Cooling of Highly Charged Ions

at

TITAN

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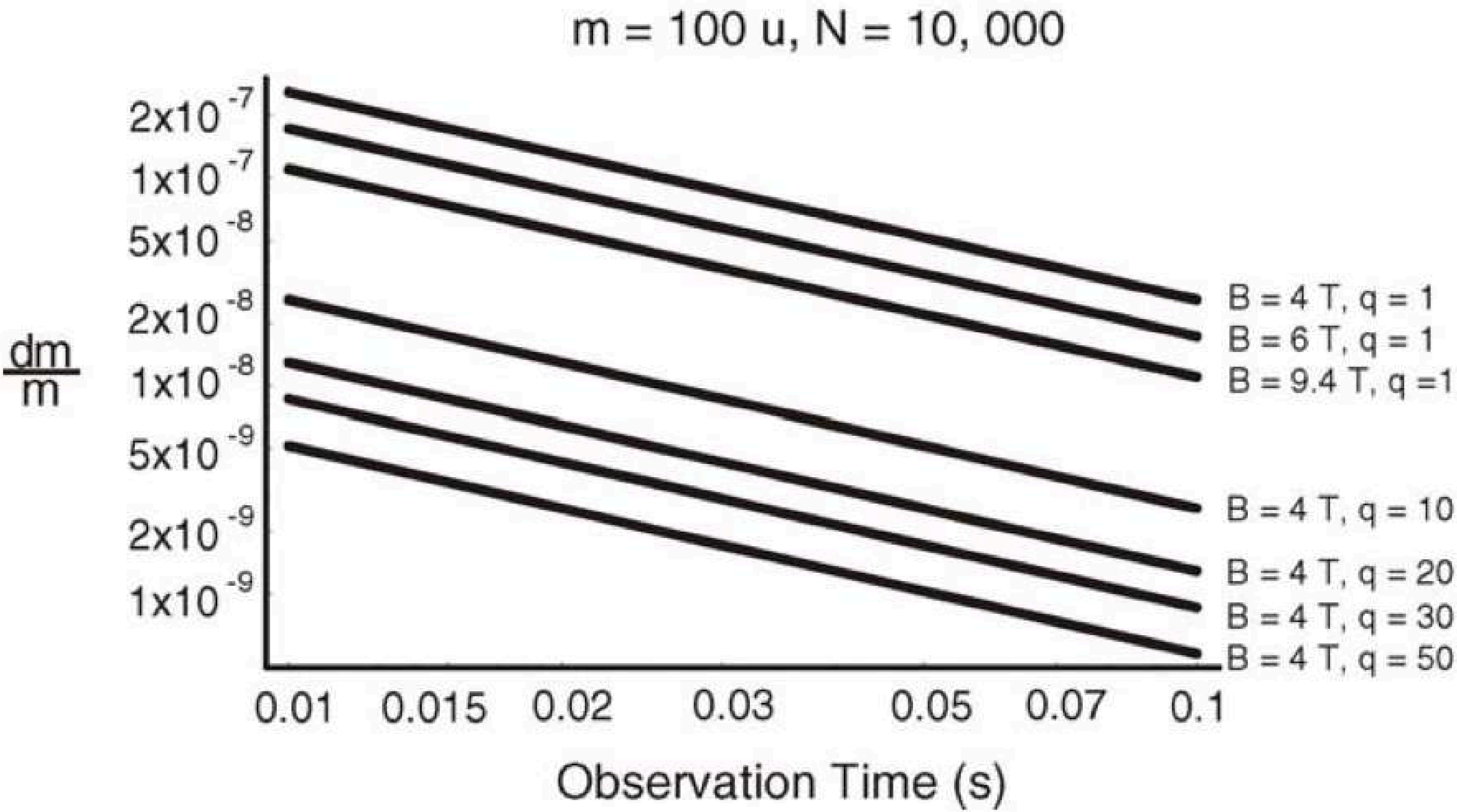
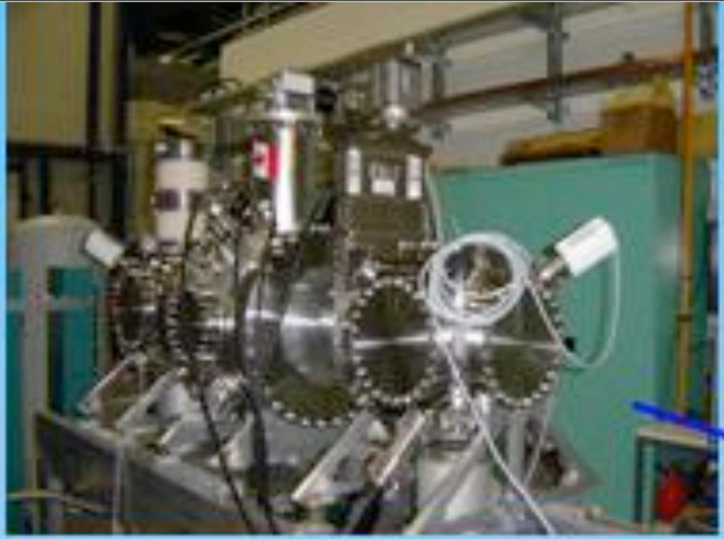
Mass measurements with highly charged ions

$$\frac{m}{\delta m} \propto \omega_c T_{\mathrm{RF}} \sqrt{N} = \frac{qB}{m} T_{\mathrm{RF}} \sqrt{N}$$



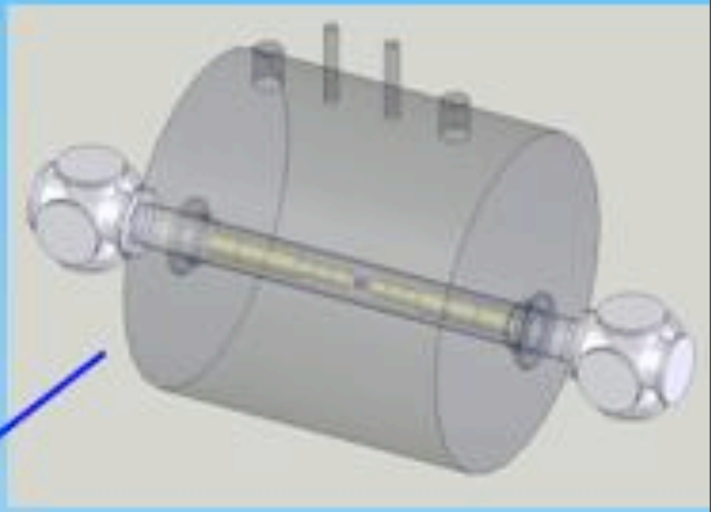
Max-Planck-Institut für Kernphysik



EBIT under testing at MPI-HD. to TRIUMF July 2005.

