

# Visible and near infra-red spectroscopy of laser plasmas for astrophysics.

HEAVYMETAL



Funded by  
the European Union



European Research Council  
Established by the European Commission

Padraig Dunne, UCD.

Observations – U Copenhagen

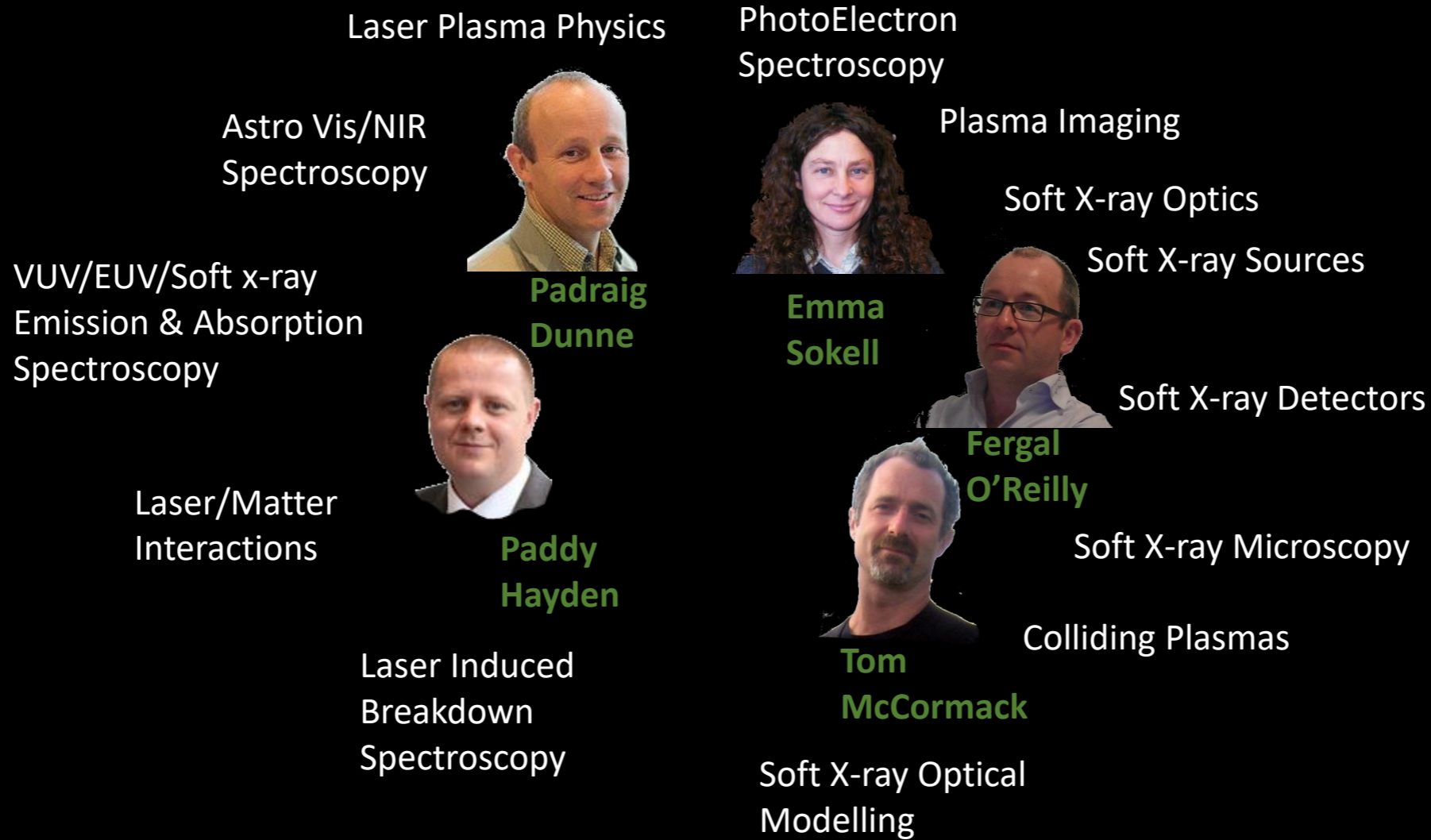
**Experiments – UCD**

Simulations – GSI Darmstadt

Spectral models – QUB



# THE SPECTROSCOPY GROUP AT UCD:



# THE SPECTROSCOPY GROUP AT UCD:



Laser Plasma Physics

PhotoElectron Spectroscopy

Astro Vis/NIR Spectroscopy

Plasma Imaging

VUV/EUV/Soft x-ray Emission & Absorption Spectroscopy

Soft X-ray Optics



**Padraig Dunne**



**Emma Sokell**

Soft X-ray Sources



**Paddy Hayden**



**Fergal O'Reilly**

Soft X-ray Detectors

Laser/Matter Interactions



**Tom McCormack**

Soft X-ray Microscopy

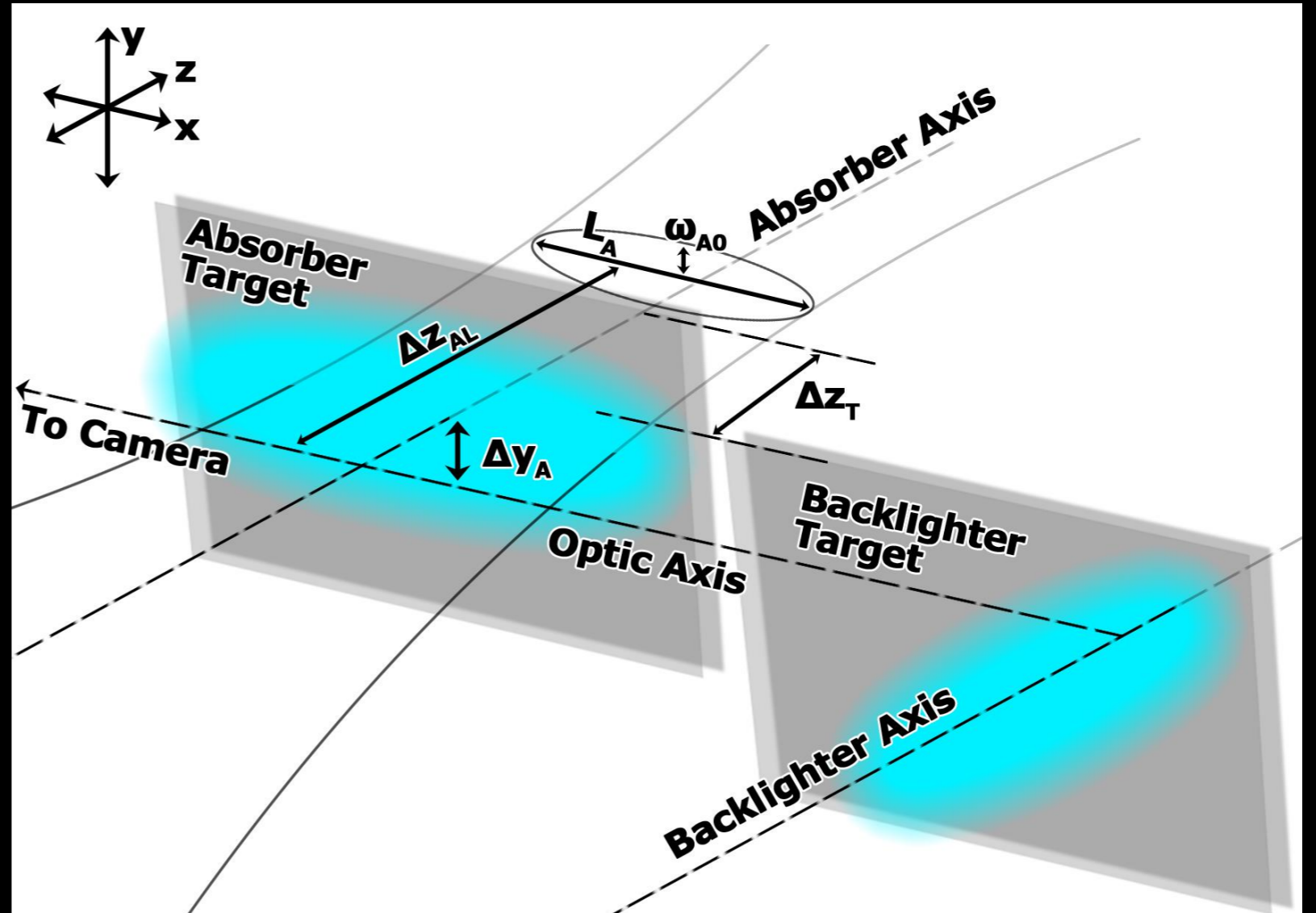
Laser Induced Breakdown Spectroscopy

Colliding Plasmas

Soft X-ray Optical Modelling

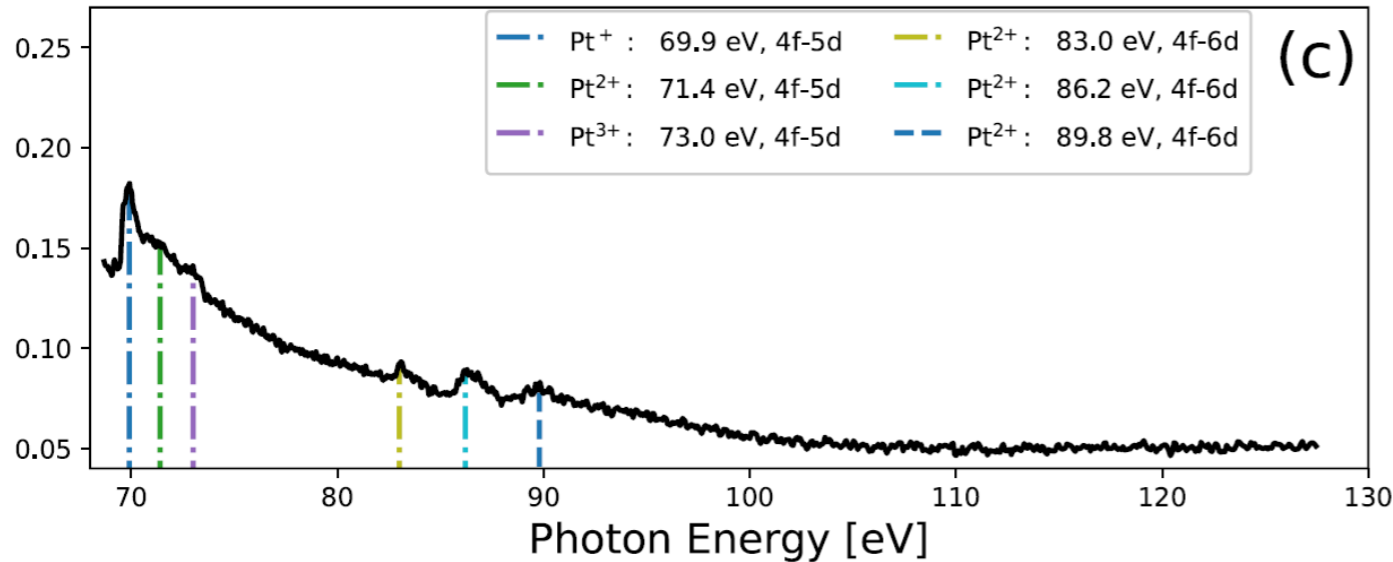
# DUAL LASER PLASMA (DLP) PHOTOABSORPTION:

- Time delay
- Power density
- $\Delta Z_T$  = Inter-Target z-displacement
- $\Delta Y_A$  = Absorber y-displacement from Optic Axis
- $\Delta Z_{AL}$  = Absorber z-displacement between Minimum Beam Waist and Optic Axis
- $\omega_{A0}$  = Absorber Minimum Beam Waist
- $L_A$  = Absorber Plasma Length
- Backlighter source target

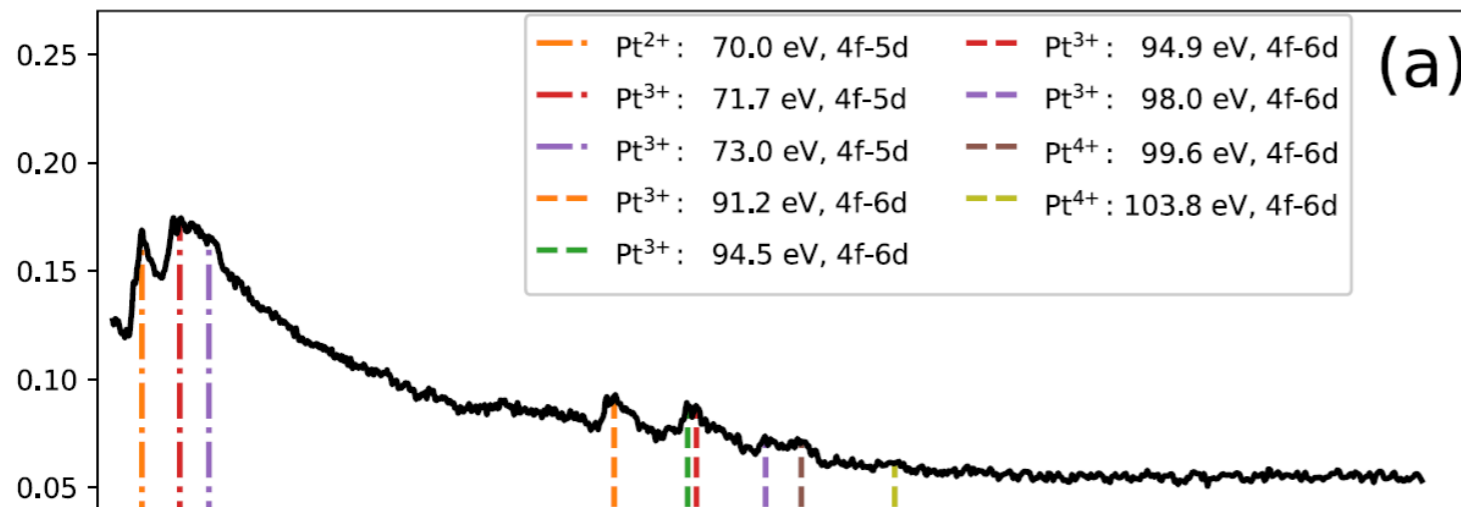


# DLP PHOTOABSORPTION

Platinum spectra ~67 eV to ~130 eV



$\Delta t = 300$  ns



$\Delta t = 100$  ns

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IOP Publishing

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J. Phys. B: At. Mol. Opt. Phys. 56 (2023) 135002 (11pp)

