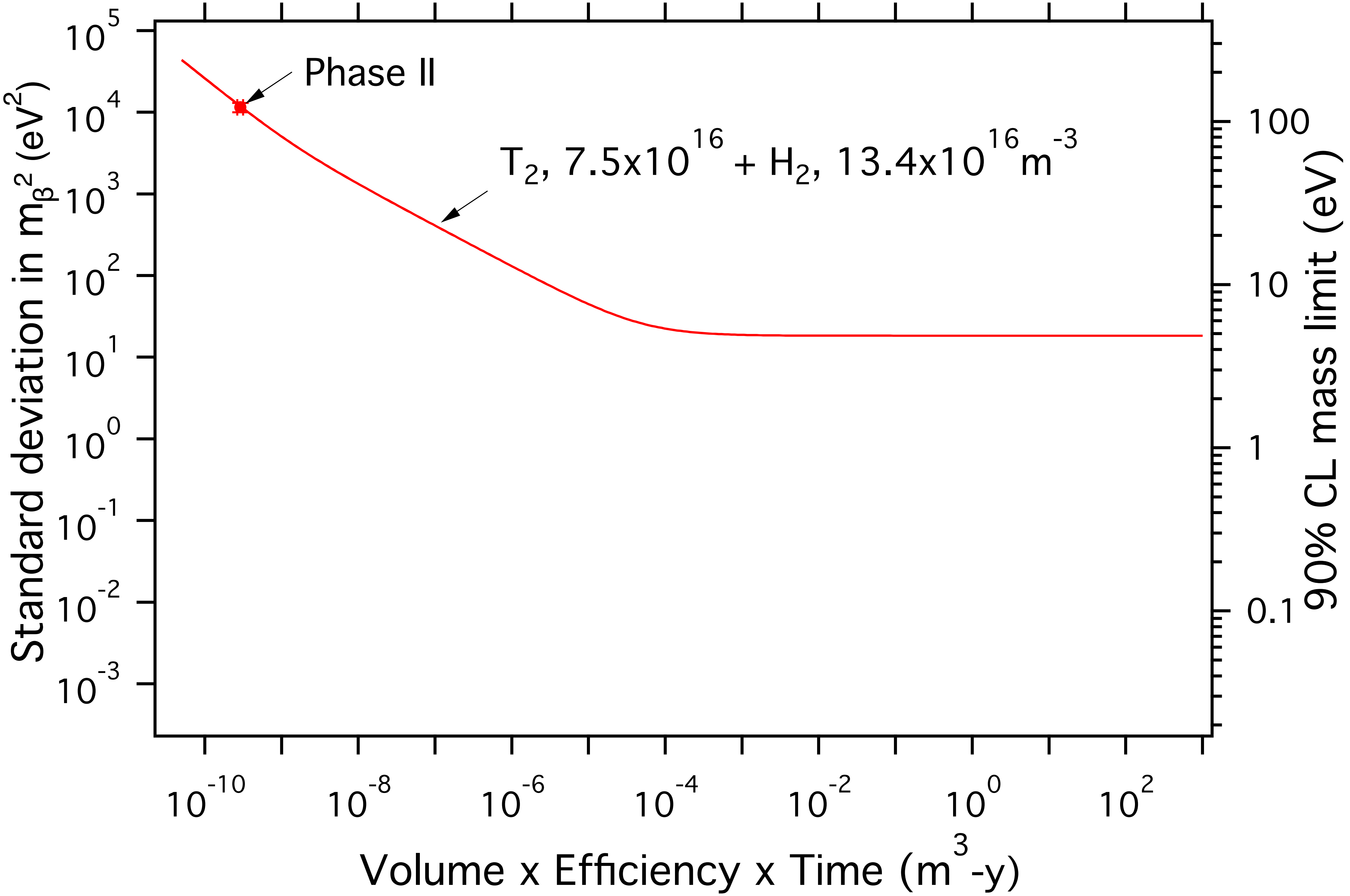
Towards an atomic tritium source for Project 8

Sebastian Böser
30 years TLK Symposium | Karlsruhe | May 24nd 2023

Potential for neutrino mass?



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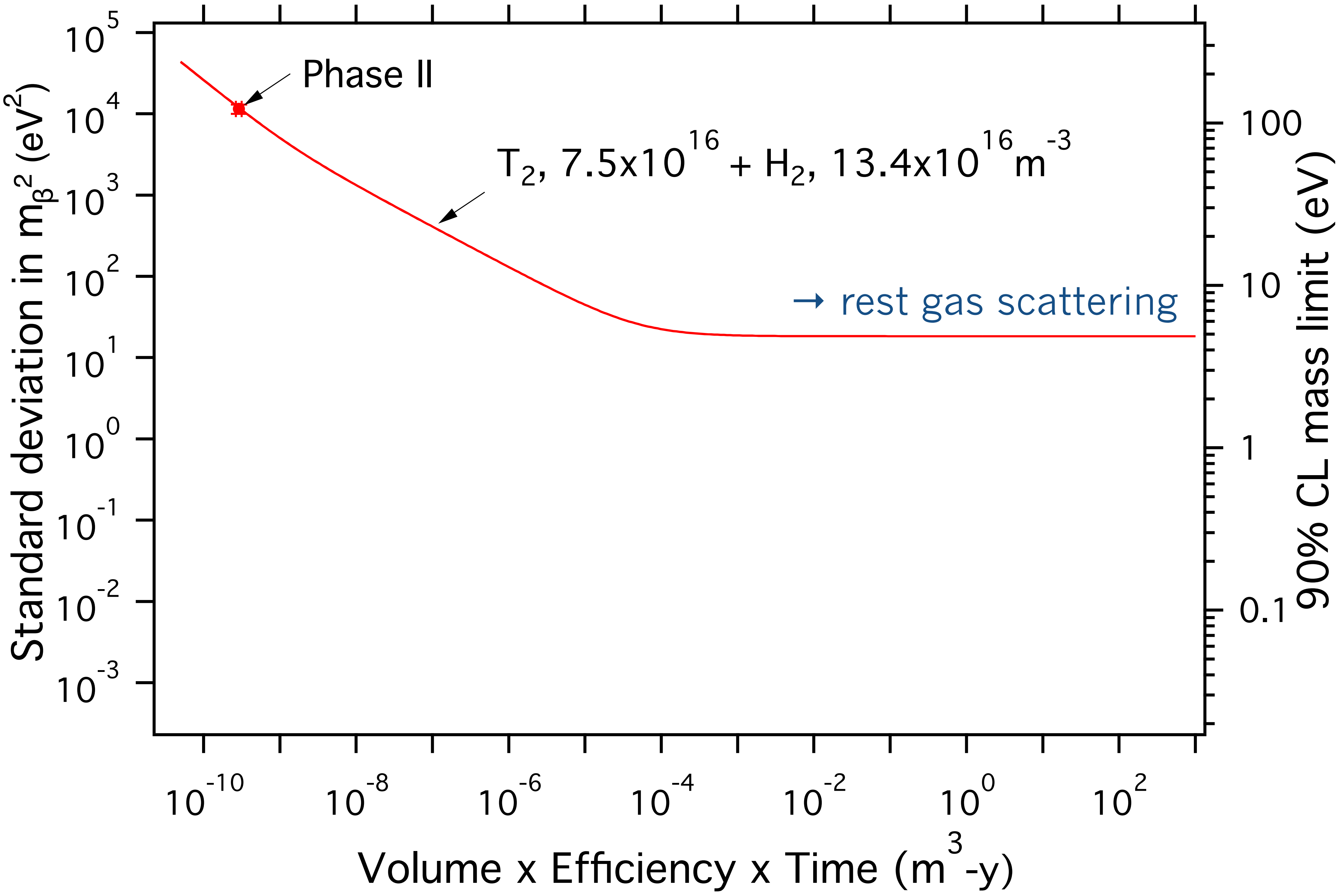

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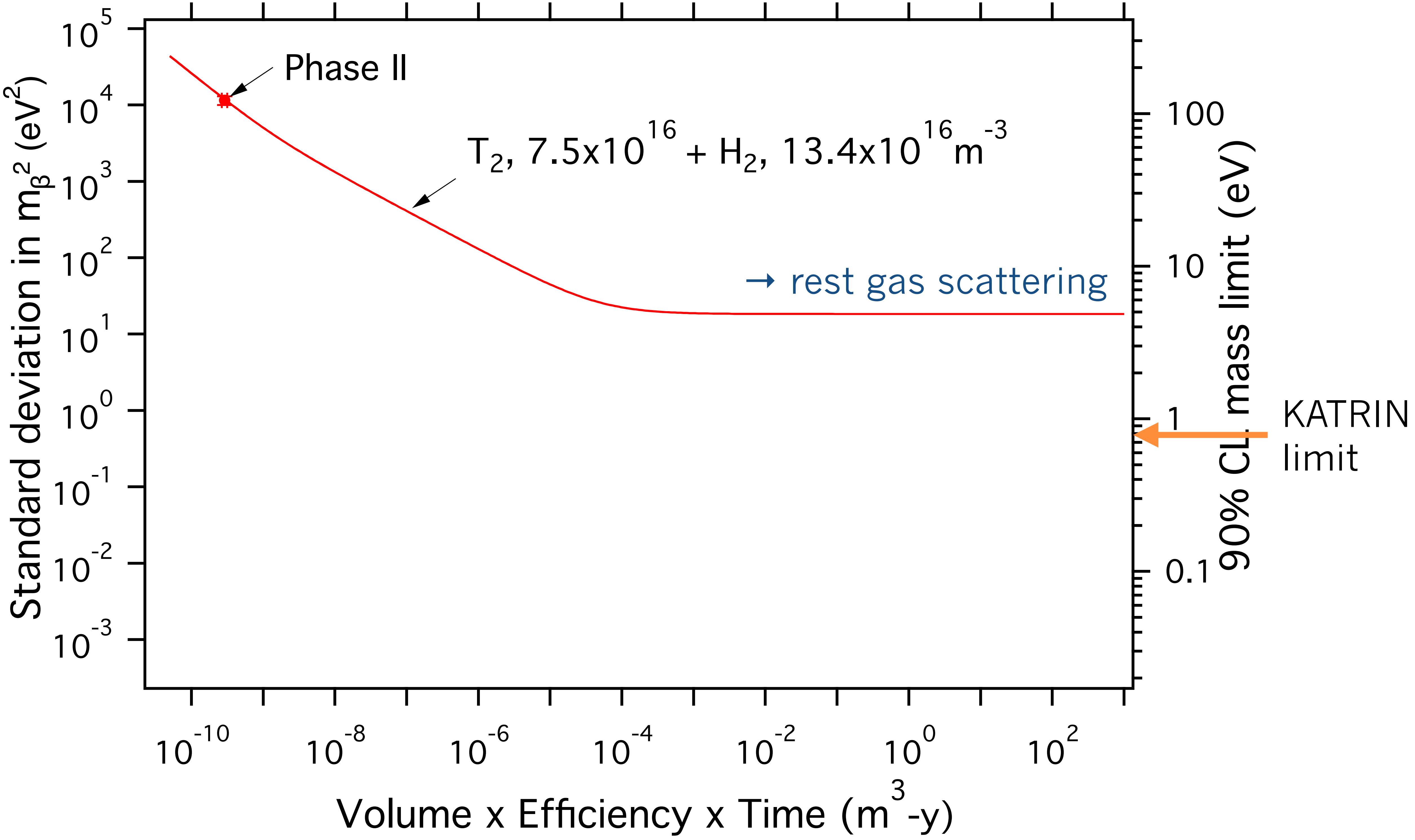

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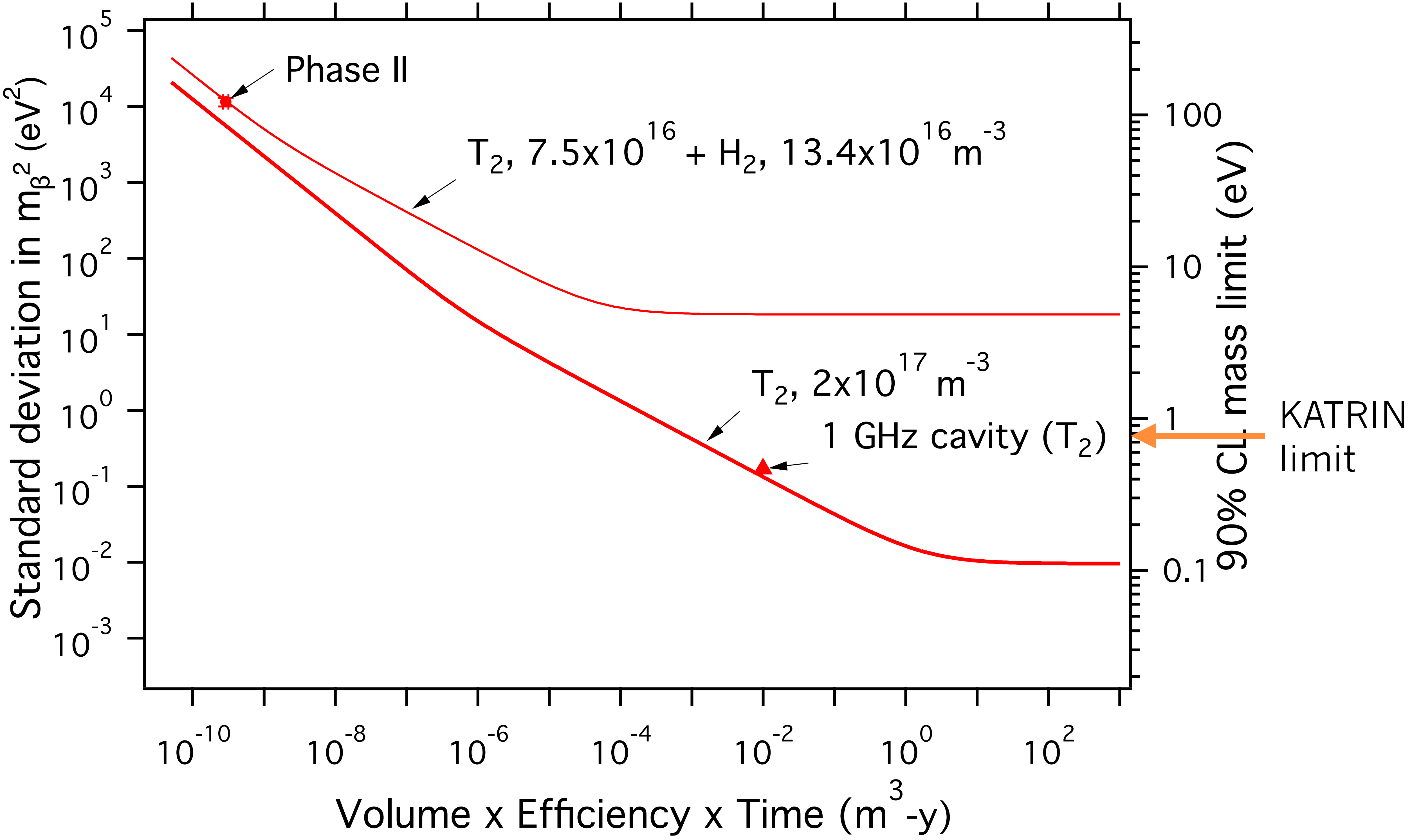

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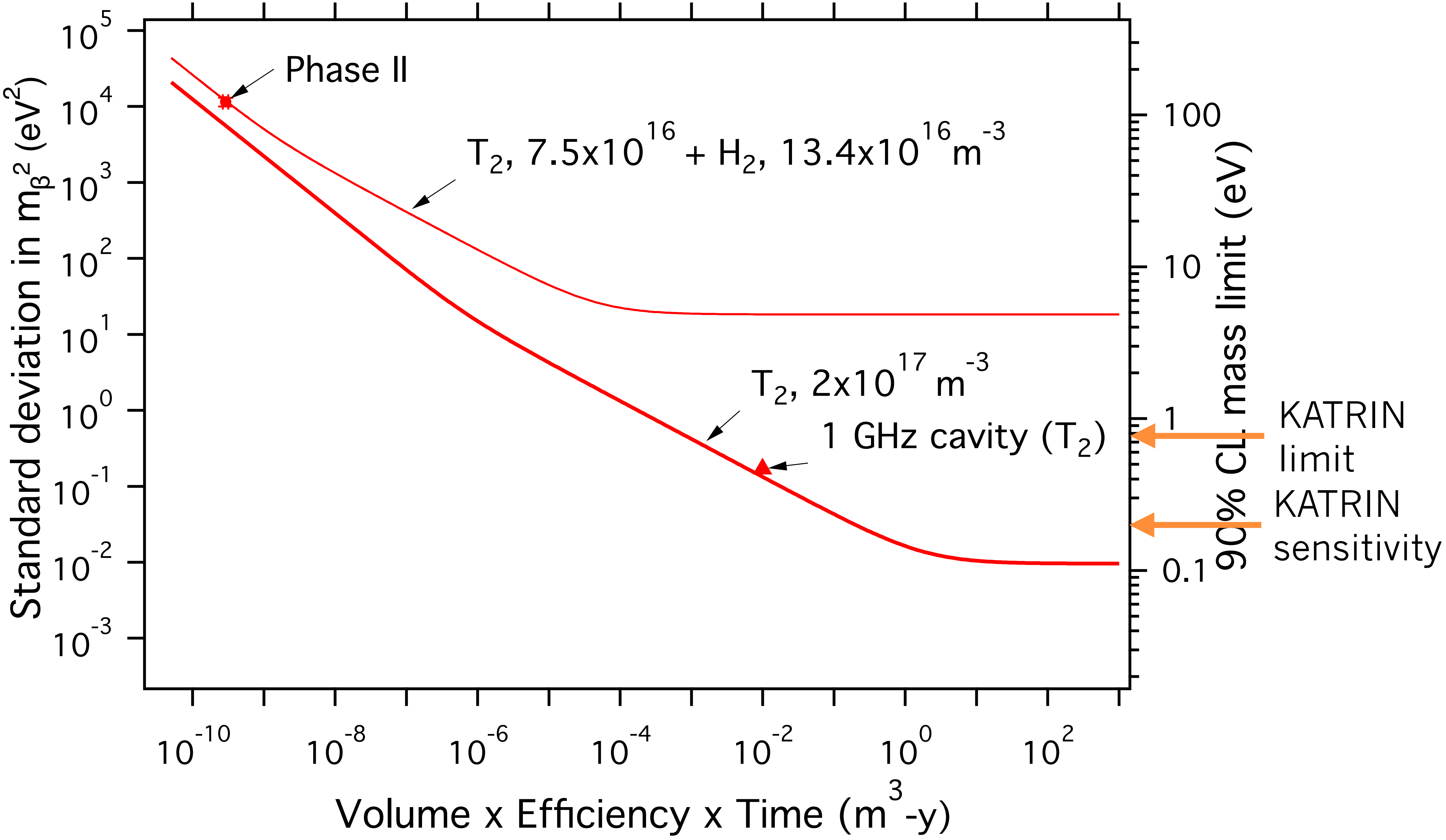

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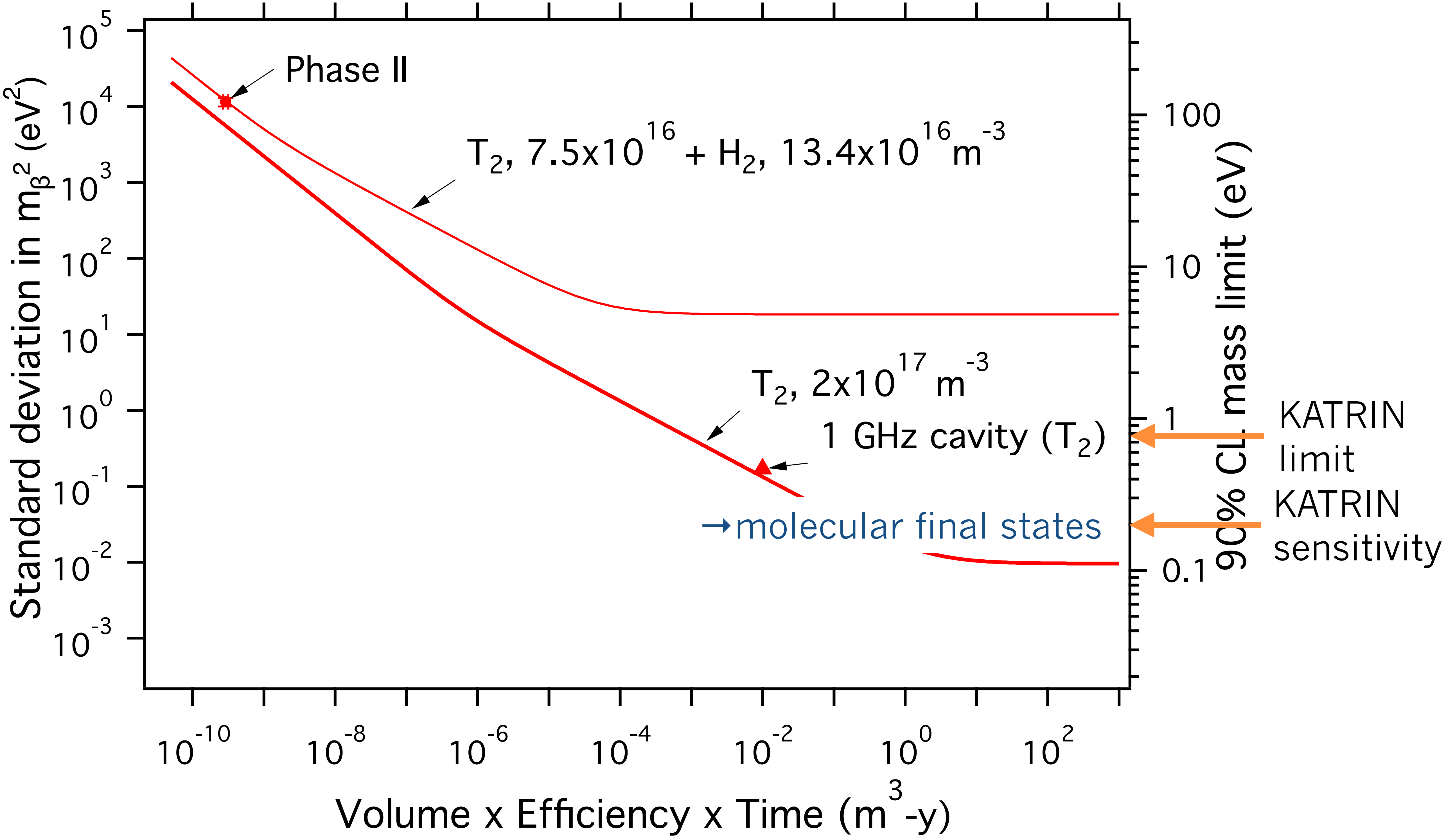

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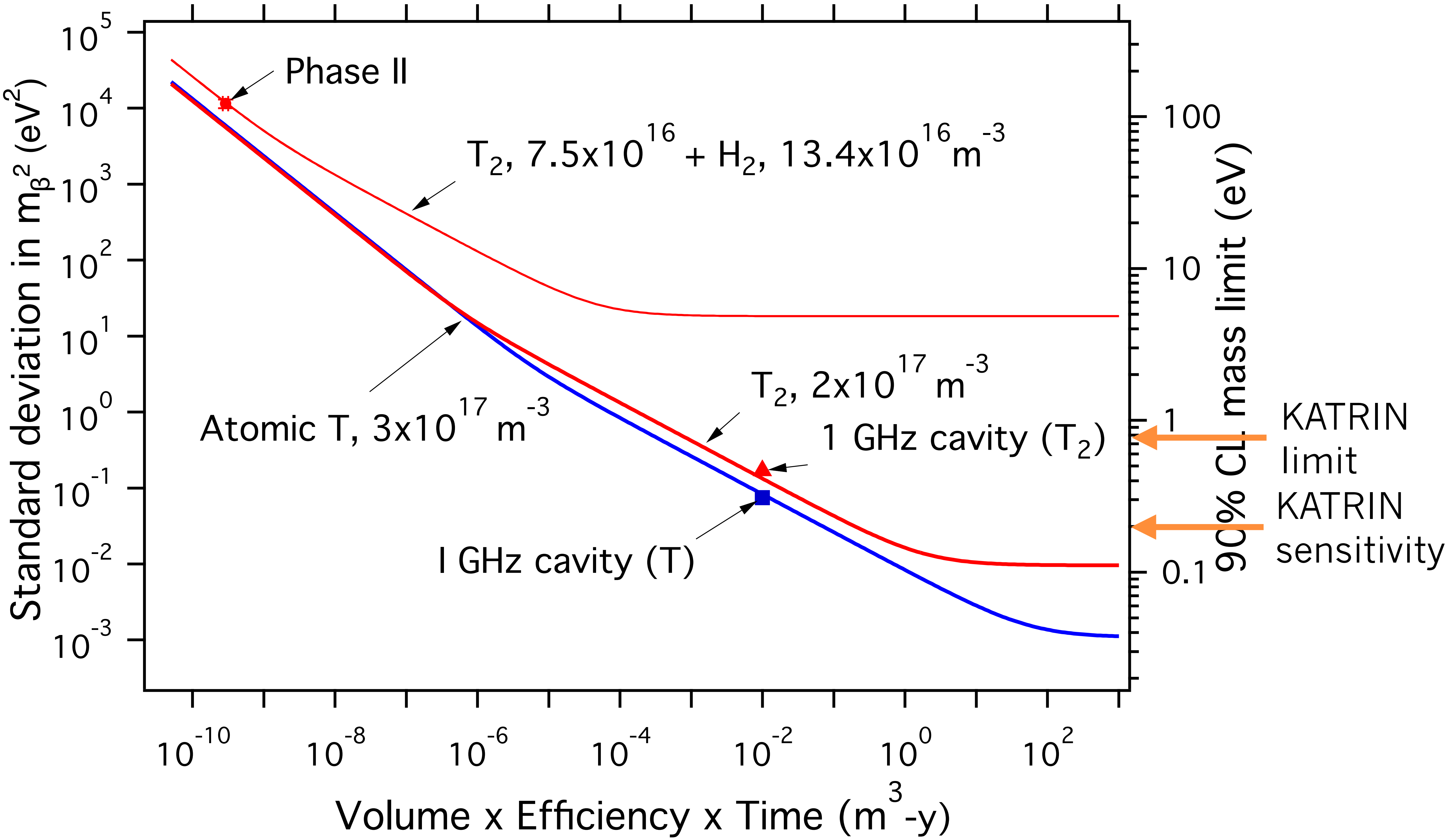

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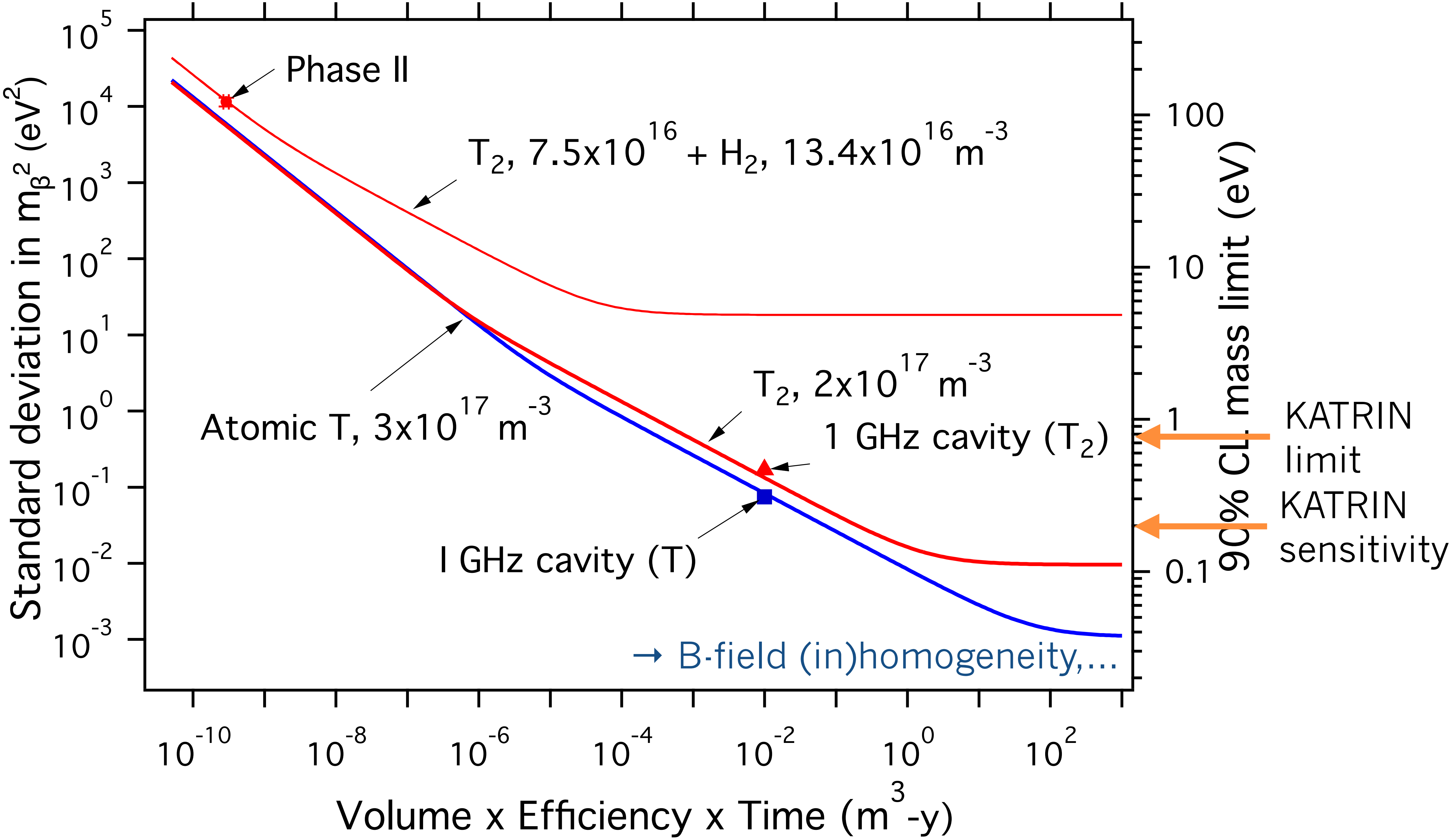

PRiSMA

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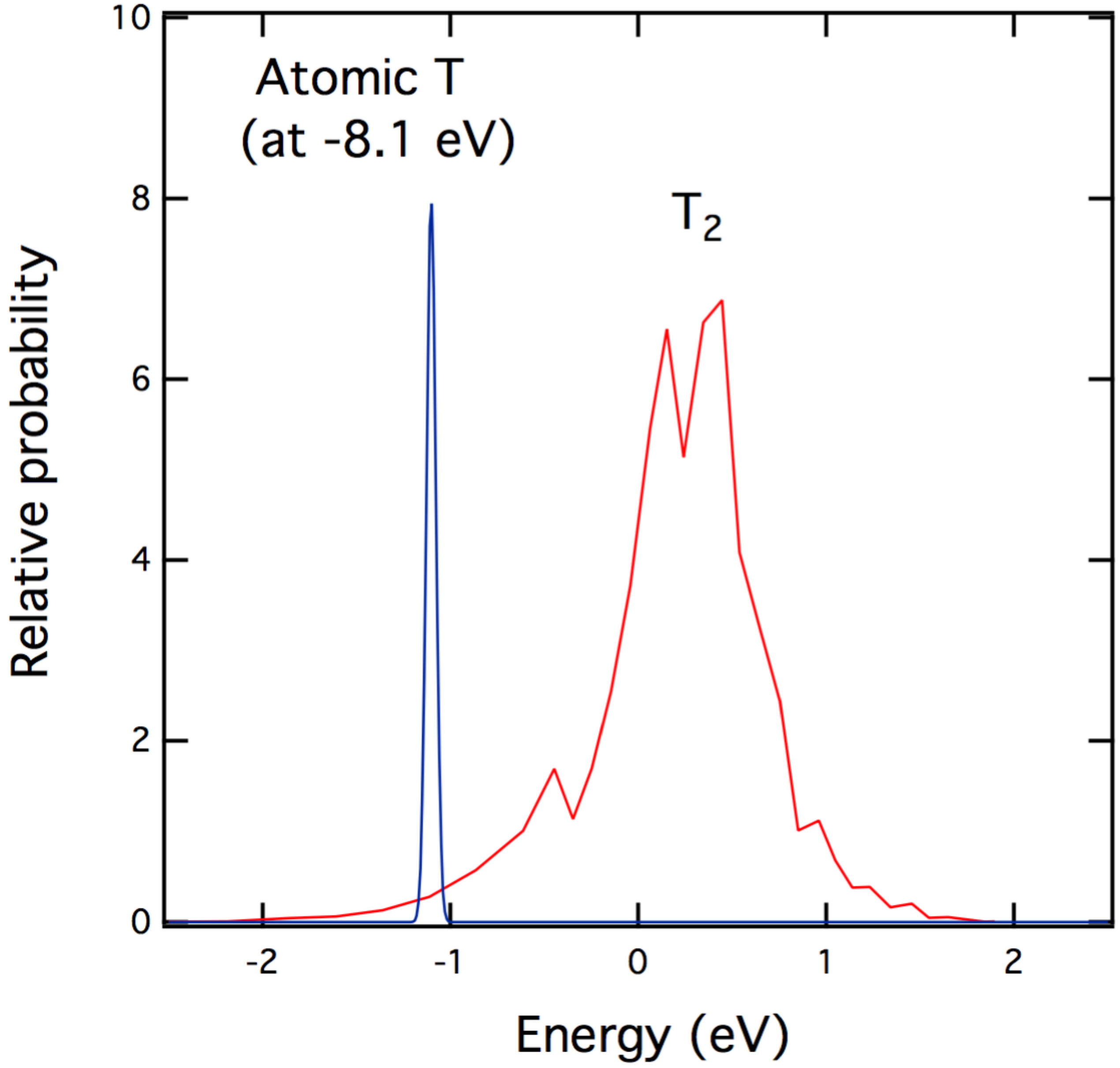
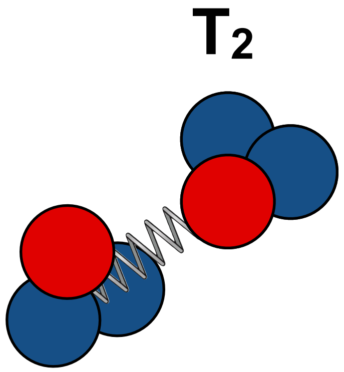
Molecular tritium limitations



