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

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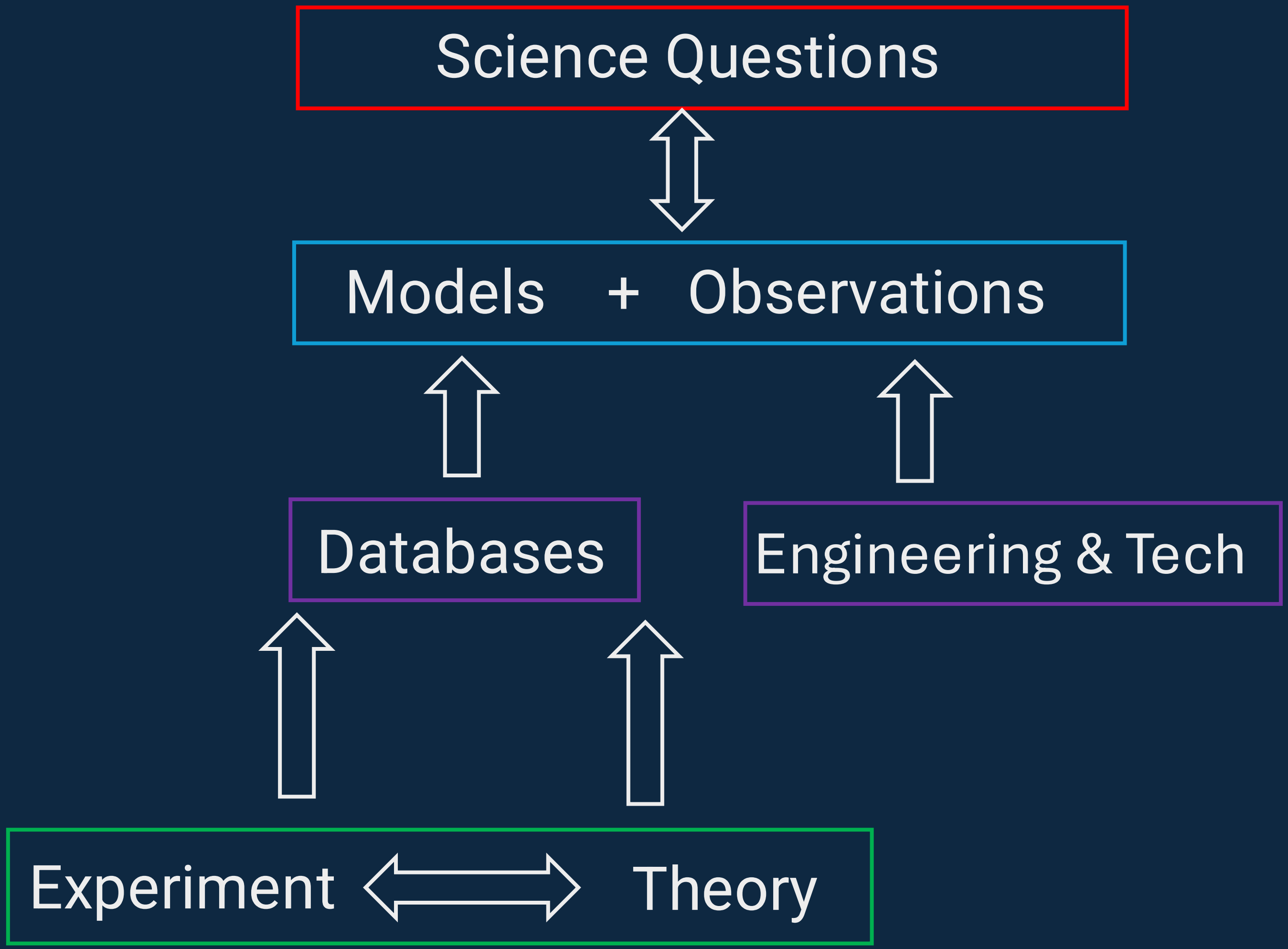
HEAVYMETAL VI
Jun 7 – 12, 2026
McDonald Forest Hills

AUBURN UNIVERSITY

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

What do we do?

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



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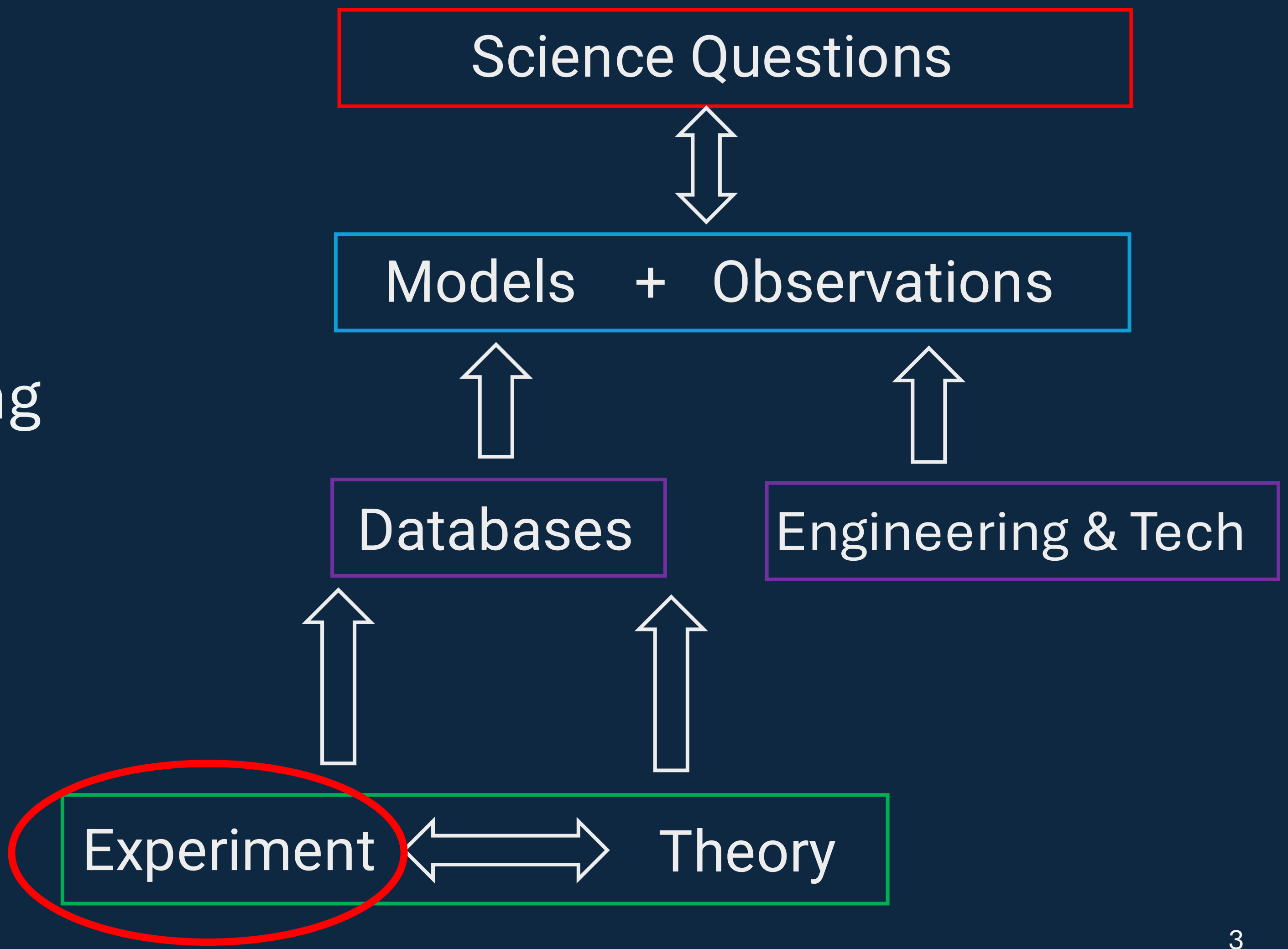

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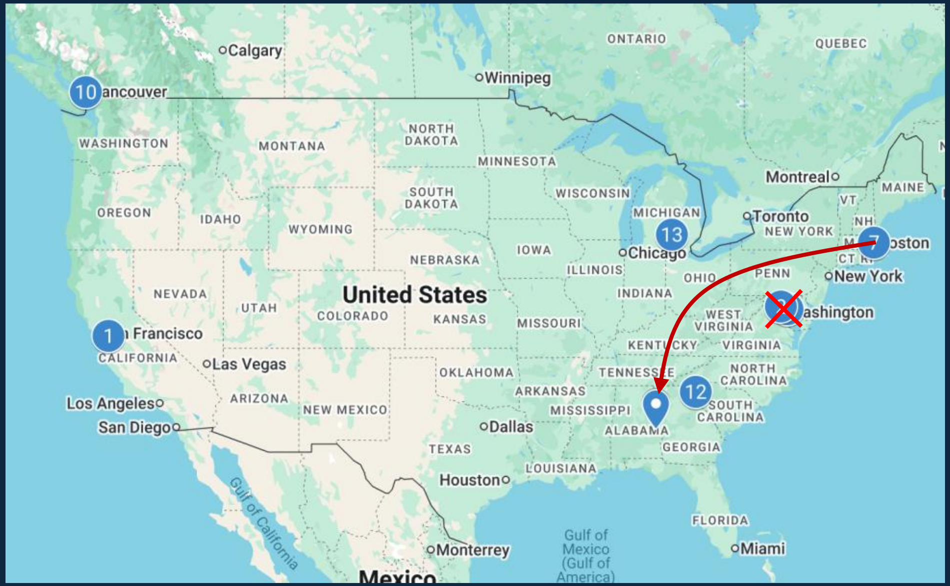
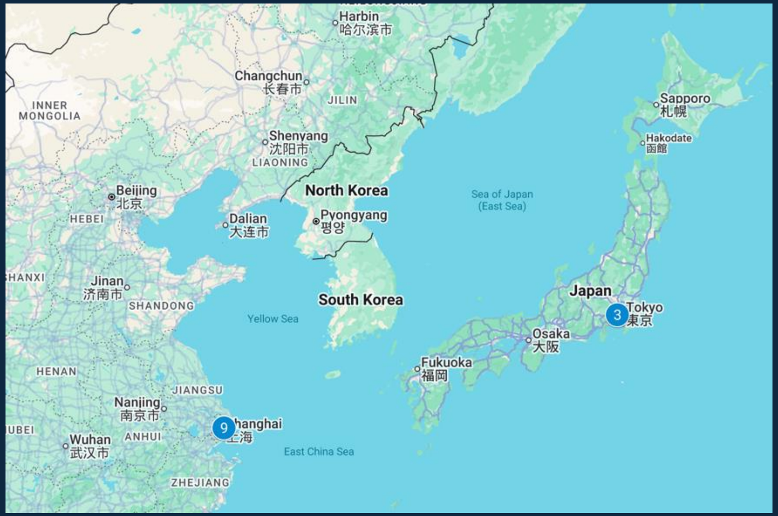
Electron Beam Ion Trap Facilities





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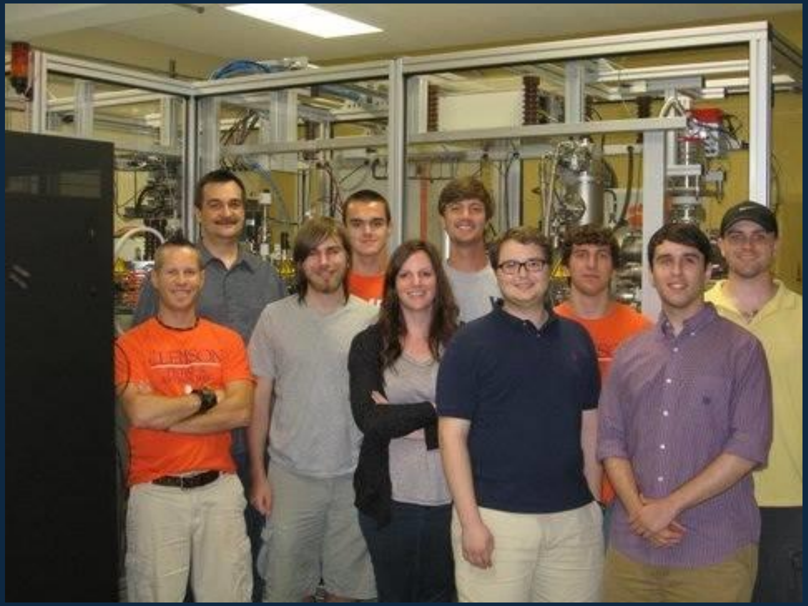
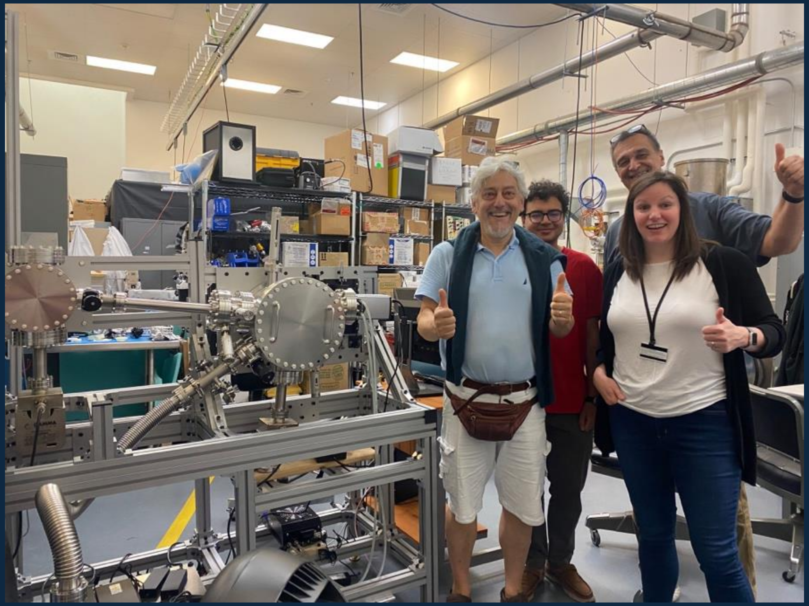


