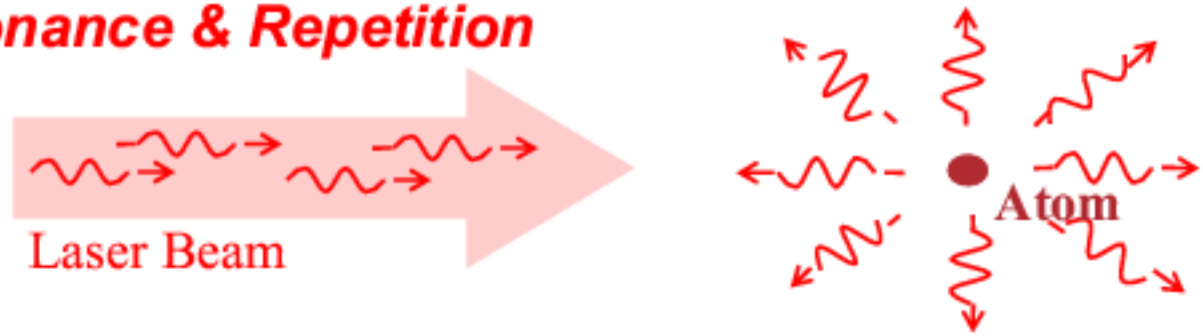
Spontaneous Scattering Light Force
Resonance & Repetition



Krypton Atom:

$1s_5$ -- $2p_9$ wavelength = 811 nm

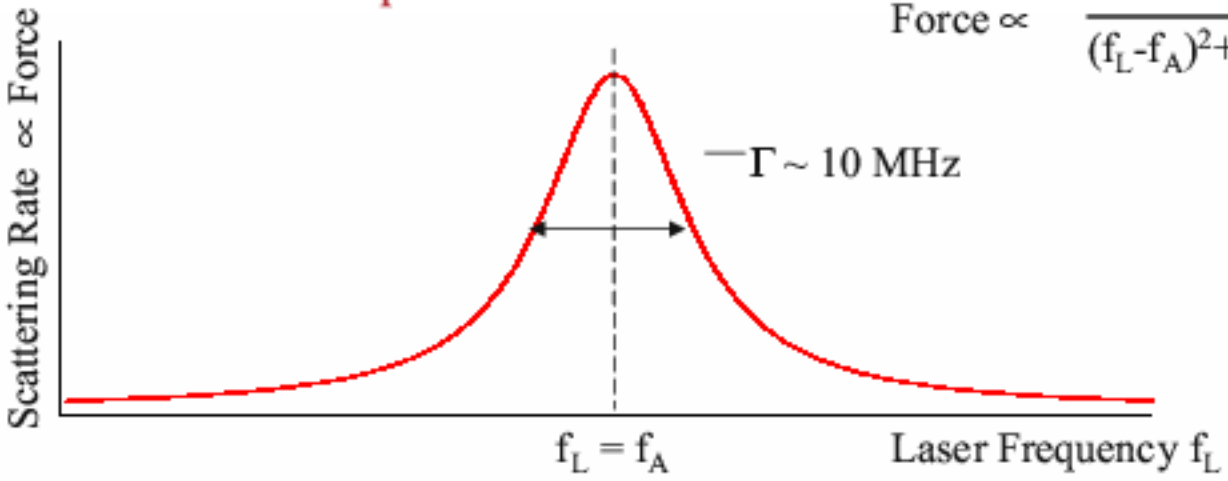
Transition rate ~ 1 x 10^7 /sec

Single photon kick δv = 6 mm/sec

Acceleration ~ 6 x 10^4 m/sec^2

Resonance Requirement

$$\text{Force} \propto \frac{1}{(f_L - f_A)^2 + (\Gamma/2)^2}$$



Trapping

F = -kx

Magnetic Field B(x)

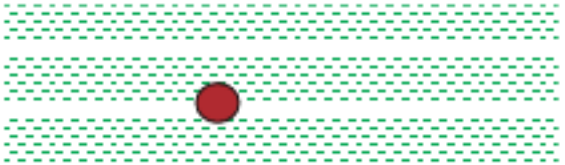
↓

$f_A(x)$

Zeeman Shift

Cooling

F = -av



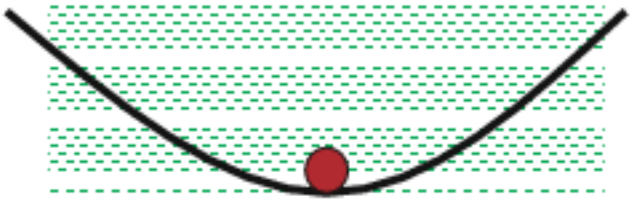
Atom Velocity

↓

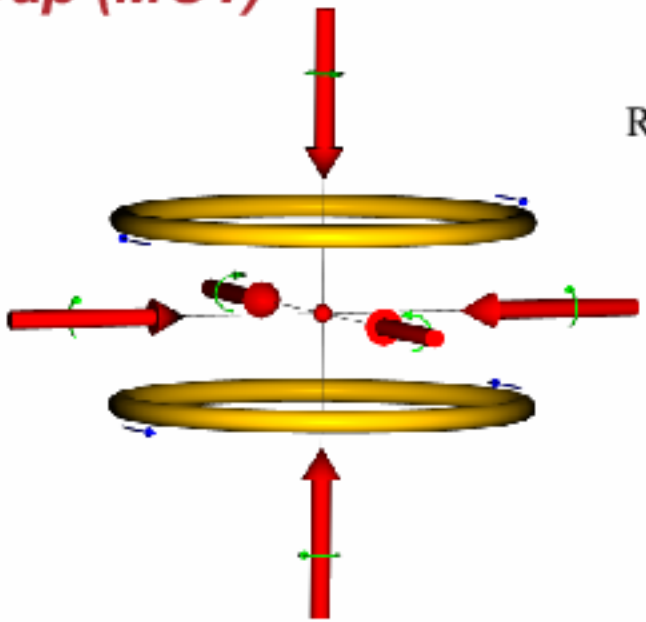
$f_L(v)$

Doppler Shift

A Trap with Cooling



Magneto-Optical Trap (MOT)



Raab et al., Bell Lab & MIT, 1987

Ingredients:

Laser beams --- alignment, frequency, polarization;
Quadrupole B-field --- 20 G/cm, anti-Helmholtz;
Ultra-high vacuum --- $\tau_{trap} \sim 1$ sec @ 1×10^{-8} Torr.

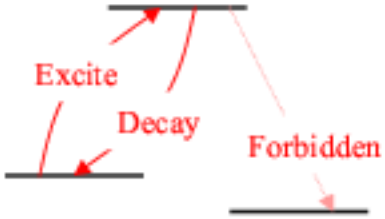
Typical Parameters:

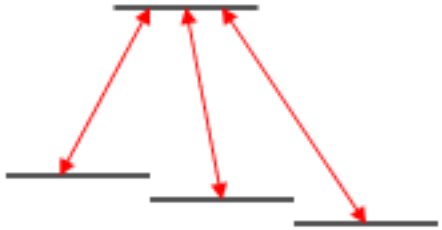
Number --- 10^{10};
Density --- 10^{8} mm^{-3} (optically thick);
Temperature --- ~ 0.1 mK, ~ 0.1 m/sec;
Capture speed --- ~ 10 m/sec.