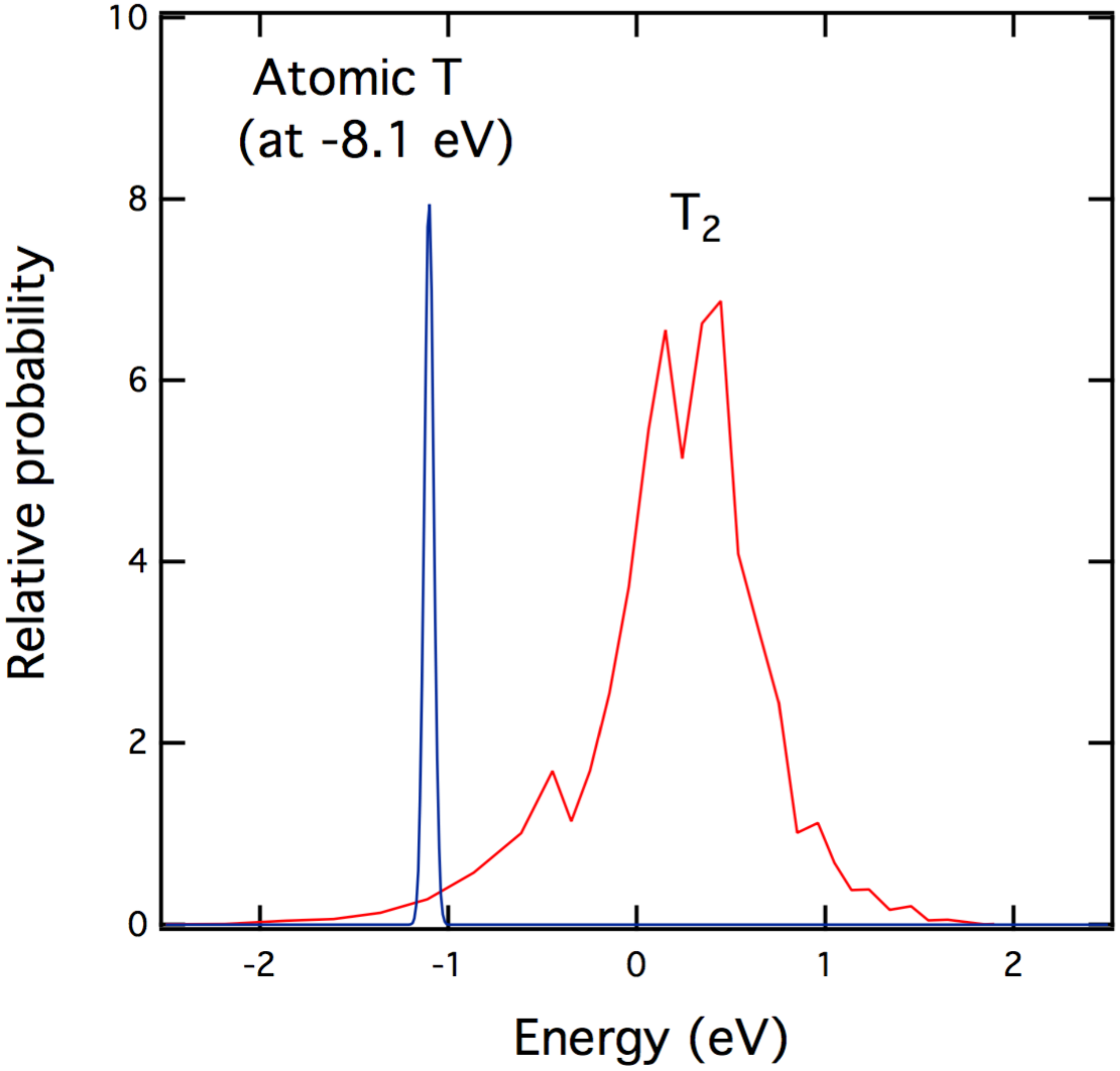


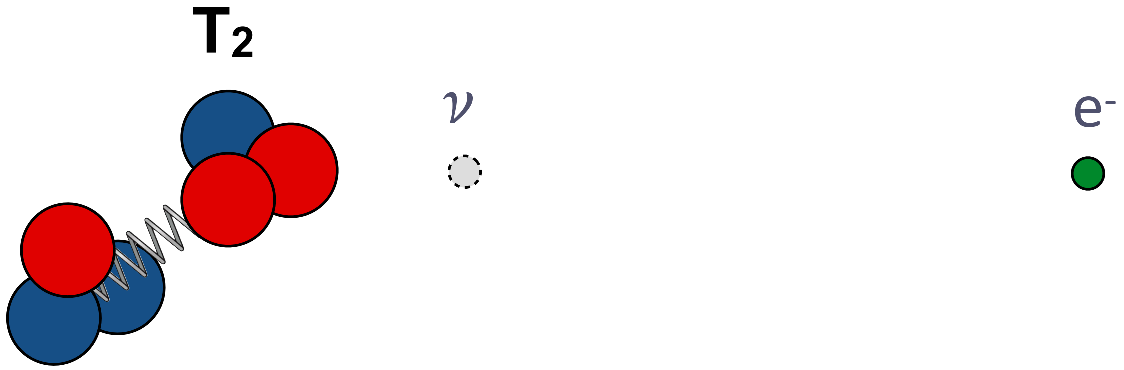
Molecular excitations
in ^{3}HeT daughter molecule

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

Need atomic tritium
for **ultimate** experiment!

Molecular tritium limitations





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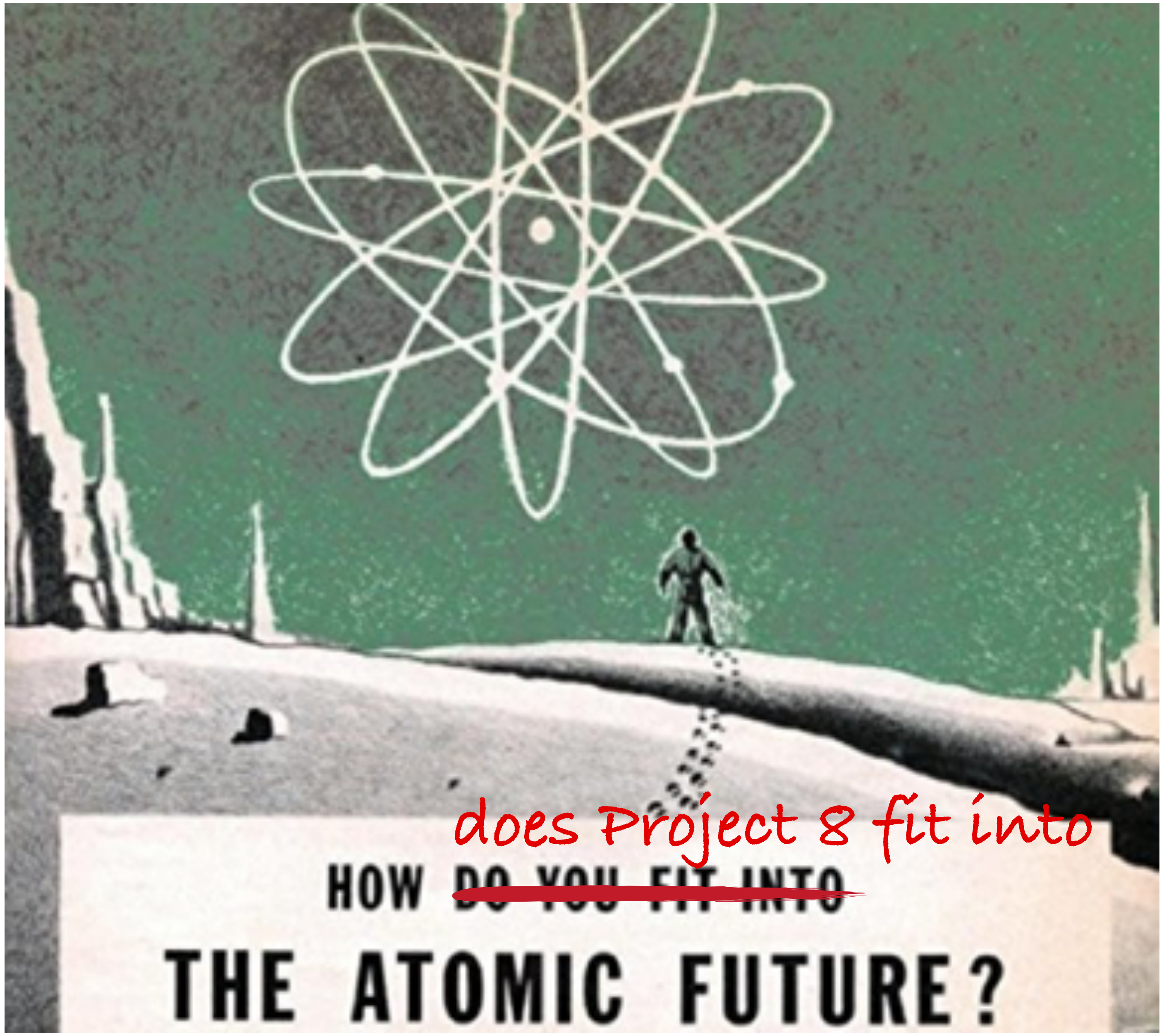

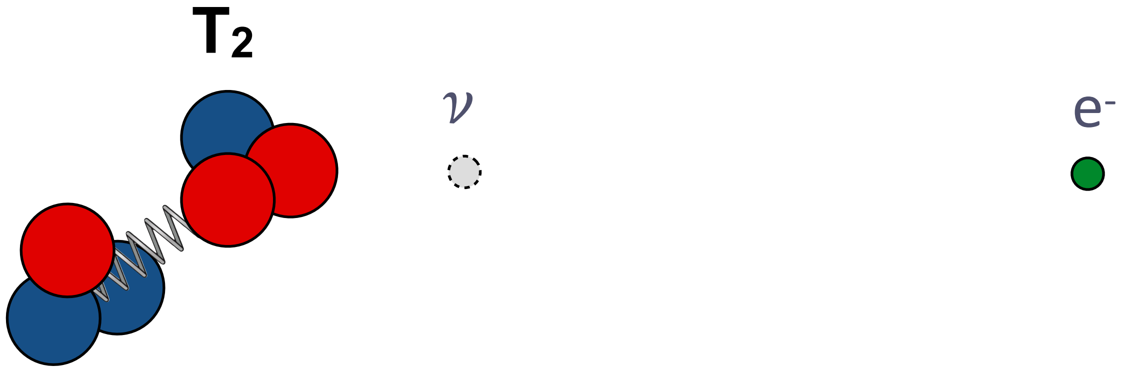

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Magnetic storage of neutral atoms

Storage of atomic T

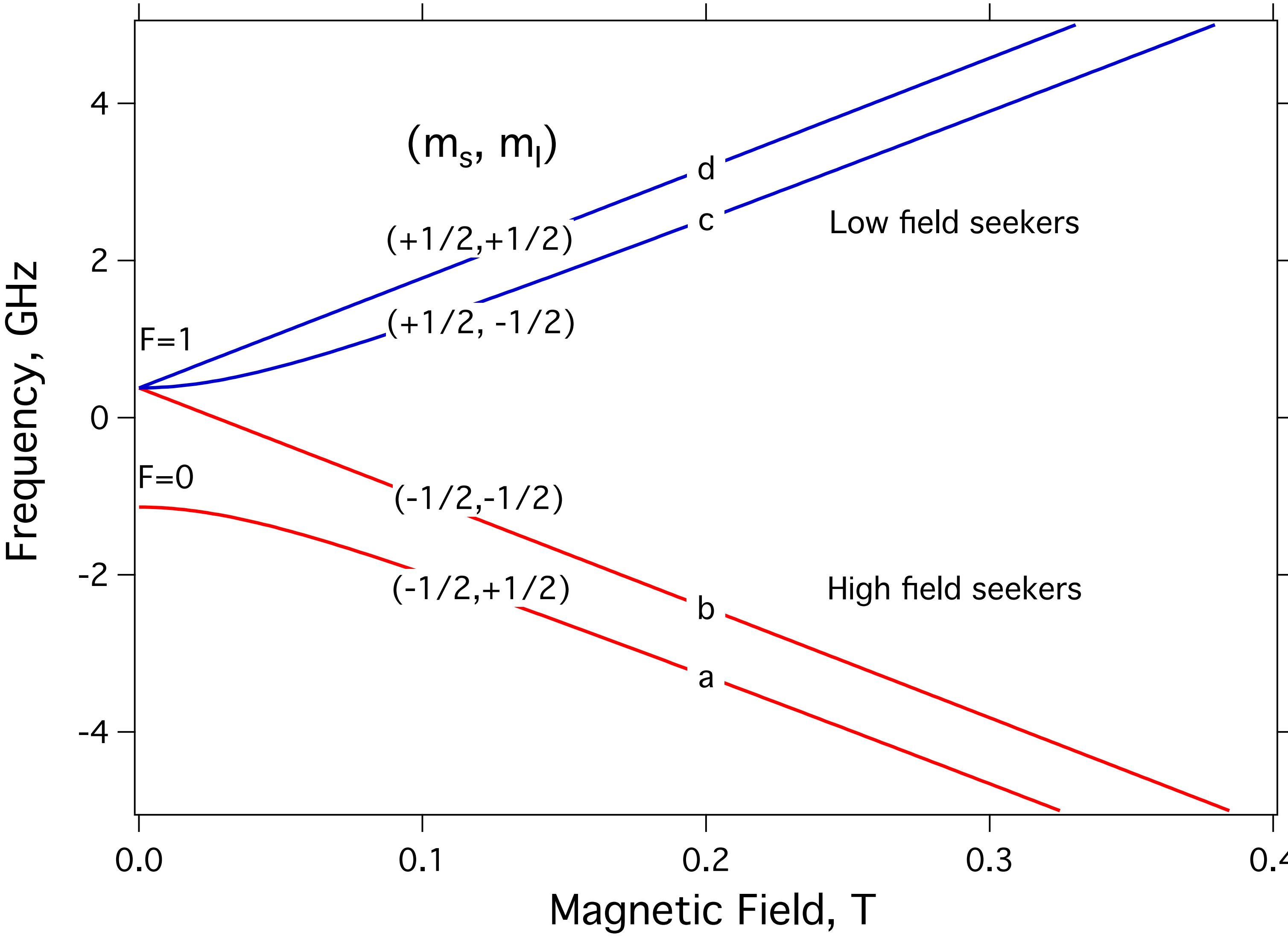
- recombination catalyzed by walls
  → difficult!

- 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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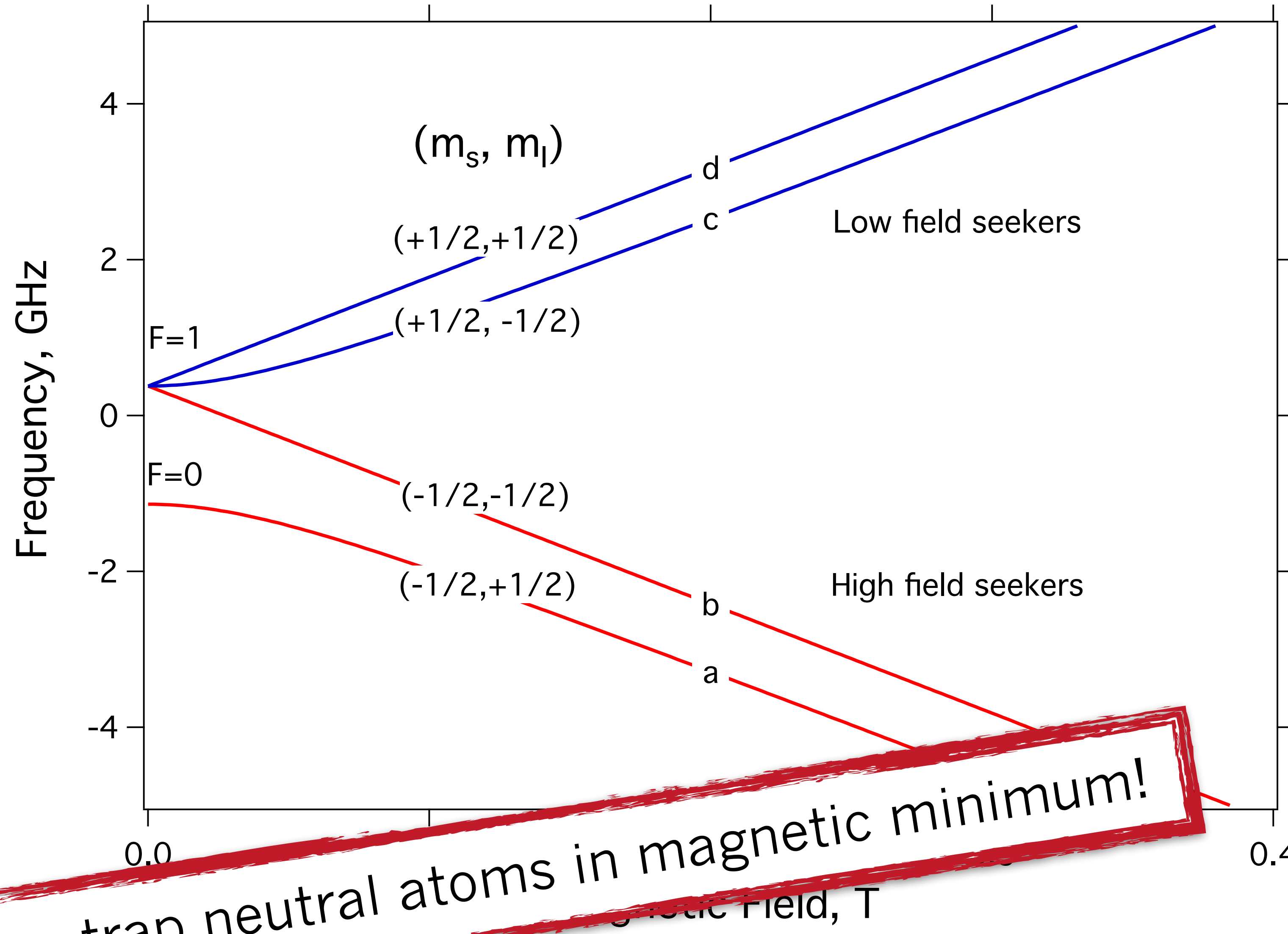
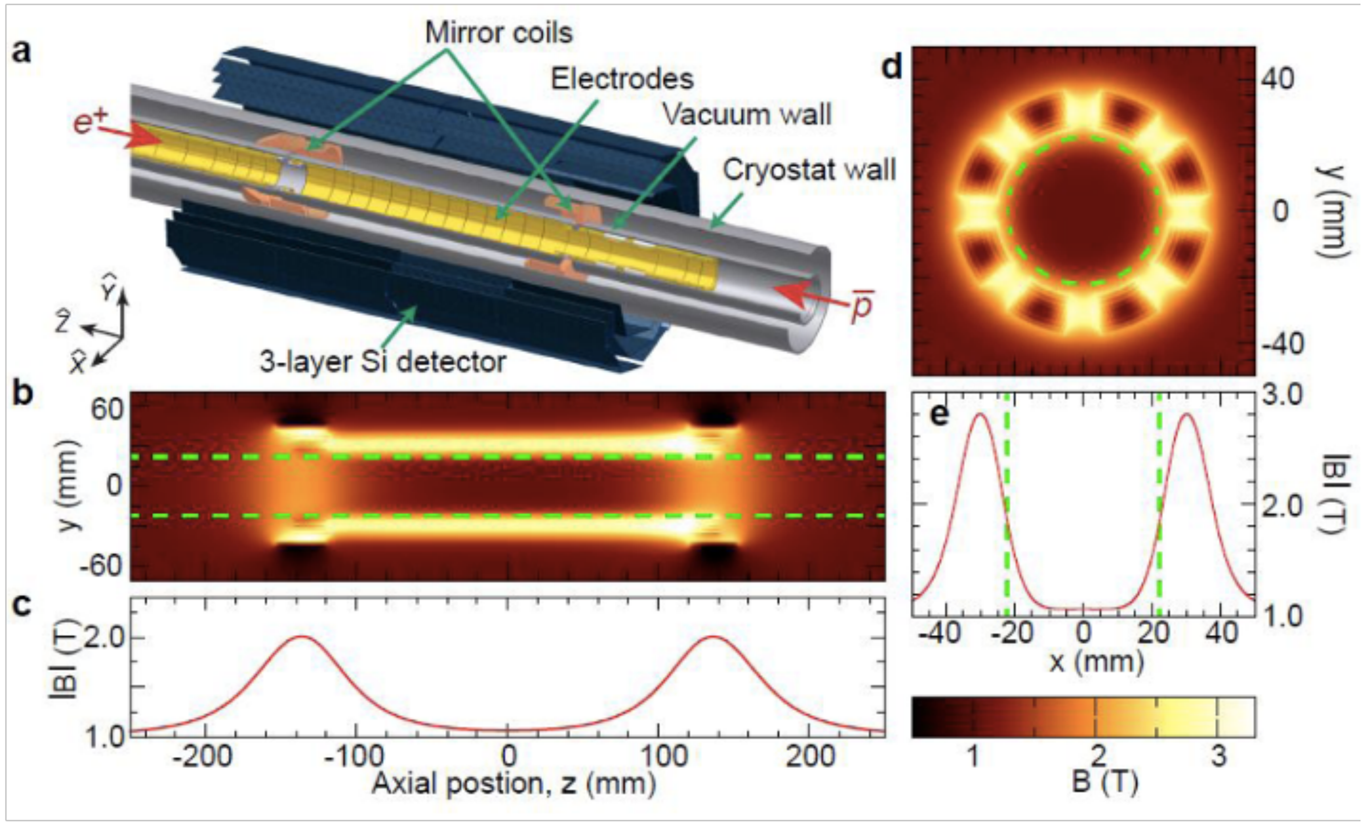
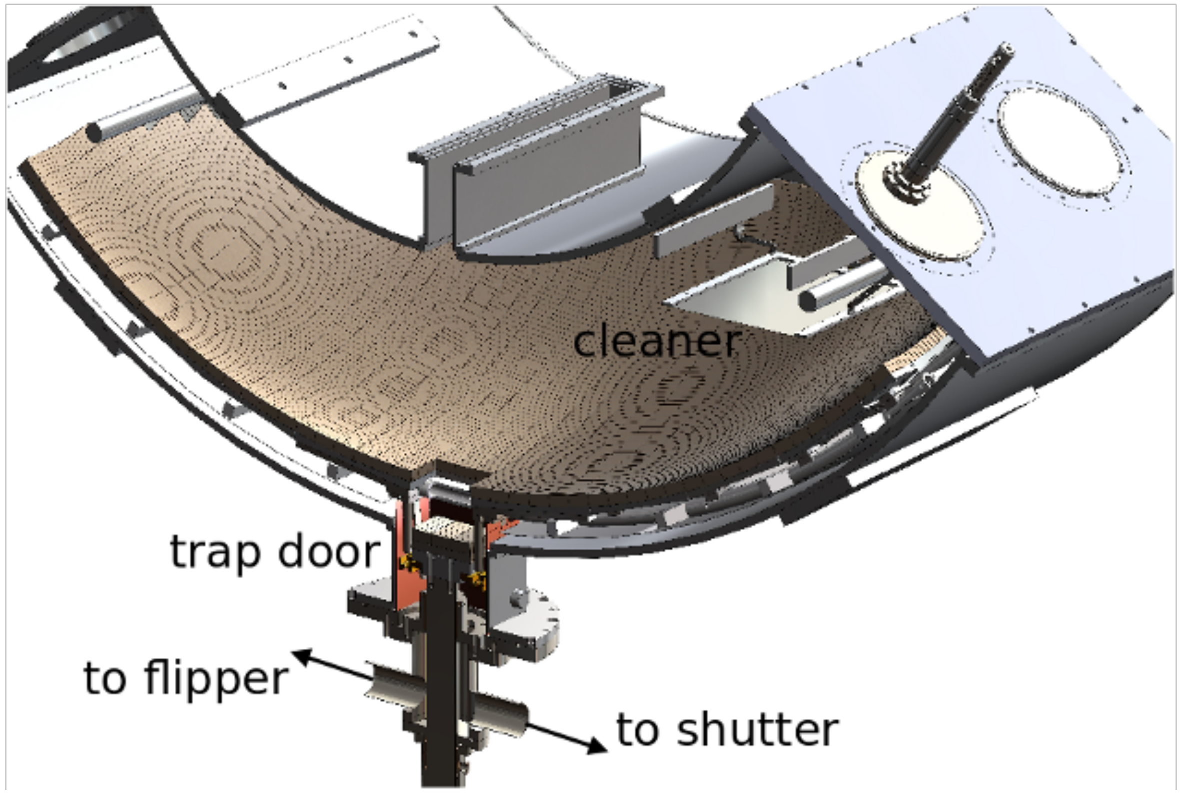


Can trap neutral atoms in magnetic minimum!

Neutral particle traps



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

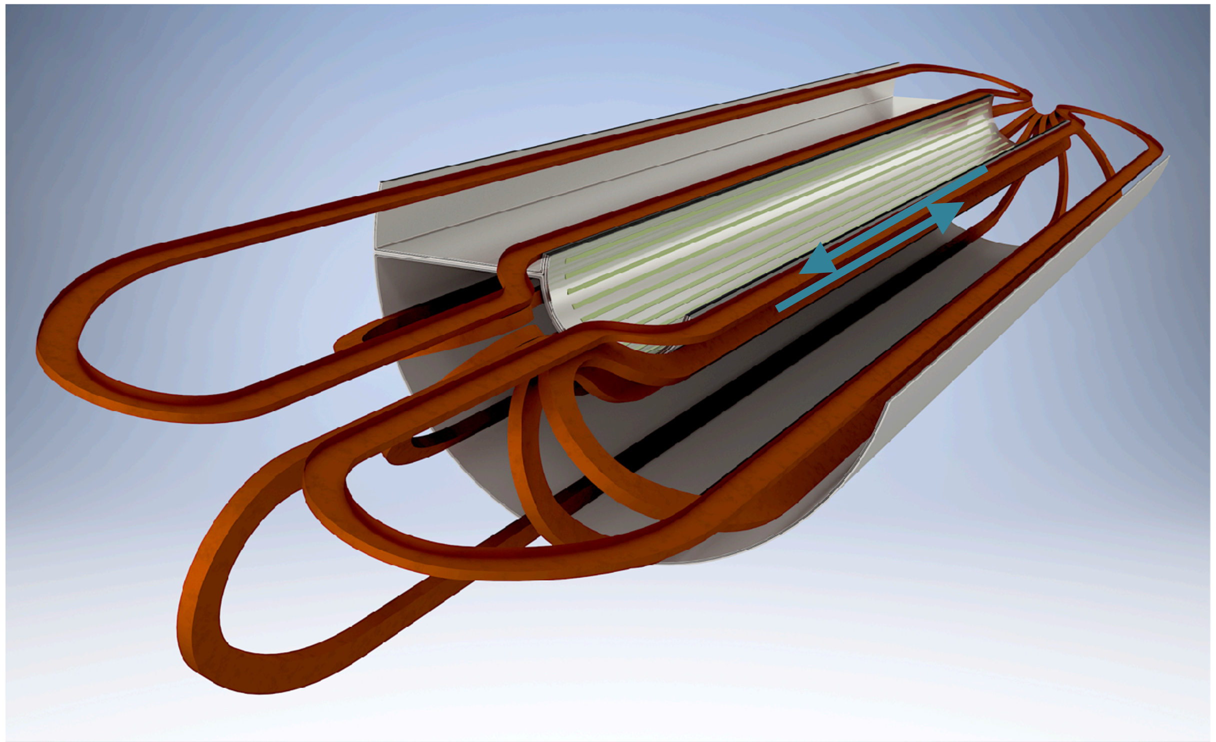


UCNtau Collaboration: Phys Rev C89, 052501, 2014; arXiv 1310.5759v3

General design

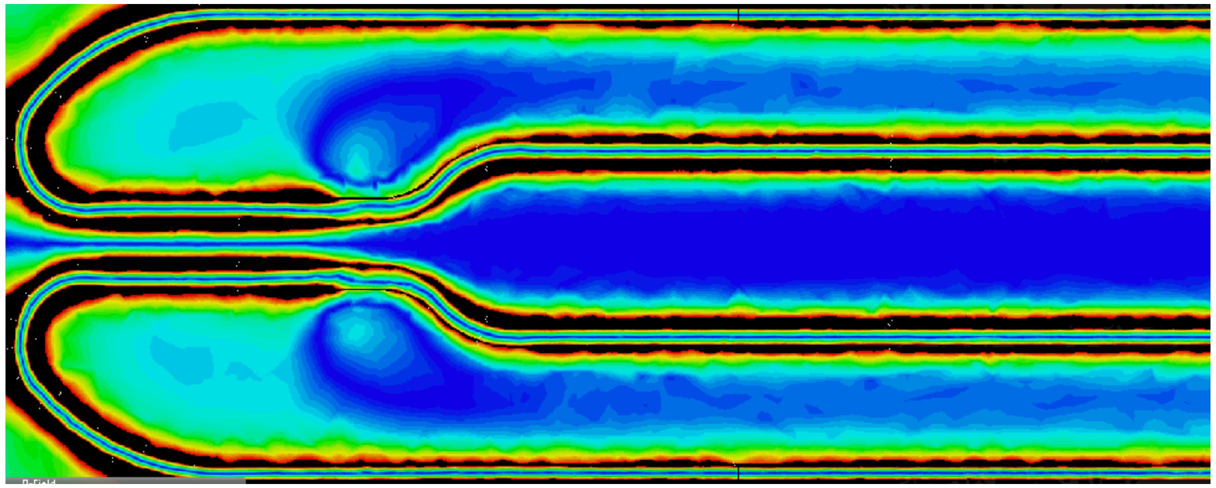
- high magnetic field at walls
- low magnetic fields in the center
  - near-field to far-field transition with opposing fields

Atom trapping



Studying 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**



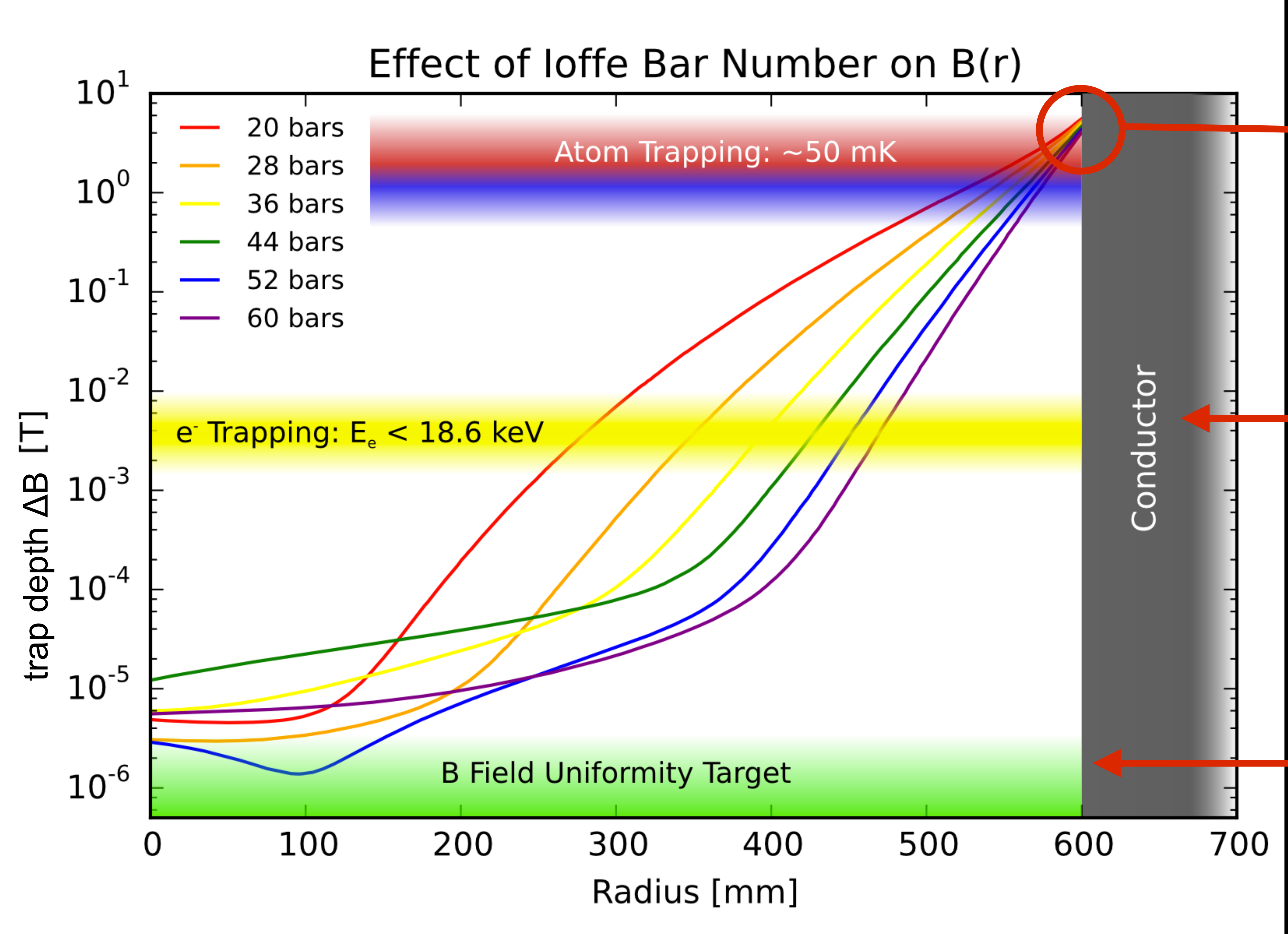
Challenges

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

PRISMA

JG|U

Atomic trapping: trap challenges



Conductor + structure size

↕

effective volume

↕

target uniformity level

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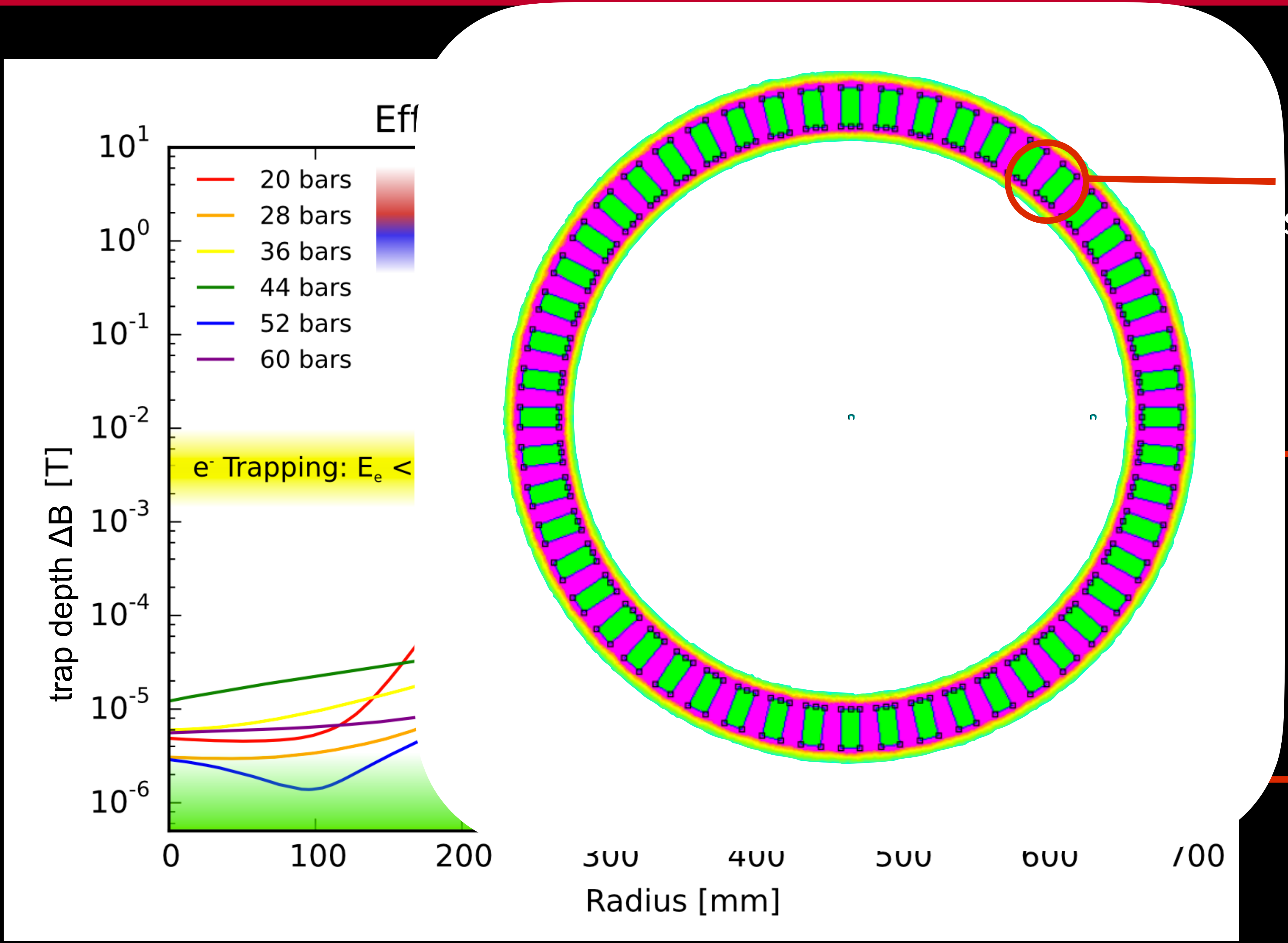

