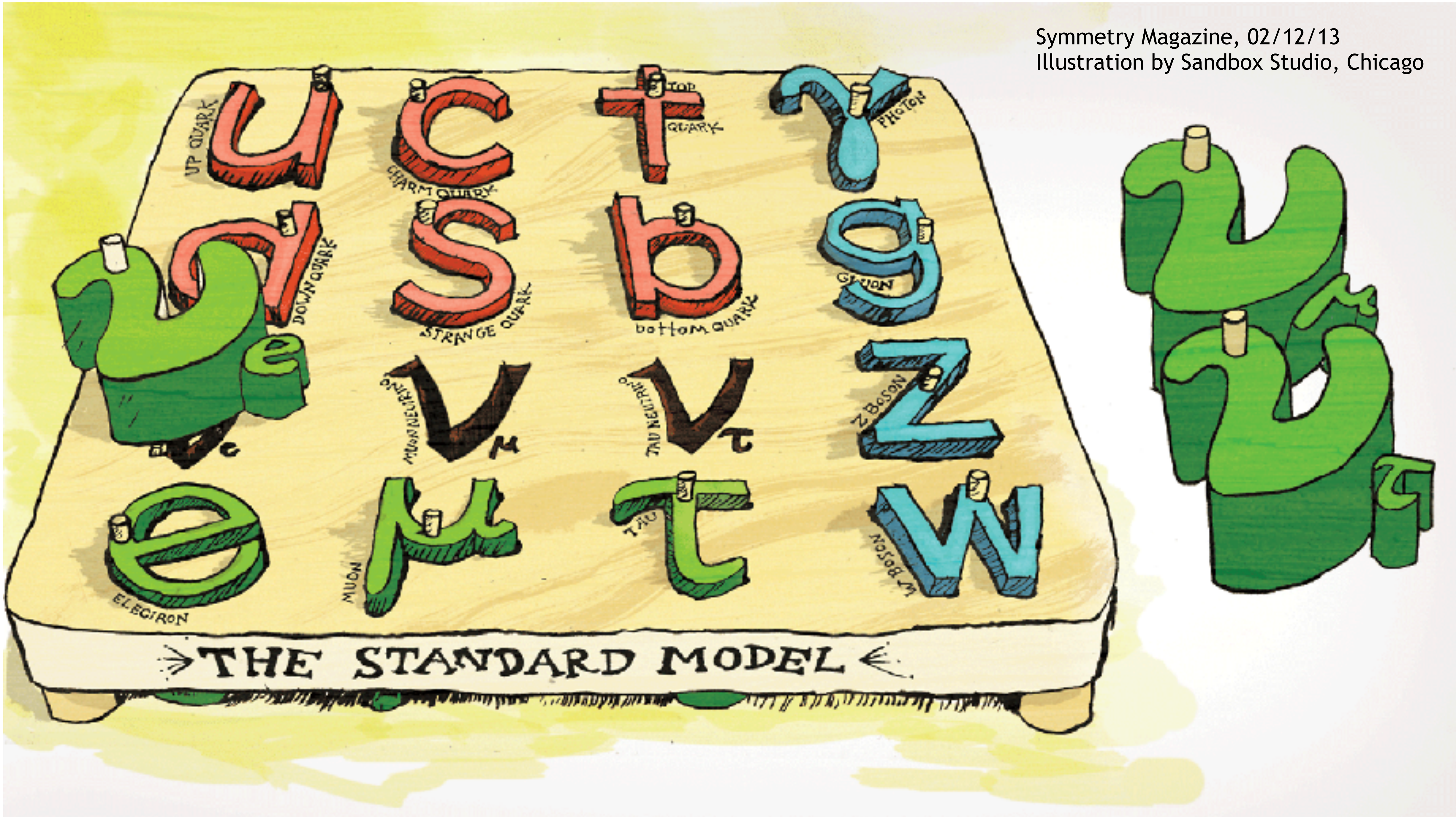
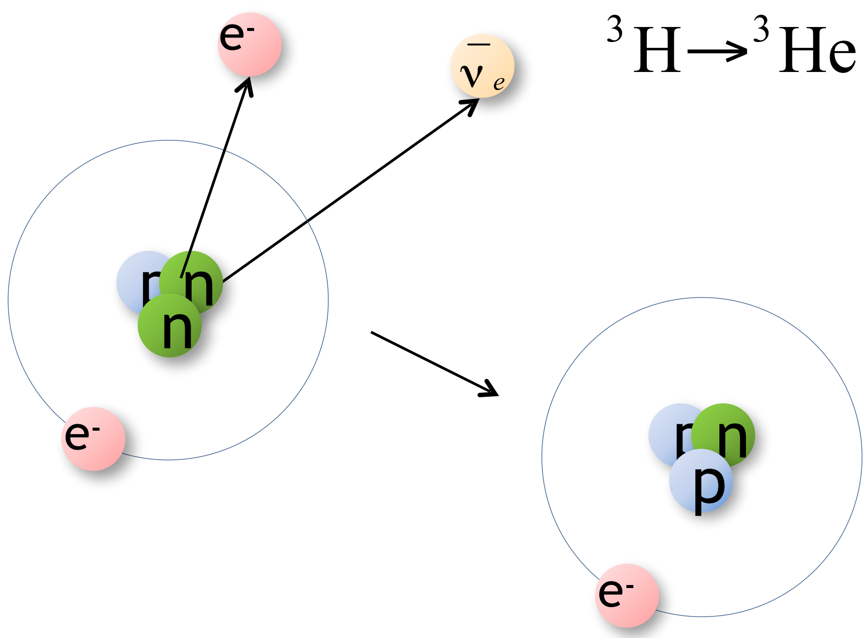
Massive Neutrinos



Symmetry Magazine, 02/12/13
Illustration by Sandbox Studio, Chicago

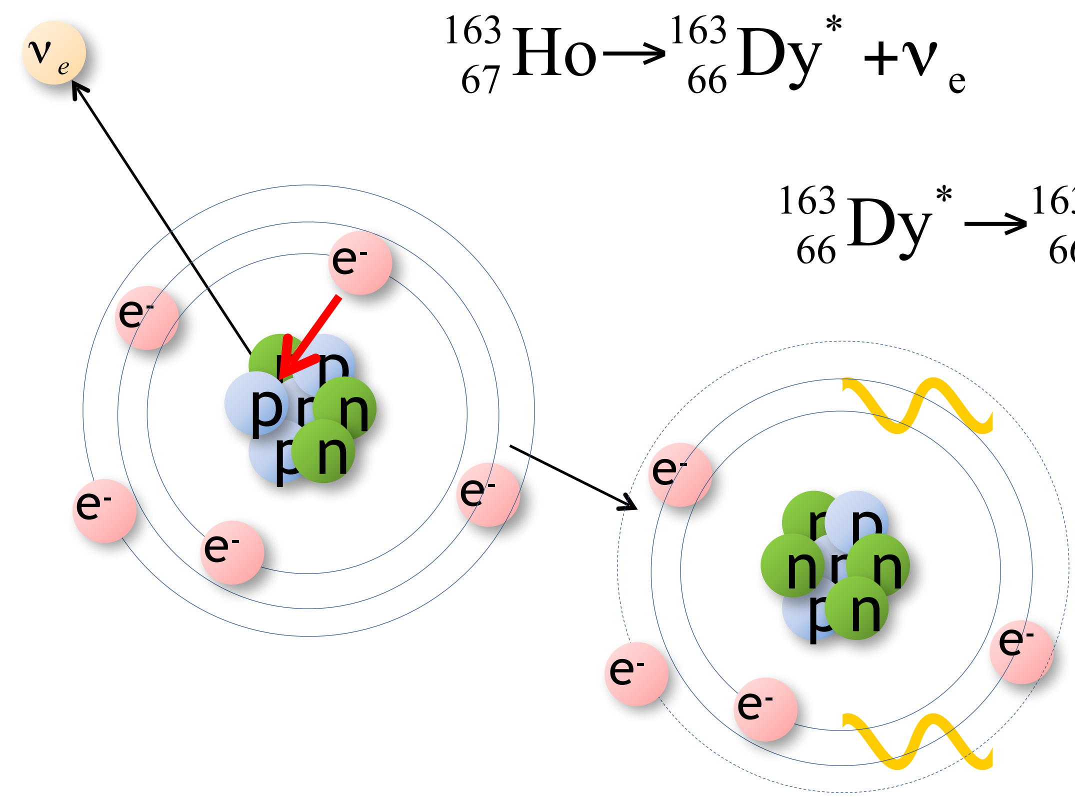
Beta decay and electron capture

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e}$$



$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{e}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{C}$$



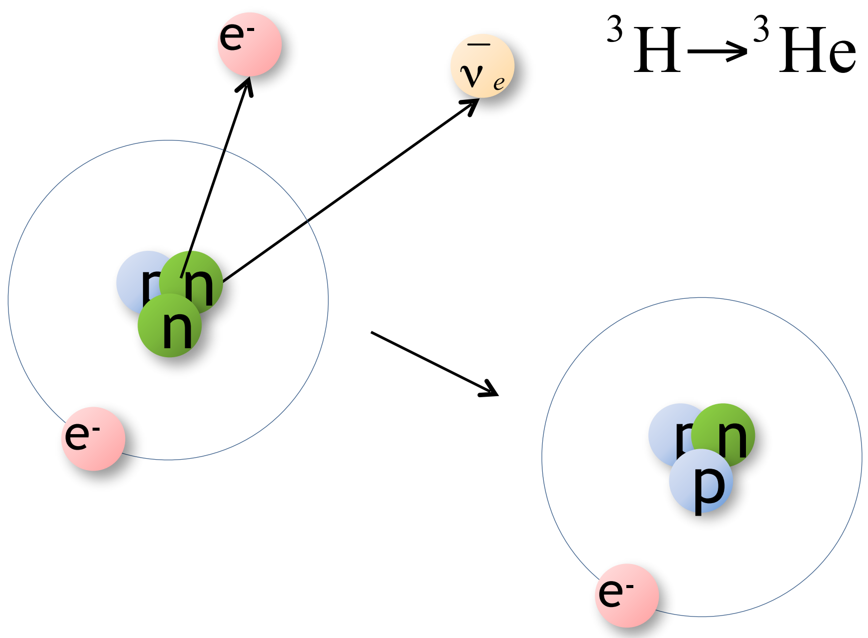
- $\tau_{1/2} \cong$ 12.3 years (4*10^8 atoms for 1 Bq)
- Q_{β} = 18 592.01(7) eV

E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

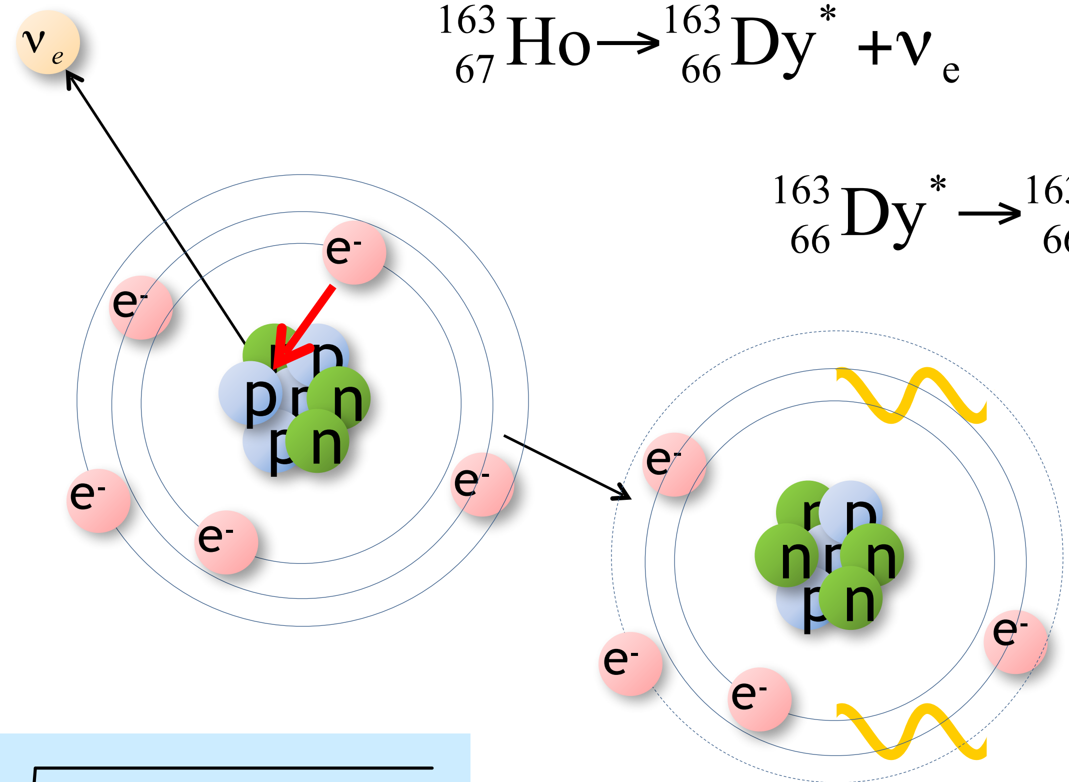
- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = (2.833 ± 0.030^{stat} ± 0.015^{syst}) keV

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Beta decay and electron capture



$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e}$$



$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{e}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

$$\frac{dW}{dE} \propto (Q - E)^{2} \sqrt{1 - \frac{m_{\nu}^{2}}{(Q - E)^{2}}}$$

- $\tau_{1/2} \cong$ 12.3 years (4*10^8 atoms for 1 Bq)
- $\tau_{1/2} \cong$ 4570 years (2*10^11 atoms for 1 Bq)

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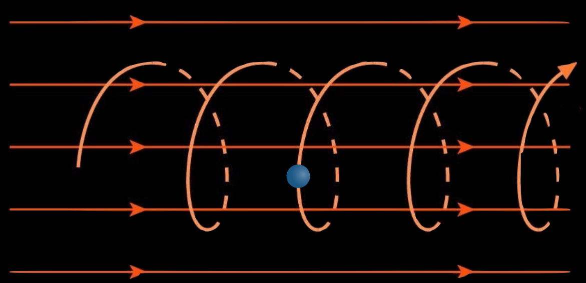
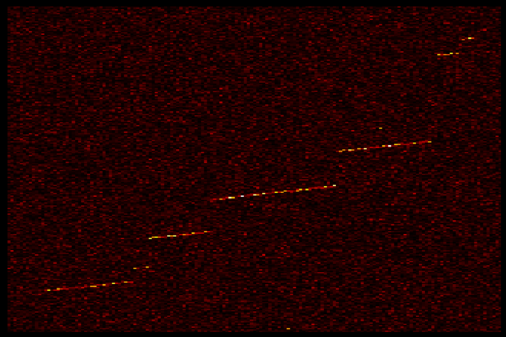
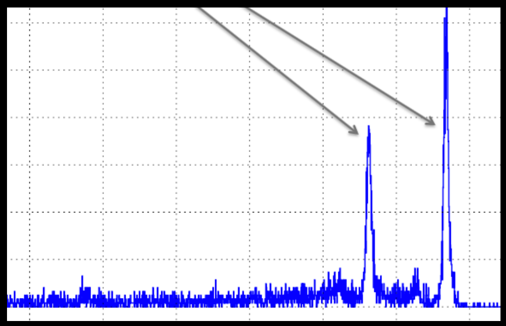
E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

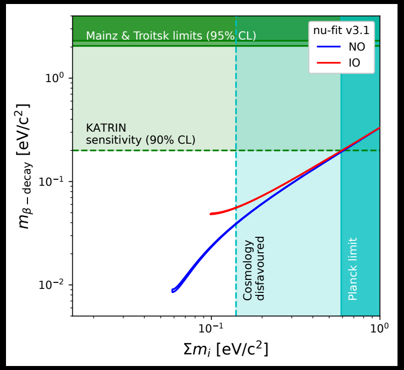
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

PROJECT 8
TOWARDS 40 meV









ALEC LINDMAN FOR SEBASTIAN BÖSER AND THE PROJECT 8 COLLABORATION

SEPTEMBER 18TH 2018 | ASTROPARTICLE PHYSICS IN GERMANY | MAINZ

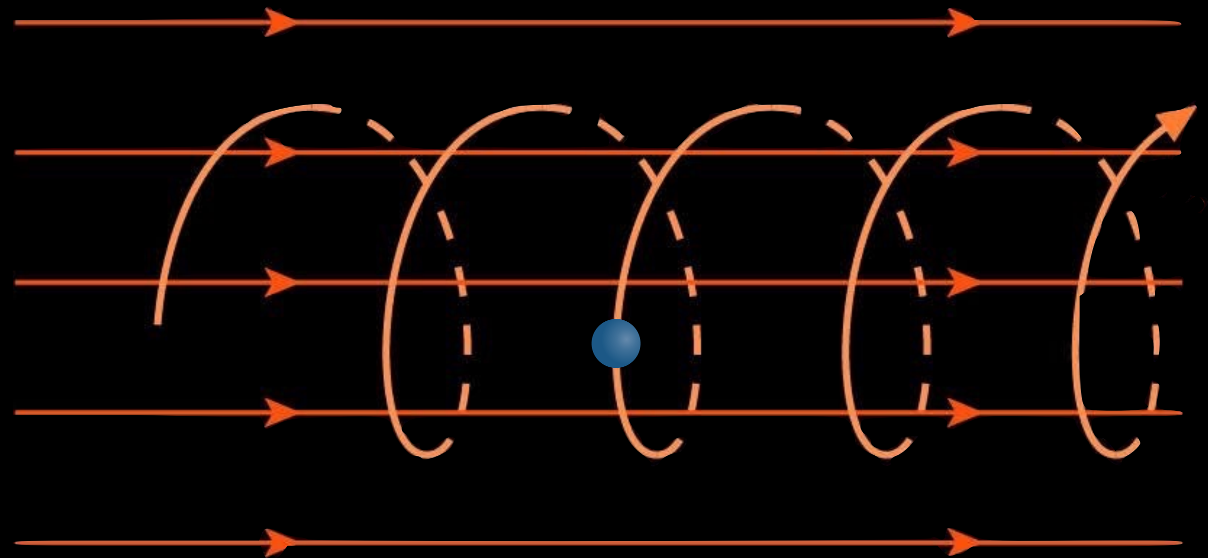
CYCLOTRON RADIATION

Cyclotron radiation

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

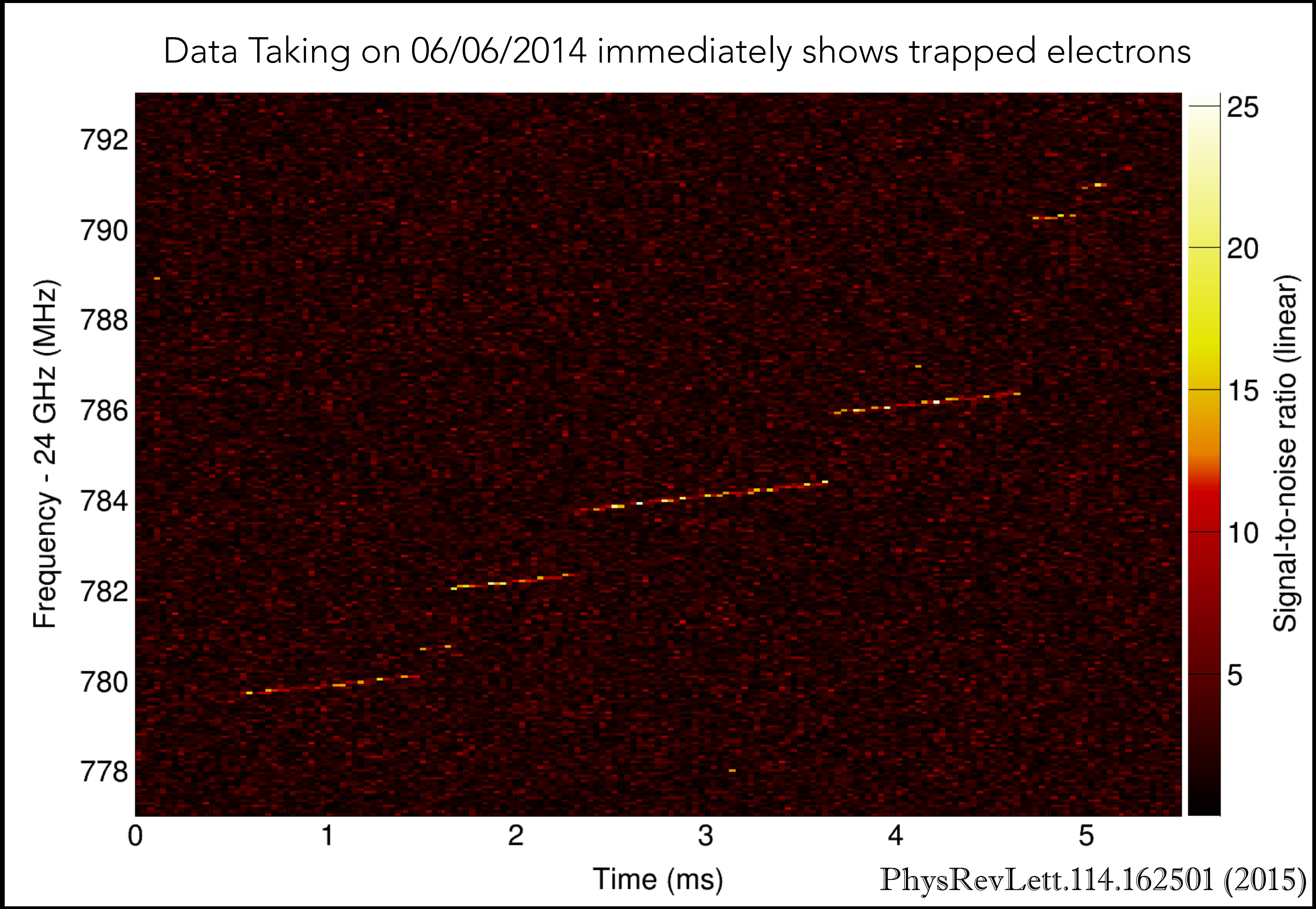
relativistic correction

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



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

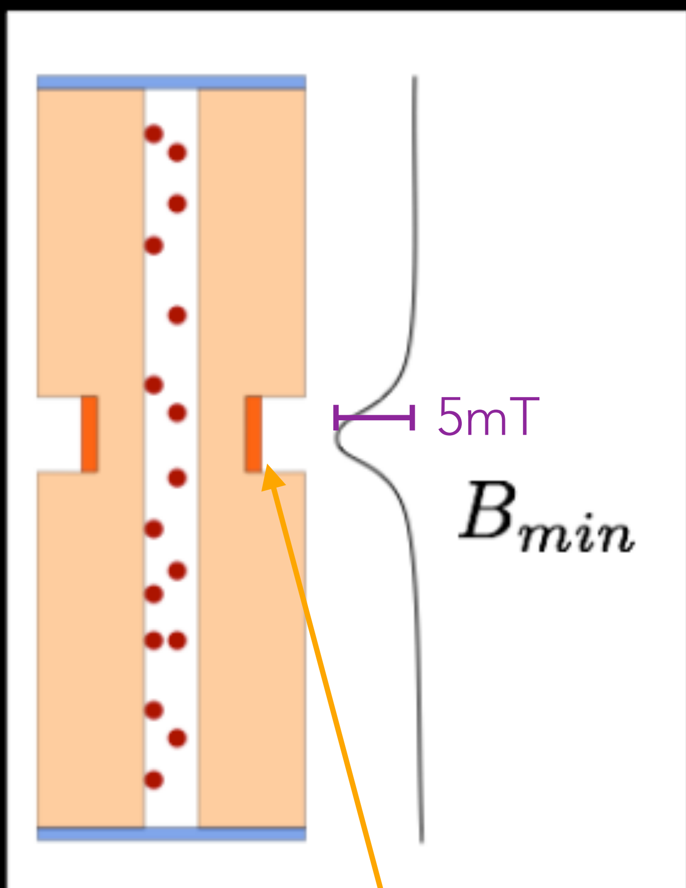
ACTUAL SPECTROGRAM

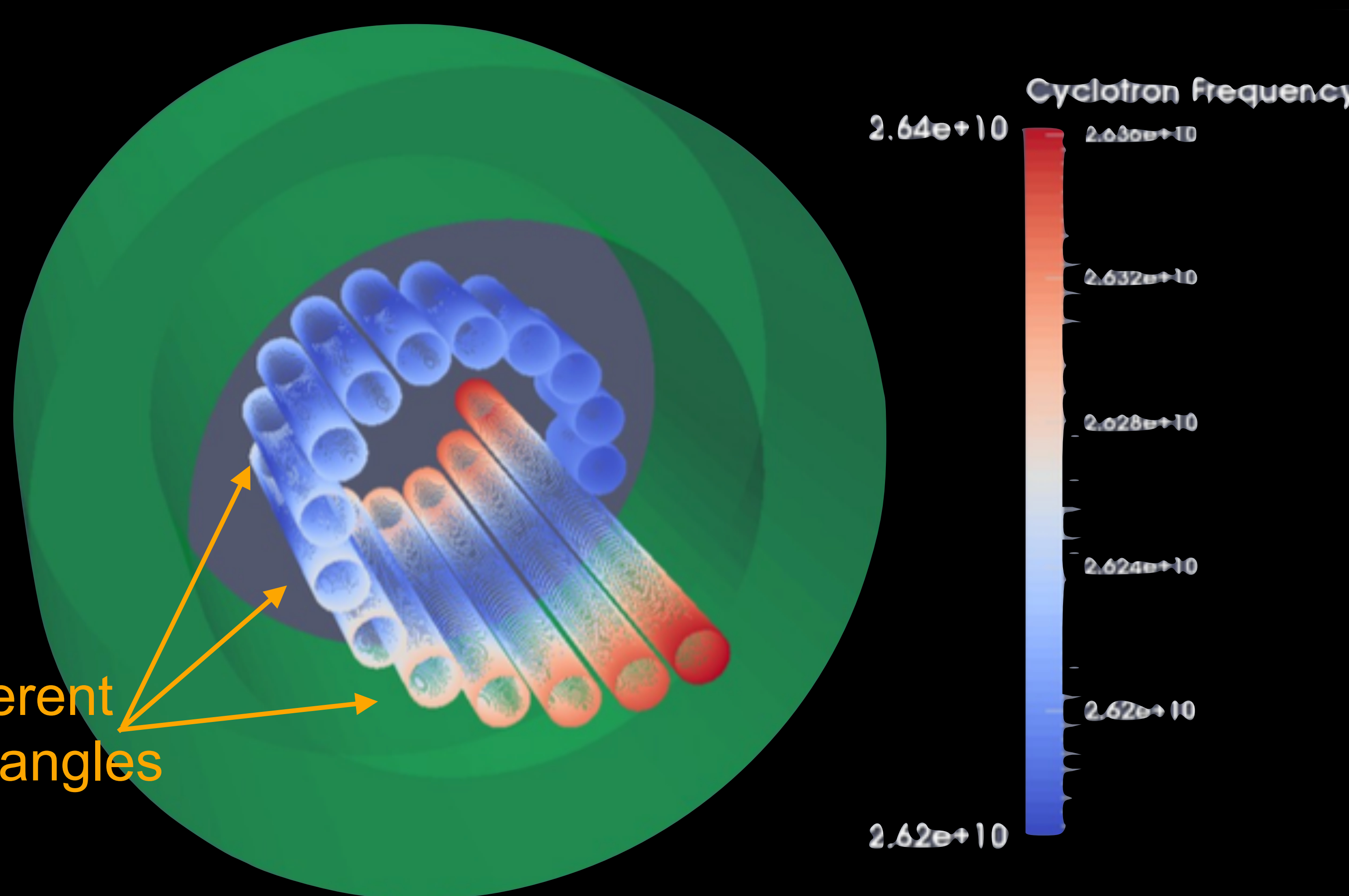


First detection of single-electron cyclotron radiation!

MAGNETIC BOTTLE

Harmonic trap → $f_\gamma = \frac{1}{2\pi}\frac{e\langle B\rangle}{m_e + E_{\text{kin}}}$ with $\langle B\rangle = B_{\min}\left(1 + \frac{\cot^2\theta}{2}\right)$





Frequency resolution limited due to field homogeneity!

PHASE II GAS CELL

Circular waveguide

- recover signal by better matching polarization (TE_{11} mode)
- larger volume

CaF2 windows

- tritium compatible

5 trap coils

- greater flexibility of trap configureation

Off-axis ESR magentometry

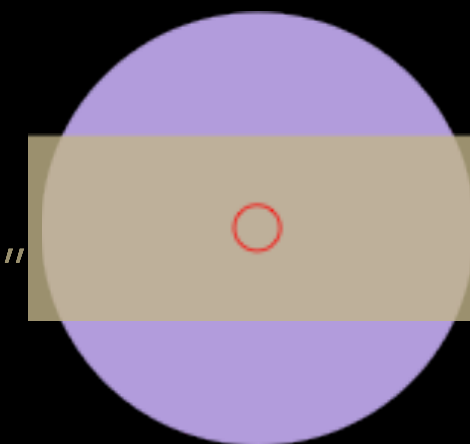
- higher precision BDPA ESR agent
  → in-situ monitoring of trapping fields

Tickler port

- in-situ RF calibration

Waveguide short

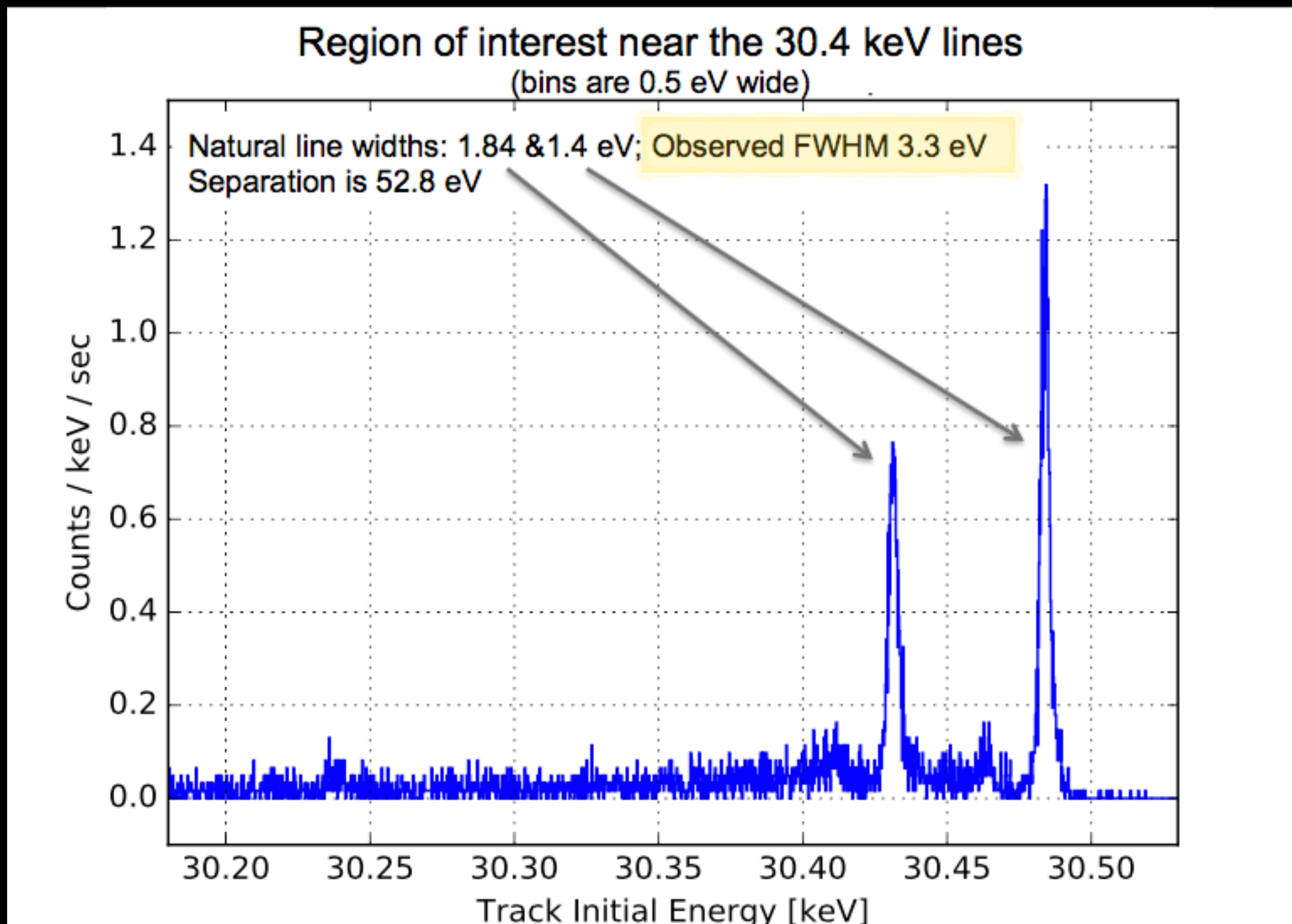
- recover signal from reflection



Phase I
0,17″ x 0,42″

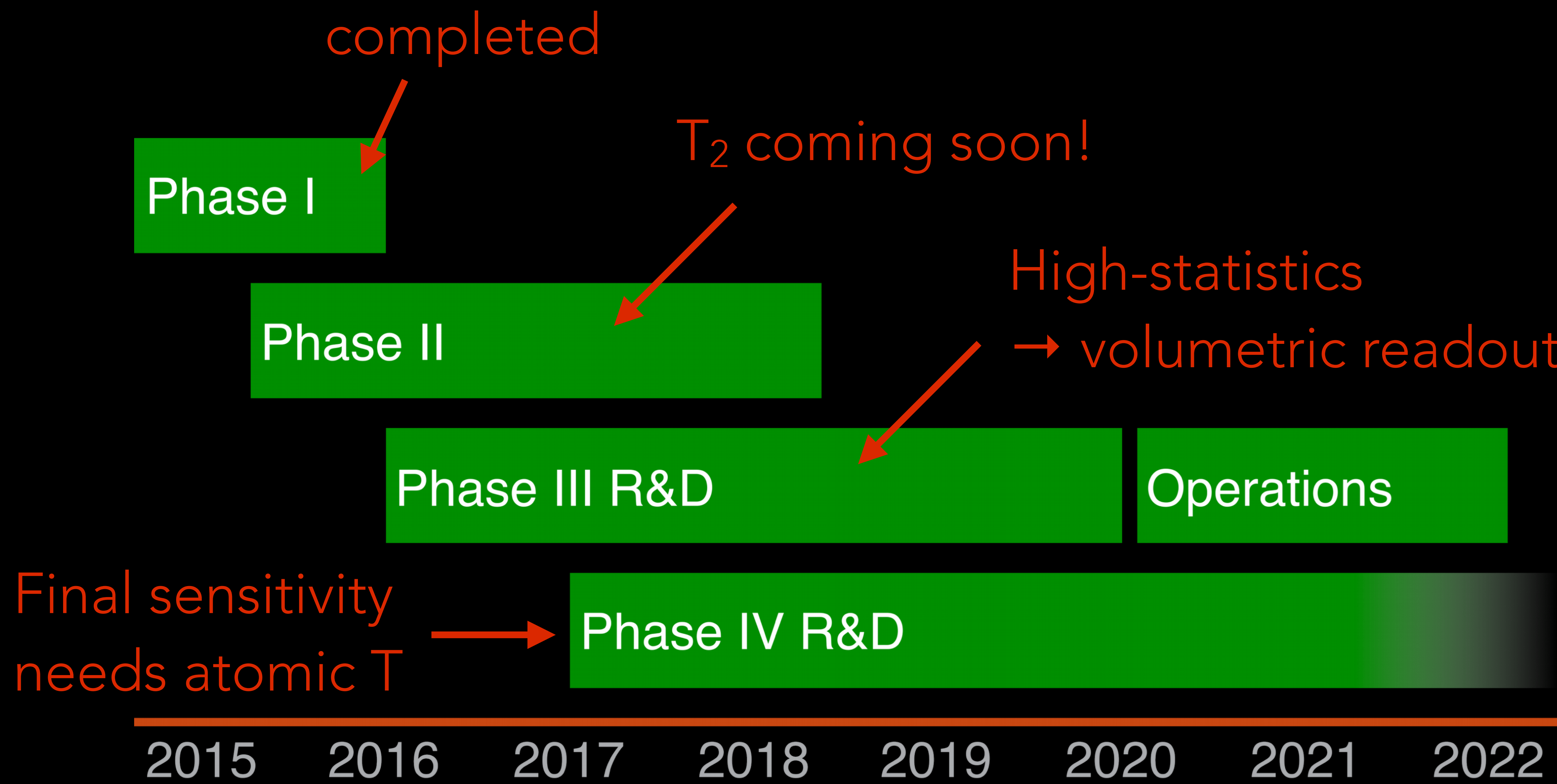
Phase II
⌀ 0.396″

CRES — CYCLOTRON RADIATION EMISSION SPECTROSCOPY

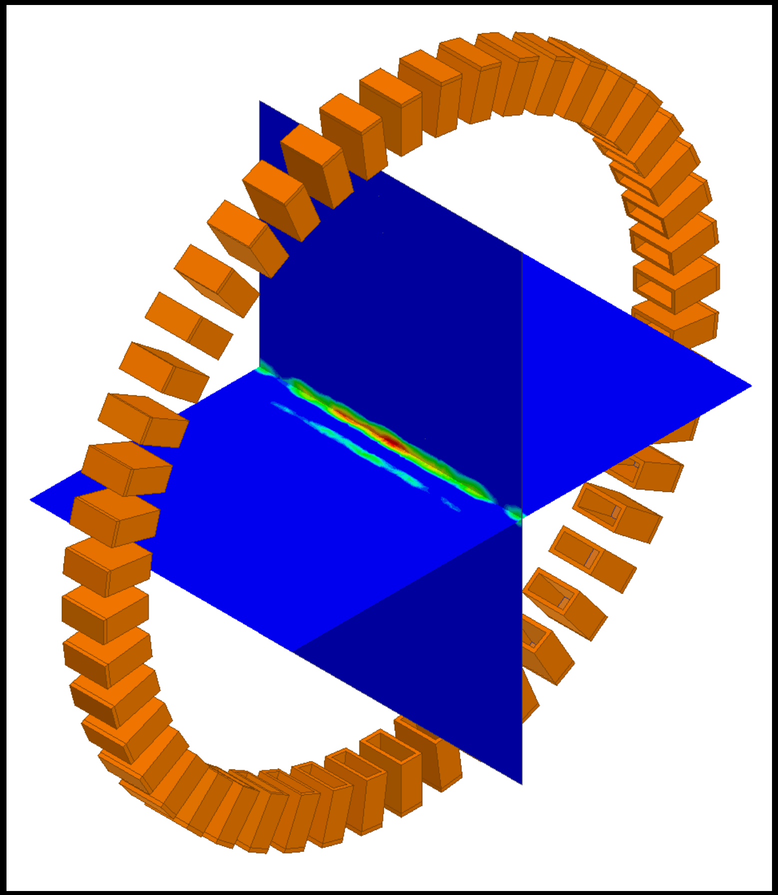


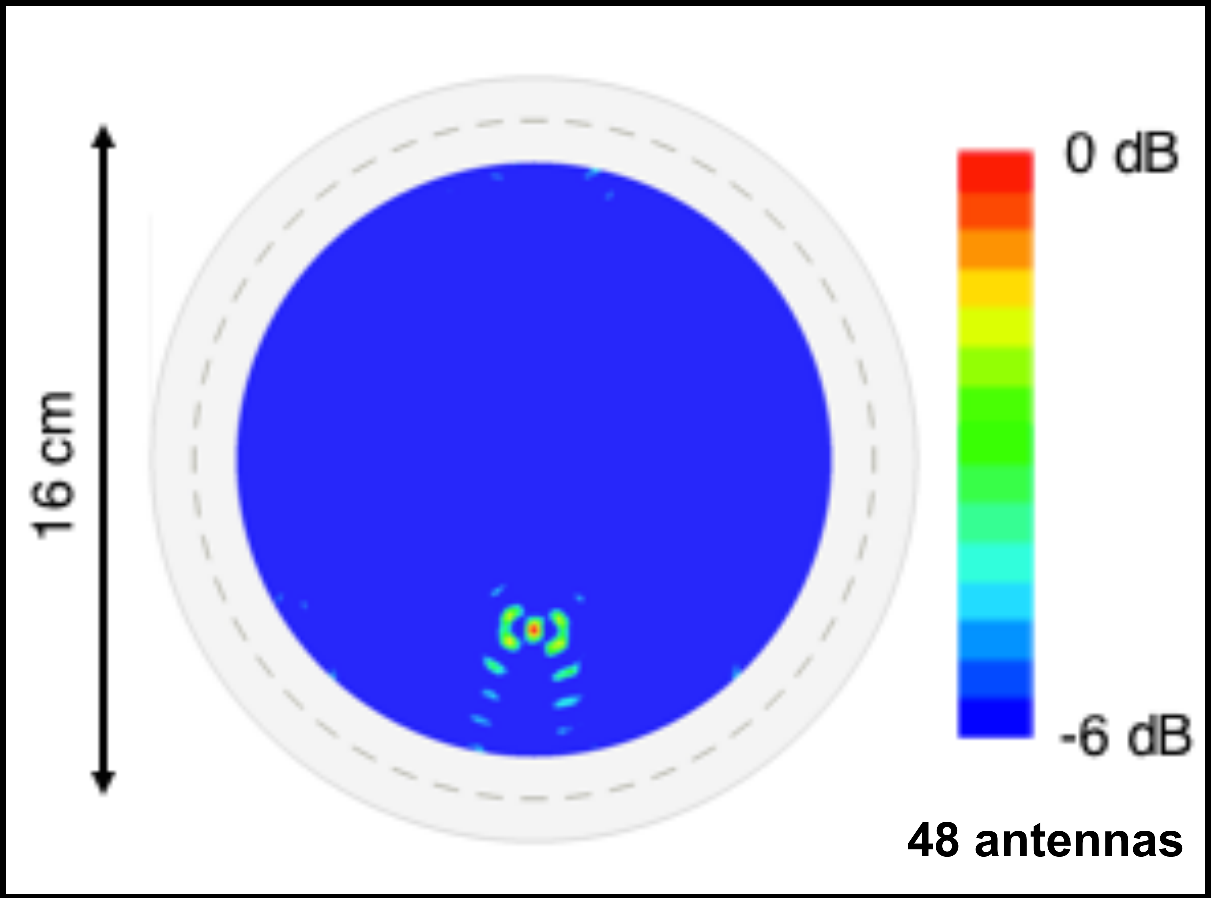
P8 Collaboration, J. Phys. G 44 (5) 2017

WHAT NEXT?


completed
Phase I
T_2 coming soon!
Phase II
High-statistics
→ volumetric readout
Phase III R&D
Operations
Final sensitivity
needs atomic T
Phase IV R&D
2015
2016
2017
2018
2019
2020
2021
2022

PHASE III - PHASED ARRAY READOUT



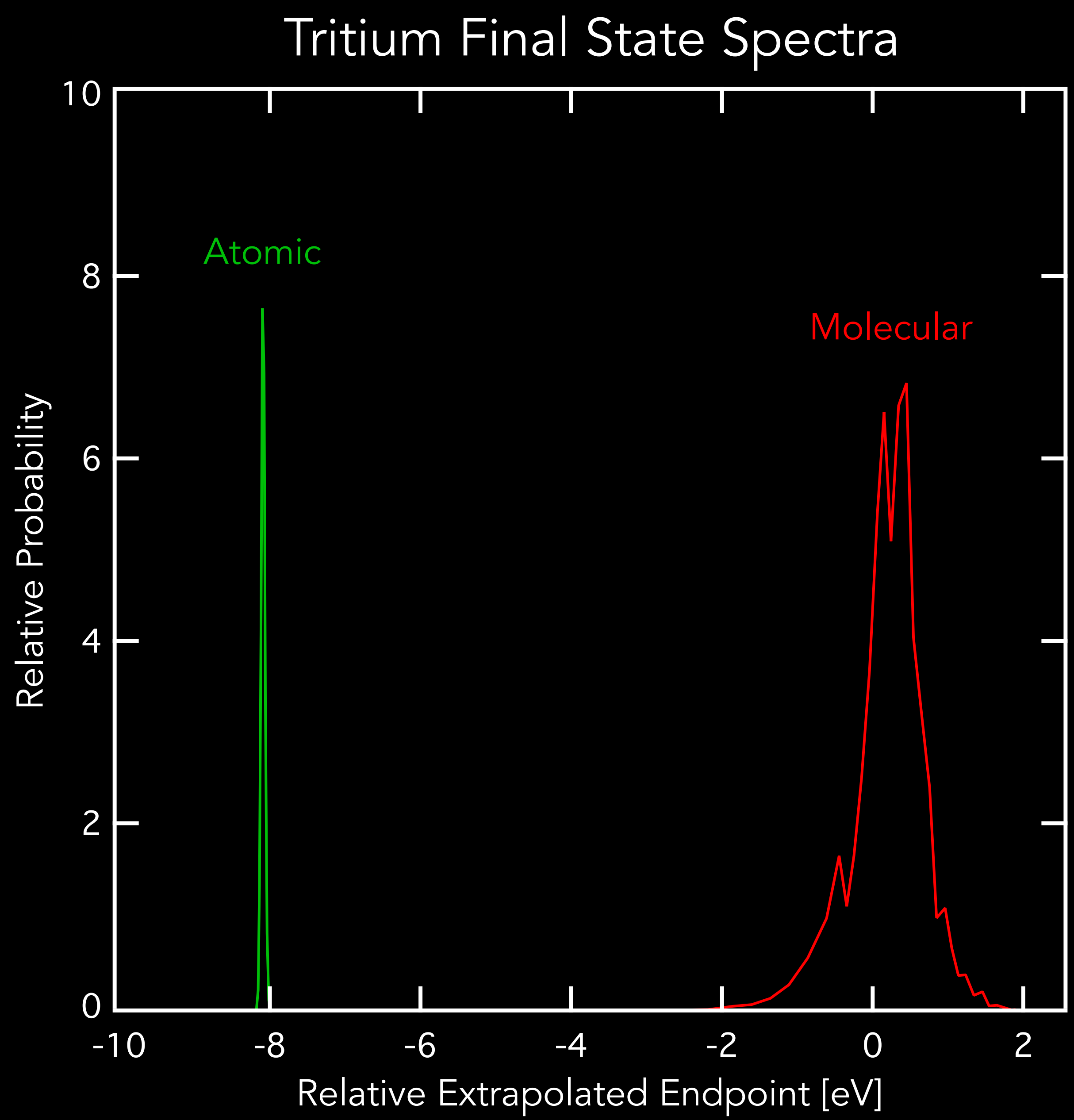


Example antenna configuration and vertex resolution being modeled

- Volumetric readout

  → Study phased array antenna configurations

MOLECULAR TRITIUM LIMITATIONS



Data: Saenz (2000)

Molecular excitations in daughter molecule

- blur tritium endpoint

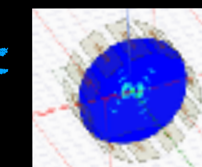
→ fundamental limit to measurement of ν-mass

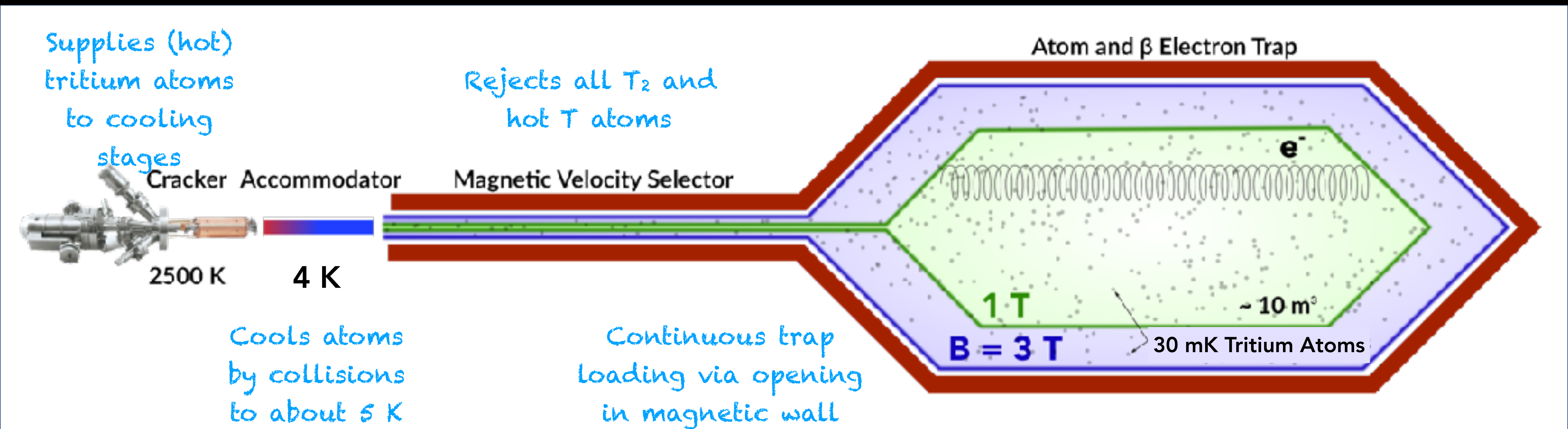
Need atomic tritium for ultimate experiment!

