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U.S. DEPARTMENT OF ENERGY
Office of Science

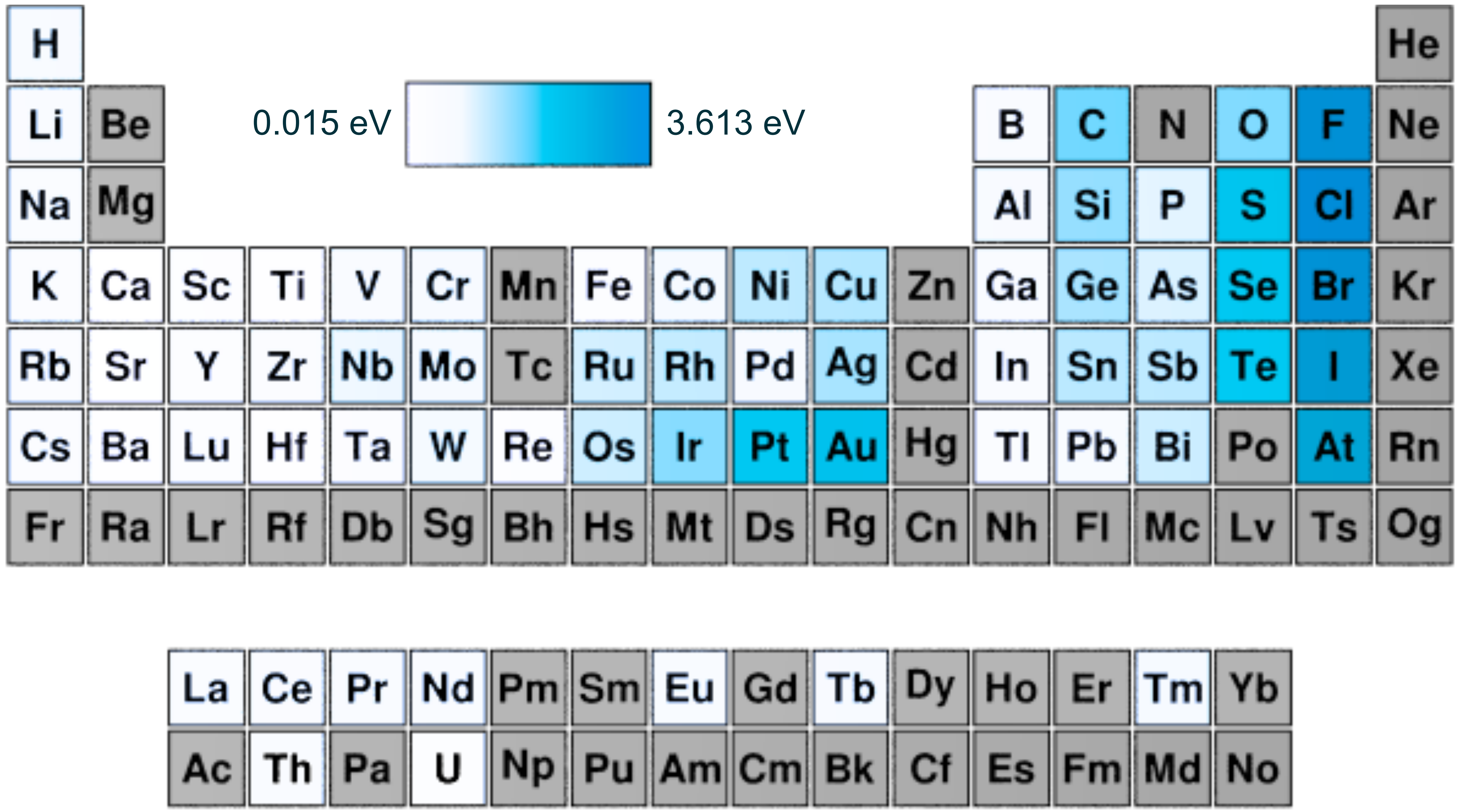
Precision Spectroscopy of Heavy and Superheavy Elements with AETHER

Erich Leistenschneider
Nuclear Science Division, Heavy Element Group

EMIS XX

The Electron Affinity Landscape

EA: energy needed to remove an electron from a negative ion



Modified from www.webelements.com

Analogous (and as fundamental) as the Ionization Potential

Of fundamental importance for chemistry:
Strongly related to how much an element is prone to form chemical bonds by sharing electrons

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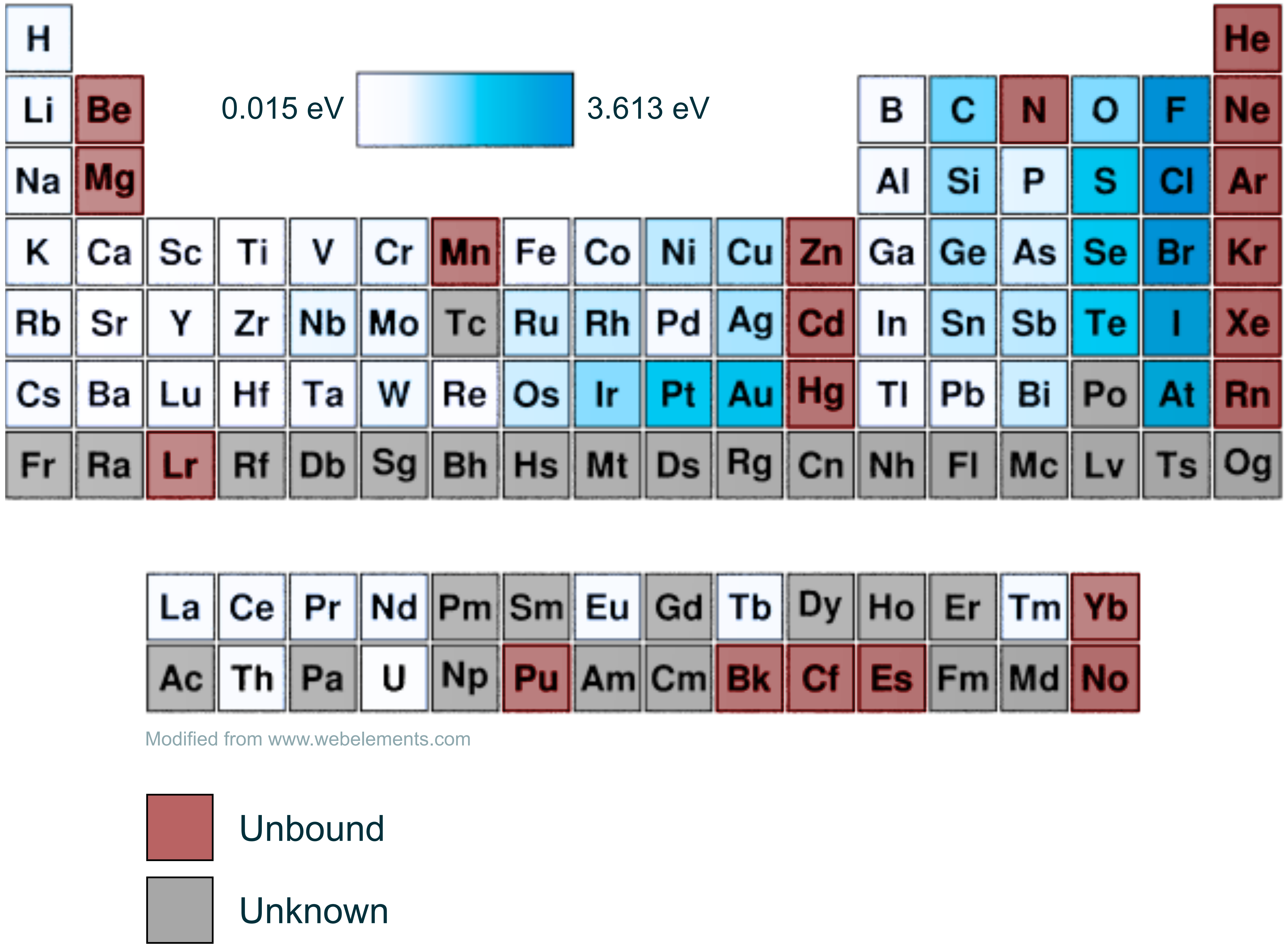

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… challenge to study experimentally

~1/3 of EAs in the Periodic Table are unknown

Techniques often require macroscopic quantities
lacks sensitivity for rare elements:

- EAs unknown for actinides/superheavies (SHE)
- not applicable to short-lived isotopes

Unexplored Opportunities:

Fundamental & applied chemistry:

- Nuclear medicine
- F-block chemistry

Atomic physics of SHE&Actinides

- highly-correlated systems
- pronounced relativistic effects

Rare isotope science

- isotope shifts in EA
- benchmark elect.-correl. in specific mass shift

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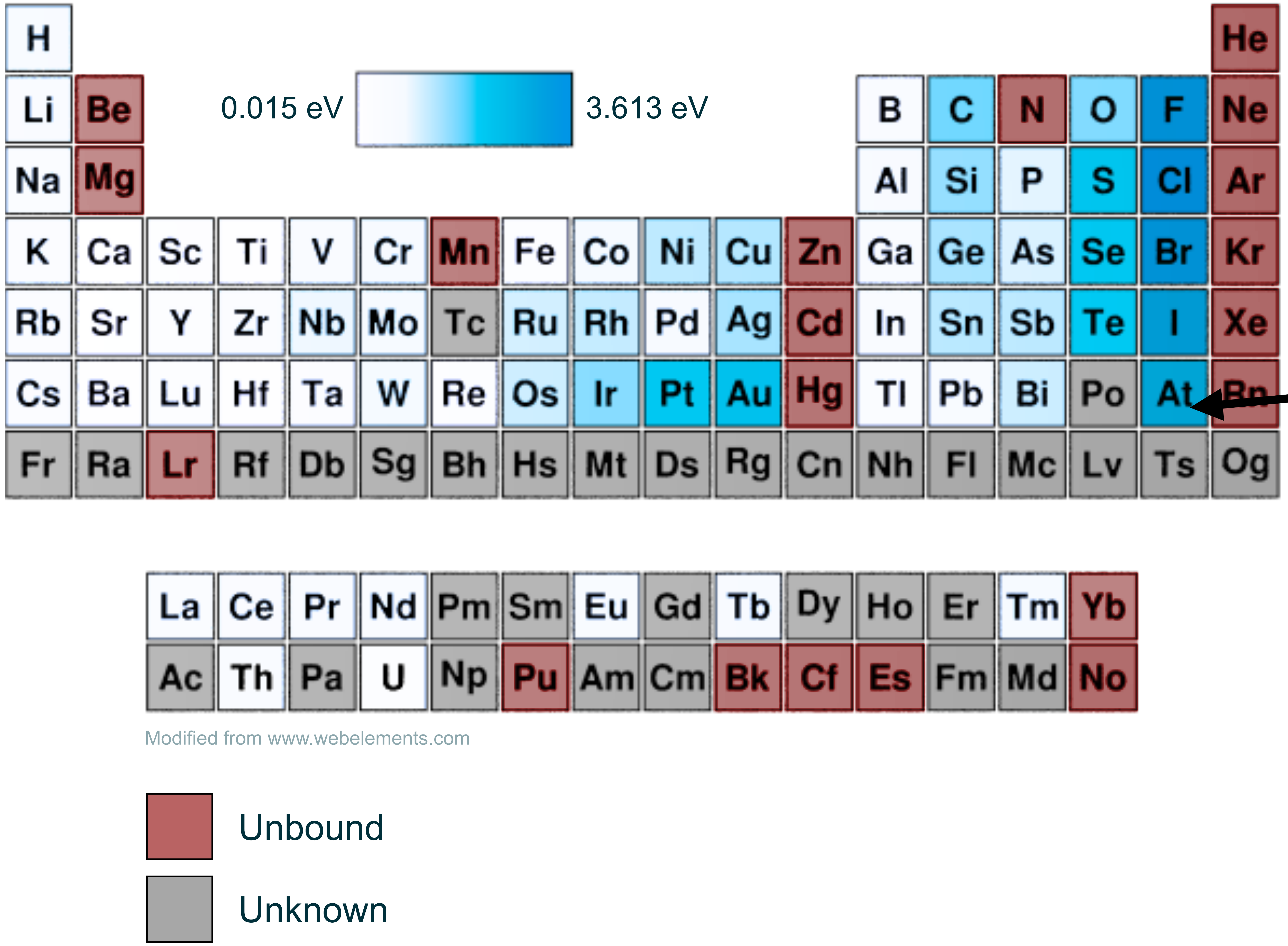

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first new EA in radioactive At

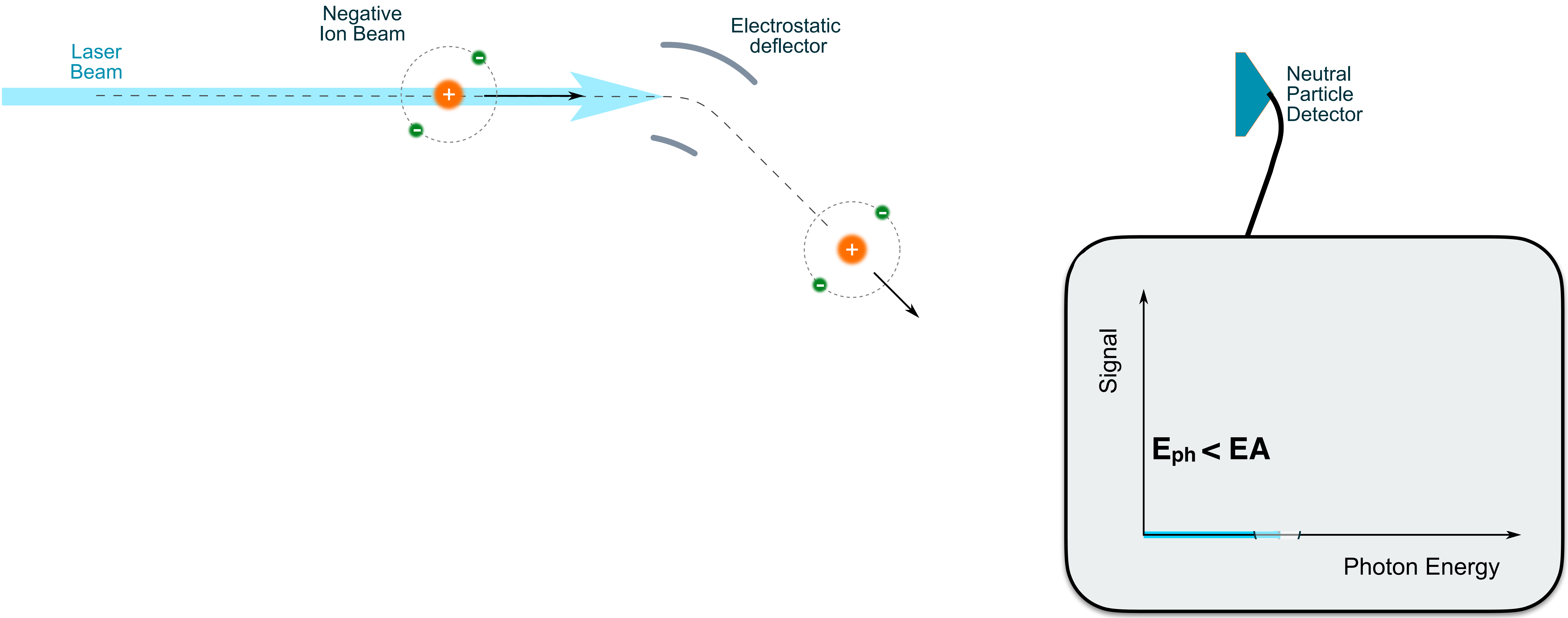
D. Leimbach et al., Nature Communications 11, 3824(2020)