McGill

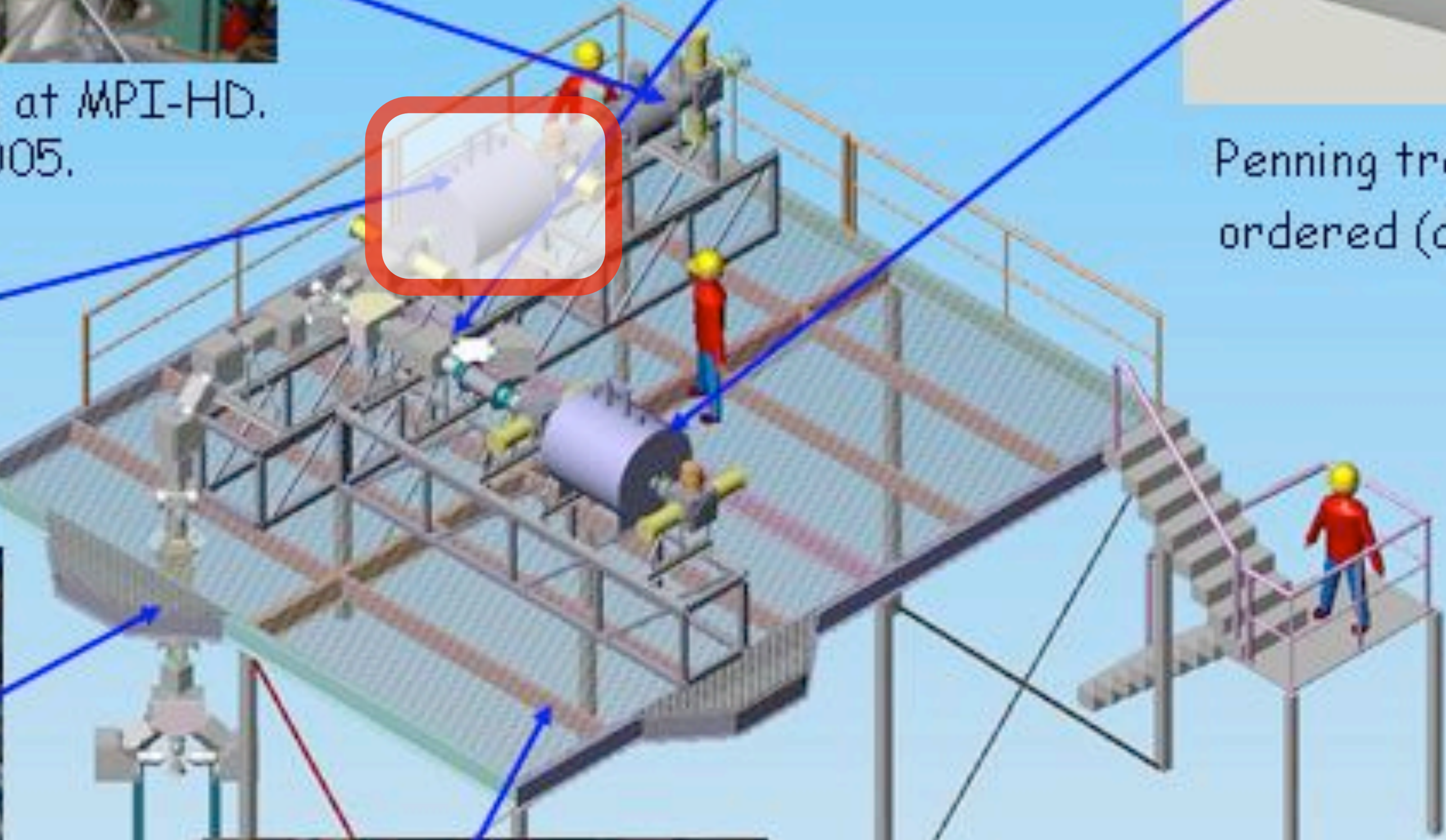
Wien filter (R=500)



Penning trap magnet ordered (del. July 2005)

Cooler trap for HCI (to be built in Manitoba, CFI grant received)

university of manitoba



RFQ operational on test bench

TRIUMF

ISAC

TITAN platform finished at ISAC

The TITAN system is under construction and will be operational for mass measurements at ISAC/TRIUMF in 2006.

Isotopes with $T_{1/2} \approx 10$ ms

$\delta m/m < 1 \cdot 10^{-8}$

Why do we need to cool HCI between the EBIT and the precision Penning trap ?

- ion temperature for mass measurement:

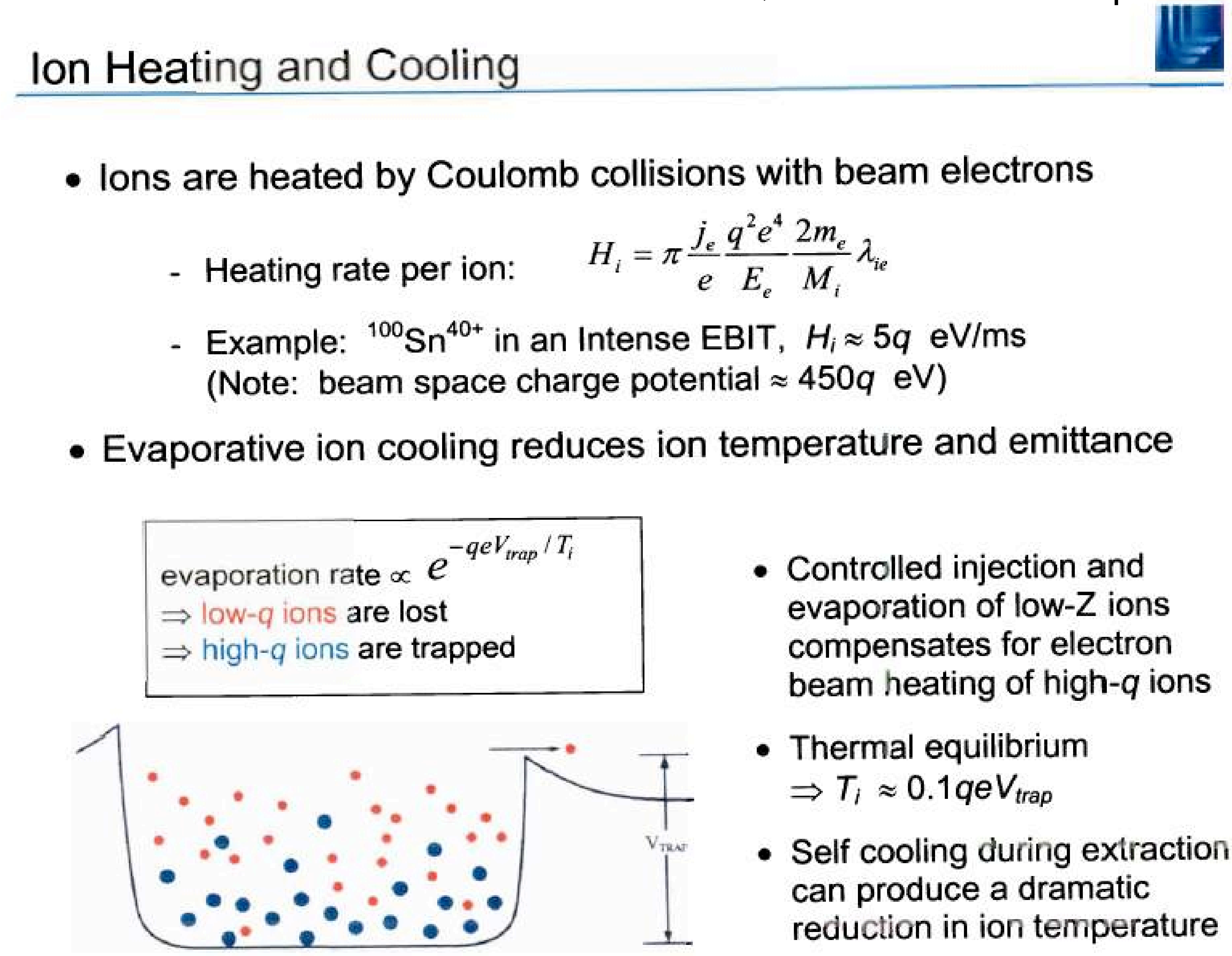
$$T_i \lesssim 1\ \text{eV/q}$$

- EBIT: $T_i \gg 1$ eV/q must be expected

What do we know about ion temperatures in EBITs ?

- REXEBIS: few 10 eV/q
- Oshima et al.: EBIS/ECRIS ”generally” $>$ 10 eV/q
- Dresden EBIT: $T_i = 3 - 6$ eV/q measured for Ar^{16+} but low j_e and E_e
- Livermore, evaporative cooling inside EBIT:
  $10 - 20$ eV/q for Dy^{66+} (no data ?)
  Penetrante et al.
- Livermore, evaporative cooling & self-cooling during extraction: $T_i \approx 0.1qeV_{\mathrm{trap}} \Rightarrow \approx 10 - 50$ eV/q
  Marrs, TITAN workshop 2002 (no data)

R. Marrs, 2002 TITAN workshop



Ion Heating and Cooling

- Ions are heated by Coulomb collisions with beam electrons
  - Heating rate per ion: $H_i = \pi \frac{j_e}{e} \frac{q^2 e^4}{E_e} \frac{2m_e}{M_i} \lambda_{ie}$
  - Example: $^{100}\mathrm{Sn}^{40+}$ in an Intense EBIT, $H_i \approx 5q$ eV/ms (Note: beam space charge potential ≈ $450q$ eV)
- Evaporative ion cooling reduces ion temperature and emittance

evaporation rate $\propto e^{-qeV_{trap}/T_i}$
$\Rightarrow$ low-q ions are lost
$\Rightarrow$ high-q ions are trapped

- Controlled injection and evaporation of low-Z ions compensates for electron beam heating of high-q ions
- Thermal equilibrium $\Rightarrow T_i \approx 0.1 qeV_{trap}$
- Self cooling during extraction can produce a dramatic reduction in ion temperature

