Atom Trap, Krypton-81, and Saharan Water

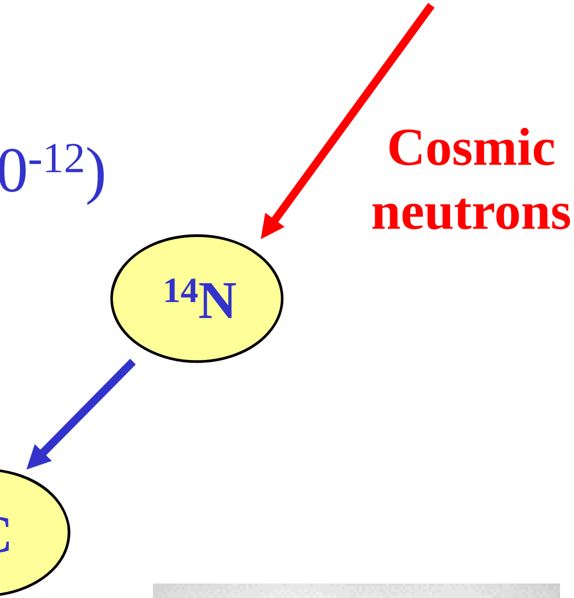
- ^{81}Kr dating
- Earlier Methods
- Atom Trap Trace Analysis (ATTA)
- Nubian Aquifer, Egypt

Supported by
DOE, Office of Nuclear Physics
NSF, Division of Earth Sciences

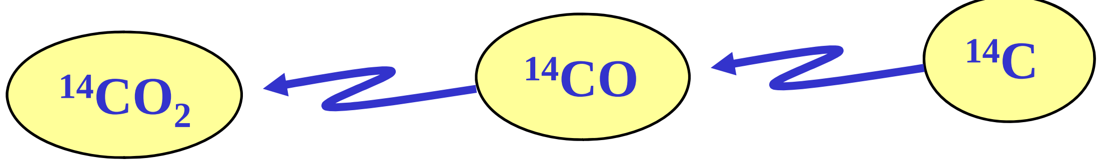
Western Desert, Egypt

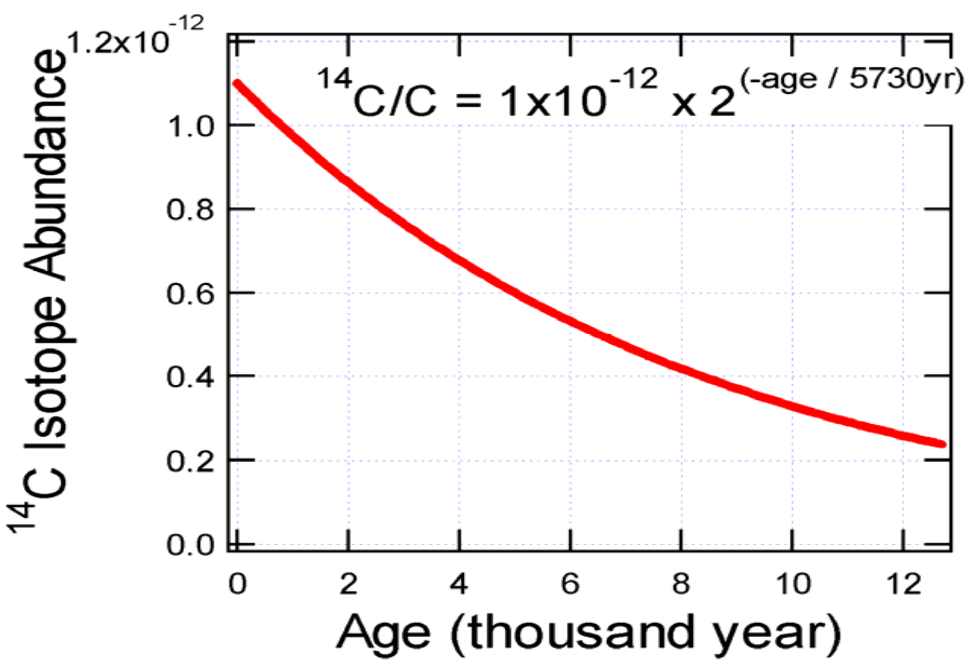
Radio-Carbon Dating

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



- Widely applied
- Limited to 50 kyr or younger

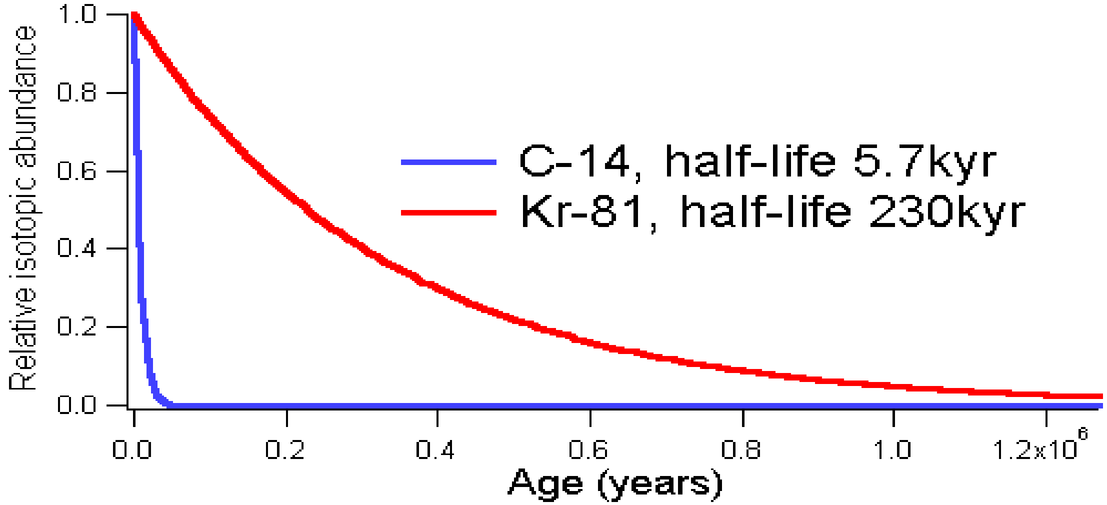


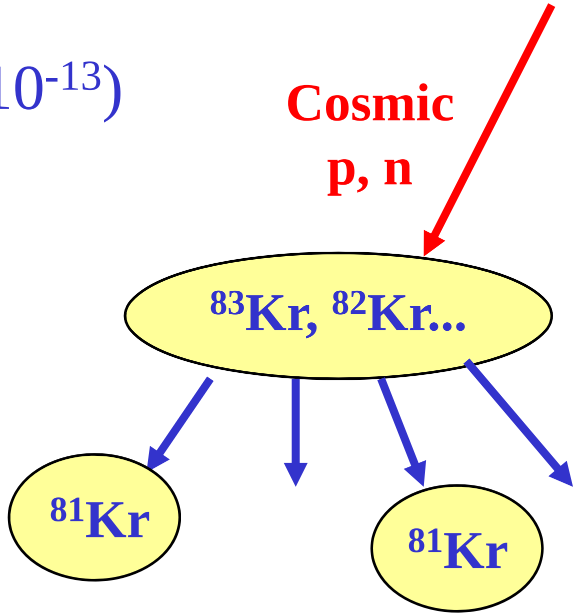


Willard Frank Libby
University of Chicago
1960 Nobel Prize in Chemistry
Arnold & Libby, Science (1949)

Radio-Krypton Dating

^{81}Kr ($t_{1/2}$ = 230kyr, I.A.= 6×10^{-13})



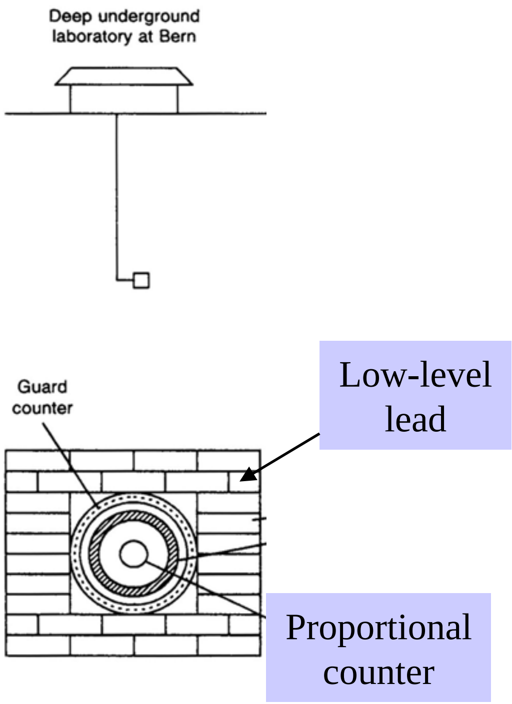


- Polar Ice as a natural archive
  - temperature
  - precipitation
  - gas composition
  - volcanic eruption
  - solar variability...

