

Spectroscopy of Highly Charged Heavy Ions with an Electron Beam Ion Trap

Amy Gall

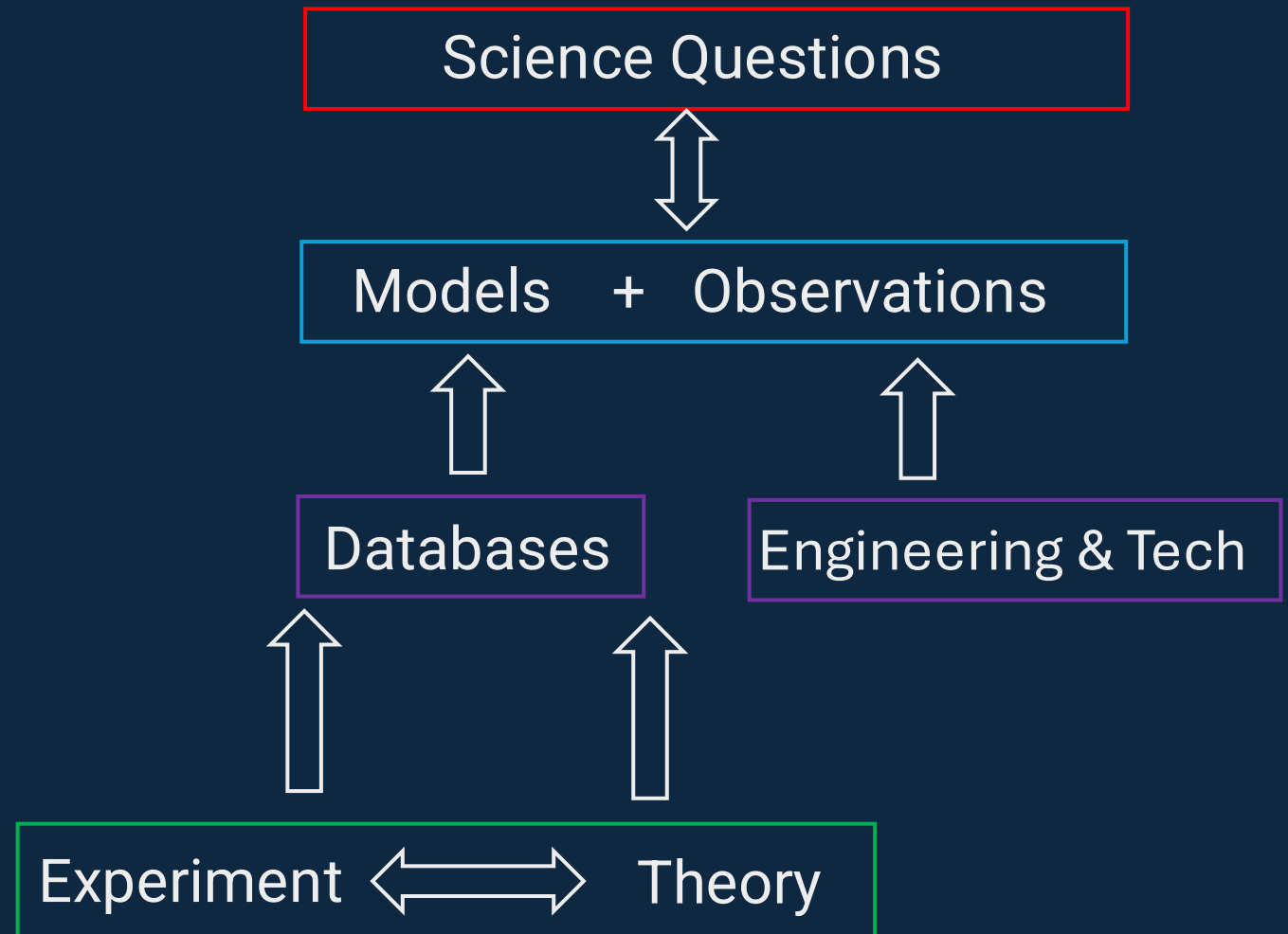
HEAVYMETAL VI

Jun 7 – 12, 2026

McDonald Forest Hills

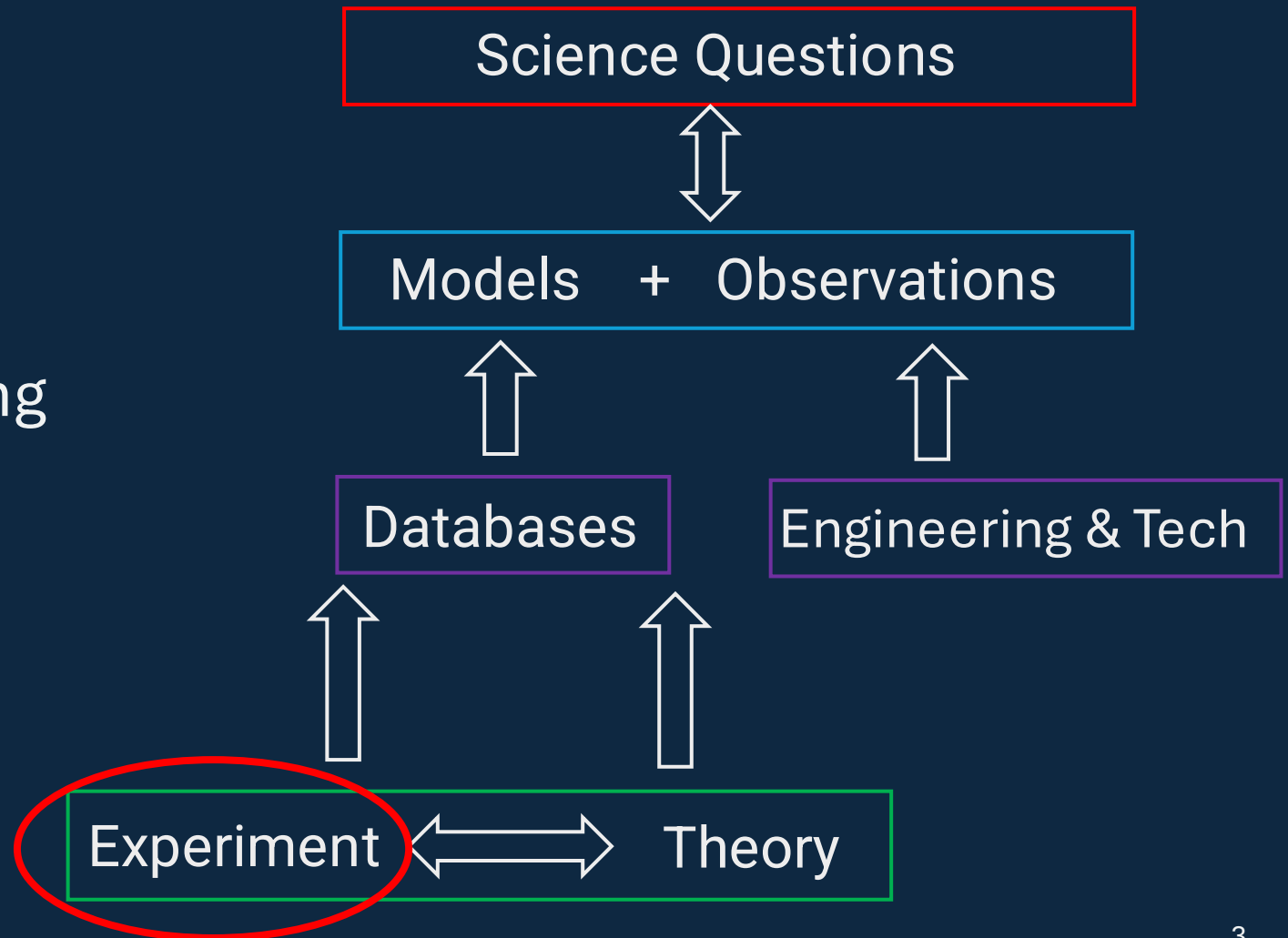
What do we do?

- Observations are interpreted through models
- Models are only as reliable as the underlying atomic data

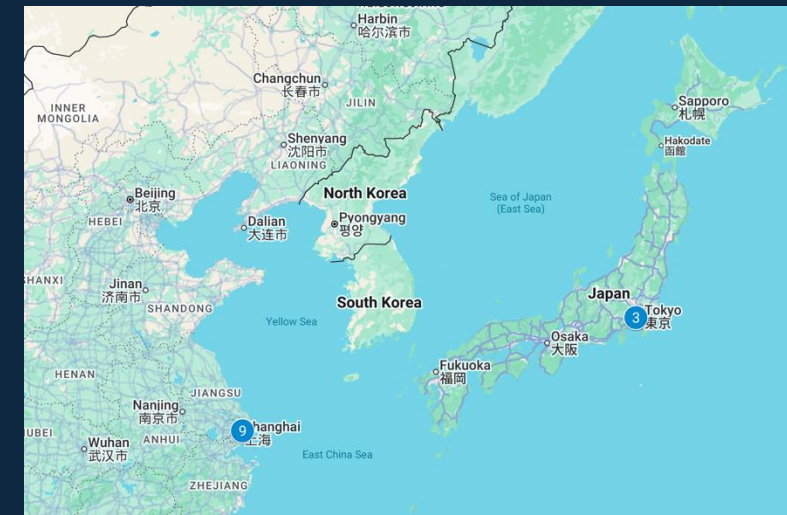
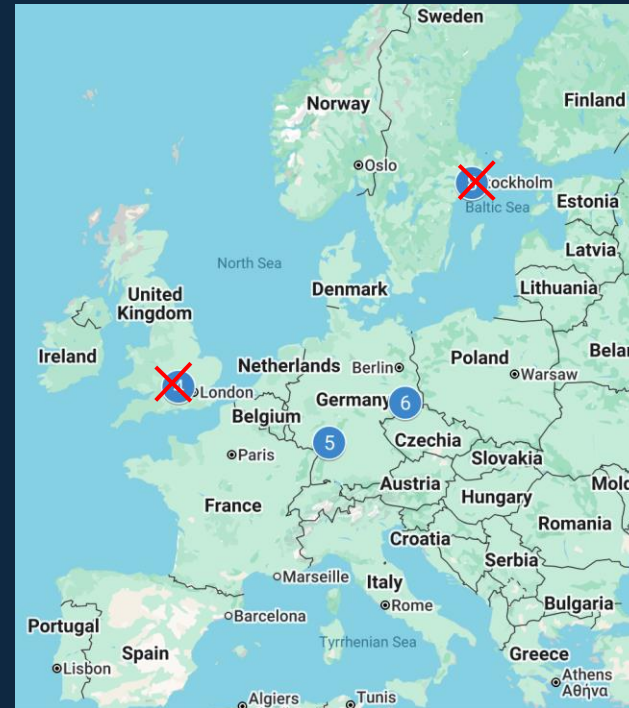
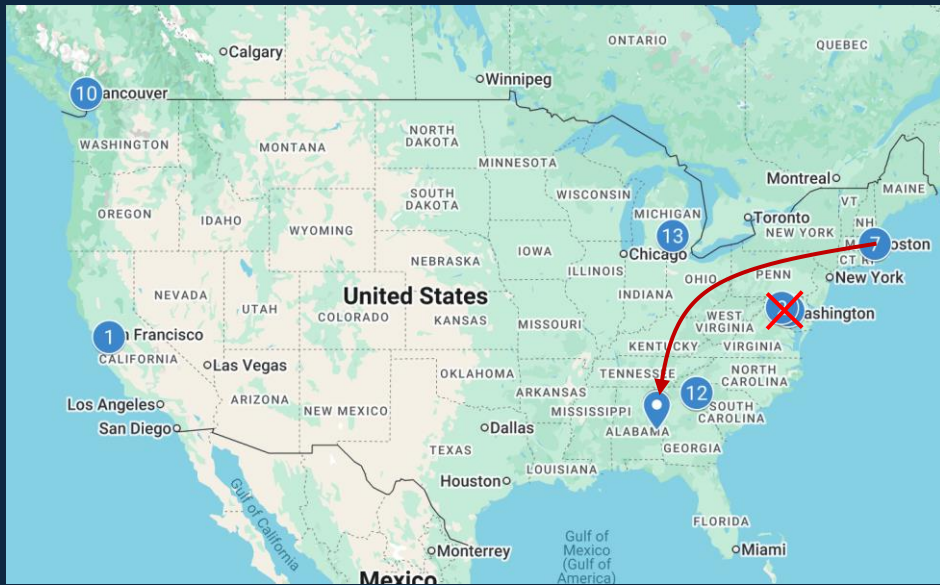


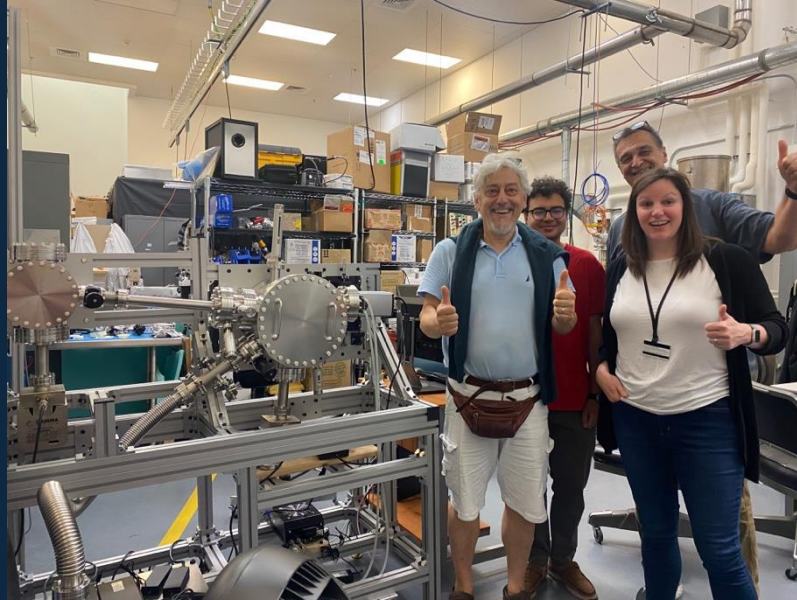
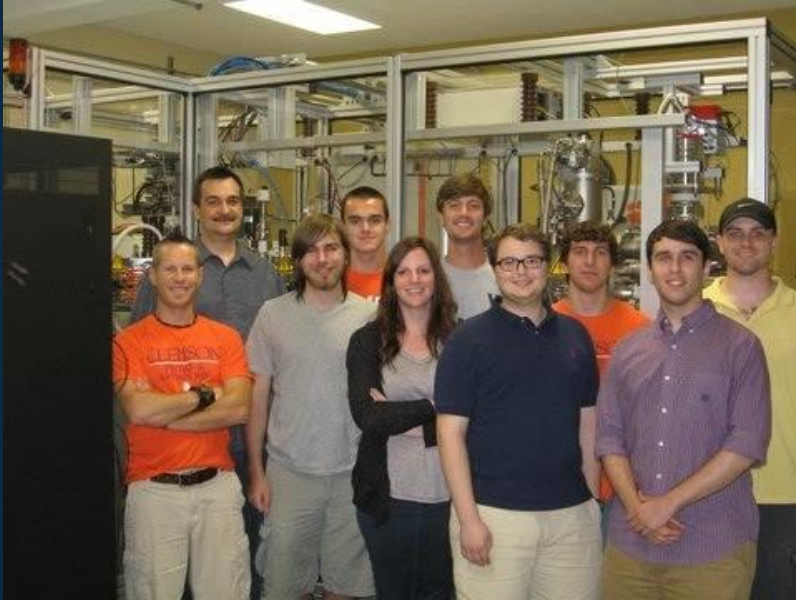
What do we do?

