# GaAs Photo-Cathodes as Sources for Low-Velocity Electron Coolers

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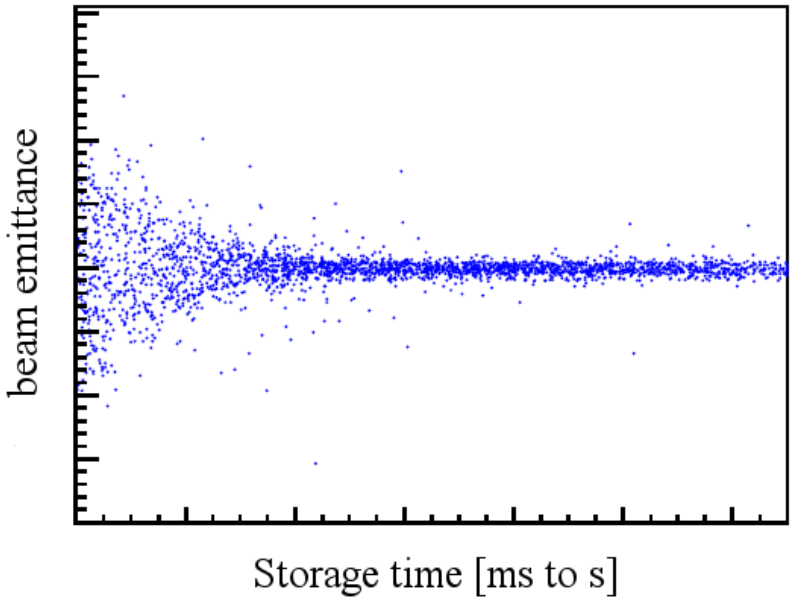
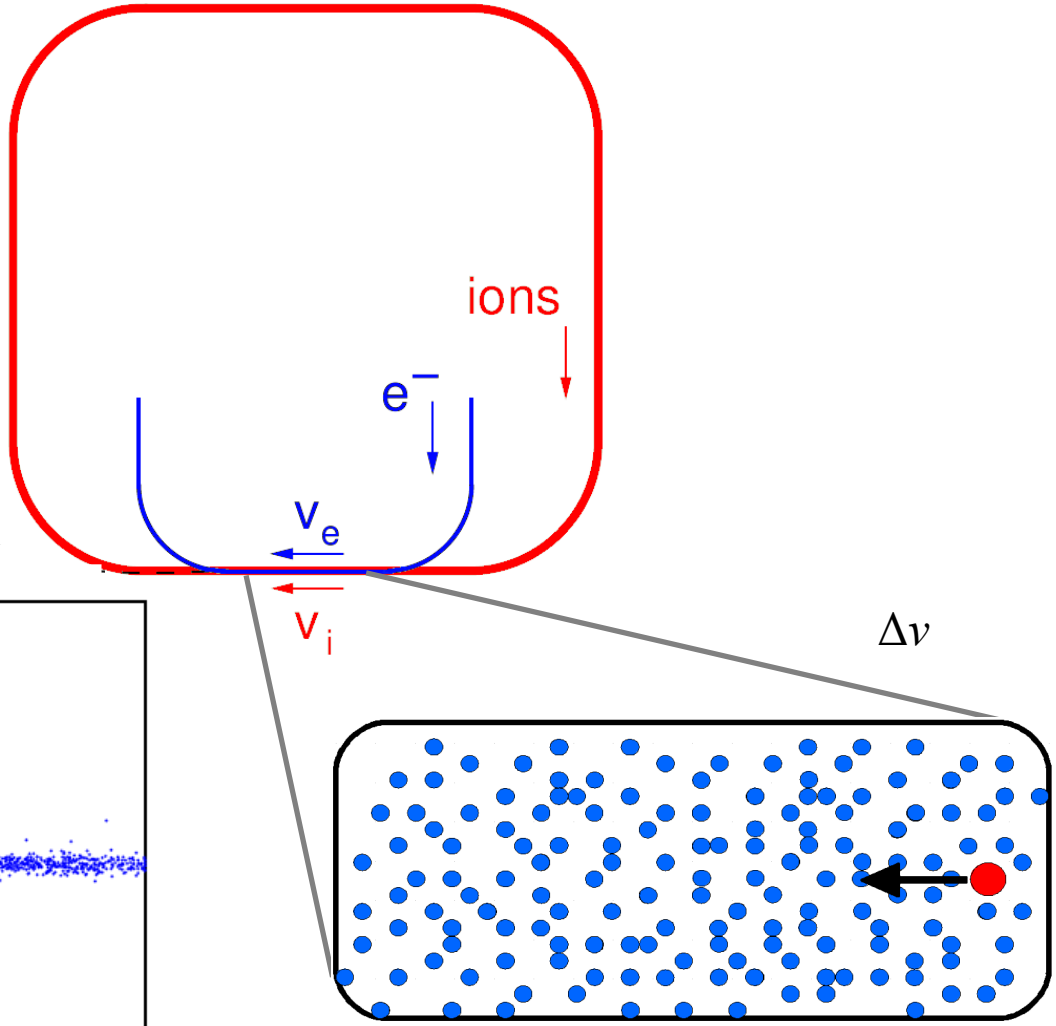
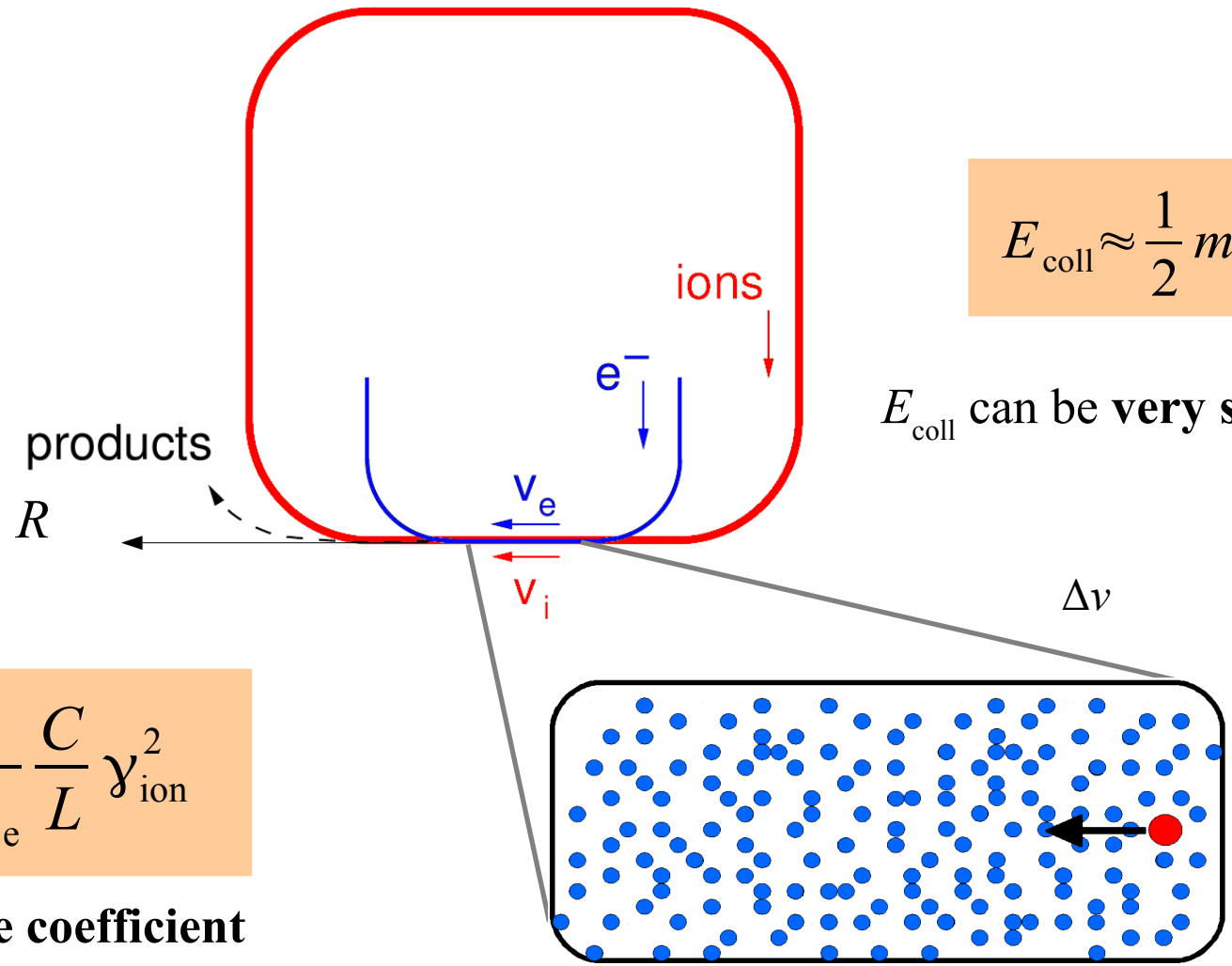
# Electron Coolers

"Electron cooler storage ring"



