Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Constraining the neutron star crust via mass measurements

Spokesperson: Pierre Delahaye (pierre.delahaye@ganil.fr)
Local contact: Vladimir Manea (vladimir.manea@cern.ch)

N. Althubiti[1], P. Ascher[2], D. Atanasov[3], F. Aymard[4], B. Bastin[5], K. Blaum[3], D. Beck[6], M. Breitenfeldt[7,8], R. B. Cakirli[9], P. Chauveau[5],T. E. Cocolios[1], G. De France[5], F. De Oliveira[5], P. Delahaye[5], S. Eliseev[3], T. Eronen[10], S. George[3], F. Gulminelli[4], F. Herfurth[6], A. Herlert[11], M. Kowalska[8], S. Kreim[3,8], Yu. A. Litvinov[6], D. Lunney[12], M. MacCormick[13], V. Manea[3], E. Minaya Ramirez[3], S. Naimi[14], D.Neidherr[6], M. Rosenbusch[15], A. de Roubin[3], H. Savajols[5], L. Schweikhard[15], A. Welker[16], F. Wienholtz[15], R. N. Wolf[3], K. Zuber[16]

[1]The University of Manchester, Manchester, United Kingdom
[2]CENBG, Bordeaux, France
[3]Max Planck Institute for Nuclear Physics, Heidelberg, Germany
[4]Laboratoire de Physique Corpusculaire Caen, France
[5]GANIL, Caen, France
[6]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[7]Grupo de Fisica Nuclear, Universidad Complutense, Madrid, Spain
[8]CERN, Geneva, Switzerland
[9]Istanbul University, Department of Physics, Istanbul, Turkey
[10]University of Jyväskylä, Finland
[11]FAIR GmbH, Darmstadt, Germany
[12]CSNSM-IN2P3-CNRS, Université Paris-Sud, Orsay, France
[13]Institut de Physique Nucléaire, IN2P3-CNRS, Université Paris-Sud, Orsay, France
[14]RIKEN, Wako, Saitama, Japan
[15]Ernst-Moritz-Arndt-University, Greifswald, Germany
[16]Technical University, Dresden, Germany

Neutron stars

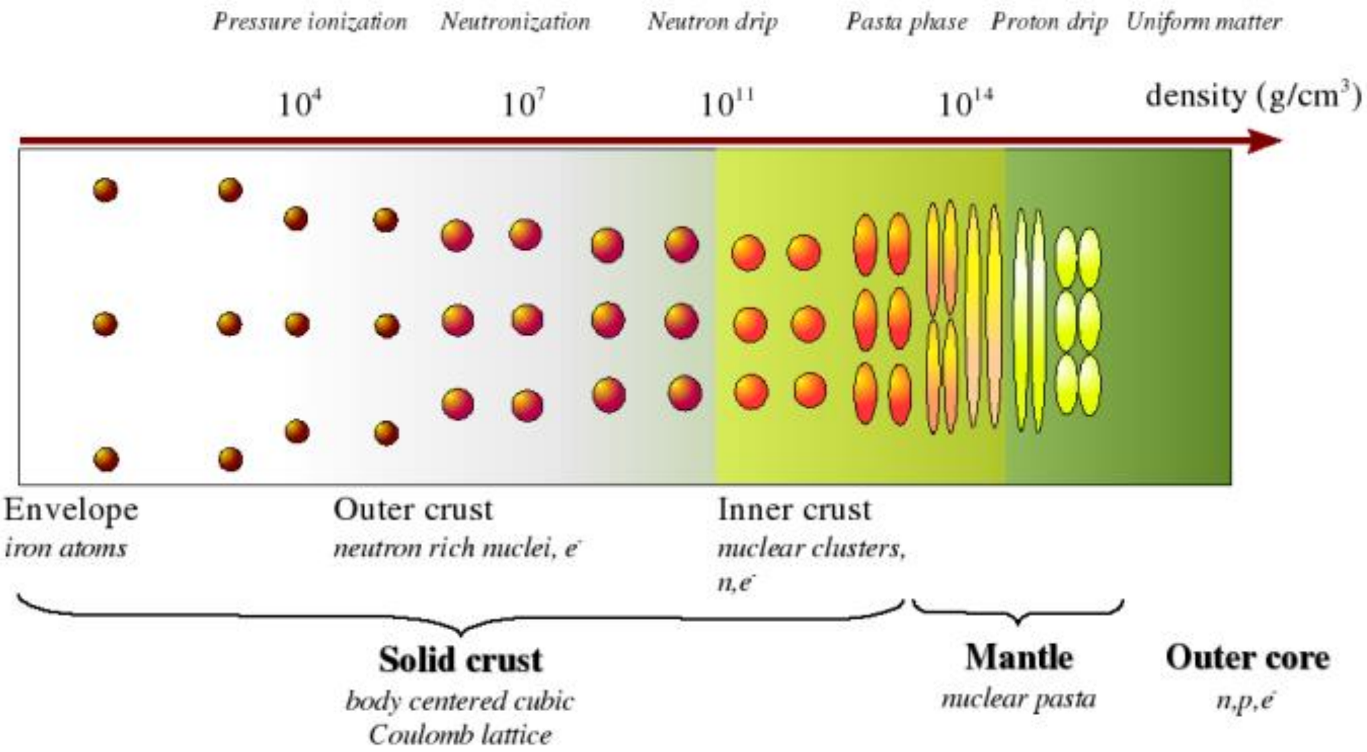
Radiation from the pulsar PSR B1509-58

- 2000 NS observed, 5% in binary systems
- Mass: 1 - 2 $M_\odot$
- Size ~ 10-20 km diameter
- Core density up to 5 -10 ρ_0
- Stellar remnant after a Supernova
- T(birth)~10 MeV
  - Thermalization ~100 years
  - Decays first via neutrino emission then gamma

Interests of studying the Neutron Star crust with T>0:

- Cooling mechanism
  - Heat capacity is mostly contained in the crust!
- Nucleosynthesis of elements beyond Fe: r-process
  - Neutron star binaries: an alternative site to supernovae for **the r-process**
  - Accretion of matter in the crust from a companion neutron star **T ~1-4MeV**

