

Gas-phase molecular astrophysics and storage-ring collision measurements

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**SPARC meeting, Krakow, Poland
19 September 2016**

Ion chemistry

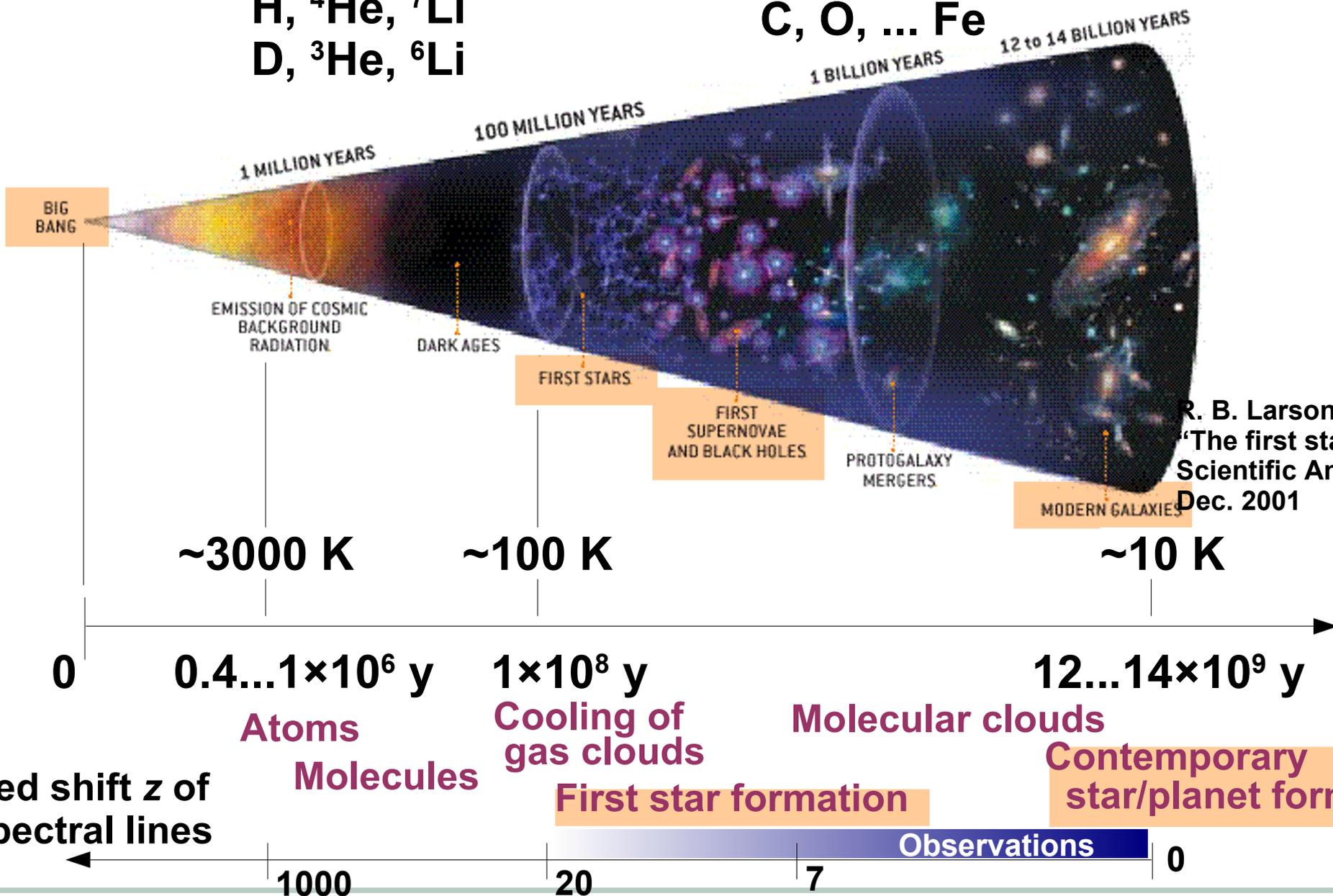
Storage ring measurements

Some results from the TSR

Star formation periods of the Universe

H, ^4He , ^7Li
D, ^3He , ^6Li

Heavy elements
C, O, ... Fe



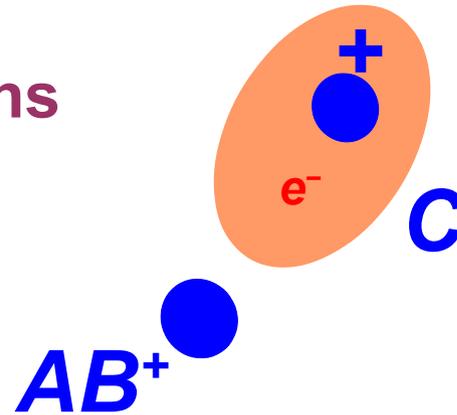
R. B. Larson, V. Bromm
"The first stars"
Scientific American
Dec. 2001

Molecular processes

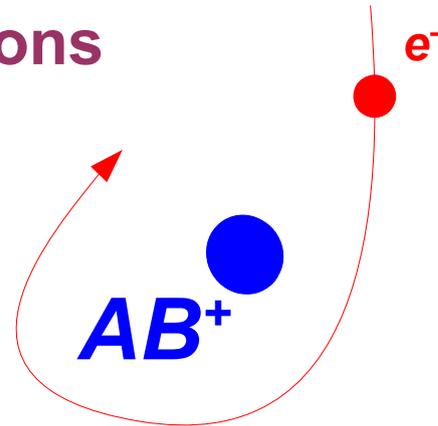
Neutral-neutral binary reactions



Ion-neutral reactions



Ion-electron reactions



Charge exchange



The first molecules

The primordial “soup” : H^+ , He^{++} , Li^{+++} , e^-

Cooling down into the 10-30 K range \rightarrow Protostars

**Recombination
in the Early Universe**

Atomic recombination



The first molecules

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Cooling down into the 10-30 K range \rightarrow Protostars

Recombination in the Early Universe

Atomic recombination



The first molecule



$$E_\gamma = h\nu \\ \sim 2 \text{ eV}$$

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Cooling down into the 10-30 K range \rightarrow Protostars

Recombination in the Early Universe

Atomic recombination



The first molecule



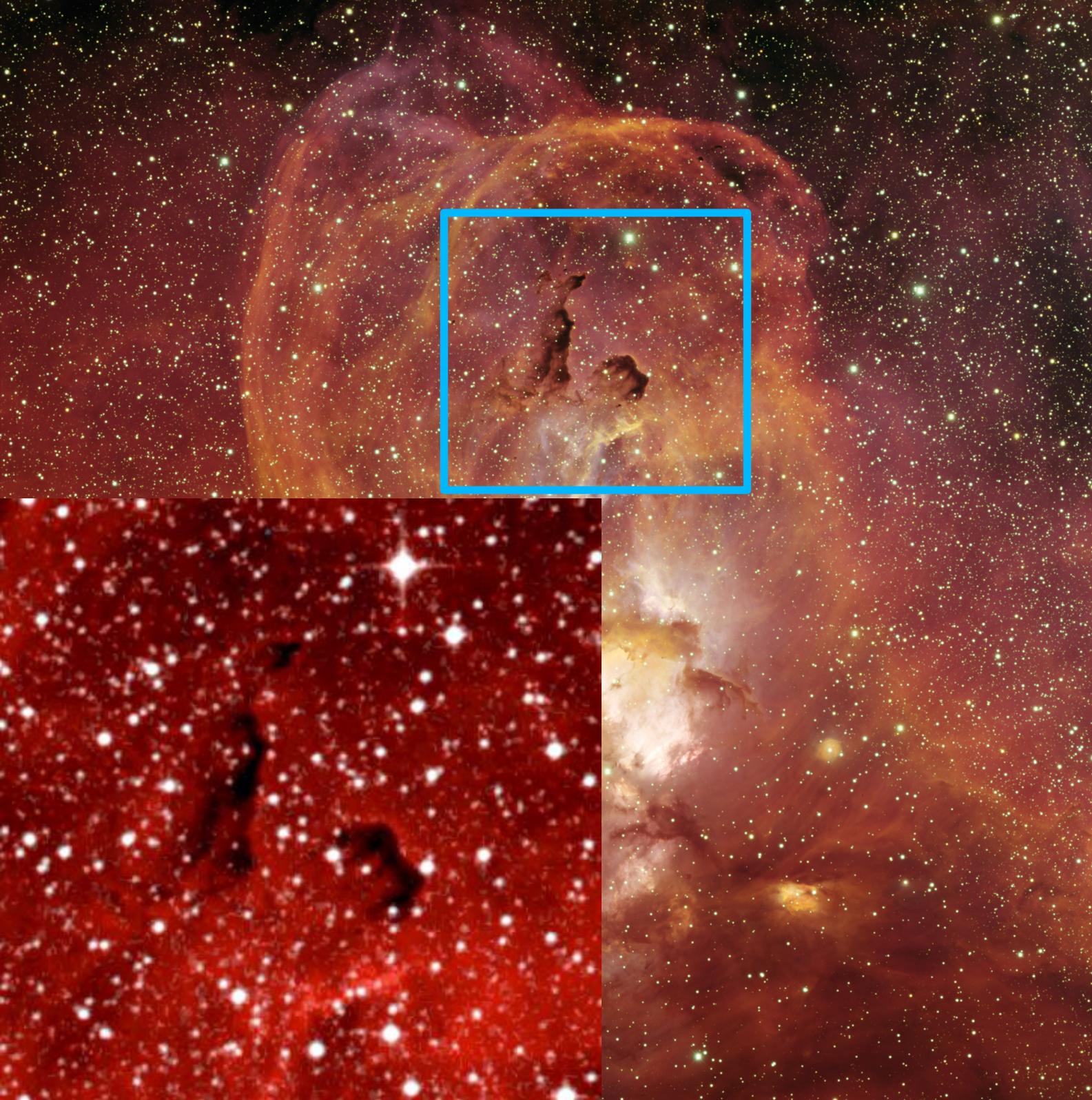
$$E_\gamma = h\nu \\ \sim 2 \text{ eV}$$



Dissociative recombination

Destruction of molecules

by capture of free electrons



Interstellar molecular clouds

Ion chemistry
density $\sim 10^4 \text{ cm}^{-3}$
temperature $\sim 10 \text{ K}$

Star forming regions

NGC 3576-86

T.A. Rector
U. of Alaska Anchorage
T. Abbott and
NOAO/AURA/NSF

Interstellar molecular clouds

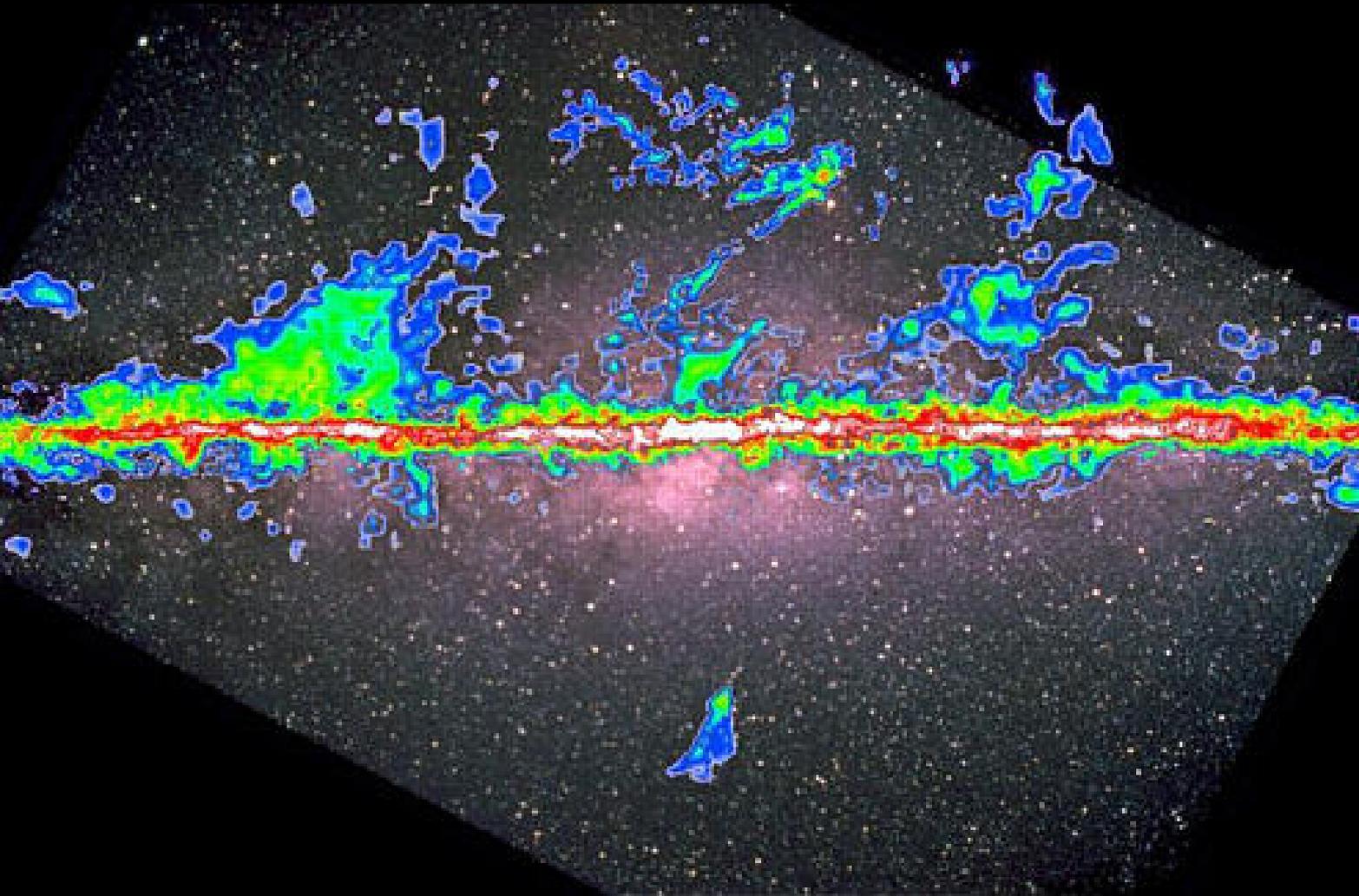
Ion chemistry
density $\sim 10^4 \text{ cm}^{-3}$
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Star forming regions

Milky Way
visible

Cerro Tololo
S. Kohle

Interstellar molecular clouds



Ion chemistry
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Star forming regions

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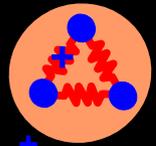
CO radio line
T. Dame
Harvard
Smithsonian

Interstellar ion chemistry

Reaction chains in interstellar clouds

- >190 observed interstellar molecules
- Heavy species: $\text{CH}_3\text{CH}_2\text{OH}$, glycoaldehyde, C_6H^- , PAH...

- Ions: CH^+
 CO^+
 CF^+
 H_3O^+
 HCO^+ , COH^+
 HCNH^+
 H_2COH^+
 NCCNH^+
 SH^+
 C_6H^- ...



