PROJECT8 — A NEW PATH TOWARDS MEASURING THE ν-MASS

SEBASTIAN BÖSER

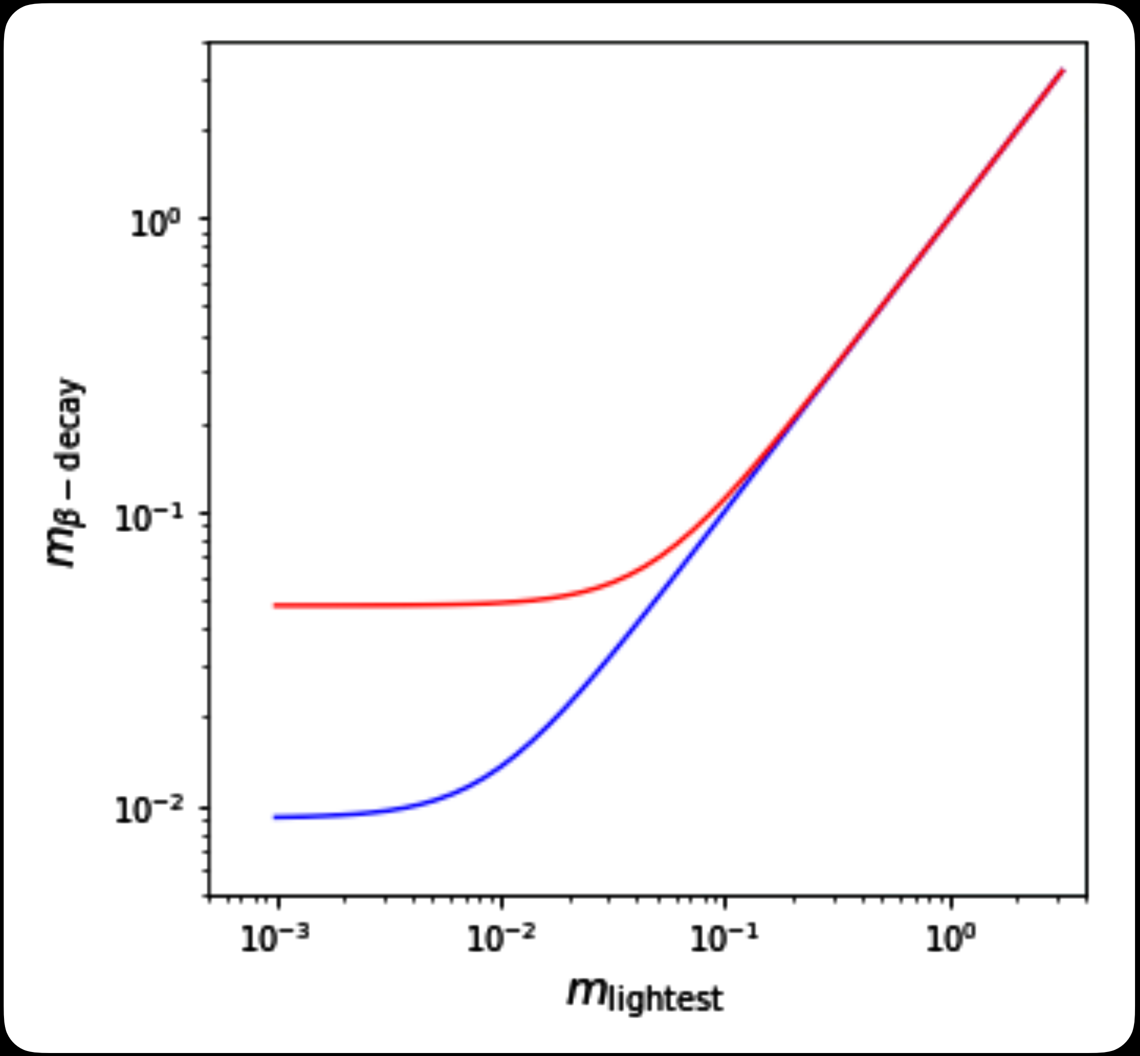
21ST SEPTEMBER 2017 | ERICE

MEASURING ν-MASS

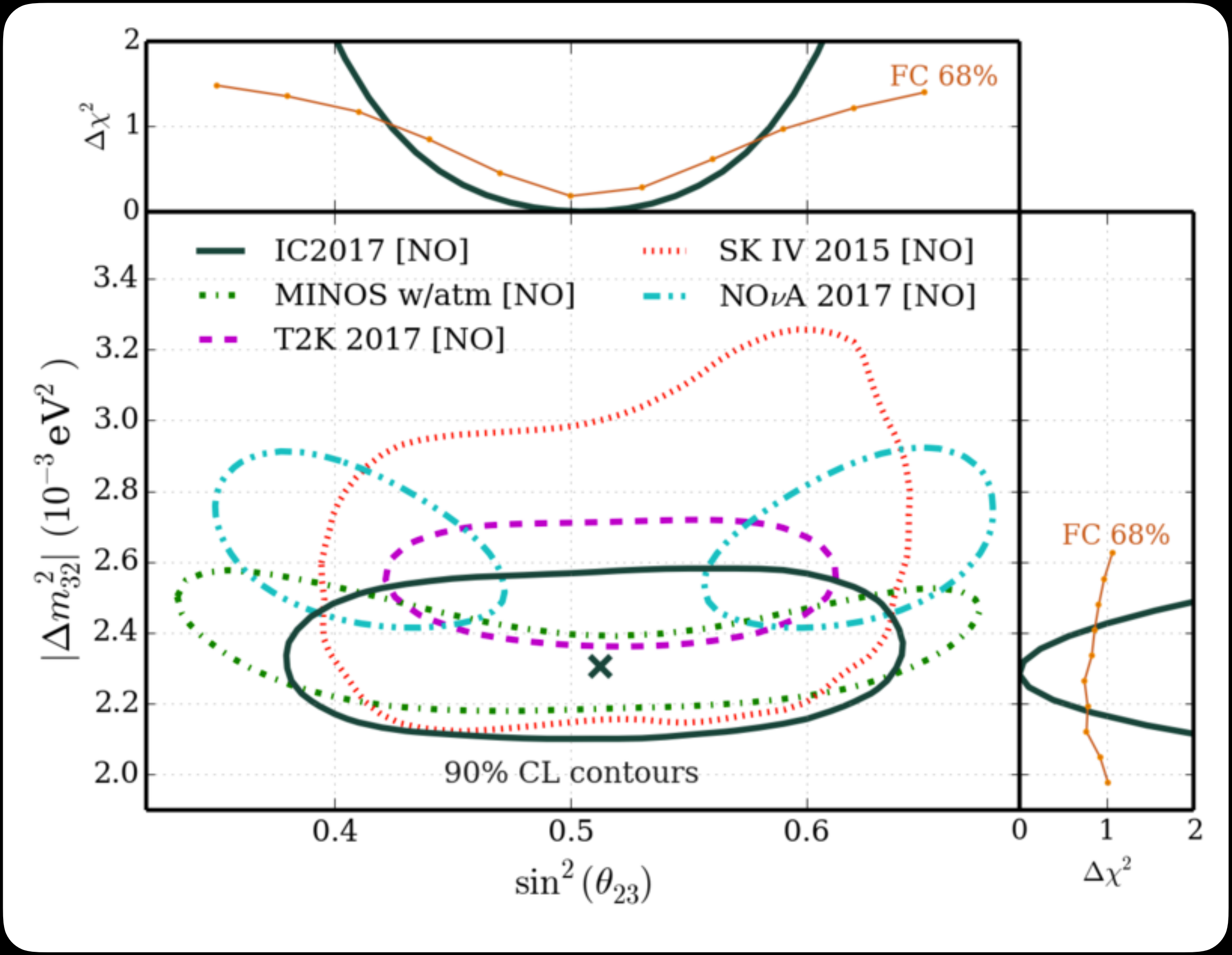
Several experiments gives us handles on neutrino mass scale

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Oscillation experiments



arXiv:1707.07081



MEASURING ν-MASS

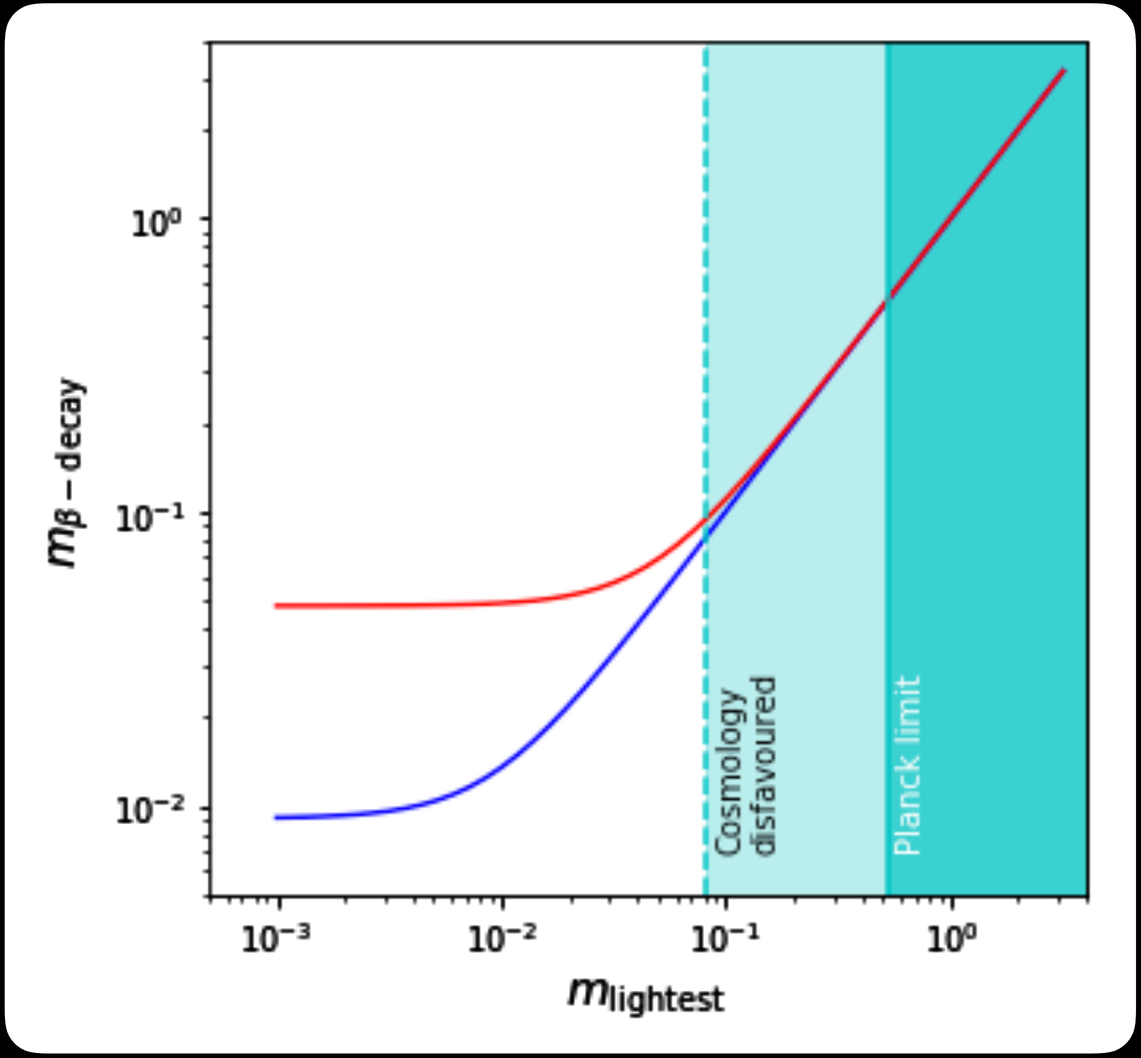
Several experiments gives us handles on neutrino mass scale

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Oscillation experiments

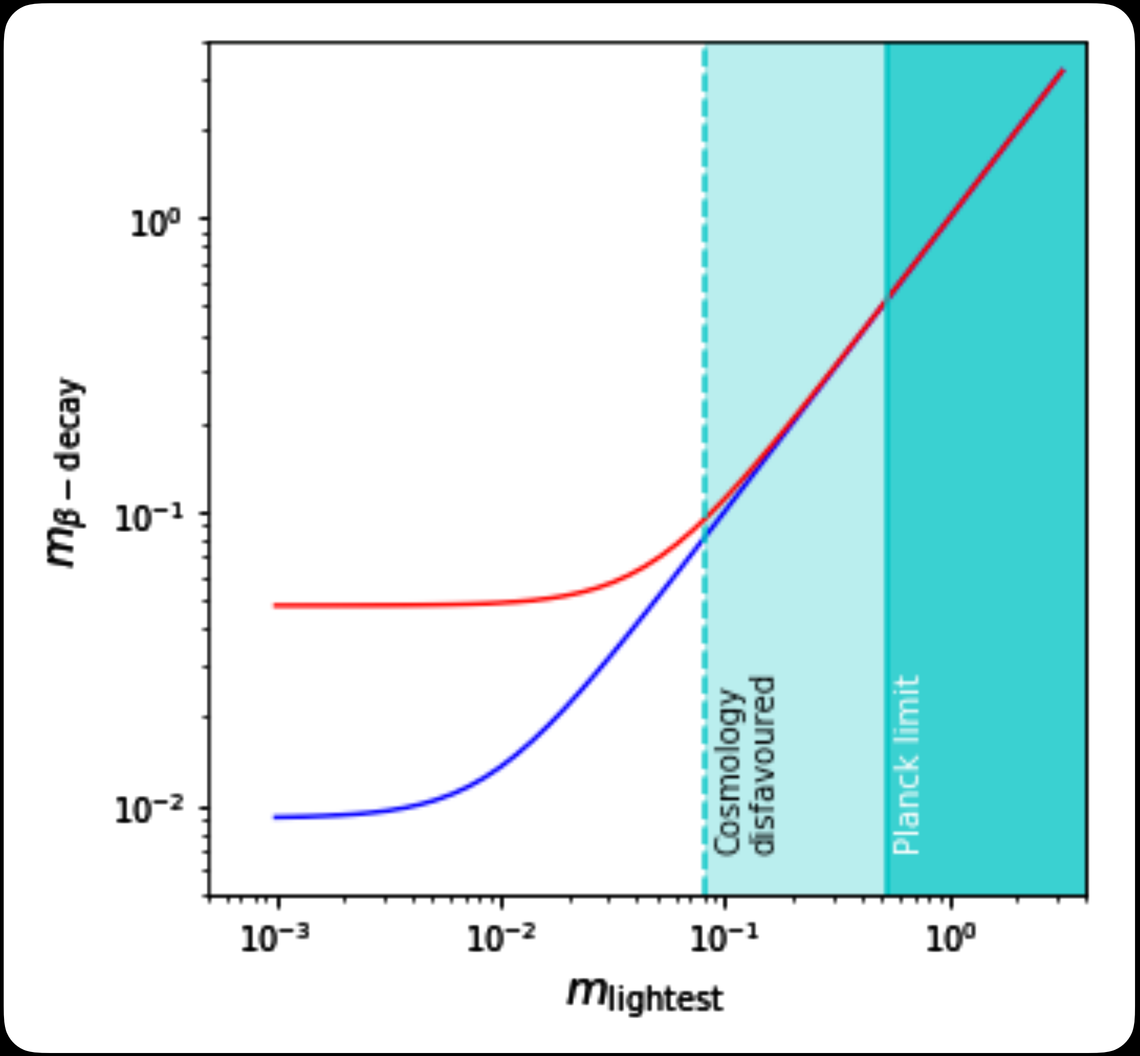
$$M = \sum_{i}^{n_\nu} m_i$$

Cosmological measurements



MEASURING ν-MASS

Several experiments gives us handles on neutrino mass scale



$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Oscillation experiments

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

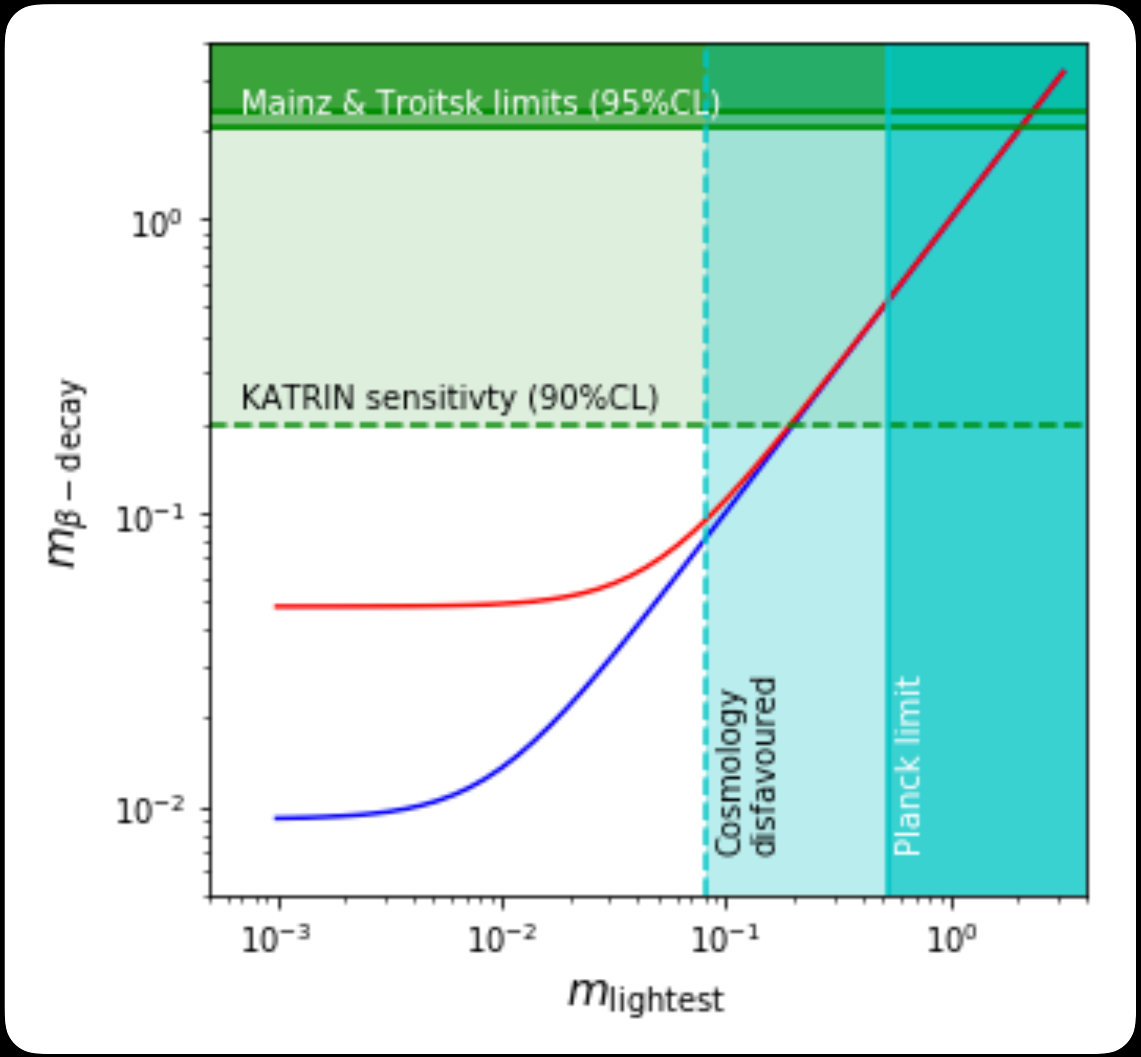
Cosmological measurements

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

0νββ decay experiments

MEASURING ν-MASS

Several experiments gives us handles on neutrino mass scale



$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Oscillation experiments

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

Cosmological measurements

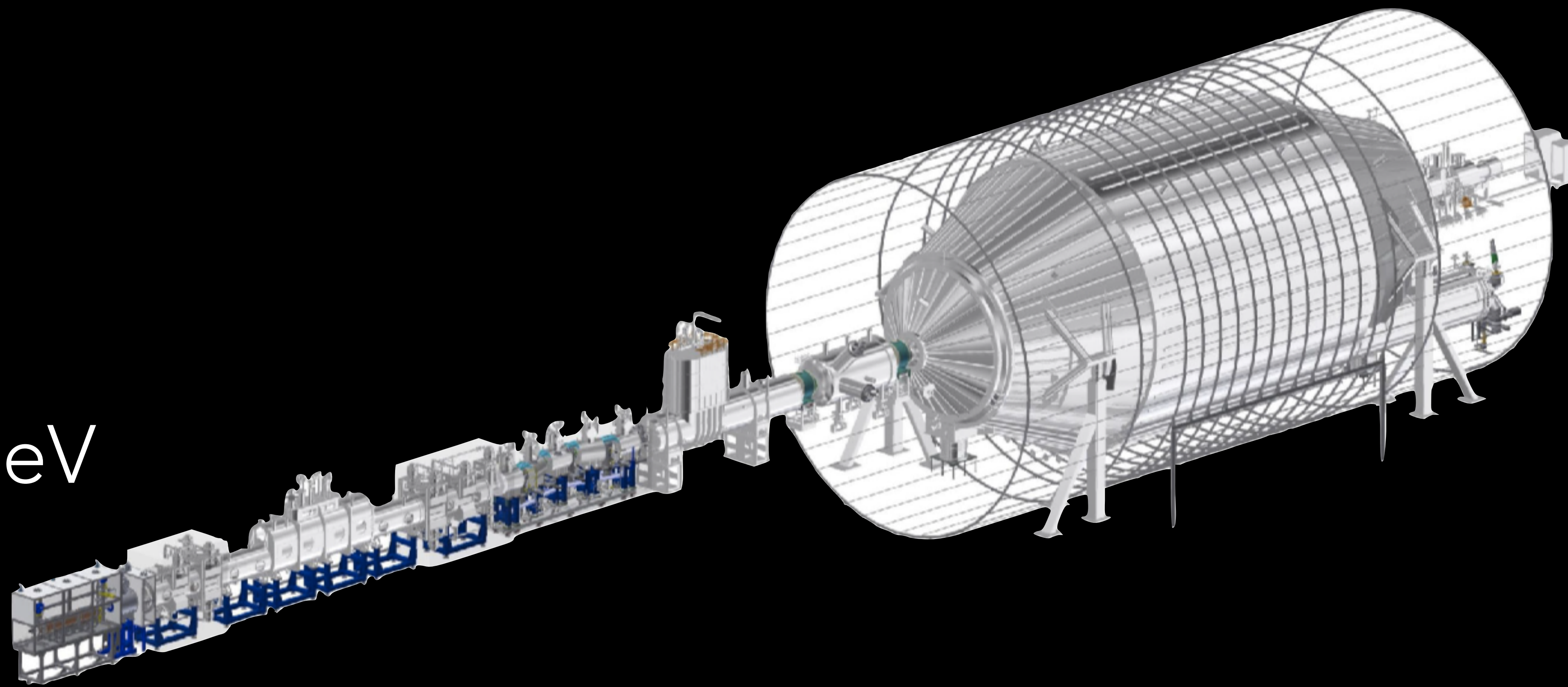
$$m_{\beta\beta}^2 = \left| \sum_i^{n_\nu} U_{ei}^2 m_i \right|^2$$

