Nuclear Masses and Neutron Stars

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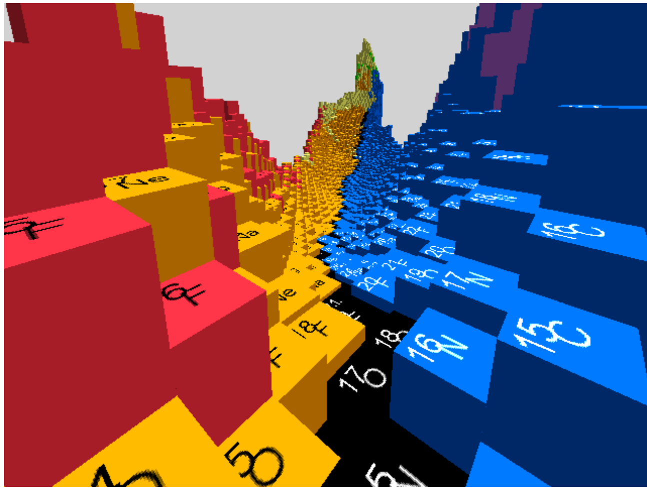
Overview

- Goal: Fathoming stellar evolution with laboratory precision
- Method: Mass spectrometry of exotic radionuclides
- Tool: Penning trap and multi-reflection time-of-flight mass spectrometer
- Application: Neutron stars and the origin of the elements



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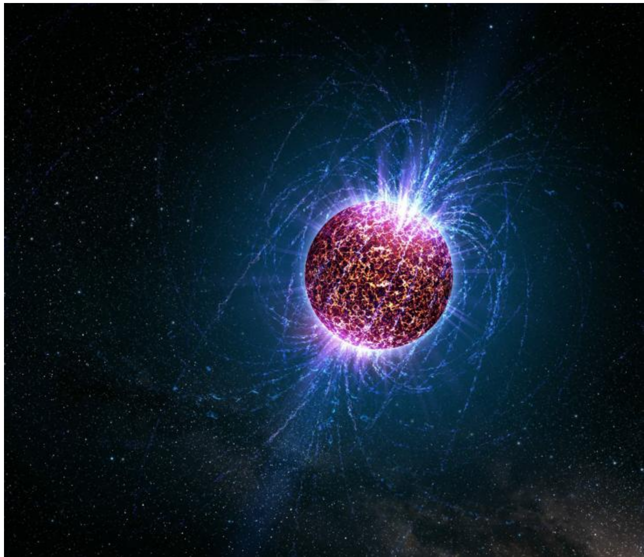
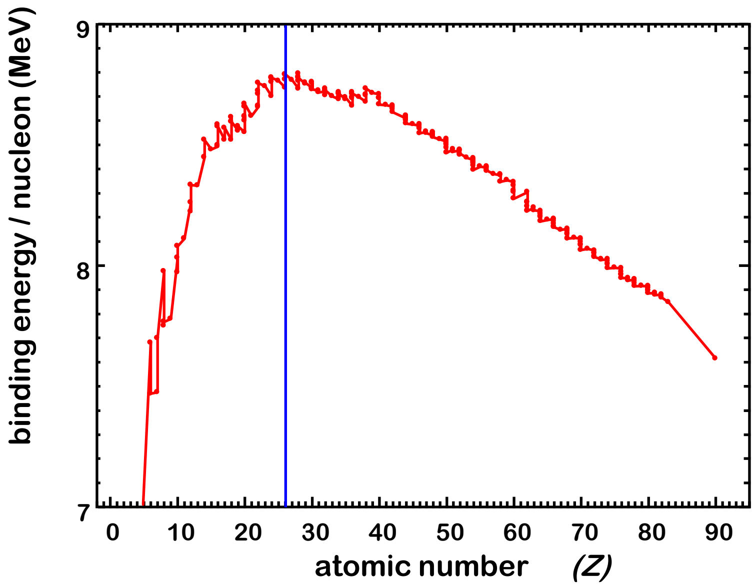
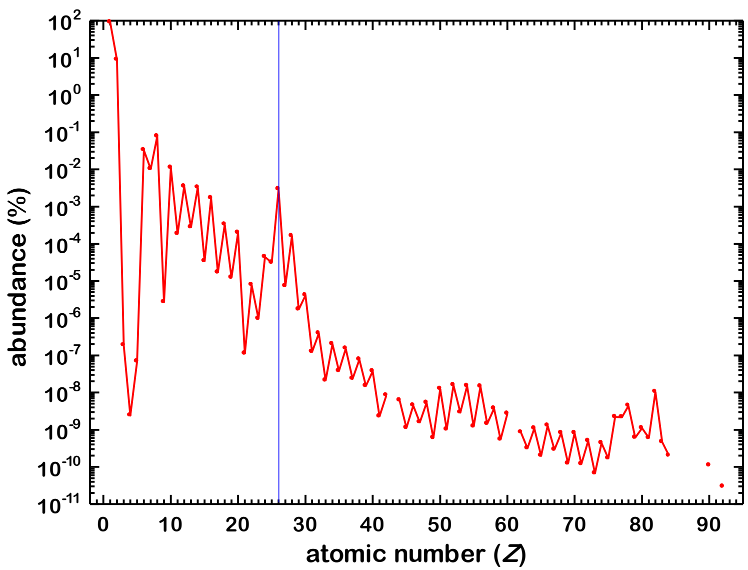
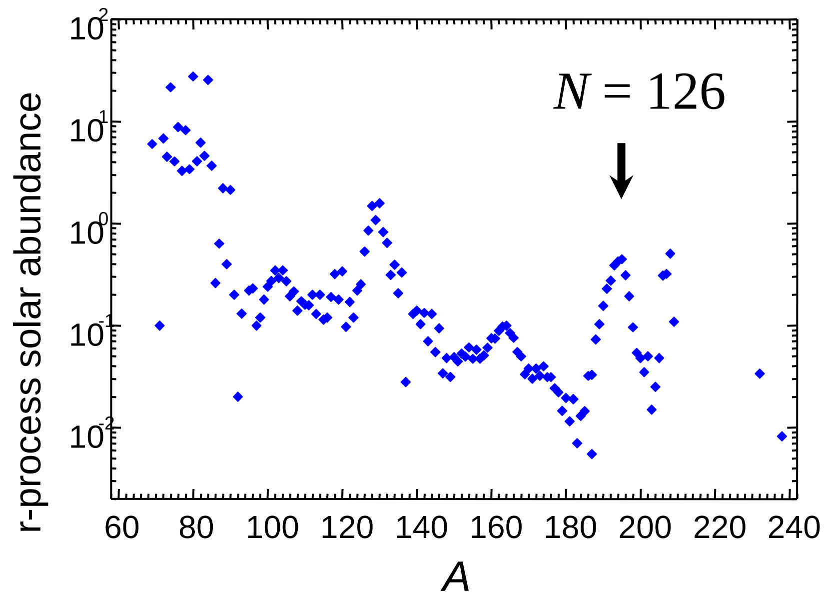


Nuclear Magicity



- An imprint of nuclear physics on nature:
  - Enhanced binding leads to enhanced abundance
  - abundance peaks at closed shells

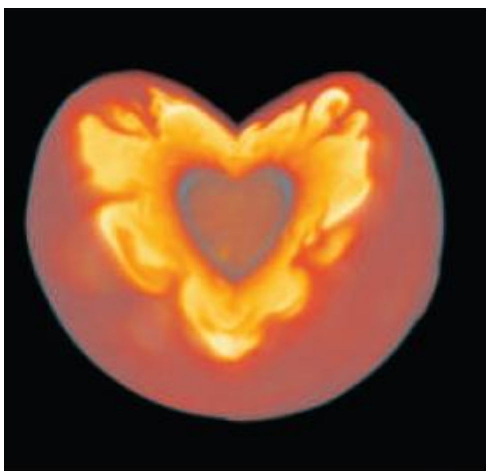


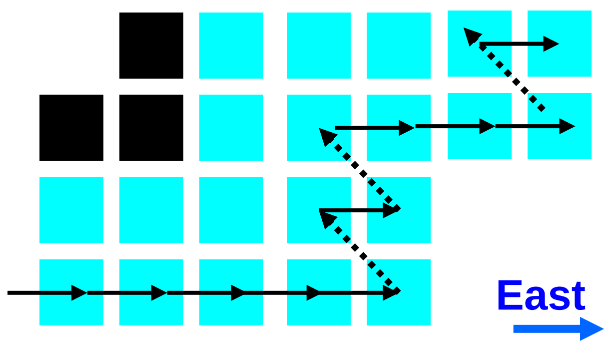


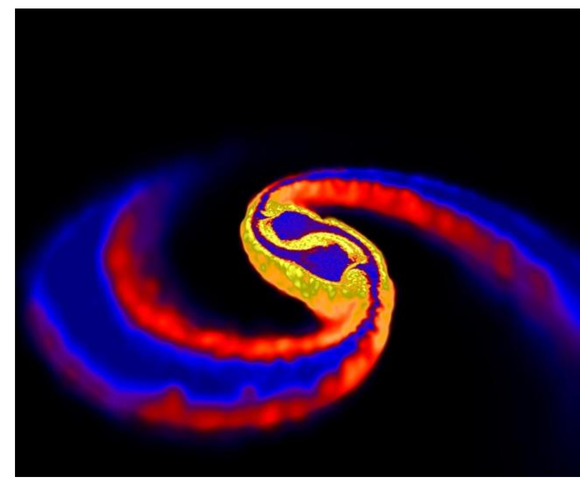
From the „11 greatest unanswered questions“