Neutron star crust



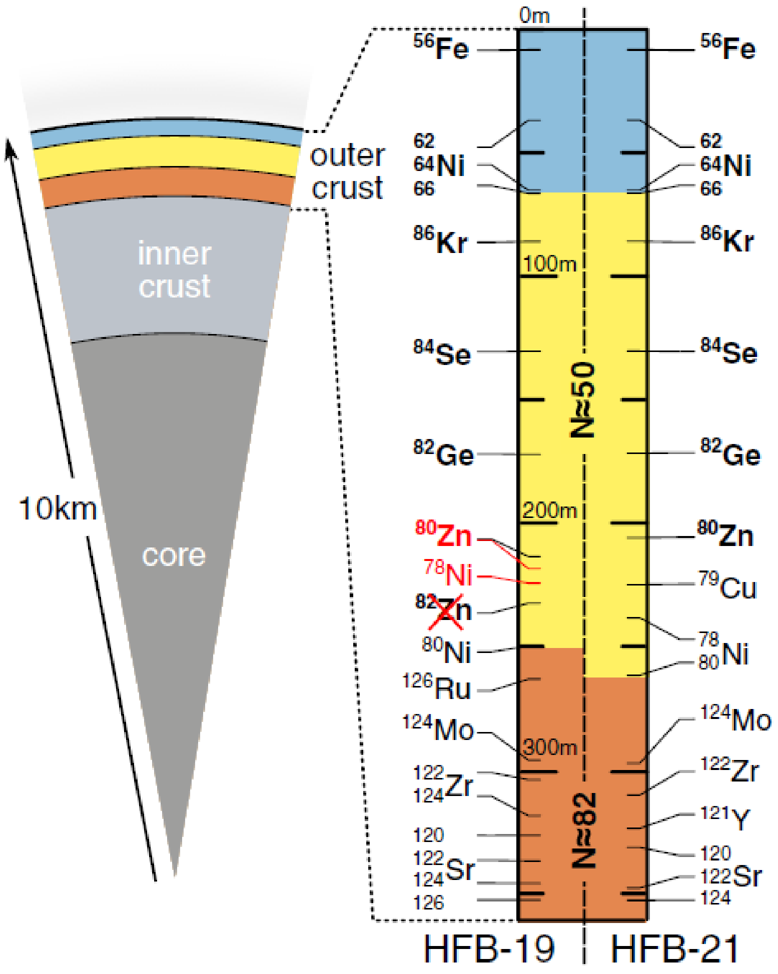
Modeling the neutron star crust is possible as $\rho<\rho_0$

- Outer crust composition defined by β – equilibrium
- T=0: crystal of nuclei, A,Z = f(depth)

Only physics input: nuclear masses!

Outer – Inner crust frontier: extremely neutron rich nuclei

Composition of the crust T=0



10 km diameter, $1.4M_{\odot}$ star

R.N. Wolf et al, PRL 110(2012)041101

ISOLTRAP: mass measurement of ^{82}Zn

Discrimination between HFB-19 and HFB-21

- ME (ISOLTRAP) = - 42.314(3) MeV/c^2
- ME (HFB19) = -42.96 MeV/c^2
- ME (HFB21) = -42.70 MeV/c^2

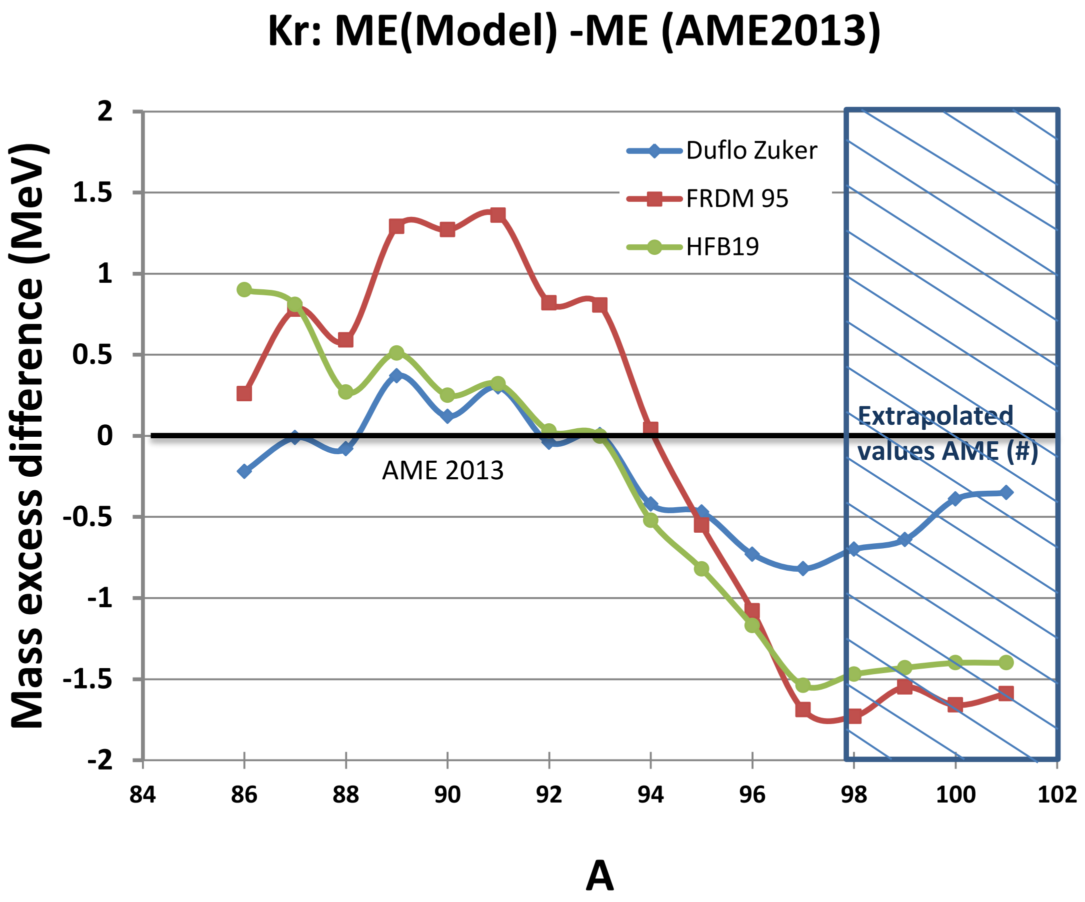
Extensive comparison of mass models:
S. Kreim et al, IJMS 349-350(2013)63

Mass models:
Accuracies better than 0.5 MeV/c^2 are needed

Going further in giving direct constraints is impossible

Accuracies of the mass models

Kr isotopic chain



Deviations from AME (σ_{rms}):