0$\nu\beta\beta$ decay experiments

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

β-decay experiments

KATRIN



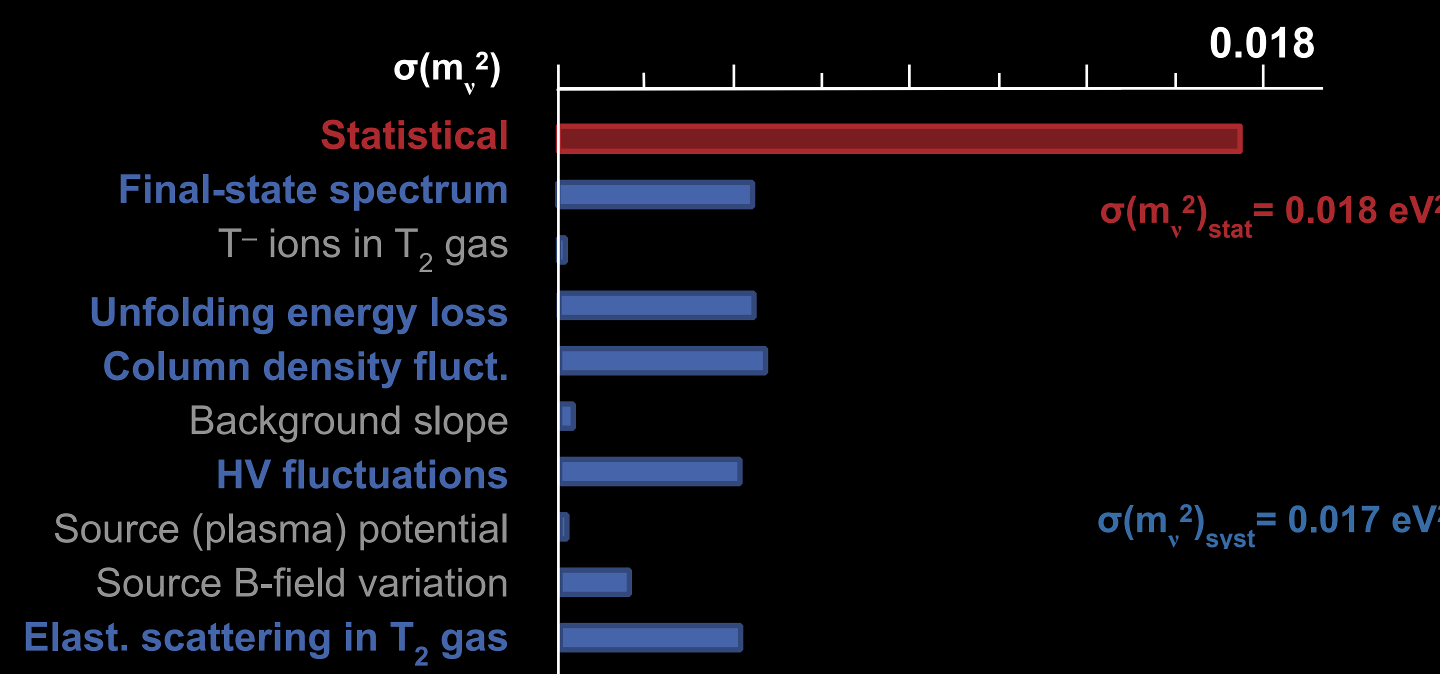
Sensitivity goal

- $m_\beta < 200\text{meV}$

Limited by

- column density
  - limits number of decays
- T_2 final state
  - limits energy resolution

➔ need a new and complementary approach

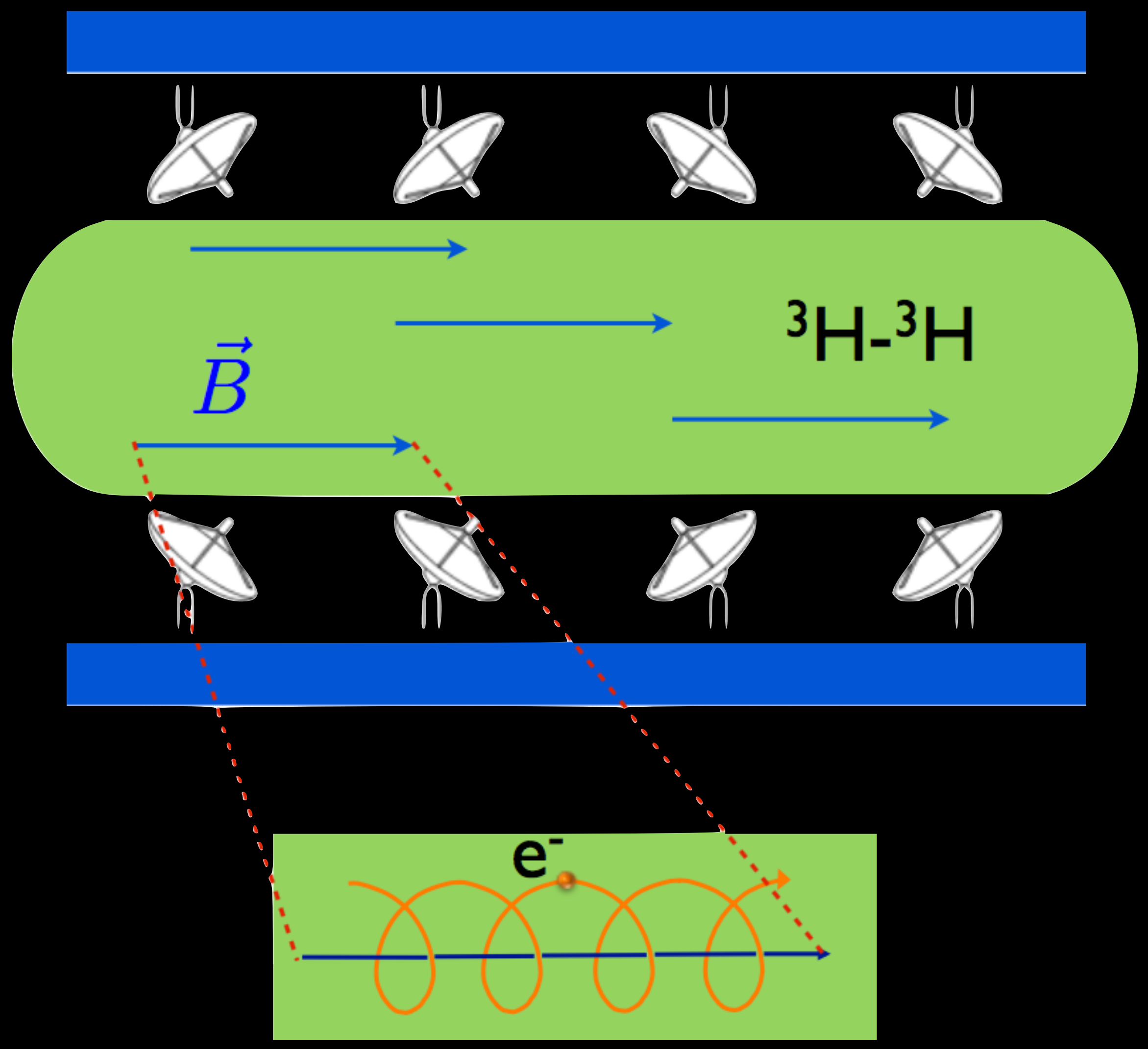


Kathrin Valerius, Erice, Sept 2017

PROJECT 8

Idea

- fill volume with ^3H gas
- add magnetic field
- decay electrons spiral around field lines
- add antennas to detect cyclotron radiation



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

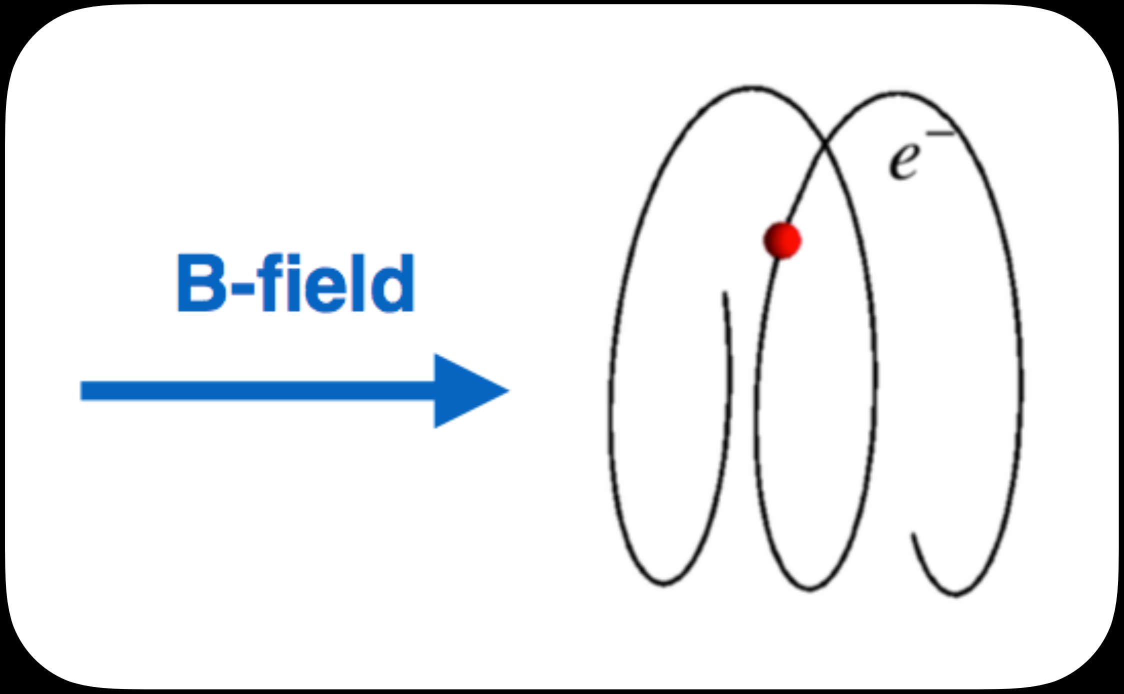
CYCLOTRON RADIATION

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

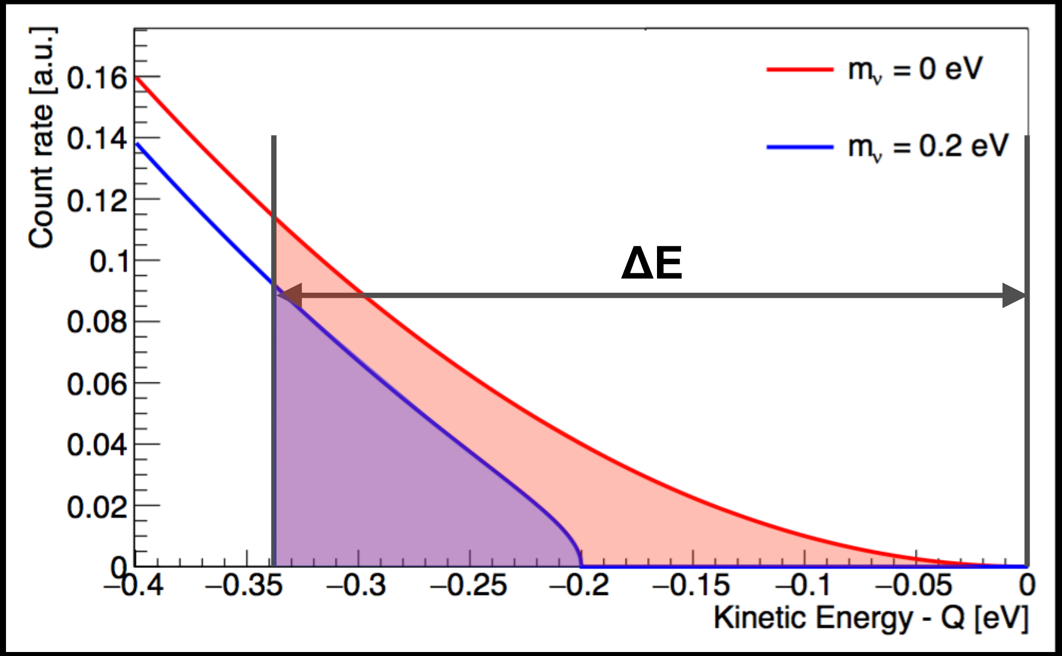
SENSITIVITY ESTIMATE

Counting experiment

- over energy window ΔE

$$\sigma_{m_\nu^2} = \frac{2}{3R_S T\Delta E}\sqrt{R_S T\Delta E + \frac{R_B T}{\Delta E}}$$

signal rate background rate



arXiv:1309.7093

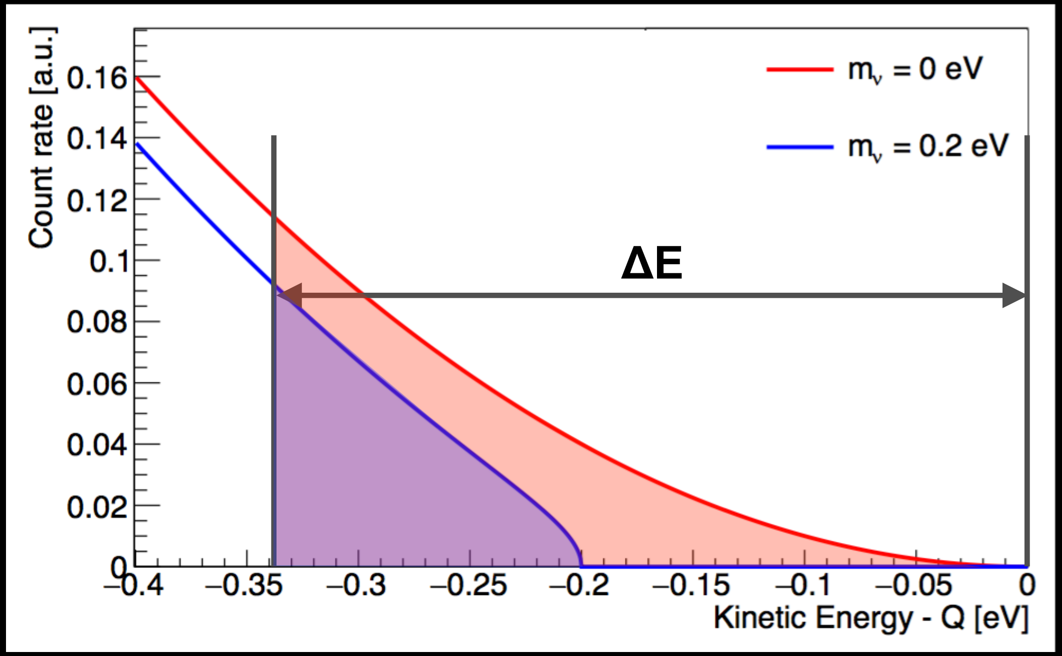
SENSITIVITY ESTIMATE

Counting experiment

- over energy window ΔE

$$\sigma_{m_\nu^2} = \frac{2}{3R_S T\Delta E}\sqrt{R_S T\Delta E + \frac{R_B T}{\Delta E}}$$

signal rate *background rate*



arXiv:1309.7093

Best energy window ΔE driven by

SENSITIVITY ESTIMATE

Counting experiment

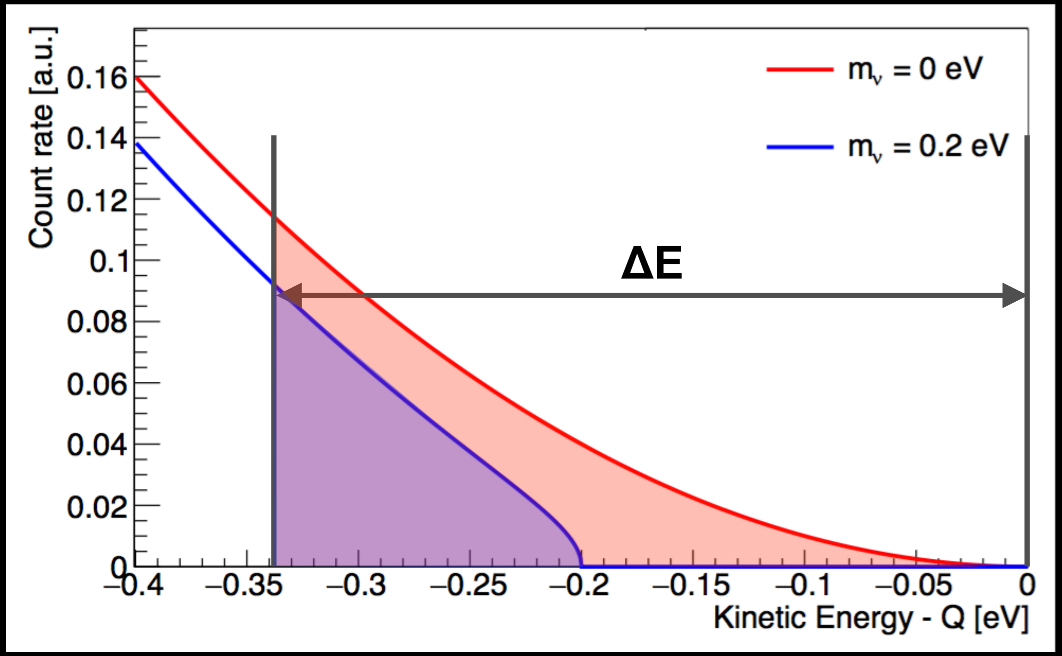
- over energy window ΔE

$$\sigma_{m_\nu^2} = \frac{2}{3R_S T\Delta E}\sqrt{R_S T\Delta E + \frac{R_B T}{\Delta E}}$$

signal rate background rate

Best energy window ΔE driven by

- signal to background ratio R_S/R_B



arXiv:1309.7093

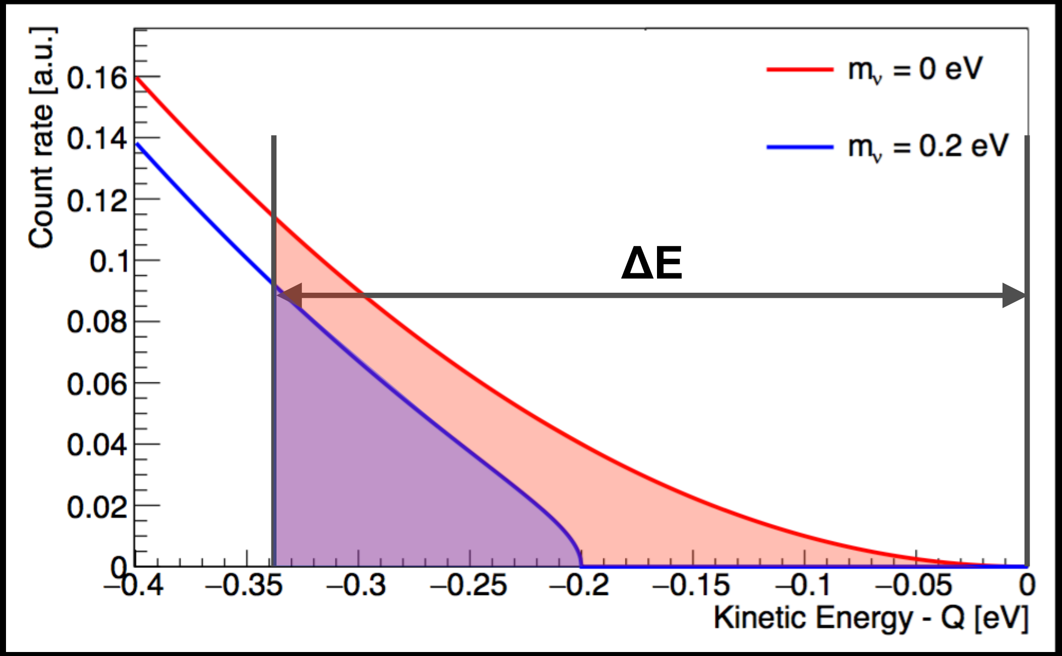
SENSITIVITY ESTIMATE

Counting experiment

- over energy window ΔE

$$\sigma_{m_\nu^2} = \frac{2}{3R_S T\Delta E}\sqrt{R_S T\Delta E + \frac{R_B T}{\Delta E}}$$

