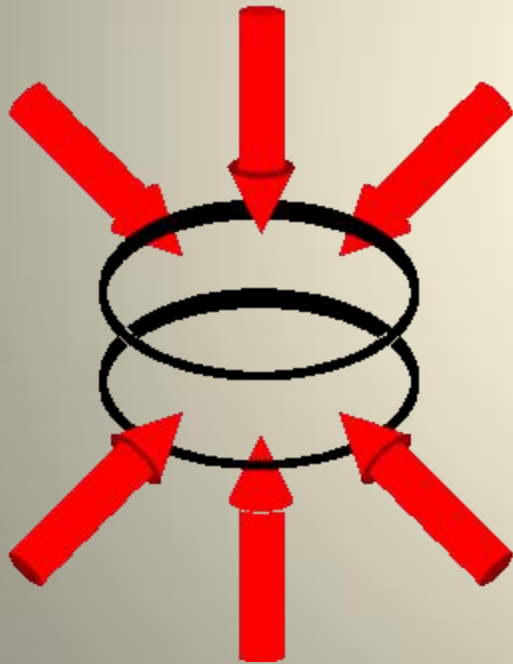
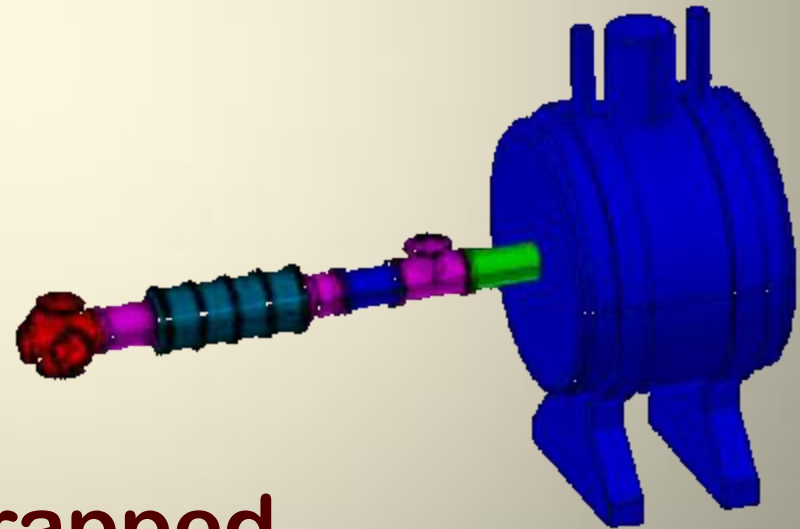


Nuclear Physics



atoms



with trapped

and

ions

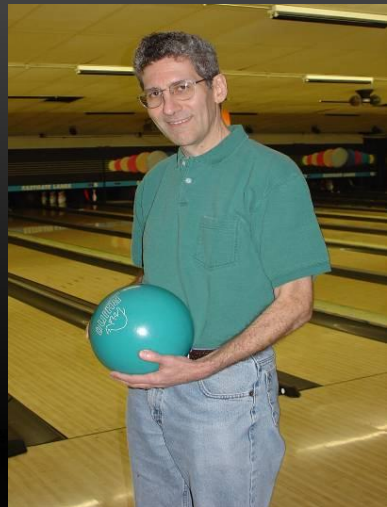
Saturday Morning Physics

- Detectors/Accelerators
- High-energy physics; the LHC and search for the Higgs

- Nuclear physics

- Cosmology and astronomy

Biophysics



Outline

- **Scope and applications of nuclear physics**
 - precision frontier compliments LHC
 - properties of nuclei used to explain celestial phenomena and conditions just after the Big Bang
 - diagnostic and therapeutic medicine

- **“Cool” tools – atom traps**
 - probing fundamental symmetries
 - (ion traps)
 - trace analysis and aquifers in the Sahara

What is Nuclear Physics?

- Began with the study of the *nucleus* after it was discovered in 1911 by Ernest Rutherford
 - Or, arguably, in 1896 when Henri Becquerel discovered *radioactivity*
- The atom is mostly *empty space*!
- Nuclear physics concerns itself with the study of the *protons* and *neutrons* making up the nucleus
 - Spawned high-energy physics
 - Explained many astrophysical observations
 - Played a huge role in developing the most rigorously-tested theory mankind has *ever* come up with: the Standard Model

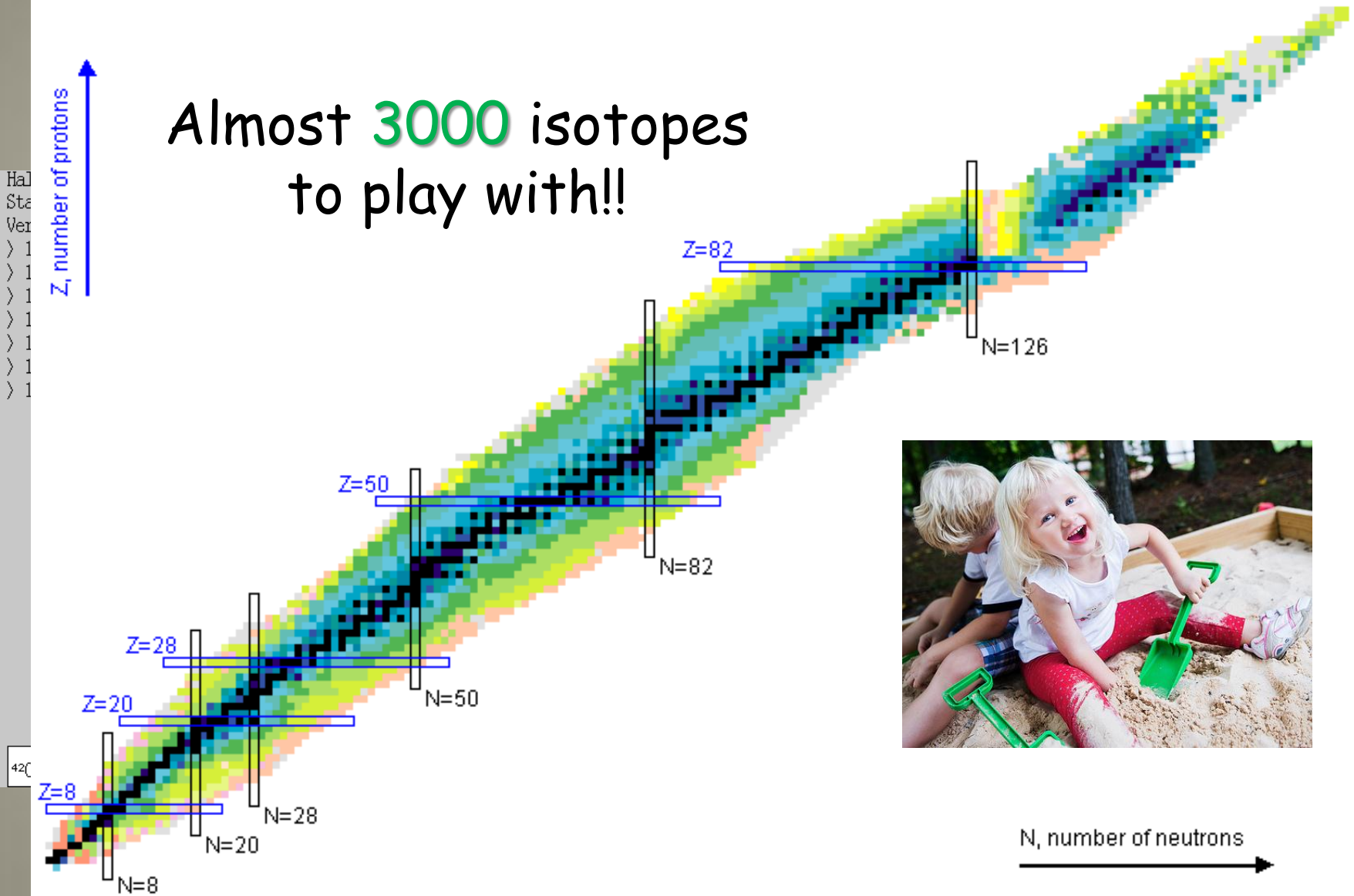
The periodic table...expanded

52 Ni	53 Ni	54 Ni	55 Ni	56 Ni	57 Ni	58 Ni	59 Ni	60 Ni	61 Ni	62 Ni			4.003 He																					
1 1.01 H Hydrogen	63 Ni	64 Ni	65 Ni	66 Ni	67 Ni	68 Ni	69 Ni	70 Ni	71 Ni	72 Ni	73 Ni	74 Ni	10 20.18 Ne																					
3 6.94 Li Lithium	4 9.01 Be Beryllium	There are 117 elements										5 10.81 B Boron	6 12.01 C Carbon	7 14.01 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.18 Ne Neon																	
11 22.99 Na Sodium	12 24.31 Mg Magnesium	13 26.98 Al Aluminum	14 28.09 Si Silicon	15 30.97 P Phosphorus	16 32.06 S Sulfur	17 35.45 Cl Chlorine	18 39.95 Ar Argon	19 39.10 K Potassium	20 40.08 Ca Calcium	21 44.96 Sc Scandium	22 47.90 Ti Titanium	23 50.94 V Vanadium	24 51.996 Cr Chromium	25 54.94 Mn Manganese	26 55.85 Fe Iron	27 58.93 Co Cobalt	28 58.70 Ni Nickel	29 63.55 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.92 As Arsenic	34 78.96 Se Selenium	35 79.90 Br Bromine	36 83.80 Kr Krypton									
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.91 Y Yttrium	40 91.22 Zr Zirconium	41 92.91 Nb Niobium	42 95.94 Mo Molybdenum	43 (98) Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.40 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.90 I Iodine	54 131.30 Xe Xenon	55 132.91 Cs Cesium	56 137.33 Ba Barium	57 138.91 La Lanthanum	58 140.12 Ce Cerium	59 140.91 Pr Praseodymium	60 144.24 Nd Neodymium	61 (145) Pm Promethium	62 150.40 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolinium	65 158.93 Tb Terbium	66 162.50 Dy Dysprosium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	71 174.97 Lu Lutetium
87 (223) Fr Francium	88 226.03 Ra Radium	89 227.03 Ac Actinium	104 (261) Rf Rutherfordium	105 (262) Db Dubnium	106 (266) Sg Seaborgium	107 (262) Bh Bohrium	108 (265) Hs Hassium	109 (266) Mt Meitnerium	110 (271) Ds Darmstadtium	111 (272) Rg Roentgenium	(277) Cn Copernicium	(284) 113	(288) 114	(288) 115	(292) 116	(294) 118	(210) 85 At Astatine	(222) 86 Rn Radon																

Lanthanides	58 140.12 Ce Cerium	59 140.91 Pr Praseodymium	60 144.24 Nd Neodymium	61 (145) Pm Promethium	62 150.40 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolinium	65 158.93 Tb Terbium	66 162.50 Dy Dysprosium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	71 174.97 Lu Lutetium
Actinides	90 232.04 Th Thorium	91 231.04 Pa Protactinium	92 238.03 U Uranium	93 237.05 Np Neptunium	94 (244) Pu Plutonium	95 (243) Am Americium	96 (247) Cm Curium	97 (247) Bk Berkelium	98 (251) Cf Californium	99 (252) Es Einsteinium	100 (257) Fm Fermium	101 (260) Md Mendelevium	102 (259) No Nobelium	103 (262) Lr Lawrencium

The periodic table...expanded

Almost **3000** isotopes
to play with!!



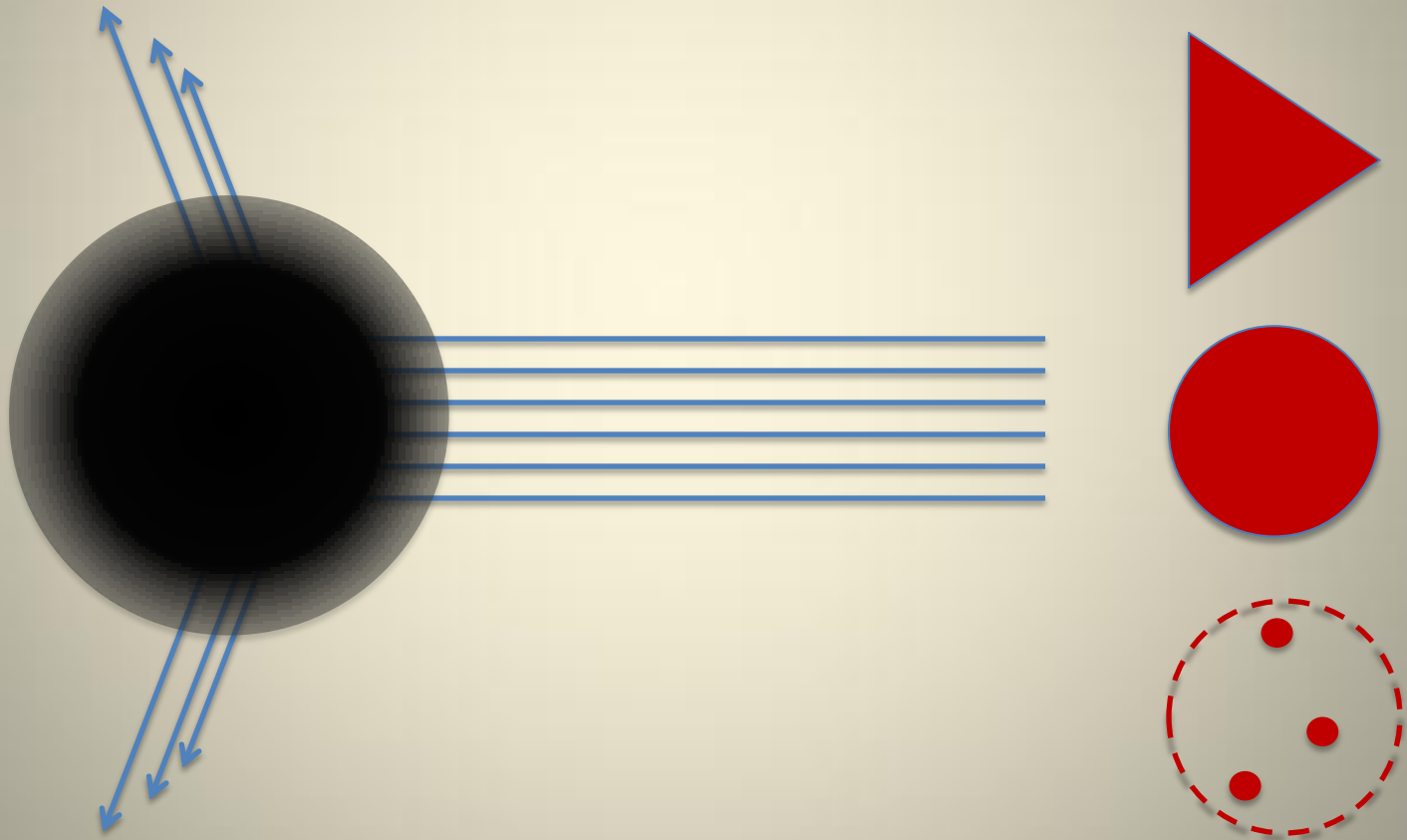
What do we do with nuclei?

We **smash 'em** together, of course!



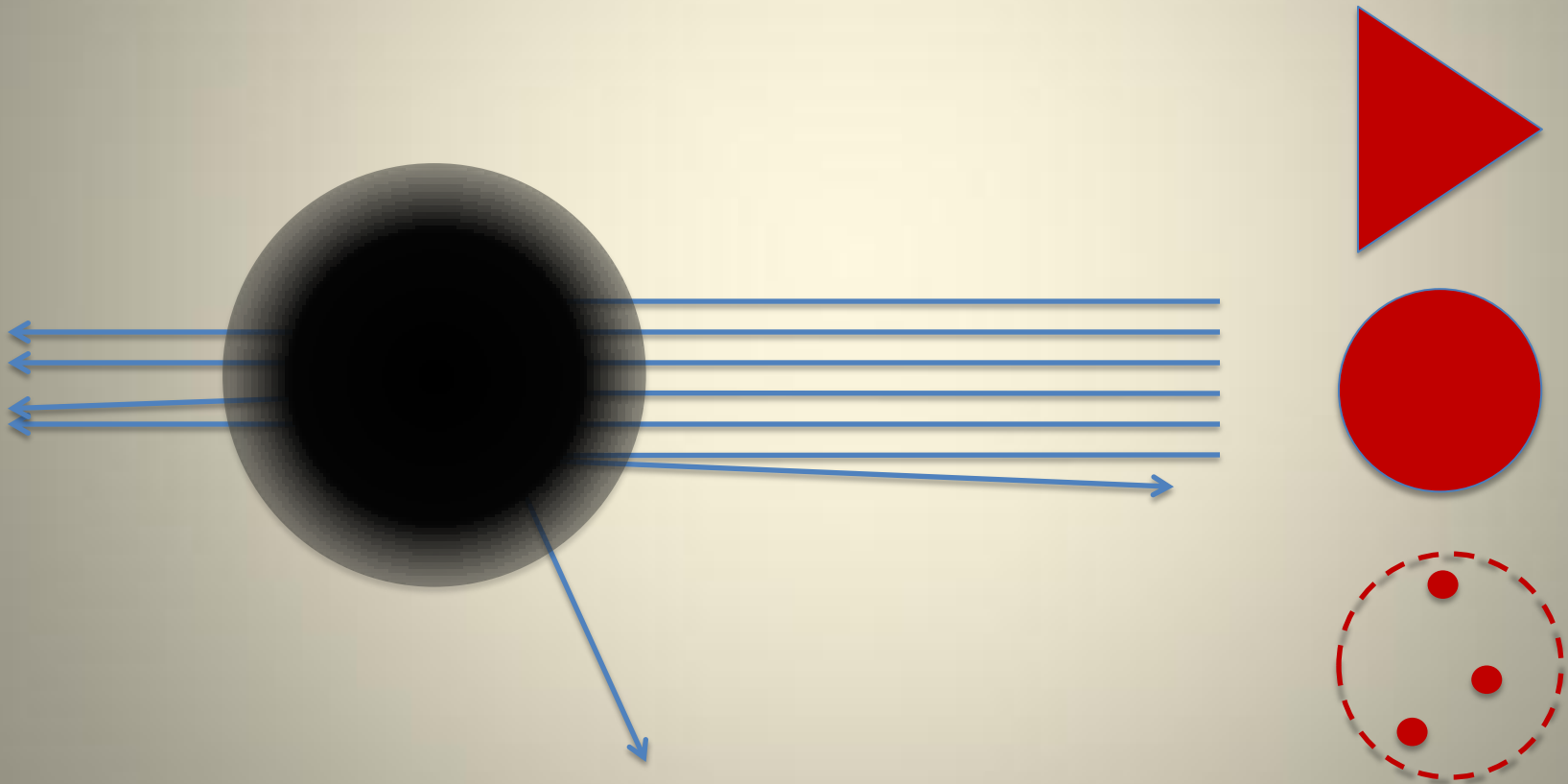
What do we do with nuclei?

