What Masses Can Teach Us About Stellar Evolution

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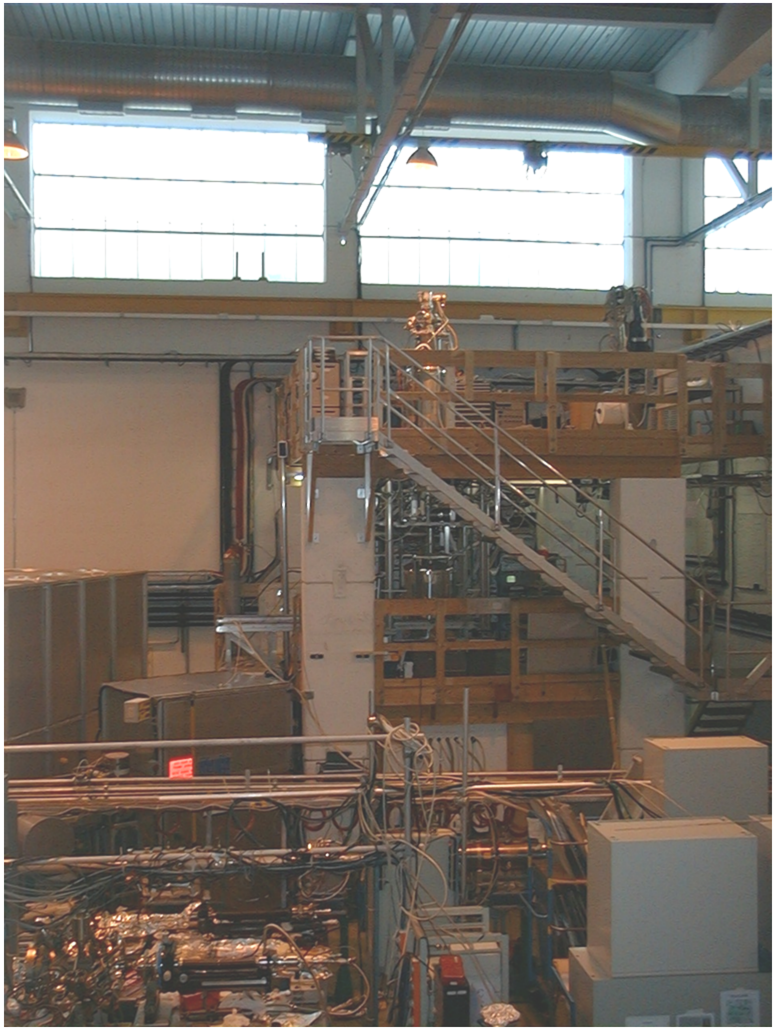
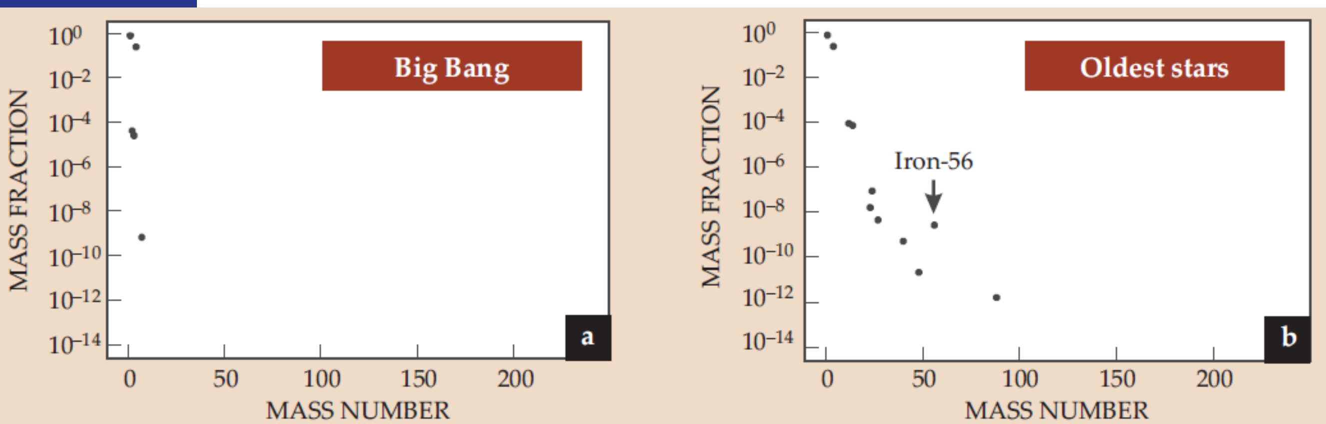
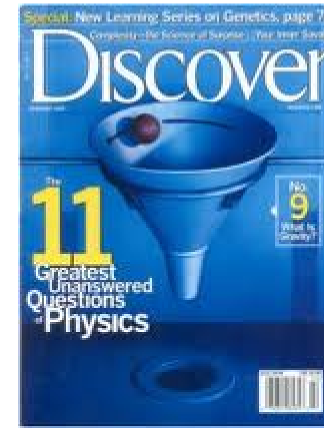
Outline

- Introduction and Motivation
- Principle of Mass Spectrometry
  - Storage rings
  - Penning traps
- The ISOLTRAP setup and Highlights
- Stellar nucelosynthesis and the origin of heavy elements
  - rp-process in the light-mass region
  - neutronisation in the crust of neutron stars
  - r-process in the heavy-mass region
- Possibilities at Future Facilities
- Summary