signal rate background rate



arXiv:1309.7093

Best energy window ΔE driven by

- signal to background ratio R_S/R_B
- limited resolution through

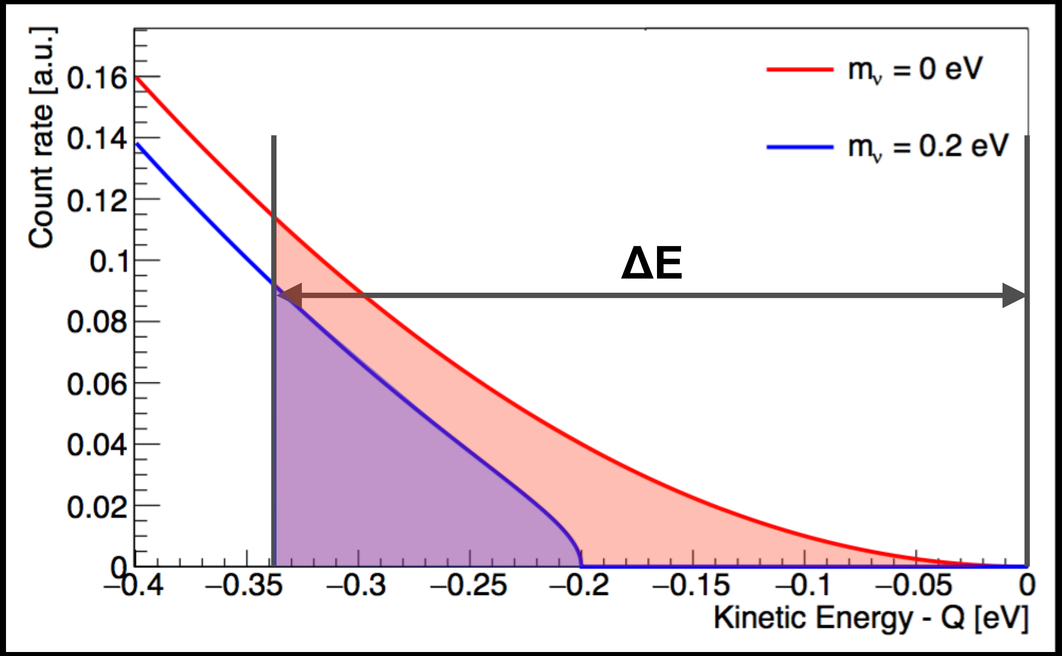
SENSITIVITY ESTIMATE

Counting experiment

- over energy window ΔE

$$\sigma_{m_\nu^2} = \frac{2}{3 R_S T \Delta E} \sqrt{R_S T \Delta E + \frac{R_B T}{\Delta E}}$$

signal rate   background rate



arXiv:1309.7093

Best energy window ΔE driven by

- signal to background ratio R_S/R_B
- limited resolution through
  - final-state broadening ΔE_{FSS}

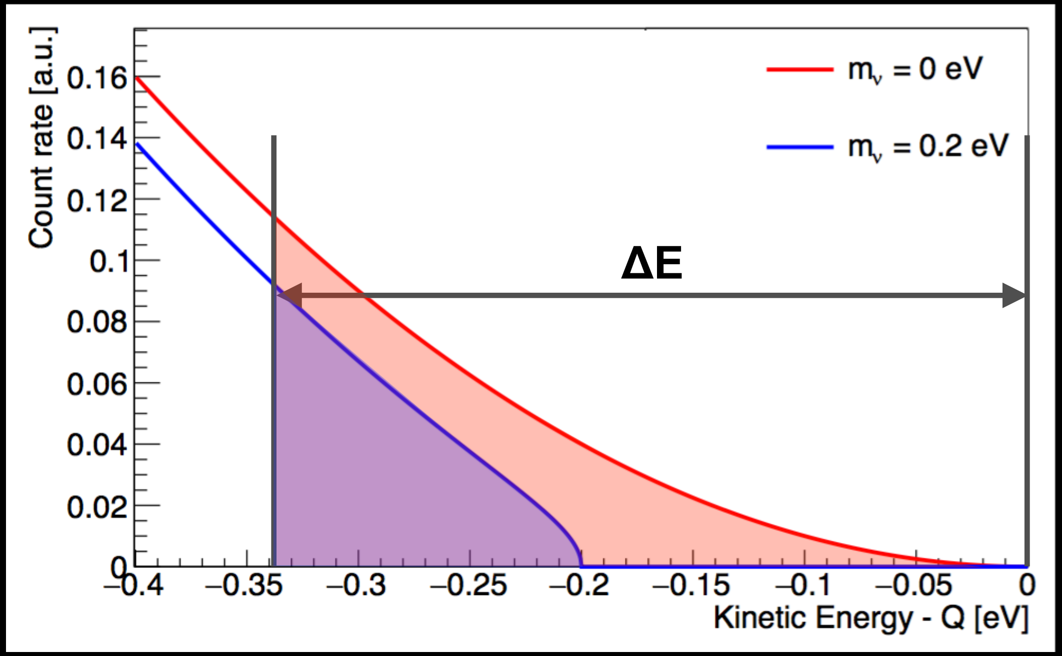
SENSITIVITY ESTIMATE

Counting experiment

- over energy window ΔE

$$\sigma_{m_\nu^2} = \frac{2}{3R_S T\Delta E}\sqrt{R_S T\Delta E + \frac{R_B T}{\Delta E}}$$

signal rate background rate



arXiv:1309.7093

Best energy window ΔE driven by

- signal to background ratio R_S/R_B
- limited resolution through
  - final-state broadening ΔE_{FSS}
  - broadening from e⁻ - scattering

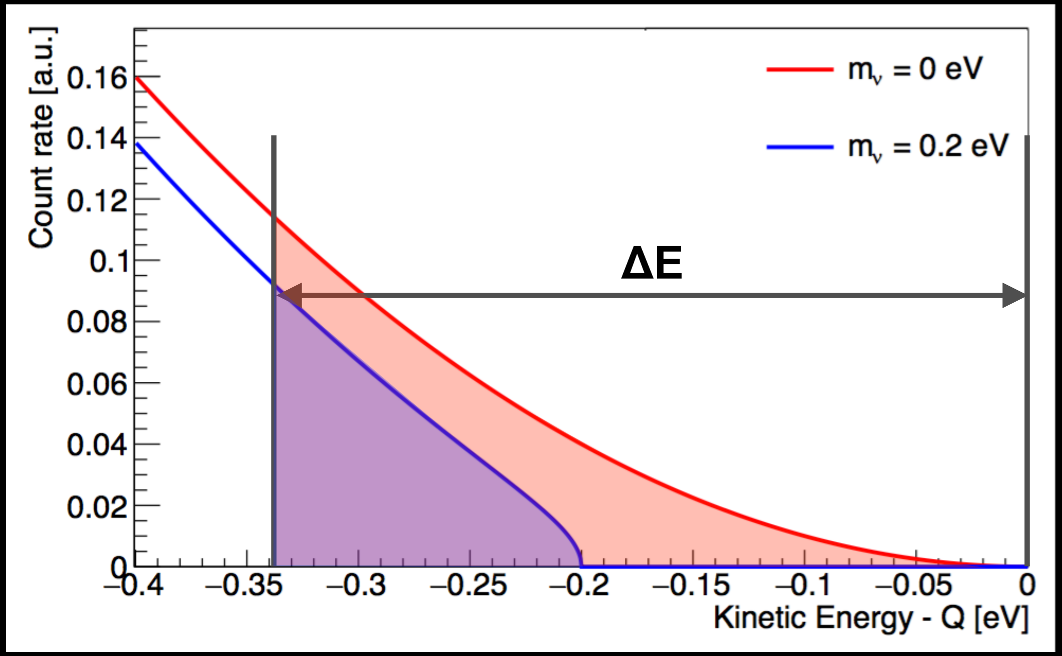
SENSITIVITY ESTIMATE

Counting experiment

- over energy window ΔE

$$\sigma_{m_\nu^2} = \frac{2}{3R_S T\Delta E}\sqrt{R_S T \Delta E + \frac{R_B T}{\Delta E}}$$

signal rate   background rate

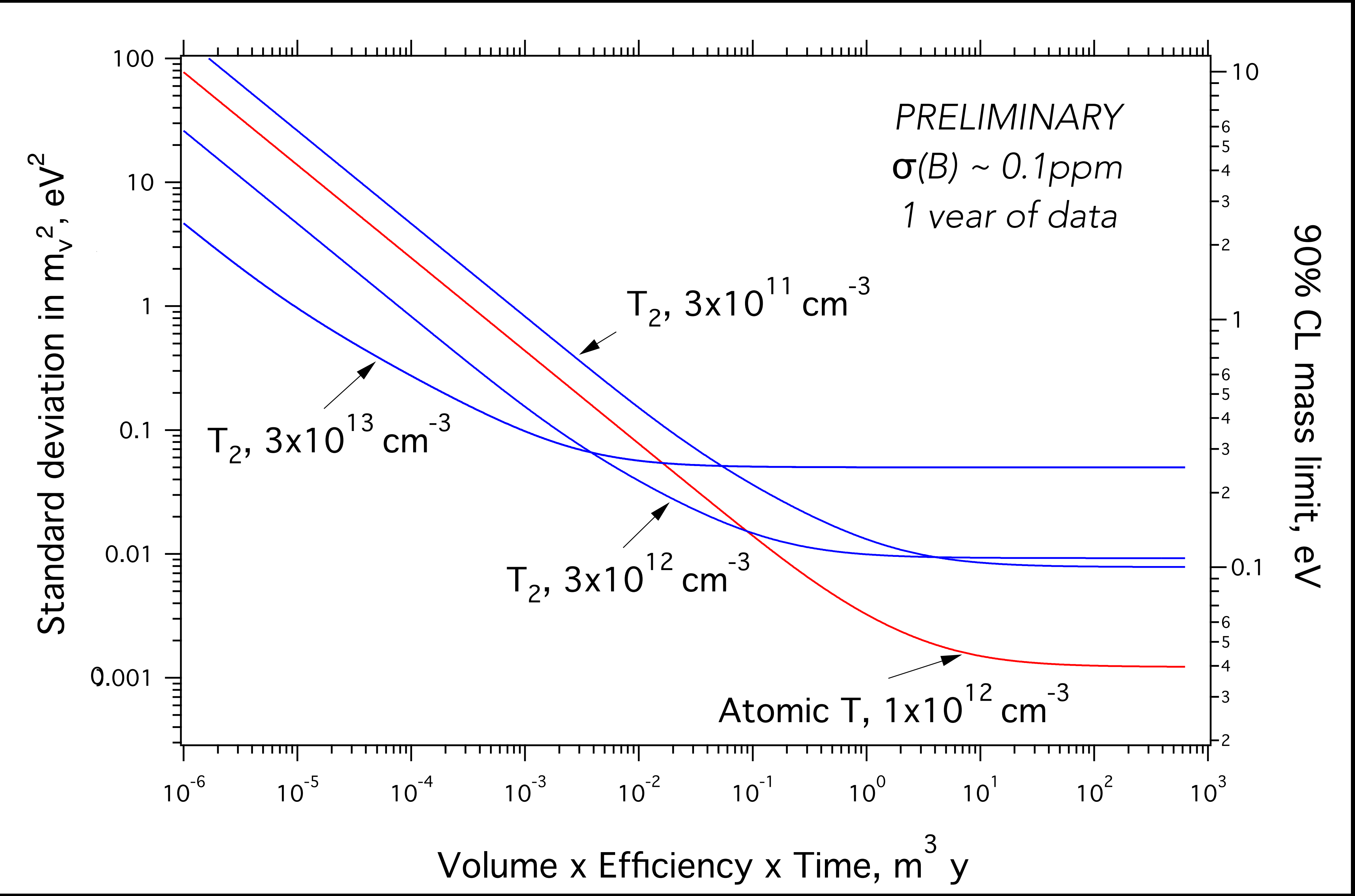


arXiv:1309.7093

Best energy window ΔE driven by

- signal to background ratio R_S/R_B
- limited resolution through
  - final-state broadening ΔE_{FSS}
  - broadening from e^- - scattering
  - broadening from B-field homegenity $\sigma(B)$

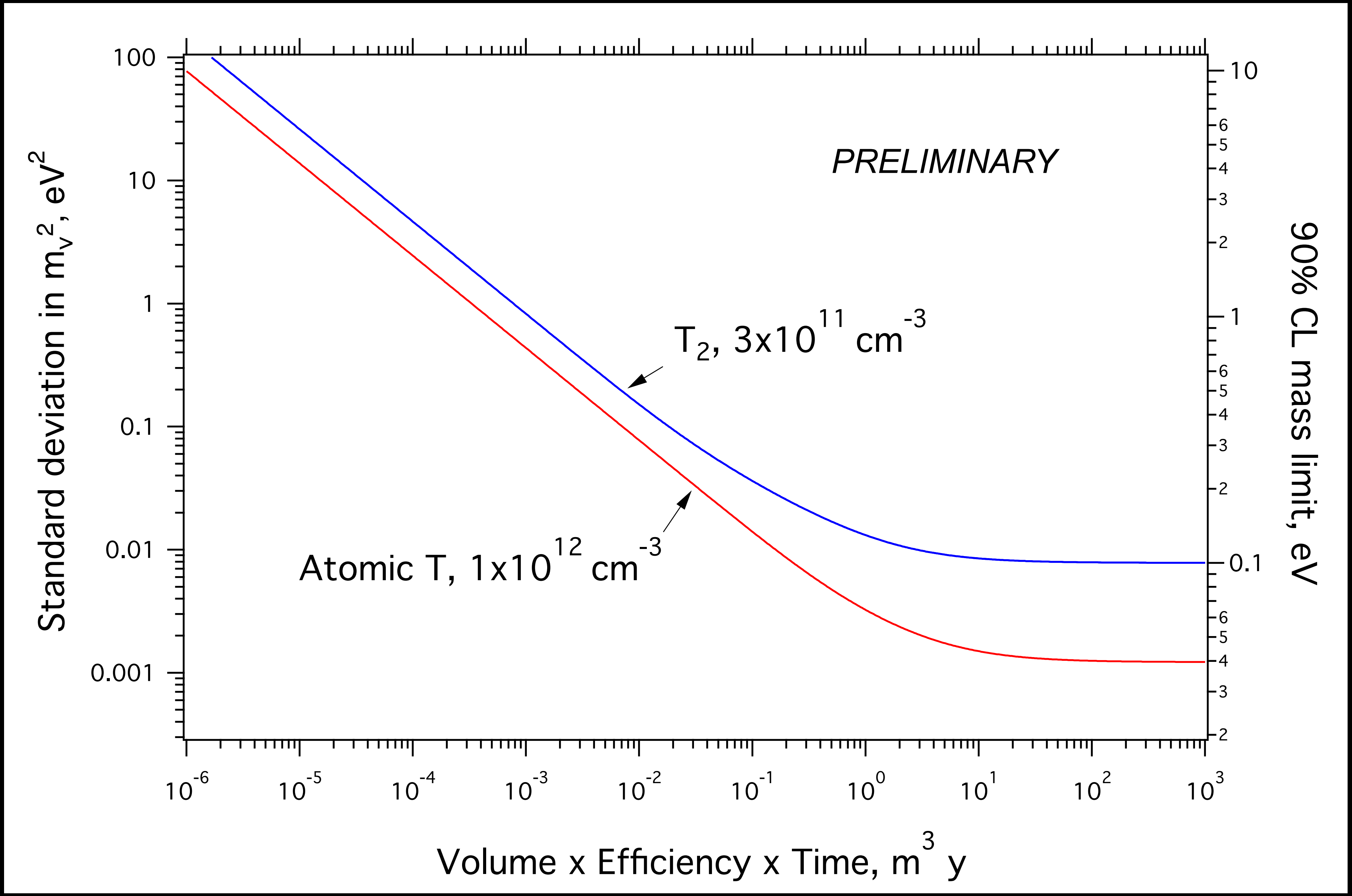
POTENTIAL ν-MASS REACH



Sensitivity limited by

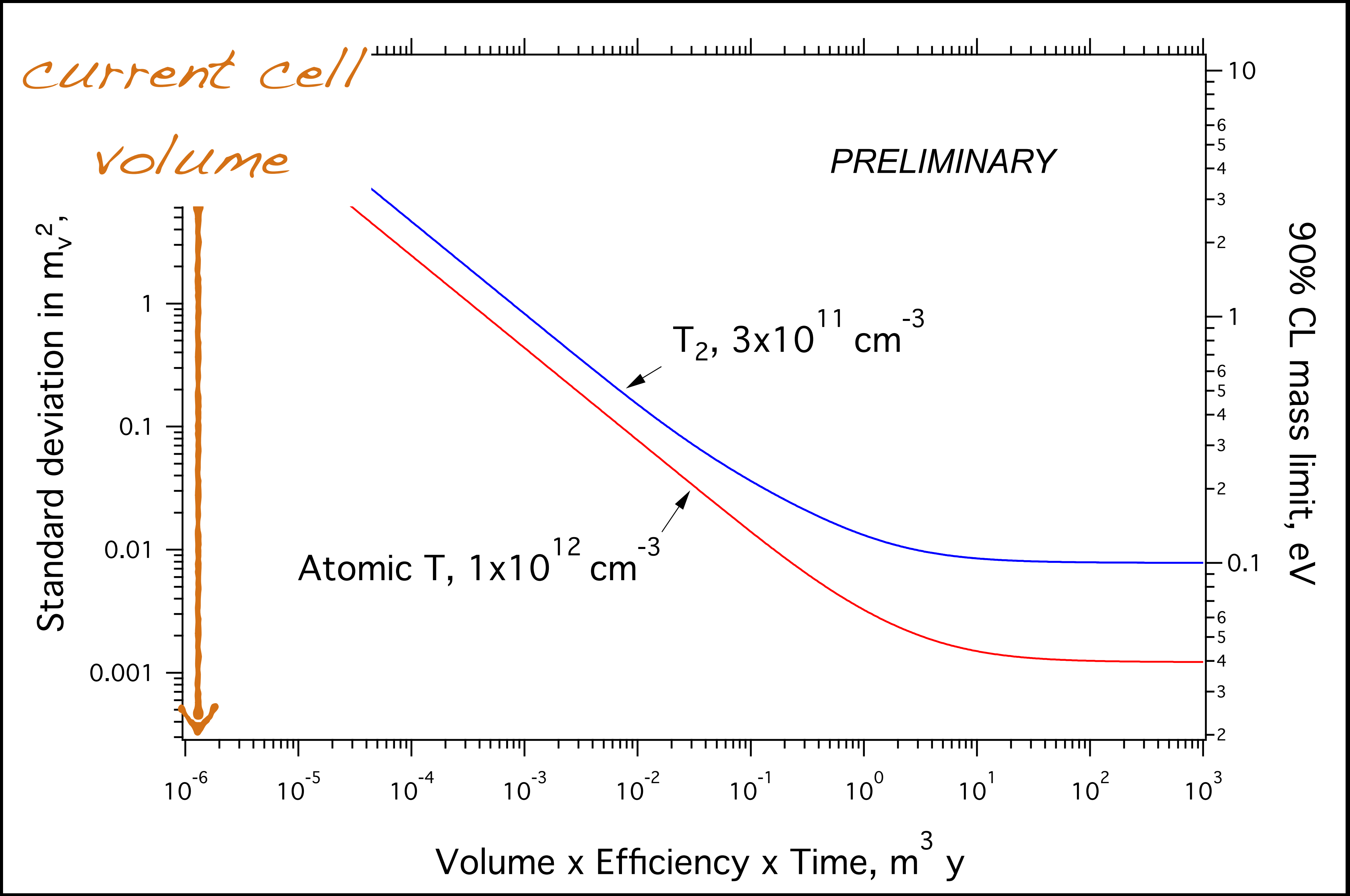
- tritium gas density
- field uniformity
- molecular effects