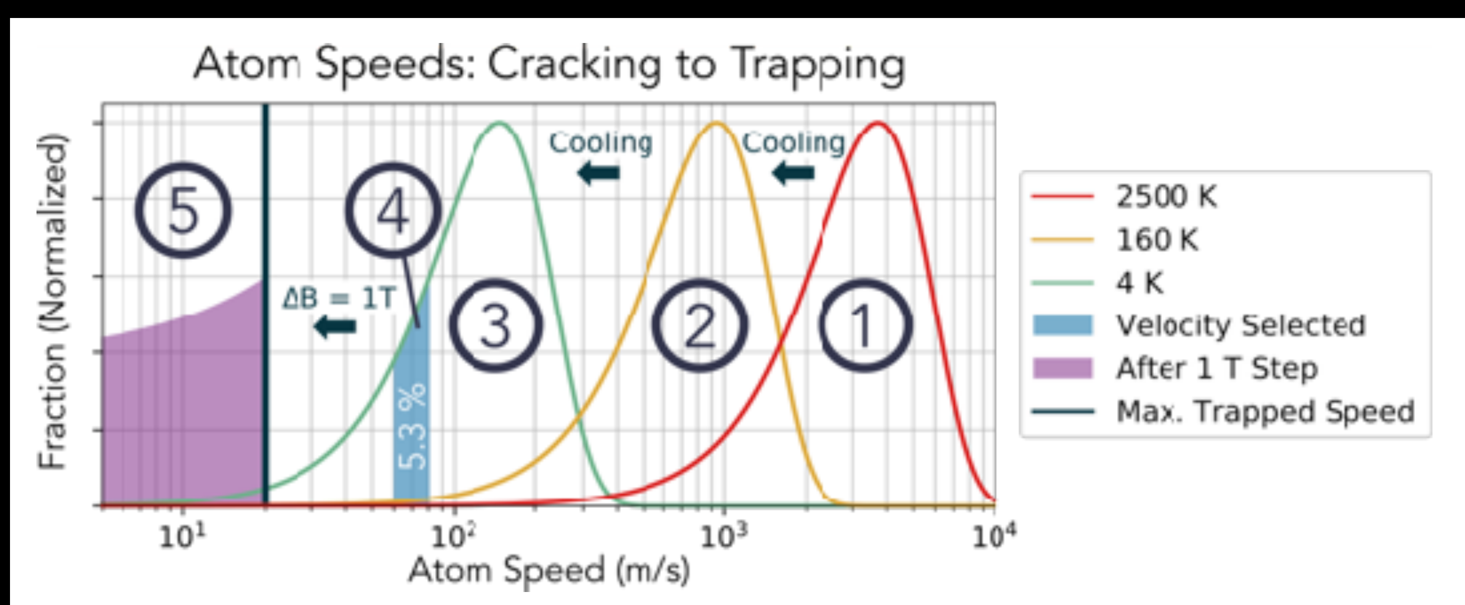
Phase IV

- 10^{18} atoms in the fiducial volume (10^9 Bq decay rate)
- Atom density: 10^{12} cm^{-3}

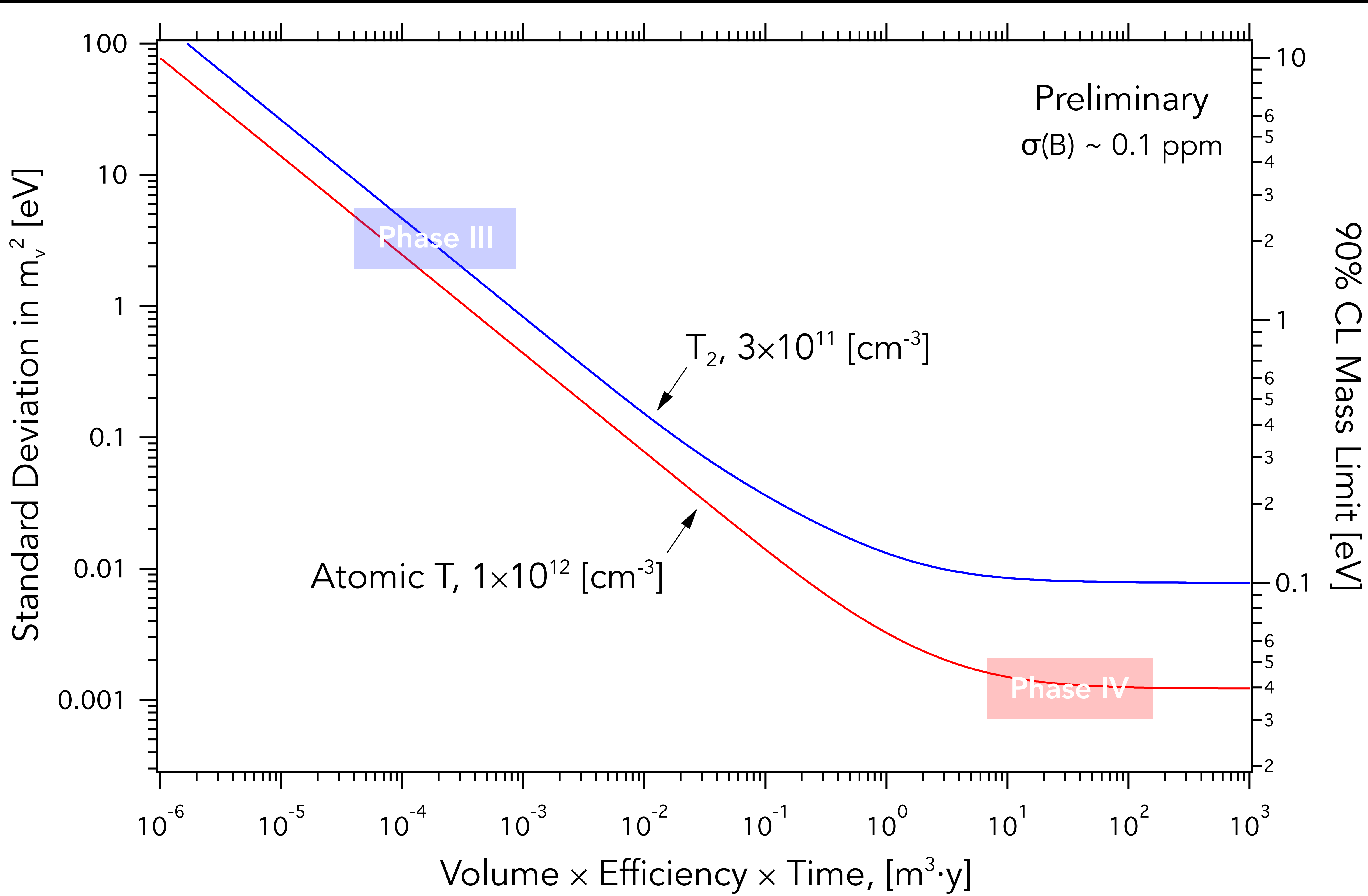
1 T solenoid and antennas not shown







Project 8: ν Mass Reach



2 eV

40 meV

^{3}H based experiments

❖ KATRIN - Karlsruhe Tritium Neutrino Experiment

Main ideas:
- high activity source: 10^{11} e^{-}/s
- high resolution MAC-E filter to select electrons close to the end point
- count electrons as function of retarding potential
  → integral spectrum

❖ Project8

Main ideas:
- Source = detector: 10^{11} – 10^{13} $^{3}H_2$ molecules /cm^3
- Use cyclotron frequency to extract electron energy
- Differential spectrum

Future Project

❖ PTOLEMY - Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

Main ideas:

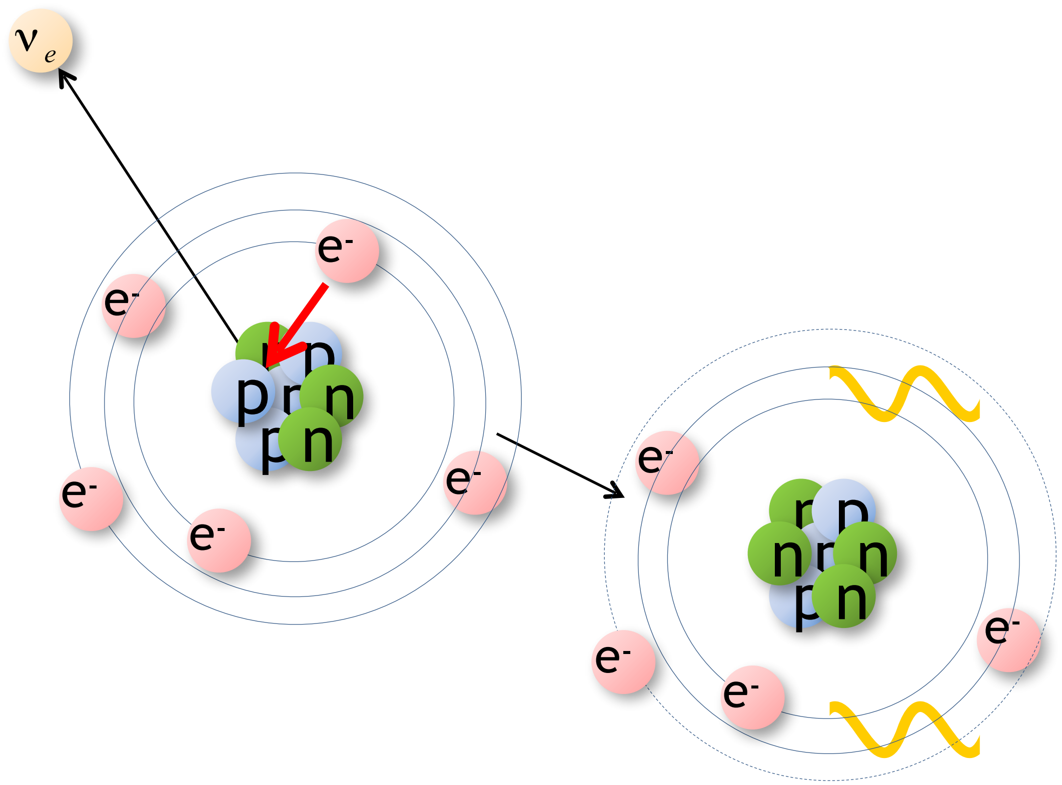
large area tritium source: 100 g atomic ^{3}H

MAC-E Filter methods

RF tracking and time-of-flight systems

cryogenic calorimetry → differential spectrum

^{163}Ho electron capture



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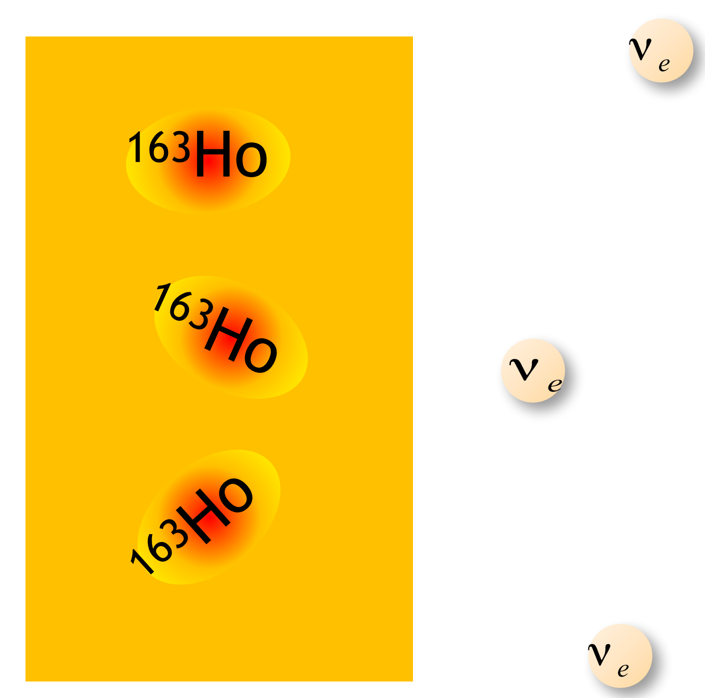
Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)

Atomic de-excitation:
- X-ray emission
- Auger electrons
- Coster-Kronig transitions

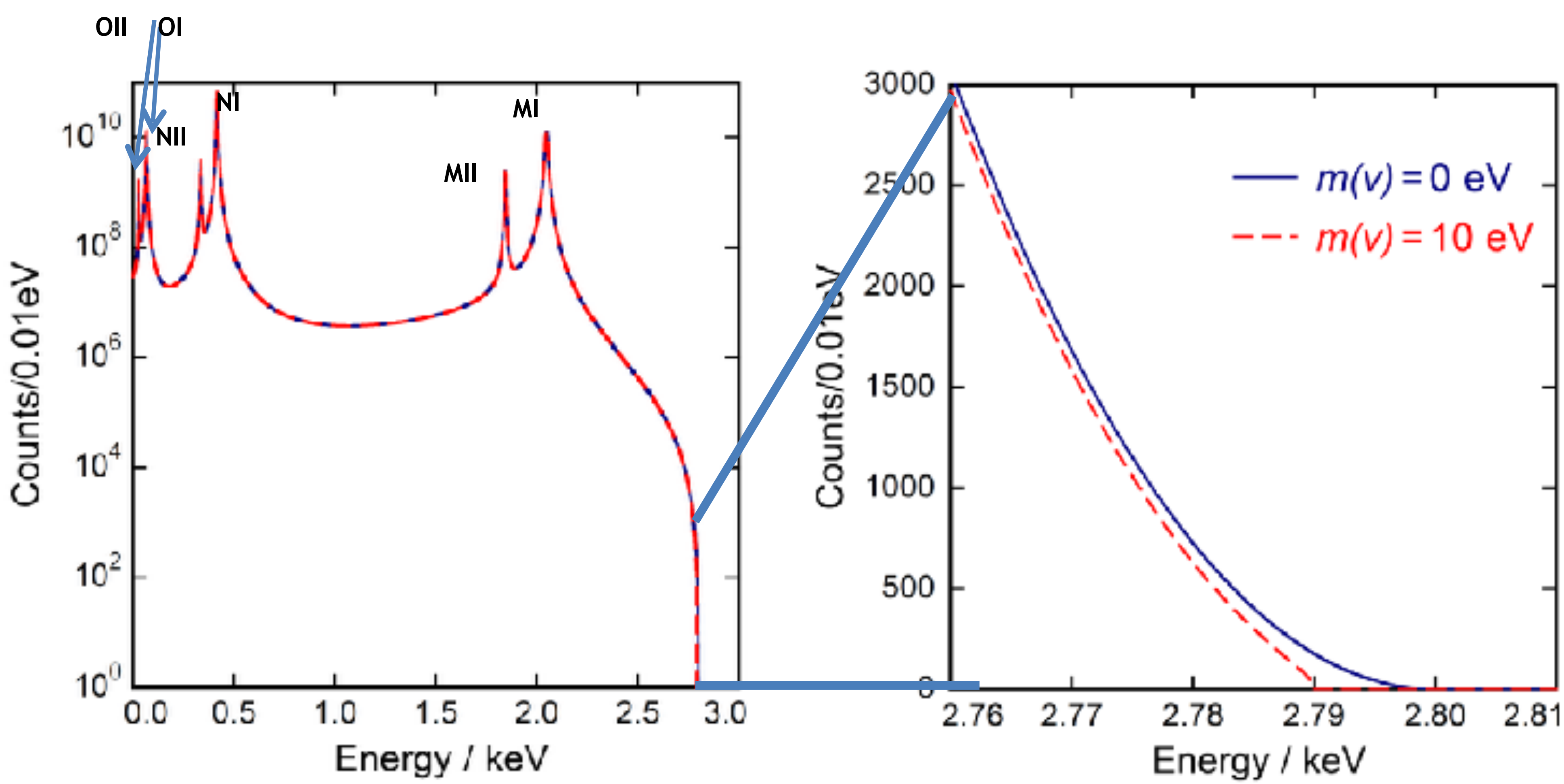
Calorimetric measurement



A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

^{163}Ho calorimetrically measured spectrum

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\ 2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\ 2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\ 2}}{4}}$$



^{163}Ho calorimetrically measured spectrum

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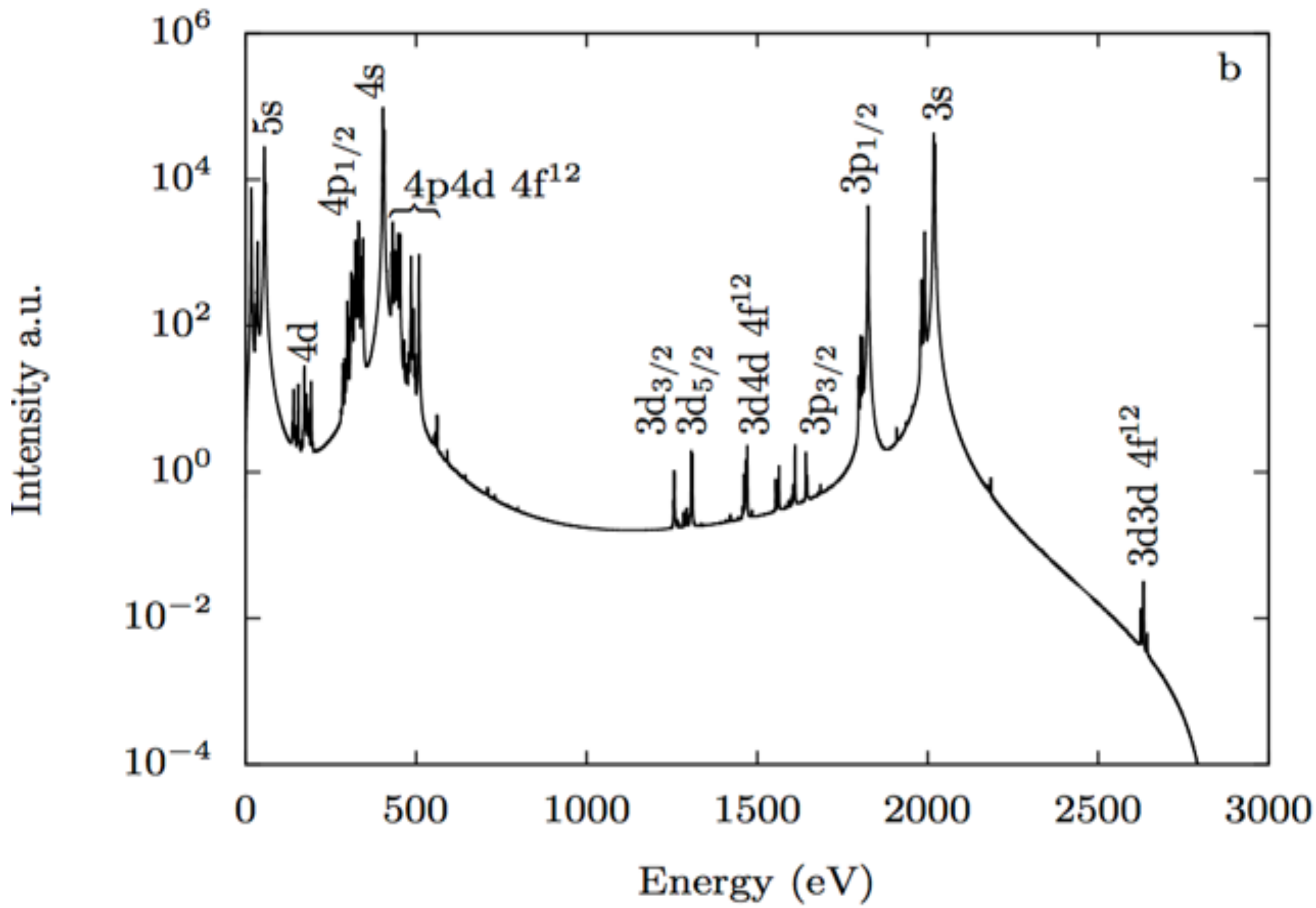
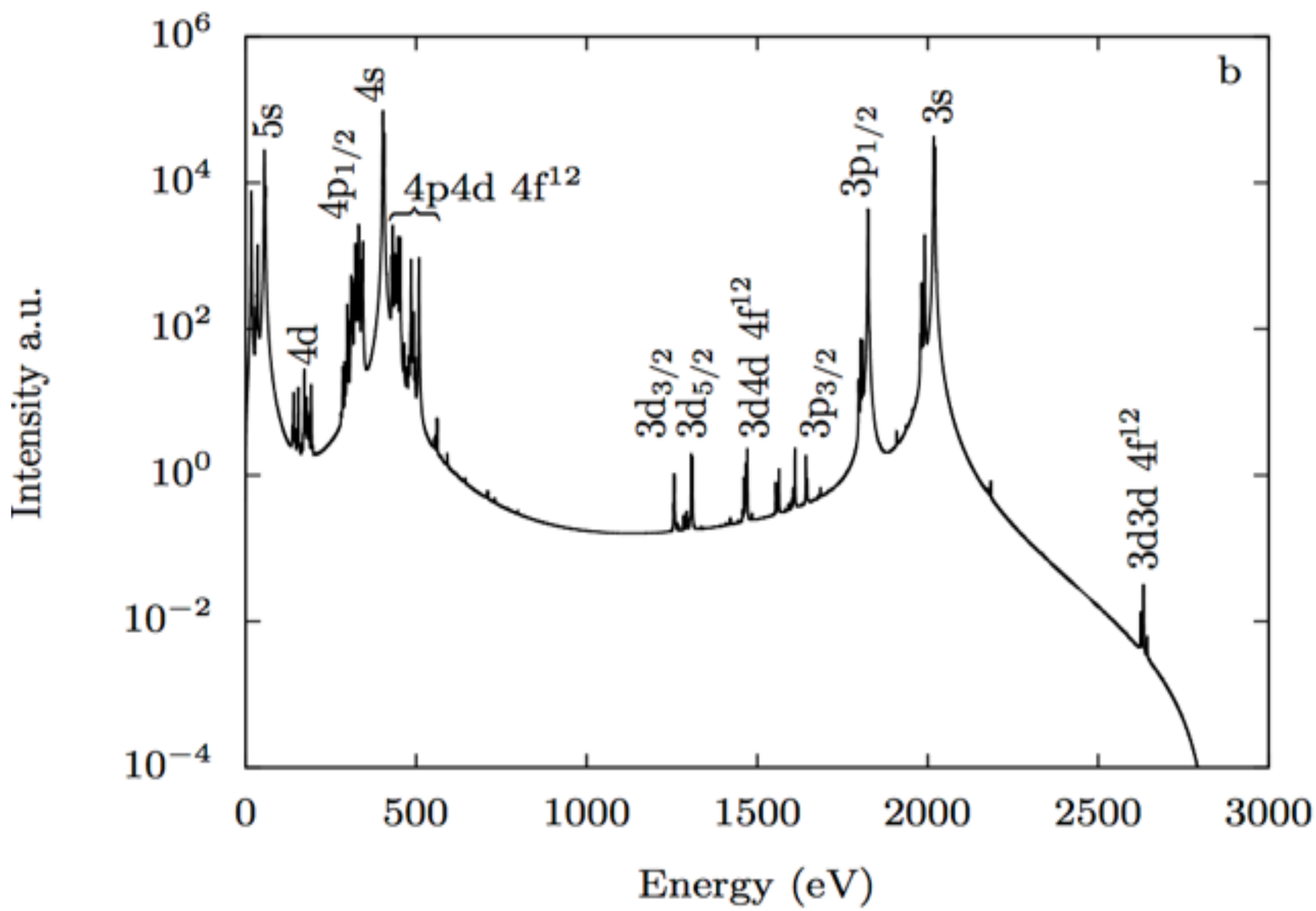


Brass et al., *Phys. Rev. C* **97** (2018) 054620

^{163}Ho calorimetrically measured spectrum

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$



The ECHo Collaboration, *EPJ-ST* **226** 8 (2017) 1623

The Holmes Collaboration Phys. J. C 75 (2015) 112

Sub-eV sensitivity: a possible scenario

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Unresolved pile-up (f_{pu} ~ $a \cdot \tau_r$)

- **f_{pu} < 10^{-5}**
- τ_r < 1 μs → a ~ 10 Bq
- 10^5 pixels → **multiplexing**

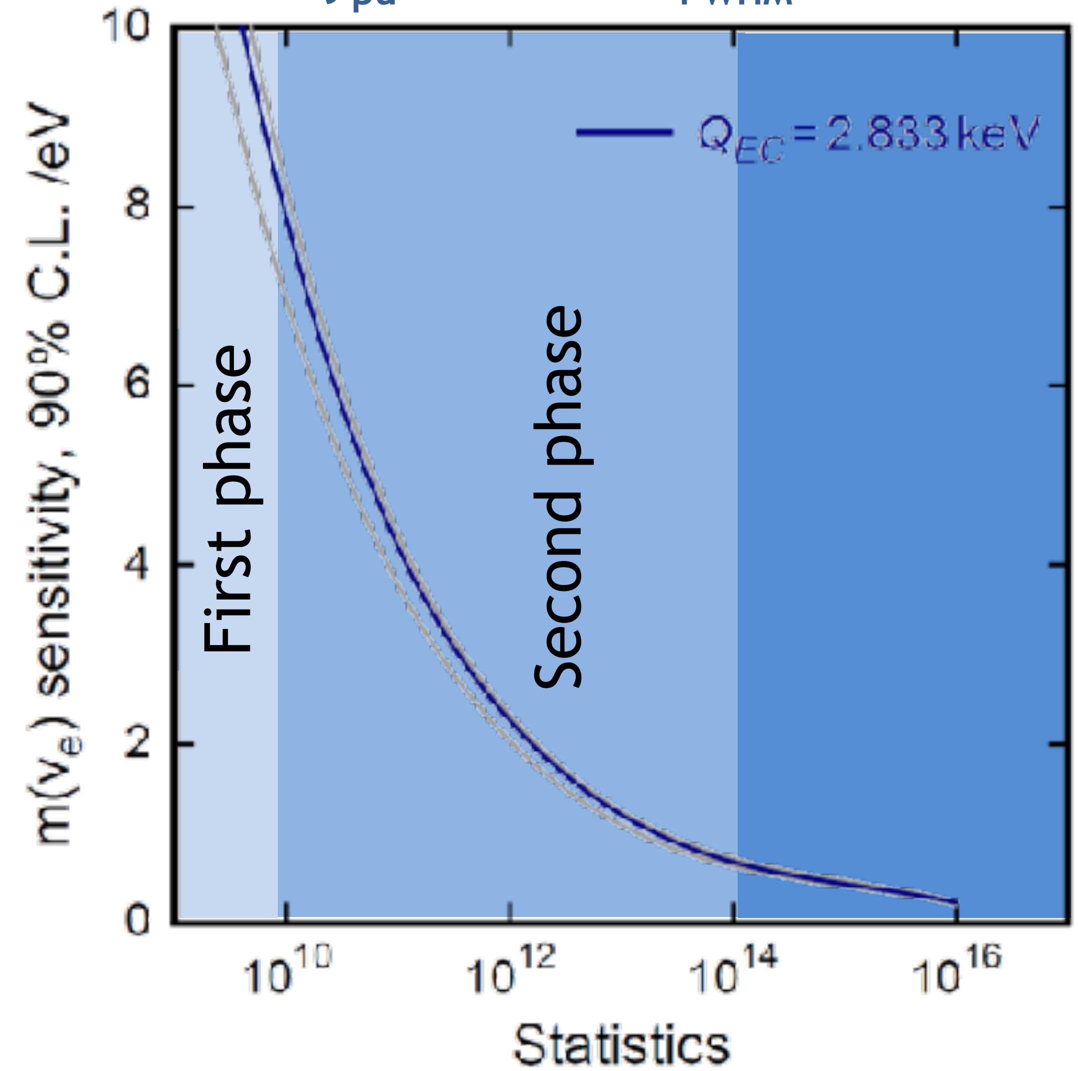
Precision characterization of the endpoint region

- **ΔE_{FWHM} < 3 eV**

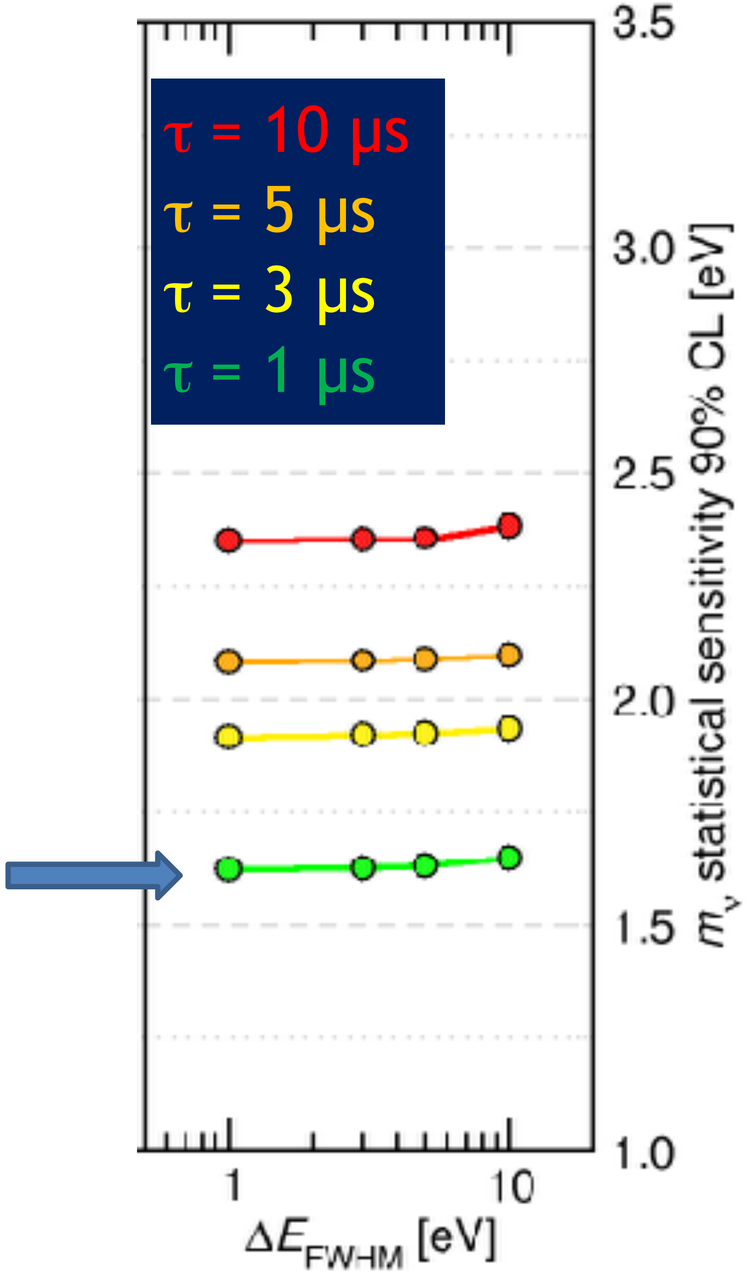
Background level

- **< 10^{-5} events/eV/det/day**

$f_{pu} = 10^{-6}$ ΔE_{FWHM} = 2 eV



Holmes: sensitivity and timeline



HOLMES baseline:

Activity per pixel: 300 Bq (6×10^{13} ^{163}Ho atoms)
Number of detectors: 1000

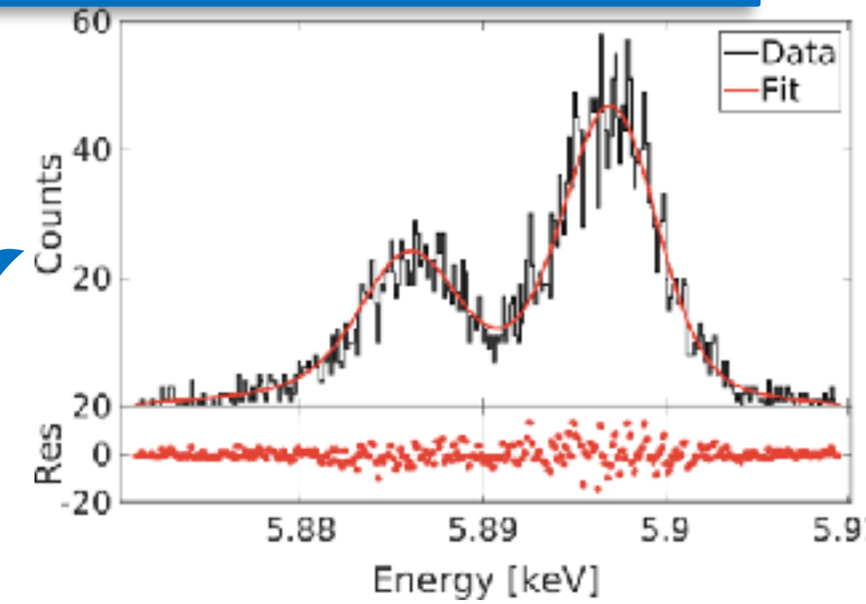
Two steps approach:

- Proof of concept (2013 – 2018):
  64 channels mid-term prototype
  t_M= 1 month
  → $m(\nu_e) < 10$ eV

- full scale (starting 2019):
  1000 channels,
  t_M= 3 years (3×10^{13} events)
  → $m(\nu_e) < 1$ eV

B. Alpert et al, Eur. Phys. J. C (2015) 75:112
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

Holmes: present status



Source production and purification:

130 MBq available for tests and experiments

Detector arrays characterization:

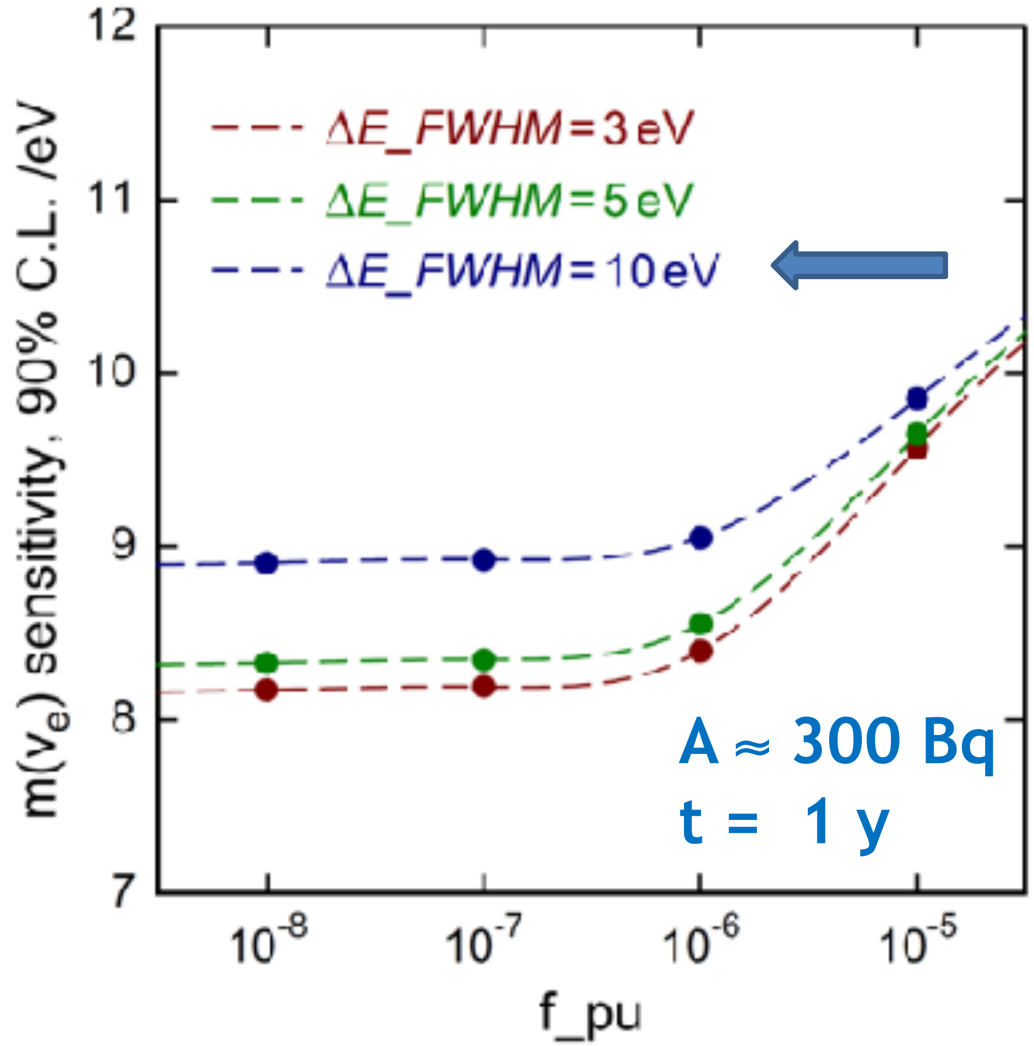
very good single pixel performance
operating microwave SQUID multiplexing
next challenge → load TES arrays with ^{163}Ho

Dedicated mass separator:

facility installed
tests of the ion source on-going
commissioning on-going

ECHo: sensitivity and timeline

ECHo-1k (2015 – 2018)

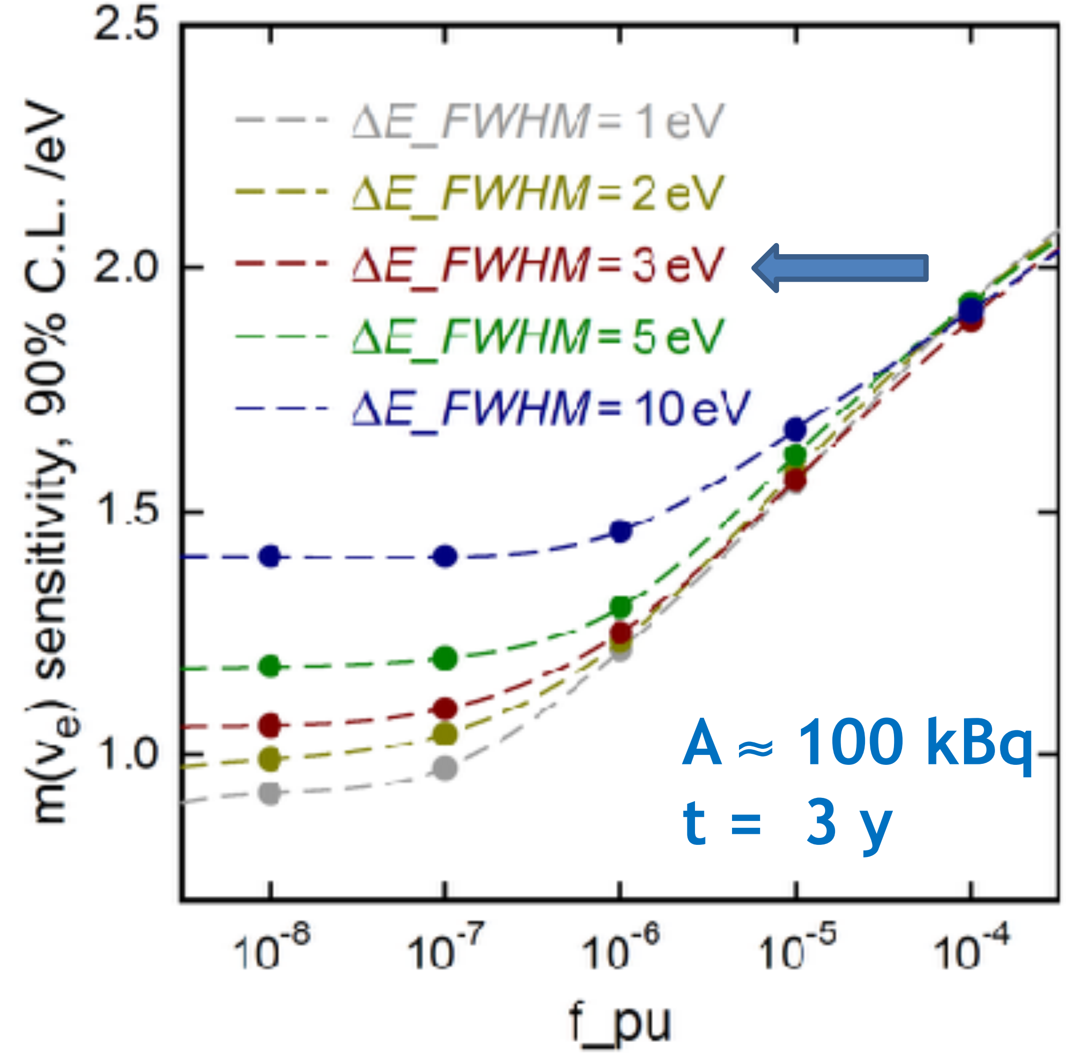


$m(\nu_e) < 10$ eV 90% C.L.

Activity per pixel 5 Bq
Number of detectors 60
Readout: parallel two stage SQUID

Supported by DFG Research Unit FOR 2022/1

ECHo-100k (2018 – 2021)

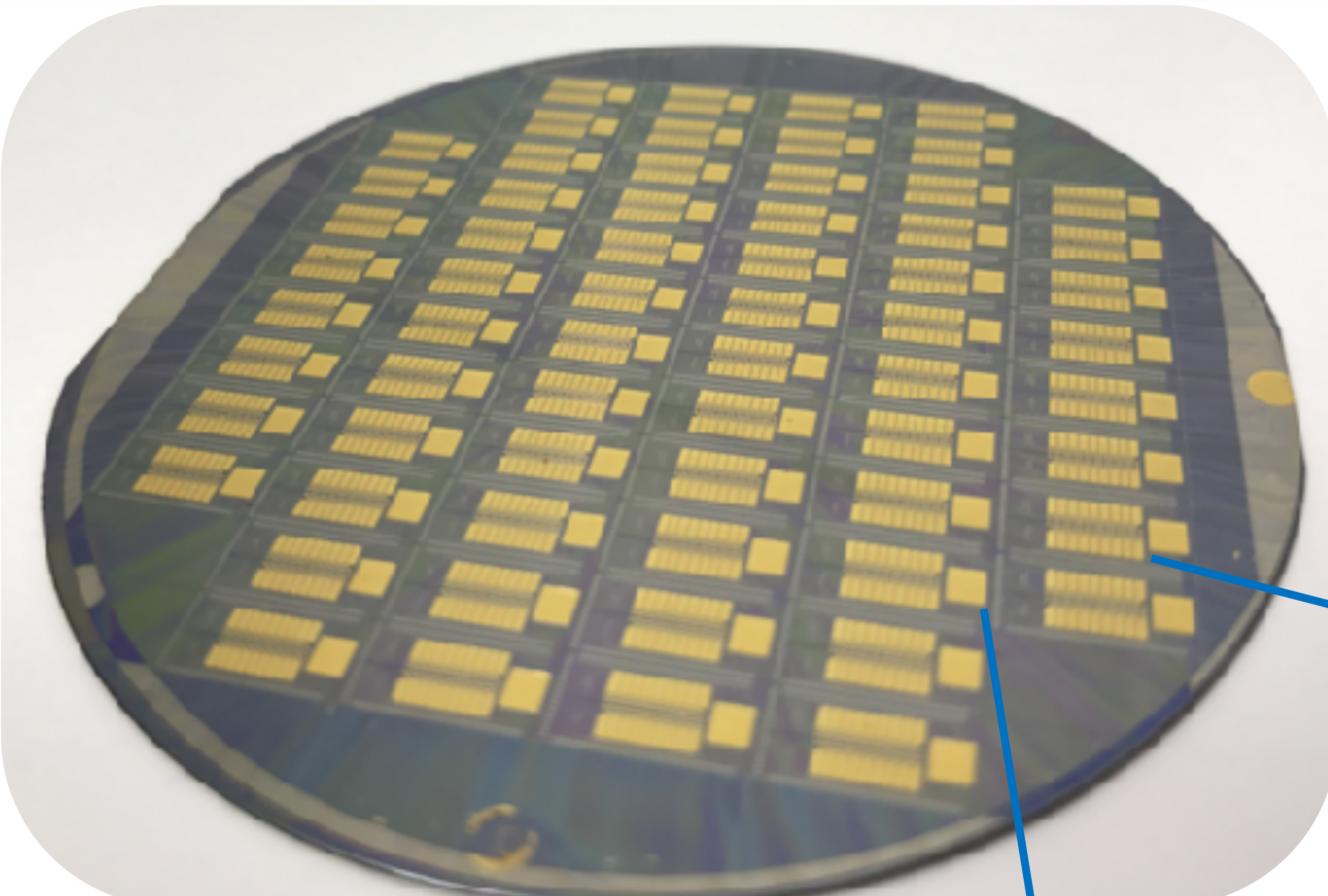


$m(\nu_e) < 1.5$ eV 90% C.L.

Activity per pixel 10 Bq
Number of detectors 12000
Readout: microwave SQUID multiplexing

Supported by DFG Research Unit FOR 2022/2

ECHo-1k array

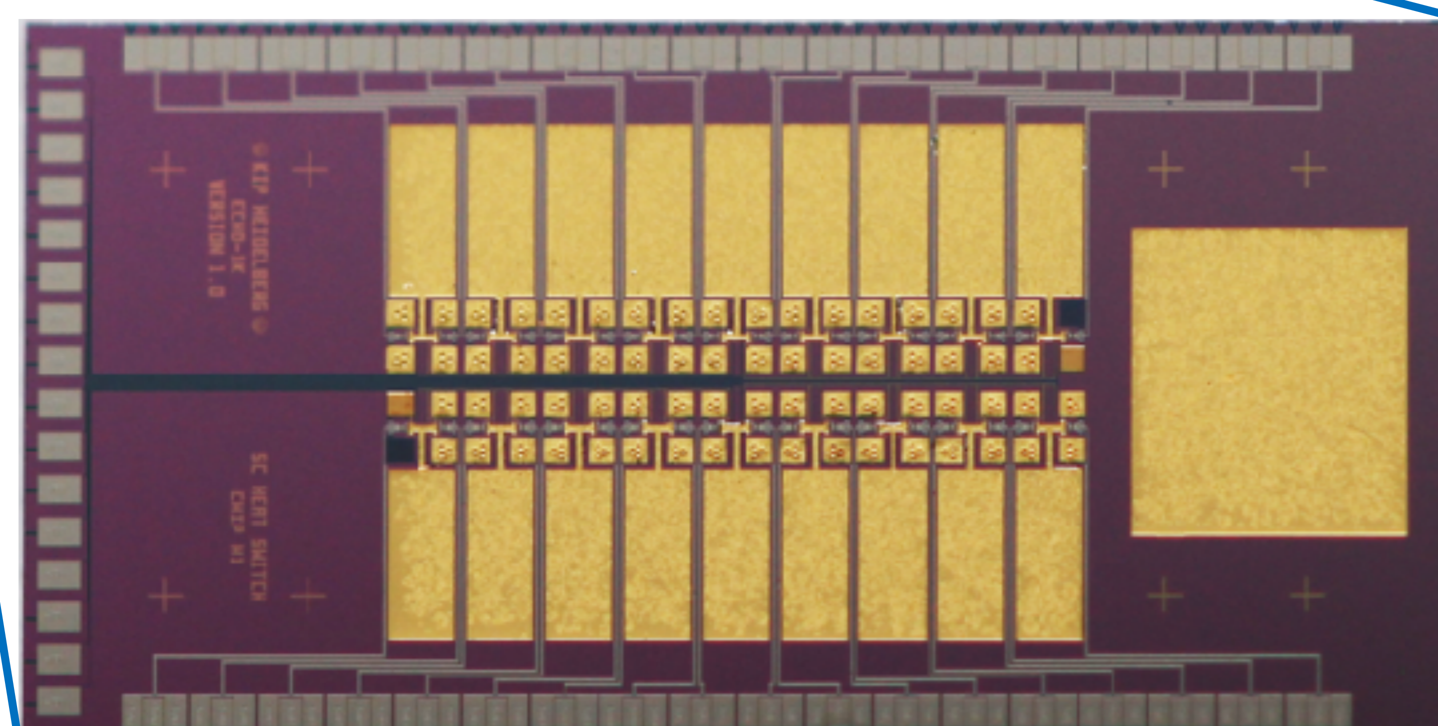


3“ wafer with 64 ECHo-1k chip

Suitable for
parallel and multiplexed readout

64 pixels which can be loaded with ^{163}Ho
+ 4 detectors for diagnostics

Design performance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)
τ_r ~ 300 ns (multiplexed read-out)



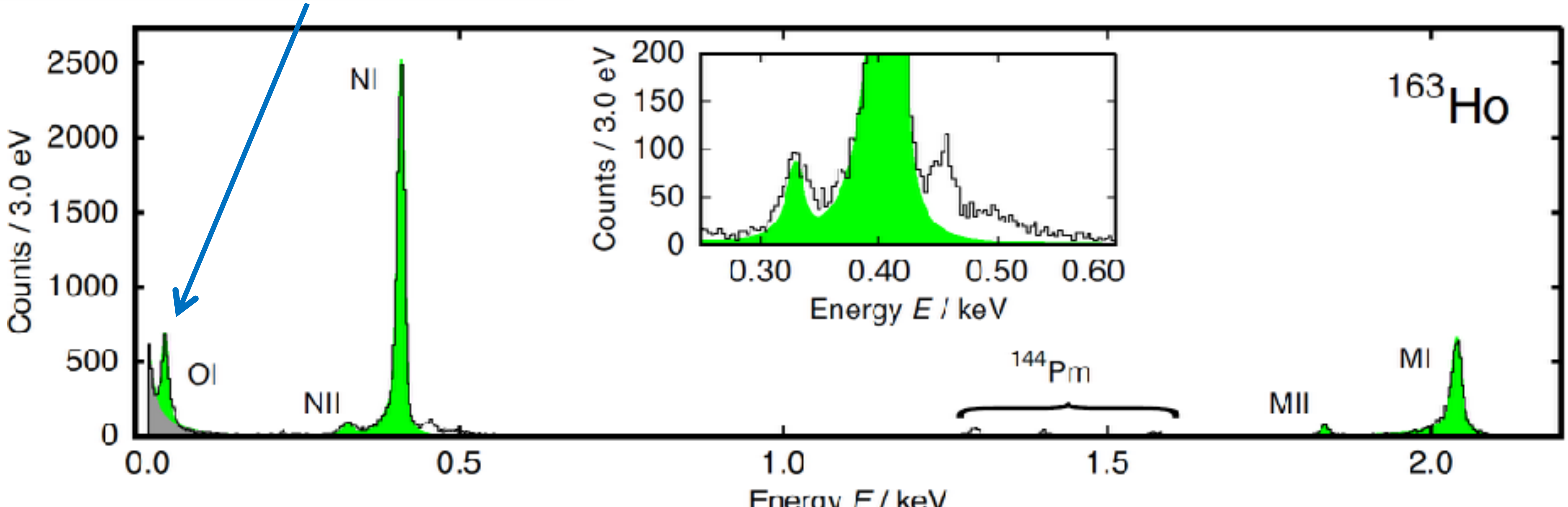
S.Kempf *et al.*, *J. Low. Temp. Phys.* **176** (2014) 426

Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV
- Non-Linearity < 1% @ 6keV

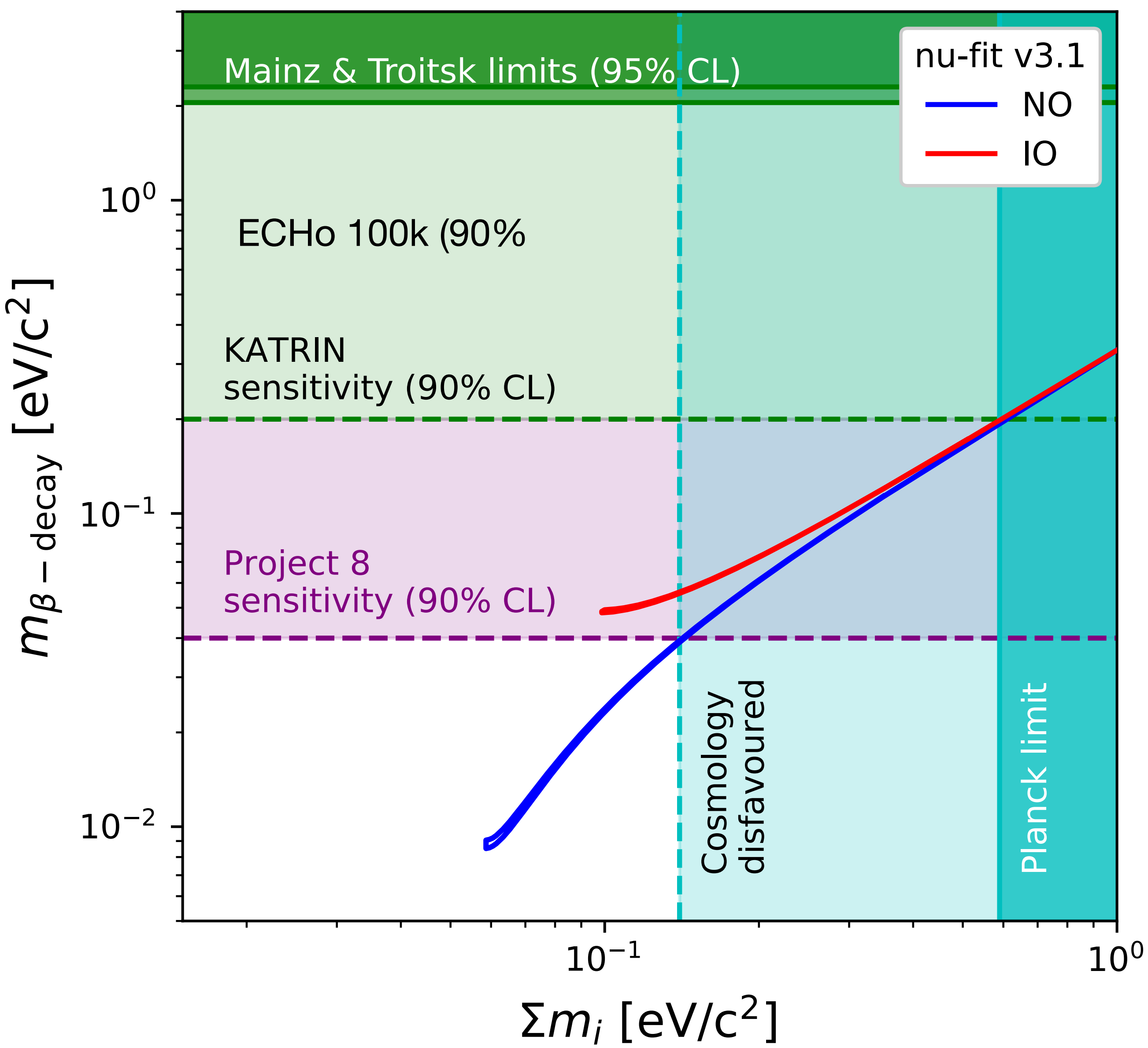
	E_H bind.	E_H exp.	Γ_H lit.	Γ_H exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3

