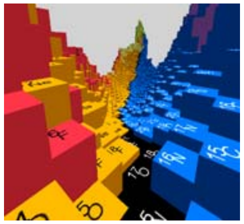
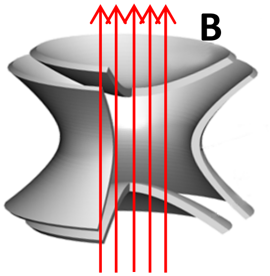
Seminaire LPNHE/UPMC – 20 juin 2013





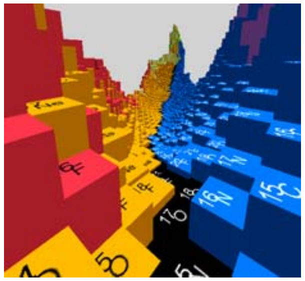
Ion traps: drilling neutron stars & dropping antimatter

David Lunney (with the ISOLTRAP & GBAR Collaborations)

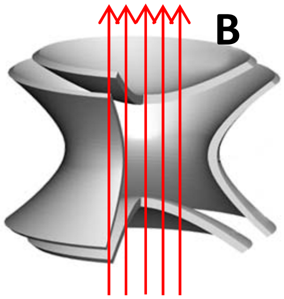
CSNSM/IN2P3-CNRS, Université de Paris-Saclay, Orsay

Overview

- Introduction
  - Nuclear and Astrophysics: a little history
  - How we measure masses and why
  - Impact of Penning traps



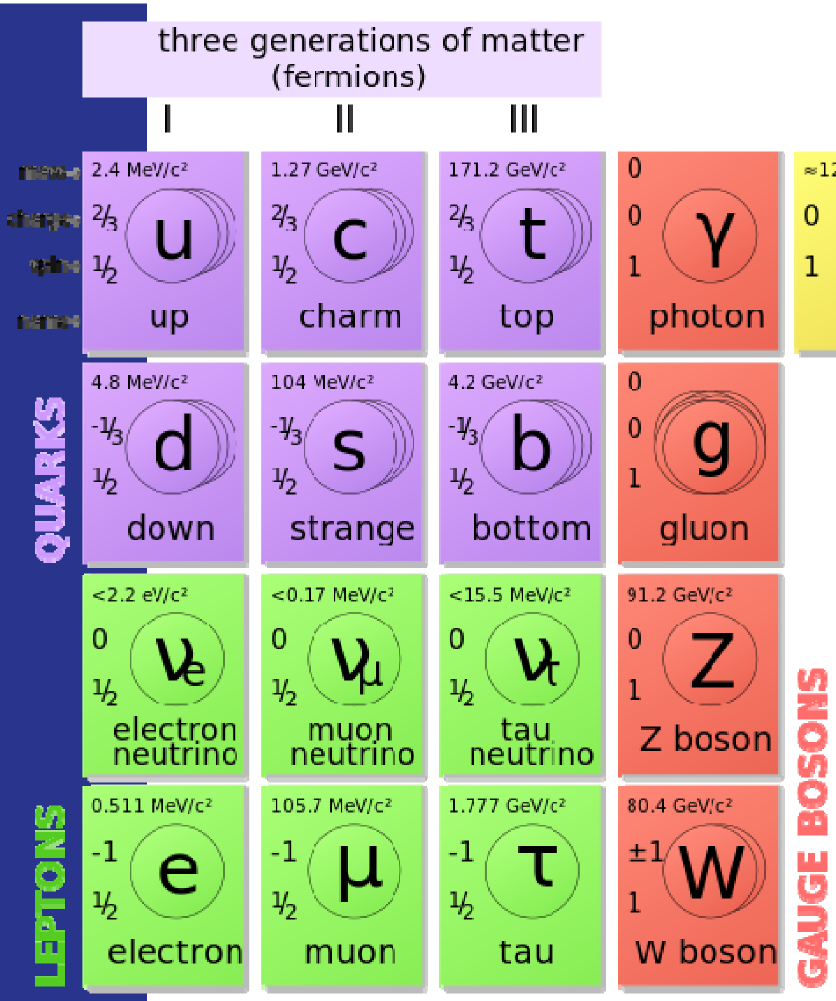
- Penning traps
  - Basic principles
  - How to prepare beams and weigh nuclides



- (some) Physics results
  - ^{82}Zn – plumbing neutron stars
  - ^{52}Ca – a new magic neutron number

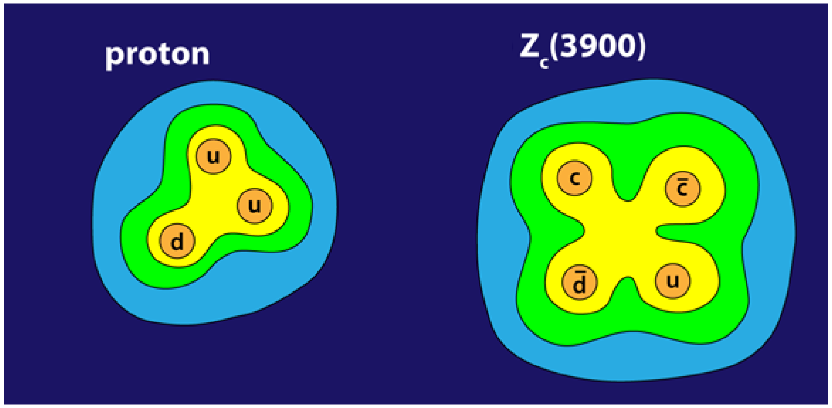
- Gravitational Behavior of Antimatter at Rest (GBAR)

The particle zoo



three generations of matter (fermions)

	I	II	III		
mass charge spin name	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	≈126 GeV/c^2 0 1 H Higgs boson
QUARKS	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	
	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 W W boson	



Nuclear chart

(as seen by a particle physicist!)

原子の周期律表　1次元（電子の数＝原子番号）

核図表　2次元

安定核以外は
不安定核
（エキゾチック核）

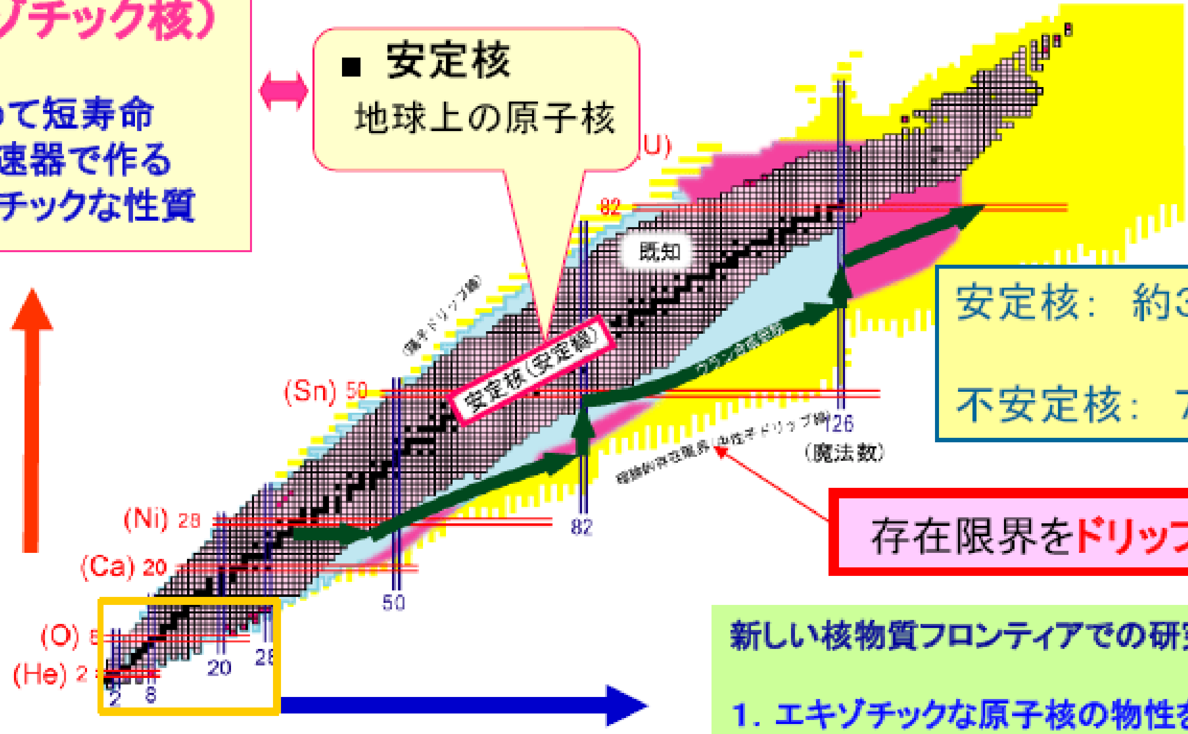
極めて短寿命
→加速器で作る
エキゾチックな性質

■ 安定核
地球上の原子核

□ 存在が実験で確認された不安定核

🟪 RIBFの到達領域

🟨 理論予想



安定核：　約300種

不安定核：　7000～10000種

存在限界を**ドリップライン**という

陽子数（元素の種類）

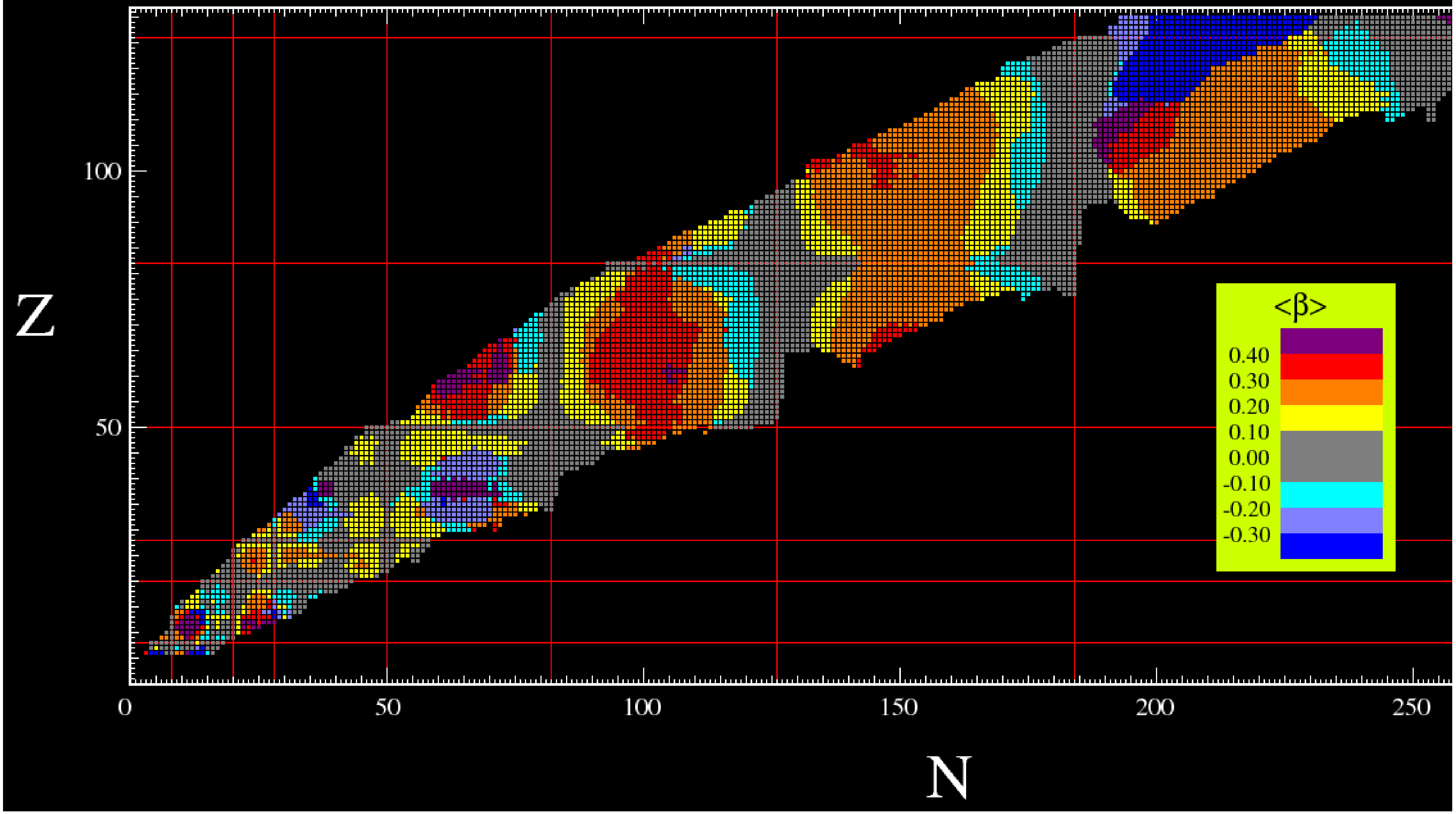
中性子数（同位元素の種類）

新しい核物質フロンティアでの研究の目標

1. エキゾチックな原子核の物性を明らかにする
2. 超新星爆発時の元素合成など物質創生の道筋、その際の異常な物理環境をさぐる
3. 物質存在の限界を極める

HFB – Gogny: D1S (S. Hilaire et al.)

http://www-phynu.cea.fr/

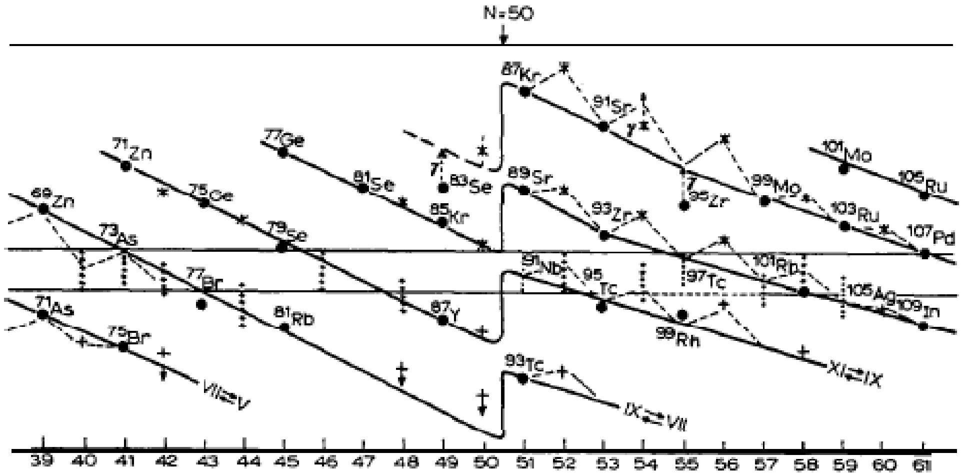


“magic” numbers

MARIA GOEPPERT MAYER

The shell model

Nobel Lecture, December 12, 1963



One

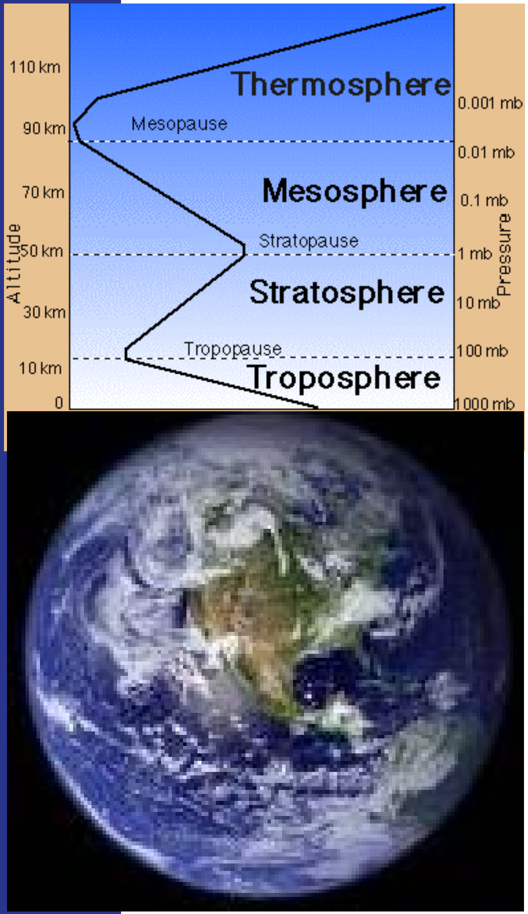
struc

My attention was then called to Elsasser’s papers written in 1933. In the year 1948 much more was known about properties of nuclei than was available to Elsasser. The magic numbers not only stood up in the new data, but they appeared more clearly than before, in all kinds of nuclear processes. It was no longer possible to consider them as due to purely accidental coincidences.

Nuclear Binding Energy

mass measurements: scale

Earth's atmosphere: 60 km

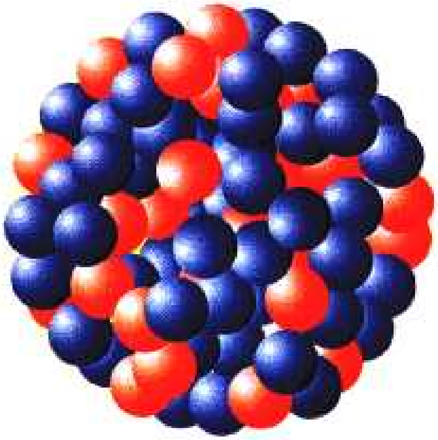


Earth's radius: 6000 km

Pairing: 400 keV

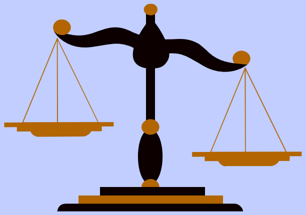
Shell gap:
3-4 MeV (~10^{-5})

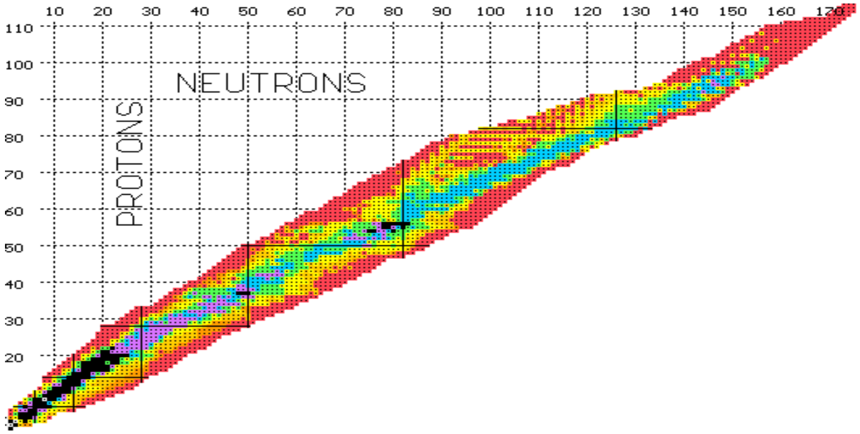
Binding Energy
A = 100: ~ 1 GeV
(about 1% total)



A = 100 nucleus
~ 100 GeV/c^2

Mass measurements: motivation





nuclear structure:
shells, shapes, pairs, halos

precision: 10^{-6} to 10^{-8}

weak interaction:
CVC and SM tests
neutrino physics

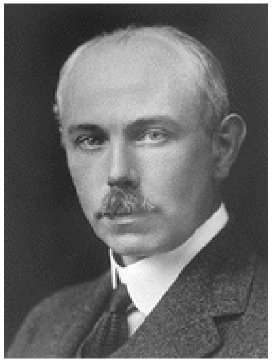
nuclear astrophysics:
nucleosynthesis, netron stars
→ orientation of mass models

precision: 10^{-8} to 10^{-9}

precision: 10^{-6} to 10^{-7}

Mass spectrometry: a long tradition

F.W.Aston (~1920's): 212 isotopes discovered
Packing fraction



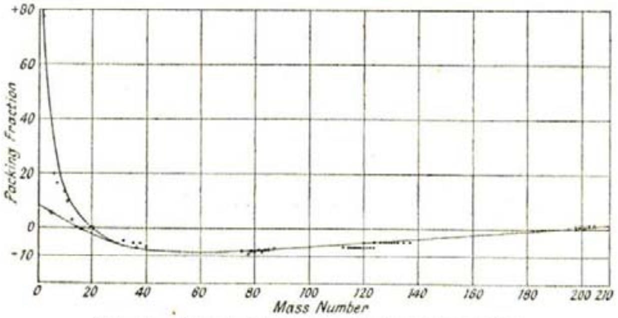
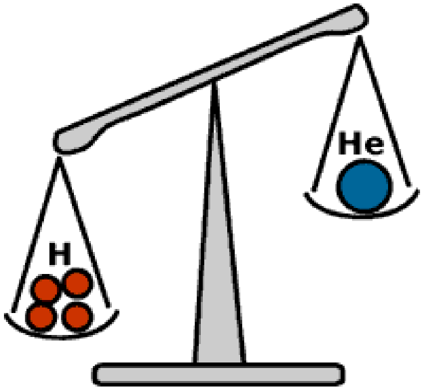


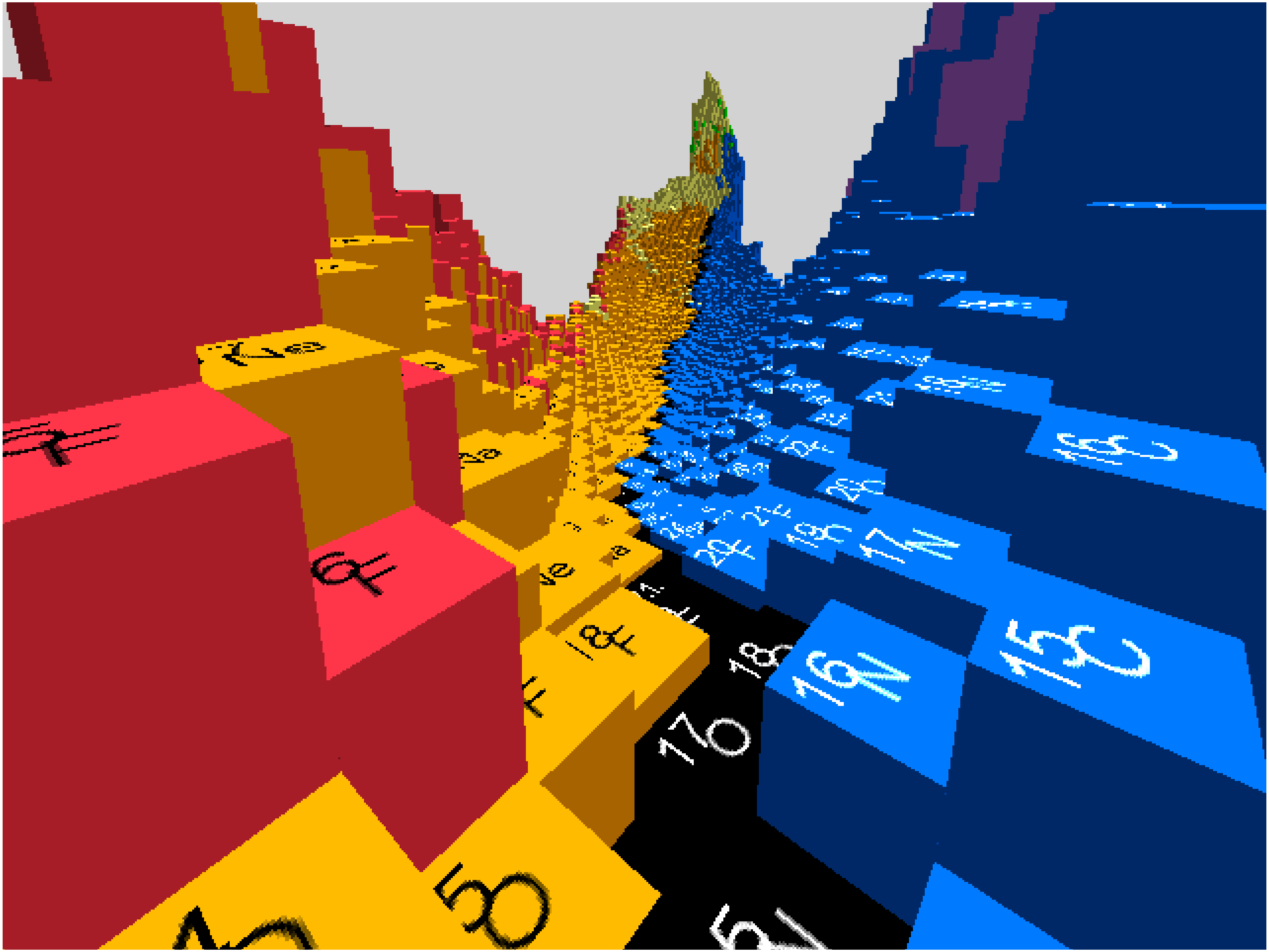
Fig. 20.—Aston's Original Packing Fraction Curve (1927).

