A century of nuclear physics

...and beyond!

Arnau Rios Huguet
Department of Physics
University of Surrey

FAN Seminar, 25 May 2011

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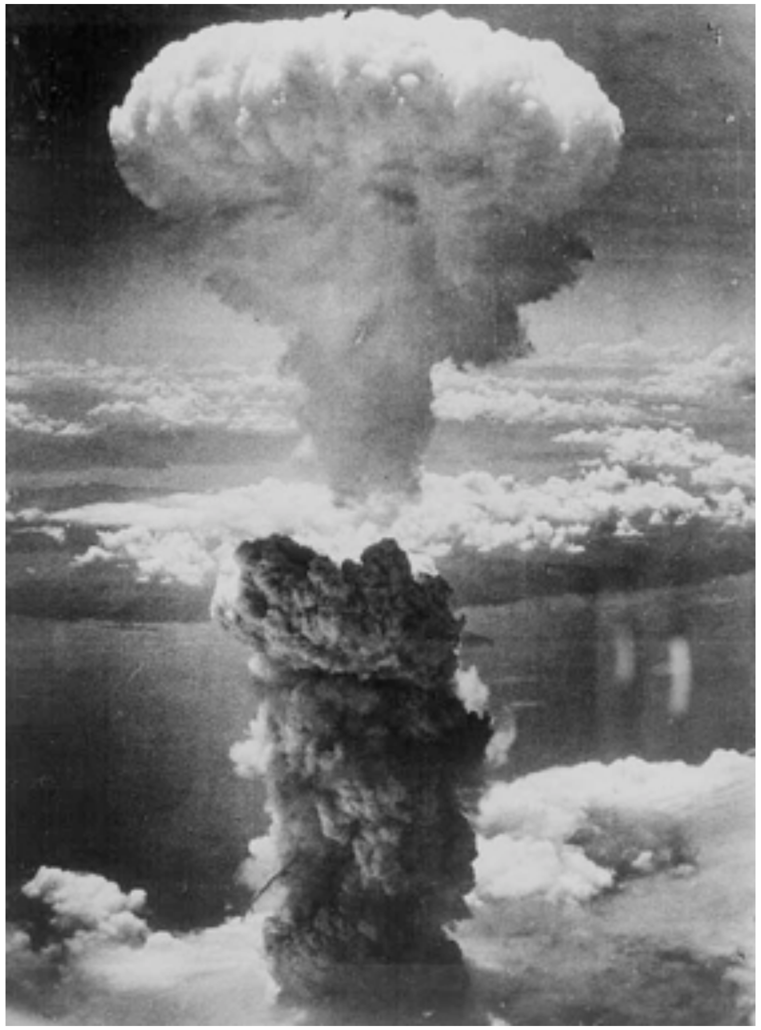
- Breaking the nuclear ice
- A brief historical overview
- Why nuclear physics motivates me?
- Review of experimental (& theoretical) advances

A confession...

- I am a nuclear physicist

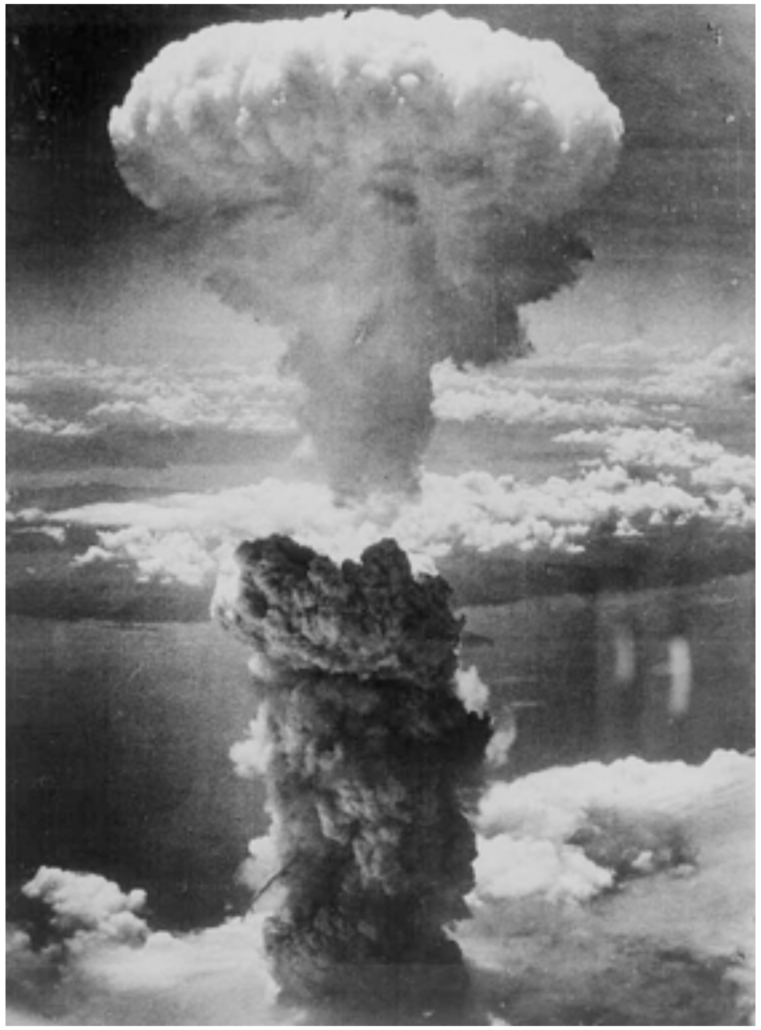
A confession...



Nagasaki (August 1945)

- I am a nuclear physicist

A confession...



Nagasaki (August 1945)

Fukushima reactor (March 2011)

- I am a nuclear physicist

A confession…

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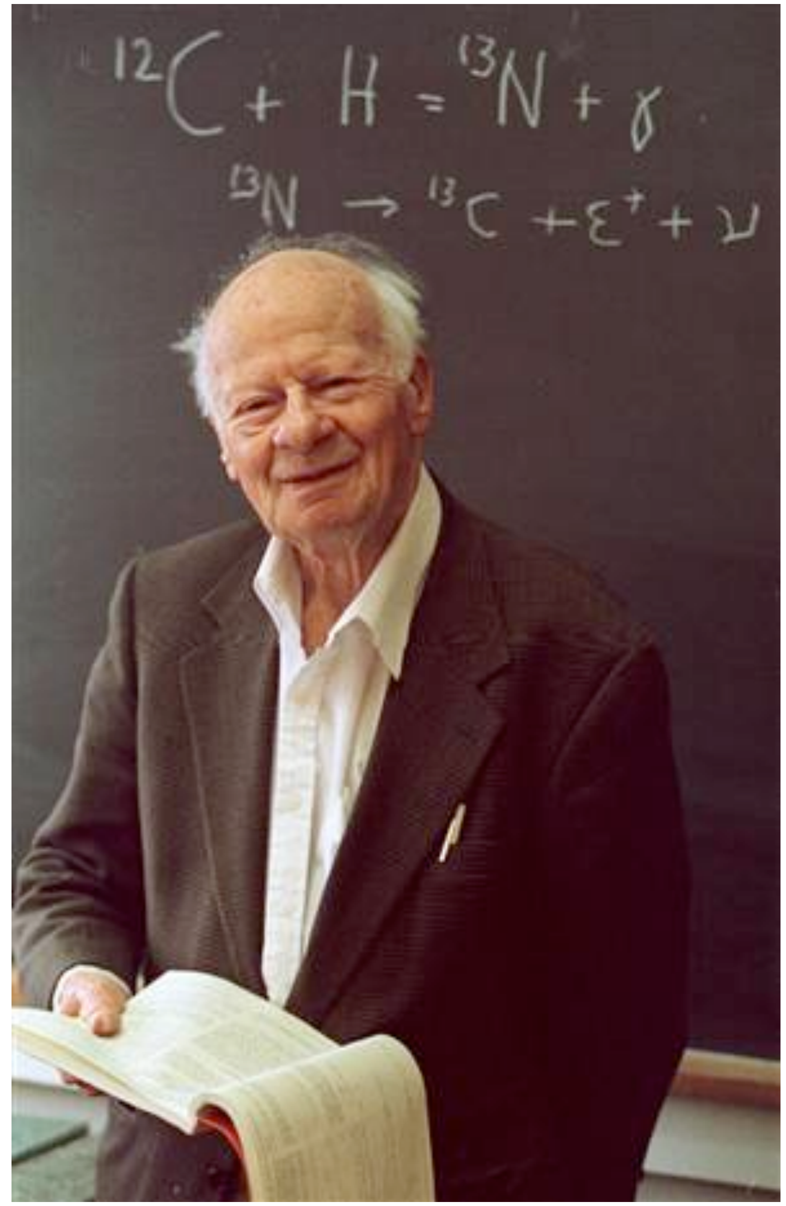


Hans Bethe (1906-2005)

- I am a nuclear physicist
- Basic research in nuclear physics?

A confession...

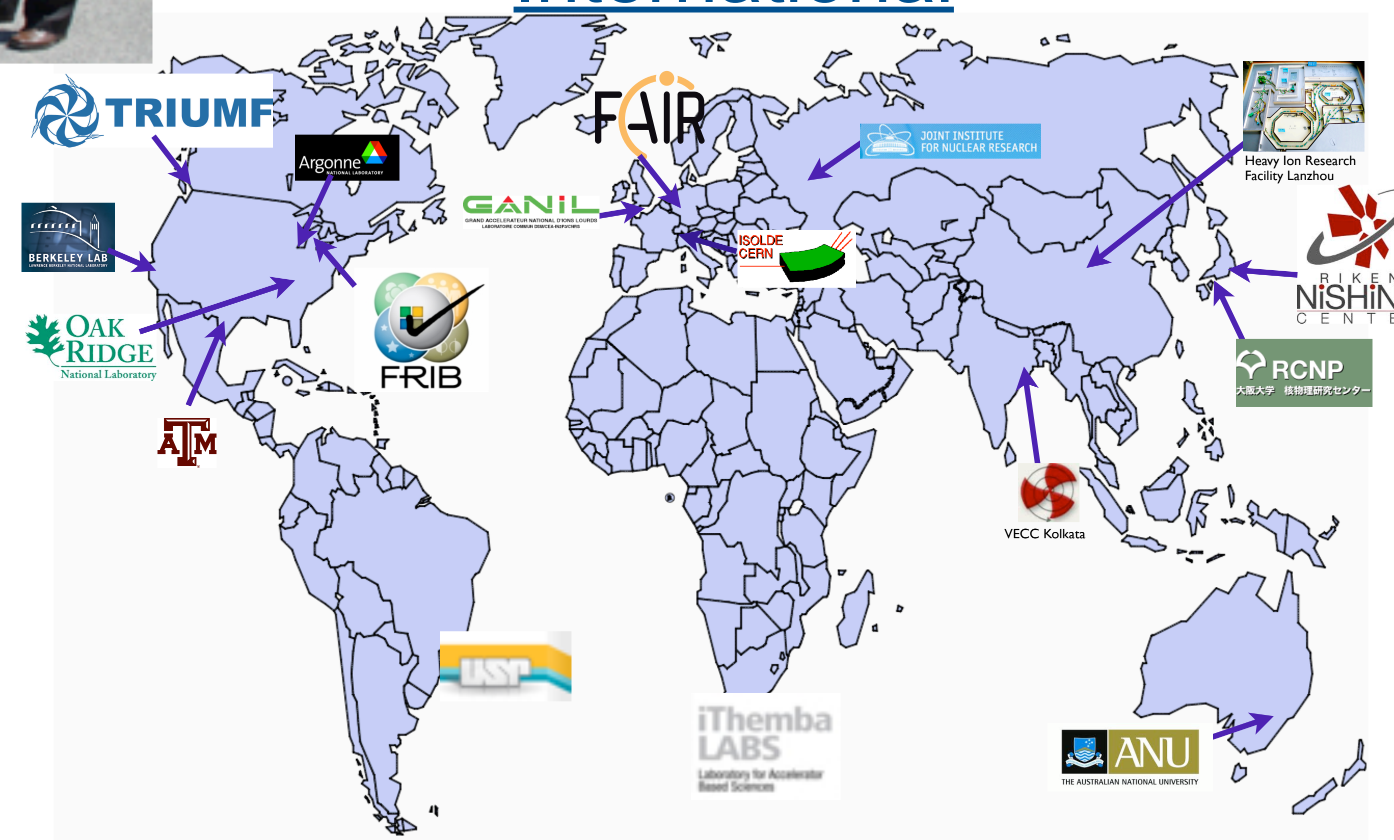
Young

Compstar 11 (Catania)

Active

US (DoE) ~ 605 M$/year
US (NSF) ~ 20 M$/year
EU ~ 200 M€/year

International



- I am a nuclear physicist
- Basic research in nuclear physics?

A century of nuclear physics

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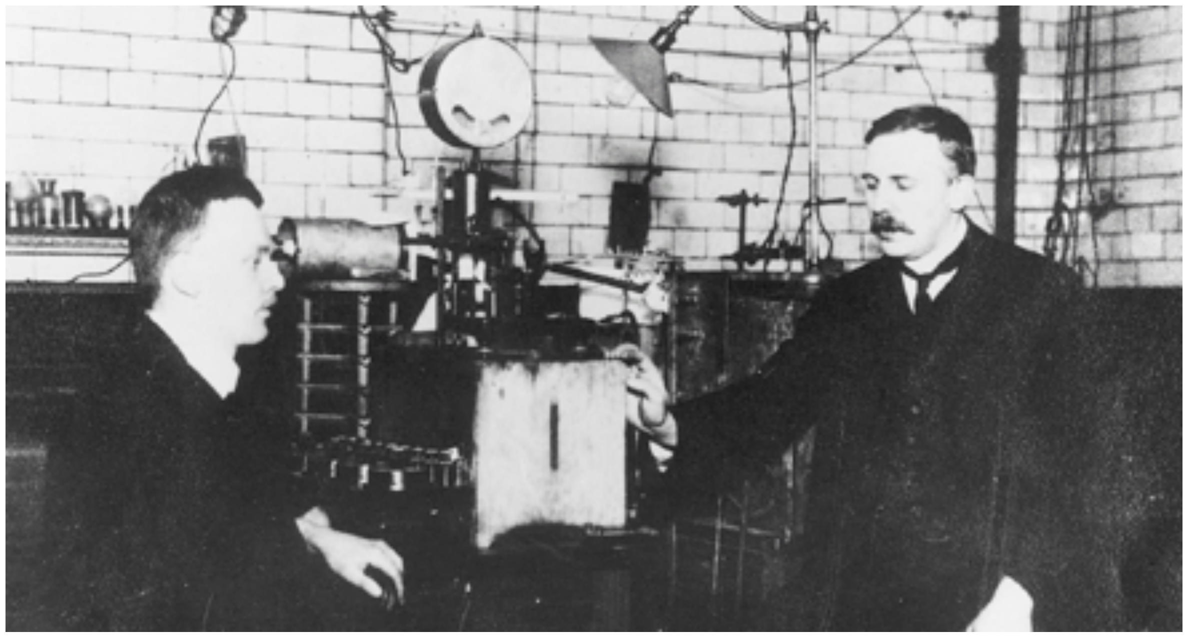
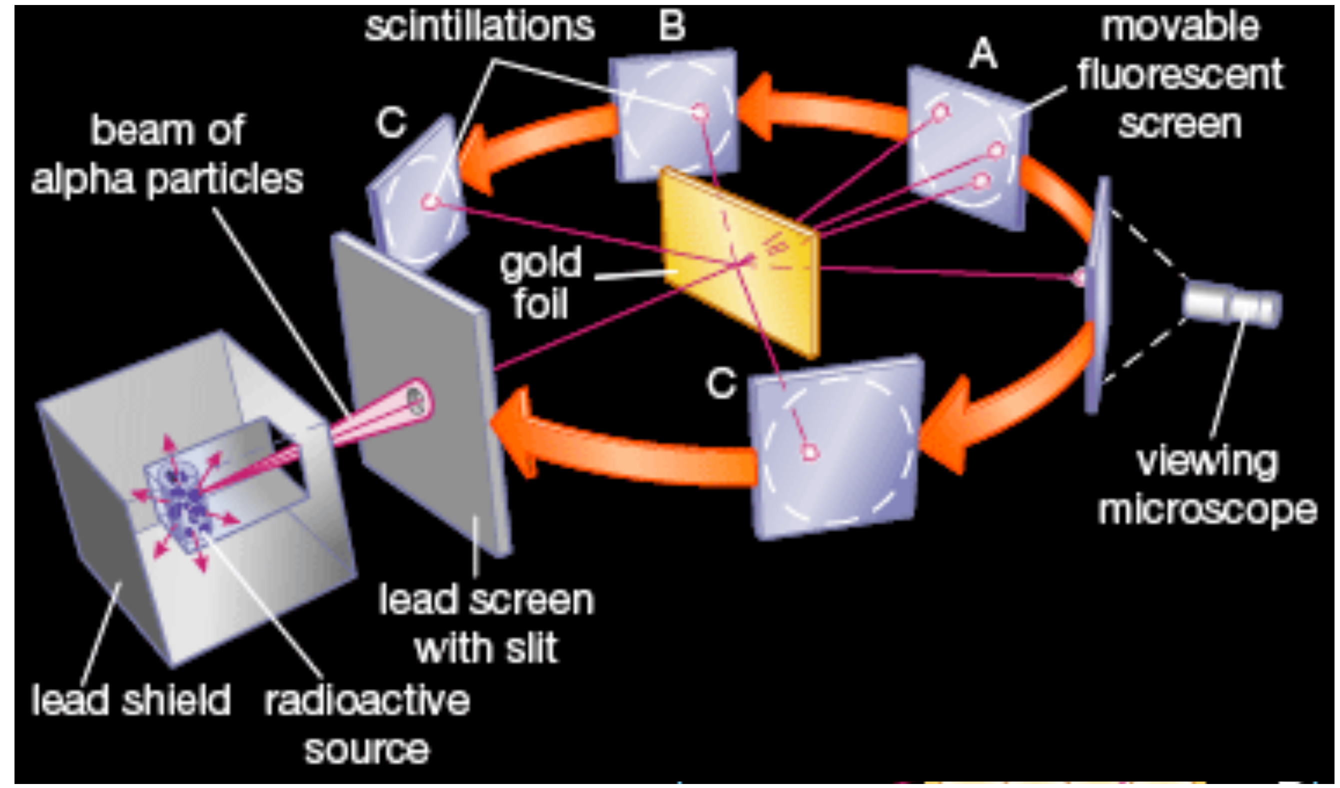
Rutherford's experiment?

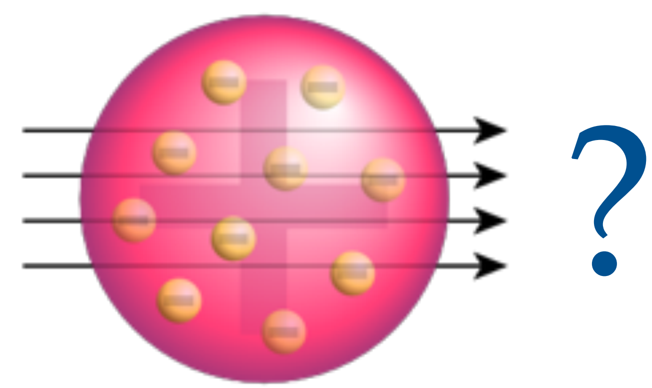
Geiger, Mardsen & Rutherford experiment



Rutherford & Geiger, Manchester (circa 1910)



Ernest Mardsen



1907 - Rutherford moves from McGill (Canada) to Manchester
1908 - Nobel prize in Chemistry
1909 - Geiger & Mardsen perform the Gold (?) foil experiment
1911 - Rutherford's atomic model: the nucleus is born!