# Electron Coolers




$$E_{\mathrm{coll}} \approx \frac{1}{2} m_{\mathrm{e}} (\Delta v)^2$$

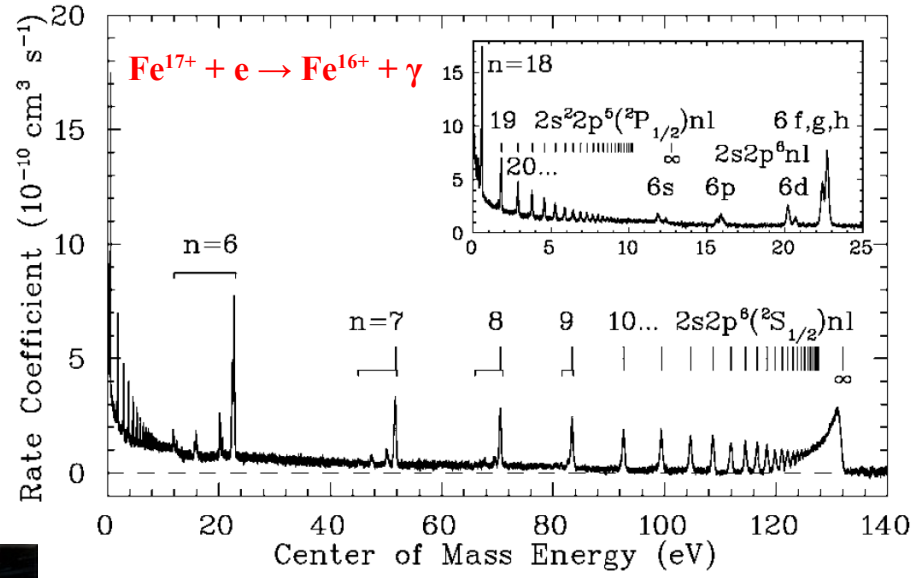
$E_{\mathrm{coll}}$ can be **very small** (meV!)

$$\alpha = \frac{R}{N_{\mathrm{ion}} n_{\mathrm{e}}} \frac{C}{L} \gamma_{\mathrm{ion}}^2$$

Reaction **rate coefficient**

# Electron Coolers

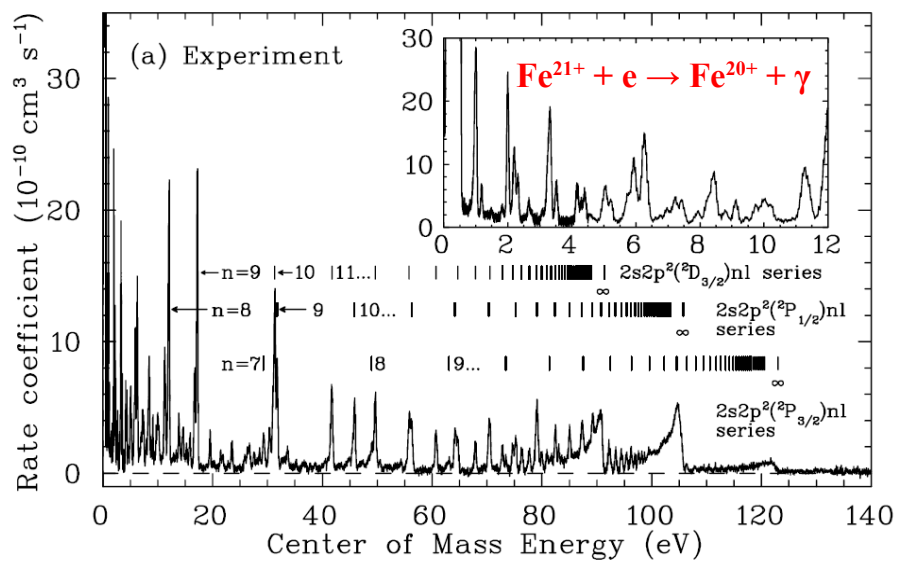
Recombination rates of HCI in astrophysical plasma




[Savin, ApJ 489 (1997)]

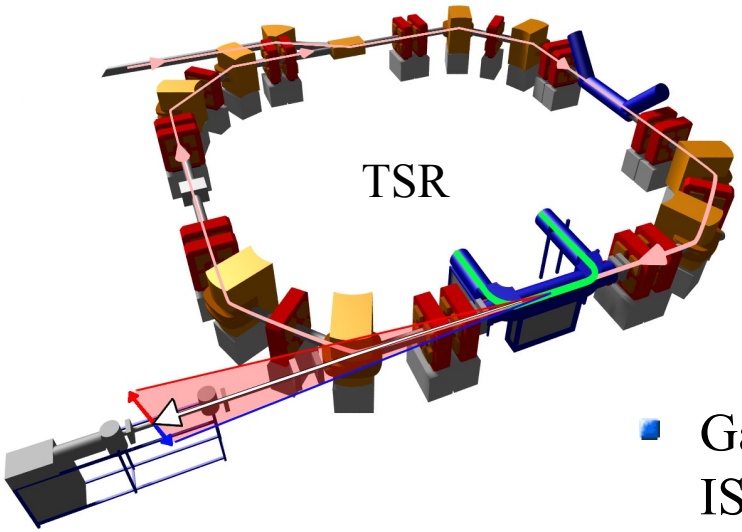
Electron Cooler

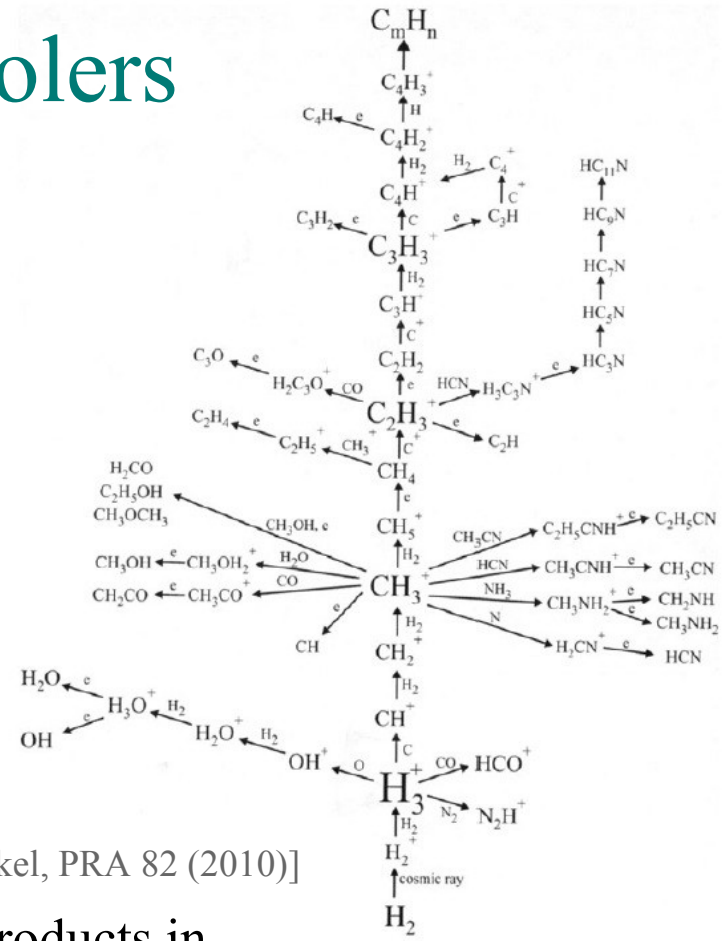
The Heidelberg Electron Cooler Storage Ring TSR




[Savin, ApJ Suppl. Ser. 147 (2003)]

# Electron Coolers




- Gas-phase chemistry in ISC:

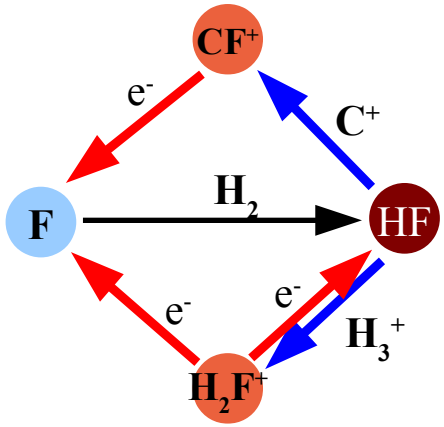
  $\mathbf{H_3^+ + e \rightarrow H + H + H}$

  e.g. [Petrignani, PRA 83 (2011); Kreckel, PRA 82 (2010)]

- A source of energetic products in cold environments

  $\mathbf{H_3O^+ + e \rightarrow H_2O^{**} + H}$ [Buhr, PRL 105 (2010)]

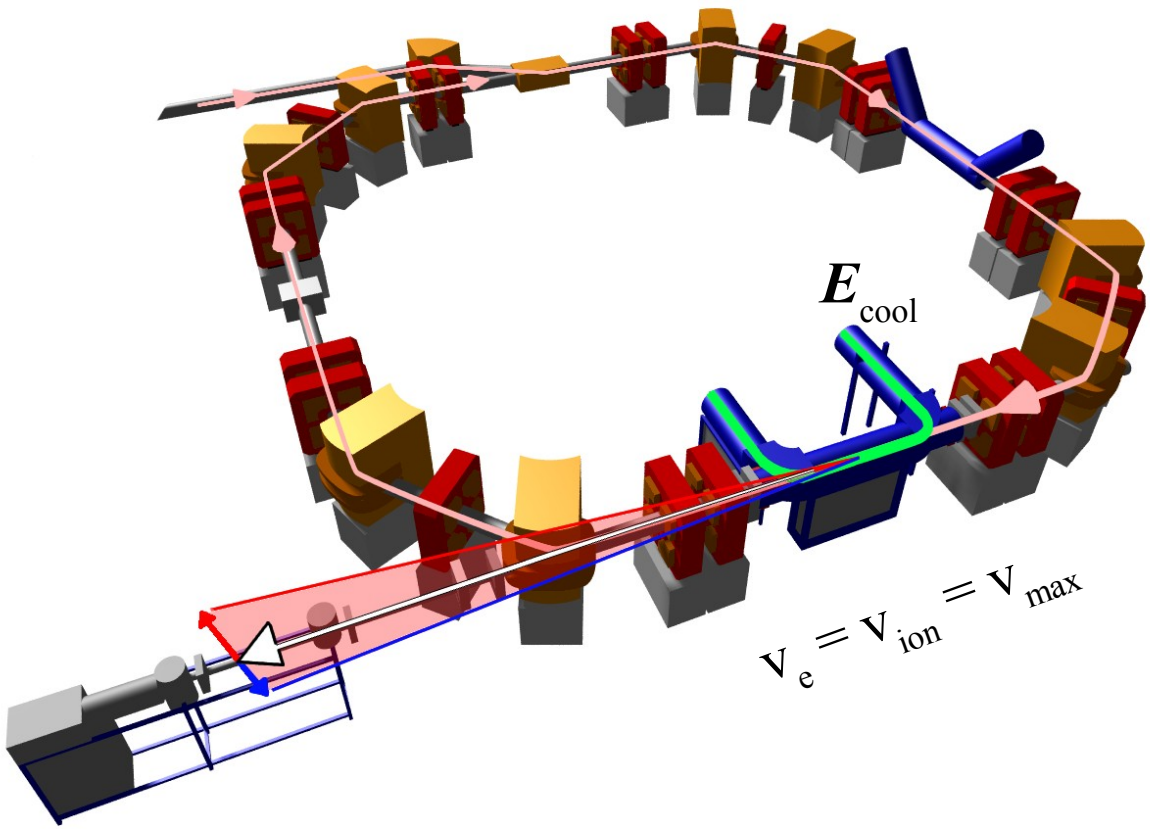
  $\mathbf{HCNH^+ + e \rightarrow HCN/CNH^{**} + H}$ [Mendes, ApJ Lett. 746 (2012)]




