Recent results and future opportunities in laboratory nuclear astrophysics

Livius Trache -IFIN-HH, Bucharest

ENSAR2 NUSPRASEN workshop, CERN
Dec. 6th, 2016

Summary

NB: 5 out of 10 contributions have NA in title!!!

(then, what is new here?!)

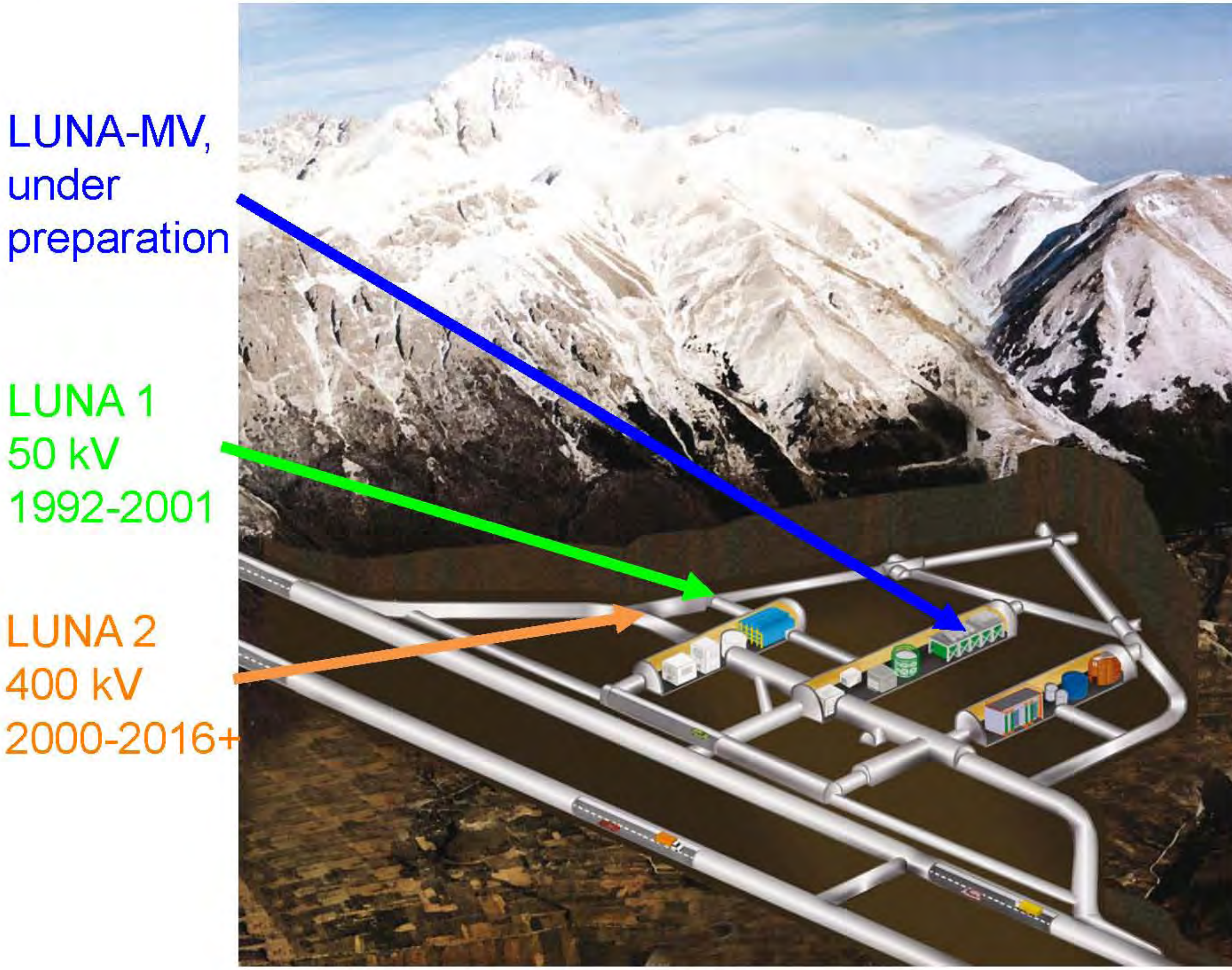
- Directions in experimental NA
- Some installations (laboratories) for NA
- Theory needs
- Planned NA activities in NUSPRASEN

