PRECISION MASSES OF $^{129-131}$Cd FOR NUCLEAR ASTROPHYSICS

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- Nuclear astrophysics – a place to begin…
- Production of heavy elements
- Theory
- Experiments with radioactive isotopes
- The mass spectrometer ISOLTRAP
- Results on $^{129\text{-}131}Cd$
- Summary

Nuclear astrophysics

Definition: *Interdisciplinary* branch *in physics which aims to understand the origin of chemical elements and the energy generation in stars.*

Nuclear physics

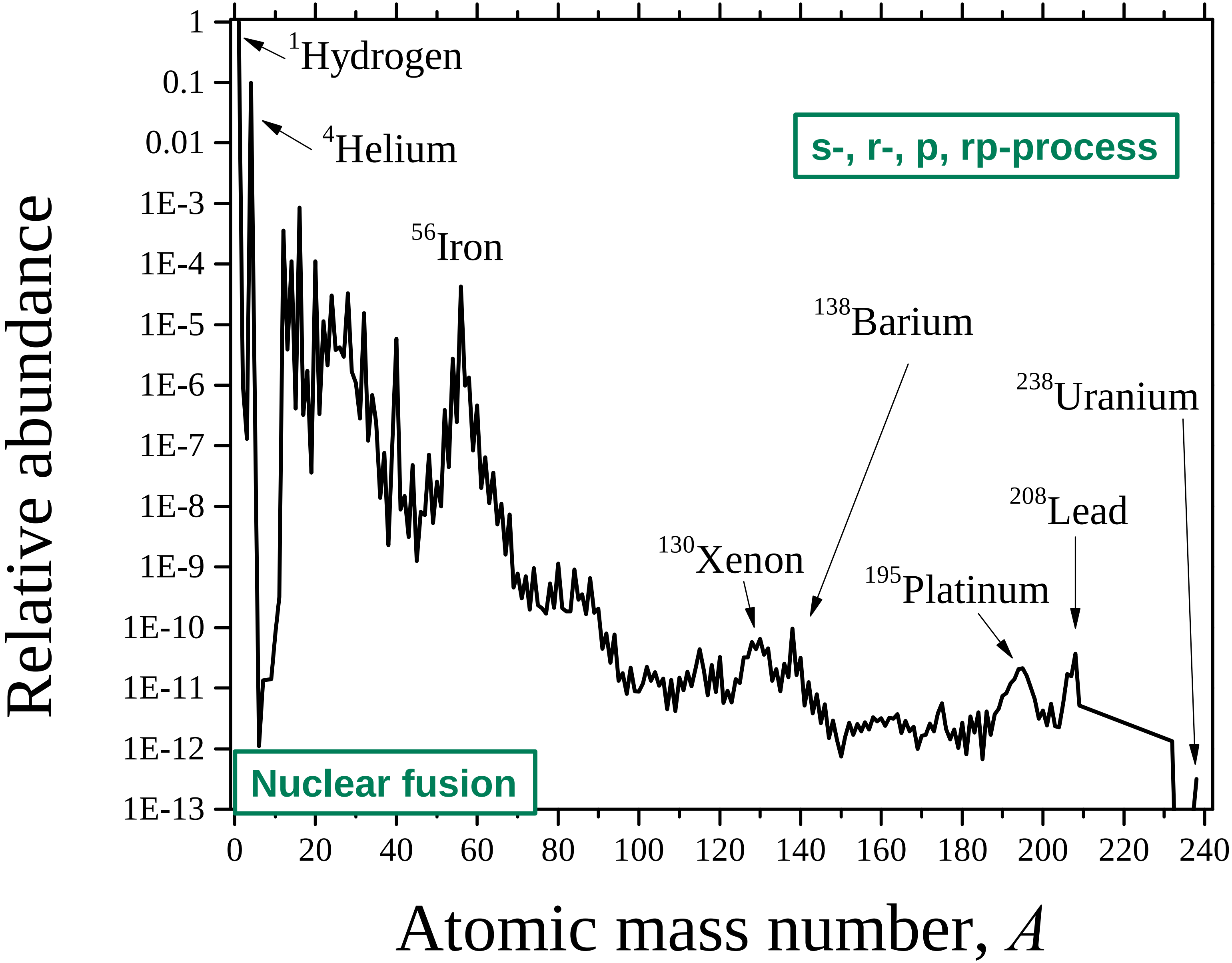
- Nuclear masses
- Half-lives
- Reaction cross sections

Astrophysics

- Stars, Star Clusters
- Galaxies
- Chemical composition

http://en.wikipedia.org/wiki/Nuclear_astrophysics

Natural abundance in the Solar system



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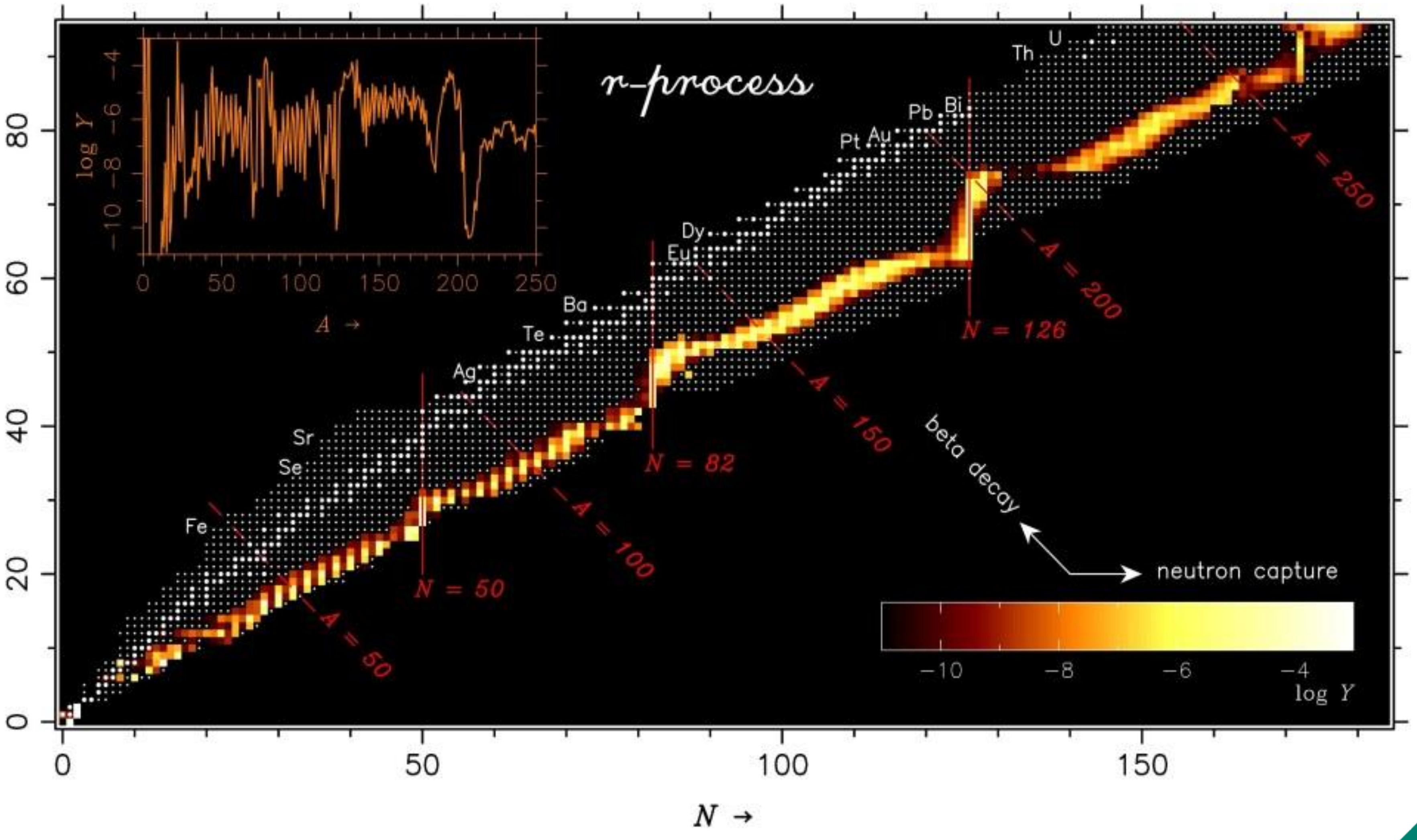
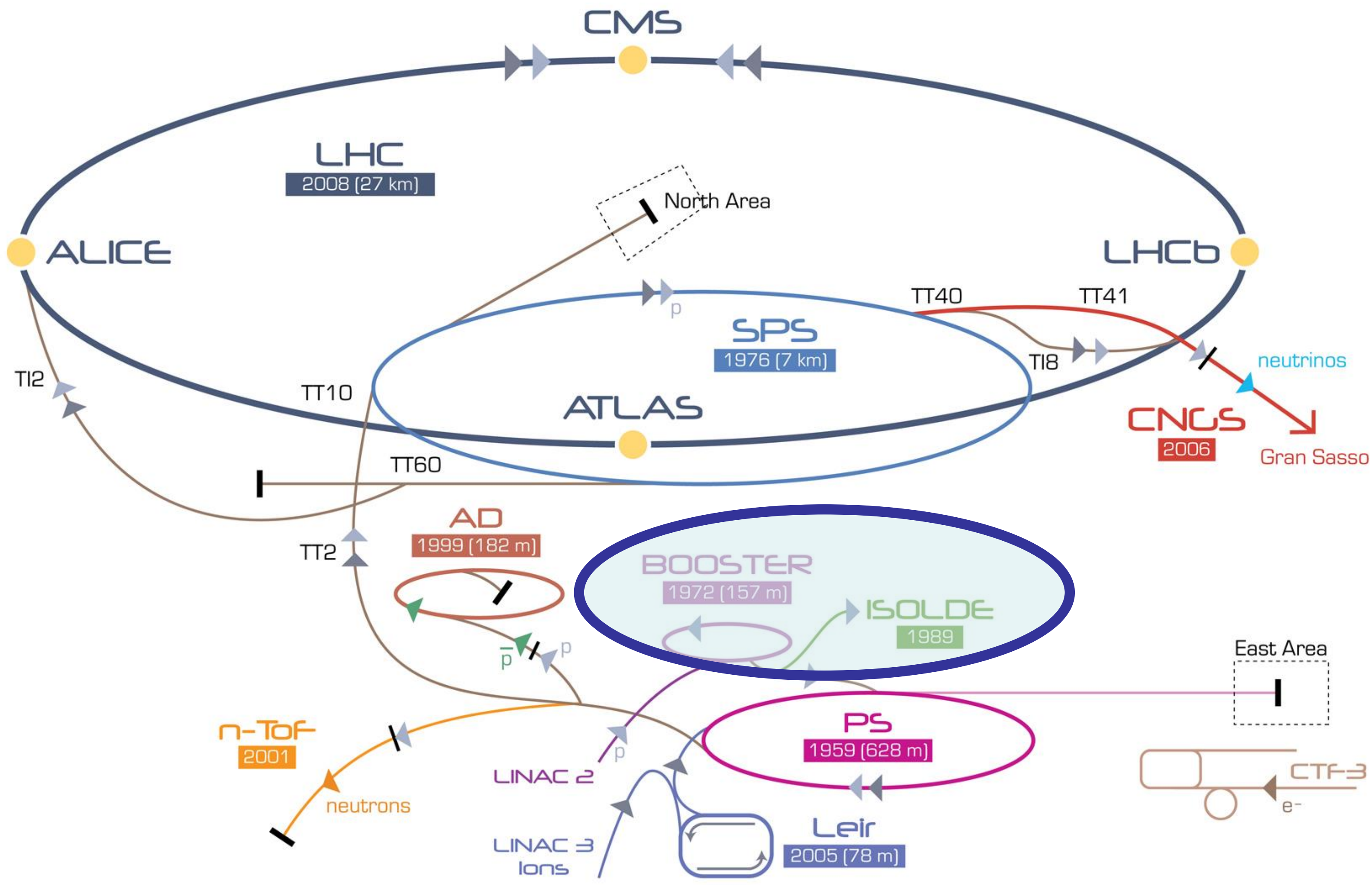
Rapid neutron capture process



