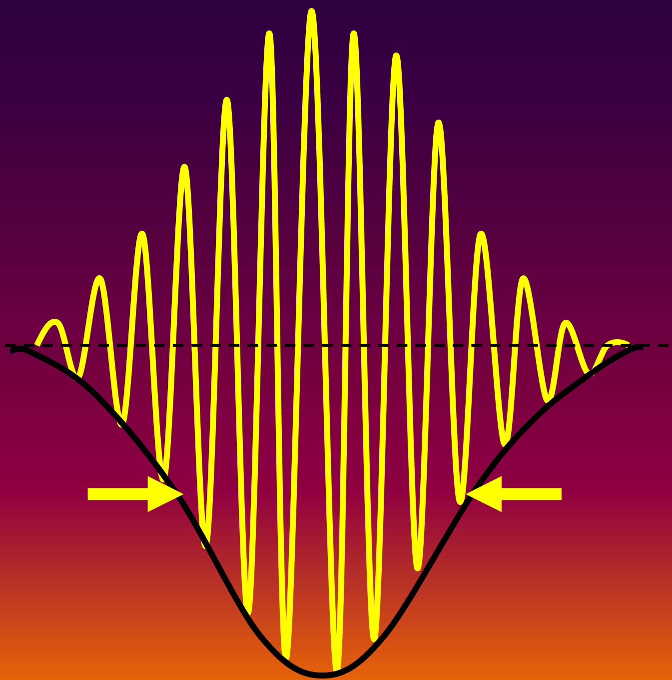
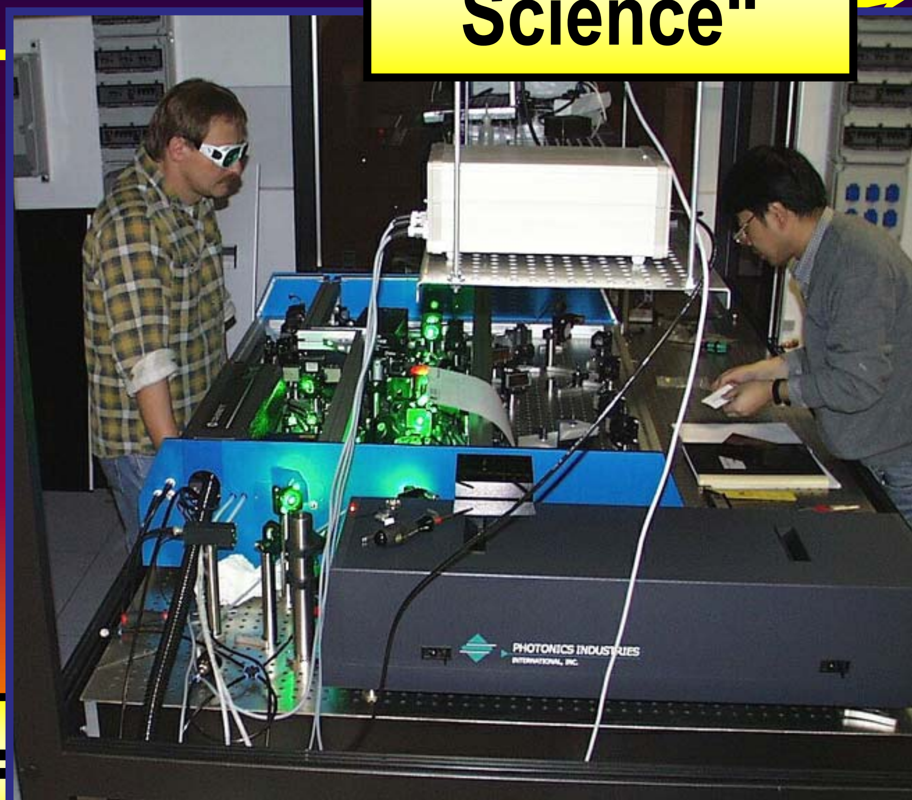
Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

I ≥ 10^{15} W/cm^2

„Attosecond Science“

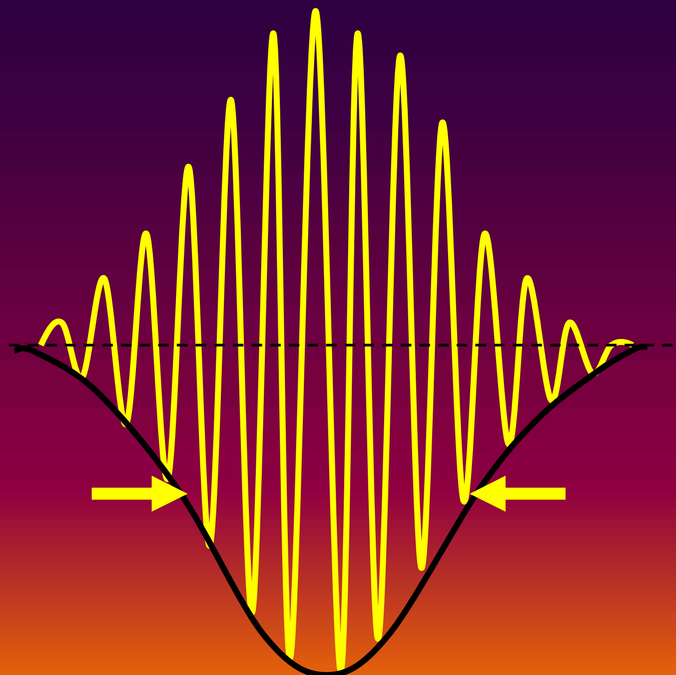




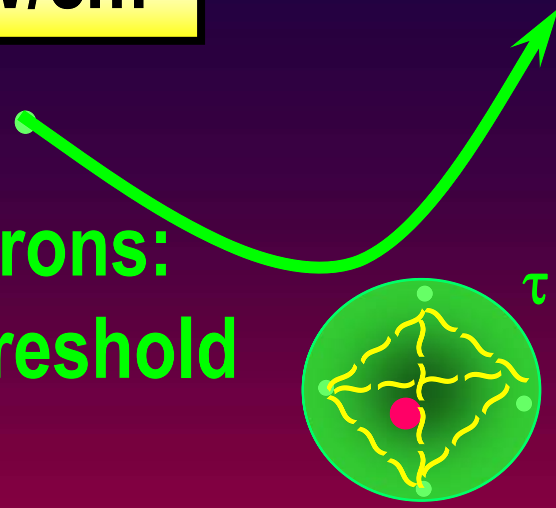
t =30 …6… 3.5 fs

Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

$I \geq 10^{15}$ W/cm^2



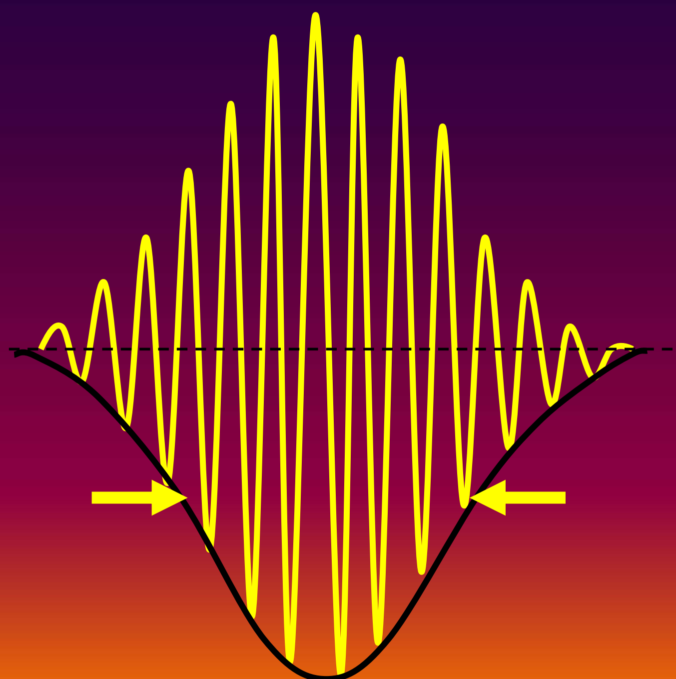
t =30 …6… 3.5 fs

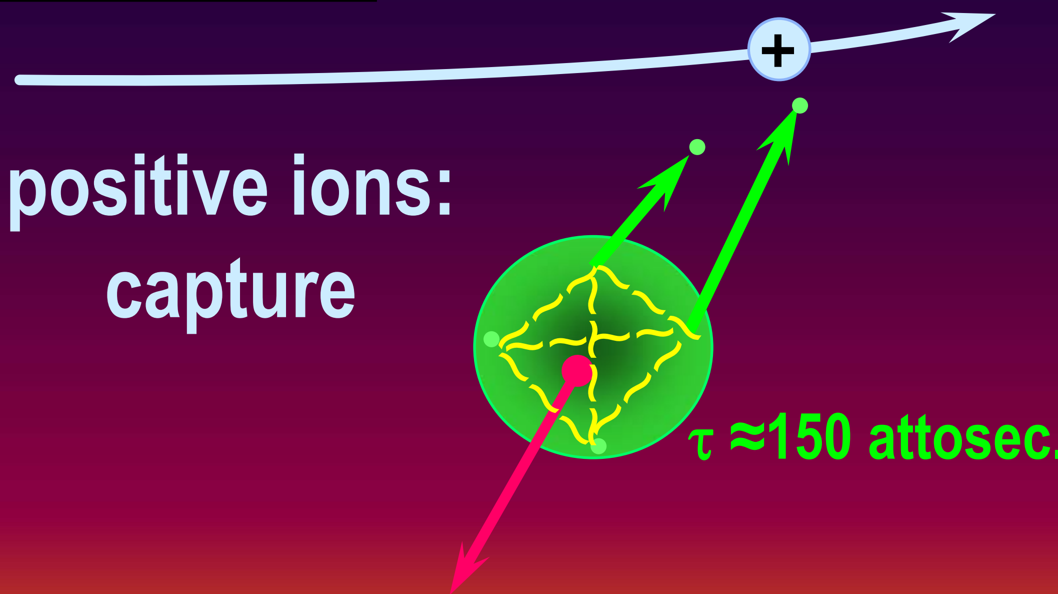


t = 5 fs…0.01as

Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

$I \geq 10^{15}$ W/cm^2

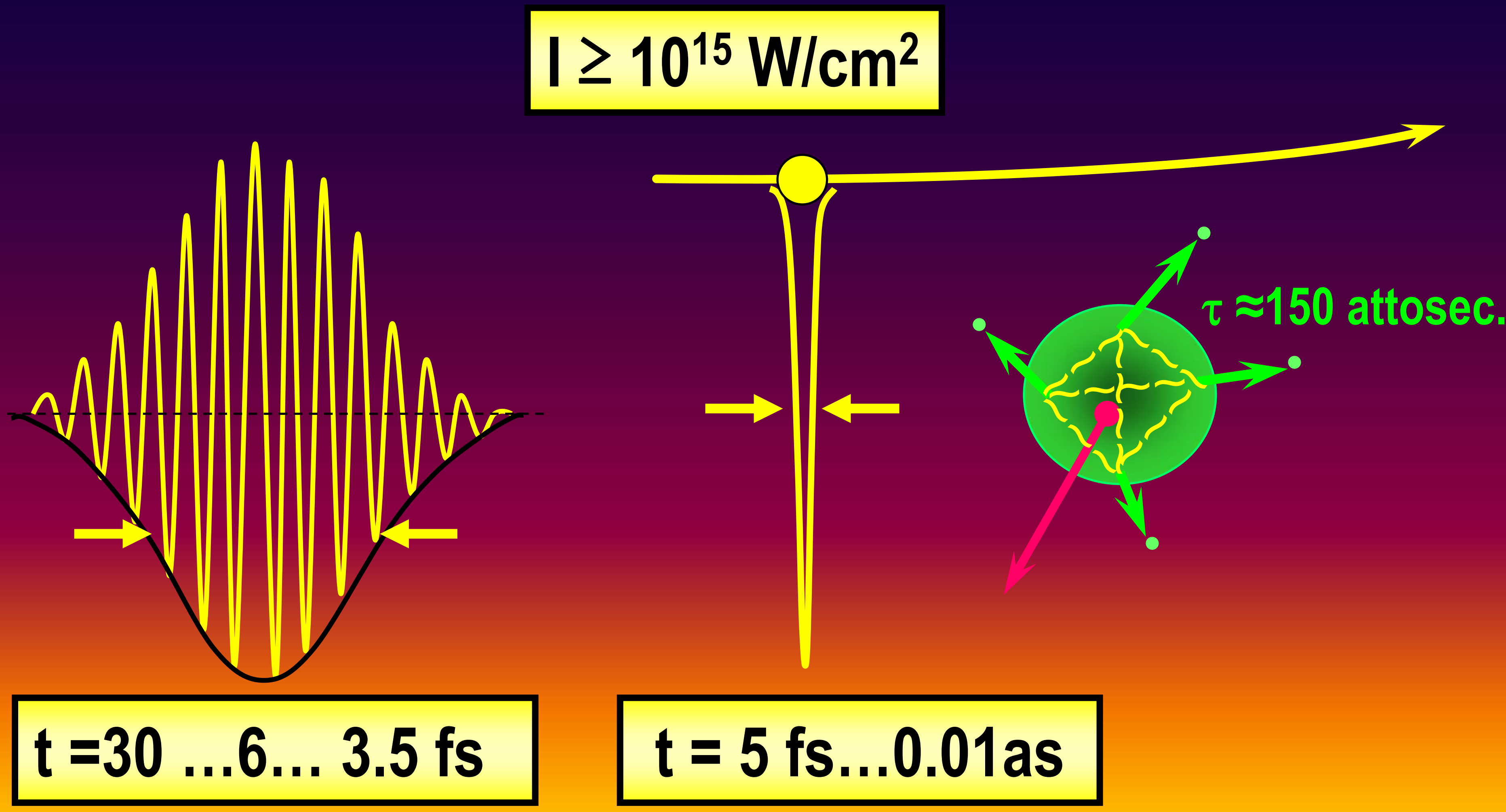




t =30 …6… 3.5 fs

t = 5 fs…0.01as

Sub-Femtosecond Correlated Dynamics Probed with Antiprotons



Why do we care?

Max–Planck–Institut für Kernphysik

Dirac 1929: *„The general theory of quantum mechanics is now almost complete...” “The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known,.....“*

Why do we care?

Max-Planck-Institut für Kernphysik

Dirac 1929:

Why do we care?

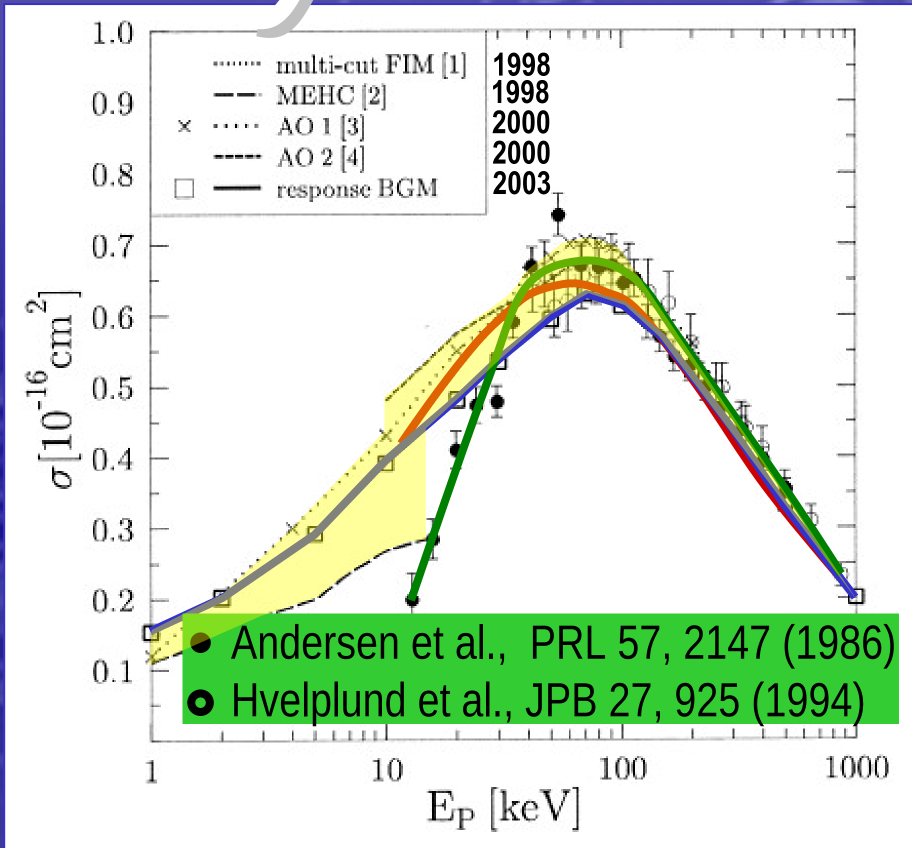
Max–Planck–Institut
für Kernphysik

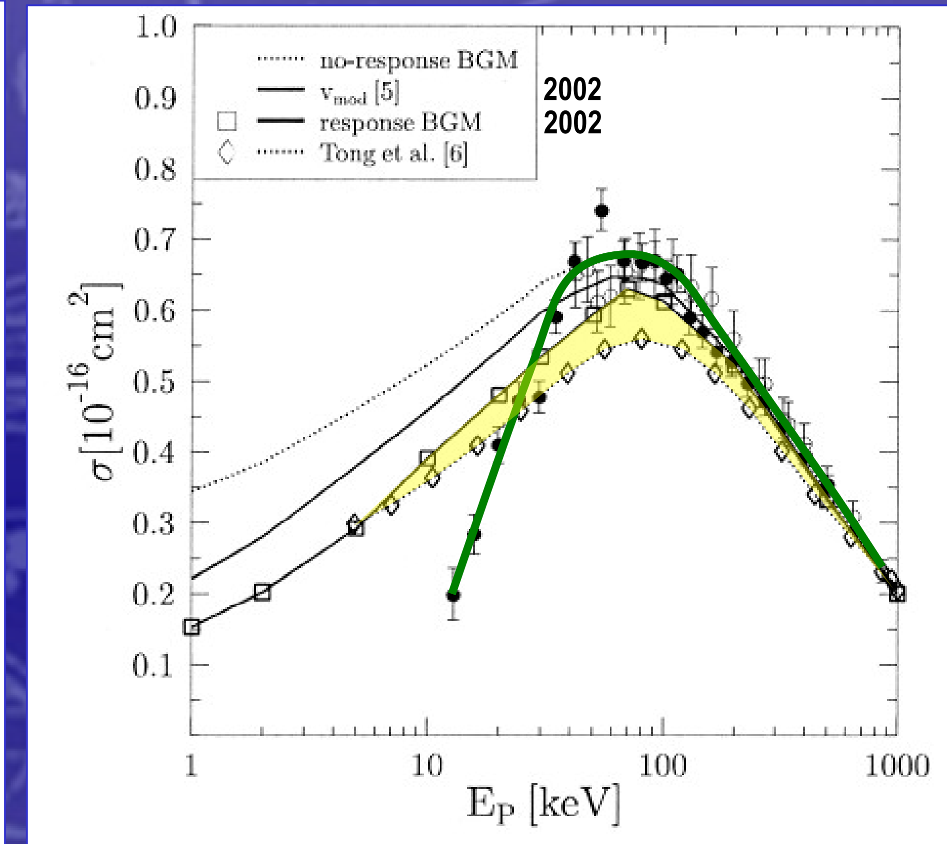
The three-body Coulomb problem solved

- Rescigno, Mc Curdy: Science 1999

Why do we care?