Current directions in NA

Usual dichotomy:

- Direct measurements
  - Several new possibilities: LUNA MV, Dresden, Bucharest + salt mine, Napoli, Canfranco, …
  - Inverse reactions: proof-of-principle *p(RIB,*γ*)* at ESR of GSI/FAIR
- Indirect methods – broad range
  - THM. Seen Aurora! But w. RIBs: see next
  - Using RIBs from new facilities: FAIR/GSI, Spiral2, HIE-ISOLDE, SPES, ELI-NP, …

LUNA laboratory at Gran Sasso / Italy



~140 km from Rome

1000 m above sea level

Easy access (motorway)

Italian national laboratory

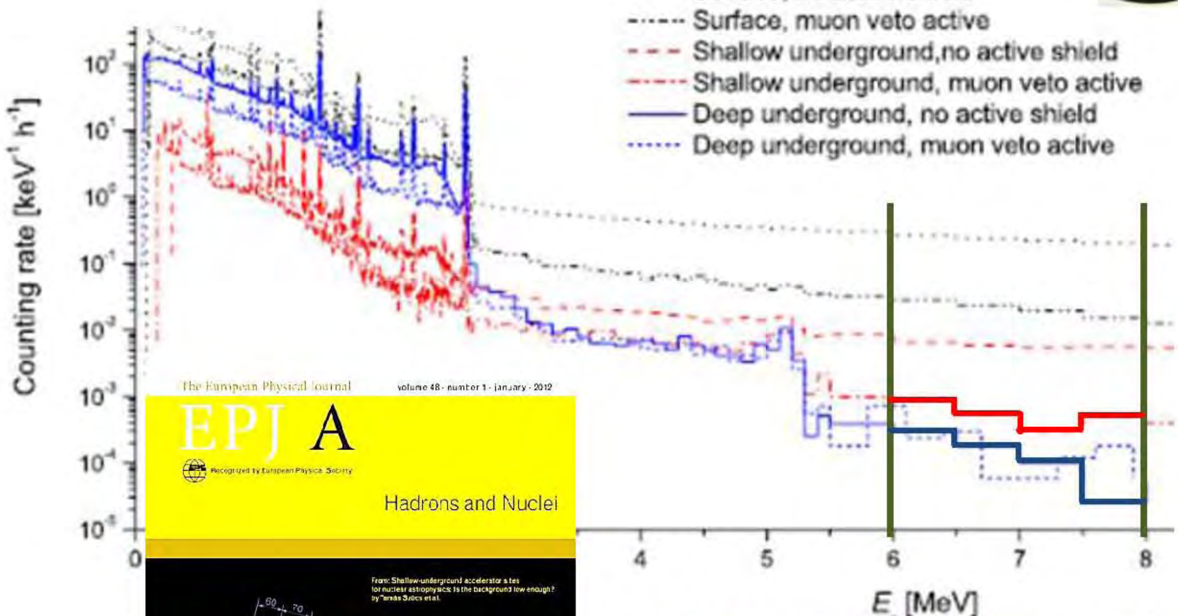
~100 local staff

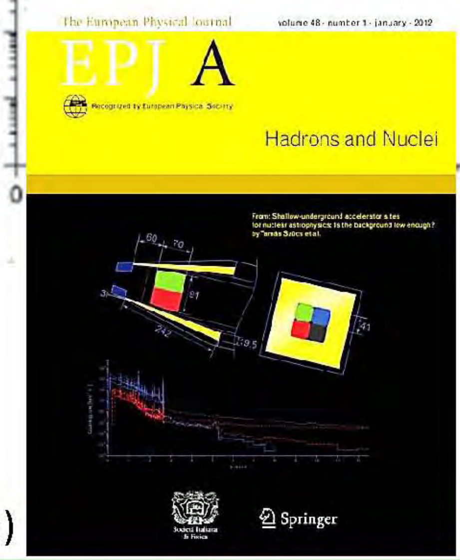
~600 external users

~1400 m rock 10^6 μ-reduction 10^3 n-reduction

Felsenkeller / Germany, 47 m deep underground laboratory

- ice cellar of former Felsenkeller brewery, 5 km from Dresden city center
- γ-counting facility founded in 1982
- Activation studies for nuclear astrophysics





