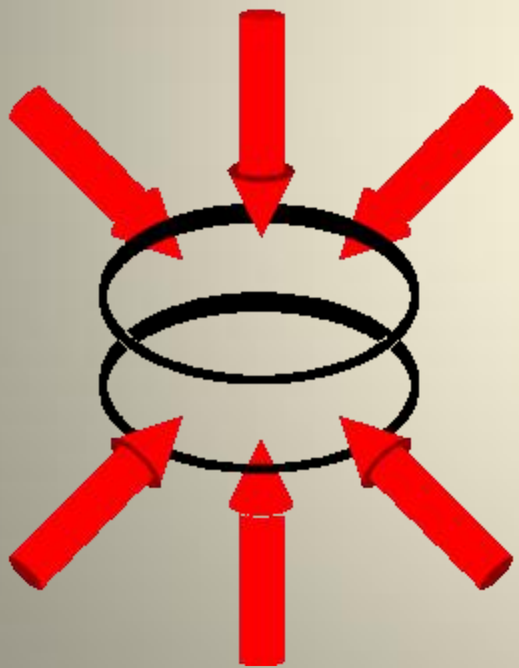
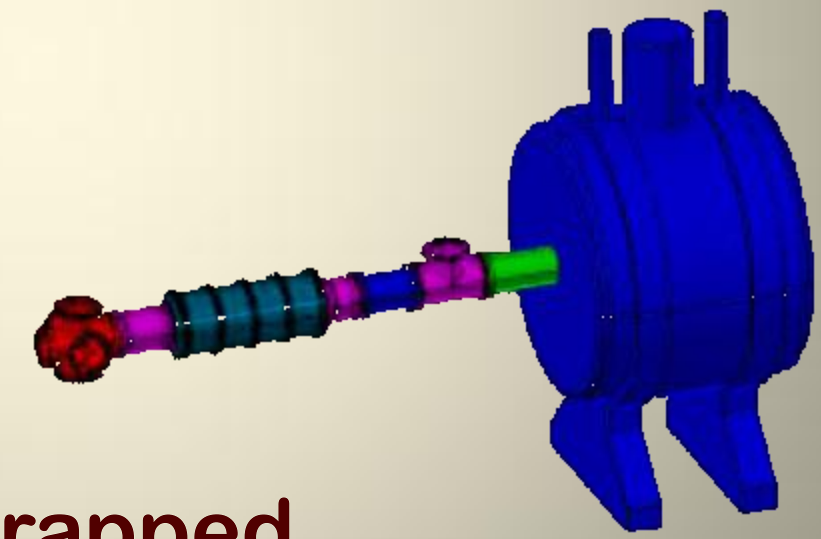
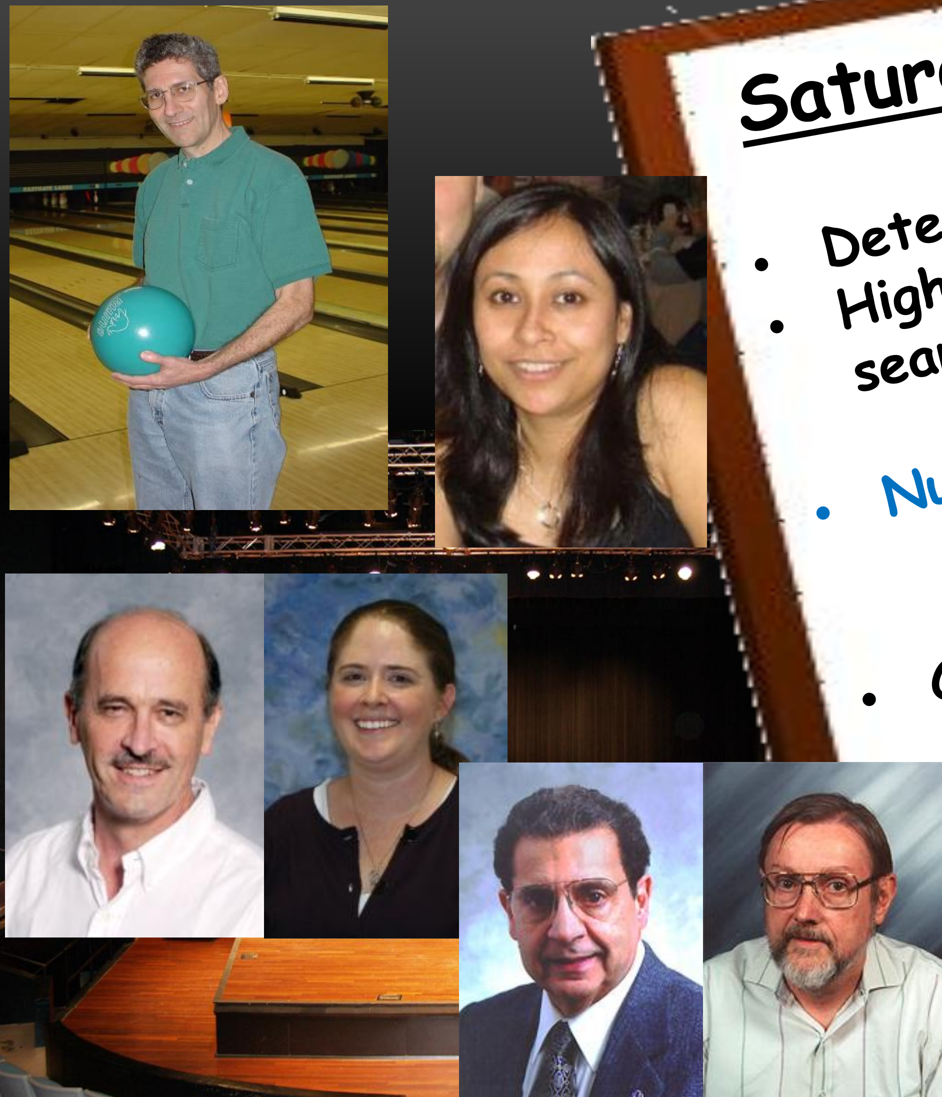
Nuclear Physics





with trapped

atoms and ions



Saturday Morning Physics

- Detectors/Accelerators
- High-energy physics: the LHC and search for the Higgs
- Nuclear physics
- Cosmology and astronomy
- Biophysics

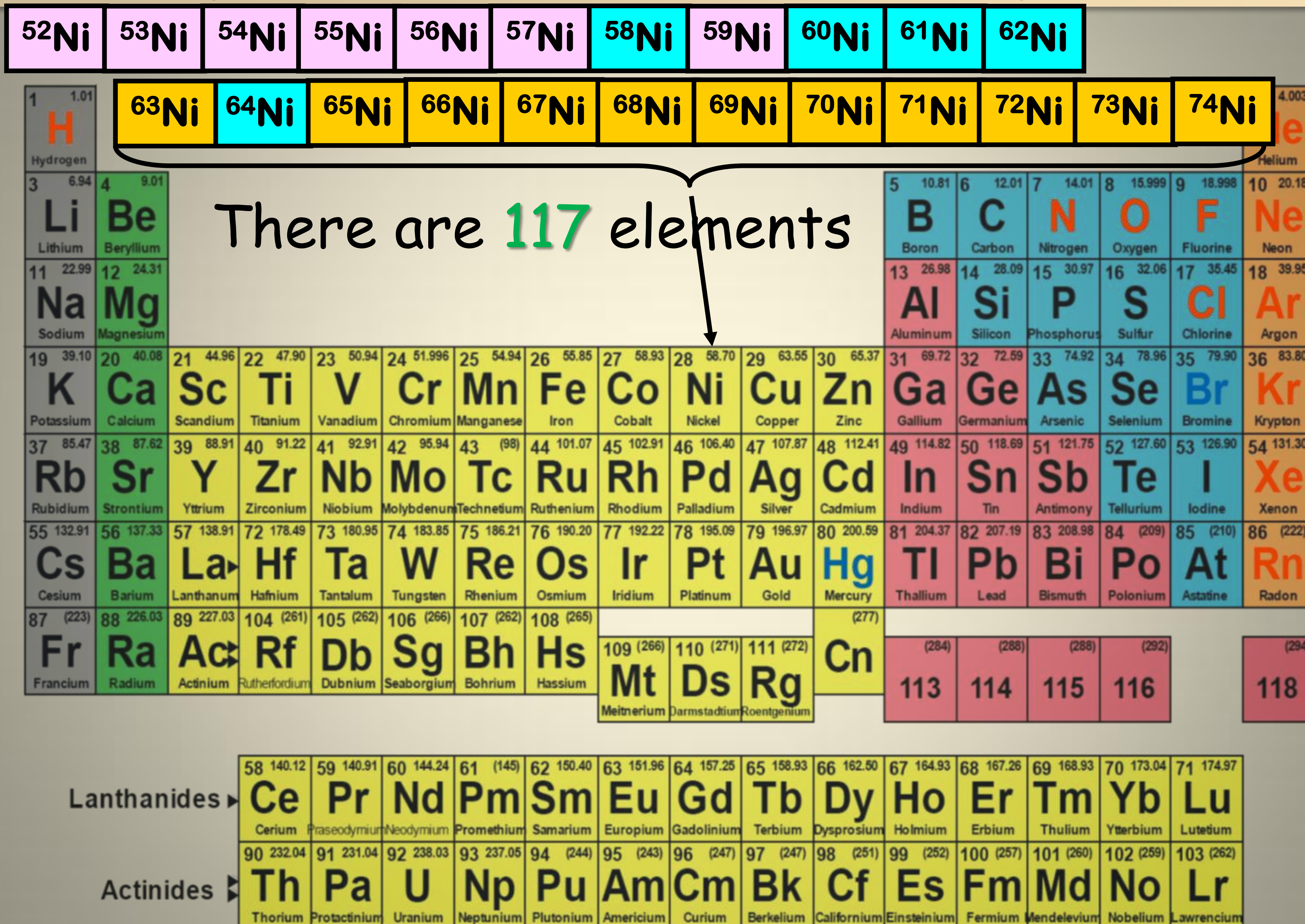
Outline

- 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?

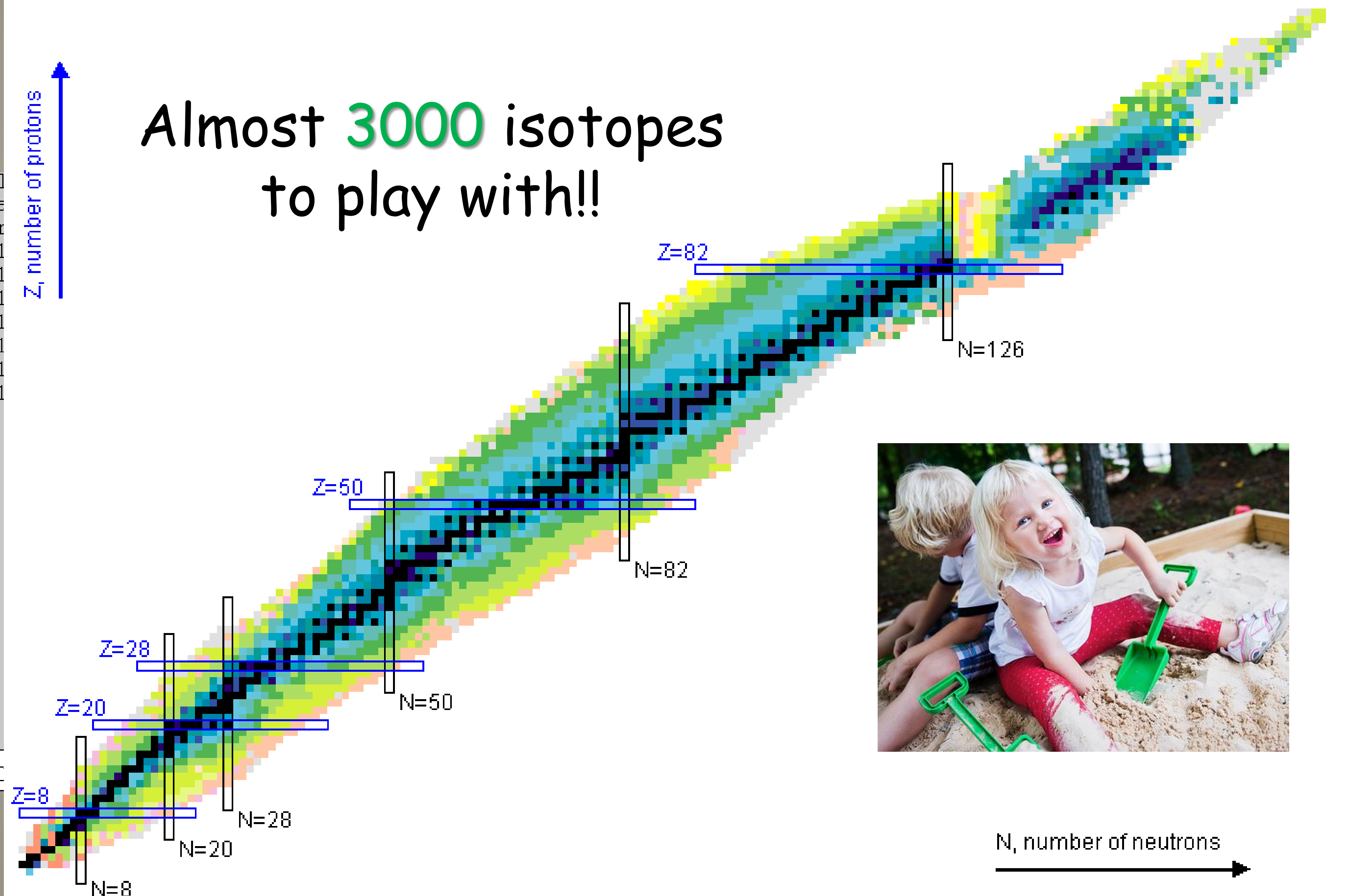
- Began with the study of the *nucleus* after it was discovered in 1911 by Ernest Rutherford
  - Or, arguably, in 1896 when Henri Becquerel discovered radioactivity
- The atom is mostly empty space!
- Nuclear physics concerns itself with the study of the protons and neutrons making up the nucleus
  - 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



The periodic table…expanded

Almost 3000 isotopes to play with!!

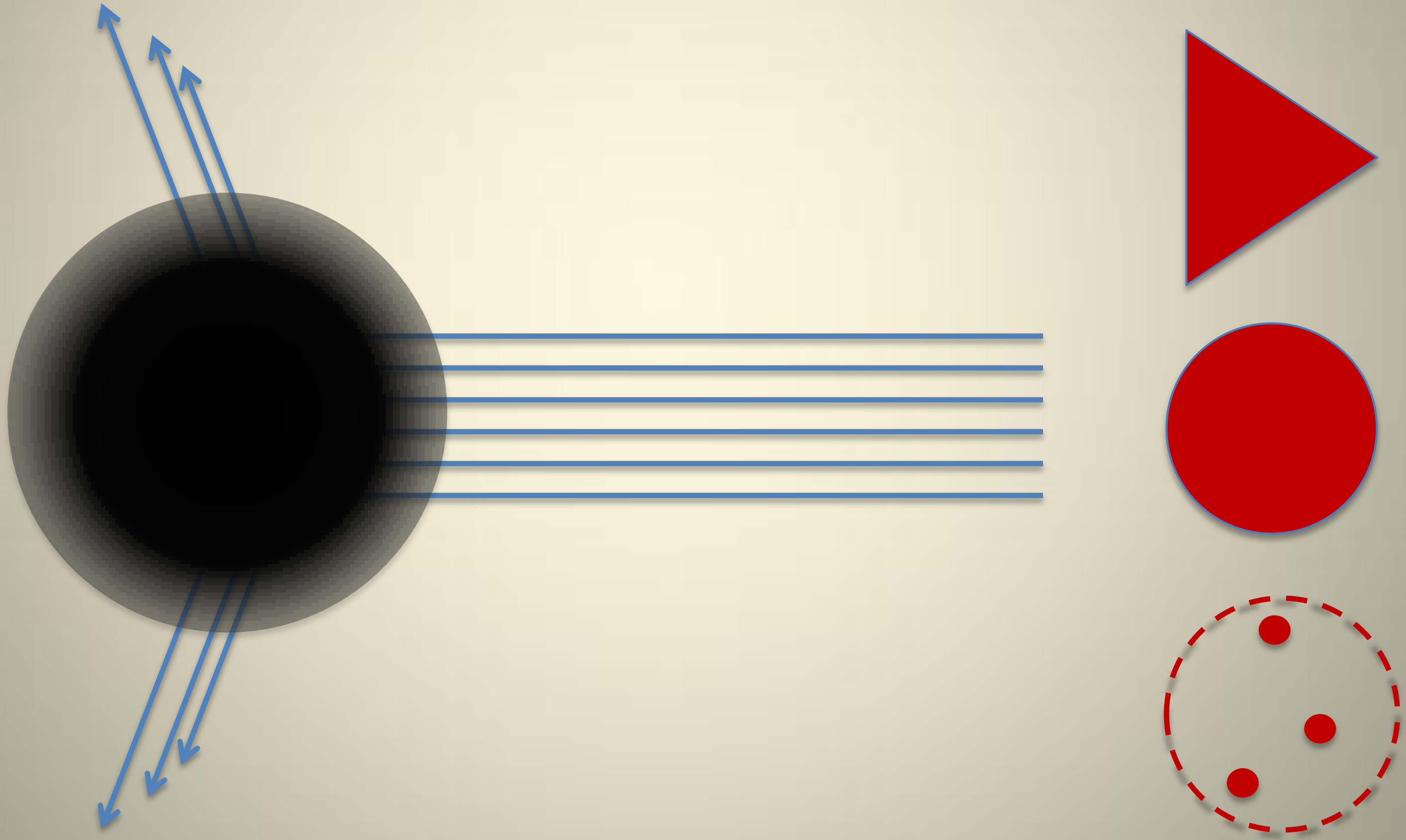


What do we do with nuclei?

