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Continuum hard-photon K-shell yields from Z-pinch implosions: present status and scaling to higher currents

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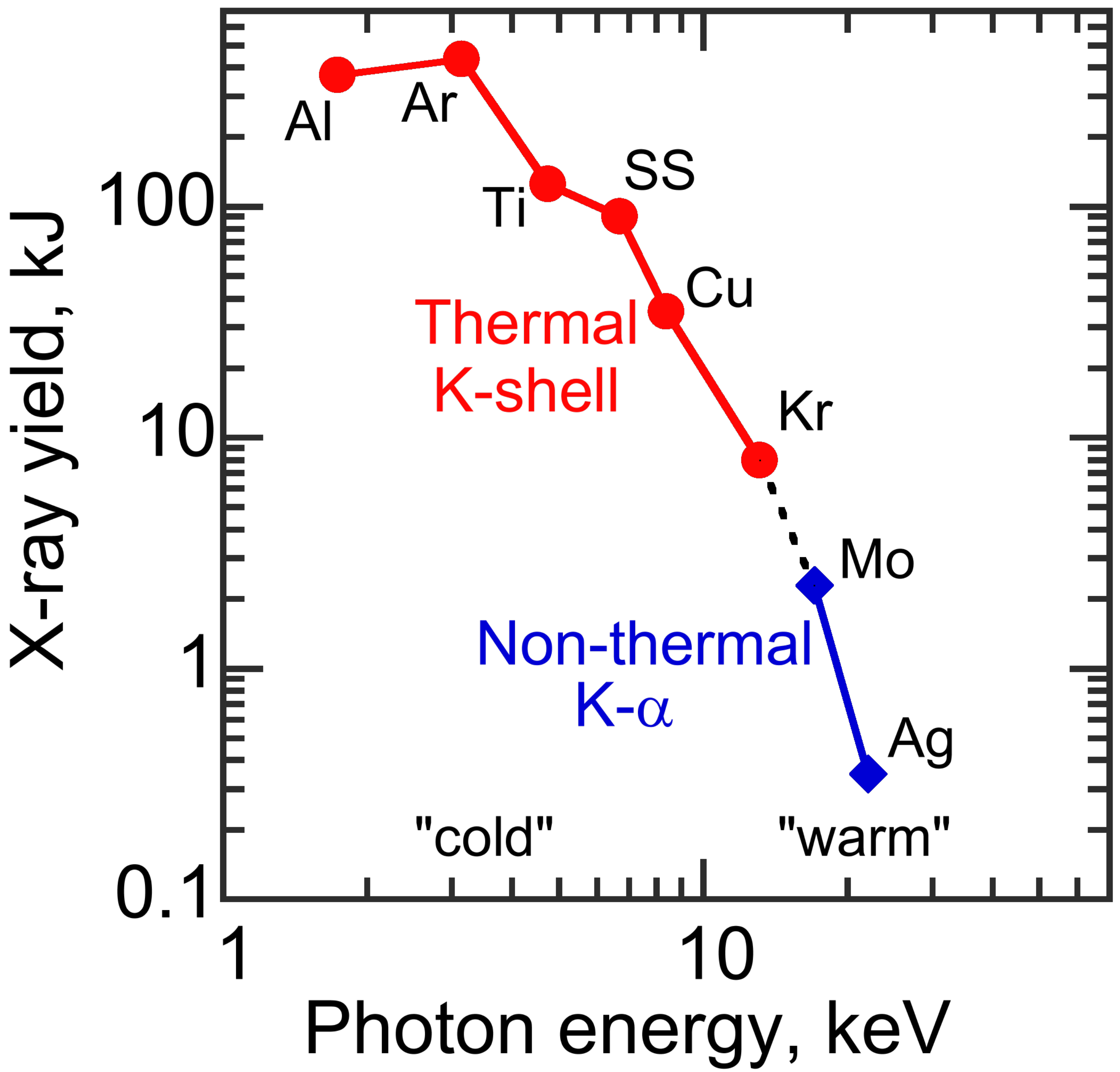
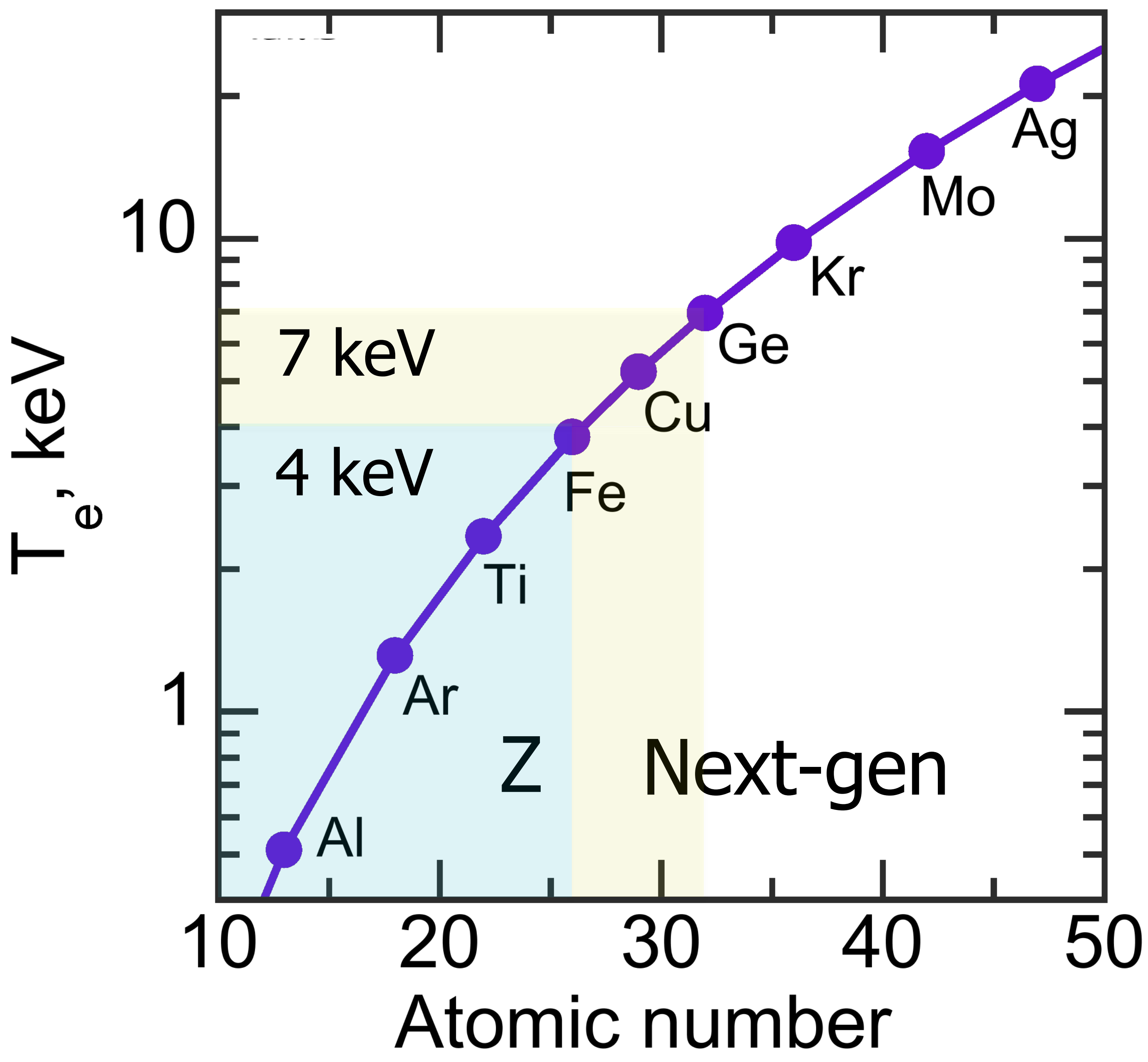
Outline

- Need for alternative paths to “warm” >15 keV x-ray production with pulsed power
- Why K-shell continuum
  - L-shell continuum will not work – too much energy for stripping high-Z_A ions to the L-shell[1]
- New data on continuum emission from Z shots since 2015
  - Ar gas puffs
  - Stainless steel wire arrays
- Spectra, continuum yields and observed trends
  - Hydrogen-like populations
  - Volume line and continuum emission for Ar, bright spots for stainless[2]
- Future research

[1]J. P. Apruzese’s concept, L-shell emission from higher-atomic number elements; see P. D. LePell *et al.*, phys. Plasmas **12**, 032701 (2005)
[2]J. P. Apruzese *et al.*, Phys. Plasmas **20**, 022707 (2013).

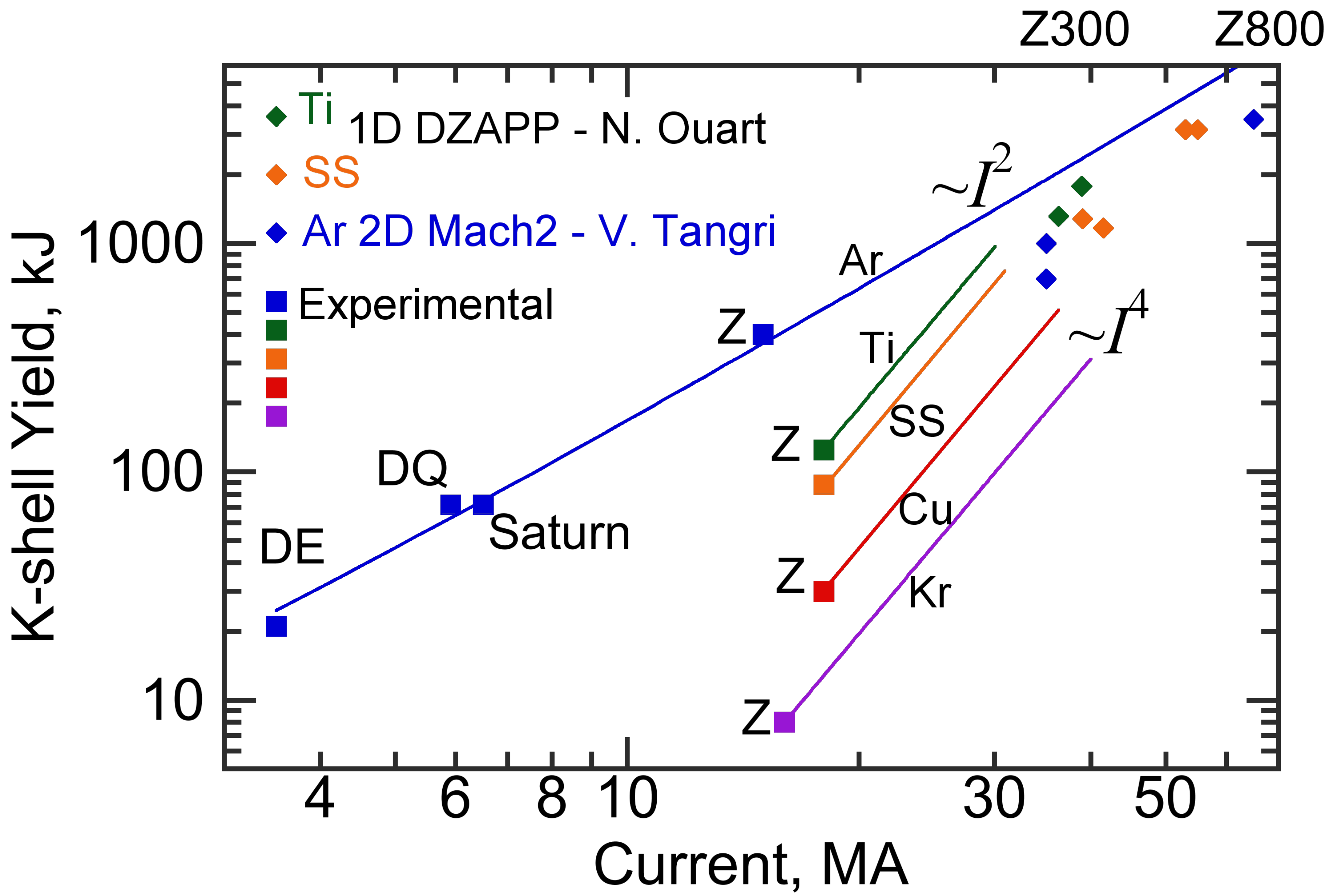
Implosion velocities limit K-shell line yields, particularly for “warm” photons





K. G. Whitney *et al.*, J. Appl. Phys. **67**, 1725 (1990).

Next-gen pulsed power facilities will generate plenty of "cold" x rays



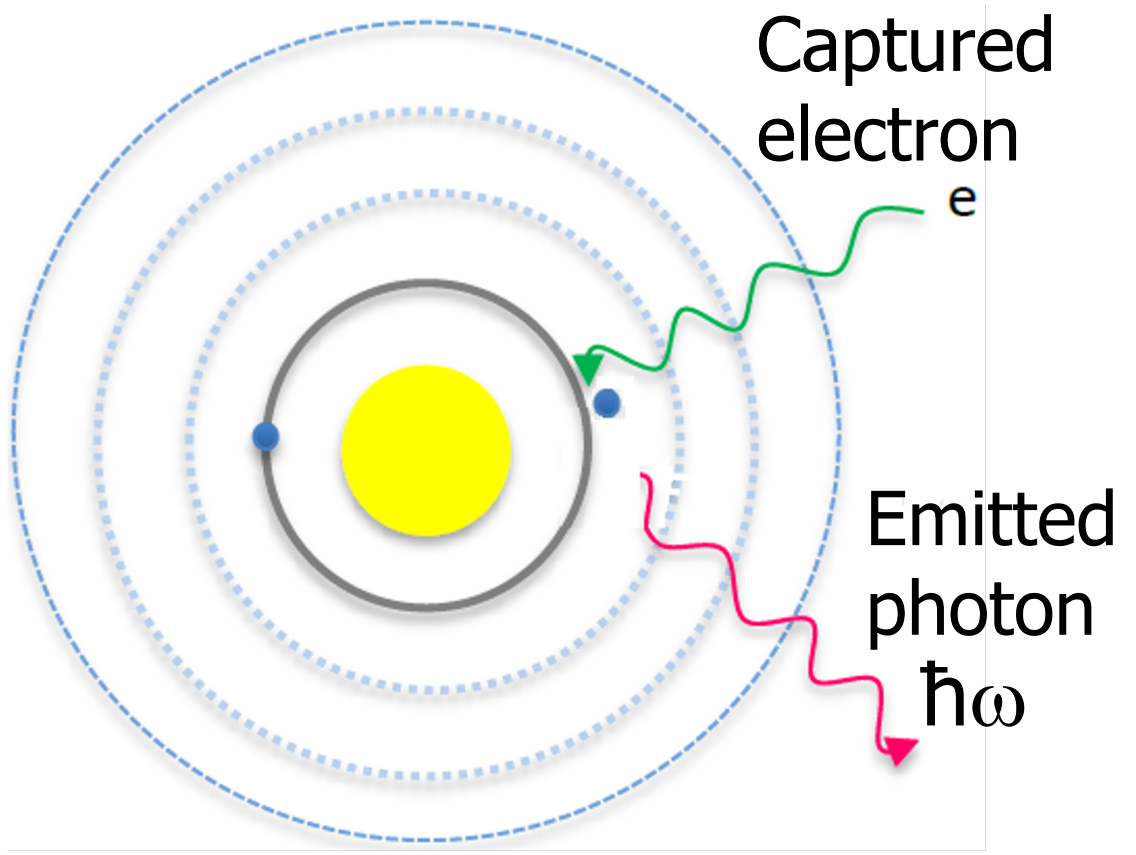
- Simulation codes and NRL scaling models have been extensively validated using data from Z, Saturn, DQ, DE, …
- Predictions for "cold" x-ray yields are optimistic
- No reasonable predictions can be made at the moment for "warm" x-ray yields at

