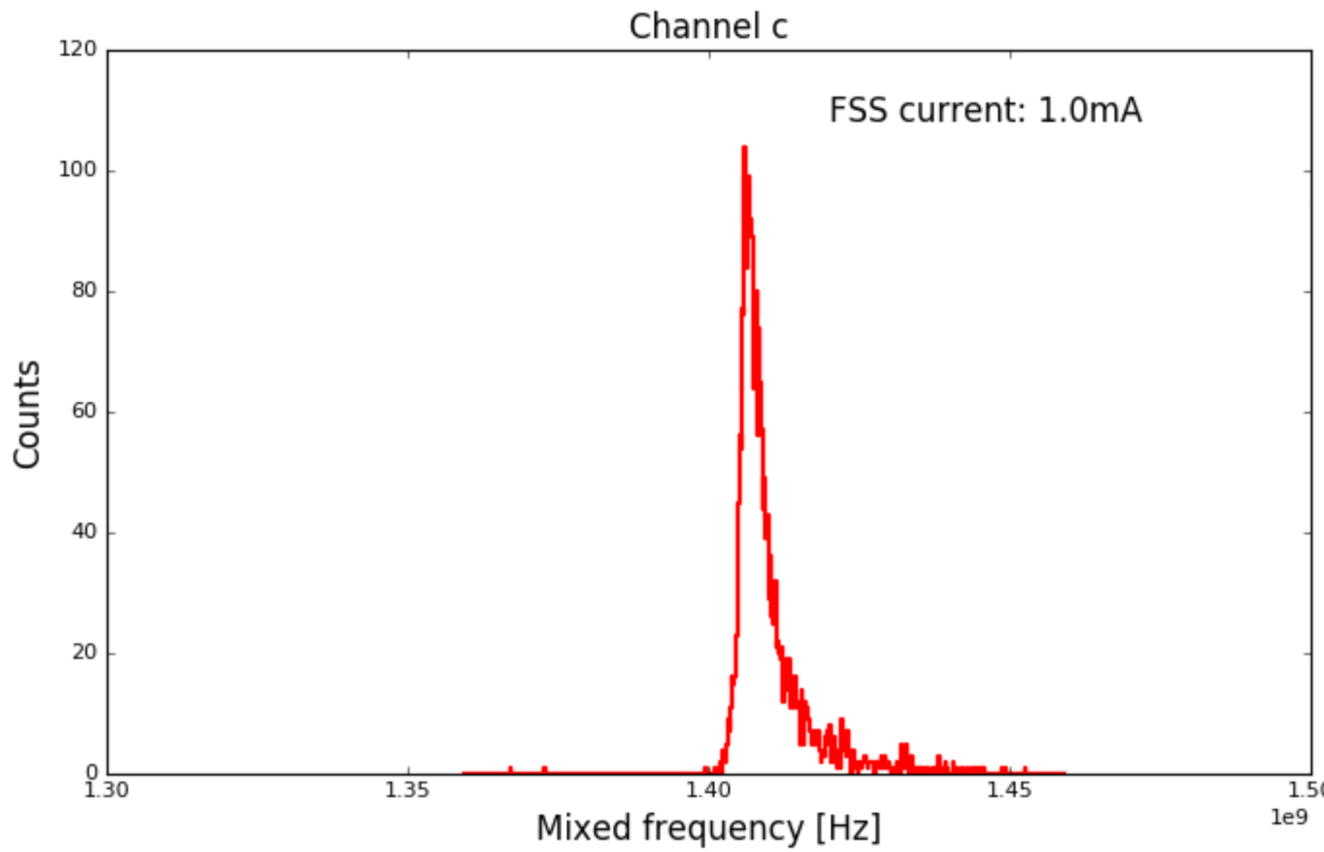
Phase II: Solenoid calibration

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)



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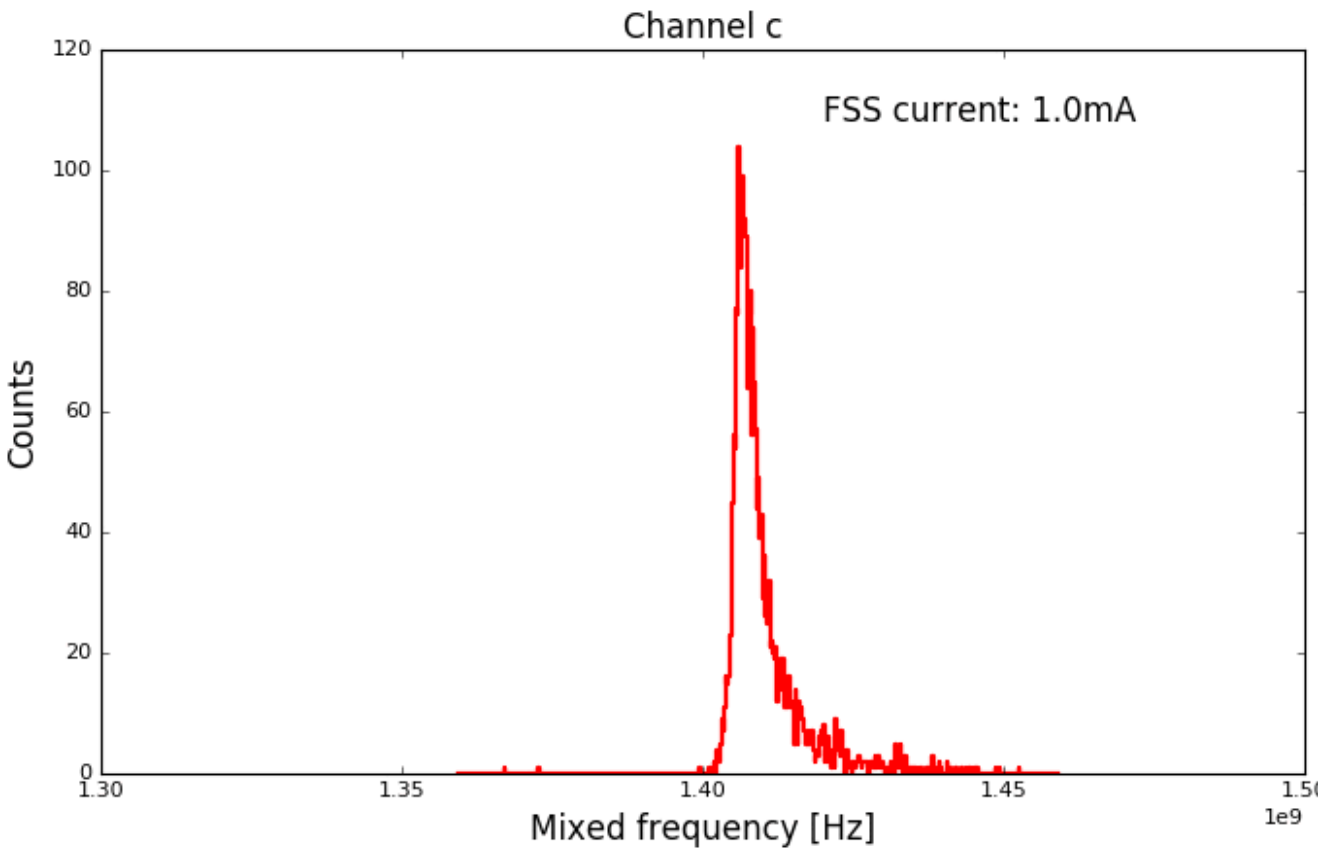

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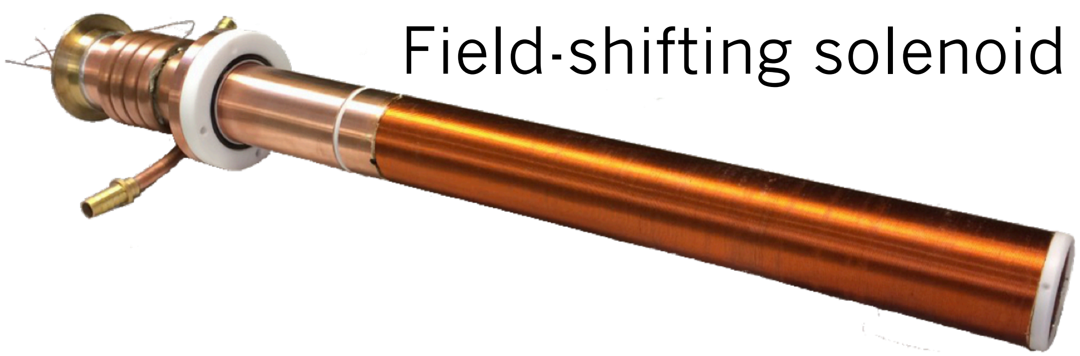
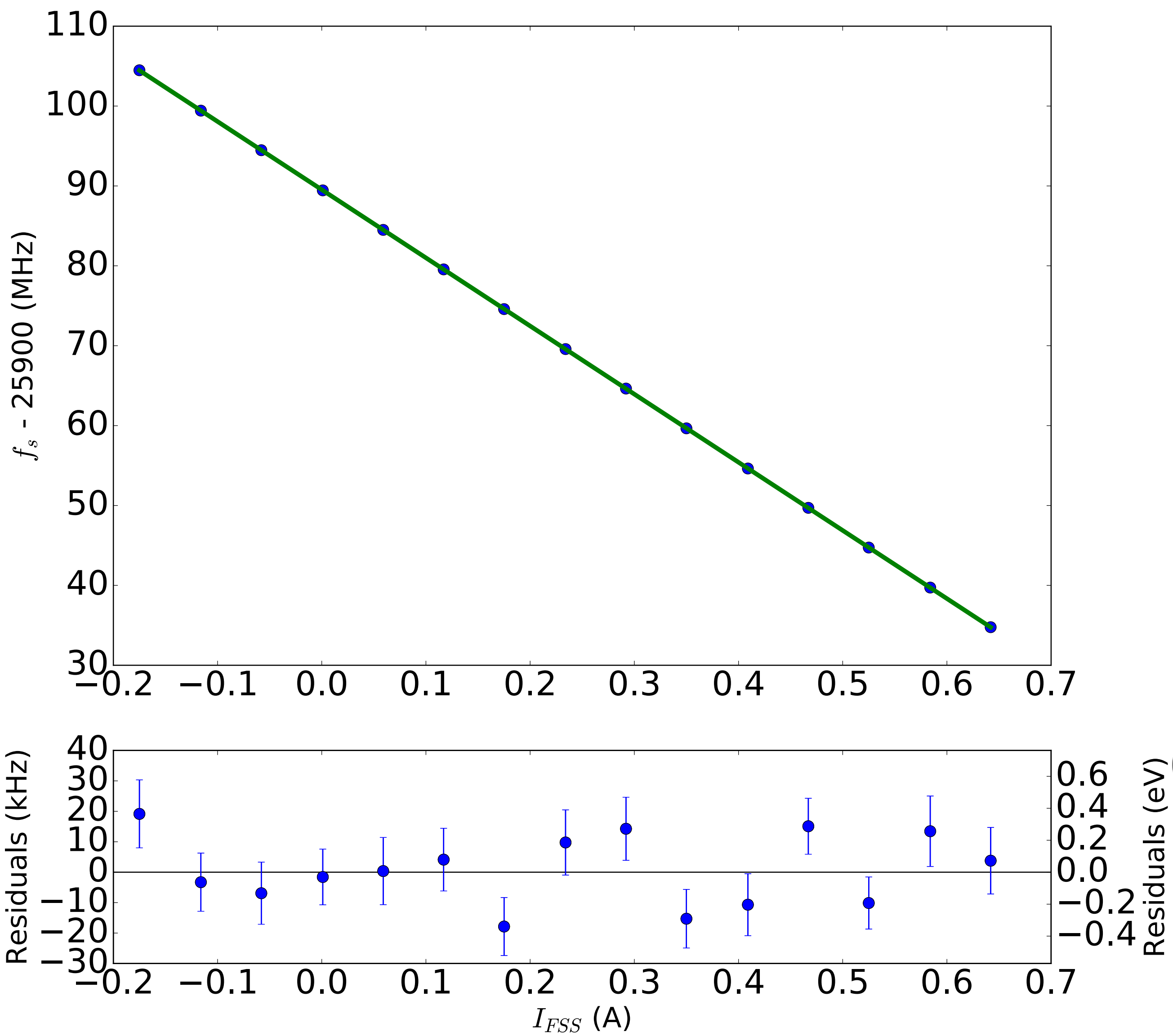




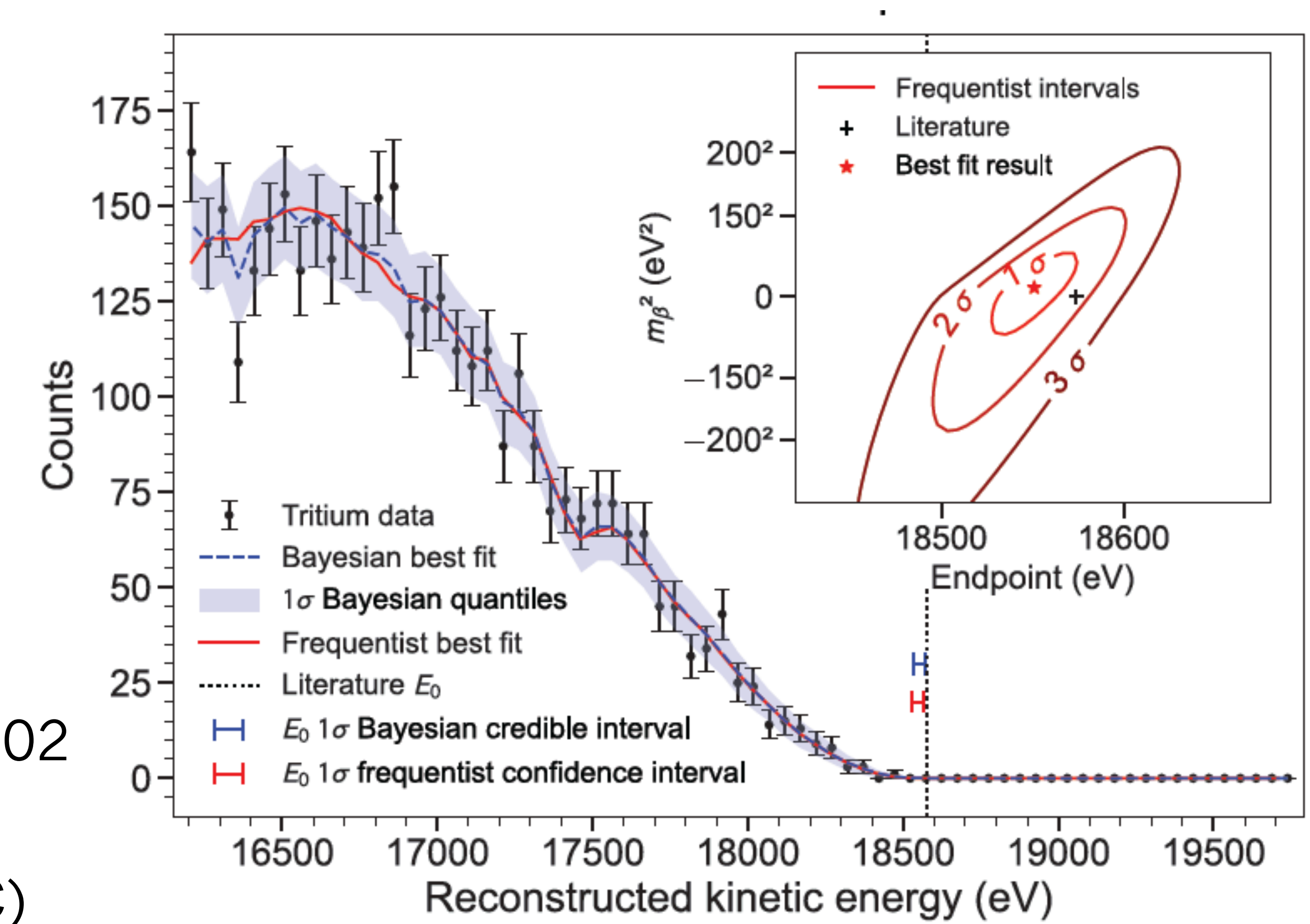
T2 analysis results

Analysis methods

- Frequentist analysis
- Bayesian analysis
  - good agreement!

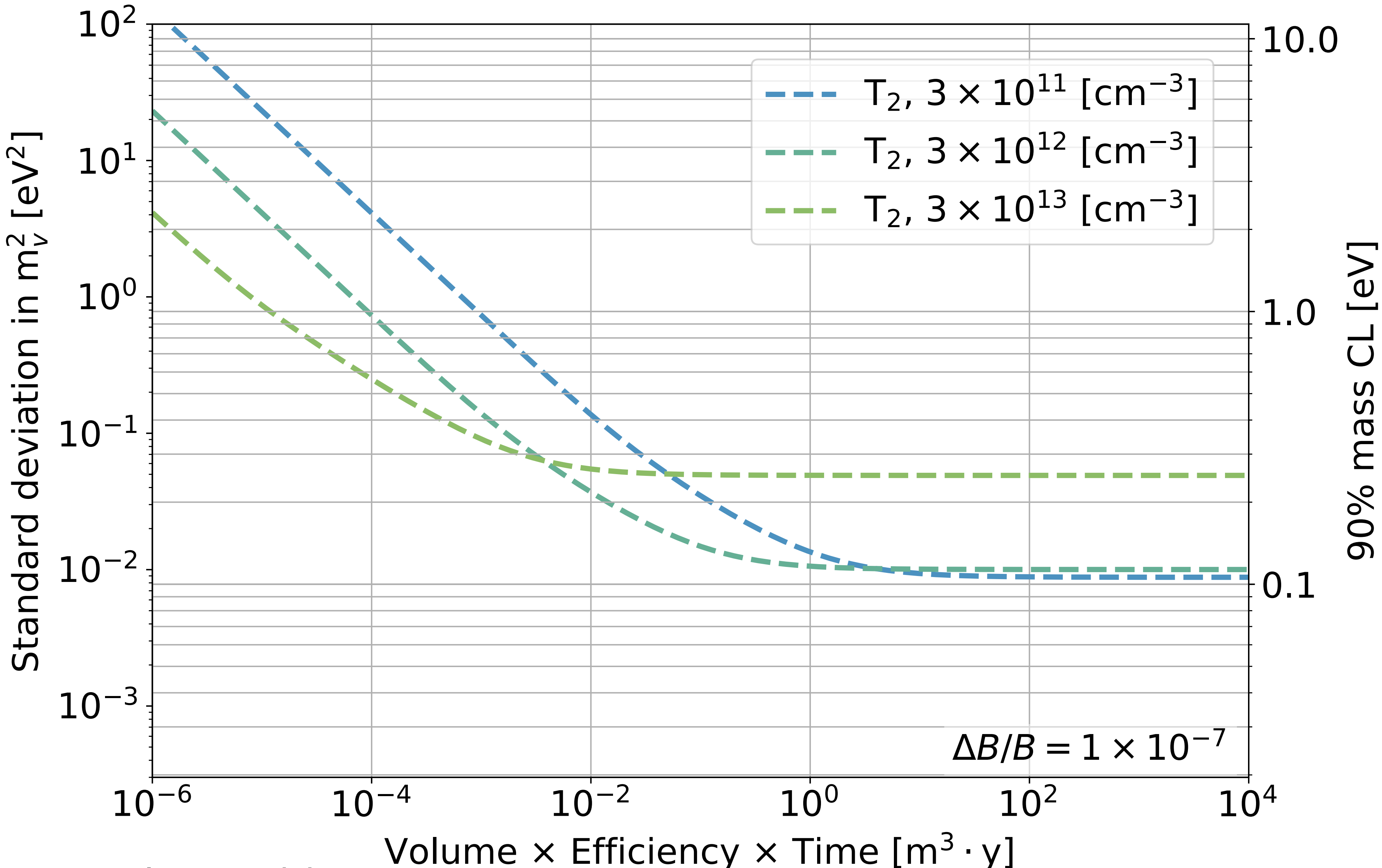
Analysis results

- main result
  - Phys. Rev. Lett. 131, 102502
- detailed discussion
  - arXiv:2302.12055 (→ PRC)



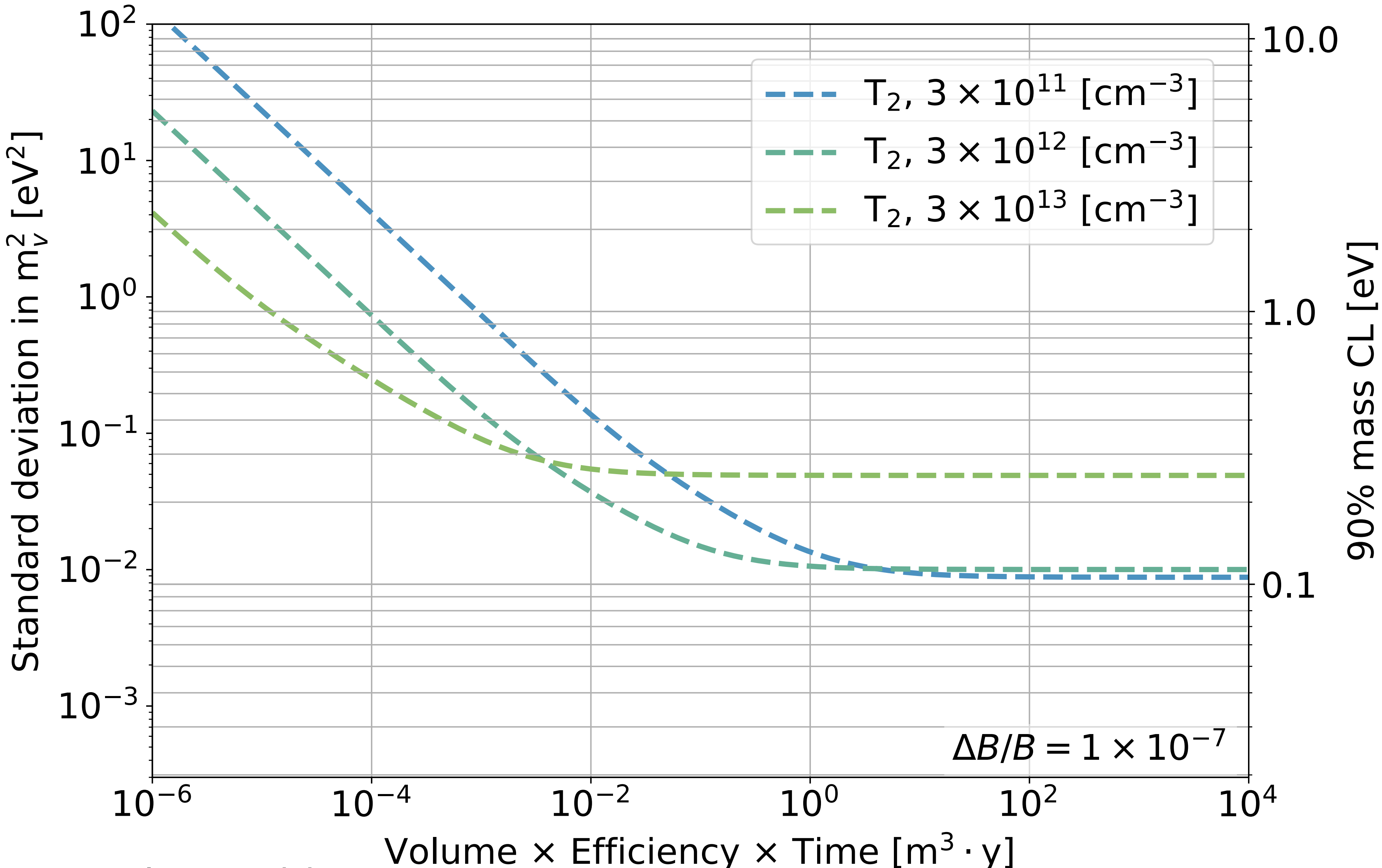
90% CL	T2 endpoint	Neutrino mass	Background rate
frequentist	$E_0 = 18548^{+19}_{-19}$ eV	$m_\beta \leq 152$ eV/c^2	$R \leq 3 \cdot 10^{-10}$ eV^{-1}s^{-1}
bayesian	$E_0 = 18553^{+18}_{-19}$ eV	$m_\beta \leq 155$ eV/c^2	

Potential for neutrino mass?



Sensitivity limited by

Potential for neutrino mass?



Sensitivity limited by

- density of tritium gas → rest gas interactions

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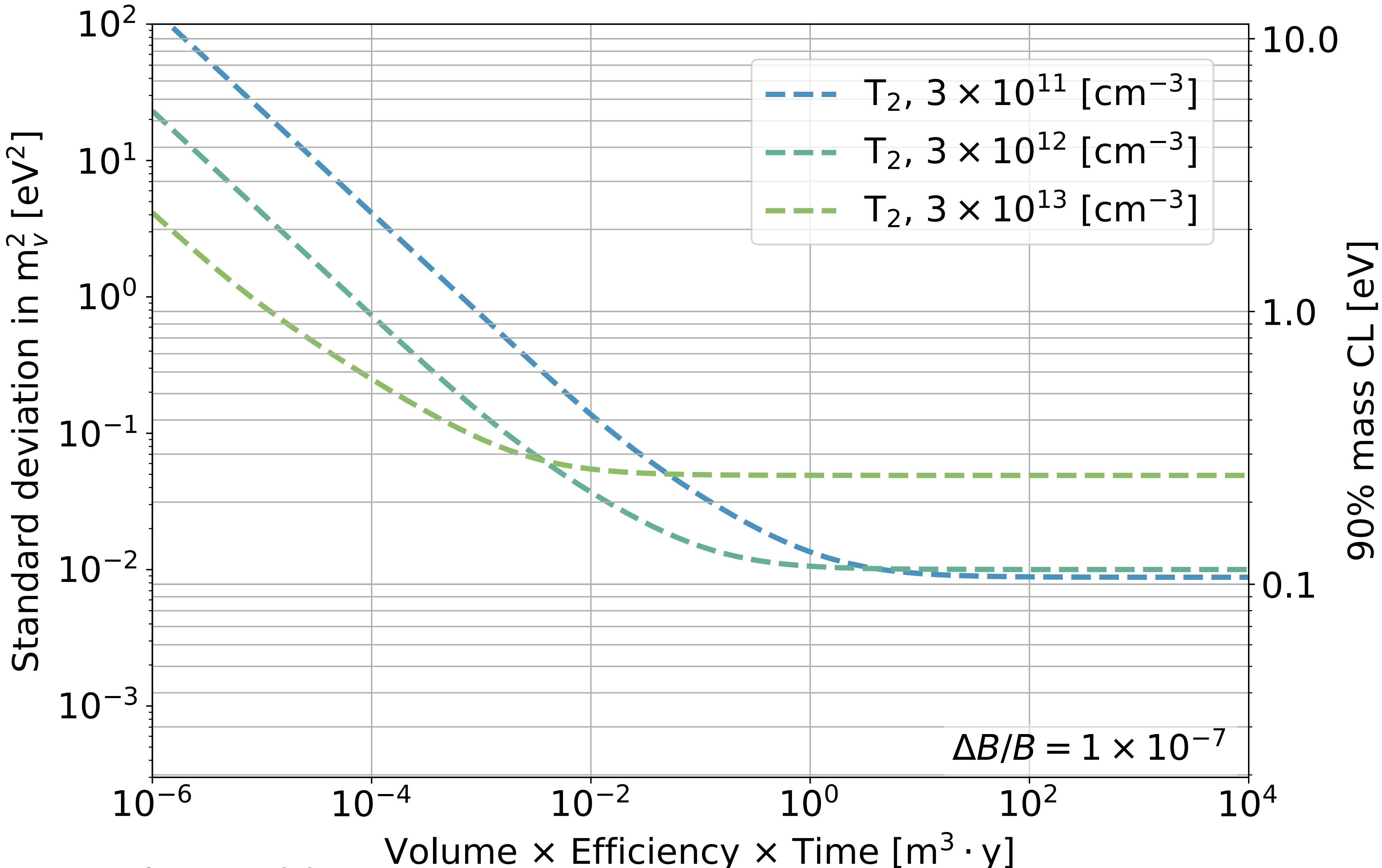

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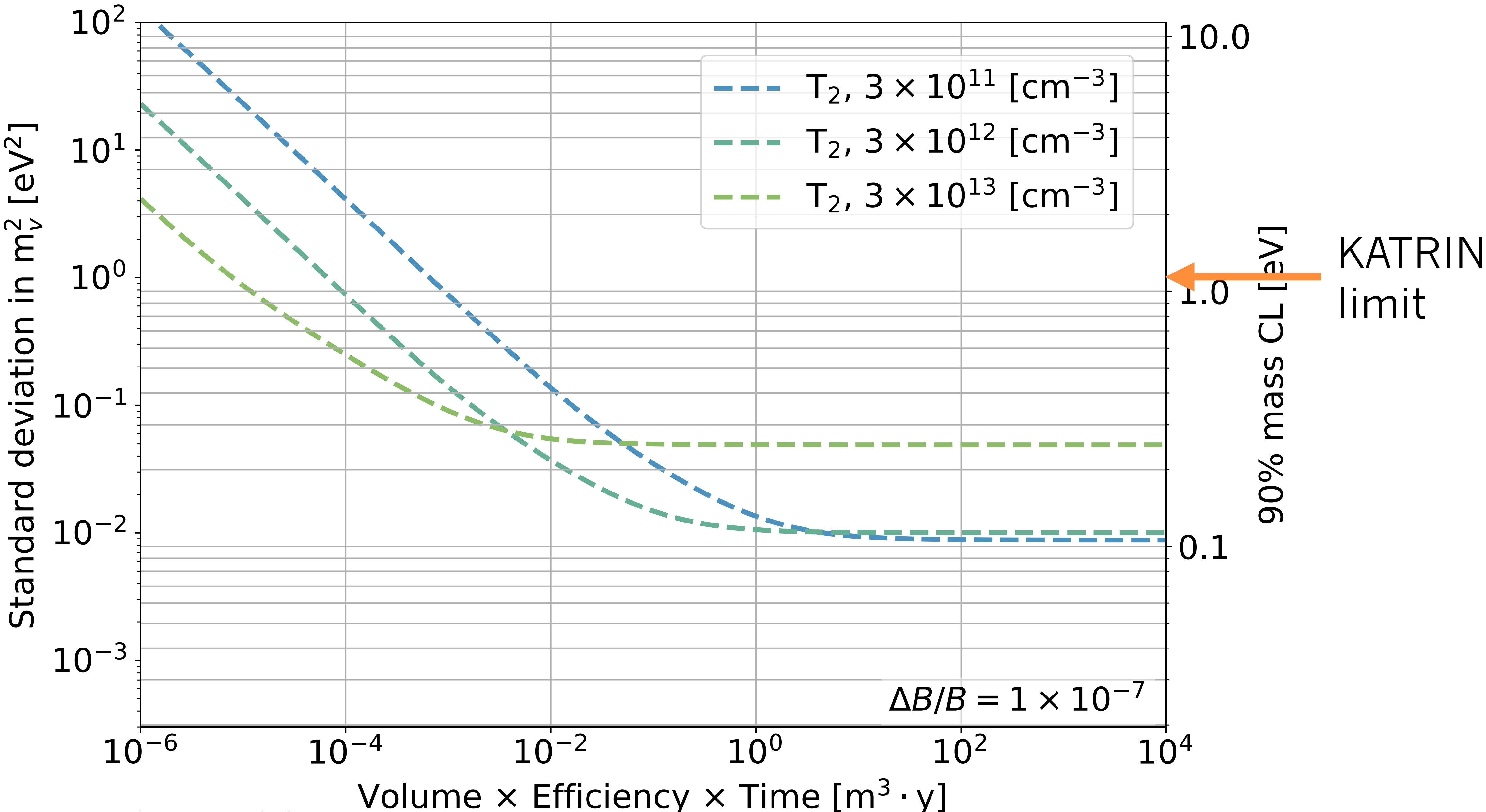

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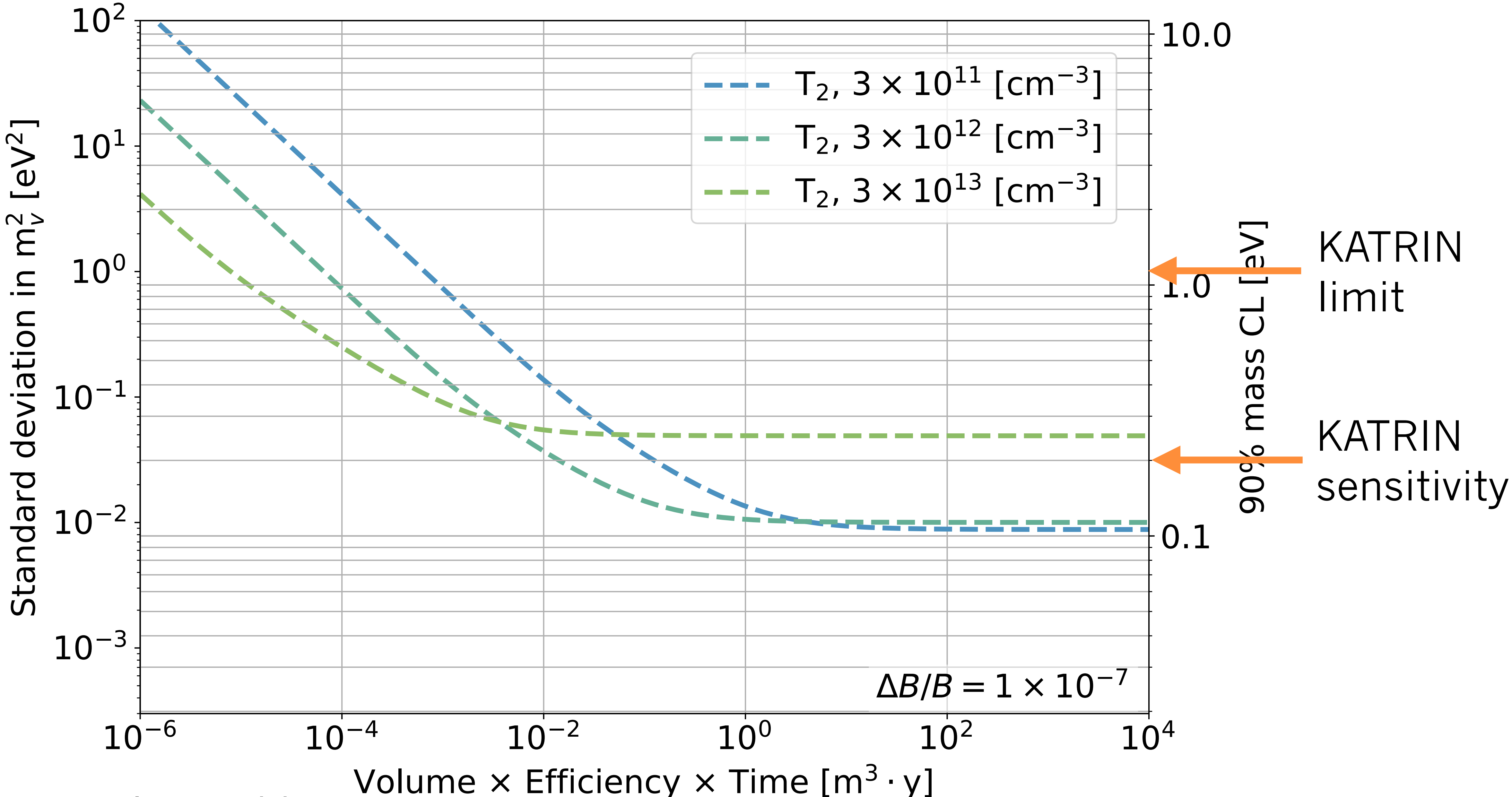