- Just like a microscope uses light to probe small objects, **particles** can be used to investigate **properties of atoms and their nuclei**



What do we do with nuclei?

- Just like a microscope uses light to probe small objects, **particles** can be used to investigate **properties of atoms and their nuclei**



What do we do with nuclei?

- Just like a microscope uses light to probe small objects, **particles** can be used to investigate **properties of atoms and their nuclei**
- Most nuclei are **not** stable...they **decay**:

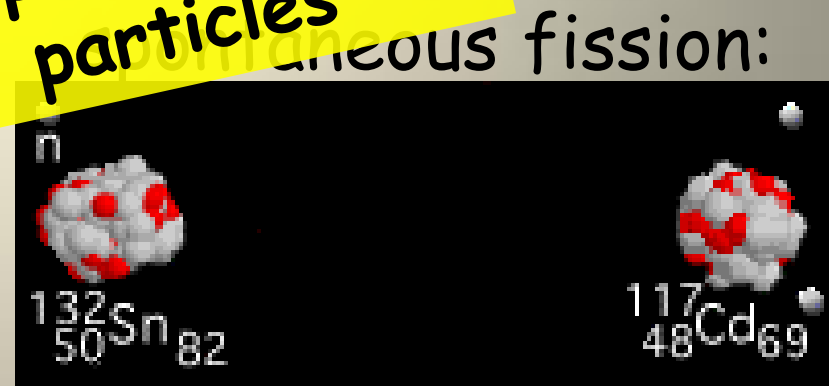
α decay:



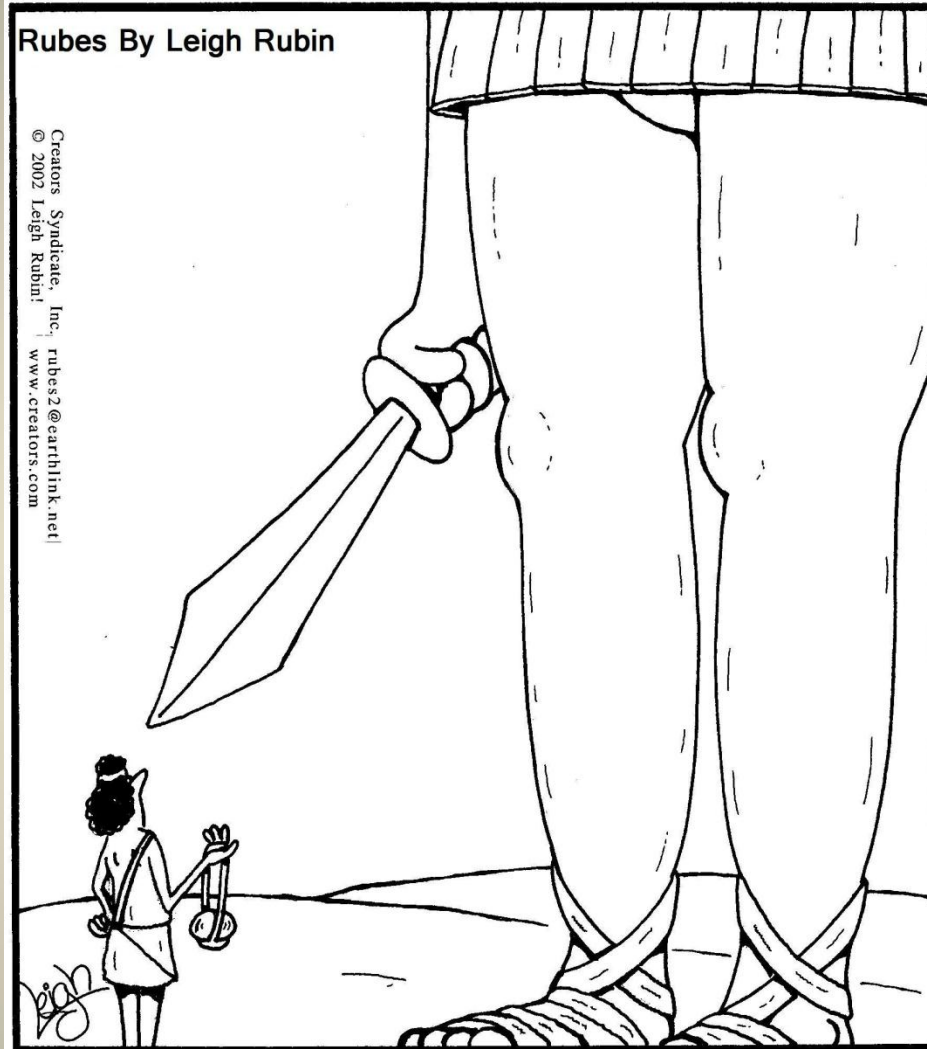
β decay:



These decays tell us about the structure within the nucleus and the forces at play between its constituent particles

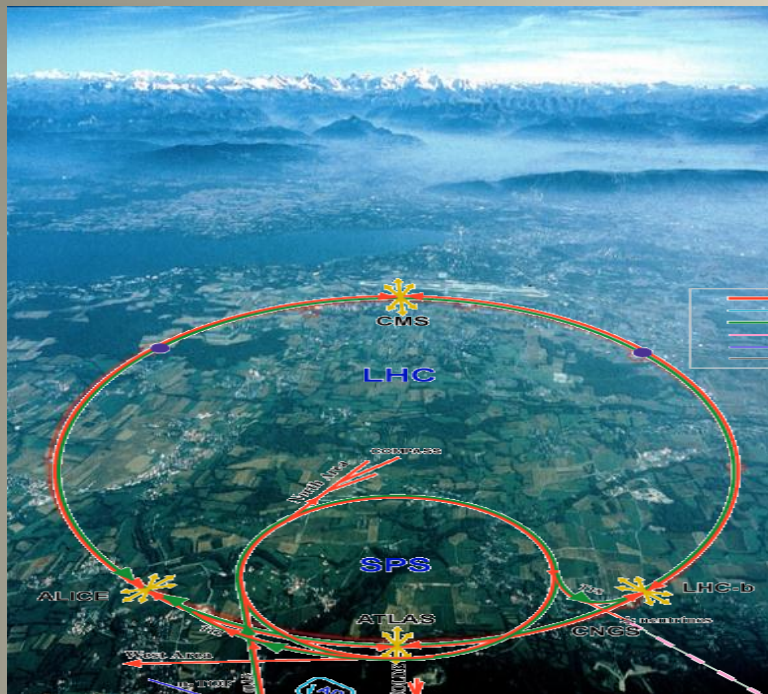


Nuclear vs high-energy physics

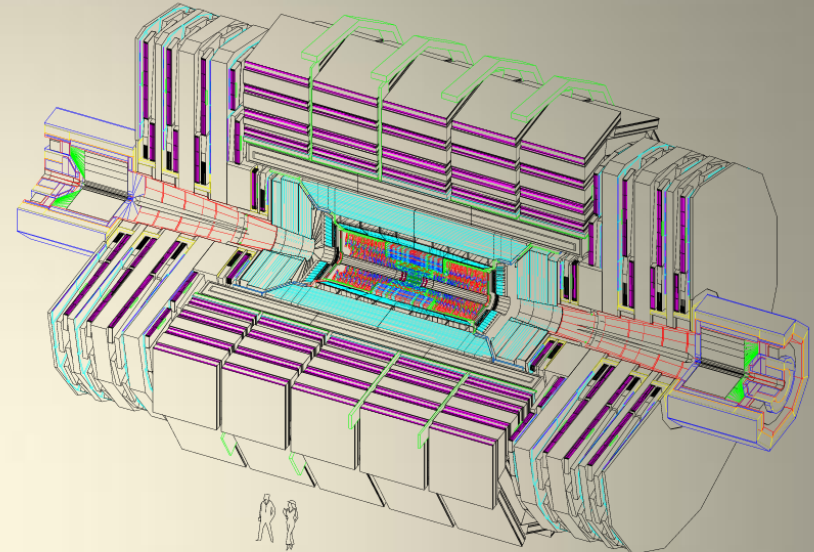


Overcoming temptation, David opted against the obvious, unsportsmanlike cheap shot.

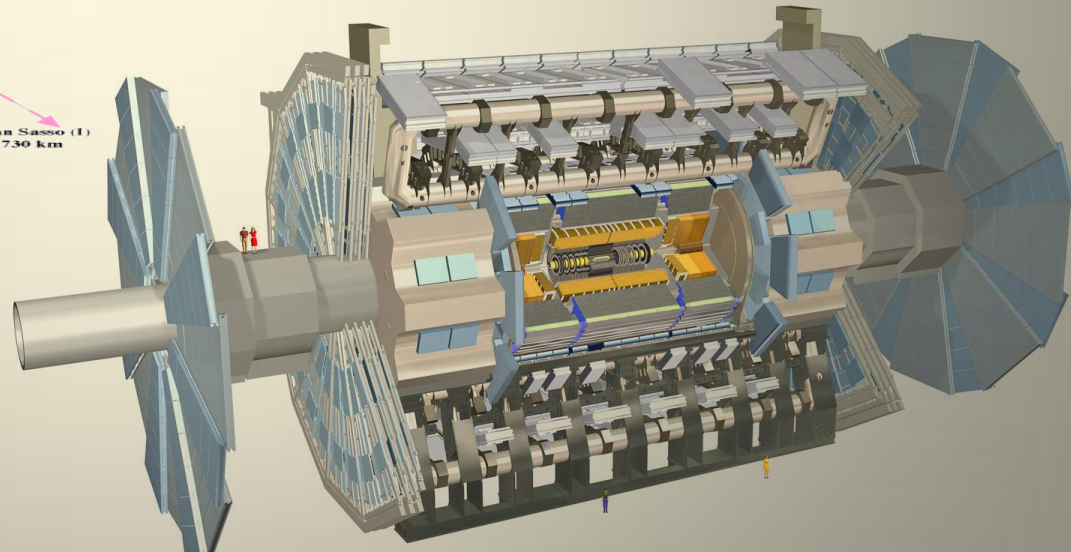
Nuclear vs high-energy physics



- protons
- antiprotons
- ions
- neutrinos to Gran Sasso
- neutrons
- electrons



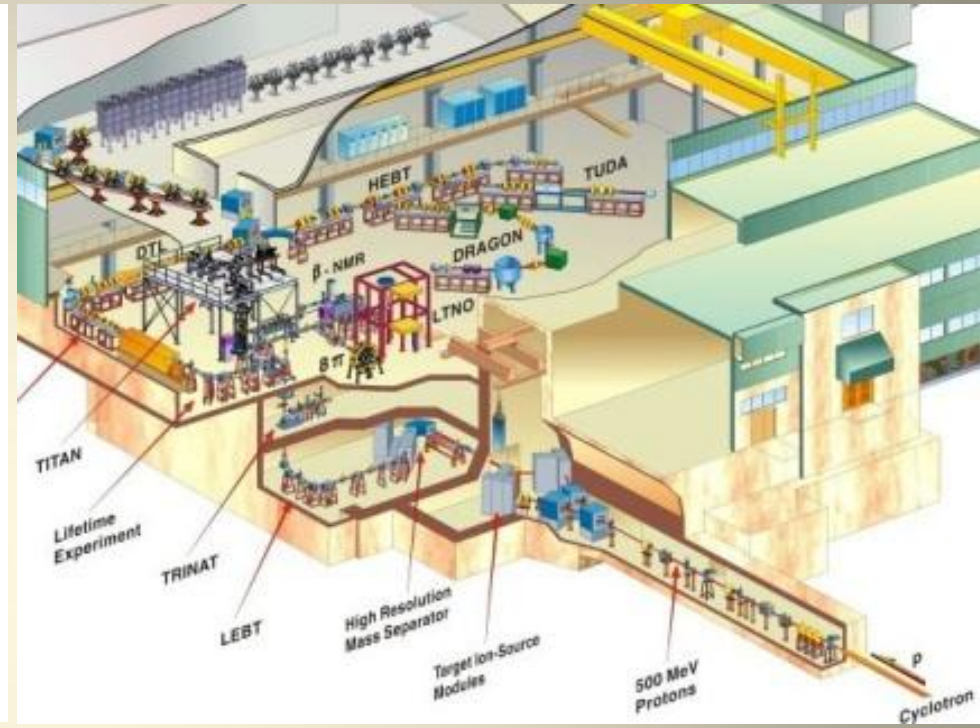
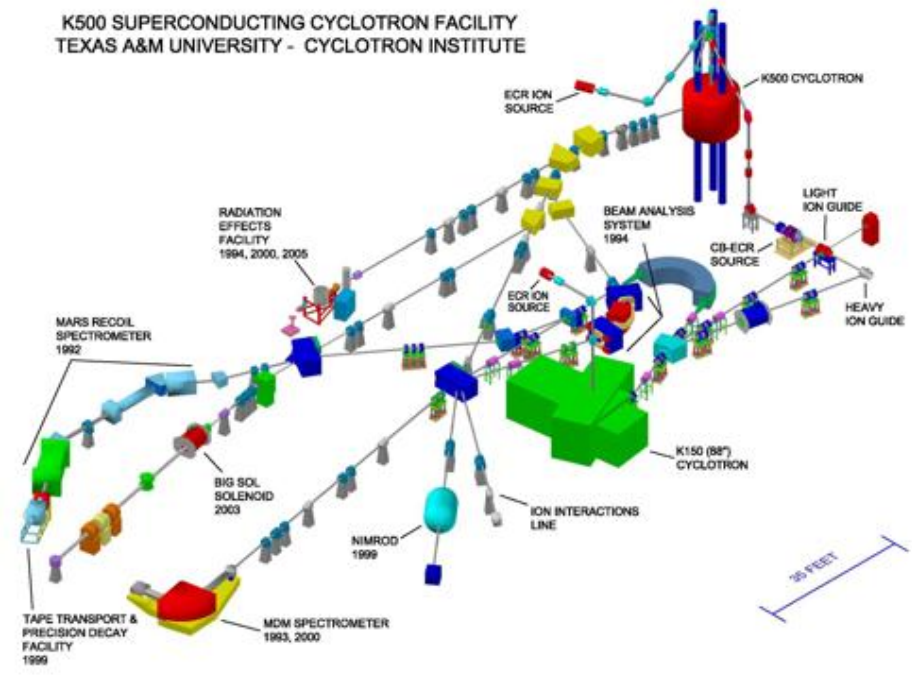
Compact Muon Solenoid



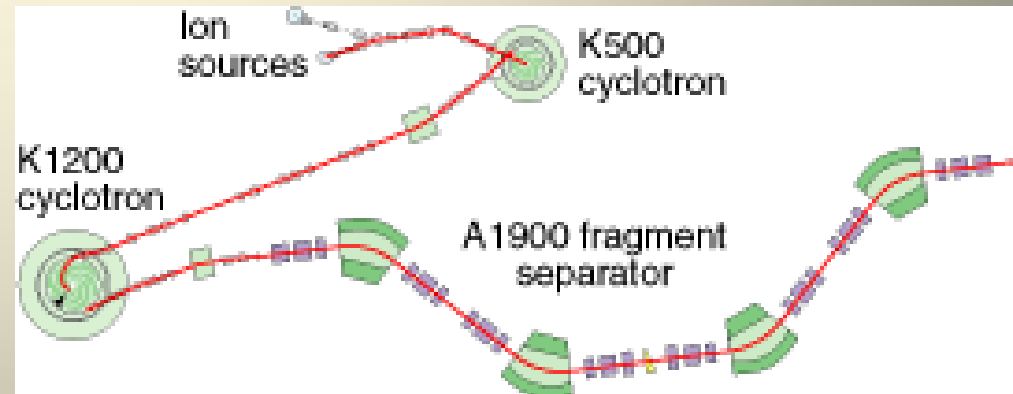
“Go big, or go home...”