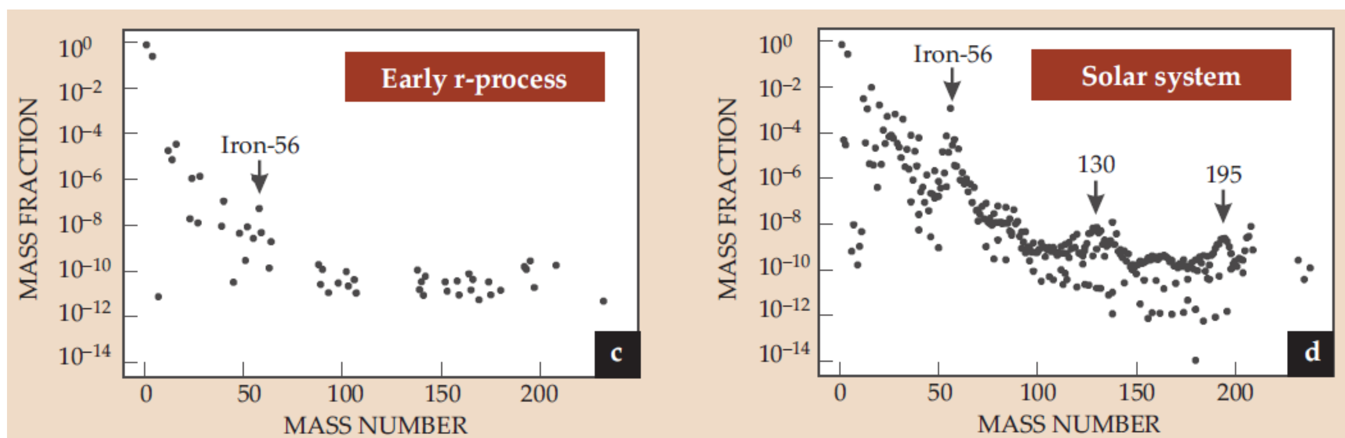


Creation of Heavy Elements





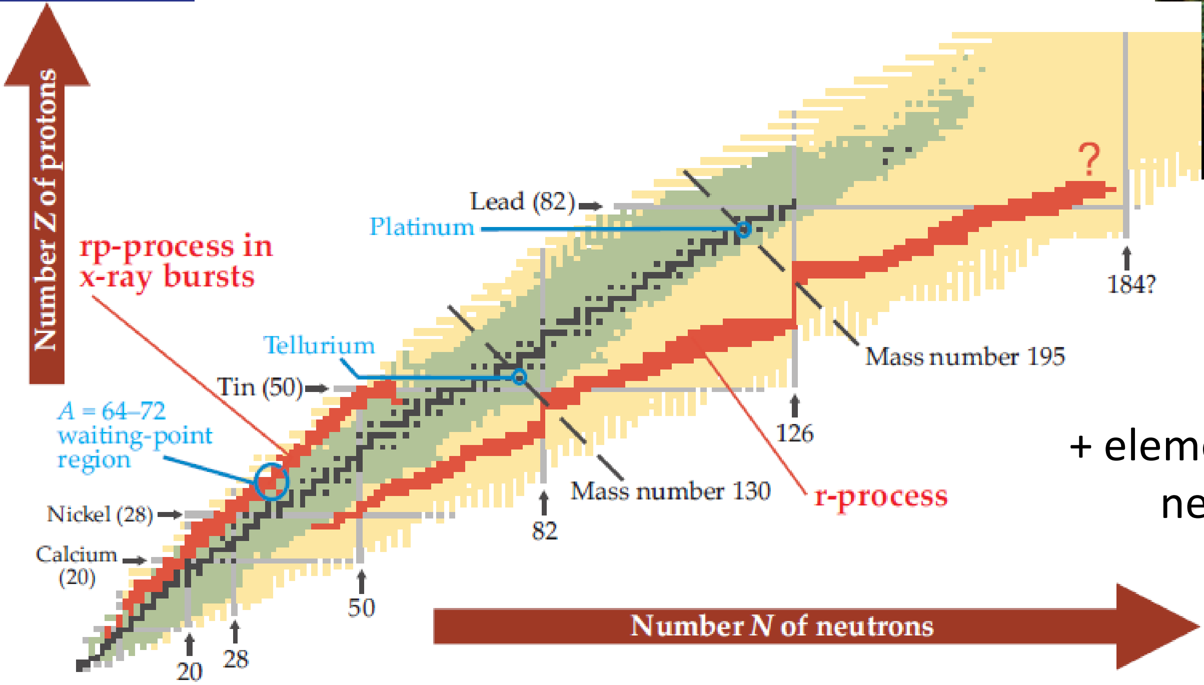
Age of the Universe



H. Schatz, Physics Today **61**, 40 (2008)

Possible Nuclear Processes

- Astrophysical models of nucleosynthesis treat an extreme environment
- Suffer from large uncertainties
  - Astrophysical site unknown
  - Theoretical predictions cannot rely on experimental data
- Precise masses needed to constrain models



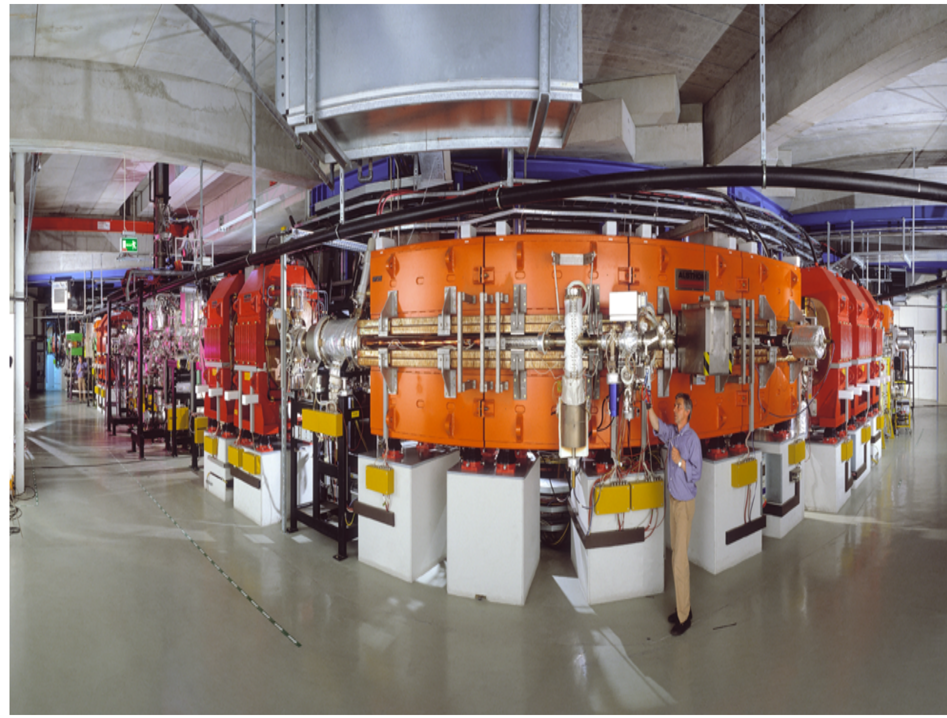
+ elemental composition of neutron-star crust