$^{14}N(p,\gamma)^{15}O$, $^{12}C(\alpha,\gamma)^{16}O$

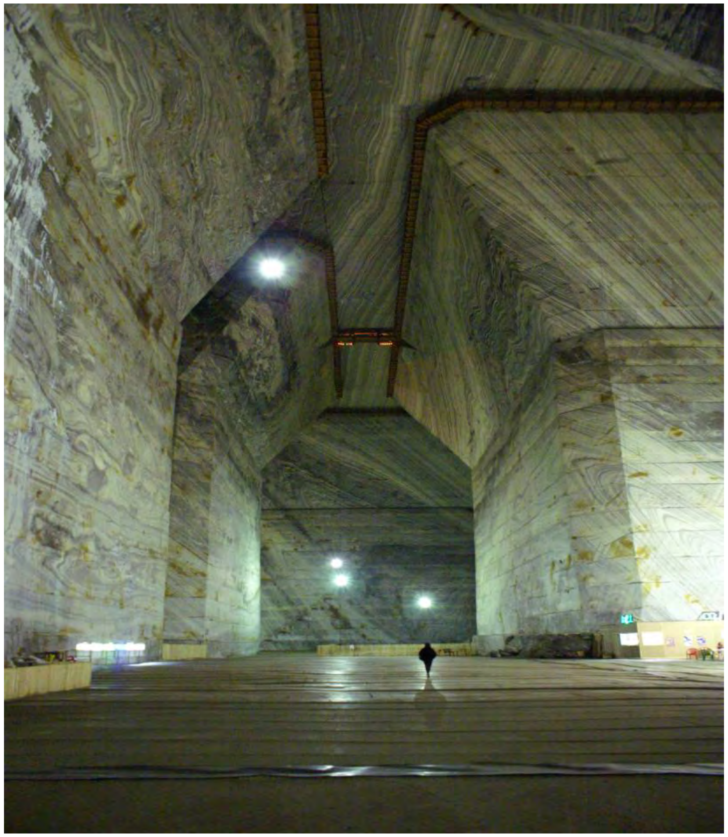
Factor of 2.3 difference

T. Szücs *et al*, EPJA **48**, 8 (2012)

IFIN-HH: Magurele & Slanic

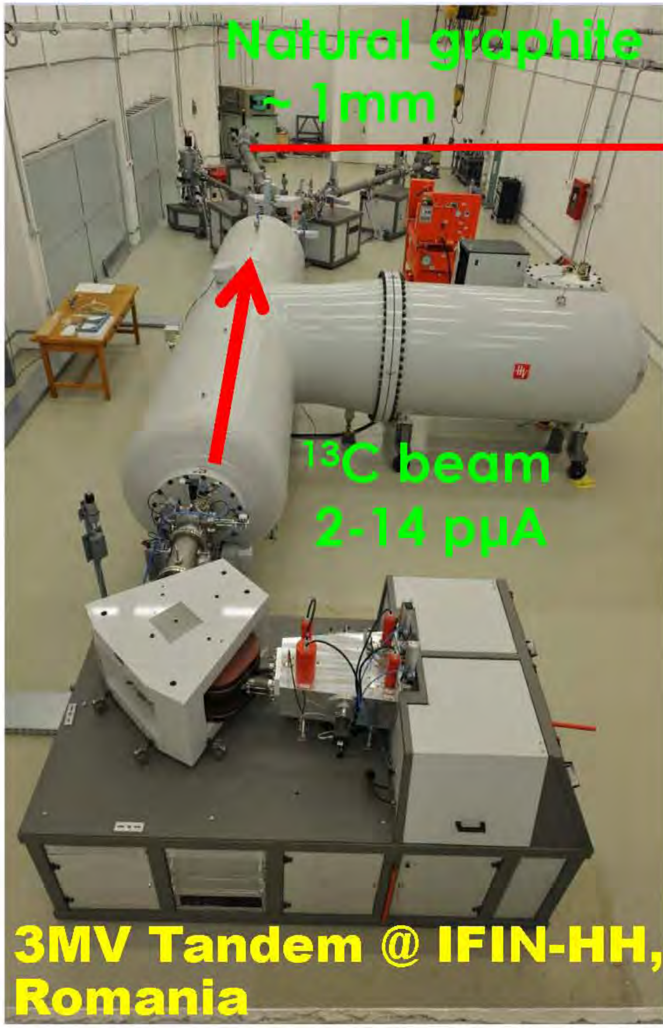
Activation in nuclear laboratory (this is a 3 MV tandetron)