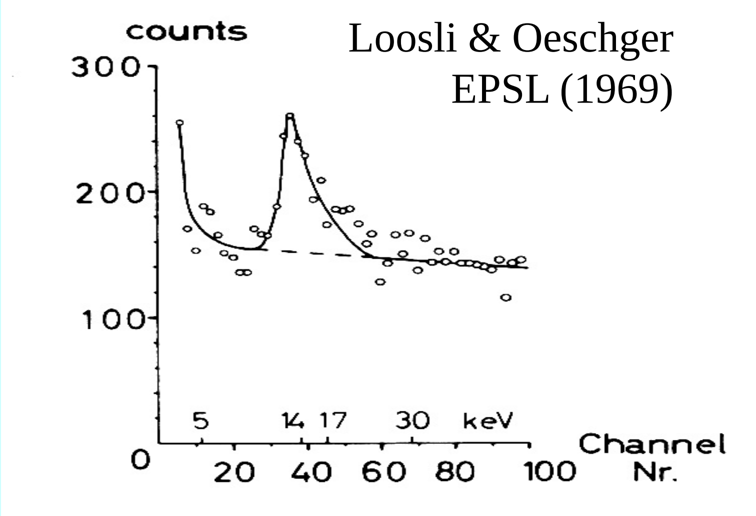
- Number of ^{81}Kr atoms in 1 liter of :

  Air → 20,000
  Water → 1,000
  Ice → 1,000

Low-Level Decay Counting (LLC)



Gas proportional counter



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

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

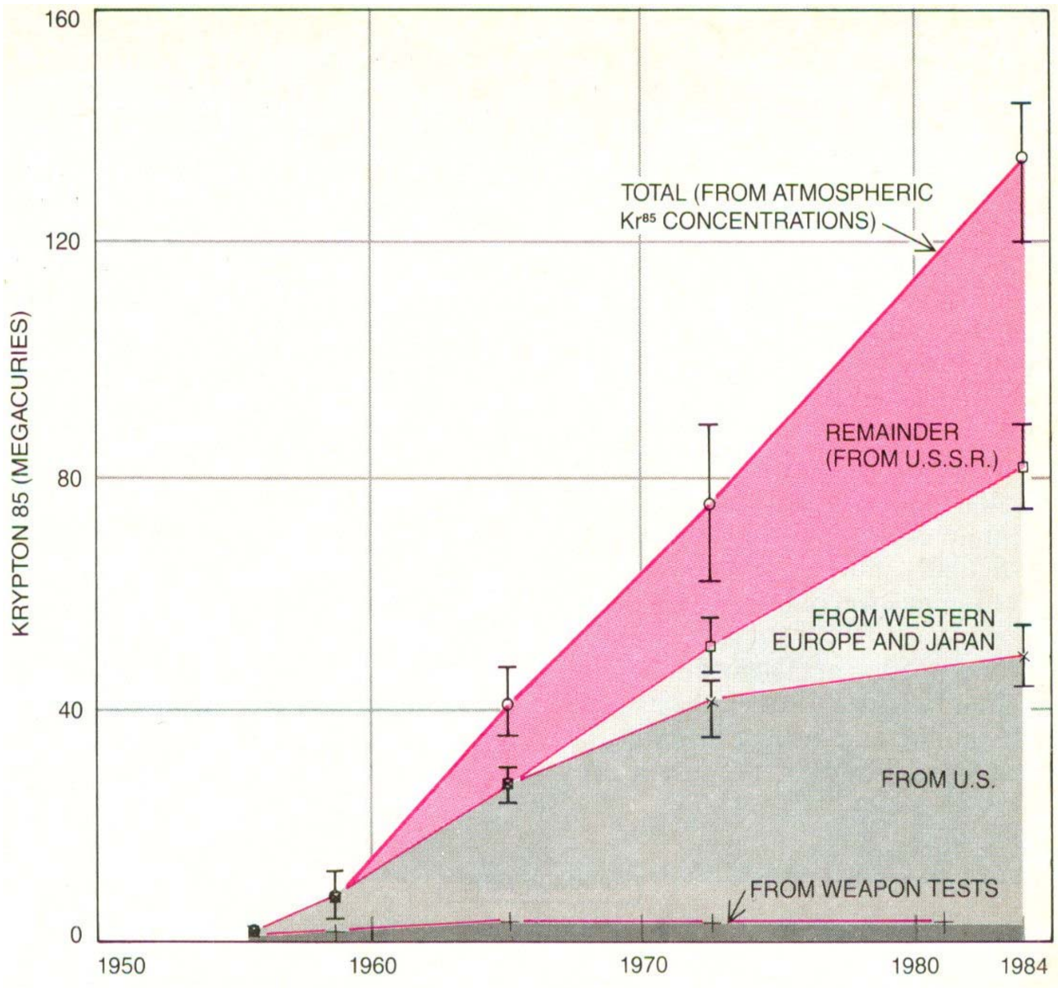
^{85}Kr (10.7 yr) activity: 3×10^{4} dpm/l Kr

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

^{85}Kr in the Atmosphere

($t_{1/2}$ = 11 yr, I.A.= 1×10^{-11})

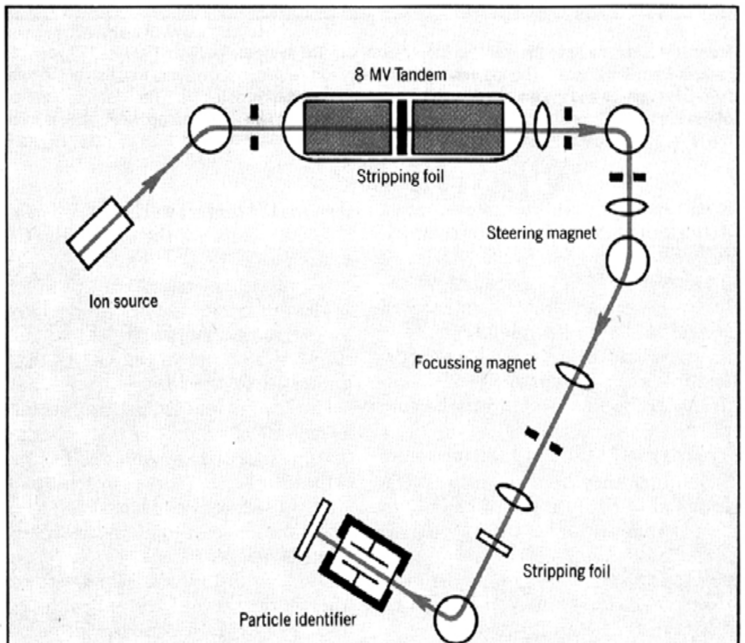
- **Nuclear non-proliferation** – Monitor fuel re-processing activities;
- **Nuclear safety** – Monitor leaks from nuclear fuel containers.



