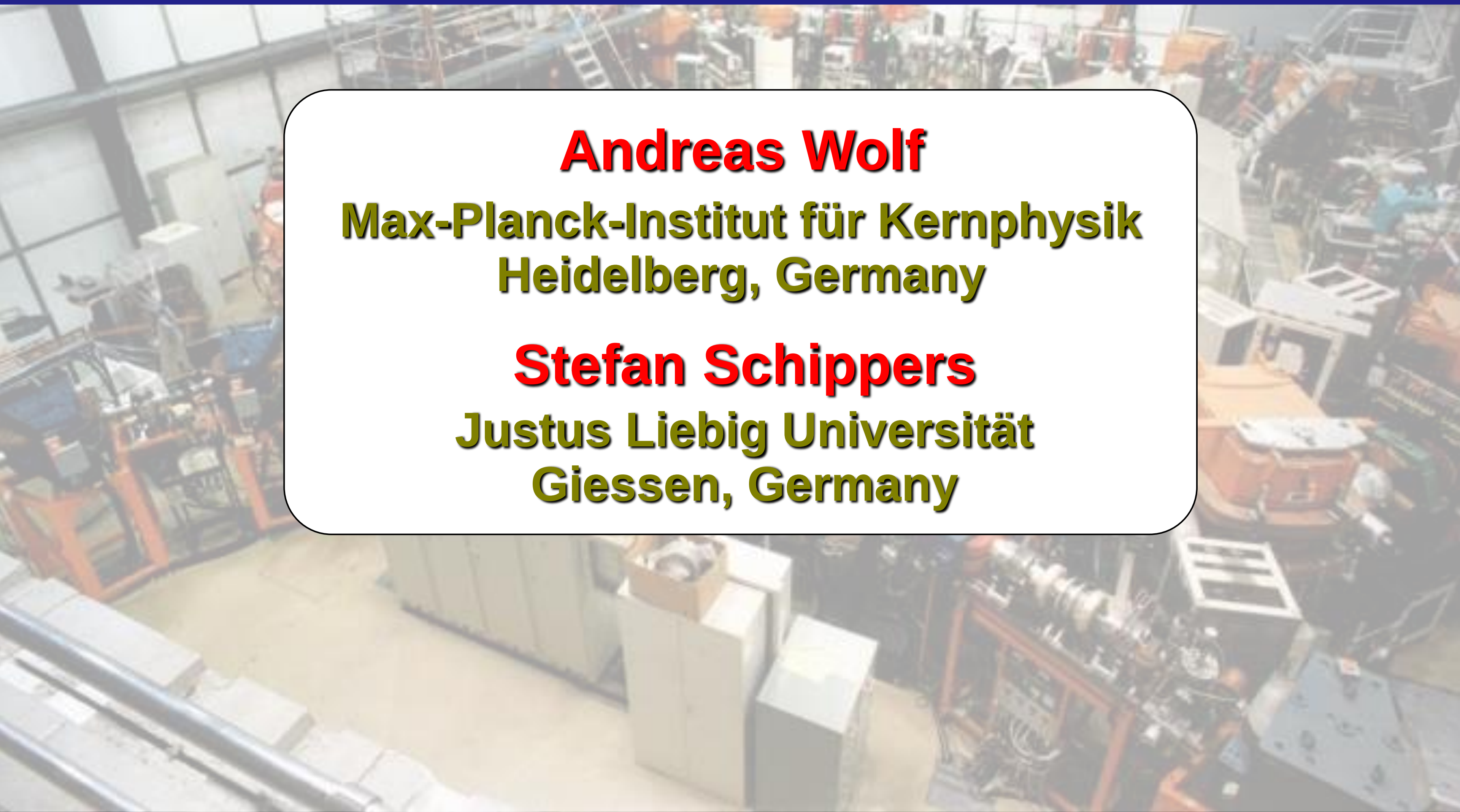
Atomic Physics Experiments with Multiply Carged Ions in TSR@ISOLDE



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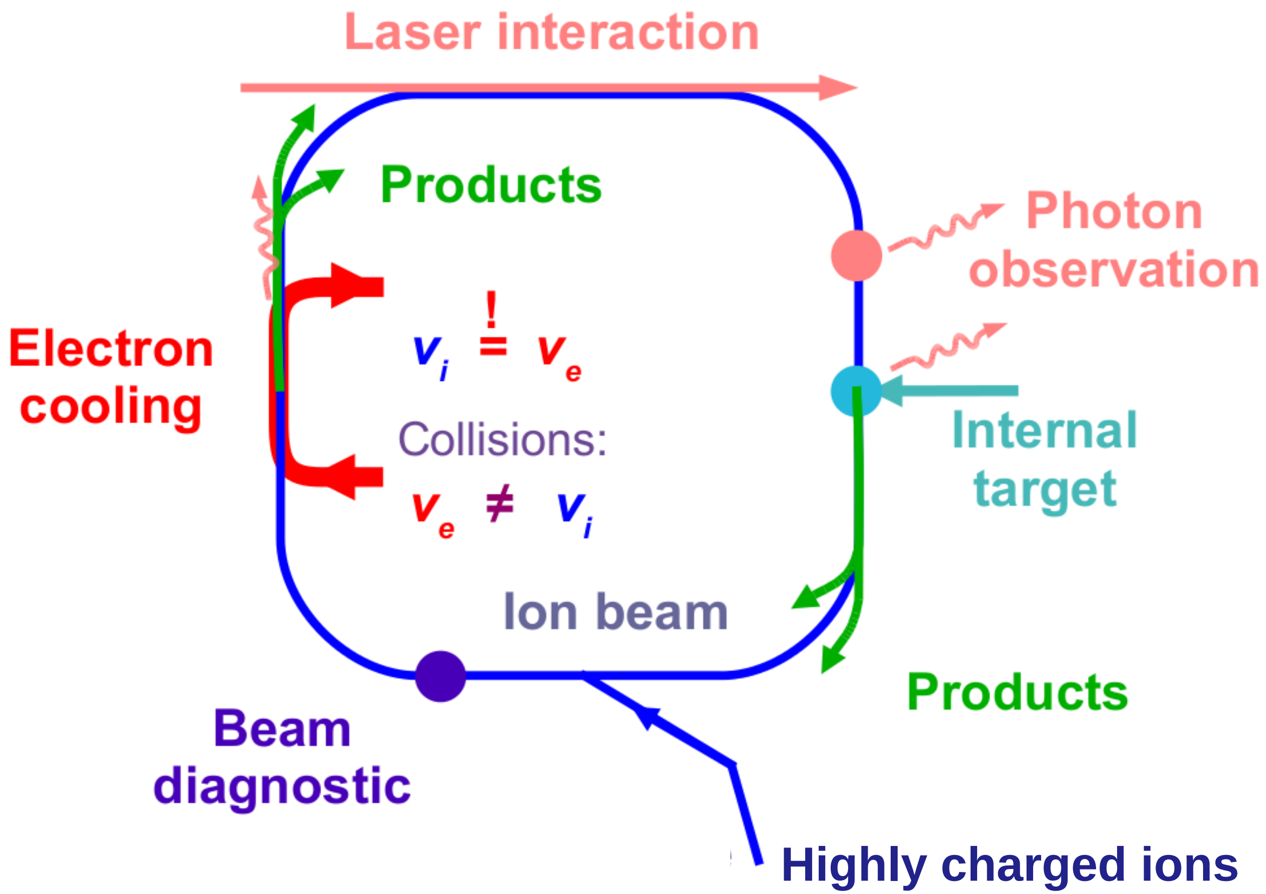
Justus Liebig Universität
Giessen, Germany

The Heidelberg TSR storage ring at MPIK

Outline

- TSR seen with the eyes of an atomic physicist
- Atomic Physics at TSR@ISOLDE
  - Atomic data for astrophyics
  - Atomic data for fusion energy research
  - Hyperfine induced atomic transitions

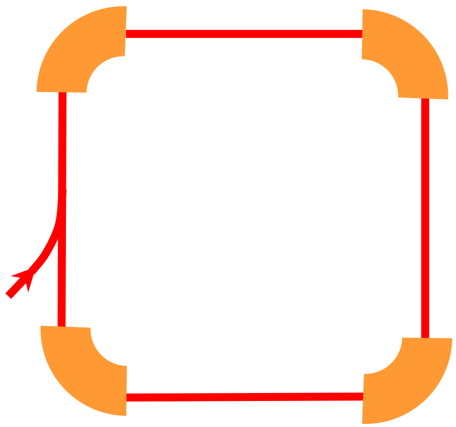
The atomic physicist's view



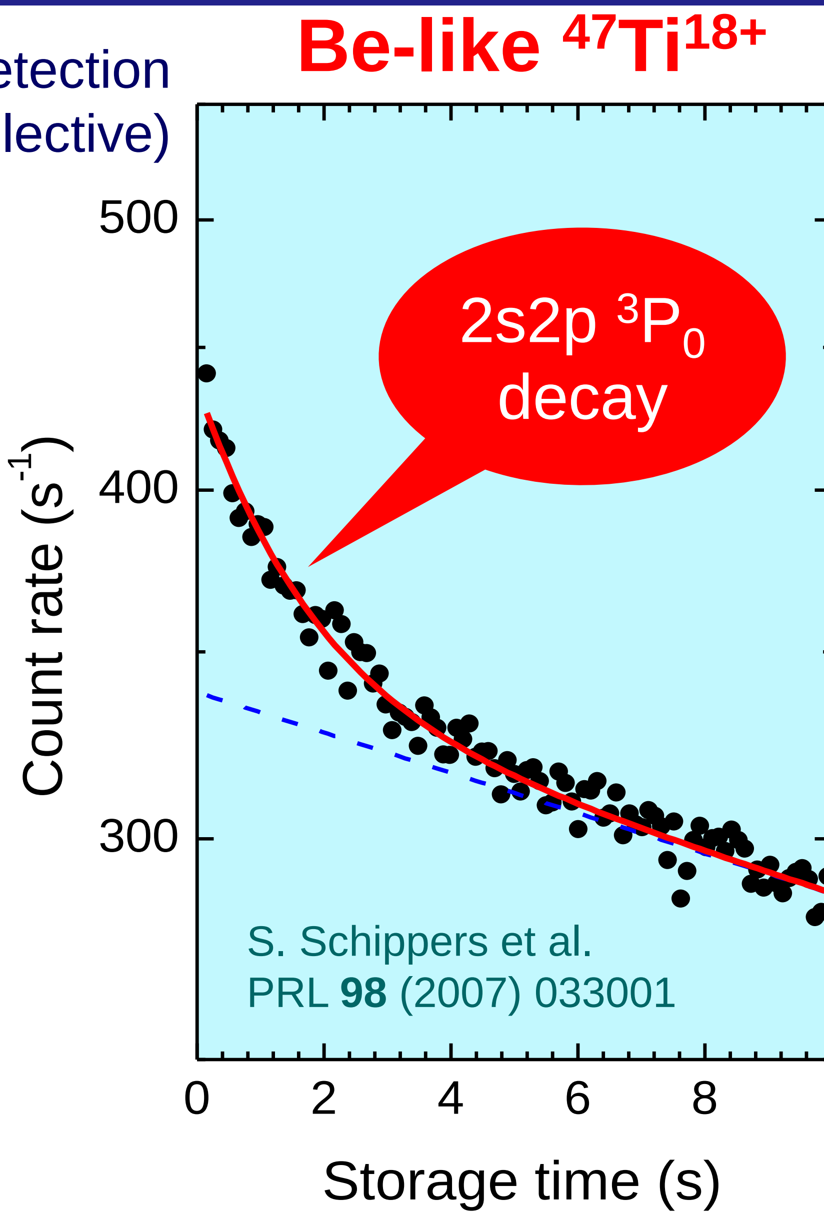
Efficient detection of fast-beam collision products

Decay of excited states

Reaction product detection
(state selective)



Simply wait until metastable ions have relaxed to their ground state.



Reactions

Electron impact ionization $\quad {}^{A}Z^{q+} + e \rightarrow {}^{A}Z^{(q+1)+} + 2e$

excitation $\quad \rightarrow ({}^{A}Z^{q+})^{*} + e$

Resonance formation (capture) $\quad \rightarrow ({}^{A}Z^{(q-1)+})^{**}$

$${}^{A}Z^{(q-1)+} + h\nu \leftarrow \quad | \quad \rightarrow {}^{A}Z^{(q+1)+} + 2e$$

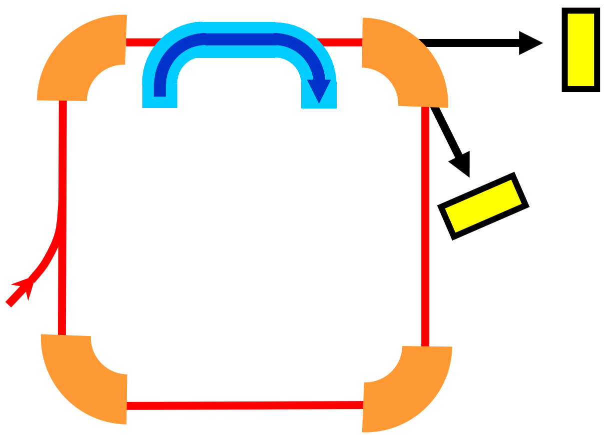
Recombination (“dielectronic”) — **Resonant impact ionization**

Excitation / autoionization $\quad \rightarrow ({}^{A}Z^{q+})^{**} + e$

$$\rightarrow {}^{A}Z^{(q+1)+} + 2e$$

Fast beam collision experiments

Charge-changing collisions



Fast-beam reaction products:

- Beams of high directionality
- High particle energies in lab frame

Near-100% detection efficiency

Collision experiments with dilute ensembles of particles

Tunable relative energy: sub **meV** to sub **MeV**

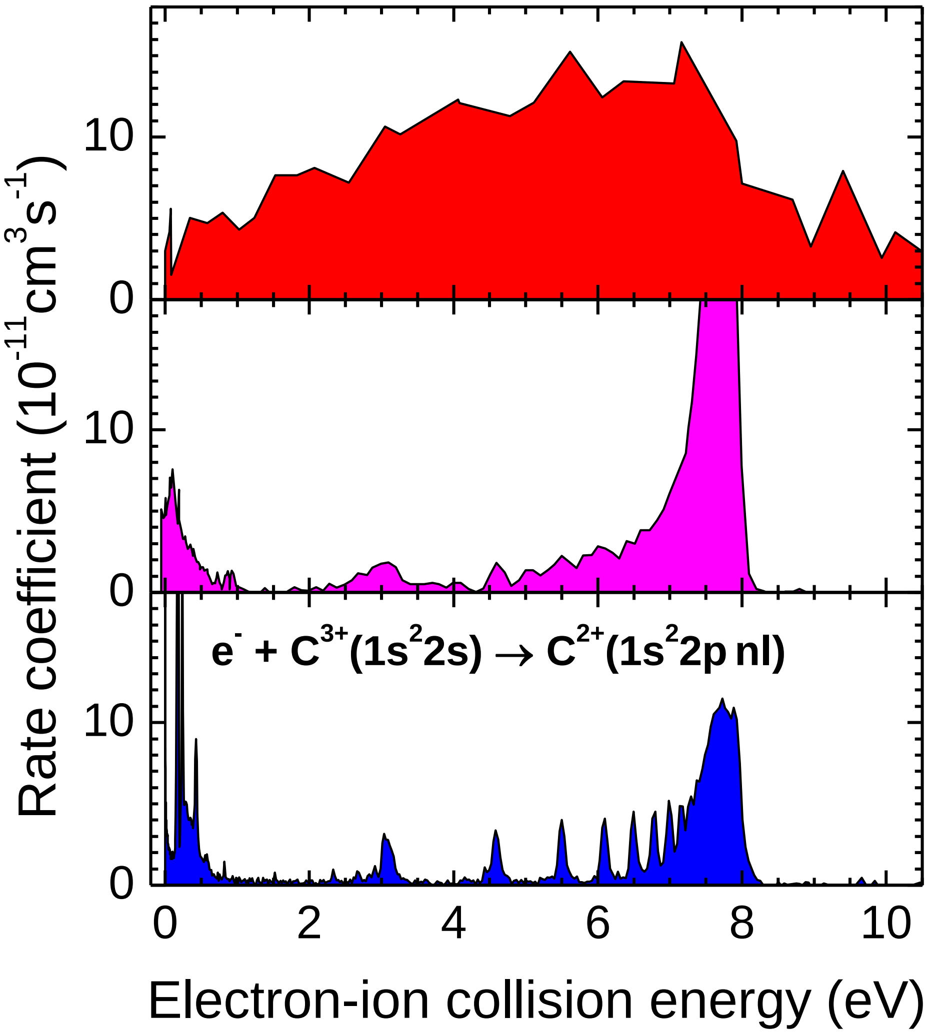
Cross sections on an absolute scale

Electron-ion recombination

Electron-impact ionization of ions

Experimental energy spread in history

Resonant (dielectronic) recombination of Li-like C^{3+}

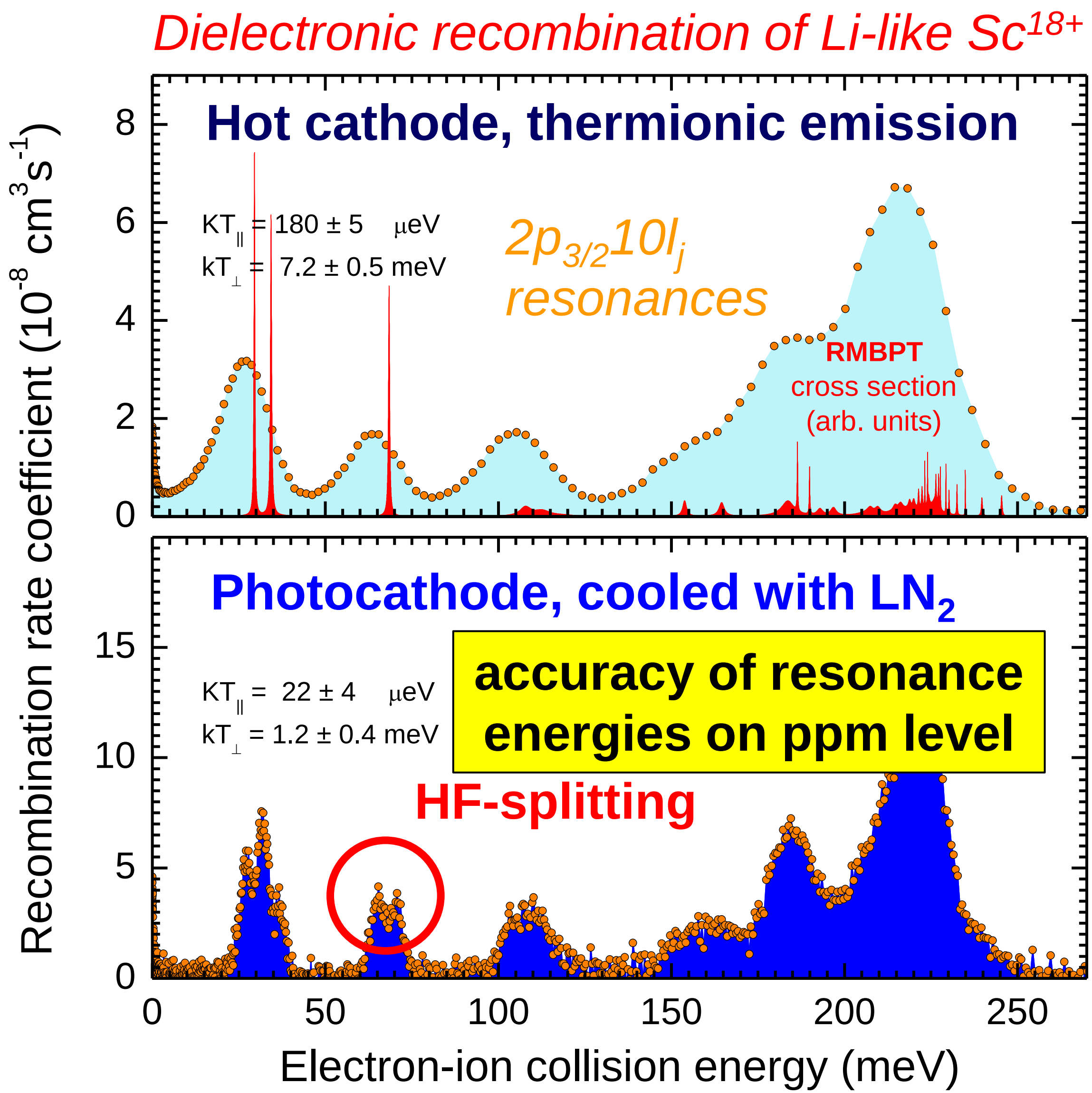


1983: Dittner et al., PRL 51, 31
Electron beam compression
No cooling of ion beam
$kT_\perp$ = 5000 meV, $kT_{||}$ = 1 meV

1990: Andersen et al., PRA 41, 1293
Constant electron-beam diameter
No cooling of ion beam
$kT_\perp$ = 135 meV, $kT_{||}$ = 1 meV

2001: Schippers et al., ApJ 555, 1027
Electron-beam expansion
Electron cooling of ion beam
$kT_\perp$ = 10 meV, $kT_{||}$ = 0.15 meV

Photocathode electron beam



TSR electron cooler

S. Kieslich et al.,
PRA **70** (2004) 042714

TSR electron target

M. Lestinsky et al.,
PRL **100** (2008) 033001

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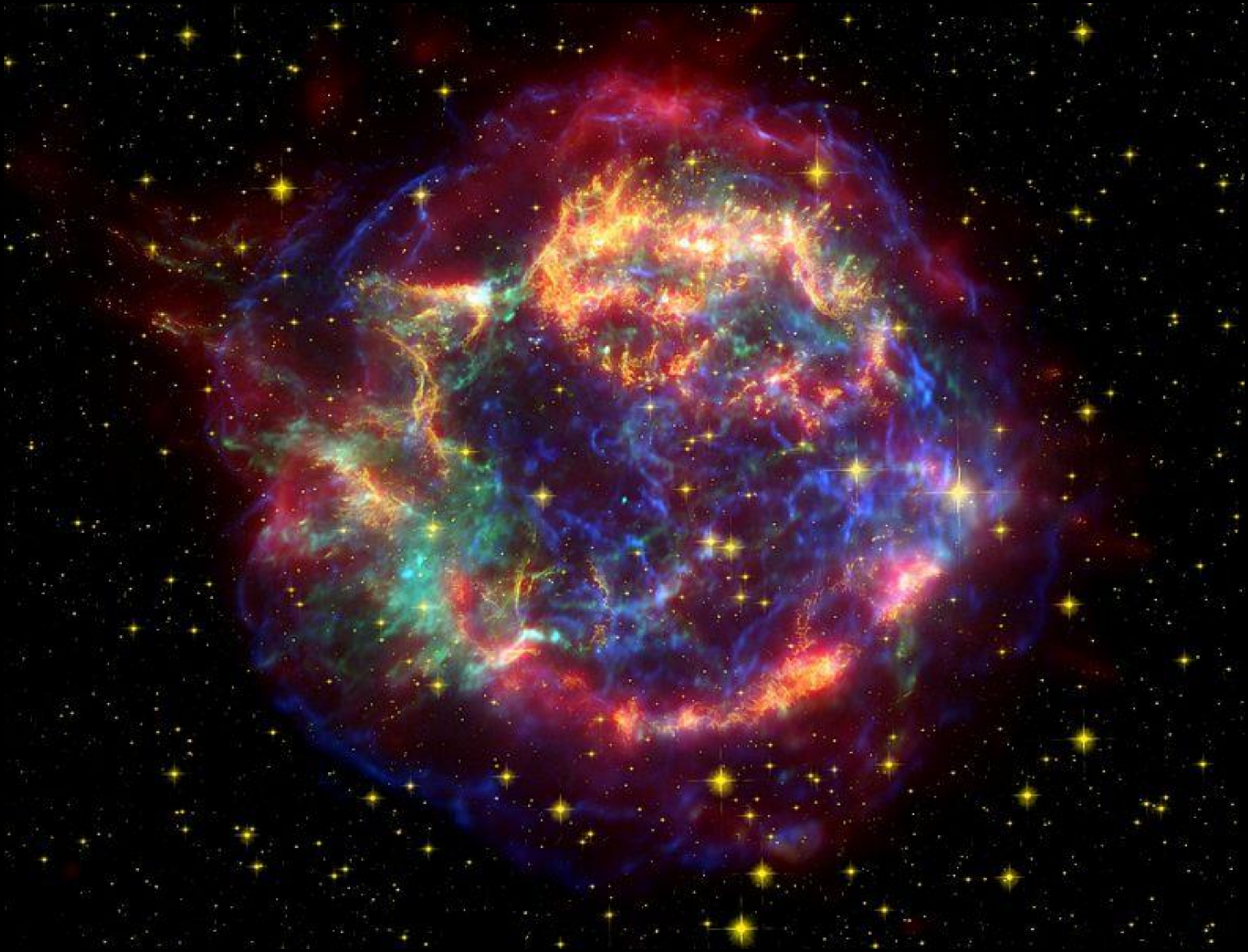
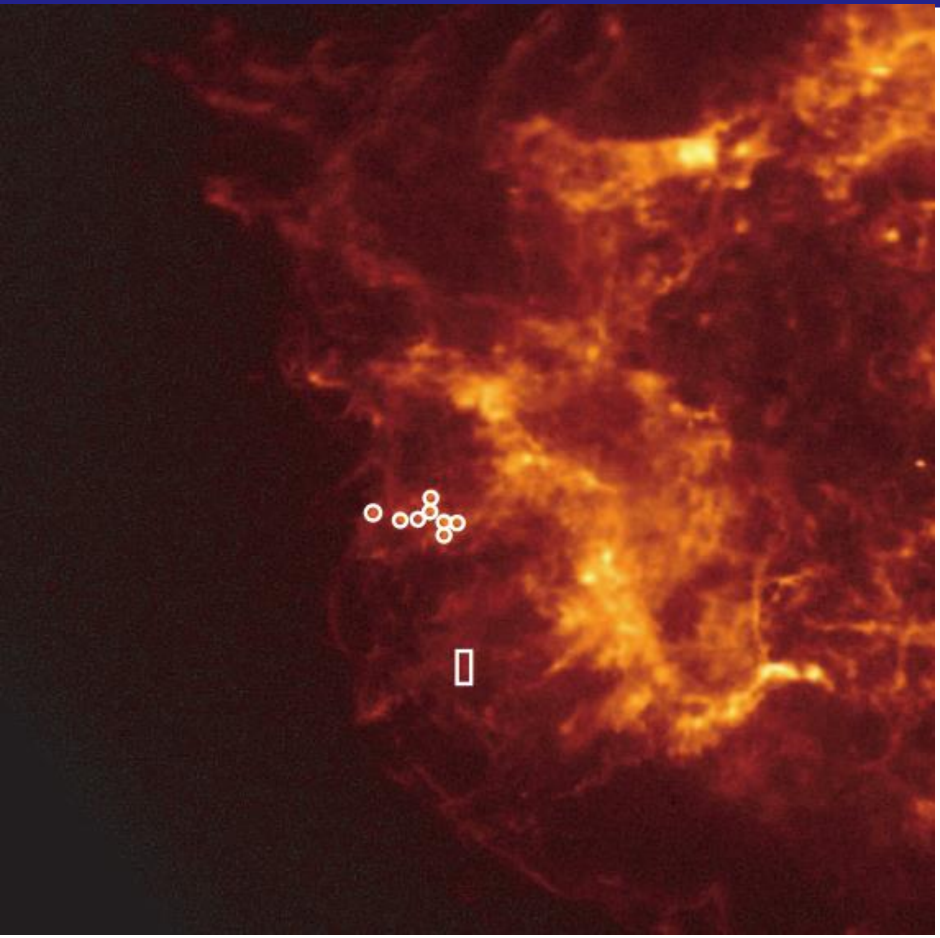
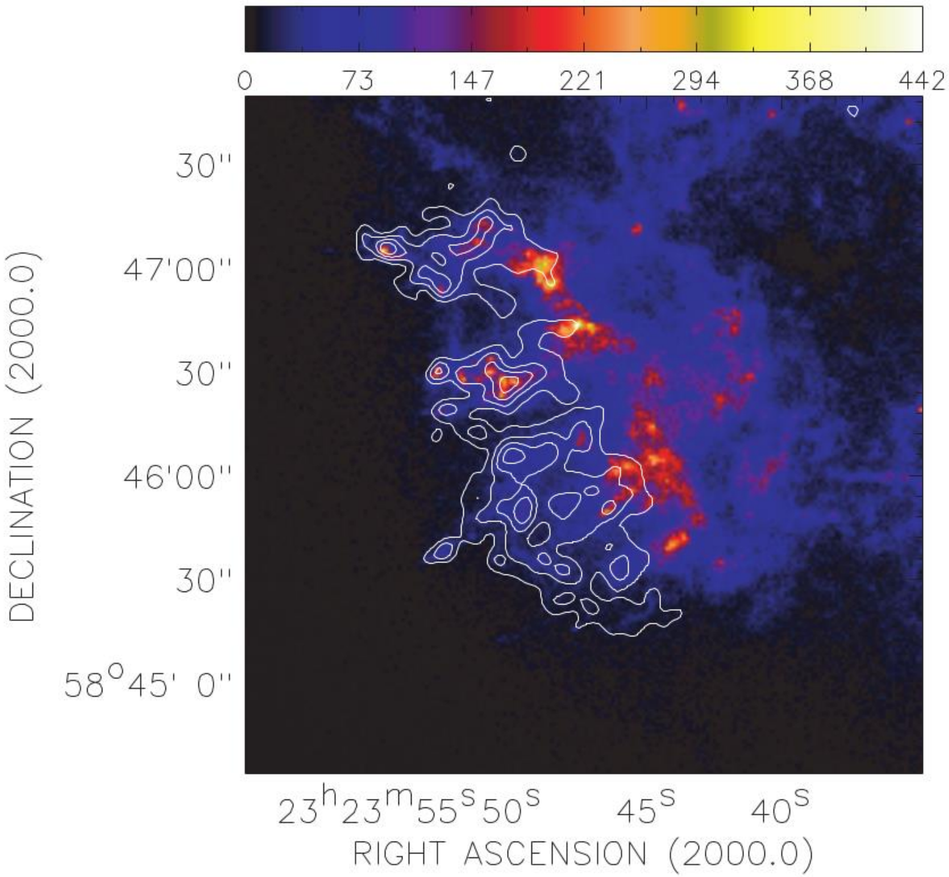
Supernova explosions