- Observations are interpreted through models
- Models are only as reliable as the underlying atomic data



Electron Beam Ion Trap Facilities





CLEMSON

CENTER FOR **ASTROPHYSICS**
HARVARD & SMITHSONIAN

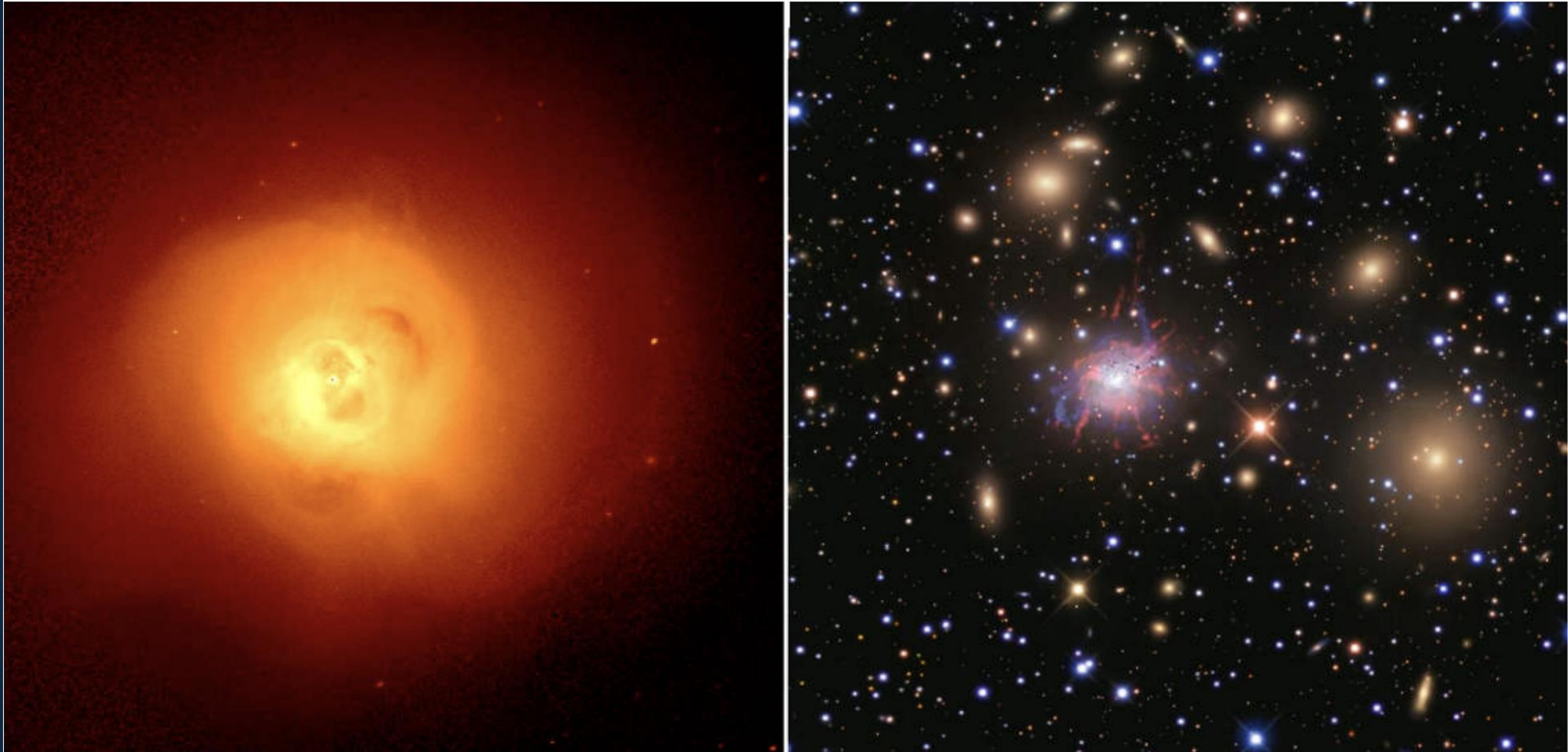
AU AUBURN UNIVERSITY

Hot Plasmas Across the Universe

CENTER FOR

ASTROPHYSICS

HARVARD & SMITHSONIAN



Fabian et al. MNRAS 2011

Goals

What Can I Measure for YOU?

PERIODIC TABLE

Atomic Properties of the Elements

Group	1	2
IA	IIA	
1	2	
¹ ₁ H	² ₂ He	
Hydrogen	Helium	
1.008	4.0026	
¹ ₃ Li	² ₄ Be	
Lithium	Beryllium	
6.94	9.0122	
¹¹ ₁₁ Na	¹² ₁₂ Mg	
Sodium	Magnesium	
22.990	24.305	
[Ne]3s ¹	[Ne]3s ²	
5.1391	7.6462	
3	4	
¹⁹ ₁₉ K	²⁰ ₂₀ Ca	
Potassium	Calcium	
39.098	40.078	
[Ar]4s ¹	[Ar]4s ²	
4.3407	6.1132	
4	5	
³⁷ ₃₇ Rb	³⁸ ₃₈ Sr	
Rubidium	Strontium	
85.468	87.62	
[Kr]5s ¹	[Kr]5s ²	
4.1771	5.6949	
5	6	
⁵⁵ ₅₅ Cs	⁵⁶ ₅₆ Ba	
Cesium	Barium	
132.91	137.33	
[Xe]6s ¹	[Xe]6s ²	
3.8939	5.2117	
6	7	
⁸⁷ ₈₇ Fr	⁸⁸ ₈₈ Ra	
Francium	Radium	
(223)	(226)	
[Rn]7s ¹	[Rn]7s ²	
4.0727	5.2784	

Atomic Number

Ground State

Symbol

Name

Standard Atomic Weight (A_r)

Ground-state Configuration

Ionization Energy (eV)

⁵⁸₅₈ Ce

Cerium

140.12

[Xe]4f¹5d¹6s²

5.5386

FREQUENTLY USED FUNDAMENTAL PHYSICAL CONSTANTS[§]

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum	c	299 792 458 m s ⁻¹	(exact)
Planck constant	h	6.626 070 15 × 10 ⁻³⁴ J Hz ⁻¹	(exact)
elementary charge	e	1.602 176 634 × 10 ⁻¹⁹ C	(exact)
Avogadro constant	N _A	6.022 140 76 × 10 ²³ mol ⁻¹	(exact)
Boltzmann constant	k	1.380 649 × 10 ⁻²³ J K ⁻¹	(exact)
electron volt	eV	1.602 176 634 × 10 ⁻¹⁹ J	(exact)
electron mass	m _e	9.109 383 71 × 10 ⁻³¹ kg	
energy equivalent	m _e c ²	0.510 998 951 MeV	
proton mass	m _p	1.672 621 92 × 10 ⁻²⁷ kg	
energy equivalent	m _p c ²	938.272 089 MeV	
fine-structure constant	α	1/137.035 999	
Rydberg energy	R _∞ hc	13.605 693 1230 eV	
Newtonian constant of gravitation	G	6.674 × 10 ⁻¹¹ m ³ kg ⁻¹ s ⁻²	

[§]For the most accurate values of these and other constants, visit pml.nist.gov/constants.

- ☐ Solids
- ☐ Liquids
- ☐ Gases
- ☐ Artificially Prepared



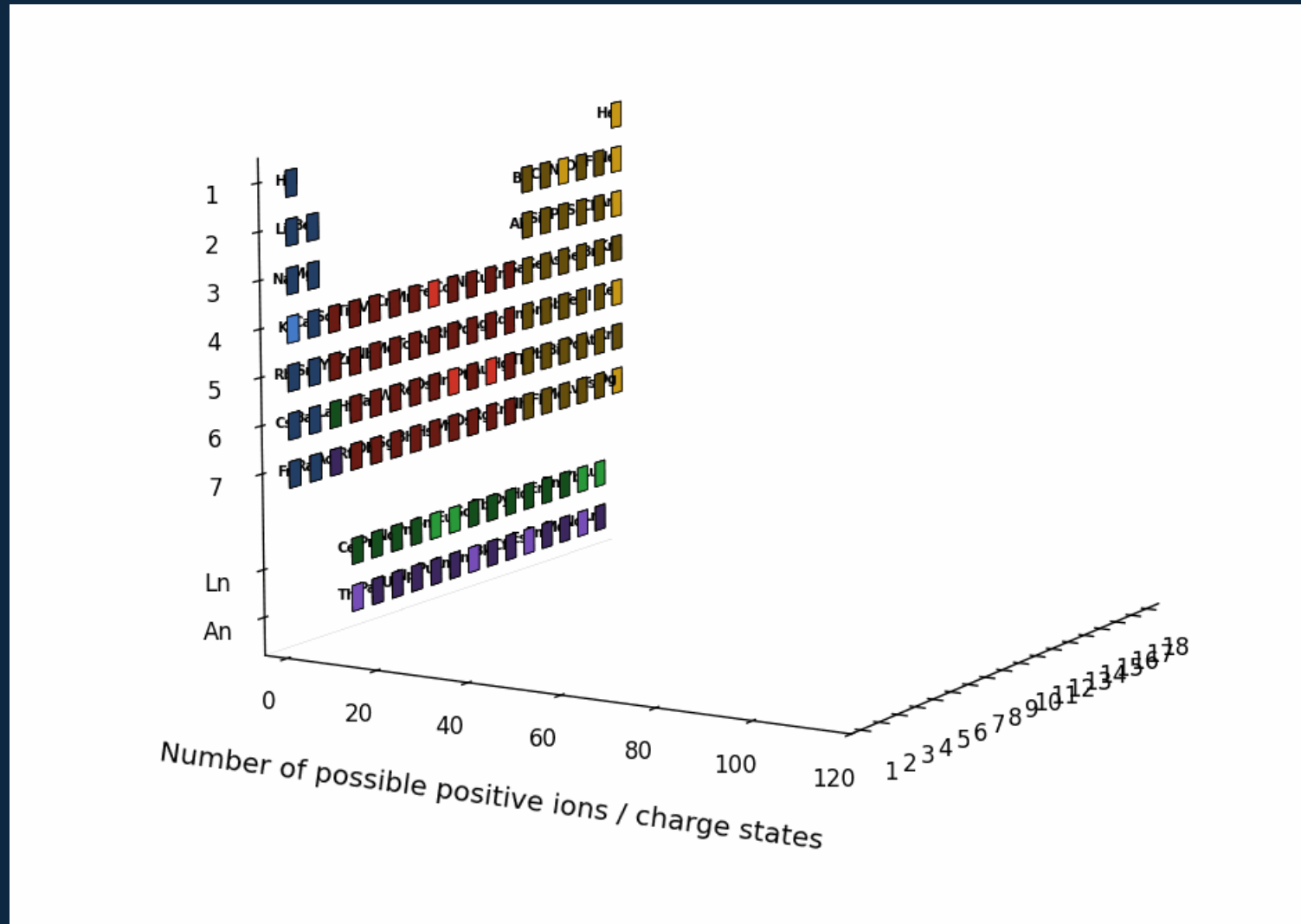
Physical Measurement Laboratory www.nist.gov/pml
Standard Reference Data www.nist.gov/srd