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



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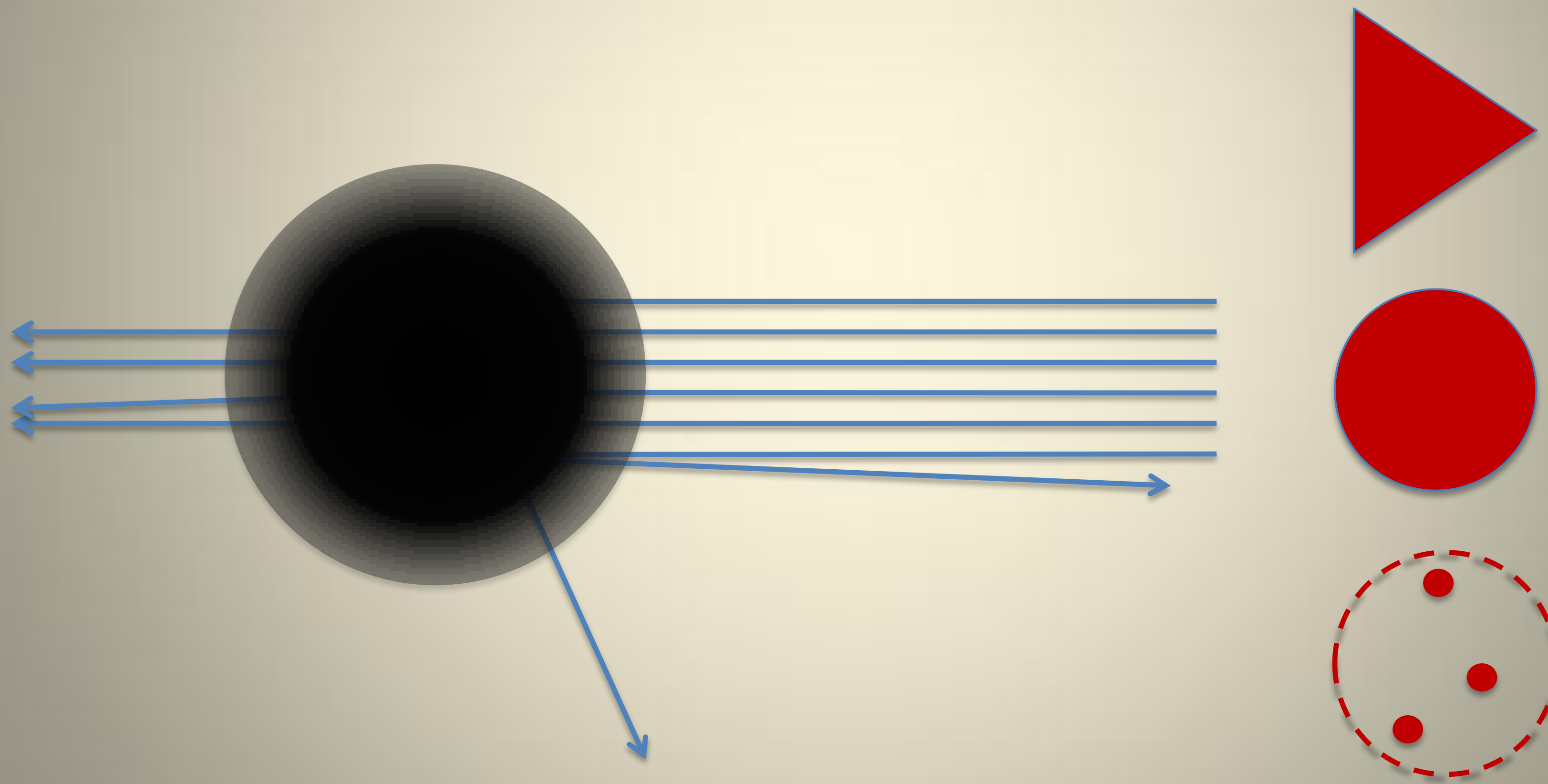


What do we do with nuclei?

- 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:

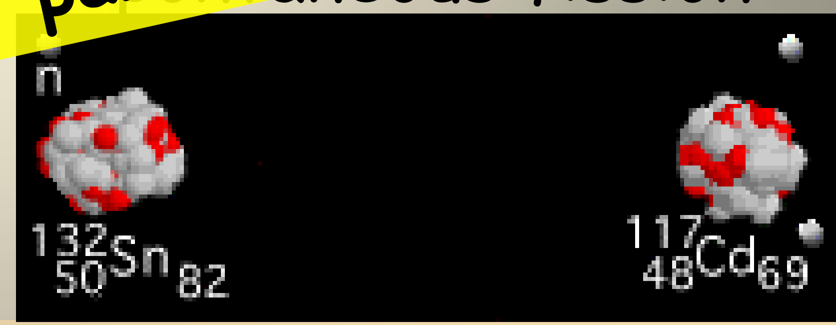
α decay:

β decay:

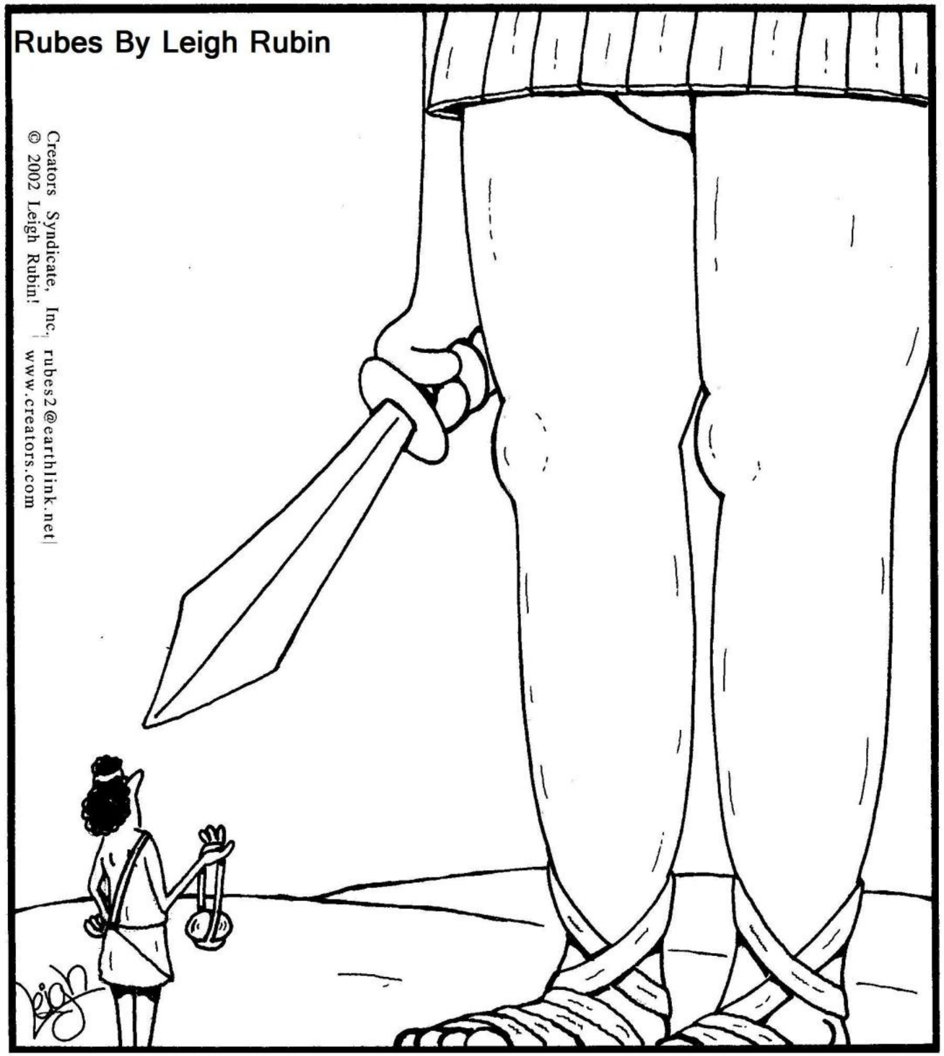
These decays tell us about the structure within the nucleus and the forces at play between its constituent particles

γ decay:

spontaneous fission:

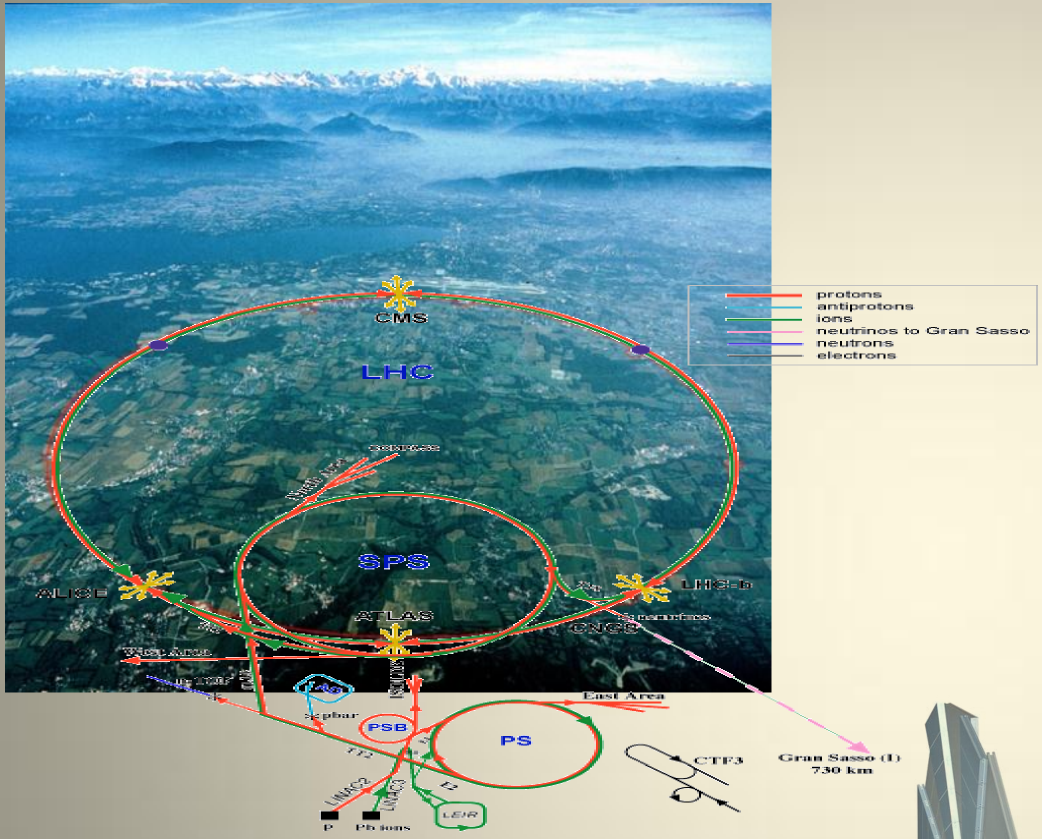


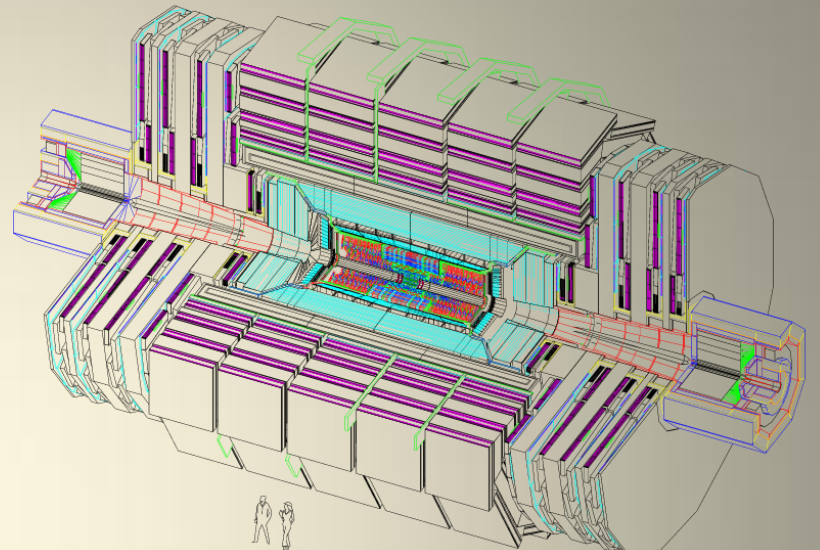
Nuclear vs high-energy physics



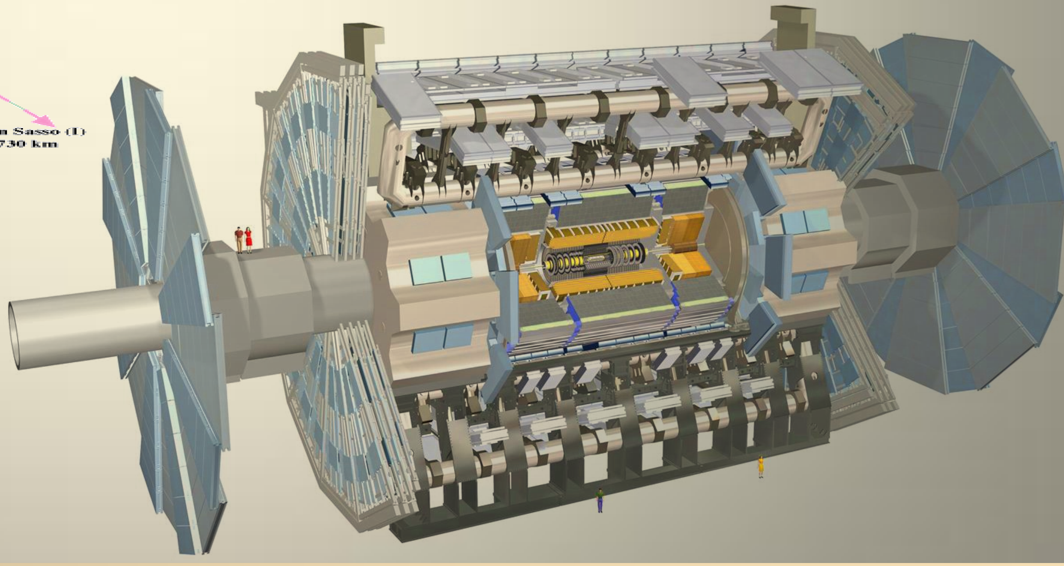
Overcoming temptation, David opted against the obvious, unsportsmanlike cheap shot.