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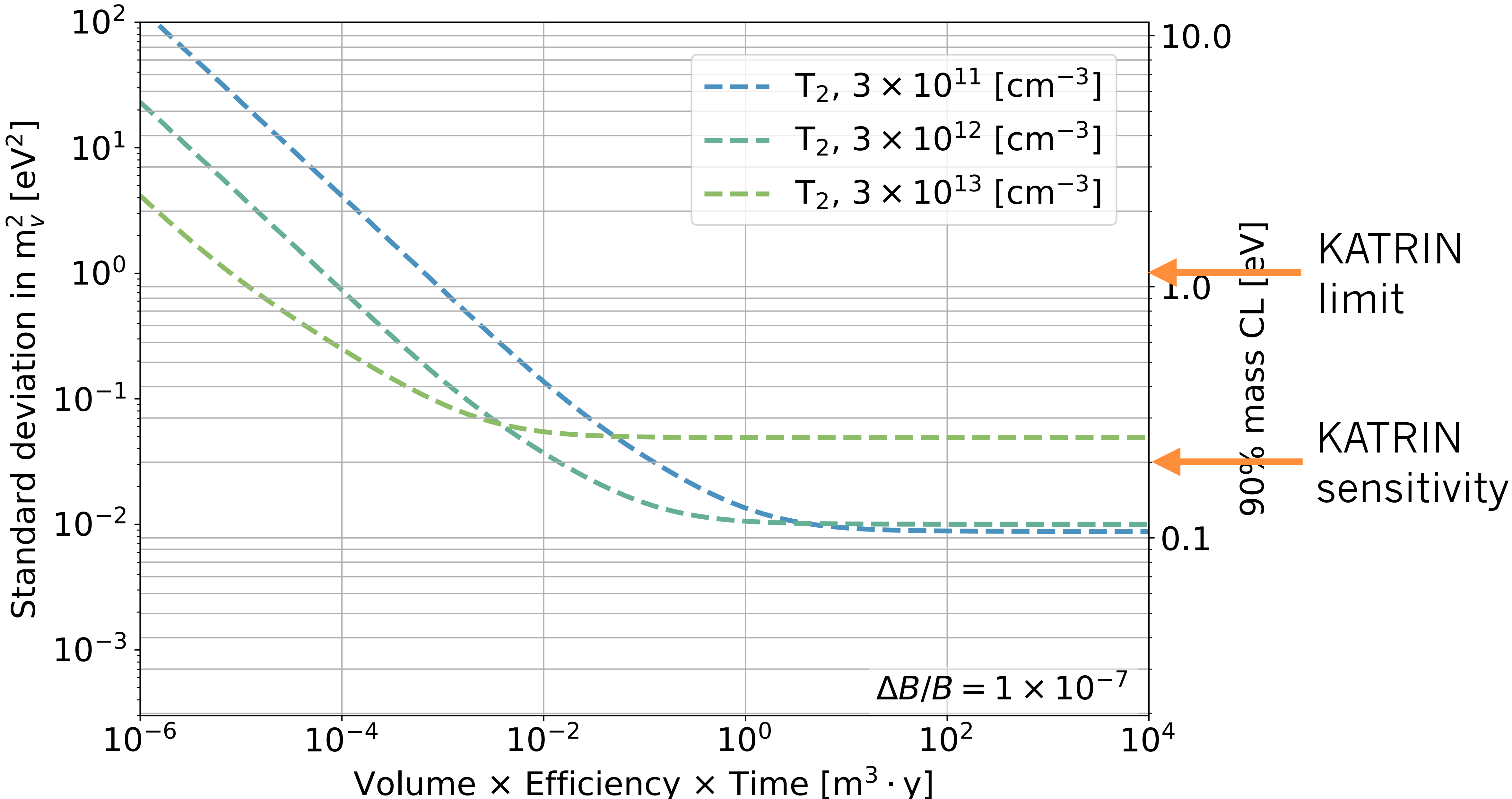
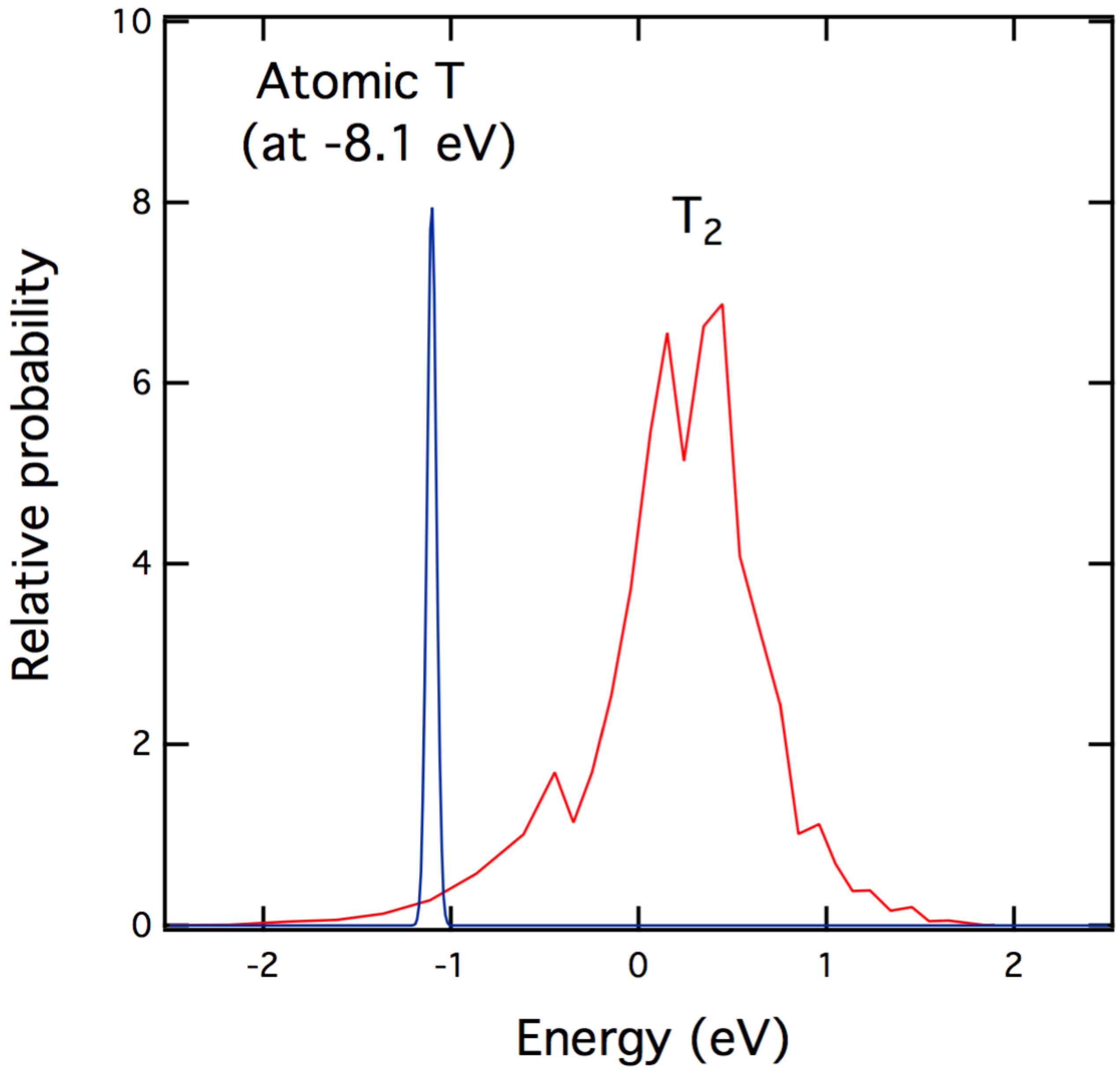
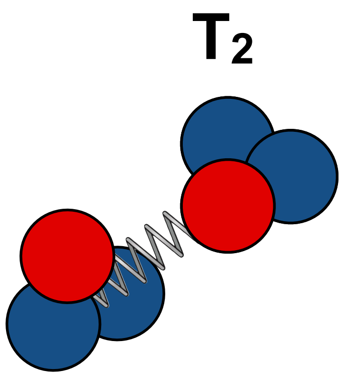


Sensitivity limited by

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

Molecular tritium limitations



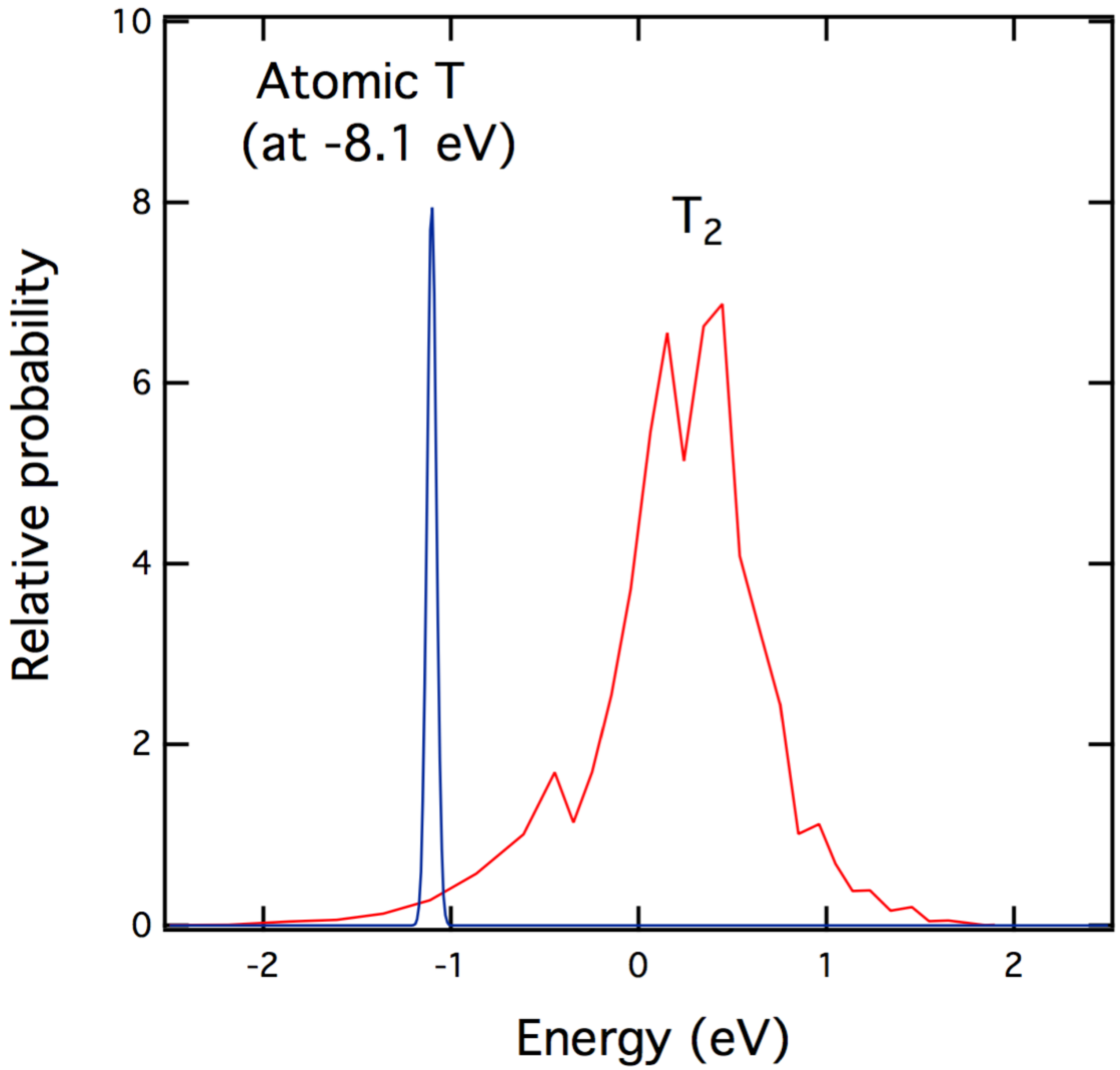


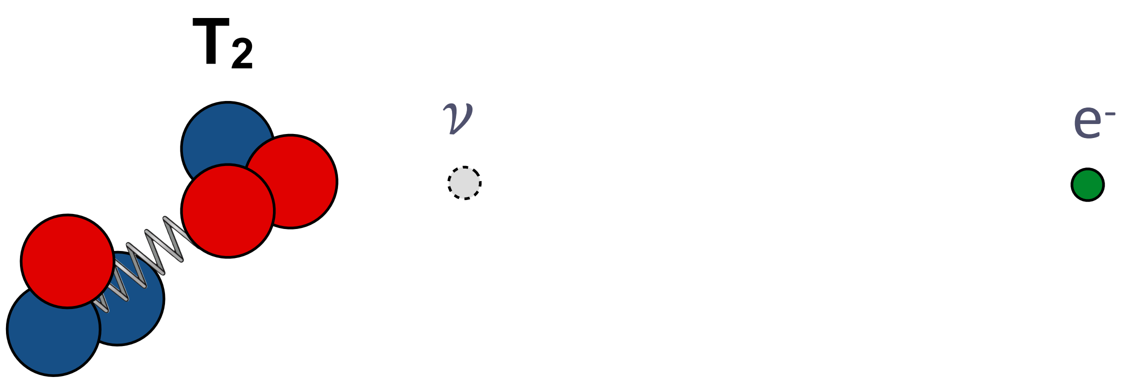
Molecular excitations
in ^{3}HeT daughter molecule

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

Need atomic tritium
for **ultimate** experiment!

Molecular tritium limitations





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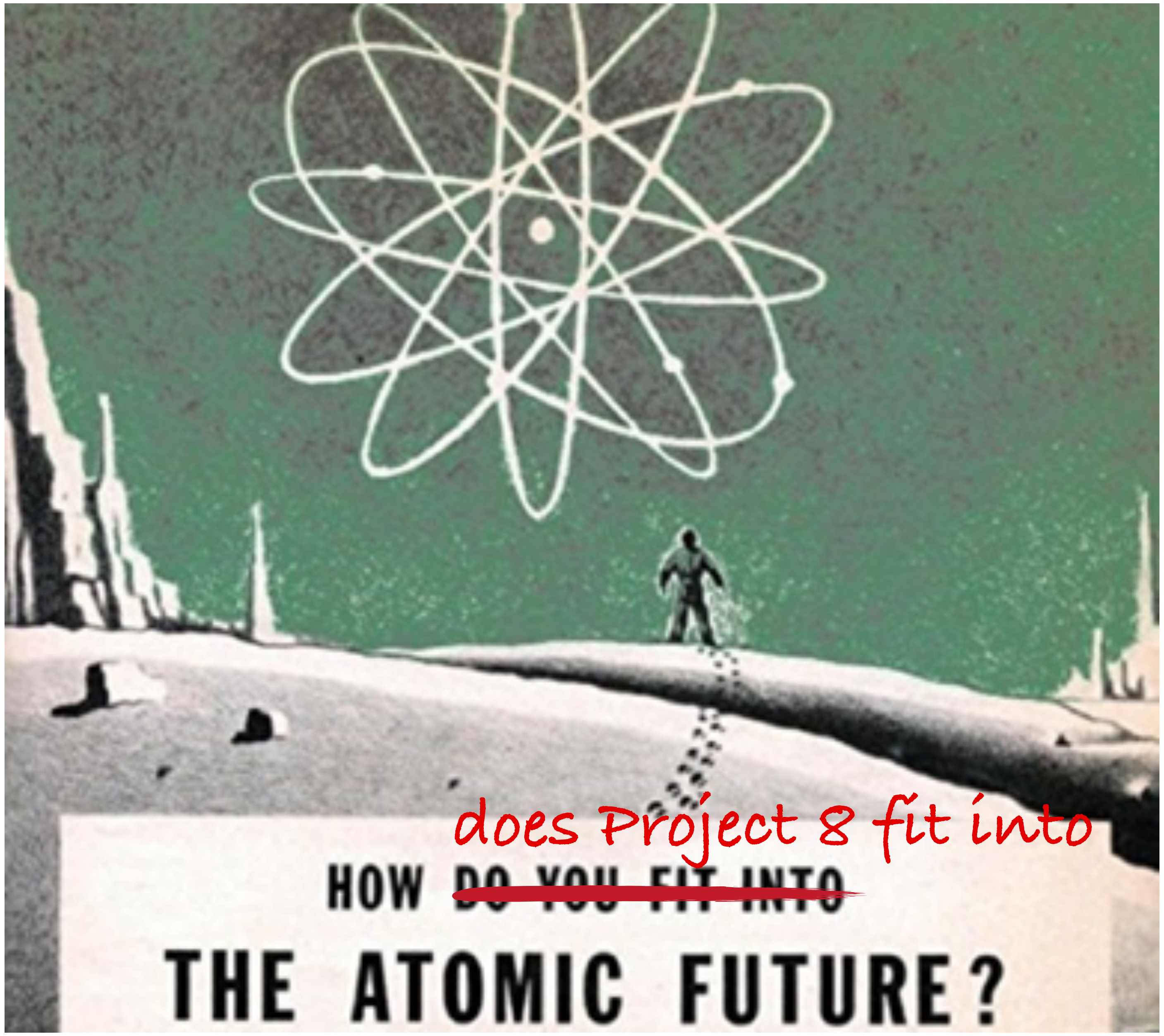

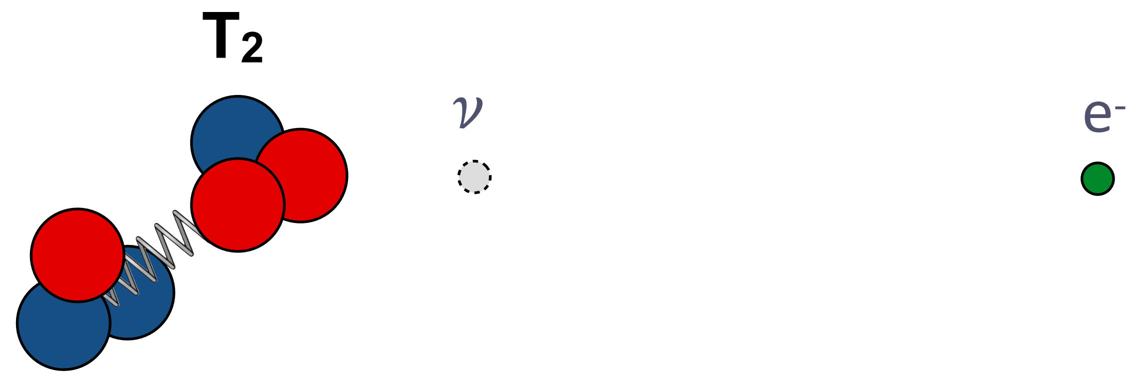

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Magnetic storage of neutral atoms

Storage of atomic T

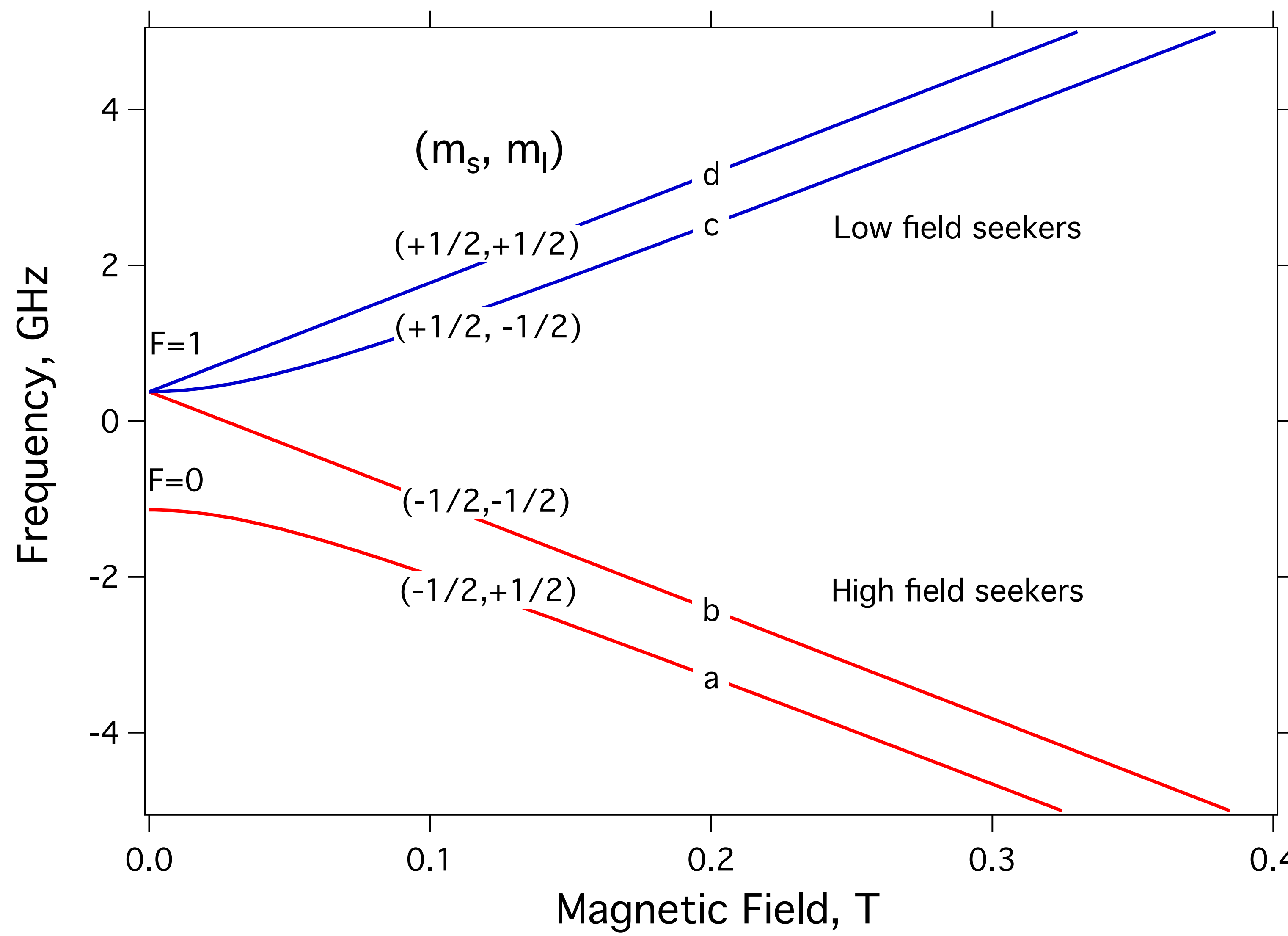
- recombination catalyzed by walls
  → difficult!

- H,D and T have unpaired e⁻
  - non-zero magnetic moment μ
  - tend to (anti-)align with B-field if change is adiabatic

Potential energy

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

→ half of spin states seek field minimum



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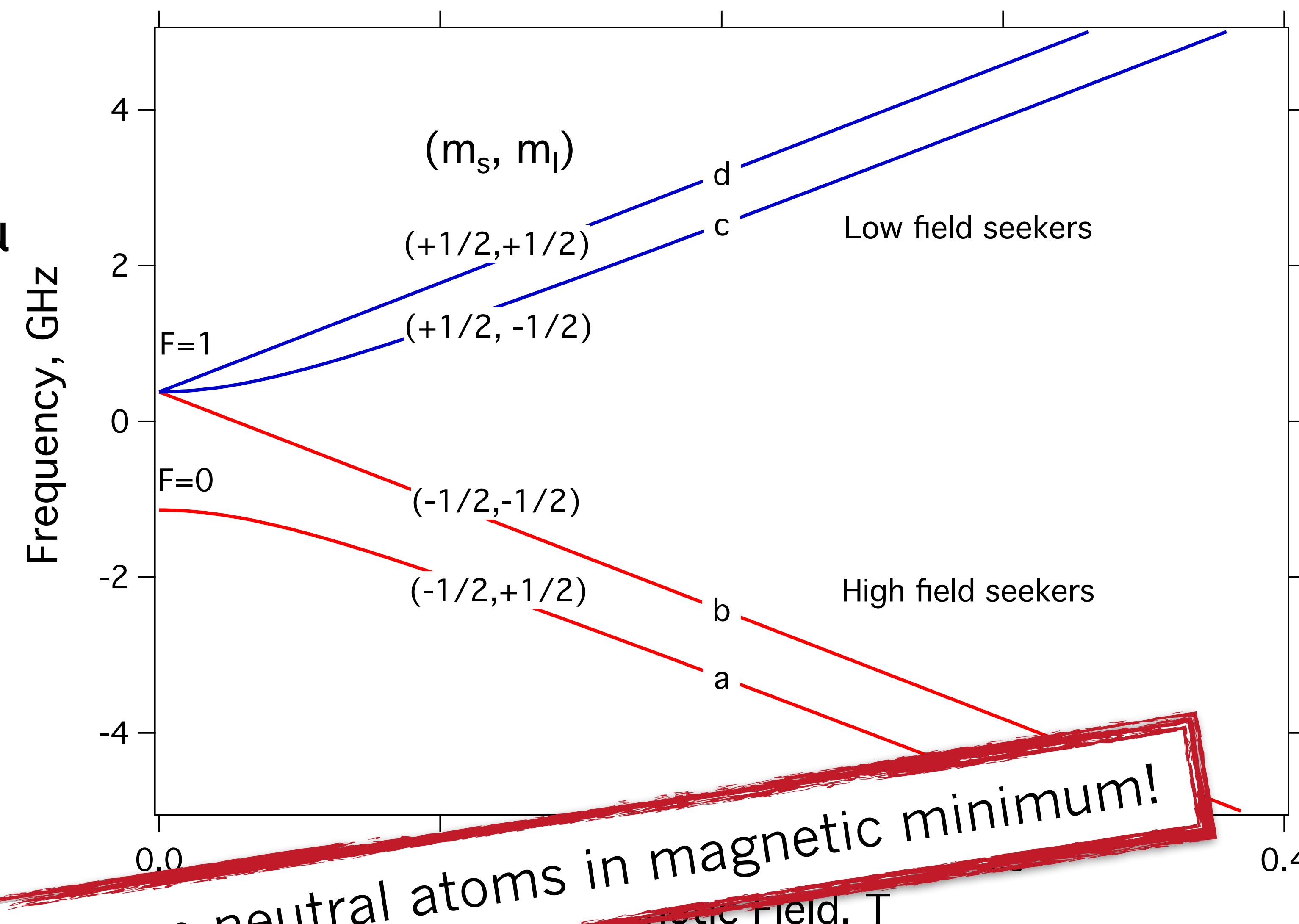


Can trap neutral atoms in magnetic minimum!

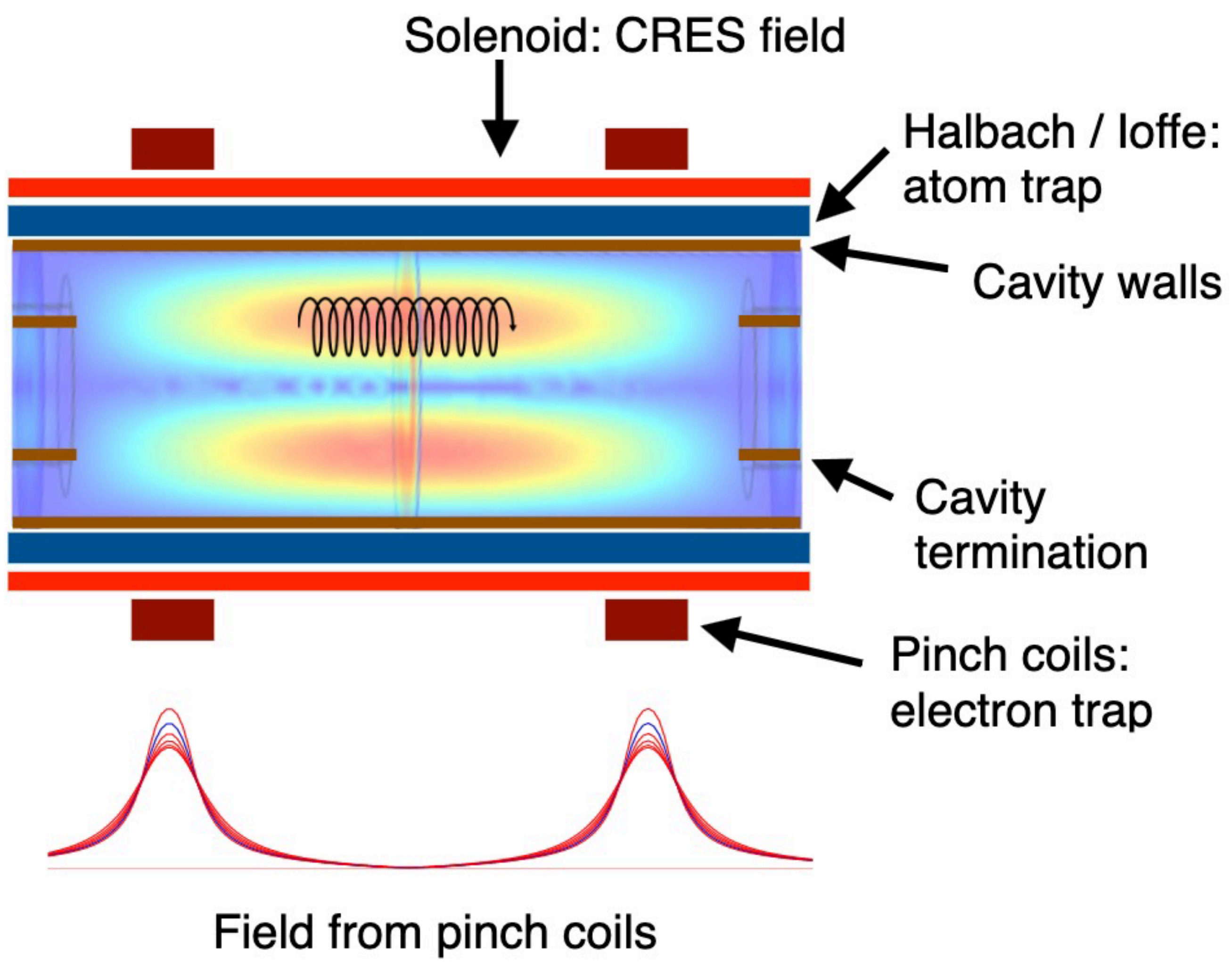
Scaling towards the future

Requirements

- high statistical power
  - large volume
  - high detection efficiency
- good energy resolution
  - atomic tritium
  - track reconstruction
- lower systematic uncertainties and easier calibration
  - cavity design with simple mode structure

Concept

- $\mathcal{O}(m^3)$ **cavity** with **atom trap**
  - TE_{01} mode at $\mathcal{O}(100\text{MHz})$

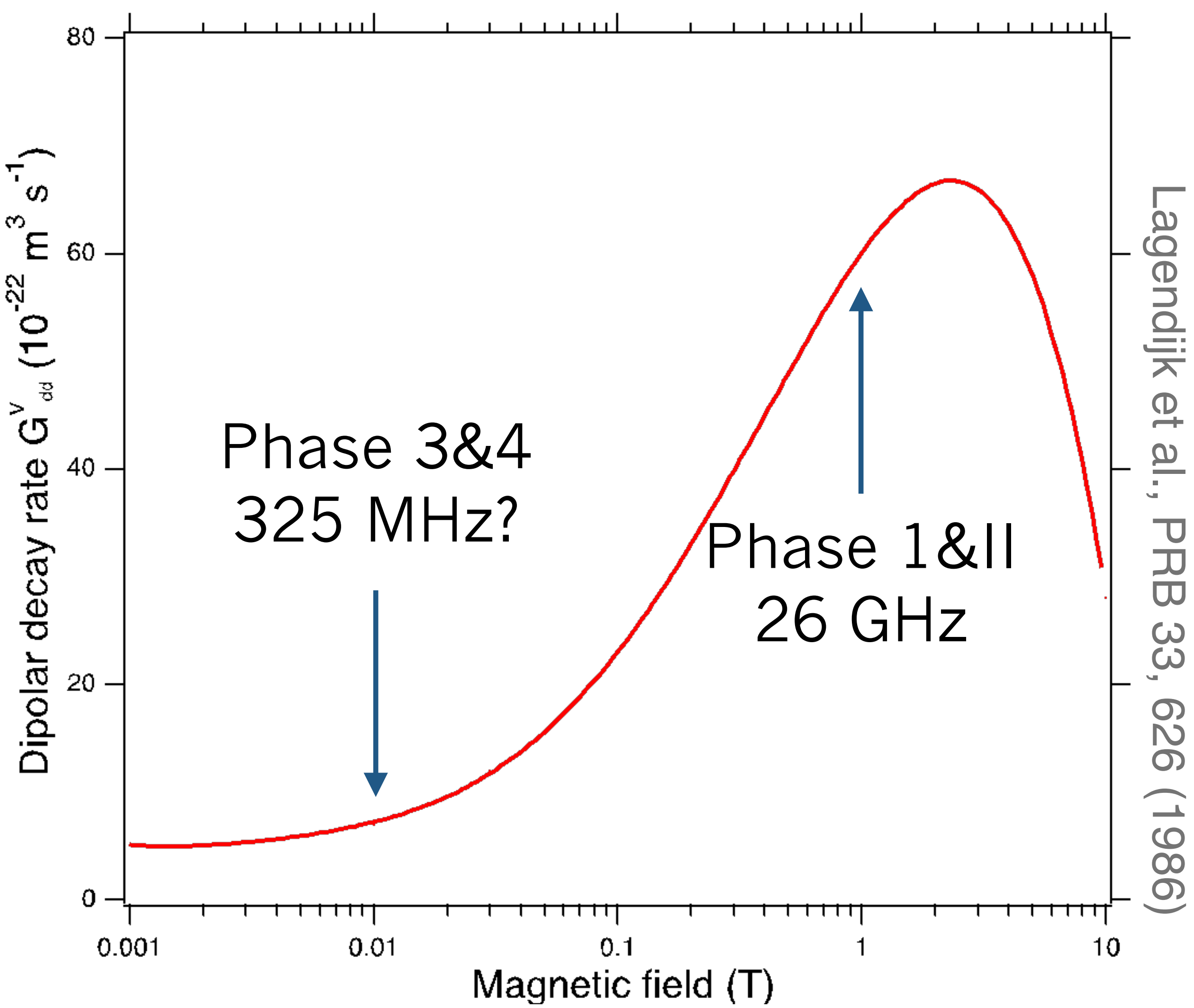


Low-frequency traps

Advantages

- lower magnetic field
  - lower dipolar spin-flip rate
  - lower atom loss rate

- larger cavity volume
  - scales with $1/f^3$
  - larger event rate

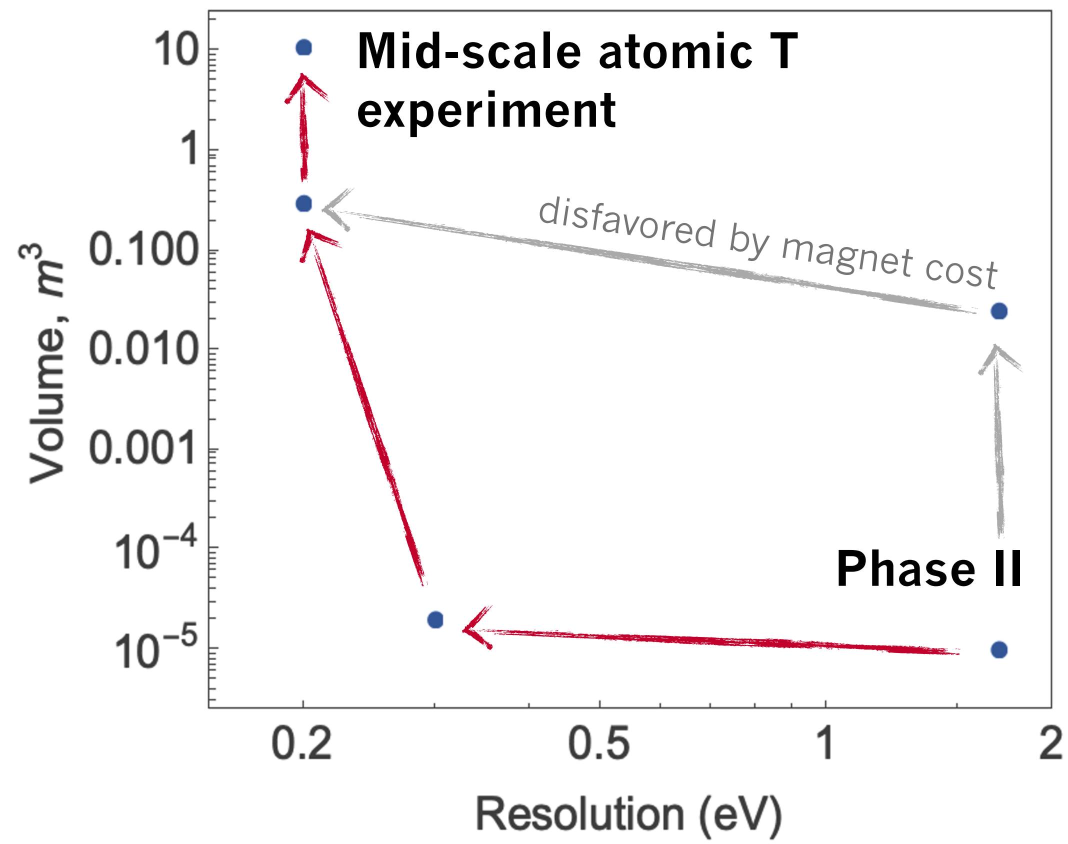


➔ push to **larger, low-frequency cavities**

Phase III: Cavity design

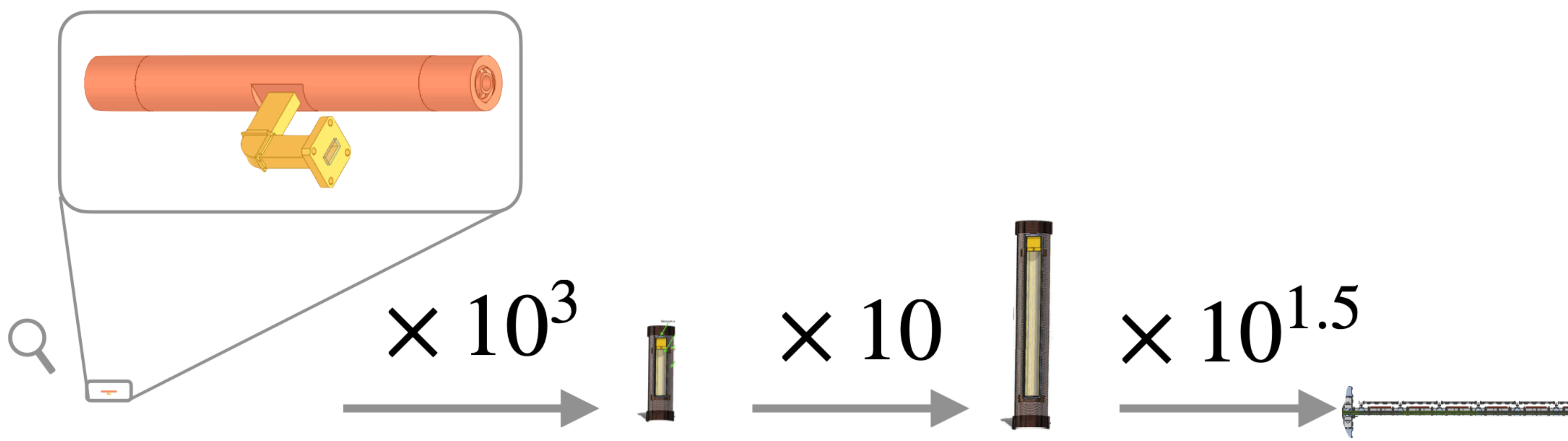
Scaling approach

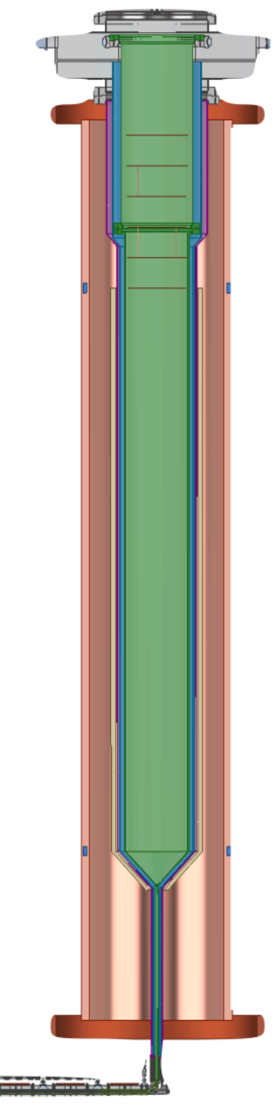
- Optimize cavity design
- Develop position-sensitive reconstruction
- Increased volume step by step!