Trappable Atoms

Transition Requirements:

- Cycling transition
- High transition rate (10^7 sec^{-1}, allowed E1)
- Practical wavelength ($\lambda > 200$ nm)

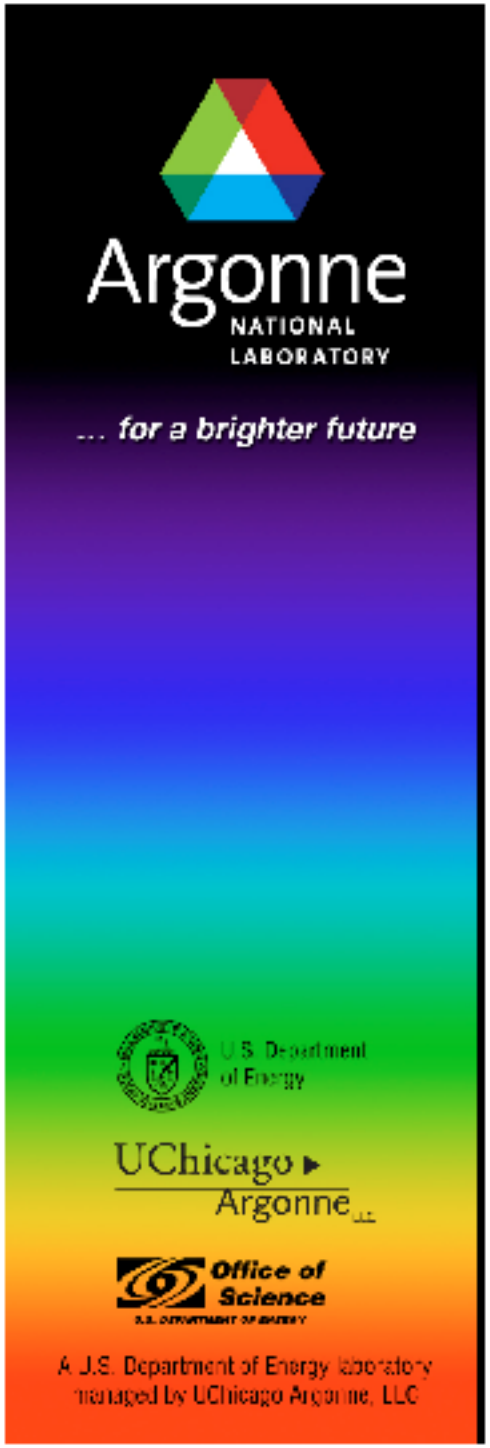




1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	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	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub		114 Uuq		116 Uuh		118 Uuo

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
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

Trap demonstrated

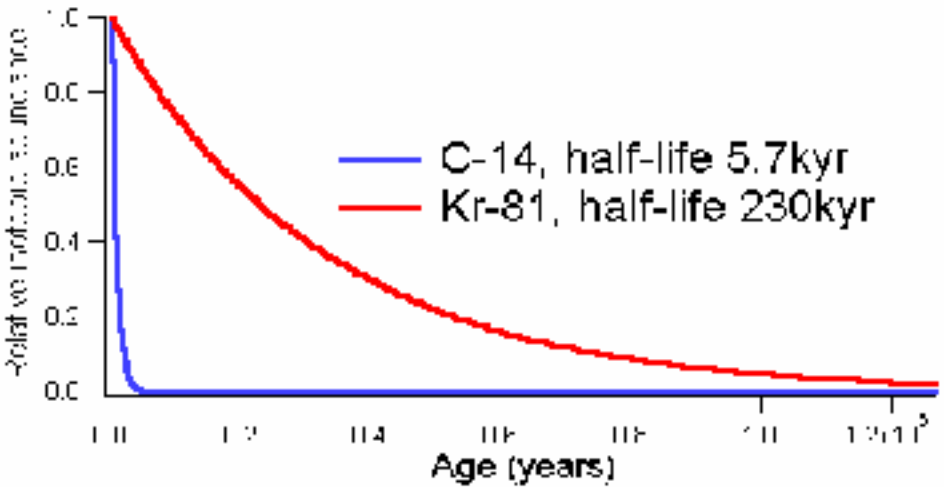


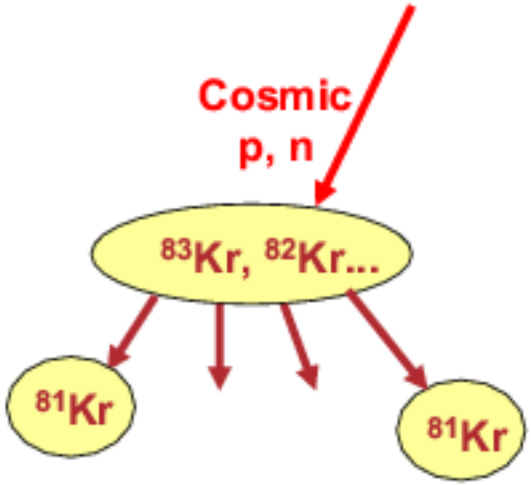
Kr-81 :