CLEMSON



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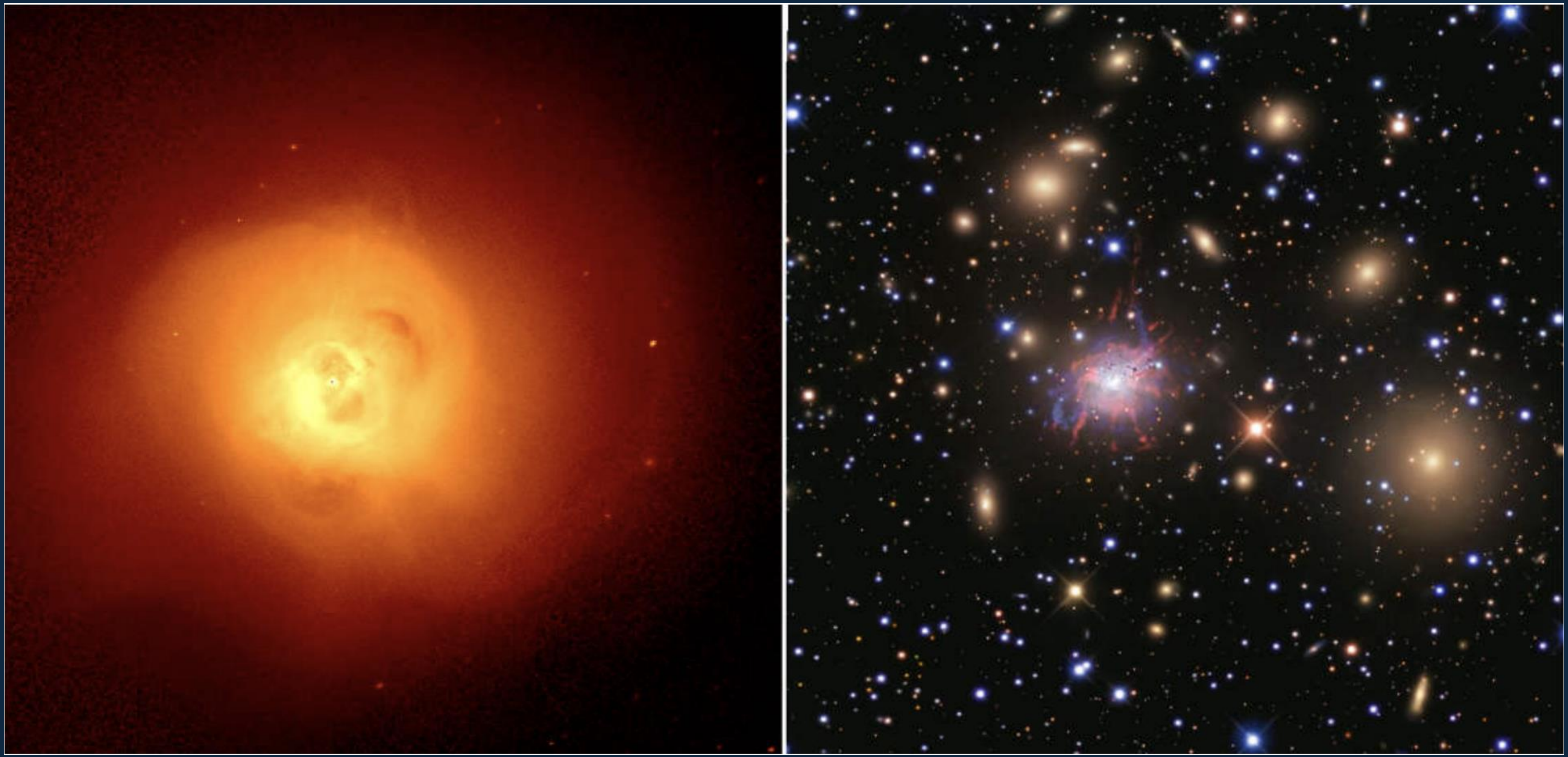
Hot Plasmas Across the Universe



Fabian et al. MNRAS 2011

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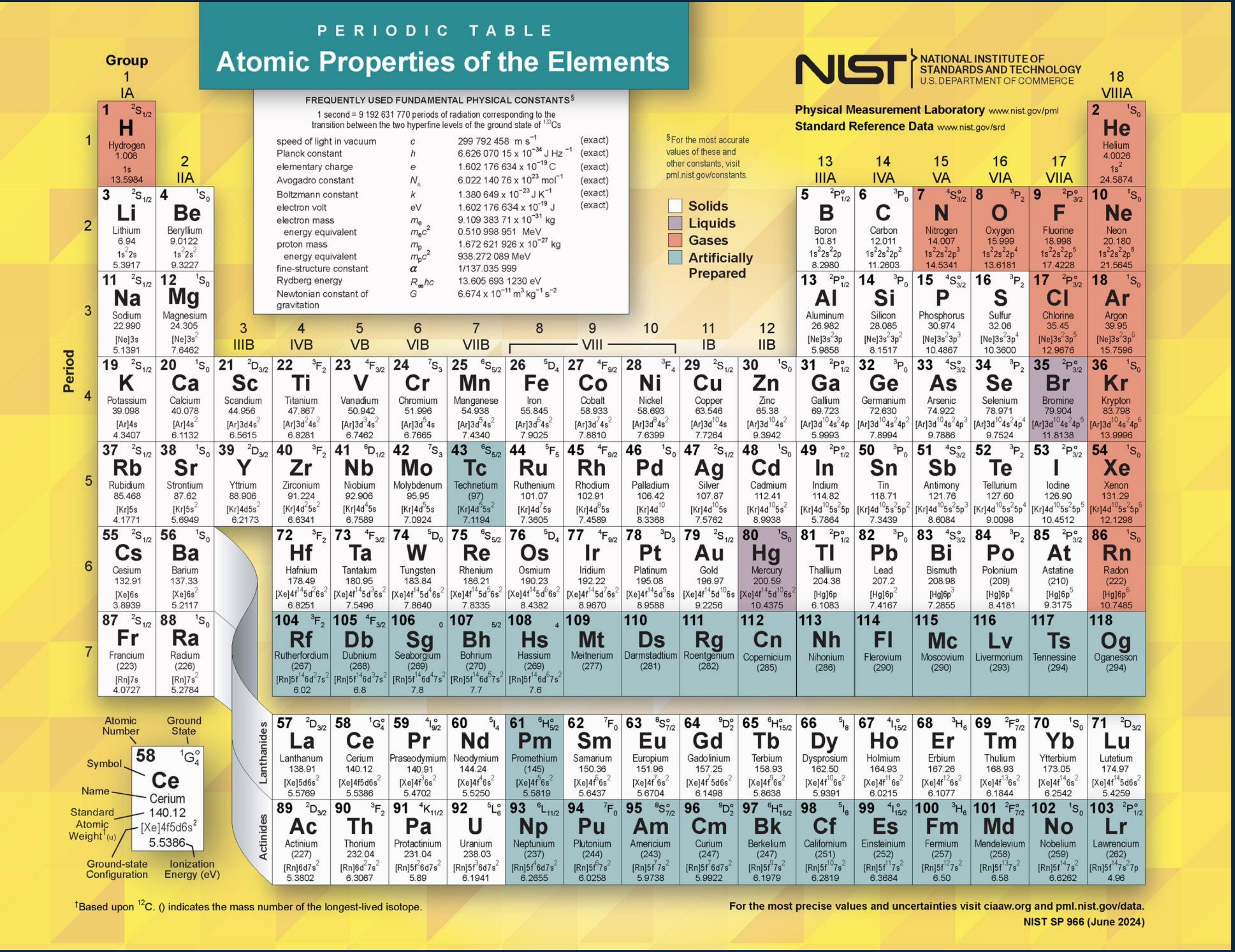
Goals

What Can I Measure for YOU?



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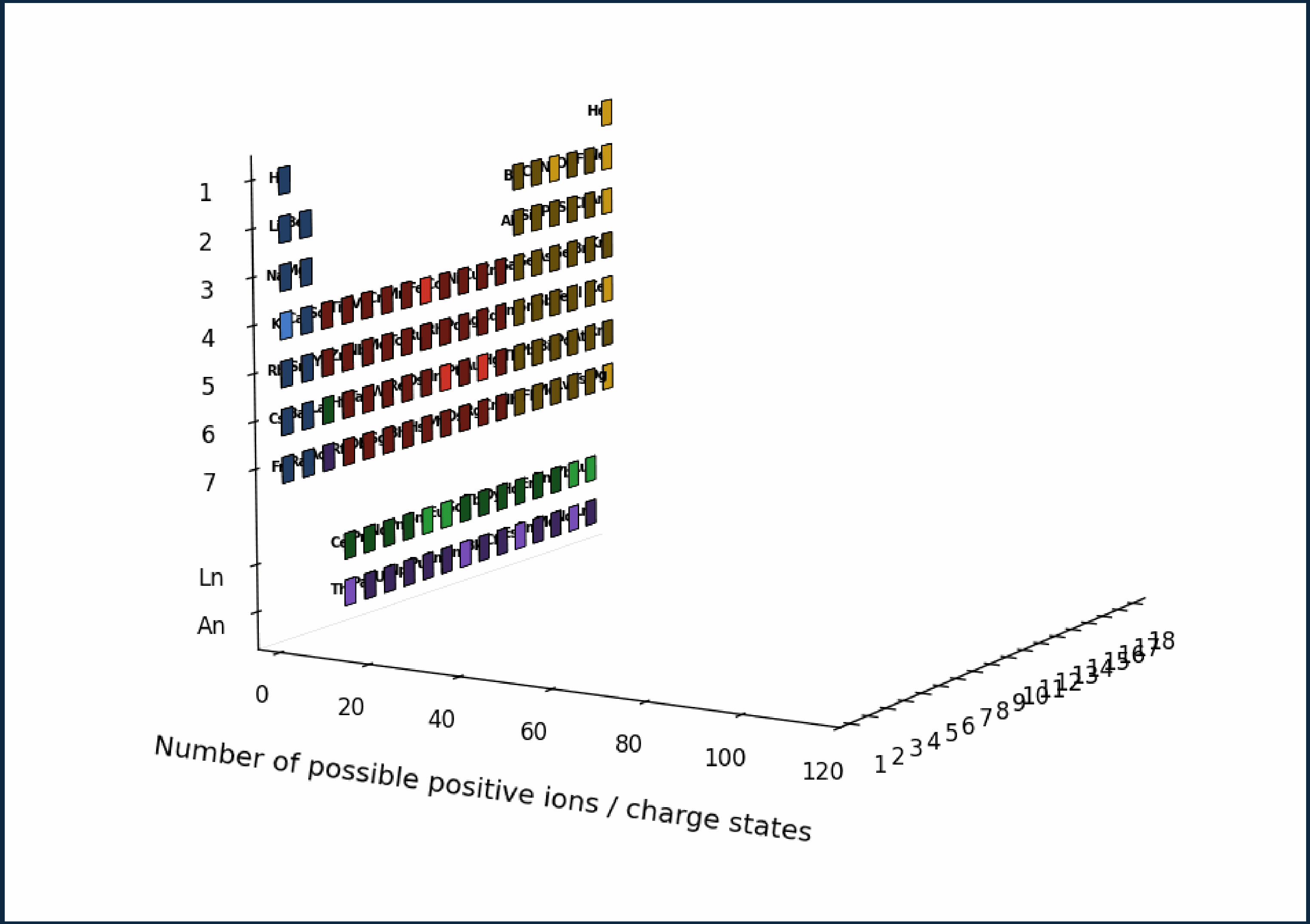
The Table of Ions



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Where Are the Gaps?