Duflo – Zuker: 0.42 MeV/c²

FRDM 95: 1.03 MeV/c²

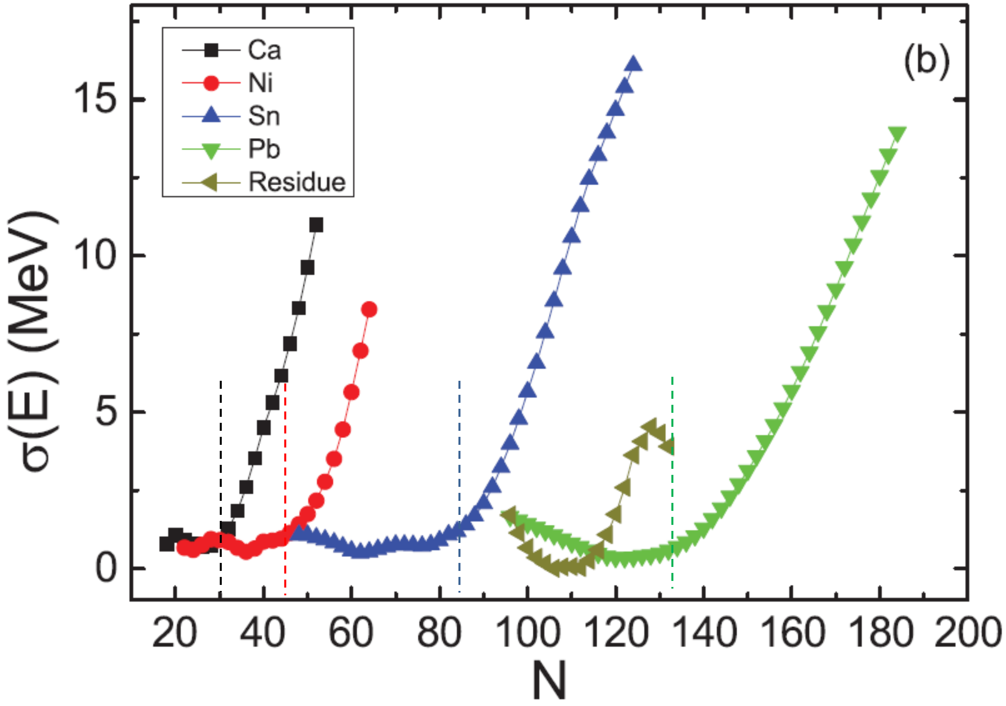
HFB19: 0.77 MeV/c²

Extrapolated masses: uncertainties

See eg: PHYSICAL REVIEW C **87**, 034324 (2013)

Propagation of uncertainties in the Skyrme energy-density-functional model

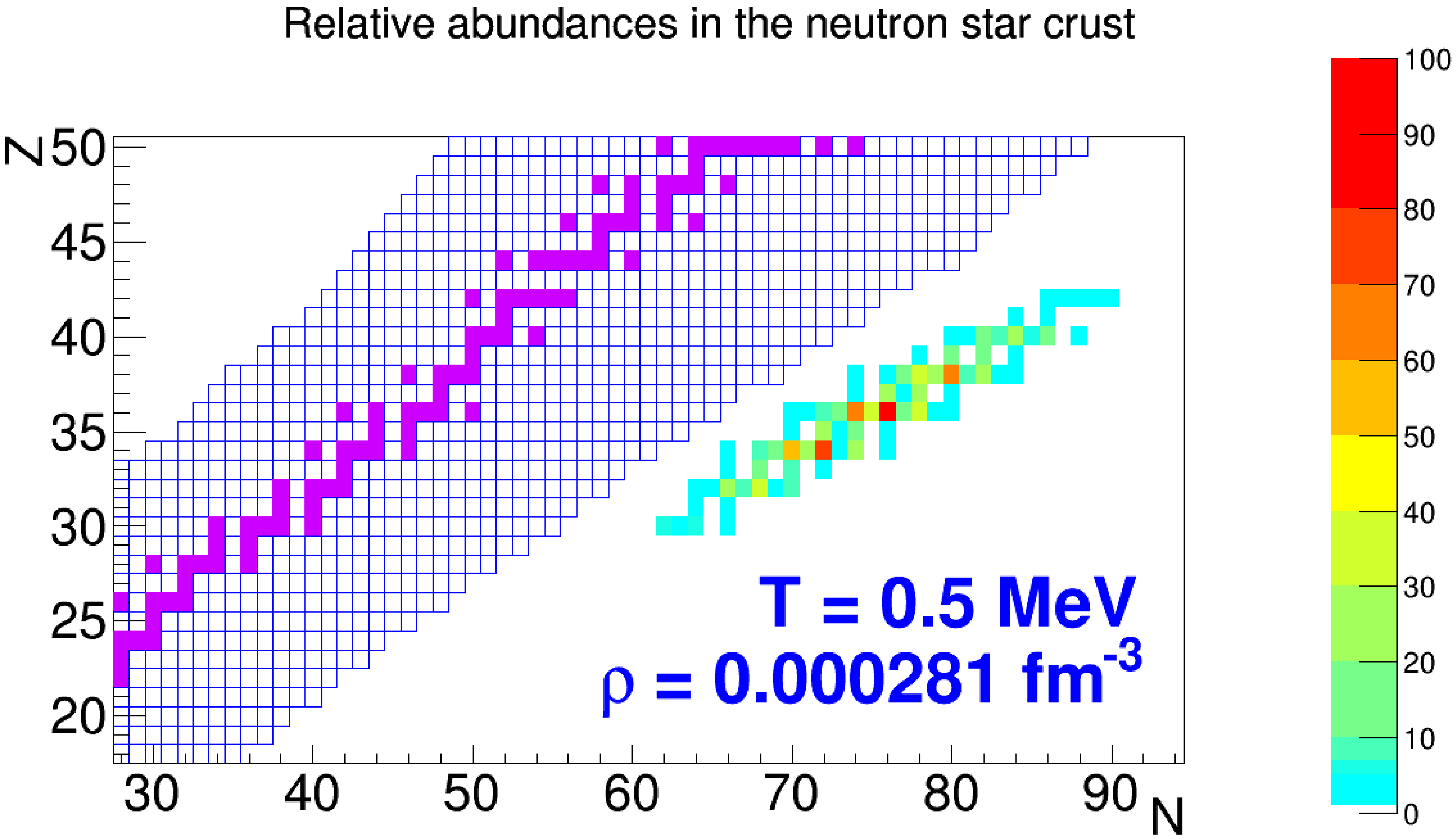
Y. Gao (高原),[1] J. Dobaczewski,[1,2] M. Kortelainen,[1] J. Toivanen,[1] and D. Tarpanov[2,3]



Dashed lines: last known nuclides

Goal: constraining the mass models as close as possible to the region of interest