Nuclear vs high-energy physics



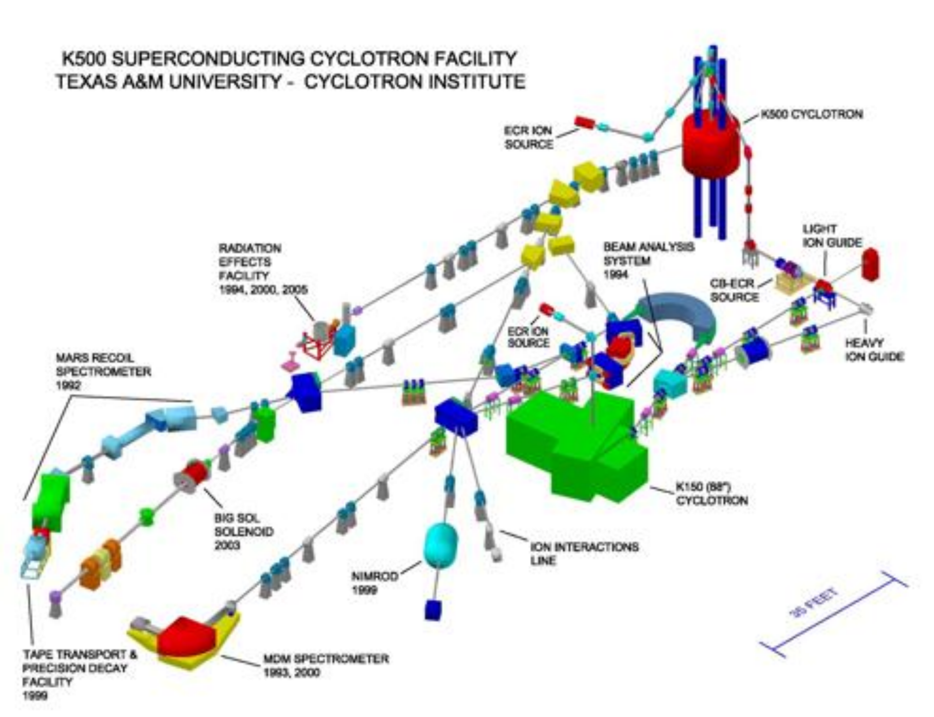


Compact Muon Solenoid

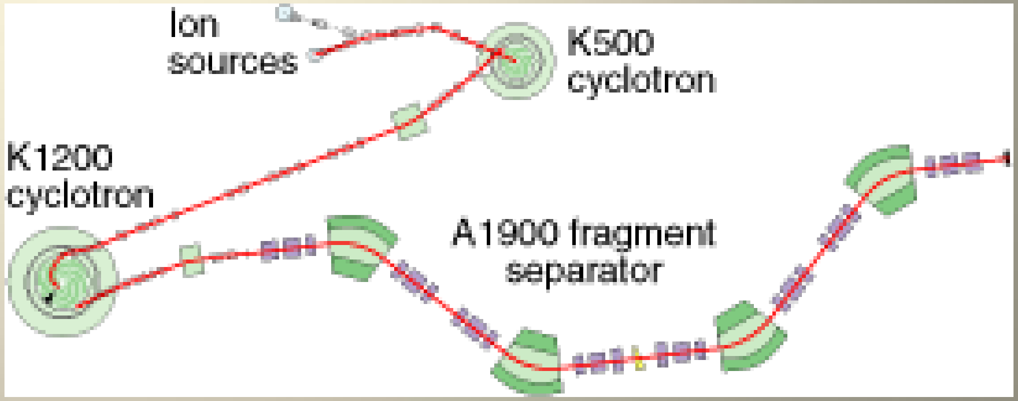


"Go big, or go home…"

Nuclear vs high-energy physics



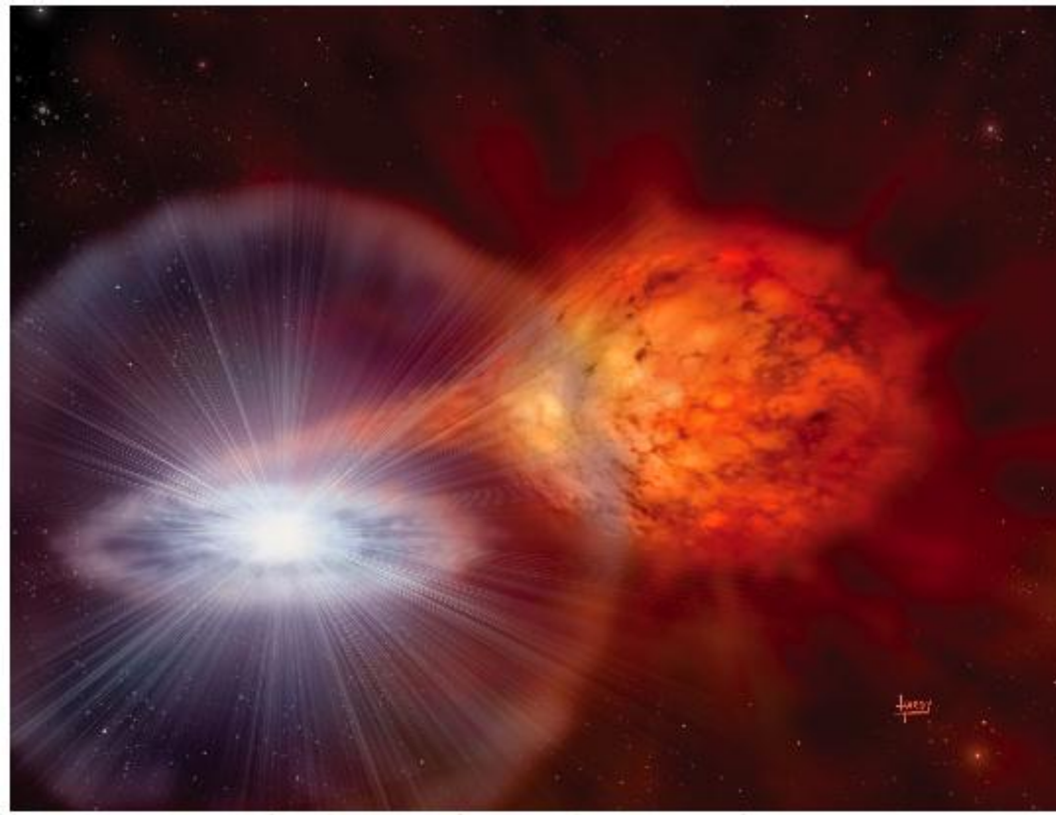
The **precision frontier** probes similar physics compared to colliders; is a **complementary** and important **cross-check**!



Nuclear physics and the cosmos

- **One example: Type 1a supernovae — thermonuclear explosions of white dwarf stars**

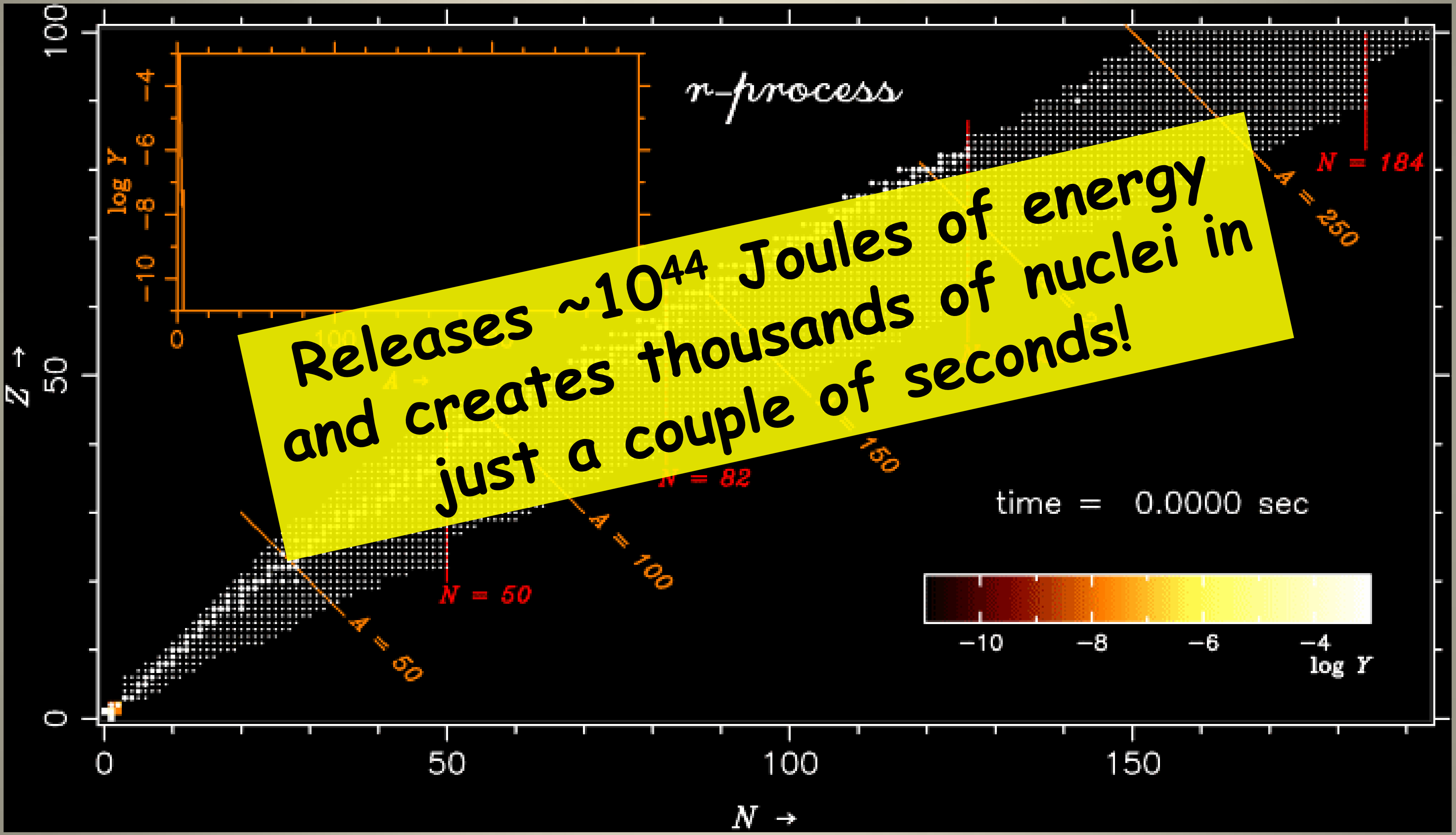
❖ Grabs mass from a binary companion star until it reaches its critical mass (1.4 solar masses)
❖ After ~1000 yrs of "cooking", a violent explosion is triggered
❖ Essentially the entire star is consumed in a *gigantic* explosion
❖ Rough analogy: like detonating a hydrogen bomb the size of the Earth that 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

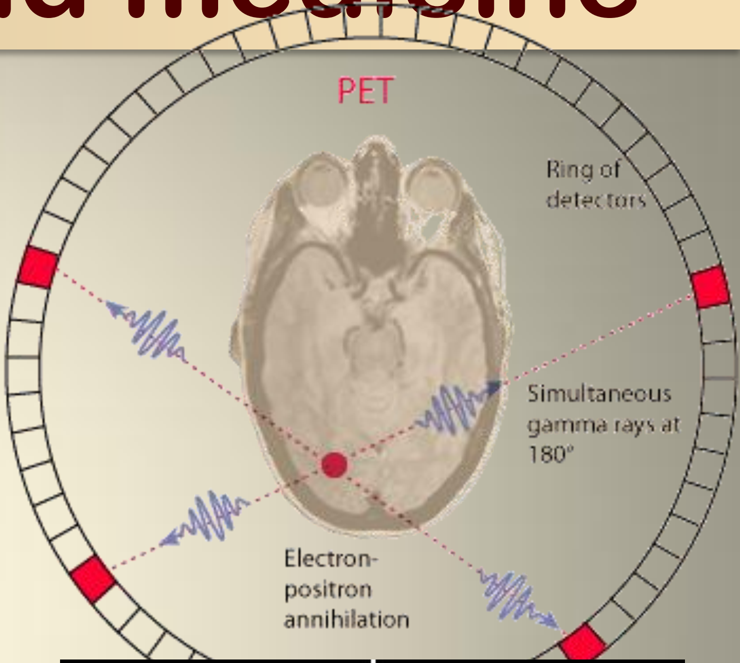


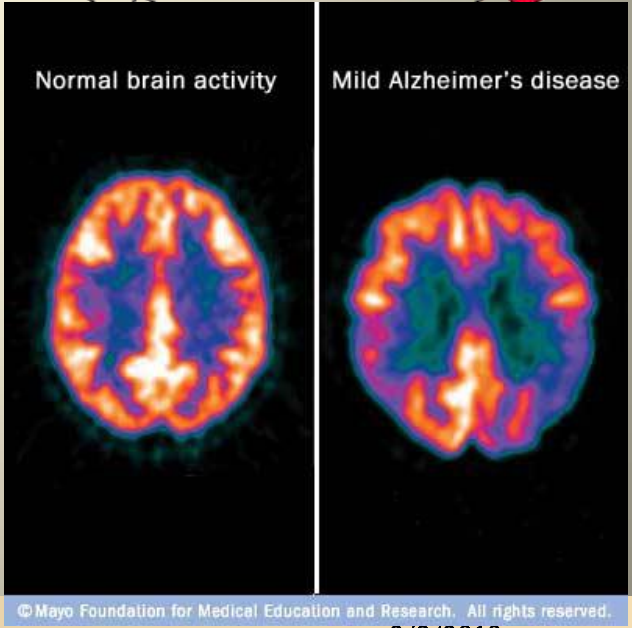
Releases ~10^{44} Joules of energy and creates thousands of nuclei in just a couple of seconds!

Nuclear physics and medicine

- One example: Positron-Emission Tomography (PET) scans

- Another is proton therapy



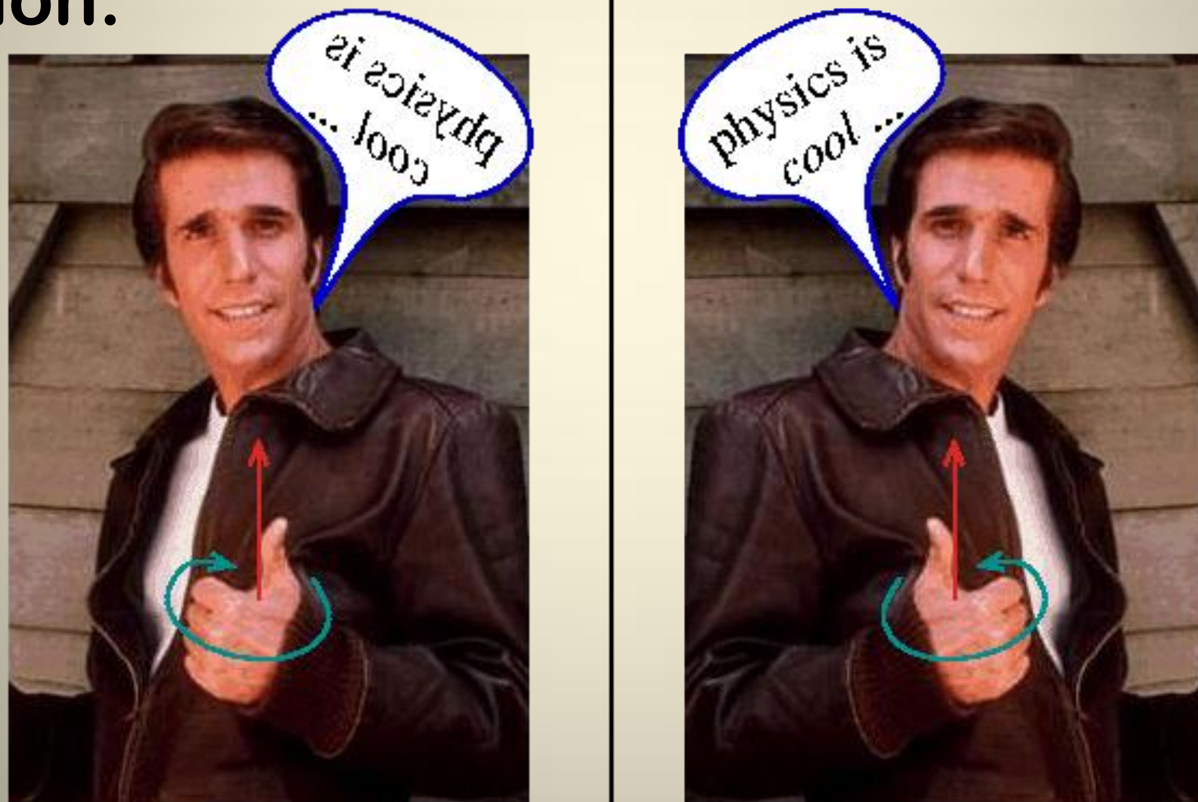


Saturday Morning Physics

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

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

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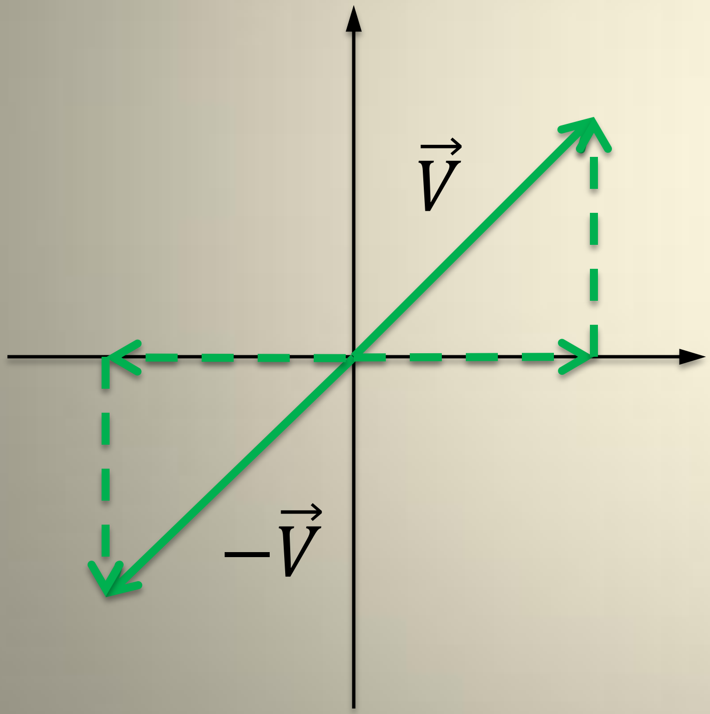
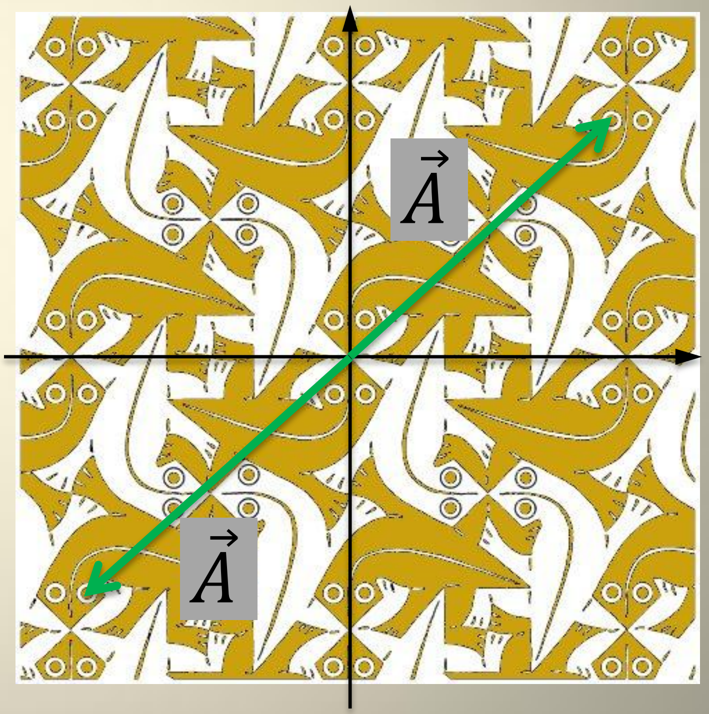


negative parity

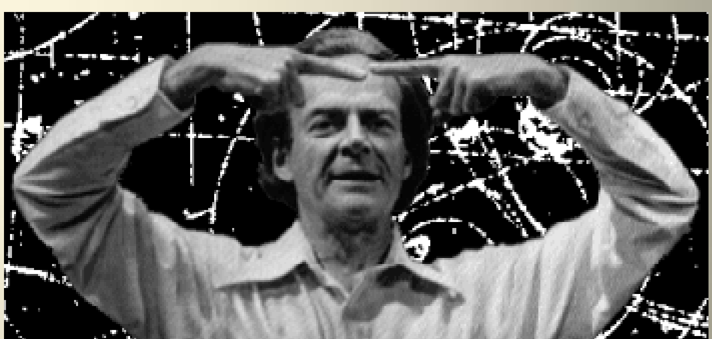


positive parity

Is parity *always* conserved…?