H_3^+



ON2
Star forming region
("Chicken" Nebula)
Infrared

UKIRT
Mauna Kea
Chris Davis (JAC)

Interstellar ion chemistry

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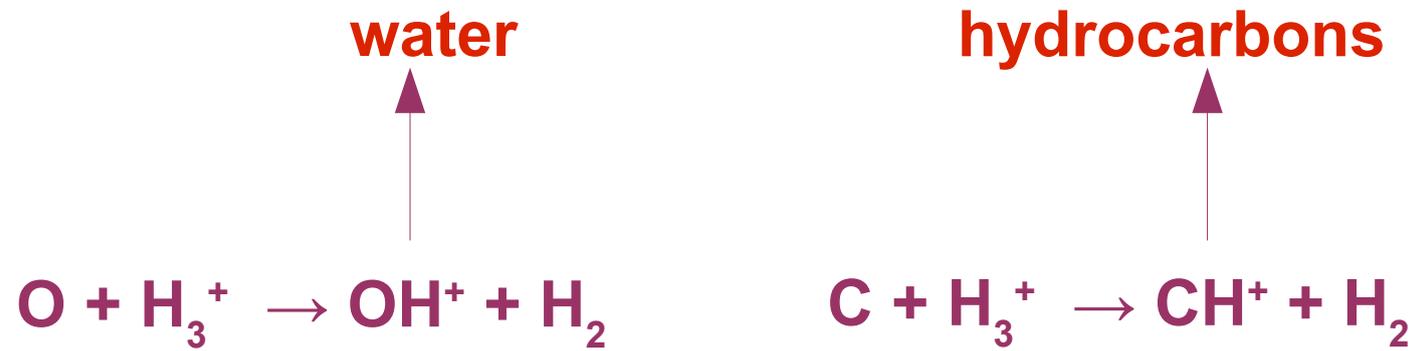
Molecules cool the star-forming regions

Observed by infrared and radio spectroscopy

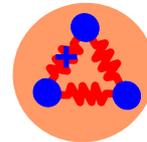
Chemistry in molecular clouds

After first star explosions : O, C, Fe, ... H₂

T ~ 10 K



Formation of the key molecule H₃⁺

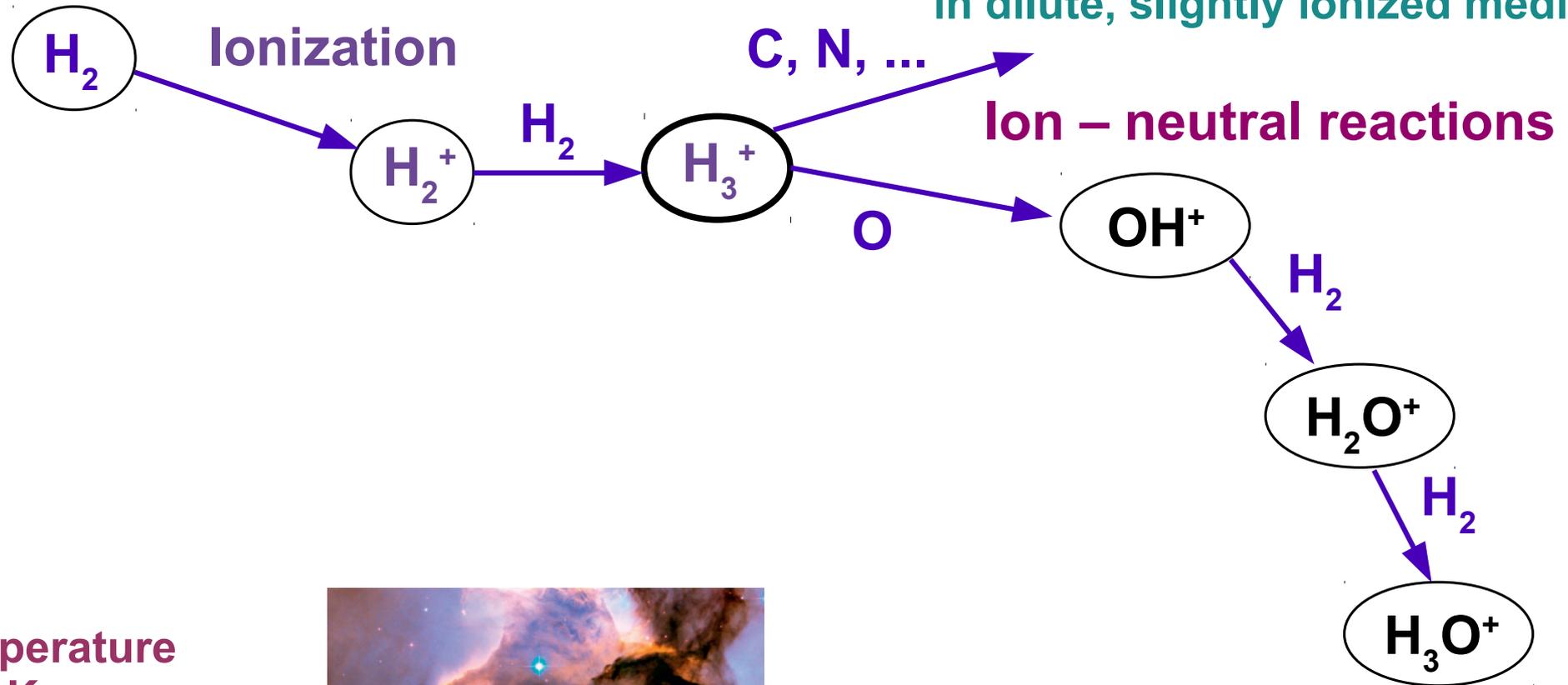


Ionization by cosmic radiation or x-rays



Ion chemistry and electron collisions

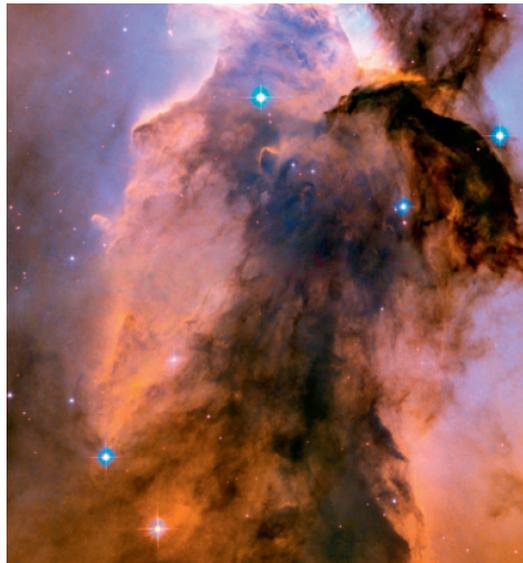
Low-temperature reactions
in dilute, slightly ionized media



Temperature
~ 10 K

Density
~ 10...10⁴ cm⁻³

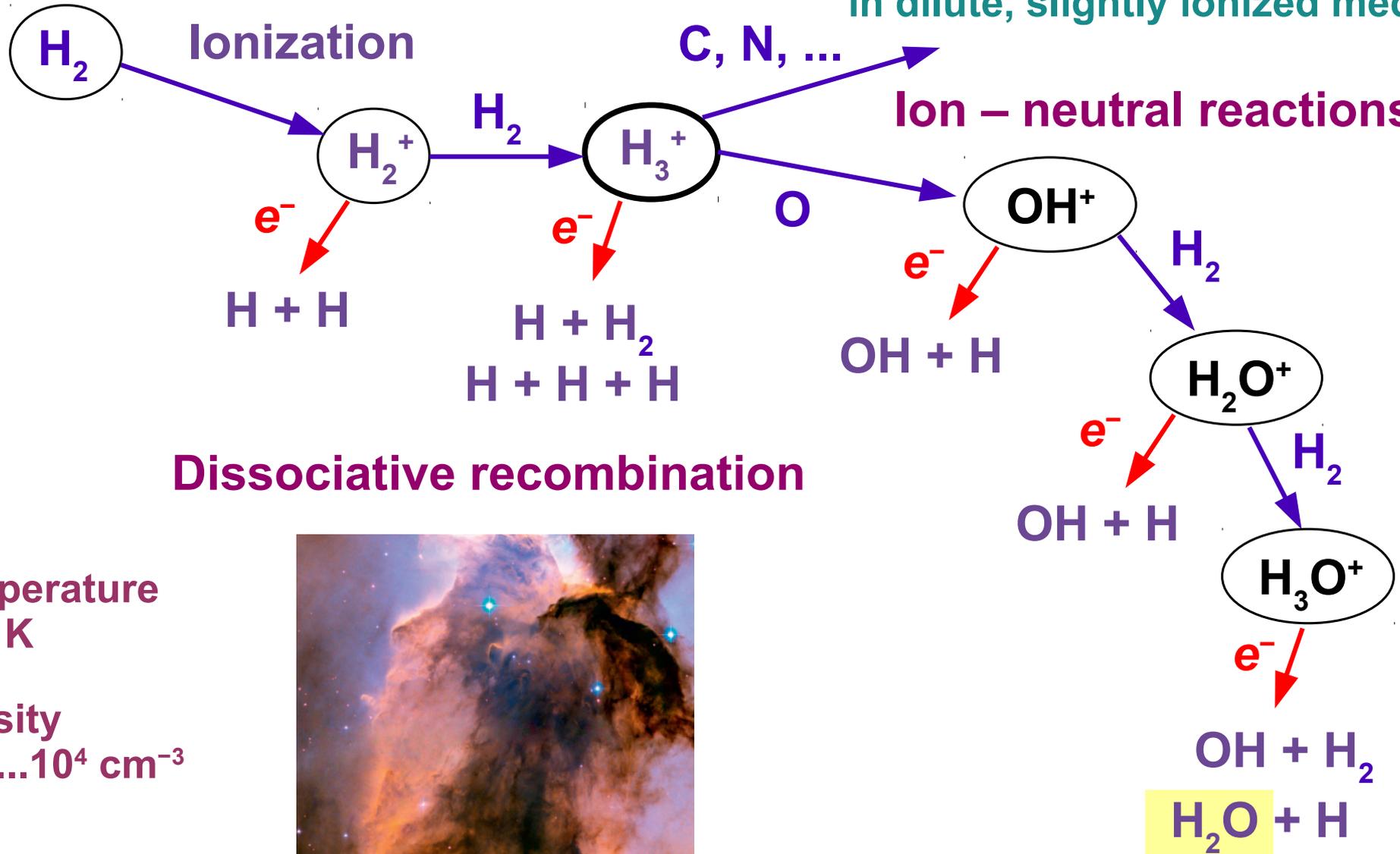
Molecular cloud
astrochemistry



Ion chemistry and electron collisions

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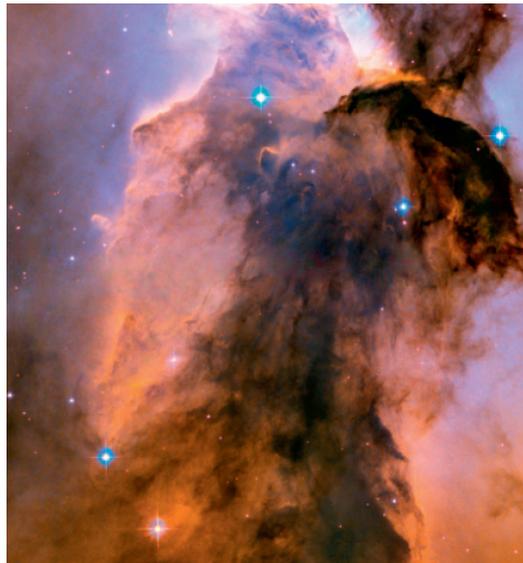
Ion – neutral reactions



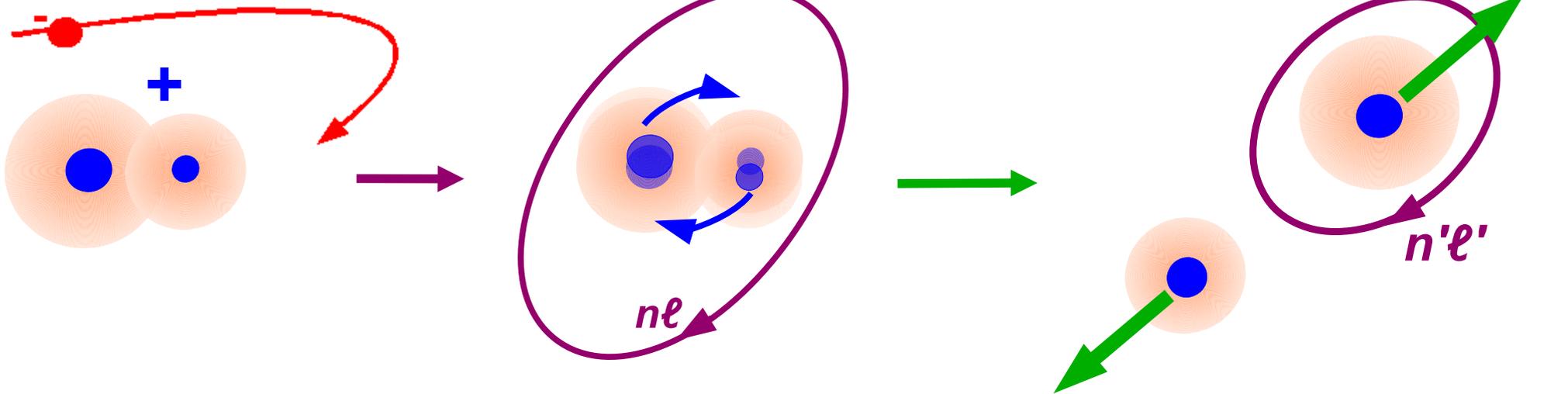
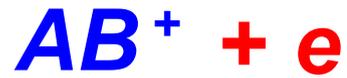
Temperature
~ 10 K

Density
~ $10 \dots 10^4 \text{ cm}^{-3}$

Molecular cloud
astrochemistry



Dissociative recombination

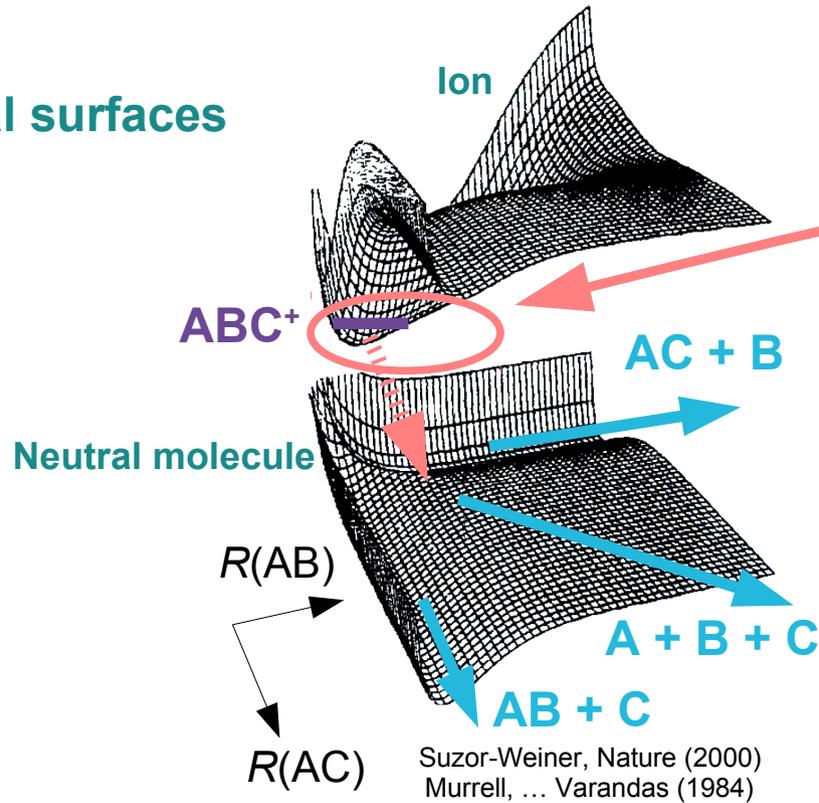


Electron capture resonance

Many resonances by electronic, vibrational or rotational excitation

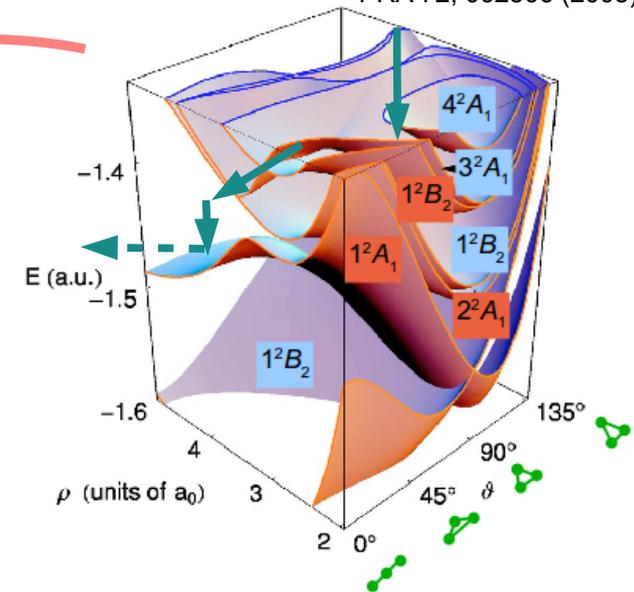
Electron capture and fragmentation

Potential surfaces



Case of H_3^+ :