Series of demonstrators

- partially parallelized





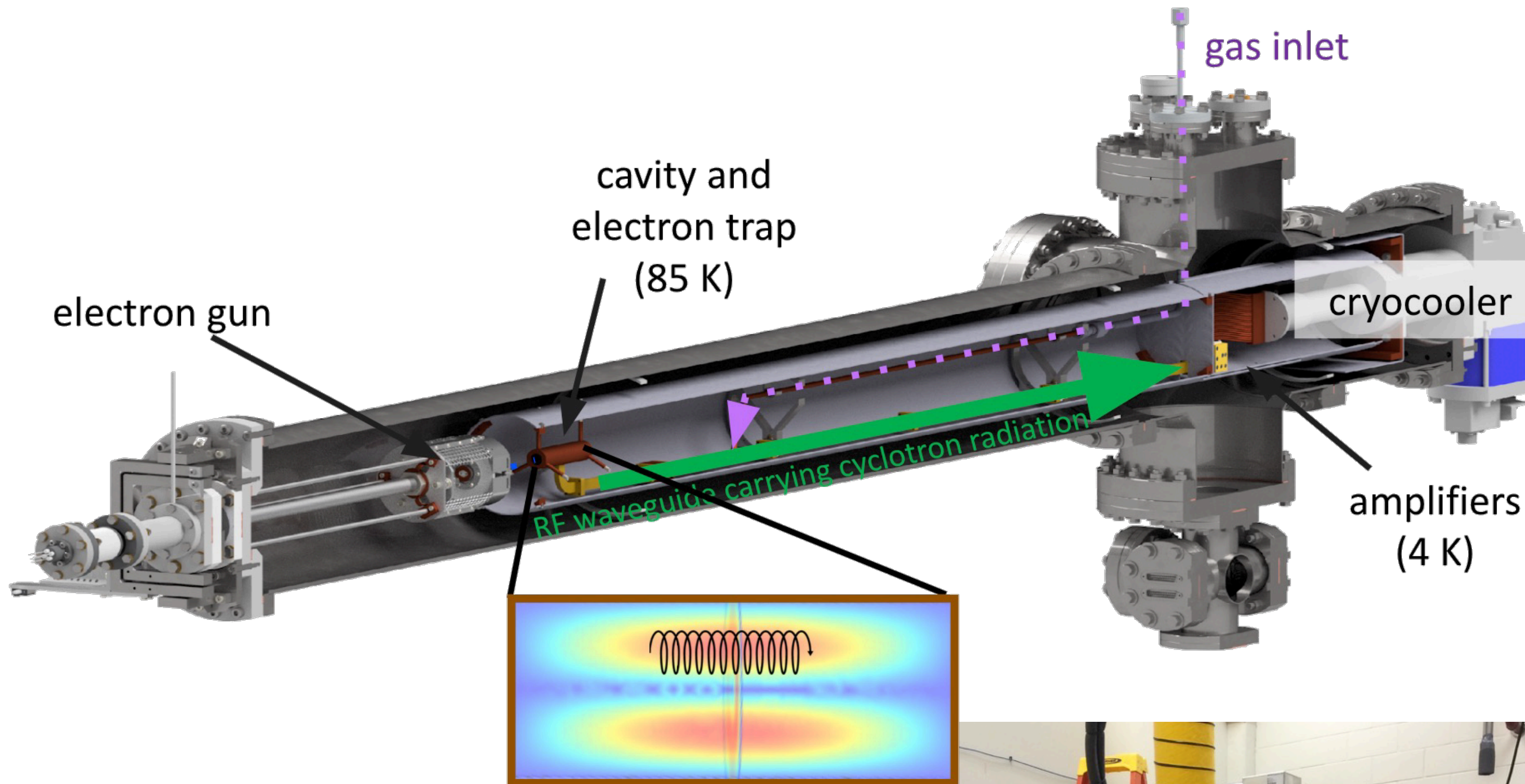
Cavity CRES Apparatus

Specifications

- cm^3 cavity at 26 GHz
- Electron sources
  - ^{83m}Kr
  - electron gun
- insert in medical MRI magnet

Goals

- Demonstrate CRES in a cavity
- Improve detection efficiency
  - $\mathcal{O}(1\%) \rightarrow \mathcal{O}(10\%)$
  - maintaining very low background
- Demonstrate electron gun calibration
- Resolution $\sigma(E) < 300$ meV
  - axial frequency reconstruction



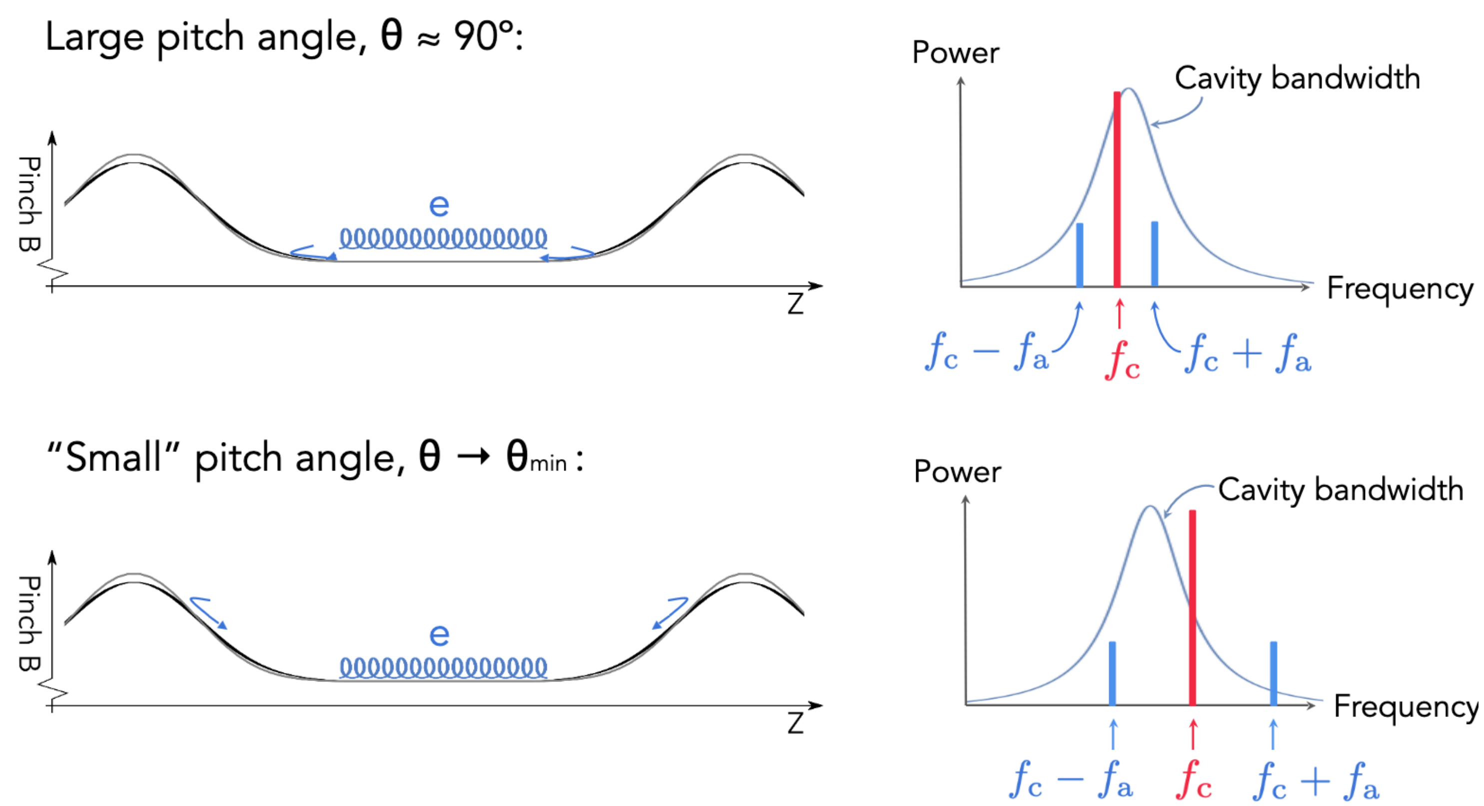
Pitch angle reconstruction

Magnetic field effects

- varies along axial motion

Electron signal is frequency modulated

- Main carrier
  - frequency proportional to average magnetic field
- Sidebands
  - spaced by axial frequency



Approach

- Detect sidebands
  - correct for axial frequency effect
- limited by radial variation in trap shape!

$$f_c = \frac{1}{2\pi} \frac{e\langle B \rangle}{m_e + E/c^2}$$

Optimization of trap design

Traps with more coils

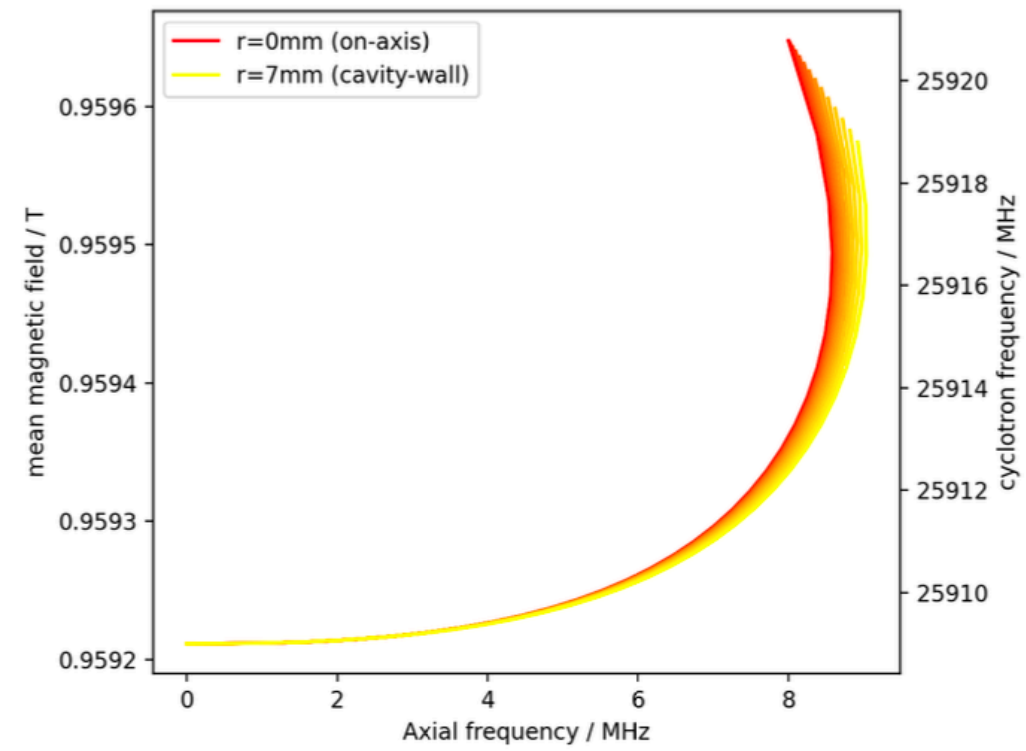
- steeper walls
  - less axial dependence
- less homogeneity in center

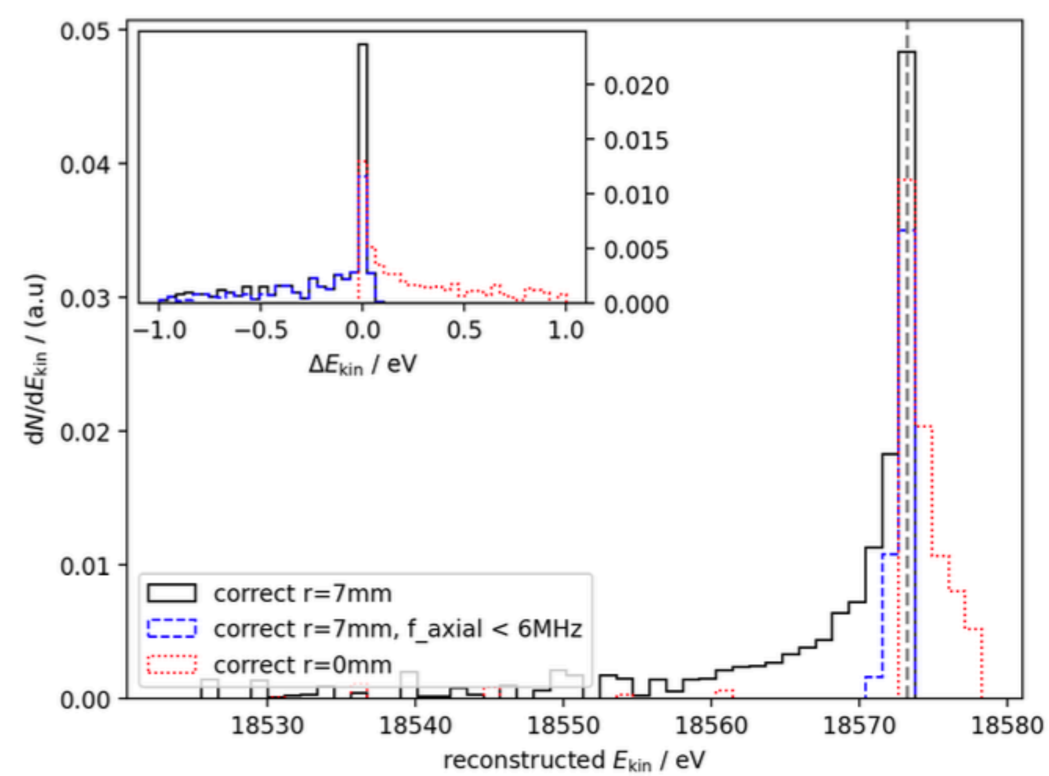
Optimization approach

- optimize many loops with individual currents
- reality constraints
  - geometry, power,...

Pitch angle correction

- limited by shape change at large radii
  - only probed at large pitch angles
- limit axial frequency for resolution goal





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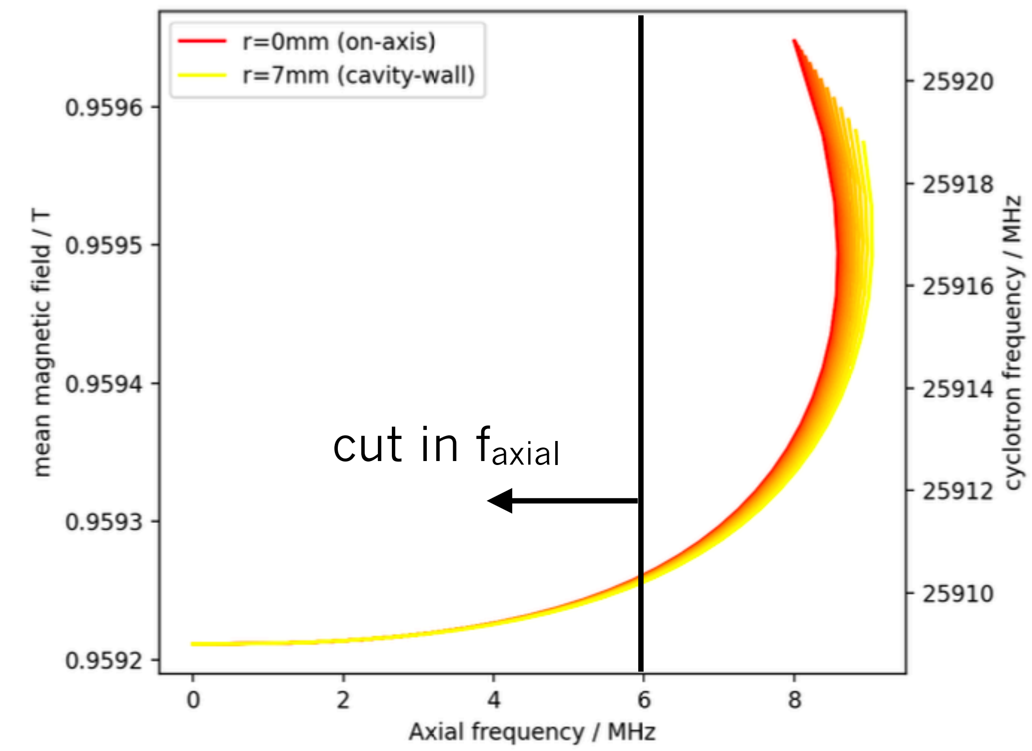

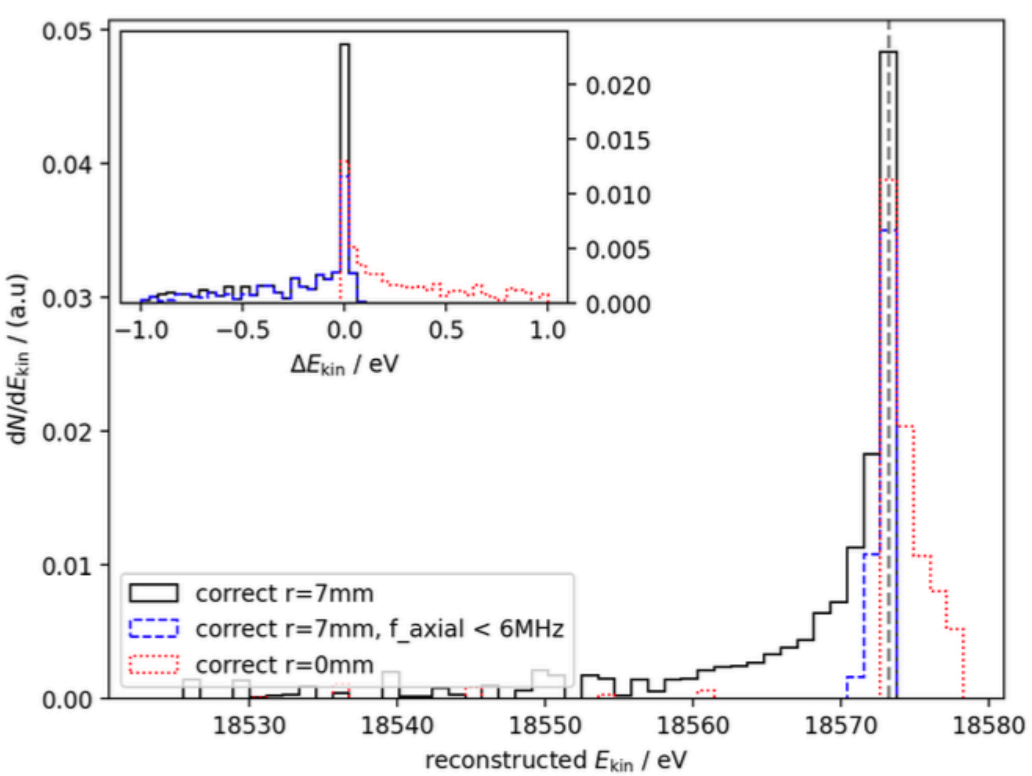

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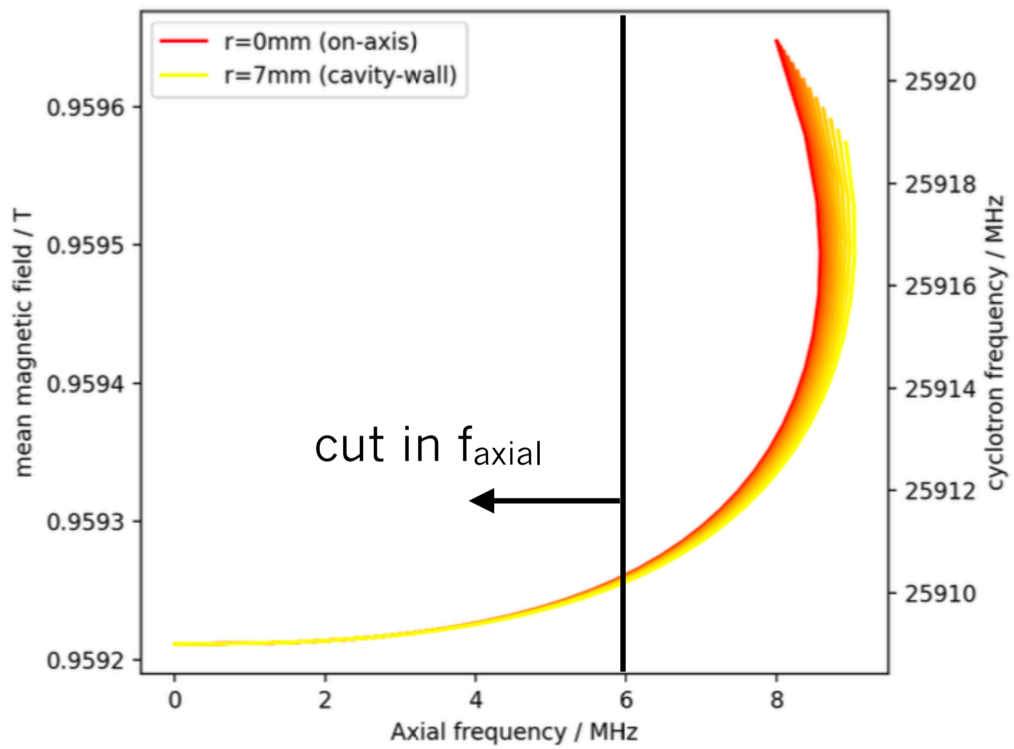
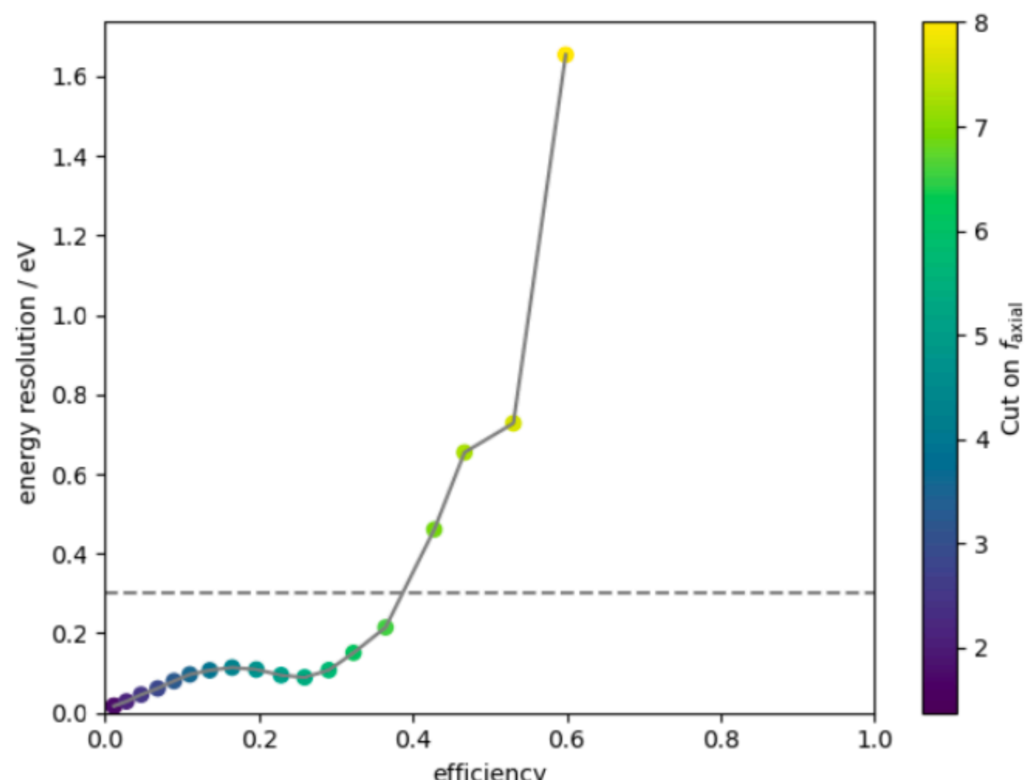
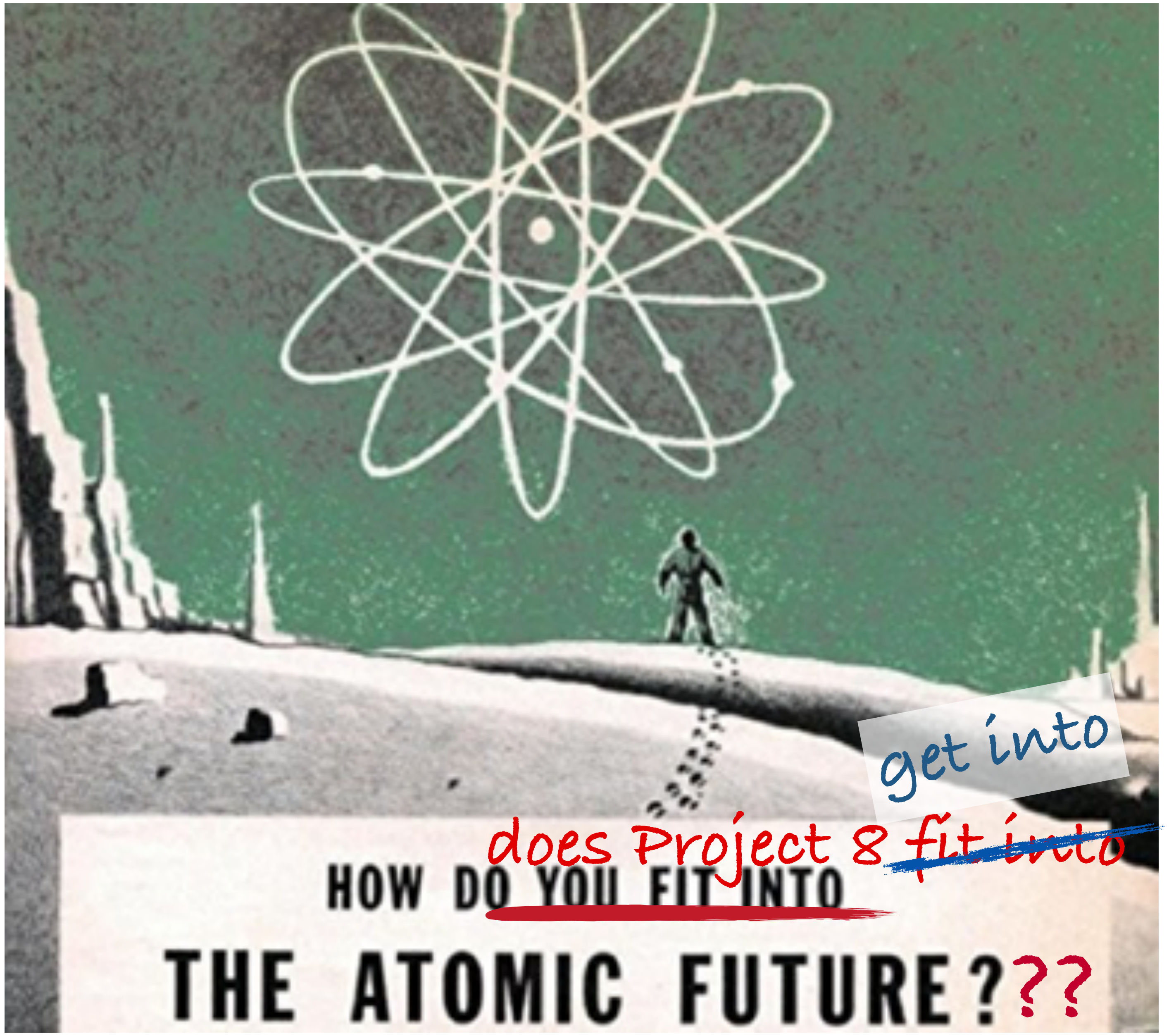
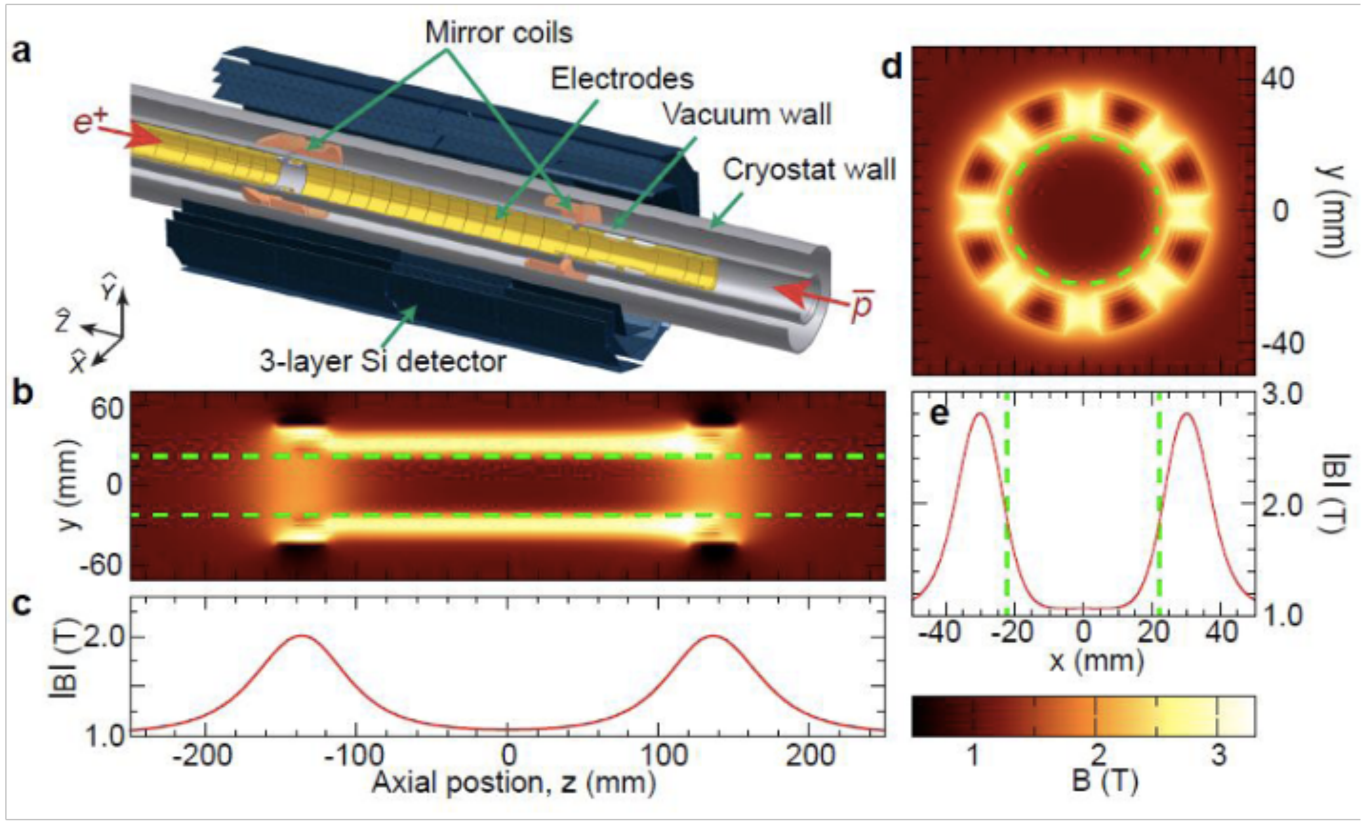




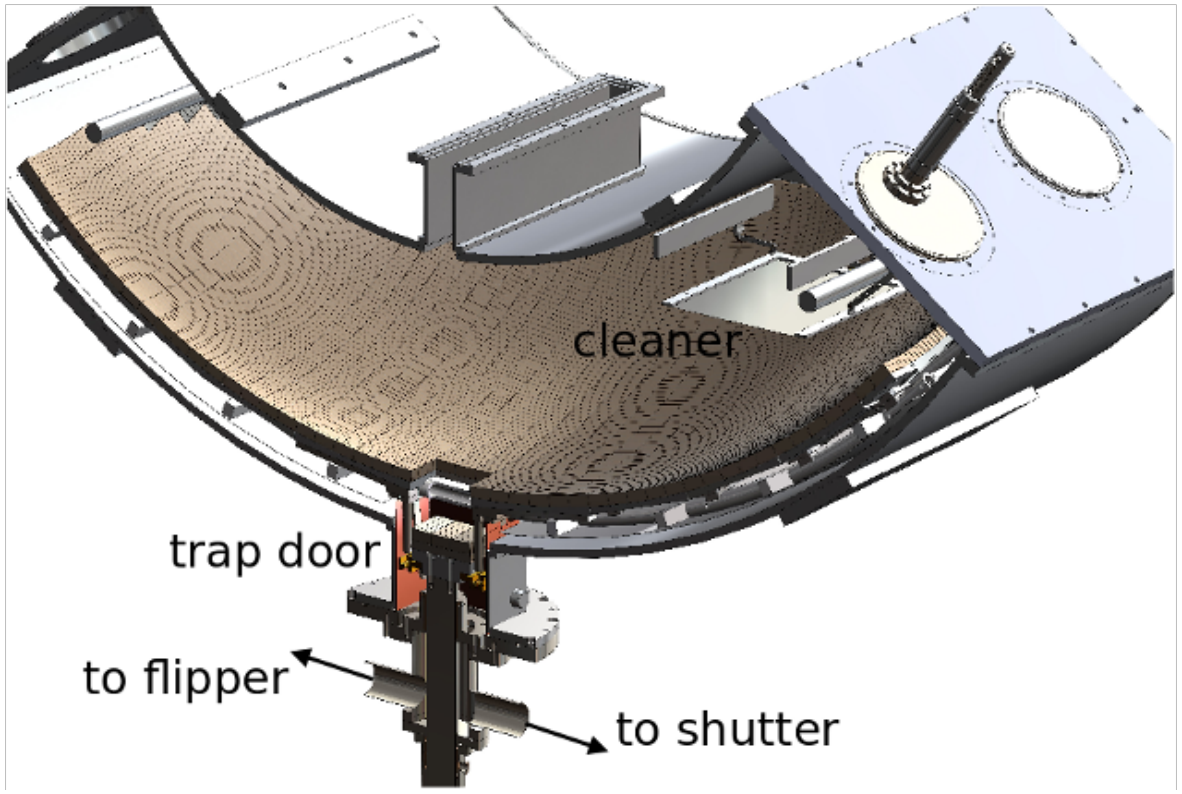
Phase III: Atomic source R&D



Neutral particle traps



ALPHA Collaboration: Nature Phys 7:558, 2011; arXiv 1104.4982

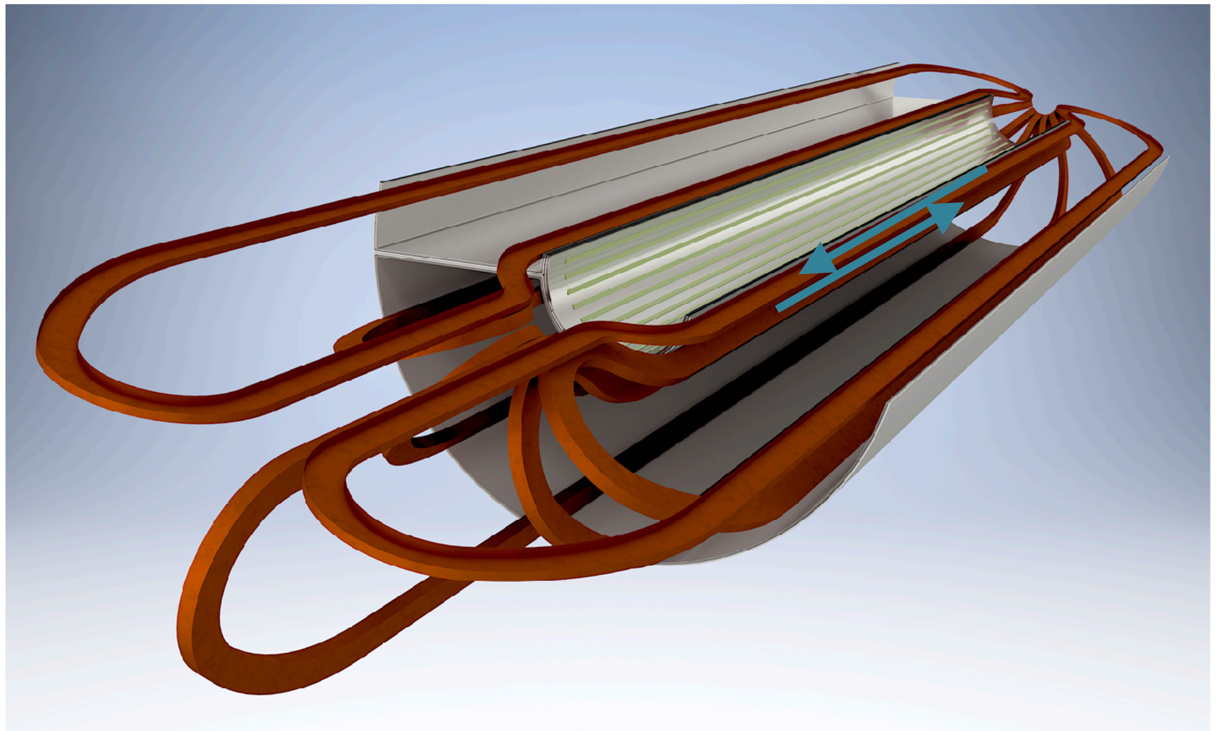


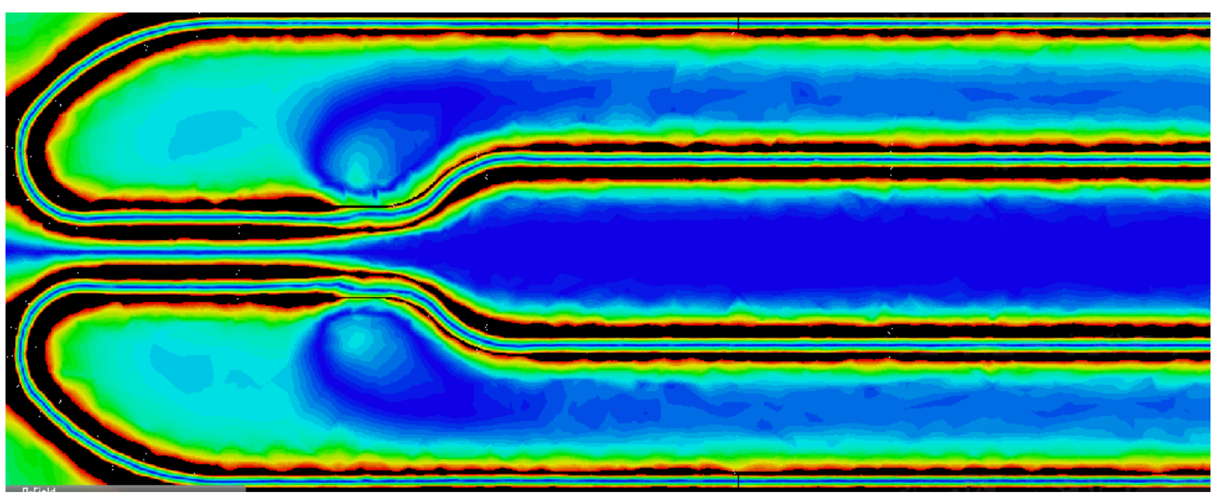
UCNtau Collaboration: Phys Rev C89, 052501, 2014; arXiv 1310.5759v3

General design

- high magnetic field at walls
- low magnetic fields in the center
  - near-field to far-field transition with opposing fields