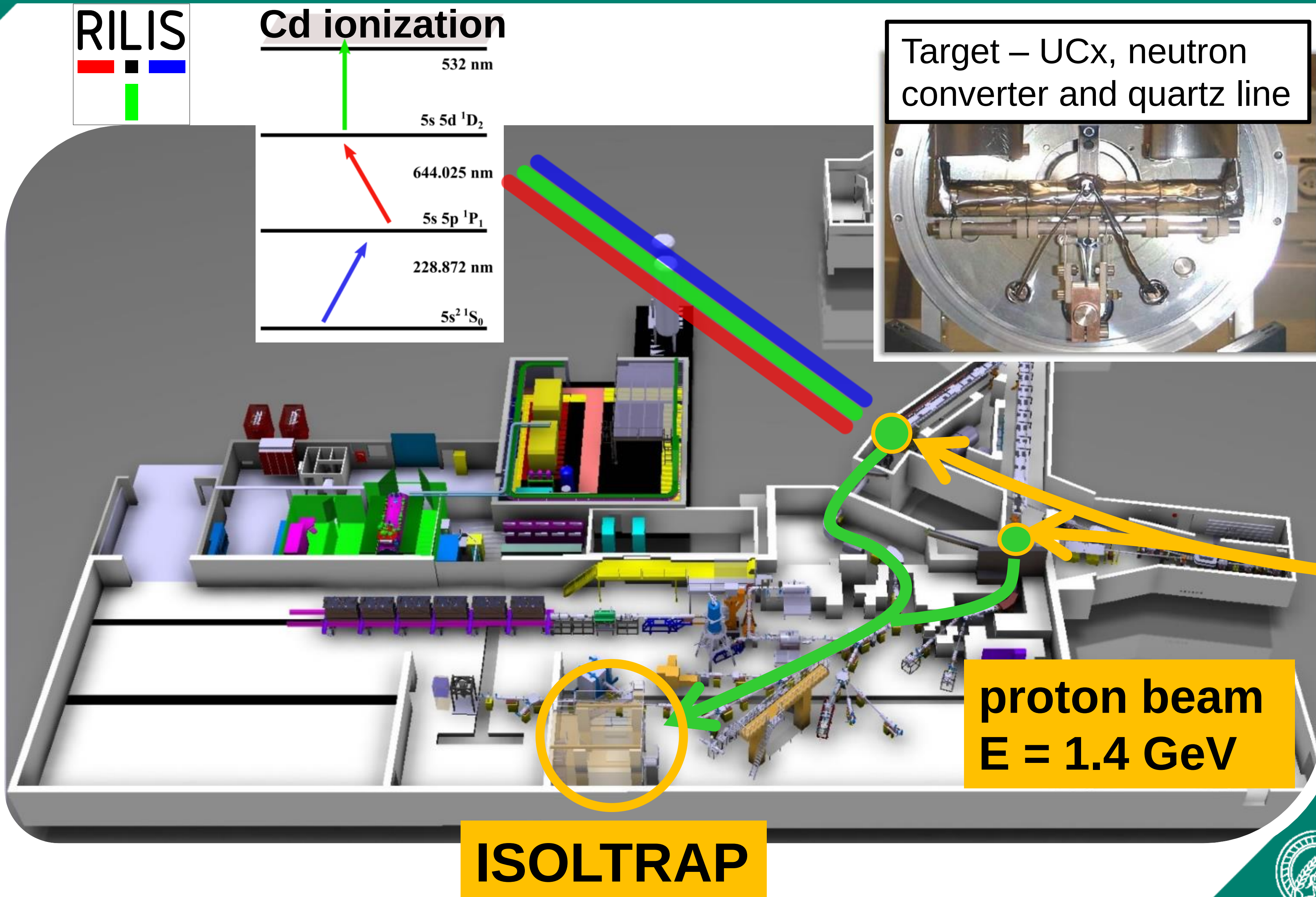
Starting conditions: τ = 10s; n = 10^{27} cm^{-3}; T = 9 GK