U. Galster, H. Helm, M. Jungen,
PRA 72, 062506 (2005)



Rydberg states

$$(ABC^+)^* + nl$$

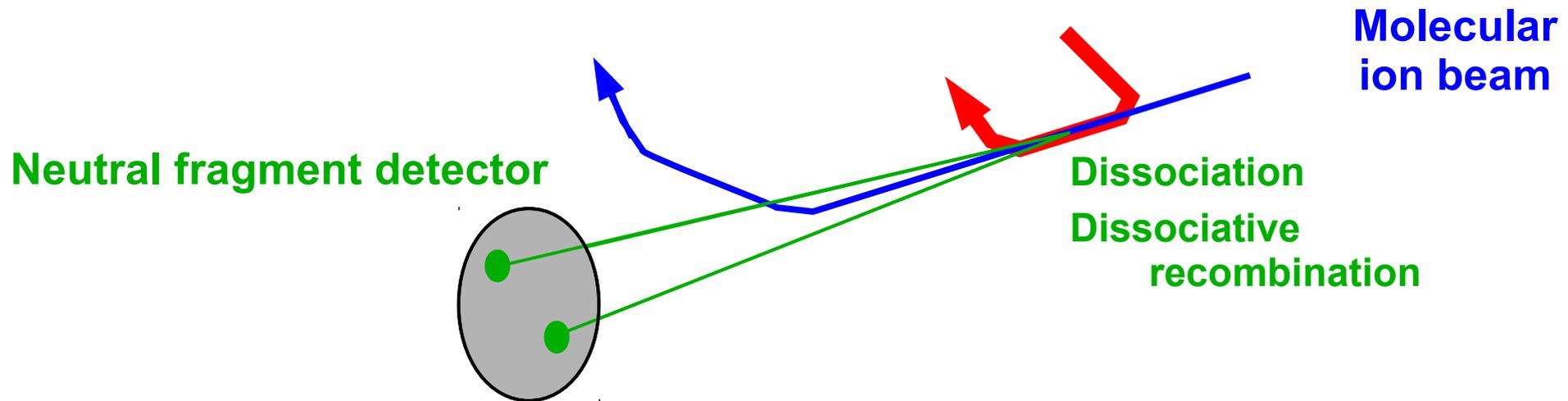
formed by core excitation
in low-energy electron collision
and free-electron capture

Experiments: fast beam fragmentation measurements

Velocity-matched electron beam

Collision energy: $E_d = \frac{1}{2} m_e (v_e - v_i)^2$

Wide scan range: $\sim 1 \text{ meV} \dots 50 \text{ eV}$



- Counting
- Momentum measurement (time + position)
- Coincidence measurements

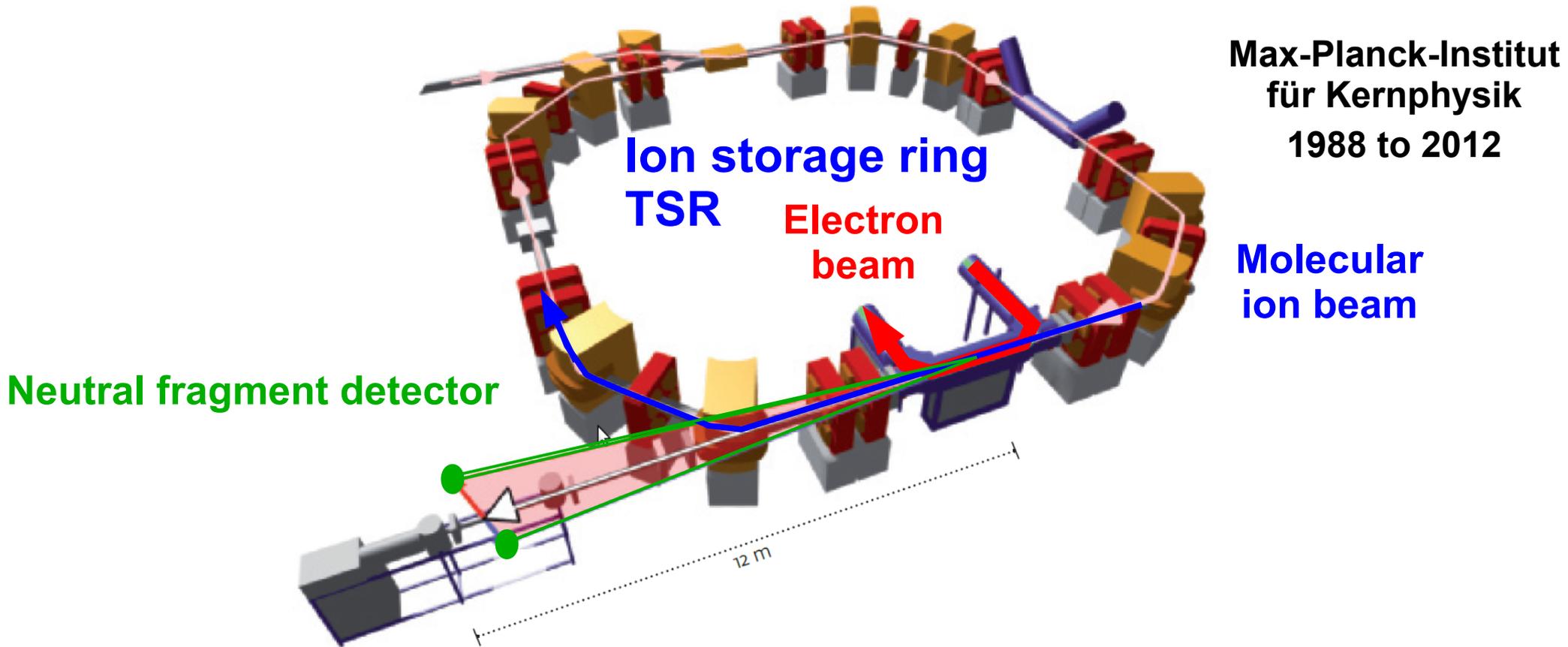
- Fragment mass identification

Fragments keep (approx.) the beam velocity v_i

→ Laboratory kinetic energy of fragment f :

$$E_f = \frac{1}{2} M_f v_i^2$$

Storage ring merged beams experiments

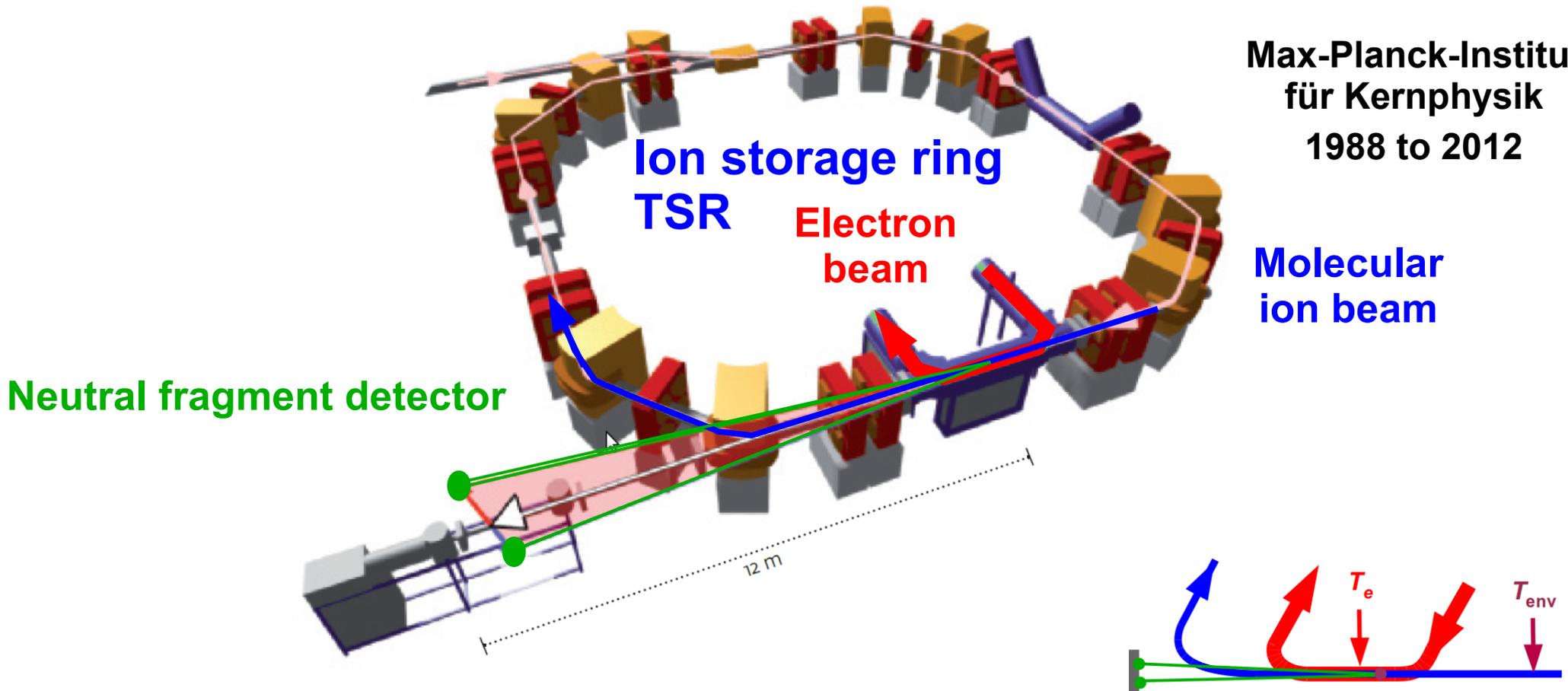


Max-Planck-Institut
für Kernphysik
1988 to 2012

Molecular
ion beam

Storage ring merged beams experiments

Max-Planck-Institut
für Kernphysik
1988 to 2012



- Store and phase-space cool molecular ion beam
- Reduce/control internal excitation of molecular ions ($T_{env} = 300$ K)
- Cold electrons ($T_e \sim 10$ K) – vary collision energy of electrons
- Neutral fragment detection: rates
product momenta
product masses

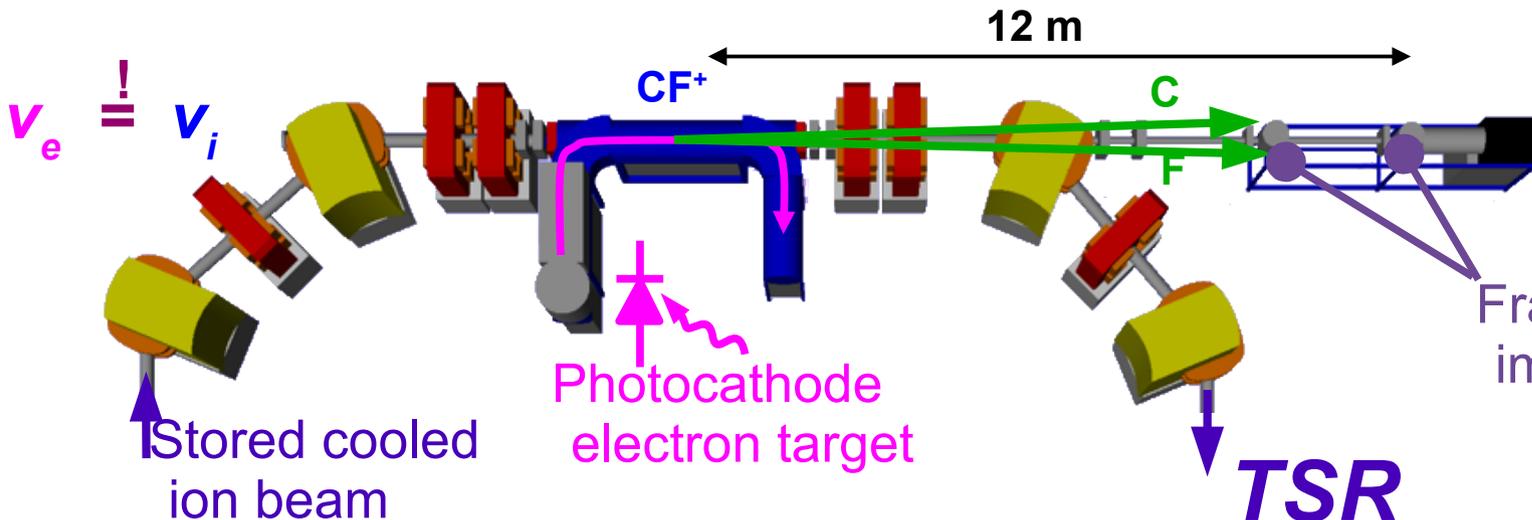
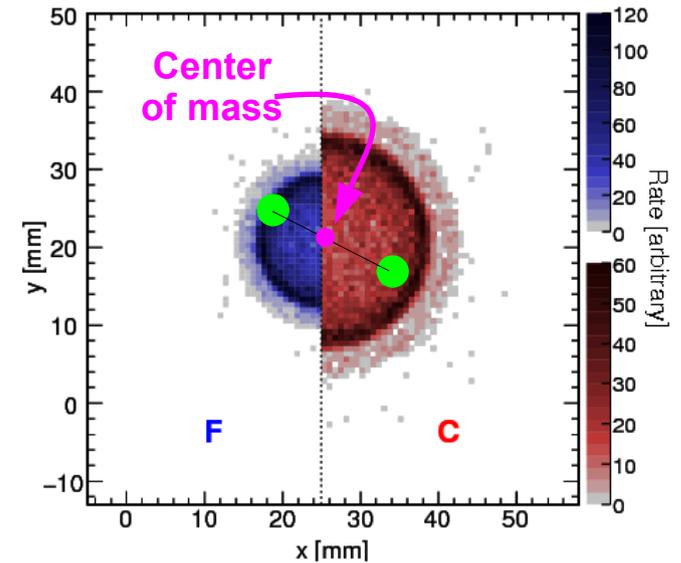
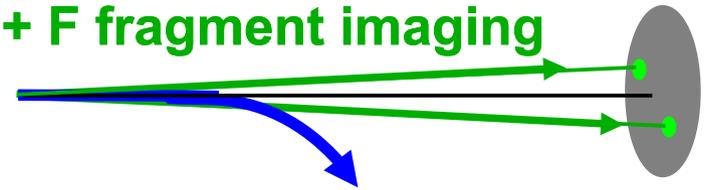
Fragmentation and phase space cooling by cold e⁻