  $\hbar\omega > 15$ keV

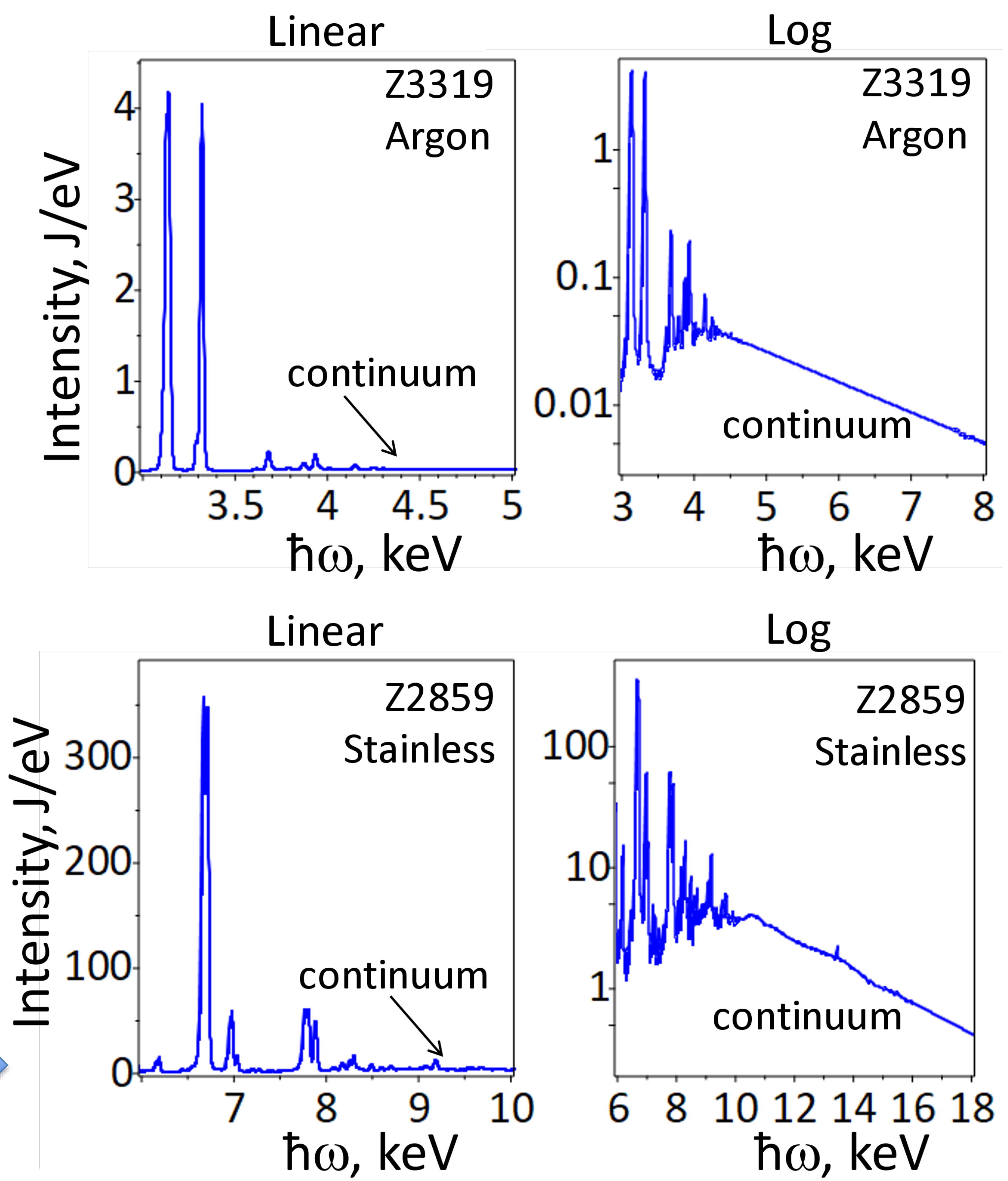
<u>This conference, Sep. 15</u>: J. Schwarz *et al.*, 8O-D-03 "A model for K-shell x-ray yield from magnetic implosions at Sandia's Z machine"; N D. Ouart *et al.*, 8O-D-05 "Investigation of CH foams doped with titanium as a cold x-ray source alternative "; V. Tangri *et al.*, 7P-C-05 "Scaling of efficient Ar K-shell emission from fast gas-puff Z-pinches in the 10 to 100 MA current range."

The continuum above the K-edge adds a fraction to the K-shell yield

Direct radiative recombination into a bare or H-like ion



X-ray spectra from Ar gas-puff and stainless steel wire-array shots on Z with most prominent continua

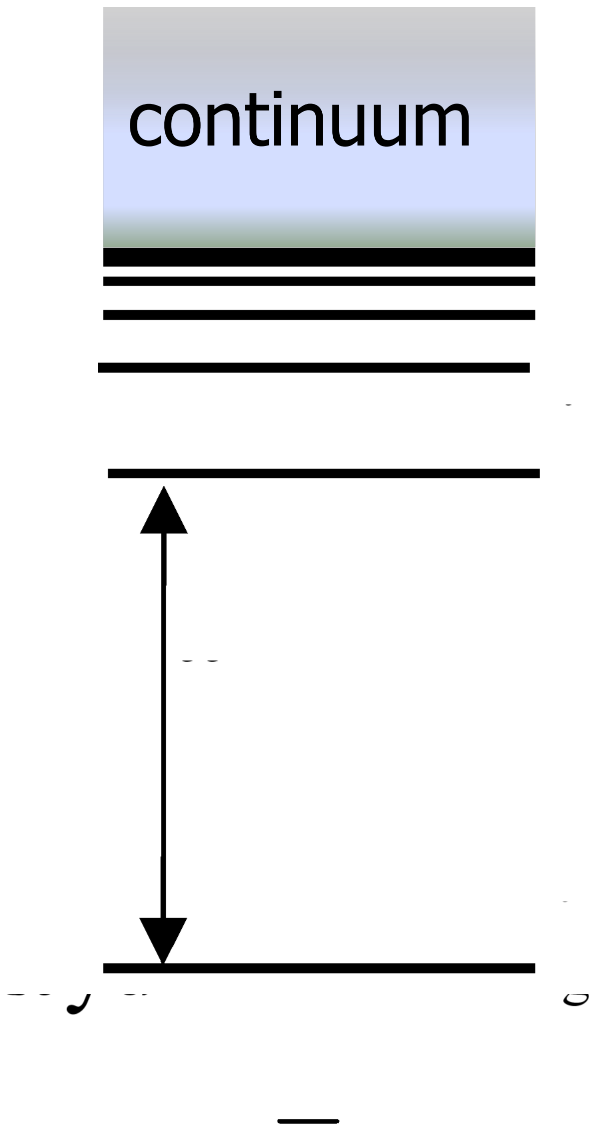


The continuum spectral intensity is low compared to strong resonant lines.

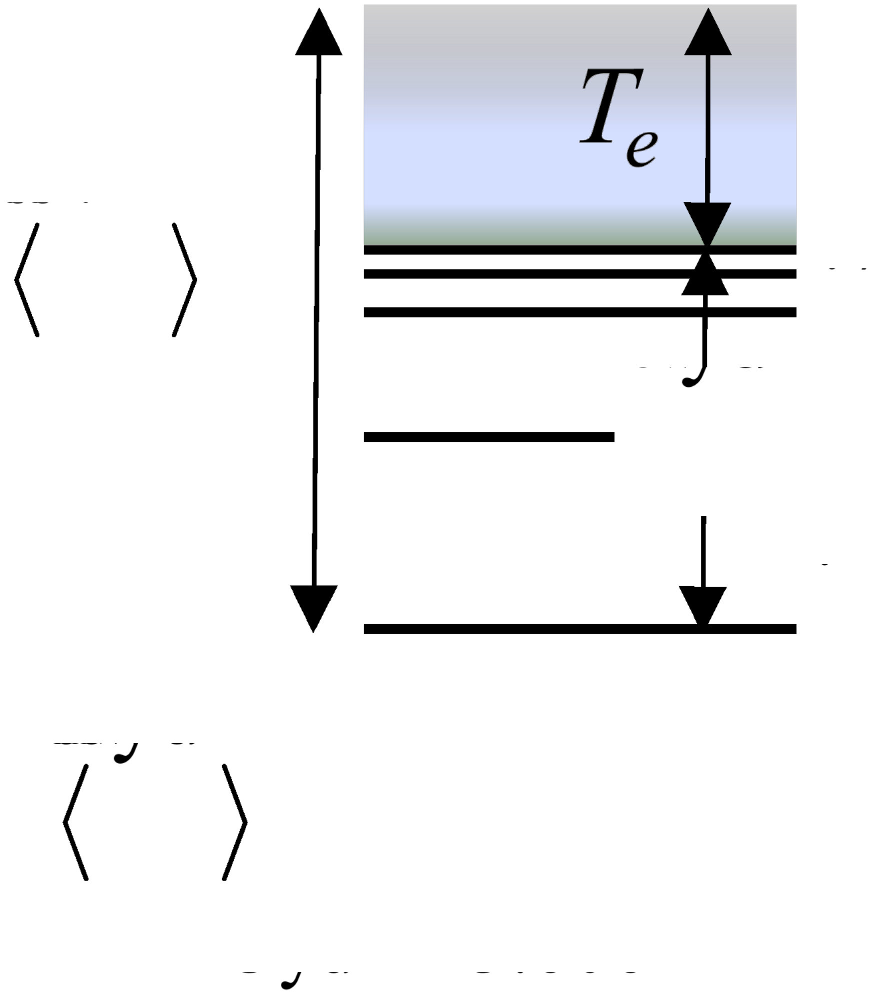
Direct radiative recombination is a robust but not efficient emission mechanism