X-ray spectrum of Cas A



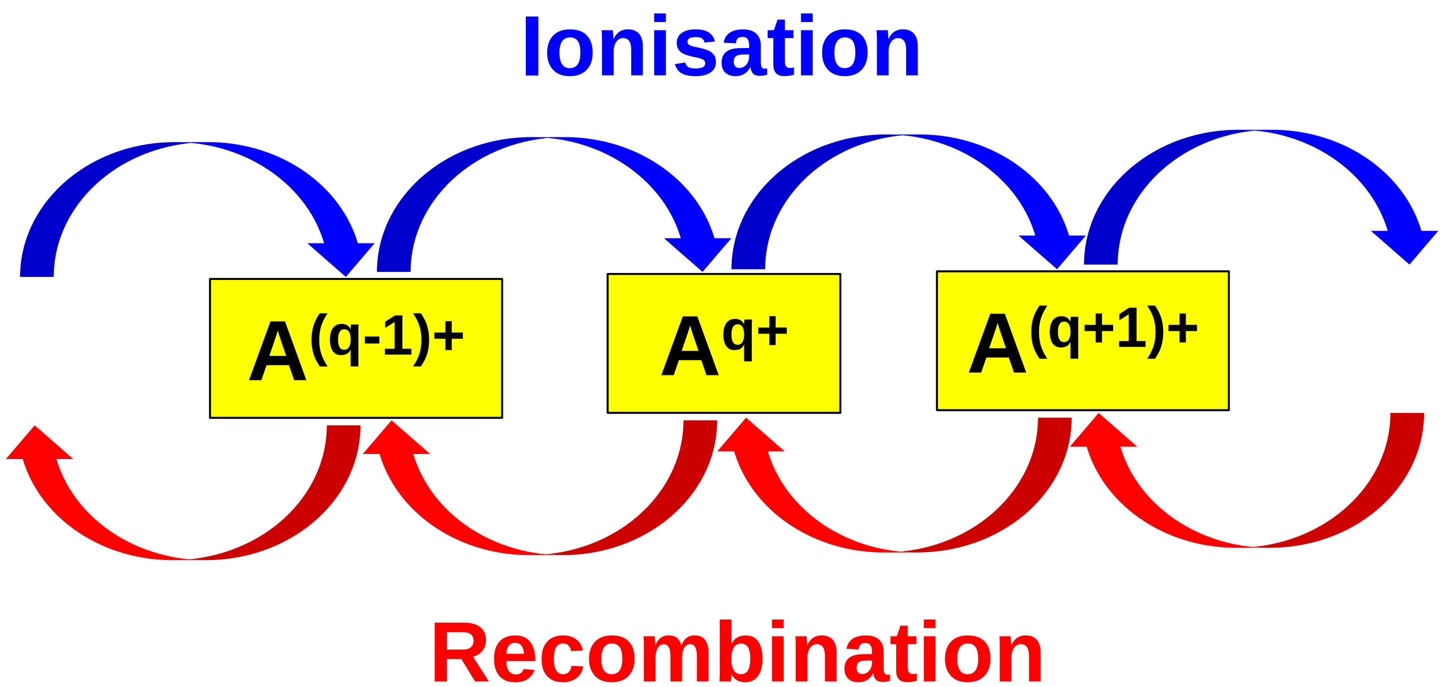


Fe L line active regions and intensity distributions

Hwang and Laming,
ApJ **597** (2003) 362

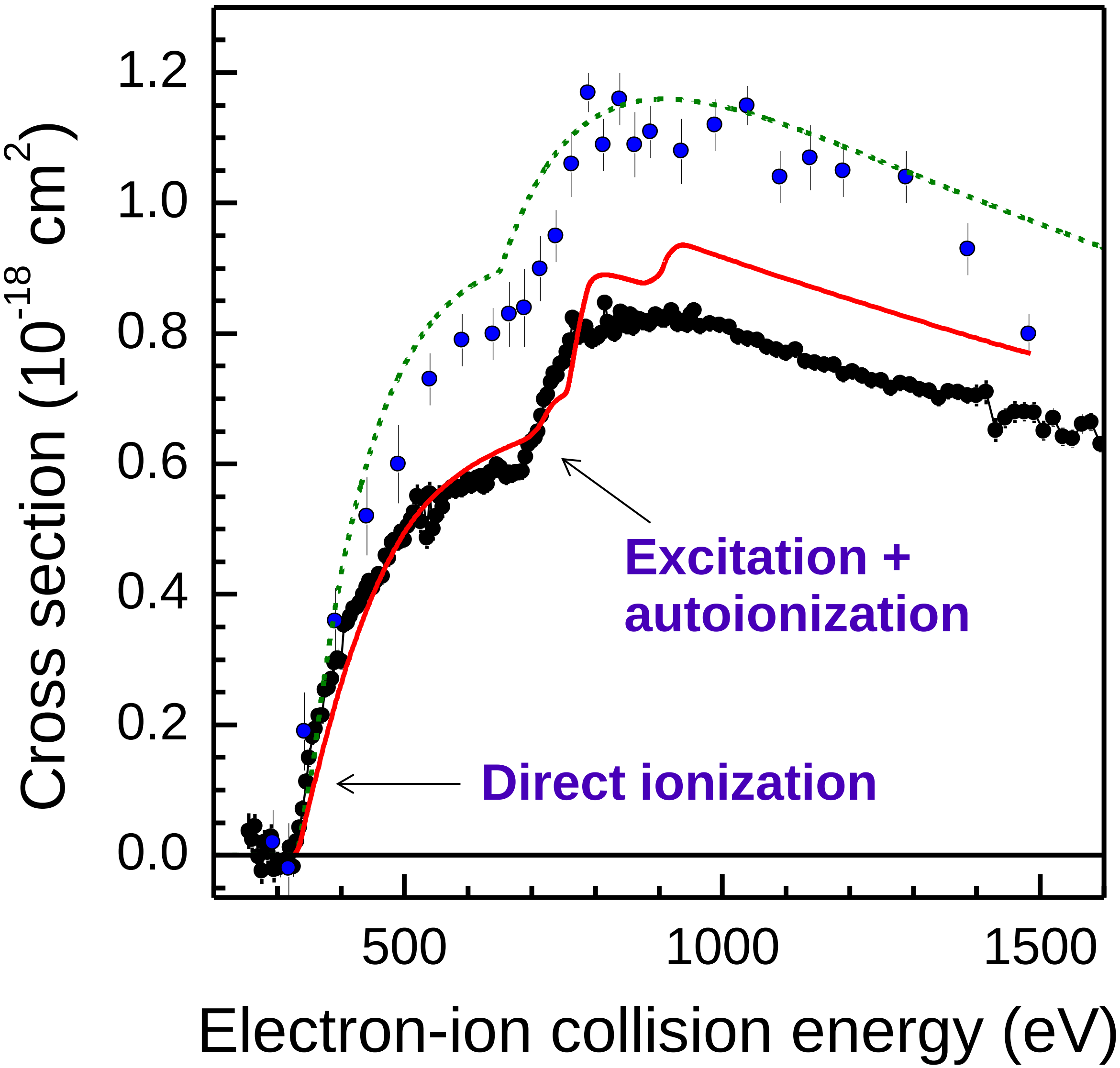
Iron and other elements:
Si, S, Ar, Ca

Ionization balance in a plasma



Rate coefficients needed for:
Electron-impact ionization
Electron-ion recombination

Electron-impact ionization of $Fe^{11+}(3s^2\ 3p^3)$



Experiment:
Gregory et al. (1987)

Recommendation:
Arnaud & Raymond (1992)

Theory:
Pindzola et al. (1986)

Experiment: TSR

False signals from metastable ionic levels

Longest lifetime:
$2s^2\ 2p^3\ ^2D_{5/2}$ **0.5 s**

Beam stored for 3 s before start of measurement:
Metastable fraction < 0.5%

M. Hahn et al., ApJ **729** (2011) 76

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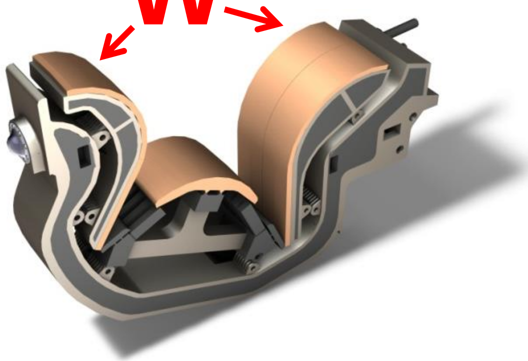
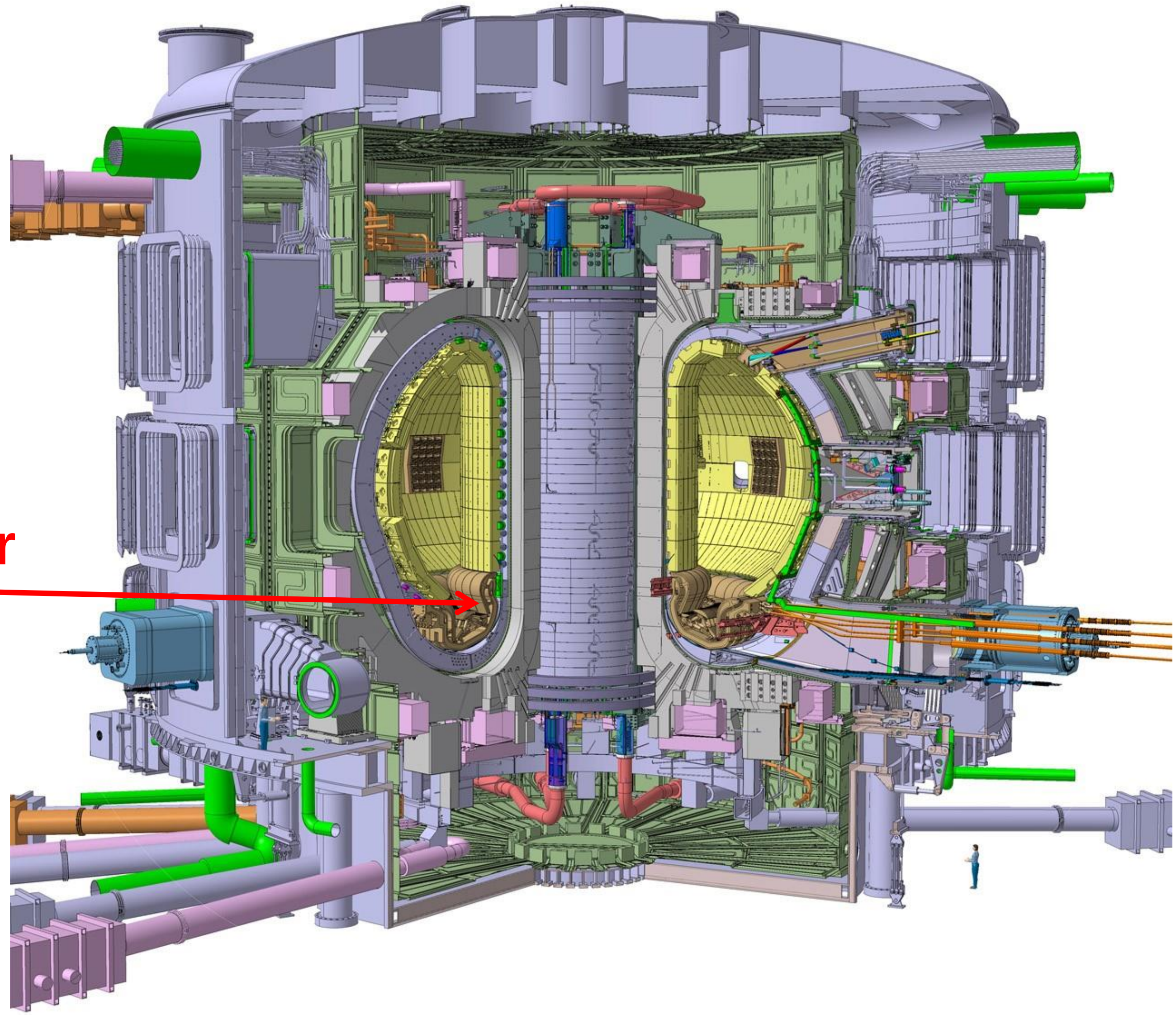
International Thermonuclear Experimental Reactor