ASD | Data: Lines Levels | Information: List of Spectra, Ground States & Ionization Energies, Bibliography, Help

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	

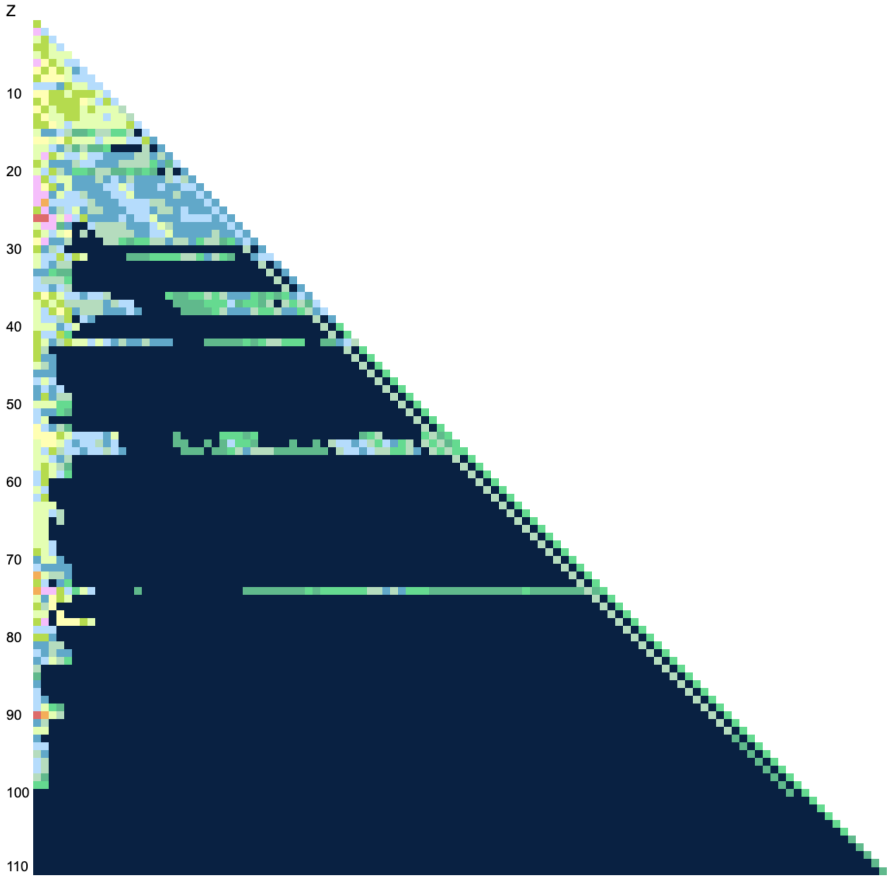
Color vs. number of lines:

N/A | ≤ 100 | ≤ 200 | ≤ 500 | ≤ 1000 | ≤ 2000 | ≤ 5000 | ≤ 10000 | > 10000

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)



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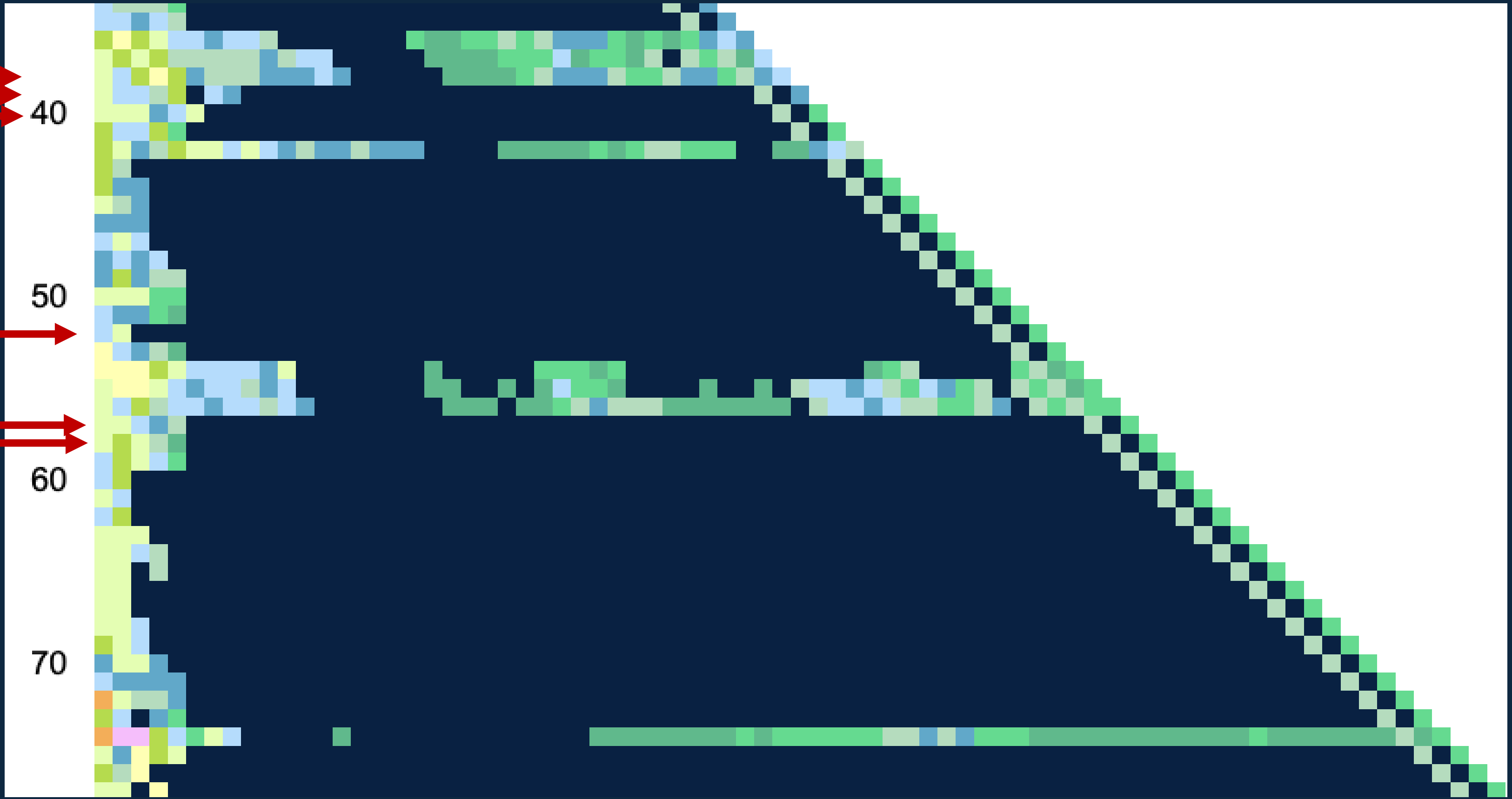
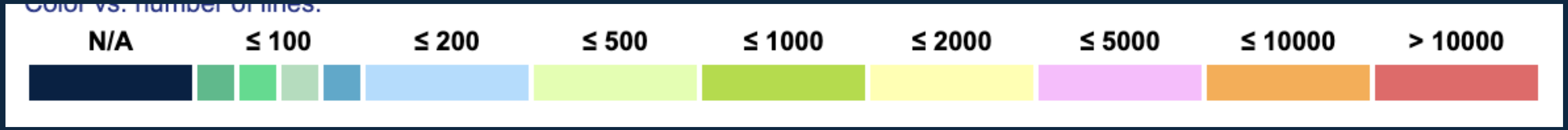
NIST Database

Strontium
Yttrium
Zirconium

Tellurium

Lanthanum
Cerium





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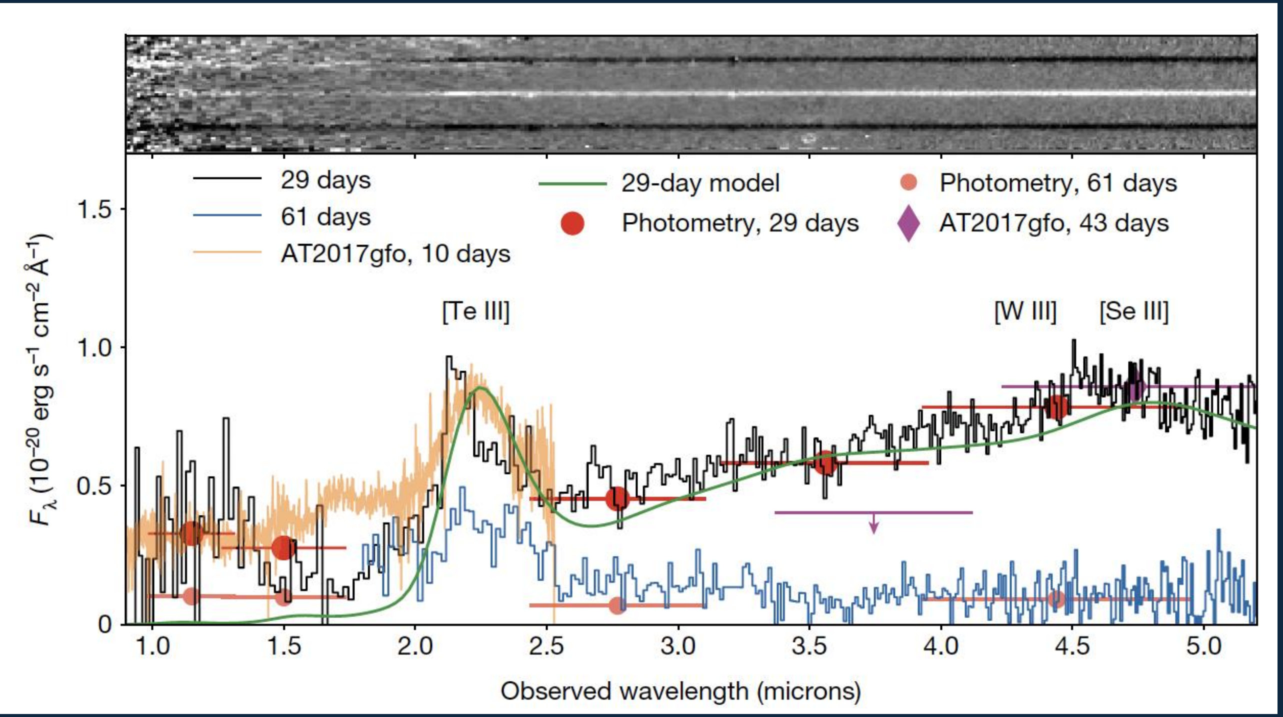
Tellurium



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)