ISOLDE yield: ≈$4 \cdot 10^6$ ions / sec

Need for highly-sensitive method for most exotic species

The EA sensitivity gap

Laser Photodetachment Threshold (LPT) probes the energy needed to dismantle the negative ion



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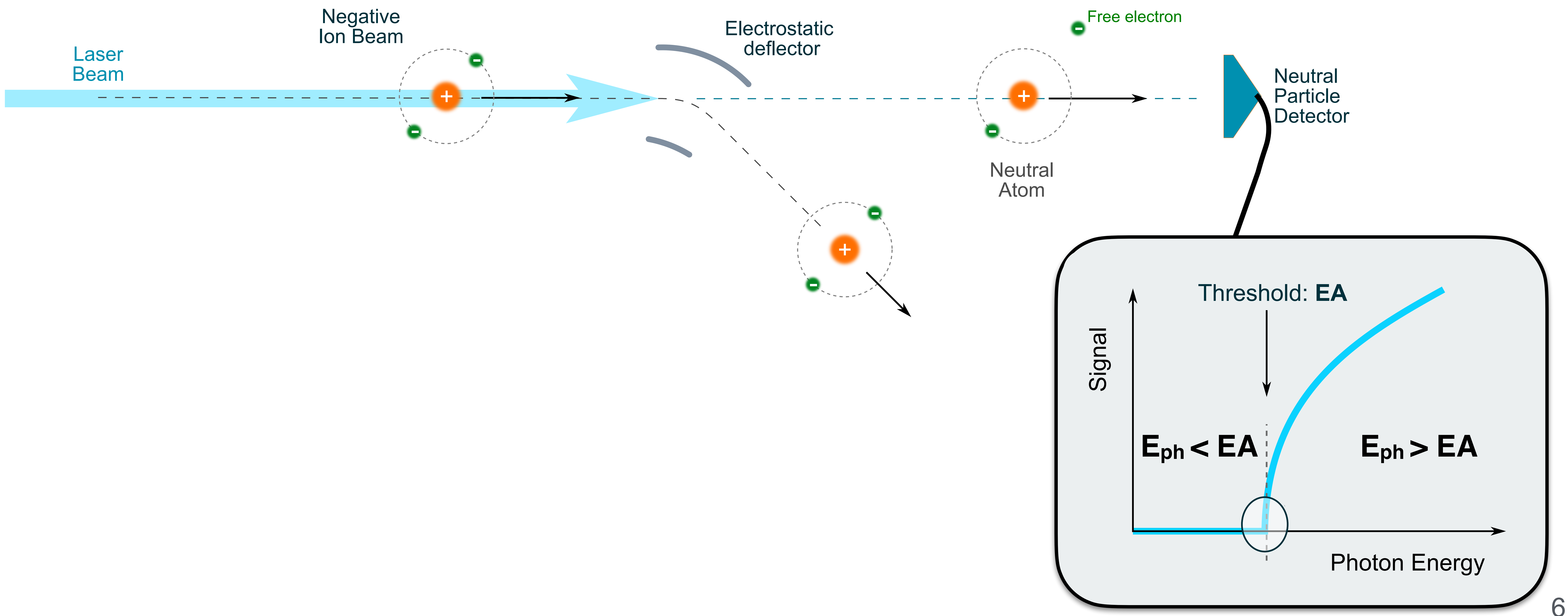

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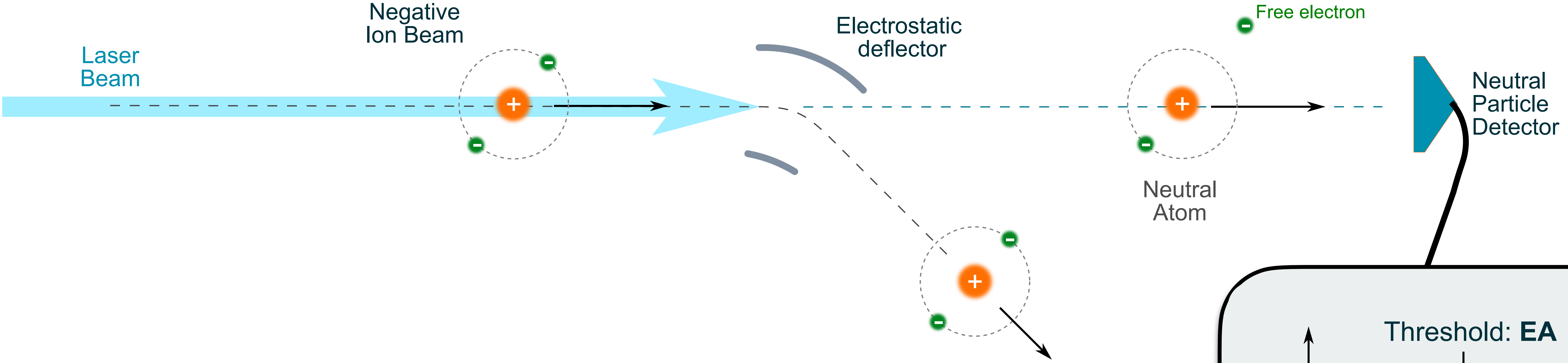
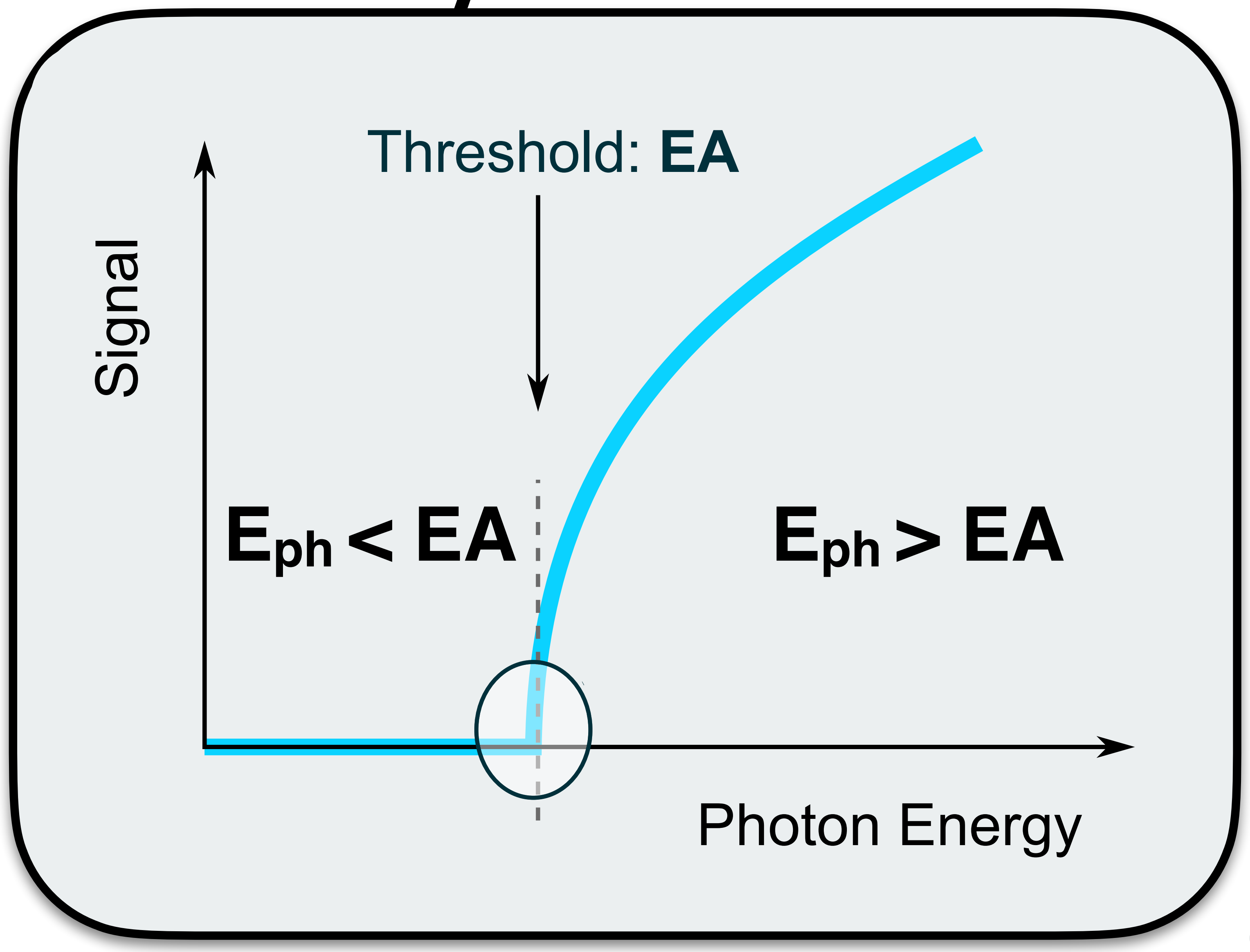




exploited for radionuclides by

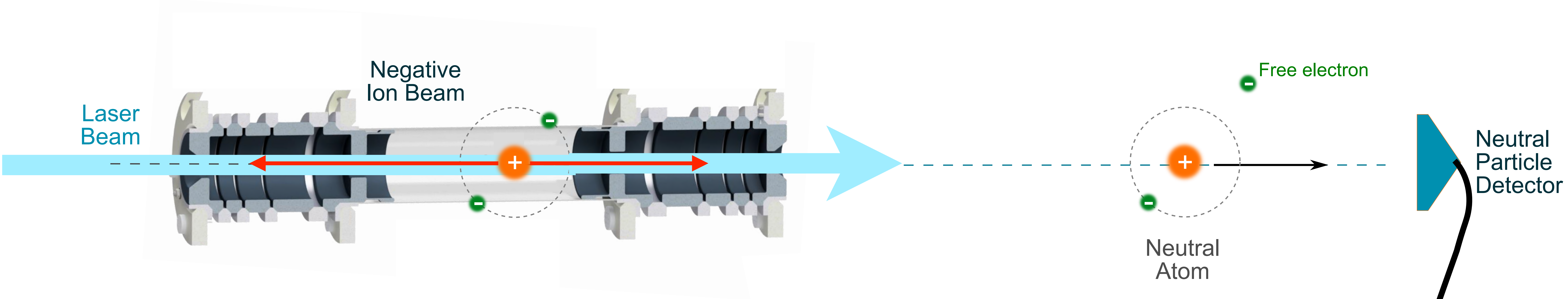
GANDALPH

Gothenburg ANion Detector for Affinity measurements by Laser PHotodetachment

S. Rothe et al., J. Phys. G: Nucl. Part.Phys. 44, 104003 (2017)
D. Leimbach et al., Nature Communications 11, 3824 (2020)

The EA sensitivity gap

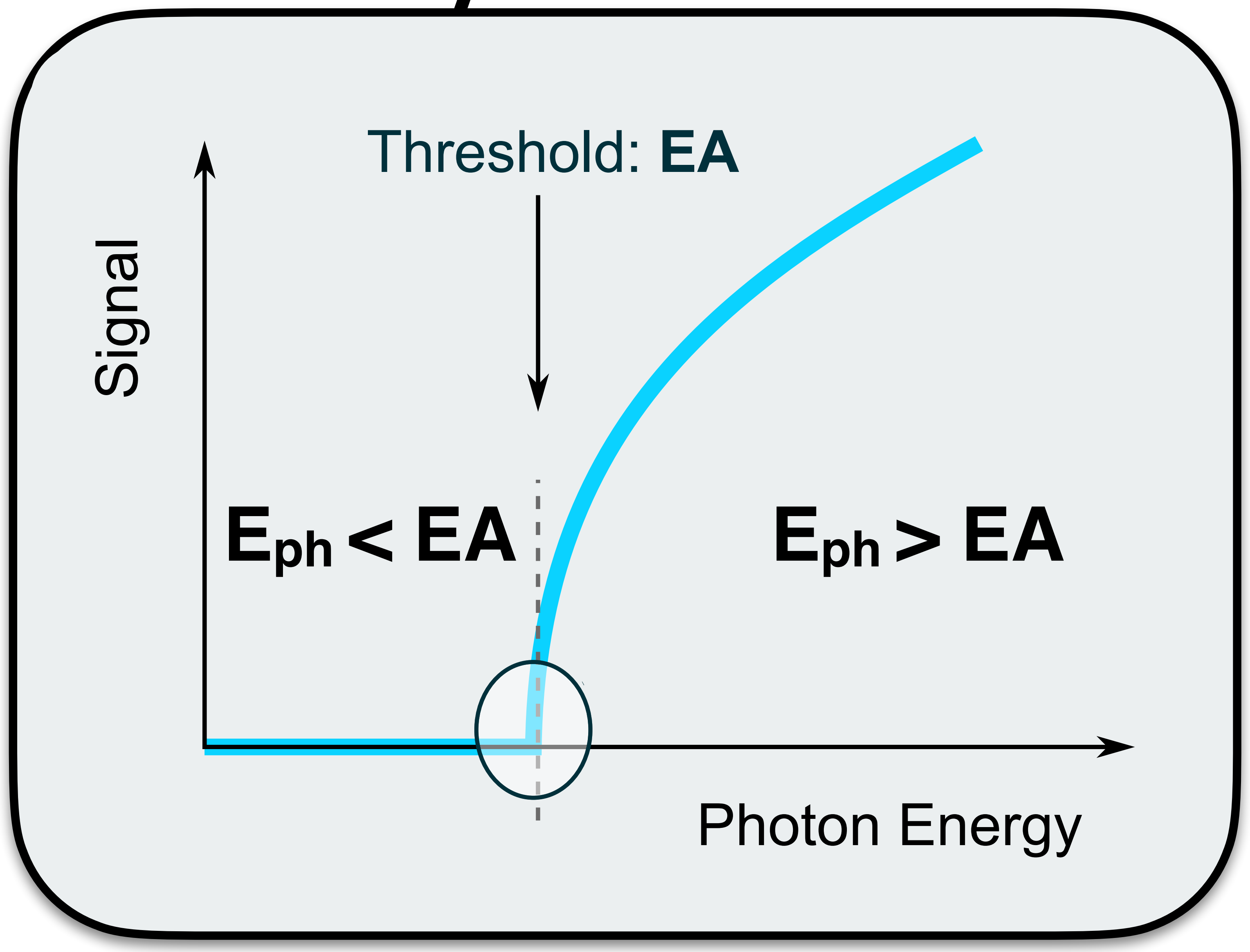
Increase exposure to laser beam by ion-beam confinement



Multi-Reflection Time-of-Flight (MR-ToF) device

- long exposure time ⇒ less particles for same signal
- neutralized atoms remain directed towards detector