- Molecular proxy for $H_2$: HF

  $\mathbf{H_2 + 2\,F \rightarrow 2\,HF + \mathit{E}}$ [Novotný, t.b.p.]

# Electron cooling of molecular (slow!) ions




- Maximum rigidity: $r\,B_{max}$
  for TSR: ≈ 1.4 Tm

- Maximum velocity:

$$v_{max} = \frac{Z_{ion}}{M_{ion}}\, r\, B_{max} \rightarrow E_{cool} \sim \frac{Z_{ion}^2}{M_{ion}^2}$$

e.g. $CHD^+$ (15 u) : $E_{cool} \sim 230$ eV
$D_3O^+$ (22 u) : $E_{cool} \sim 110$ eV
$DCND^+$ (30 u) : $E_{cool} \sim 55$ eV

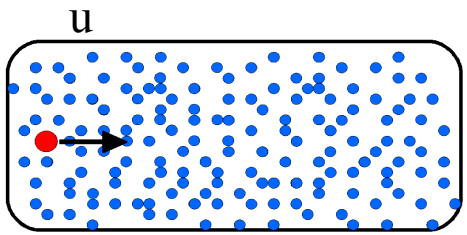
- But: $I_e \sim E_{cool}^{3/2}$ !

  electron density **degrades**

  ion beam lifetime **degrades**

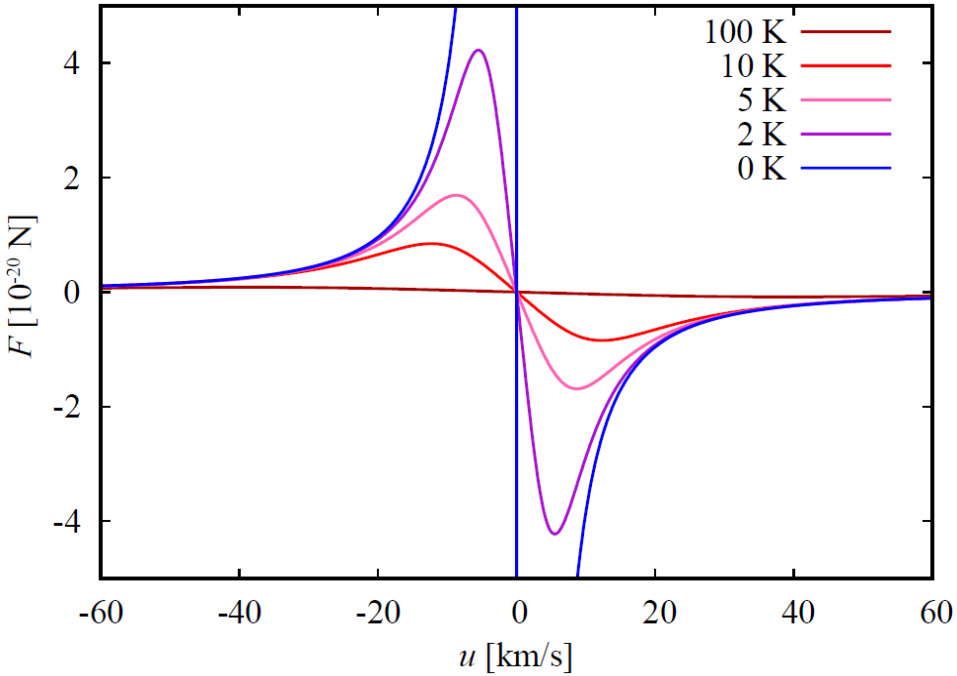
- There is a **practical** $M_{ion,max}$
  Ion loss rate exceeds
  electron cooling rate ...

# Cooling force

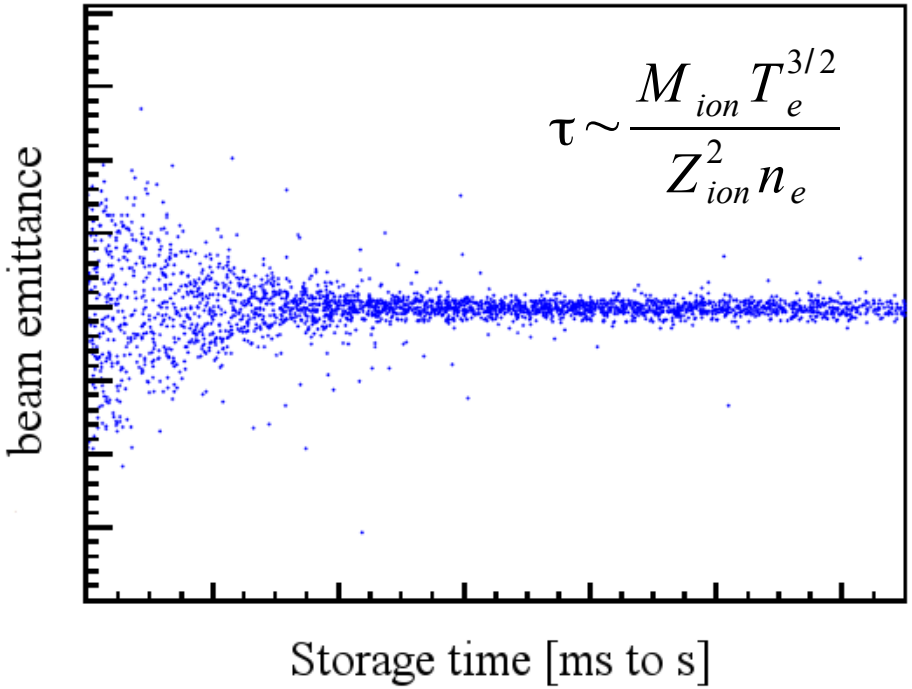



"Stopping time"

Electron temperature




Cooling time




$$\tau \sim \frac{M_{ion} T_e^{3/2}}{Z_{ion}^2 n_e}$$

Molecular ions:

$M_{ion}$ → **large**

$Z_{ion}$ → **1**

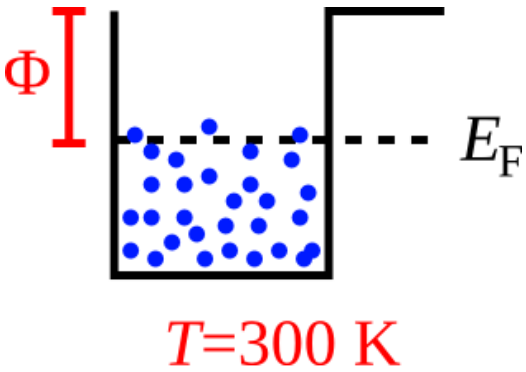
$n_e$ → **limited ($I \sim U^{3/2}$)**

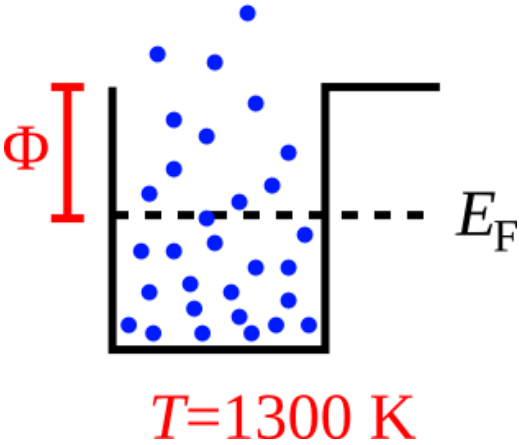
$T_e$ → **??**

# Cold cooler electron source

Standard cooler electron source:
**thermionic cathode**

$$J \sim T^2 \exp\left(\frac{-\Phi}{k_B T}\right)$$



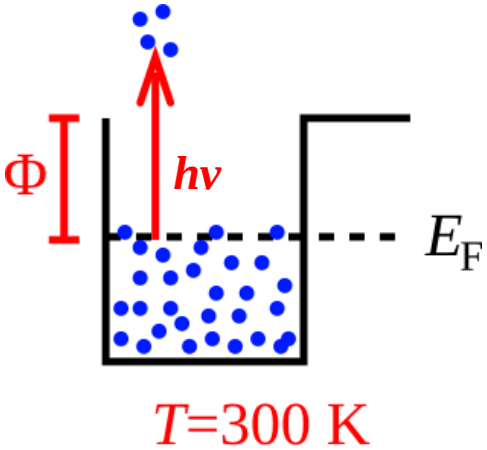

established technology
high $J$ are possible …

high electron-$T$
**($k_B T$ > 100 meV)**

# Cold cooler electron source

TSR electron cooler:
**GaAs:(Cs/O) photocathodes**

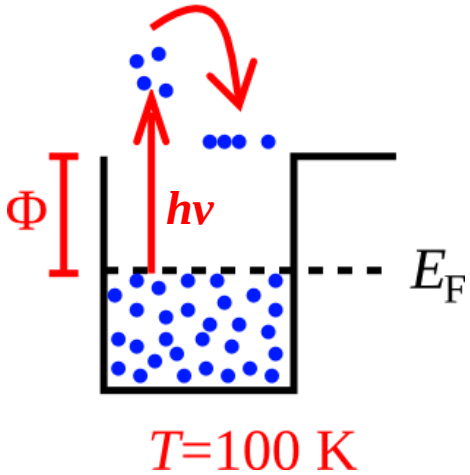
- Electrons overcome Φ by **absorbtion of photons** ($h\nu > \Phi$)




- *Negative Electron Affinity* (**NEA**)
  e's can **thermalise to a state close to vacuum energy**.