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

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







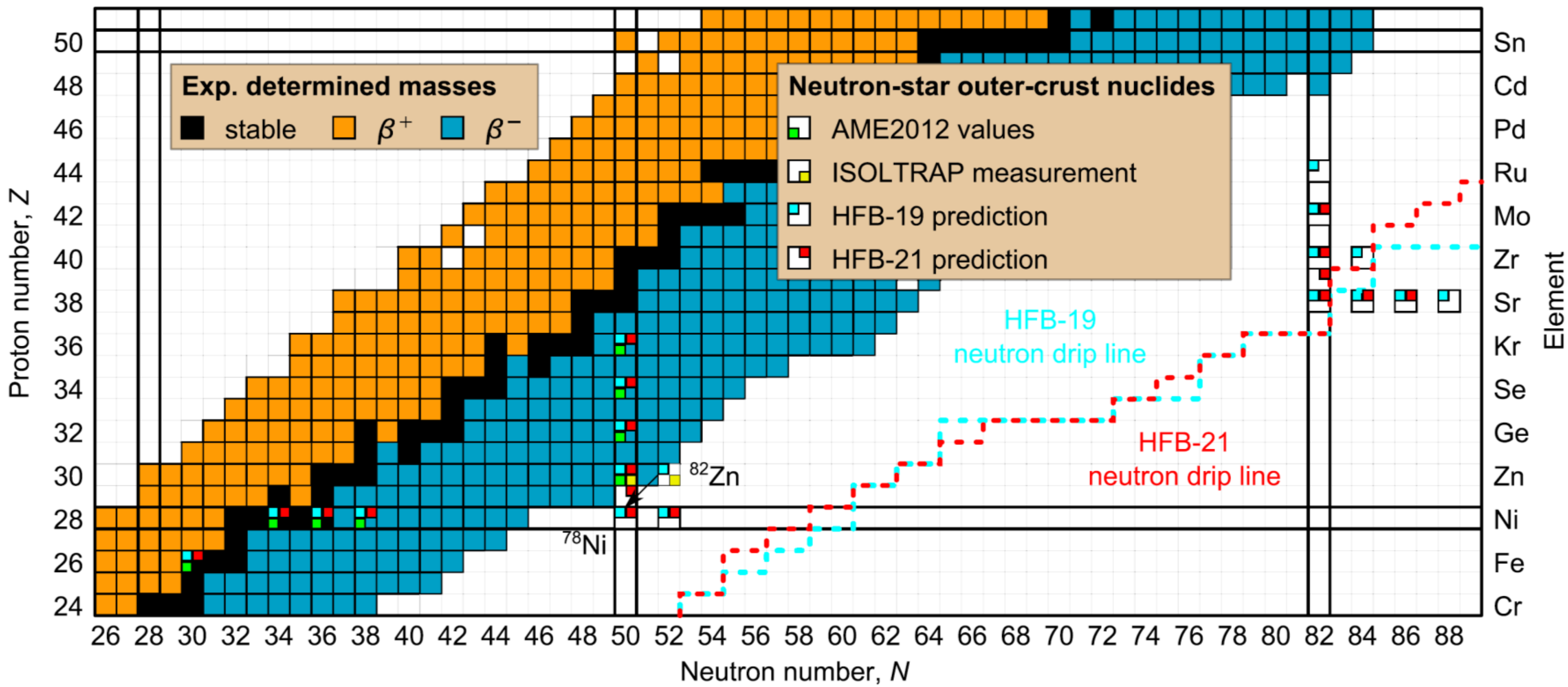
Core-collapse supernovae

Neutron-star mergers

S. Woosley and T. Janka, Nature Physics **1**, 147 (2005)

D. Price and S. Rosswog, Science **312**, 719 (2006)

Composition of Neutron-Star Crust

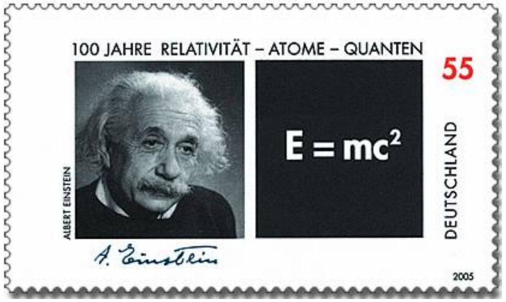


- For a given pressure, modeling the composition depends mainly on the binding energy of the nucleus!
- Depth profile of a neutron star by using experimental masses and mass models as input for equation of state

J. M. Pearson *et al.*, Phys. Rev. C **83** (2011)
R. N. Wolf *et al.*, PRL **110**, 041101 (2013)

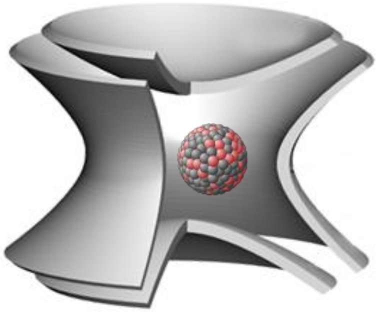
Nuclear Masses

$$B(N,Z)=\left(Nm_n+Zm_p-m(N,Z)\right)c^2$$



- A mass measurement yields the binding energy which comprises information on all underlying interactions

- Mass determination through frequency measurement of trapped, charged particles was invented by Paul and Dehmelt (Nobel Prize 1989)



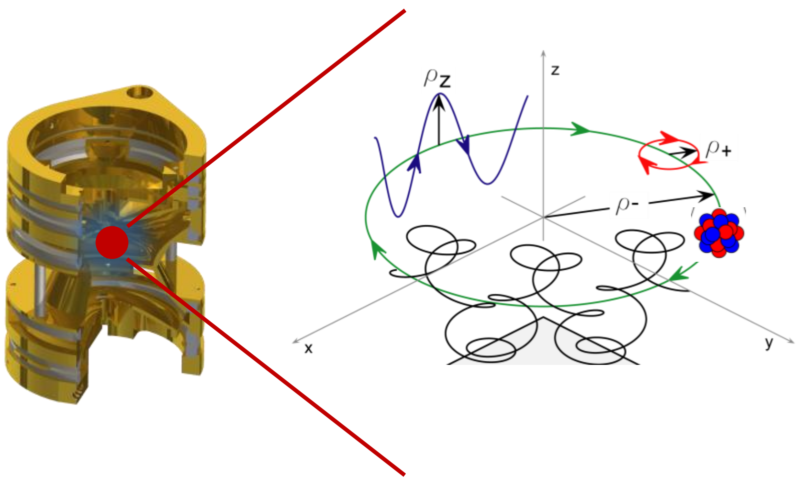
- Measurements with relative uncertainties of 10^{-6} required for insight into nuclear structure

Distance Dresden – CERN

Measure to +/- 10mm

Penning-Trap Mass Spectrometry

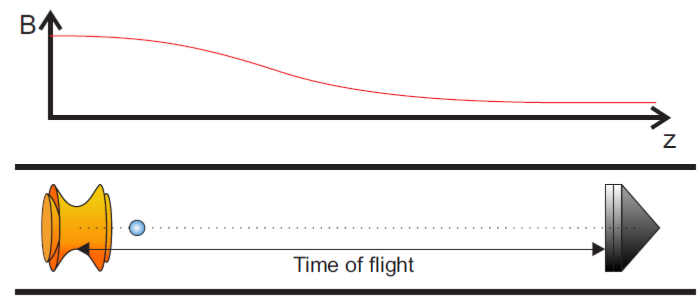
- Particle stored by superposition of magnetic field and electrostatic potential
- Trapped particle exhibits three characteristic eigenmotions