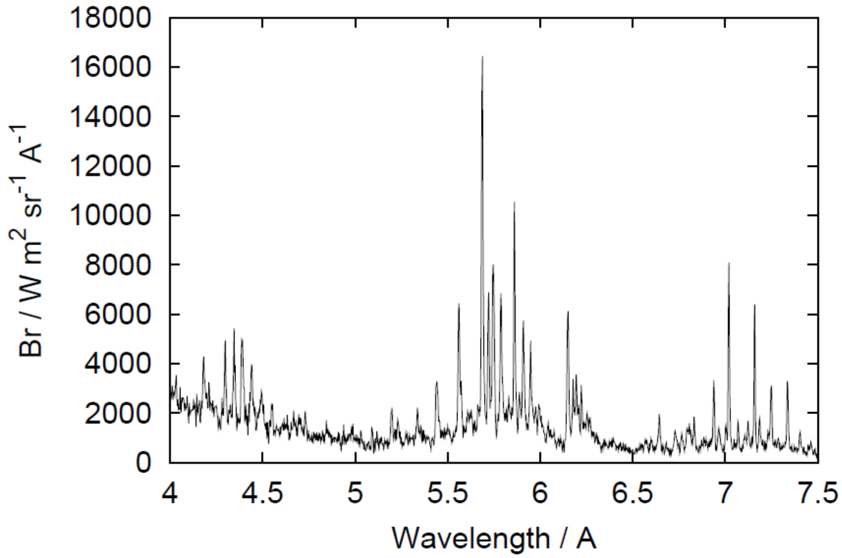
china eu india japan korea russia usa

Site: Cadarache/France
Plasma volume: 840 m^3
Plasma mass: 0.5 g
Energy gain: 10
Output power: 0.5 GW
Price: 13 G€
First plasma: 2019

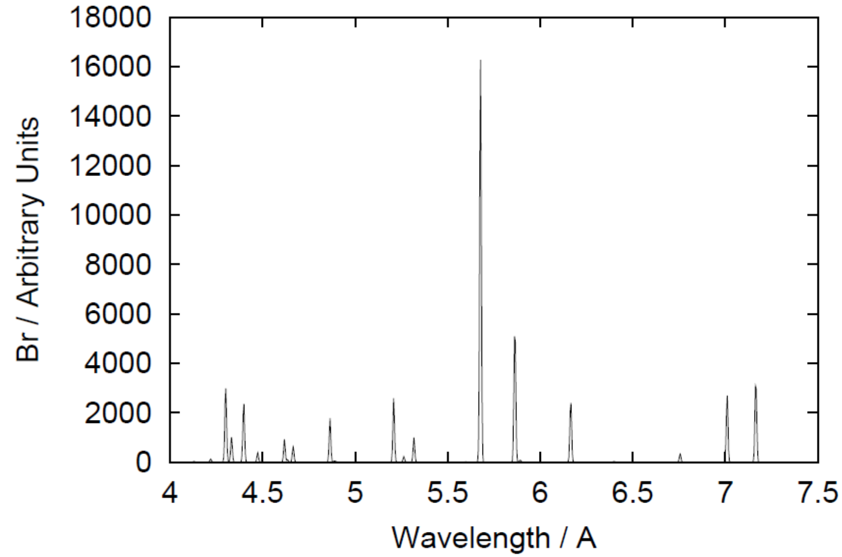




Plasma spectroscopy



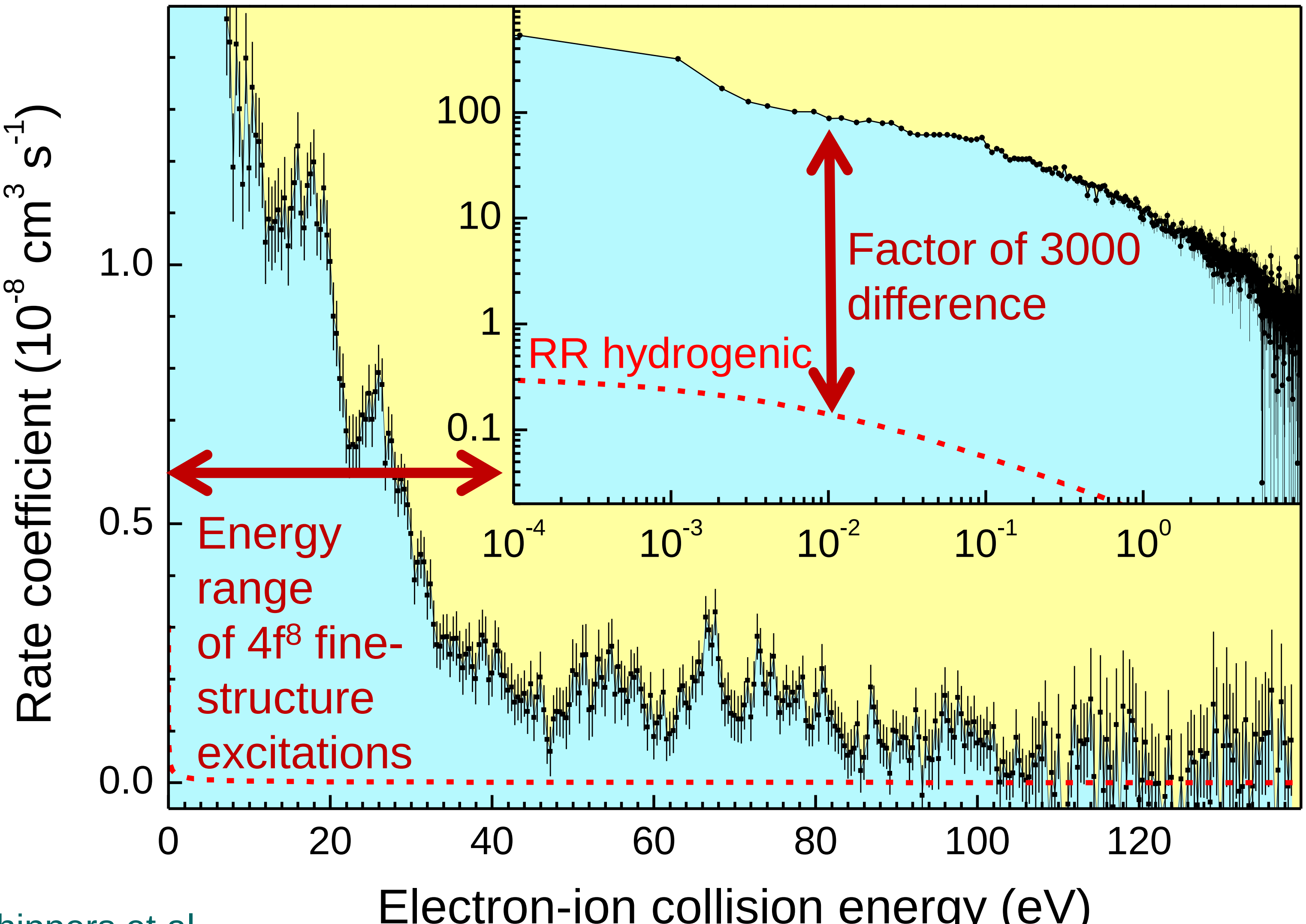
Emission from W^{46+} in ASDEX-U



Model prediction for W^{46+} emission

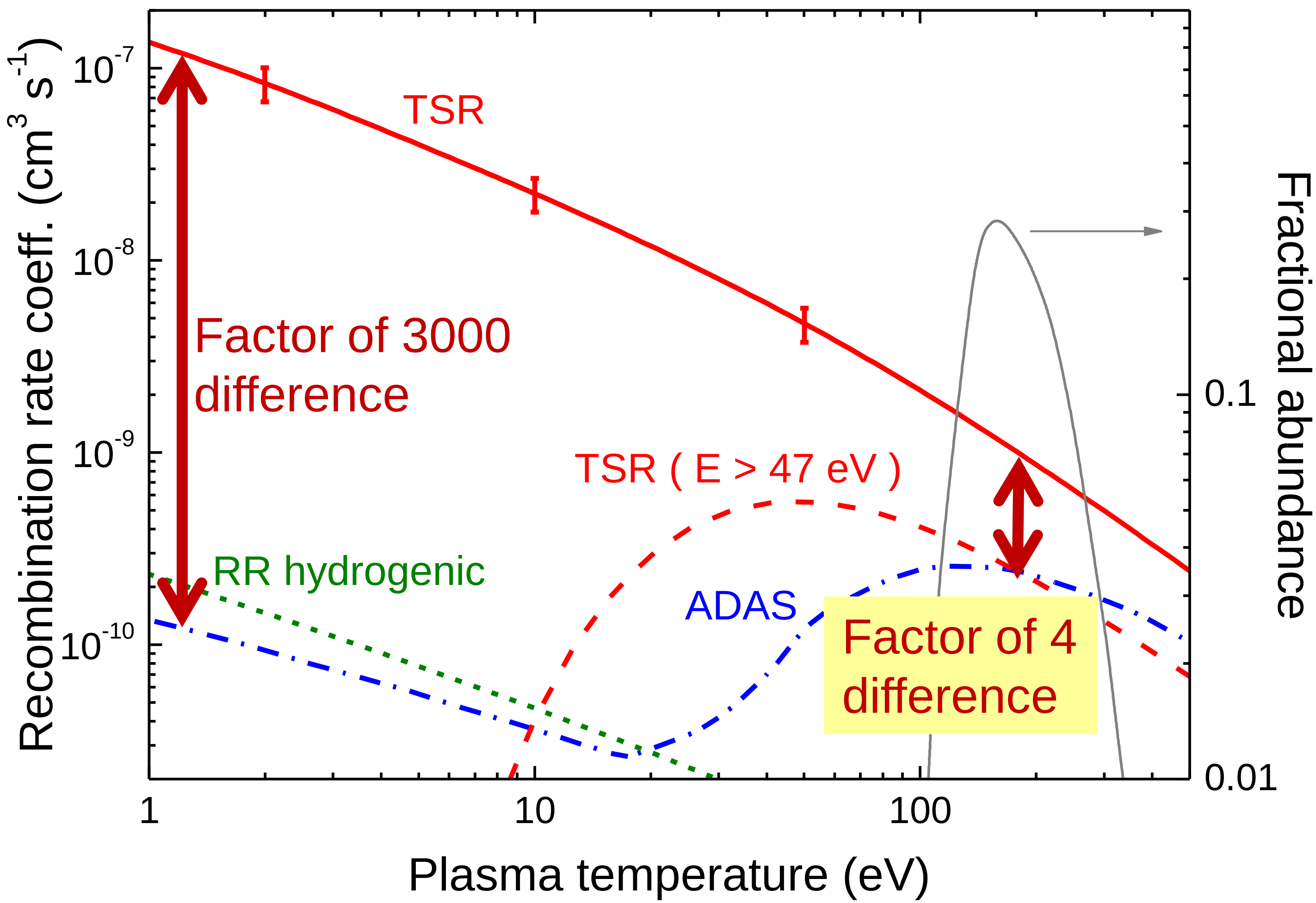
A. Whiteford, PhD Thesis,
University of Strathclyde, UK (2004)