Nuclear vs high-energy physics

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE

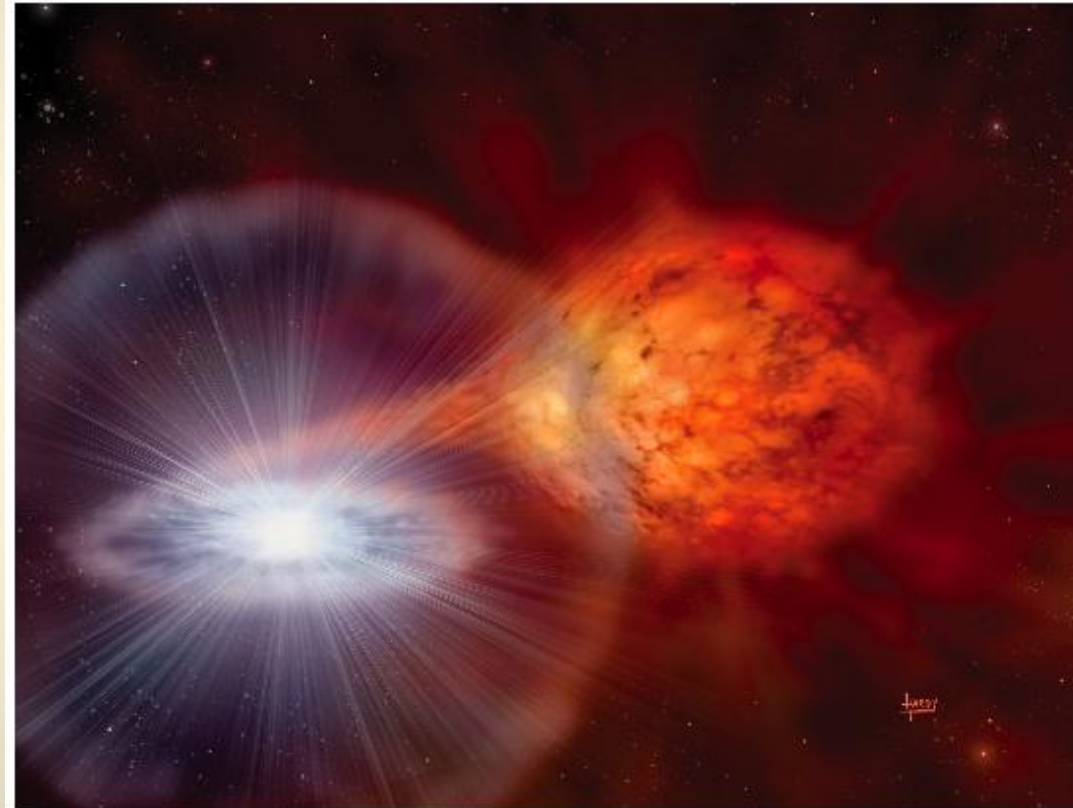


The **precision frontier** probes similar physics compared to colliders; is a **complementary** and important **cross-check**!



Nuclear physics and the cosmos

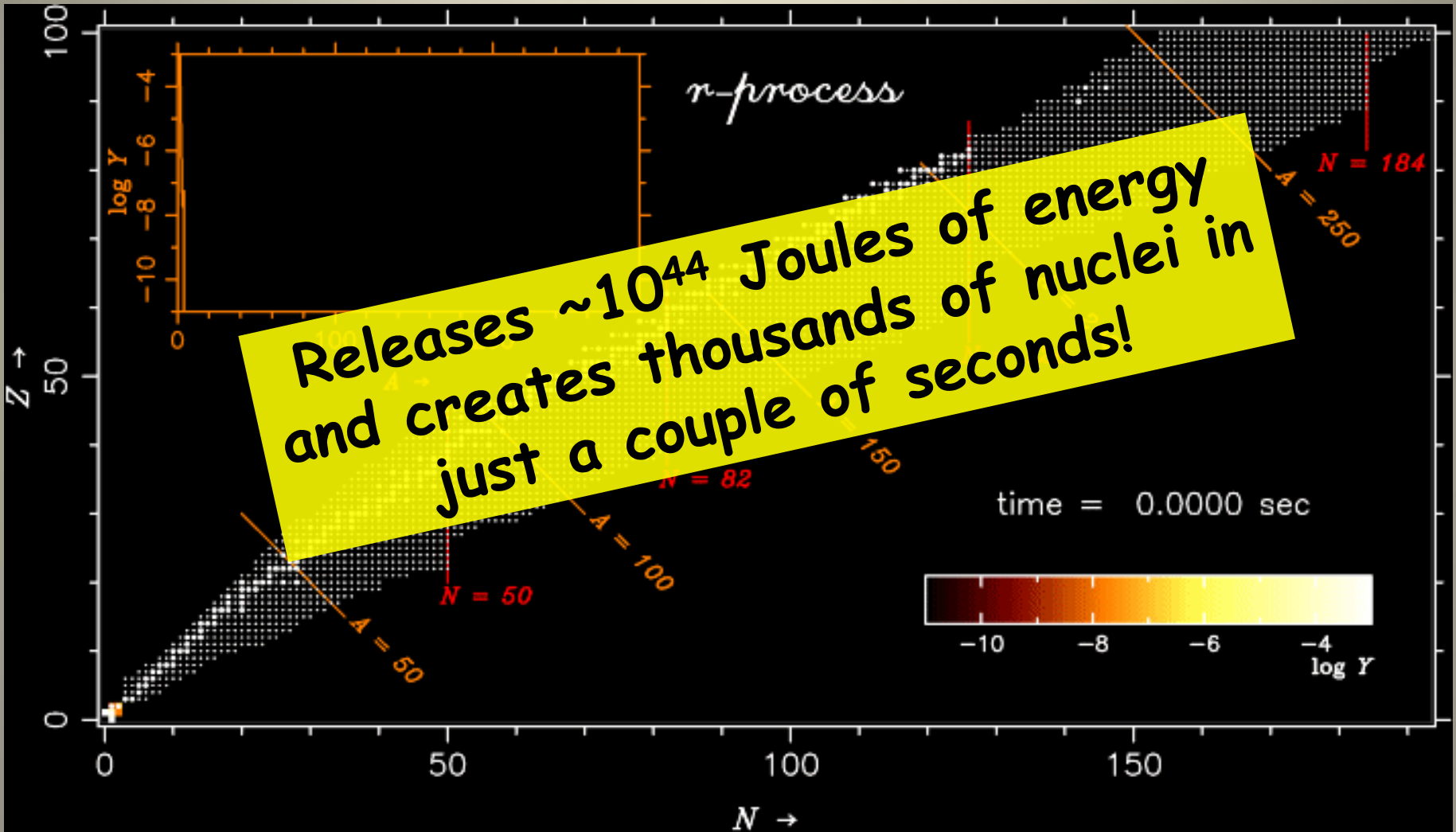
- One example: Type 1a supernovae — thermonuclear explosions of white dwarf stars
 - ❖ Grabs mass from a binary companion star until it reaches its critical mass (1.4 solar masses)
 - ❖ After ~1000 yrs of “cooking”, a violent explosion is triggered
 - ❖ Essentially the entire star is consumed in a *gigantic* explosion
 - ❖ Rough analogy: like detonating a hydrogen bomb the size of the Earth that has the mass of the Sun



Artist's rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly-degenerate.

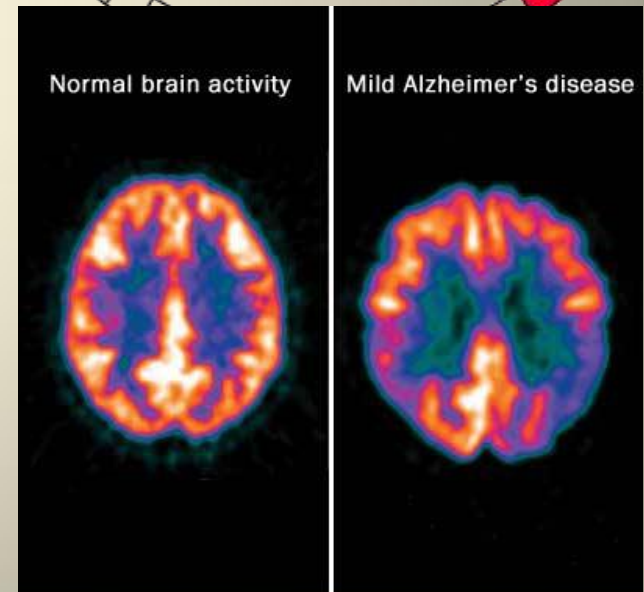
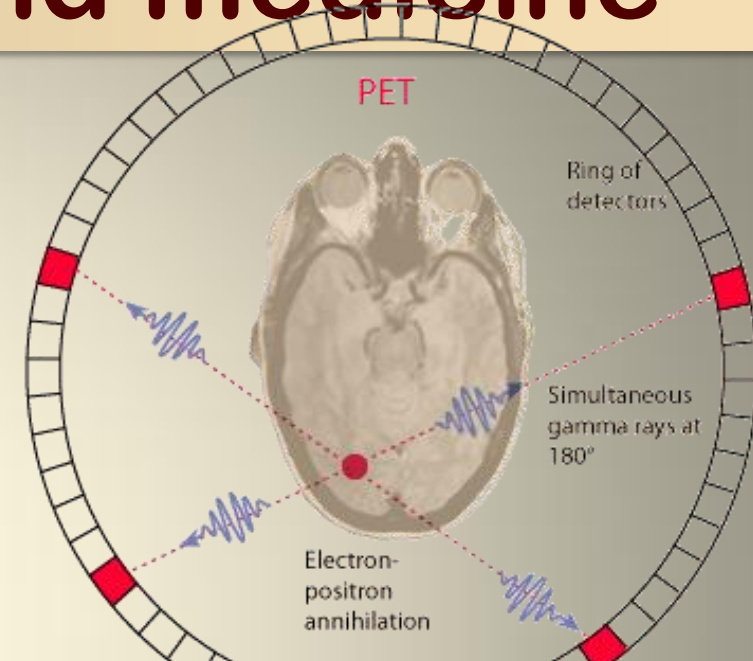
Image courtesy of David A. Hardy, © David A. Hardy/www.astroart.org.

Nuclear physics and the cosmos



Nuclear physics and medicine

- One example: Positron-Emission Tomography (PET) scans
- Another is proton therapy





Saturday Morning Physics

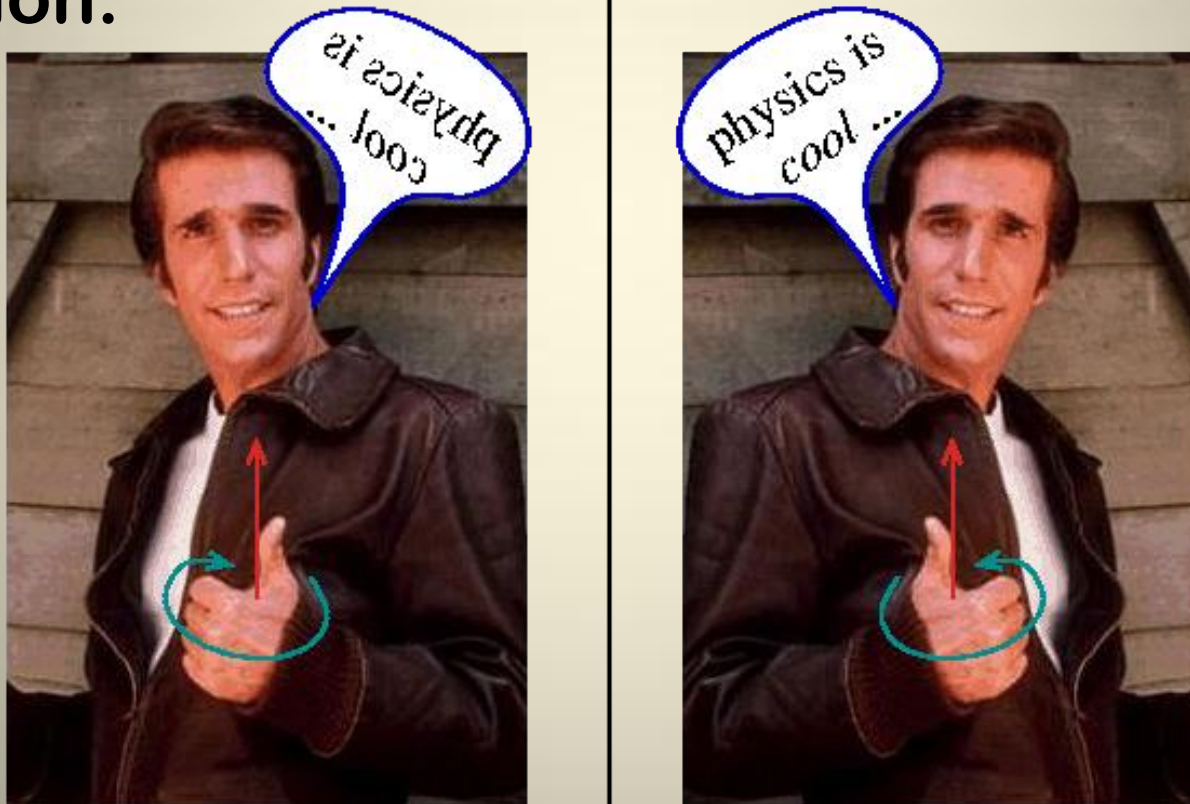
- Detectors/Accelerators
High-energy physics; the LHC and search for the Higgs
- Nuclear physics with "cool" technologies
- Cosmology and astronomy
- Biophysics



Dan Melconian

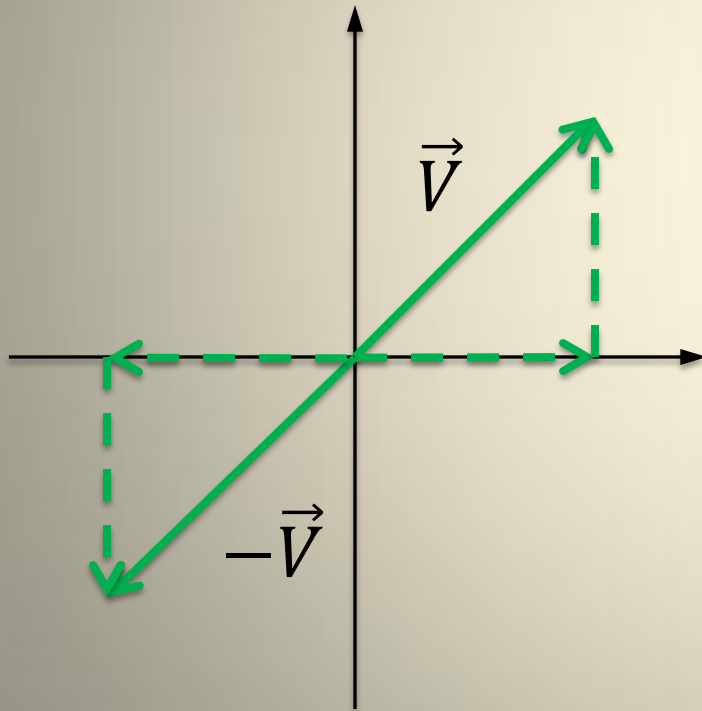
Back to fundamentals

- Symmetries play an important role in physics
- Parity — or “mirror symmetry” — is the symmetry under the transformation of space inversion:

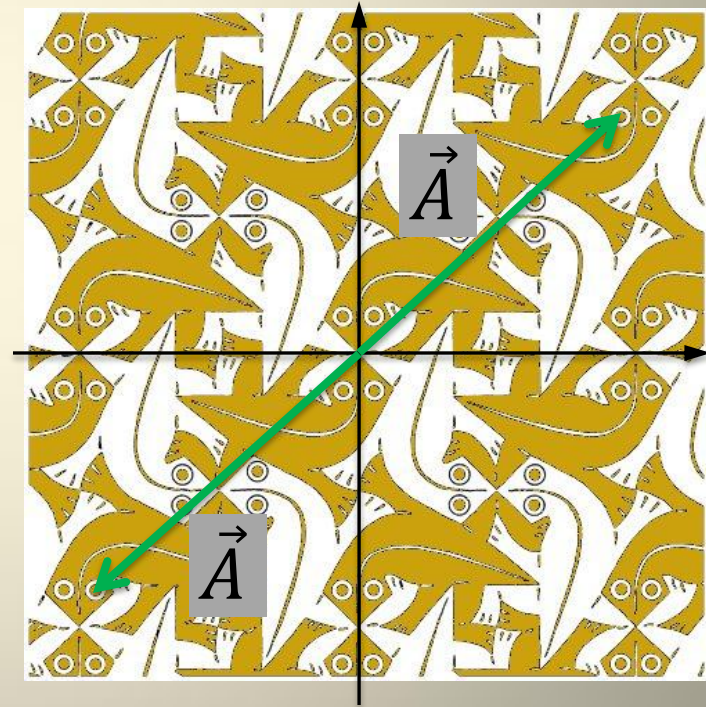


Back to fundamentals

- Symmetries play an important role in physics
- Parity — or “mirror symmetry” — is the symmetry under the transformation of space inversion:



negative parity

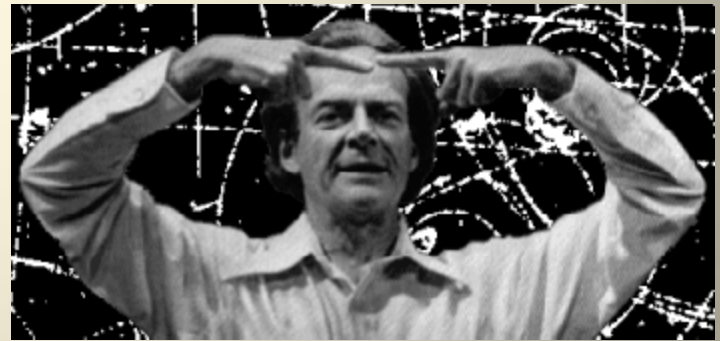
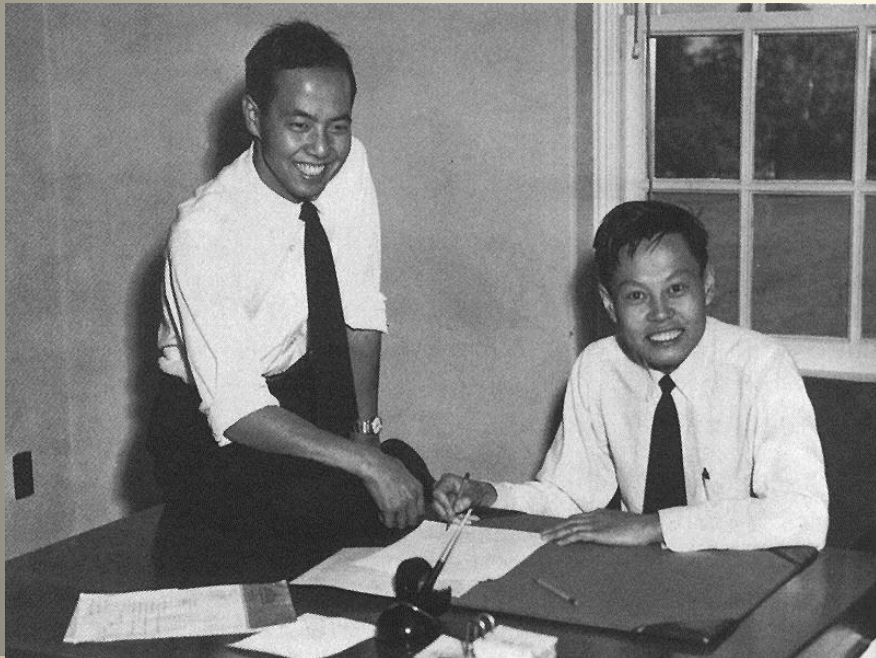


positive parity

Is parity *always* conserved...?