} gain in sensitivity



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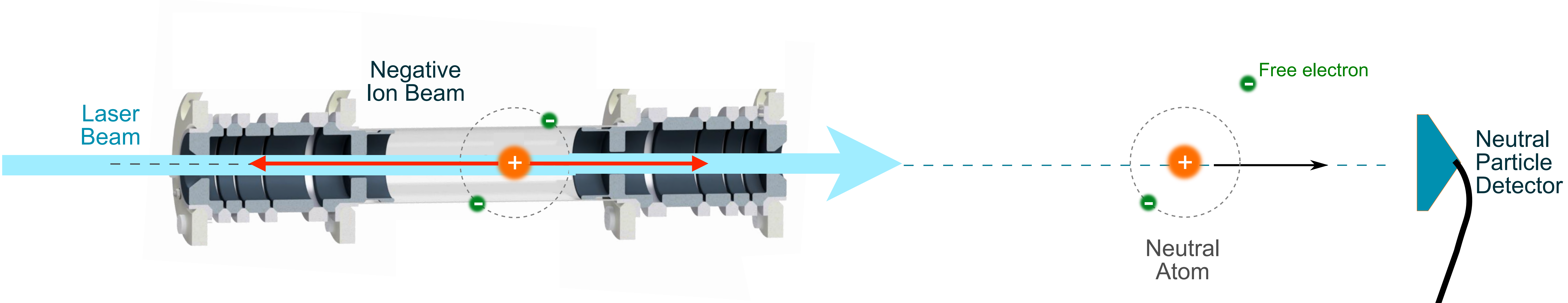

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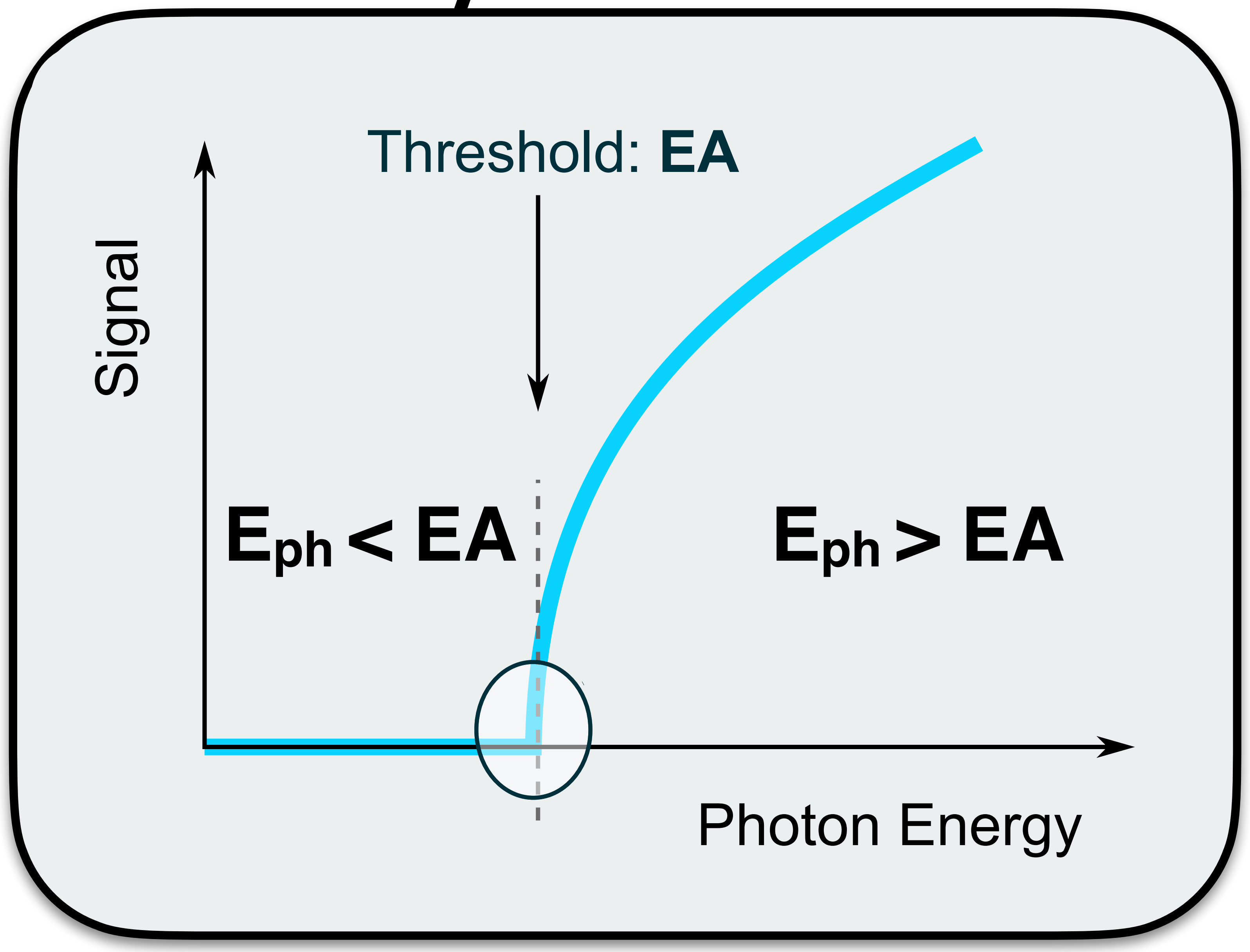

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\+ MIRACLS

S. Sels et al., Nucl. Instr. Meth. B 463, 310 (2020)
F.M. Maier et al., Nucl. Instr. Meth.. A, 1048, 167927 (2023)

Demonstrator experiment with MIRACLS at ISOLDE

ISOLDE negative ion source

B. Vosicki, Nucl. Instr. Meth. 186, 307–313 (1981)

+

MIRACLS low-energy setup

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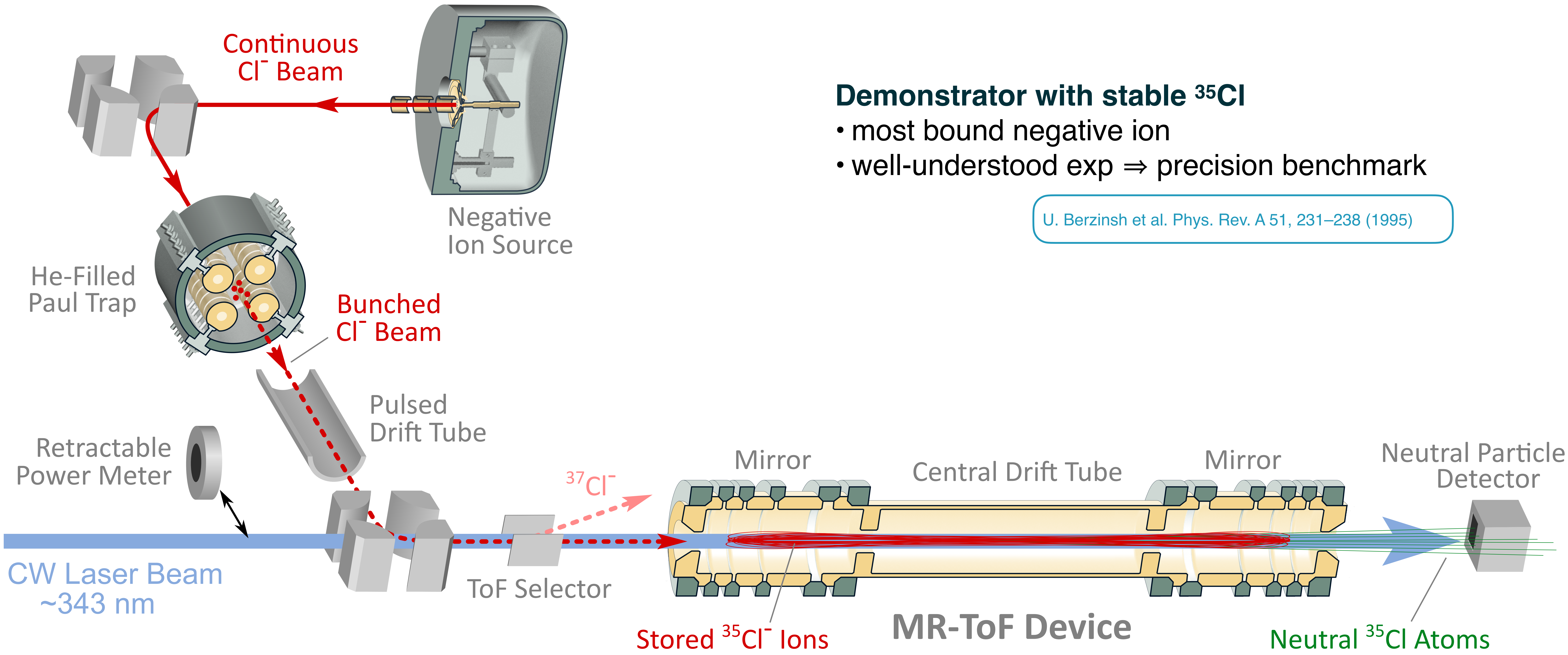

Demonstrator with stable ^{35}Cl

- most bound negative ion
- well-understood exp ⇒ precision benchmark

U. Berzinsh et al. Phys. Rev. A 51, 231–238 (1995)

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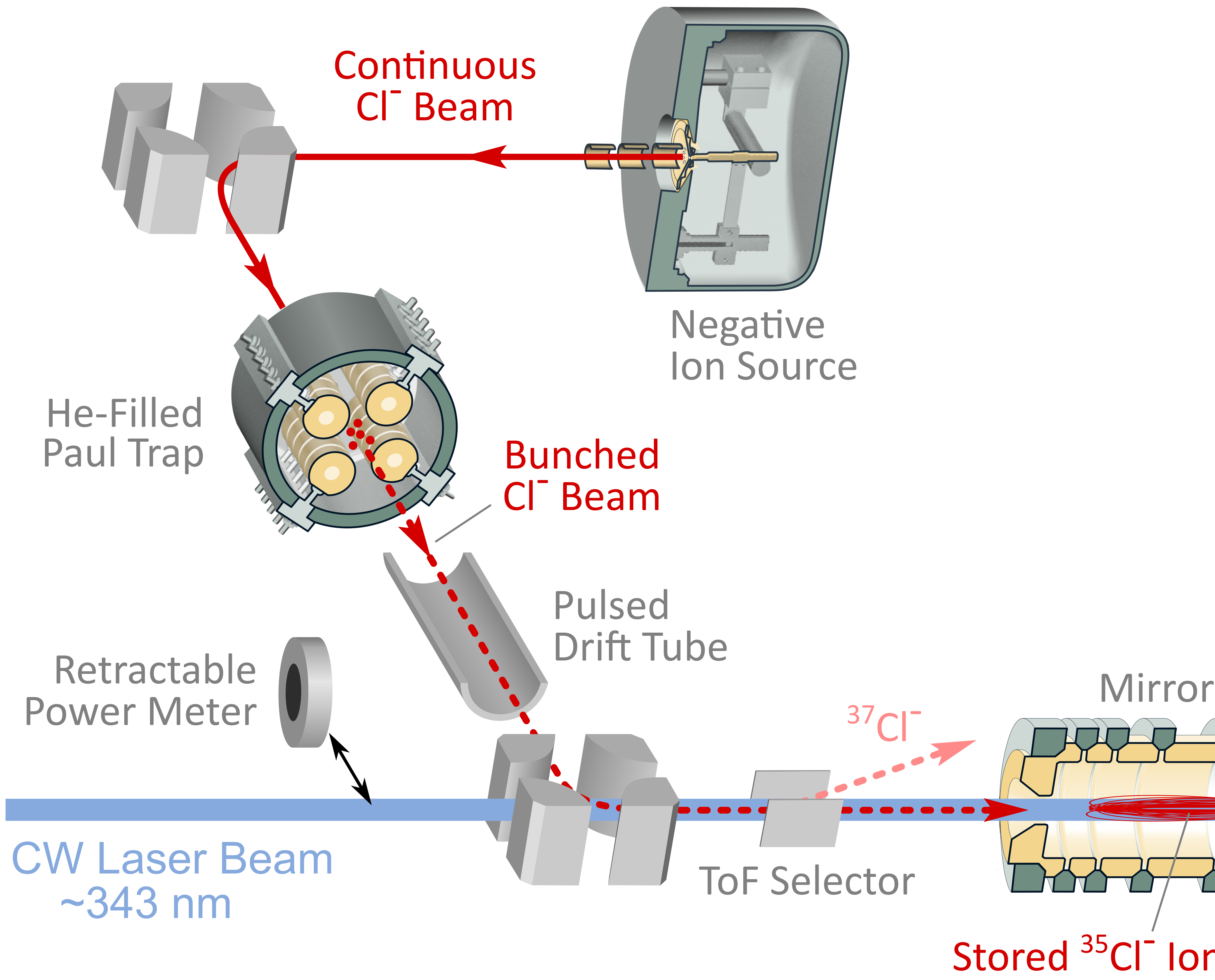
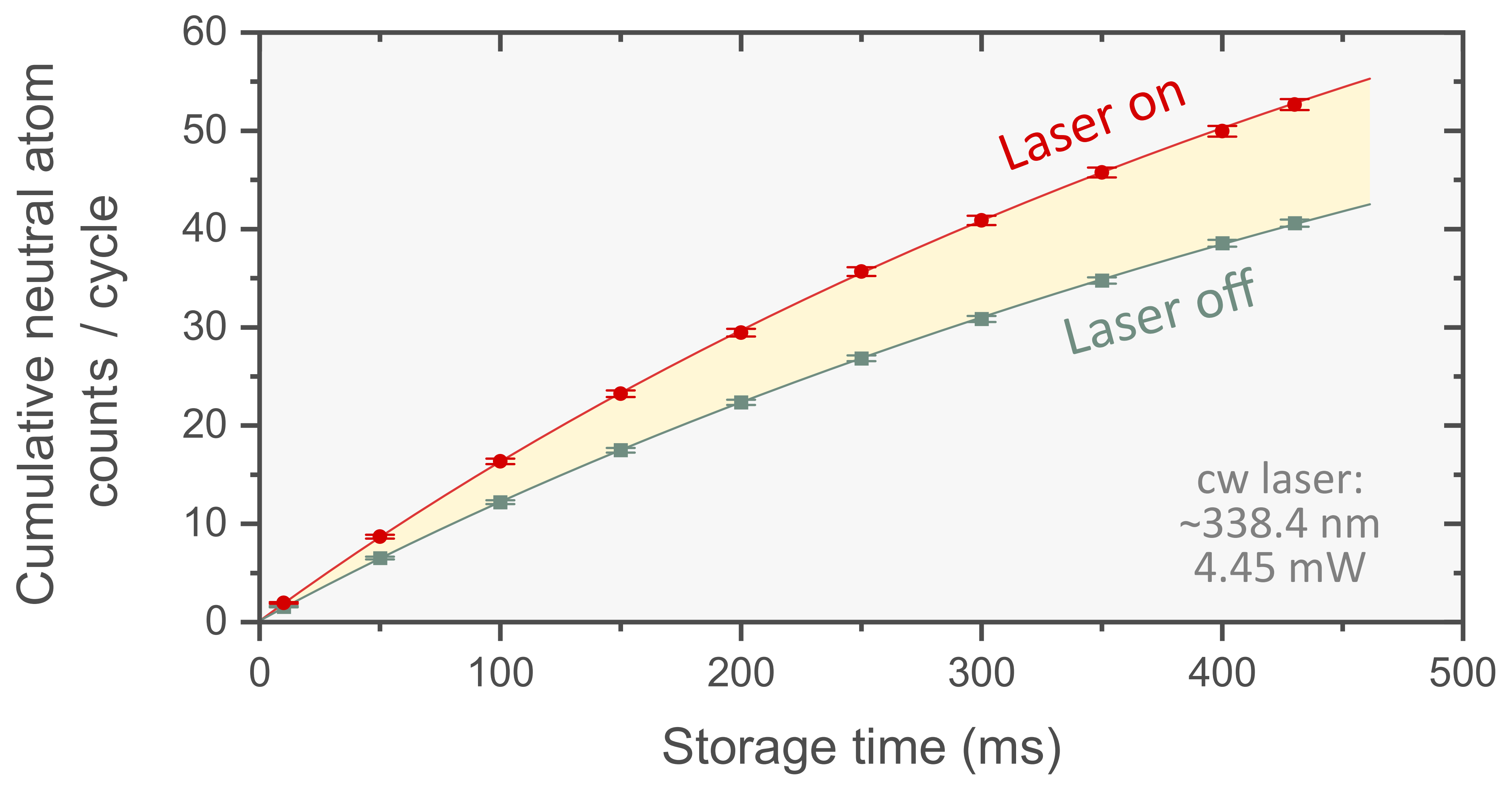
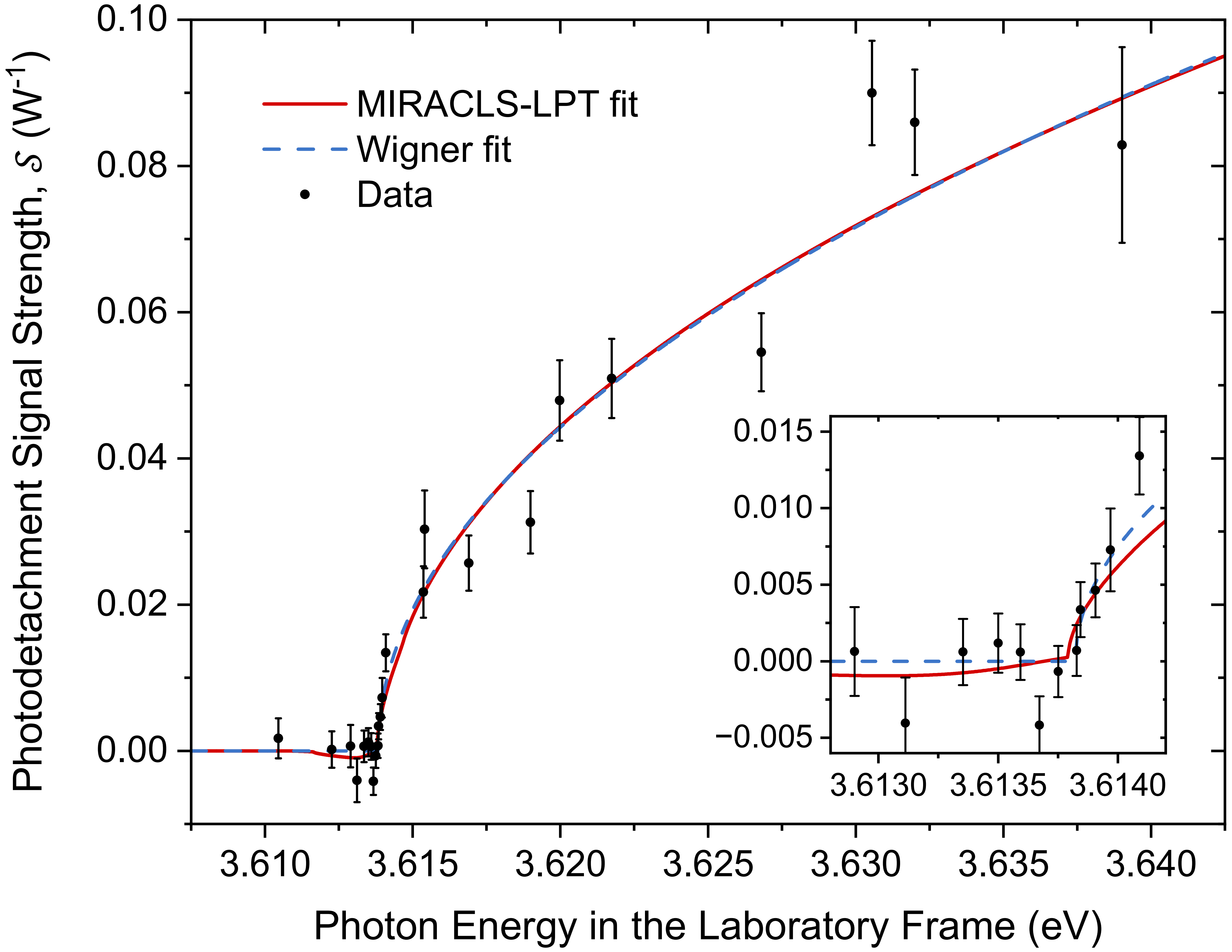