- **In 1956, Lee and Yang noted:**

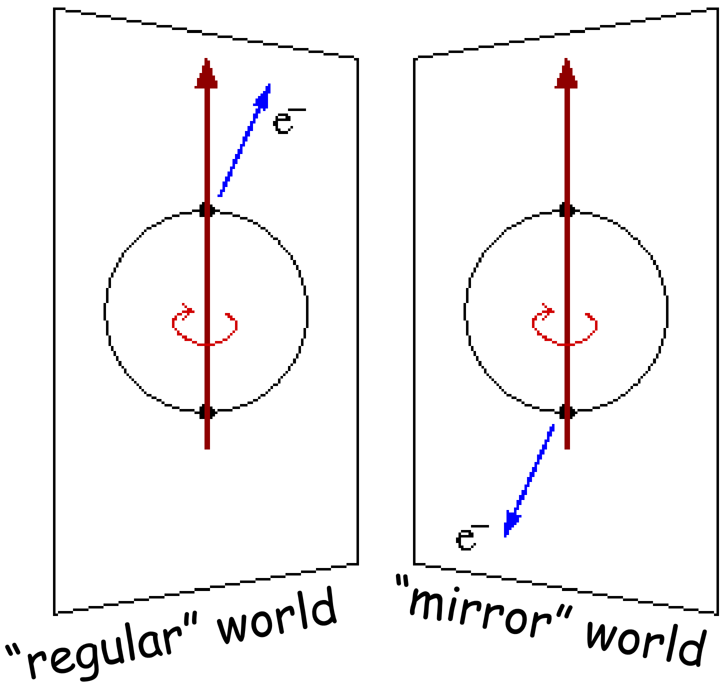
"…existing experiments do indicate parity conservation in strong and electromagnetic interactions, but that for weak interactions … parity conservation is so far only an extrapolated hypothesis, unsupported by experimental evidence."



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

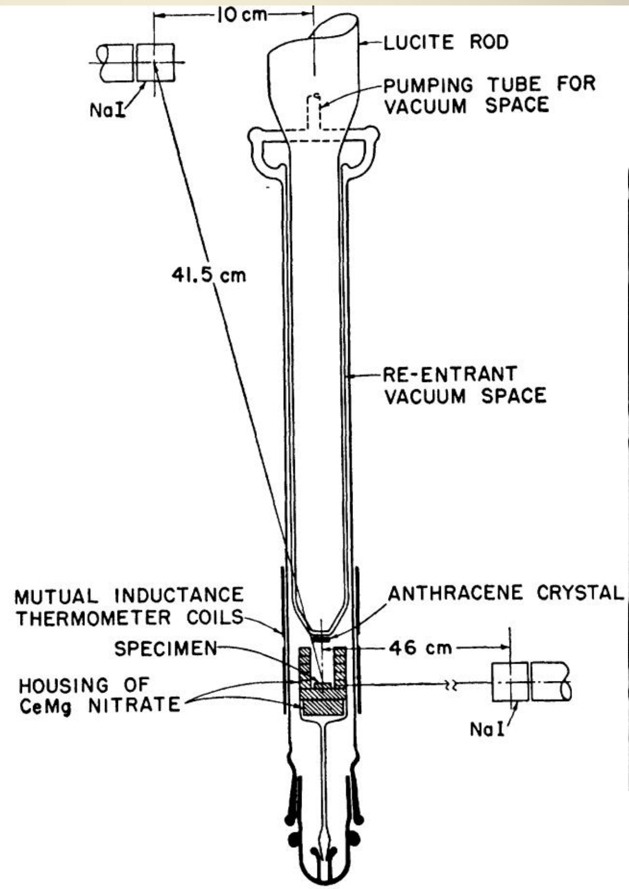
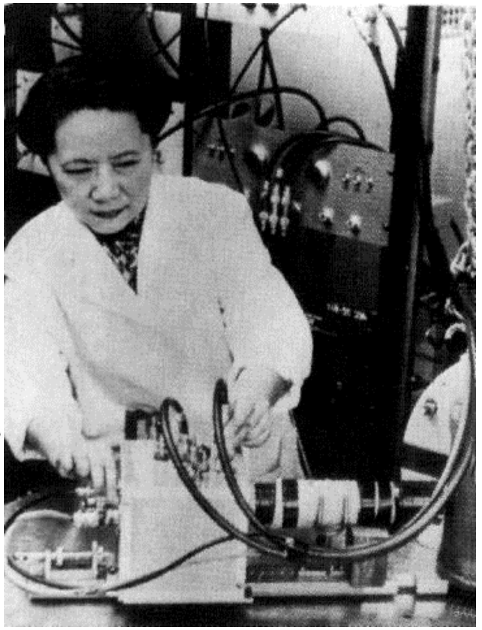
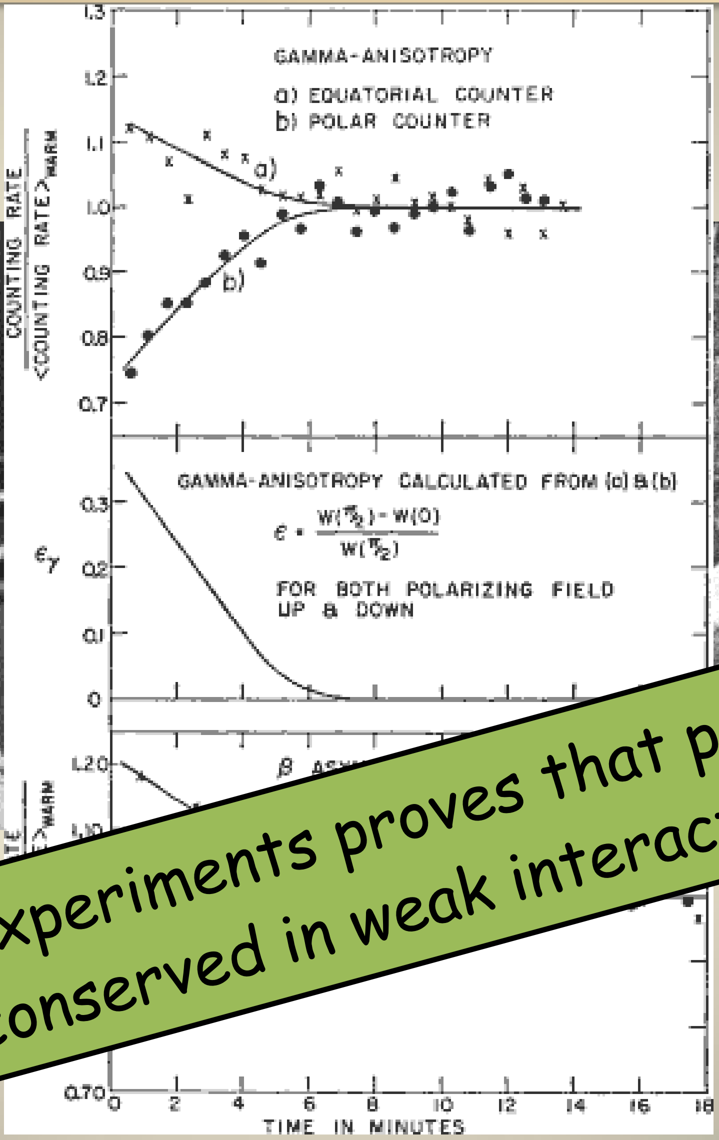


FIG. 1. Schematic drawing of the lower part of the cryostat.



Feynman loses $50



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

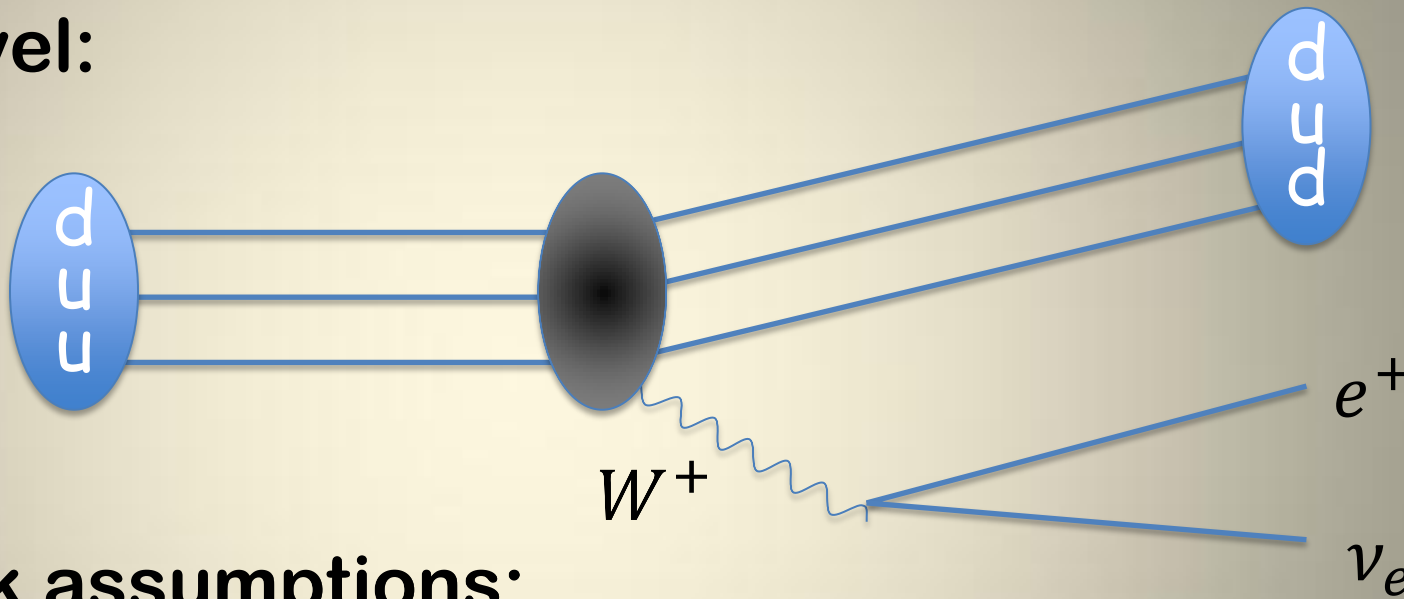
But, is it *maximally* violated?

- 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:

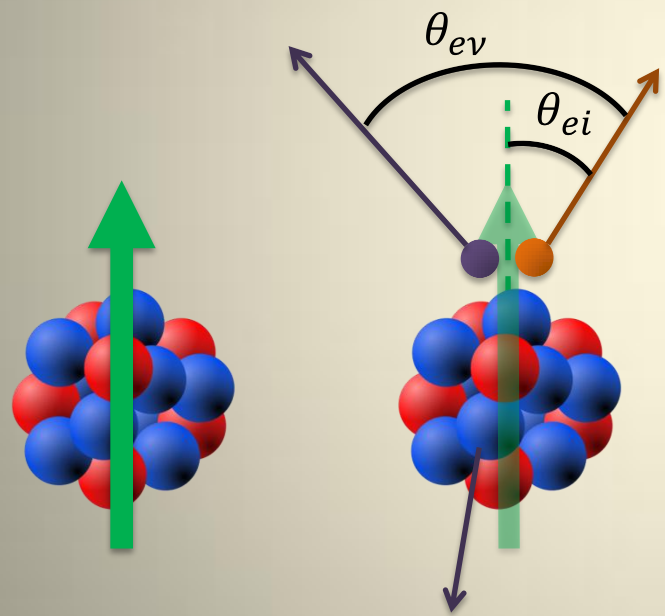


- Textbook assumptions:
  1. The decay occurs from rest
  2. The decay occurs from a point in space
  3. Particles escape without distortions
  4. Nucleus is perfectly polarized

Basic idea: improve upon Wu

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

  ⇒ pretty demanding!



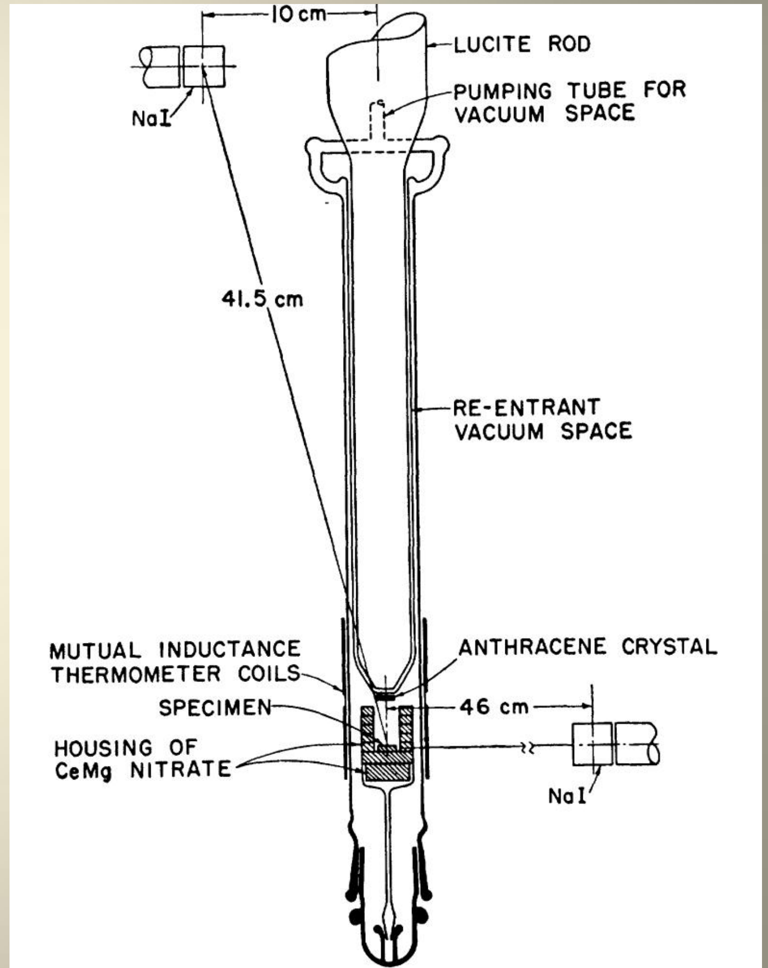
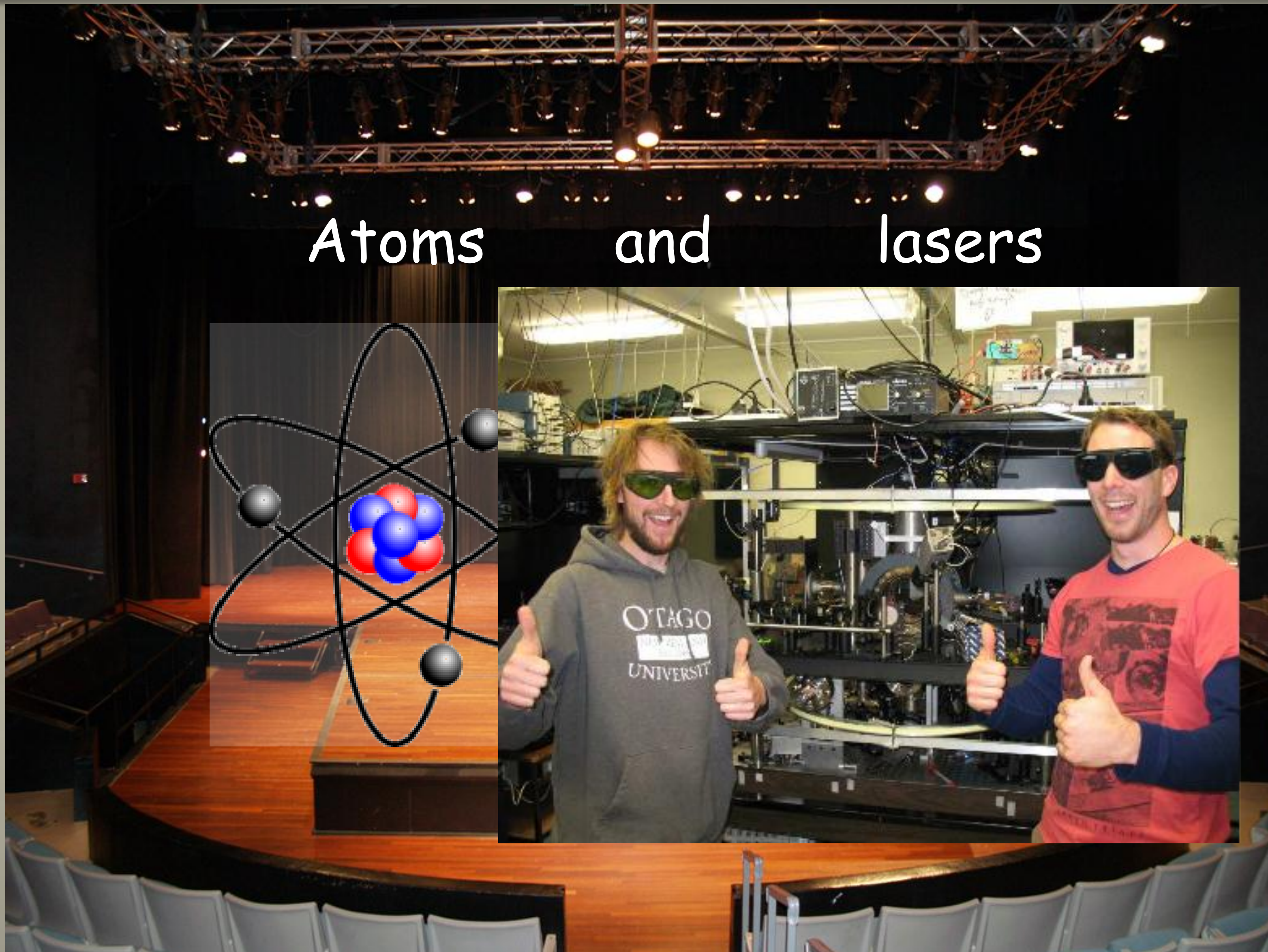


FIG. 1. Schematic drawing of the lower part of the cryostat.