Max–Planck–Institut für Kernphysik

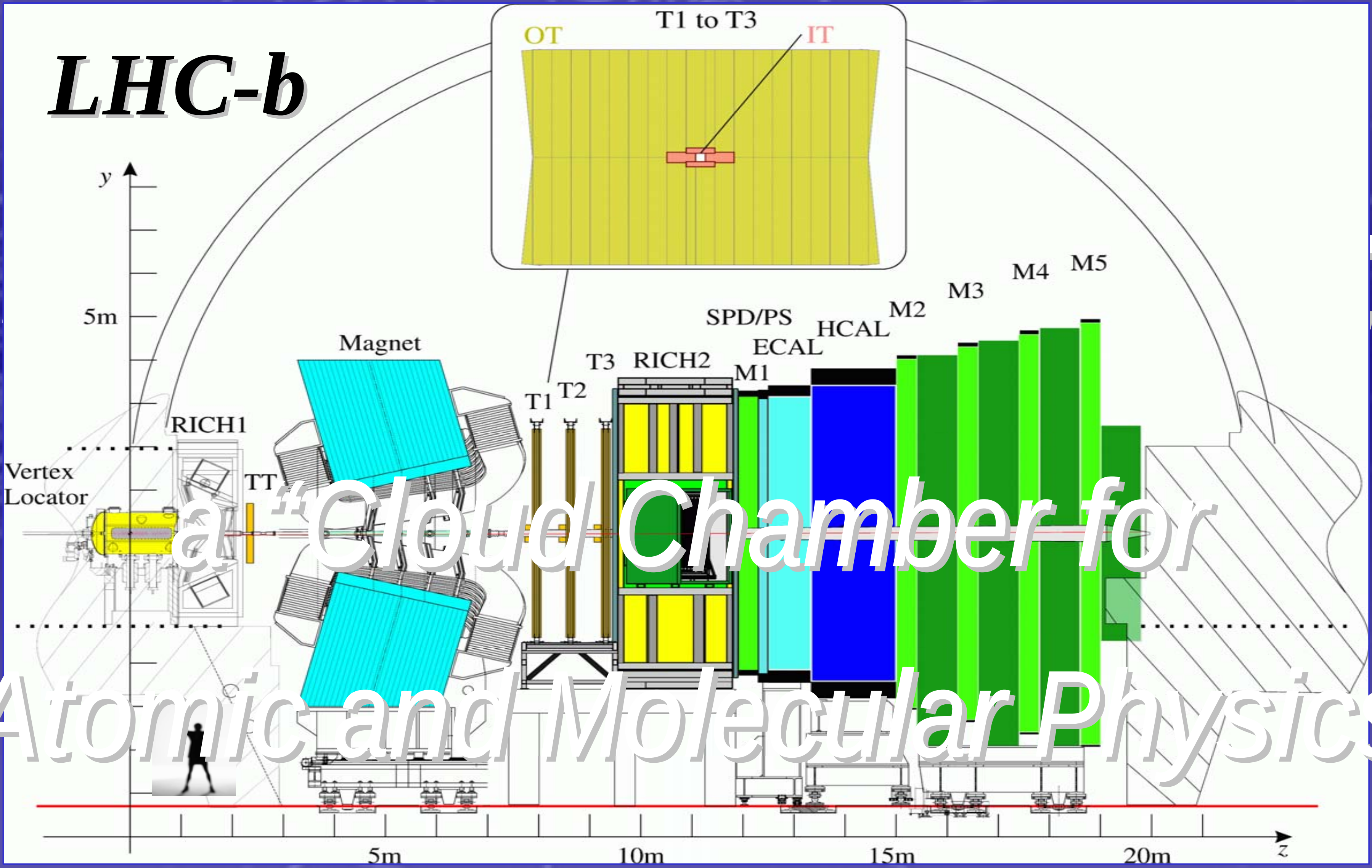




Benchmark system for ionization in the presence of correlation

Not understood even for total cross sections!
What about (fully) differential cross sections?

How do we care?



a “Cloud Chamber for Atomic and Molecular Physics

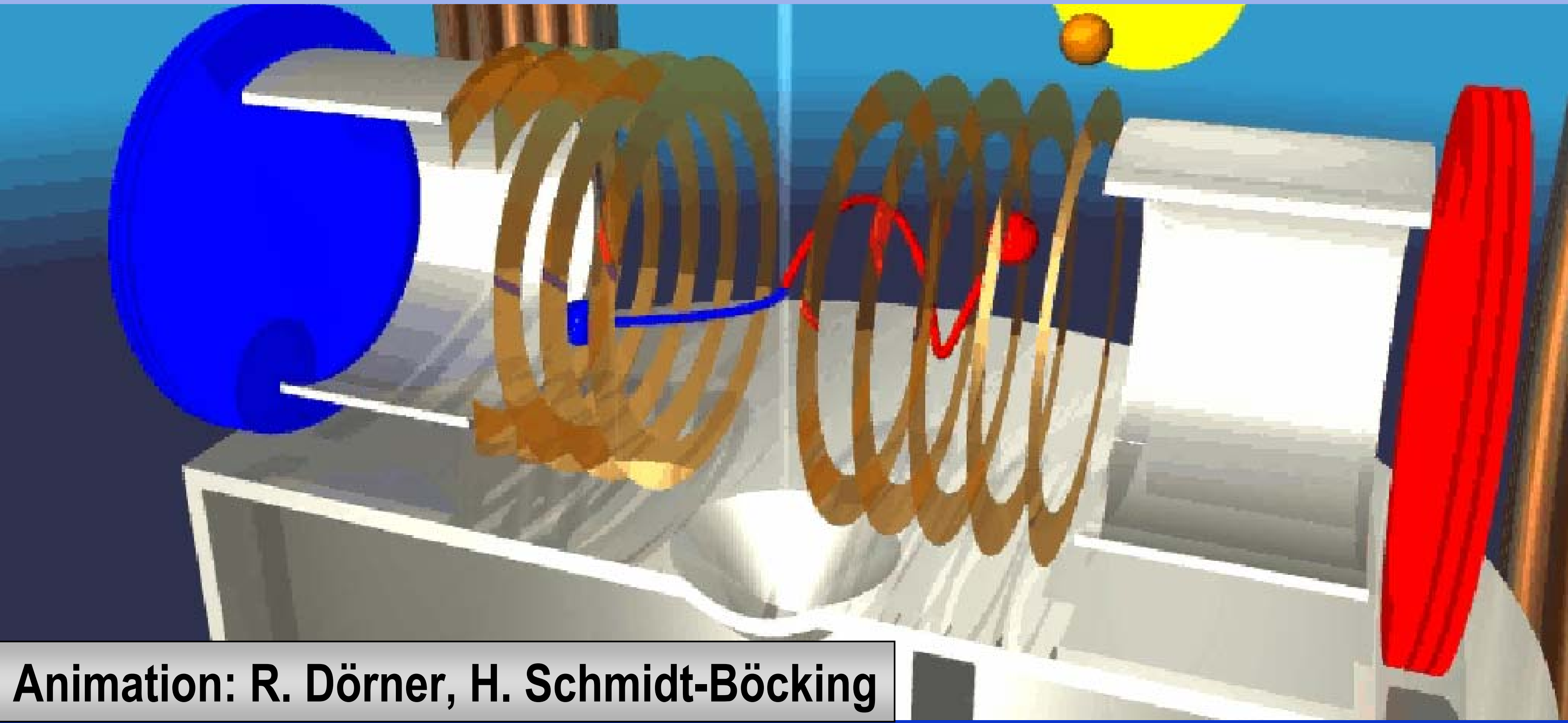
Outline of the Talk

Max-Planck-Institut für Kernphysik

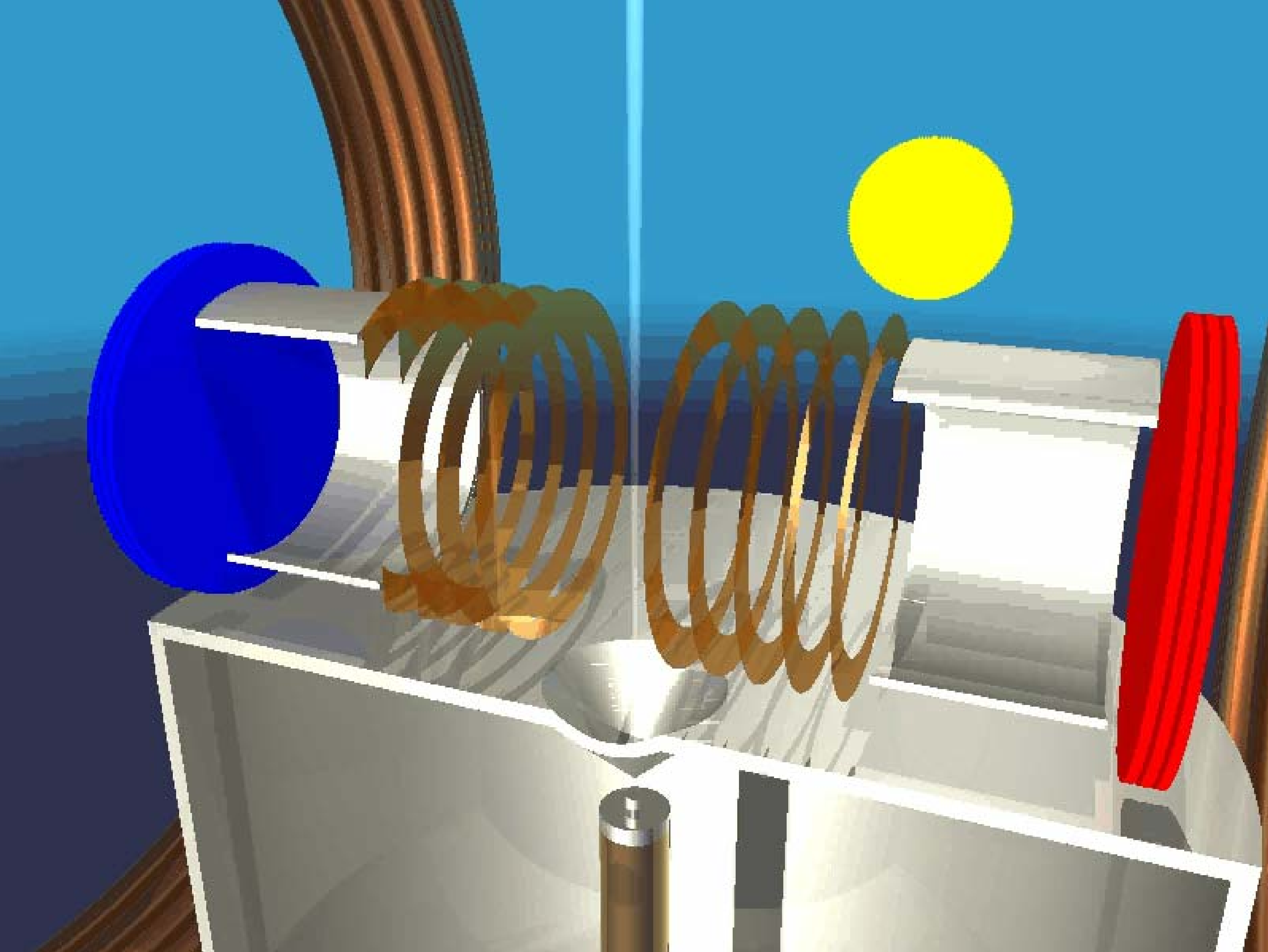
- Reaction Microscopes
- Single Ionization
- Double Ionization
- Antiproton Capture
- How to do the Experiments ?
- Plenty of other Reactions !

Reaction Microscopes

The "Cloud Chambers"



Fragmentation in 3D



Outline of the Talk

Max–Planck–Institut
für Kernphysik

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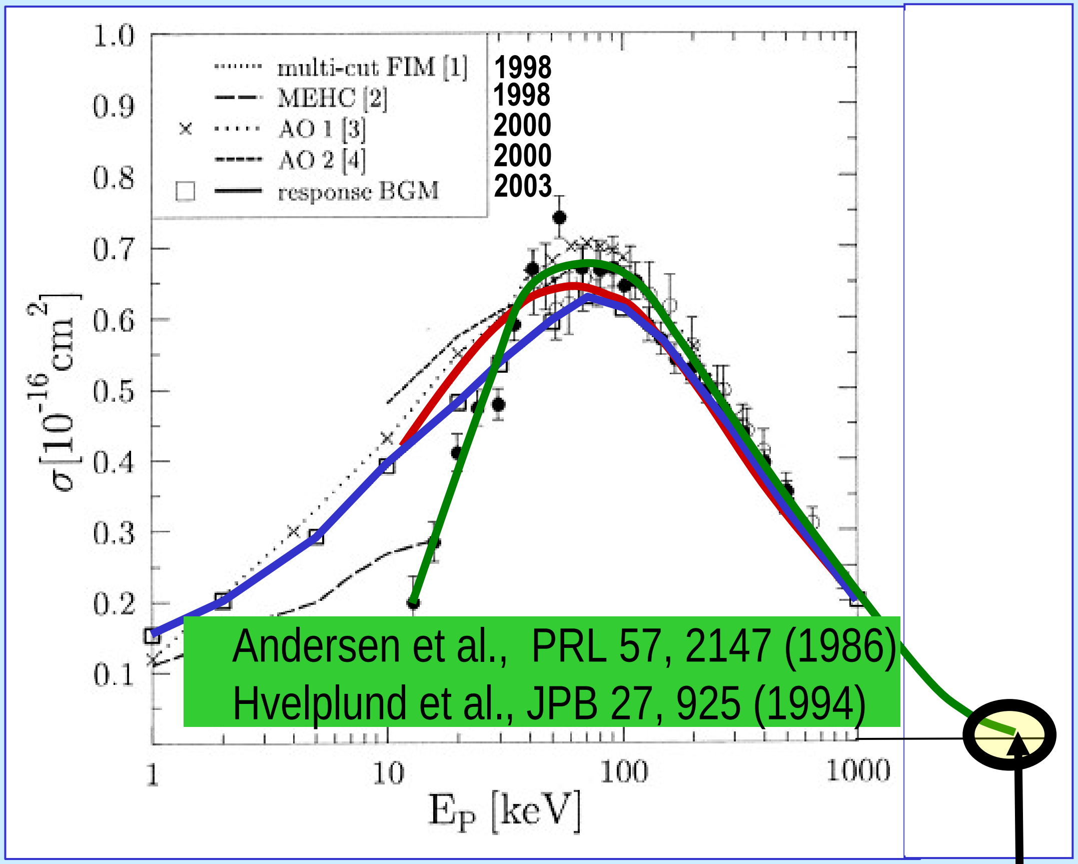
- *How to do the Experiments ?*
- *Plenty of other Reactions !*

Kinematically Complete: Surprise!

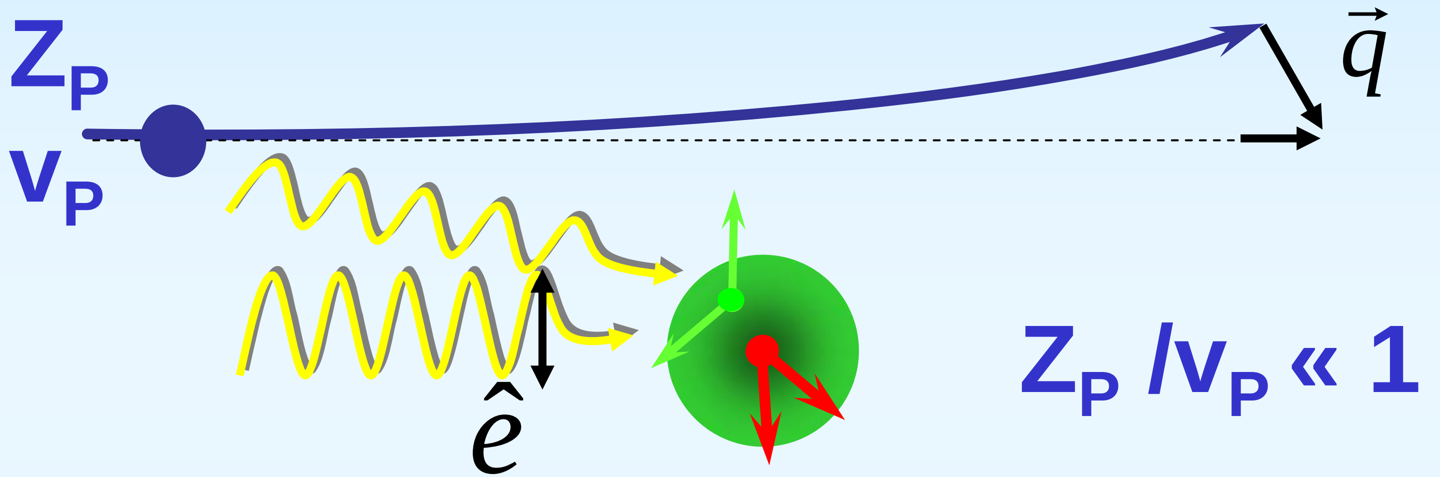


At high energies: weak field limit
- all theories converge
- no proton-antiproton difference

He Single Ionization

Max-Planck-Institut für Kernphysik

From the optical limit to 1st Born



1st Born approximation: Dipole limit

$$d\sigma \propto \left| \left\langle \phi_f \left| e^{i\vec{q}\cdot\vec{r}} \right| \phi_i \right\rangle \right|^2 \approx \left| \left\langle \phi_f \left| \vec{q}\cdot\vec{r} \right| \phi_i \right\rangle + \left\langle \phi_f \left| O(\vec{q}^{\,2}) \right| \phi_i \right\rangle \right|^2$$

Photo-ionization:

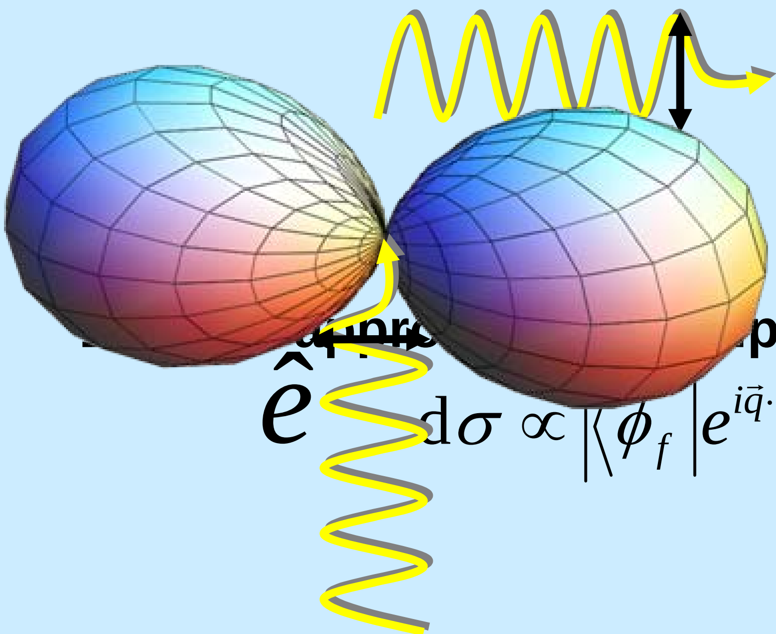
$$d\sigma \propto \left| \left\langle \phi_f \left| \hat{e}\cdot\vec{r} \right| \phi_i \right\rangle \right|^2$$

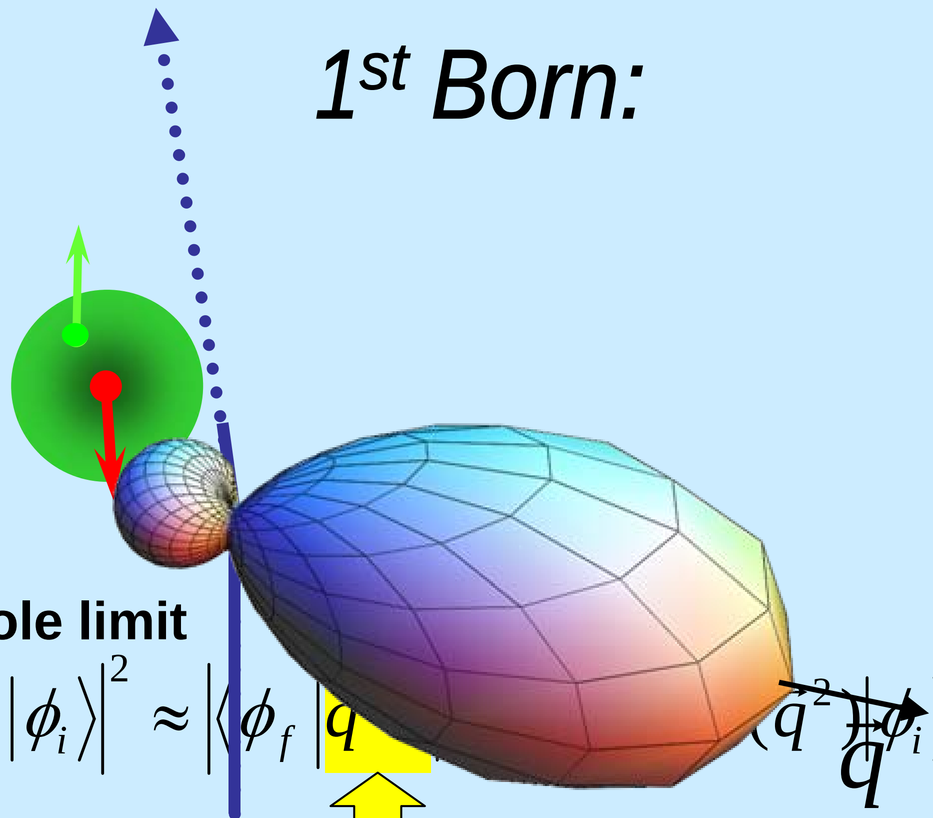
He Single Ionization

Max–Planck–Institut für Kernphysik

Photo-ionization

1st Born:





…pole limit

$$d\sigma \propto \left|\langle \phi_f \left| e^{i\vec{q}\cdot\vec{r}} \right| \phi_i \rangle\right|^2 \approx \left|\langle \phi_f \left| \vec{q} \cdots (\vec{q}^{\,2}) \right| \phi_i \rangle\right|^2$$

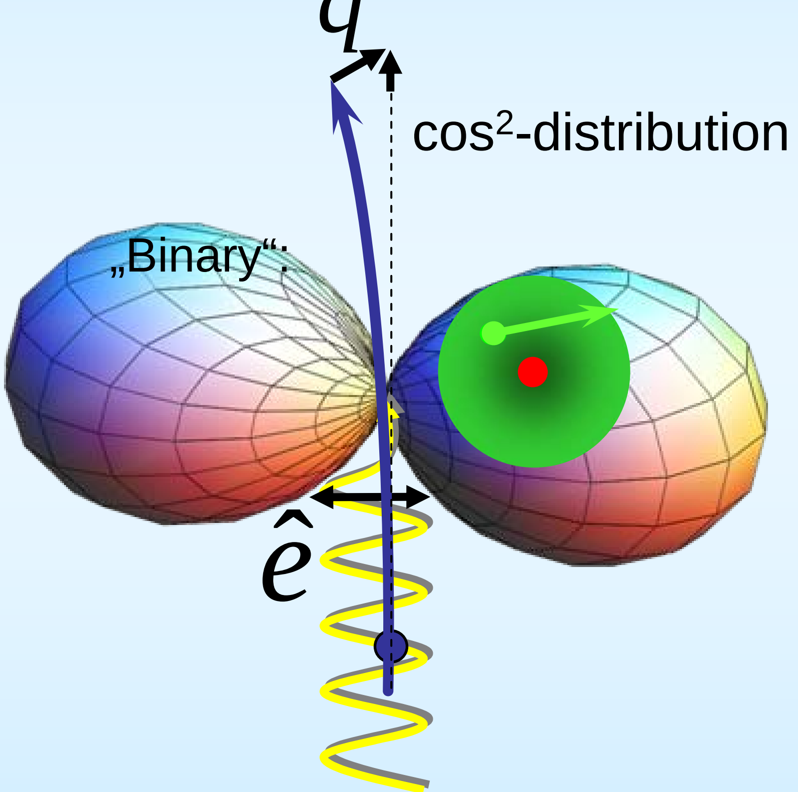
Photo-ionization:

$$d\sigma \propto \left|\langle \phi_f \left| \hat{e}\cdot\vec{r} \right| \phi_i \rangle\right|^2$$

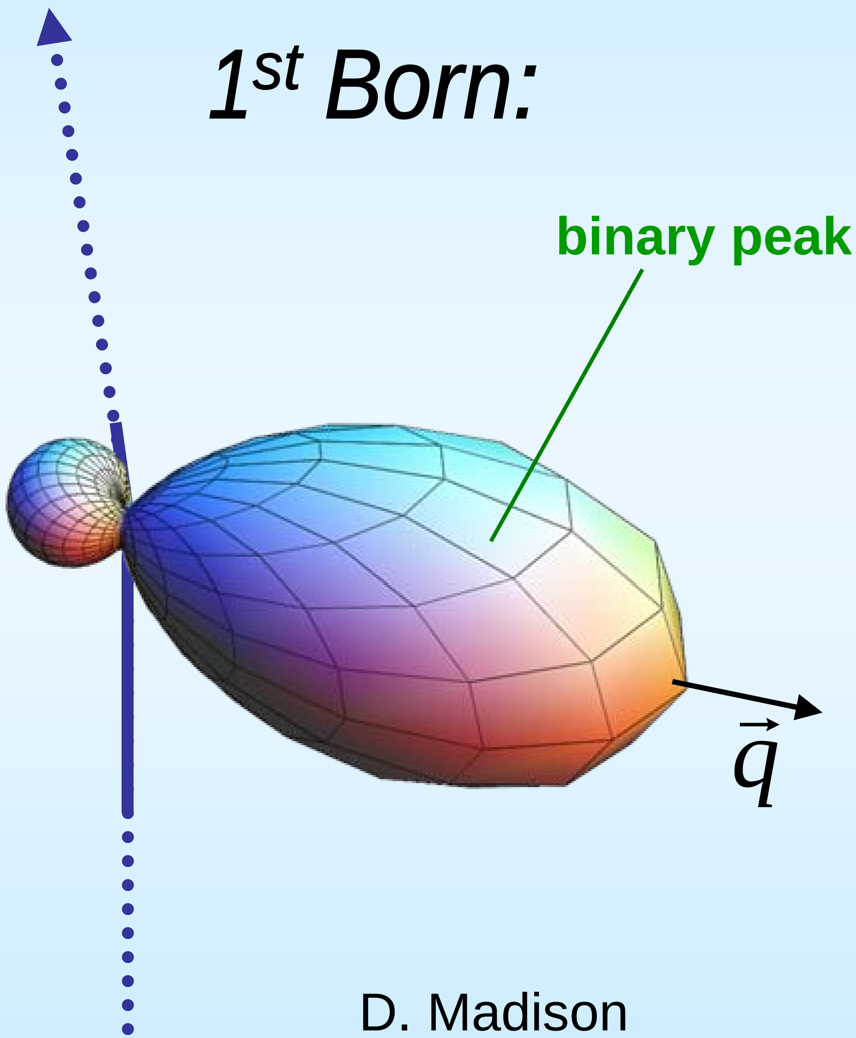
D. Madison

Single Ionization

Photo-ionization



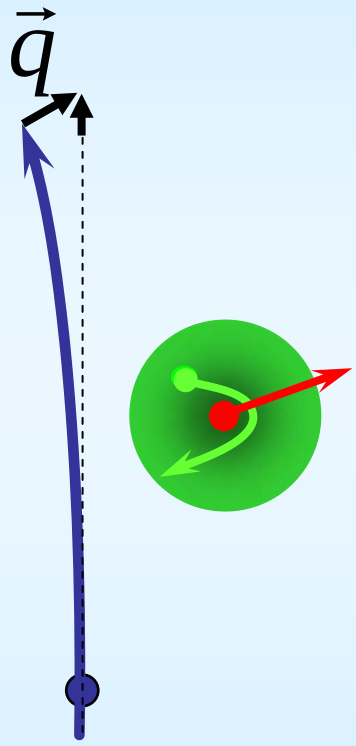
1st Born:



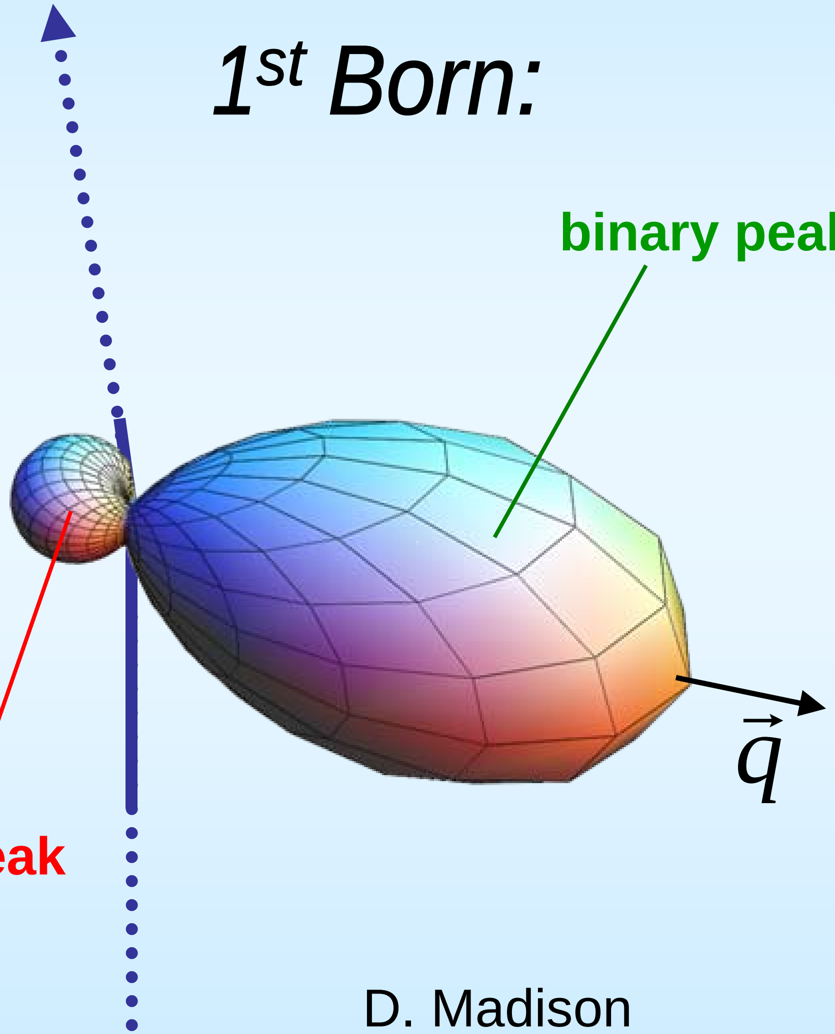
D. Madison

Classical Picture

„Binary“:
„Recoil“:

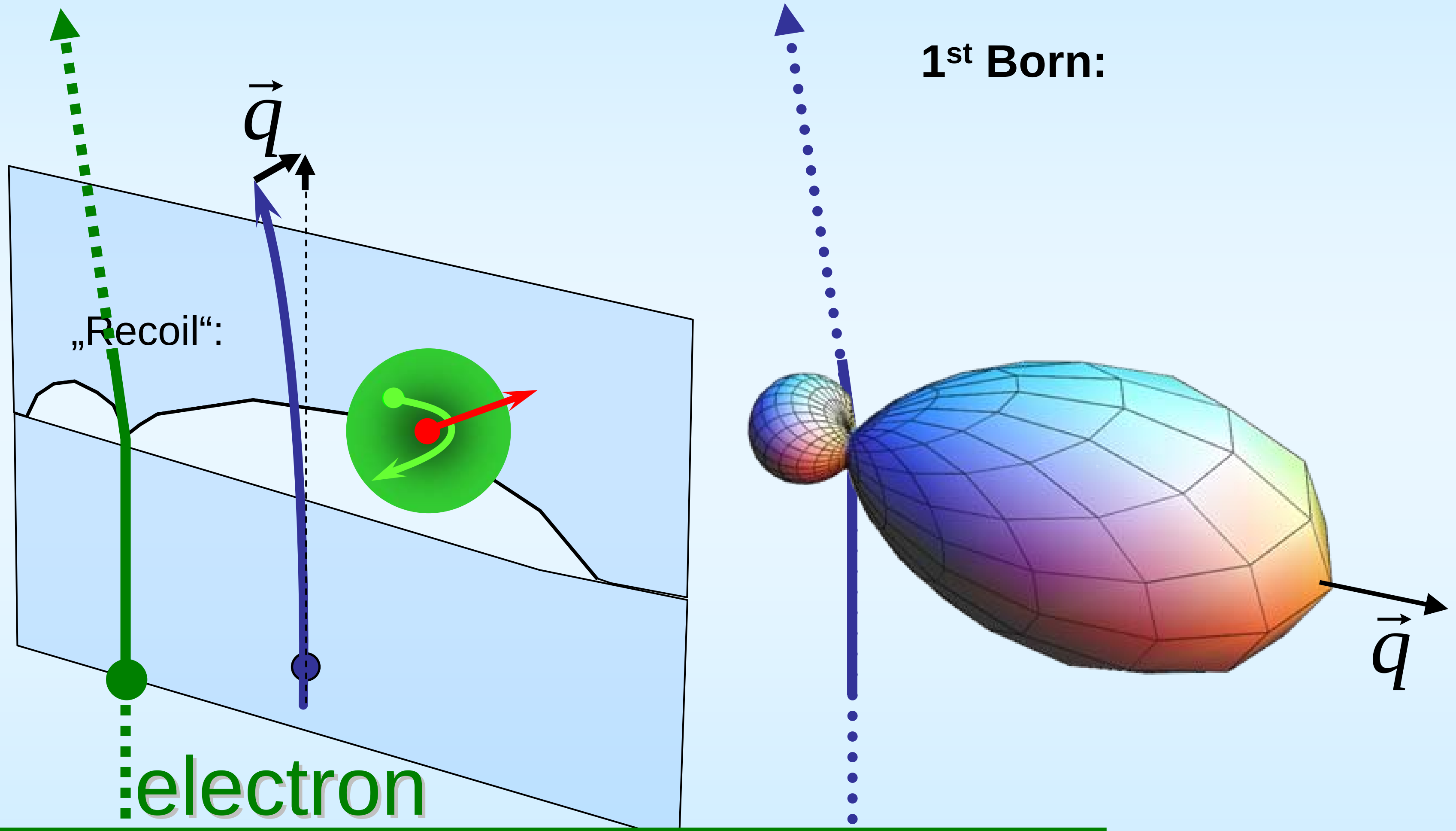


1st Born:



D. Madison

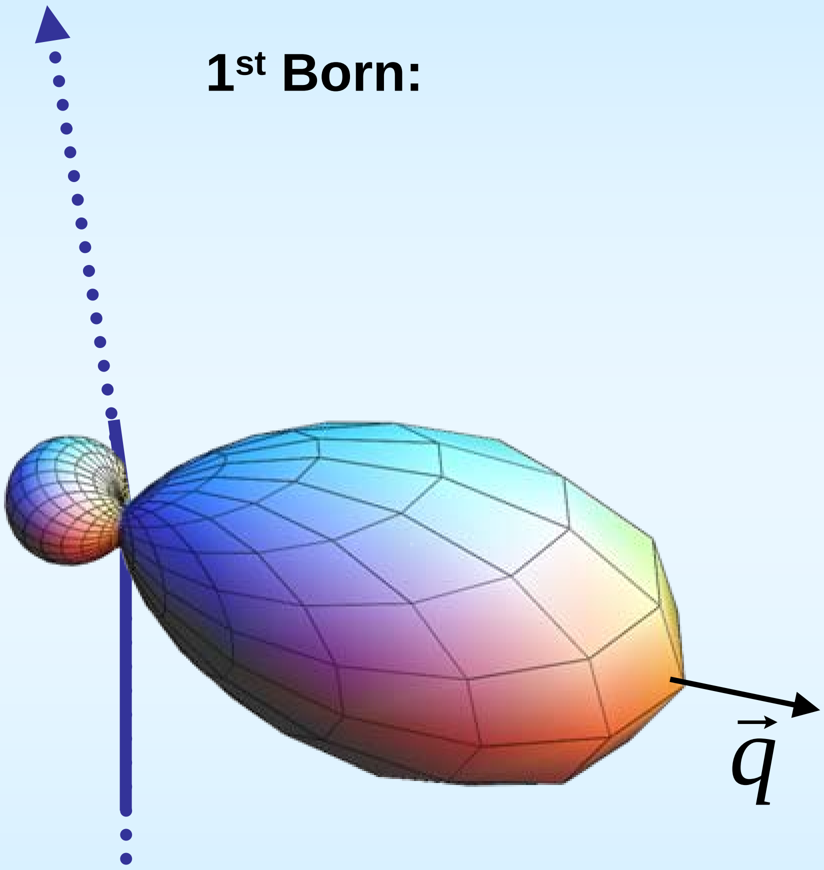
In-Plane Scattering



Explored since about 30 years: “understood”
Theory: Bray, Resigno, Bartschak: “solved”