<https://doi.org/10.1088/1361-6455/acd9b7>

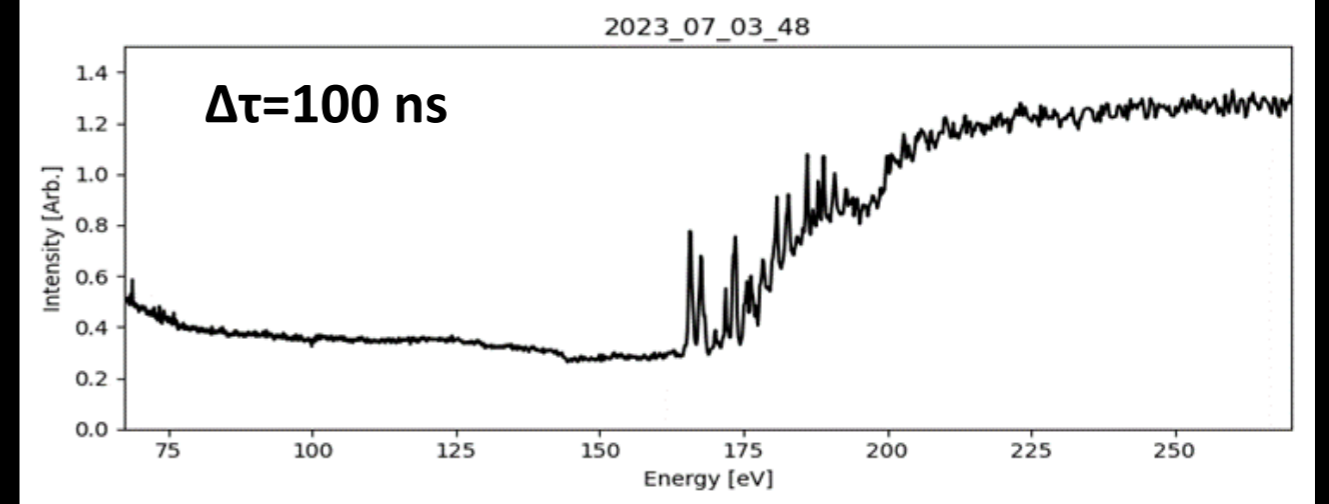
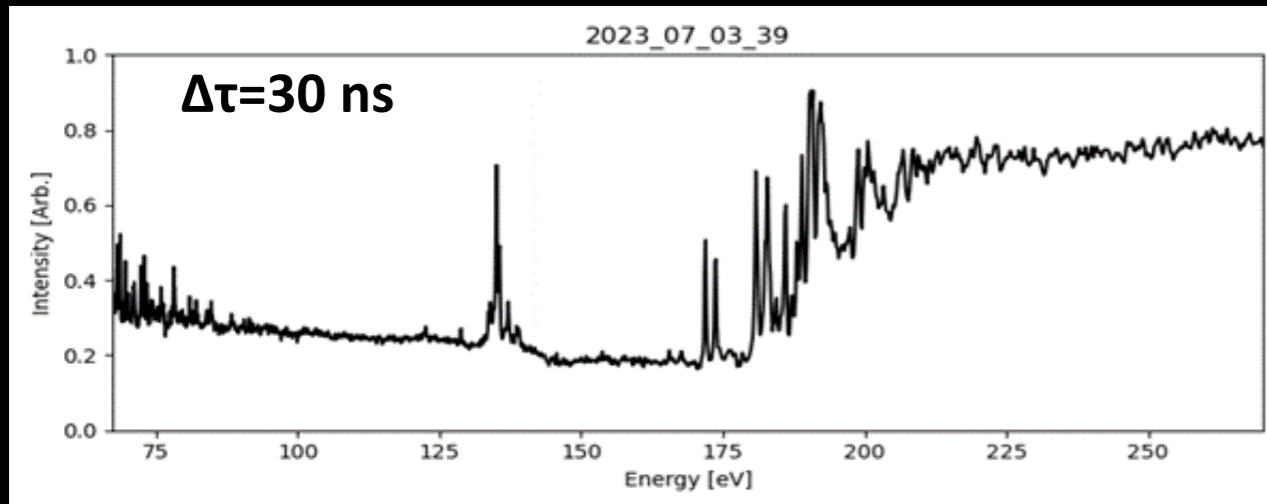
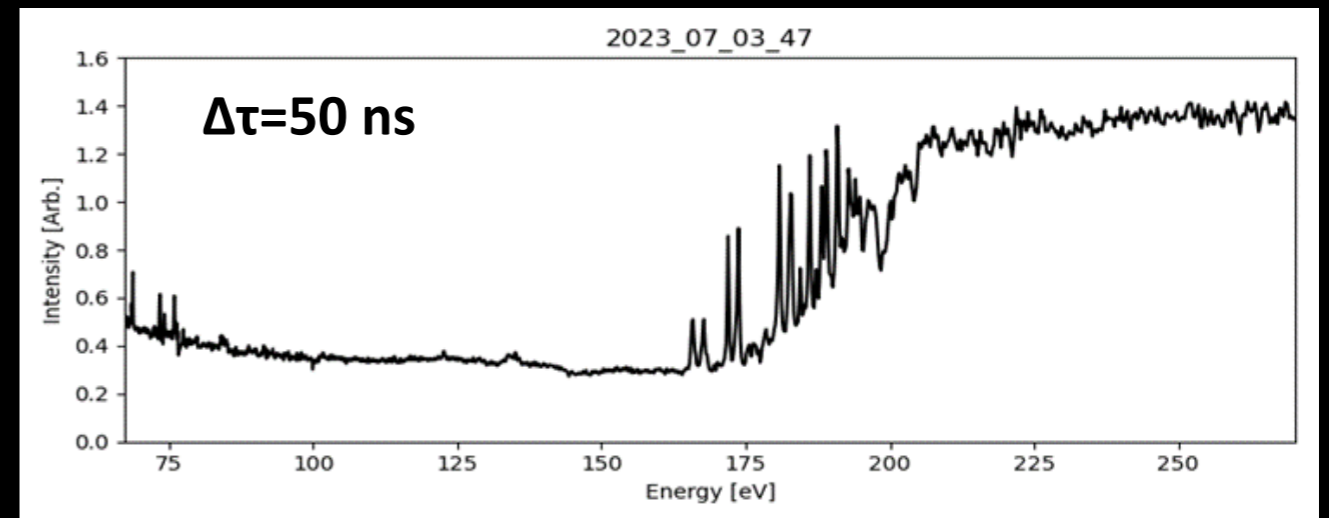
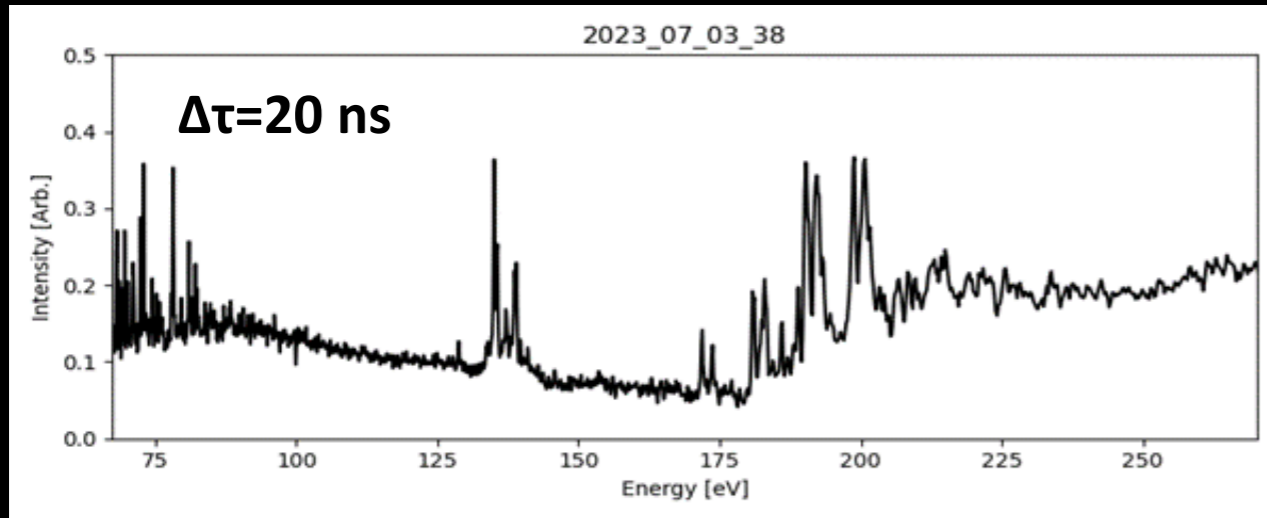
## 4f photoabsorption in Pt<sup>+</sup> to Pt<sup>4+</sup>

Eric Doyle<sup>\*</sup>, Gerry O'Sullivan<sup>✉</sup>, Patrick Hayden<sup>✉</sup>  