Results for Cl's EA



F.M. Maier, E. Leistenschneider et al., accepted Nature Communications

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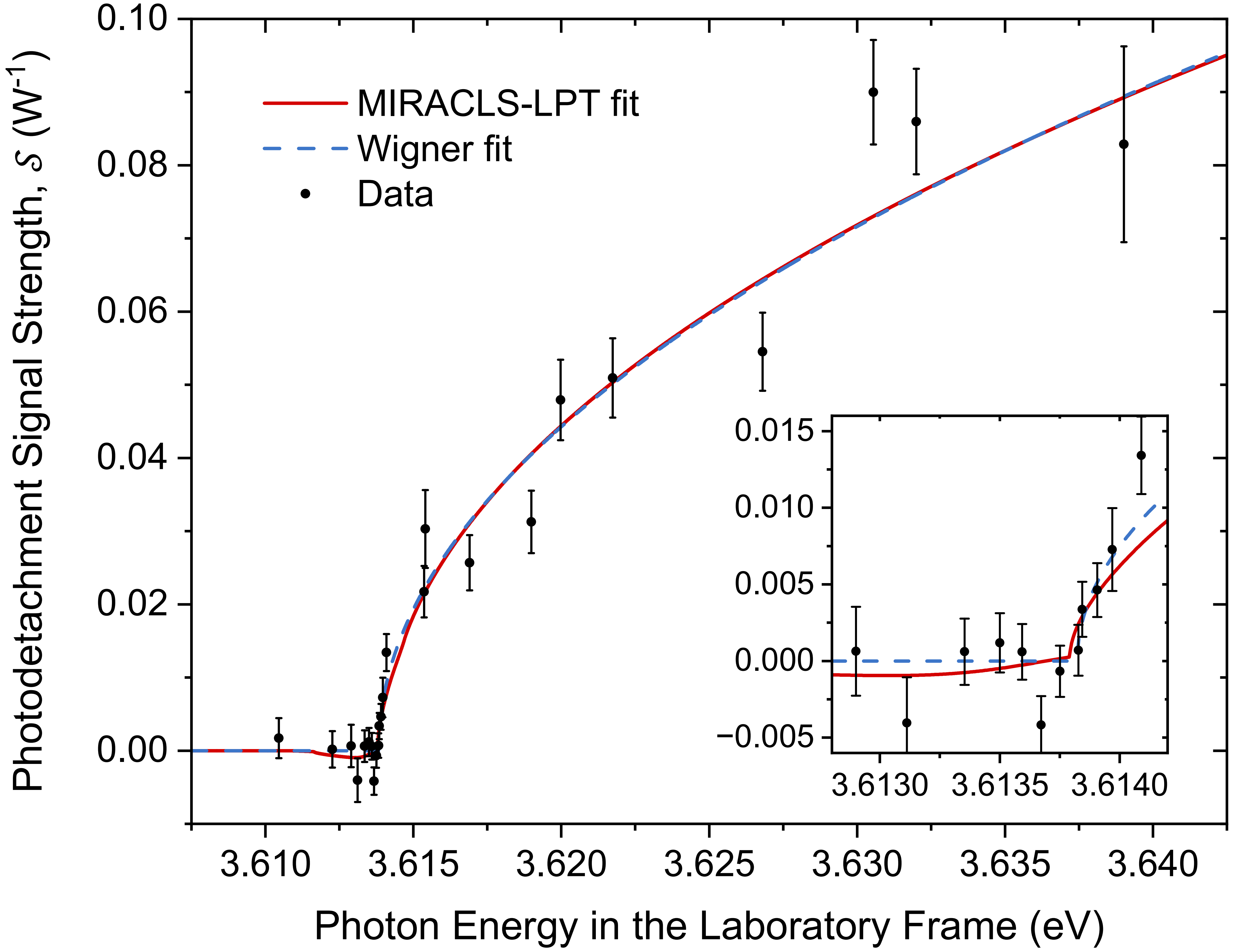