Storage and Cooling Techniques

Penning trap

Particles nearly at rest

Storage ring

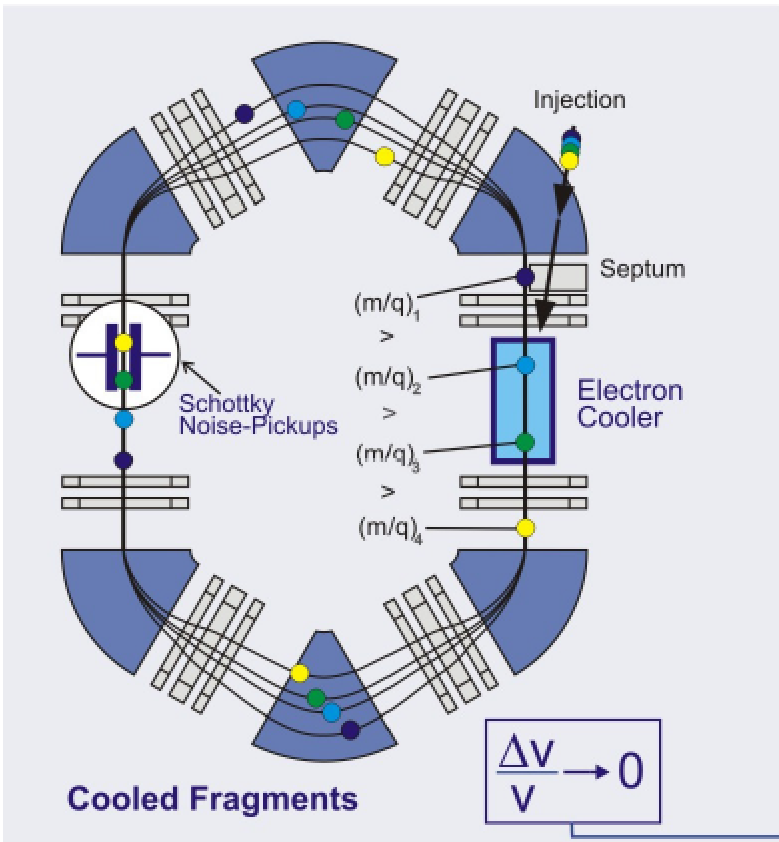


Relativistic particles

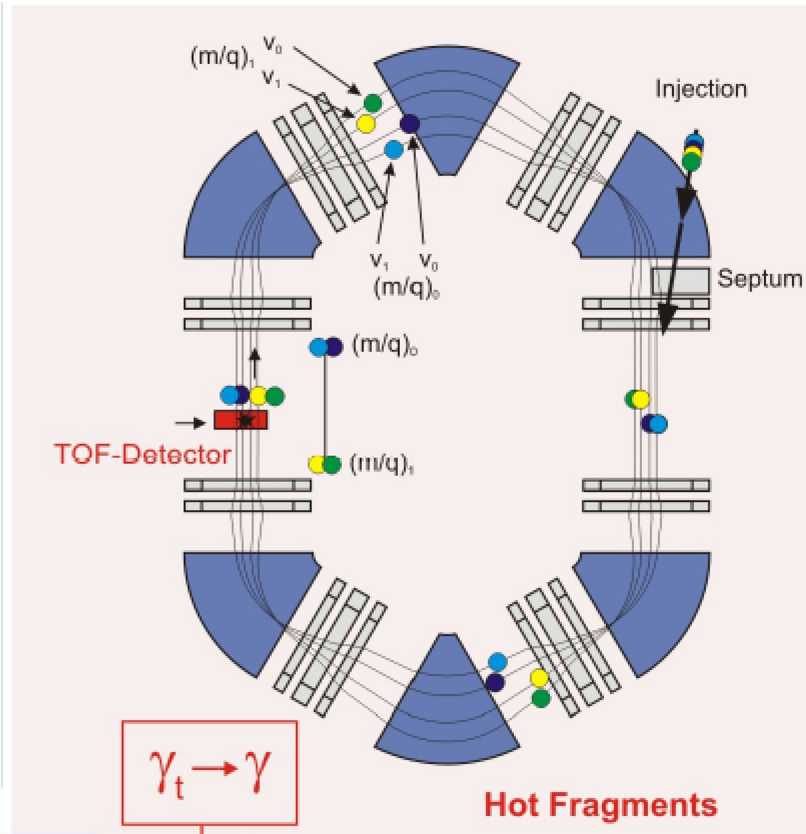
- Ions can be cooled and stored for very long times
- Single-ion sensitivity
- High accuracy achievable

Storage-Ring Spectrometry

Schottky mass spectrometry



Isochronous mass spectrometry

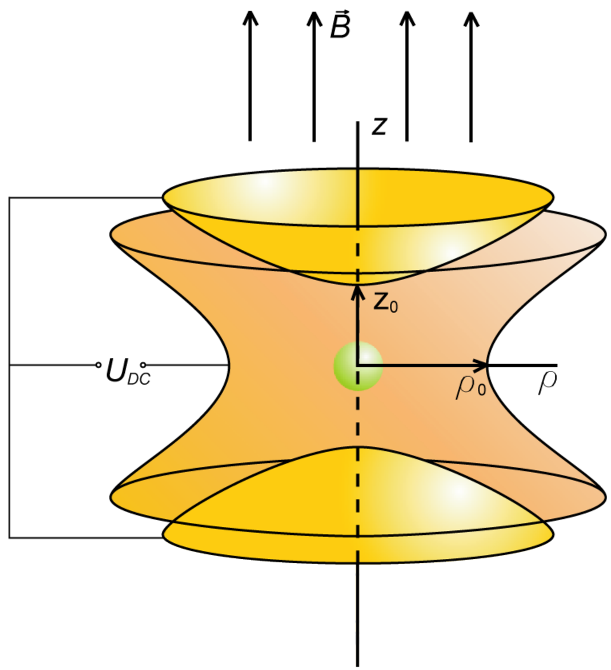


$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

B. Franzke *et al.*, Mass Spectrometry Reviews **27** (2008) 428

Penning-Trap Spectrometry

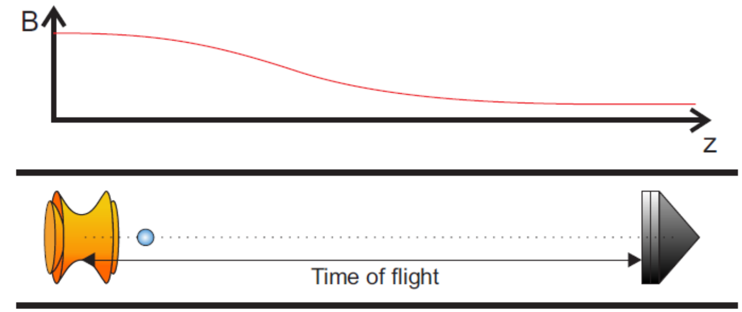
- Particle stored by superposition of strong homogeneous magnetic field in z direction and weak, electrostatic potential for axial confinement

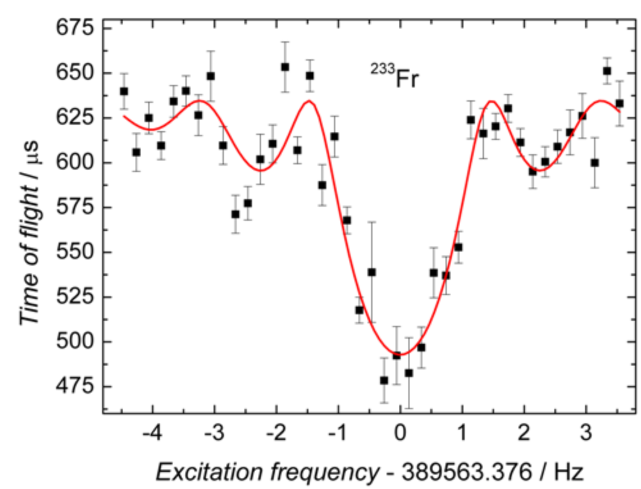


$$\omega_c = \omega_+ + \omega_- \quad \Rightarrow \quad \omega_c = \frac{q}{m} B$$

L. S. Brown *et al.*, Rev. Mod. Phys. **56**, 233 (1986)

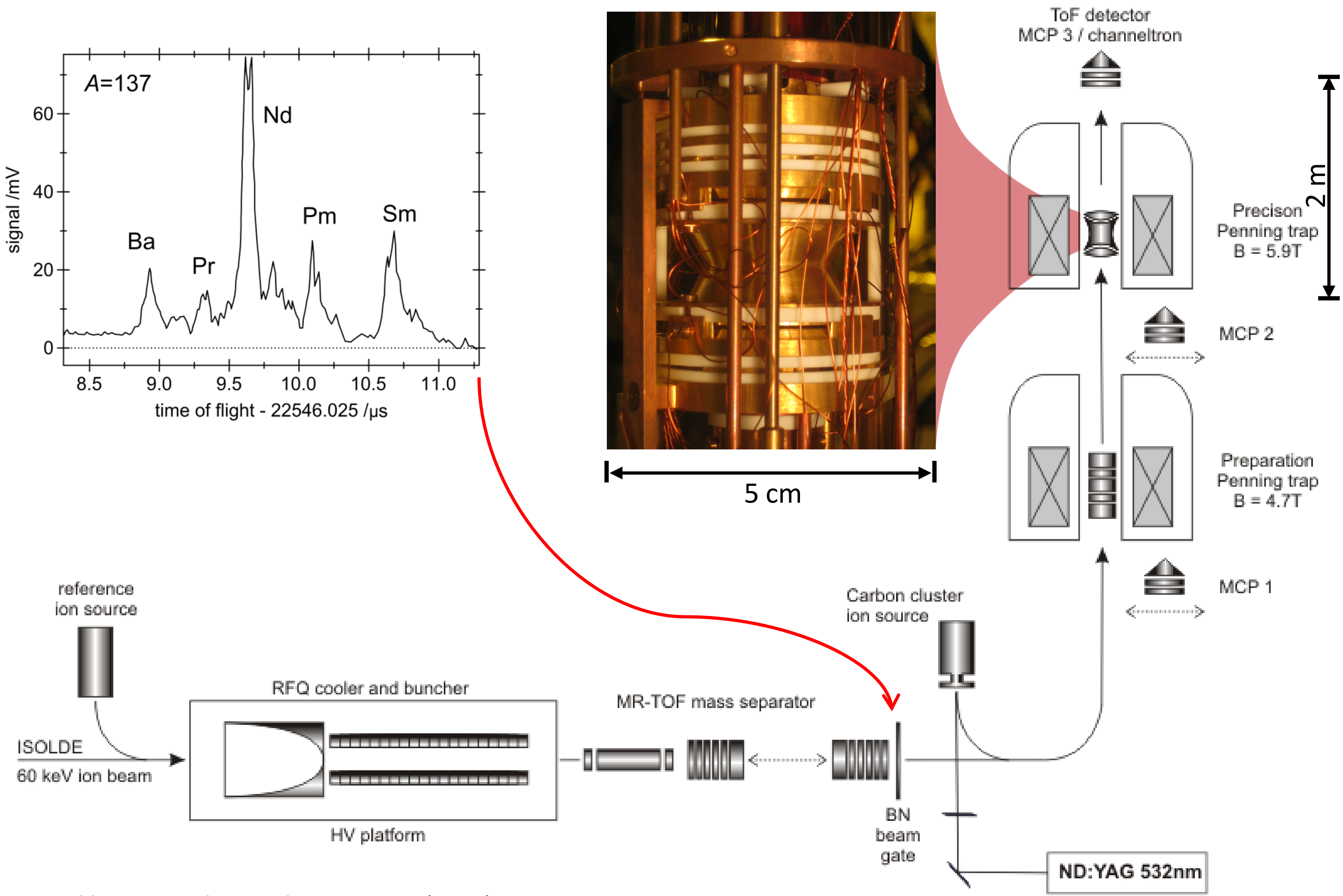
- From frequency to mass using time-of-flight ion-cylotron resonance technique