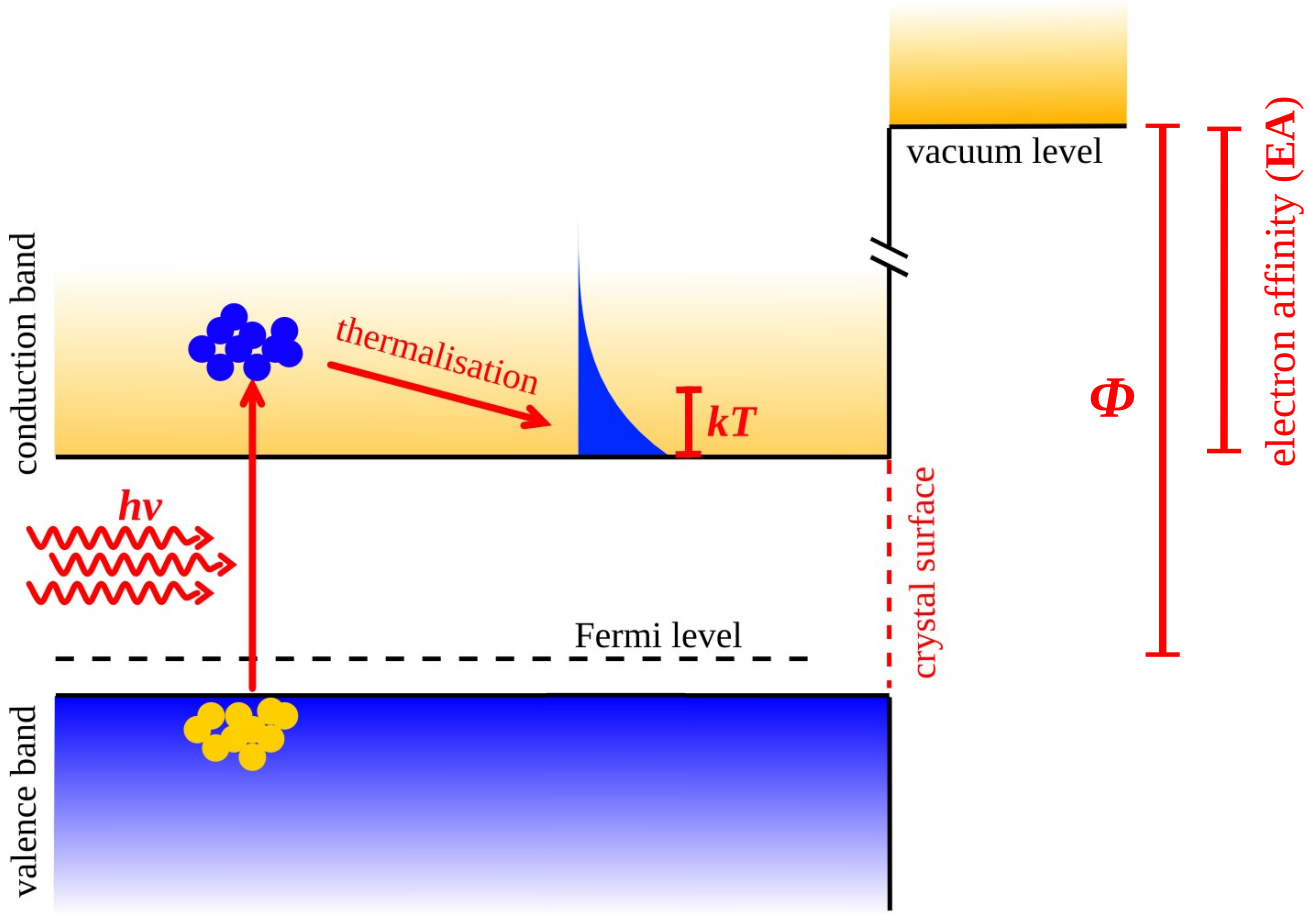
$$T_e \sim T_{cath}$$

**($k_B T \approx 10$ meV)**



# GaAs:(Cs/O) electron source

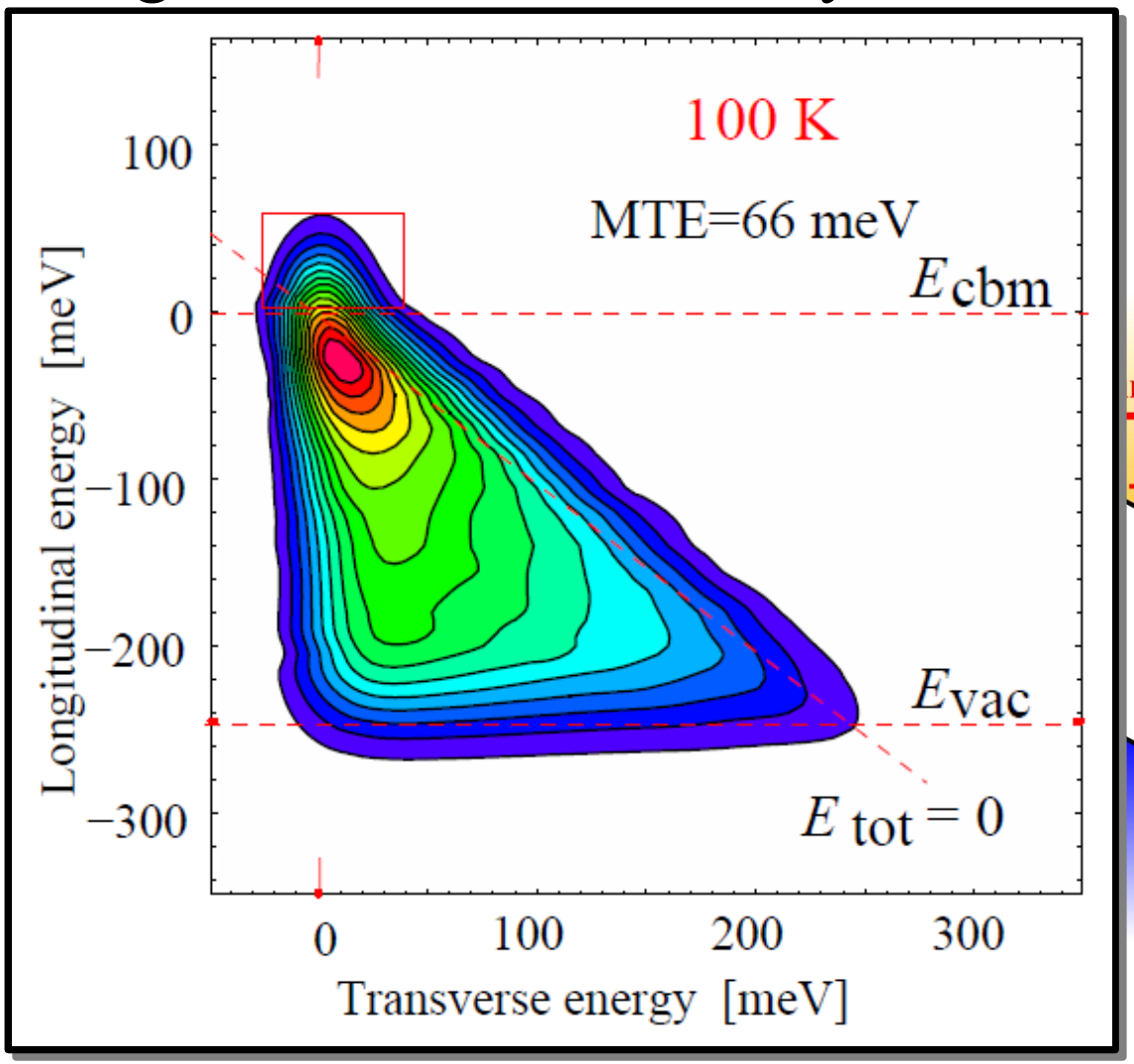
- Negative Electron Affinity:



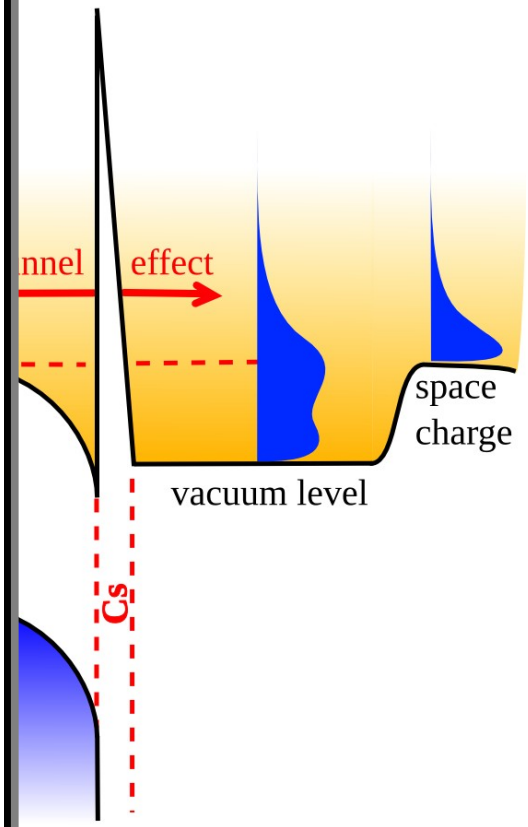

*p*-GaAs

# GaAs:(Cs/O) Electron Source

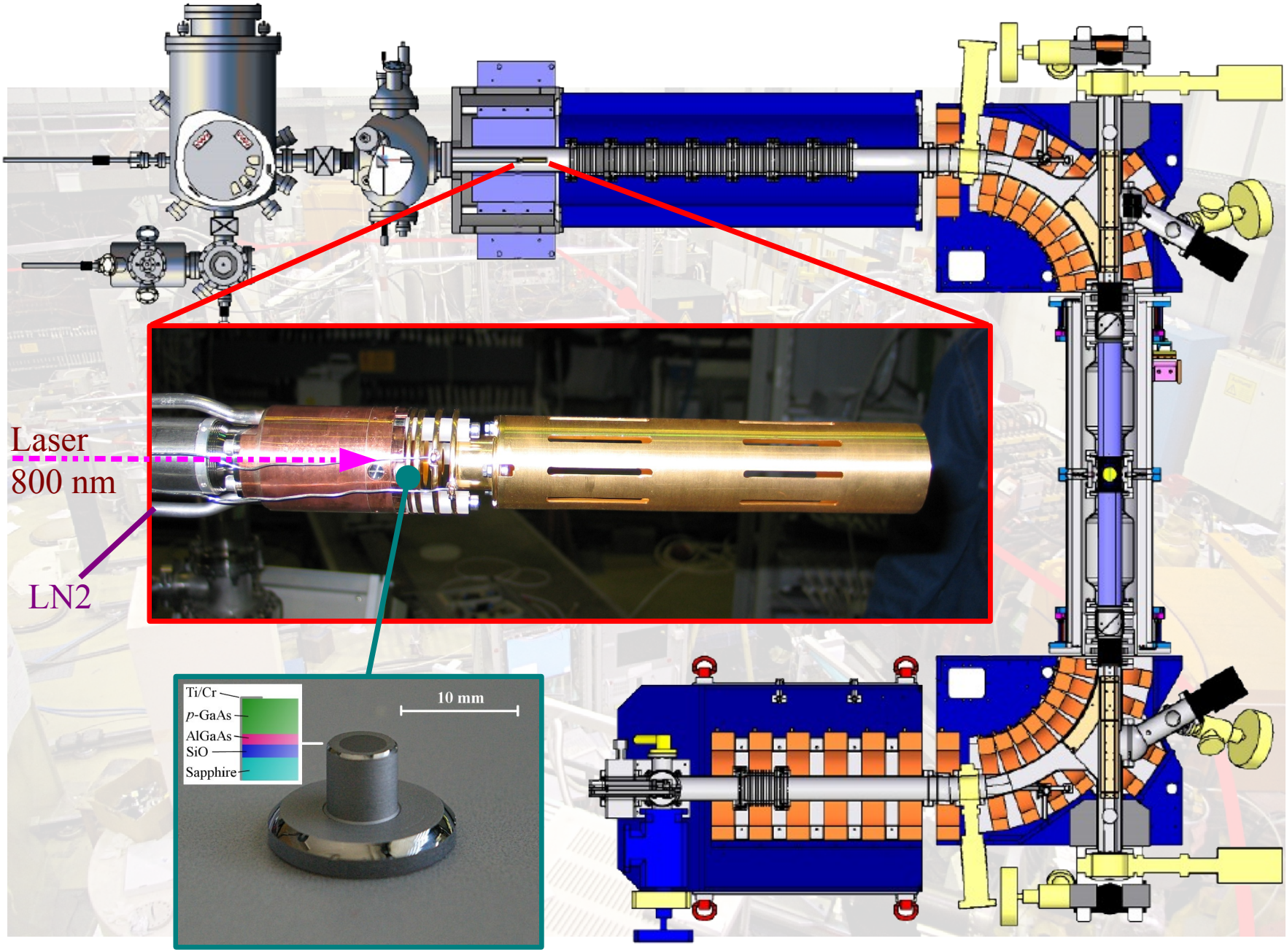
- Negative Electron Affinity:



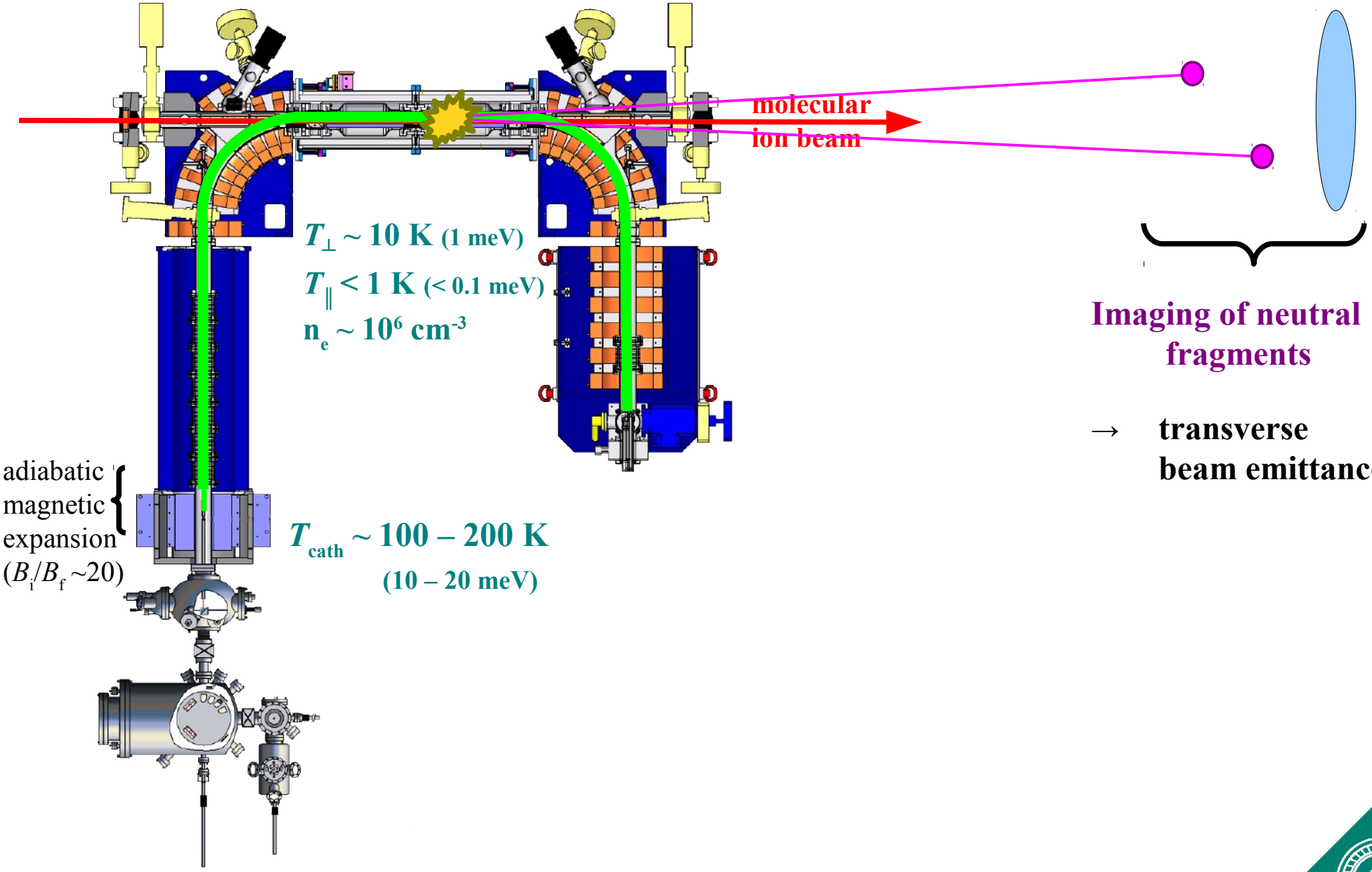

[D.A. Orlov, Appl. Phys. Lett 78 (2001), 2721]