POTENTIAL ν-MASS REACH



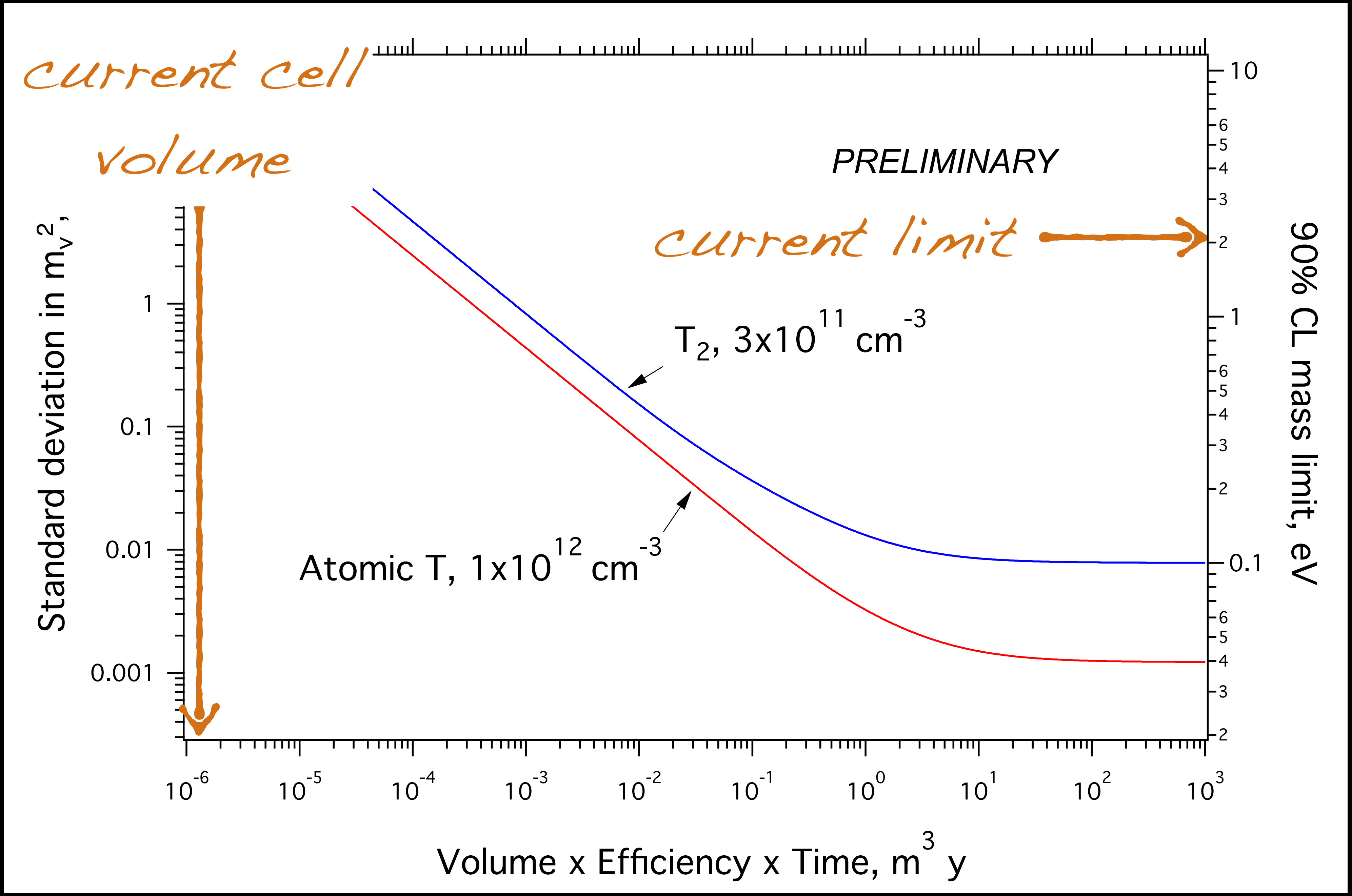
Inverted hierarchy lower bound in reach with **large** volume and **atomic** tritium!

POTENTIAL ν-MASS REACH



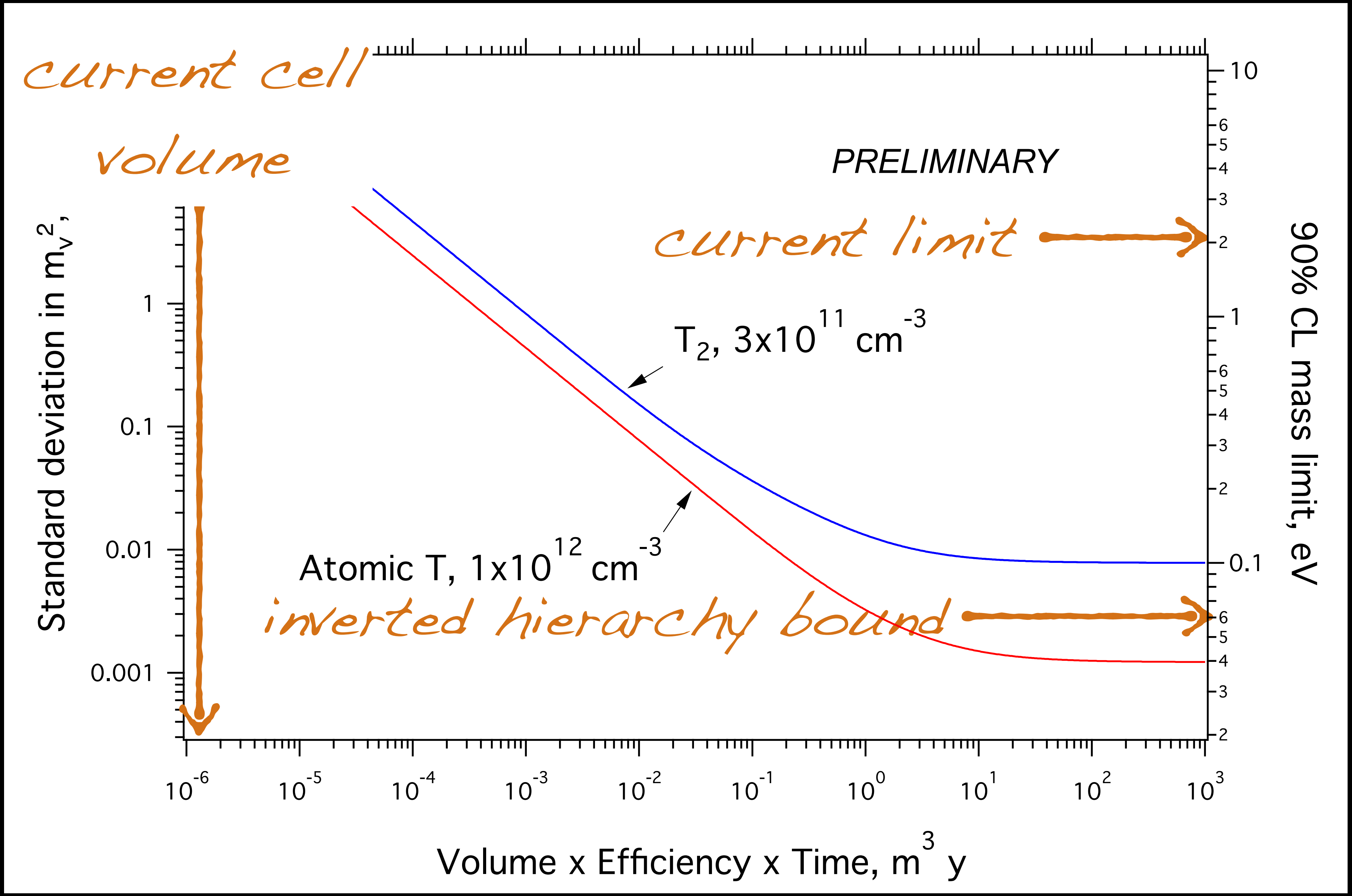
Inverted hierarchy lower bound in reach with **large** volume and **atomic** tritium!

POTENTIAL ν-MASS REACH



Inverted hierarchy lower bound in reach with **large** volume and **atomic** tritium!

POTENTIAL ν-MASS REACH



Inverted hierarchy lower bound in reach with **large** volume and **atomic** tritium!

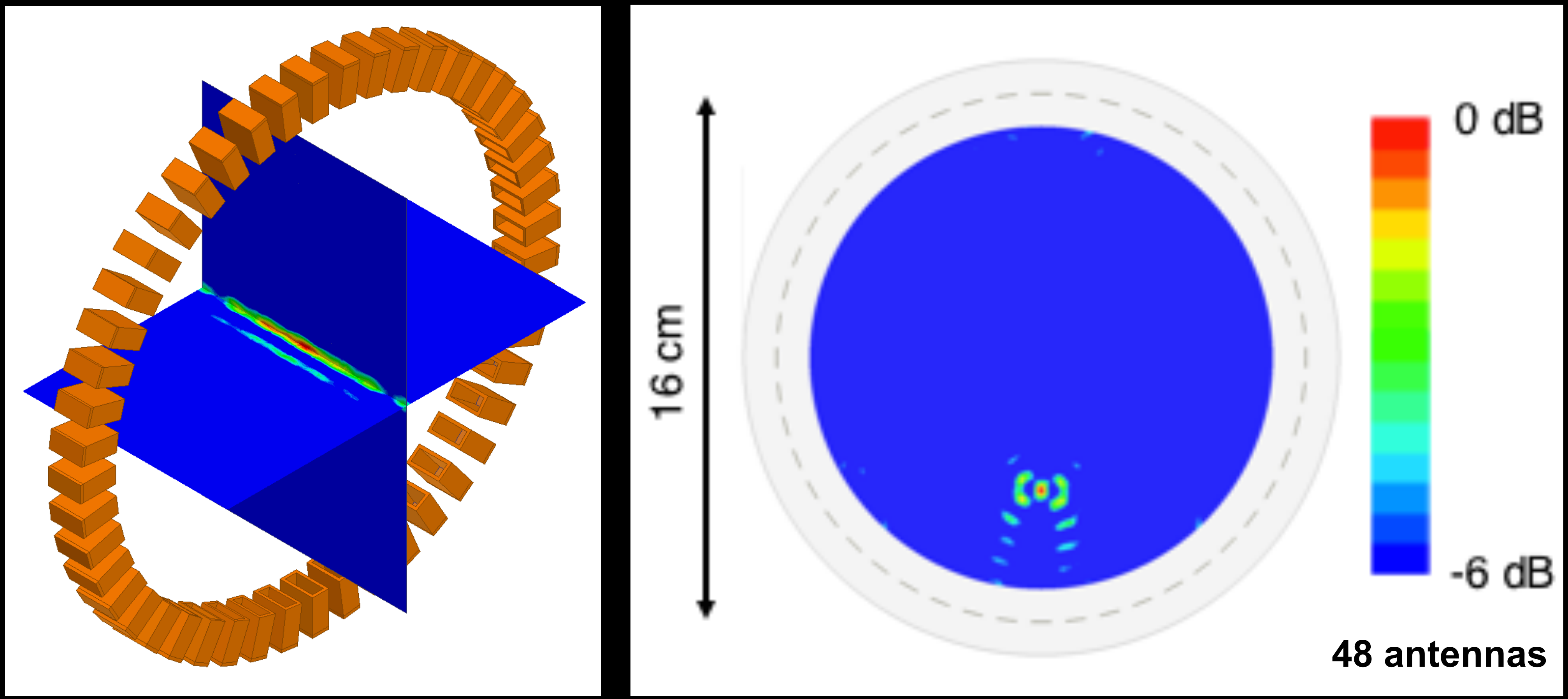
A PHASED APPROACH

Phase	Timeline	Source	R&D Milestones	Science Goals
I	2010-2016	^{83m}Kr	• single electron detection • proof of concept	• conversion electron spectrum of 83m... COMPLETED
II	2015-2018	now: ^{83m}Kr next: T_2	• Kurie plot • systematic studies	• Final-state spectrum • $^3H-^3He$ mass difference RUNNING
III	2016-2022	T_2	• 300cm^3 active volume • B-Field homogeneity	• $m_\nu < 2$ eV/c^2 THIS TALK
IV	2017...	T	• ϕ(m^3) active volume • atomic tritium source	• $m_\nu < 40$ meV/c^2 • measure m_ν or determine normal hierarchy

PHASE III - LARGE VOLUME

- Use existing larger bore ~1T magnet
  Ø = 90cm, L = 1.4m
- Trap-, cryo- and **antenna** design started

PHASE III - ANTENNA DESIGN



Example antenna configuration and vertex resolution being modeled

- Volumetric readout
  → Study phased array antenna configurations

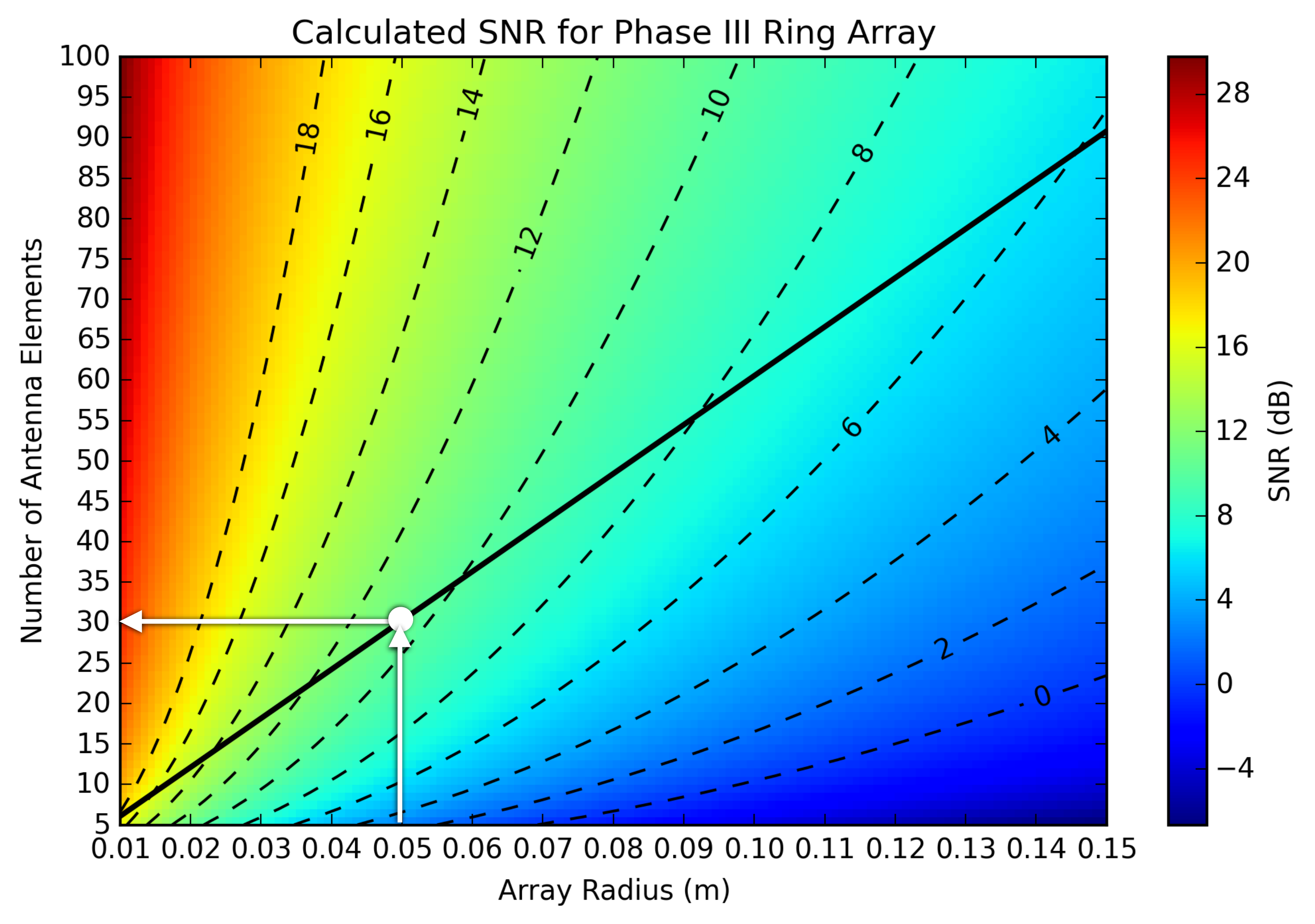
PHASED ARRAY OPTIMIZATION

Single array with

- equidistant centrally-located source
- 10 kHz receiver bandwidth
- 0.9λ azimuthal spacing at 26 GHz

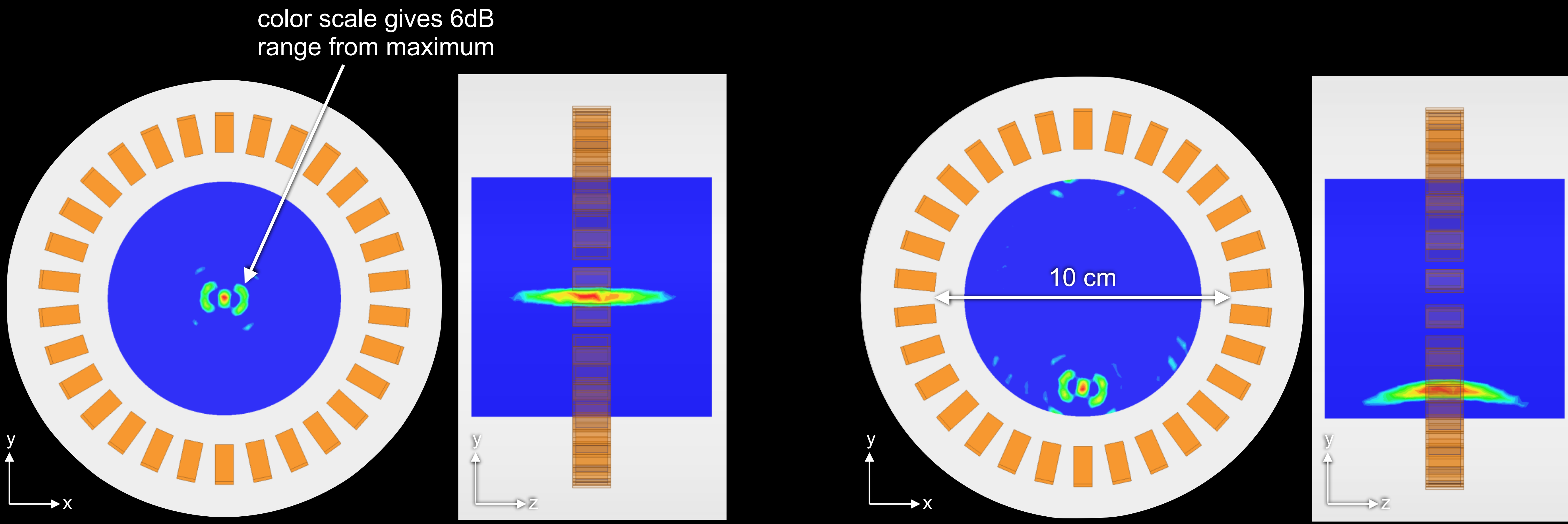
→ maximize SNR for given radius

Quantity	Symbol	Value	Unit
Receiver processing bin bandwidth	B	10000	Hz
Electron beam directivity	G_T	1.4	dBi
Receive antenna gain	G_R	7.5	dBi
Antenna noise temperature	T_A	30	K
Effective receiver noise temperature	T_E	20	K



SPATIAL RESOLUTION

Elements phased to place focal point in cross-section



→ main lobe well discernible
(other sidelobe features exist below -6 dB level)

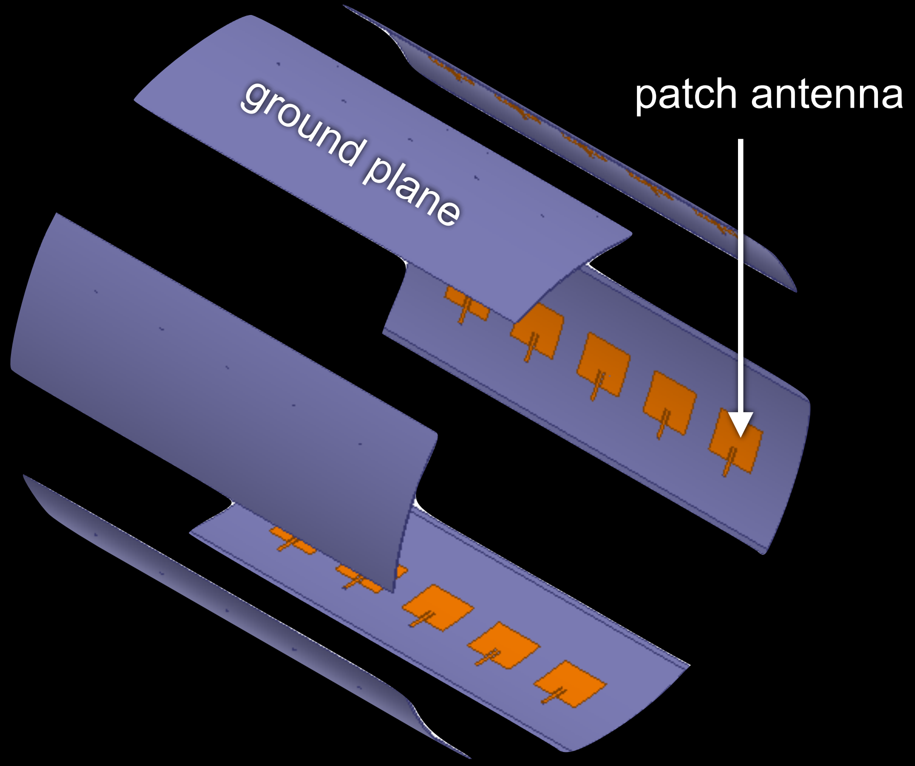
→ ~200cm^3 sensitive volume per ring (multi-ring design?)