M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995)

The ISOLTRAP Setup

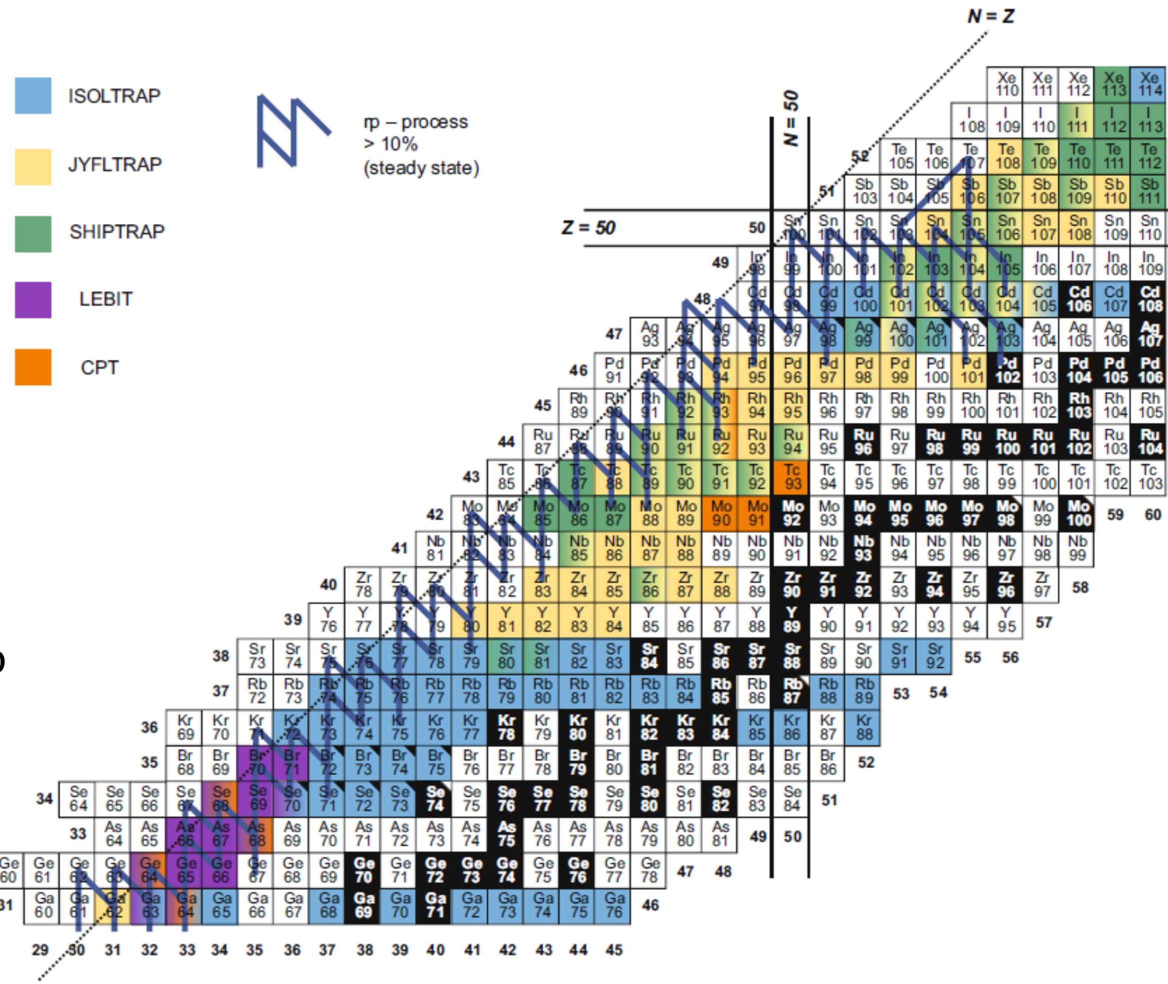


M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)

R. N. Wolf *et al.*, IJMS **313**, 8 (2012)

RP-Process above Z=32

- Precise masses used to calculate possible rp-process path using nuclear reaction networks
- International effort to improve calculation on element synthesis
- Well-known masses allow for an extrapolation towards the proton dripline
- Understanding of nuclear physics helps to assess amount of hydrogen in x-ray burst



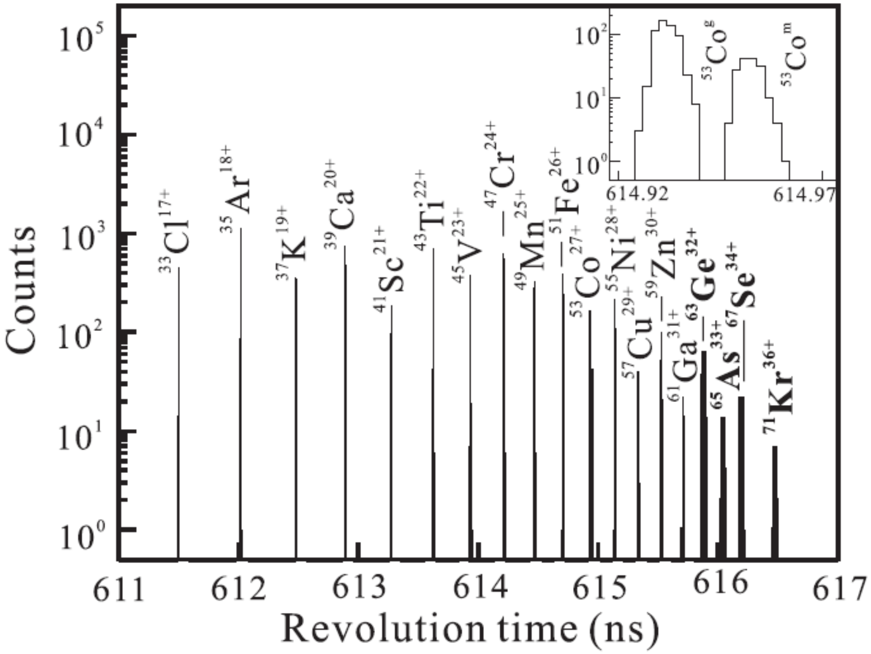
F. Herfurth *et al.*, EPJA **47**, 75 (2011)