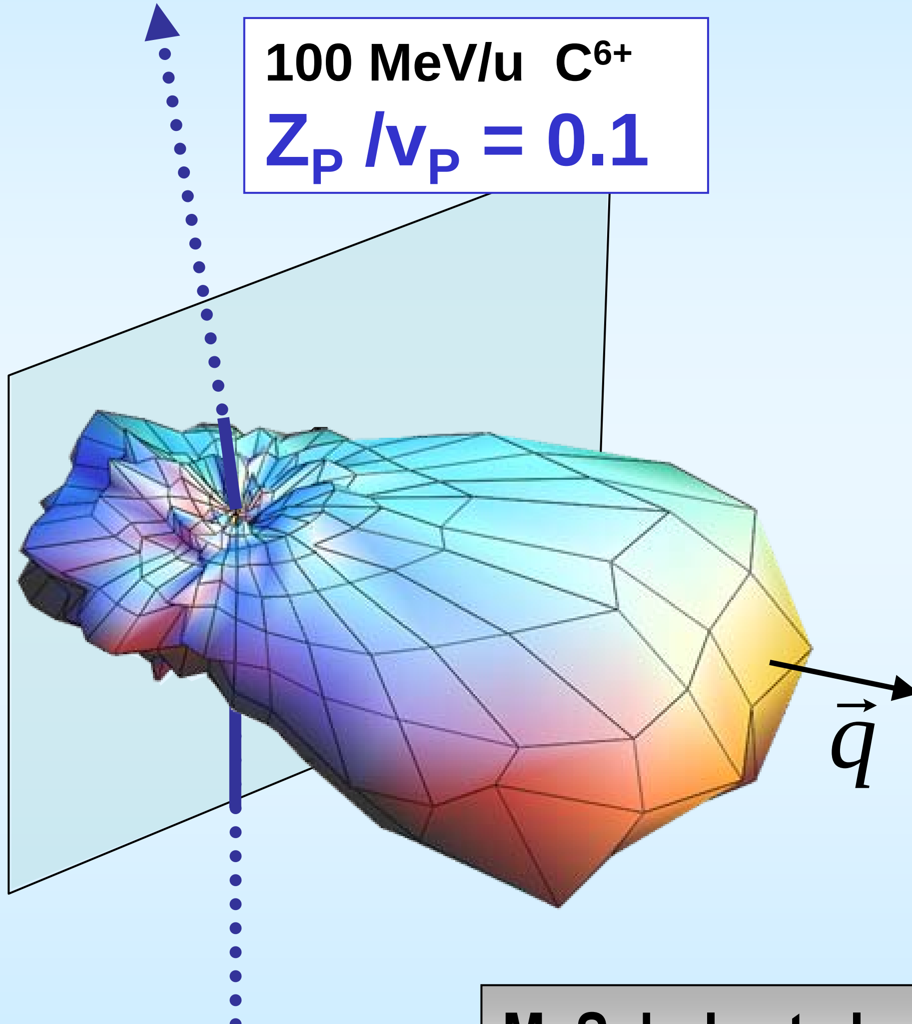
3-D Imaging

1st Born:



100 MeV/u C^{6+}

$Z_P / v_P = 0.1$



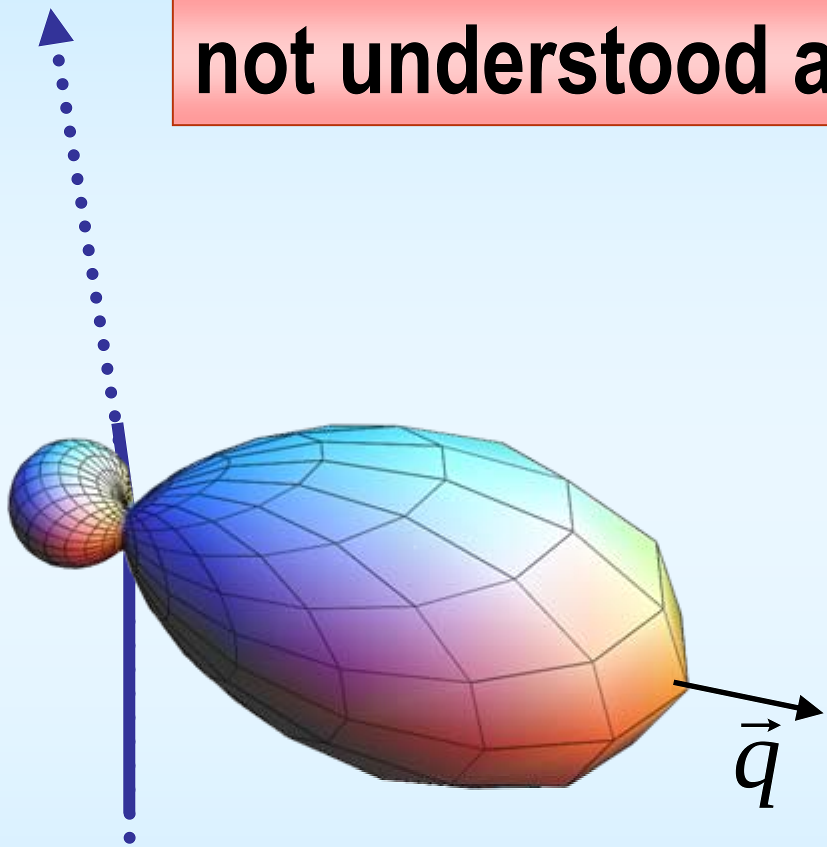
first experiment: D. Fischer, R. Moshammer, M. Schulz: surprises in 3 dimensions!

M. Schulz et al. Nature 48 (2003)

"Perpendicular" Plane

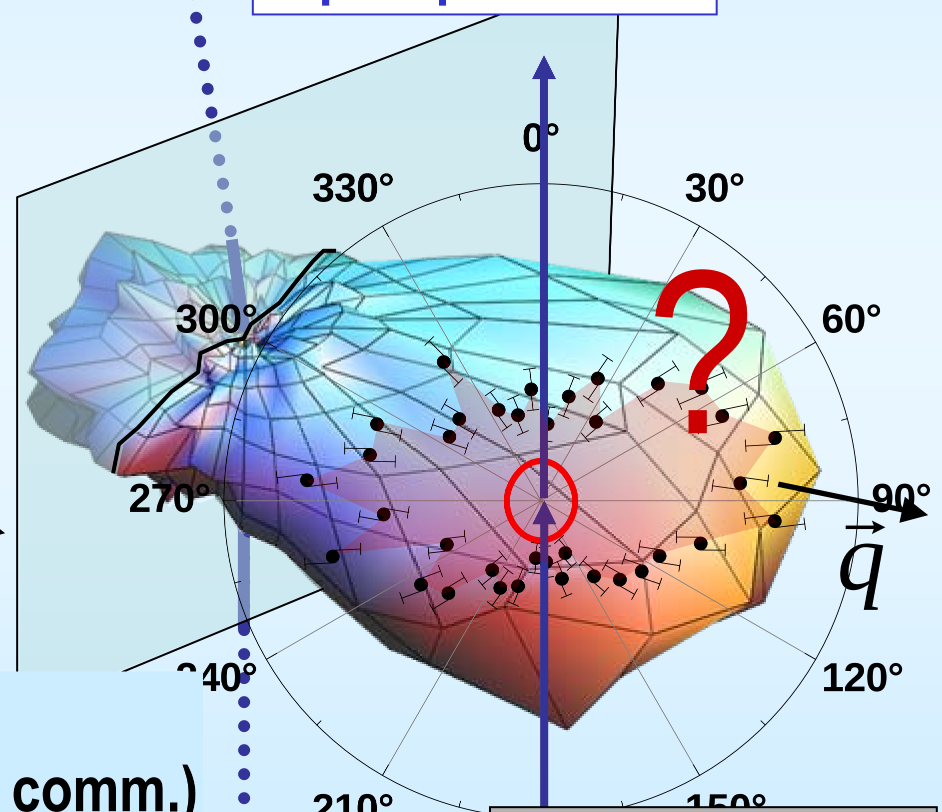
Max-Planck-Institut für Kernphysik

not understood at all



100 MeV/u C^{6+}

$Z_P / v_P = 0.1$



Olson: - interaction with nucleus
- special trajectories (priv. comm.)

Voitkiv: - interaction with nucleus

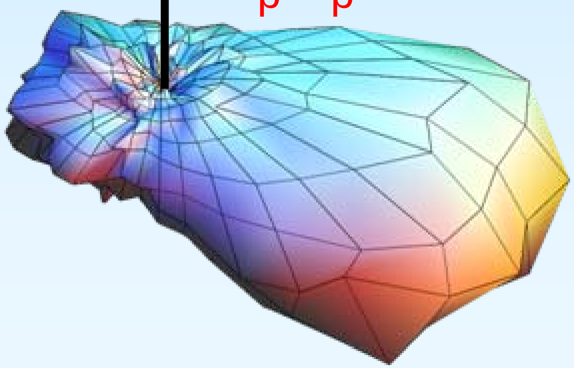
Madison: - failure of CCC at small distances

M. Schulz et al.
Nature 48 (2003)

Towards large Perturbations

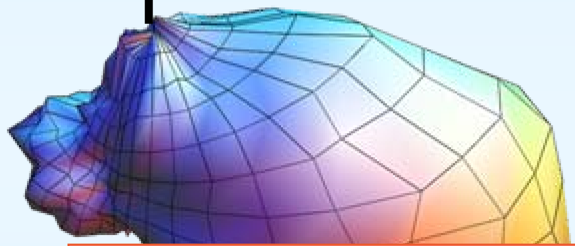
100 MeV/u C^{6+}

$Z_p/v_p = 0.1$

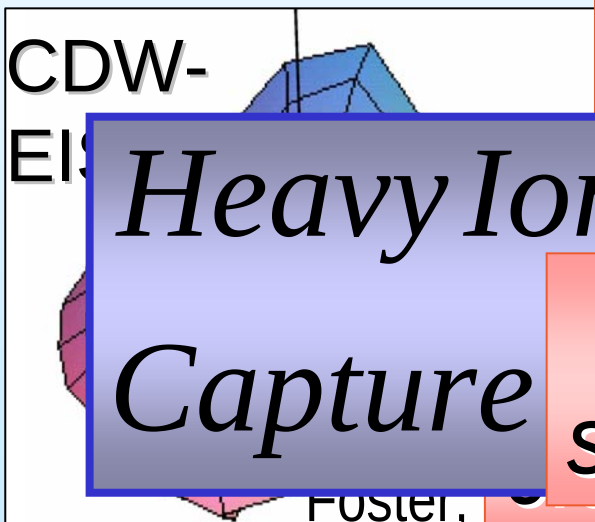


2 MeV/u C^{6+}

$Z_p/v_p = 0.7$



Madison et al. PRL 2003
JPB 2002
Fischer et al., JPB 2002
JPB 2003
PRA 2003
JPB 2004
Schulz et al., JPB 2003



CDW-
EI

Foster,

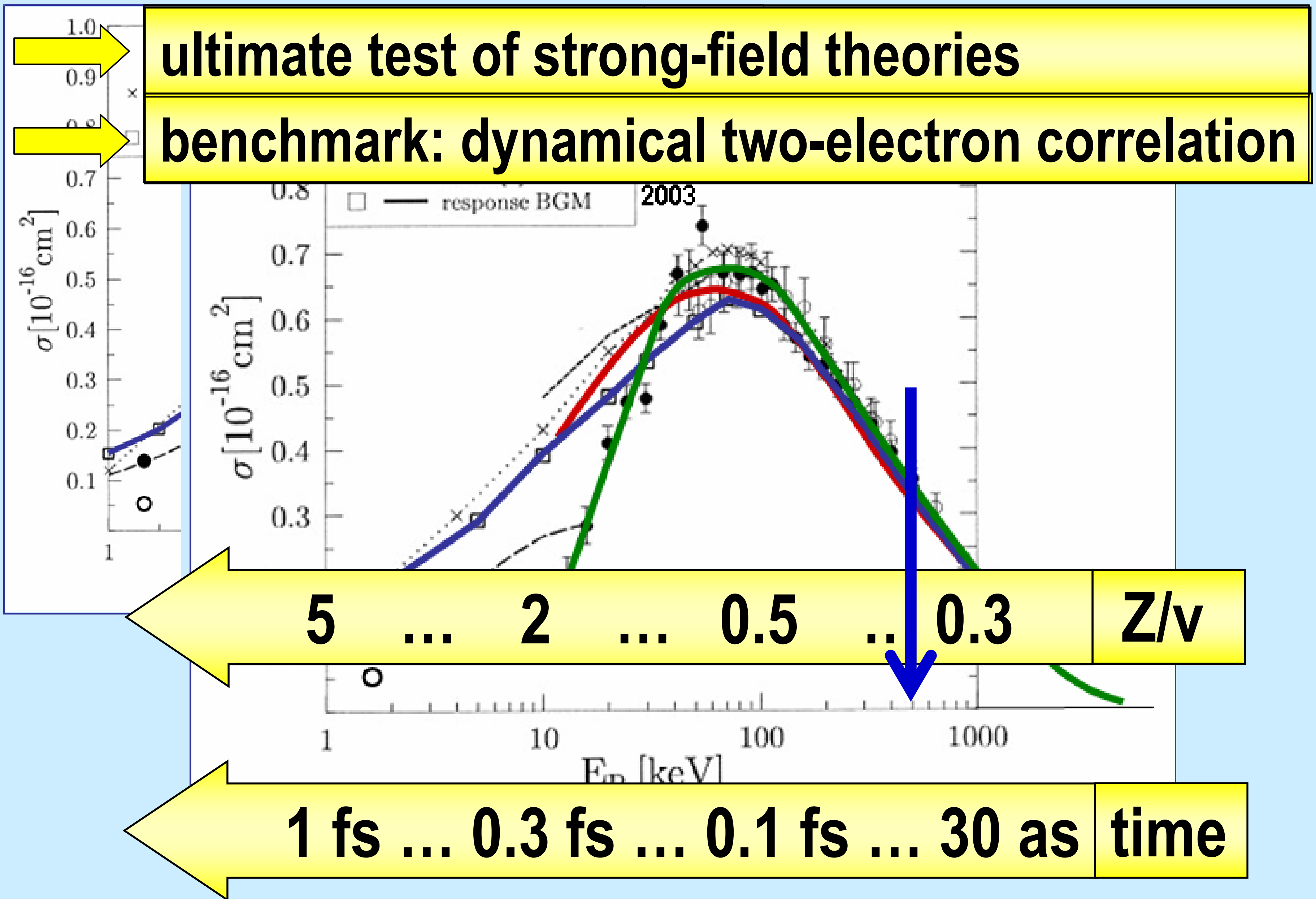
all theoretical predictions fail

Heavy Ions : Capture

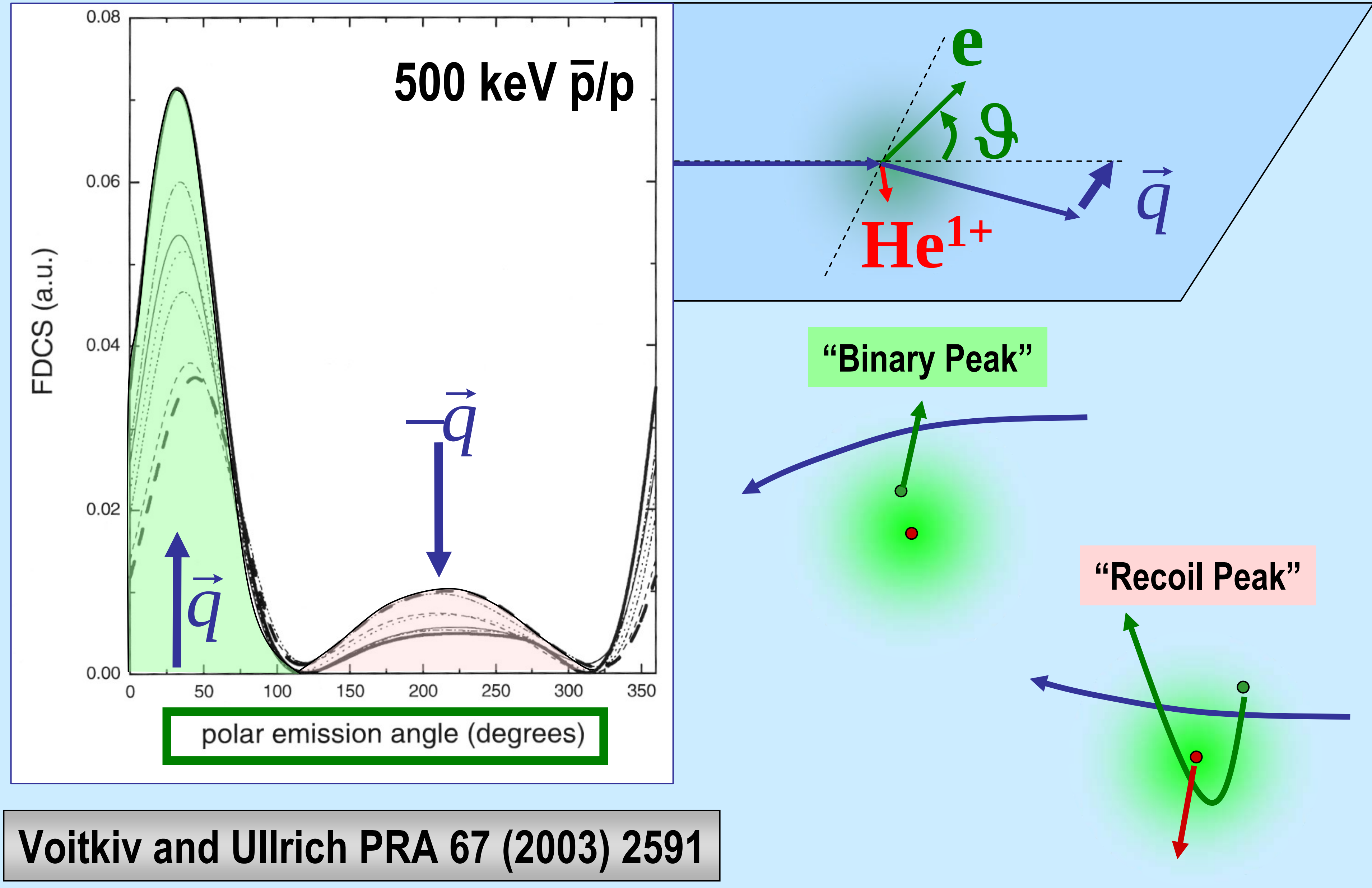
total cross sections correct!

?