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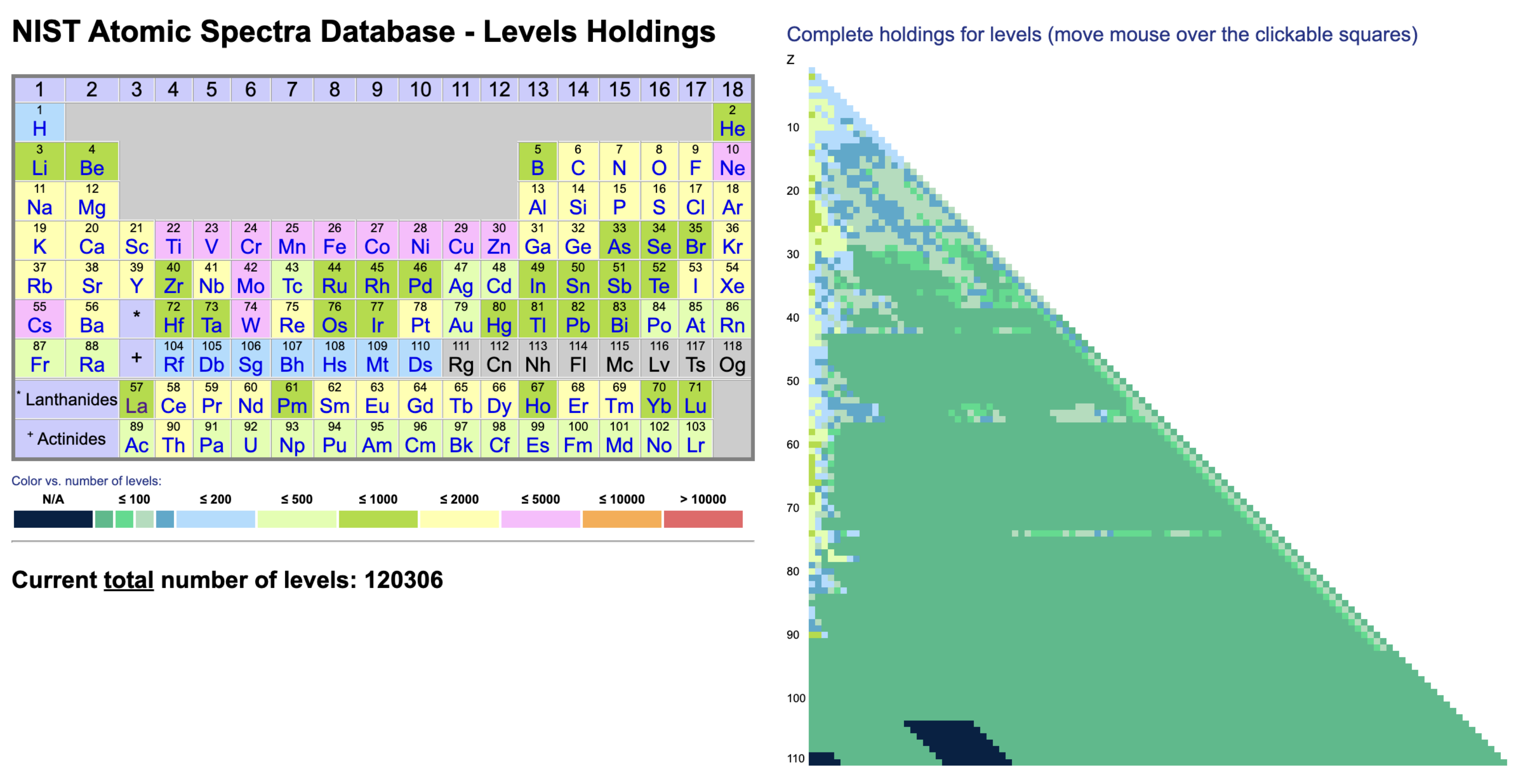
Energy levels

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



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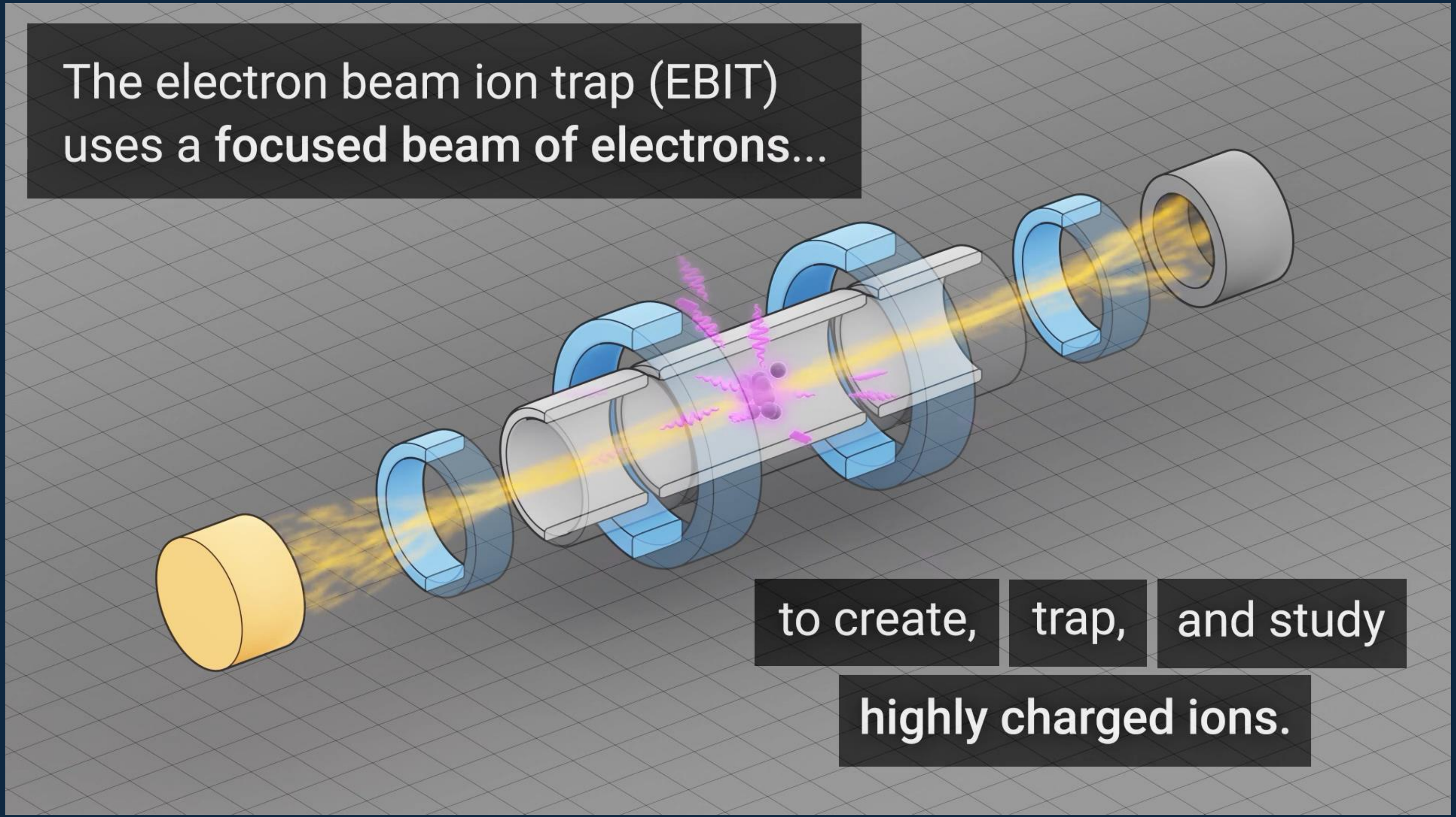
“What we need”

- 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

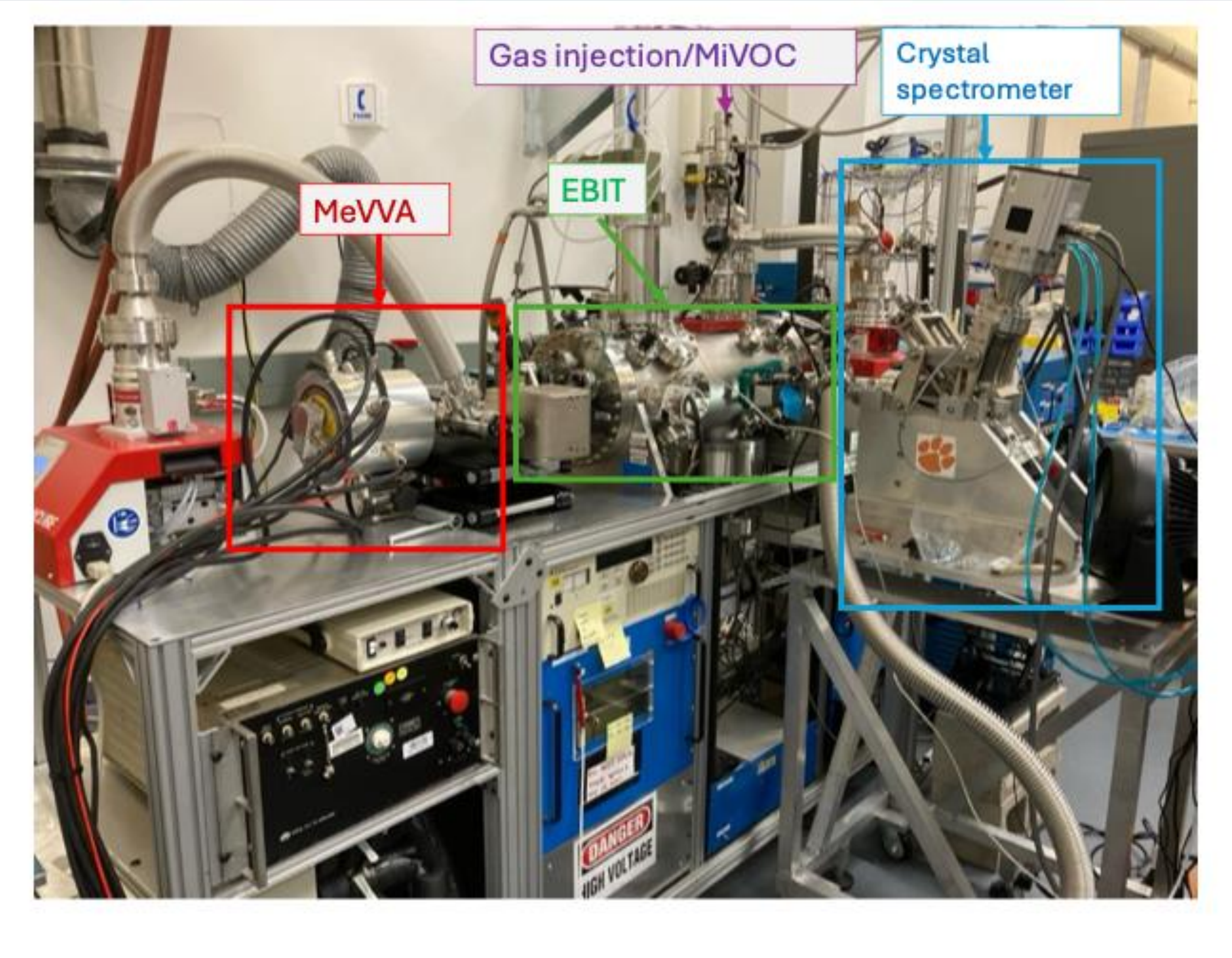
What Is an Electron Beam Ion Trap?

- 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



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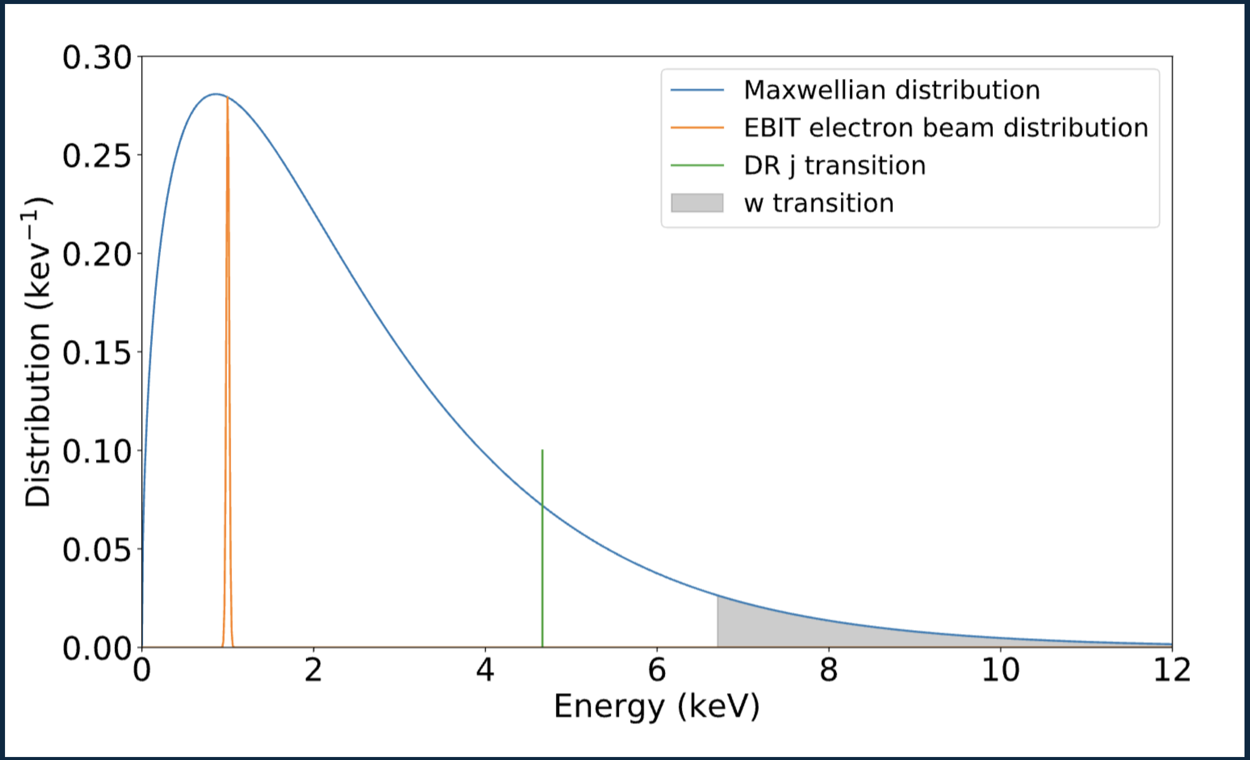
Unique Capabilities of EBITs