Enter: “Cool” Technologies



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 ✓

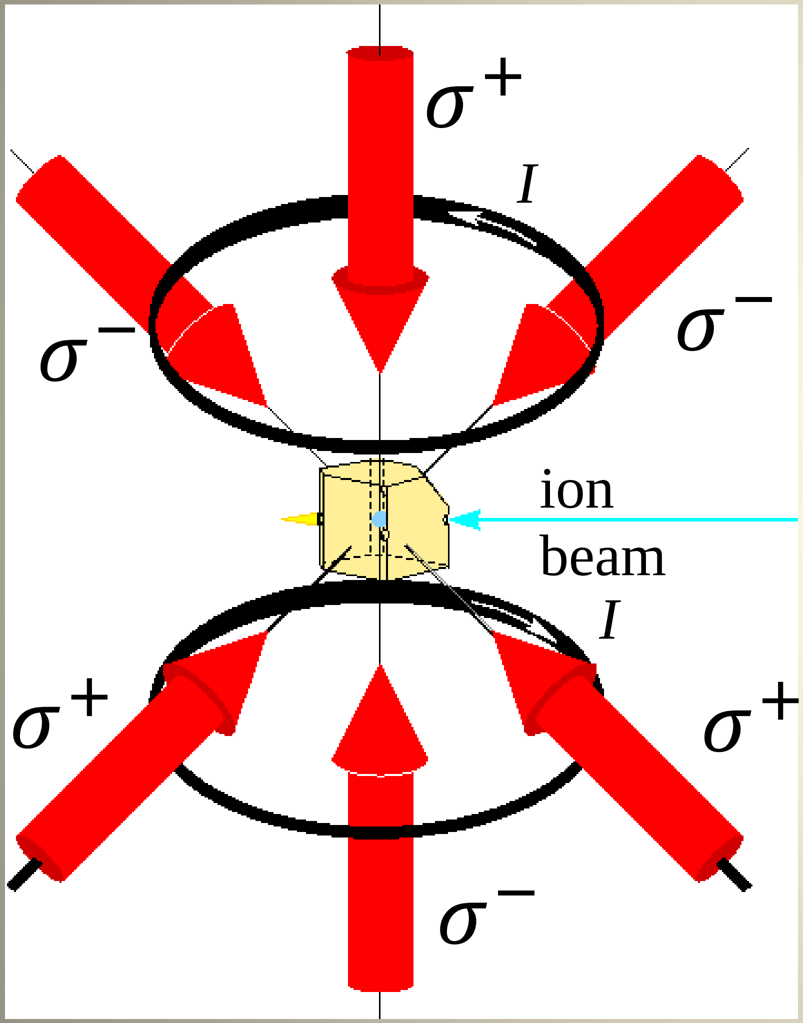
Steven Chu

Claude Cohen-Tannoudji

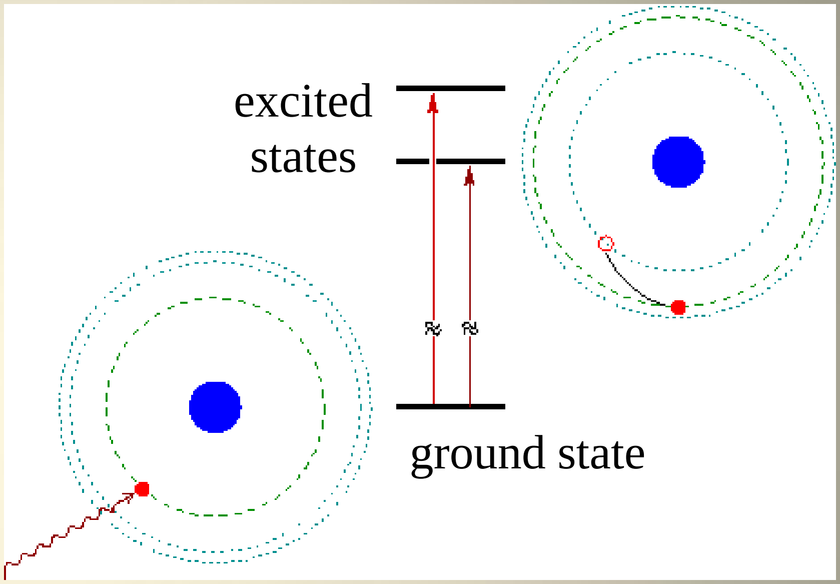
William Philips

1997  "For development of methods to cool & trap atoms with laser light"

A vapour-cell MOT

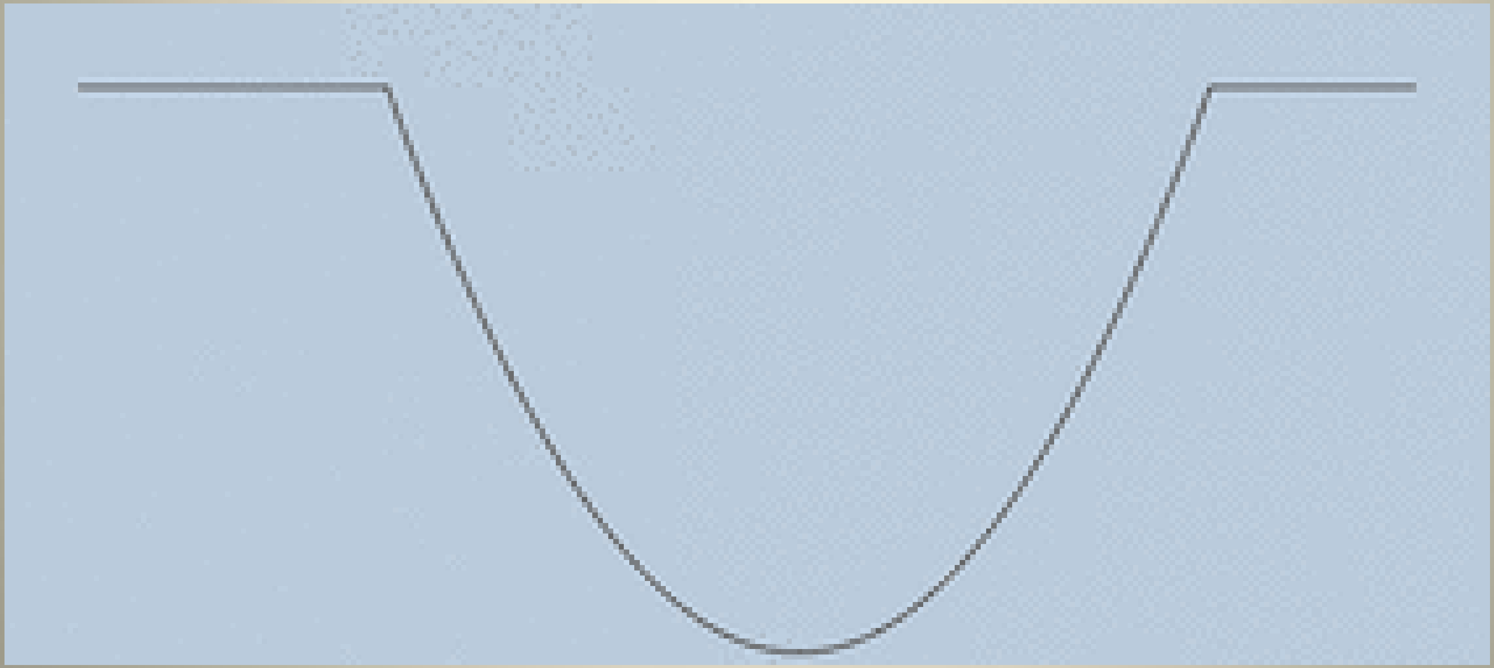


Laser excites atomic transitions:



Basic idea behind *any* trap

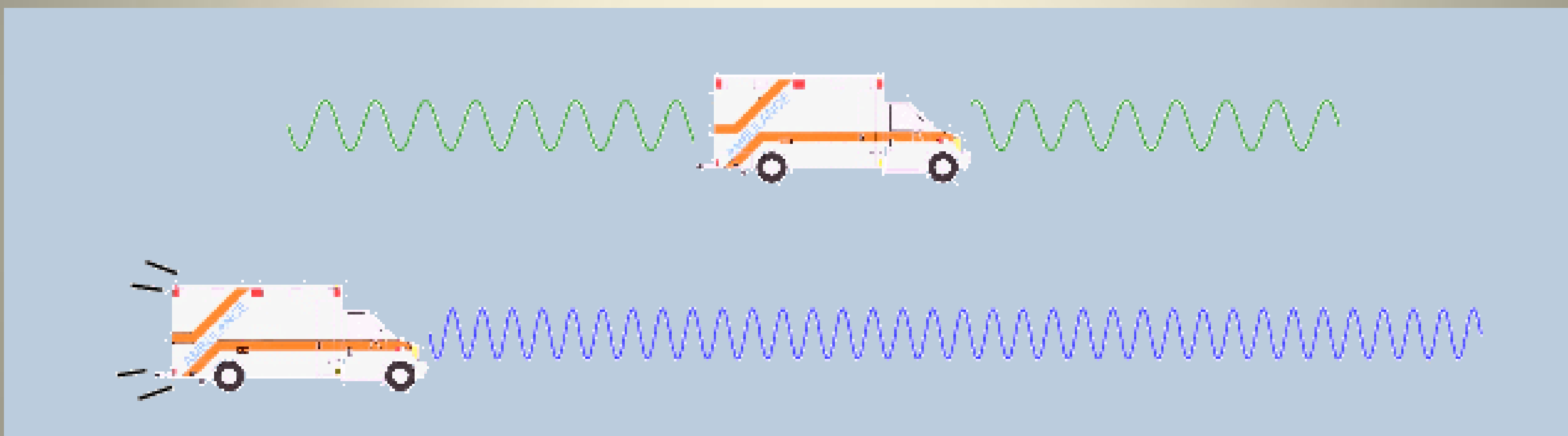
- Speed-dependent force: dampens the motion and slows the particle down
- Position-dependent force: defines where particles get trapped



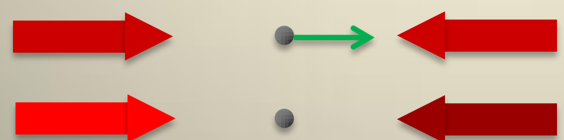
E.g.: Ball in a valley … *with* friction

How does a MOT work?

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



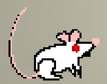
Lab frame:
Atom's frame:



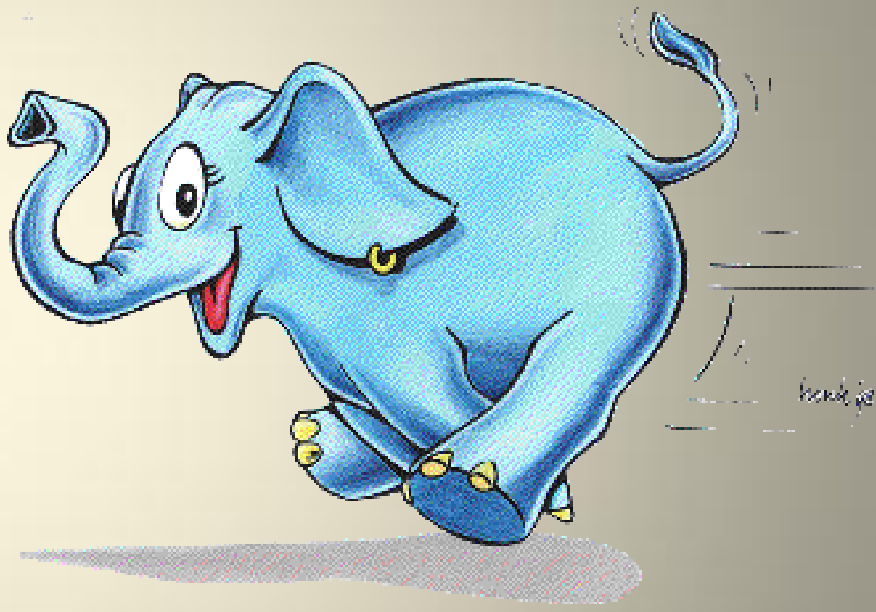
The Doppler effect changes rate of absorbing laser beam

Atom—photon interactions

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



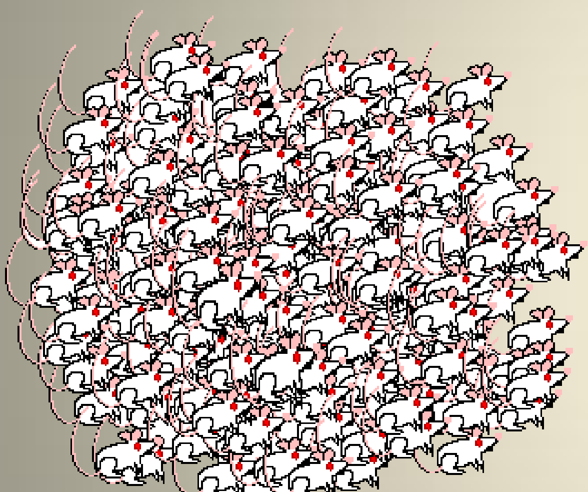
vs.