Von Hippel, Albright, Levi
Sci. Am. (Sept., 1985)

Accelerator Mass Spectrometry (AMS)

Science (1977): R.A. Muller / Nelson *et al*. / Bennett *et al.*



R.A. Muller, Physics Today

Charge and mass measurements

- Particle identification based on energy loss
- Stripping eliminates molecular isobars
- Negative ion tricks eliminates atomic isobars

$^{14}N^-$ vs. $^{14}C^-$

Advantages of atom counting:

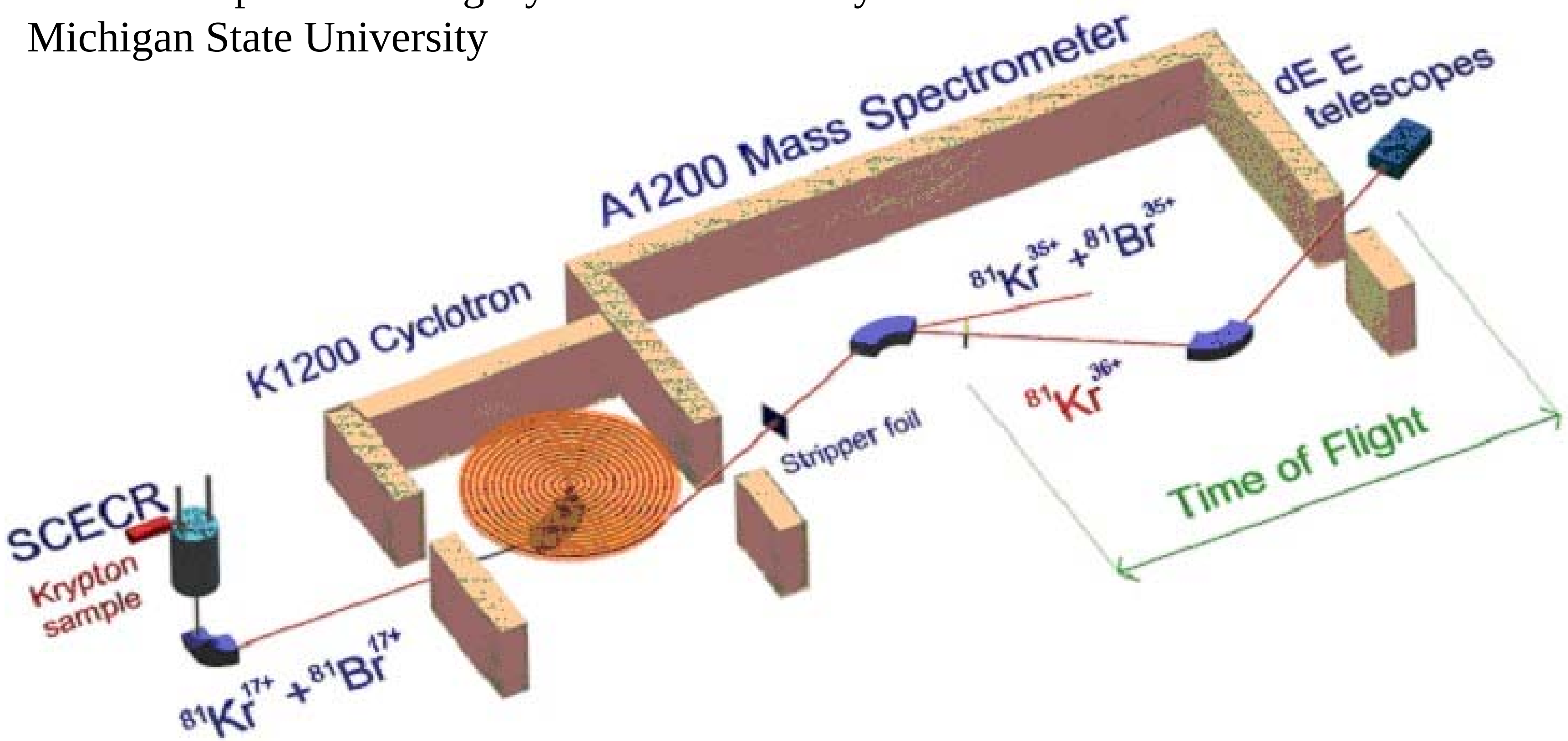
- Fast, Sensitive; AMS / LLC = 10^5 (^{14}C)
- Not bothered by decay background

Accelerator Mass Spectrometry of Kr-81

Kutschera *et al*., NIM B (1994); Collon *et al*., NIM B (1997)

Full stripping at high energy (~ 4 GeV) for isobar separation: $^{81}Kr^{36+}$ vs. $^{81}Br^{35+}$.

National Superconducting Cyclotron Laboratory
Michigan State University

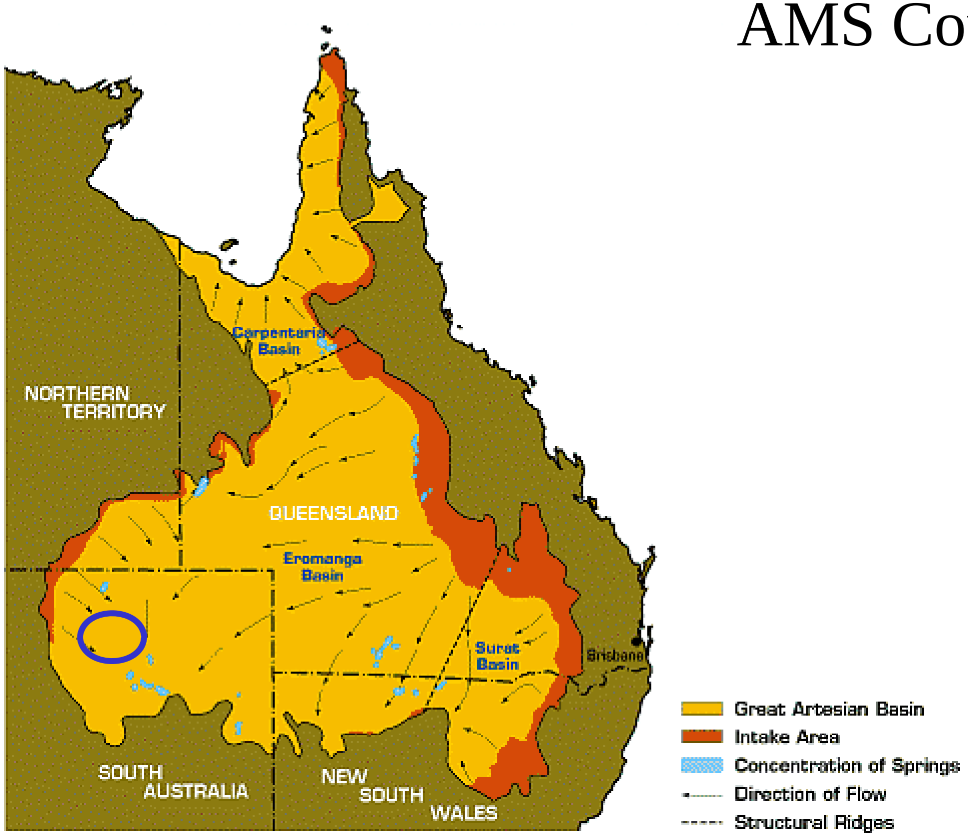


First ^{81}Kr-Dating of Old Groundwater

P. Collon *et al*., Earth Planet Sci. Lett. **182**, 103 (2000)

16,000 liters of water → (Chemitry) → 0.5 ccSTP Kr ~ 2×10^6 ^{81}Kr → (AMS) → 56 ^{81}Kr counts in 9 hours