*S.Wanajo et al ApJ, **606**, 1057-1069, 2004*

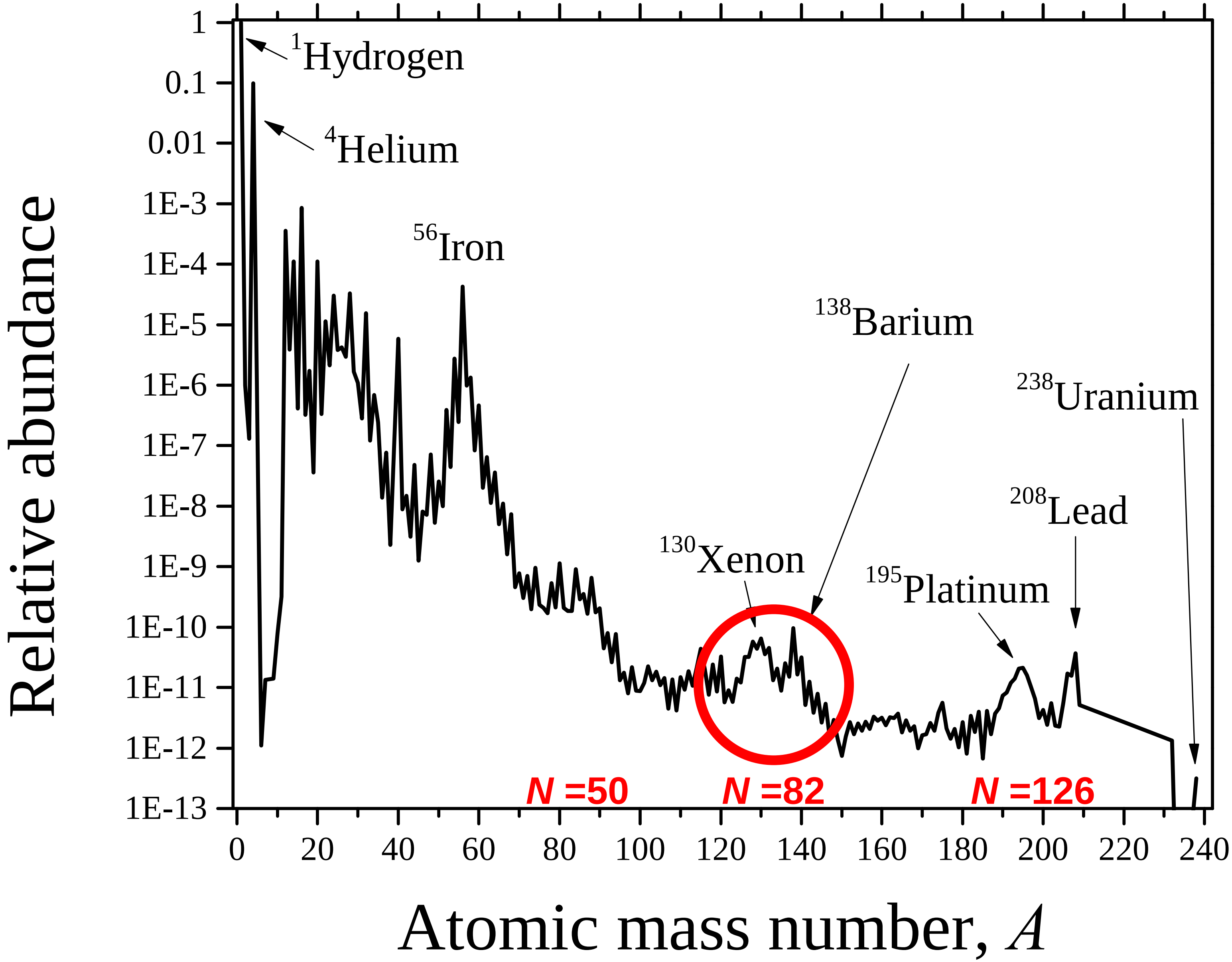
Experimental facility



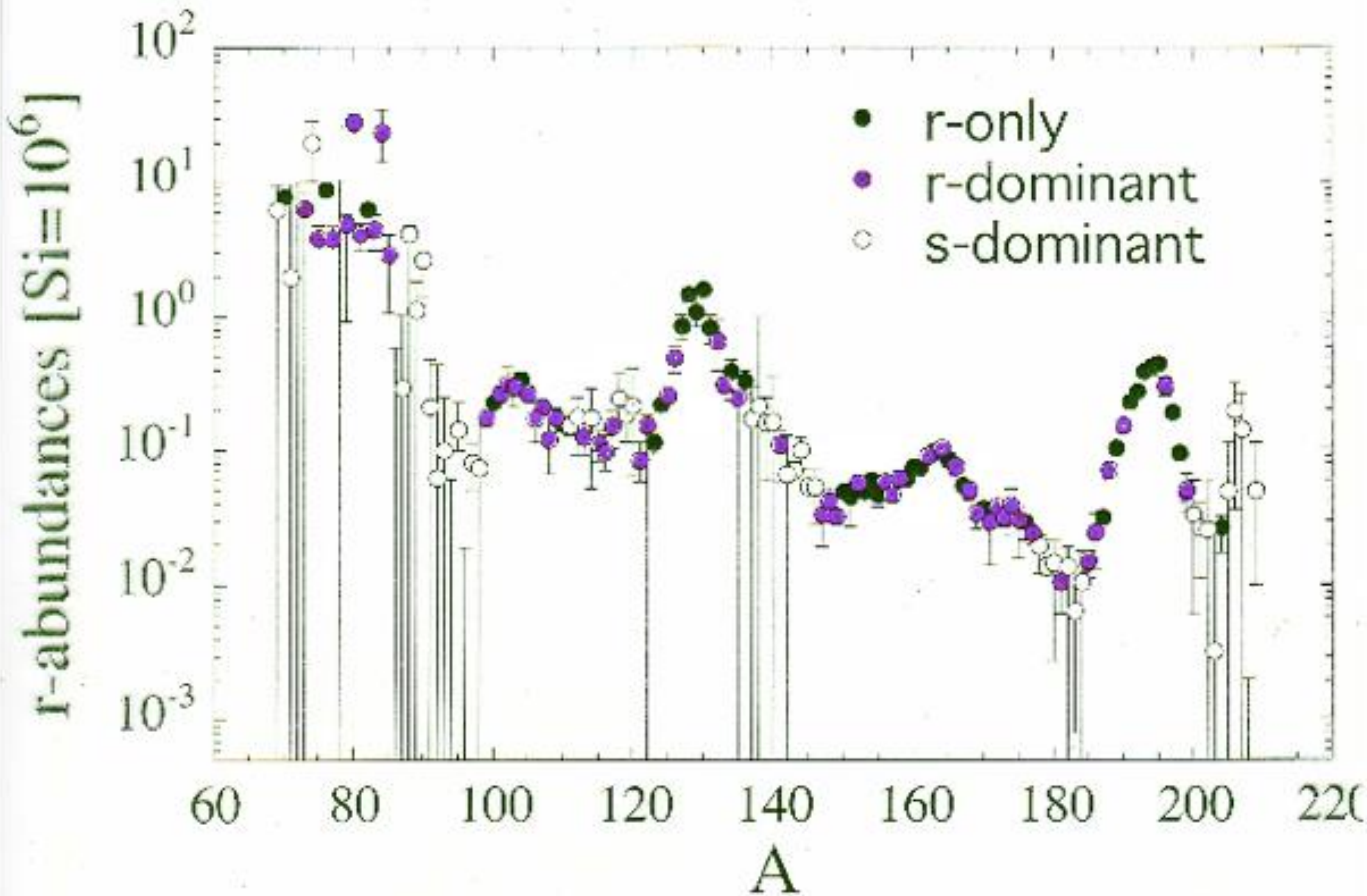
Online radioactive isotope production



Natural abundance in the Solar system



Natural abundance in the Solar system



LARGE UNCERTAINTIES, ESP. FOR S-DOMINANT NUCLIDES

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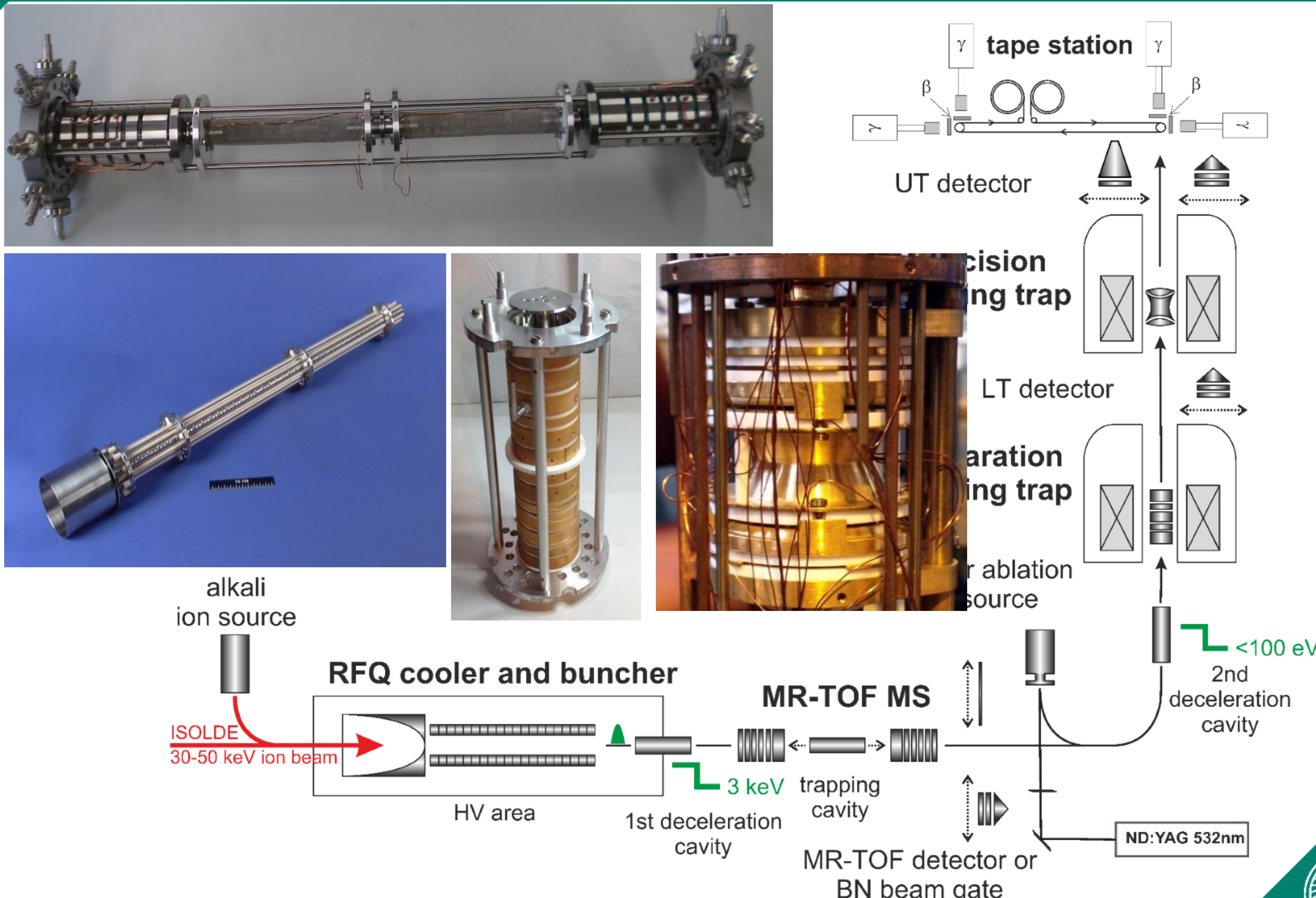
ISOLTRAP setup



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M. Mukherjee *et al.*, Eur. Phys. J. A **35**, 1 (2008); S. Kreim *et al.*, Nucl. Instrum. Methods B **317**, 492 (2013).

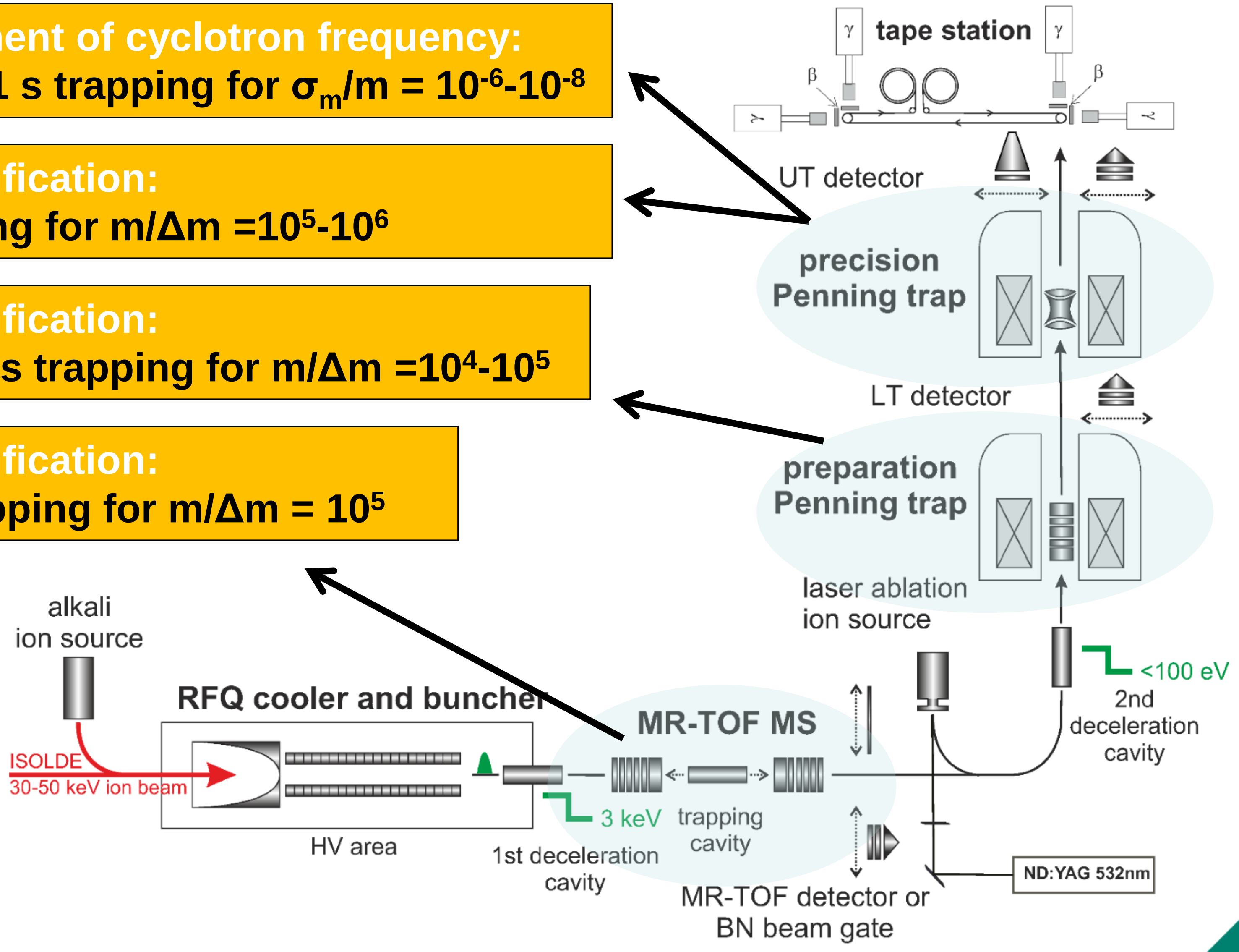
ISOLTRAP setup

Measurement of cyclotron frequency:
100 ms – 1 s trapping for $\sigma_m/m = 10^{-6}$-10^{-8}

Beam purification:
1 s trapping for $m/\Delta m = 10^5$-10^6

Beam purification:
200-300 ms trapping for $m/\Delta m = 10^4$-10^5

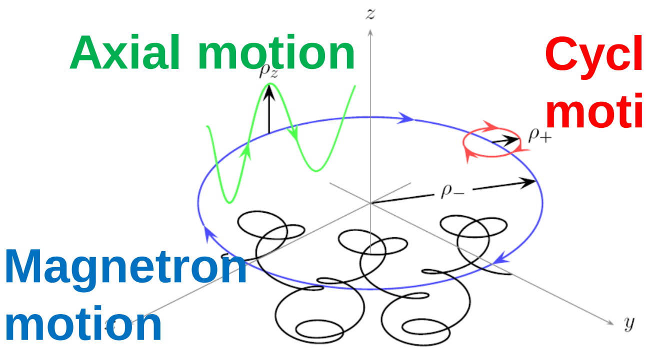
Beam purification:
30 ms trapping for $m/\Delta m = 10^5$