and Padraig Dunne<sup>\*</sup>

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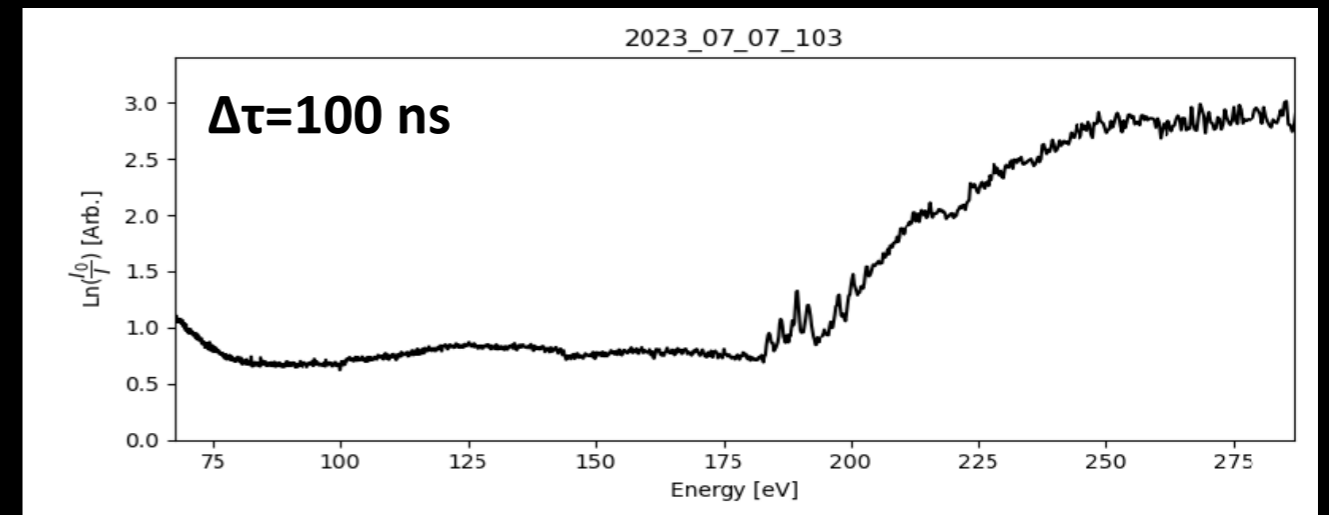
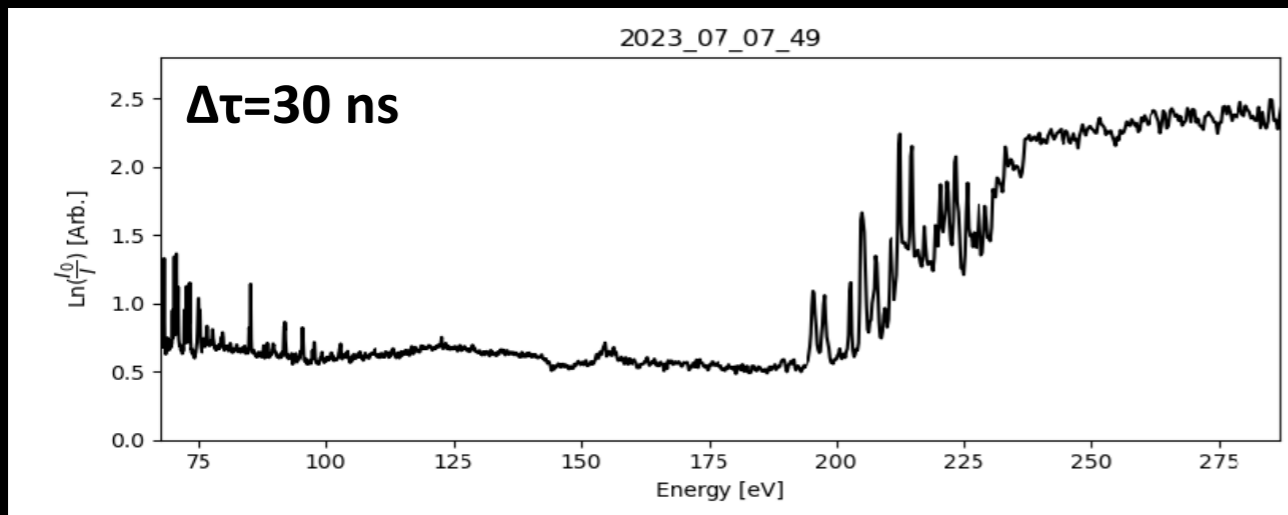
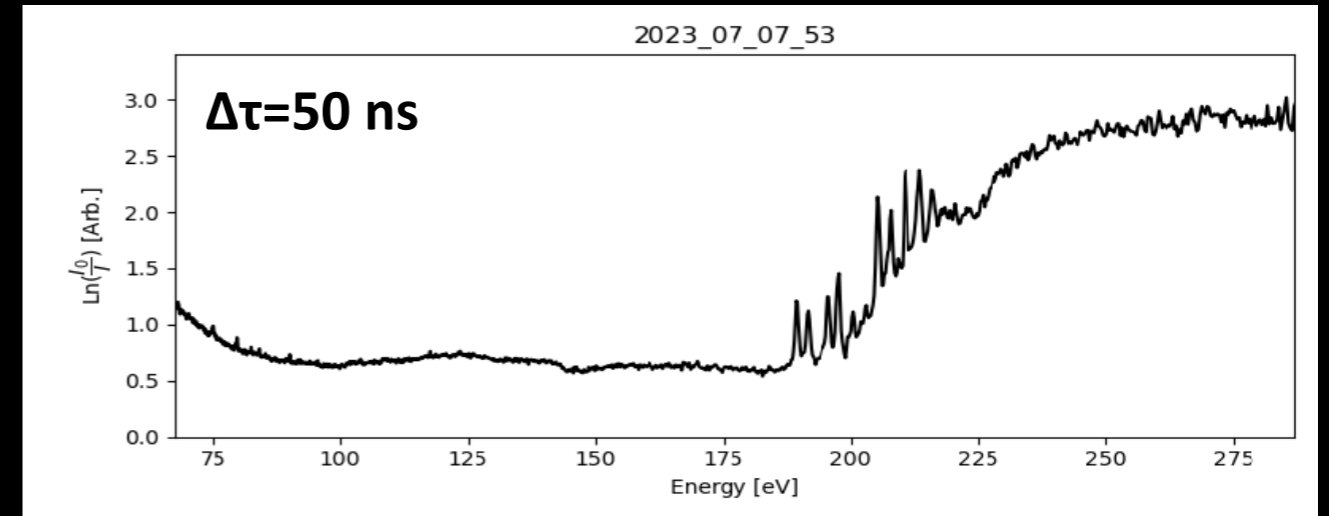
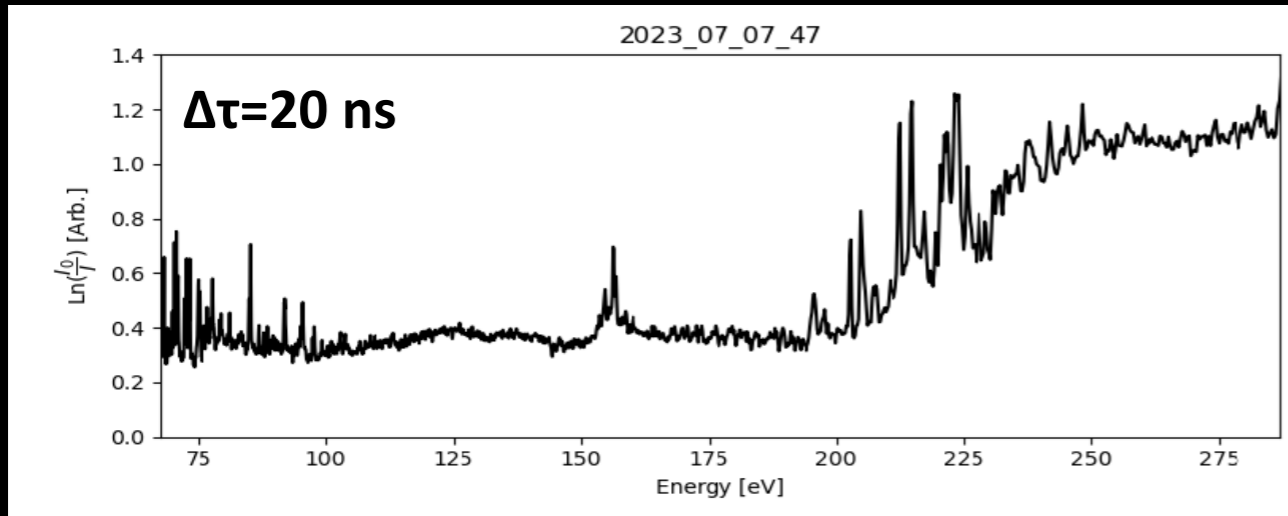
# DLP PHOTOABSORPTION:

Yttrium spectra  $\sim 48$  eV to  $\sim 280$  eV

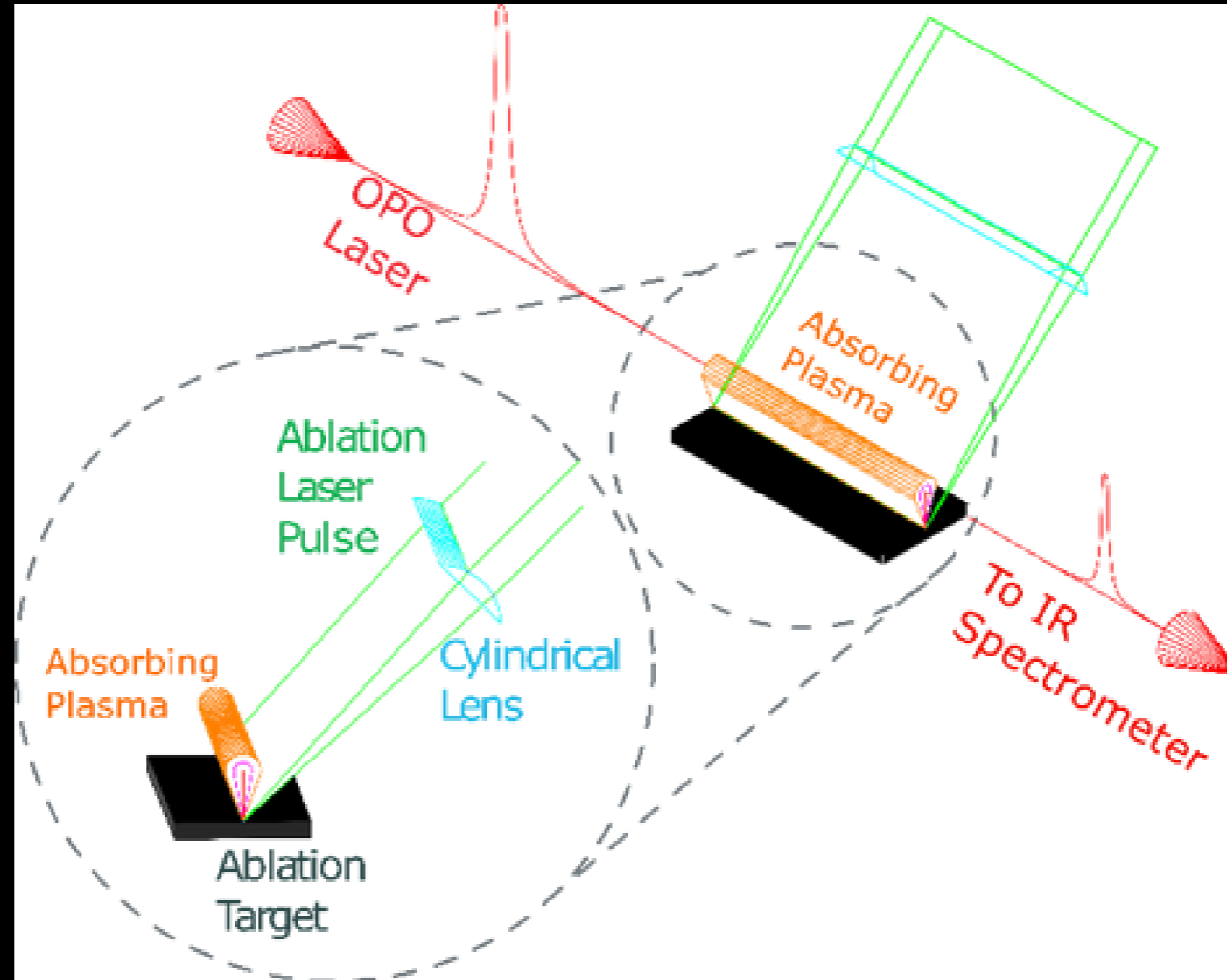


# DLP PHOTOABSORPTION:

Zirconium spectra ~48 eV to ~280 eV



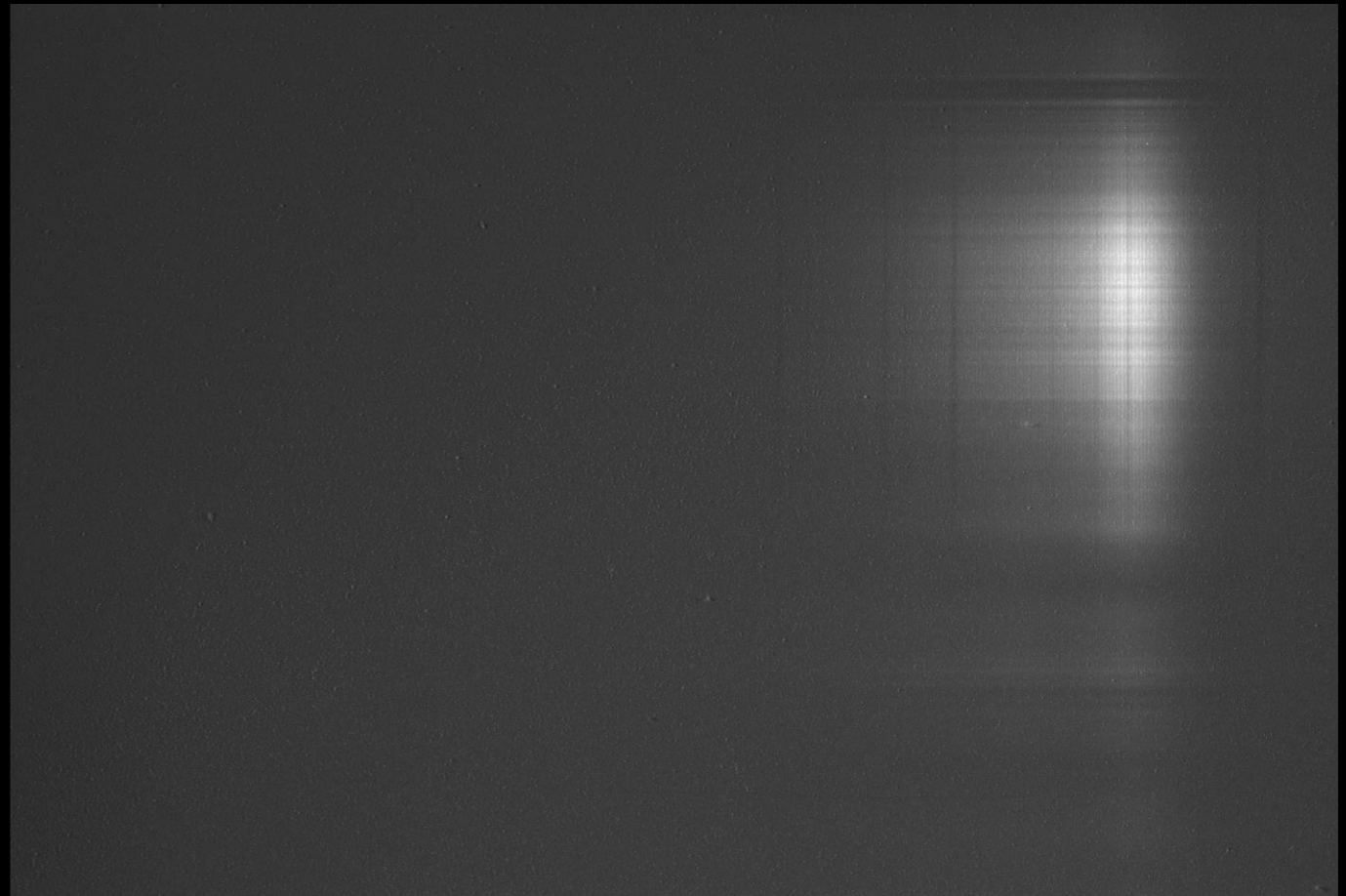
