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Atom Trap Trace Analysis (ATTA) with Krypton and Argon

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U.S. Department of Energy

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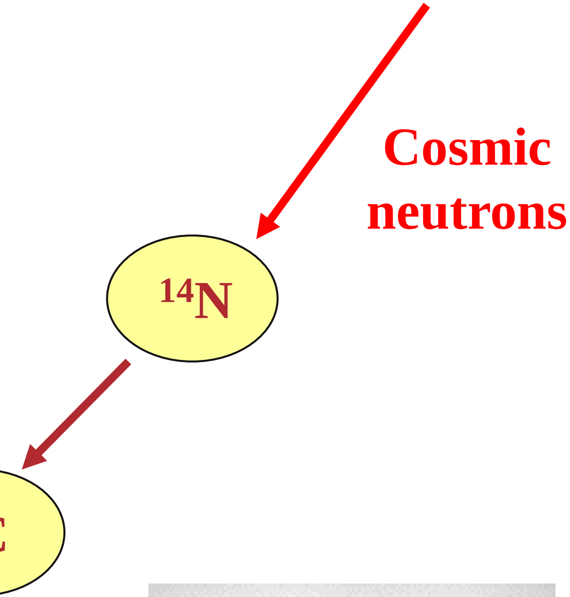
THE UNIVERSITY OF CHICAGO

Office of Nuclear Physics Exploring Nuclear Matter - Quarks to Stars

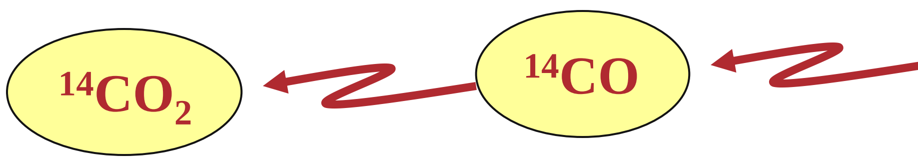
NSF

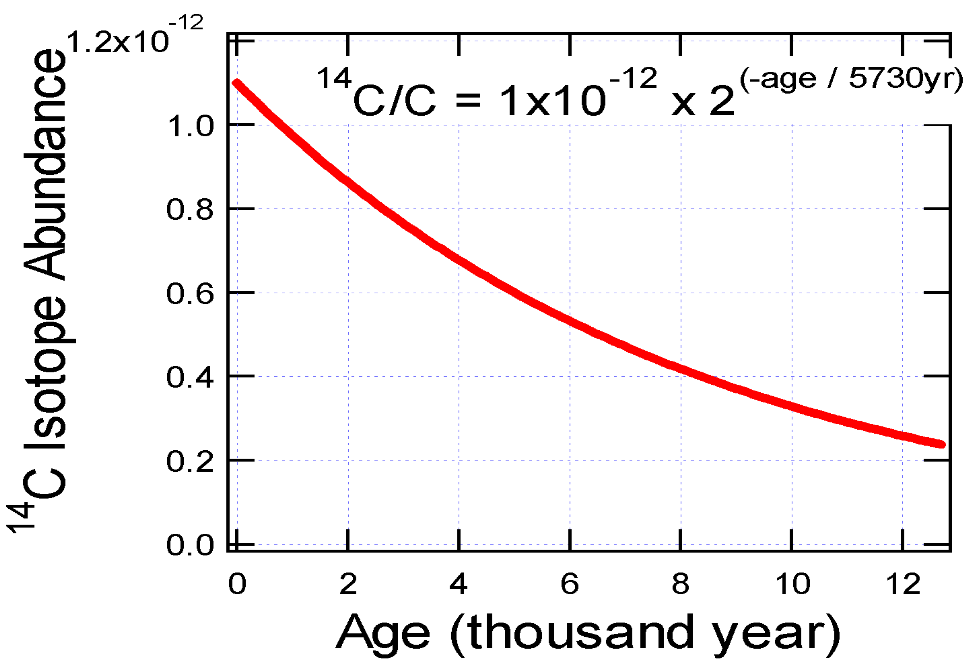
Radio Carbon Dating

^{14}C ($t_{1/2}$ = 5730yr, I.A.= 1 10^{-12})



- Widely applied
- Limited to 50 kyr or younger





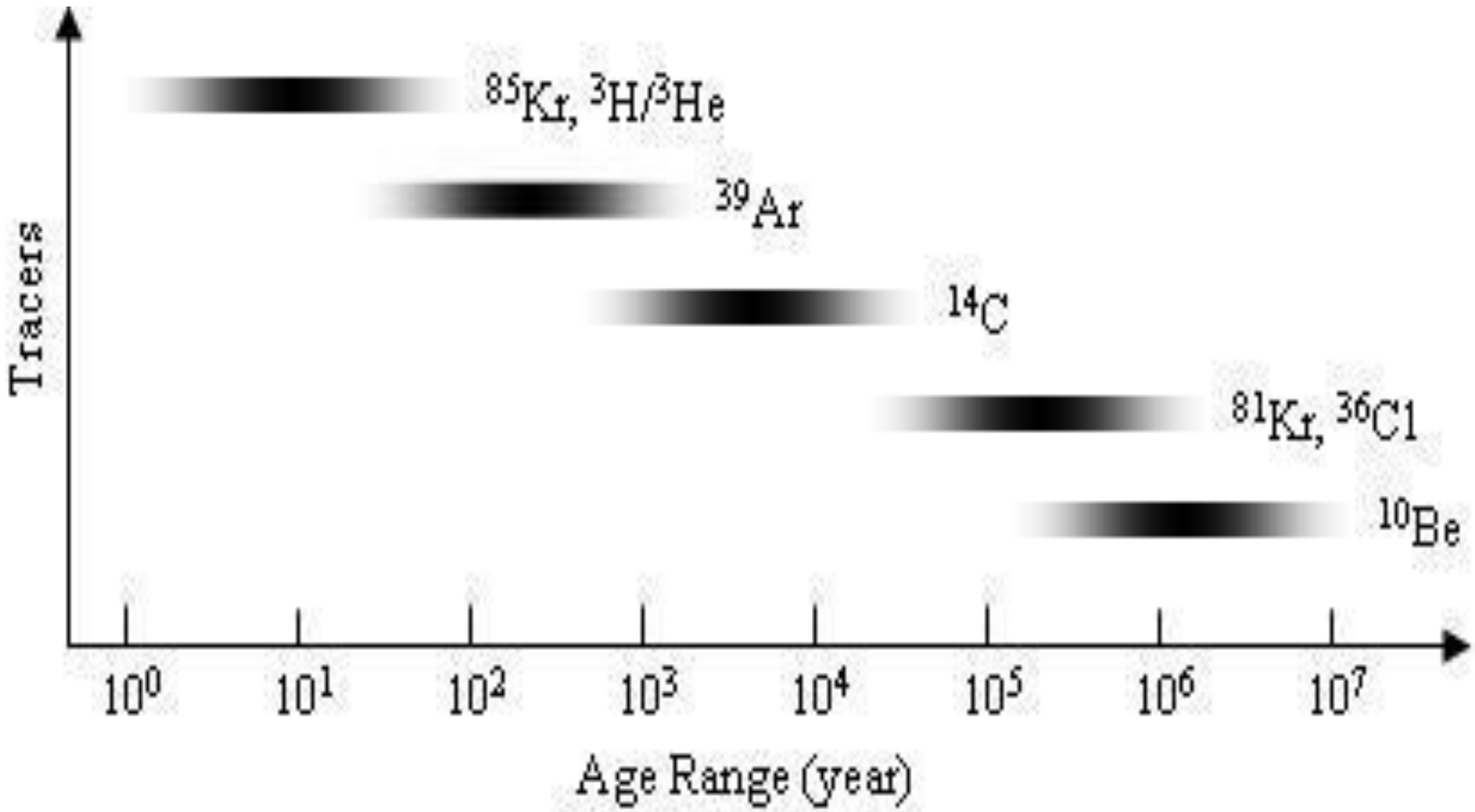
Willard Frank Libby

University of Chicago

1960 Nobel Prize in Chemistry

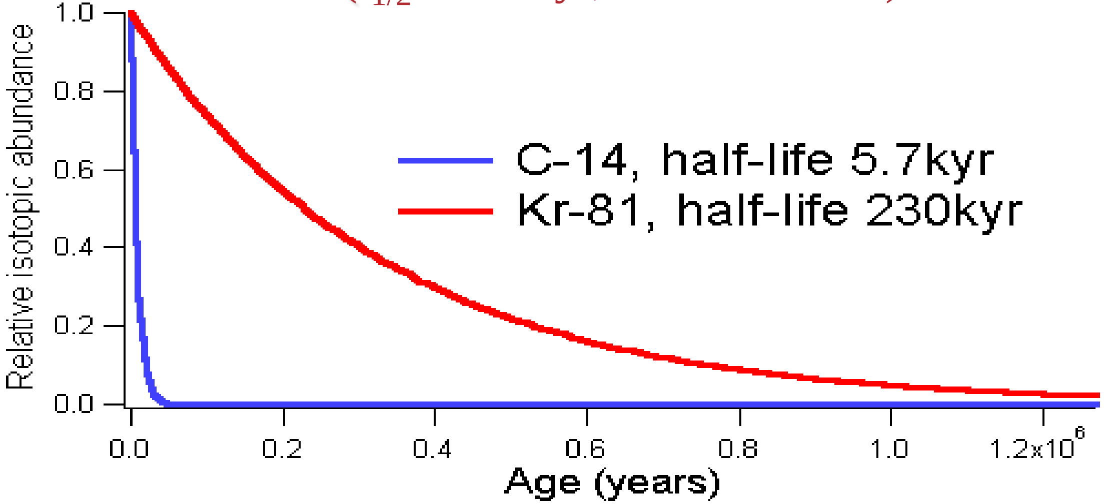
Arnold&Libby, Science 110, 678 (1949)