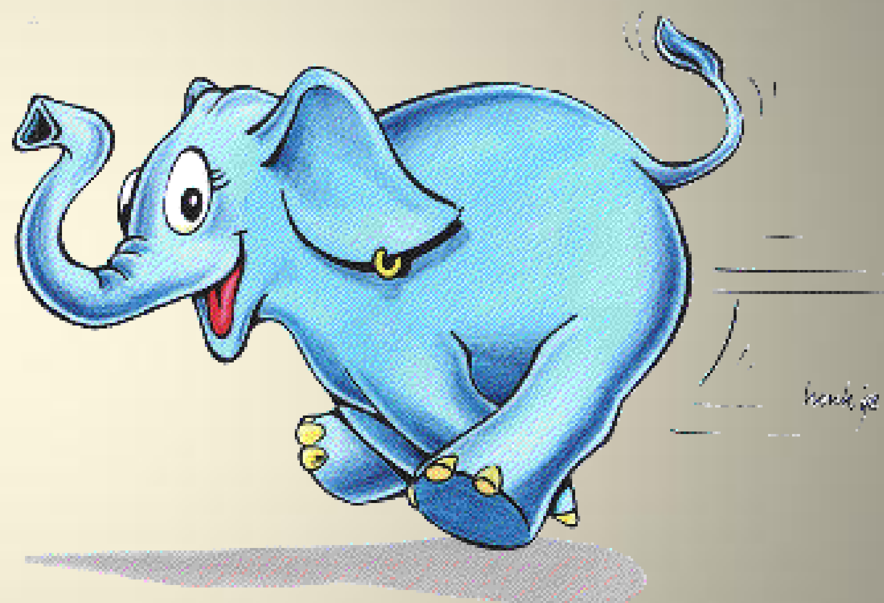


$\hbar\vec{k} \sim 1.5$ eV/c

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

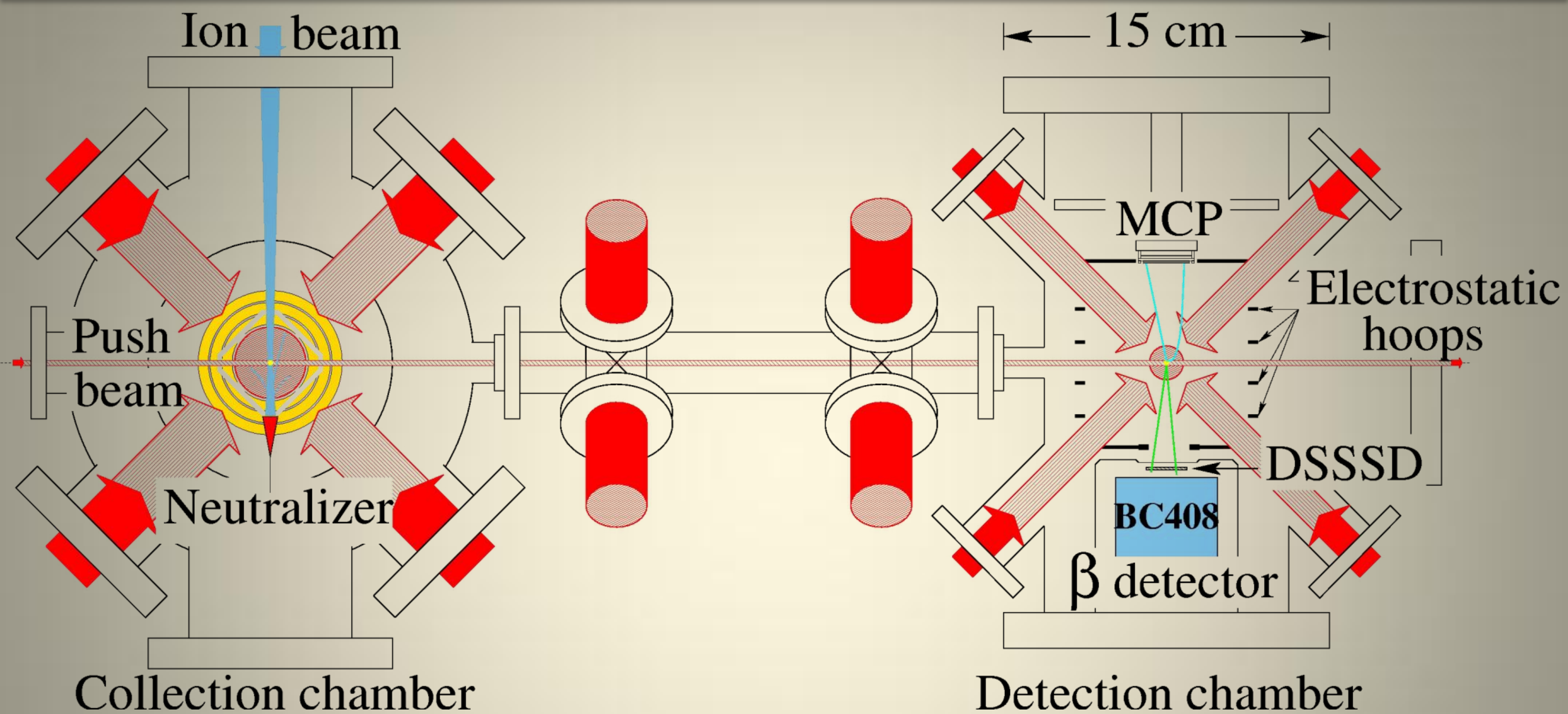
Atom—photon interactions





Cycling transitions!!

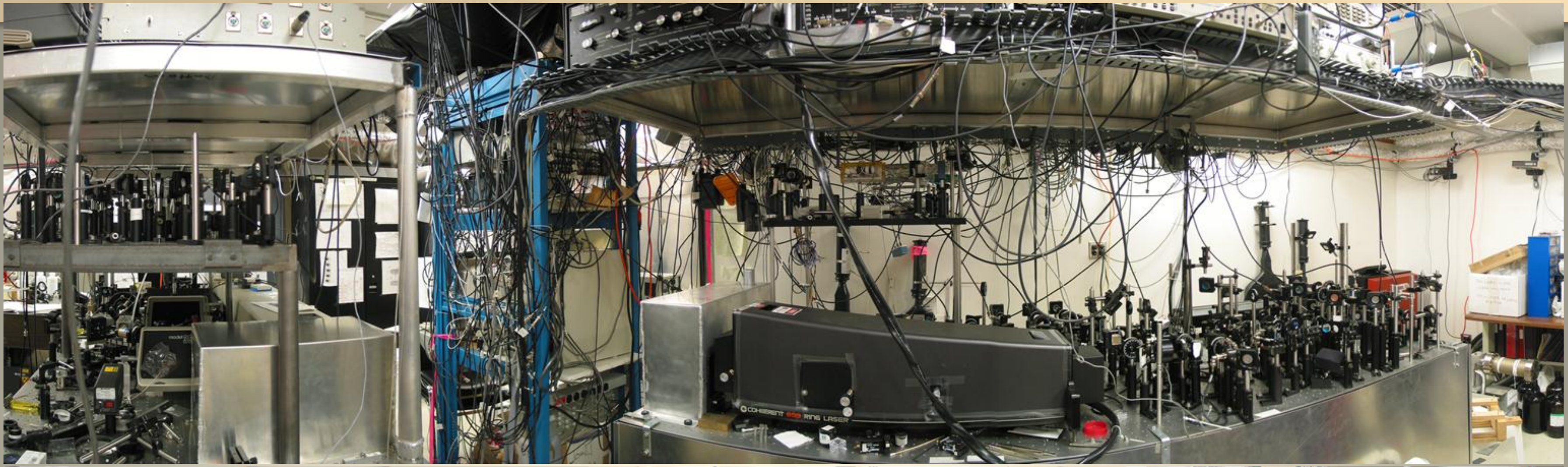
A double-MOT system

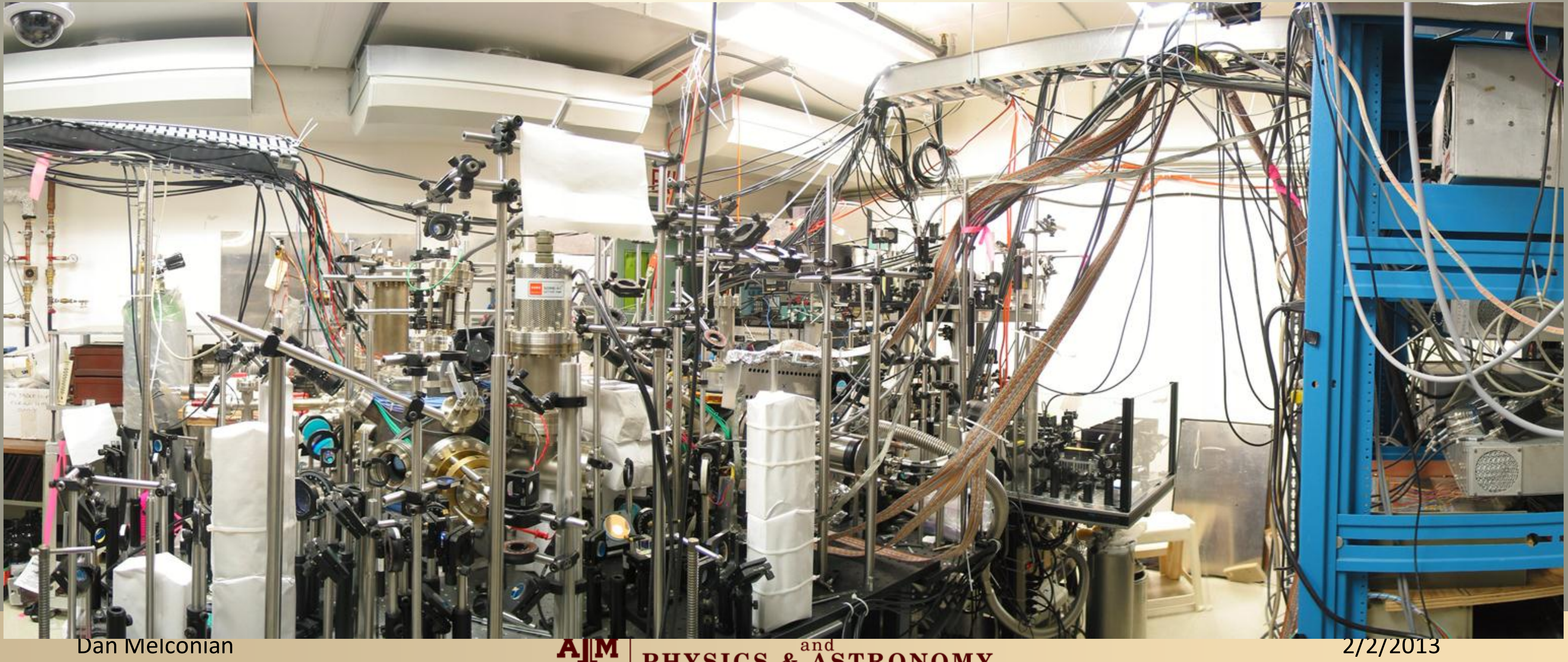


Traps provide a **backing-free**, **cold** (~1mK), **localized** (~1mm³) source of **short-lived** radioactive atoms

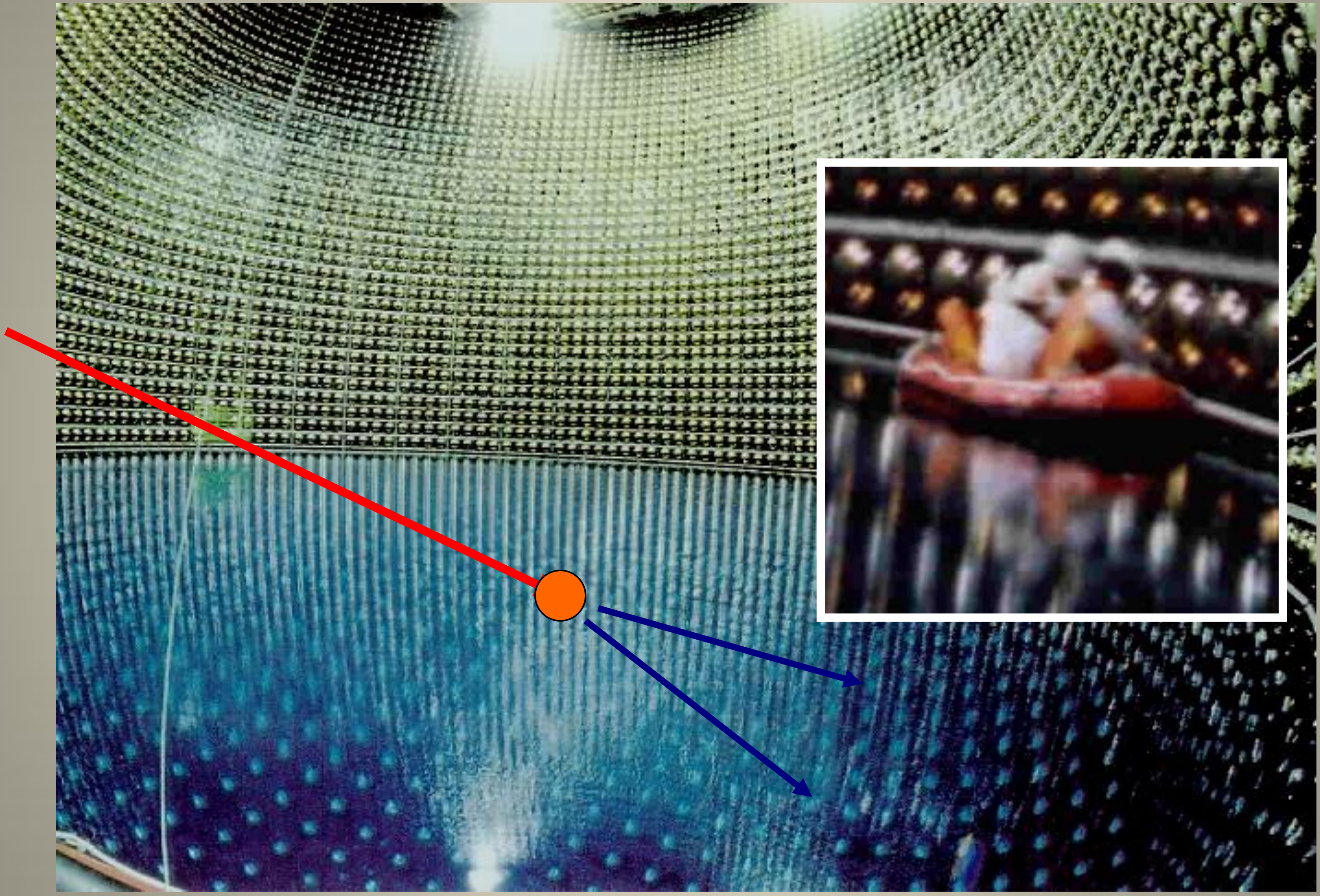
Detect $\vec{p}_e$ and $\vec{p}_{\mathrm{recoil}} \Rightarrow$ deduce $\vec{p}_\nu$ event-by-event!!

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

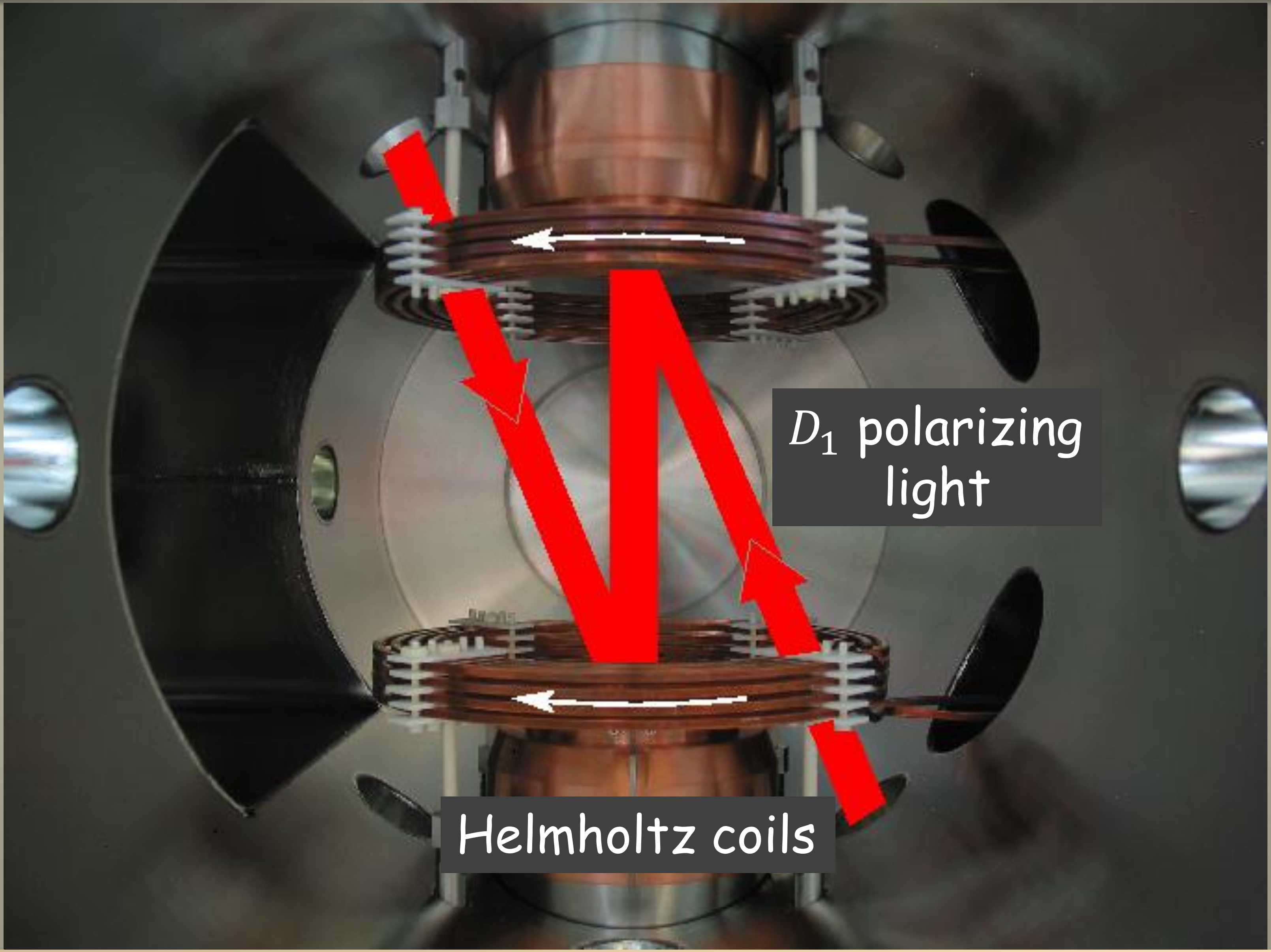




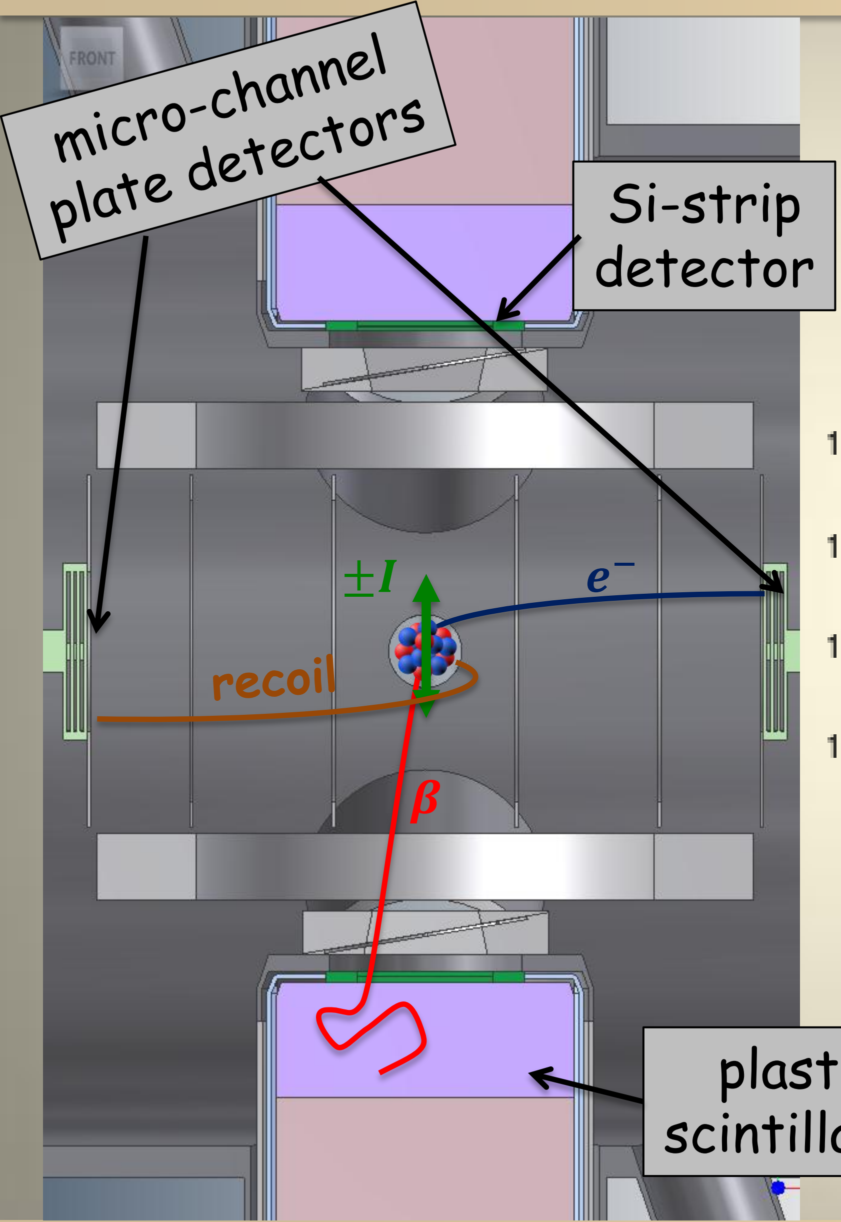
(but it's still easier than this :-P)