Antiprotons: Kinematically Complete

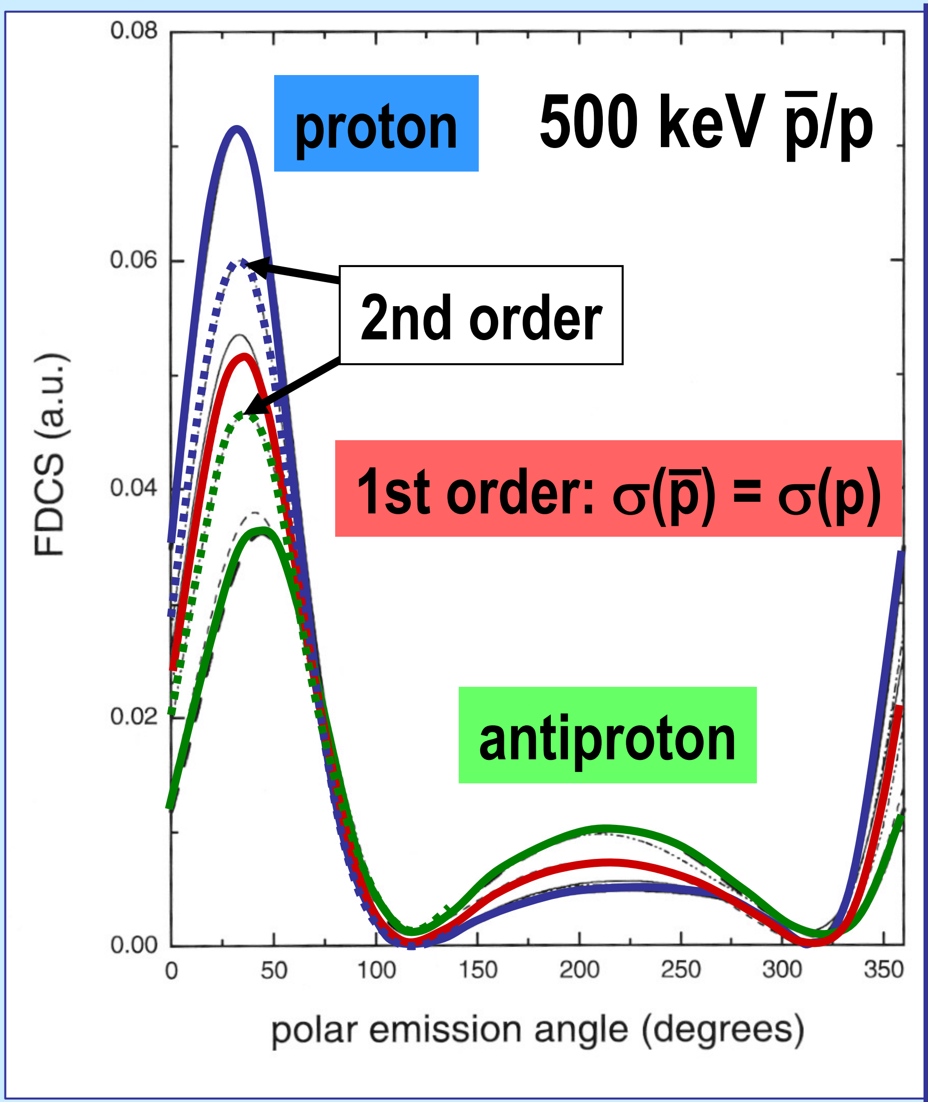


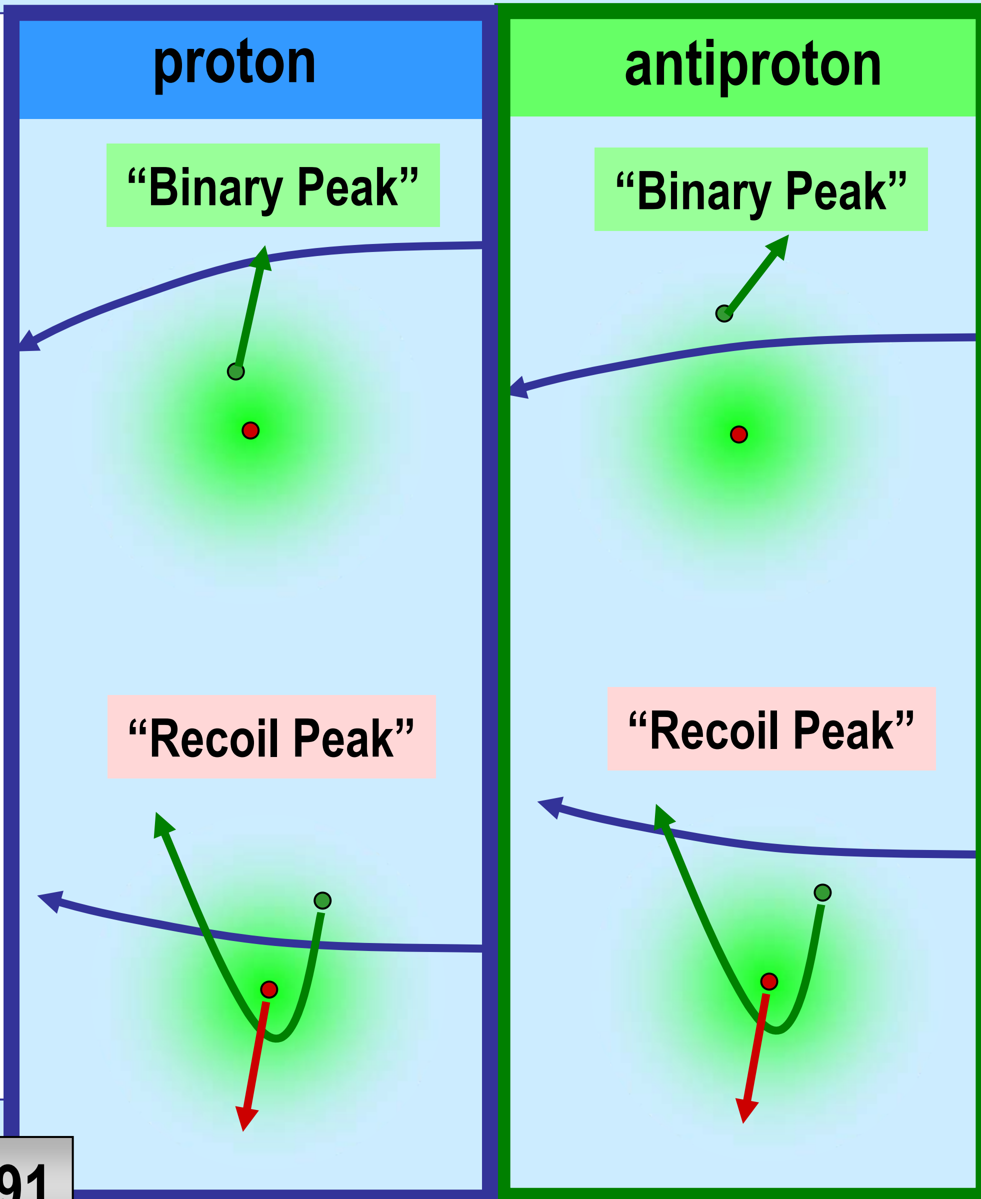
The Ultimate Test: p,$\bar{p}$ + H,He



Voitkiv and Ullrich PRA 67 (2003) 2591

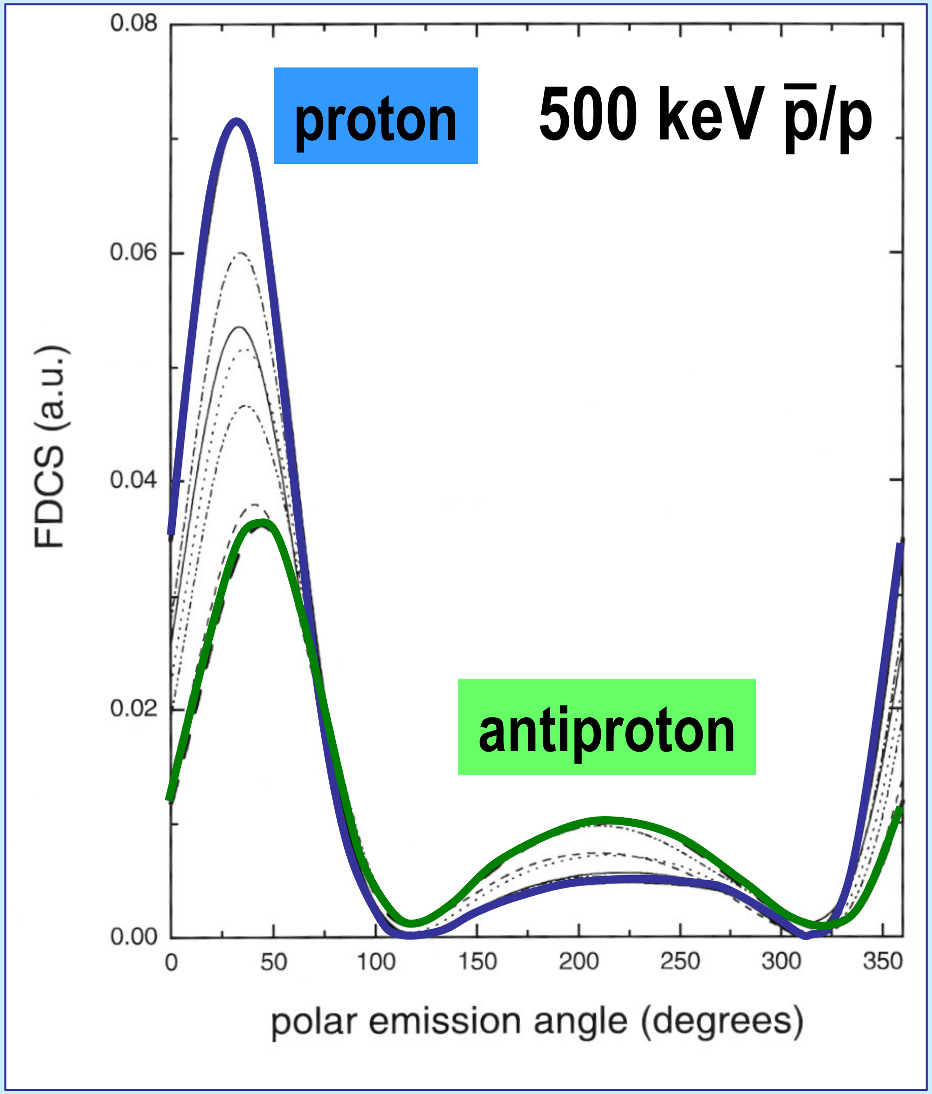
The Ultimate Test: p,$\bar{p}$ + H,He

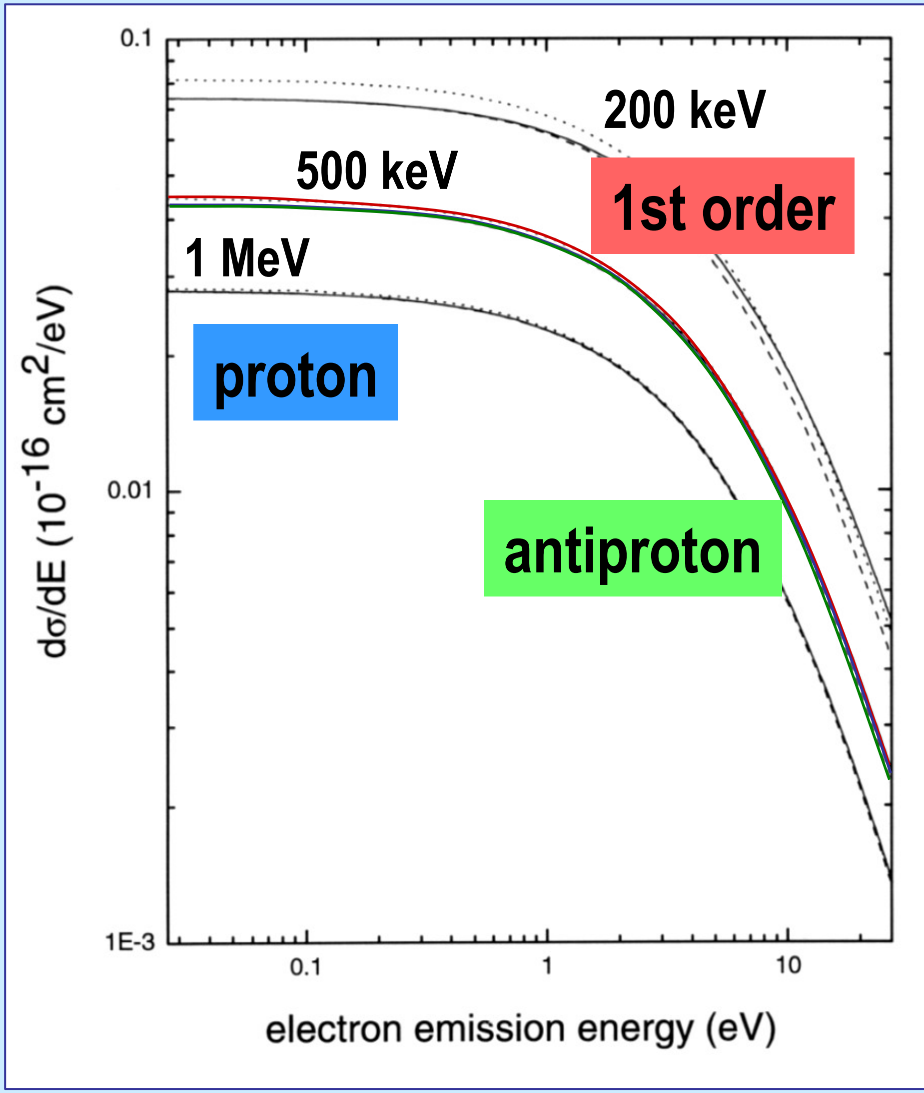




Voitkiv and Ullrich PRA 67 (2003) 2591

The Ultimate Test: p,$\bar{p}$ + H,He





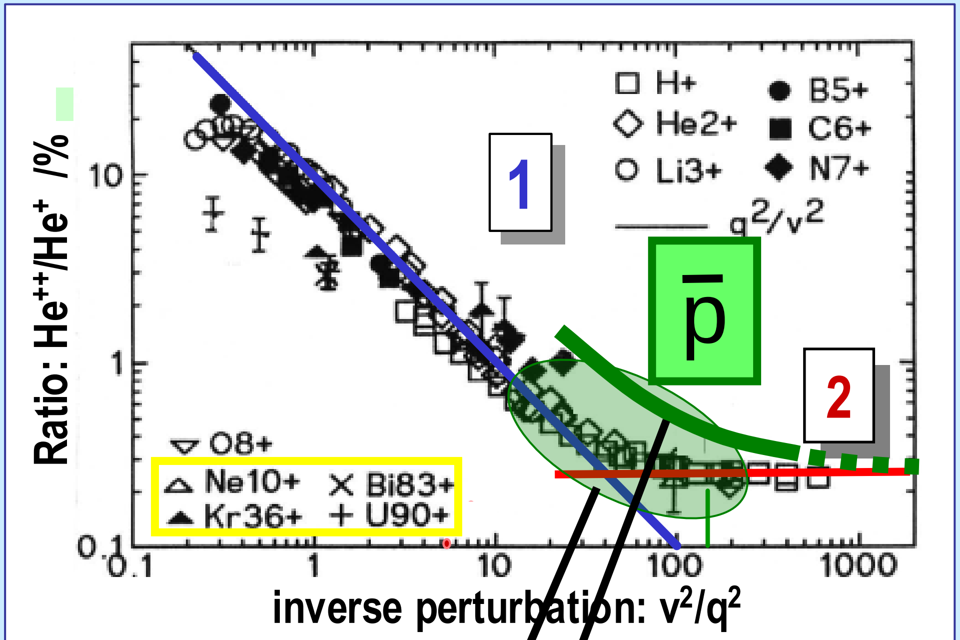
Voitkiv and Ullrich PRA 67 (2003) 2591

Outline of the Talk

Max–Planck–Institut für Kernphysik

- Reaction Microscopes
- Single Ionization
- Double Ionization
- Antiproton Capture
- How to do the Experiments ?
- Plenty of other Reactions !