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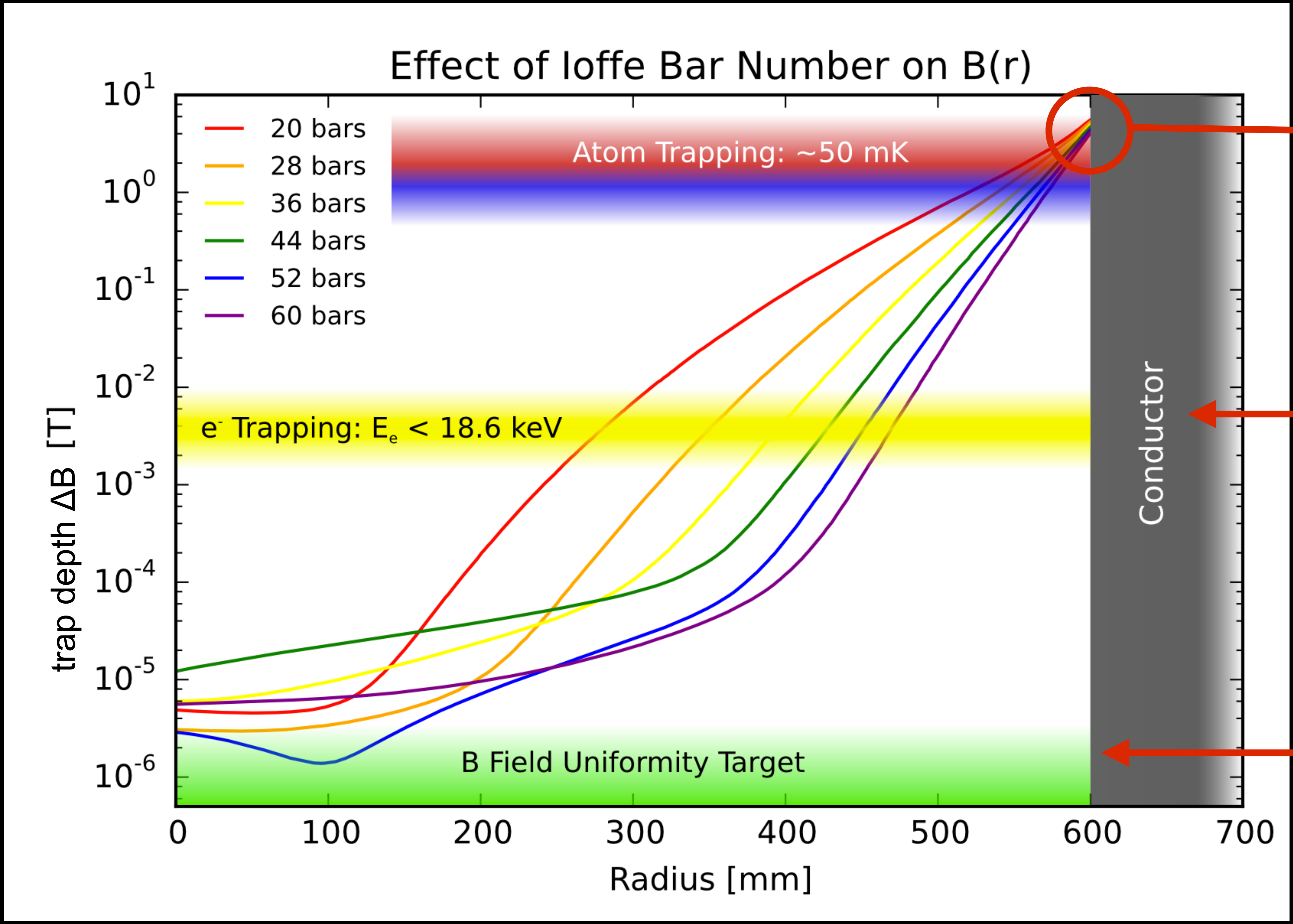

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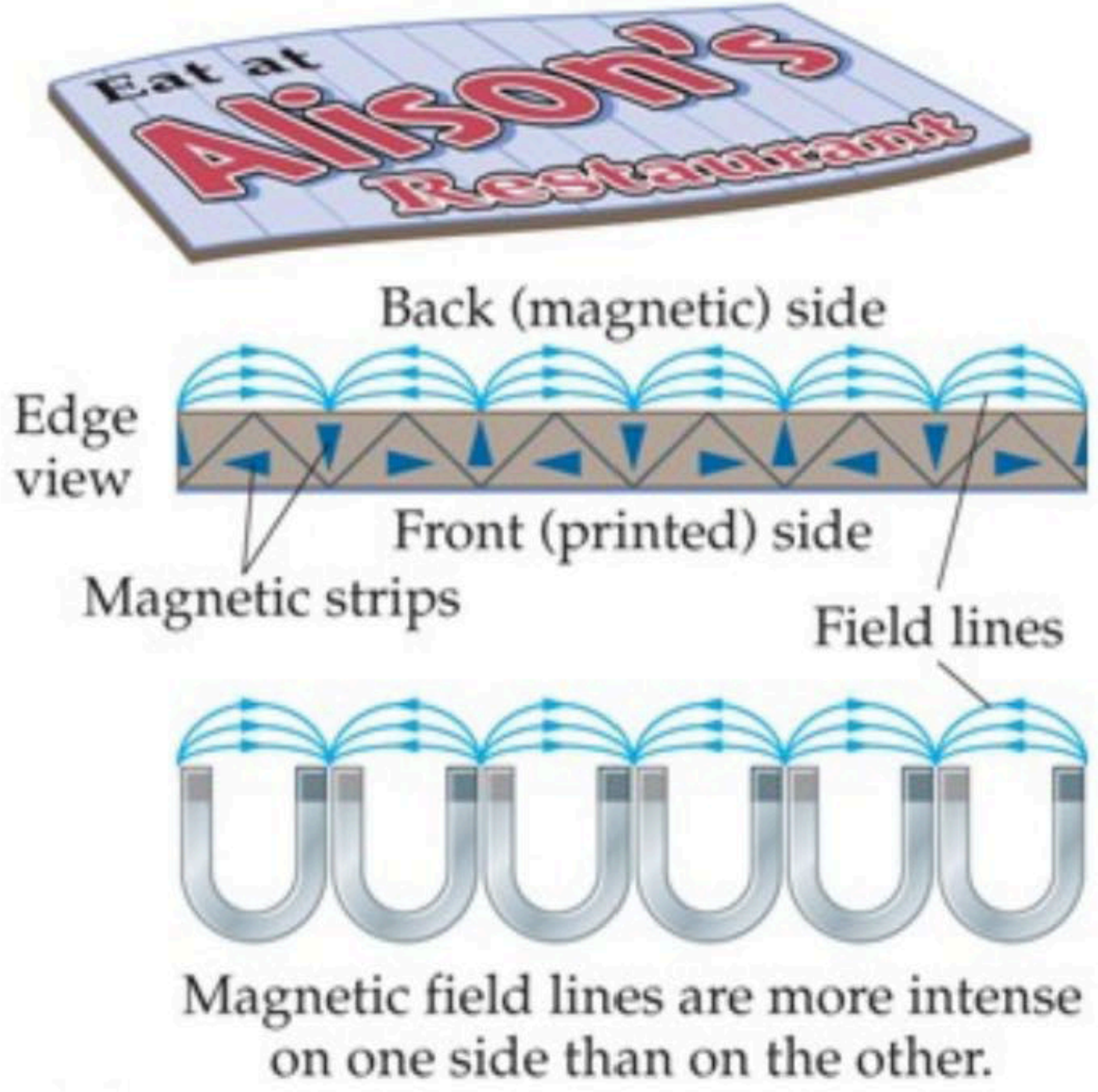
Halbach arrays

Permanent magnet configuration

- alternate orientations
  - strong near field
  - weak far field
- circular flux configuration
  - one “*magnetic*” side
  - one “*non-magnetic*” side



Magnetic field lines are more intense on one side than on the other.

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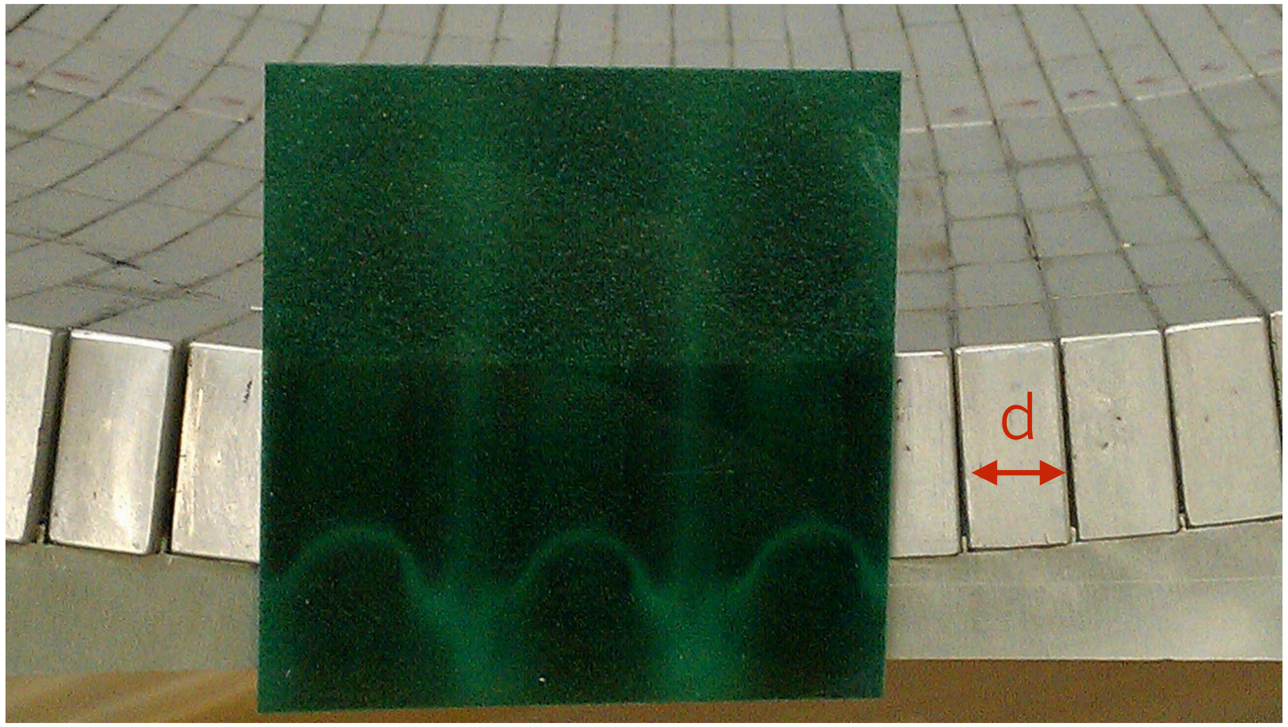

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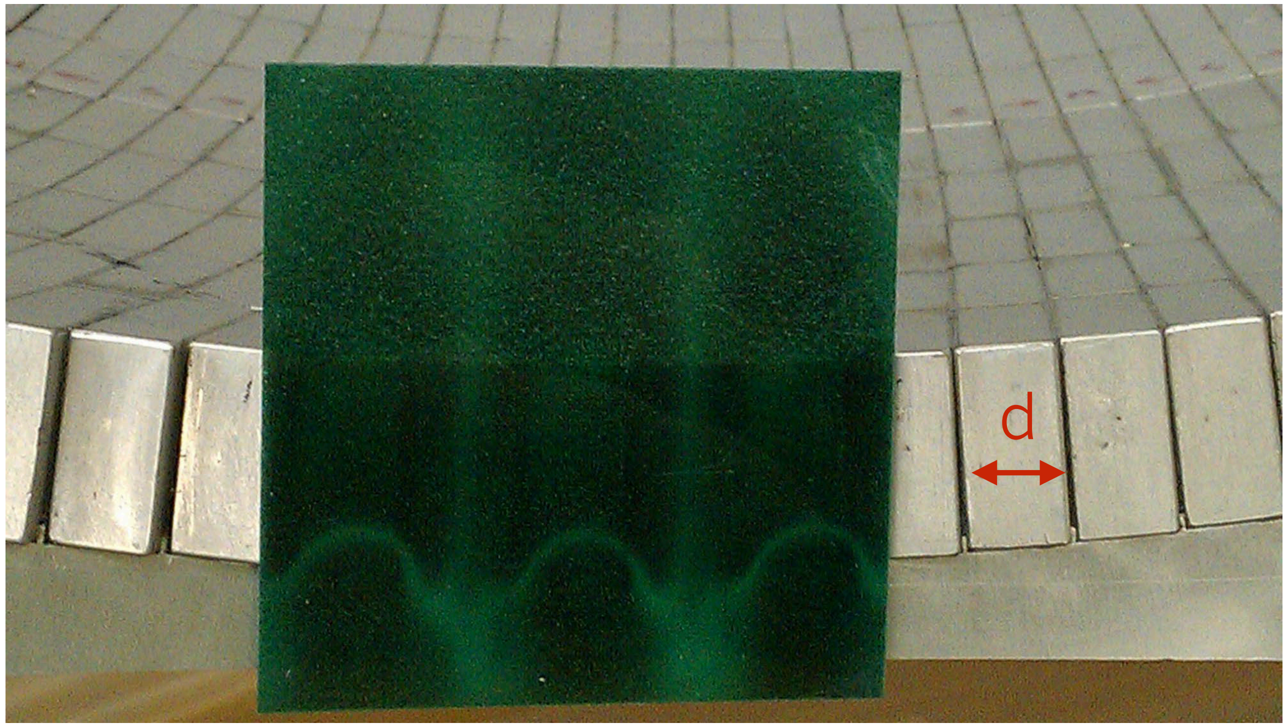
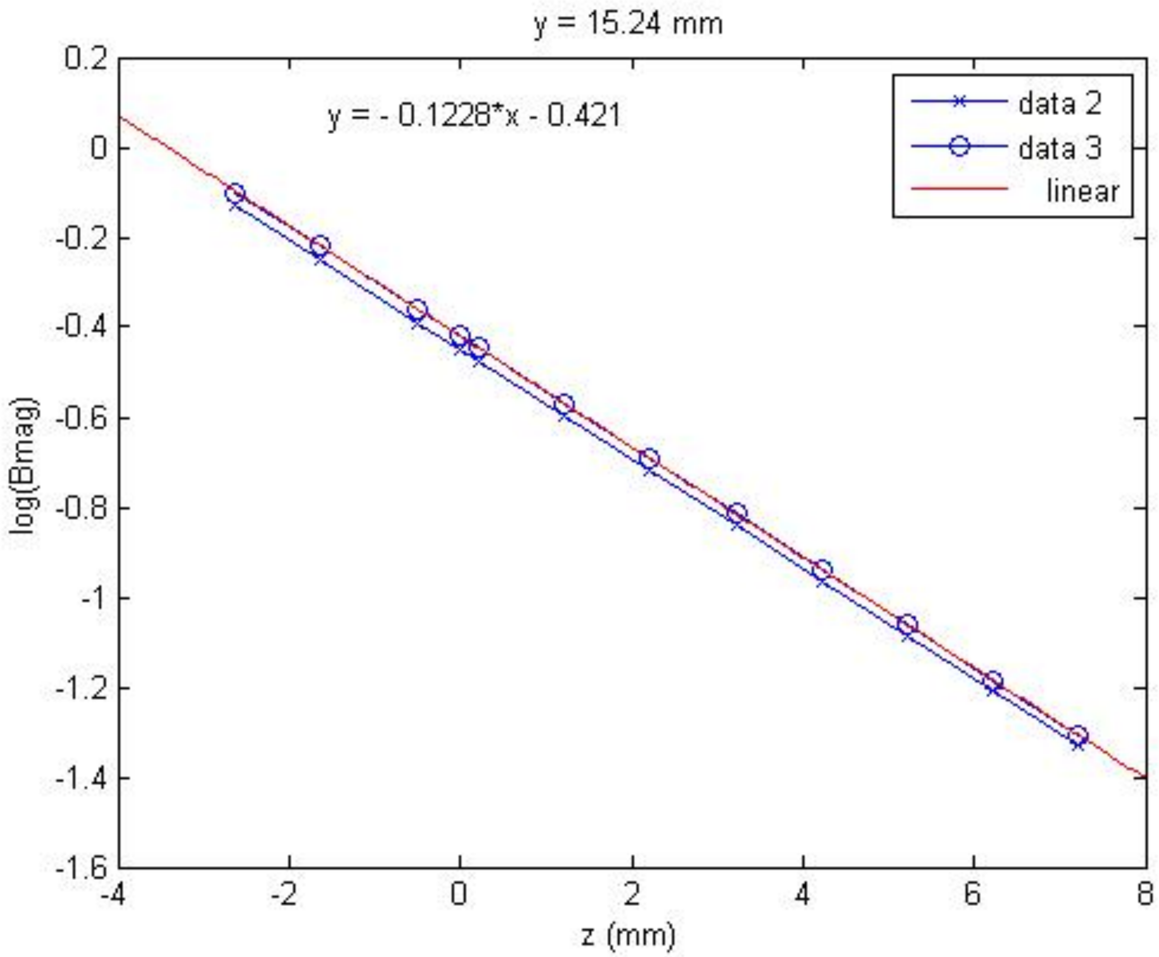


Flat Halbach array

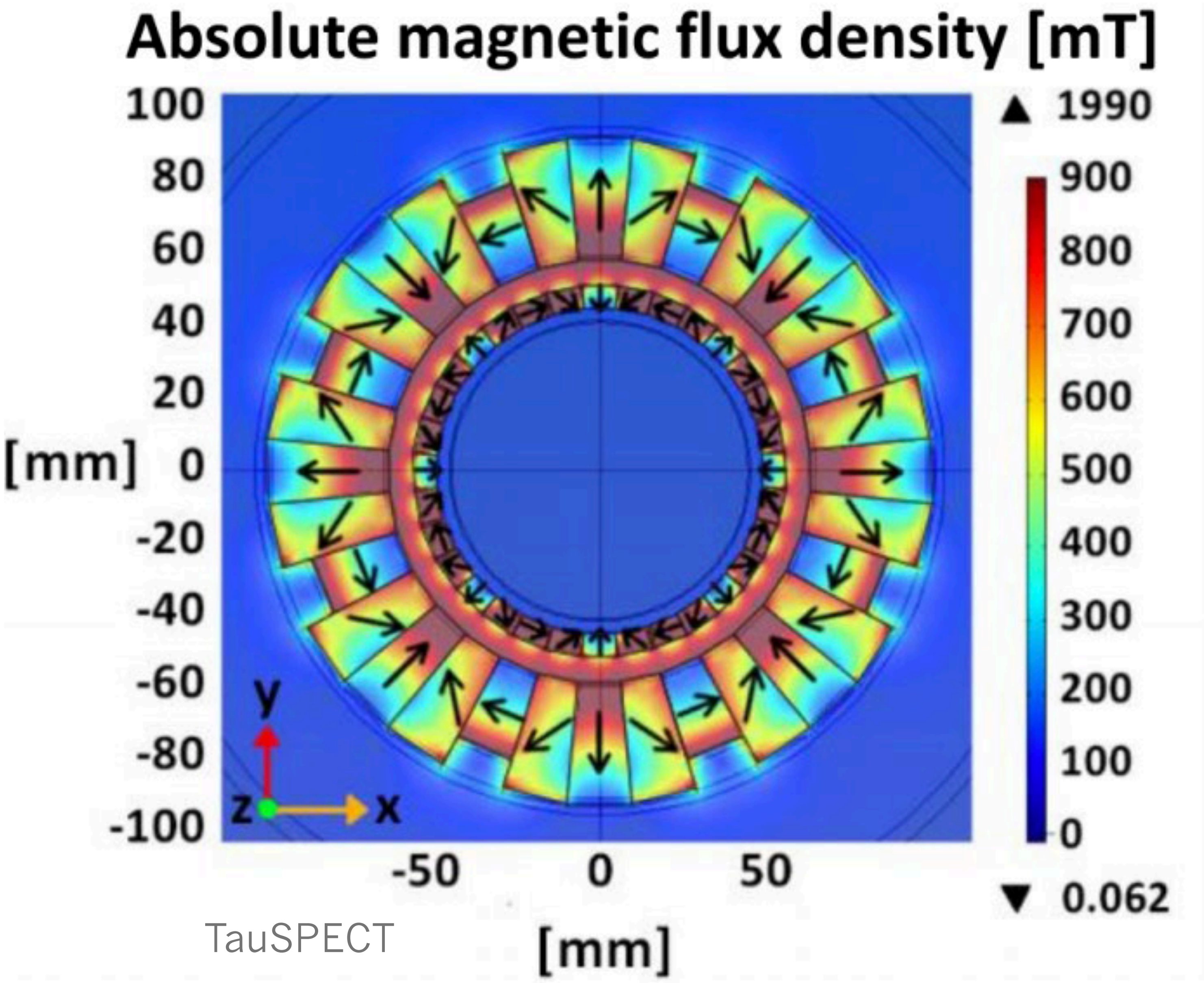
- field falls exponentially with

  characteristic length $l = \dfrac{2d}{\pi}$

  - weak far field



Halbach arrays for Project 8



TauSPECT

Halbach arrays for Project 8

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Field configuration

- cylindrical configuration

  $$\overrightarrow{B}_{\text{Halbach}} = \overrightarrow{B}_{\rho} + \overrightarrow{B_{\varphi}}$$

  - no cancellation with solenoid electron field

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Choice of permanent magents

- rare earth give highest field strength
- phase transition in NdFeB
  - not suitable below 140K
- SmCo, PrFeB,...

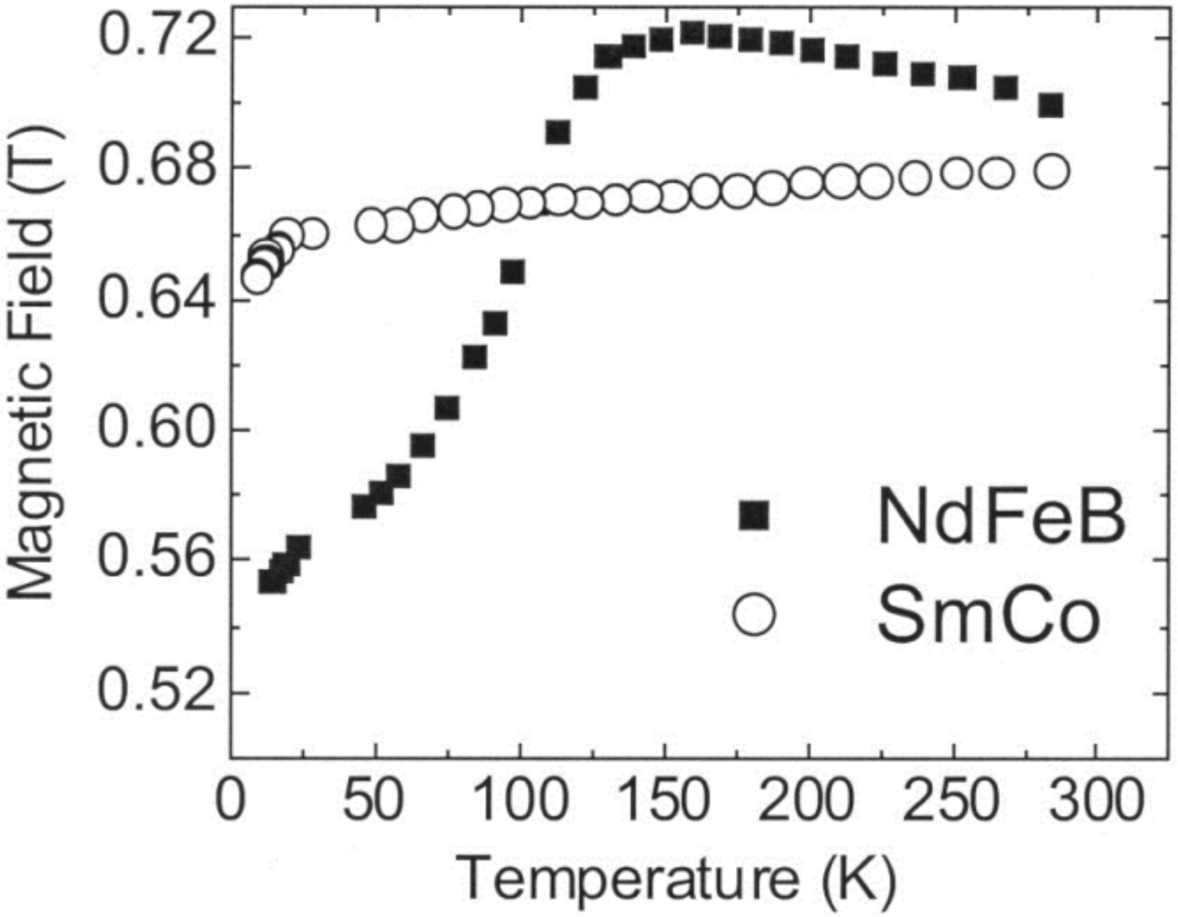


Figure 4. Magnetic Field as a Function of Temperature for NdFeB and SmCo. [6]

Magneto-gravitational trap

Magnetic trapping

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

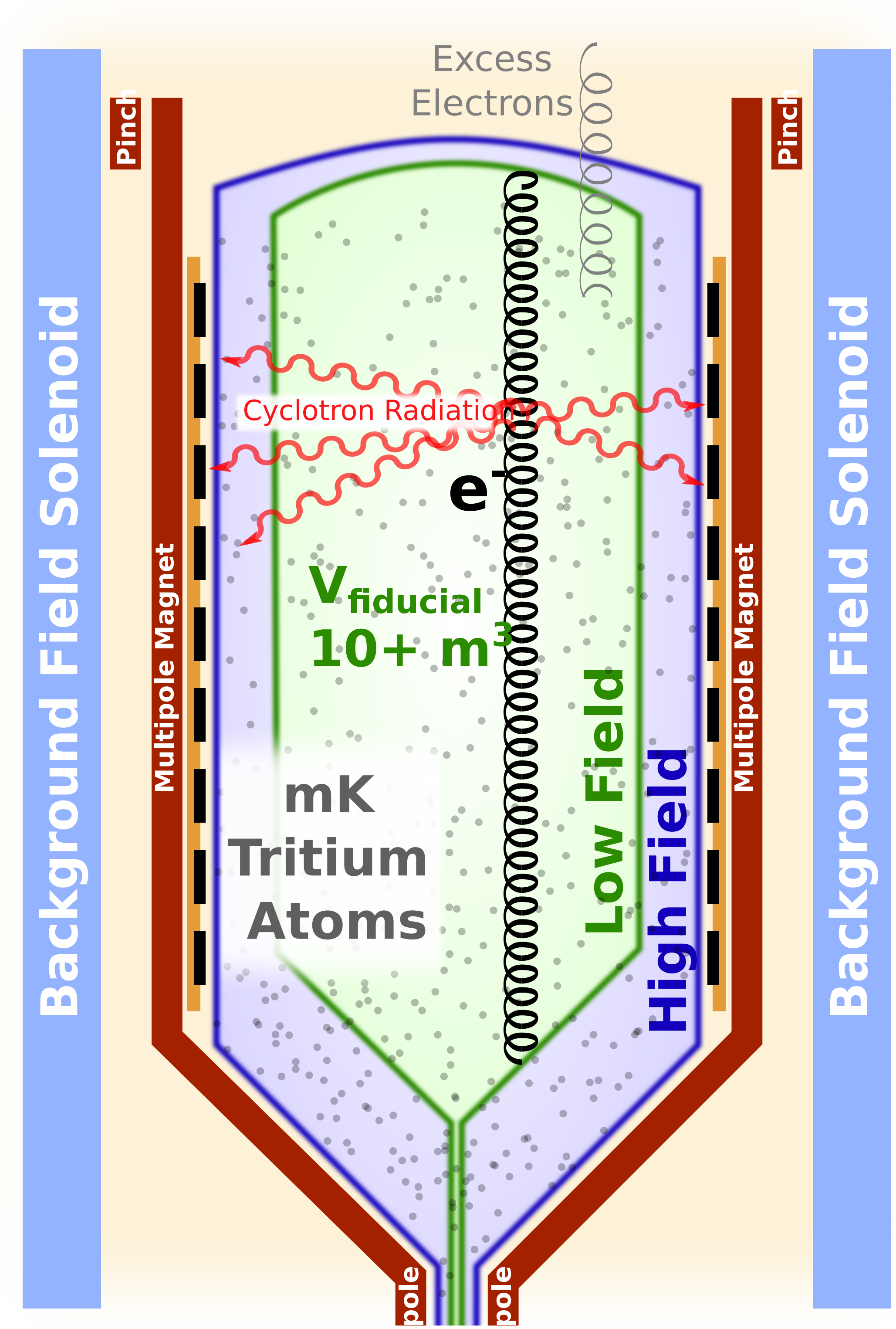
Gravitational trapping

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

Energy of cold atomic beam

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

➔ For 1mK cold beam, it takes 0.21 meters of gravity and 11 gauss of B-field to trap.



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Spin-flip loading ?