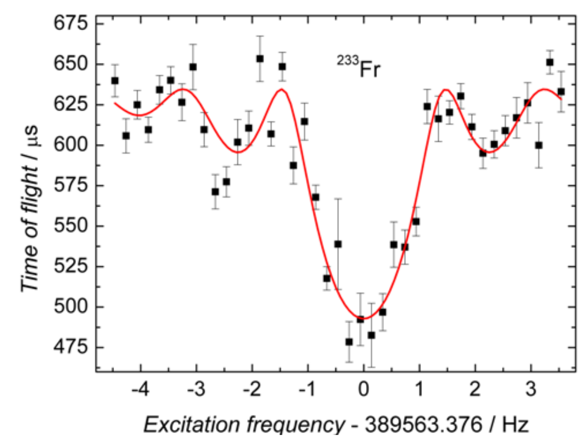


$$\omega_c = \omega_+ + \omega_- \rightarrow \omega_c = \frac{q}{m} B$$

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

- From frequency to mass using time-of-flight ion-cyclotron resonance technique
- Single-ion experiment

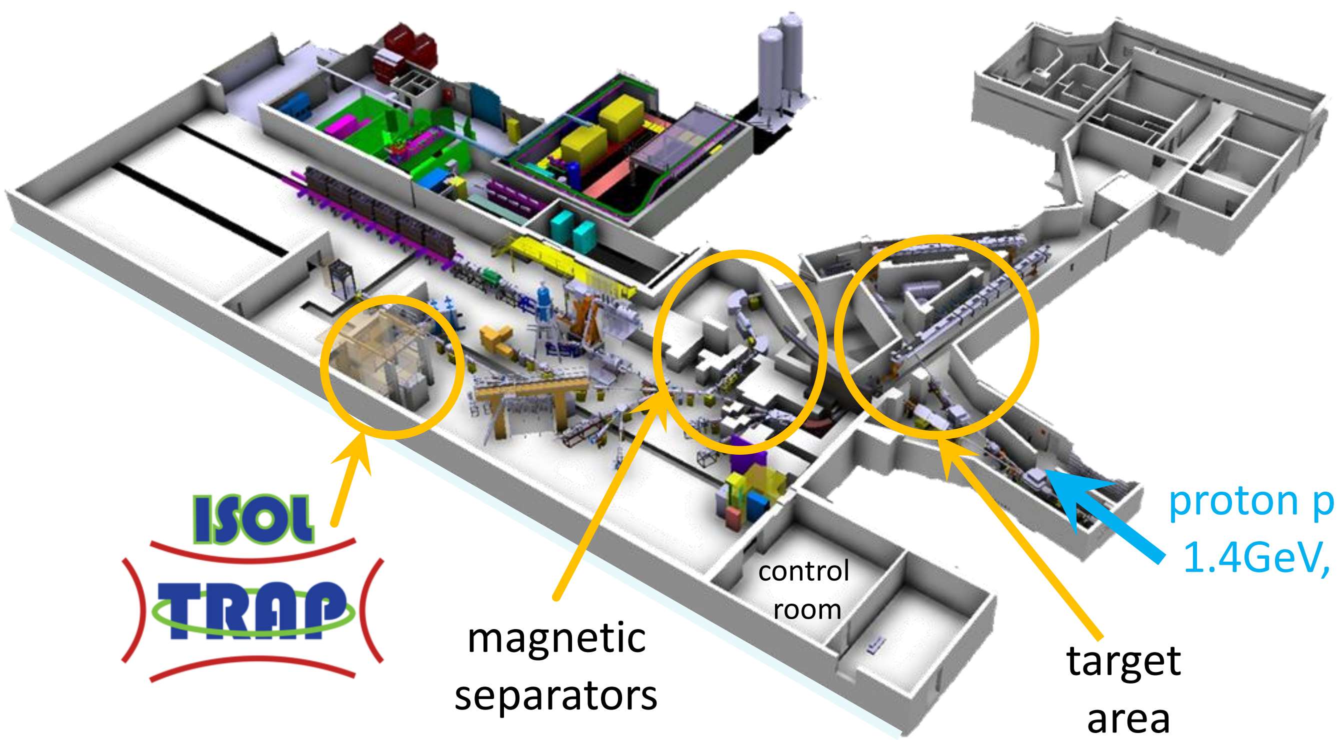




M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995)
S. Kreim *et al.*, PRC **90,** 024301(2014)

ISOLDE Hall

spallation, fission, fragmentation of UCx targets



magnetic separators

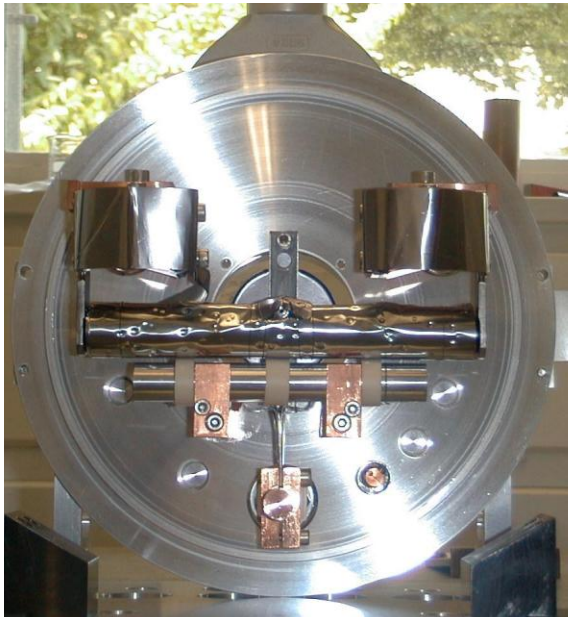
$$\frac{m}{\Delta m} \approx 5000$$

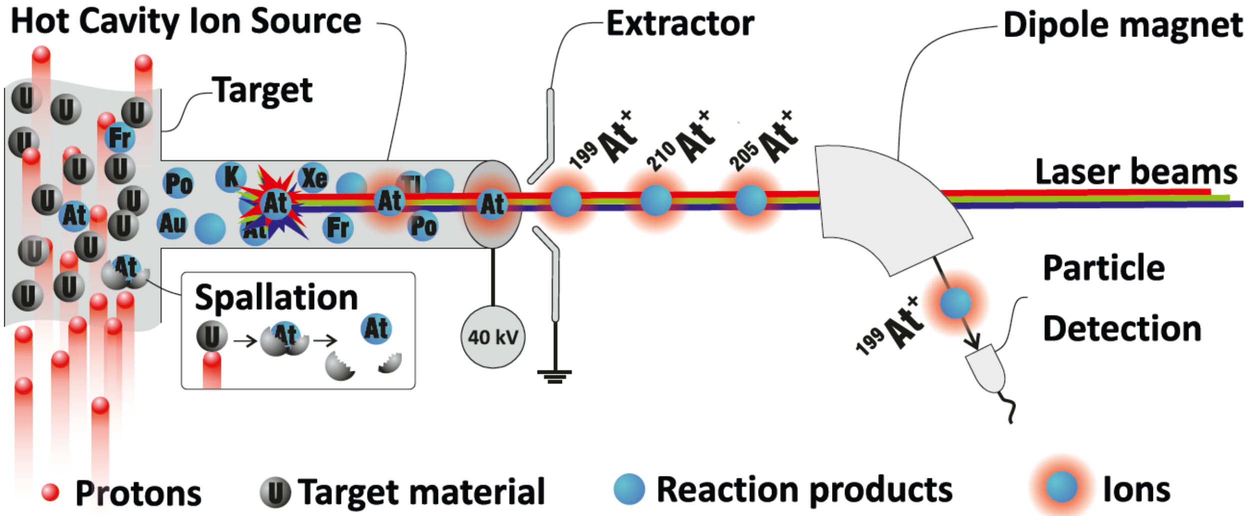
target area

proton pulses
1.4GeV, 2uA

Radionuclides from ISOLDE/CERN

- Radioactive beam is provided by ISOL technique:
  - 1.4-GeV protons hit thick target material
  - Low-energy beam
  - Singly-charged ions
  - Isotopically pure beam
  - Mixture of isobars