Double Ionization: p ↔ $\bar{p}$



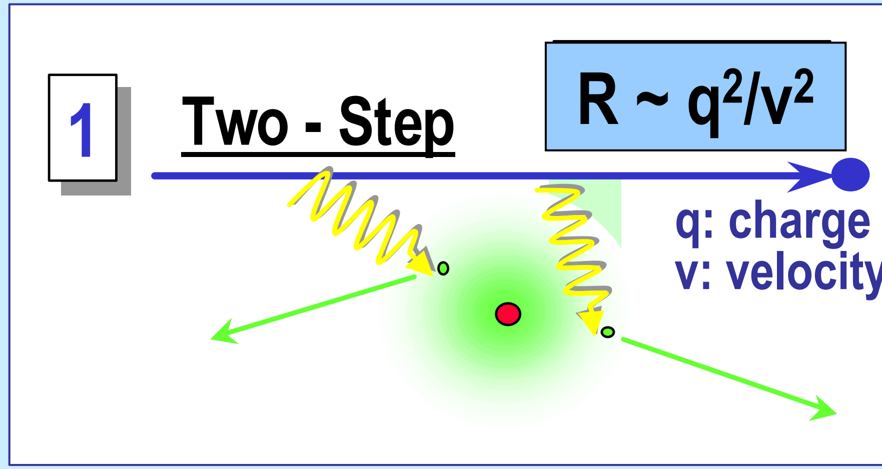
Ullrich et al. PRL (1994); NIM B (1994)

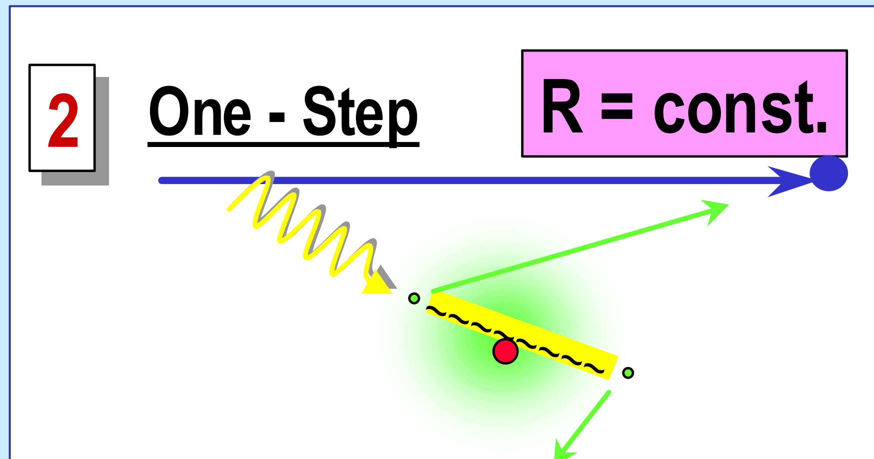
Interference 1st and 2nd order:

$\sigma \sim q^2 + q^3 + q^4 \ldots$

Antiproton data from

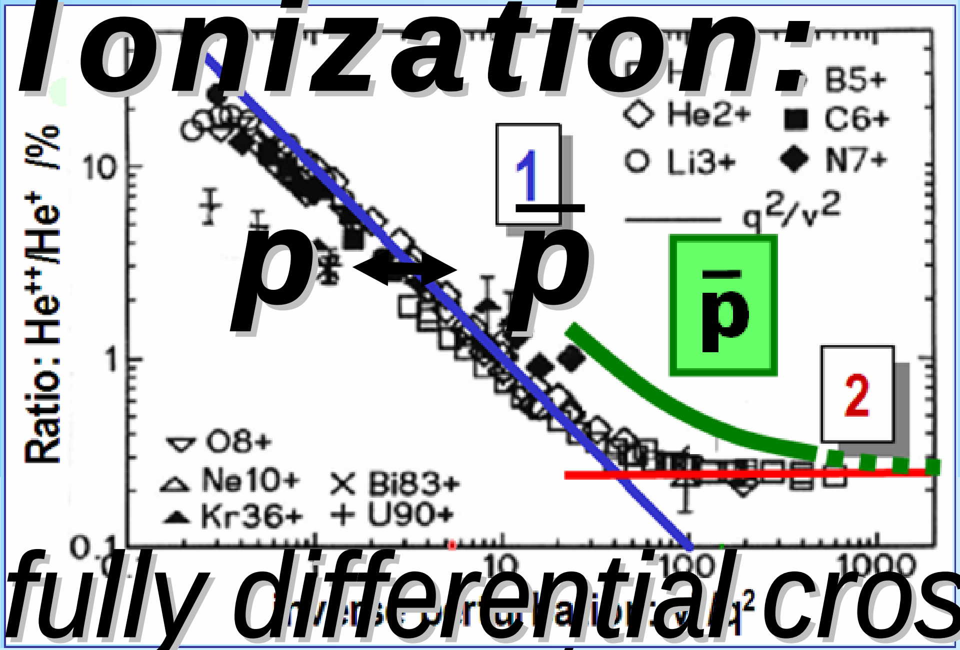
LEAR at CERN



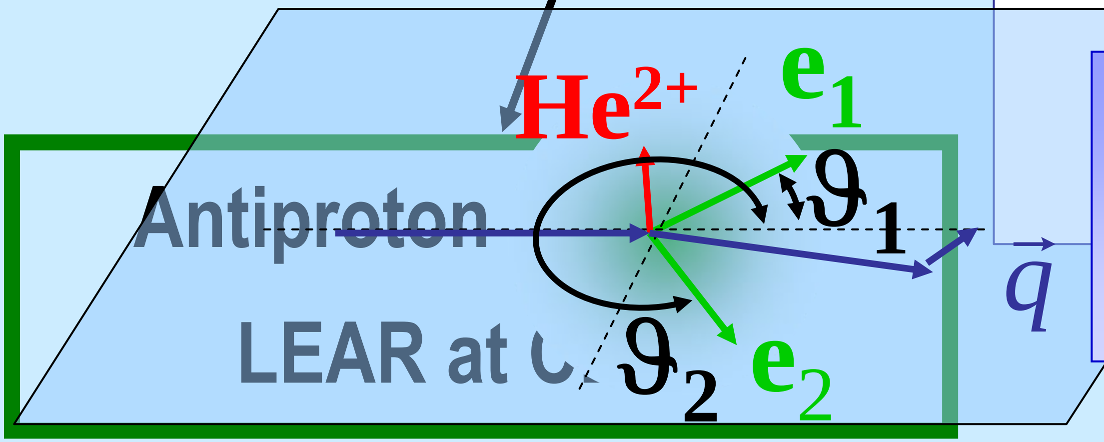


L. Andersen, H. Knudsen, E. Uggerhoj et al.,

Double Ionization:



fully differential cross sections:



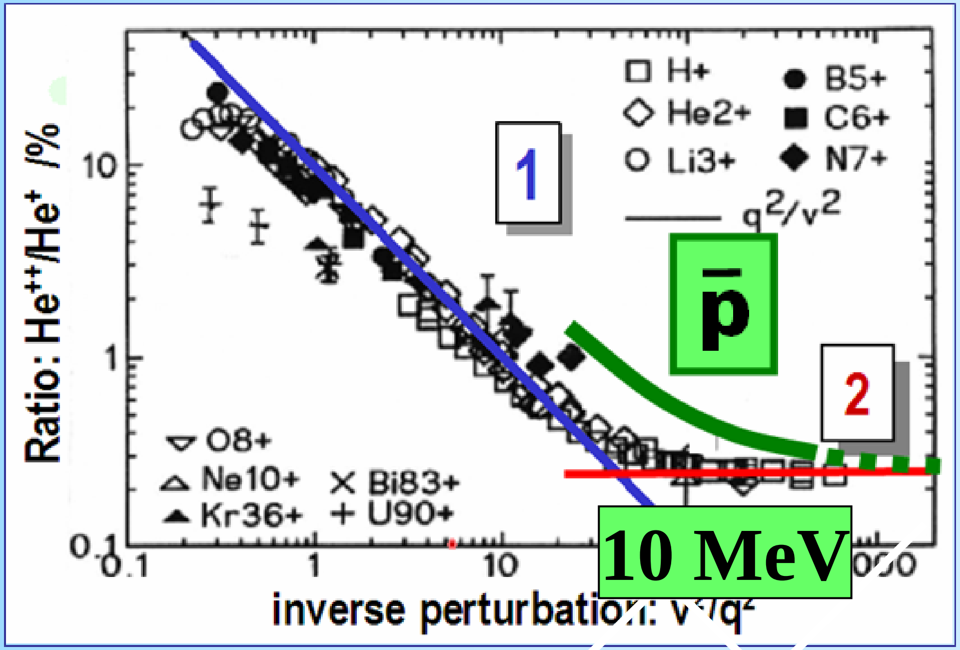
- co-planar
- $E_{electron1} = E_{electron2}$

L. Andersen, H. Knudsen, E. Uggerhoj et al.,

PRL 2002

Fischer et al., PRL 2003

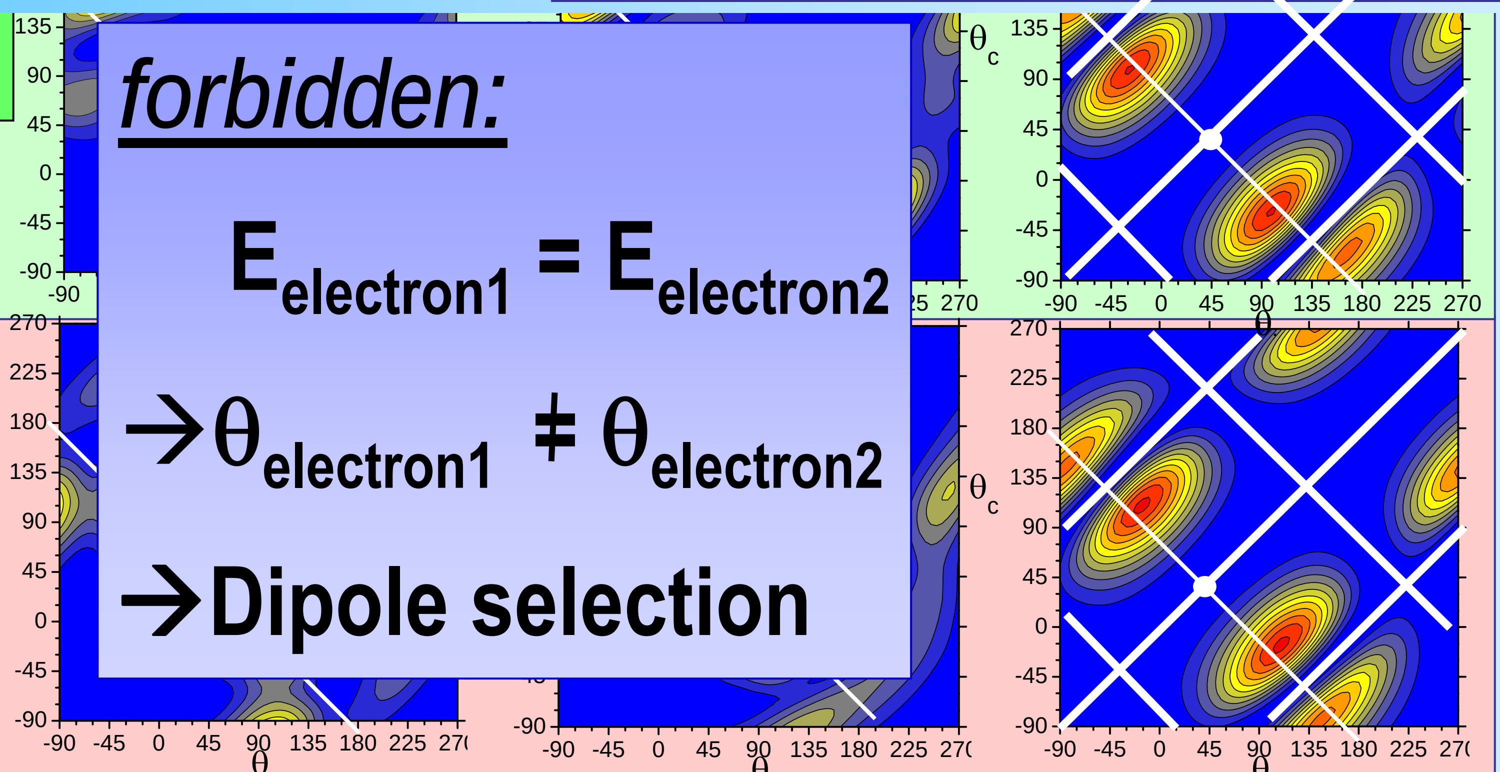
Double Ionization: $p \leftrightarrow \bar{p}$



impact

Proton impact

no theory so far !



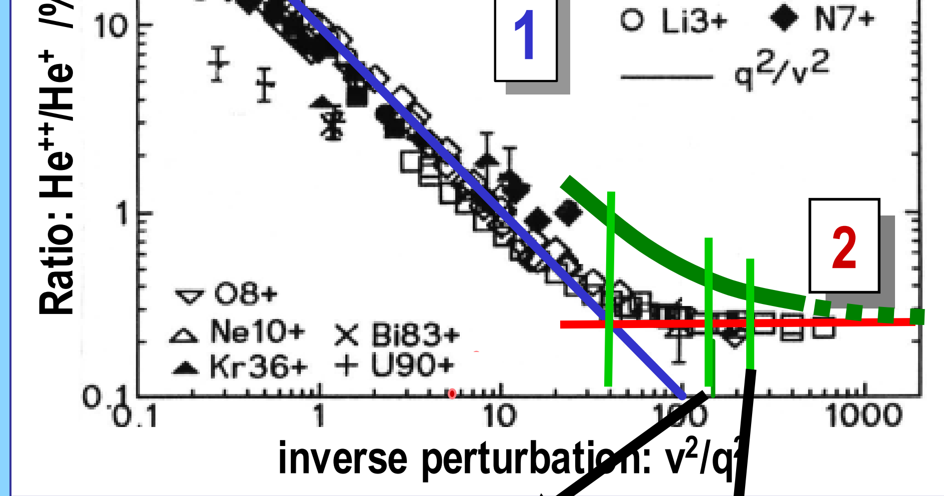
forbidden:

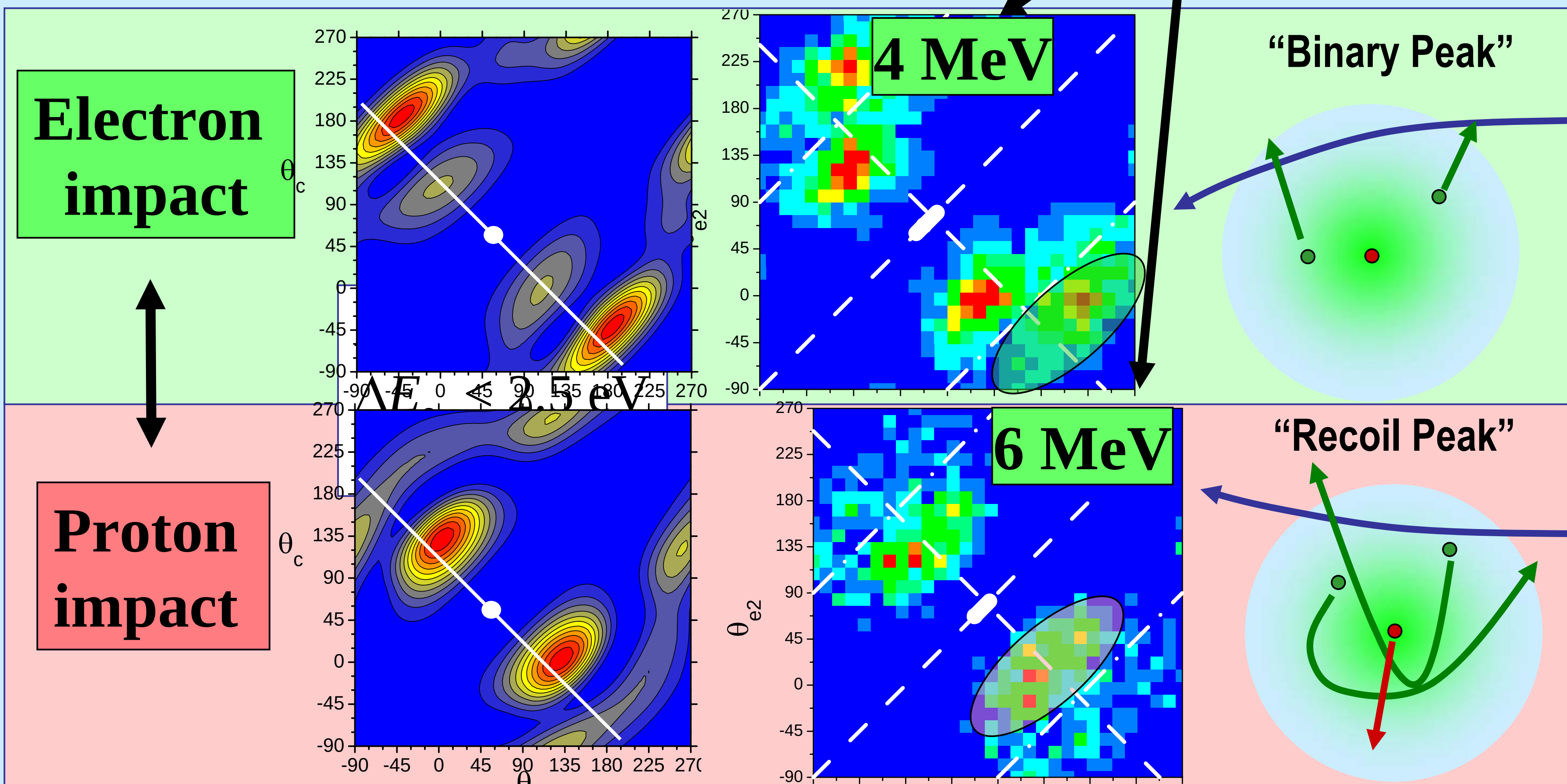
$$E_{electron1} = E_{electron2}$$

$$\rightarrow \theta_{electron1} \neq \theta_{electron2}$$

→ Dipole selection

The $p \leftrightarrow \bar{p}$ difference





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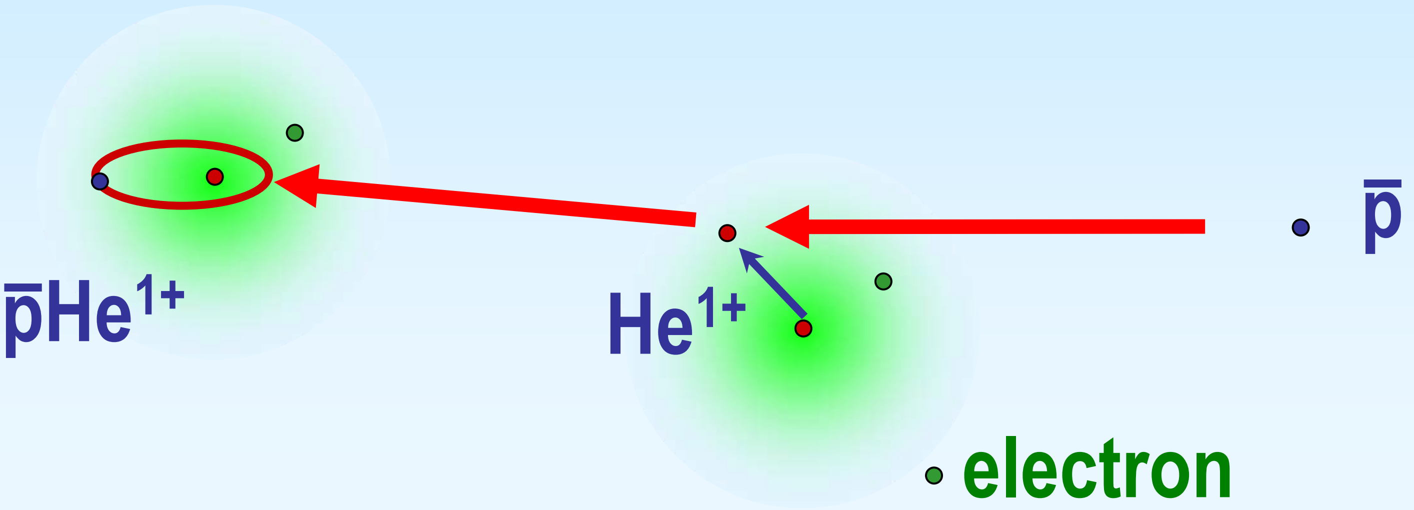
- *Double Ionization*
- *Antiproton Capture*
- *How to do the Experiments ?*
- *Plenty of other Reactions !*