Atom Trap and Saharan Water

Radiokrypton Dating – ^{81}Kr

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

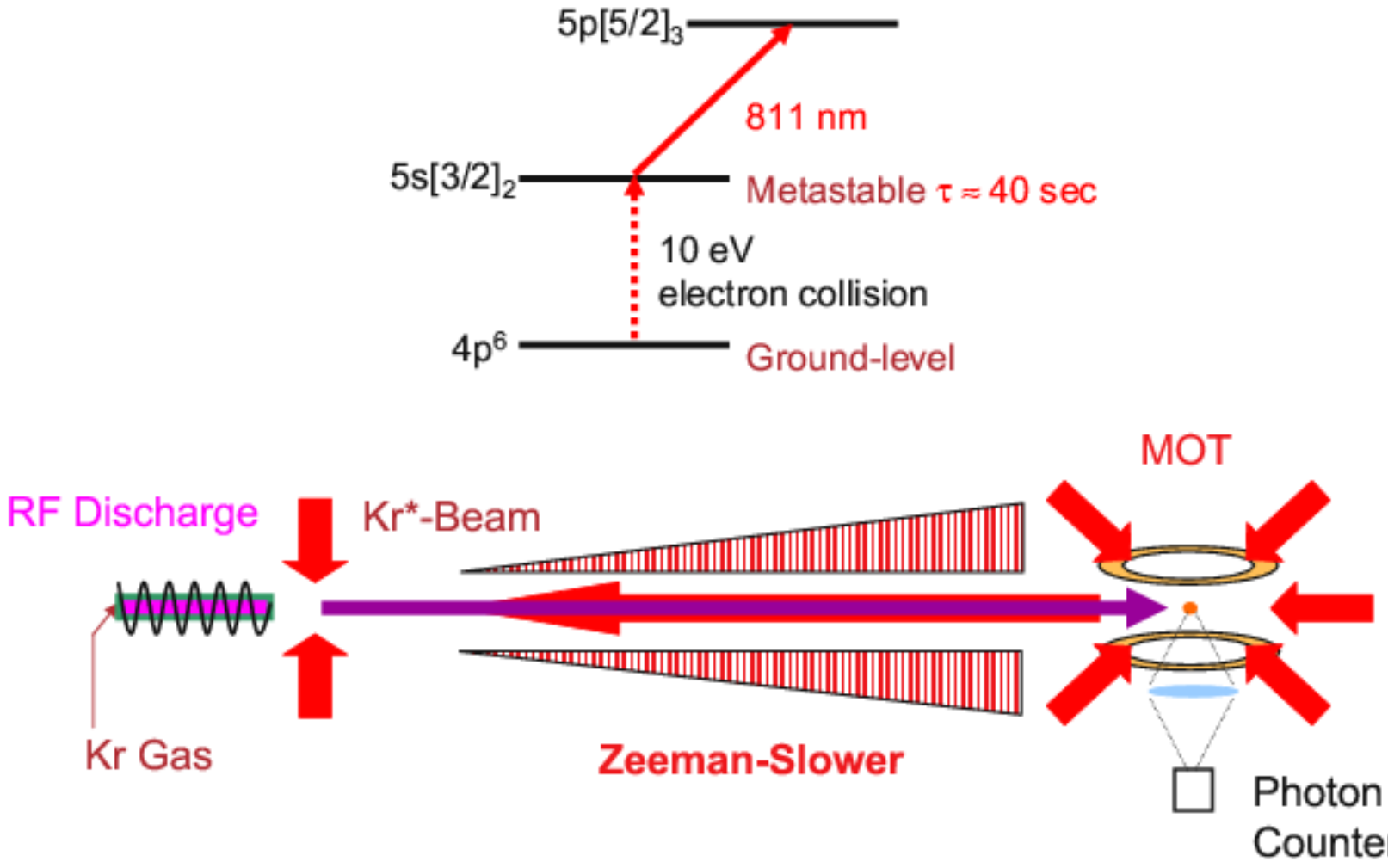




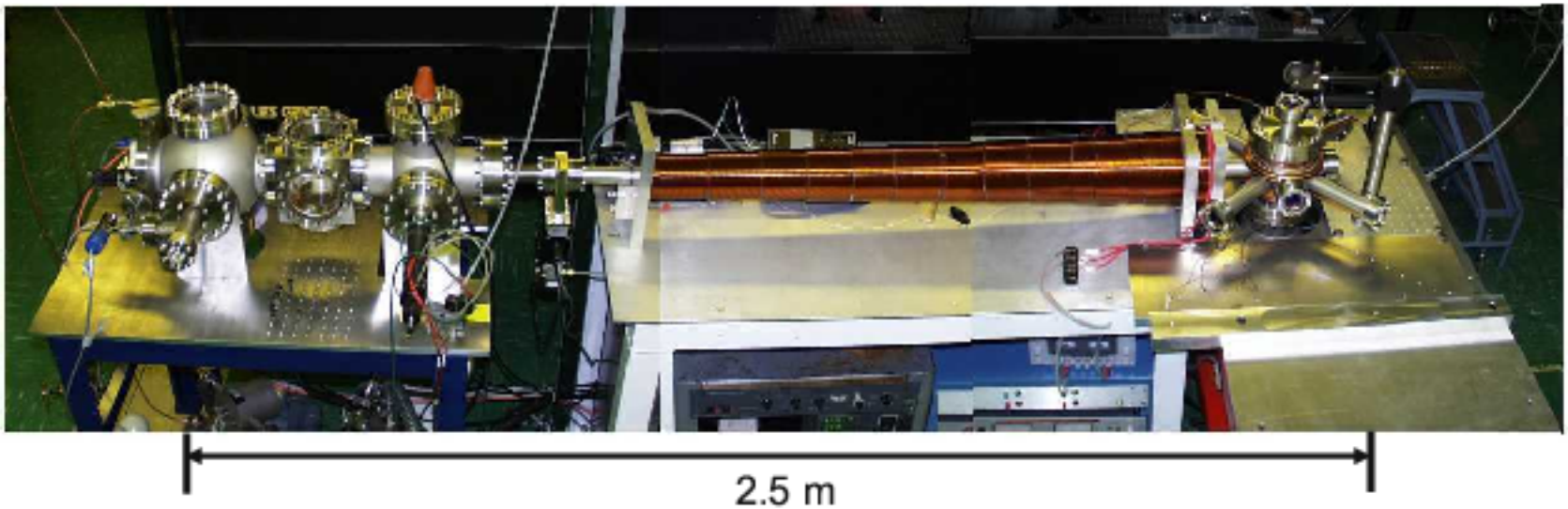
- Ideal for dating ancient groundwater
- Polar ice as a natural climate archive
- Number of ^{81}Kr atoms in 1 liter of

  Air ~ 20,000
  Water, Ice ~ 1,000

Atom Trapping of Krypton

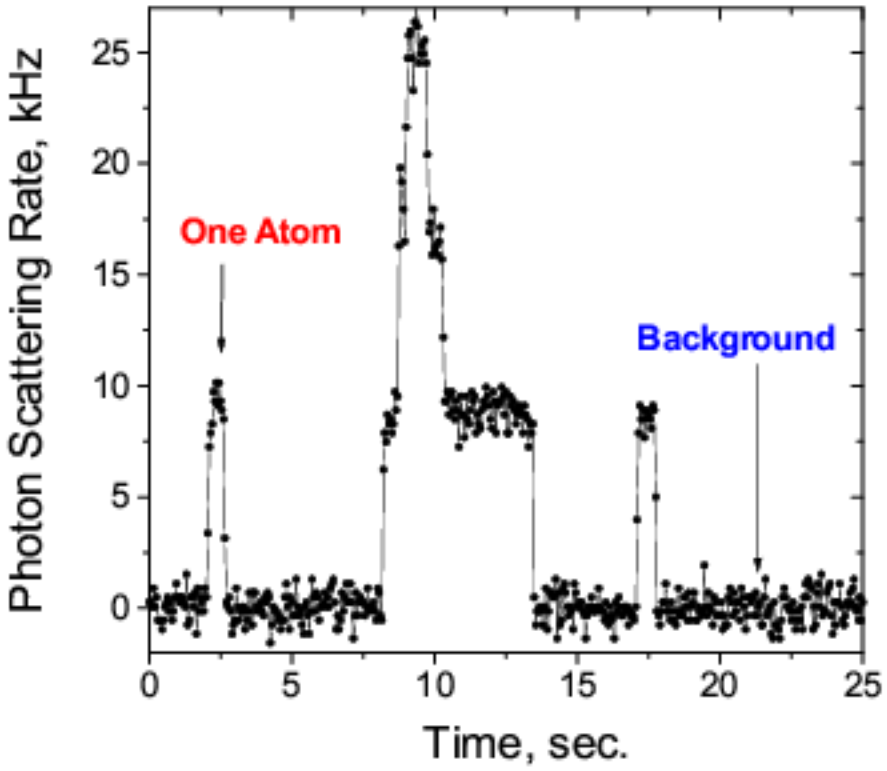


Atom Trapping of Krypton



Single Atom Detection

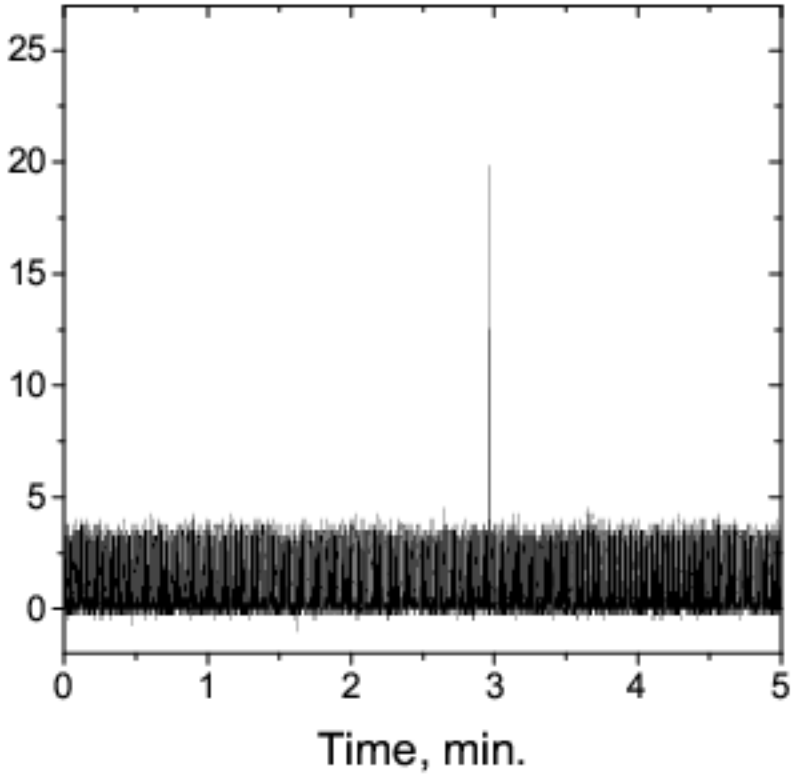
Stable Isotope: ^{83}**Kr** (11.5% I.A.)



Reduce ^{83}Kr loading rate to < 1/s

Max. ^{83}Kr loading rate ~ 10^9/s

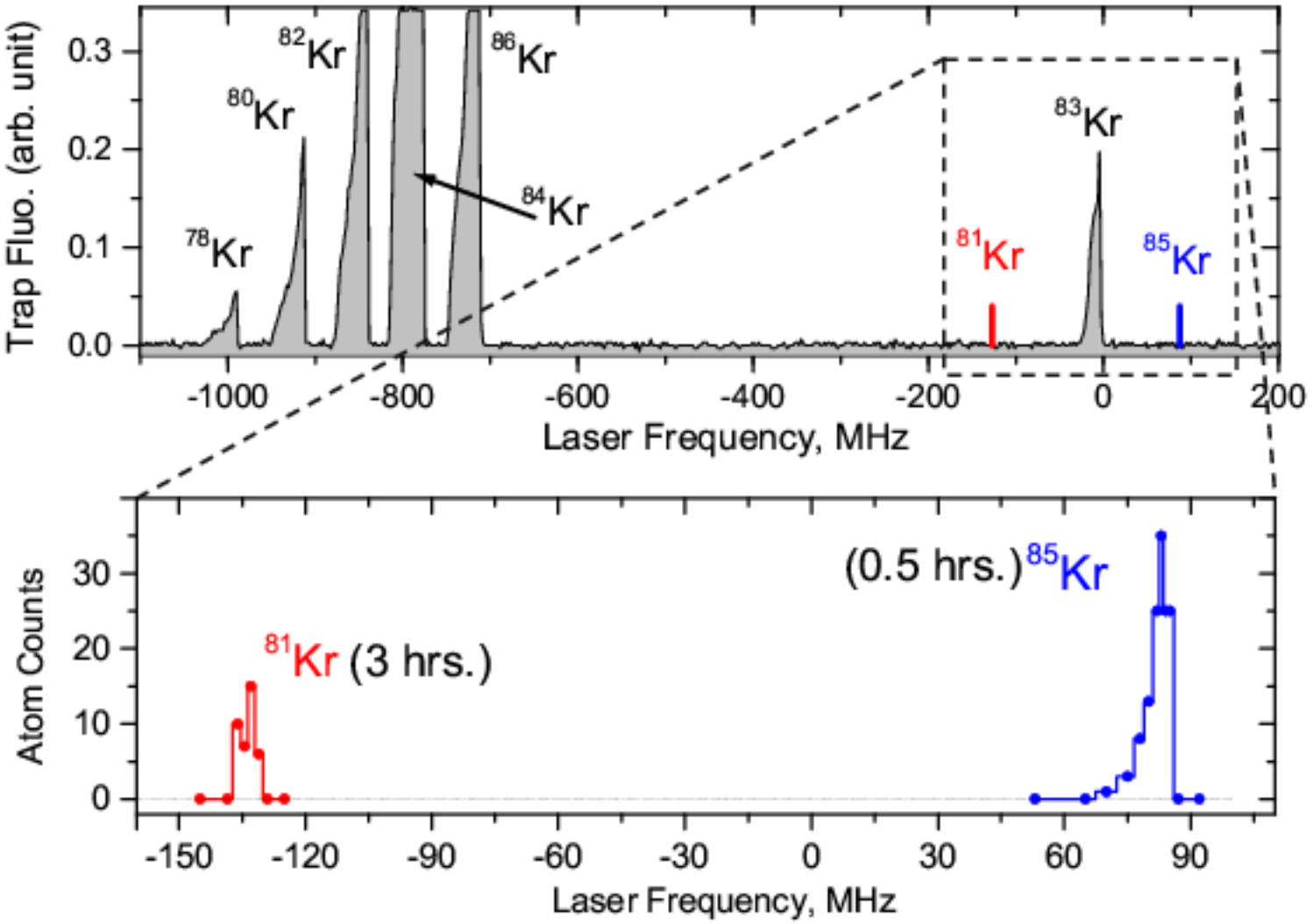
Atmospheric: ^{81}**Kr** (~10^{-12} I.A.)