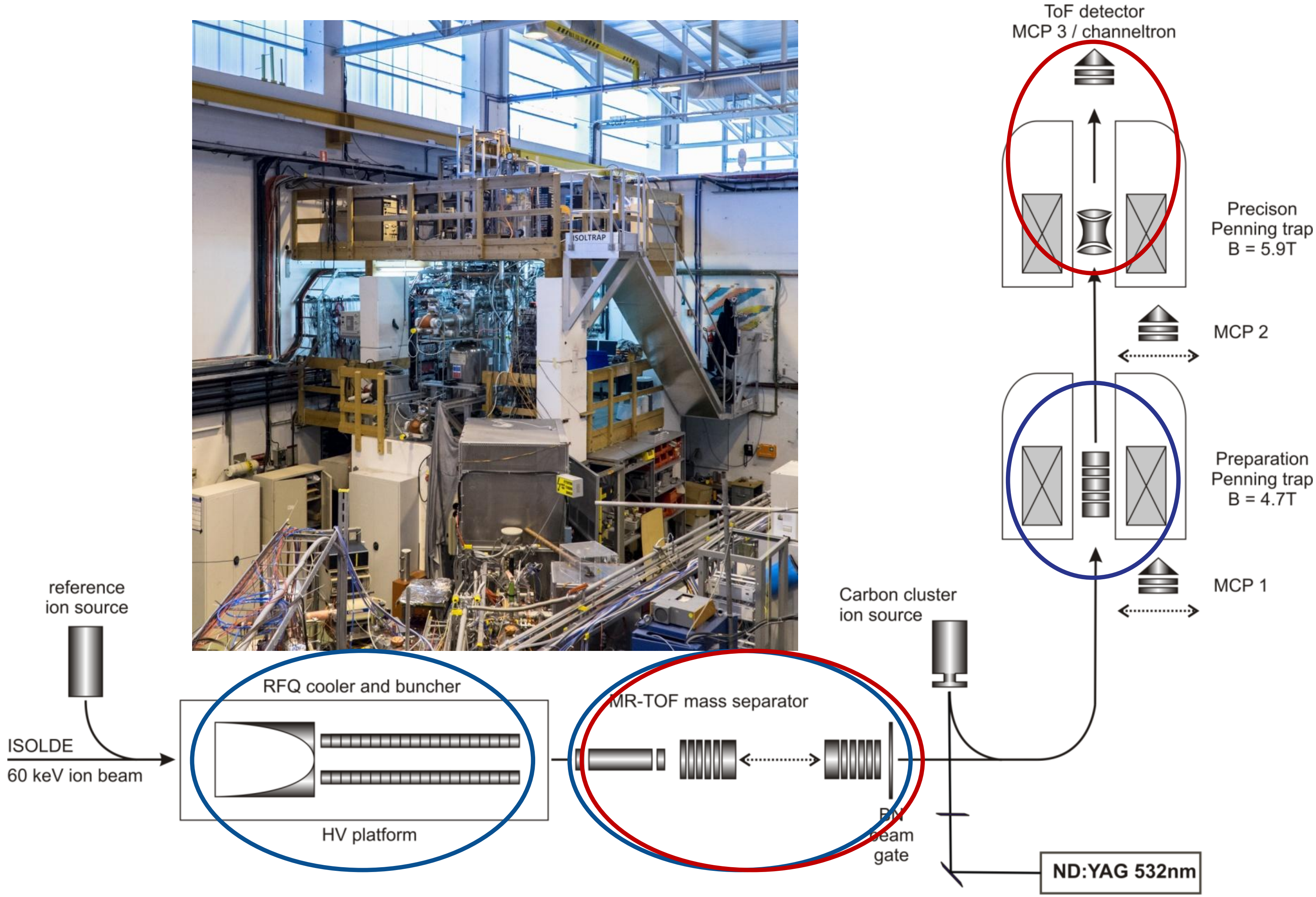




Courtesy Sebastian Rothe

G. D. Alkhazov *et al.,* NIM B **69** (1992) 517, V. N. Fedosseev *et al.,* NIM B **266**, 4378 (2008), U. Koester *et al.,* Nucl. Phys. A **701**, 441 (2002)

The ISOLTRAP Experiment

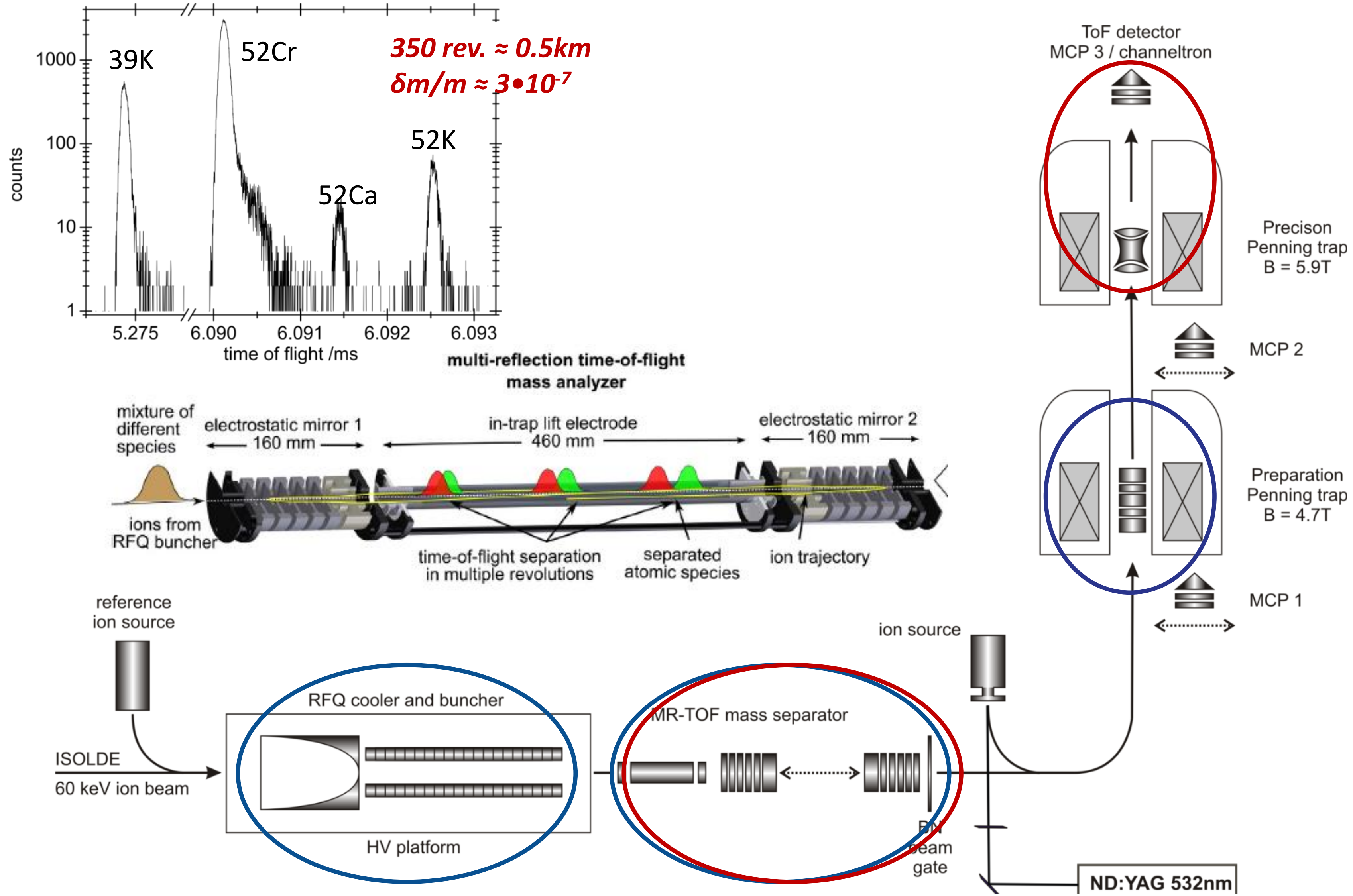


M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)
R. N. Wolf *et al.*, IJMS **349-350**, 123 (2013)