ANTENNA CONFIGURATION

ANTENNA CONFIGURATION

Patch antenna array

- Near field focused with power-combining feed network
- maximizes available volume



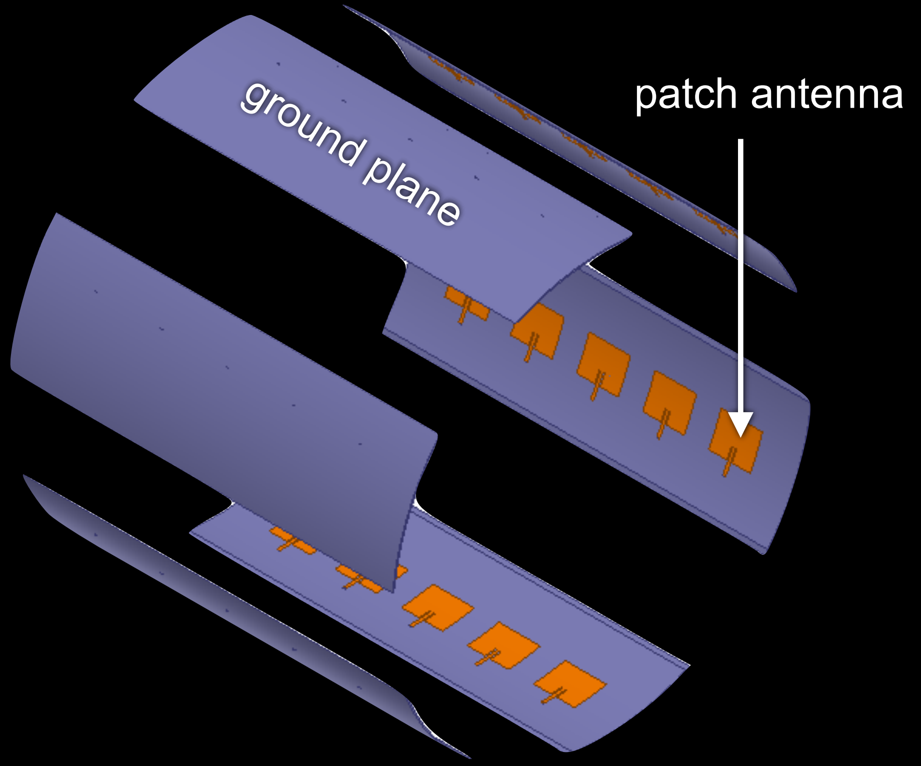
ANTENNA CONFIGURATION

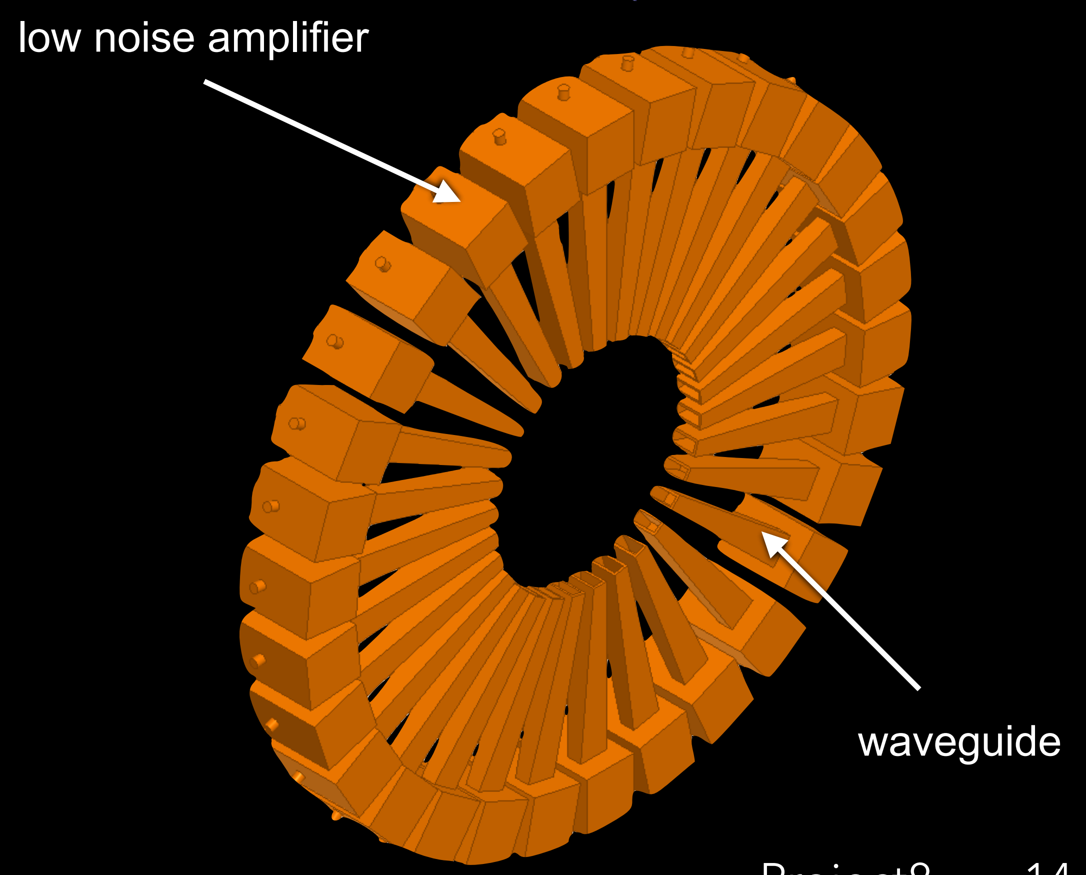
Patch antenna array

- Near field focused with power-combining feed network
- maximizes available volume

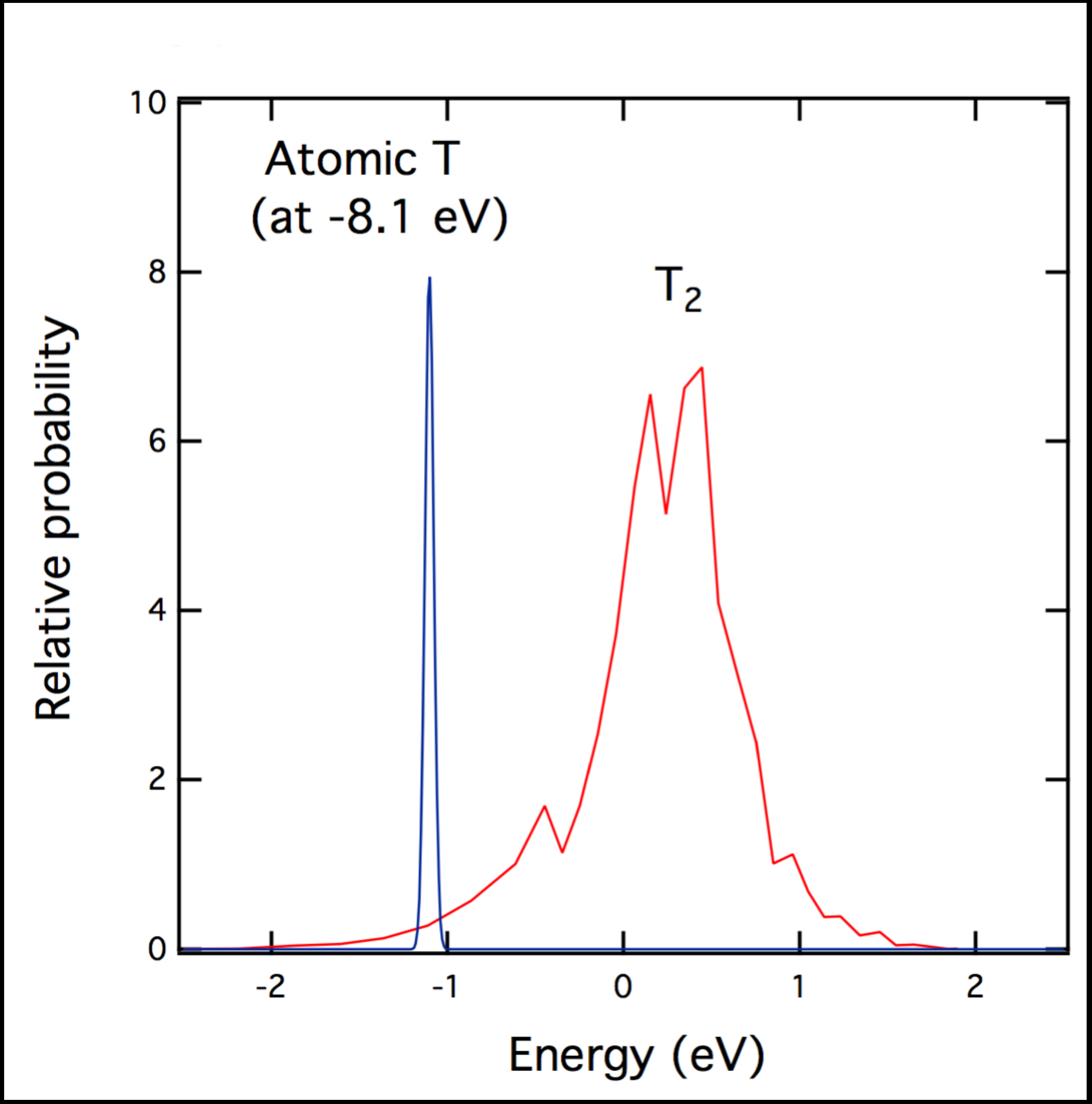
Waveguide antenna array

- No backing groundplane
- Larger bandwidth
- Mates directly with LNA input
- Low-loss waveguide feedline





MOLECULAR TRITIUM LIMITATIONS



Plot: E. Machado Data: Saenz (2000)

Molecular excitations in daughter molecule

- blur tritium endpoint

→ fundamental limit to measurement of ν-mass

Need atomic tritium for ultimate experiment!

MAGNETIC GUIDING OF NEUTRAL ATOMS

H,D and T have unpaired e^-

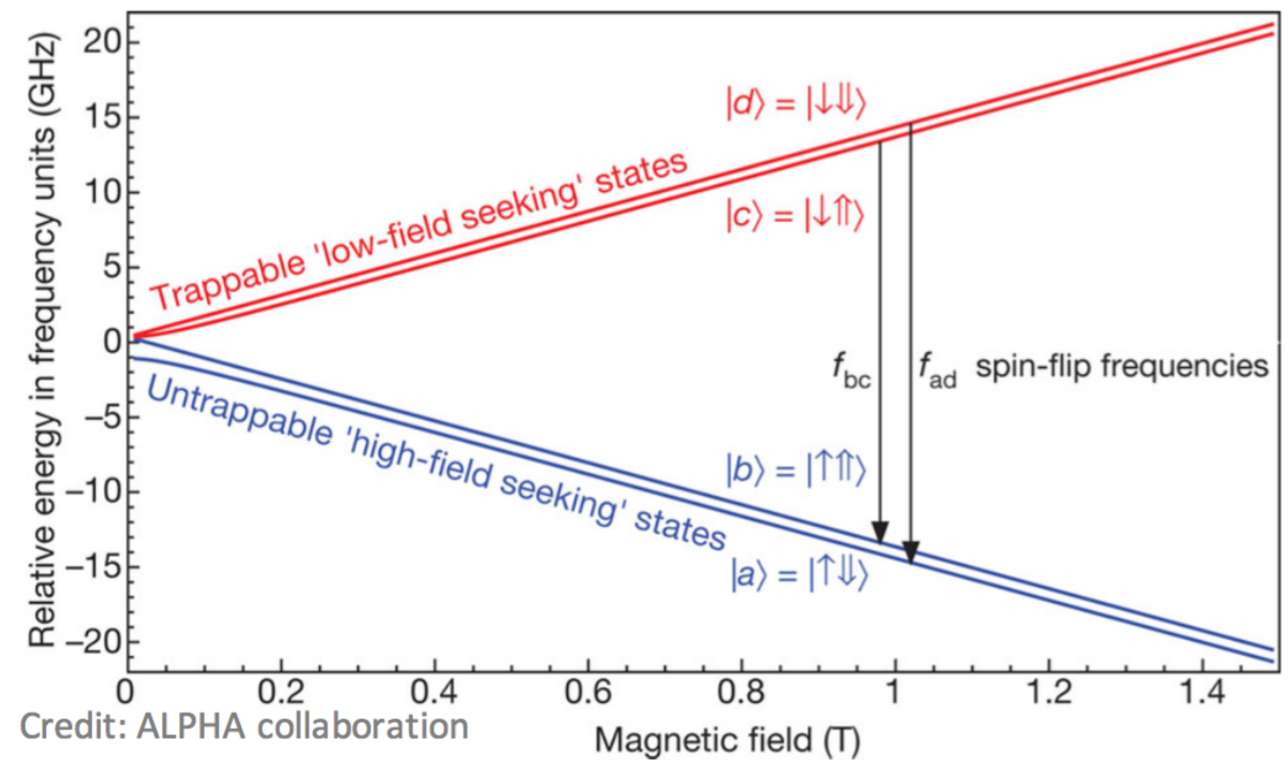
→ non-zero μ

→ tend to (anti-)align with B-field if change is adiabatic

Potential energy

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

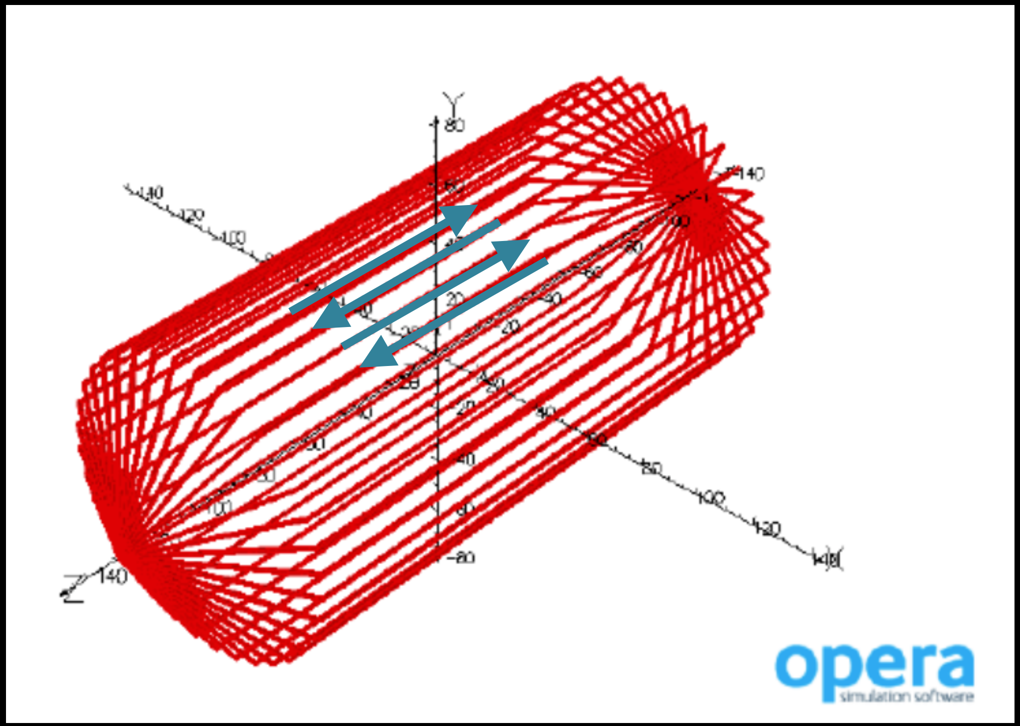
→ follow field minimum

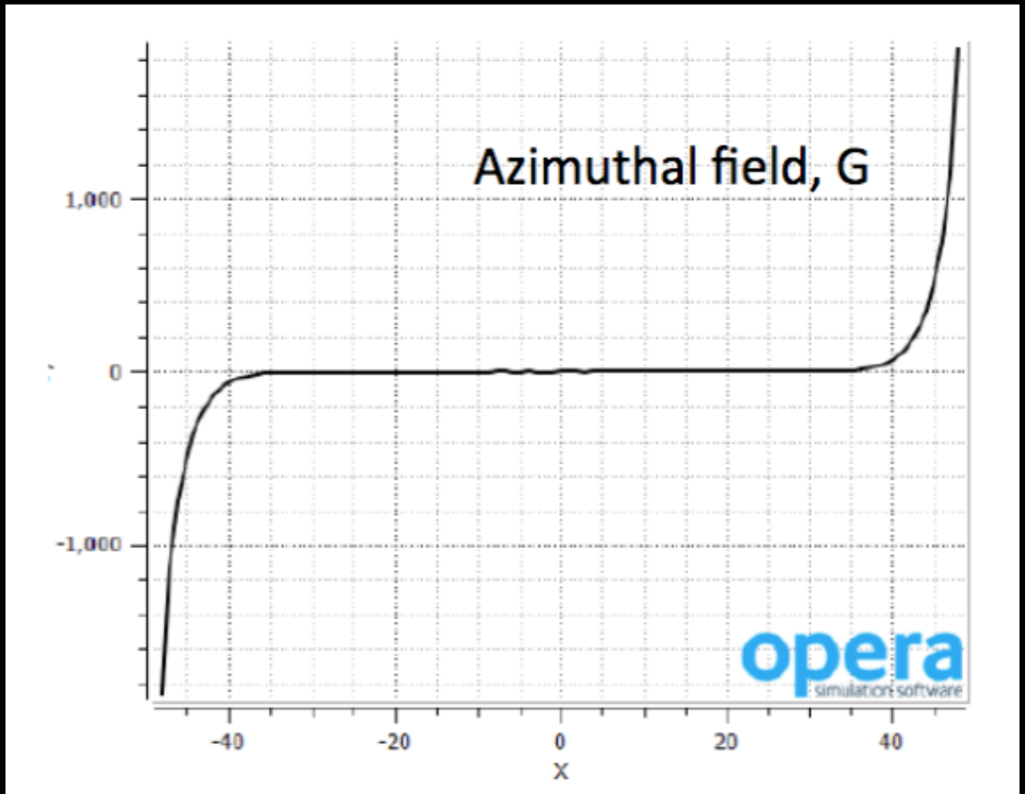


Credit: ALPHA collaboration

Can trap neutral atoms in radial field configurations

PHASE IV: ATOM TRAPPING





Alexi Radovinsky, MIT Magnet Lab

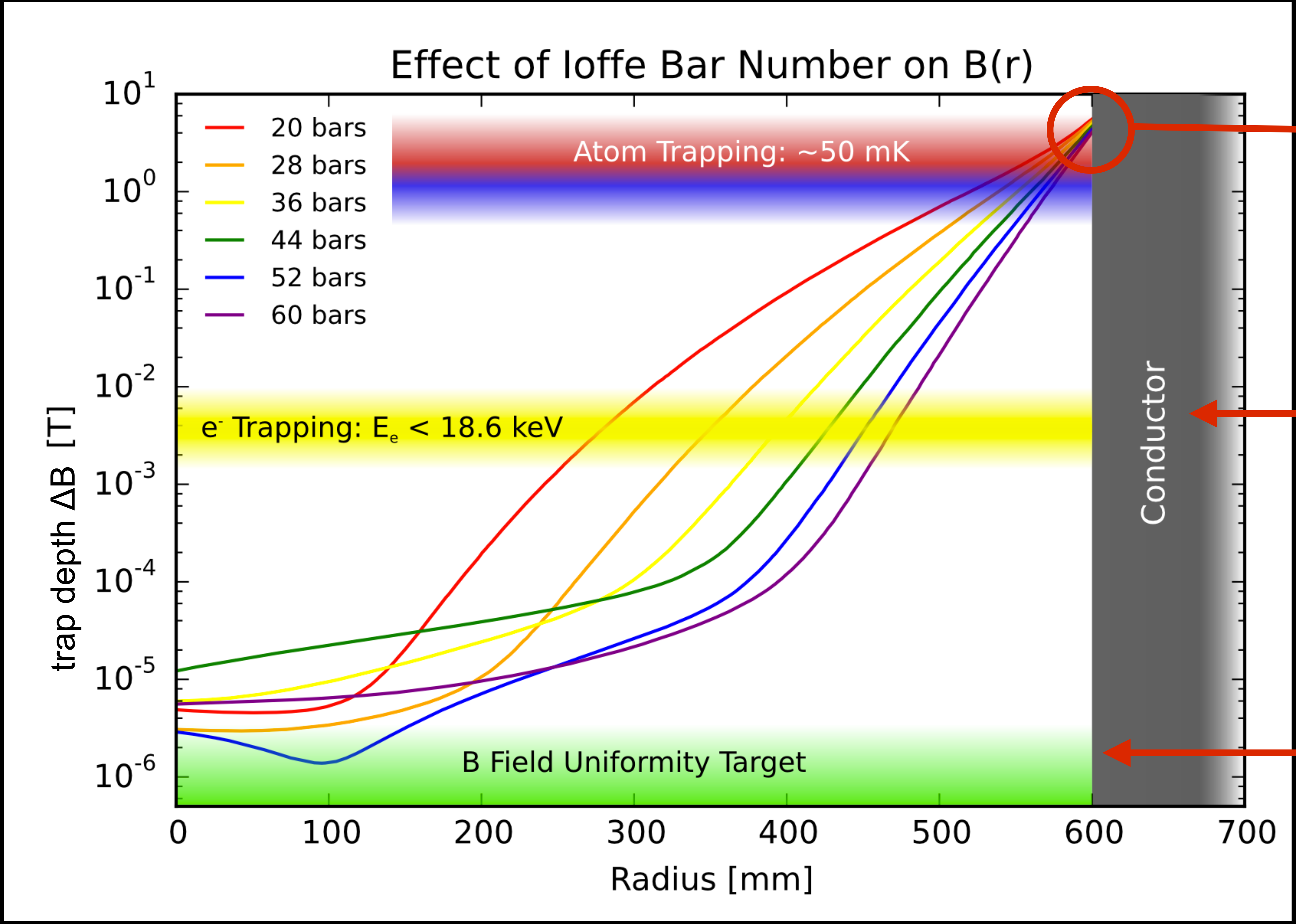
Studying Ioffe-Pritchard trap

- atom magnetic moment
  → T_{max} = 50meV @ ΔB=2T
  for $\varepsilon_{loss} = 10^{-10}$ (thermal)
- similar to UCN and anti-hydrogen traps (ALPHA)

