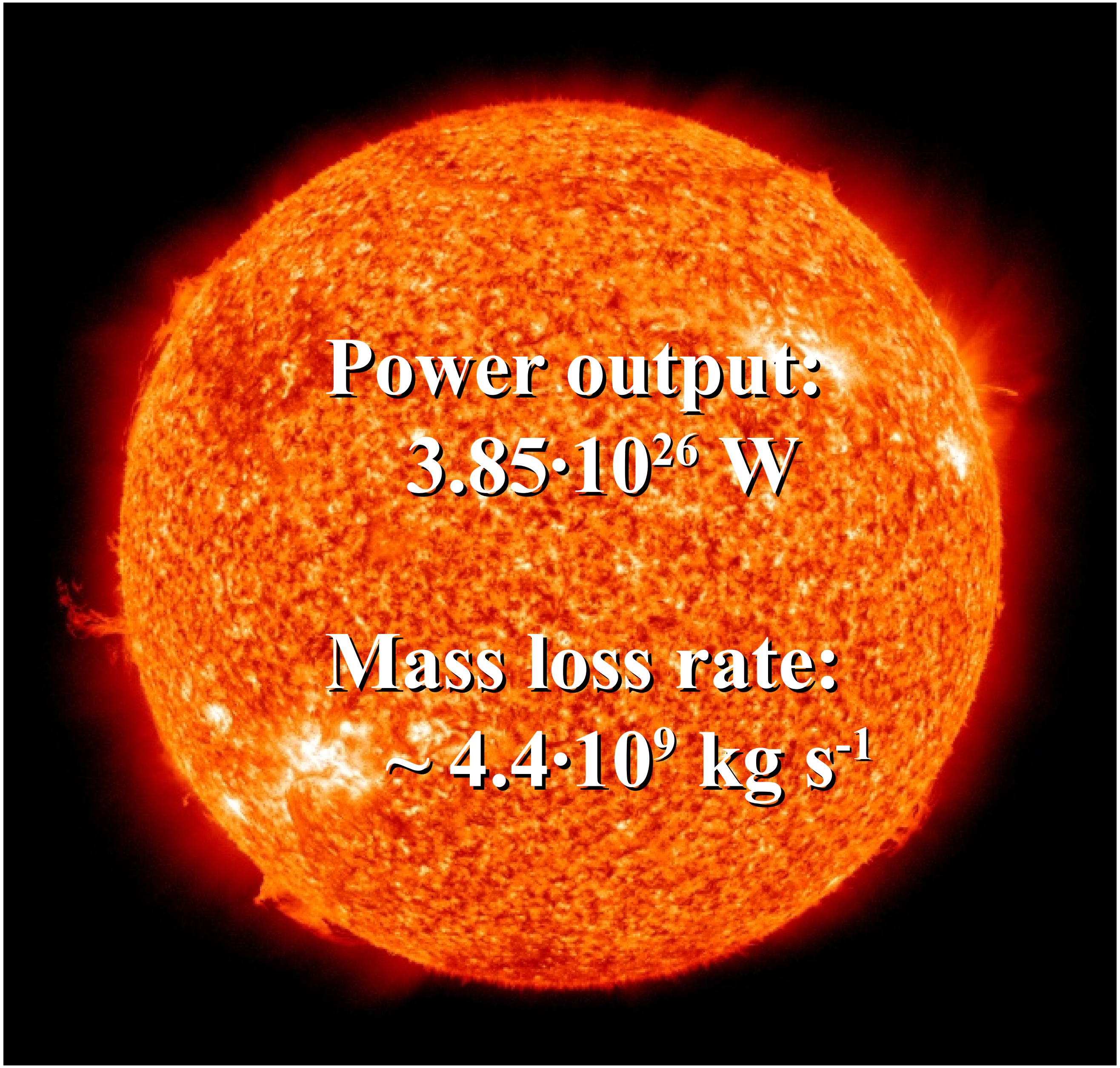
Absolute recombination rate coefficients for open f-shell tungsten ions

Claude Krantz

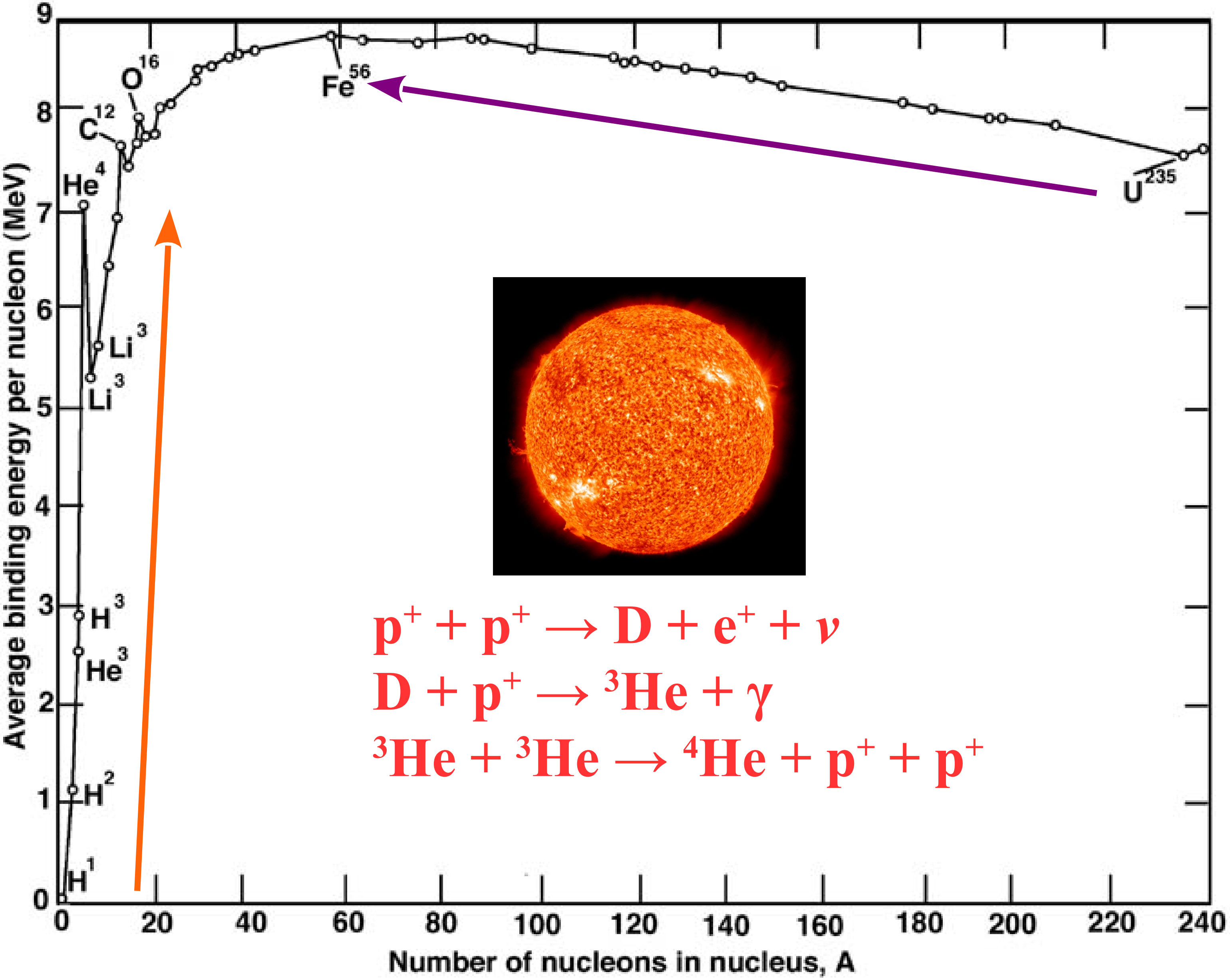
Max Planck Institute for Nuclear Physics

Fusion plasma



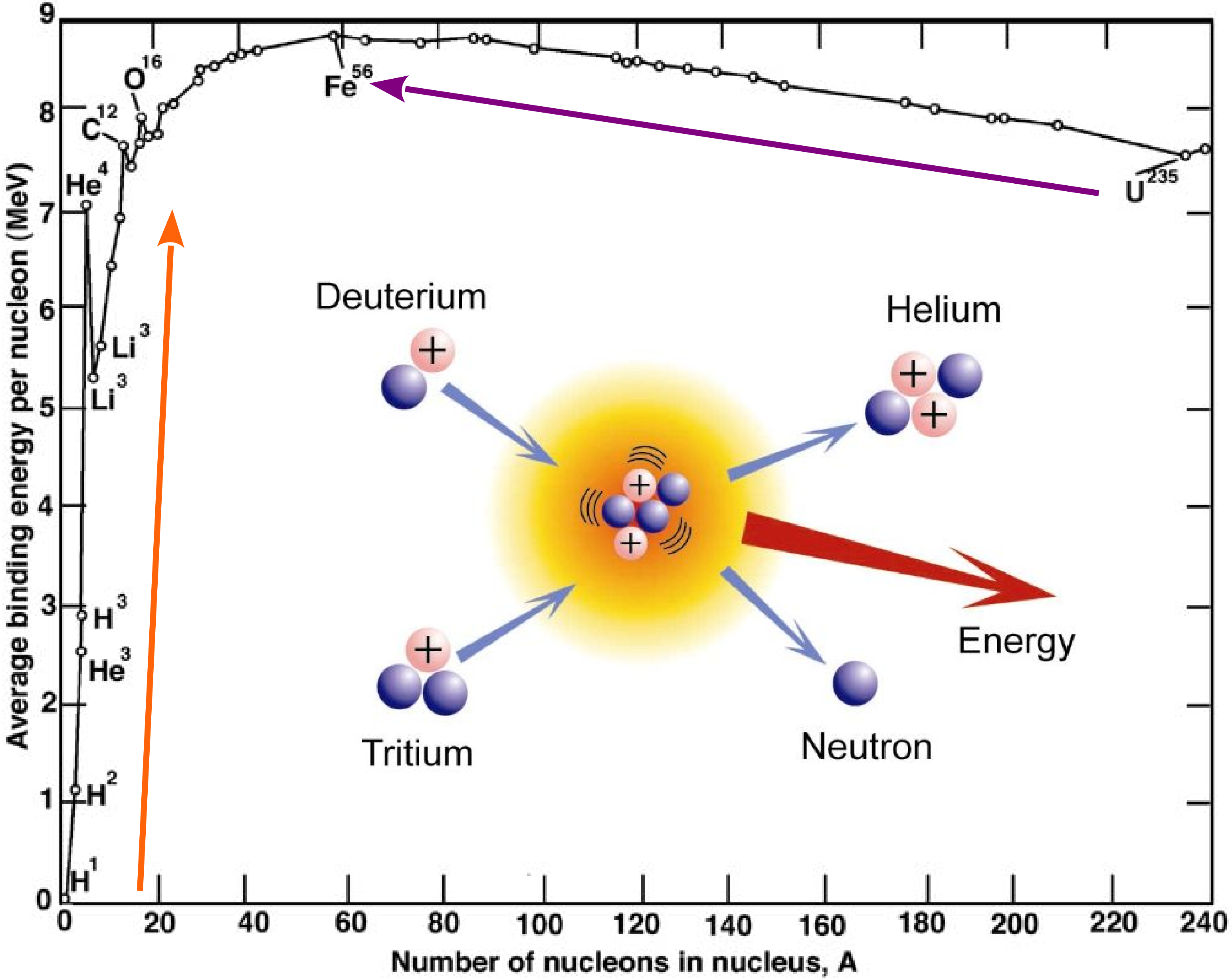
[nasa.gov]

Fusion plasma

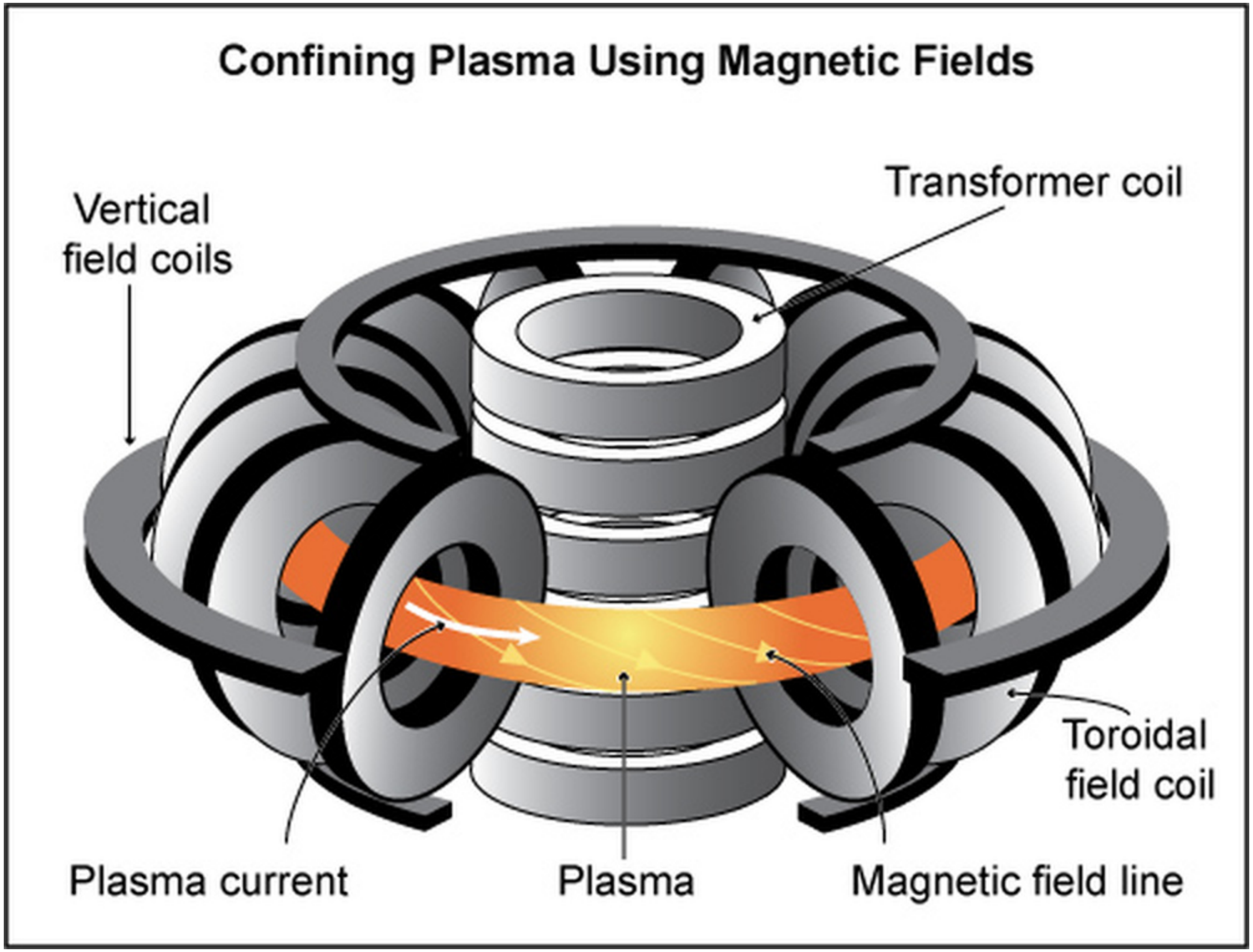


$$p^+ + p^+ \rightarrow D + e^+ + \nu$$
$$D + p^+ \rightarrow {}^3He + \gamma$$
$${}^3He + {}^3He \rightarrow {}^4He + p^+ + p^+$$

Fusion plasma

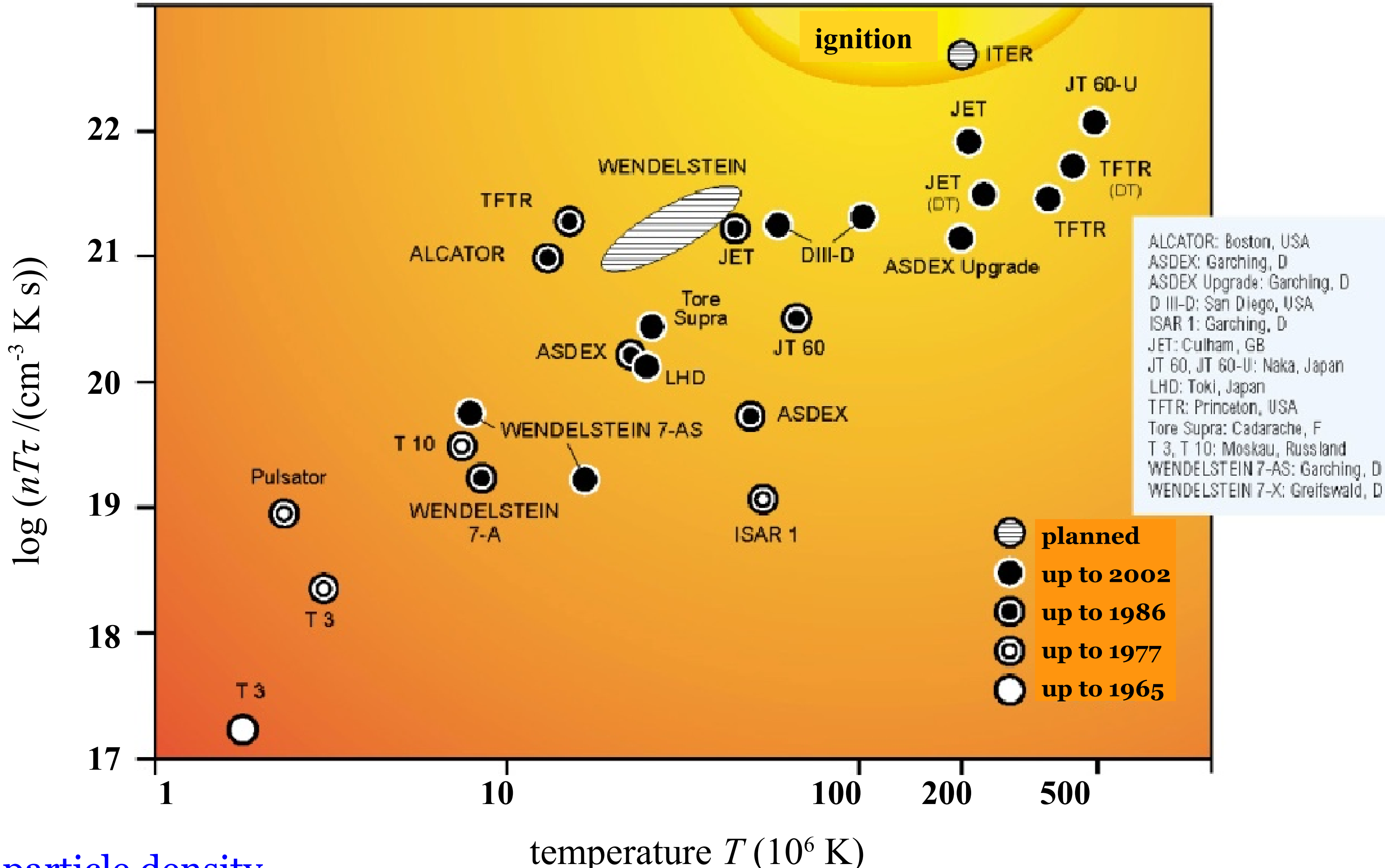


Fusion tokamaks



[generalfusion.com]

Fusion tokamaks



n: particle density
T: plasma temperature
τ: energy confinement time

Fusion tokamaks

High-energy plasma damages
walls of vacuum vessel

Choice of wall materials is critical
for **practical reactor operation**.

