Analog and Digital Simulations of Maxwellian Plasmas for Astrophysics

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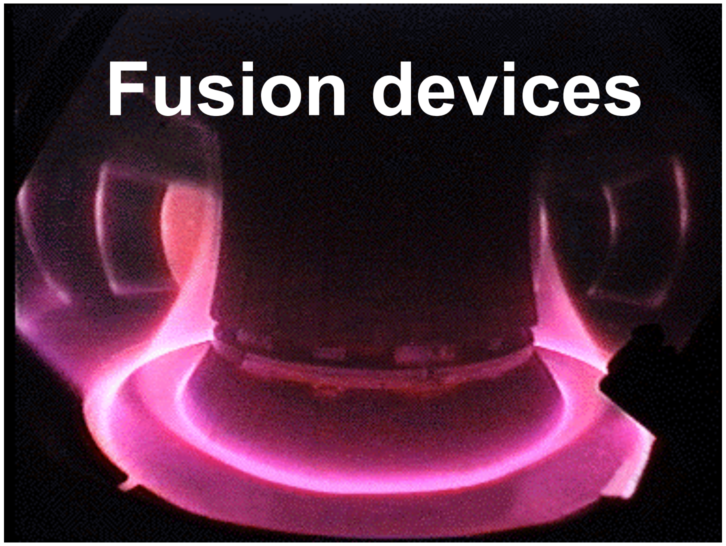
Outline

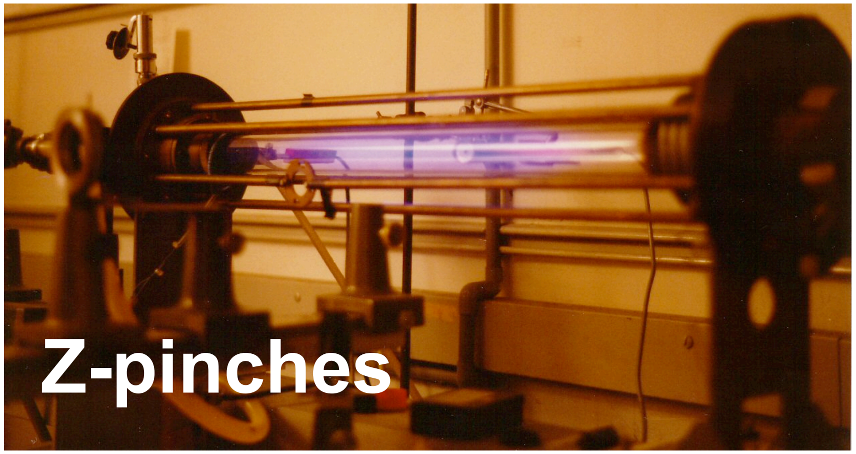
I. Maxwell-Boltzmann (MB) plasmas
II. Simulating MB plasmas in EBIT
III. Testing the simulations
IV. Collisional Ionization Equilibrium (CIE)
V. New CIE results
VI. Future needs

Plasmas with Maxwell-Boltzman (MB) electron distributions are ubiquitous.


Sun, stars,…

Yohkoh SXT 14:49 UT, June 7, 2000


Fusion devices


Z-pinches


Laser plasmas

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Interpreting or predicting the properties of MB plasmas is challenging.

- Atomic data are needed for thousands upon thousands of processes.
- Experiments provide only a fraction of the needed data.
- Theory provides the bulk of the data but approximations are made to keep calculations tractable.
- Plasma models can’t include all needed data without becoming computationally prohibitive.

So let's solve the problem by building an analog computer in the laboratory.

- Create an MB plasma in the lab under controlled conditions to benchmark plasma models.
- This tests everything at once, the plasma model and the underlying atomic data.

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How to simulate an MB plasma in EBIT.

Sweep the electron beam energy *E* in time so

$$\frac{d\tau}{\tau_0} = P(E,T_e)dE.$$

In an MB plasma

$$P(E,T_e)dE = \frac{2\sqrt{E}}{\sqrt{\pi}\,(kT_e)^{3/2}}\exp(-E/kT_e)dE.$$

Solving for *τ* yields

$$\tau(E)=\tau_0\left(erf(x)-\frac{2xe^{-x^2}}{\sqrt{\pi}}\right)$$

where $x=(E/kT_e)^{1/2}$, and n_e is kept constant.

Why we keep n_e constant as E is swept.

- Keeps space charge and trapping conditions largely unchanged.
- Maintains a constant electron-ion overlap vs. beam energy.
- Ensures all electron-ion collision processes go forward at the correct plasma rates.

How to maintain a constant n_e in EBIT.

The current from the gun is given by

$$I_e = pV_a^{3/2}.$$

The beam density is

$$n_e \propto \frac{I_e}{v_e} \propto \frac{V_a^{3/2}}{E^{1/2}}.$$

Hence V_a should vary as

$$V_a(\tau) = (V_a)_r \left(\frac{E(\tau)}{E_r} \right).$$

EBIT technical limitations constrain the implementation of the MB simulation.

- E can only swept between E_{min} and E_{max}.
- $E_{min} \sim 0.2$ keV, though most collision processes of interest occur for $E > 0.2$ keV.
- $E_{max} \sim 5kT_e$ so ≤ 2% of the MB distribution is not sampled.
- Capacitances limit dE/dt and dV_a/dt to ≤ 30 V/µs.
- Space charge needs to be accounted for.
- Need to sweep faster than timescale over which the EBIT charge balance changes (~ 5 ms).

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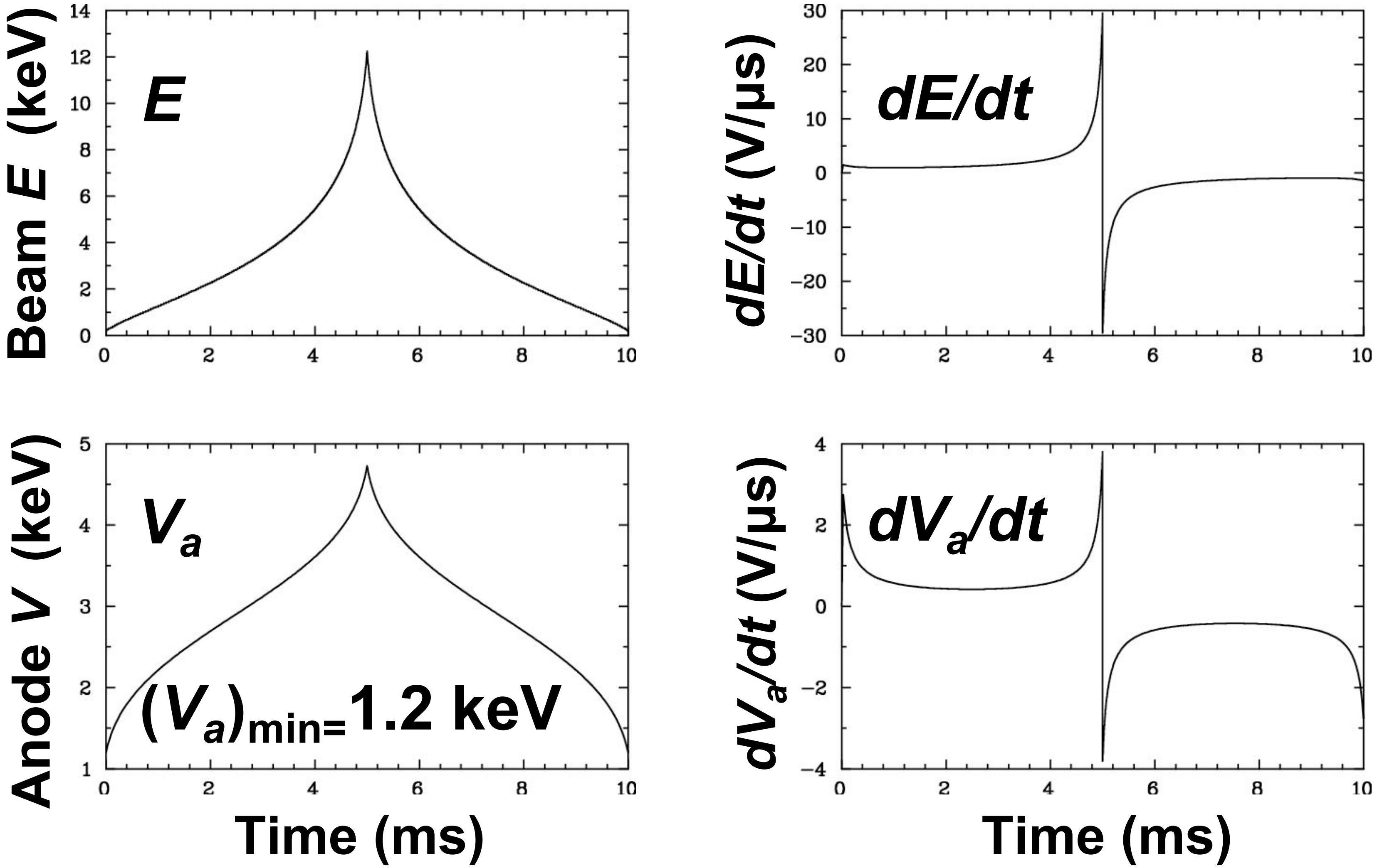
Digitized E and V_a timing patterns and slew rates for k_BT_e = 2.0 keV.