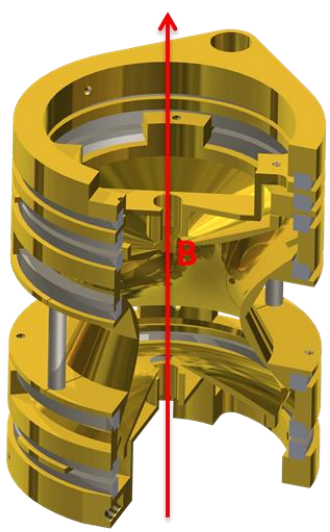
F. Herfurth *et al.*, NIM A **469**, 254 (2001); R. N. Wolf *et al.*, Int. J. Mass Spectrom **313**, 8 (2012); G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991);

Mass measurements at ISOLTRAP

Penning trap measurements



$$\nu_c = \frac{qB}{2\pi\, m}$$

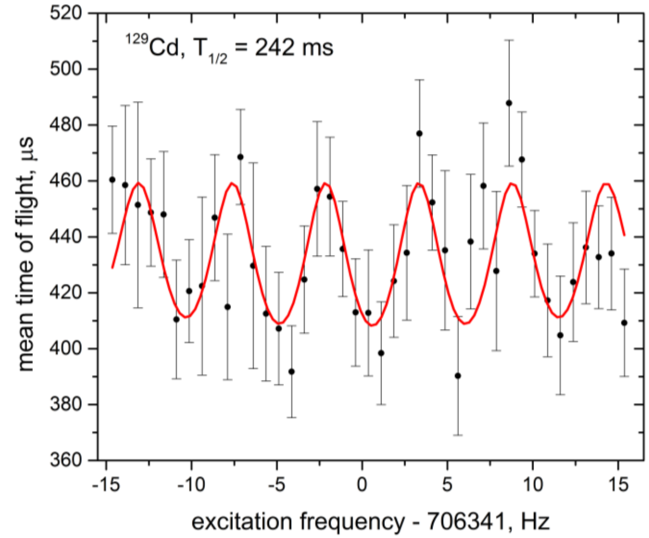


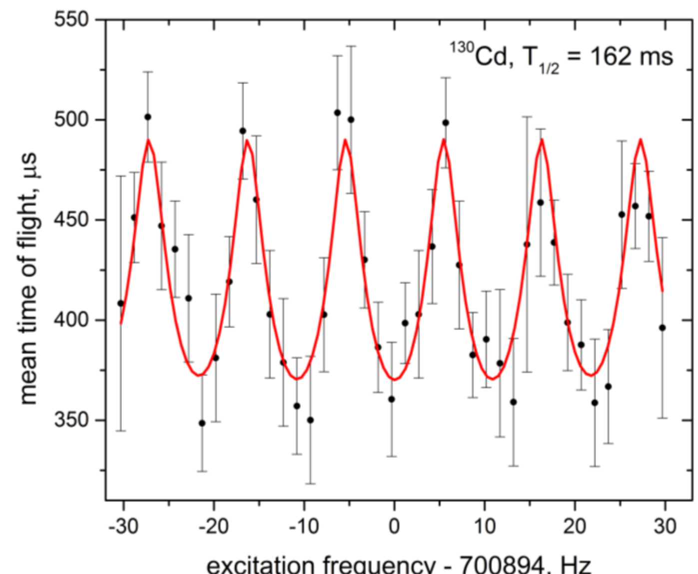
rf excitation

$$\nu_c = \nu_+ + \nu_-$$

t_{ex}(^{129}Cd) = 20-160-20 ms

t_{ex}(^{130}Cd) = 10-80-10 ms





PRELIMINARY

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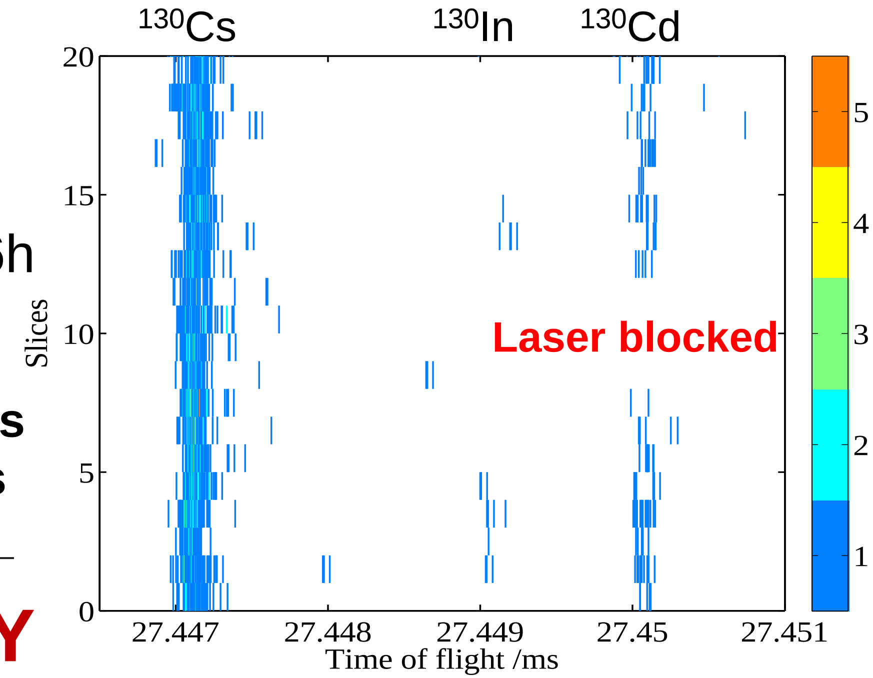
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995); S. George *et al.*, Phys. Rev. Lett. **98**, 162501 (2007);

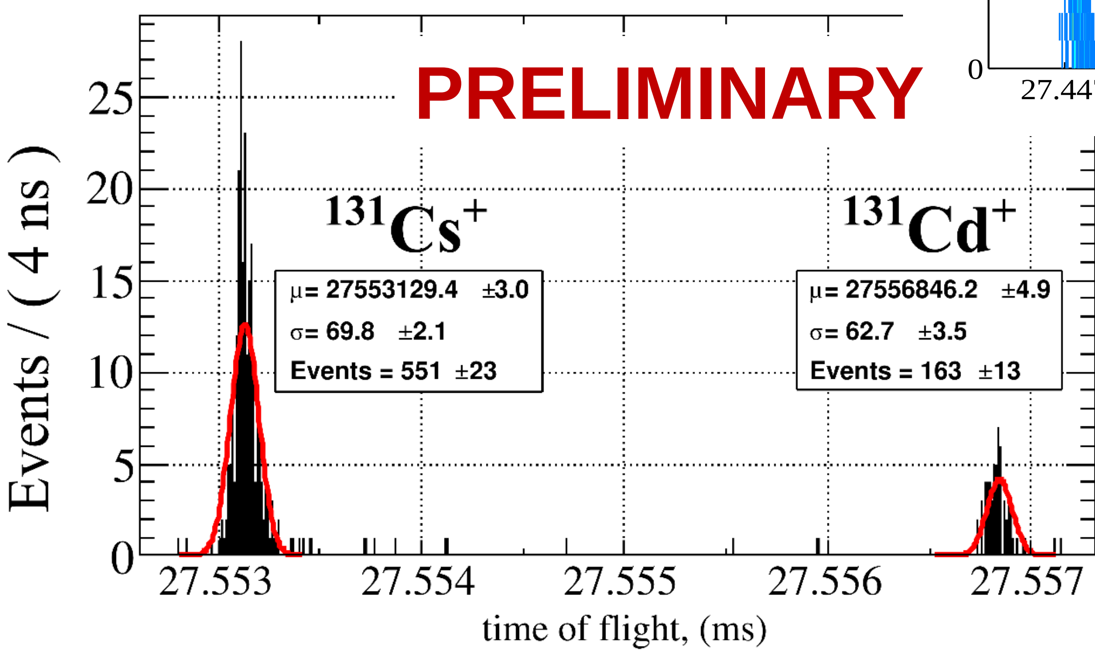
Mass measurements at ISOLTRAP

MR-TOF MS

- ≈ 88 ions/s from ISOLDE
- Total of 1366 ions collected for ≈6.6h

ions of interest ^{131}Cd ≈ 0.2 ions / 160 ms
contamination ^{131}Cs ≈ 0.6 ions / 160 ms