- In 1956, Lee and Yang noted:

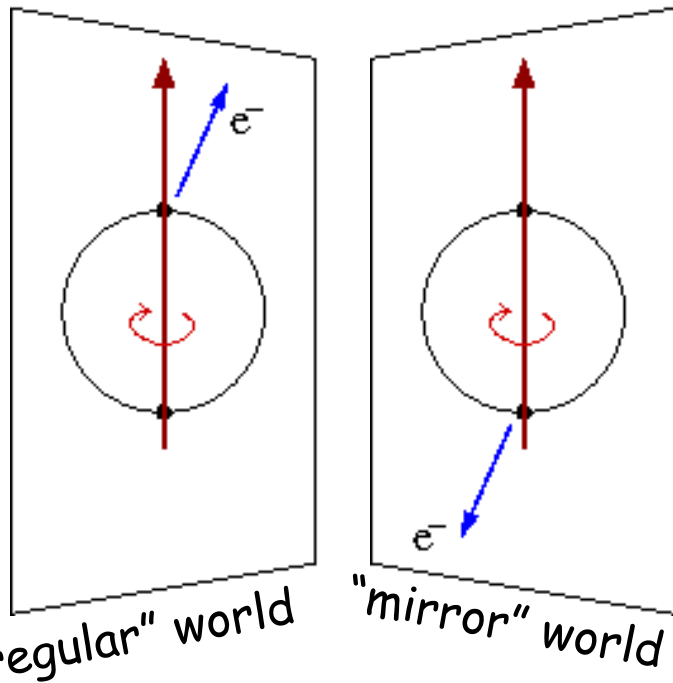
"...existing experiments do indicate parity conservation in strong and electromagnetic interactions, but that for weak interactions ... parity conservation is so far only an extrapolated hypothesis, unsupported by experimental evidence."



Feynman bets parity will be found to be conserved by the weak force too

C.S. Wu's experiment

If there is a correlation between the e^- and *spin*,
parity is not conserved



e^- direction: negative parity
nuclear spin: positive parity

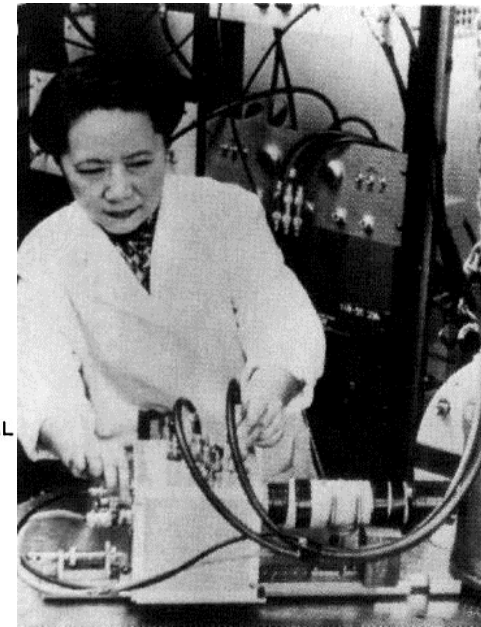
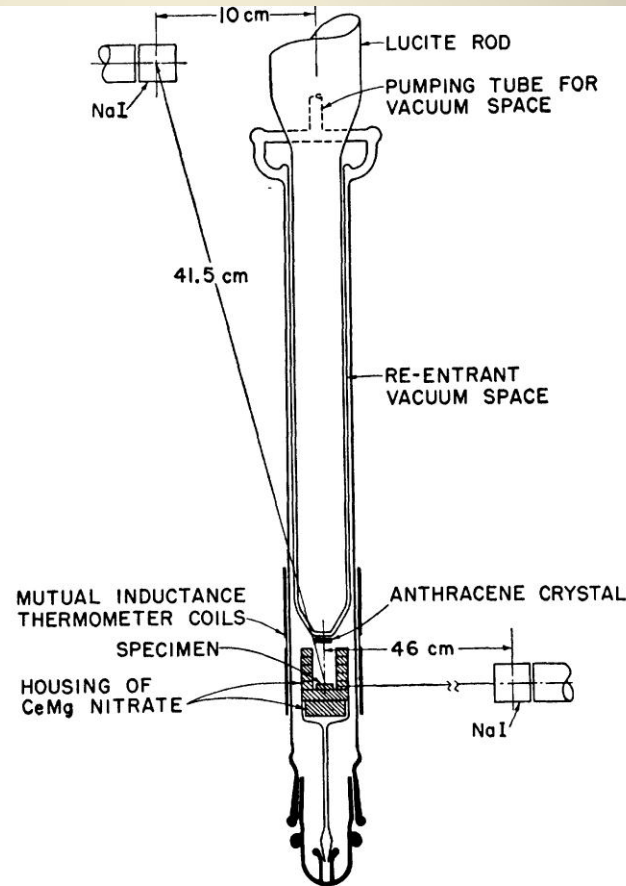
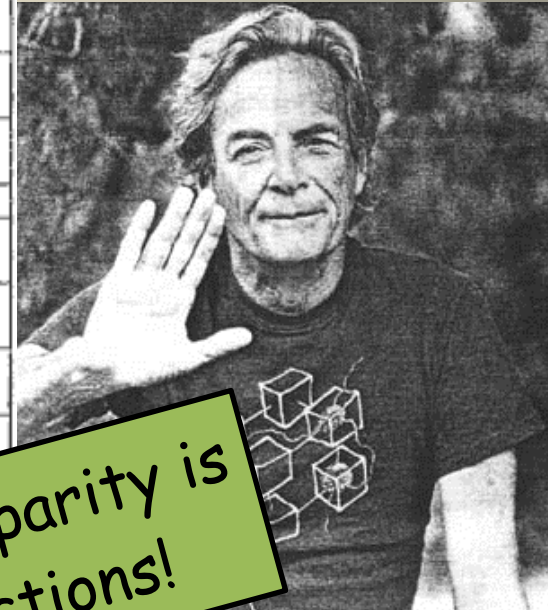
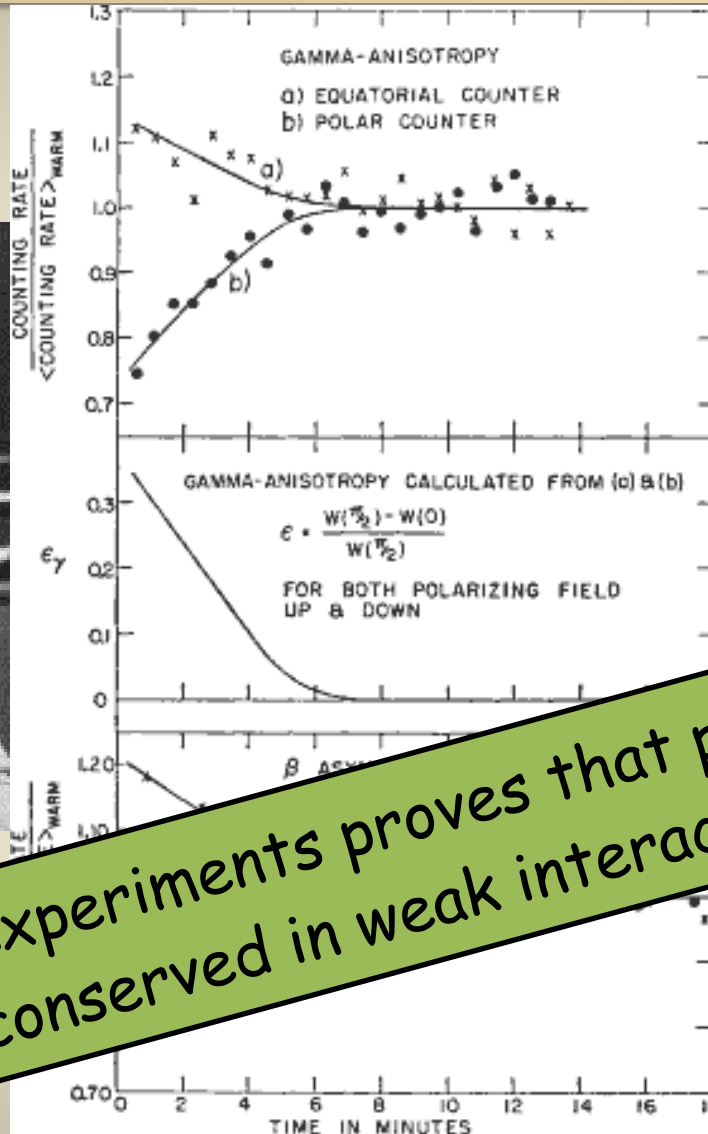


FIG. 1. Schematic drawing of the lower part of the cryostat.

Feynman loses \$50



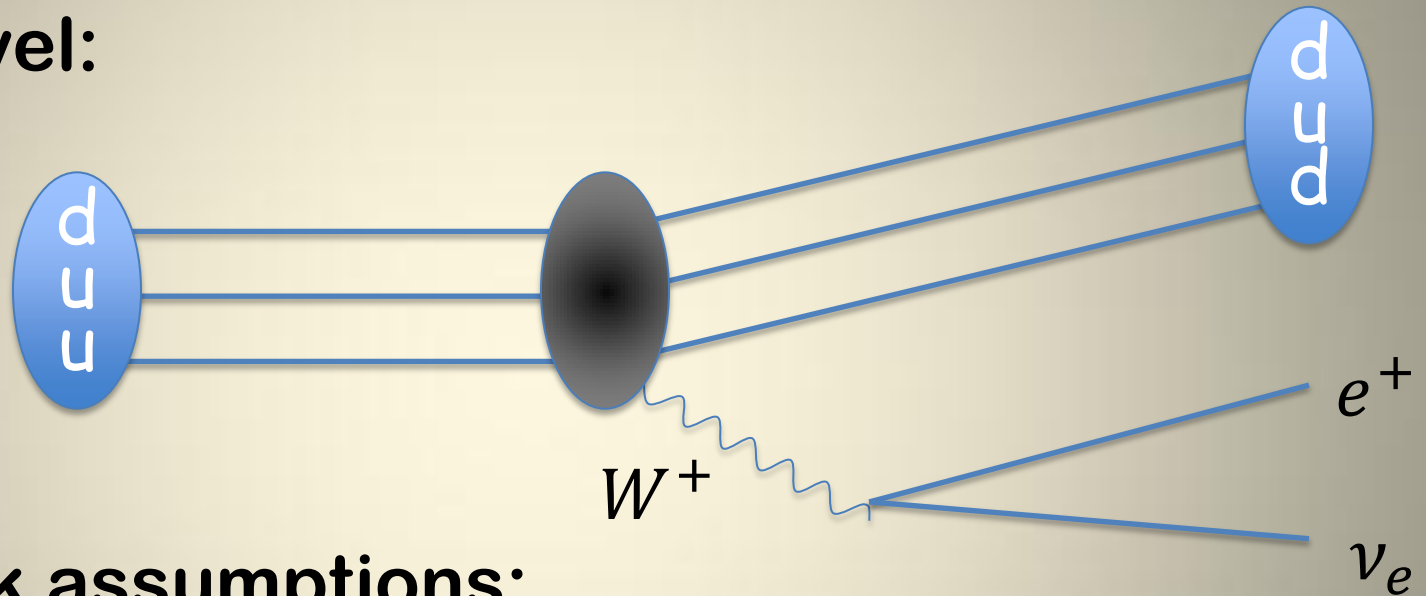
Nuclear experiments proves that parity is NOT conserved in weak interactions!

But, is it *maximally* violated?

- The Standard Model that you've heard is built upon a “ $V - A$ ” form for the weak interaction
- This violates parity as much as possible
(versus $V - 0.98A$, for example)
- Maybe there are $V + A$ aka “right-handed” components that are just hard to see?
- Personally, I find it hard to believe Nature isn't ambidextrous
- Nuclear physics continues the search...

Nuclear β decay

- Zooming in, β decay is described by a weak interaction occurring within the nucleus at the quark level:



- Textbook assumptions:
 1. The decay occurs from rest
 2. The decay occurs from a point in space
 3. Particles escape without distortions
 4. Nucleus is perfectly polarized

Basic idea: improve upon Wu

- To complement high-energy searches, correlation experiments need to reach precisions of $\sim 0.1\%$

\Rightarrow pretty demanding!

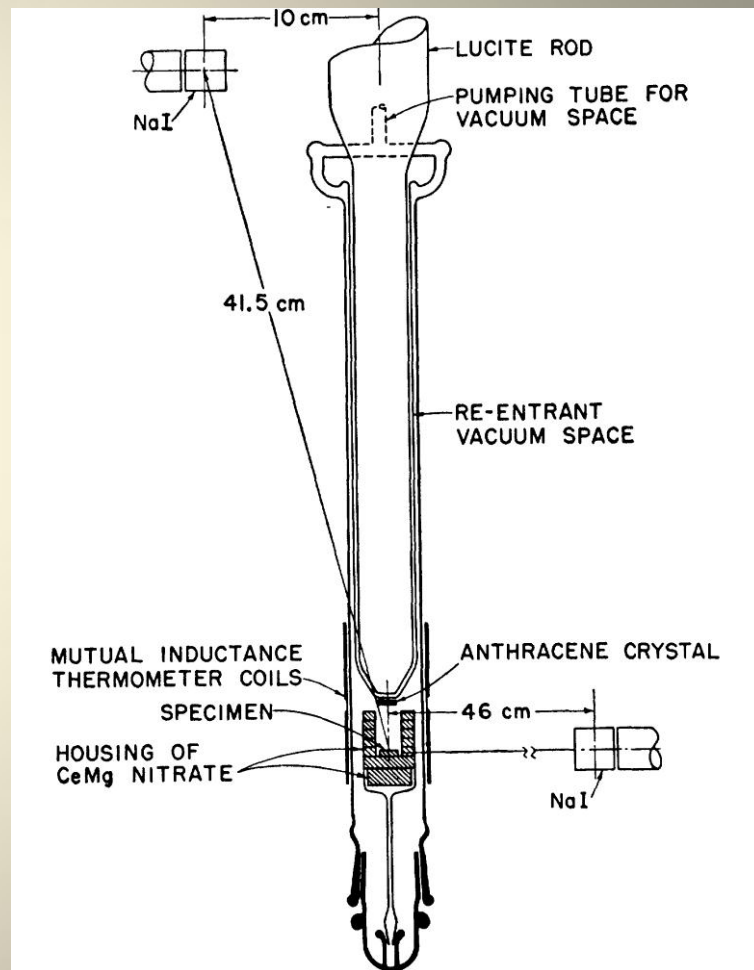
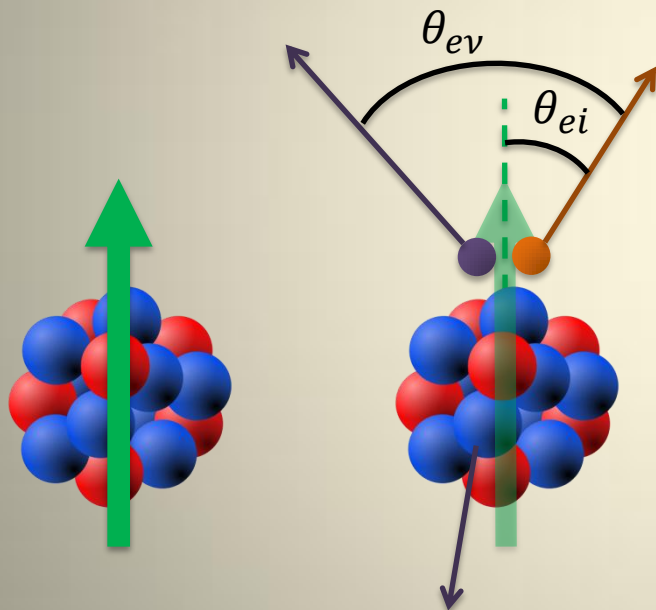
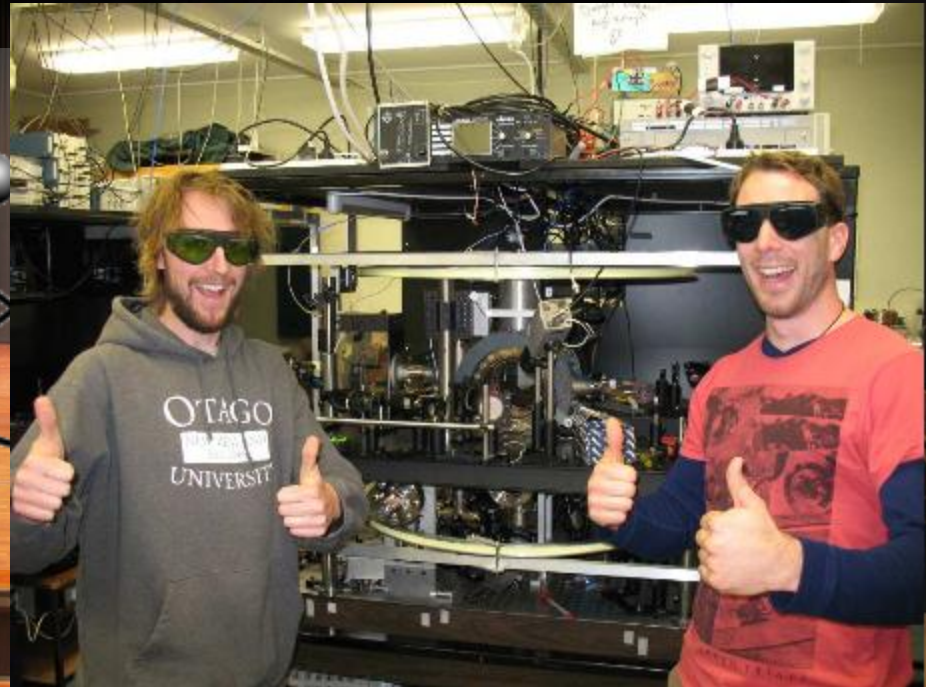
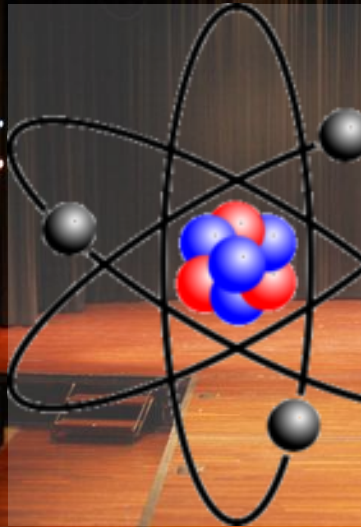