- Flip atom spin at trap edge
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- But: stimulated emission
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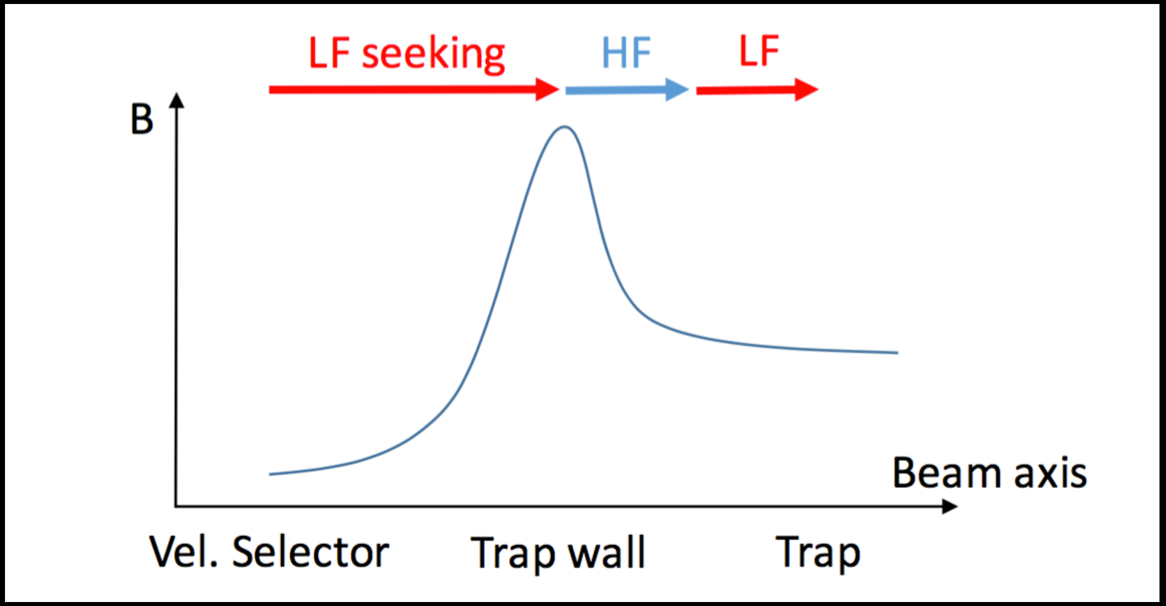

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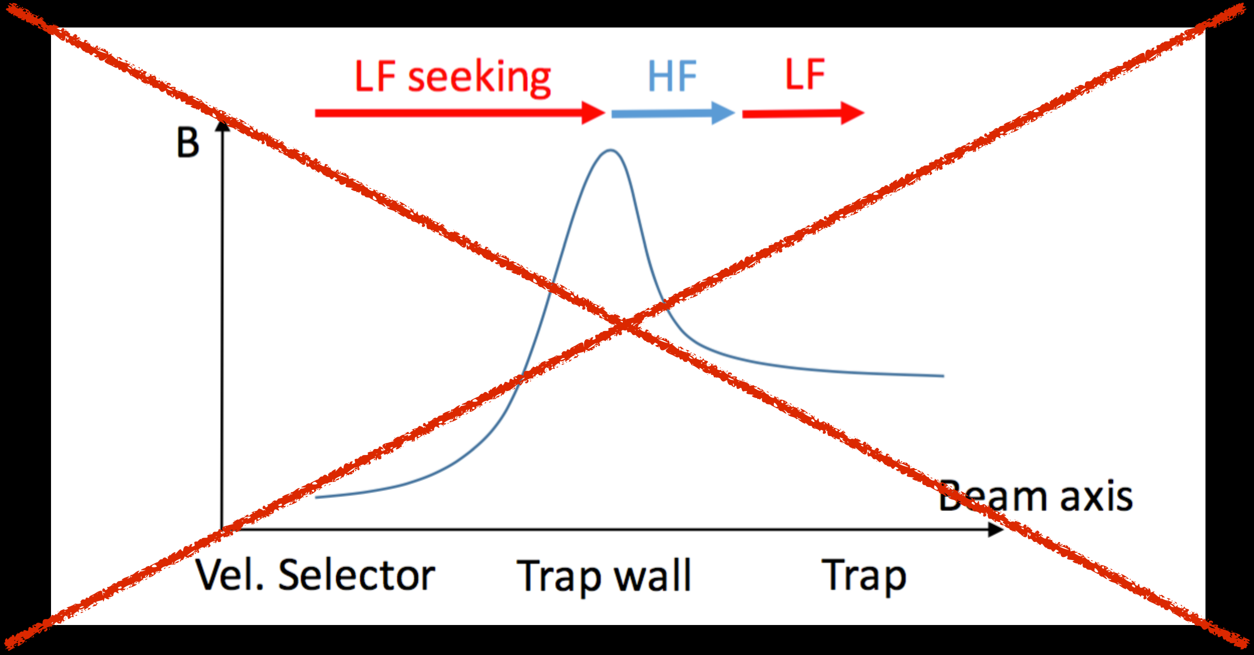

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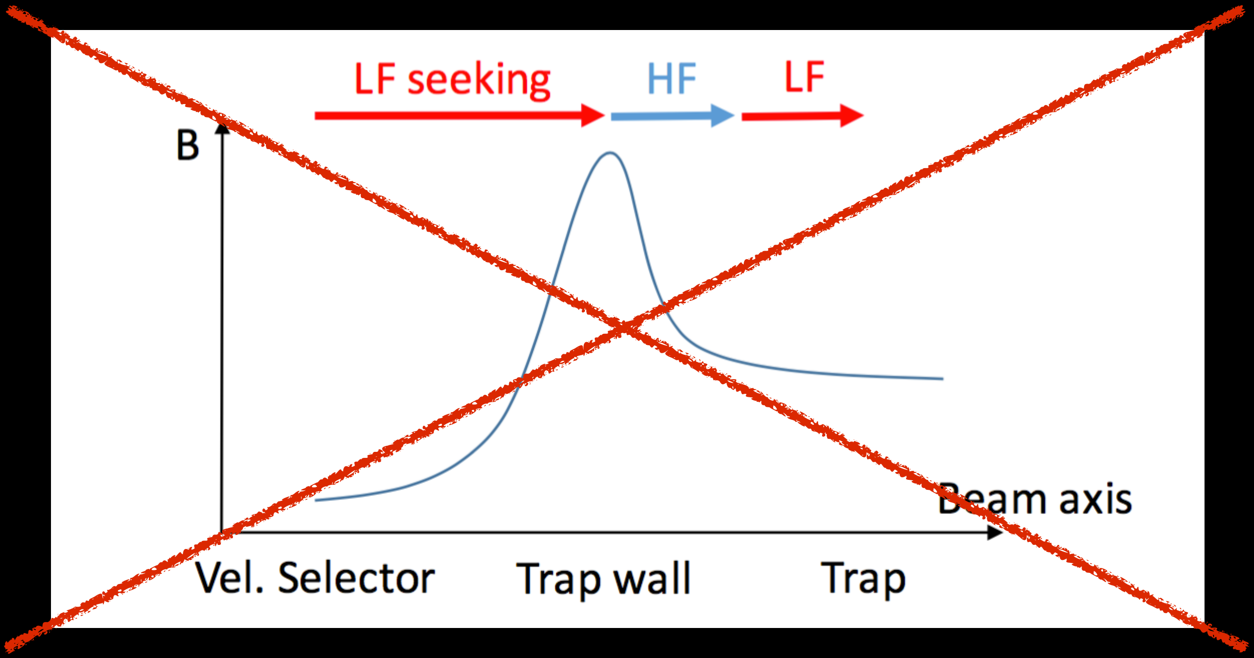
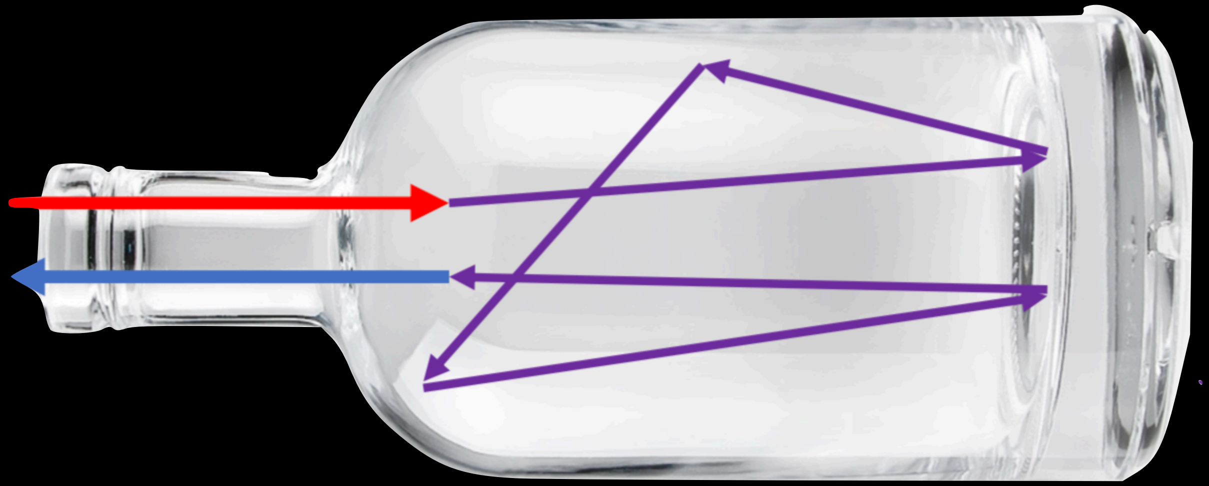


Cornucopia* loading

- Blow cold atoms into trap
  → accept loss through entrance hole
- required input flux for 1cm hole @ 50mK
  - $5\cdot10^{12}$ atoms/sec



* horn of plenty

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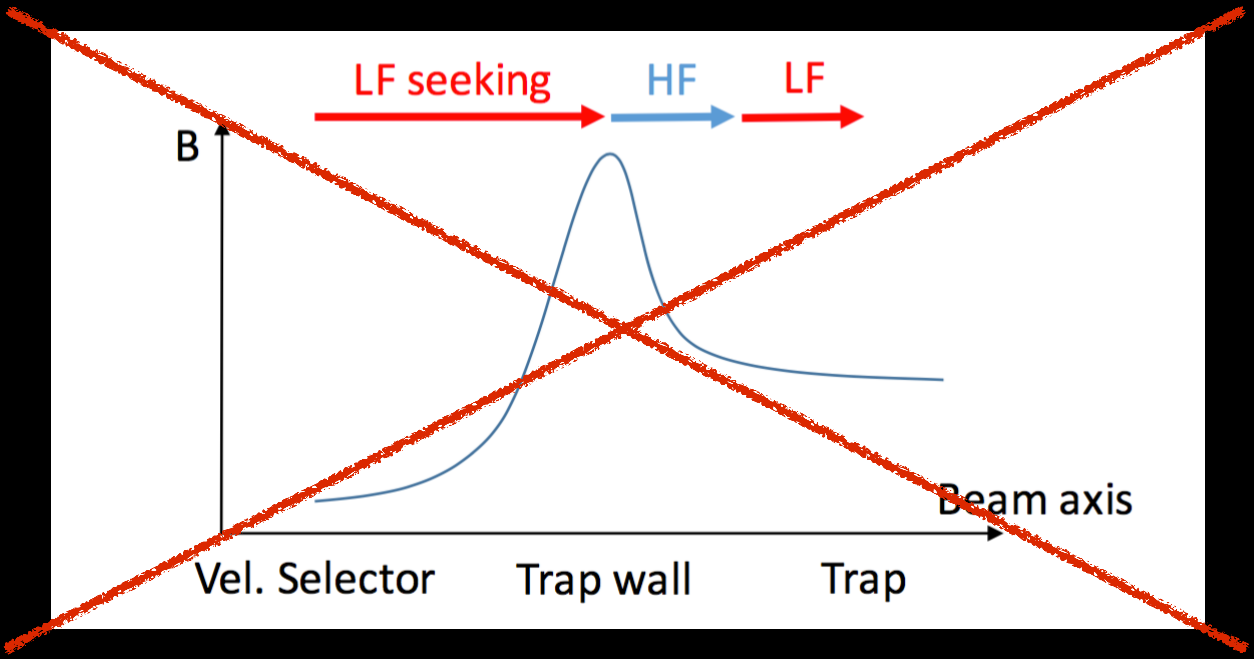

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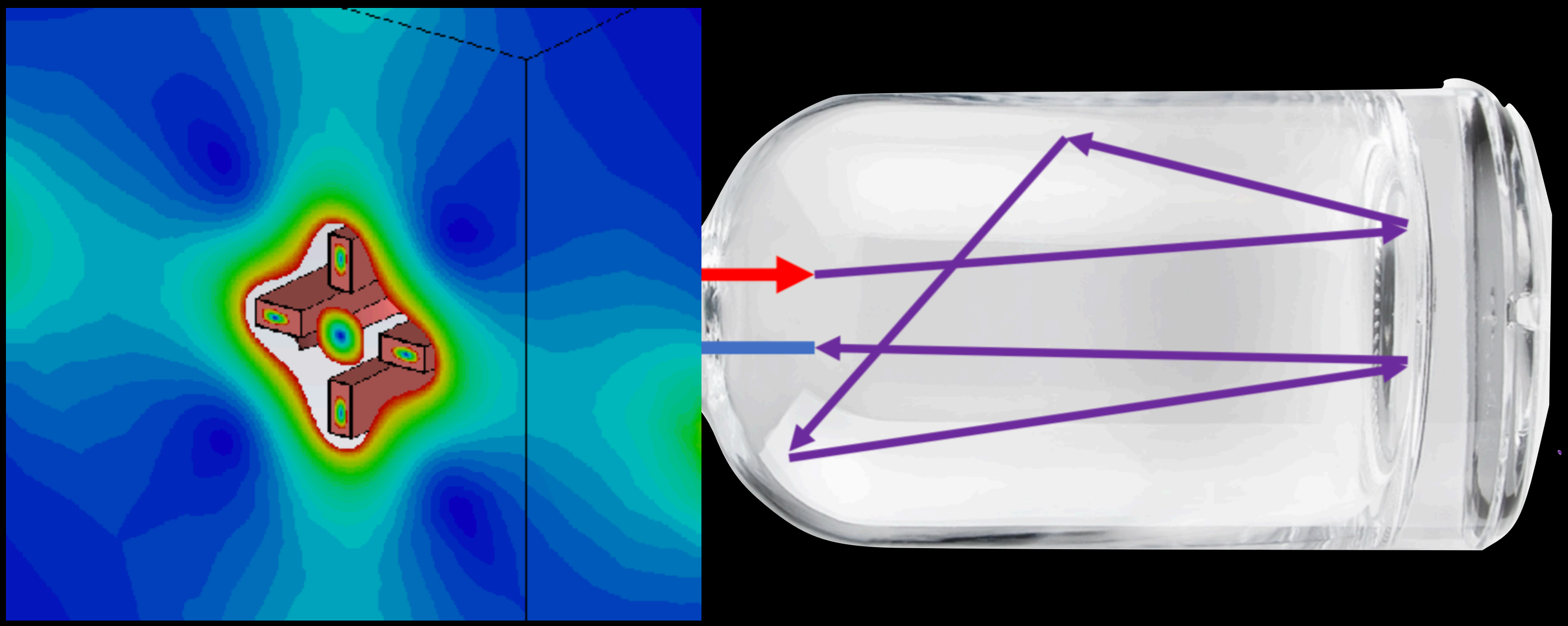

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Project 8: Designs concepts

Atomic T source

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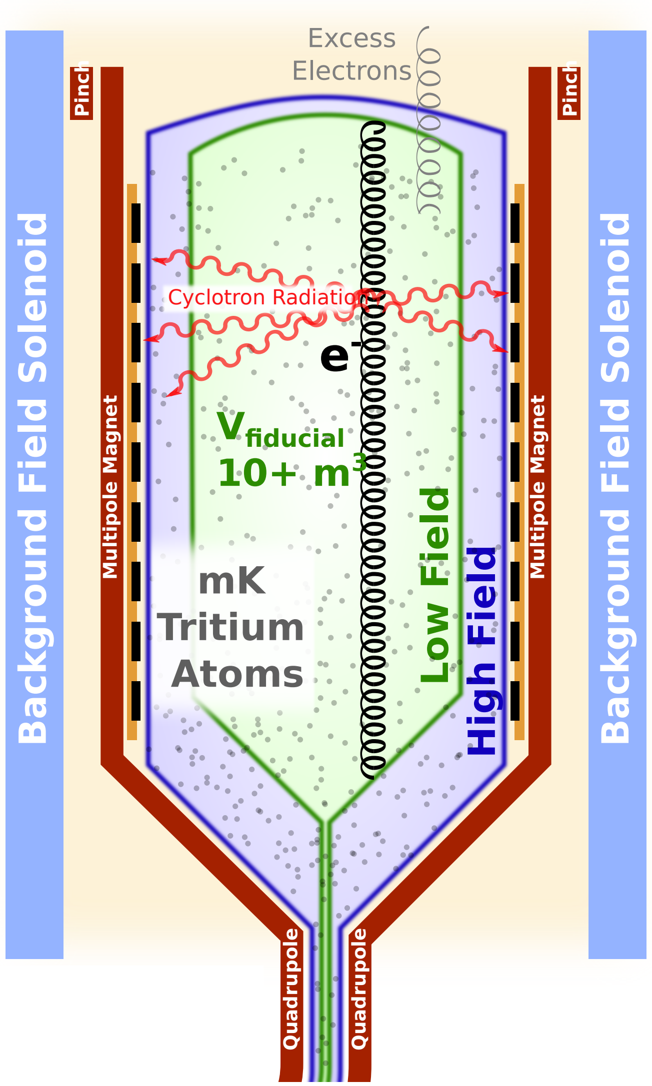

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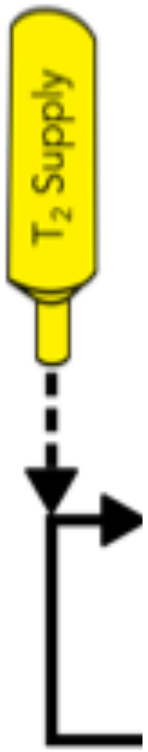

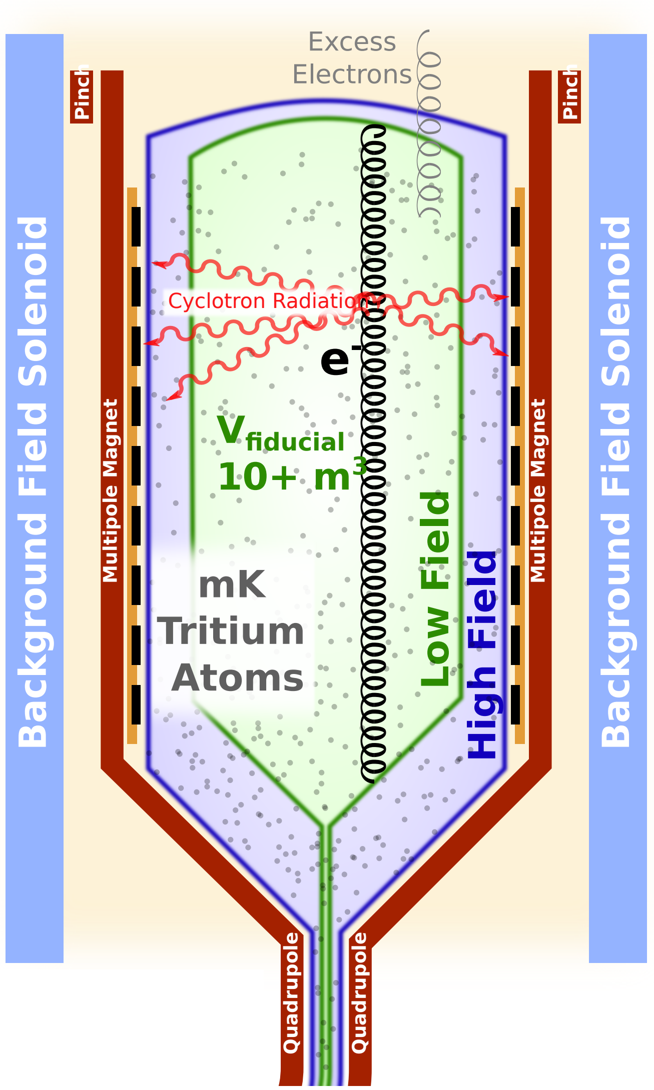

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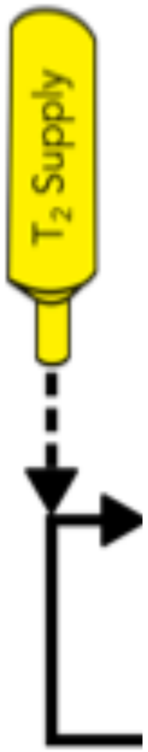
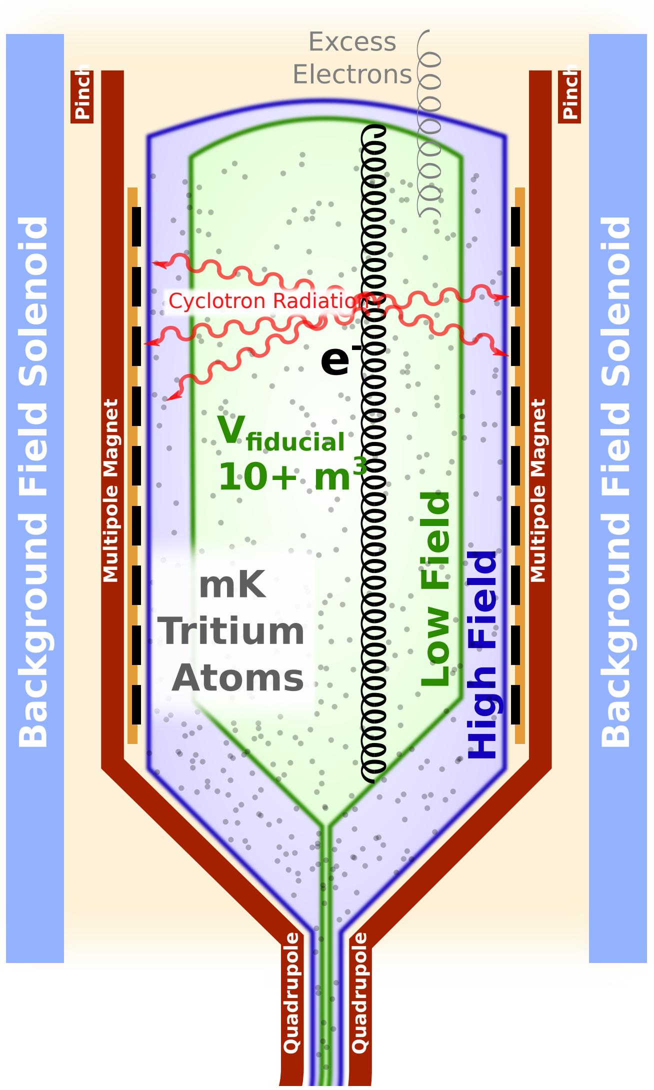
Atomic T source

- Injection ✓
- Trapping ✓





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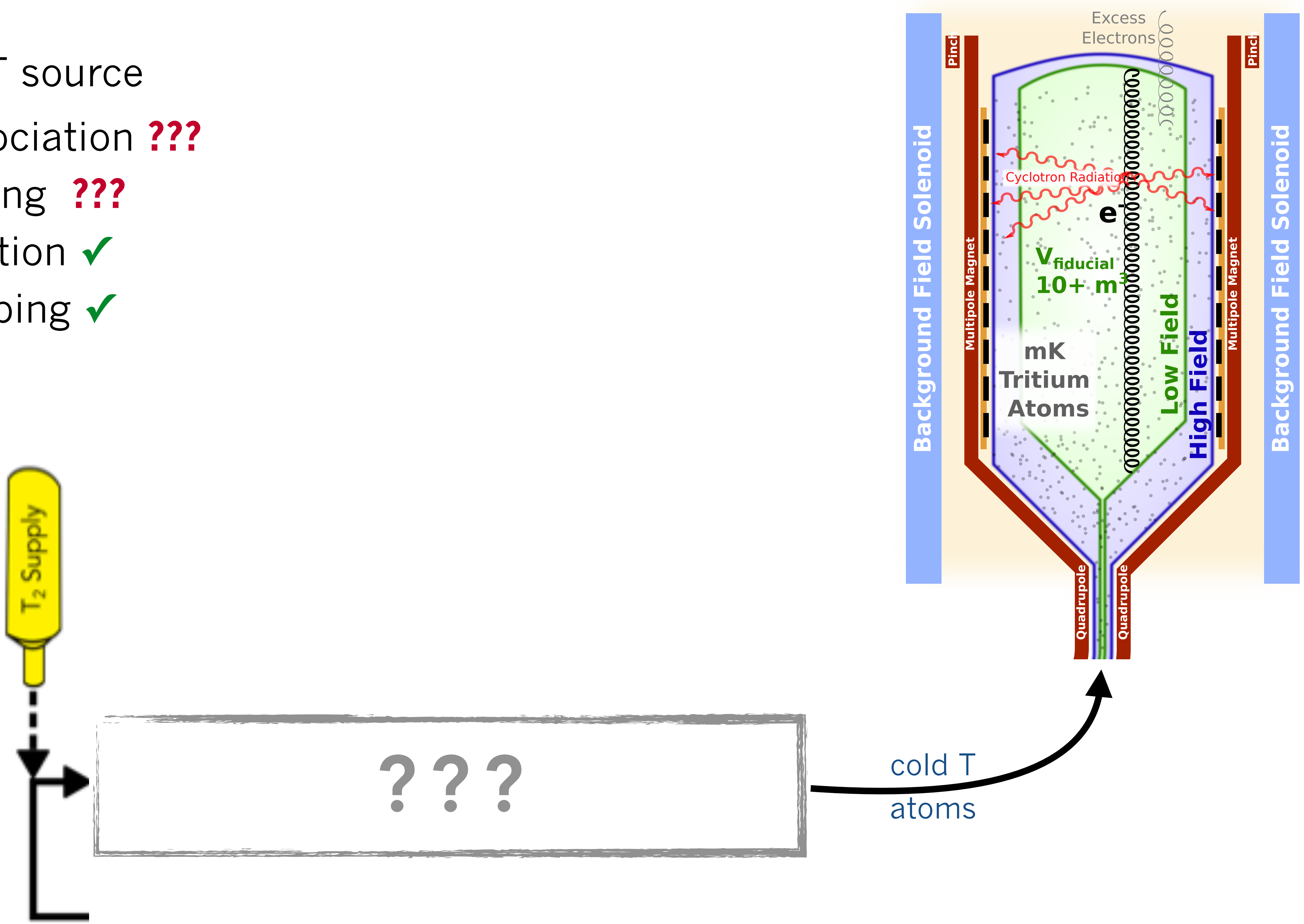

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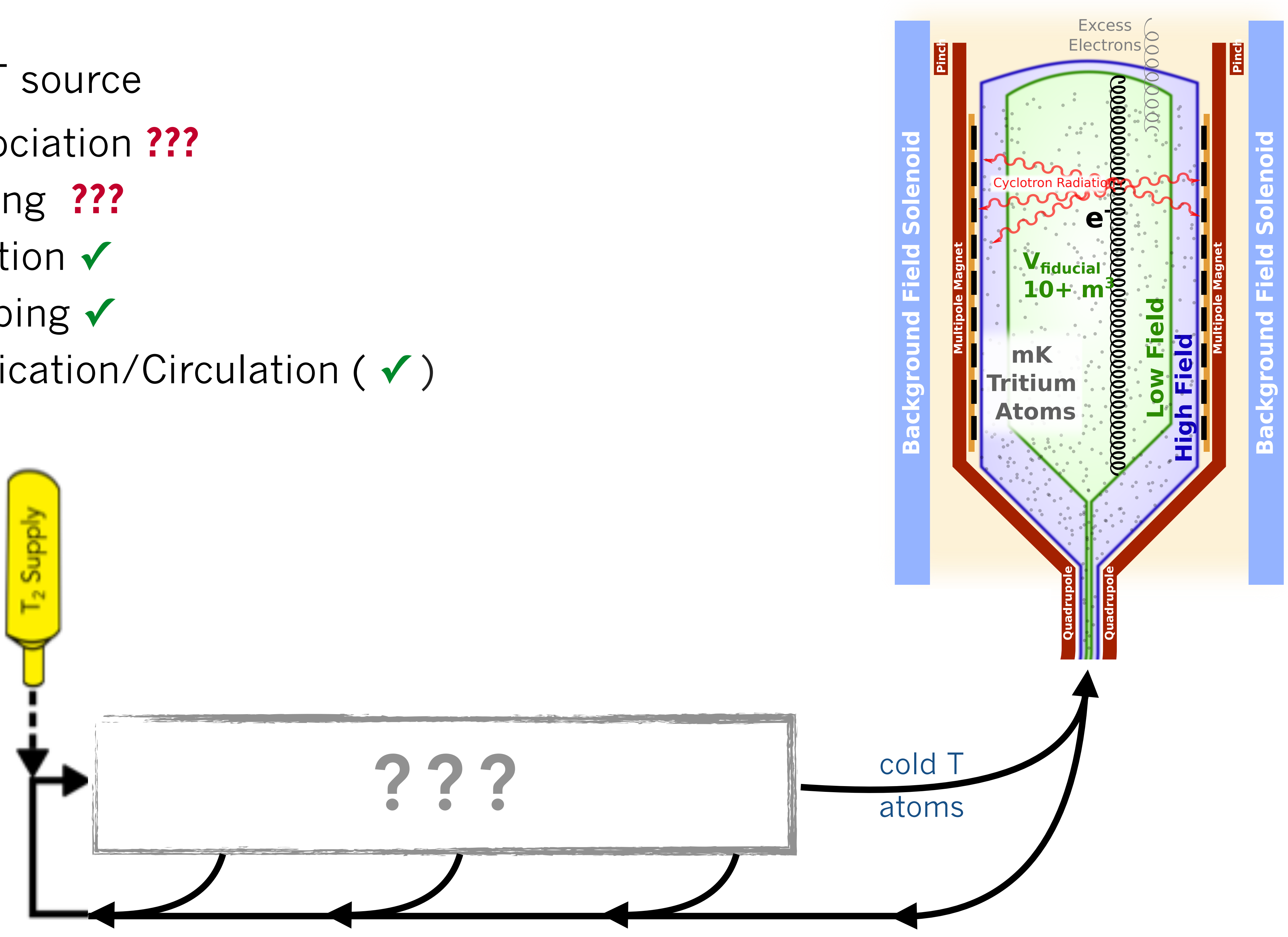

? ? ?

cold T atoms

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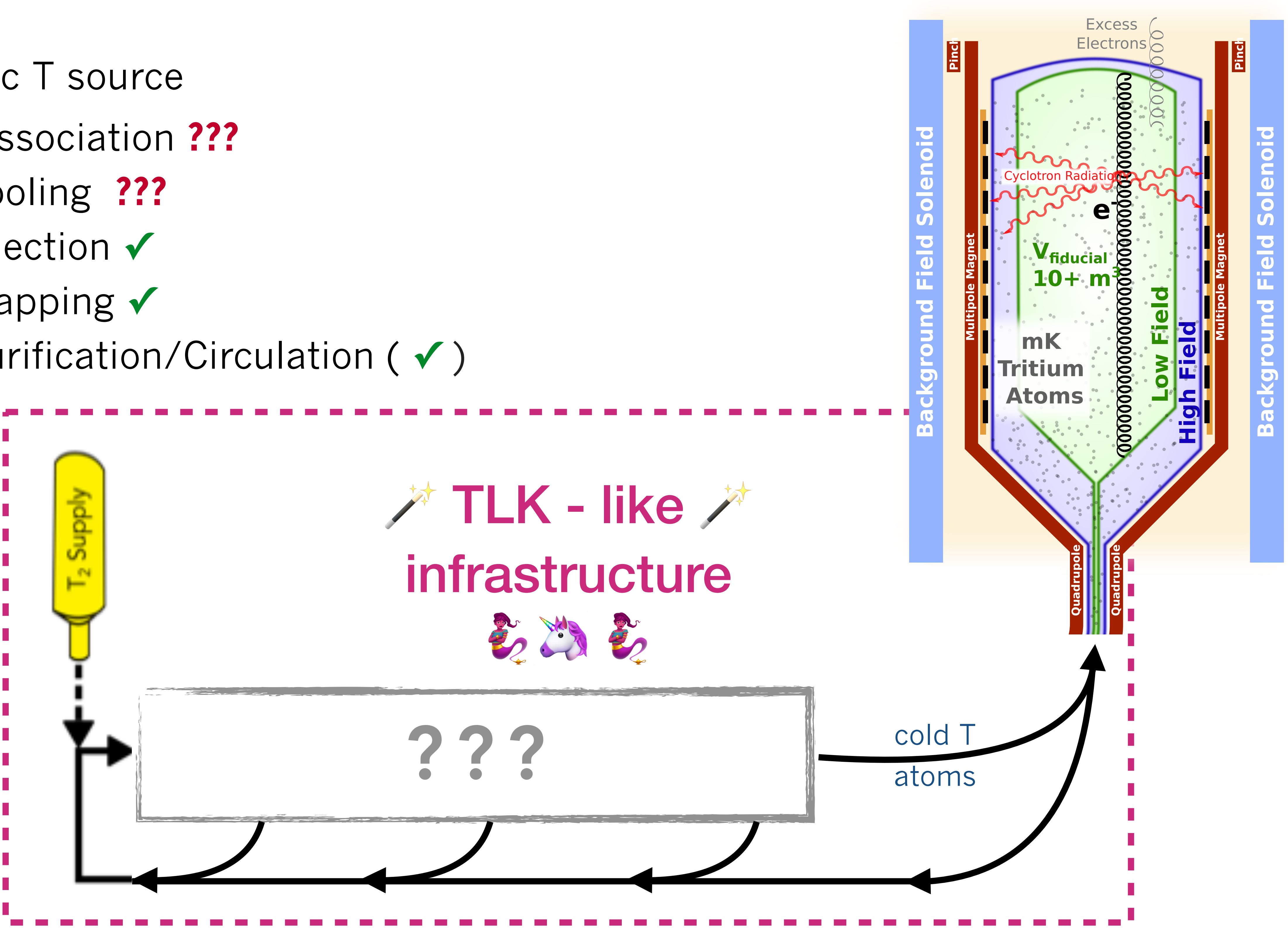


🪄 TLK - like 🪄 infrastructure
🧞‍♀️🦄🧞‍♀️

T_2 dissociation schemes

Microwave dissociation @ 151MHz

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

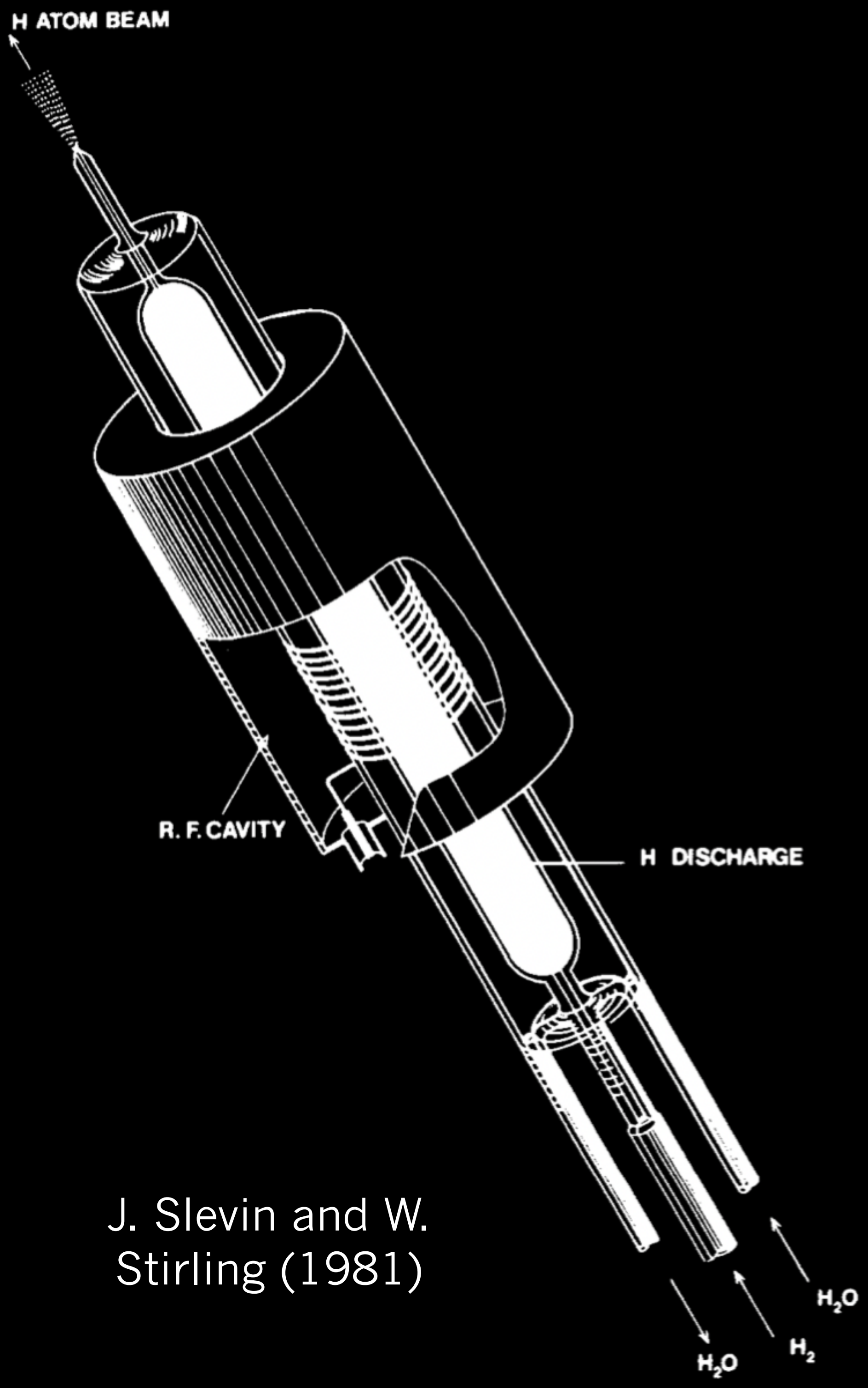
Laser dissociation

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

Coulomb explosion

- difficult to re-neutralize

...