Need to absorb **high thermal loads**

1. Low-Z materials

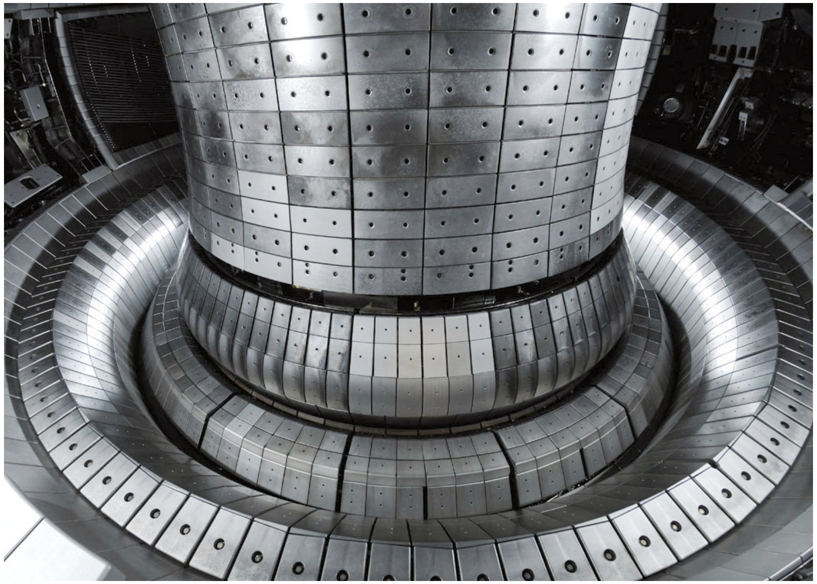
C

Be

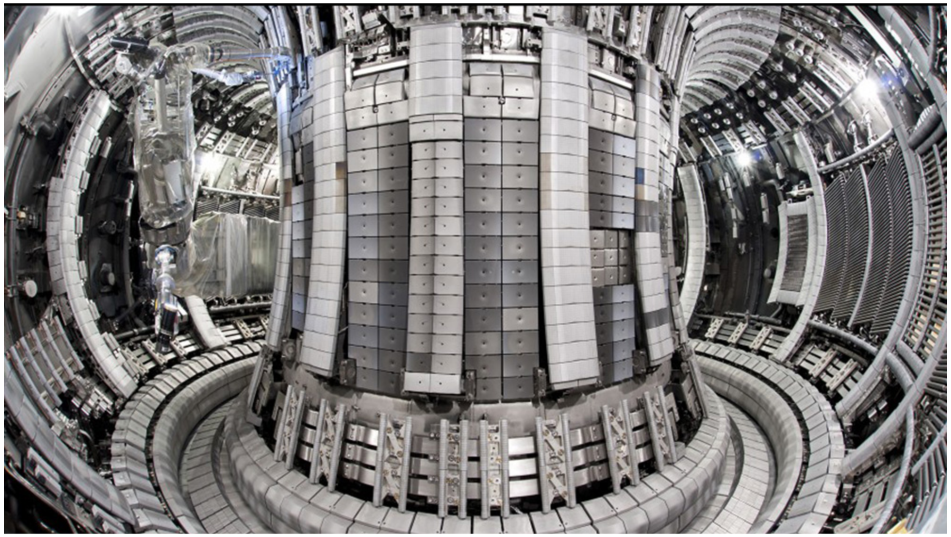
2. High-Z materials

W

ASDEX-Upgrade Germany



ipp.mpg.de



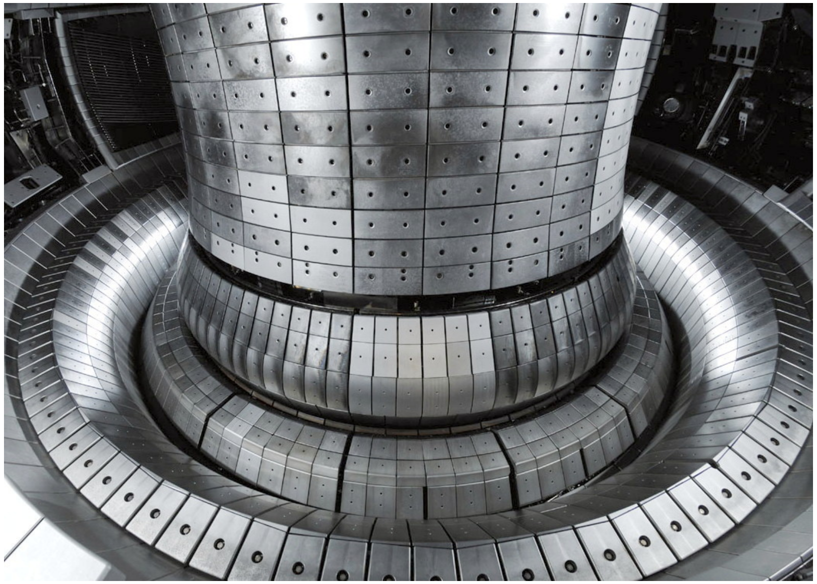
JET, UK

ipp.mpg.de

Max-Planck-Institut für Kernphysik

Fusion tokamaks

ASDEX-Upgrade, Germany



ipp.mpg.de

High-energy plasma damages **walls of vacuum vessel**

Choice of wall materials is critical for **practical reactor operation**.

Need to absorb **high thermal loads**

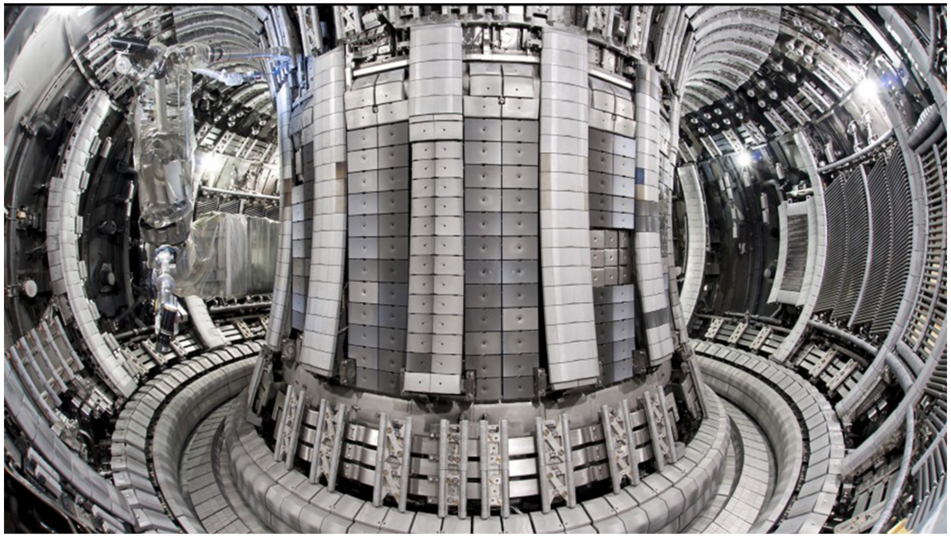
1. Low-Z materials

C fuel retention via hydrocarbons

Be

2. High-Z materials

W



JET, UK

ipp.mpg.de

Max-Planck-Institut für Kernphysik

Fusion tokamaks

International Thermonuclear Experimental Reactor (ITER)

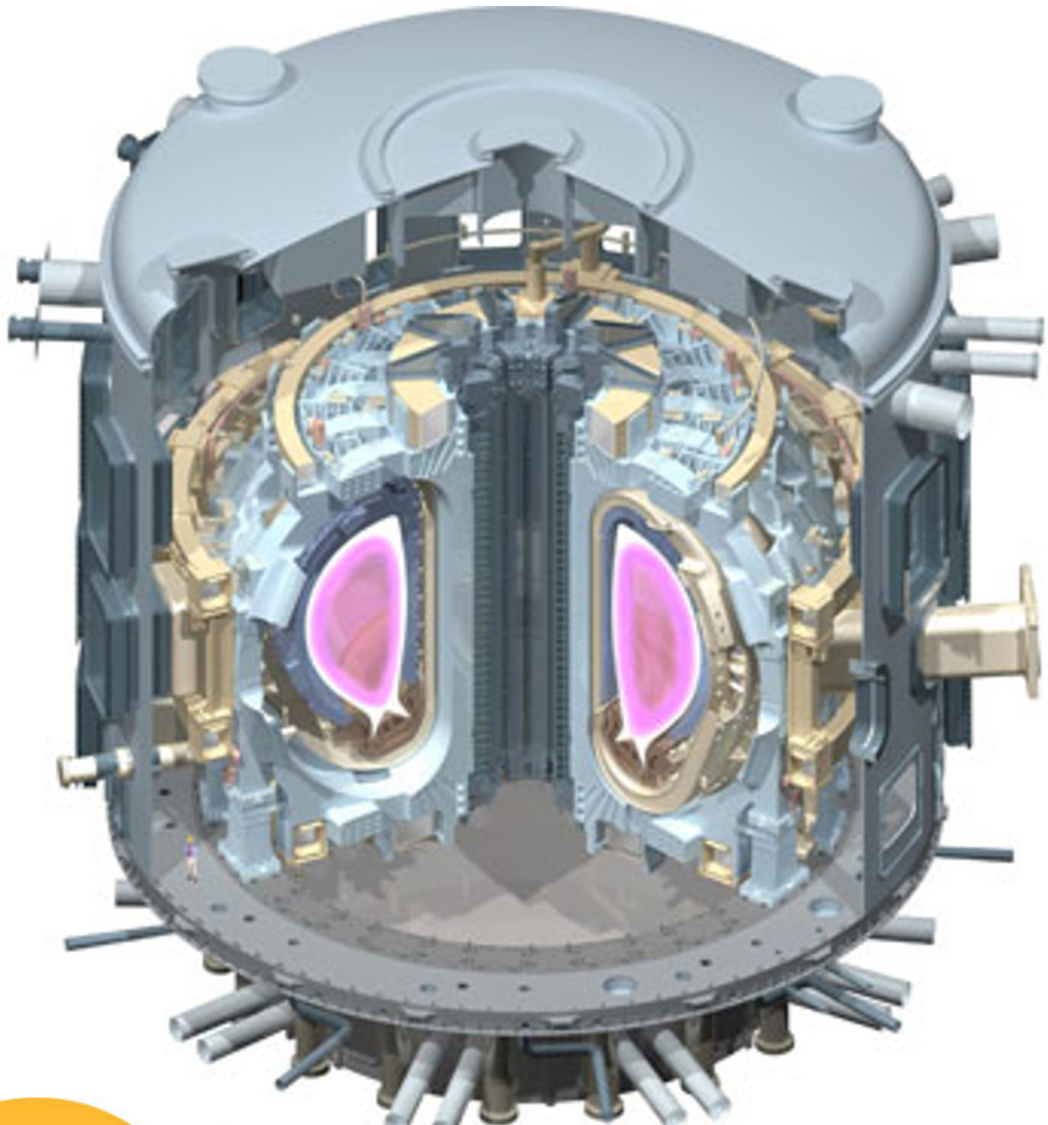
~ 4 x bigger than JET
first plasma: 2019
power output: 0.5 GW
" consumption: 50 MW