AMS Counting Efficiency ~ 3×10^{-5}

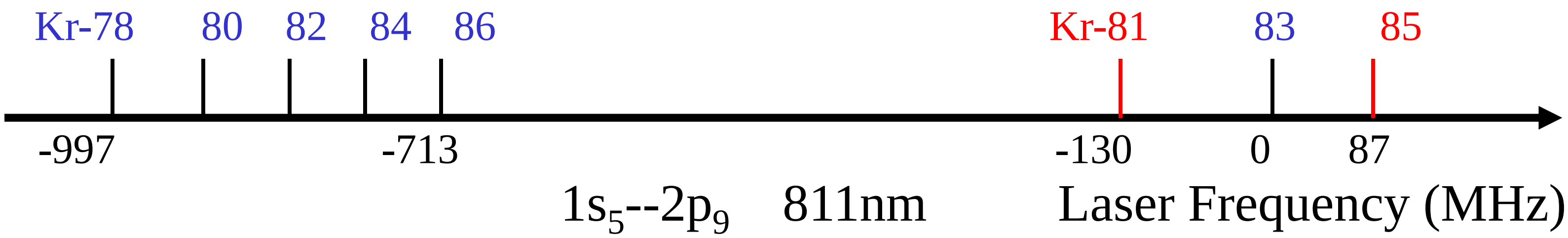


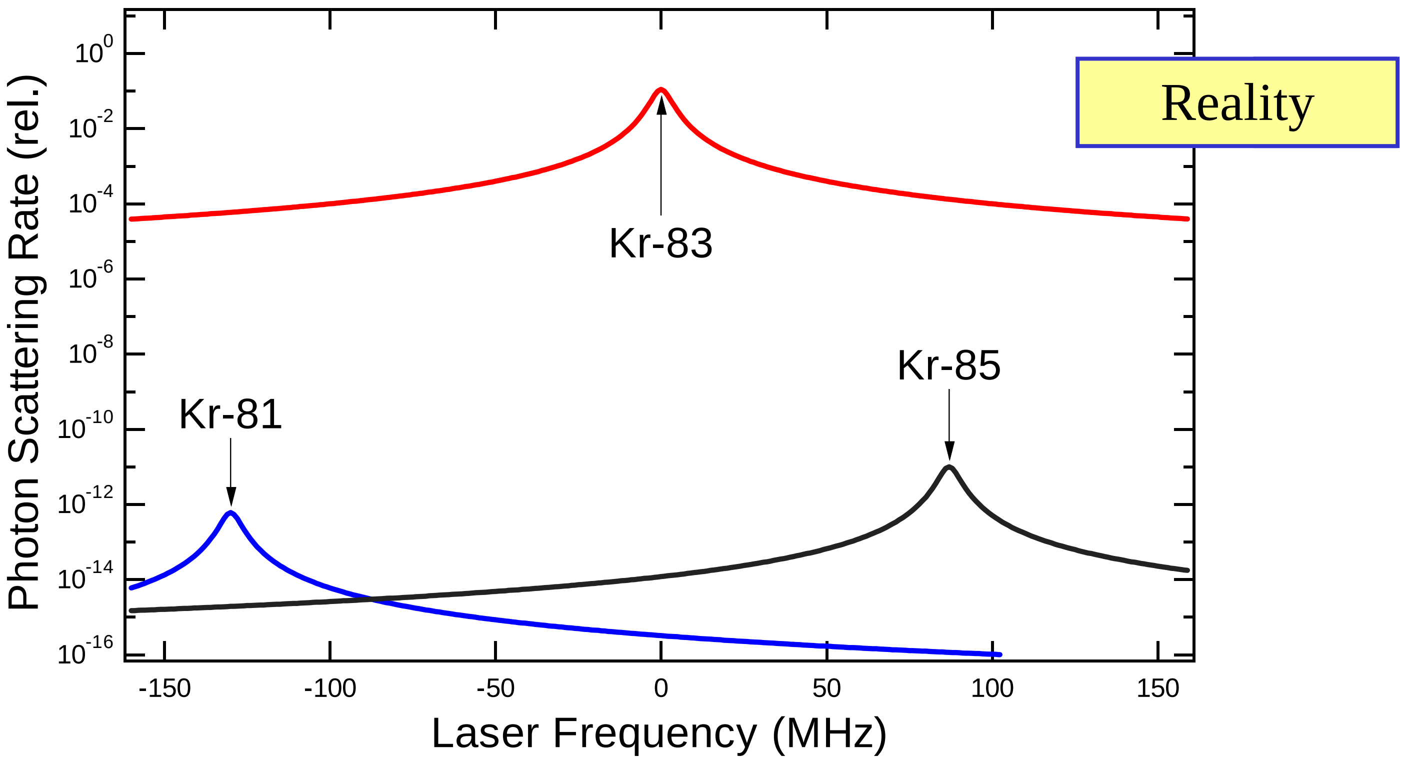
The Great Artesian Basin

Watson Creek	$(4.02 \pm 0.51) \times 10^5$ yr
Oodnadatta	$(3.54 \pm 0.50) \times 10^5$ yr
Duck Hole	$(2.87 \pm 0.38) \times 10^5$ yr
Raspberry Creek	$(2.25 \pm 0.42) \times 10^5$ yr

Laser Methods Based on Isotope Shifts

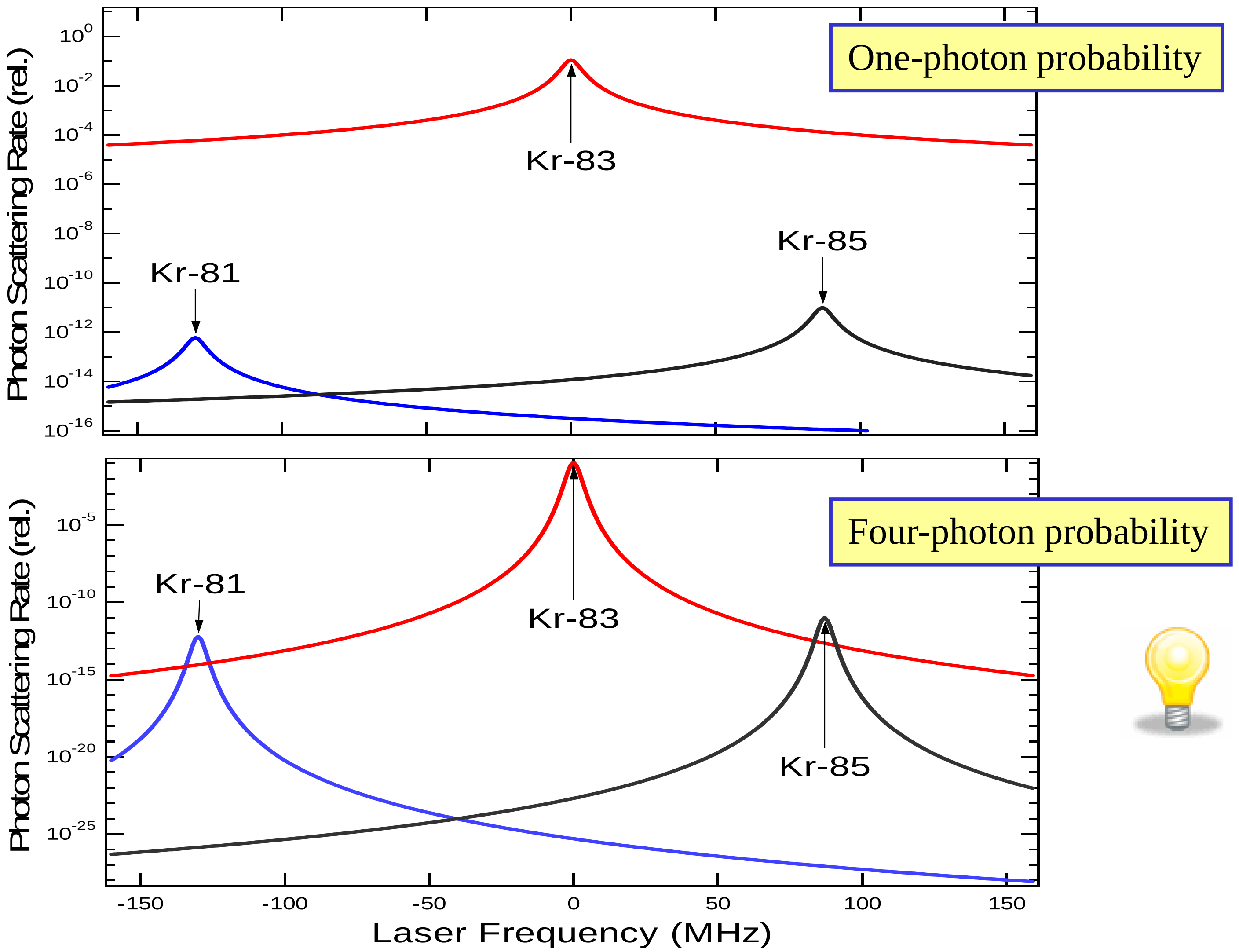
Isotope shift due to the change in nuclear mass, charge radii and moments



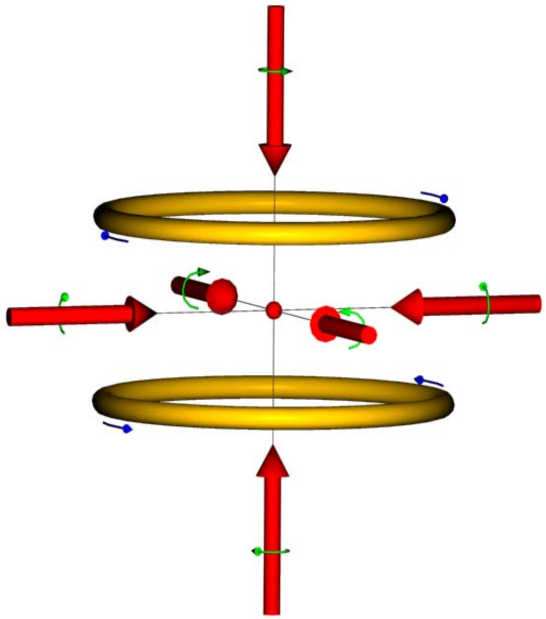


Photon Burst Spectroscopy

Greenlees *et al*., Opt. Commun. (1977);   Balykin *et al*., JETP Lett. (1977)