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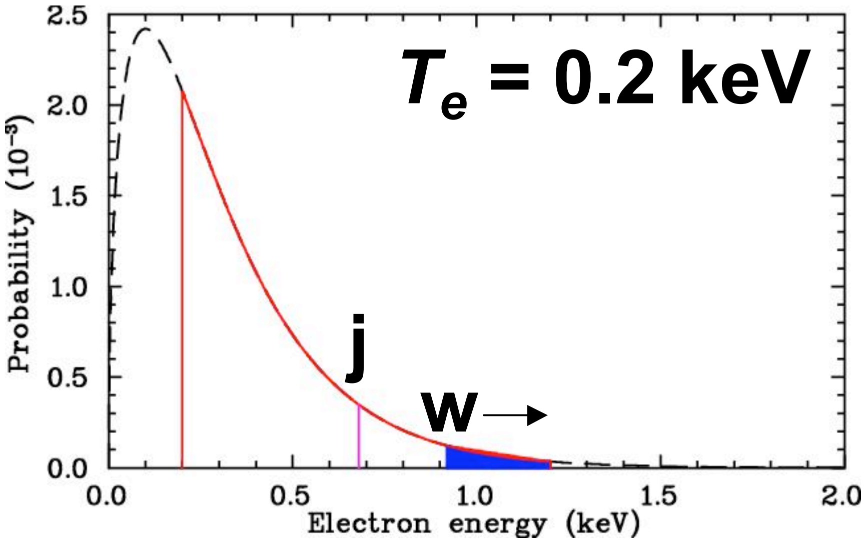
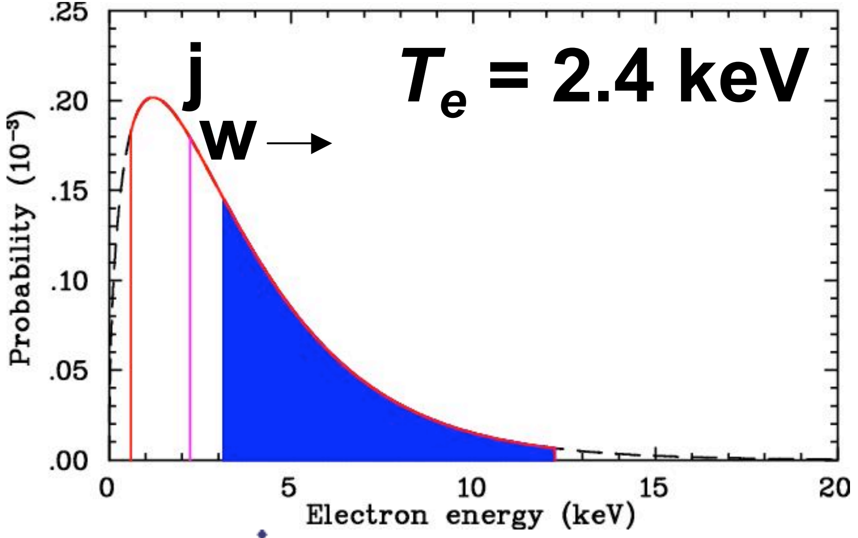
The simulation fidelity was tested using the j/w T_e diagnostic of He-like ions.

- Simulations carried out for 0.2 to 2.4 keV.
- The line **j** is formed by the dielectronic recombination, a resonant process.
- The line **w** is formed by electron impact excitation.