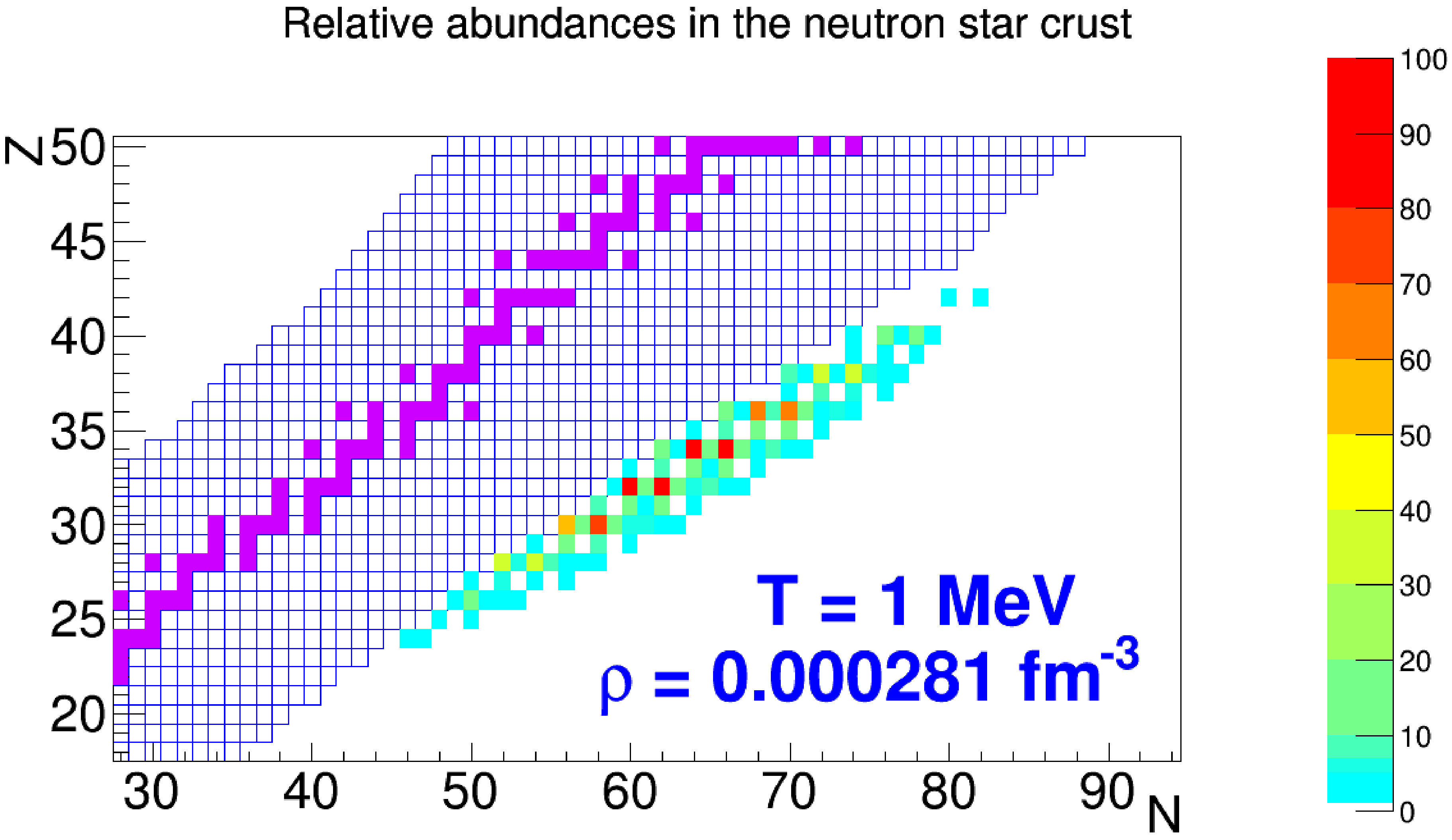
T>0



Modelisation: F. Gulminelli, F. Aymard and A. Raduta

Masses: AME 2013 and E. Chabanat et al., Nucl. Phys. A 635 (1998) 231.

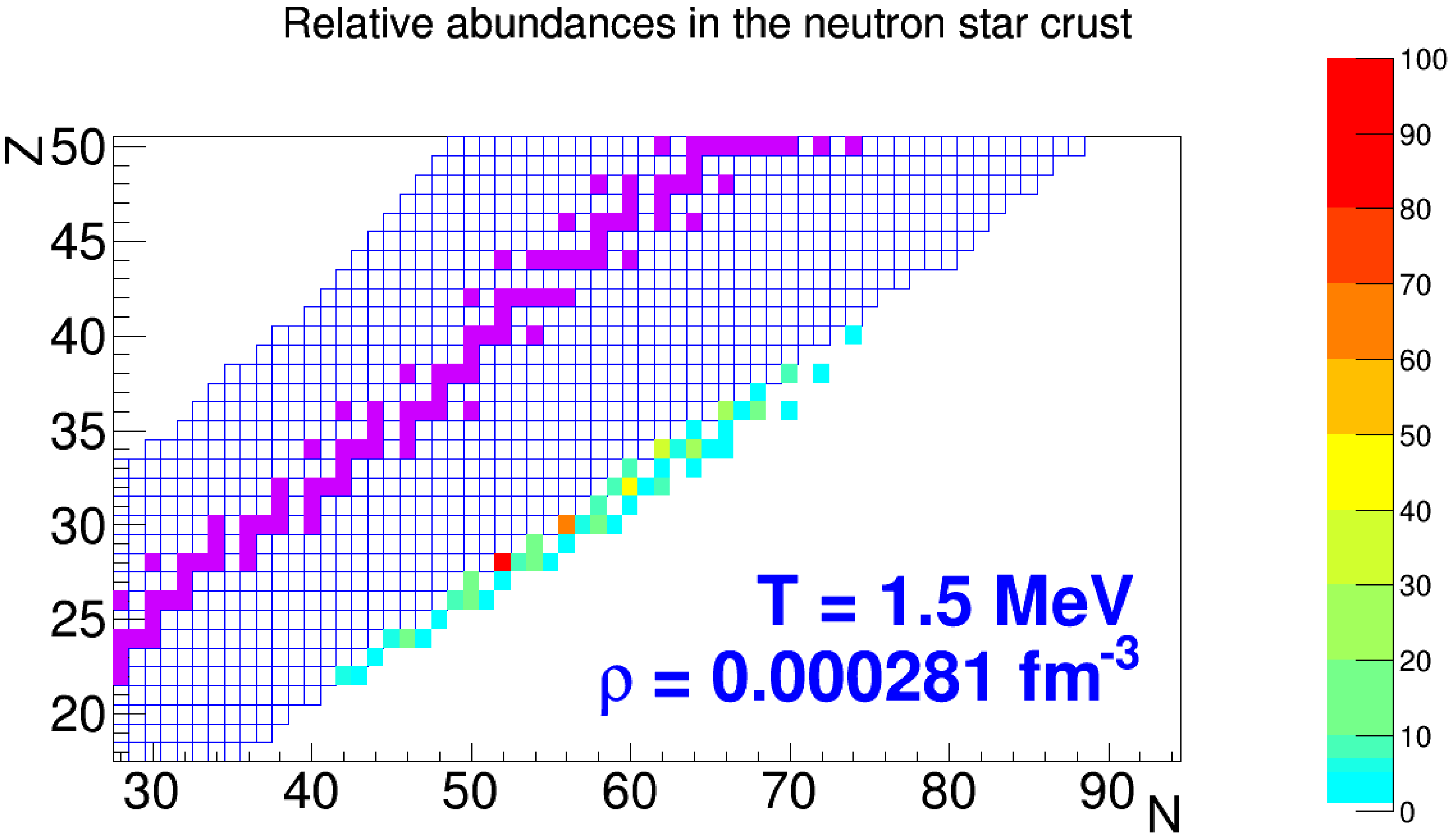
T>0



Modelisation: F. Gulminelli, F. Aymard and A. Raduta

Masses: AME 2013 and E. Chabanat et al., Nucl. Phys. A 635 (1998) 231.