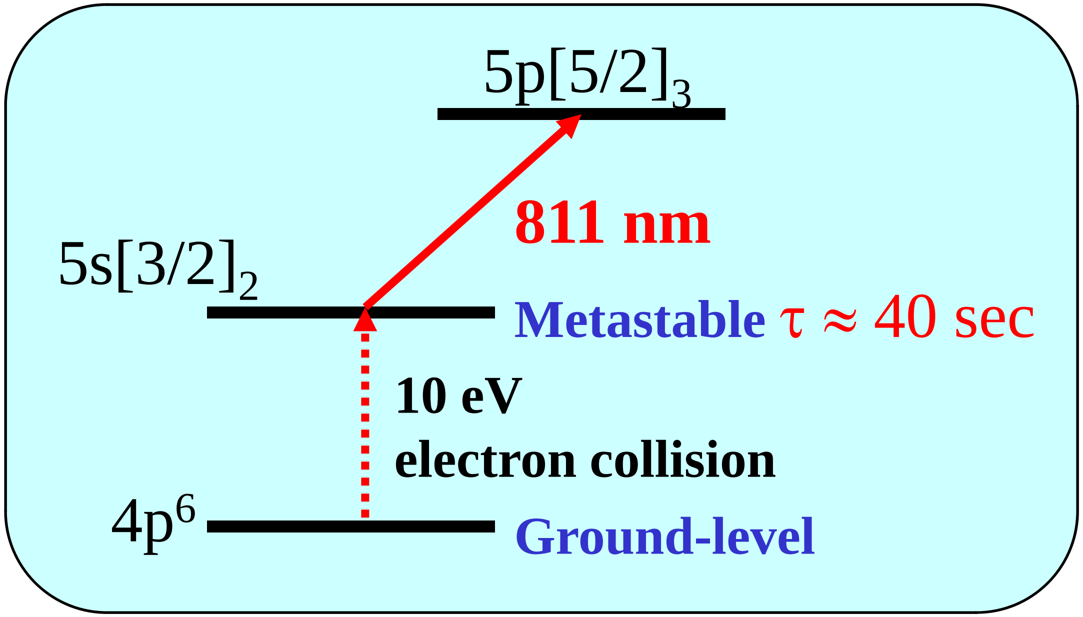
Magneto-Optical Trap (MOT)

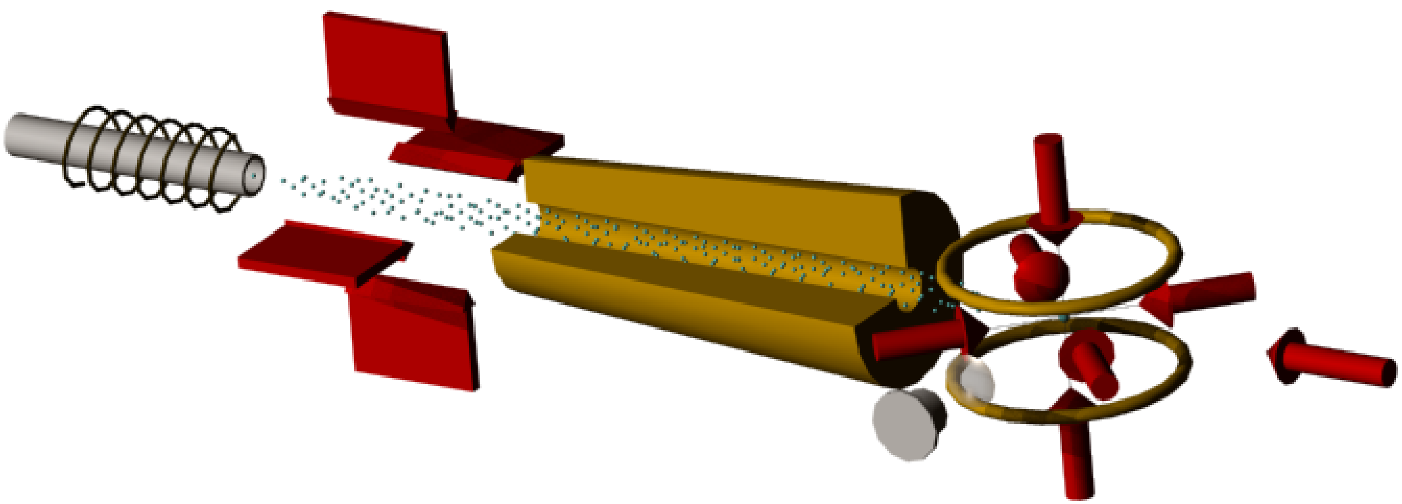


MOT Advantages

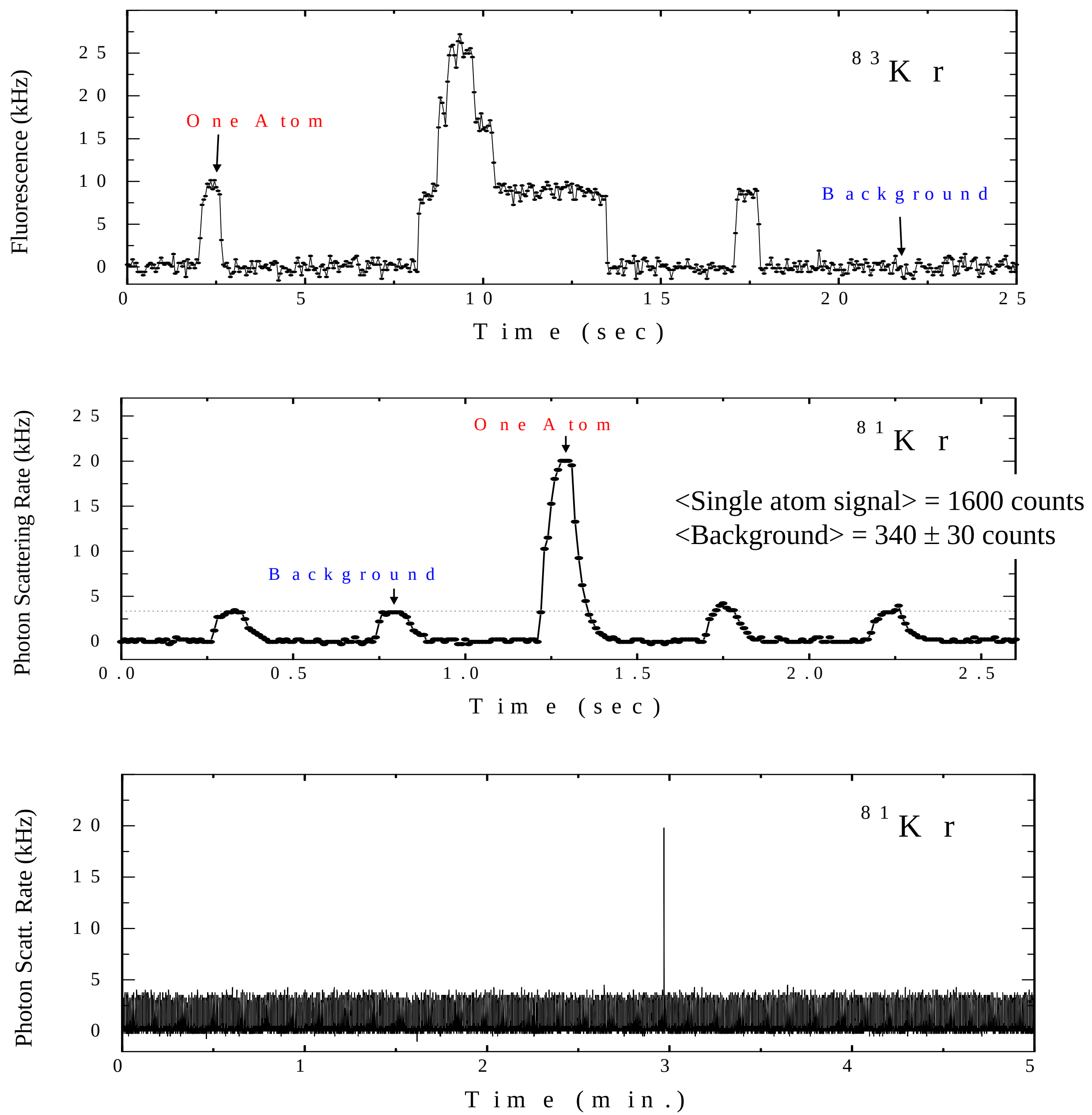
- Long observation time -- 100 ms;
- High capture rate -- 10^9-10^{12} s^{-1};
- Narrow linewidth -- Doppler broadening negligible;
- Spatial confinement -- trap size < 1 mm;
- Storage -- separation of loading and detection.