1. Low-Z materials

C fuel retention via hydrocarbons
Be

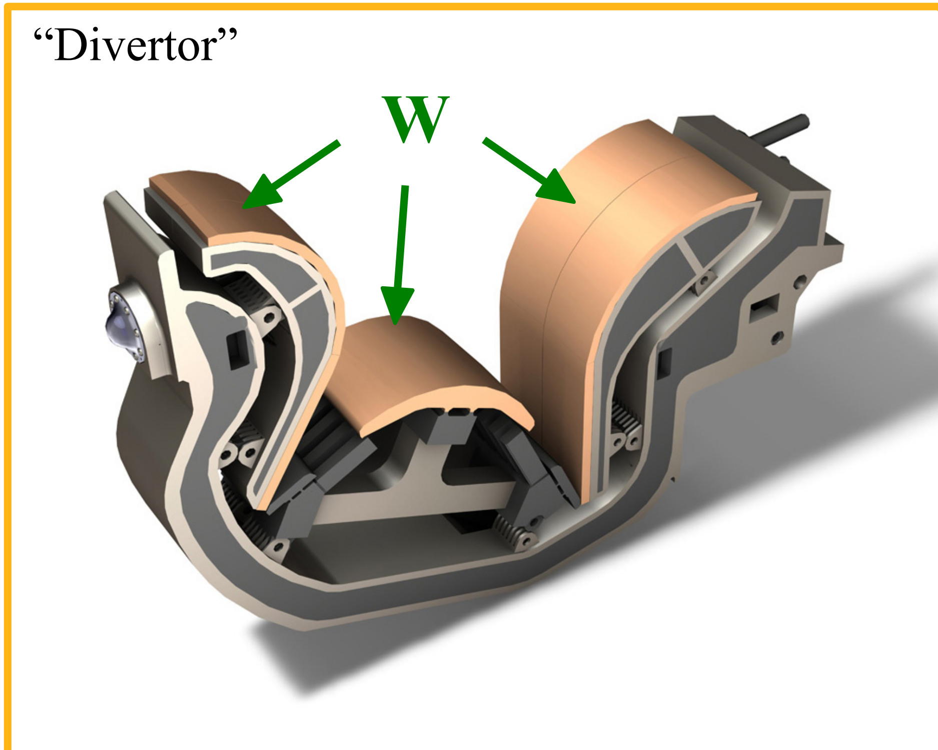
2. High-Z materials

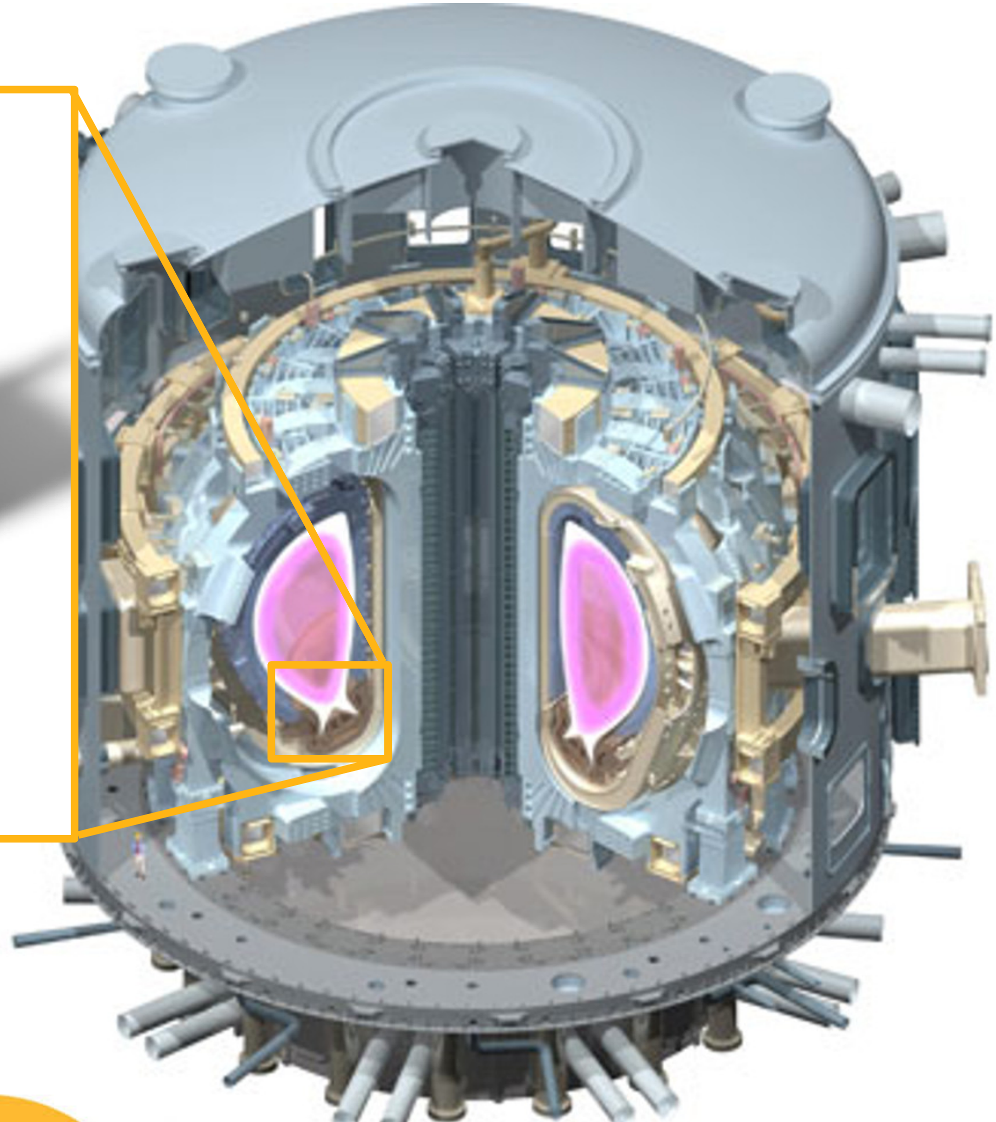
W



iter
china eu india japan korea russia usa

Tungsten in fusion tokamaks





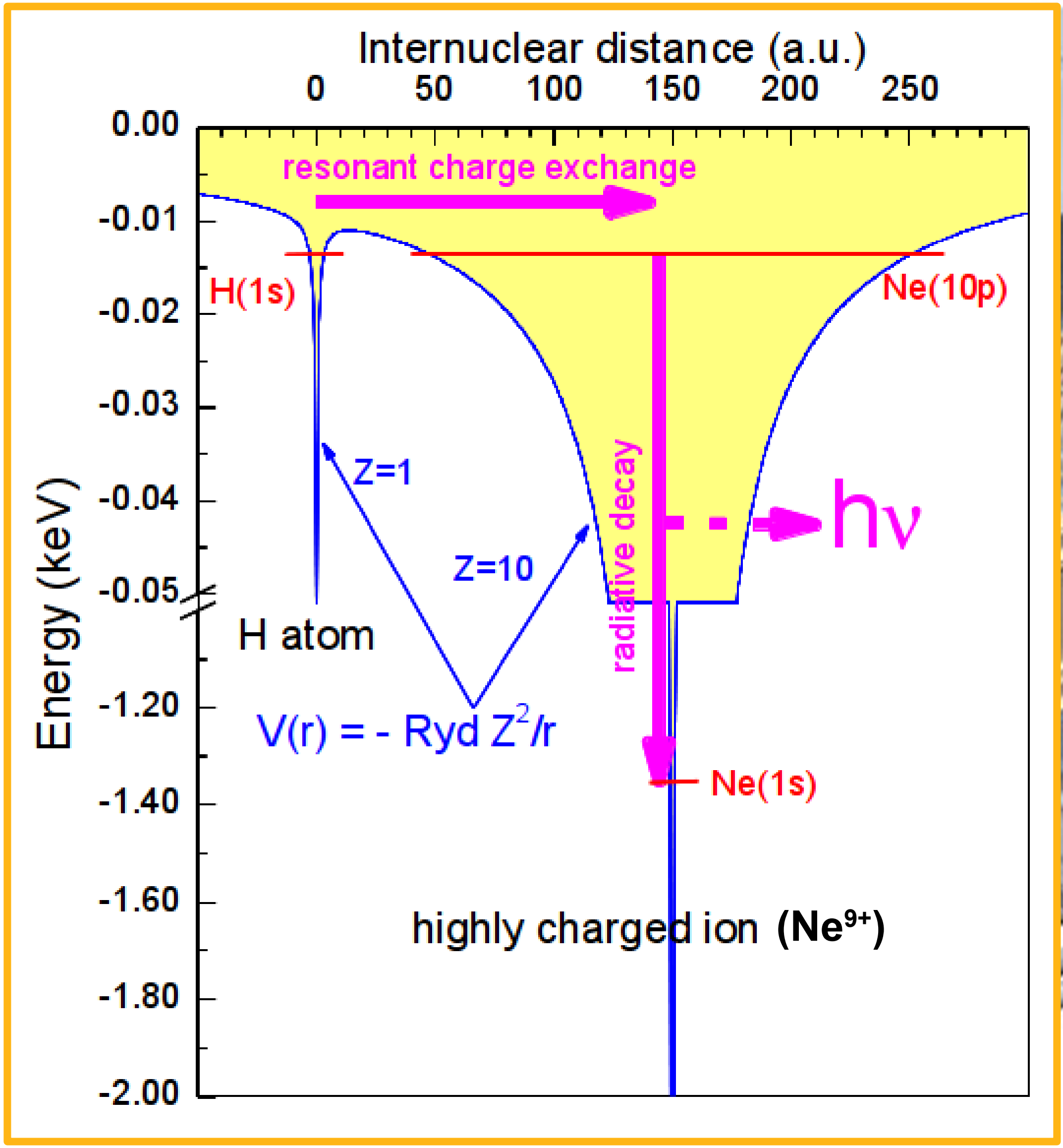
2. High-Z materials

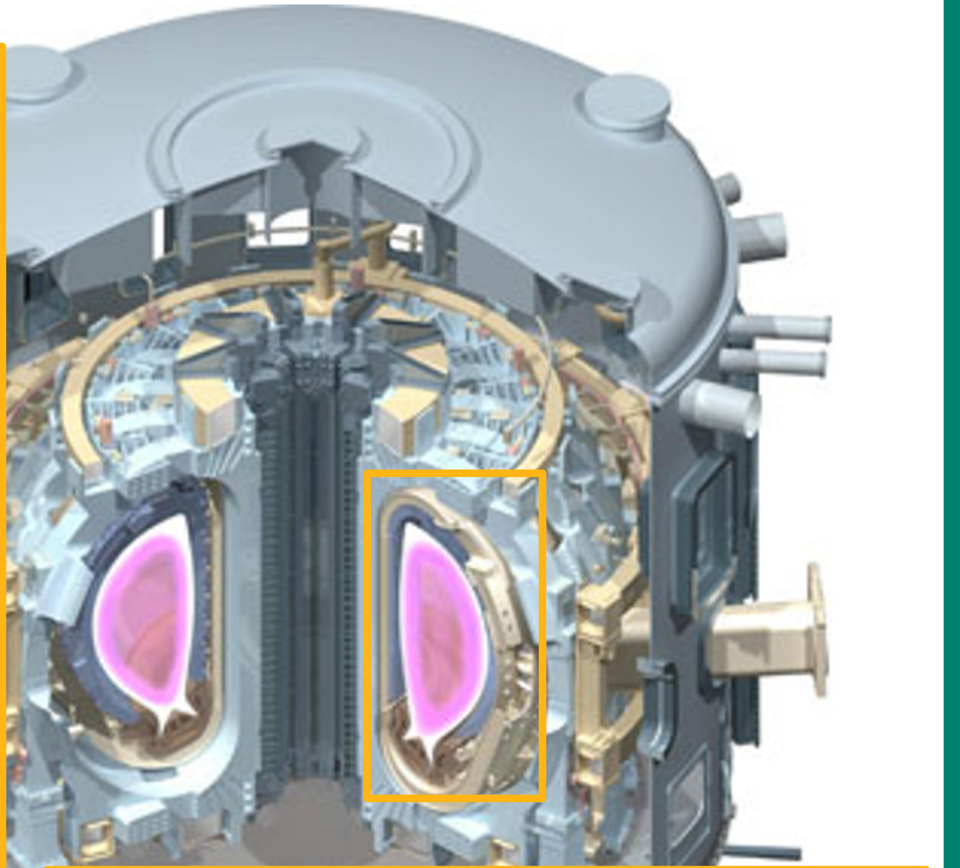
W highest thermal loads

iter
china eu india japan korea russia usa

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Tungsten in fusion tokamaks



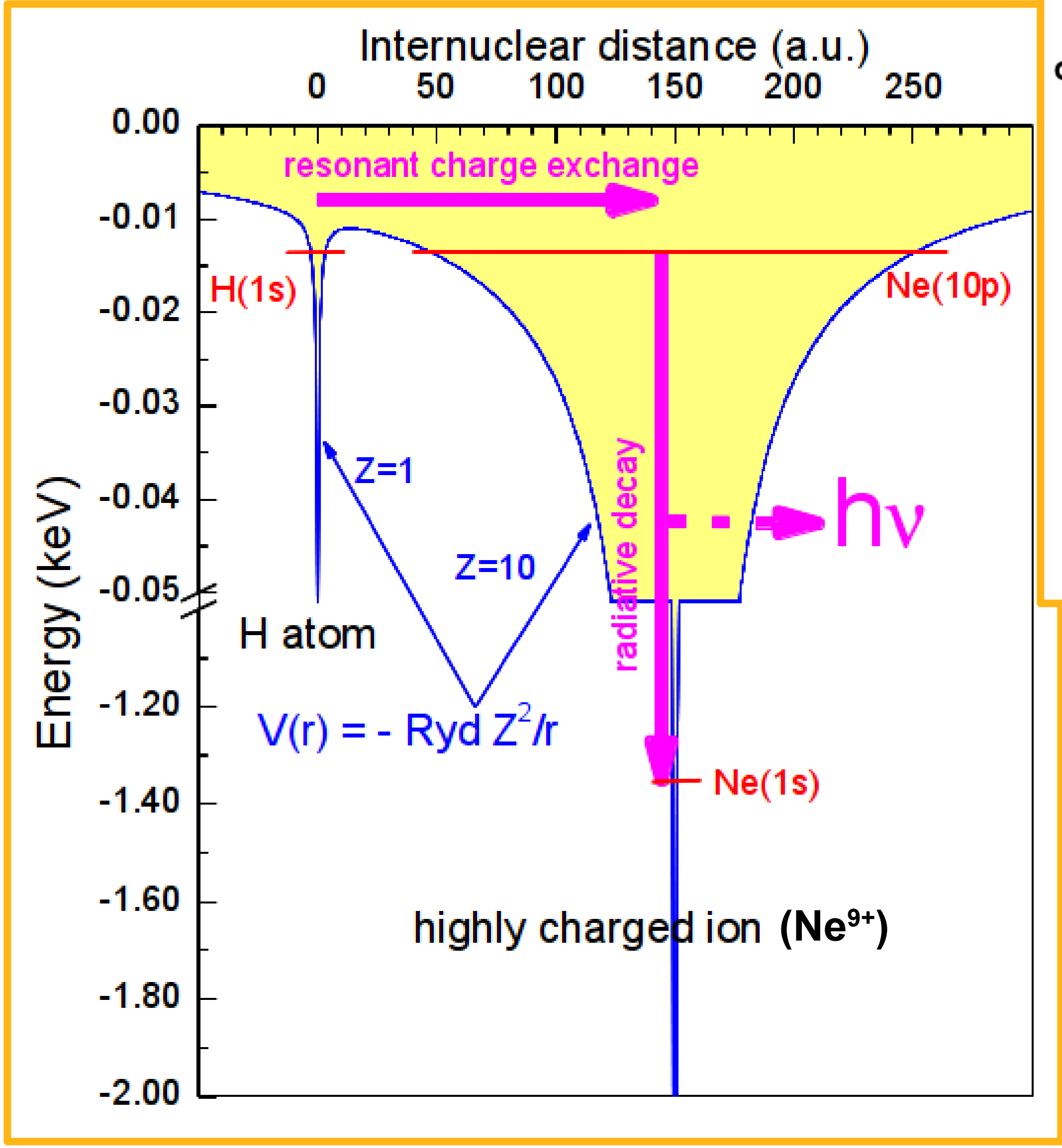


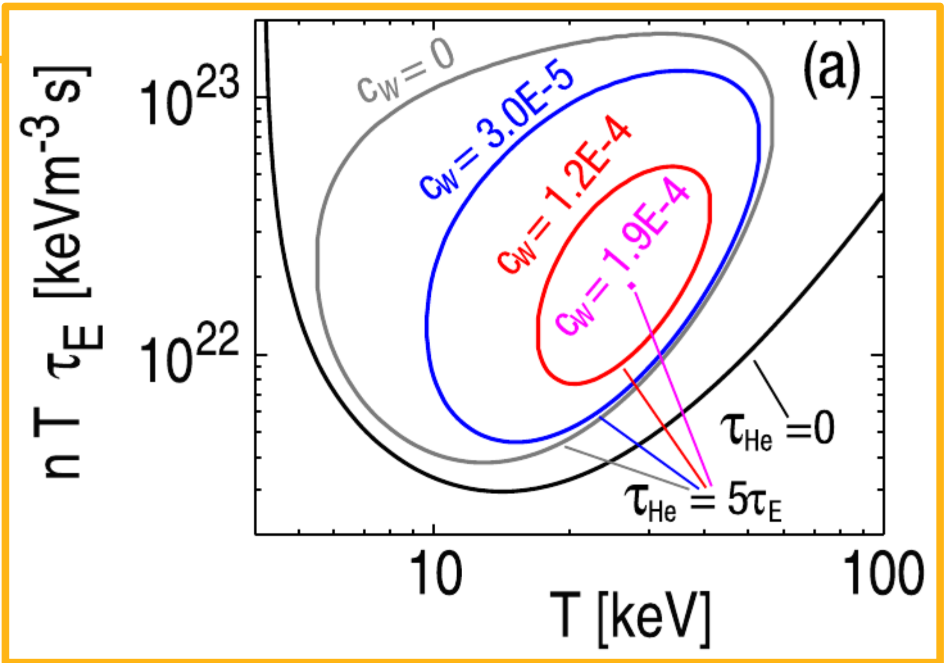
Energy loss by HCI line radiation

e.g., **Ne^{9+}** (injection into ITER: 0.5%)

→ **70 MW** of radiation loss (total 300 MW)

Tungsten in fusion tokamaks





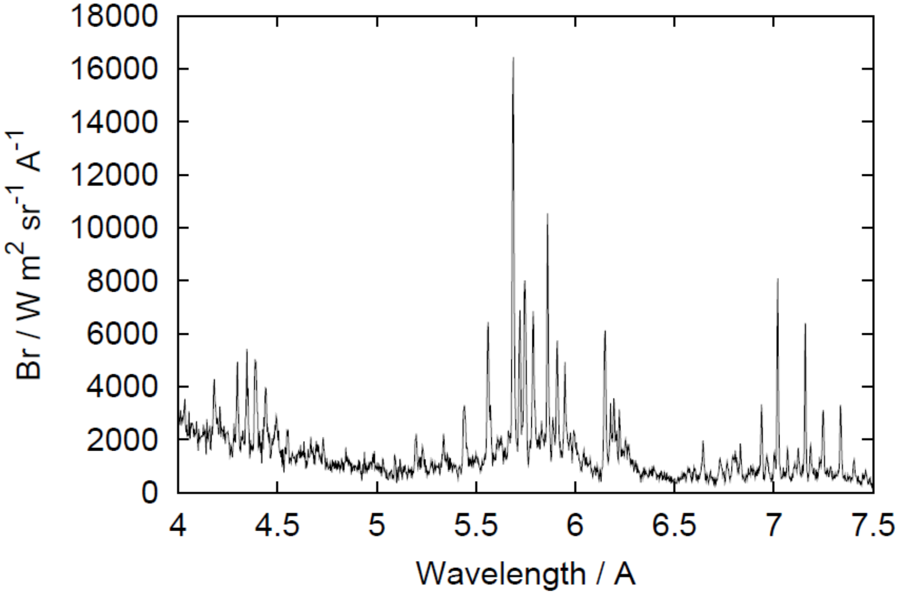
Energy loss by HCI line radiation

e.g., **Ne^{9+}** (injection into ITER: 0.5%)
→ **70 MW** of radiation loss (total 300 MW)

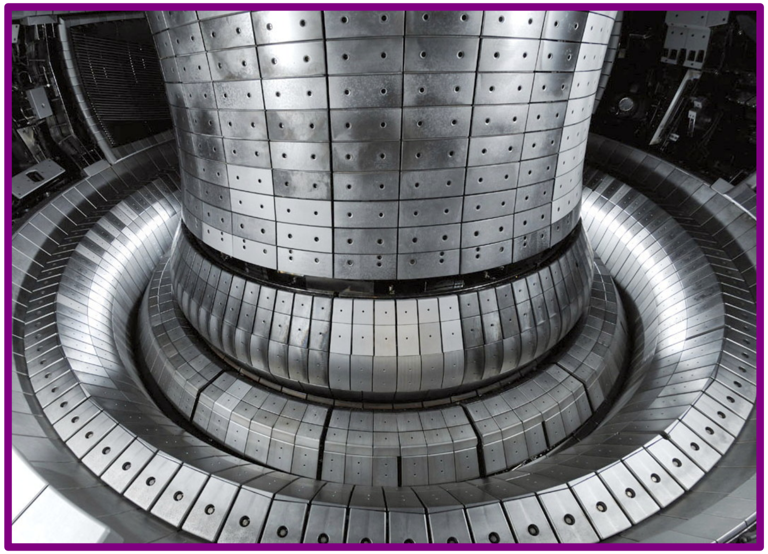
High charge states of **tungsten** are **even better coolants**!

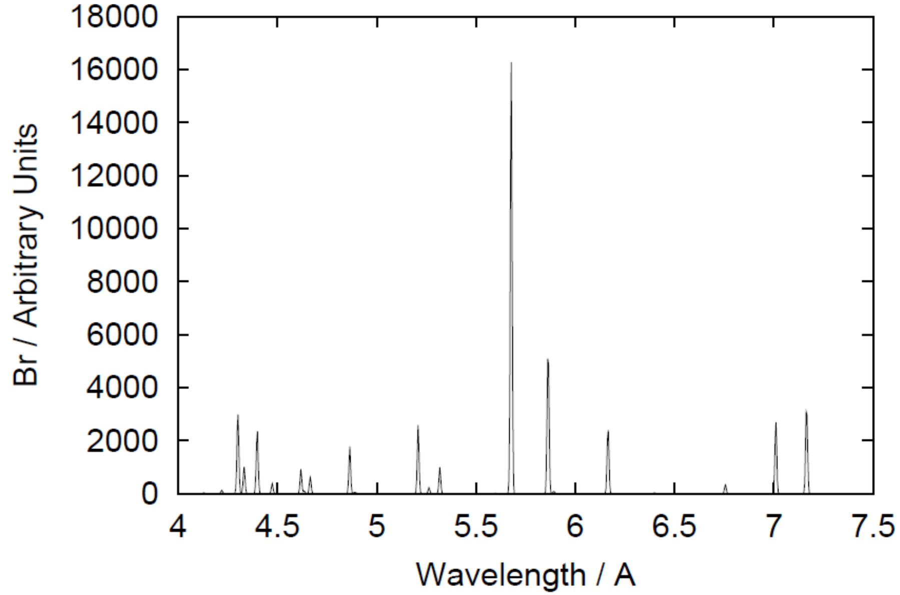
[Pütterich, Nucl. Fusion 50 (2010)]

Tungsten in fusion tokamaks



measured emission spectrum from W^{46+}
(core plasma at ASDEX-Upgrade)





modelled emission spectrum from W^{46+}

[Whiteford, PhD Thesis, University of Strathclyde, UK (2004)]

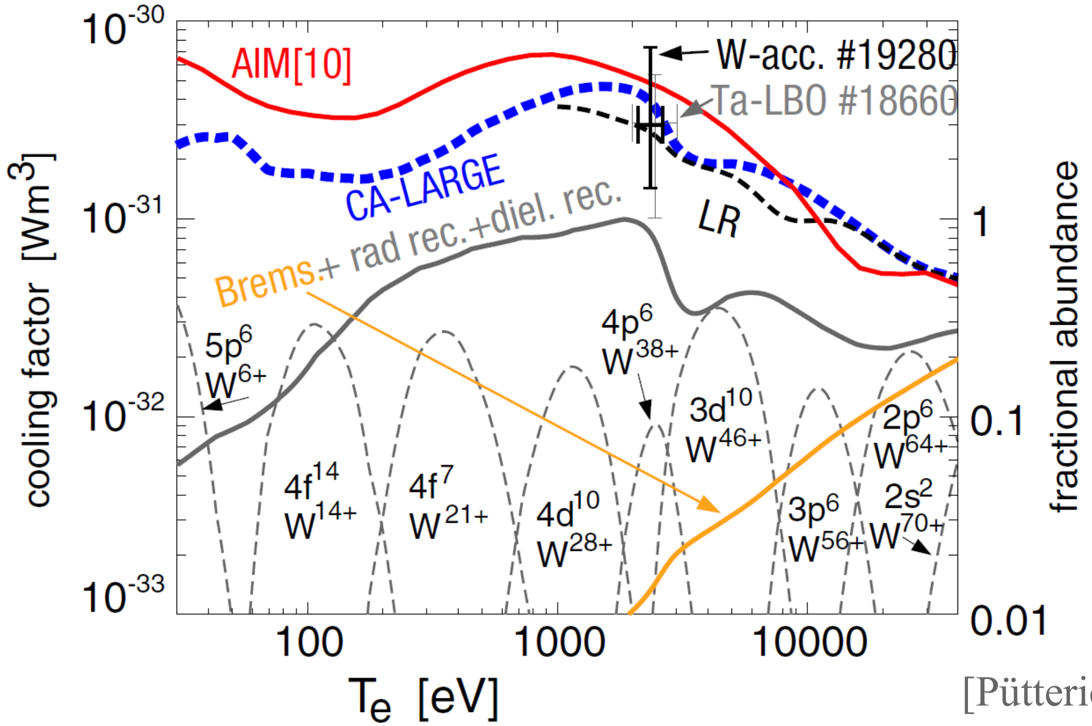
Tungsten in fusion tokamaks

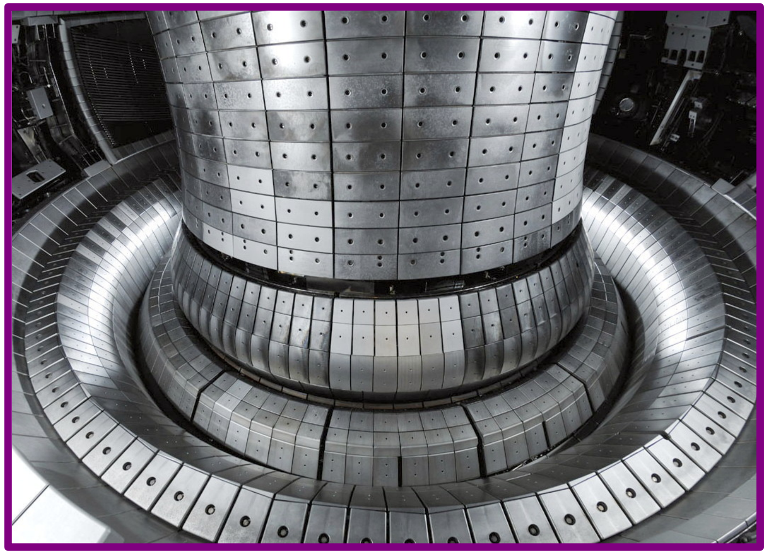
recombination

$$W^{(q-1)+} \overset{e^-}{\longleftrightarrow} W^{q+} \overset{e^-}{\longleftrightarrow} W^{(q+1)+}$$

impact ionisiation

Charge states are in equilibrium
of electron recombination and impact ionization.

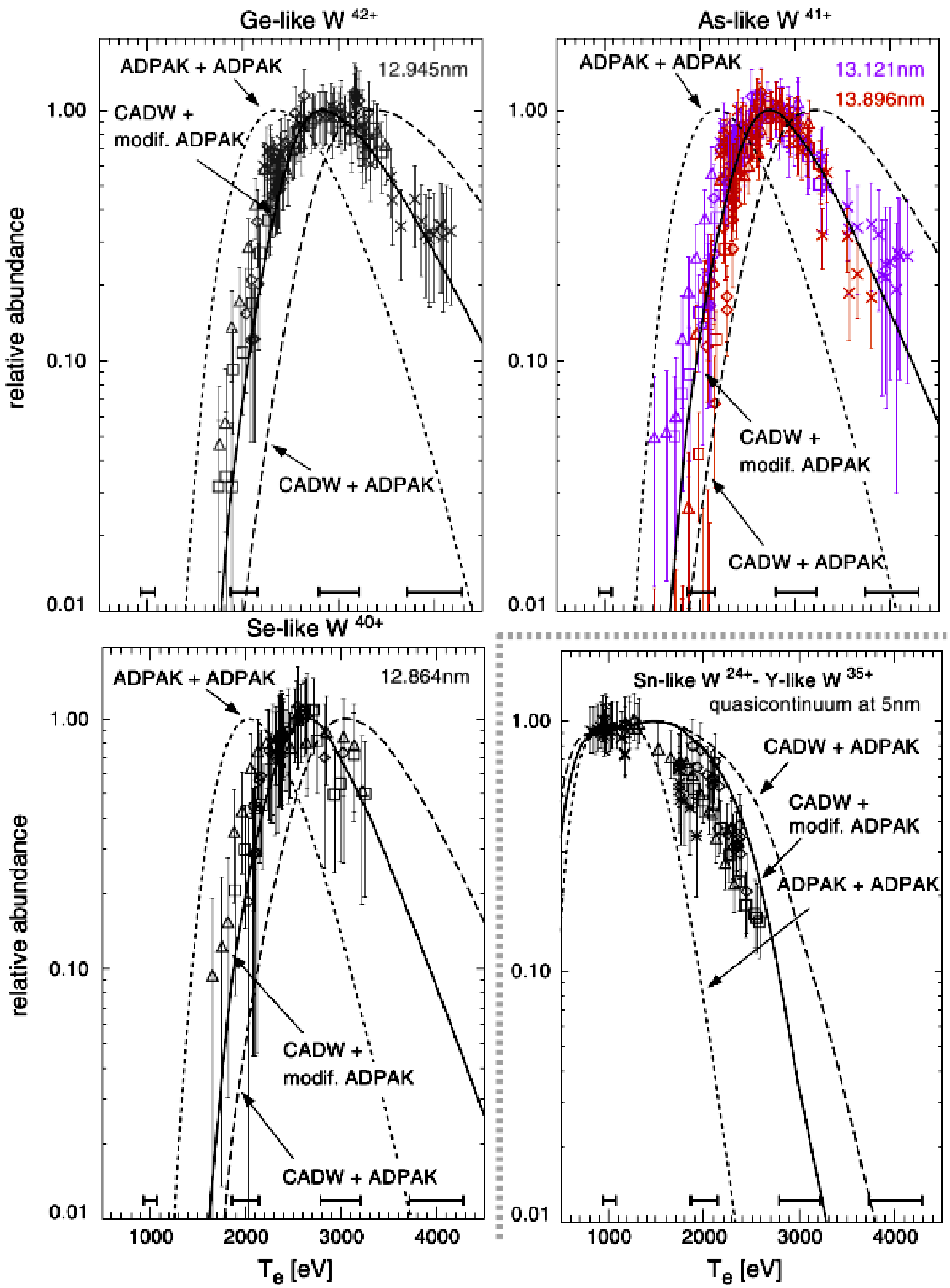




[Pütterich, Nucl. Fusion **50** (2010)]

Max-Planck-Institut für Kernphysik

Tungsten in fusion tokamaks



Ionization + recombination rates from **ADAS** do not agree with data.