FIG. 1. Schematic drawing of the lower part of the cryostat.

Enter: “Cool” Technologies

Atoms and lasers



Magneto-optical traps

- Textbook assumptions:
 1. The decay occurs from rest ✓
 2. The decay occurs from a point in space ✓
 3. Particles escape without distortions ✓
 4. Nucleus is perfectly polarized ✓



Steven Chu



Claude Cohen-Tannoudji



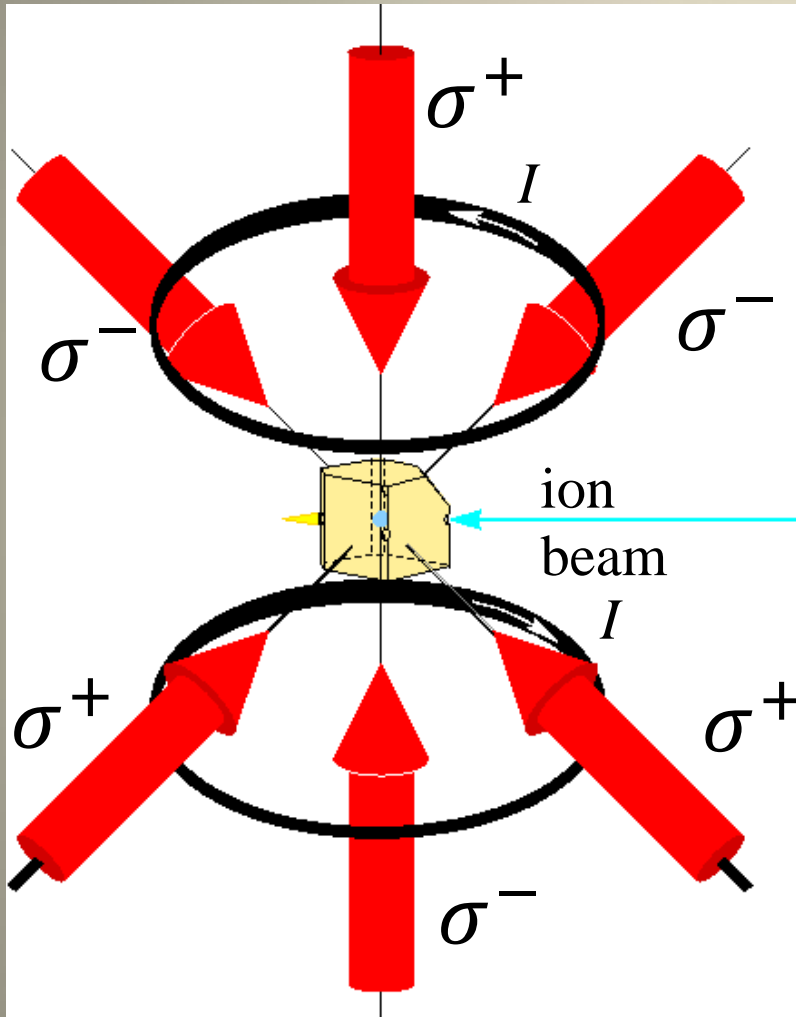
William Philips

1997

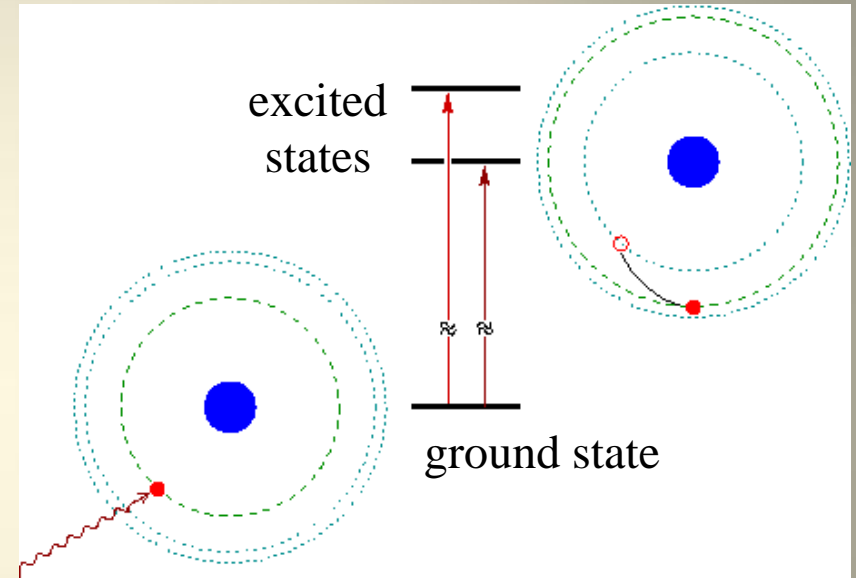


"For development of methods to cool & trap atoms with laser light"

A vapour-cell MOT

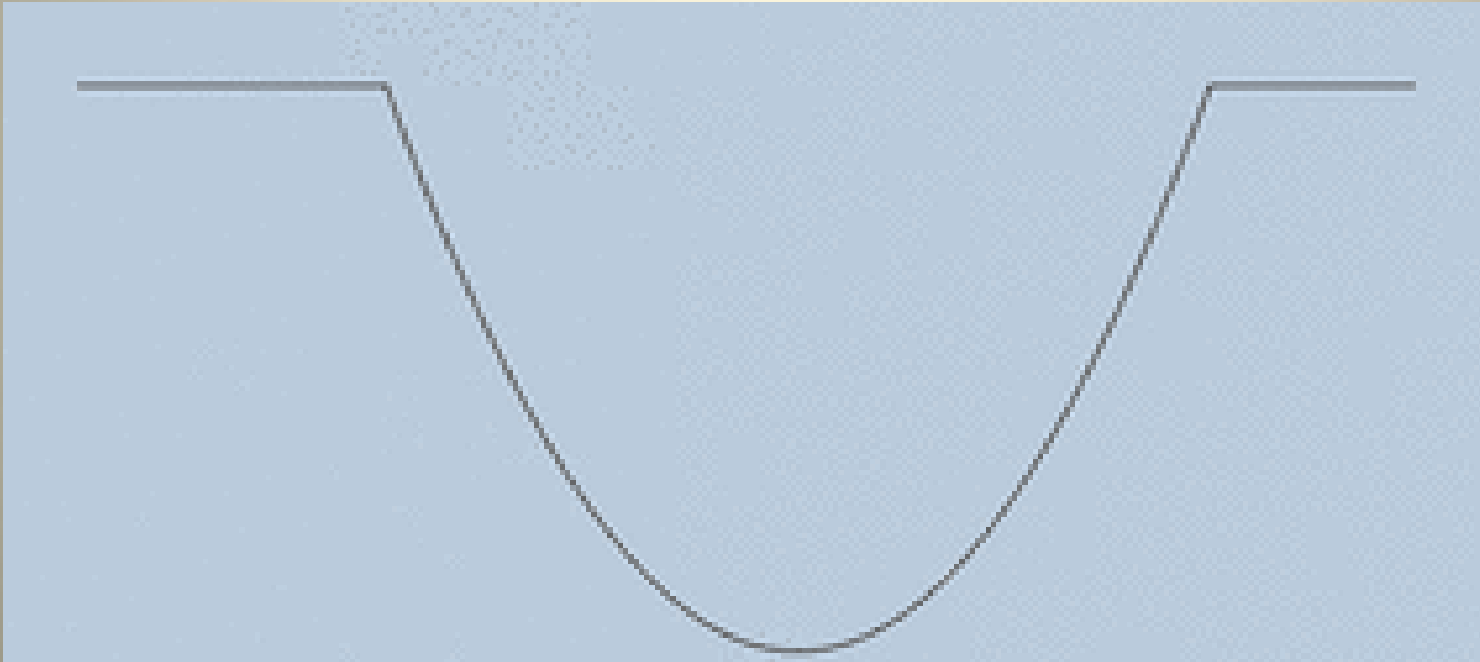


Laser excites atomic transitions:



Basic idea behind *any* trap

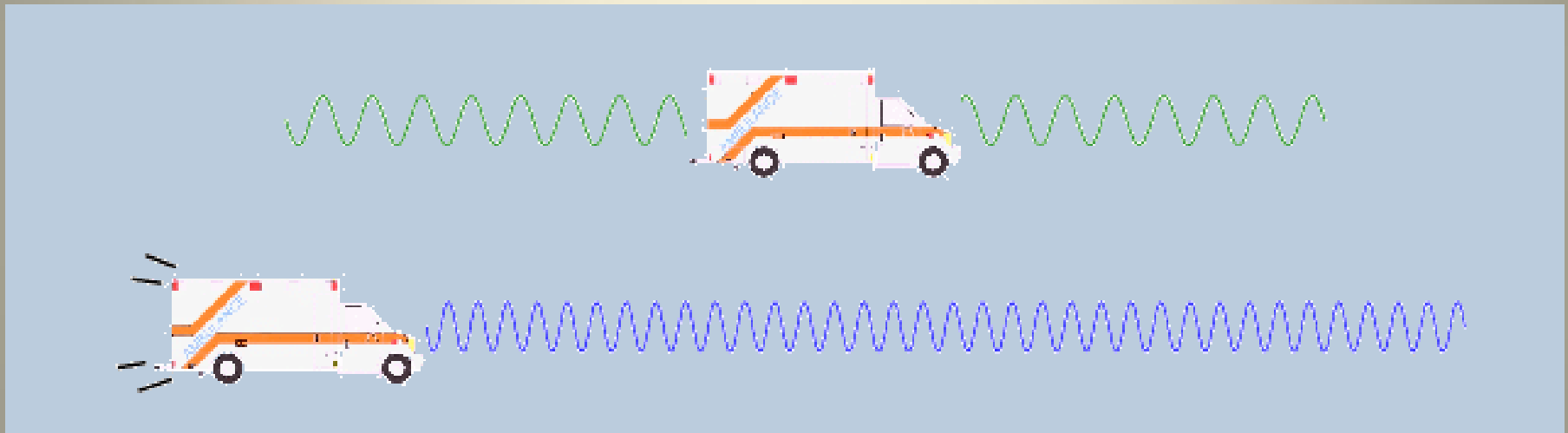
- **Speed**-dependent force: **dampens** the motion and slows the particle down
- **Position**-dependent force: defines **where** particles get trapped



E.g.: Ball in a valley ... *with* friction

How does a MOT work?

- **Speed**-dependent force: the **Doppler effect**
- **Position**-dependent force: **magnetic fields** make absorption rate depend on distance from centre



Lab frame:   
Atom's frame:  

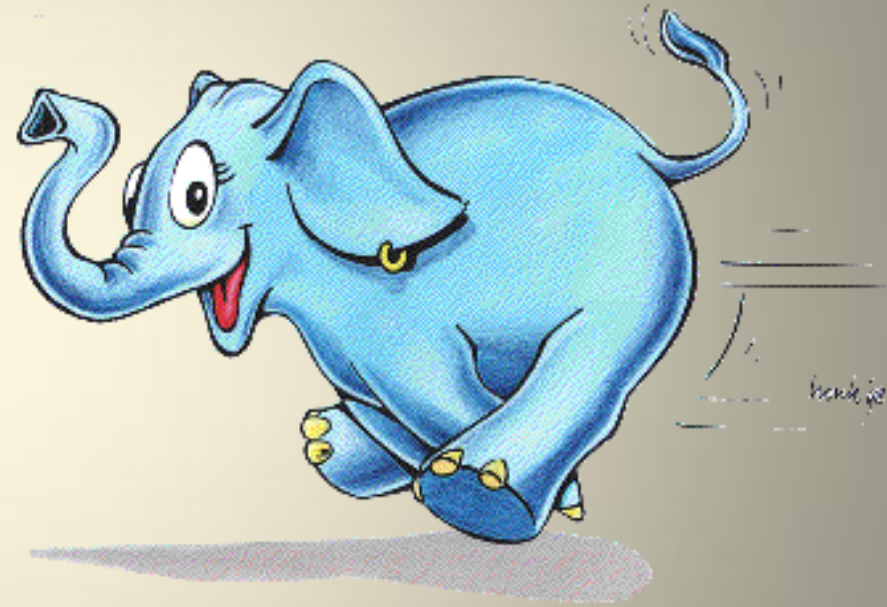
The Doppler effect changes rate of absorbing laser beam

Atom—photon interactions

- How can light seriously affect a thermal atom?!?