A. Eddington (~1920)
Stellar combustion



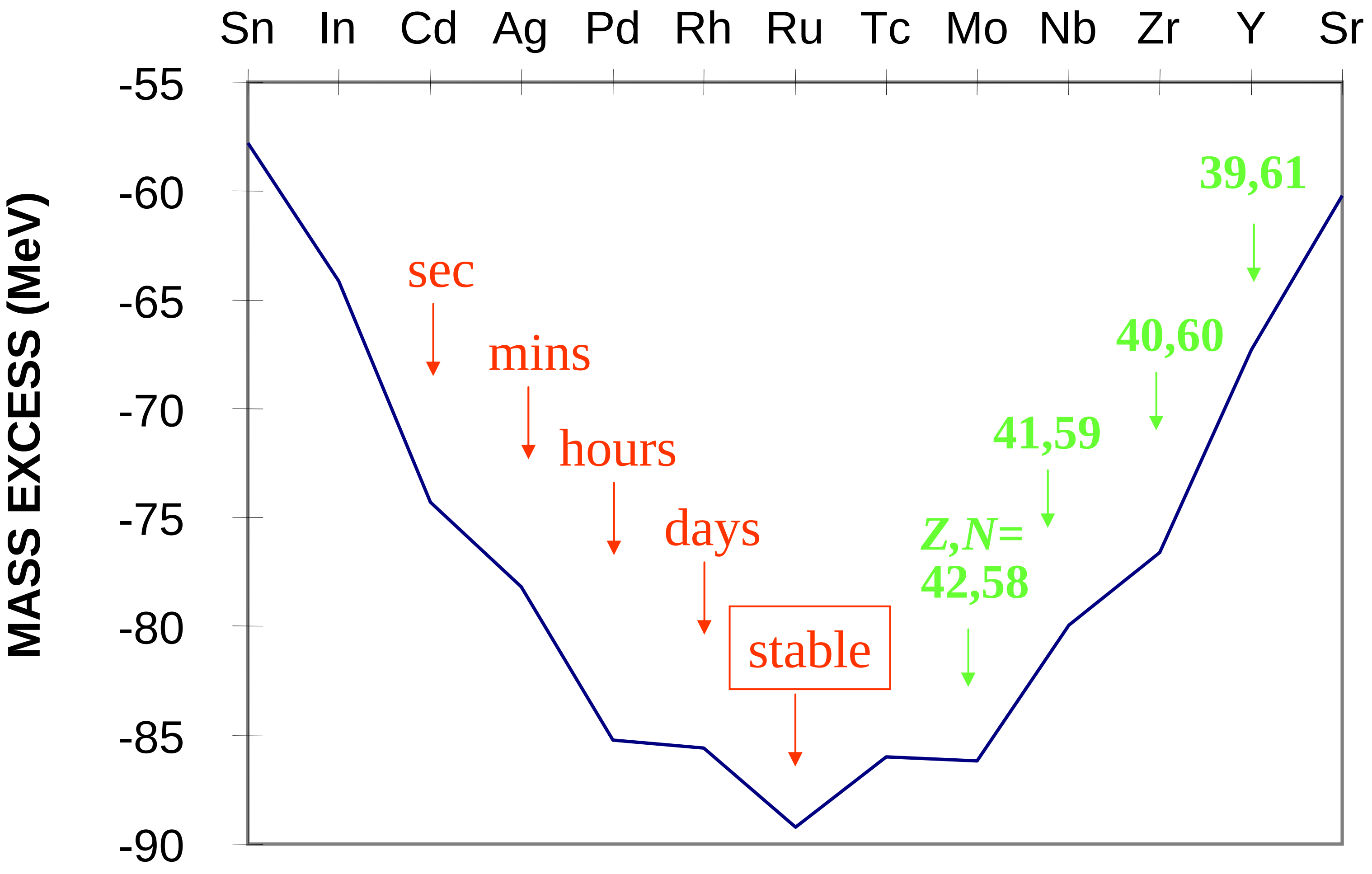
$$E = mc^2$$

Firing the stellar furnace;
and resolving questions
about the age of the sun

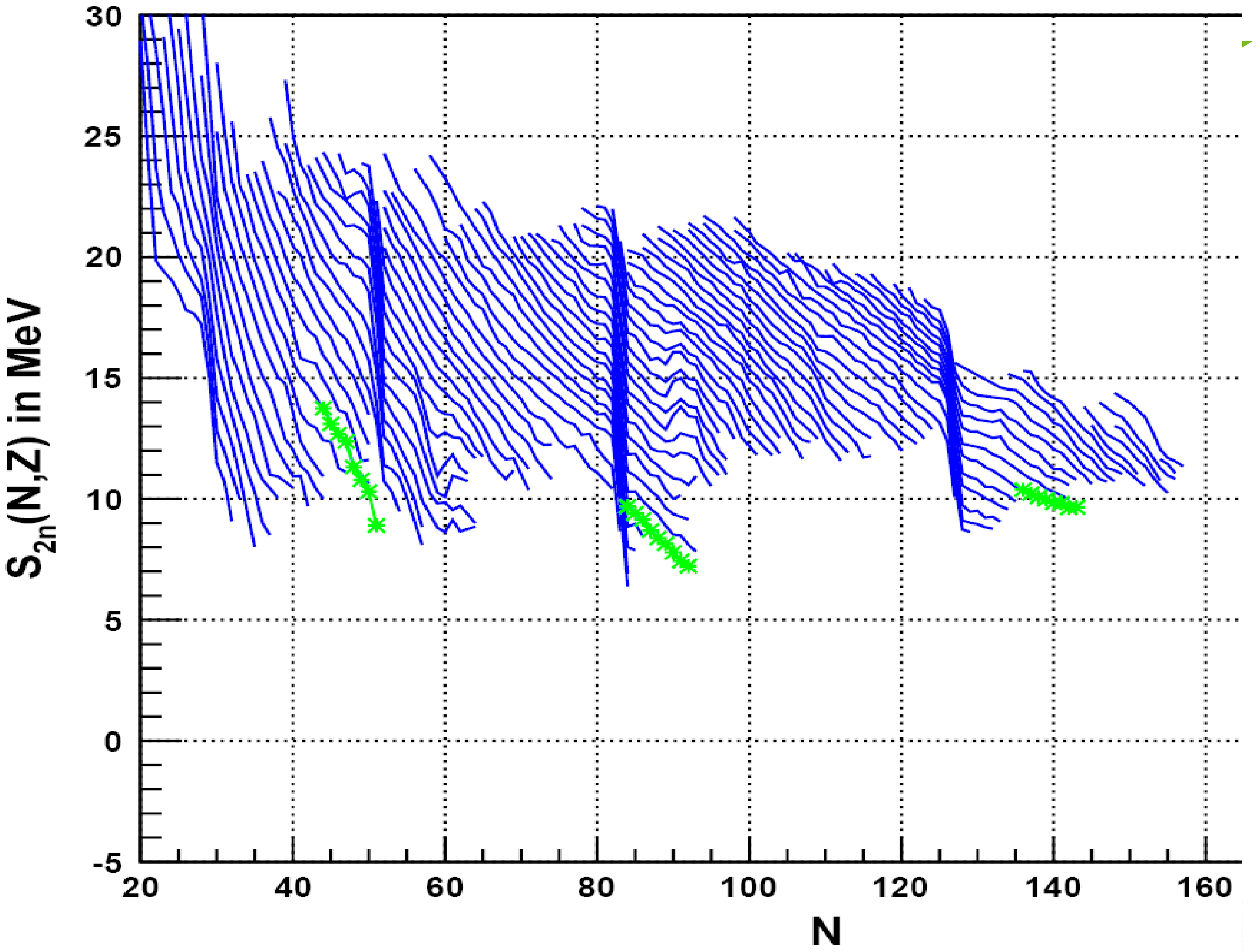


15C
16N
17N
18C
20F
16C
17O
18F
58

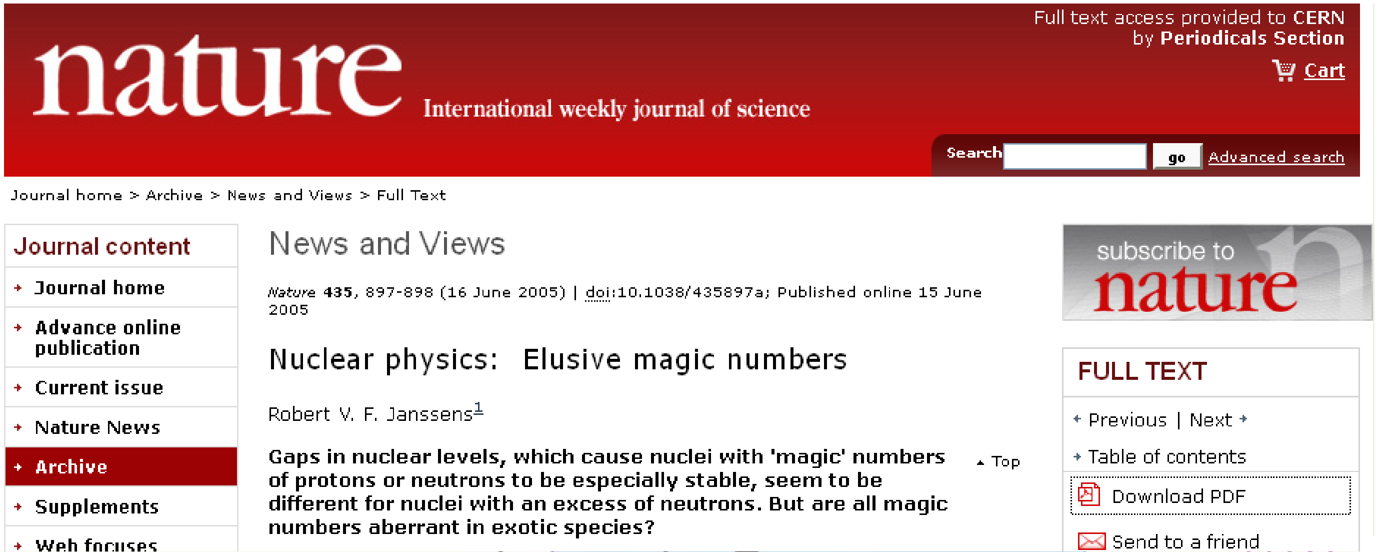
Mass excess



(A = 100 isobars)


30
25
20
15
10
5
0
-5
$S_{2n}(N,Z)$ in MeV
20
40
60
80
100
120
140
160
N

Where has the magic gone?



nature International weekly journal of science

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News and Views

Nature **435**, 897-898 (16 June 2005) | doi:10.1038/435897a; Published online 15 June 2005

Nuclear physics: Elusive magic numbers

Robert V. F. Janssens[1]

Gaps in nuclear levels, which cause nuclei with 'magic' numbers of protons or neutrons to be especially stable, seem to be different for nuclei with an excess of neutrons. But are all magic numbers aberrant in exotic species?

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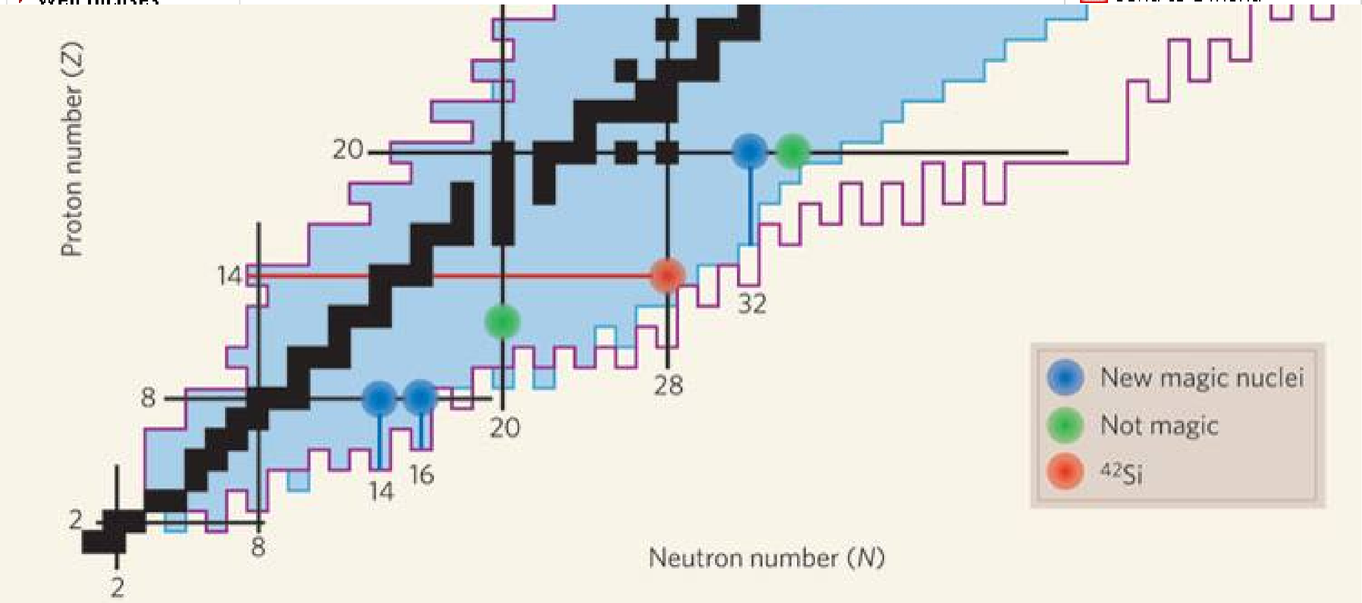
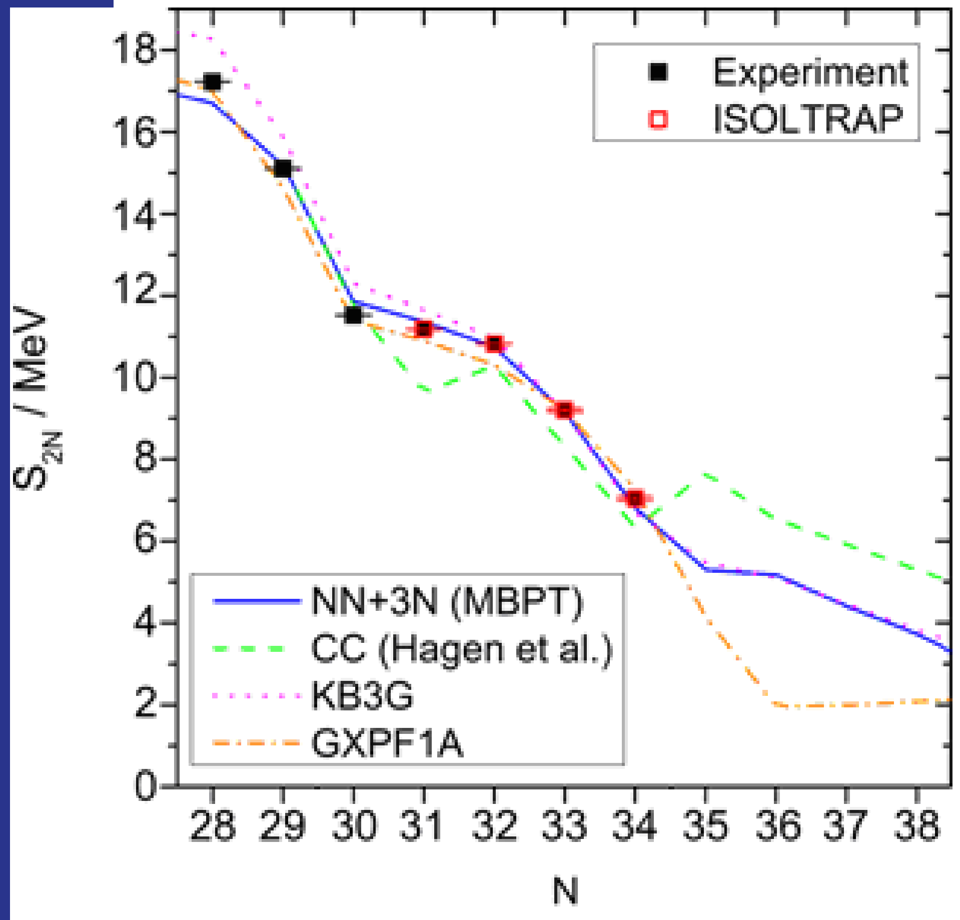
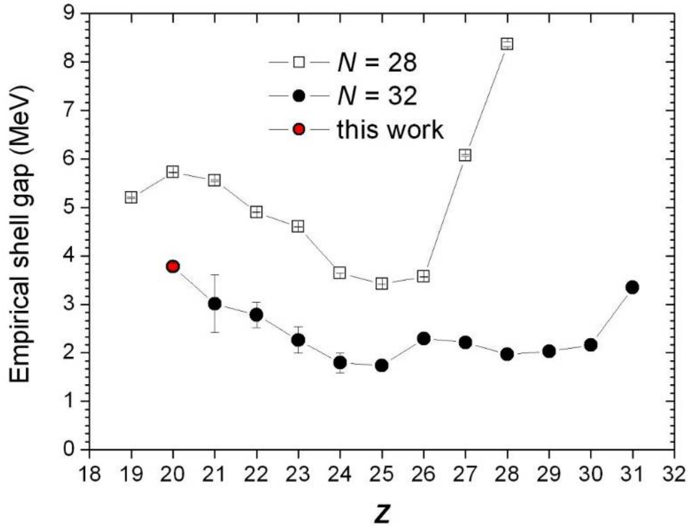


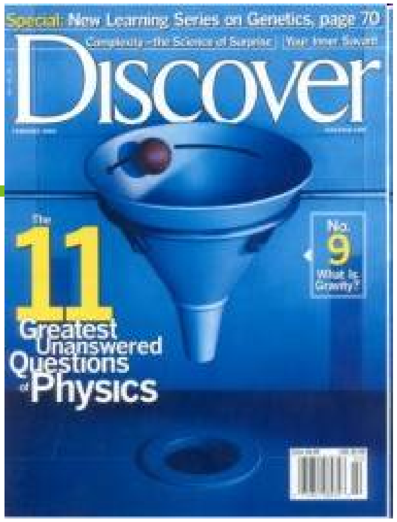
(New) magic number *N* = 32 !





F. Wienholz et al. *Nature* (2013) today!

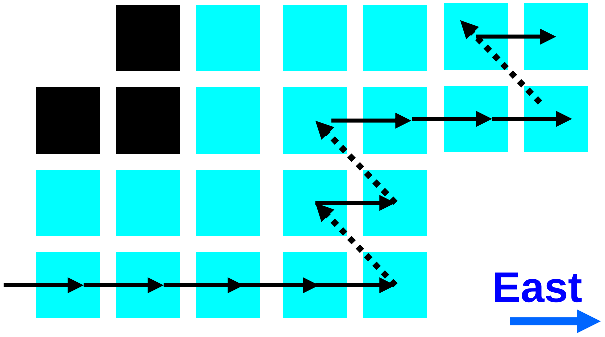
From the “eleven greatest unanswered questions”:

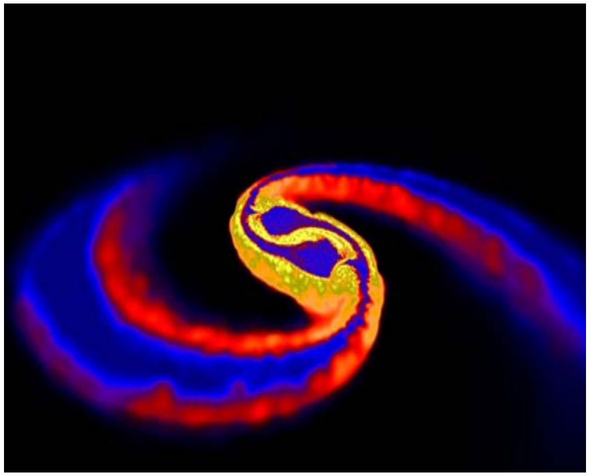


3. How were the heavy elements from iron to uranium made?

rapid neutron-capture (*r*) process:
Burbidge, Burbidge, Fowler and Hoyle, *Rev. Mod. Phys.* (1957)
Arnould, Goriely, Takahashi, *Physics Reports* (2007)

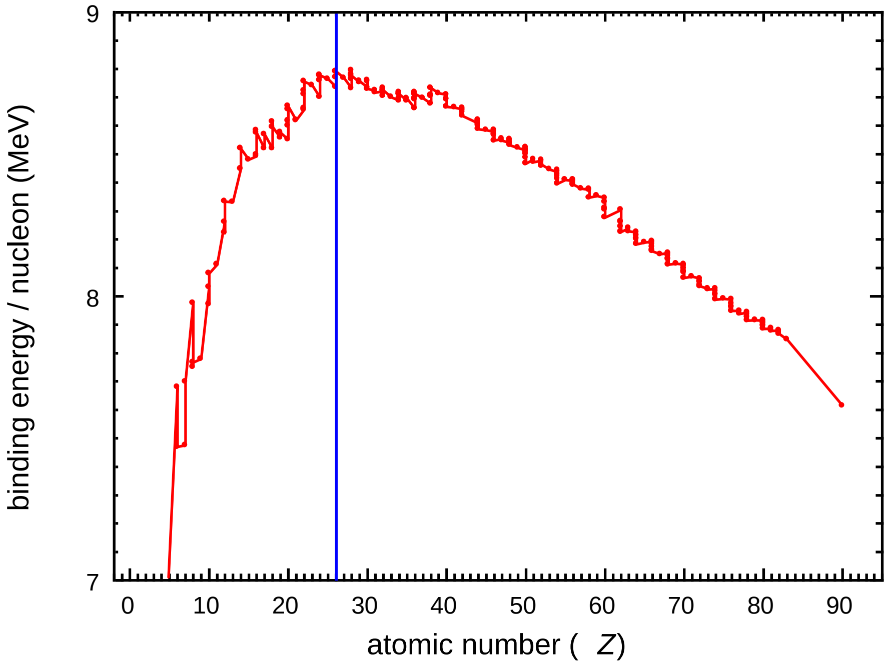
S. Woosley and T. Janka,
Nature Physics (2005)

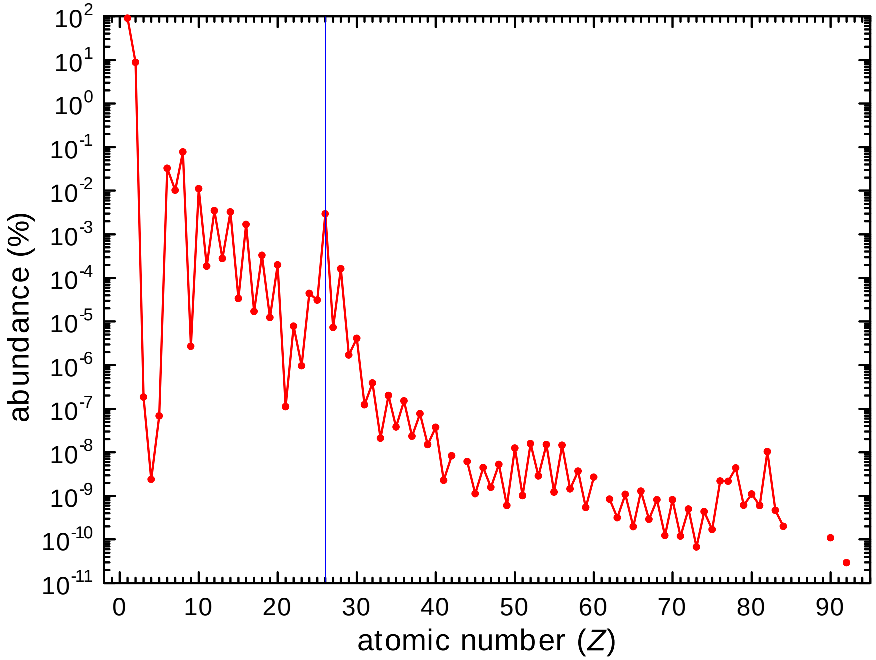


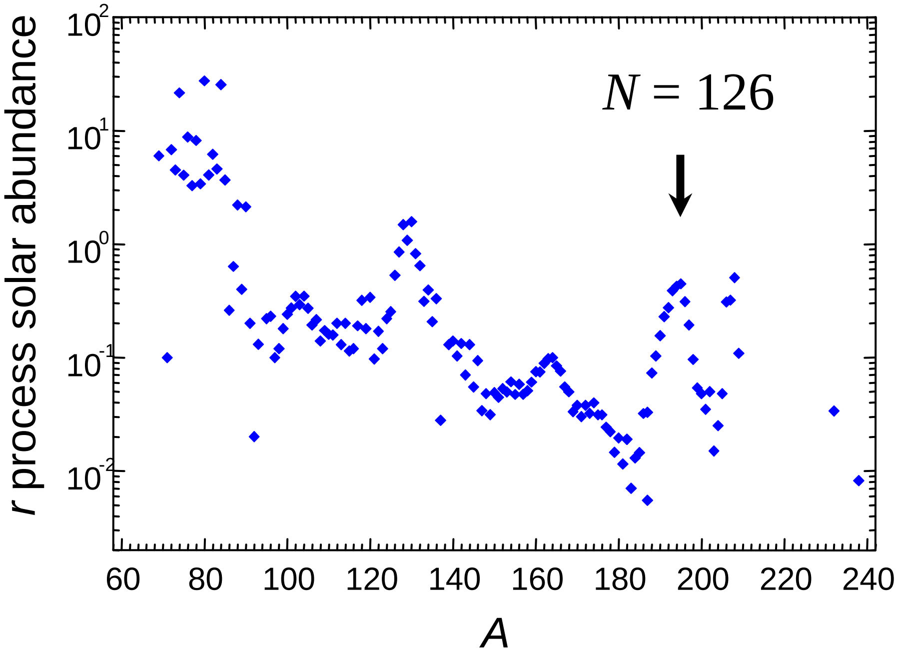


D. Price and S. Rosswog,
Science (2006)

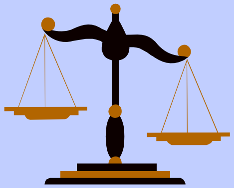
An imprint of nuclear physics on nature: magic number abundance peaks







Techniques



Indirect

reactions:

$A(a,b)B$

$Q = M_A + M_a - M_b - M_B$

decays:

$A \rightarrow B + \alpha$

$Q_\alpha = M_B - M_A$

Direct

(mass spectrometry)

time of flight:

SPEG/CSS2 - GANIL

NSCL, ESR - GSI

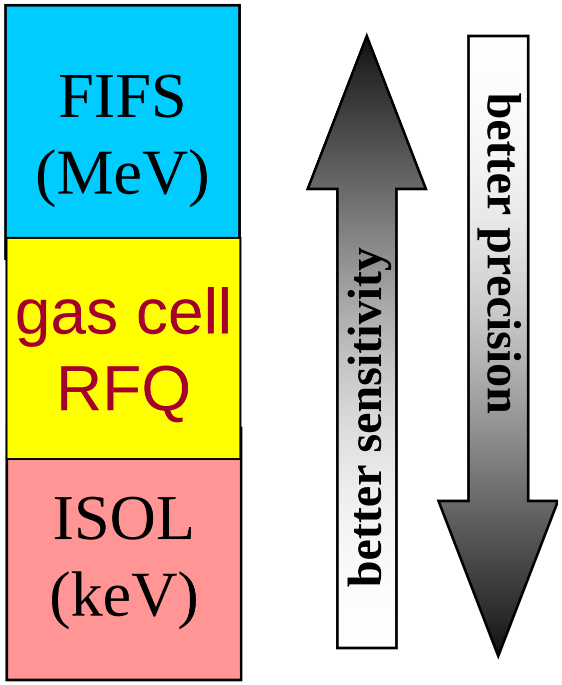
cyclotron frequency:

Penning-trap

Mass spectrometry

ISOLTRAP and…

PRODUCTION SCHEME



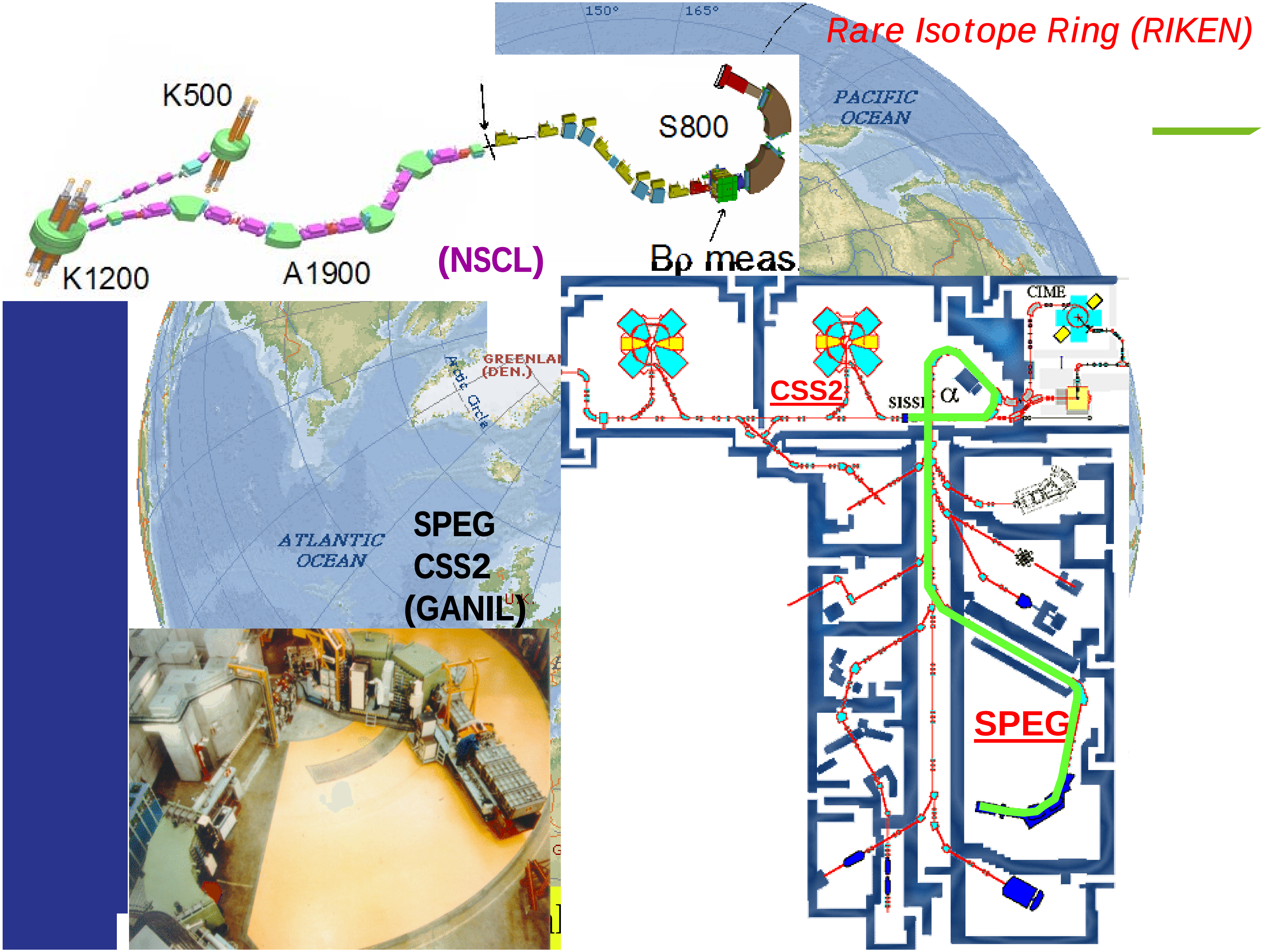
FIFS (MeV)

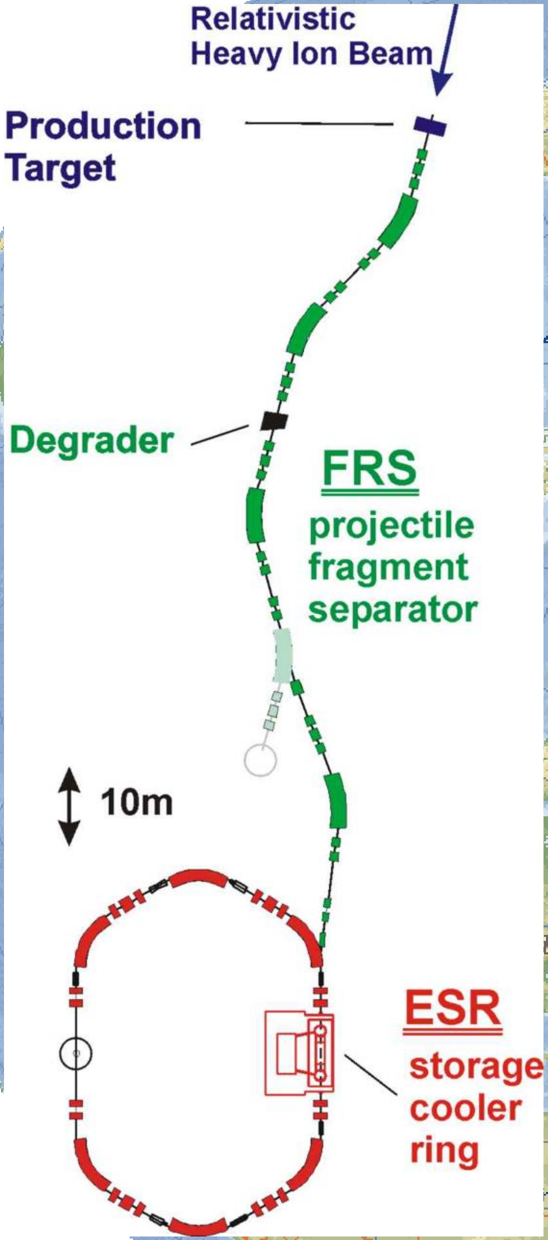
gas cell RFQ

ISOL (keV)