13	14	15	16	17	18
IIIA	IVA	VA	VIA	VIIA	VIIIA
5	6	7	8	9	10
² ₅ B	³ ₆ C	⁴ ₇ N	³ ₈ O	² ₉ F	¹ ₁₀ Ne
Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon
10.81	12.011	14.007	15.999	18.998	20.180
1s ² 2s ² 2p ¹	1s ² 2s ² 2p ²	1s ² 2s ² 2p ³	1s ² 2s ² 2p ⁴	1s ² 2s ² 2p ⁵	1s ² 2s ² 2p ⁶
8.2890	11.2603	14.5341	13.6181	17.4228	21.5645
13	14	15	16	17	18
² ₁₃ Al	³ ₁₄ Si	³ ₁₅ P	³ ₁₆ S	³ ₁₇ Cl	⁴ ₁₈ Ar
Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon
26.982	28.085	30.974	32.06	35.45	39.95
[Ne]3s ² 3p ¹	[Ne]3s ² 3p ²	[Ne]3s ² 3p ³	[Ne]3s ² 3p ⁴	[Ne]3s ² 3p ⁵	[Ne]3s ² 3p ⁶
5.9858	8.1517	10.4867	10.3600	12.9676	15.7596
4	5	6	7	8	9
¹⁹ ₁₉ K	²⁰ ₂₀ Ca	²¹ ₂₁ Sc	²² ₂₂ Ti	²³ ₂₃ V	²⁴ ₂₄ Cr
Potassium	Calcium	Scandium	Titanium	Vanadium	Chromium
39.098	40.078	44.956	47.867	50.942	51.996
[Ar]4s ¹	[Ar]4s ²	[Ar]3d ¹ 4s ²	[Ar]3d ² 4s ²	[Ar]3d ³ 4s ²	[Ar]3d ⁴ 4s ²
4.3407	6.1132	6.5615	6.7462	6.7665	7.4340
5	6	7	8	9	10
³⁷ ₃₇ Rb	³⁸ ₃₈ Sr	³⁹ ₃₉ Y	⁴⁰ ₄₀ Zr	⁴¹ ₄₁ Nb	⁴² ₄₂ Mo
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum
85.468	87.62	88.906	91.224	92.906	95.95
[Kr]5s ¹	[Kr]5s ²	[Kr]4d ¹ 5s ²	[Kr]4d ² 5s ²	[Kr]4d ³ 5s ²	[Kr]4d ⁴ 5s ²
4.1771	5.6949	6.2173	6.6341	6.7589	7.0924
6	7	8	9	10	11
⁵⁵ ₅₅ Cs	⁵⁶ ₅₆ Ba	⁵⁷ ₅₇ La	⁵⁸ ₅₈ Ce	⁵⁹ ₅₉ Pr	⁶⁰ ₆₀ Nd
Cesium	Barium	Lanthanum	Cerium	Praseodymium	Neodymium
132.91	137.33	138.91	140.12	140.91	144.24
[Xe]6s ¹	[Xe]6s ²	[Xe]5d ¹ 6s ²	[Xe]4f ¹ 5d ¹ 6s ²	[Xe]4f ² 6s ²	[Xe]4f ³ 6s ²
3.8939	5.2117	5.5789	5.5386	5.4702	5.5250
7	8	9	10	11	12
⁸⁷ ₈₇ Fr	⁸⁸ ₈₈ Ra	⁸⁹ ₈₉ Ac	⁹⁰ ₉₀ Th	⁹¹ ₉₁ Pa	⁹² ₉₂ U
Francium	Radium	Actinium	Thorium	Protactinium	Uranium
(223)	(226)	(227)	232.04	231.04	238.03
[Rn]7s ¹	[Rn]7s ²	[Rn]5f ¹ 6d ¹ 7s ²	[Rn]6d ² 7s ²	[Rn]5f ² 6d ¹ 7s ²	[Rn]5f ³ 6d ¹ 7s ²
4.0727	5.2784	5.3802	6.3067	5.89	6.1941

For the most precise values and uncertainties visit ciaaw.org and pml.nist.gov/data.
NIST SP 966 (June 2024)

[†]Based upon ¹²C. () indicates the mass number of the longest-lived isotope.

The Table of Ions



Where Are the Gaps?



NIST Atomic Spectra Database - Lines Holdings

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	* 	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	+ 	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
* Lanthanides		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
+ Actinides		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

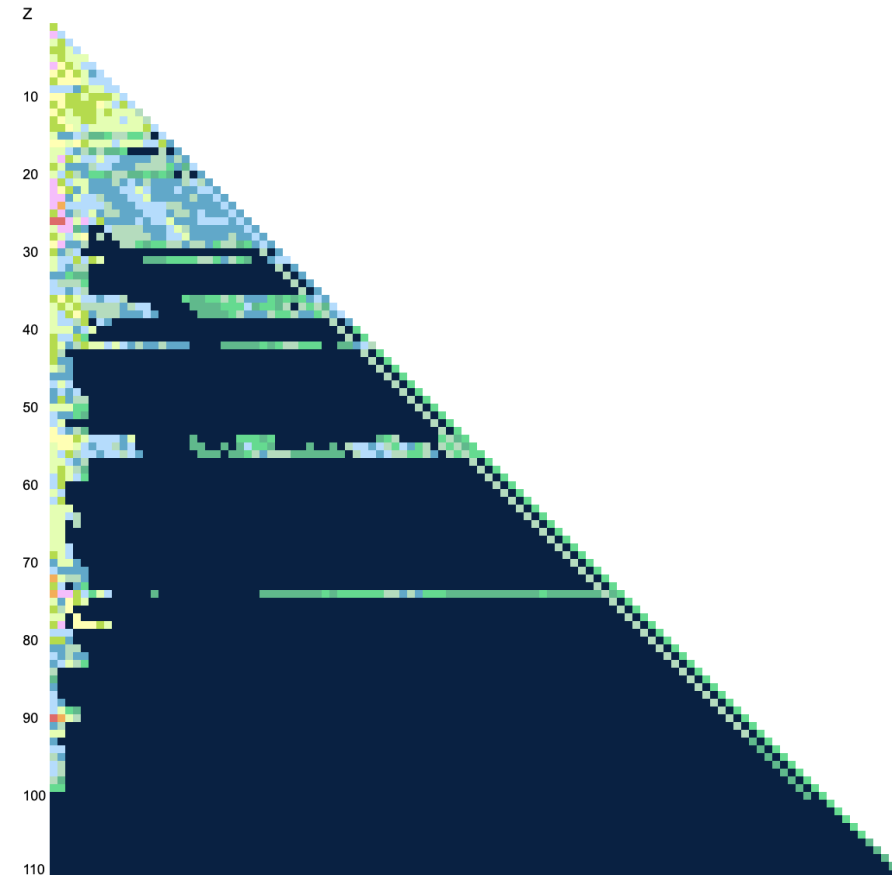
Color vs. number of lines:



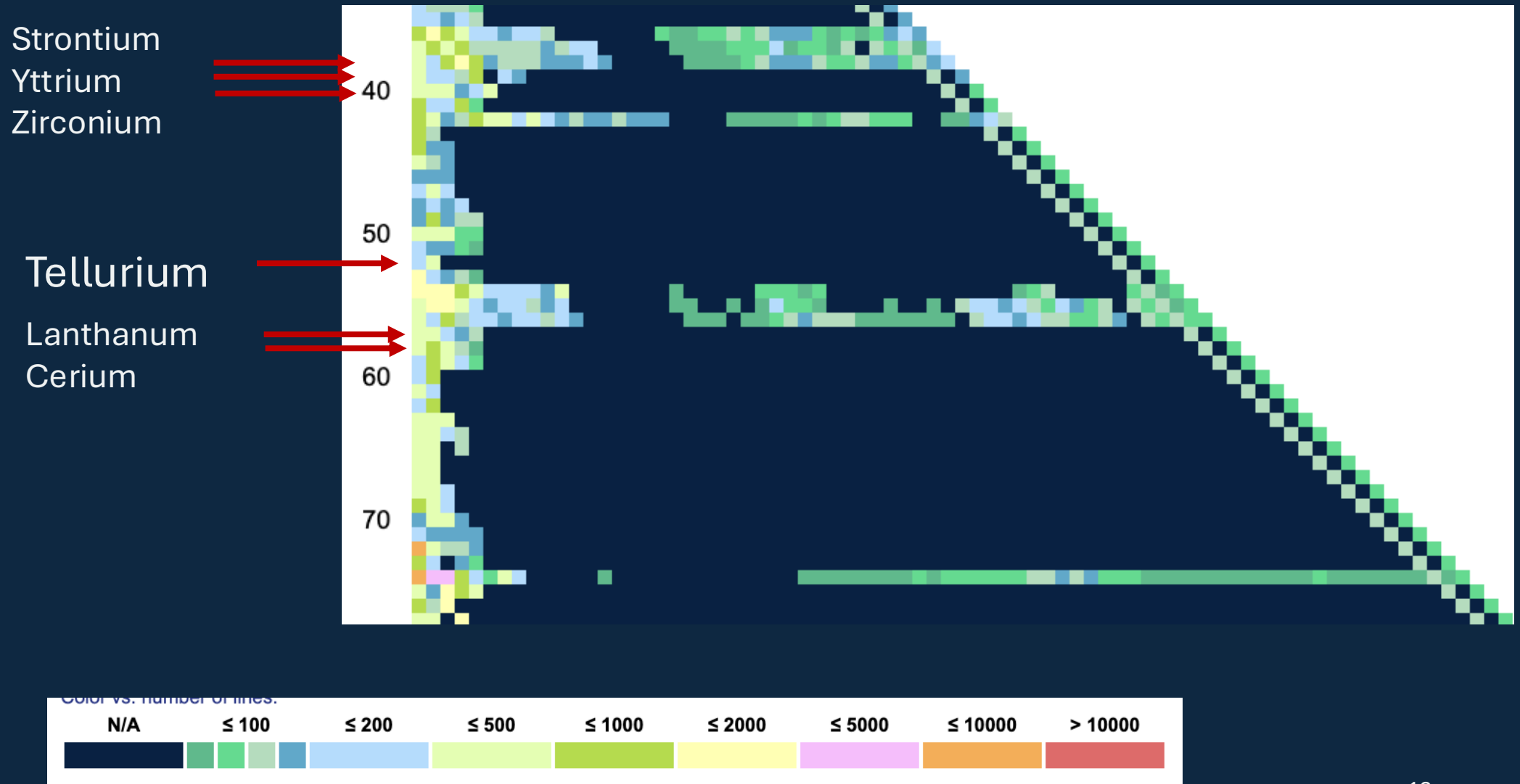
Current total number of lines: 300833

Current total number of lines with transition probabilities: 128870

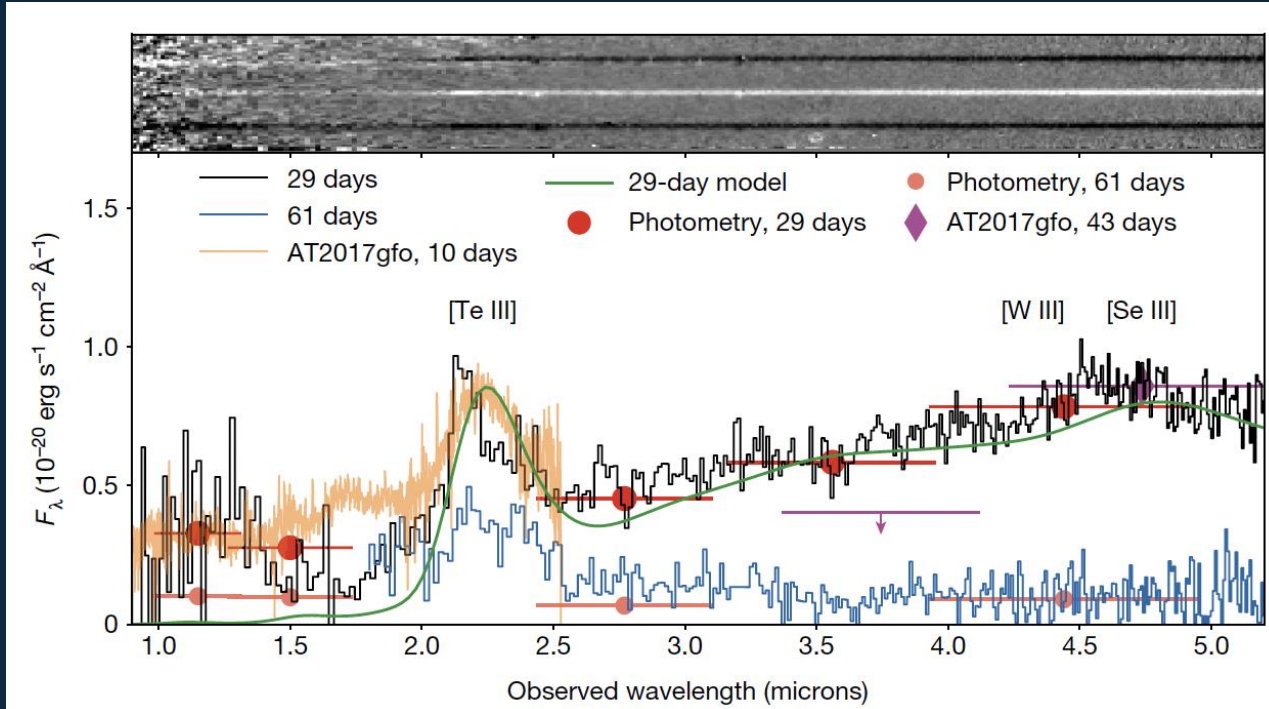
Complete holdings for lines (move mouse over the clickable squares)



NIST Database



Tellurium



Ion	No. of lines	Lines with transition probabilities	Lines with level designations
Te I	133	6	112
Te II	345	0	310
Te L	26	0	26
Te LII	13	12	13
Total:	517	18	461

Levan, A. J., et al. (2024)

Energy levels

Ion No. of levels

Te I	120
Te II	129
Te III	55
Te IV	16
Te V	45
Te VI	9
Te VII	60
Te VIII	2
Te IX	2
Te X	2
Te XI	2
Te XII	2
Te XIII	2
Te XIV	2
Te XV	2