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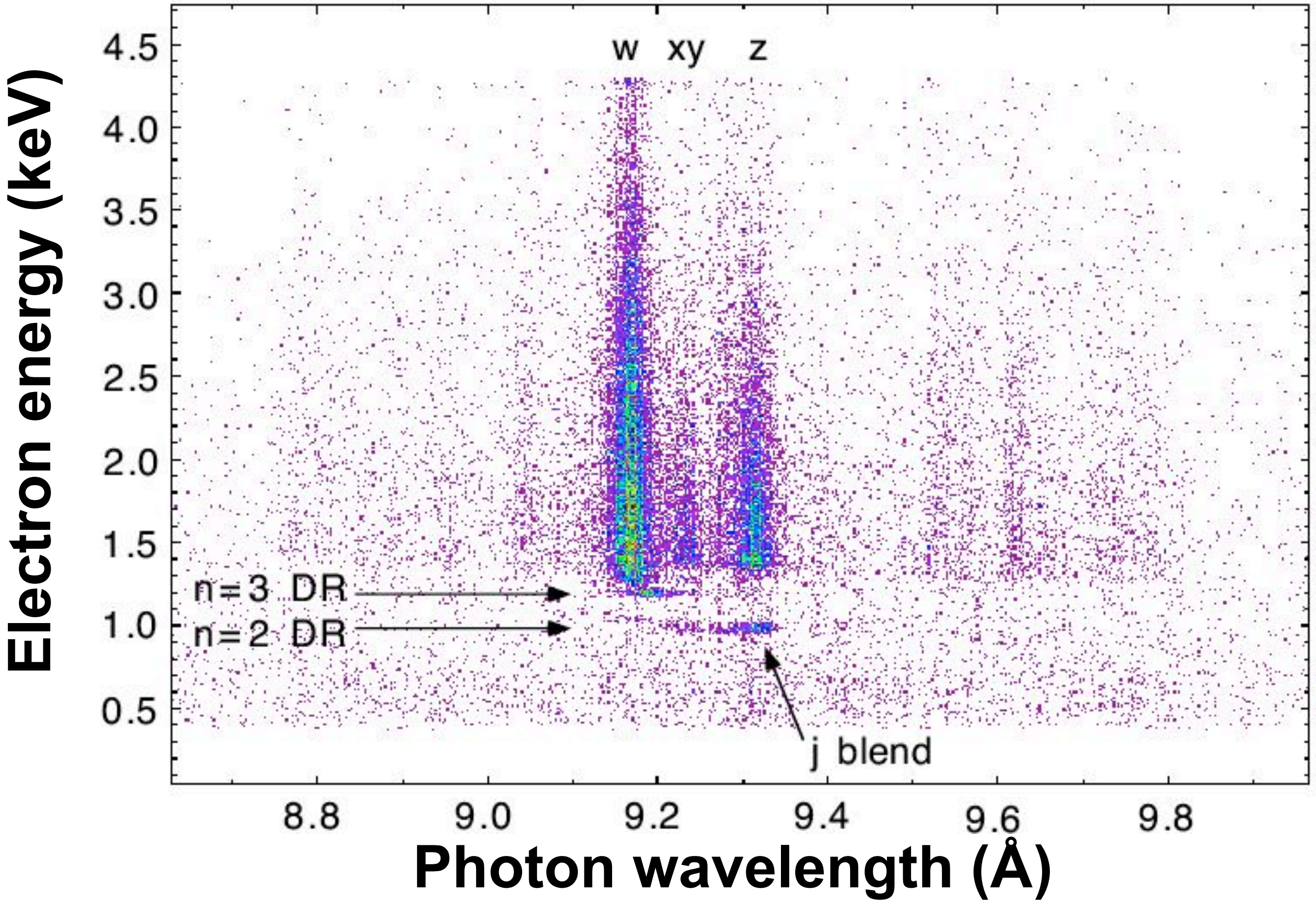
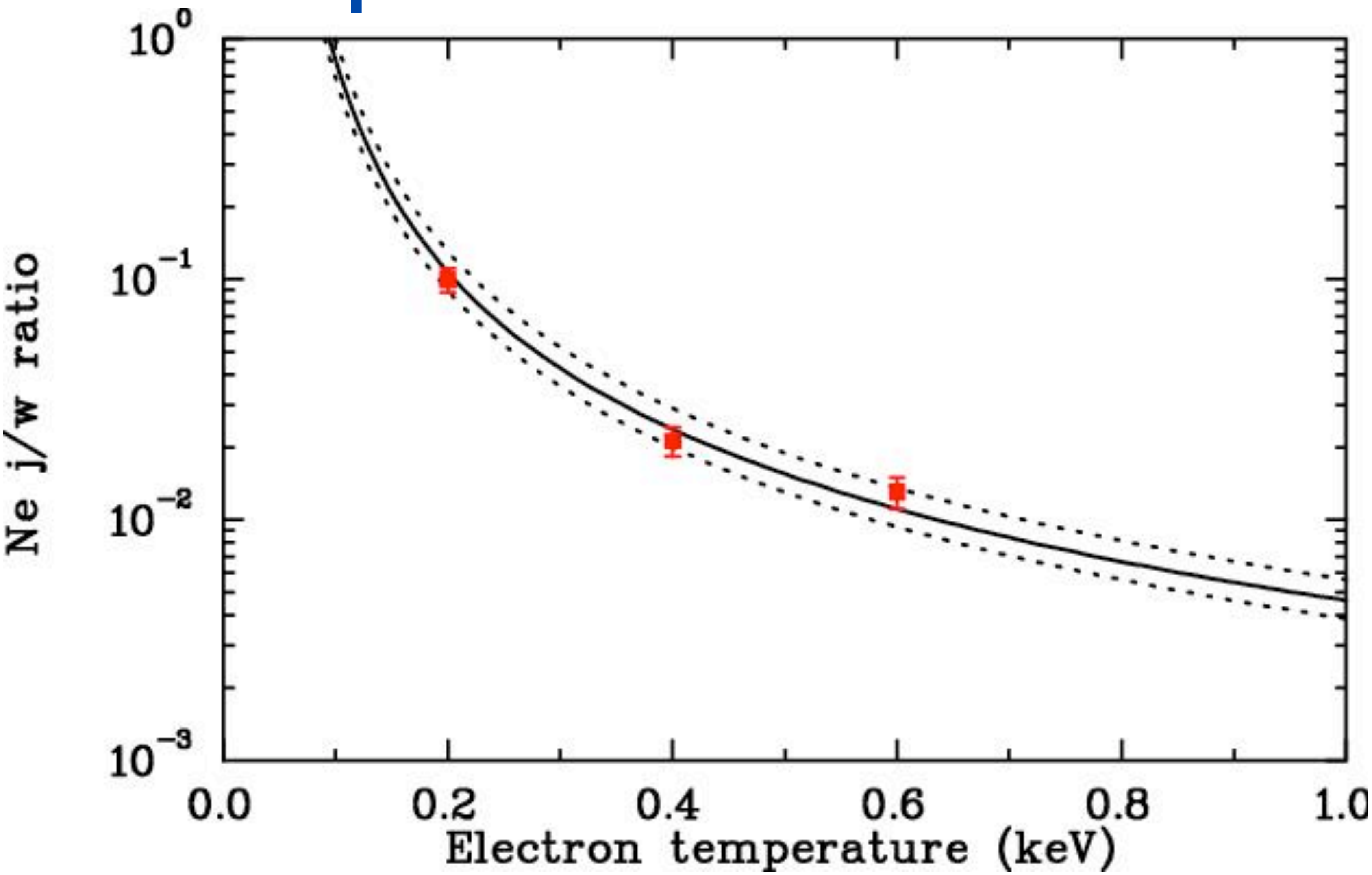
Representative scatter plot for Mg^{10+} at T_e = 0.7 keV



Measured **j/w** ratios and theoretical predictions for Ne^{8+}



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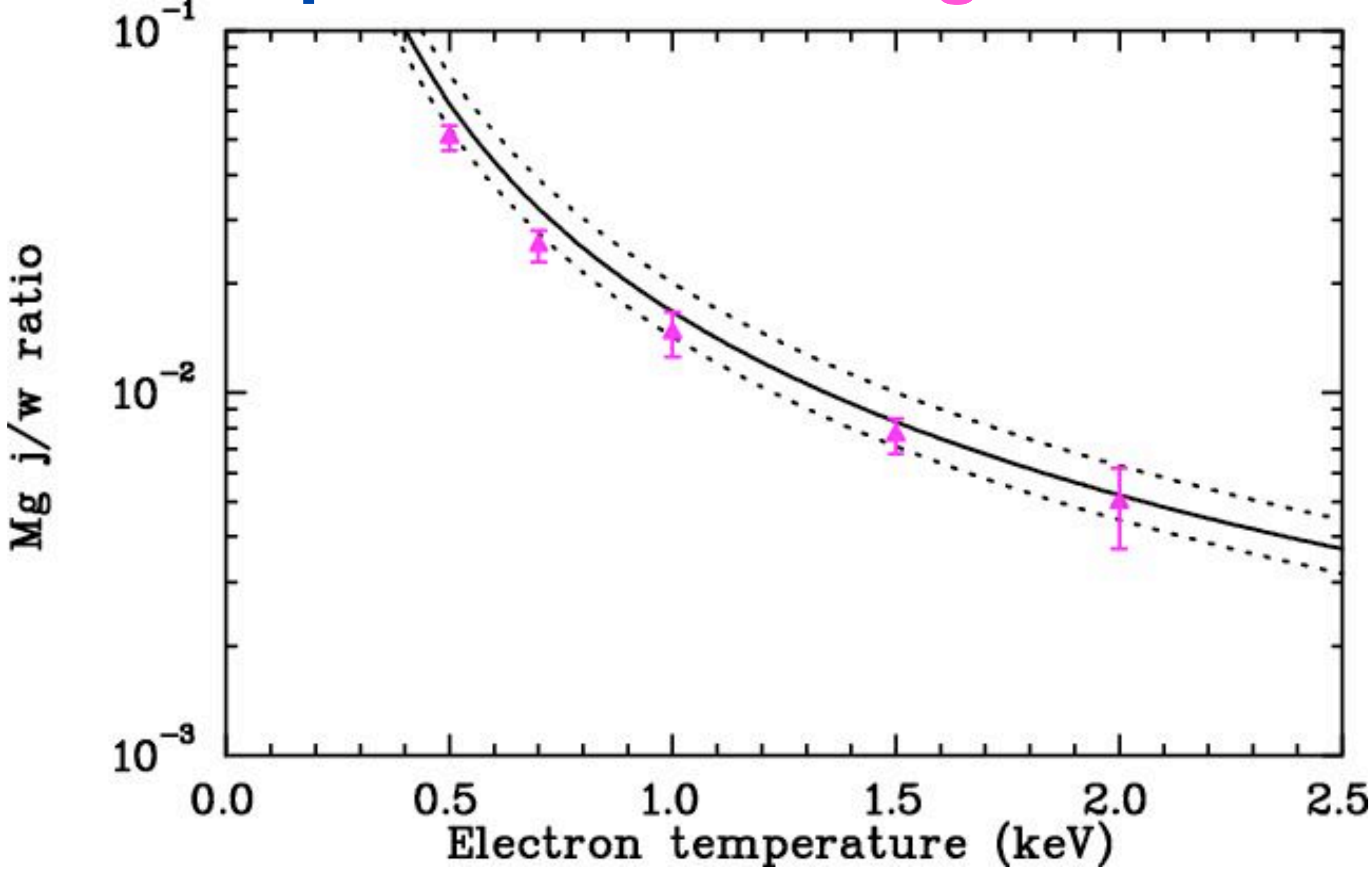
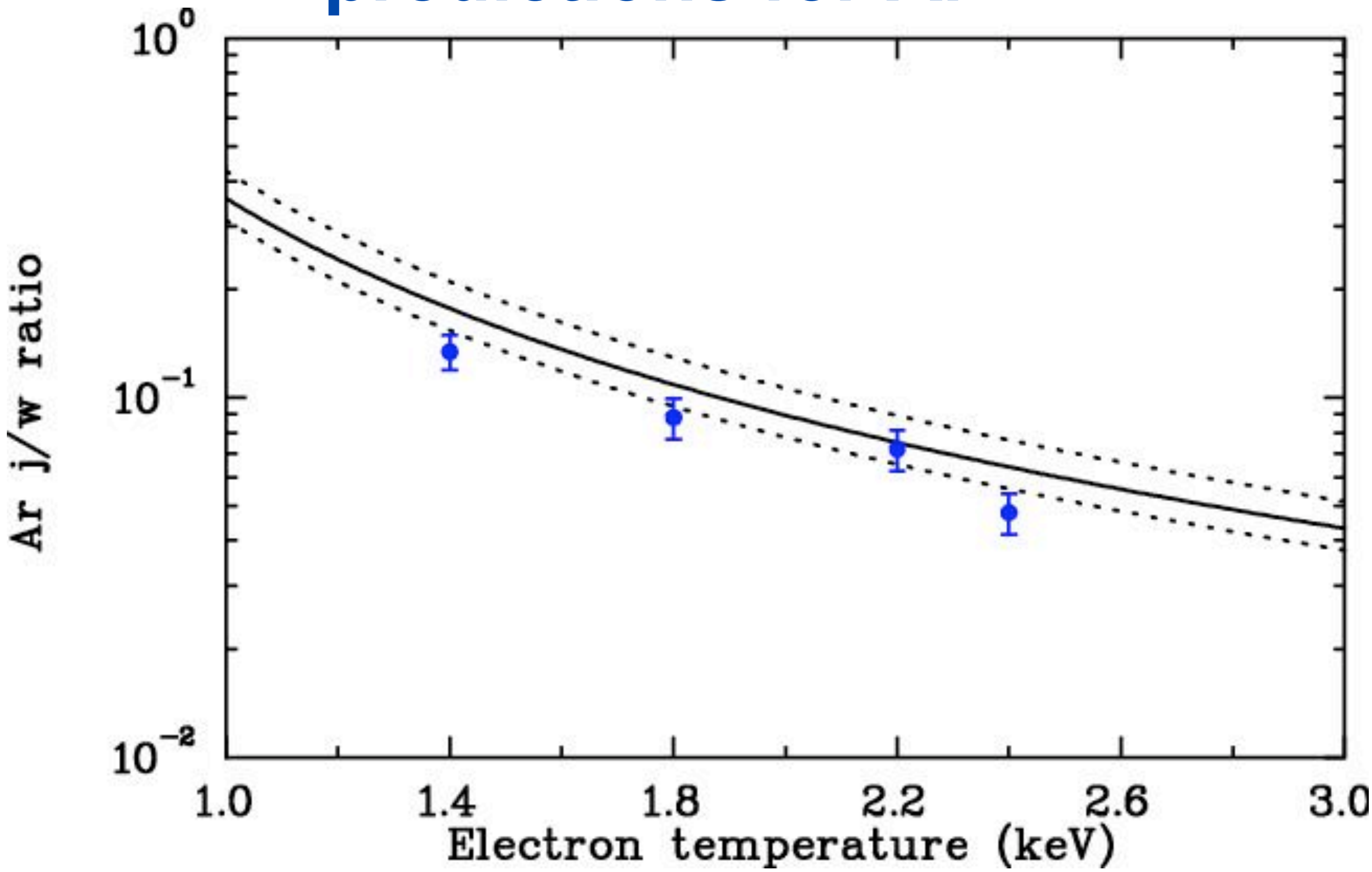
Measured **j/w** ratios and theoretical predictions for Mg^{10+}