CF⁺ (31 amu) at 90 keV/amu

50 eV electrons
~1 mA electron current



C + F fragment imaging



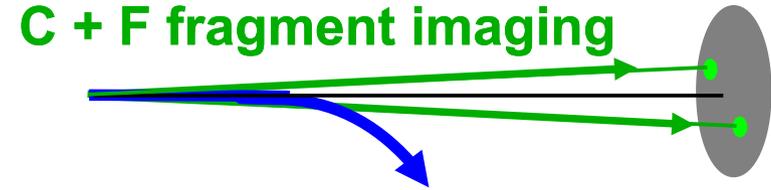
O. Novotný et al.,
J. Phys. Chem. A
114, 4870 (2010)

Fragment counting/
imaging detectors

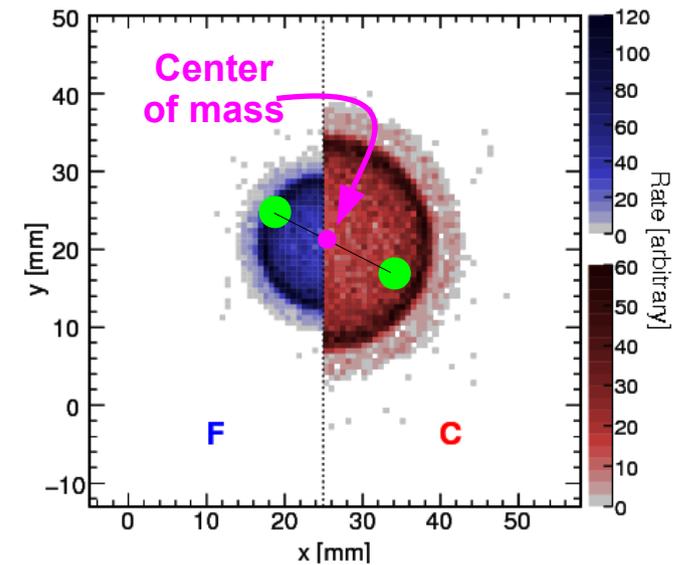
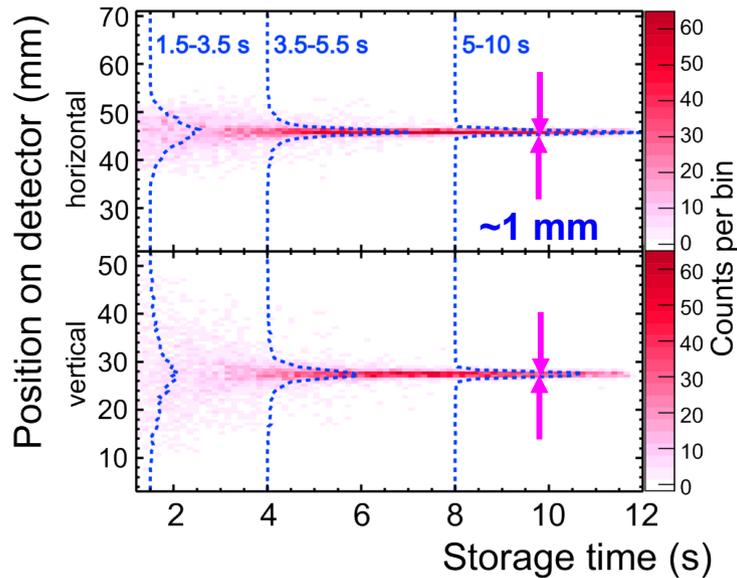
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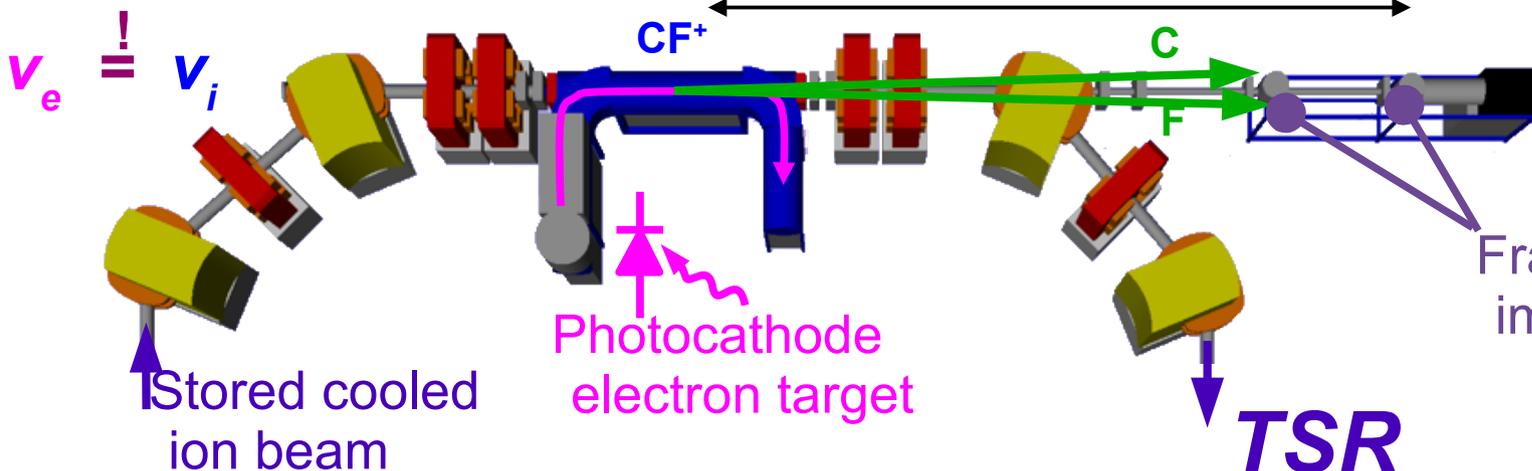
50 eV electrons
 ~1 mA electron current $CF^+ + e \rightarrow C + F$



Fragment center of mass



12 m



O. Novotný et al.,
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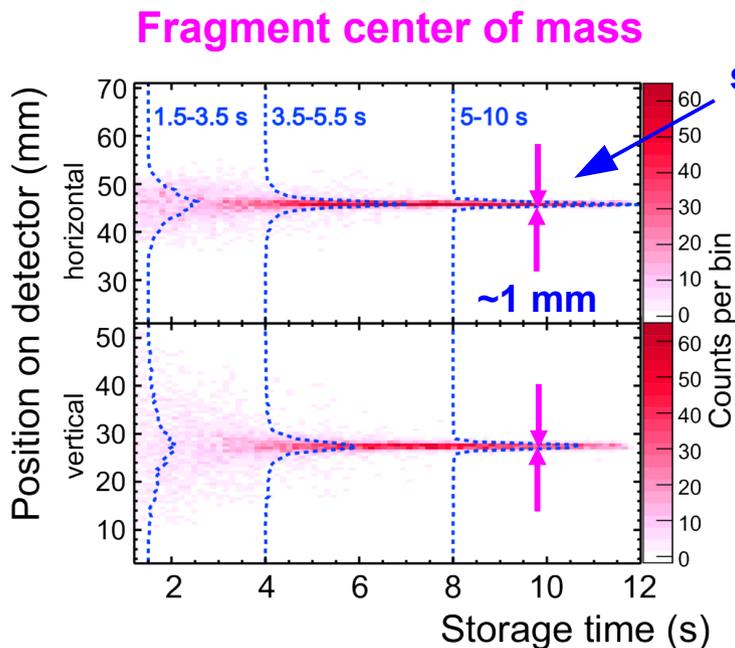
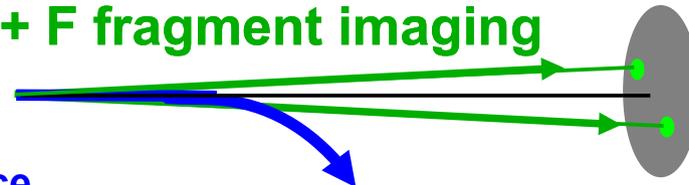
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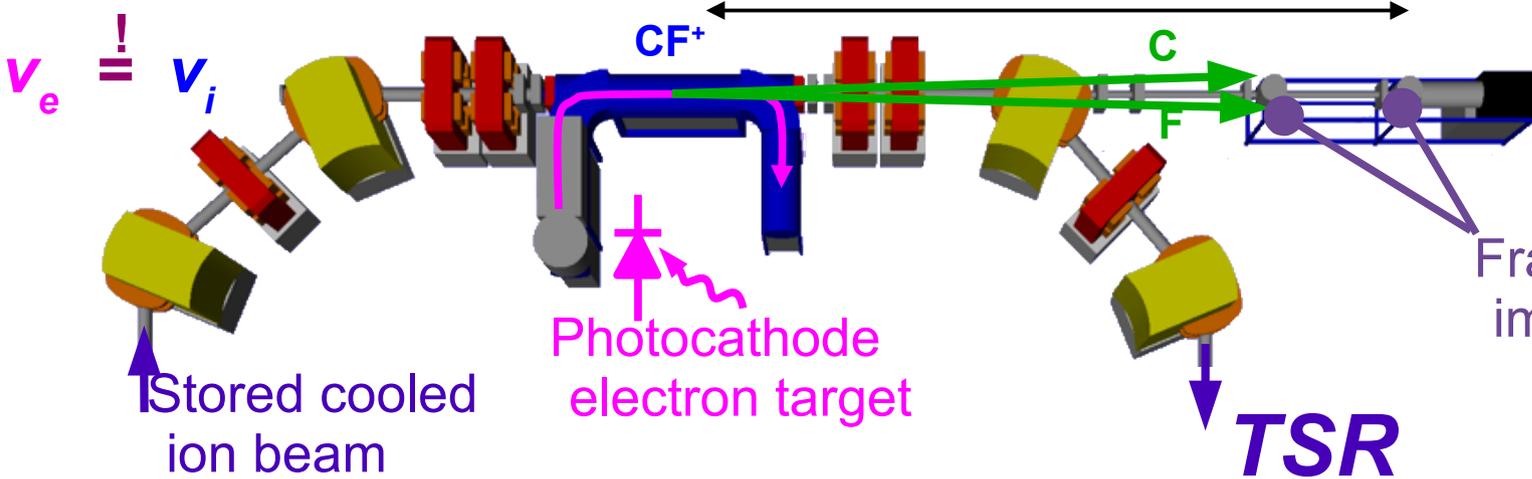
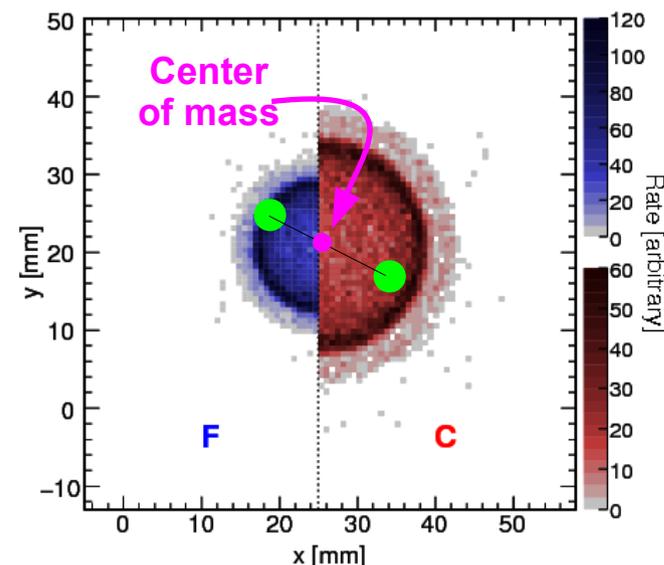
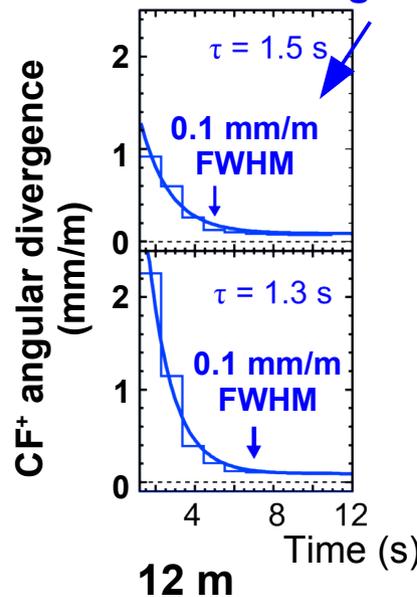
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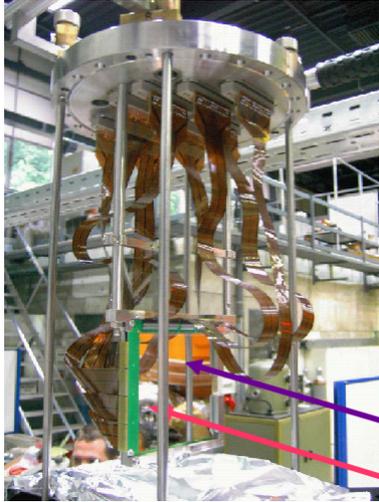
Ion beam: divergence angle



O. Novotný et al.,
J. Phys. Chem. A
114, 4870 (2010)

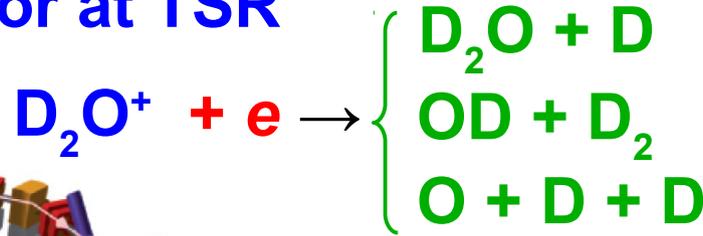
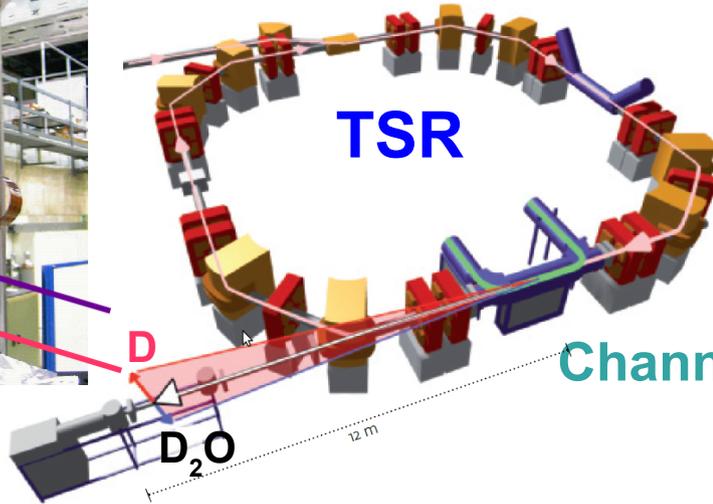
Polyatomic recombination measurements