Low-Z_A free-bound continuum substitutes for the high-Z_A K-shell line emission

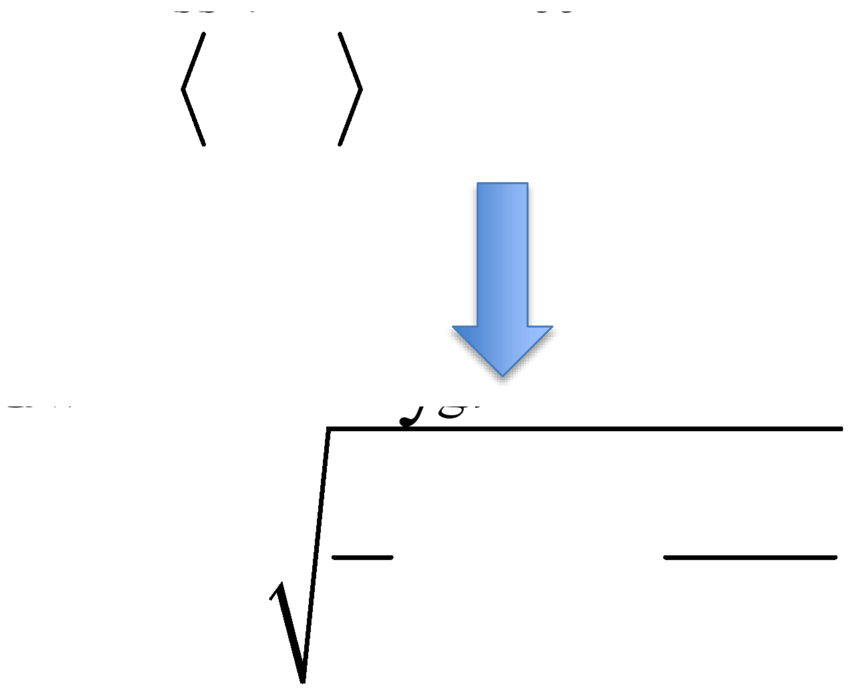
High-Z_A K-shell line emission



Low-Z_A direct radiative recombination

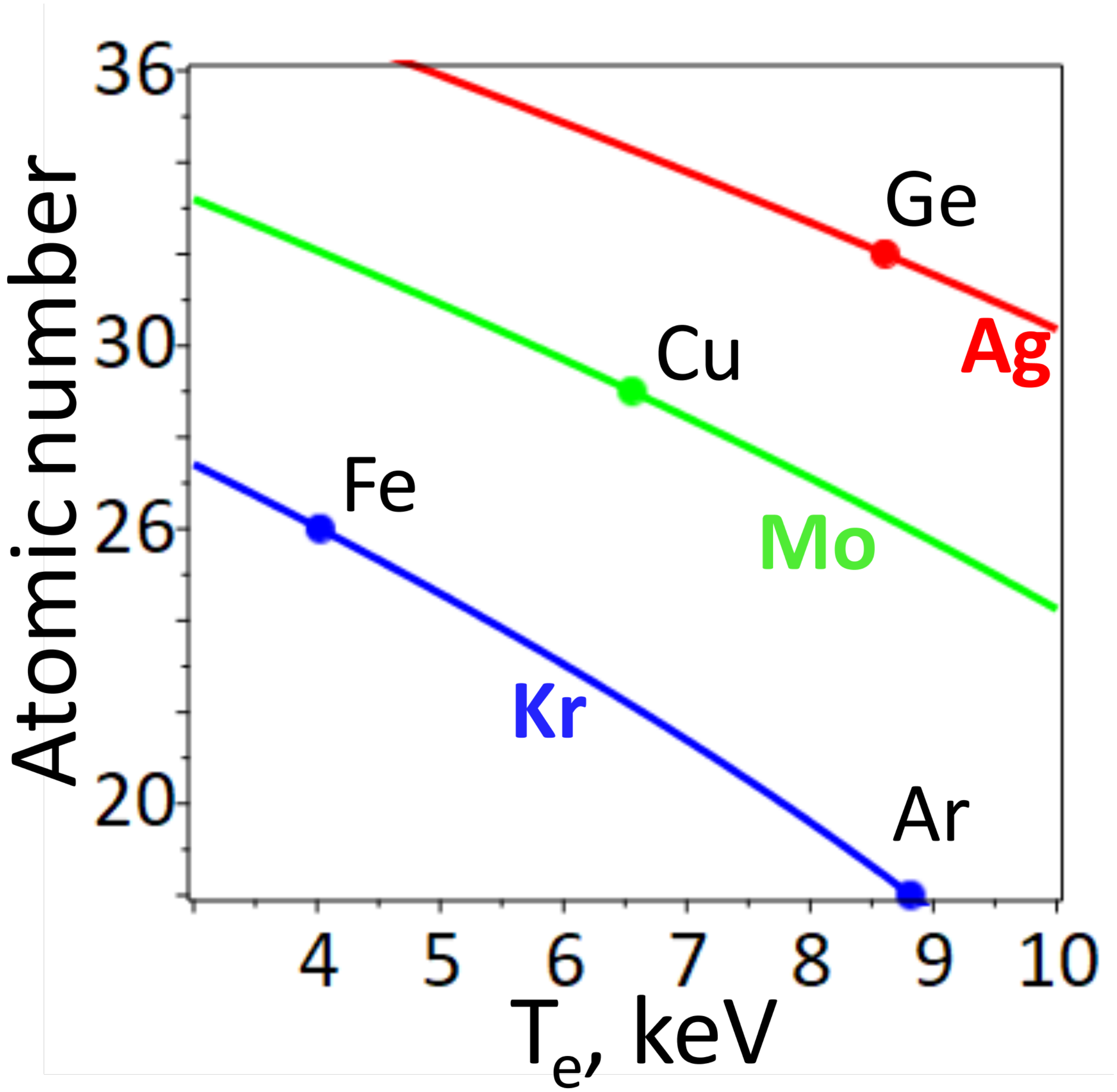


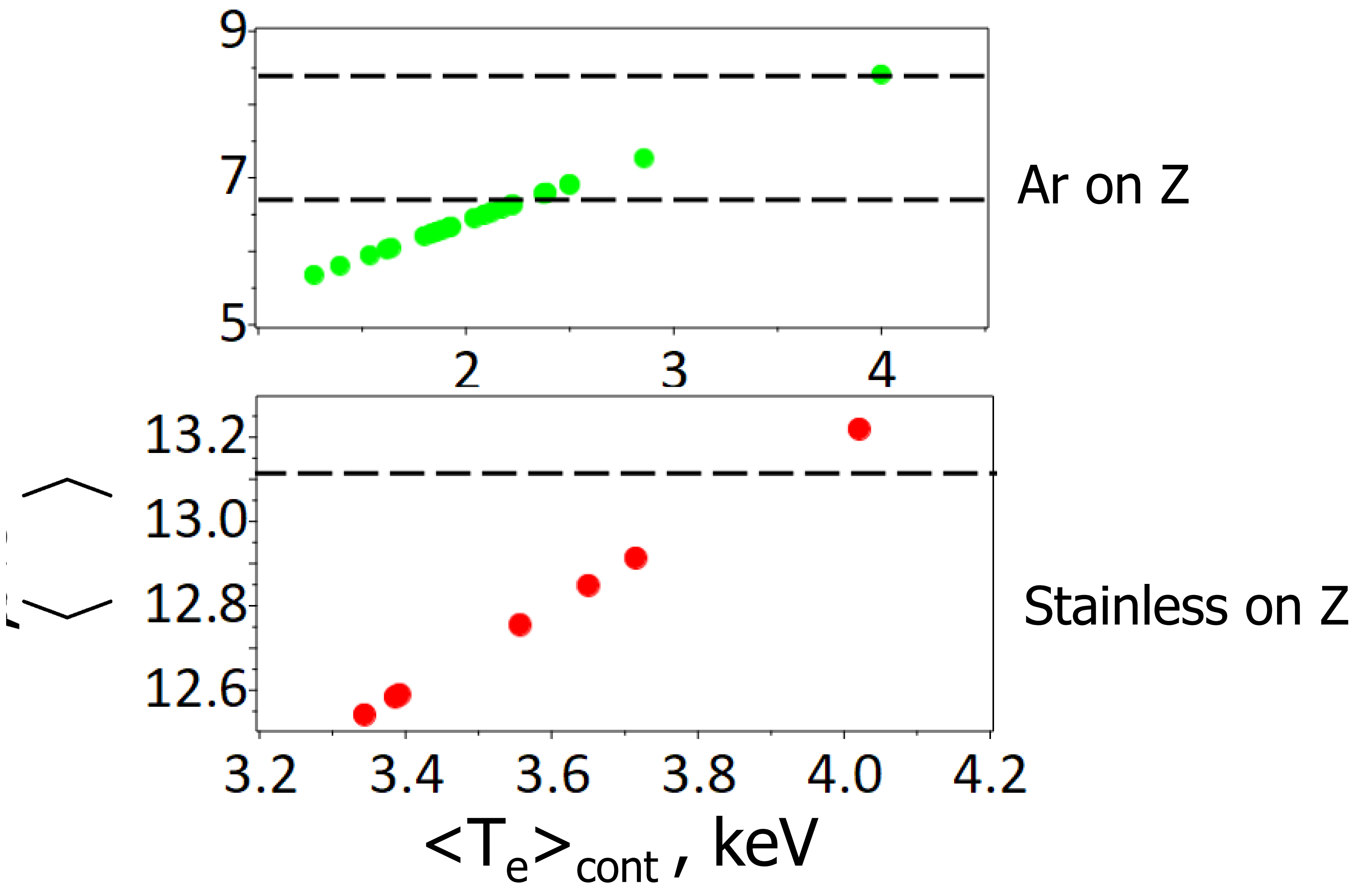
Average low-Z_A continuum photon energy equals high-Z_A K-shell line photon energy



A. L. Velikovich *et al.*, Phys. Plasmas **8**, 4509 (2001); IEEE Trans. Plasma Sci. **38**, 618 (2010); J. W Thornhill *et al.*, **34**, 2377 IEEE Trans. Plasma Sci. (2006).

Lower-Z_A continuum can be in the energy range of higher-Z_A K-shell emission

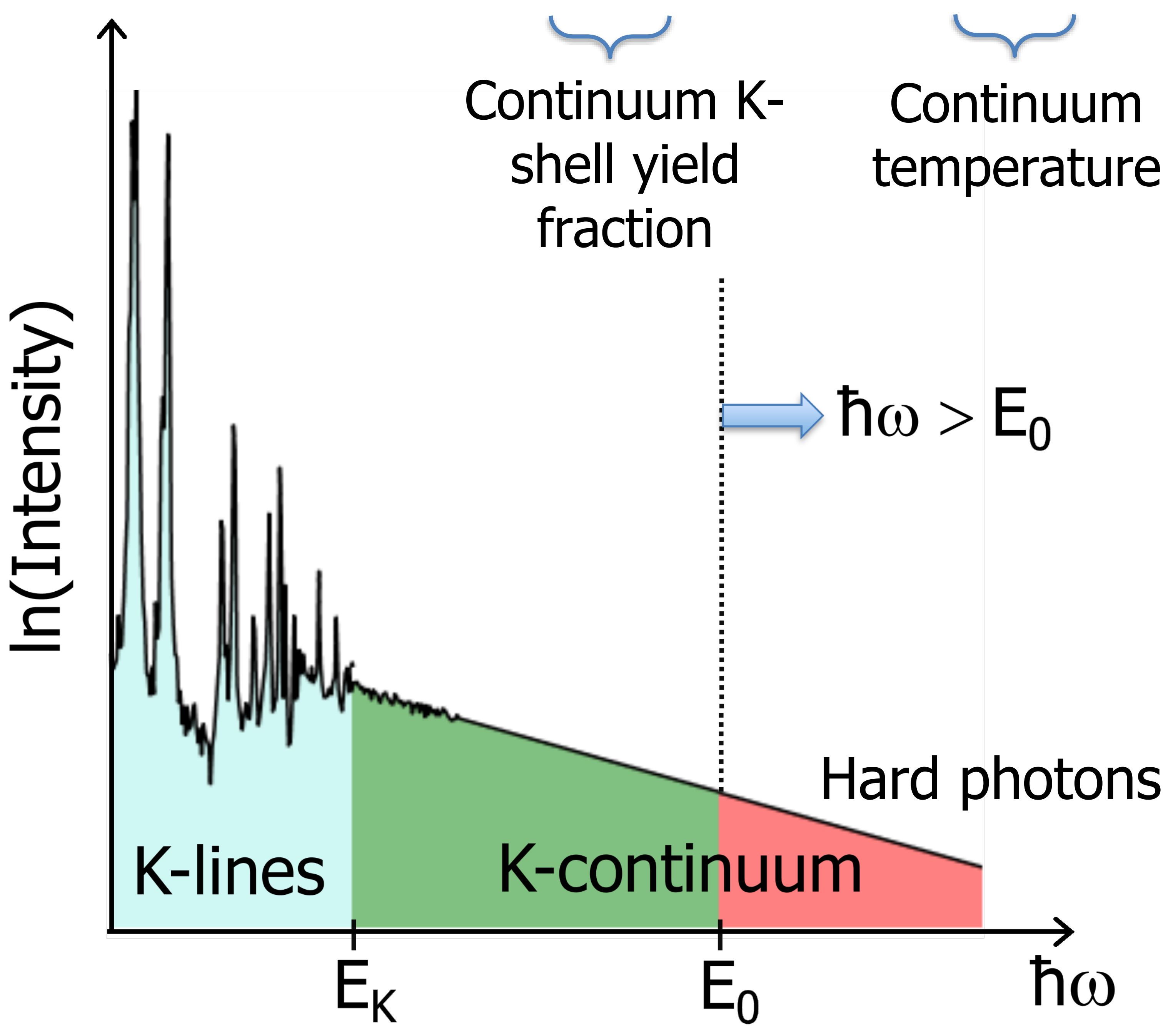




- Iron at 4 keV – same average continuum photon energy as Kr K-shell (demonstrated on Z)
- Copper at 6.6 keV - same as Mo K-shell
- Germanium at 8.6 keV - same as Ag K-shell

} Projections for next-gen facilities

Contradictory requirements for increasing hard-photon continuum yields



- To generate "warm" photons, we need
  - High K-shell yield
  - High electron temperature
  - High continuum fraction
  - Low difference E_0 - E_K

  (High K-shell yield and high electron temperature: Favor low Z_A; high continuum fraction and low difference E_0 - E_K: Favor high Z_A)
- Estimated for Fe and Cu at next-gen
  - K-shell yield 1000 kJ
  - T_e = 5 - 6 keV
  - Continuum fraction 30%
- => Continuum yields above E_0 = 17 keV (Mo) and 22 keV (Ag), respectively:
  - 63 - 82 kJ and 23 - 35 kJ for Fe
  - 100 - 119 kJ and 36 - 52 kJ for Cu

Hard-photon K-shell continuum emission observed at multi-MA currents

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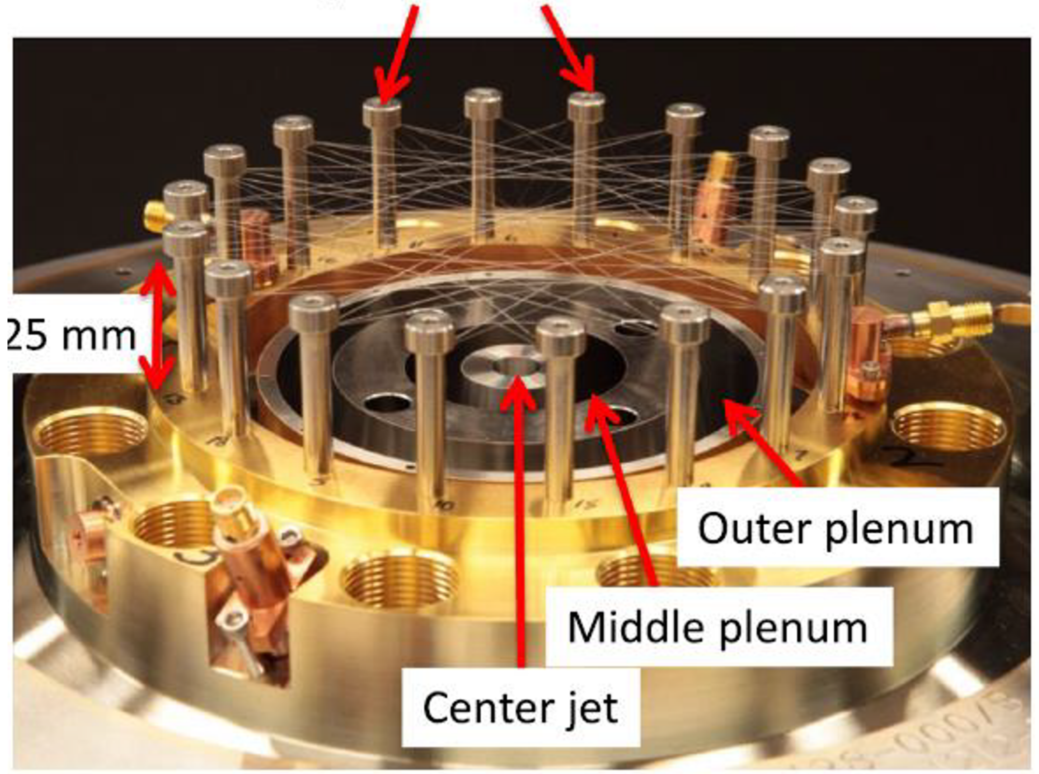
Facility	Current, MA	Material	K-shell yield, kJ	Continuum fraction	Year/Ref.
MAGPIE	1	Al	Not measured	At bright spots only	2006 [1]
Decade Quad	6	Ar	35	6-10%	2006 [2]
Z	19	Al	160	>25%	1998 [3]
	~15	Ar	275	29%?	2000 [4, 5]
			250	12%	2014 [6]
			up to 400	10-20%	Since 2015 – present work
	20-22	Stainless steel	90	7 to 20%?	

[1] G. Hall *et al.* Phys. Plasmas **13**, 082701 (2006); [2] F. C. Young *et al.*, IEEE Trans. Plasma Sci. **34**, 2312 (2006); [3] J. P. Apruzese *et al.*, Phys. Plasmas **5**, 4476 (1998); [4] H. Sze *et al.*, Phys. Plasmas **7**, 4223 (2000); [5] P. L. Coleman *et al.*, IEEE Trans. Plasma Sci. **35**, 31 (2007); B. Jones *et al.*, IEEE Trans. Plasma Sci. **42**, 1145 (2014).

Argon and stainless steel PRS load designs optimized for K-shell emission

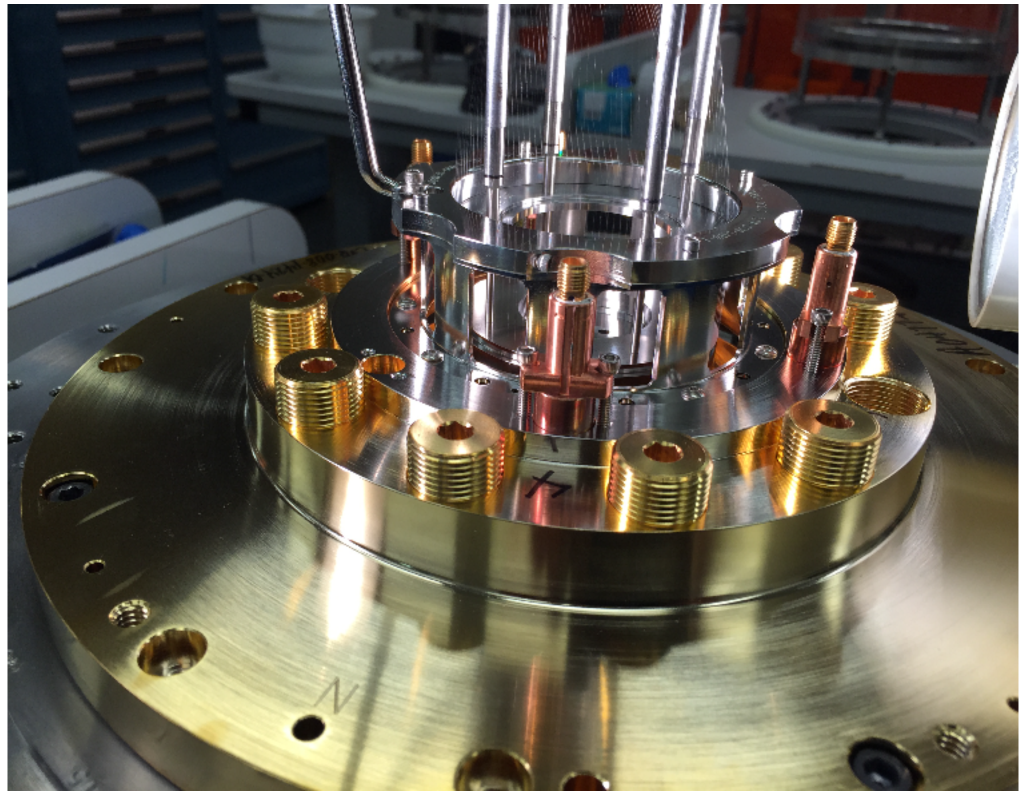
NRL PPD

Argon, 25 shots



- Double-shell ∅80 mm gas puff
- Most shots w/o central jets
- Line masses ~385/616 μg/cm
- Height 3 cm

Stainless steel, 8 shots



- Nested wire array, ∅70/35 mm, 112/56 wires
- Wire diameter 8.56 μm
- Total mass ~1.533 mg
- Height 2 cm

B. Jones *et al.*, Phys. Plasmas **22**, 020706 (2015); A. J. Harvey-Thompson *et al.*. Phys. Plasmas **23**, 101203 (2016); D. J. Ampleford, *et al.*, Phys. Plasmas **21**, 056708 (2014).