Measured **j/w** ratios and theoretical predictions for Ar^{16+}



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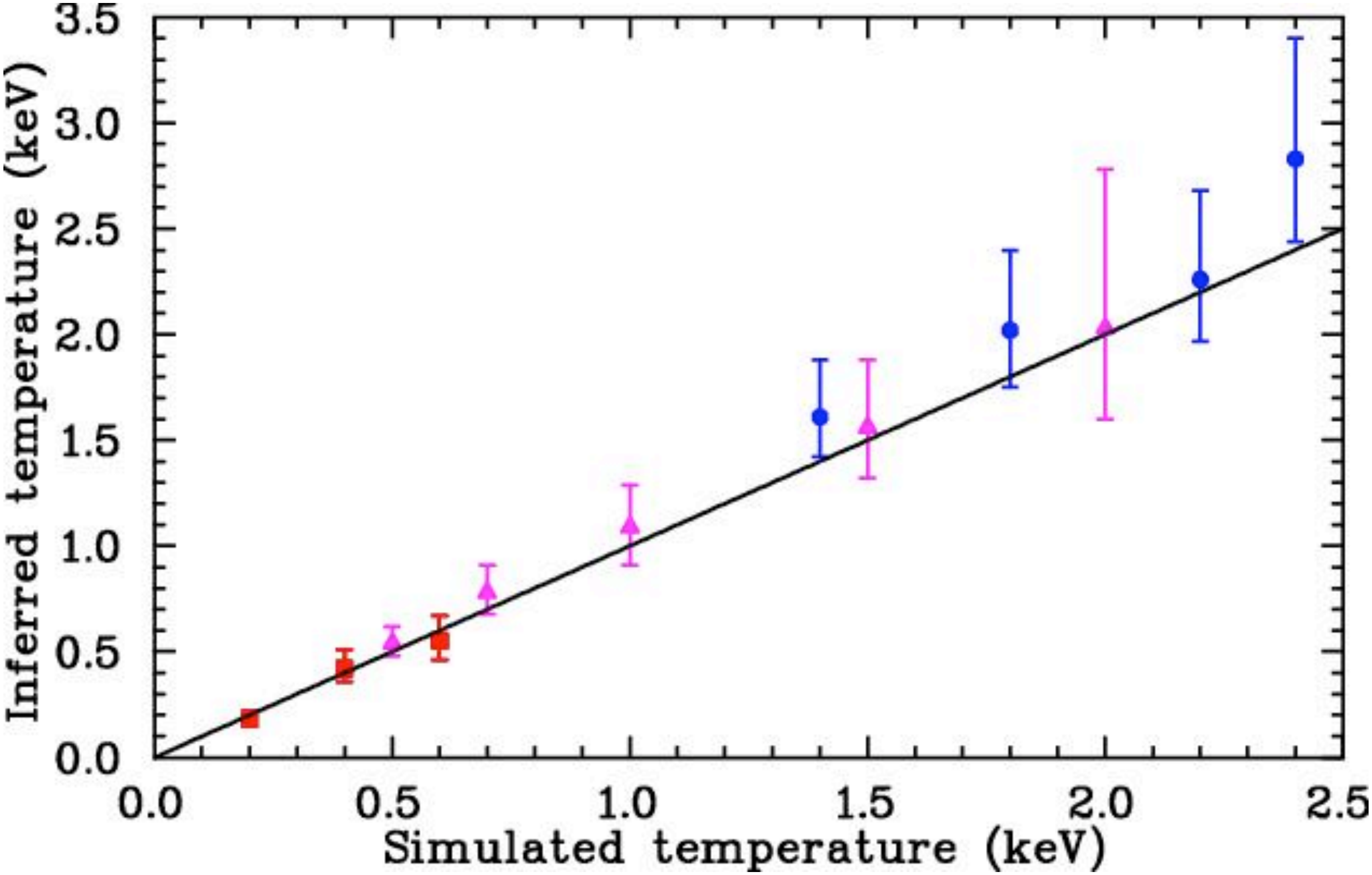
We find good agreement between the inferred T_e and the simulated T_e.