NIST Atomic Spectra Database - Levels Holdings

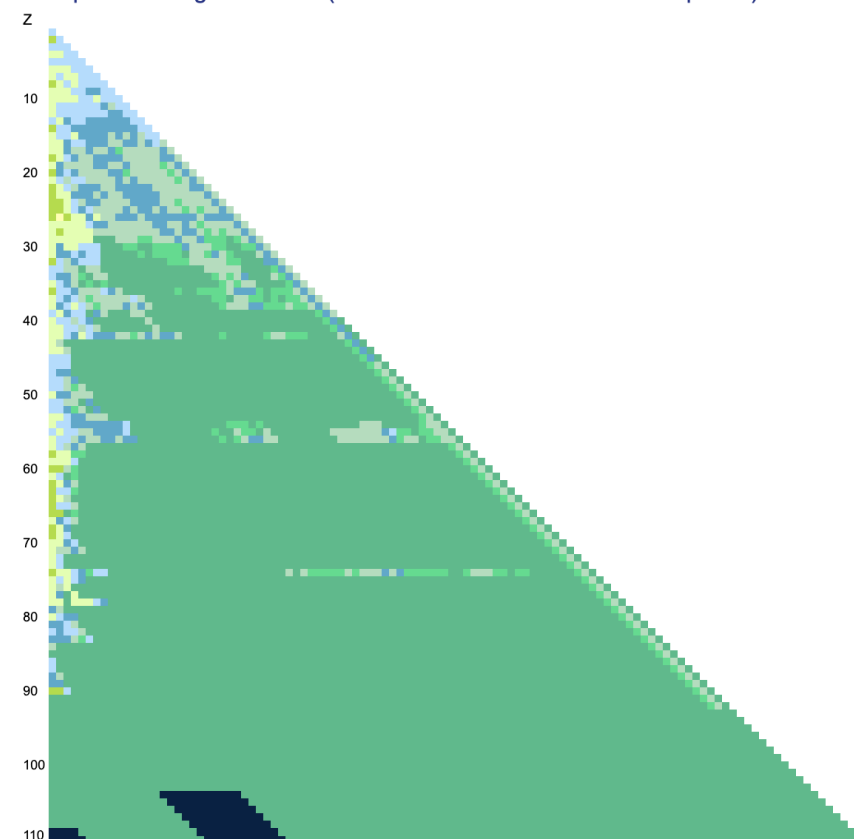
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	* 	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	+ 	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
* Lanthanides		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
* Actinides		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Color vs. number of levels:



Current total number of levels: 120306

Complete holdings for levels (move mouse over the clickable squares)



“What we need”

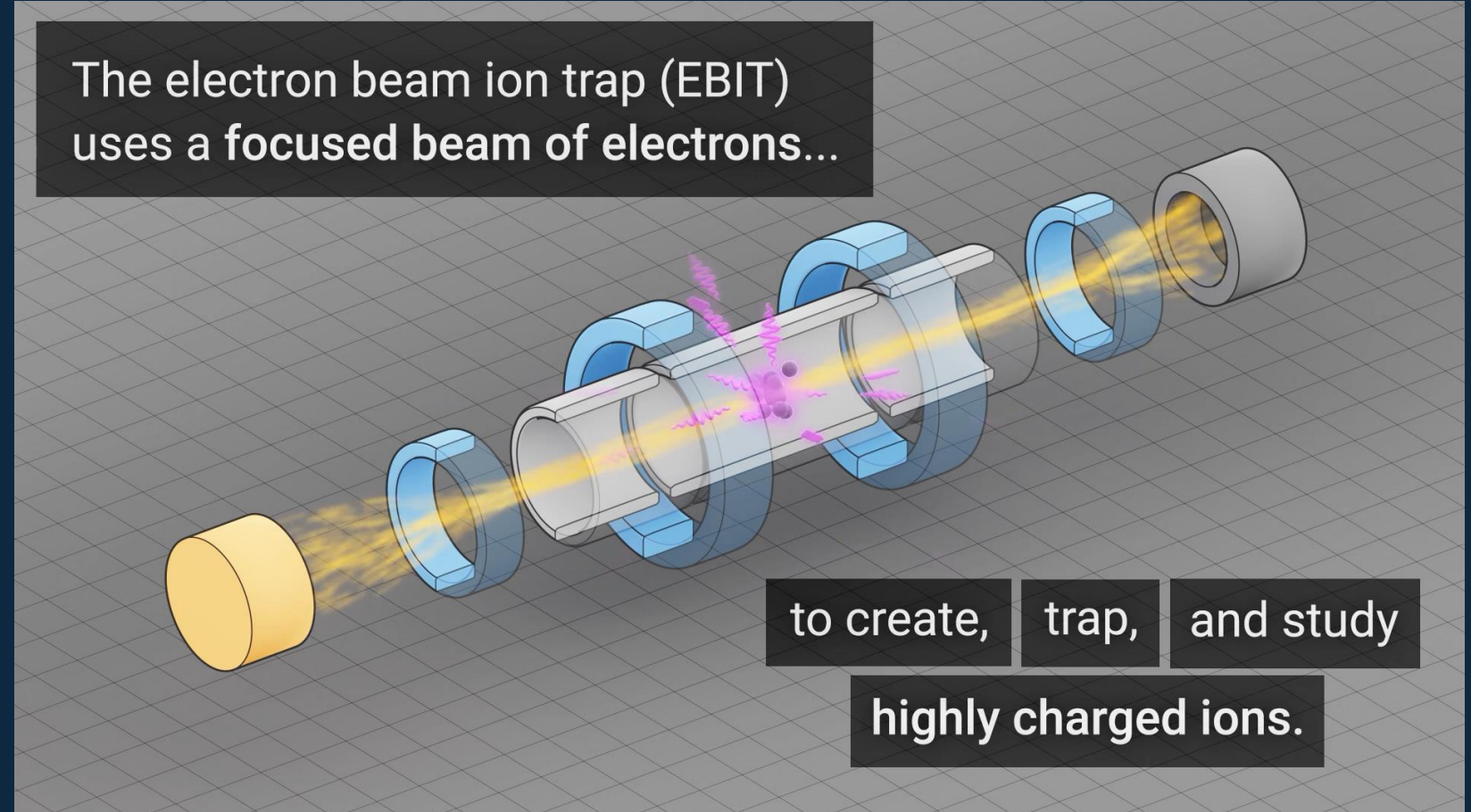
- **A-values**
- **Wavelengths**
- **Recombination rates (RR and DR)**
- **Photoionization data**
- **Electron impact excitation rates**
- **Radioactive heating rates**
- **Data for strong transitions from all elements to unambiguously identify lines**



We Need Laboratory Benchmarks

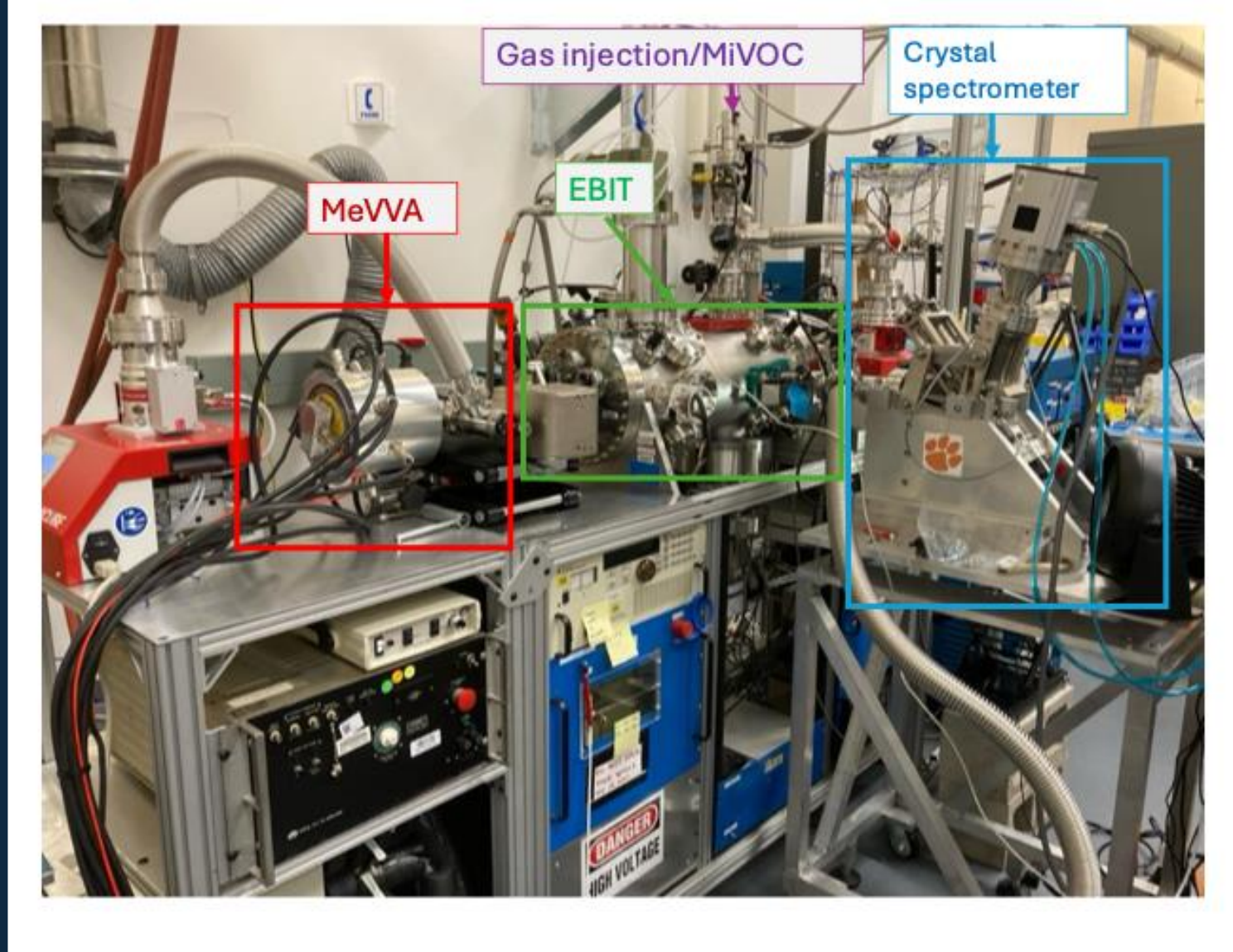
What Is an Electron Beam Ion Trap?

- Collisionally ionized plasma
- Quasi-monoenergetic electron beam
- Isolated charge states



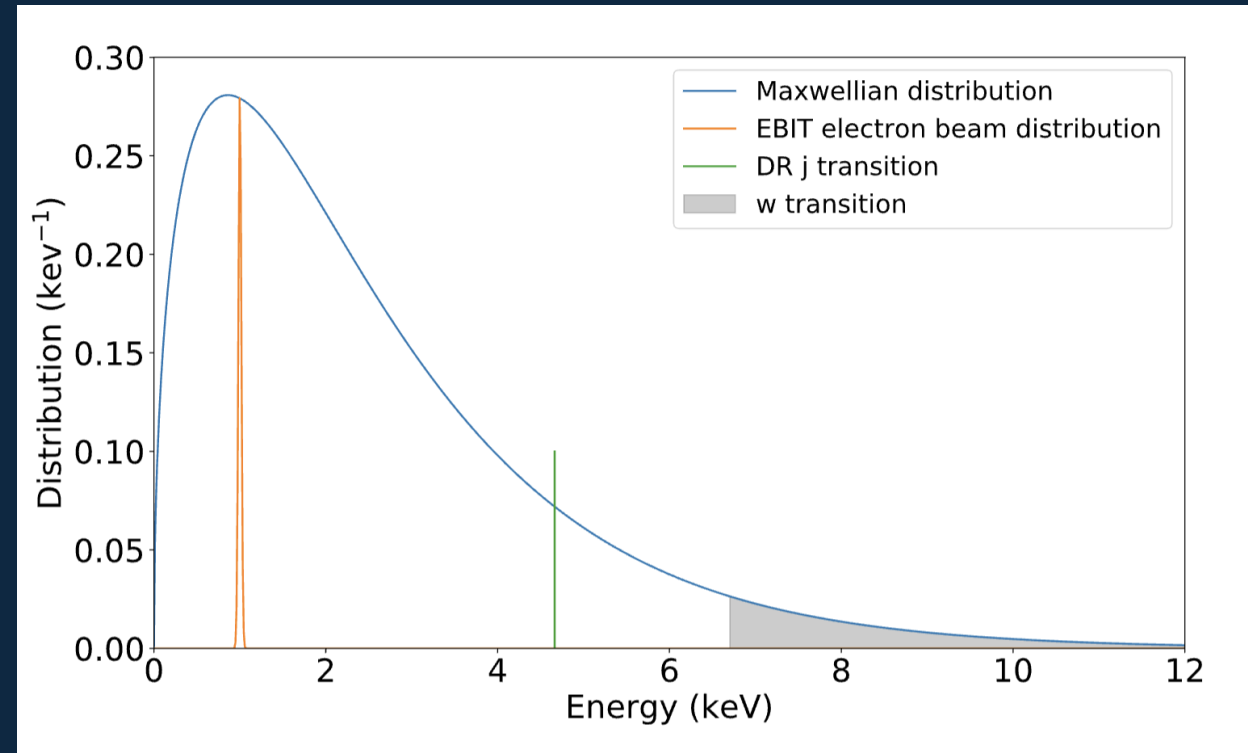
The SAO EBIT

- 100 eV – 20 keV beam energy
- 30 mA electron beam current
- Electron density 10^{10}
- High-resolution X-ray, EUV spectrometers