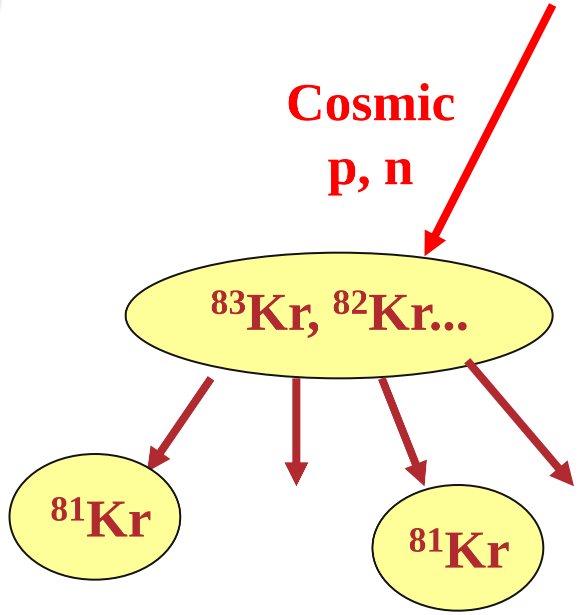
Age Range for Different Elements



Radio-Krypton Dating

^{81}Kr ($t_{1/2}$ = 230kyr, I.A.= 5 10^{-13})





Dating polar ice to study the climate history of the Earth

Dating old groundwater to study the source, sink, and flow pattern of aquifers

Applicable age range, 100 kyr – 1 Myr, is beyond the reach of ^{14}C-dating

- Number of ^{81}Kr atoms in 1 liter of :

  Air → 20,000

  Water → 1,000

  Ice → 1,000

Task

1) How do you find 1 atom in 10^{12} atoms which all look very similar?
2) Can we make it efficient?

Isotope	Abundance	Half-Life
78	0.0035	2.3 x 10^{20}y
80	0.0225	Stable
81	5 x 10^{-13}	2.3 x 10^{5} y
82	0.116	Stable
83	0.115	Stable
84	0.57	Stable
85	2 x10^{-11}	10.75 y
86	0.173	Stable

Earlier Dating Methods

Low Level Counting

$$\text{Efficiency} = \frac{\text{Count Time}}{\text{Life Time}} = \frac{100\,hr}{230\,kyr} = 5\times 10^{-8}$$

Accelerator Mass Spectrometry (AMS)

Fast, Sensitive; AMS / LLC = 10^5 (^{14}C)

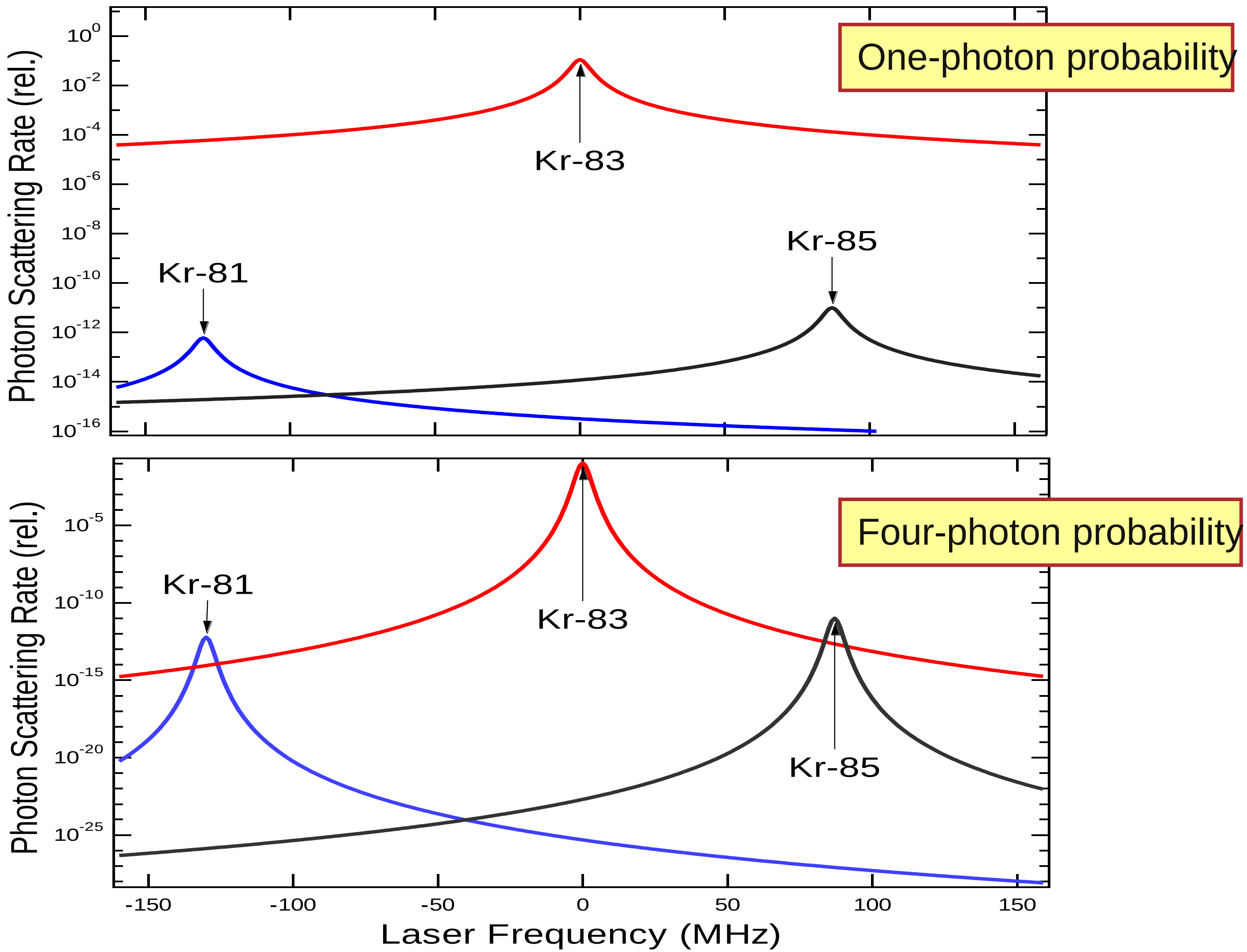
Not bothered by decay background

Existing Laser Methods Based on Isotope Shifts

Resonance Ionization Spectroscopy (RIS)