# OPO PHOTOABSORPTION:





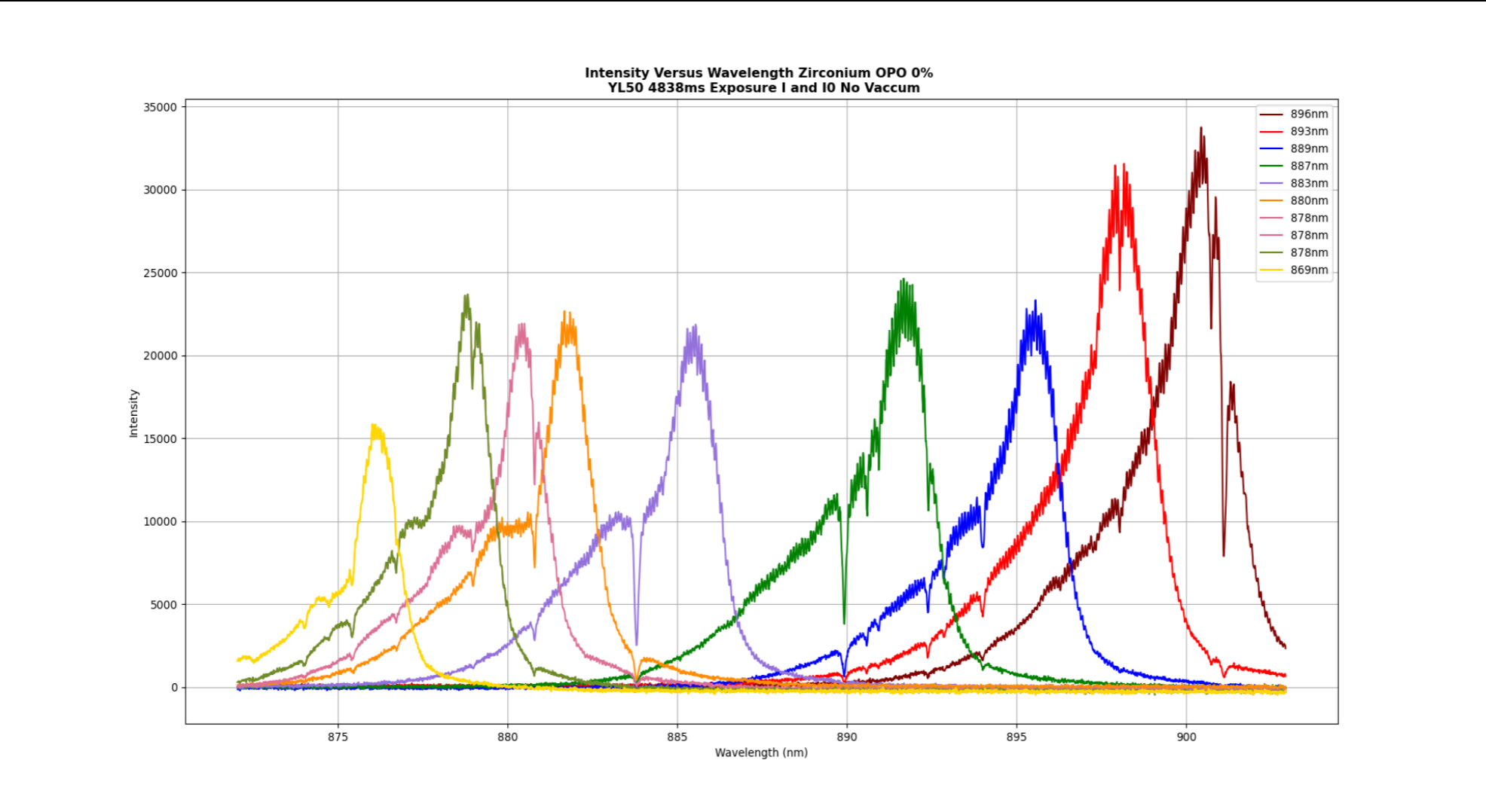
# OPO PHOTOABSORPTION:

Zirconium  $\sim 1.38$  eV to  $\sim 1.39$  eV



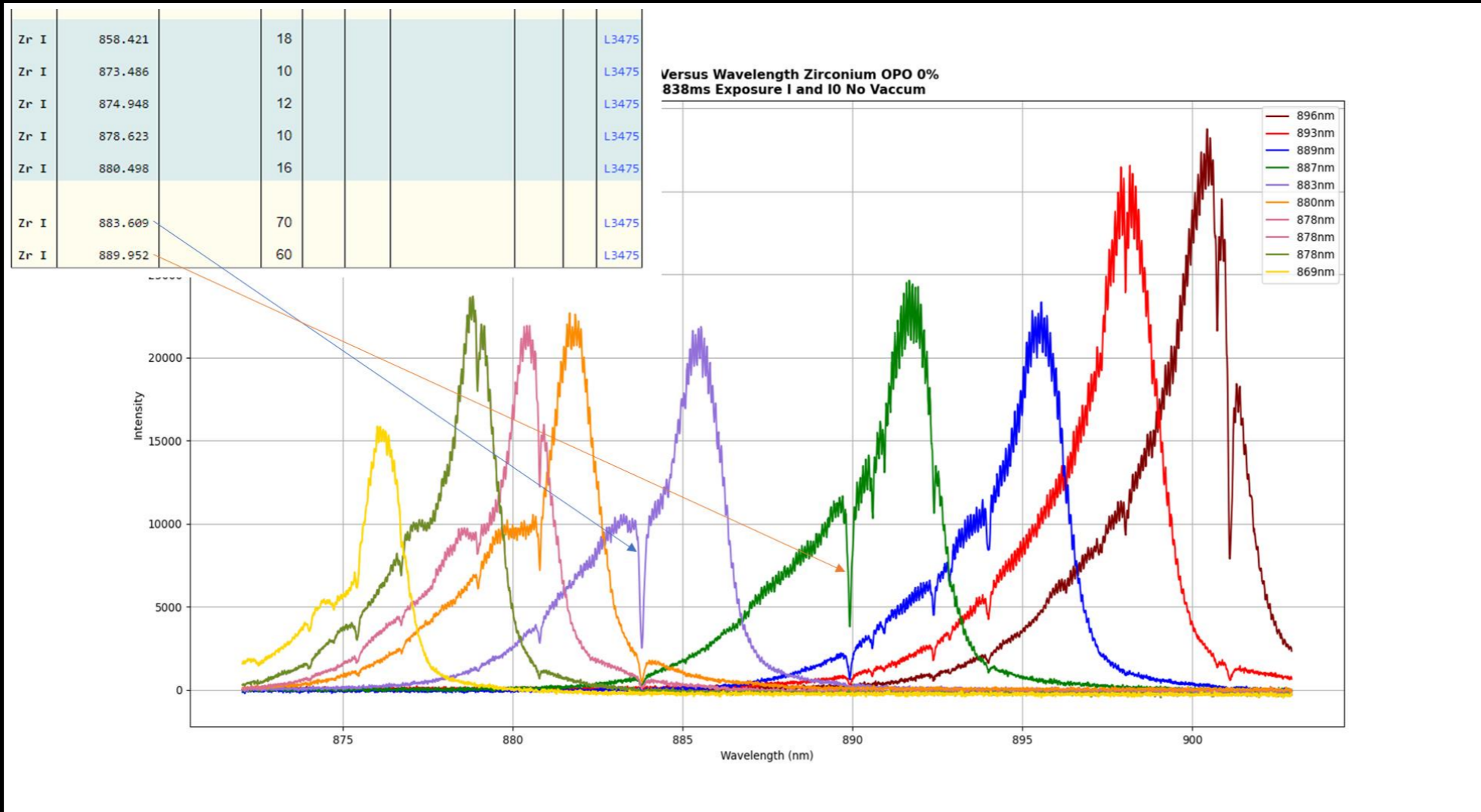
# OPO PHOTOABSORPTION:

Zirconium spectra  $\sim 1.38 \text{ eV}$  to  $\sim 1.42 \text{ eV}$



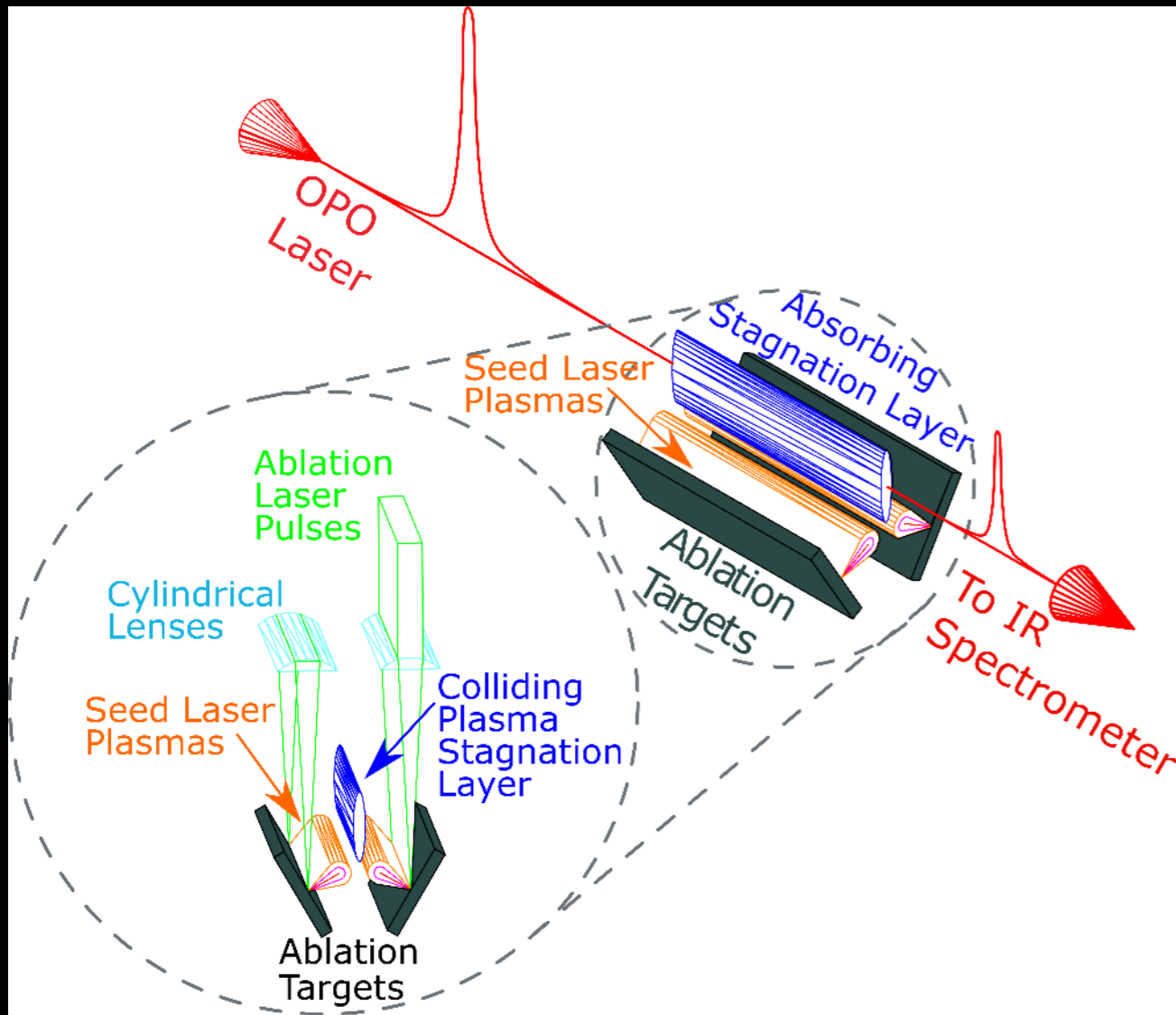
# OPO PHOTOABSORPTION:

Zirconium spectra  $\sim 1.38$  eV to  $\sim 1.42$  eV

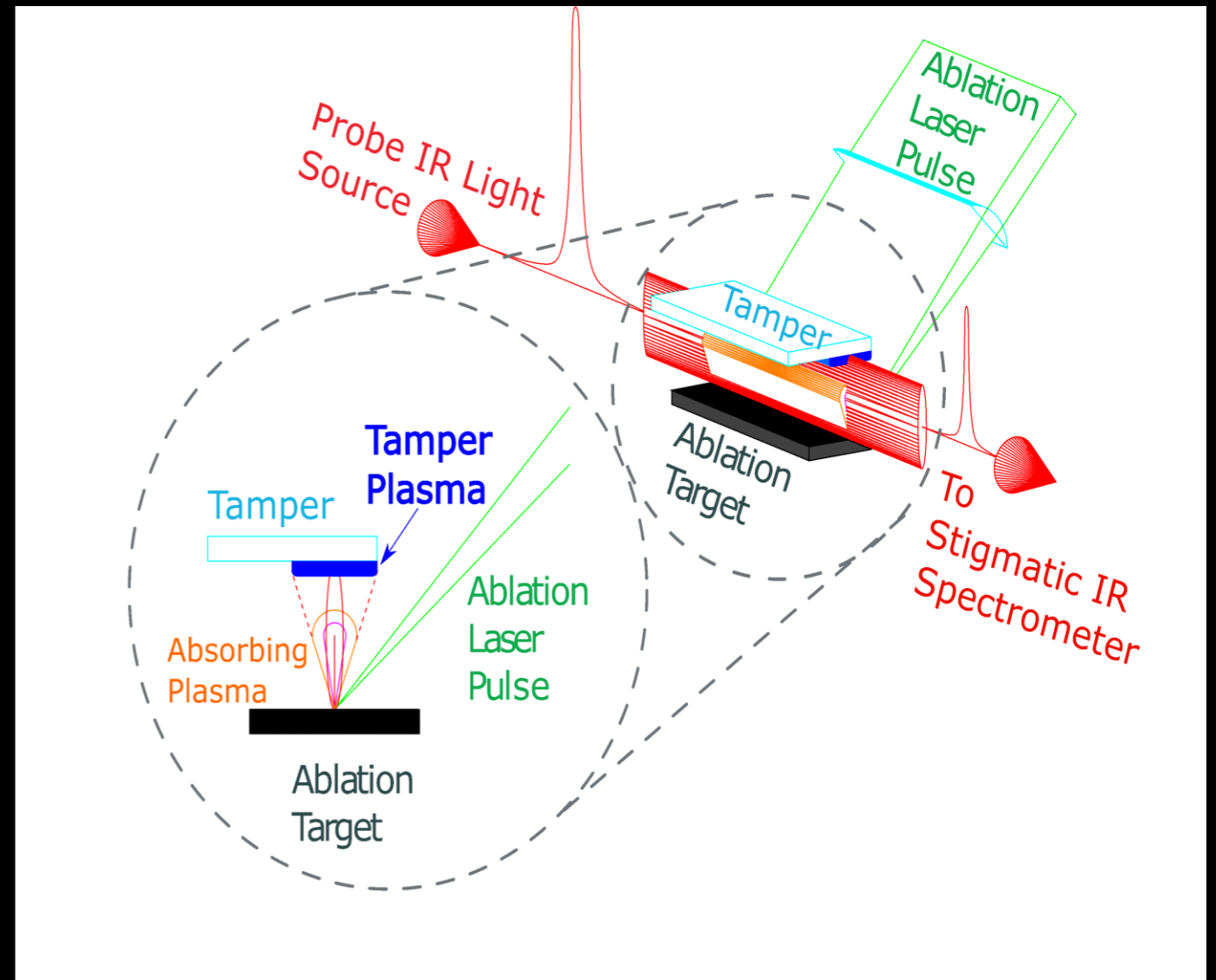


# OTHER PHOTOABSORPTION SCHEMES:

## Colliding Plasmas



## Tamper Plasmas



# WHERE TO NEXT?

Build the UCD HEAVYMETAL team:

- 5 PIs
- 2-3 Post docs
- 5 PhD students

Develop new techniques:

- Colliding Laser Plasma
- Tamper Plasma
- Broadband OPO
- Fibre-optic setups
- Super Continuum source
- Dual-Comb Spectroscopy
- Near-UV Continuum for Photoabsorption.