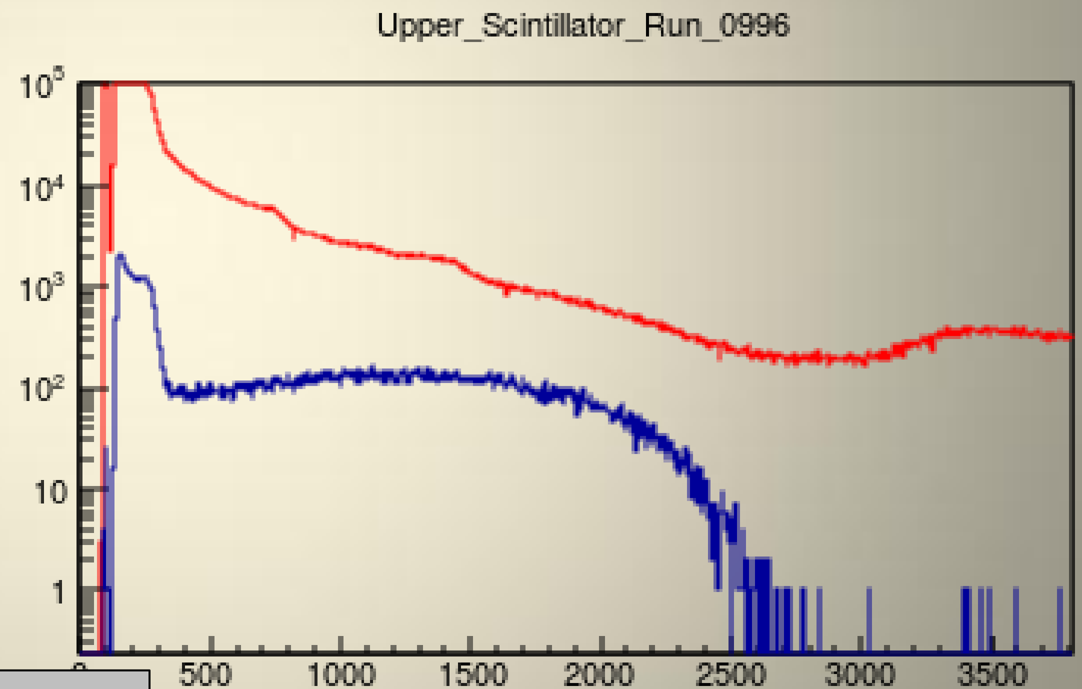
Latest generation of expts



Worked beautifully in December



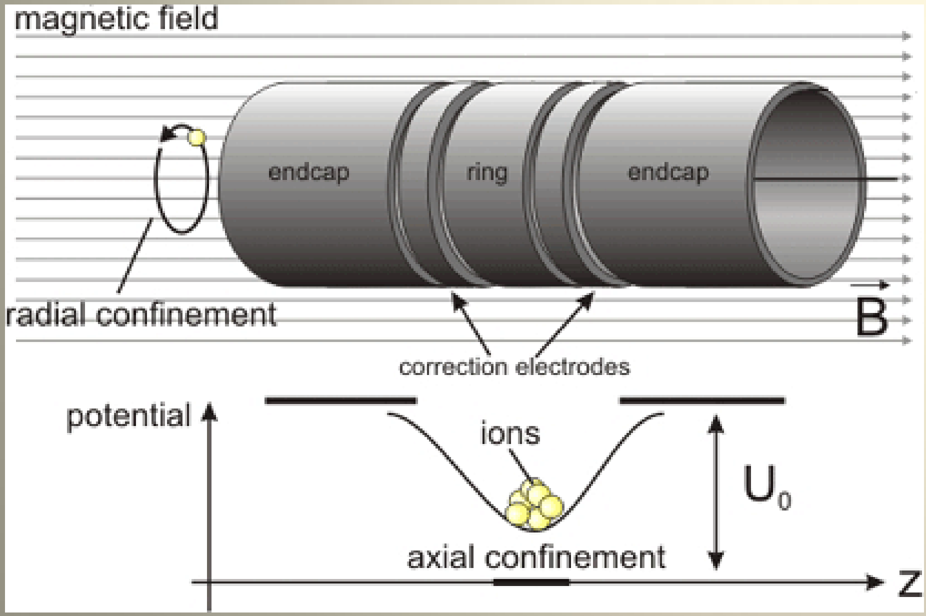
$$\text{Asymmetry} = \frac{N_+ - N_-}{N_+ + N_-} \sim PA_\beta$$



Stay tuned for recent results!

No time for ion traps ☹

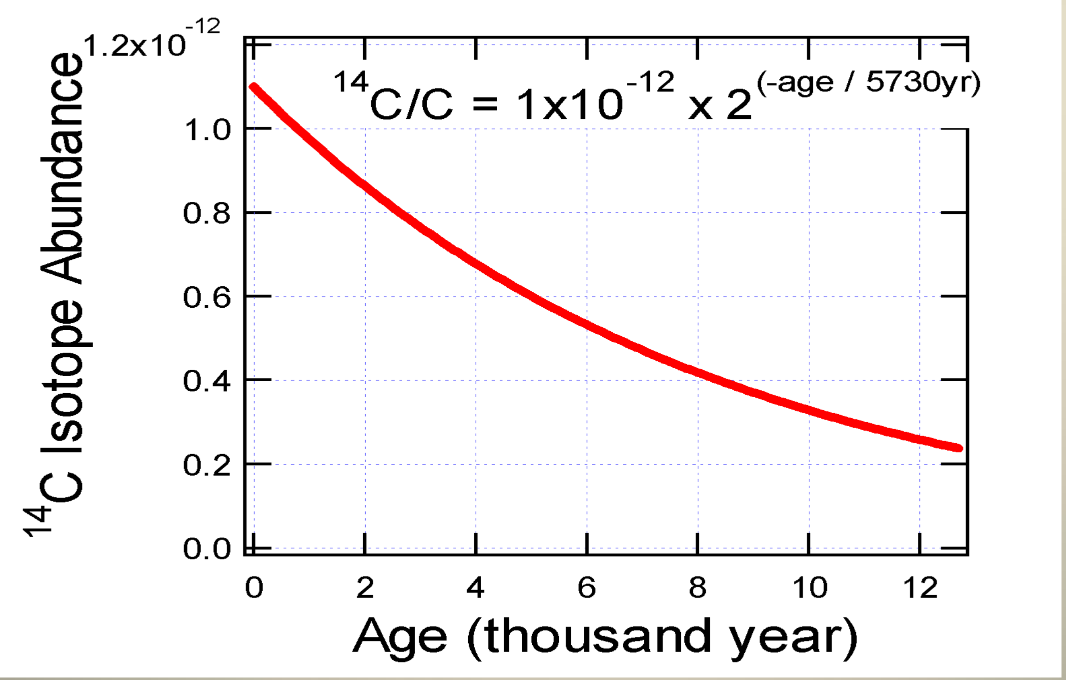
- **MOTs are a wickedly *cool* technology that provide an ideal source of short-lived atoms**
- **Unfortunately, MOTs are very particular about what they can trap**
- **Ion traps do not suffer from this drawback!**



http://youtu.be/PYpbKSmOnNc

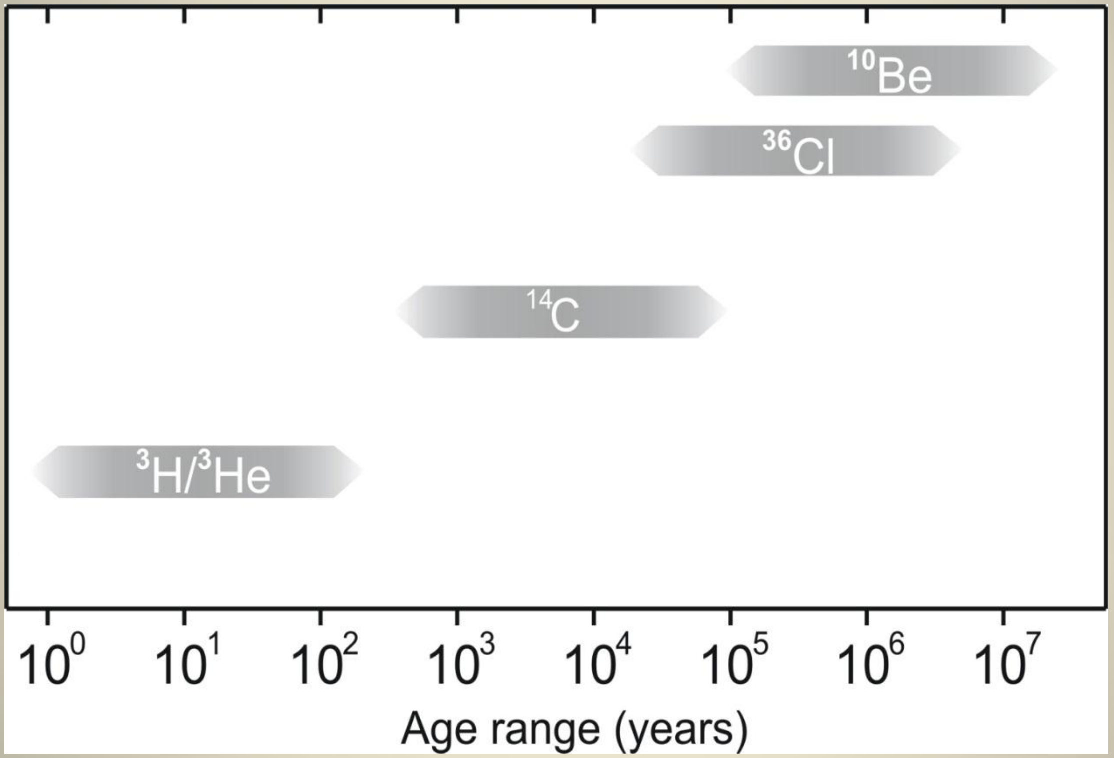
Nuclear physics and geology

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



And there are others

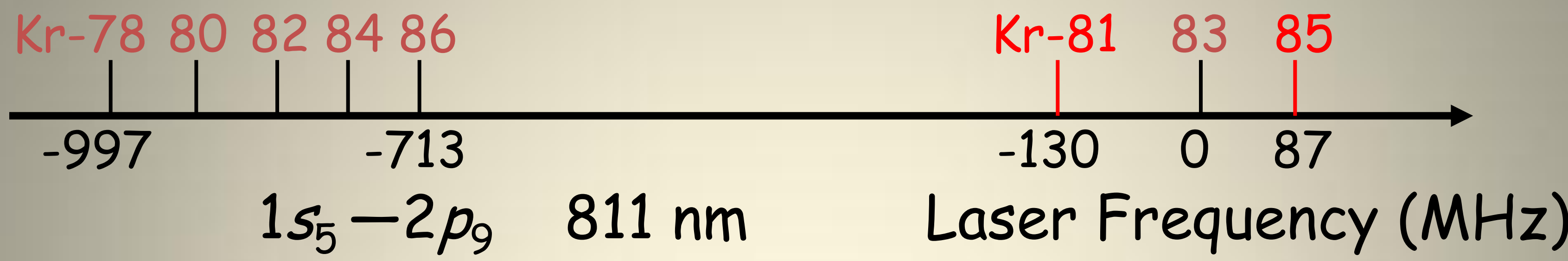
- To cover different times in history, need isotopes with longer/short half-lives

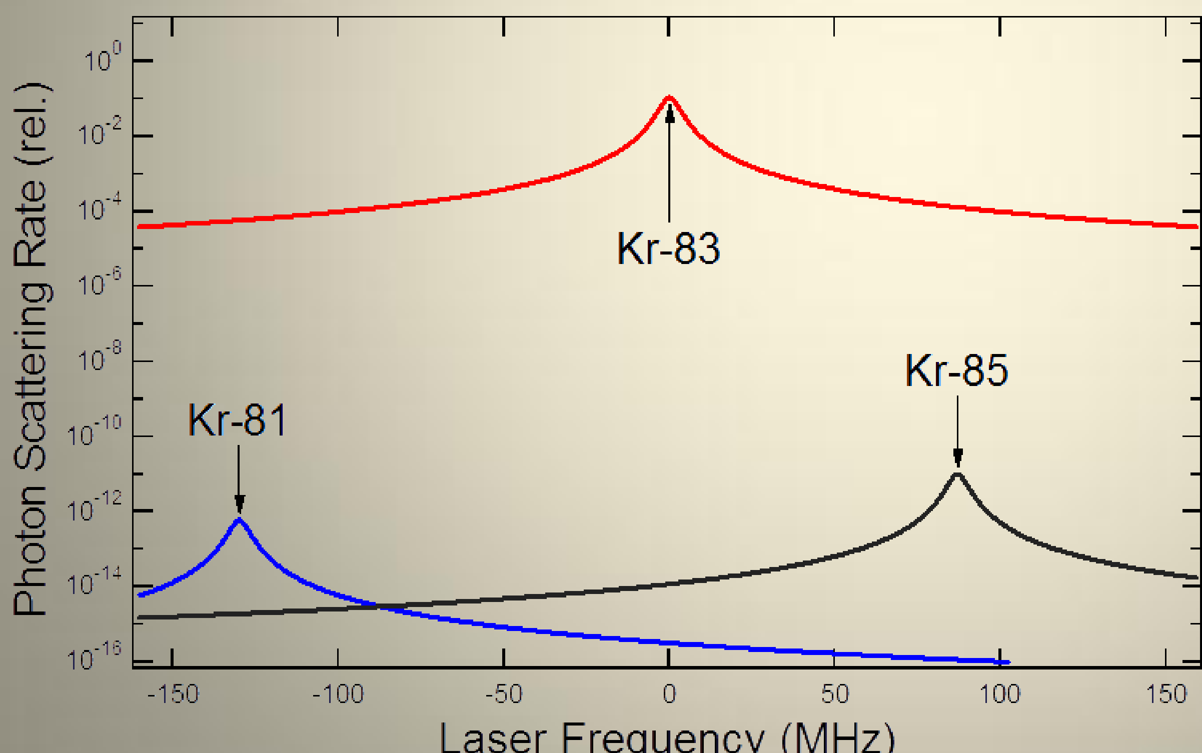


- Noble gases can fill in the gaps

How to measure trace amounts?