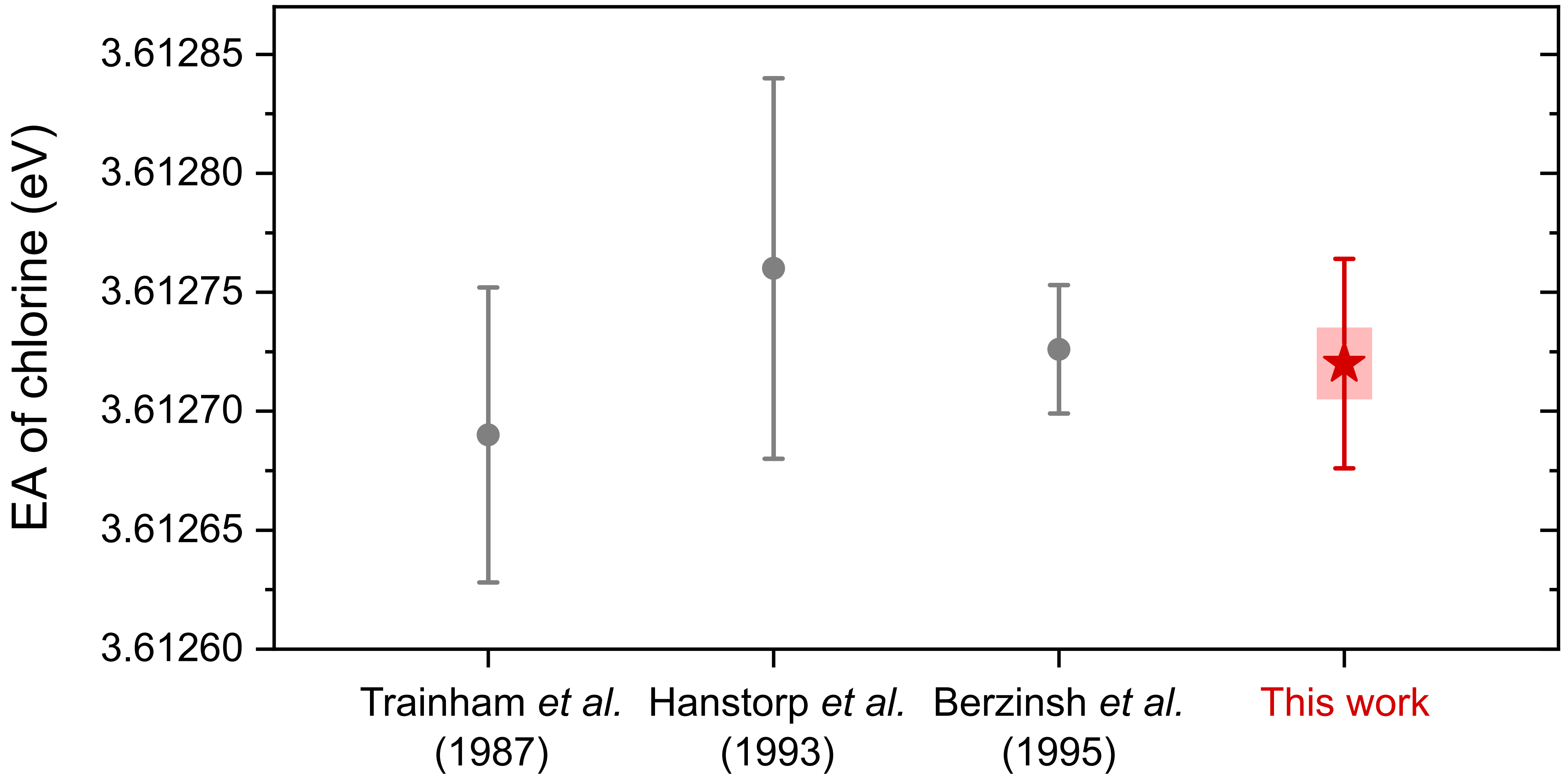

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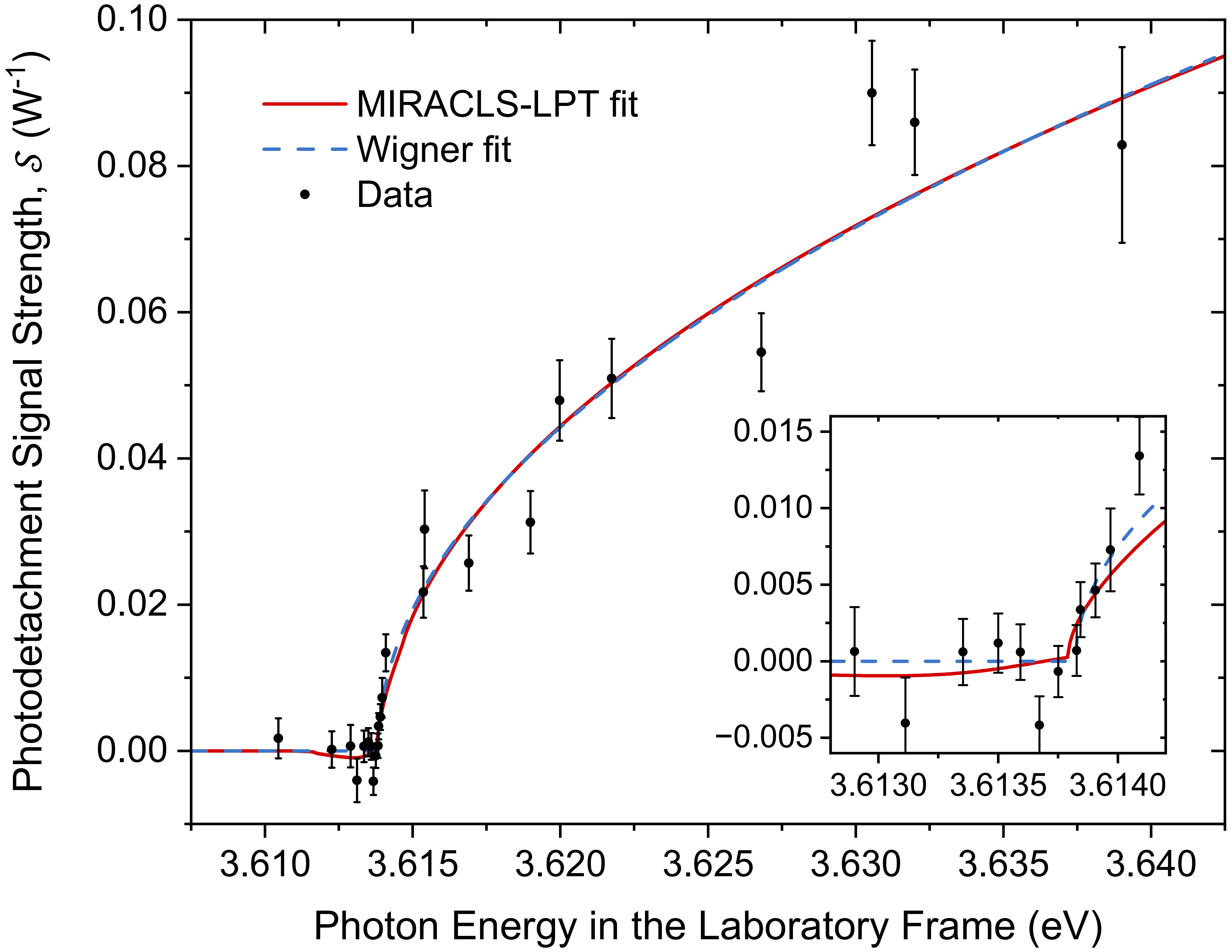
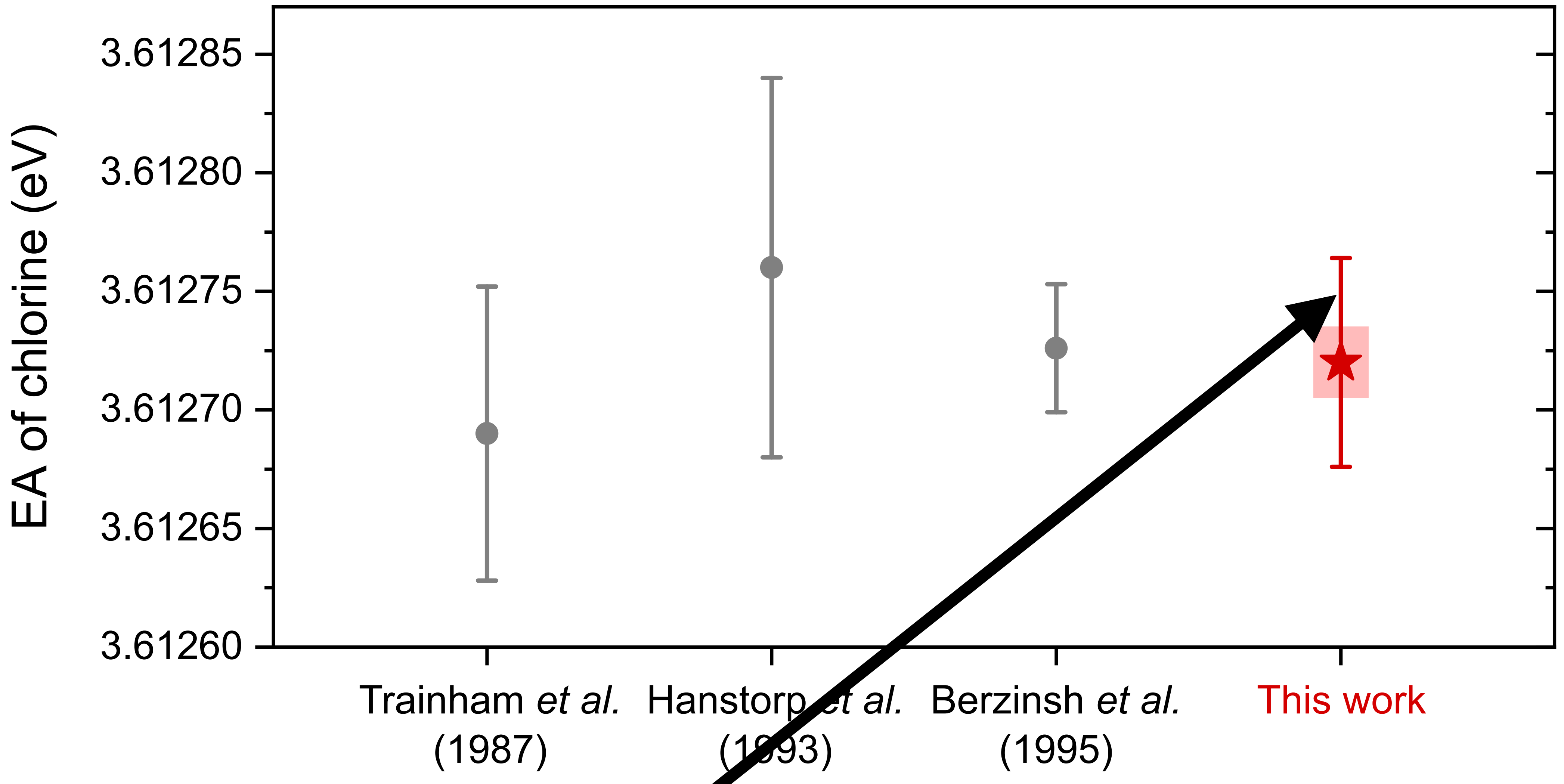
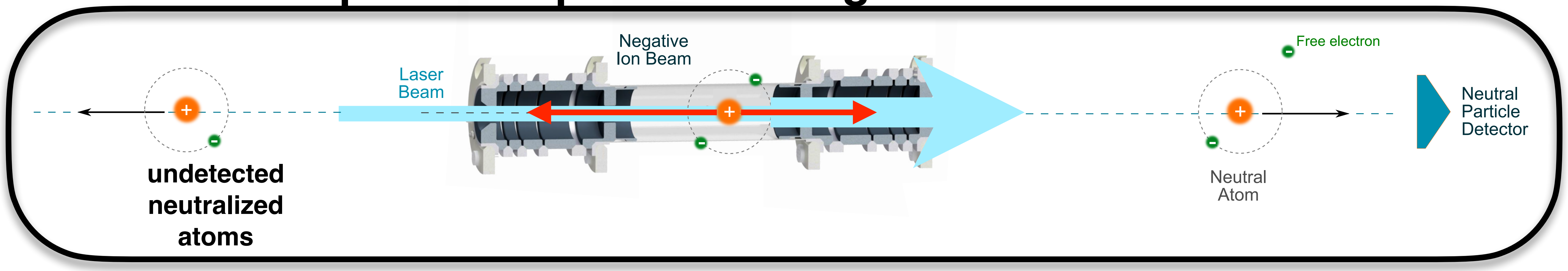




blue-shift depletion in present configuration



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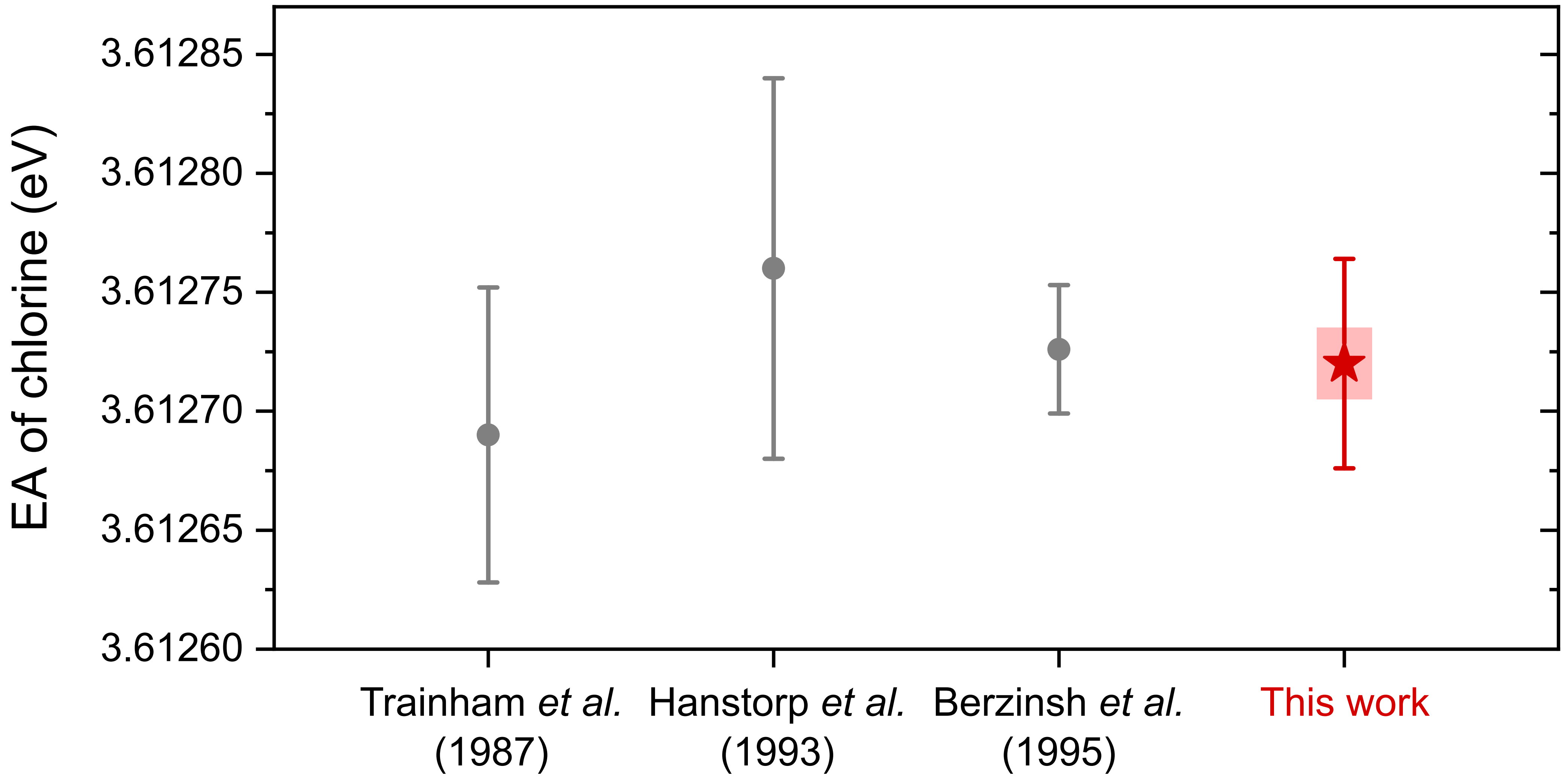
Re-evaluated EA of 35Cl:

	MIRACLS	Berzinsh et al.*
EA (eV)	3.612720(44)	3.612726(27)
Ion rate (pps)	~3000	~10^9
Avg. laser power (mW)	~2.0	~13.0
Ion-laser exposure	520 ms 60k "passes"	few µs single pass



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- lower power
- narrow band

pulsed laser
- high power
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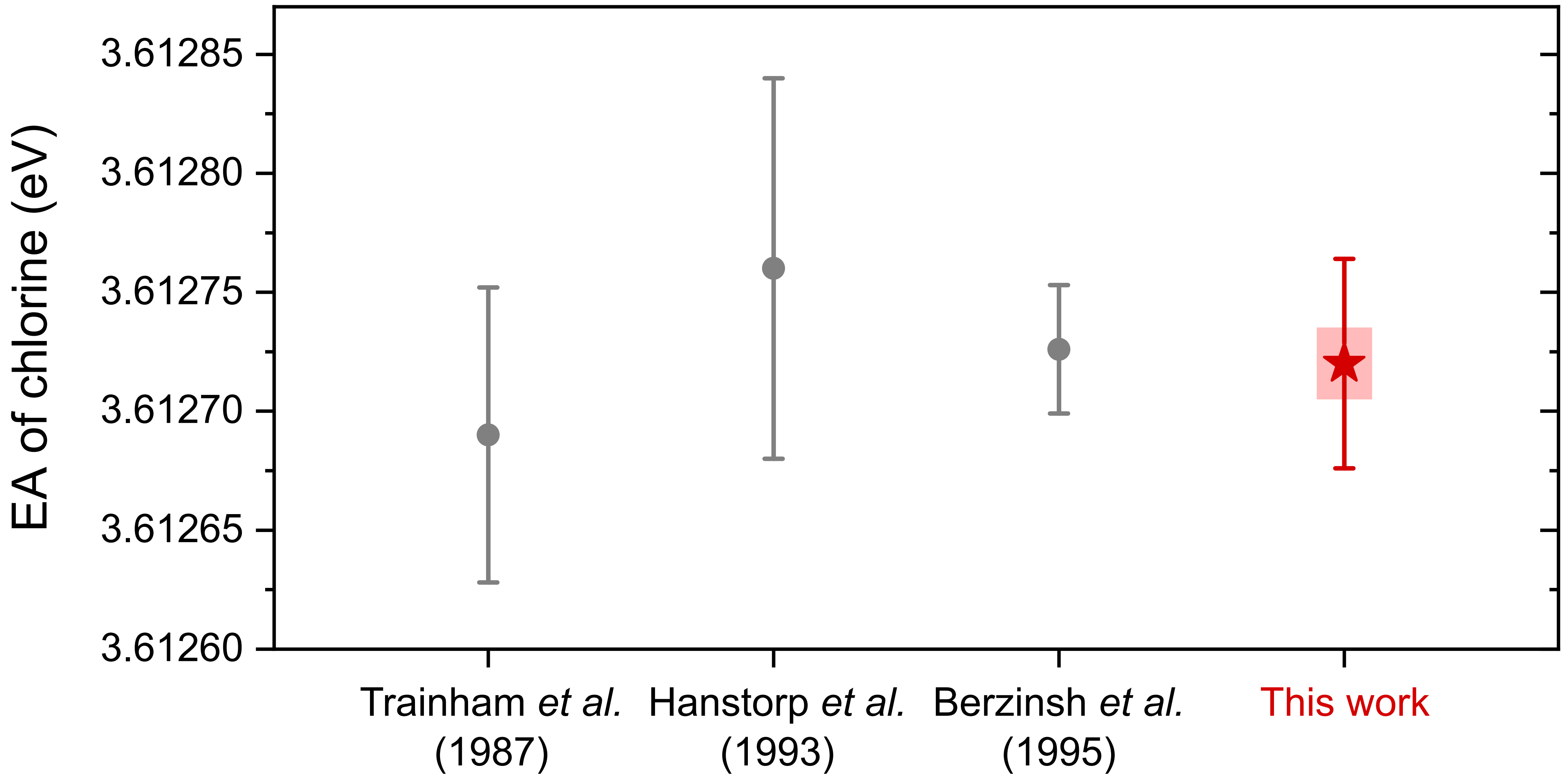

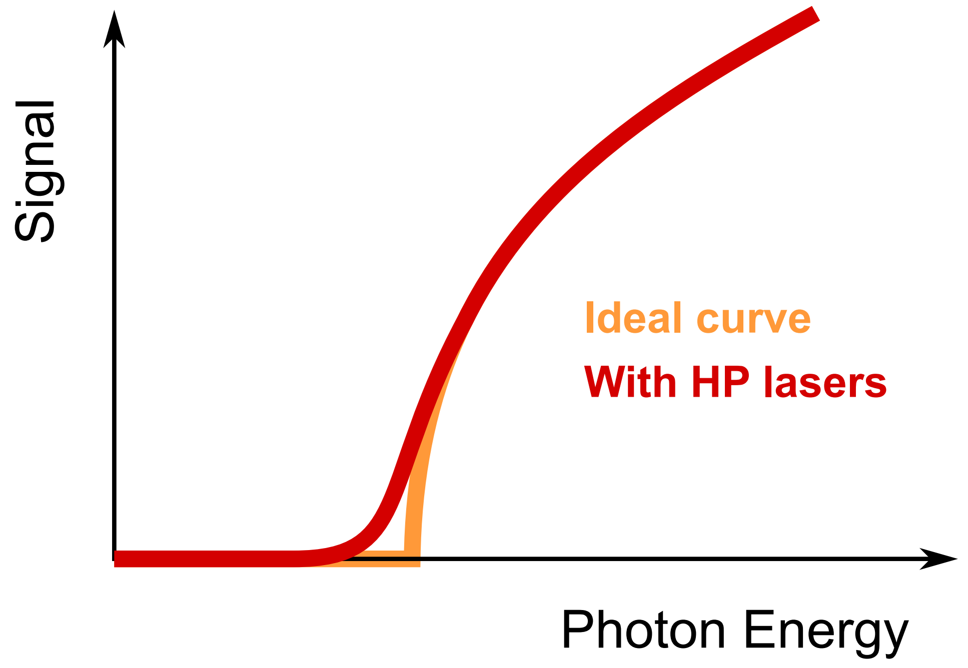

MIRACLS advantages:
- recycling of negative ions
- option to use narrow-band lasers