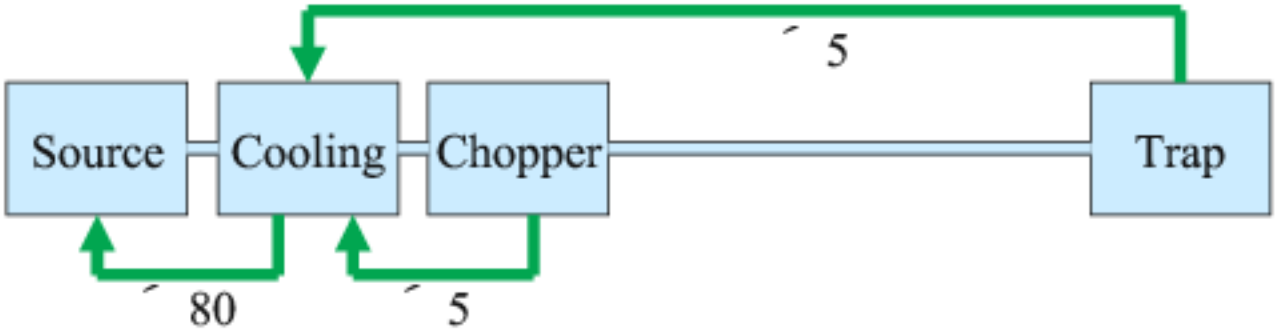
Loading rates ^{81}Kr ~ 20/h

^{85}Kr ~ 240/h

Isotopic Selectivity



Increasing the Efficiency



Gas recirculation scheme

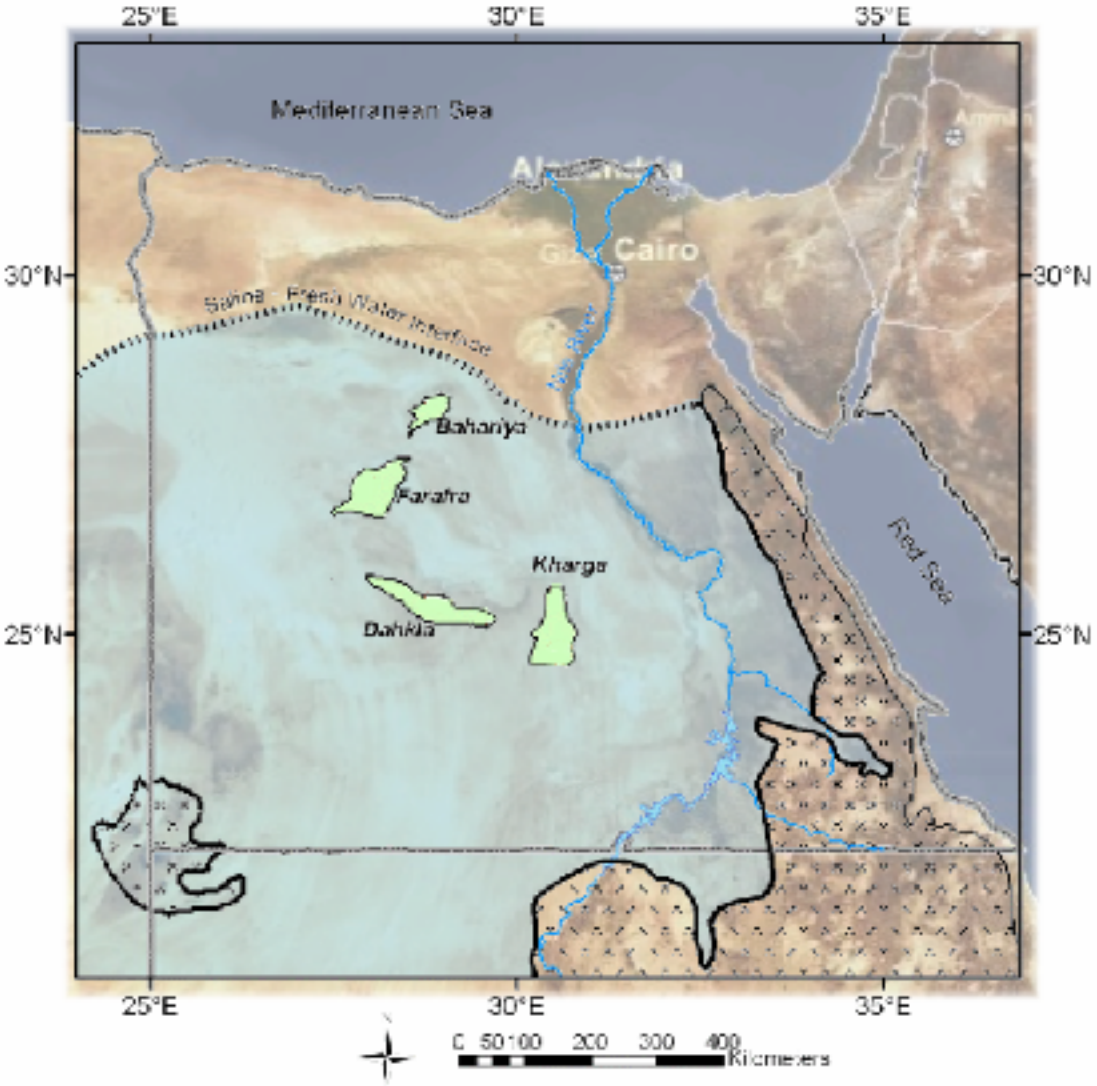
Total Eff. =	2 ´ 10^{-4}
Metastable prod.	10^{-3}
Beam divergence	10^{-3}
Trap capture	10^{-1}
Recirculation	10^{3}