Mass measurements worldwide

Rare Isotope Ring (RIKEN)





Storage RING (Lanzhou)

NESR (FAIR)

ESR-FRS (GSI)

TITAN (TRIUMF)

LEBIT (NSCL)

CPT (ANL)

ISOLTRAP (CERN)

SHIPTRAP (GSI)

JYFLTRAP (IGIS

MLLTRAP (SPIRAL2)

TRIGATRAP

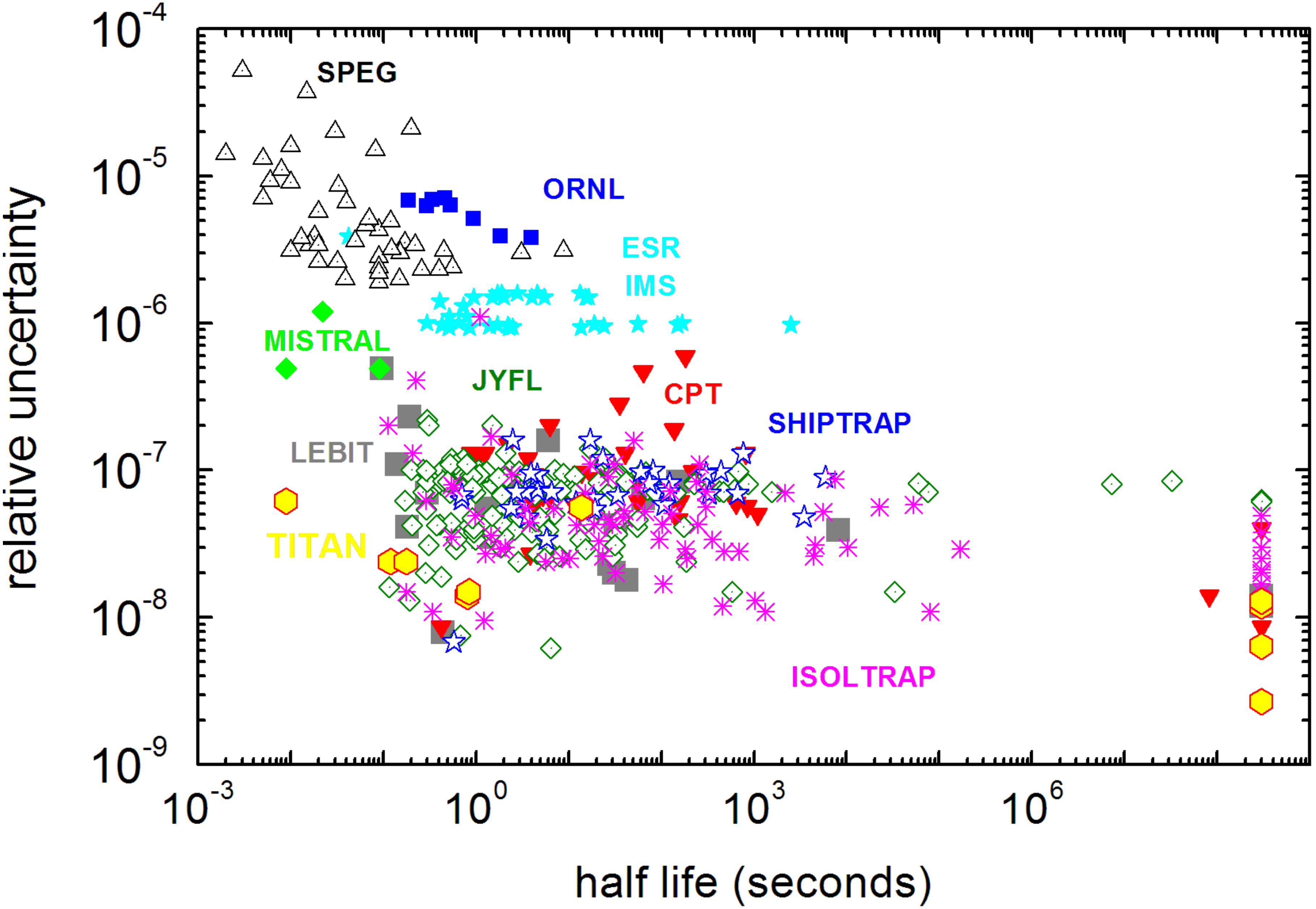
Complementarity

- Penning traps at radioactive ion-beam facilities

Production	ISOLTRAP CERN	TITAN TRIUMF	SHIPTRAP GSI	MLLTRAP LMU	JYFLTRAP	LEBIT NSCL	CPT ANL	TRIGA-TRAP
ISOL	X	X						
Fusion-evaporation			X	X				
IGISOL					X			
Fragmentation						X		
Spontaneous Fission							X	
Neutron-induced fission								X

- Traps in planning or for other purposes
  - THeTRAP, FSU-TRAP, SMILETRAP II (Shanghai-EBIT)
  - HITRAP, PENTATRAP, MATS, Lanzhou-TRAP, RIKEN-TRAP
  - WITCH, LPC-TRAP

complementarity



Ion traps: the 1989 Nobel Prize

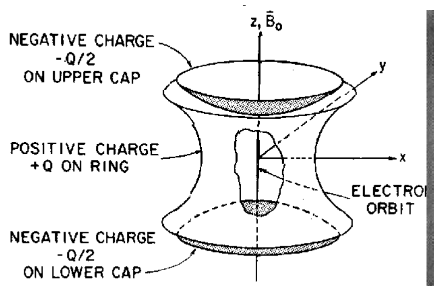
Physica Scripta Vol. T59, 87-92, 1995

"That I May Know the Inmost Force that Binds the World and Guides its Course"

Hans Dehmelt

Department of Physics, FM-15, University of Washington, Seattle, WA 98195, U.S.A.

Abstract: This talk touches upon the following subjects: Geothe's *Faust*, the magic of Democratus' "ατομον", ... seeing an atom with my eyes, bringing an electron to rest, ... and the cosmon, the simplest thing that ever was.



$$Dirac: R_{elec} = 0$$

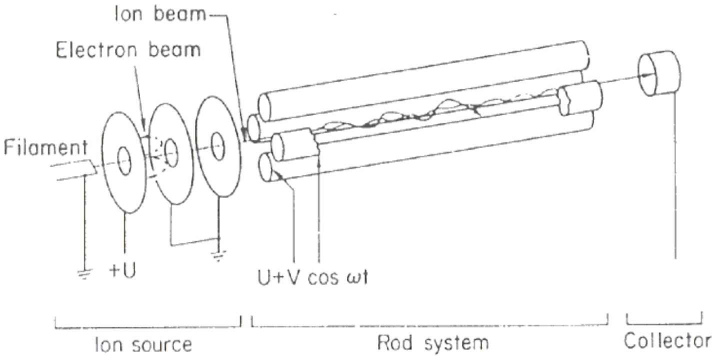
$$\Rightarrow g = 2\frac{\mu}{I}\frac{m}{q} = 2.0$$

$$Dehmelt:$$

$$g - 2 < 10^{-12}$$

$$\Rightarrow R_{elec} > 0 \ \ ?!$$

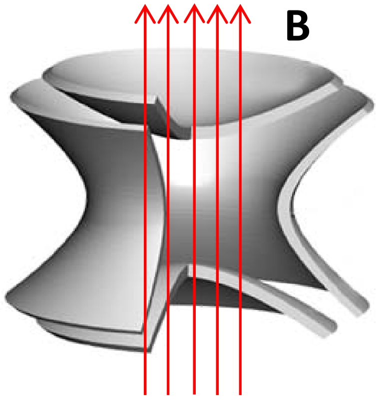
Wolfgang Paul
Bonn University
(1913 - 1993)



YOU WANTED enhanced sensitivity AND selectivity FROM OUR HIGH PERFORMANCE LC/MS/MS system

The API 3000 LC/MS/MS System

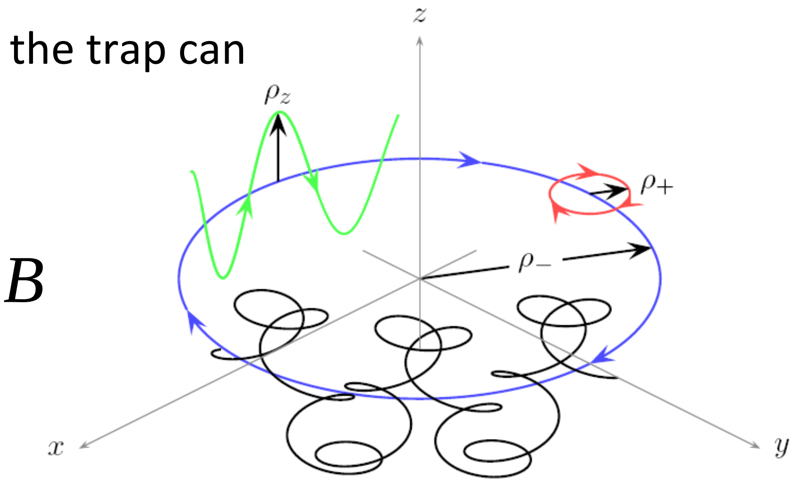
Penning trap



- Charged particle stored by superposition of strong homogeneous magnetic field in z direction and weak, electrostatic potential for axial confinement
  - Frequency measurement
  - Long storage times
  - Single-ion sensitivity
  - High precision

- Frequency measurement: eigenmotion in the trap can be used to determine mass

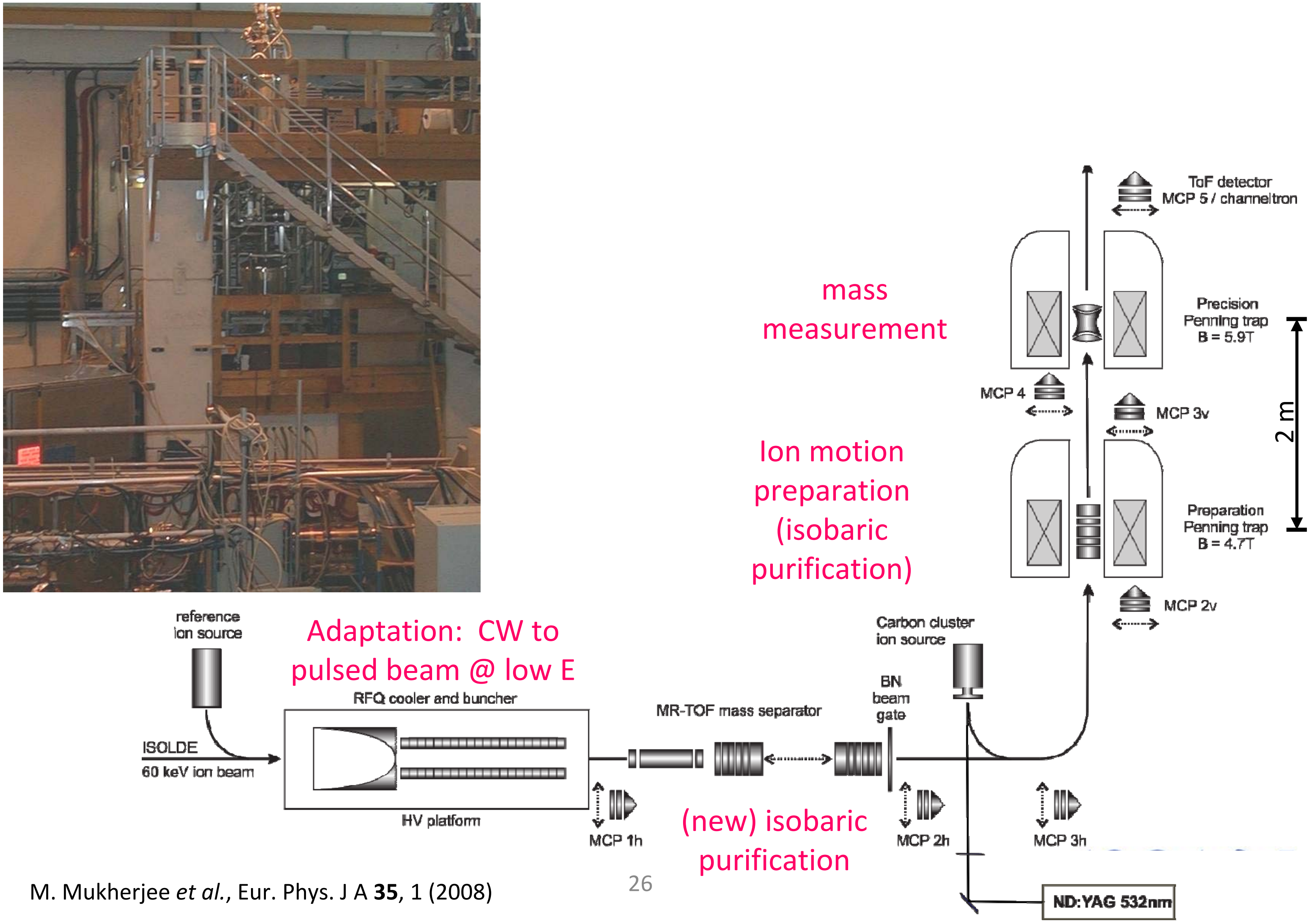
$$\nu_c = \nu_+ + \nu_- \Longrightarrow \nu_c = \frac{1}{2\pi}\frac{q}{m}B$$



L. S. Brown and G. Gabrielse , Rev. Mod. Phys. **58**, 233 (1986)

H. Dehmelt: 1989 Nobel Prize in Physics

ISOLTRAP operation



mass measurement

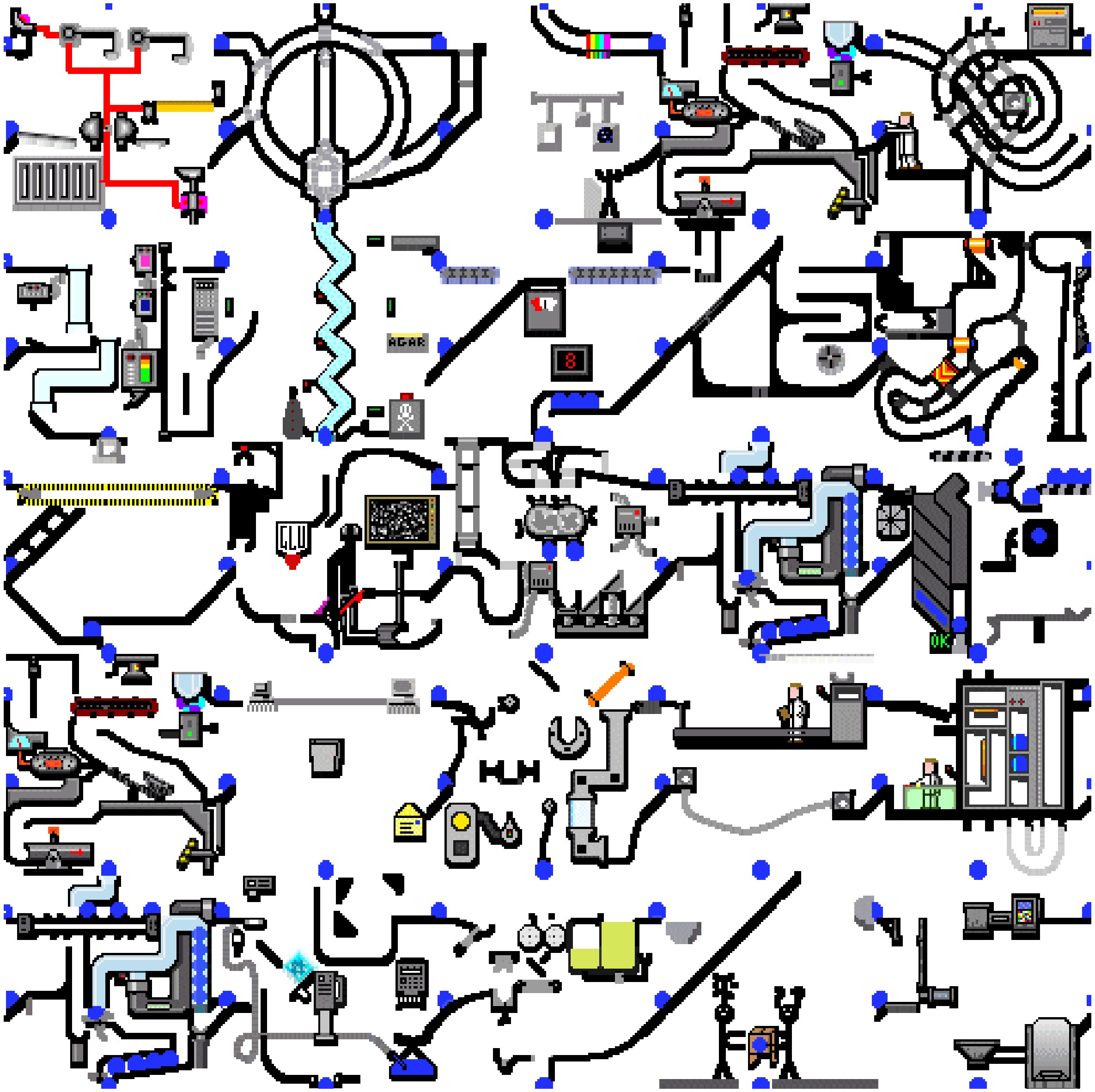
Ion motion preparation (isobaric purification)

Adaptation: CW to pulsed beam @ low E

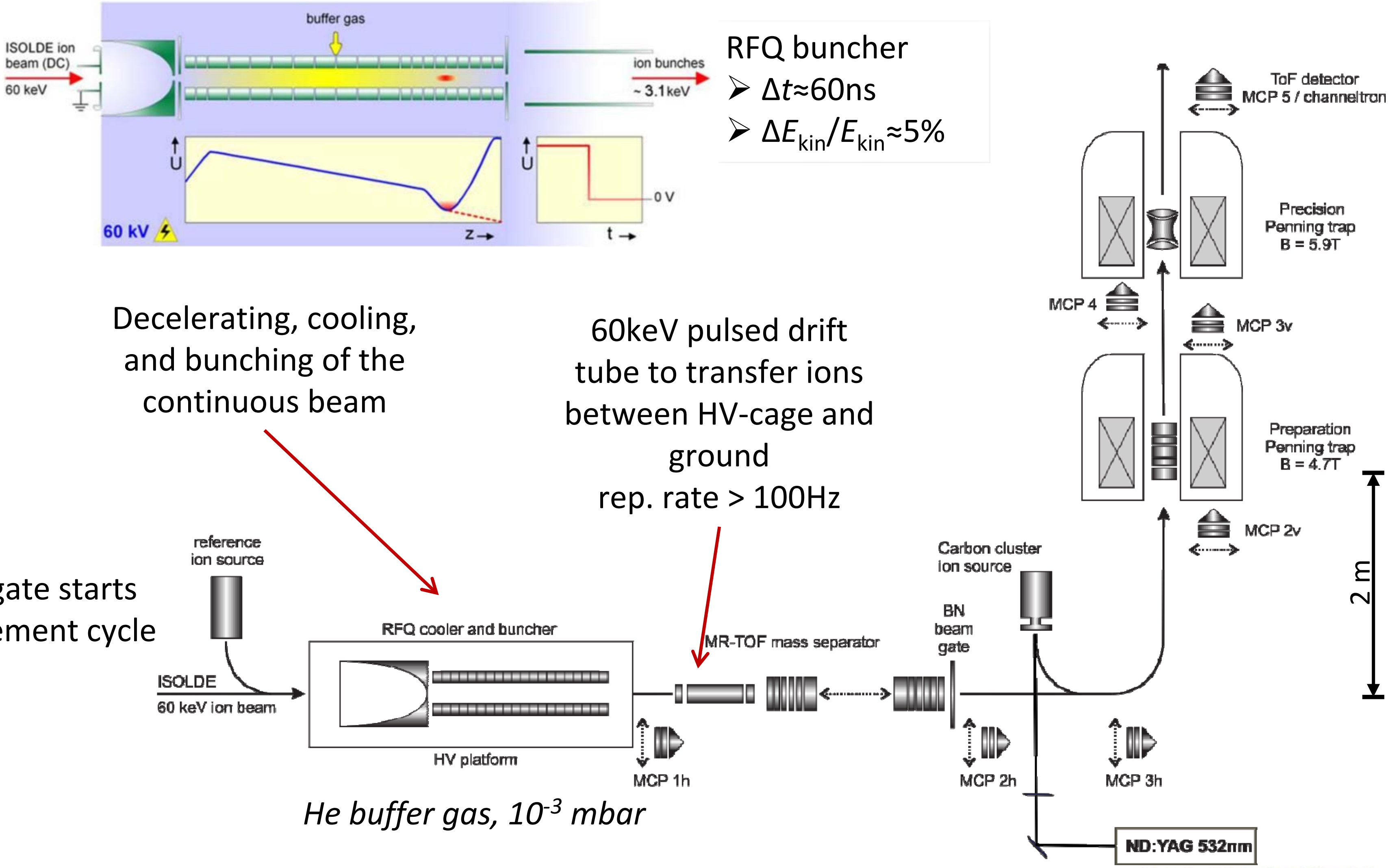
(new) isobaric purification

M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)

ISOLTRAP : un veritable usine à gaz!



Preparing an Ion Ensemble



RFQ buncher

- $\Delta t \approx 60\text{ns}$
- $\Delta E_{kin}/E_{kin} \approx 5\%$

Decelerating, cooling, and bunching of the continuous beam

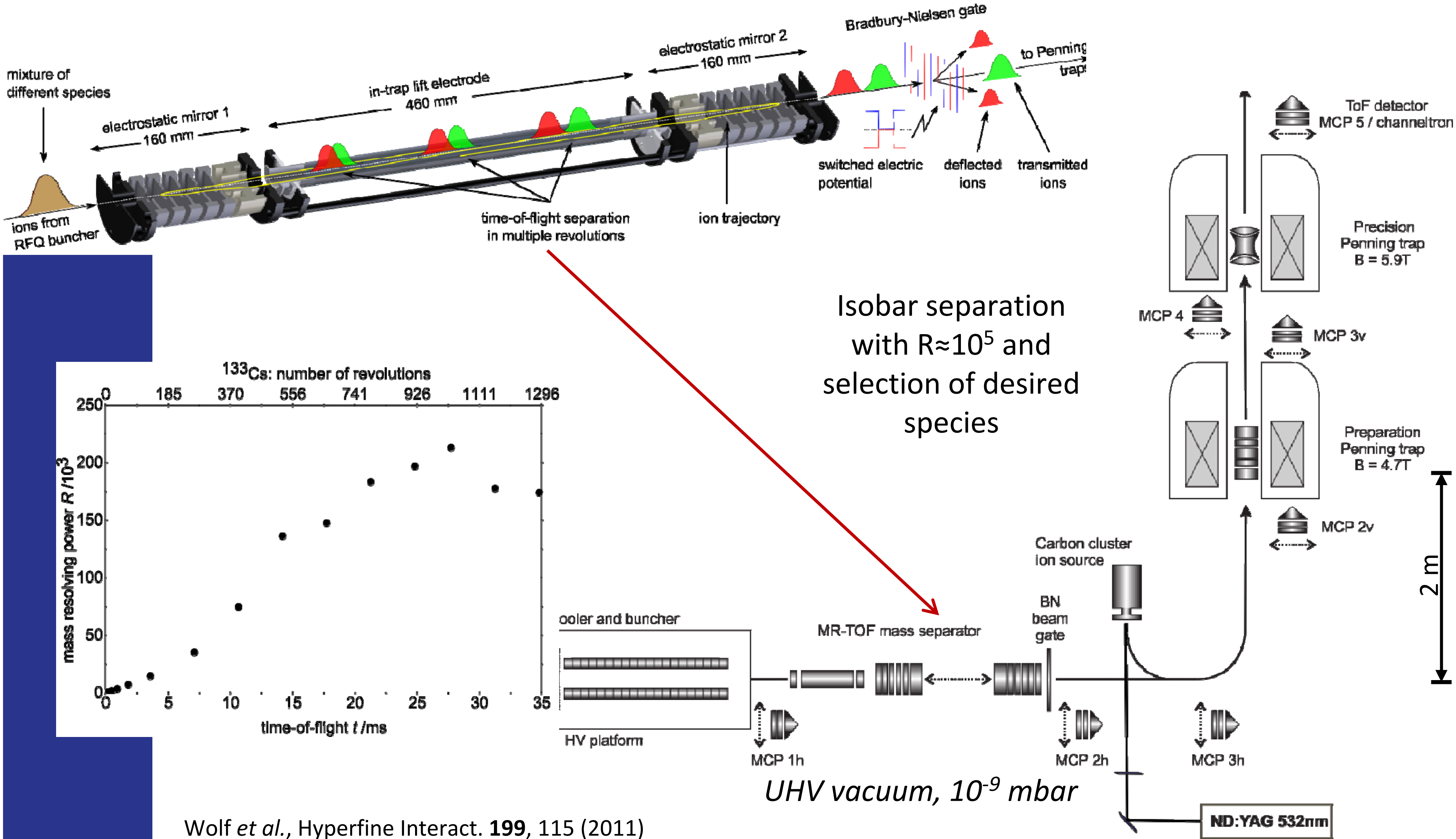
60keV pulsed drift tube to transfer ions between HV-cage and ground
rep. rate > 100Hz

Beam gate starts measurement cycle

He buffer gas, 10^{-3} mbar

M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)
F. Herfurth *et al.*, NIM A **469**, 254 (2001)

Purification of Ion Bunches

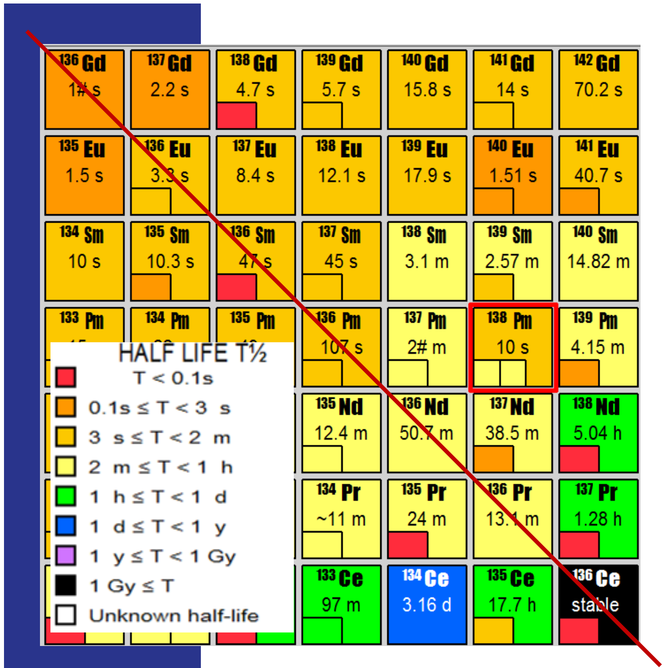


Isobar separation with R≈10^5 and selection of desired species

UHV vacuum, 10^{-9} mbar

Wolf *et al.*, Hyperfine Interact. **199**, 115 (2011)
Wolf *et al.*, IJMS **313**, 8 (2012)
Wolf *et al.*, NIM A **686**, 82 (2012)