} MR-ToF enabled ⇒ **competitive precision yet >10^5 fewer ions**

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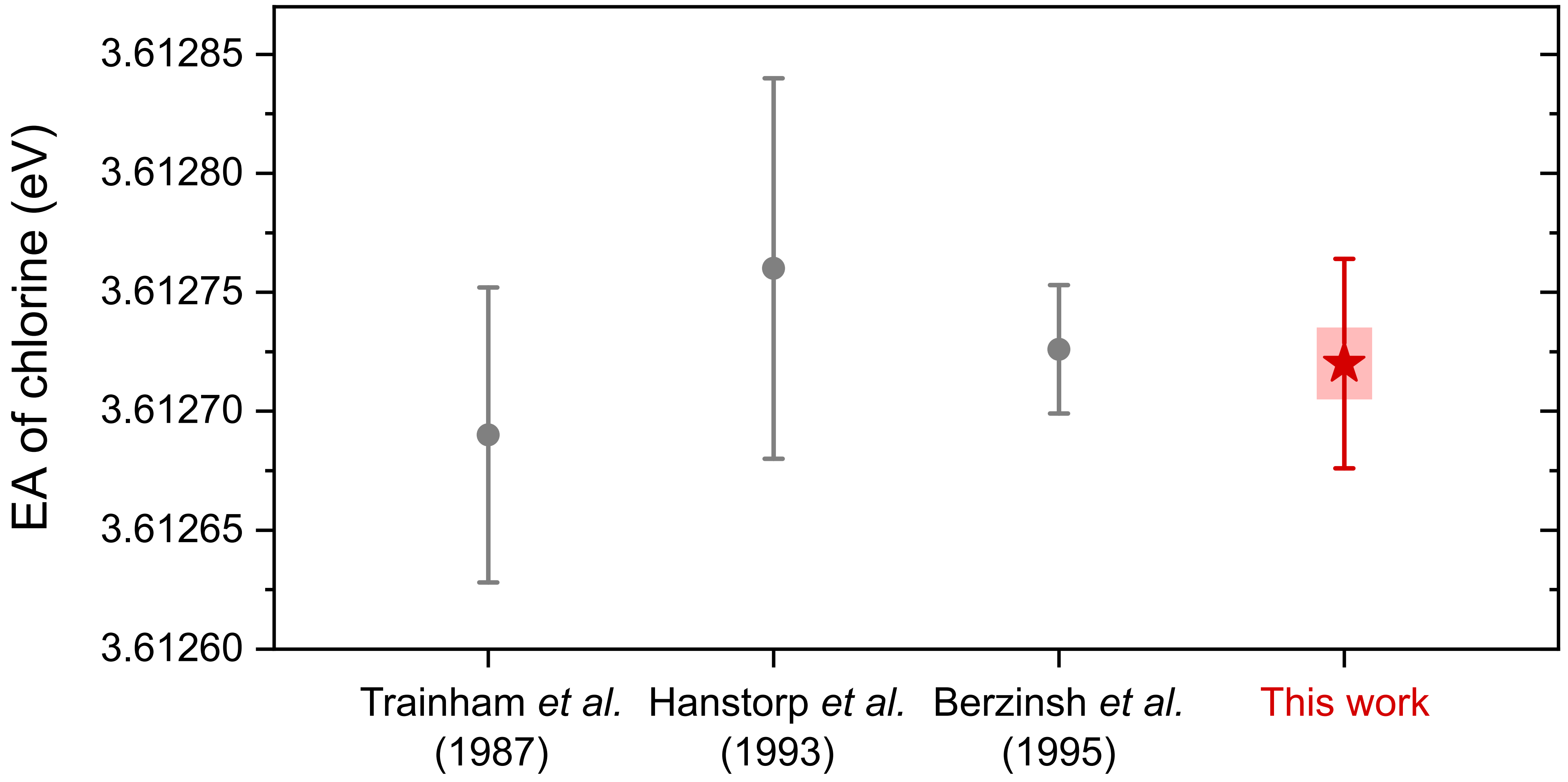

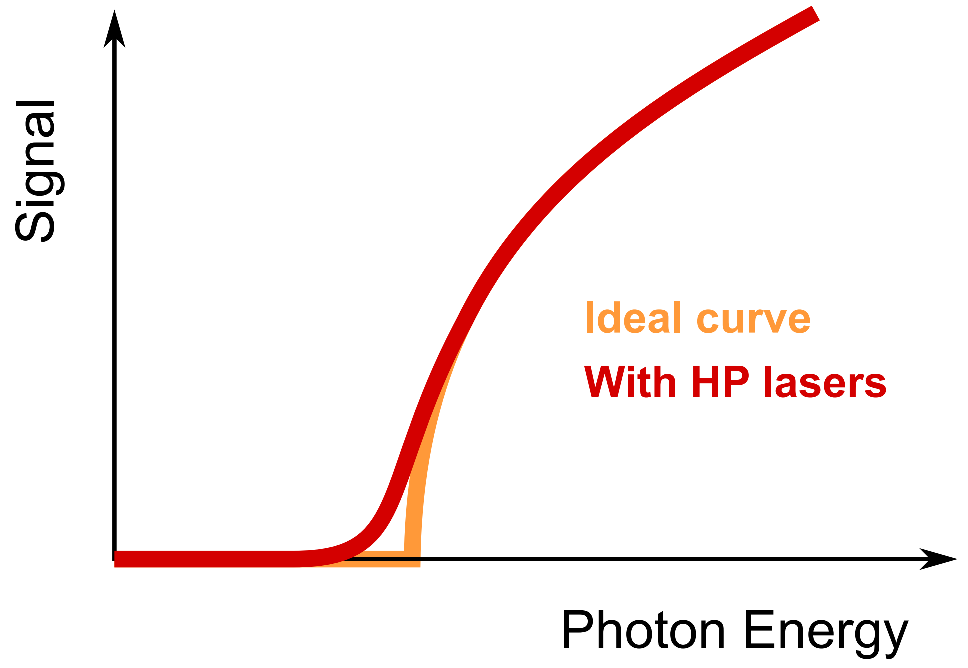

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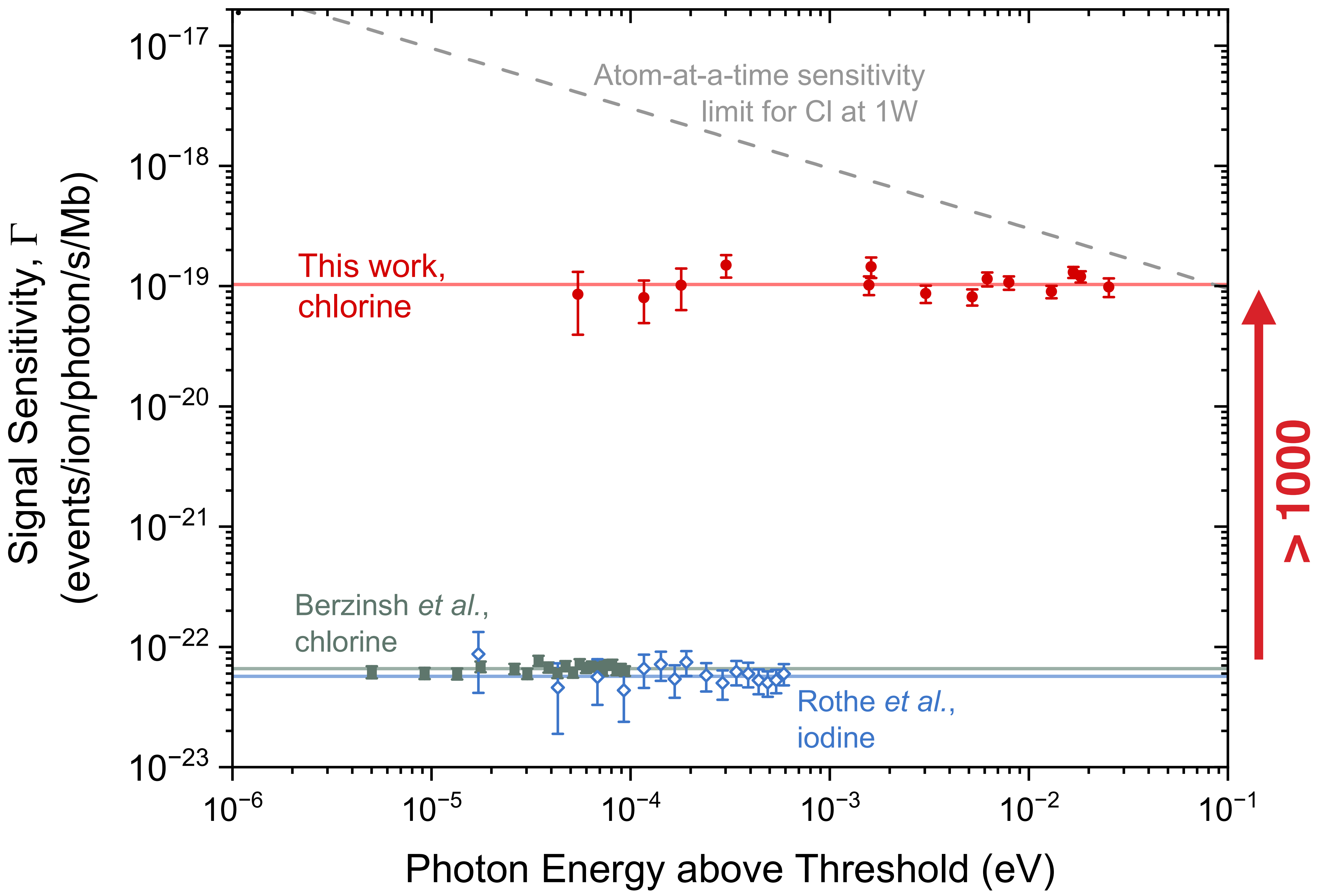
allows study of EA isotope shifts and hyperfine structure

F.M. Maier, E. Leistenschneider et al., accepted Nature Communications

Enhanced Signal Sensitivity



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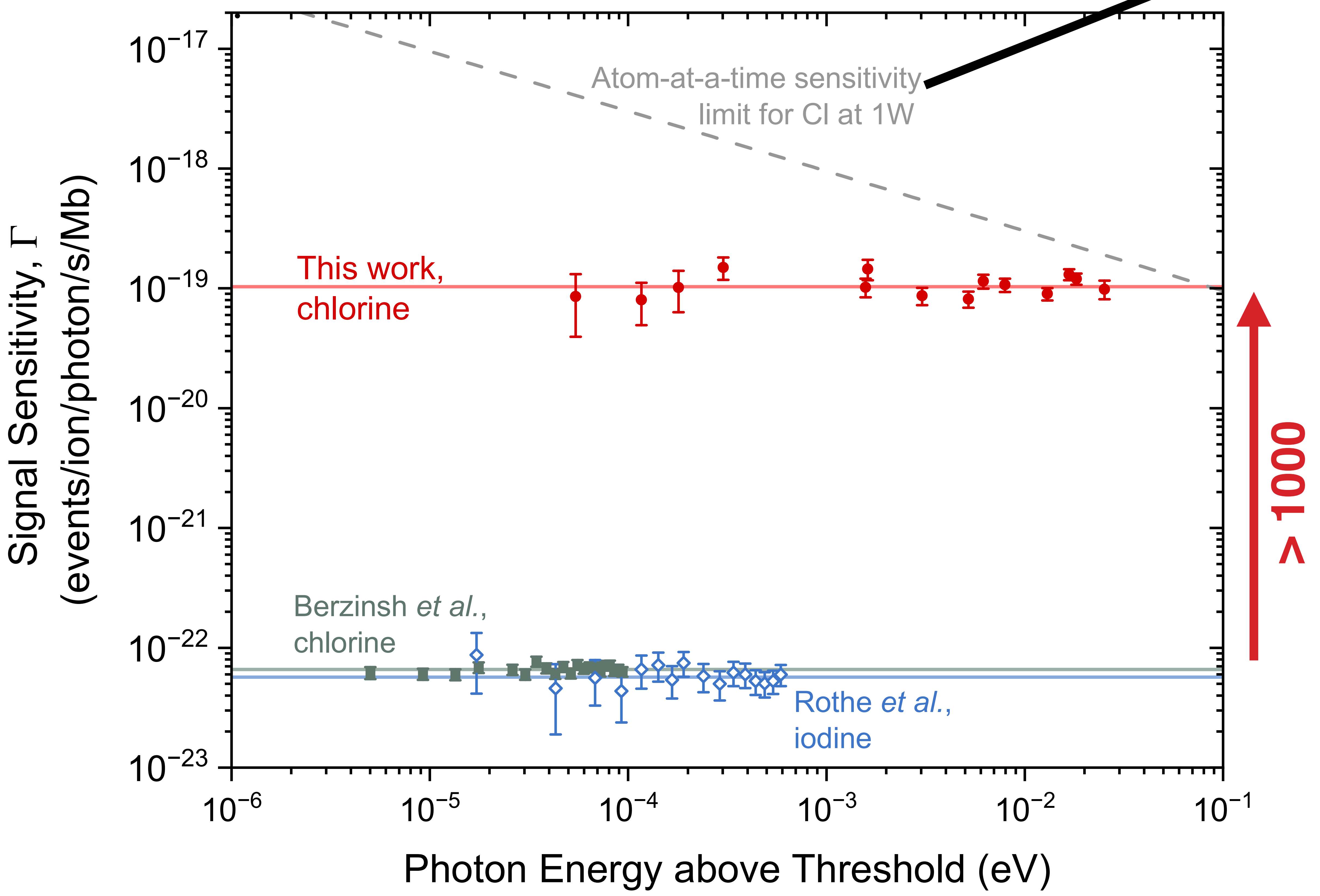

Today's potential (with 1W)
EA measurement with Δ ≈ 0.1 eV
with single ion trapped at a time