Photon Burst Spectroscopy

Photon Burst Spectroscopy

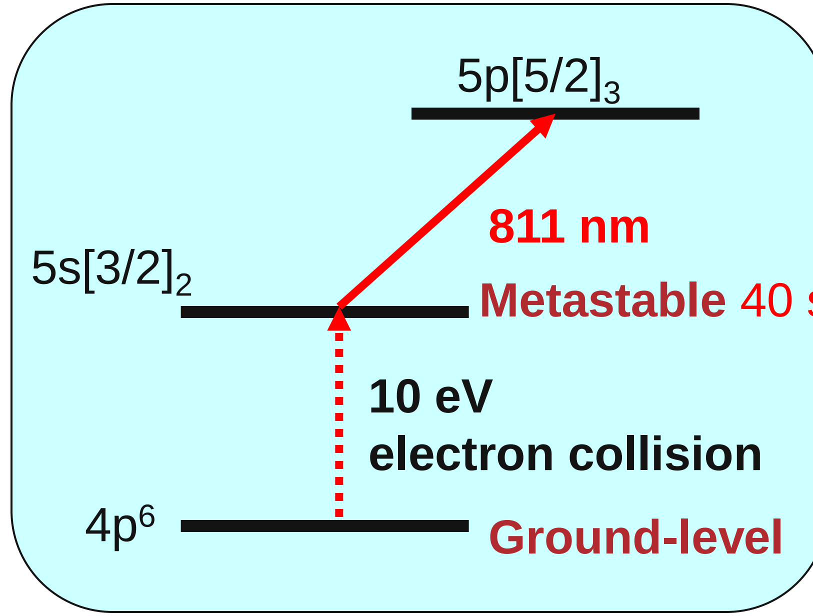


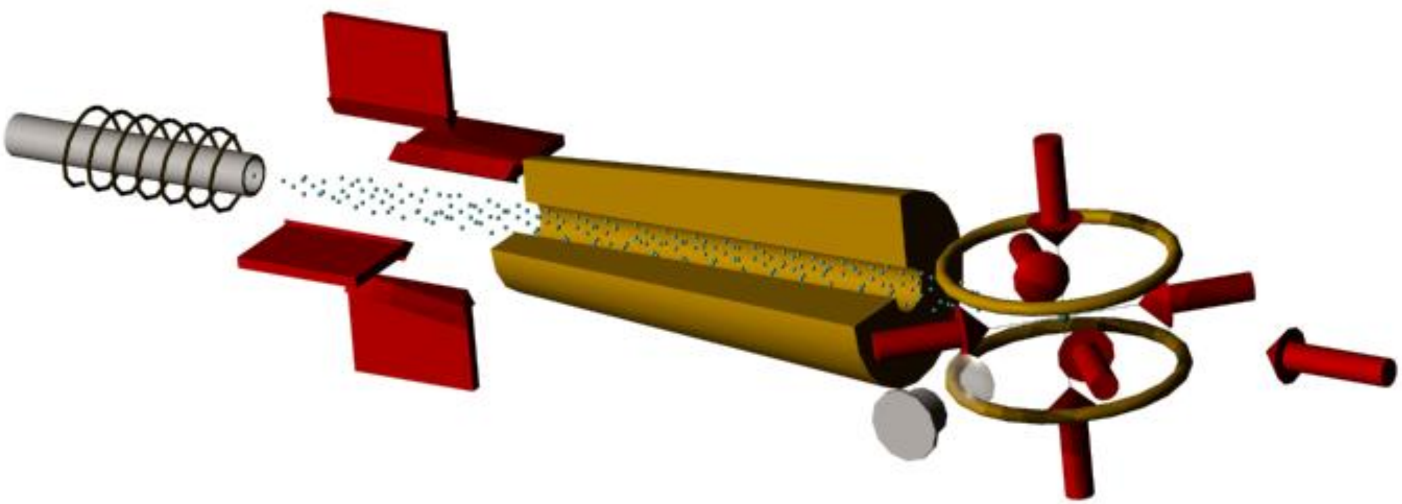
G.W. Greenlees *et al*., Opt. Commun. 23, 236 (1977)
V.I. Balykin *et al*., JETP Lett. 26, 357 (1977)

Magneto-Optical Trap (MOT)

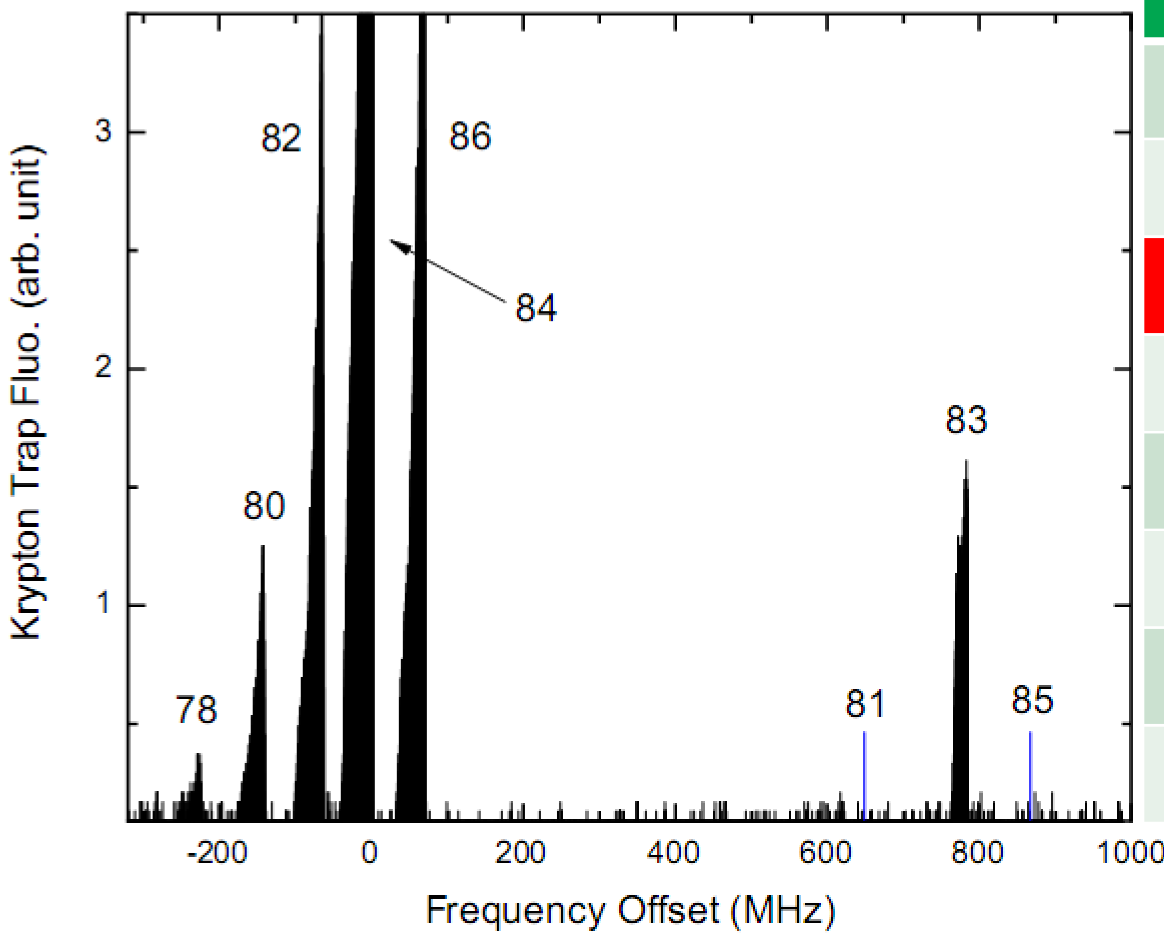
Resonance & Repetition

- Long observation time -- 100 ms
- High capture rate -- 10^9-10^{12} s^{-1}
- Narrow linewidth – natural linewidth
- Spatial confinement -- trap size < 1 mm