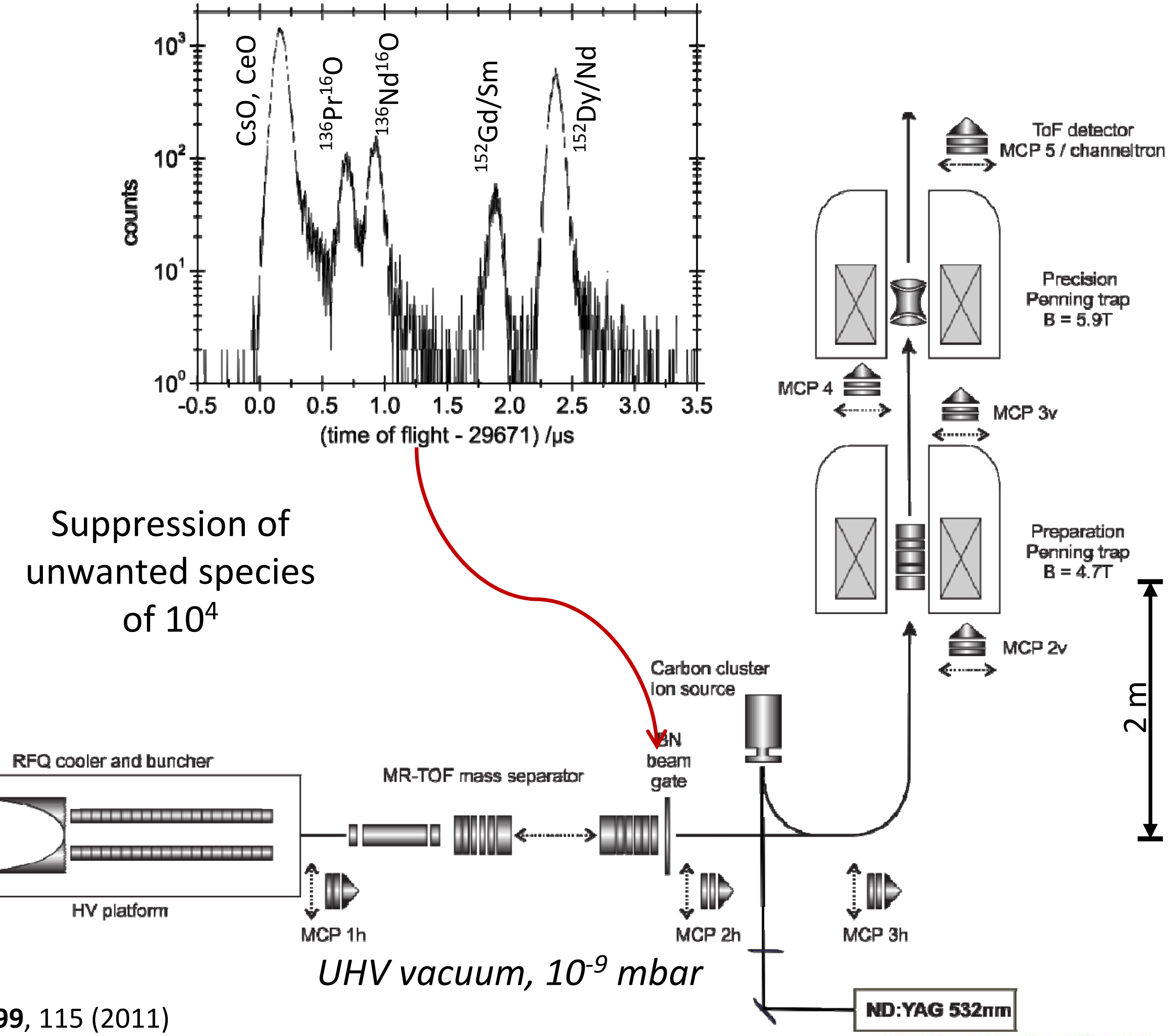
Purification of Ion Bunches



136 Gd 1# s	137 Gd 2.2 s	138 Gd 4.7 s	139 Gd 5.7 s	140 Gd 15.8 s	141 Gd 14 s	142 Gd 70.2 s
135 Eu 1.5 s	136 Eu 3.3 s	137 Eu 8.4 s	138 Eu 12.1 s	139 Eu 17.9 s	140 Eu 1.51 s	141 Eu 40.7 s
134 Sm 10 s	135 Sm 10.3 s	136 Sm 47 s	137 Sm 45 s	138 Sm 3.1 m	139 Sm 2.57 m	140 Sm 14.82 m
133 Pm	134 Pm	135 Pm	136 Pm 107 s	137 Pm 2# m	138 Pm 10 s	139 Pm 4.15 m
			135 Nd 12.4 m	136 Nd 50.7 m	137 Nd 38.5 m	138 Nd 5.04 h
			134 Pr ~11 m	135 Pr 24 m	136 Pr 13.1 m	137 Pr 1.28 h
			133 Ce 97 m	134 Ce 3.16 d	135 Ce 17.7 h	136 Ce stable

HALF LIFE T½

- 🟥 T < 0.1s
- 🟧 0.1s ≤ T < 3 s
- 🟨 3 s ≤ T < 2 m
- 🟨 2 m ≤ T < 1 h
- 🟩 1 h ≤ T < 1 d
- 🟦 1 d ≤ T < 1 y
- 🟪 1 y ≤ T < 1 Gy
- ⬛ 1 Gy ≤ T
- ☐ Unknown half-life



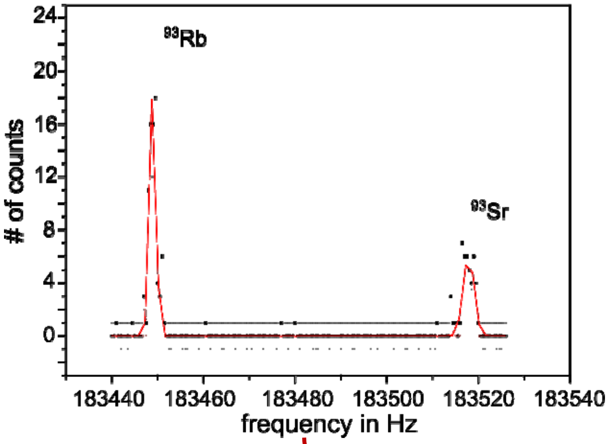
Suppression of unwanted species of 10^4

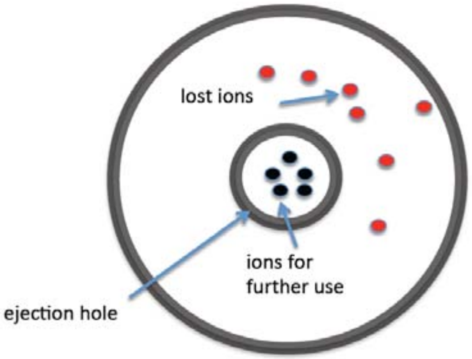
UHV vacuum, 10^{-9} mbar

Wolf *et al.*, Hyperfine Interact. **199**, 115 (2011)
Wolf *et al.*, IJMS **313**, 8 (2012)
Wolf *et al.*, NIM A **686**, 82 (2012)

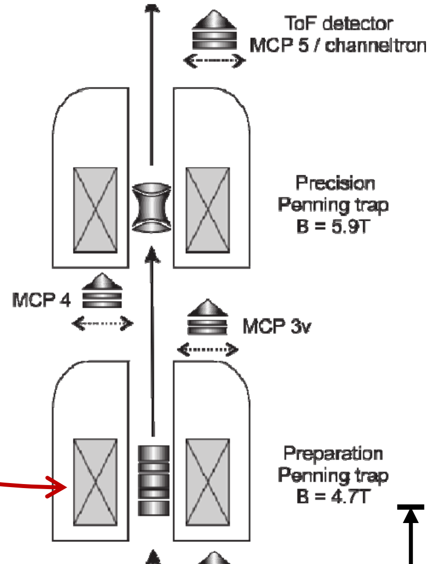
Purification and Preparation

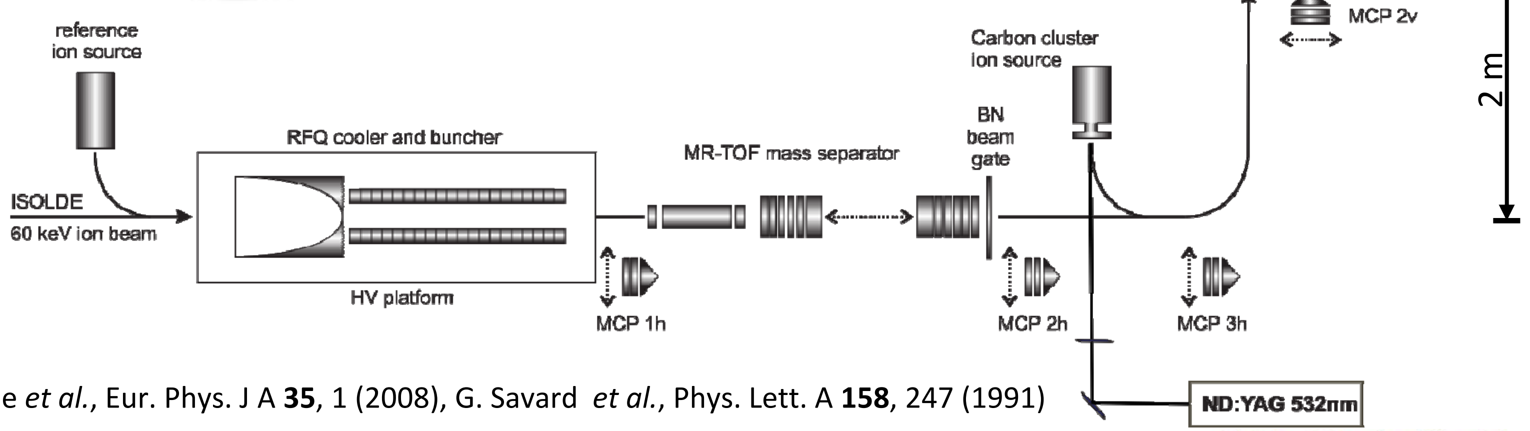
Further elimination of undesired contaminations with R≈ 10^5 and preparation for injection into measurement trap





He buffer gas, 10^{-5} mbar





M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008), G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991)

Alternative purification in buffer –gas environment: Octupole Cleaning

M. Rosenbusch et al., IJMS **314**, 6 (2012)

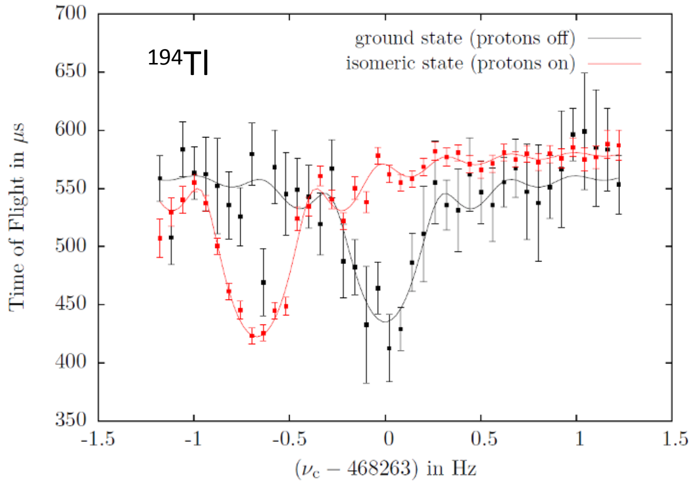
Measurement Possibilities

Cyclotron frequency: mass

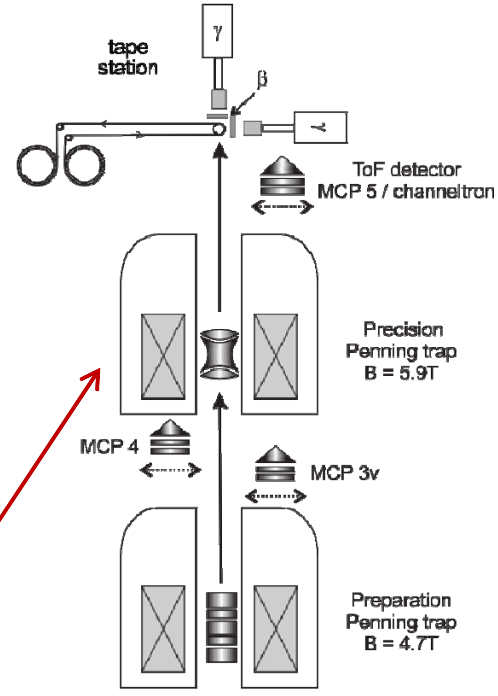
even on *isomeric* states!

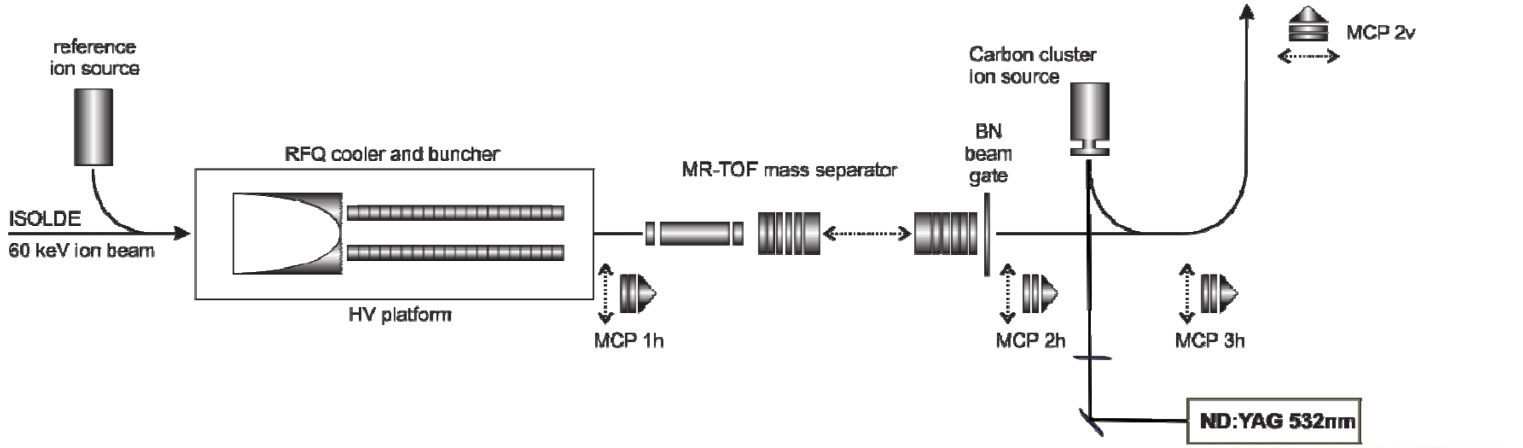
requires excitations > 1 s

Decay spectroscopy on
pure samples



UHV vacuum, 10^{-9} mbar

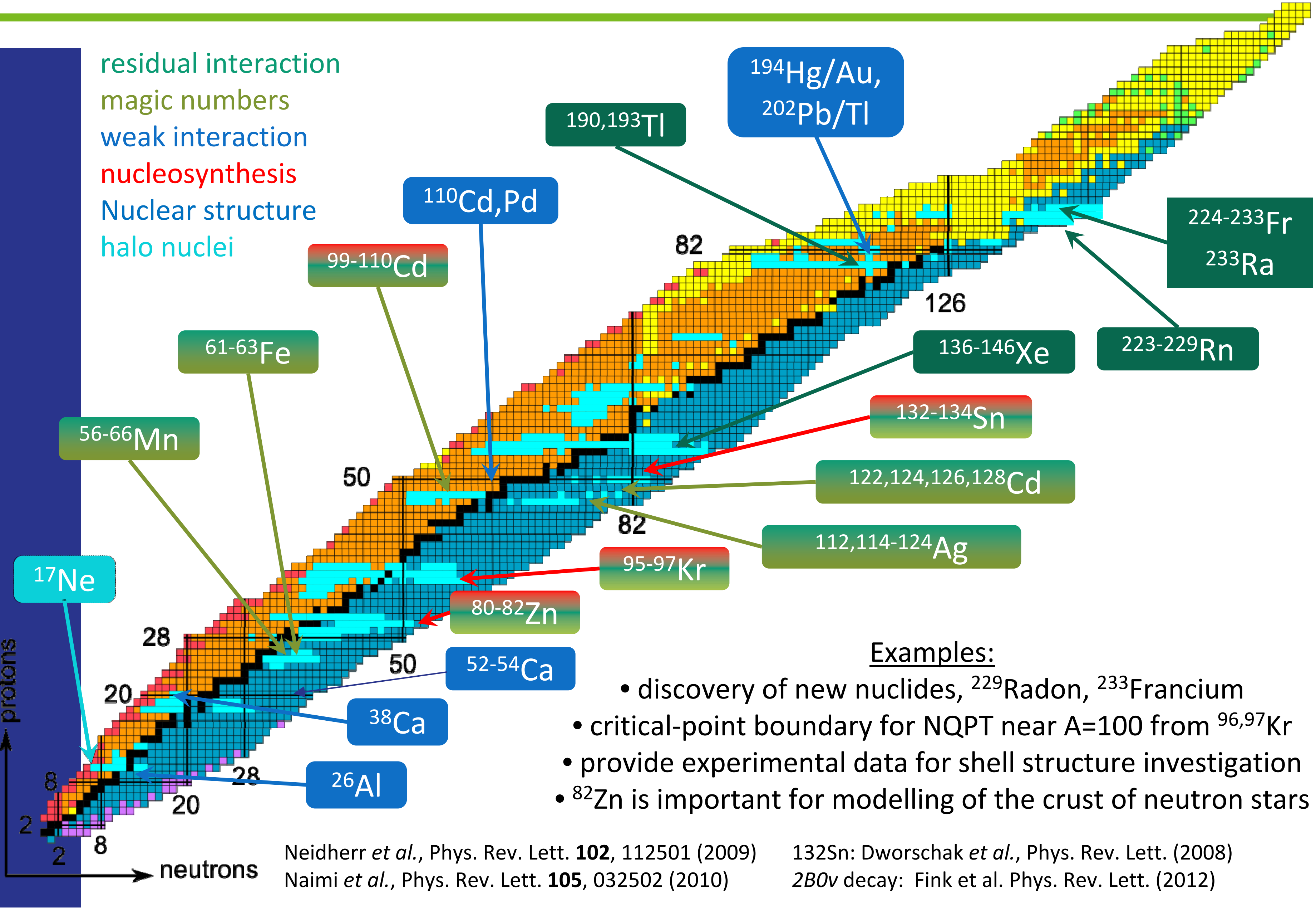




M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)
M. Kowalska *et al.*, NIMA A **689**, 102 (2012)

Physics with ISOLTRAP 2004-2011

residual interaction
magic numbers
weak interaction
nucleosynthesis
Nuclear structure
halo nuclei



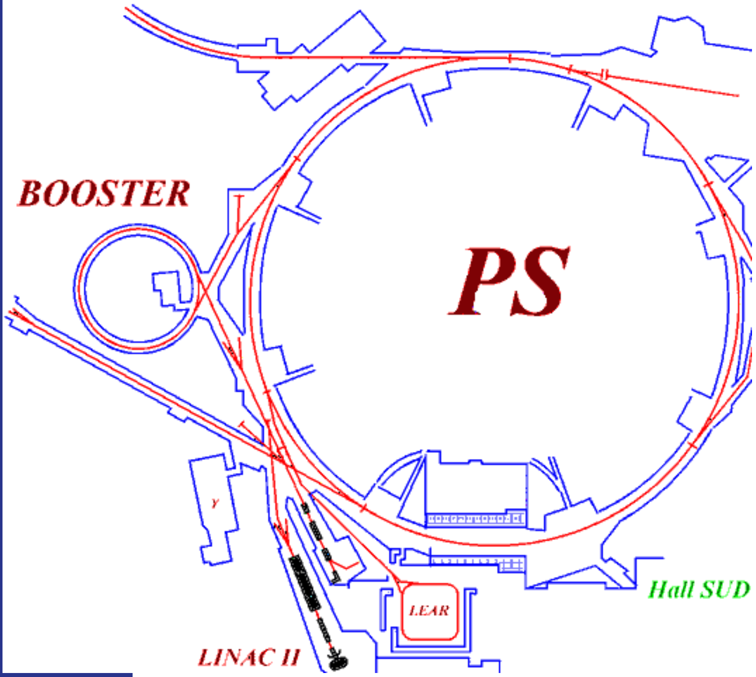
Examples:

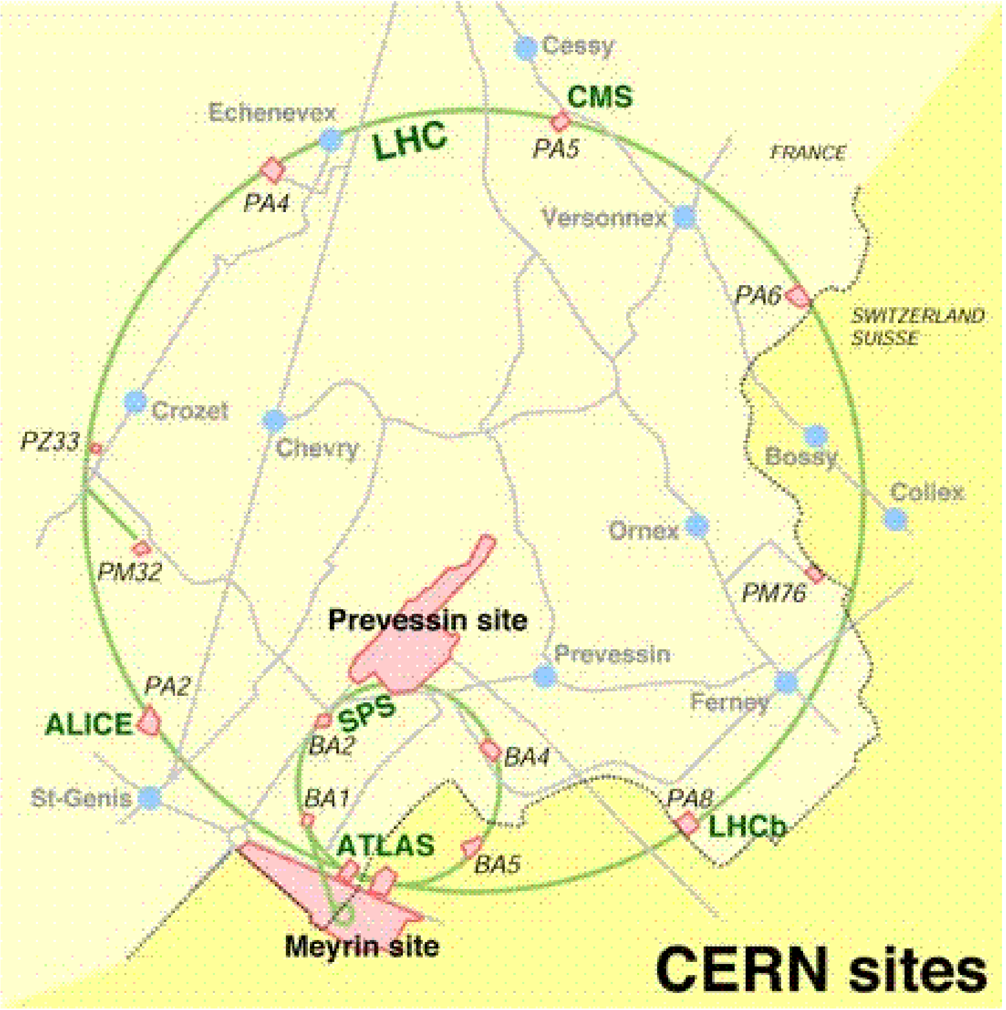
- discovery of new nuclides, ^{229}Radon, ^{233}Francium
- critical-point boundary for NQPT near A=100 from ^{96,97}Kr
- provide experimental data for shell structure investigation
- ^{82}Zn is important for modelling of the crust of neutron stars

Neidherr *et al.*, Phys. Rev. Lett. **102**, 112501 (2009)
Naimi *et al.*, Phys. Rev. Lett. **105**, 032502 (2010)

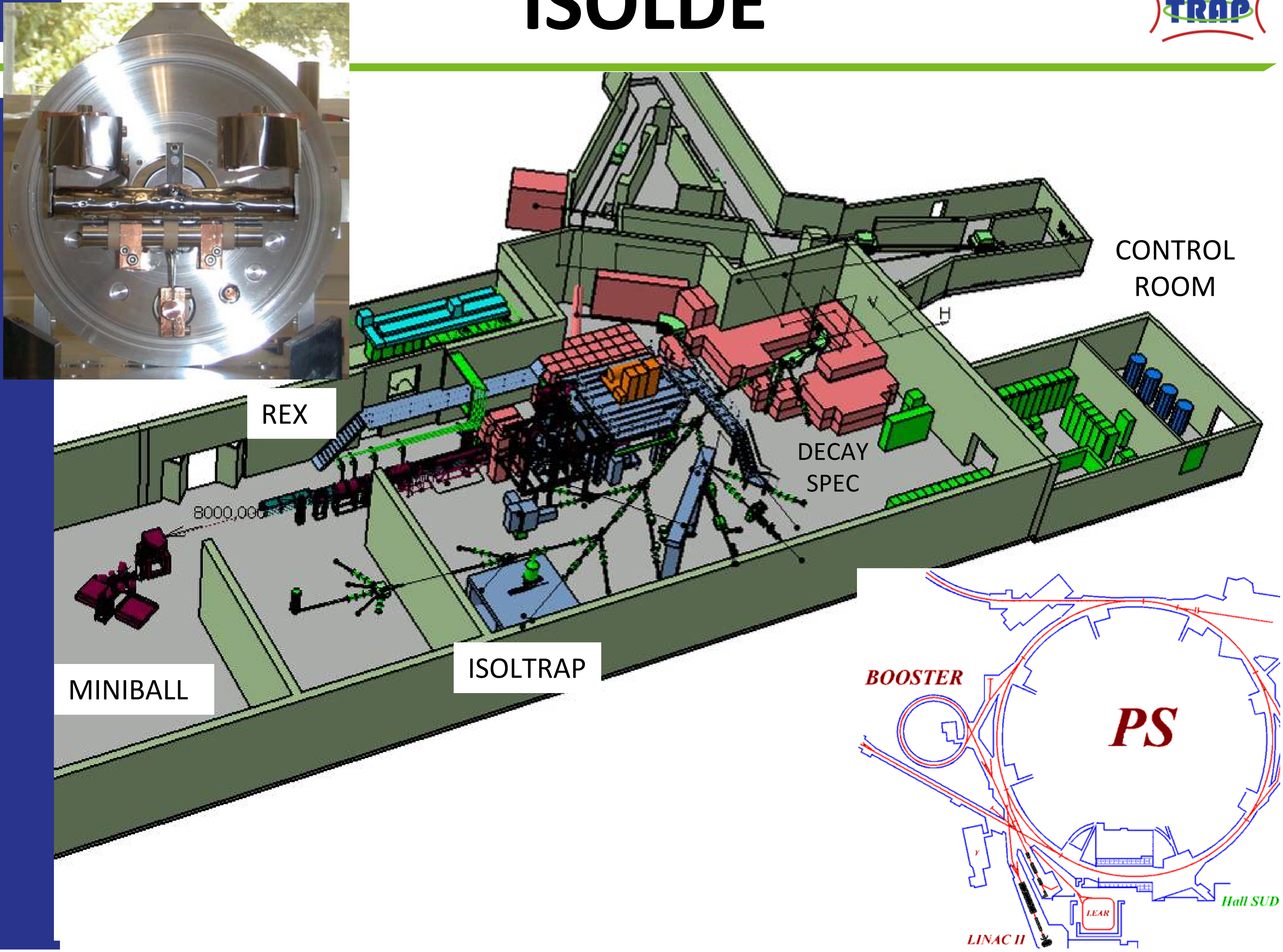
132Sn: Dworschak *et al.*, Phys. Rev. Lett. (2008)
2B0v decay: Fink et al. Phys. Rev. Lett. (2012)