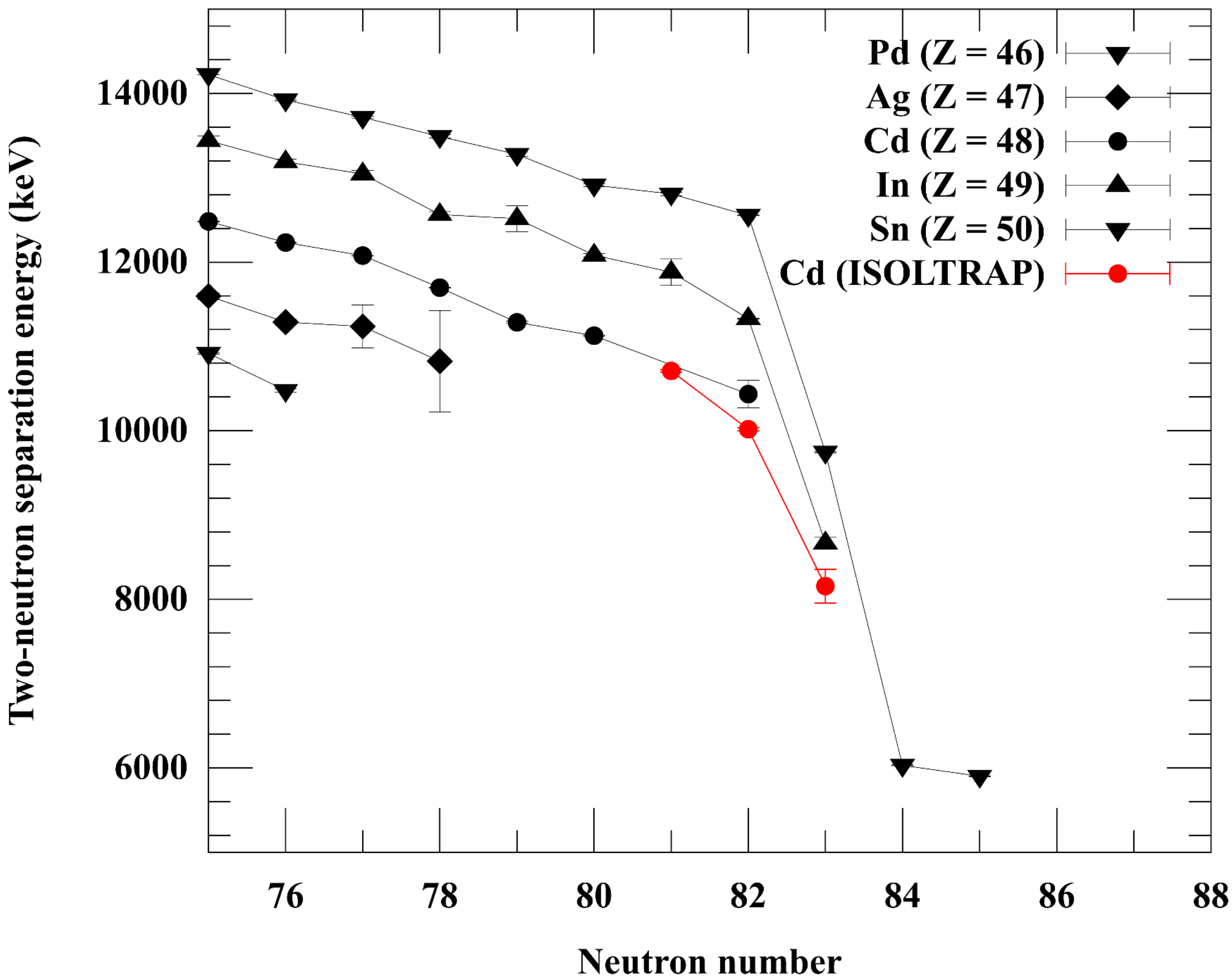


$$t = a.\sqrt{m/q} + b$$

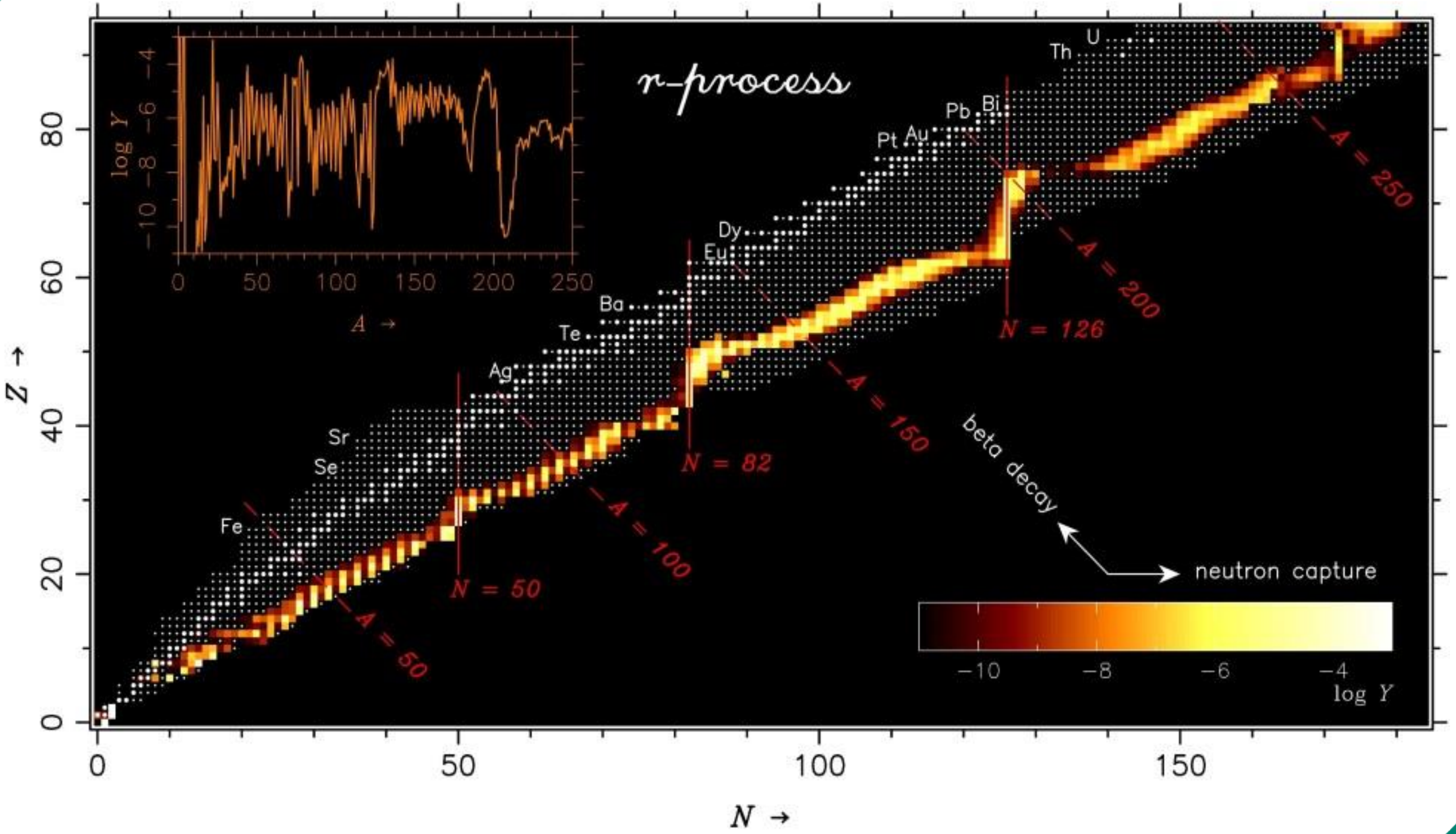
R. N. Wolf *et al.*, IJMS **313**, 8 (2012); F.Wienholtz *et al.*, Nature **489**, 346 (2013)

Results

$$S_{2n}(N,Z) = ME(N-2,Z) - ME(N,Z) + 2 \cdot ME(n)$$



Rapid neutron capture



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Canonical model

The nuclide abundance equation in explosive burning

$$\frac{d\,N(A,Z)}{dt}$$
$$= \lambda_n(A-1,Z)N(A-1,Z) - \lambda_n(A,Z)N(A,Z)$$
$$+ \lambda_\beta(A,Z-1)N(A,Z-1) - \lambda_\beta(A,Z)N(A,Z)$$
$$+ \lambda_\gamma(A+1,Z)N(A+1,Z) - \lambda_\gamma(A,Z)N(A,Z)$$
$$+ termination\ terms\ due\ to\ fission\ (A = 260)$$

The number density for isotope with *(A, Z)*

$$N(A,Z) = \omega(A,Z)\left(\frac{AM_\mu k\,T}{2\,\pi\,\hbar^2}\right)^{3/2}\frac{N_n^{(A-Z)}N_P^Z}{2^A}\,e^{\frac{Q(A,Z)}{k\,T}}$$

Canonical model

Waiting-point approximation

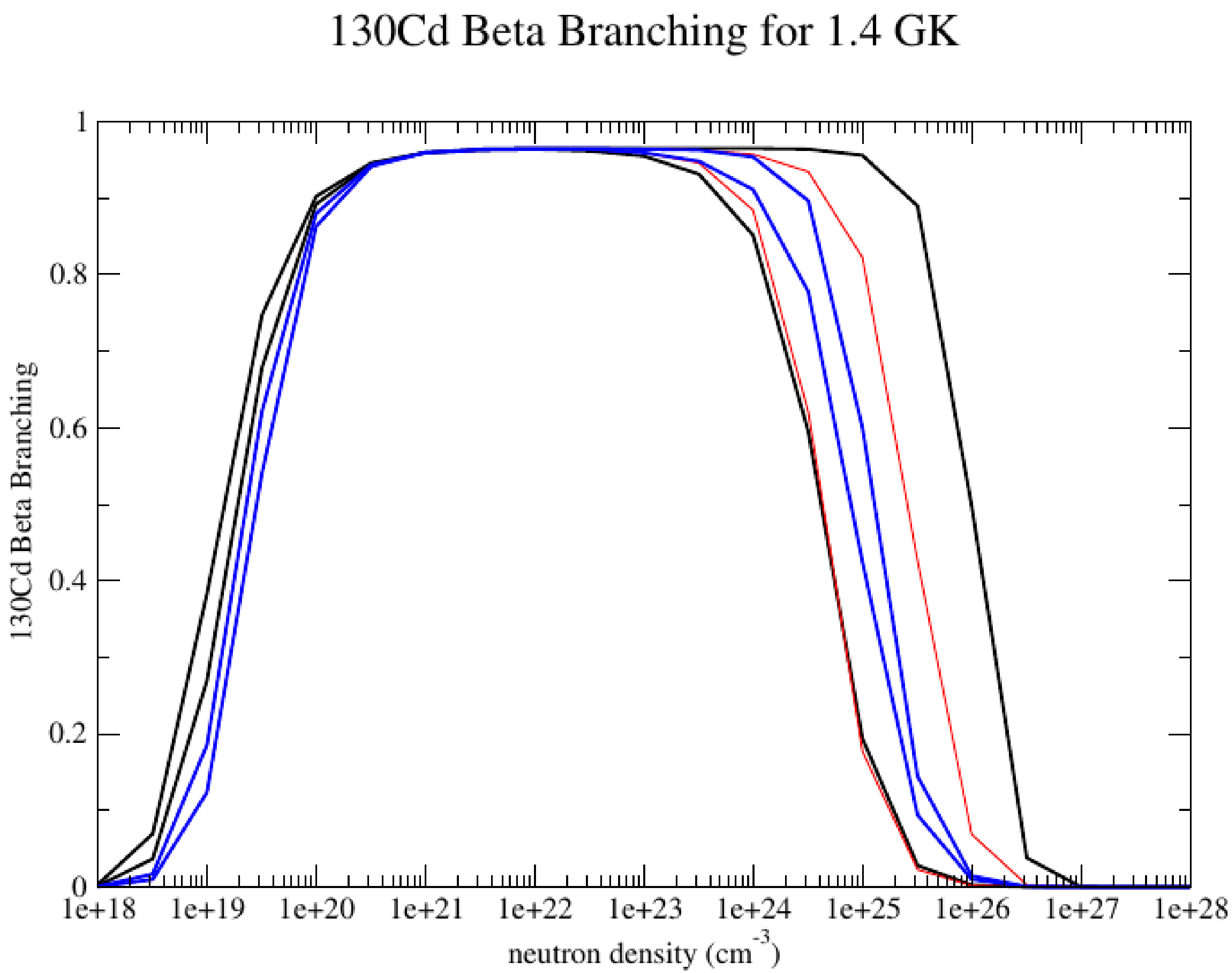
$\lambda_n \gg \lambda_\beta$ and having (n,γ) ↔ (γ, n)

$$\frac{dN(A,Z)}{dt} = \lambda_\beta(A,Z-1)N(A,Z-1) - \lambda_\beta(A,Z)N(A,Z)$$

$$\log\frac{N(A+1,Z)}{N(A,Z)} = \log N_n - 34.07 - \frac{3}{2}\log T_9 + \frac{5.04\, Q_n}{T_9}$$