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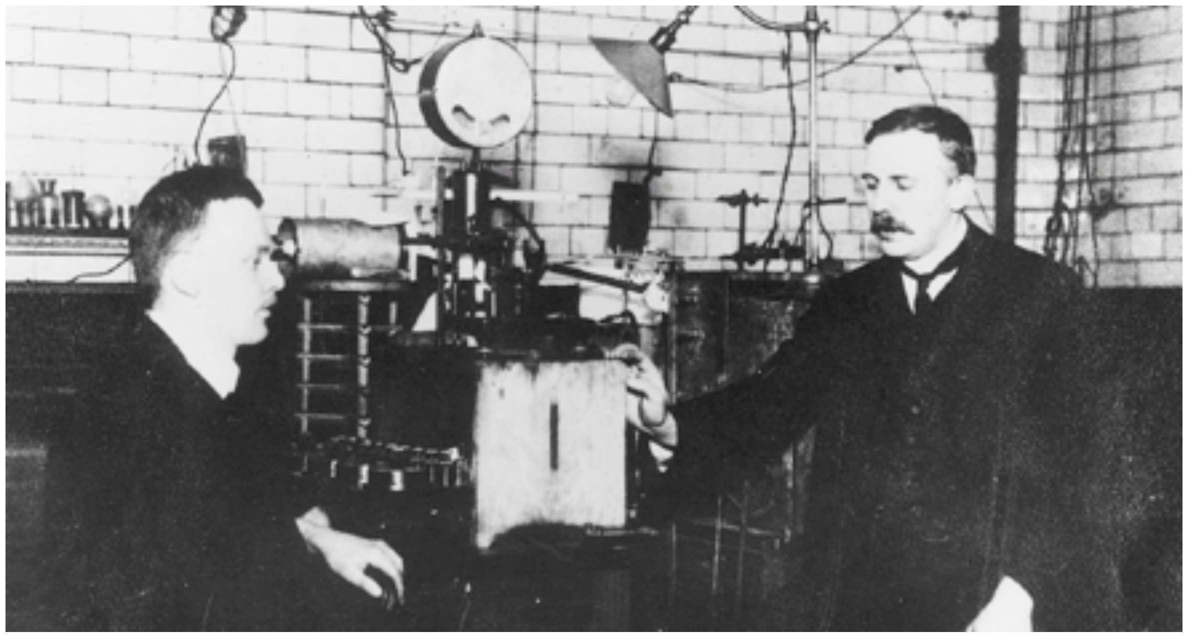
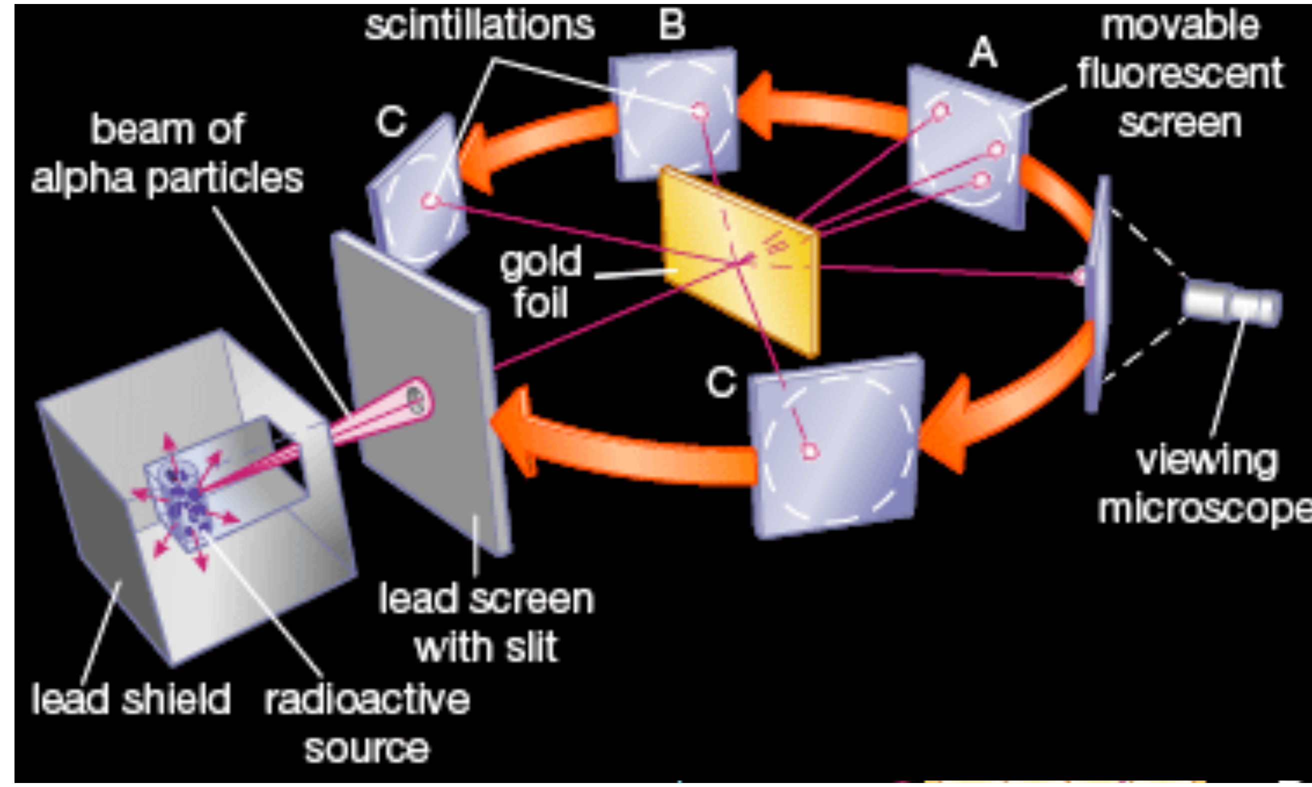
Rutherford's experiment?



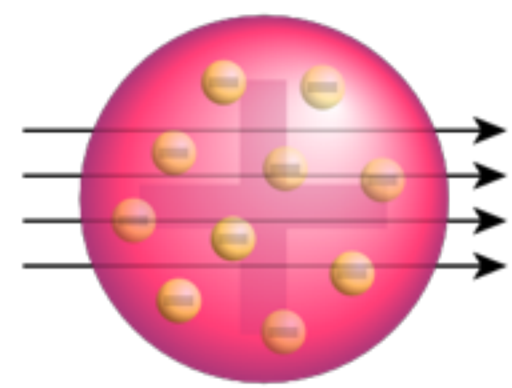
Rutherford & Geiger, Manchester (circa 1910)

Geiger, Mardsen & Rutherford experiment



Ernest Mardsen

I was an undergraduate!



?

1907 - Rutherford moves from McGill (Canada) to Manchester
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Results of the experiment

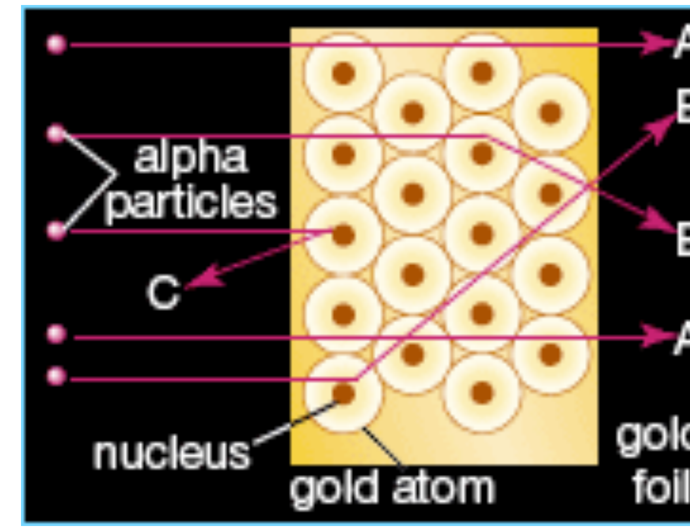
On a Diffuse Reflection of the α-Particles.

By H. GEIGER, Ph.D., John Harling Fellow, and E. MARSDEN, Hatfield Scholar, University of Manchester.

(Communicated by Prof. E. Rutherford, F.R.S. Received May 19,—Read June 17, 1909.)

In the following experiments, however, conclusive evidence was found of the existence of a diffuse reflection of the α-particles. A small fraction of the α-particles falling upon a metal plate have their directions changed to such an extent that they emerge again at the side of incidence. To form an

Proceedings of the Royal Society of London, Series A, vol. **82,** 557 (1909)



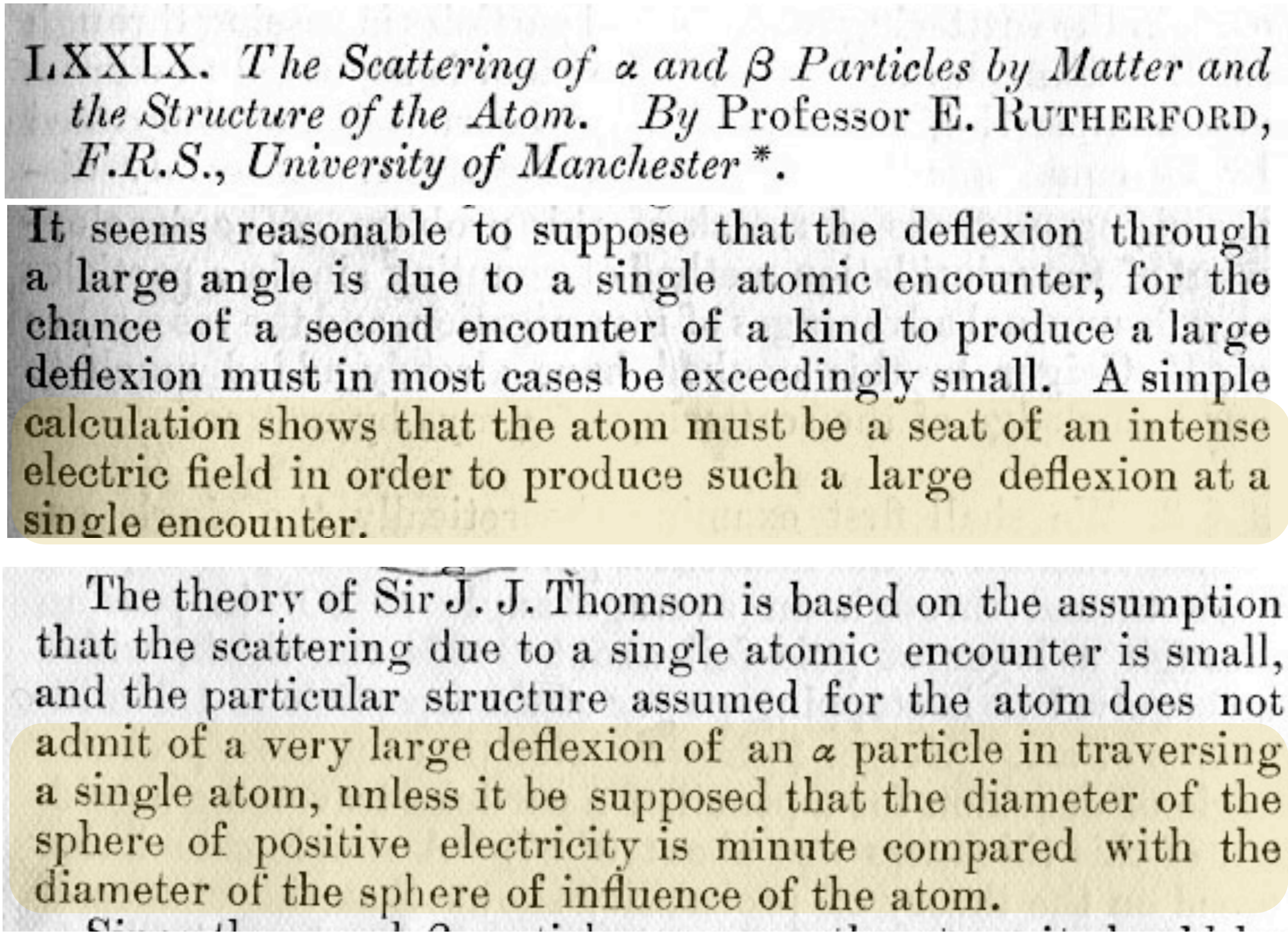
A Transmitted beams (little or no deflection)
B Scattered beam (small deflection)
C Scattered beam (large deflection)

"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a bullet at a piece of tissue paper and it came back and hit you"

Rutherford

Interpretation

Ernest Rutherford



LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* By Professor E. RUTHERFORD, F.R.S., *University of Manchester* *.

It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

The theory of Sir J. J. Thomson is based on the assumption that the scattering due to a single atomic encounter is small, and the particular structure assumed for the atom does not admit of a very large deflexion of an α particle in traversing a single atom, unless it be supposed that the diameter of the sphere of positive electricity is minute compared with the diameter of the sphere of influence of the atom.

Philosophical Magazine, Series 6, vol. **21**, 669 (May, 1911)

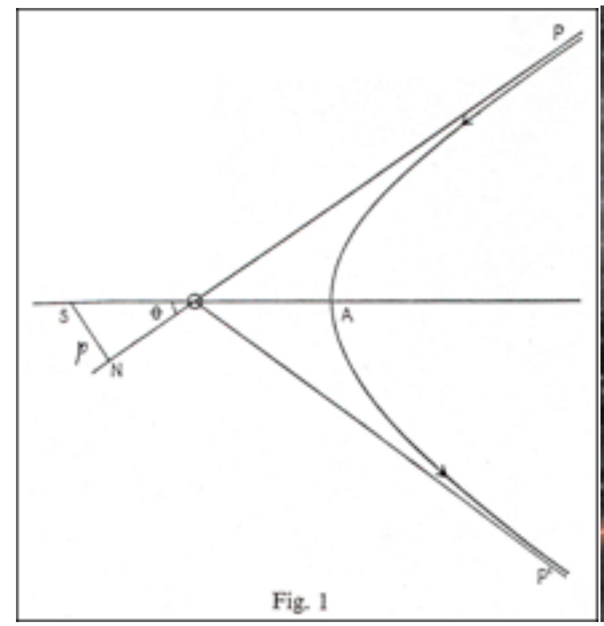
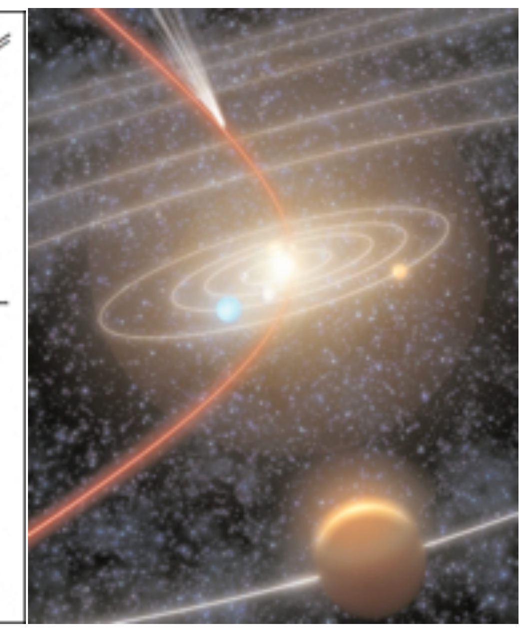


Fig. 1

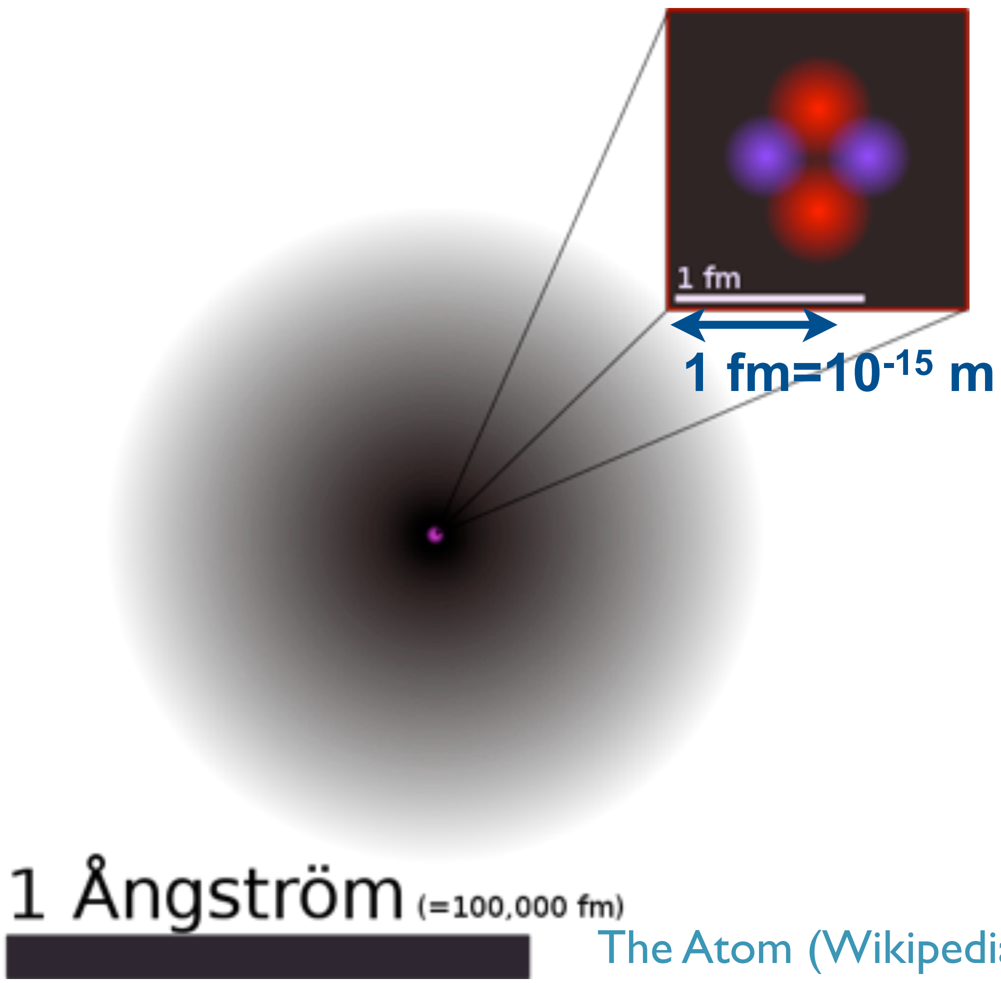


$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v_0^2}\right)^2 \csc^4\left(\frac{\Theta}{2}\right)$$

It takes Rutherford 18 months to figure it out: it is *revolutionary!*

- Dec. 1910: single scattering & hyperbolic trajectory
- March 1911: talk at the Manchester Literary & Philosophical Society
- April 1911: submits paper to *Philosophical Magazine*
- May 1911: paper published

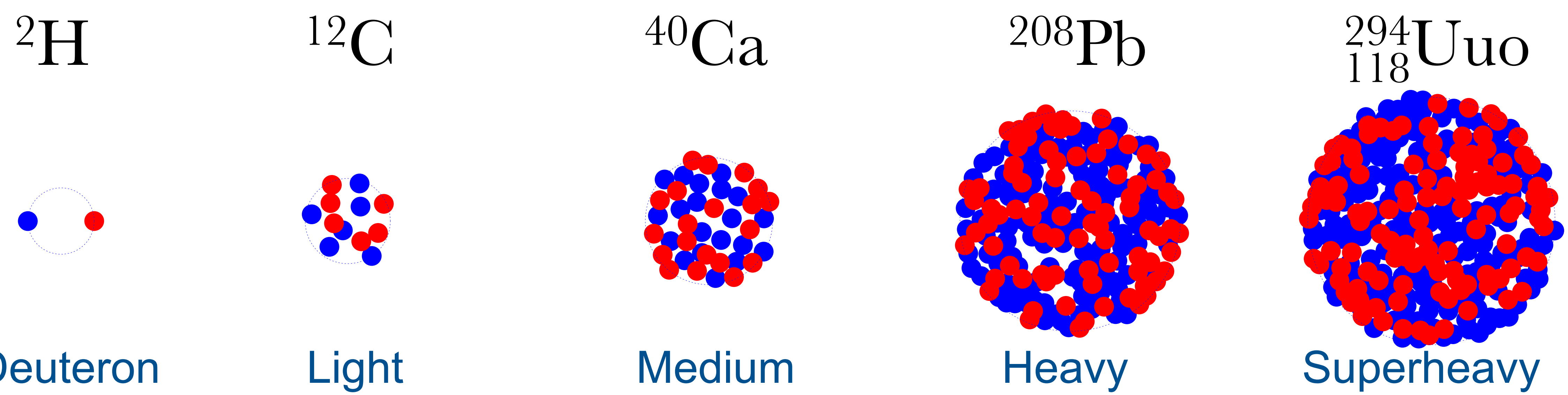
The nucleus in the 1910s



The Atom (Wikipedia)

- Why is stable? → it is quantal! (Bohr, 1913)
- It is very small
- Contains > 99% mass of the atom
- Isotopes of same element have similar chemistry
- Proton number is the atomic number, Z
- Some isotopes decay radioactively: α, β and γ
- 1932: neutrons determine the mass number, A=N+Z

Nuclear sizes: $R = 1.2\, A^{1/3}$ [fm]



What happened after?