$\bar{p}$–Capture: Structure & Dynamics

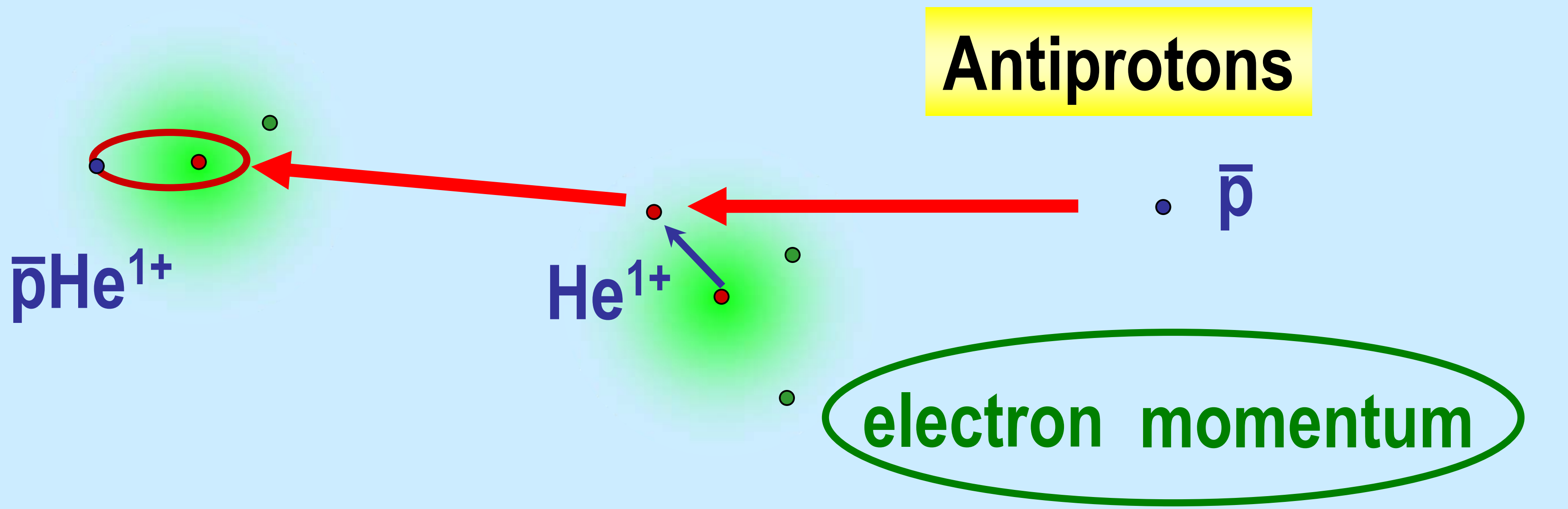


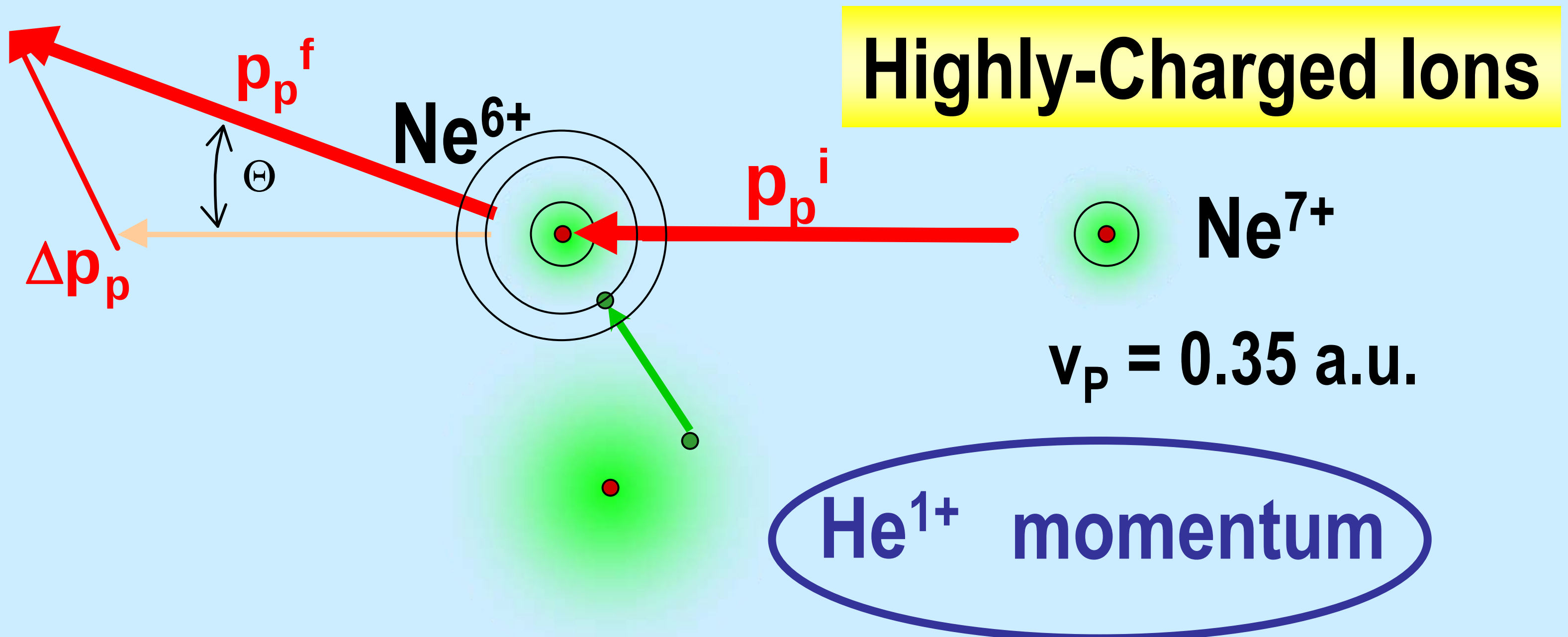
Questions:

- capture cross section
- few-particle dynamics at 10 to 100 fs time-scale
- n,l distributions
- spectroscopy of states

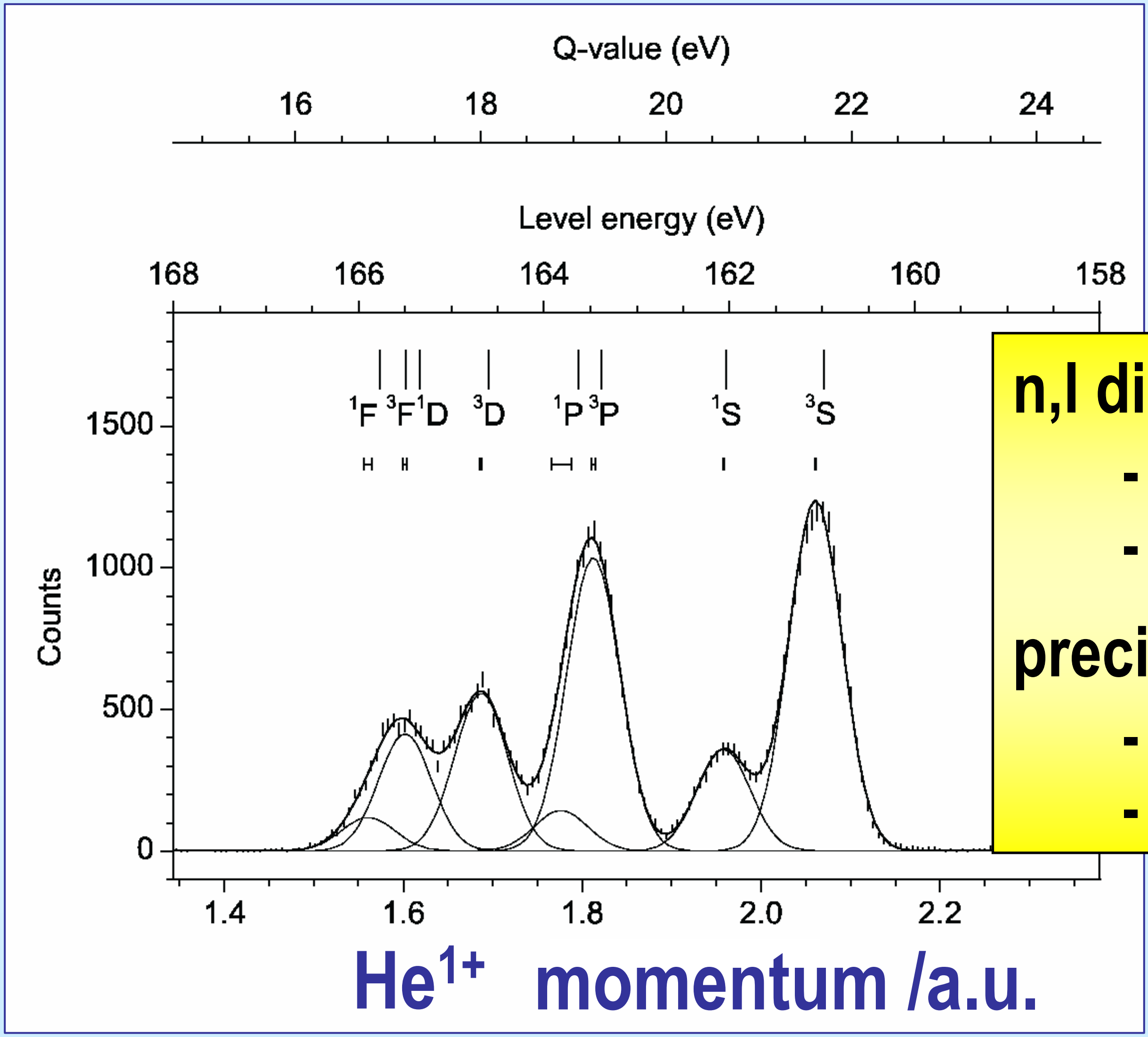
Exp.: no single collision conditions

$\bar{p}$–Capture: Structure & Dynamics





p̄–Capture: Structure & Dynamics



n,l distributions for
- antiprotonic atoms
- protonium

precision spectroscopy?
- all states that are formed
- $\Delta\lambda/\lambda \approx \ldots 10^{-6}$

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für Kernphysik

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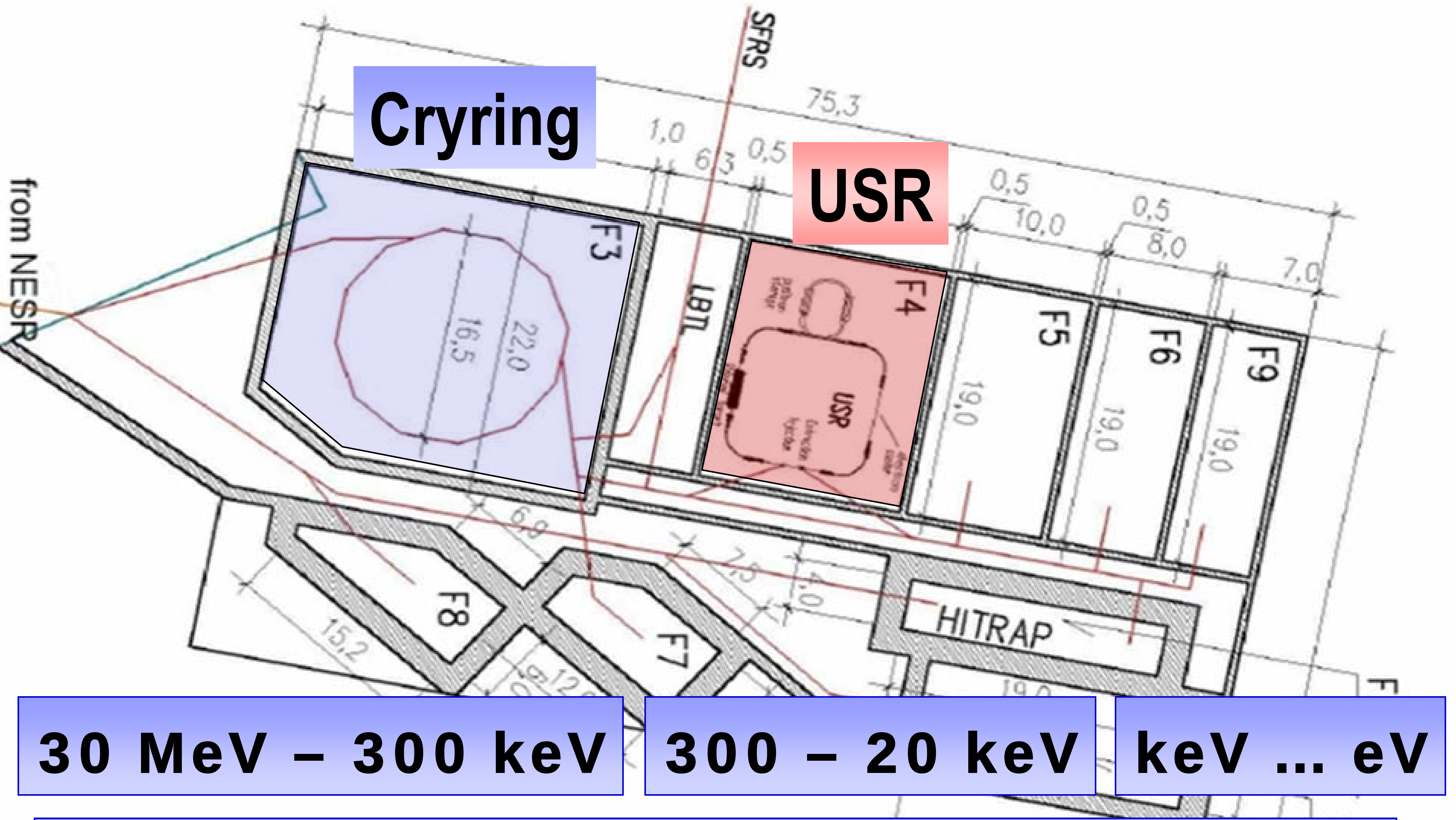
Experimental Needs