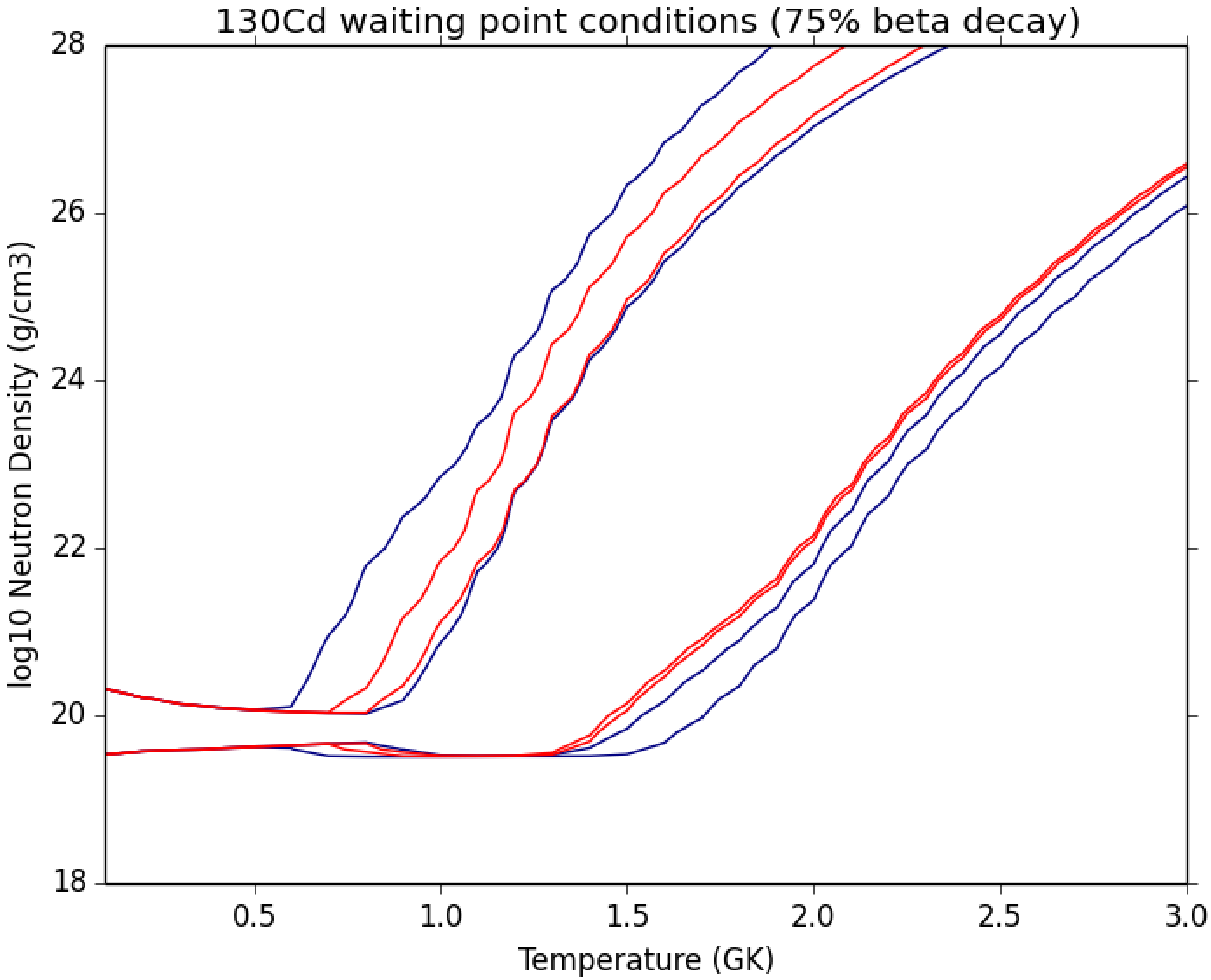
N_n – neutron density; T_9 – temperature in GK; Q_n – neutron separation energy