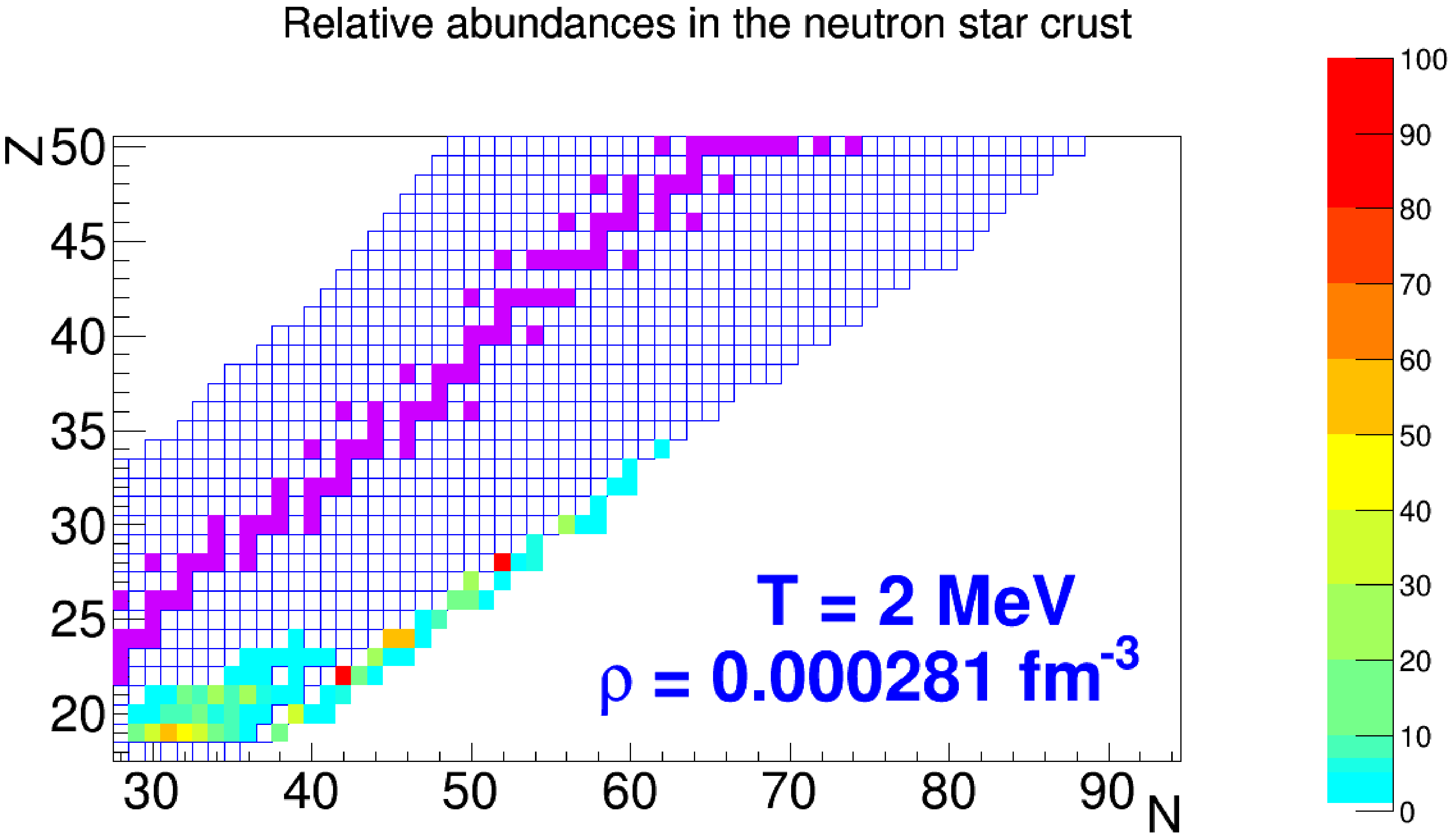
T>0



Modelisation: F. Gulminelli, F. Aymard and A. Raduta

Masses: AME 2013 and E. Chabanat et al., Nucl. Phys. A 635 (1998) 231.