Volume and lifetime of the K-shell emitting plasma are confidently measured

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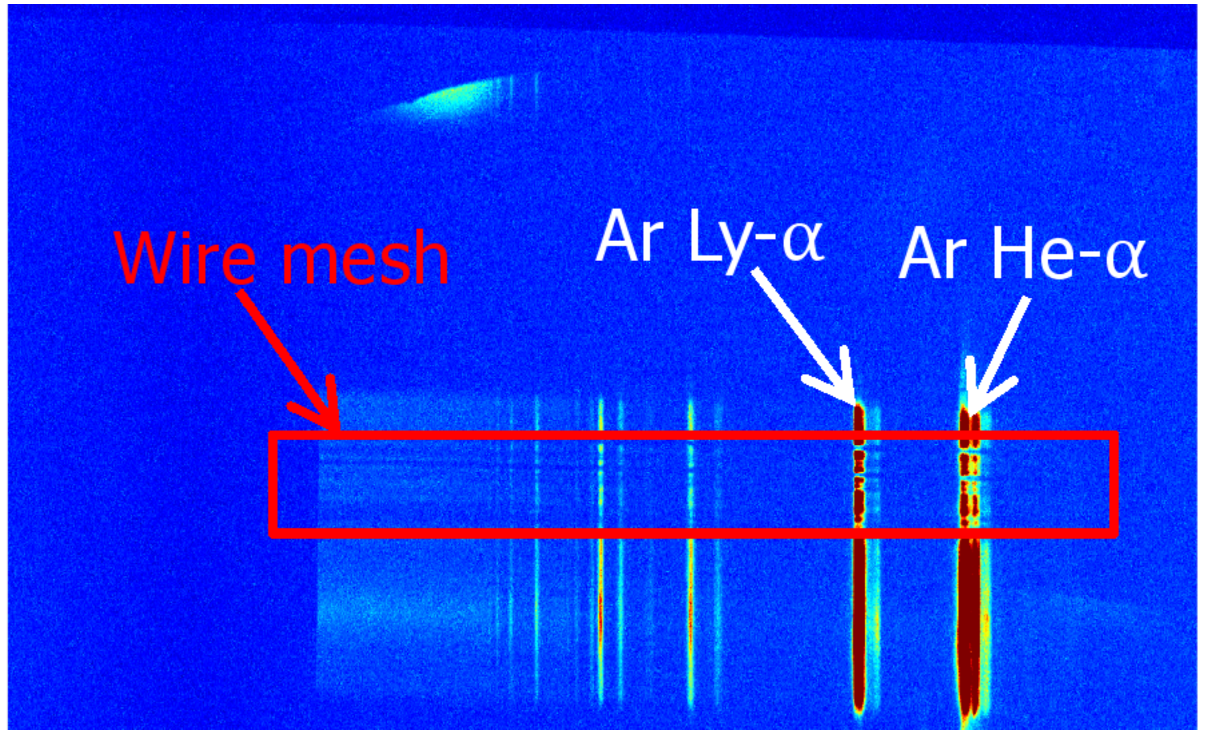
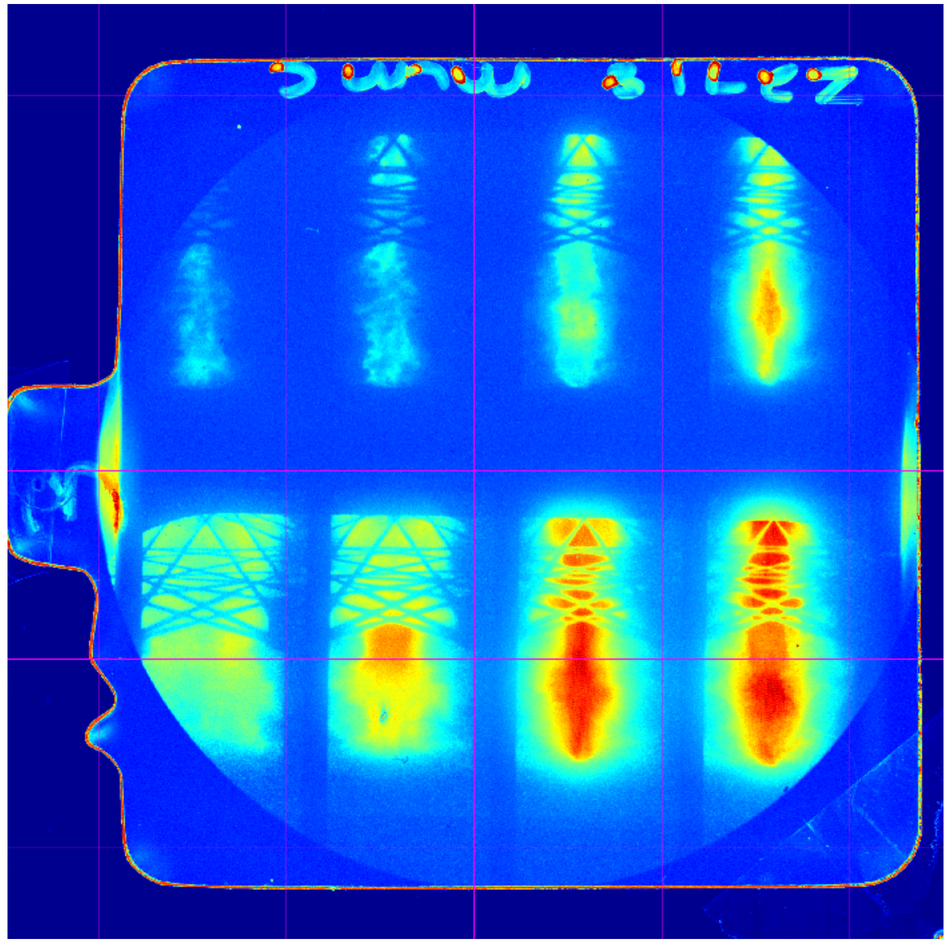
Time-integrated, axially resolved spectroscopy



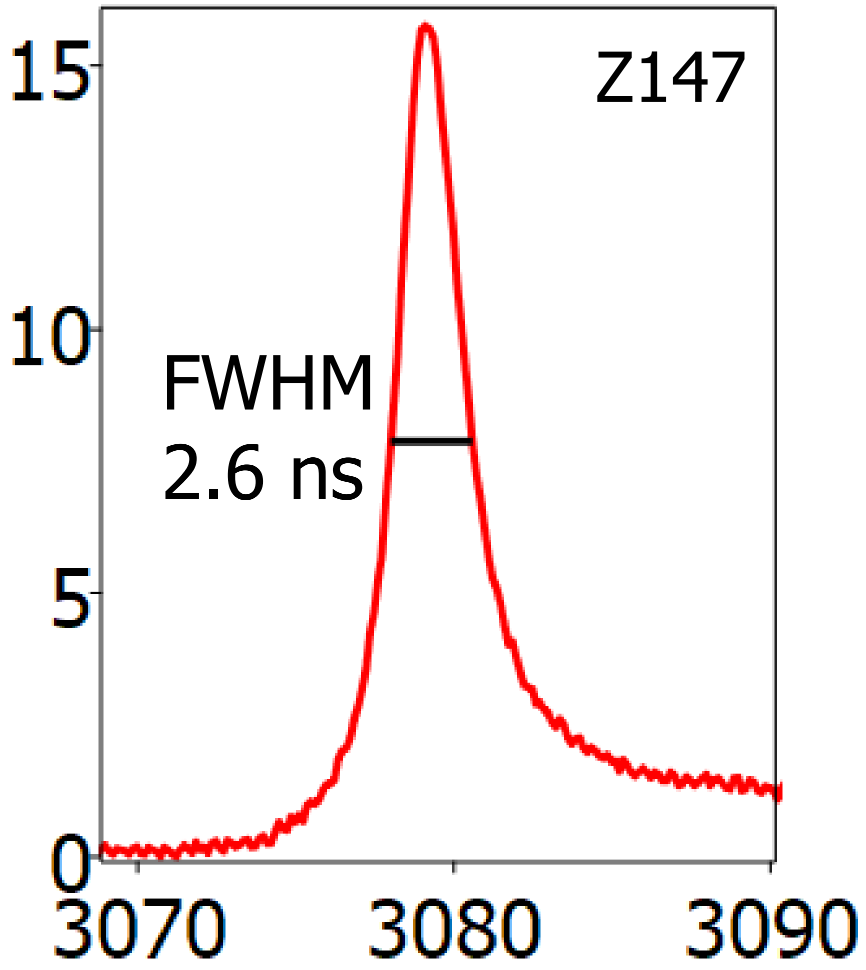
K-shell height Ar

K-shell diameter Ar

Time-gated multi-layer-mirror (MLM) x-ray camera



X-ray power signal, arb. units



K-shell FWHM SS

	Height, mm	Diameter, mm	Volume, cm^3	FWHM, ns
Argon	2.5 to 3.5	1 to 3	0.05 to 0.36	4 to 12
Stainless	2	0.8	0.01	2.5 to 3.5

Absolutely calibrated spectra for stainless steel shots

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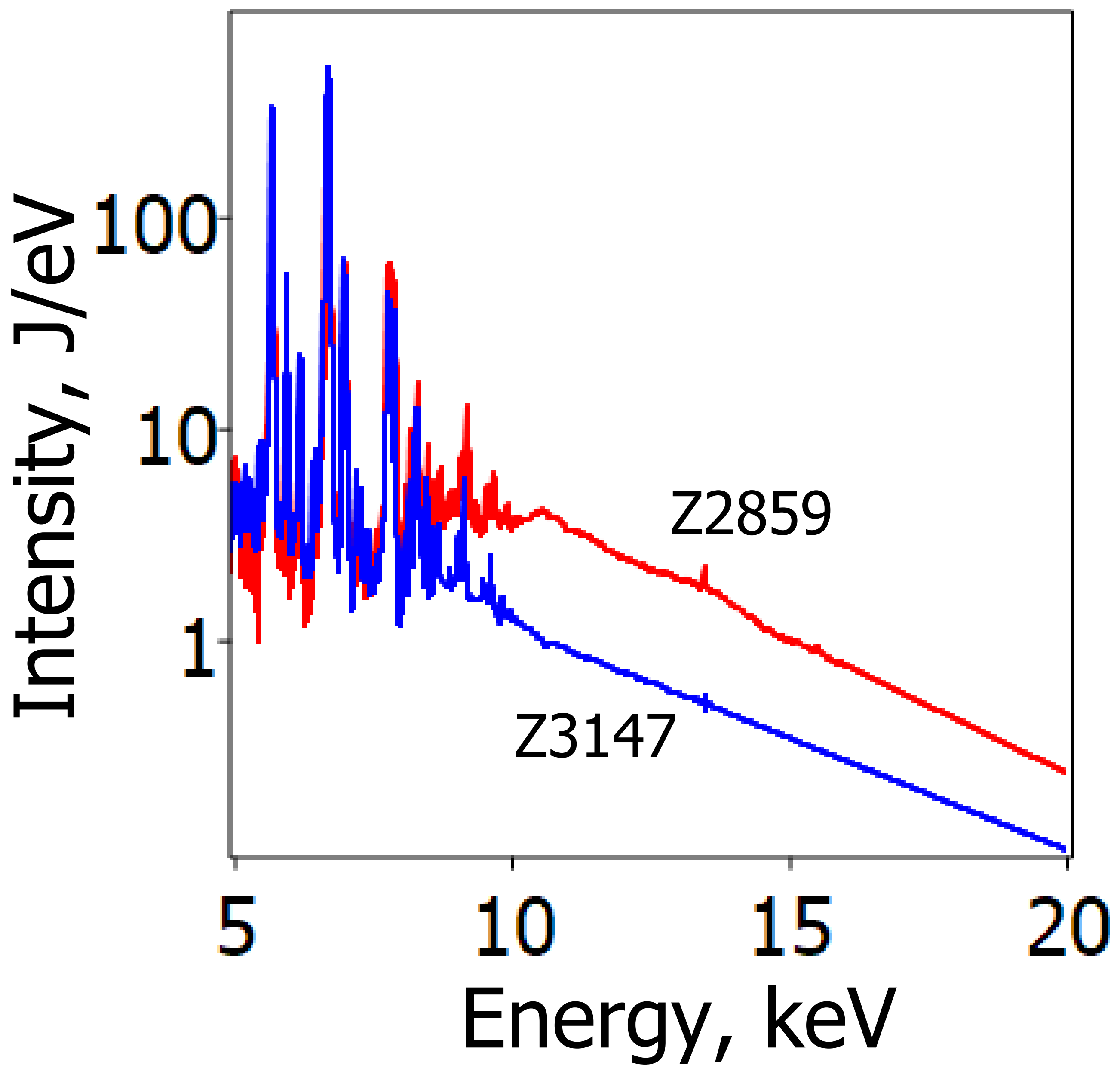
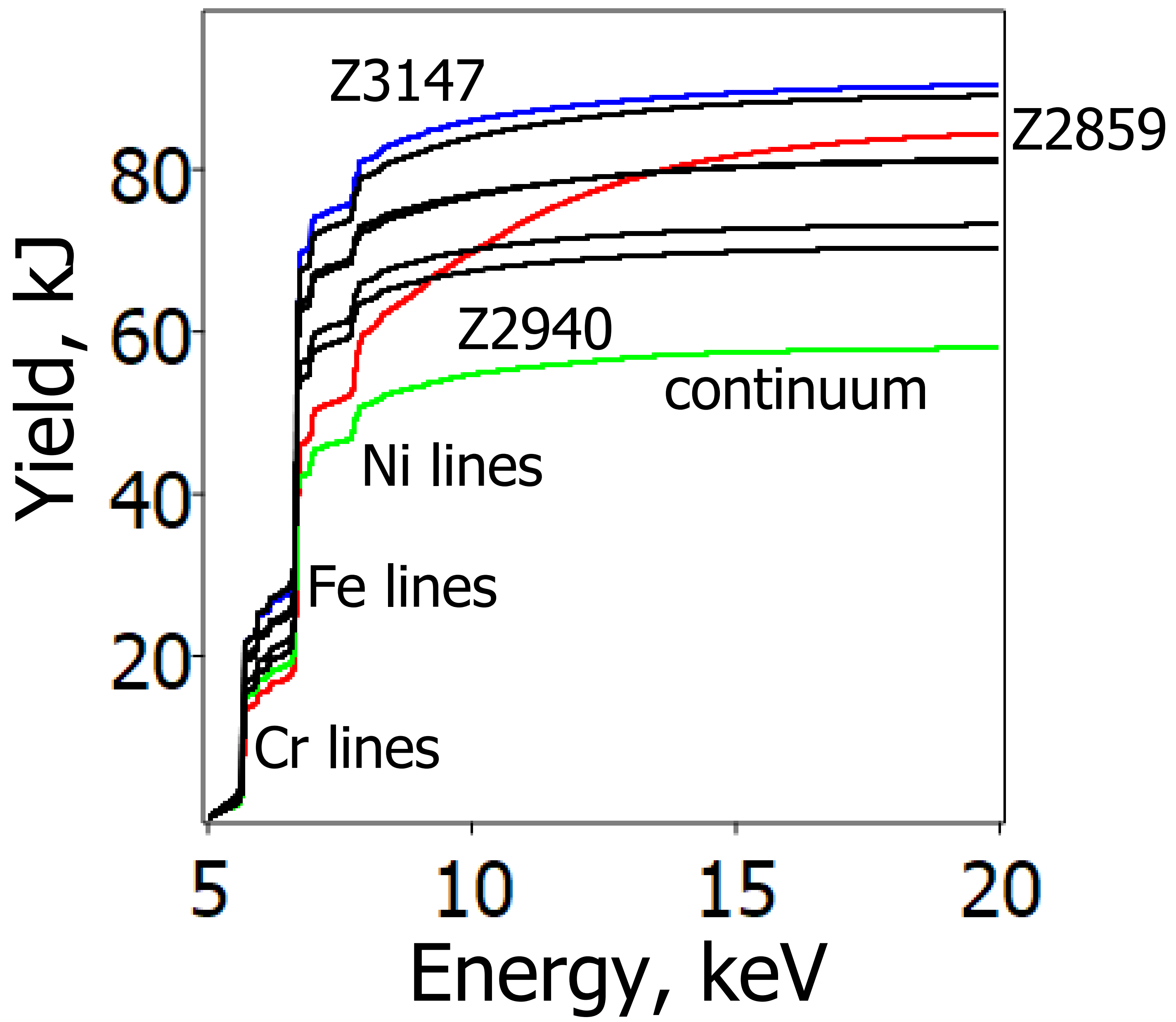
TIXTL-AR and CRITR spectrometers; calorimeter, bolometer, and PCDs for absolute yield calibration