**PERIODIC TABLE**  
**Atomic Properties of the Elements**

FREQUENTLY USED FUNDAMENTAL PHYSICAL CONSTANTS<sup>§</sup>  
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of <sup>133</sup>Cs

speed of light in vacuum	<i>c</i>	299 792 458 m s <sup>-1</sup>	(exact)
Planck constant	<i>h</i>	6.626 070 15 × 10 <sup>-34</sup> J Hz <sup>-1</sup>	(exact)
elementary charge	<i>e</i>	1.602 176 634 × 10 <sup>-19</sup> C	(exact)
Avogadro constant	<i>N<sub>A</sub></i>	6.022 140 76 × 10 <sup>23</sup> mol <sup>-1</sup>	(exact)
Boltzmann constant	<i>k</i>	1.380 649 × 10 <sup>-23</sup> J K <sup>-1</sup>	(exact)
electron volt	eV	1.602 176 634 × 10 <sup>-19</sup> J	(exact)
electron mass	<i>m<sub>e</sub></i>	9.109 383 70 × 10 <sup>-31</sup> kg	(exact)
energy equivalent	<i>m<sub>e</sub>c<sup>2</sup></i>	0.510 998 950 MeV	(exact)
proton mass	<i>m<sub>p</sub></i>	1.672 621 624 × 10 <sup>-27</sup> kg	(exact)
energy equivalent	<i>m<sub>p</sub>c<sup>2</sup></i>	938.272 088 MeV	(exact)
fine-structure constant	<i>α</i>	1/137.035 999	(exact)
Rydberg energy	<i>R<sub>∞</sub>hc</i>	13.605 663 1230 eV	(exact)
Newtonian constant of gravitation	<i>G</i>	6.674 × 10 <sup>-11</sup> m <sup>3</sup> kg <sup>-1</sup> s <sup>-2</sup>	(exact)

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

Legend:  
■ Solids  
■ Liquids  
■ Gases  
■ Artificially Prepared

Group	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	<b>H</b> Hydrogen 1.008 1s 13.5984																	<b>He</b> Helium 4.0026 1s <sup>2</sup> 24.5874
2	<b>Li</b> Lithium 6.94 1s <sup>2</sup> 2s 5.3917	<b>Be</b> Beryllium 9.0122 1s <sup>2</sup> 2s <sup>2</sup> 9.3227											<b>B</b> Boron 10.81 1s <sup>2</sup> 2s <sup>2</sup> 2p 8.2980	<b>C</b> Carbon 12.011 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>2</sup> 11.2603	<b>N</b> Nitrogen 14.007 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>3</sup> 14.5341	<b>O</b> Oxygen 15.999 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>4</sup> 13.6181	<b>F</b> Fluorine 18.998 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>5</sup> 17.4228	<b>Ne</b> Neon 20.180 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>6</sup> 21.5645
3	<b>Na</b> Sodium 22.990 [Ne]3s 5.1391	<b>Mg</b> Magnesium 24.305 [Ne]3s <sup>2</sup> 7.6462											<b>Al</b> Aluminum 26.982 [Ne]3s <sup>2</sup> 3p 5.9858	<b>Si</b> Silicon 28.085 [Ne]3s <sup>2</sup> 3p <sup>2</sup> 8.1517	<b>P</b> Phosphorus 30.974 [Ne]3s <sup>2</sup> 3p <sup>3</sup> 10.4867	<b>S</b> Sulfur 32.06 [Ne]3s <sup>2</sup> 3p <sup>4</sup> 10.3600	<b>Cl</b> Chlorine 35.45 [Ne]3s <sup>2</sup> 3p <sup>5</sup> 12.9676	<b>Ar</b> Argon 39.948 [Ne]3s <sup>2</sup> 3p <sup>6</sup> 15.7596
4	<b>K</b> Potassium 39.098 [Ar]4s 4.3407	<b>Ca</b> Calcium 40.078 [Ar]4s 6.1132	<b>Sc</b> Scandium 44.956 [Ar]3d <sup>1</sup> 4s 6.5615	<b>Ti</b> Titanium 47.867 [Ar]3d <sup>2</sup> 4s 6.8281	<b>V</b> Vanadium 50.942 [Ar]3d <sup>3</sup> 4s 6.7462	<b>Cr</b> Chromium 51.996 [Ar]3d <sup>5</sup> 4s 6.7665	<b>Mn</b> Manganese 54.938 [Ar]3d <sup>5</sup> 4s 7.4340	<b>Fe</b> Iron 55.845 [Ar]3d <sup>6</sup> 4s 7.9025	<b>Co</b> Cobalt 58.933 [Ar]3d <sup>7</sup> 4s 7.7810	<b>Ni</b> Nickel 58.693 [Ar]3d <sup>8</sup> 4s 7.6399	<b>Cu</b> Copper 63.546 [Ar]3d <sup>10</sup> 4s 7.7264	<b>Zn</b> Zinc 65.38 [Ar]3d <sup>10</sup> 4s 9.3942	<b>Ga</b> Gallium 69.723 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p 5.9993	<b>Ge</b> Germanium 72.630 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>2</sup> 7.8994	<b>As</b> Arsenic 74.922 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>3</sup> 9.7886	<b>Se</b> Selenium 78.971 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>4</sup> 9.7524	<b>Br</b> Bromine 79.904 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>5</sup> 11.8138	<b>Kr</b> Krypton 83.798 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>6</sup> 13.9996
5	<b>Rb</b> Rubidium 85.468 [Kr]5s 4.1771	<b>Sr</b> Strontium 87.62 [Kr]5s 5.6949	<b>Y</b> Yttrium 88.906 [Kr]4d <sup>1</sup> 5s 6.2173	<b>Zr</b> Zirconium 91.224 [Kr]4d <sup>2</sup> 5s 6.6341	<b>Nb</b> Niobium 92.906 [Kr]4d <sup>4</sup> 5s 6.5341	<b>Mo</b> Molybdenum 95.95 [Kr]4d <sup>5</sup> 5s 6.7589	<b>Tc</b> Technetium (97) [Kr]4d <sup>5</sup> 5s 7.1194	<b>Ru</b> Ruthenium 101.07 [Kr]4d <sup>6</sup> 5s 7.5762	<b>Rh</b> Rhodium 102.91 [Kr]4d <sup>8</sup> 5s 8.4369	<b>Pd</b> Palladium 106.42 [Kr]4d <sup>10</sup> 5s 8.9369	<b>Ag</b> Silver 107.87 [Kr]4d <sup>10</sup> 5s 9.2256	<b>Cd</b> Cadmium 112.41 [Kr]4d <sup>10</sup> 5s 10.4375	<b>In</b> Indium 114.82 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p 5.7864	<b>Sn</b> Tin 118.71 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>2</sup> 7.3439	<b>Sb</b> Antimony 121.76 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>3</sup> 8.6084	<b>Te</b> Tellurium 127.60 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>4</sup> 9.0097	<b>I</b> Iodine 126.90 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>5</sup> 10.4513	<b>Xe</b> Xenon 131.29 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>6</sup> 12.1298
6	<b>Cs</b> Cesium 132.91 [Xe]6s 3.6939	<b>Ba</b> Barium 137.33 [Xe]6s 5.2117		<b>Hf</b> Hafnium 178.49 [Xe]4f <sup>14</sup> 5d <sup>2</sup> 6s 6.8251	<b>Ta</b> Tantalum 180.95 [Xe]4f <sup>14</sup> 5d <sup>3</sup> 6s 7.5496	<b>W</b> Tungsten 183.84 [Xe]4f <sup>14</sup> 5d <sup>4</sup> 6s 7.8640	<b>Re</b> Rhenium 186.21 [Xe]4f <sup>14</sup> 5d <sup>5</sup> 6s 7.8335	<b>Os</b> Osmium 190.23 [Xe]4f <sup>14</sup> 5d <sup>6</sup> 6s 8.4382	<b>Ir</b> Iridium 192.22 [Xe]4f <sup>14</sup> 5d <sup>7</sup> 6s 8.9670	<b>Pt</b> Platinum 195.08 [Xe]4f <sup>14</sup> 5d <sup>9</sup> 6s 8.9588	<b>Au</b> Gold 196.97 [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s 9.2256	<b>Hg</b> Mercury 200.59 [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s 10.4375	<b>Tl</b> Thallium 204.38 [Hg]6p 6.1083	<b>Pb</b> Lead 207.2 [Hg]6p 7.4167	<b>Bi</b> Bismuth 208.98 [Hg]6p 7.2855	<b>Po</b> Polonium (209) [Hg]6p 8.414	<b>At</b> Astatine (210) [Hg]6p 9.3175	<b>Rn</b> Radon (222) [Hg]6p 10.7485
7	<b>Fr</b> Francium (223) [Rn]7s 4.0727	<b>Ra</b> Radium (226) [Rn]7s 5.2784		<b>Rf</b> Rutherfordium (267) [Rn]5f <sup>14</sup> 6d <sup>2</sup> 7s 6.02	<b>Db</b> Dubnium (268) [Rn]5f <sup>14</sup> 6d <sup>3</sup> 7s 6.8	<b>Sg</b> Seaborgium (269) [Rn]5f <sup>14</sup> 6d <sup>4</sup> 7s 7.8	<b>Bh</b> Bohrium (270) [Rn]5f <sup>14</sup> 6d <sup>5</sup> 7s 7.7	<b>Hs</b> Hassium (269) [Rn]5f <sup>14</sup> 6d <sup>6</sup> 7s 7.6	<b>Mt</b> Meitnerium (278) [Rn]5f <sup>14</sup> 6d <sup>7</sup> 7s 7.6	<b>Ds</b> Darmstadtium (281) [Rn]5f <sup>14</sup> 6d <sup>8</sup> 7s 7.6	<b>Rg</b> Roentgenium (282) [Rn]5f <sup>14</sup> 6d <sup>9</sup> 7s 7.6	<b>Cn</b> Copernicium (285) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s 7.6	<b>Nh</b> Nihonium (286) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s 7.6	<b>Fl</b> Flerovium (289) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s 7.6	<b>Mc</b> Moscovium (289) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s 7.6	<b>Lv</b> Livermorium (293) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s 7.6	<b>Ts</b> Tennessine (294) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s 7.6	<b>Og</b> Oganesson (294) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s 7.6
			<b>La</b> Lanthanum 138.91 [Xe]5d <sup>1</sup> 6s 5.5769	<b>Ce</b> Cerium 140.12 [Xe]4f <sup>1</sup> 5d <sup>1</sup> 6s 5.5386	<b>Pr</b> Praseodymium 140.91 [Xe]4f <sup>2</sup> 6s 5.4702	<b>Nd</b> Neodymium 144.24 [Xe]4f <sup>3</sup> 6s 5.5250	<b>Pm</b> Promethium (145) [Xe]4f <sup>4</sup> 6s 5.577	<b>Sm</b> Samarium 150.36 [Xe]4f <sup>6</sup> 6s 5.6437	<b>Eu</b> Europium 151.96 [Xe]4f <sup>7</sup> 6s 5.6704	<b>Gd</b> Gadolinium 157.25 [Xe]4f <sup>7</sup> 5d <sup>1</sup> 6s 6.1498	<b>Tb</b> Terbium 158.93 [Xe]4f <sup>9</sup> 6s 5.8638	<b>Dy</b> Dysprosium 162.50 [Xe]4f <sup>10</sup> 6s 5.9391	<b>Ho</b> Holmium 164.93 [Xe]4f <sup>11</sup> 6s 6.0215	<b>Er</b> Erbium 167.26 [Xe]4f <sup>12</sup> 6s 6.1077	<b>Tm</b> Thulium 168.93 [Xe]4f <sup>13</sup> 6s 6.1843	<b>Yb</b> Ytterbium 173.05 [Xe]4f <sup>14</sup> 6s 5.4259	<b>Lu</b> Lutetium 174.97 [Xe]4f <sup>14</sup> 5d <sup>1</sup> 6s 5.4259	
			<b>Ac</b> Actinium (227) [Rn]6d <sup>1</sup> 7s 5.3802	<b>Th</b> Thorium 232.04 [Rn]6d <sup>2</sup> 7s 6.3067	<b>Pa</b> Protactinium 231.04 [Rn]5f <sup>1</sup> 6d <sup>1</sup> 7s 5.89	<b>U</b> Uranium 238.03 [Rn]5f <sup>3</sup> 6d <sup>1</sup> 7s 6.1941	<b>Np</b> Neptunium (237) [Rn]5f <sup>4</sup> 6d <sup>1</sup> 7s 6.2655	<b>Pu</b> Plutonium (244) [Rn]5f <sup>6</sup> 7s 6.0258	<b>Am</b> Americium (243) [Rn]5f <sup>7</sup> 7s 5.9738	<b>Cm</b> Curium (247) [Rn]5f <sup>8</sup> 7s 5.9914	<b>Bk</b> Berkelium (247) [Rn]5f <sup>9</sup> 7s 6.1978	<b>Cf</b> Californium (251) [Rn]5f <sup>10</sup> 7s 6.2817	<b>Es</b> Einsteinium (252) [Rn]5f <sup>11</sup> 7s 6.3676	<b>Fm</b> Fermium (257) [Rn]5f <sup>12</sup> 7s 6.50	<b>Md</b> Mendelevium (258) [Rn]5f <sup>13</sup> 7s 6.58	<b>No</b> Nobelium (259) [Rn]5f <sup>14</sup> 7s 6.66	<b>Lr</b> Lawrencium (266) [Rn]5f <sup>14</sup> 7p 4.96	