Measurement in salt mine Slanic Prahova (2.5 hrs from Bucharest - very low gamma-ray bkg)



Studying $^{13}C+^{12}C$ fusion reaction at deep sub-barrier energies

Online Measurment

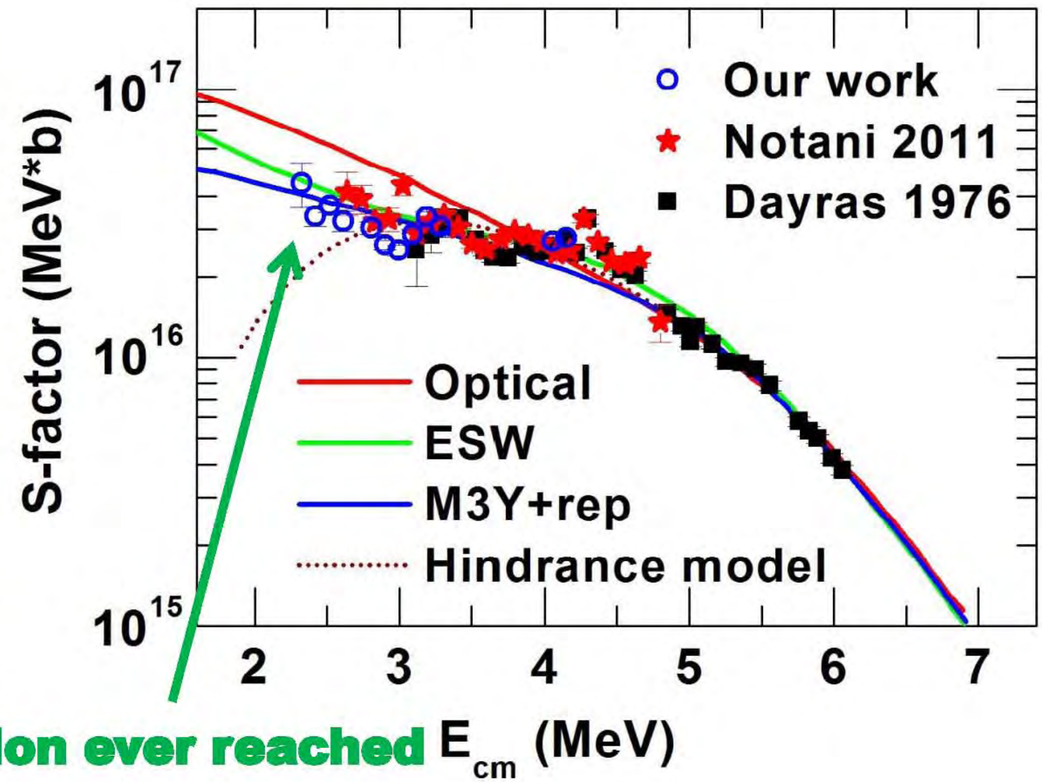


90 pb

Products: ^{24}Na, ^{24}Mg, ^{21}Ne

^{24}Na: $T_{1/2}$=15 hours,

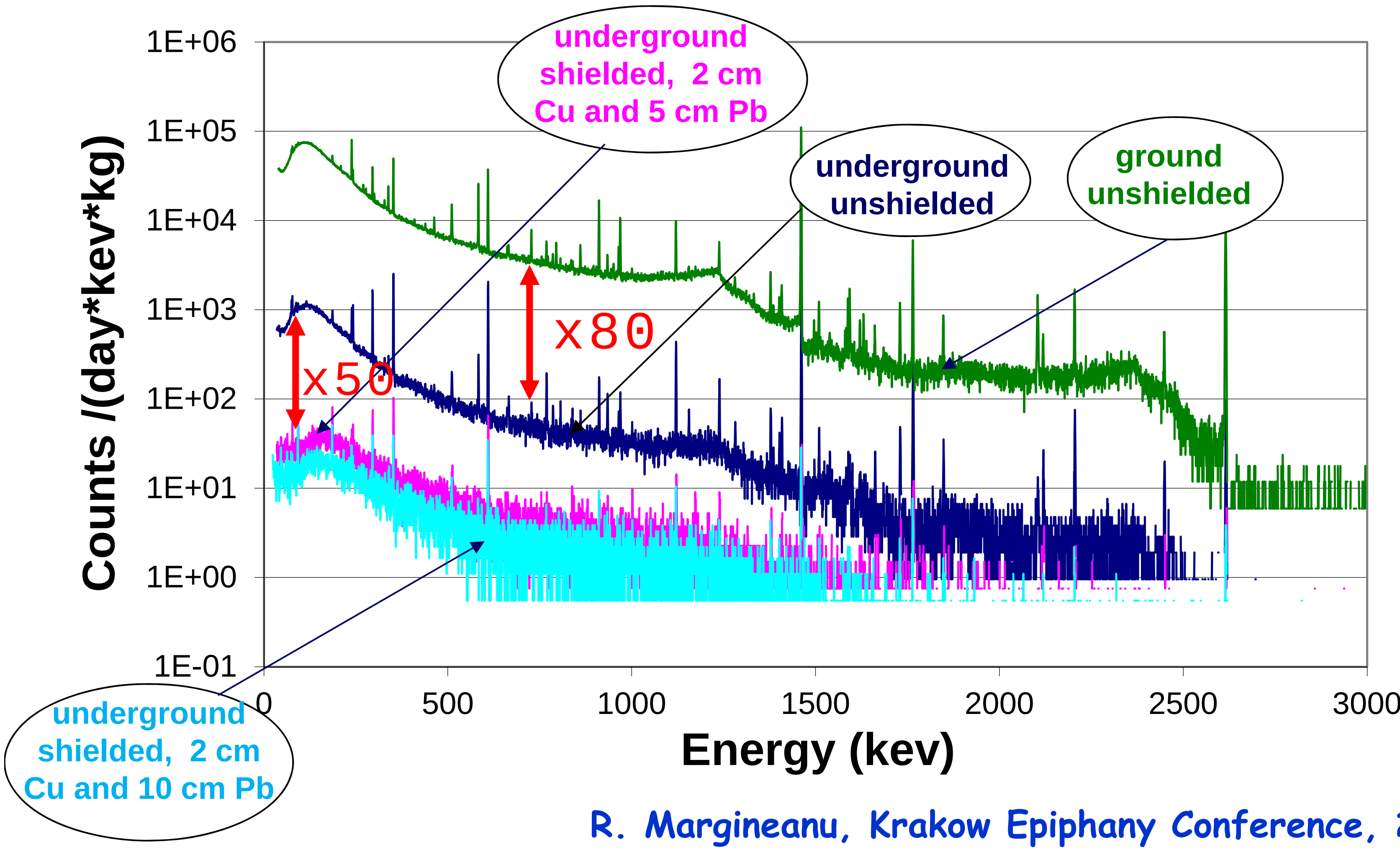
(Activity measurement in the underground salt mine)