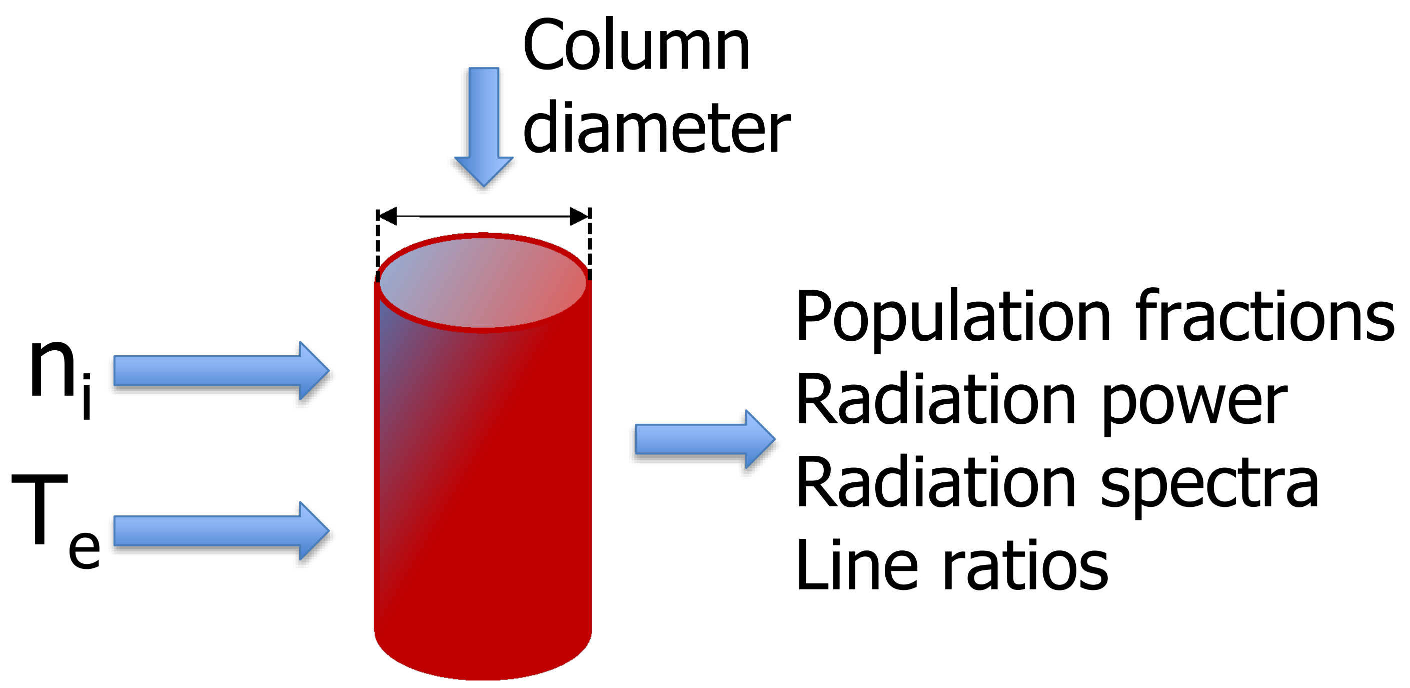


Cumulative K-shell x-ray yields above 5 keV



Models and codes used for 0-D diagnostics and scaling

- NRL atomic / radiation codes Drachma-I and Drachma-II, in some cases PrismSPECT
- Detailed collisional-radiative model with non-LTE atomic model
- Atomic population-rate equations are solved
  - All ground levels and excited levels with $n < 5$ are kept at fine-structure levels
  - For $5 \leq n \leq 7$ configuration-averaged level structures are used
- Atomic processes involved in level calculations
  - Spontaneous radiative decay
  - Collisional excitation and ionization
  - Photoexcitation and photoionization
  - Dielectronic recombination
- Radiation transport/opacity effect
  - Probability of escape method
  - Multifrequency method
- No hydro, single zone for density and temperature, single or multiple zones for radiation transport and ion populations



NRL method of evaluating the temperature of the K-shell emitting plasma from the observed ratio of Ly-a to He-a + IC lines and radiation power[1,2]

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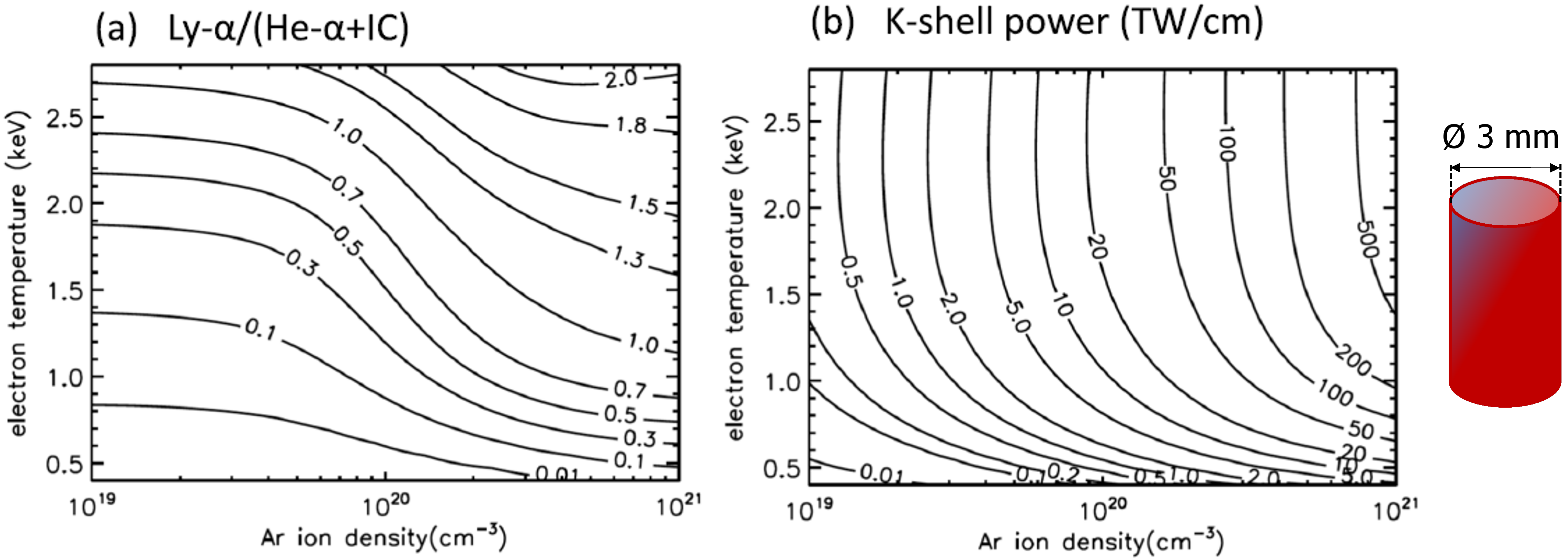


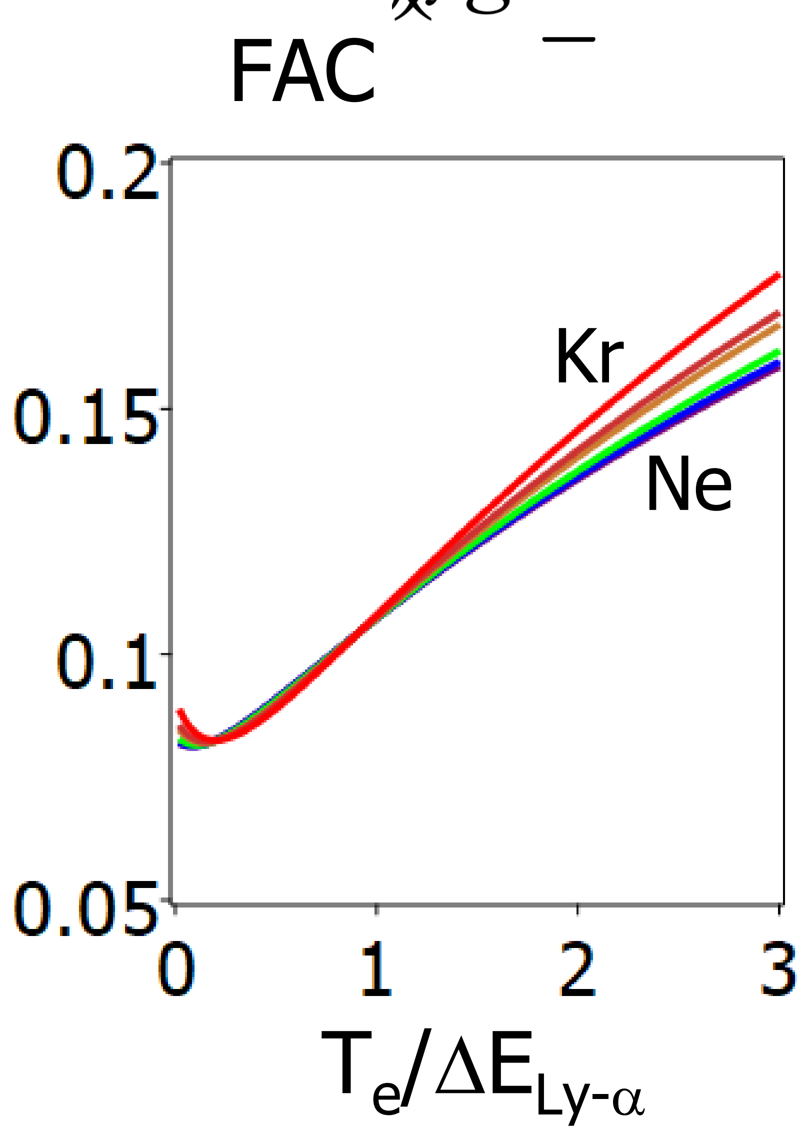
(a) Contours of the ratio of the radiated power in the Ly-α line to the to He-α plus IC lines for a ∅3-mm Ar plasma. (b) Contours of the K-shell power above 3 keV for the same conditions. Superpose and find the intersection. Data courtesy of John Apruzese.

[1]J. P. Aprusese *et al.*, JQSRT **57**, 41 (1997).
[2]J. L. Giuliani and R. J. Commisso, IEEE Trans. Plasma Sci. **43**, 2385 (2015).

Two-level Seaton's and Kramers' formulas used for sanity checks

Analytical formulas for optically thin radiation power density

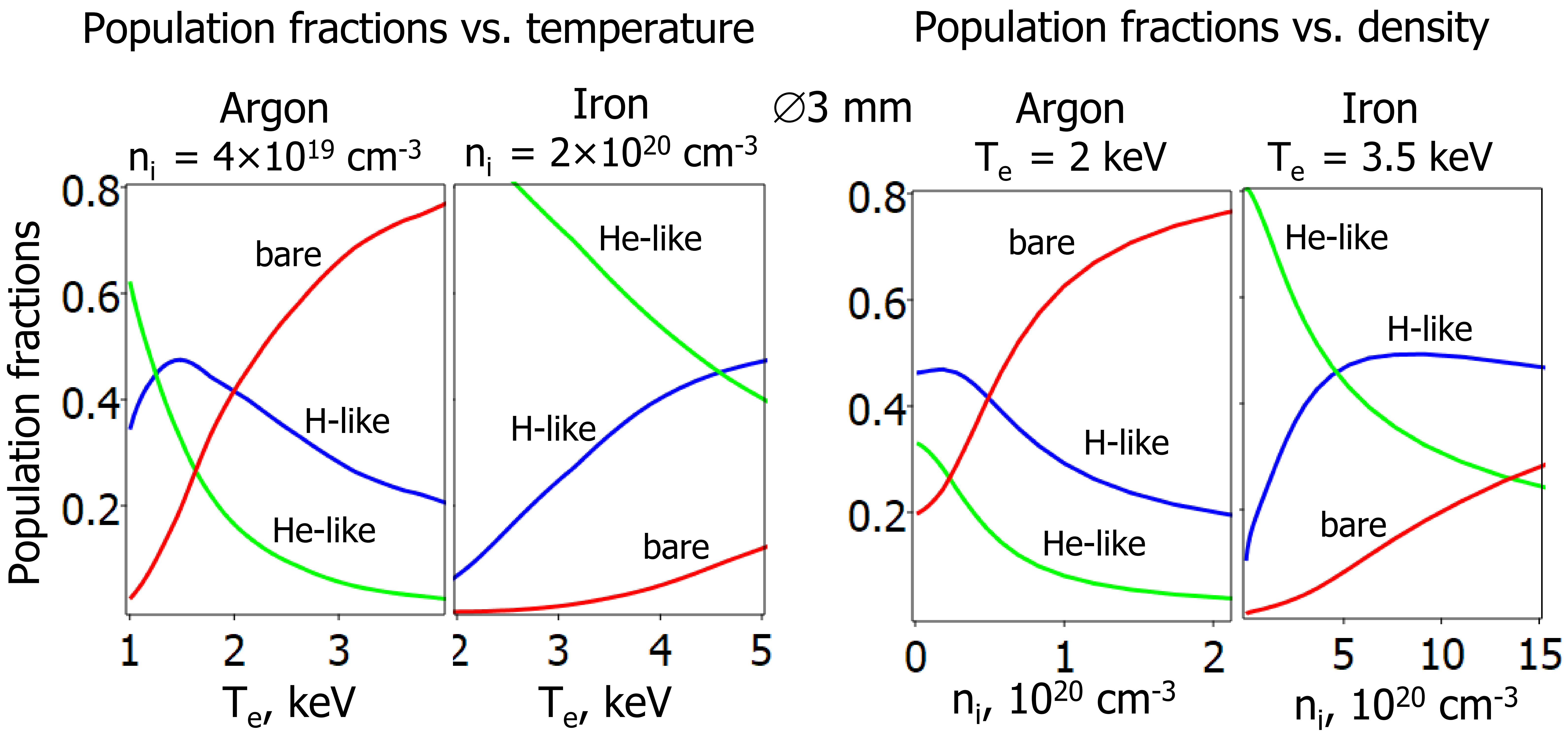
Favors high Z_A $\quad$ T_e-dependent, of order unity



Formulas used in deriving of NRL scaling laws. Updated by using the Flexible Atomic Code to calculate the Maxwellian-averaged product of the oscillator strength and the Gaunt factor.

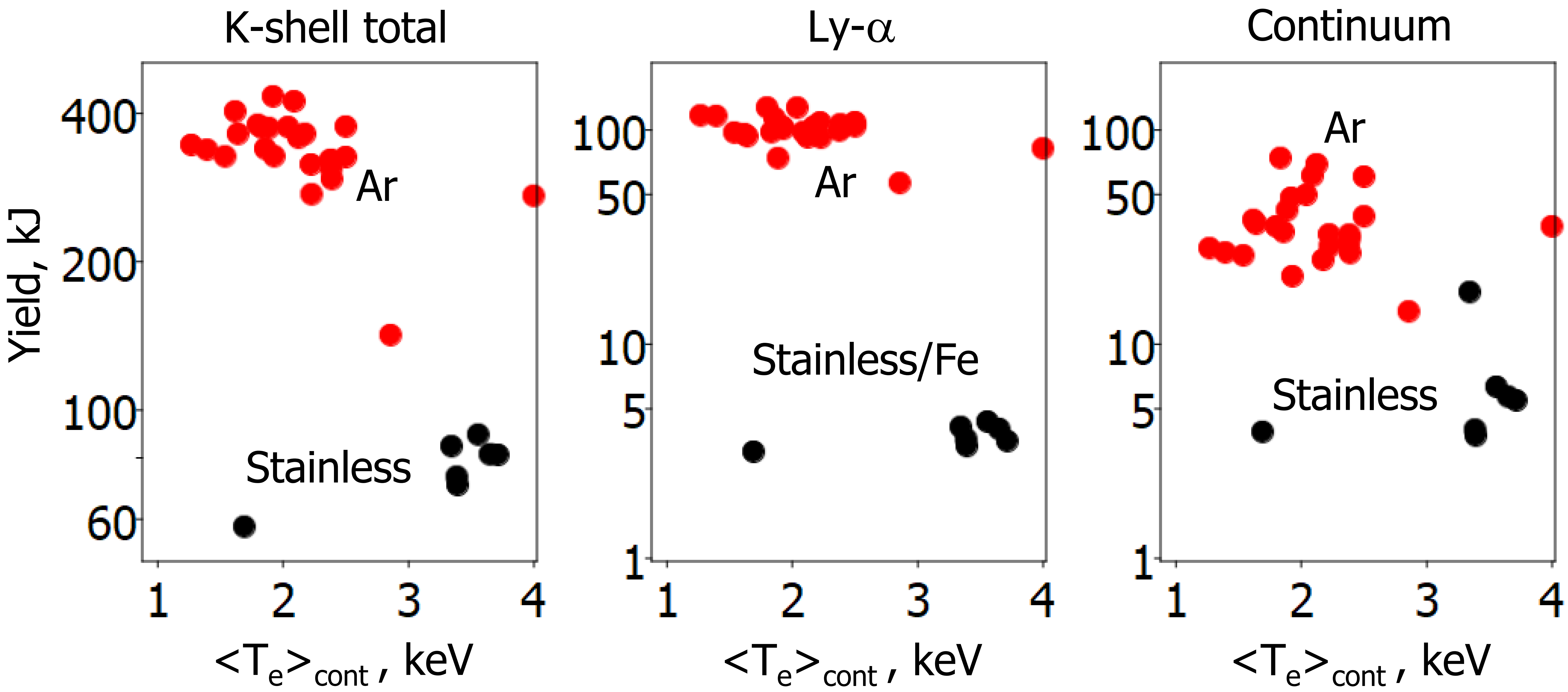
K. G. Whitney *et al.*, J. Appl. Phys. **67**, 1725 (1990); D. Mosher *et al.*, IEEE Trans. Plasma Sci. **26**, 1052 (1998).