Si multistrip detector at TSR



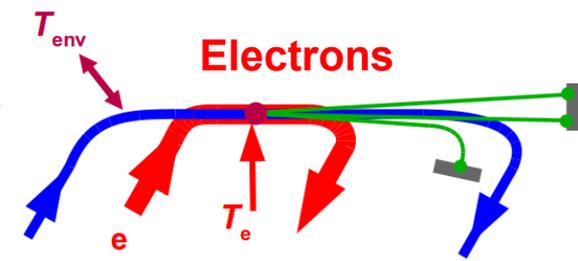
EMU detector

H. Buhr et al.,
PRA 81, 062702 (2010)



Imaging detector with fragment
mass recognition

Channel-specific energy release measurement

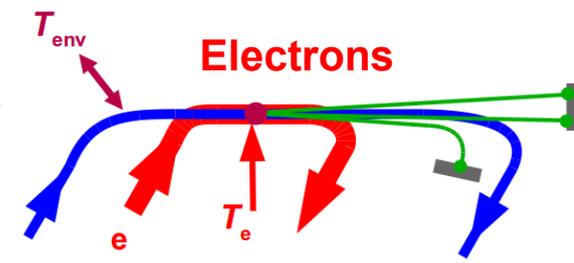
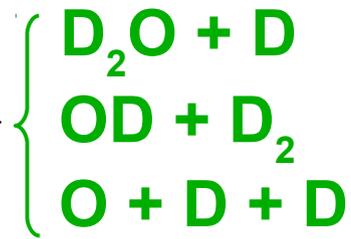
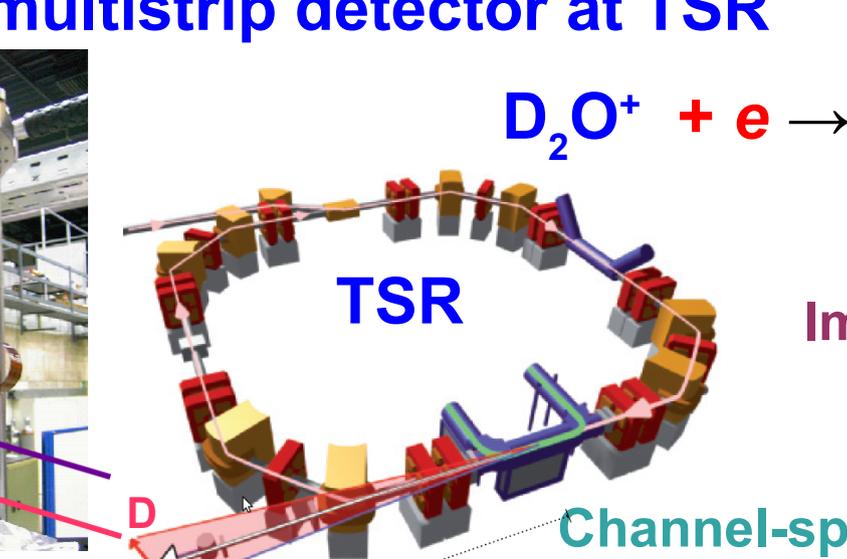


Polyatomic recombination measurements

Si multistrip detector at TSR

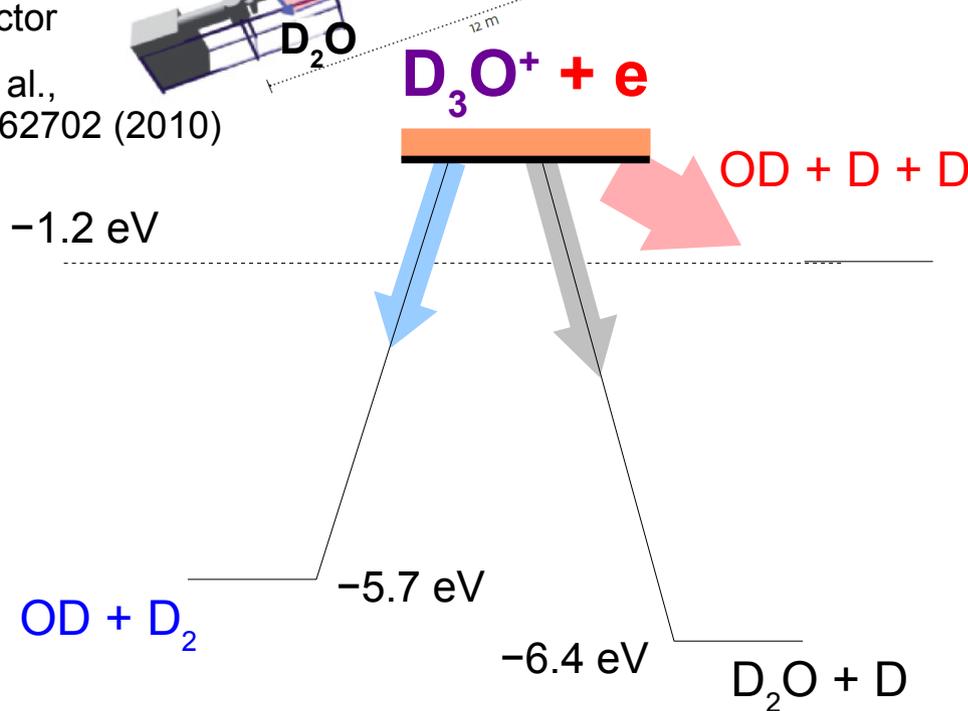


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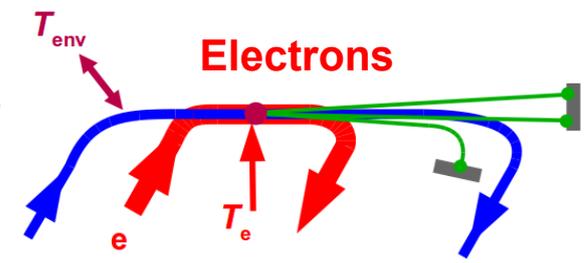
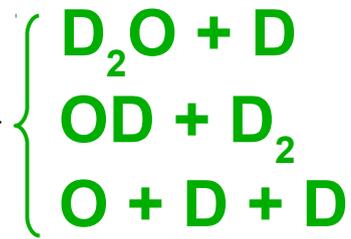
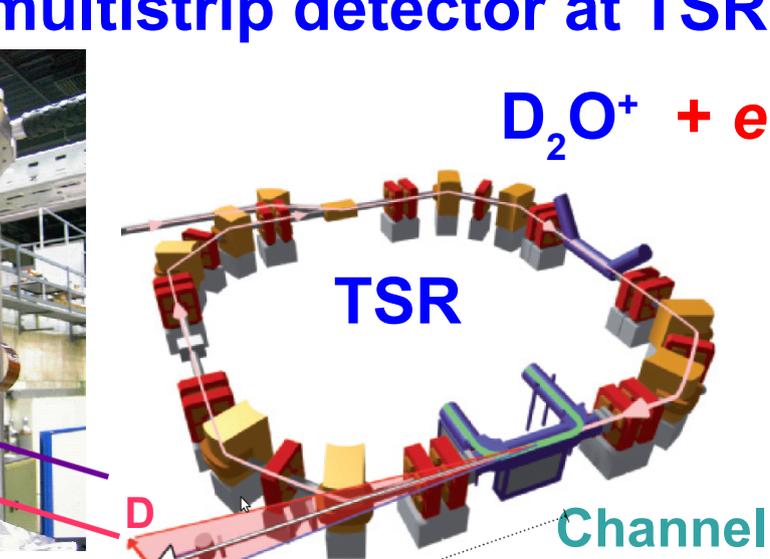
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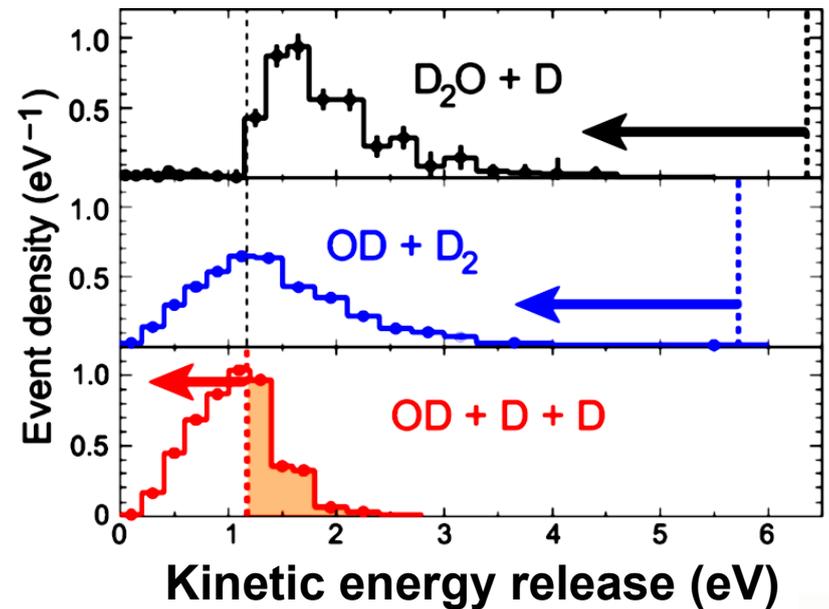
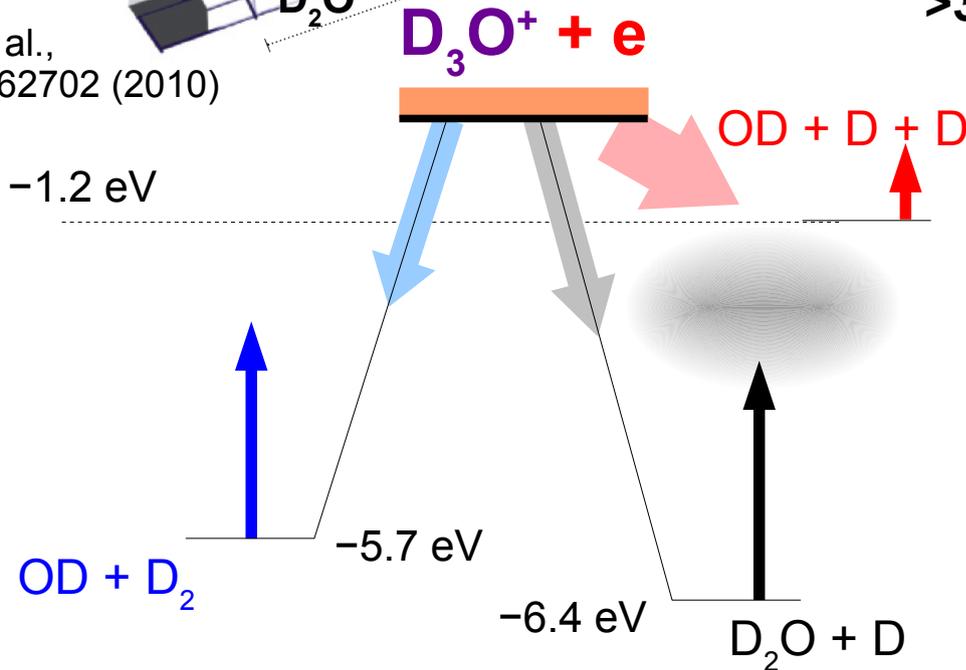


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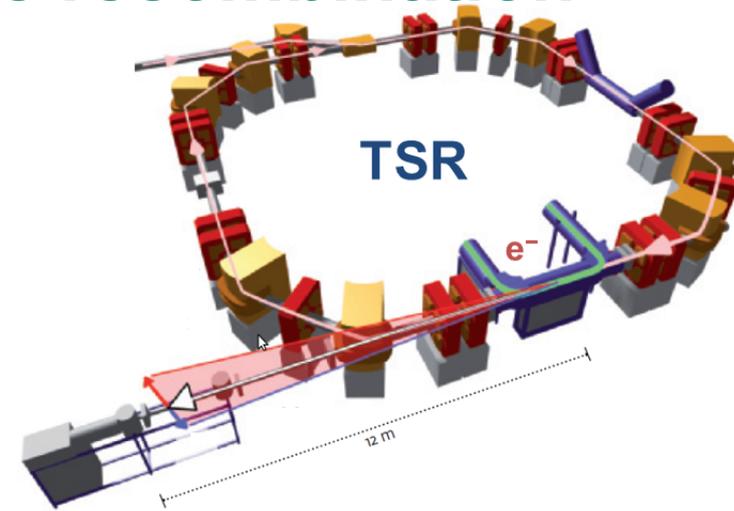
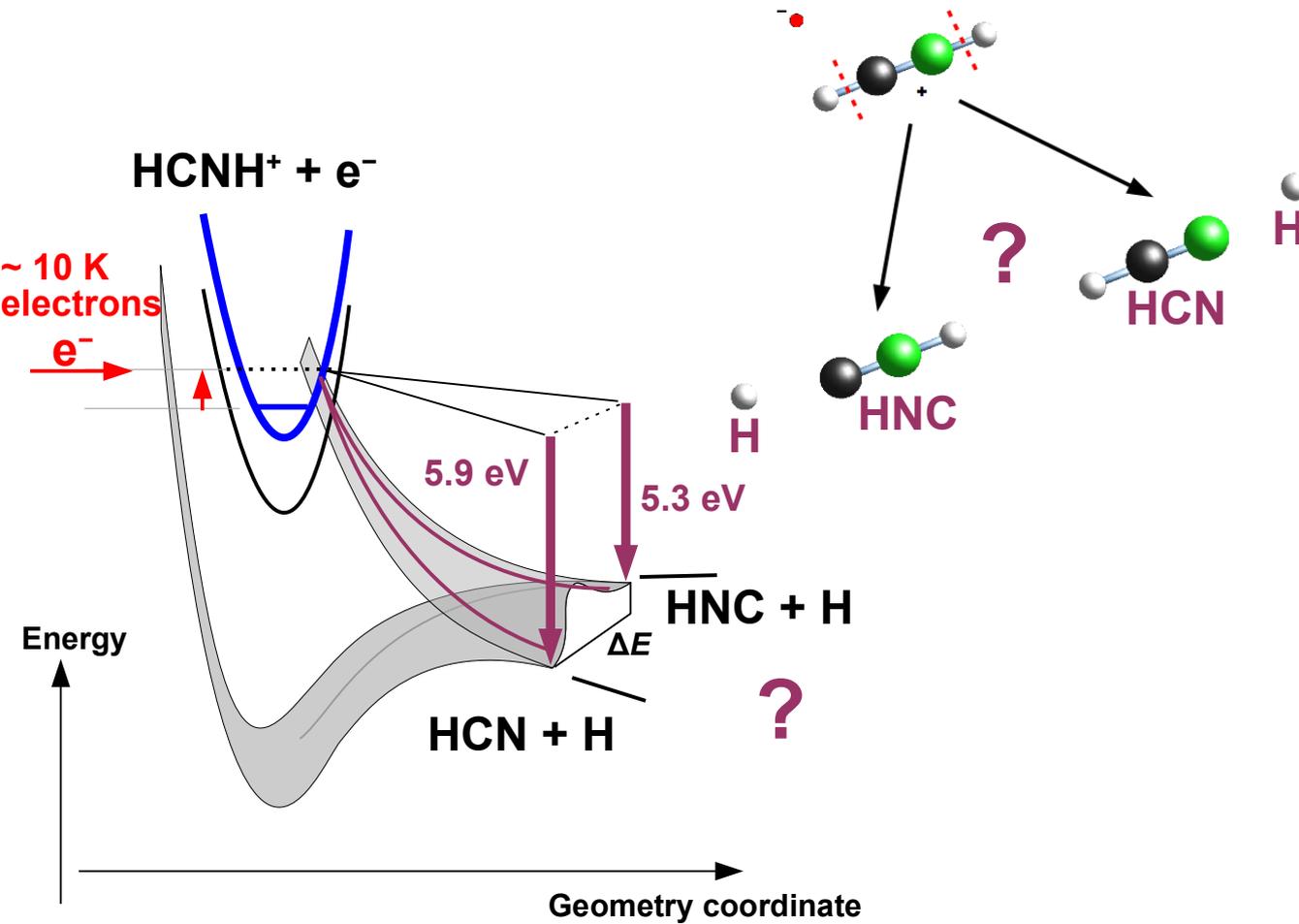
Channel-specific energy release measurement