preparation measurement

The ISOLTRAP Experiment

See talk by Frank Wienholtz this afternoon

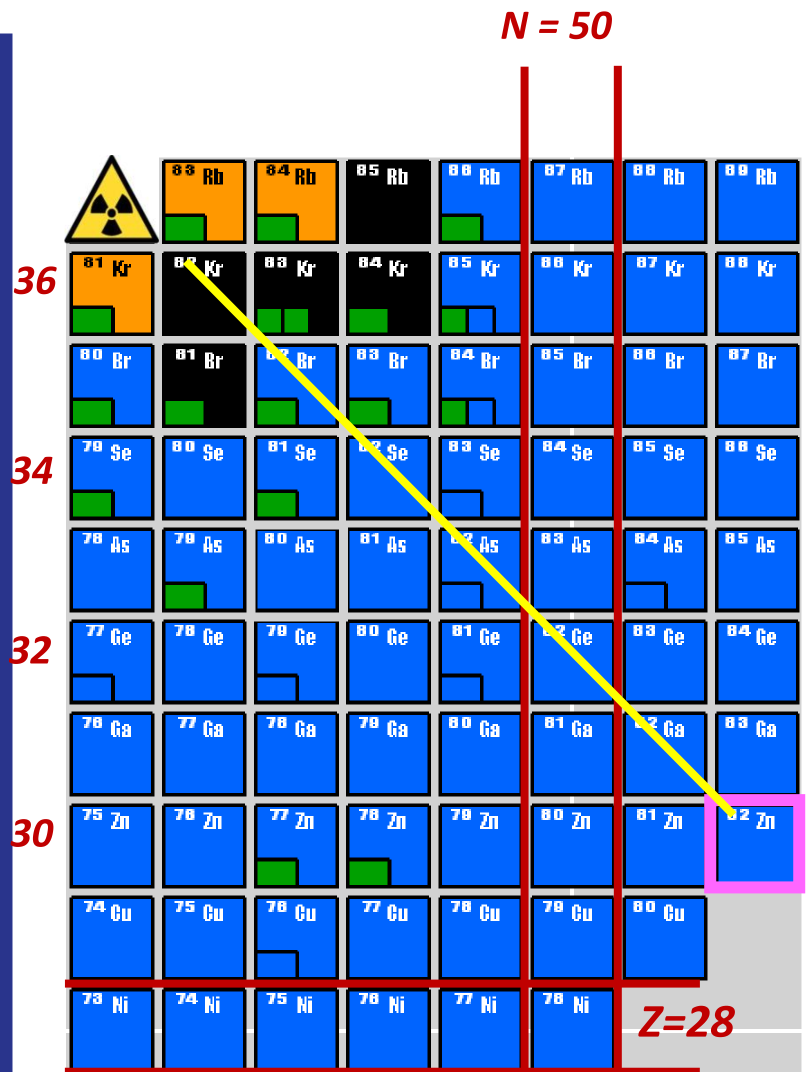


M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)

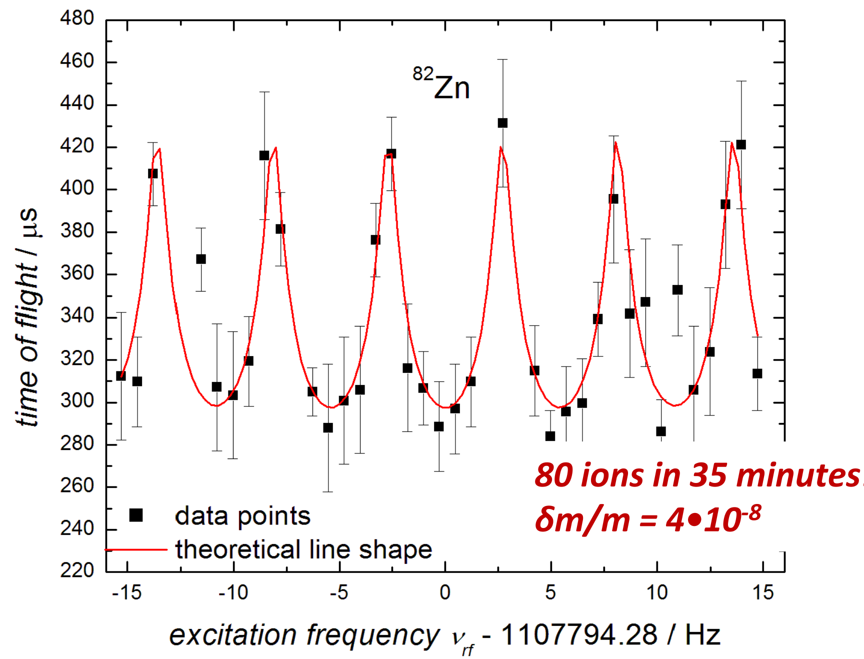
R. N. Wolf *et al.*, IJMS **349-350**, 123 (2013)

preparation measurement

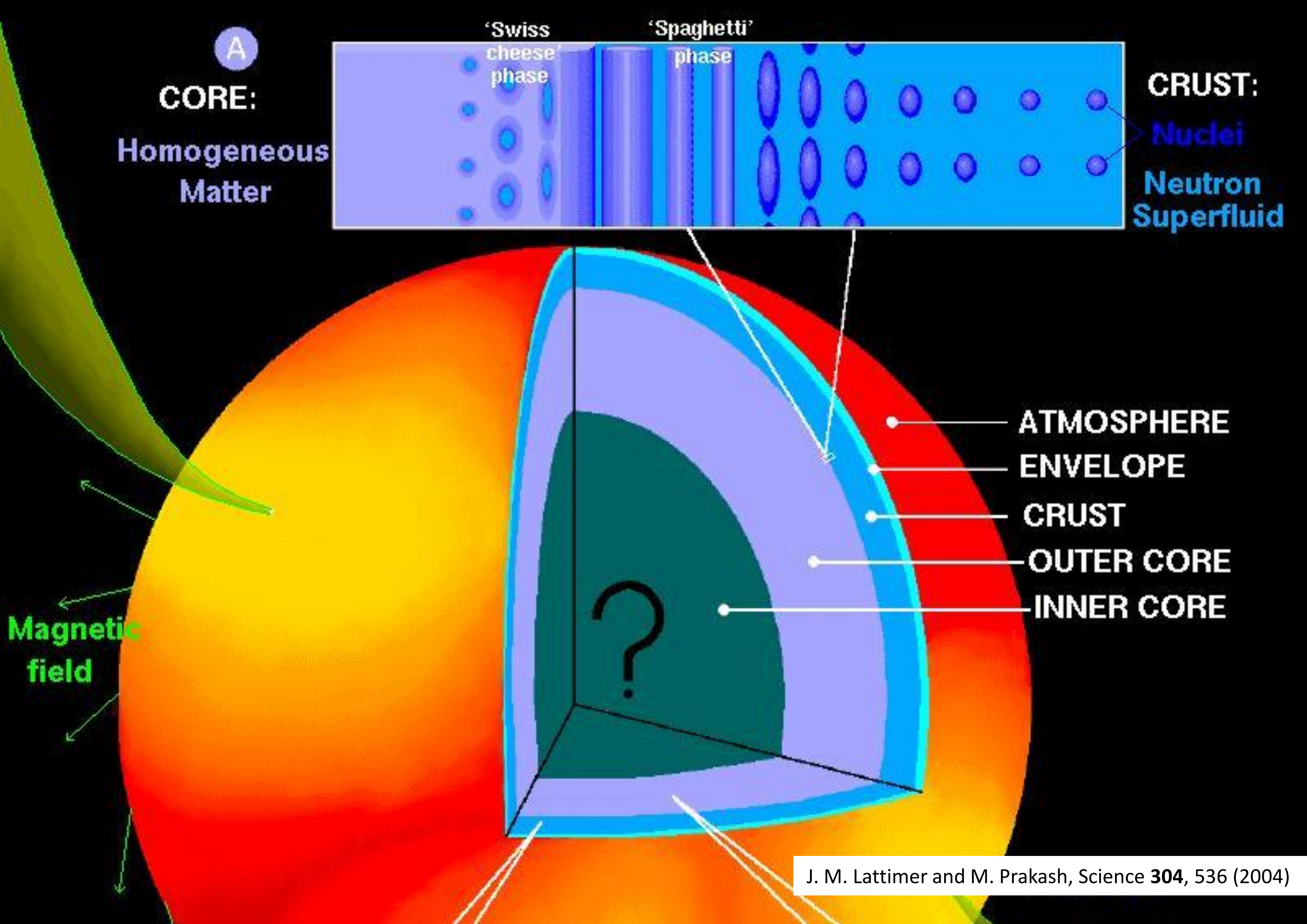
^{82}Zn: Meeting the Challenge



- MR-TOF with ISOLTRAP
- Combined all ISOLDE tricks to perform this measurement
  - Neutron converter for fission
  - Quartz tranfer line to stop Rb
  - Laser ionization of Zn
    - ✓ ^{82}Zn: 100/s, $t_{1/2} \approx$ 200ms
    - ✓ ^{82}Rb: 8000/s, $t_{1/2} \approx$ 6 hr