- self-cooling requires slow (ms) spills — not suitable in our case

Ion temperature on extraction from EBIT

- actual data appears sparse
- no definite conclusions possible
- emittance/temperature measurements from TITAN EBIT will be necessary, and also interesting in general
- For now must assume that HCI have temperatures of 10…100 eV/q

  ⇒ additional cooling before precision trap most likely necessary

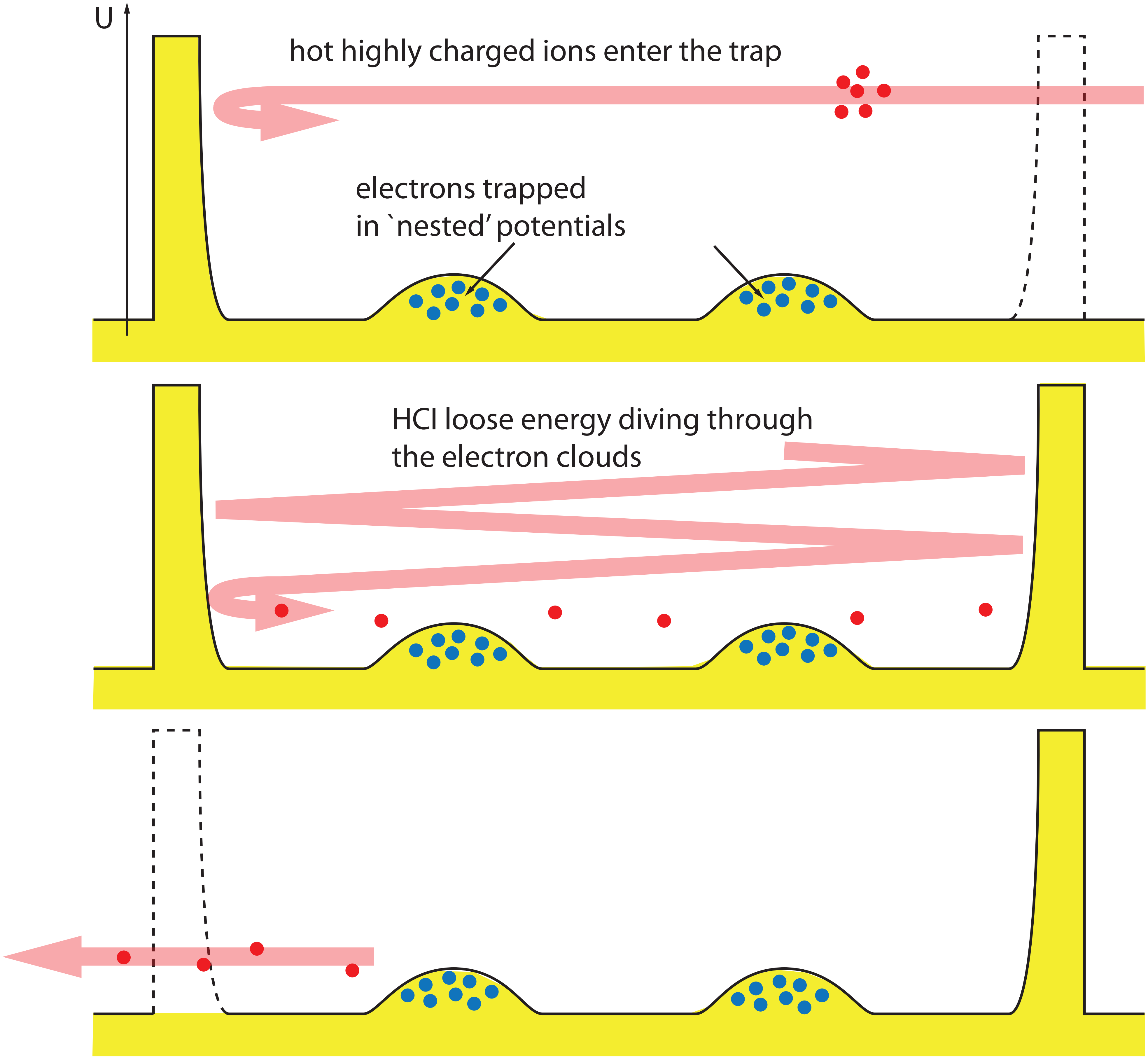
Techniques for ion cooling

- buffer gas cooling
  - well established method for SCI
    NO (charge exchange)
- resistive cooling
  - well established, fast enough — if Q high enough → would require cryogenic operation
  - ion specific tuning of resonant circuit required

- electron cooling
  - demonstrated for (anti)protons and HCI at $T_i \gtrsim$ few eV/q
  - advantage: electrons self-cool via synchrotron radiation
  - disadvantage: electron-ion recombination
- positron cooling
  - avoids recombination, but technically more involved (mCi level source)
- ion-ion cooling with light, cool ions (protons, He^{2+})
  - no recombination issues
  - but no synchrotron cooling, need initially cold light ions

laser cooling?

Electron cooling in a nested Penning trap



Simulations of Electron Cooling

- Ignore magnetic field
- simple two-component plasma model
  - Spitzer (1956), Rolston & Gabrielse (1989), Bernard *et al.* (2004)

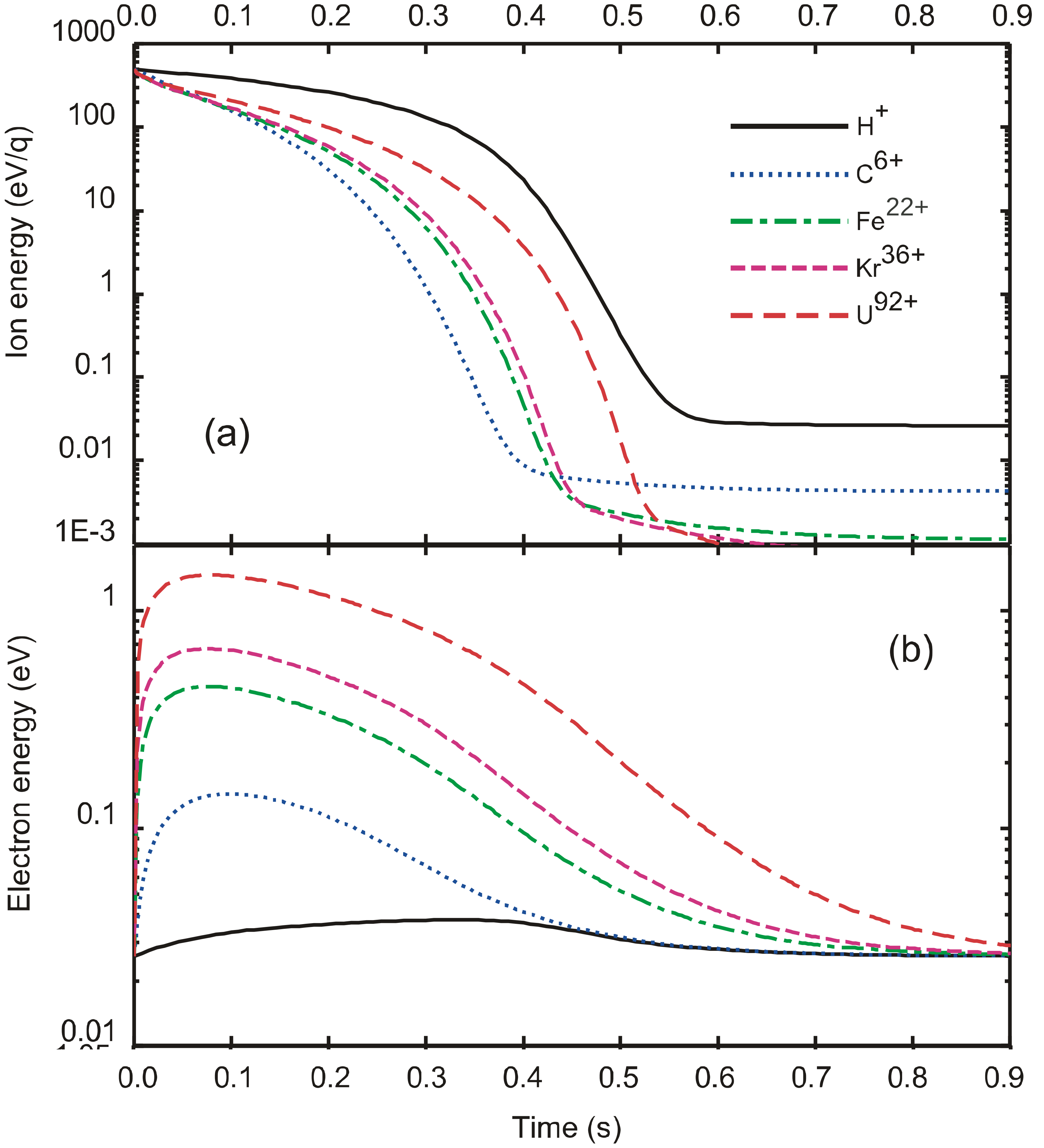
$$\frac{dT_e}{dt} = \frac{1}{\tau_i}\frac{N_i}{N_e}(T_i - T_e) - \frac{1}{\tau_e}(T_e - T_{res}),$$