CERN

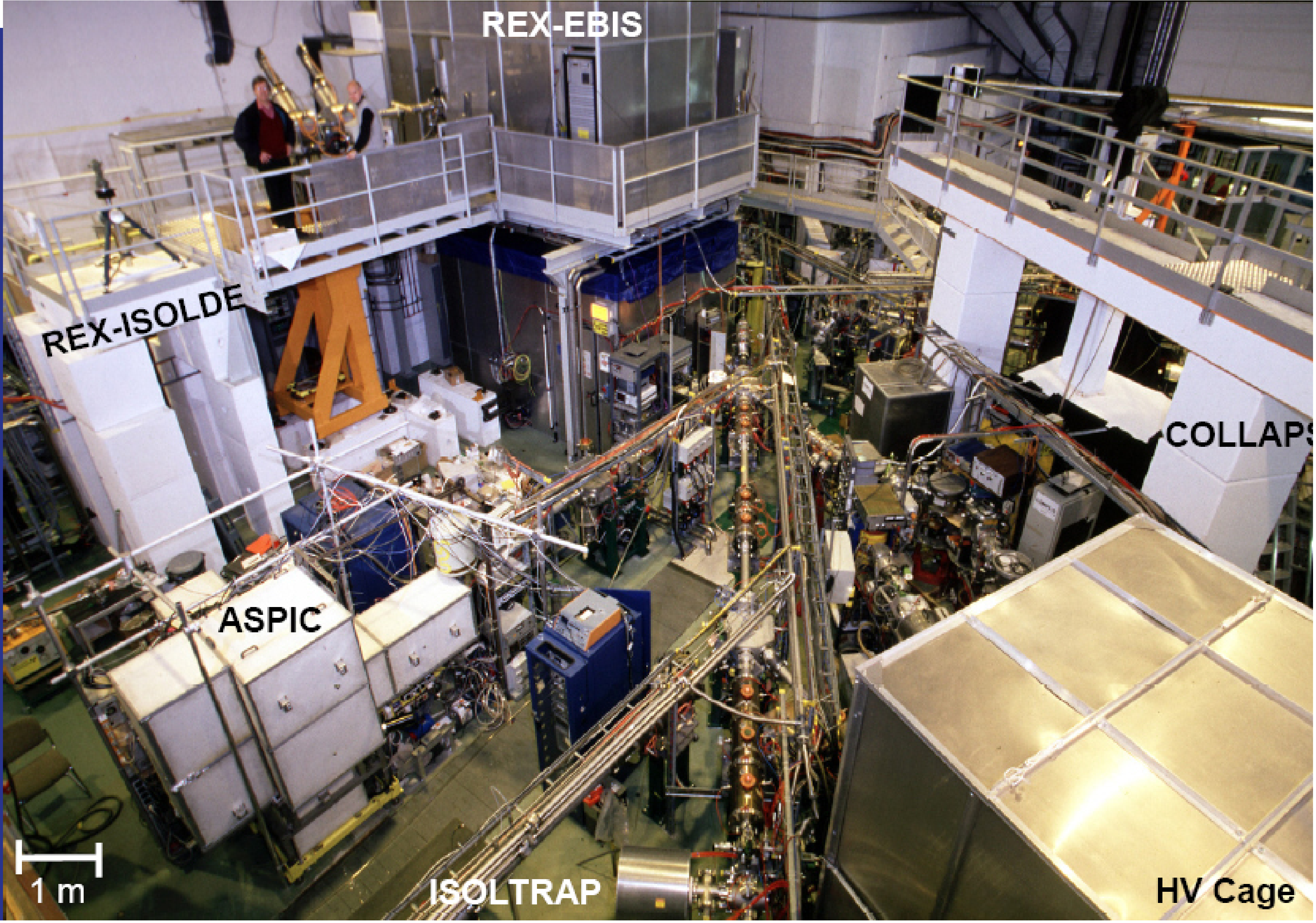

BOOSTER
PS
Hall SUD
LEAR
LINAC II


Cessy
CMS
PA5
Echenevex
LHC
PA4
FRANCE
Versonnex
PA6
SWITZERLAND
SUISSE
Crozet
PZ33
Chevry
Bossy
Collex
Ornex
PM32
PM76
Prevessin site
Prevessin
PA2
ALICE
SPS
BA2
Ferney
BA4
St-Genis
BA1
PA8
LHCb
ATLAS
BA5
Meyrin site
CERN sites

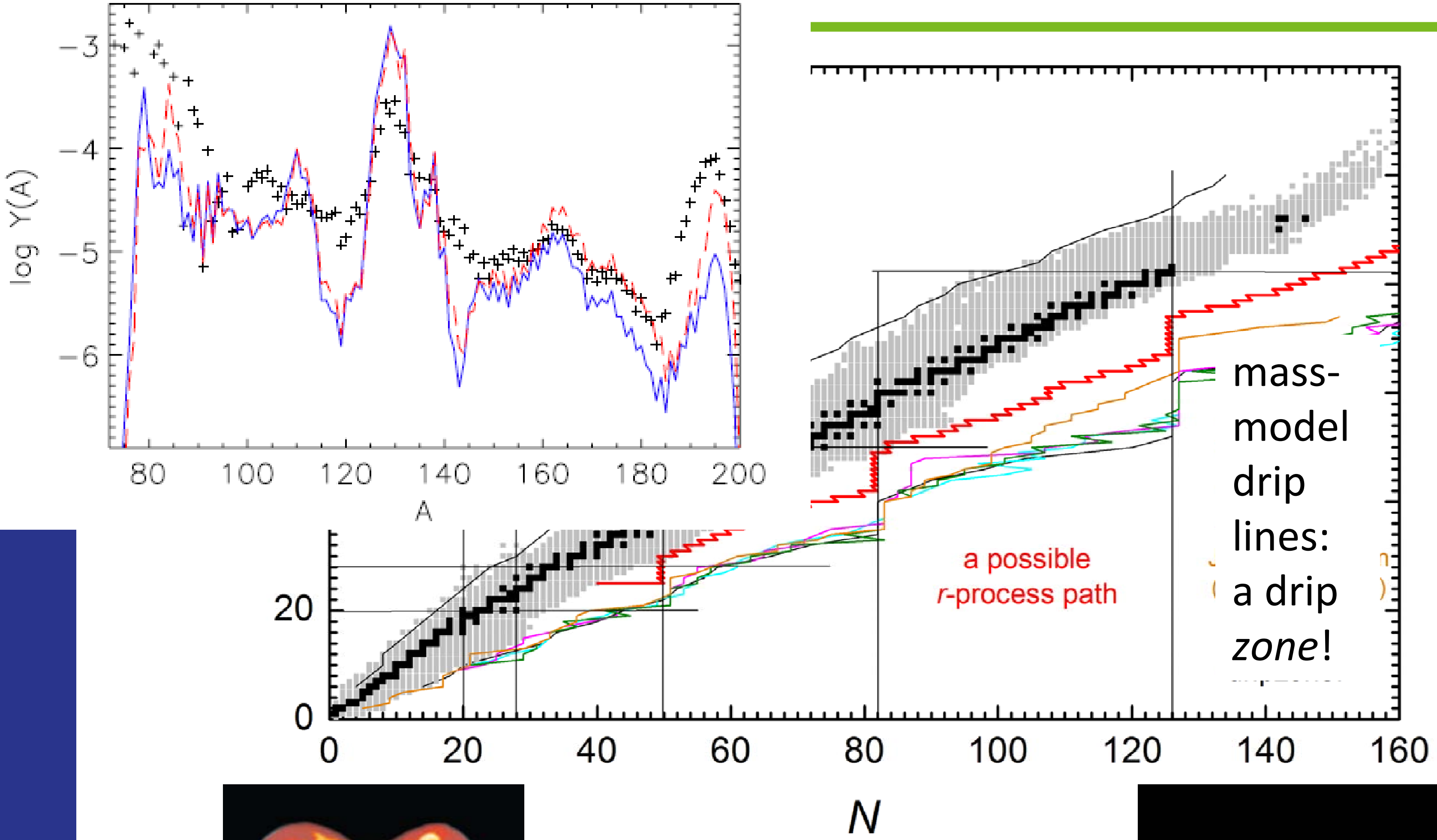
ISOLDE


REX
CONTROL ROOM
V
H
DECAY SPEC
8000,000
MINIBALL
ISOLTRAP
BOOSTER
PS
Hall SUD
LEAR
LINAC II

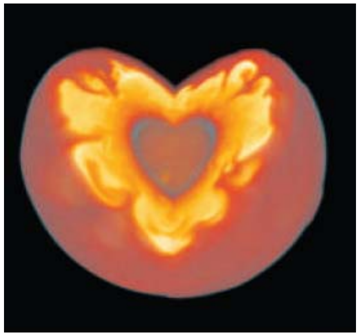
Photograph of ISOLDE hall



Where does the *r* process happen?!

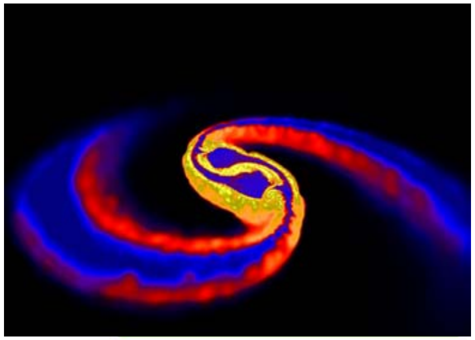


mass-model drip lines: a drip *zone*!

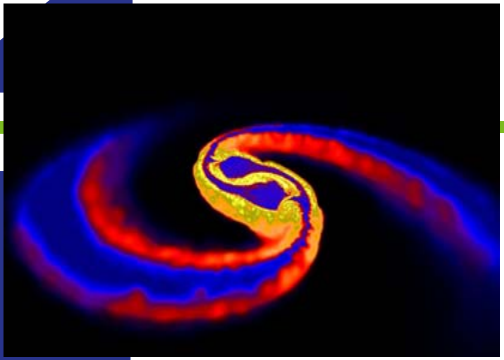


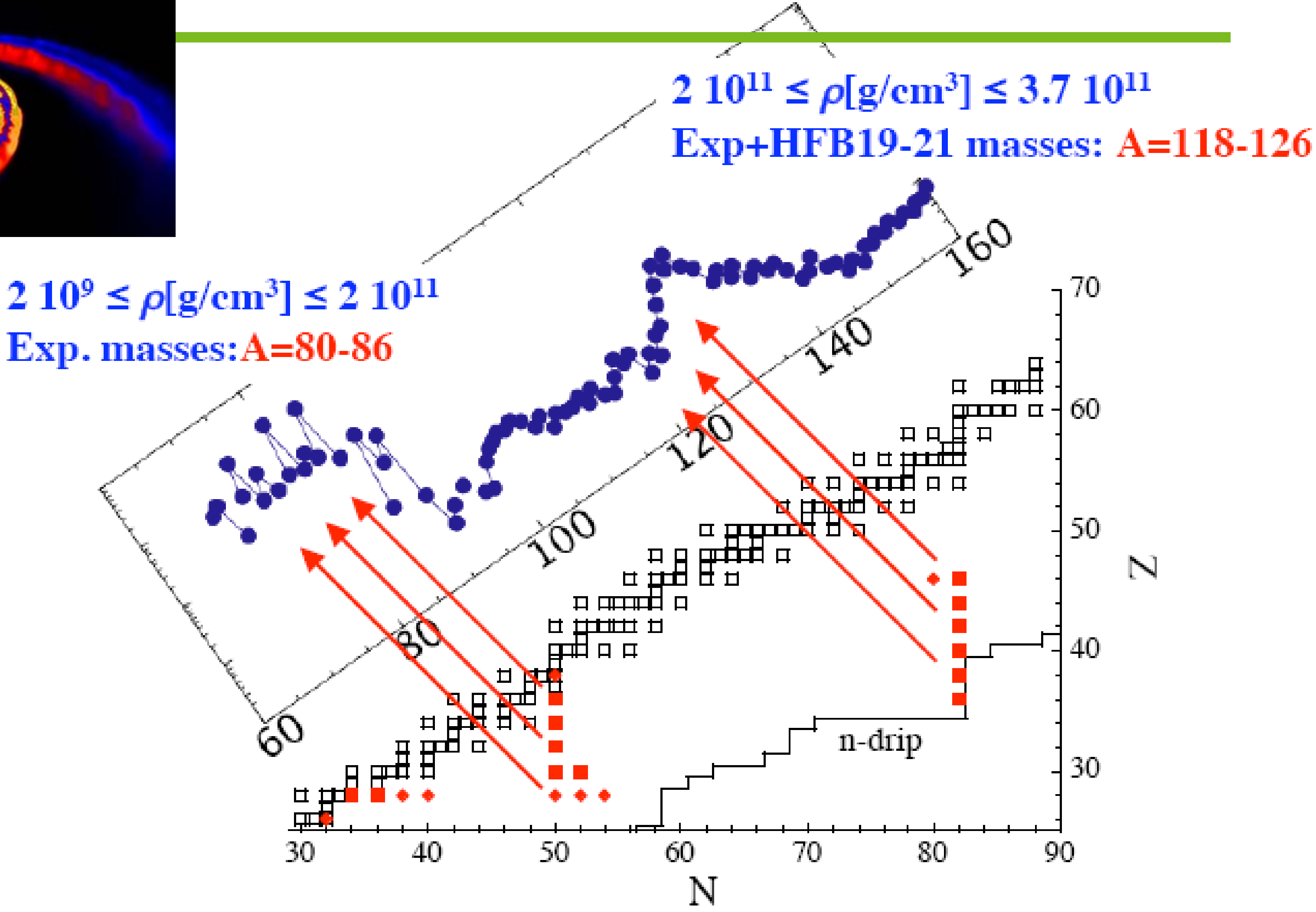
type-II (core-Collapse) supernova

neutron-star merger



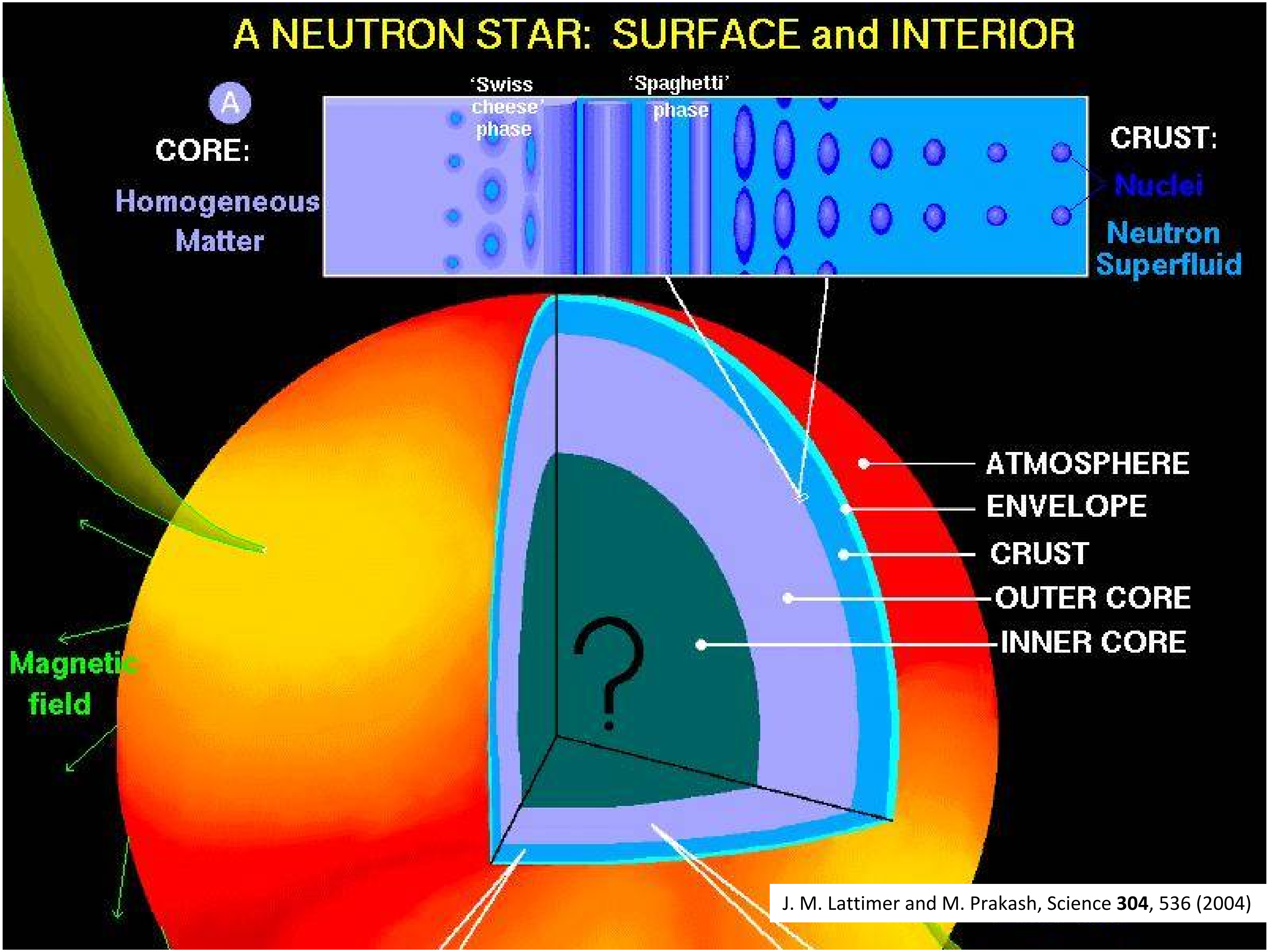
Composition of the cold outer crust



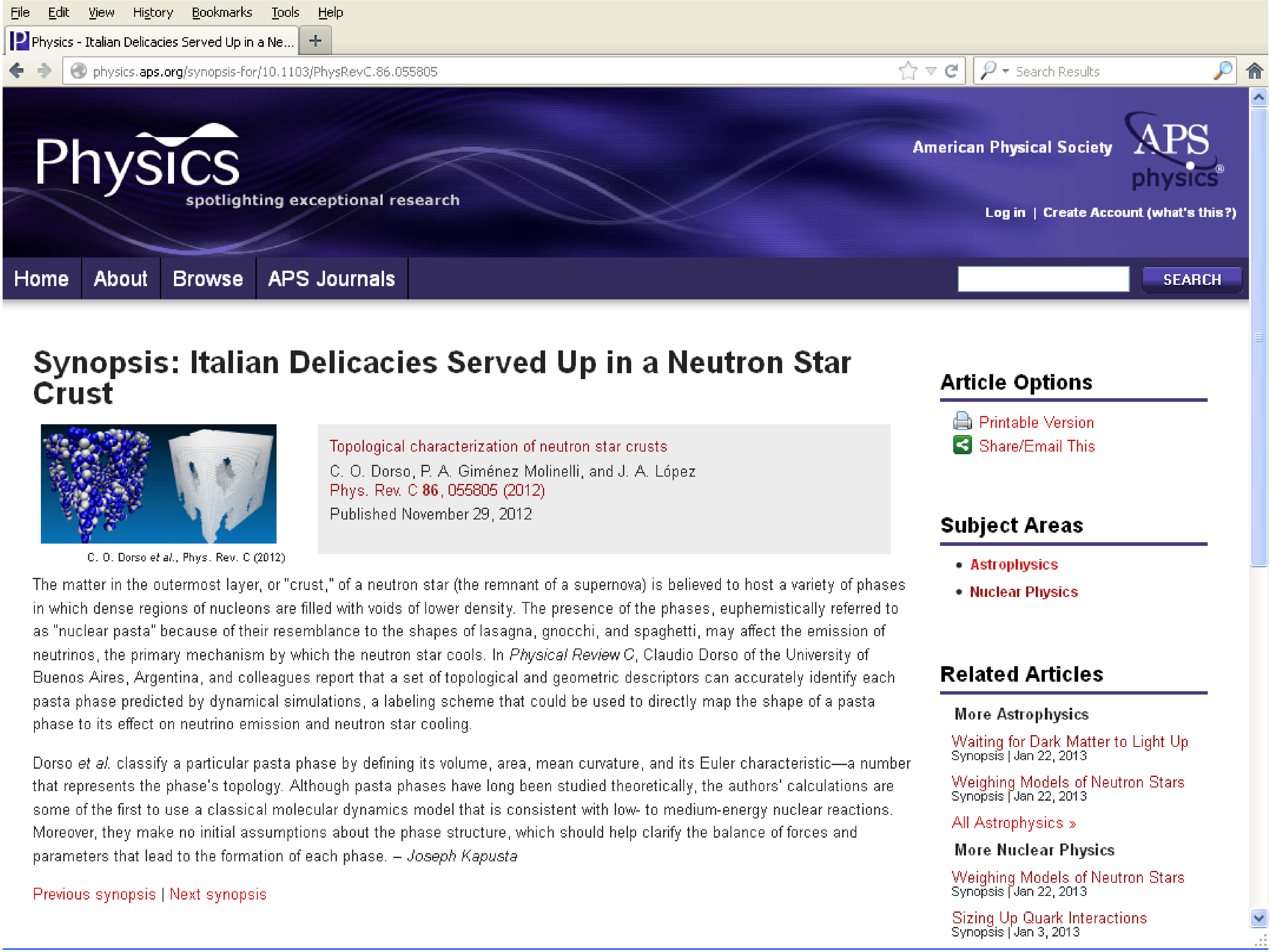


Ejection of the outer crust material: enrichment of nuclei up to A~130 !

S. Goriely, N. Chamel, H.-T. Janka, J.M. Pearson, A&A (2011)



J. M. Lattimer and M. Prakash, Science **304**, 536 (2004)



Synopsis: Italian Delicacies Served Up in a Neutron Star Crust

C. O. Dorso *et al.*, Phys. Rev. C (2012)

Topological characterization of neutron star crusts

C. O. Dorso, P. A. Giménez Molinelli, and J. A. López

Phys. Rev. C **86**, 055805 (2012)

Published November 29, 2012

The matter in the outermost layer, or "crust," of a neutron star (the remnant of a supernova) is believed to host a variety of phases in which dense regions of nucleons are filled with voids of lower density. The presence of the phases, euphemistically referred to as "nuclear pasta" because of their resemblance to the shapes of lasagna, gnocchi, and spaghetti, may affect the emission of neutrinos, the primary mechanism by which the neutron star cools. In *Physical Review C*, Claudio Dorso of the University of Buenos Aires, Argentina, and colleagues report that a set of topological and geometric descriptors can accurately identify each pasta phase predicted by dynamical simulations, a labeling scheme that could be used to directly map the shape of a pasta phase to its effect on neutrino emission and neutron star cooling.

Dorso *et al.* classify a particular pasta phase by defining its volume, area, mean curvature, and its Euler characteristic—a number that represents the phase's topology. Although pasta phases have long been studied theoretically, the authors' calculations are some of the first to use a classical molecular dynamics model that is consistent with low- to medium-energy nuclear reactions. Moreover, they make no initial assumptions about the phase structure, which should help clarify the balance of forces and parameters that lead to the formation of each phase. – *Joseph Kapusta*

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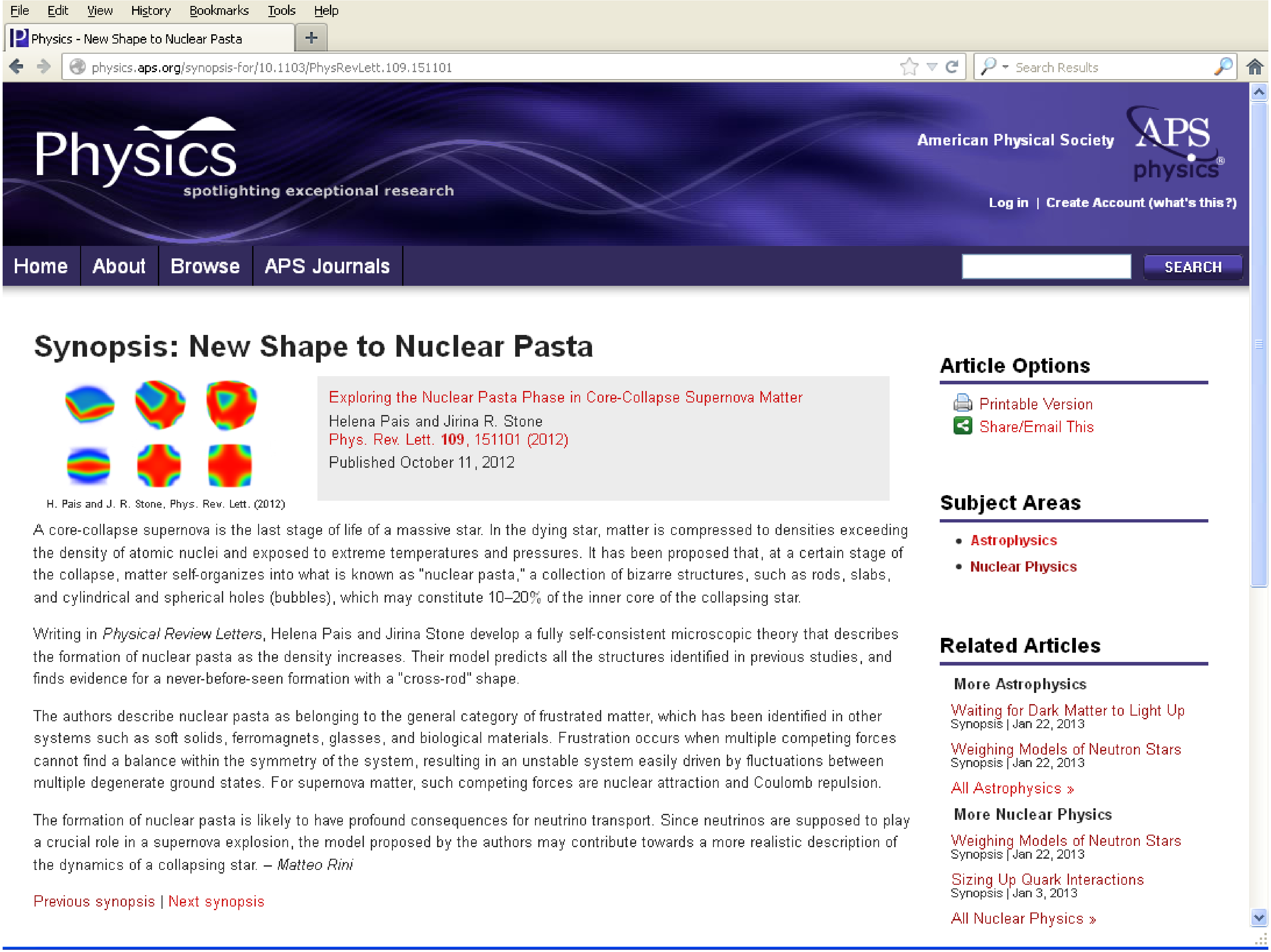
Synopsis | Jan 22, 2013

Sizing Up Quark Interactions
Synopsis | Jan 3, 2013



Synopsis: New Shape to Nuclear Pasta

H. Pais and J. R. Stone, Phys. Rev. Lett. (2012)

Exploring the Nuclear Pasta Phase in Core-Collapse Supernova Matter
Helena Pais and Jirina R. Stone
Phys. Rev. Lett. **109**, 151101 (2012)
Published October 11, 2012

A core-collapse supernova is the last stage of life of a massive star. In the dying star, matter is compressed to densities exceeding the density of atomic nuclei and exposed to extreme temperatures and pressures. It has been proposed that, at a certain stage of the collapse, matter self-organizes into what is known as "nuclear pasta," a collection of bizarre structures, such as rods, slabs, and cylindrical and spherical holes (bubbles), which may constitute 10–20% of the inner core of the collapsing star.

Writing in *Physical Review Letters*, Helena Pais and Jirina Stone develop a fully self-consistent microscopic theory that describes the formation of nuclear pasta as the density increases. Their model predicts all the structures identified in previous studies, and finds evidence for a never-before-seen formation with a "cross-rod" shape.

The authors describe nuclear pasta as belonging to the general category of frustrated matter, which has been identified in other systems such as soft solids, ferromagnets, glasses, and biological materials. Frustration occurs when multiple competing forces cannot find a balance within the symmetry of the system, resulting in an unstable system easily driven by fluctuations between multiple degenerate ground states. For supernova matter, such competing forces are nuclear attraction and Coulomb repulsion.