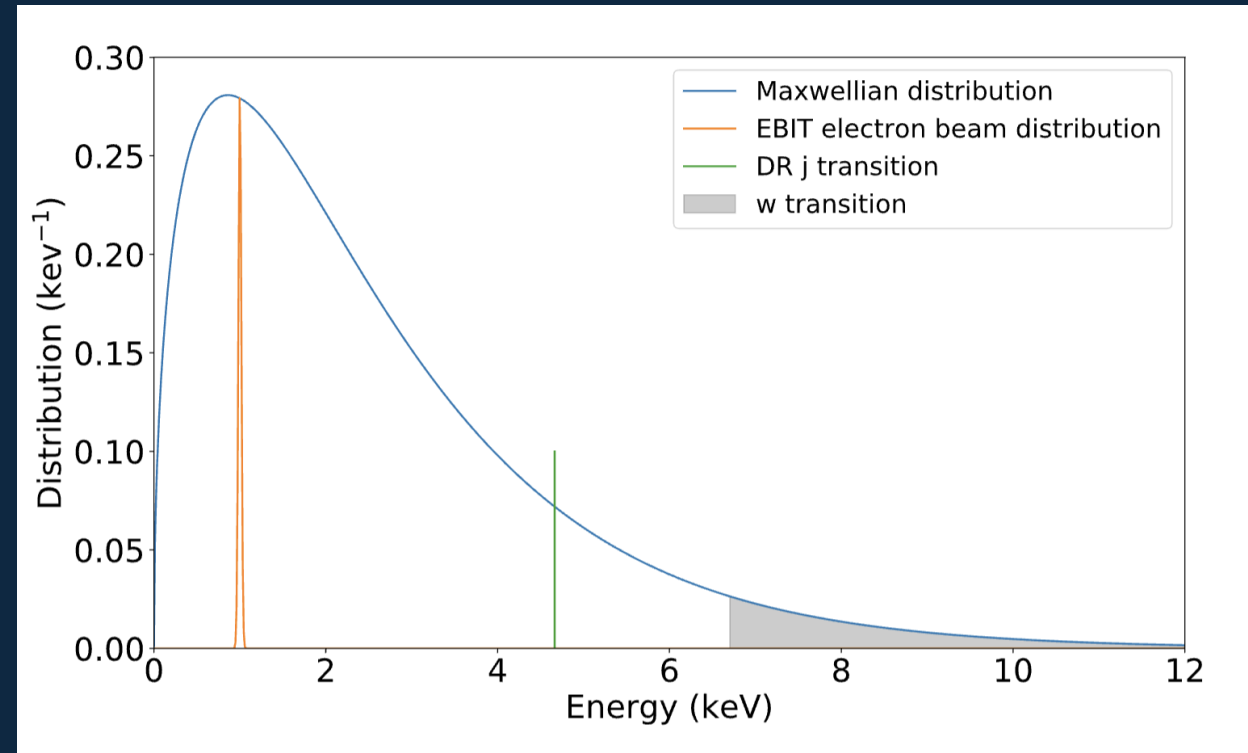
Unique Capabilities of EBITs

- Narrow electron energy distribution (non-Maxwellian)
- Beam energy tuned to target specific charge states
- Direct control of ionization stage
- Controllable conditions for benchmarking



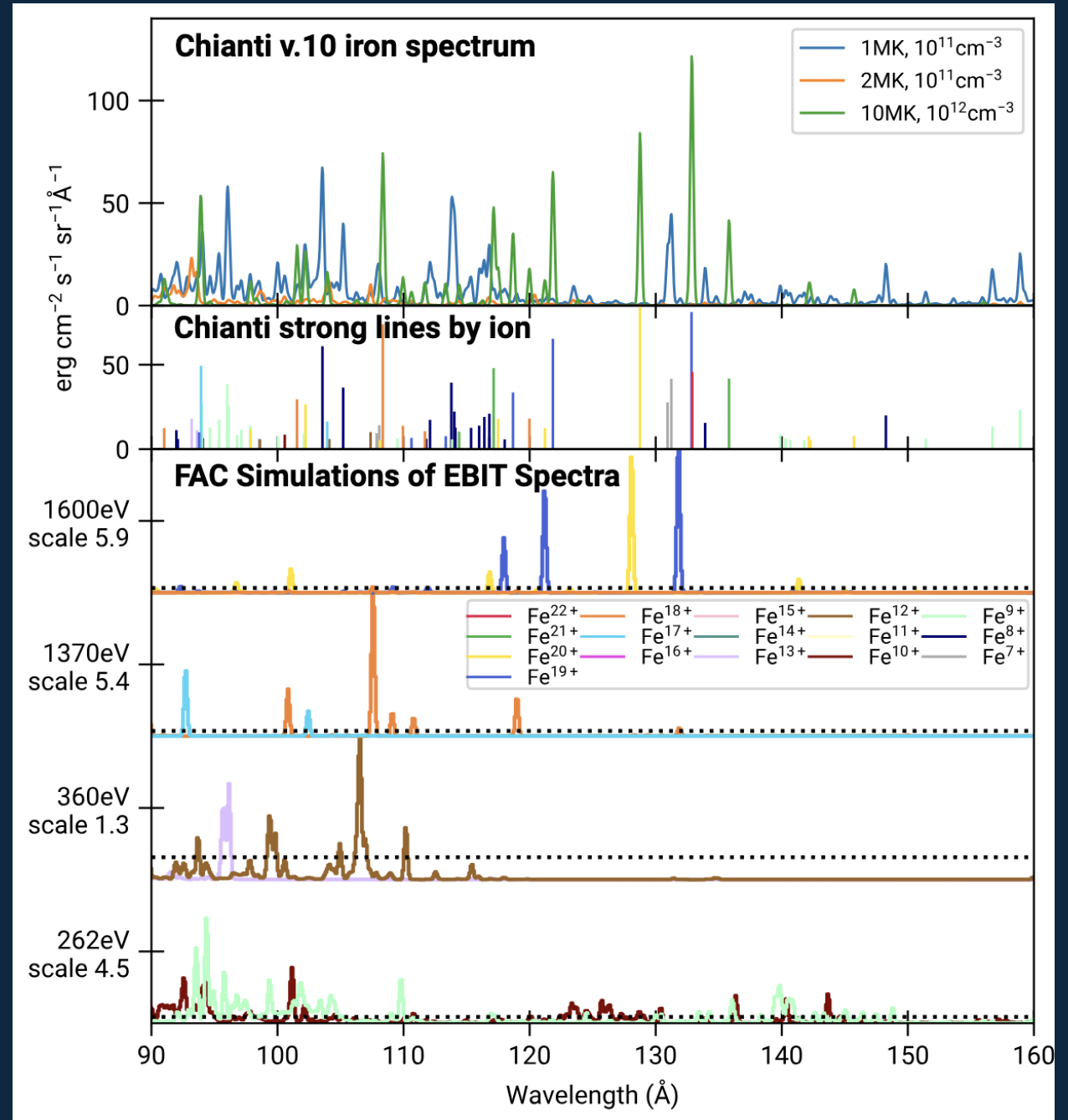
Charge-State Control

Charge State		IE (eV)
Fe X	+9	262.10
Fe XI	+10	290.9
Fe XII	+11	330.8
Fe XIII	+12	361.0
Fe XIV	+13	392.2
Fe XV	+14	456.2
Fe XVI	+15	489.312
Fe XVII	+16	1 262.7
Fe XVIII	+17	1 357.8
Fe XIX	+18	1 460
Fe XX	+19	1 575.6
Fe XXI	+20	1 687.0
Fe XXII	+21	1 798.4
Fe XXIII	+22	1 950.4



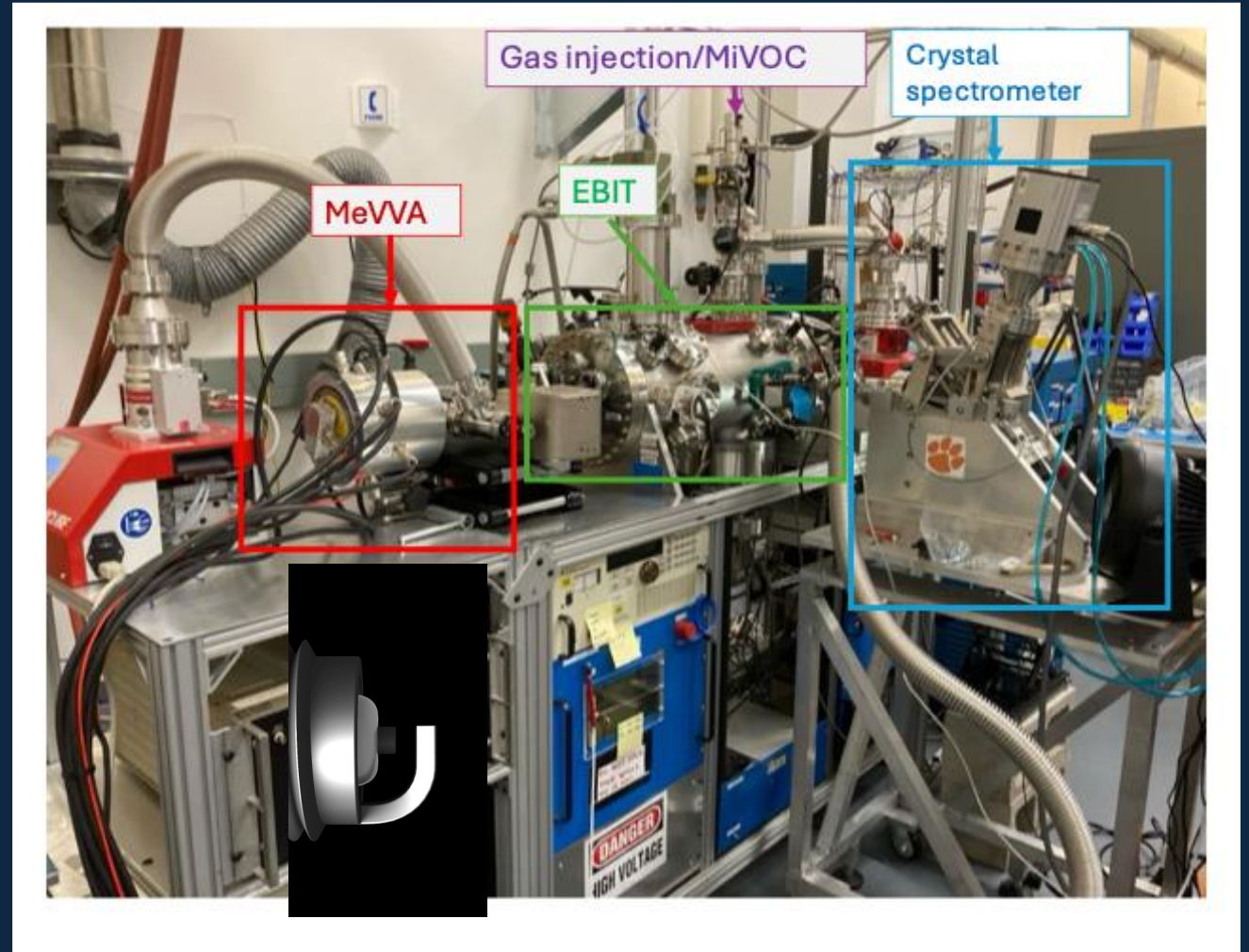
Production of Charge States

Charge State		IE (eV)
Fe X	+9	262.10
Fe XI	+10	290.9
Fe XII	+11	330.8
Fe XIII	+12	361.0
Fe XIV	+13	392.2
Fe XV	+14	456.2
Fe XVI	+15	489.312
Fe XVII	+16	1 262.7
Fe XVIII	+17	1 357.8
Fe XIX	+18	1 460
Fe XX	+19	1 575.6
Fe XXI	+20	1 687.0
Fe XXII	+21	1 798.4
Fe XXIII	+22	1 950.4



What elements can we study?

- Gas injection
- Metal Vapor Vacuum Arc
- Laser Ablation

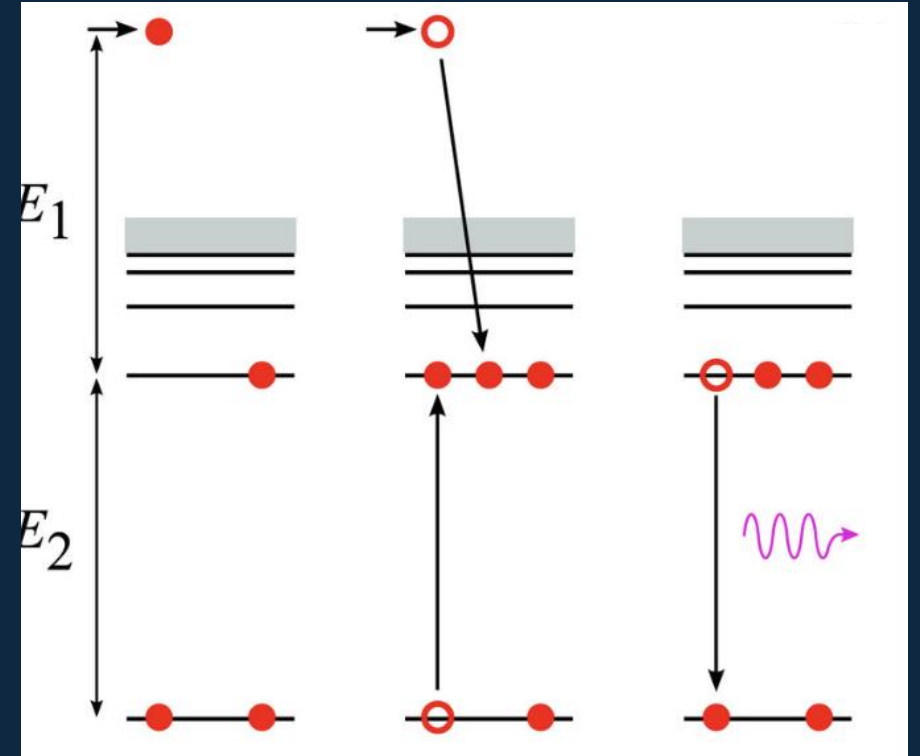


What Processes can we study?