Challenges

- cooling to sub-Kelvin level
- keep high T/T_2 purity
- field uniformity

PHASE IV: TRAP UNIFORMITY



Conductor + structure size

↕

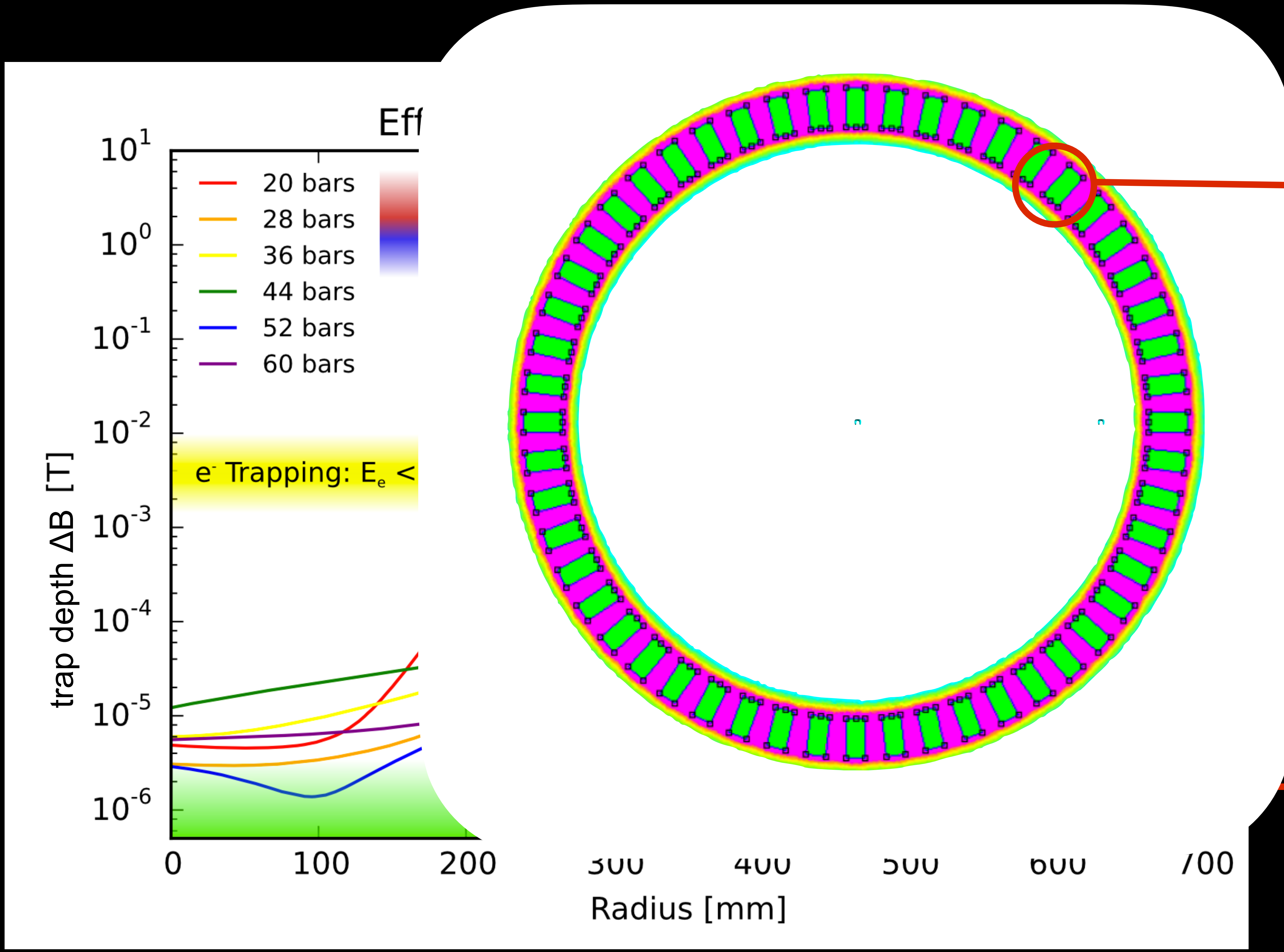
effective volume

↕

target uniformity level

A. Lindman, PRISMA/JGU Mainz

PHASE IV: TRAP UNIFORMITY



Conductor + structure size

↕

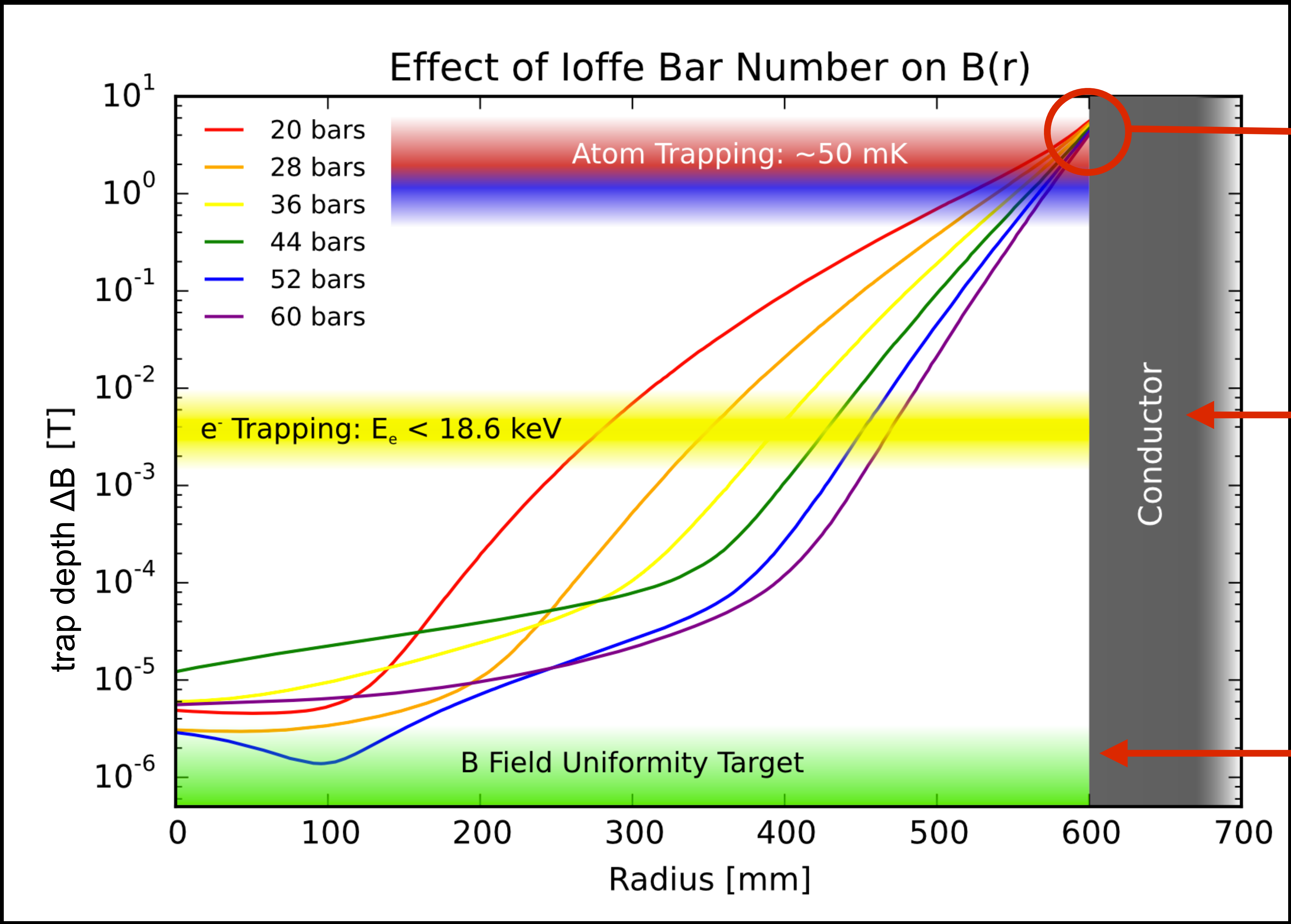
effective volume

↕

target uniformity level

A. Lindman, PRISMA/JGU Mainz

PHASE IV: TRAP UNIFORMITY



Conductor + structure size

↕

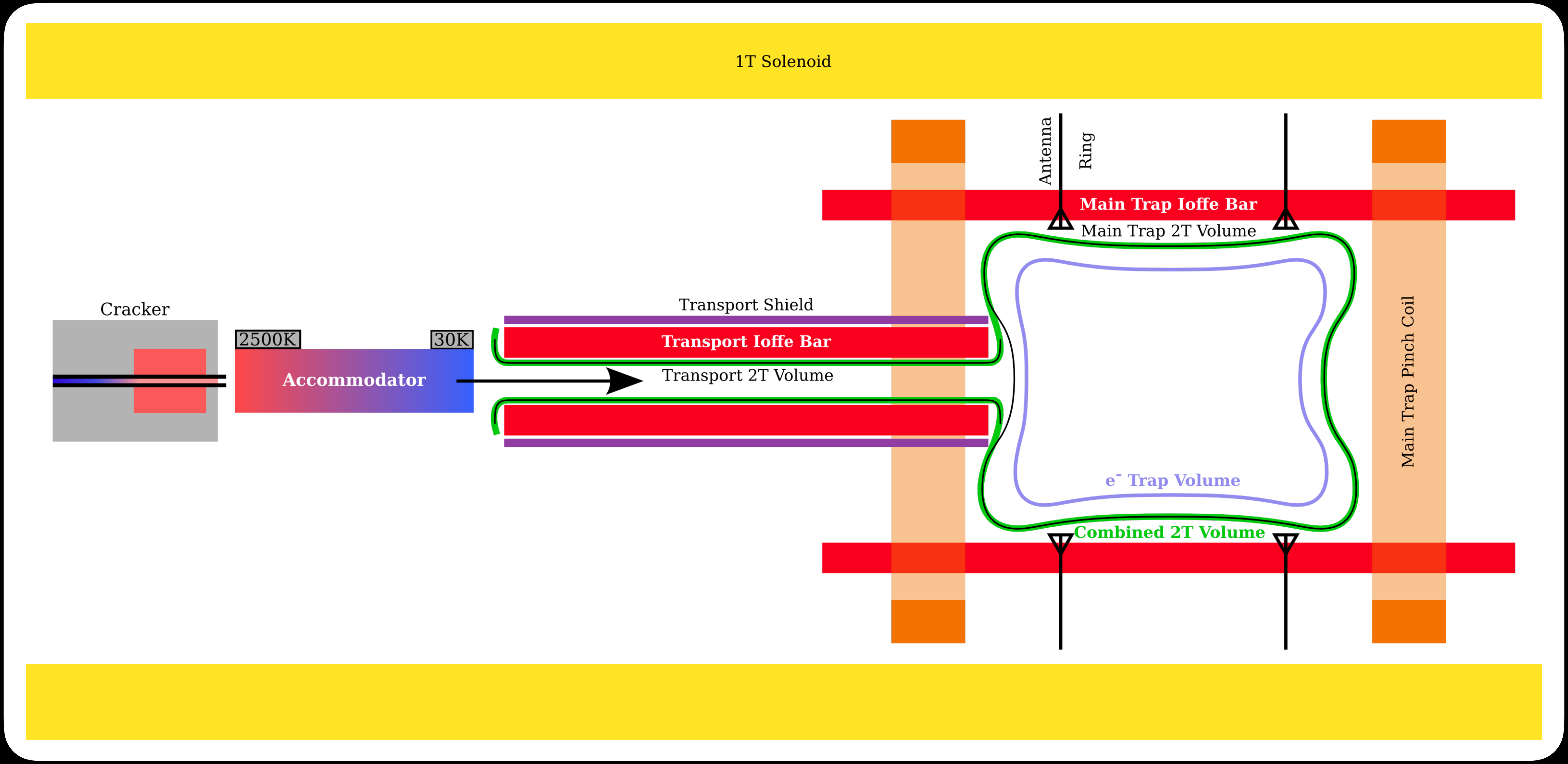
effective volume

↕

target uniformity level

A. Lindman, PRISMA/JGU Mainz

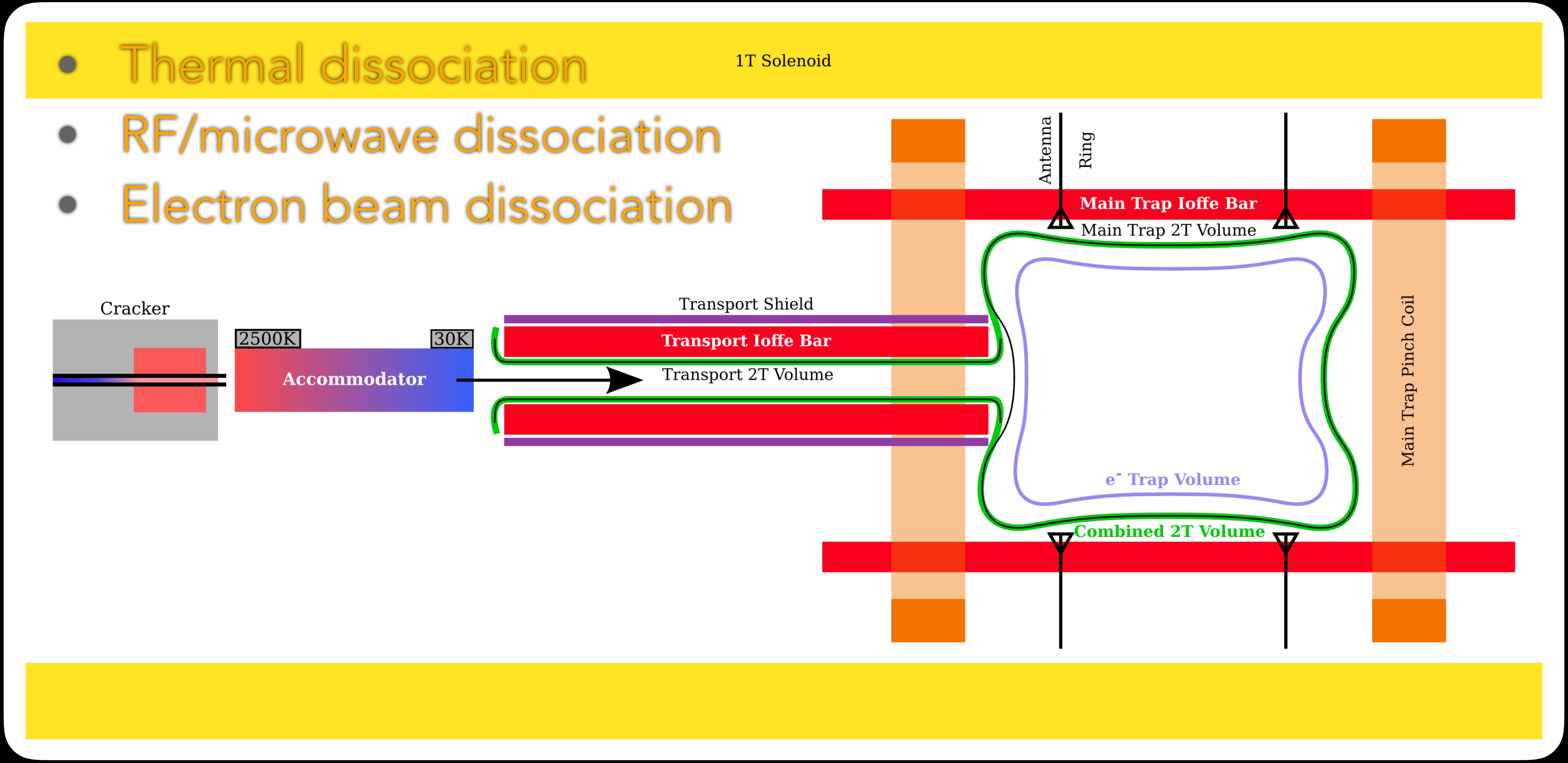
PHASE IV: DESIGN IDEAS



PHASE IV: DESIGN IDEAS

Source:

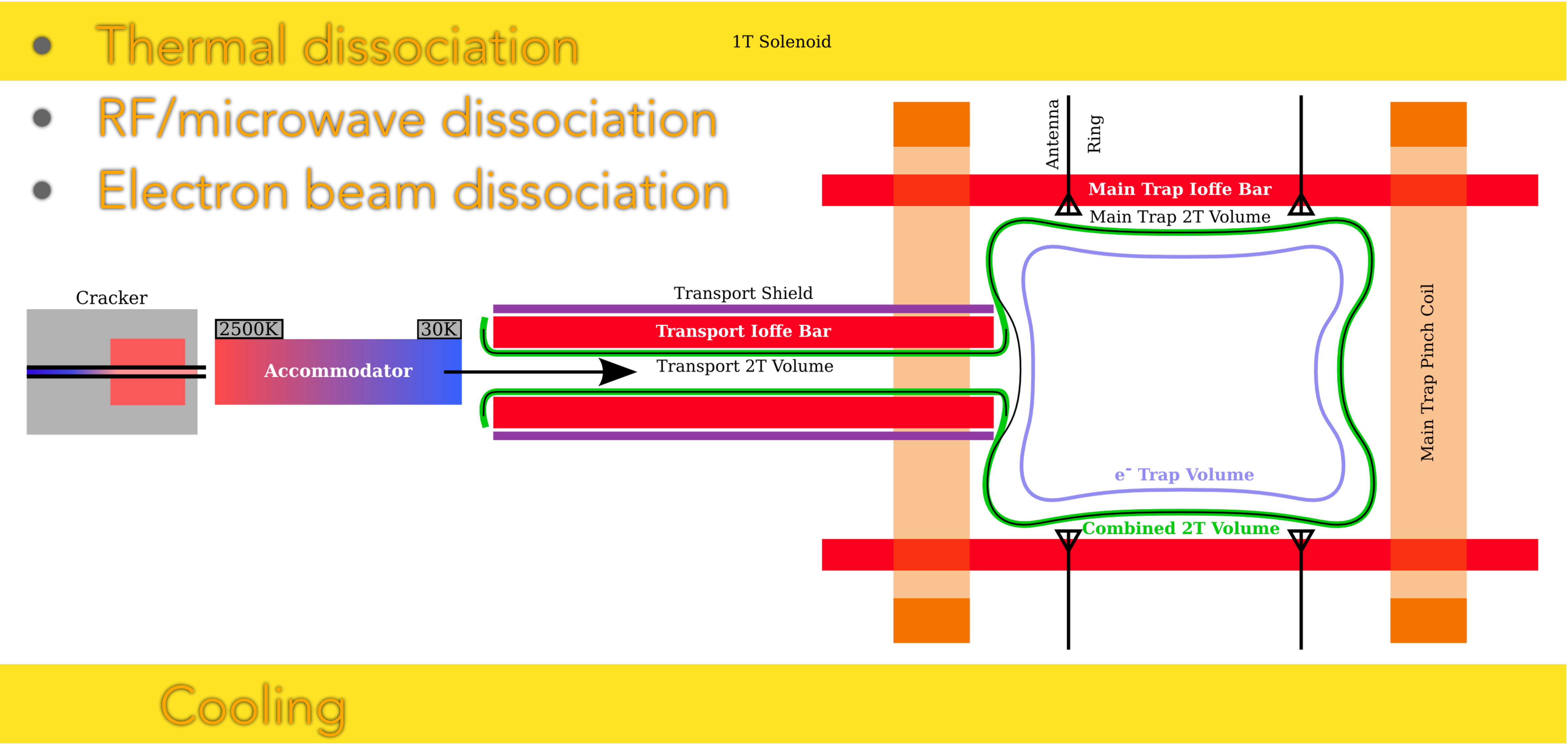
- Thermal dissociation
- RF/microwave dissociation
- Electron beam dissociation



PHASE IV: DESIGN IDEAS

Source:

- Thermal dissociation
- RF/microwave dissociation
- Electron beam dissociation



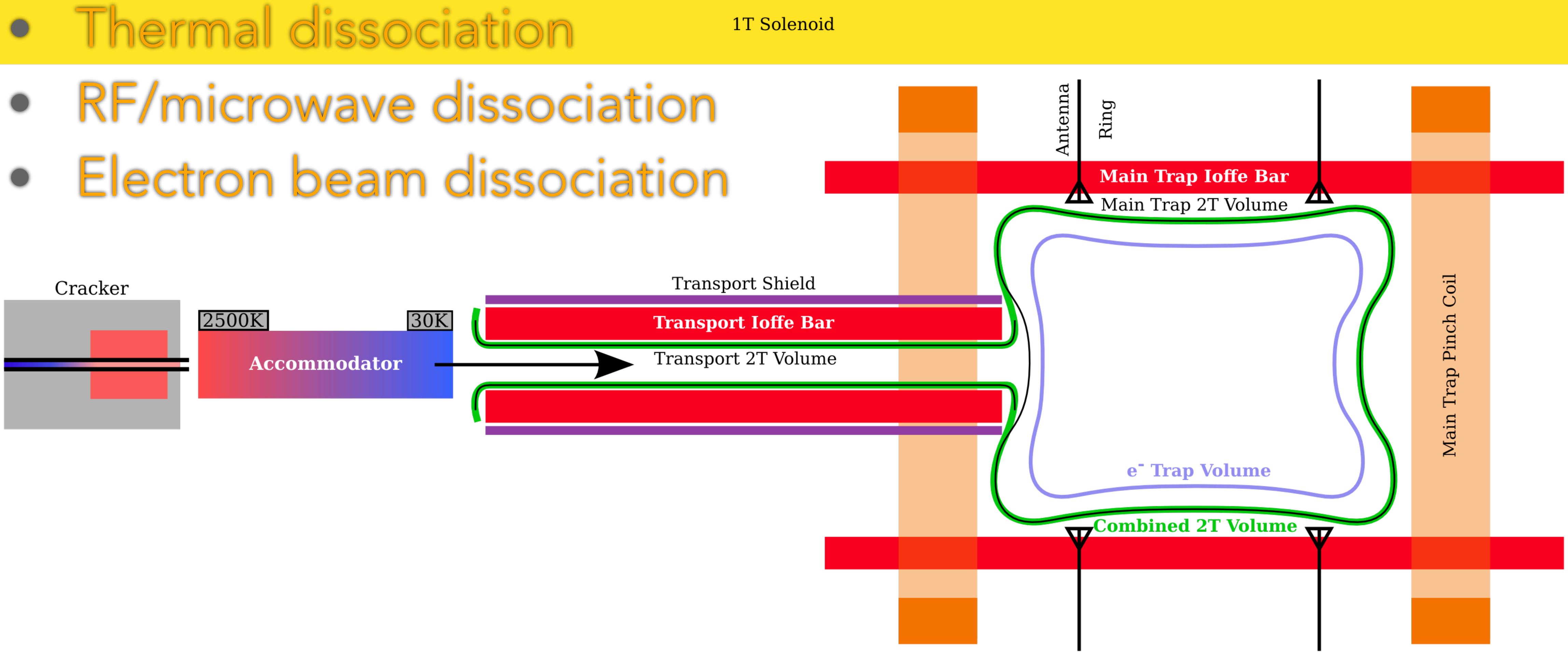
Cooling

- Accommodators
- Velocity selector
- Coilgun

PHASE IV: DESIGN IDEAS

Source:

- Thermal dissociation
- RF/microwave dissociation
- Electron beam dissociation



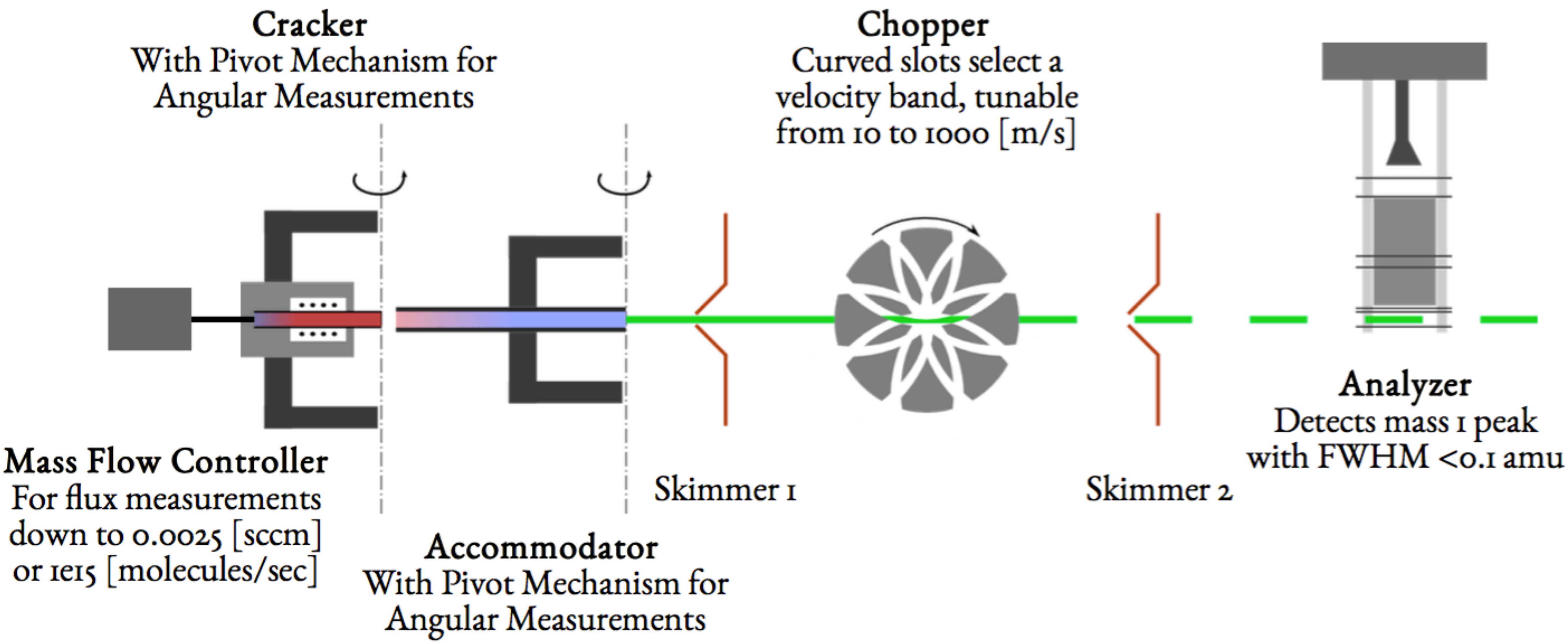
Cooling

- Accommodators
- Velocity selector
- Coilgun

Injection

- Spin-flip cooling
- Cornucopia loading
- Side-coupled injector

THERMAL SOURCE TEST SETUP



Major goal is to determine maximum flow rate, efficiency, temperature and emission profile

THERMAL SOURCE TEST SETUP

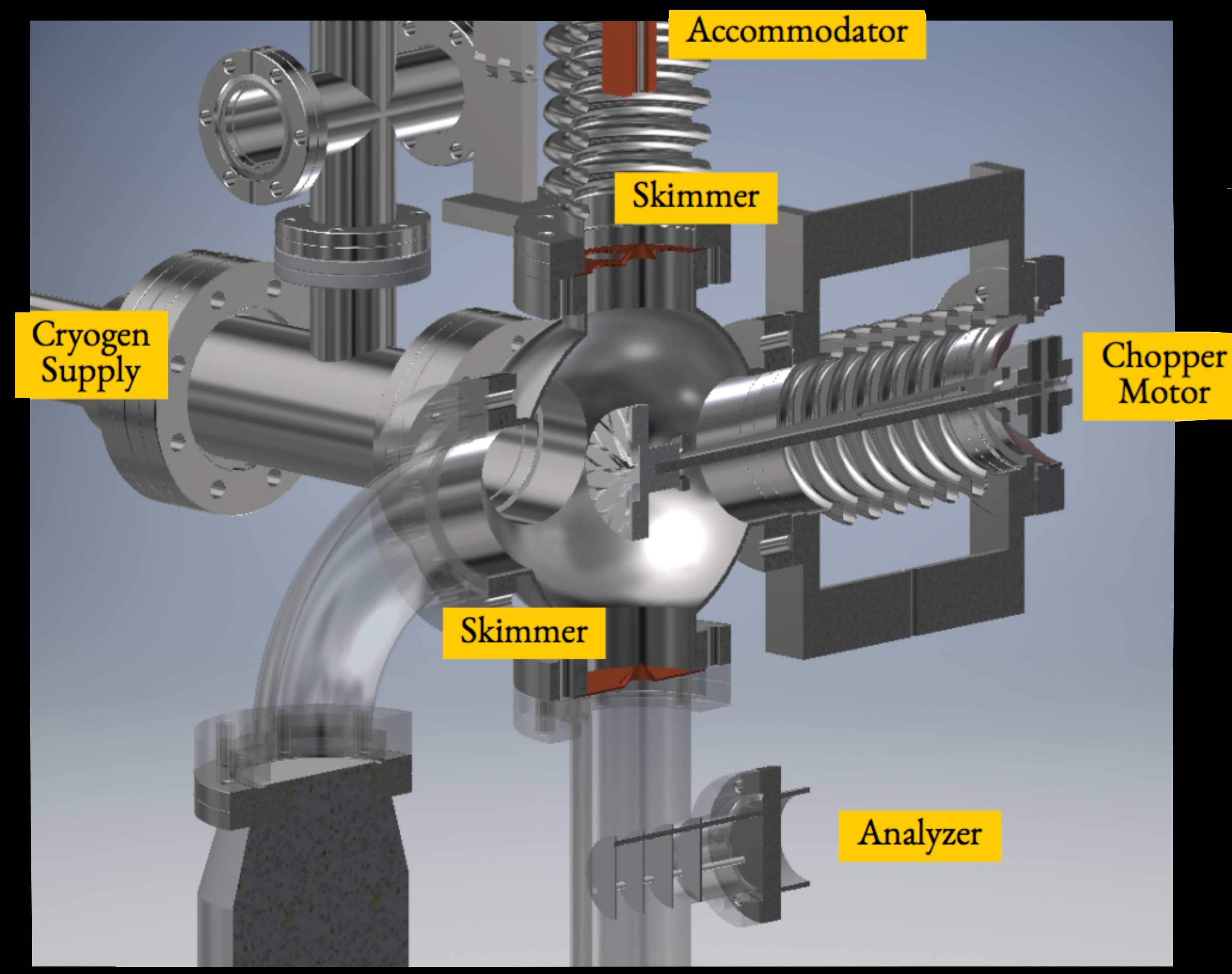
Commercial source

- Flux 10^{17} atoms/sec
- 99% dissociation efficiency

→ used for atomic beam eptiaxy

Challenge

- verify performance
- accommodation to 30K?



A. Lindman, PRISMA/JGU Mainz

RF SOURCE TEST SETUP

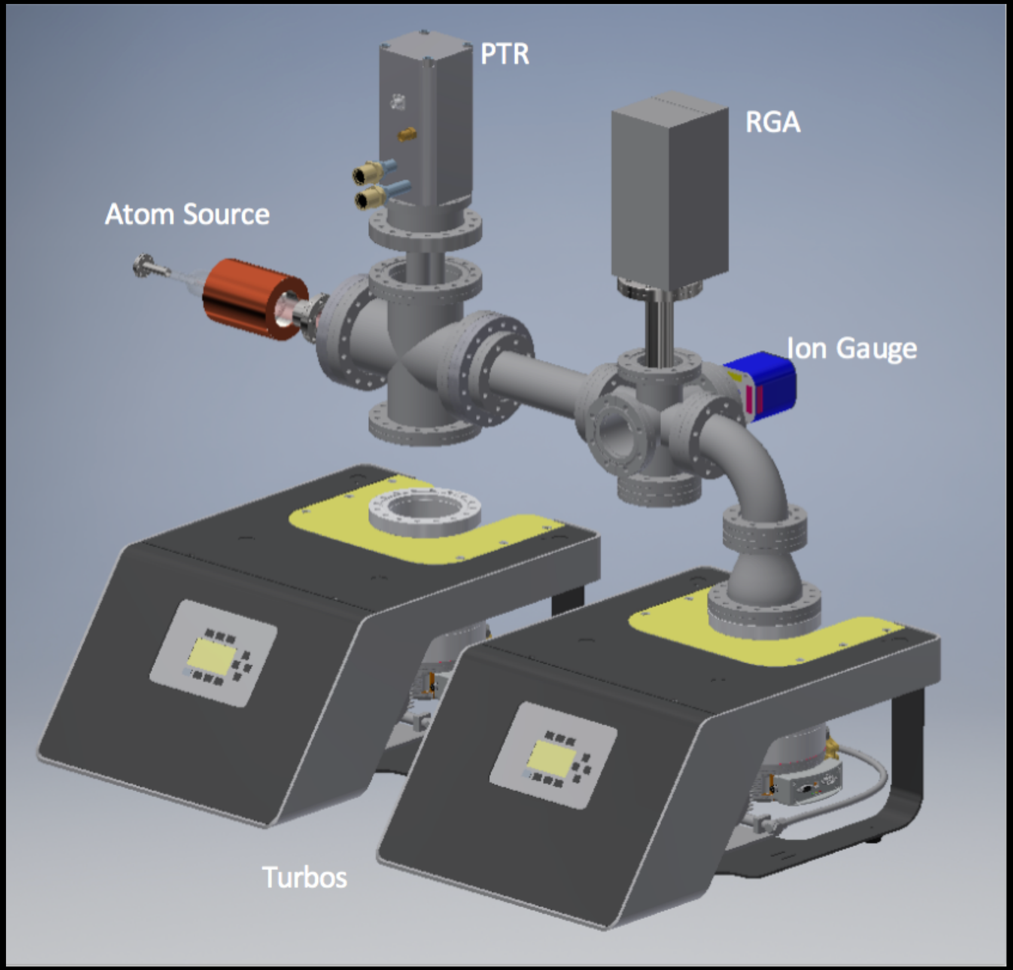
Custom build

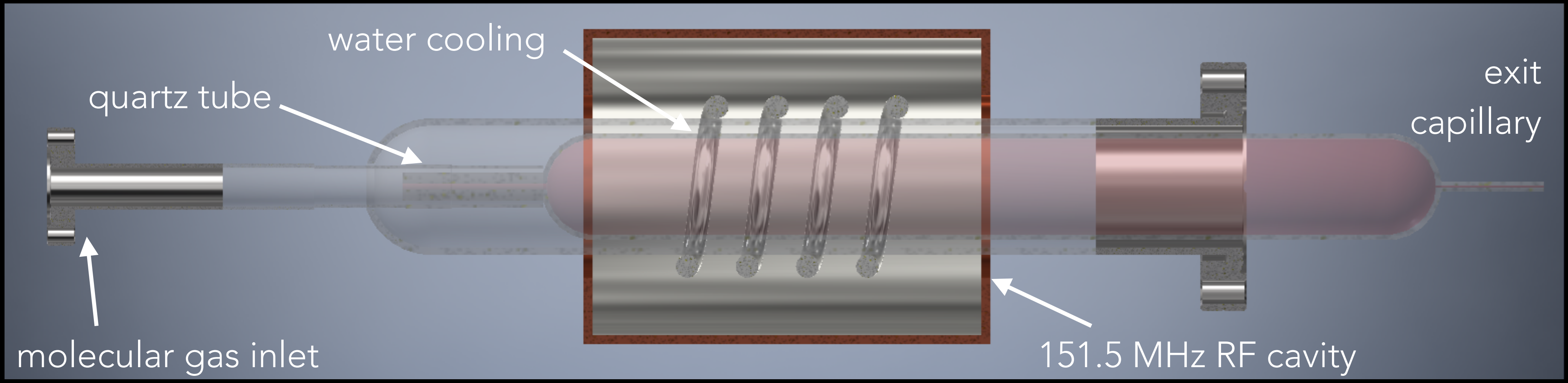
RF dissociation source

(follows design of Slevin & Stirling)

- Flux $2 \cdot 10^{17}$ atoms/sec
- 95% dissociation efficiency
- colder initial beam

  → easier to accomodate





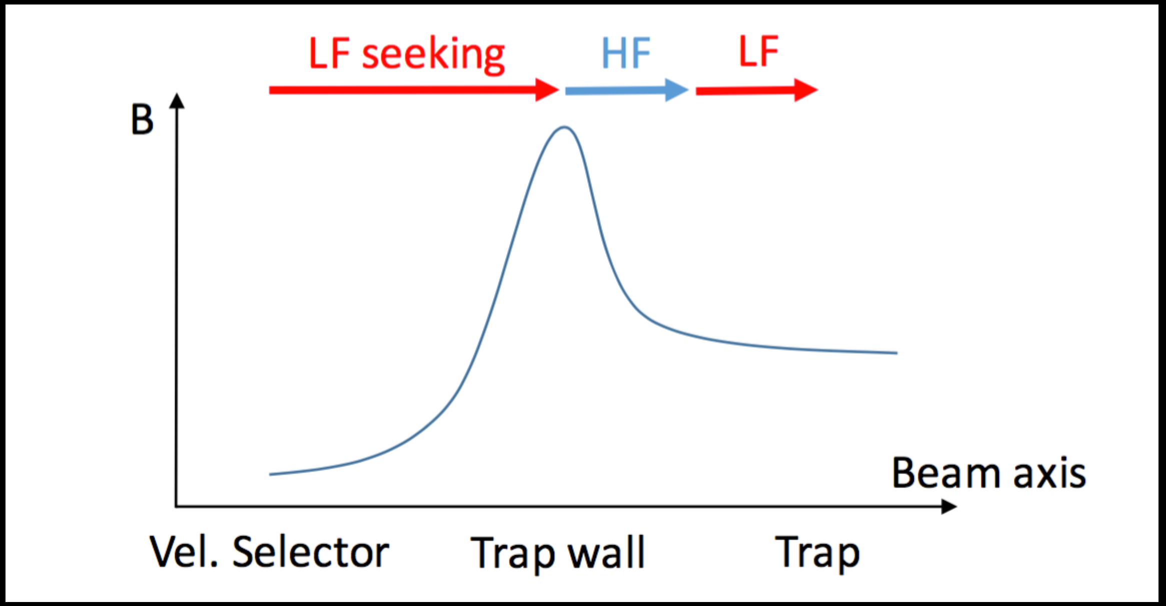
E. Machado, UW Seattle

HOW TO FILL THE TRAP?

HOW TO FILL THE TRAP?

Spin-flip loading ?

- Carry atoms over potential wall (+ energy loss)
- But: stimulated emission



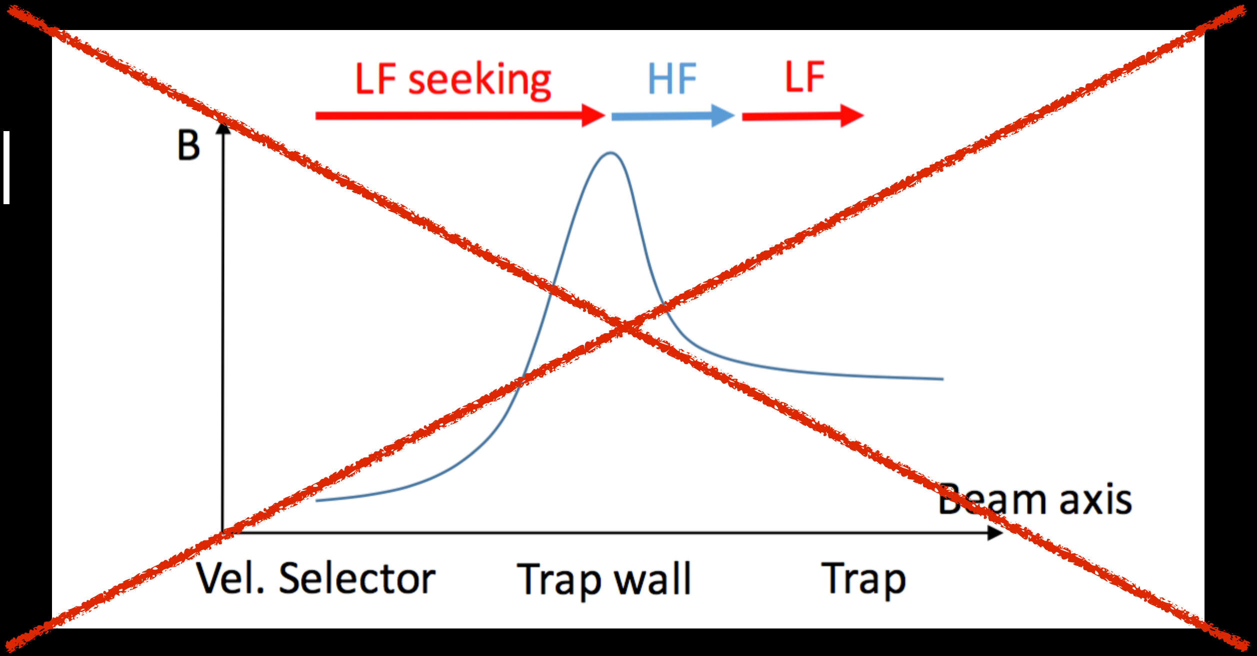
E. Machado, UW Seattle

HOW TO FILL THE TRAP?

Spin-flip loading ?