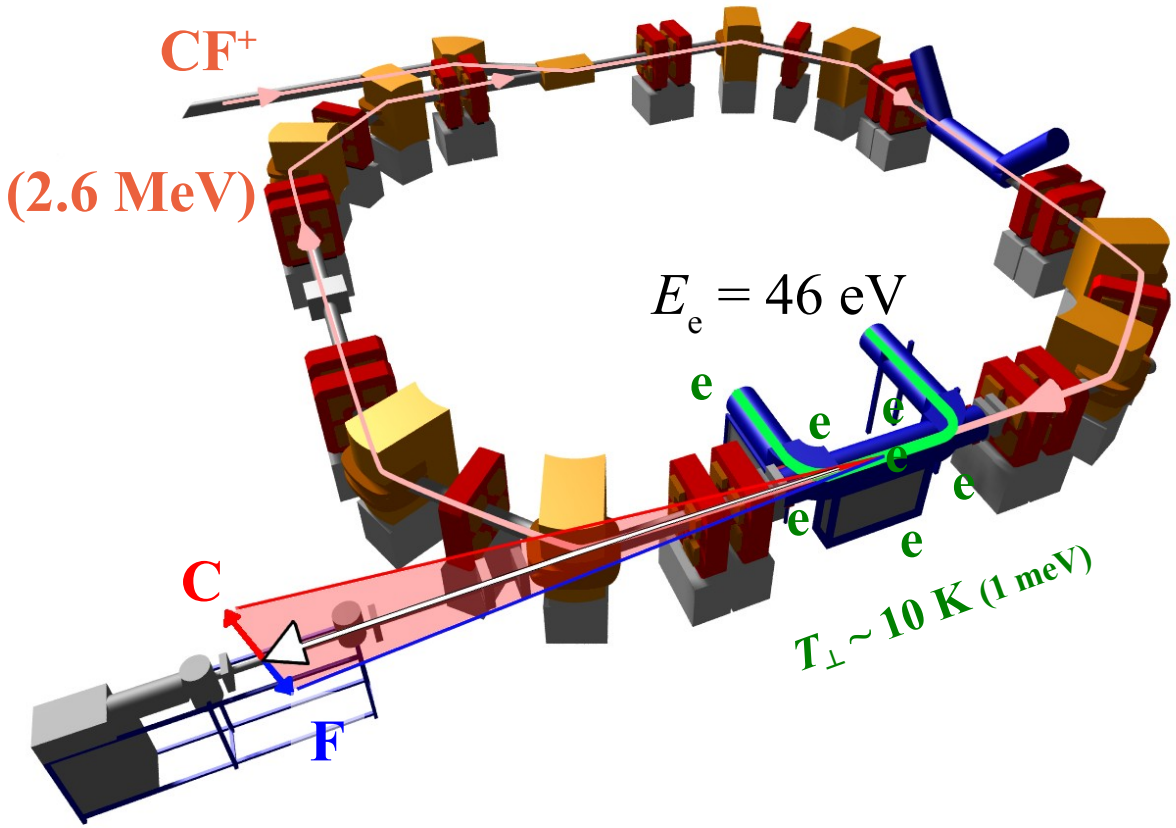
# Photo-cathode electron cooler

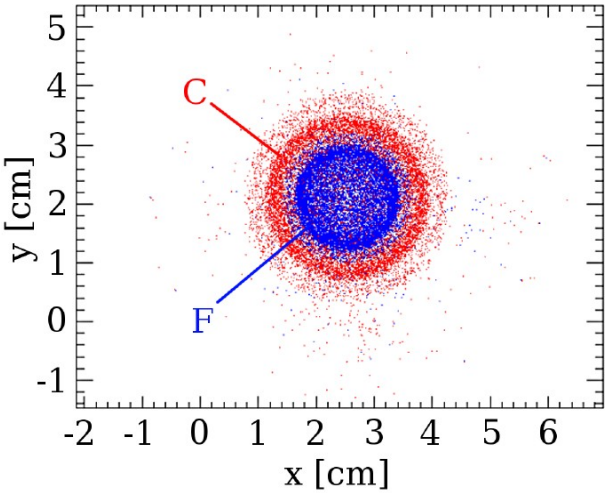


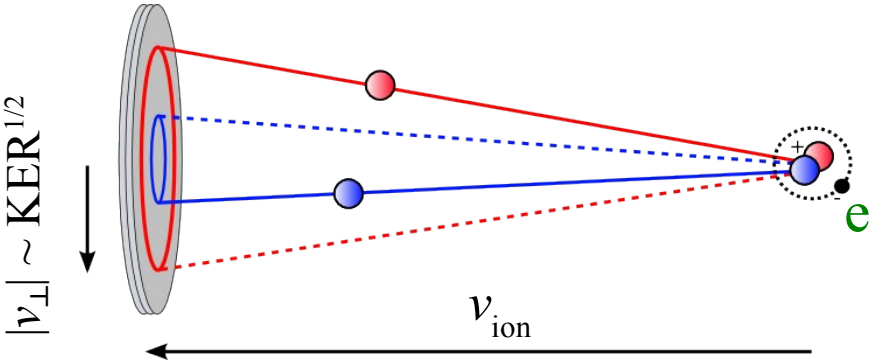
# Electron cooling at low velocity



# Electron cooling at low velocity



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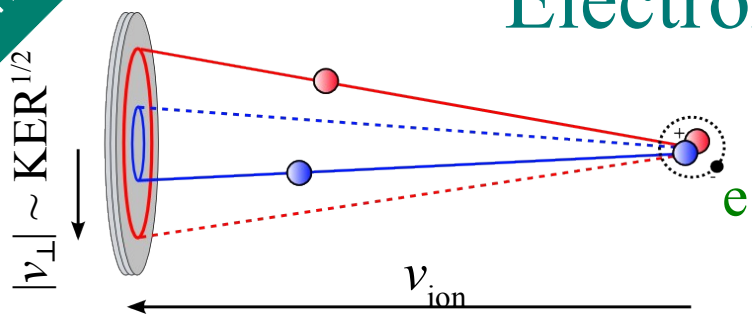


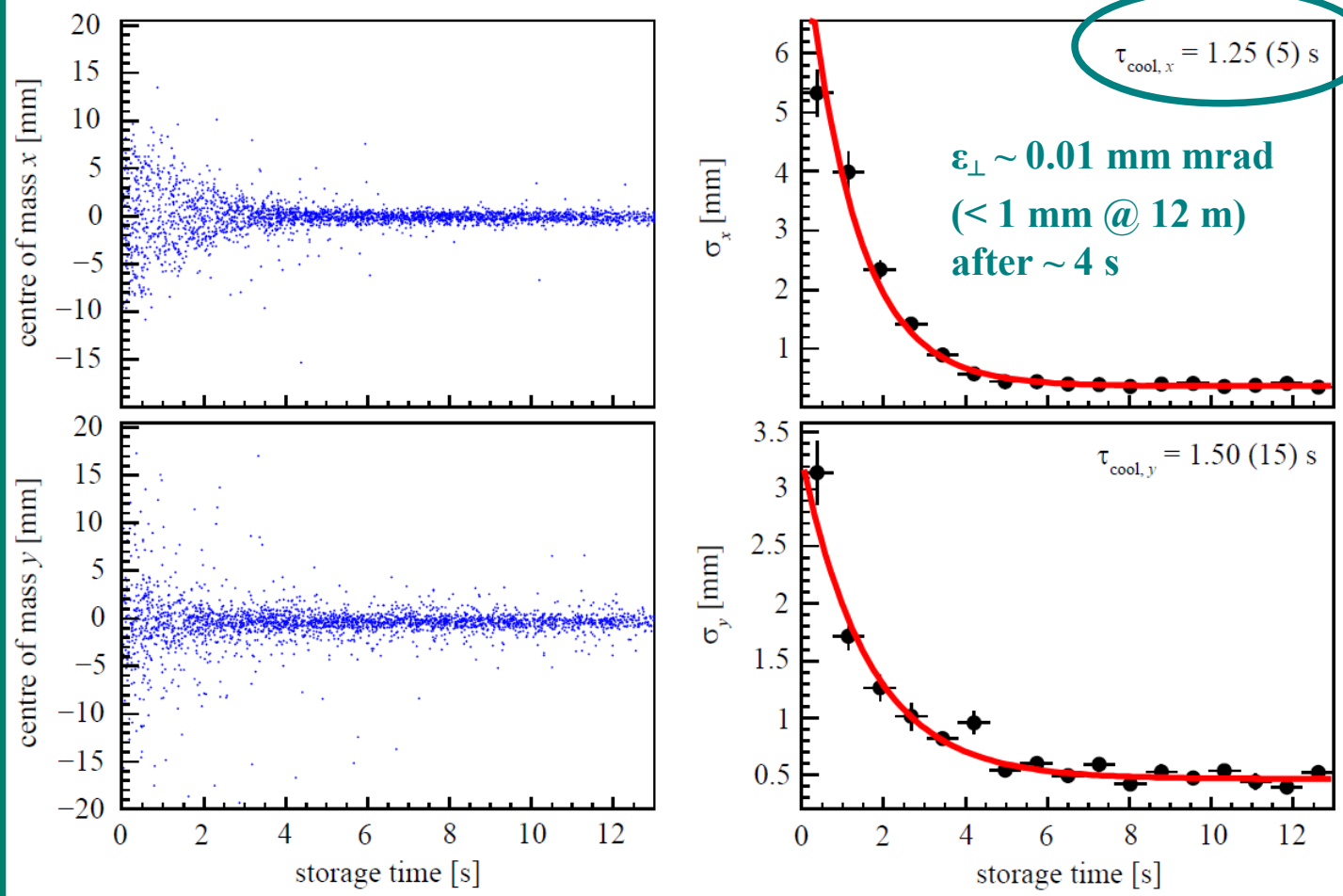

$$\tau \sim \frac{M_{ion} T_e^{3/2}}{Z_{ion}^2 n_e}$$

fits with

$T_{e,\perp}$ = 15 (3) K

We **need** a cold electron source!