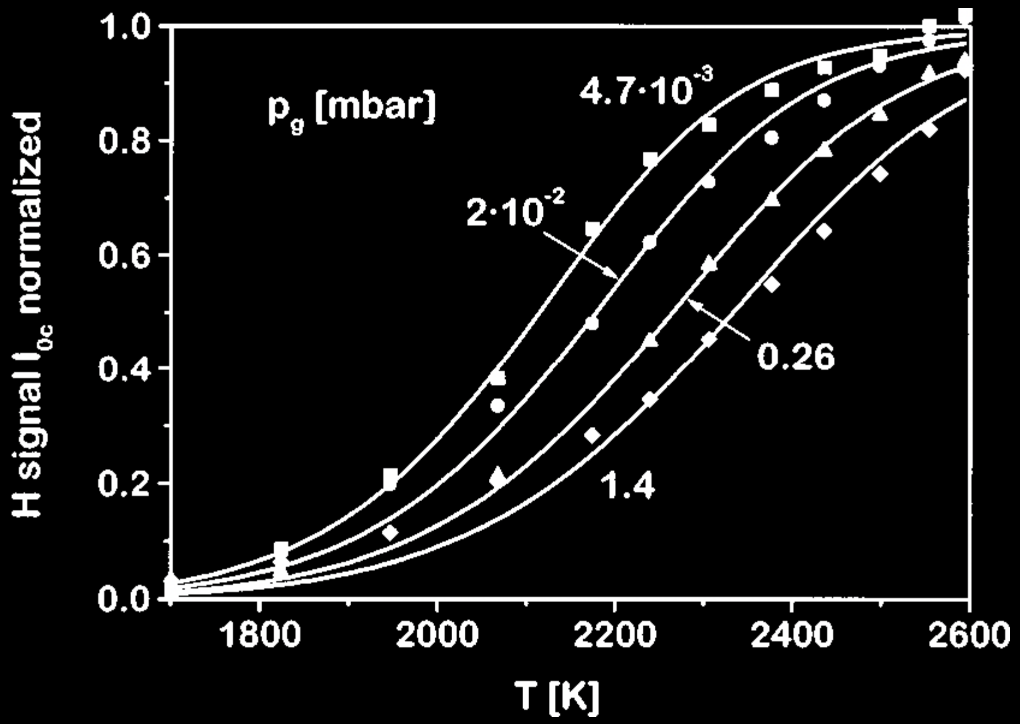
J. Slevin and W. Stirling (1981)

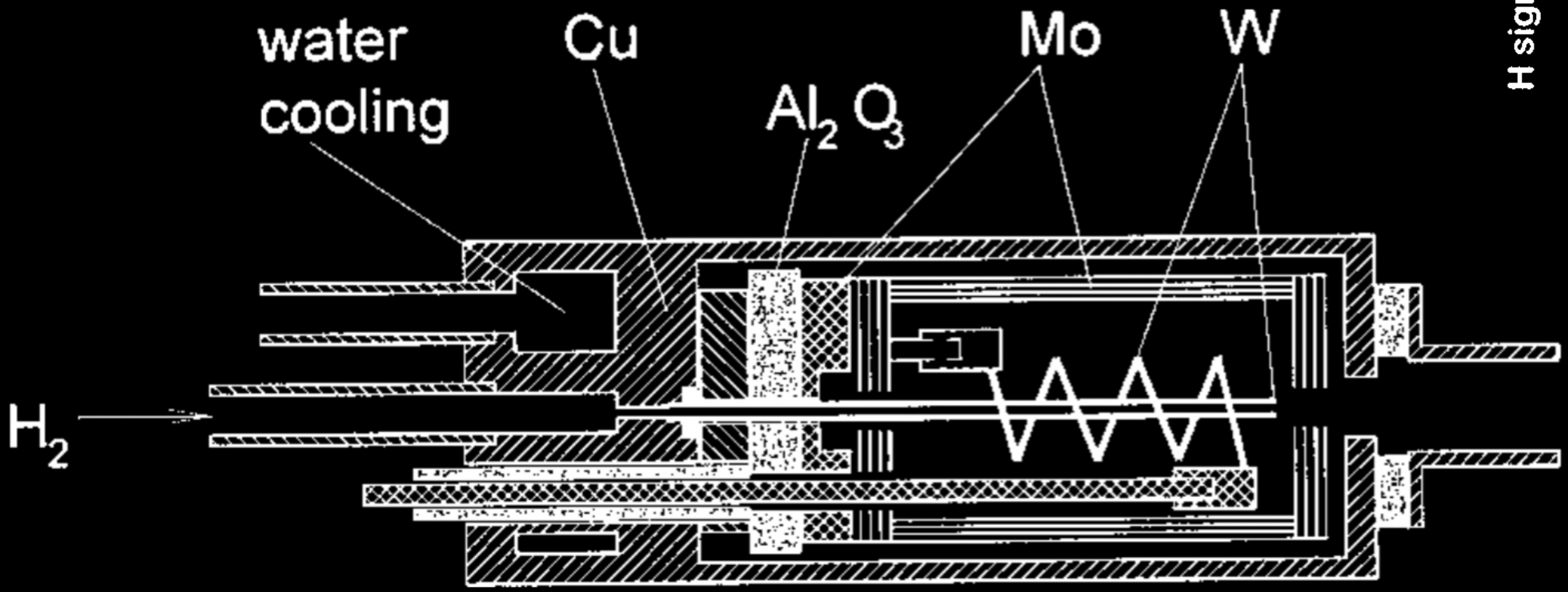
Thermal Dissociator

Hot tungsten tube heated to 2500K

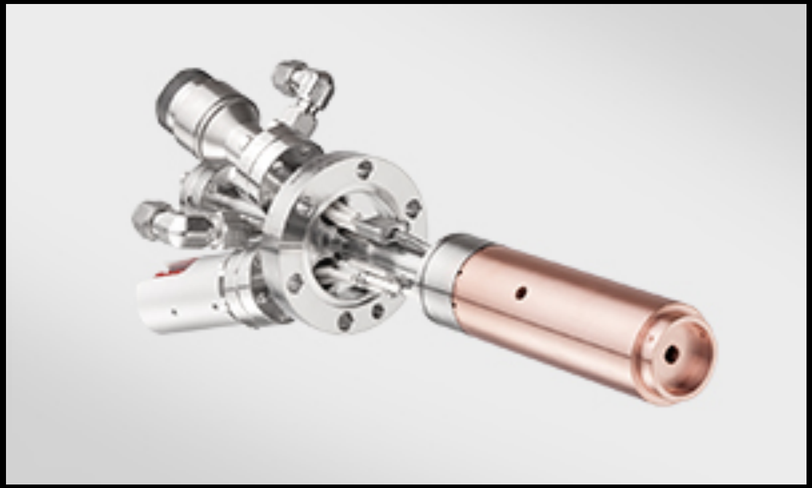
- radiatively or
- by electron bombardment
  - commercial devices available

Tscherisch (1999)





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



HABS hydrogen cracker

Cooling atomic hydrogen

Hydrogen recombination

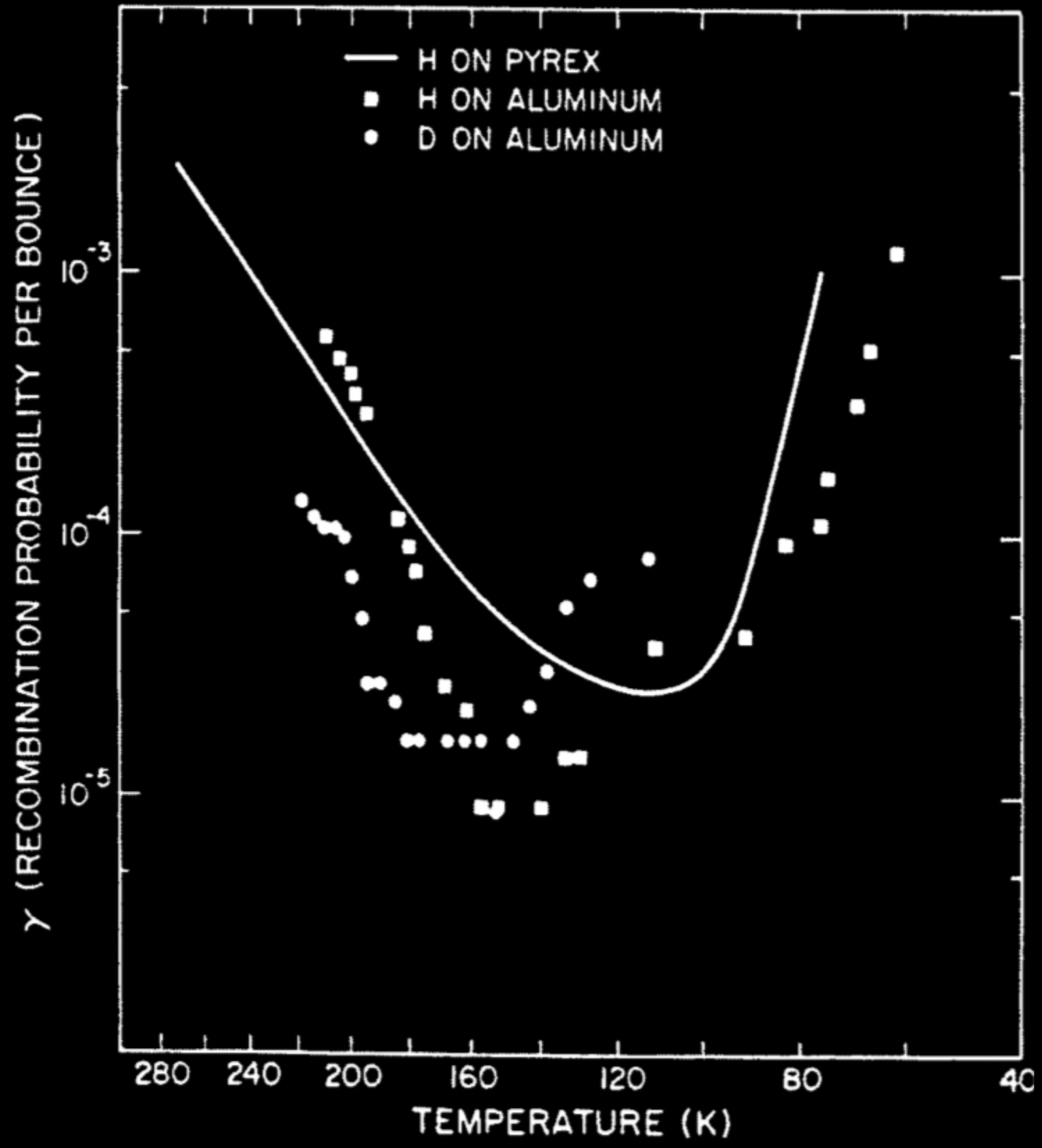
- three-body gas interactions
  - small rate
- wall interactions
  - long *sticking* time
  - dominates recombination

Probability depends on

- temperature
- material
- hydrogen isotope

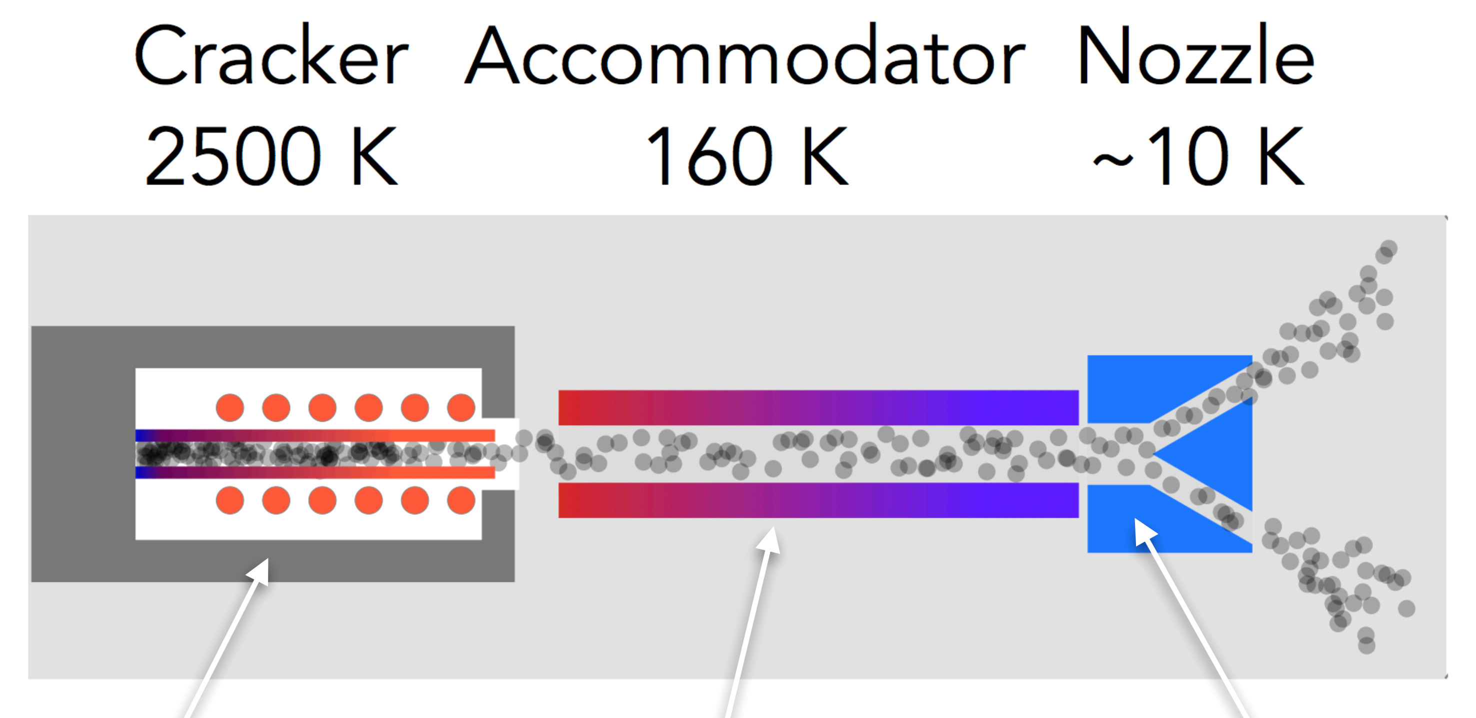
Superfluid He containment

- 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

→ purity vs. flow

Accommodator

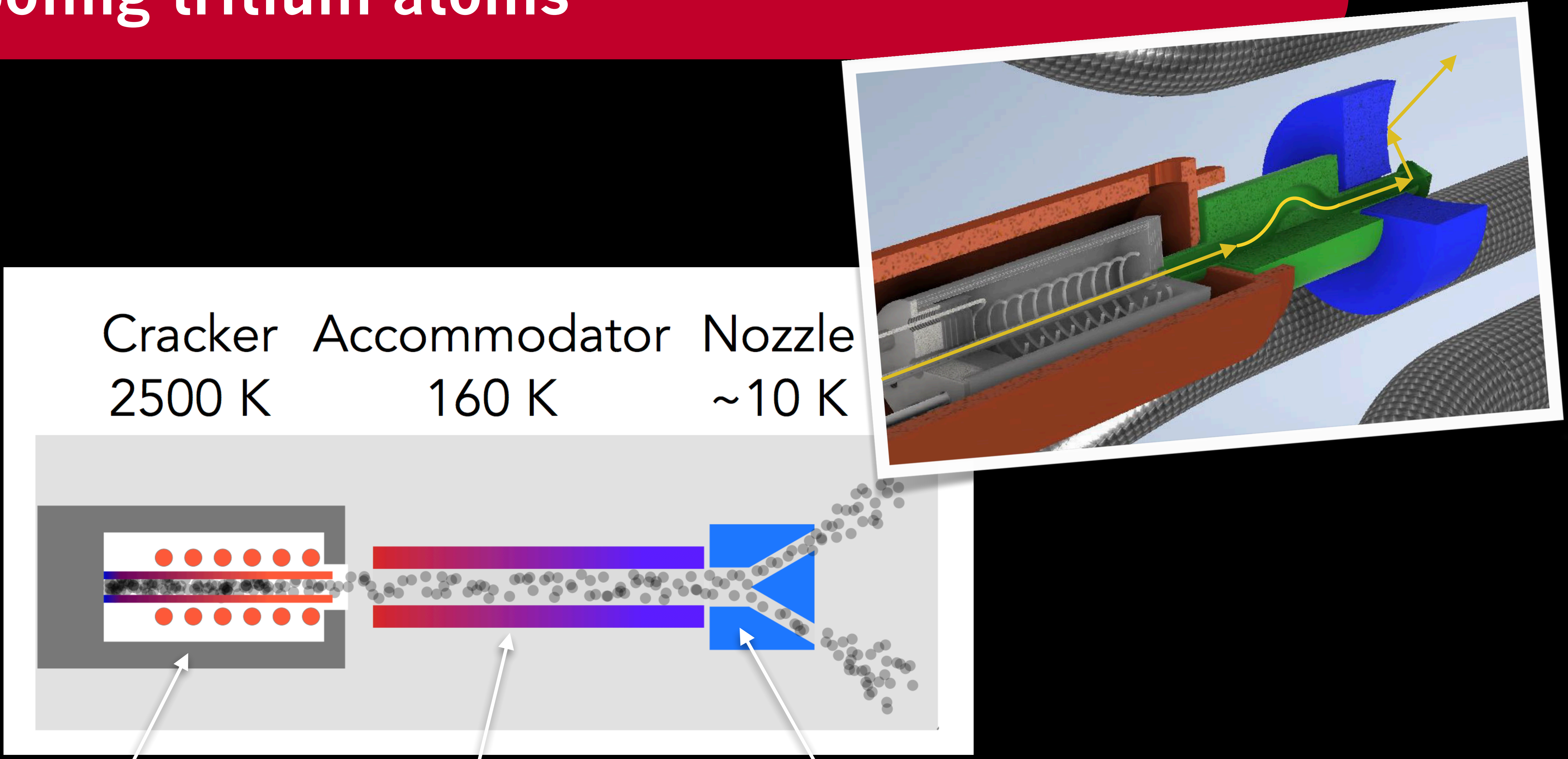
(liquid nitrogen)

Final nozzle

- design for few bounces
- freeze-out 30K

  → periodic purging

Cooling tritium atoms



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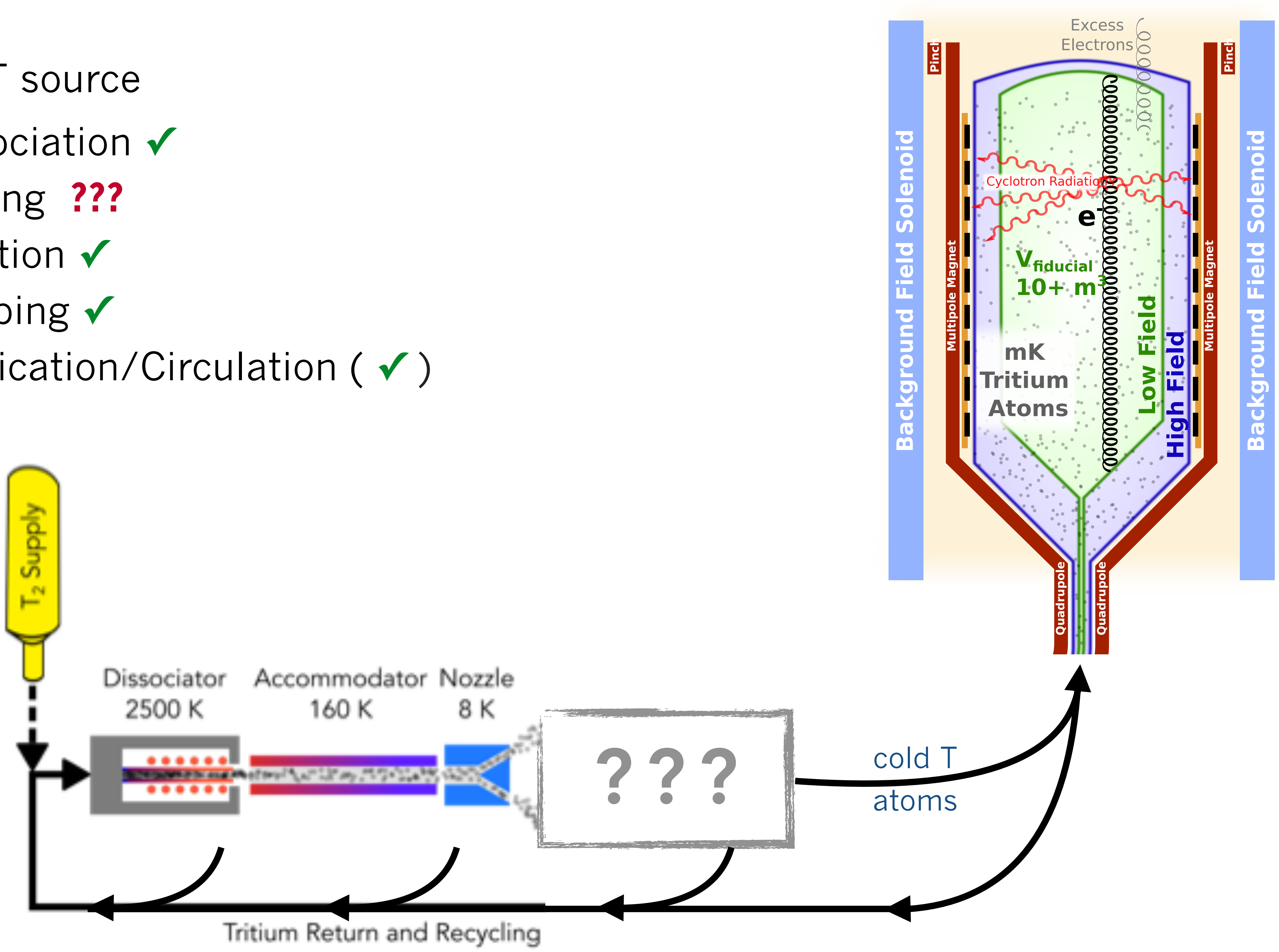
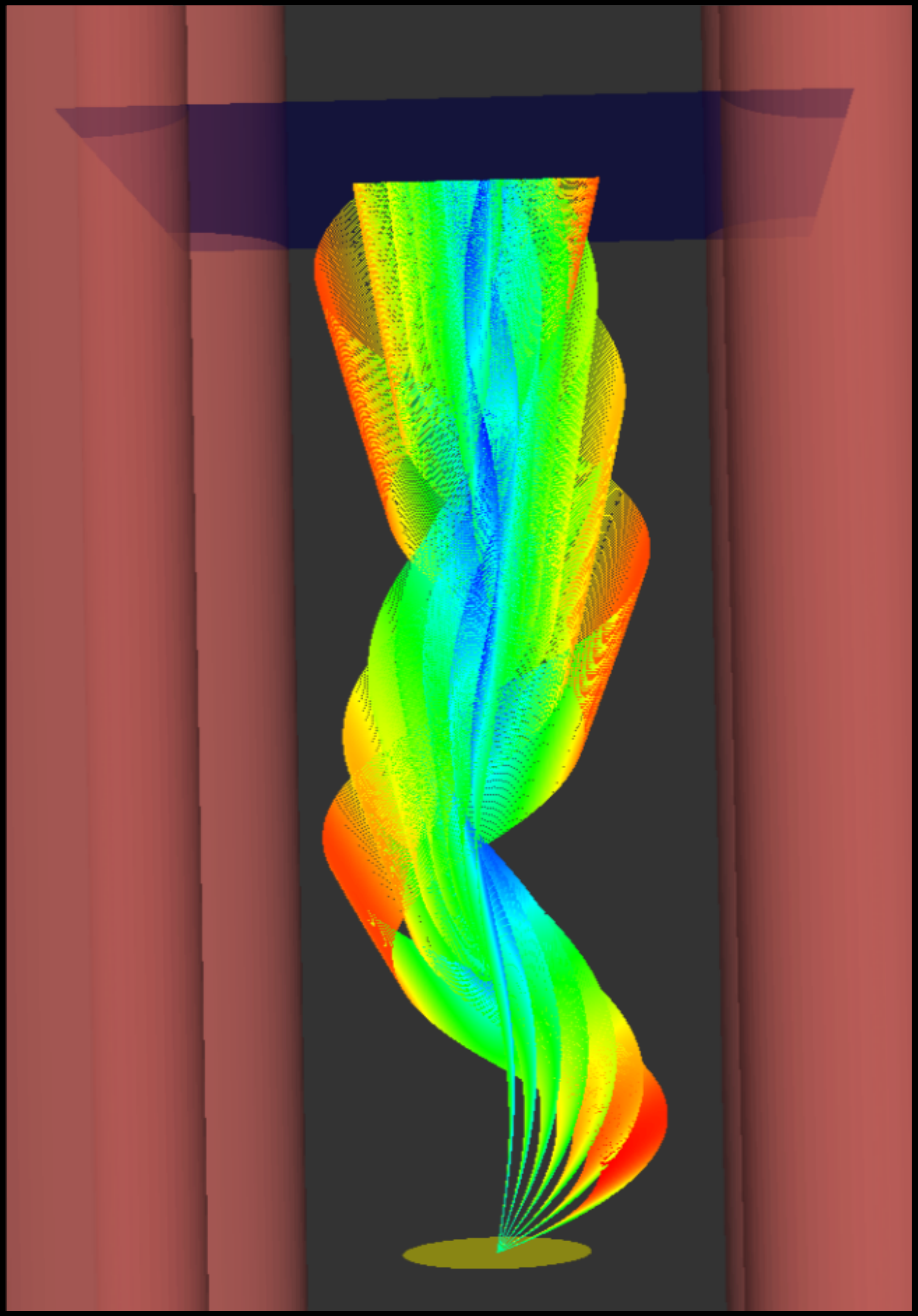


Velocity and State Selectors

Only atomic T guided magnetically

- (bend) quadrupole with skimmers



Velocity and State Selectors

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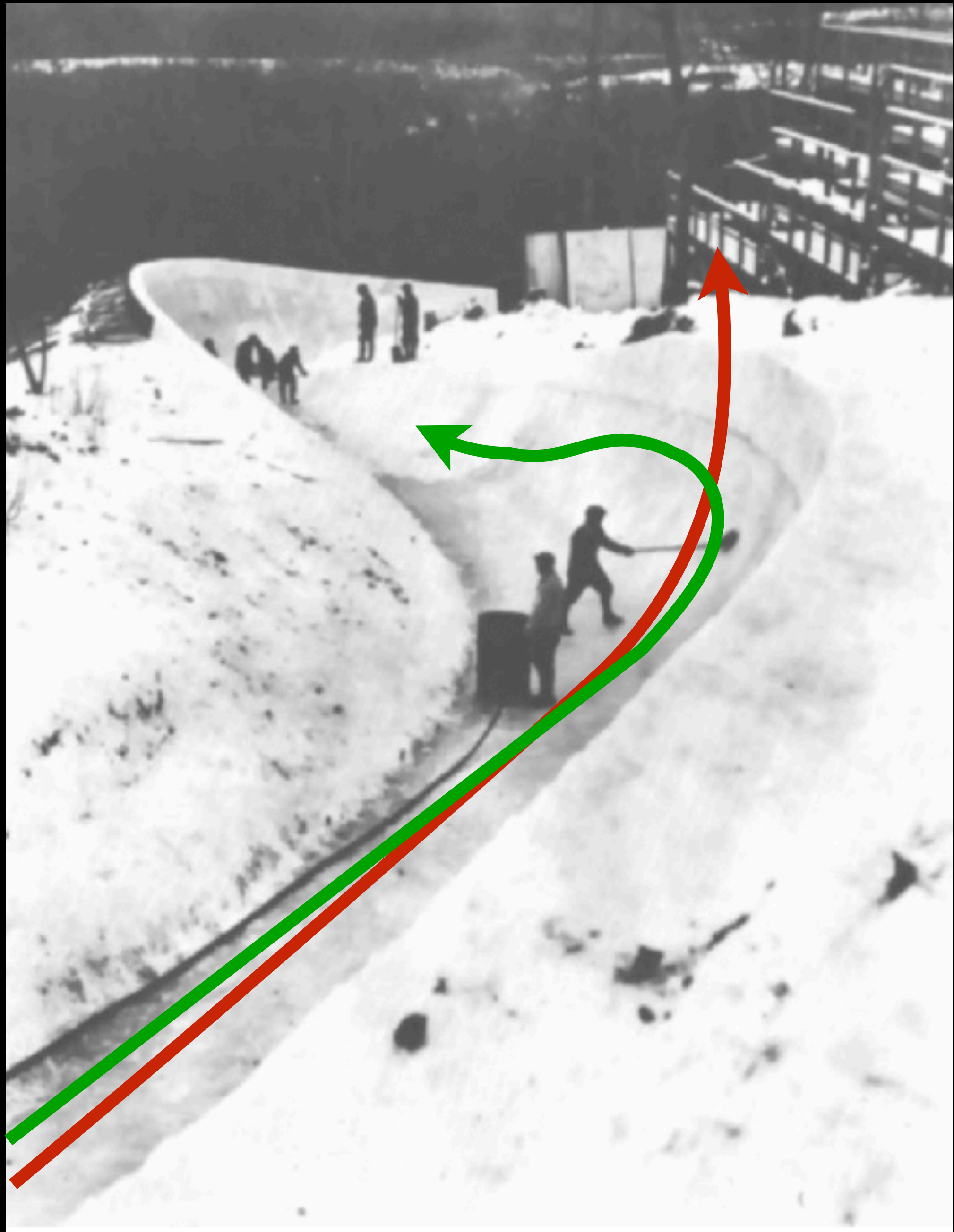