Krypton Atom Level Diagram

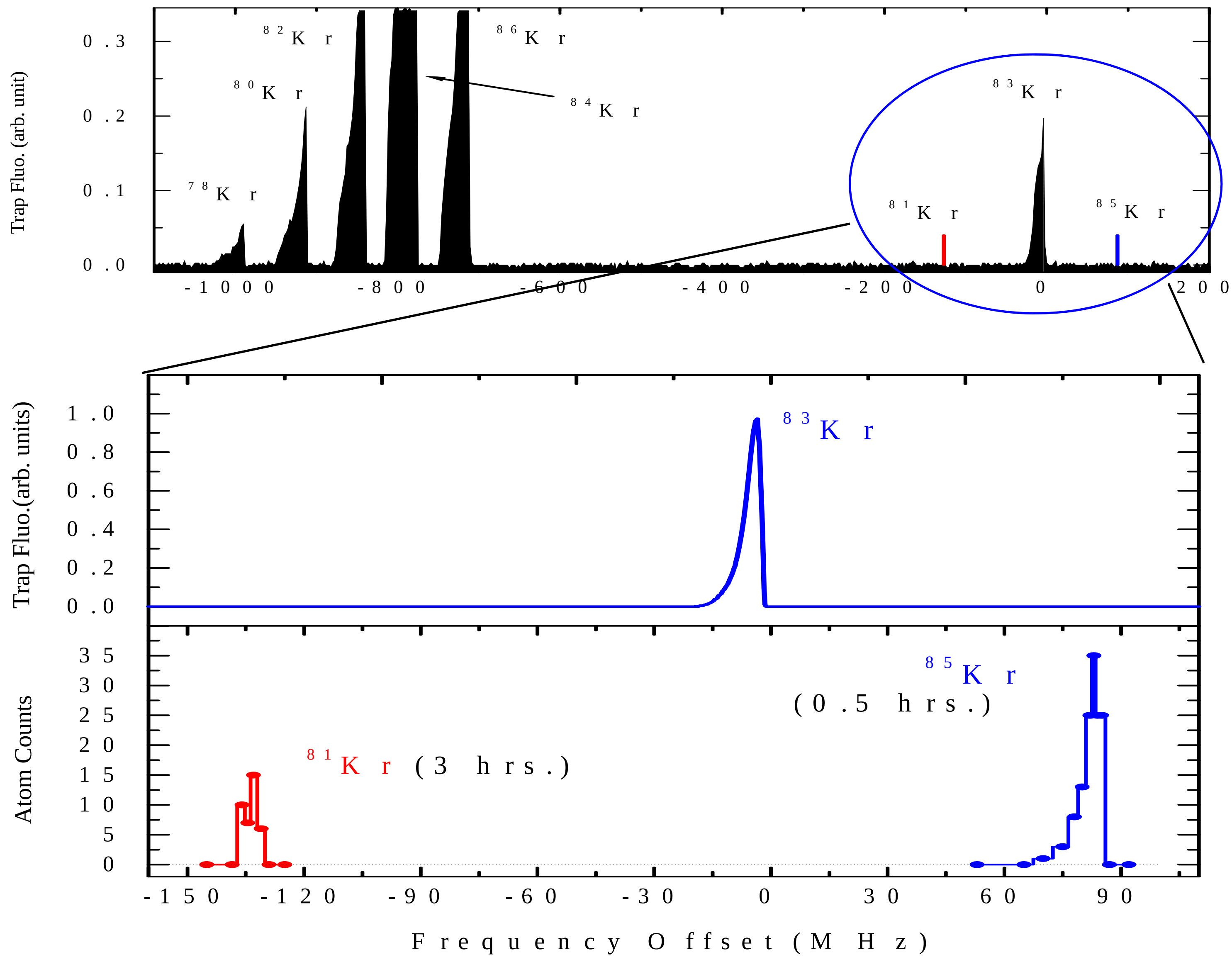




Single Atom Detection

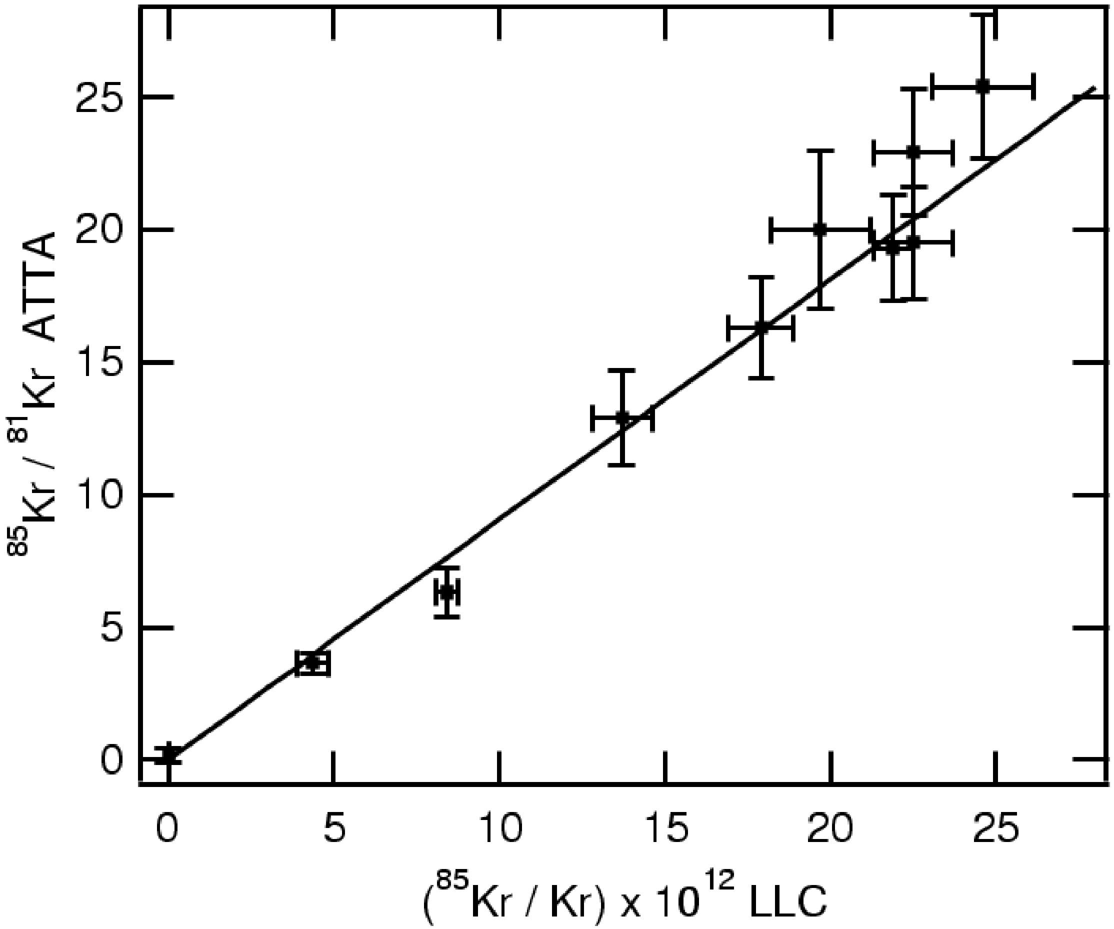


Counting ^{81}Kr and ^{85}Kr



Calibration: ATTA vs. Low-Level Counting

Du *et al.*, Geophys. Res. Lett. (2003)
ATTA at Argonne, LLC at Bern



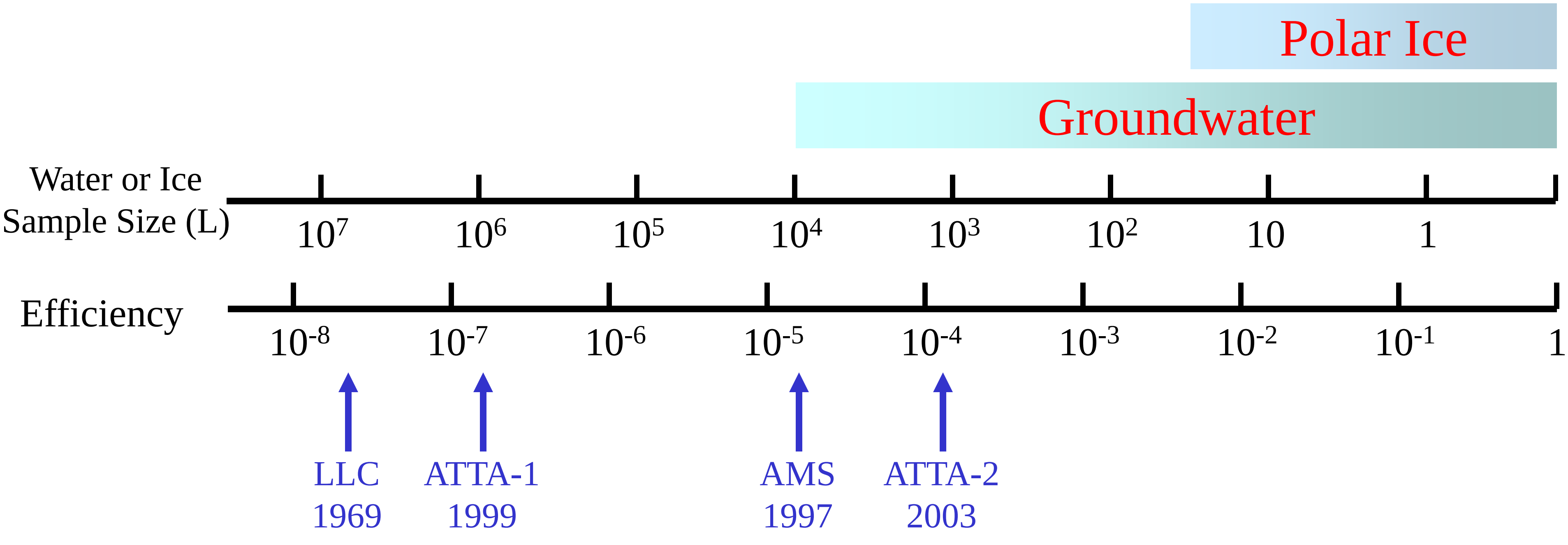
Atom Trap Trace Analysis (ATTA)

ATTA-1: *Chen et al., Science (1999)*