Corrections and empirical scaling factors to recombination rate coefficients were needed.

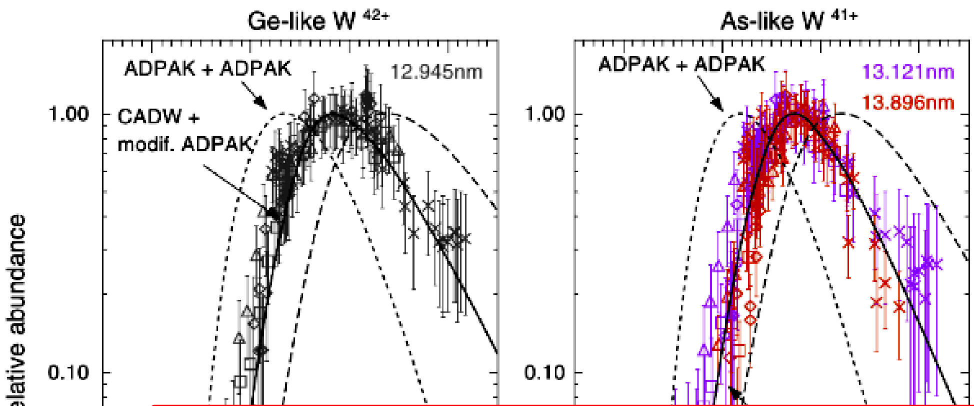
W^{21+} - W^{35+} could not be disentangled:

... no visible lines

... no reliable rate coefficients

[Pütterich, Phys. Control Fusion **50** (2008)]

Tungsten in fusion tokamaks



Ionization + recombination rates from **ADAS** do not agree with data.

Corrections and empirical scaling factors to recombination rate coefficients were needed.

…angled:

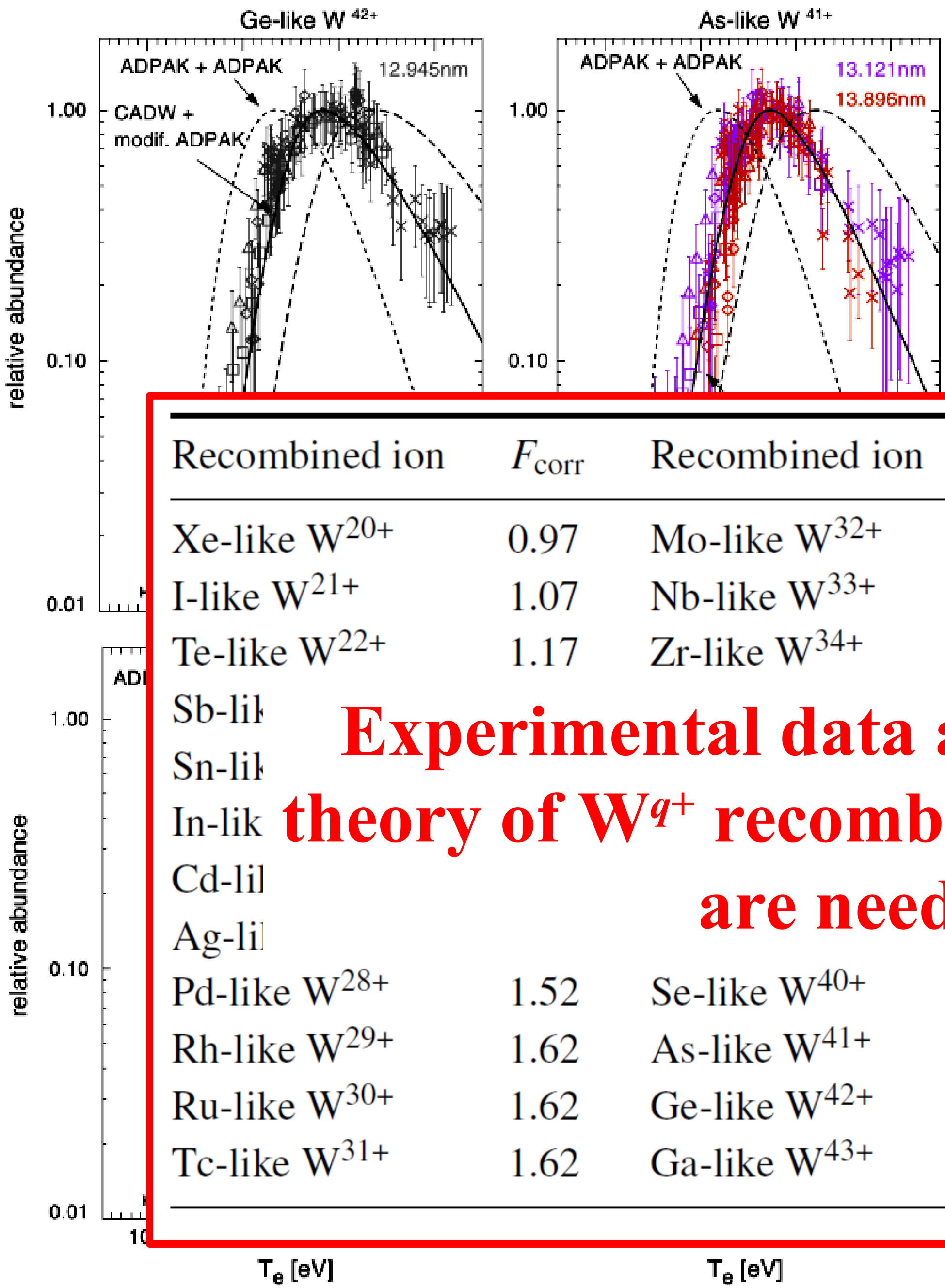
…*ients*

Recombined ion	F_{corr}	Recombined ion	F_{corr}	Recombined ion	F_{corr}
Xe-like W^{20+}	0.97	Mo-like W^{32+}	1.62	Zn-like W^{44+}	0.47
I-like W^{21+}	1.07	Nb-like W^{33+}	1.62	Cu-like W^{45+}	0.39
Te-like W^{22+}	1.17	Zr-like W^{34+}	2.25	Ni-like W^{46+}	1.78
Sb-like W^{23+}	1.27	Y-like W^{35+}	2.15	Co-like W^{47+}	0.60
Sn-like W^{24+}	1.37	Sr-like W^{36+}	2.05	Fe-like W^{48+}	0.99
In-like W^{25+}	1.47	Rb-like W^{37+}	1.76	Mn-like W^{49+}	0.99
Cd-like W^{26+}	1.58	Kr-like W^{38+}	1.76	Cr-like W^{50+}	0.96
Ag-like W^{27+}	1.52	Br-like W^{39+}	1.10	V-like W^{51+}	0.95
Pd-like W^{28+}	1.52	Se-like W^{40+}	1.33	Ti-like W^{52+}	0.94
Rh-like W^{29+}	1.62	As-like W^{41+}	0.34	Sc-like W^{53+}	0.95
Ru-like W^{30+}	1.62	Ge-like W^{42+}	0.26	Ca-like W^{54+}	0.97
Tc-like W^{31+}	1.62	Ga-like W^{43+}	0.45	K-like W^{55+}	0.98

T_e [eV] T_e [eV]

[Pütterich, Phys. Control Fusion **50** (2008)]

Tungsten in fusion tokamaks



Ionization + recombination rates from **ADAS** do not agree with data.

Corrections and empirical scaling factors to recombination rate coefficients were needed.

angled:

ients

Recombined ion	F_{corr}	Recombined ion	F_{corr}	Recombined ion	F_{corr}
Xe-like W^{20+}	0.97	Mo-like W^{32+}	1.62	Zn-like W^{44+}	0.47
I-like W^{21+}	1.07	Nb-like W^{33+}	1.62	Cu-like W^{45+}	0.39
Te-like W^{22+}	1.17	Zr-like W^{34+}	2.25	Ni-like W^{46+}	1.78
Sb-lik					.60
Sn-lik					.99
In-lik					.99
Cd-lil					.96
Ag-li					.95
Pd-like W^{28+}	1.52	Se-like W^{40+}	1.33	Ti-like W^{52+}	0.94
Rh-like W^{29+}	1.62	As-like W^{41+}	0.34	Sc-like W^{53+}	0.95
Ru-like W^{30+}	1.62	Ge-like W^{42+}	0.26	Ca-like W^{54+}	0.97
Tc-like W^{31+}	1.62	Ga-like W^{43+}	0.45	K-like W^{55+}	0.98

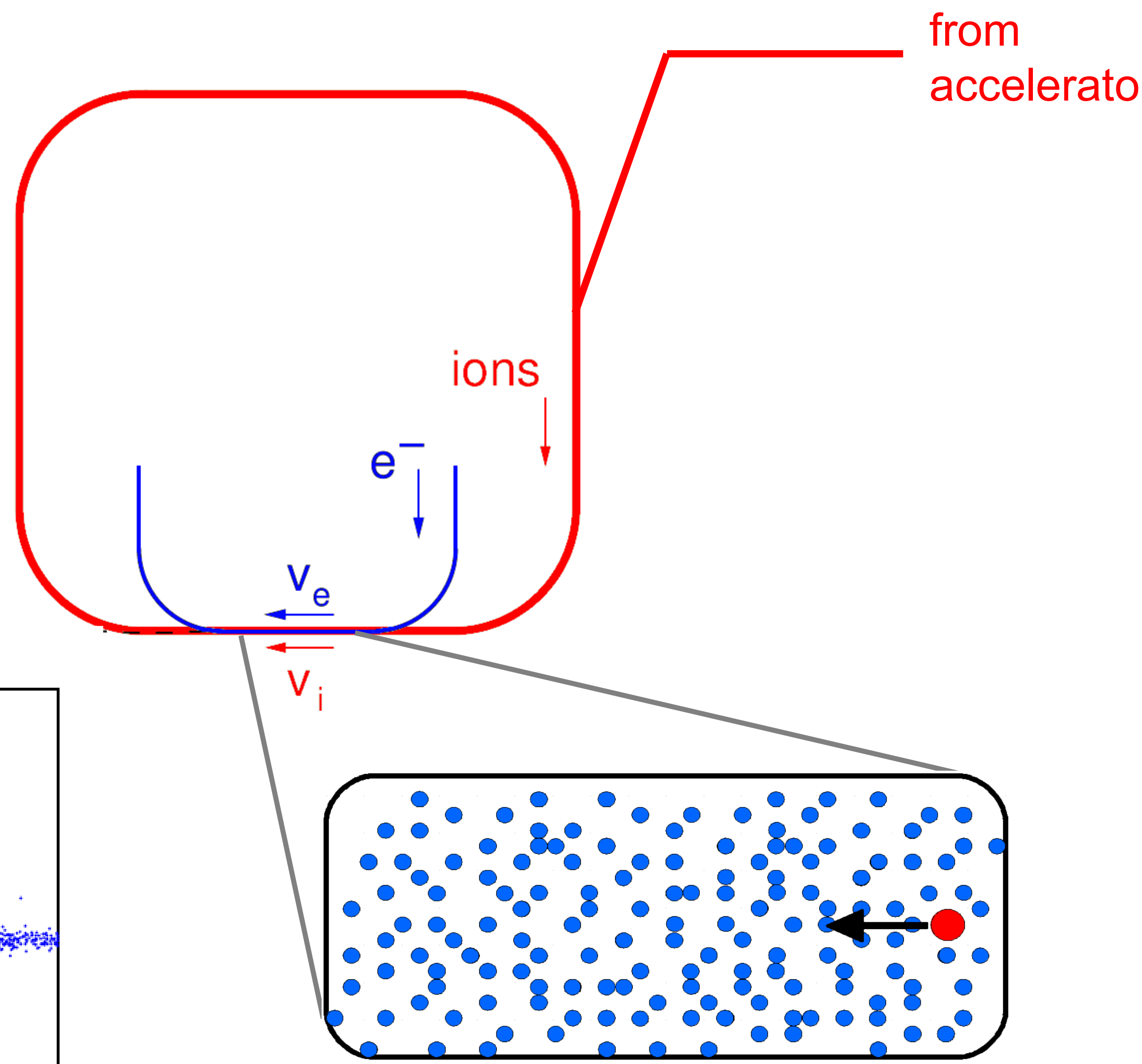
Experimental data and/or reliable theory of W^{q+} recombination rate coef. are needed.

[Pütterich, Phys. Control Fusion **50** (2008)]

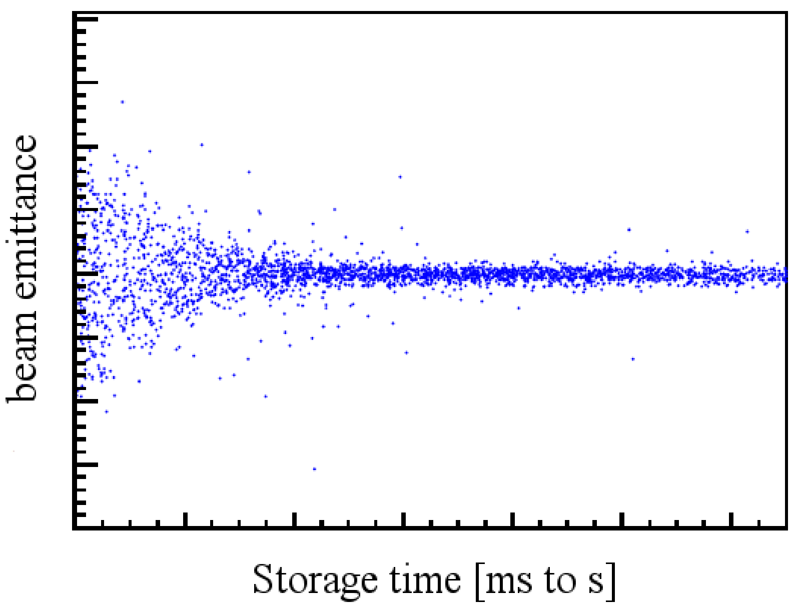
Recombination in Electron Coolers

Electron cooler
ion storage ring

- m/q-selection
- de-excitation of ions
- electron cooling



collision velocity $v = |v_i - v_e| \approx 0$



Recombination in Electron Coolers

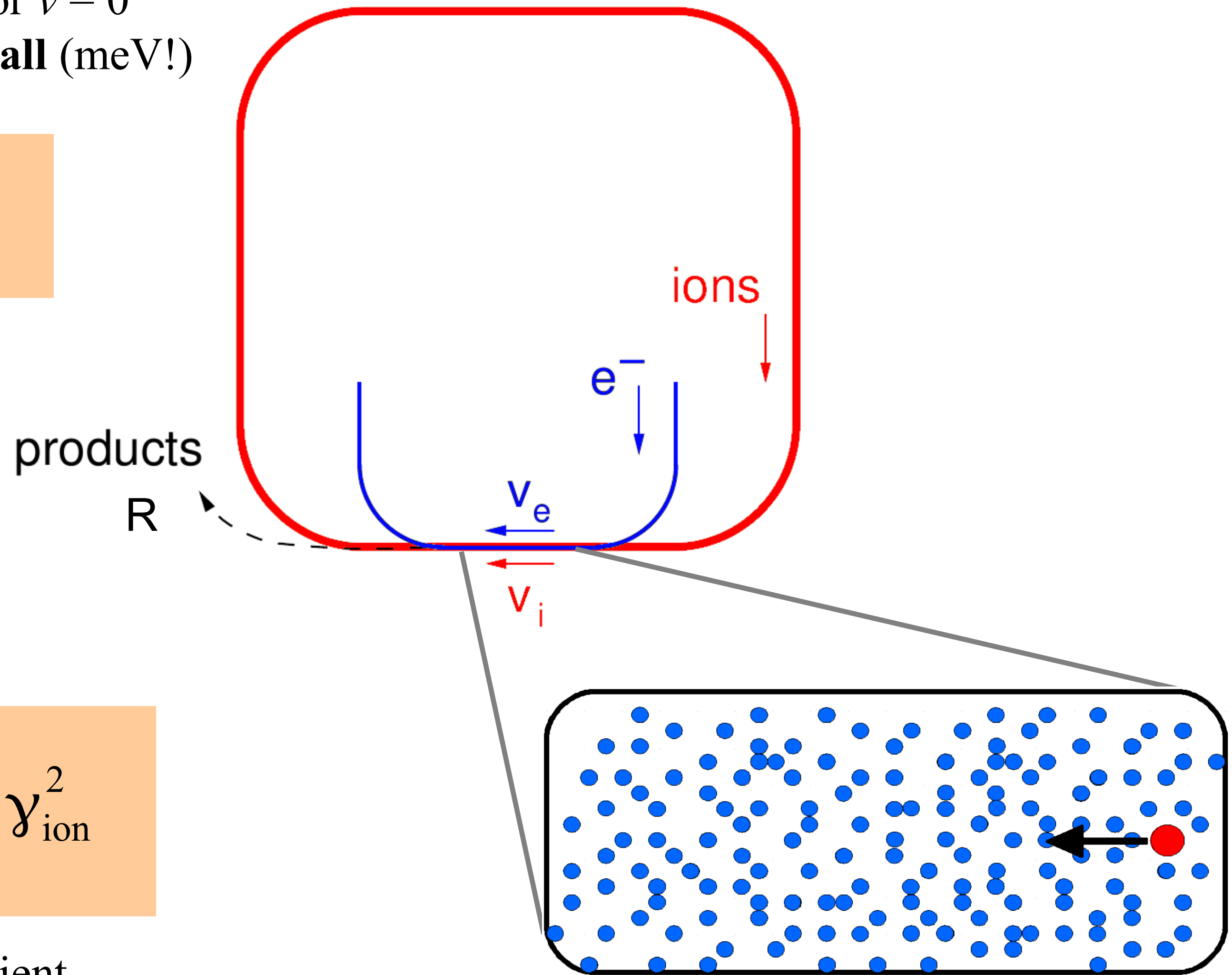
Cooler is "designed" for $v = 0$
→ E_{coll} can be **very small** (meV!)