First calorimetric measurement of the OI-line



P. C.-O. Ranitzsch et al., *Phys. Rev. Lett.*, 119, 122501 (2017)

Conclusions and outlook

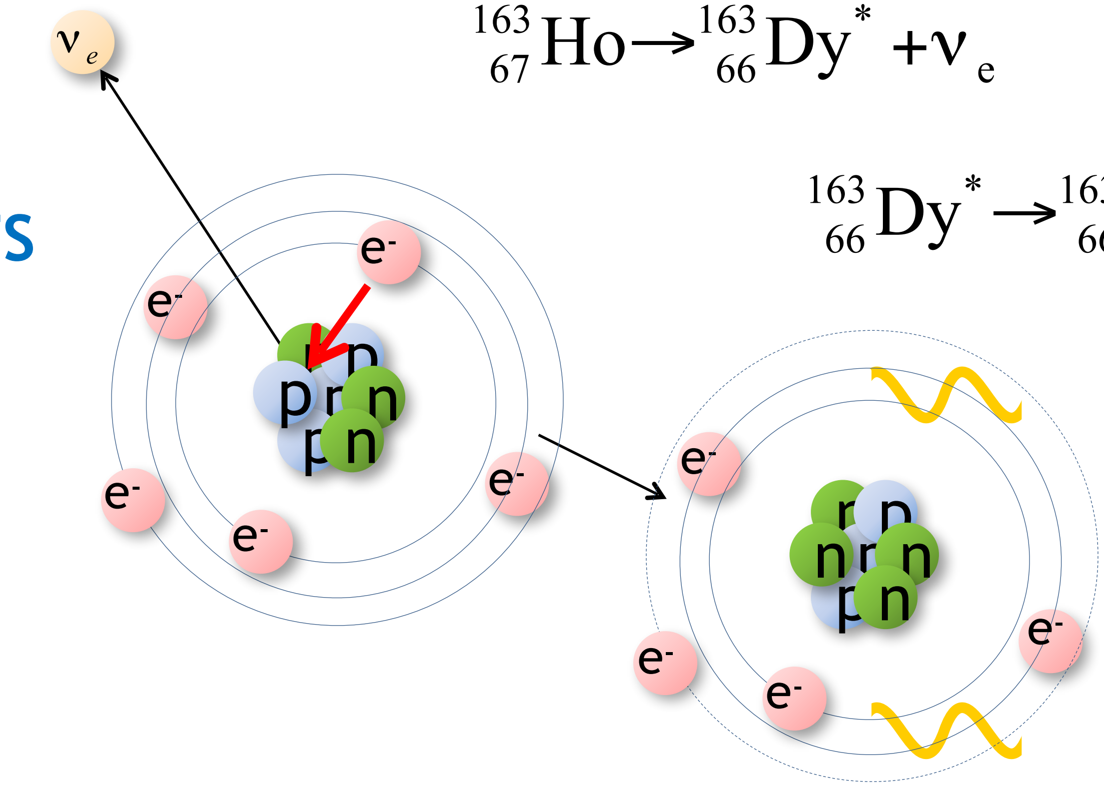


ECHo

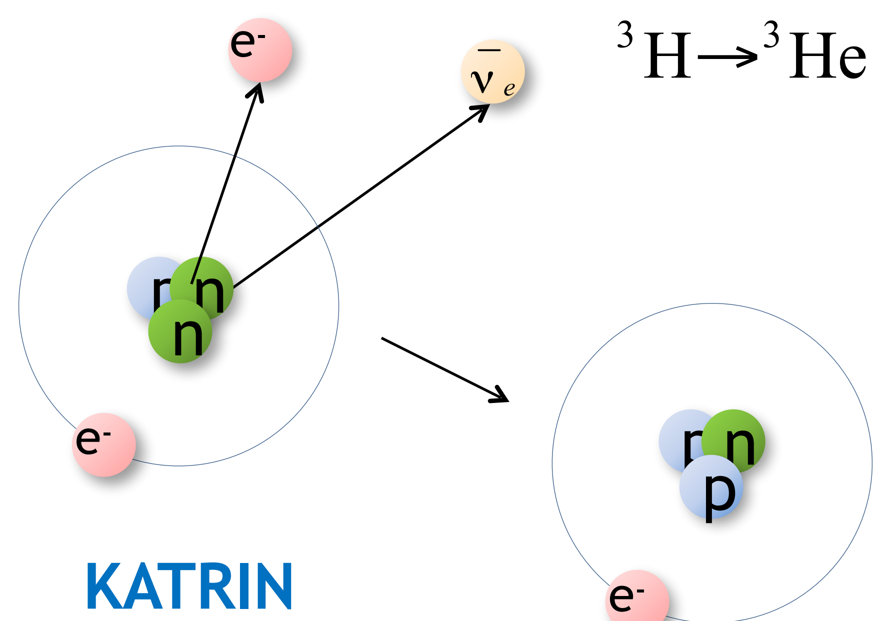
HOLMES

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$



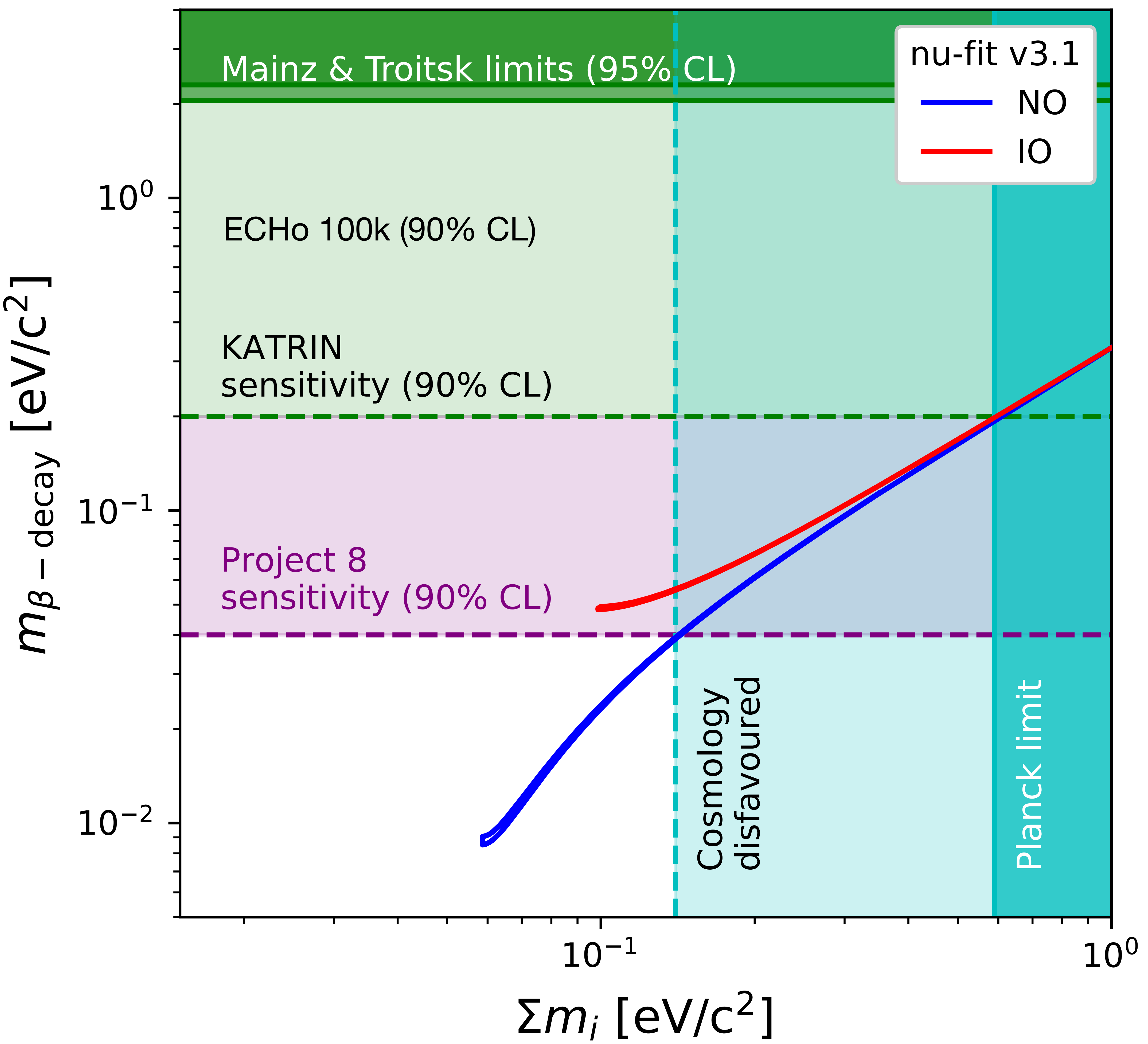
$$^{3}\mathrm{H} \rightarrow ^{3}\mathrm{He} + e^- + \bar{\nu}_e$$



KATRIN

PROJECT8

PTOLEMY



Mainz & Troitsk limits (95% CL)
nu-fit v3.1
NO
IO
ECHo 100k (90% CL)
KATRIN
sensitivity (90% CL)
Project 8
sensitivity (90% CL)
Cosmology
disfavoured
Planck limit
10^{0}
10^{-1}
10^{-2}
$m_{\beta-\mathrm{decay}}$ [eV/c^2]
Σm_i [eV/c^2]

PROJECT 8 COLLABORATION

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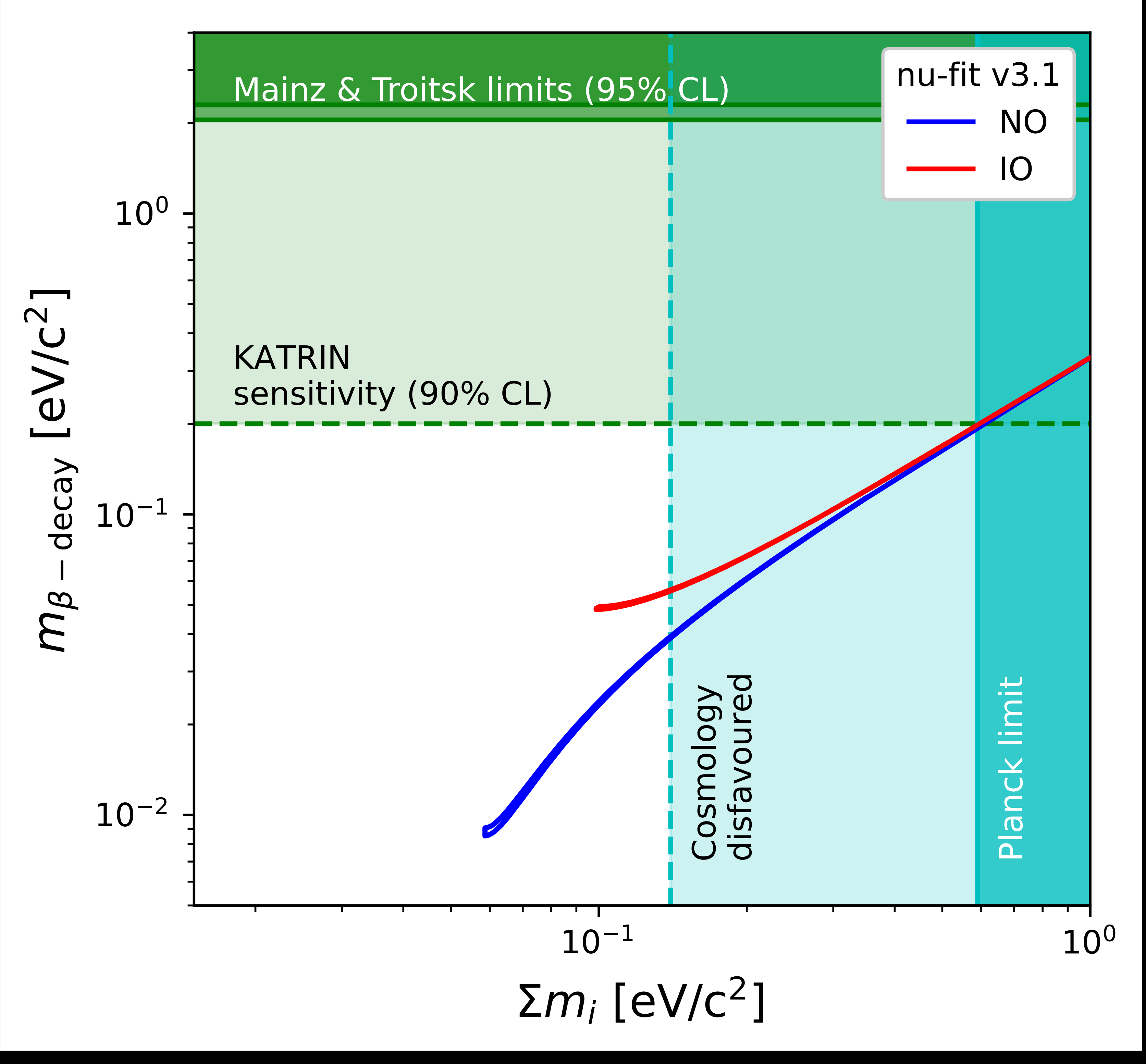
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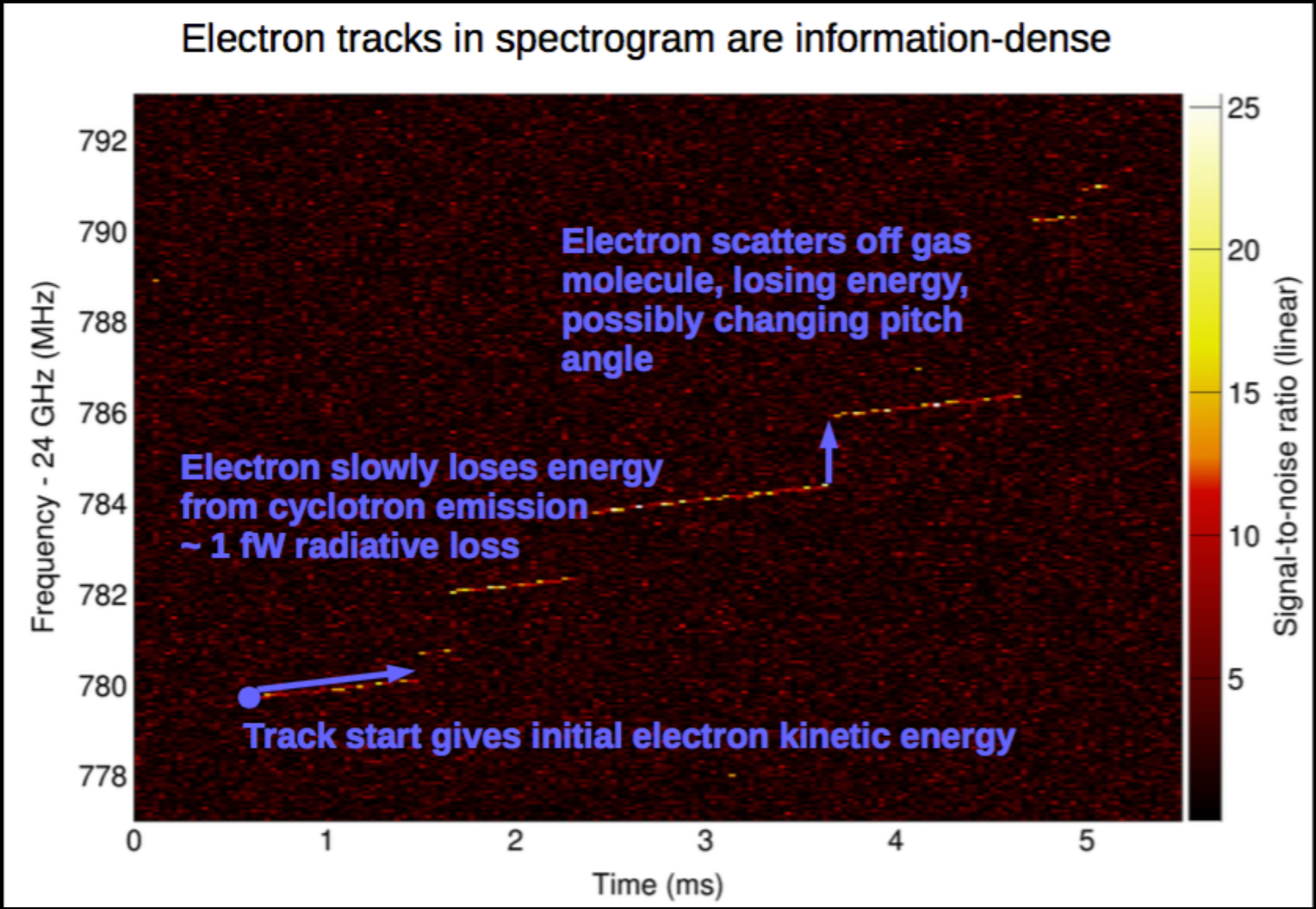
$m_{\beta-\mathrm{decay}}$ [eV/c^2]
Σm_i [eV/c^2]

SPECTROGRAM INFORMATION

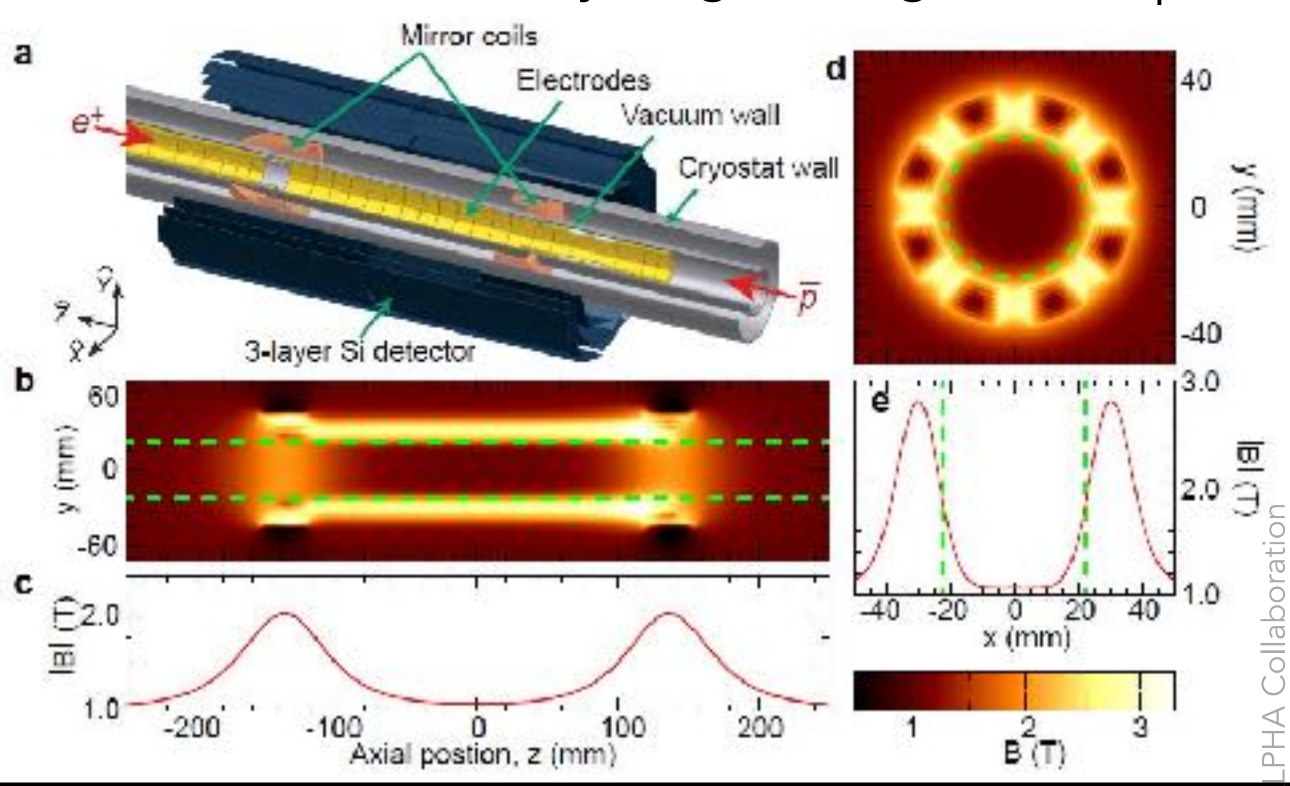
Scale:
100eV



A Bottle of Atoms

- We already have a shallow axial magnetic “bathtub” trap for holding the CRES electrons, which we can make deeper to hold atoms as well
- We can add a multipole field to provide radial confinement
- Such “Ioffe-Prichard” traps are established technology

The ALPHA Antihydrogen Magnetic Trap



ALPHA Collaboration

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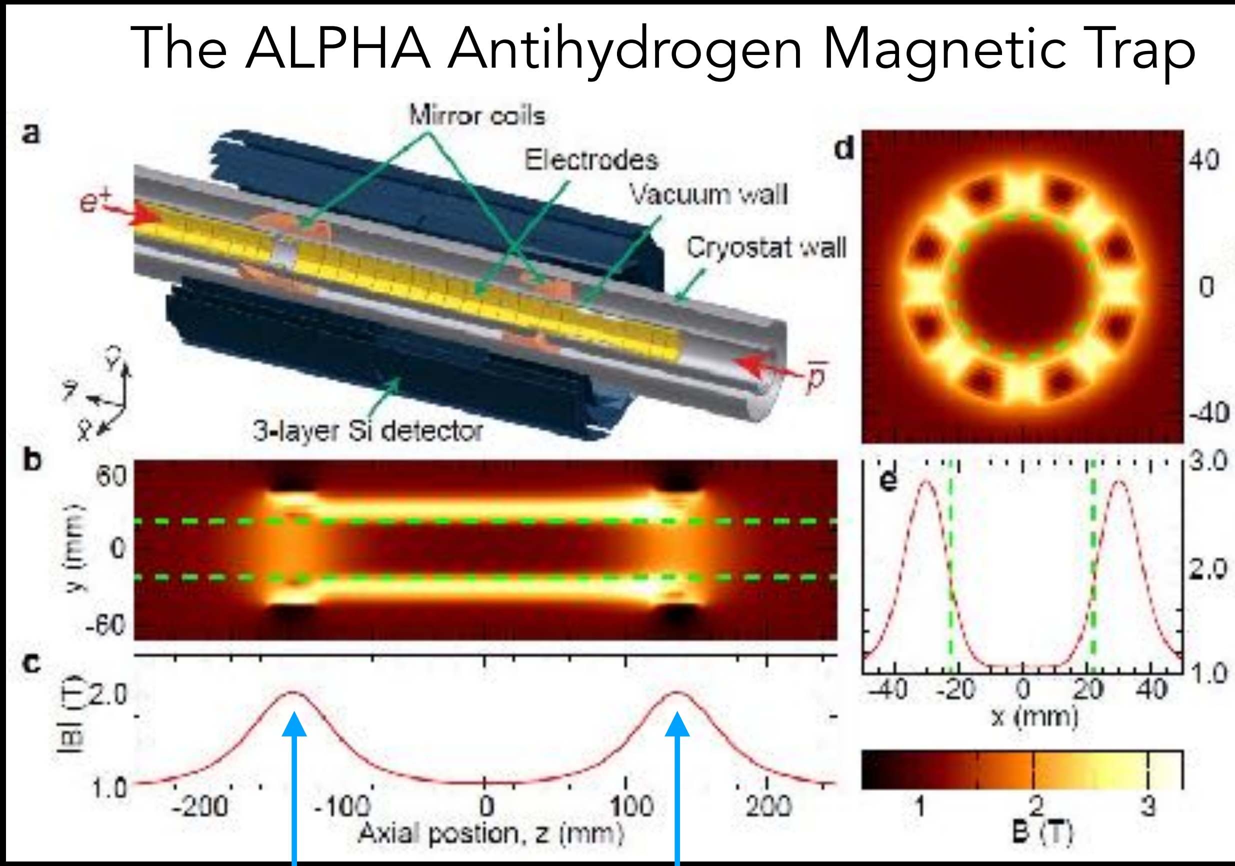
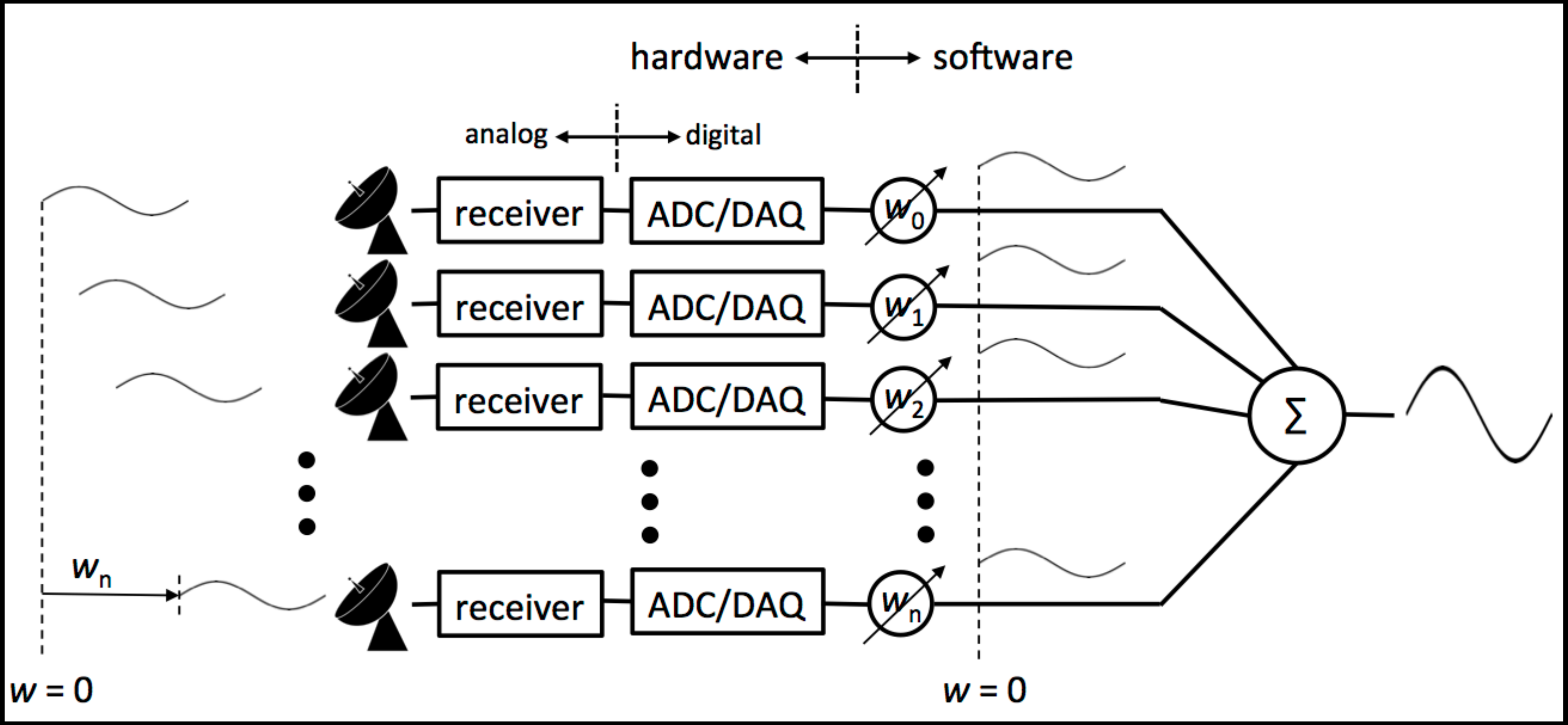


ALPHA Collaboration

Deeper version of
CRES electron
bathtub trap

DIGITAL BEAM FORMING



Digitize per channel / φ-segment

- (digital) phase delay → forms focal point in volume

Needs high real-time processing power!

TRIGGER DEVELOPMENT

Data transfer scheme

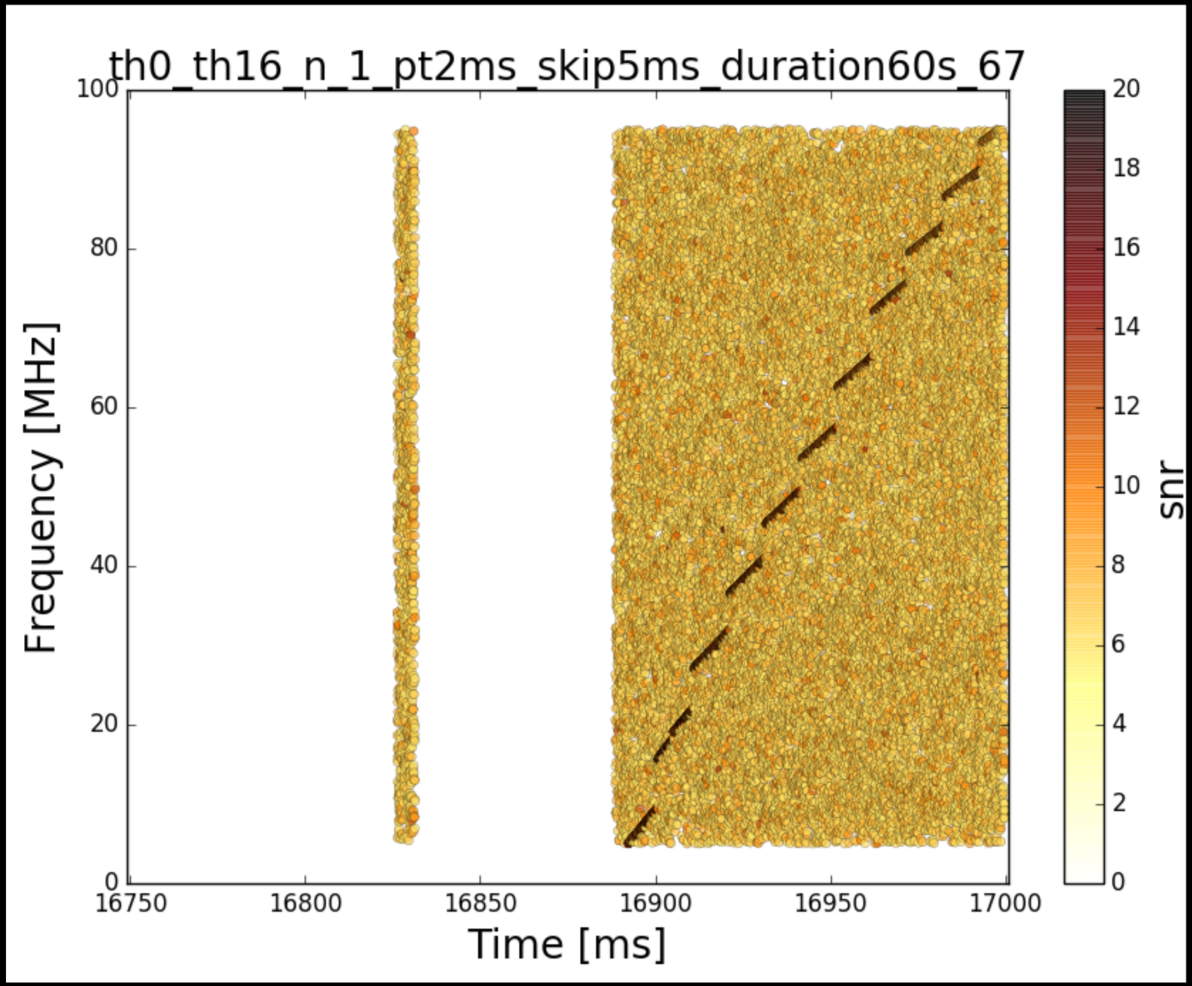
- Fourier transform on FPGA → send time (T) and frequency (F) packets to server

Frequency mask trigger

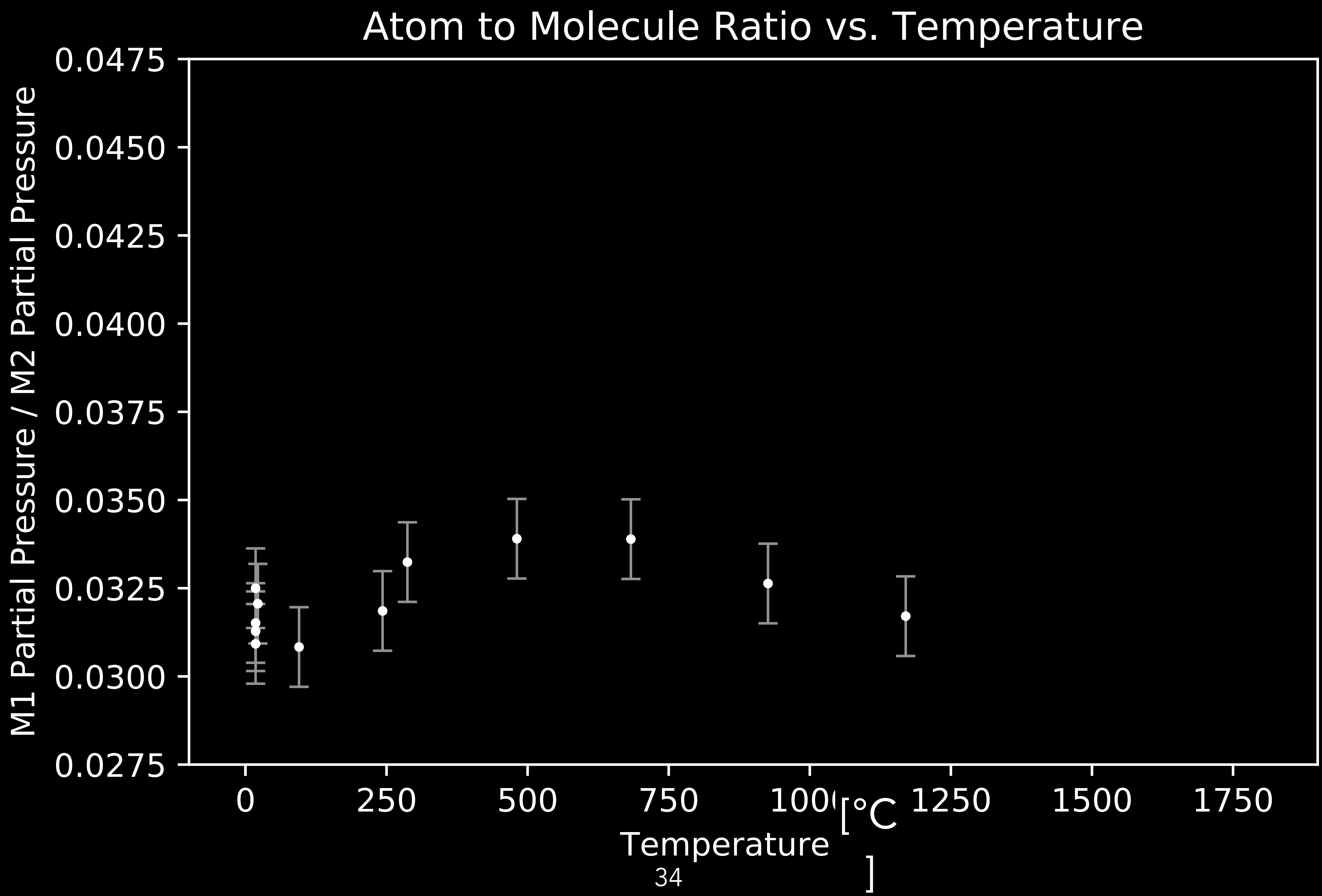
- SNR threshold

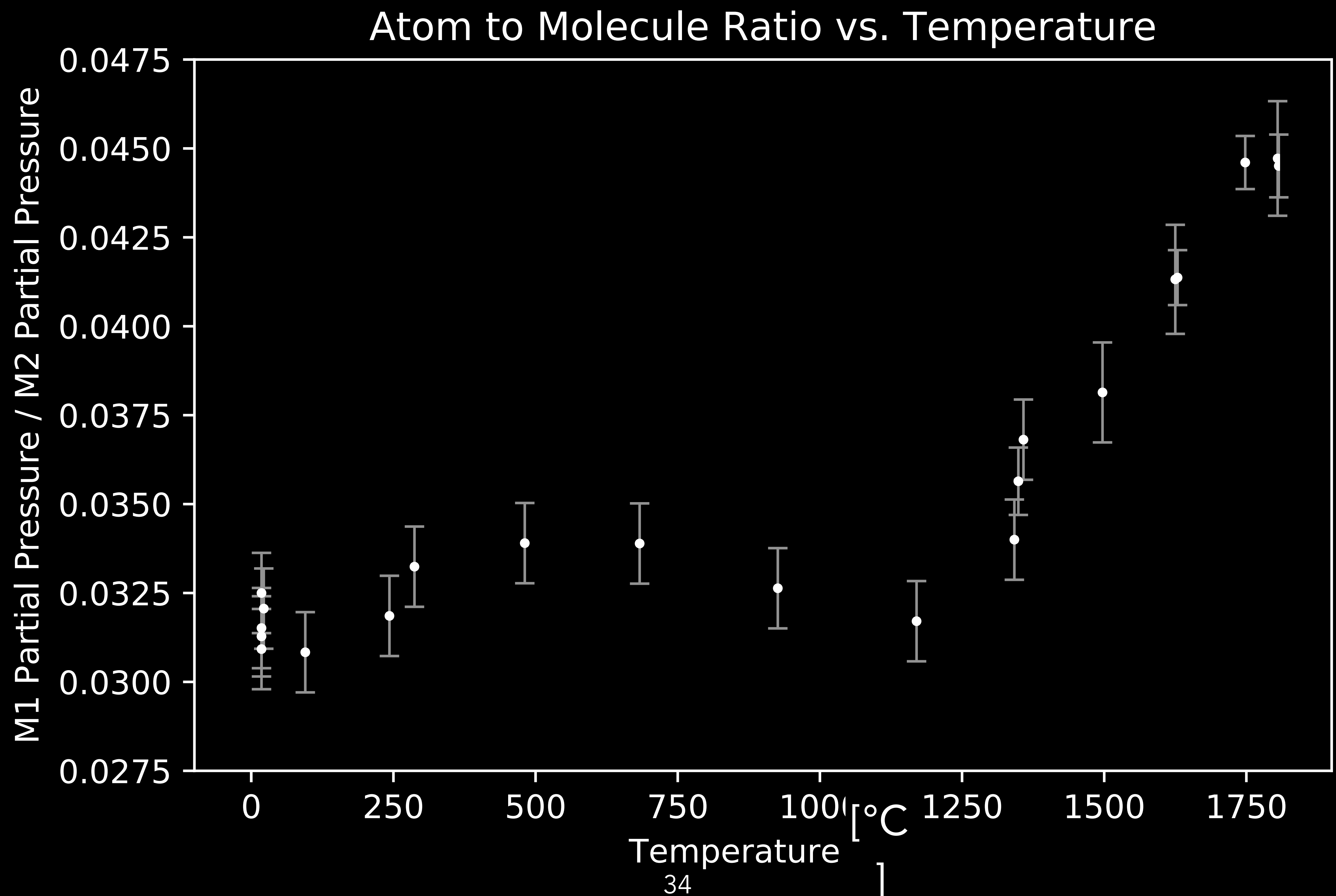
Event builder

- pre-/post-trigger and skipping times adjustable
- no dead-time!



First successful tests of software trigger on December 1st 2017


Atom to Molecule Ratio vs. Temperature
M1 Partial Pressure / M2 Partial Pressure
0.0475
0.0450
0.0425
0.0400
0.0375
0.0350
0.0325
0.0300
0.0275
0
250
500
750
1000
1250
1500
1750
Temperature [°C]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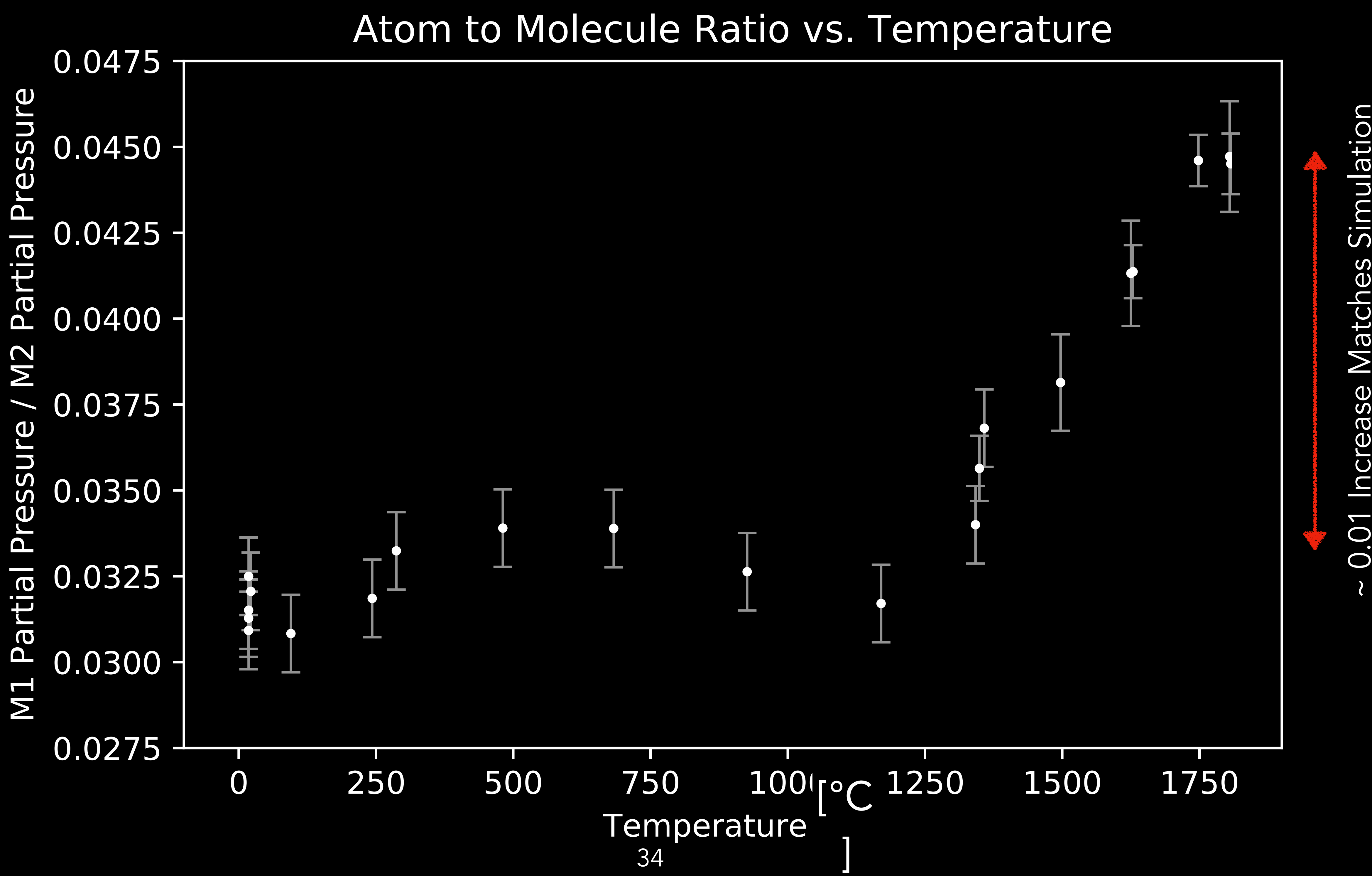

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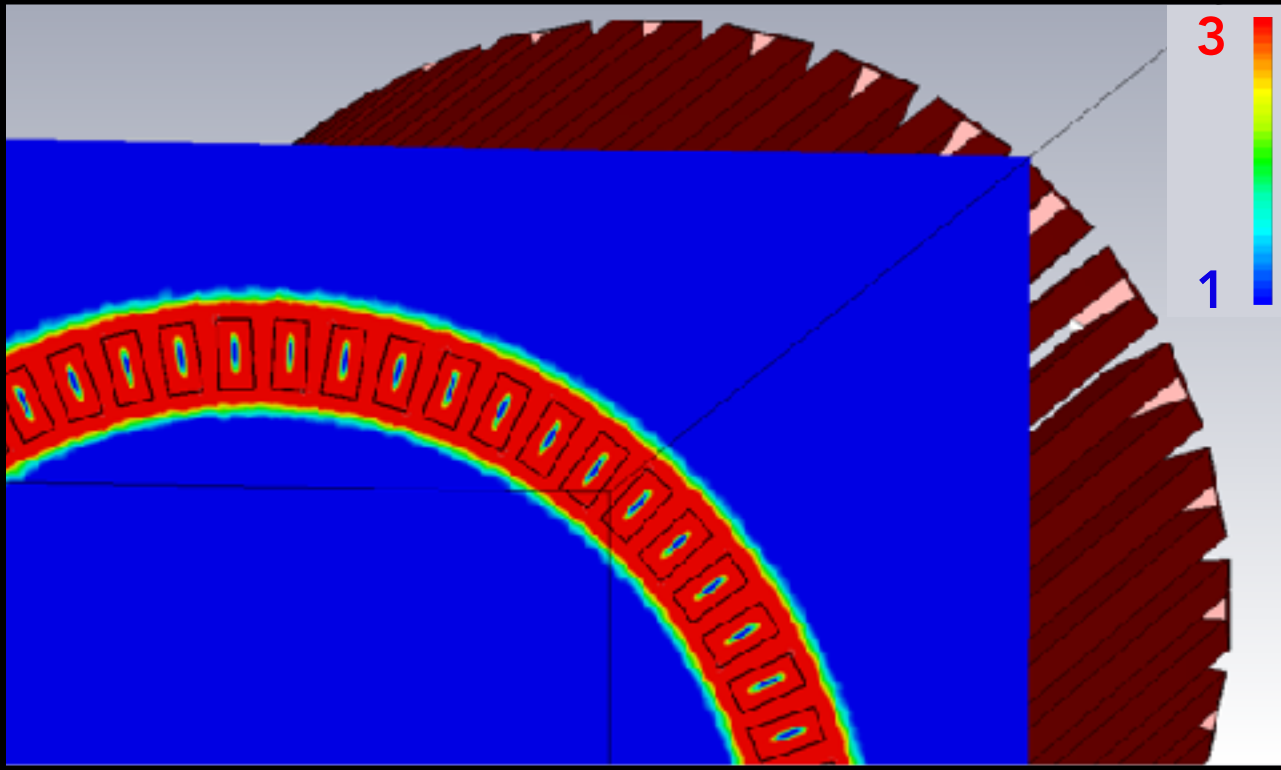
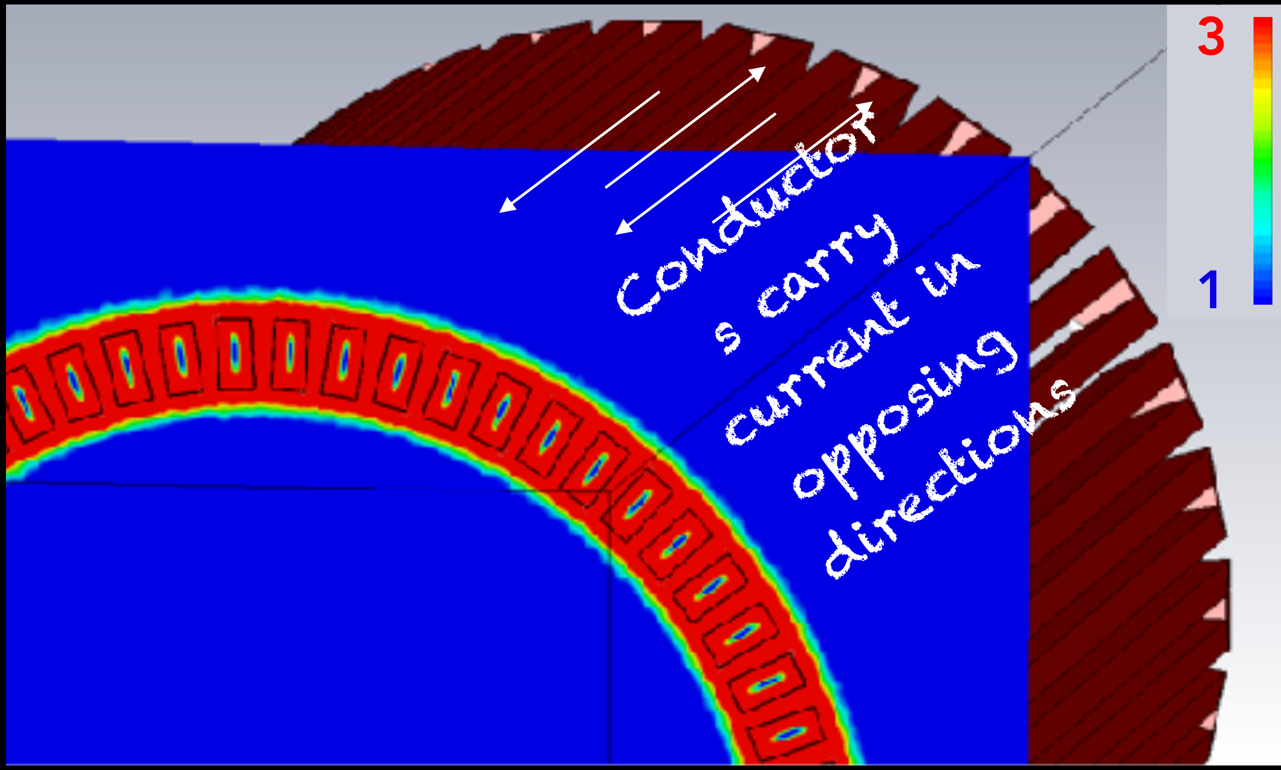
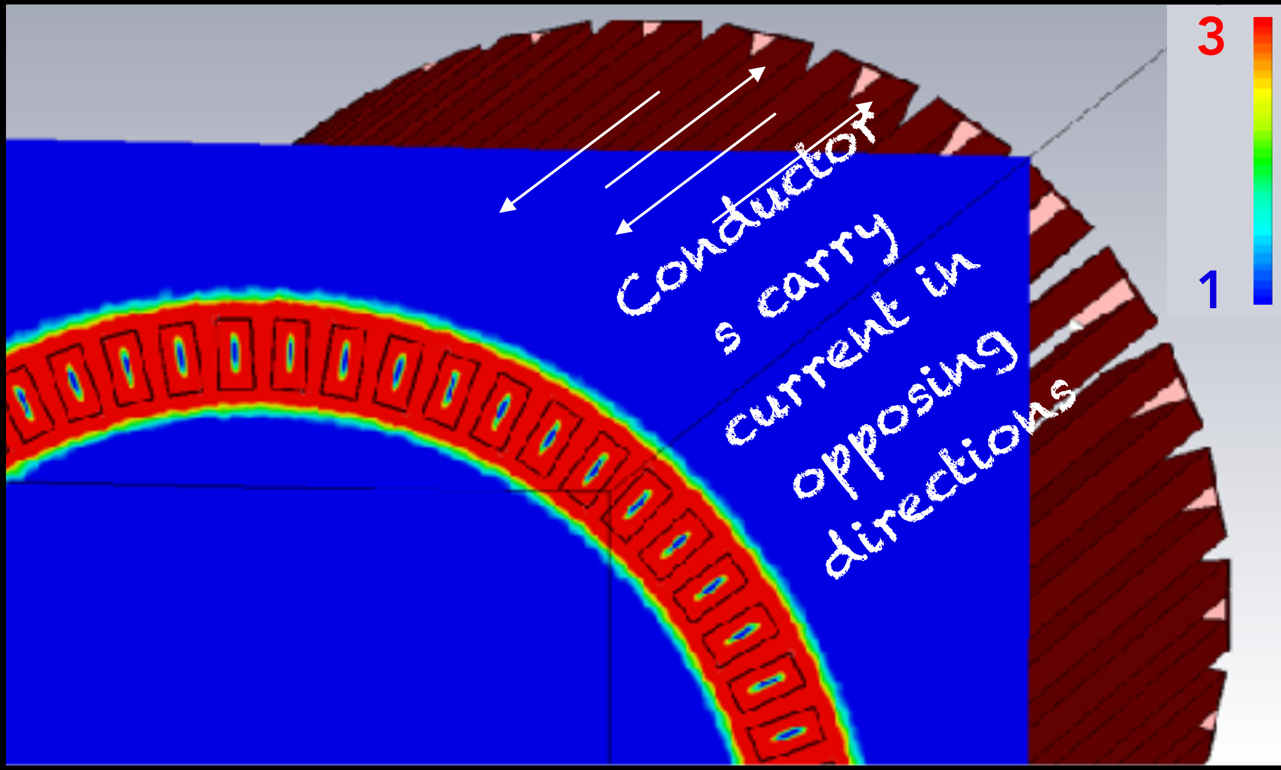
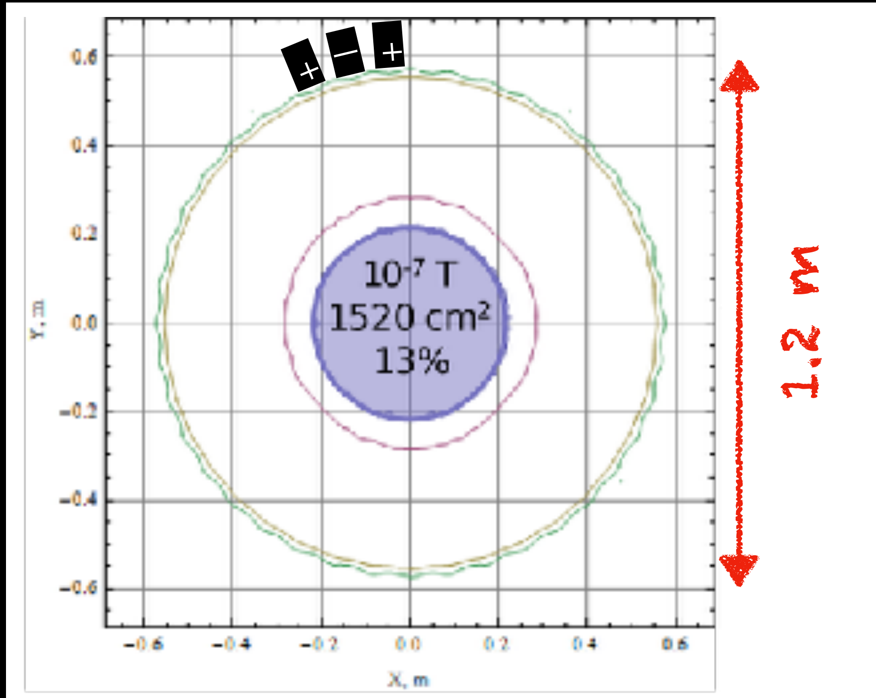
Temperature [°C]
~ 0.01 Increase Matches Simulation