$$\frac{dT_i}{dt} = -\frac{1}{\tau_i}(T_i - T_e),$$

$$\tau_i = \frac{3(4\pi\epsilon_0)^2 m_e m_i c^3}{8\sqrt{2\pi} n_e q^2 e^4 ln(\Lambda)}\left(\frac{kT_i}{m_i c^2} + \frac{kT_e}{m_e c^2}\right)^{\frac{3}{2}}$$

$$ln(\Lambda) = \ln\left(4\pi\left(\frac{\epsilon_0 k}{e^2}\right)^{\frac{3}{2}}\frac{1}{q}\sqrt{\frac{T_e}{n_e}}(T_e + \frac{m_e}{m_i}T_i + 2\sqrt{\frac{m_e}{m_i}}\sqrt{T_e T_i}\right)$$

Electron cooling I: Cooling



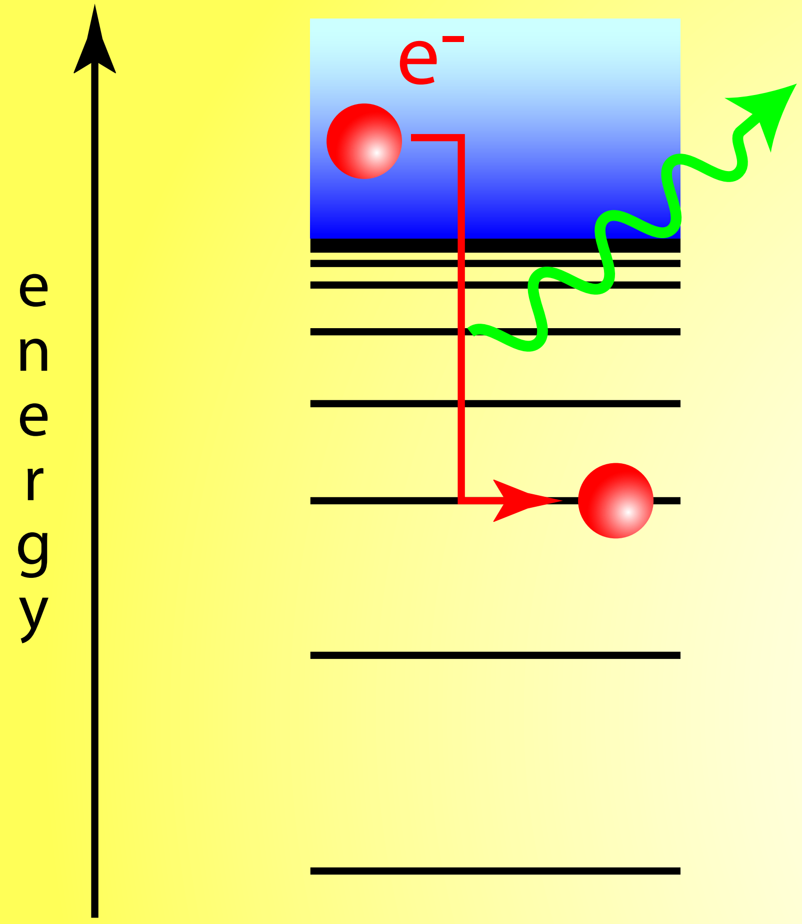
$$n_e = 10^7\ \mathrm{cm}^{-3}$$

$$N_i/N_e = 10^{-4}$$

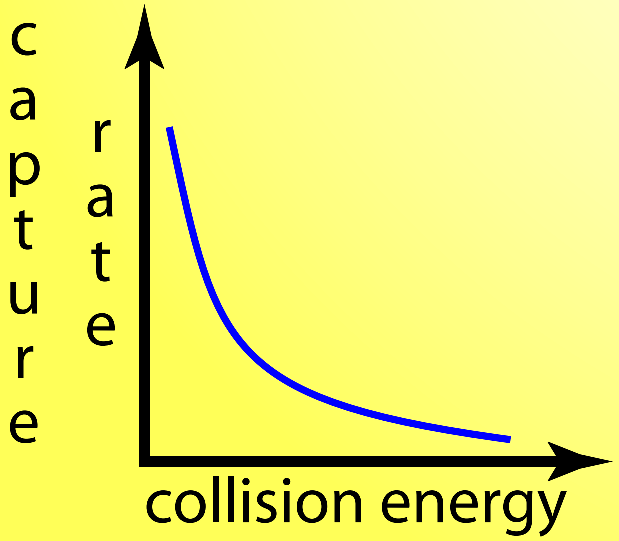
$$T_{\mathrm{res}} = 300K$$

Photorecombination of free electrons and ions

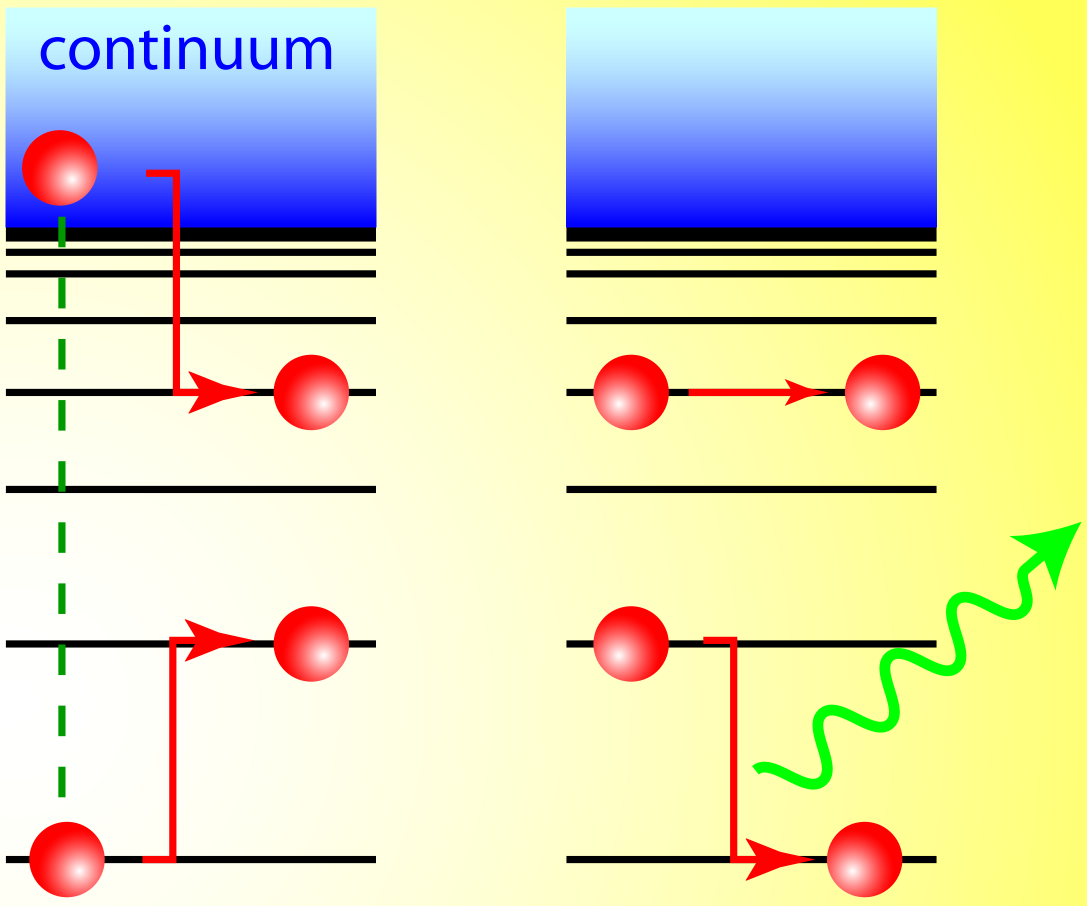
radiative recombination (RR)