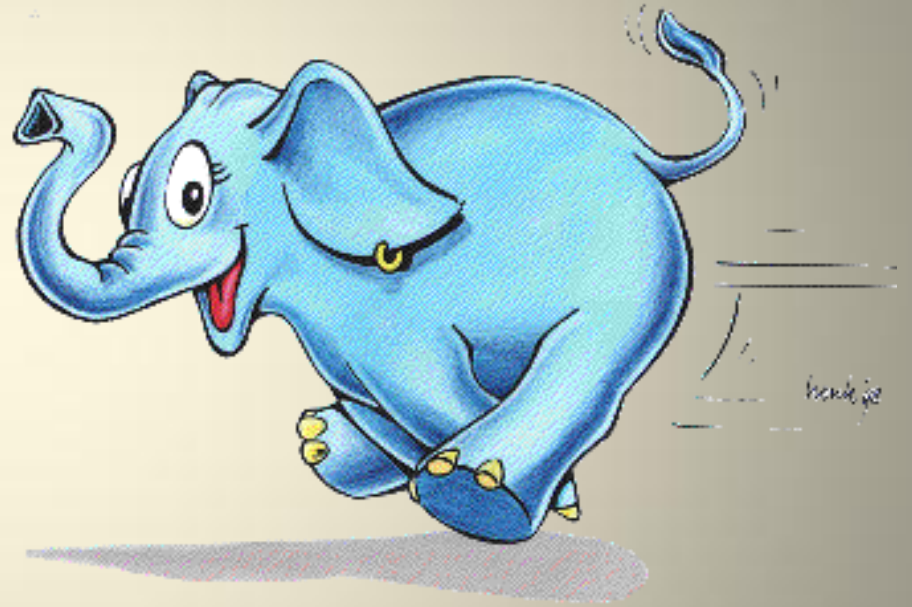
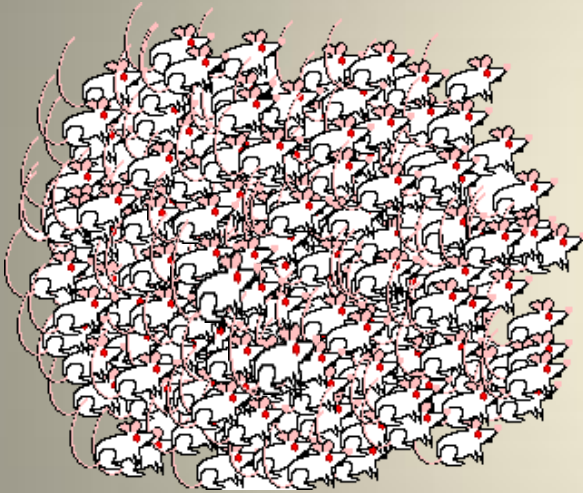
VS.



$$\hbar \vec{k} \sim 1.5 \text{ eV}/c$$

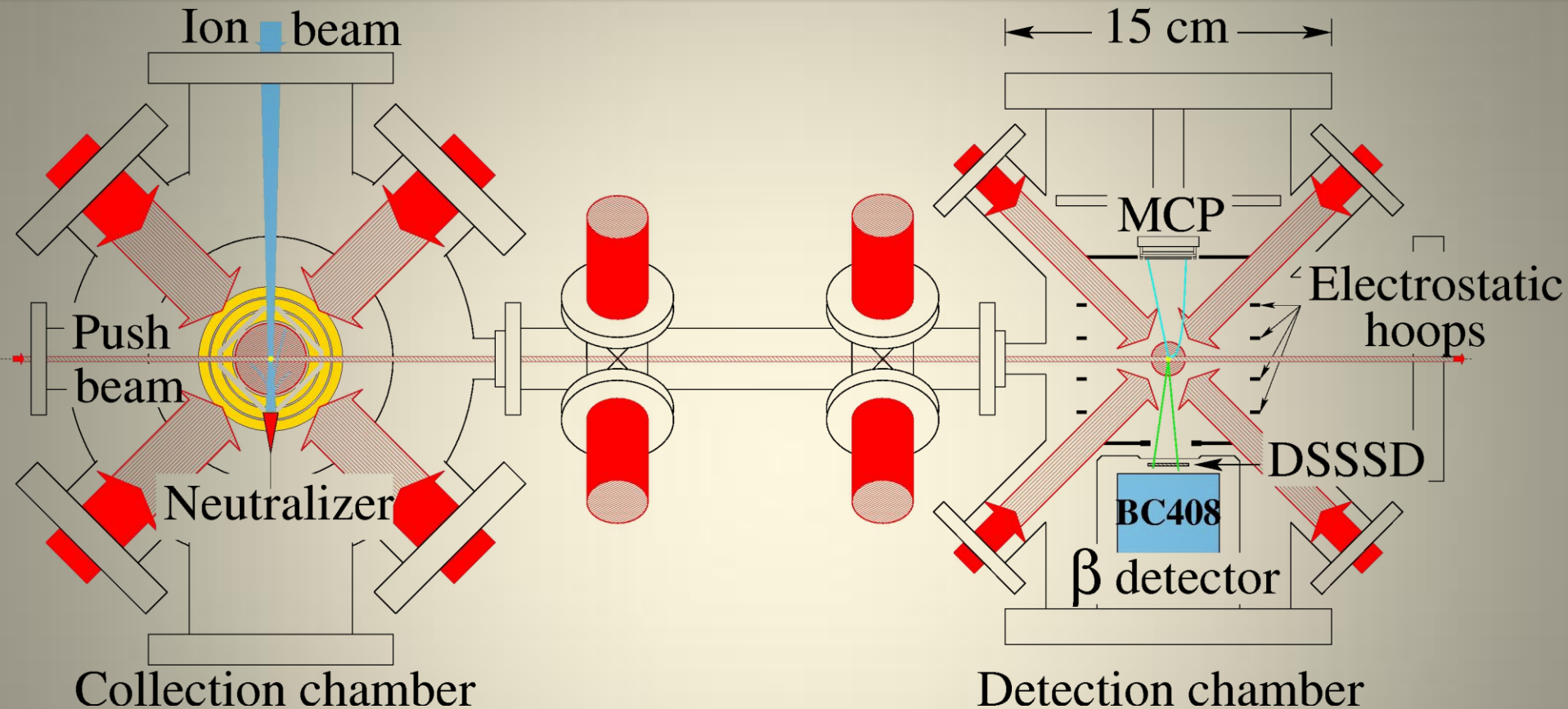
$$M\vec{v} \sim 45,000 \text{ eV}/c$$

Atom—photon interactions



Cycling transitions!!

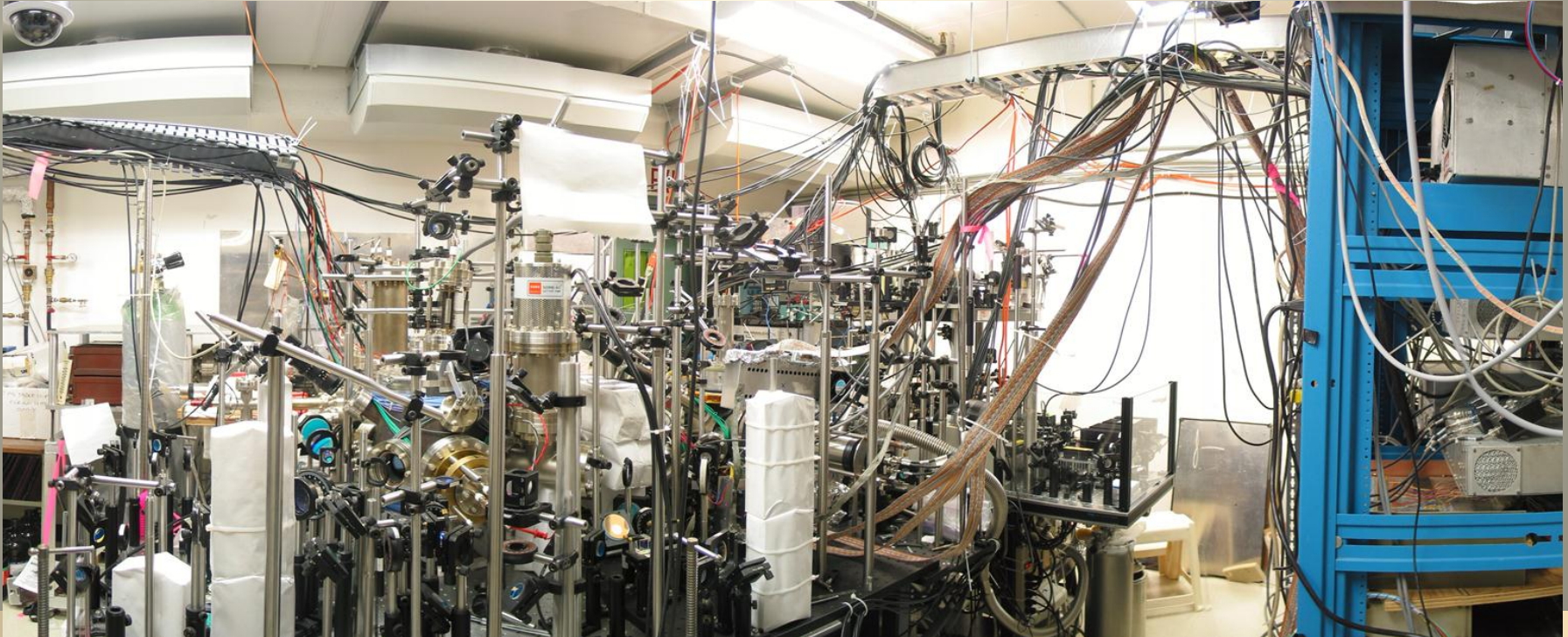
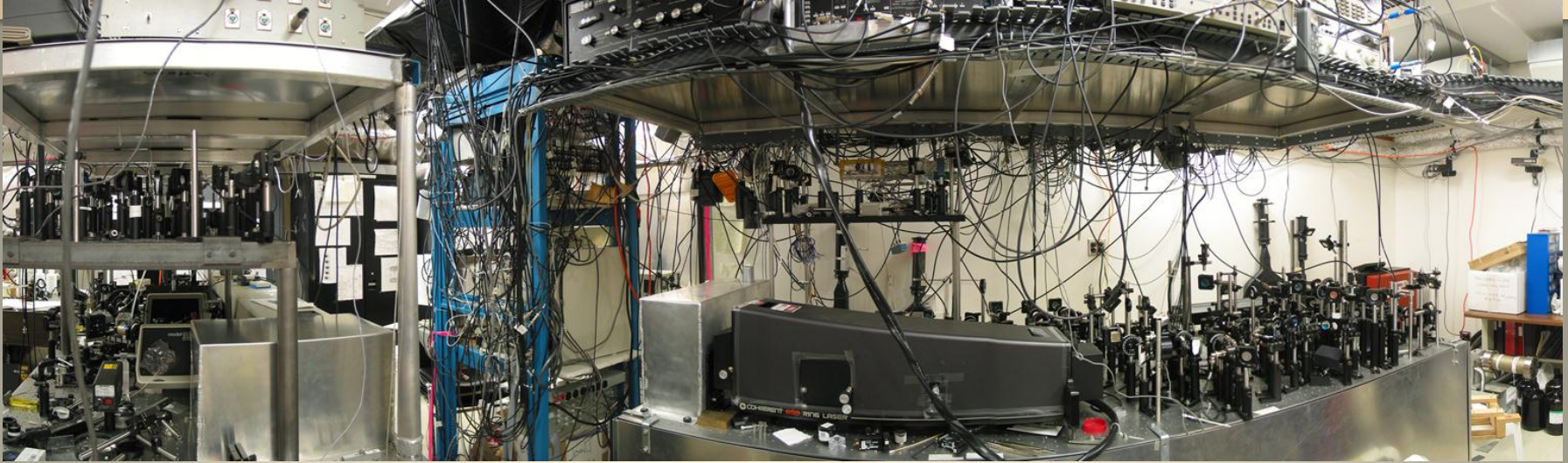
A double-MOT system



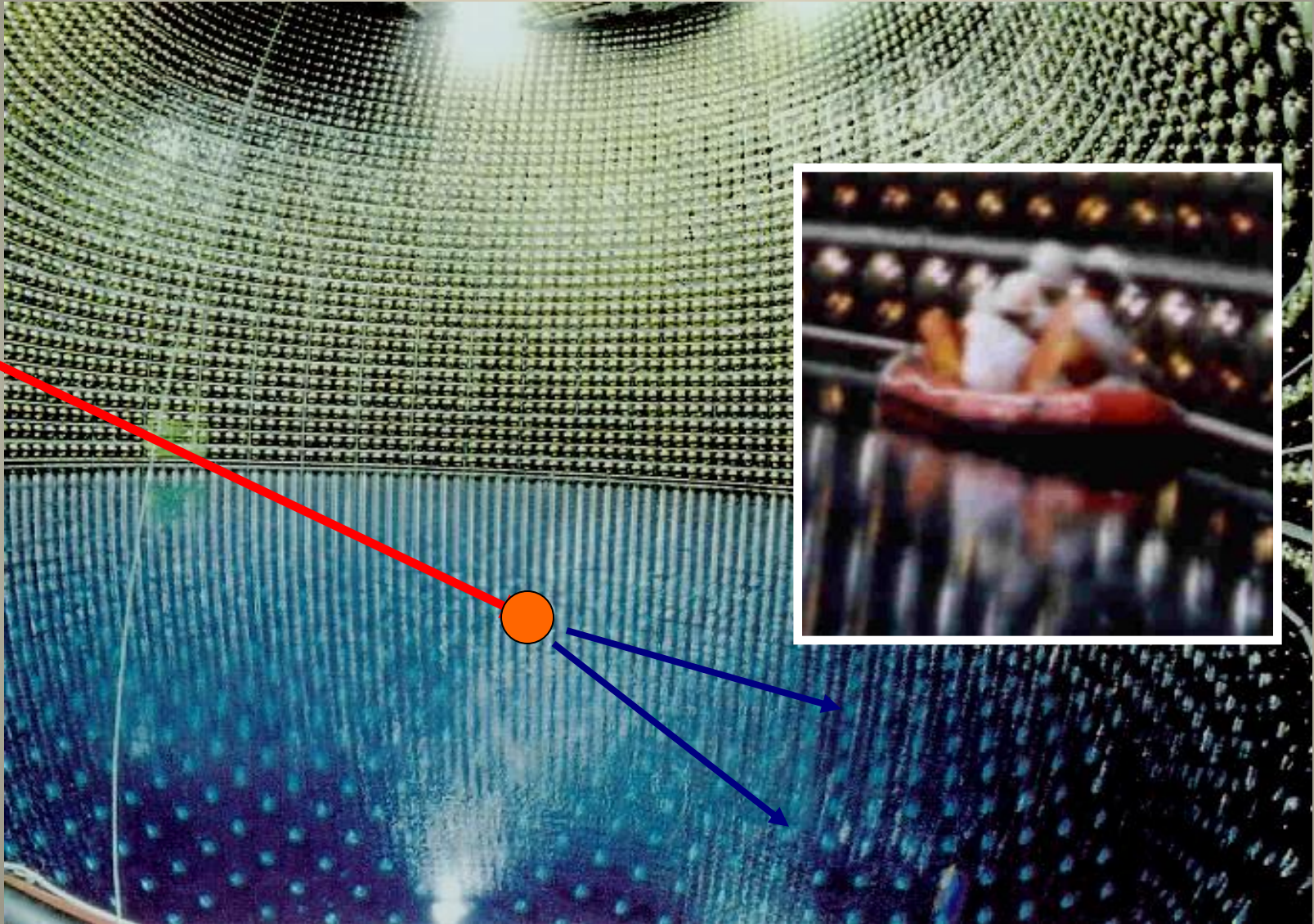
Traps provide a **backing-free**, **cold** ($\sim 1\text{mK}$), **localized** ($\sim 1\text{mm}^3$) source of **short-lived** radioactive atoms

Detect \vec{p}_e and $\vec{p}_{\text{recoil}} \Rightarrow$ deduce \vec{p}_ν event-by-event!!

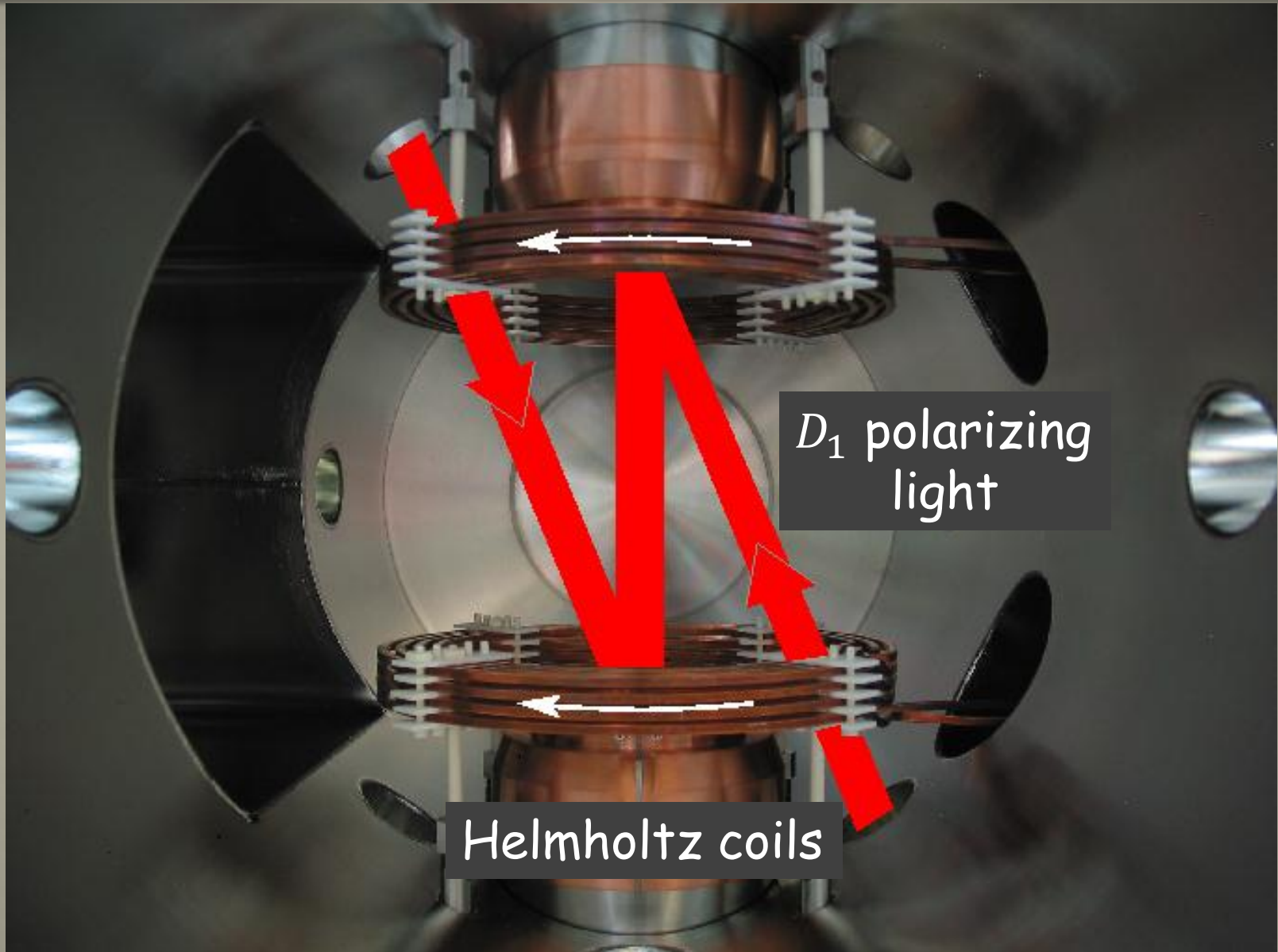
Just in case you thought it was *easy*...!!