Dielectronic recombination of Xe-like $W^{20+}(4f^8)$



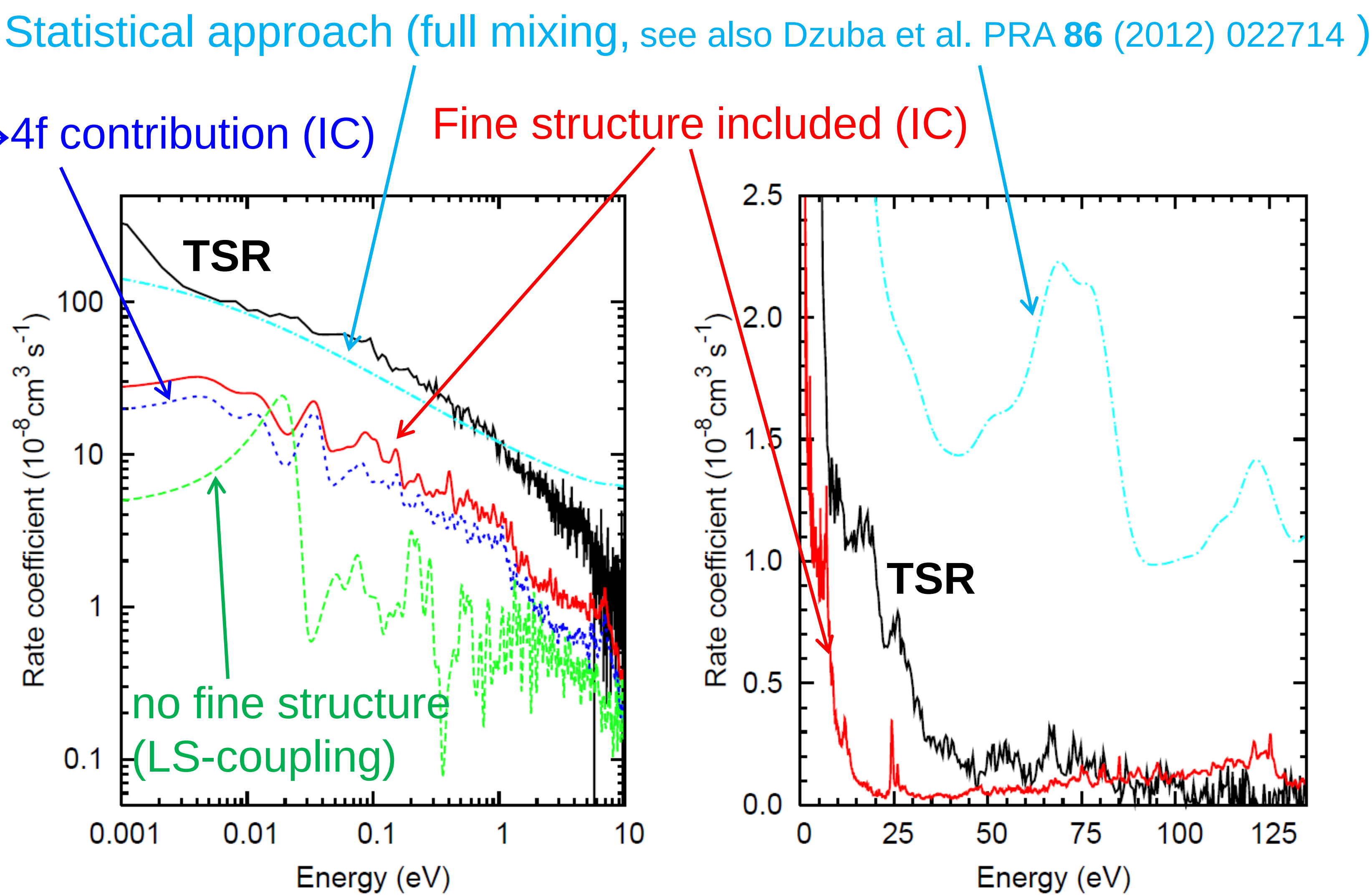
S. Schippers et al.,
PRA **83** (2011) 012711

W^{20+} DR rate coefficient in a plasma



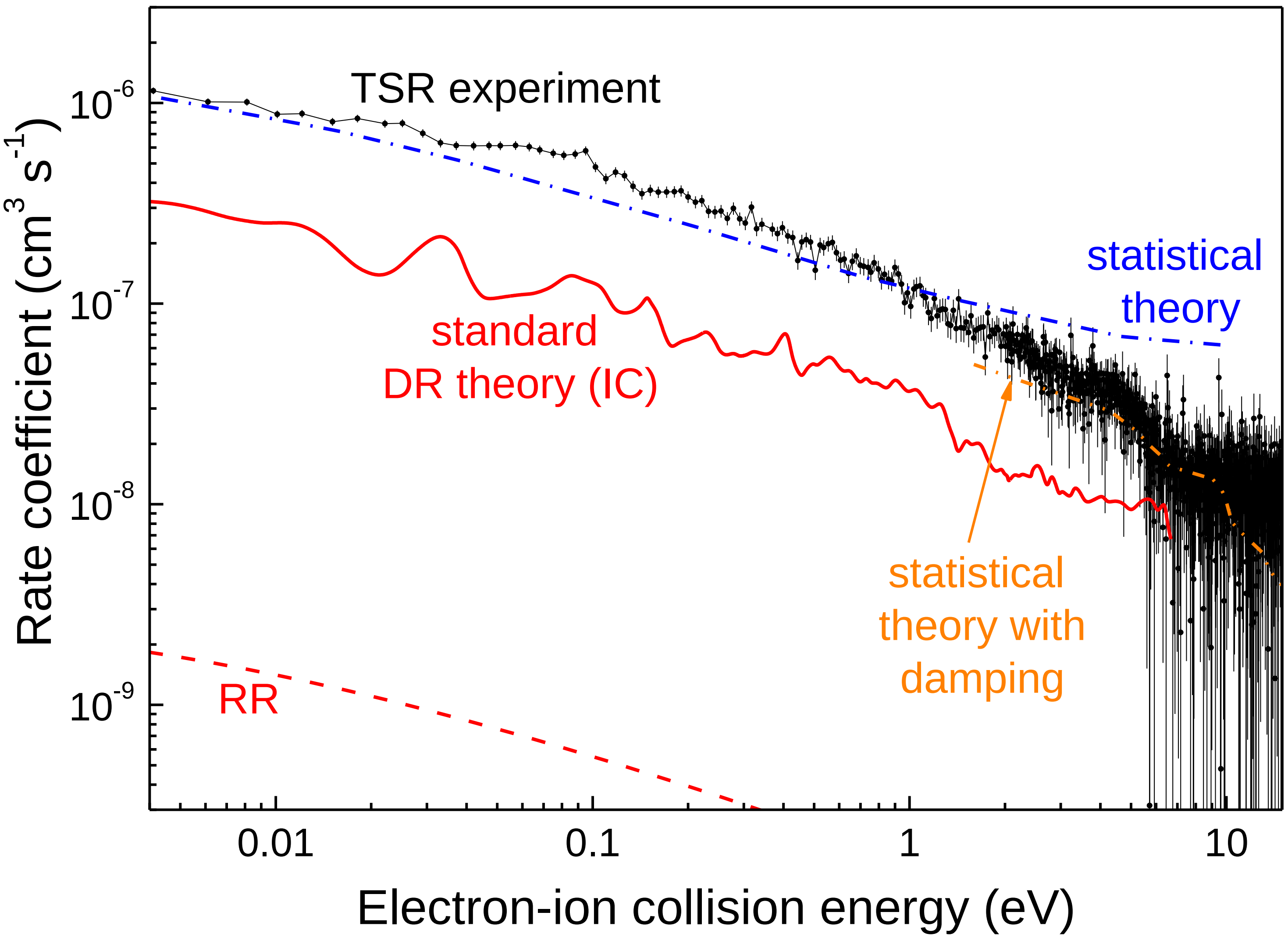
S. Schippers et al., PRA **83** (2011) 012711

New theoretical W^{20+} DR calculations



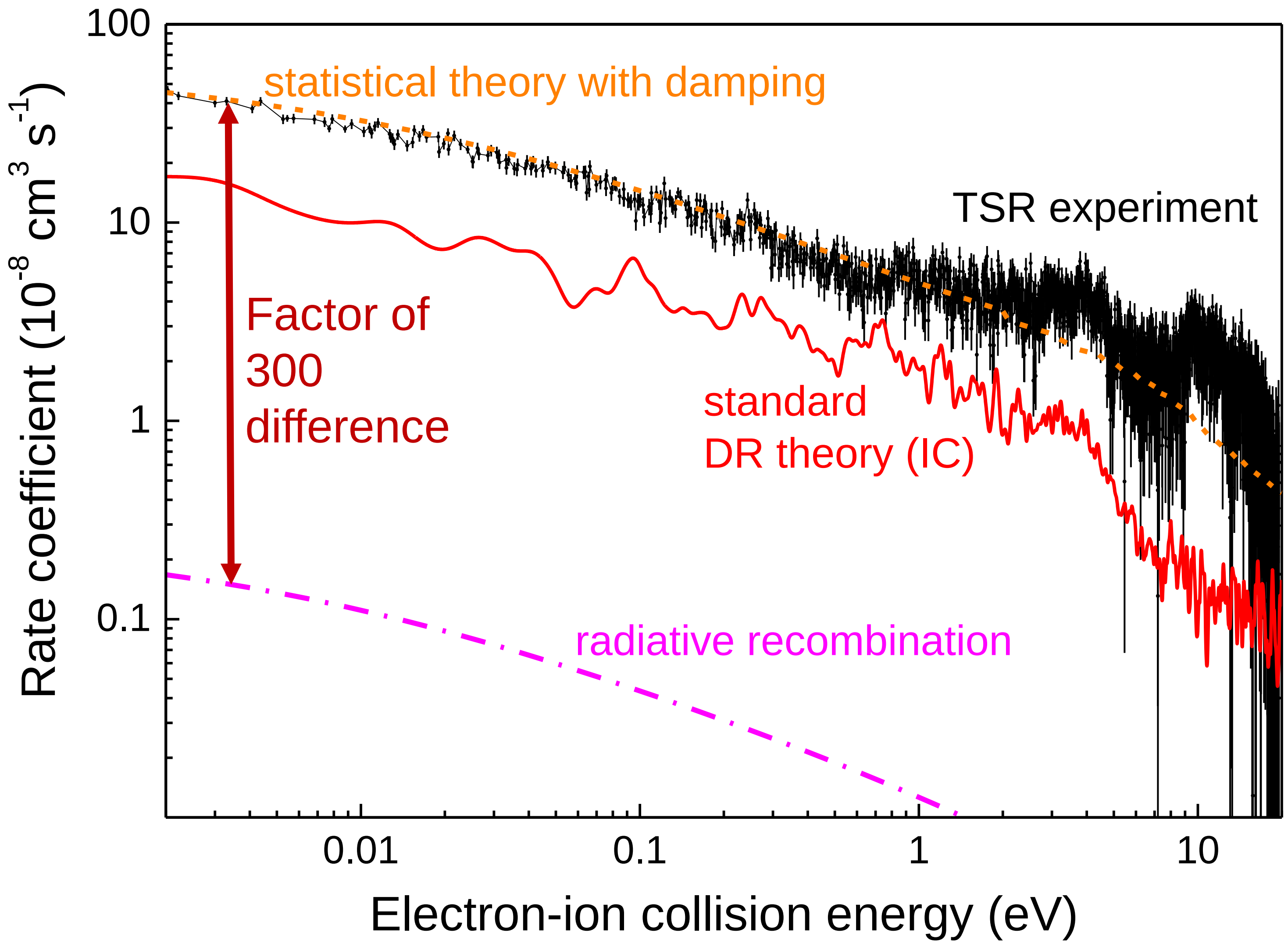
N. R. Badnell, C. P. Ballance, D. C. Griffin, M. O'Mullane, PRA **85** (2012) 052716

New theoretical W^{20+} DR calculations II



statistical theory with damping: V. A. Dzuba, PRA **88** (2013) 062713

Recombination of $W^{18+}(4d^{10}\ 4f^{10})$



K. Spruck, N. R. Badnell et al., PRA **90** (2014) 032715

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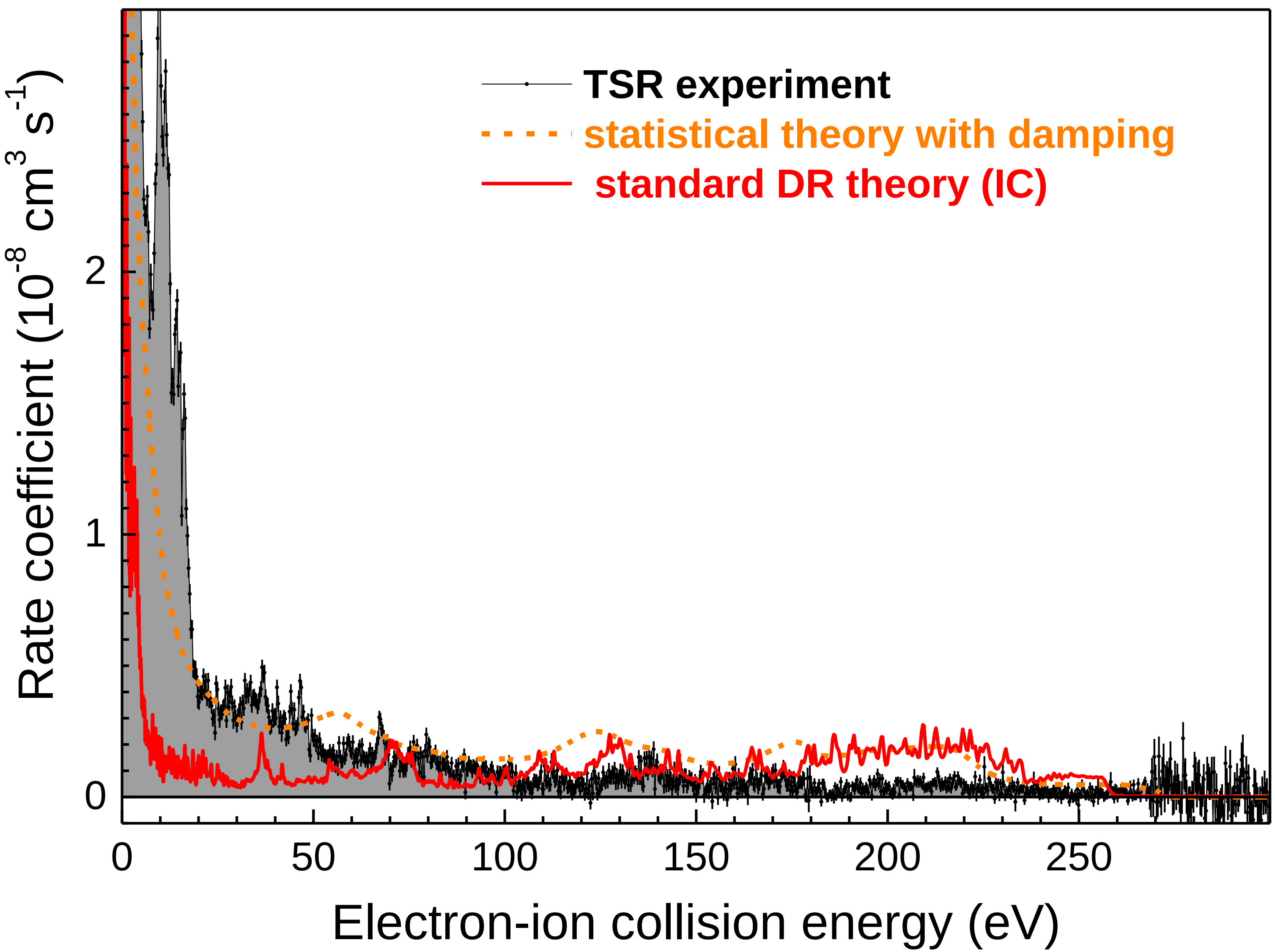