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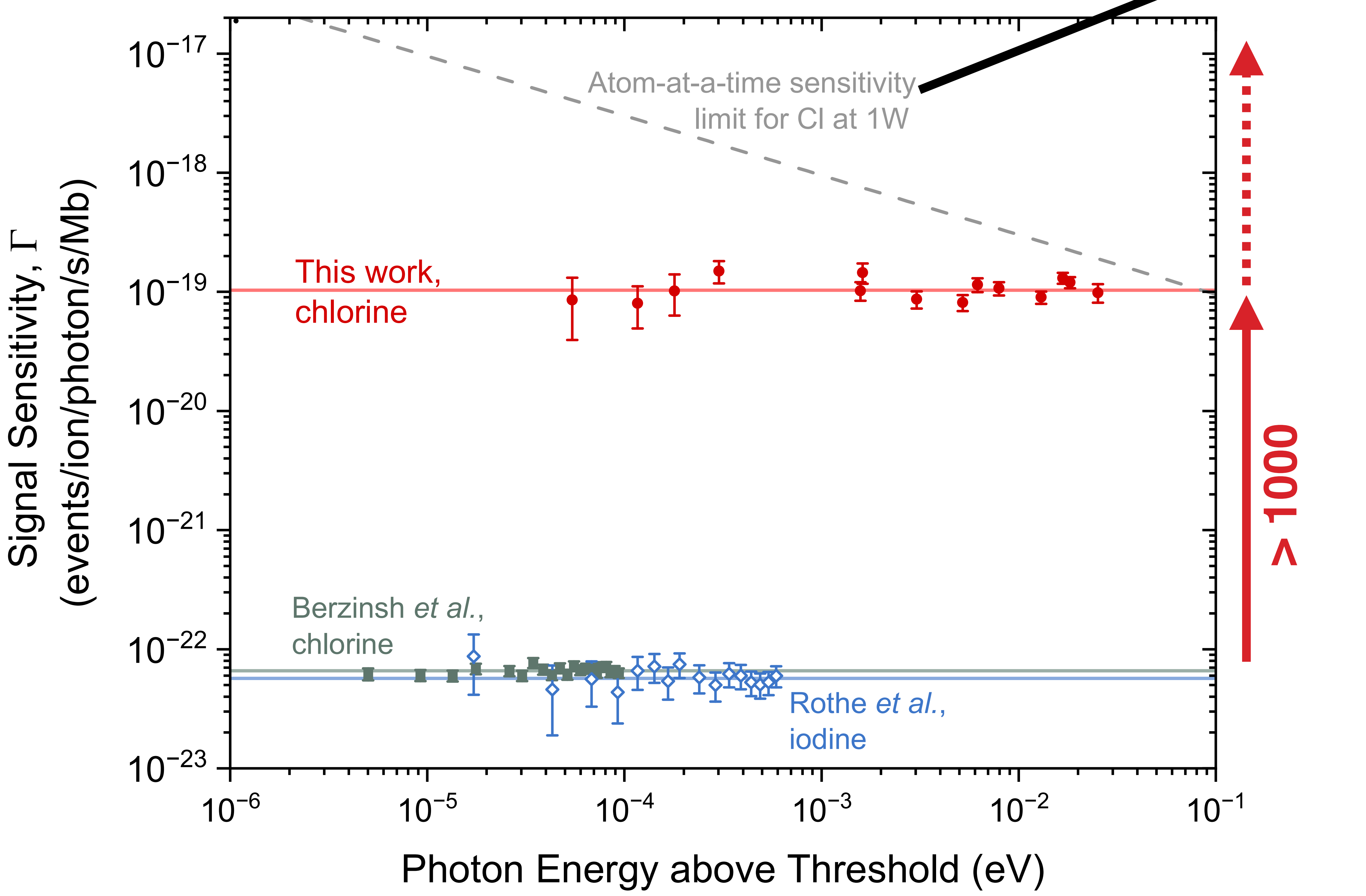


Today's potential (with 1W)
EA measurement with $\Delta \approx 0.1$ eV
with single ion trapped at a time

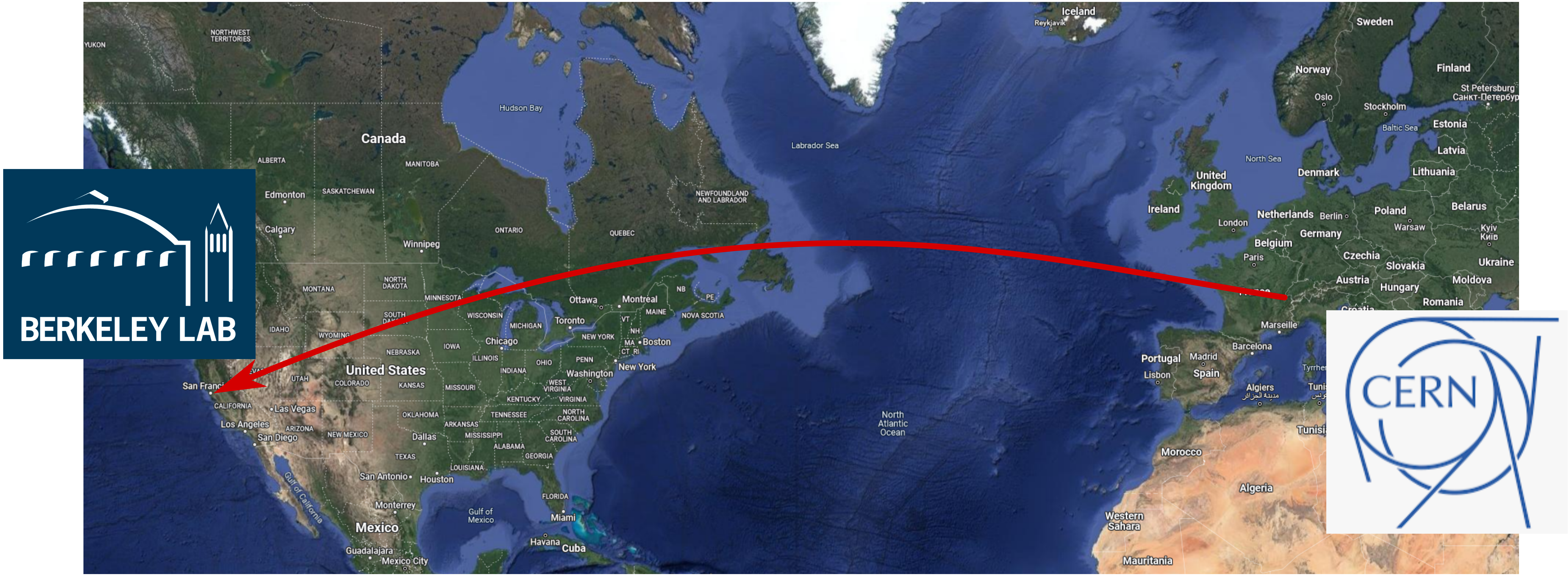
Anticipated improvements:

- higher cw laser power
- higher detector efficiency
- detectors in collinear & anticollinear direction
- (better vacuum ⇒ lower background ⇒ better S/N)

F.M. Maier, E. Leistenschneider et al., accepted Nature Communications

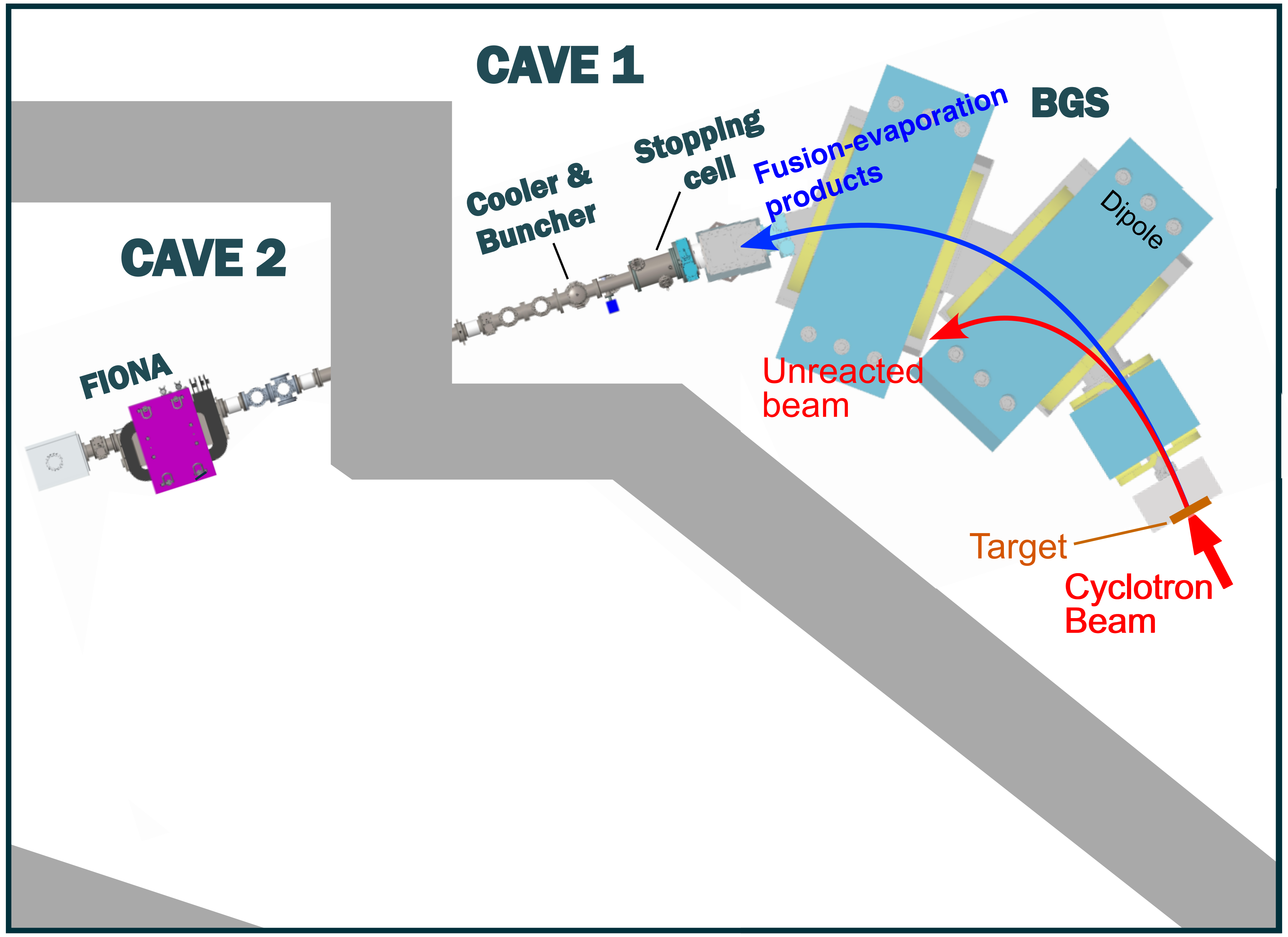
Advanced Electrostatic Trap for Heavy Element Research (AETHER)

MIRACLS low-energy system sent to LBNL to seed the new infrastructure



AETHER’s concept

Superheavy element production with BGS @ LBNL’s 88-inch cyclotron



efficient separation at Berkeley Gas-filled Separator (BGS)

stopping cell and cooler-buncher already in place for FIONA

one of very few systems in the world capable of producing ALL of the elements whose EA is unknown

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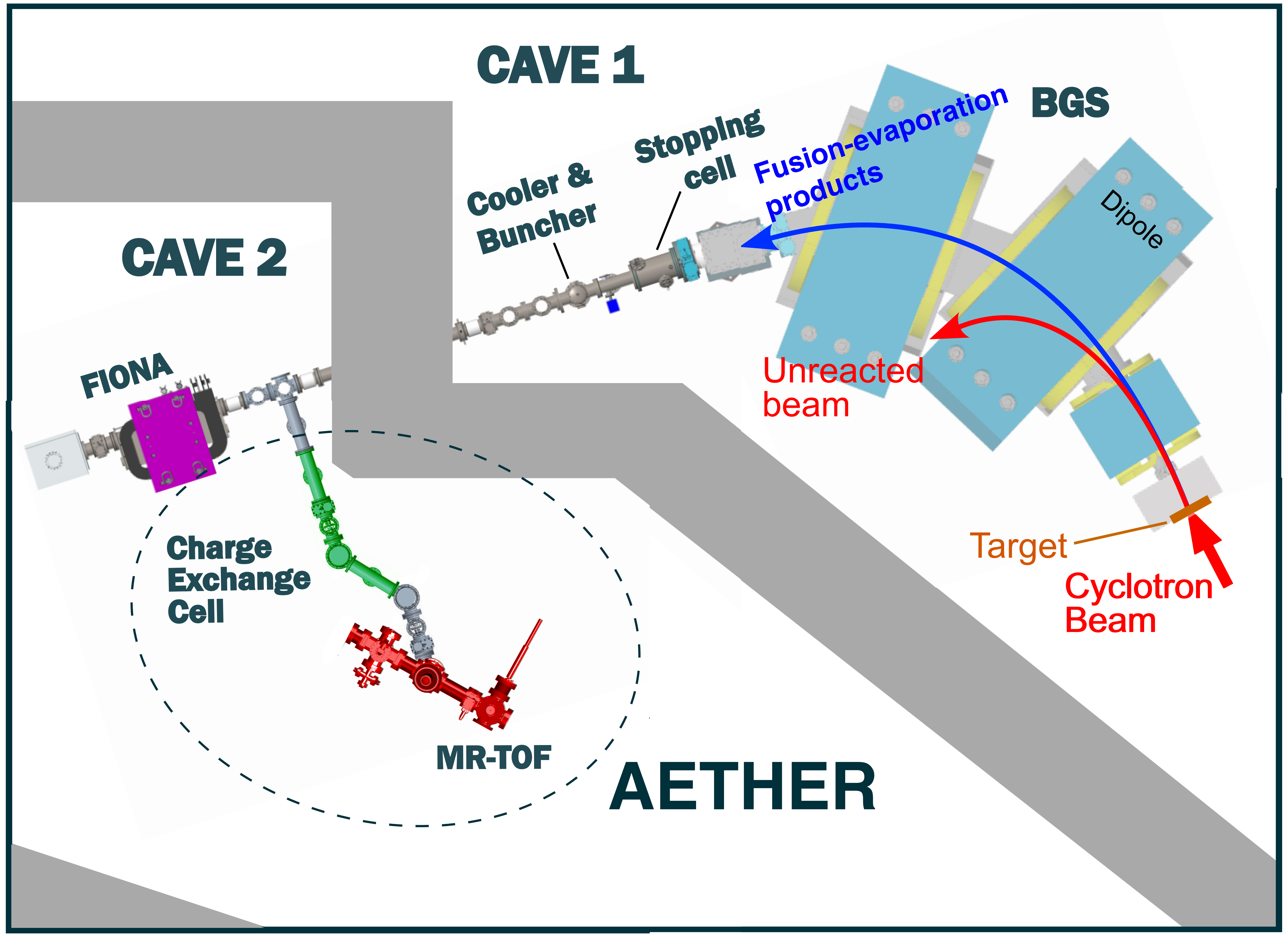