$$E_{coll} \approx \frac{1}{2} m_e v^2$$

$$\alpha = \frac{R}{N_{ion} n_e} \frac{C}{L} \gamma_{ion}^2$$

reaction rate coefficient

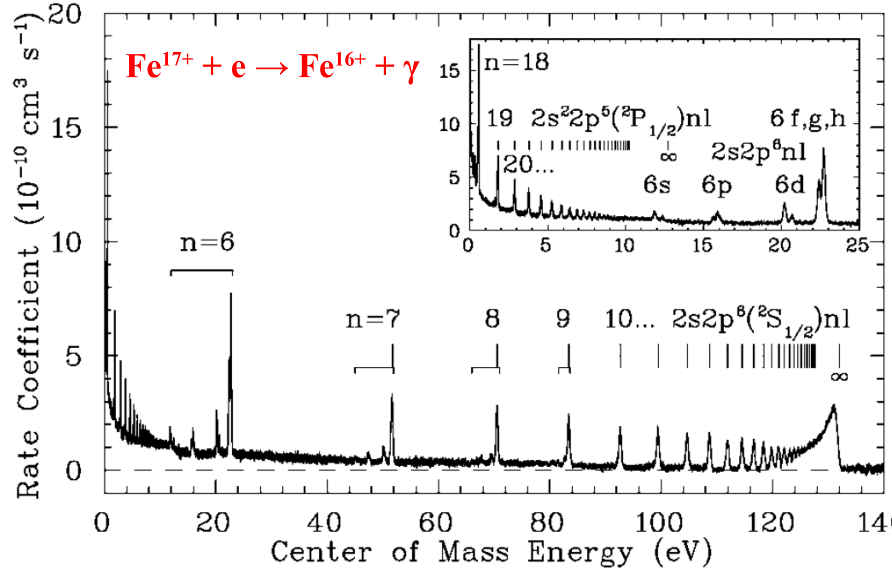
$$\alpha = \langle \sigma(v) v \rangle$$



collision velocity $v = |v_i - v_e| > 0$

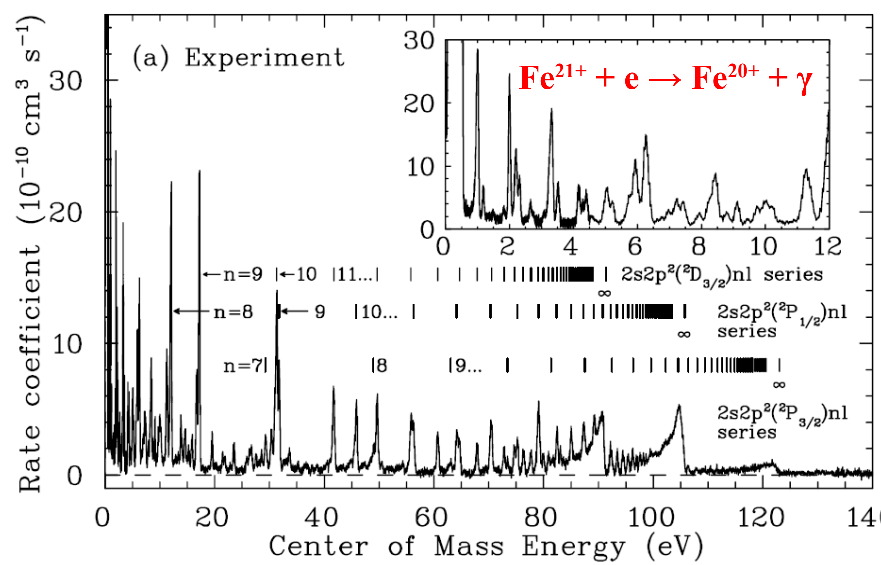
Recombination in Electron Coolers

e.g.,
Dielectronic recombination (DR)
of HCI in astrophysical plasma



[Savin, ApJ 489 (1997)]

TSR (MPIK) 1988 - 2012

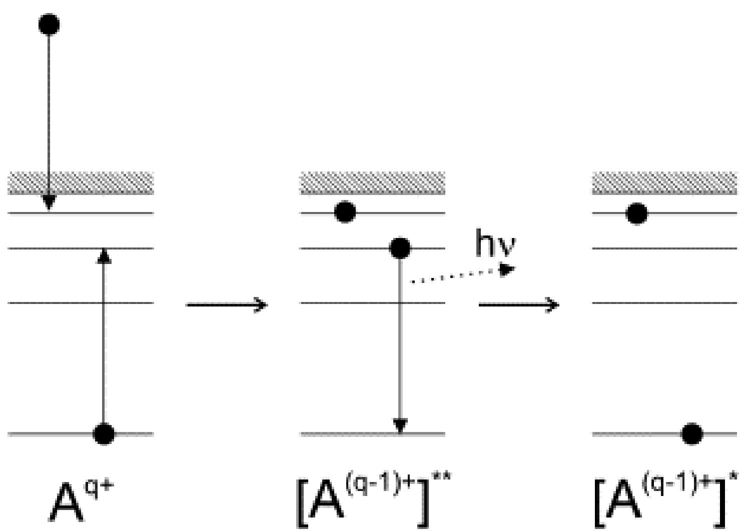


[Savin, ApJ Suppl. Ser. 147 (2003)]

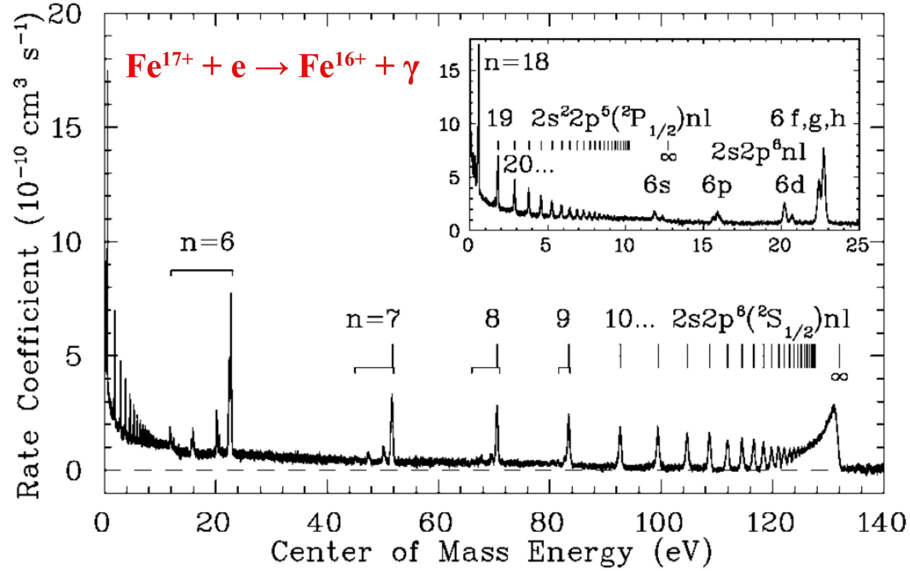
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Dielectronic Recombination

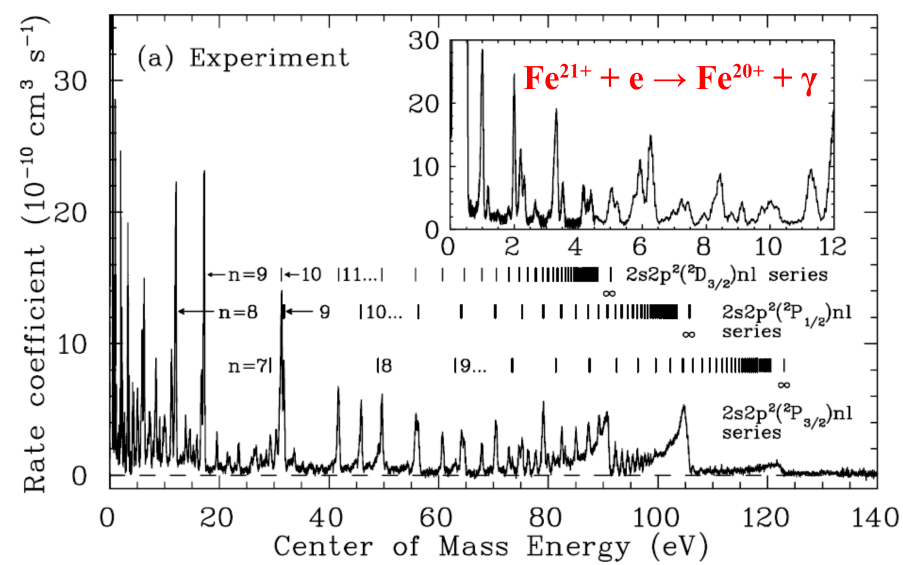
Recombination via **autoionizing states**



→ prominent “Rydberg-resonances” for ions with simple valence shells



[Savin, ApJ 489 (1997)]



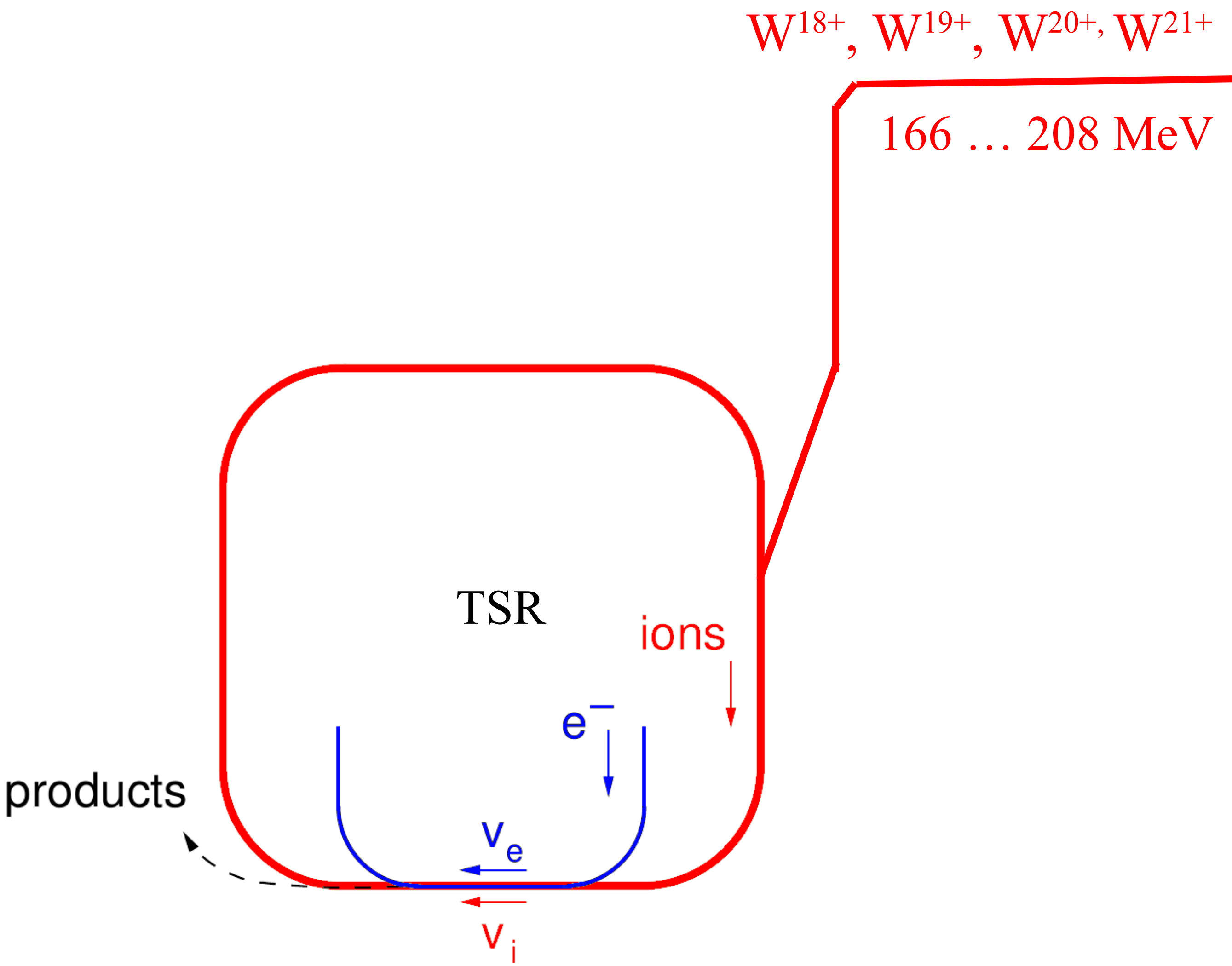
[Savin, ApJ Suppl. Ser. 147 (2003)]

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Recombination in Electron Coolers

TSR (MPIK) 1988 - 2012

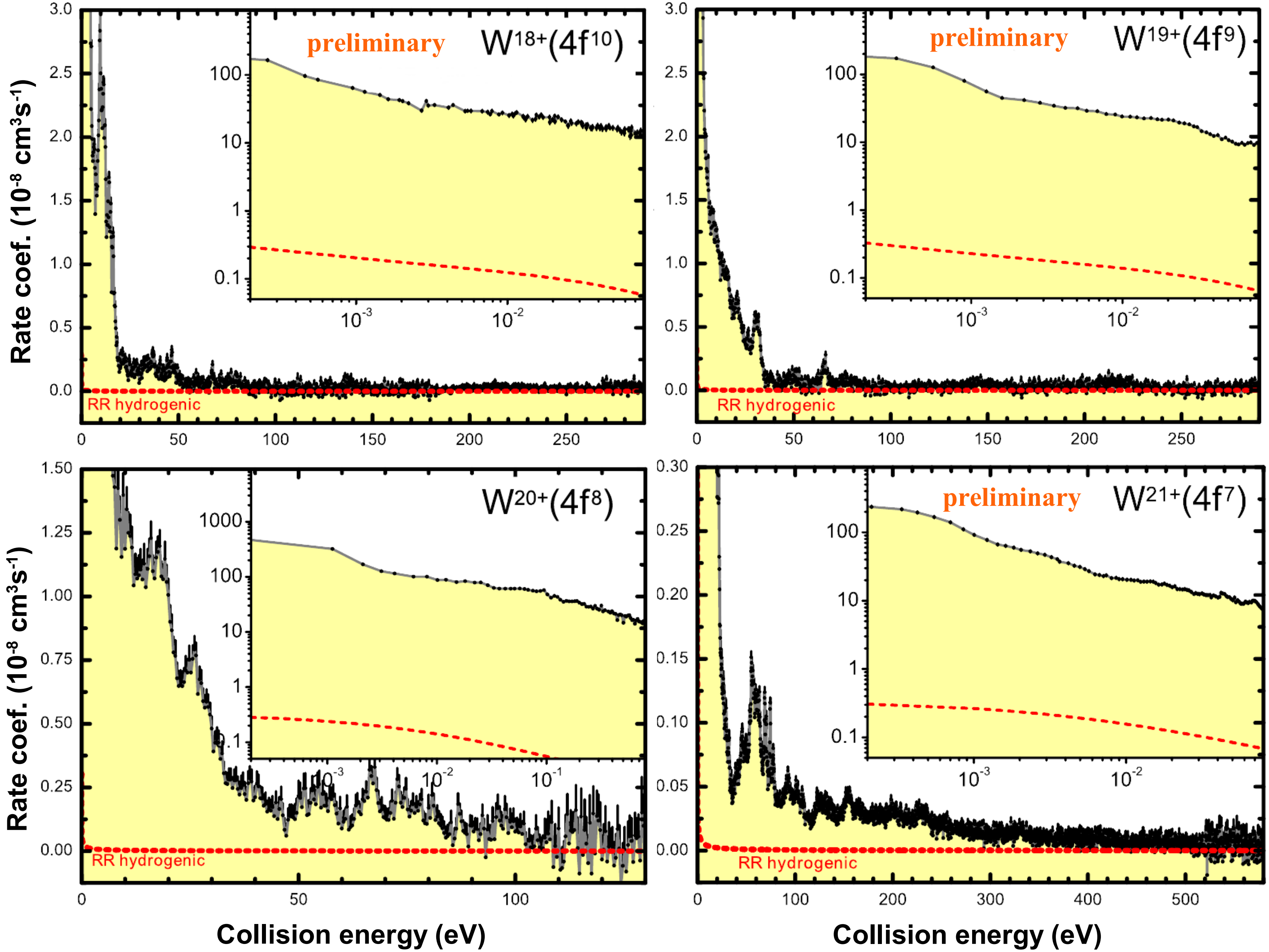
Recombination of W^{18+}, W^{19+}, W^{20+} and W^{21+}