The formation of nuclear pasta is likely to have profound consequences for neutrino transport. Since neutrinos are supposed to play a crucial role in a supernova explosion, the model proposed by the authors may contribute towards a more realistic description of the dynamics of a collapsing star. – *Matteo Rini*

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Sizing Up Quark Interactions
Synopsis | Jan 3, 2013

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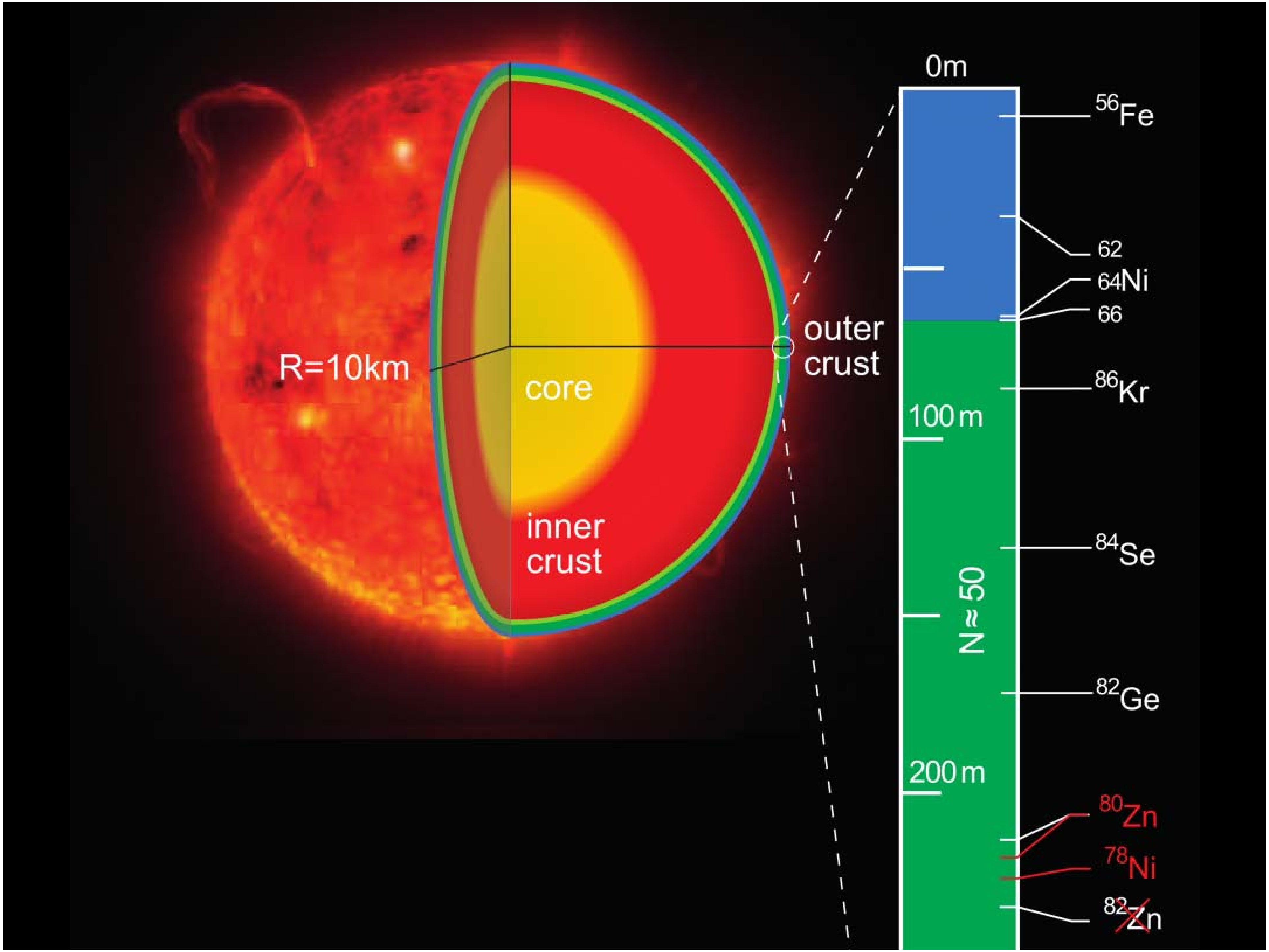
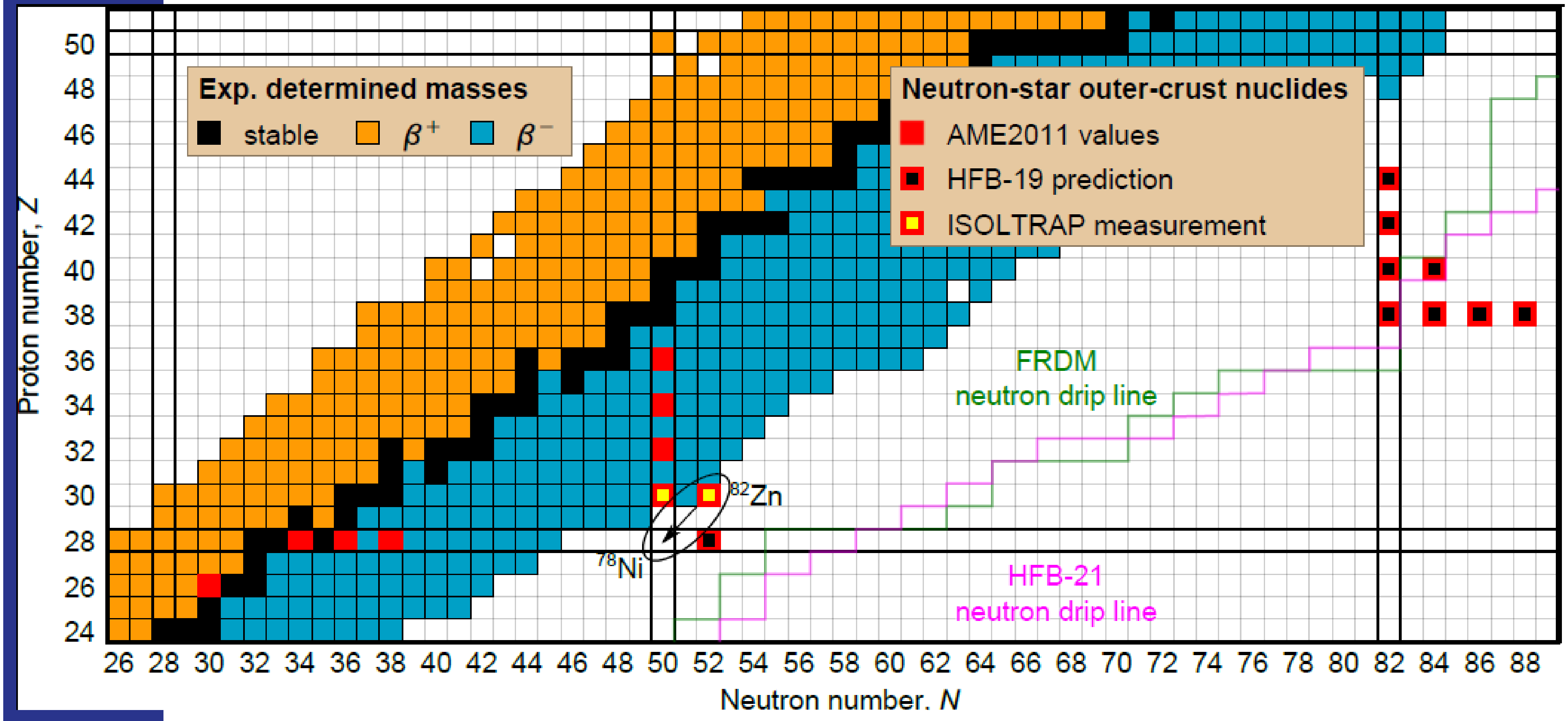

R=10km
core
inner
crust
outer
crust
0m
100 m
200 m
N ≈ 50
^{56}Fe
62
^{64}Ni
66
^{86}Kr
^{84}Se
^{82}Ge
^{80}Zn
^{78}Ni
^{82}Zn

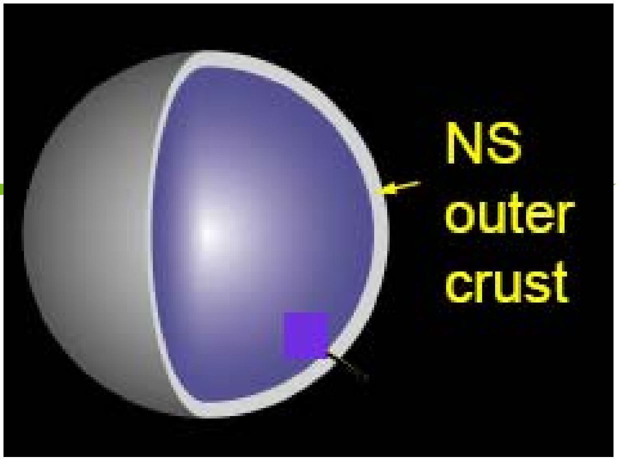
Composition of the Neutron-Star Crust

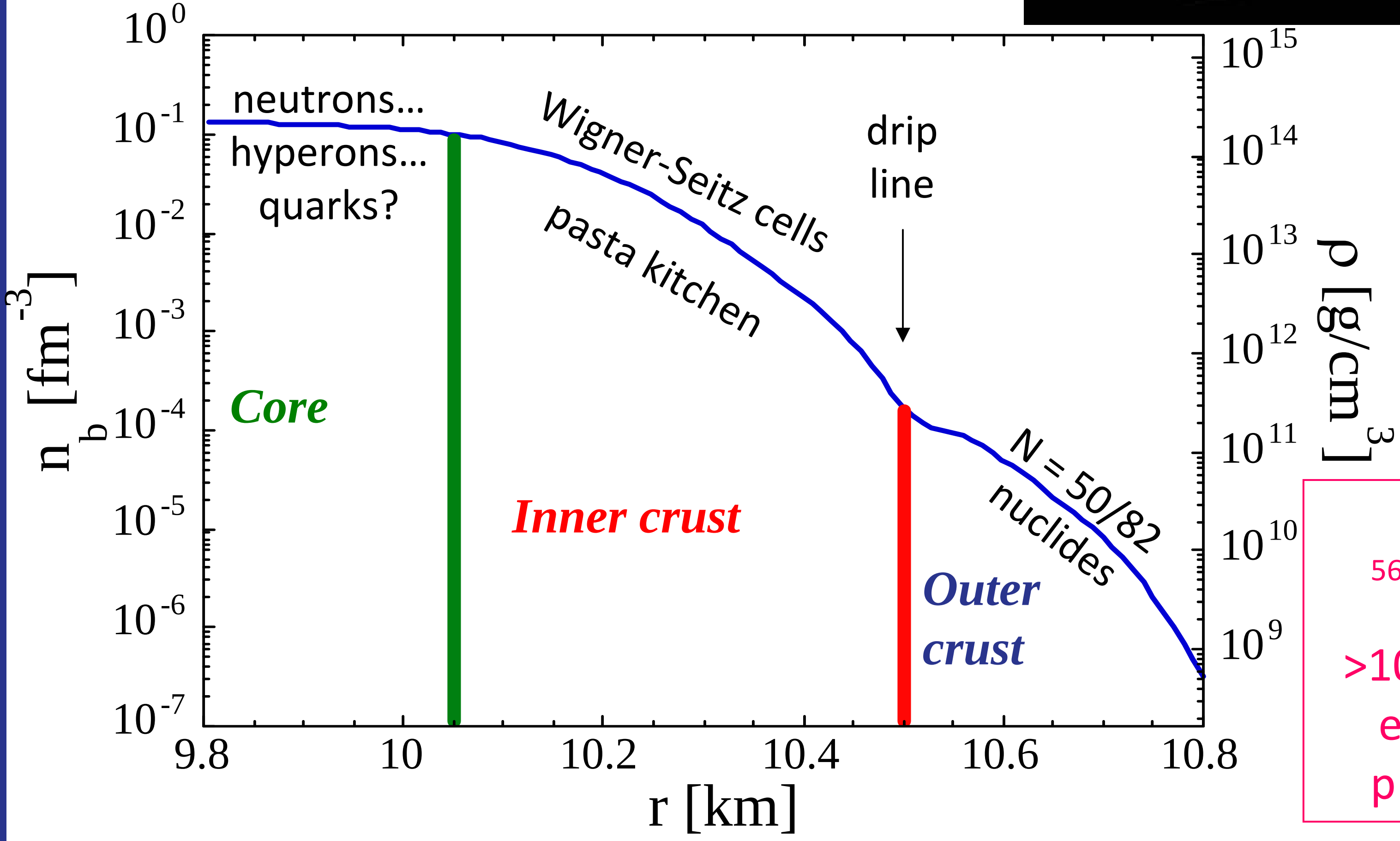


(figure) R.N. Wolf et al. Phys. Rev. Lett. (2013)

J.M. Pearson, S. Goriely and N. Chamel, PRC 83 (2011)

Neutron-Star density profile





Surface:
^{56}Fe; ^{62}Ni;

$>10^6$ g/cm^3
e degen.:
p + e → n

J.M. Pearson, S. Goriely and N. Chamel, PRC 83 (2011)

Calculating the NS-crust composition

Within the WS cell approximation, the composition in complete thermodynamic equilibrium can be determined by minimizing the Gibbs energy of the WS cell at a given pressure (Baym et al. 1971; Hilf et al. 1974; Haensel et al. 1994, Ruster et al. 2006)

$$\boxed{G_{cell}(Z,A)=W_N(Z,A)+W_L(Z,n_N)+[\varepsilon_e(Z,n_e)+P]/n_N}$$

- *$W_N(Z,A)$: total energy of the nucleus (including rest mass of nucleons)*
- $W_L(Z,n_N)$: Body-centered cubic lattice energy per cell
- $\varepsilon_e(Z,n_e)$: mean electron energy density
- $P=P_e(Z,n_e)+P_L(Z,n_N)$: Total pressure
- n_N: number density of nuclei;

J.M. Pearson, S. Goriely and N. Chamel, PRC 83 (2011)

Gibbs free energy & nuclear binding energy

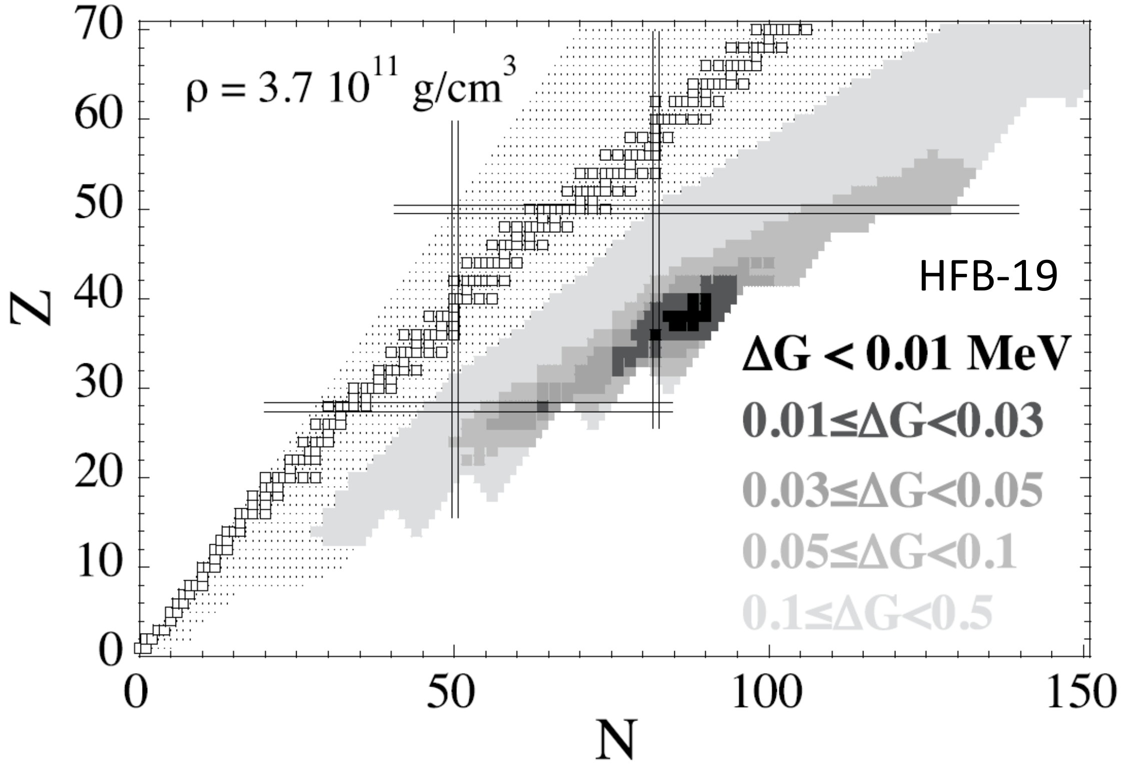
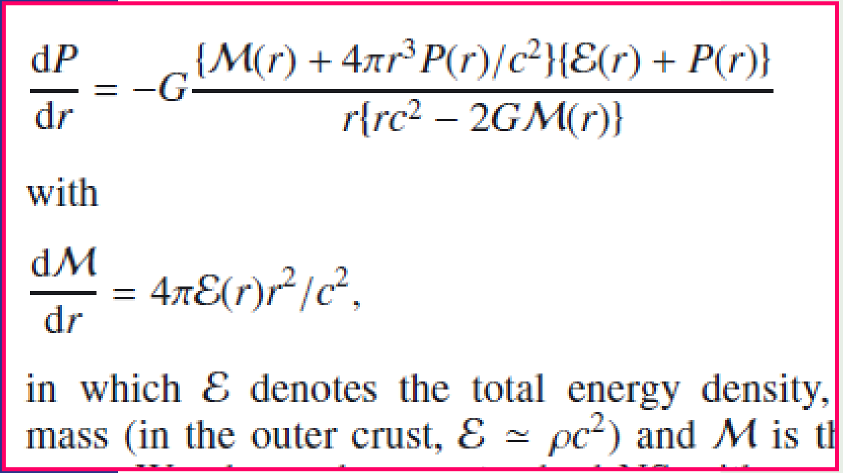


Fig. 3. Distribution of the Gibbs free energy per nucleon at $T = 0$ and $\rho = 3.7 \times 10^{11}$ g/cm^3. ΔG corresponds to the difference of the free energy per nucleon with respect to the minimum value obtained at this

S. Goriely, N. Chamel, H.-T. Janka, J.M. Pearson, A&A 531, A78 (2011)

Plumbing…

- Depth profile of a neutron star using experimental masses, models & equation of state
- Solve (relativistic) Tolman-Oppenheimer-Volkov equations:



$$\frac{dP}{dr} = -G\frac{\{\mathcal{M}(r) + 4\pi r^3 P(r)/c^2\}\{\mathcal{E}(r) + P(r)\}}{r\{rc^2 - 2G\mathcal{M}(r)\}}$$

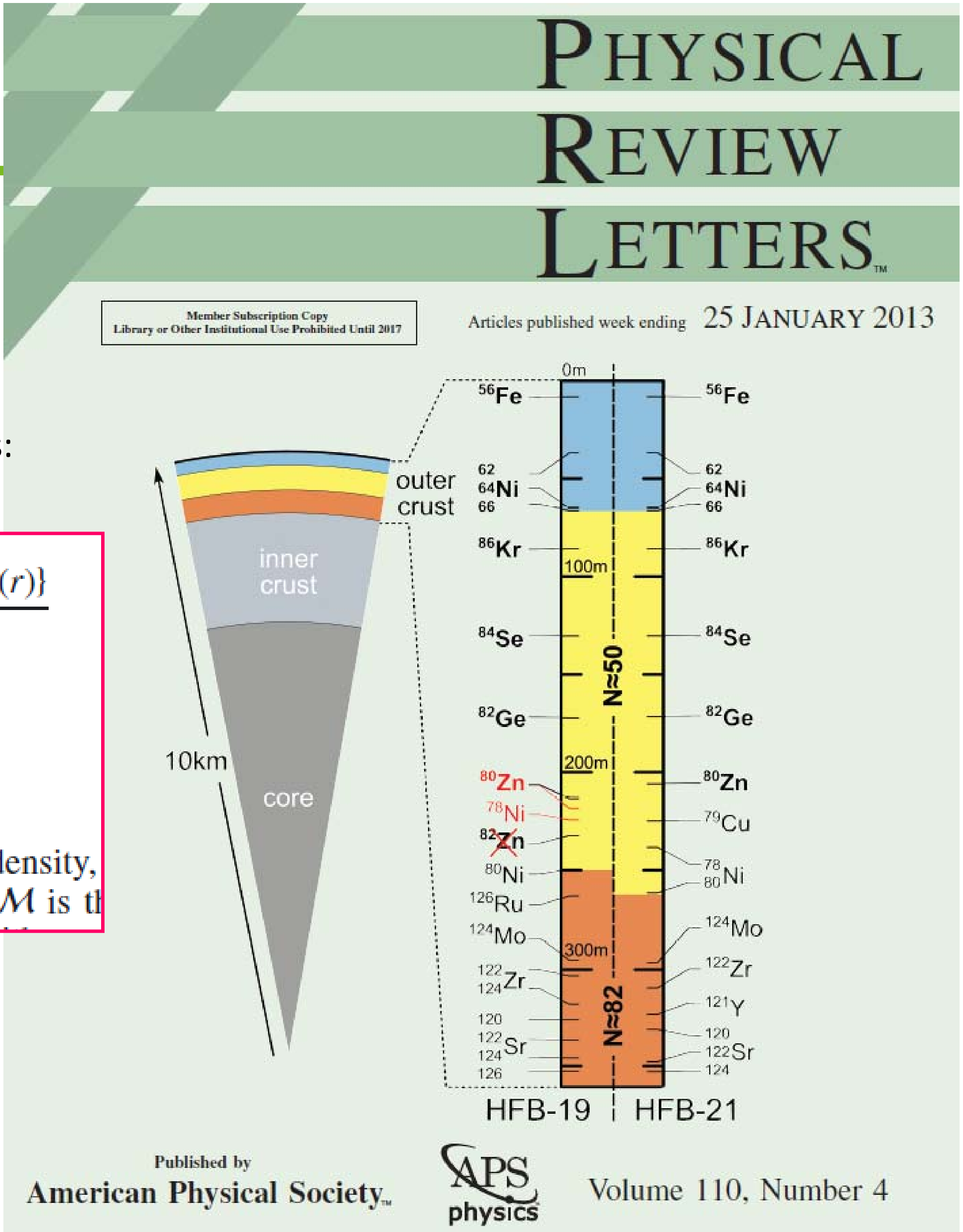
with

$$\frac{d\mathcal{M}}{dr} = 4\pi\mathcal{E}(r)r^2/c^2,$$

in which $\mathcal{E}$ denotes the total energy density, mass (in the outer crust, $\mathcal{E} \simeq \rho c^2$) and $\mathcal{M}$ is t

J.M. Pearson, S. Goriely, and N. Chamel, PRC 83 (2011)

R.N. Wolf et al. Phys. Rev. Lett. (2013)



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Published by
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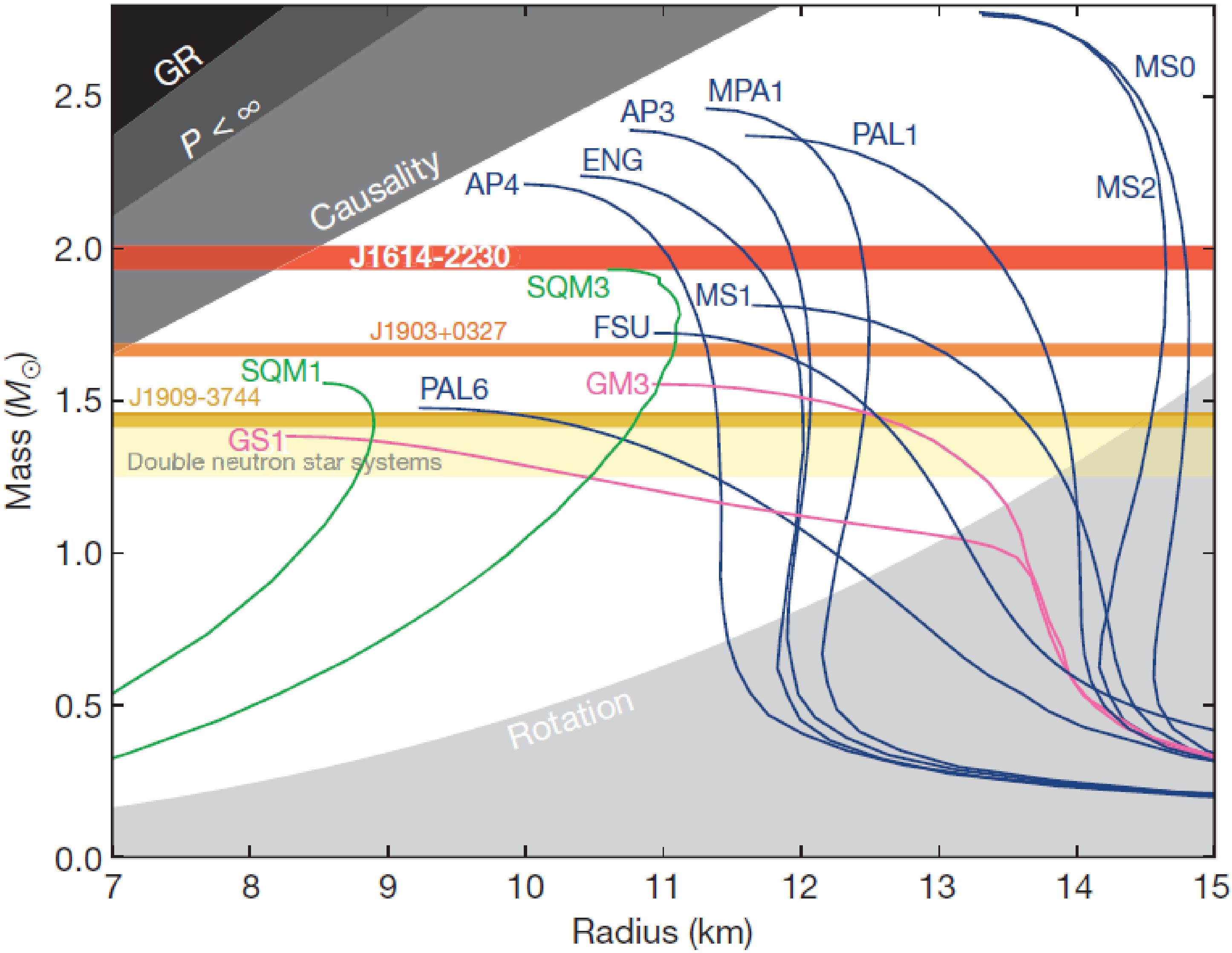
APS physics

Volume 110, Number 4

Mass measurements… of neutron stars!

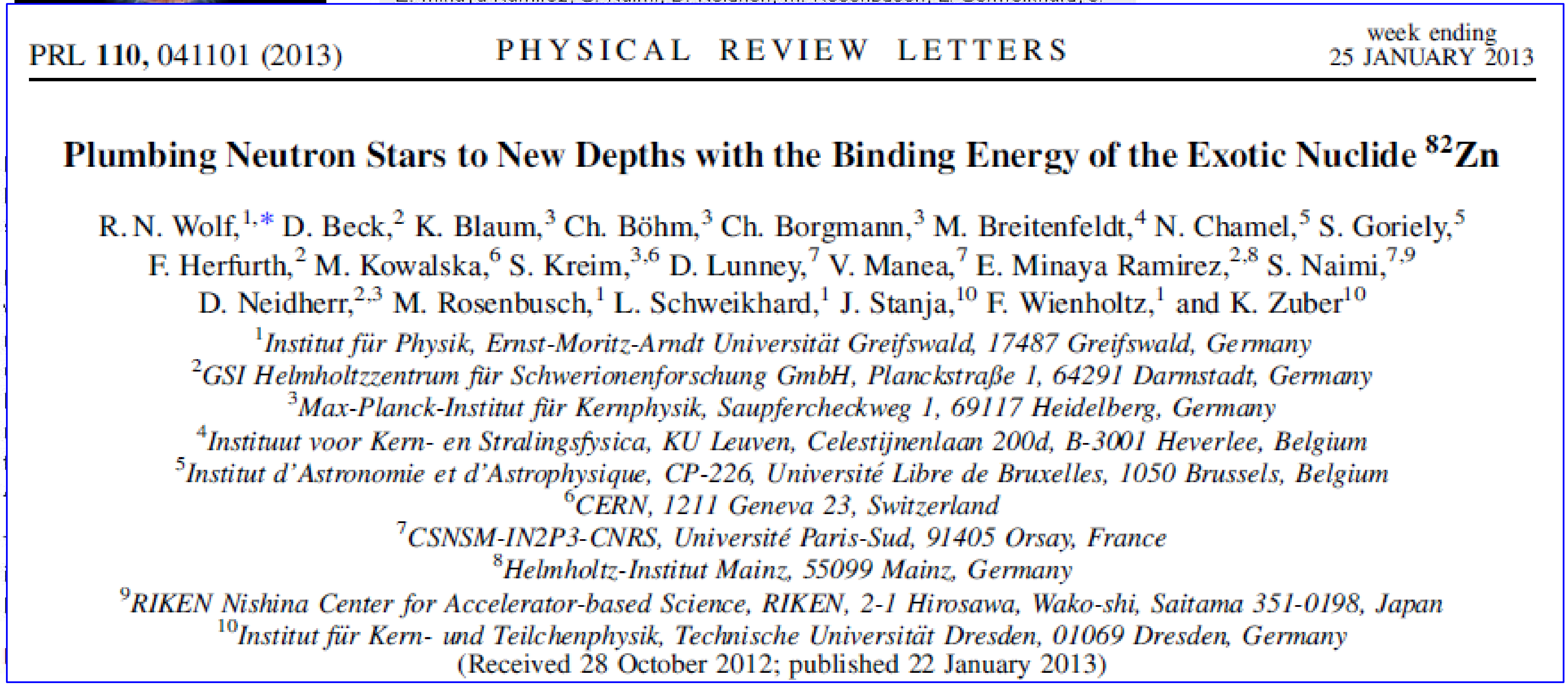


P.B. Demorest et al. Nature (2010)

Synopsis: Weighing Models of Neutron Stars

Plumbing Neutron Stars to New Depths with the Binding Energy of the Exotic Nuclide ^{82}Zn

R. N. Wolf, D. Beck, K. Blaum, Ch. Böhm, Ch. Borgmann, M. Breitenfeldt, N. Chamel, S. Goriely, F. Herfurth, M. Kowalska, S. Kreim, D. Lunney, V. Manea, E. Minaya Ramirez, S. Naimi, D. Neidherr, M. Rosenbusch, L. Schweikhard, J.