>3 eV vibrational excitation of water

H. Buhr et al., PRL 105, 103202 (2010)

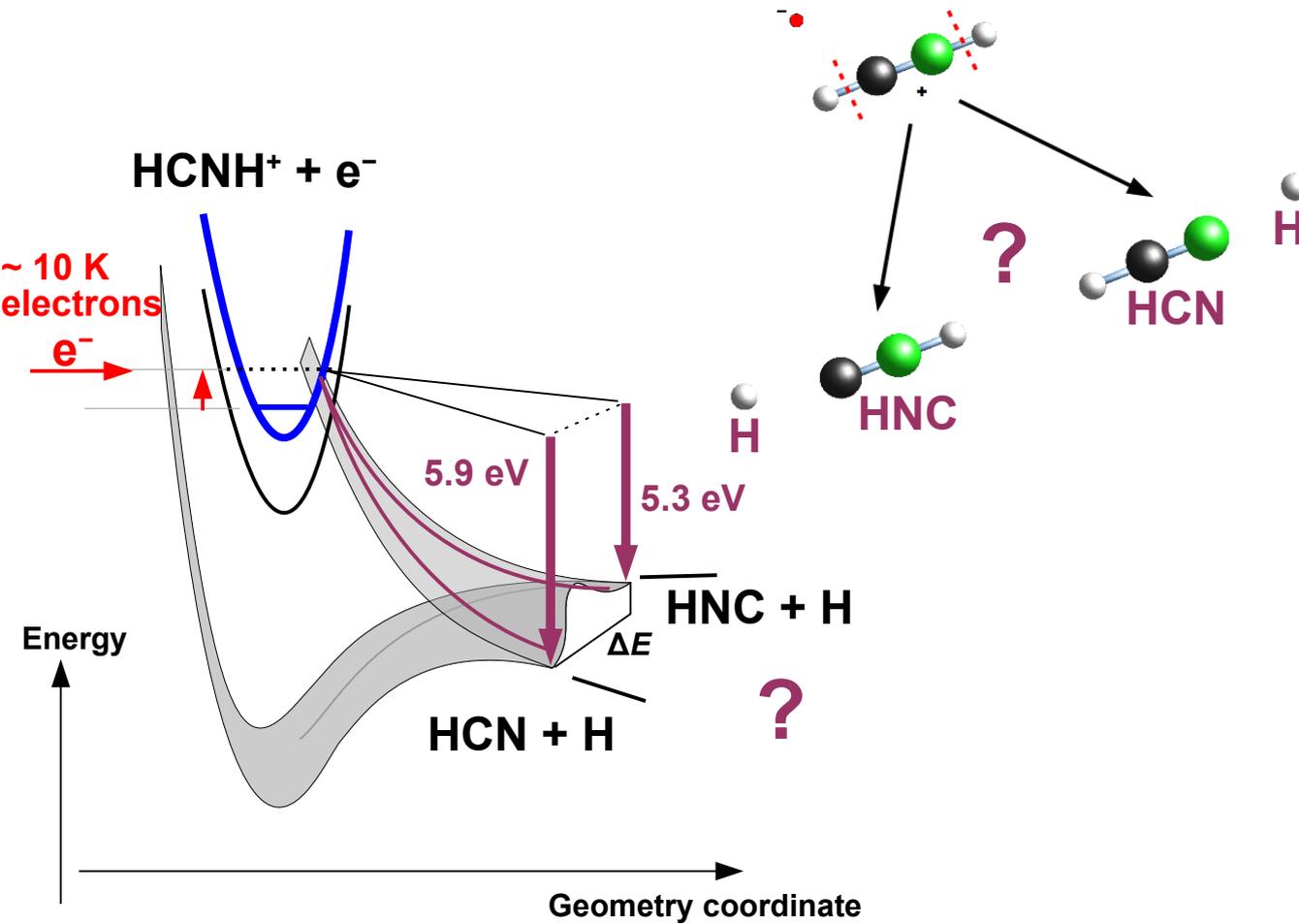


Isomeric fragments of dissociative recombination



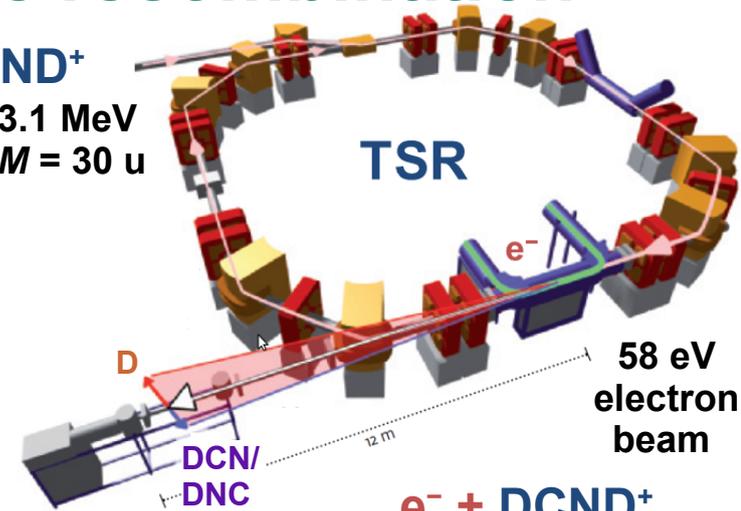
Fragment kinetic energy measurement

Isomeric fragments of dissociative recombination

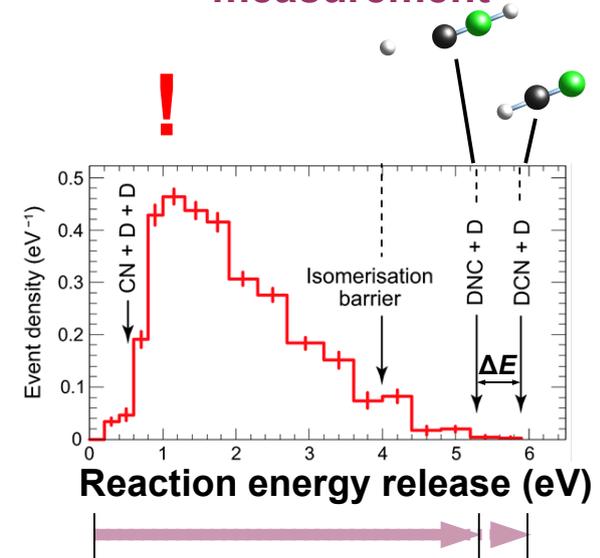


DCND⁺

3.1 MeV
M = 30 u

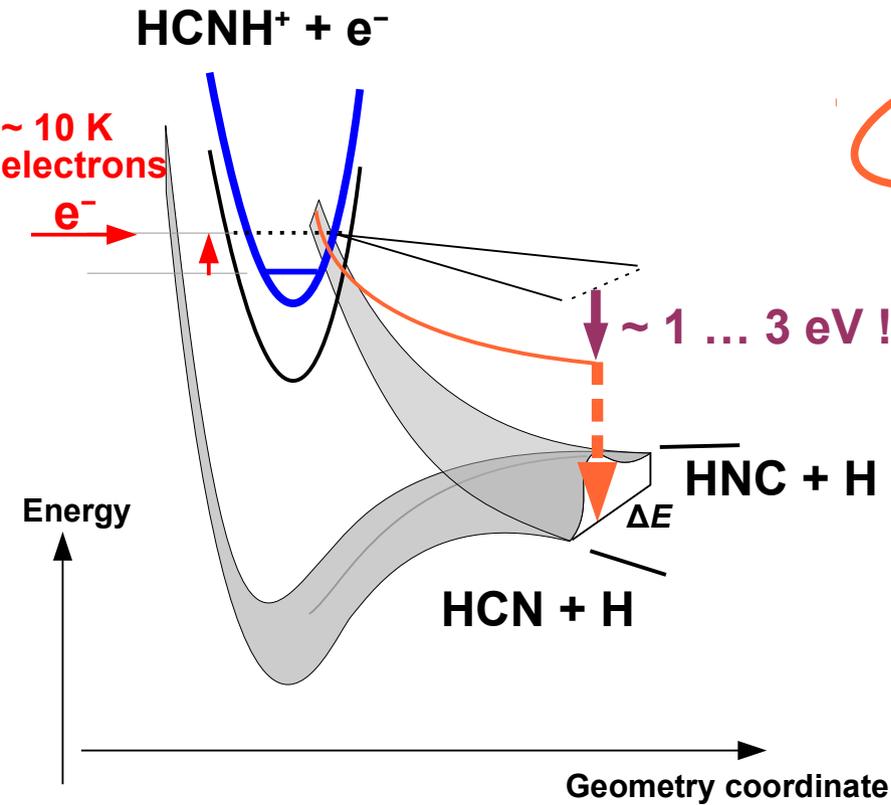
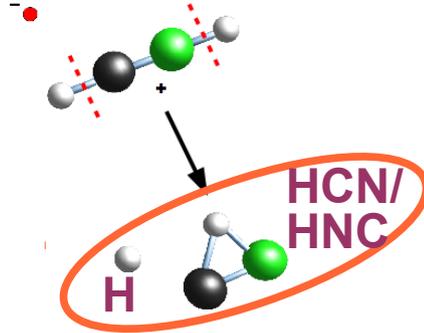


Fragment kinetic energy measurement



M. Mendes et al.,
Astrophys. J. Lett. 476, L8 (2012)

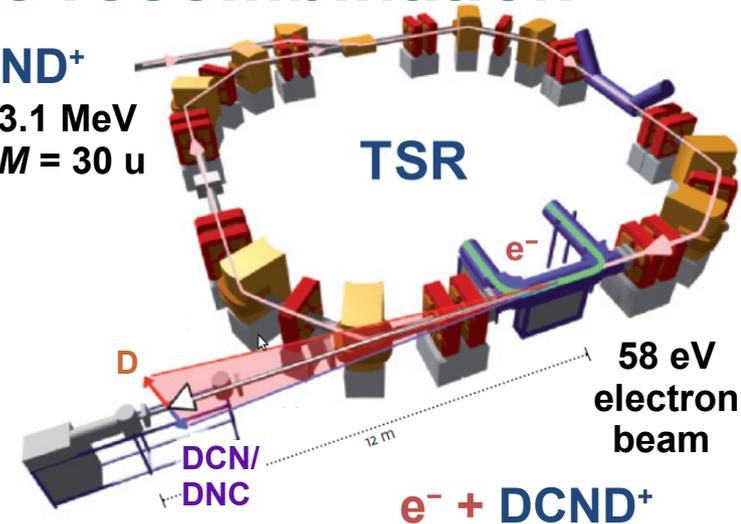
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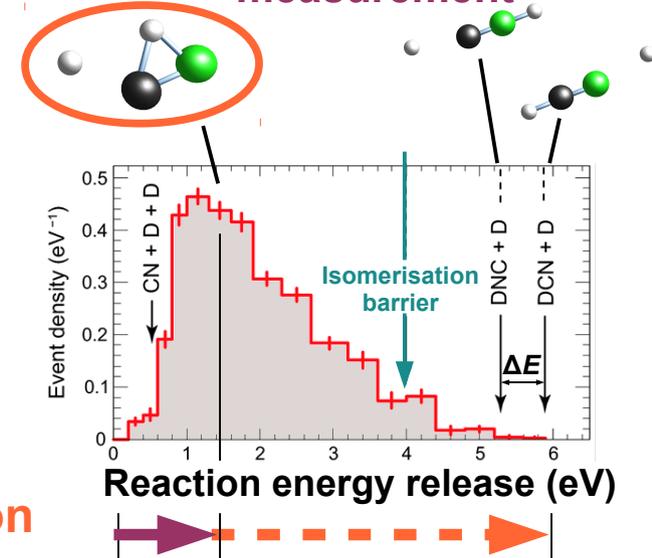
~ 3 ... 5 eV
product excitation

DCND⁺

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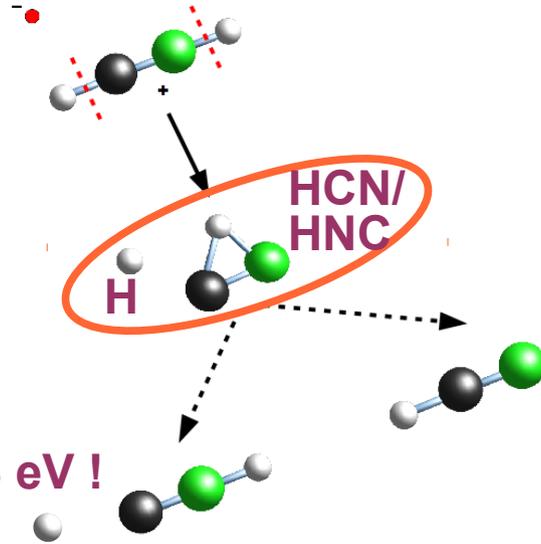
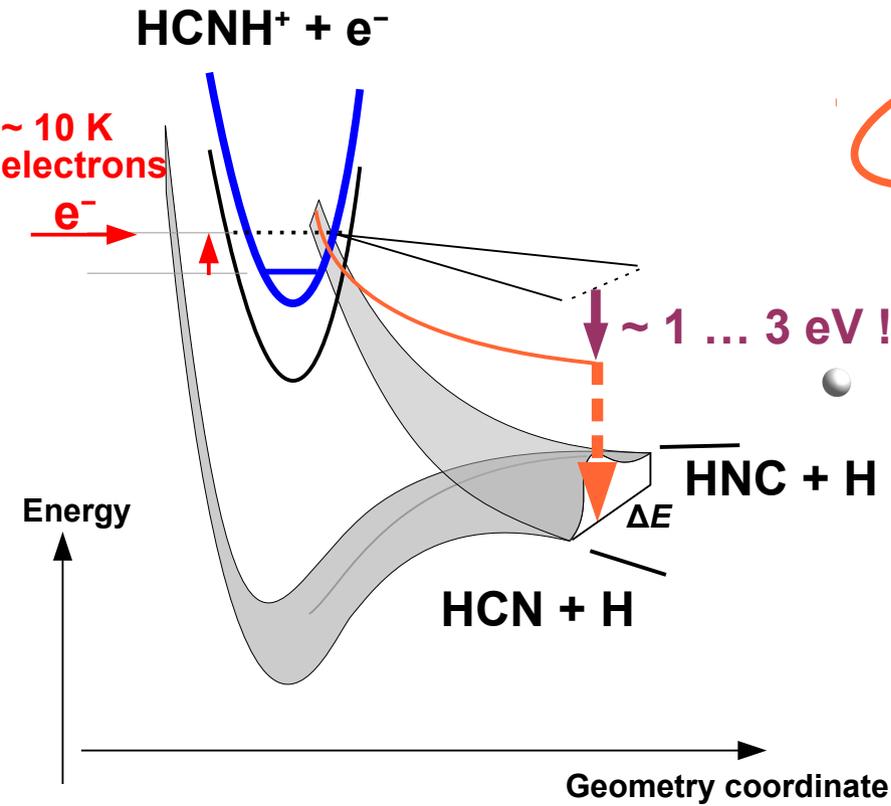


Fragment kinetic energy
measurement



M. Mendes et al.,
Astrophys. J. Lett. 476, L8 (2012)

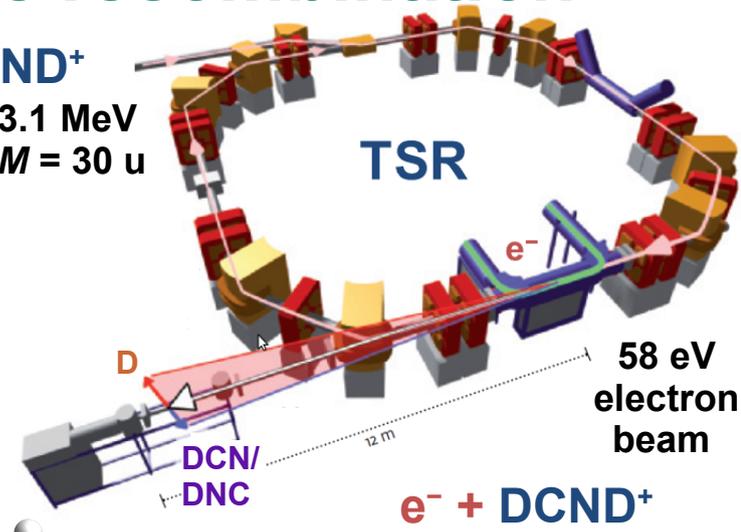
Isomeric fragments of dissociative recombination