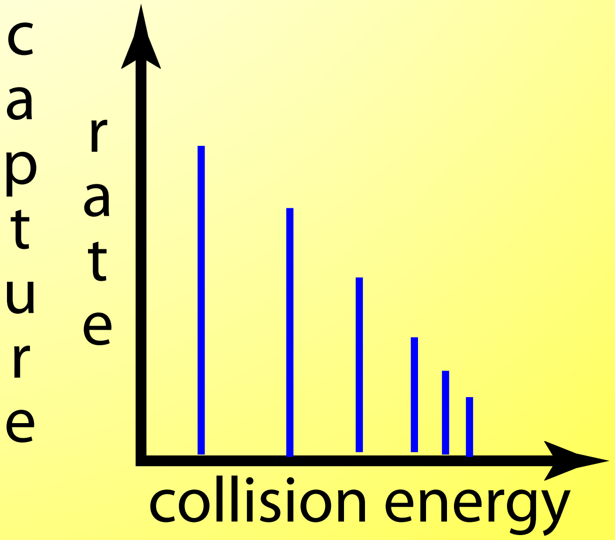
$$A^{q+} + e^- \rightarrow A^{(q-1)+} + h\nu$$



dielectronic recombination (DR)



$$A^{q+} + e^- \rightarrow A^{(q-1)+\,**} \rightarrow A^{(q-1)+} + h\nu$$



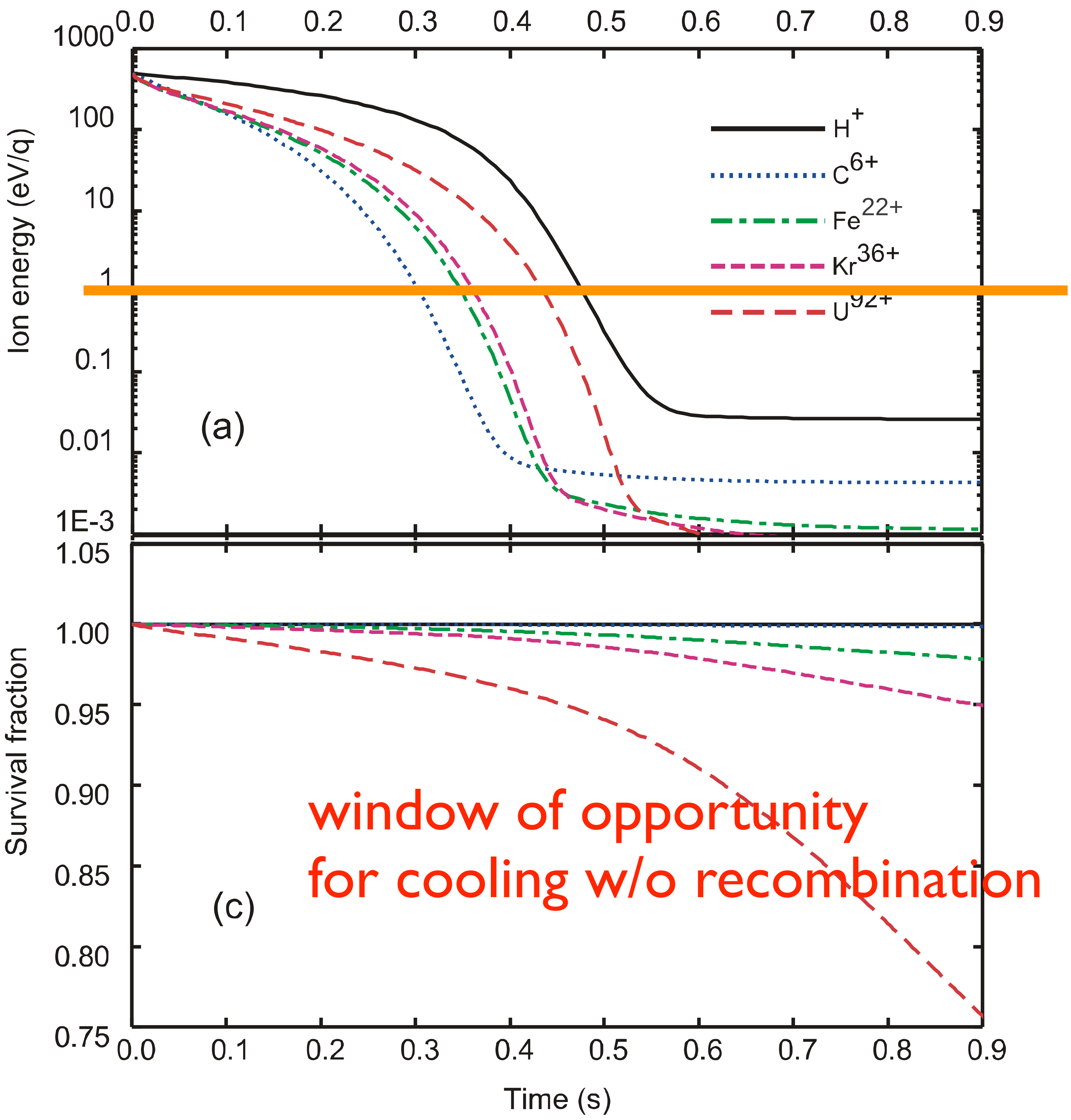
Electron cooling II: Recombination

$$\frac{dP}{dt} = (\alpha_{\mathrm{RR}} + \alpha_{\mathrm{DR}} + \alpha_{\mathrm{TBR}})n_e$$

$$\begin{aligned}\alpha_{\mathrm{RR}} &= 5.2 \times 10^{-14}\,\mathrm{Z}_{\mathrm{eff}}\sqrt{\frac{E_\infty}{T_{\mathrm{eff}}}}\left(0.43 + \frac{1}{2}\ln\left(E_\infty/T_{\mathrm{eff}}\right)\right. \\ &\quad \left. + 0.469(E_\infty/T_{\mathrm{eff}})^{-1/3}\right)\ \mathrm{cm}^3\ \mathrm{s}^{-1}\end{aligned}$$

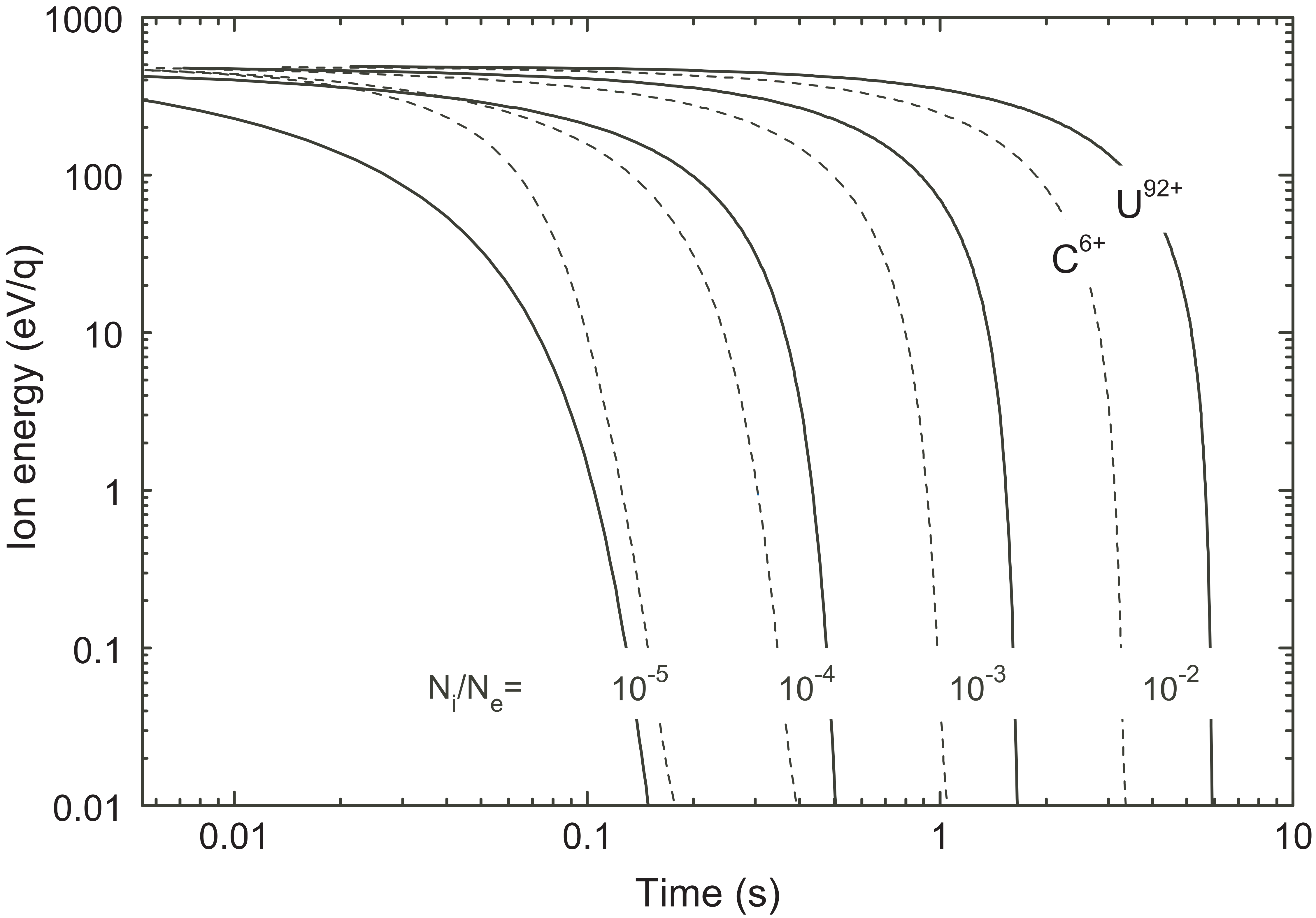
$$\alpha_{\mathrm{TBR}} = [2.0 \times 10^{-27}\ \mathrm{cm}^6\ \mathrm{s}^{-1}]\, q^3\, T_{\mathrm{eff}}^{-4.5} n_e$$