PRL 110, 041101 (2013) PHYSICAL REVIEW LETTERS week ending 25 JANUARY 2013

Plumbing Neutron Stars to New Depths with the Binding Energy of the Exotic Nuclide ^{82}Zn

R. N. Wolf,[1,*] D. Beck,[2] K. Blaum,[3] Ch. Böhm,[3] Ch. Borgmann,[3] M. Breitenfeldt,[4] N. Chamel,[5] S. Goriely,[5] F. Herfurth,[2] M. Kowalska,[6] S. Kreim,[3,6] D. Lunney,[7] V. Manea,[7] E. Minaya Ramirez,[2,8] S. Naimi,[7,9] D. Neidherr,[2,3] M. Rosenbusch,[1] L. Schweikhard,[1] J. Stanja,[10] F. Wienholtz,[1] and K. Zuber[10]

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[3]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
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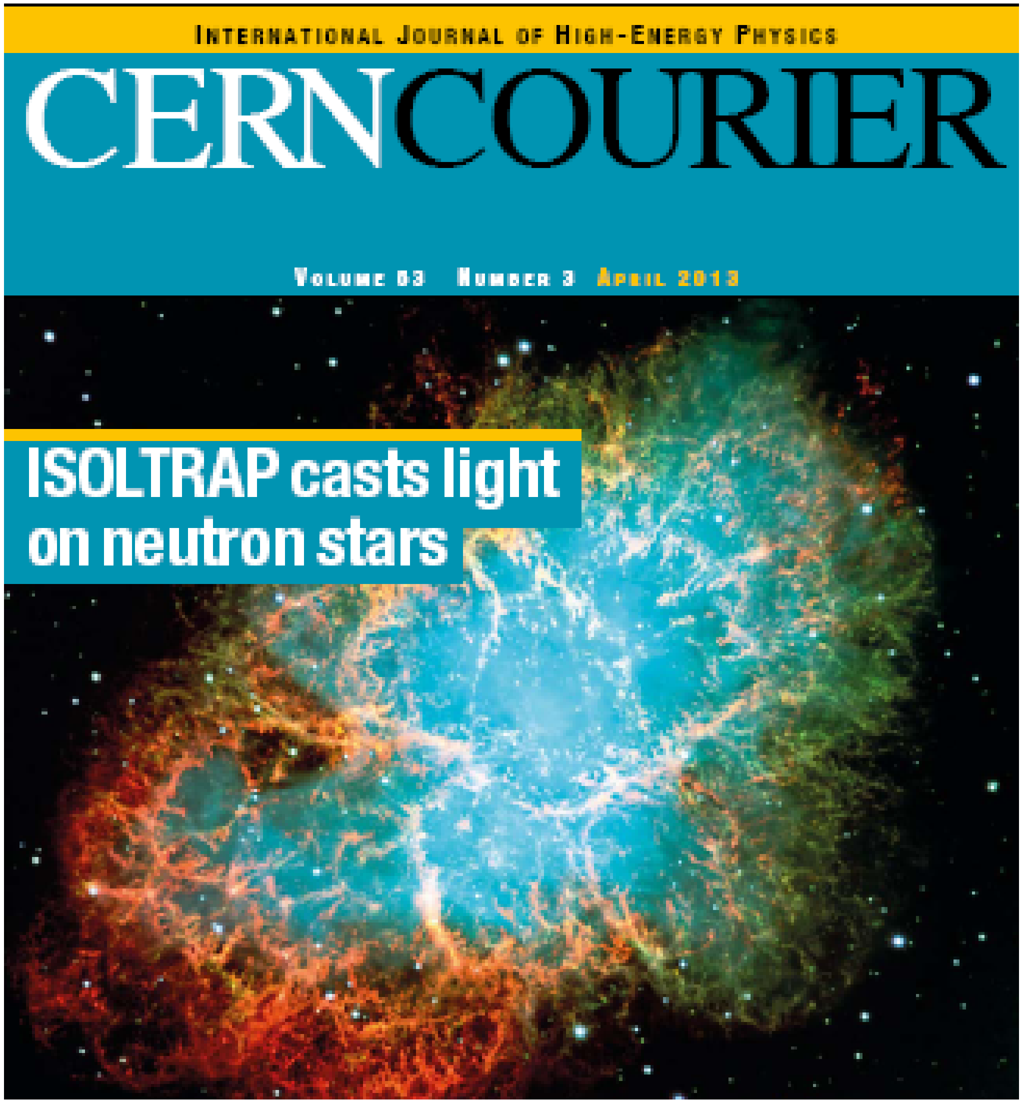
[5]*Institut d'Astronomie et d'Astrophysique, CP-226, Université Libre de Bruxelles, 1050 Brussels, Belgium*
[6]*CERN, 1211 Geneva 23, Switzerland*
[7]*CSNSM-IN2P3-CNRS, Université Paris-Sud, 91405 Orsay, France*
[8]*Helmholtz-Institut Mainz, 55099 Mainz, Germany*
[9]*RIKEN Nishina Center for Accelerator-based Science, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan*
[10]*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, 01069 Dresden, Germany*

(Received 28 October 2012; published 22 January 2013)

From cover to cover…



International Journal of High-Energy Physics

CERNCOURIER

Volume 53 Number 3 April 2013

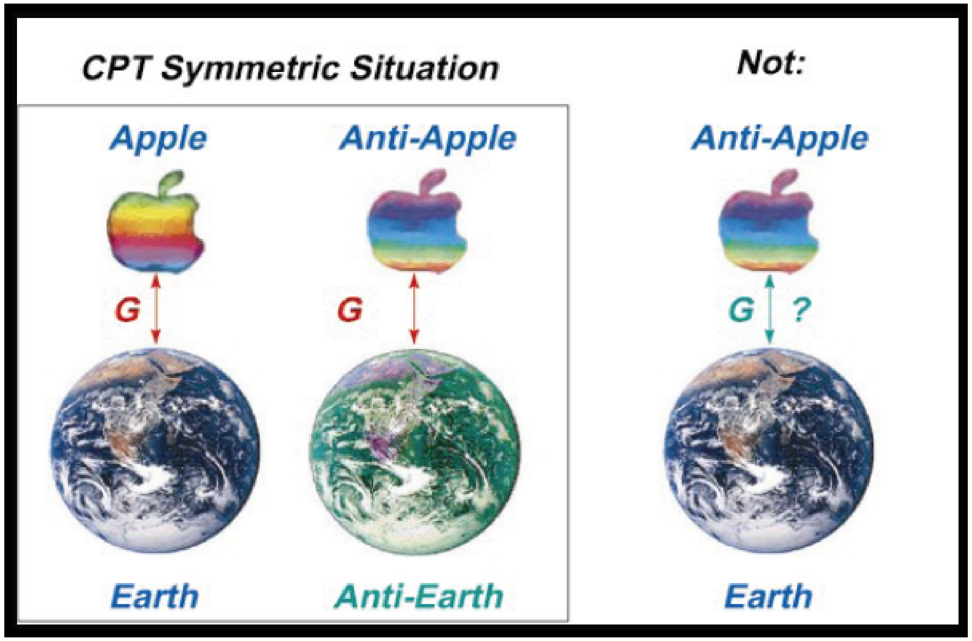
ISOLTRAP casts light on neutron stars

Ion traps: drilling neutron stars & dropping antimatter

The GBAR Experiment (CERN AD-7)

Gravitational Behavior of Antimatter at Rest

Goal: measure $\overline{g}$ for (first) WEP test using antimatter



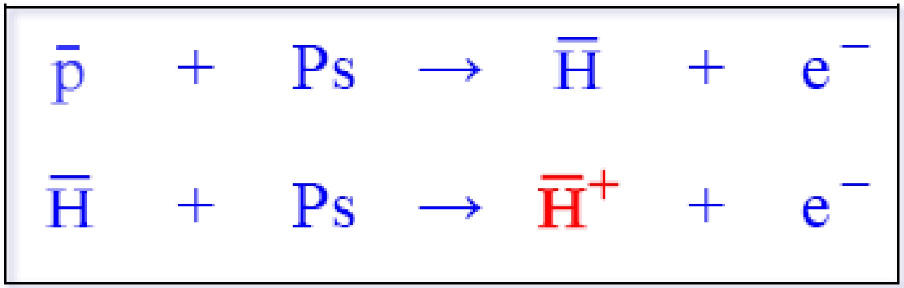
A. Knecht, LEAP (2013)

GBAR (AD-7; SPSC-P-342): P. Perez, spokesperson; SPP/IRFU-Saclay; Collaboration: CSNSM-Orsay; ETH-Zurich; RIKEN; U. Swansea; U. Mainz; LKB/ENS-UPMC; NCBJ-Otvosk; LPI-Moscow; Uppsala U.; Tokyo U.; U. Tokyo; ILL-Grenoble; IPCMS-Strasbourg

Antimatter and Gravity

Goal: measure $\overline{g}$ for (first) WEP test using antimatter

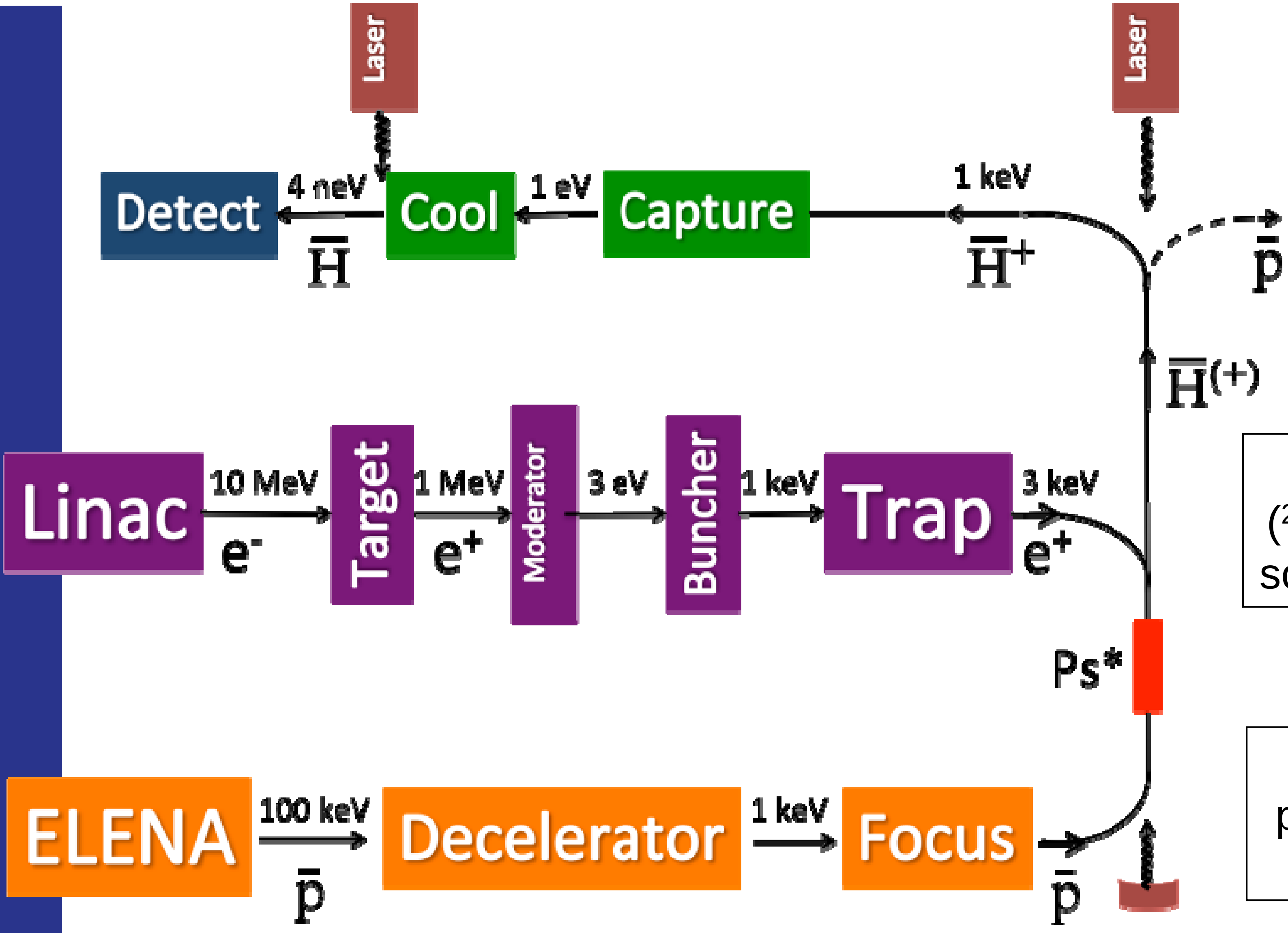
Method: “easier” manipulation of H^+ (Walz & Hänsch, 2004)



$$\bar{p} + Ps \rightarrow \overline{H} + e^-$$

$$\overline{H} + Ps \rightarrow \overline{H}^+ + e^-$$

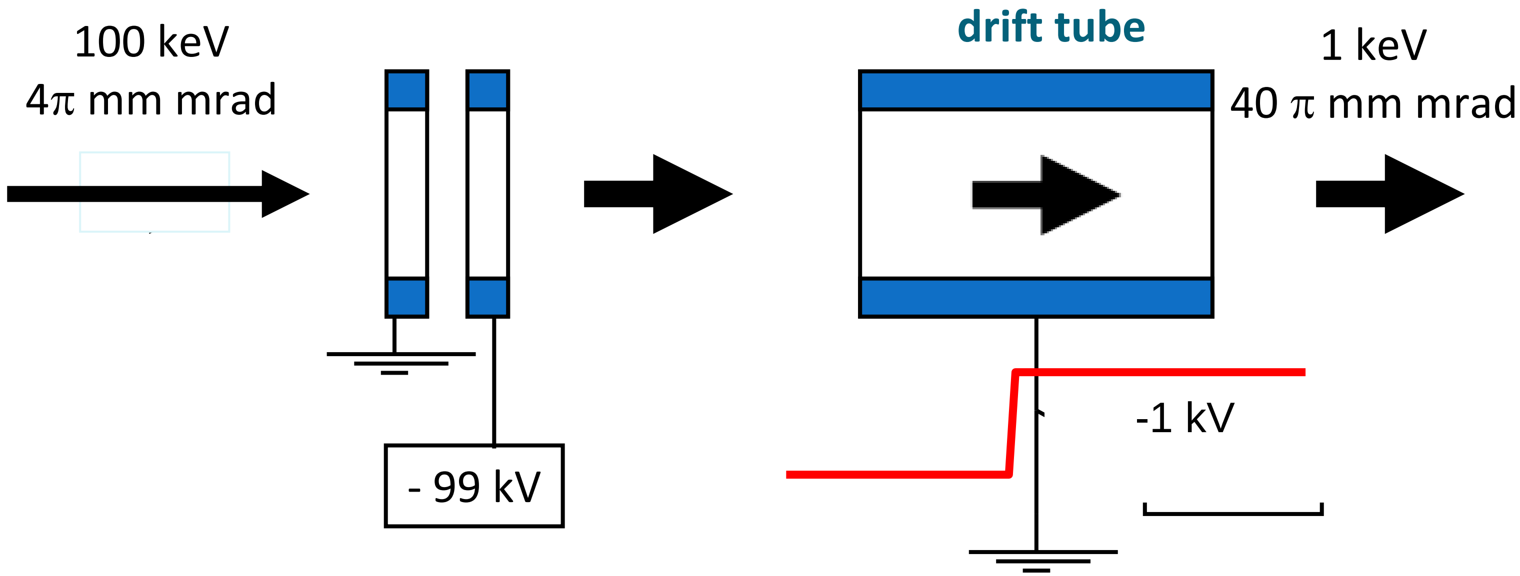
GBAR Schematic



no
(^{22}Na)
source

no
p-bar
trap

GBAR antiproton decelerator



100 keV
4π mm mrad

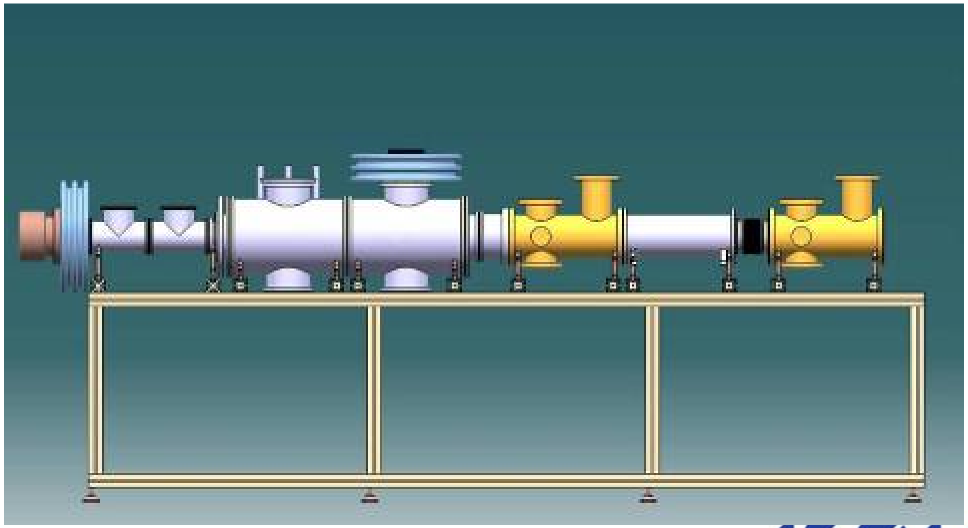
drift tube

1 keV
40 π mm mrad

- 99 kV

-1 kV

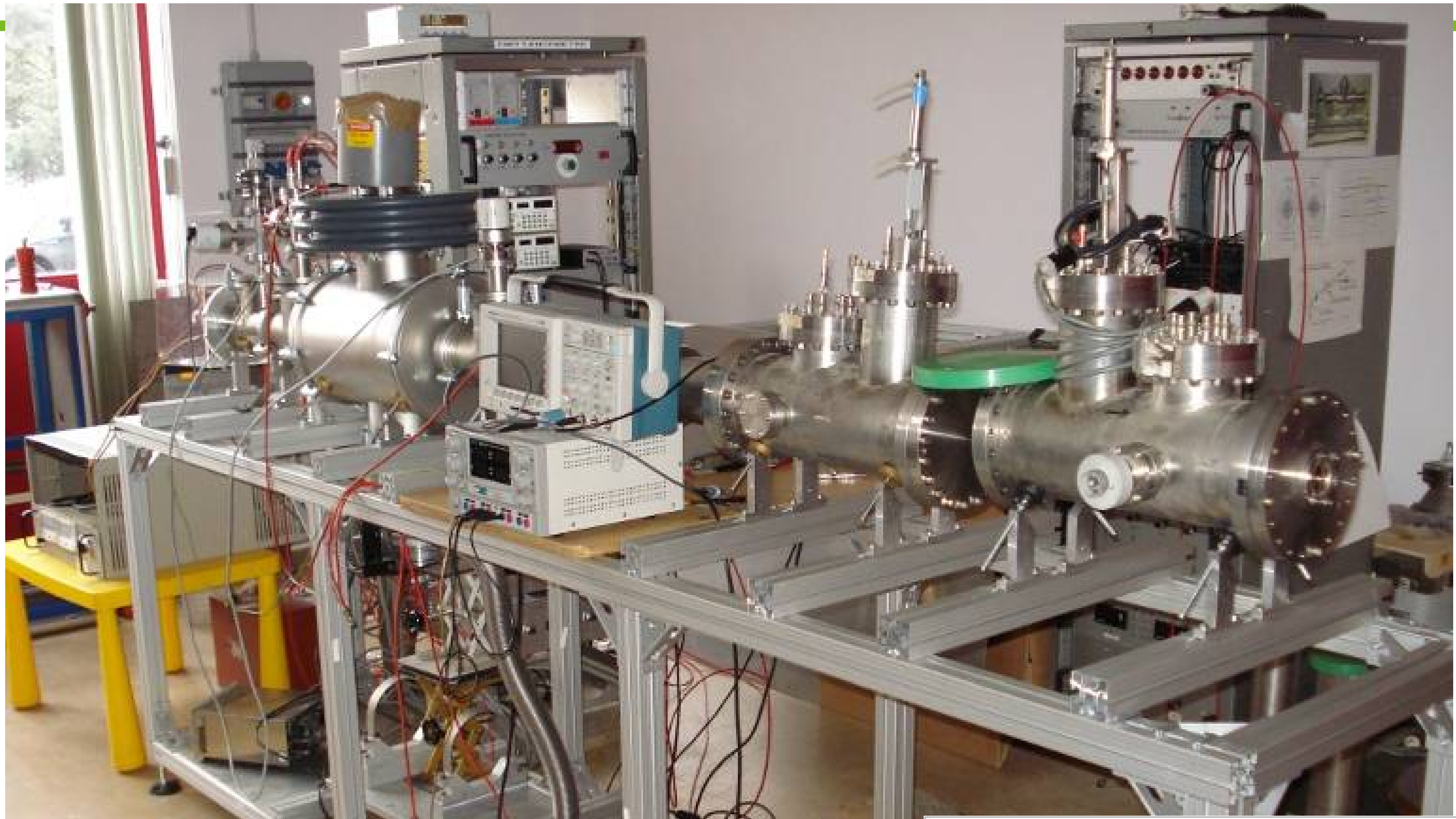
pulsed drift tube
(ion elevator)
used at ISOLDE
and with many
Trap setups

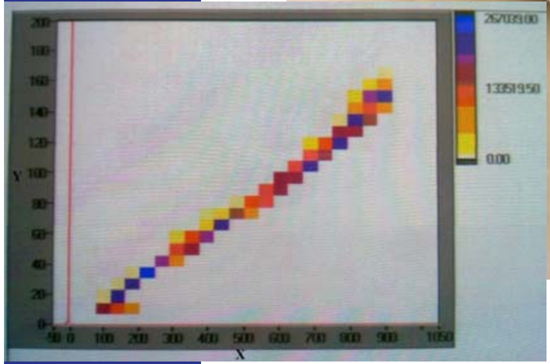


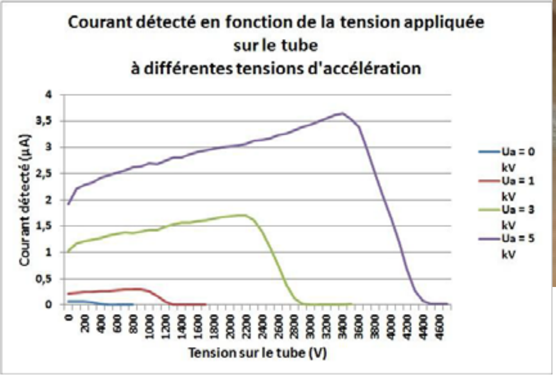
4 meters

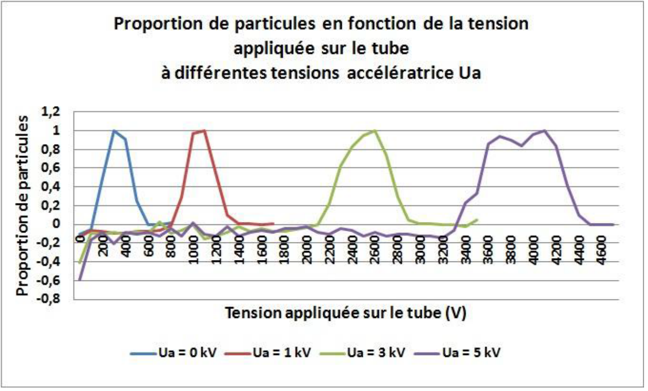
Decelerator test-bench in Orsay

5 keV
N^+ beams
1 uA CW
or 100 ns
pulses

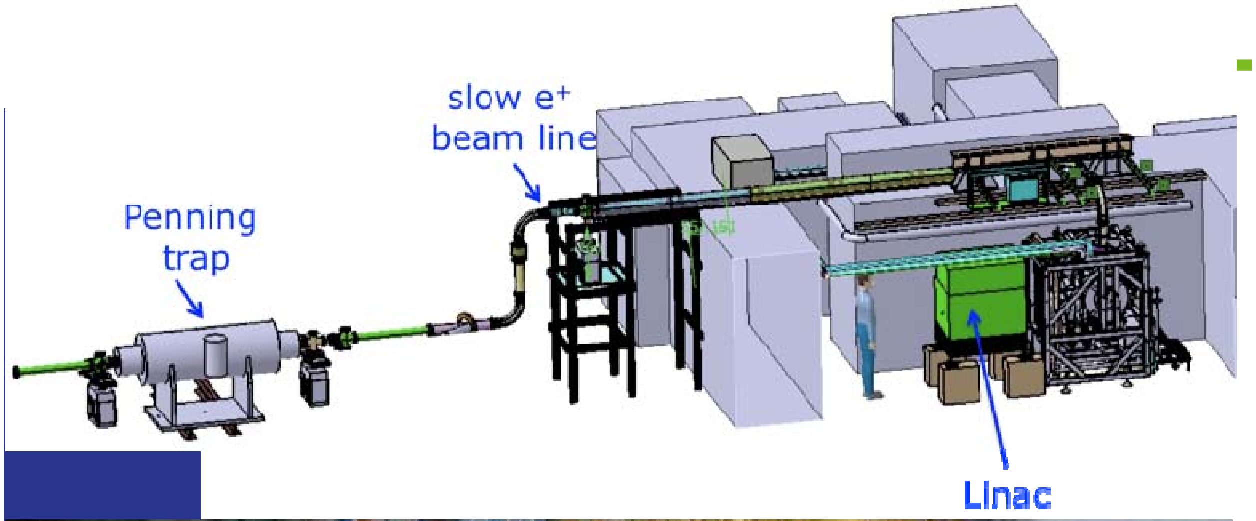






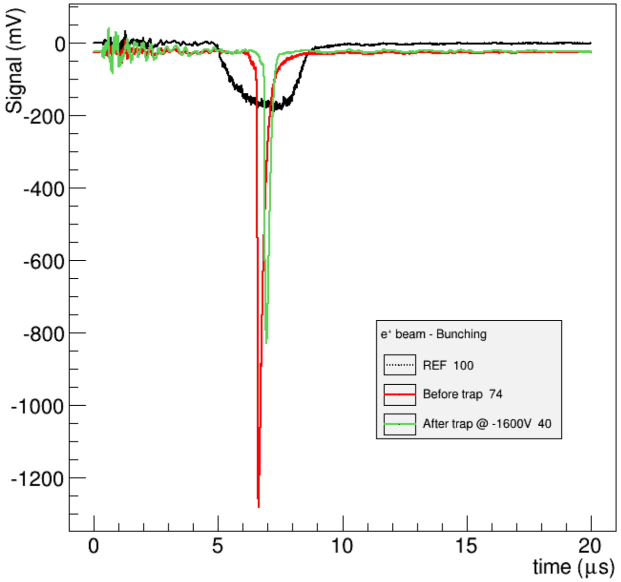


e⁺/Ps demonstrator in Saclay



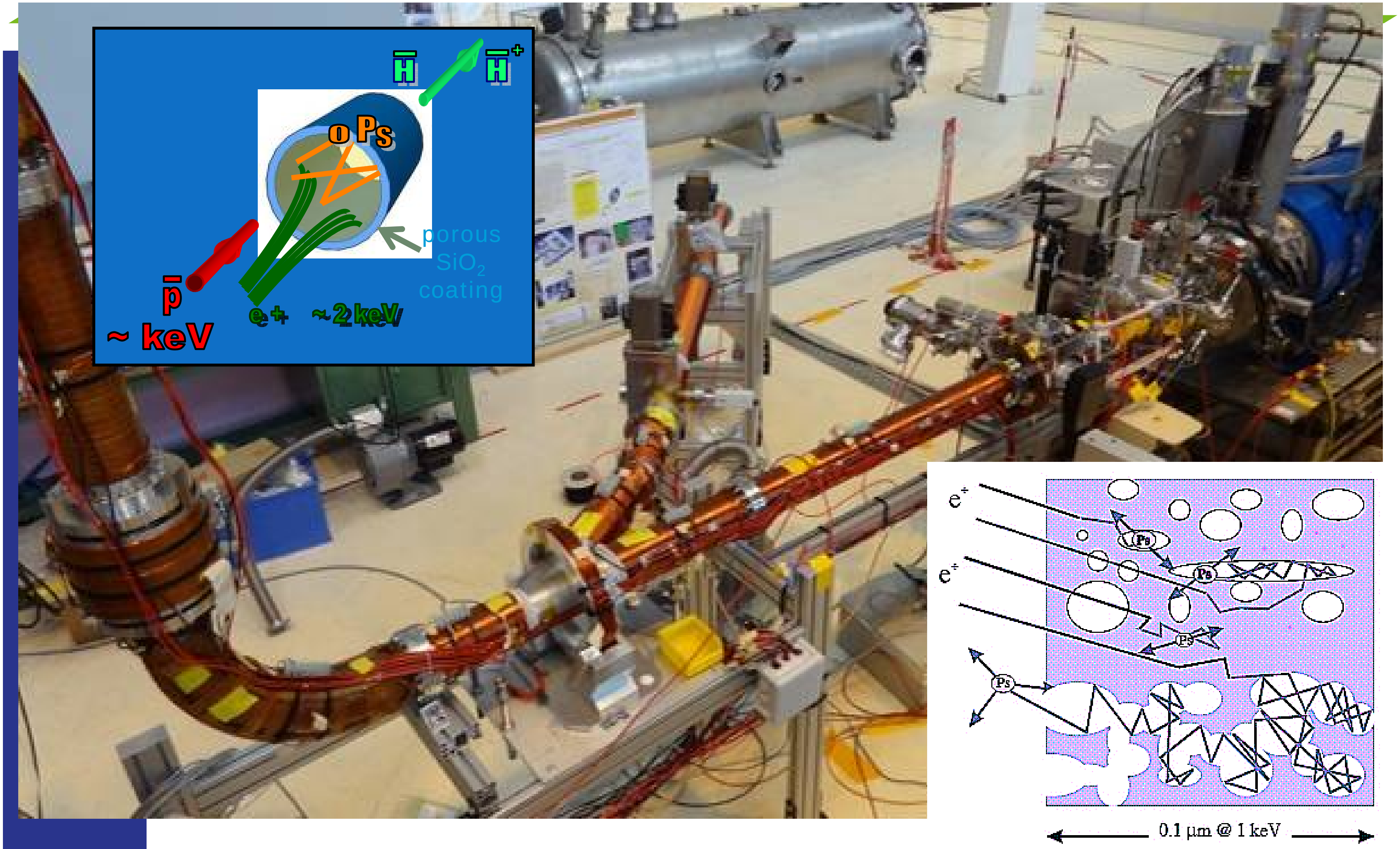
- 4.3 MeV /200 Hz/2.5 µs/120 µA
- 3 10^6 slow e⁺/s
- with first W mesh moderator
- Penning trap on beam line
  (from RIKEN)

P. Grandemange, CSNSM
U. Paris-Sud, Ph.D. (2013)



P. Dupré, *A new scheme to accumulate positrons in a Penning-Malmberg trap with a Linac-based pulsed source*, 10th International Workshop on Non-Neutral Plasmas, 27-30 August 2012, Greifswald (Germany); AIP Conf. Proc. (2013) in print.