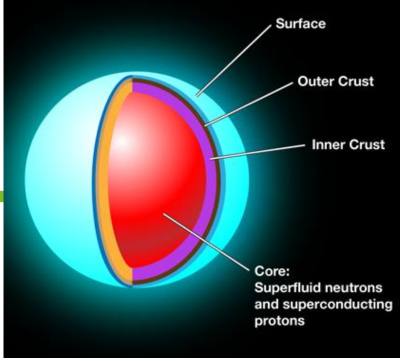


A NEUTRON STAR: SURFACE and INTERIOR

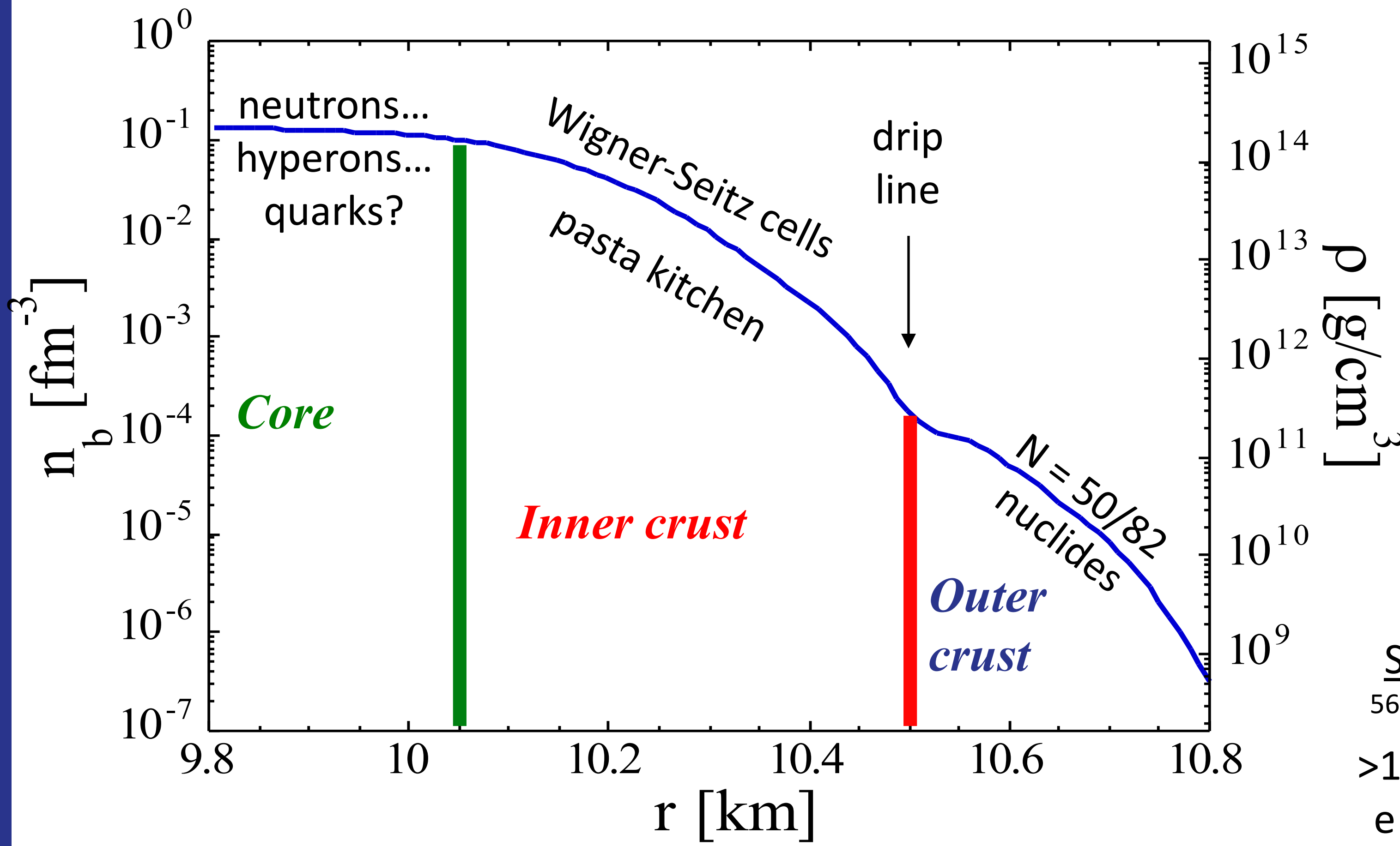


J. M. Lattimer and M. Prakash, Science **304**, 536 (2004)

Neutron-Star Density Profile



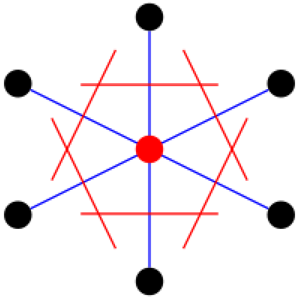
nuclear density: 2×10^{8} g/cm^{3}



Surface:
^{56}Fe; ^{62}Ni;
$>10^{7}$ g/cm^{3}
e degen.:
$p + e \rightarrow n$

J. M. Pearson *et al.*, PRC **83**, 065810 (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)

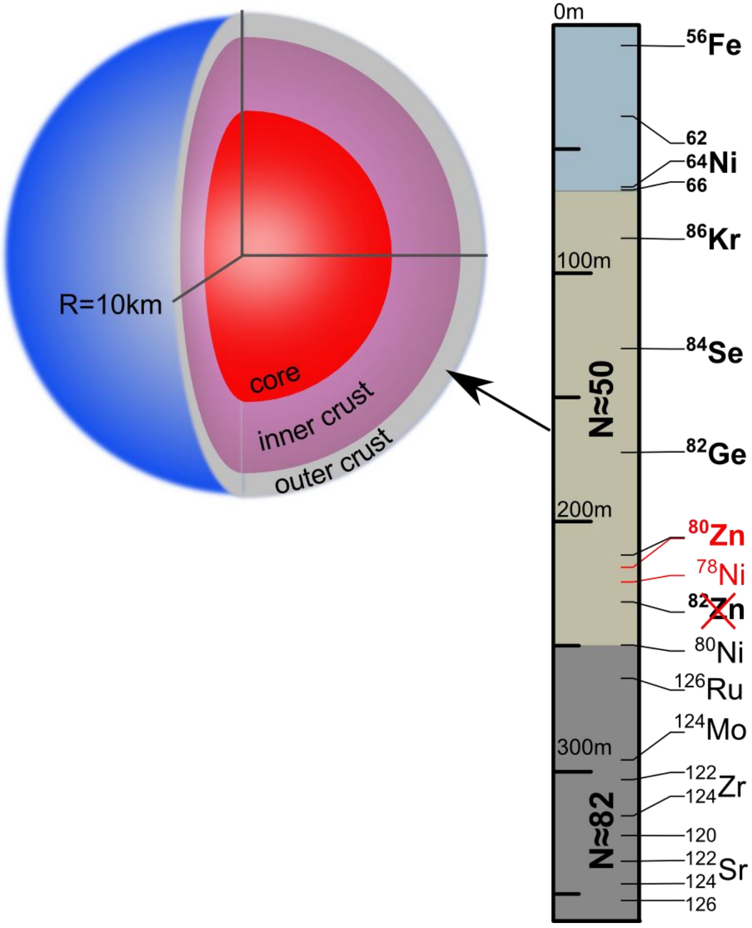
$$G_{cell}(Z,A)=W_N(Z,A)+W_L(Z,n_N)+[\varepsilon_e(Z,n_e)+P]/n_N$$

- *$W_N(Z,A)$: 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 *et al.*, PRC **83**, 065810 (2011)