Mass Measurements at CSRe

NUCLEAR ASTROPHYSICS

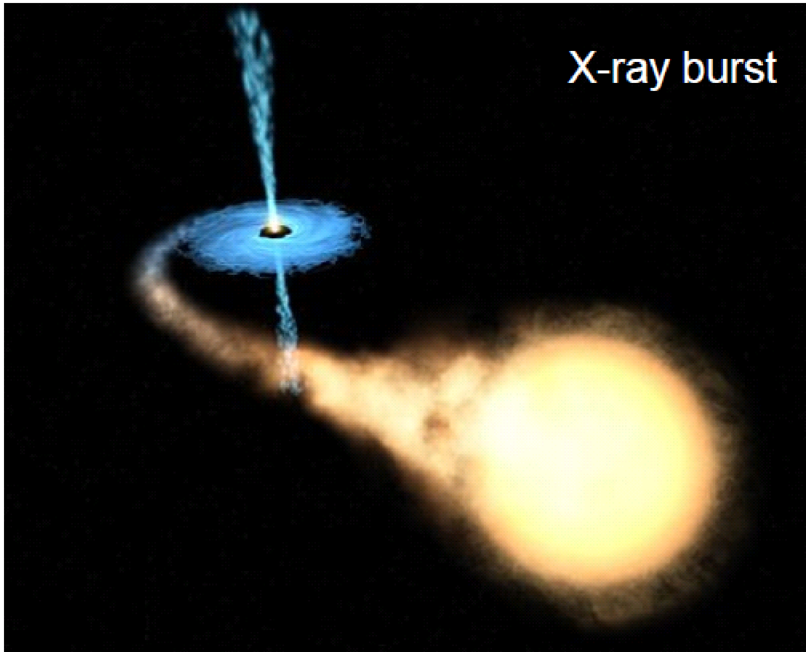
Star bursts pinned down

One of the main uncertainties in the burn-up of X-ray bursts from neutron stars has been removed with the weighing of a key nucleus, ^{65}As, at a new ion storage ring.



New masses: ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr

-> ^{64}Ge not a waiting point

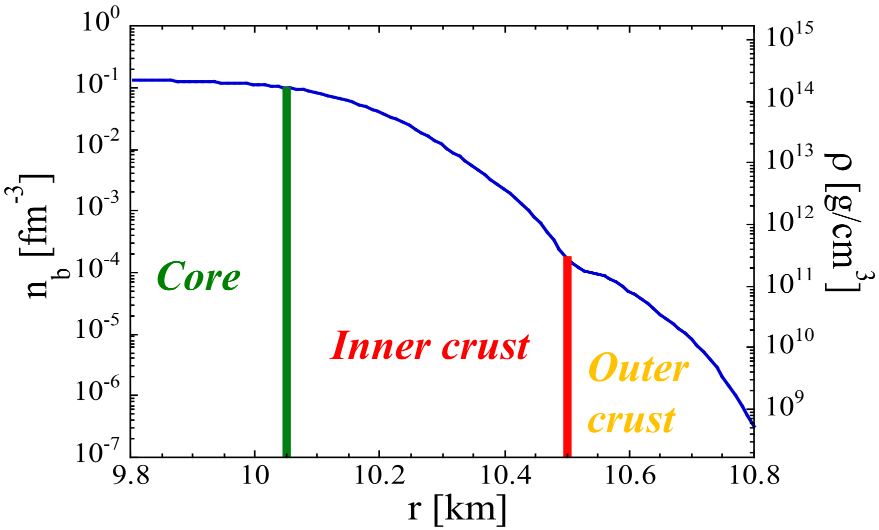


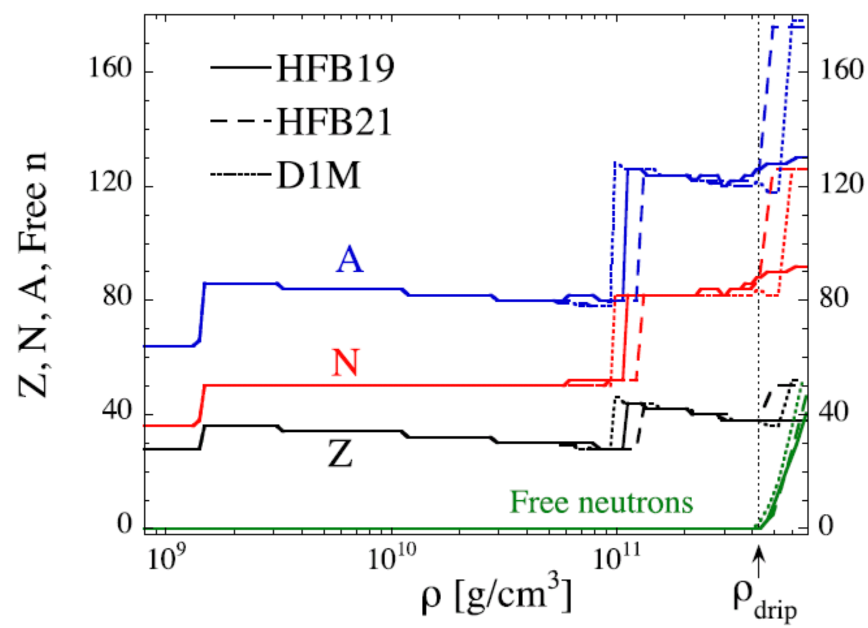
X. Tu *et al.*, Phys. Rev. Lett. **106**, 112501 (2011)

X. Tu *et al.*, NIM A **654**, 213 (2011)

Neutron Stars – Birthplace of Heavy Elements?

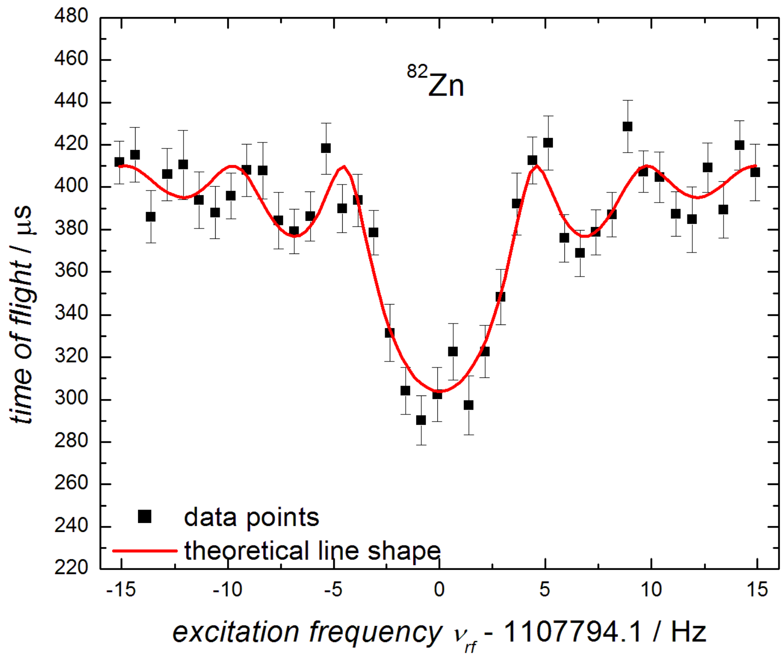
- Neutronization of matter: neutron-rich nuclei become “equilibrium nuclei”
- Ground-state composition of outer crust can be modeled even at zero temperature
- Two groups of nuclides constituting the outer crust: *N*=50 and *N*=82
- Mass models used whenever experimental masses not available
- Is ^{82}Zn part of outer crust?