K. Spruck, N. R. Badnell et al., PRA **90** (2014) 032715

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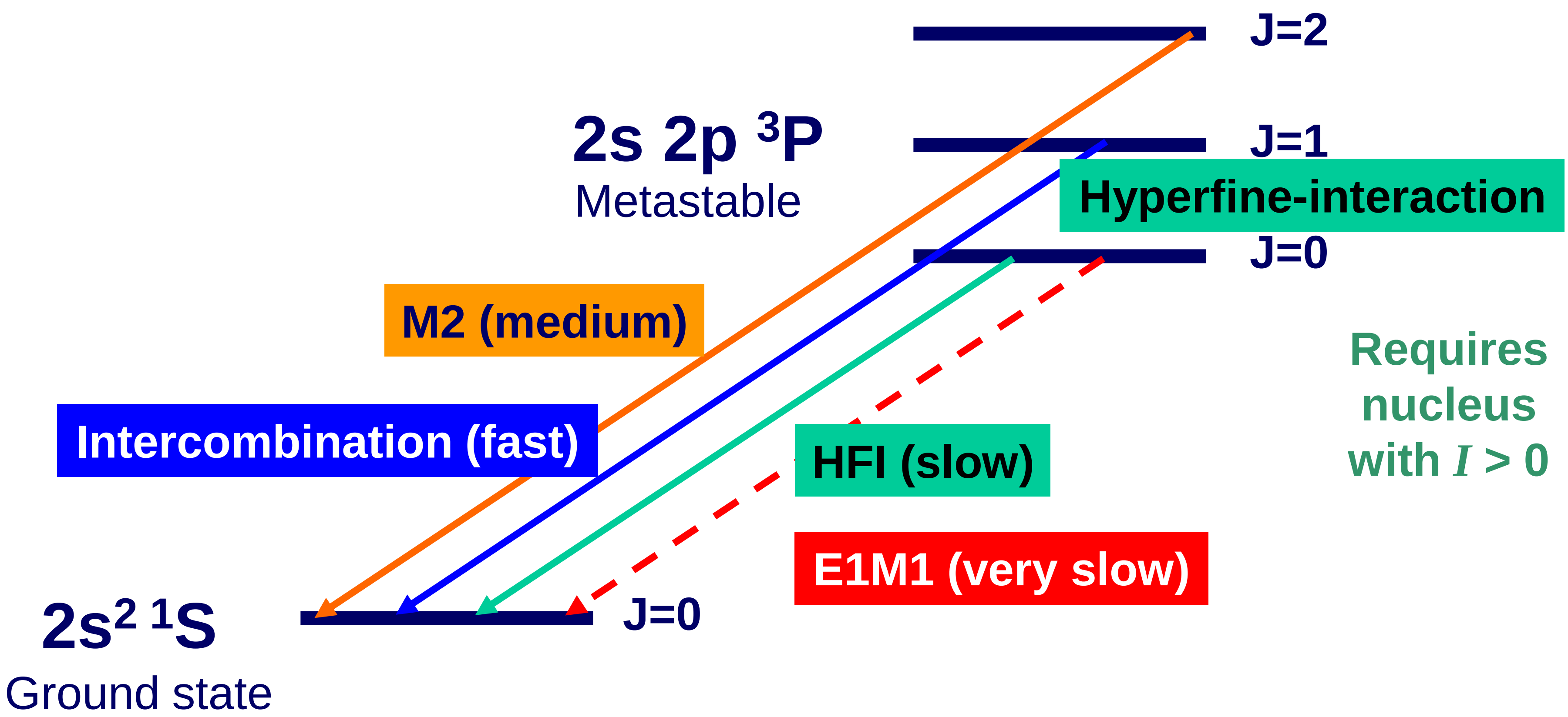
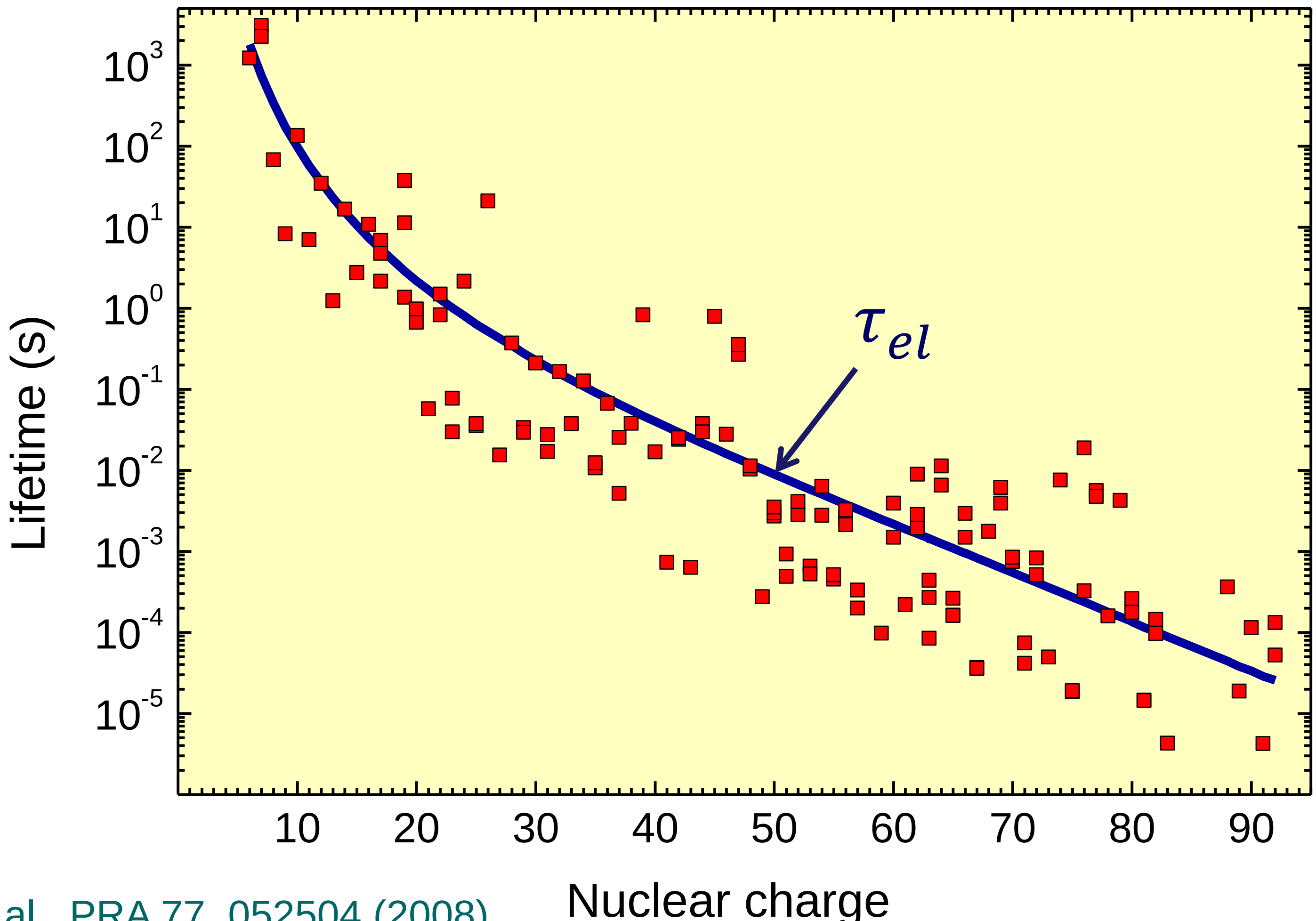
2s2p ^{3}P – 2s^2 ^{1}S transitions in Be-like ions



Theoretical predictions of 2s2p $^3P_0$ lifetimes

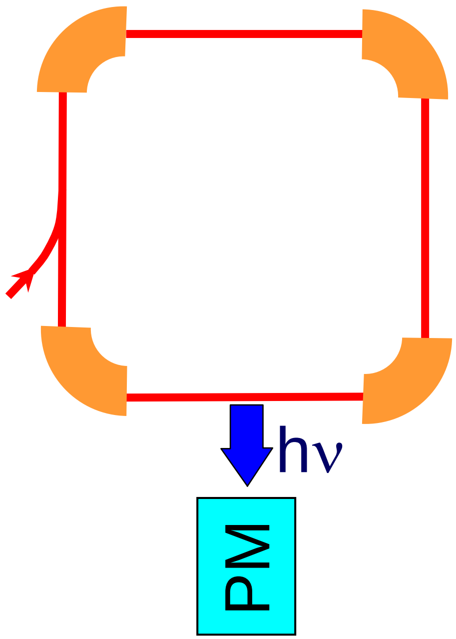
$$\frac{1}{\tau_{HFI}} \approx \mu^2 \left(1 + \frac{1}{I}\right) \frac{1}{\tau_{el}}$$



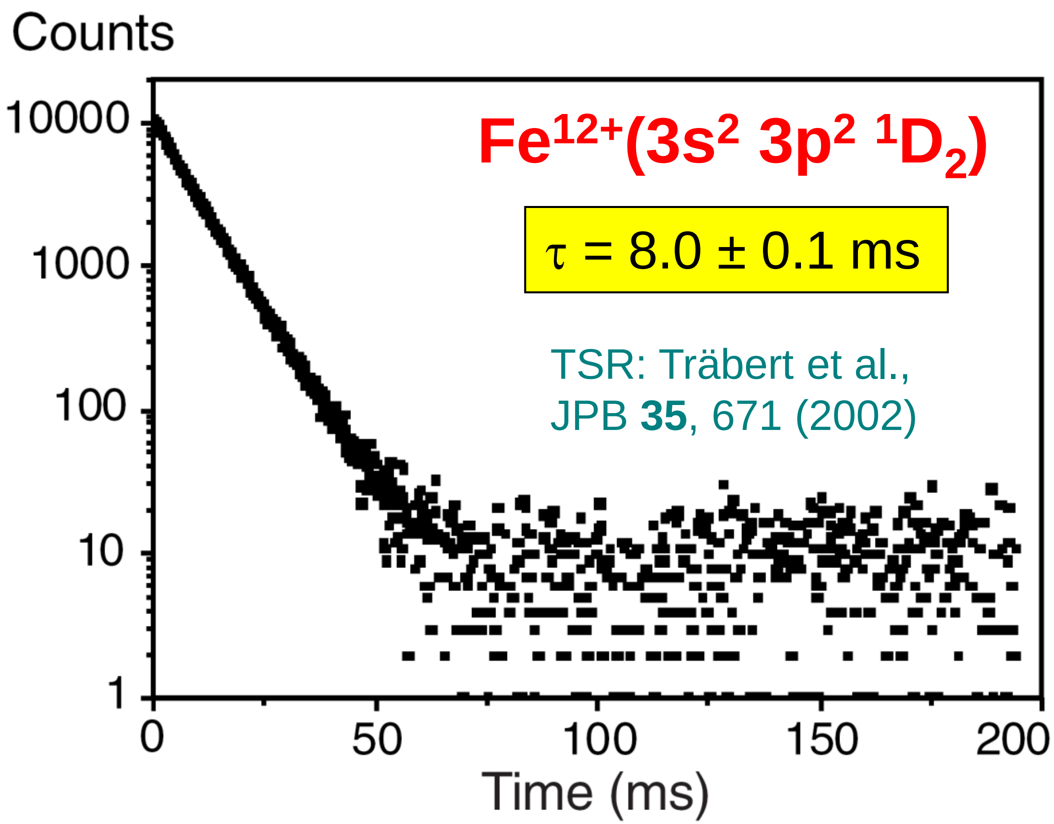
Cheng et al., PRA 77, 052504 (2008)

Detection of photons from excited state

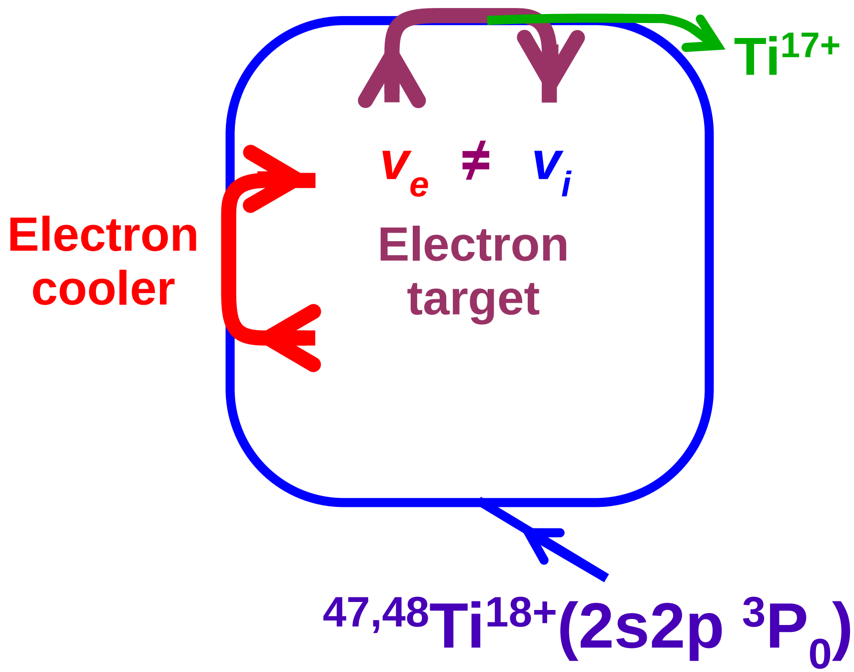
Injection of ions in metastable states



Most photons miss the detector!