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



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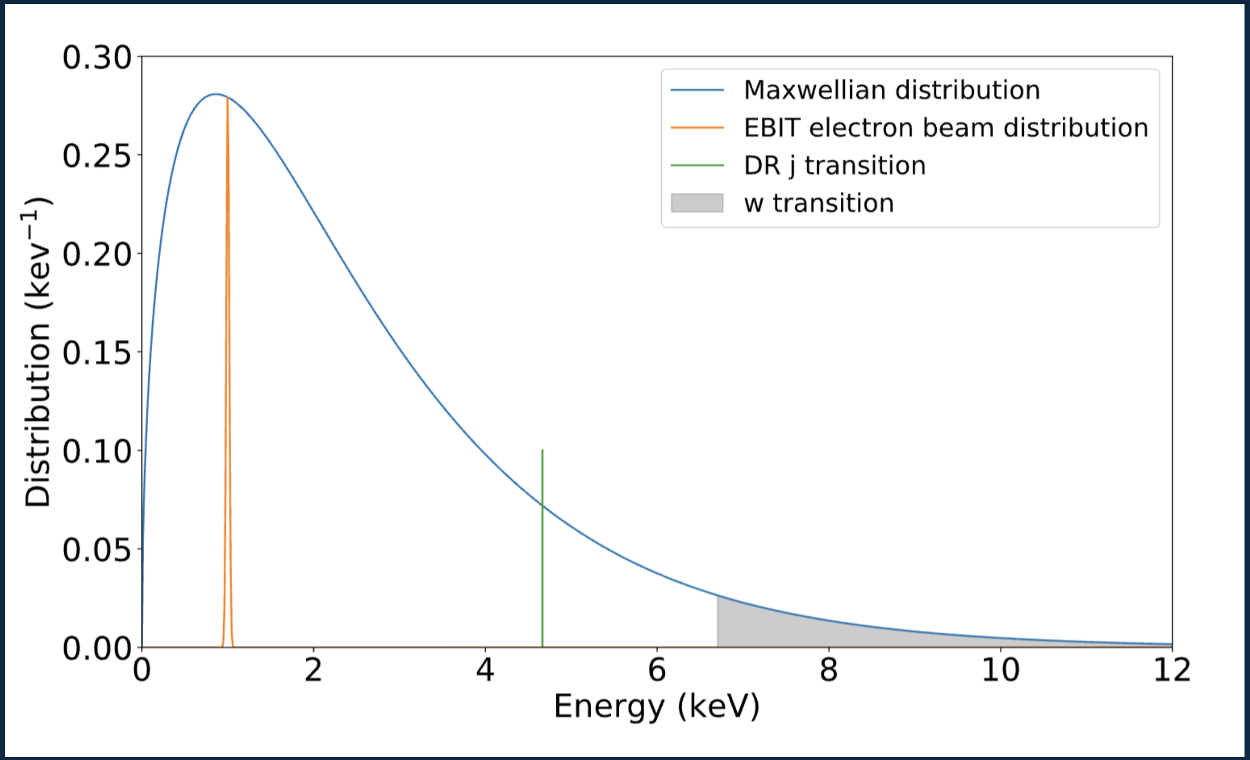
Charge-State Control

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
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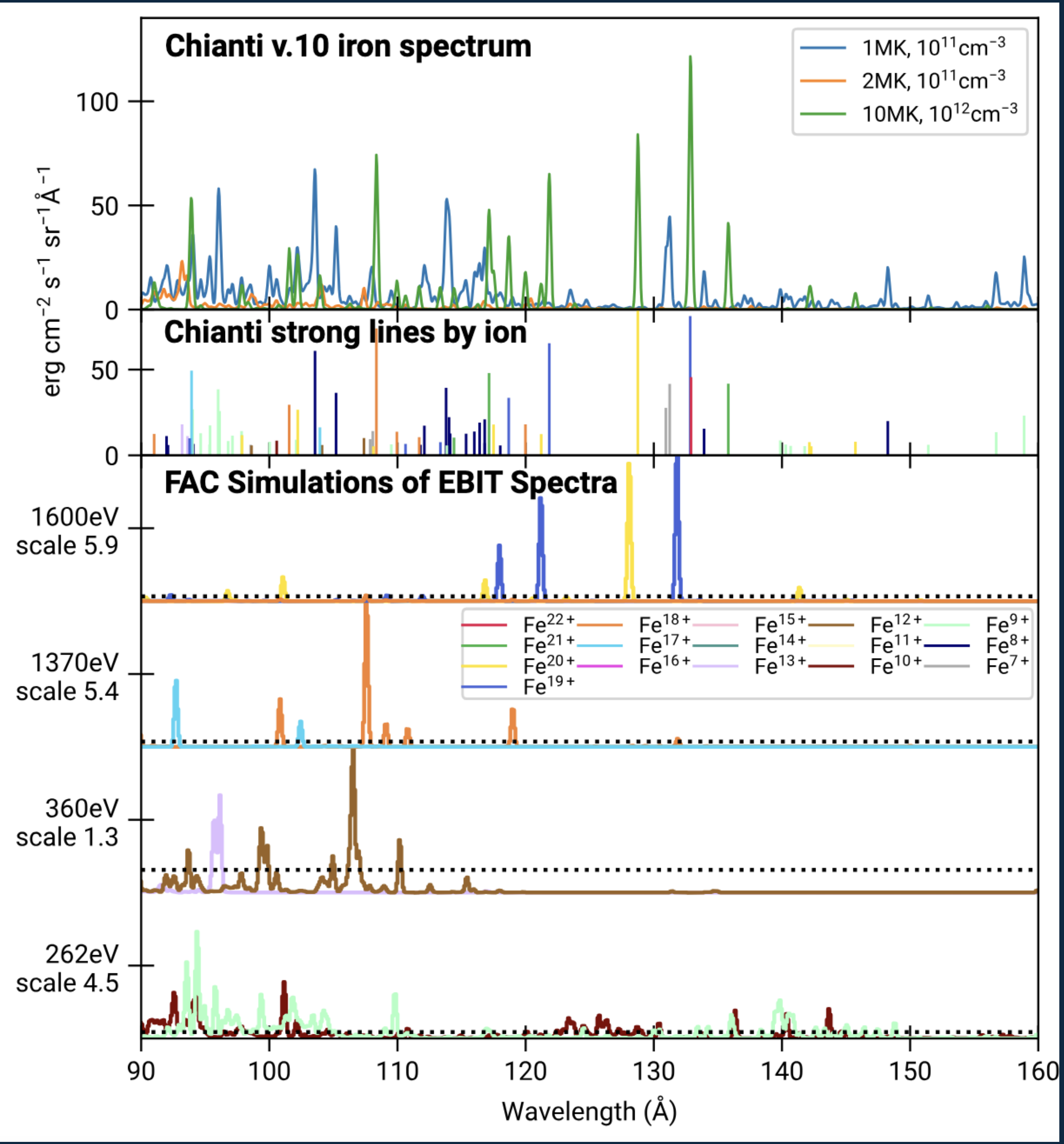

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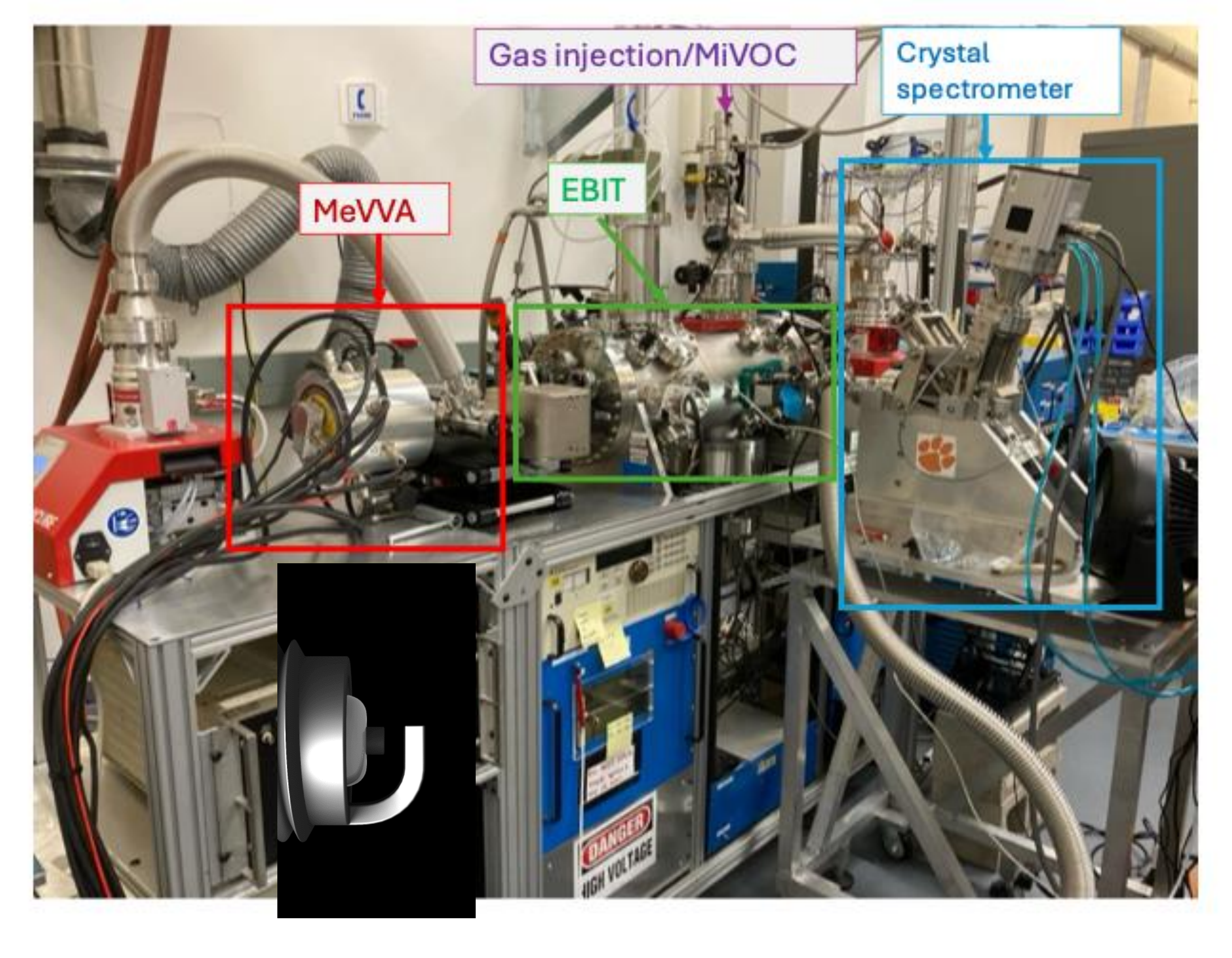
What elements can we study?

- Gas injection
- Metal Vapor Vacuum Arc
- Laser Ablation



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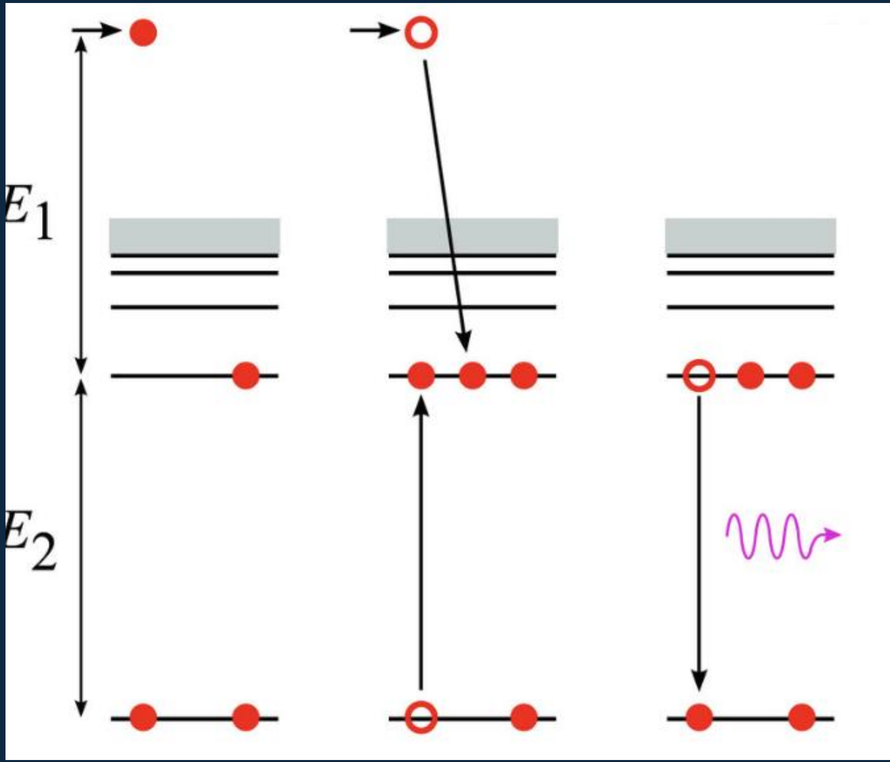
What Processes can we study?