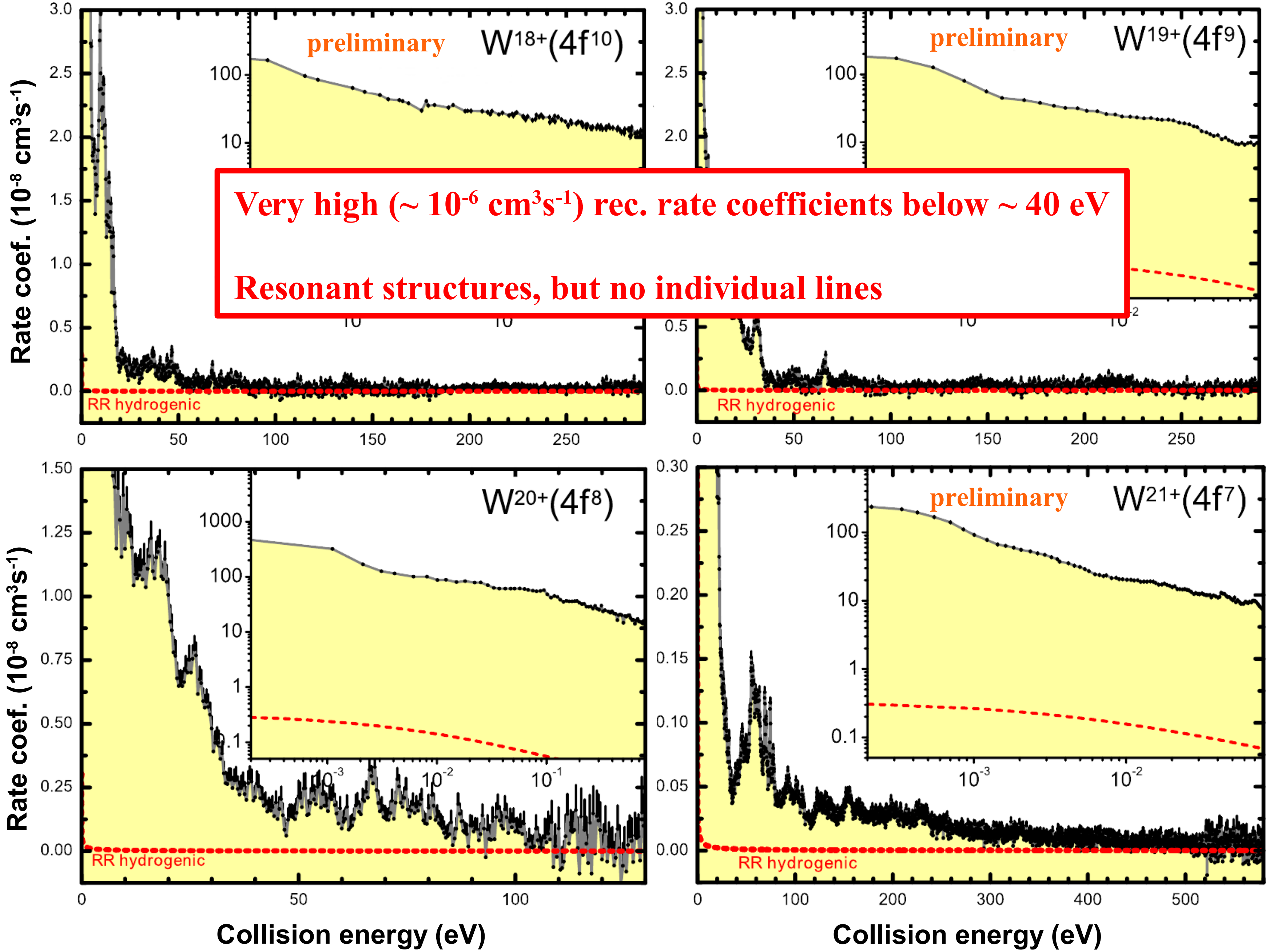
eCool for ~ 2 s

MPIK tandem accelerator

Recombination of W^{18+}, W^{19+}, W^{20+} and W^{21+}



Recombination of W^{18+}, W^{19+}, W^{20+} and W^{21+}

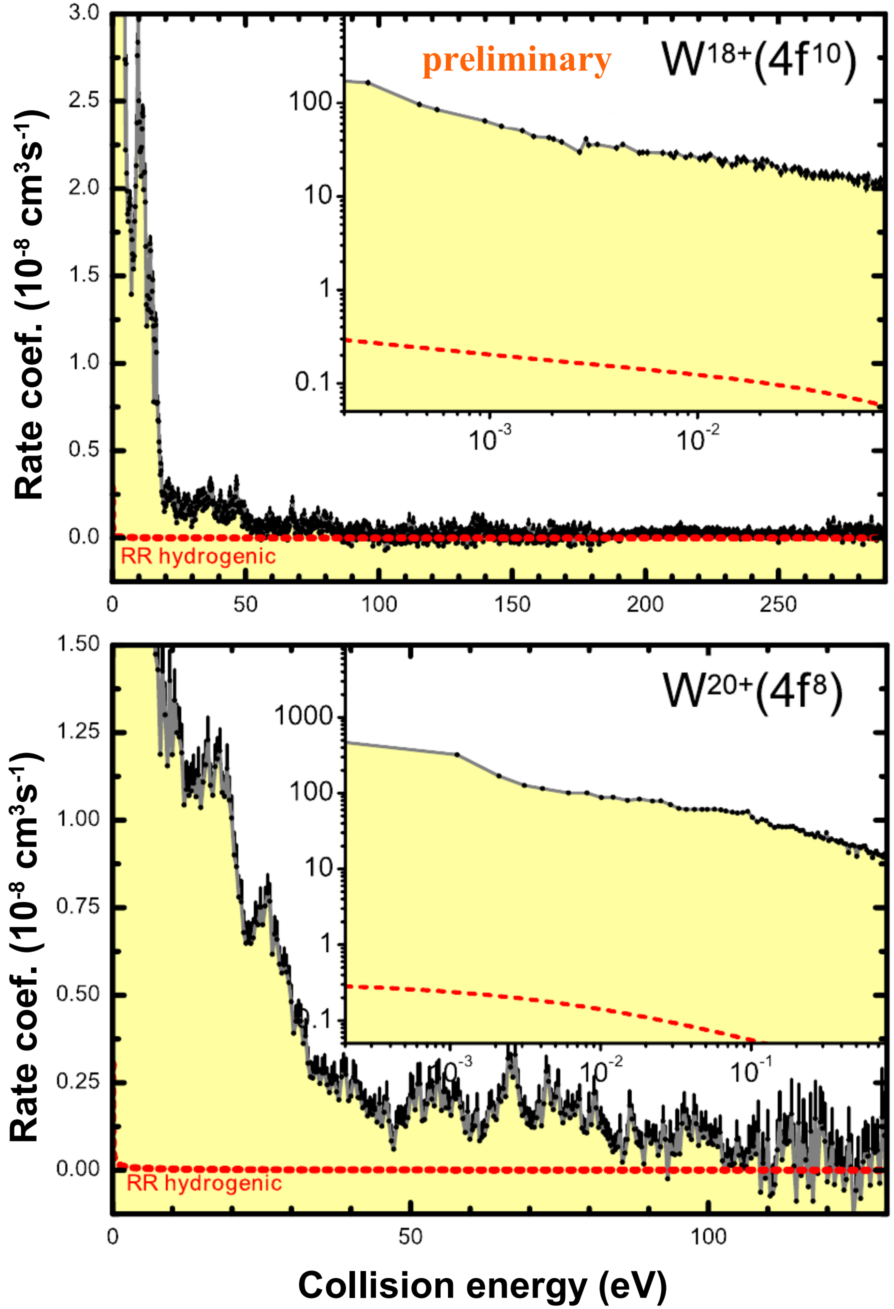


Very high (~ 10^{-6} cm^3s^{-1}) rec. rate coefficients below ~ 40 eV

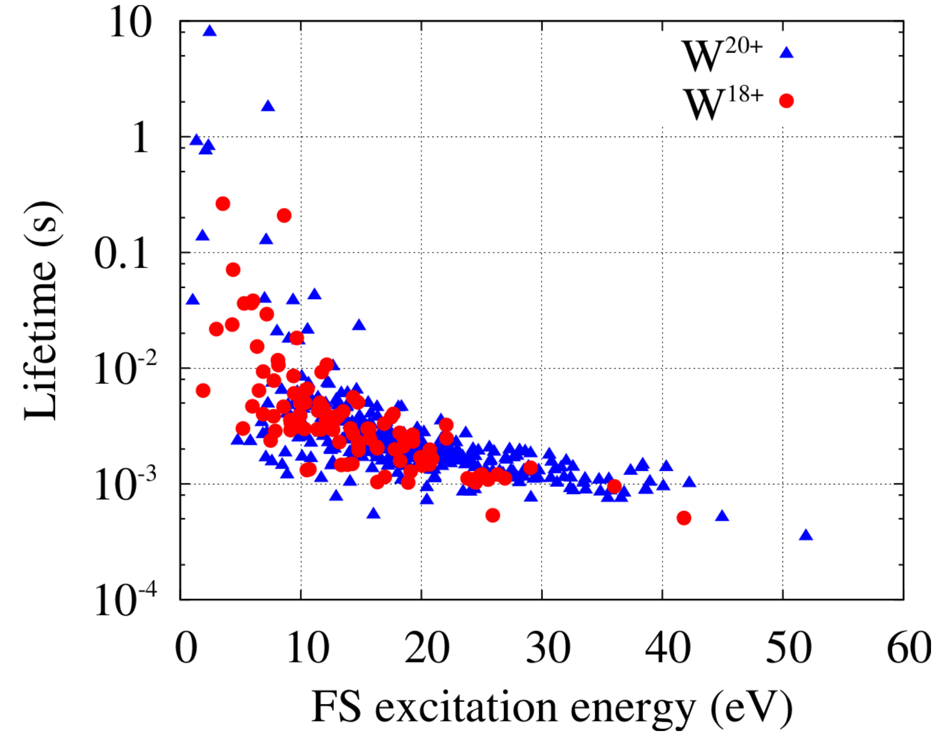
Resonant structures, but no individual lines

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Examples: $W^{18+}(4f^{10})$ and $W^{20+}(4f^{8})$



[Schippers, Phys. Rev A 83 (2011)]

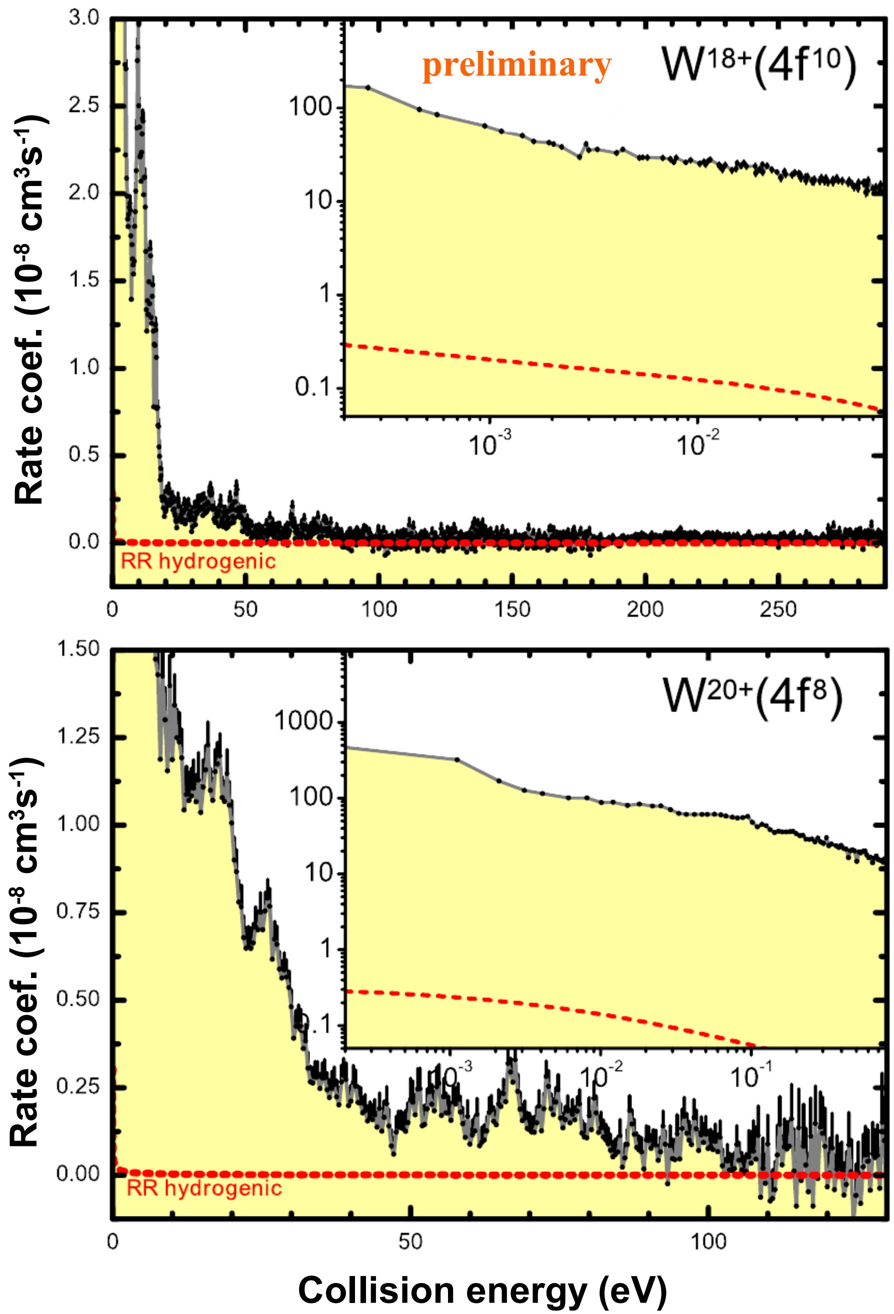


Fine structure excitations (Cowan):

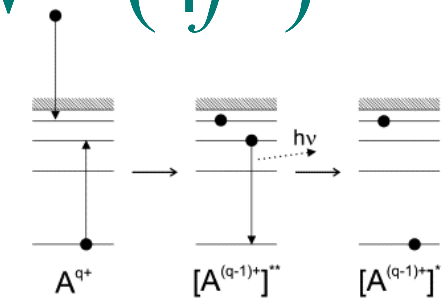
W^{18+} (gl: $4d^{10}\ 4f^{10}\ {}^{5}I_{8}$): **105 levels**

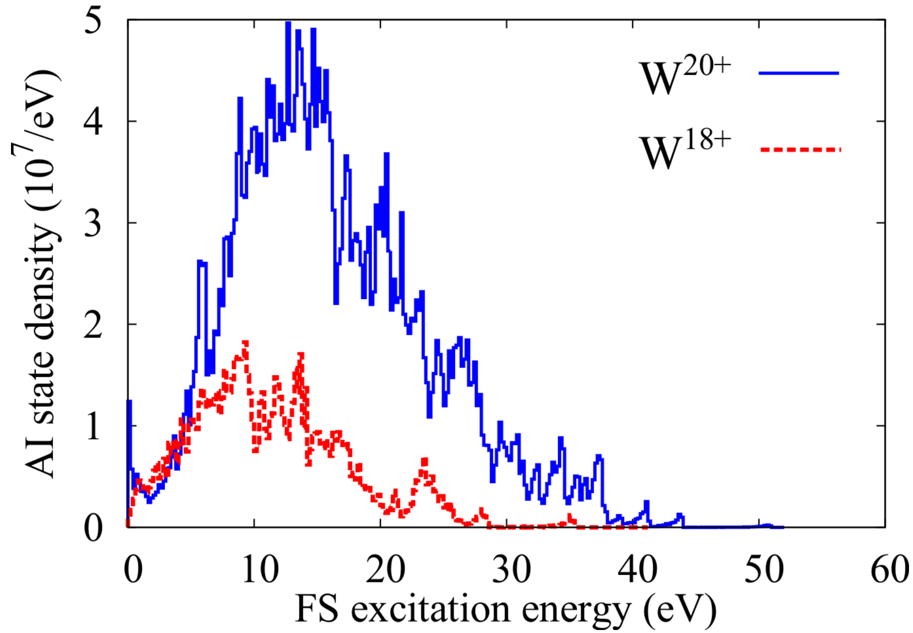
W^{20+} (gl: $4d^{10}\ 4f^{8}\ {}^{7}F_{6}$): **292 levels**

Examples: $W^{18+}(4f^{10})$ and $W^{20+}(4f^{8})$



[Schippers, Phys. Rev A 83 (2011)]





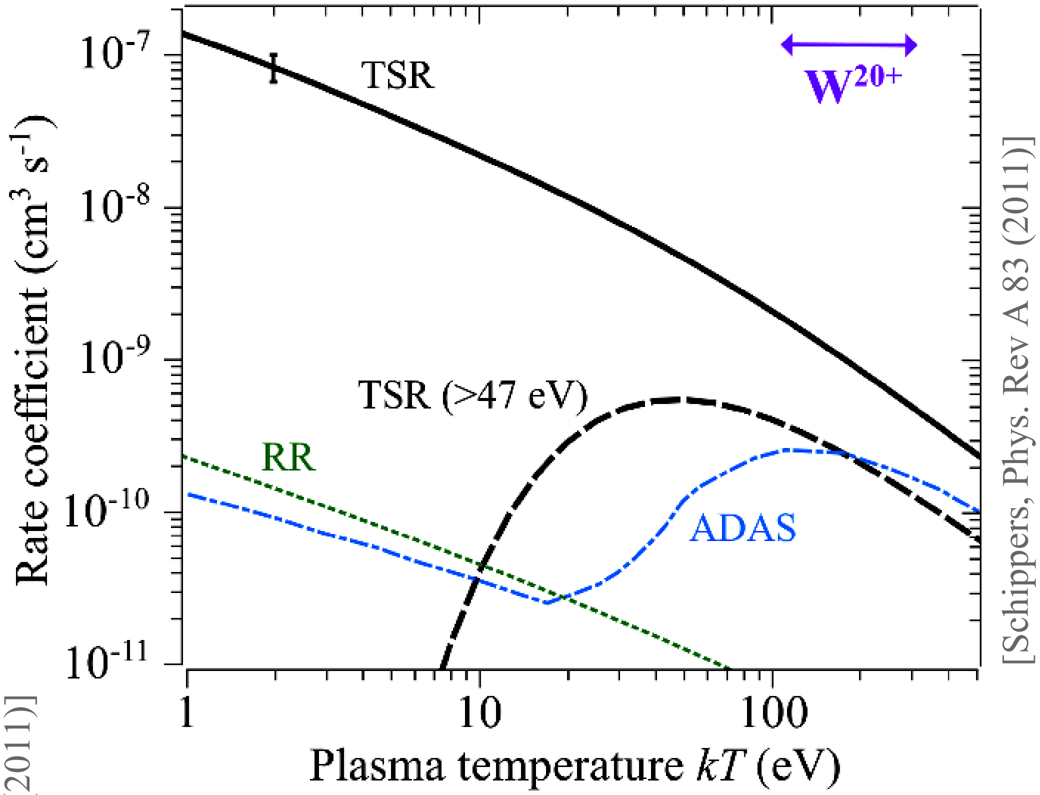
Number of AI states in DR

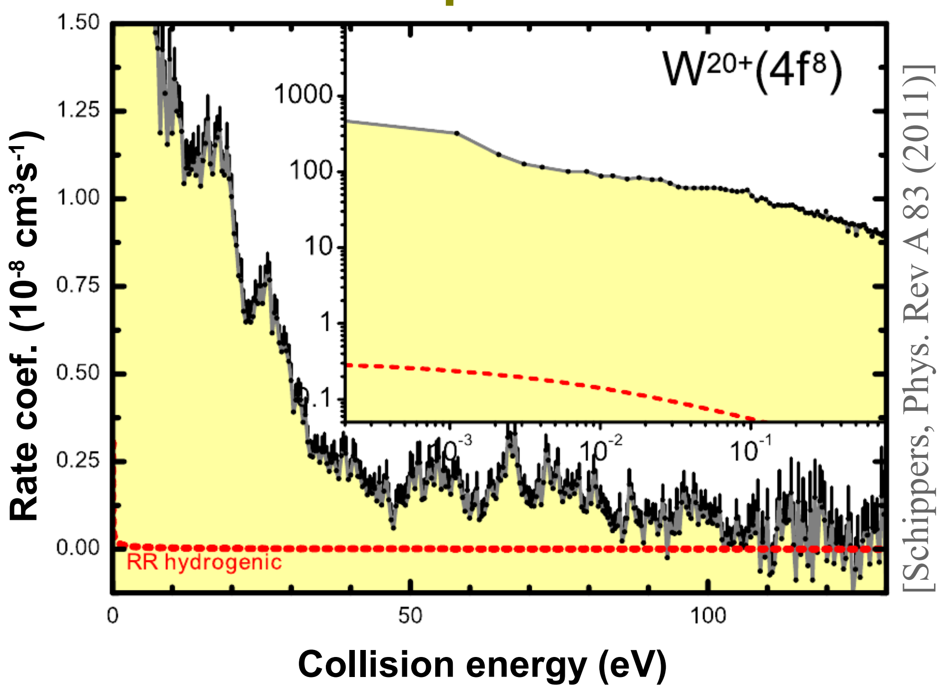
W^{18+} (gl: $4d^{10}\ 4f^{10}\ {}^5I_8$): ~ **$2\cdot10^8$**

W^{20+} (gl: $4d^{10}\ 4f^{8}\ {}^7F_6$): ~ **$7\cdot10^8$**

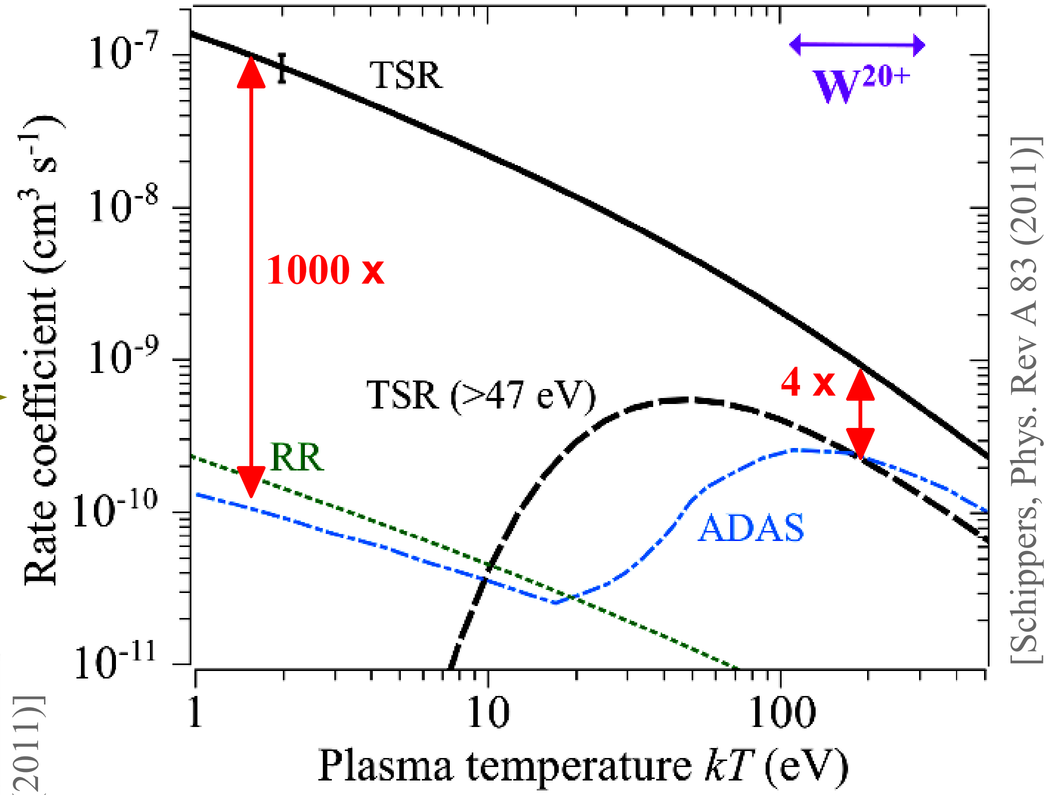
$W^{20+}(4f^{8})$: Plasma rate coefficient