—Associated Press

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

Velocity and State Selectors

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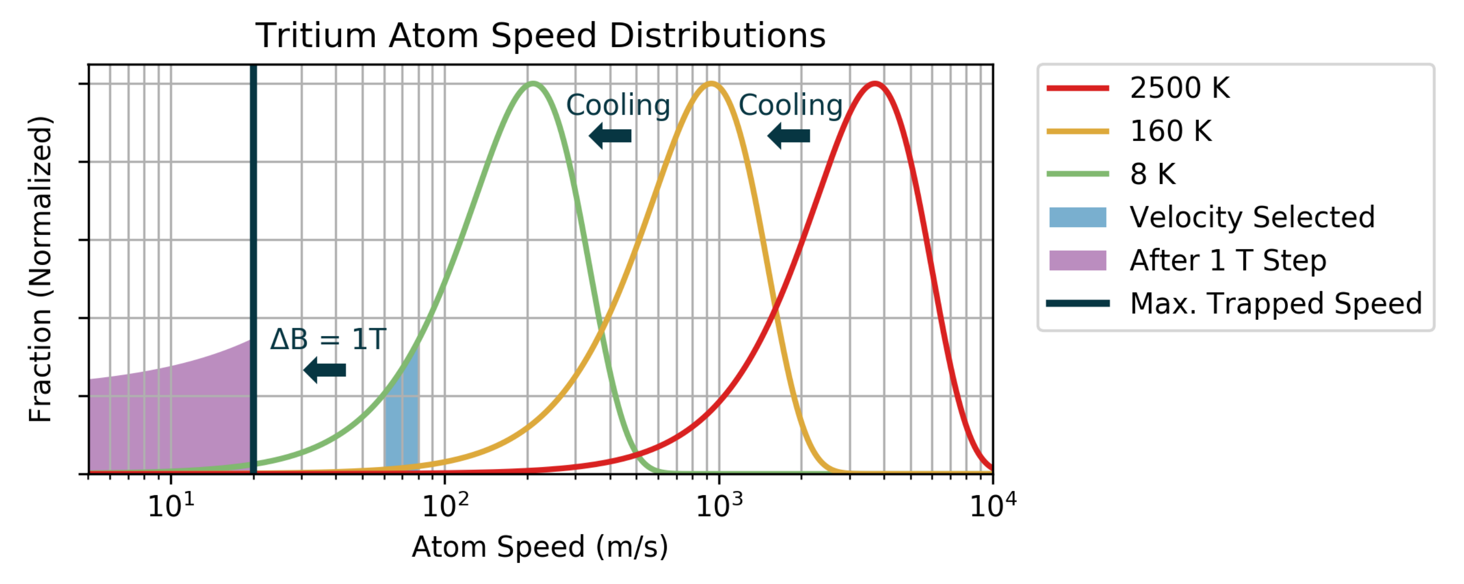
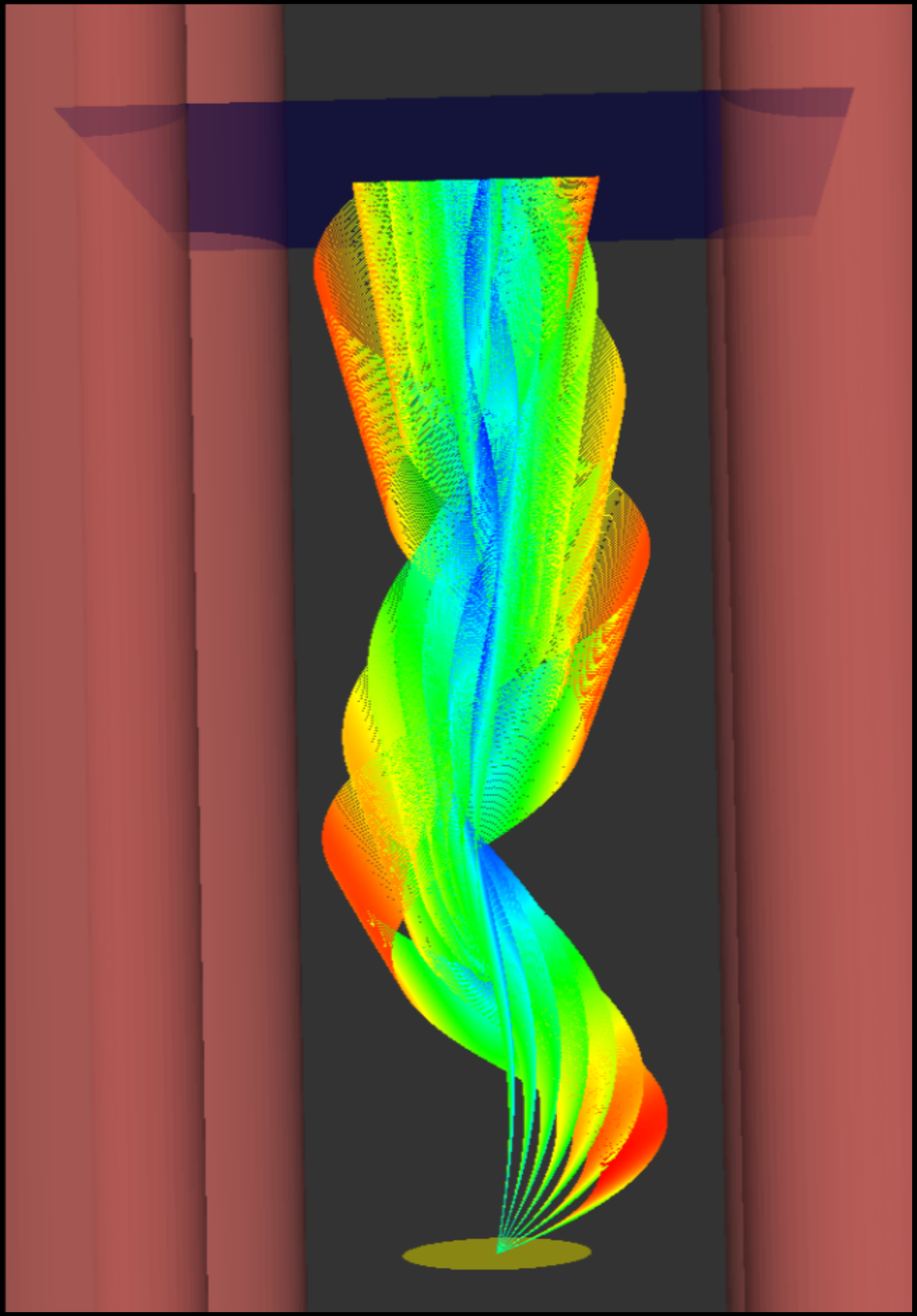
Tune acceptance for

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


Tritium Atom Speed Distributions



Velocity and State Selectors

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- (bend) quadrupole with skimmers

Tune acceptance for

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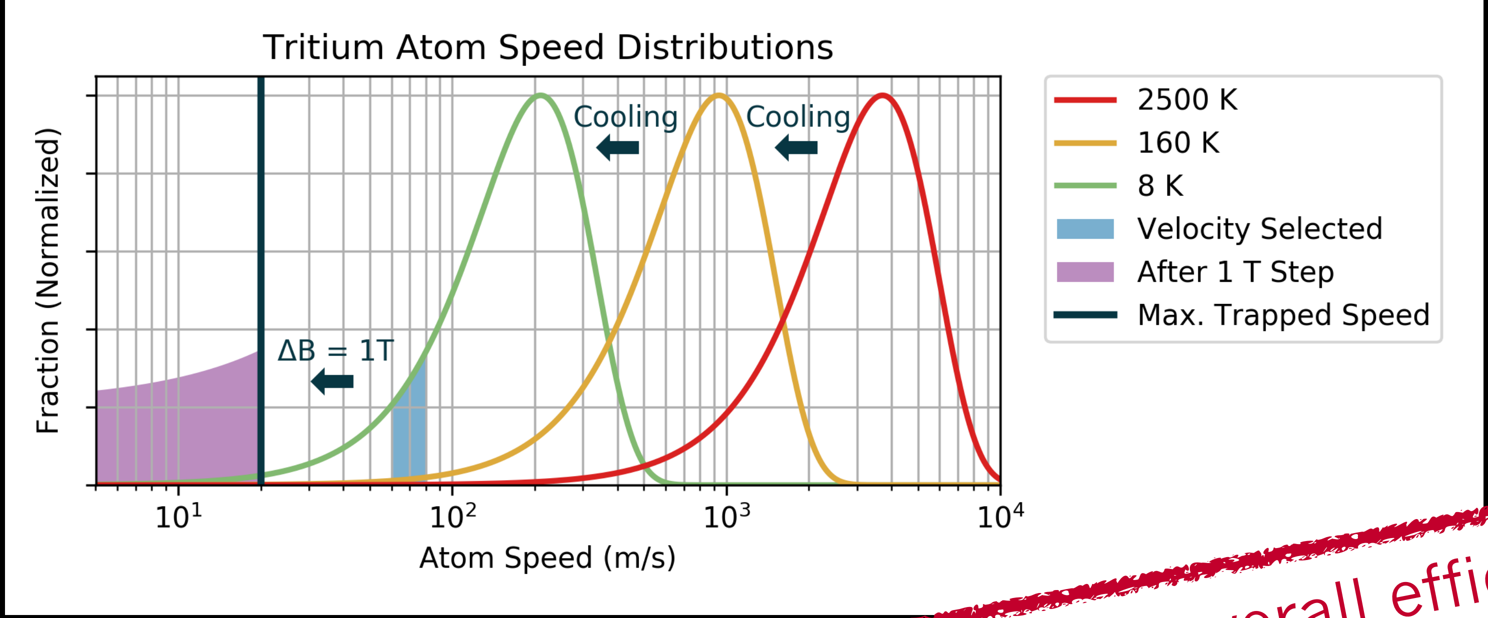
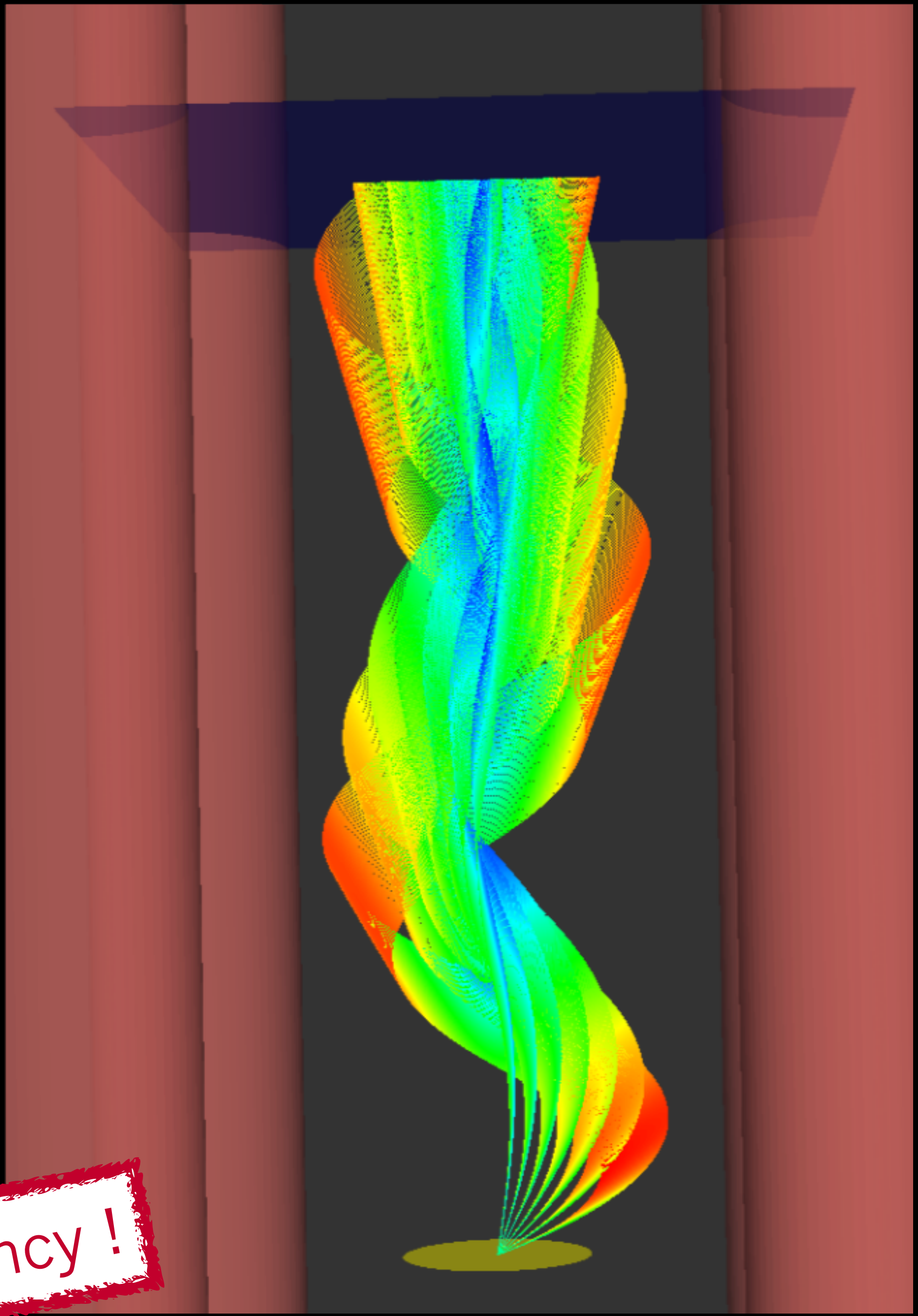
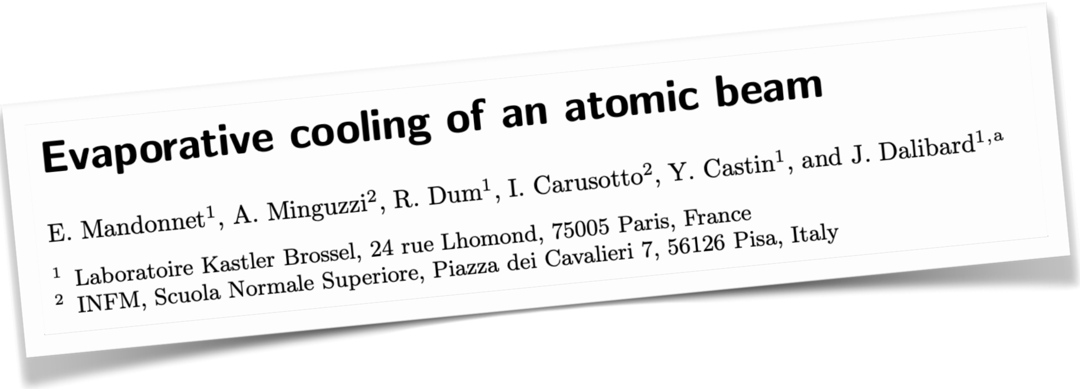
  - efficiency $\varepsilon_{cold} \sim 25\%$-$100\%$





→ but poor overall efficiency !

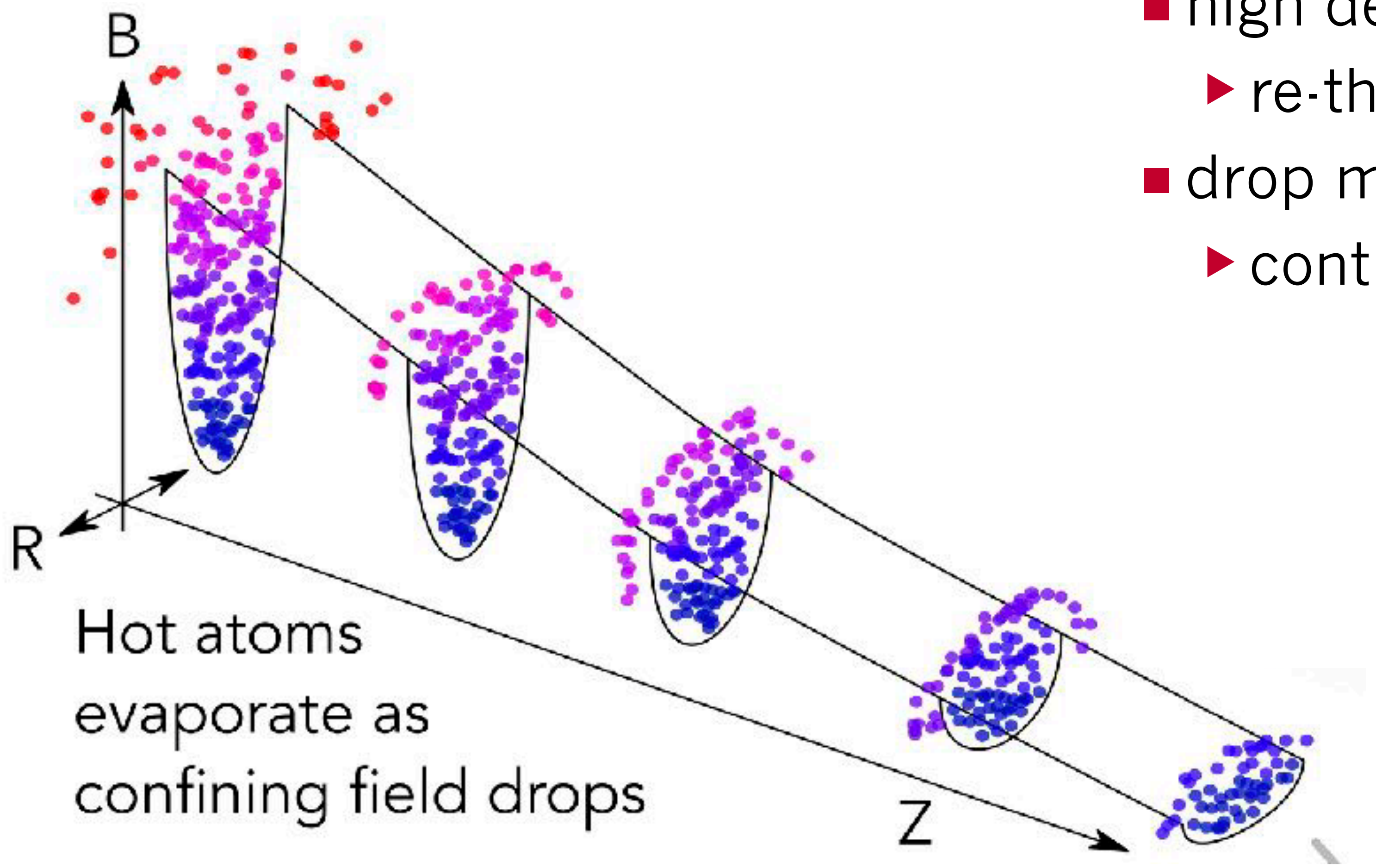
Evaporative cooling



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]

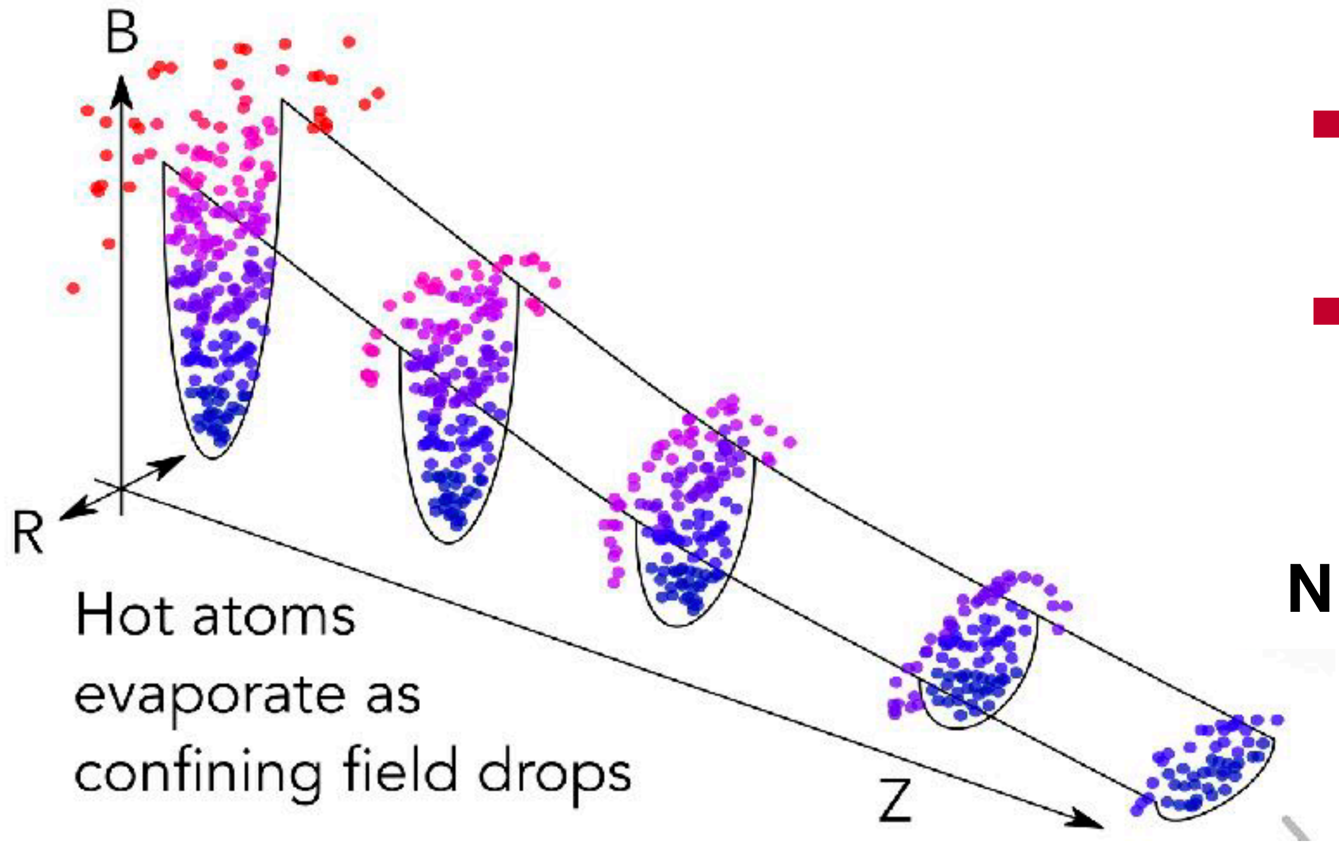
[1] Laboratoire Kastler Brossel, 24 rue Lhomond, 75005 Paris, France
[2] INFM, Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy



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



→ assumes equilibrium !

Evaporation efficiency η_{ev}

$$\mu B(z) = \eta_{\mathrm{ev}} k_B T(z)$$

- large η_{ev}
  - slow cooling, high efficiency
- small η_{ev}
  - fast cooling, low efficiency

Number density

$$n \propto T^{1/\gamma} \text{ with } \gamma = \frac{2}{3}\left(\eta_{ev} + \frac{1}{2} - C\right)$$

- optimal value ($C = 2$, $\eta_{ev} = 4.5$)
  - $\gamma = 2 \quad \rightarrow \quad n \propto T^{\frac{1}{2}}$

Evaporative cooling: the hard math

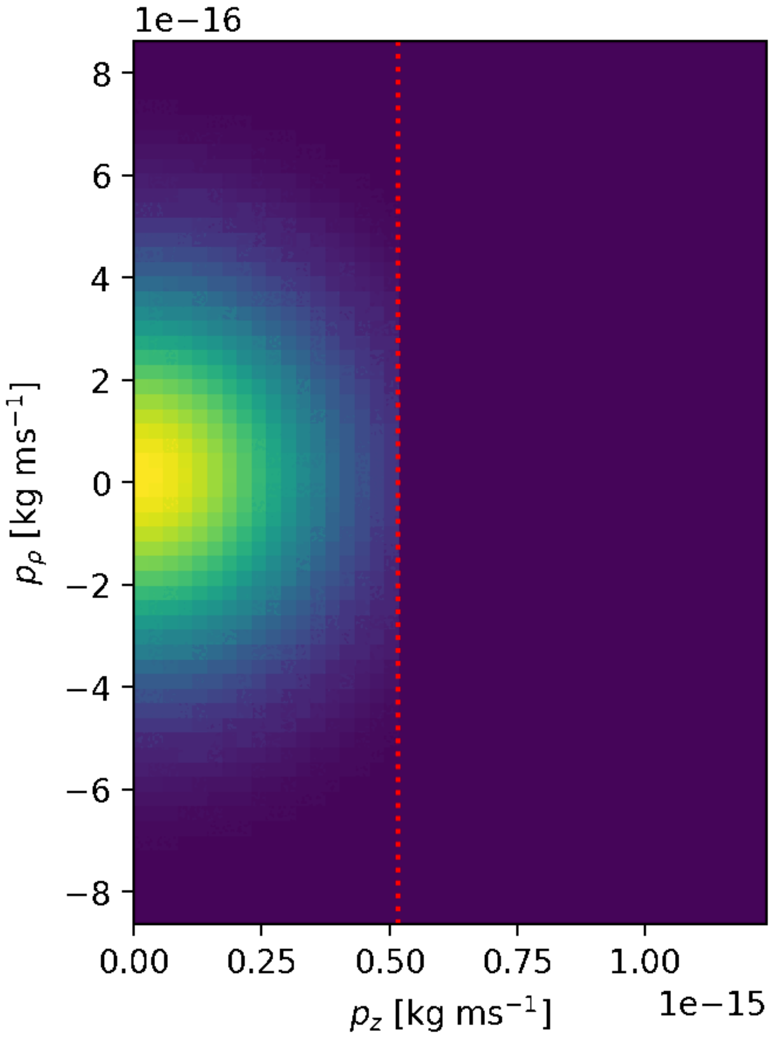
Boltzman transport equation

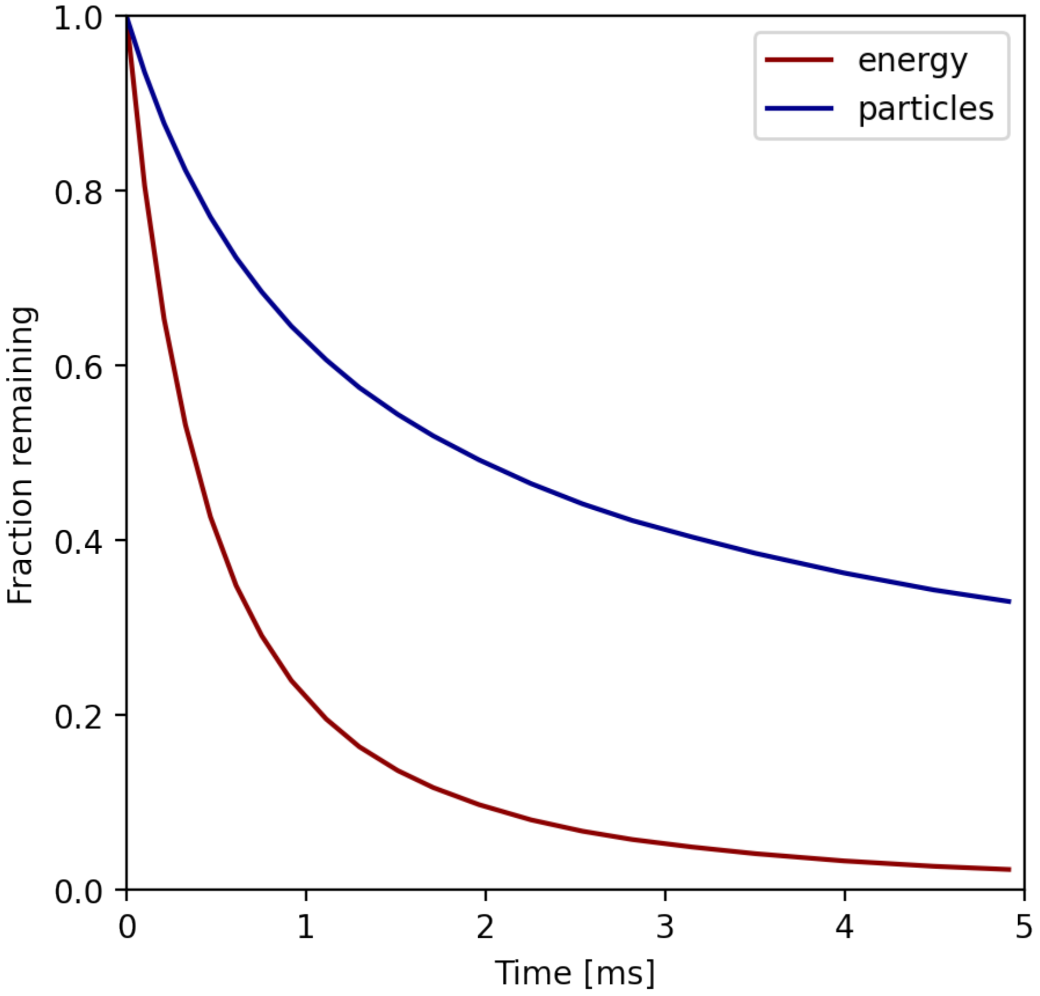
$$\left(\frac{p}{m}\nabla_r - \nabla_r U.\nabla_p + \frac{\partial}{\partial t}\right) f(r,p) = \frac{1}{\pi m^2}\int d^3p_2 \int d^3p_3 \int d^3p_4 \frac{d\sigma}{d\Omega}(p_1,p_2,p_3,p_4)(f(r,p_3)f(r,p_4) - f(r,p)f(r,p_2))$$

kinetic terms

collision integral

- solve numerically





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

Evaporative cooling: the hard math

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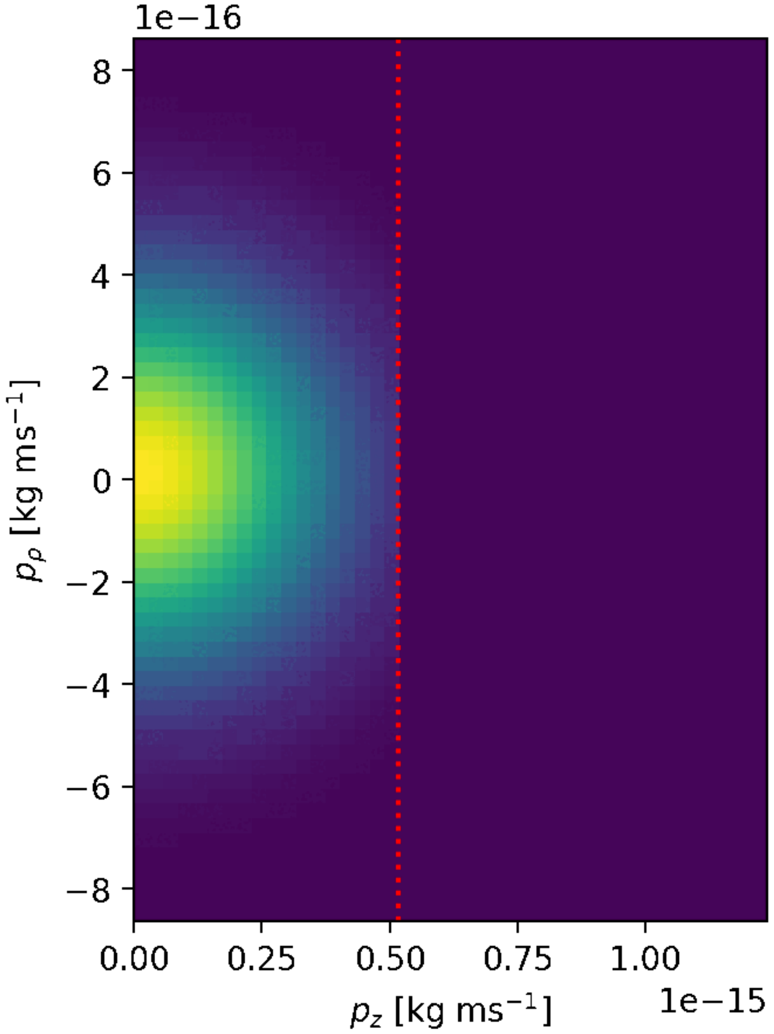

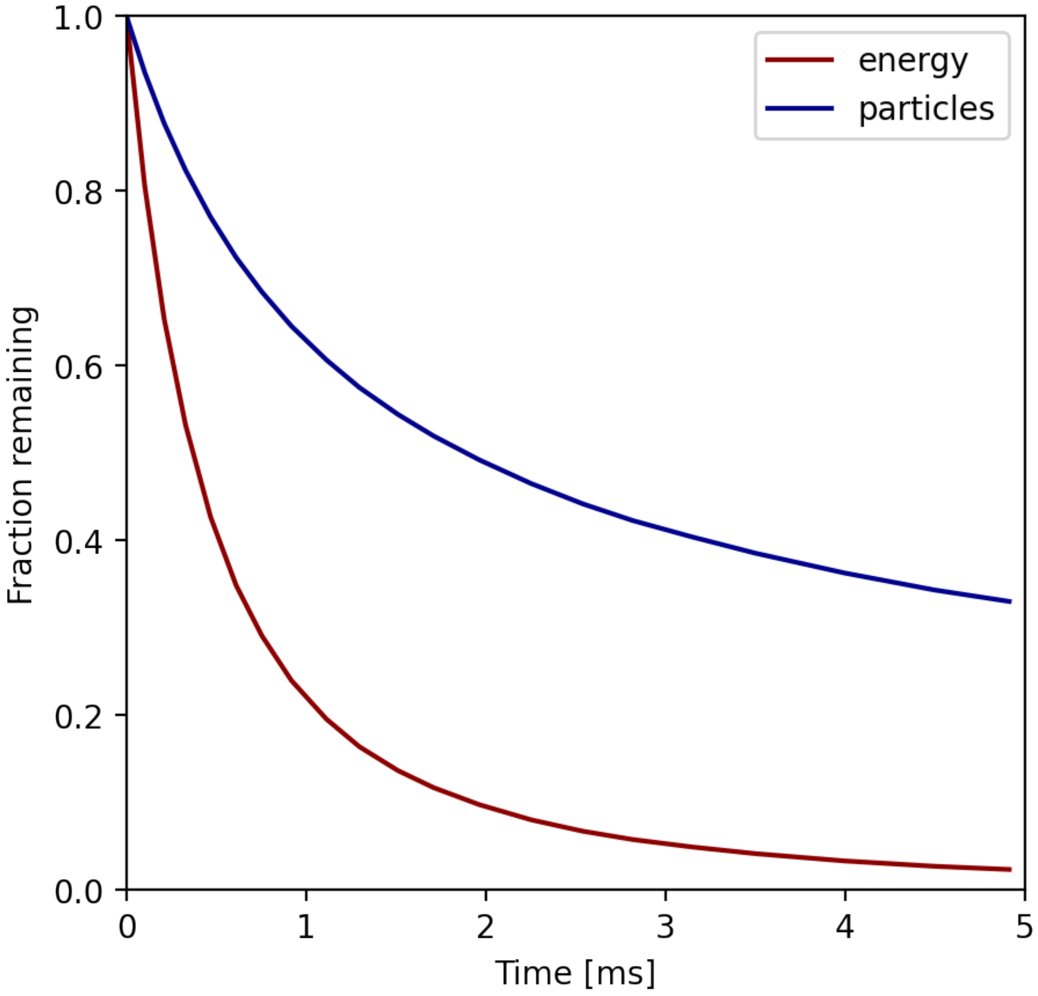

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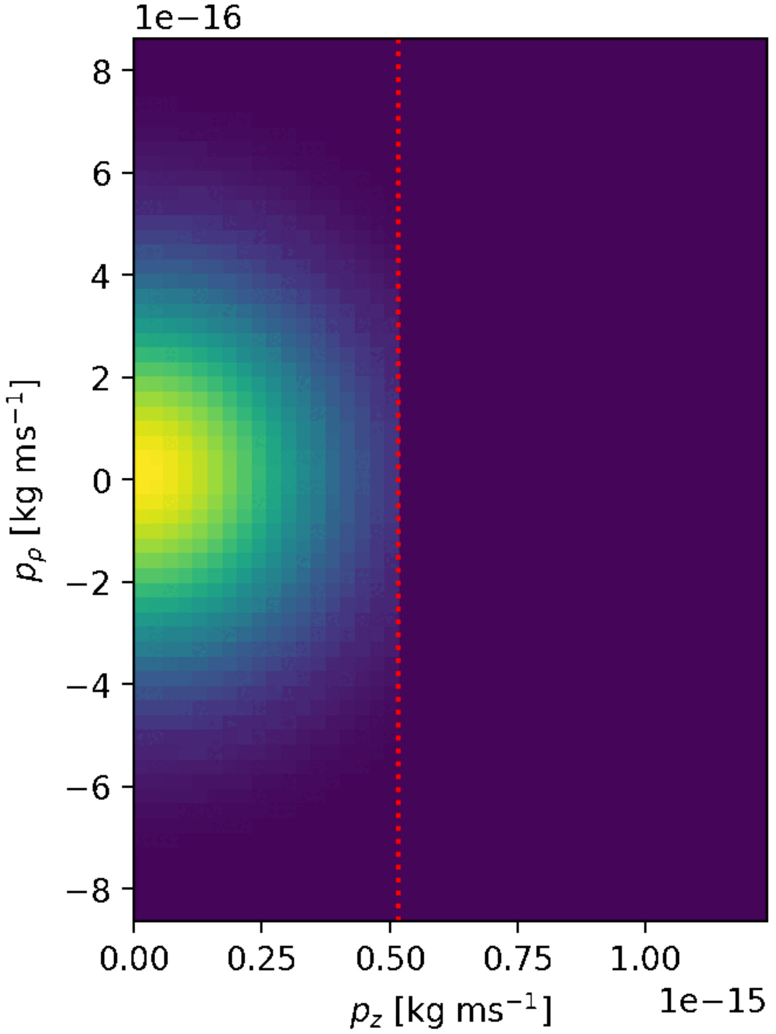