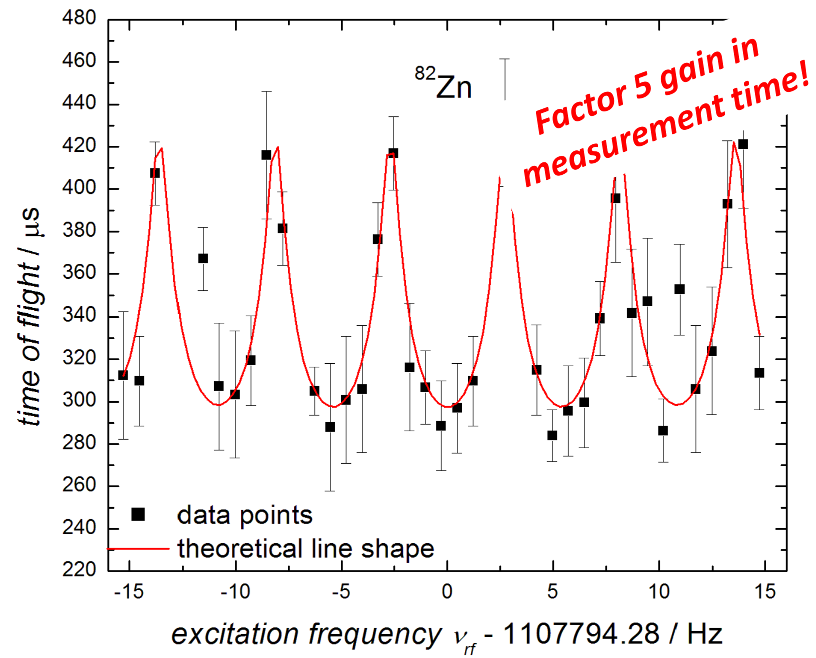




S. Goriely et al., A&A **531**, A78 (2011)

^{82}Zn Mass and Half-Life



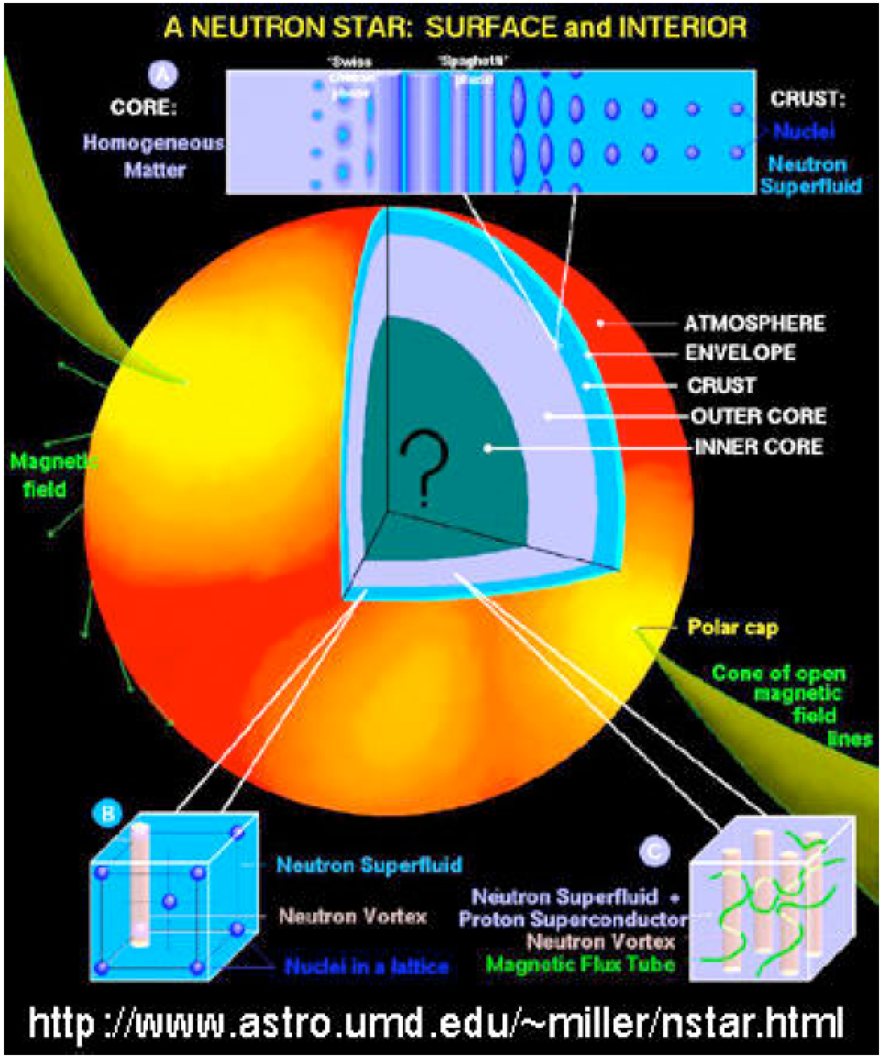


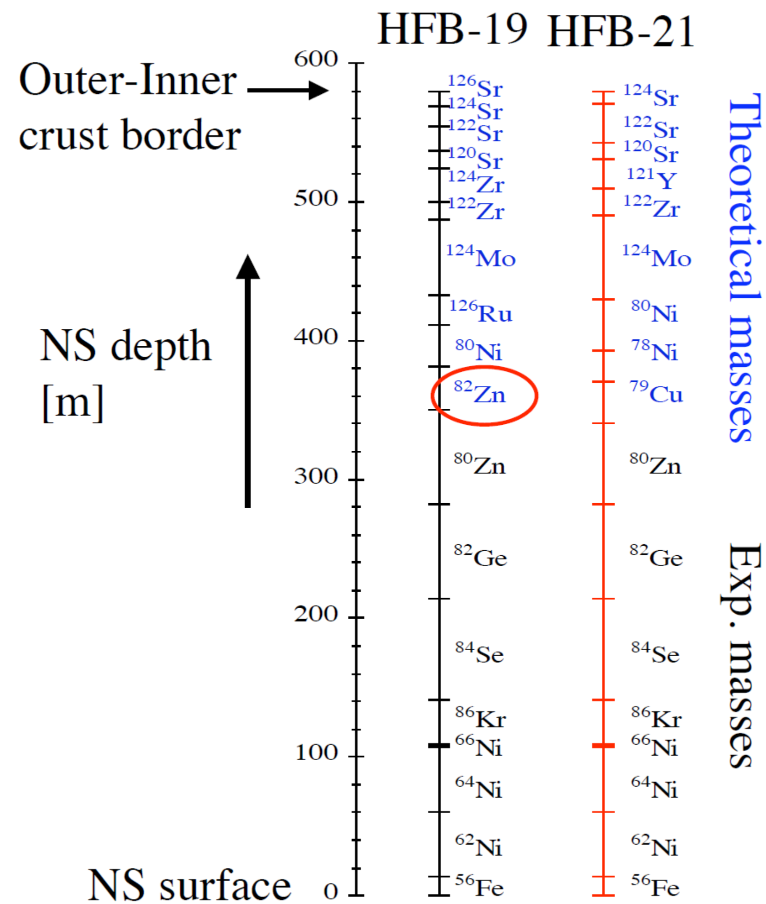
- Combined all ISOLDE know-how to realize this measurement
  - Special measurement cycle at ISOLTRAP
  - UCx target with quartz transfer line
  - neutron converter
  - RILIS (tune every 15 min.)

Isotope	Uncertainty	
	Mass	Half-life
^{80}Zn	4 keV	27 ms
^{81}Zn	4 keV	26 ms
^{82}Zn	6 keV	70 ms

S. George *et al.*, Phys. Rev. Lett. **98**, 162501 (2007)
M. Kretzschmar, Int. J. Mass Spectrom. **264**, 122 (2007)
and many others...