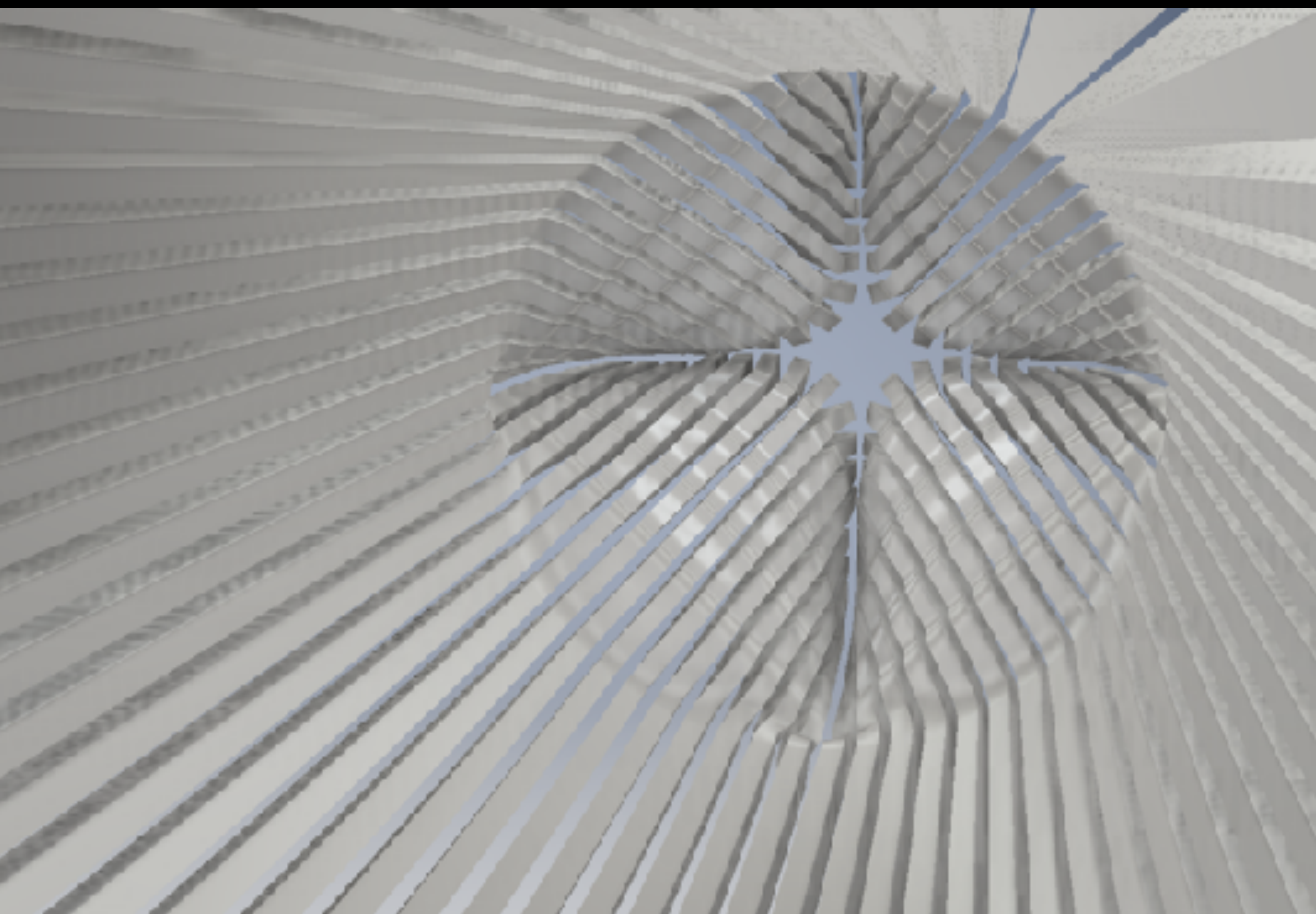

3
1

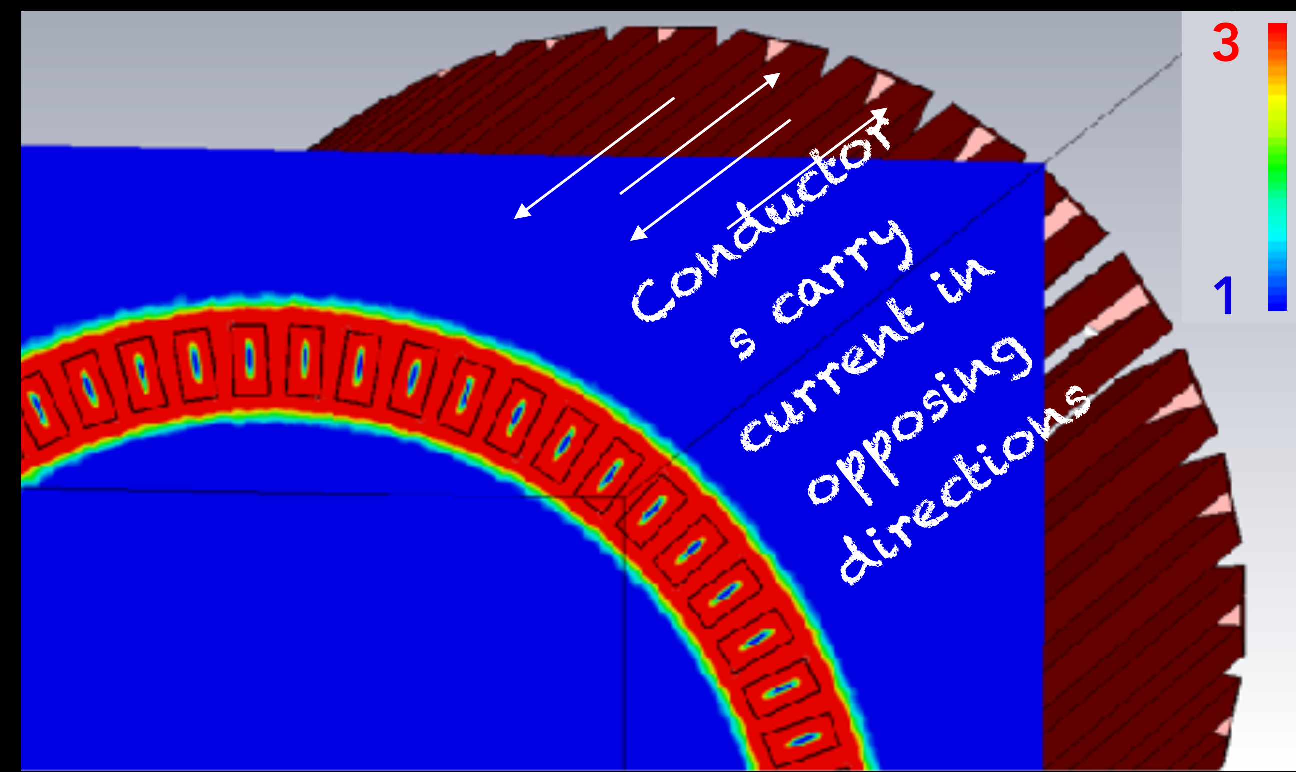

3
1
Conductors carry current in opposing directions

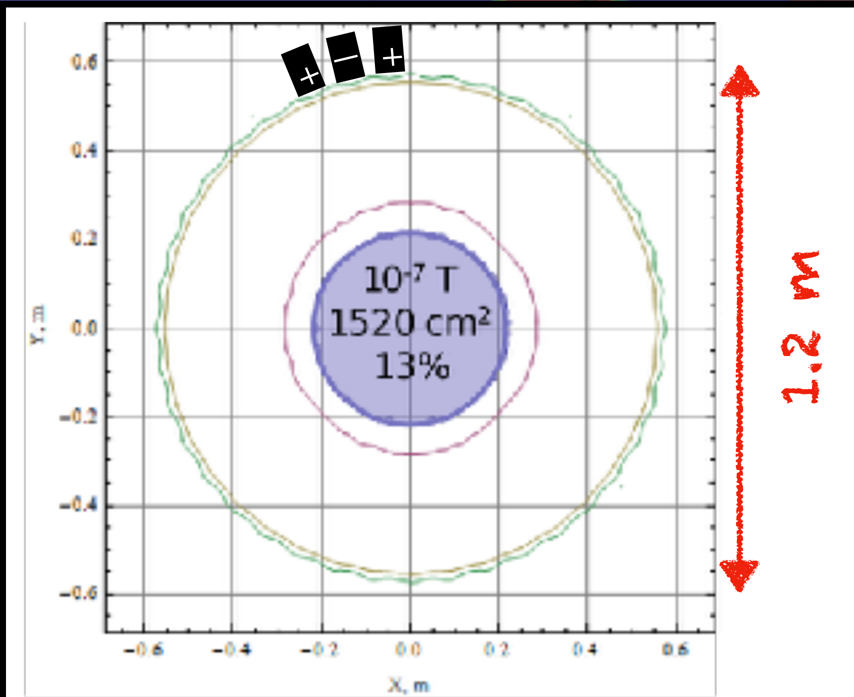




40 Ioffe Bars; 1 MA/bar; 200







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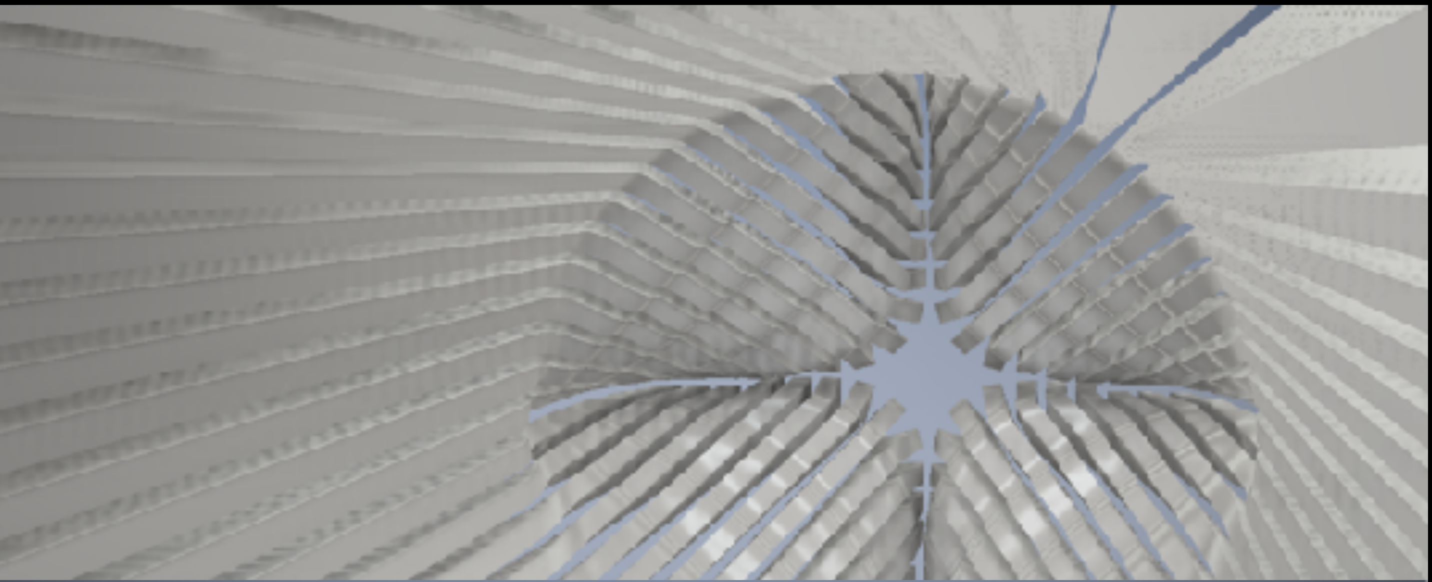

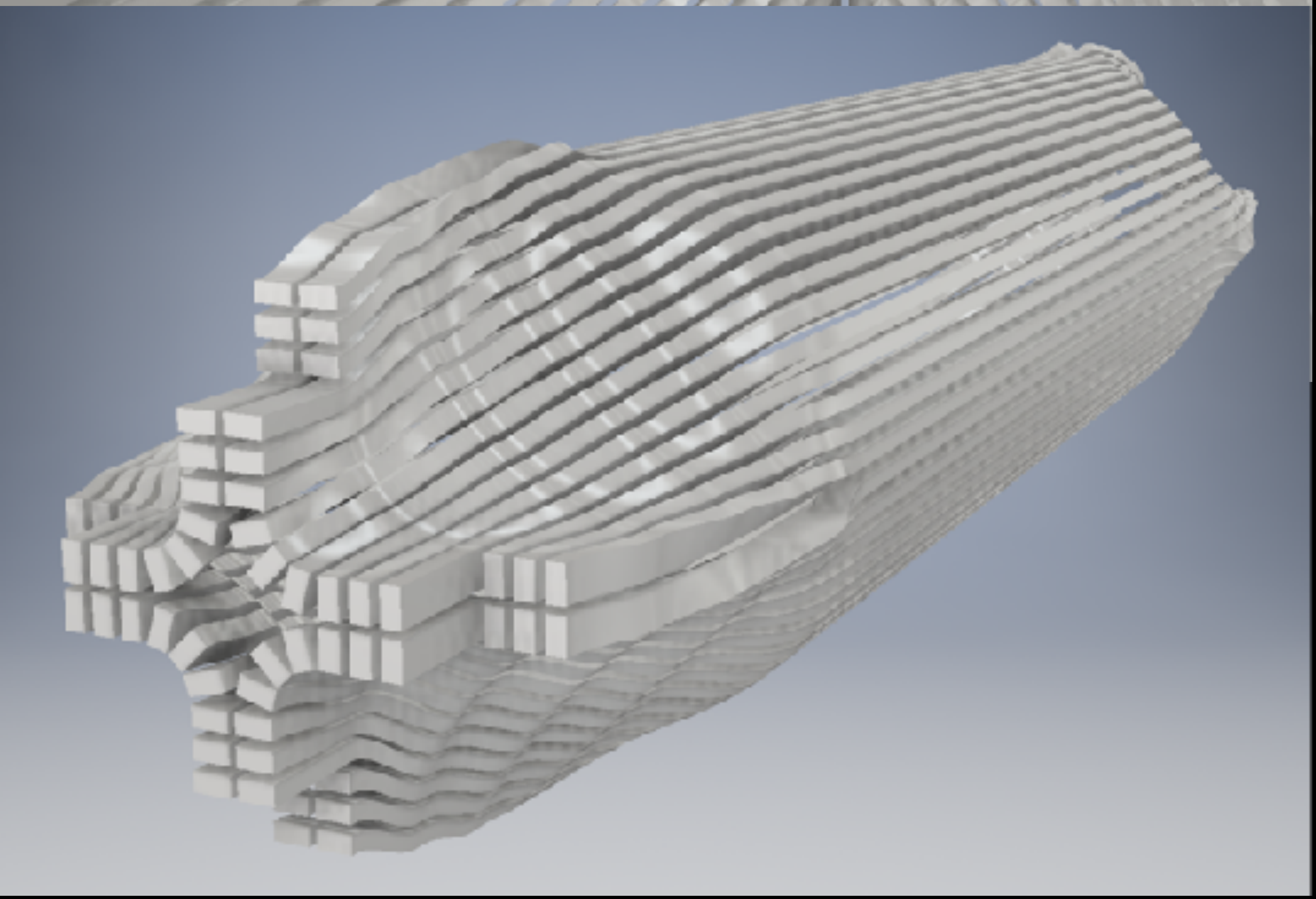

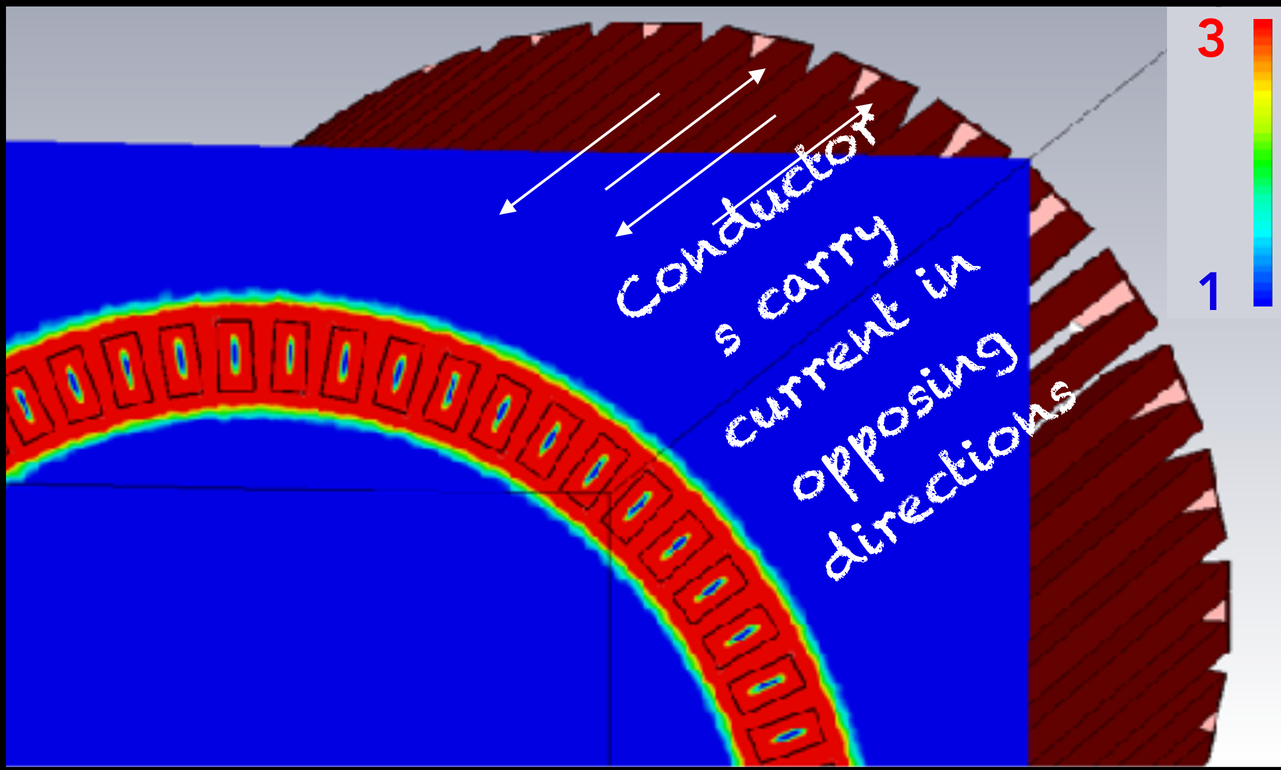

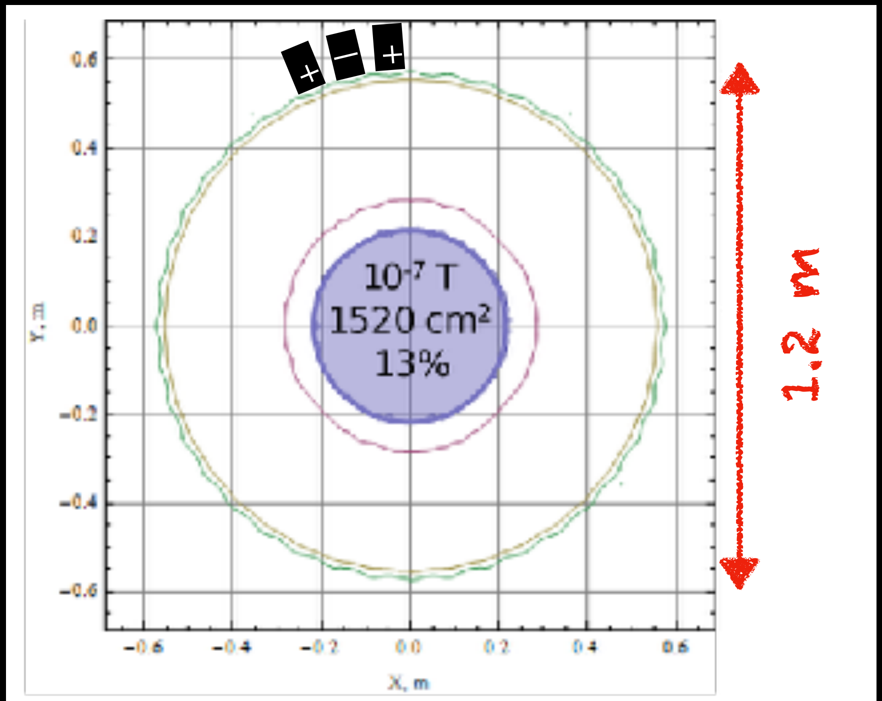

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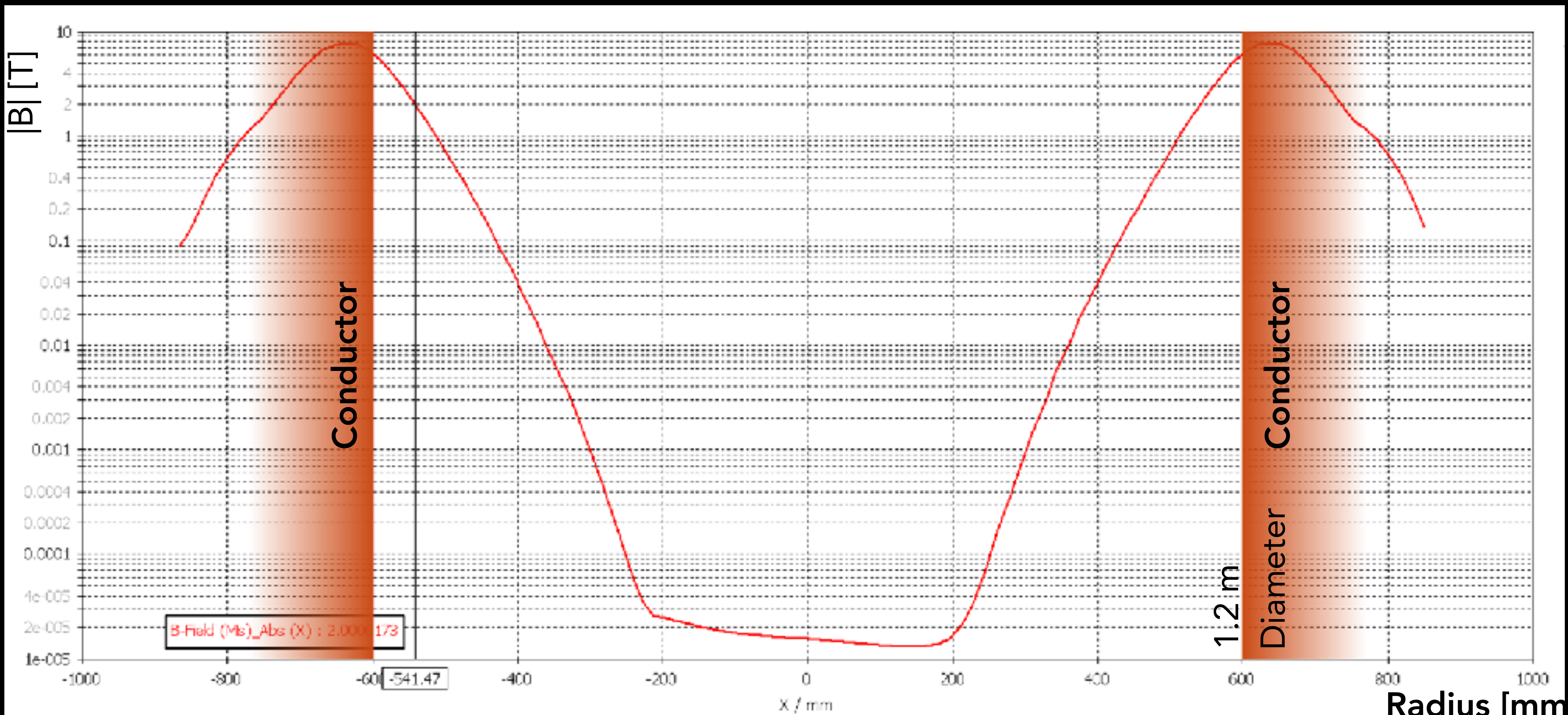
Radial Magnetic Field Profile



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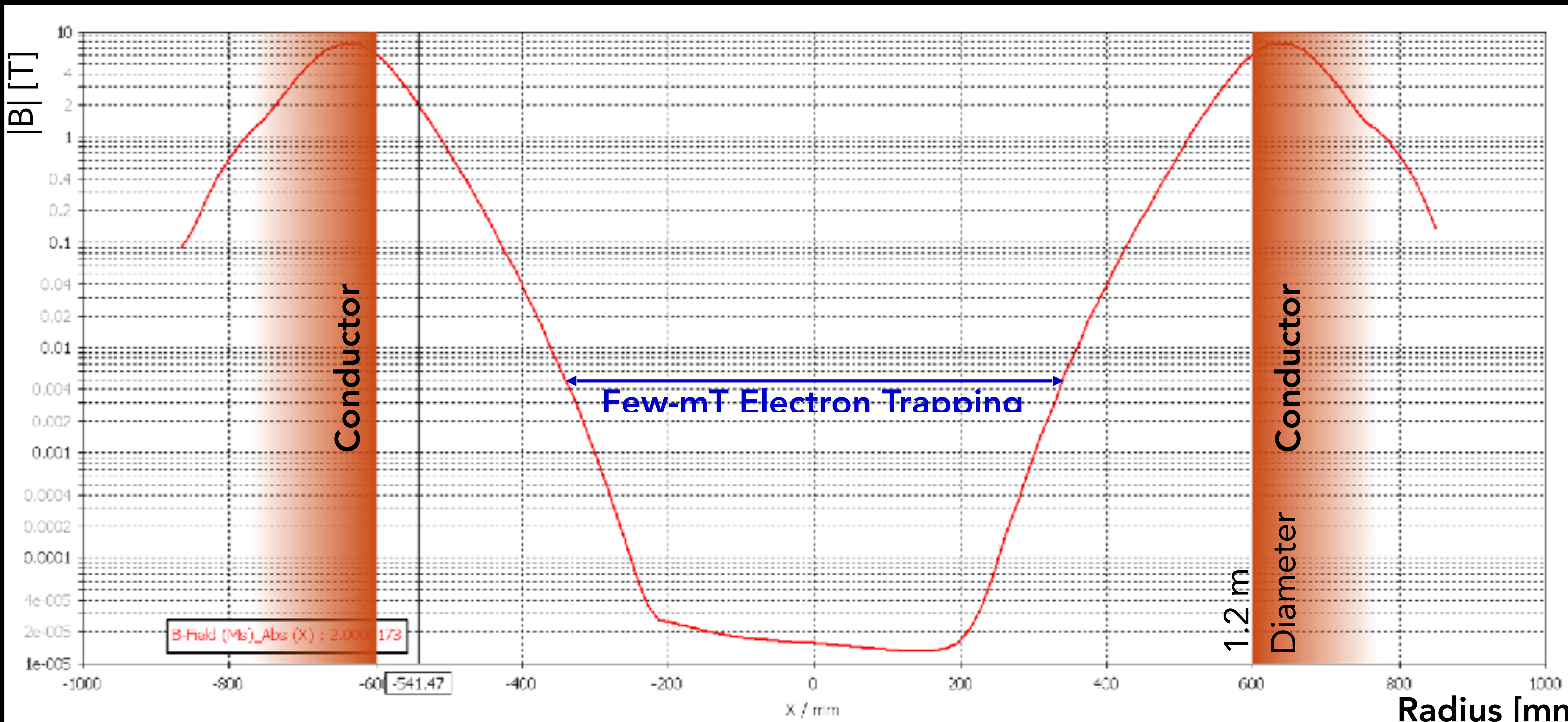

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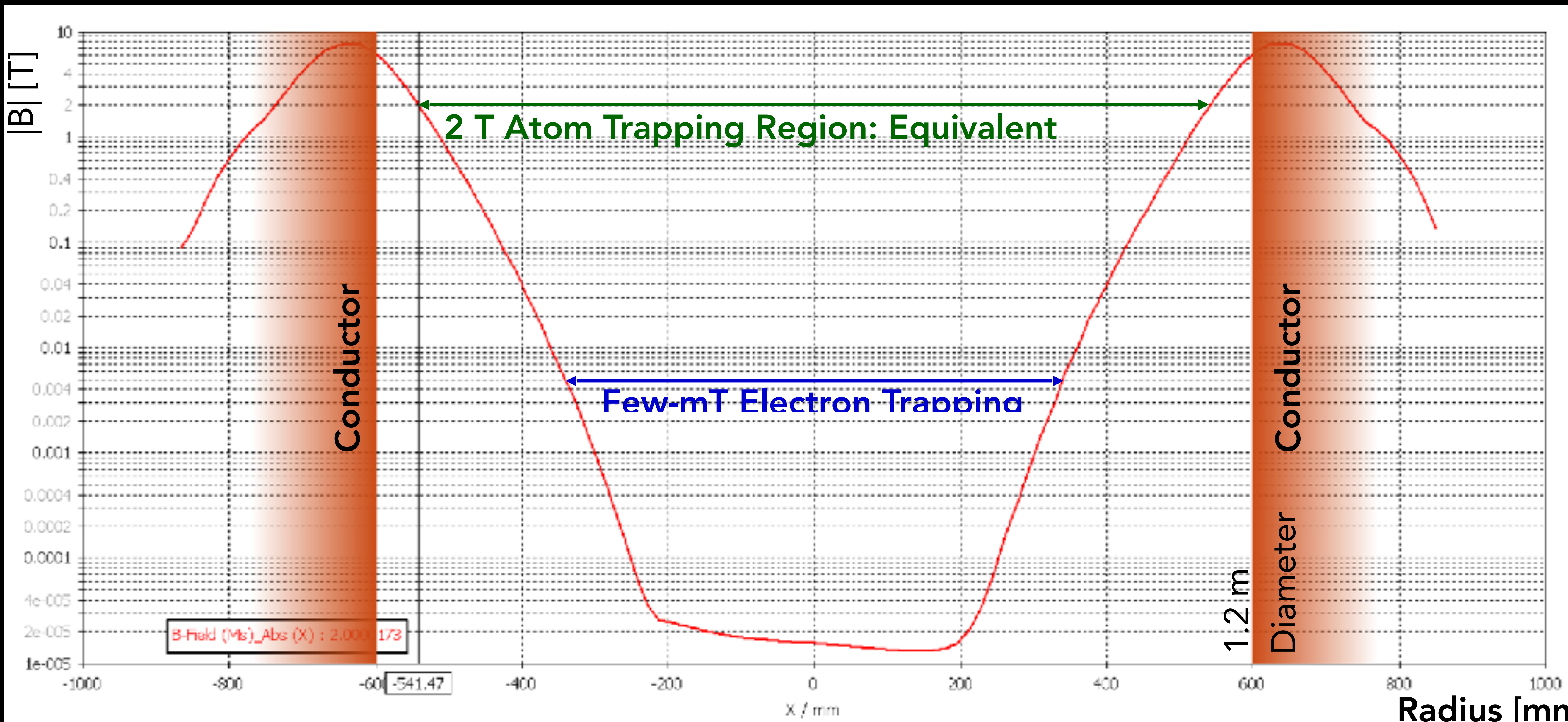

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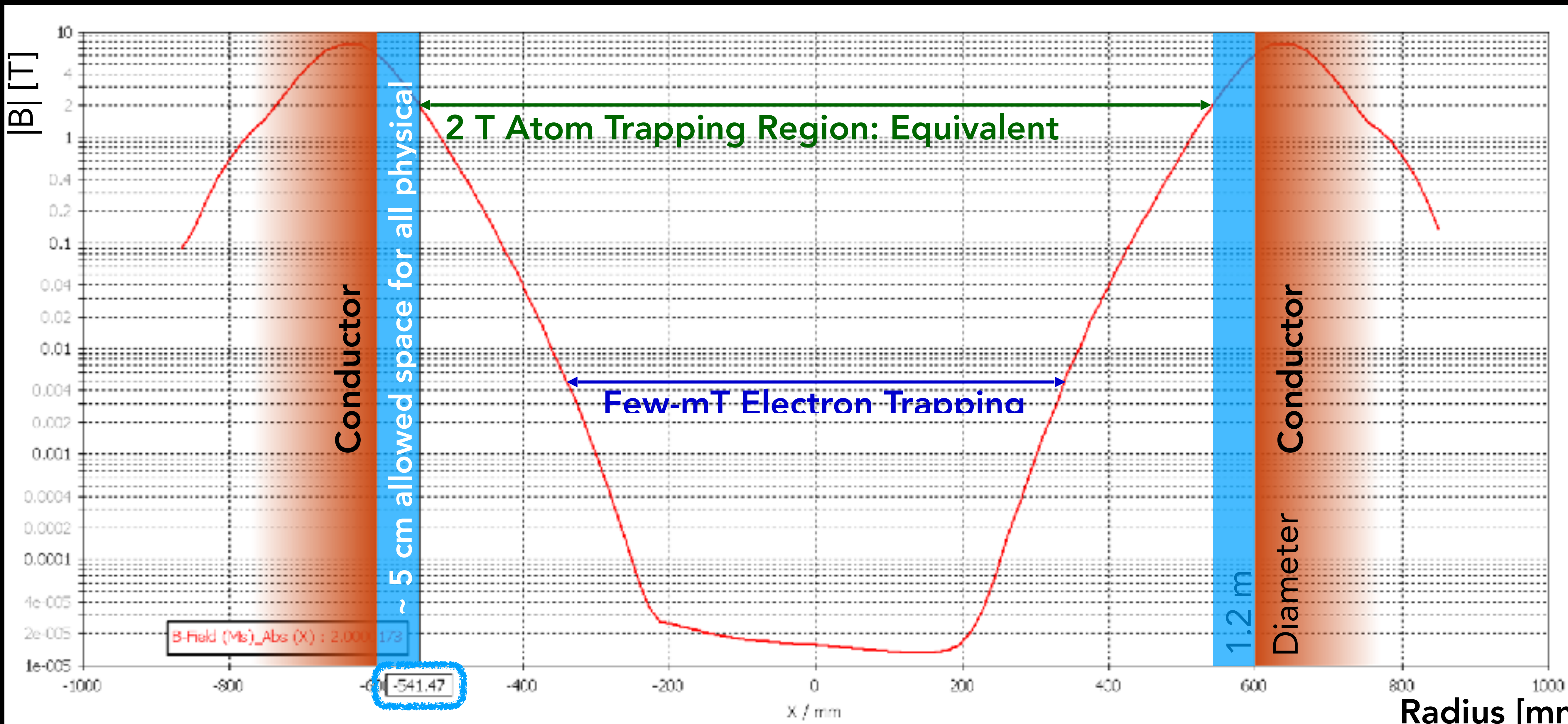

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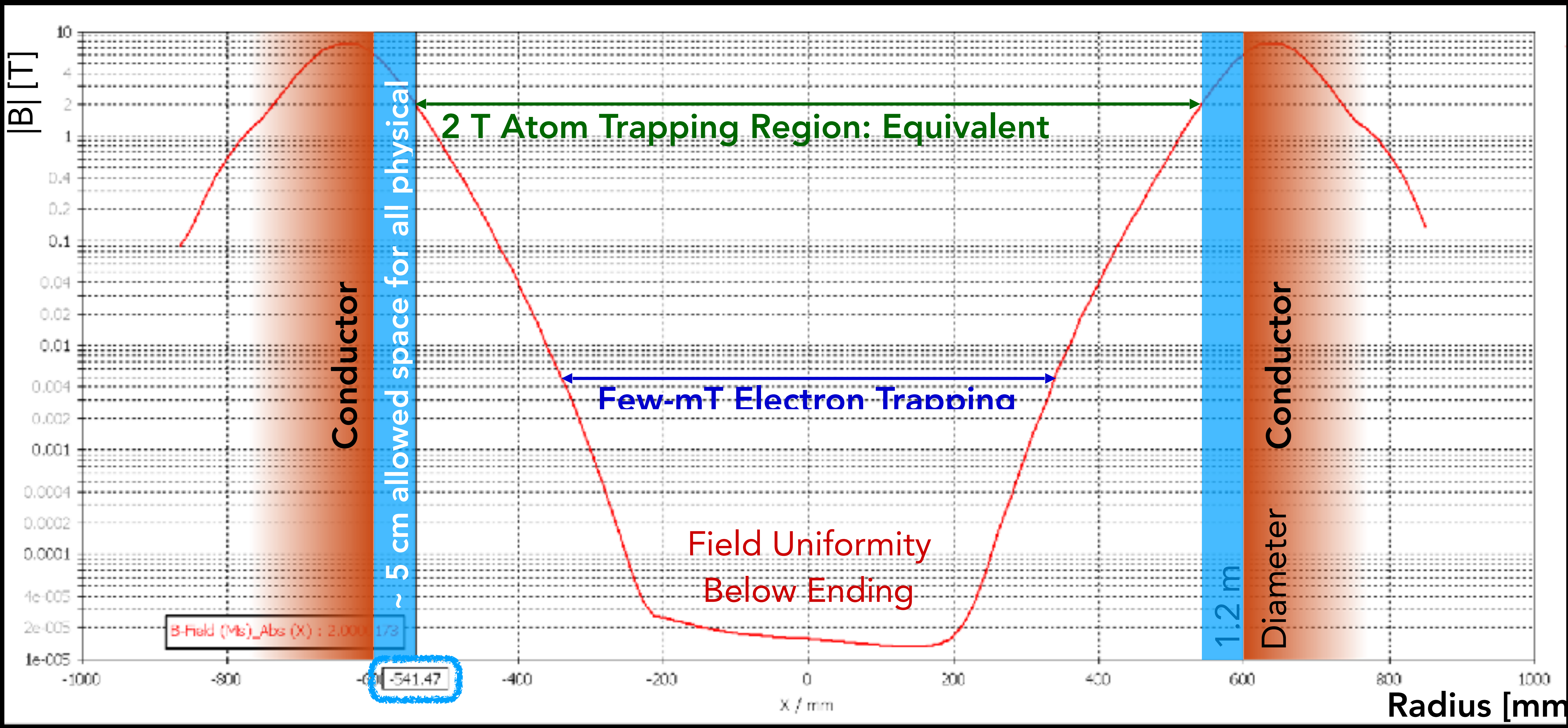
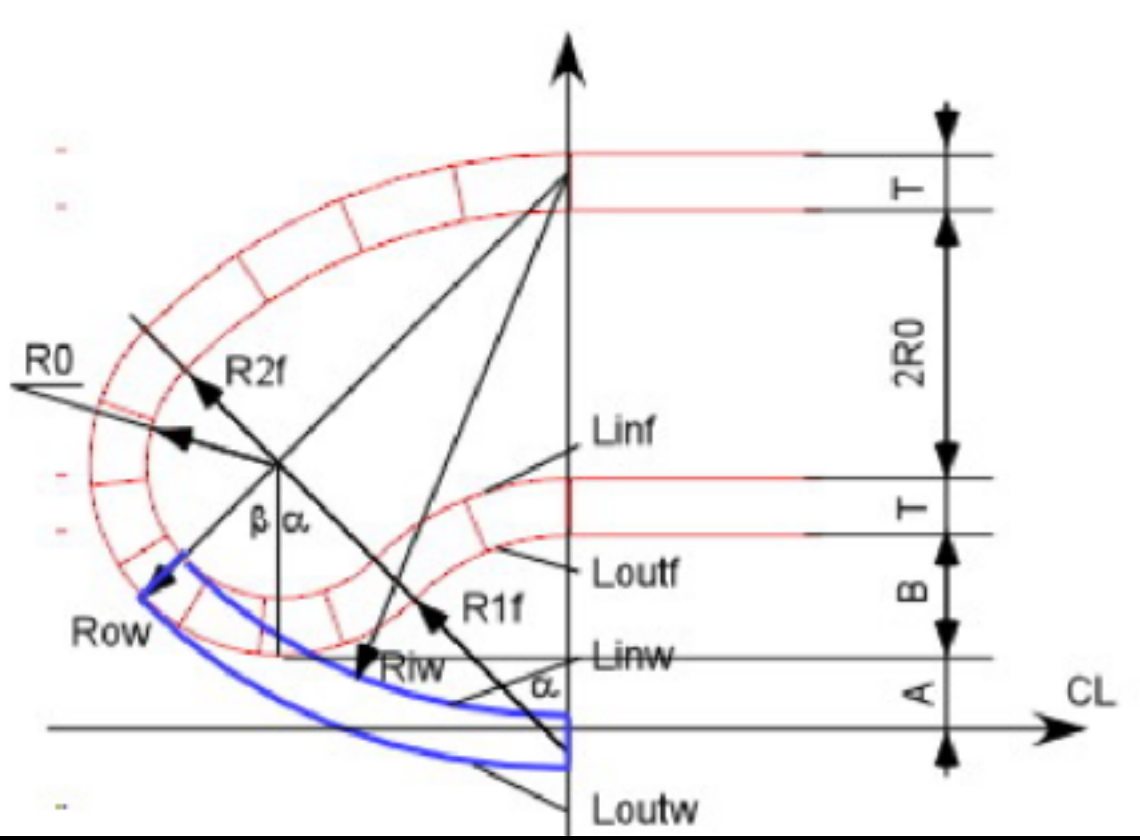


Ioffe Trap Demonstrator



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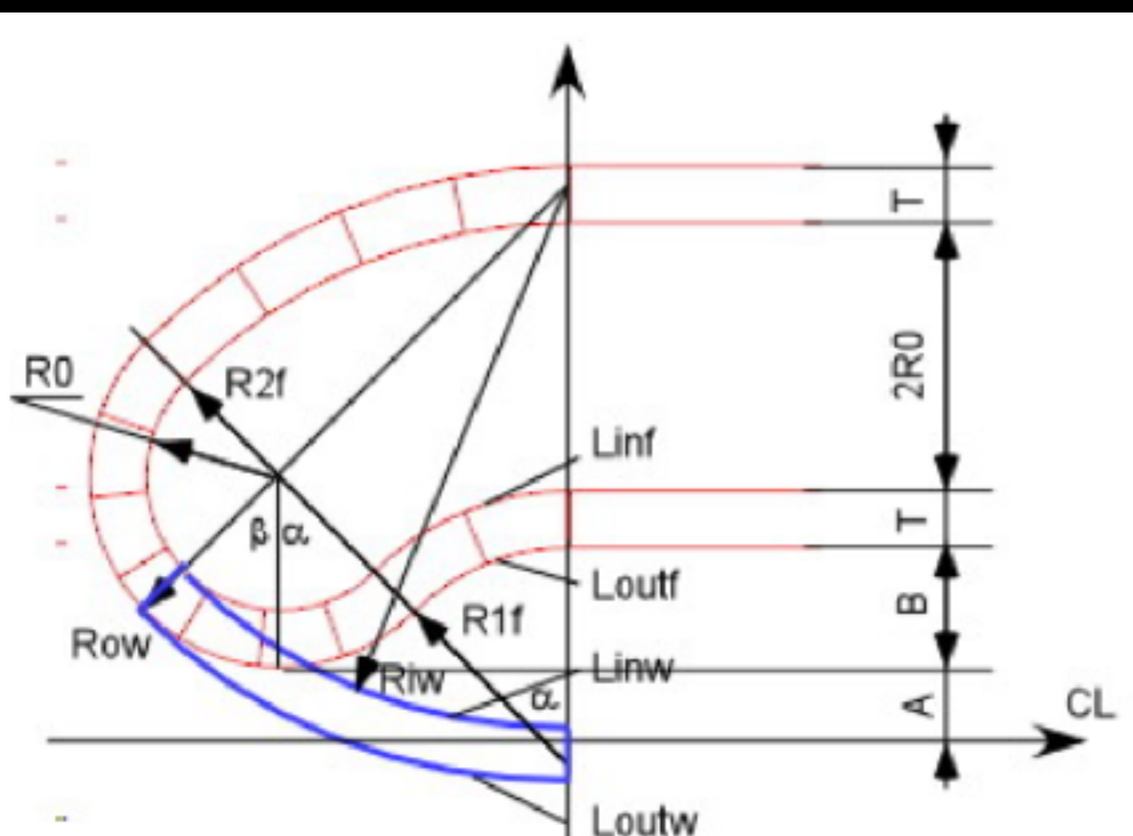