Goal

10^{-4} Date groundwater
~ 50μL Kr STP
~ 1000 L water

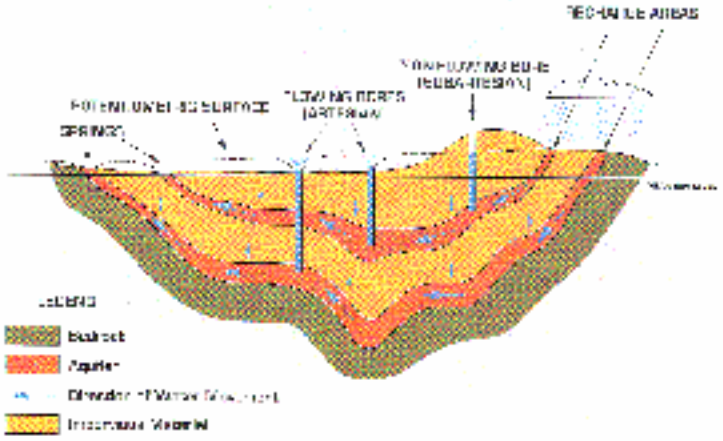
10^{-1} Date polar ice
~ 1 L water

Dating Egyptian Groundwater



Nubian Aquifer

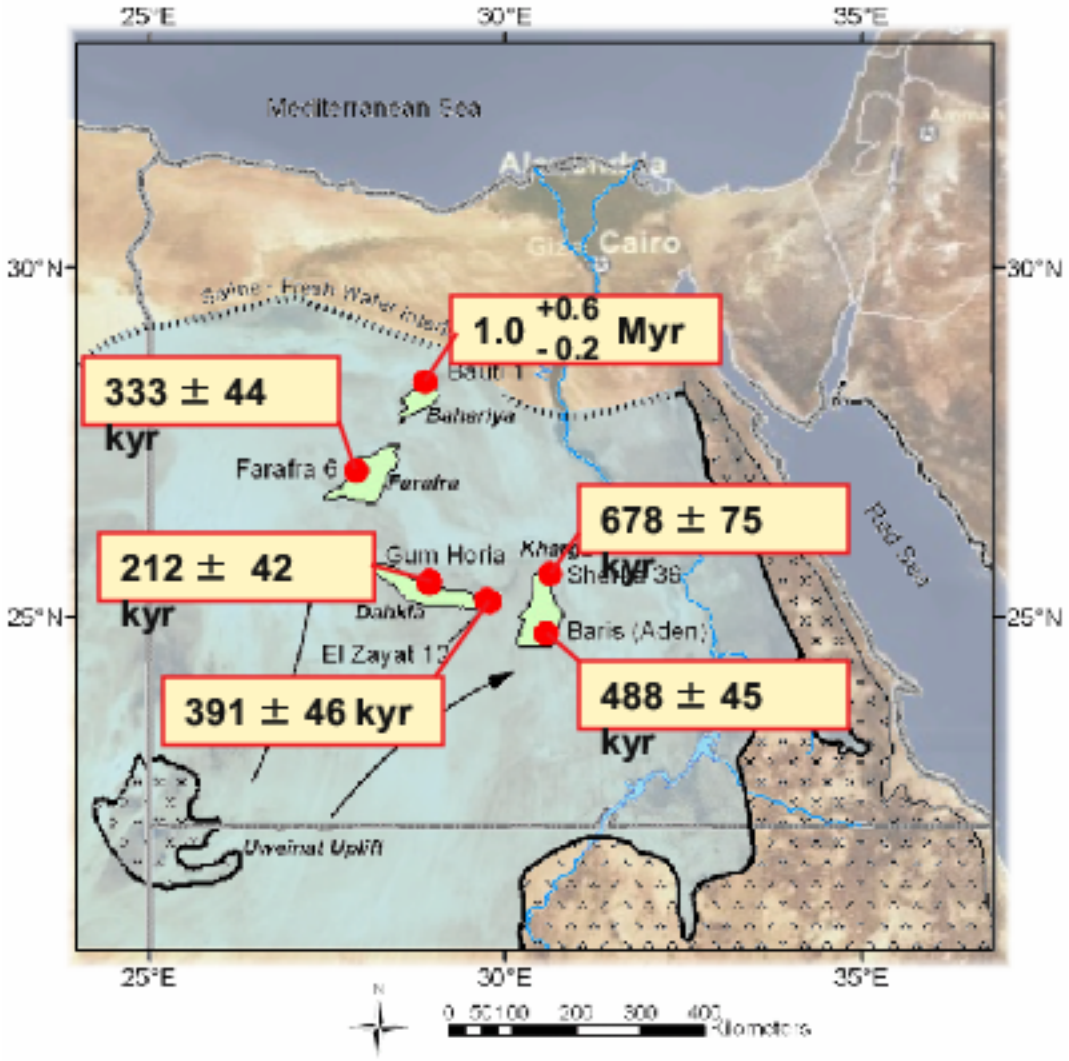
- Area ~ 2 x 10^6 km^2
- Volume ~ 5 x 10^4 km^3
- 500 years of Nile discharge
- "Age" > 50000 years



Water Sampling

On-Site Gas Extraction

One Million Years of Groundwater History

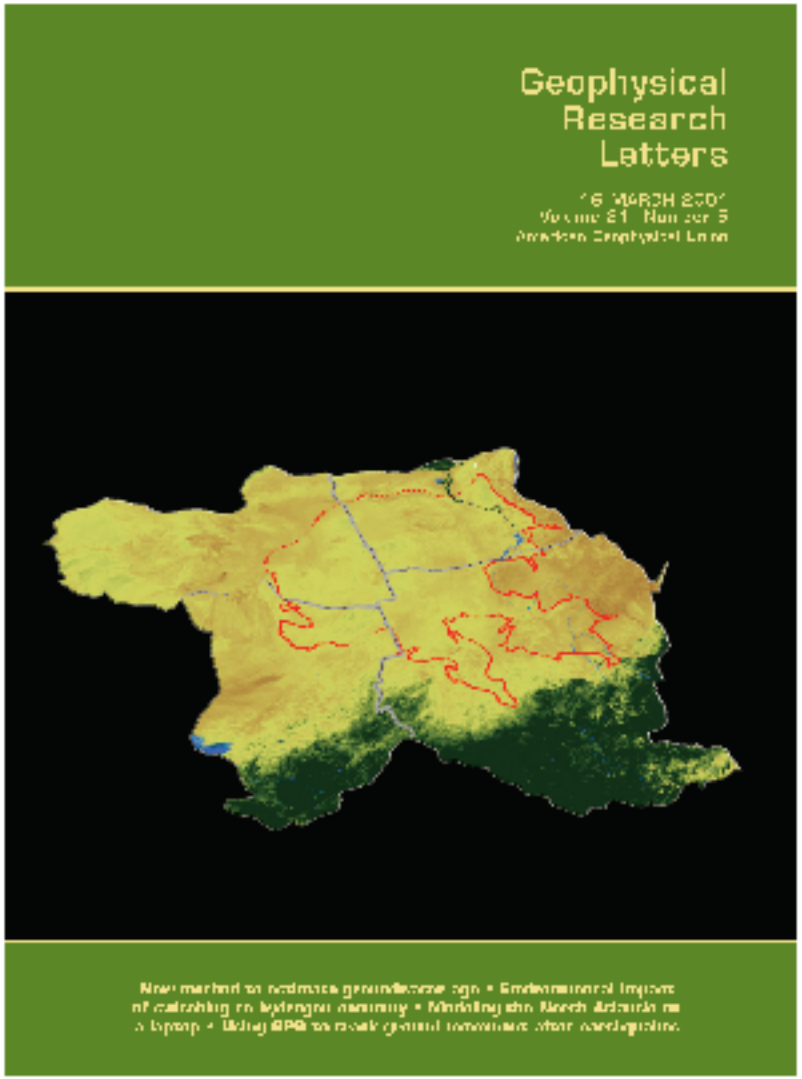


- Groundwater at six sites dated
  mean residence time
  200 000 – 1 000 000 years
- Flow direction and speed measured
  NE direction with ~1 m/year
- Source determined
  Uweinat Uplift

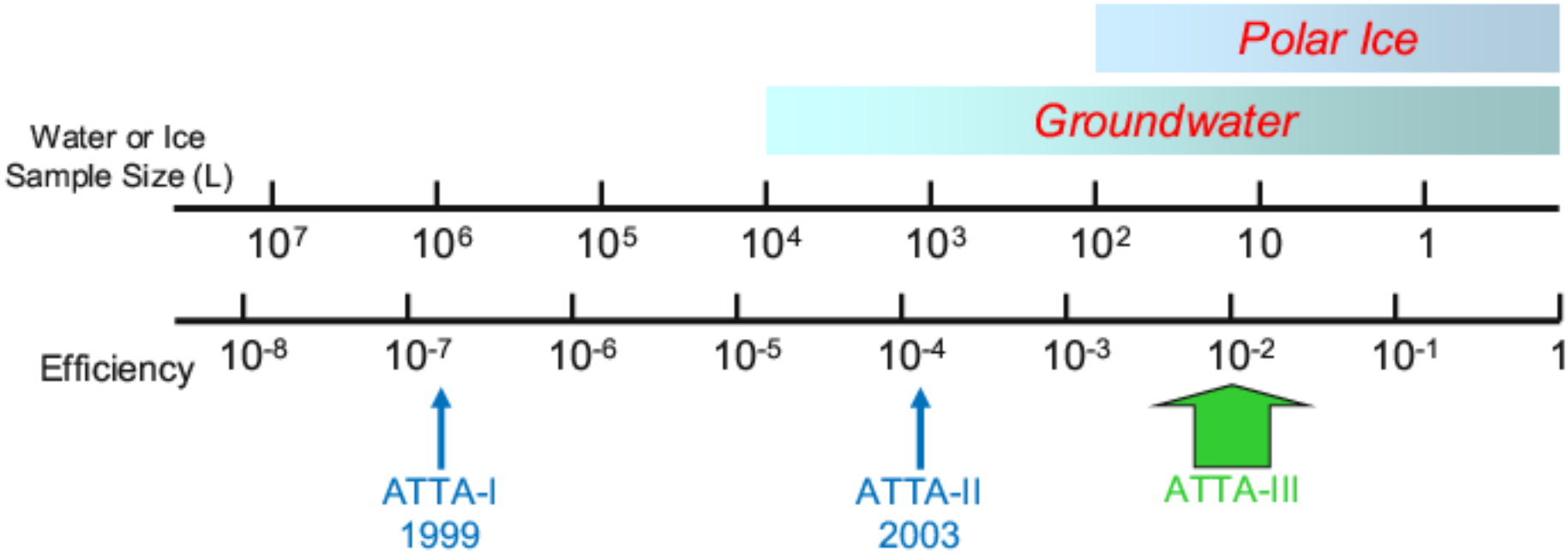
"A new method of measuring ^{81}Kr and ^{85}Kr abundances in environmental samples
X. Du et al.,
Geophys. Res. Lett. **30**, 2068 (2003)