T>0

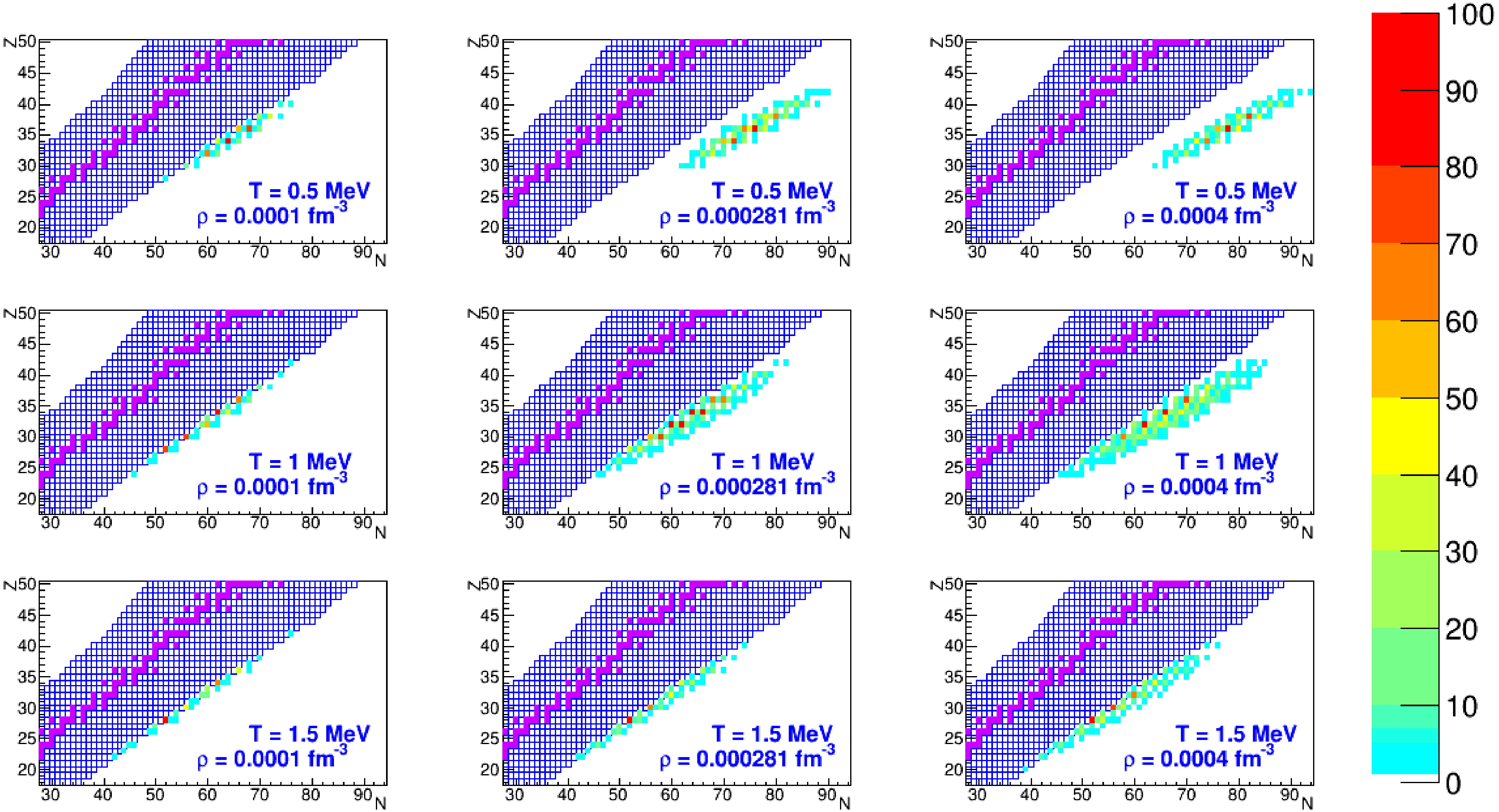


Modelisation: F. Gulminelli, F. Aymard and A. Raduta

Masses: AME 2013 and E. Chabanat et al., Nucl. Phys. A 635 (1998) 231.

T>0

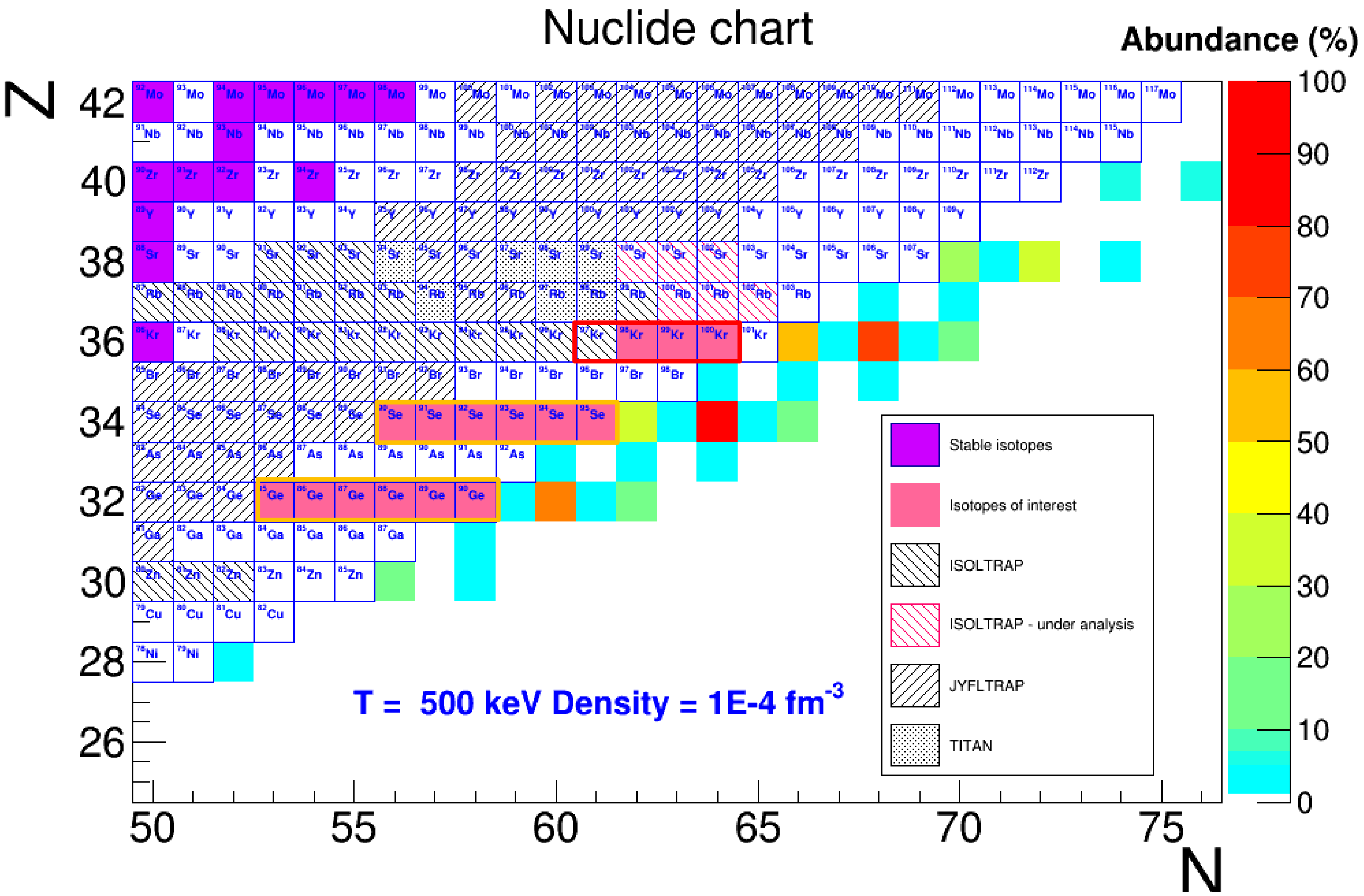
Relative abundances in the neutron star crust



Modelisation: F. Gulminelli, F. Aymard and A. Raduta

Masses: AME 2013 and E. Chabanat et al., Nucl. Phys. A 635 (1998) 231.