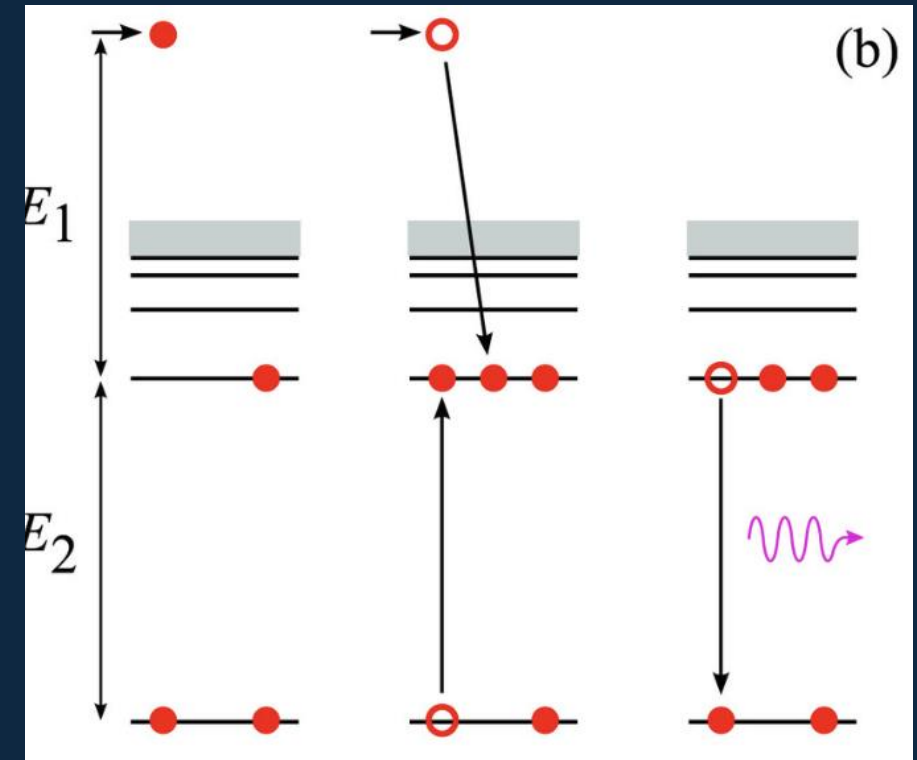
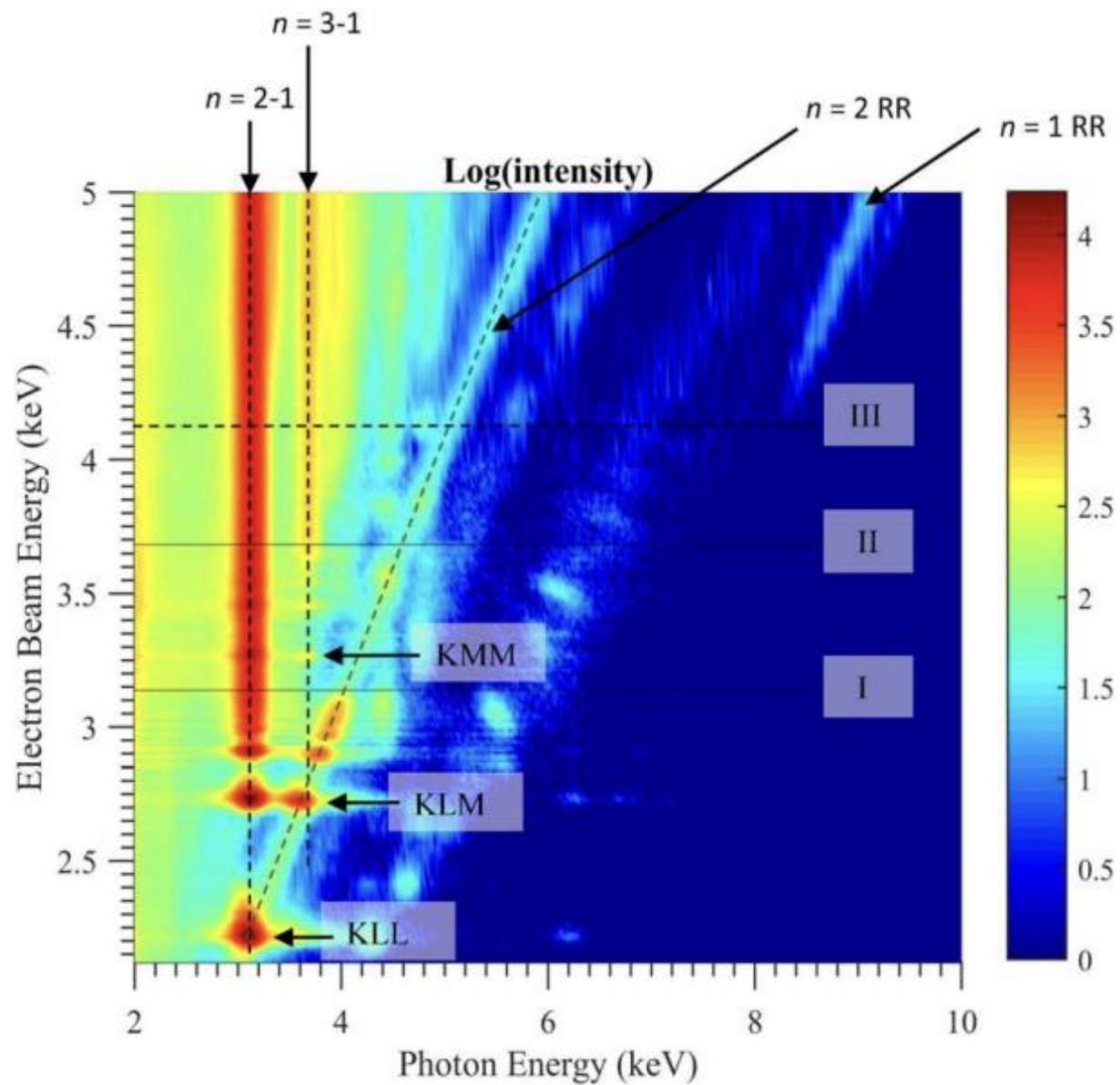
- Electron Impact Ionization
- Electron Impact Excitation
- Inner shell processes
- Dielectronic Recombination*

Dielectronic Recombination

- Two-step recombination process
- Resonant Process
- Very sensitive to electron temperature



Nakamura et al. (2016)





What do we need from an
EBIT?

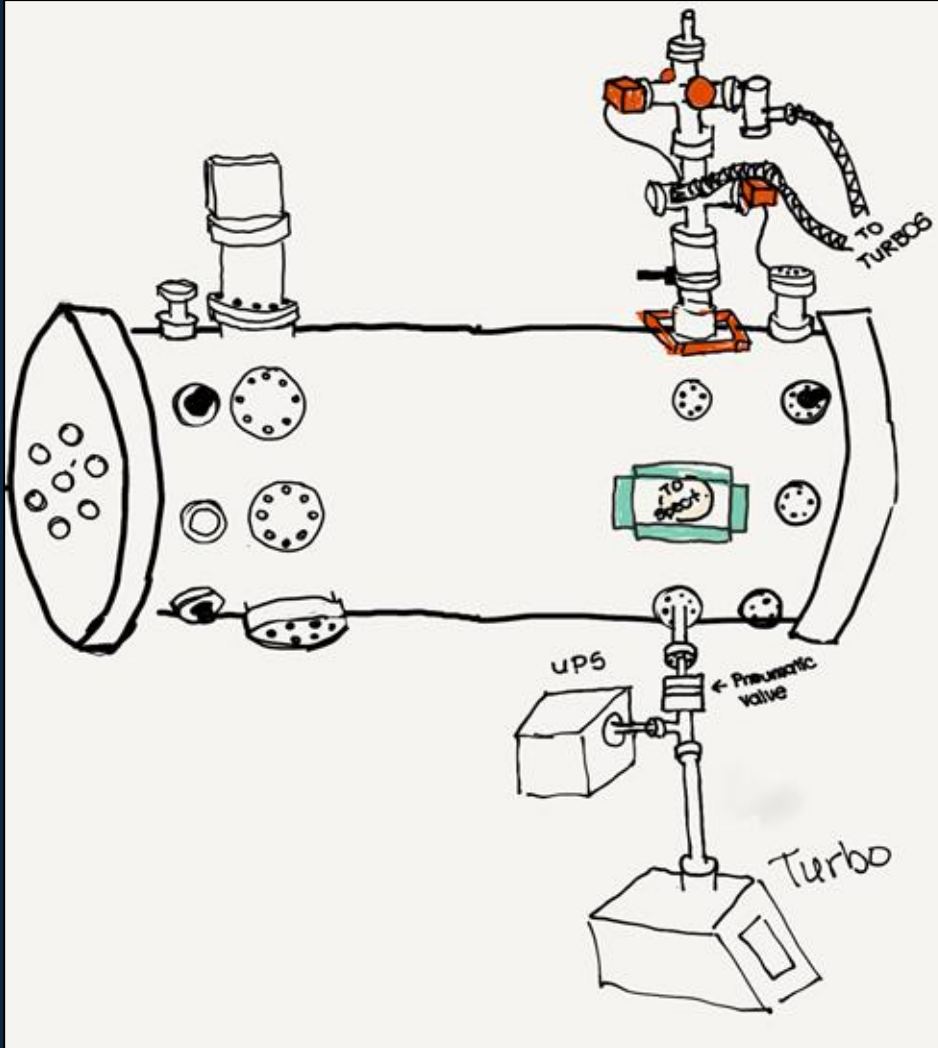
Can EBITs help this community?

Atomic Data Needed	Required EBIT Characteristic(s)
A-values	Long trapping time + high-resolution spectroscopy
Wavelengths	High-resolution spectroscopy
RR/DR rates	Narrow electron energy distribution
Photoionization data	Photon-beam access
Electron impact excitation cross sections	Narrow electron energy distribution + stable beam energy
Low-charge ion data (strong transitions from all)	Low electron beam energy

Key EBIT Characteristics

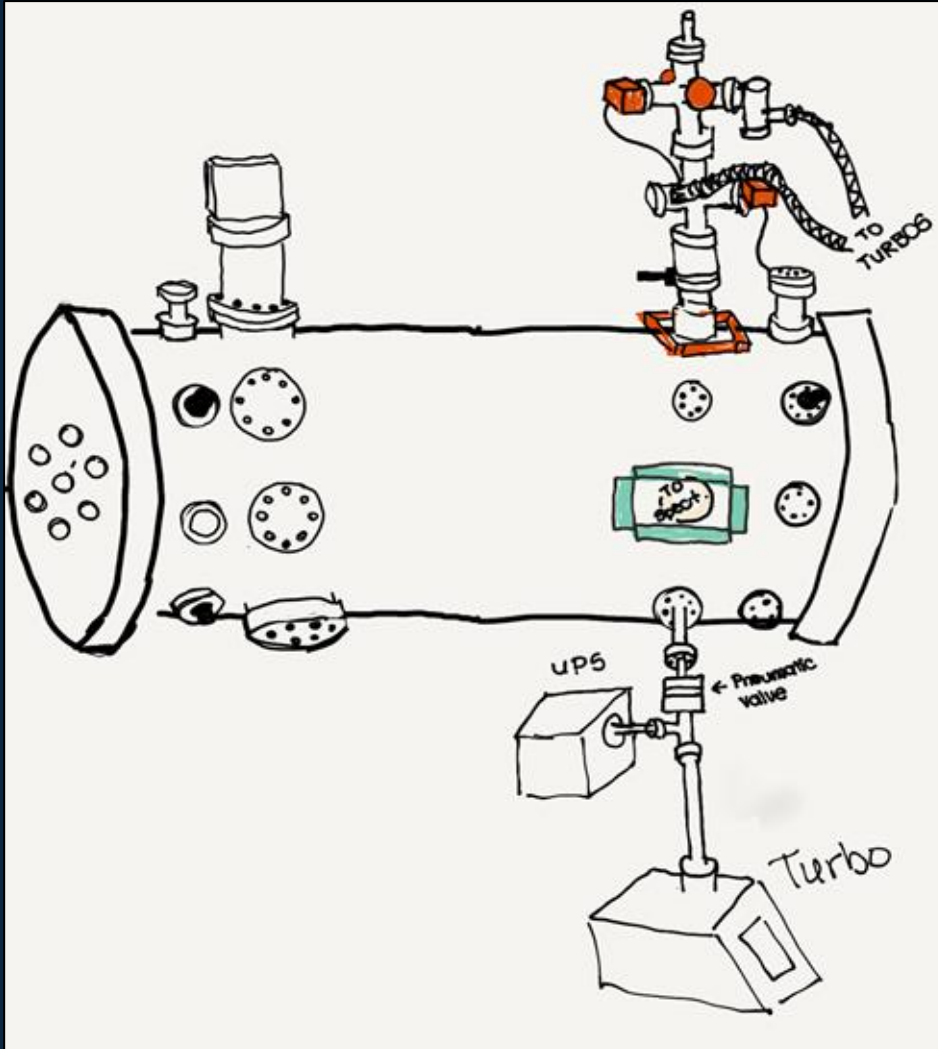
- Narrow electron energy
- Create low charge states
- High electron beam current
- Photoionization

SAO EBIT (typical EBIT)



- Narrow electron energy
- Create low charge states
- High electron beam current
- Photoionization

SAO EBIT (typical EBIT)

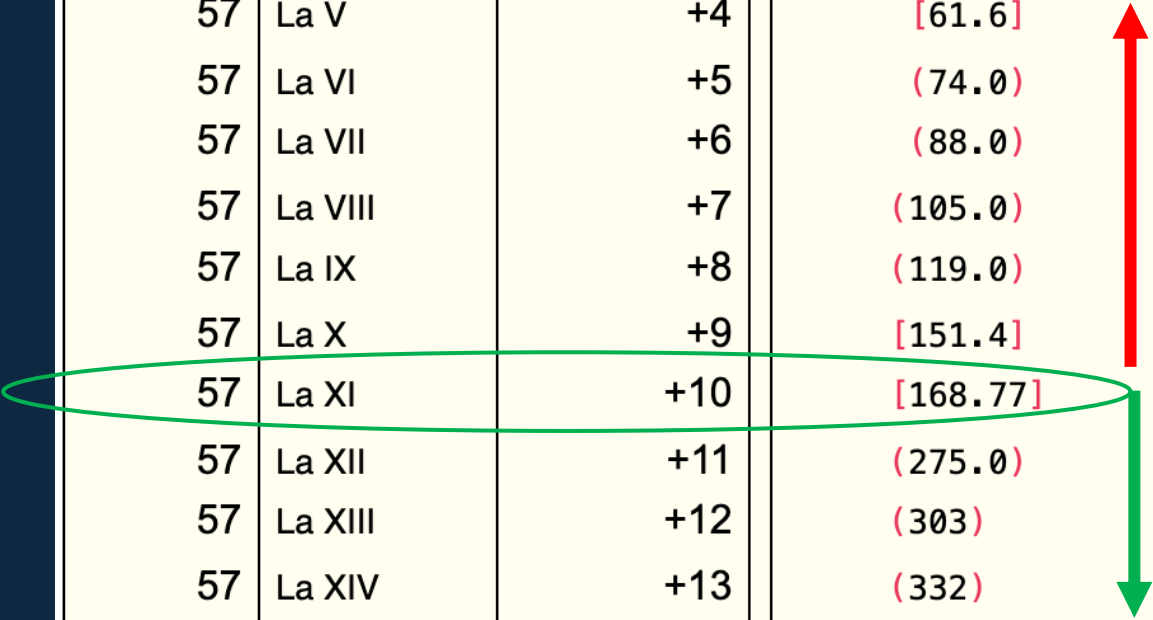


- ~~Narrow electron energy~~
- ~~Create low charge states~~
- High electron beam current
- ~~Photoionization~~