Krypton Isotope Fluorescence



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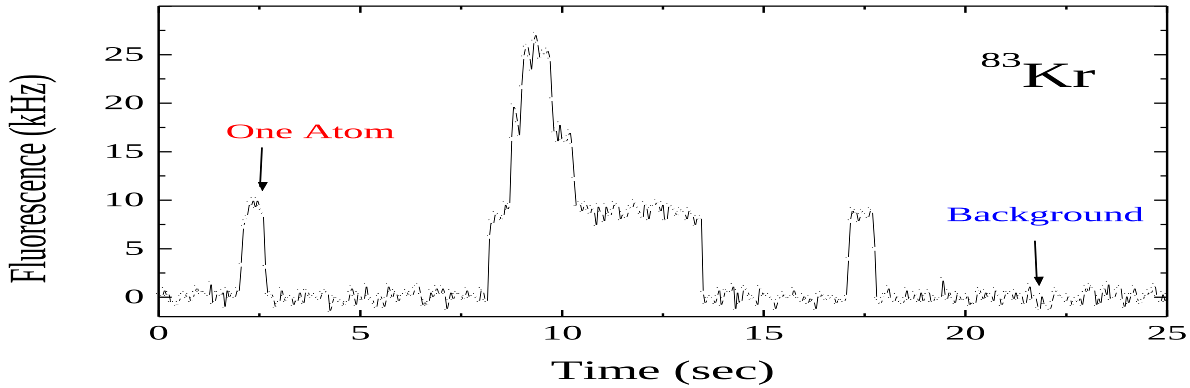
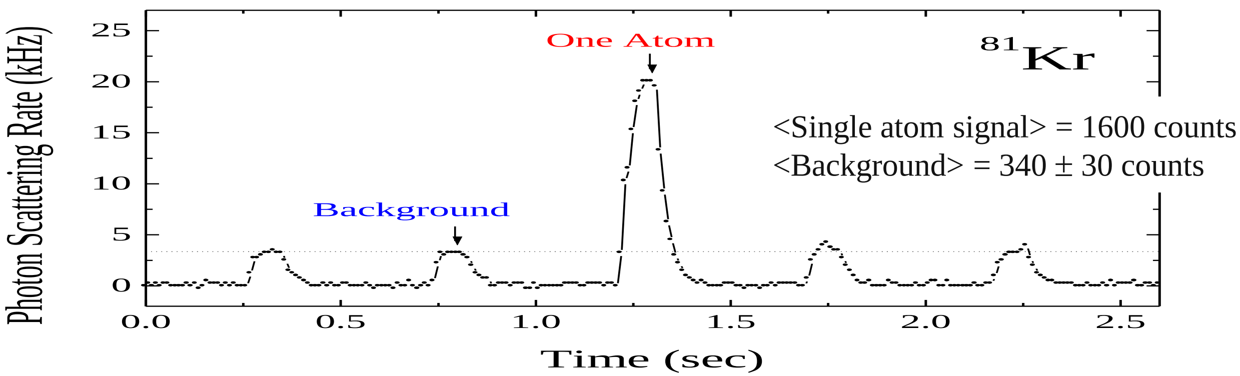
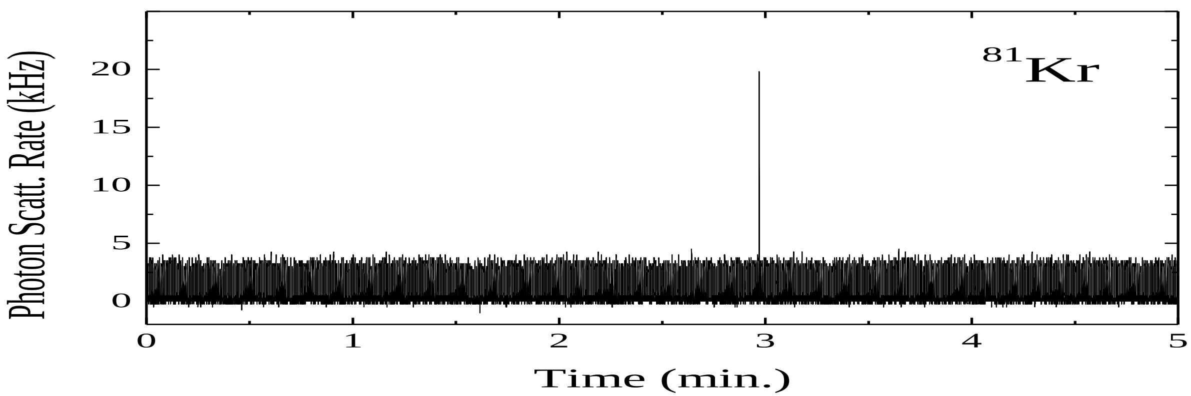
85	2 x10^{-11}	10.75 y
86	0.173	Stable

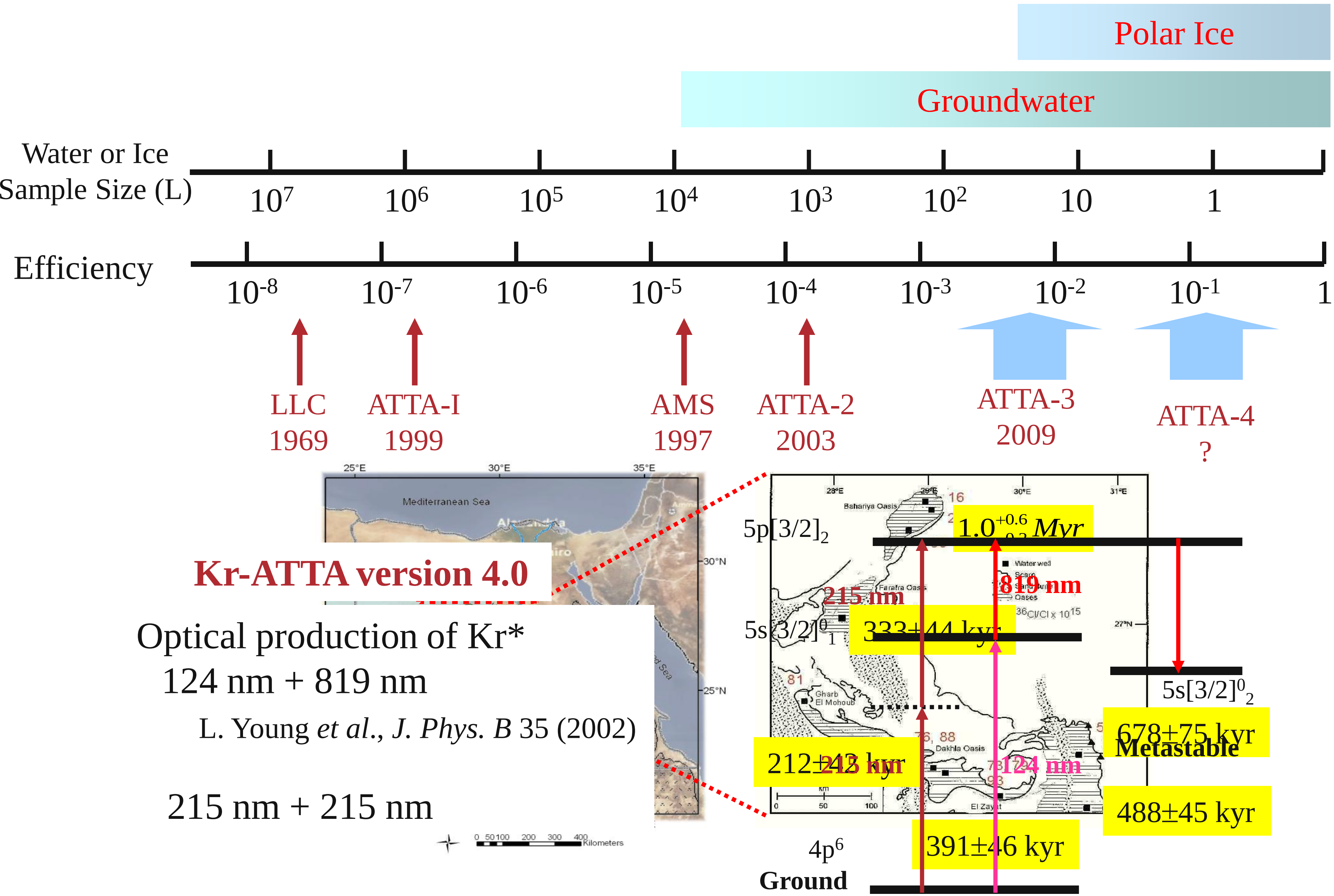
Single Atom Detection







^{81}Kr Dating



Polar Ice
Groundwater
Water or Ice
Sample Size (L)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Efficiency
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
1
LLC
1969
ATTA-I
1999
AMS
1997
ATTA-2
2003
ATTA-3
2009
ATTA-4
?
Kr-ATTA version 4.0
Optical production of Kr*
124 nm + 819 nm
L. Young et al., J. Phys. B 35 (2002)
215 nm + 215 nm
Mediterranean Sea
25°E
30°E
35°E
30°N
25°N
Kilometers
5p[3/2]2
5s[3/2]01
5s[3/2]02
Metastable
4p6
Ground
215 nm
819 nm
124 nm
Bahariya Oasis
Farafra Oasis
Dakhla Oasis
Gharb El Mohoub
El Zayat
Water well
28°E
30°E
31°E
27°N
333±44 kyr
212±43 kyr
391±46 kyr
678±75 kyr
488±45 kyr