Atom trapping





Ioffe-Pritchard trap

- plausible field step
  - $\Delta B = 2$ T
- limit thermal loss fraction
  - $\varepsilon_{loss} = 10^{-10}$
- maximum allowed temperature
  - T_{max} = **30 mK**

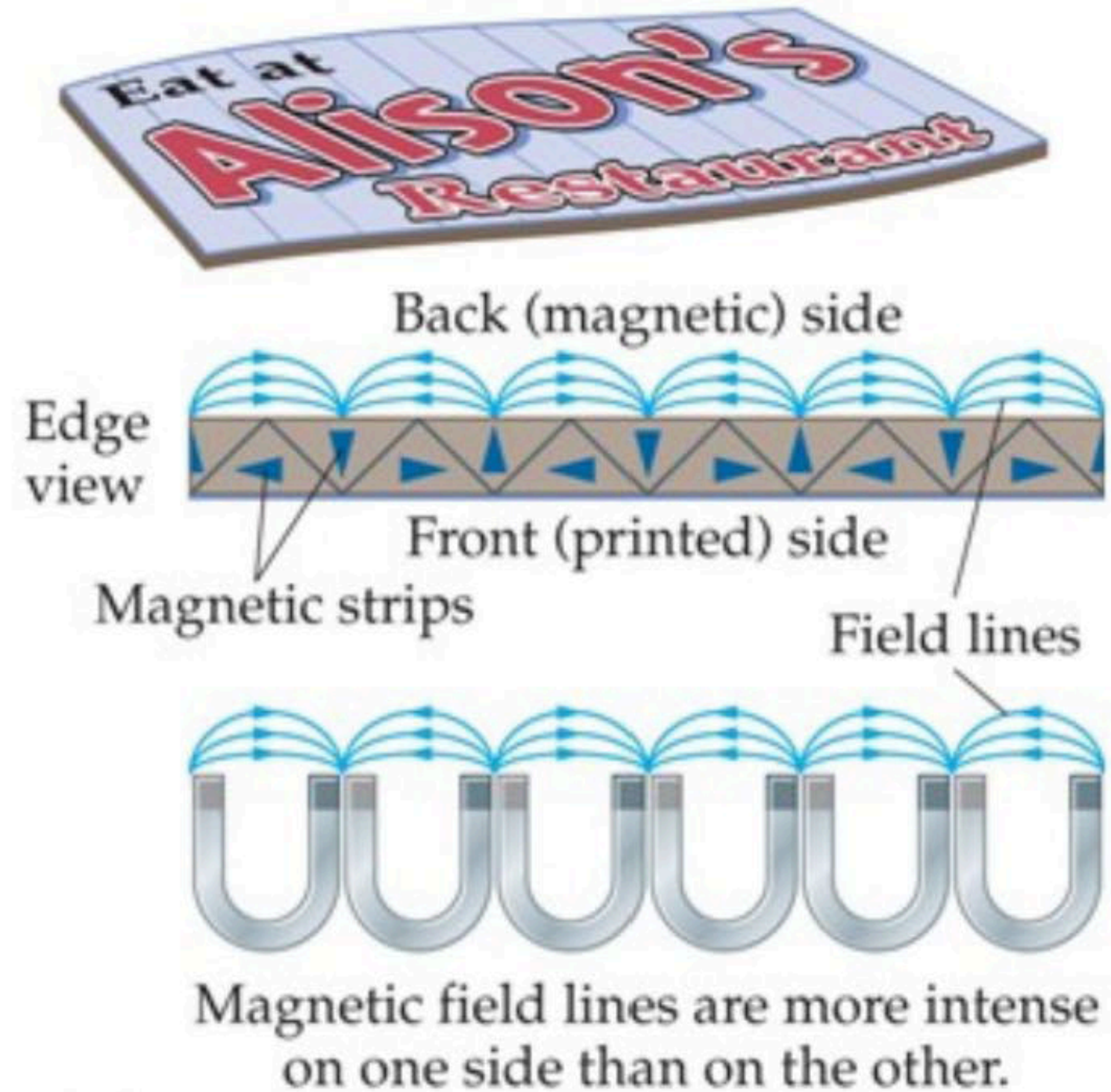
Challenges

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

Halbach arrays

Permanent magnet configuration

- alternate orientations
- circular flux configuration
  - one "*magnetic*" side
  - one "*non-magnetic*" side



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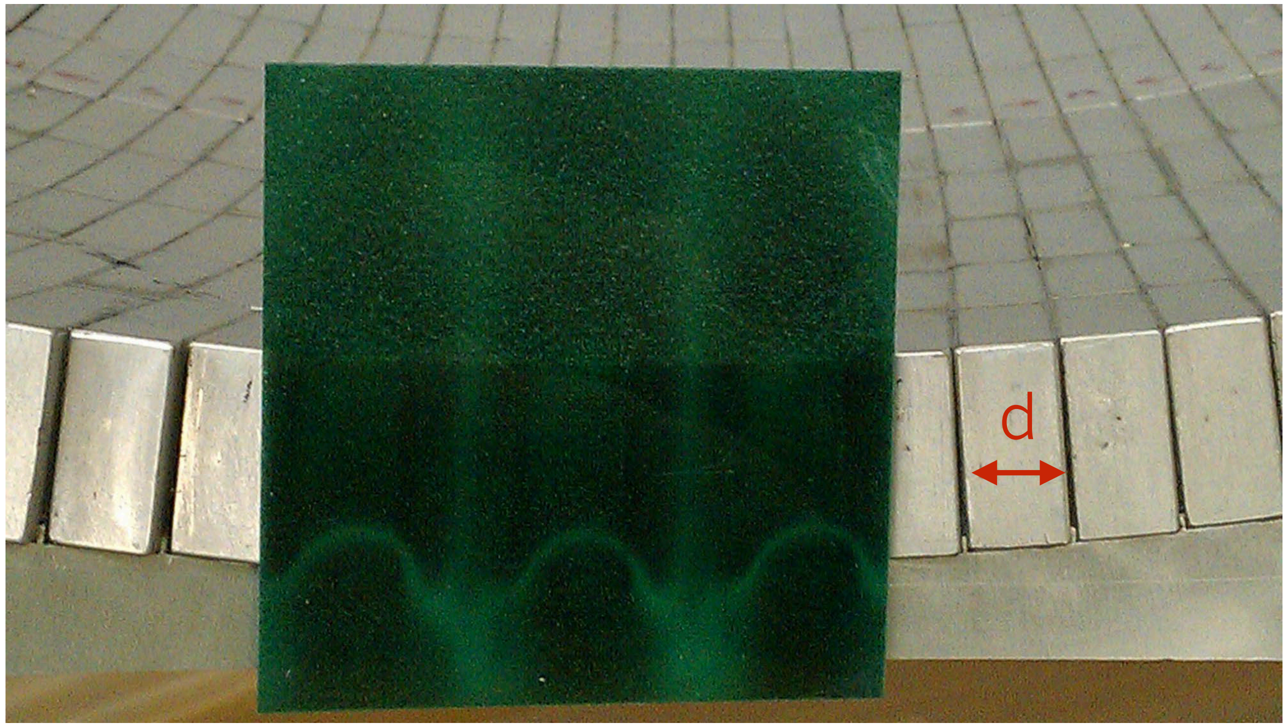

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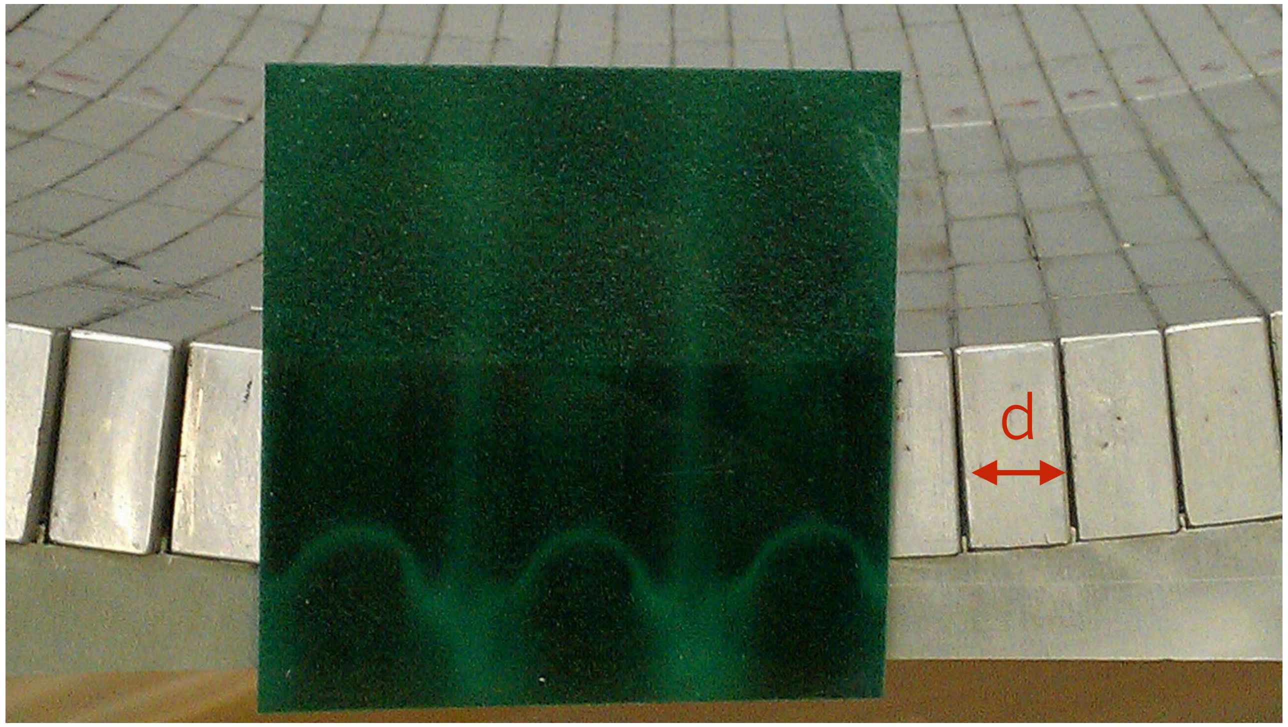
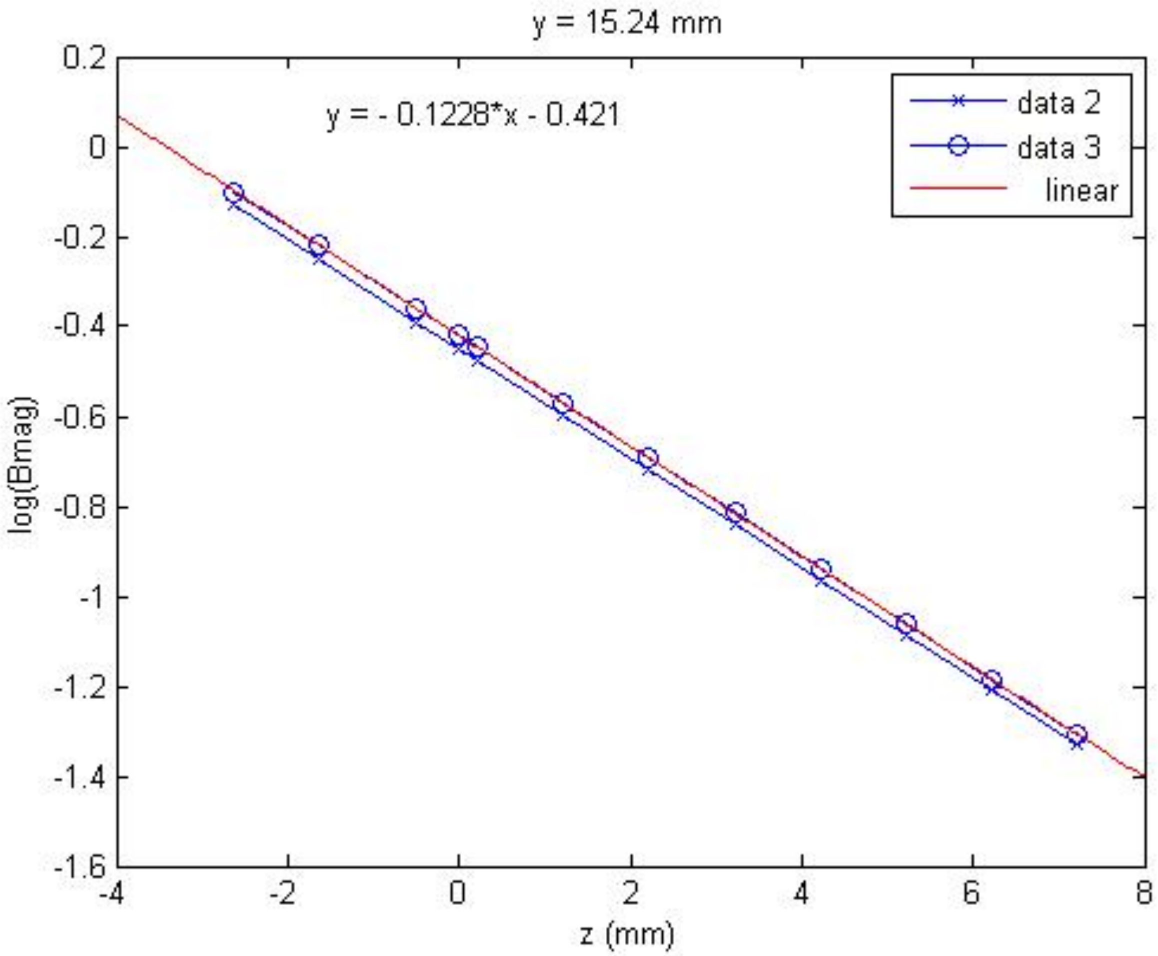


Flat Halbach array

- field falls exponentially with characteristic length $l = \frac{2d}{\pi}$
  - weak far field

Challenges

- low temperatures
- overall field strength → evaporative loss



PRiSMA

Magneto-gravitational trap

Magnetic trapping

- $E_m = \mu_B B = 58\,\mu\text{eV/T}$

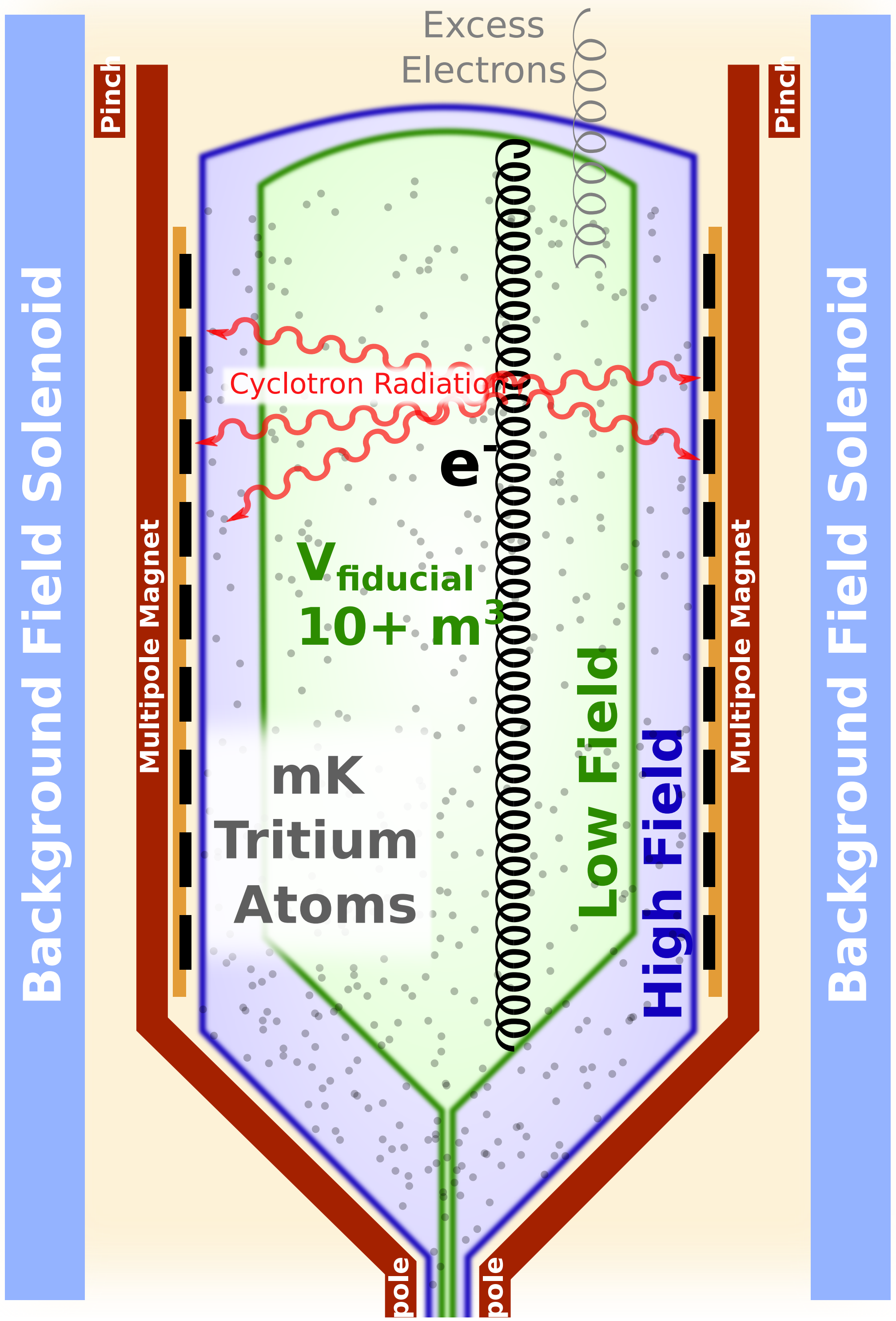
Energy of cold atomic beam

- $E_k = k_B T = 64\,\mu\text{eV/K}$

Gravitational trapping

- $E_g = mgh = 0.3\,\mu\text{eV/m}$

➔ For 10mK cold beam, it takes 2.1 meters of gravity and 0.7T of B-field to trap.



How to fill the trap?

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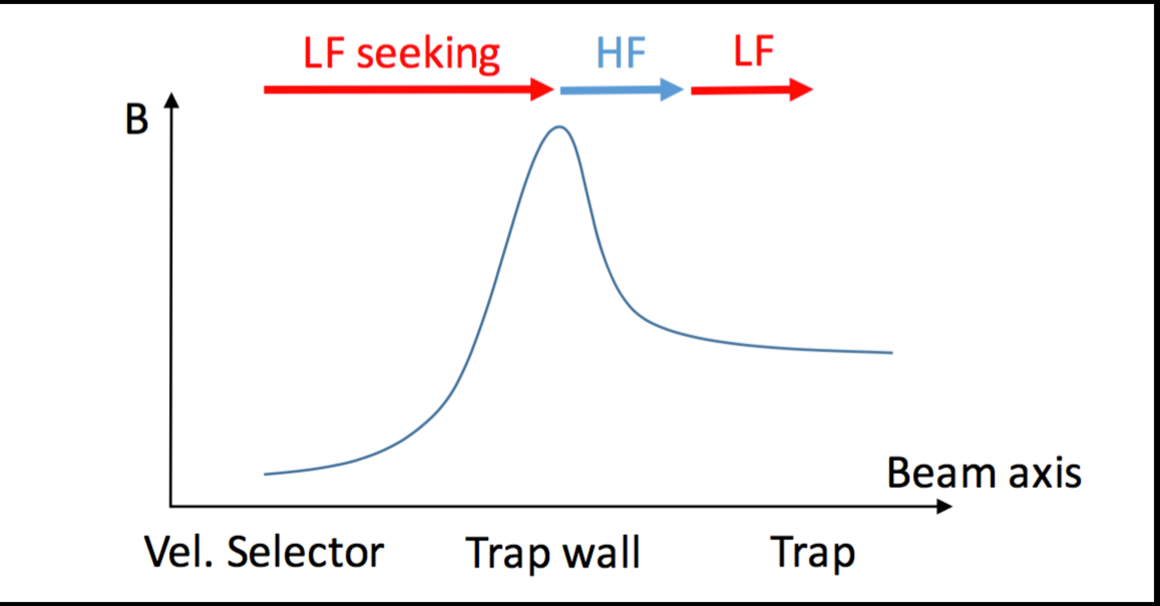
Spin-flip loading ?

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



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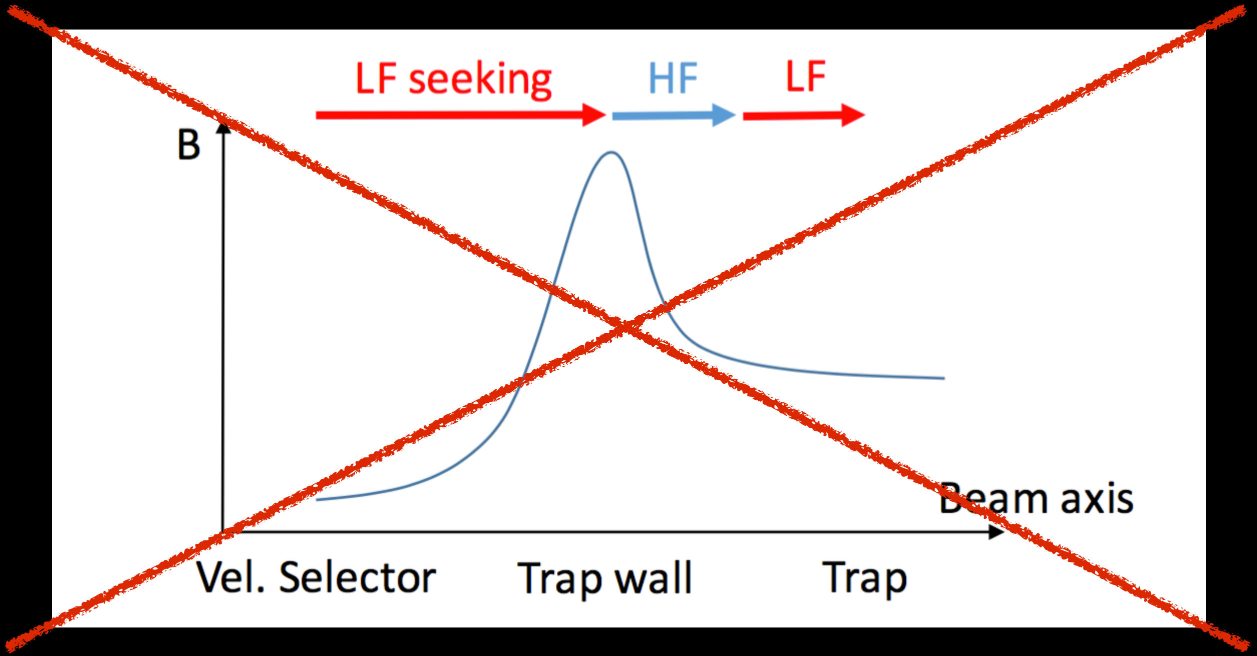

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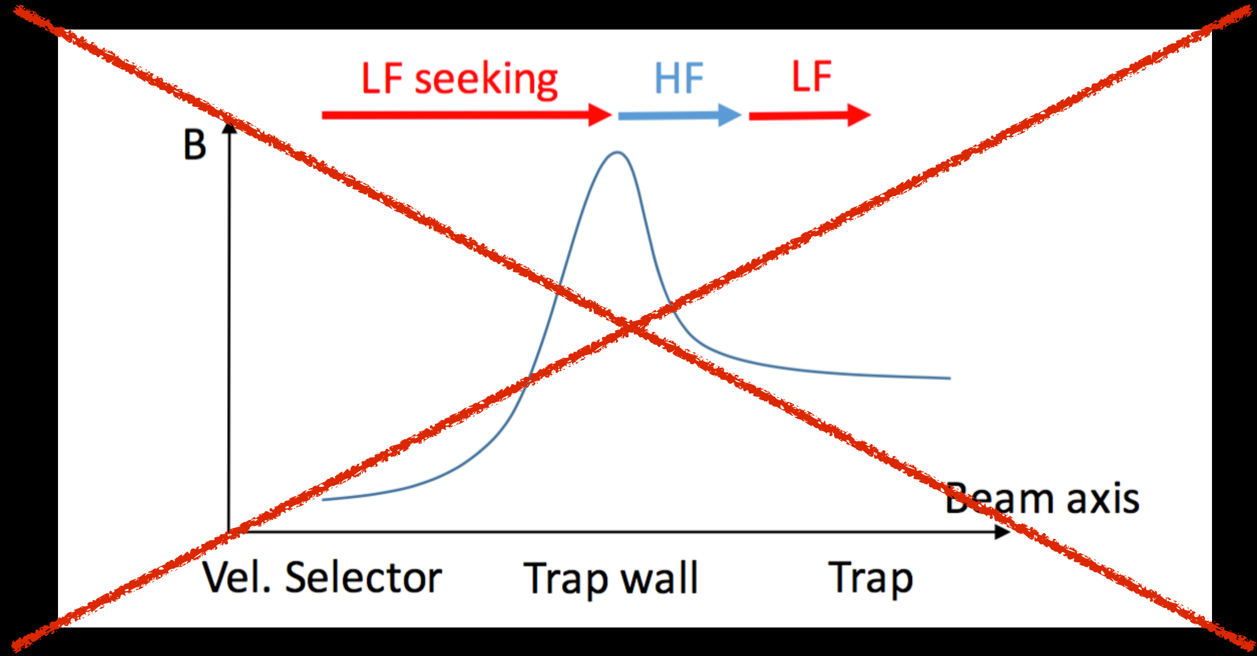
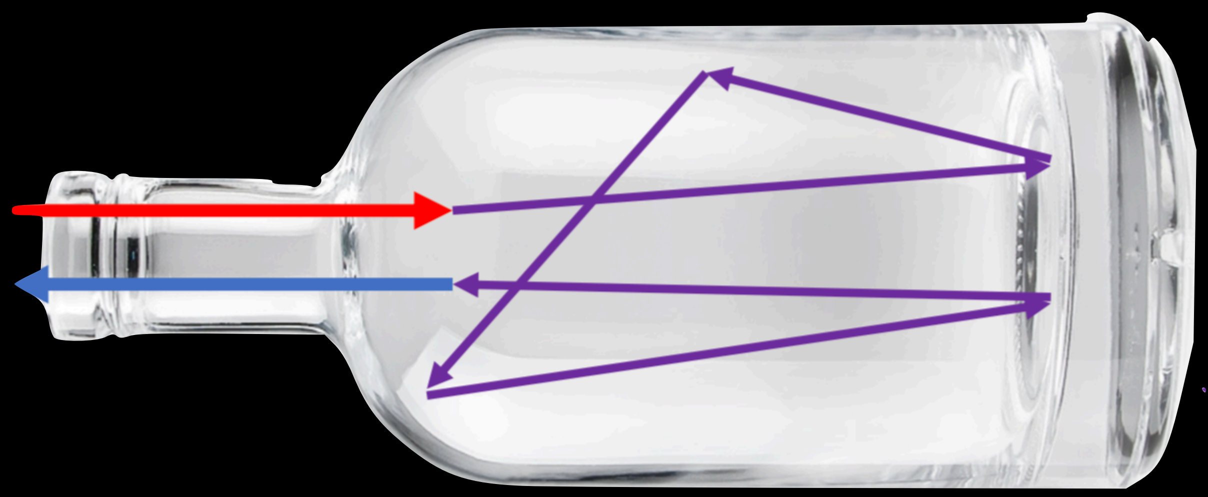


Cornucopia* loading

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



* horn of plenty

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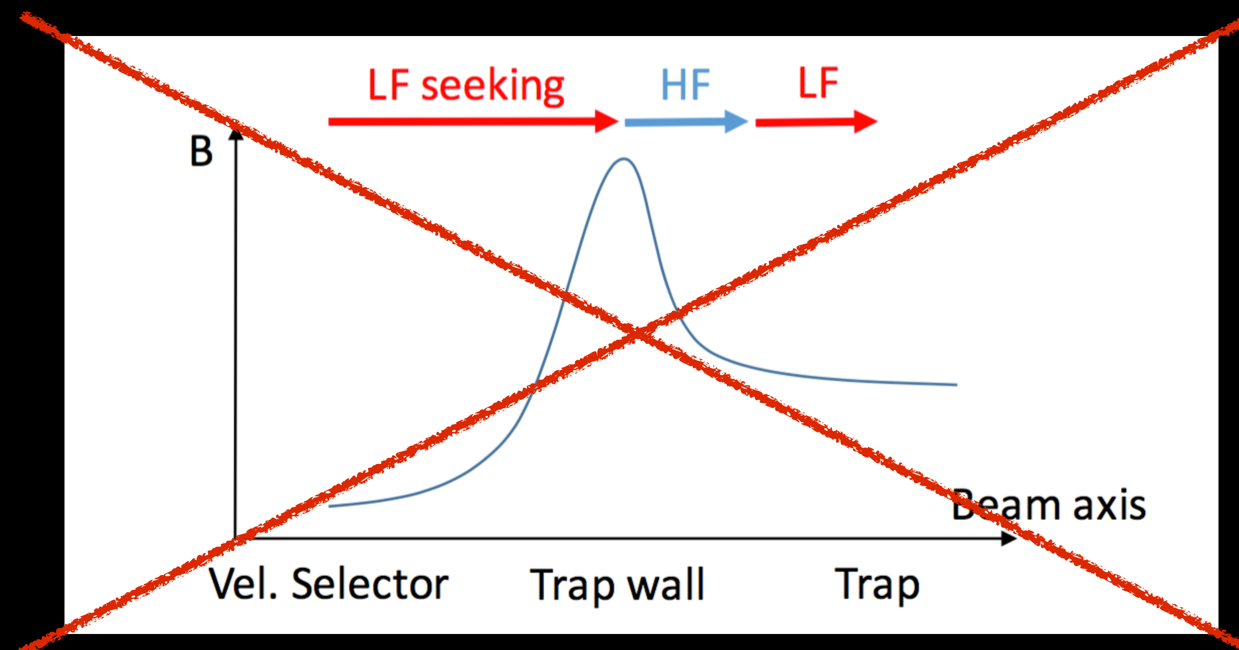

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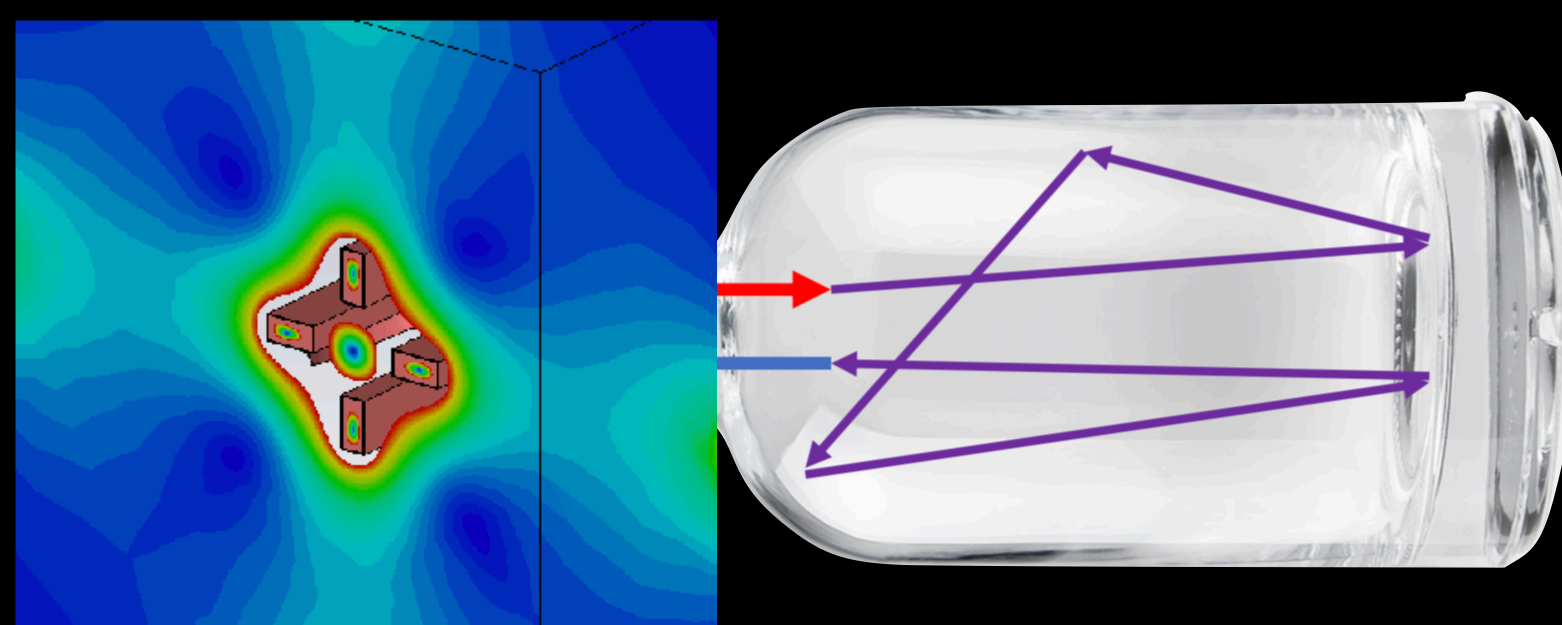

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Project 8: Designs concepts

Atomic T source

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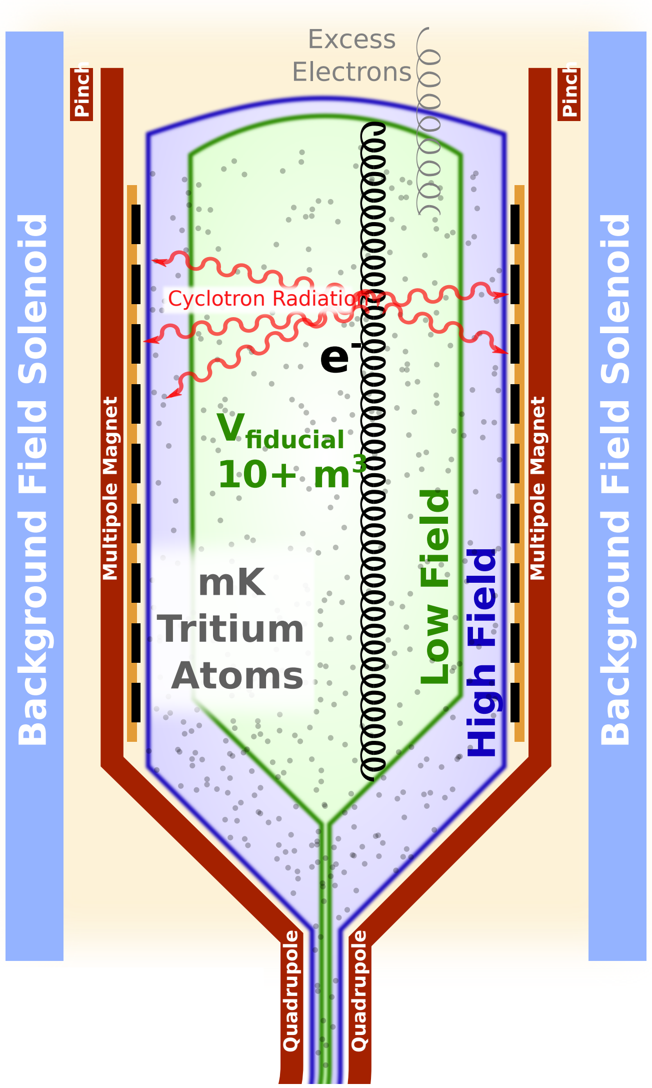

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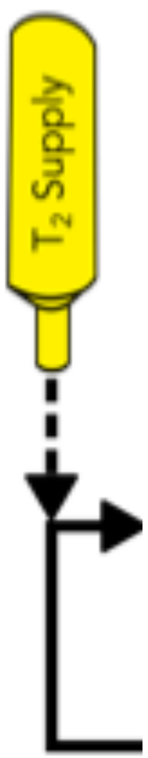
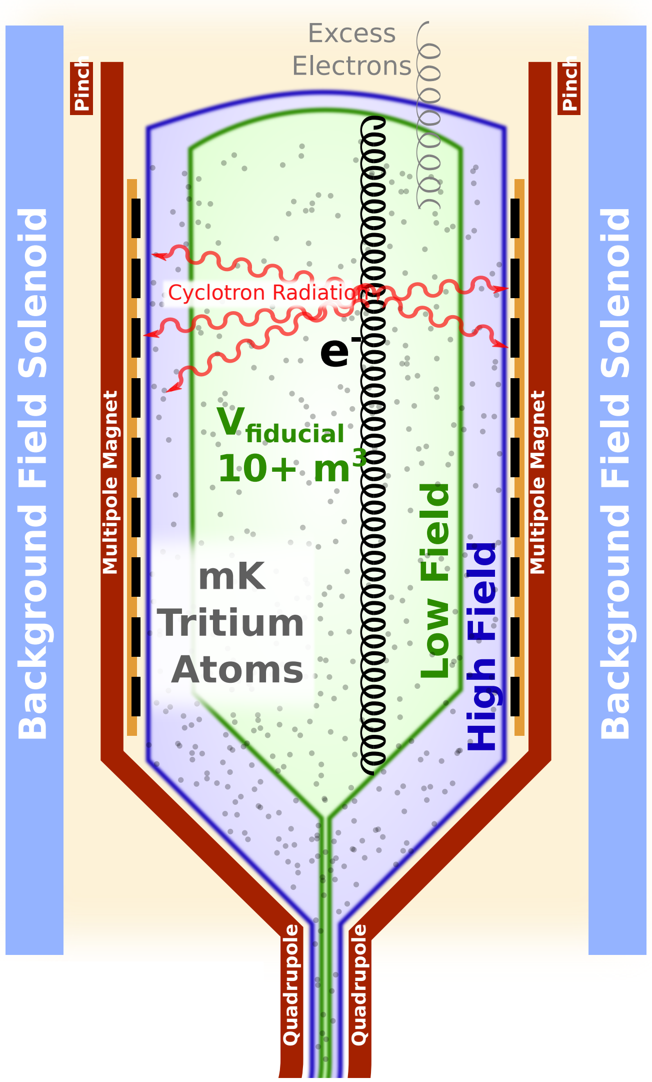
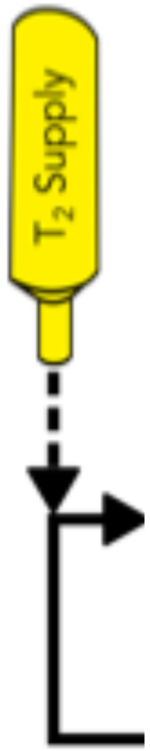