†Based upon <sup>12</sup>C. () indicates the mass number of the longest-lived isotope.

For the most precise values and uncertainties visit [ciaaw.org](http://ciaaw.org) and [pml.nist.gov/data](http://pml.nist.gov/data).  
NIST SP 966 (July 2019)

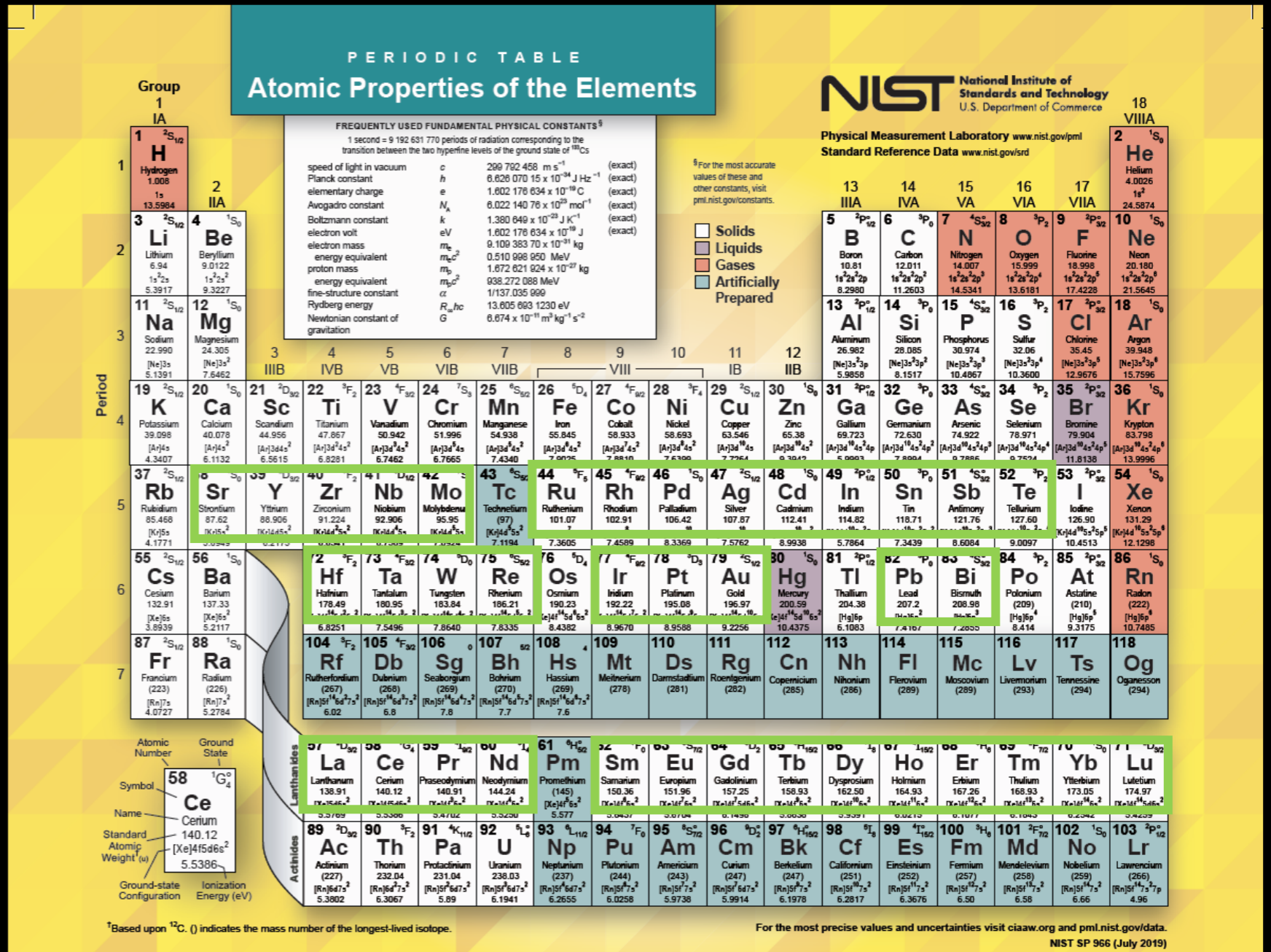
# WHERE TO NEXT?

Observe any element that is solid, non-lethal & can be made in a planar form.

Emission & Absorption Spectroscopy from SXR – NIR

Iterate with QUB Theory: Cathy Ramsbottom, Connor Ballance & their teams.

Collaborate with the HEAVYMETAL team & beyond.



# Thank You.



**RISING**  
TO THE  
**FUTURE**  
UCD Strategy 2020-2024



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