Krypton vs Argon

Krypton

Isotope	Abundance	Half-Life
78	0.0035	2.3 x 10^{20}y
80	0.0225	Stable
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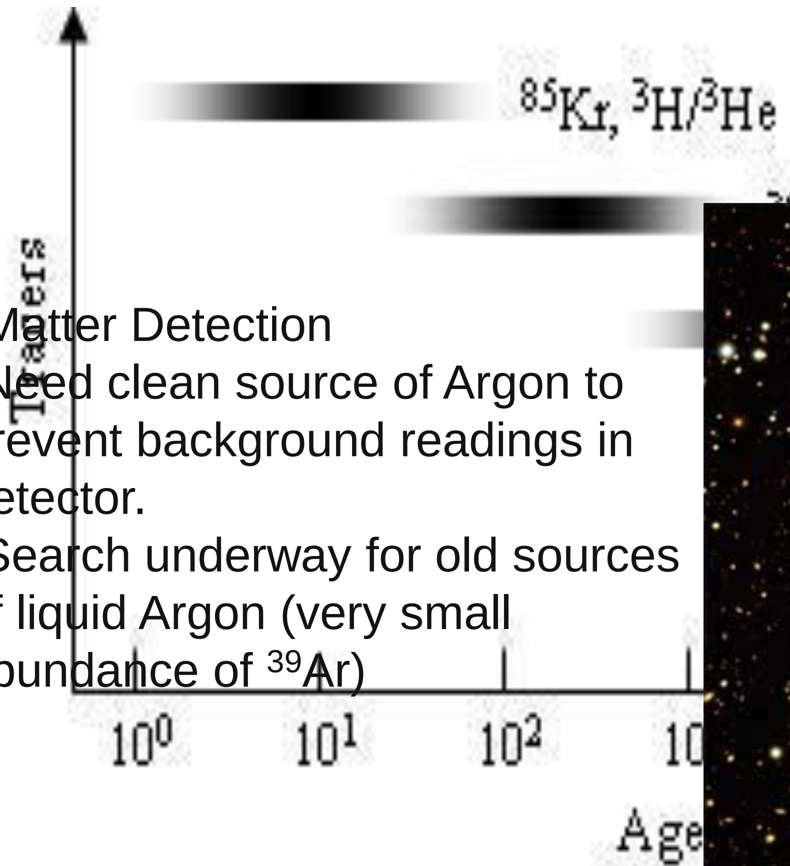
86	0.173	Stable

Argon

Isotope	Abundance	Half-Life
36	0.003336	Stable
38	0.000629	Stable
39	8 x 10^{-16}	269 y
40	0.996	Stable

We will now look for 1 atom in 10^{15} atoms all which look very similar

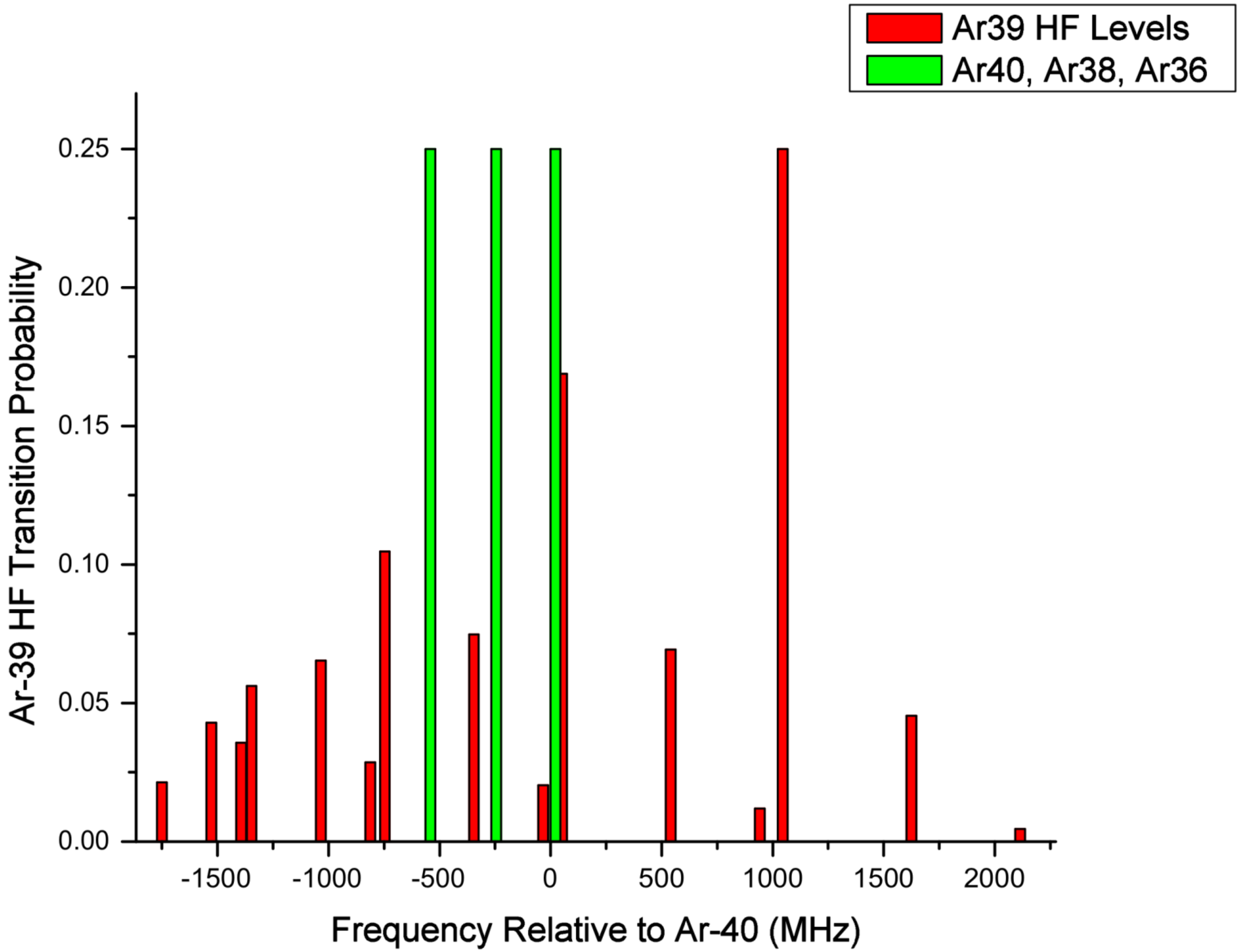
Why Argon?



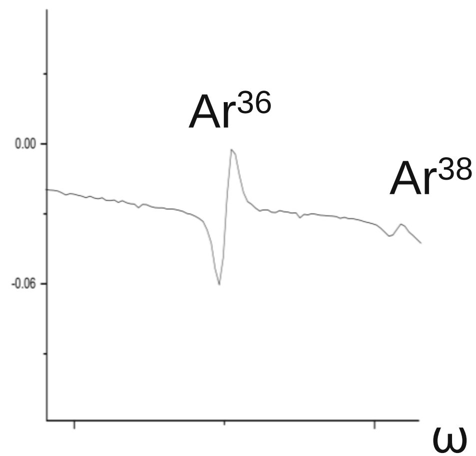
Dark Matter Detection

- Need clean source of Argon to prevent background readings in detector.
- Search underway for old sources of liquid Argon (very small abundance of ^{39}Ar)