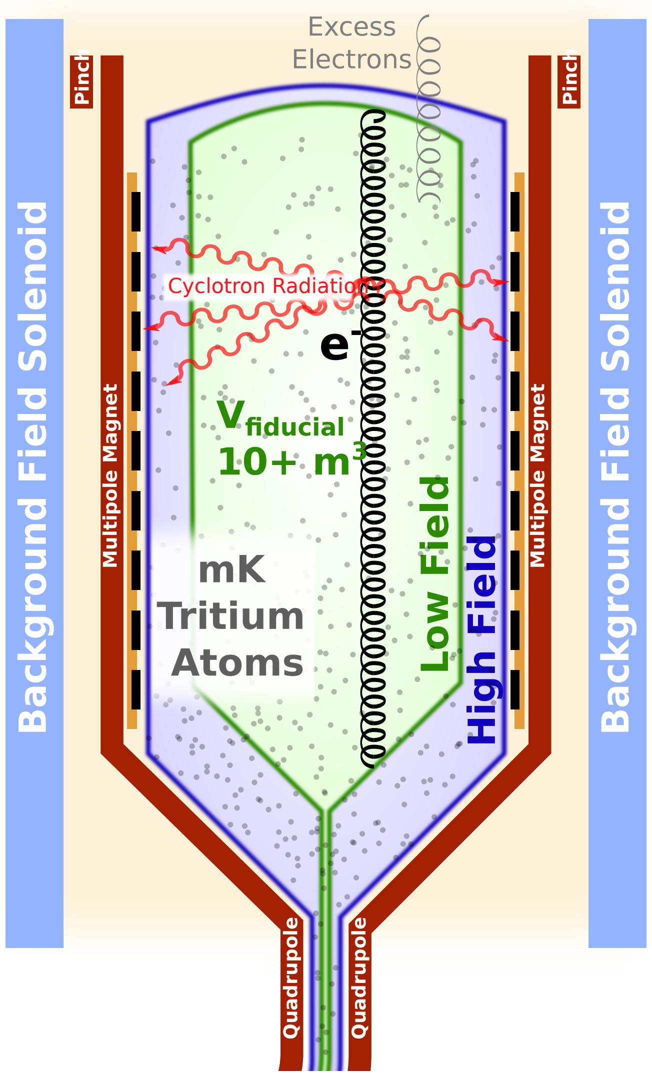


Project 8: Designs concepts

Atomic T source

- Injection ✓
- Trapping ✓

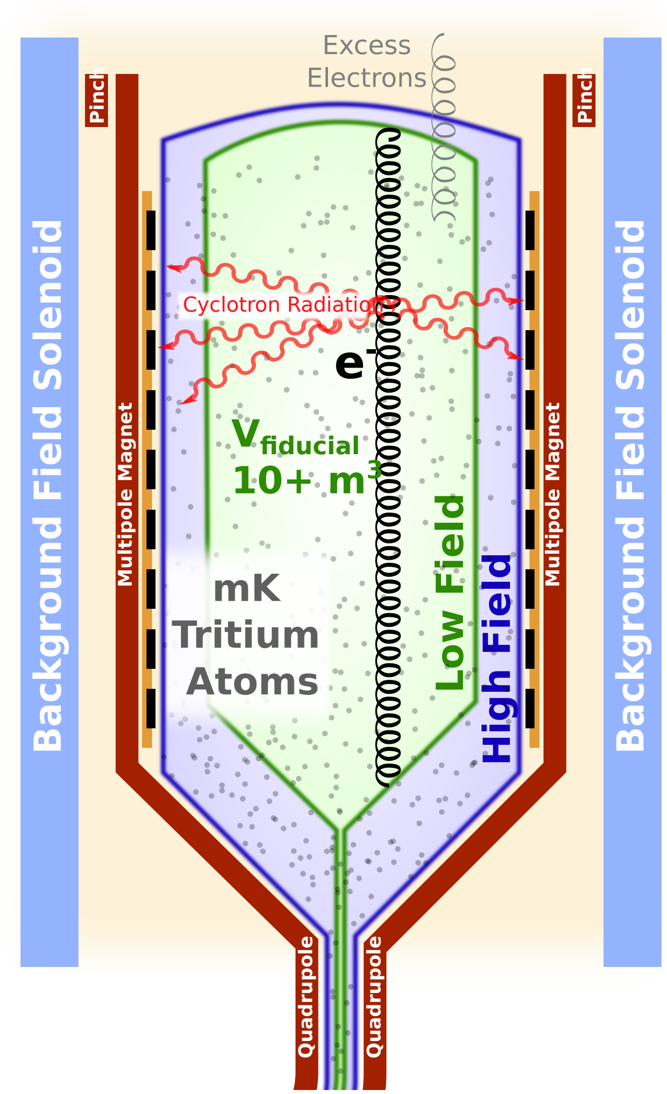




Project 8: Designs concepts

Atomic T source

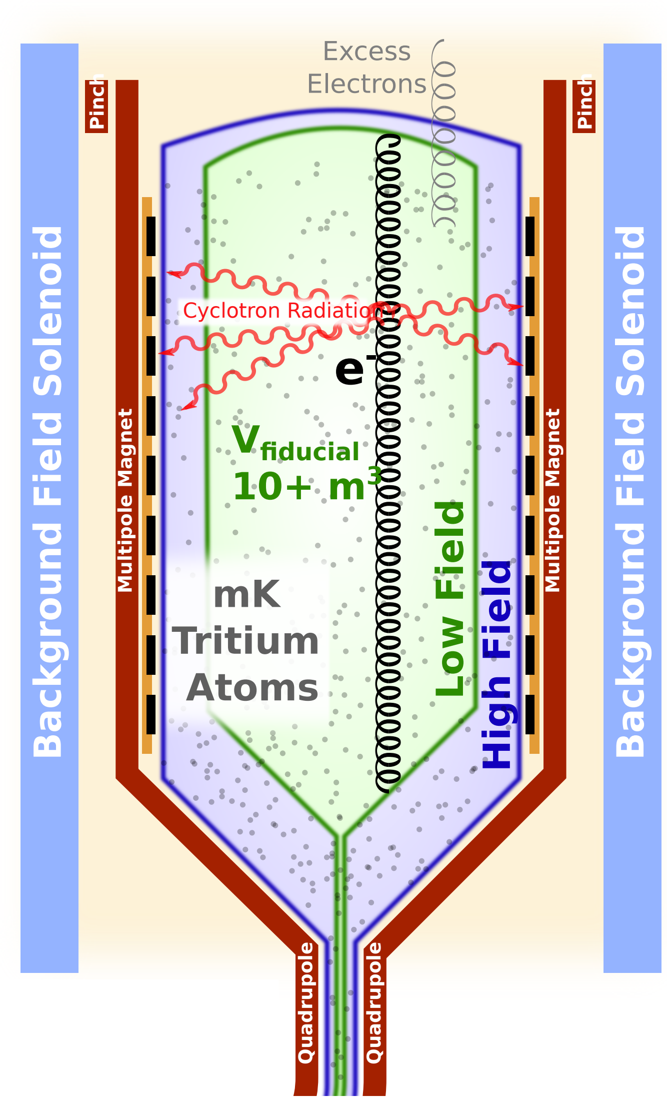
- Dissociation **???**
- Cooling **???**
- Injection ✓
- Trapping ✓

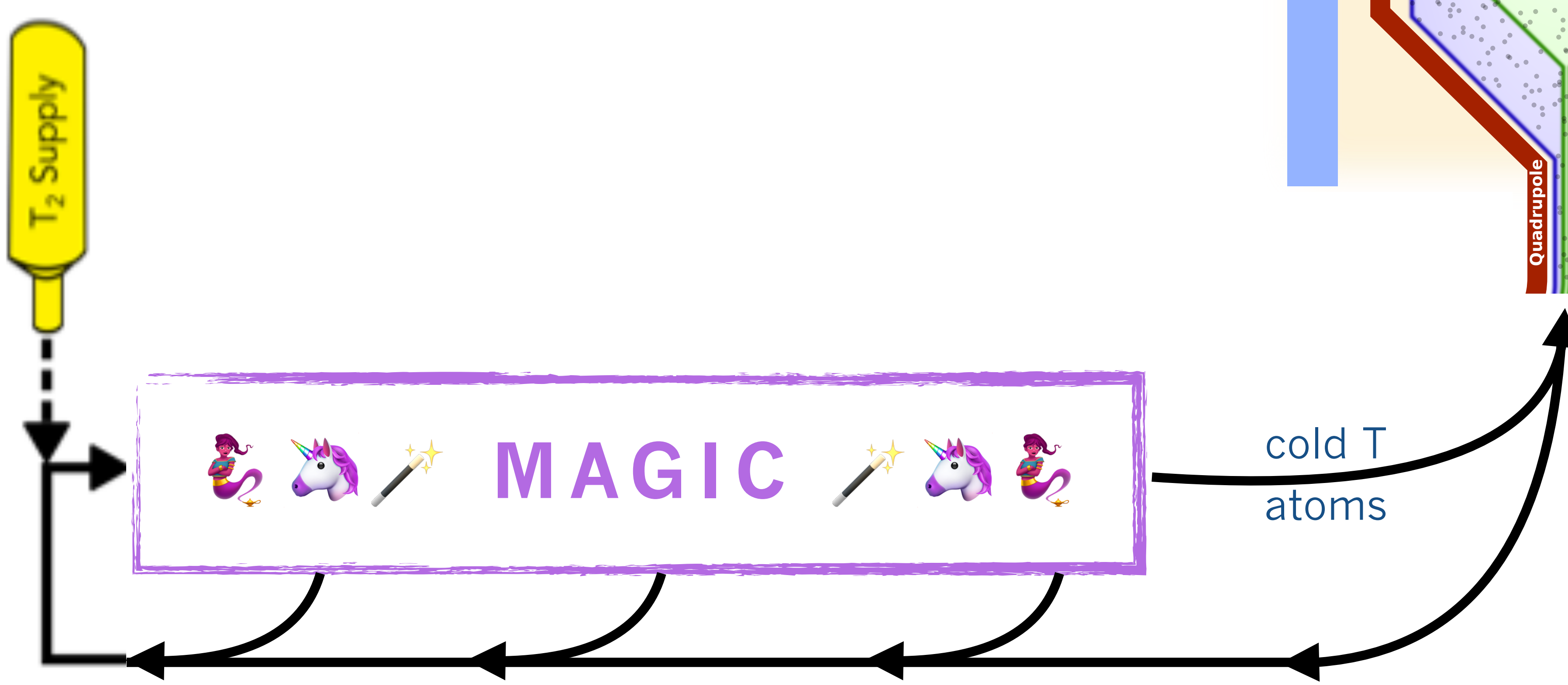


Project 8: Designs concepts

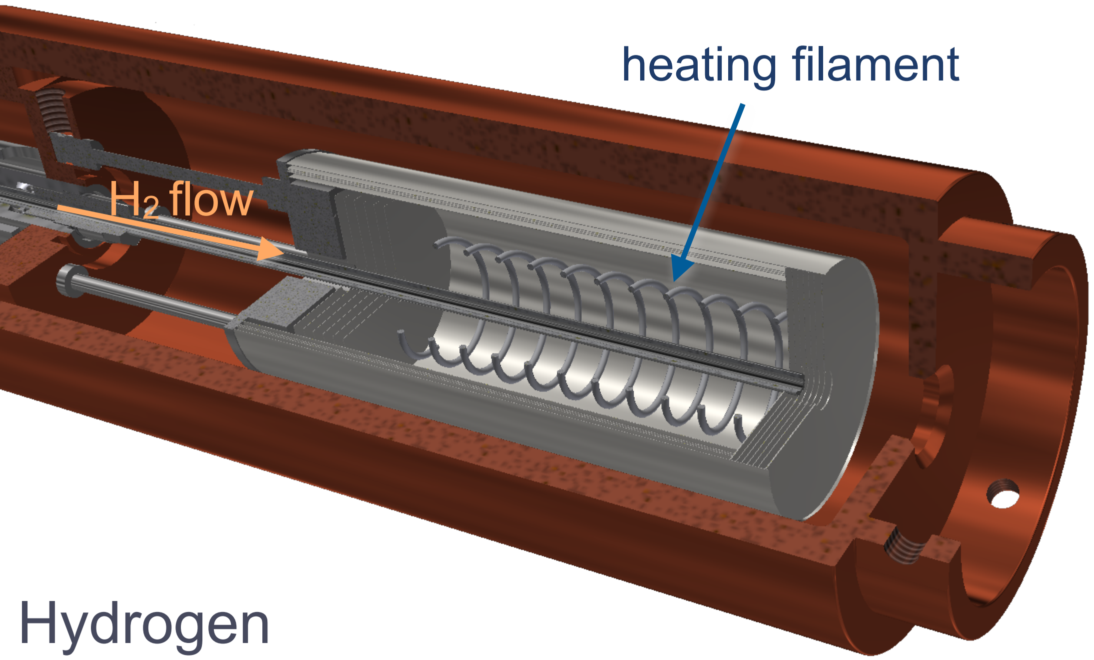
Atomic T source

- Dissociation **???**
- Cooling **???**
- Injection ✓
- Trapping ✓
- Purification/Circulation (✓)

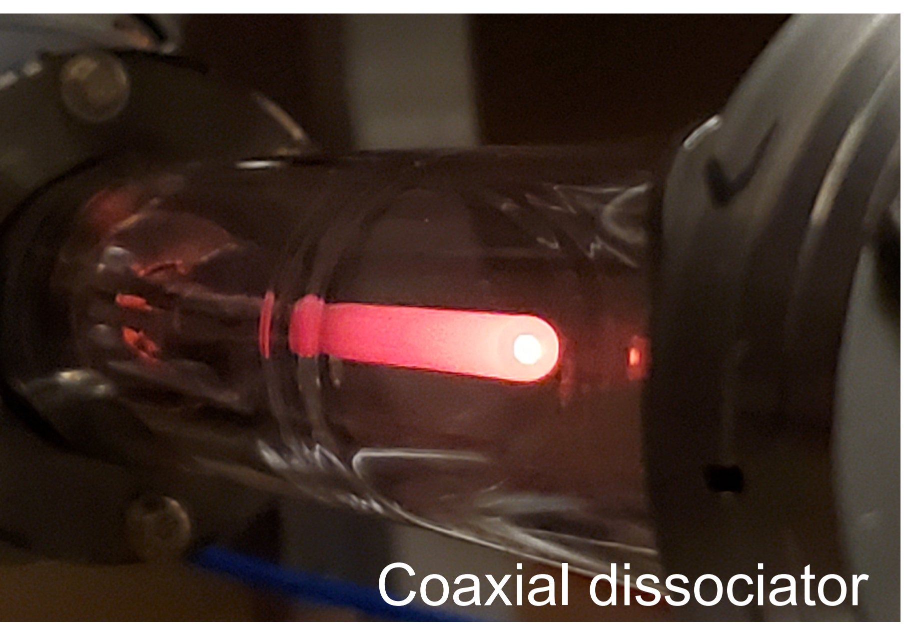




Thermal dissociation sources



Hydrogen
Atom Beam Source (HABS)



Working principle

- Dissociation on hot tungsten surface
- Temperatures 2200K - 2500K
- radiative or electron bombardment heating of capillary

Advantages

- Several models commercially available
- Partly well characterised
- MBE components "*HABS*"
  Tschersich, K. G. et. al. J. Appl. Phys. 84 (1998), 8, 4065-4070
  Tschersich, K. G. J. Appl. Phys. 87 (2000), 5, 2565-2573
  Tschersich, K. G. et. al. J. Appl. Phys. 104 (2008) , 034908
- Principle can be adapted for higher flows

➔ Good starting point

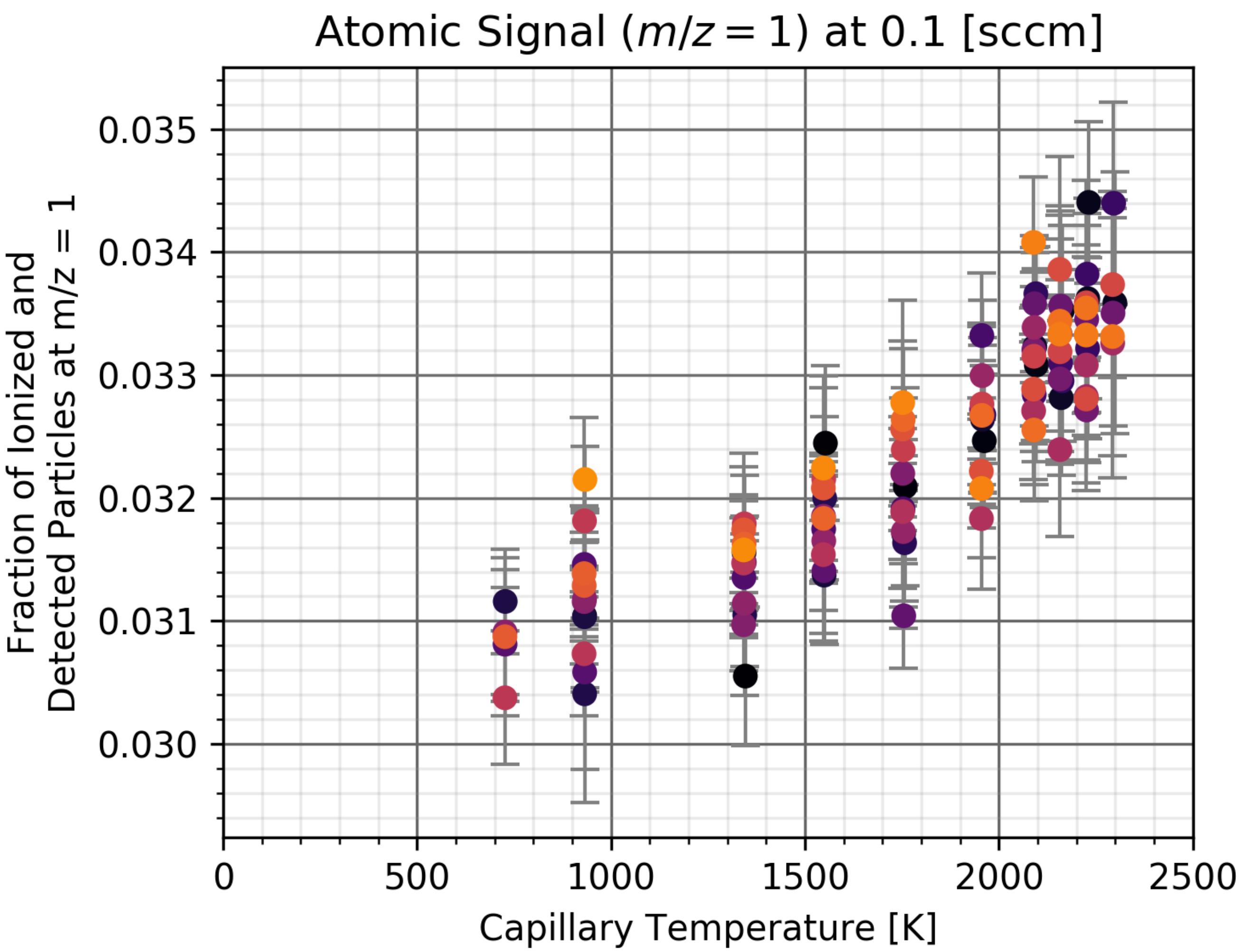
Source characterization

Measure dissociation efficiency

- Detect with ionizing mass spectrometer

Primary challenge

- Dissociative ionization background
  - $H_2 + e^- \rightarrow H^+ + H + 2e^-$
- require very good H_2 suppression
  - but $H \rightarrow H_2$ recombination with efficiency $\varepsilon \sim 1$!



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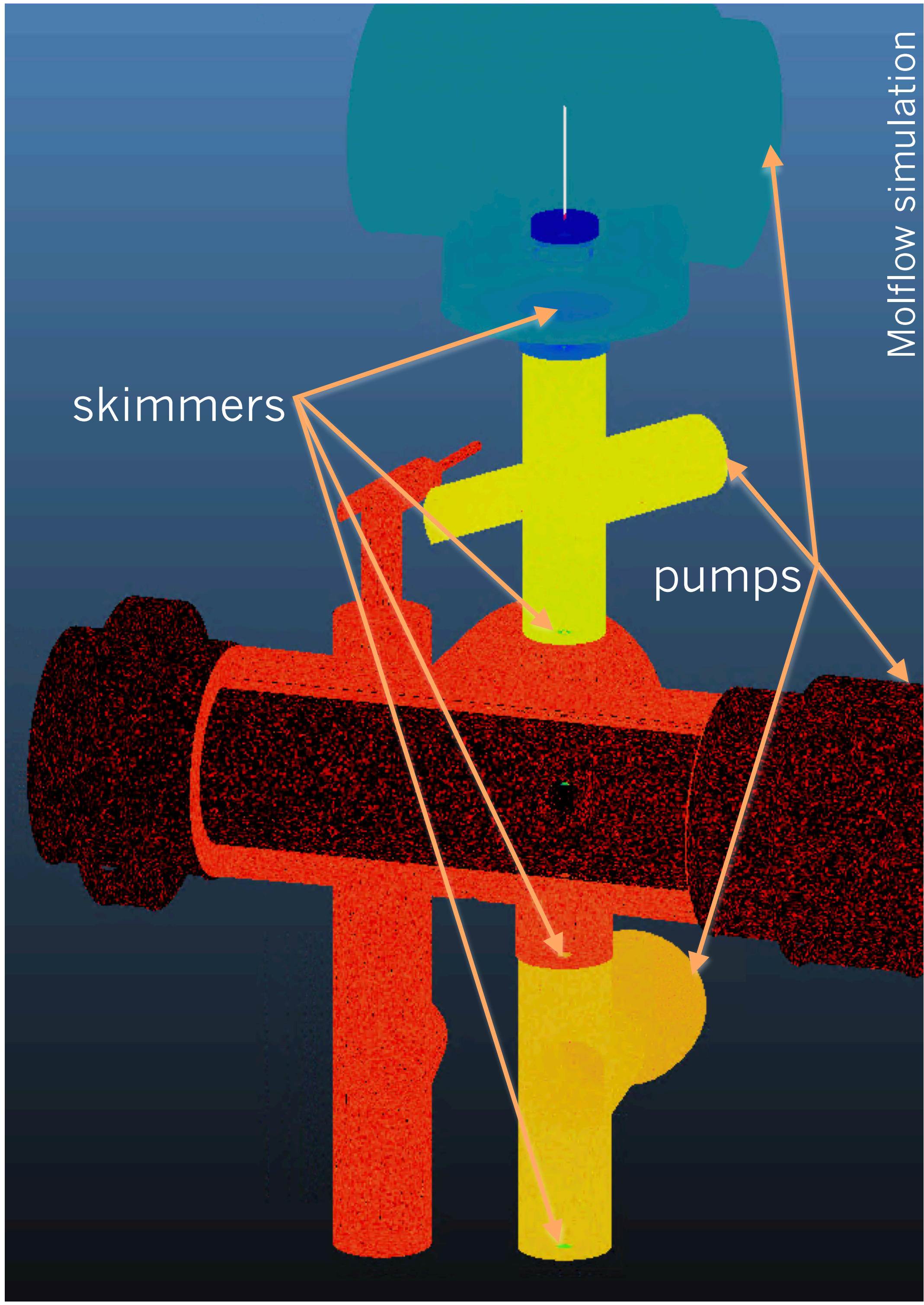
Differential pumping

- optimized rejection of recombined H_2
  - retain good SNR



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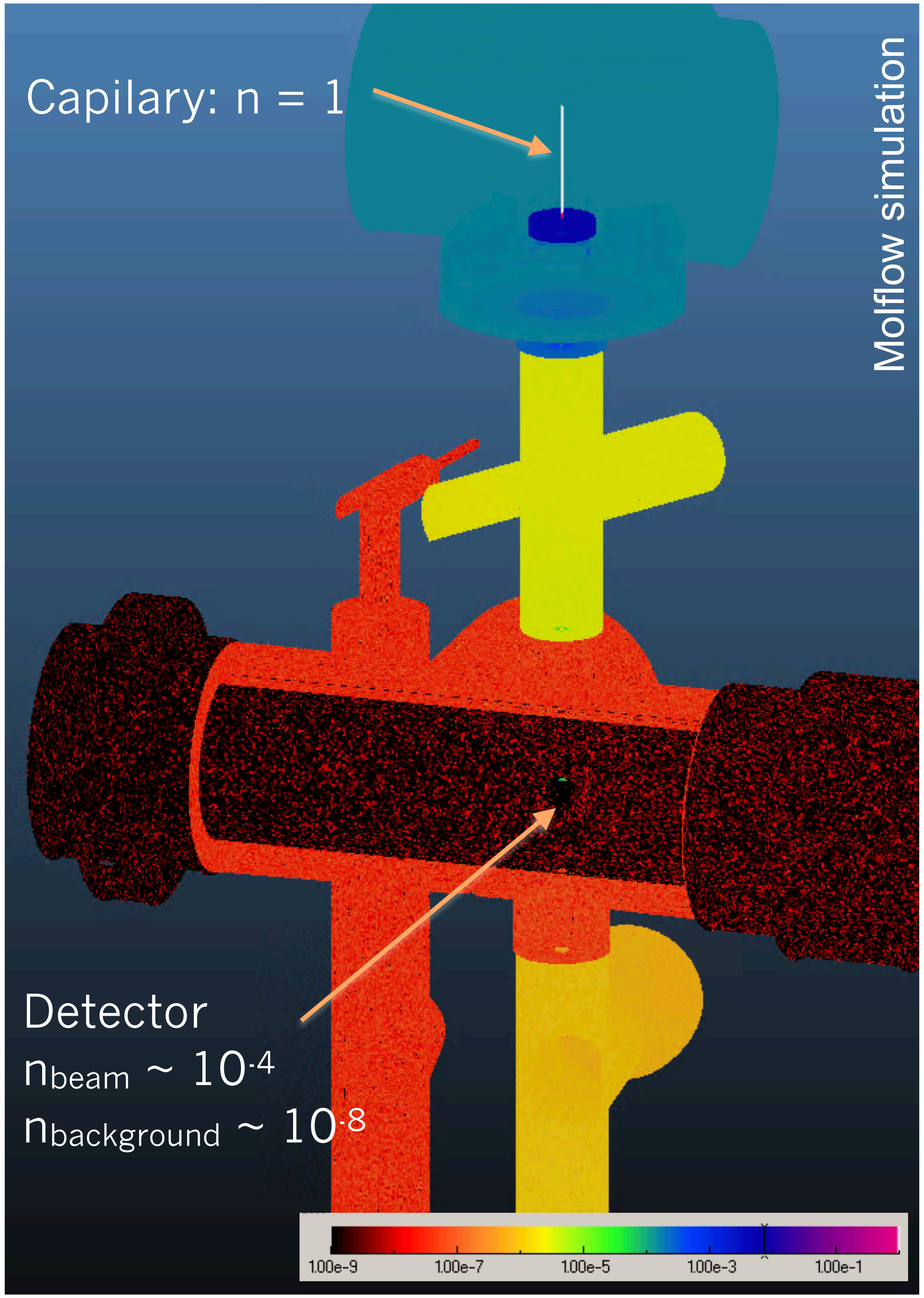

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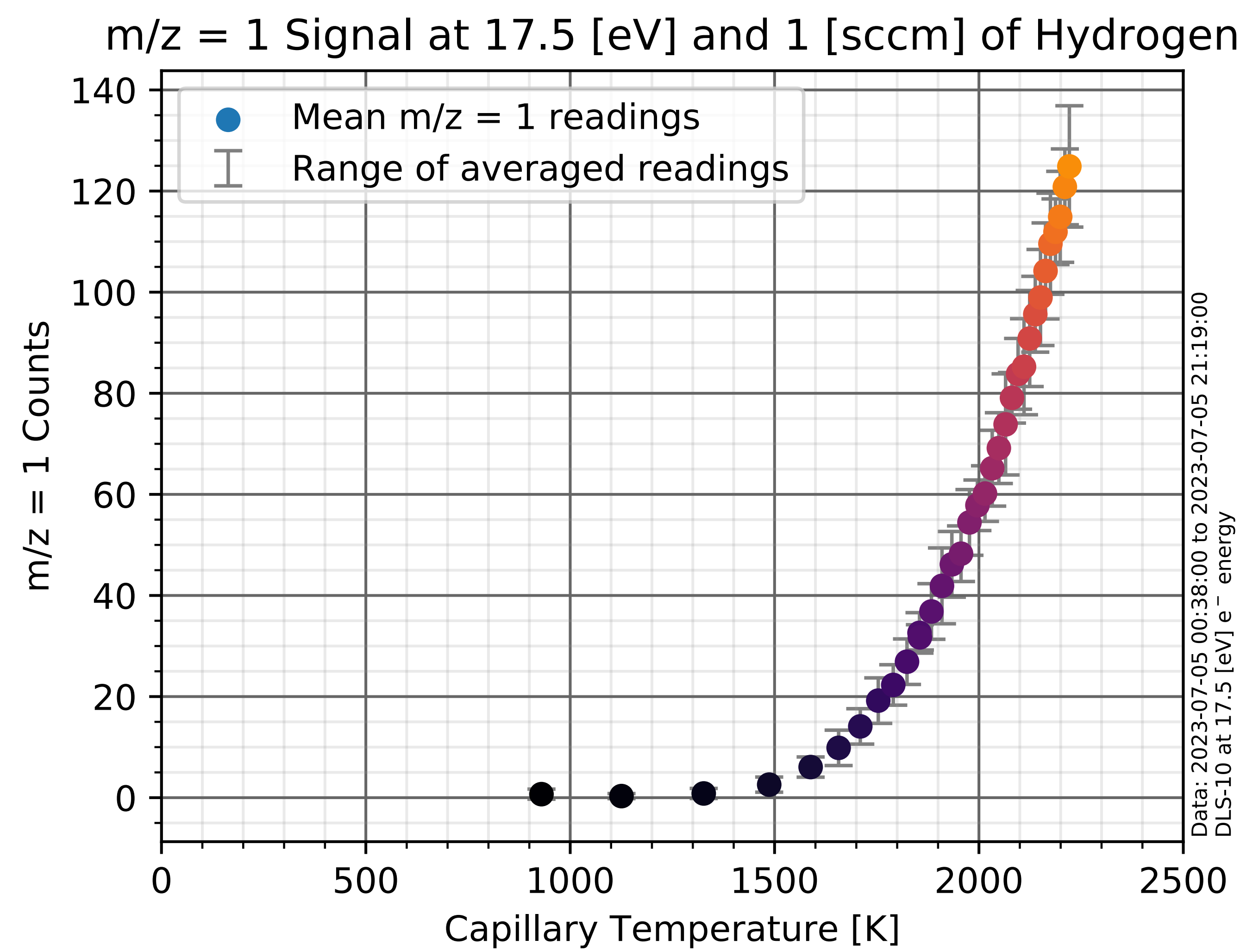
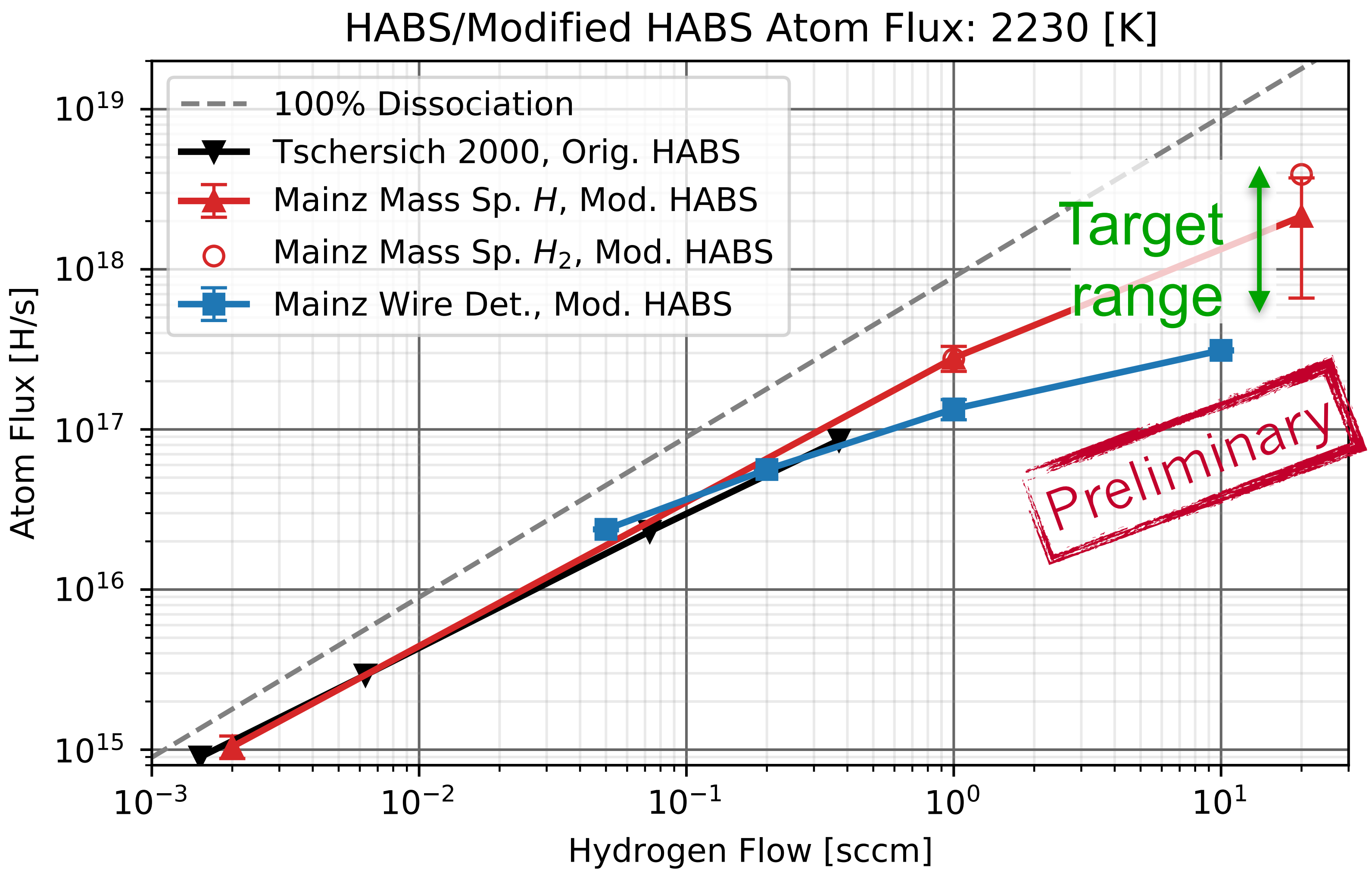


Hydrogen isotopes

Hydrogen

- Mainz atomic test stand
  - result so far



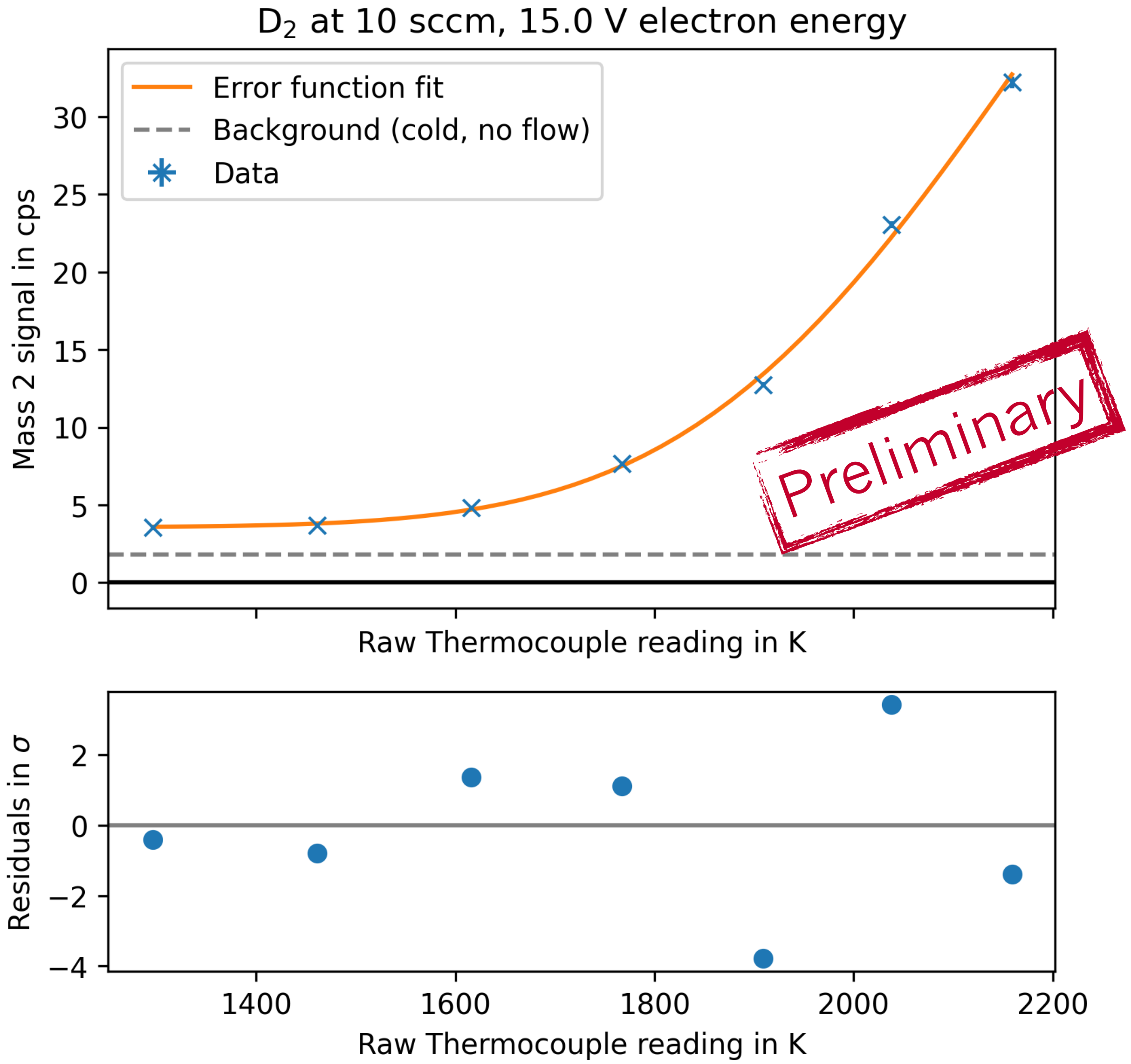
Hydrogen isotopes

Hydrogen

- Mainz atomic test stand
  - result so far

Deuterium

- UW atomic test stand
  - first dissociation signal



Hydrogen isotopes

Hydrogen

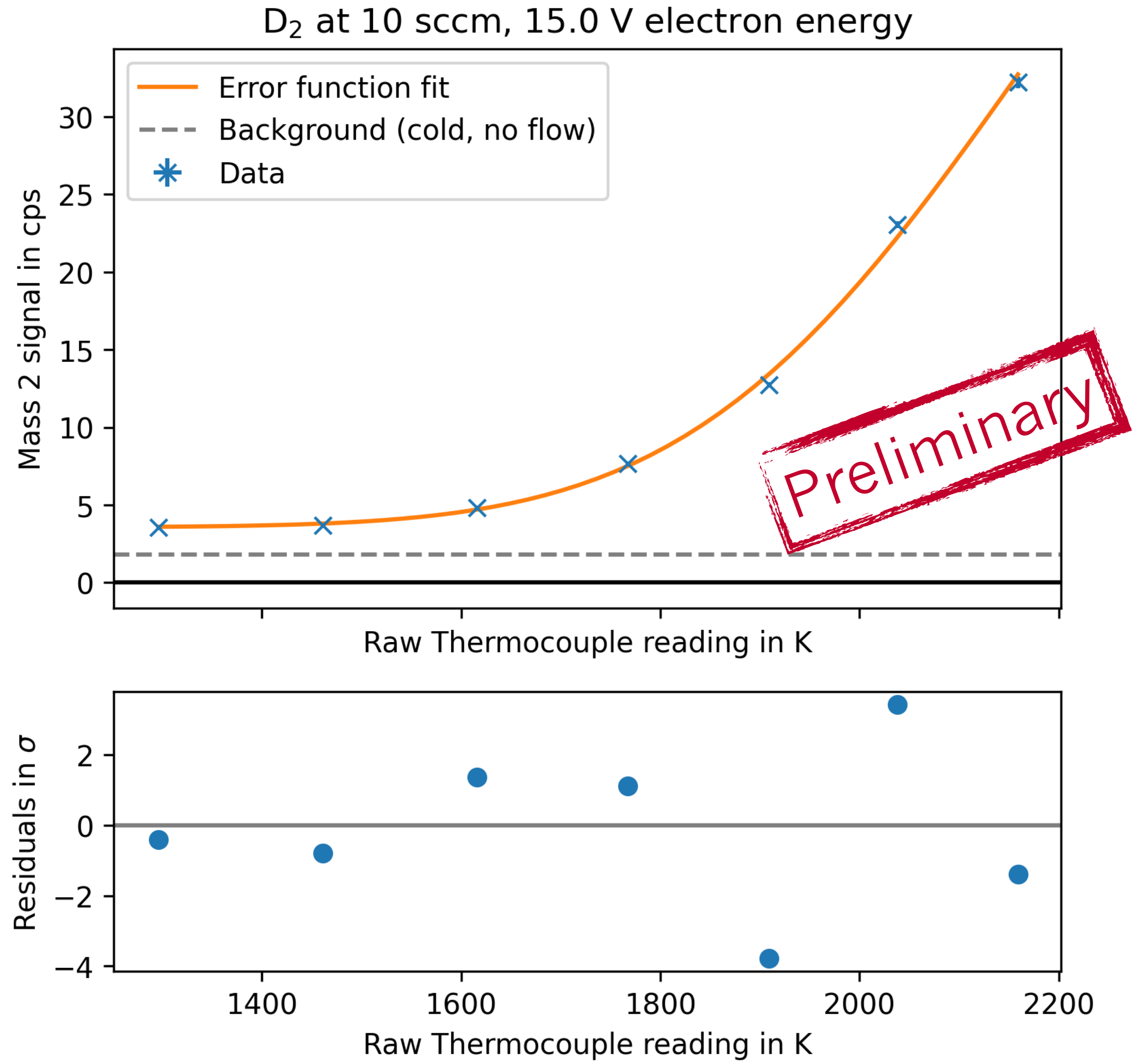
- Mainz atomic test stand
  - result so far