"One million year old groundwaterin the Sahara revealed by krypton-81 and chlorine-36"
N. C. Sturchio et al.,
Geophys. Res. Lett. **31**, L05503 (2004)

ATTA Covered



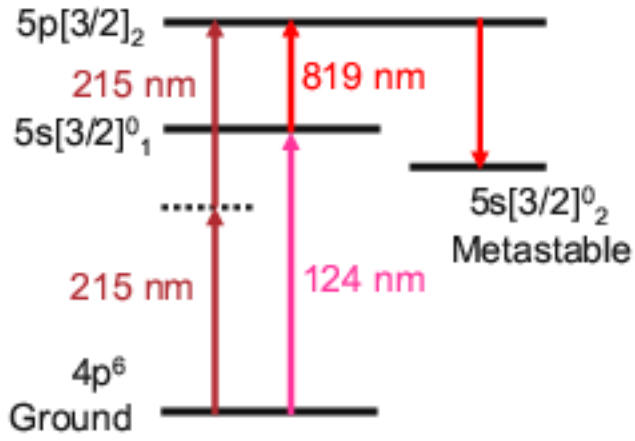
^{81}Kr-Dating: Past, Present, Future

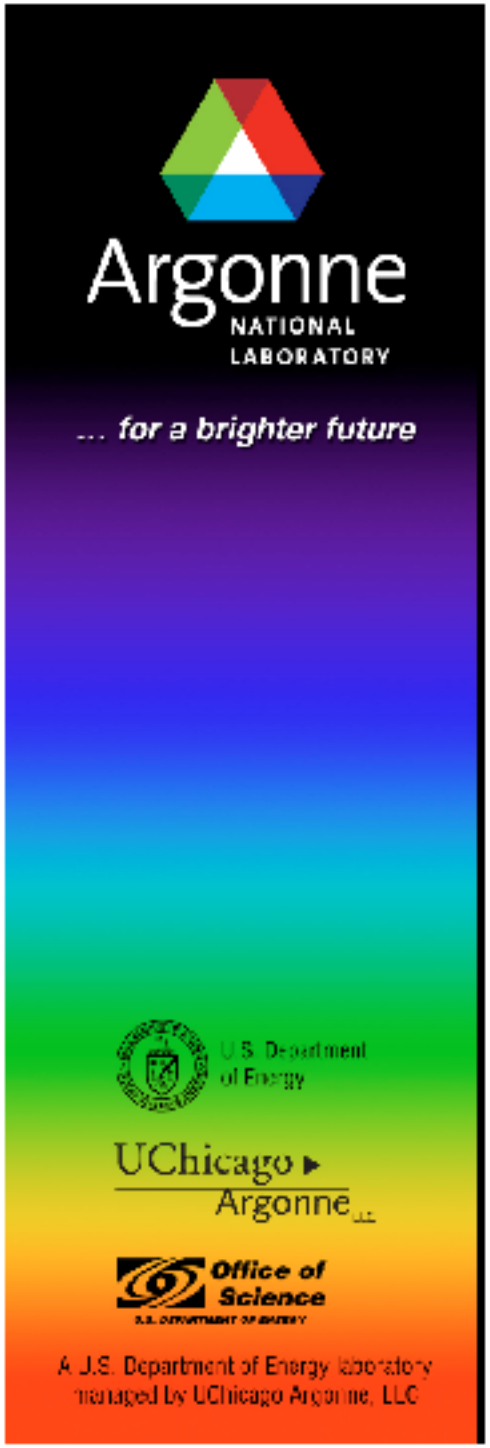


ATTA III

Incremental Improvements
More laser power;
Fancier techniques.

*Optical excitation of Kr**
124 nm + 819 nm





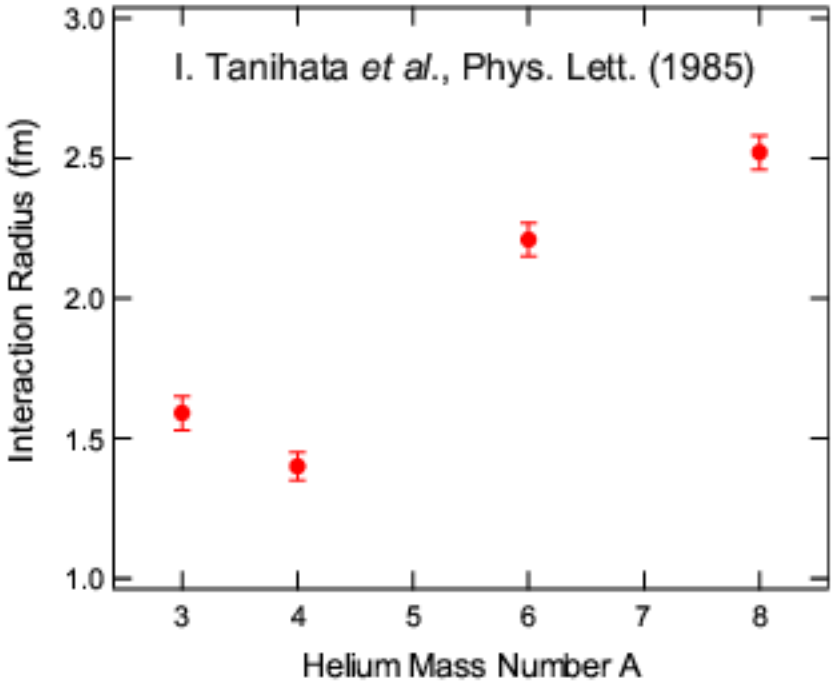
He-6 and He-8:

Laser Spectroscopic Determination of Nuclear Charge Radii

Neutron Halo Nuclei ^{6}He and ^{8}He

Isotope	Half-life	Spin	Isospin	Core + Valence
He-6	807 ms	0^+	1	α + 2n
He-8	119 ms	0^+	2	α + 4n

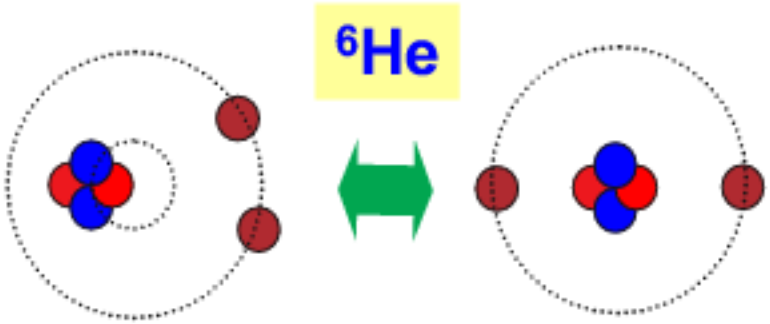
Borromean



Core-Halo Structure

$$\sigma_I(^6He) - \sigma_I(^4He) = \sigma_{-2n}(^6He)$$

I. Tanihata *et al.*, Phys. Lett. (1992)

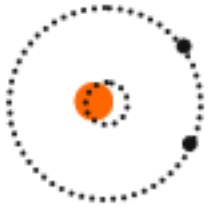


Atomic Isotope Shift

Isotope Shift $\delta\nu = \delta\nu_{MS} + \delta\nu_{FS}$

Mass shift:

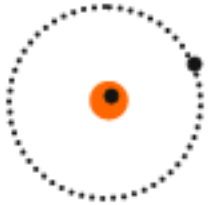
due to nucleus recoil



$$\delta\nu_{MS} \propto \frac{A - A'}{AA'}$$

Field shift:

due to nucleus size



$$\delta\nu_{FS} \propto Z \times \Delta[\Psi(0)]^2 \times \delta\langle r^2\rangle$$

For $2^3S_1 - 3^3P_2$ transition @ 389 nm:

$$\delta\nu = \delta\nu_{MS} + C_{FS}\,\delta\langle r^2\rangle$$

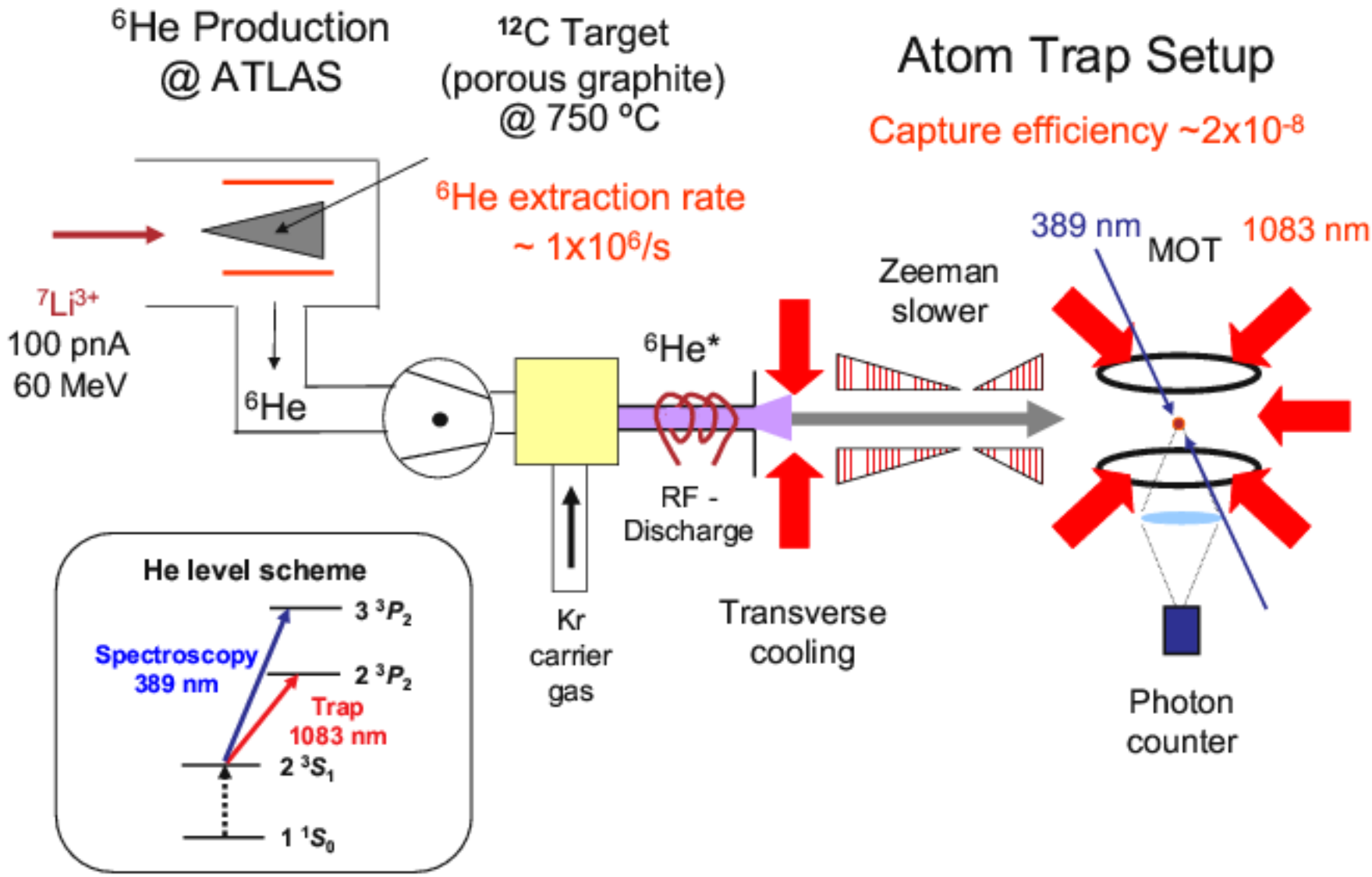
^{6}He - ^{4}He : $\delta\nu_{6,4}$ = 43196.202(16) MHz + 1.008 ($\langle r^2\rangle_{He4} - \langle r^2\rangle_{He6}$) MHz/fm^2

^{8}He - ^{4}He : $\delta\nu_{8,4}$ = 64702.410(70) MHz + 1.008 ($\langle r^2\rangle_{He4} - \langle r^2\rangle_{He8}$) MHz/fm^2

G.W.F. Drake, Univ. of Windsor, *Nucl. Phys. A737c, 25 (2004)*

100 kHz error in IS ←→ ~ 1% error in radius

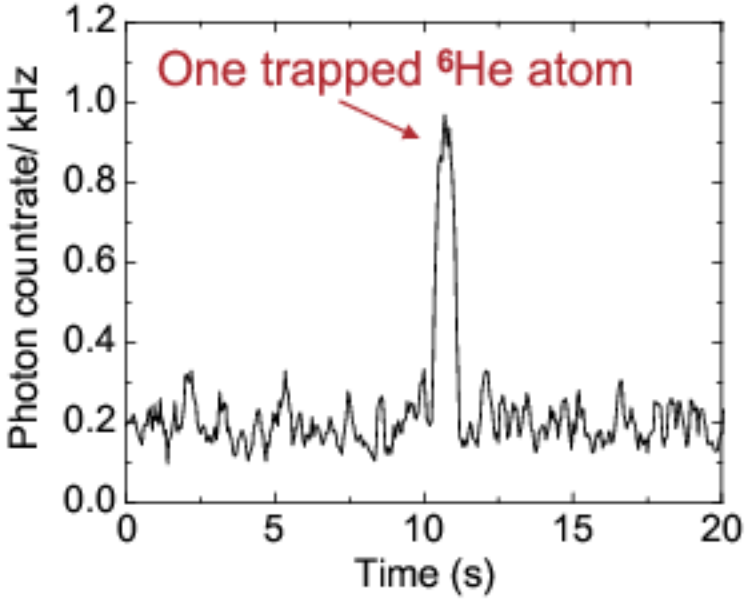
Atom Trapping of ^{6}He



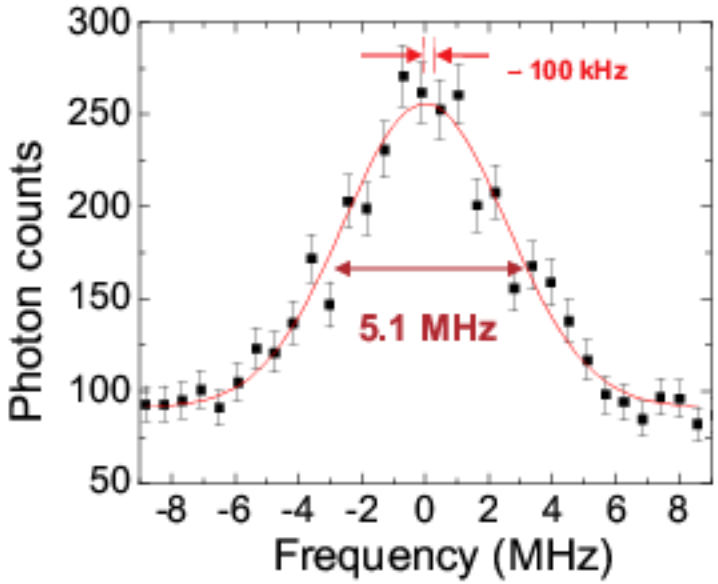
^{6}He - Single Atom Spectroscopy

Capture efficiency ~ 10^{-8} ⇨ Single atom detection necessary!