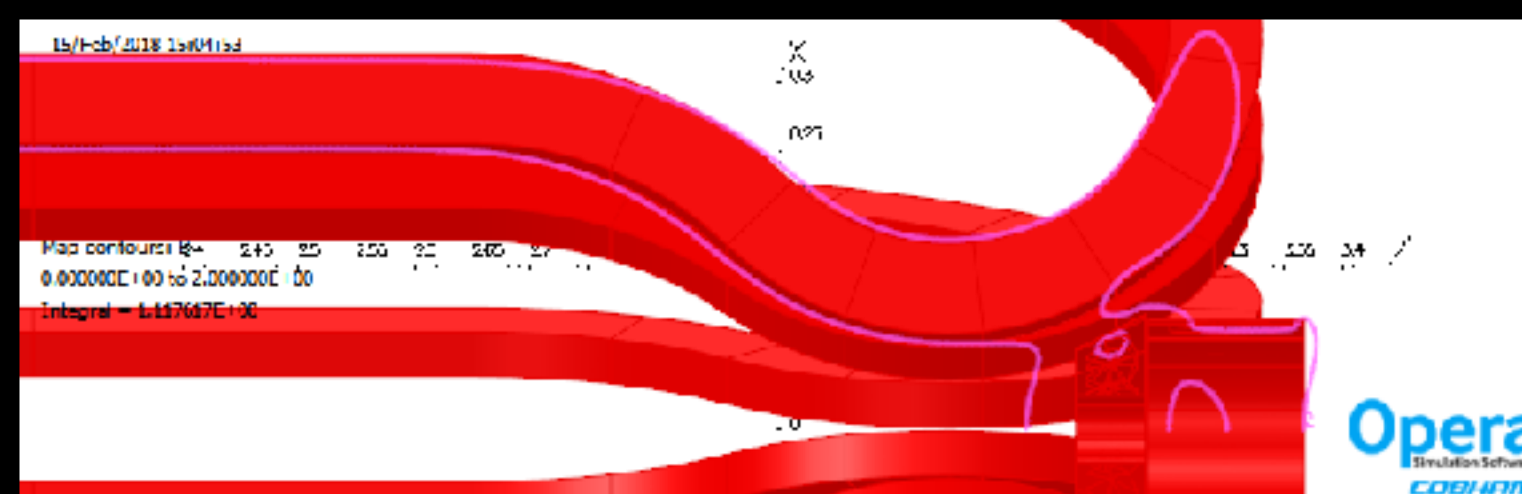

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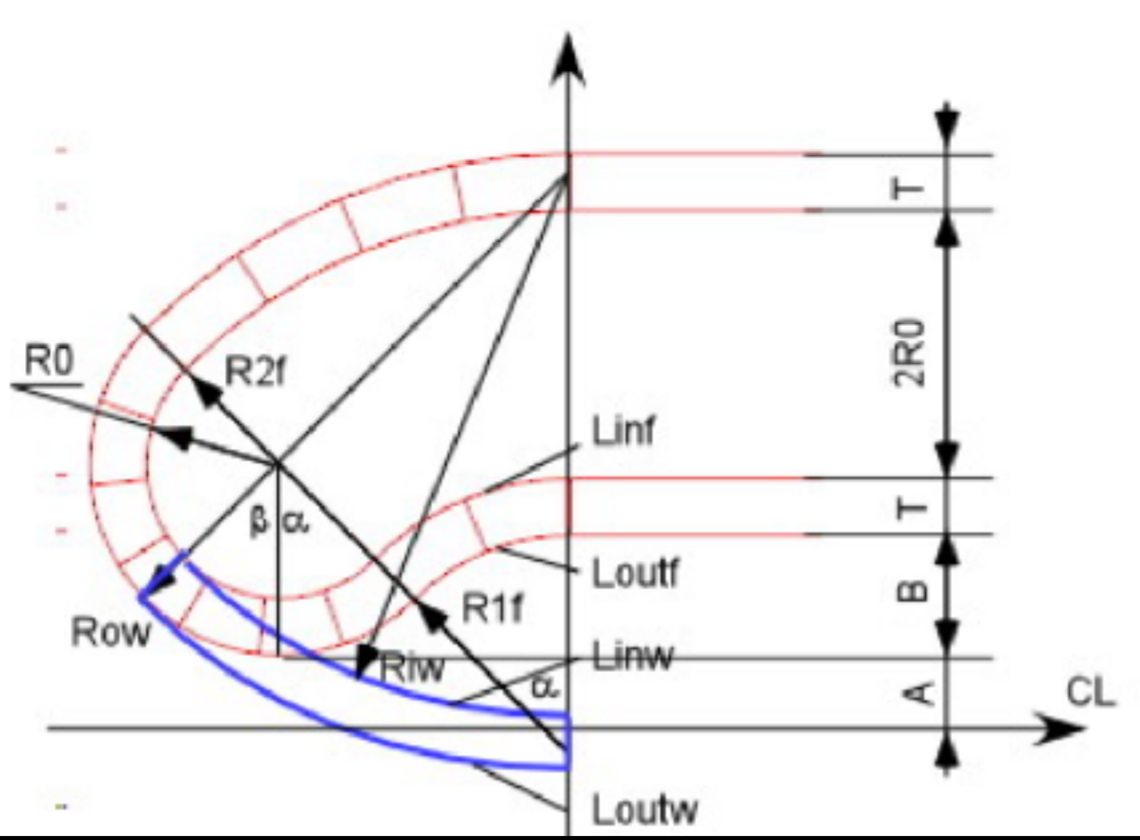

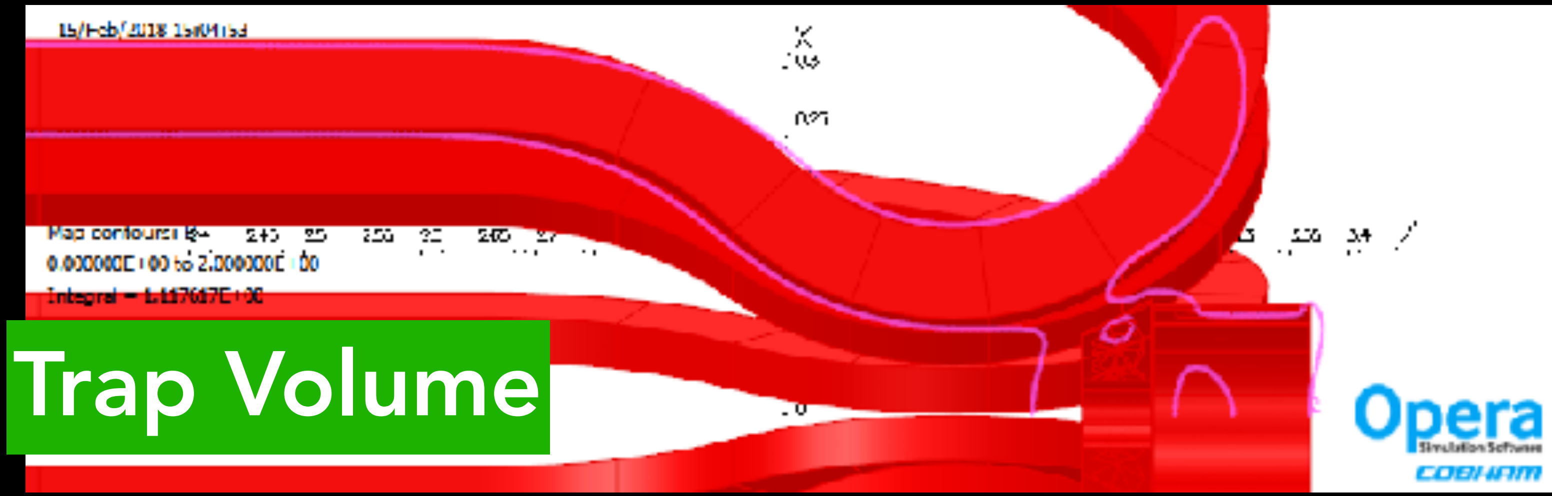

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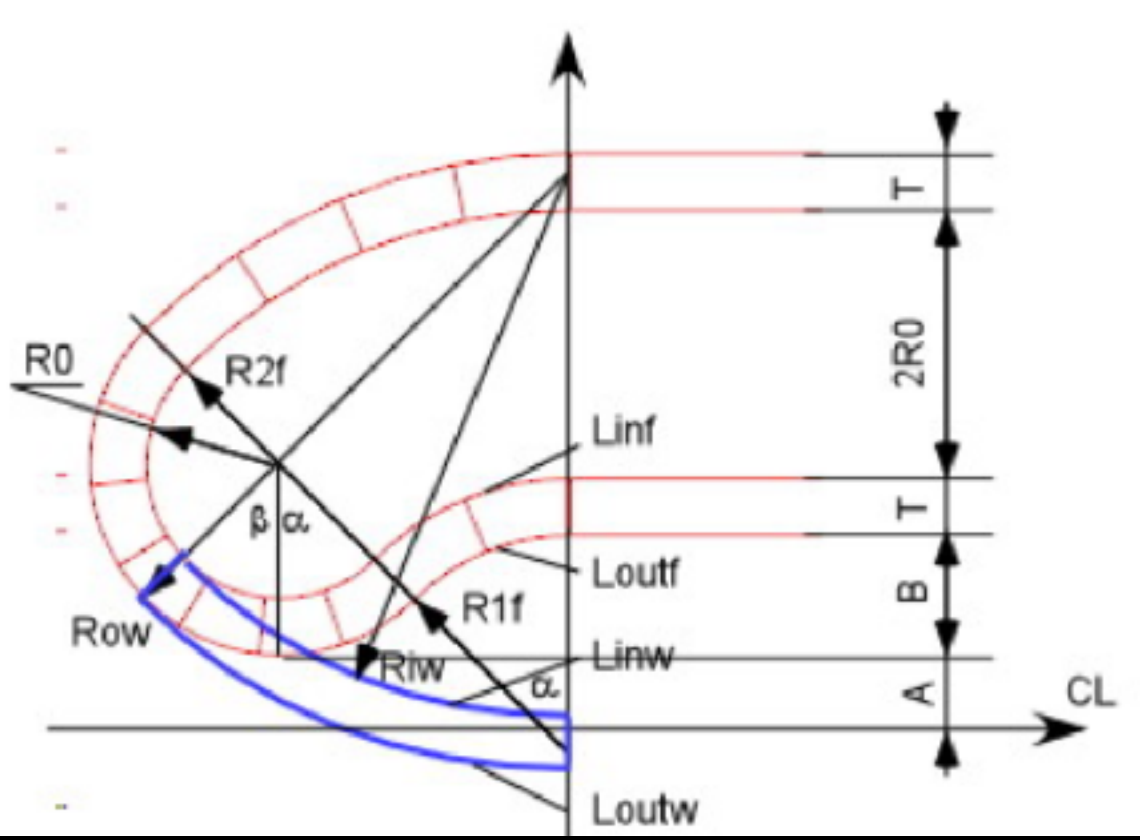

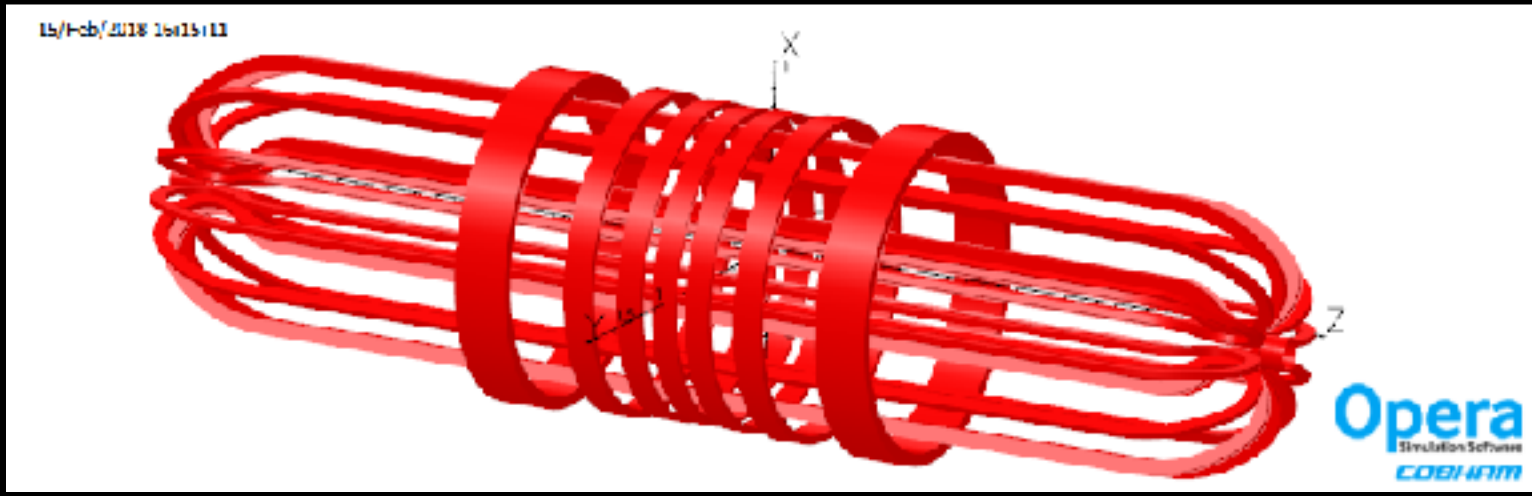

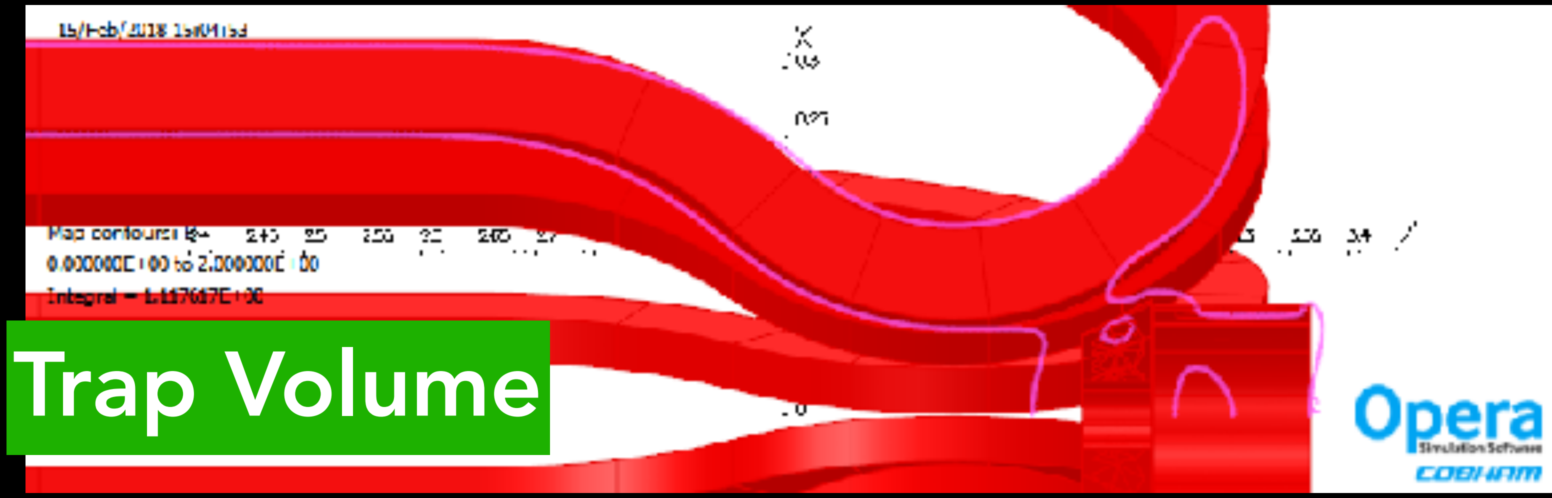

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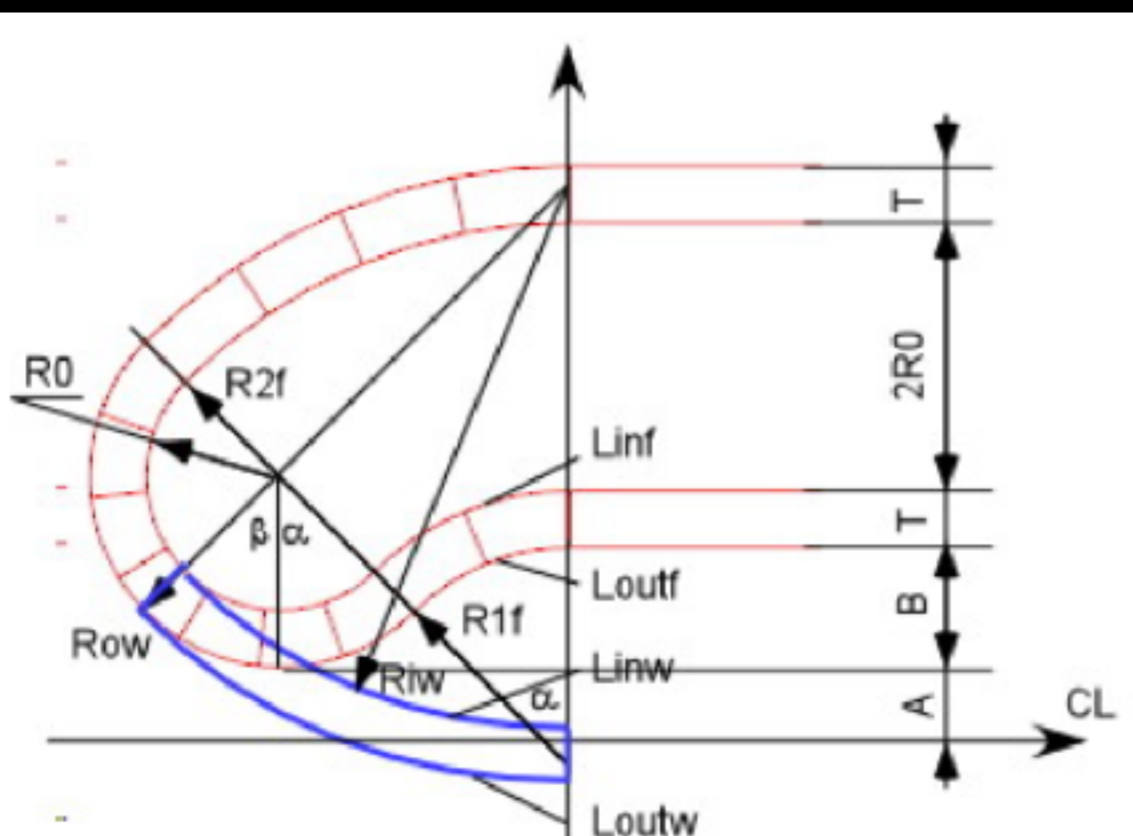
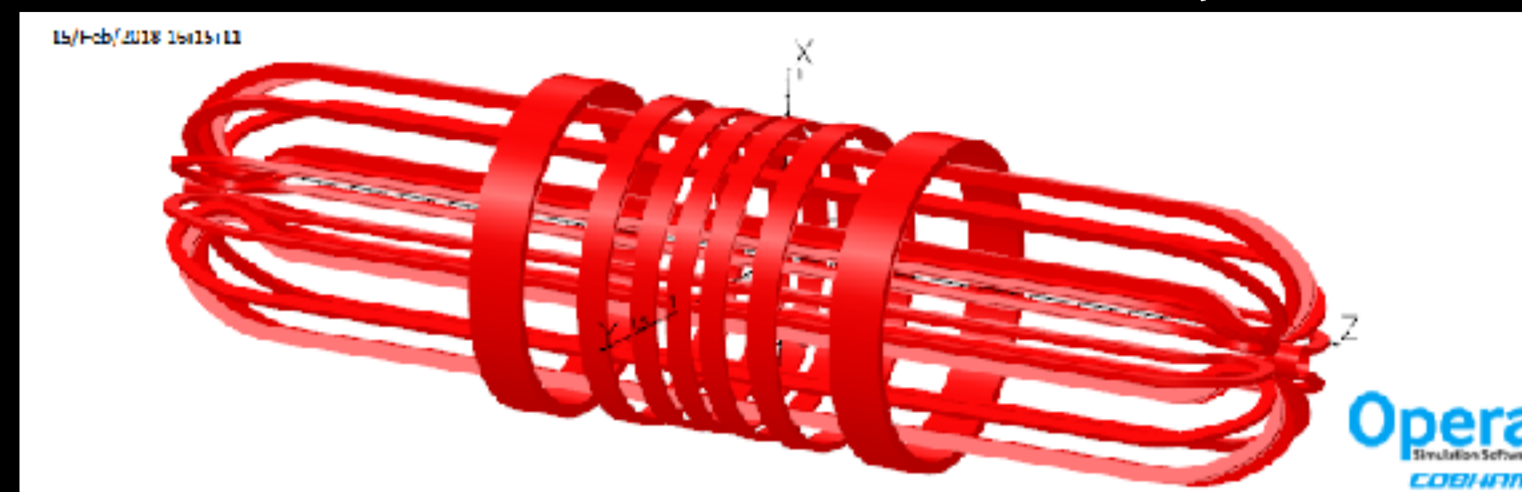


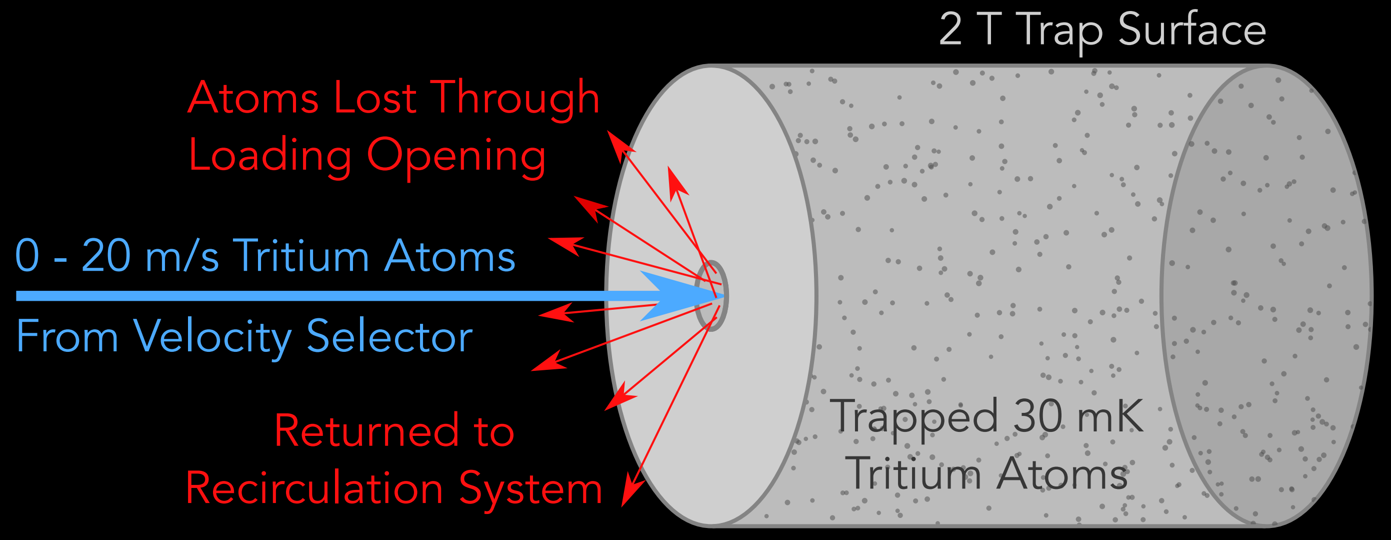
7 m



Trap Loading

- The low maximum gas density (10^{12} cm^{-3}) makes collisional cooling ineffective

- Instead, we create an opening in the trap surface; an intense beam of cold, trappable atoms compensates for the losses through this opening



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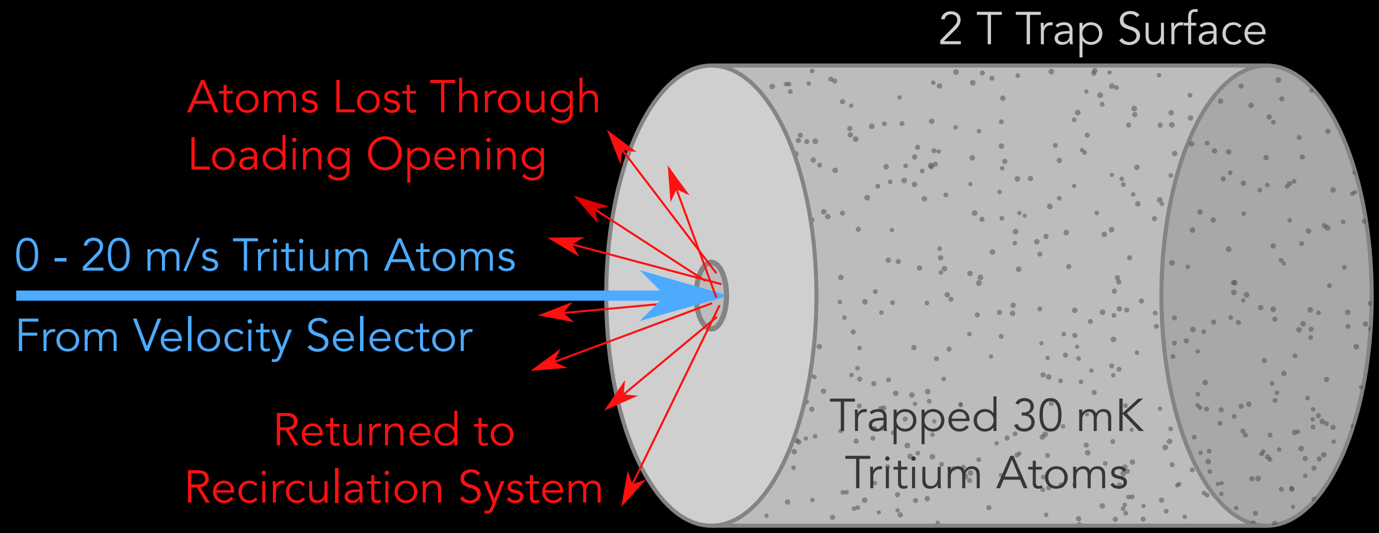

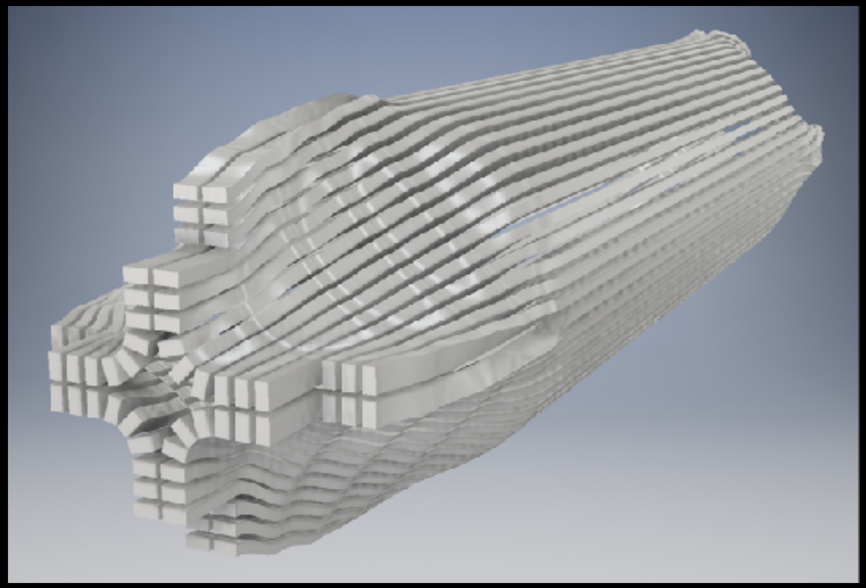

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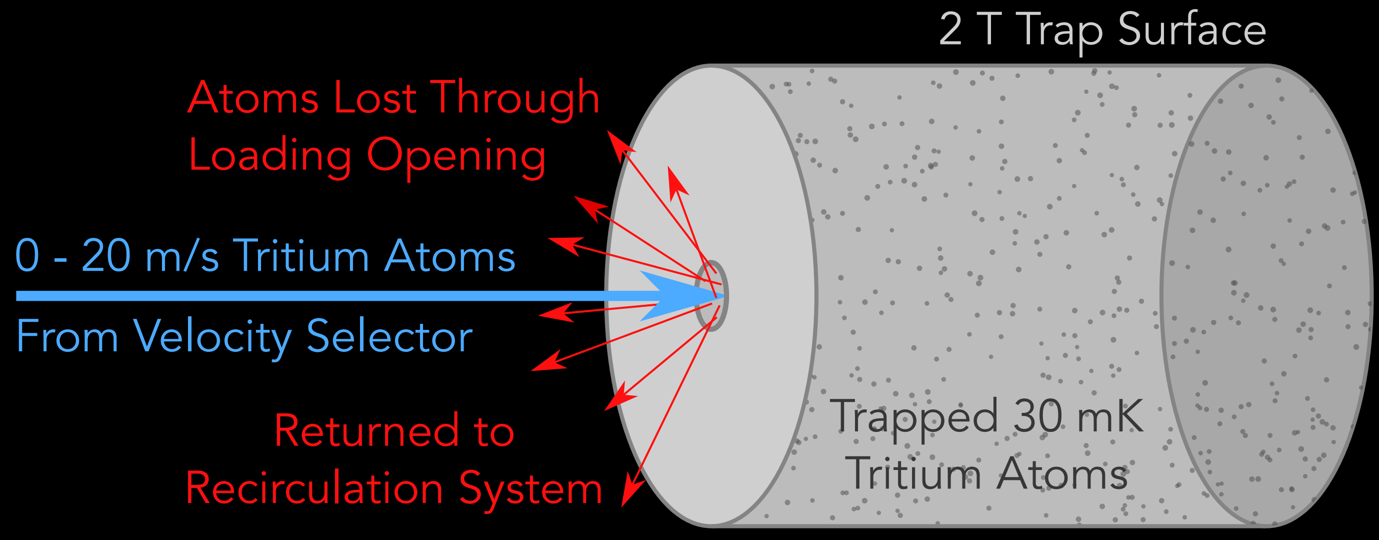

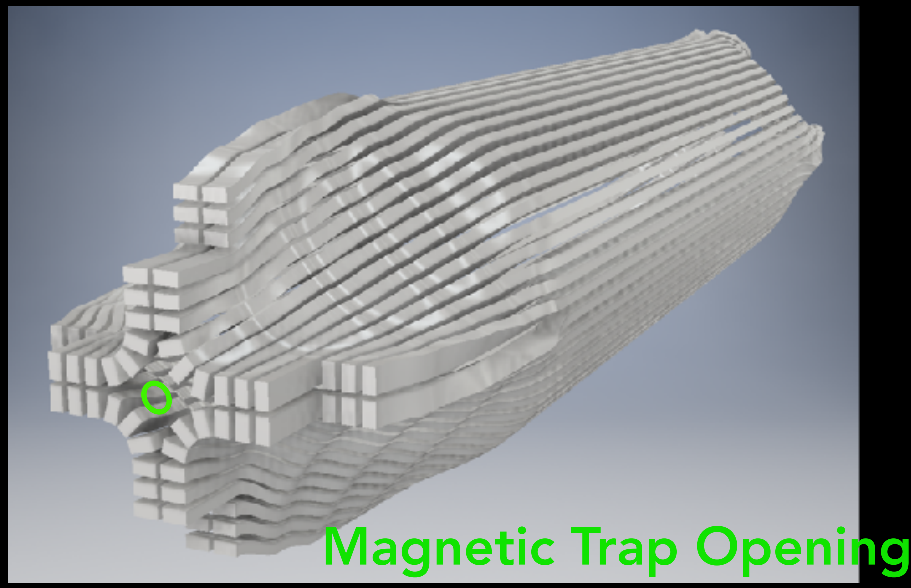

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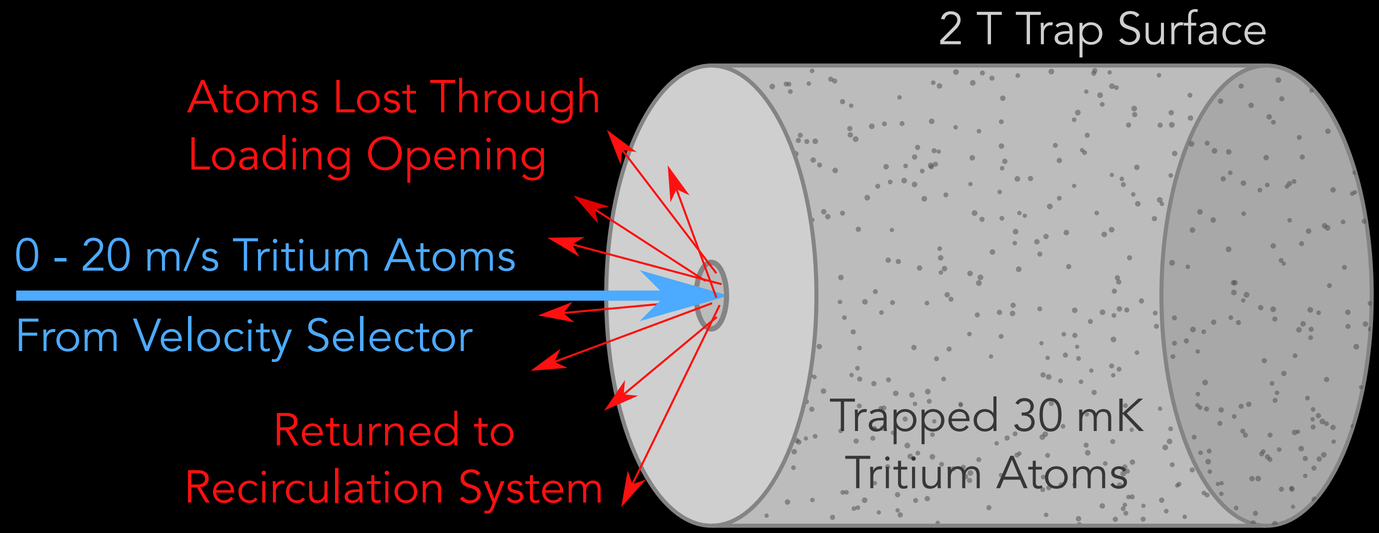

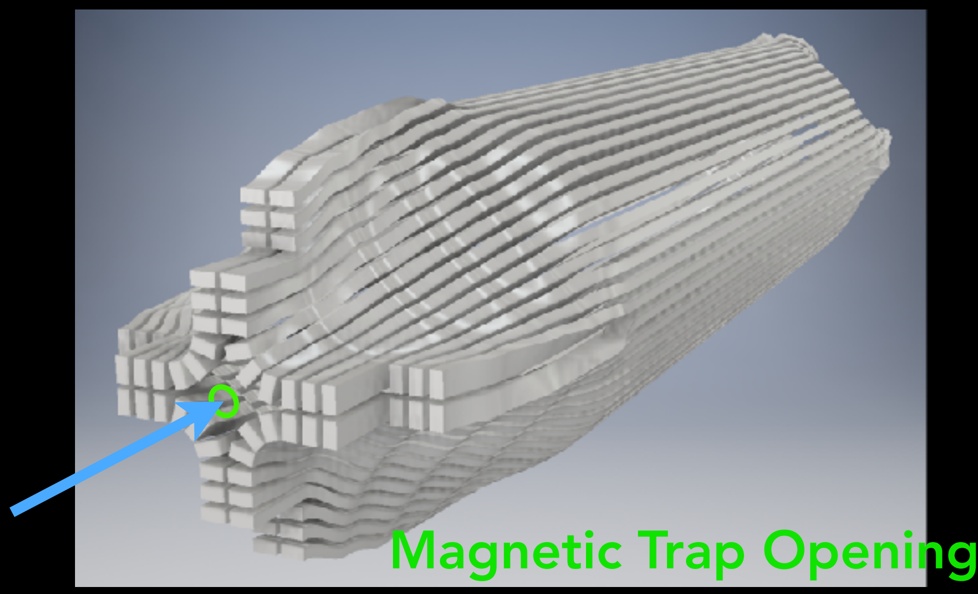

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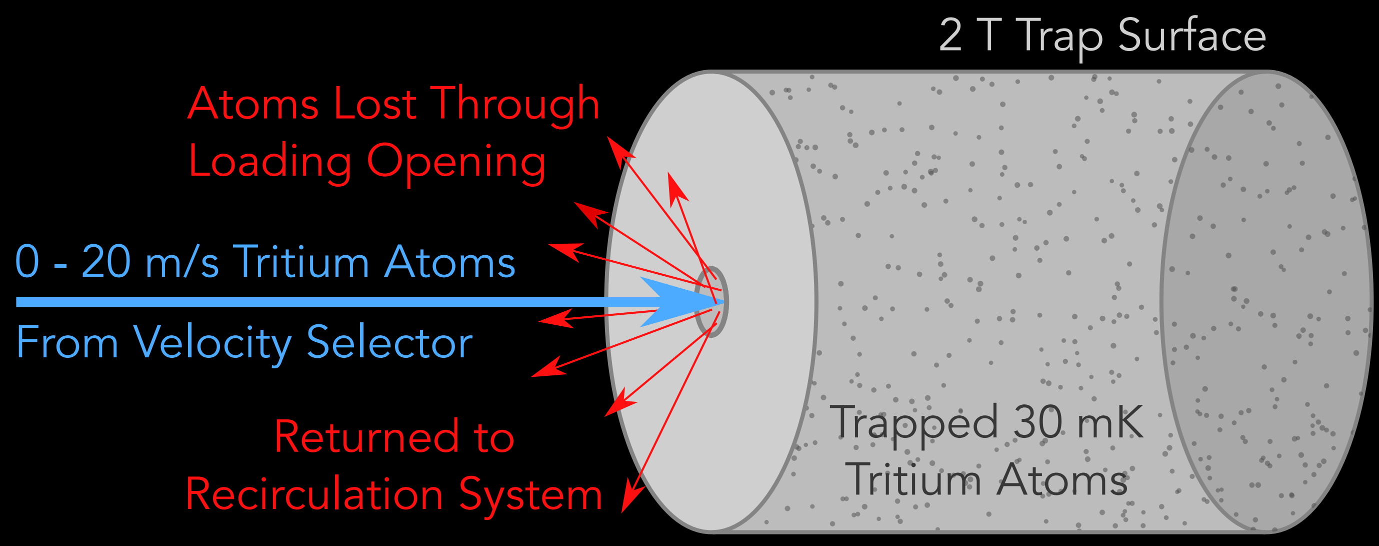
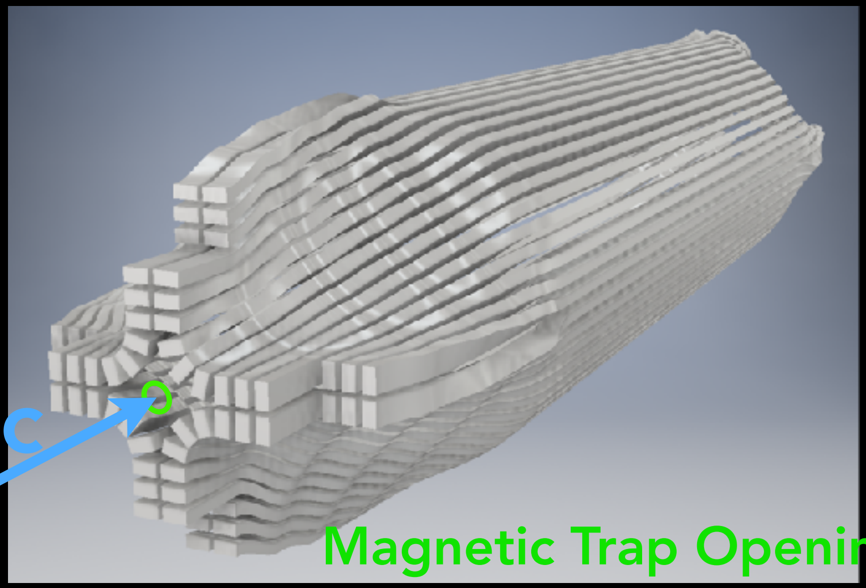


1 cm^2 opening

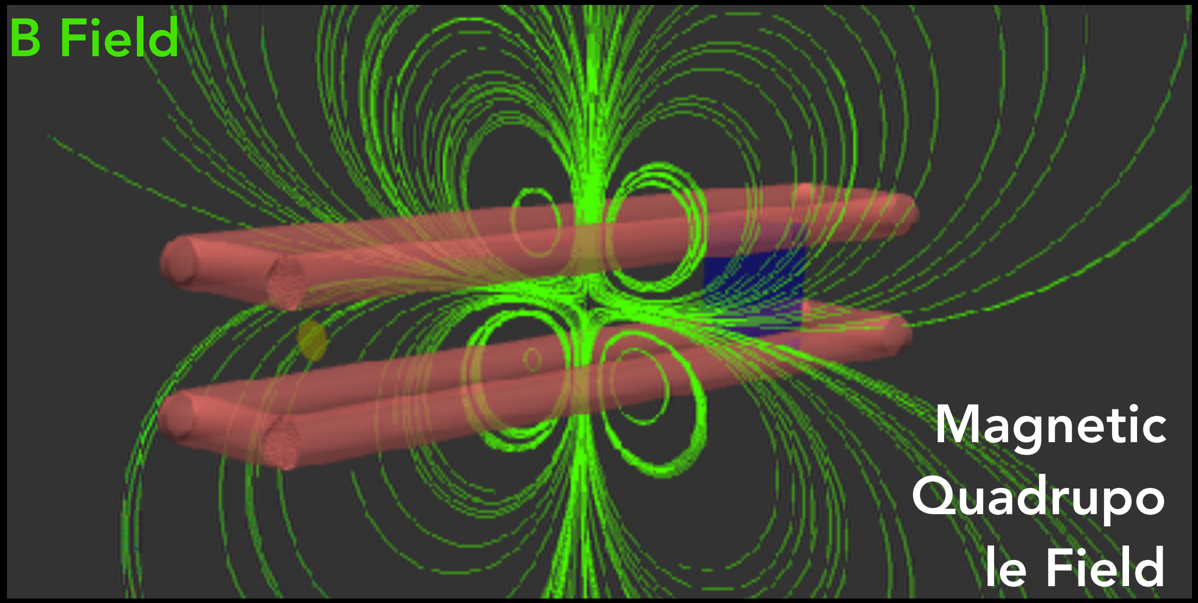
=

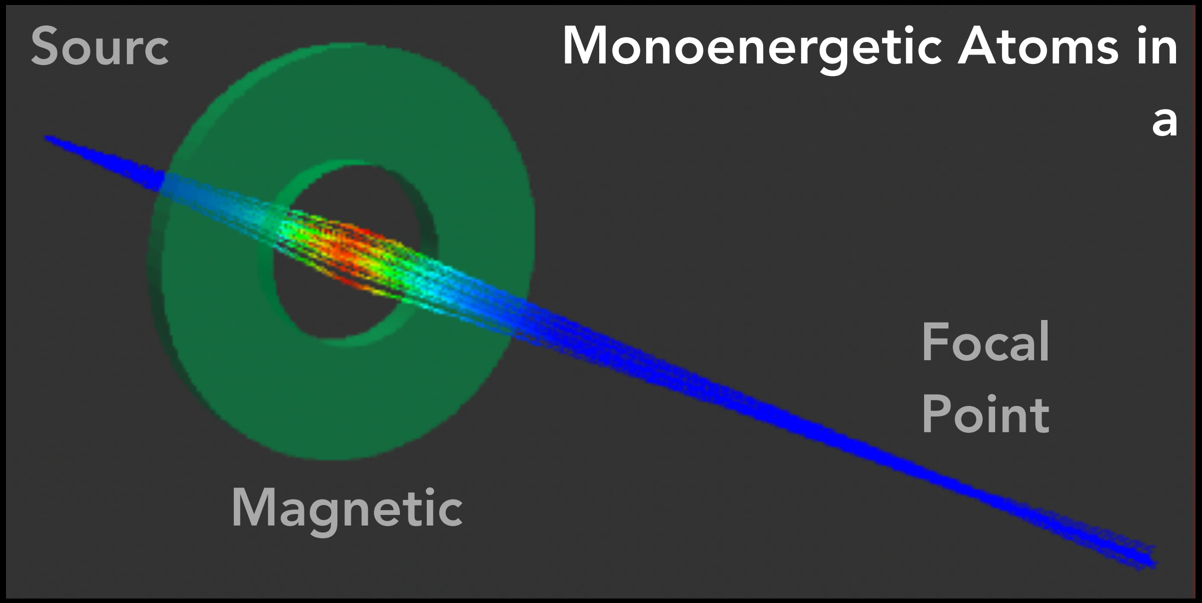
8×10^{14} atoms/sec



Velocity Selection

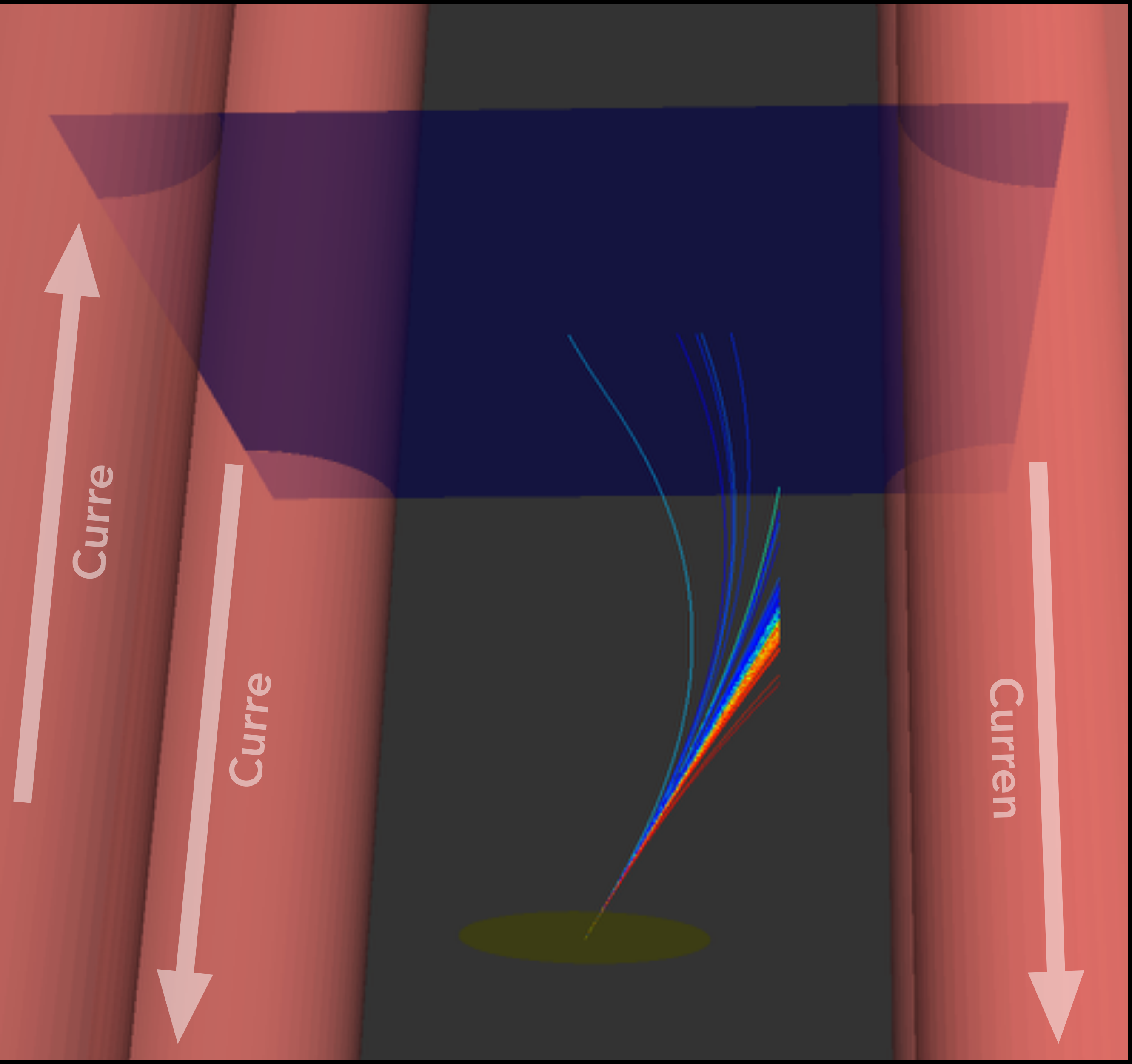
- The fraction of atoms in a 30 K Maxwell-Boltzmann distribution between 60 and 80 m/s is 2.5×10^{-3}
- Rather than relying on the trap to separate trappable (slow) and untrappable (fast) atoms, we will magnetically separate them before trap loading





Quadrupole Selector

Quadrupole Selector



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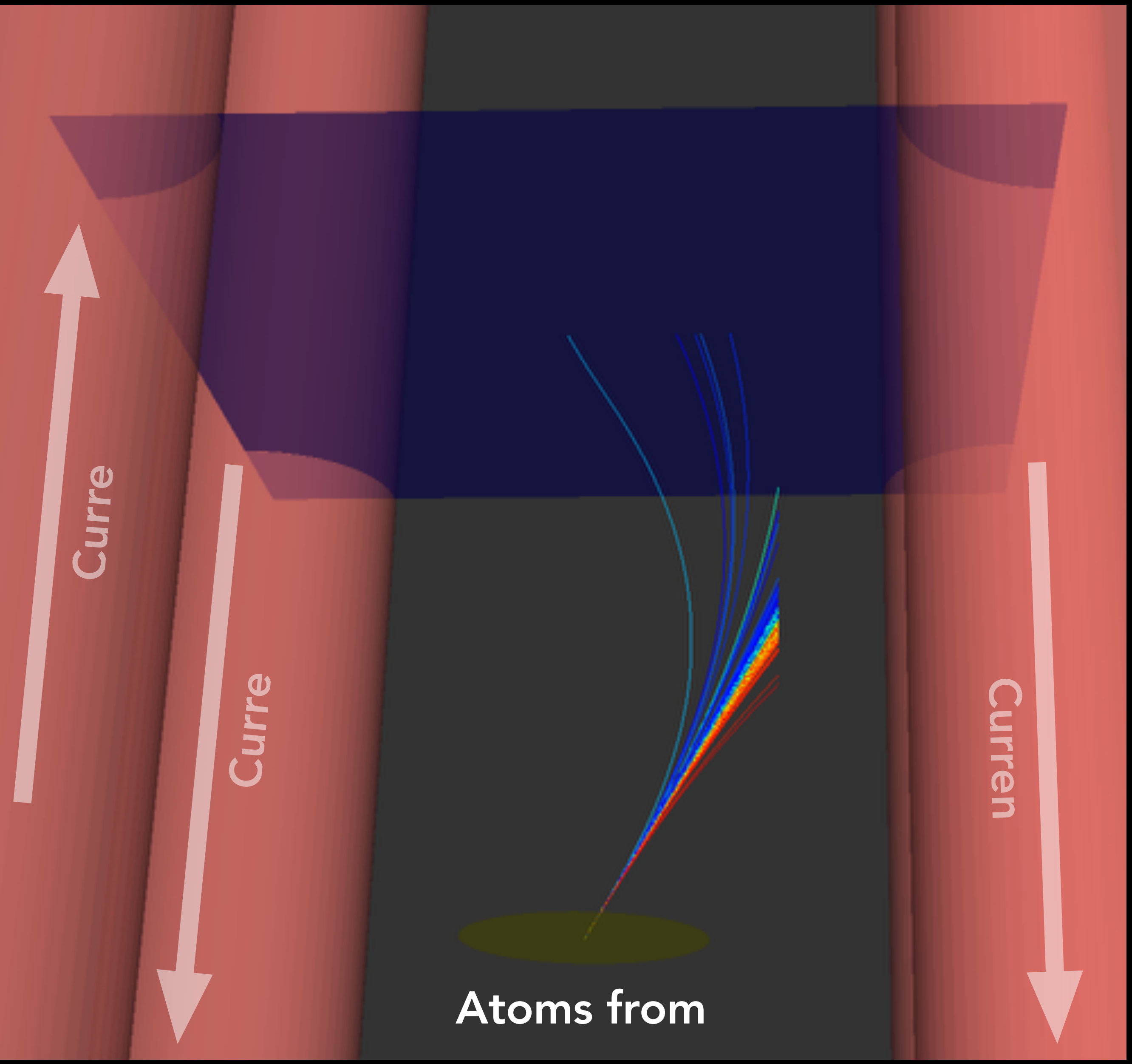