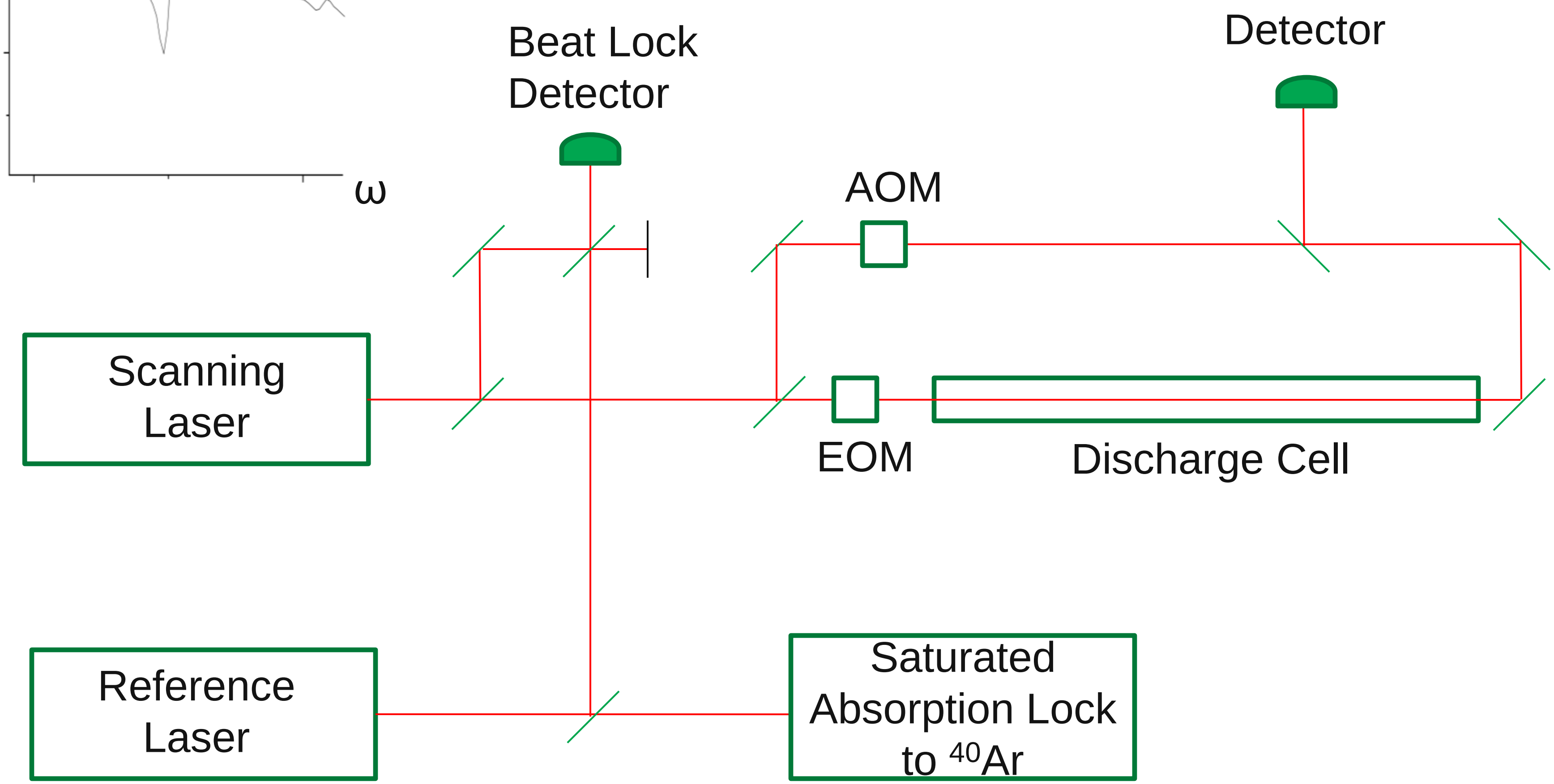
Argon Energy Levels



Argon Spectroscopy



Isotope	Abundance	Half-Life
38	0.000629	Stable
39 Enriched	~0.001	269 y

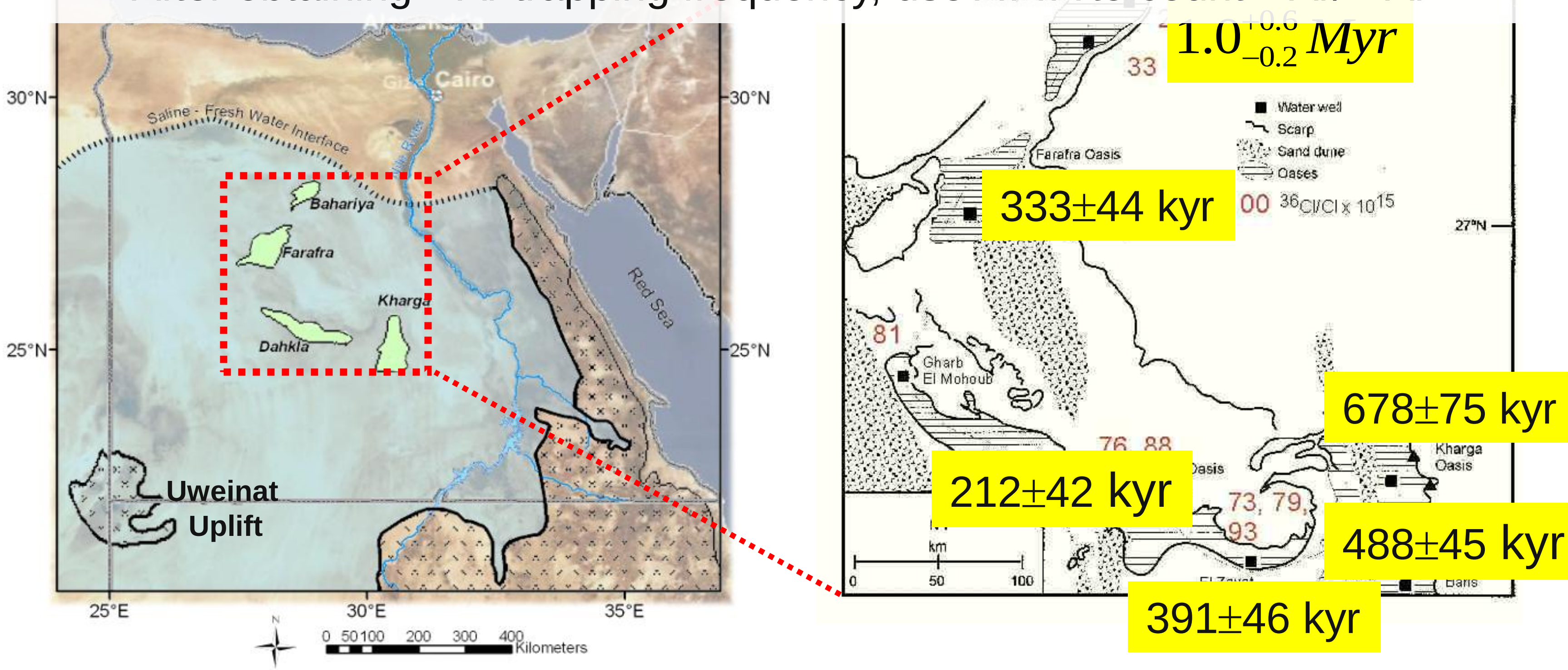


Summary

- We can successfully trap and detect single ^{81}Kr atoms with an efficiency of ~ 5×10^{-3}
- ATTA has been used to age underground water in the Sahara Desert

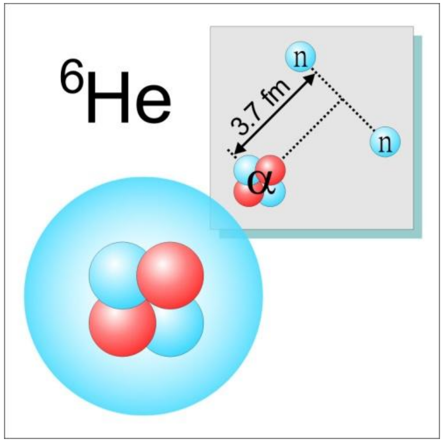
Future Direction:

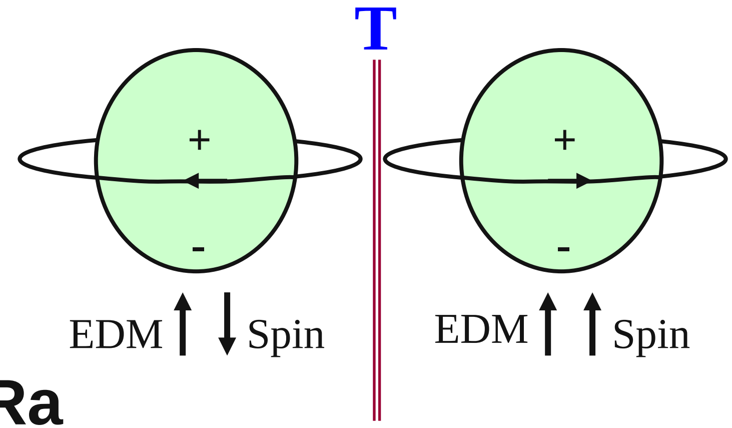
- Continue to improve efficiency by optimizing system
- Use optical fields to get to metastable state instead of discharge
- After obtaining ^{39}Ar trapping frequency, use ATTA to count $^{39}Ar/^{40}Ar$

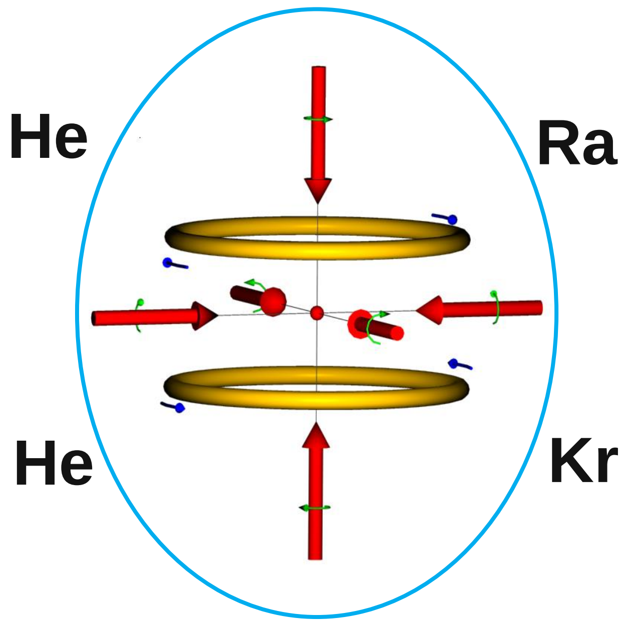


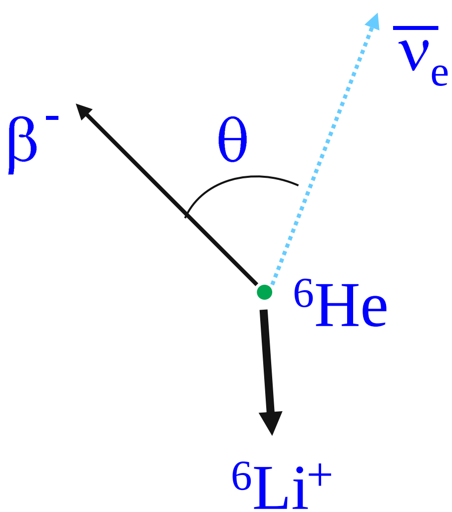
Sturchio *et al*., Geophys. Res. Lett. (2004)