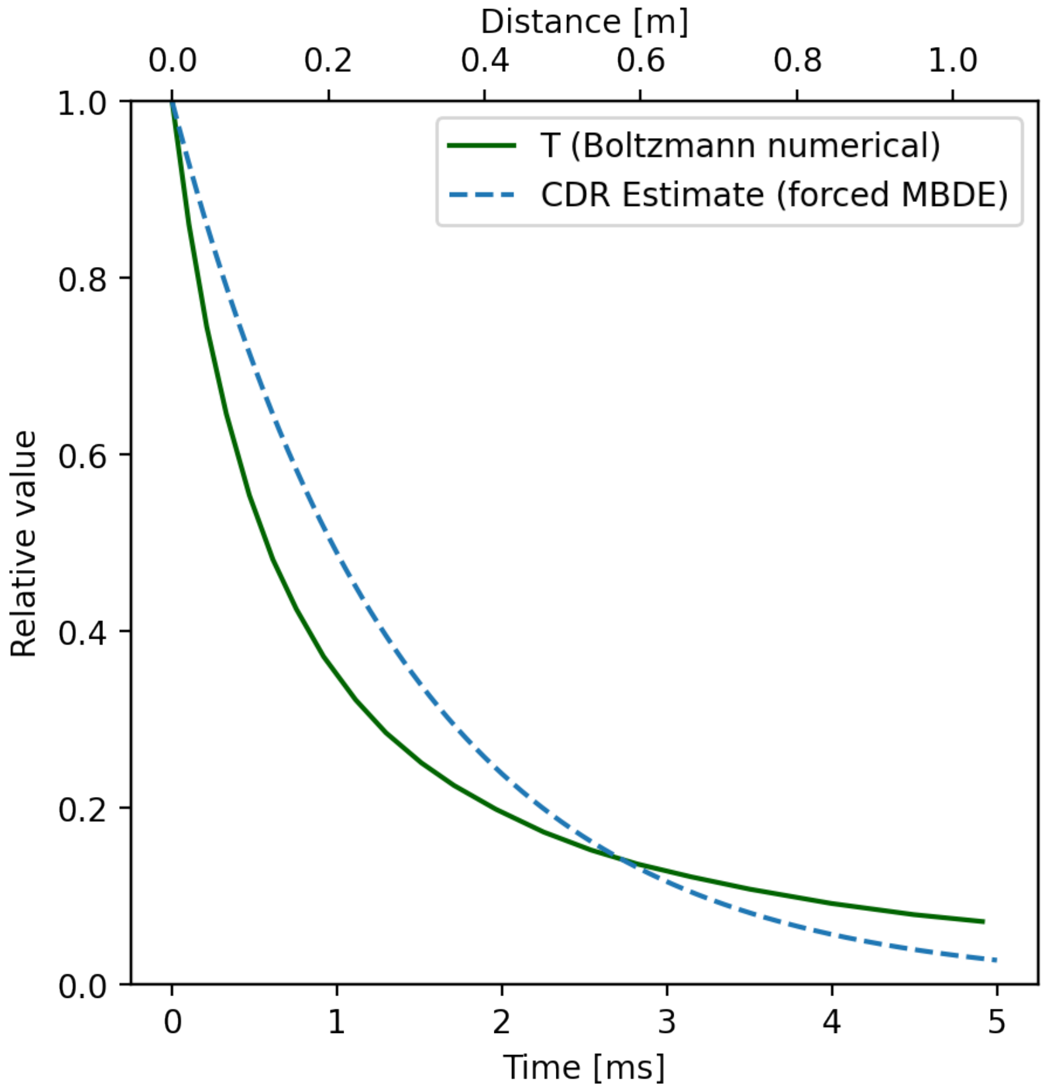

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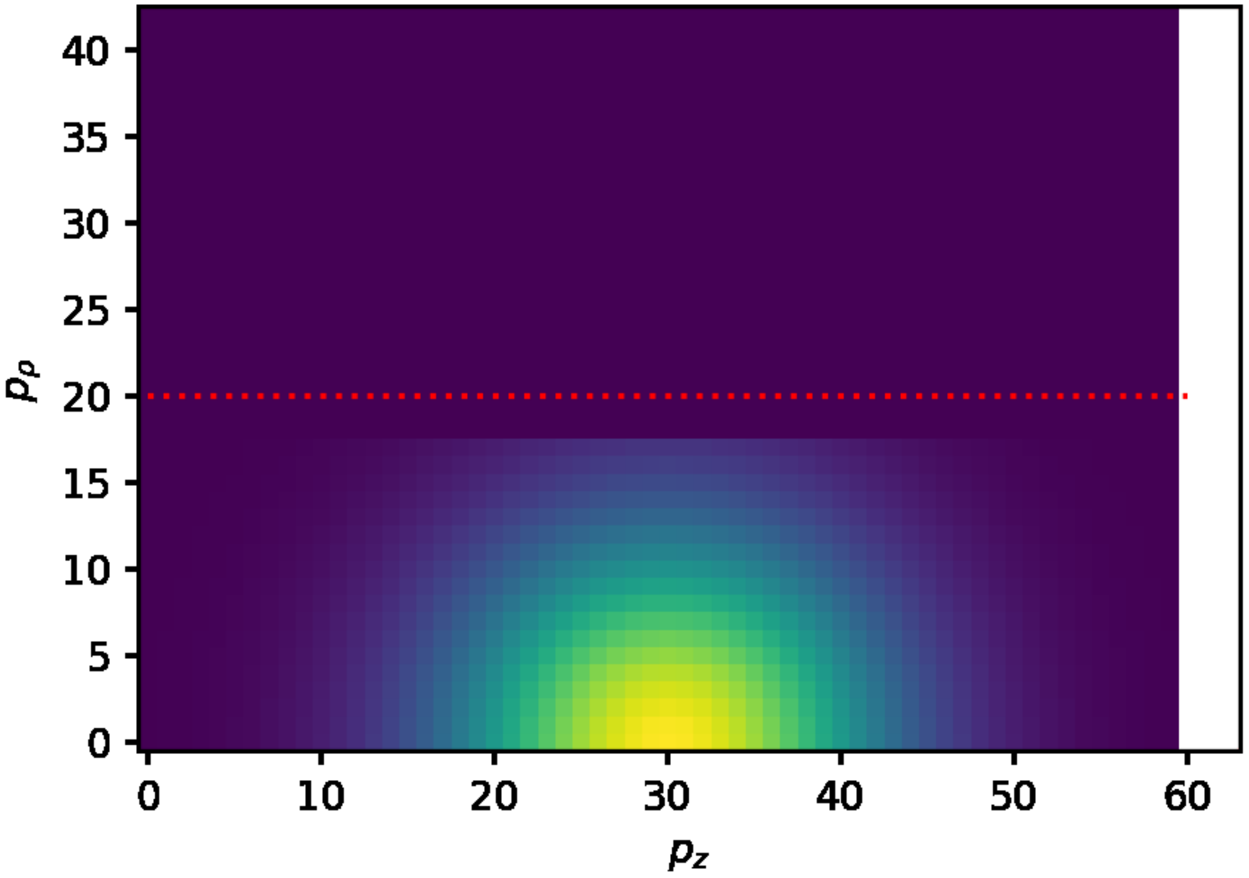
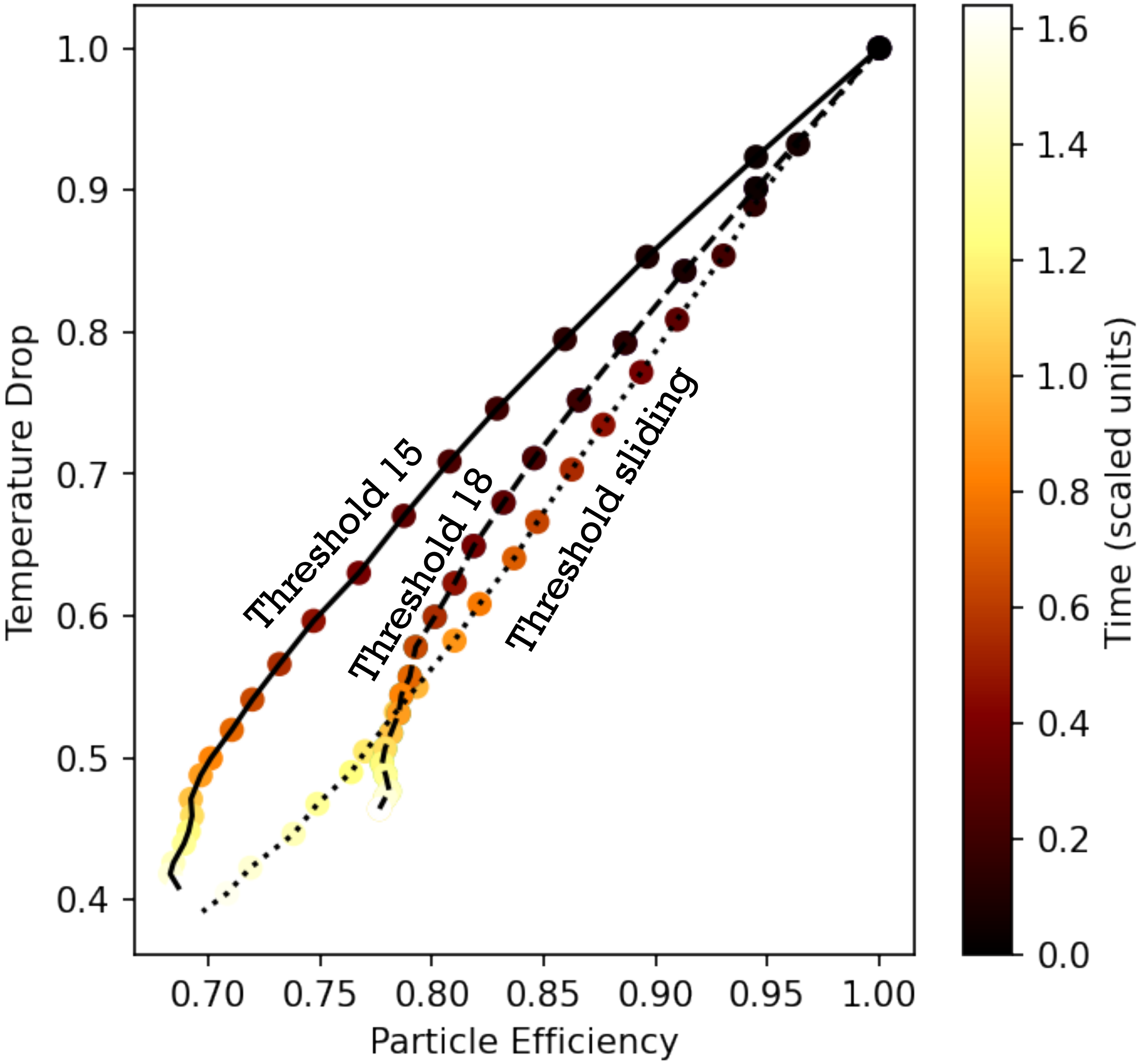
Evaporative cooling: sliding threshold

Original idea

- decrease wall height with time
  - faster cooling (initially)

→ large phase space left to explore





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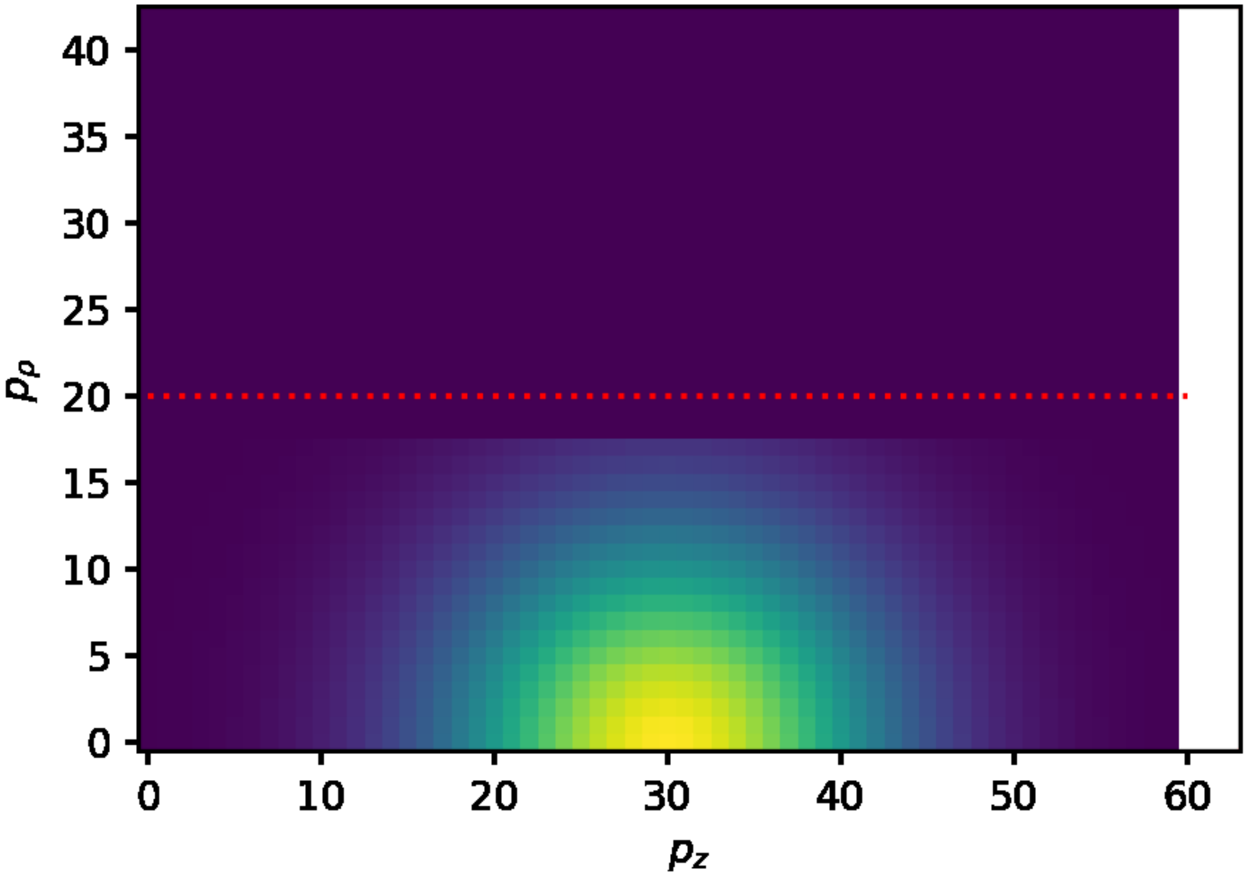
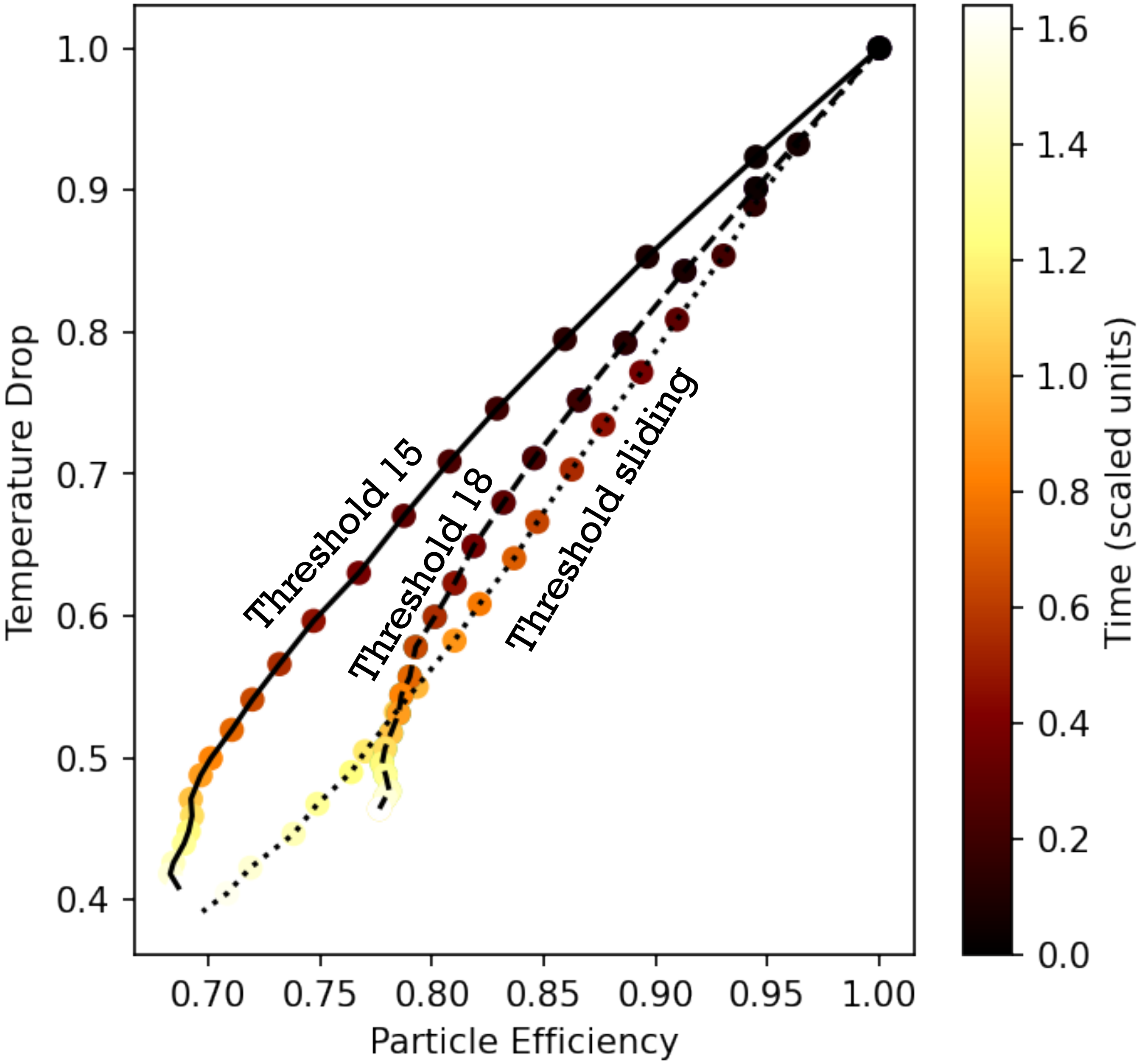




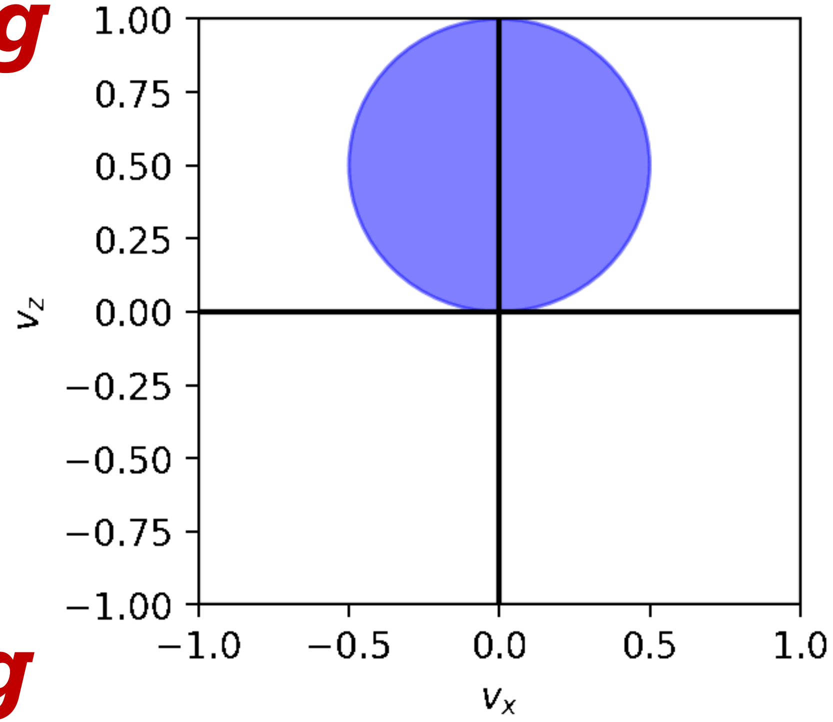
Cooling vs slowing

Initial atomic *beam*

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

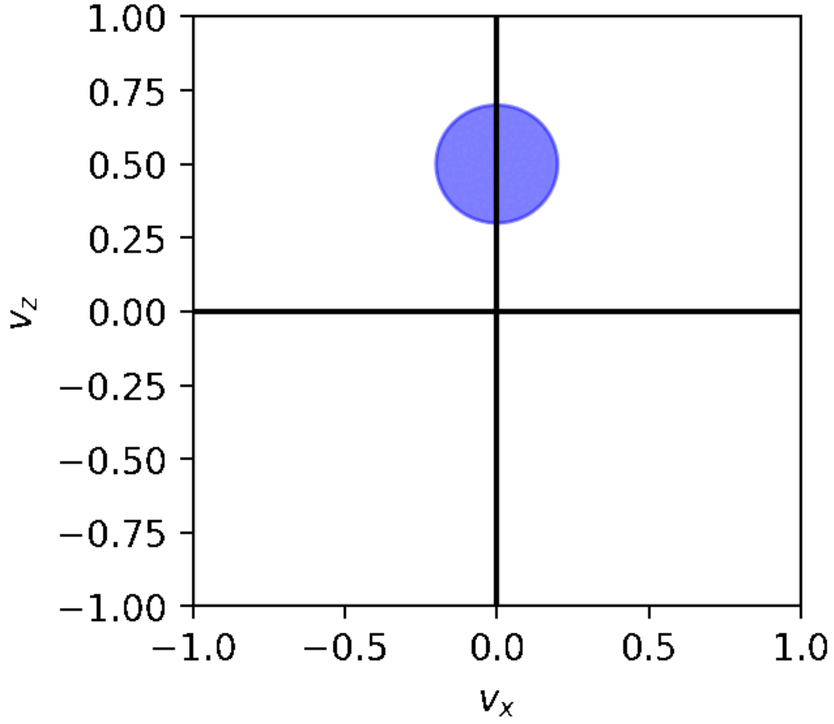
Cooling

Mean(p) conserved



Slowing

Mean(p) reduced



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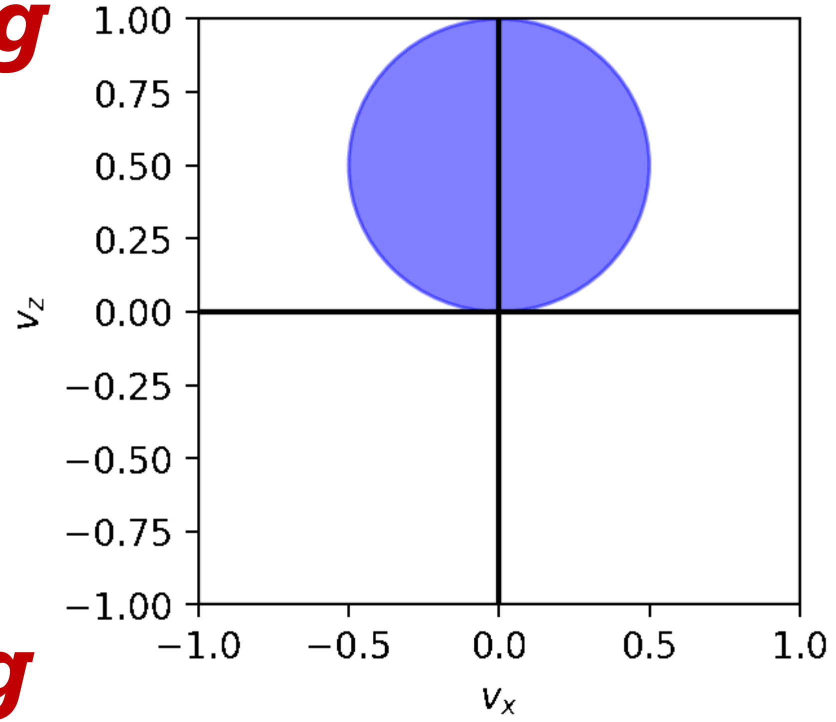

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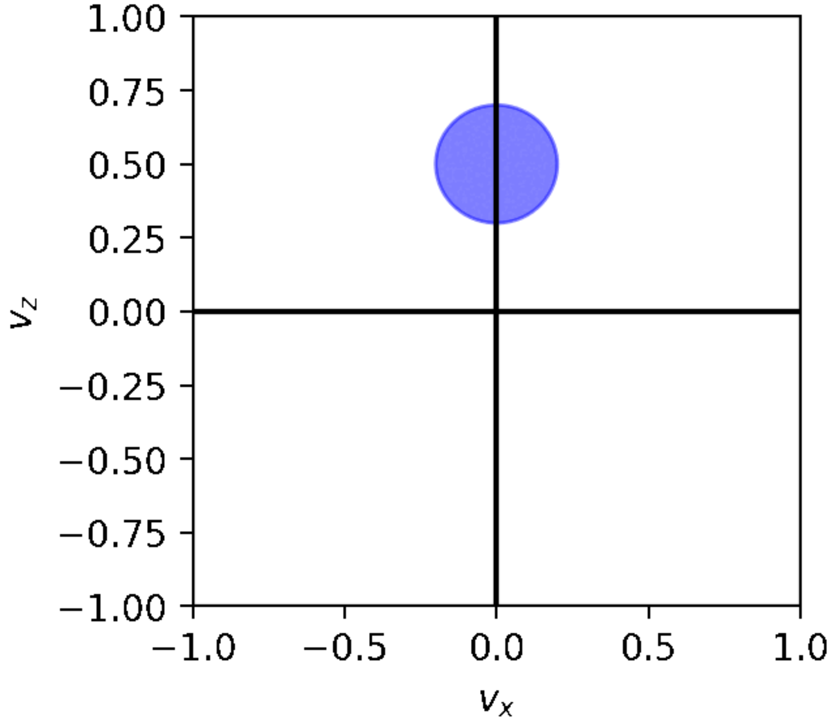

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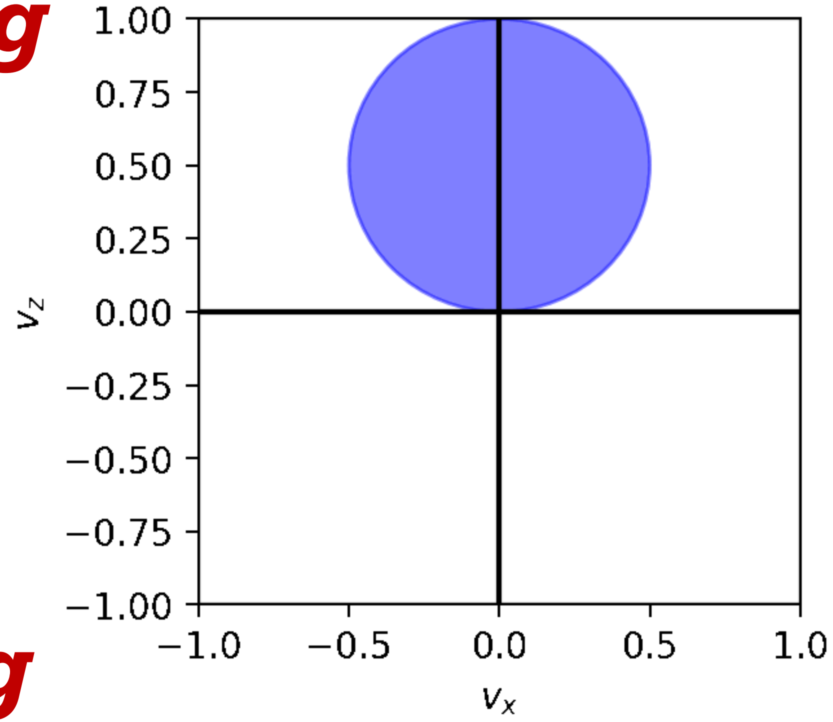

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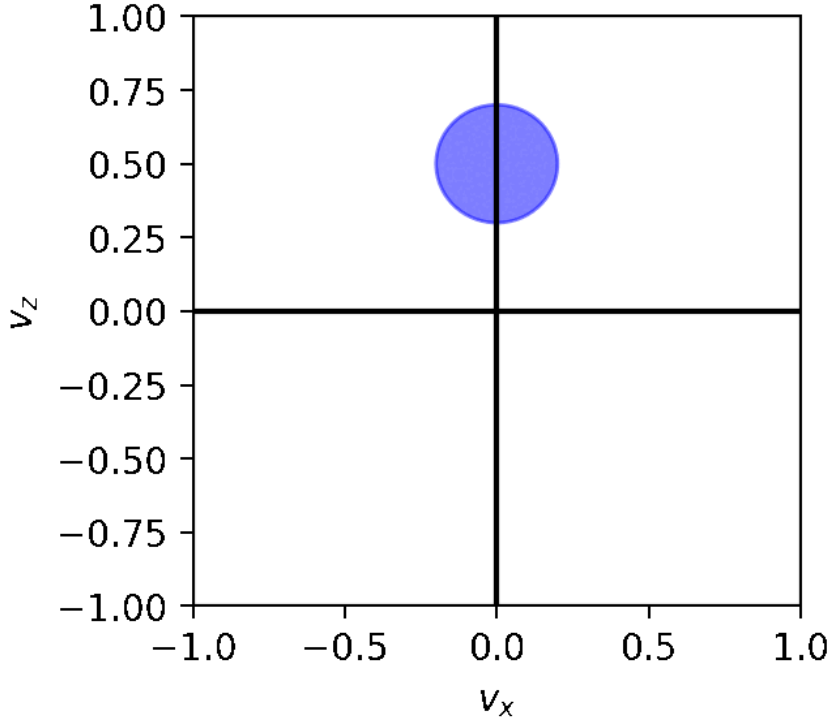

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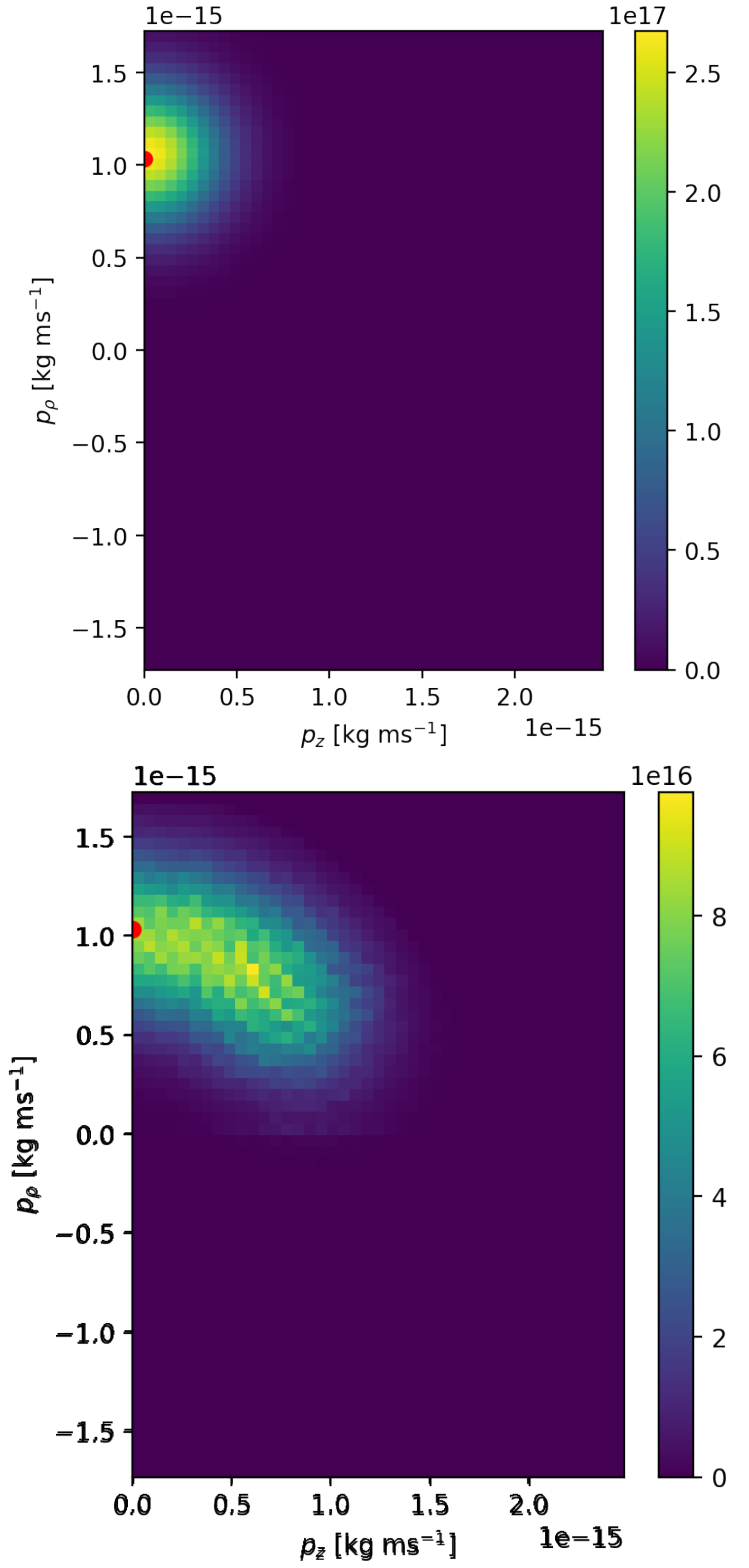
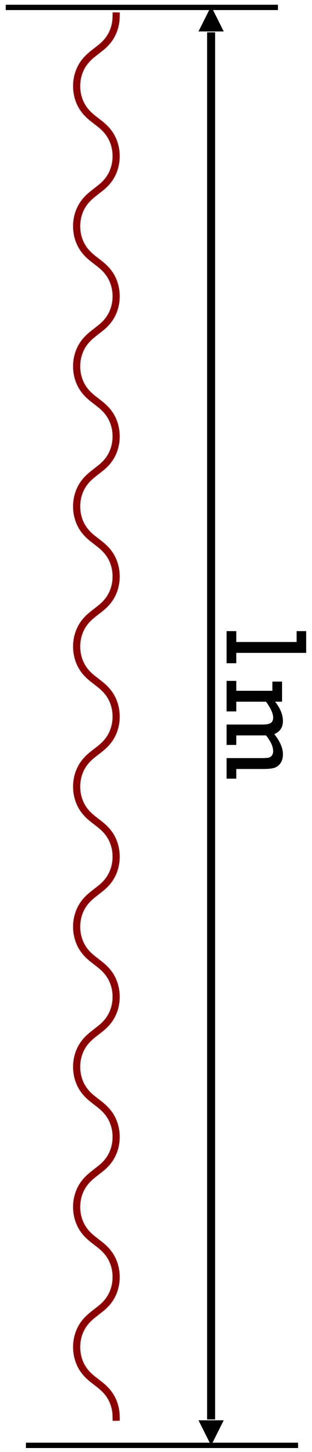
The *wiggler*