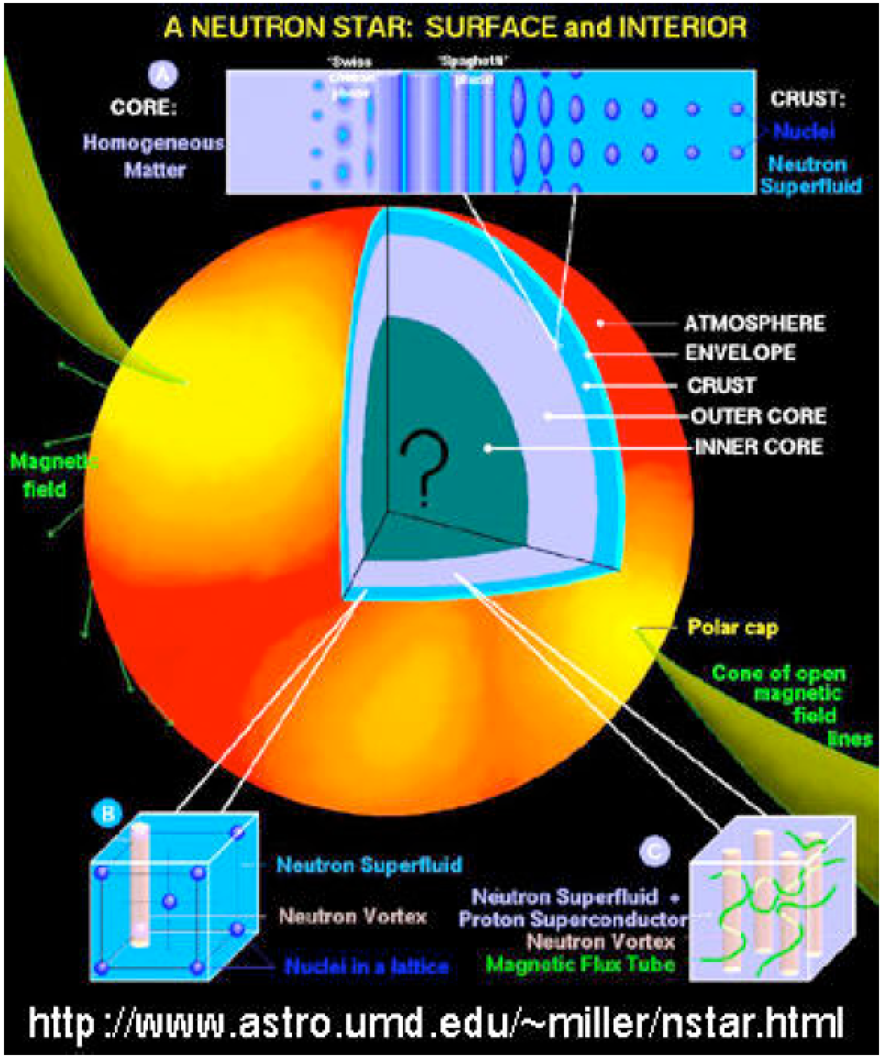
Depth profiling of a Neutron Star





Courtesy S. Goriely

Depth profiling of a Neutron Star



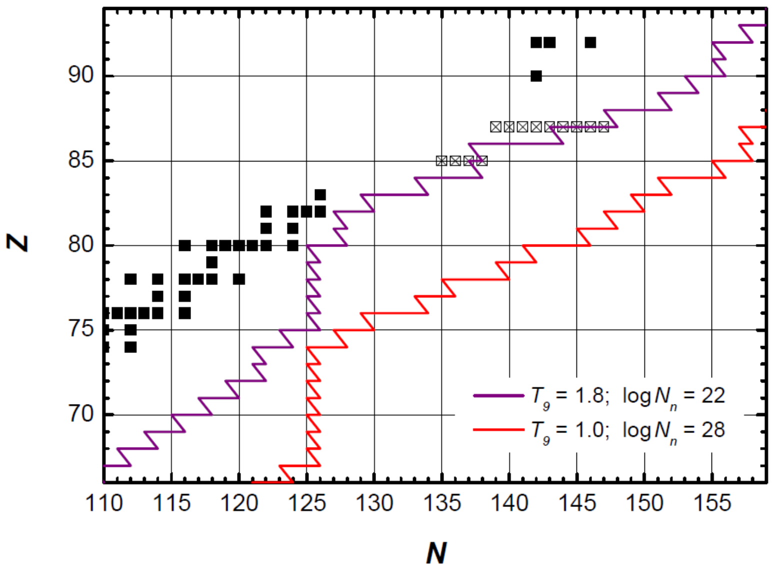
Results removed from presentation

Courtesy S. Goriely

R-Process Above *A*=200

- Focus: Precision mass measurements of nuclei with $N>1.5Z$ and $t_{1/2}$ in ms range
  - Uncertainties of 10^{-6} needed to impact modelling
  - Beta-decay half-lives offer information about stellar evolution

- Experimental challenge
  - Low production yields
  - High contamination ratios



Results removed from presentation

Neutron-rich masses on Fr, Ra, Rn, and At also from storage-ring spectrometry at GSI.

L. Chen et al., Nucl. Phys. A **882**, 71 (2012)

What Comes Next?