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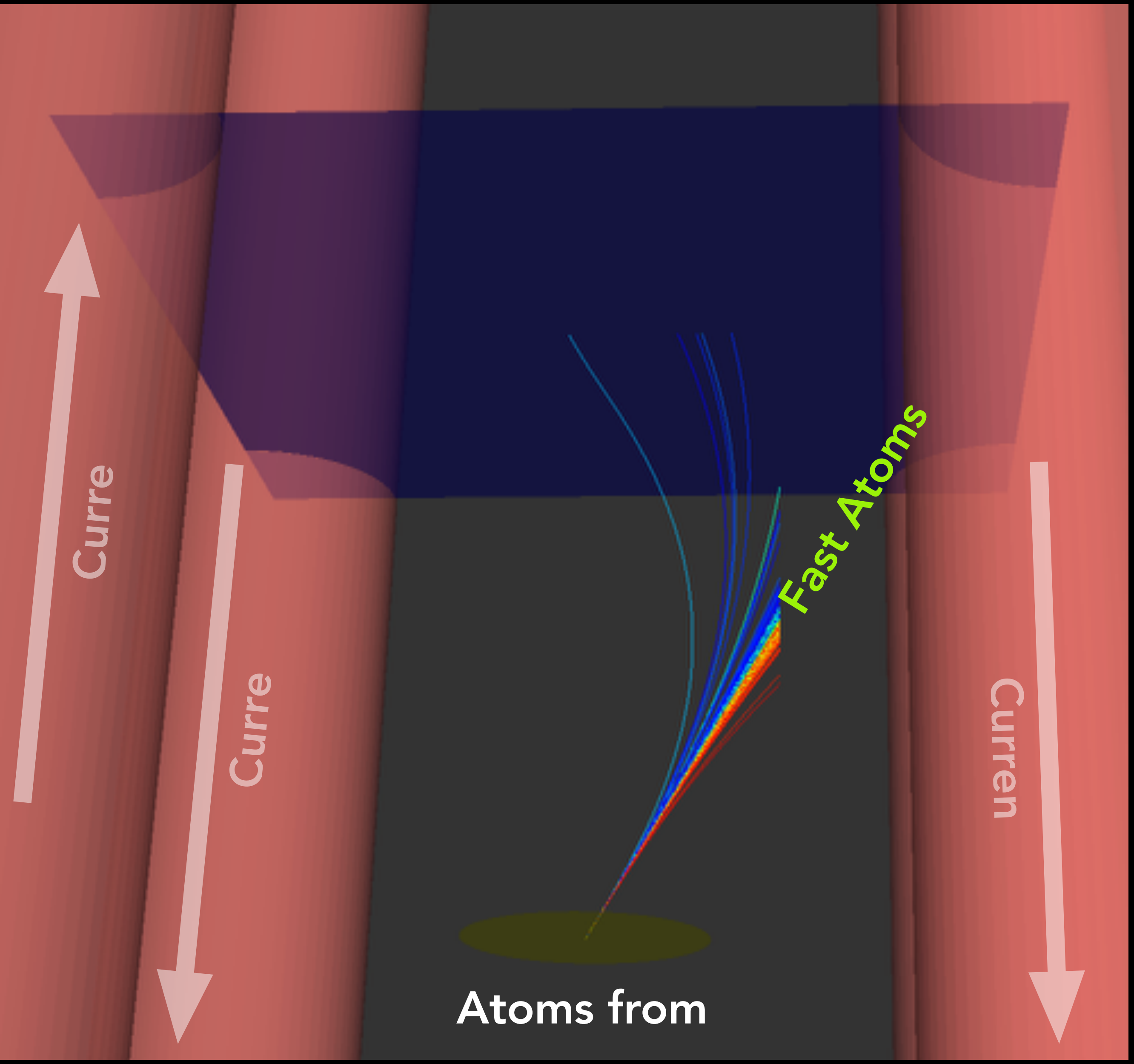

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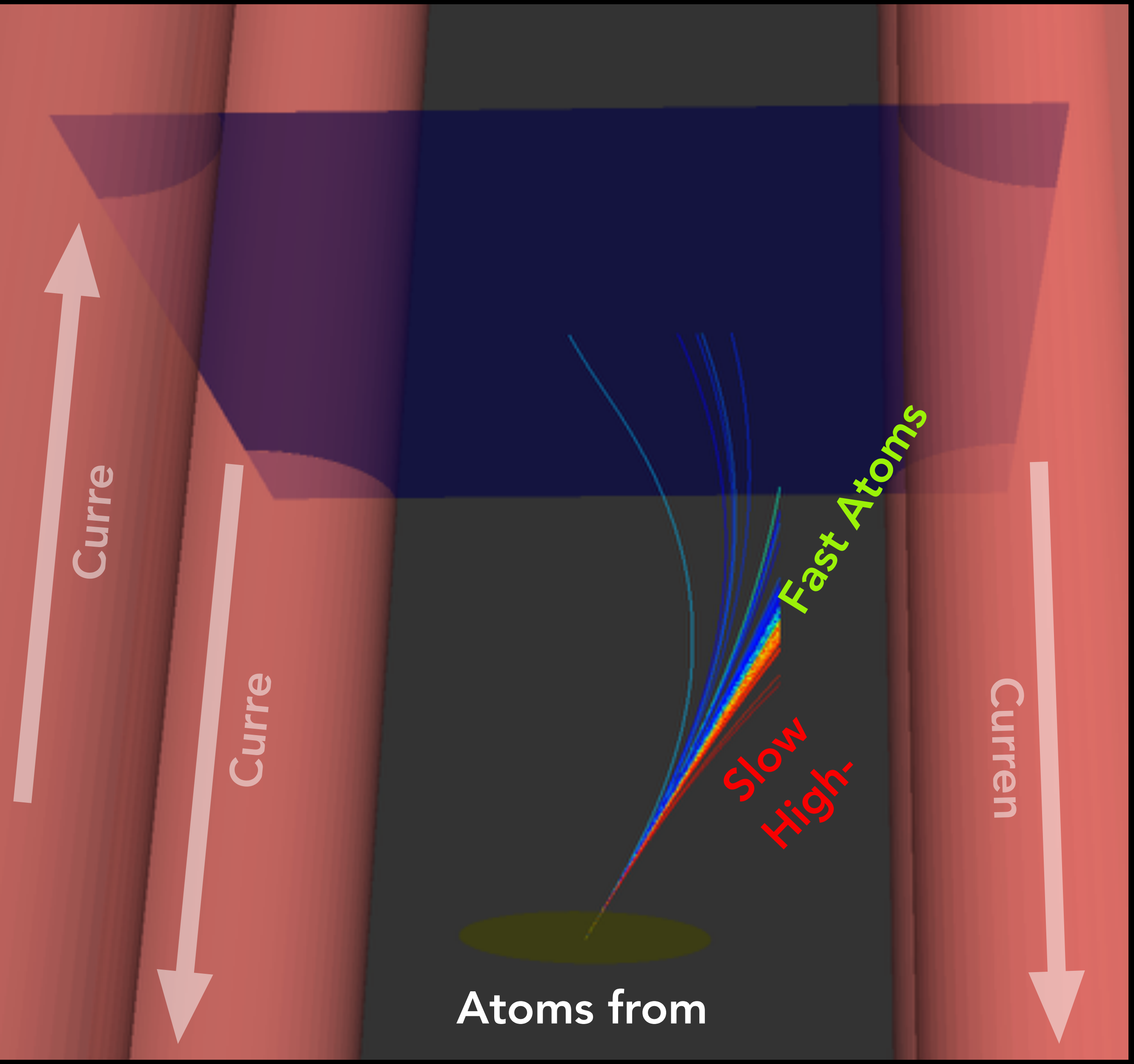

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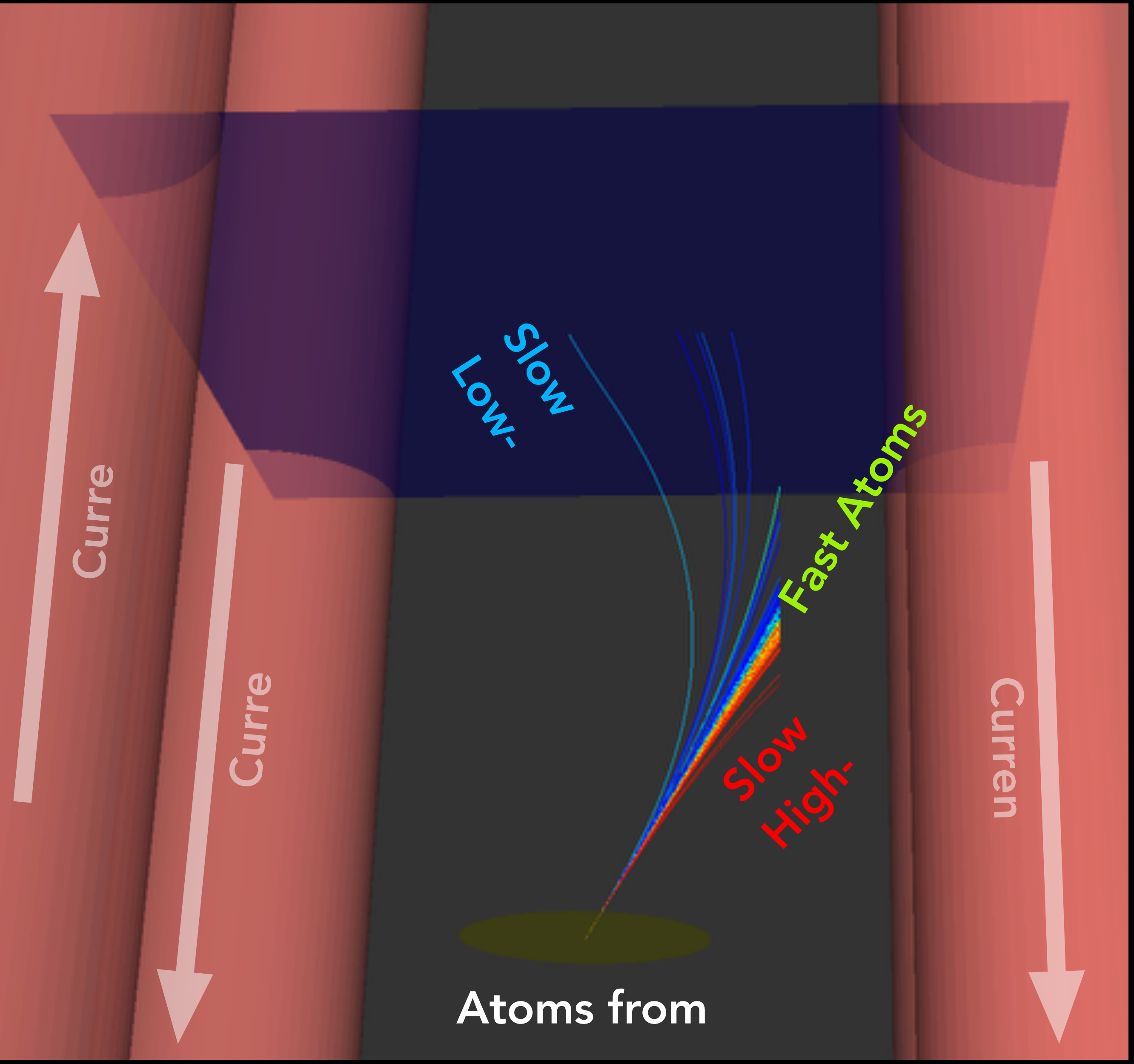

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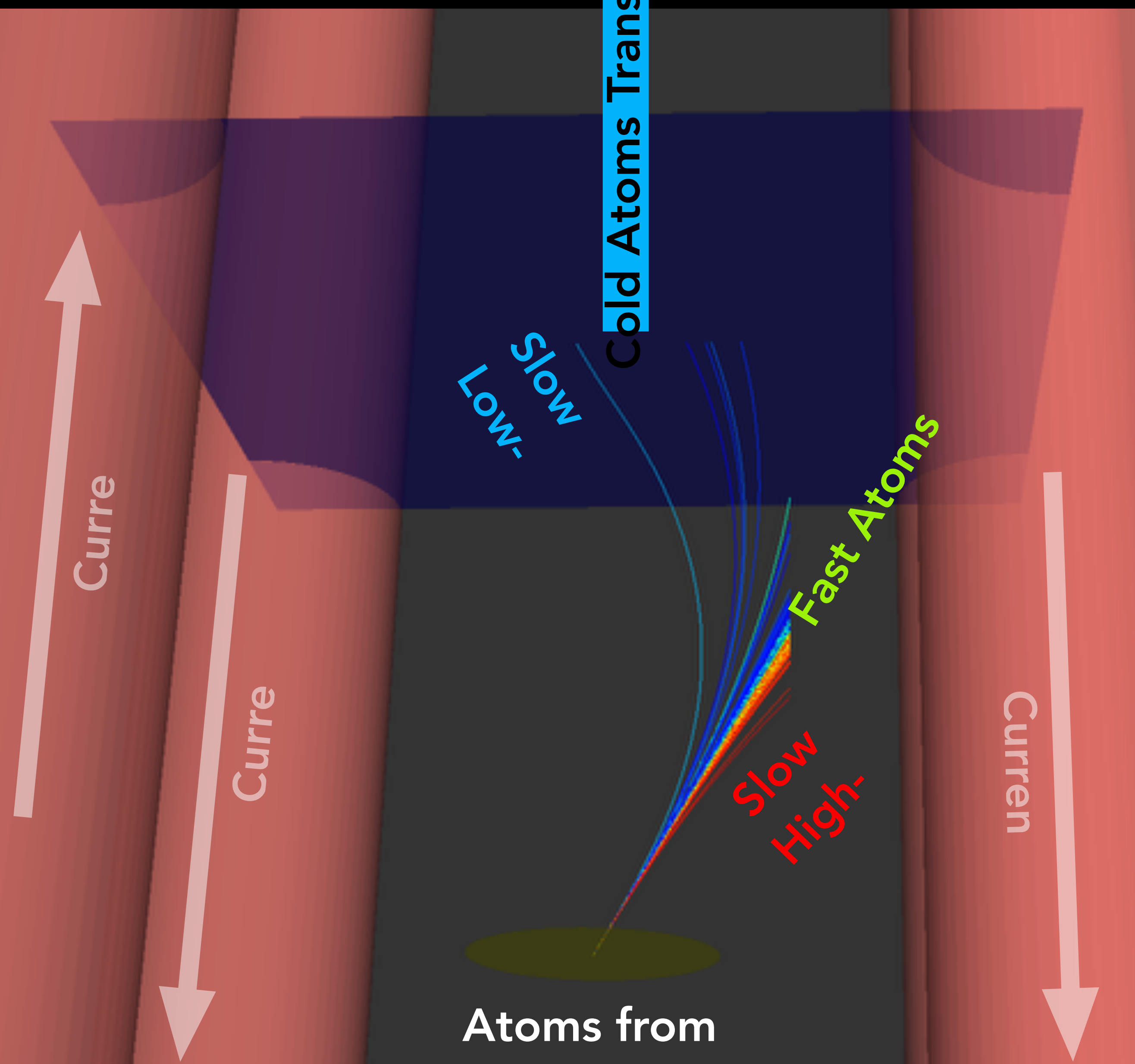

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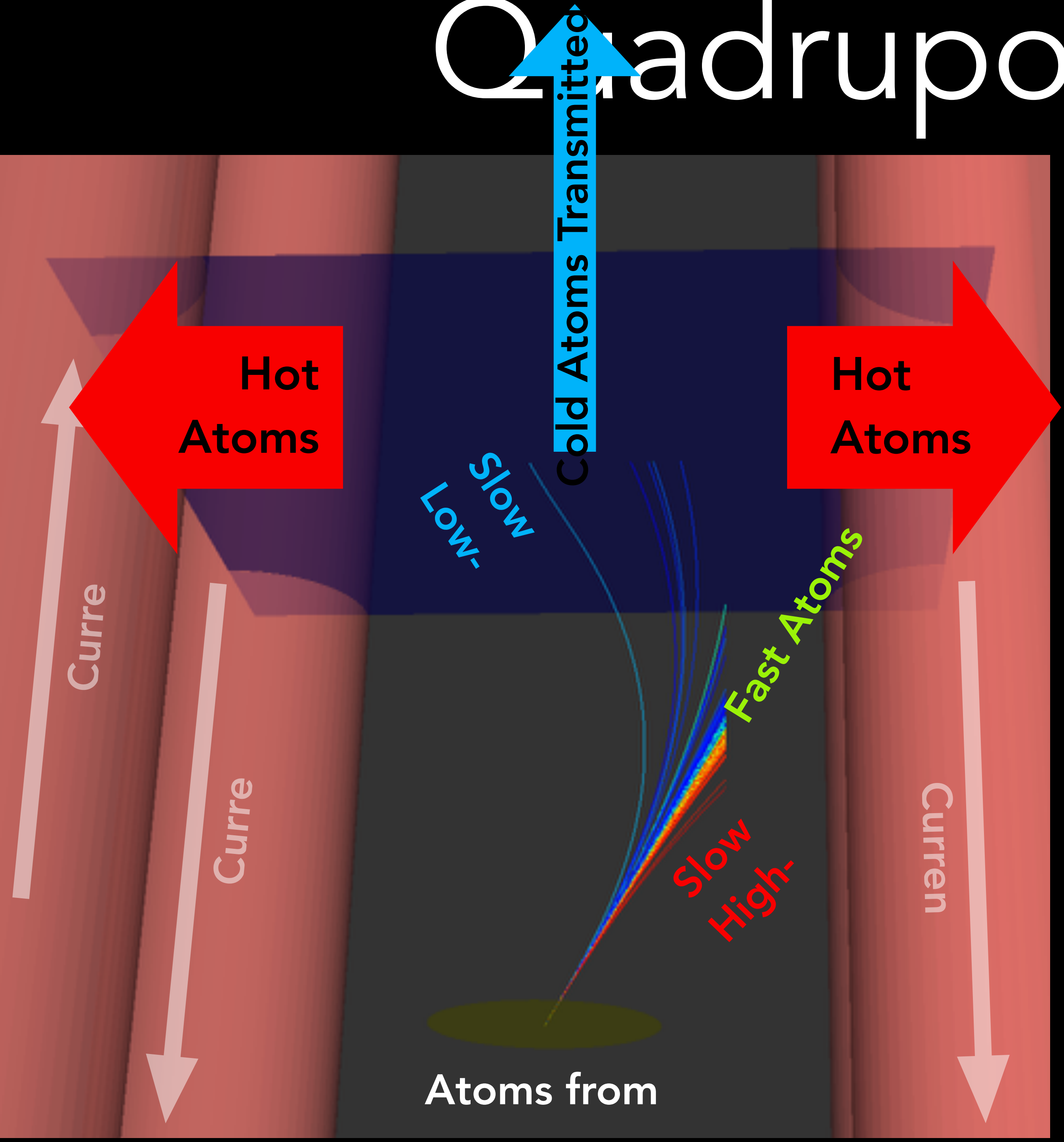

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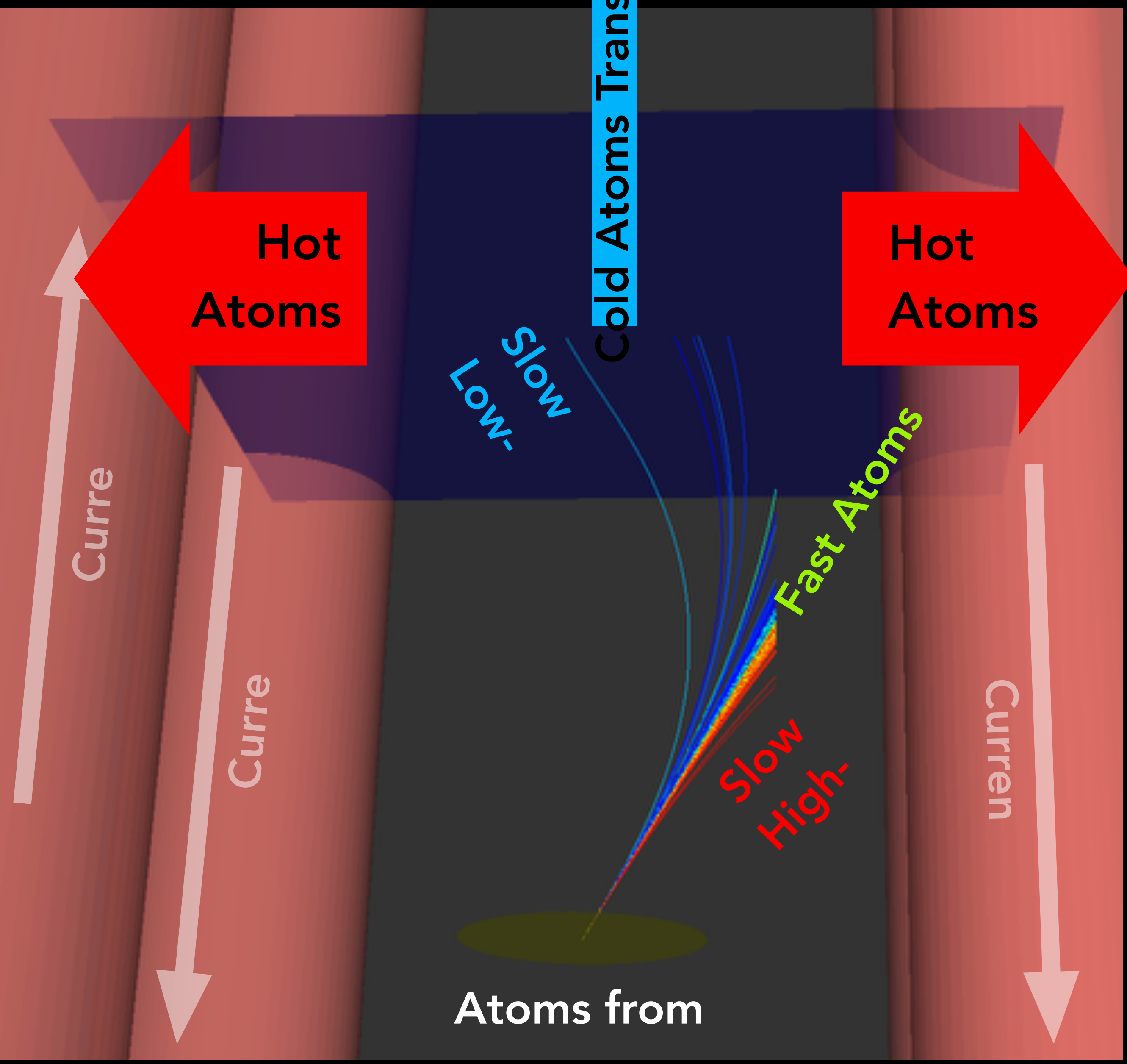

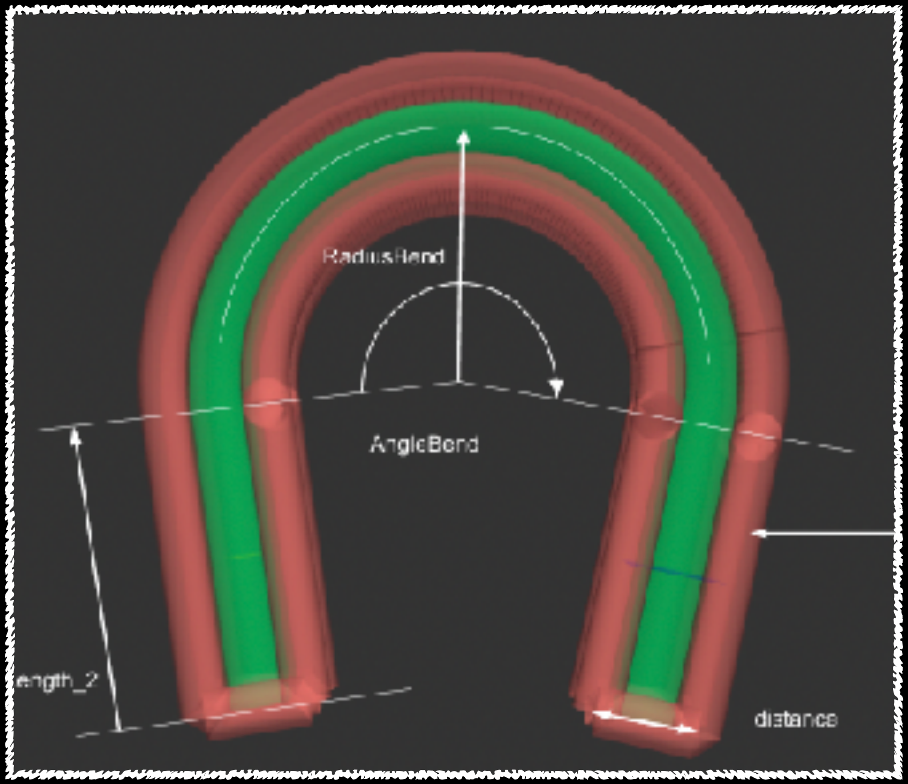

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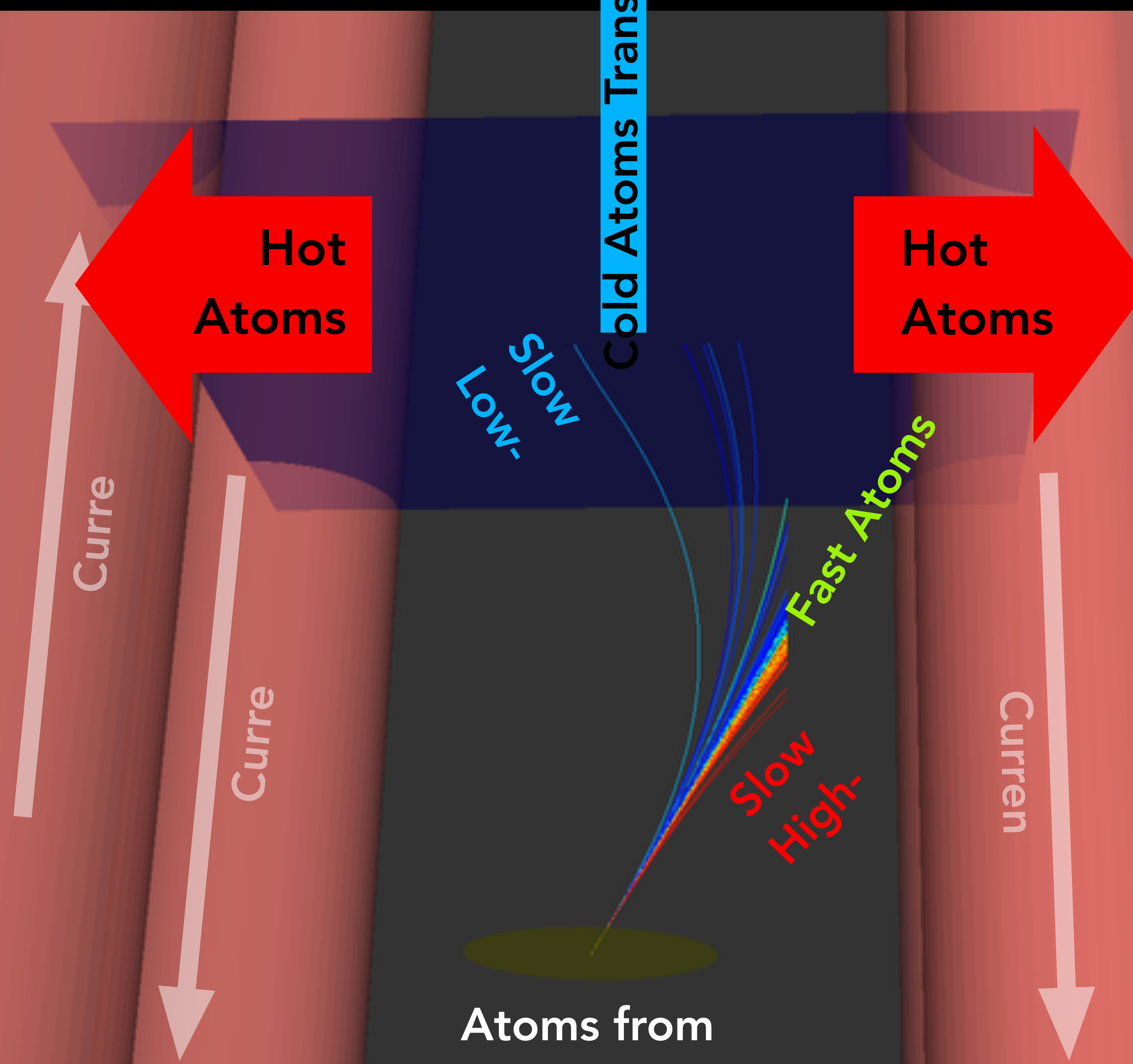

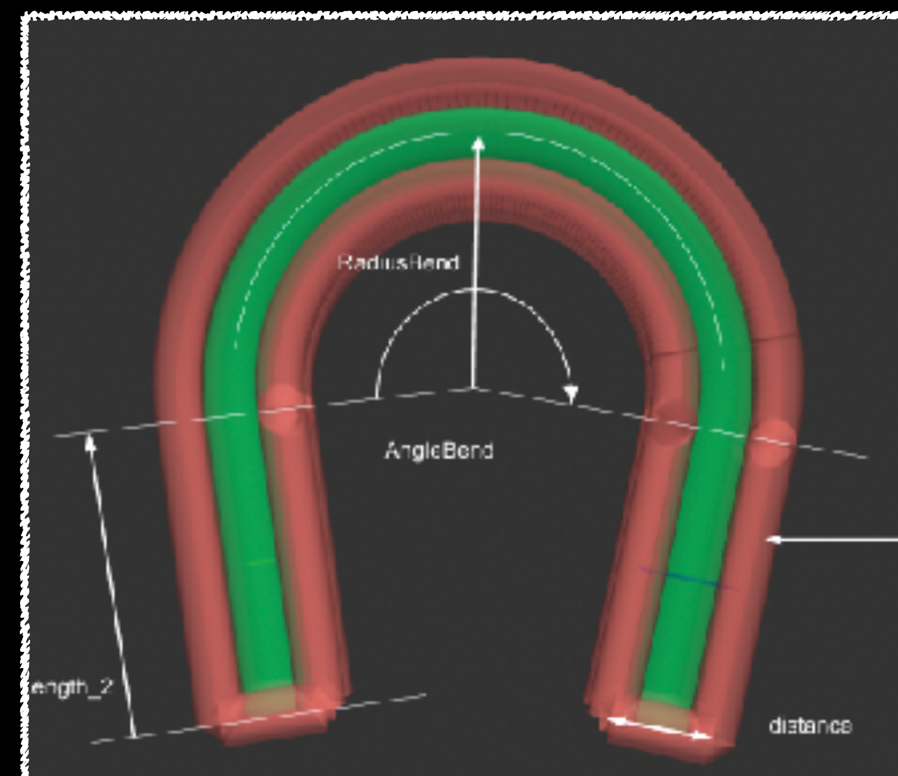

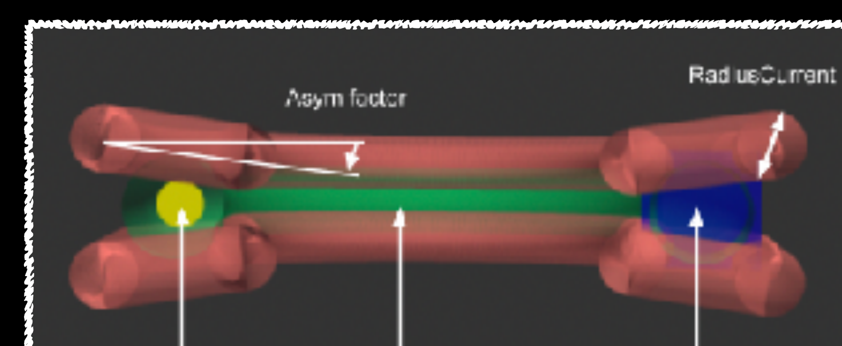

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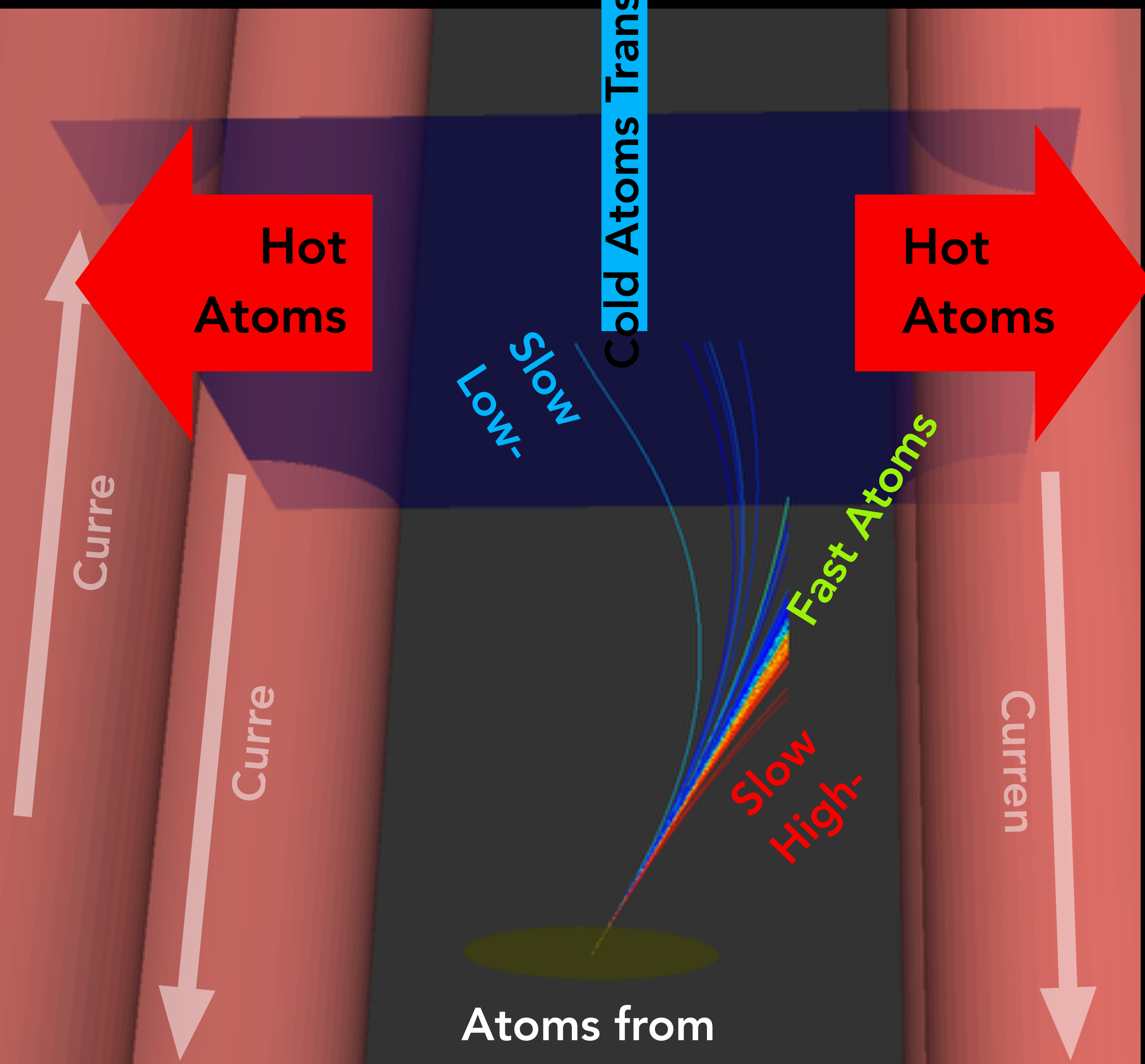

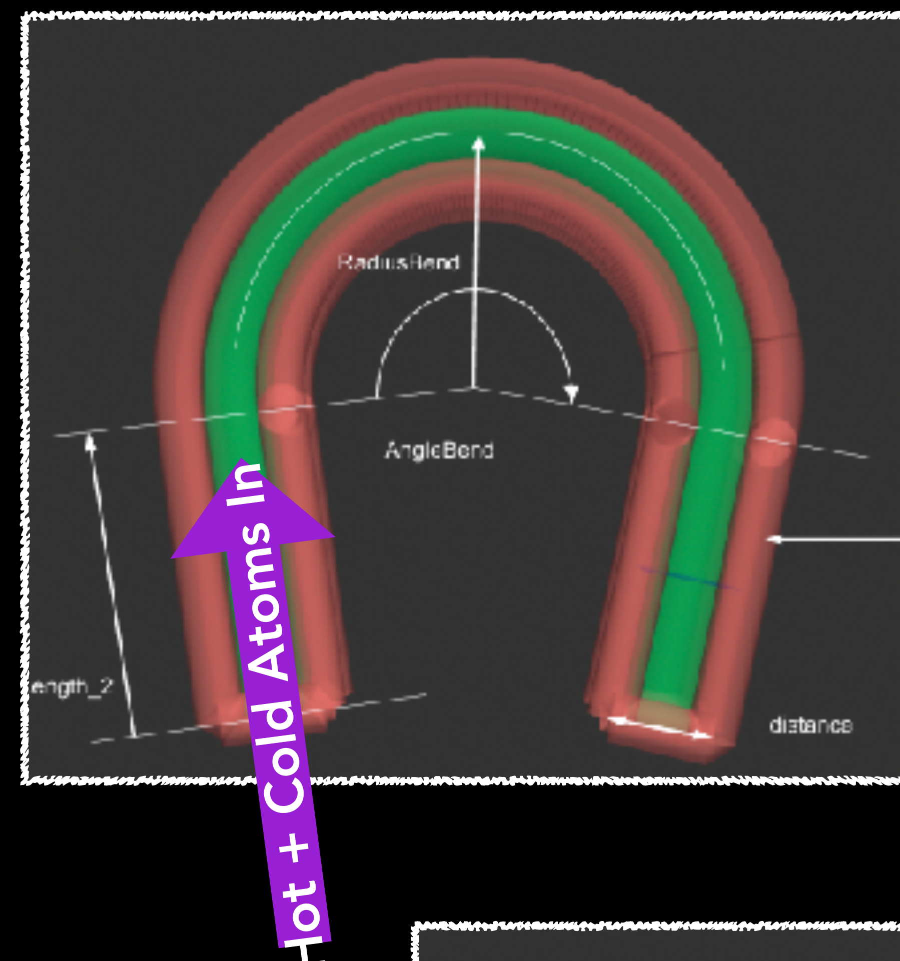

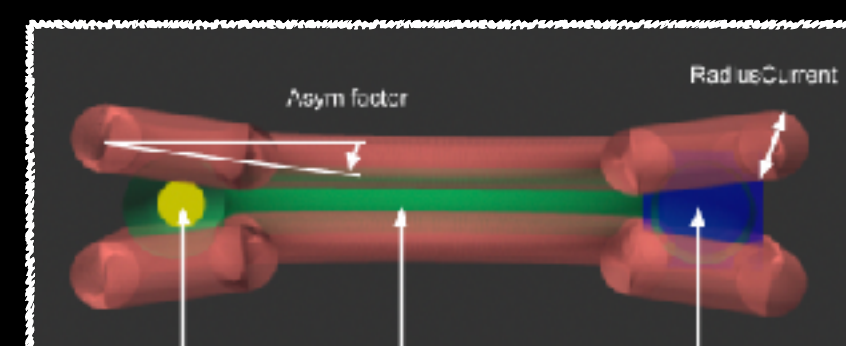

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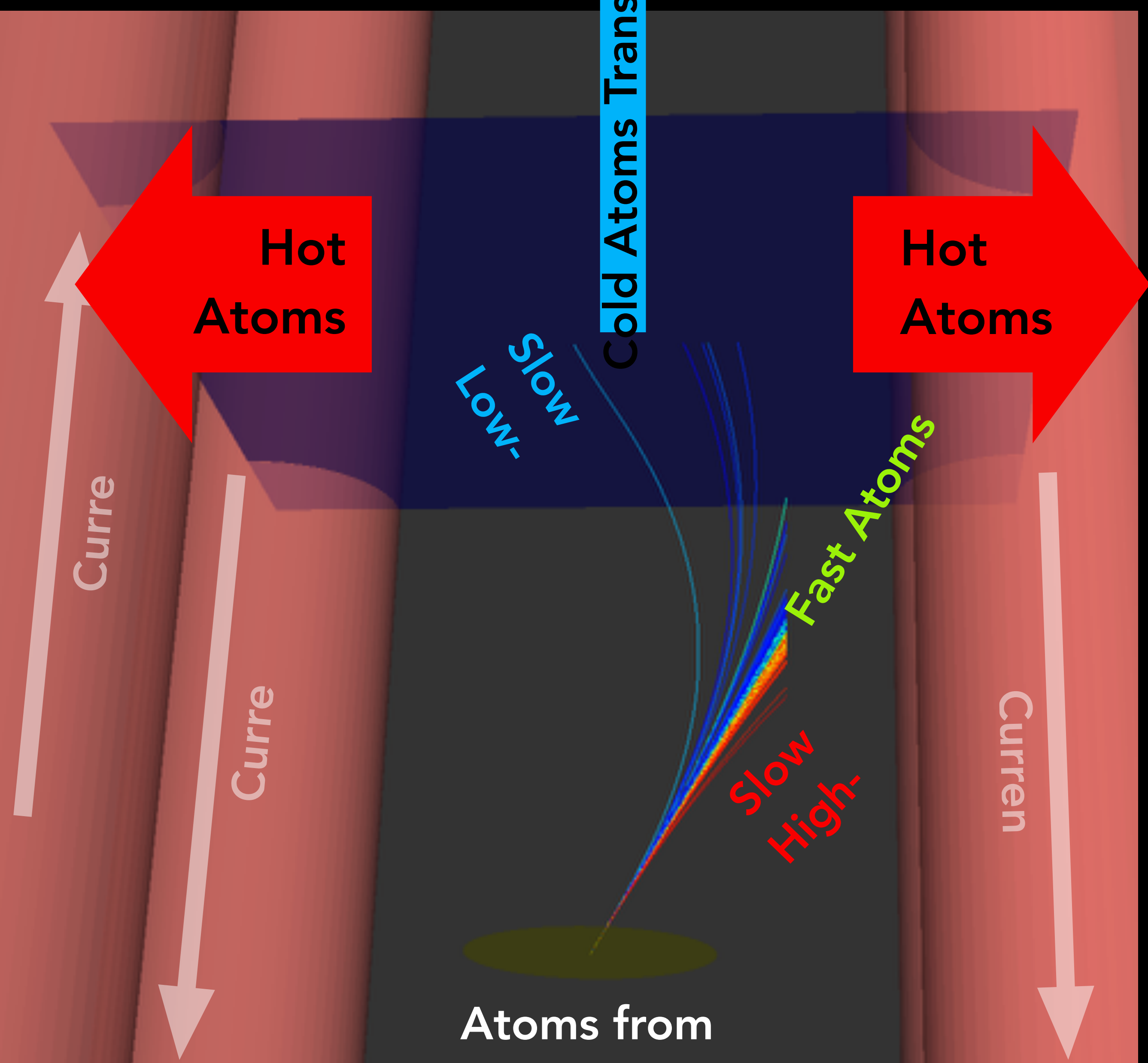

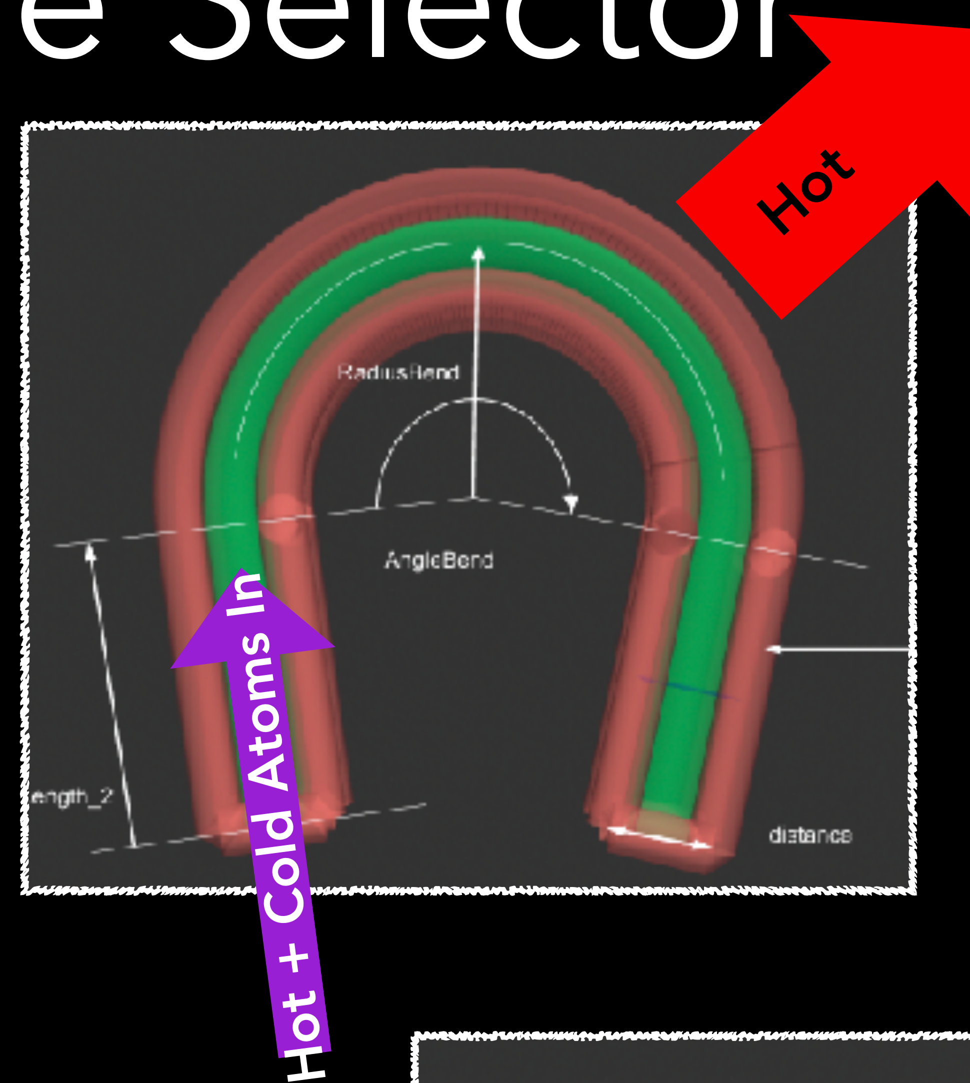

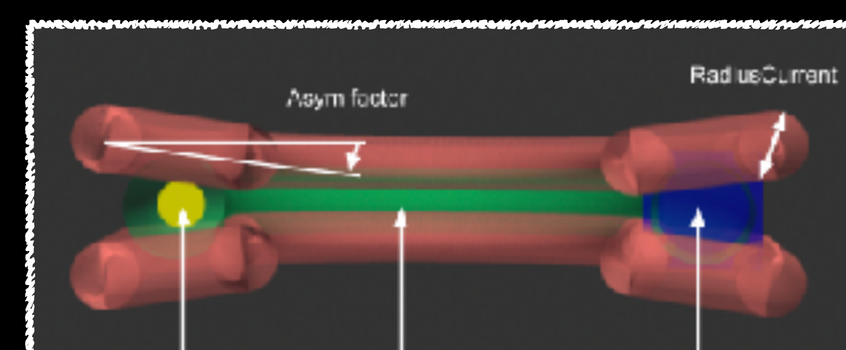

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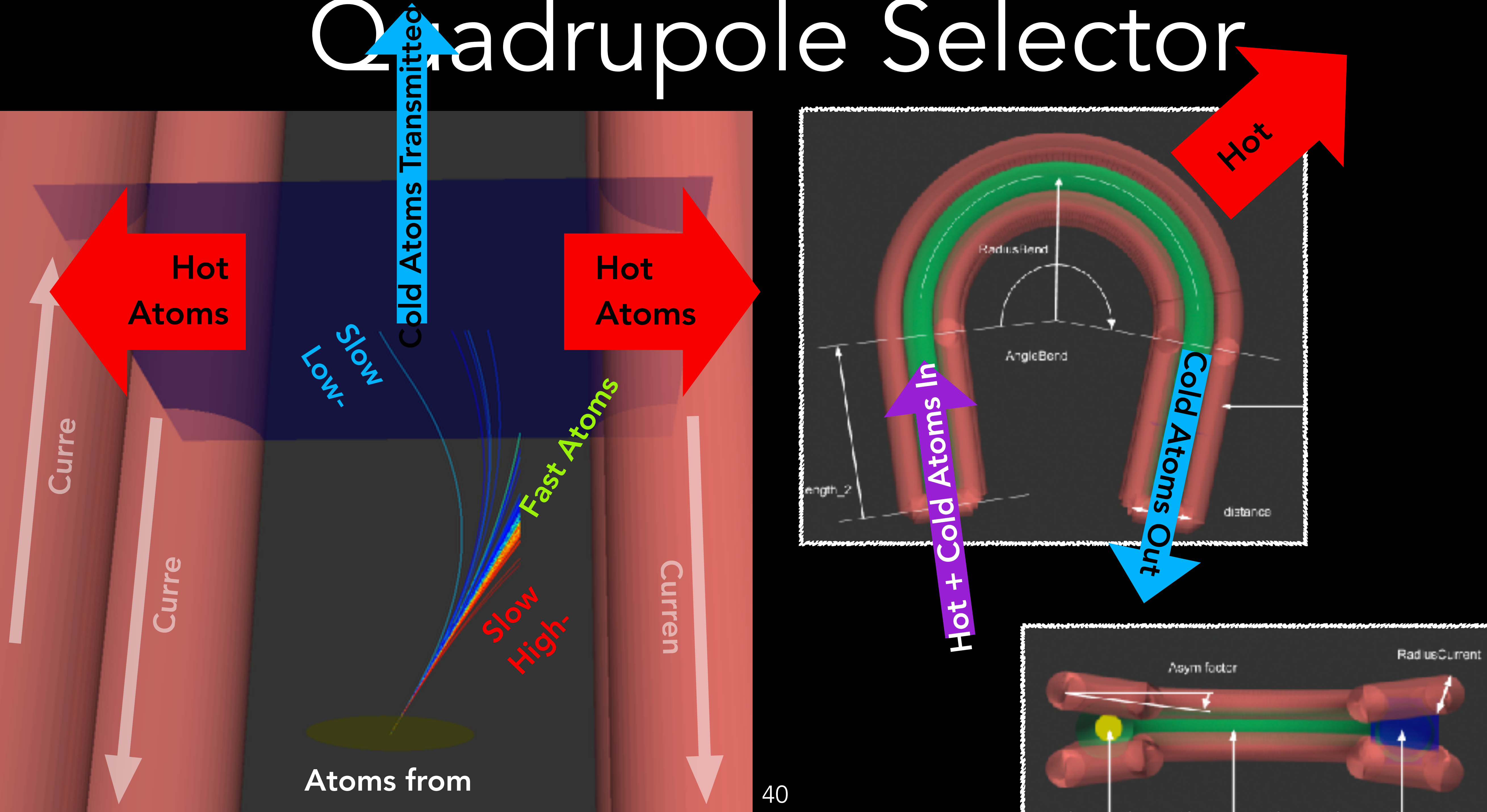