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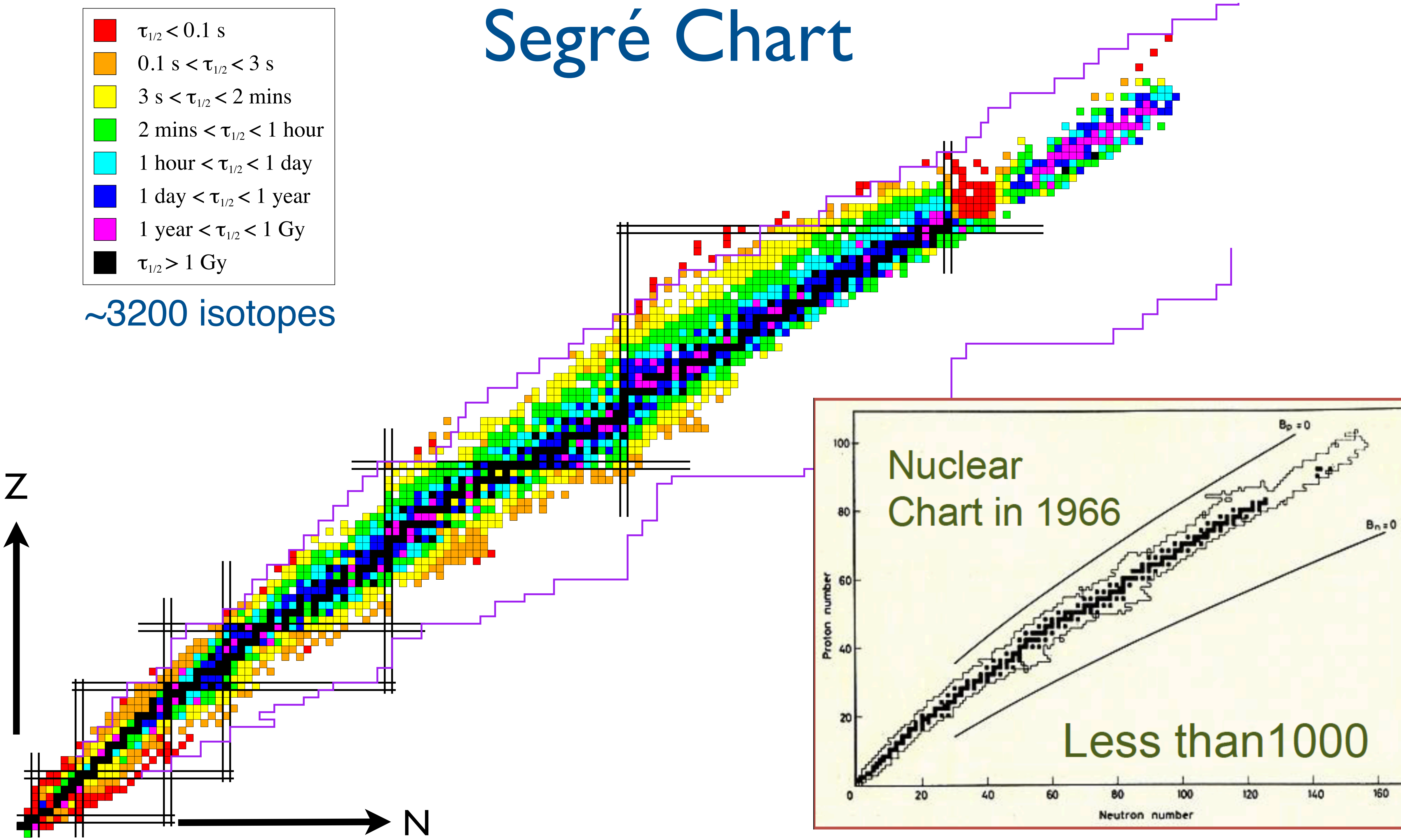
A (personal) modern physics timeline

1911	Nucleus	Rutherford
1919	Proton	Rutherford
1923	Photon	Compton
1931	Neutrino	Pauli
1932	Neutron	Chadwick
1932	Positron	Anderson
1934	β decay	Fermi
1939	Fission	Bohr, Wheeler
1945	Atomic bomb	Manhattan project
1948	Nucleosynthesis	Alpher, Bethe, Gamow
1956	Electron neutrino	Cowan & Reines
1964	Quarks	Gell-Mann, Zweig
1967	Electroweak unification	Weinberg, Salam
1977	Bottom quark	Lederman et al @ Fermilab
1983	W, Z bosons	Rubbia et al @ CERN
1991	World Wide Web	Berners Lee @ CERN
1994	Top quark	CDF & D0 @ Fermilab
2000	Dark energy	Supernova teams
2011	Higgs?	

Wait a minute...

What about the nucleus?

Segré Chart



~3200 isotopes

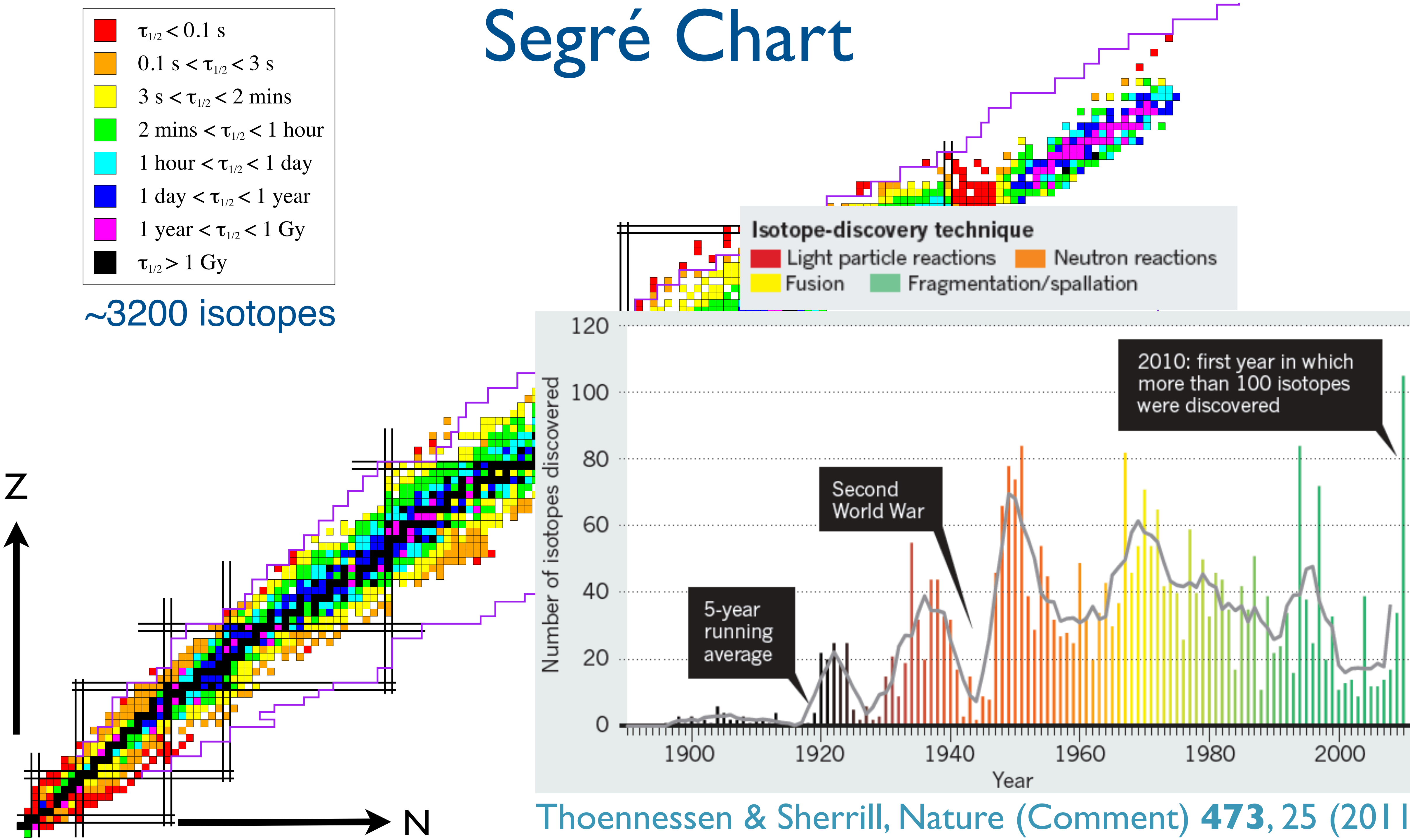
Wait a minute...

What about the nucleus?

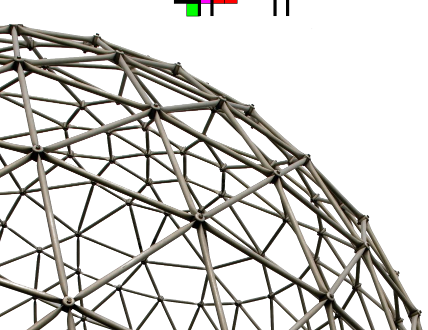
red	$\tau_{1/2} < 0.1$ s
orange	0.1 s $< \tau_{1/2} < 3$ s
yellow	3 s $< \tau_{1/2} < 2$ mins
green	2 mins $< \tau_{1/2} < 1$ hour
cyan	1 hour $< \tau_{1/2} < 1$ day
blue	1 day $< \tau_{1/2} < 1$ year
magenta	1 year $< \tau_{1/2} < 1$ Gy
black	$\tau_{1/2} > 1$ Gy

~3200 isotopes

Segré Chart



Thoennessen & Sherrill, Nature (Comment) **473**, 25 (2011)



Why study nuclear physics?

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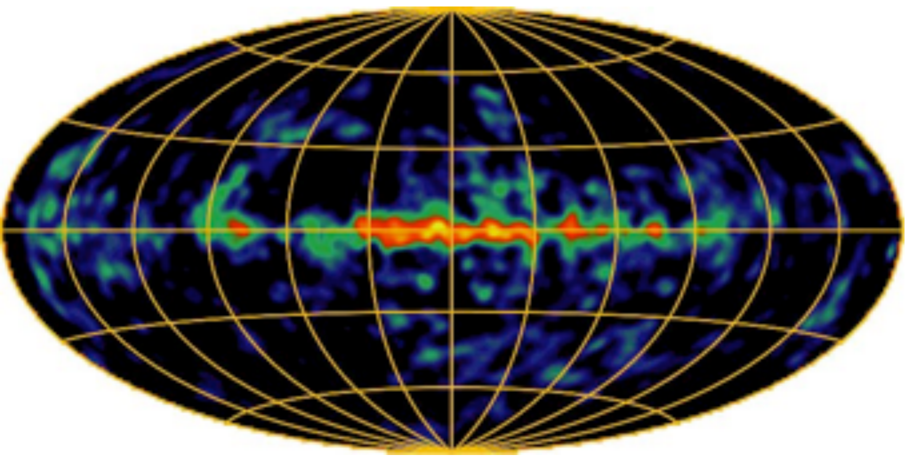
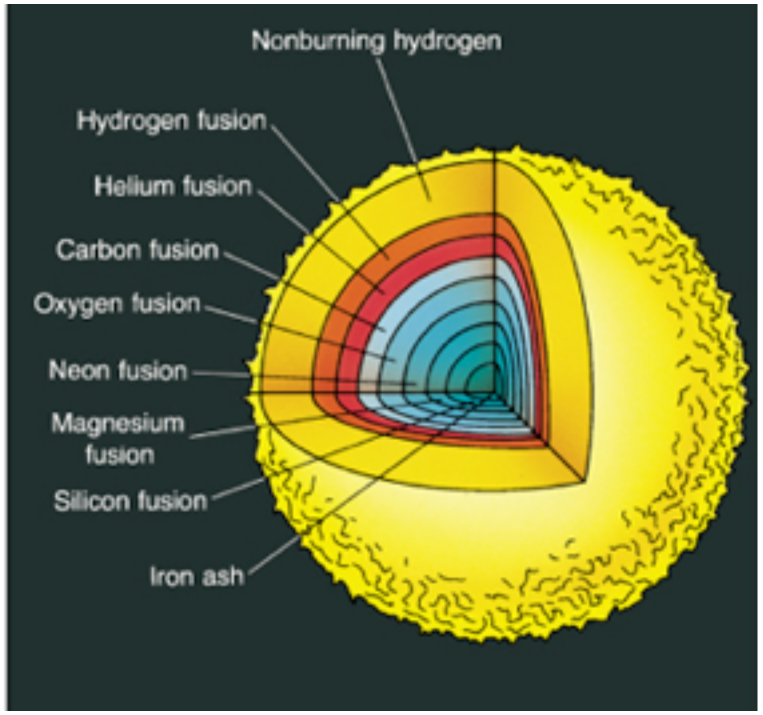
COMPTEL map (1.8 MeV)

Gammas in ^{26}Mg following ^{26}Al GS β-decay



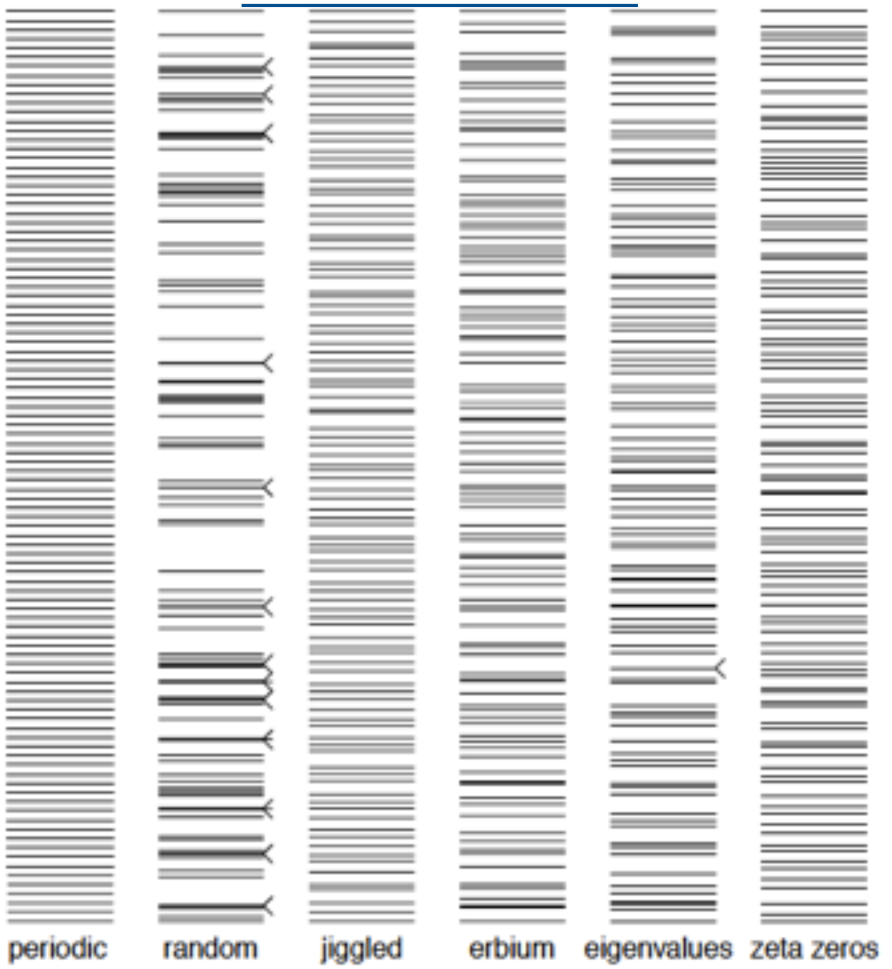
http://heasarc.gsfc.nasa.gov/W3Browse/cgro/comptel.html

Nuclear burning in stars



http://astronomy.nju.edu.cn/~lixd
Pearson Prentice Hall

Chaos in nuclei



Hayes, Am. Sci. 91, 296 (2003)

- Nuclei comprise 99.9% of matter we see in the Universe
- Nuclei are the fuel that burns in stars
- 3 of 4 fundamental forces are relevant!
- Nuclei exhibit all modern physics phenomena
  - ✦Chaos
  - ✦Superfluidity
  - ✦Supersymmetry & quantum phase transitions
  - ✦Astrophysics
  - ✦Statistical physics

XXIst century nuclear labs

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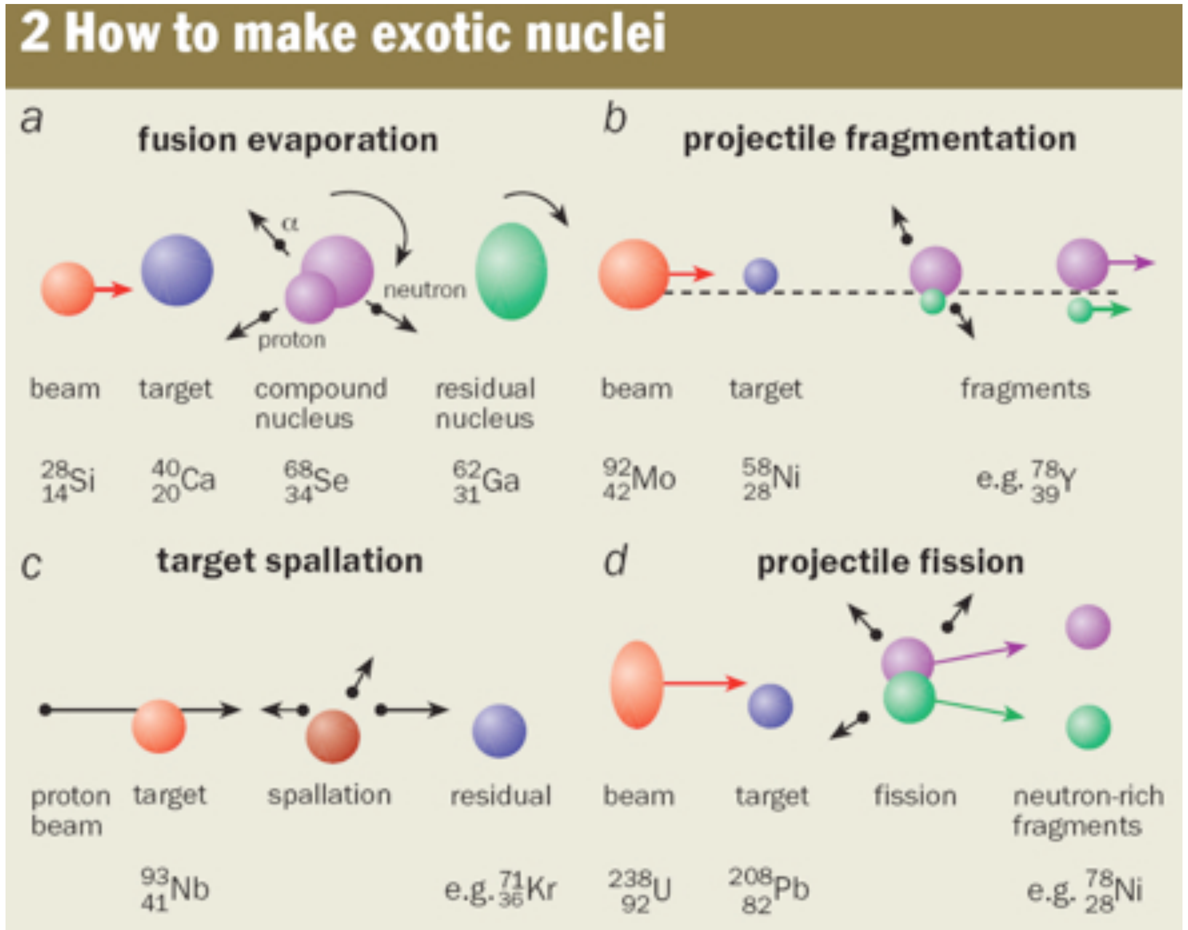
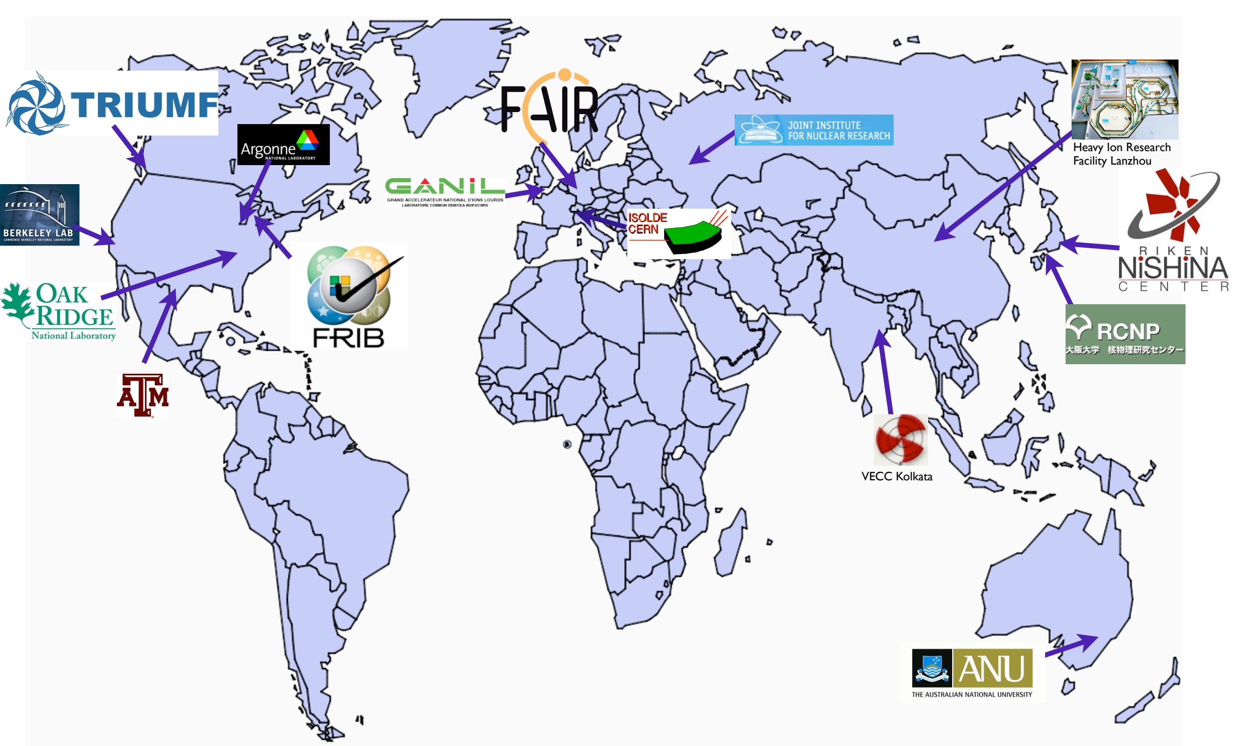
Designer nuclei