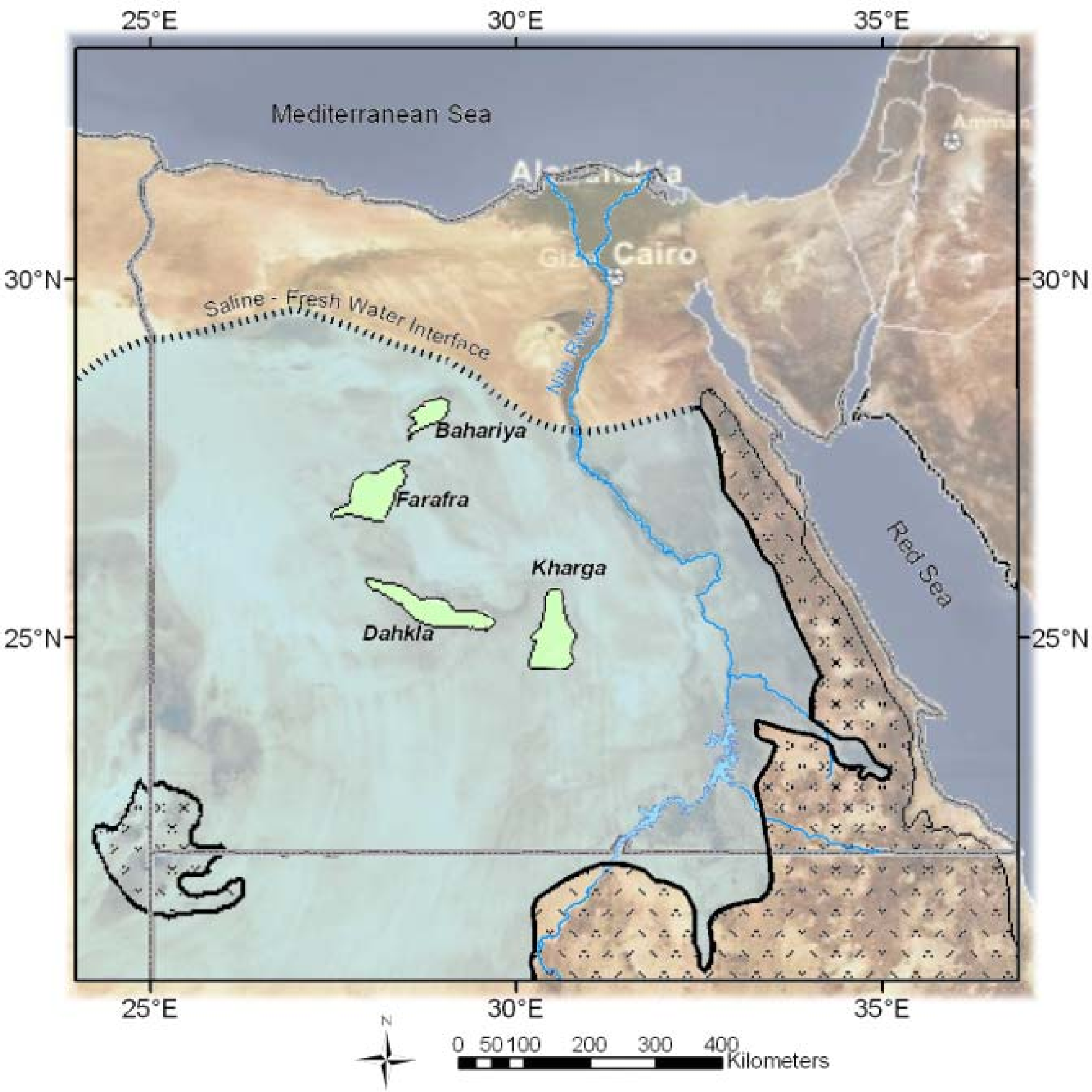
ATTA-2: *Du et al., Geophys. Res. Lett. (2003)*

Present Status of ATTA-2:

- Selectivity requirement: Done;
- Efficiency requirements: Practical, but far from perfection.

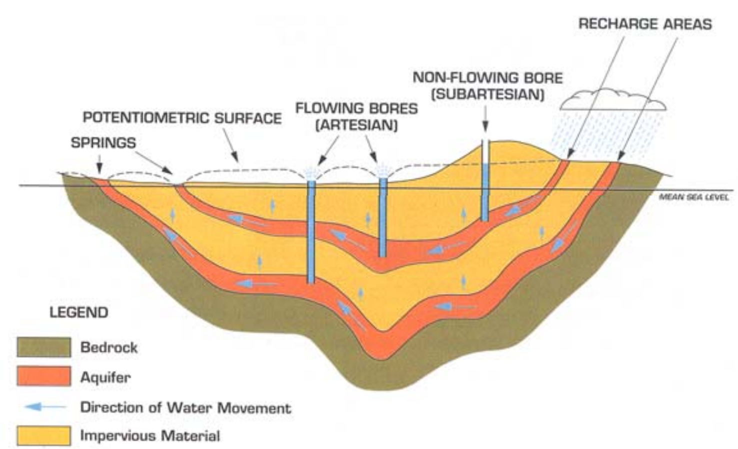


First Applications: Nubian Aquifer, Egypt



Nubian Aquifer

- Area ~ 2 x 10^6 km^2
- Volume ~ 5 x 10^4 km^3
- 500 years of Nile discharge
- Age ~ 10^5 years