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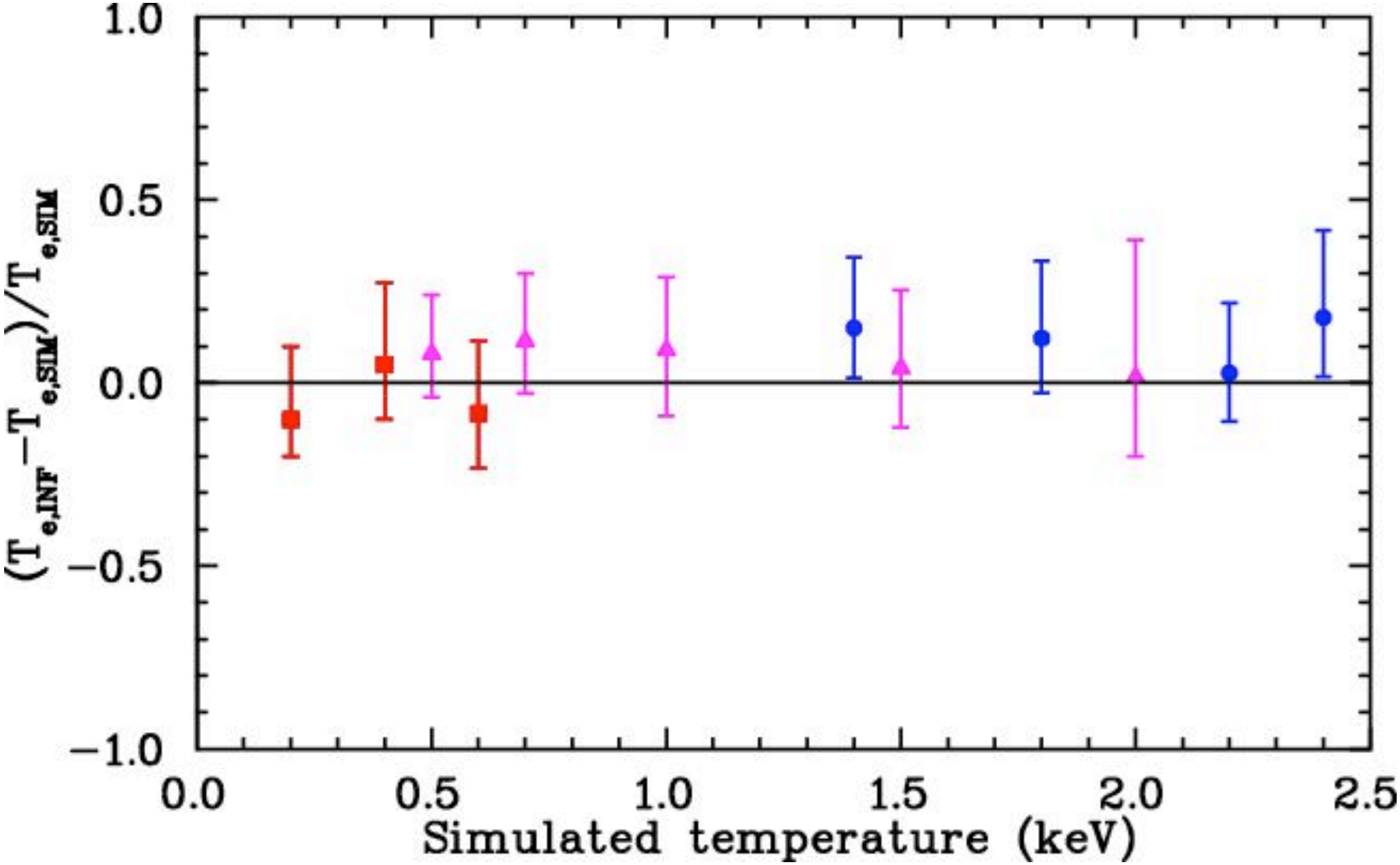
The inferred T_e agree on average to within 10% with the simulated T_e.



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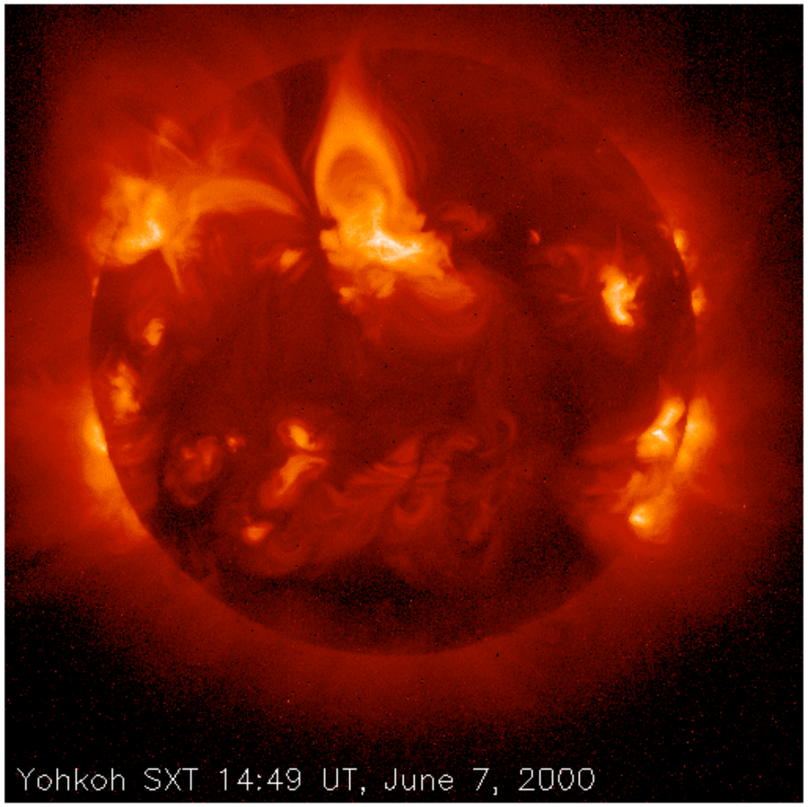
What is CIE?

- Plasma properties
  - Optically thin
  - Low density
  - Dust free
  - Steady state
- Ionization rate equals recombination rate
  - Accuracy of these rates determines reliability of CIE models



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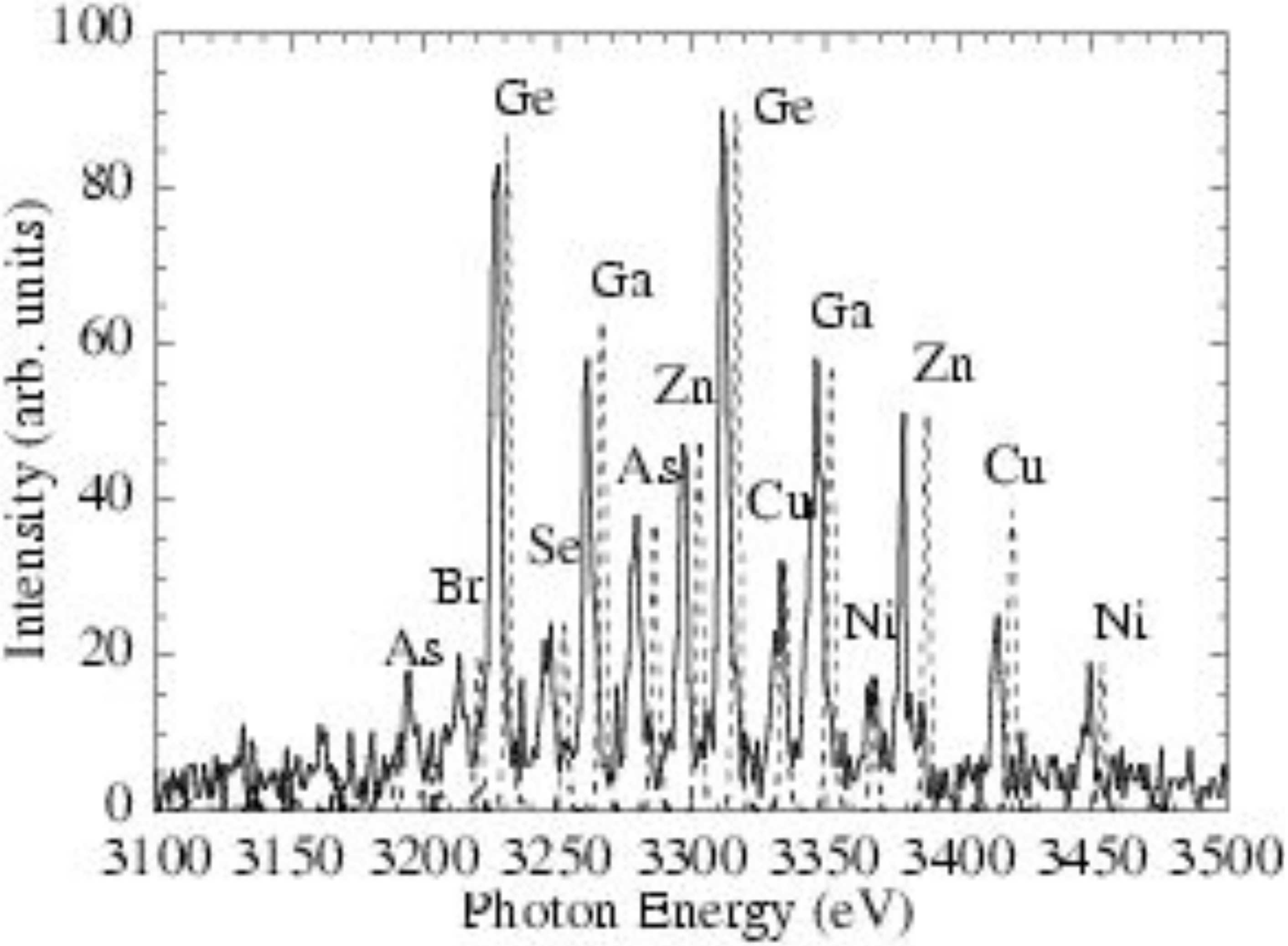
Major CIE calculations for astrophysics since the 1980s.