- Carry atoms over potential wall (+ energy loss)
- But: stimulated emission

→ Will lose trapped atoms



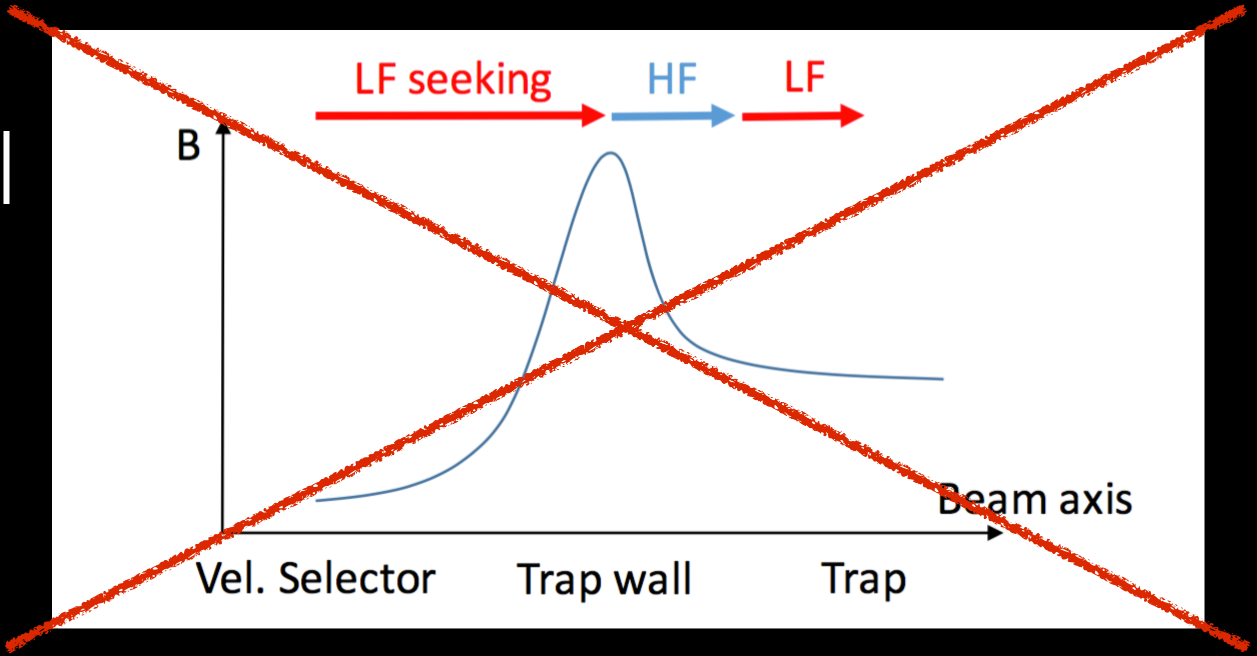
E. Machado, UW Seattle

HOW TO FILL THE TRAP?

Spin-flip loading ?

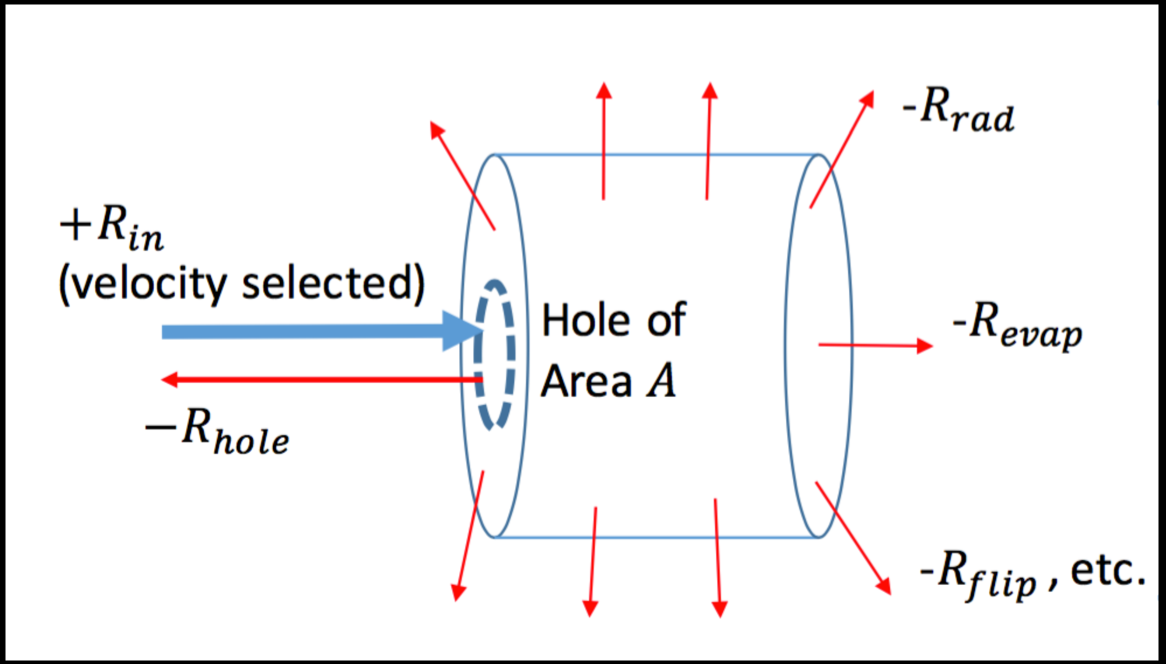
- Carry atoms over potential wall (+ energy loss)
- But: stimulated emission

→ Will lose trapped atoms



Cornucopia* loading

- Trap loss negligible
- Hole loss rate = refill rate
  $8 \cdot 10^{14}$ atoms/sec/cm^2
- Trapping time $\tau_{90\%}$ ~ 700s



E. Machado, UW Seattle

* horn of plenty

TRITIUM TEMPERATURE

Requirement

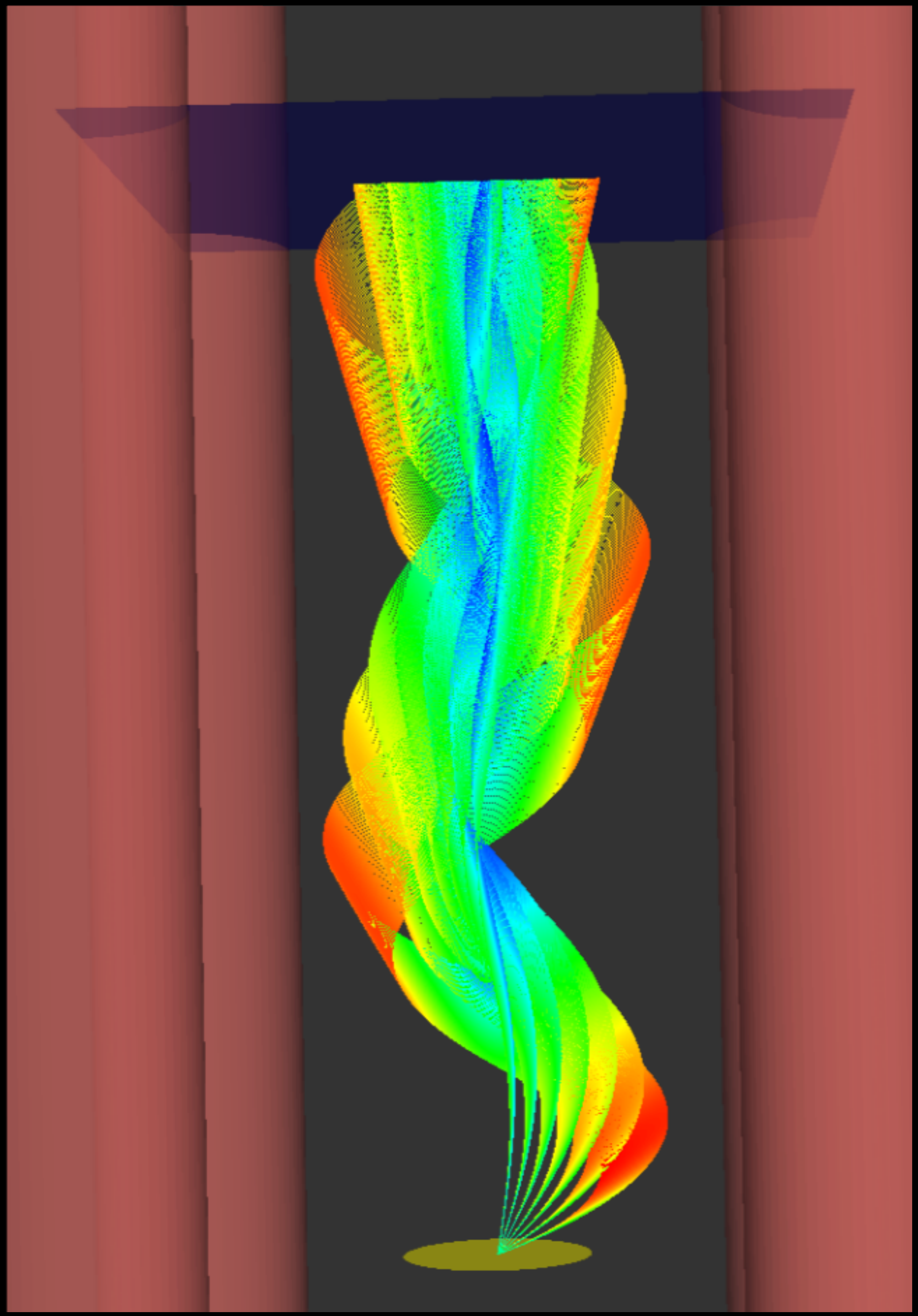
- $T_{T\ atoms} = 50mK$

Passive cooling

- T_2 recombination @ few K
  → cooling (?) and/or
  velocity selector

Ideas

- Coilgun (→ RF noise?!)
- Chopper
- Magnetic selector ε_{cold} ~ 25%

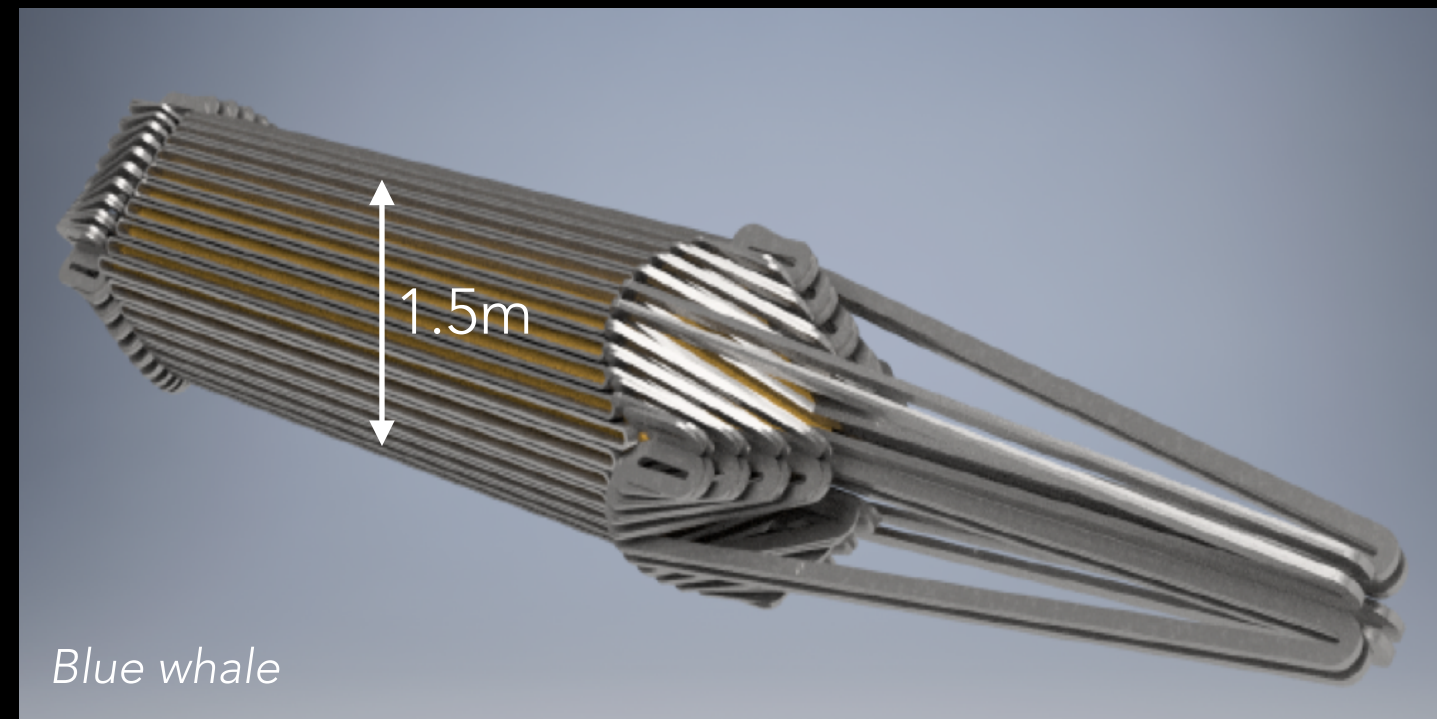


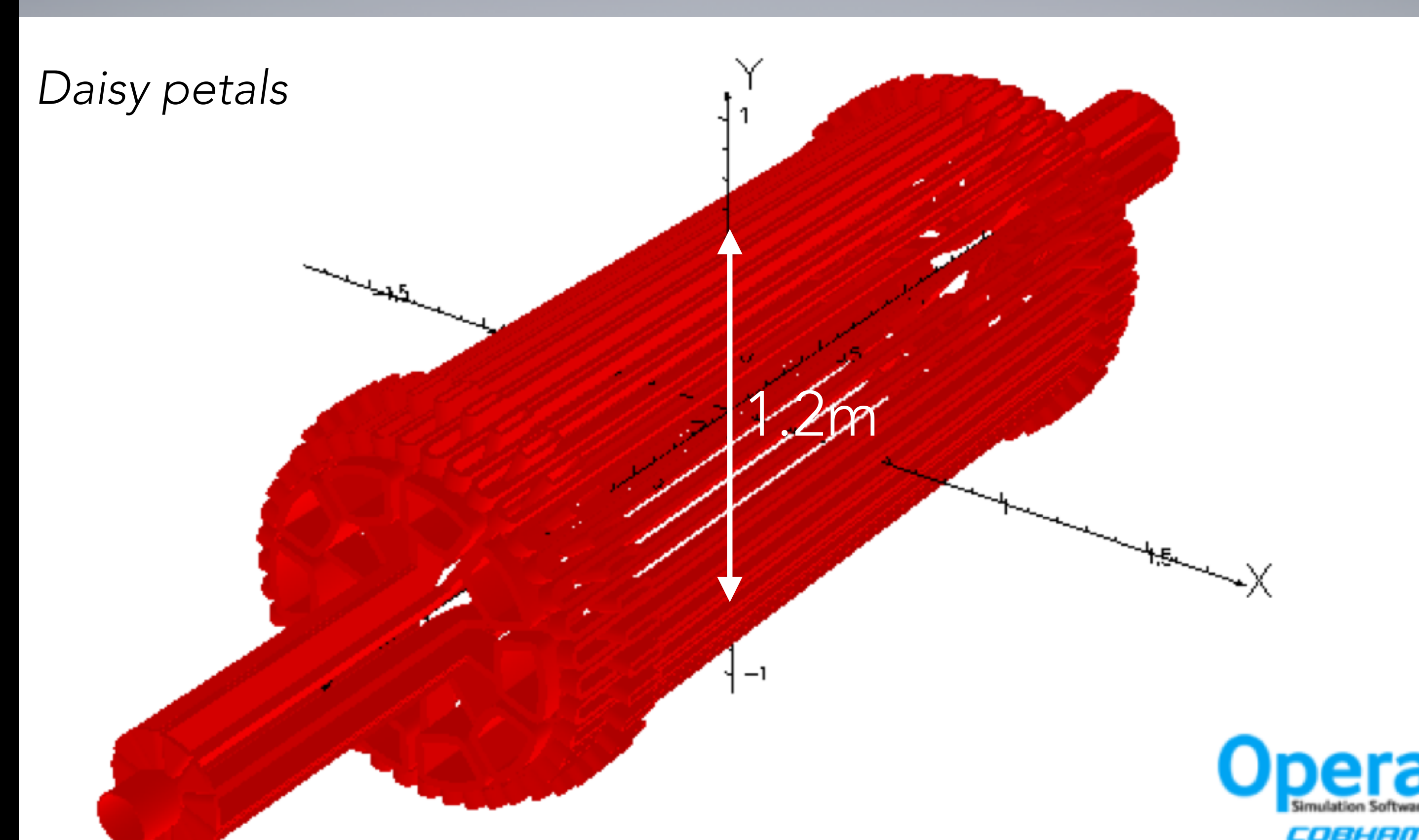
A. Etienney, INP Grenoble & U. Mainz

PHASE IV: FIRST TRAP DESIGNS

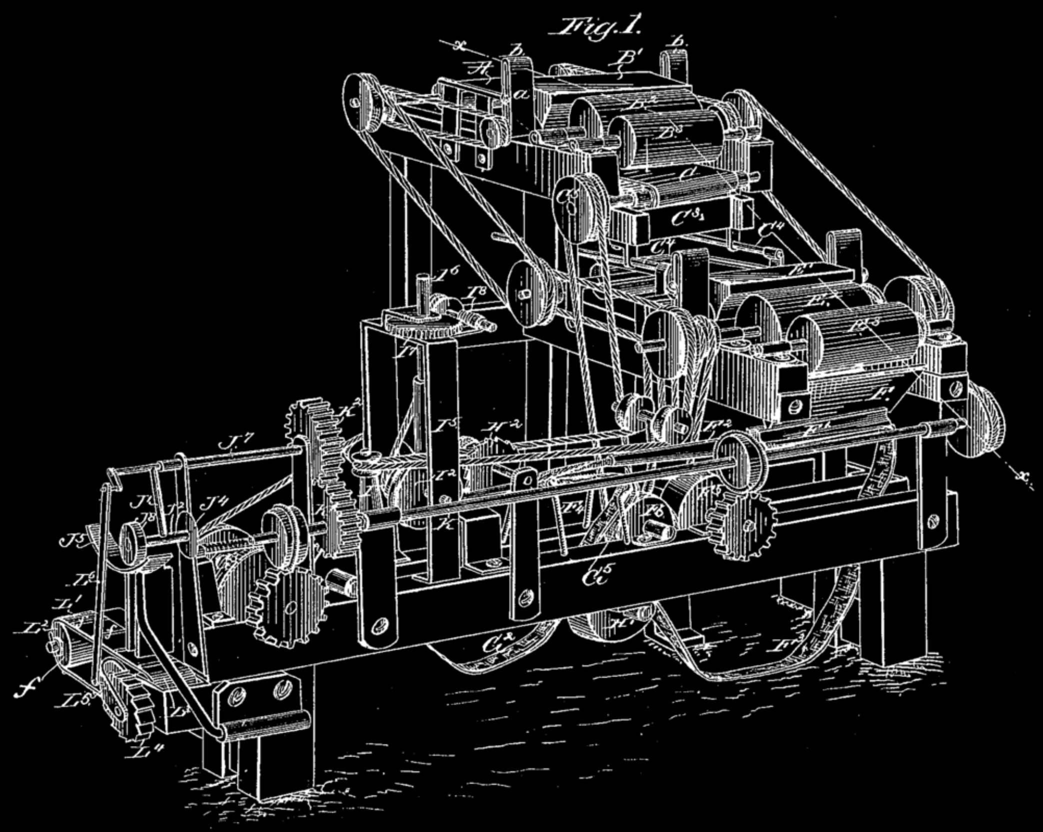
Design challenges

- contours outside all structures
- large homo-geneous trap volume
- manufacturing and operation stability
- compatible with antenna array





FINAL DESIGN?



What is the final design?

→ We don't know yet!

"Schwierigkeiten lauern auf den,
der nicht auf das Leben reagiert." *
— M. S. Gorbatschow

Have to stay flexible and adjust the design for the challenges we encounter!

* Often wrongly translated as "Wer zu spät kommt, den bestraft das Leben."

SUMMARY

Tritium endpoint spectroscopy

- kinematic approach to neutrino mass
  → most sensitive laboratory measurements

Project8:

- CRES - Cyclotron Radiation Emission Spectroscopy
  → new technology with sensitivity to IH scale

Approach requires

- volumetric RF readout → phased array
- intense atomic T source at mK level
  → R&D started

PROJECT 8 COLLABORATION

B. Monreal, Y. H. Sun, L. Gladstone
Case Western

S. Doelman, J. Weintroub, A. Young
Smithsonian Astrophysical Observatory

S. Böser, C. Claessens, A. Lindman
Johannes Gutenberg-Universität, Mainz

T. Thümmler, M. Walter
Karlsruhe Institute of Technology

K. Kazkaz
Lawrence Livermore National Laboratory

K. Heeger, J.A. Nikkel, L. Saldana, P. Slocum
Yale University

J. Formaggio, N. Buzinsky, E. Zayas,
J. P. Johnston, V. Sibille
Massachusetts Institute of Technology

L. de Viveros, T. Wendler
Penn State University

B. VanDevender, M. Guigue, A. M. Jones, J. Tedeschi, E. C. Finn, N. Oblath, B. LaRoque
Pacific Northwest National Laboratory

R.G.H. Robertson, P. Doe, A. Ashtari Esfahani, M. Fertl, E. Machado,
L. Rosenberg, G. Rybka, R. Cervantes, W. C. Pettus, E. Novitski
University of Washington, Center for Experimental Nuclear Physics and Astrophysics