Regan & Blank, Physics World (2000)



XXIst century nuclear labs

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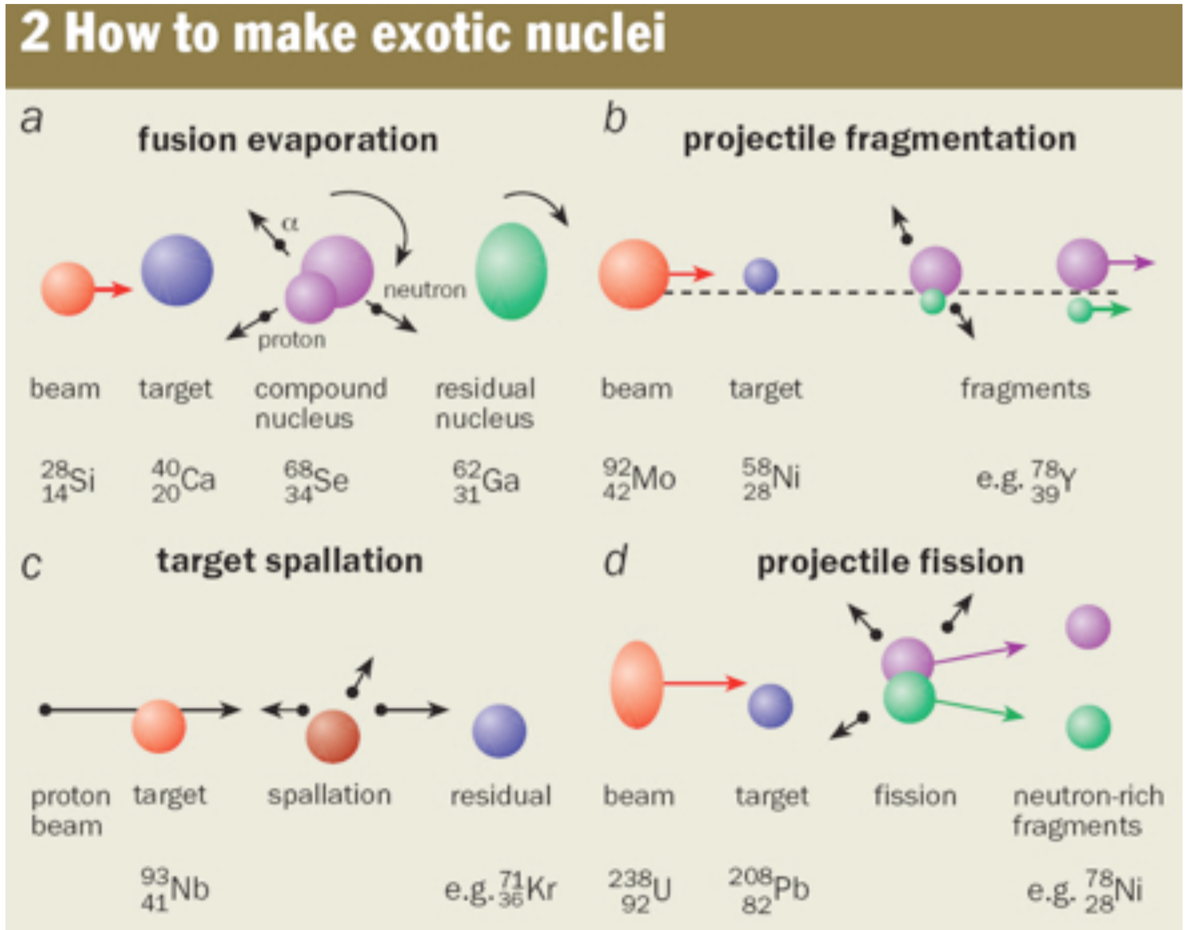
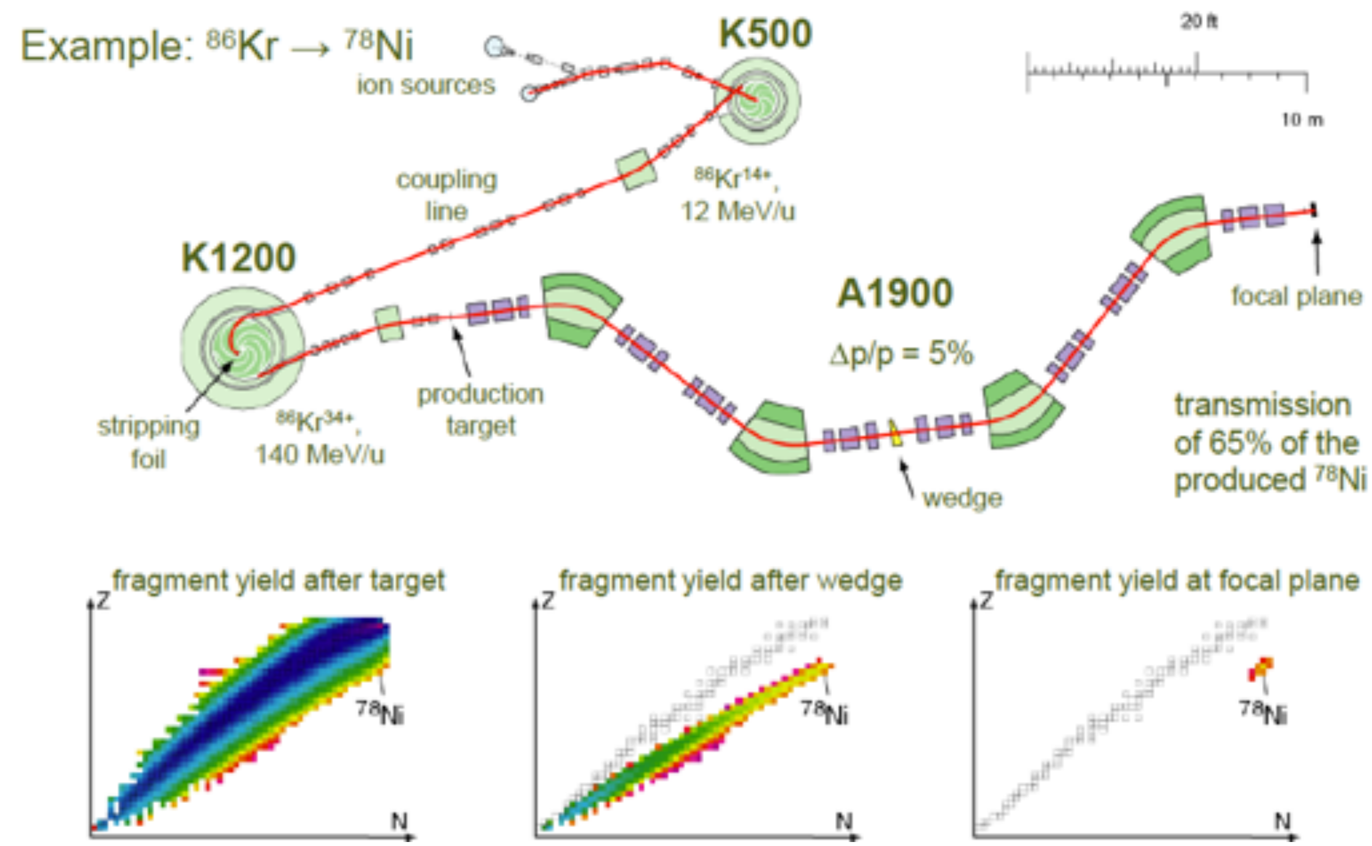
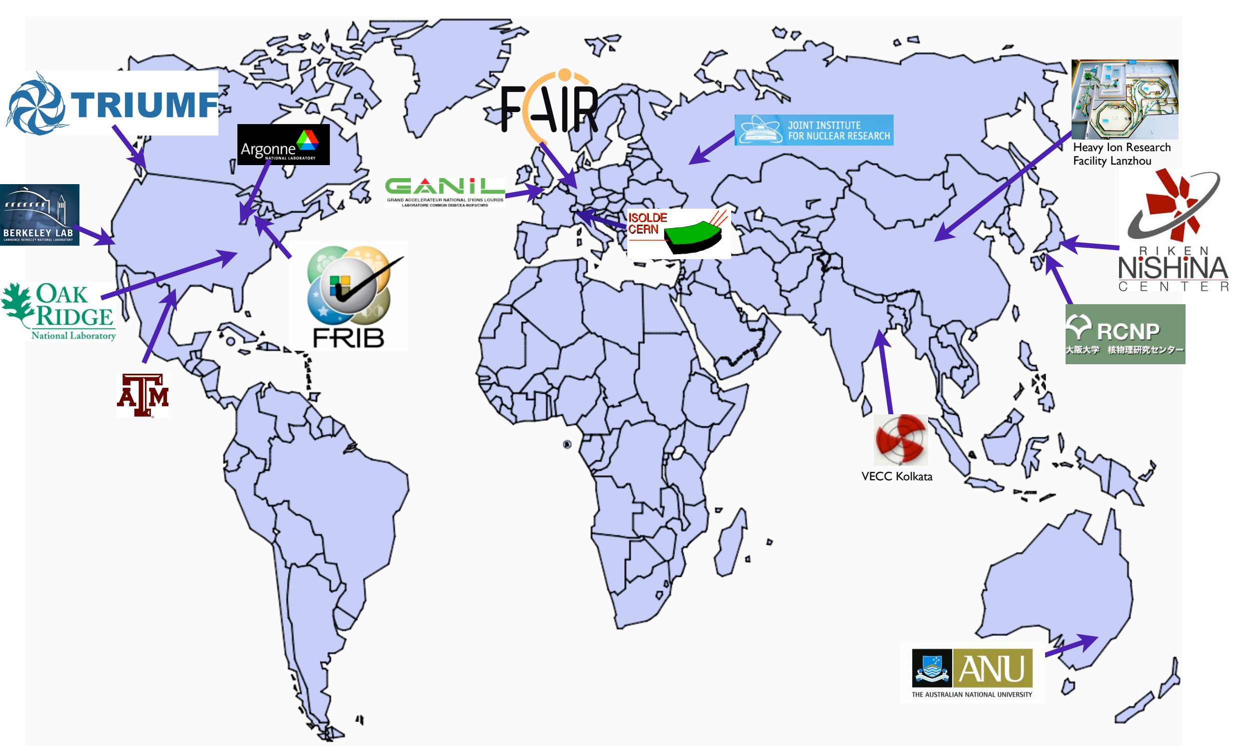


Regan & Blank, Physics World (2000)

NSCL CCF





Measuring exotic nuclei

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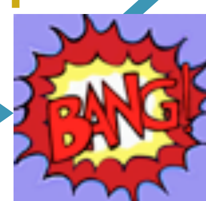
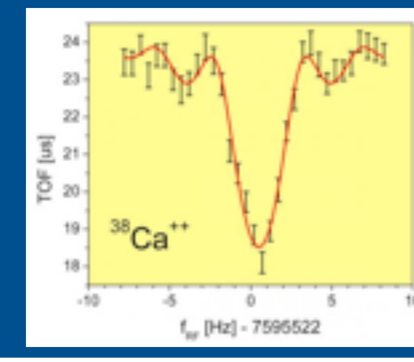
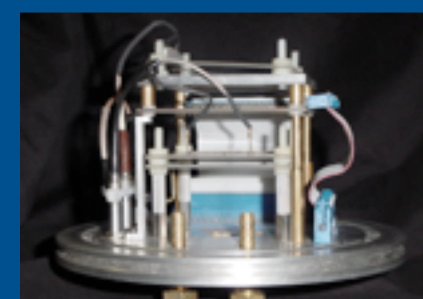
Secondary beam



Weight the isotope using Penning traps





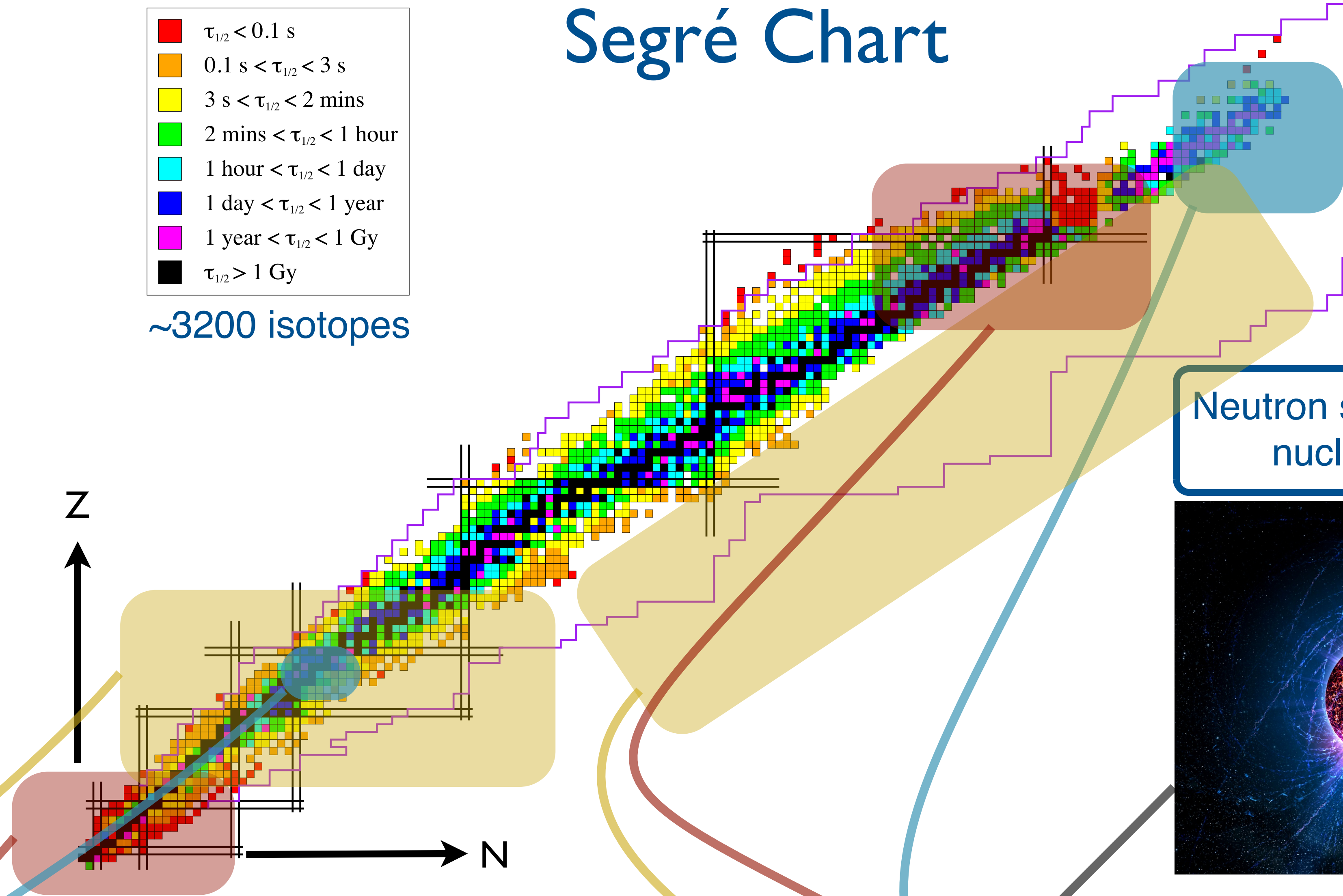
Implant & watch it decay

Fragmentation: measure all fragments after secondary reaction

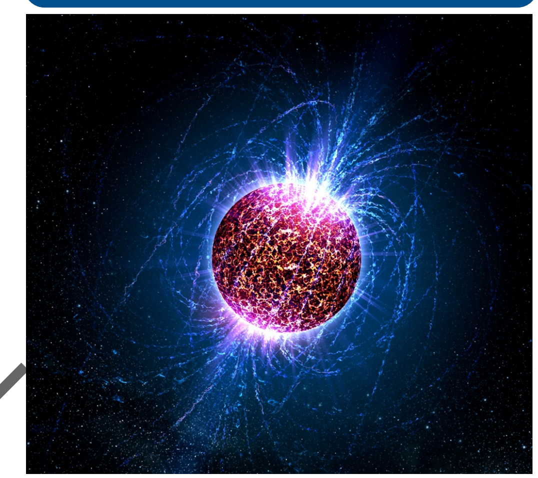
Spectrograph: mass & momentum distribution

A selection of topics

Segré Chart



Neutron stars are also nuclear labs!



Nuclear systems are interesting in themselves!