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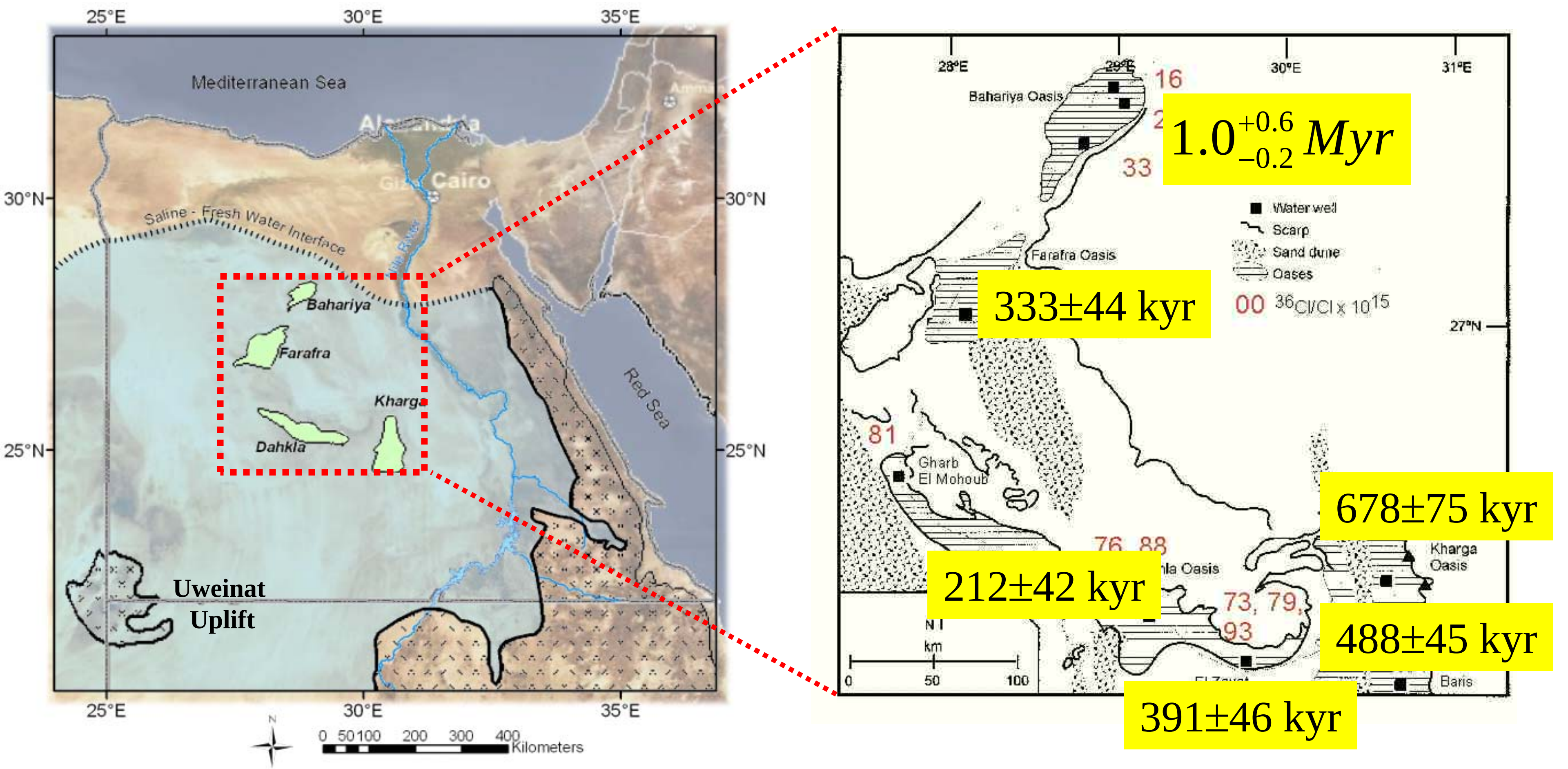
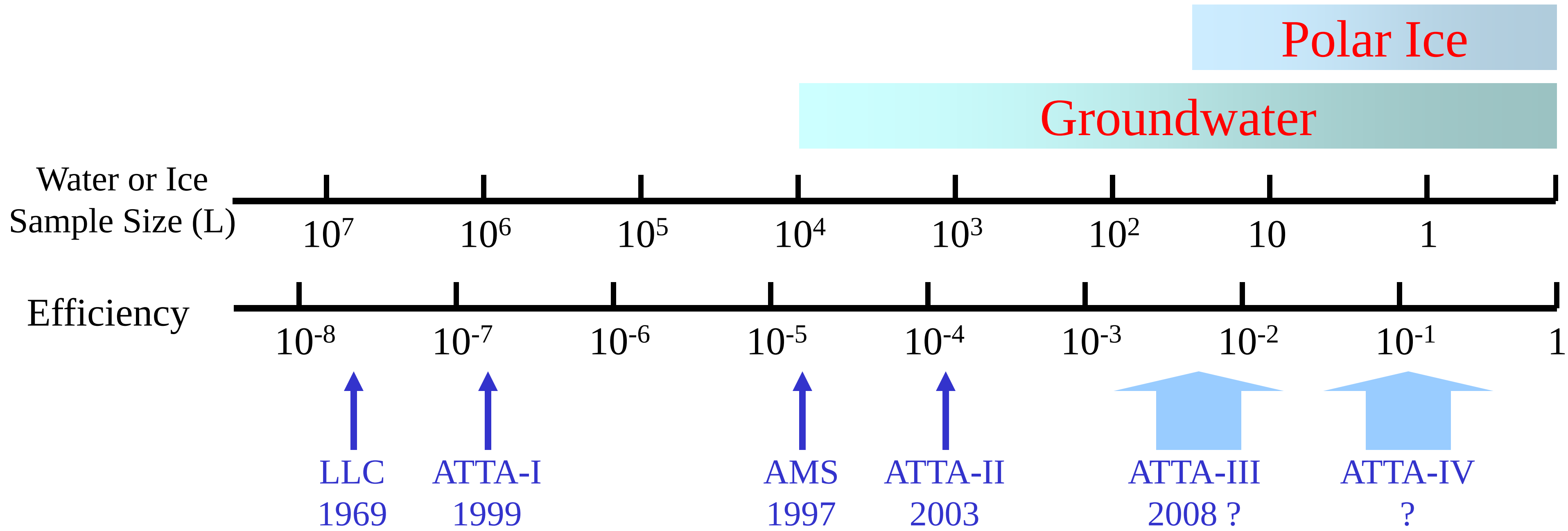
One Million Years of Nubian Aquifer Groundwater History

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

- Groundwater at six sites dated;
- Flow direction and speed measured;
- Source determined.



^{81}Kr Dating: From Dream to Practice



Kr-ATTA version 4.0

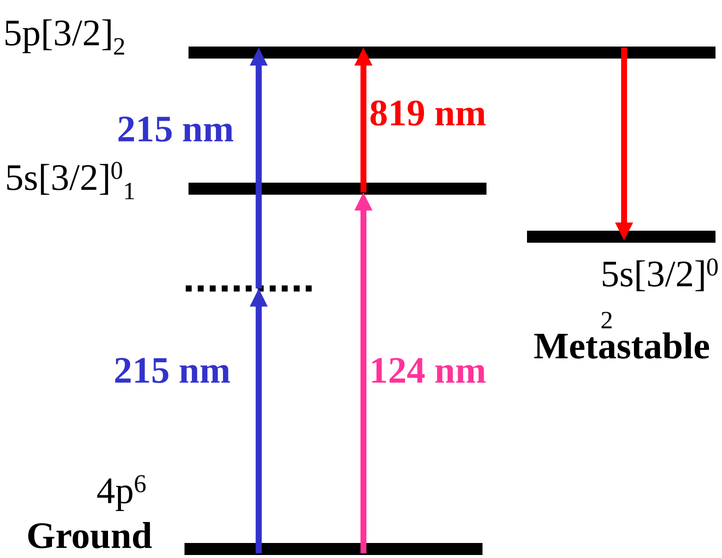
Optical production of Kr*

124 nm + 819 nm

Young *et al.*, *J. Phys. B* (2002)

215 nm + 215 nm

Wendt *et al.*



Argonne Atom Trapper

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