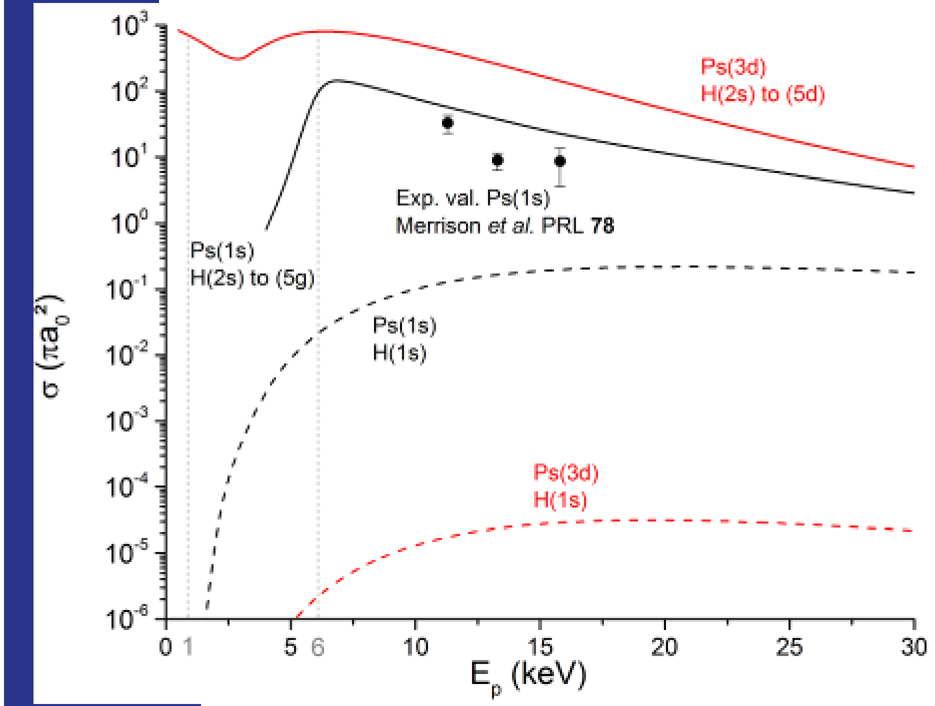
new e+ line for Ps and materials research



L. Liszkay et al. (2012)

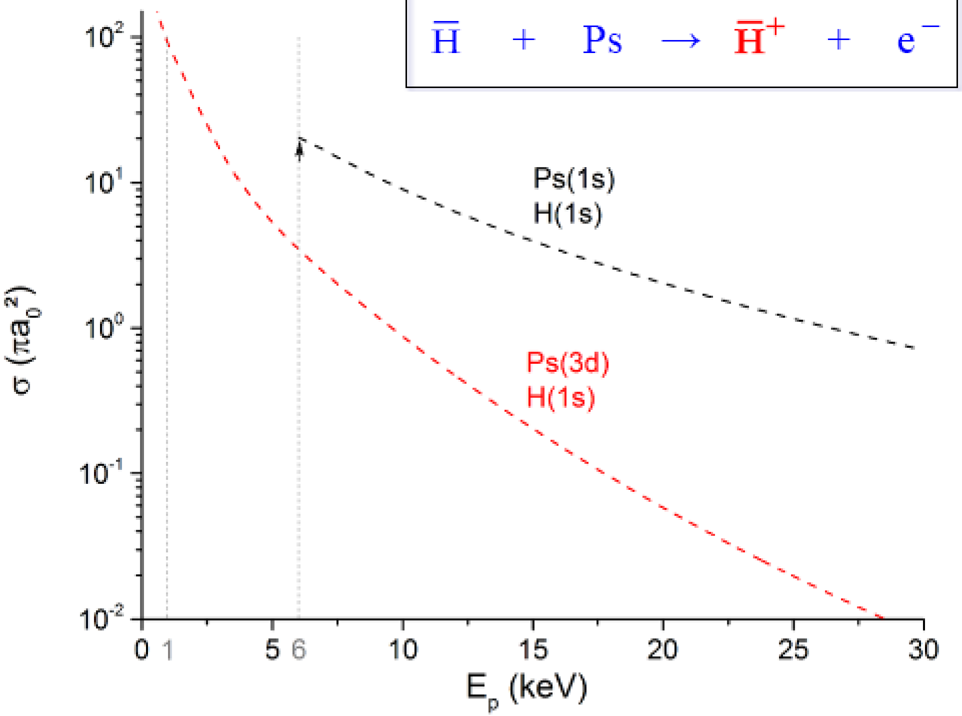
Calculation of $\overline{\mathrm{H}}^{+}$ production

Reaction 1



Reaction 2

$$\bar{p} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}} + e^{-}$$
$$\overline{\mathrm{H}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}}^{+} + e^{-}$$



Production of excited $\overline{\mathrm{H}}$ from $\bar{p}$

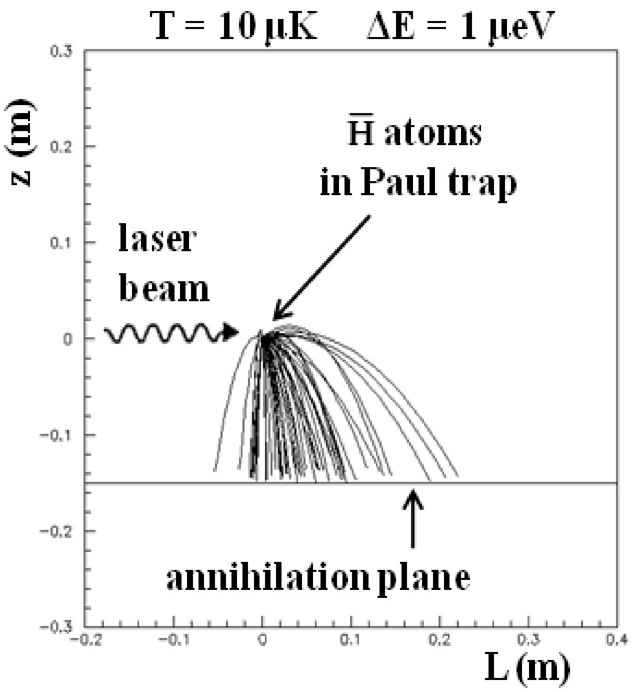
Production of $\overline{\mathrm{H}}^{+}$ from $\overline{\mathrm{H}}(1s)$

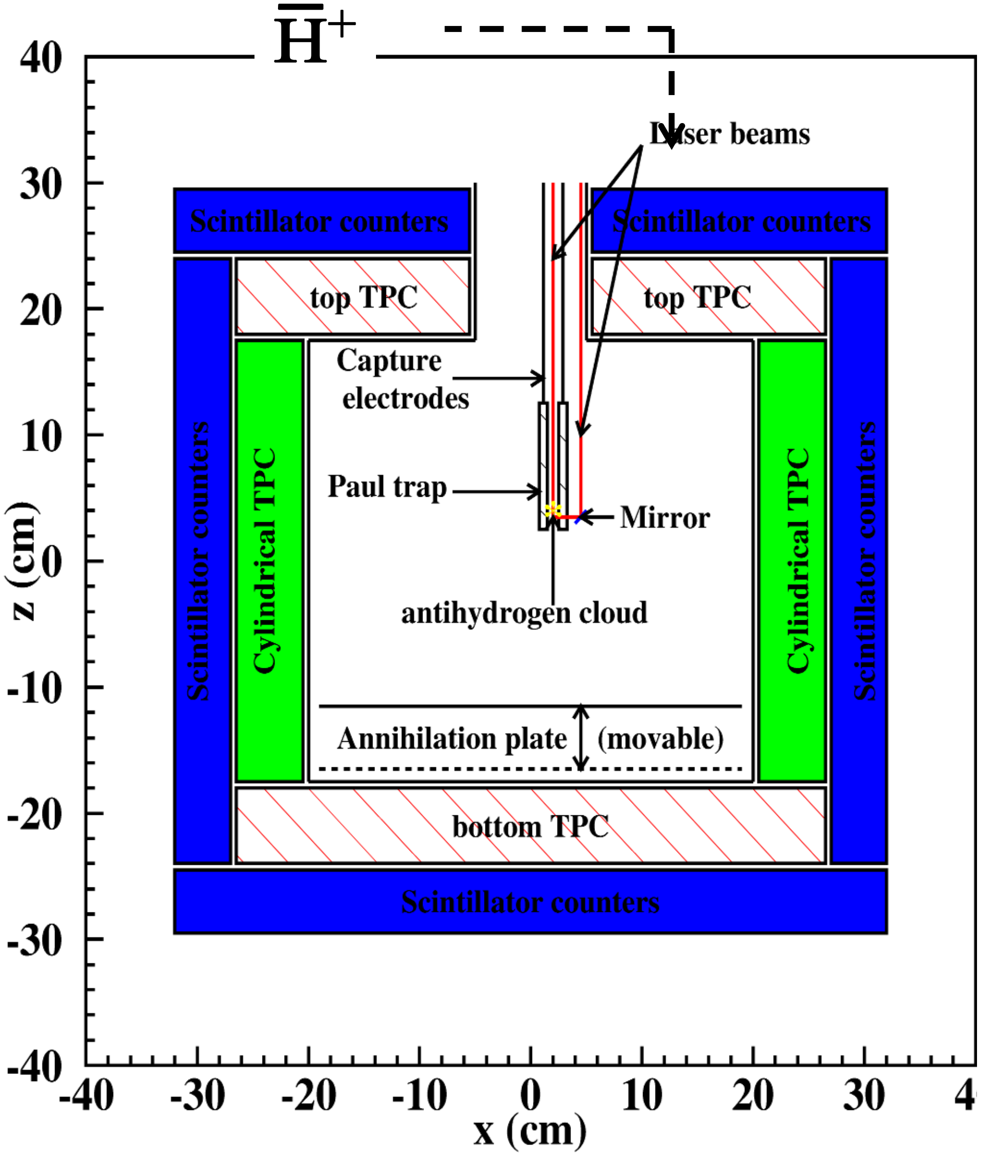
Laser: 410 nm; 1-mJ, 50-ns pulse → 30% Ps(3d) available

Realisation in progress with LKB (thesis work of P. Comini)

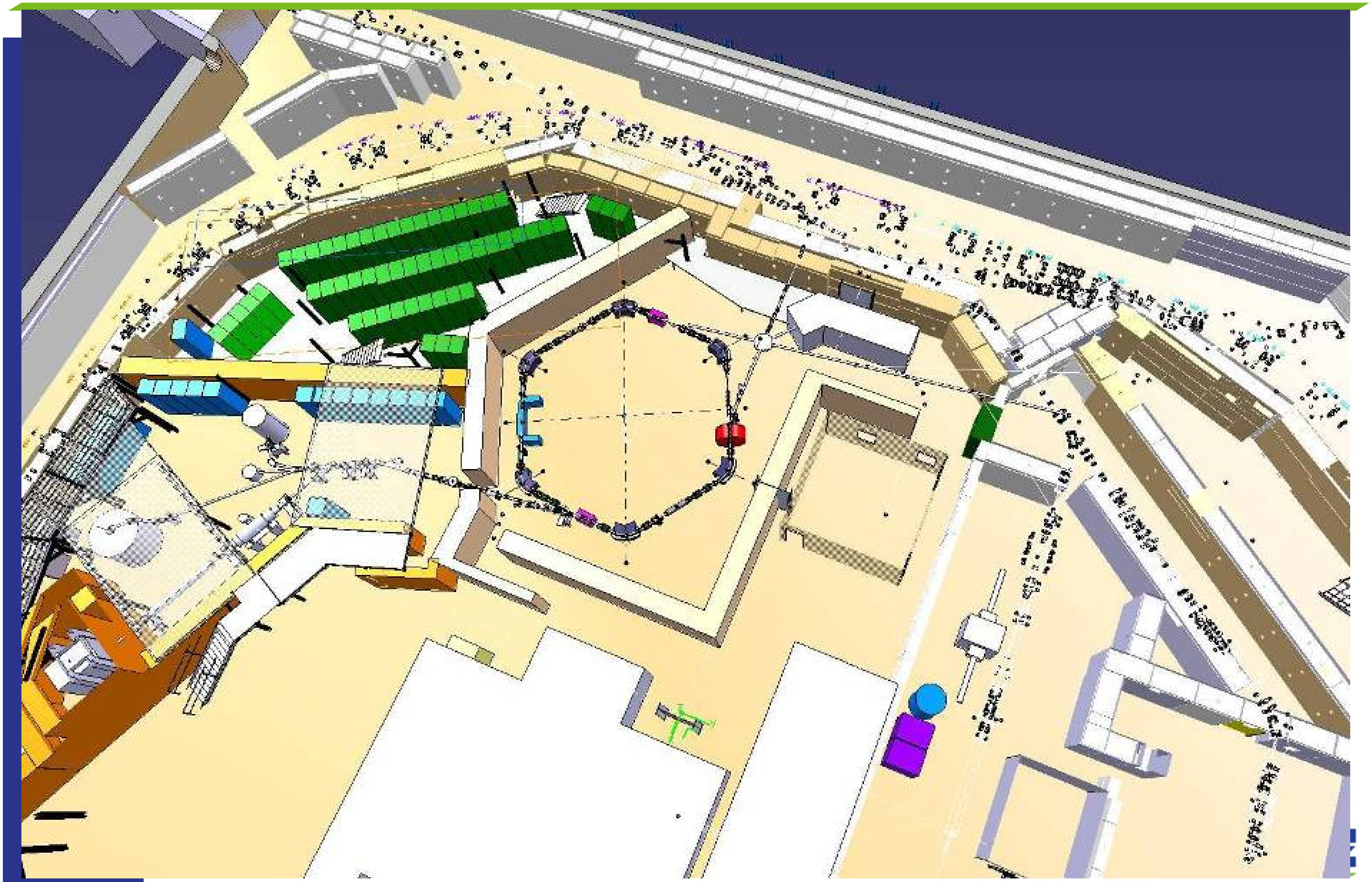
P. Comini and P-A. Hervieux, *H and H+ production cross sections for the GBAR experiment,* Proc. 16th Int. Conf. Positron Annihilation, 19-24 August 2012, Bristol, UK (2013) in print

Detection setup

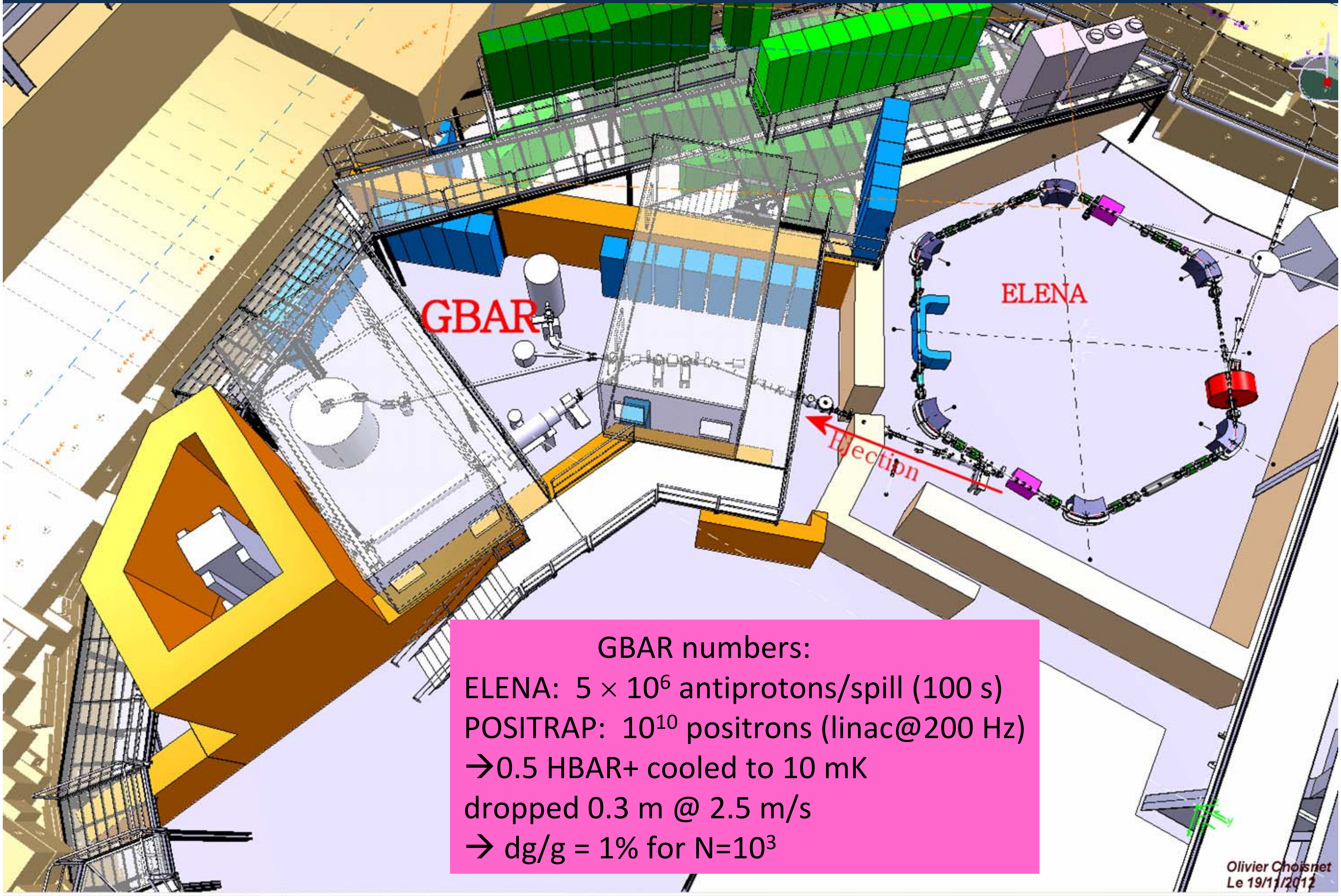




AD Hall with ELENA (and GBAR)



present GBAR layout



GBAR numbers:

ELENA: 5×10^6 antiprotons/spill (100 s)
POSITRAP: 10^{10} positrons (linac@200 Hz)
→0.5 HBAR+ cooled to 10 mK
dropped 0.3 m @ 2.5 m/s
→ dg/g = 1% for $N=10^3$

Other tasks (workpackages…)

Conceptual Design Report & MoU in progress

Work Package	**Institutes**
Fast e^+	NCBJ, IRFU
Slow e^+	IRFU, Swansea, TUS
e^+ accumulation	RIKEN, IRFU, CSNSM
Positronium	LKB, IRFU, ETHZ
Antiproton deceleration	CSNSM, IRFU, LKB, Tokyo
$\bar{H}$ & $\bar{H}^+$	Swansea, IRFU, LKB
$\bar{H}^+$ cooling	Mainz, LKB, ILL
Detector	ETHZ, IRFU, Mainz
Theory	IPCMS, LKB, Lebedev, Uppsala
Slow control, DAQ	IRFU, all
Quantum States	ILL, LKB

… et si il y avait LPNHE?!

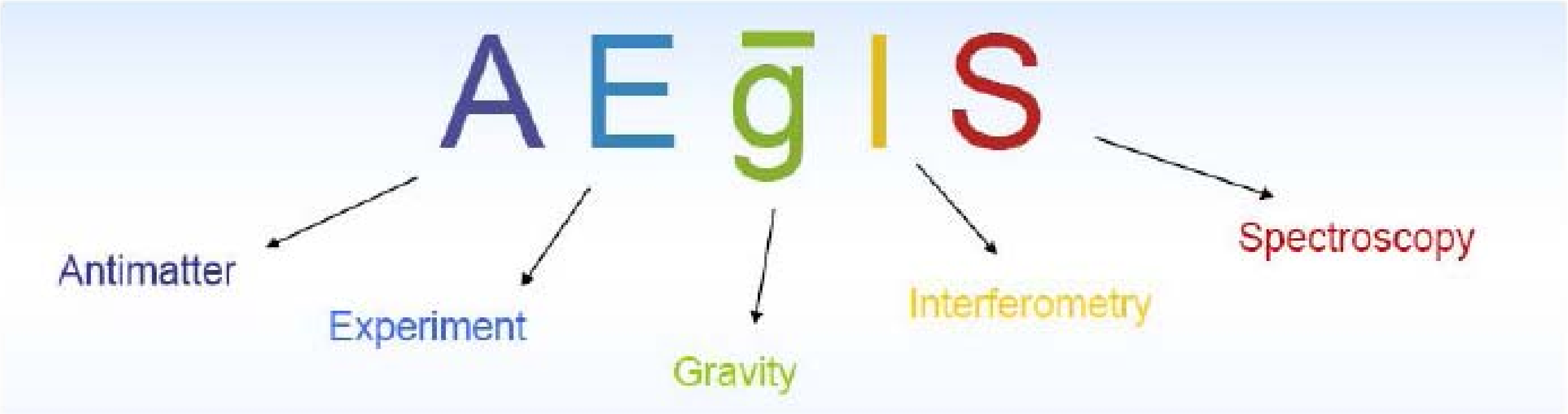
GBAR Timeline

Letter of Intent SPSC-2007-038		Research Board AD-7		ELENA BPPC		
2007	2011	2012/05	2012/06	2012/09	2012/11	2013
	Proposal SPSC-P-342		ADUC		ADUC	

GBAR development	GBAR off-line commissioning	GBAR installation	GBAR on-line commissioning	Run?
2013	2014	2015	2016	2017
GBAR MoU		ELENA installation	ELENA commissioning	

Proposition pour une participation
à l’expérience AEGIS/AD-6

e+ oPs $\overline{H}$



A E $\bar{g}$ I S

Antimatter

Experiment

Gravity

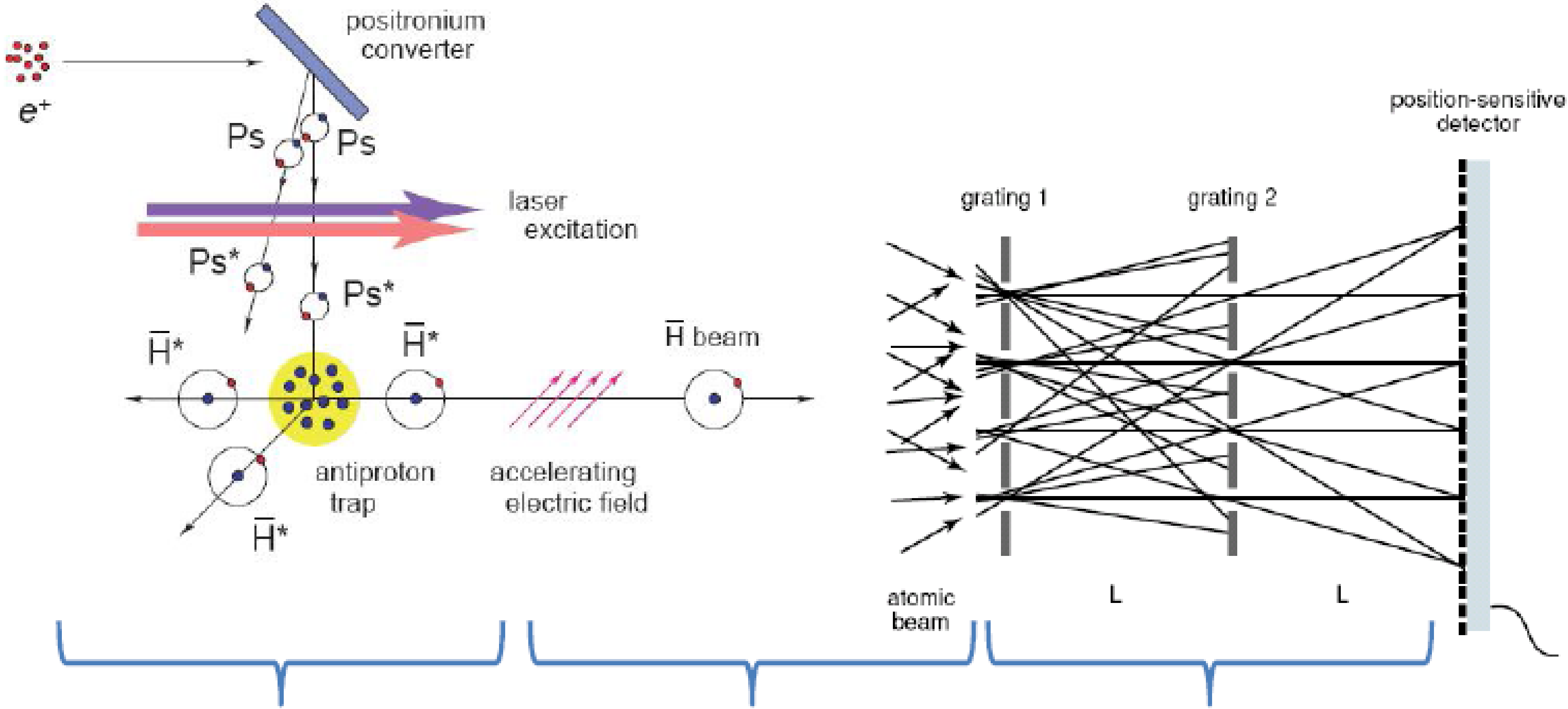
Interferometry

Spectroscopy

Principe :

$$\boxed{\bar{p} + (Ps)^{*} \rightarrow \bar{H}^{*} + e^{-}}$$

$\boxed{e^{+} e^{-}}$



1)Hbar formation 2)beam formation 3) Trajectory measurement

The *AEgIS* collaboration (~50 ϕ)

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Conclusion

- Penning trap: versatile tool that achieves the ultimate (state-of-the-art) performance
- 20-year legacy in mass spectrometry of exotic nuclides
- Recent (exciting) results in nuclear physics, astrophysics
- Reaches to other fields involving fundamental physics; i.e. antimatter: ALPHA/ATRAP and soon AEgIS/GBAR
- Wouldn't *you* like to join us?!

Le Monde (juin 2011)

ISOLTRAP Collaboration

ISOL TRAP

Max-Planck-Institut für Kernphysik

D. Atanasov, K. Blaum, Ch. Böhm, Ch. Borgmann, R. B. Cakirli, S.Eliseev, S. Naimi

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CSNSM

G. Audi, D. Lunney, M. Wang, V. Manea

GSI

D. Beck, F. Herfurth, Y. Litvinov, E. Minaya-Ramirez, D. Neidherr

TECHNISCHE UNIVERSITÄT DRESDEN

J. Stanja, K. Zuber

ISOLDE

T. Cocolios, D. Fink, M. Kowalska, S. Kreim

KATHOLIEKE UNIVERSITEIT LEUVEN

M. Breitenfeldt

Merci pour l’invitation!

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