Cooling $CF^+$ at $E_e$ = 46 eV




~~expected for thermionic electron cooler:~~

~~($T_\perp$ ~ 100 K)~~

~~$\tau$ ~ 30 s~~

~~(longer than ion lifetime)~~

# Electron cooling at low velocity

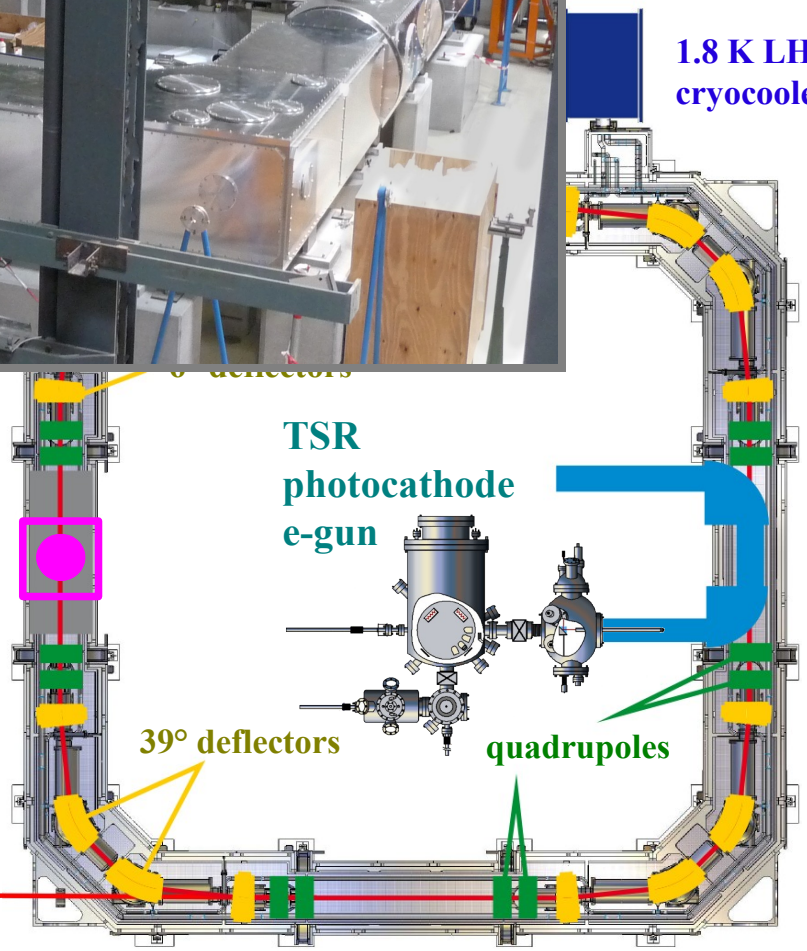
| | |
|---|---|
| $H_3^+$ | $E_e = 735$ eV |
| $HD_2^+$ | $E_e = 327$ eV |
| $CHD^+$ | $E_e = 231$ eV |
| $HF^+$ | $E_e = 125$ eV |
| $D_3O^+$ | $E_e = 112$ eV |
| $DCND^+$ | $E_e = 56$ eV |
| $N_2D$ | $E_e = 50$ eV |
| $HS^+$ | $E_e = 47$ eV |
| $CF^+$ | $E_e = 46$ eV |
| $^{18}O^{16}O^+$ | $E_e = 43$ eV |
| $HCl^+$ | $E_e = 40$ eV |
| $HCl^+$ | $E_e = 37$ eV |
| $D_2Cl^+$ | $E_e = 30$ eV |

We are approaching the limit of the TSR storage ring.

# ...age Ring (CSR)

@ MPIK

with cooling: 1 … 160 u



# Thank you!

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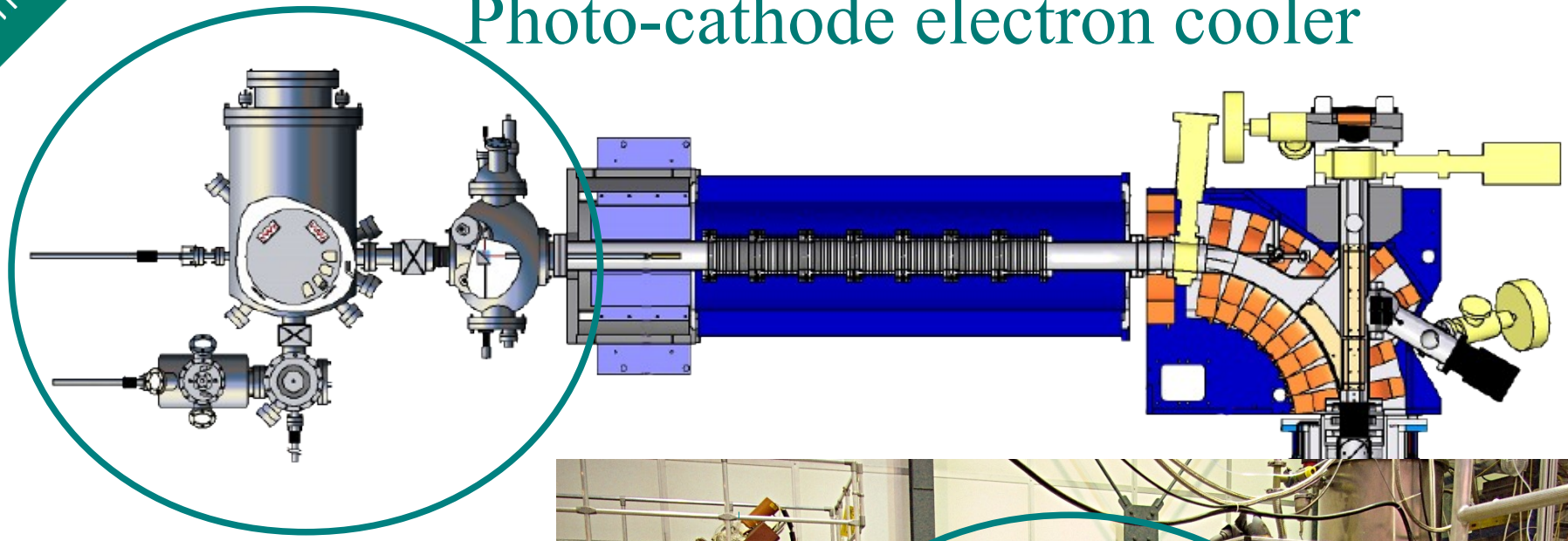
Daniel W. Savin