- **Atomic transitions are *extremely* selective!**

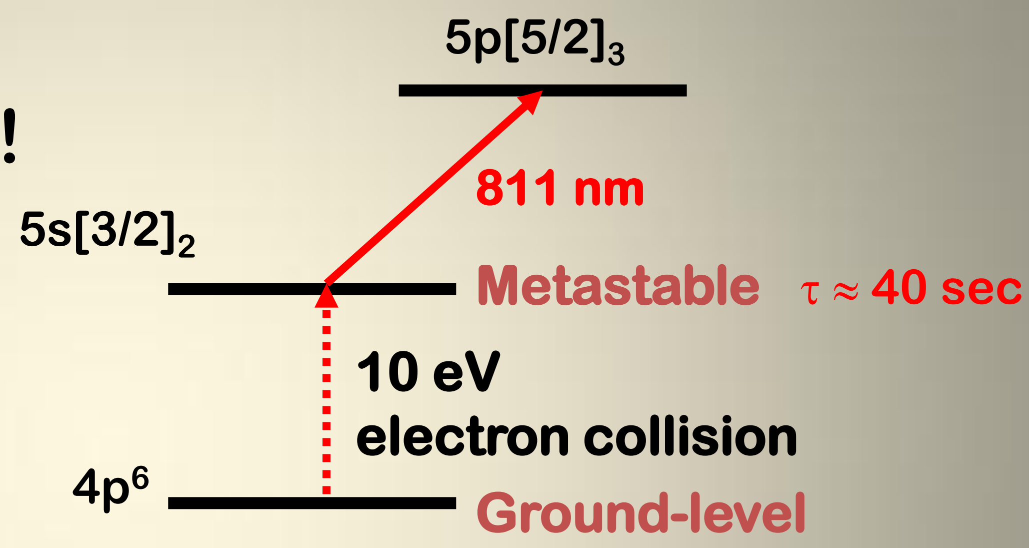


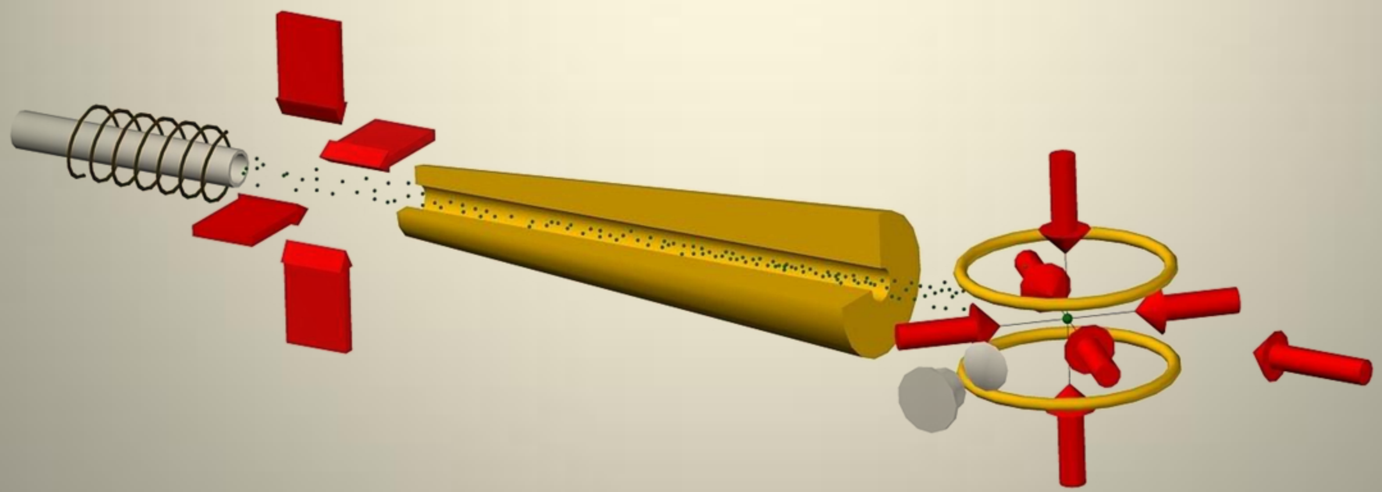


Due to Doppler-broadening, ^{83}Kr is still 100,000,000x bigger than the ^{81}Kr signal!

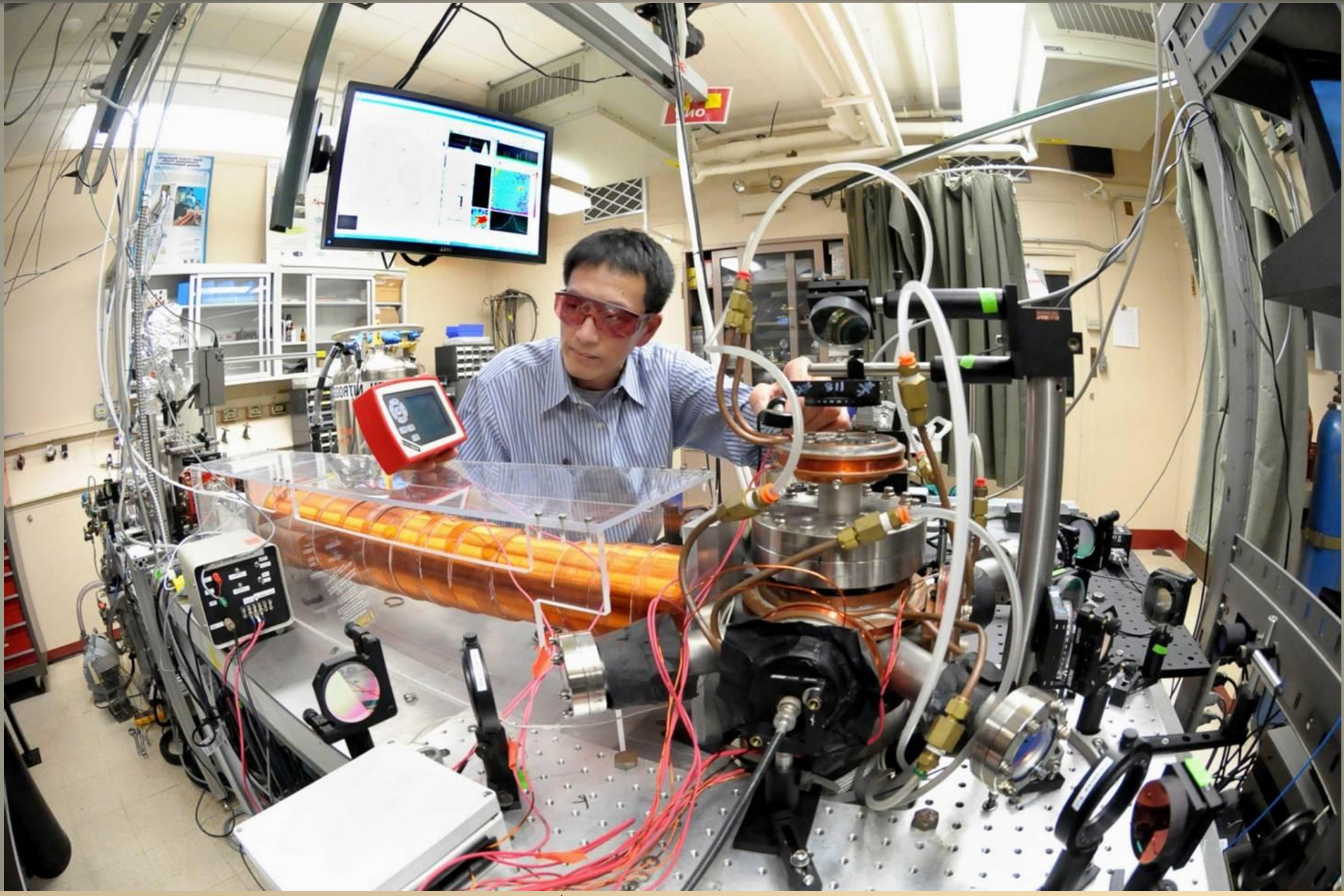
How to measure trace amounts?

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



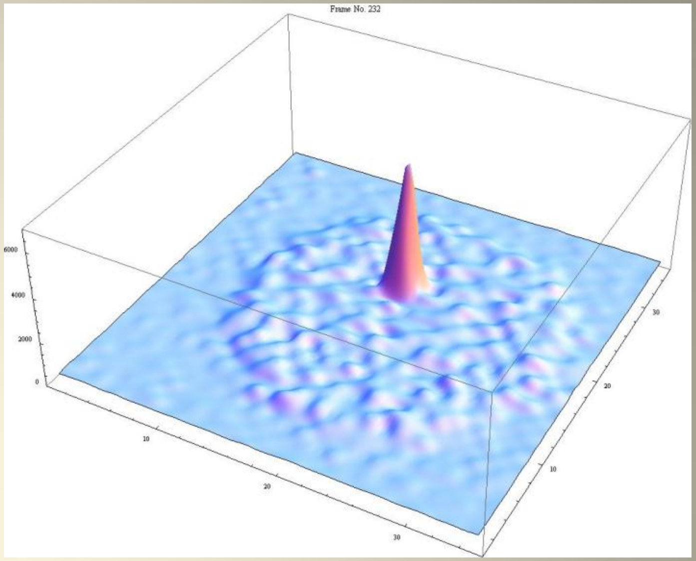


ATTA at ANL

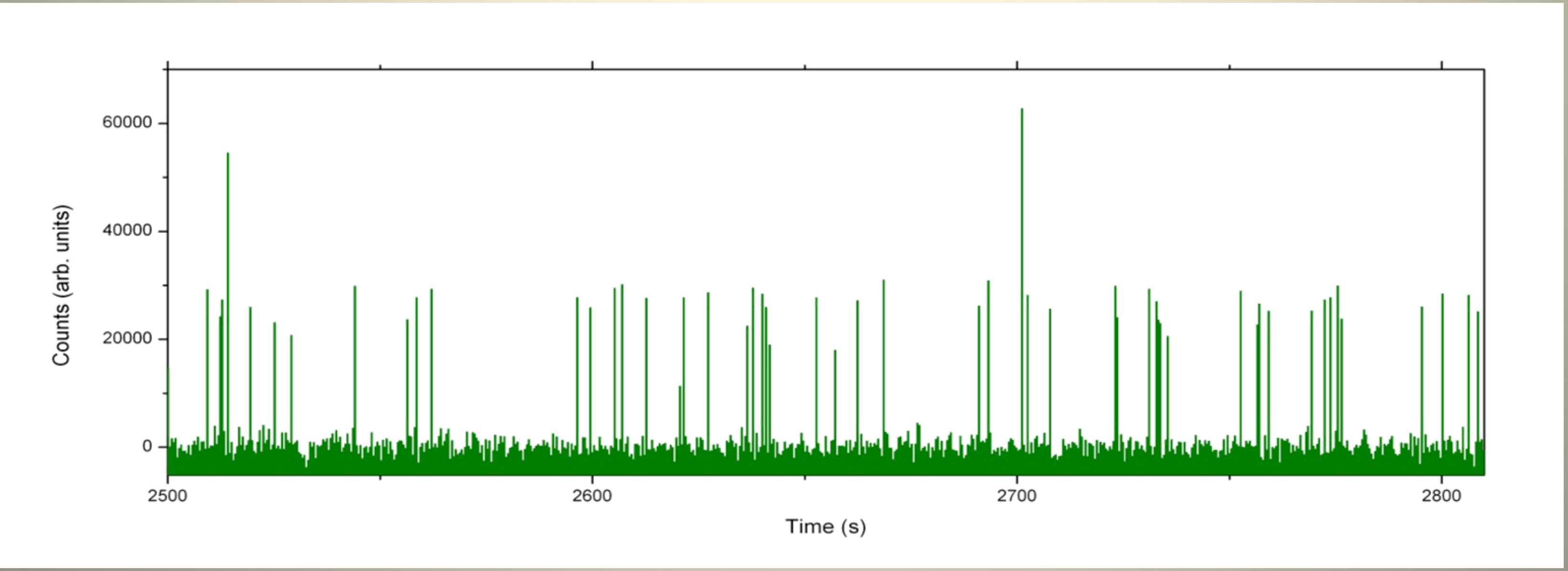


Single atom detection

- CCD image profile of a *single* ^{81}Kr atom



- $^{81}\text{Kr/Kr} = 6 \times 10^{-13} = 0.6\ \text{ppt}$



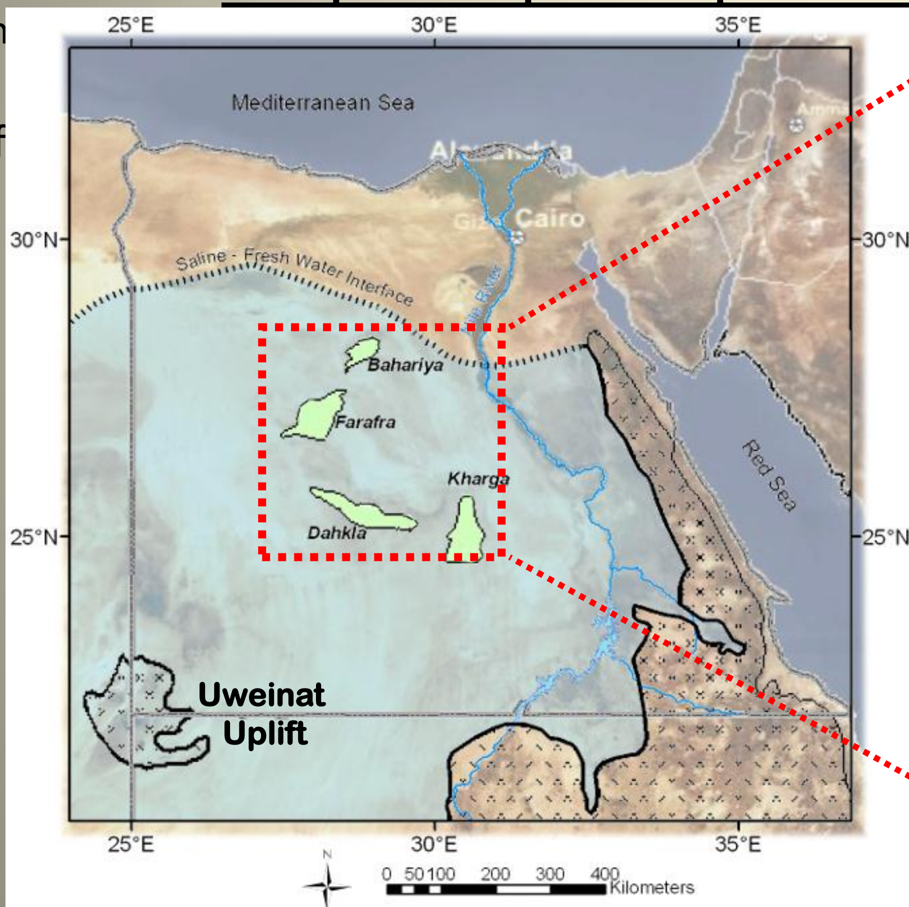
^{81}Kr dating: from dream to reality

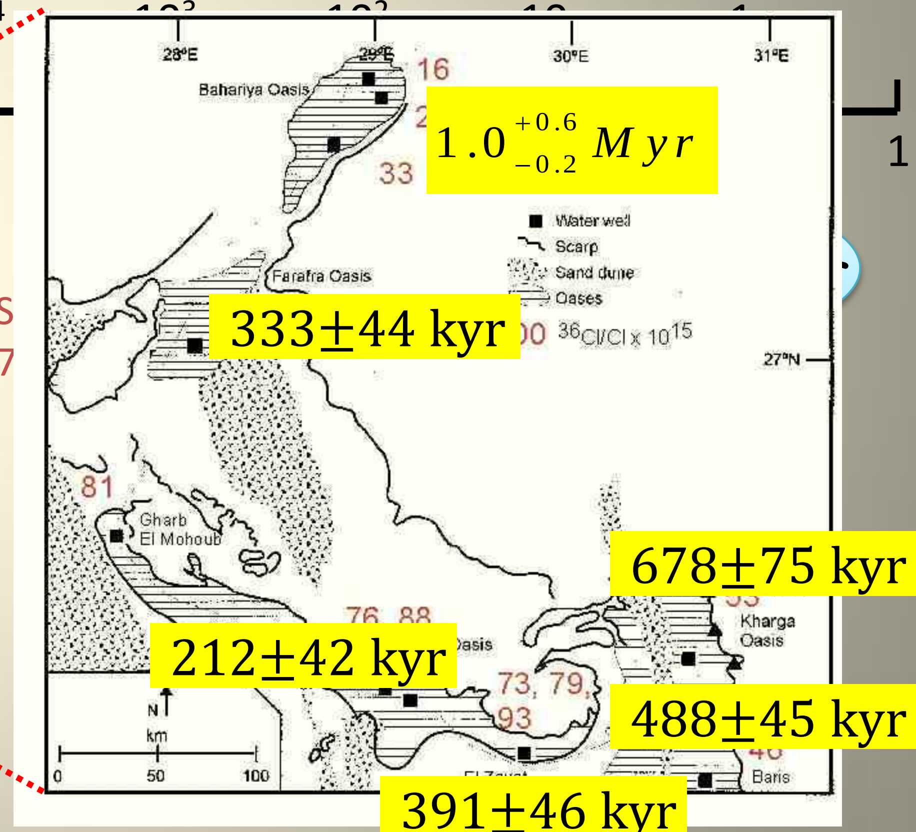
ATTA-1: *C.-Y. Chen et al., Science (1999)*
ATTA-2: *X. Du et al., Geophys. Res. Lett. (2003)*
ATTA-3: *W. Jiang et al., Phys. Rev. Lett. (2011)*

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

star burning

Homeland security

Big Bang nucleosynthesis

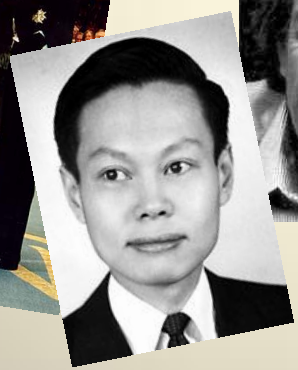
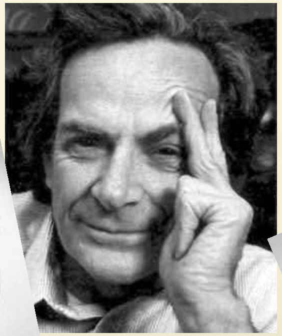
nuclear structure

super-heavy elements

archaeology/art

- So many great scientists involved





Maybe you'll be next?!