convolve with
Maxwellian

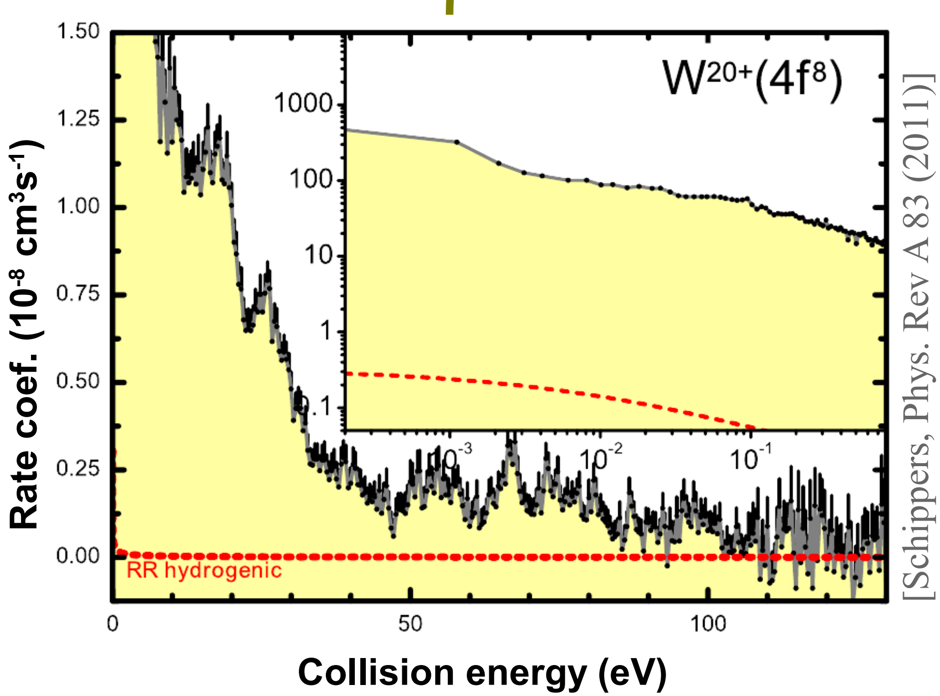




$W^{20+}(4f^{8})$: Plasma rate coefficient



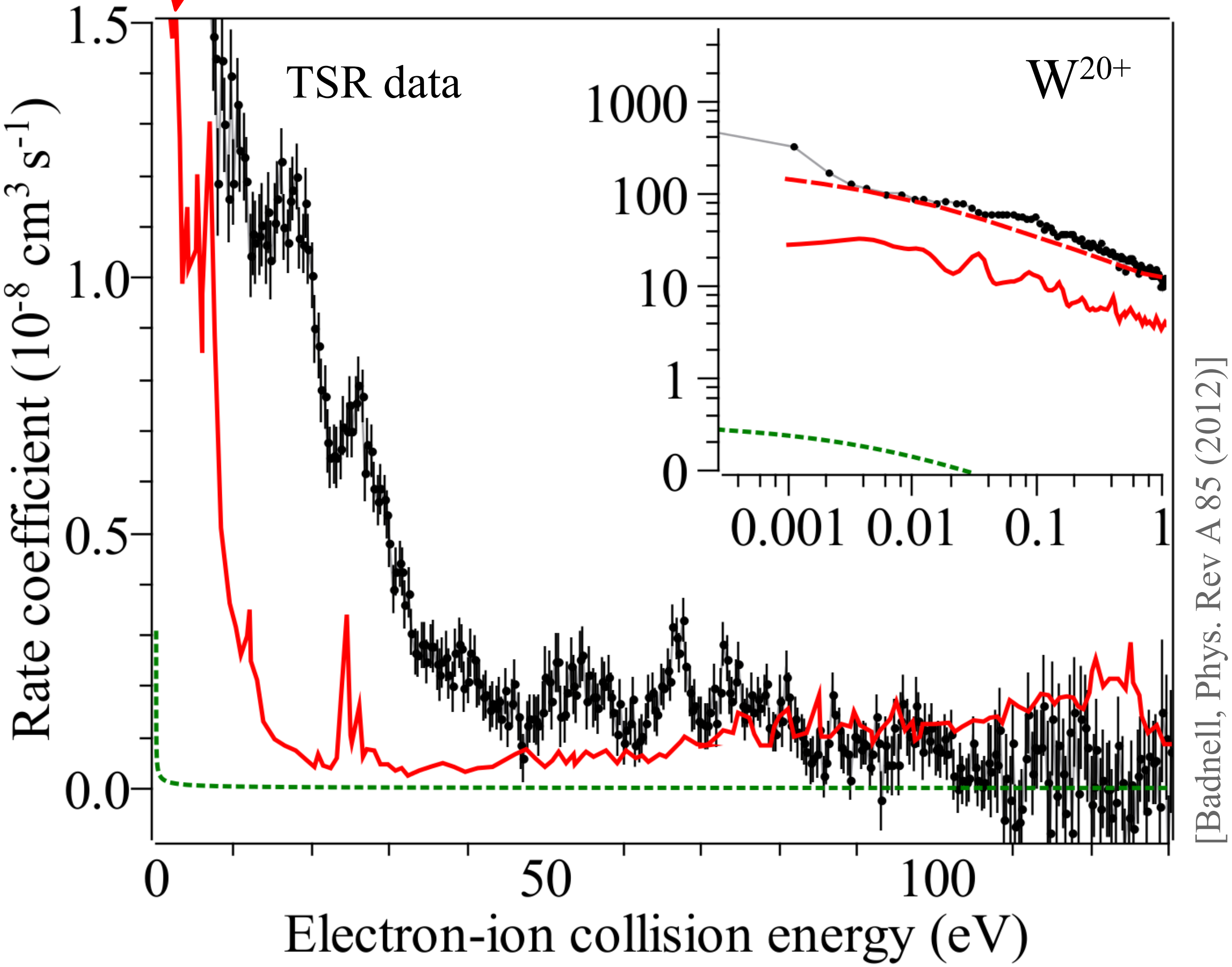
convolve with
Maxwellian



Much better agreement if data < 47 eV is rejected

→ Suggests that ground term FS is neglected in ADAS

$W^{20+}(4f^8)$: Updated theories



AUTOSTRUCTURE calculation:

[Badnell, PRA 85 (2012)]

"Intermediate Coupling (IC)"

Allows mixing of autoionizing levels of given *J*, e.g.,

$W^{20+}(^7F_6) + e^-$

↓

$\mathbf{W^{19+**}\ (^{2S+1}L_J)}$

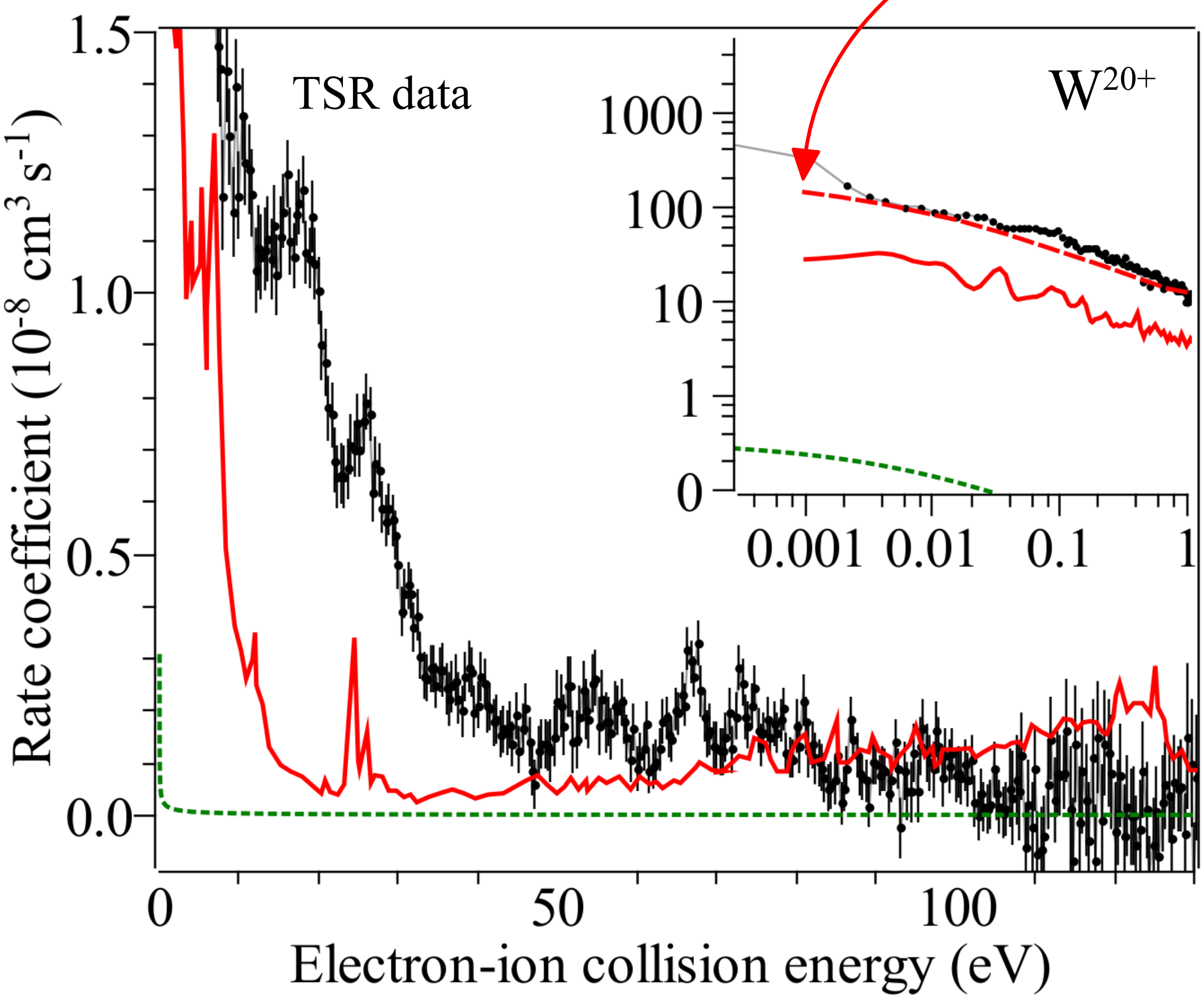
↙ ↘

$W^{20+} + e^-$ $\quad$ $W^{19+} + \gamma$

In principle *not restricted to single-electron* excitations of W^{20+}.

→ Is actually not "DR" ...

$W^{20+}(4f^{8})$: Updated theories



[Badnell, Phys. Rev A 85 (2012)]

"Full partitioning":

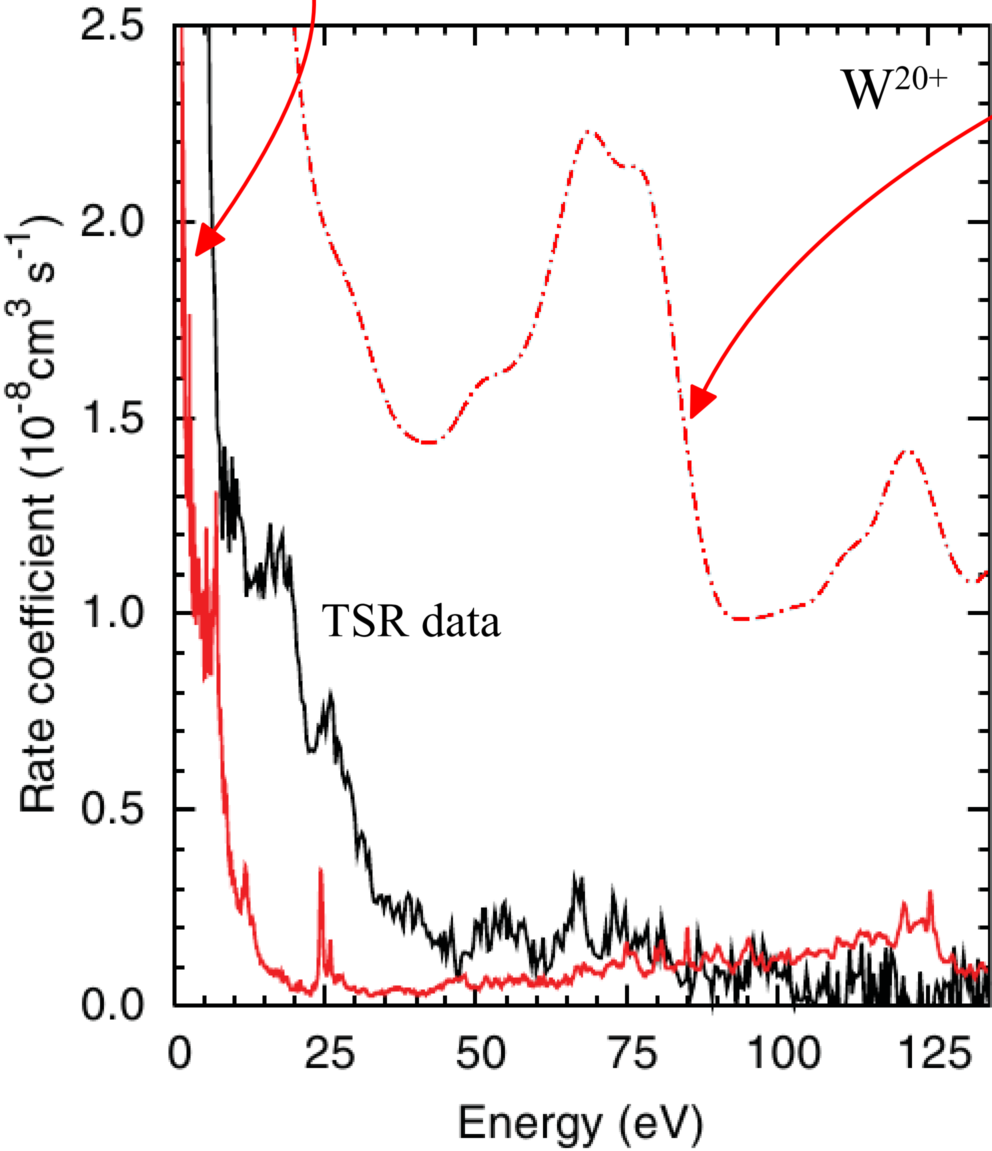
[Badnell, PRA 85 (2012)]

Mixes all AI levels in a broad energy range.

Statistical approach, compensates for limited number of states in IC calculation.

$W^{20+}(4f^8)$: Updated theories

Intermediate Coupling



[Badnell, Phys. Rev A 85 (2012)]

"Full partitioning":

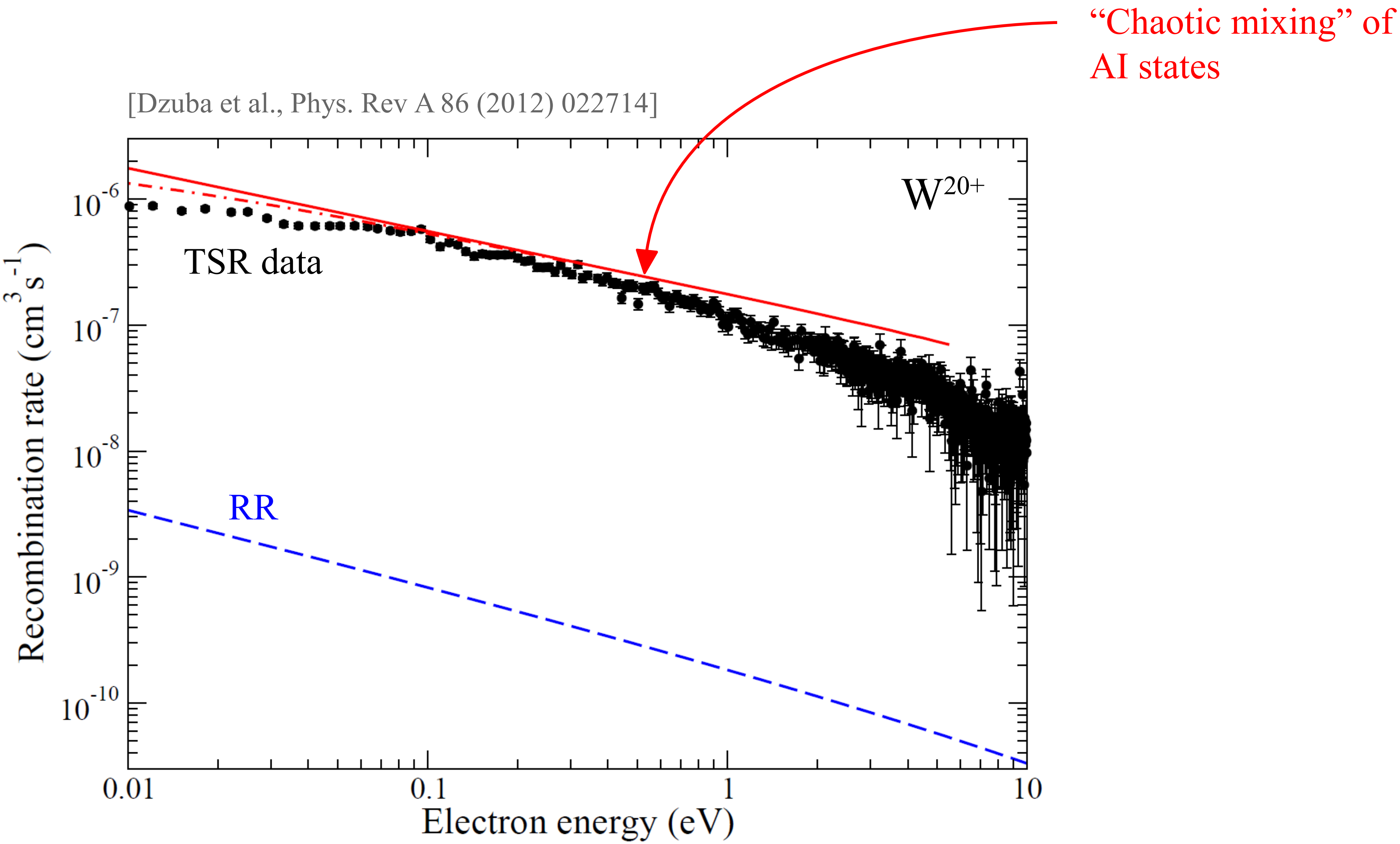
[Badnell, PRA 85 (2012)]

Mixes all AI levels in a broad energy range.

Statistical approach, compensates for limited number of states in IC calculation.

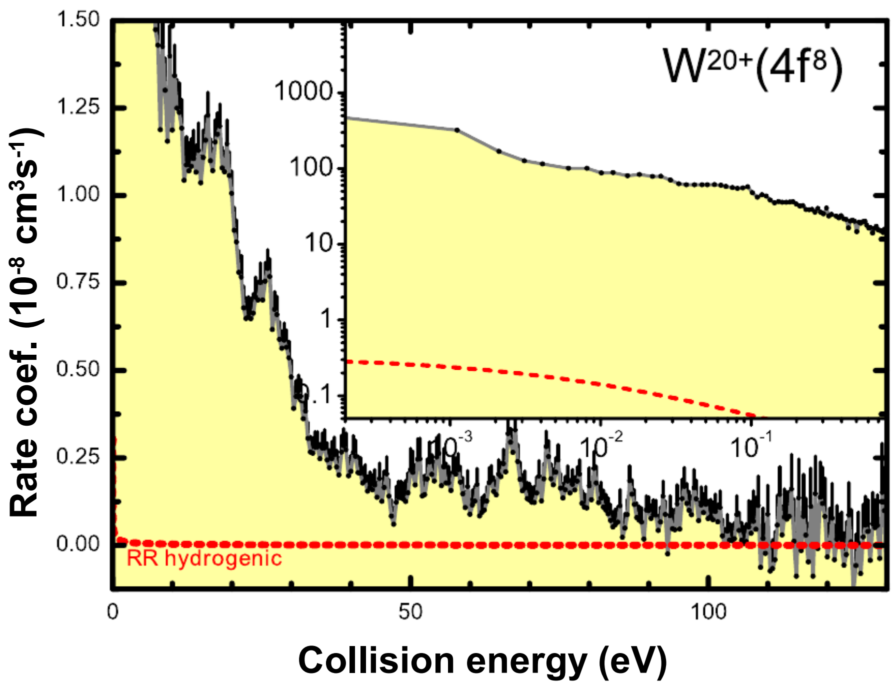
But:
Overestimates
at high energy!