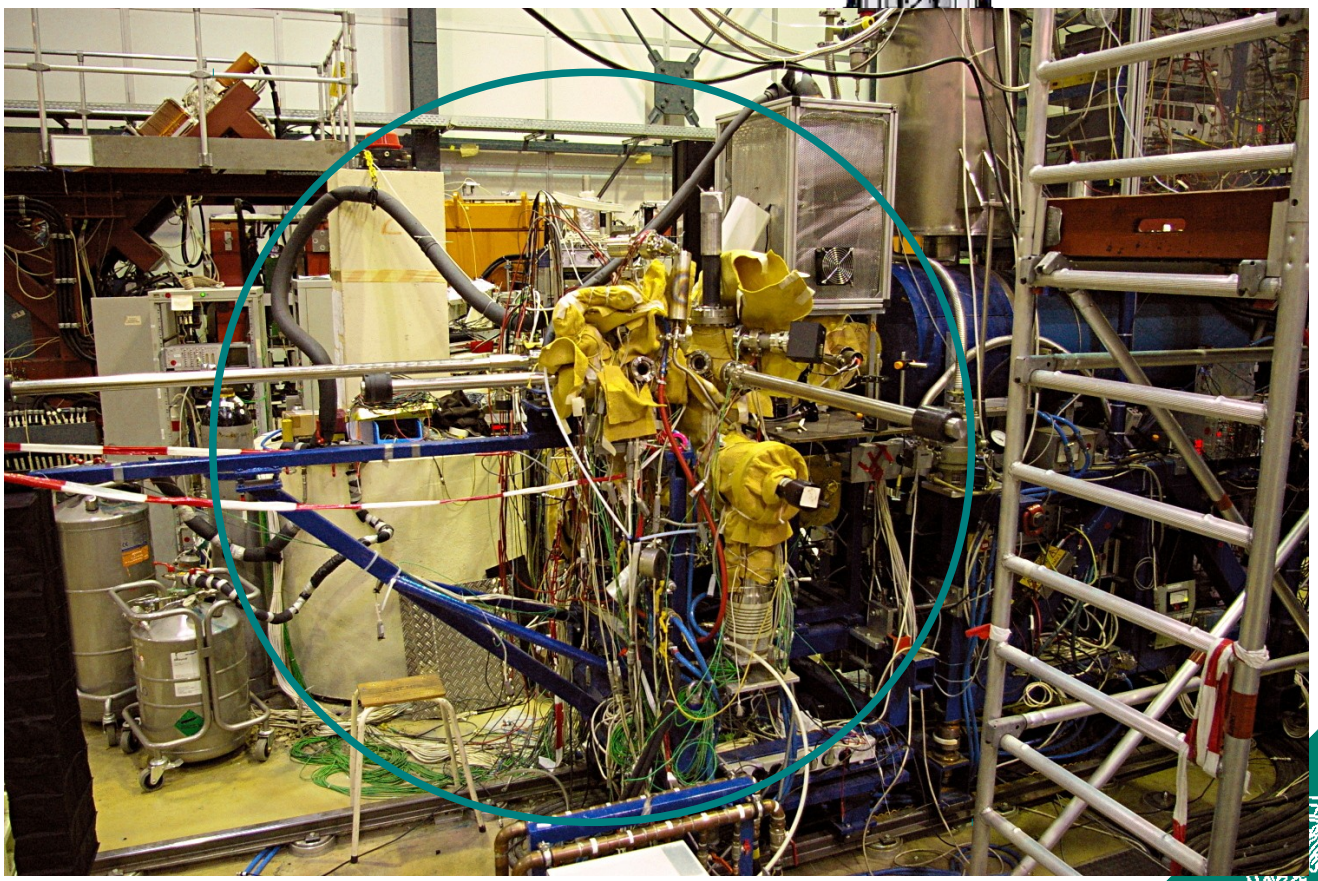
**Justus-Liebig Universität, Giessen**

Kaija Spruck

Stefan Schippers

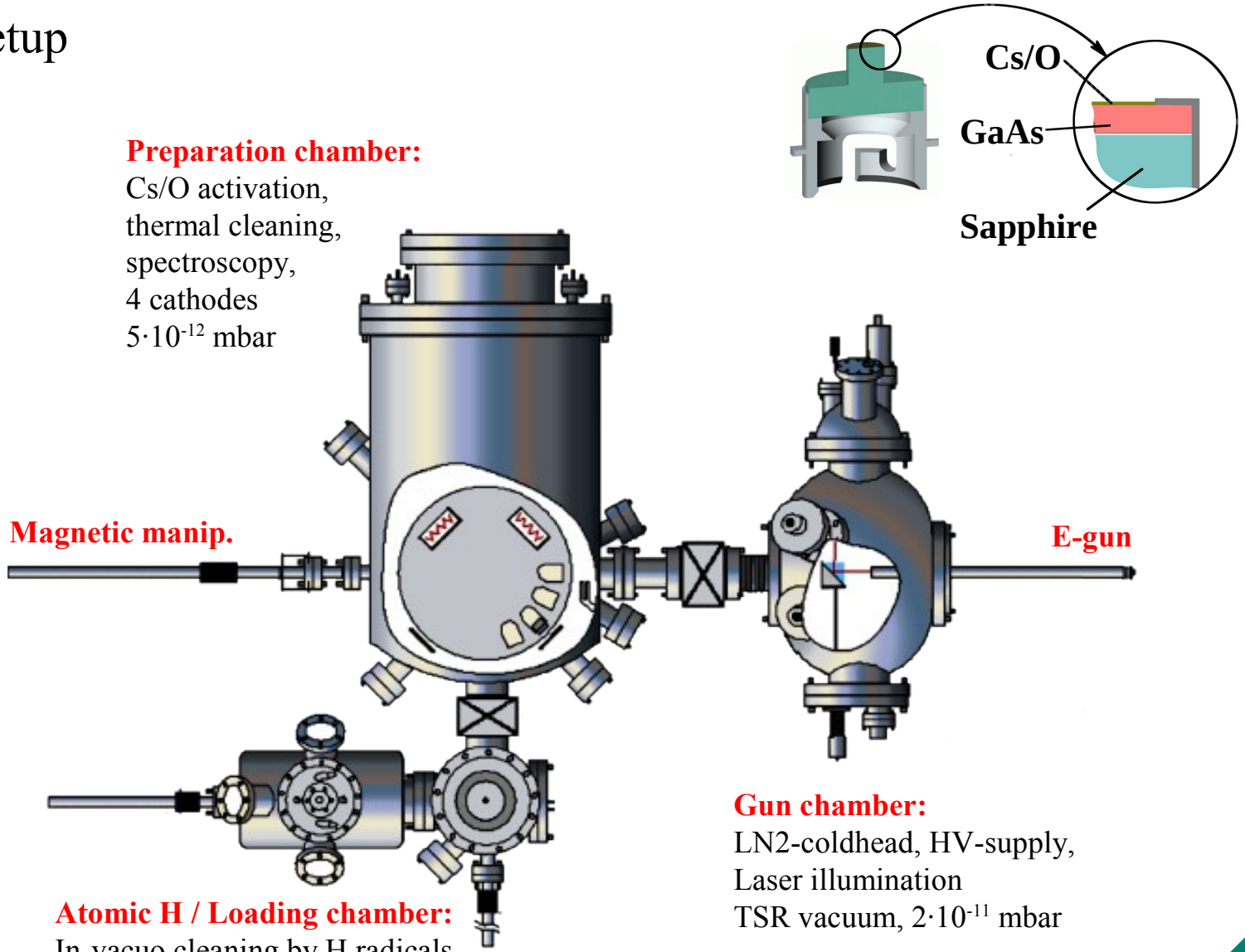
# Photo-cathode electron cooler





# Photo-cathode electron cooler

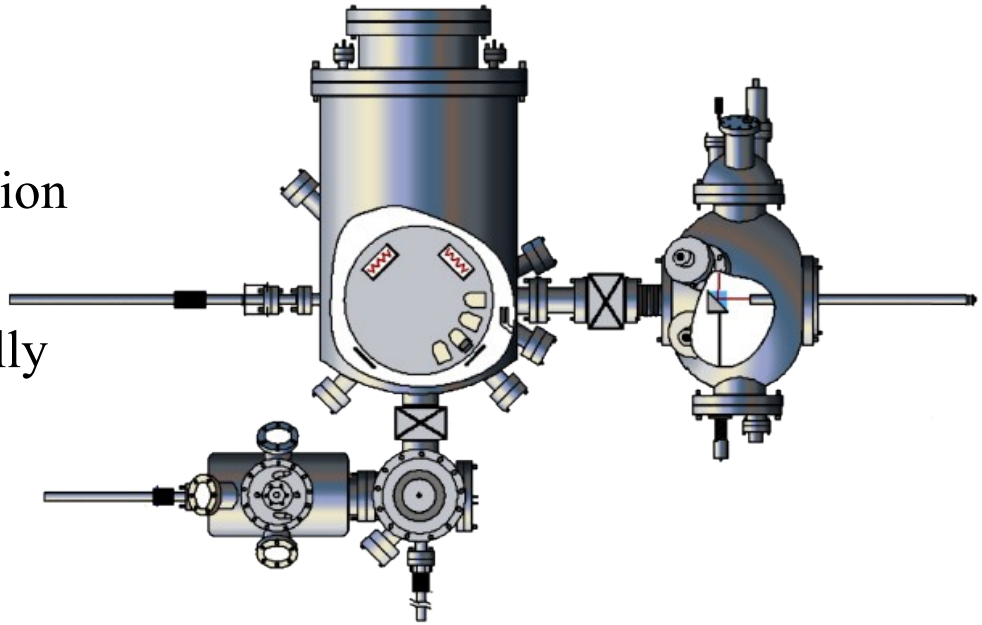
## Photocathode setup

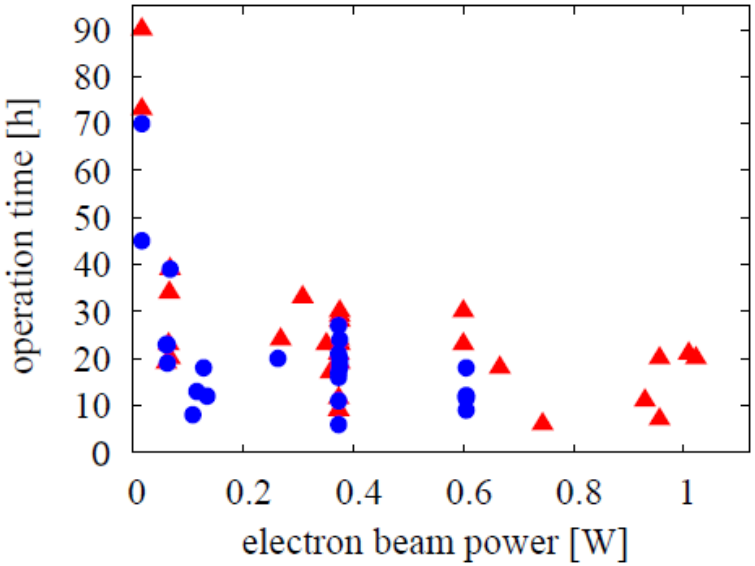


# Photo-cathode electron cooler

## Electron beam performance

- In vacuum **closed-cycle** operation
- re-activation of cathode typically after 1 day of operation
  (for molecular ion beams)
- typical $n_e \sim 10^6$ **cm**$^{-3}$
- cathode **lifetime** $\sim (I_e U_{cool})^{-1}$
  vacuum degradation ...





# Photo-cathode electron cooler

## Surface cleaning by H radicals

- Cathode **cleaning by bakeout** can be done **3-4 times**.
  (non-volatile Ga- and As-oxides accumulate on the surface.)
  → **Gradual decrease of the quantum efficiency**.

- Ga-oxides can be removed by

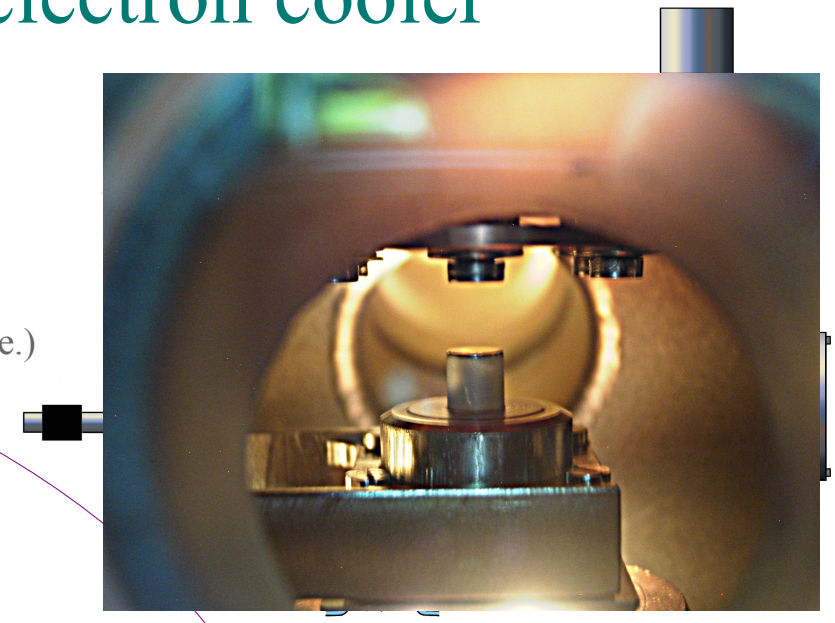
  1. etching in HCl solution.
     → **Requires removal of cathode from setup**. ☹

  2. Exposure to **H• radicals** in vacuum

$$Ga_2O_3 + 4\ H \rightarrow Ga_2O + 2\ H_2O\ ,$$

$$As_2O_3 + 6\ H \rightarrow 3\ H_2O + As_2\left(\frac{1}{2}\ As_4\right)$$

→ **Cathode can stay in vacuum.** ☺



[Orlov, J. Appl. Phys. 106 (2009)]