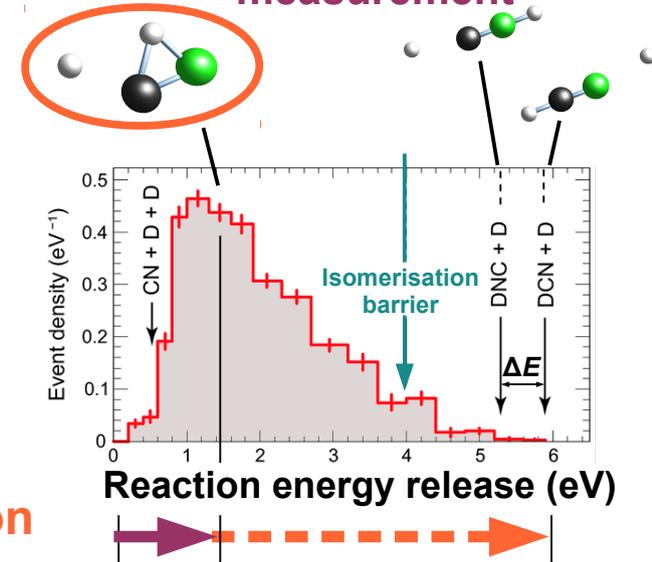
Electron capture in a cold medium produces energetic isomers

~ 3 ... 5 eV product excitation

DCND⁺
3.1 MeV
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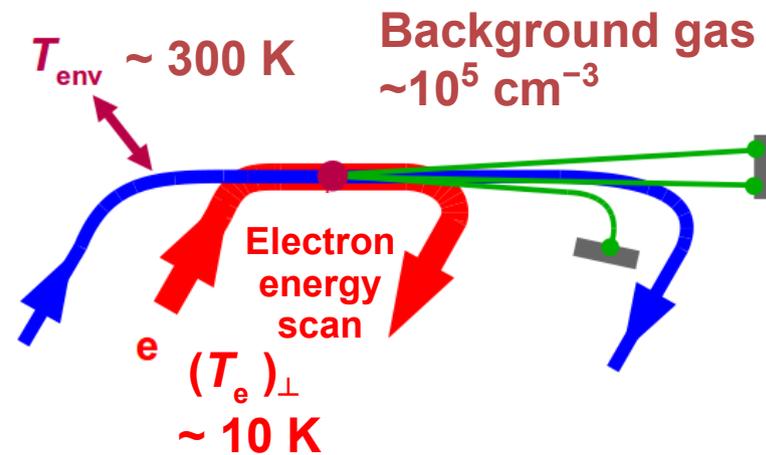
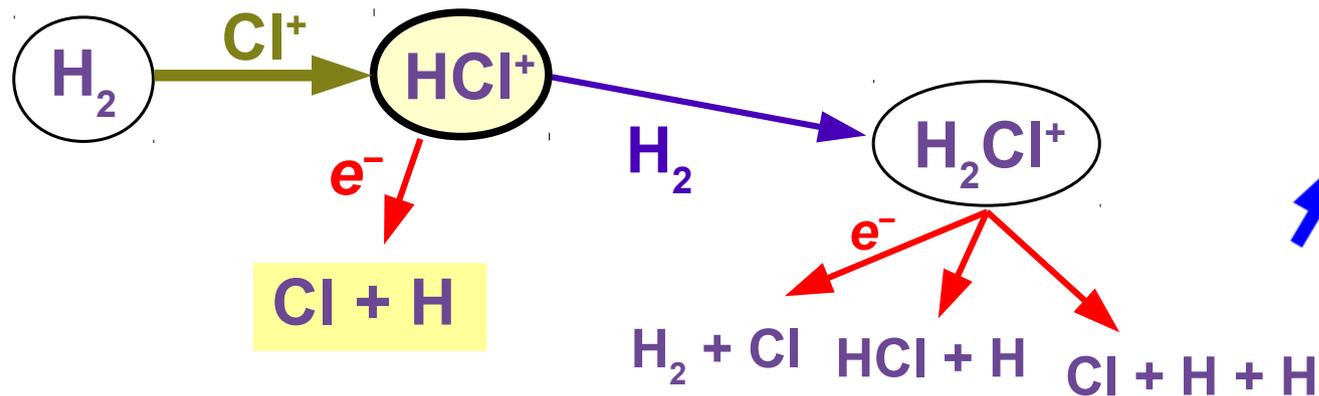


e⁻ + DCND⁺
Fragment kinetic energy measurement



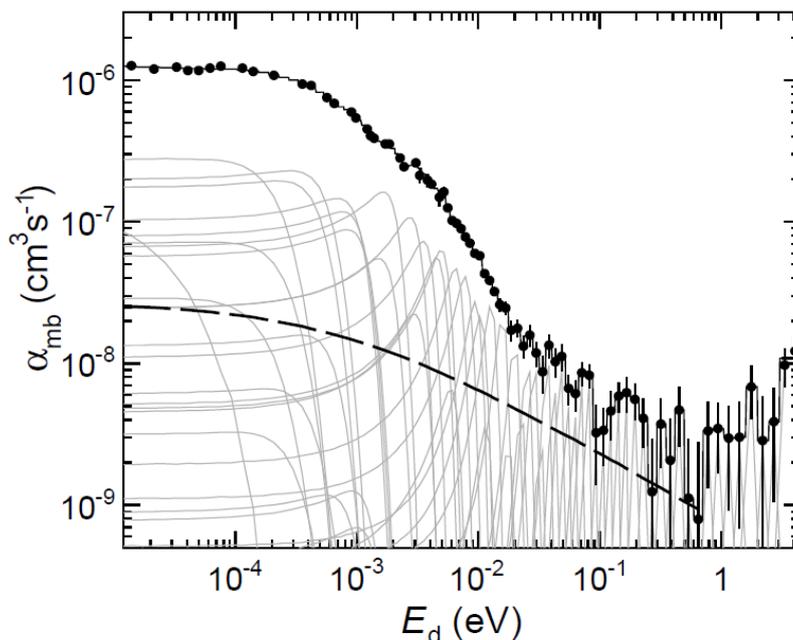
**M. Mendes et al.,
Astrophys. J. Lett. 476, L8 (2012)**

Low-energy DR of heavier ions: HCl⁺



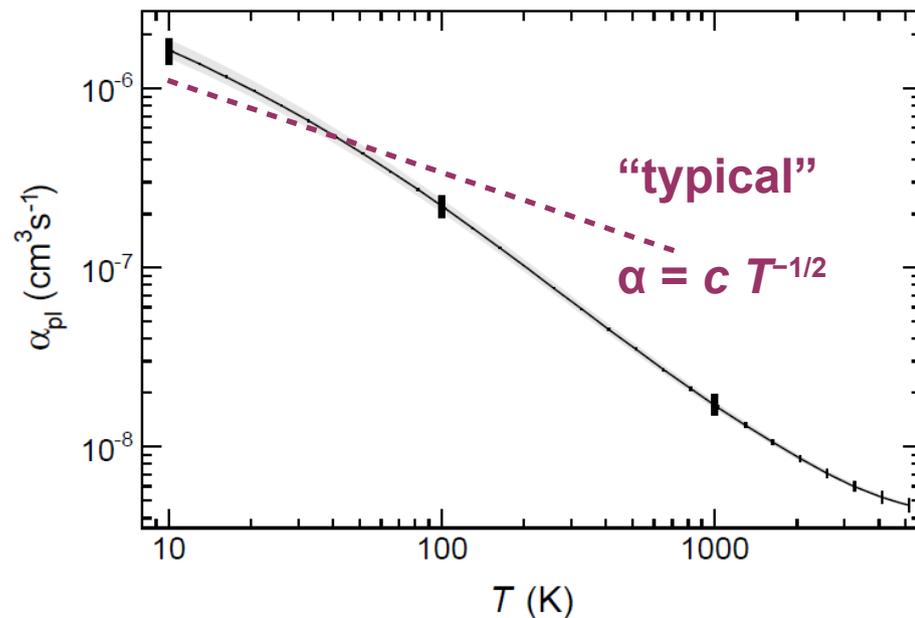
Energy-tuned DR rate (decomposition into model resonances)

Columbia
(D. Savin)
Heidelberg
ISM-SPP

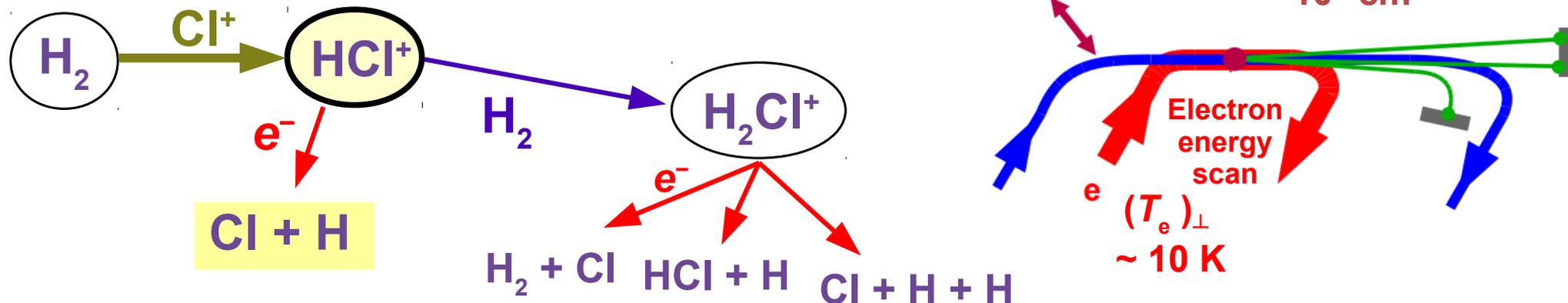


O. Novotný et al., *Astrophys. J.* 777, 54 (2013)

Plasma rate coefficient

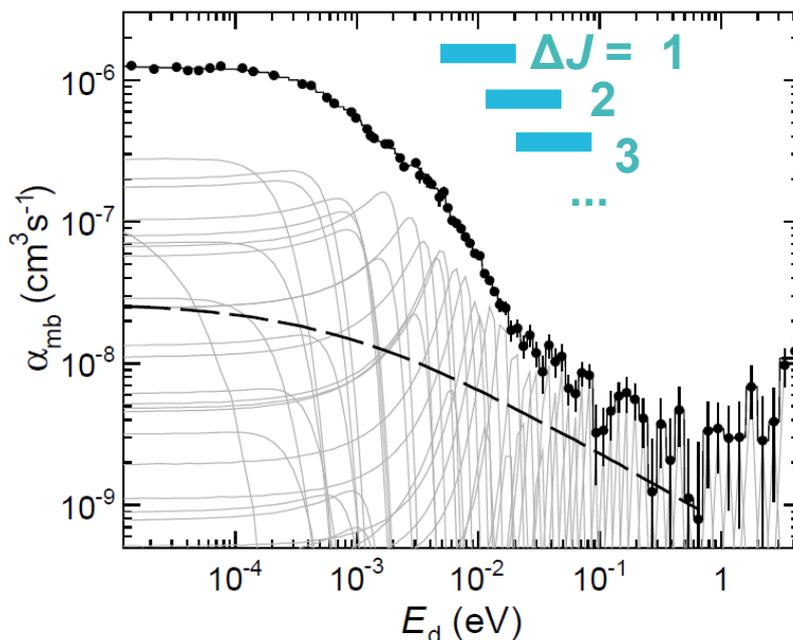


Low-energy DR of heavier ions: HCl⁺



Energy-tuned DR rate (decomposition into model resonances)

~300 K HCl⁺ ions

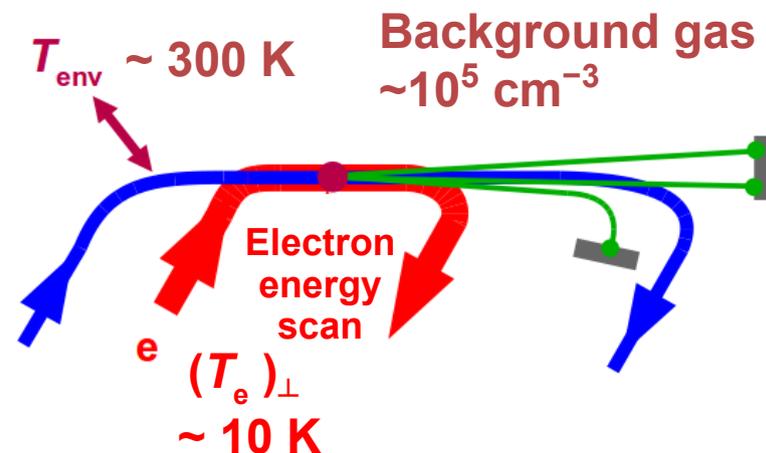
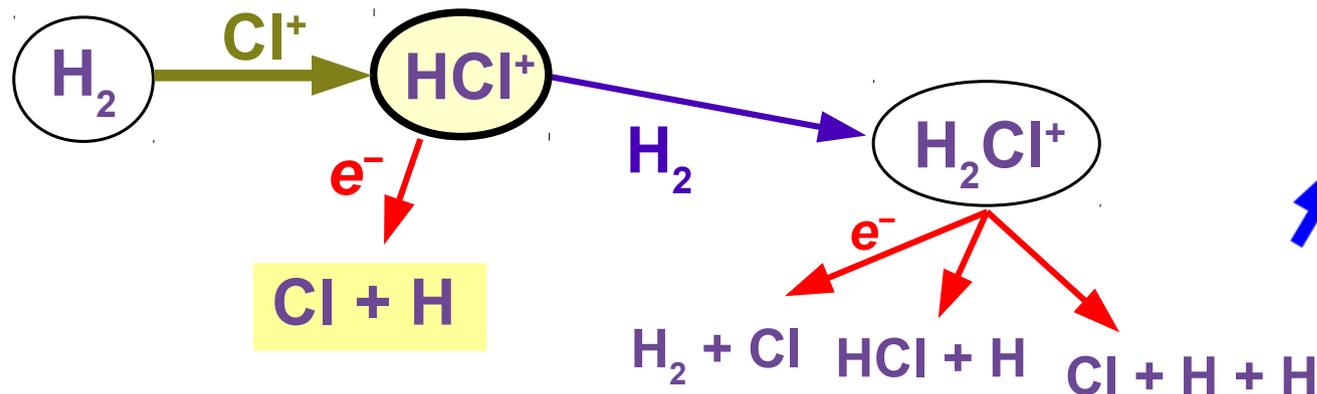