- 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)

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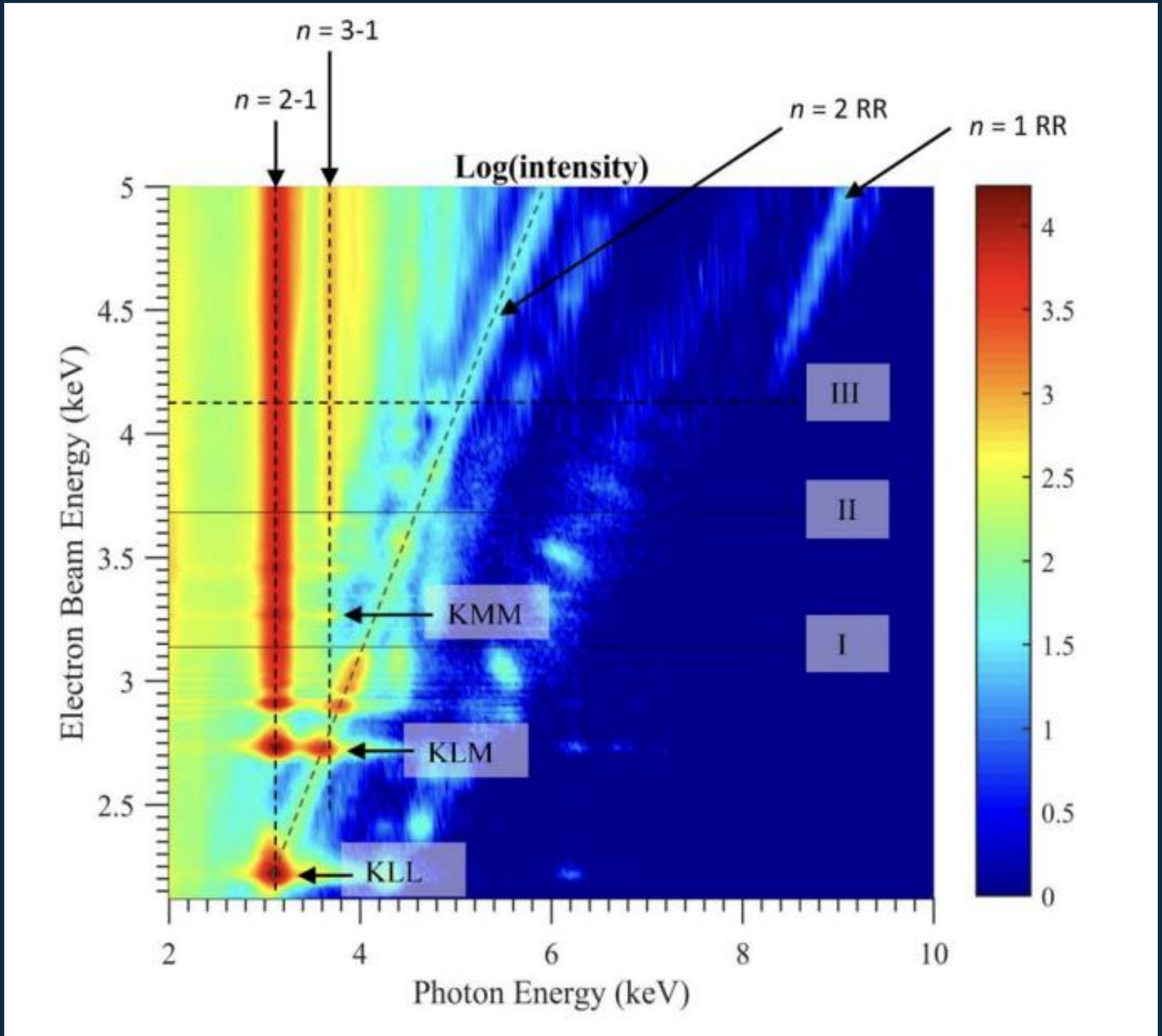
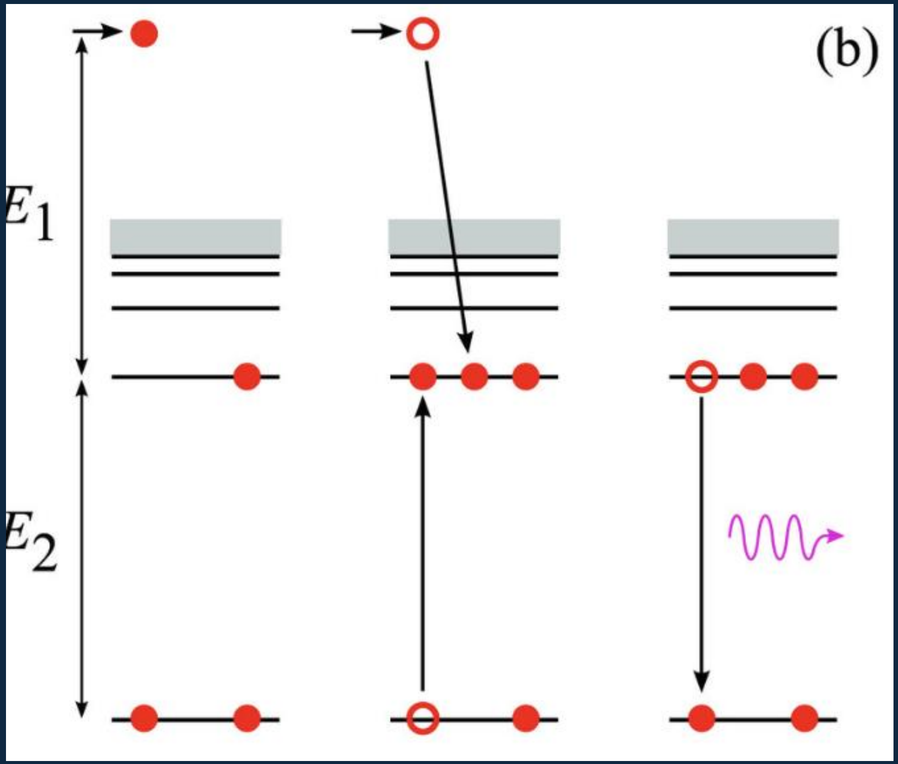

n = 3-1
n = 2-1
n = 2 RR
n = 1 RR
Log(intensity)
Electron Beam Energy (keV)
Photon Energy (keV)
III
II
I
KMM
KLM
KLL
5
4.5
4
3.5
3
2.5
2
4
6
8
10
4
3.5
3
2.5
2
1.5
1
0.5
0


(b)
E_1
E_2

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

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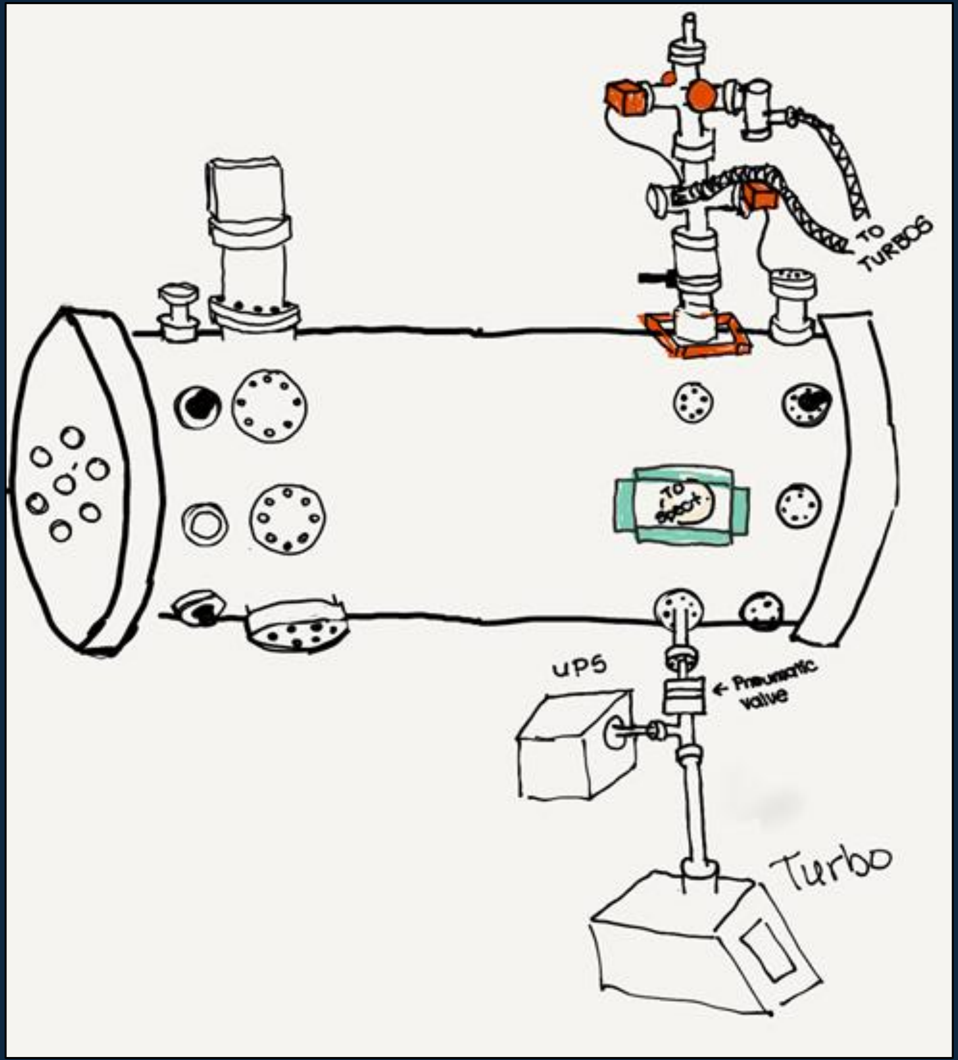
Key EBIT Characteristics

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

SAO EBIT (typical EBIT)



- Narrow electron energy
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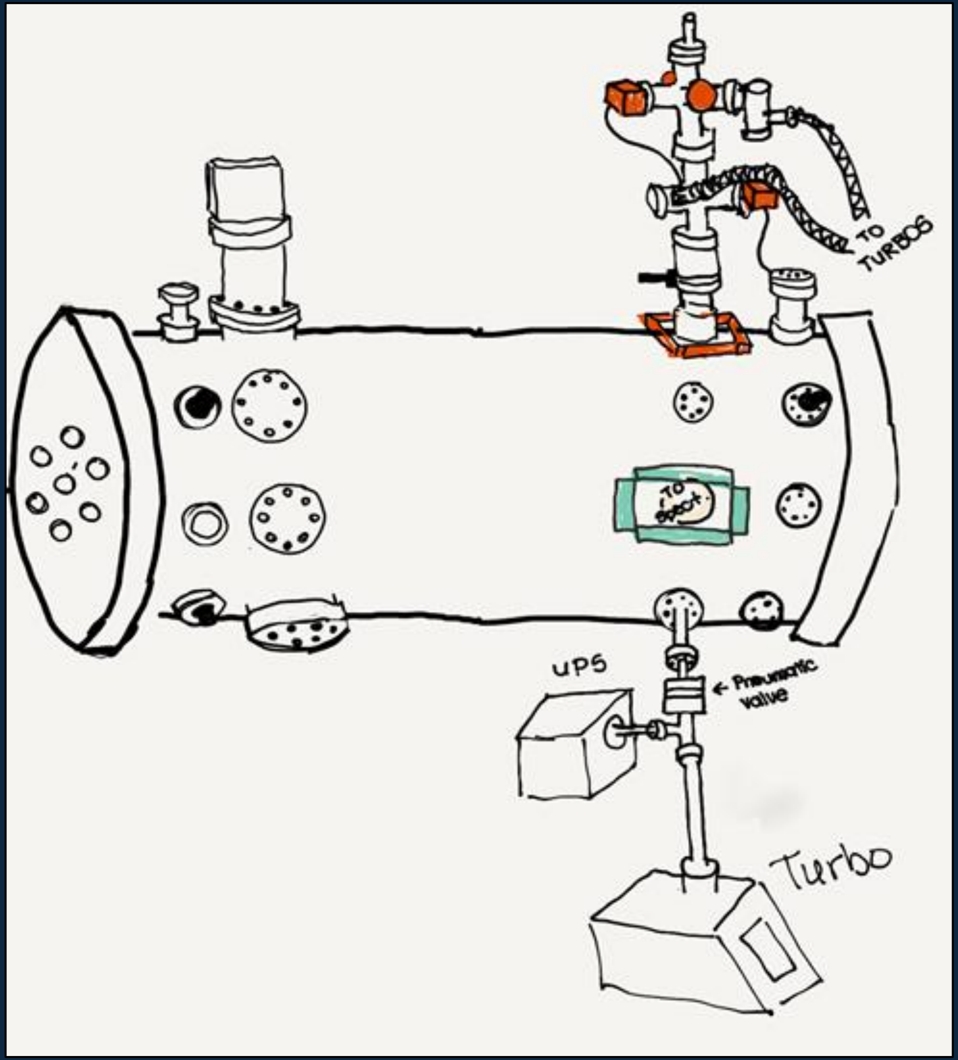
SAO EBIT (typical EBIT)