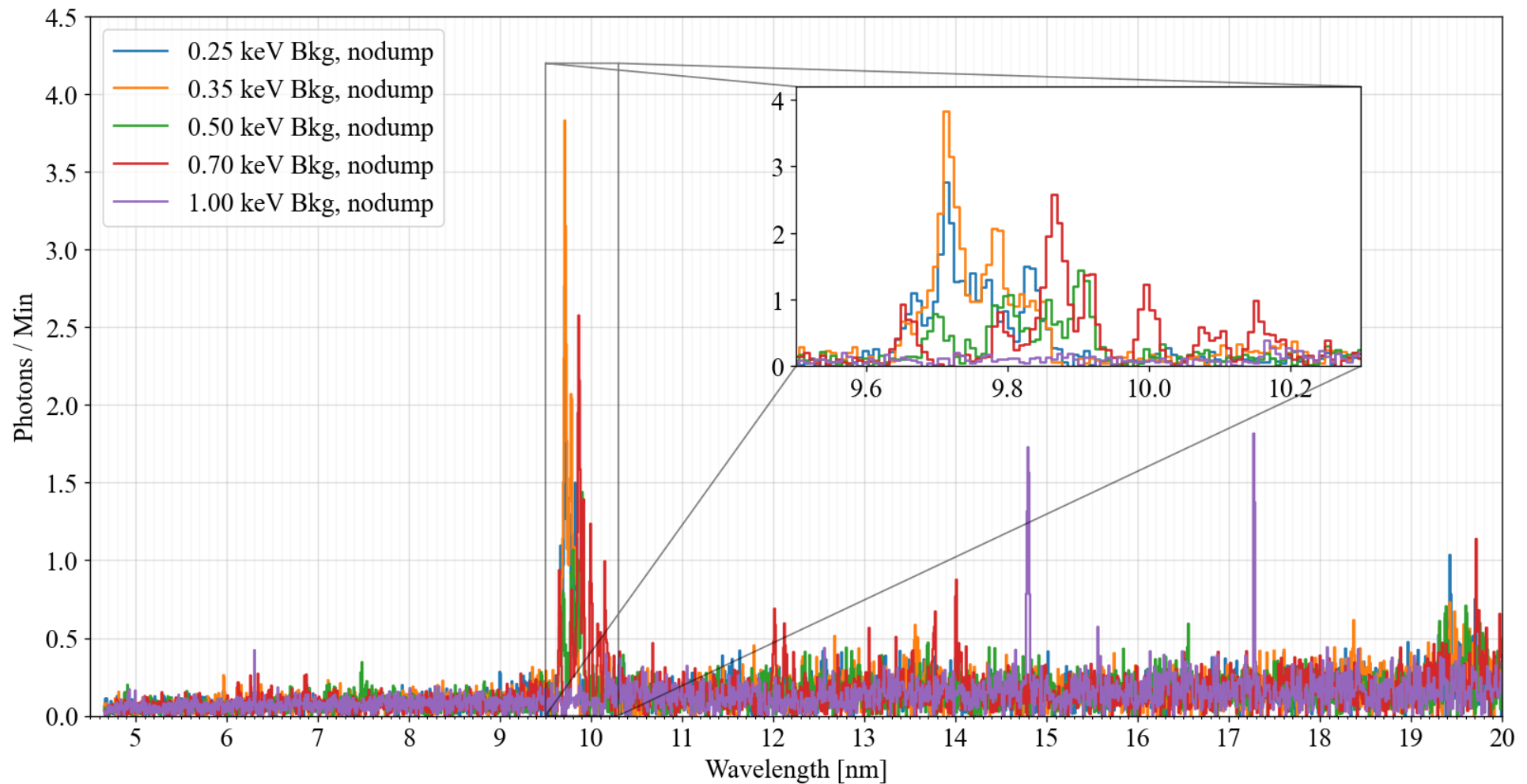
What charge states can we produce? : Typical EBIT

- ~200 eV minimum energy
- Lanthanum : La XII and higher

At. Num.	Sp. Name.	Ion Charge	Ionization Energy (eV)
57	La I	0	5.5769
57	La II	+1	11.18496
57	La III	+2	19.1773
57	La IV	+3	[49.95]
57	La V	+4	[61.6]
57	La VI	+5	(74.0)
57	La VII	+6	(88.0)
57	La VIII	+7	(105.0)
57	La IX	+8	(119.0)
57	La X	+9	[151.4]
57	La XI	+10	[168.77]
57	La XII	+11	(275.0)
57	La XIII	+12	(303)
57	La XIV	+13	(332)
57	La XV	+14	(364)
57	La XVI	+15	(393)
57	La XVII	+16	(431)



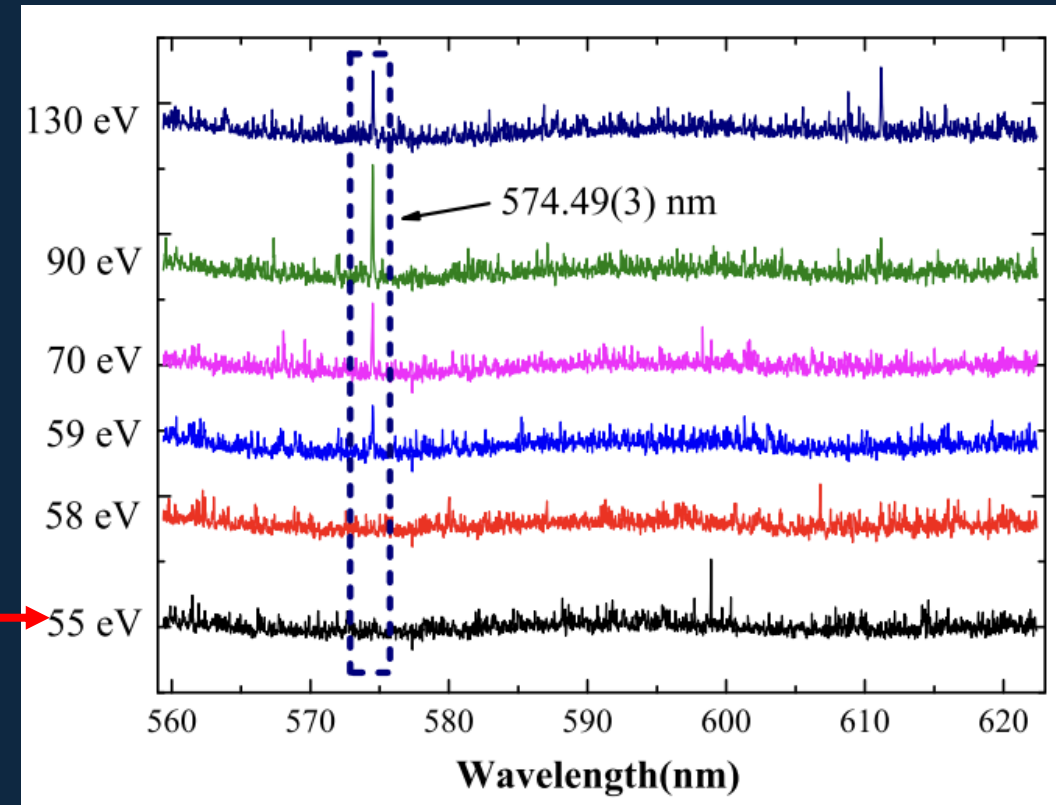
SAO EBIT



What charge states can we produce?

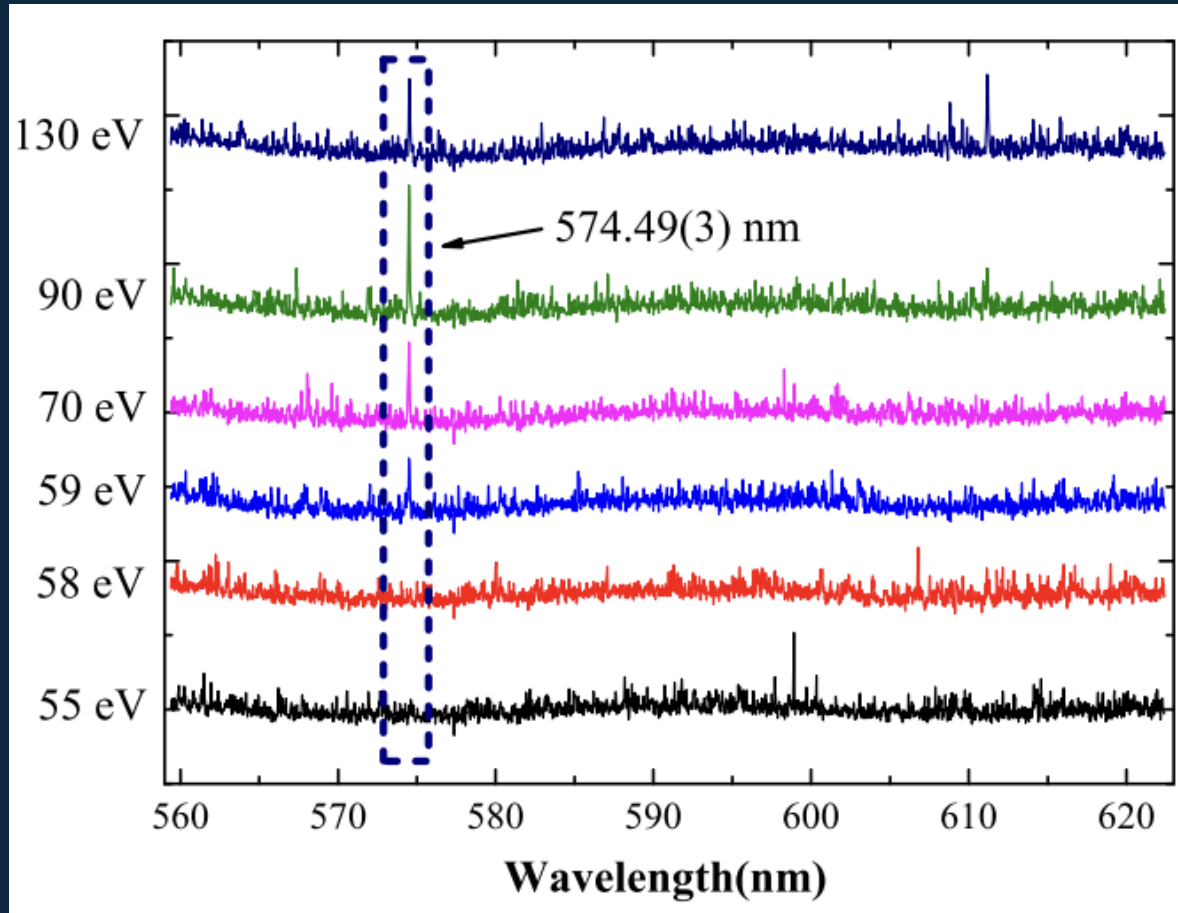
- Some can go lower, 30 eV
- Some higher, up to 150 keV.