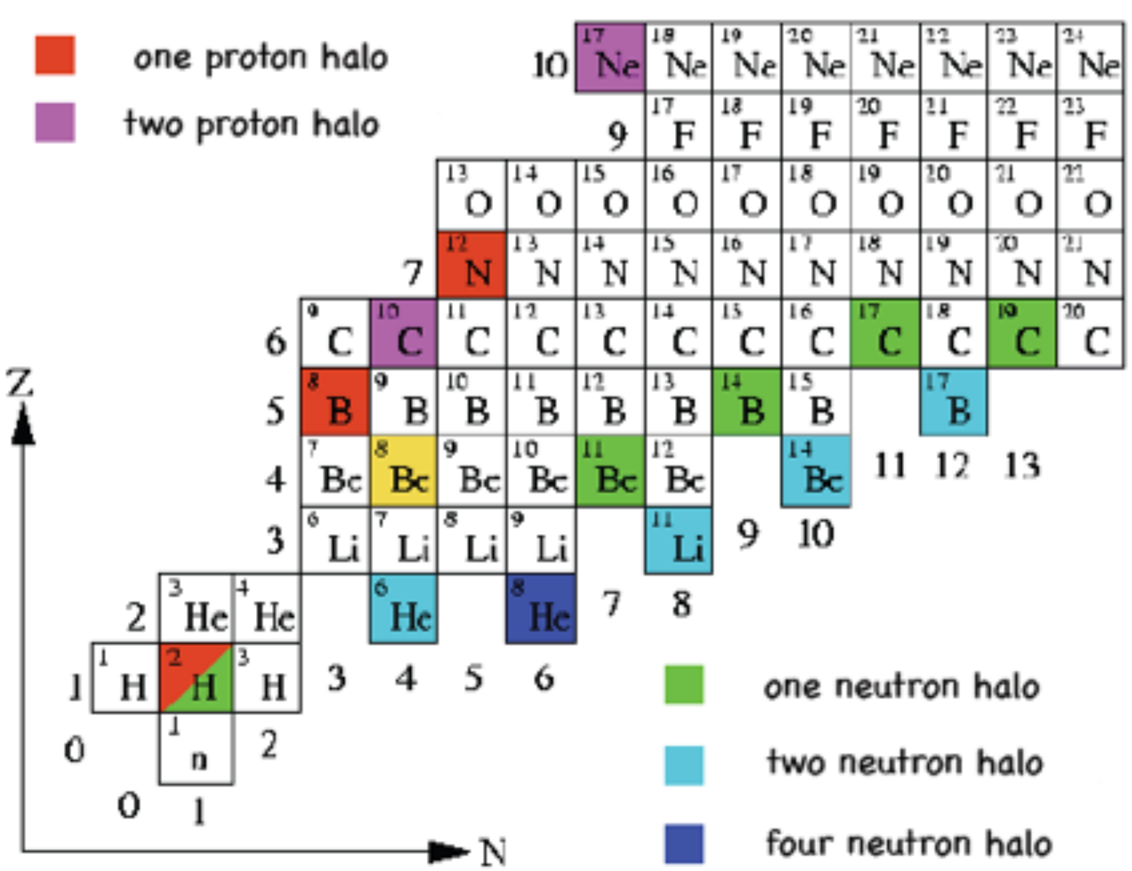
- Nuclear halos
- New magic numbers
- New decay modes

- Shape coexistence
- Nuclear astrophysics
- Superheavy elements
- Neutron stars

See also: NuPECC 2010 Long Range Plan

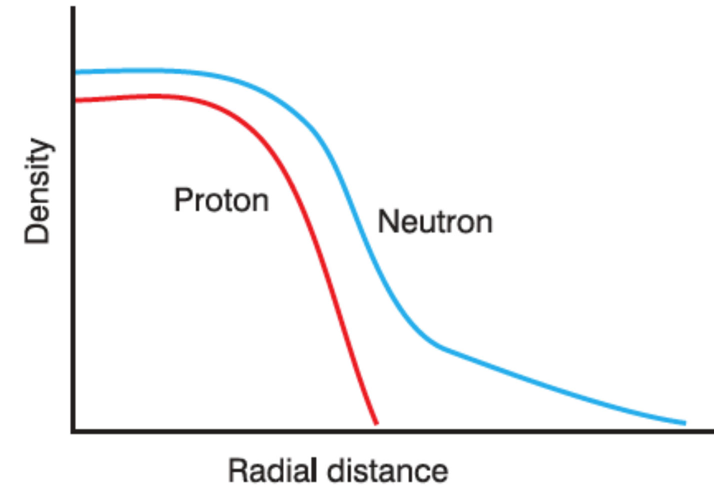
Light nuclei: halos

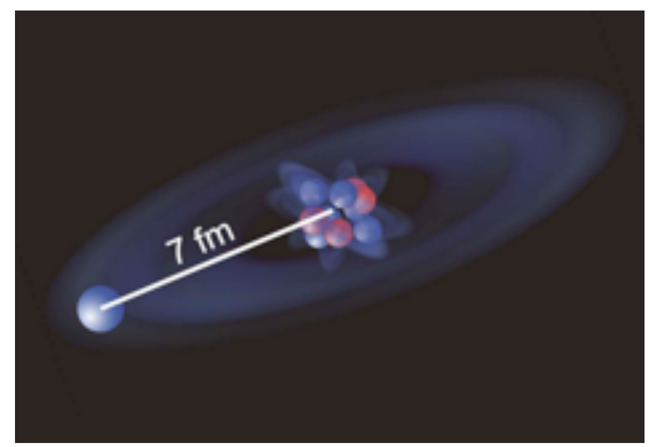
Large, light & Borromean nuclei



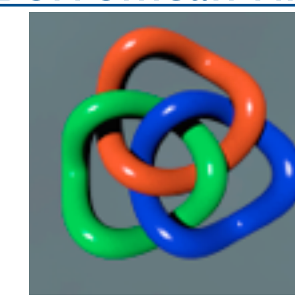
Zhukov et al., Phys. Rep. **231**, 151 (1993)

Halo matter distribution

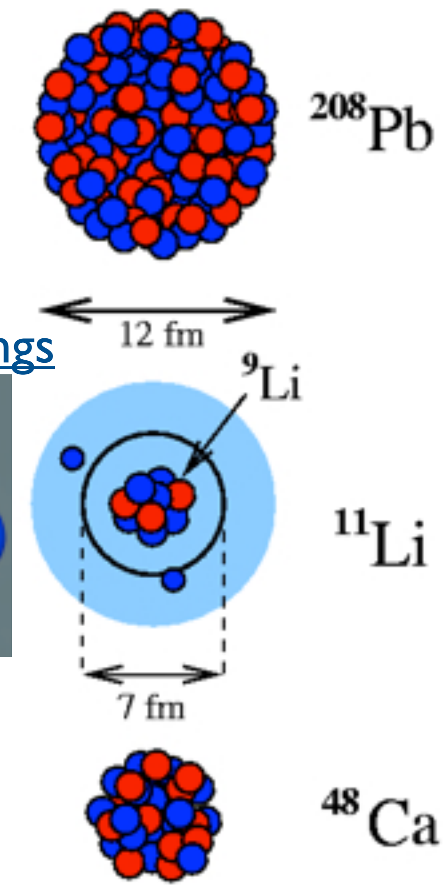




Borromean rings



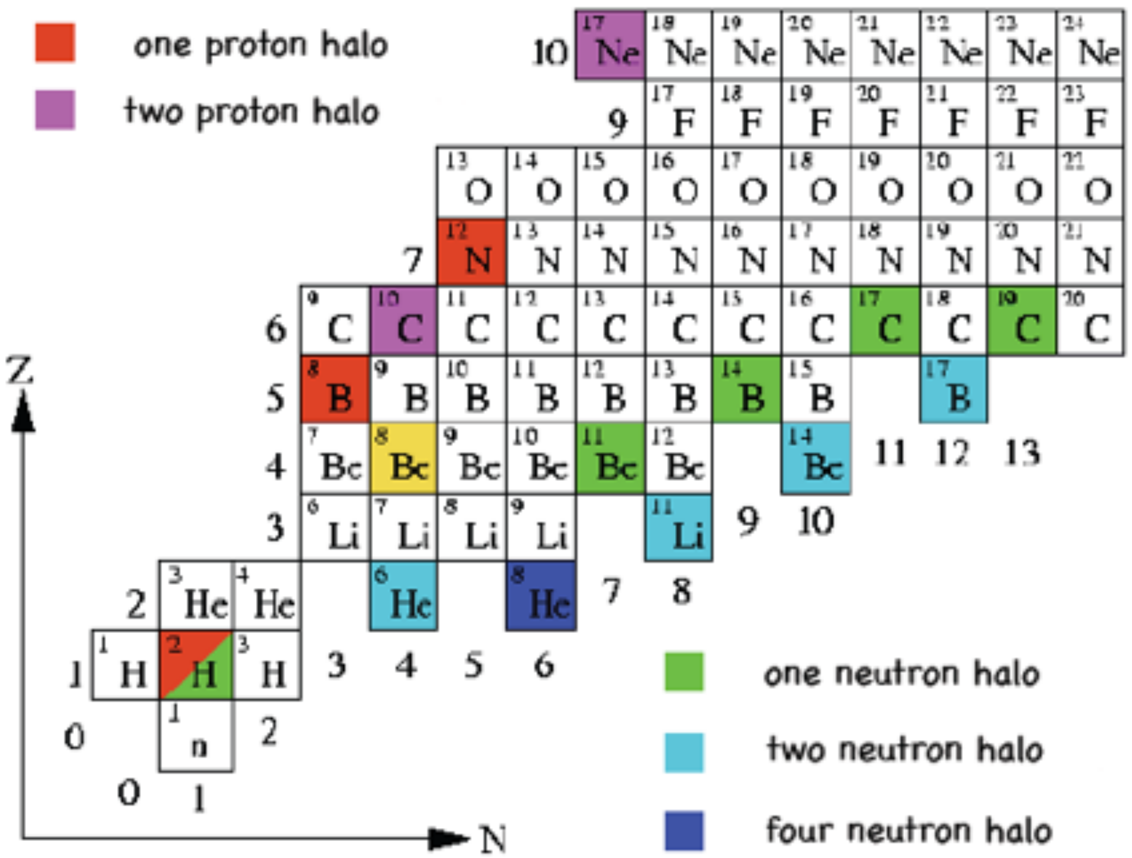
Two-neutron halos



- Light nuclei with large reaction cross sections
- One (or two) particles barely bound
- The subsystems are not stable
- Extremely rare & difficult to produce (discovery 1988)

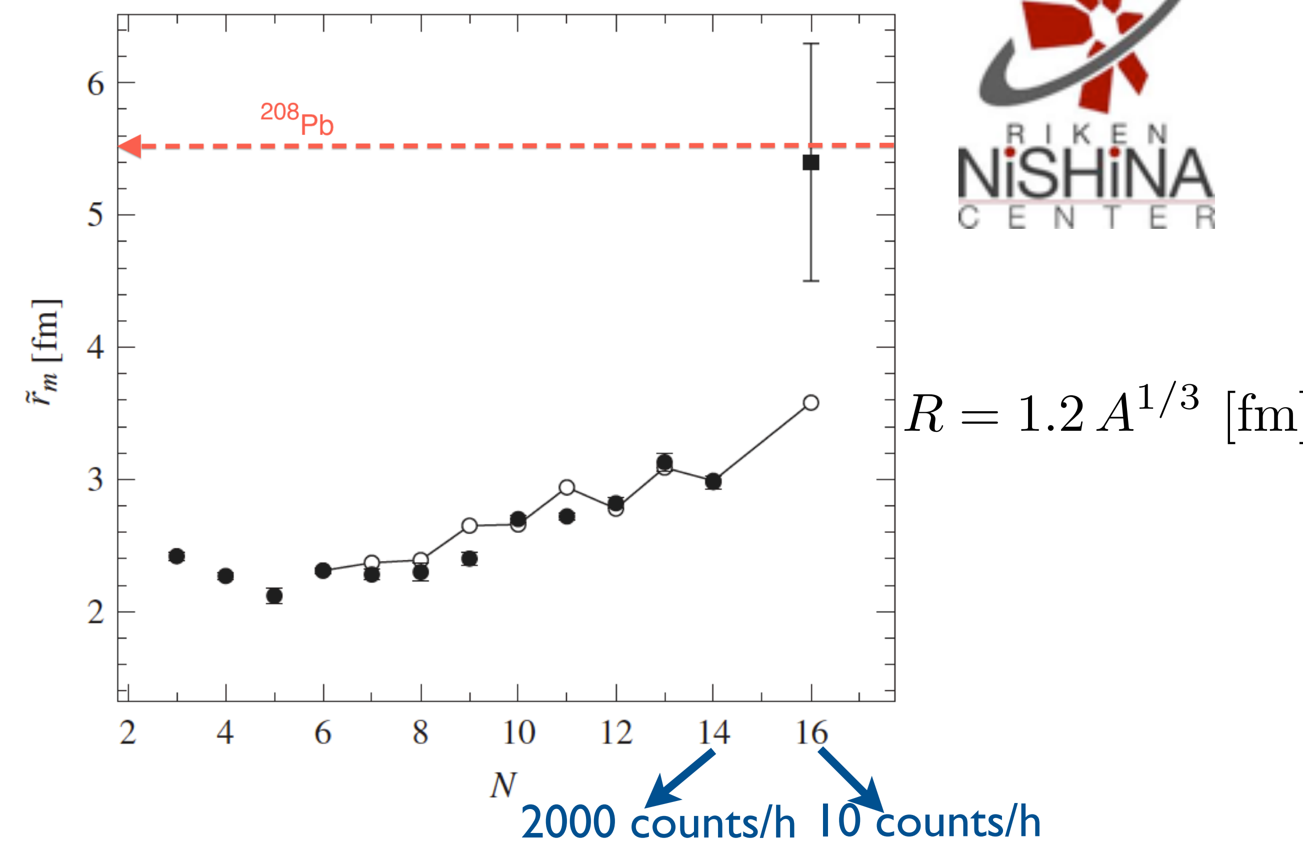
Light nuclei: halos

Large, light & Borromean nuclei



Zhukov et al., Phys. Rep. **231**, 151 (1993)

Heaviest 2 neutron halo: ^{22}C



Tanaka *et al.*, Phys. Rev. Lett. **104**, 062701 (2010)

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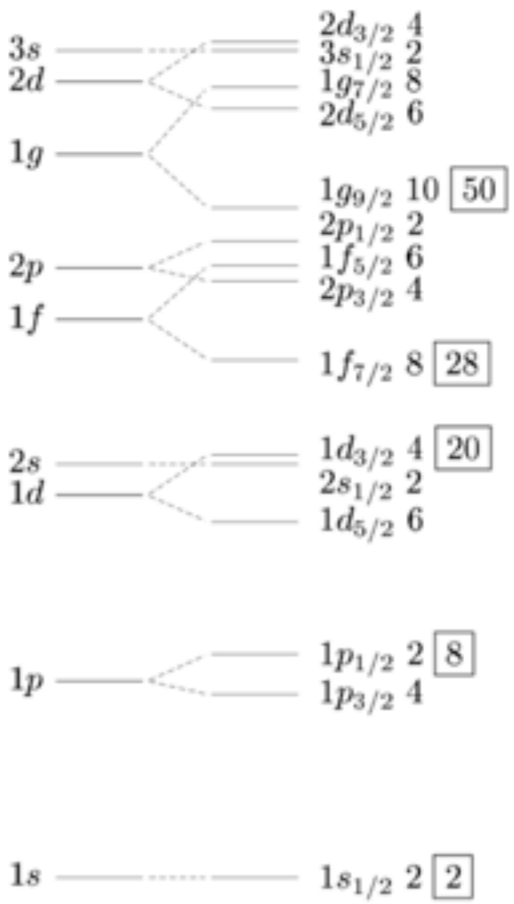
New magic numbers

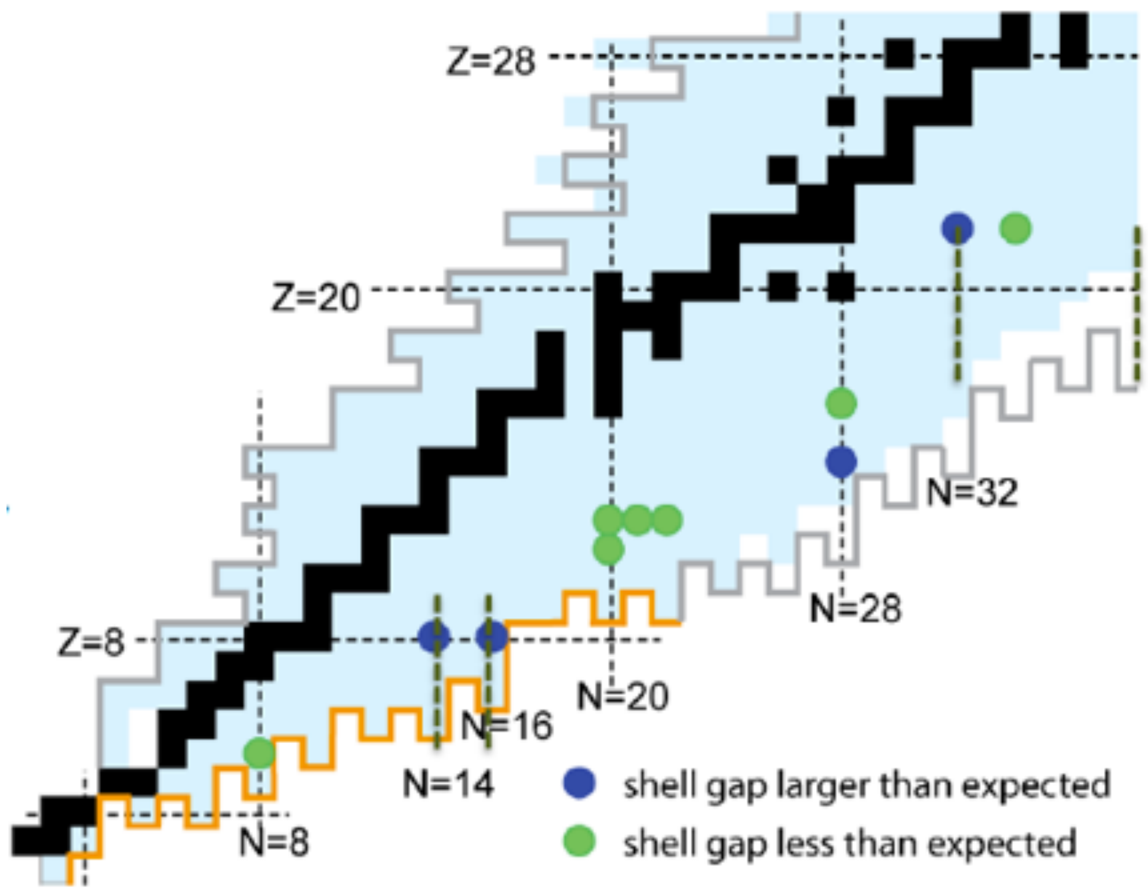
Questioning the shell model

Nuclear shell model



Goeppert-Mayer, Wigner & Jensen, Nobel Prize 1963

Where are the shell gaps?



Catford et al., Phys. Rev. Lett. **104**, 192501 (2010)

Tensor effect on s.o. partners

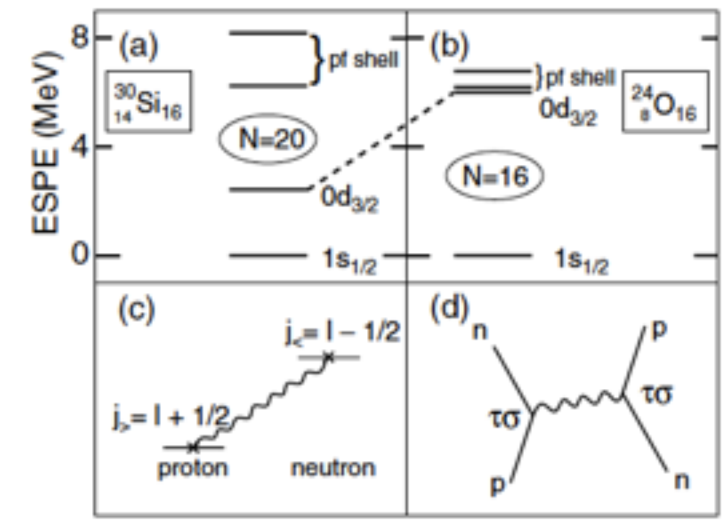


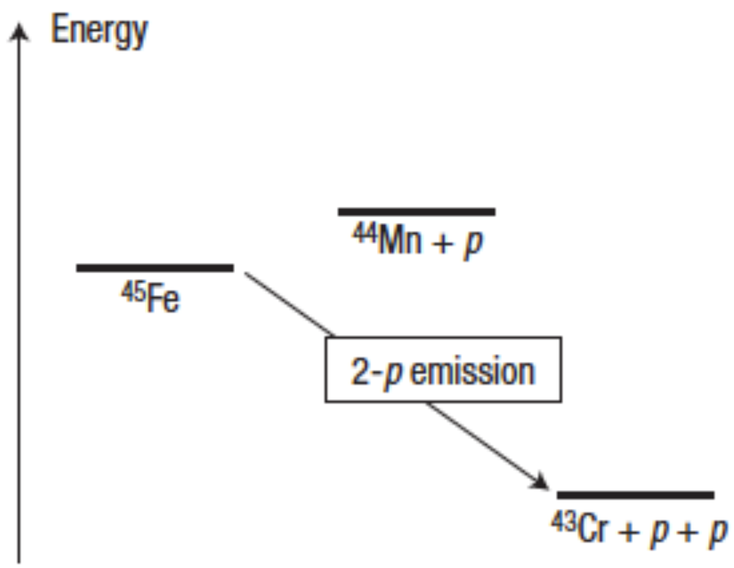
FIG. 1. Neutron ESPE's for (a) ^{30}Si and (b) ^{24}O, relative to $1s_{1/2}$. The dotted line connecting (a) and (b) is drawn to indicate the change of the $0d_{3/2}$ level. (c) The major interaction producing the basic change between (a) and (b). (d) The process relevant to the interaction in (c).