Single atom signal



^{6}He spectroscopy



- Single-atom signal ~ 1.0 kHz
- Single-atom S/N ~ 10 in 100 ms

- Spectroscopy with ~150 ^{6}He in one hour

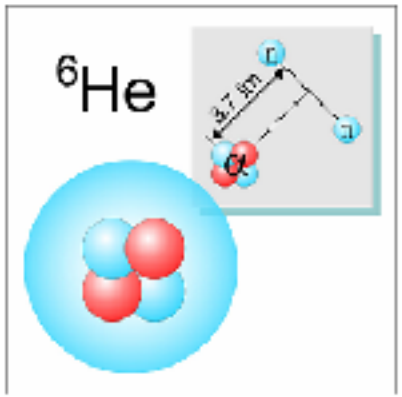
^{6}He Nuclear Charge Radius

Isotope shift
($2^3S_1 - 3^3P_2$, ^{6}He – ^{4}He)

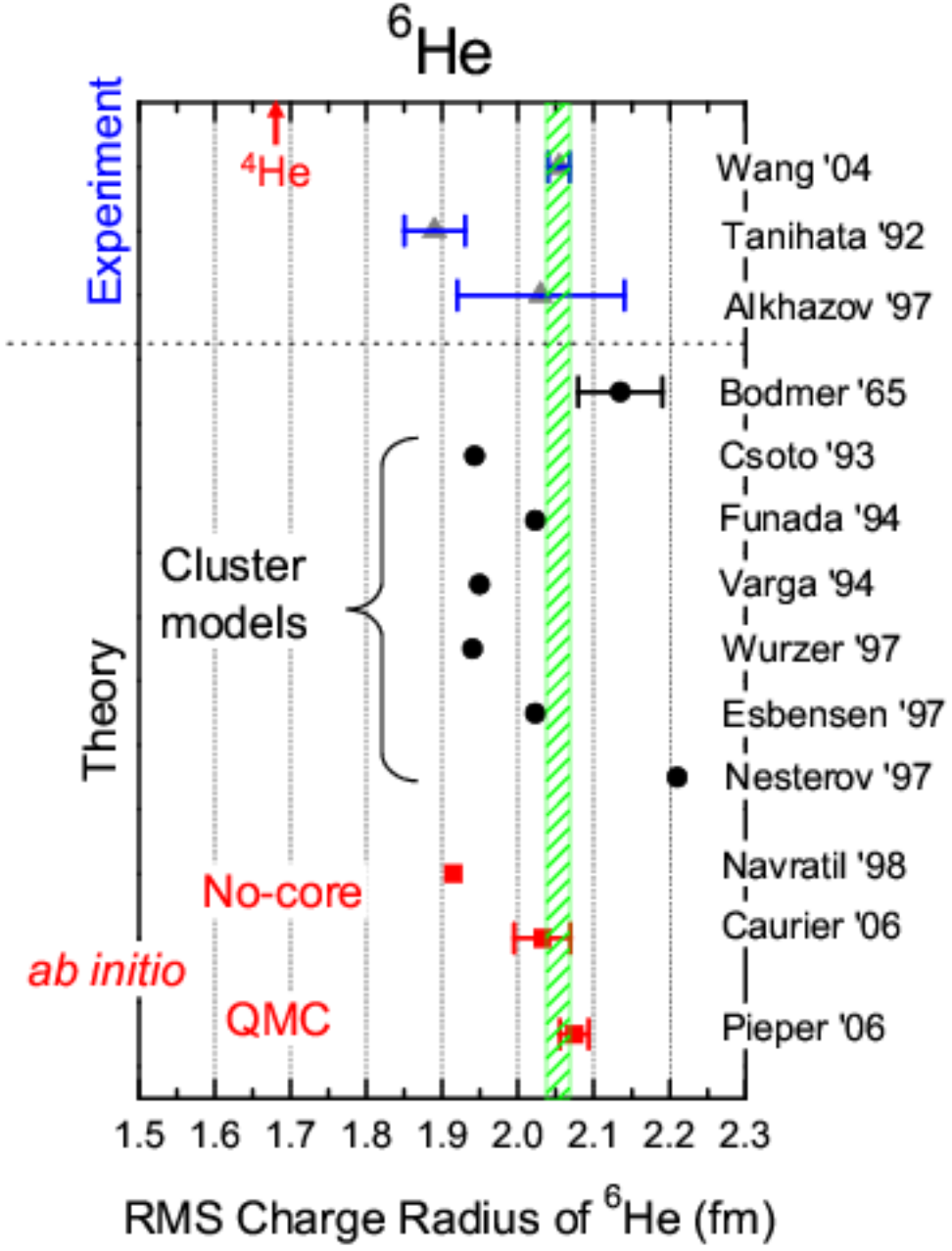
43 194.772(56) MHz

^{6}He rms charge radius

2.054(14) fm (0.7%)



L.-B. Wang *et al.*,
PRL **93**, 142501 (2004)

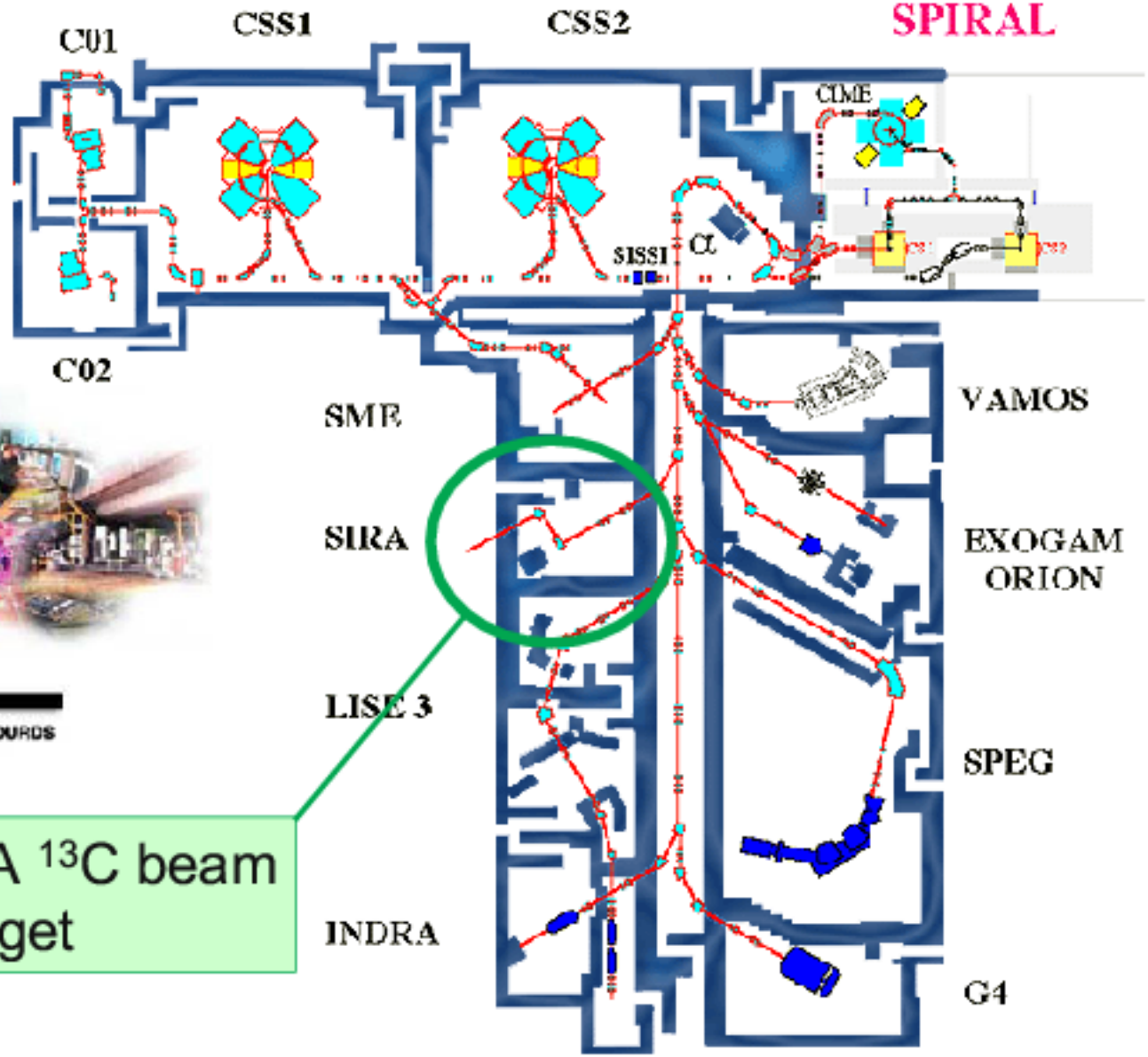


He-8 @ GANIL

GANIL

GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS



75 MeV/u, 0.4 pμA ^{13}C beam on ^{12}C target

Atom Trappers with an ATTAtude

Physics Division, Argonne

Kevin Bailey
Yun Ding
Zheng-Tian Lu
Jeff Guest
Roy Holt
Peter Mueller
Thomas O'Connor
Ibrahim Sulai
Jin Wang

www-mep.phy.anl.gov/atta/