- Shull & van Steenberg (1982)
  - An early compilation of published DR, RR, and EII data
- Arnaud & Rothenflug (1985)
  - Updated atomic database
- Arnaud & Raymond (1992)
  - Updated Fe
- Mazzotta et al. (1998)
  - Re-evaluated and updated recombination data
- Bryans et al. (2006)
  - State-of-the-art DR and RR for all K- and L-shell ions of H through Zn.

Au line emission from EBIT for a 2.5 keV MB simulation (Wong et al. 2003).



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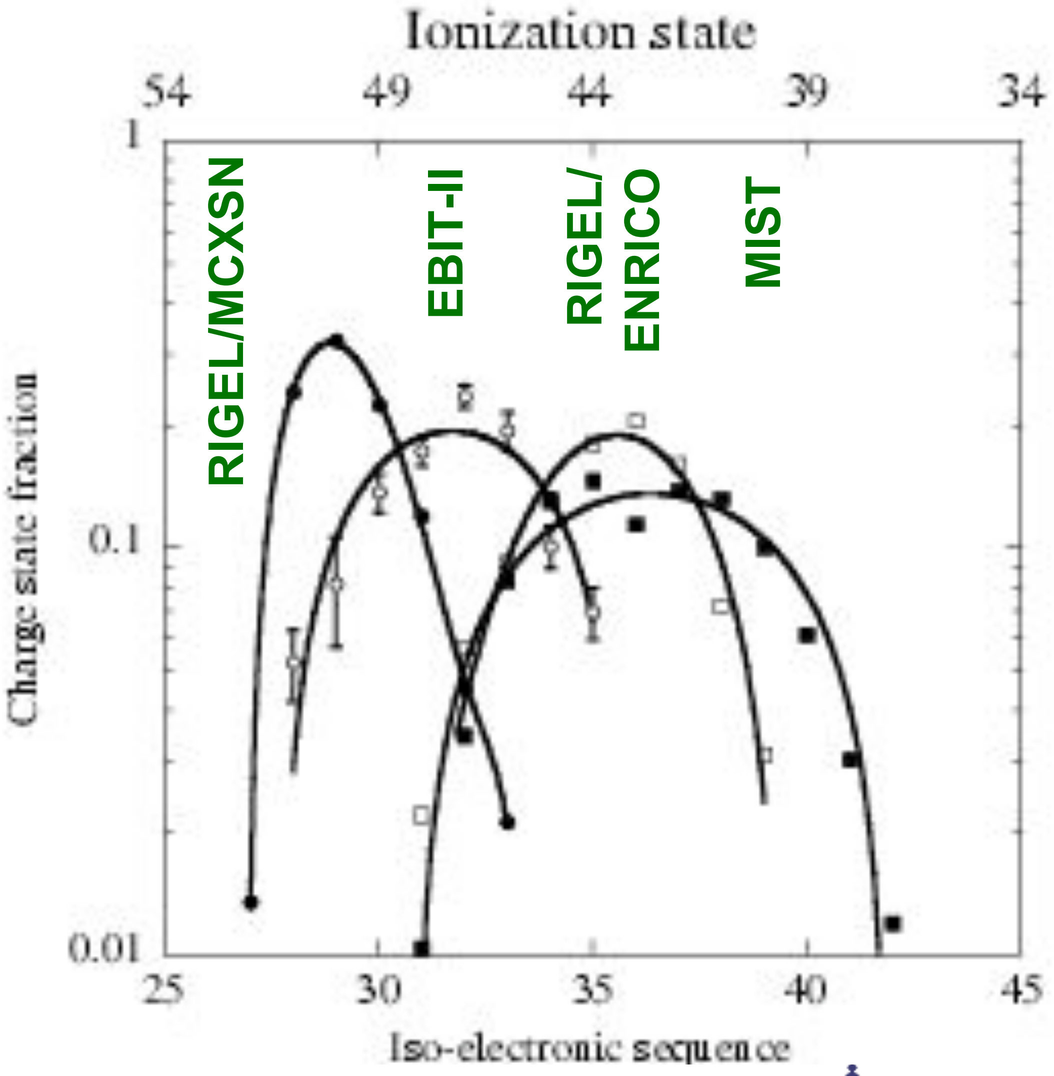
Inferred Au charge balance distribution (Wong et al. 2003).



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There have been significant theoretical advances in RR and DR.

- **Modern calculations exist for K-, L-, and some M-shell ions (Badnell et al. 2003-6; Gu 2003-4).**
- **For an ion at CIE formation temperatures, modern theory agree with one another to < 25%.**

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Measurements have been used to benchmark modern DR calculations

- K-shell ions well studied using EBITs and storage rings – agreement with theory is ~ 20%.
- L-shell ions less well studied – agreement with theory is ~ 35% but additional studies needed.
- DR theory is much less reliable at ~ 10^4 K and lab work needed for ions forming at these T_e's.

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How our new CIE results differ from Mazzotta et al. (1998).

- Peak fractional abundances differ by up to 60%.
- At 0.1 fractional abundances, differ by of up to a factor of 5.
- At 0.01, differ of up to a factor of 11.
- Peak formation T_e can shift by up to 20%.
- Ions with particularly large differences include Mg, Al, Ca, Fe, Co, and Ni.