High temperature and high density contribute to continuum emission



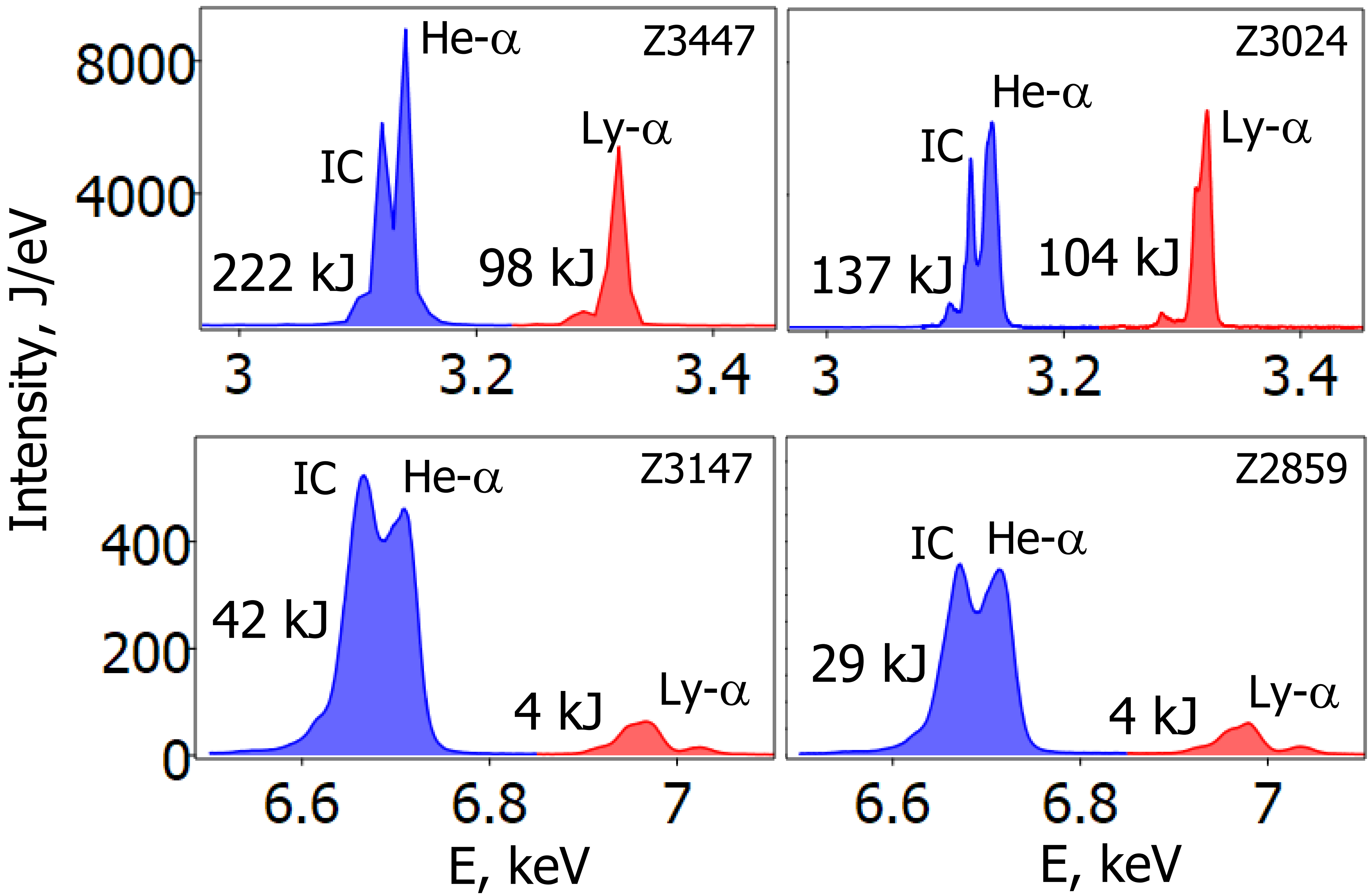
The stagnation density is easier to increase than the temperature on next-gen facility

Measured yields from Ar gas puffs and stainless steel wire arrays



More scatter in continuum yields

Substantial H-like populations are produced in both Ar and stainless Z shots



Argon: large Ly-α/He-α ratio

Yield = shaded area below the line shape

Stainless steel / Fe: small Ly-α/He-α ratio

Inferred temperatures and densities for K-shell emitting Ar are consistent

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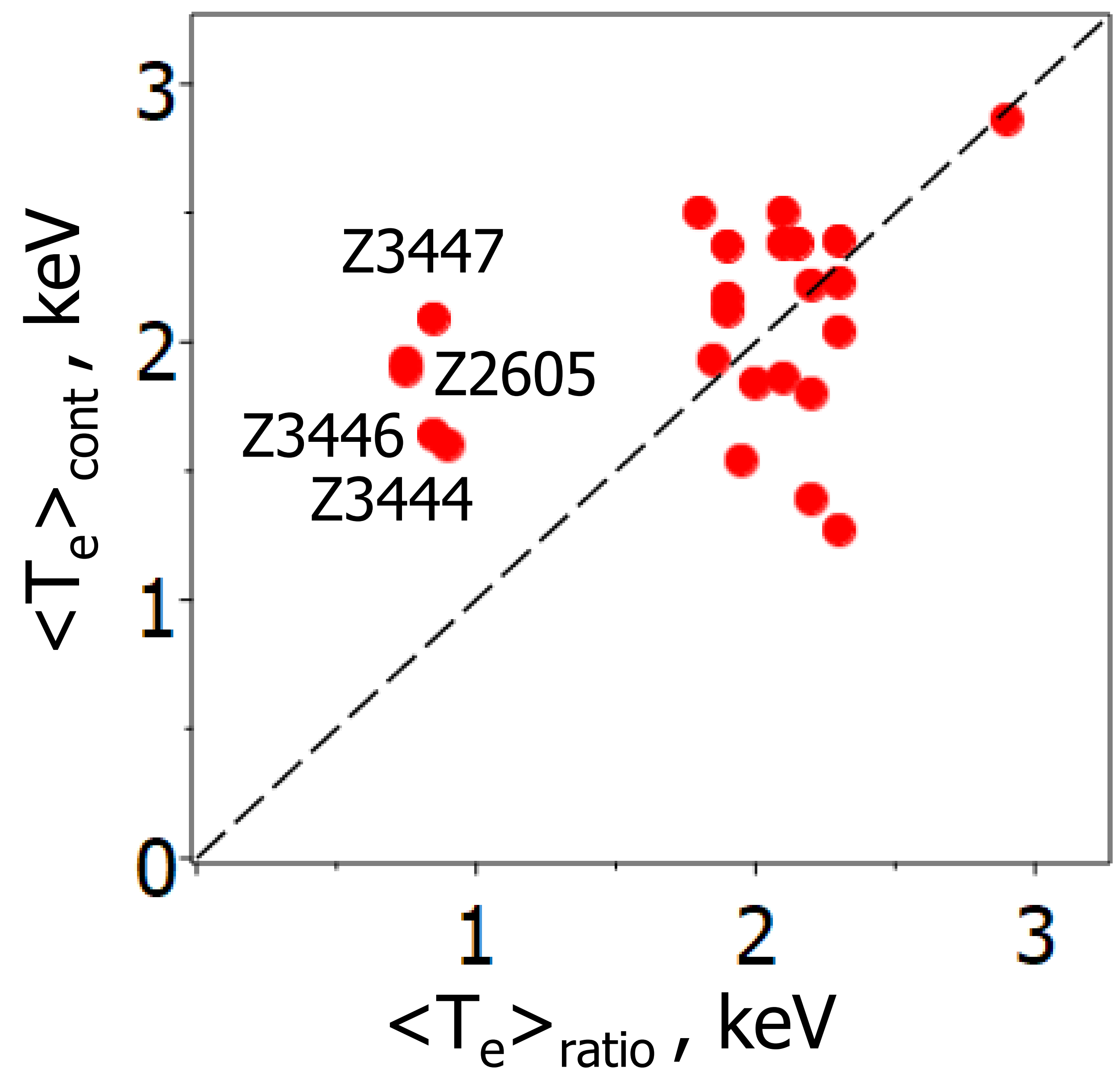
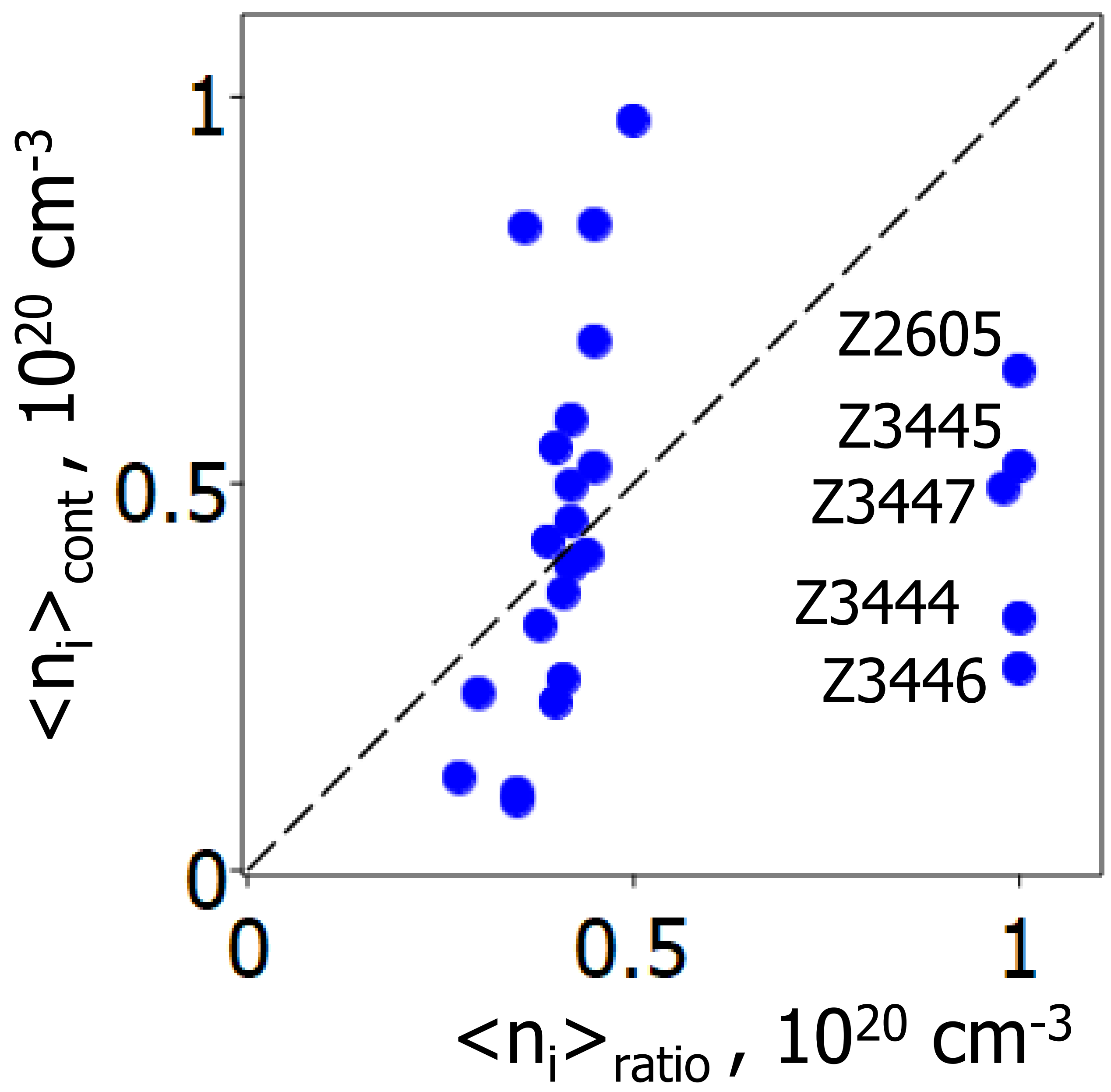
Electron temperatures