Deuterium

- UW atomic test stand
  - first dissociation signal

Tritium

- requires tritium handling facility
  - joint effort with TLK *"KAMATE"*



Tritium Laboratory Karlsruhe

Cooling tritium atoms

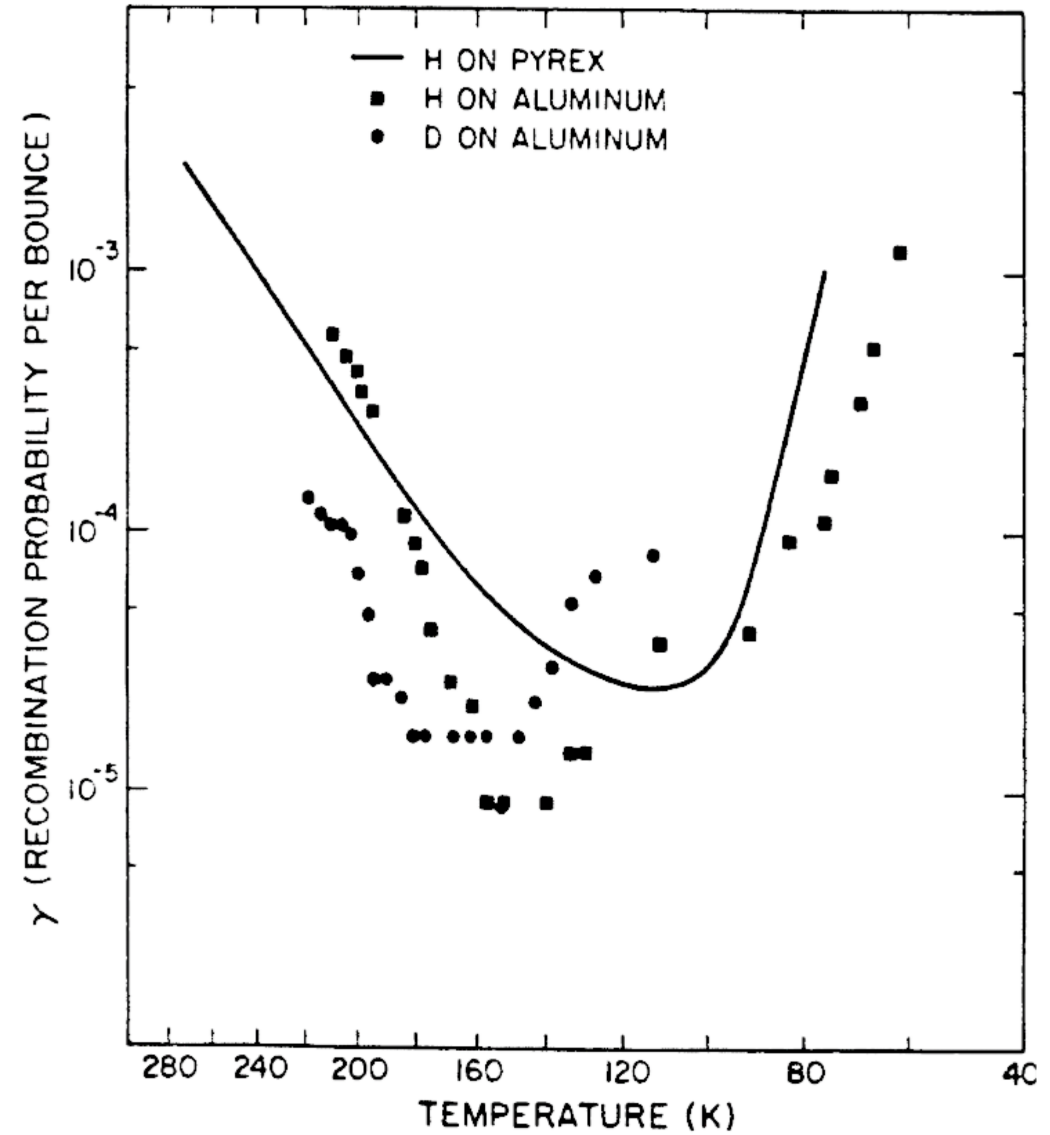
Recombination processes

- Eley– Rideal
  $H^{gas} + H^{surf} \rightarrow H_2^{gas}$
  - decreases with T and adsorbed H^{surf}
- Langmuir–Hinshelwood
  $H^{surf} + H^{surf} \rightarrow H_2^{gas}$
  - increases with H^{surf} mobility

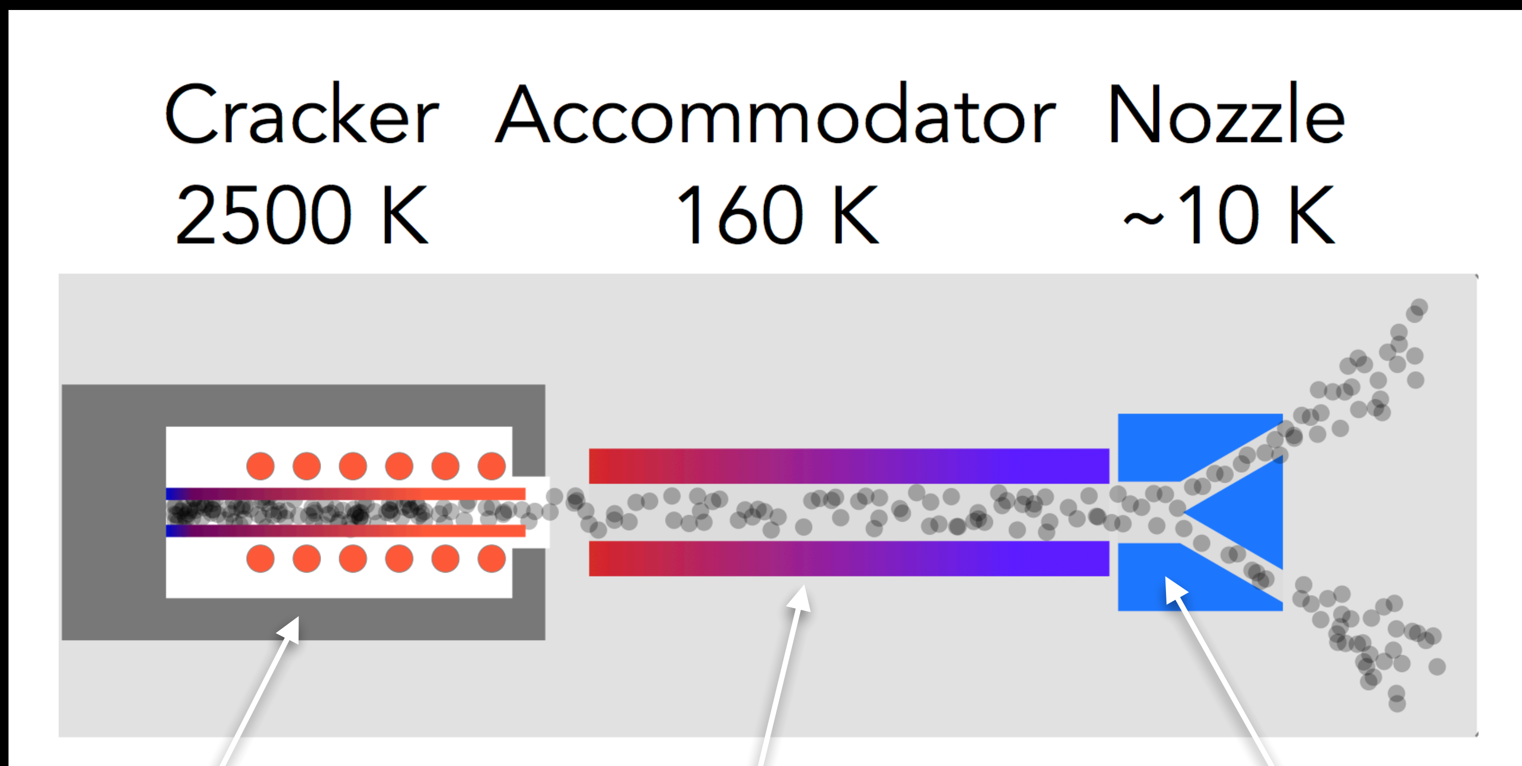
Surface cooling approach

- first step to recombination minimum (100-150 K) ➔ *accomodator*
- second step to freeze-out (10K) with limited wall interactions ➔ *nozzle*

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



Cooling tritium atoms



Cracker

→ purity vs. flow

Accommodator

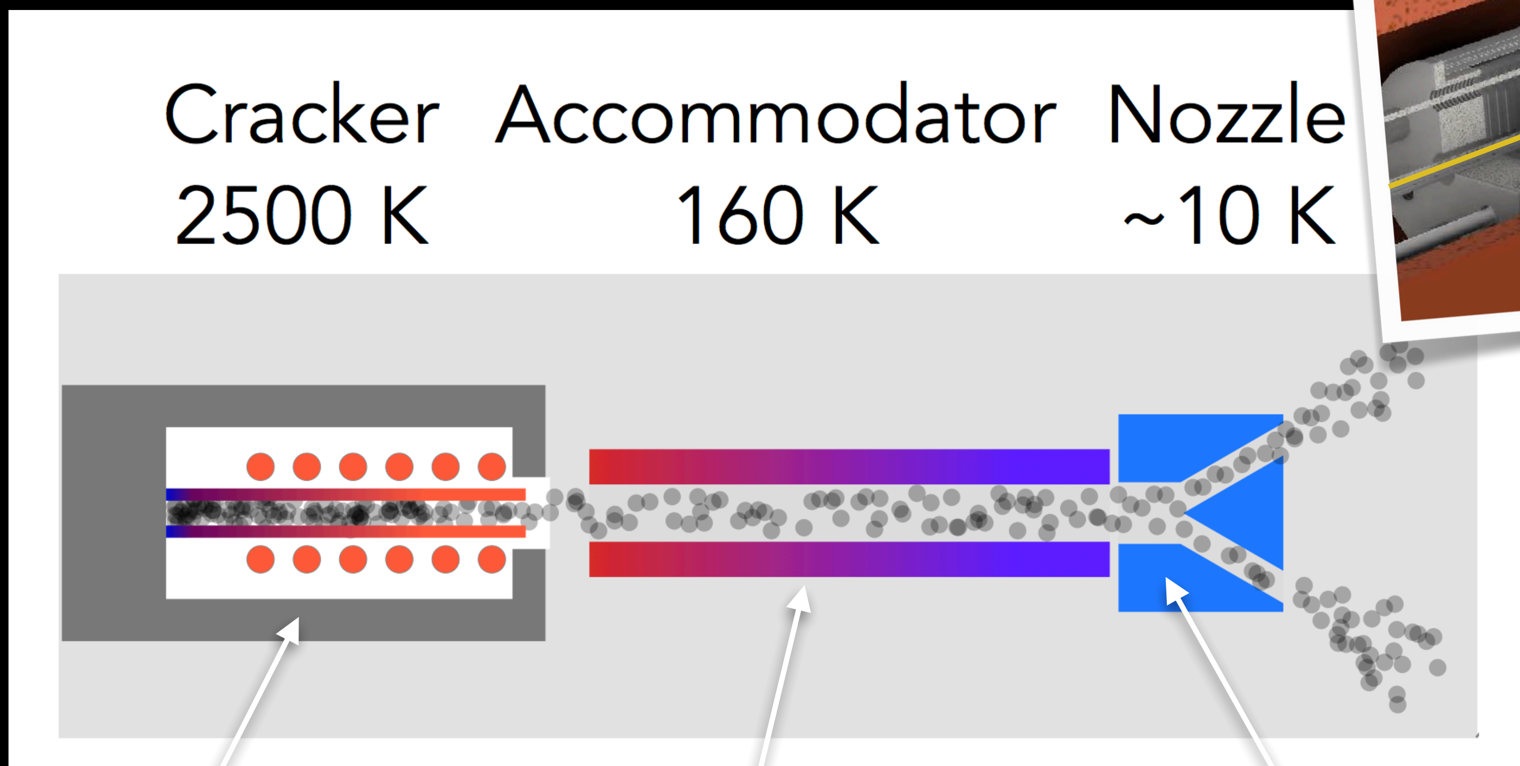
(liquid nitrogen)

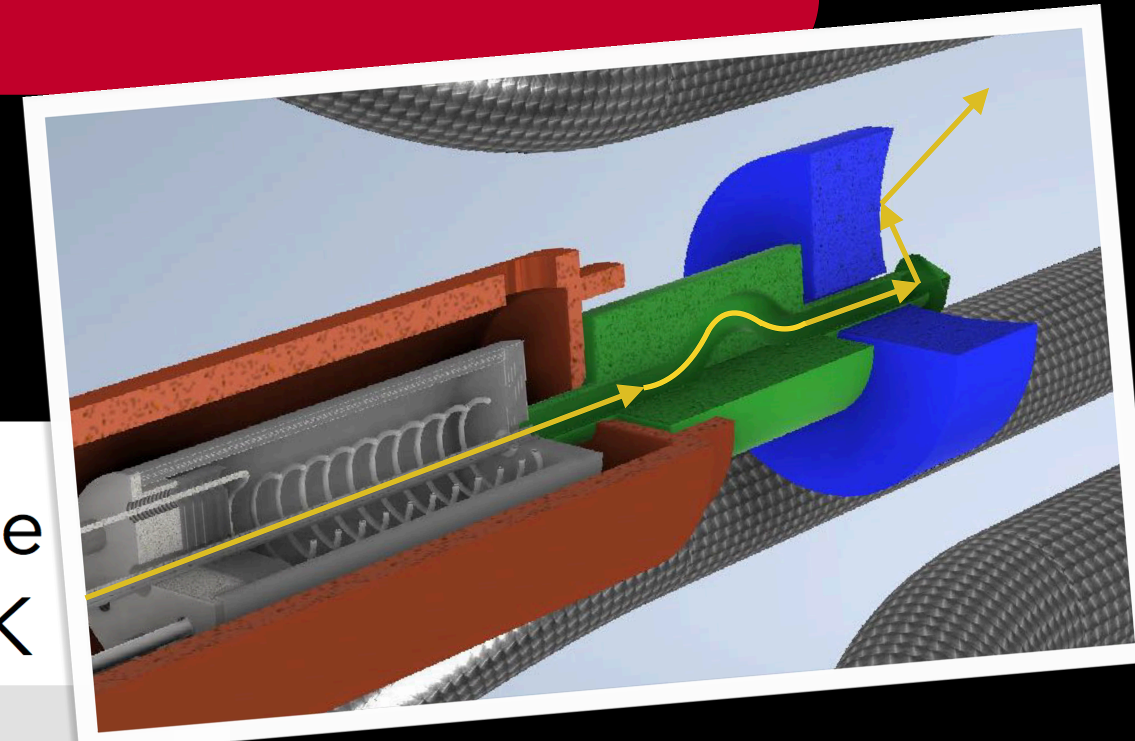
Final nozzle

- design for few bounces
- freeze-out 30K

  → periodic purging

Cooling tritium atoms





Cracker
→ purity vs. flow

Accommodator
(liquid nitrogen)

Final nozzle
- design for few bounces
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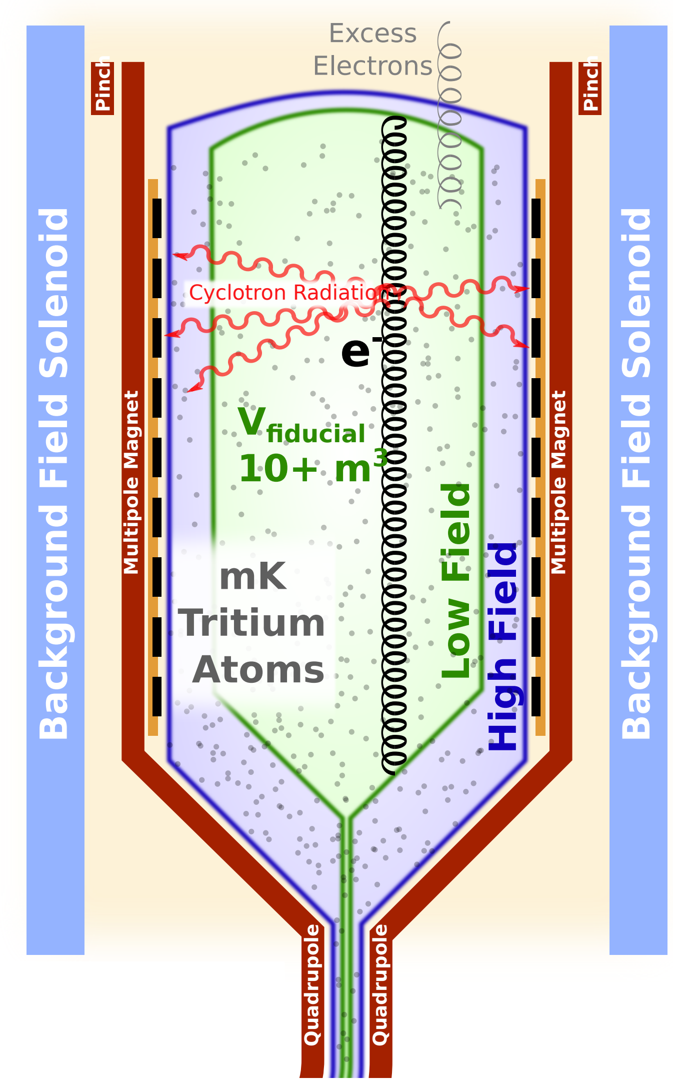
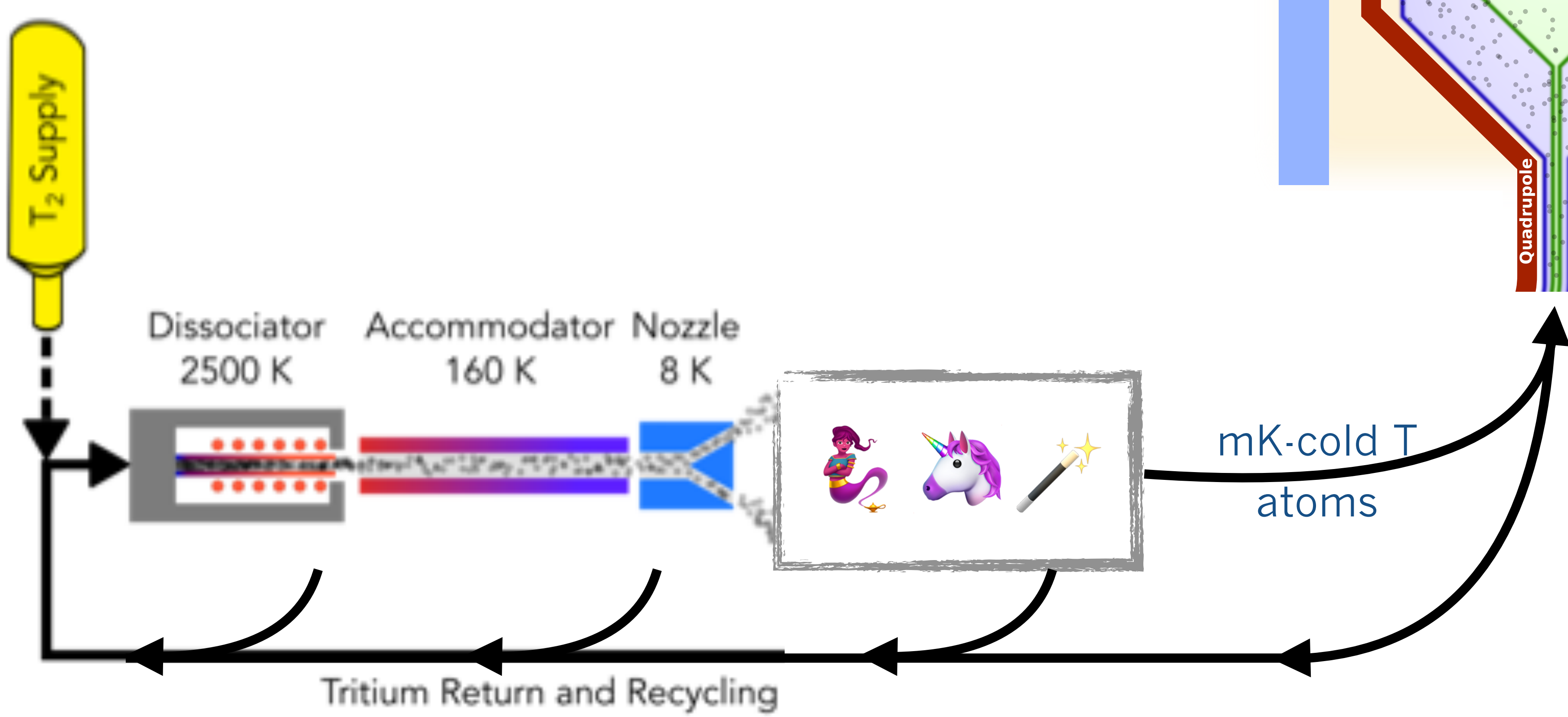
Project 8: Design concepts

Atomic T source

- Dissociation ✓
- Cooling **???**
- Injection ✓
- Trapping ✓
- Purification/Circulation (✓)

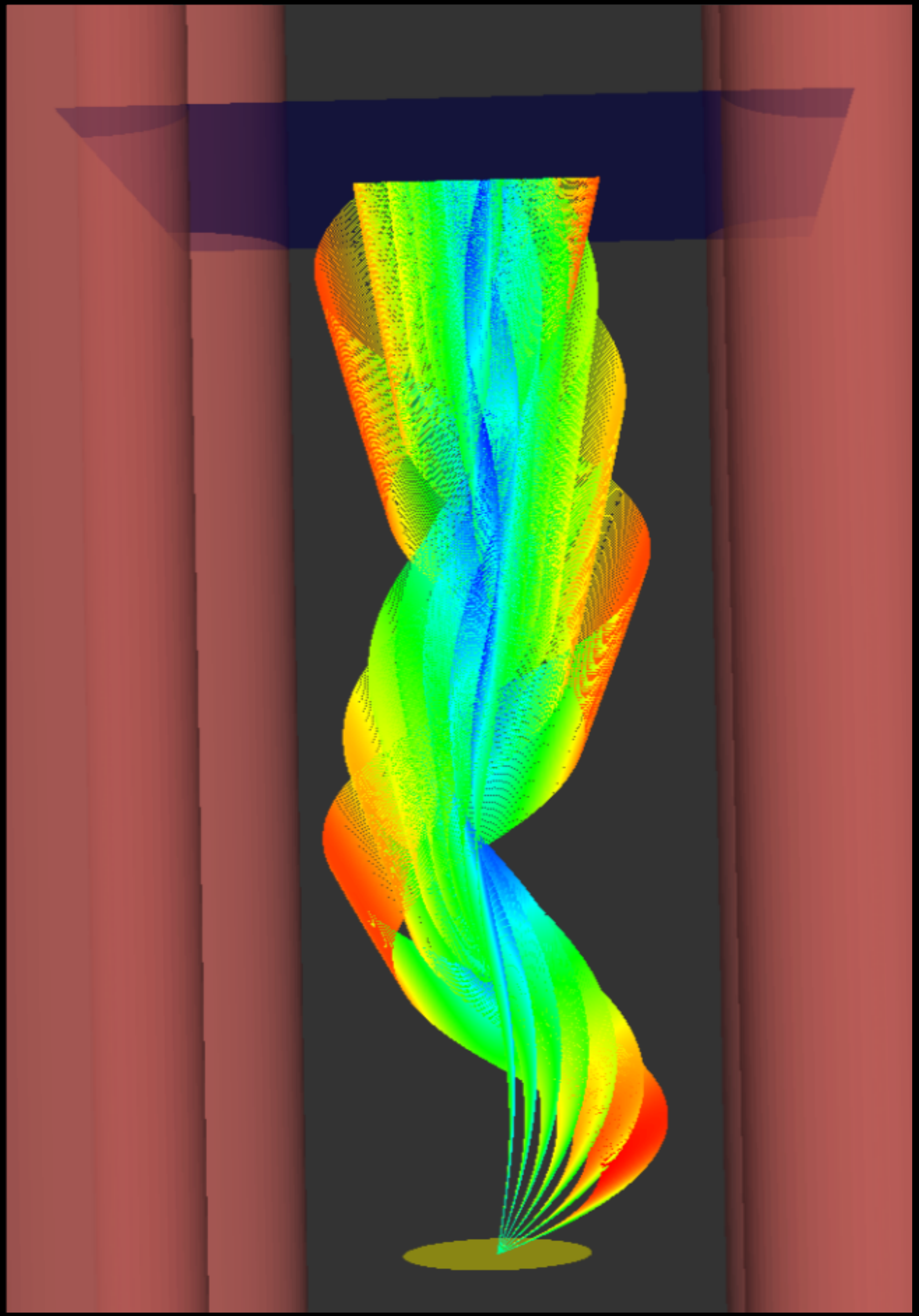




Velocity and State Selectors

Only atomic T guided magnetically

- (bend) quadrupole with skimmers



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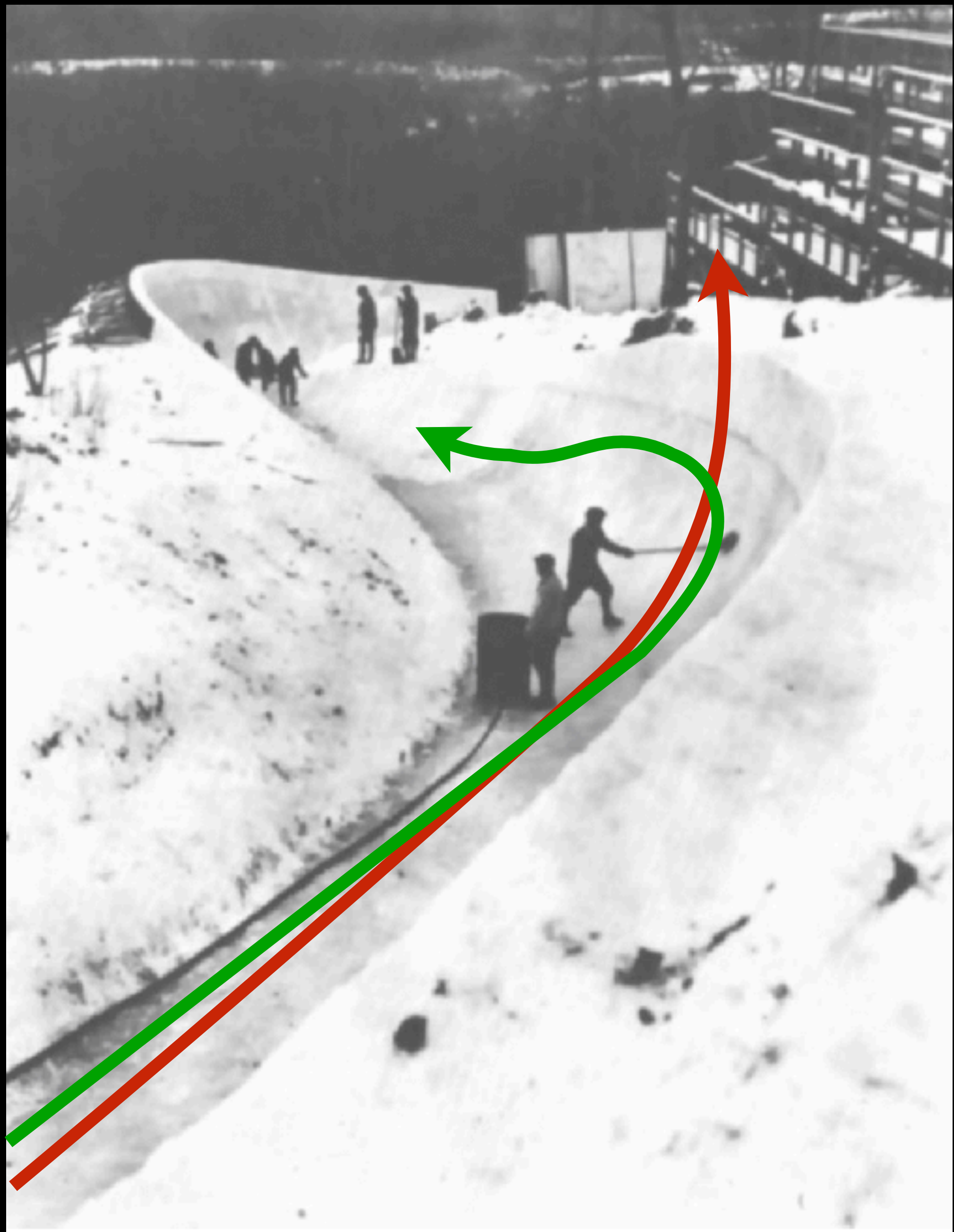


Workmen putting the finishing touches on Zig-zag turn, Mt Van Hoevenberg Olympic bobsled run