Otsuka et al., Phys. Rev. Lett. **87**, 082502 (2001)

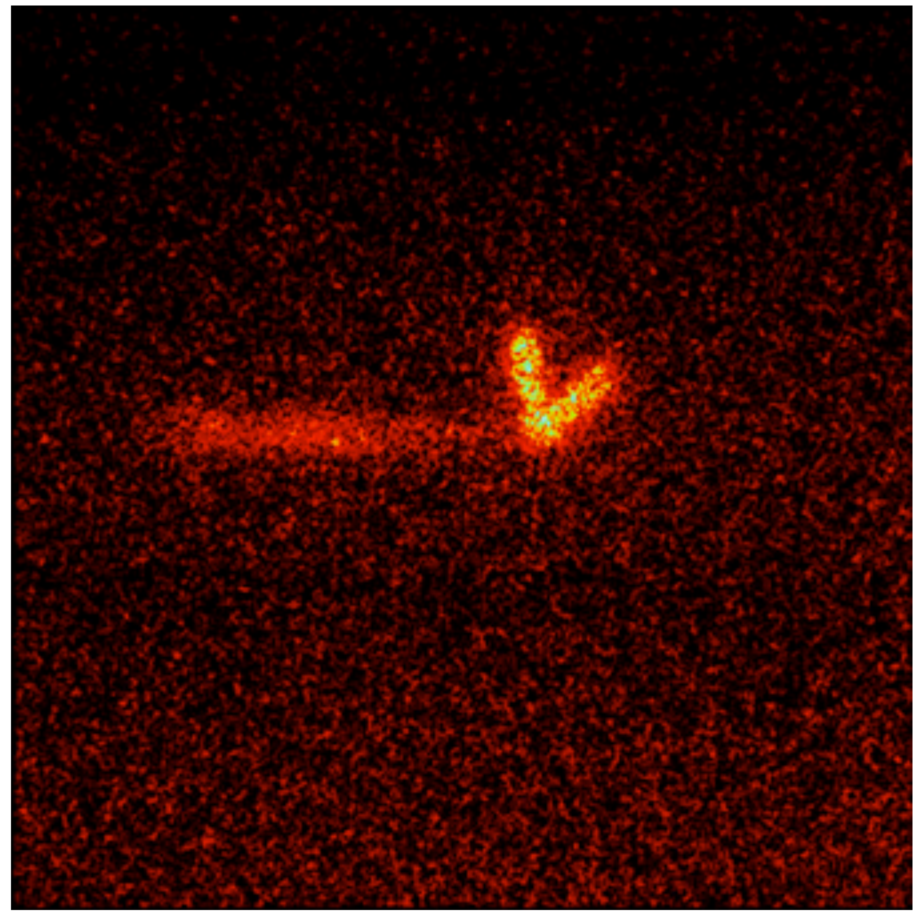
- Standard magic numbers only valid for near stable isotopes
- Tensor, 3BF & continuum modify magic numbers
- (d,p) and N knockout reactions to probe structure
- Textbooks are not true anymore?

New radioactivity!

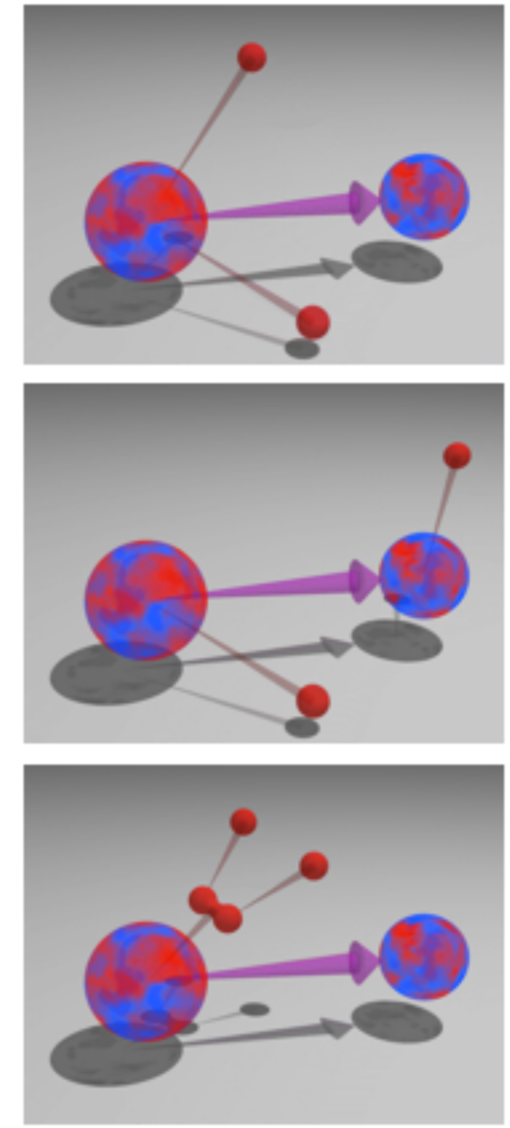
Two proton decay in ^{45}Fe



Pfutzner *et al.*, Eur. Phys. J. A **14**, 279 (2002)
Giovinazzo *et al.*, PRL **89**, 102501 (2002)



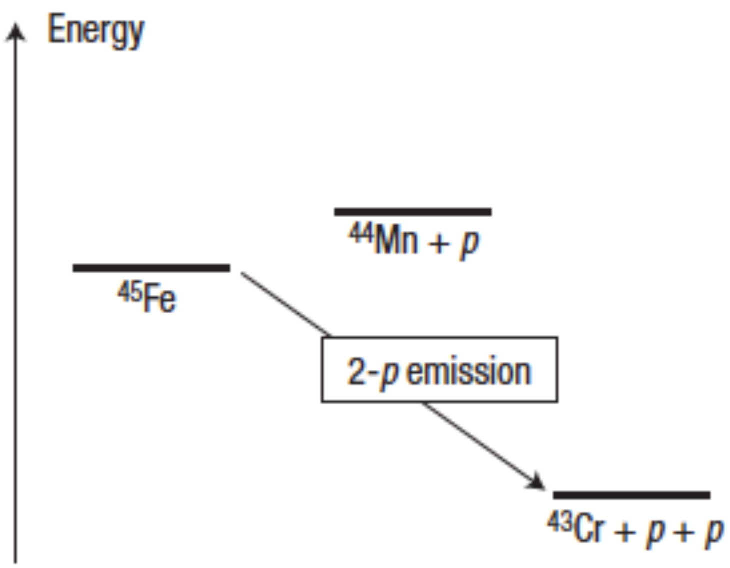
Miernik *et al.*, Phys. Rev. Lett. **99**, 192501 (2007)
Walker & Johnson, Nature Physics **3**, 836 (2007)



V. I. Goldansky, Nucl. Phys. **19**, 482 (1960)
Hofmann *et al.*, Z. Phys. A **305**, 111 (1982)

- Predicted together with 1p radioactivity (1982, ^{151}Lu)...
- 2p radioactiviy only discovered recently (2002)
- Gas time-projection detection chamber with a CCD camera
- @ MSU by Warsaw University: 9 days, 125 (75) decays

New radioactivity!



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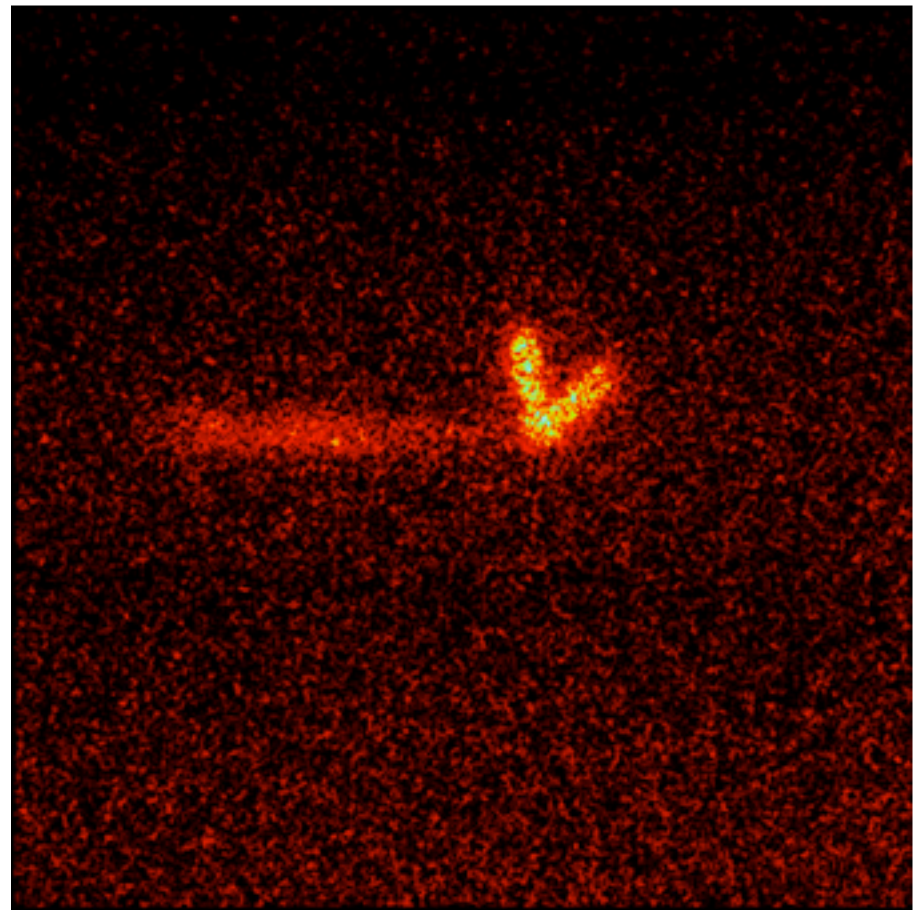

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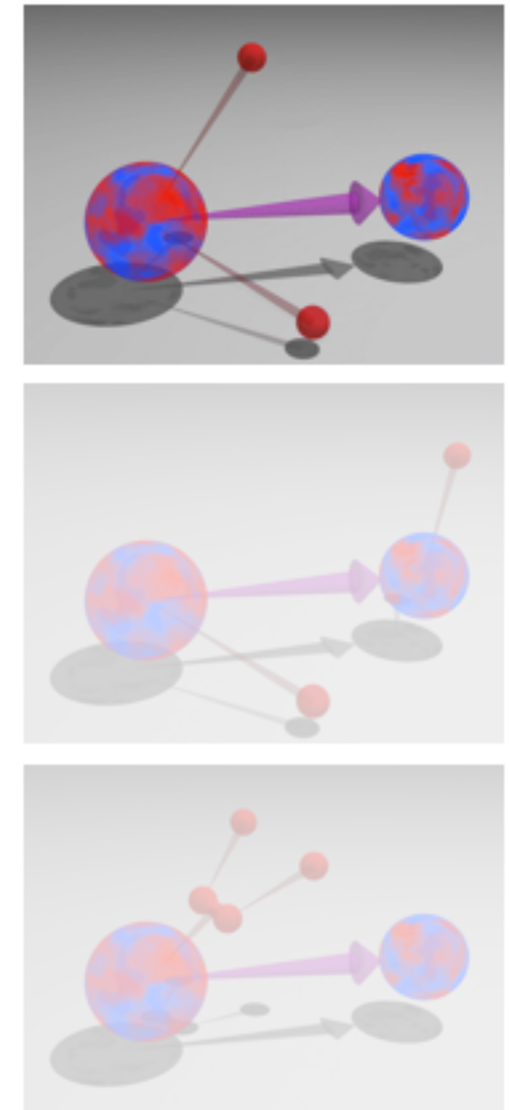

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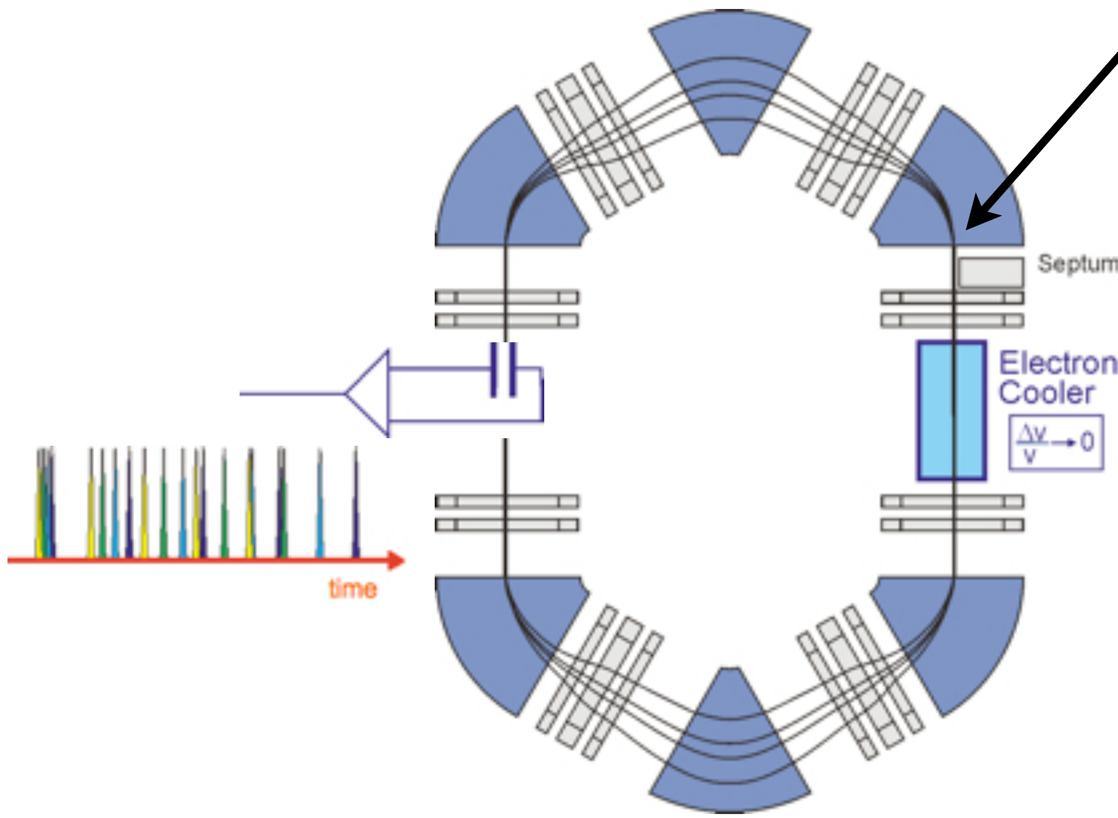
New isomers

Recent developments

Schottky mass spectrometry

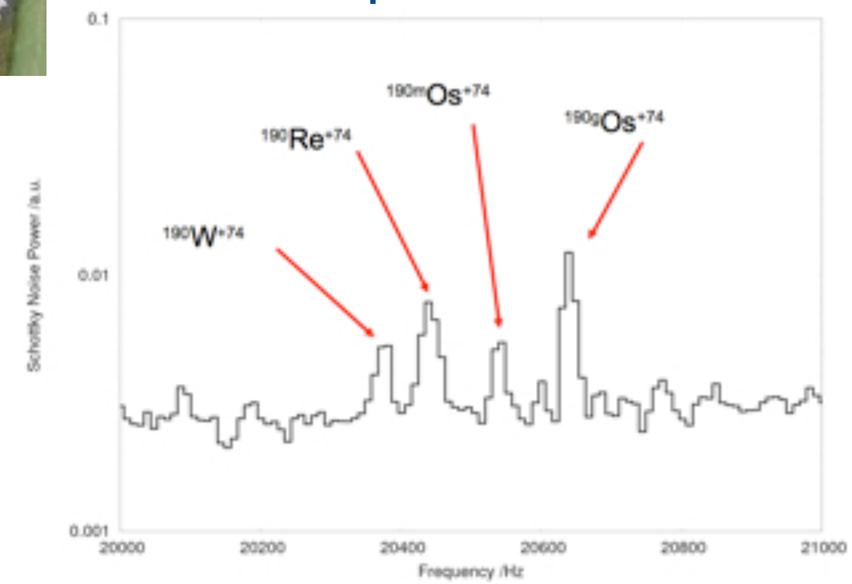
Injector from GSI



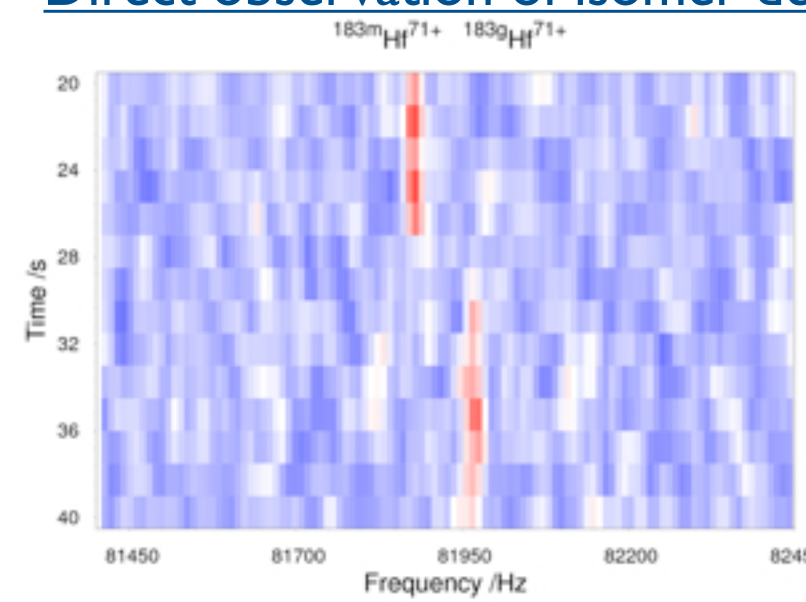
M.W. Reed *et al*., Phys. Rev. Lett. **105**, 172501 (2010)