Mass measurements



This proposal

Associated LoI

Mass measurements

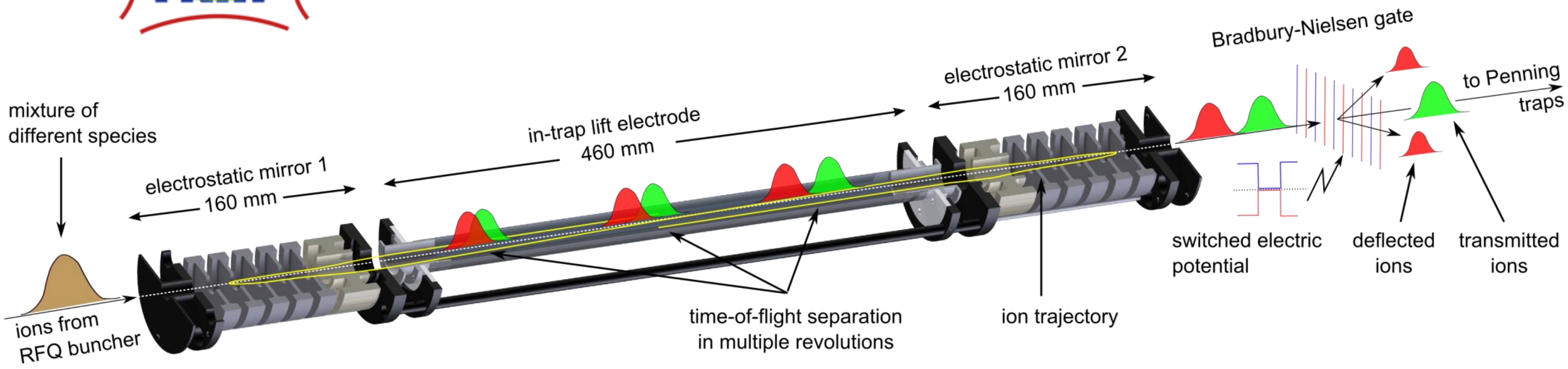
- Typical trapping time: 10 ms
- Resolving power: up to 10^5
- Mass measurement: $\delta m/m \sim 5.10^{-7}$

ISOLTRAP MR ToF MS:

R. Wolf et al., IJMS 349 (2013)123 and ref therein

$^{53-54}$Ca mass measurements:

F. Wienholtz et al., Nature **498** (2013) 346-349



Photograph Courtesy : R. N. Wolf (University of Greifswald)

Mass measurements

- ➢ intensities down to ~1pps
- ➢~50 keV mass uncertainties

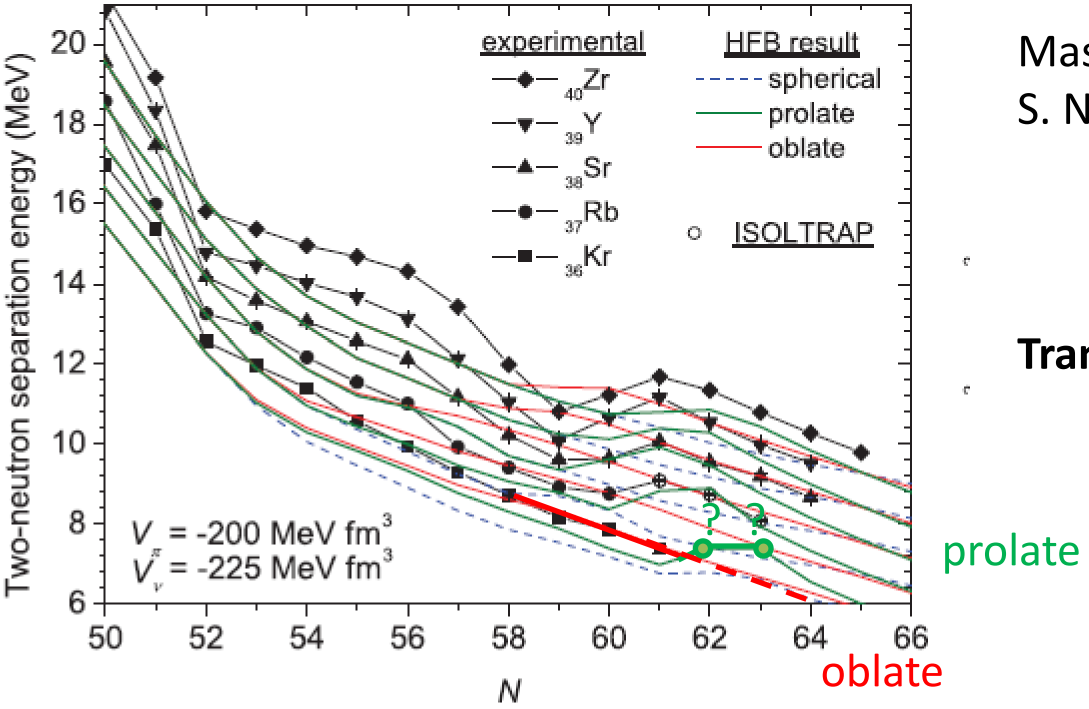
Identification and Yield measurement

- ➢ intensities down to a fraction of pps

Highly suited to these measurements
Complementary to the Penning traps

The Kr chain

V. Manea et al, Phys. Rev. C 88(2013)054322



Mass measurements Kr isotopes
S. Naimi et al, PRL

Transition in Kr isotopes: N=62?

HFB calculations for masses and charge radii

N=60 shape transition: emergence of a prolate shape

Delayed in Kr chain?

Masses of $^{98\text{-}99}$Kr needed

Beam request

A	**Element**	**Half life (ms)**	**δm (keV)**	**Yield (ions/μC)**	**Method proposed**	**Measurement time (UT=8h)**
97	Kr	62.2	130	6500	Penning//MR-ToF	6
98	Kr	42.8	300#	470	Penning//MR-ToF	
99	Kr	40	500#	9	MR-ToF	4
100	Kr	12	400#	-	MR-ToF	2 (+2)
		Kr beamtime			**Preparation**	2
					Total (UT)	**16**