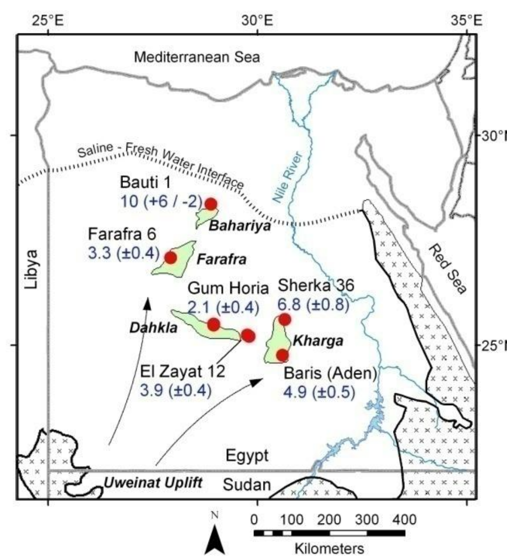
Atom traps @ Argonne



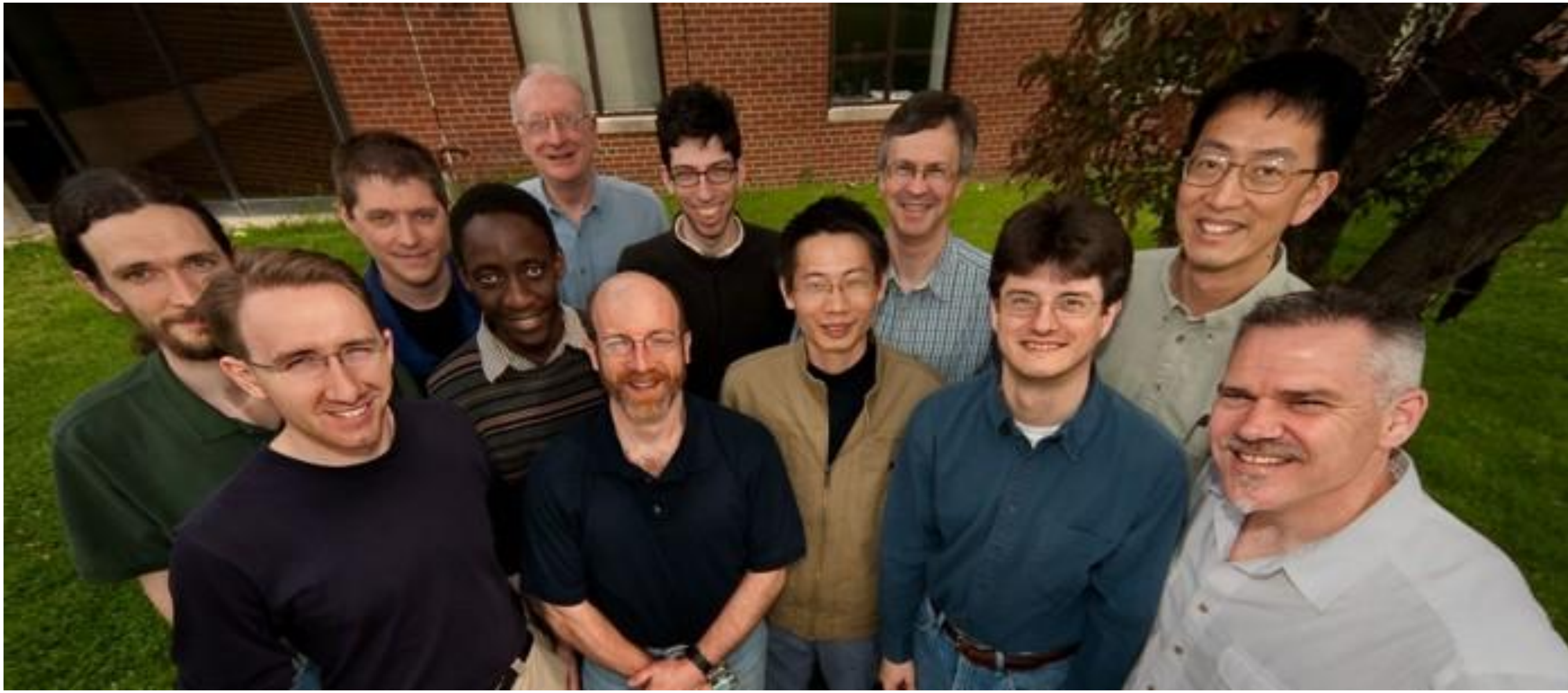








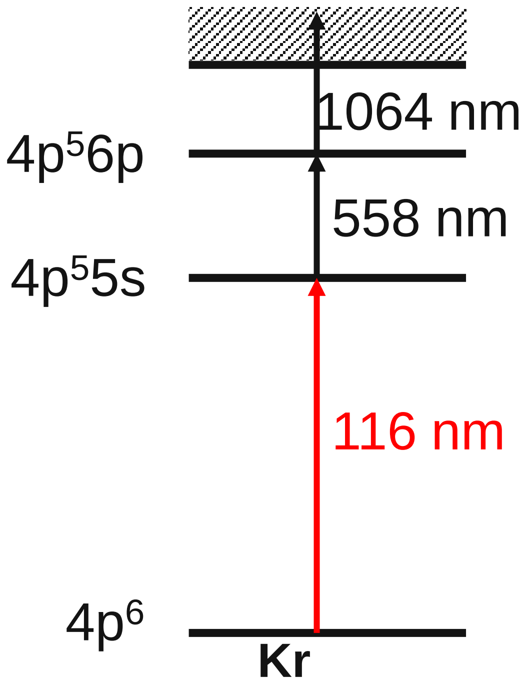
ATTA Group at Argonne National Lab

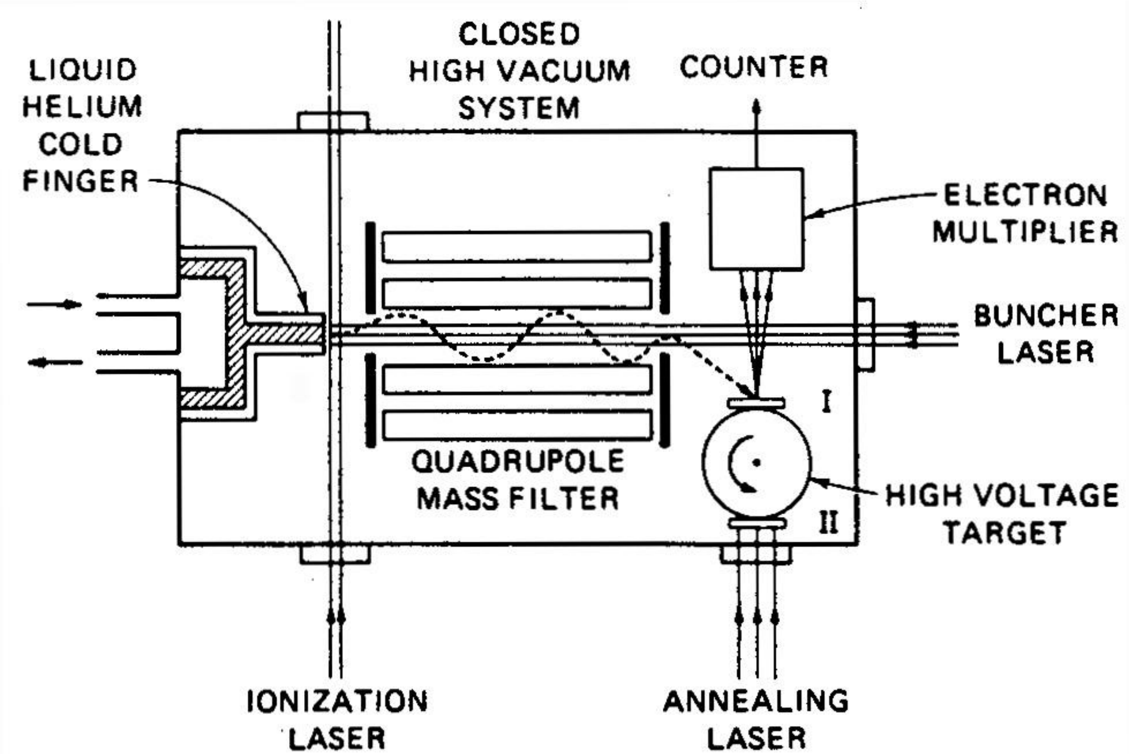


From left to right: William Trimble, Brent Graner, Will Williams, Ibrahim Sulai, Roy Holt, Kevin Bailey, Kenneth Rudinger, Bob Yu Sun, Wolfgang Korsch, Peter Mueller, Zheng-Tian Lu, Tom O'Connor