Ion densities

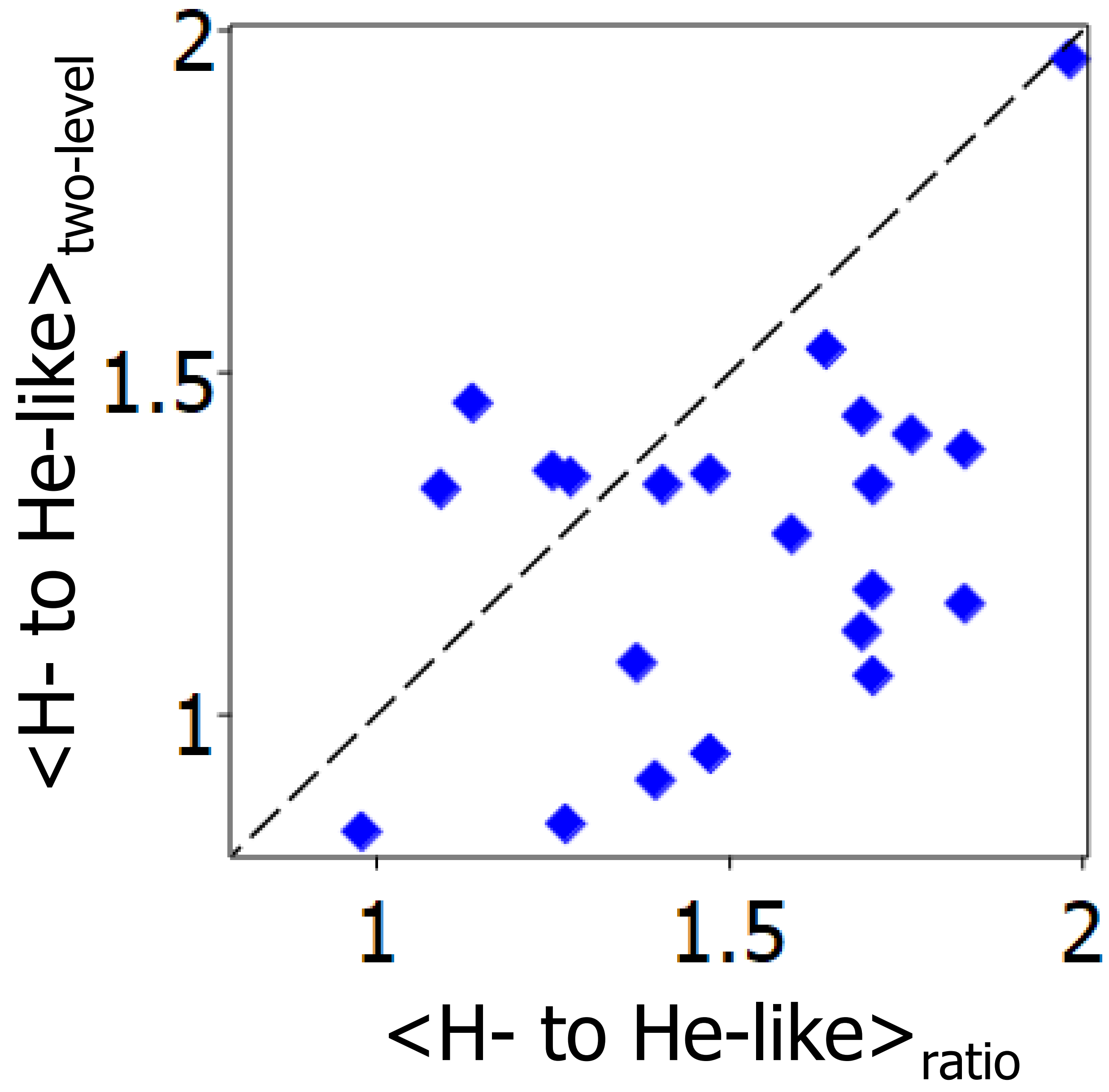


More scatter in all continuum estimates

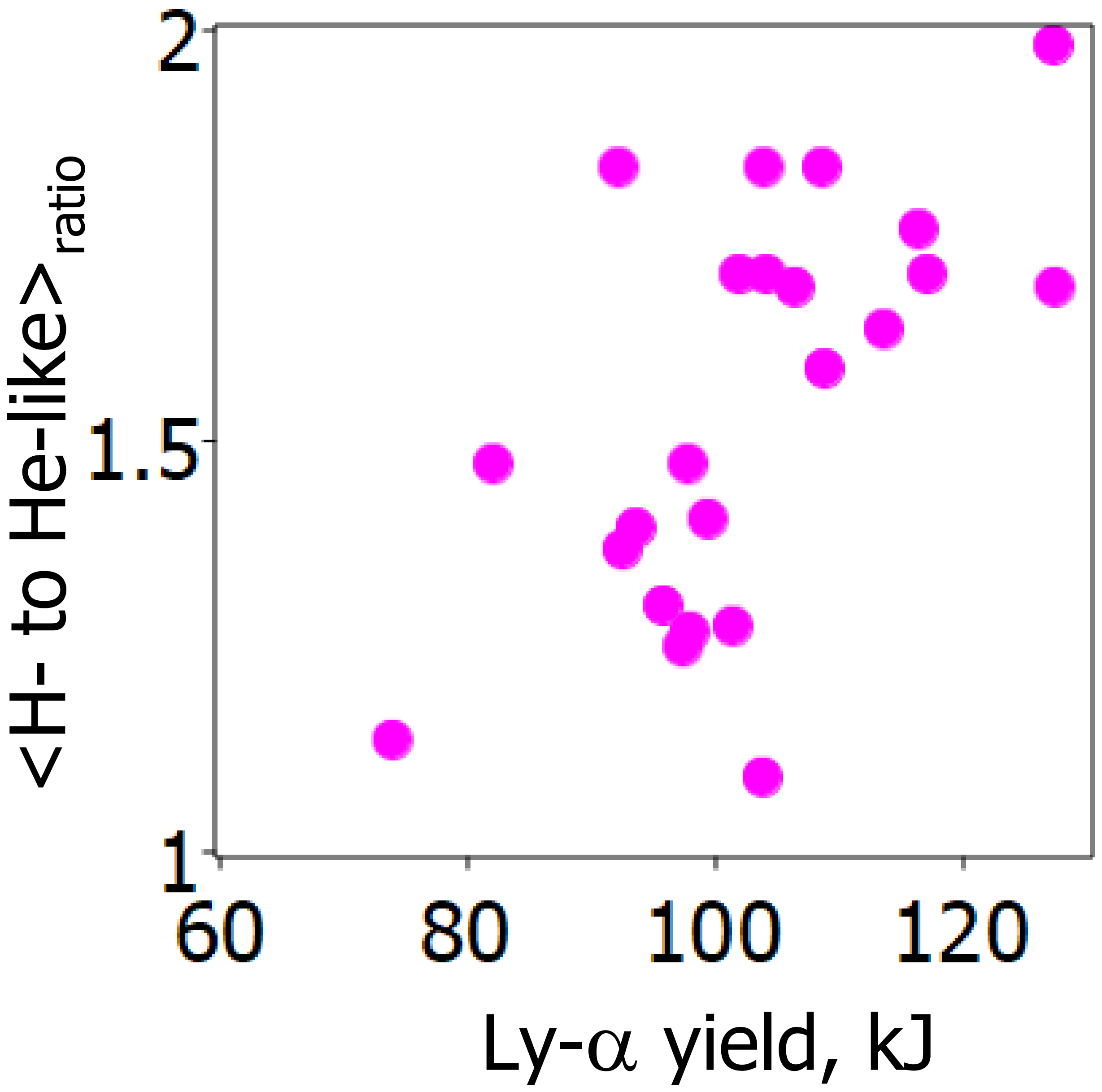
Al on Z: J. P. Apruzese *et al.*, Phys. Plasmas **5**, 4476 (1998)
Ar on Z: B. Jones *et al.*, IEEE Trans. Plasma Sci. **42**, 1145 (2014).

The H-like Ar ion population emitting in K-shell is larger than the He-like

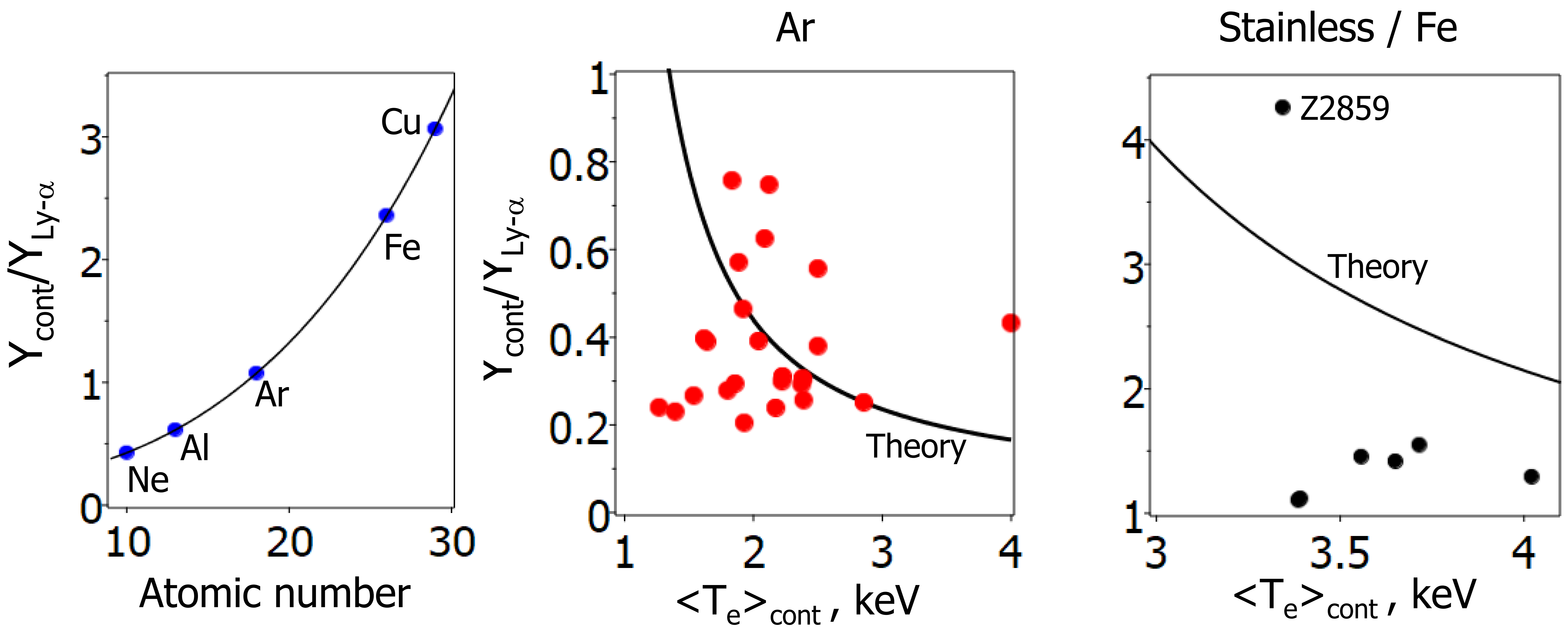
Two-level vs line ratio estimates



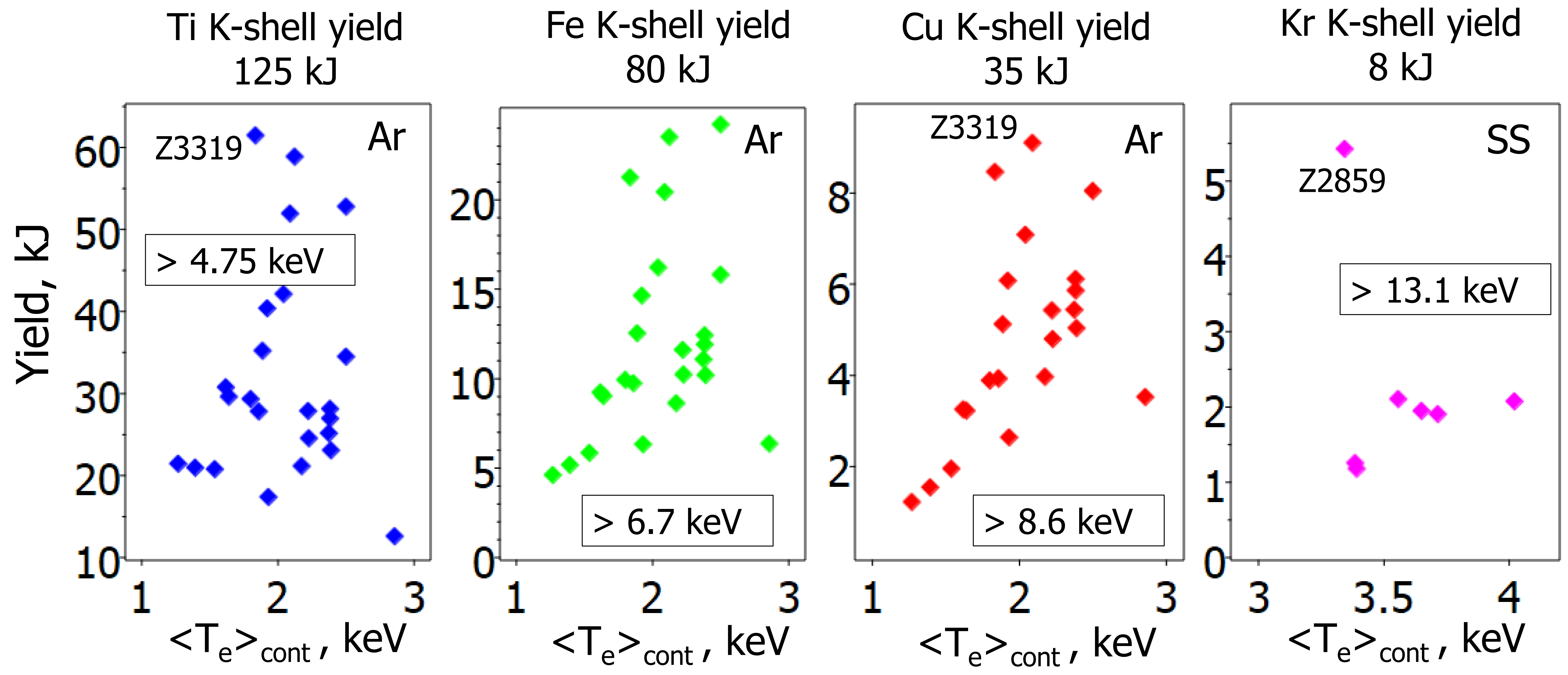
Population ratio vs Ly-α yield



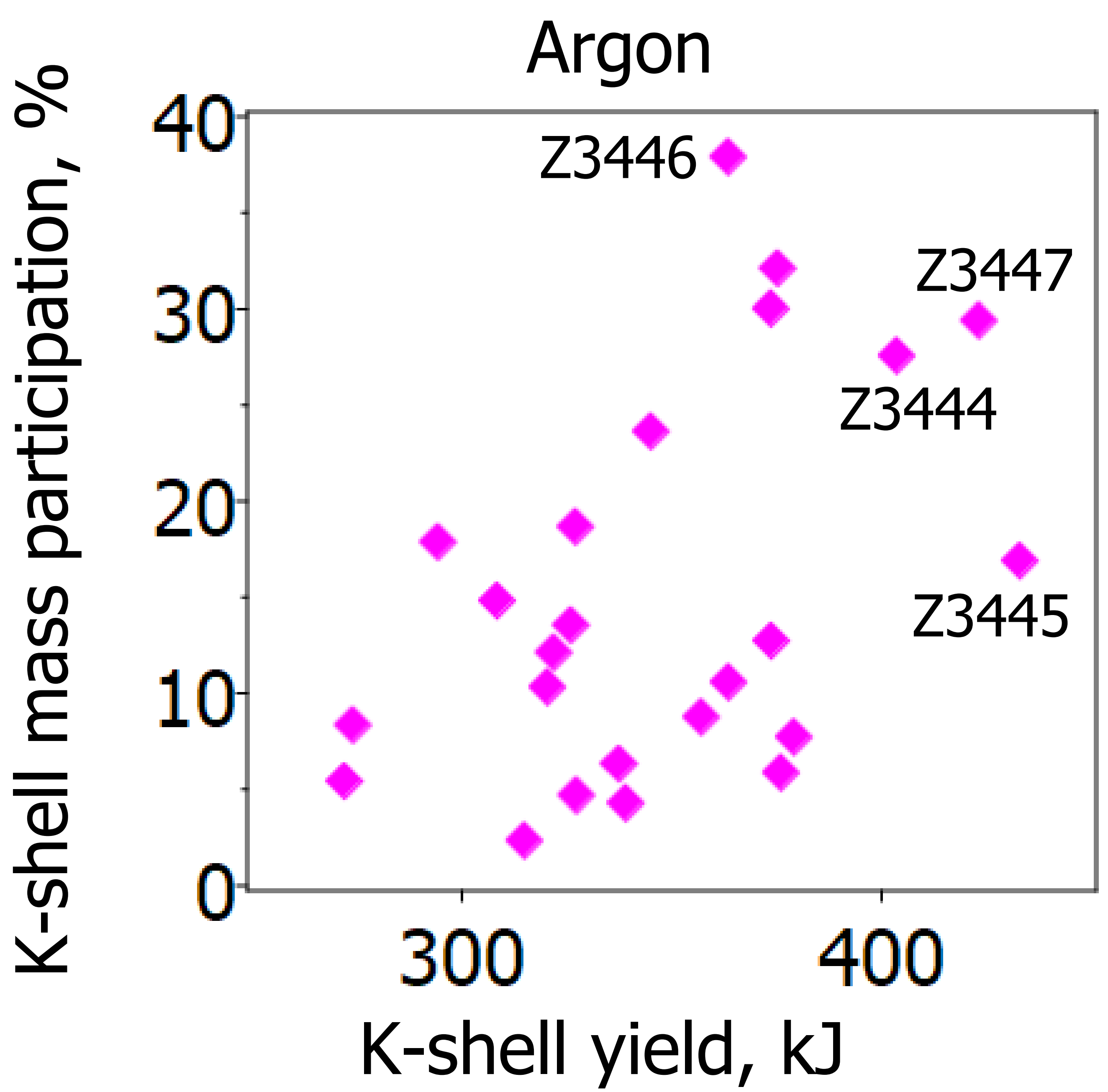
Continuum emission from H-like ions increases with the atomic number and decreases with the temperature

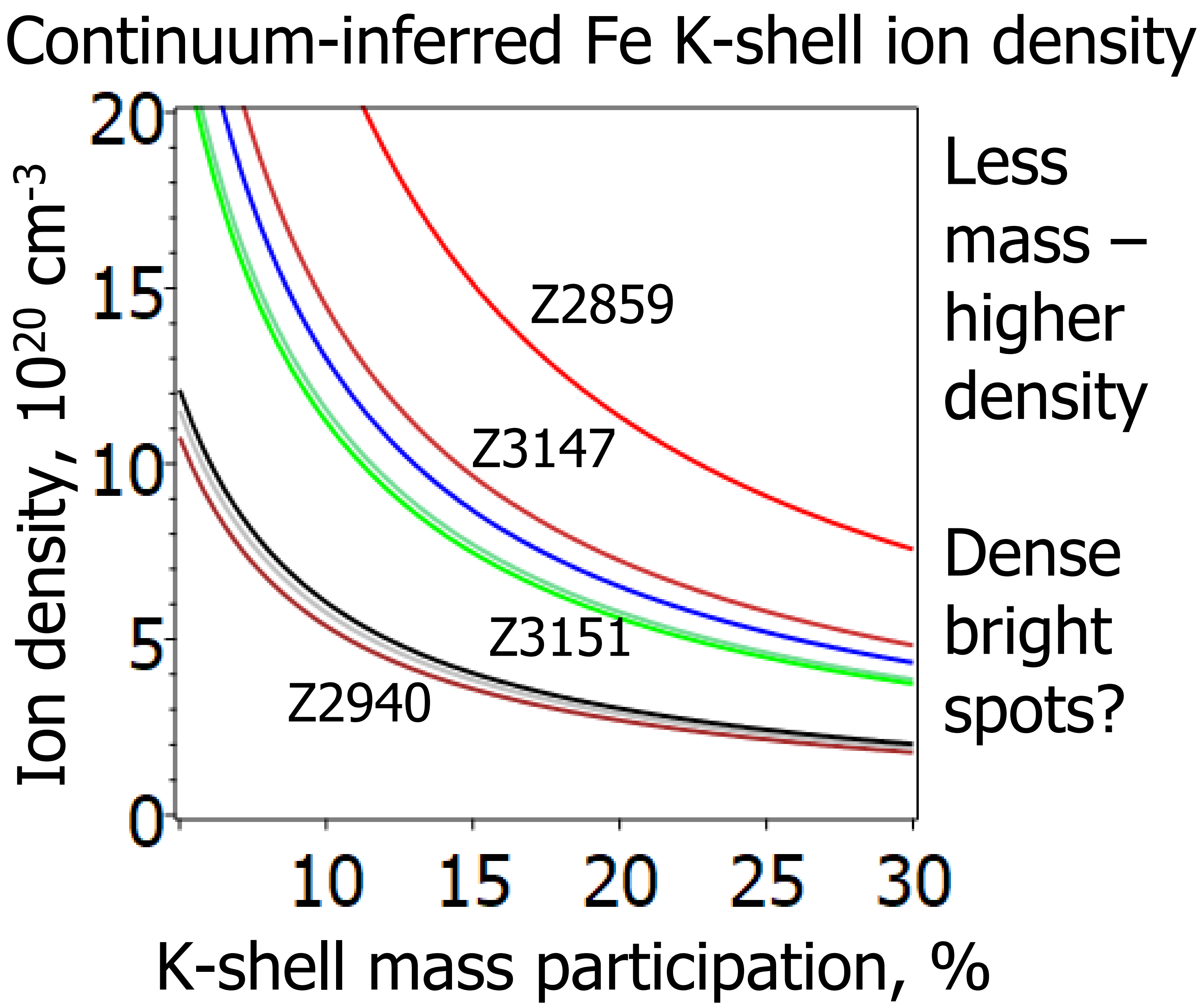


Where available, K-shell line yield is greater than comparable continuum



Argon data is consistent with the radiating cylinder model. Stainless is not.