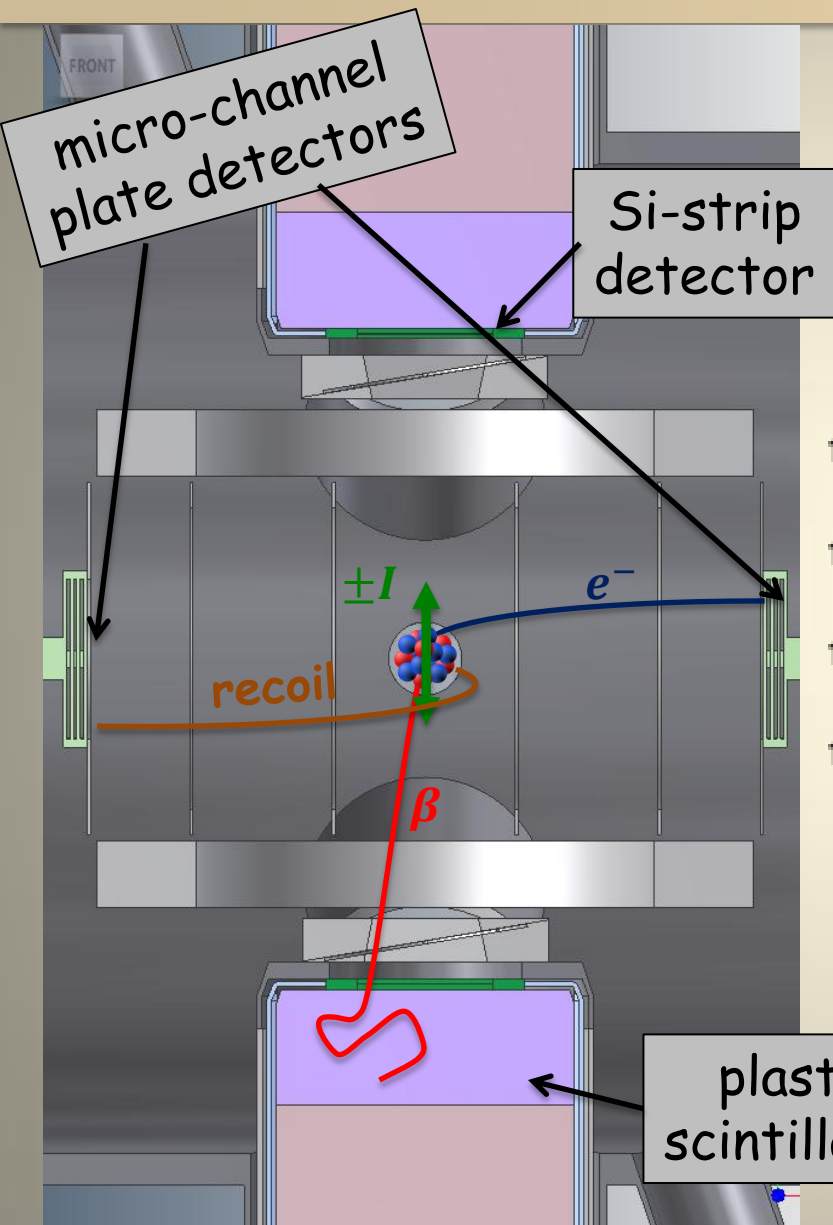
(but it's still easier than this :-P)



Latest generation of expts

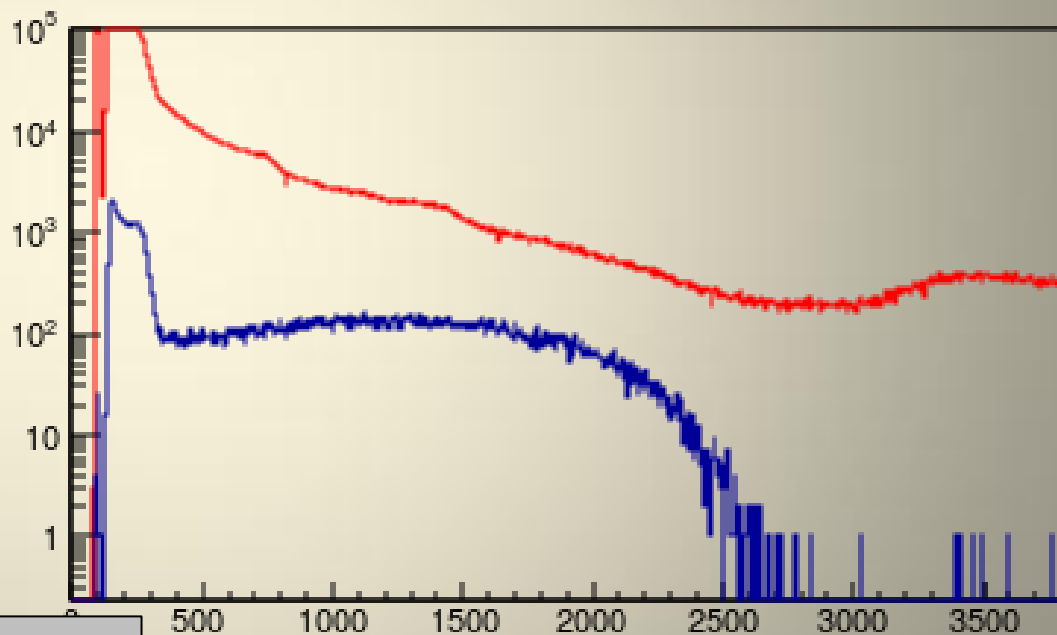


Worked beautifully in December



$$\text{Asymmetry} = \frac{N_+ - N_-}{N_+ + N_-}$$
$$\sim PA_\beta$$

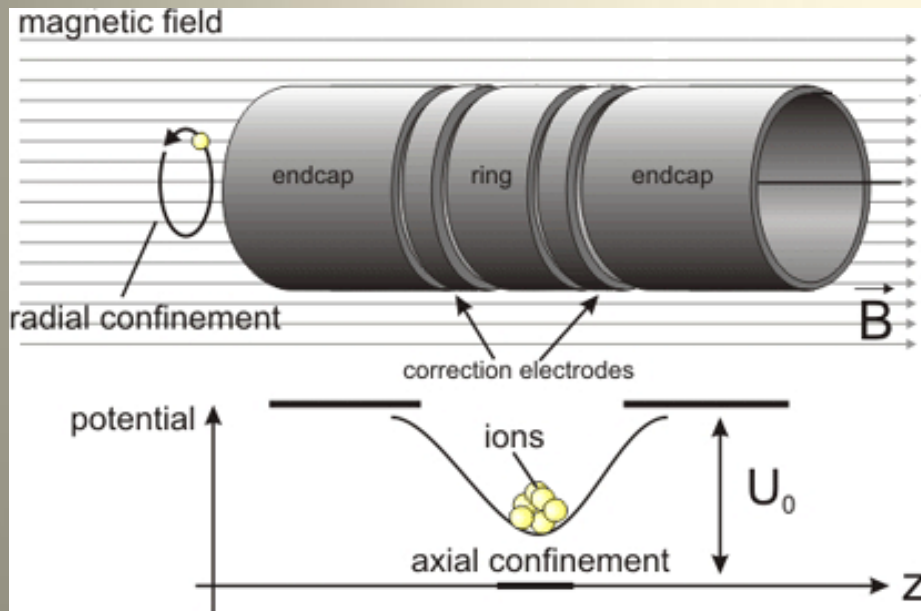
Upper_Scintillator_Run_0996



Stay tuned for recent results!

No time for ion traps ☹️

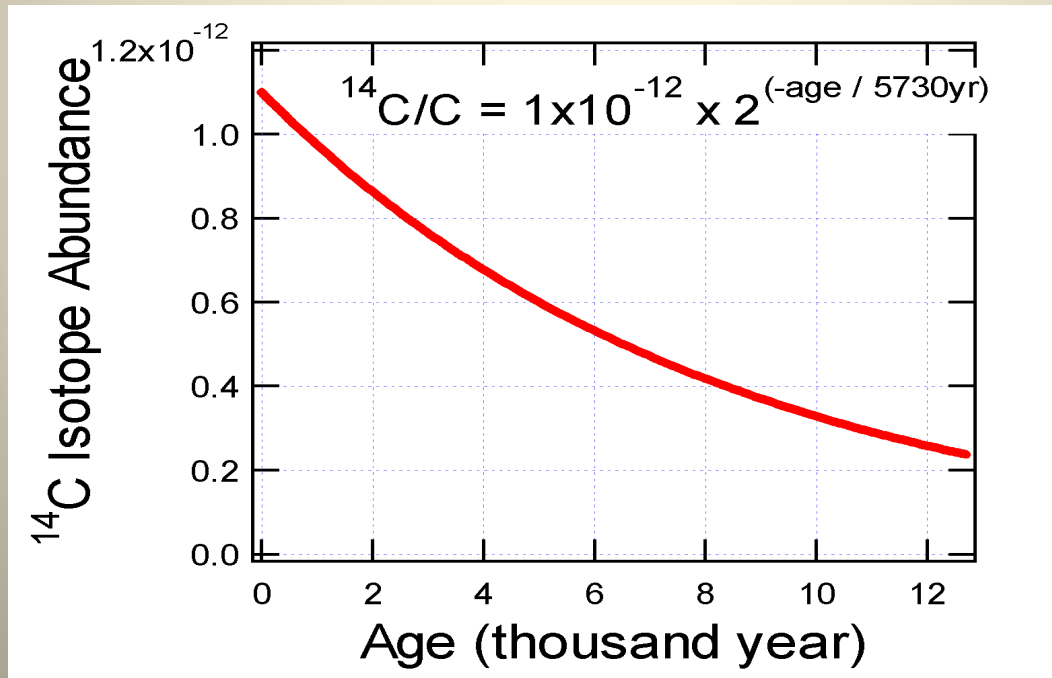
- MOTs are a wickedly *cool* technology that provide an ideal source of short-lived atoms
- Unfortunately, MOTs are very particular about what they can trap
- Ion traps do not suffer from this drawback!



<http://youtu.be/PYpbKSmOnNc>

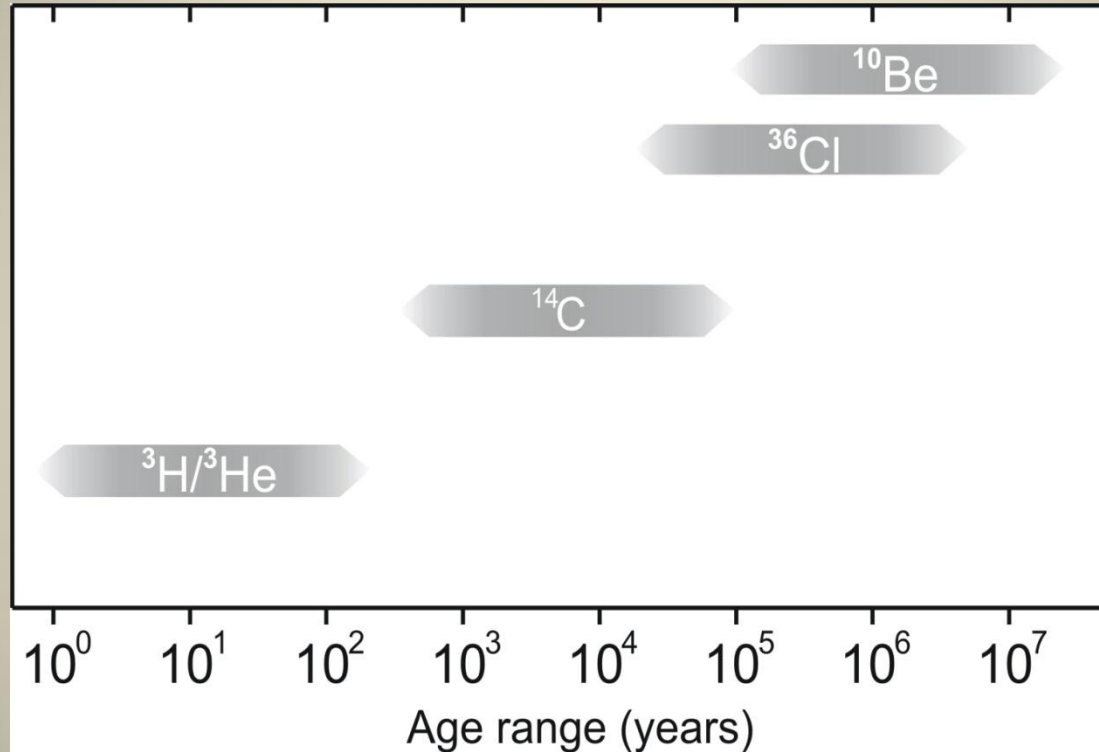
Nuclear physics and geology

- ^{14}C is well-known for radio-carbon dating
 - Half-life is $t_{1/2} = 5730$ yrs
 - Isotopic abundance is 1×10^{-12}
 - Widely accepted
 - Limited to 50,000 yrs or less



And there are others

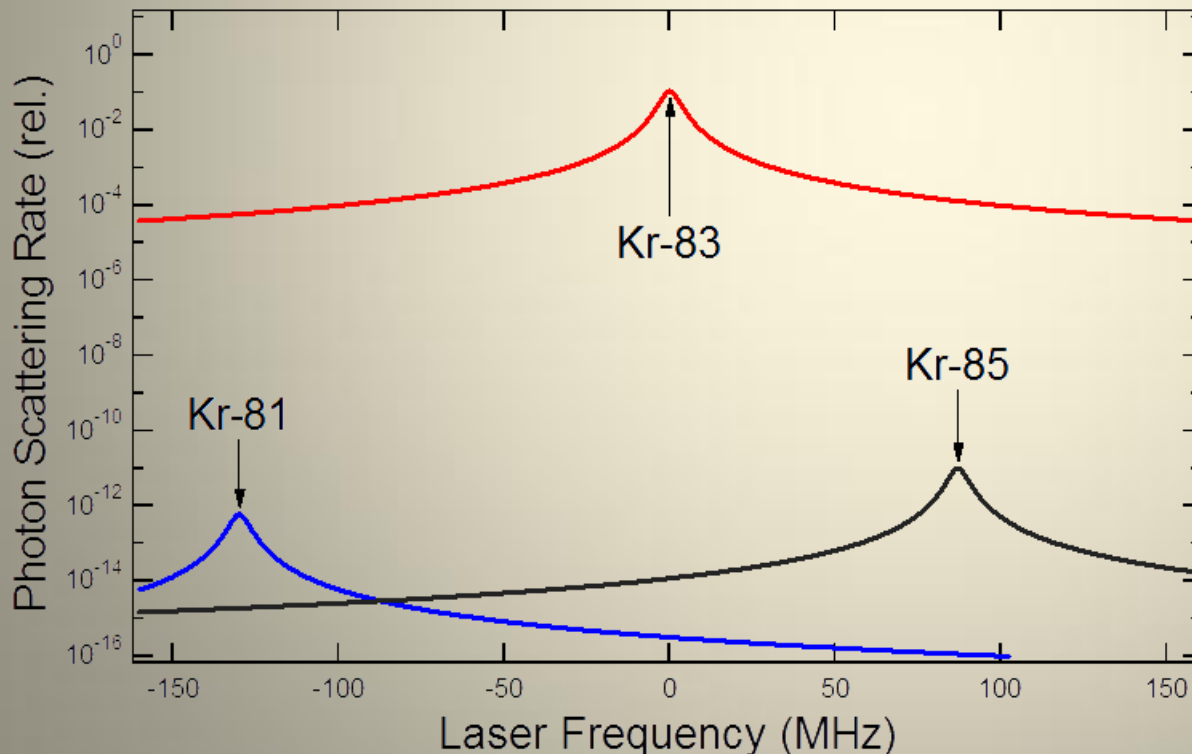
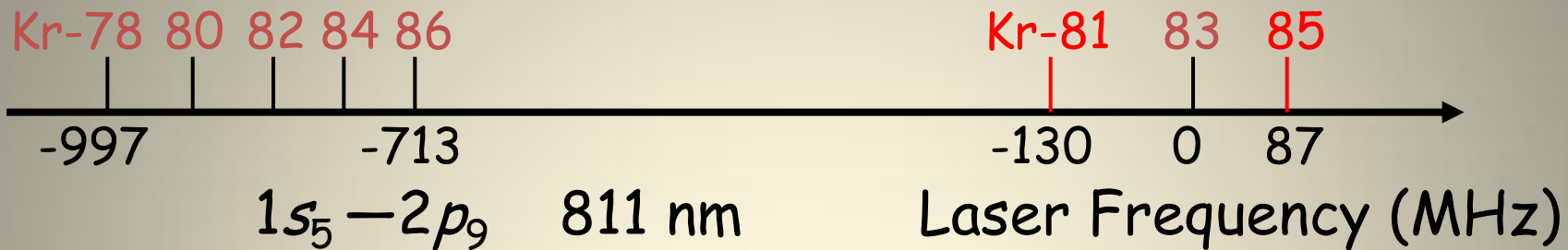
- To cover different times in history, need isotopes with longer/short half-lives



- Noble gases can fill in the gaps

How to measure trace amounts?