FFT

Isotopes & isomers



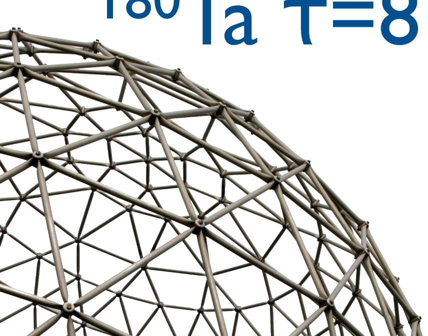
Direct observation of isomer decay



A famous isomer

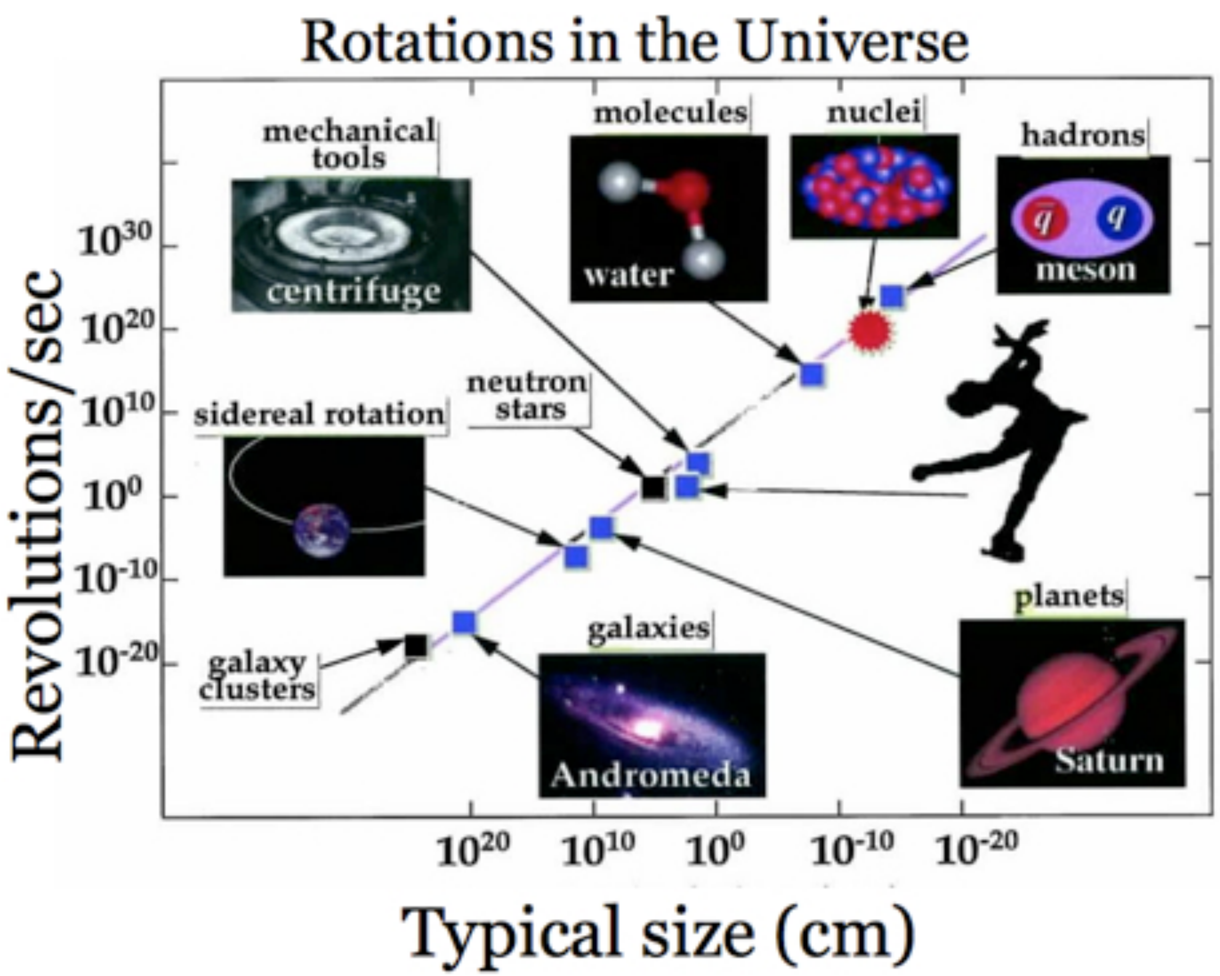
^{180m}Ta $\tau=10^{15}$ y

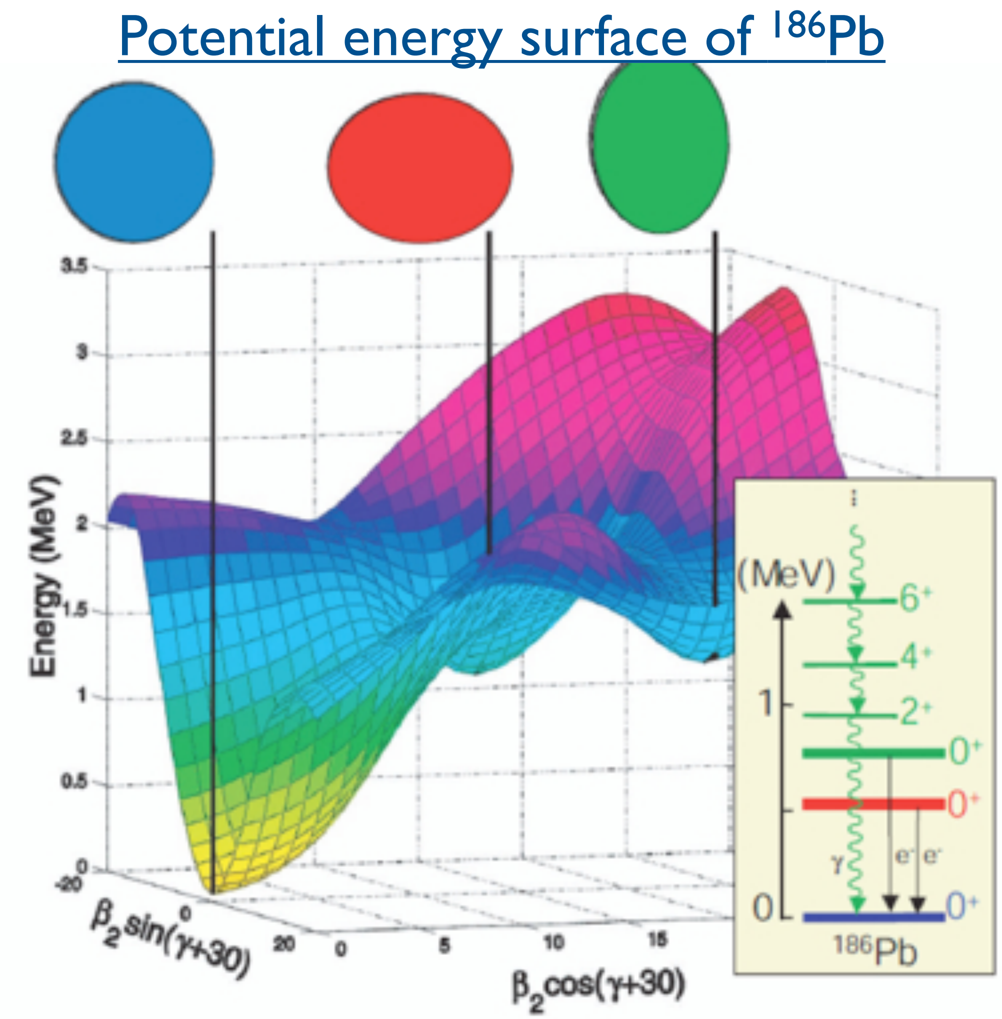
^{180}Ta $\tau=8$ h



- Nuclear isomers are metastable excited states
- Storage ring at GSI to circulate ions
- 4 Hf & 2 Ta new isomers

Shape coexistence



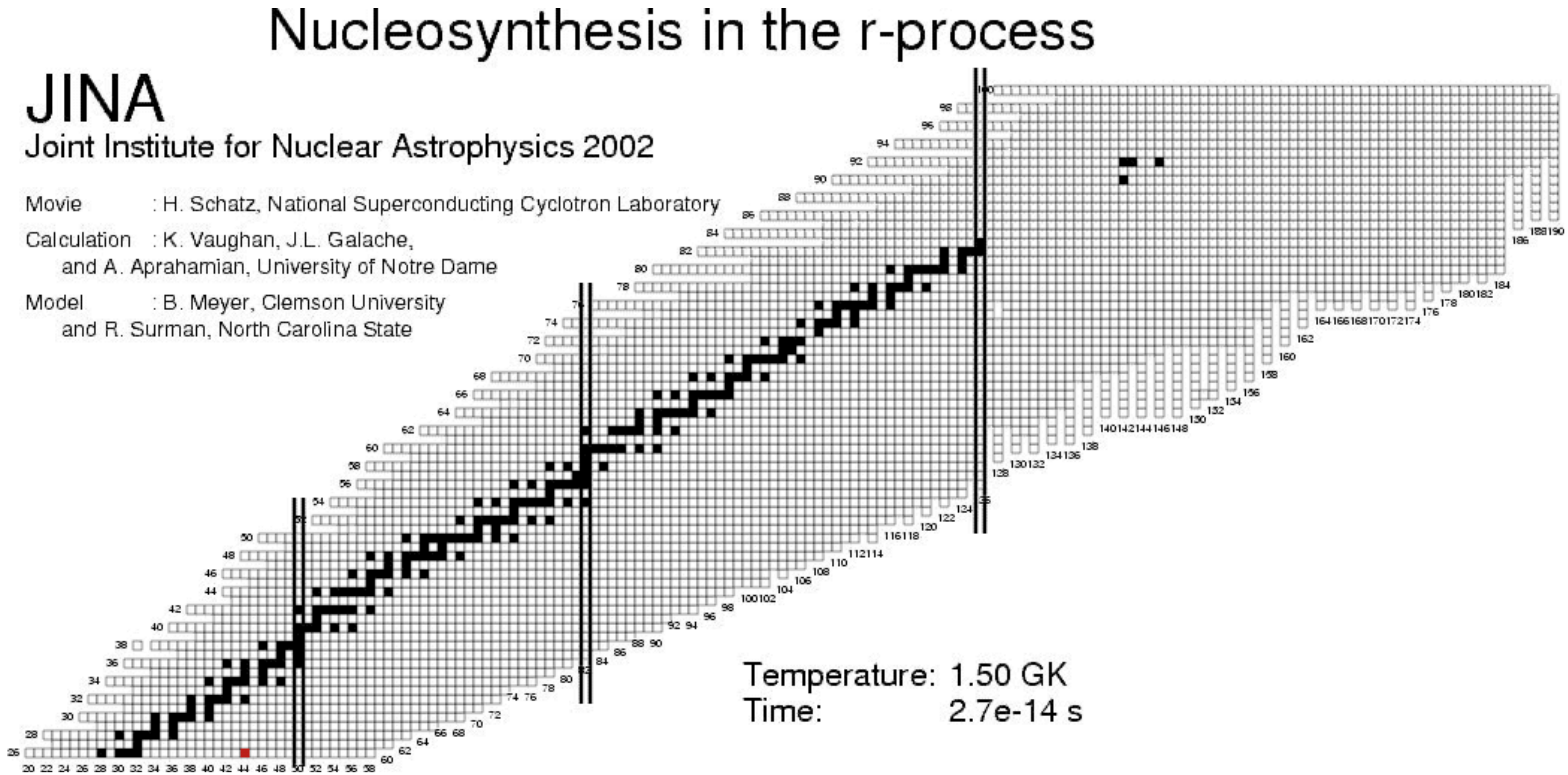


Andreyev et al, Nature **405**, 430 (2000)
Cwiok, Heenen & Nazarewicz, Nature **433**, 705 (2005)

- Excited nuclear states have different shapes
- Rotations excite different shapes

Nuclear astrophysics

... or why we are here

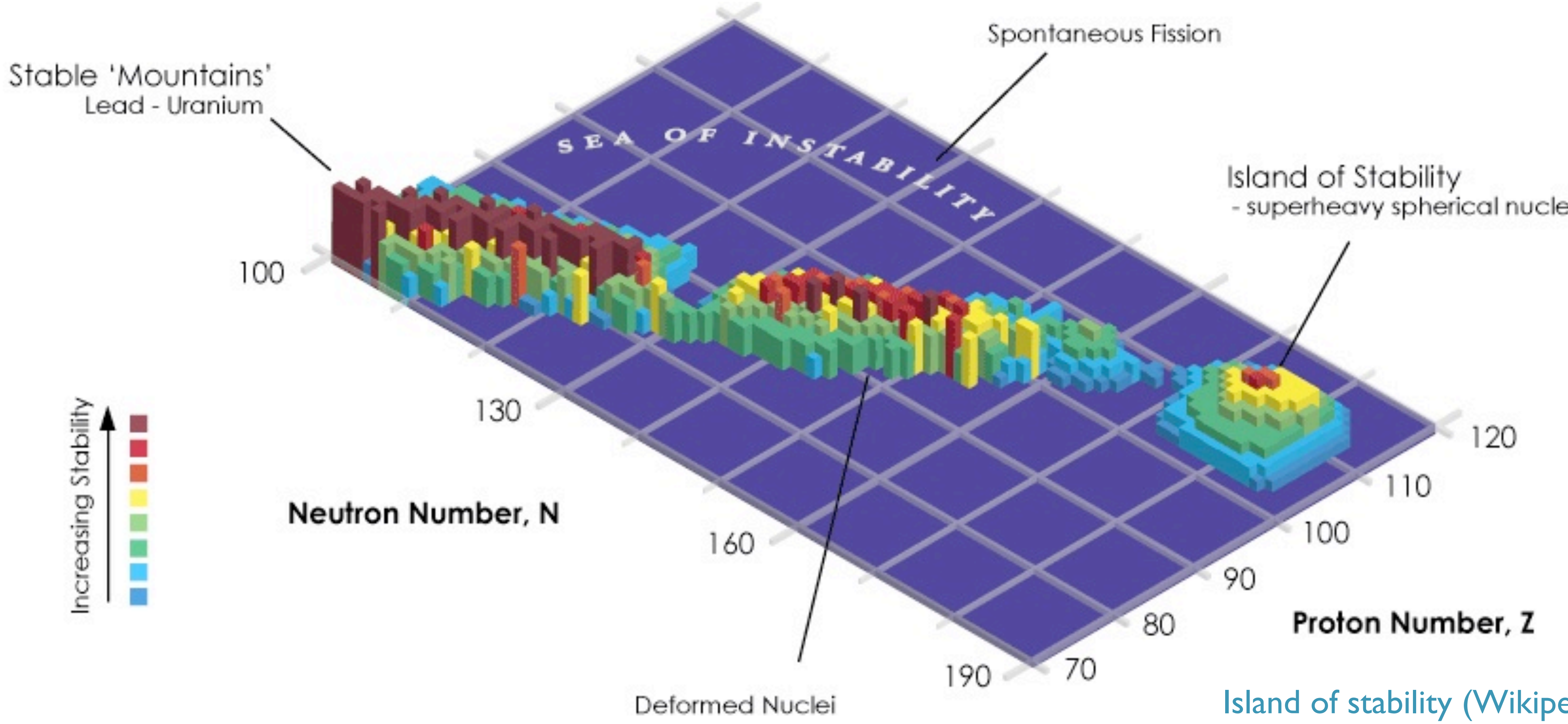


Burbidge, Burbidge, Fowler & Hoyle, Rev. Mod. Phys. **29**, 547 (1957)

- r-process responsible for half n-rich, Z>26 isotopes
- Neutron-rich & hot environment (where?)
- Motivates measurements towards drip-line (extrapolations?)

Superheavy elements

The new alchemists



Island of stability (Wikipedia)

- Island of stability is predicted above Pb
- Unique facilities: Dubna, Berkeley, GSI & Lanzhou
- New reaction techniques: fusion with ^{48}Ca+^{249}Bk (330 d)
- New experimental techniques allow mass measurements

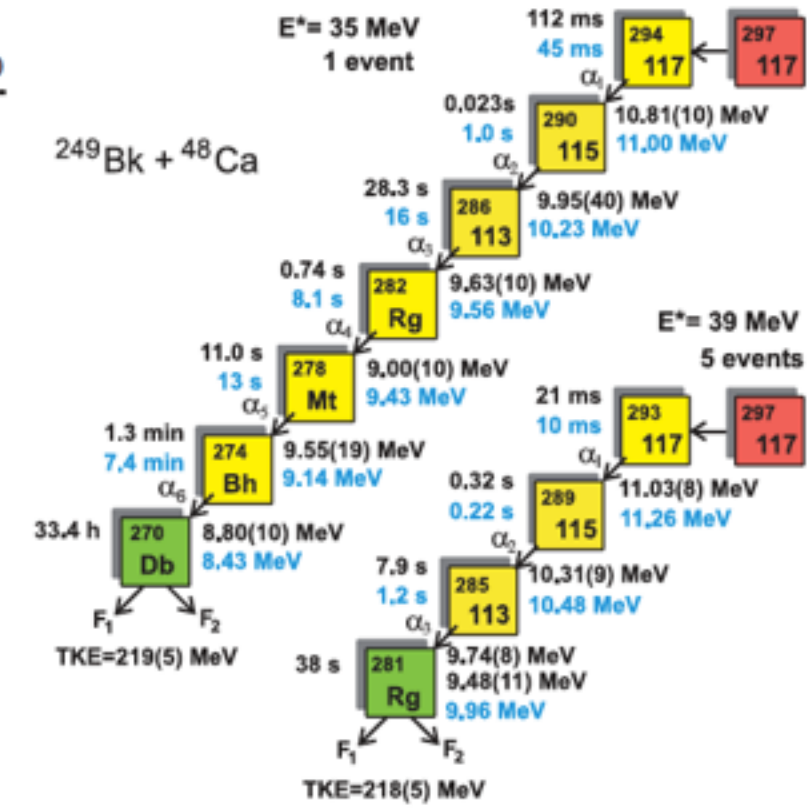
Superheavy elements

The new alchemists

Selected for a Viewpoint in *Physics*
PRL **104**, 142502 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Synthesis of a New Element with Atomic Number $Z = 117$

Yu. Ts. Oganessian,[1,*] F. Sh. Abdullin,[1] P. D. Bailey,[2] D. E. Benker,[2] M. E. Bennett,[3] S. N. Dmitriev,[1] J. G. Ezold,[2] J. H. Hamilton,[4] R. A. Henderson,[5] M. G. Itkis,[1] Yu. V. Lobanov,[1] A. N. Mezentsev,[1] K. J. Moody,[5] S. L. Nelson,[5] A. N. Polyakov,[1] C. E. Porter,[2] A. V. Ramayya,[4] F. D. Riley,[2] J. B. Roberto,[2] M. A. Ryabinin,[6] K. P. Rykaczewski,[2] R. N. Sagaidak,[1] D. A. Shaughnessy,[5] I. V. Shirokovsky,[1] M. A. Stoyer,[5] V. G. Subbotin,[1] R. Sudowe,[3] A. M. Sukhov,[1] Yu. S. Tsyganov,[1] V. K. Utyonkov,[1] A. A. Voinov,[1] G. K. Vostokin,[1] and P. A. Wilk[5]
[1]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russian Federation*
[2]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[3]*University of Nevada Las Vegas, Las Vegas, Nevada 89154, USA*
[4]*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*
[5]*Lawrence Livemore National Laboratory, Livermore, California 94551, USA*
[6]*Research Institute of Atomic Reactors, RU-433510 Dimitrovgrad, Russian Federation*
(Received 15 March 2010; published 9 April 2010)



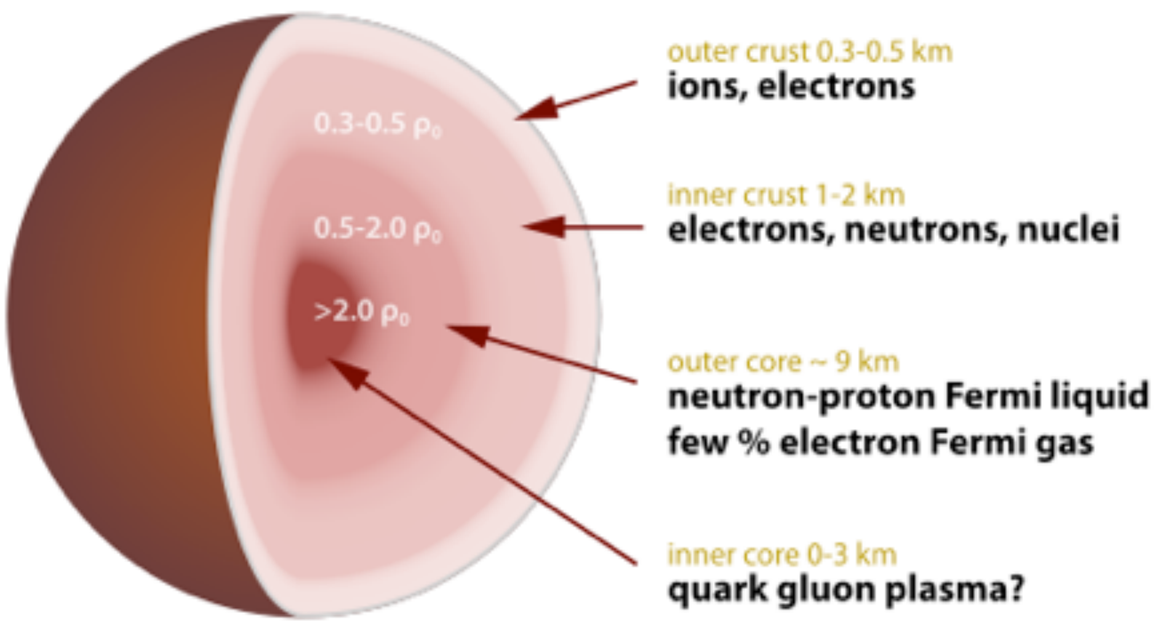
Z=114 *Dubna* Nature 400, 242 (1999) + *Berkeley* Phys. Rev. Lett. 103, 132502 (2009)
Z=115 *Dubna* Phys. Rev. C 69, 021601 (2004)
Z=116 & **118** *Dubna* Phys. Rev. C 74, 044602 (2006)
Penning trap mass measurements: *GSI* Block, Nature 463, 785 (2010)

- Island of stability is predicted above Pb
- Unique facilities: Dubna, Berkeley, GSI & Lanzhou
- New reaction techniques: fusion with ^{48}Ca+^{249}Bk (330 d)
- New experimental techniques allow mass measurements

Pulsars & neutron stars

UNIVERSITY OF SURREY

Radiography of a neutron star



R~10 km
M~1-2M$_\odot$

Neutron star (Wikipedia)

Radio spectrum of **PSR B1919+21**

also cover of Joy Division's *Unknown Pleasures*!