Less mass – higher density

Dense bright spots?

Assuming the continuum-radiating H-like ions fill the whole K-shell emitting volume, 0.01 cm_{-3}, we arrive at unrealistically high K-shell mass participation. Limiting the mass participation, results in high Fe ion densities, likely above 6×10^{20} cm^{-3}. Consistent with Y. Maron's spectroscopic bright-spot density estimates. J. P. Apruzese *et al.*, Phys. Plasmas **20**, 022707 (2013).

Continuum fraction of the K-shell yield increases with current

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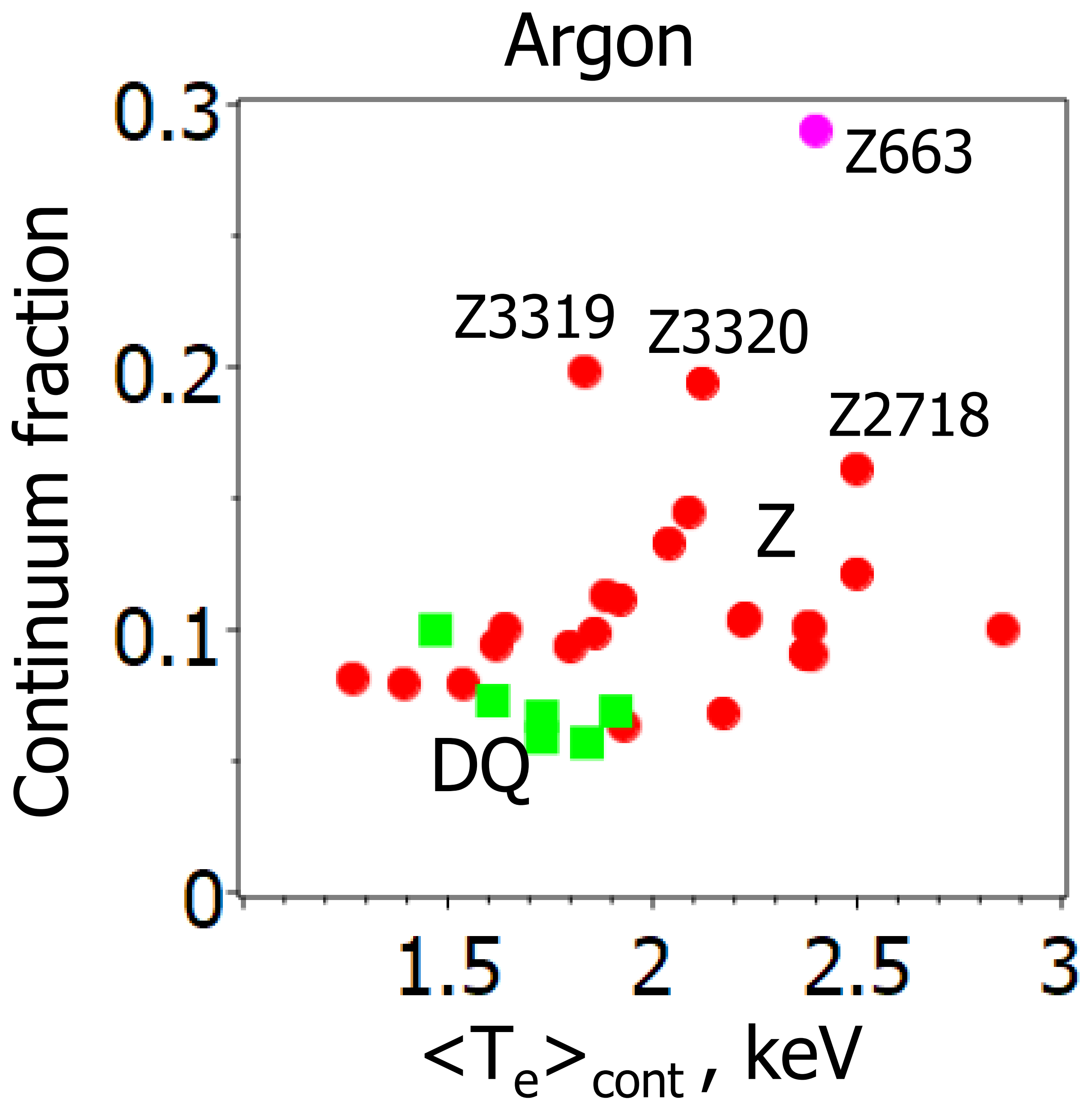
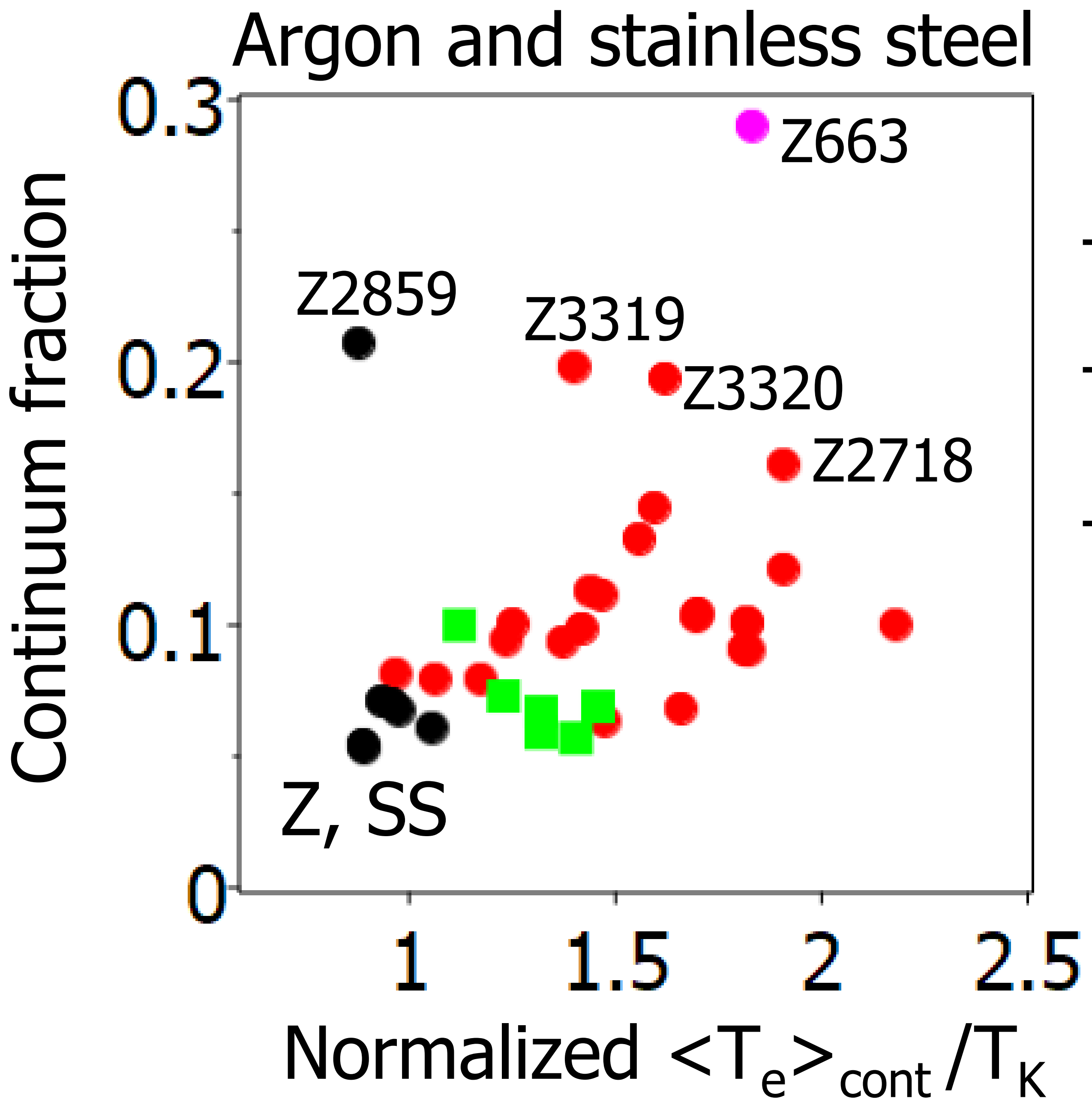




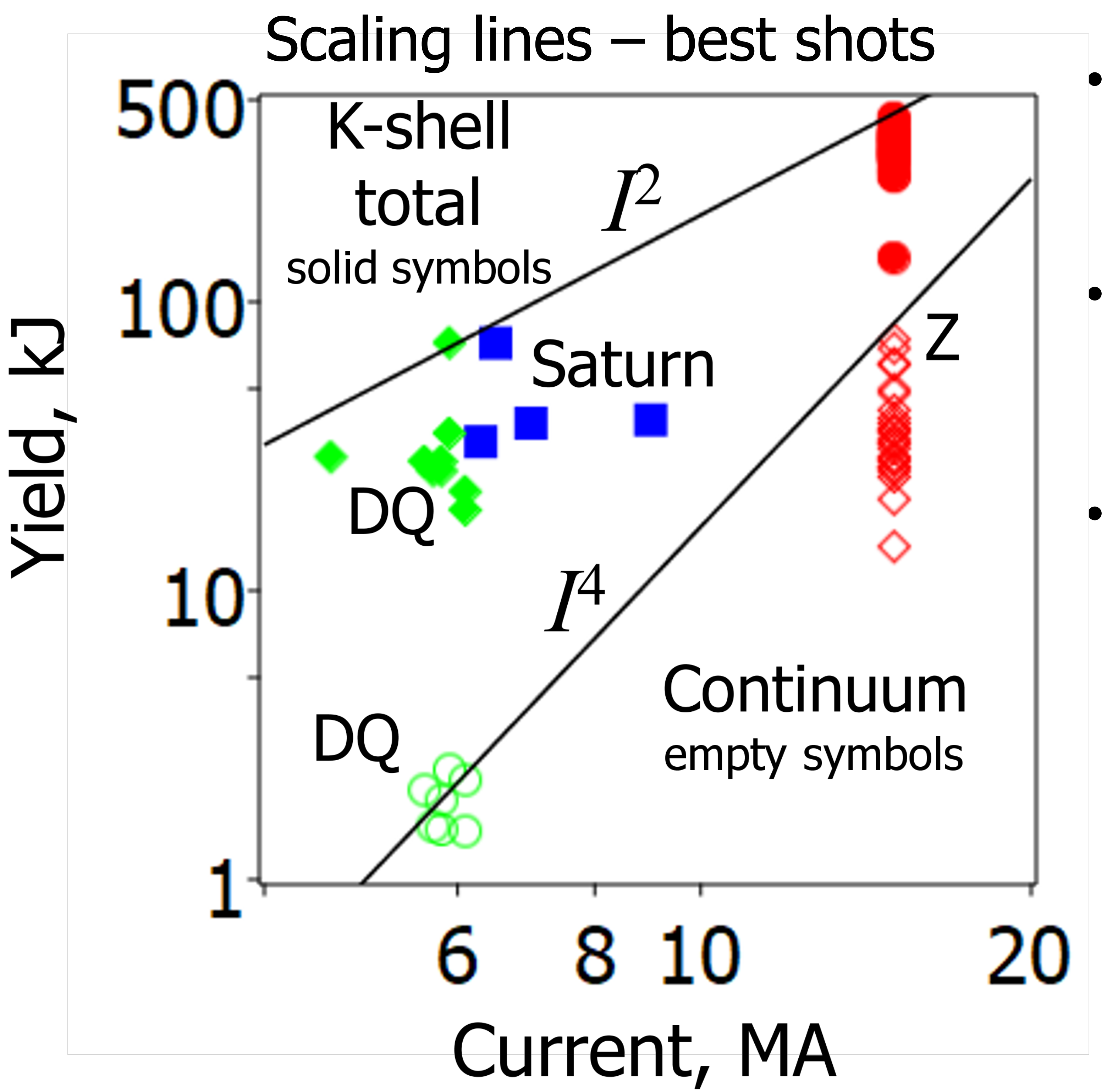
$T_K = 0.3 \times Z_A^{2.9}$ eV

$T_K(Ar) = 1.3$ keV

$T_K(Fe) = 3.8$ keV

Z is about as effective for producing continuum with stainless steel loads as Decade Quad with argon loads. Higher density appears to make difference.

Hard-photon continuum Ar yield on Z scales as I^4



- Efficient regime of Ar K-shell emission is above 6 MA, Saturn – Decade Quad
  - Total K-shell yield scales as I^2 up to Z and beyond
- Continuum emission is still inefficient at 15 MA
  - Continuum yield scales as I^4
  - Continuum fraction will be higher for the next-gen
- Increasing the populations of He-like and bare ions for Fe and Cu at ~40 MA => higher continuum fraction, up to 30%
  - Continuum yield of Fe and Cu increases with the drive current faster than I^4

This conference, Sep. 15: J. Schwarz *et al.*, 8O-D-03, V. Tangri *et al.*, 7P-C-05

Conclusions

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- Thermal K-shell continuum option can be viable for generating "warm" photons on next-gen pulsed power facility
  - Transition from the inefficient bright-spot to the efficient volume emission regime
  - Higher peak temperatures and densities will shift population balance toward H-like and bare ions in Fe and Cu
- The contribution, formation mechanism and structure of bright/dense/hot spots is still an issue to be studied on existing facilities, primarily Z:
  - Detailed spectroscopic diagnostic revealing the spatial structure of the K-shell emitting plasma (Y. Maron,[1] J. P. Apruzese[2]) must be systematically applied
  - Monochromatic curved-crystal imaging of the radiating plasma (S. Pikuz, G. Hall)[3] in its K-shell lines and continuum needs to be developed
  - Affecting the bright-spot formation, e. g., with an external magnetic field[4]

[1]Y. Maron, personal communication (2016).
[2]J. P. Apruzese *et al.*, Phys. Plasmas **20**, 022707 (2013).
[3]G. Hall *et al.* Phys. Plasmas **13**, 082701 (2006).
[4]K. N. Mitrofanov *et al.*, Plasma Phys. Rep. **44**, 55 (2018).