Canonical model



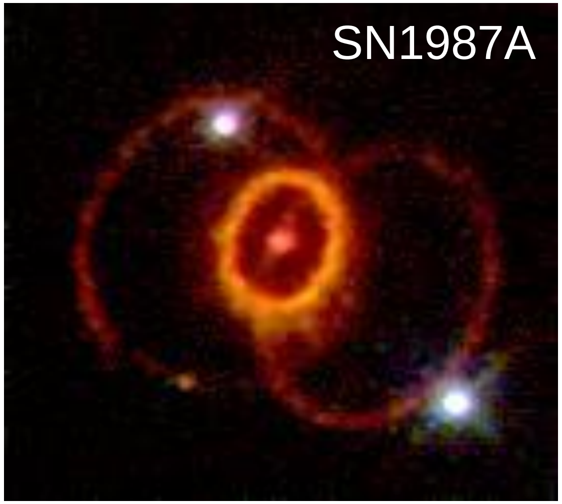
Calculations performed by H.Schatz

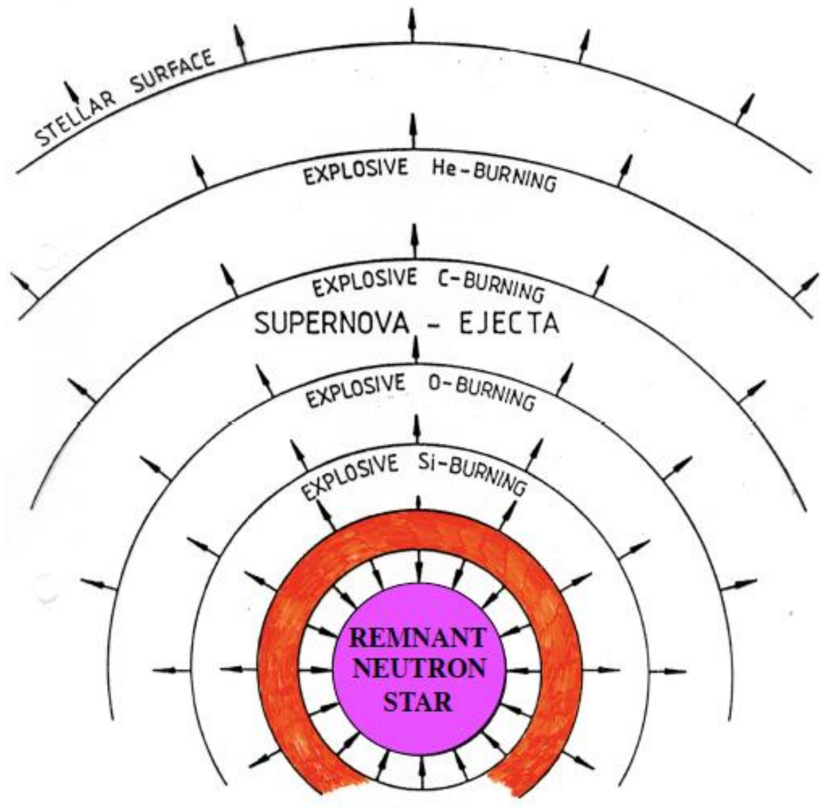
Canonical model



Calculations performed by H.Schatz

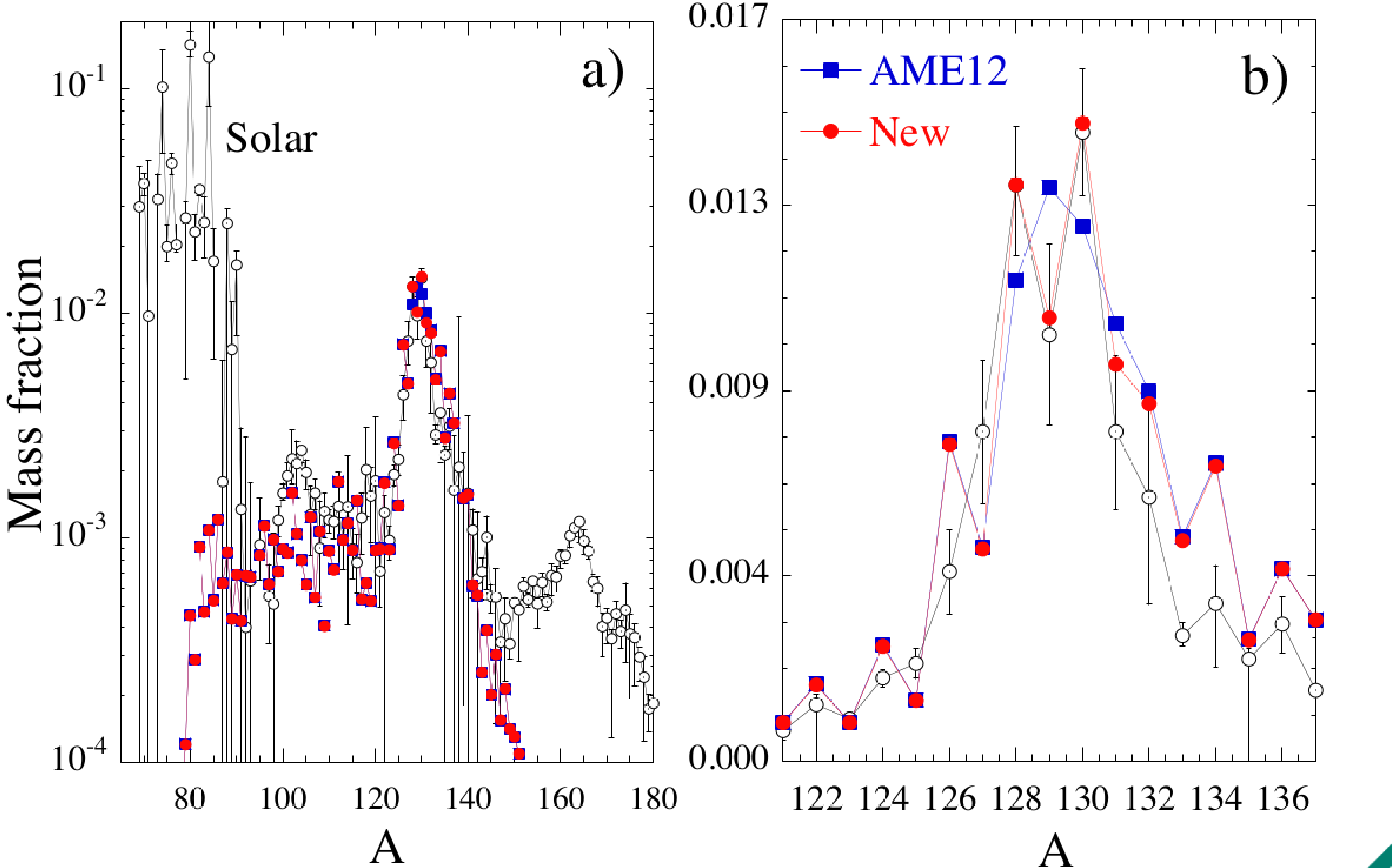
Collapse scenarios - Supernovae





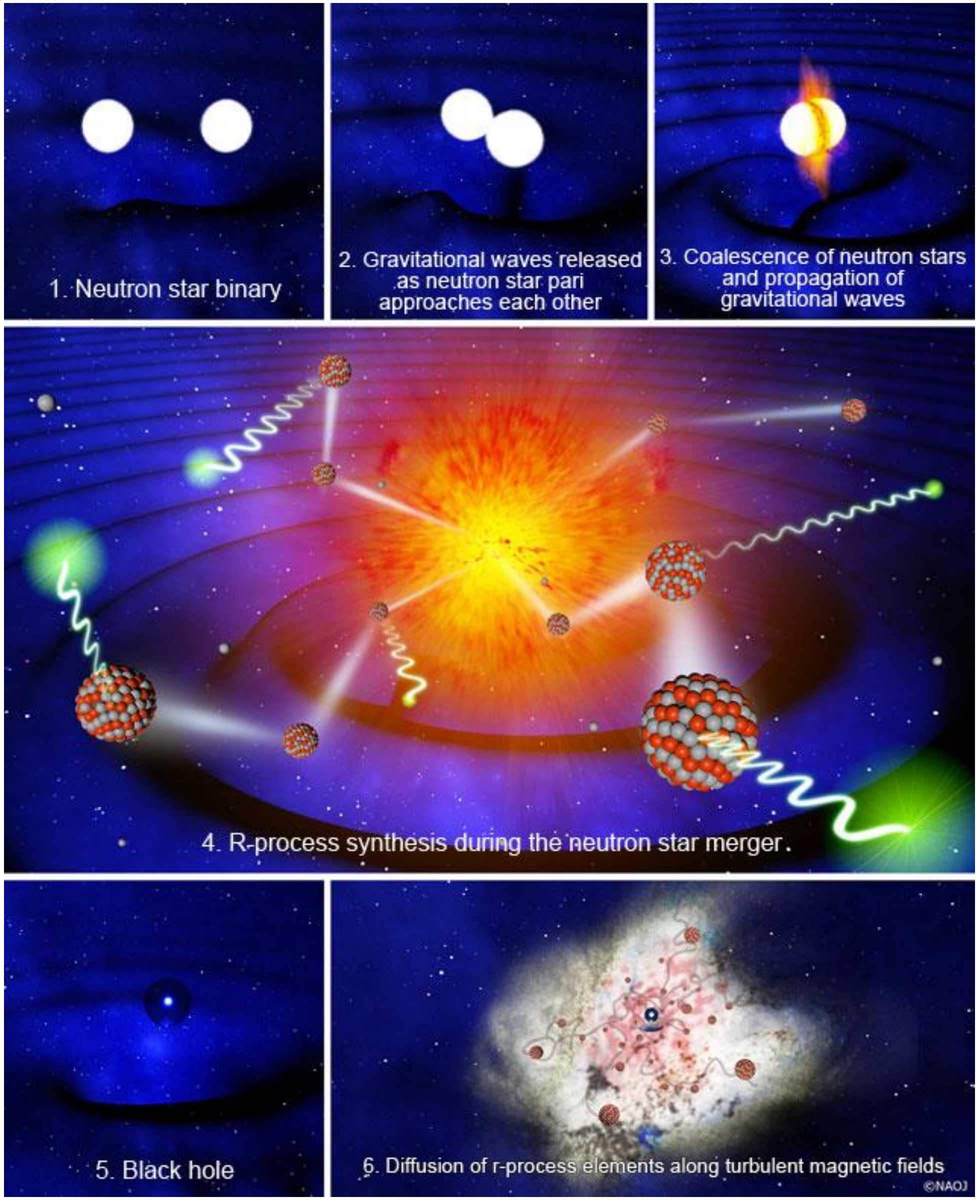
Core-collapse supernova

Collapse scenarios - Supernovae



Calculations performed by S.Goriely

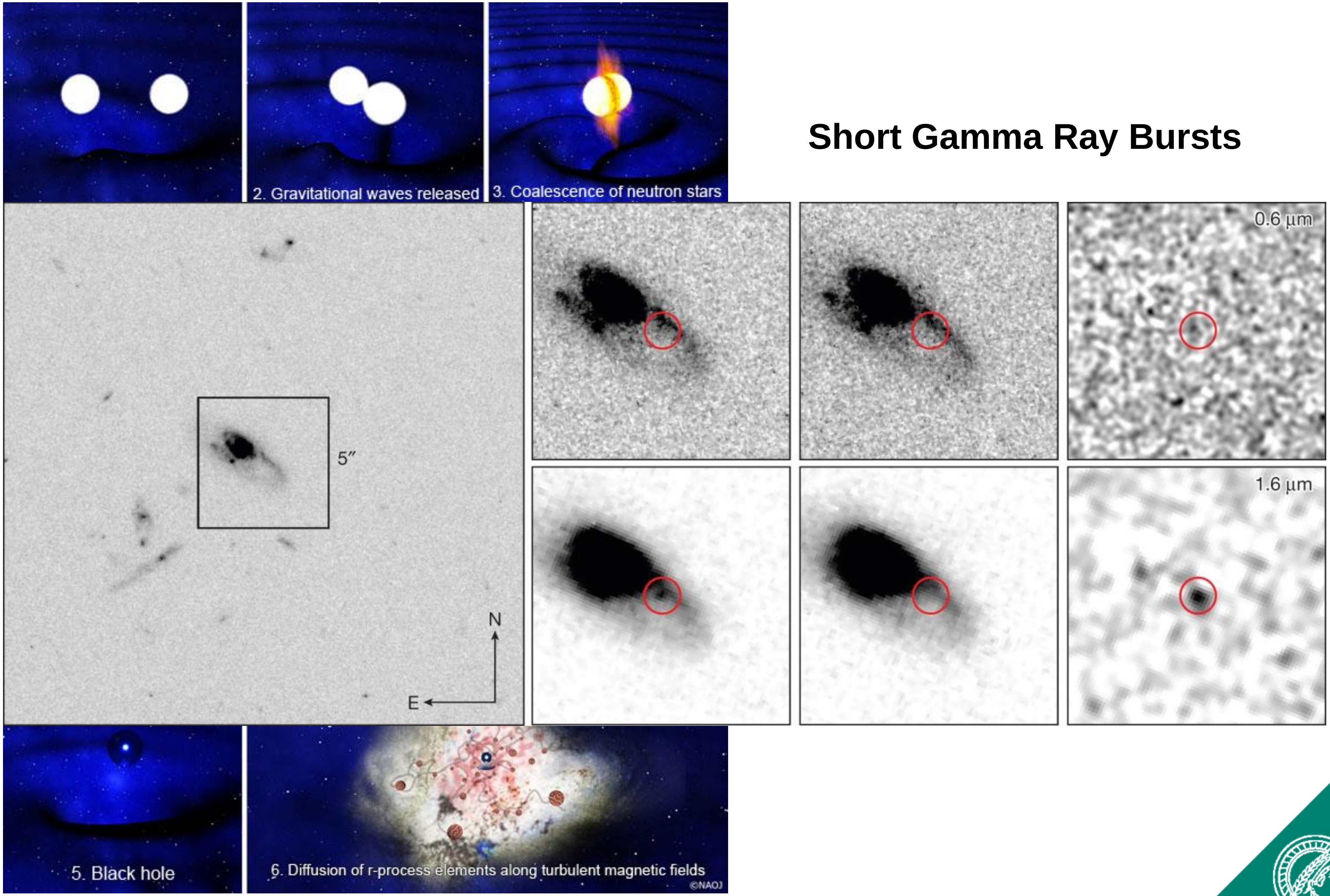
Collapse scenarios – Neutron Star Mergers



*T. Tsujimoto A&A **565** L5 2014 , NR Tanvir et al. Nature , 1-3 (2013)*

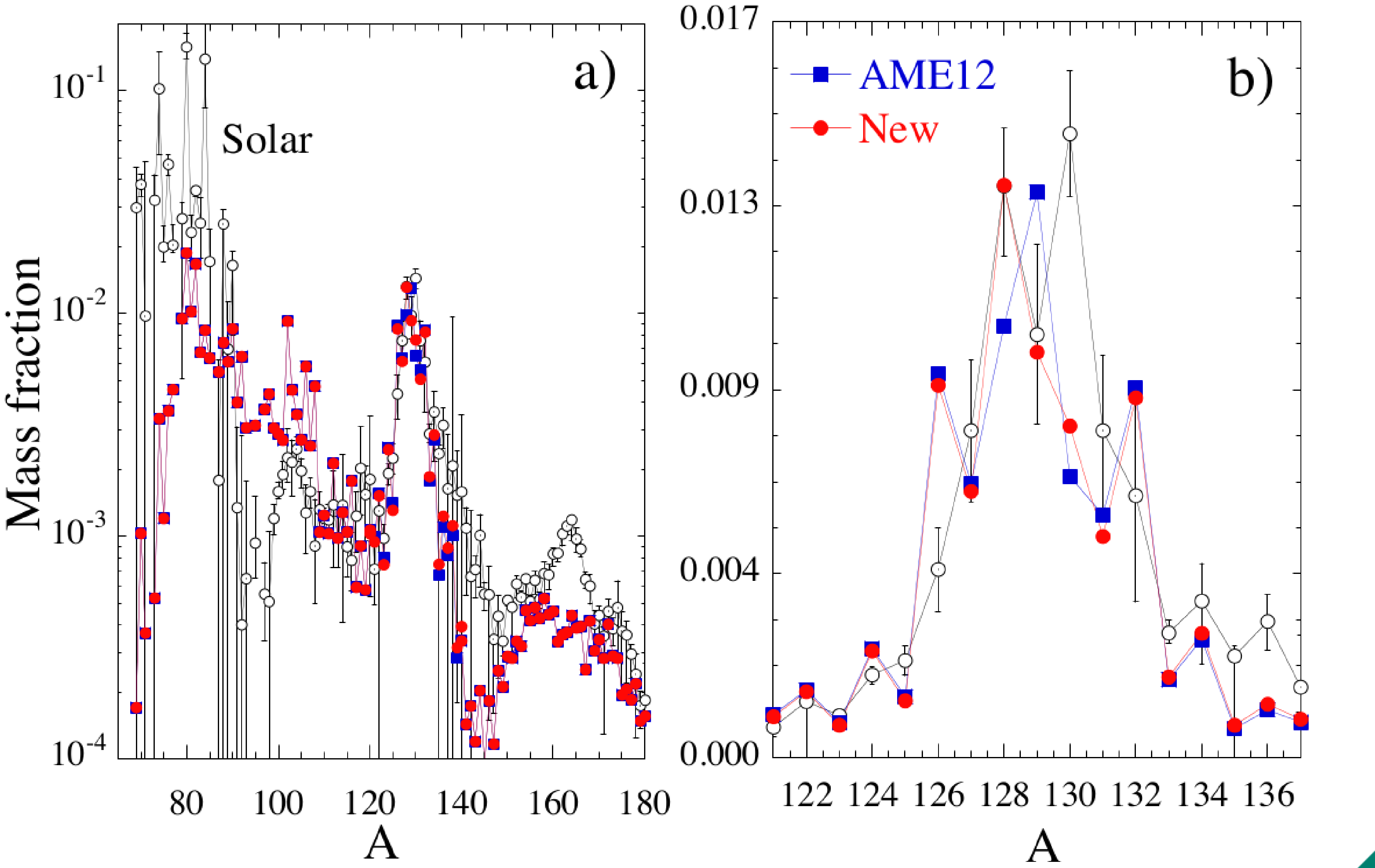
Collapse scenarios – Neutron Star Mergers