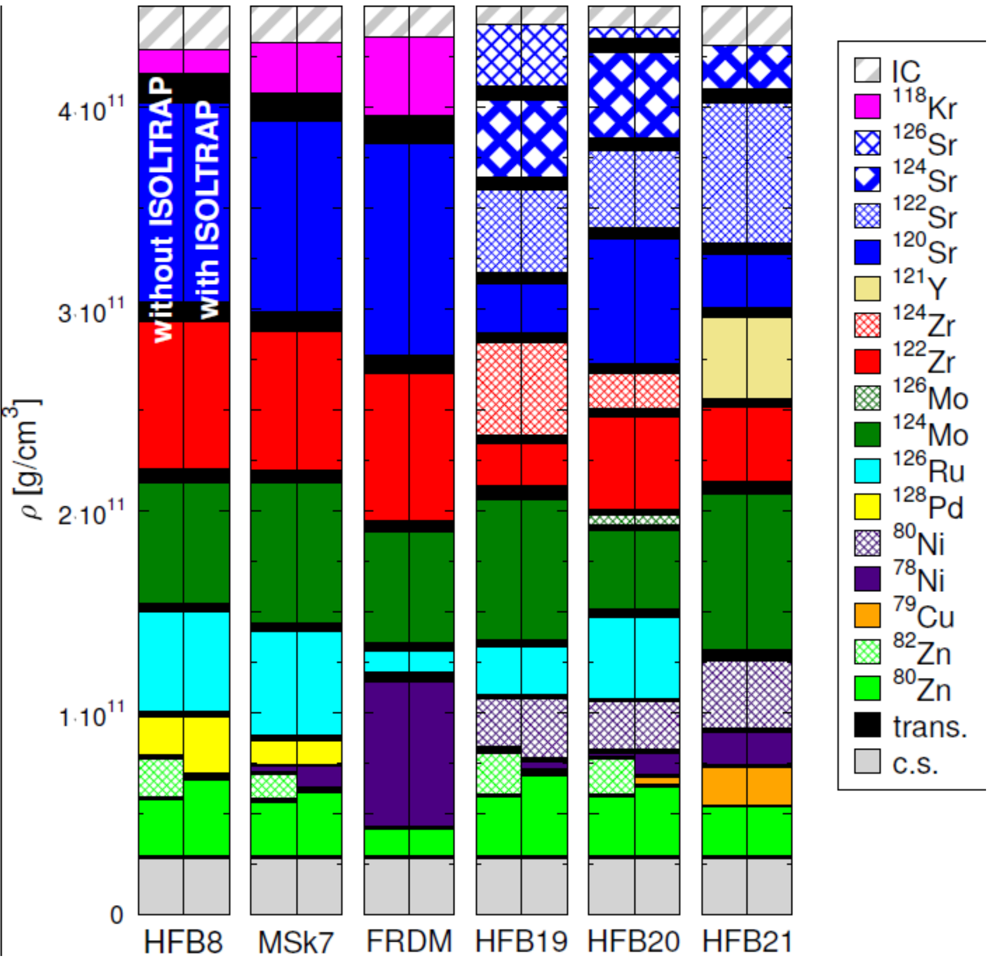
Crustal Composition

- Sequence of nuclei now determined to 223 m (10km radius, 1.4 solar mass NS)
- Mass excess ME(^{82}Zn) = m – Au = -42.314(3) MeV/c^2
  - Uncertainty δm/m = 4•10^{-8}
  - 500keV less bound
- Most exotic nuclei measured for neutron-star crustal composition
- The presence of ^{82}Zn in the outer crust of neutron stars can be excluded



R. N. Wolf *et al.*, PRL **110**, 041101 (2013)
S. Kreim, *et al.*, IJMS **349-350**, 63 (2013)

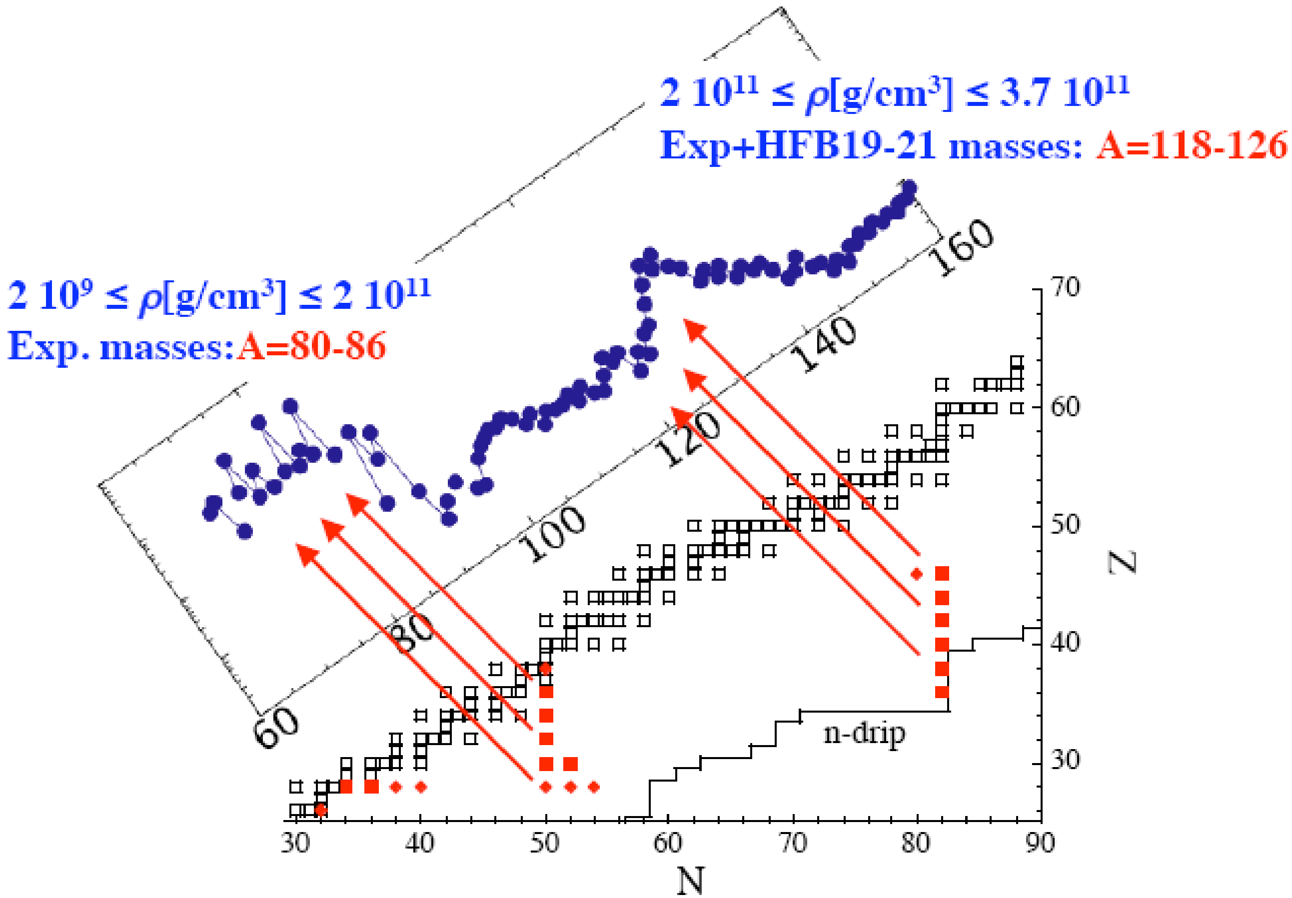
Crustal Composition



- 25 different nuclear mass models tested
  - All exclude ^{82}Zn from the outer crust of a neutron star
- Validate up to a density of $5*10^{10}$ g/cm^3
  - crustal composition determined only by experimental data
  - ^{80}Zn being the corresponding nucleus
- Nuclear structure prevails in astrophysical environment
  - Magic neutron shells *N*=50 and *N*=82 play a major role for crustal composition

S. Kreim *et al.*, IJMS **349-350**, 63 (2013)

Composition of the Cold Outer Crust

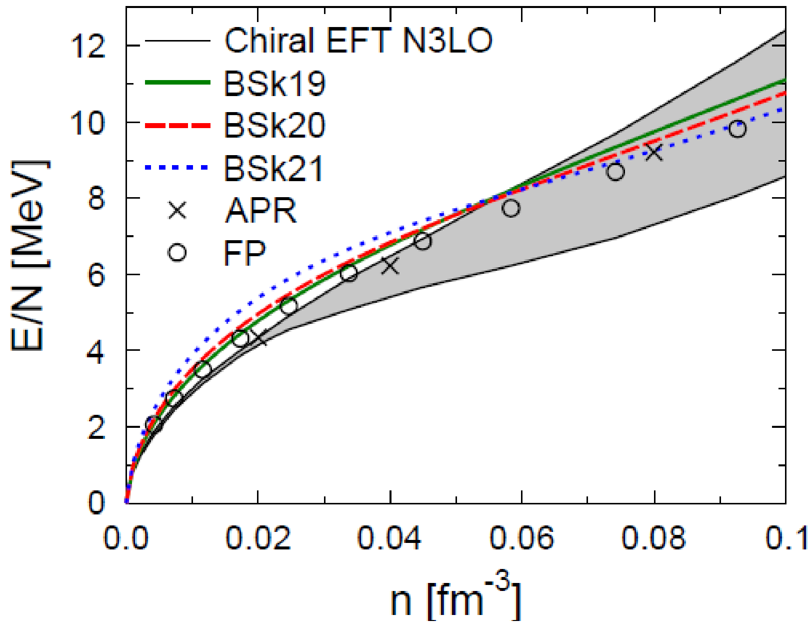


Ejection of the outer crust material: enrichment of nuclei up to A~130 !