Chandra X-ray image Crab Nebula

http://chandra.harvard.edu/photo/1999/0052/

- Neutron stars predicted early (Baade, Zwicky 1934)
- Supported by neutron degeneracy (Pauli principle in action!)
- Radio emission as pulsars (Bell-Burnett, 1967)
- Core is very dense (10^7 kg/m^3) & neutron-rich (90%)
- A macroscopic isotope?

The Equation of State

From nuclear physics to compact astrophysical objects

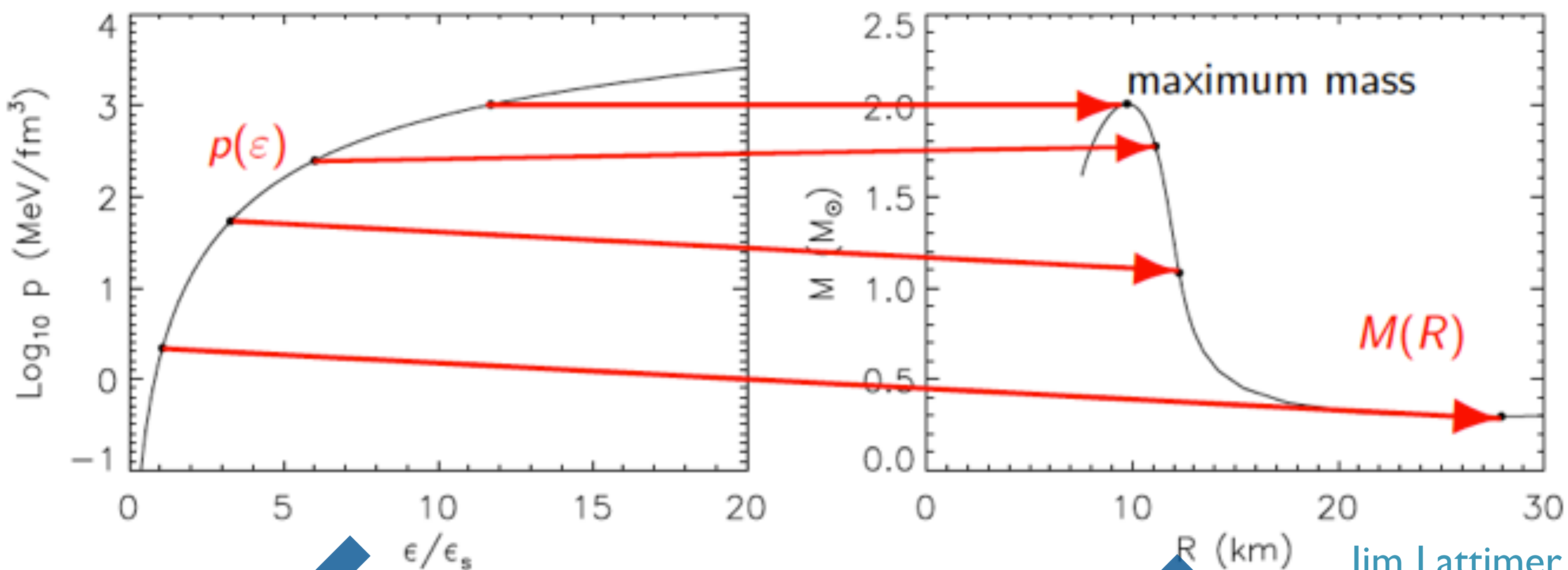
Tolman-Oppenheimer-Volkov equations

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m+4\pi pr^3)(\varepsilon+p)}{r(r-2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2$$

Equation of State

Mass-Radius relation



Jim Lattimer

Nuclear observable

Astrophysical observable

- EoS determines mass and radius of NS
- Connection between nuclear & astrophysical observables
- Inferred EoS from Bayesian statistical analysis

The Equation of State

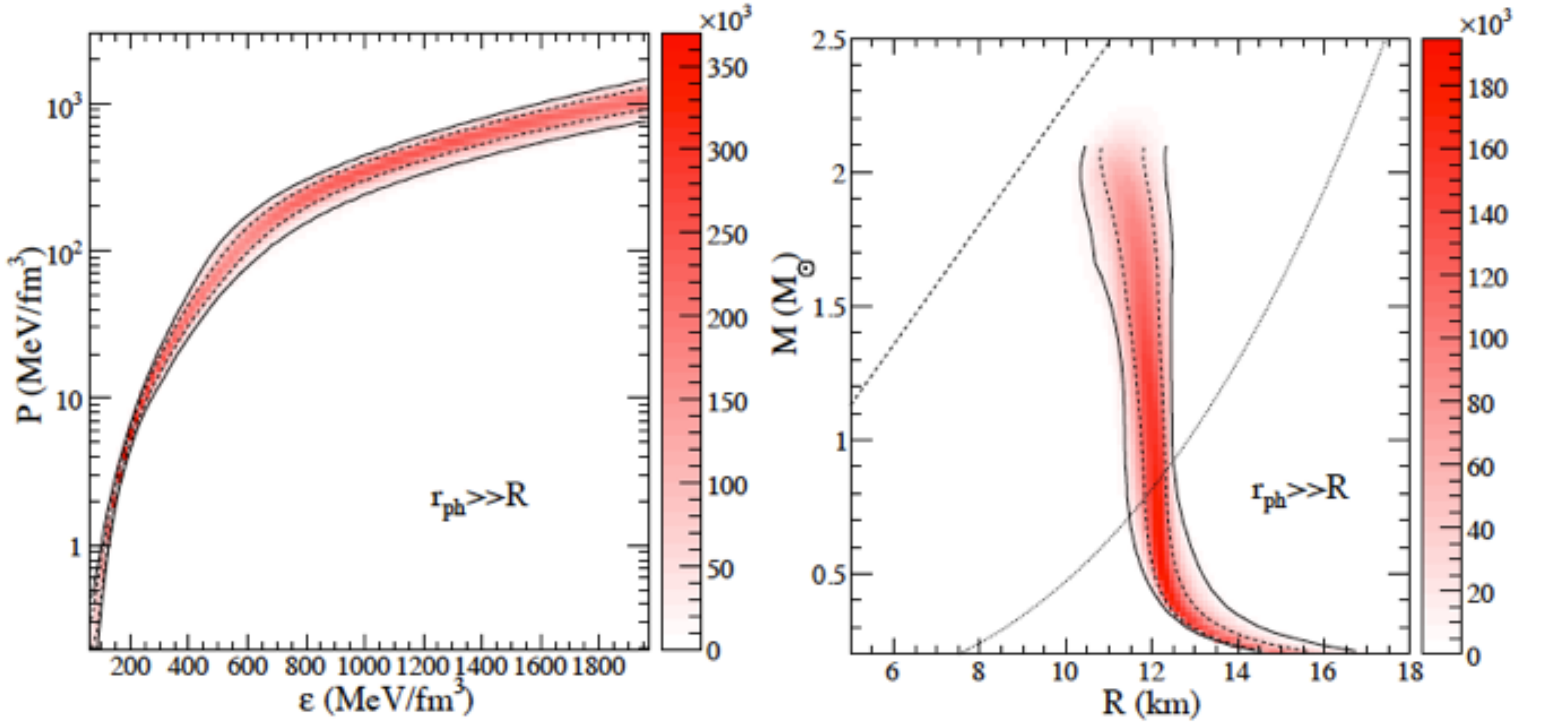
From nuclear physics to compact astrophysical objects

Tolman-Oppenheimer-Volkov equations

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m+4\pi pr^3)(\varepsilon+p)}{r(r-2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2$$

Inferred EoS and M-R relation from observations



Steiner, Lattimer & Brown, ApJ **722**, 33 (2010)

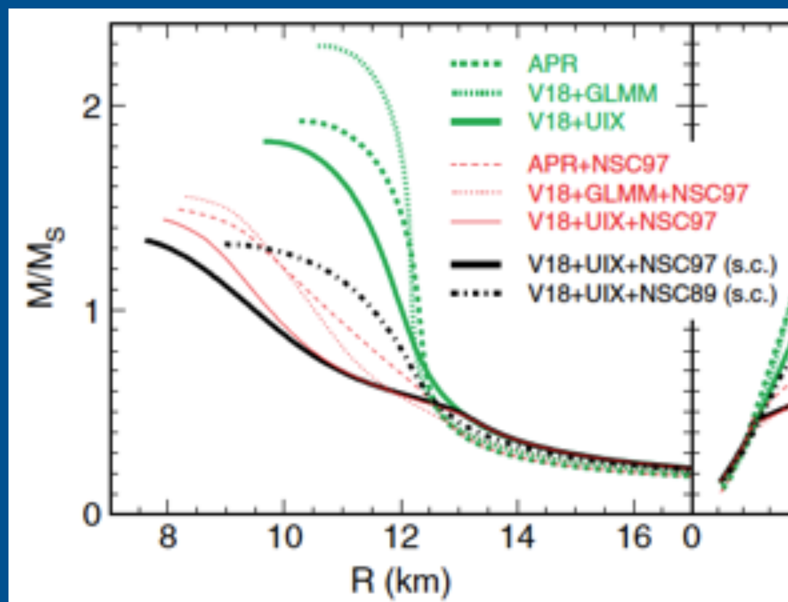
3 X-ray bursts, 3 X-ray binaries & 1 isolated NS

- EoS determines mass and radius of NS
- Connection between nuclear & astrophysical observables
- Inferred EoS from Bayesian statistical analysis

The Barcelona connection

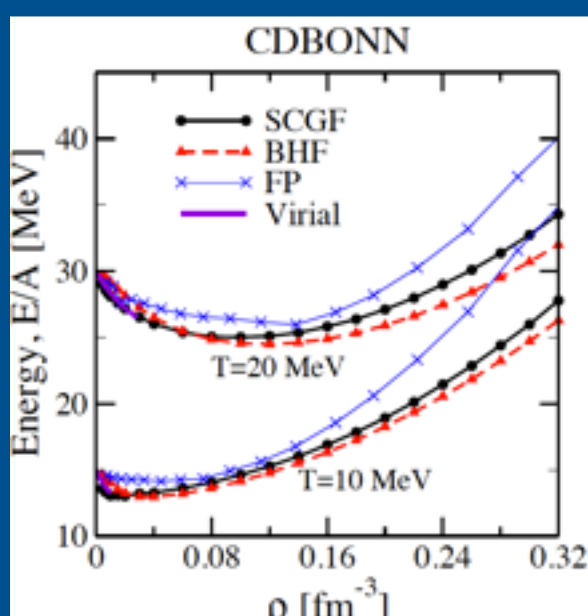
Microscopic EoS

BHF with hyperons



Schulze, Vidaña, Polls & Ramos, Phys. Rev. C **73**, 058801 (2006)

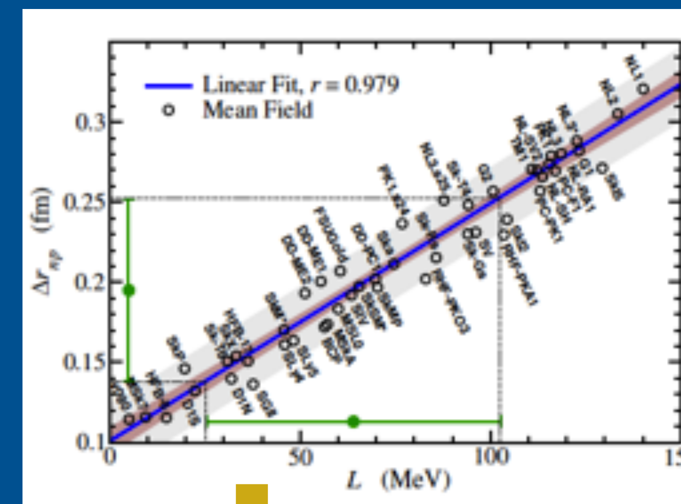
SCGF... with 3BF?

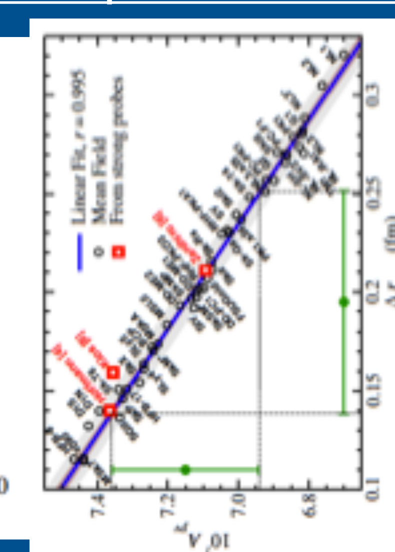


Rios, Vidaña & Polls, Phys. Rev. C **79**, 025802 (2009)
Carbone, Polls, Rios 2012-2013

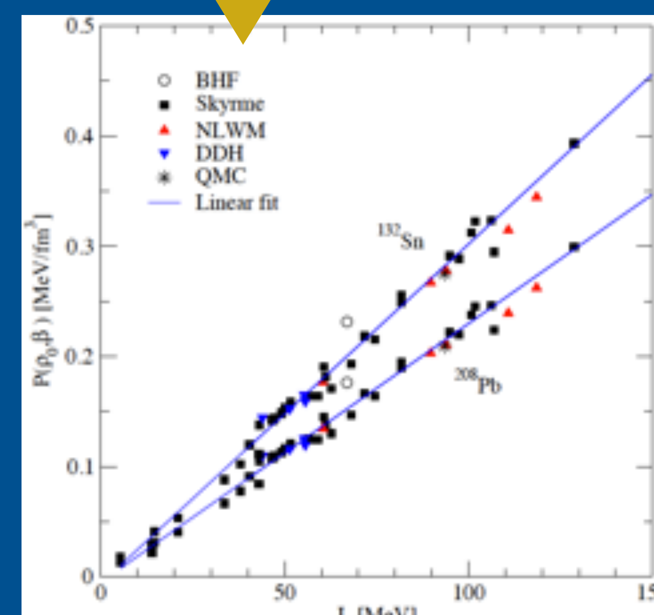
Connection to PVES experiments

Neutron skin radius, $\Delta r = R_n - R_p$, vs. slope coefficient, L





EoS of neutron matter



PAS

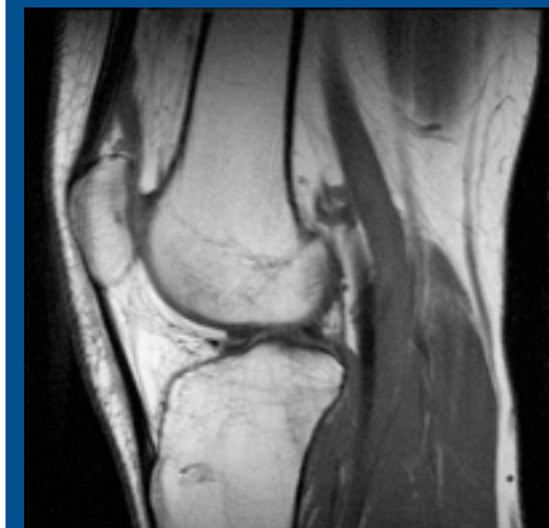
Centelles, Roca-Maza, Viñas & Warda, PRL **102**, 122502 (2009)
Roca-Maza, Centelles, Viñas & Warda, arXiv:1103.1762

Applications of nuclear research

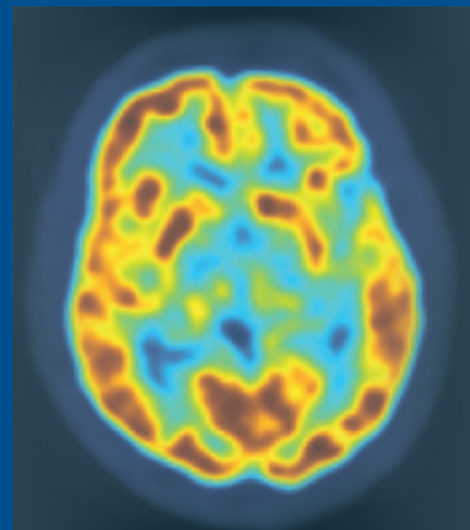
UNIVERSITY OF SURREY

Medical applications

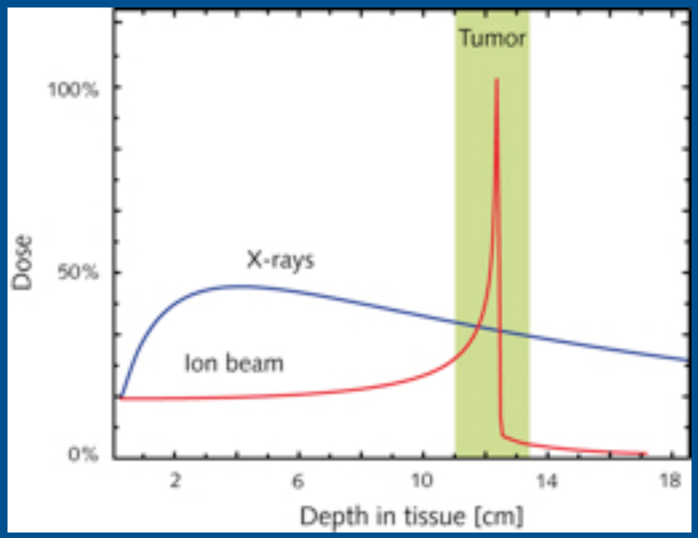
MRI



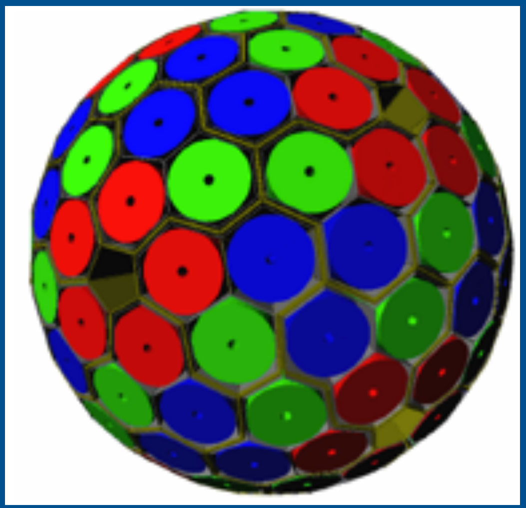
Radioisotope imaging



Hadrontherapy



Better detectors



Agata

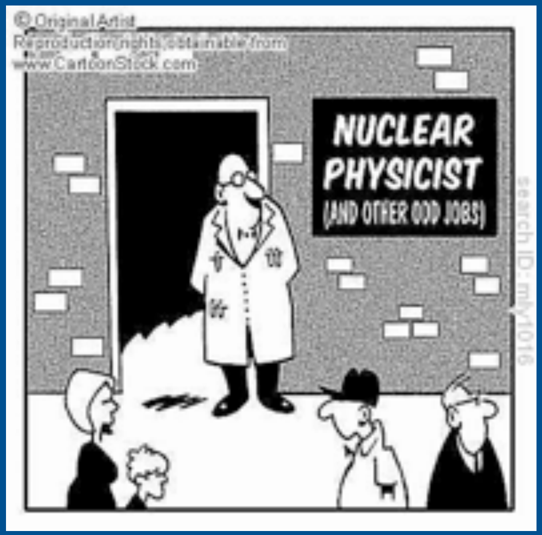
Radioactive dating

LABEC/INFN

Energy

- **Generation IV**
- **Transmutation**
- **Thorium cycle**
- **Fusion**

Manpower!



Thank you!

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Thanks to J. Al-Khalili, P. Regan & M. Reed (Surrey) for useful slides