Electron cooling II: Recombination

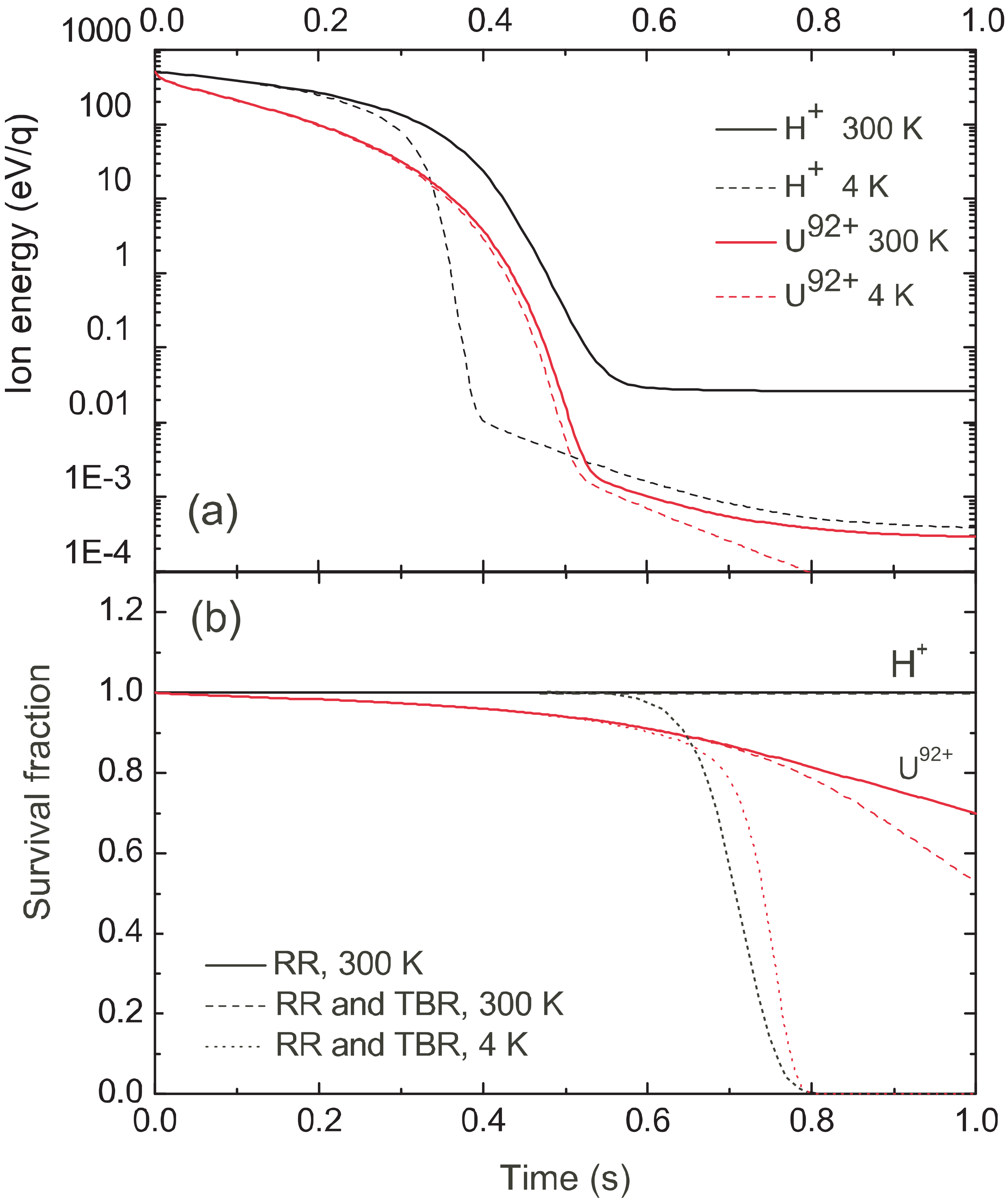


window of opportunity
for cooling w/o recombination

Cooling speed as a function of N_i/N_e



Influence of three-body recombination

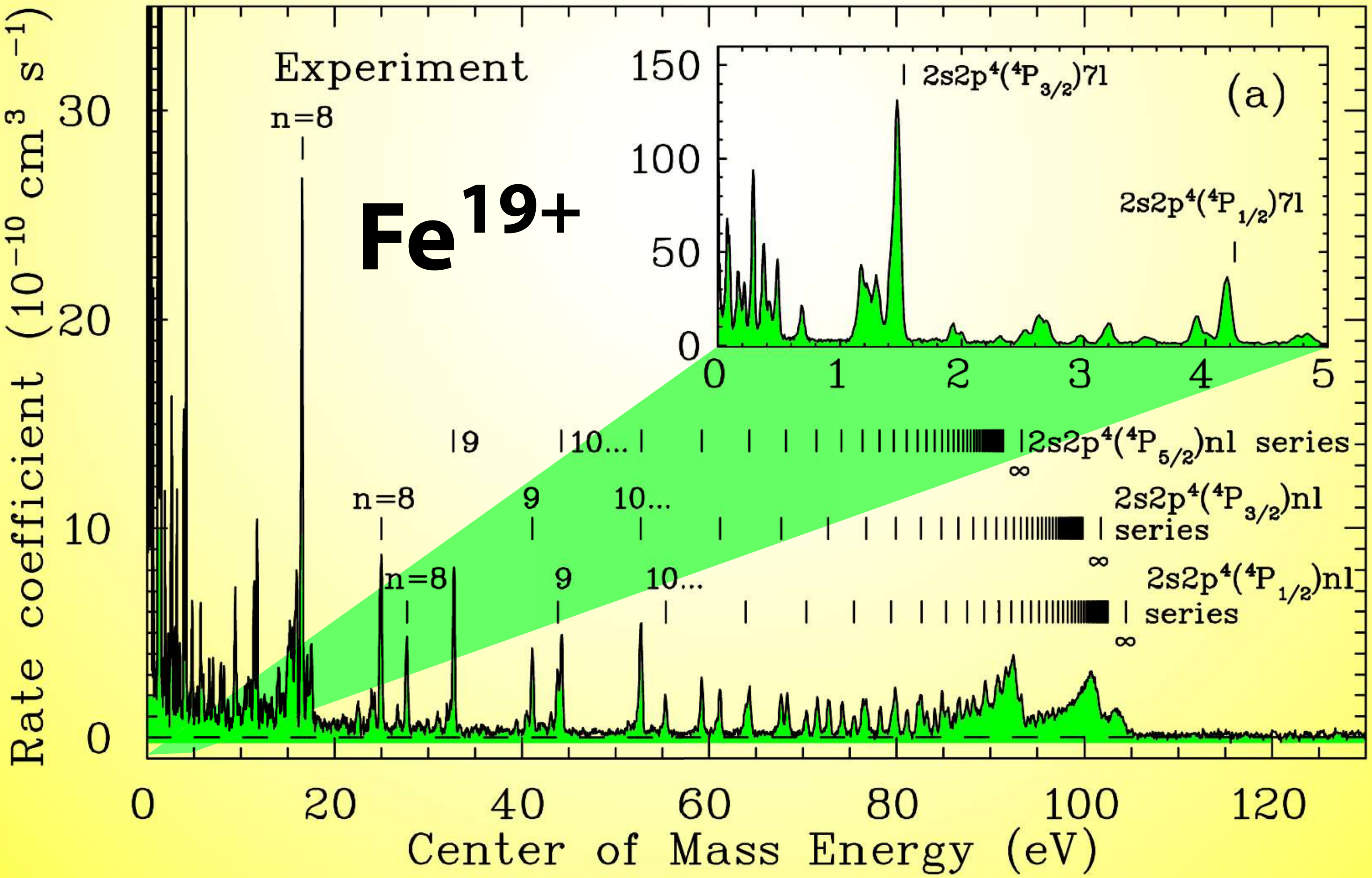


Photorecombination: application to astrophysics

collaboration with D.W. Savin, Columbia University

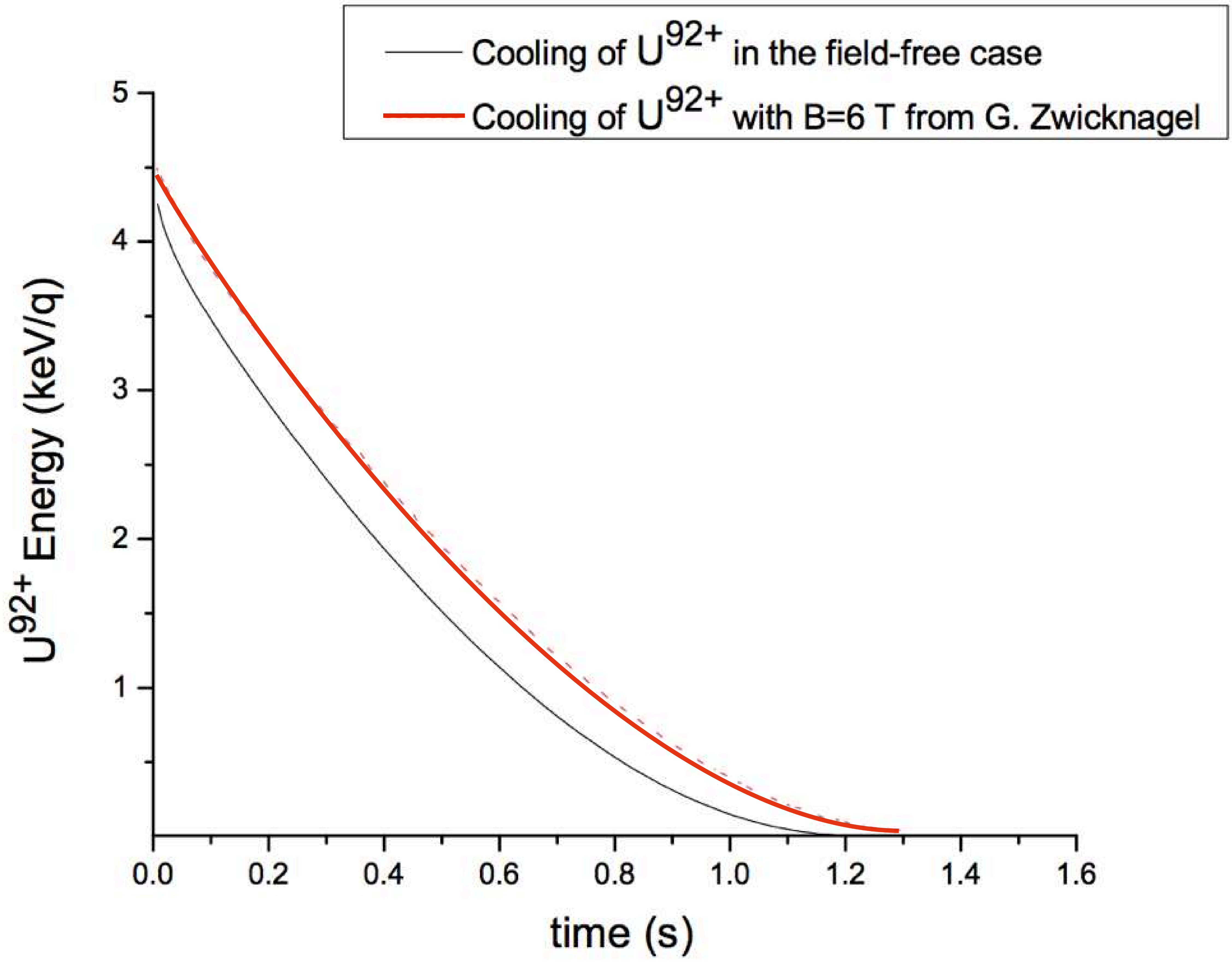