PRISMA

JG|U

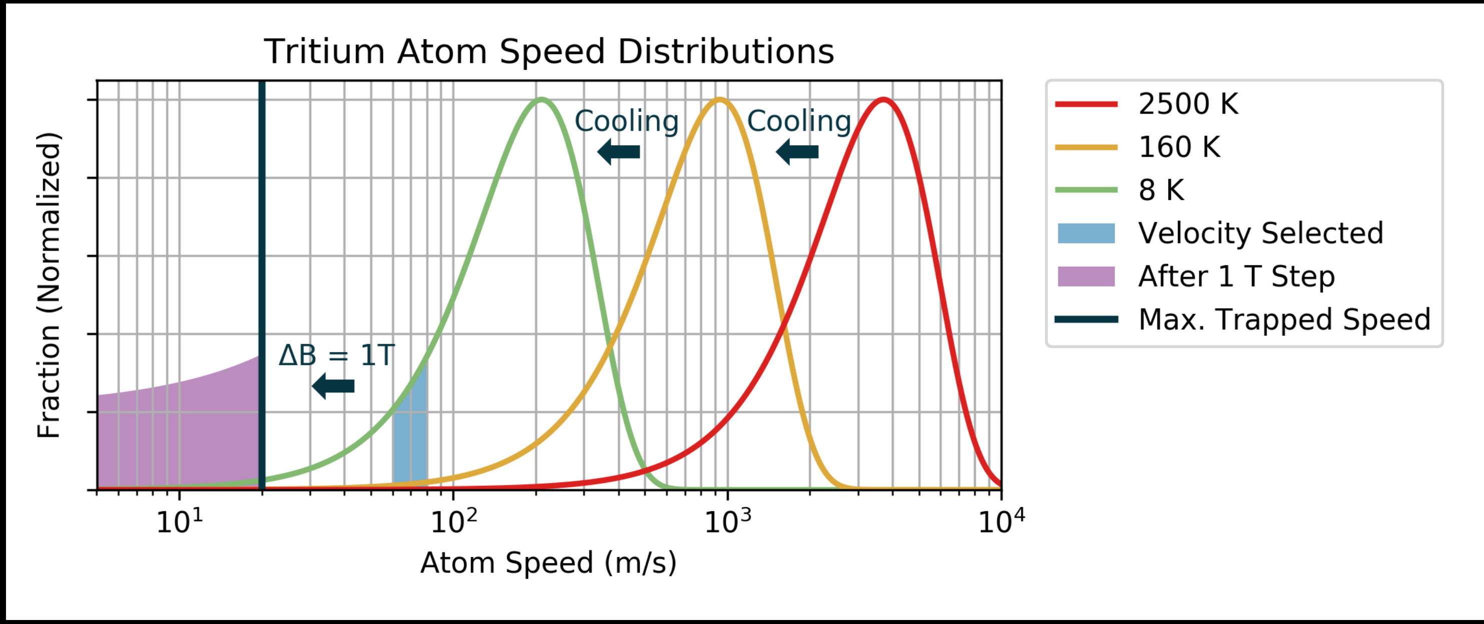
Velocity and State Selectors

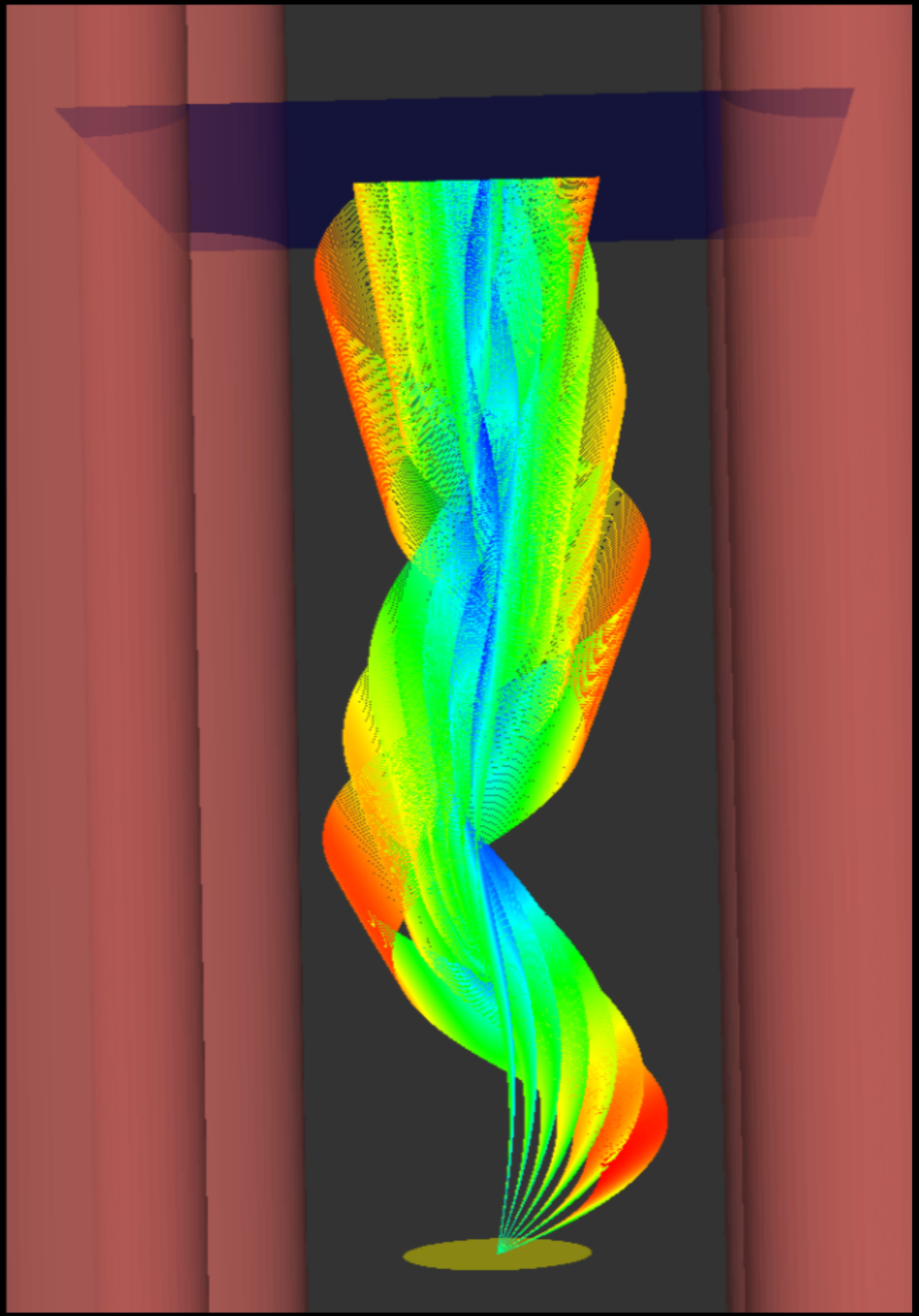
Only atomic T guided magnetically

- (bend) quadrupole with skimmers

Tune acceptance for

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





PRiSMA

JG|U

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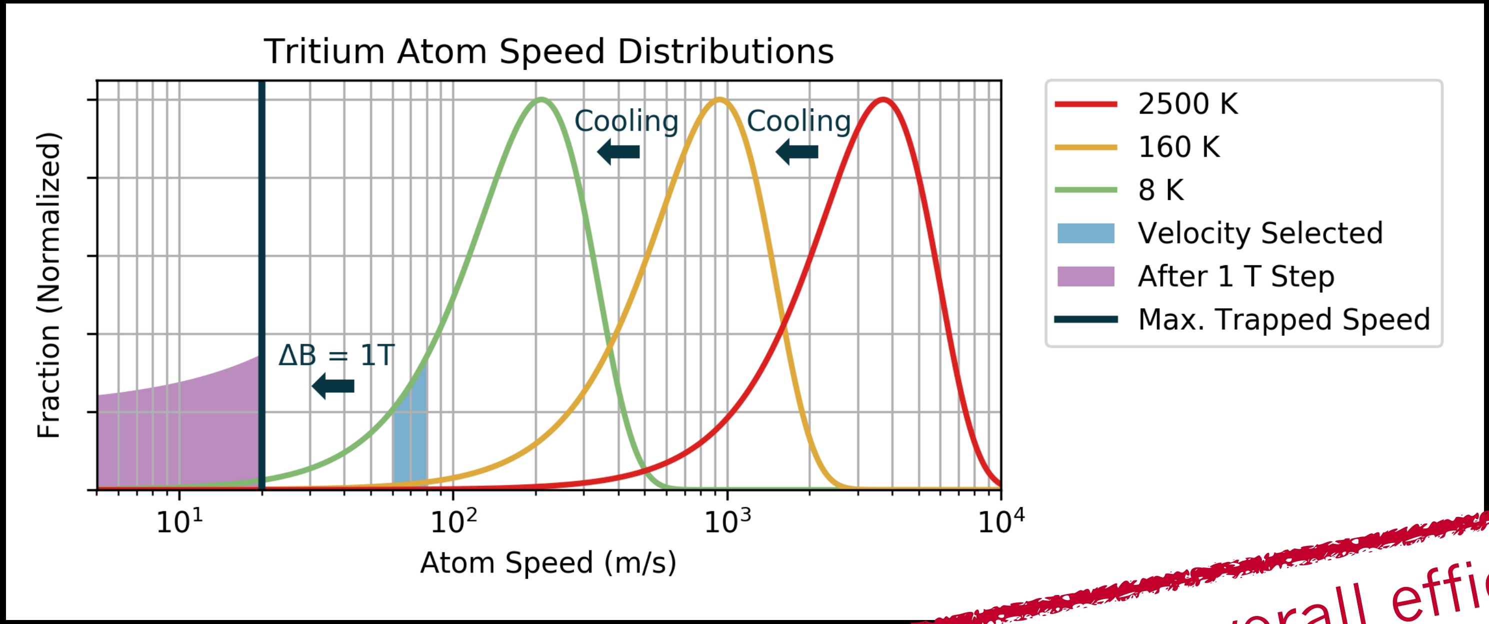
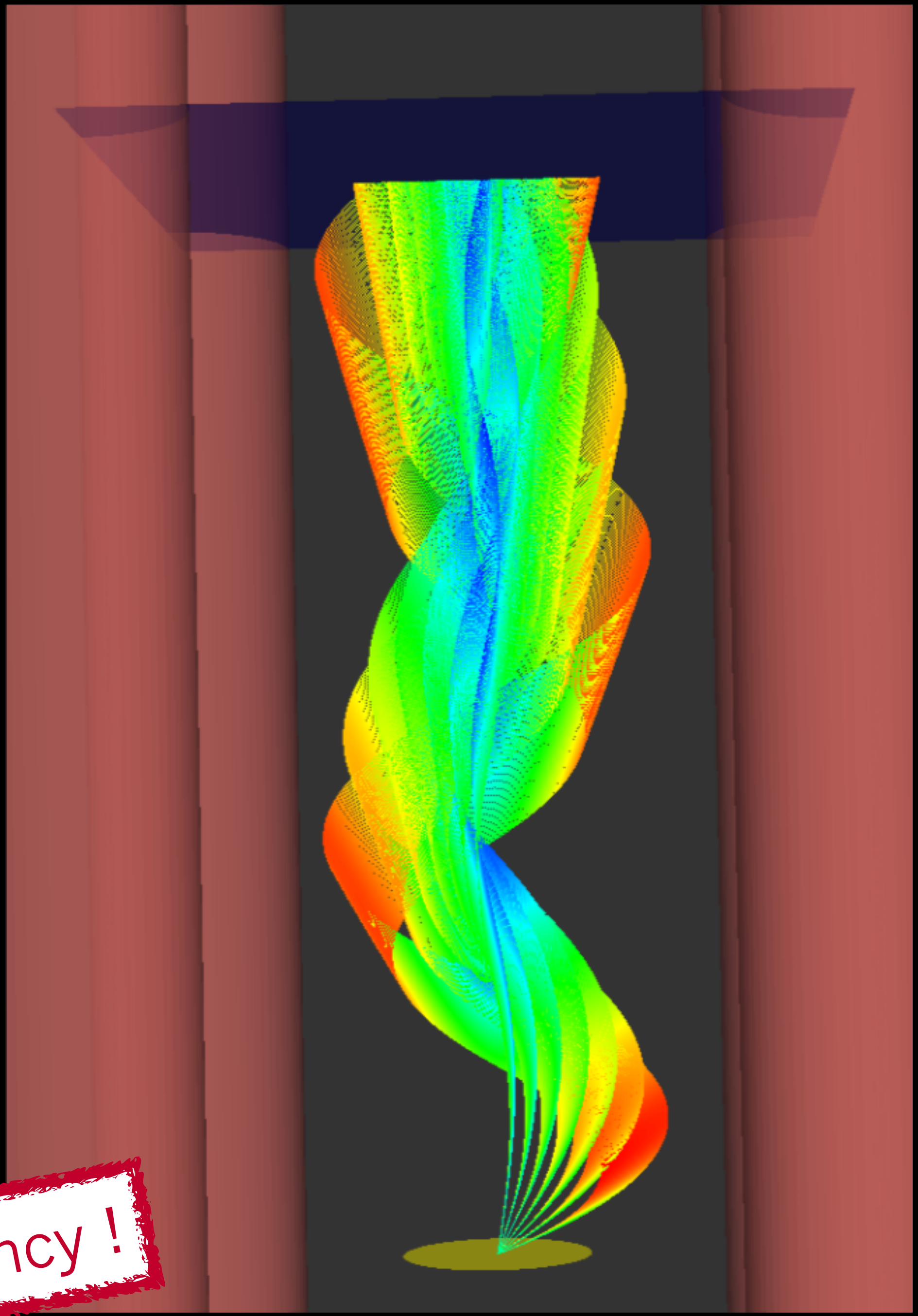


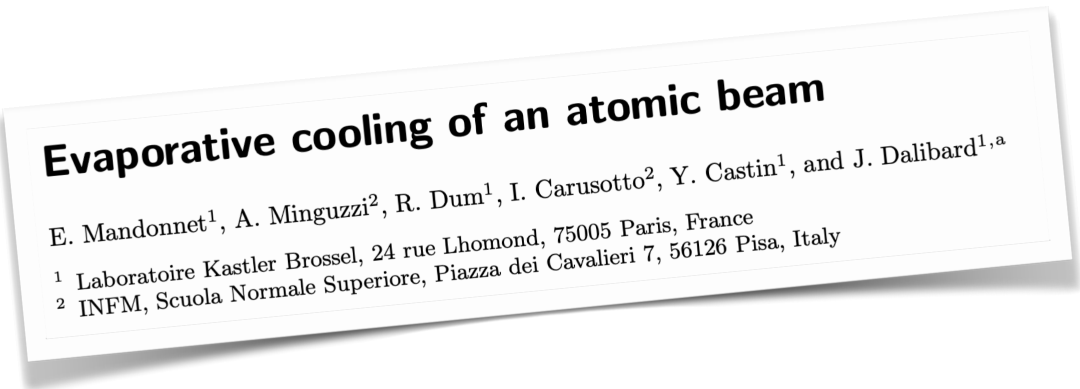


→ but poor overall efficiency !

PRISMA

JG|U

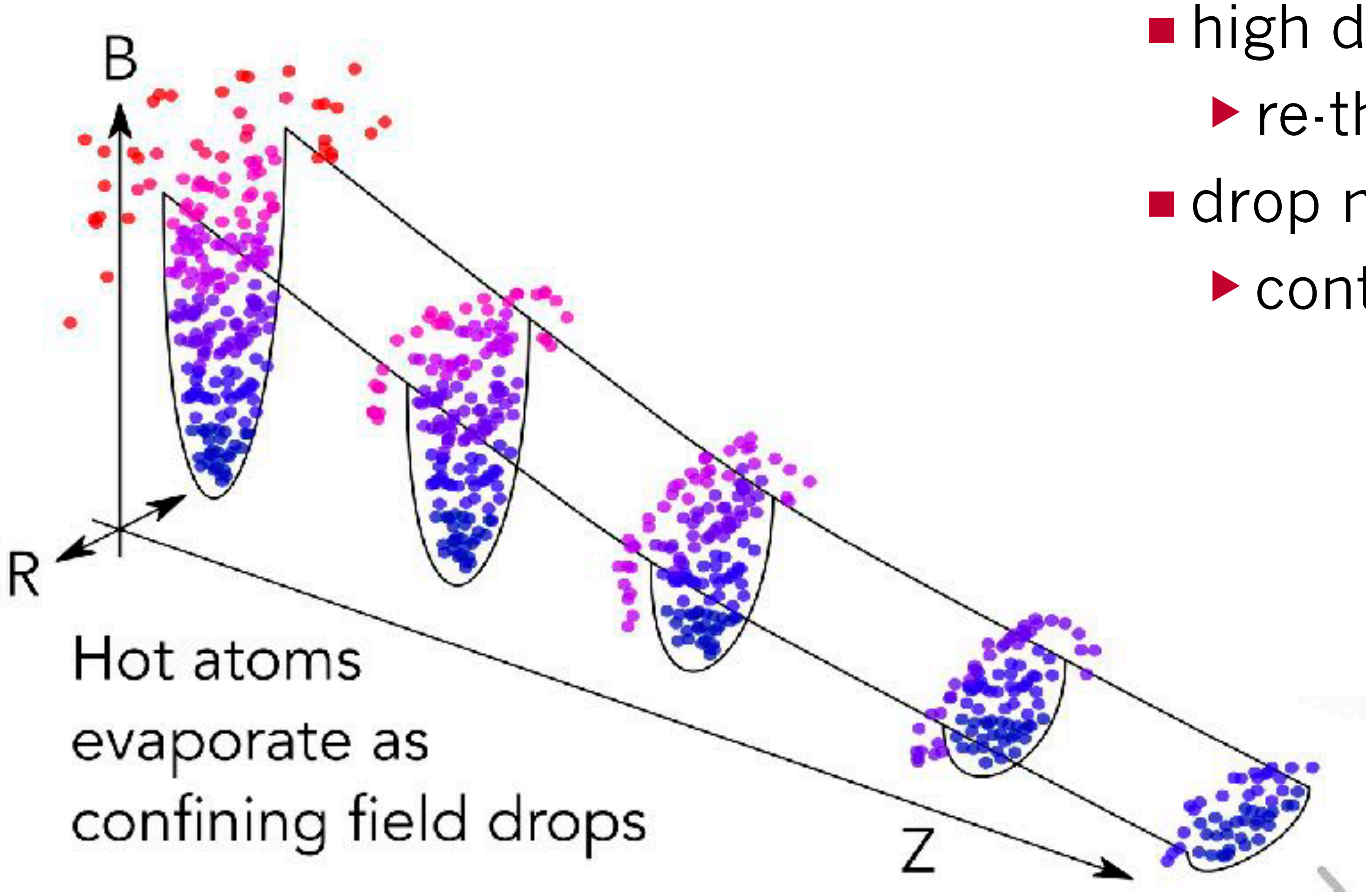
Evaporative cooling



Evaporative cooling of an atomic beam

E. Mandonnet[1], A. Minguzzi[2], R. Dum[1], I. Carusotto[2], Y. Castin[1], and J. Dalibard[1,a]

[1] Laboratoire Kastler Brossel, 24 rue Lhomond, 75005 Paris, France
[2] INFM, Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy



Basic idea

- magnetic wall
  - loose *hot* atoms (high $p_\perp$)
- high density
  - re-thermalization
- drop magnetic field along beam
  - continuous cooling

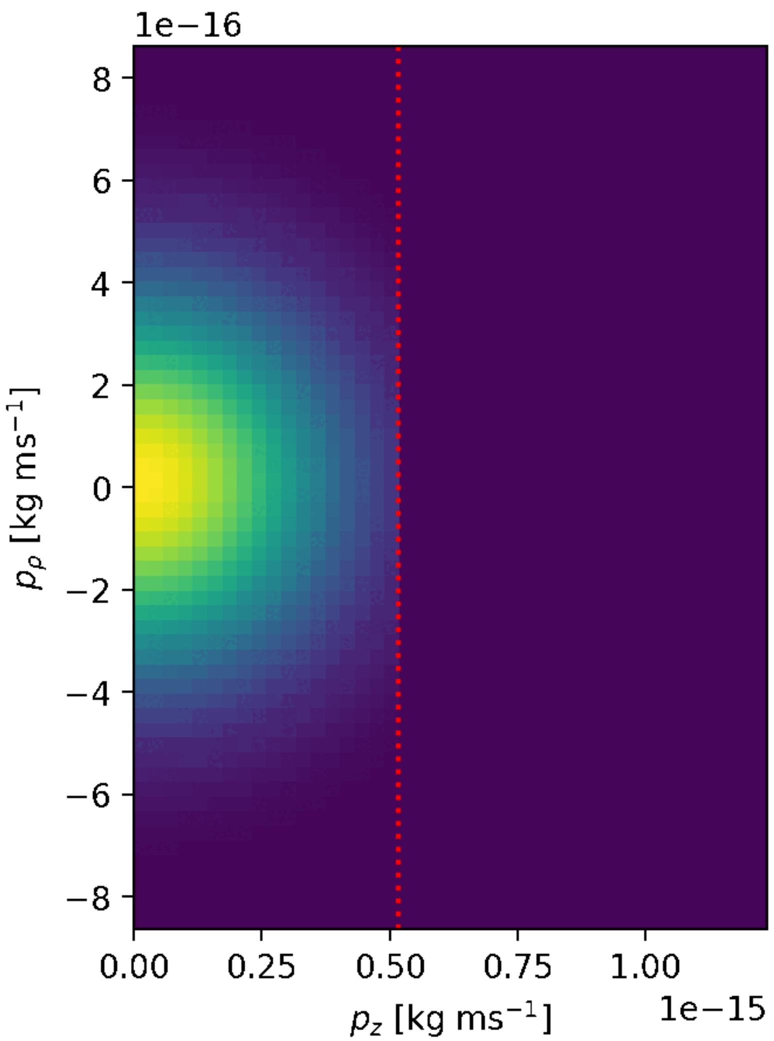
Evaporative cooling: the math

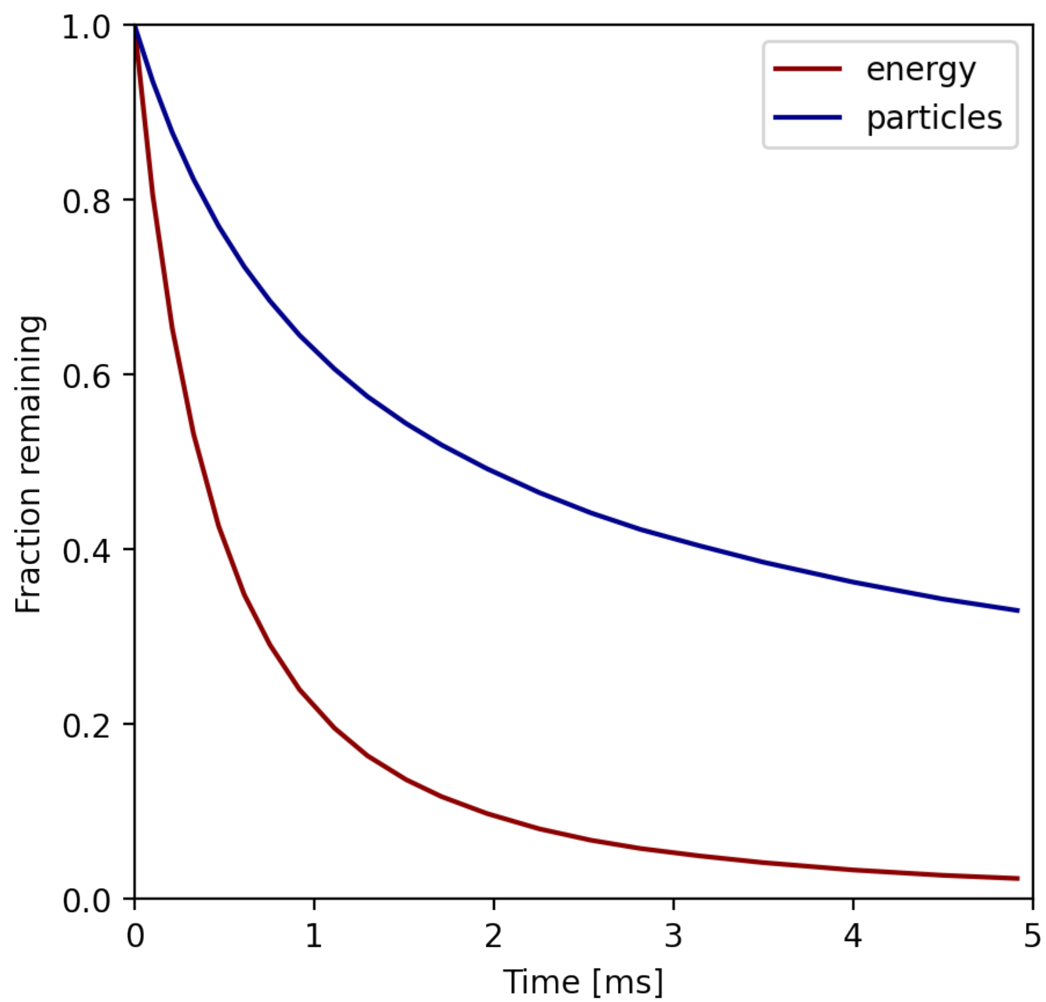
Boltzman transport equation

$$\left(\frac{p}{m}\nabla_r - \nabla_r U.\nabla_p + \frac{\partial}{\partial t}\right) f(r,p) = \frac{1}{\pi m^2}\int d^3p_2 \int d^3p_3 \int d^3p_4 \frac{d\sigma}{d\Omega}(p_1,p_2,p_3,p_4)(f(r,p_3)f(r,p_4) - f(r,p)f(r,p_2))$$

kinetic terms **collision integral**

- solve numerically





- Losing energy faster than particles means cooling
- Radial cooling also cools longitudinal motion since collisions redistribute momentum

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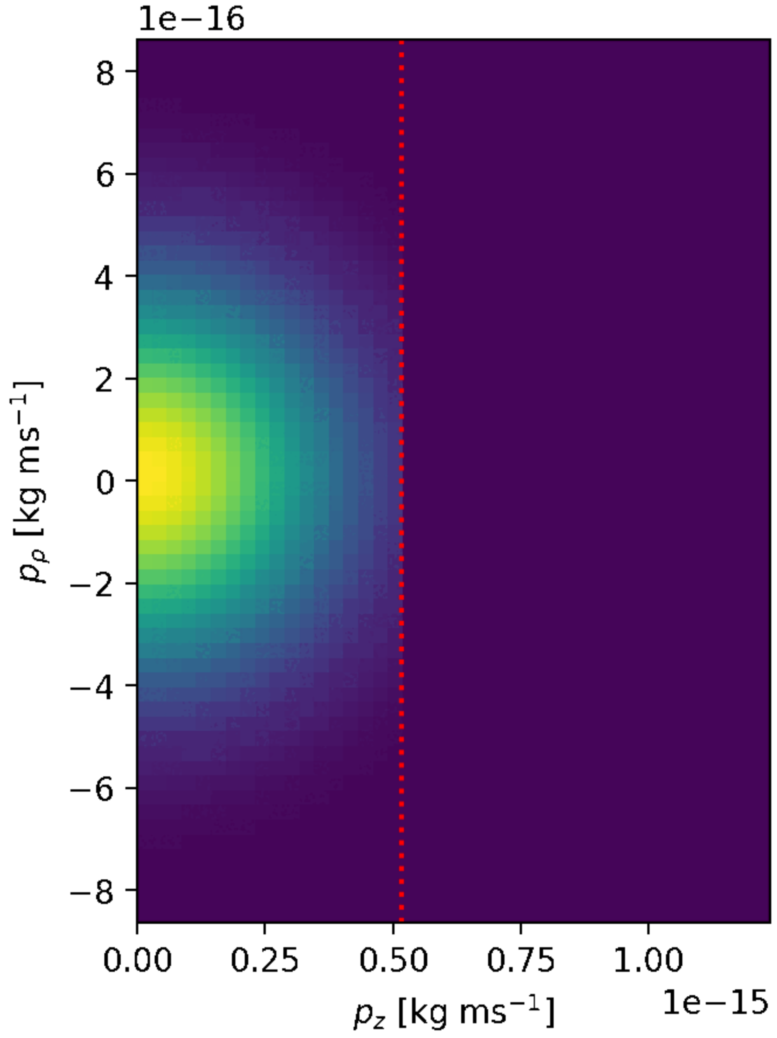

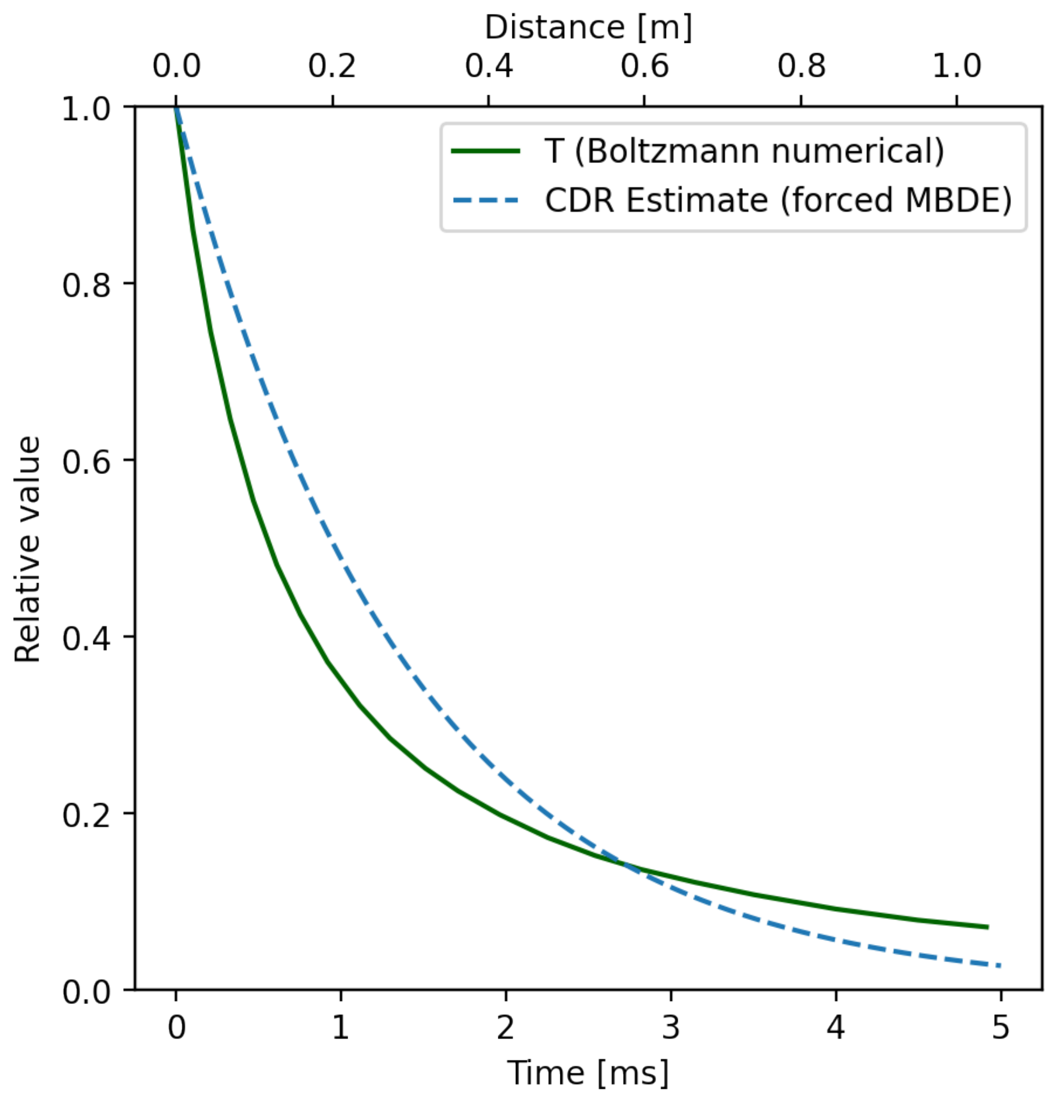

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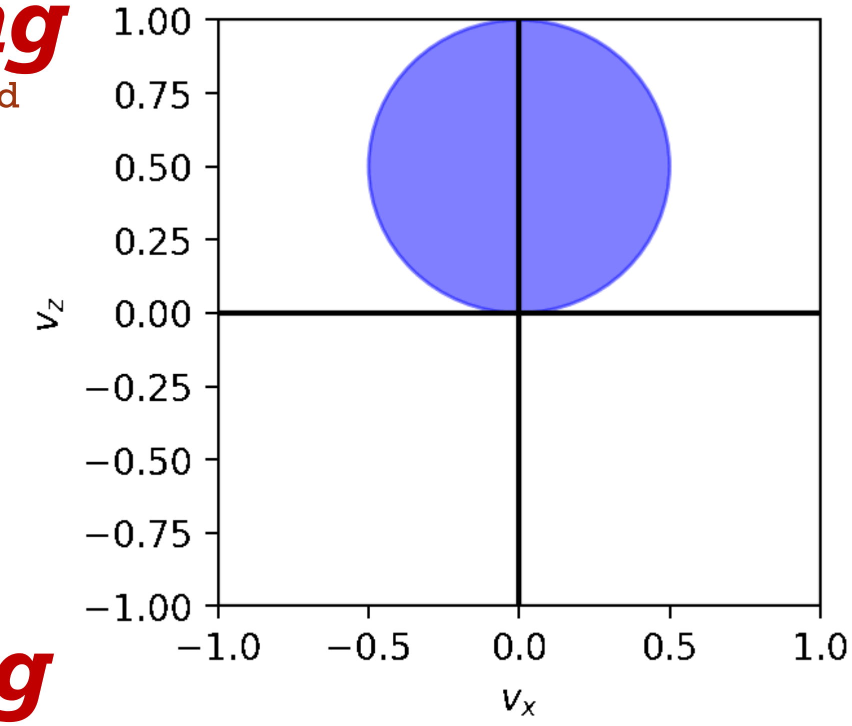
Cooling vs slowing

Initial atomic *beam*

- net forward momentum
  - need **cooling** and **slowing**

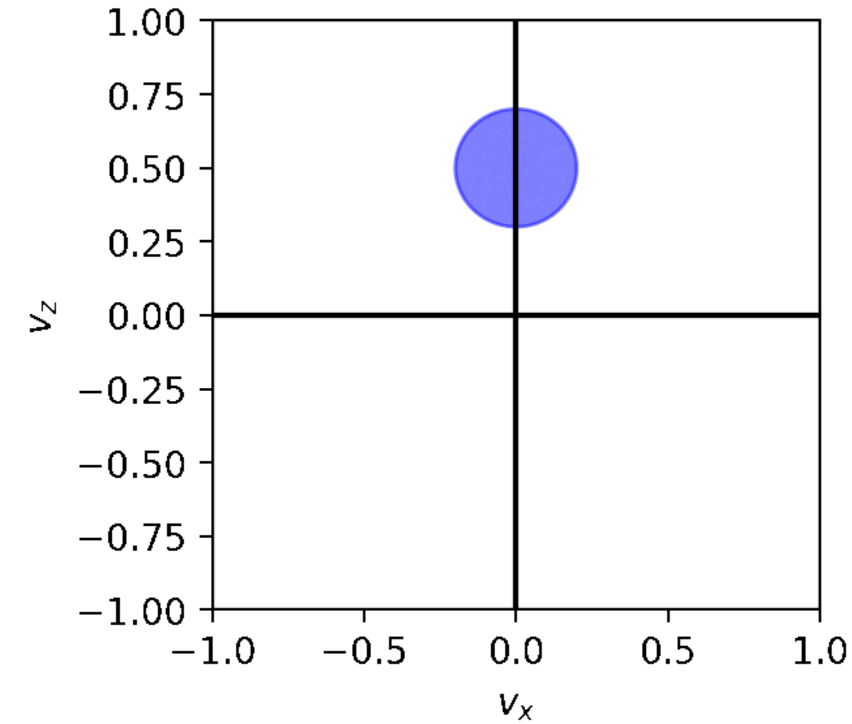
Cooling

Mean(p) conserved



Slowing

Mean(p) reduced



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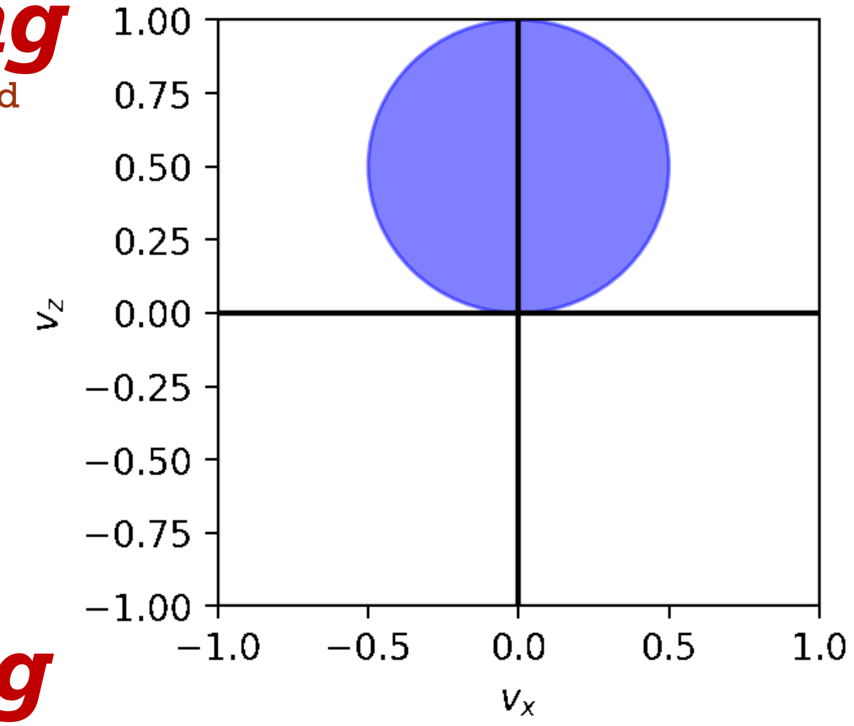

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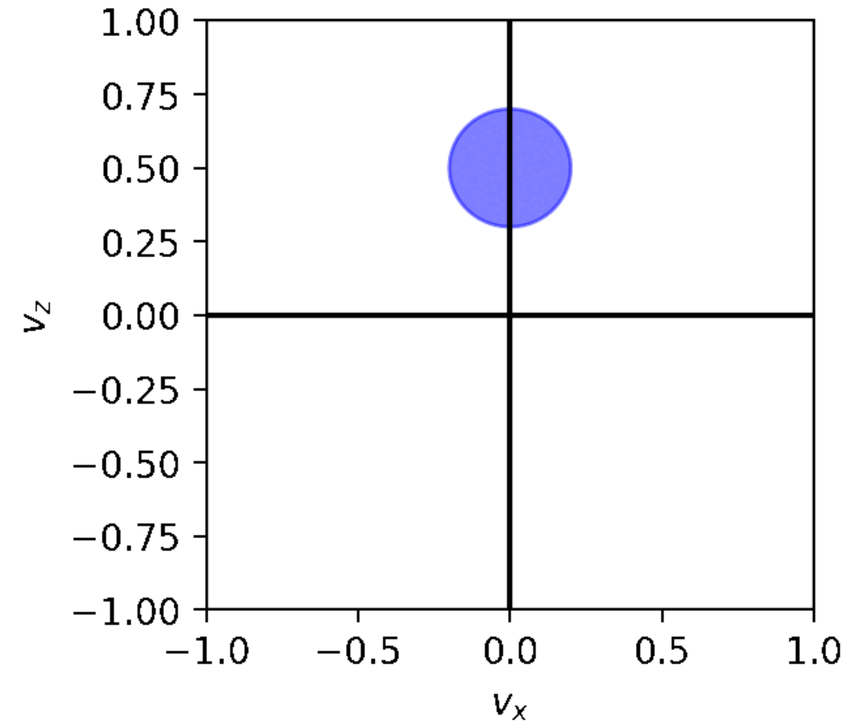

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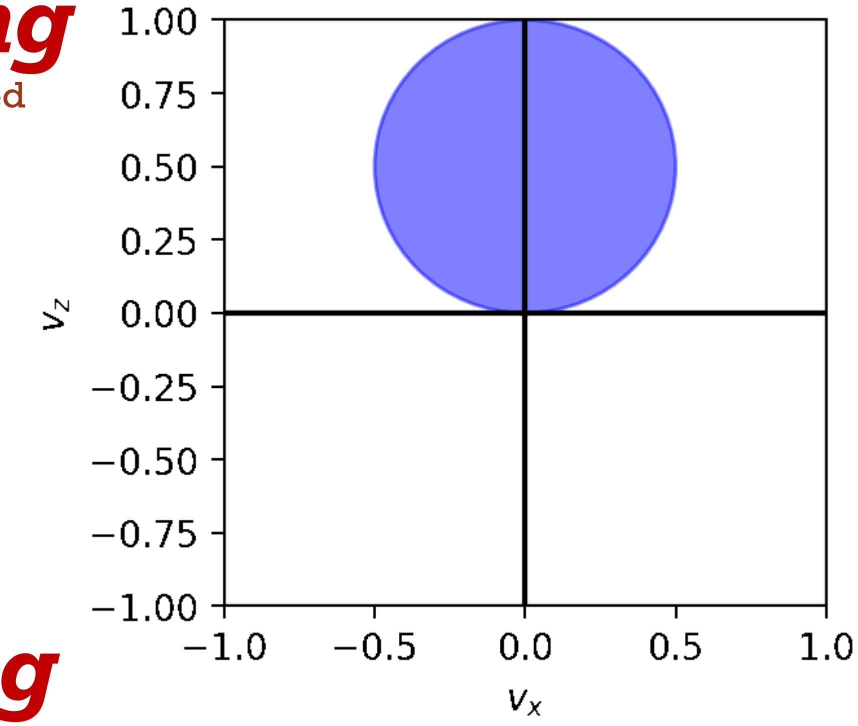

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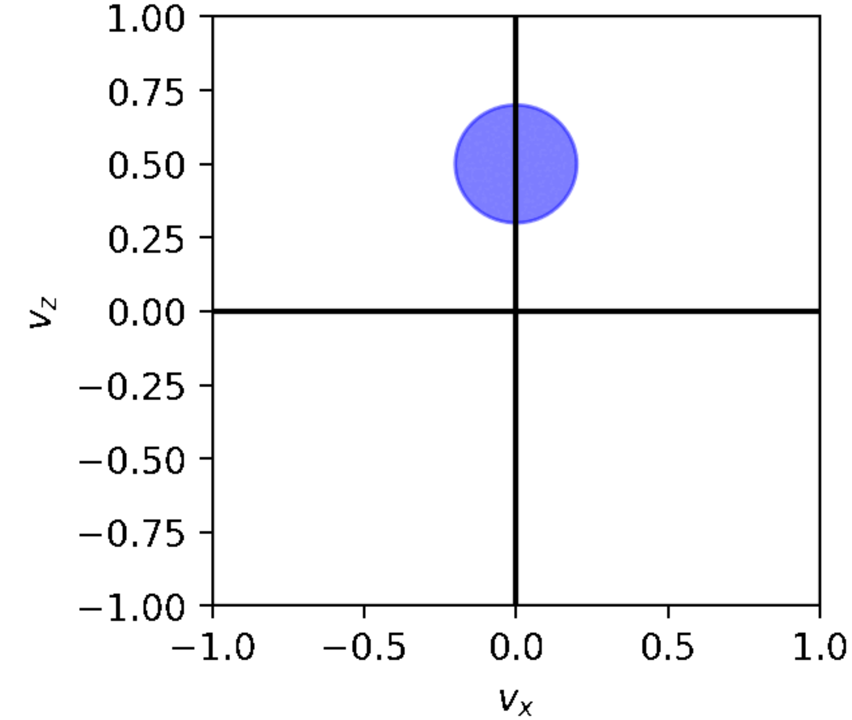