- ~~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)

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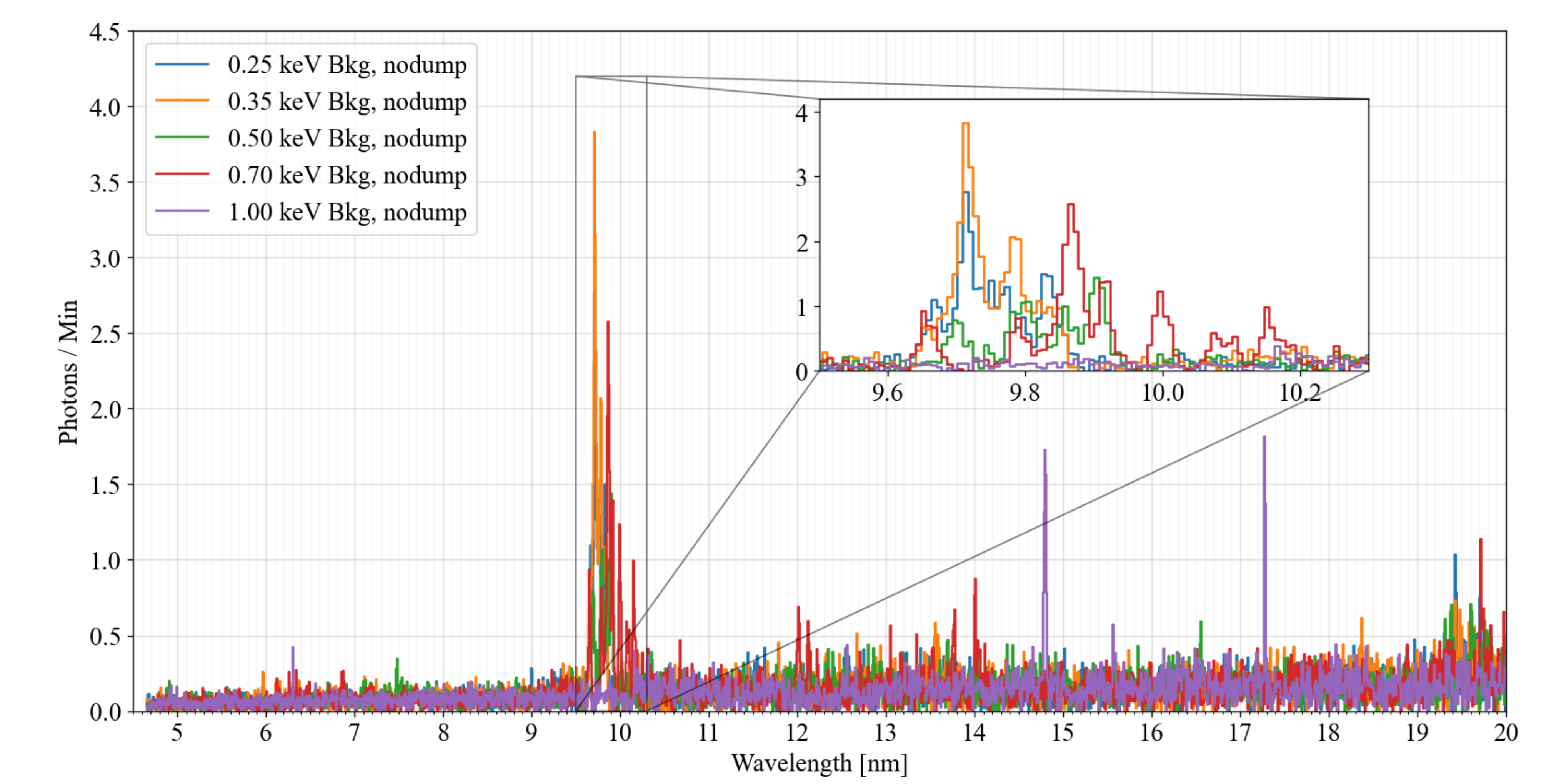
SAO EBIT



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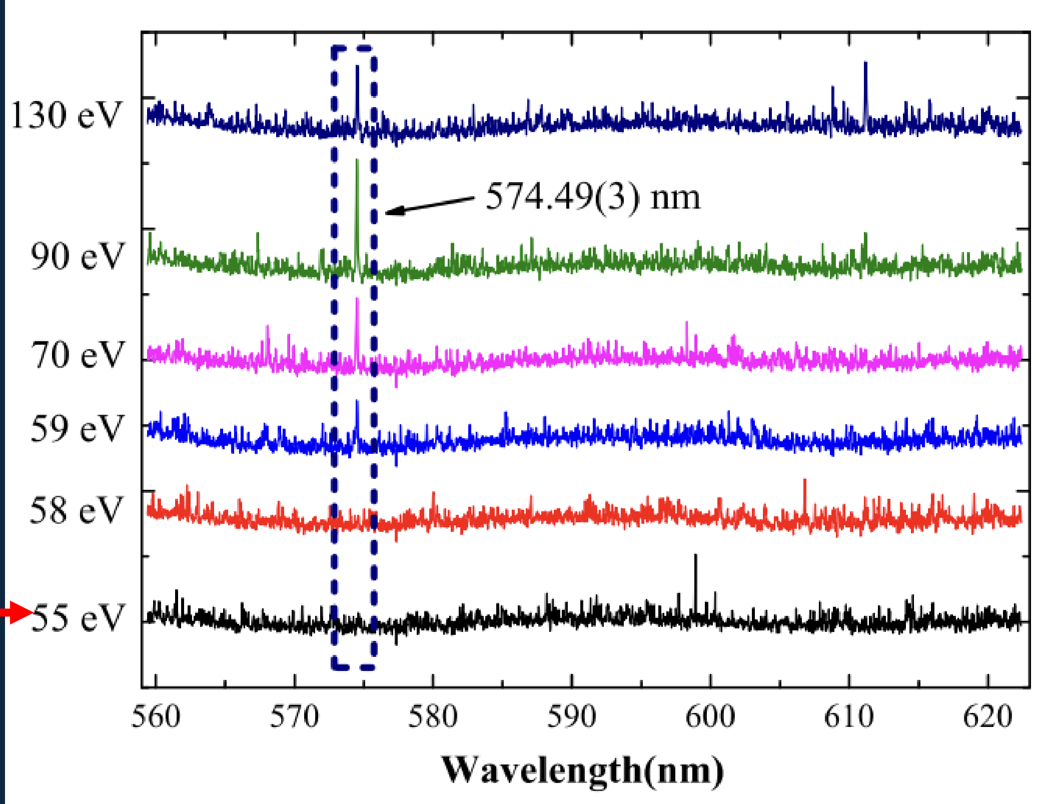
What charge states can we produce?

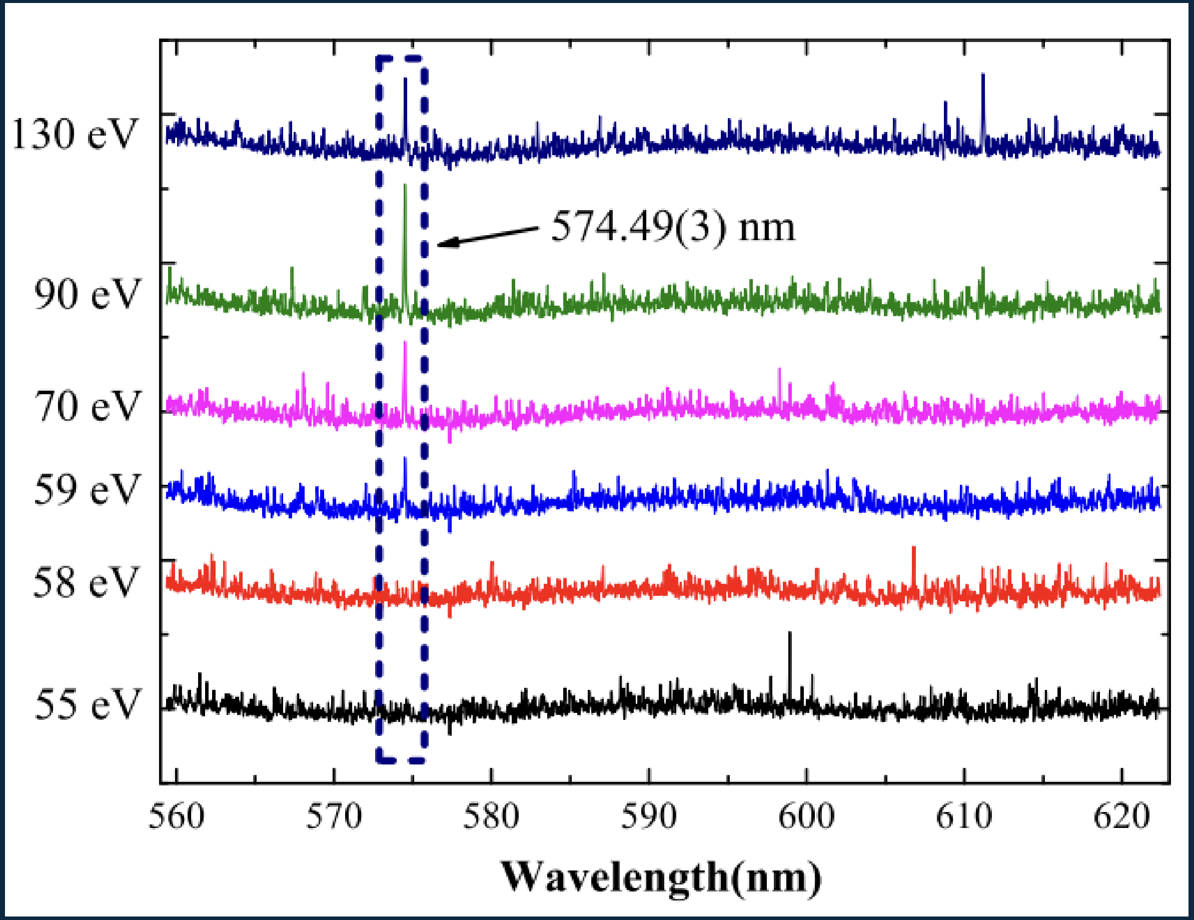
- Some can go lower, 30 eV
- Some higher, up to 150 keV.