Problem: modelling codes for photoionized nebulae typically use **theoretical DR rates** calculated with **production codes**

To check the reliability, we have systematically surveyed DR rates in astrophysically relevant **L-shell iron (Fe^{16+}… Fe^{23+})**

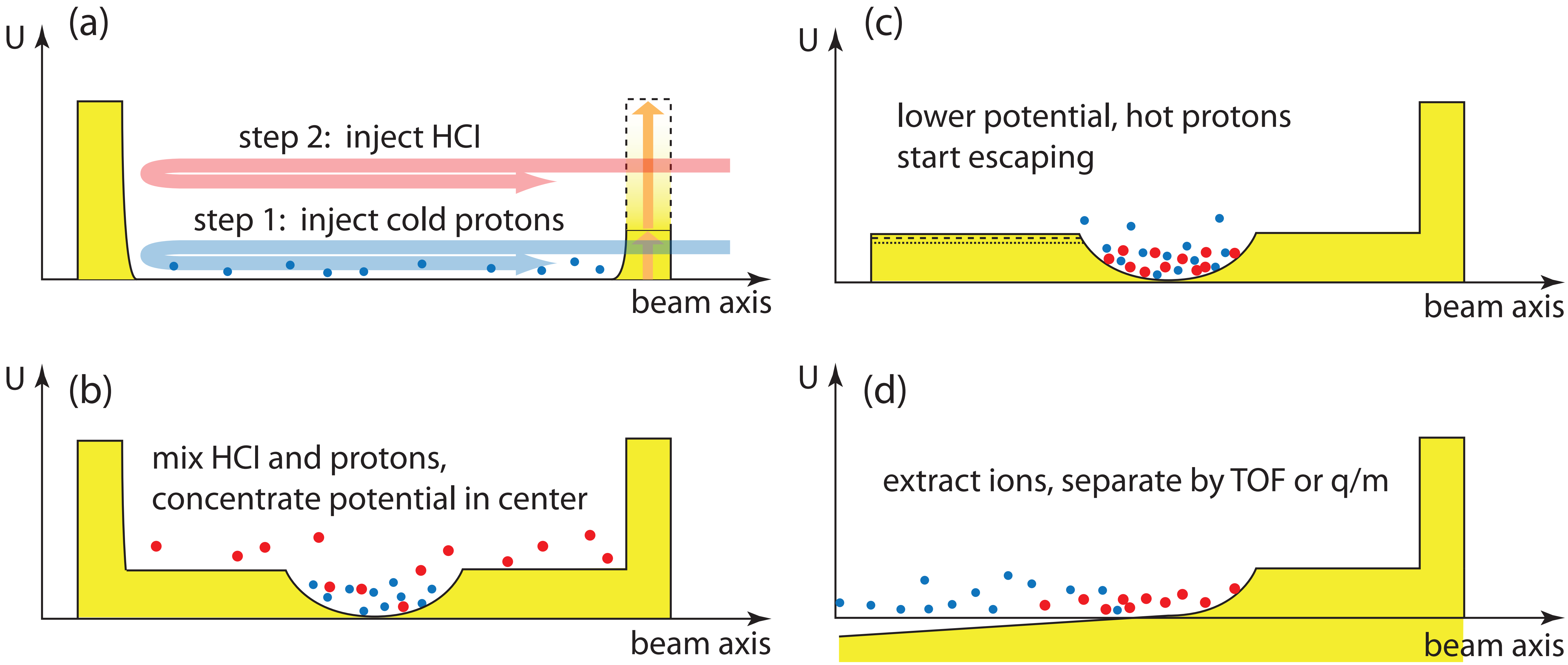


D.W. Savin et al., accepted for publication in Astrophysical Journal

Does the magnetic field play a role?