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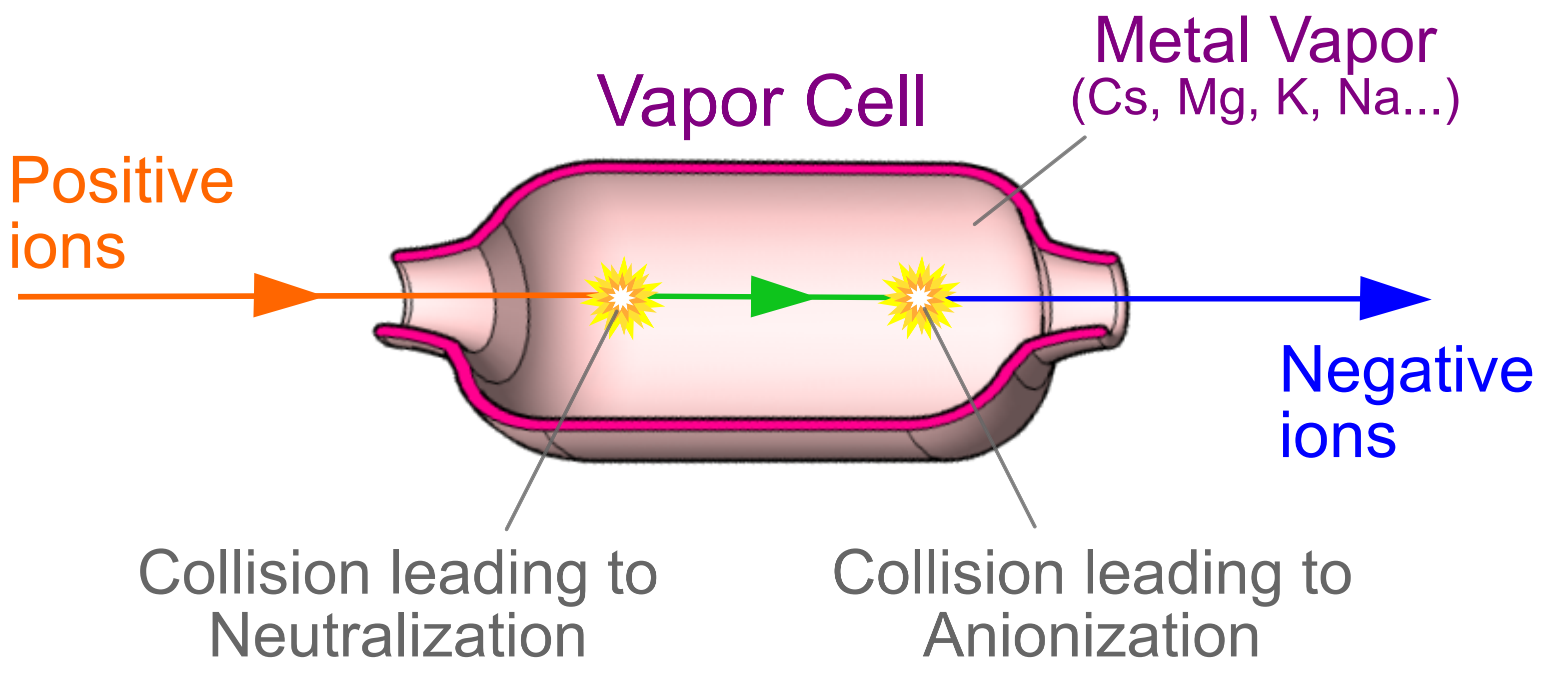
AETHER for EA measurements

- MR-ToF based measurements of unknown EA
- formation of negative ions via double-charge exchange



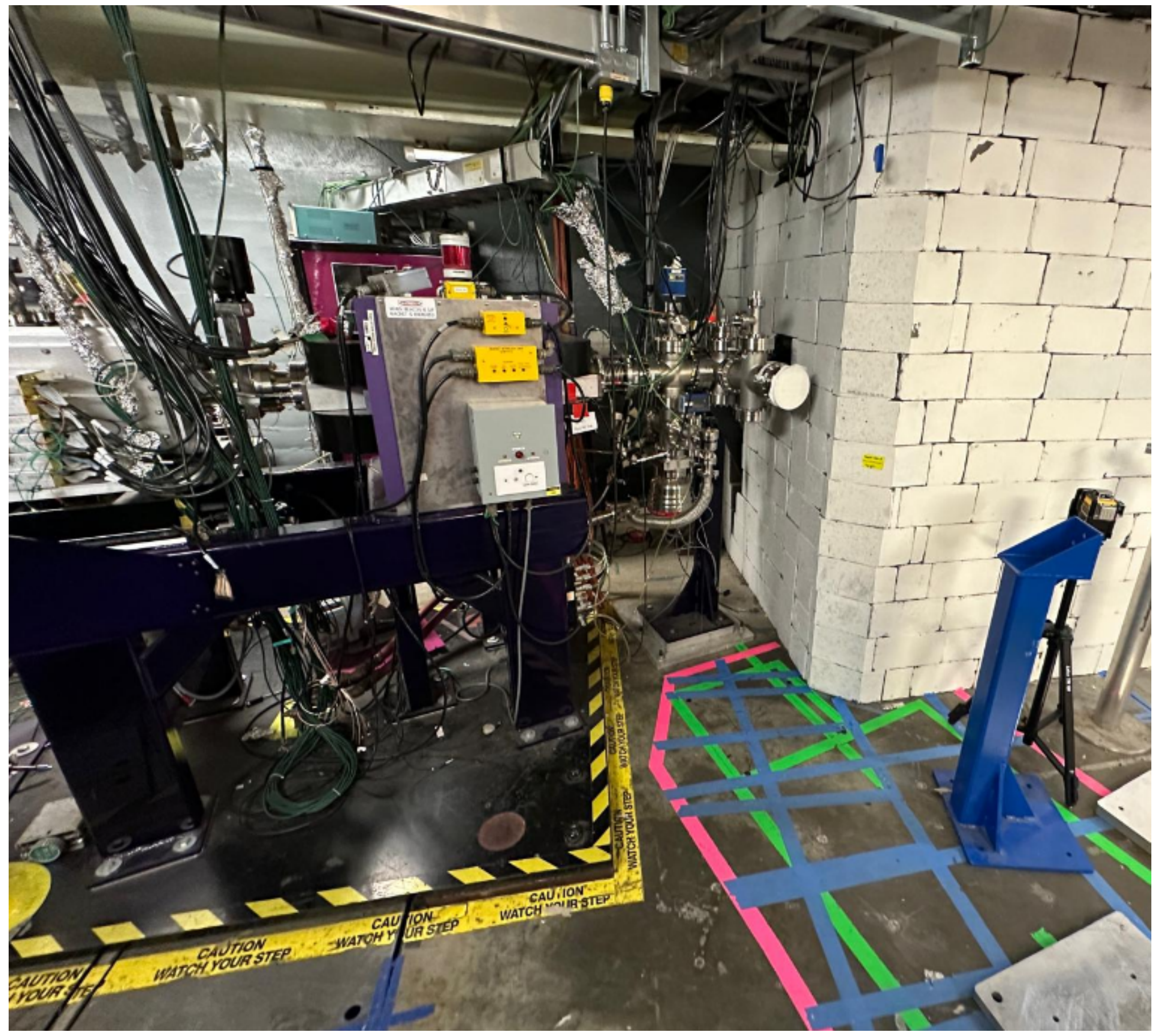
AETHER's integration

Strategy:

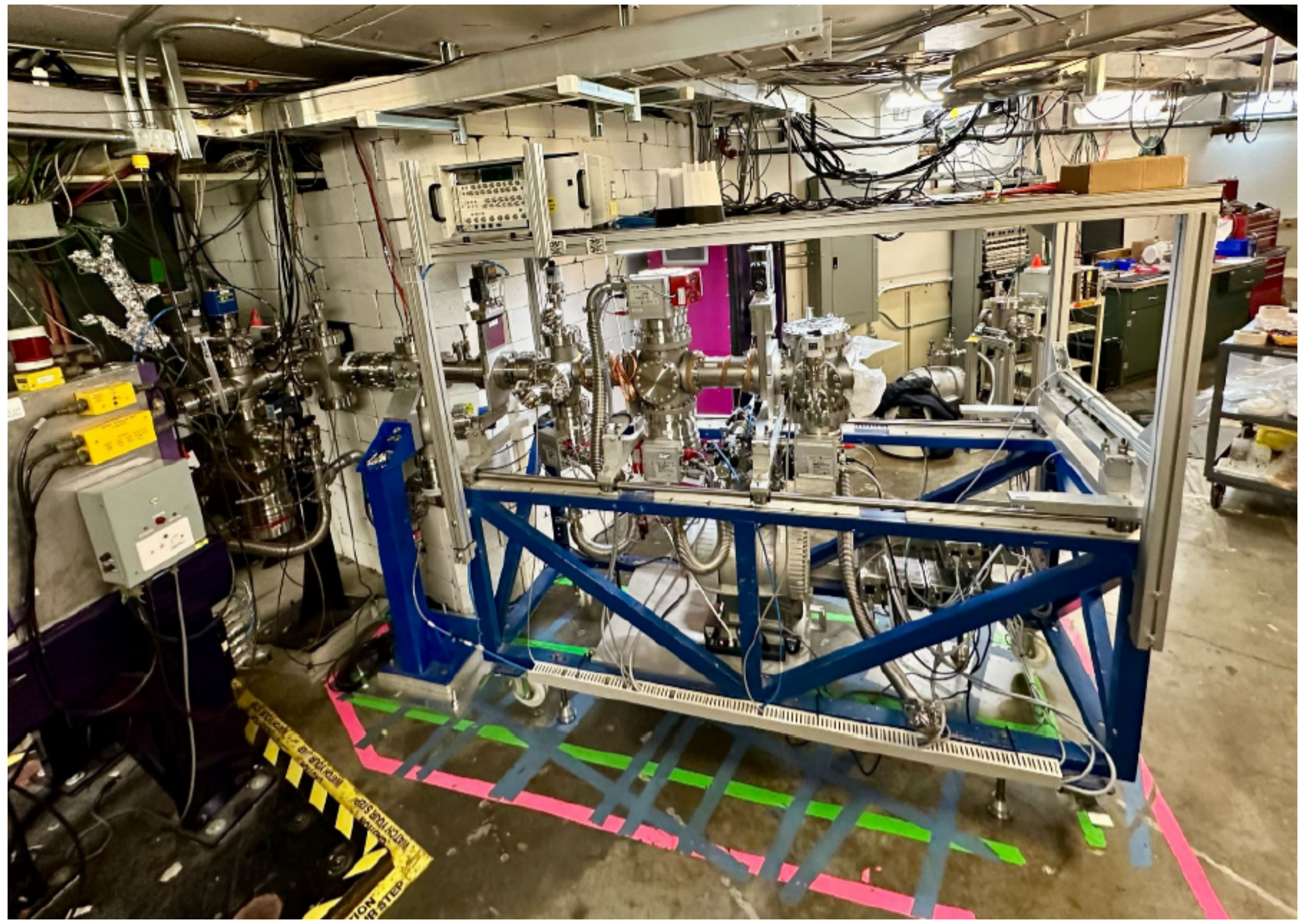
- couple MR-ToF directly to cooled BGS-enabled beams next to FIONA for SHE mass measurements
- develop efficient infrastructure for double-charge exchange
- upgrade neutral particle detectors and MR-ToF system

see talk by
M. Lykiardopoulou

October 2023
MR-TOF arrives from CERN



2024
Clearing of Cave 2 and coupling to beamline



Summer 2025
Beamline commissioning

Summary

- Electron Affinities (EA) critical information for chemistry, medical isotopes & fundamental physics

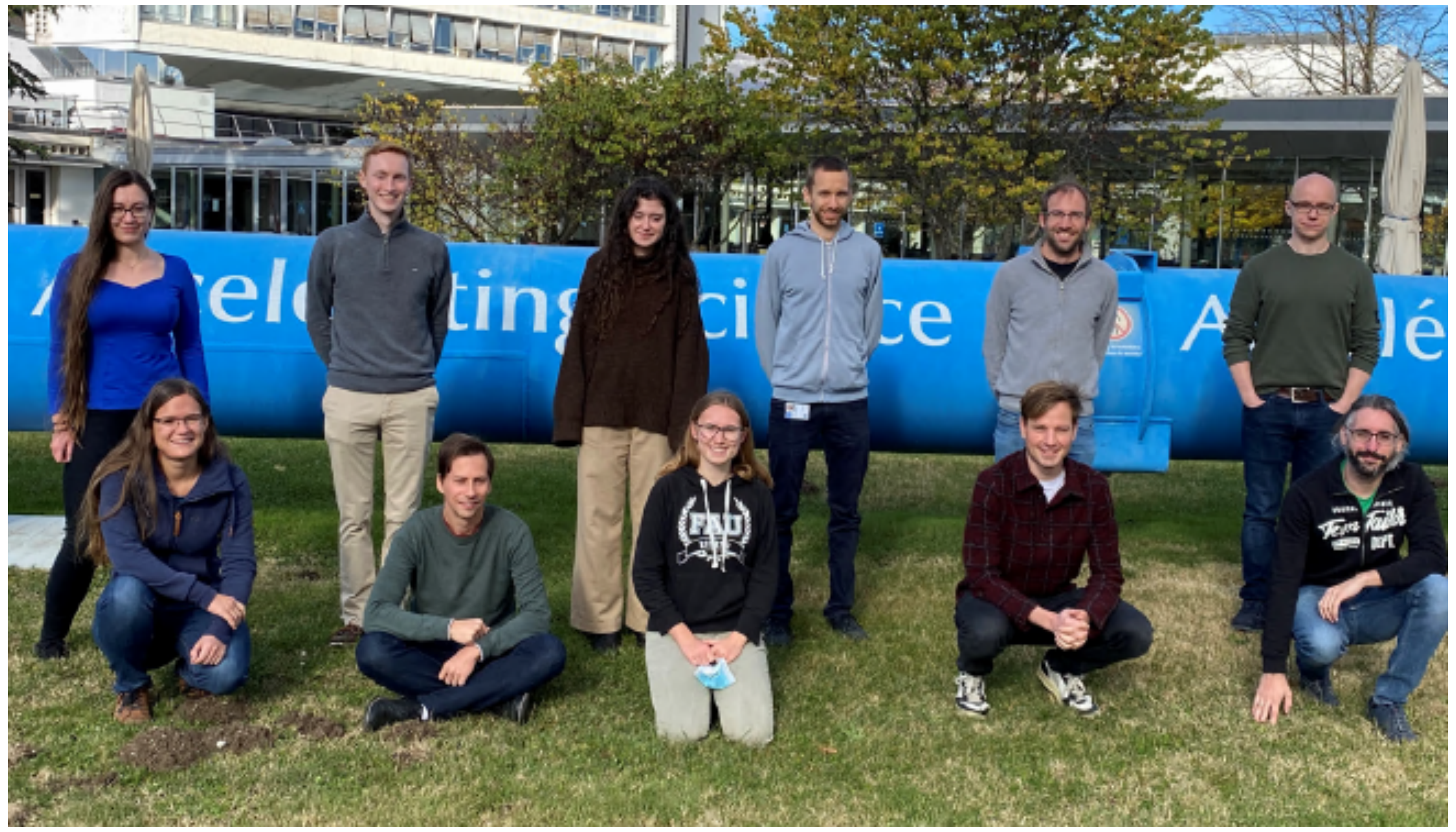
- ~1/3 of EAs in the Periodic Table are unknown
  - ➡ conventional methods requires sizeable quantities
  - ➡ generally lack sensitivity for radioactive elements, including (super)heavy elements

- exploiting MR-ToF devices: enhances sensitivity of LPT technique

- demonstrator experiment on ^{35}Cl with MIRACLS
  - ➡ > 1000x higher signal sensitivity
  - ➡ allows use of narrow-band lasers
  - ➡ improved precision of EA in Cl
  - ➡ <u>!! competitive precision with 10^5 less ions !!</u>

- AETHER
  - ➡ coupled to BGS @ LBL
  - ➡ unique opportunity to measure currently unknown EA’s in (super)heavy elements
  - ➡ bonus: MR-ToF for SHE mass measurements

Thank you!



Heavy Elements Group at LBNL:
Jacklyn Gates
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Rodney Orford
Erich Leistenschneider
Marilena Lykiardopoulou
John Gooding
Mirza Grebo

MIRACLS Team at CERN-ISOLDE:
F. Maier (CERN)
S. Malbrunot-Ettenauer (TRIUMF)
E. Ganzke (KIT)
V. Lagaki (CERN)
S. Lechner (CERN)
P. Plattner (CERN)
L. Schweikhard (U. Greifswald)
M. Vilen (CERN)
M. Au (CERN)
M. Reponen (JYFL)
S. Rothe (CERN)
U. Berzinsh (U. Latvia)
D. Hanstorp (U. Gothenburg)
D. Leimbach (U. Gothenburg)
M. Nichols (U. Gothenburg)
J. Warbinek (U. Gothenburg)