BEAM ENERGY



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

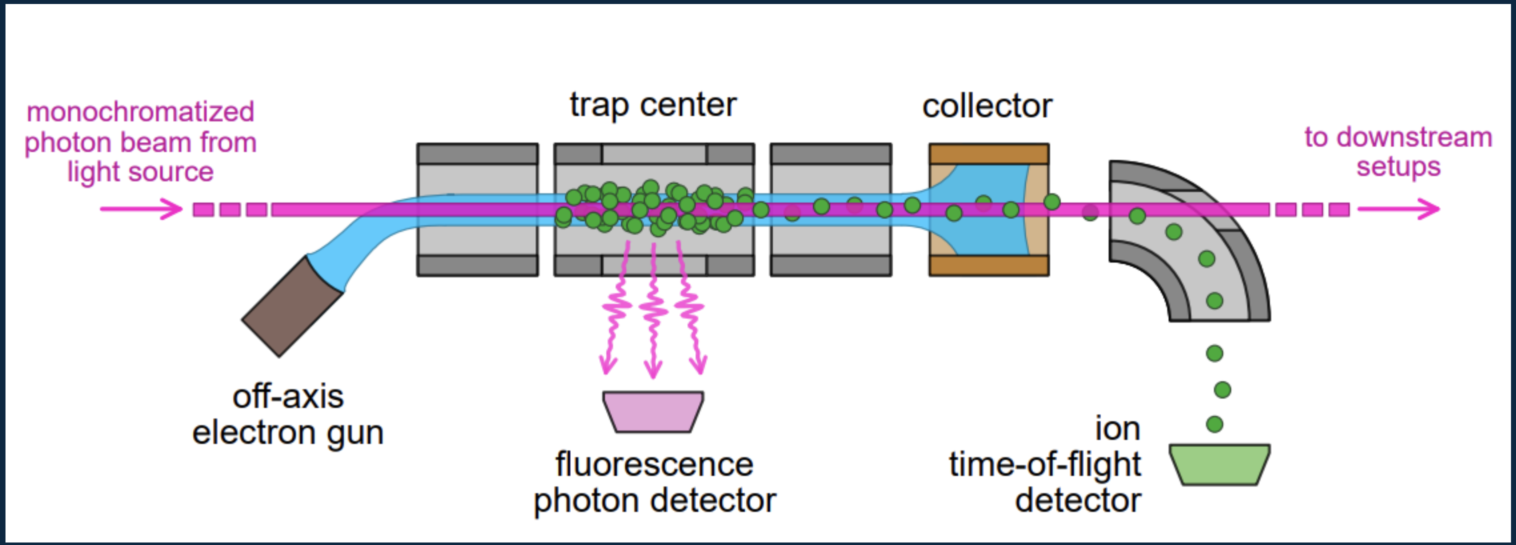
SH-HtscEBIT : low energies



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
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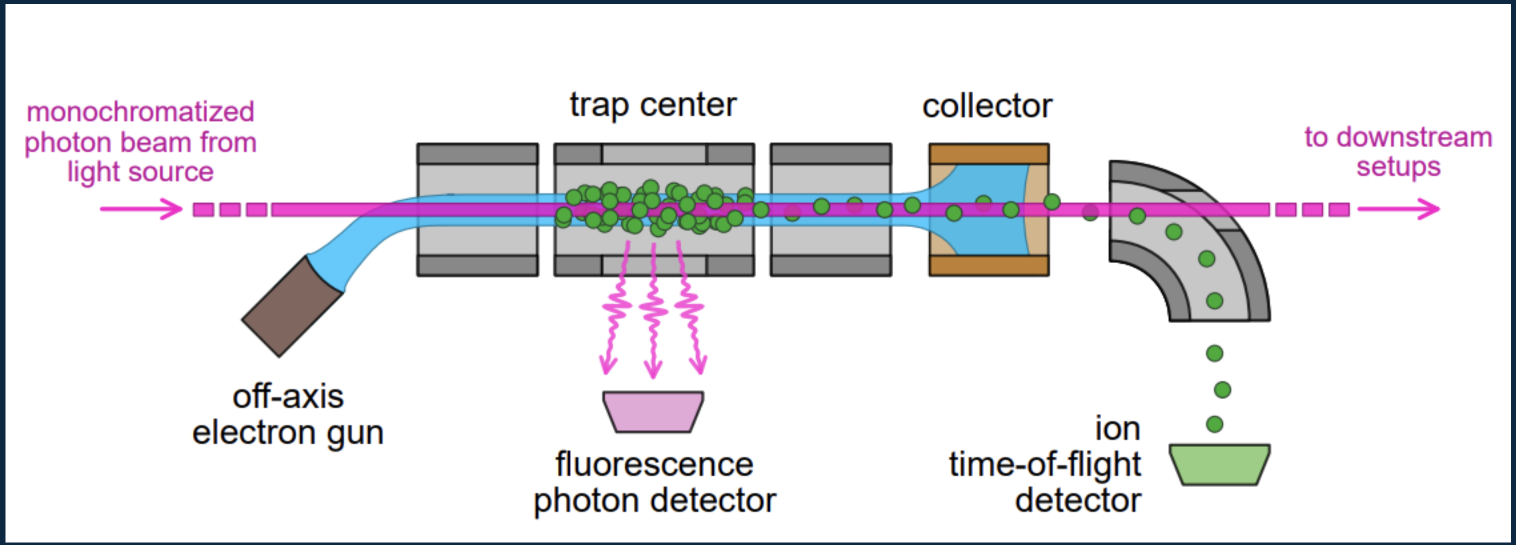
Polar-X EBIT : off-axis gun



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

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

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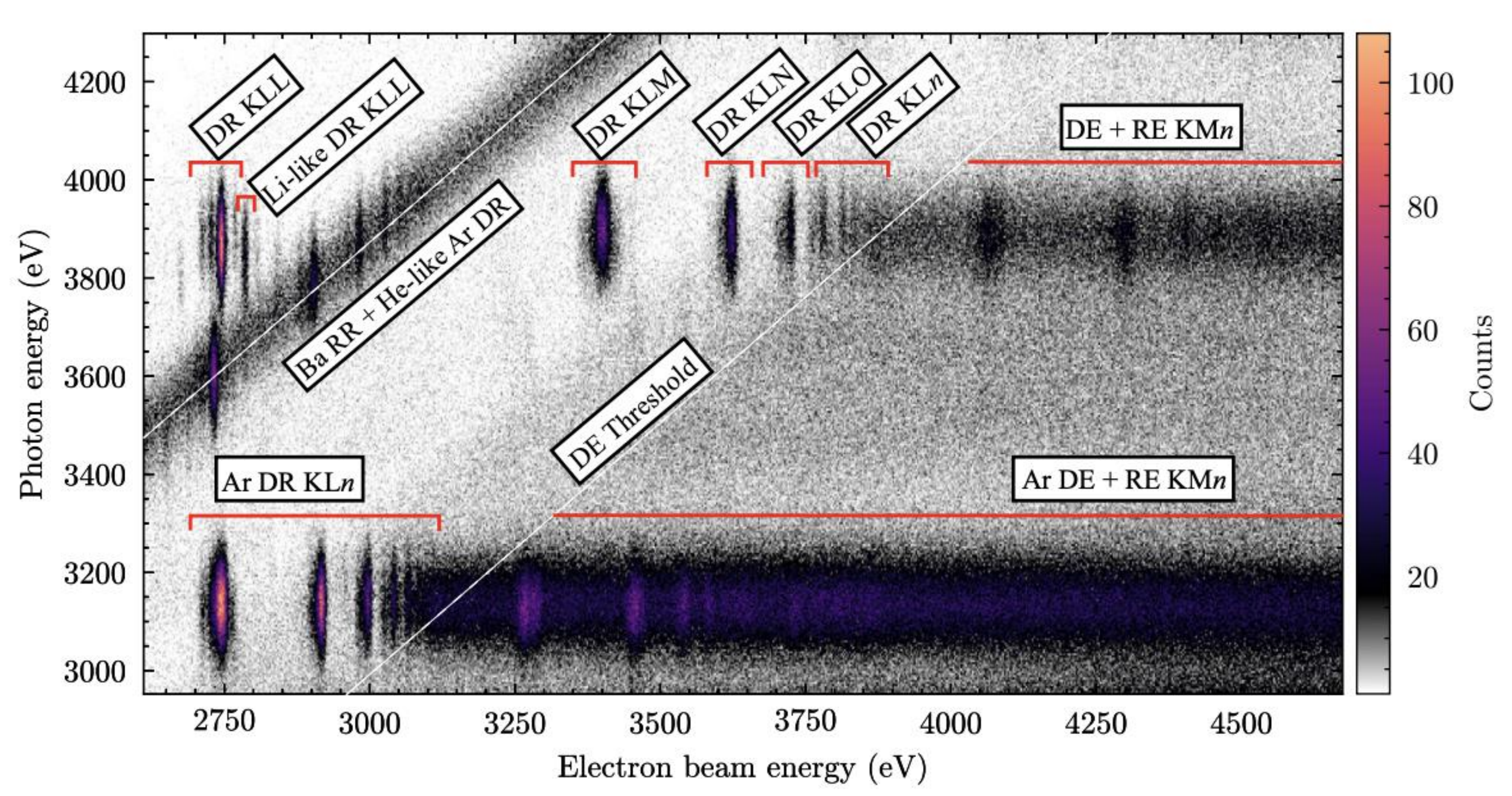
Flash EBIT : narrow energy



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

- Narrow electron energy
- Create low charge states
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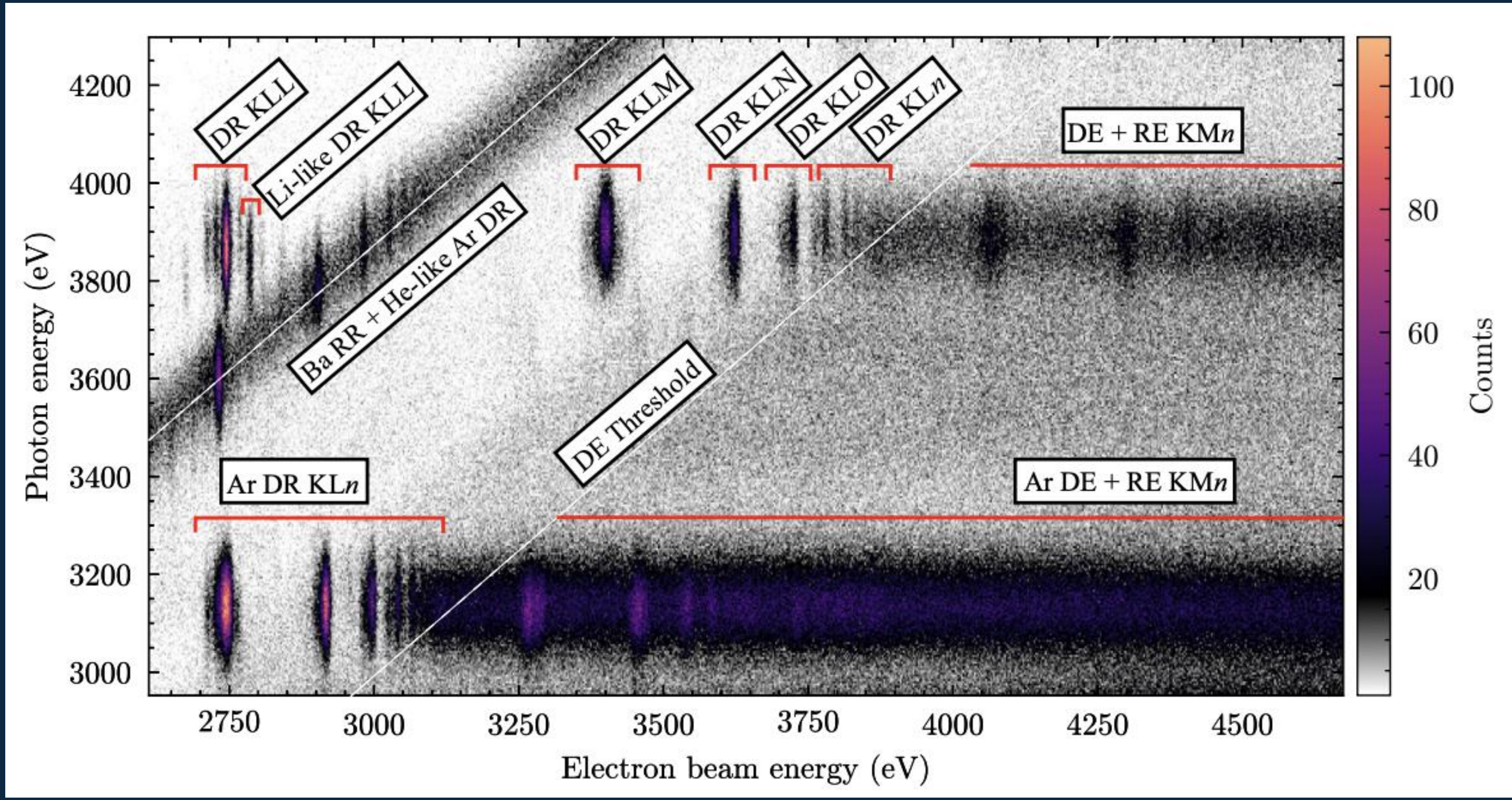
- Photoionization

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	✅	✅	✅	⭐⭐⭐

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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.

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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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