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





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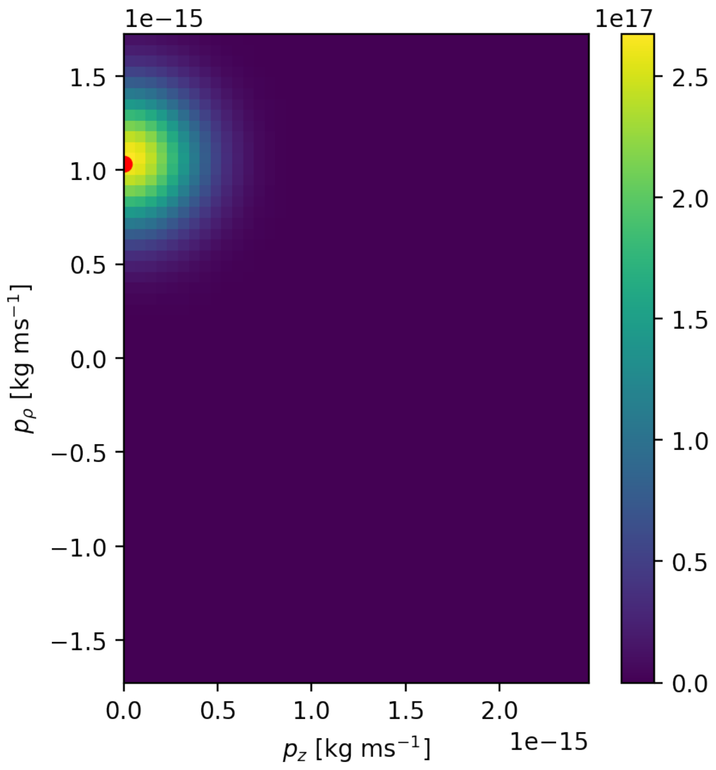

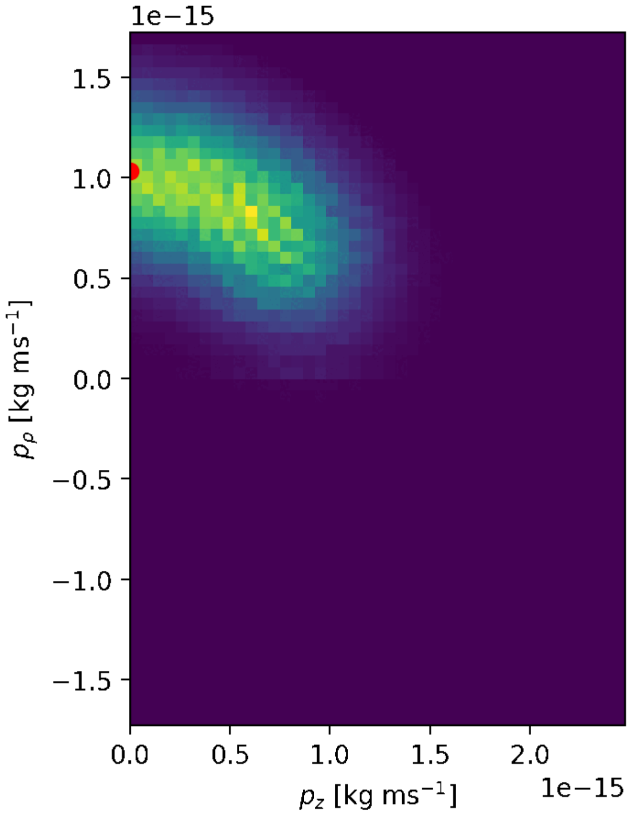

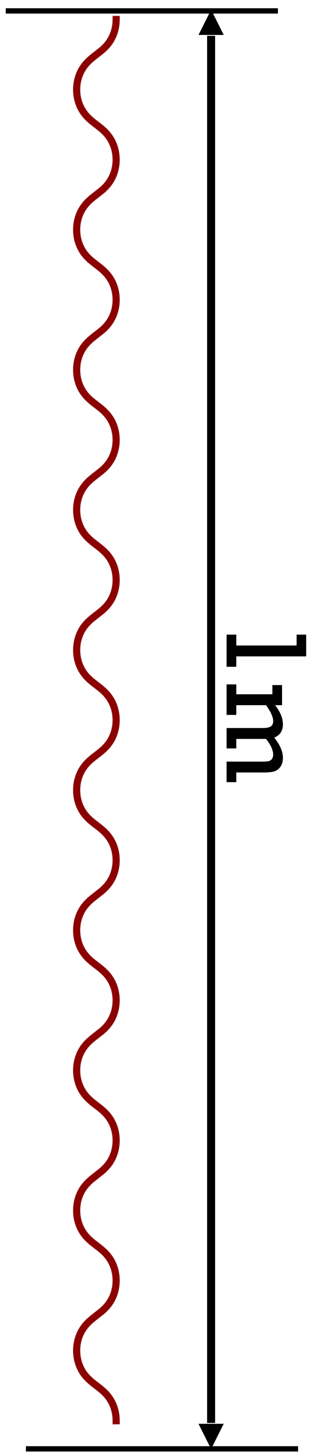

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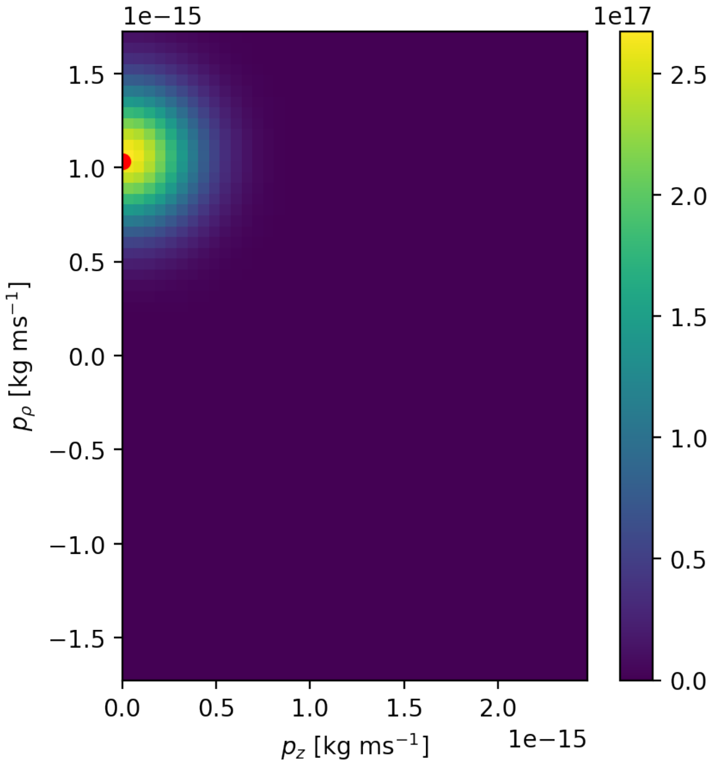
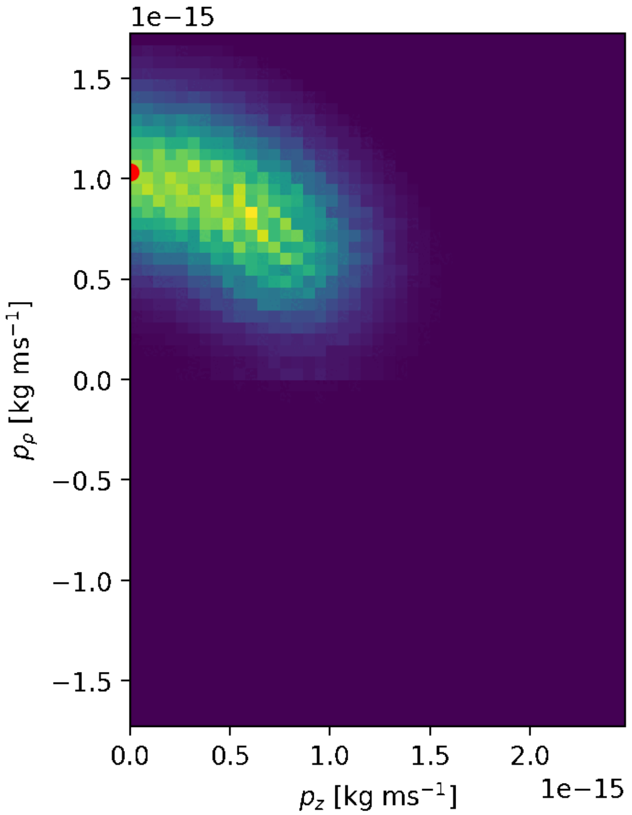
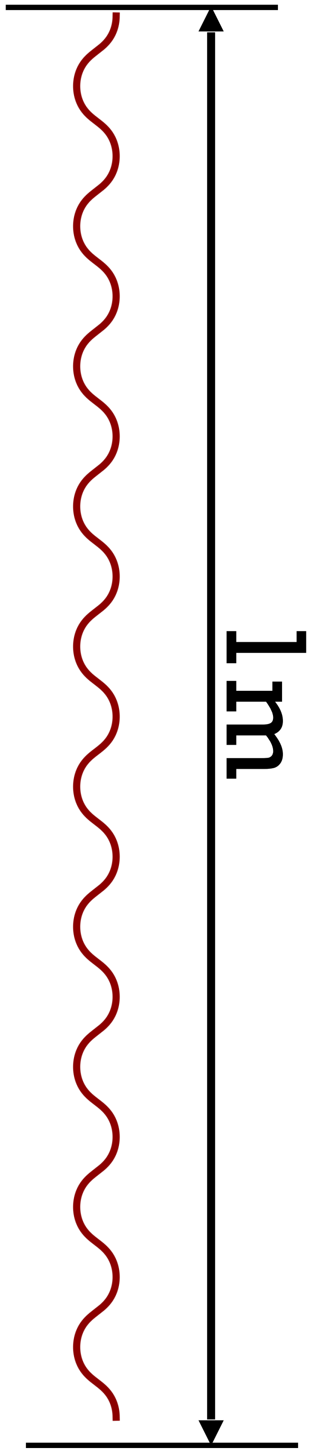
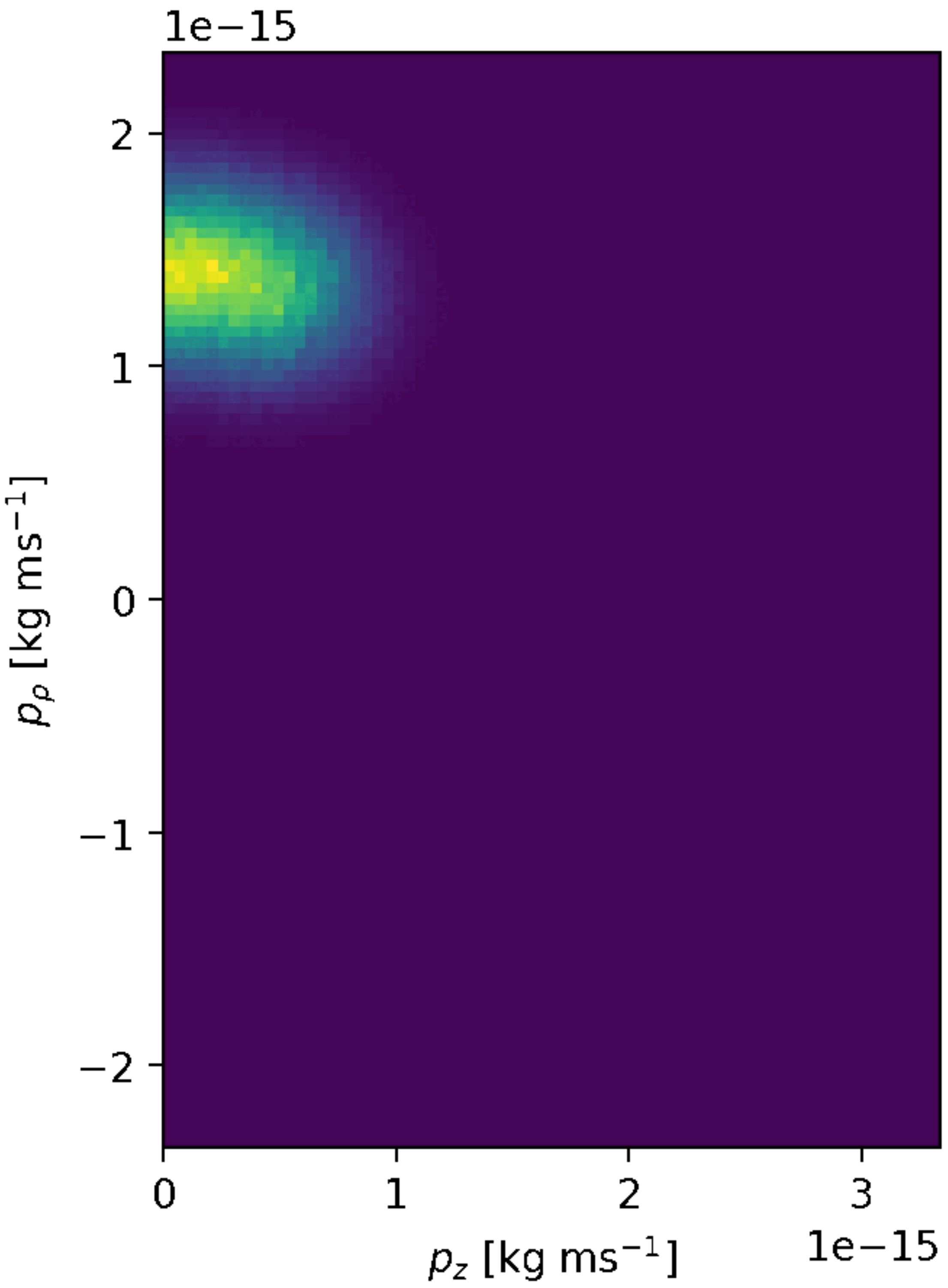




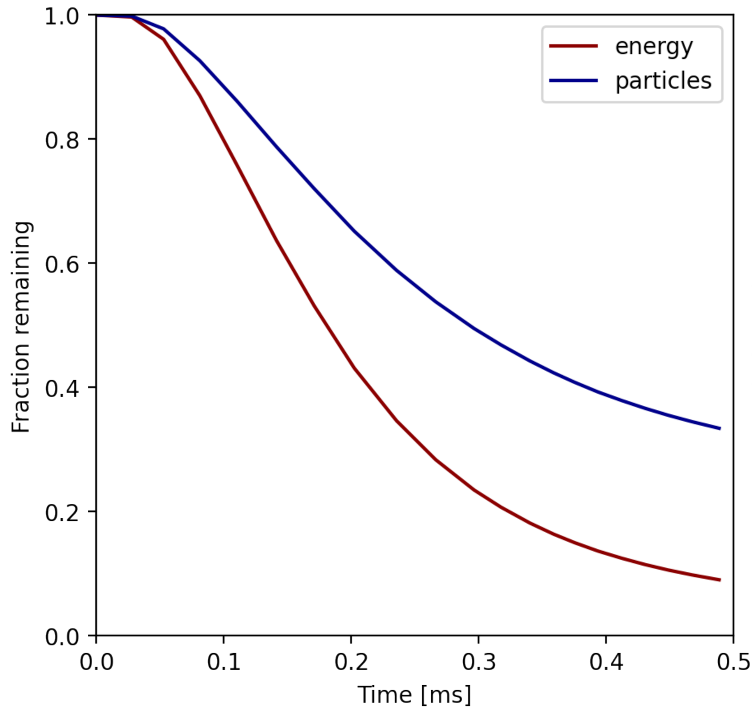


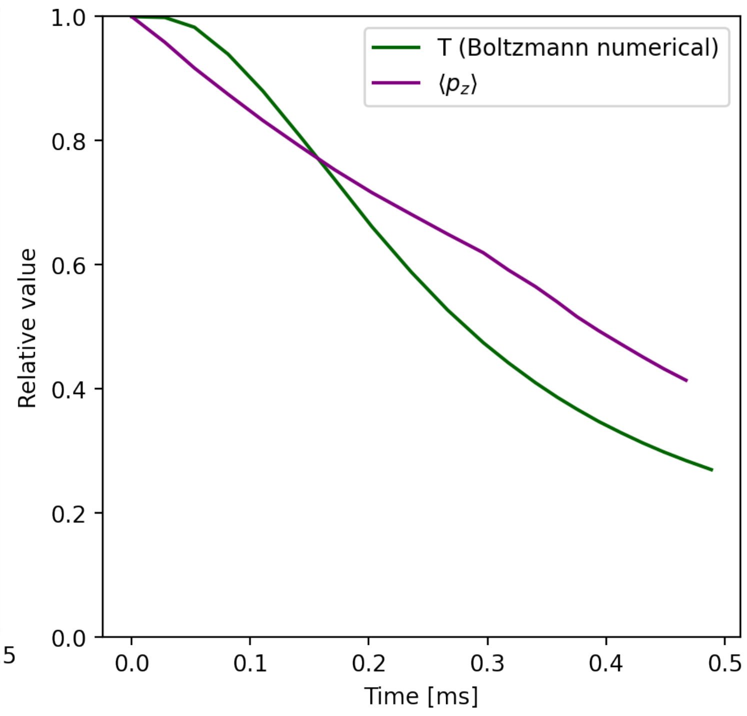
Evaporative wiggle-cooling (or cool wiggeling?)



Simultaneous

- evaporative cooling
- wiggeling
- re-thermalization
  - distribution gets **colder** and **slower**





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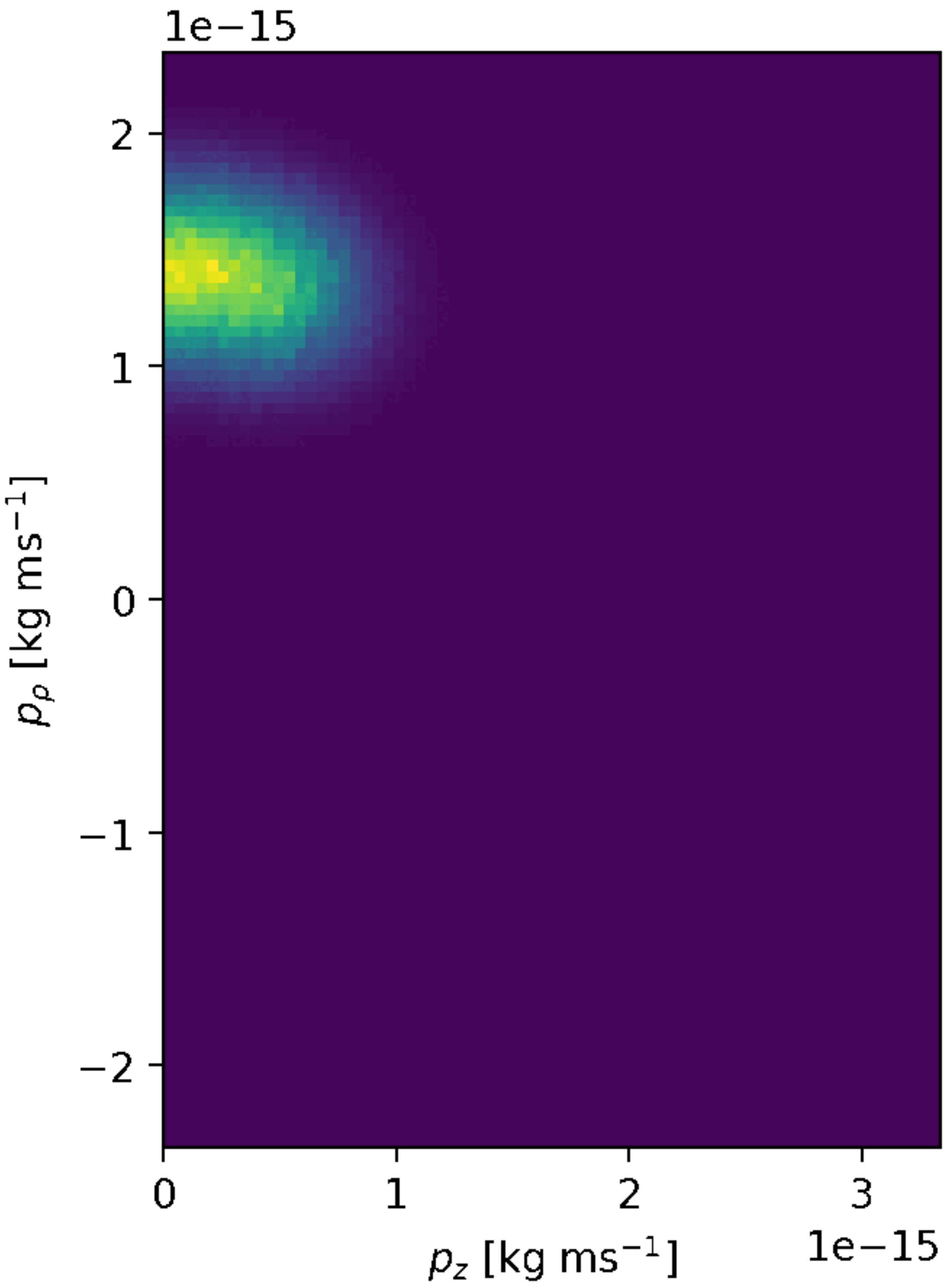

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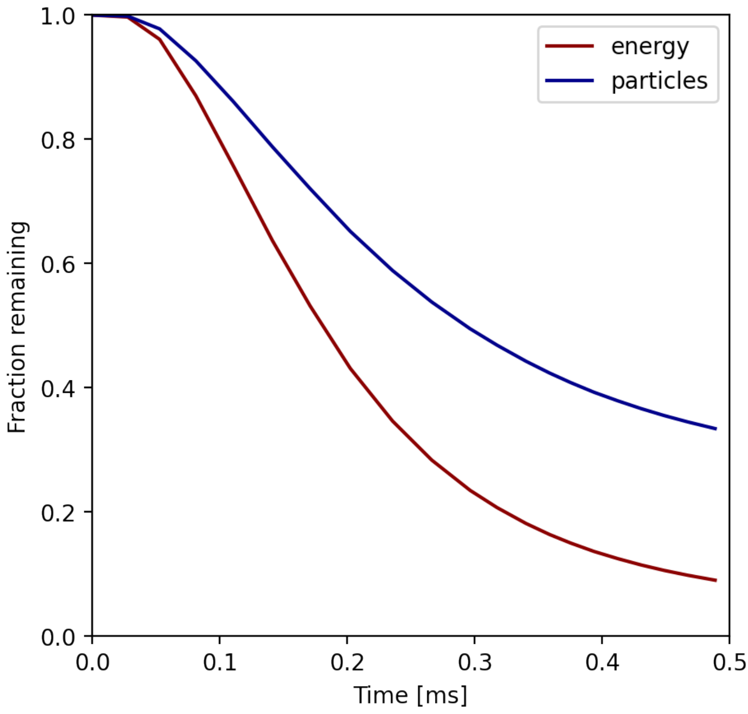
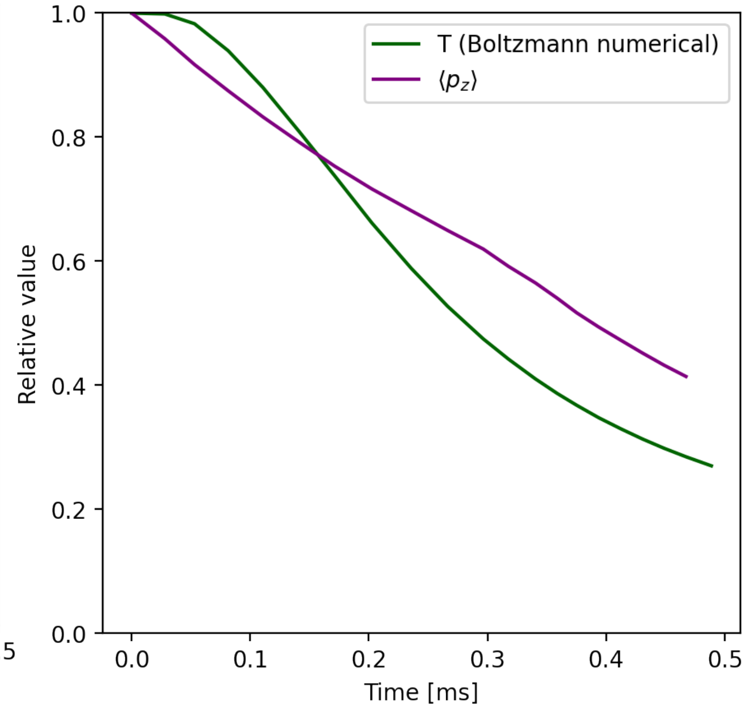




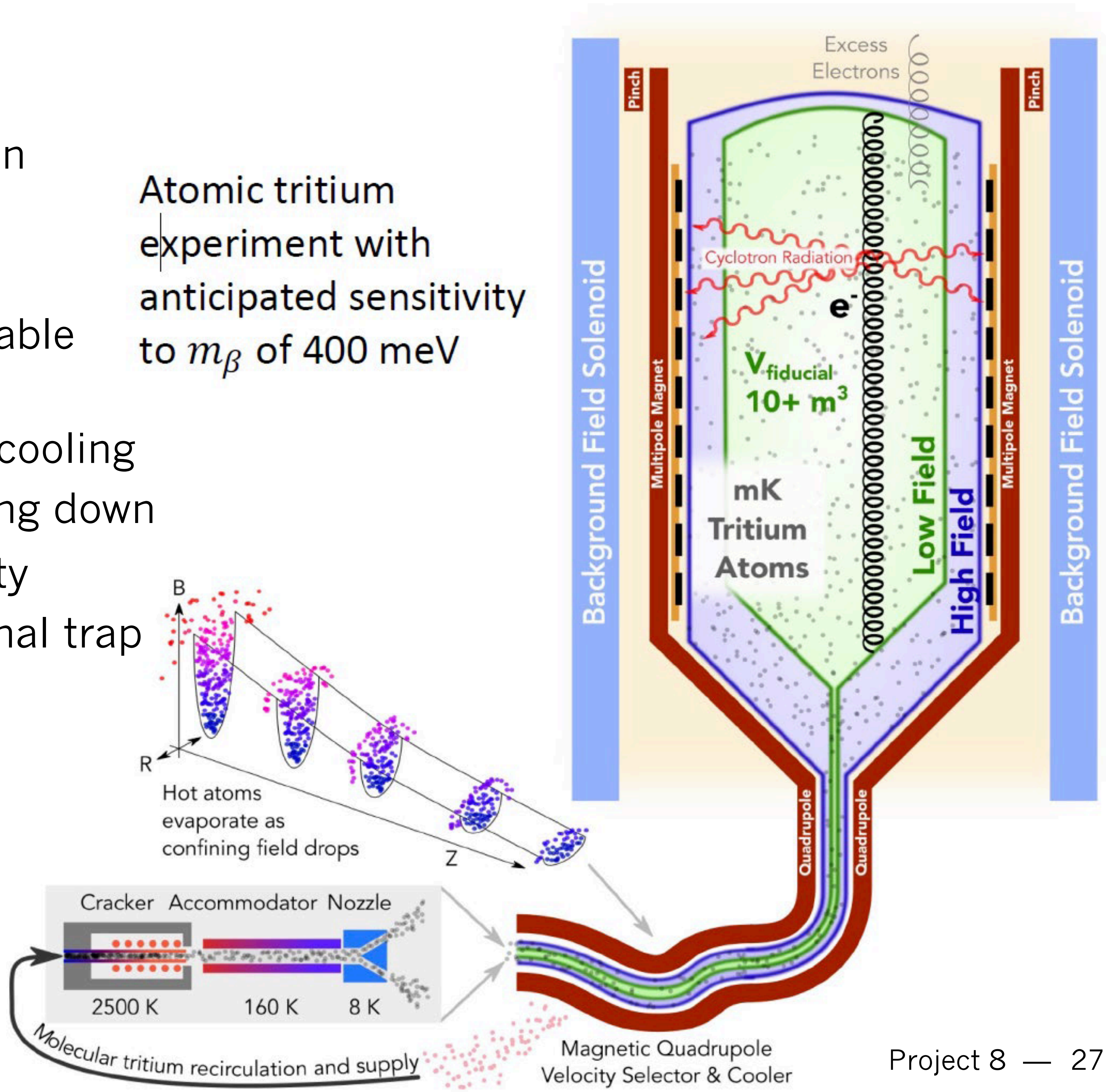
Atomic tritium experiment

PROJECT 8

Conceptual design

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

Atomic tritium experiment with anticipated sensitivity to m_β of 400 meV



Atomic beam demonstration: next steps

Dissociation and accommodation

- surface physics critical
  - establish experimentally

Evaporative wiggle cooling

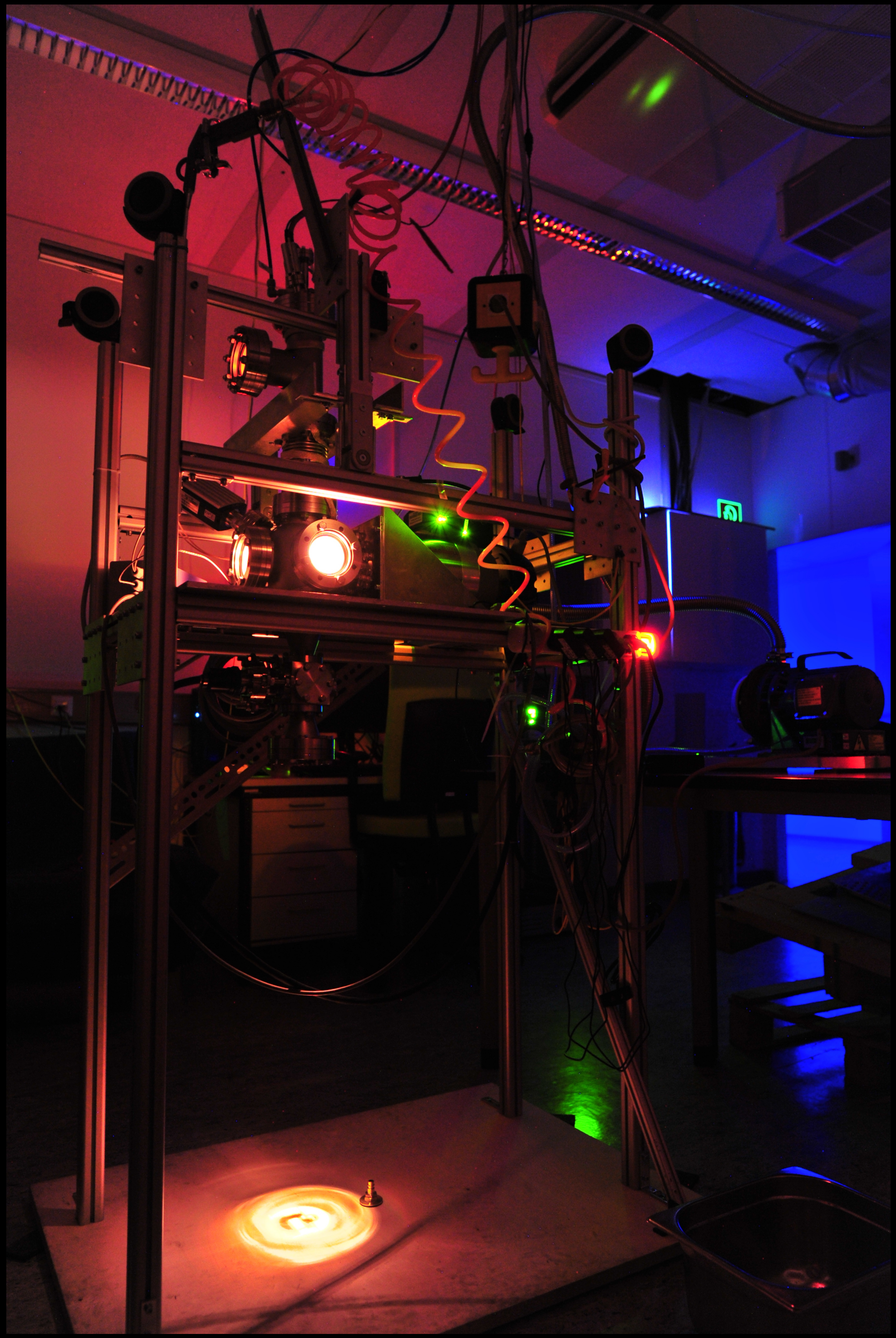
- magneto-thermodynamics
  - enter design phase

Trapping

- fix temperature and density
  - enter design phase

Overall approach

- start with H_2 and D_2
  - see talk by A. Lindman
- vet with T_2
  - see the future



Thank you!

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Pacific Northwest
NATIONAL LABORATORY

KIT
Karlsruher Institut für Technologie

CfA

JG|U

CASE
WESTERN
RESERVE
EST. 1826 UNIVERSITY
think beyond the possible

Project 8 collaboration