S. Goriely *et al.*, A&A **531**, A78 (2011)

Equation of State

- 3-body forces from chiral effective field theory applicable to neturon matter
- First N^{3}LO calculations of neutron matter energy
- Mass predictions at present limited to A~60

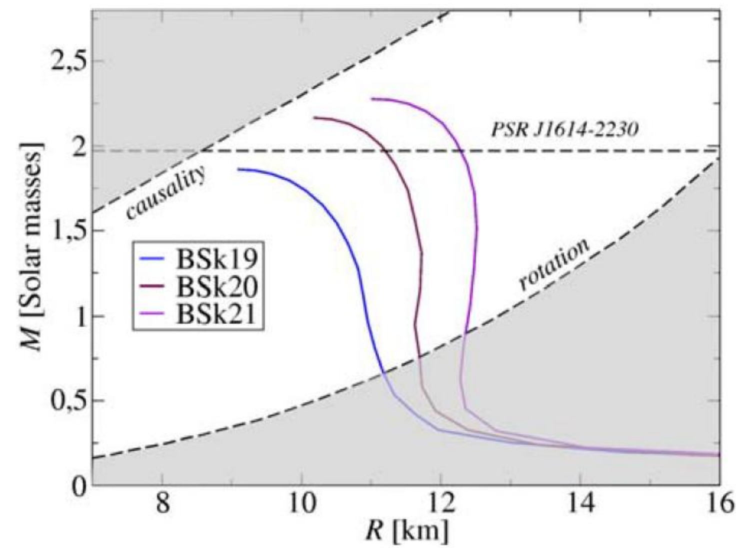


I. Tews *et al.*, PRL **110**, 032504 (2013)

B. Friedman, V. R. Pandharipande, Nucl. Phys. A **361**, 502 (1981)

A. Akmal et al., Phys. Rev. C **58**, 1804 (1998)

- Effective Skyrme forces calculated with HFB method
- BSk19-21 provide consistently EOS and nuclear mass tables
- HFB19-21 predict composition of outer crurst of neutron stars

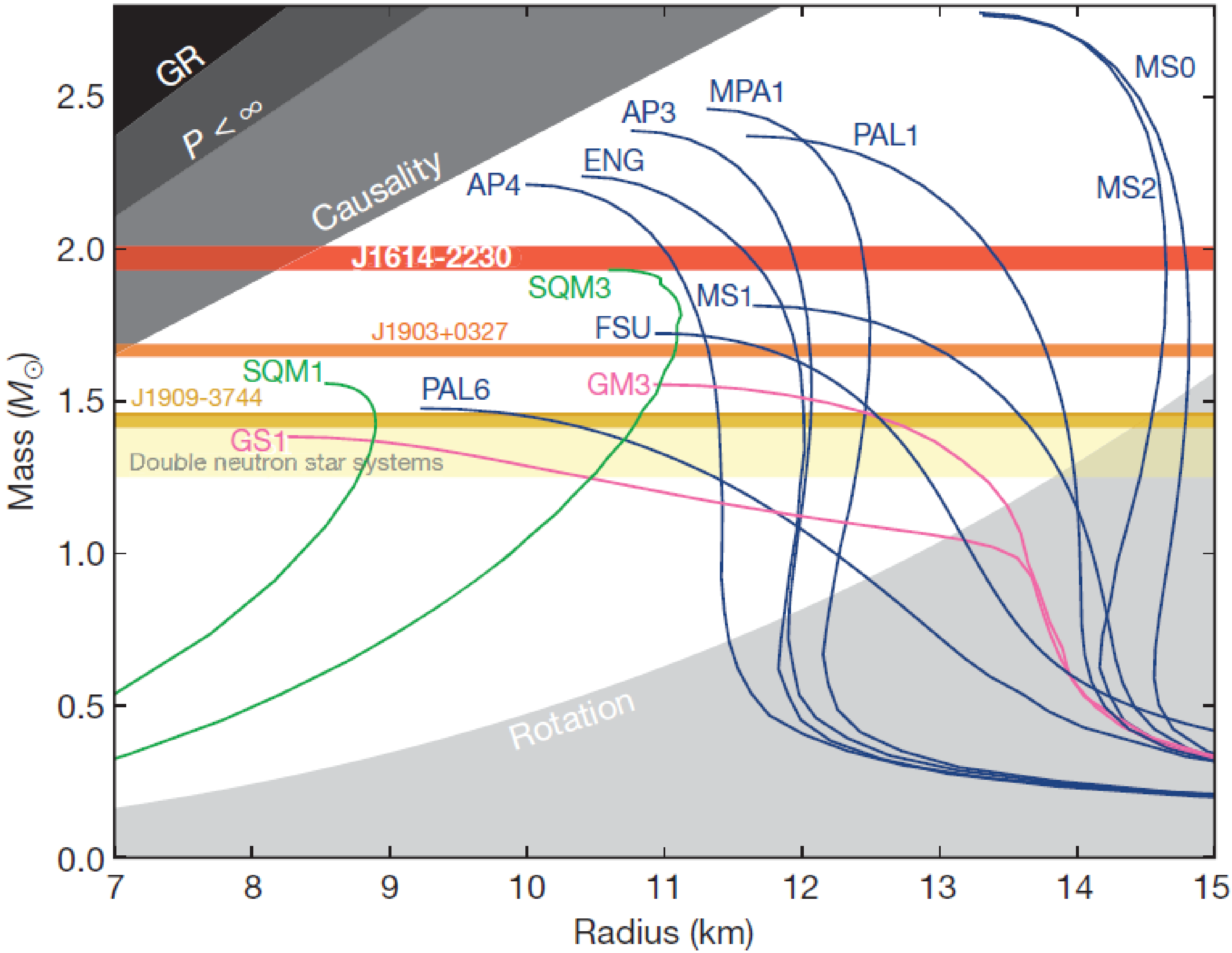


P.B. Demorest *et al.* Nature **467**, 1081 (2010)

J. M Pearson *et al*, PRC **85**, 065803 (2012)

S. Kreim *et al.*, IJMS **349-350**, 63 (2013)

Mass Measurements … of Neutron Stars



P.B. Demorest *et al.* Nature **467**, 1081 (2010)

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Ch. Böhm, G. Bollen,
Ch. Borgmann, M. Breitenfeldt,
R. B .Cakirli, T. E. Cocolios,
S. Eliseev, T. Eronen,
S. George, F. Herfurth,
A. Herlert, D. Kisler

ISOLTRAP

J. Kluge, M. Kowalska, S. Kreim,
Yu. A. Litvinov, D. Lunney,
V. Manea, E. Minaya Ramirez,
S. Naimi, D. Neidherr,
M. Rosenbusch, S. Schwarz,
L. Schweikhard, J. Stanja,
M. Wang, A. Welker,
F. Wienholtz, R. Wolf, K. Zuber

Federal Ministry of Education and Research

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ISOLDE

ENSAR

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CERN

Calculations:

UNIVERSITÉ LIBRE DE BRUXELLES — N. Chamel, S. Goriely

UNI BASEL — M. Hempel

GOETHE UNIVERSITÄT FRANKFURT AM MAIN — J. Schaffner-Bielich

Conclusions

- MR-TOF MS a new step forward in mass spectrometry
  - Can act as a mass purifier or a mass spectrometer:
    - ✓ ^{82}Zn for astrophysics (R. N. Wolf *et al.*, PRL 110, 041101 2013)
    - ✓ ^{54}Ca for nuclear-structure (F. Wienholtz *et al.*, Nature **498**, 346 2013)
  - Similar devices developed for GSI and SLOWRI @ RIKEN

- r-process nucleosynthesis requires nuclear physics
  - High-precision mass measurements
  - Nuclear physics methods enhance description of astophysical processes
  - Could the kilonova reveal the r-process site?
    - ✓ N. R. Tanvir *et al.*, Nature **500**, 547 (2013)