Proton cooling



step 2: inject HCI

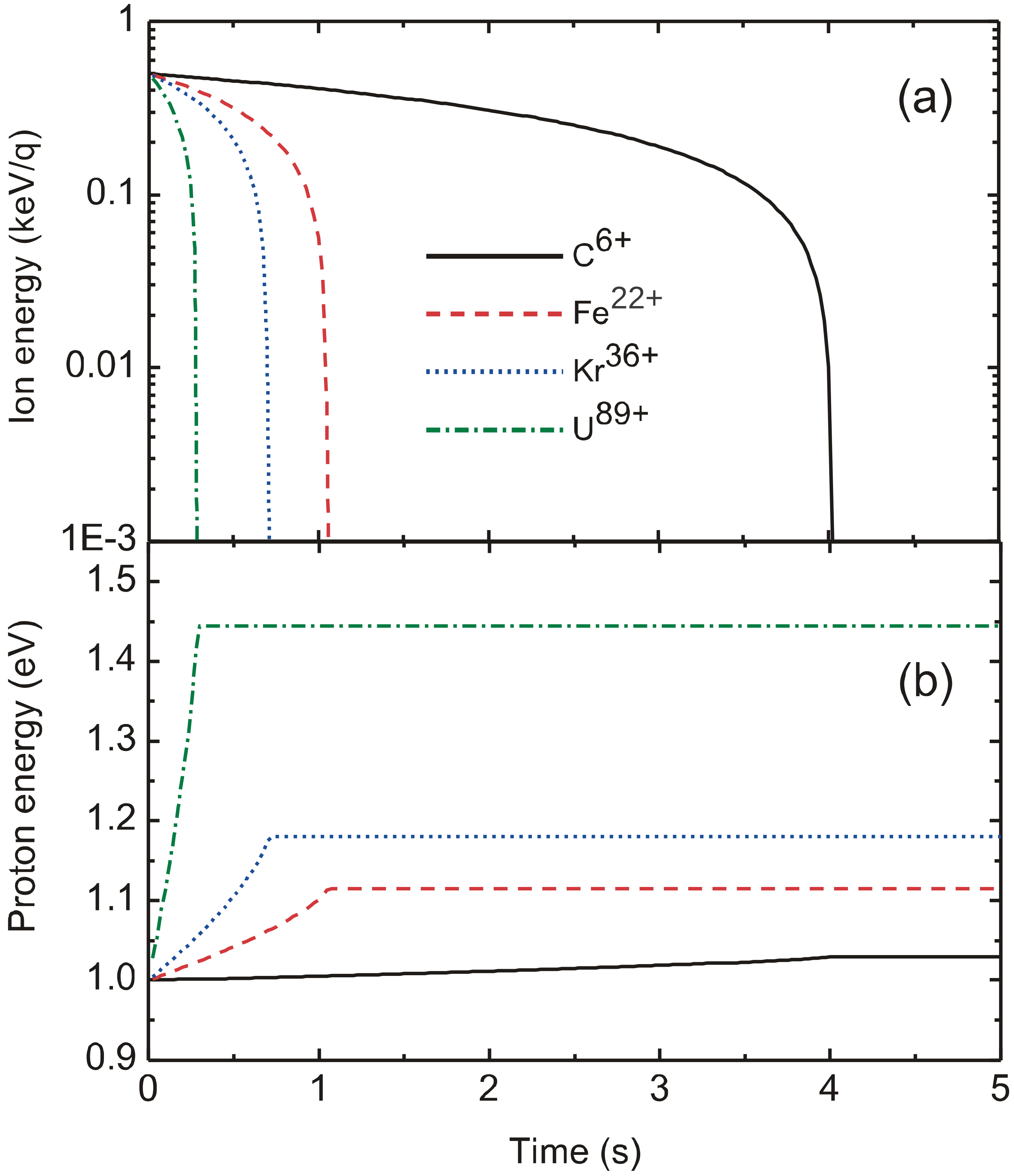
step 1: inject cold protons

mix HCI and protons,
concentrate potential in center

lower potential, hot protons
start escaping

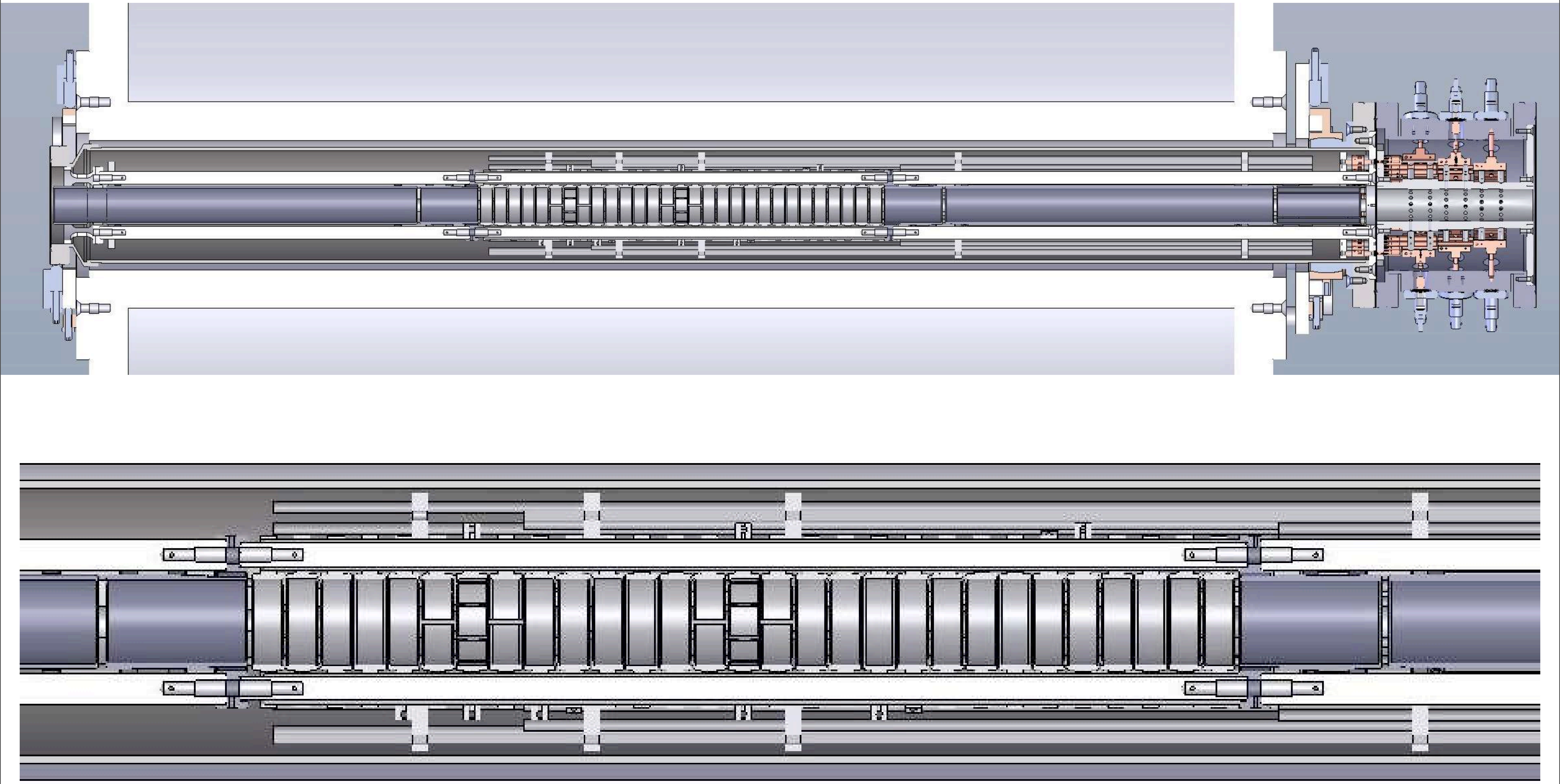
extract ions, separate by TOF or q/m

Proton cooling



$$n_p = 10^8\ \mathrm{cm}^{-3}$$
$$N_i / N_p = 10^{-5}$$

Layout of the cooler trap



details in the next talk by Vanessa