Energy ranges
of rotational Rydberg resonances

Columbia
(D. Savin)
Heidelberg
ISM-SPP

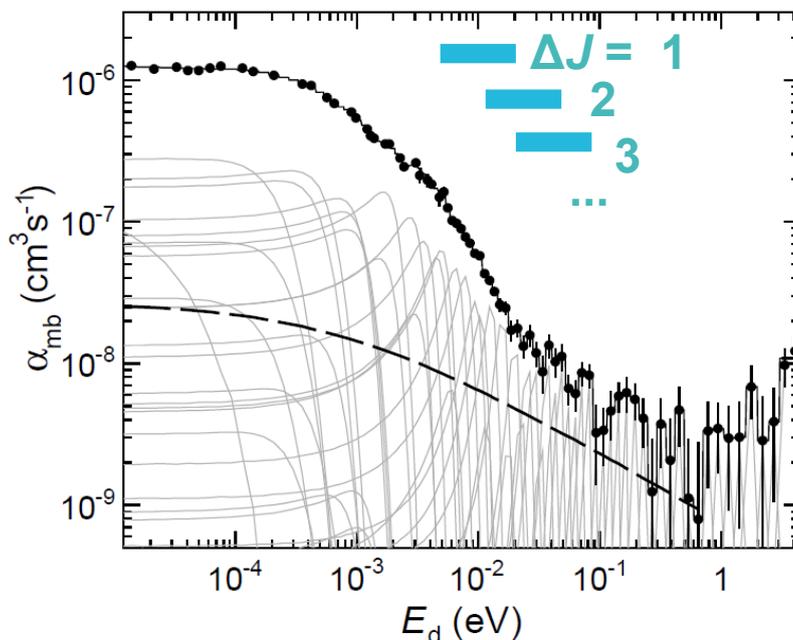
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Energy ranges
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Columbia
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Other systems measured
at TSR:



O. Novotný et al., *Astrophys. J.* 777, 54 (2013)

Stored and Cooled Ions (K. Blaum)

Atomic and molecular quantum dynamics

Atomic and
molecular physics

Electron target

Photocathode

A. W.

O. Novotný

H. Buhr (*)

C. Krantz

A. Petrigiani (*)

B. Jordon-Thaden (*)

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X. Urbain



Stored and cooled ion instrumentation

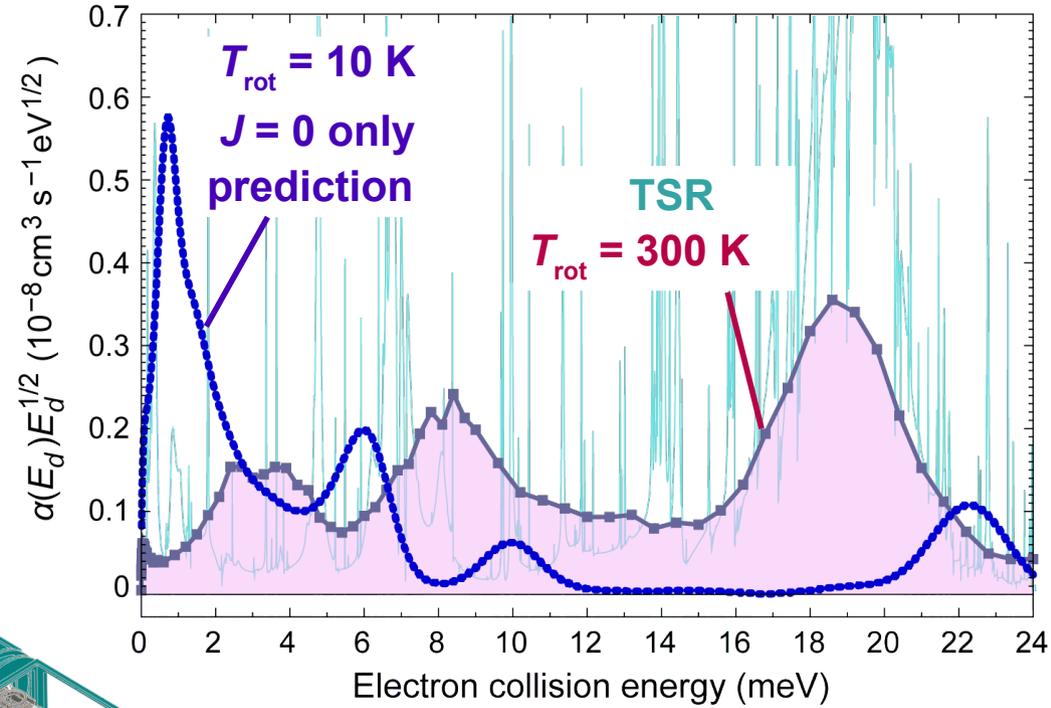
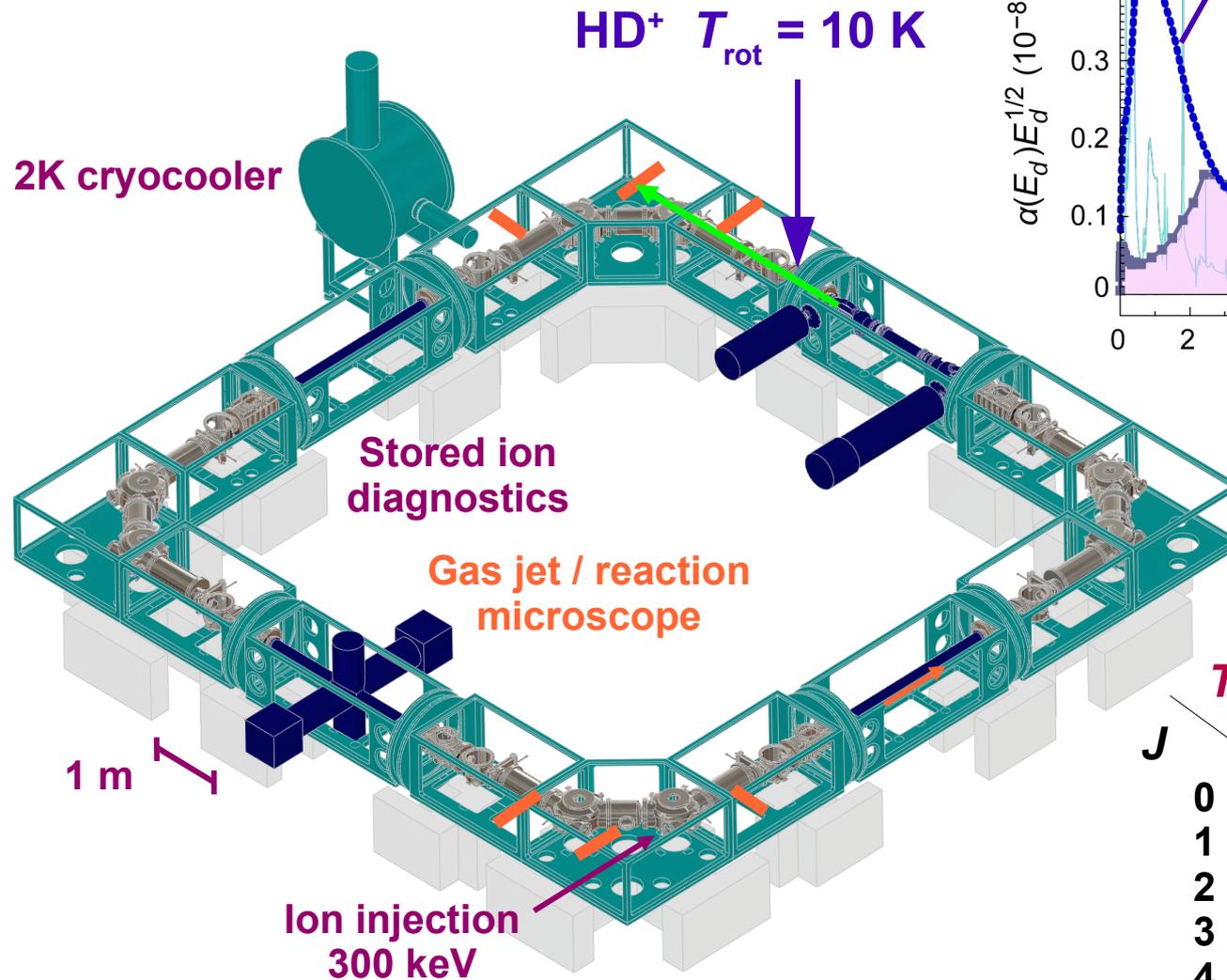
TSR and accelerator

M. Grieser

R. Repnow

R. von Hahn

Toward cryogenic ion beam experiments

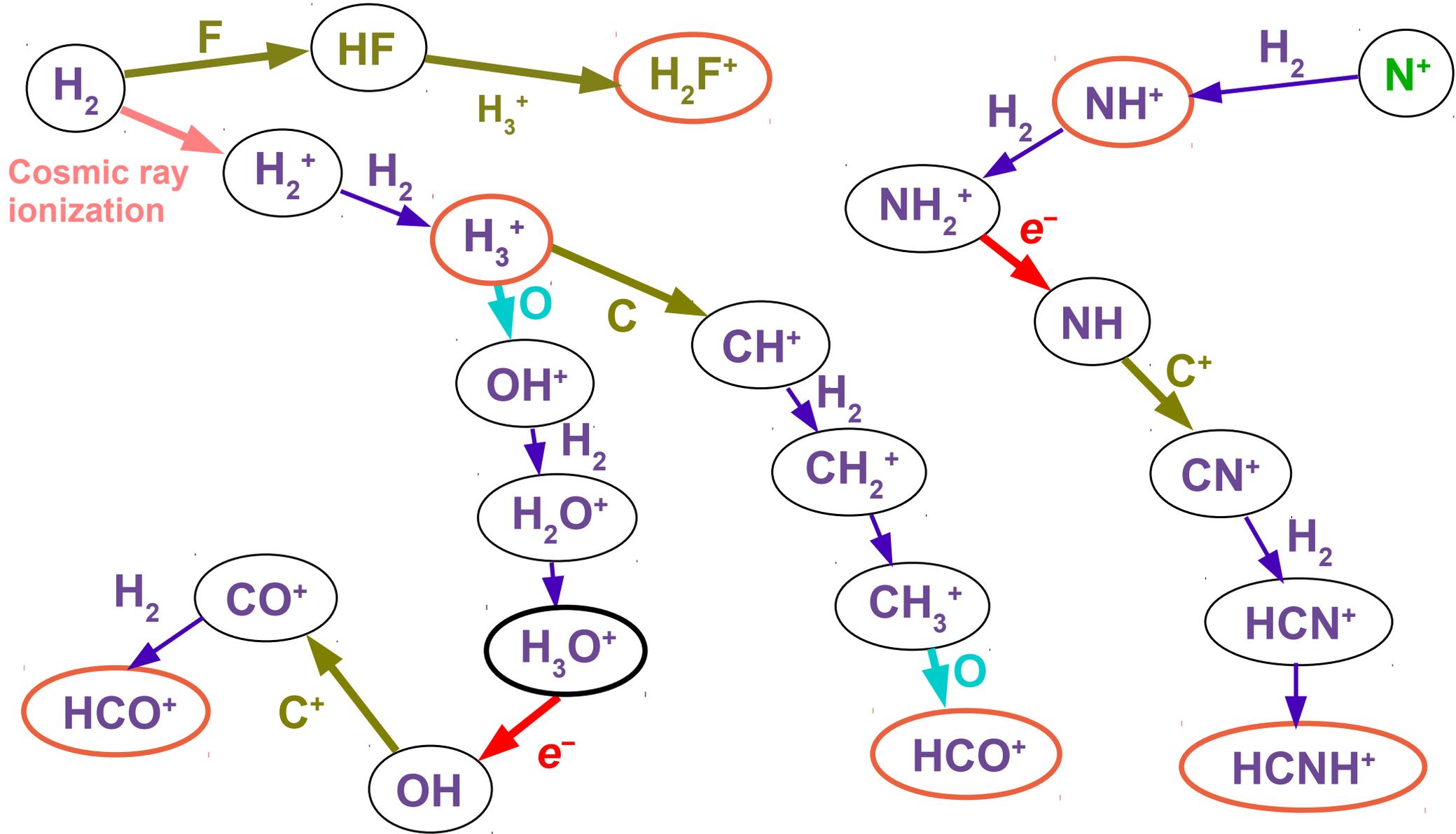


Rydberg capture resonances at low rotation

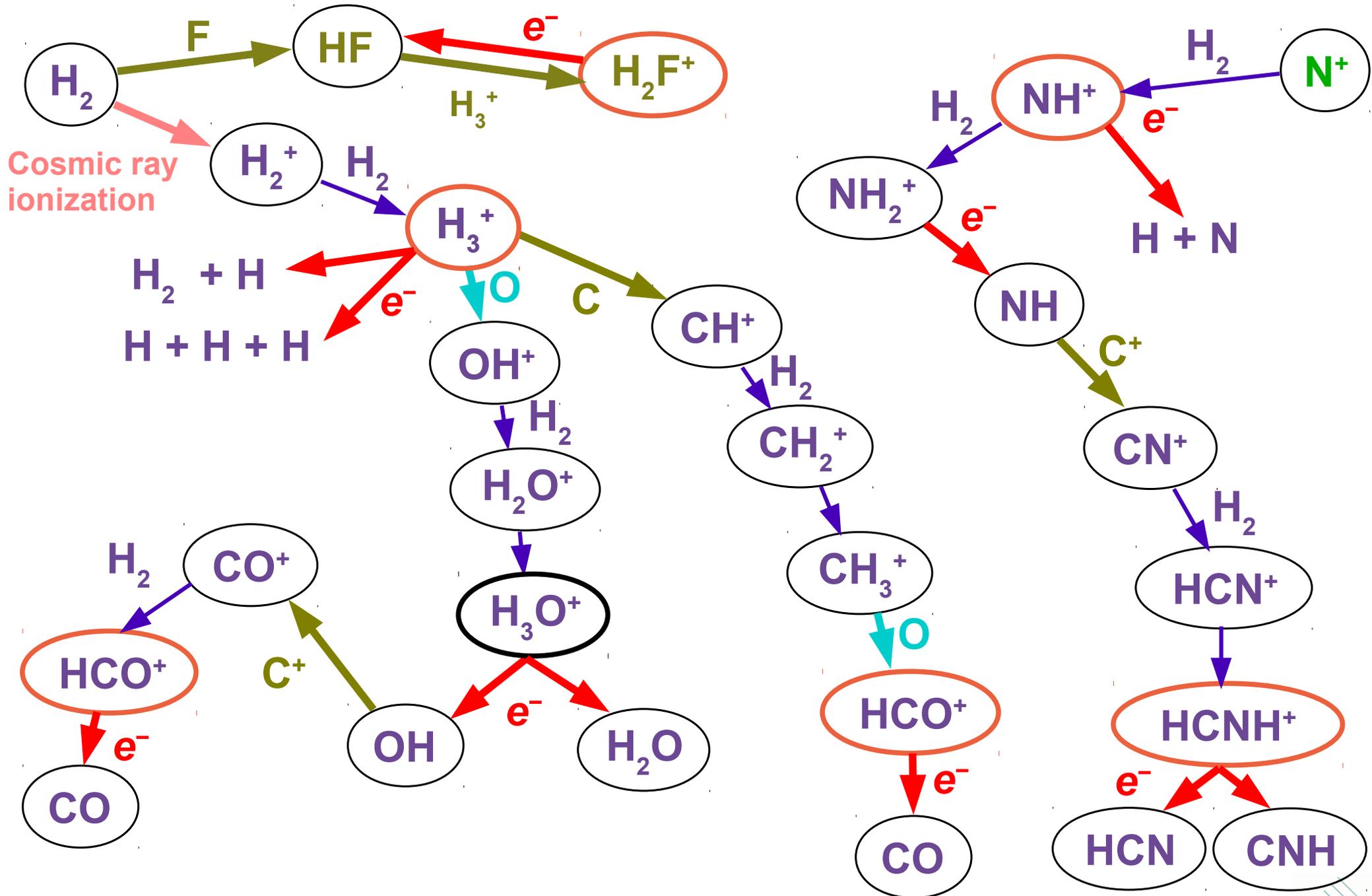
J	$T_{rot} = 300 \text{ K}$	$T_{rot} = 10 \text{ K}$
0	0.104	0.995
1	0.251	0.005
2	0.271	0.0
3	0.199	0.0
4	0.108	0.0



Ion chemistry and electron collisions



Ion chemistry and electron collisions



Ion chemistry and electron collisions