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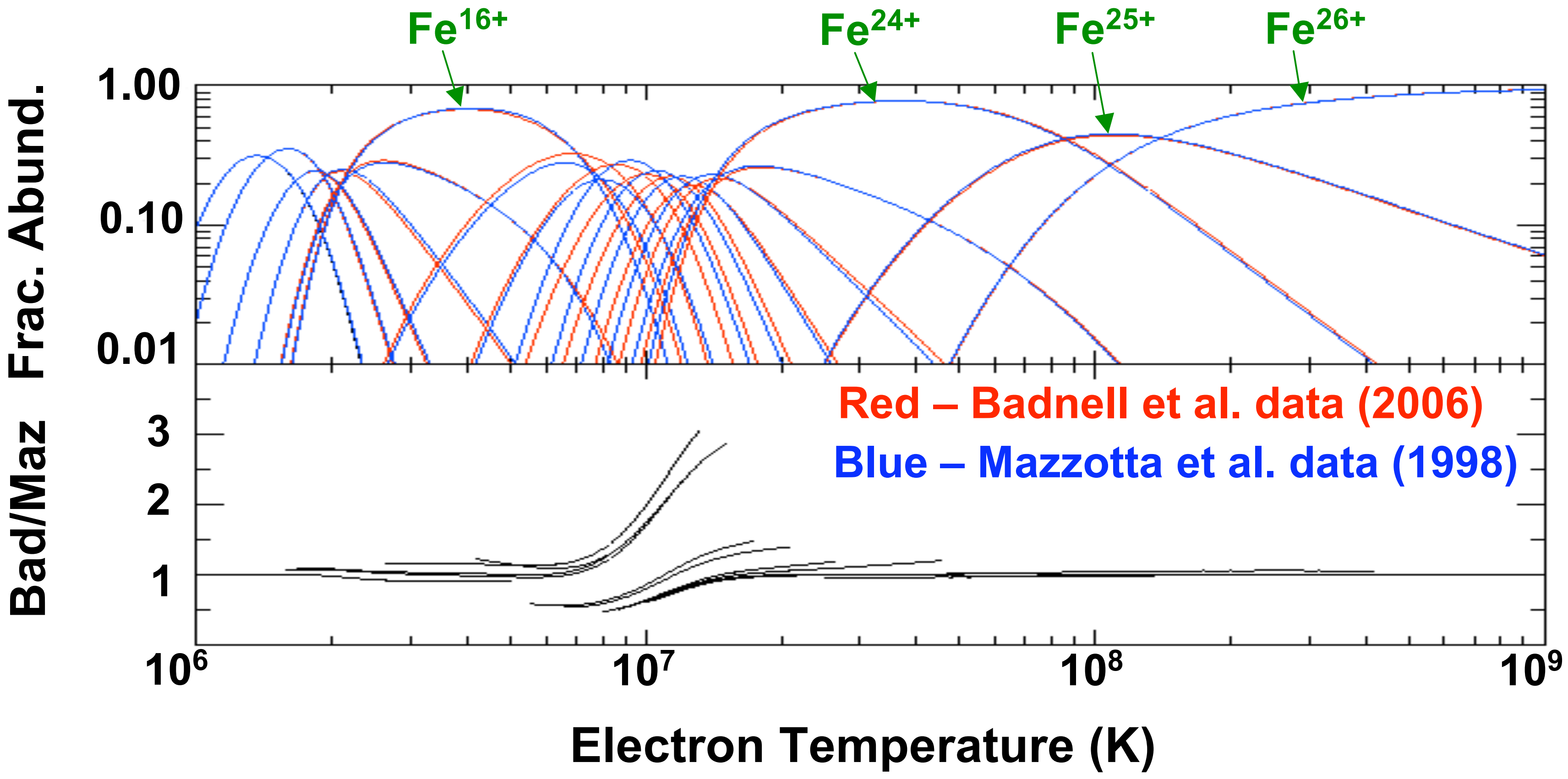
Comparison between our CIE result and Mazzotta et al. for Fe (Bryans et al.)



CIE models using the data of Badnell et al. and Gu are in good agreement

- Peak fractional abundance differs by < 10%.
- At 0.1 fractional abundances, differ by up to 30%.
- At 0.01 differences up to 50%.

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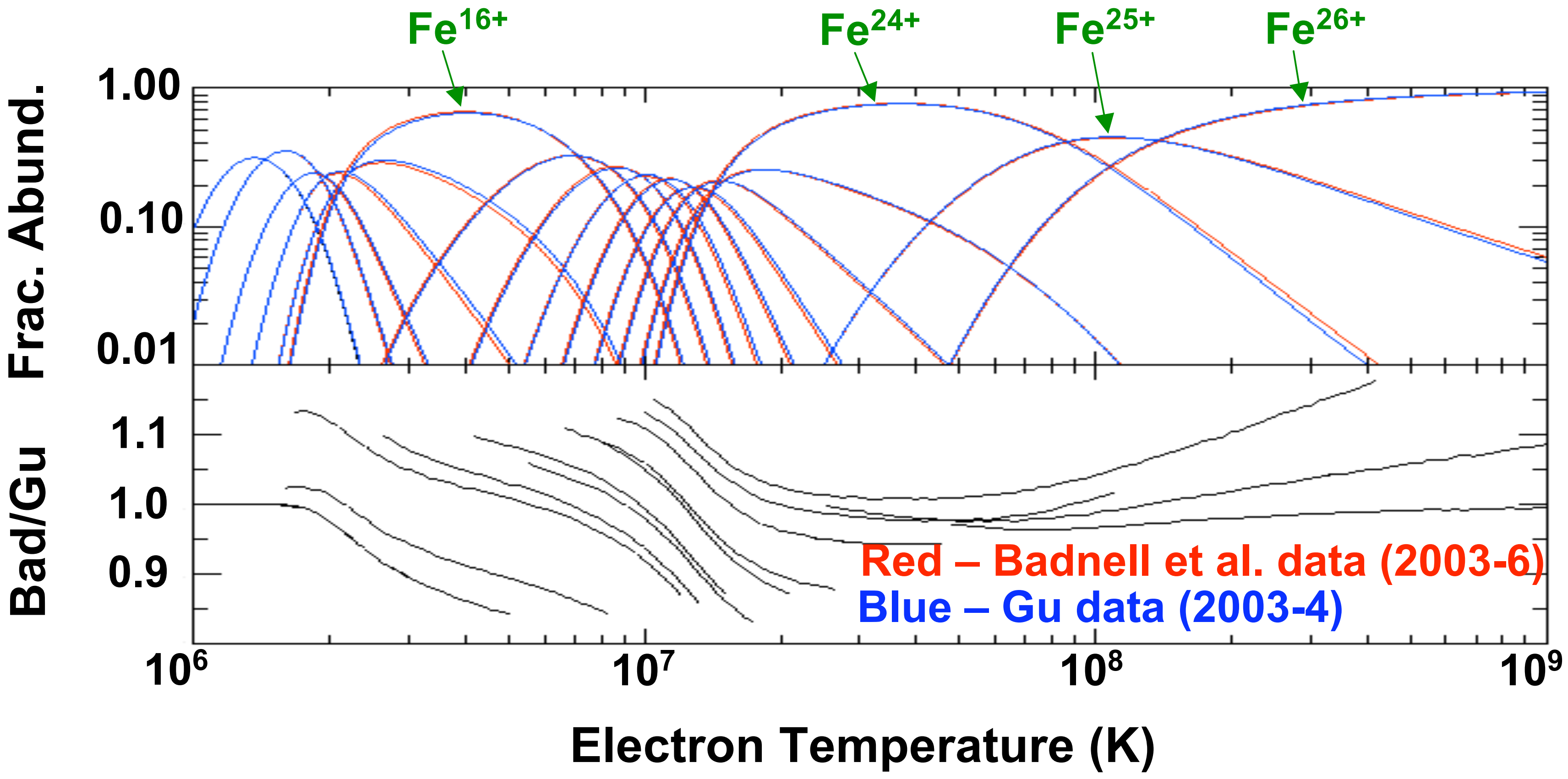
Comparison of CIE results using Badnell et al. and Gu data for Fe (Bryans et al.)



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Further RR theoretical and experimental work is needed.

- **Data for M-shell ions**

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Further DR experimental and theoretical work is needed.

- L-shell ions laboratory benchmarking for
  - $\Delta n=0$ DR in B-, C-, N-, O-, and F-like ions.
  - $\Delta n=1$ DR in B-, C-, N-, O-, F-, and Ne- like ions.

- Reliability of theory at ~ 10^4 K is poor and lab data needed for ions forming at these T_e's.

- More accurate atomic structure codes could remove much of the uncertainties in the theory.

- Significant work remains for all M-shell ions (except for Na-like).