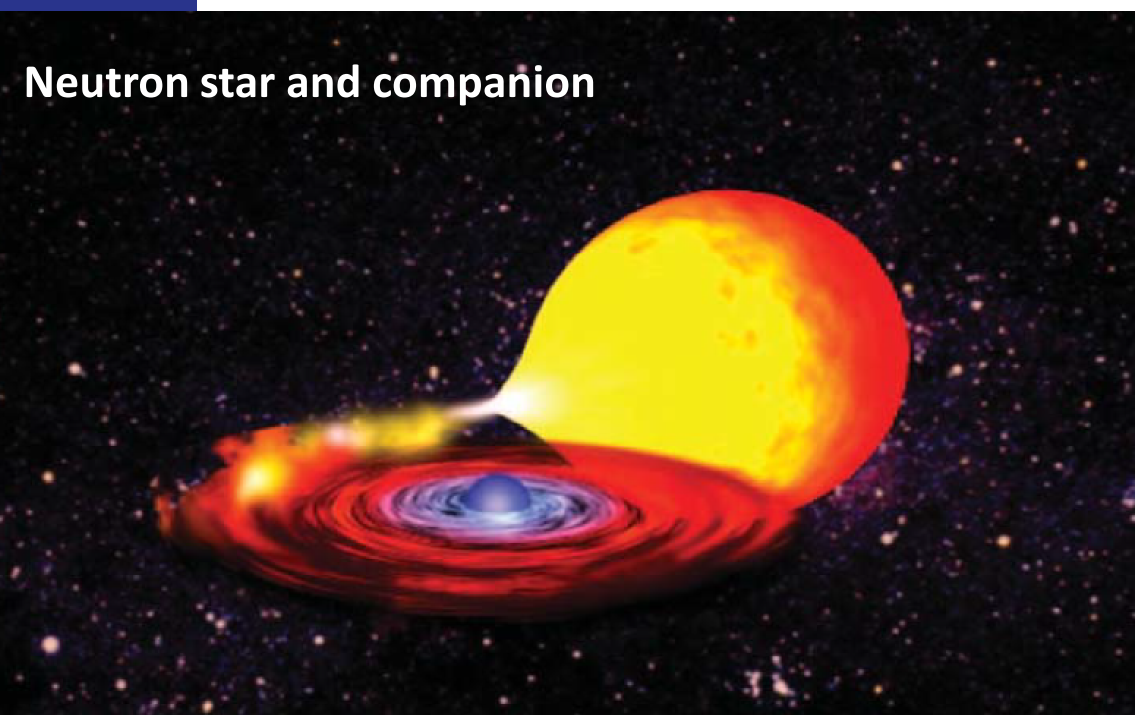
LETTER

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

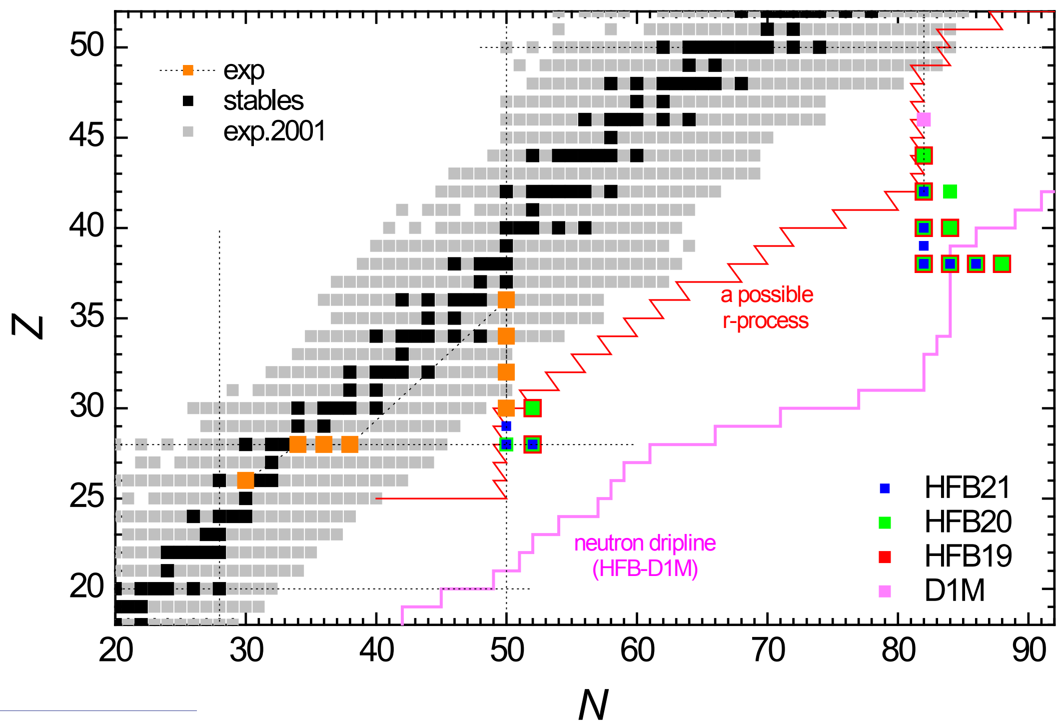
- Heaviest neutron star with $1.97\pm0.04M_{sun}$

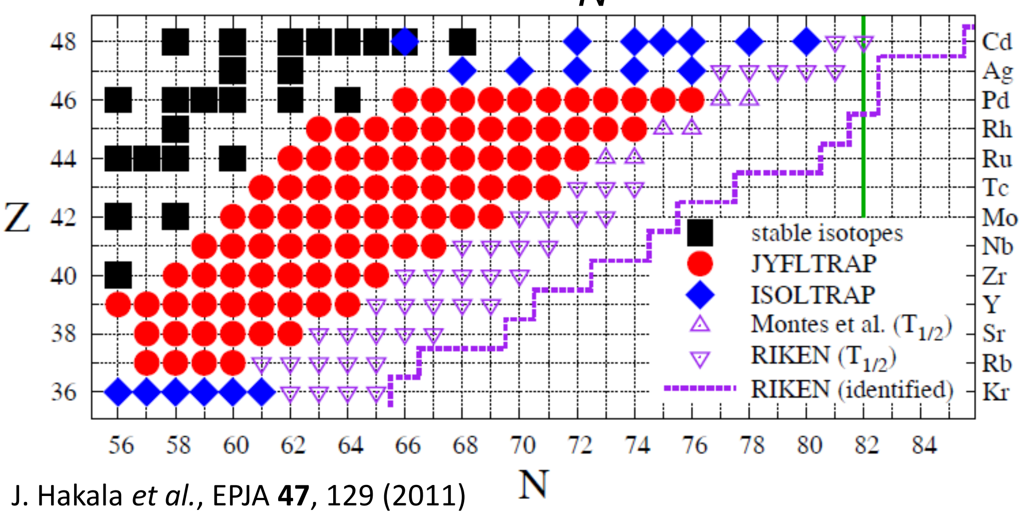


- Direct measurement of neutron-star mass from increase in signal-travel time near companion
- Heavy constraint on equation of state and thus model space of stellar nucleosynthesis
  - Impact of 3N-forces on neutron matter (group of A. Schwenk)

ISOLDE

Measurement Possibilities





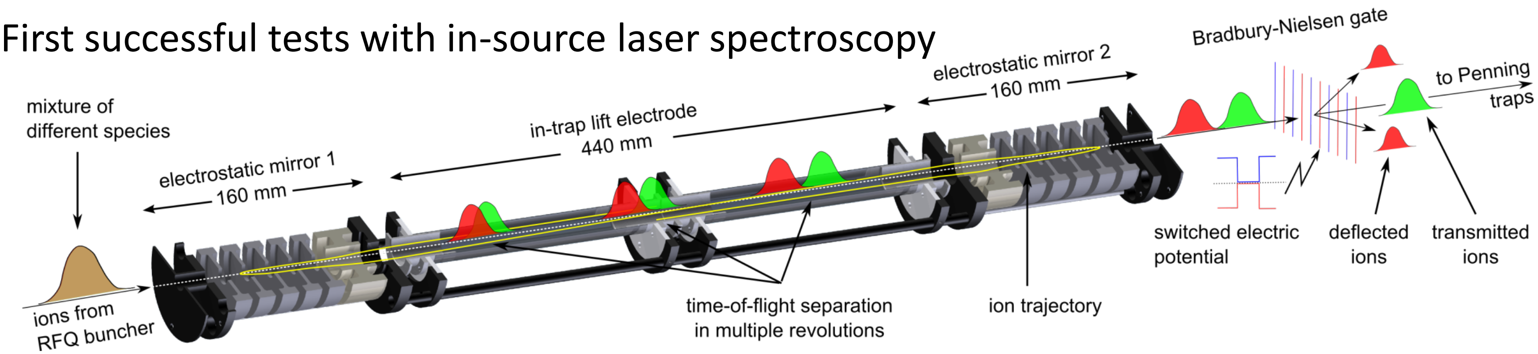
J. Hakala *et al.*, EPJA **47**, 129 (2011)

- *N*=82 nuclei constitute outer crust according to models of nucleosynthesis
- MLLTRAP + MR-TOF at SPIRAL 2: higher yields on n-induced fission
  - Groups of P. Thirolf and W. Plass
- HIE-ISOLDE: increase in proton energy to 2GeV and proton current to 5μA will enhance fission products

more neutron-rich, heavy nuclei!

Summary

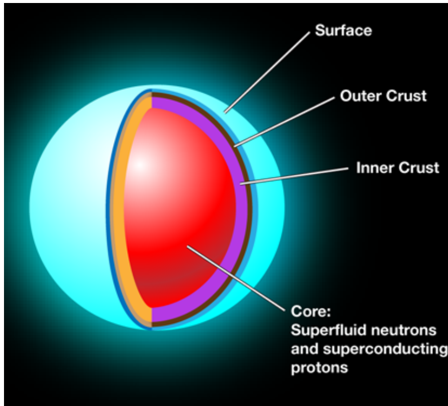
- Current ISOLTRAP setup and highlights presented
  - Mass database: www.cern.ch/isoltrap/database/isodb.asp
  - Successfully comissioned MR-TOF with online data (similar work at GSI)
  - First successful tests with in-source laser spectroscopy



- Comprehensive understanding of stellar processes requires precise mass values but also progress in theory. Recent examples:
  - A. Estradé *et al.*, PRL **107**, 172503 (2011)
  - A. Arcones and G. F. Bertsch, PRL **108**, 151101 (2012)

- The mass of ^{82}Zn is the most exotic yet measured for modelling neutron stars

- The very neutron-rich *N*=82 nuclei will play a big role in the modelling of neutron stars



ISOLTRAP Collaboration

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

S. George, M. Rosenbusch, R. Wolf, L. Schweikhard, F. Wienholtz

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S. Schwarz, G. Bollen

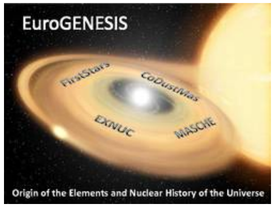
M. Breitenfeldt

S. Naimi

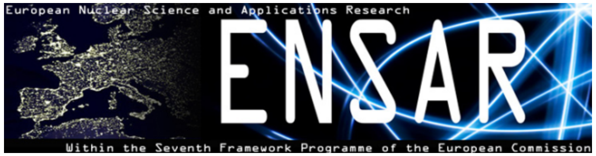
Thanks...

- ... the ISOLDE Target, RILIS and Technical Team
- ... for funding: BMBF, GSI, CERN, ISOLDE, MPG

Part of...



NAVI @ GSI



Thank you for your attention!

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