2 shifts: beam preparation, tuning FEBIAD and target parameters

Possibility of using a state of the art UCx target, tested within ACTILAB

- Carbon nanotube target
- Short diffusion time of Rb demonstrated

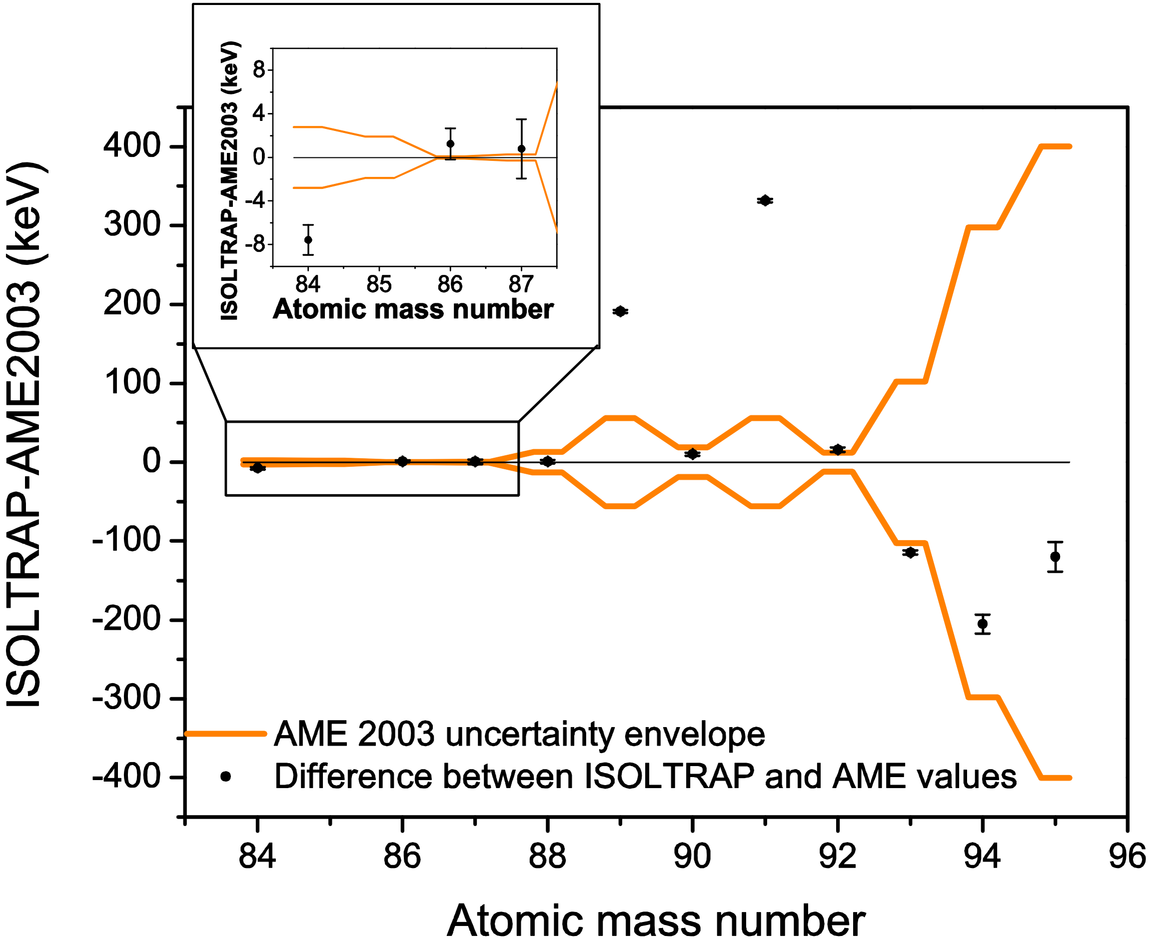
12 shifts: mass measurements

+2 additional ones if the mass measurement of ^{100}Kr is feasible

Total: 16 UTs

Backup slides

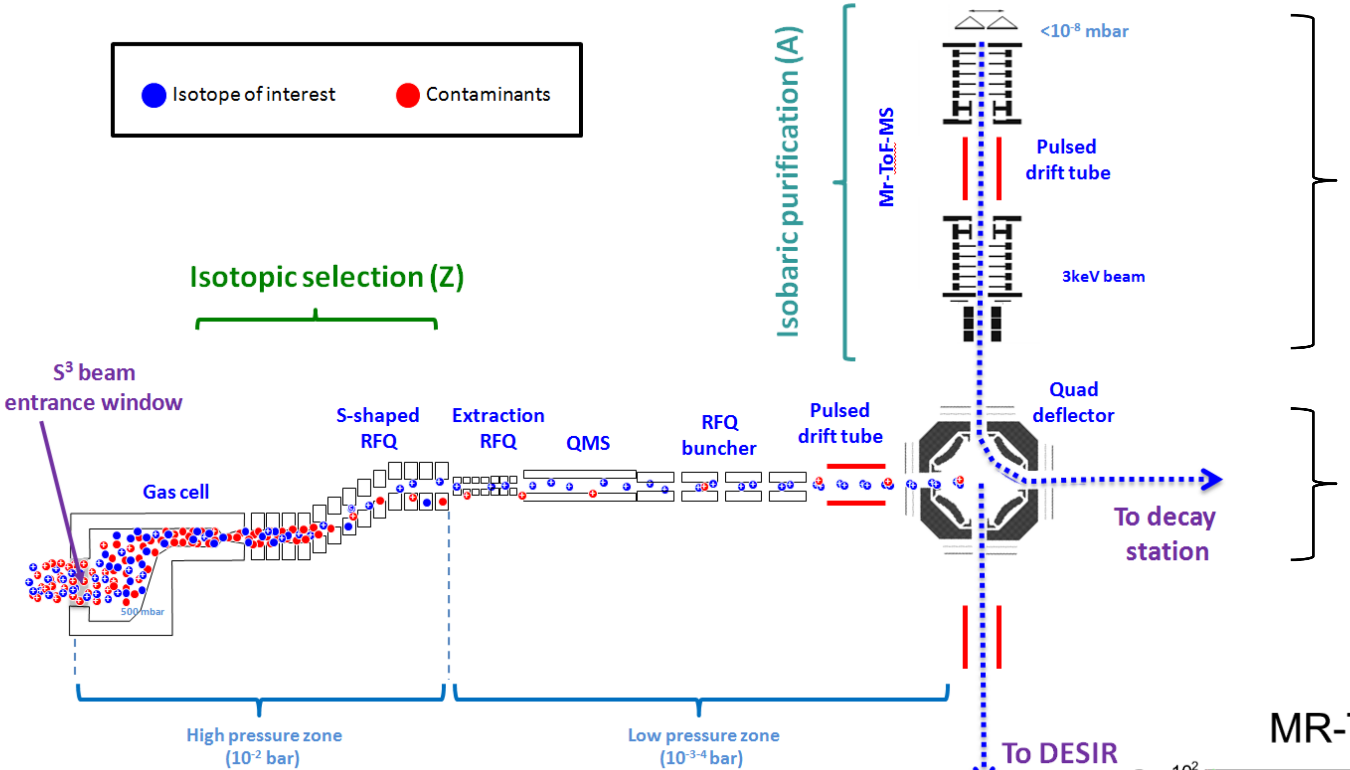
AME reliability



Sometimes even measured data is wrong!

PhD Pierre Chauveau

PILGRIM @ S3-LEB



PILGRIM = Piège à Ion Linéaire du Ganil pour la Résolution des Isobares et leur mesure de Masse

90 degree quadrupolar Deflector

Connection to DESIR :

- Beam delivery
- PIPERADE :
  - same deflector
  - prototype of MRToFMS

Goals :

- R=m/δm≈10^5
- σm/m ≈5.10^-7
- T ≈10ms

MR-ToF-MS operating range