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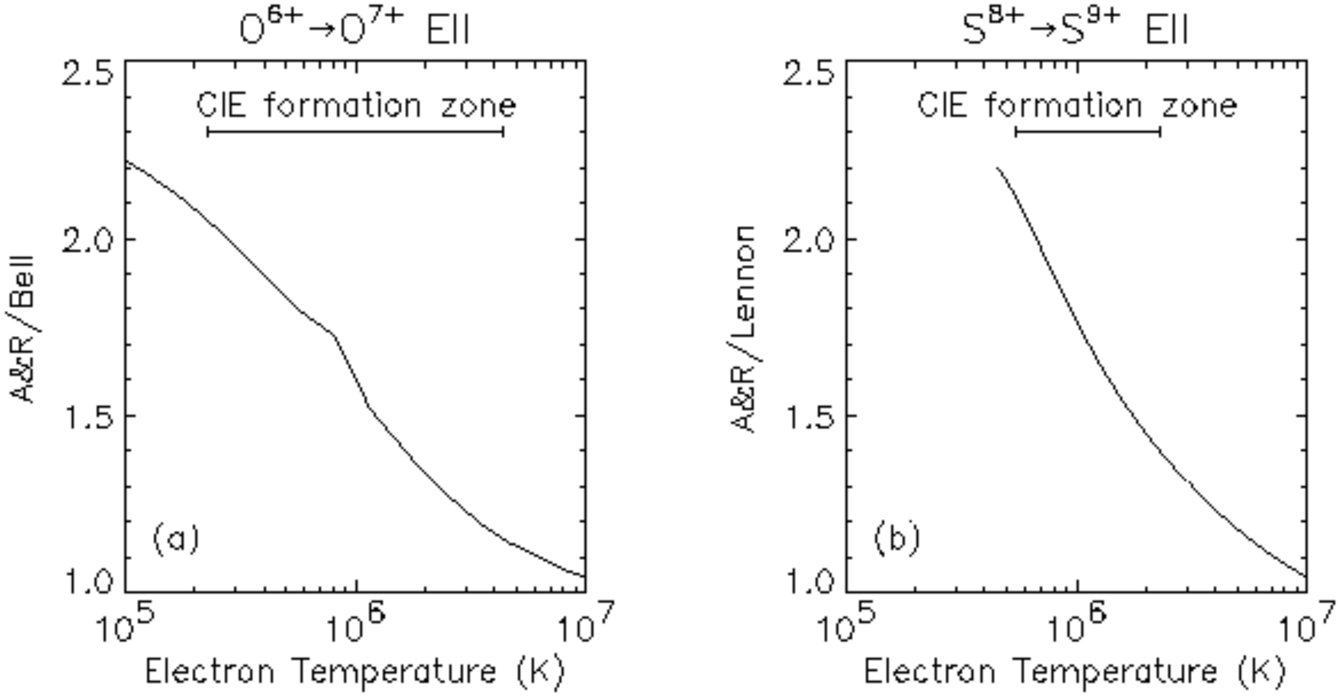
Electron impact ionization (EII) data have remained unchanged for almost 20 years



- **Kato et al. (1991) found factor of 2-3 difference between various recommended data sets.**

An updating of the EII database is sorely needed.

- Much of the existing data are based on experiments with unknown metastable fractions.
- The recommended EII data used in astrophysics has not been updated since around 1990.
- This is partly because almost no new laboratory measurements exist.

Charge Transfer (CT) needs to be incorporated into CIE models.

- **CT is most important for near-neutral systems (charge ≤ 4).**
- **CT with H is important at $T_e \leq 25{,}000$ K.**

Atomic data needs for future CIE models

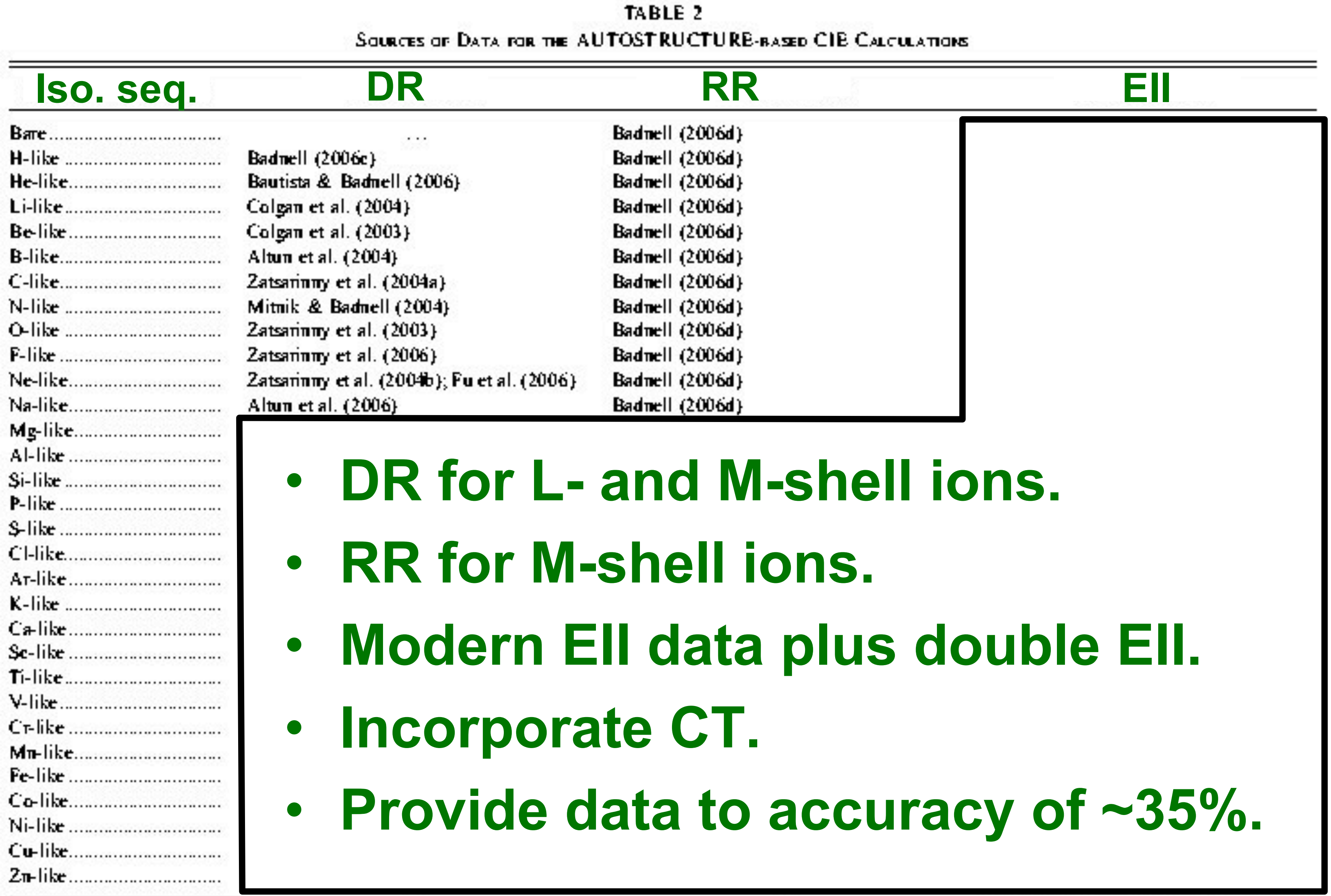


TABLE 2

Sources of Data for the AUTOSTRUCTURE-based CIE Calculations

Iso. seq.	DR	RR	EII
Bare	...	Badnell (2006d)	
H-like	Badnell (2006c)	Badnell (2006d)	
He-like	Bautista & Badnell (2006)	Badnell (2006d)	
Li-like	Colgan et al. (2004)	Badnell (2006d)	
Be-like	Colgan et al. (2003)	Badnell (2006d)	
B-like	Altun et al. (2004)	Badnell (2006d)	
C-like	Zatsarinny et al. (2004a)	Badnell (2006d)	
N-like	Mitnik & Badnell (2004)	Badnell (2006d)	
O-like	Zatsarinny et al. (2003)	Badnell (2006d)	
F-like	Zatsarinny et al. (2006)	Badnell (2006d)	
Ne-like	Zatsarinny et al. (2004b); Fu et al. (2006)	Badnell (2006d)	
Na-like	Altun et al. (2006)	Badnell (2006d)	
Mg-like			
Al-like			
Si-like			
P-like			
S-like			
Cl-like			
Ar-like			
K-like			
Ca-like			
Sc-like			
Ti-like			
V-like			
Cr-like			
Mn-like			
Fe-like			
Co-like			
Ni-like			
Cu-like			
Zn-like			

- DR for L- and M-shell ions.
- RR for M-shell ions.
- Modern EII data plus double EII.
- Incorporate CT.
- Provide data to accuracy of ~35%.

From Bryans et al.

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