Resonance Ionization Spectroscopy (RIS)

V.S. Letokhov (Russia), G.S. Hurst (ORNL) 1970's



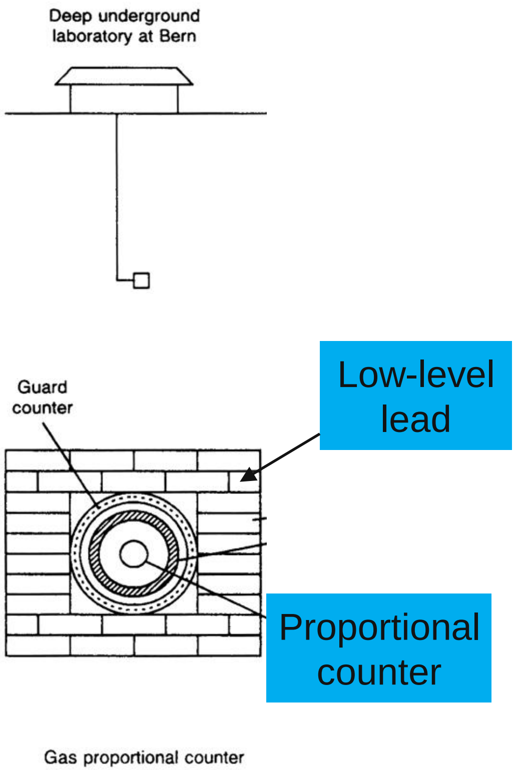


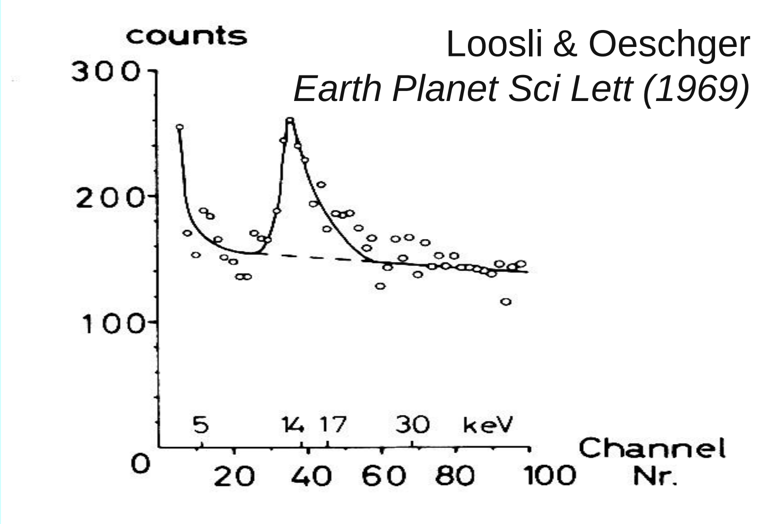
^{81}**Kr**: Efficiency: >50%

Isotope Selectivity: 10^3-10^4

S.D. Kramer *et al.*, Nucl. Instr. Meth. **B17**, 395(1986)

Low-Level Decay Counting (LLC)





X-ray @ 13.5 keV
2 liters of krypton, 100 hours

^{81}Kr (230 kyr) activity: 0.1 dpm/l Kr

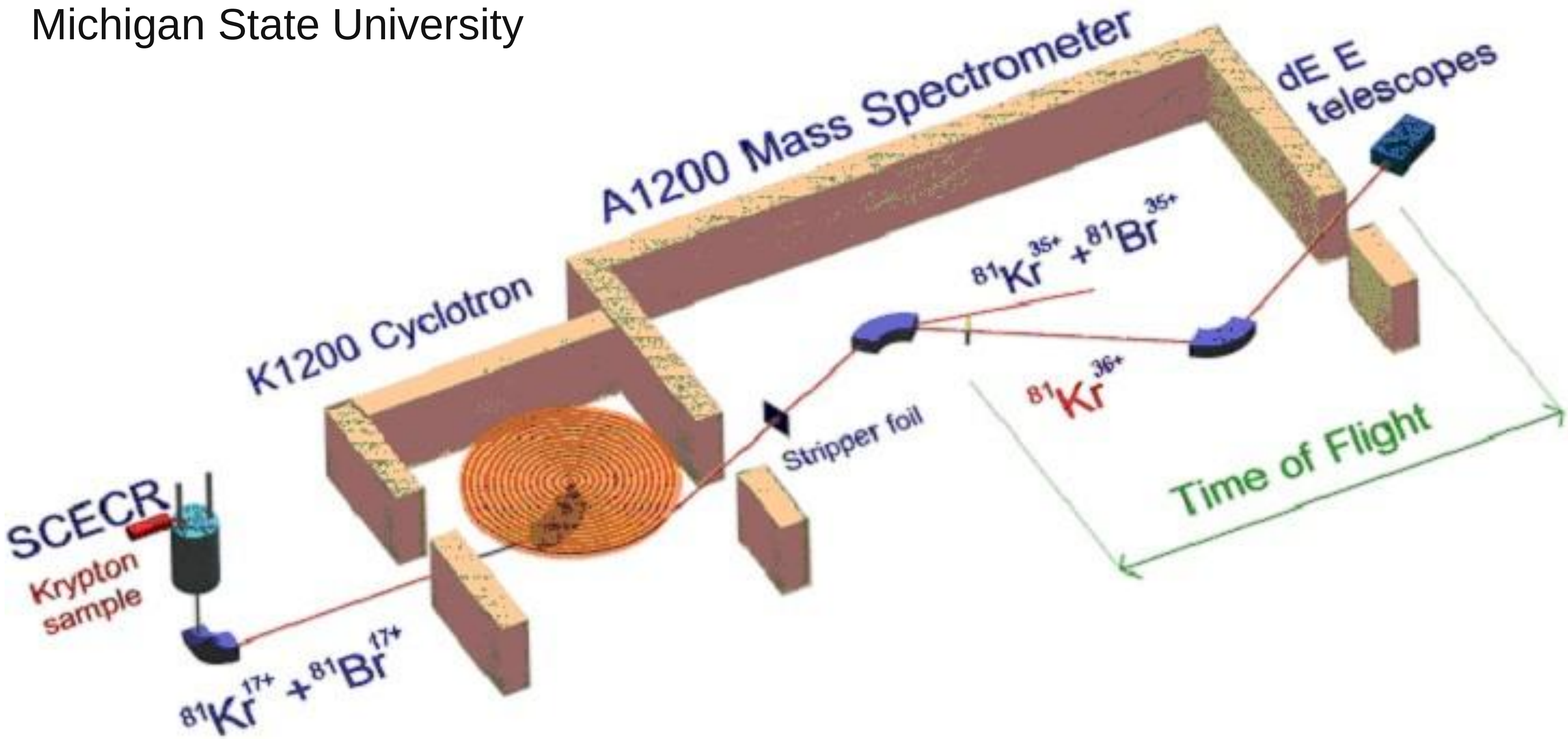
^{85}Kr (10.7 yr) activity: 3×10^4 dpm/l Kr

$$Efficiency = \frac{Count\ Time}{Lifetime} = \frac{100\ hr}{330\ kyr} = 3\times10^{-8}$$

Accelerator Mass Spectrometry of Kr-81

Full stripping at high energy (~ 4 GeV) for isobar separation: $^{81}Kr^{36+}$ vs. $^{81}Br^{3}$

National Superconducting Cyclotron Laboratory
Michigan State University



W. Kutschera *et al*., NIM B29, 241 (1994
P. Collon *et al*., NIM B123, 122 (1997)

Argon Levels (Theory)