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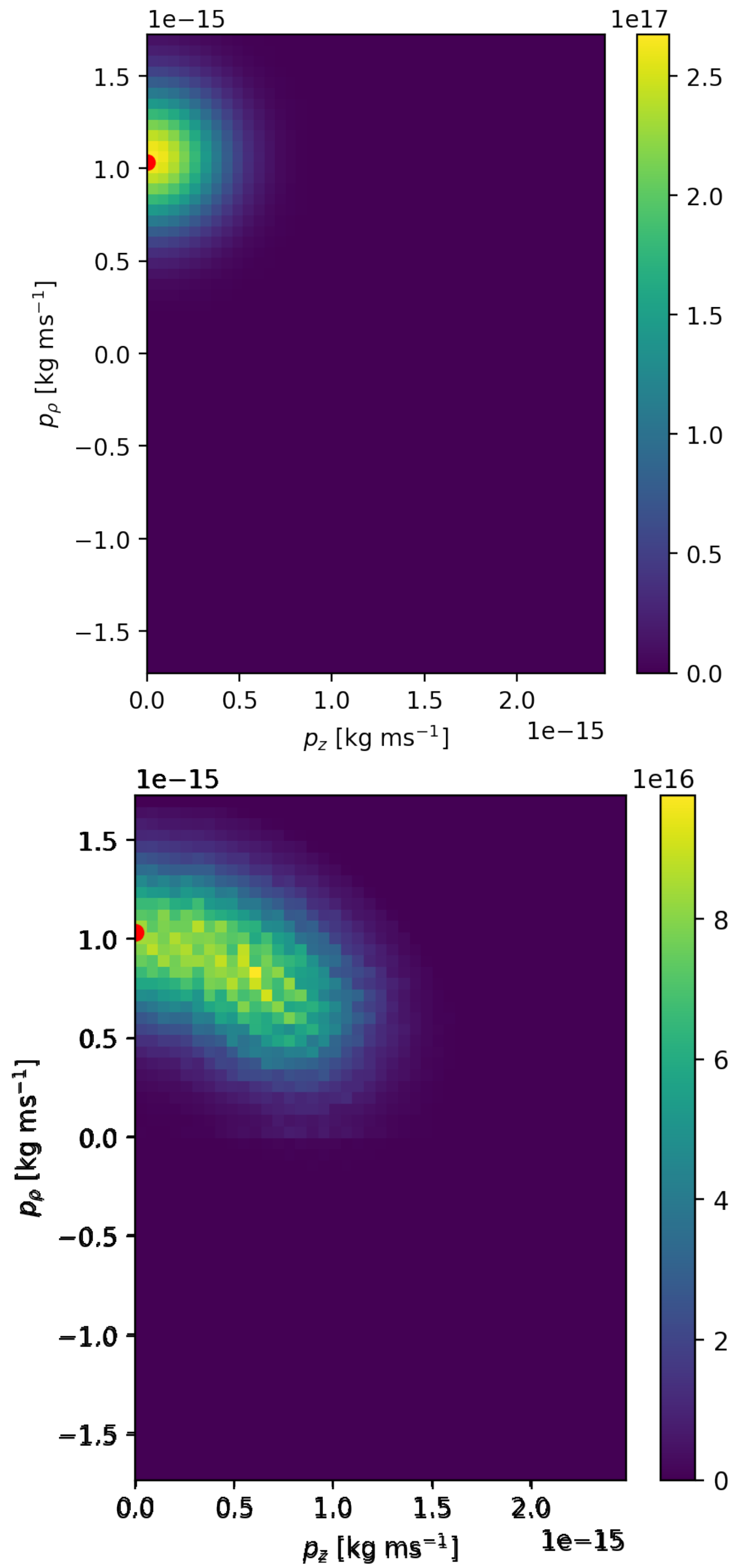
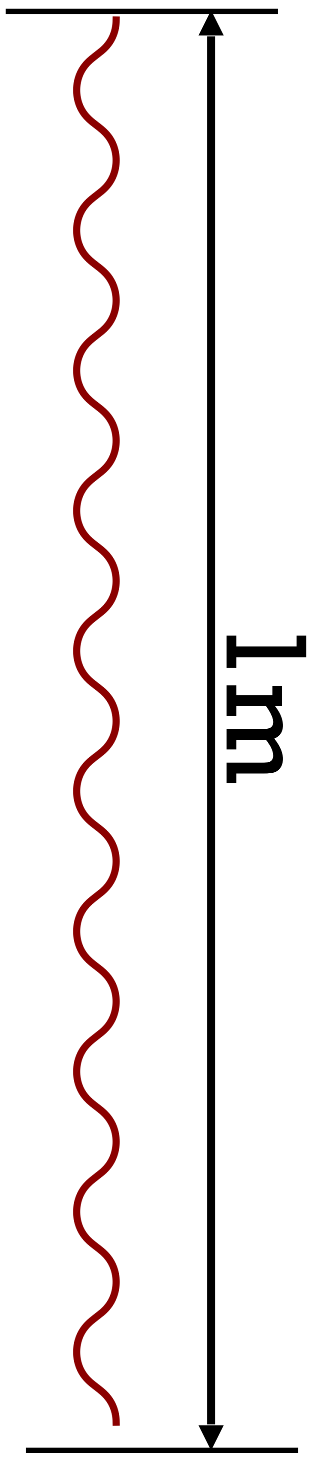
- several wiggles within mean free path
  - transfer longitudinal to perpendicular momentum
- re-thermalization
  - slows down beam





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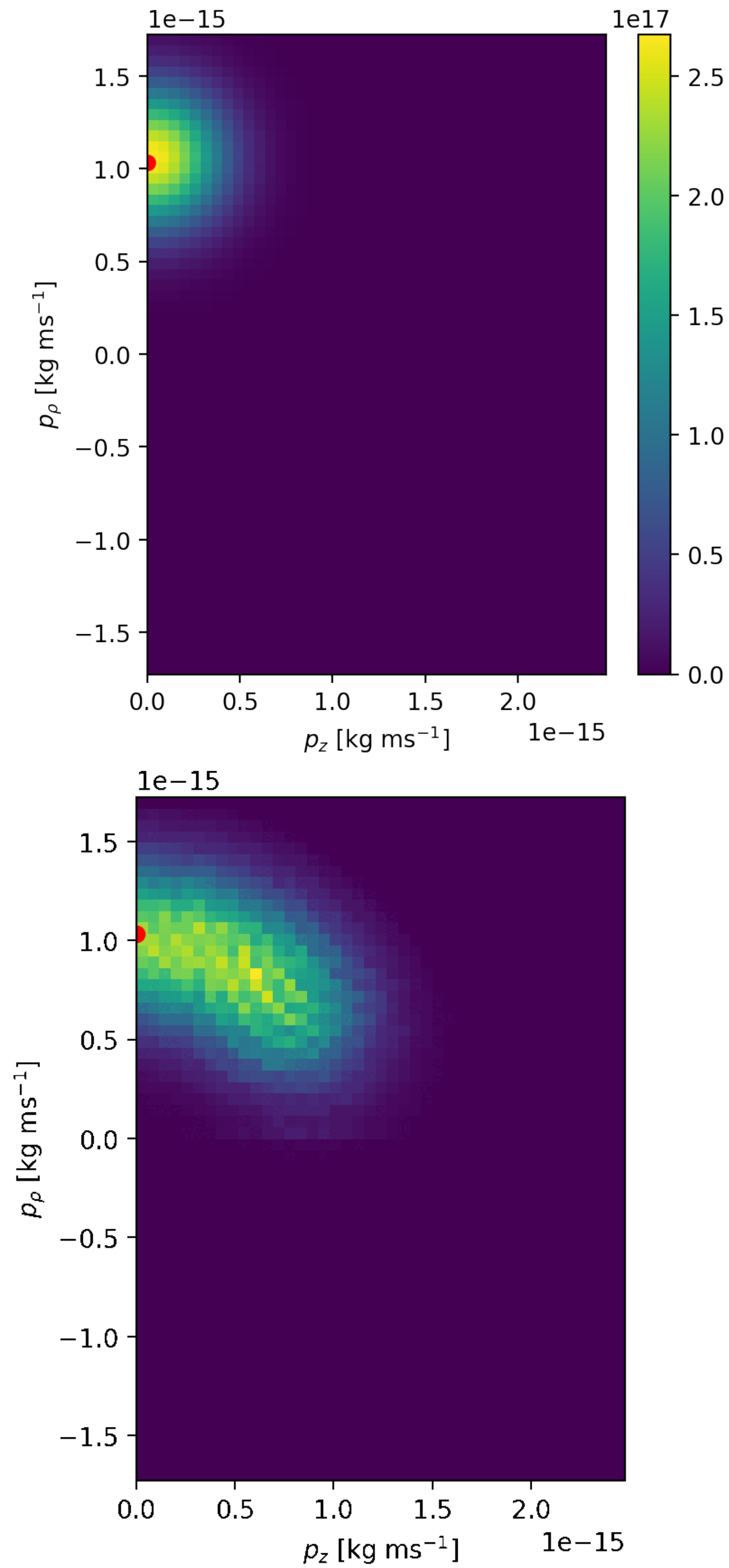

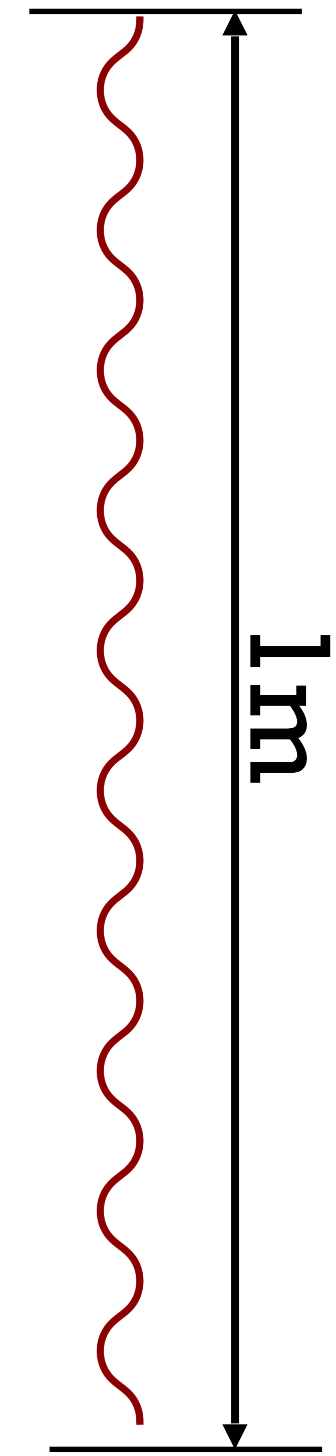

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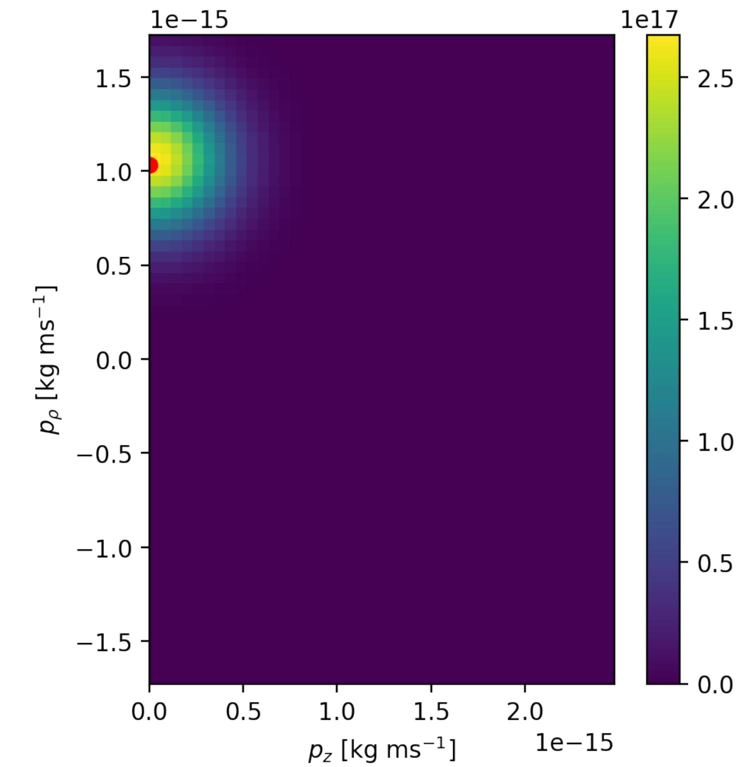
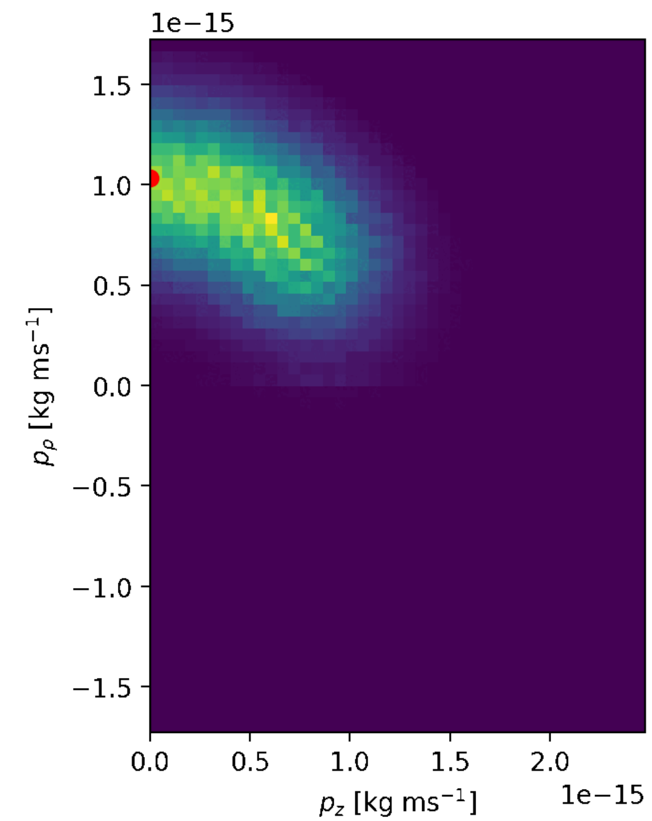
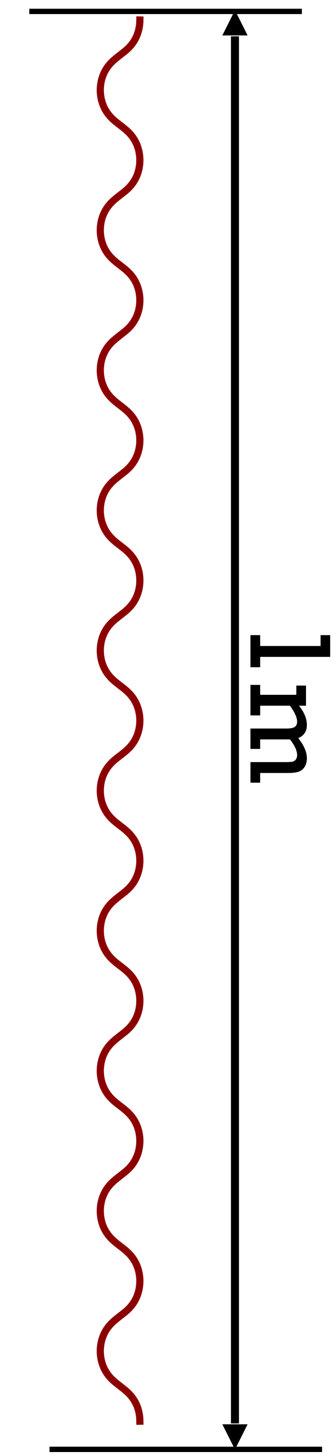


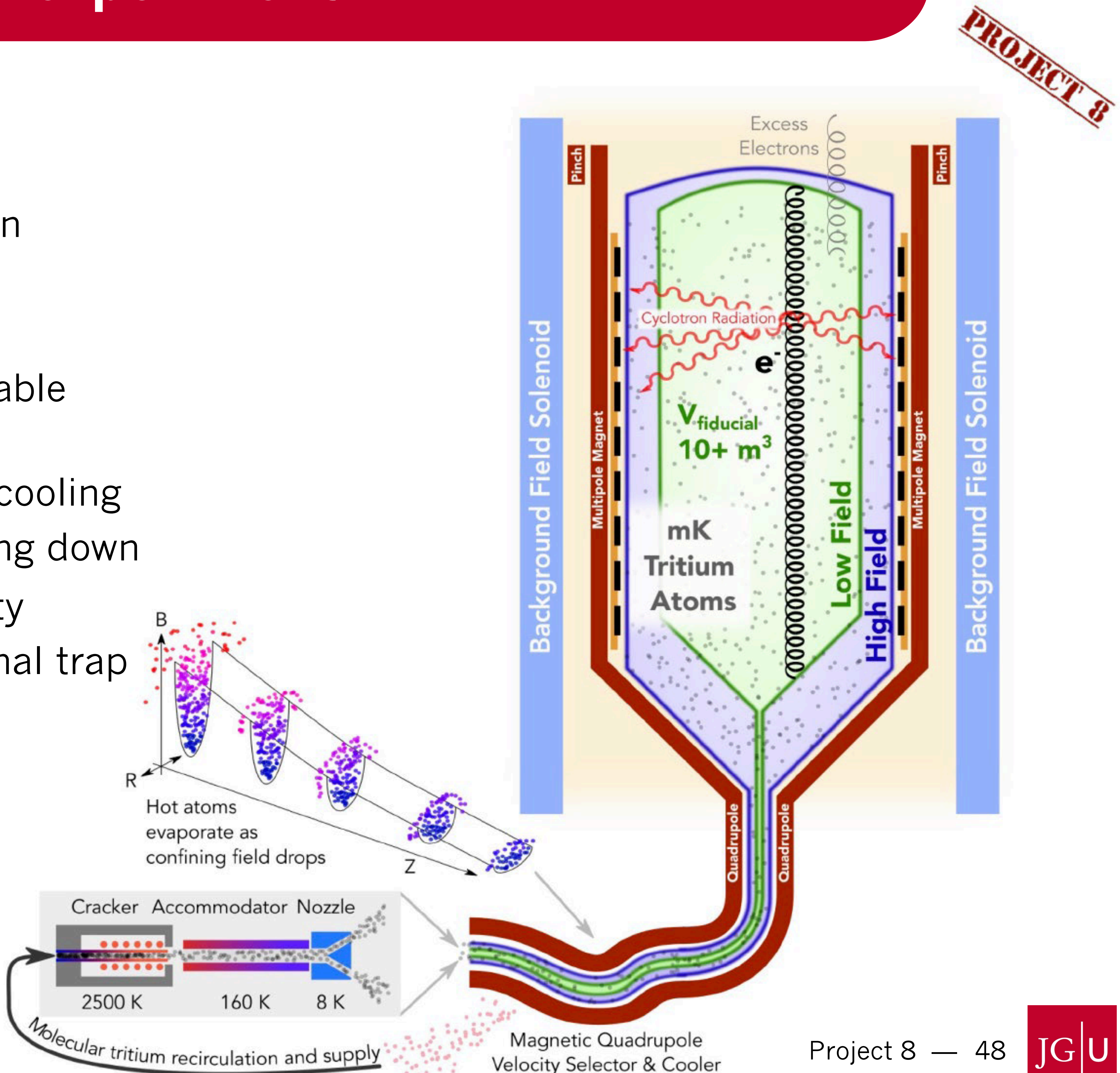




Atomic tritium experiment

Conceptual design

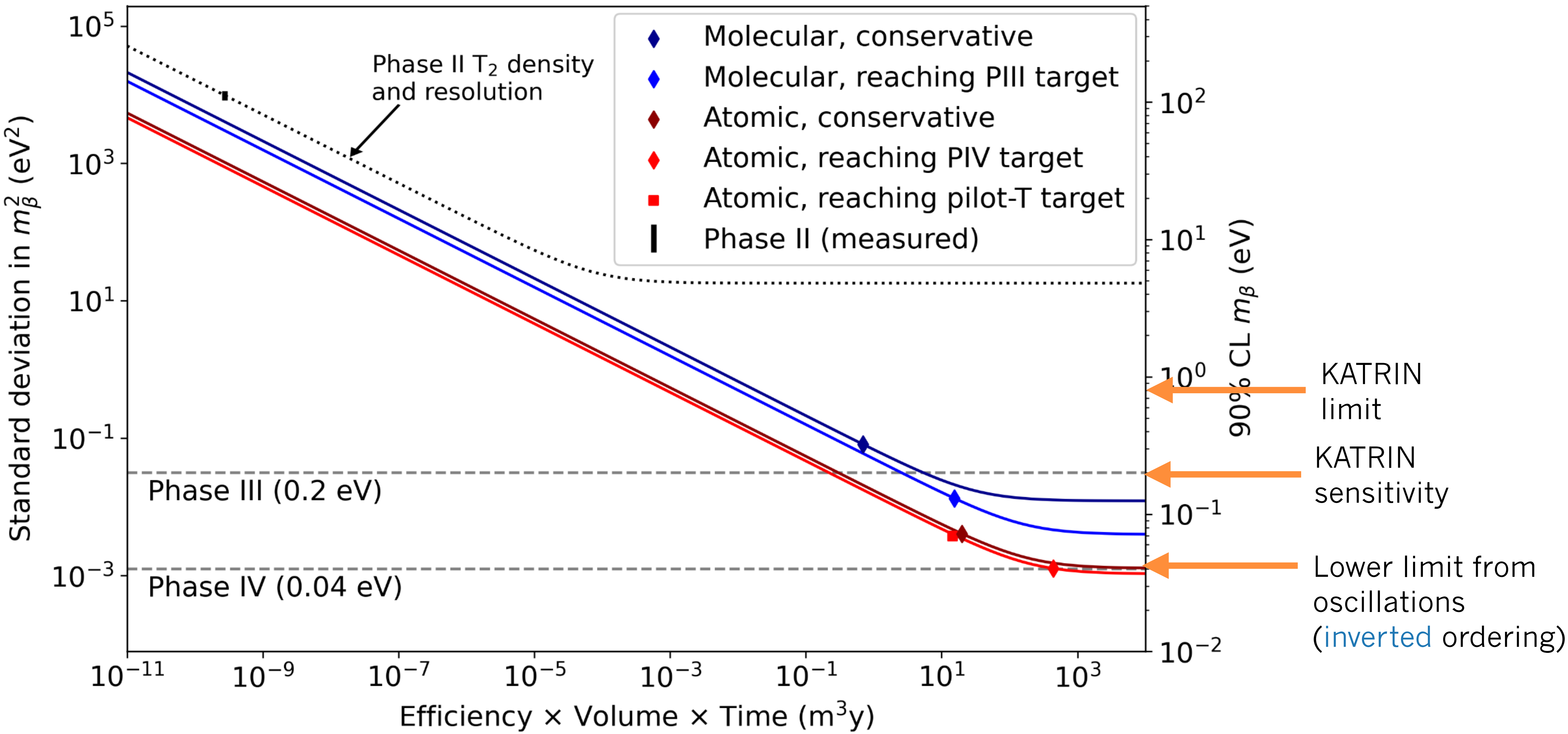
- thermal dissociation
  - $T_2 \rightarrow T$
- accomodation
  - ⌀(K) with acceptable recombination
- evaporative wiggle cooling
  - ⌀(mK) and slowing down
  - high atomic purity
- Magneto-gravitational trap
  - Halbach array



PRiSMA

JG|U

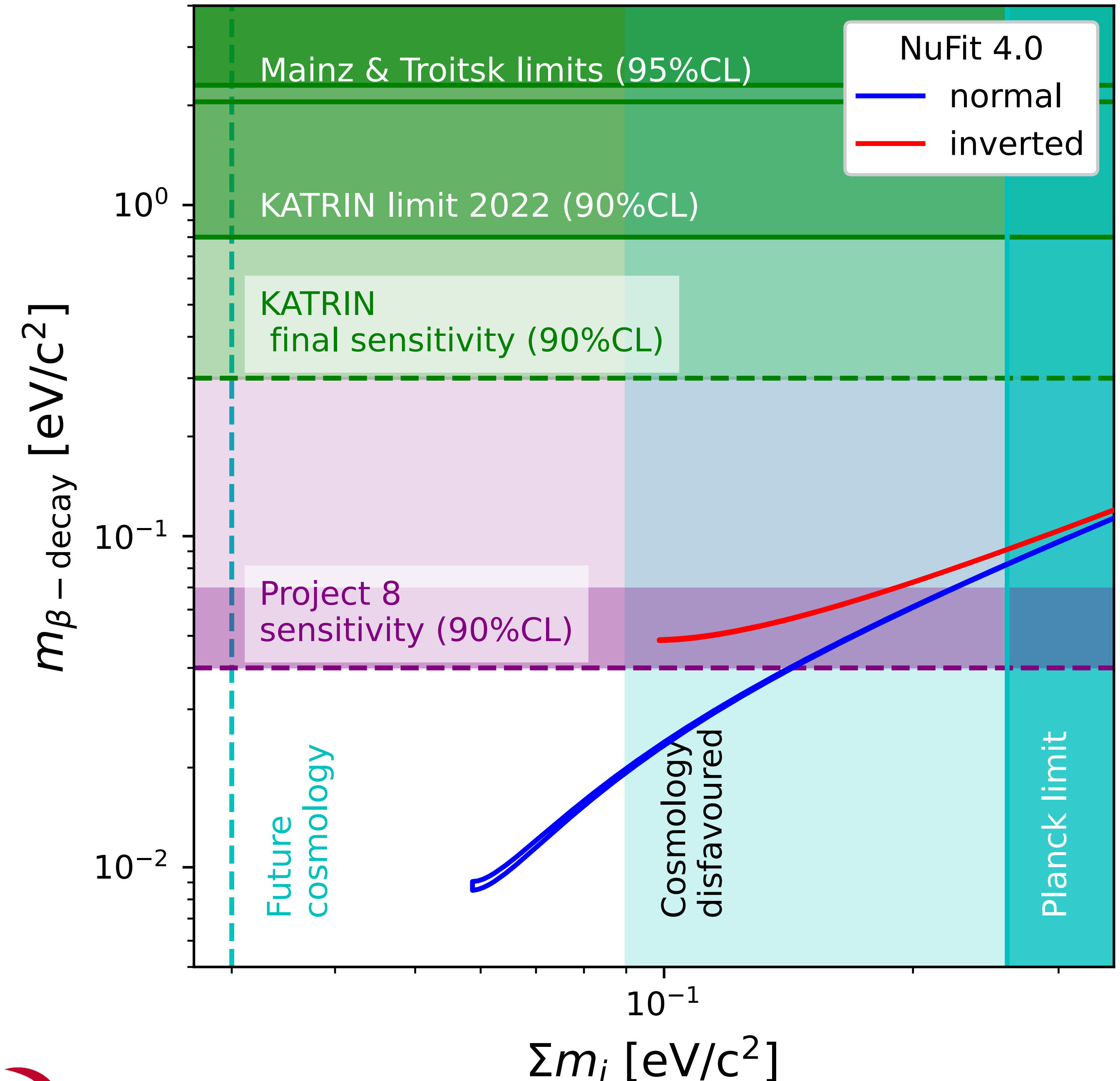
Potential for neutrino mass!



Comparison of methods

Measuring neutrino masses

- approaches are complementary



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

Oscillation experiments

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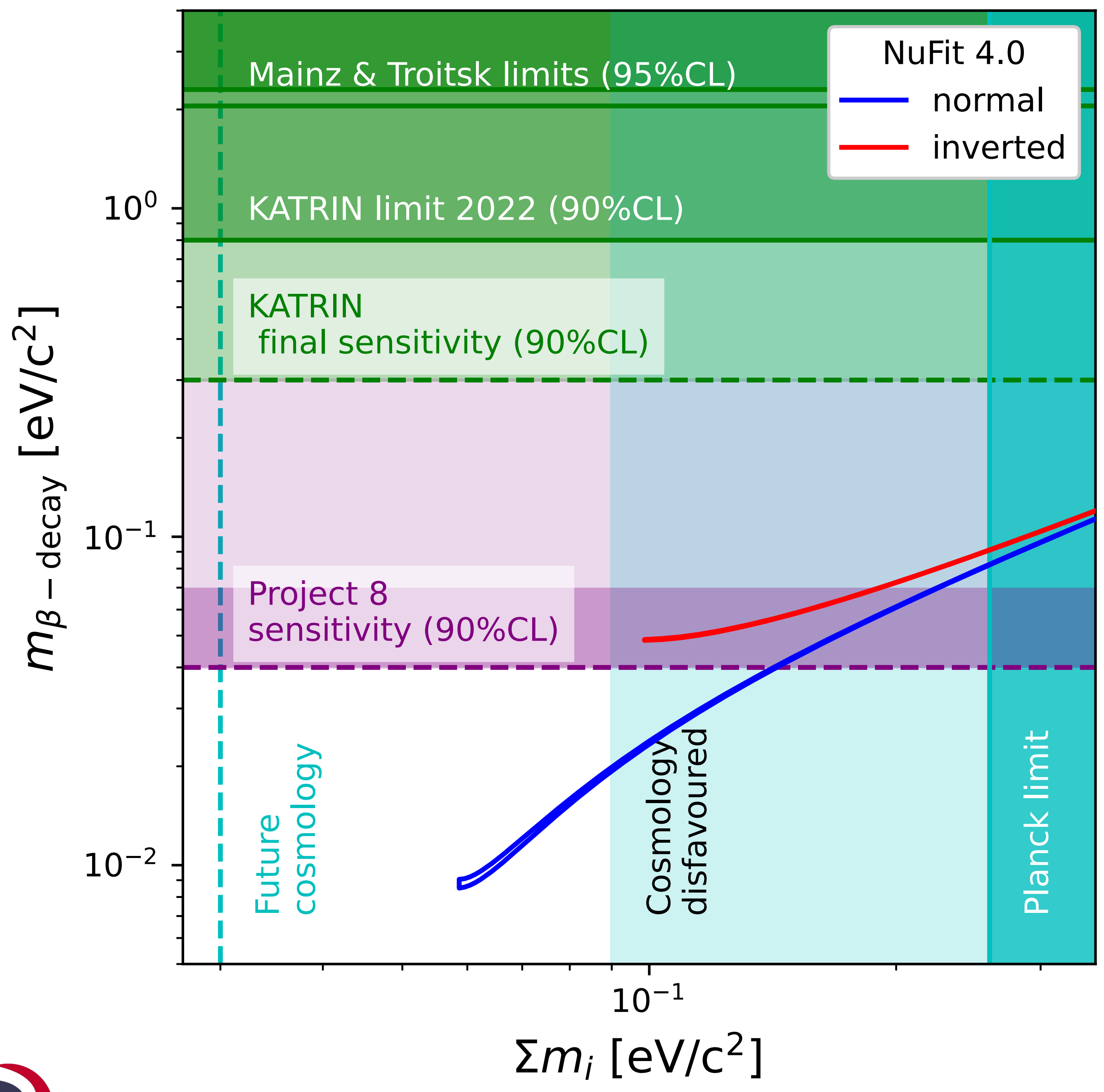

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Oscillation experiments

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

Cosmological measurements

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Measuring neutrino masses

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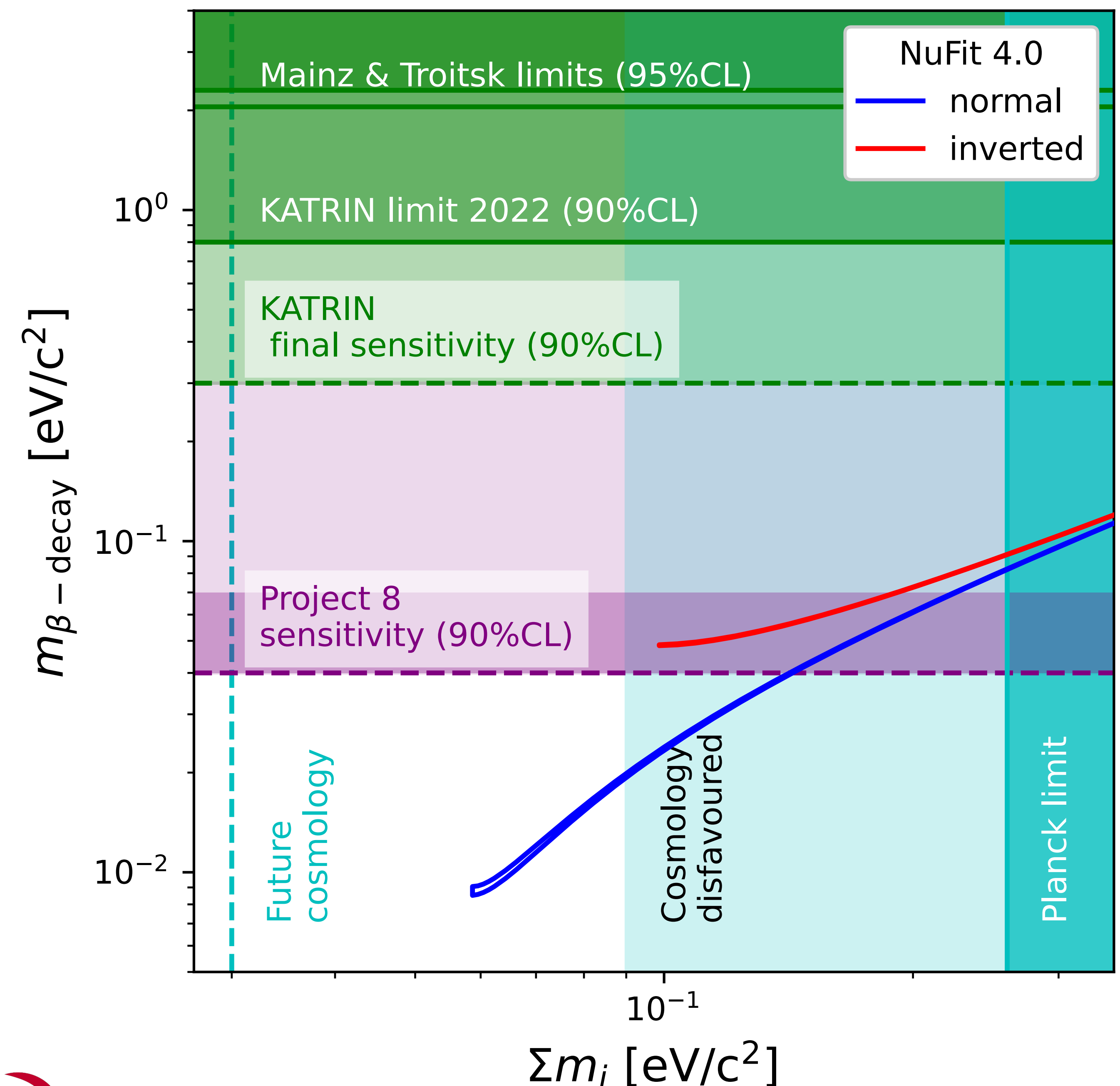

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$$m_{\beta\beta}^2 = \left| \sum_i^{n_\nu} U_{ei}^2 m_i \right|^2$$

$0\nu\beta\beta$ decay experiments

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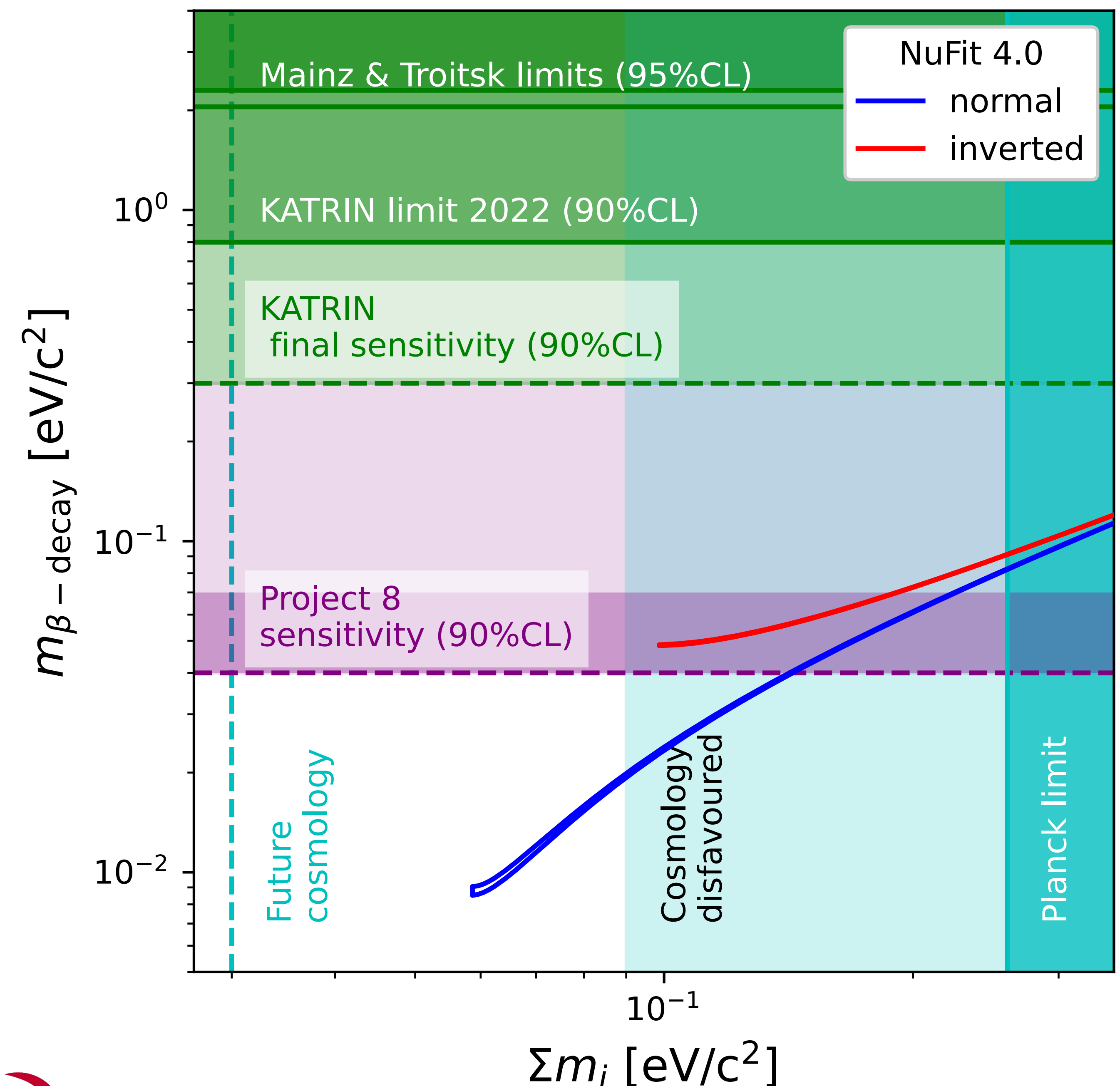

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0νββ decay experiments

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

β-decay experiments

Project 8 collaboration

Thank you!