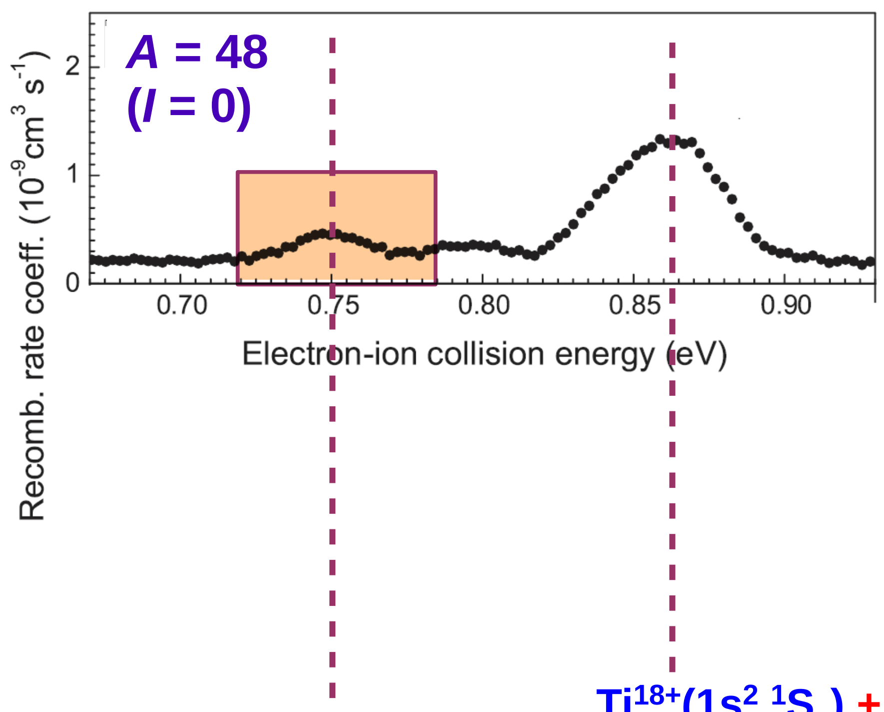


Detection of metastables by resonant recombination



DR rate at electron target

Time average over ~50 s beam lifetime



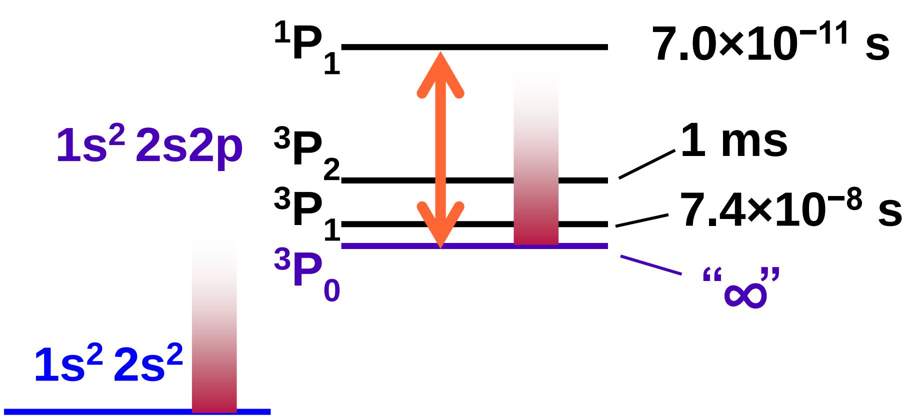
Ti^{18+}(2s2p $^3P_0$) + e →

{ Ti^{17+}([2s2p $^3P_2$] 26ℓ)

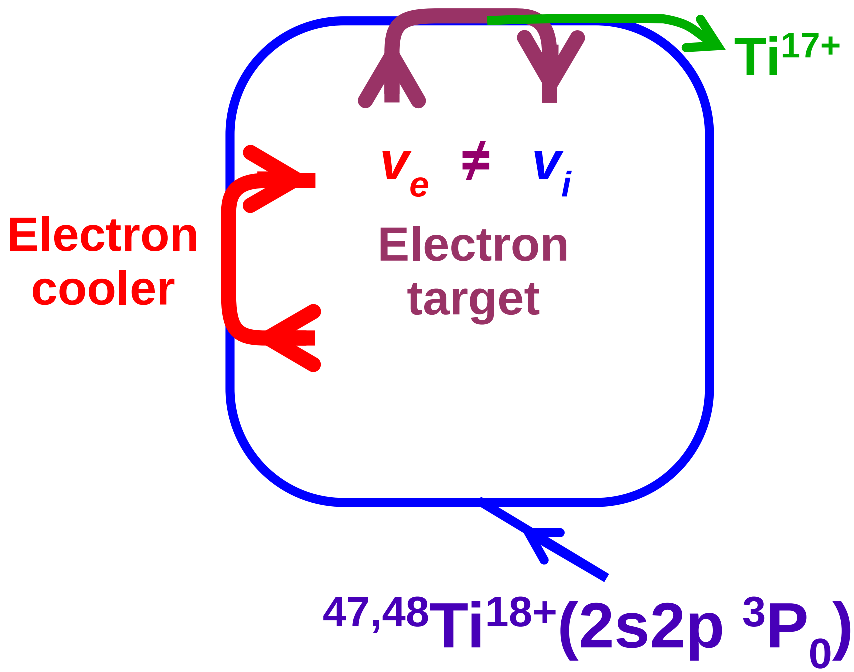
Ti^{17+}([2s2p $^1P_1$] 11d) }

Ti^{18+}(1s^2 $^1S_0$) + e →

Ti^{17+}([2s2p $^3P_1$] 11p)



Detection of metastables by resonant recombination



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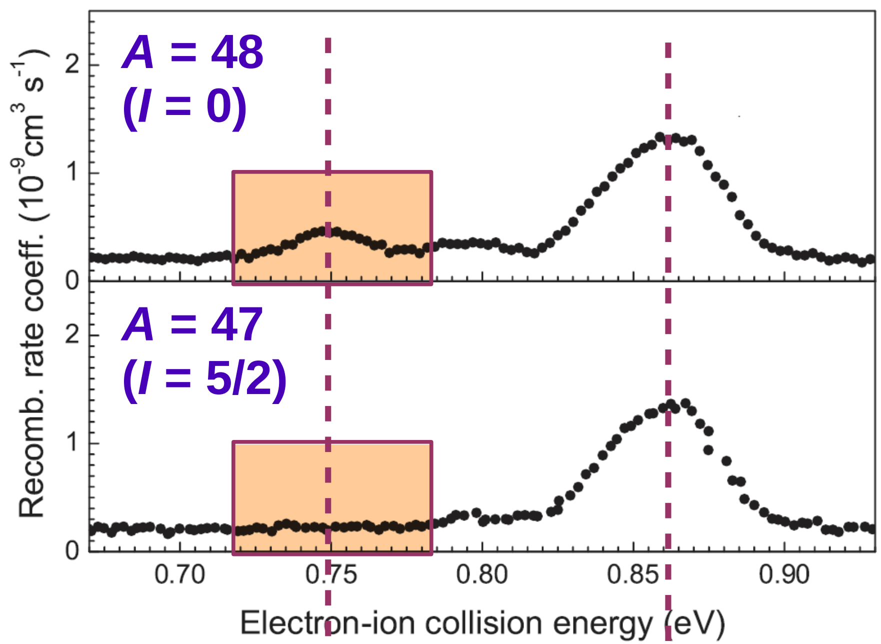
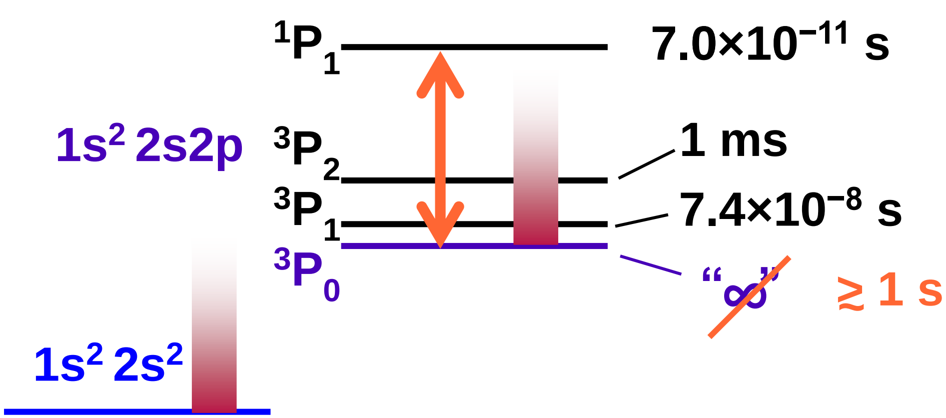
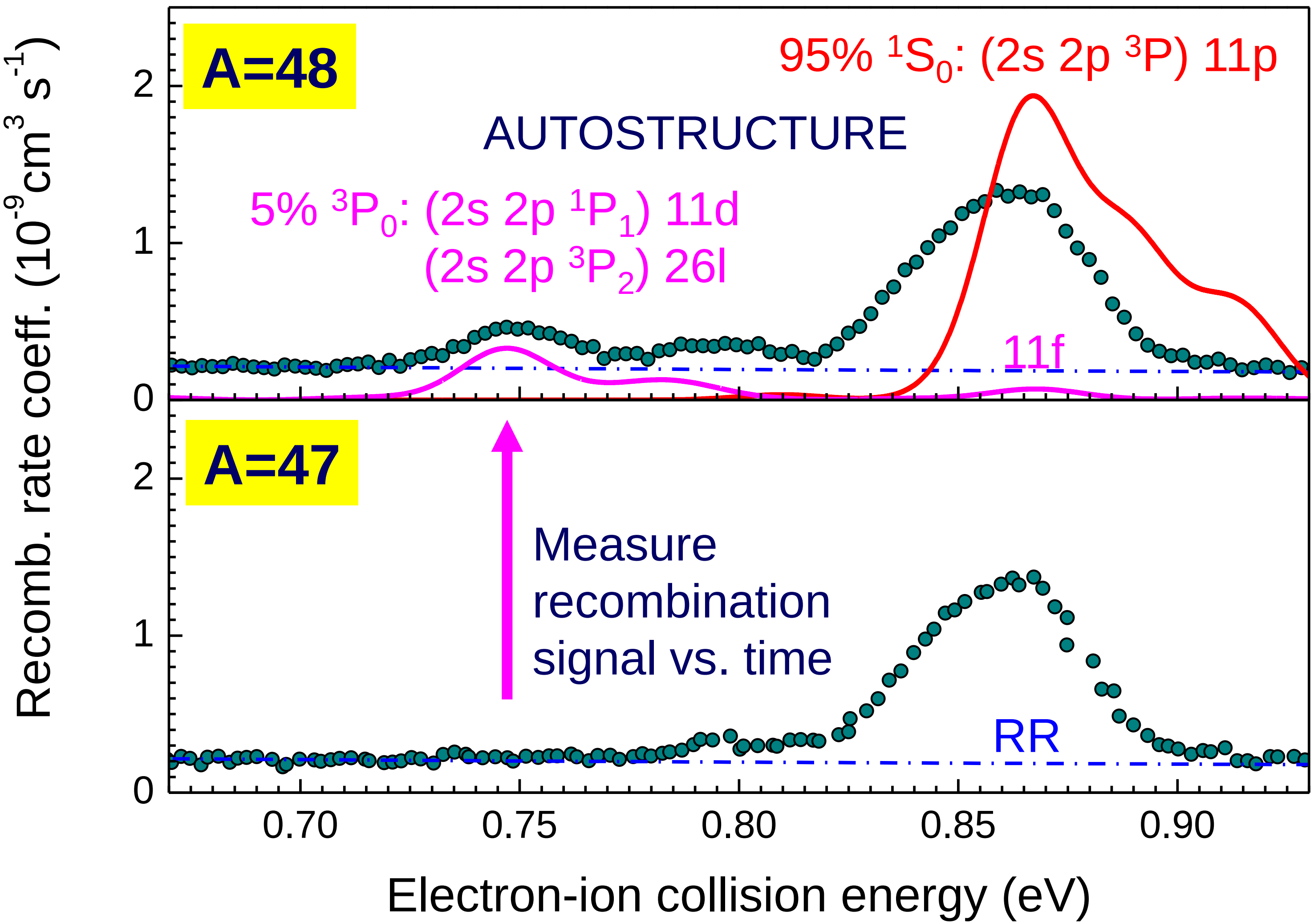


$Ti^{18+}(2s2p\ ^3P_0) + e \rightarrow$
{ $Ti^{17+}([2s2p\ ^3P_2]\ 26\ell)$
$Ti^{17+}([2s2p\ ^1P_1]\ 11d)$ }