Short Gamma Ray Bursts



T. Tsujimoto A&A **565** L5 2014 , NR Tanvir et al. Nature , 1-3 (2013)

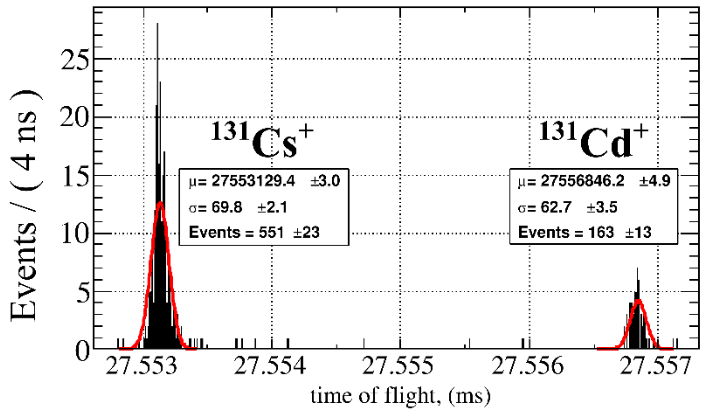
Collapse scenarios – Neutron Star Mergers

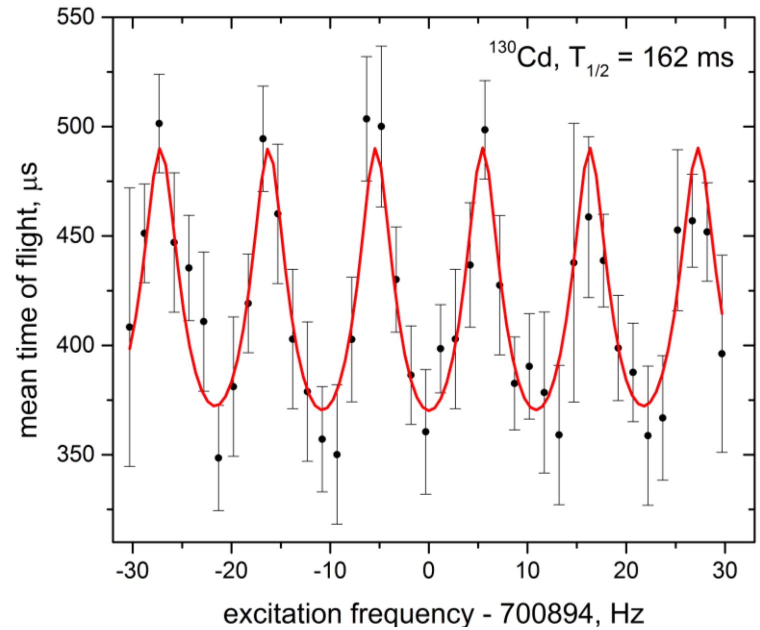


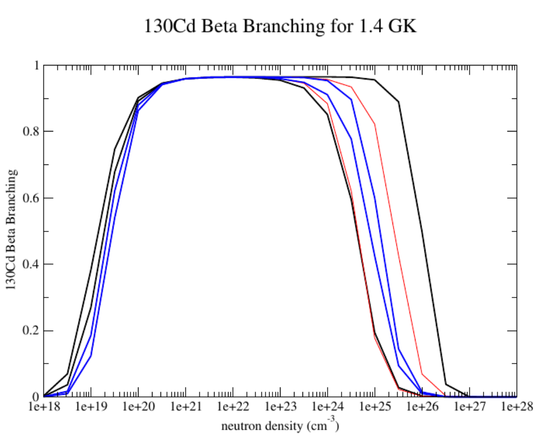
Calculations performed by S.Goriely

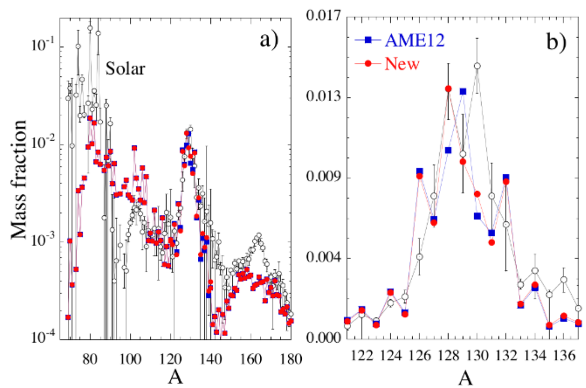
Summary

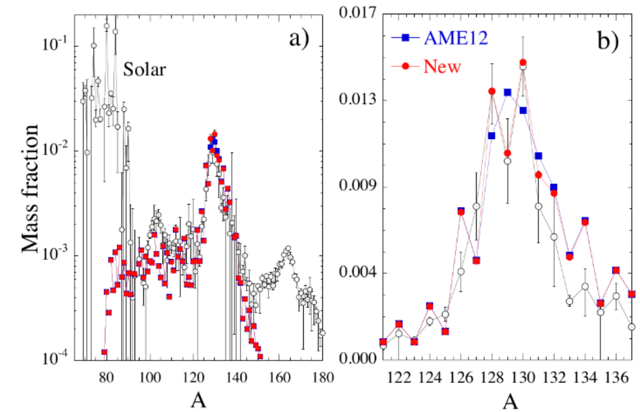
- Mass measurement of $^{129-131}Cd$
- Bring further reliability in r-process calculations











http://isoltrap.web.cern.ch

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P. Ascher, D. Beck, K. Blaum, Ch. Böhm, M. Breitenfeldt, R. B. Cakirli, T. Cocolios, S. Eliseev, T. Eronen, S. George, F. Herfurth, A. Herlert, M. Kowalska, S. Kreim, V. Manea, E. Minaya-Ramirez, Yu. A. Litvinov, D. Lunney, S. Naimi, D. Neidherr, A. de Roubin M. Rosenbusch, L. Schweikhard, A. Welker, F. Wienholtz, R. Wolf, K. Zuber,

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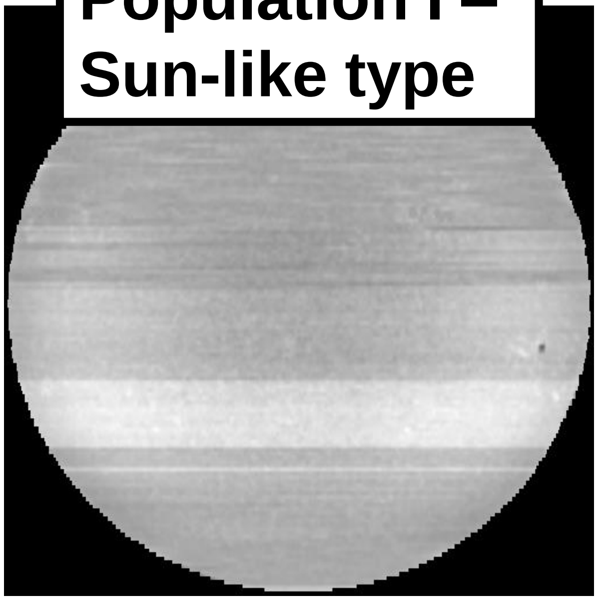
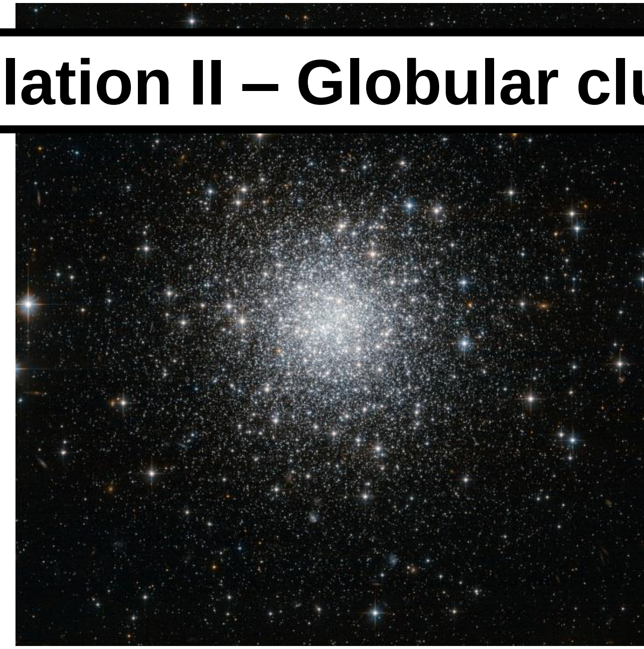
Where to look for ?

Population I – Sun-like type

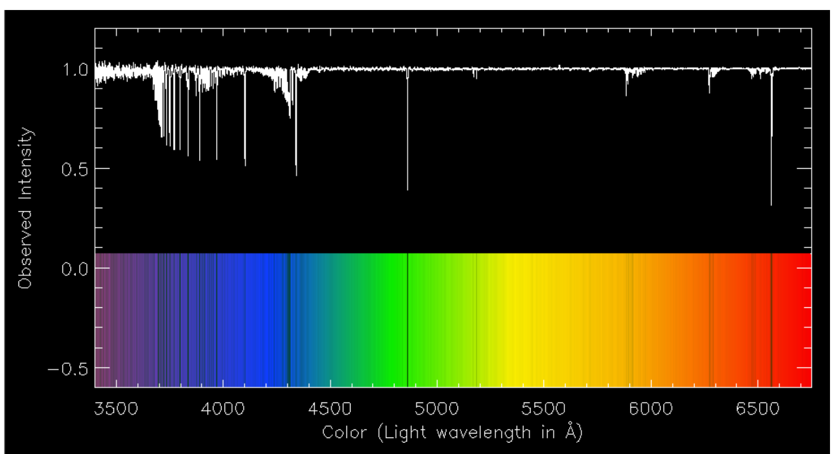


Credits: *Mt. Wilson Observatory*

Population II – Globular clusters



Credits: *ESA/Hubble & NASA*



Credits: *Brian Koberlein*

Metallicity

$$[\mathrm{Fe/H}] = log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{star} - log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\odot}$$

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ToF-ICR and Ramsey excitation