Max-Planck-Institut für Kernphysik

- *High Luminosity: …10^{-21} cm^2…*

FLAIR: Cold Antiprotons



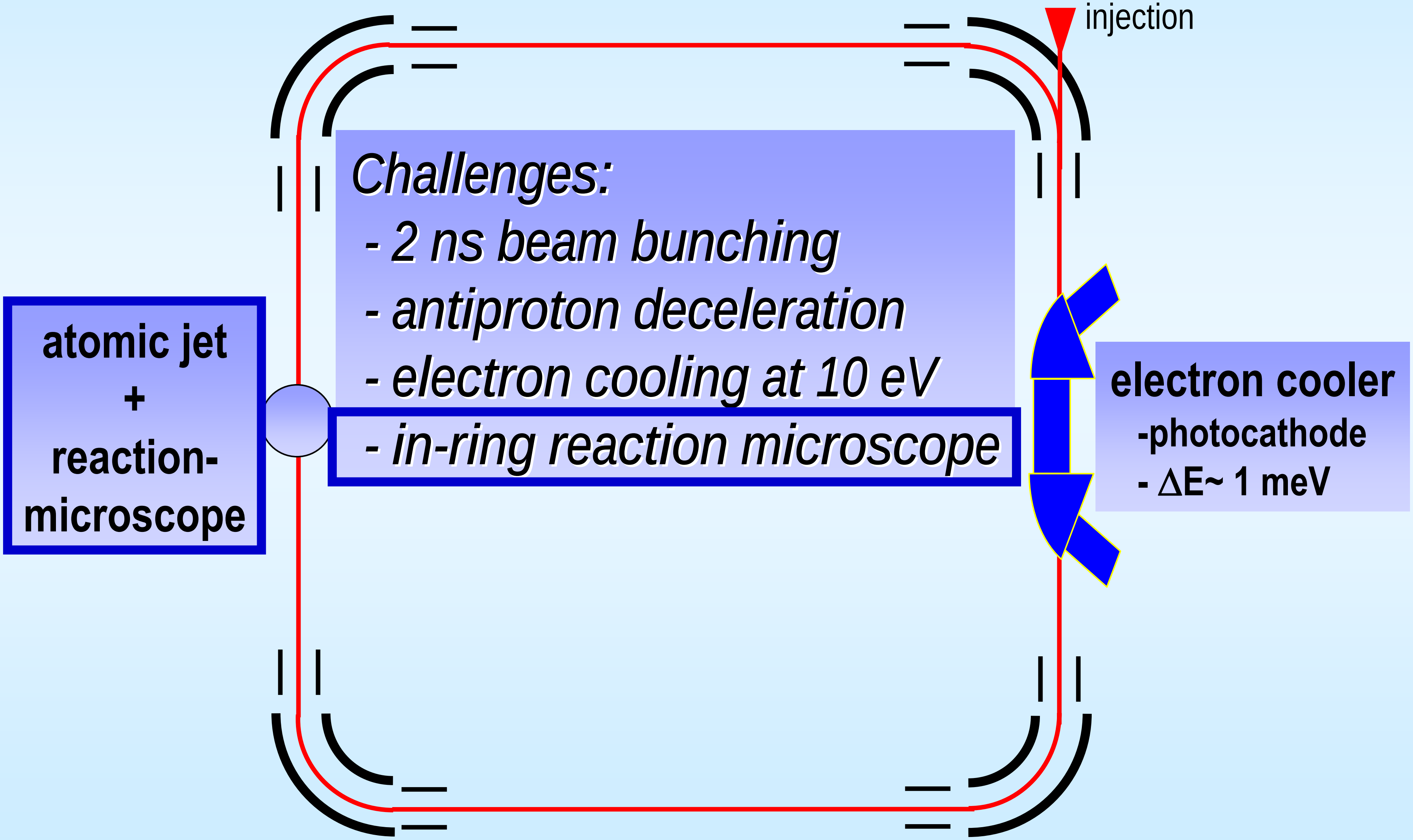
30 MeV – 300 keV

300 – 20 keV

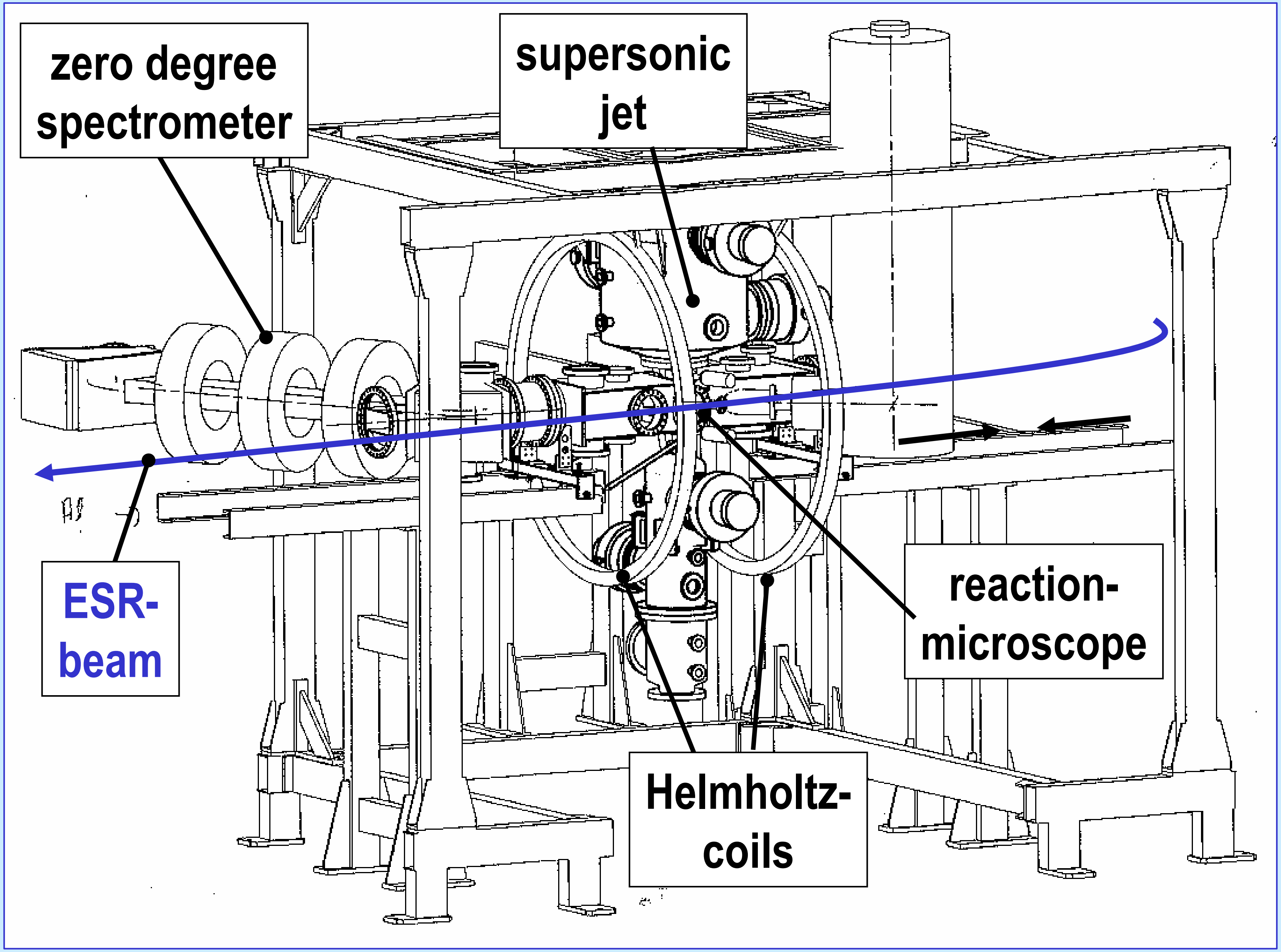
keV ... eV

10^5 times: antiprotons/second in the ring

The USR: Design



The In-Ring Reaction Microscope

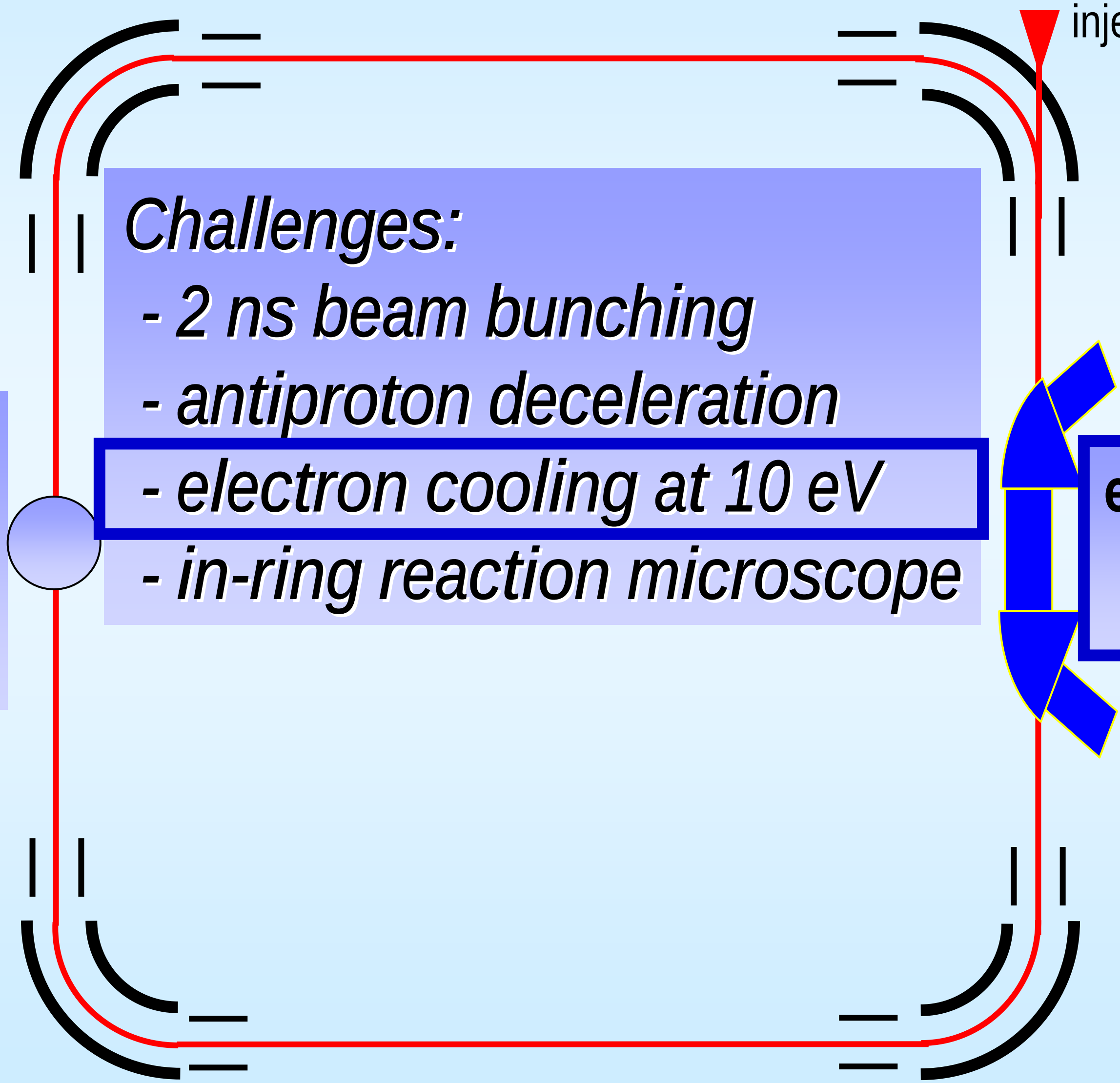


The In-Ring Reaction Microscope

- successfully tested
- ESR: end of 2005

- K. Küne: USR design

The USR: Design

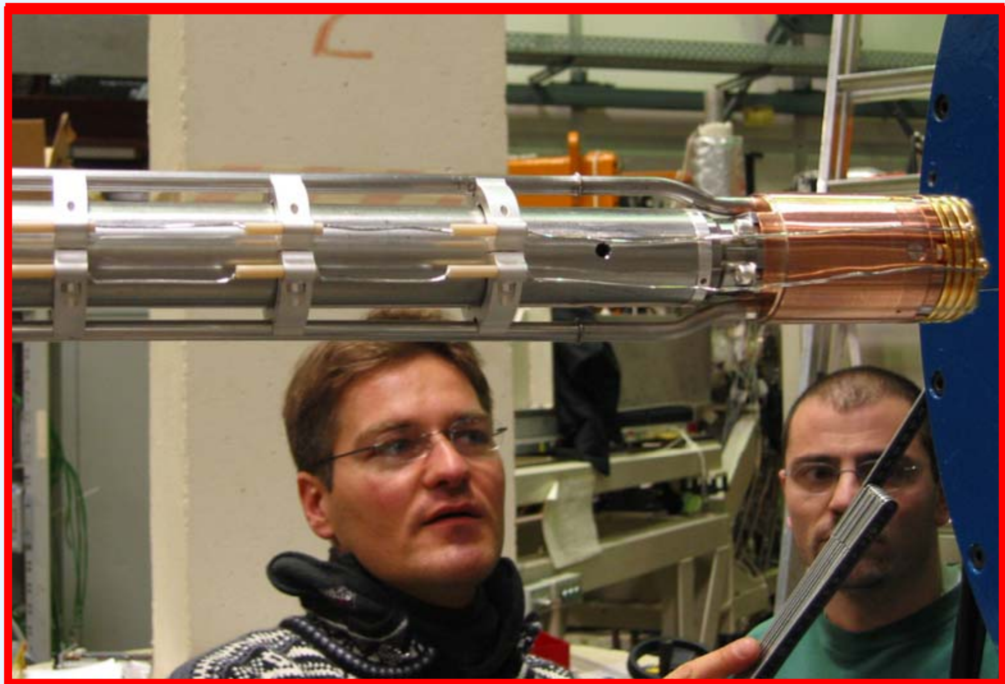


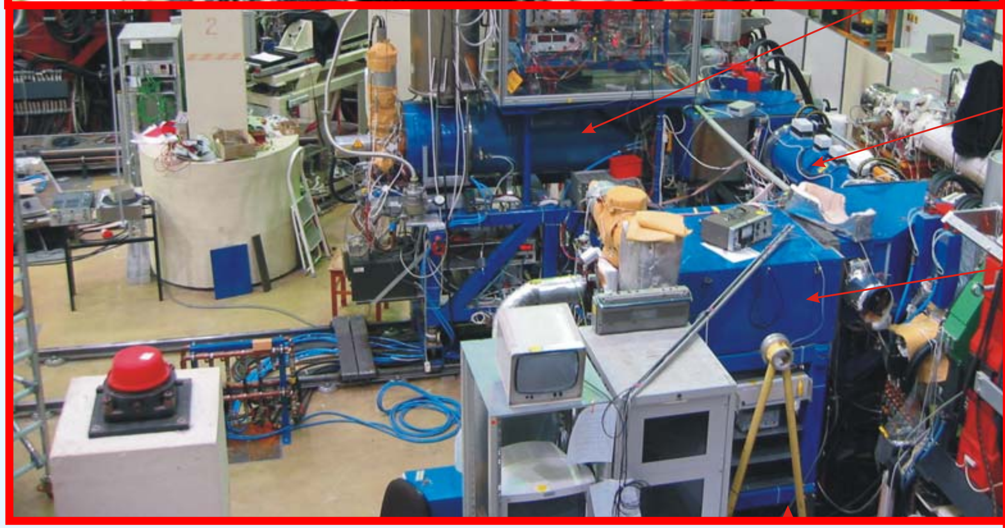
Challenges:
- *2 ns beam bunching*
- *antiproton deceleration*
- *electron cooling at 10 eV*
- *in-ring reaction microscope*

atomic jet
+
reaction-microscope

electron cooler
-photocathode
- ΔE~ 1 meV

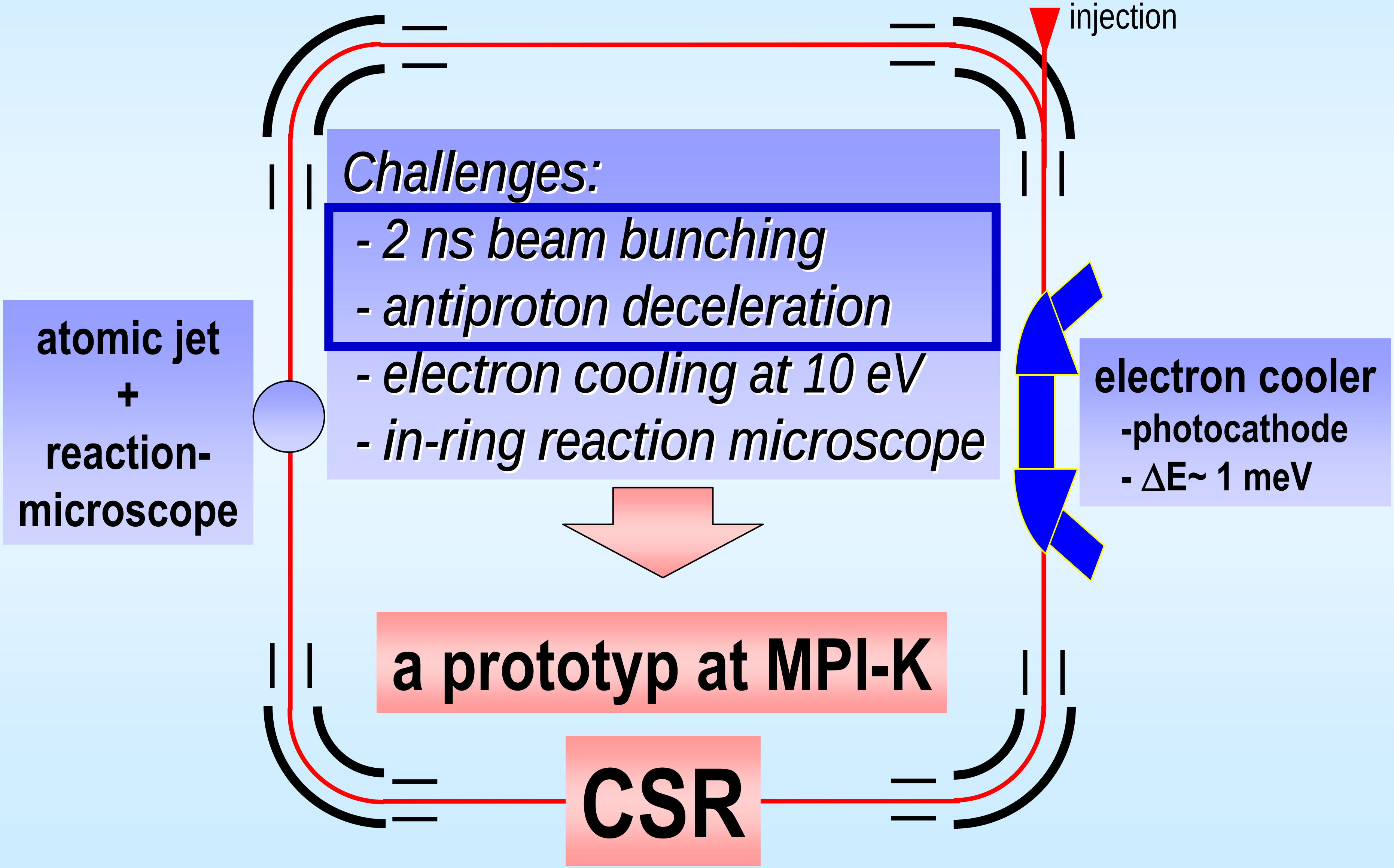
TSR: ultra-cold e$^-$ target





A. Wolf
D. Orlov
U. Weigel
F. Sprenger
M. Lestinsky

The USR: Design

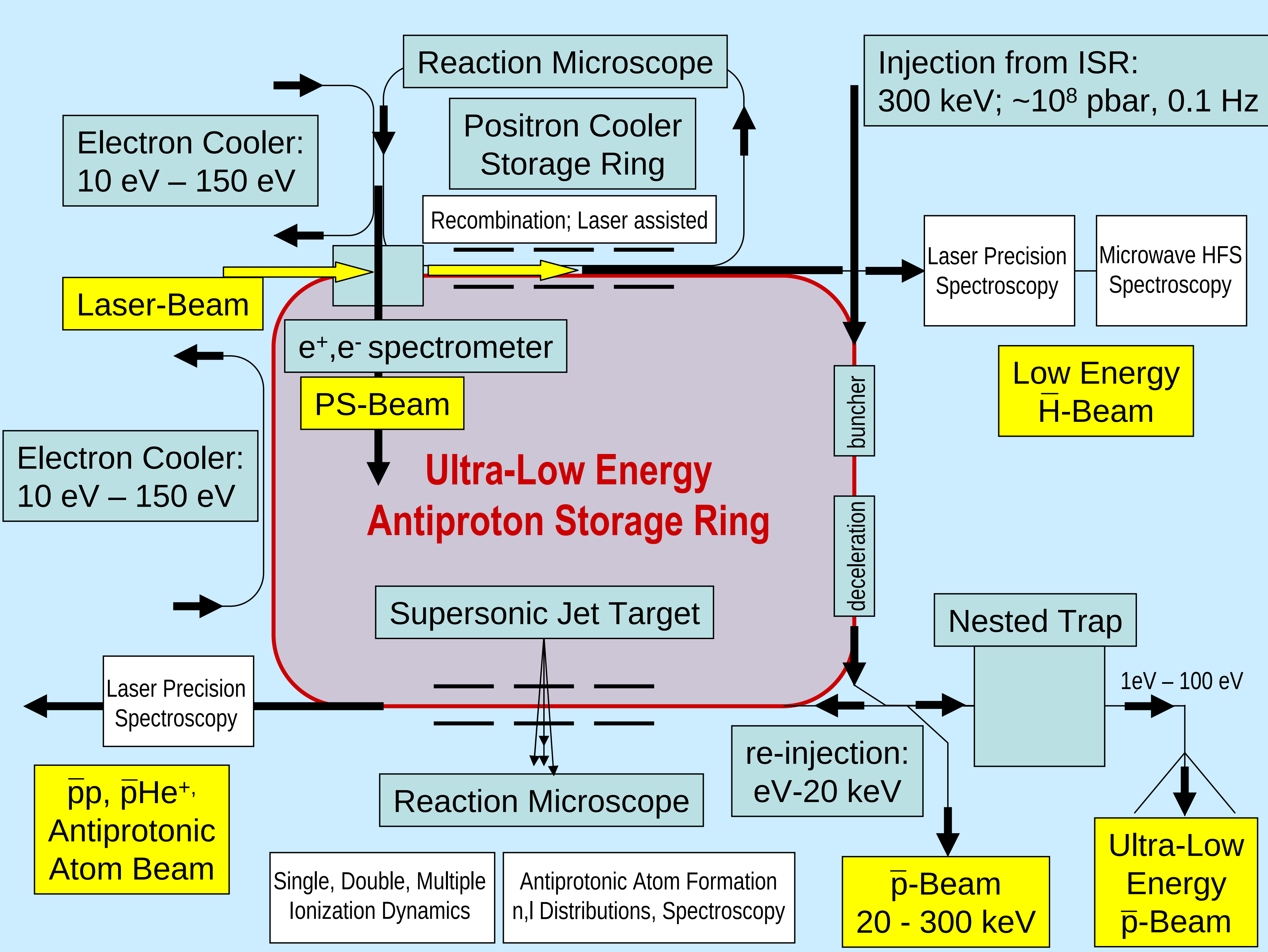


Space for the CSR

Summary:

Max-Planck-Institut für Kernphysik

- *Reaction Microscope + USR:*
  "Cloud Chamber" + high luminosity
- *Sub-fs Correlated Dynamics*
  Single, double multiple ionization
  Antiproton Capture .....
- *Plenty of other Reactions?*



Reaction Microscope
Injection from ISR:
300 keV; ~10⁸ pbar, 0.1 Hz
Electron Cooler:
10 eV – 150 eV
Positron Cooler
Storage Ring
Recombination; Laser assisted
Laser Precision
Spectroscopy
Microwave HFS
Spectroscopy
Laser-Beam
e⁺,e⁻ spectrometer
PS-Beam
Low Energy
H̄-Beam
buncher
Electron Cooler:
10 eV – 150 eV
Ultra-Low Energy
Antiproton Storage Ring
deceleration
Supersonic Jet Target
Nested Trap
1eV – 100 eV
Laser Precision
Spectroscopy
re-injection:
eV-20 keV
p̄p, p̄He⁺,
Antiprotonic
Atom Beam
Reaction Microscope
Single, Double, Multiple
Ionization Dynamics
Antiprotonic Atom Formation
n,l Distributions, Spectroscopy
p̄-Beam
20 - 300 keV
Ultra-Low
Energy
p̄-Beam