$W^{20+}(4f^8)$: Updated theories

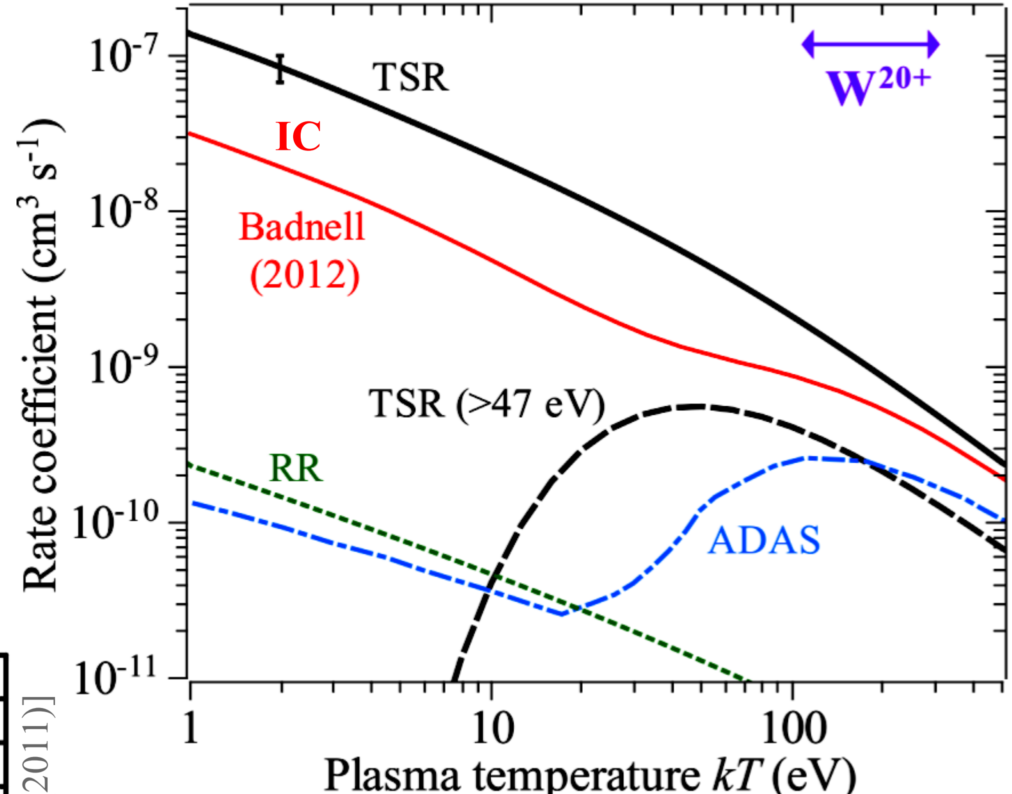


$W^{20+}(4f^{8})$: Plasma rate coefficient

convolve with Maxwellian

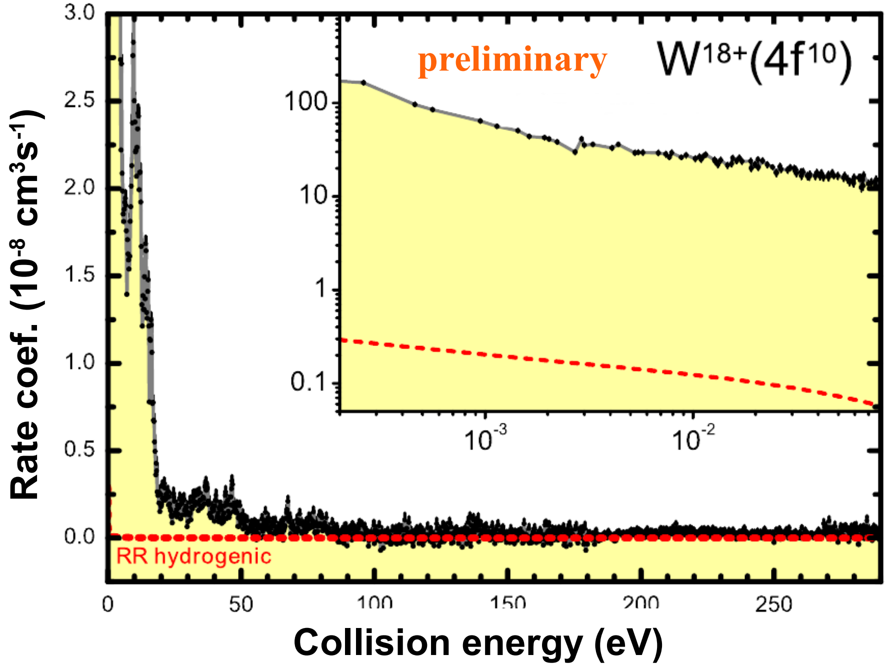


[Schippers, Phys. Rev A 83 (2011)]



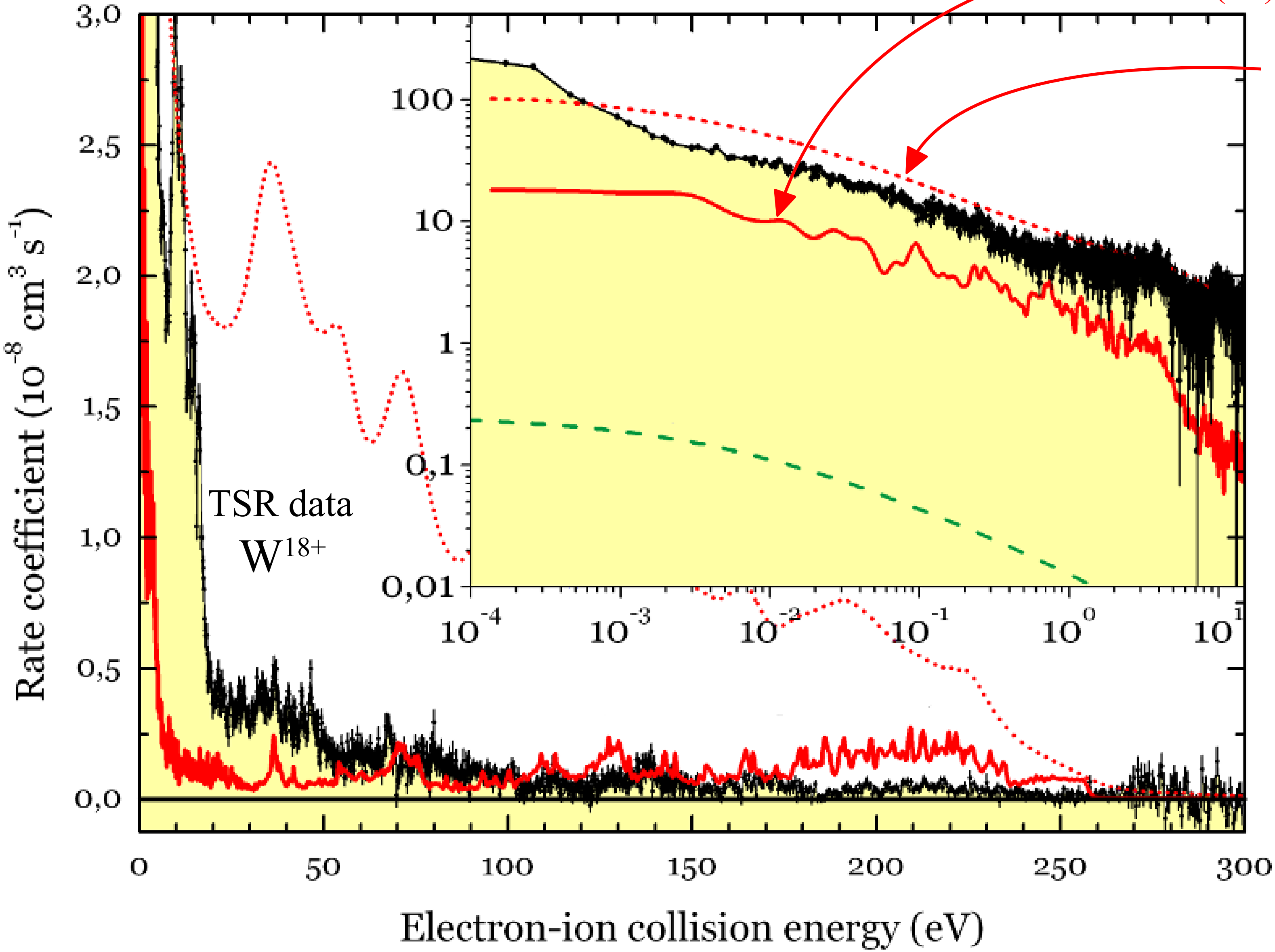
[Badnell, Phys. Rev A 85 (2012)]

$W^{18+}(4f^{10})$: Updated theory

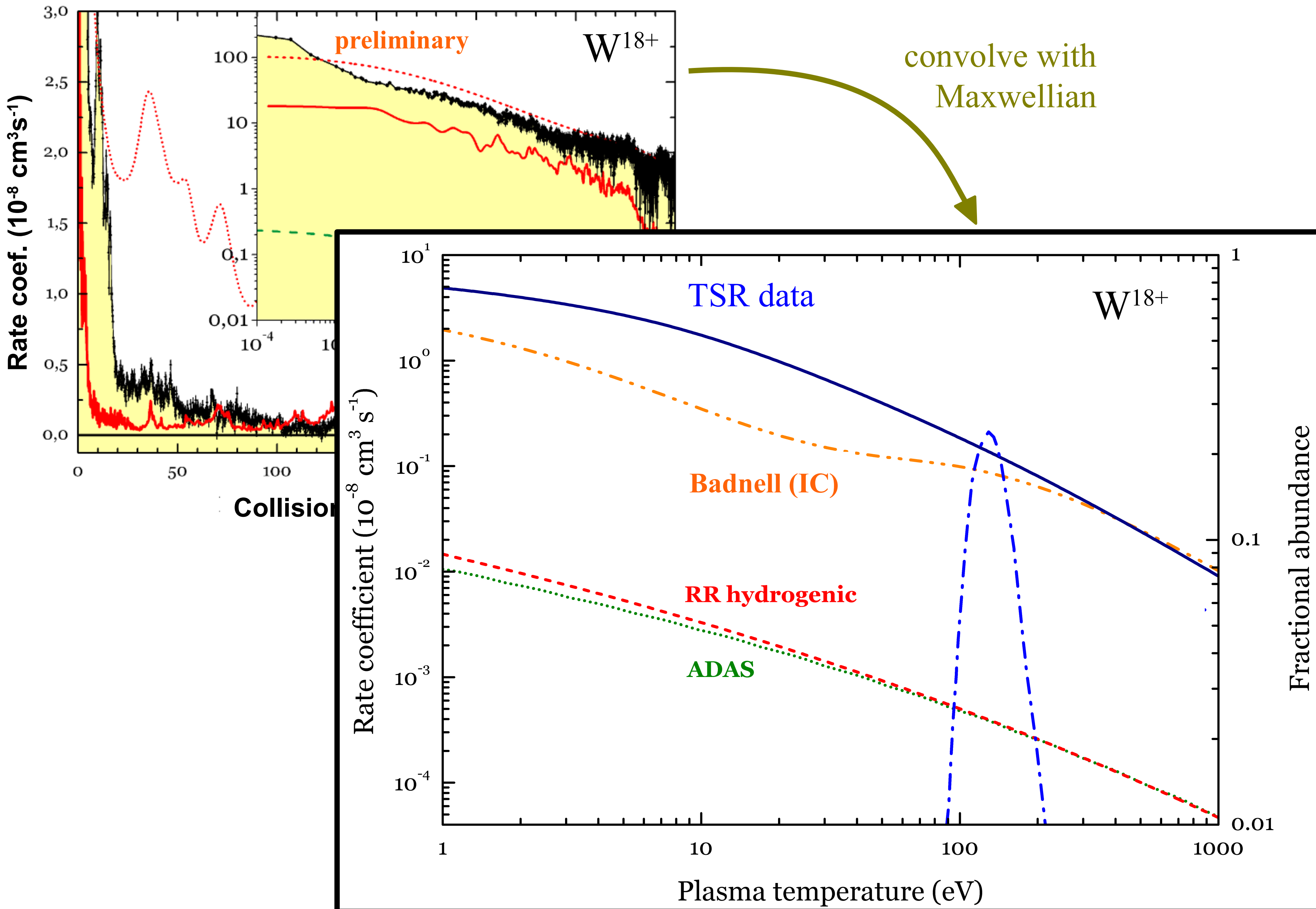


$W^{18+}(4f^{10})$: Updated theory

preliminary! [Spruck, Badnell et al., in prep.]



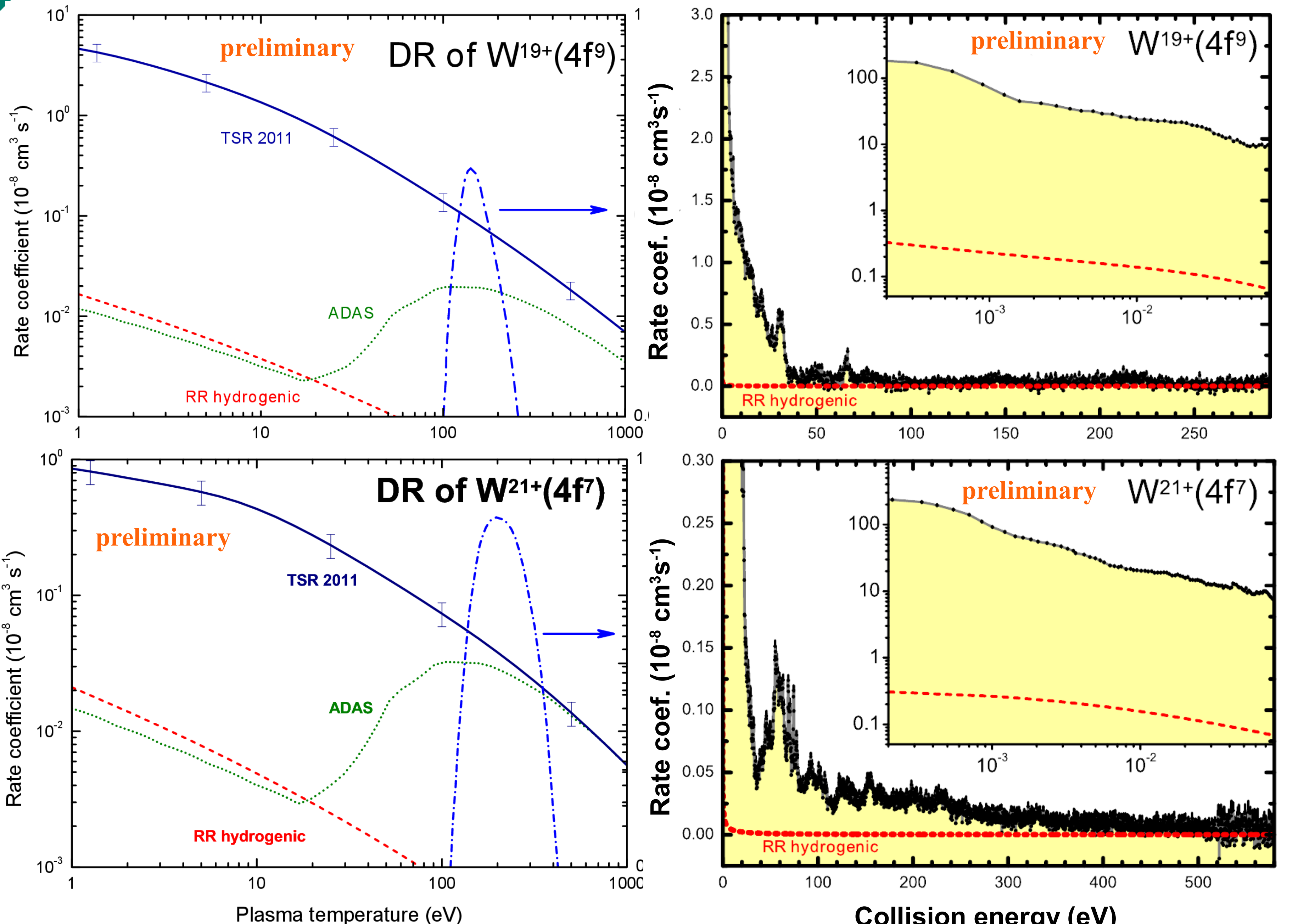
$W^{18+}(4f^{10})$: Updated theory



[Spruck, Badnell et al., in prep.]

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

W^{19+} and W^{21+}: Work ongoing ...



Summary

We have measured absolute recombination rate coefficients for W^{18+}, W^{19+}, W^{20+} and W^{21+}.

We find very fast recombination at E ~ few 10 eV. Not accounted for in ADAS data for any of the charge states.

This enhances the plasma recombination rate coefficient also at much higher temperatures, where the charge states are abundant in fusion plasmas.

An updated AUTOSTRUCTURE theory can somewhat explain the fast recombination by mixing of AI levels ...

… but can not predict the experiment in every detail yet.

Thank you.

Max Planck Institute for Nuclear Physics, Heidelberg

Arno Becker

Manfred Grieser

Roland Repnow

Andreas Wolf

C. K.

University of Strathclyde, Glasgow

Nigel R. Badnell

Justus-Liebig University, Gießen

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Kaija Spruck

Dietrich Bernhardt

Alfred Müller

Stefan Schippers

Columbia University, New York

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Michael Hahn

Oldřich Novotný

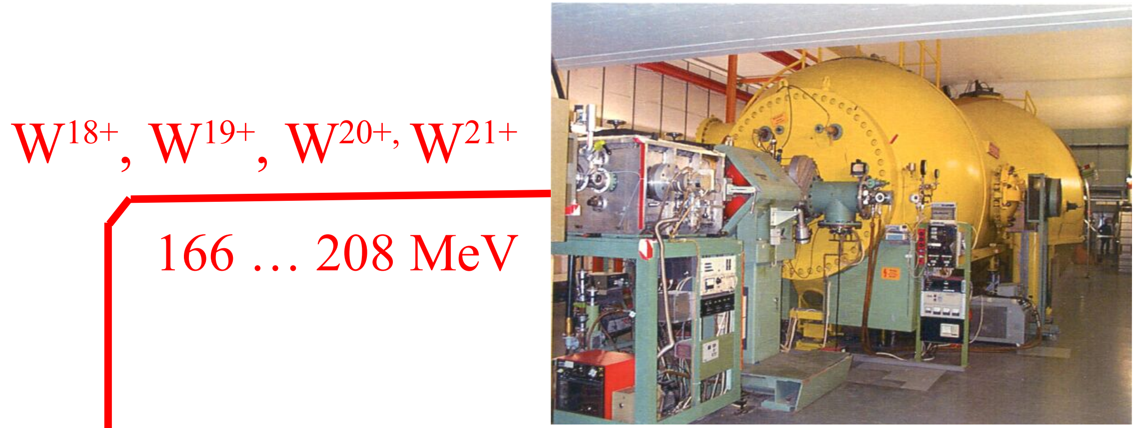
Daniel W. Savin

Recombination of W^{18+}, W^{19+}, W^{20+} and W^{21+}

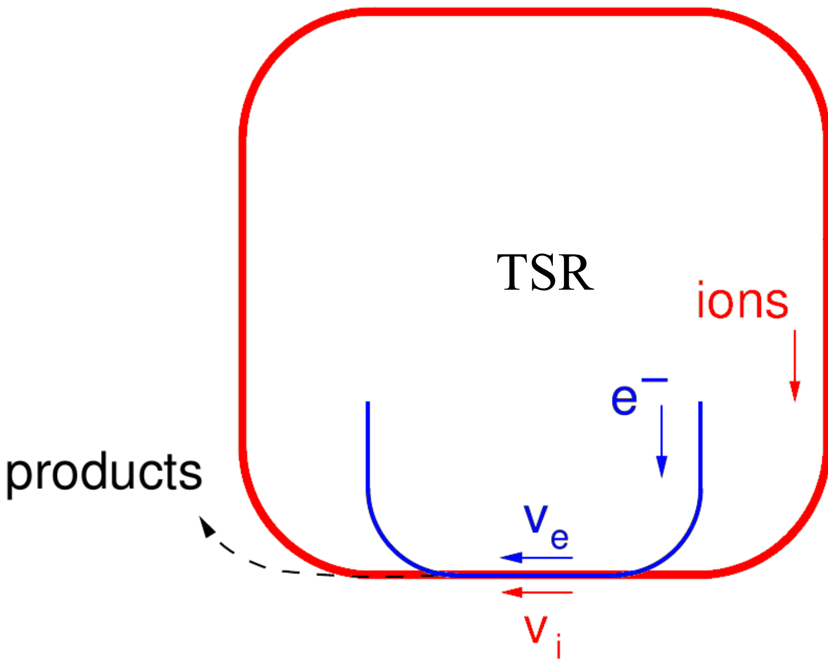
Technical challenges:

- low production efficiency
- short beam lifetime (~ few s)

→ very low (few nA) stored ion current



MPIK tandem accelerator



eCool for ~ 2 s