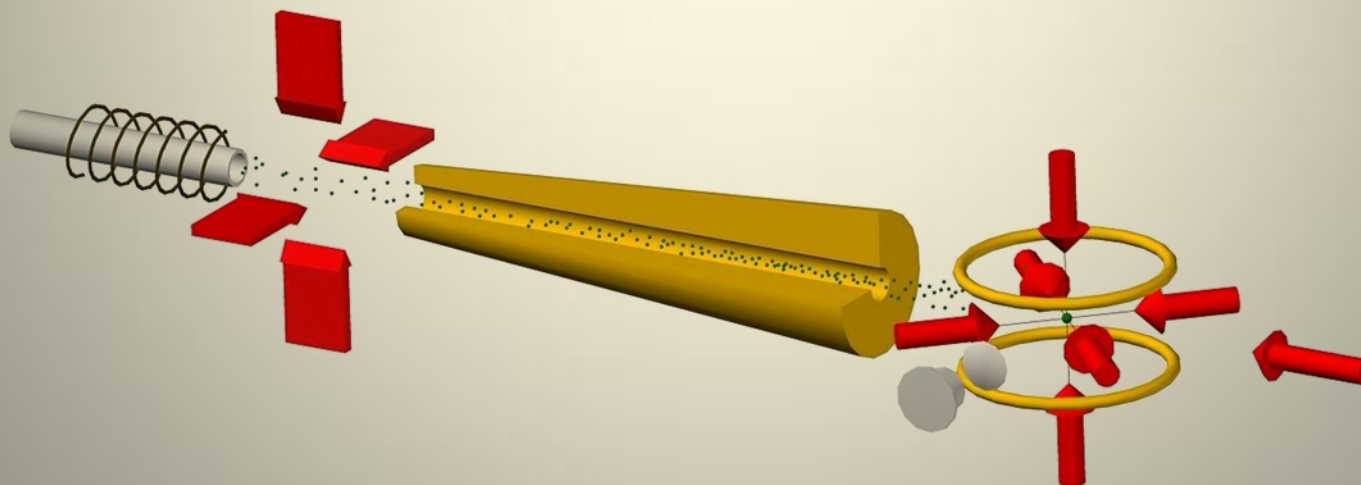
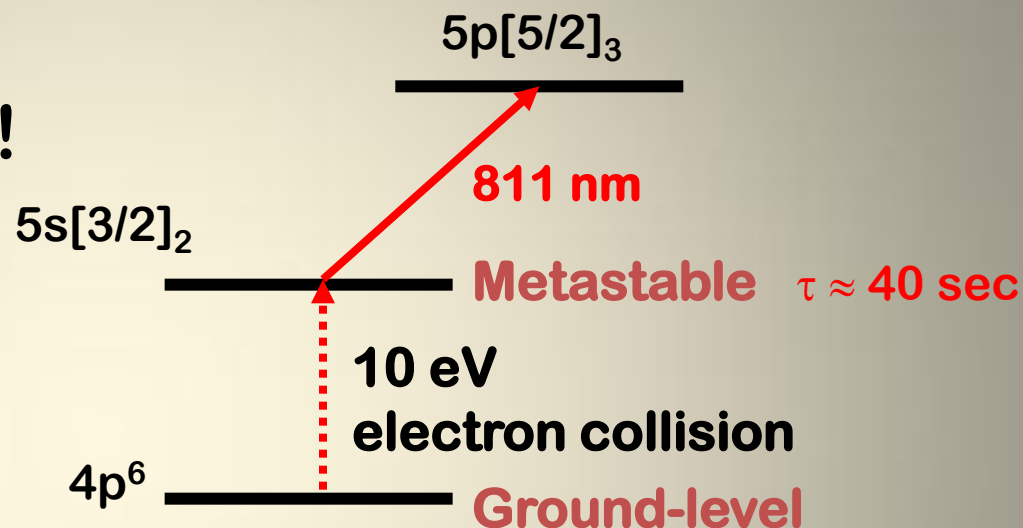
- Atomic transitions are *extremely* selective!



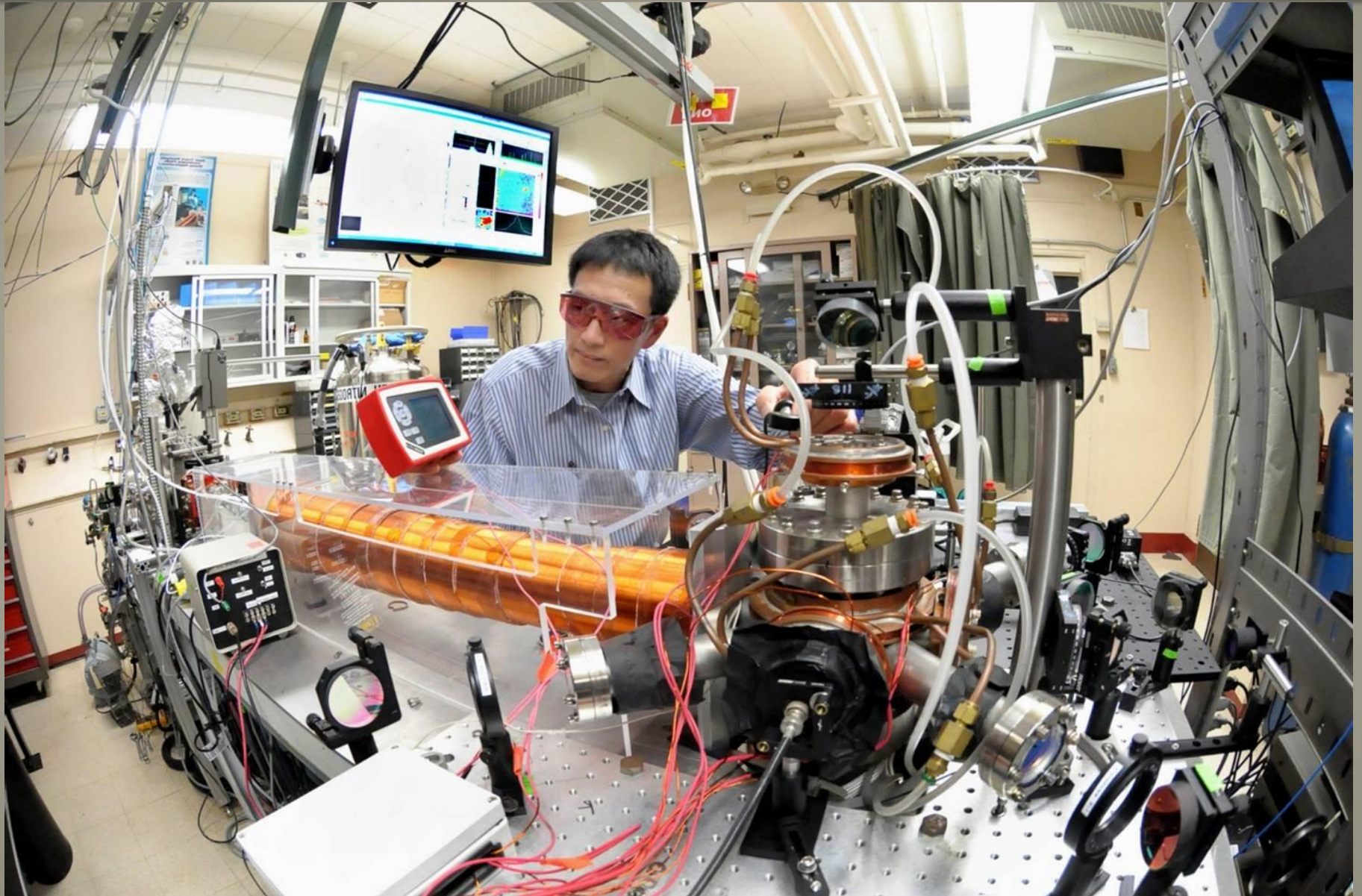
Due to Doppler-broadening, ^{83}Kr is still 100,000,000x bigger than the ^{81}Kr signal!

How to measure trace amounts?

- Put your laser on resonance, and repeat repeat repeat
- Trap them in a MOT!!



ATTA at ANL

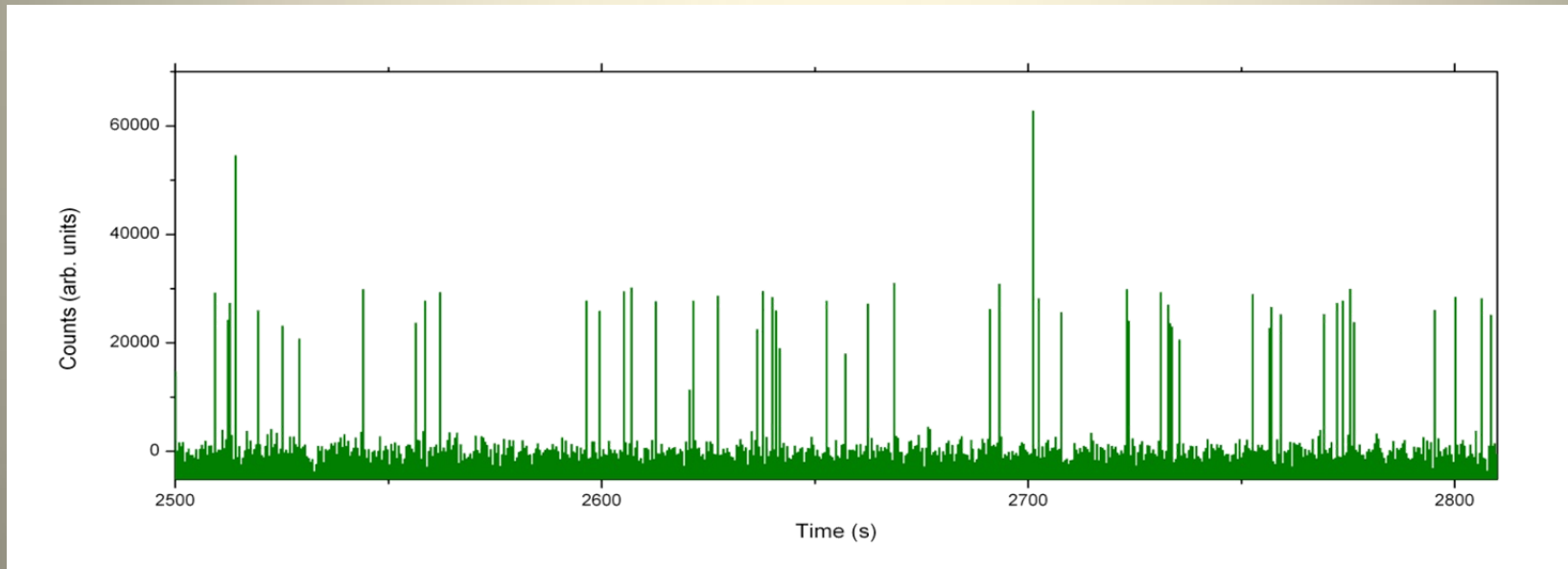
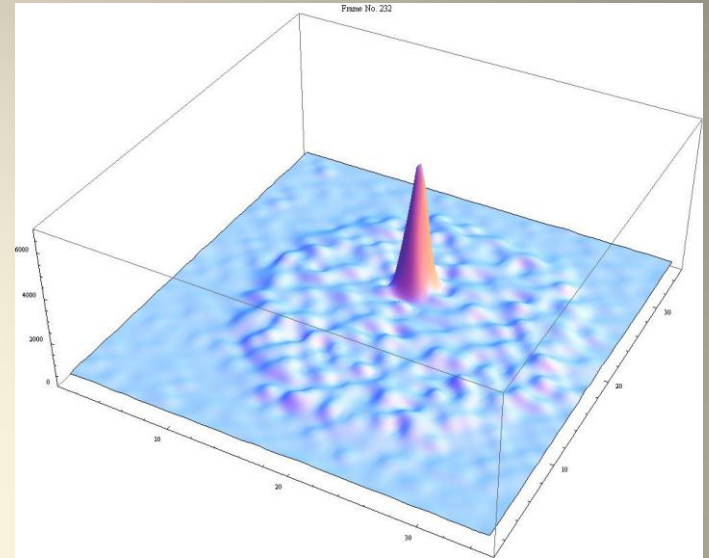


Dan Melconian



Single atom detection

- CCD image profile of a *single* ^{81}Kr atom
- $^{81}\text{Kr}/\text{Kr} = 6 \times 10^{-13}$
= 0.6 ppt



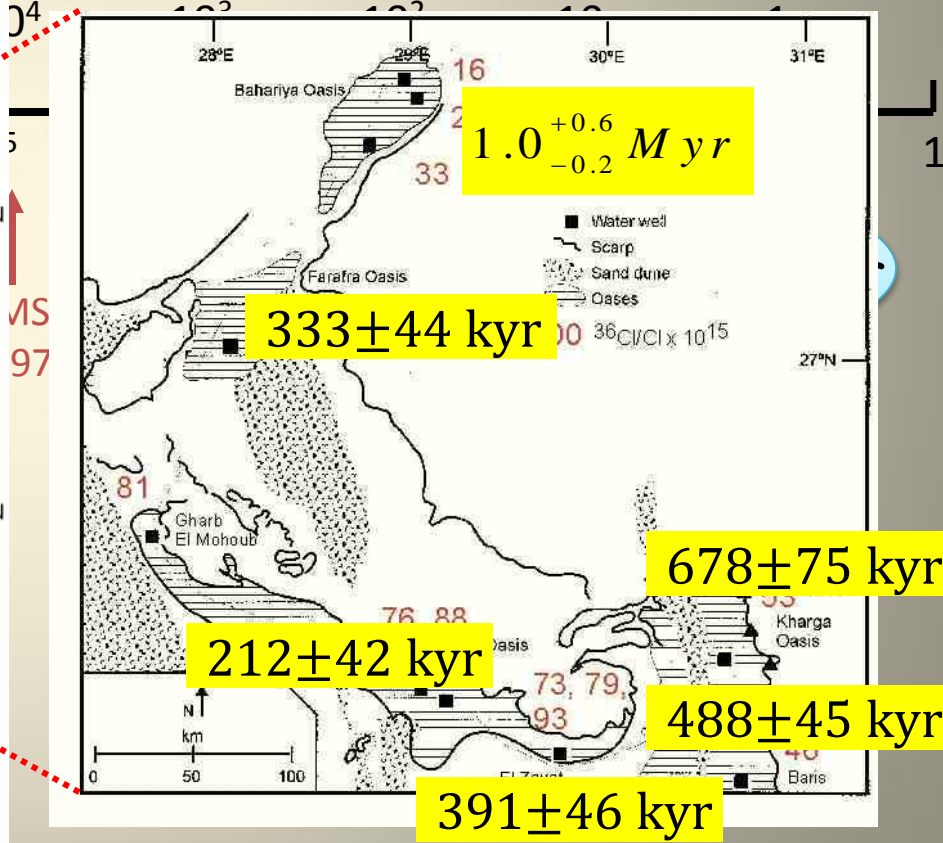
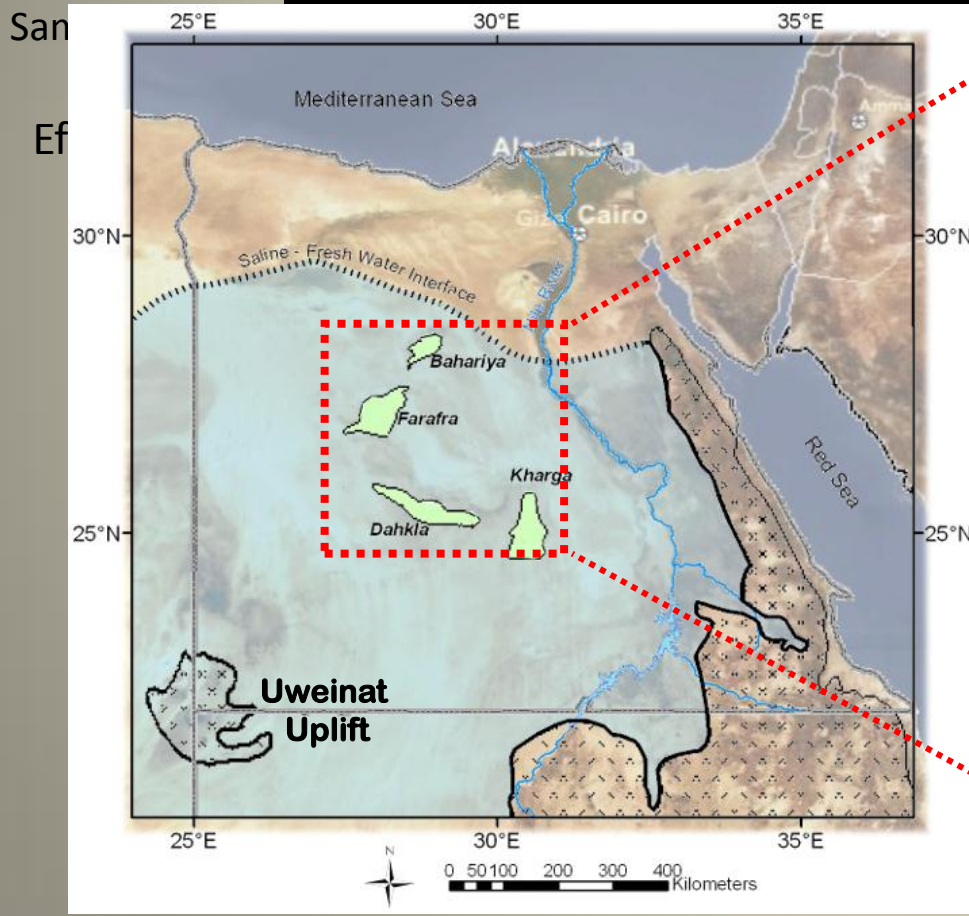
^{81}Kr dating: from dream to reality

- ATTA-1: C.-Y. Chen et al., *Science* (1999)
- ATTA-2: X. Du et al., *Geophys. Res. Lett.* (2003)
- ATTA-3: W. Jiang et al., *Phys. Rev. Lett.* (2011)

Polar Ice

Groundwater

Water or Ice



And there's still so much more...

- So many more examples and applications we didn't have time to discuss

material science energy Homeland security Big Bang nucleosynthesis super-heavy elements
star burning nuclear structure archaeology/art

- So many great scientists involved



Maybe you'll be next?!