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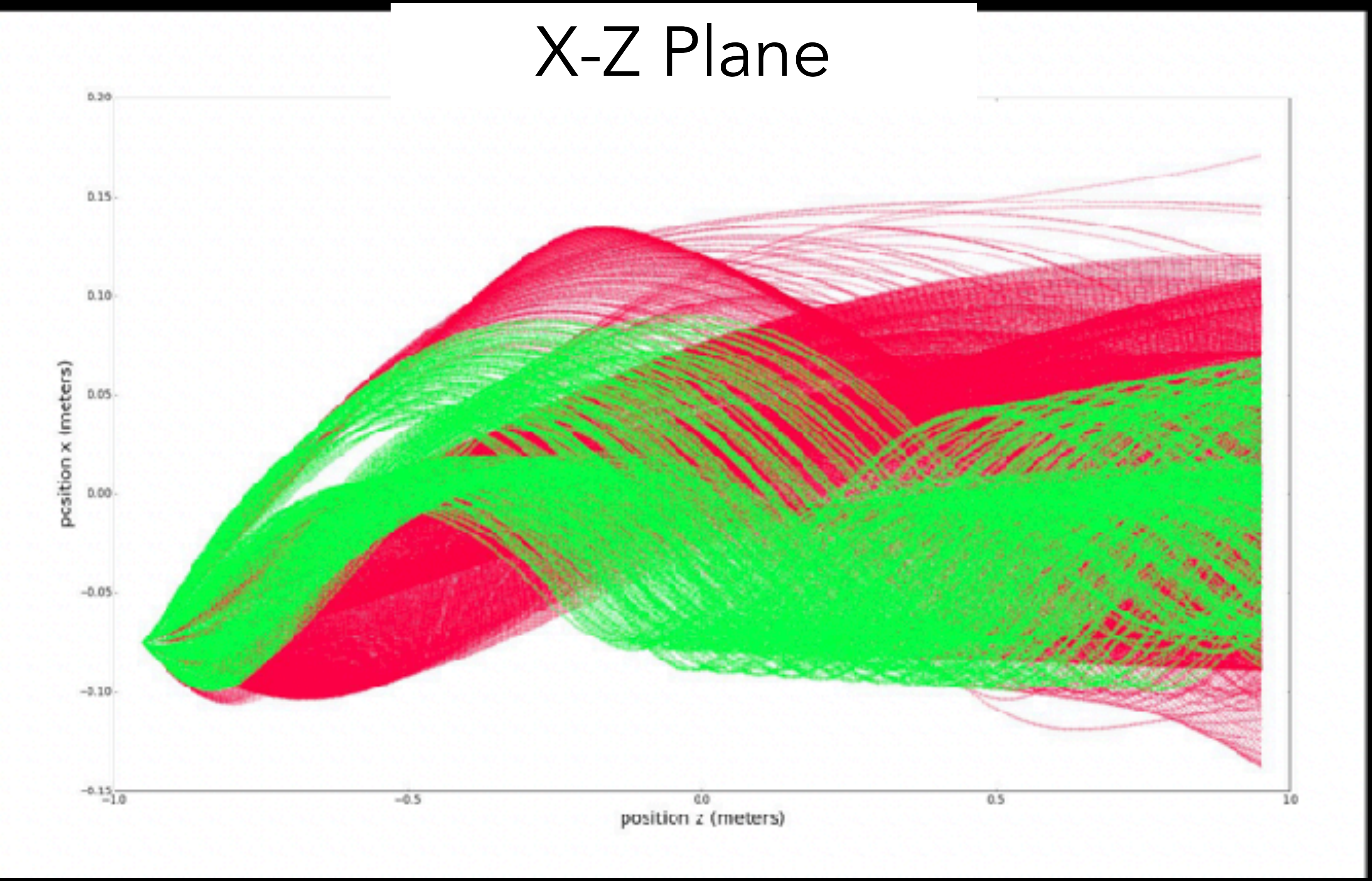
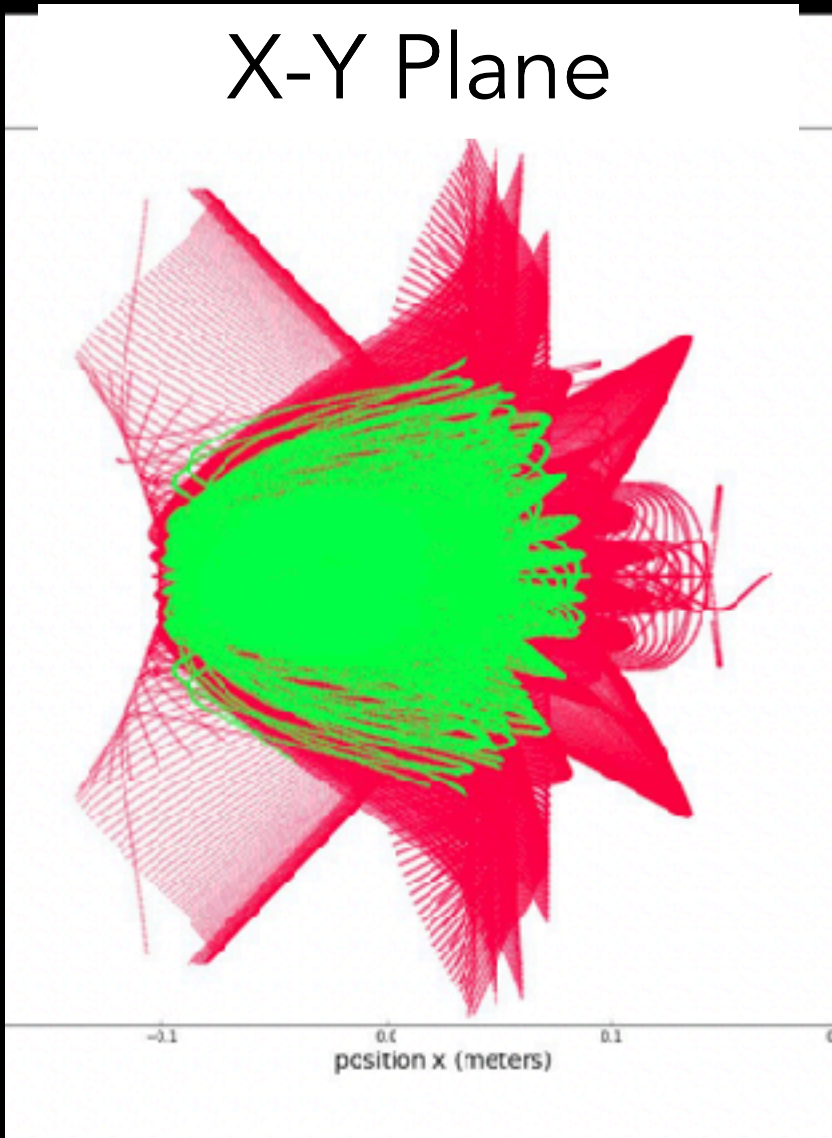
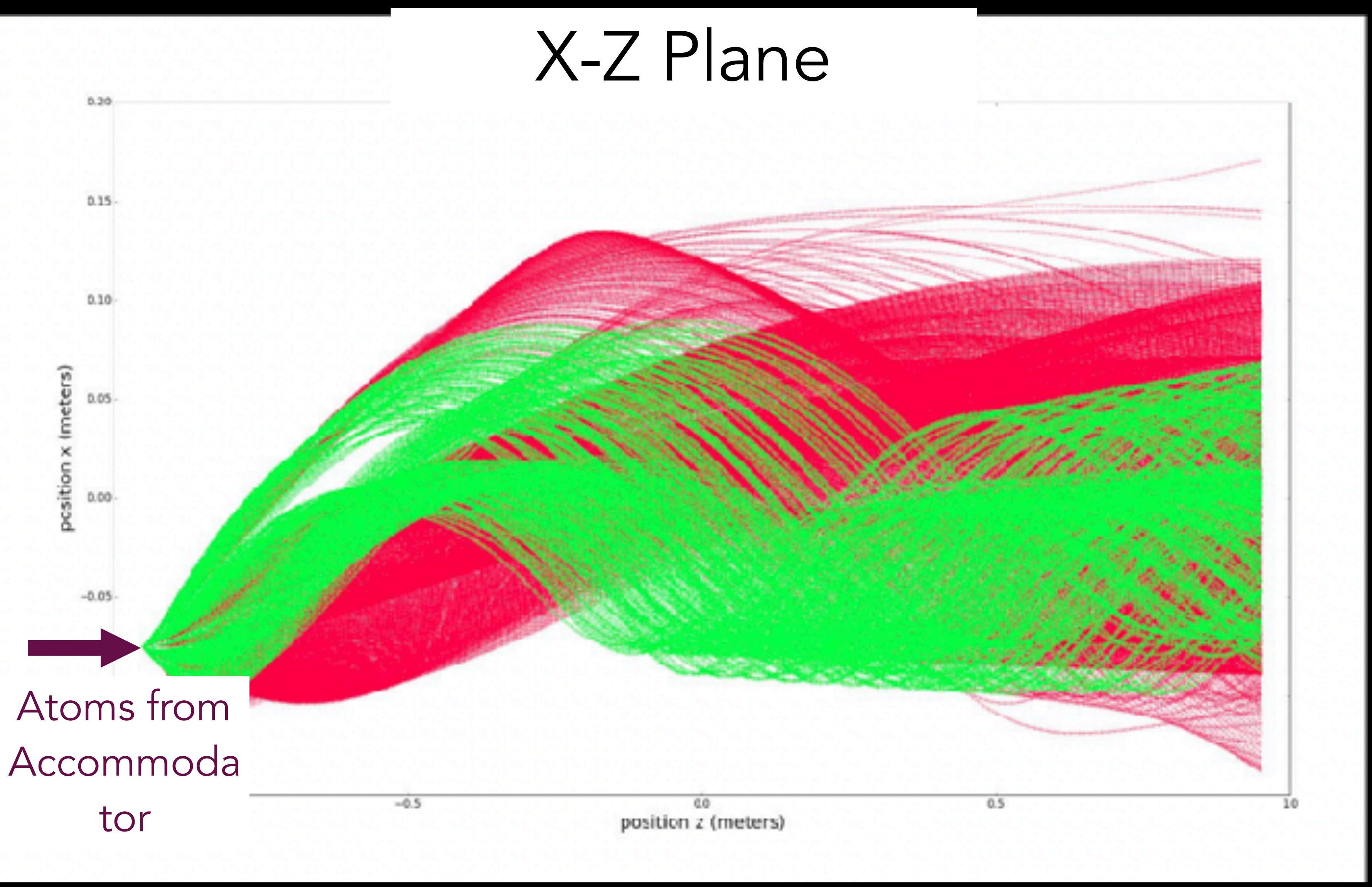
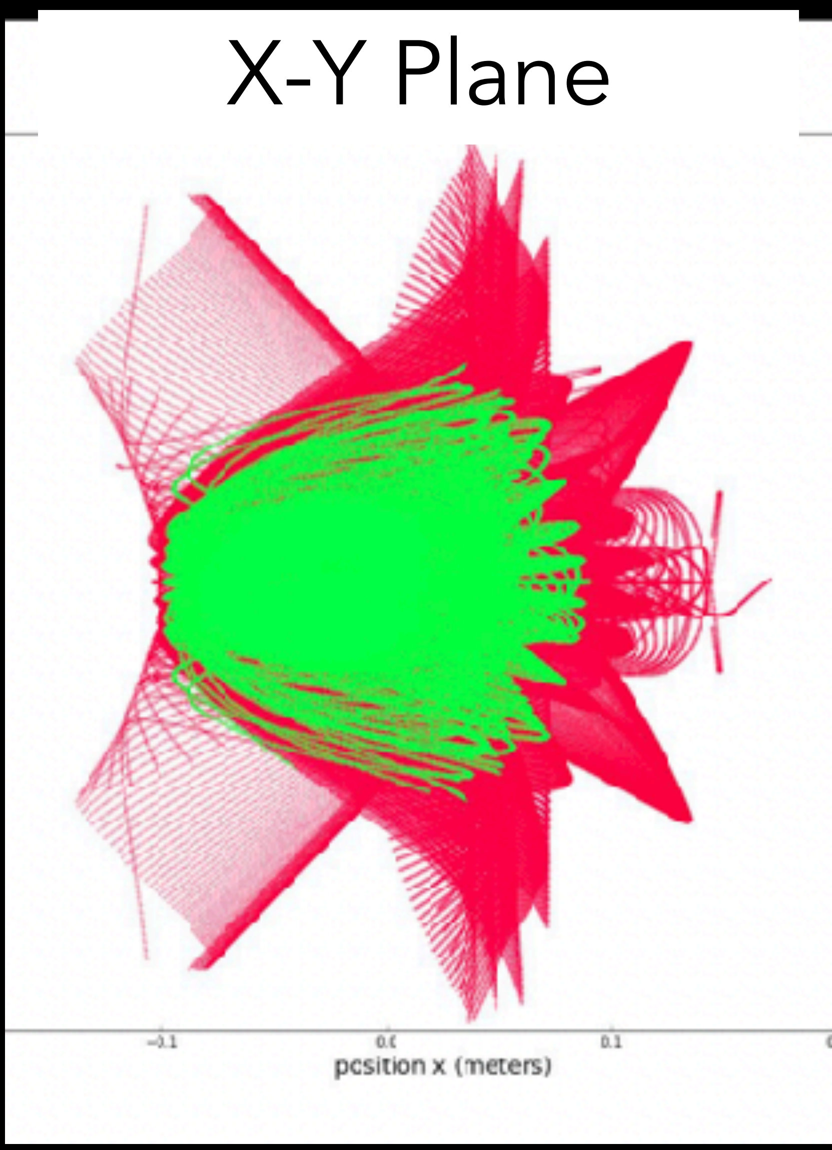




Quadrupole Selector





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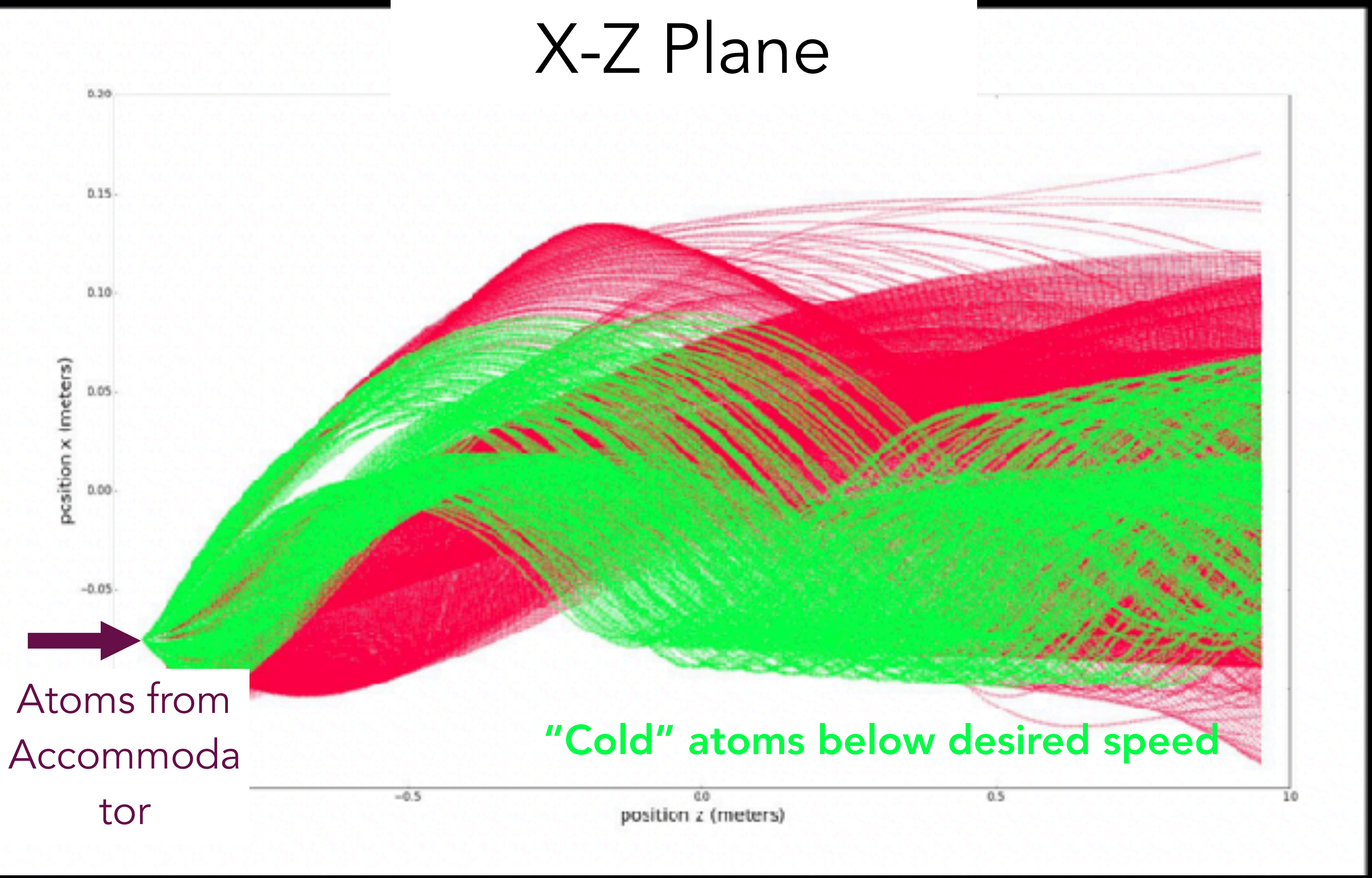

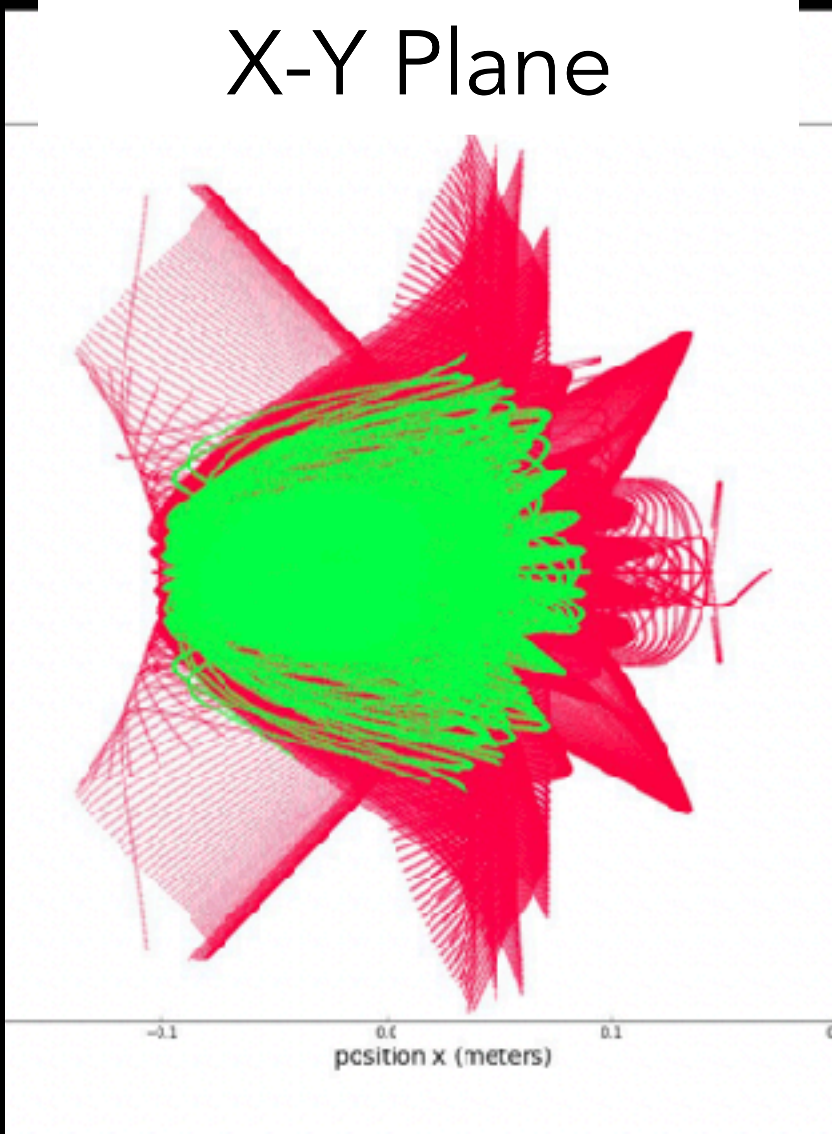

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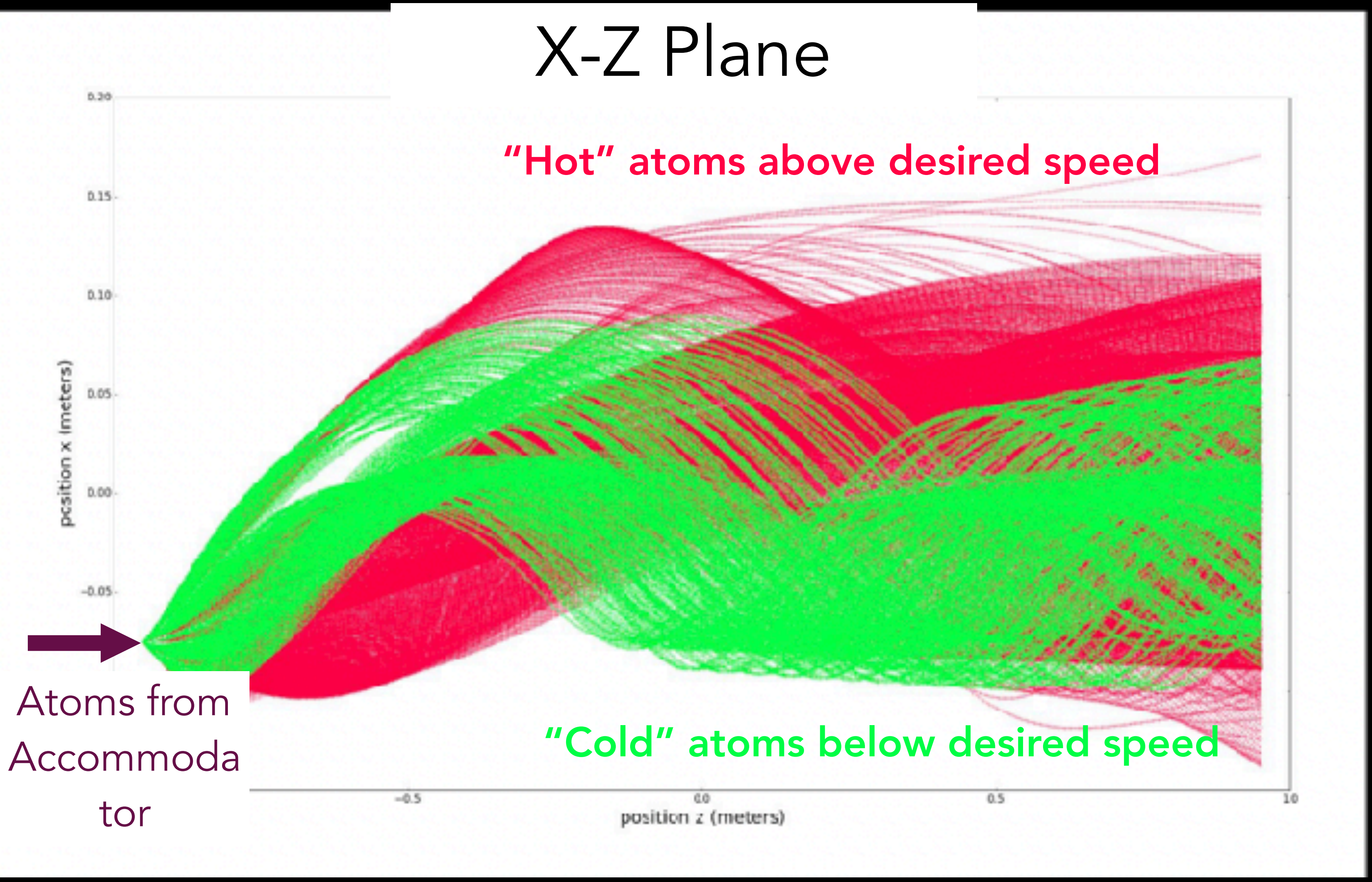

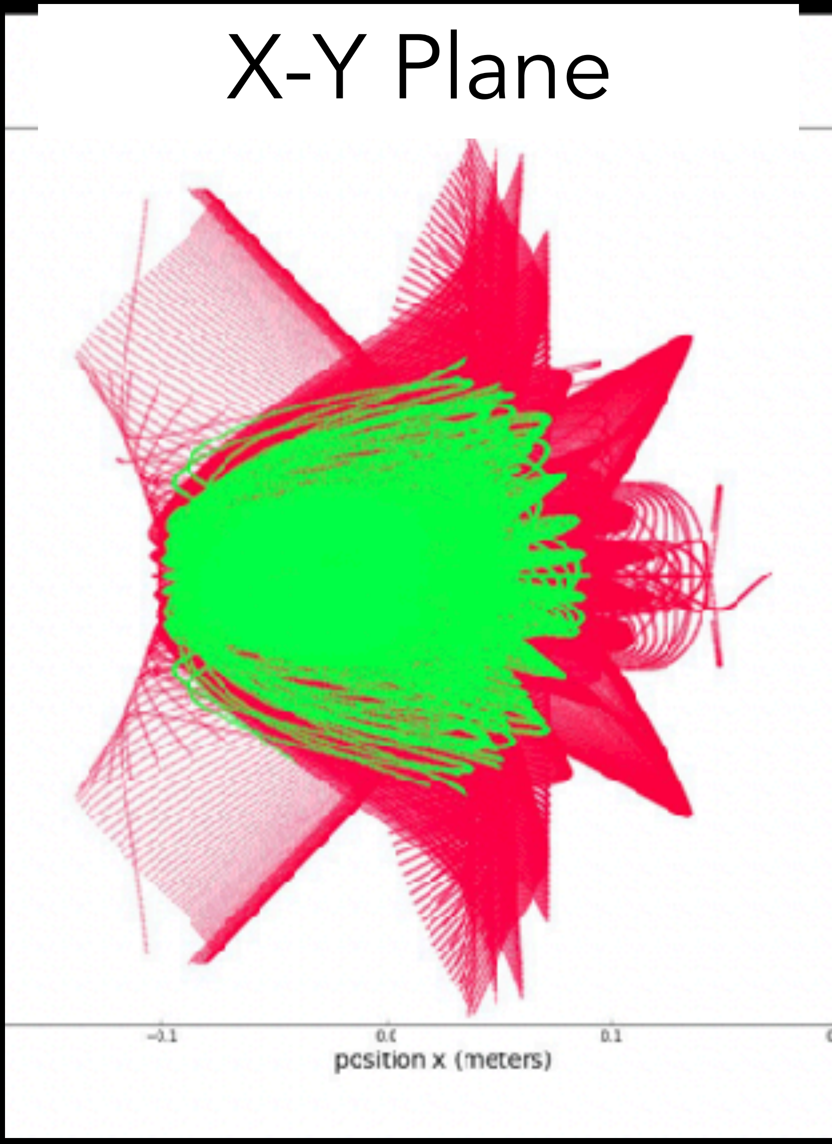

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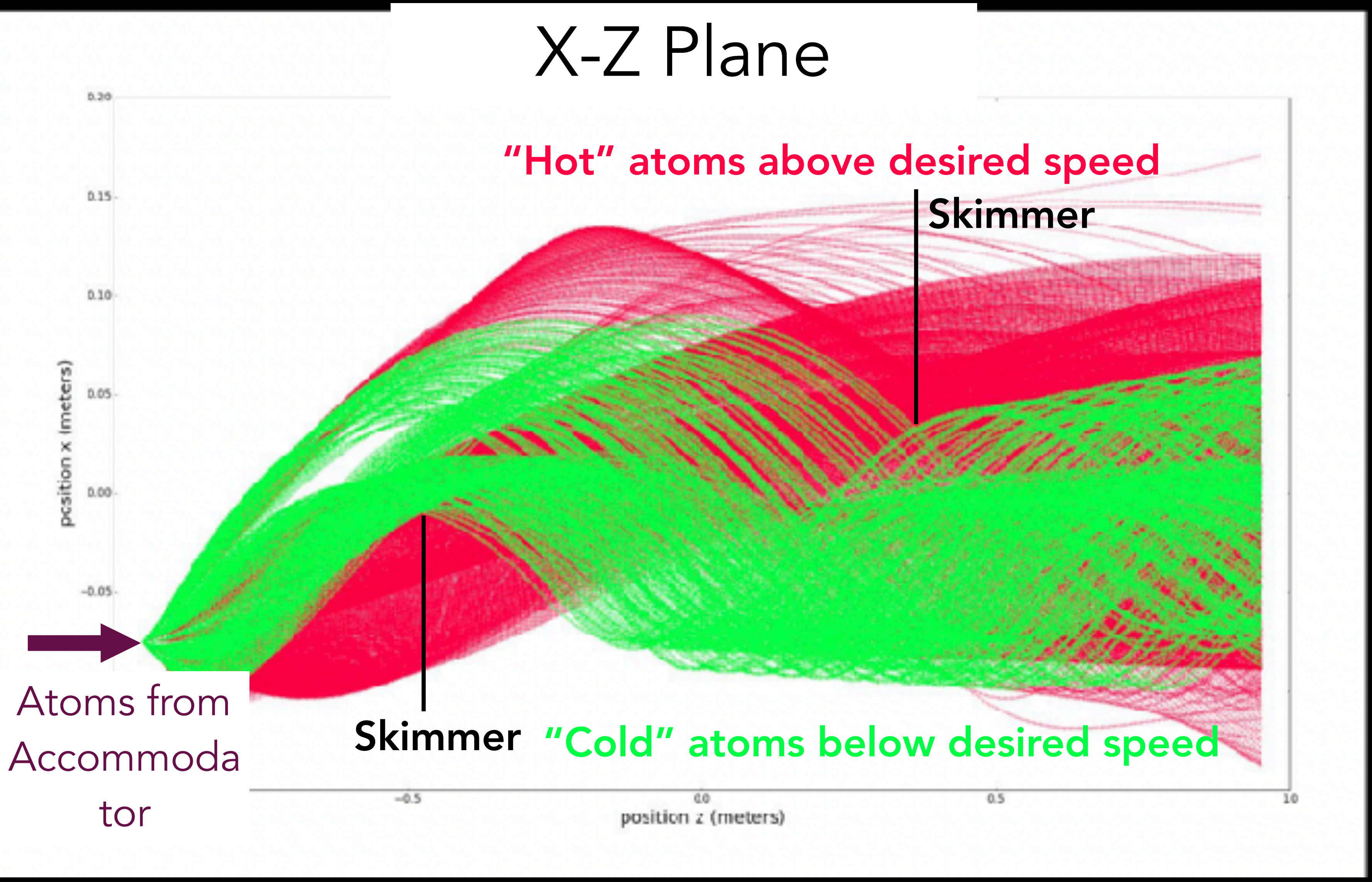

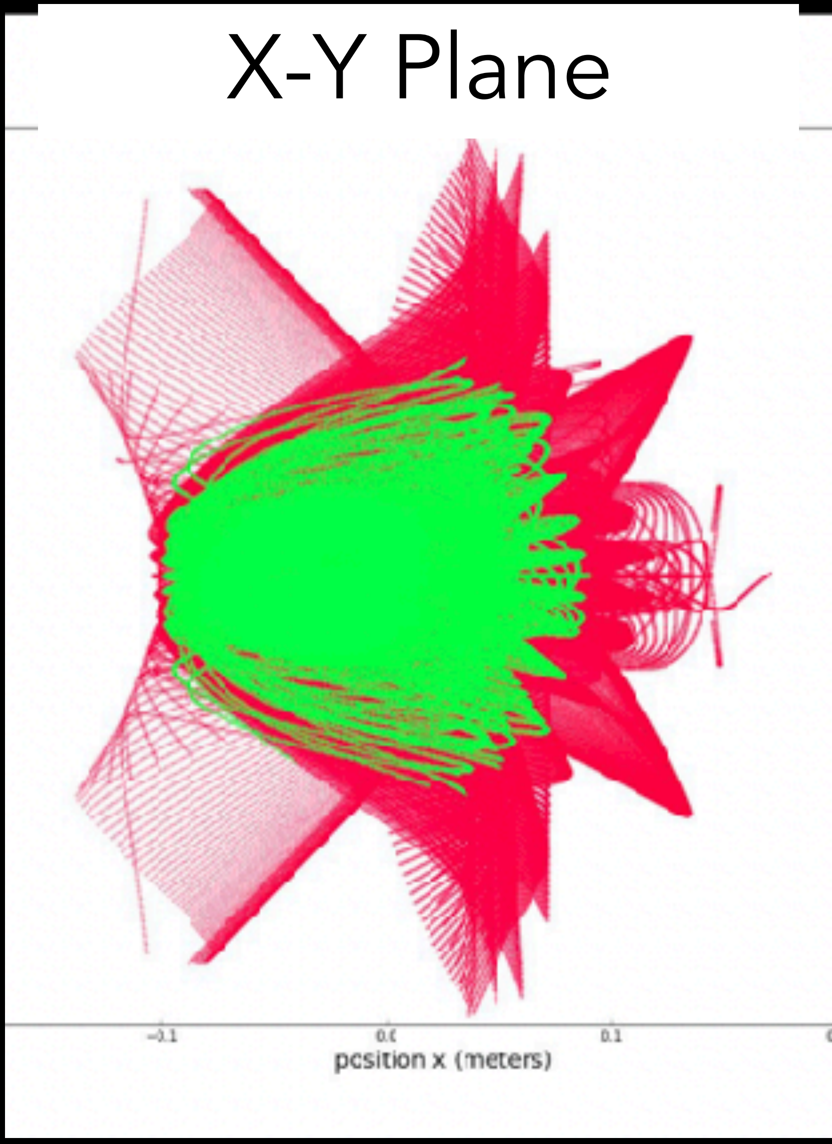

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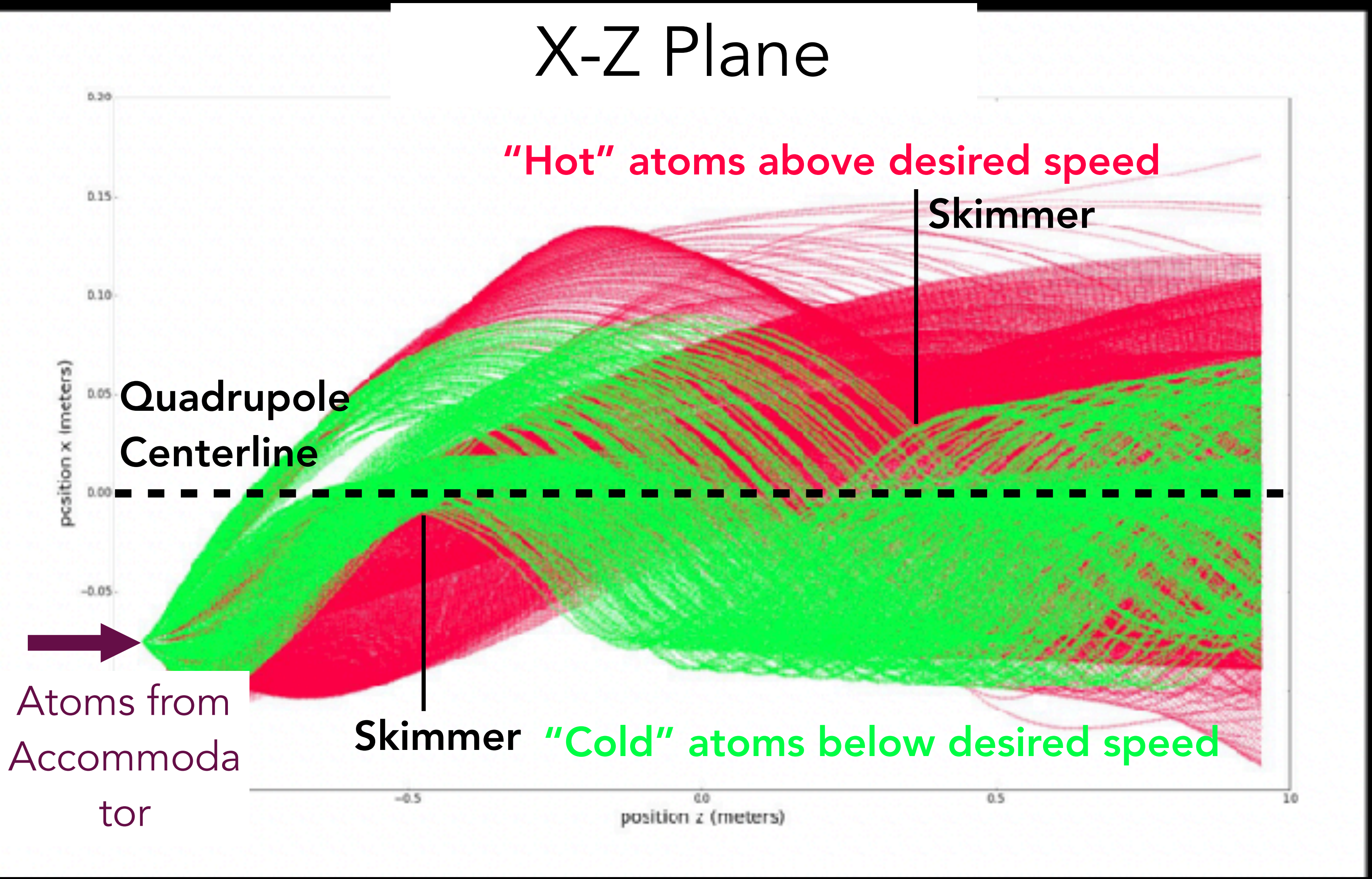
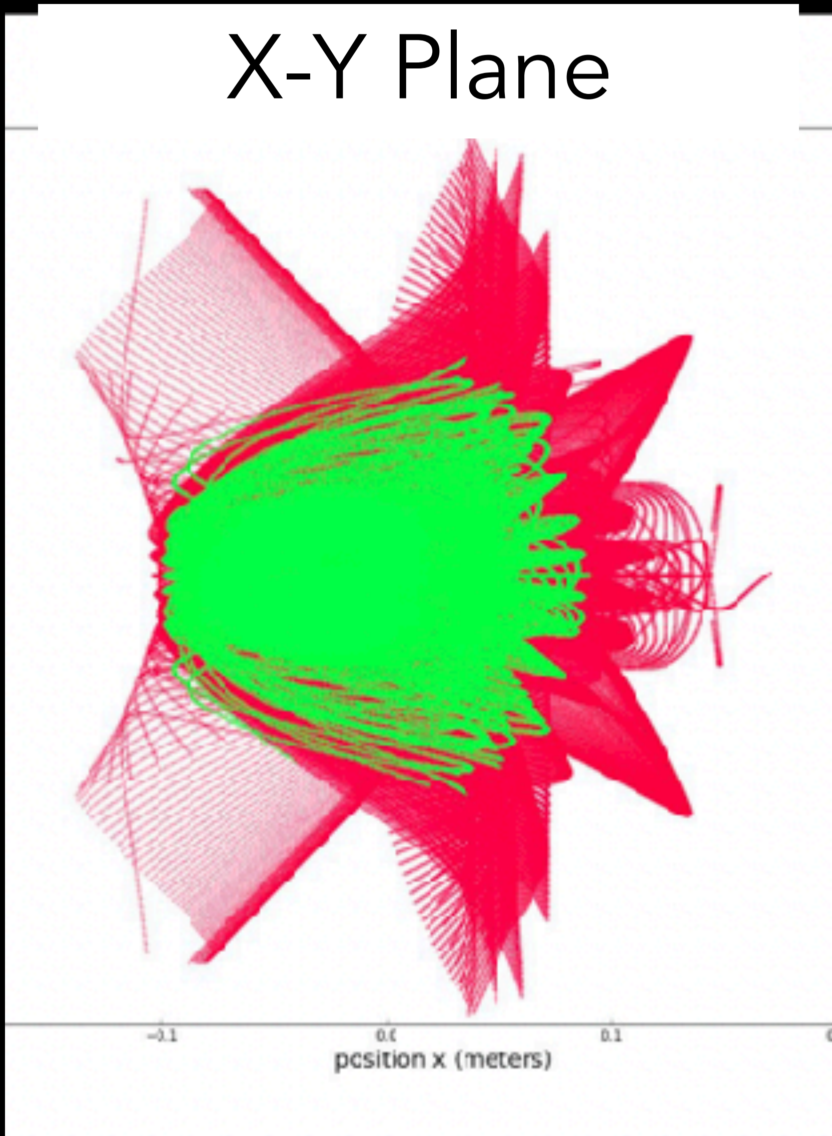
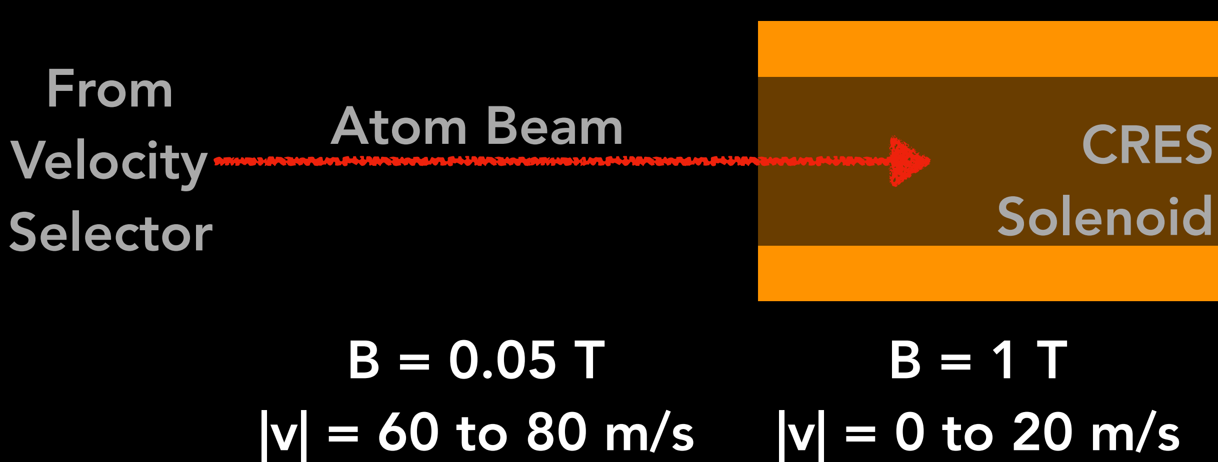
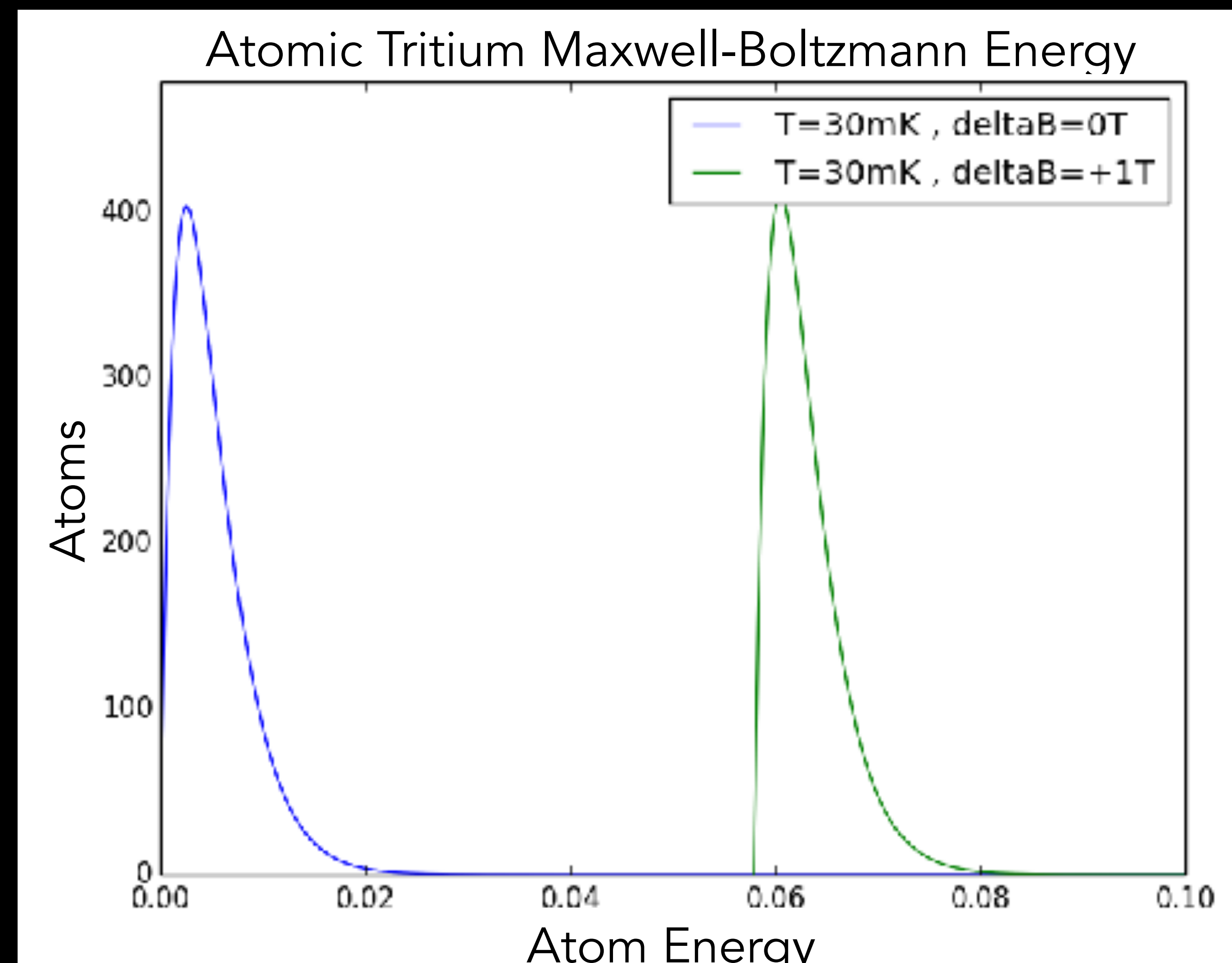




Magnetic Step Cooling

- We have a 1 T field to work with—let's use it
- This energy loss corresponds to 60 m/s
- Source-to-trap efficiency ~ 10^{-5}
    - Required hot atom flux 10^{19} atoms/s





$T_2 \rightarrow T$

- RF dissociation is the traditional approach for hydrogen
    - An oxide (aluminum or silicon) vessel contains the gas while remaining transparent to RF from an external cavity
    - **Not compatible with tritium**: the energetic environment extracts oxygen from the vessel, which immediately forms T_2O or related species
- Thermal dissociation is the best alternative
    - All-metal structure is inherently tritium compatible
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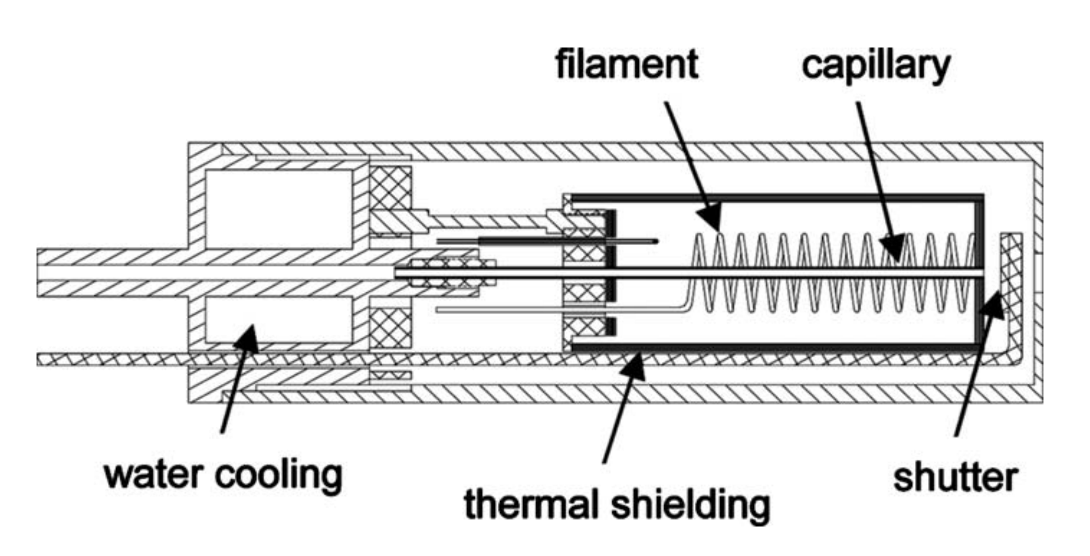

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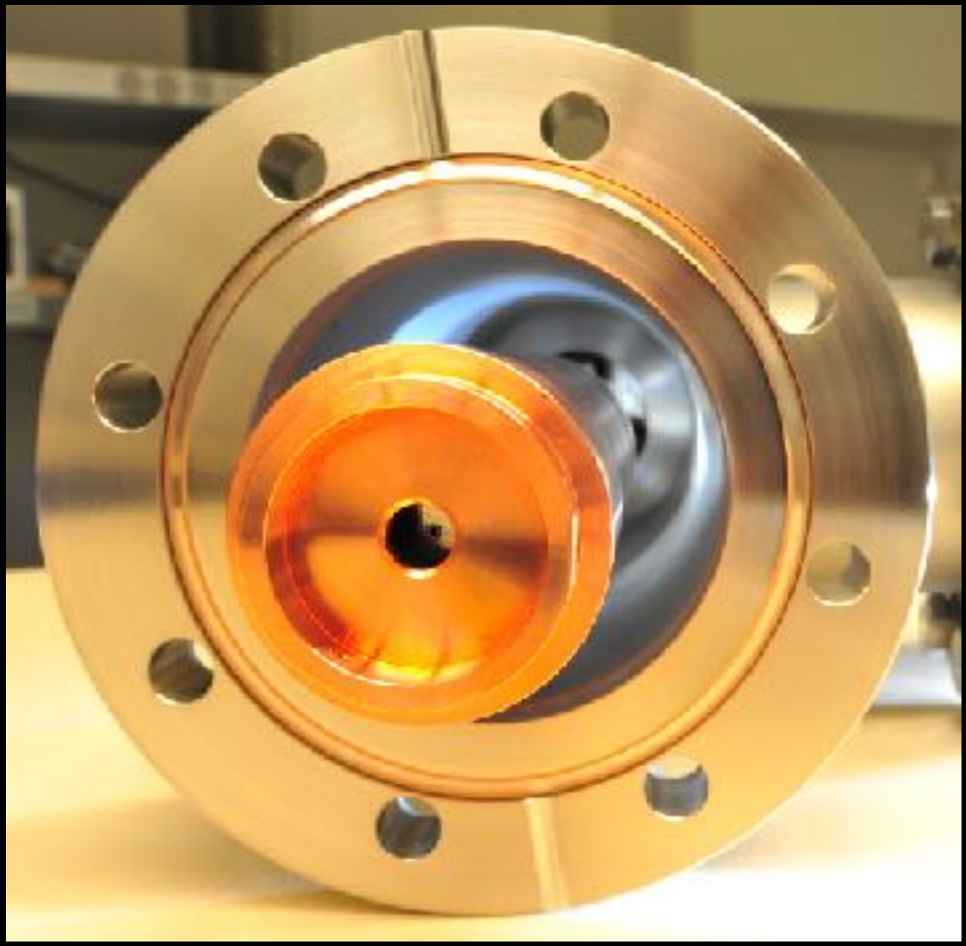