$Ti^{18+}(1s^2\ ^1S_0) + e \rightarrow$
$Ti^{17+}([2s2p\ ^3P_1]\ 11p)$

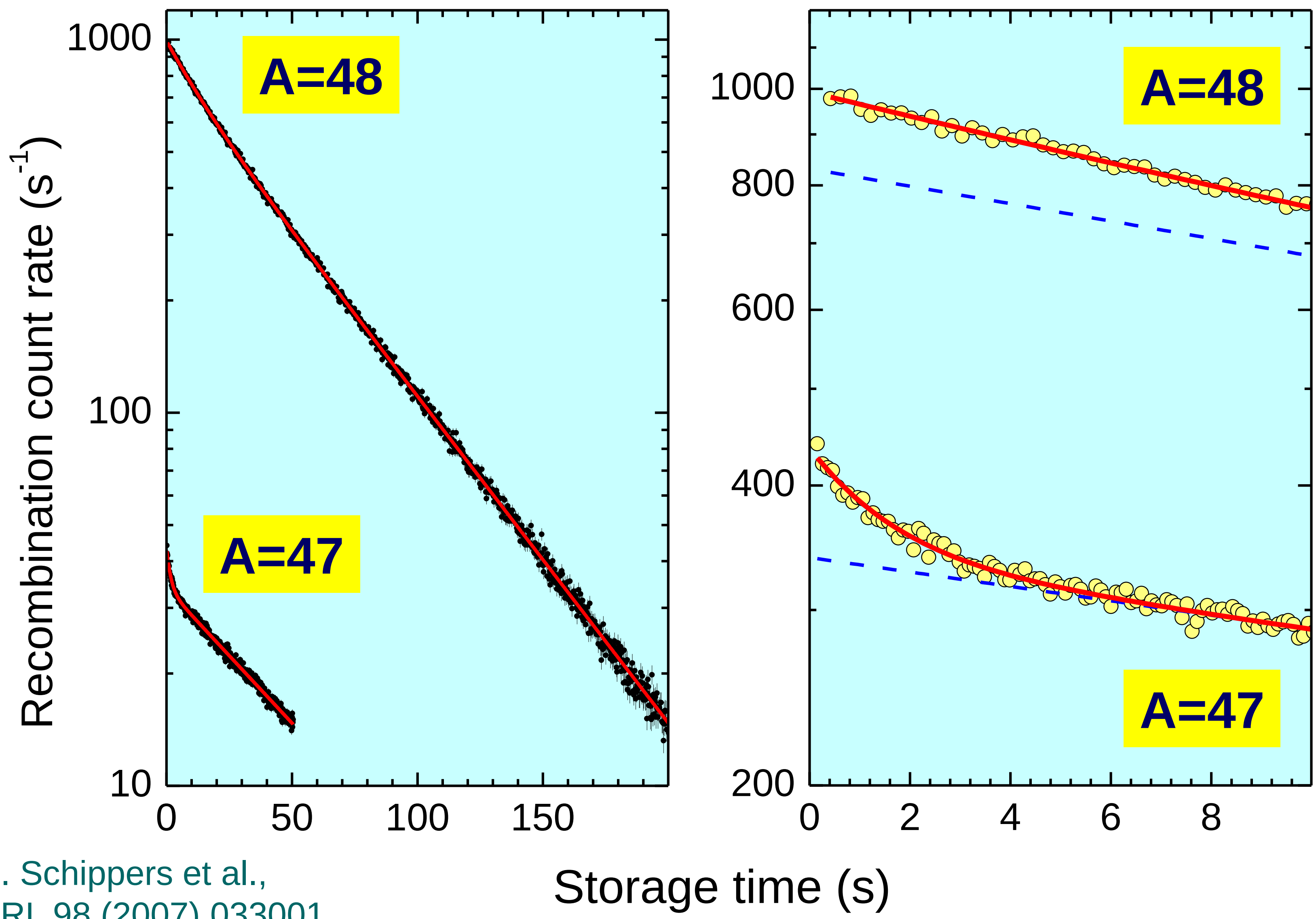


Ti^{18+} DR spectrum at low energies



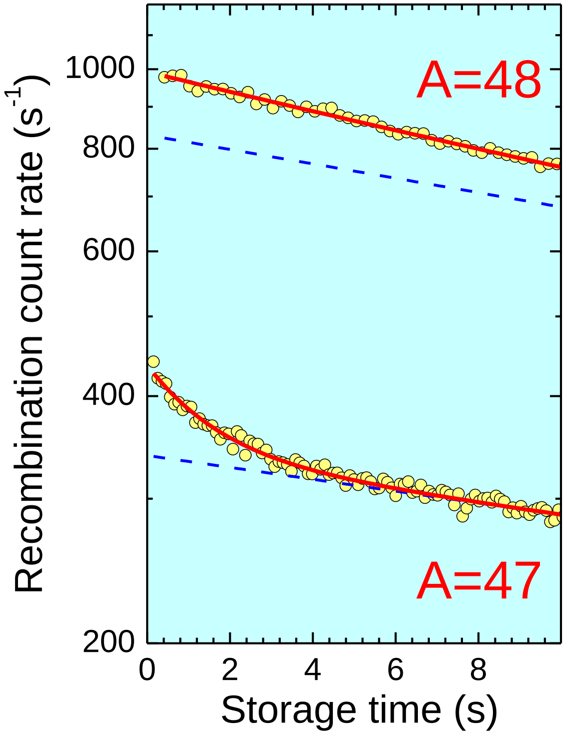
S. Schippers et al., JPCS 58 (2007) 137

Recombination signal at 0.75 eV vs. time



S. Schippers et al.,
PRL 98 (2007) 033001

Data analysis



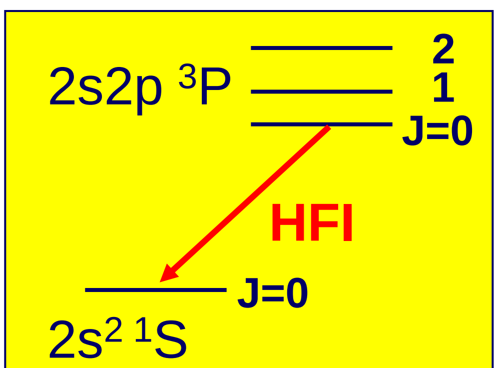
Essential feature of the method:
Usage of two isotopes

Fit: $F^{(A)}(t) = c_m^{(A)} e^{-\lambda_m^{(A)} t} + c_g^{(A)} e^{-\lambda_g^{(A)} t}$

m = $^3P_0$
g = $^1S_0$

isotope	$\lambda_m^{(A)}$ (s^{-1})	$\lambda_g^{(A)}$ (s^{-1})	$c_m^{(A)}$ (s^{-1})	$c_g^{(A)}$ (s^{-1})
$A = 48$	0.070(2)	0.0202(5)	161(35)	831(48)
$A = 47$	0.62(3)	0.01665(6)	9.8(3)	33.86(6)

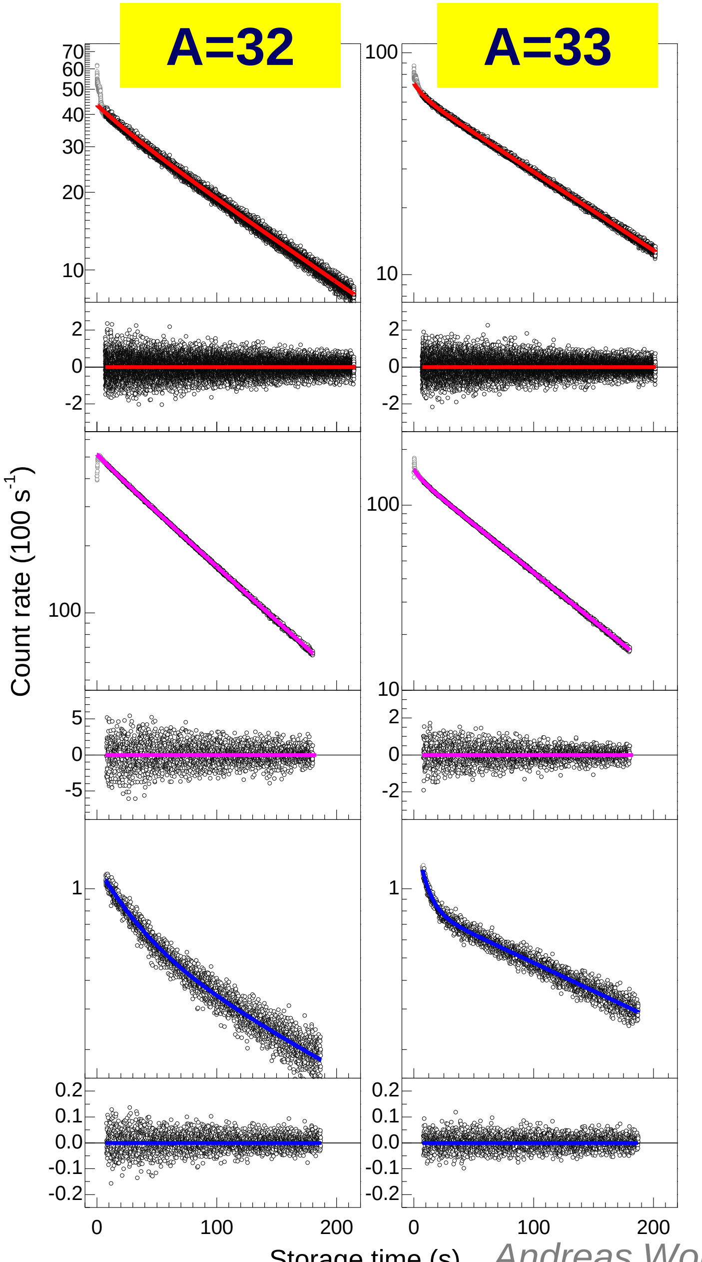
Largest contribution to the experimental uncertainty



$$A_{\mathrm{HFI}} = \gamma^{(47)}[\lambda_m^{(47)} - \lambda_g^{(47)} - \lambda_m^{(48)} + \lambda_g^{(48)}]$$

$^{47}Ti^{18+}$: A_{HFI} = 0.56(3) s^{-1}

New measurements with Be-like $^{A}S^{12+}$ ions



B = 0.44 T

τ_{HFI} = 10.5(7) s

S^{12+} hyperfine-limited lifetime

Theory:	**27.69 s**	Marques et al. (1993)
Theory:	**10.73 s**	Cheng et al. (2008)
Theory:	**10.69 s**	Andersson et al. (2009)
Experiment:	**10.4(5) s**	TSR (2011)

B = 0.88 T

τ_{HFI} = 10.2(7) s

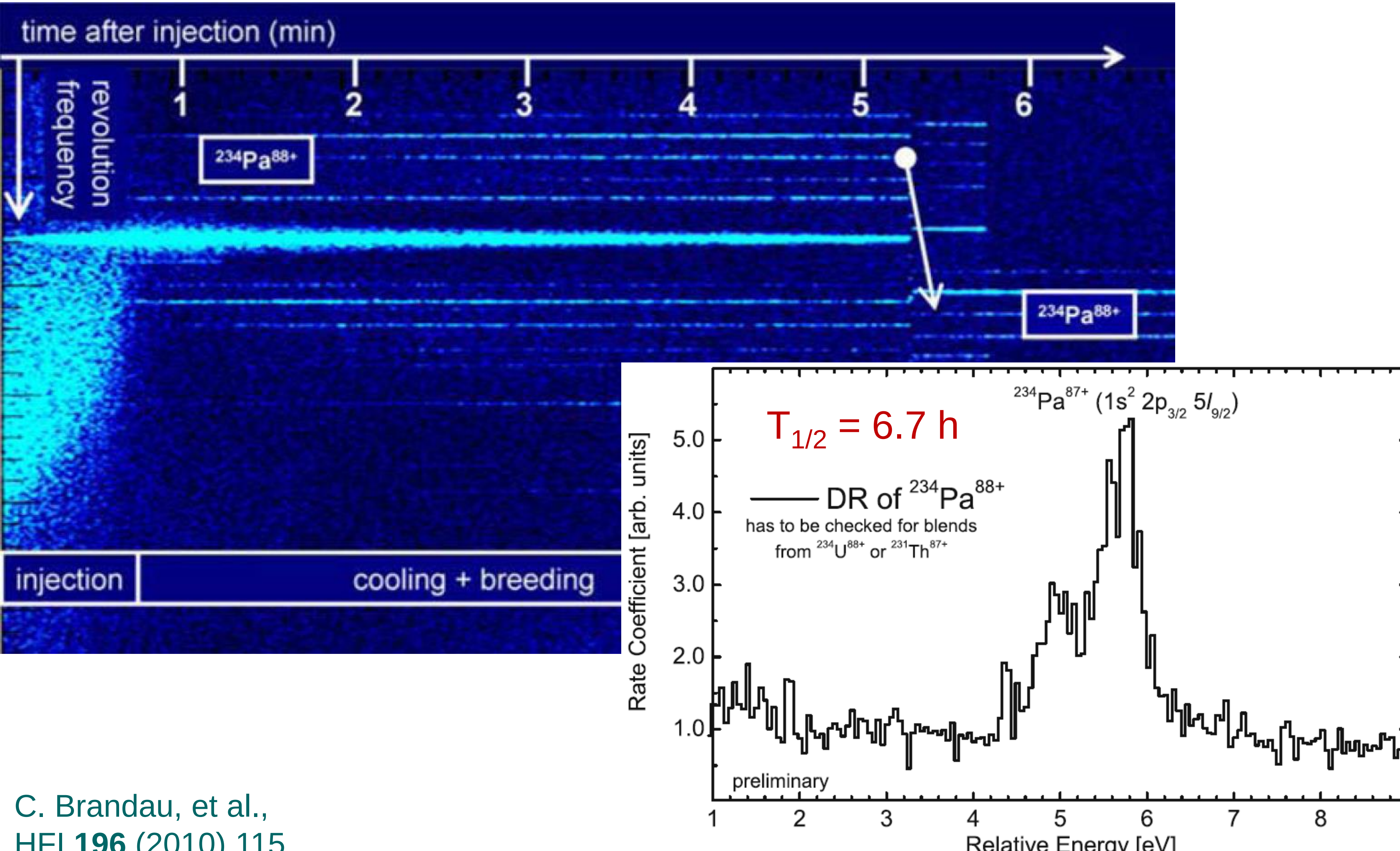
S. Schippers et al., PRA 85 (2012) 012513

Some uncertain nuclear moments

	Z	A	$t_{1/2}$	μ / μ_n	$\Delta\mu / \mu$
S	16	35	87.4 d	1.00	4%
Ni	28	65	2.52 d	0.69	9%
Cu	29	70	44.5 s	1.60	44%
As	33	69	15.2 min	1.58	10%
Br	35	72	79 s	0.60	17%
Br	35	74	46 min	1.68	11%
Br	35	75	97 min	0.76	24%

Values from N. J. Stone, ADNDT **80** (2005) 17

Electron-ion recombination with in-flight produced nuclei



C. Brandau, et al.,
HFI **196** (2010) 115

Summary

- **Atomic data for astrophysics**
  - Uncertainties of electron-impact ionization (EII) data limit understanding of supernova explosions
  - TSR@ISOLDE: cross sections for EII of Si & Fe & … ions

- **Atomic data for fusion energy research**
  - Recombination of tungsten ions with complex electronic structure
  - TSR@ISOLDE: Recombination rate coefficients for more highly-charged tungsten ions from (upgraded) charge breeder

- **Hyperfine induced (HFI) transitions**
  - First laboratory measurements of HFI transitions in Be-like ions
  - TSR@ISOLDE: Determination of nuclear magnetic moments

Current TSR collaborators & Funding

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MAX-PLANCK-GESELLSCHAFT

DFG

NASA