BEAM ENERGY



Lu et al., Phys. Rev. A **99**, 042510 (2019)
SH-HtscEBIT

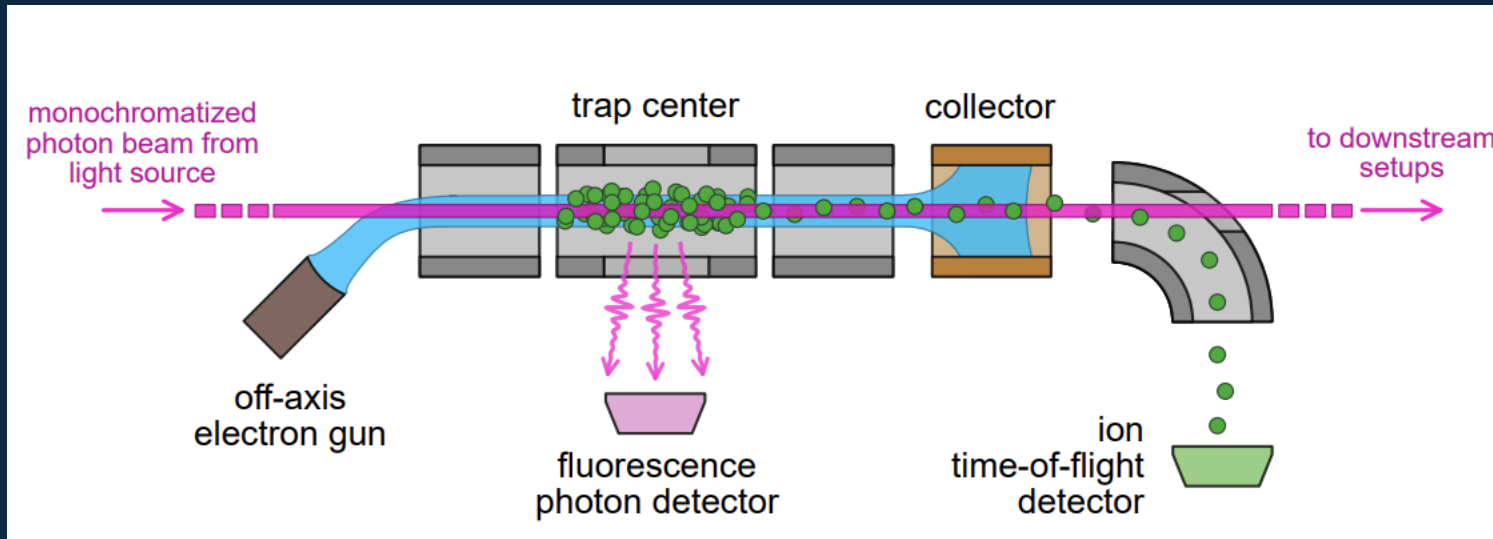
SH-HtscEBIT : low energies



Lu et al., Phys. Rev. A **99**, 042510 (2019)

- ~~Narrow electron energy~~
- Create low charge states
- ~~High electron beam current~~
- ~~Photoionization~~

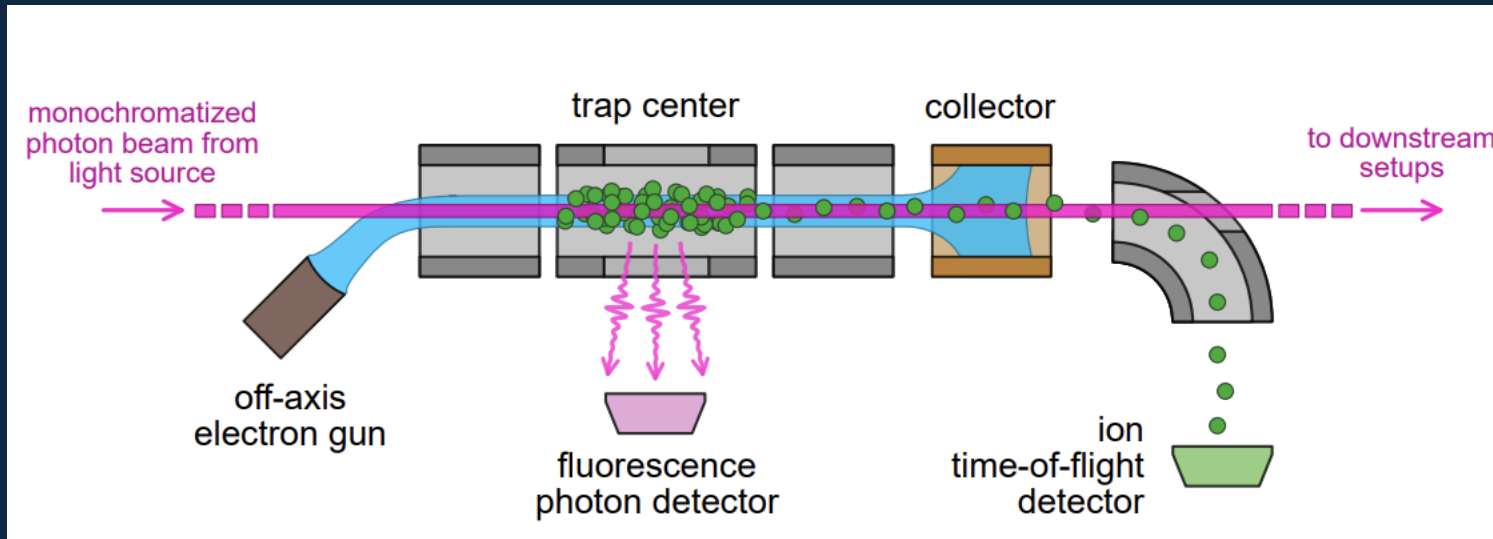
Polar-X EBIT : off-axis gun



Bernitt *et al* 2025 *JINST* **20** C03030

- Narrow electron energy
- Create low charge states
- High electron beam current
- Photoionization

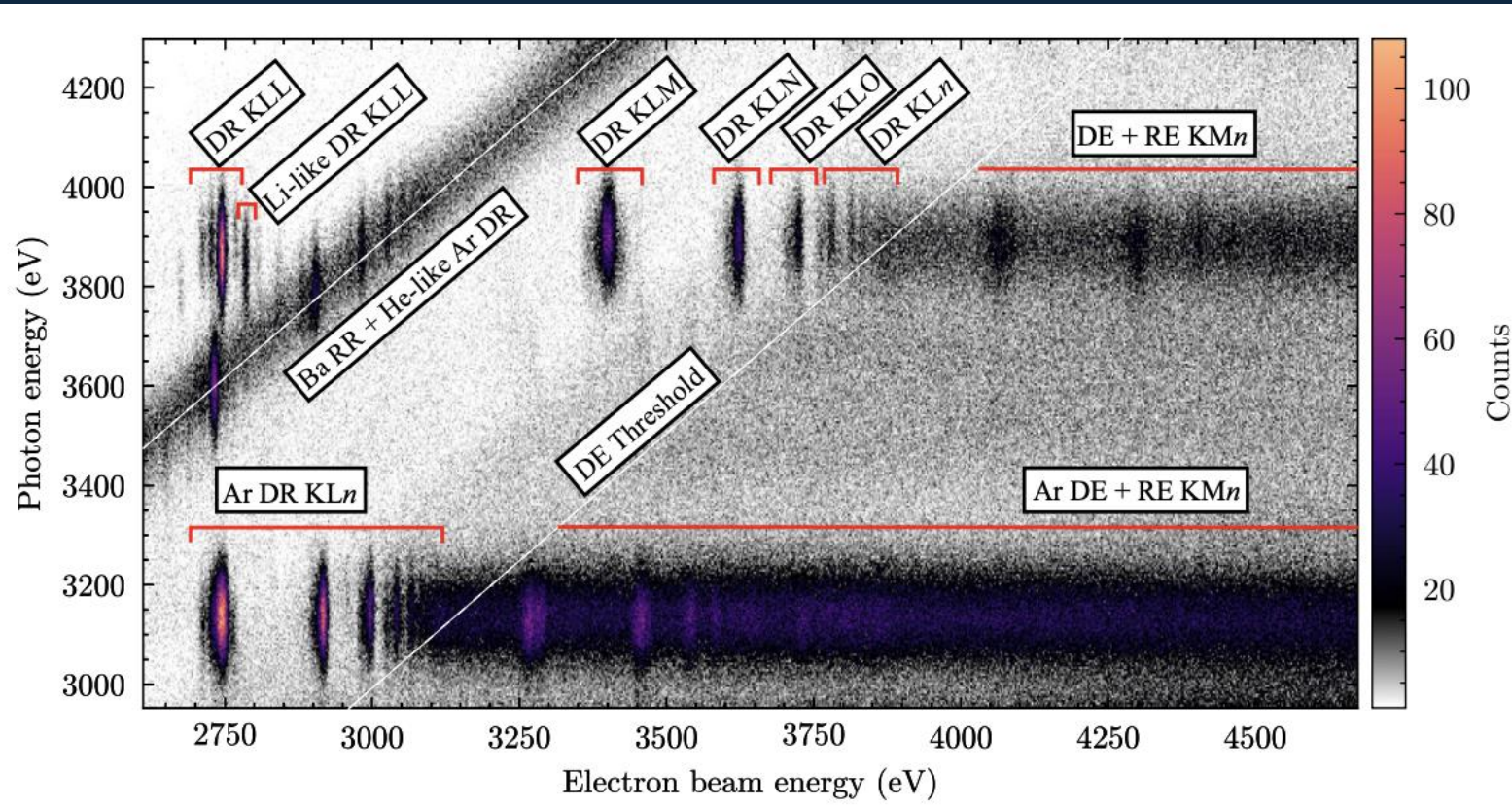
Polar-X EBIT : off-axis gun



Bernitt *et al* 2025 *JINST* 20 C03030

- ~~Narrow electron energy~~
- ~~Create low charge states~~
- High electron beam current
- Photoionization

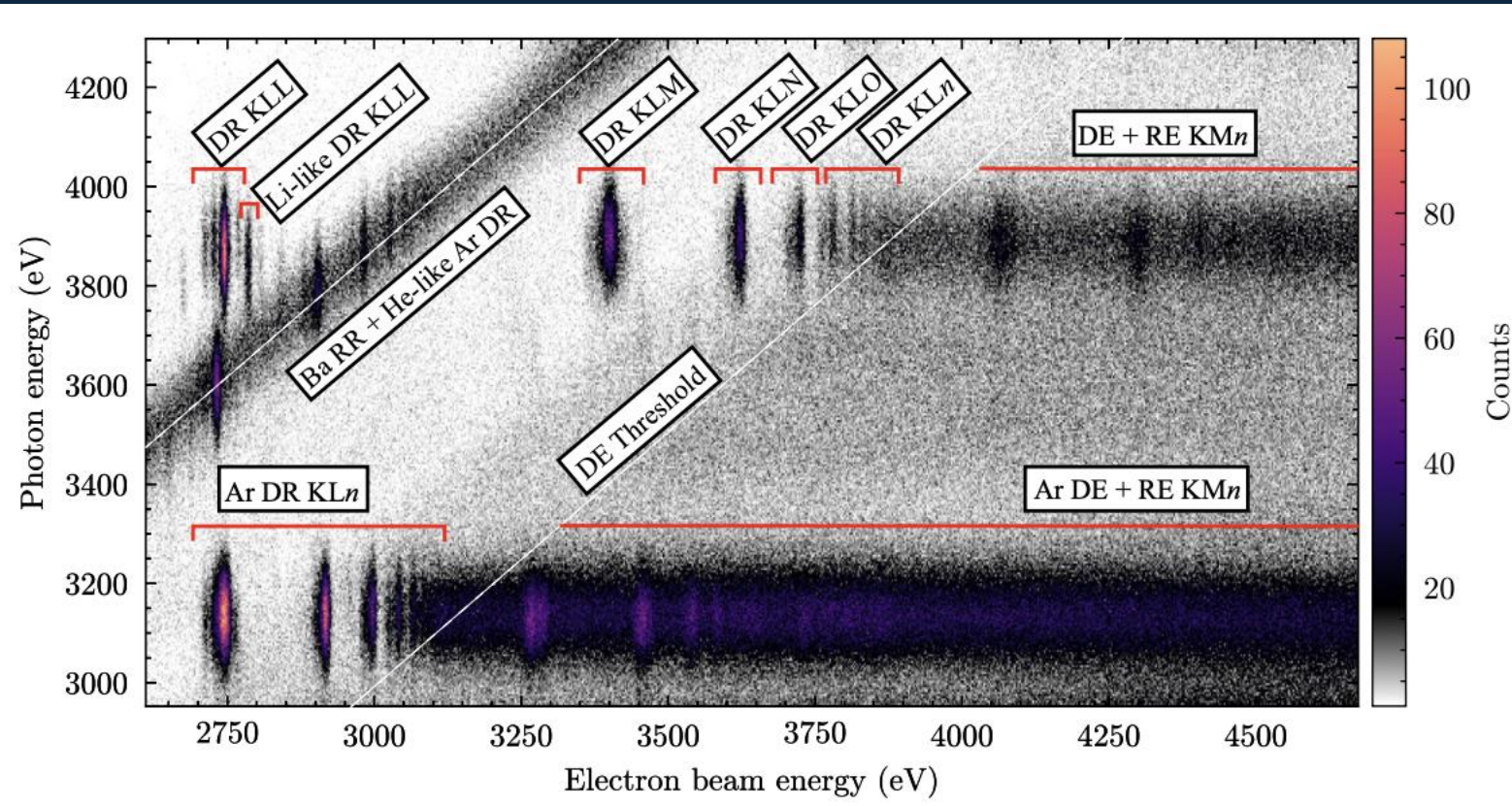
Flash EBIT : narrow energy



- Narrow electron energy
- Create low charge states
- High electron beam current
- Photoionization

Grilo et al., Phys. Rev. A **113**, 032819 (2026)

Flash EBIT : narrow energy



Grilo et al., Phys. Rev. A **113**, 032819 (2026)

- Narrow electron energy
- ~~Create low charge states~~
- ~~High electron beam current~~
- ~~Photoionization~~

Tradeoffs

Characteristic	SAO	SH	Polar-X	FLASH
Low energy	✗	✓	✗	✗
High current	✓	✗	✓	✗
Photon access	✗	✗	✓	✗
Narrow electron energy distribution	✓	✓	✓	★ ★ ★



There is no Unicorn EBIT

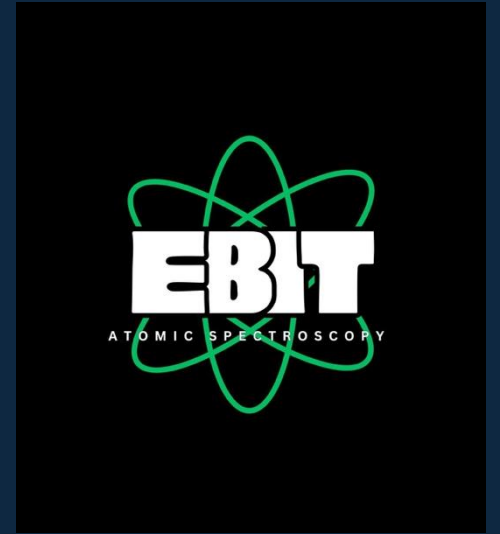
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Summary

- Measuring all the data for thousands of ions is not possible.
- EBITs are great at providing certain benchmark atomic data, but different EBIT designs excel at different measurements.
- Matching the facility to the scientific question is essential.

Tell me specifically how I can help!

- Which elements? – **is it injectable?**
- Which charge states? – **higher is better**
- Which transitions? – **required instrument resolution**
- Which atomic processes? **Collisional or photoionized ?**
- Which measurements would most improve your models?



Thank you!

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