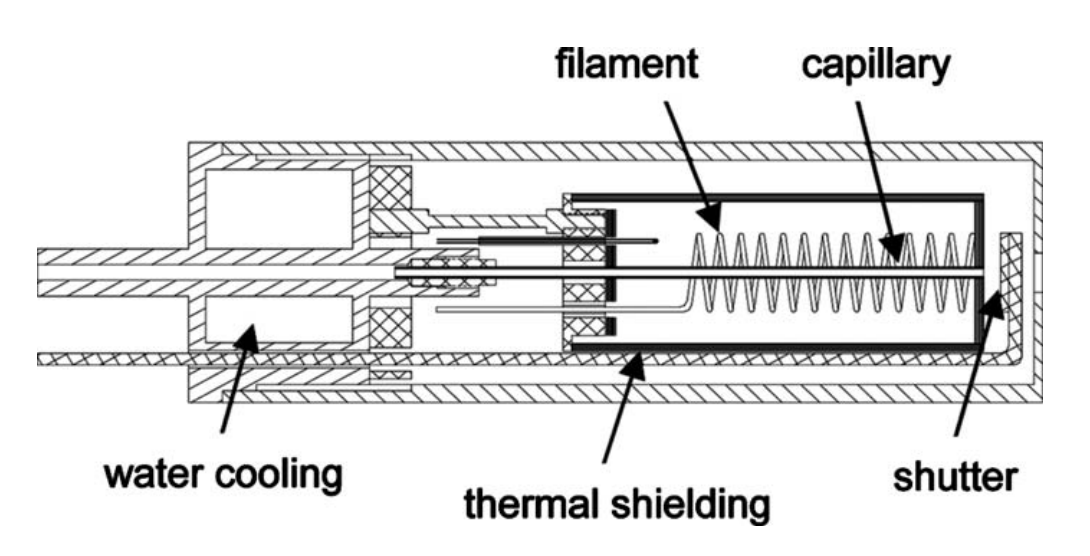

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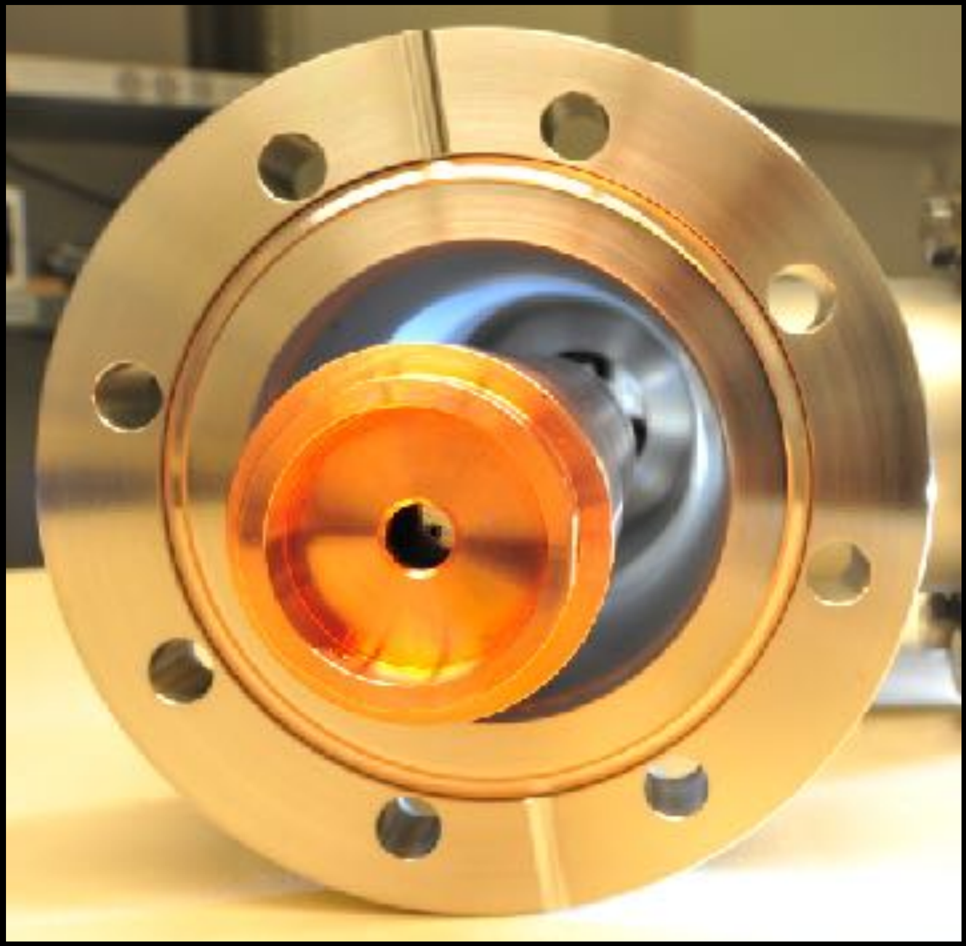
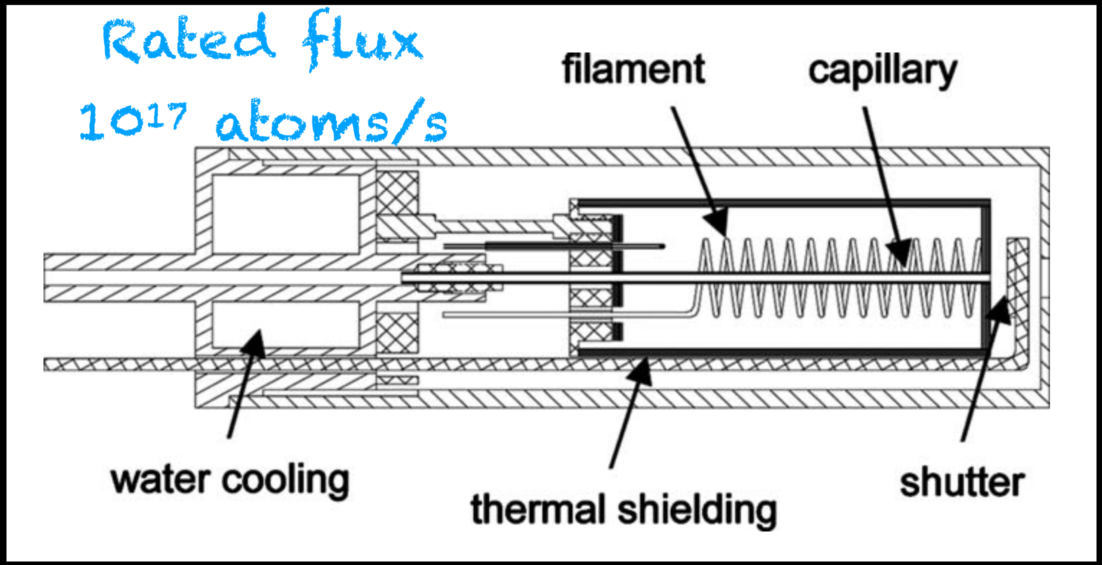
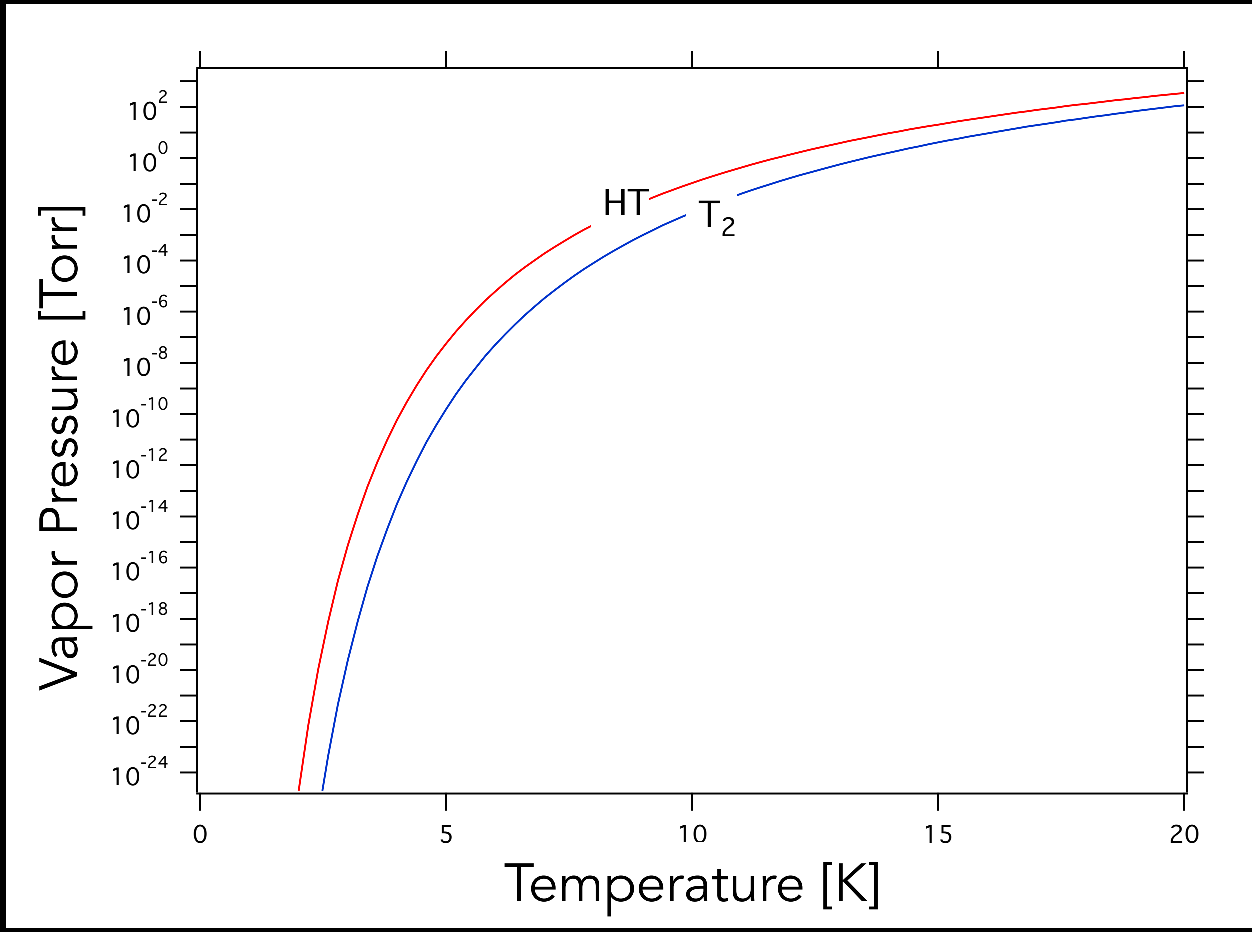




Why Trap the Atoms?

- Our design sensitivity assumes a T_2/T ratio of less than 10^{-6}
  - Contact with physical surfaces strongly catalyzes recombination
  - A magnetic bottle holds T, preventing surface recombination, but not T_2, providing continuous purification



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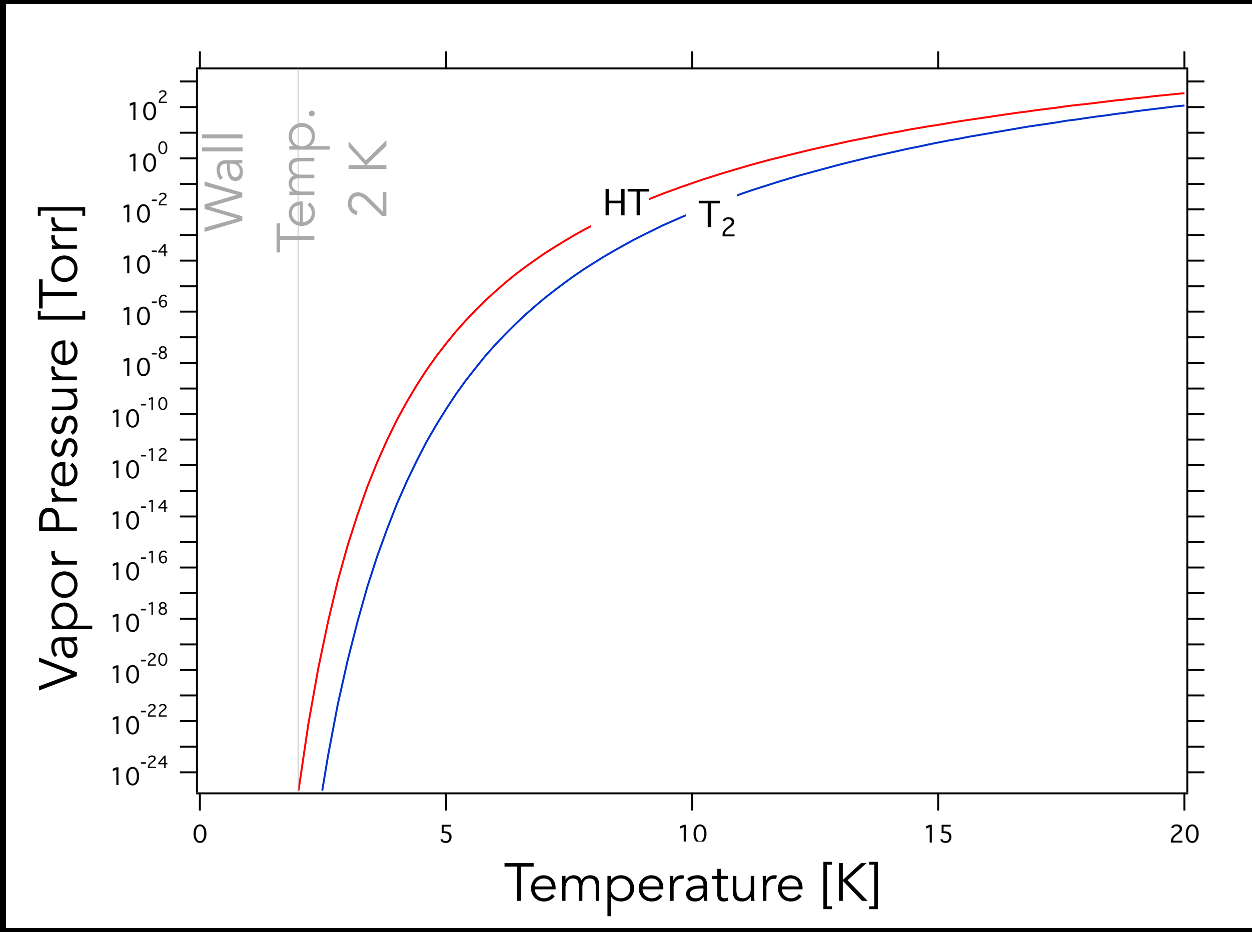

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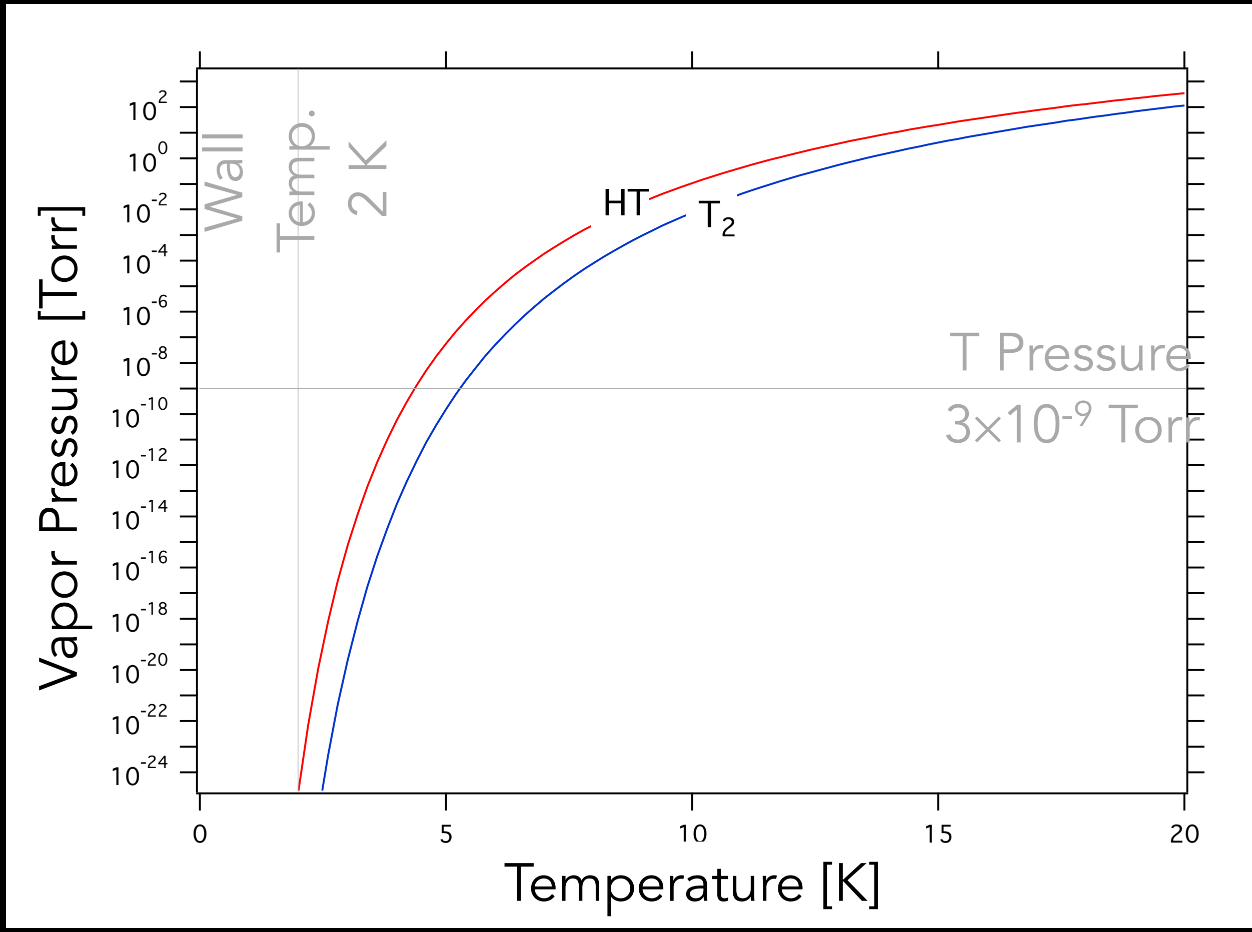

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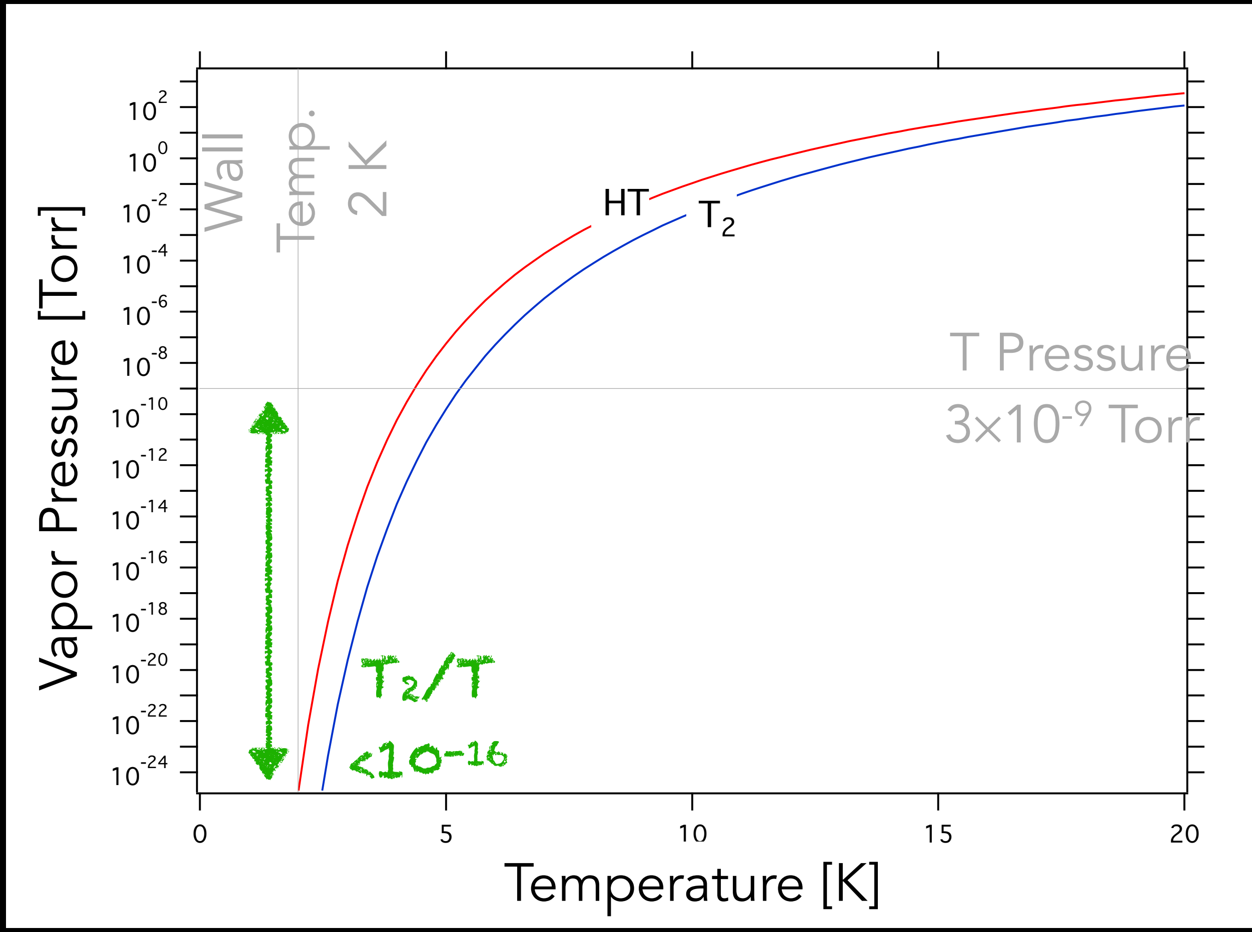
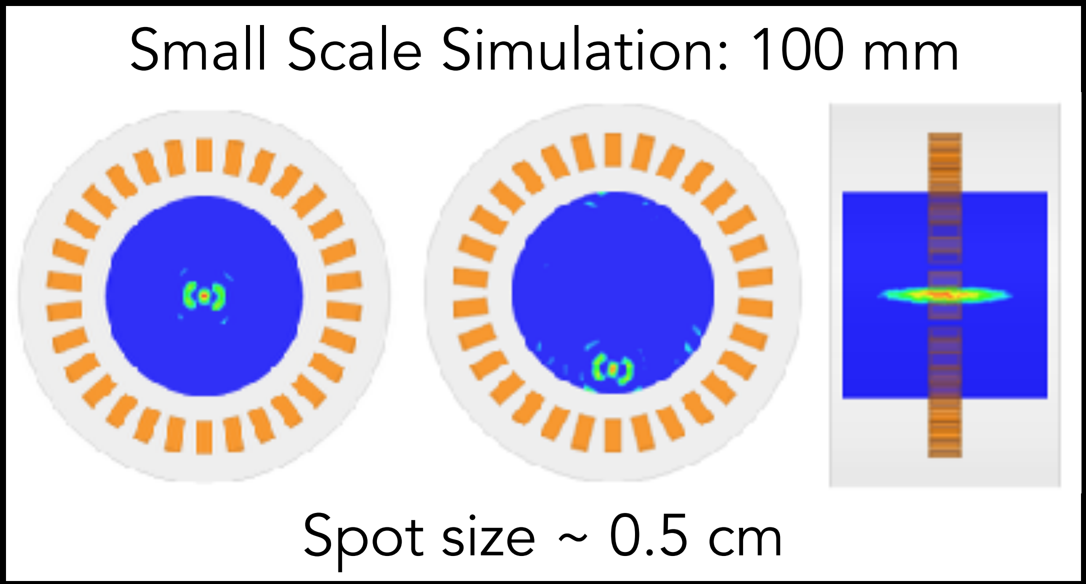


Pileup Mitigation

- The event rate (10^9 Hz) and event duration (10^{-2} s) result in many simultaneous events; separation is required to avoid pileup
- Digital beamforming with a cylindrical array of antennas enables segmenting the trap volume in the transverse plane
- Cyclotron diameter ~ 0.2 cm



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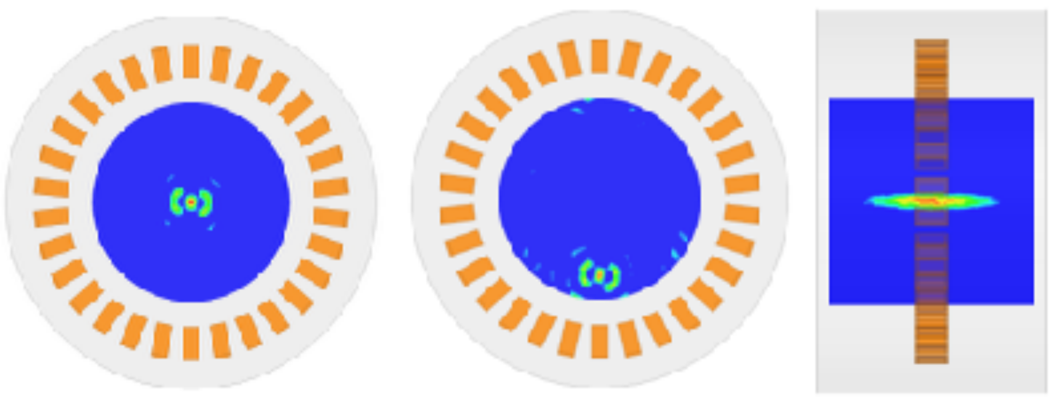

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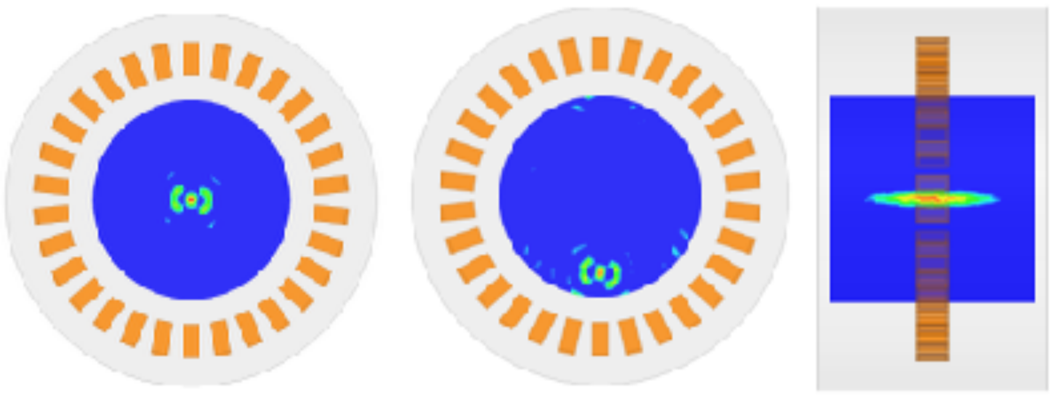

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Conservative (large) pitch angle acceptance

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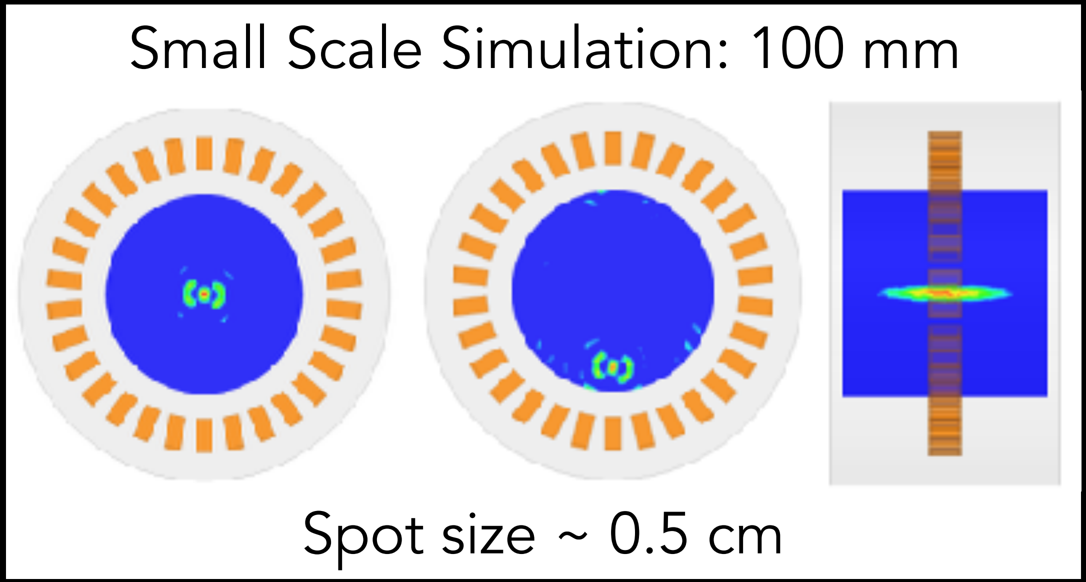

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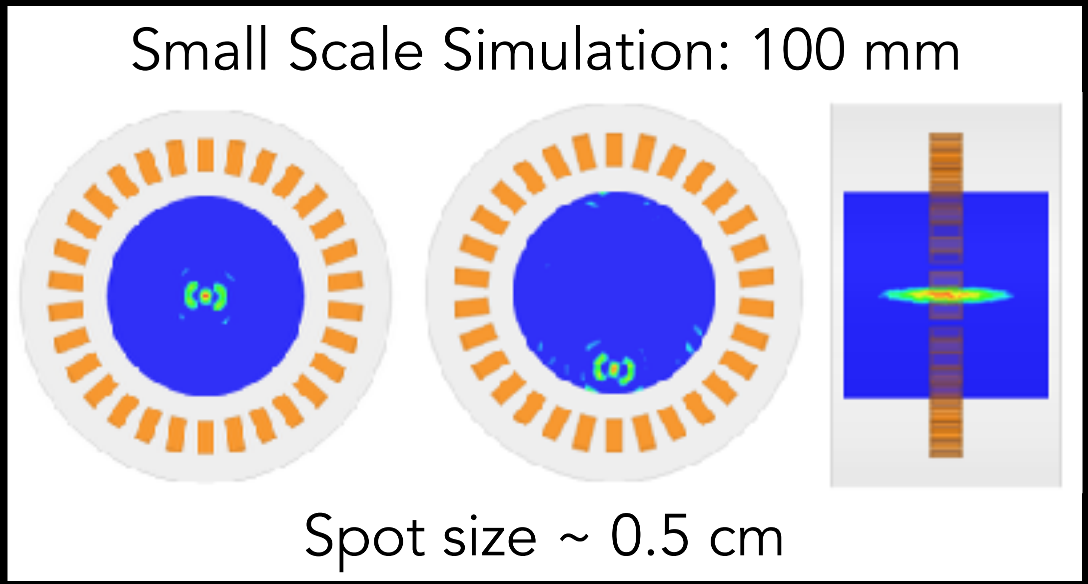

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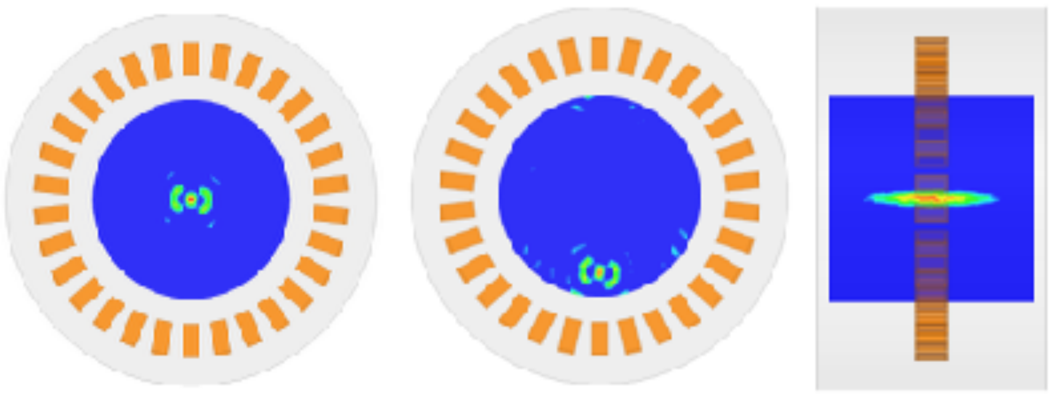

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Area with

$\Delta B/B < 10^{-}$

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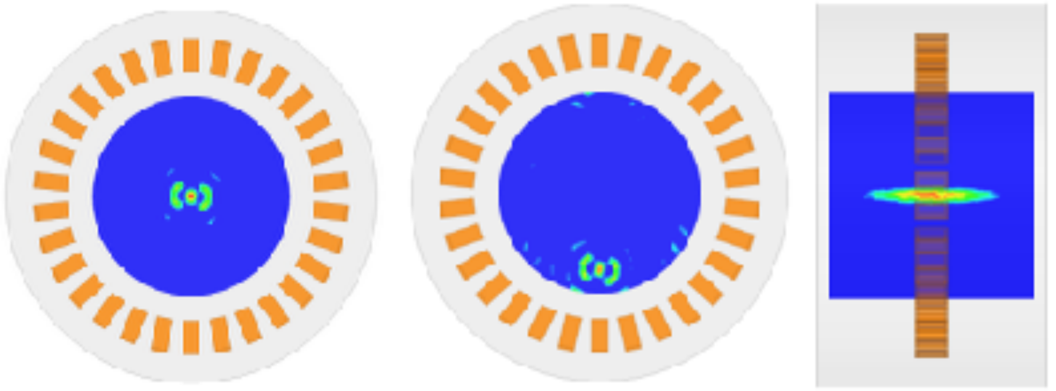

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Minimum track separatio

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Area with

$\Delta B/B < 10^{-7}$

$$d_{\text{max}} = 2\sqrt{\frac{A_{\text{fiducial}}}{\pi \cdot S_{\text{min}}}} = 1.2\ [\text{cm}]$$

Mainz Test Stand

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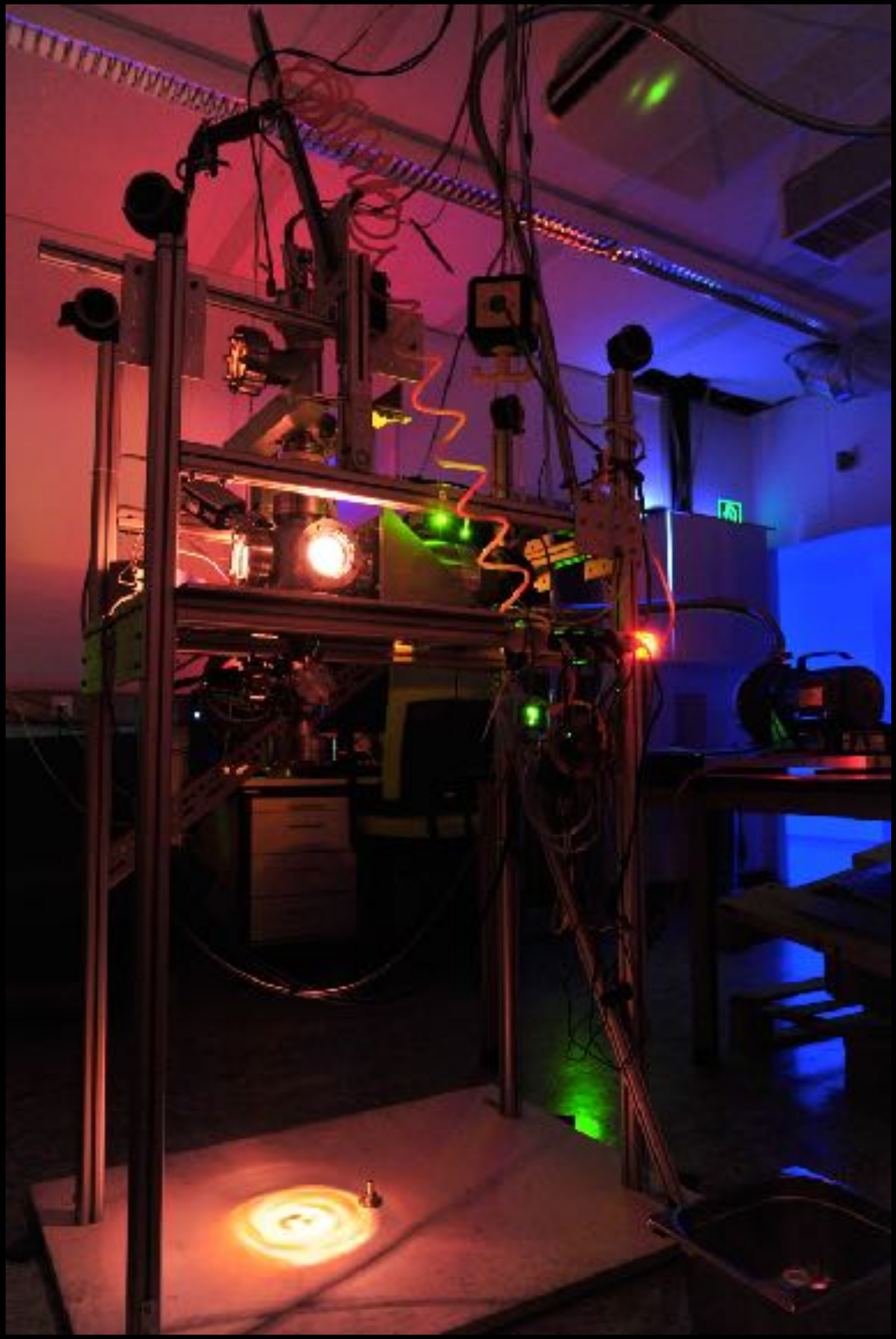

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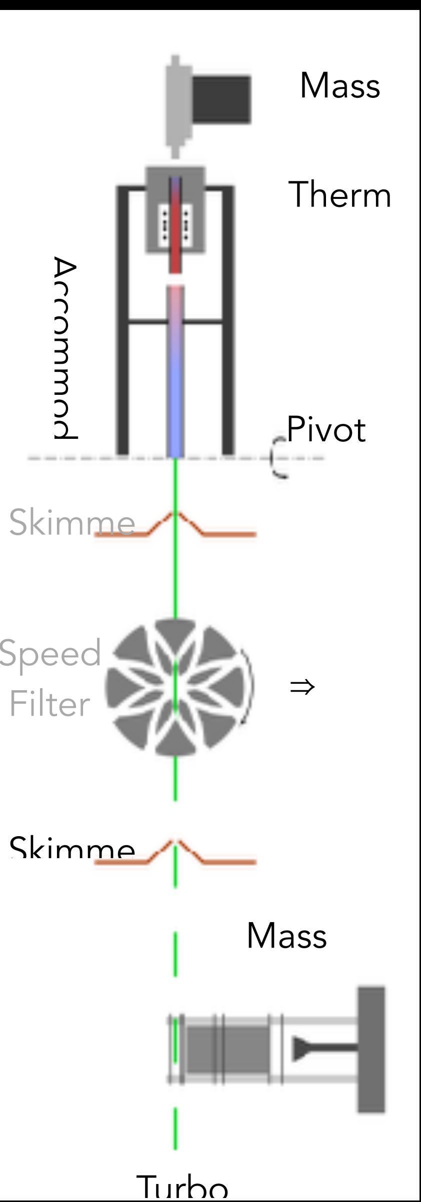
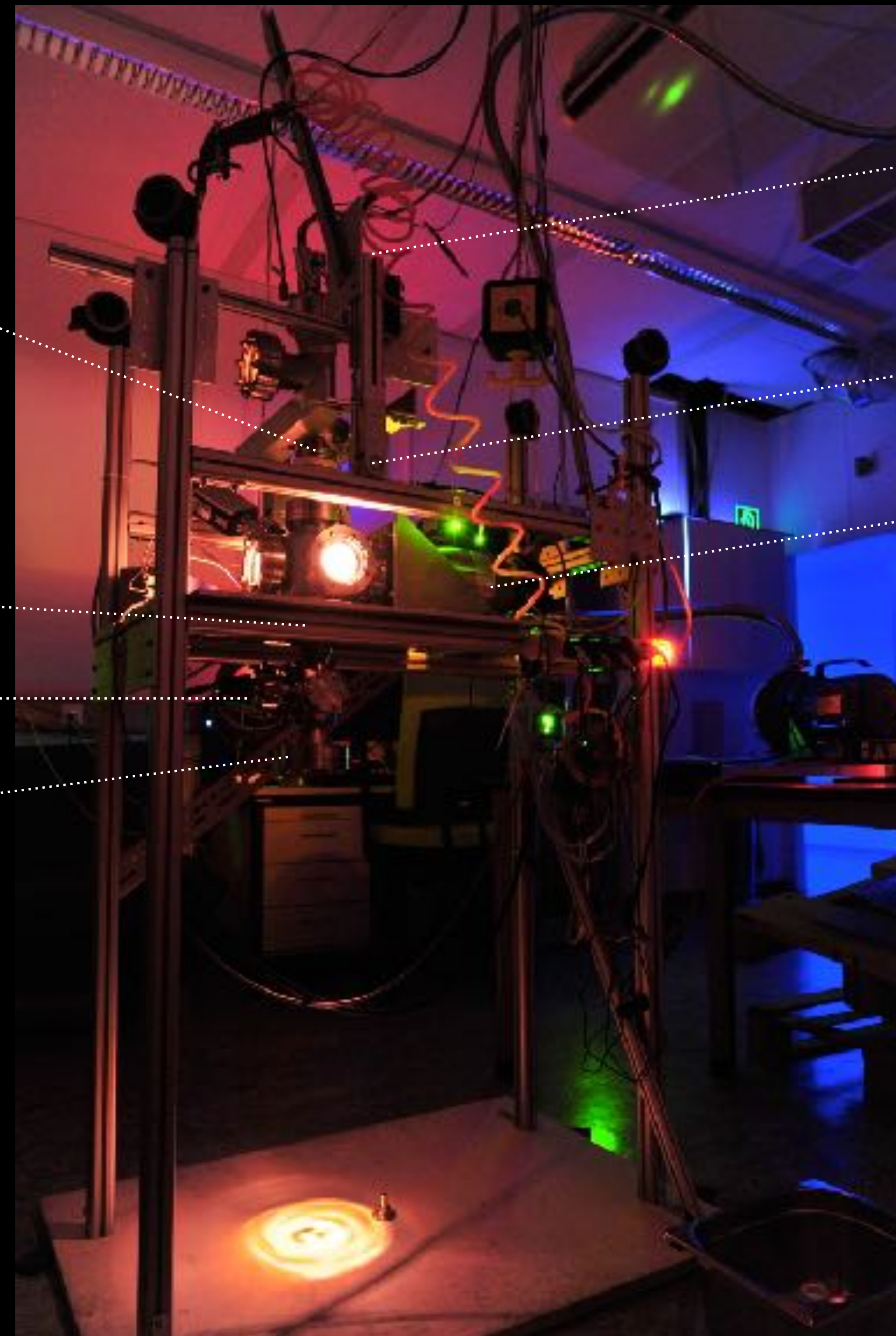


Thermal Cracker

Skimmer

Mass Spec

Differential Turbopump
(not shown)

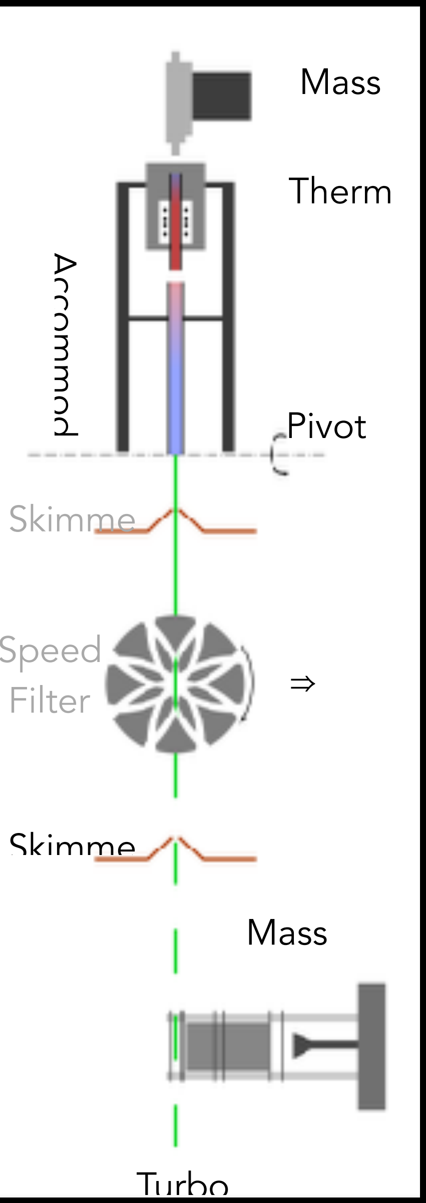


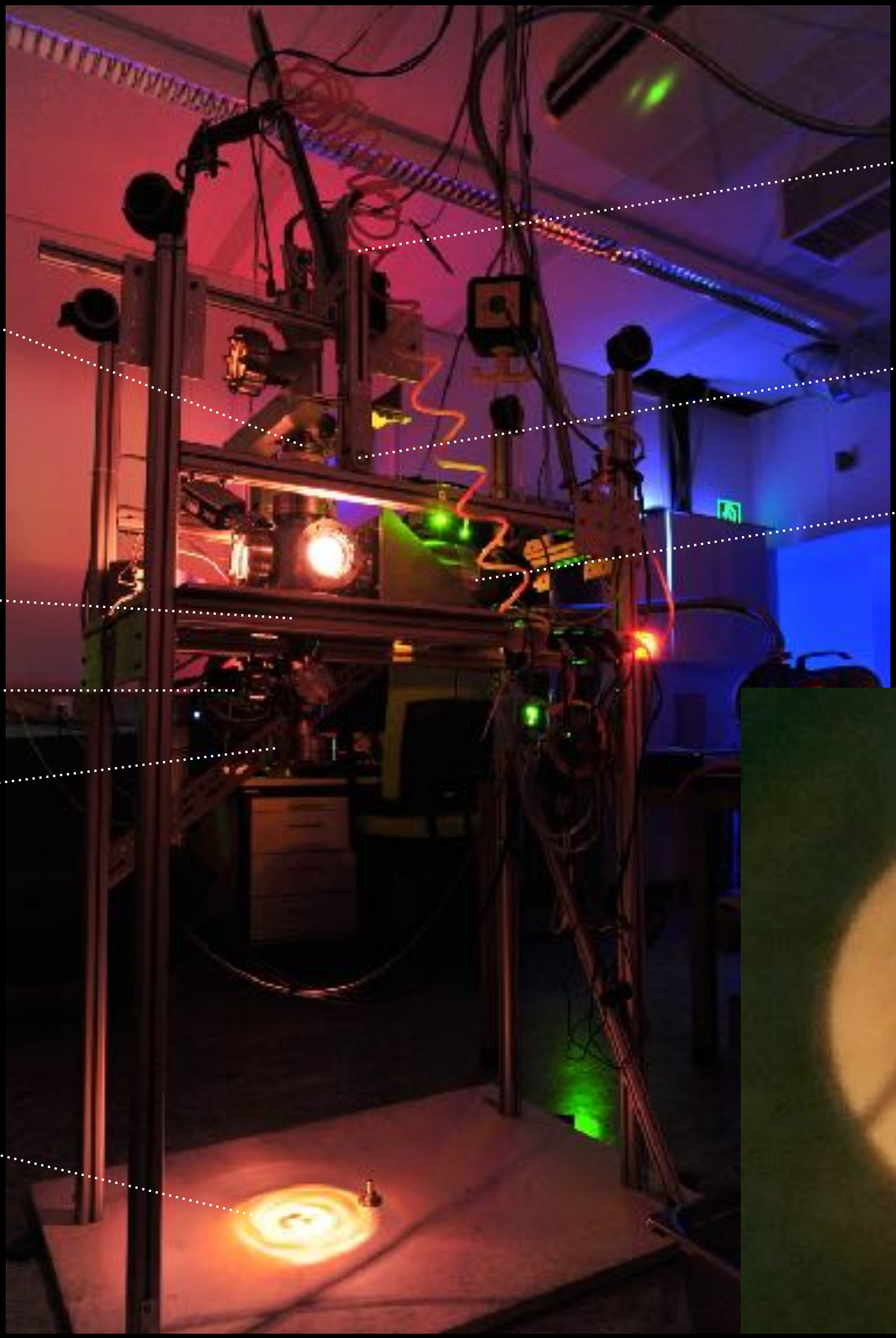
Hydrogen Gas Supply,
Mass Flow Controller,
and Leak Valve

Pivot Mechanism

Main Turbopump

Mainz Test Stand

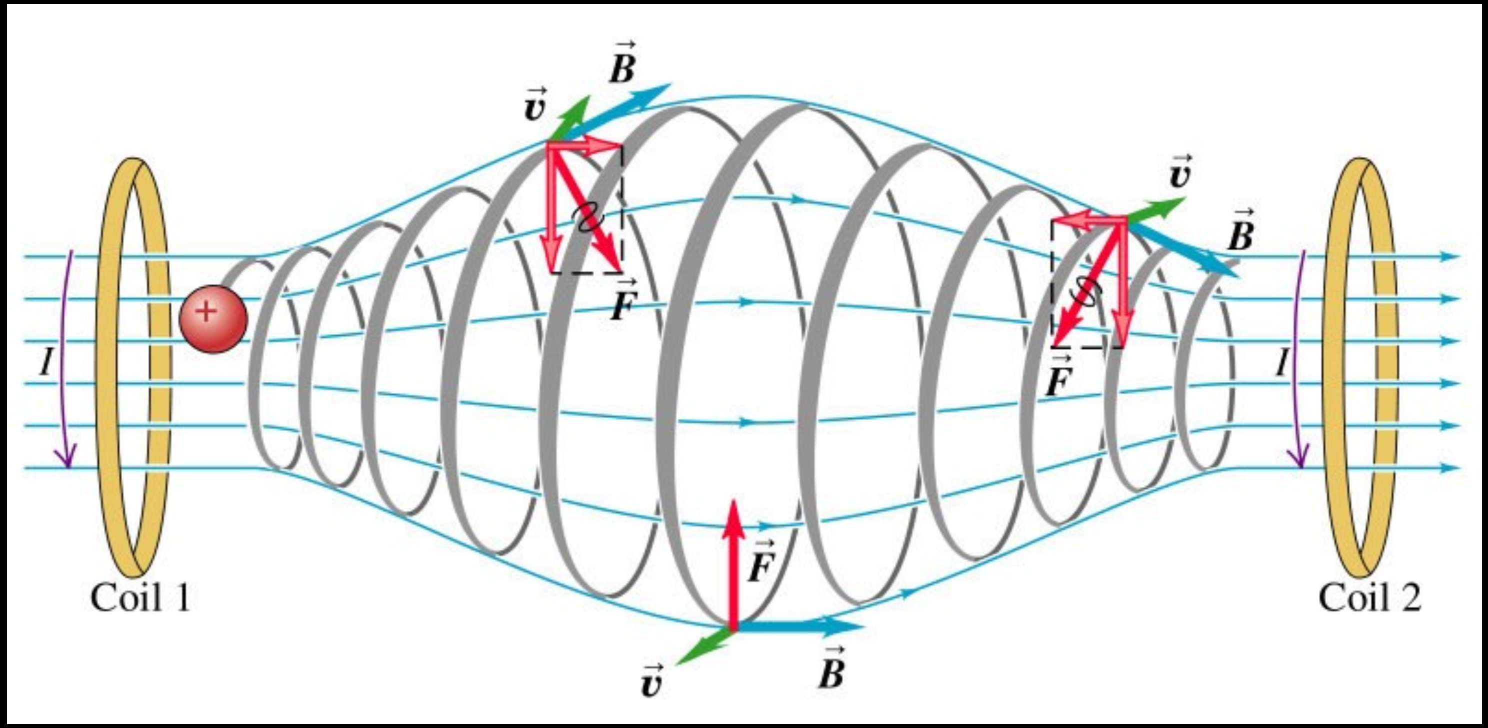




RESOLUTION

Energy resolution

- $\Delta E/E \sim \Delta f/f \sim$ ppm
  → easy!



Frequency resolution

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

- observation time $\Delta t = 20\mu s \sim 1400m$ @ 18keV
  → hard!

Need to store electrons in magnetic trap!