0.2 nb, lowest cross section ever reached

“microBq” Lab

Background spectra collected with a HPGe detector with 100% relative efficiency

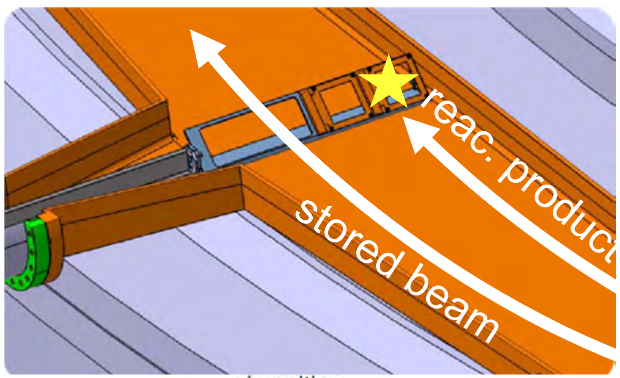


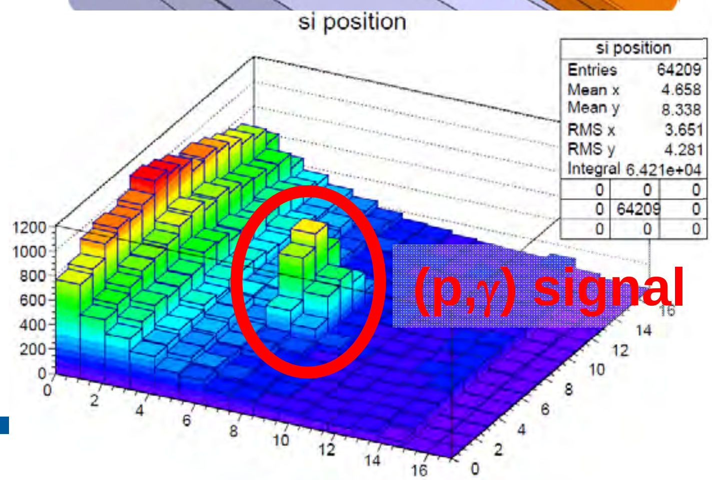
R. Margineanu, Krakow Epiphany Conference, 2010

Direct Reaction Measurement for Astrophysics

at ESR

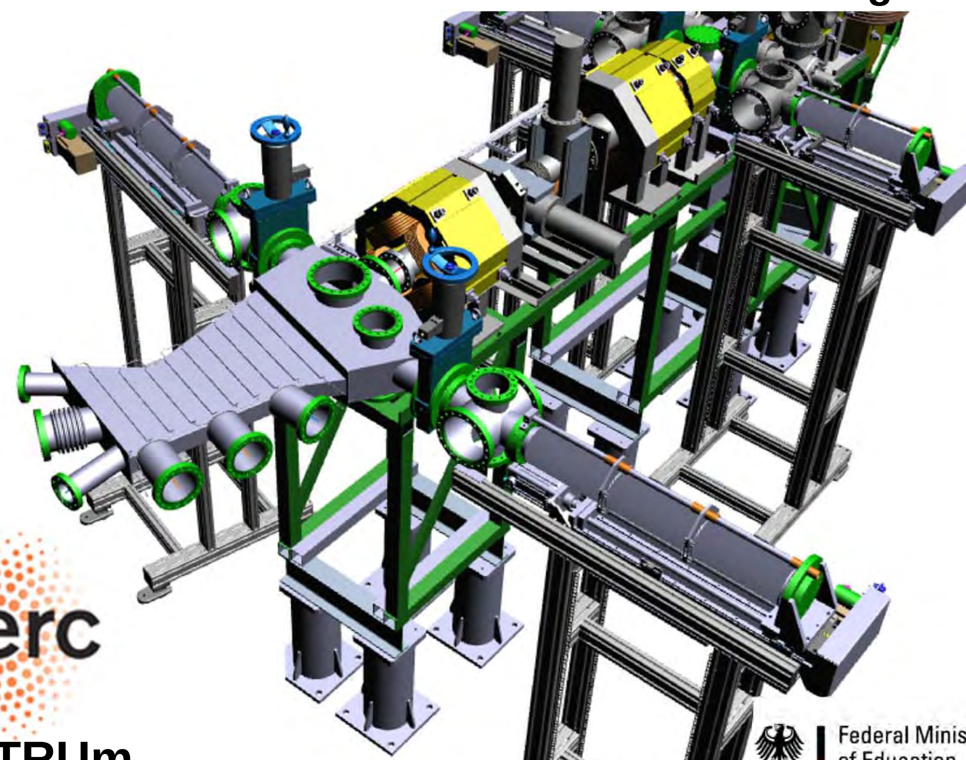
- UHV grade silicon detector
- advanced detector manipulator
- successful proof-of-concept:
  ^{124}Xe(p,γ) reaction measured in 07/2016
- ➢ **promising method for radioactive ions**





at CRYRING

- design of diagnosis chamber finished
  - ✓ construction in process
- design of setups similar to ESR
  - ✓ CAD drawings being finalized
- ➢ **extension of method to lowest energies**



ASTRUm

Federal Ministry of Education and Research

Indirect methods

Broad possibilities, increasingly broad panoply of methods

News from use of RIBs, in particular

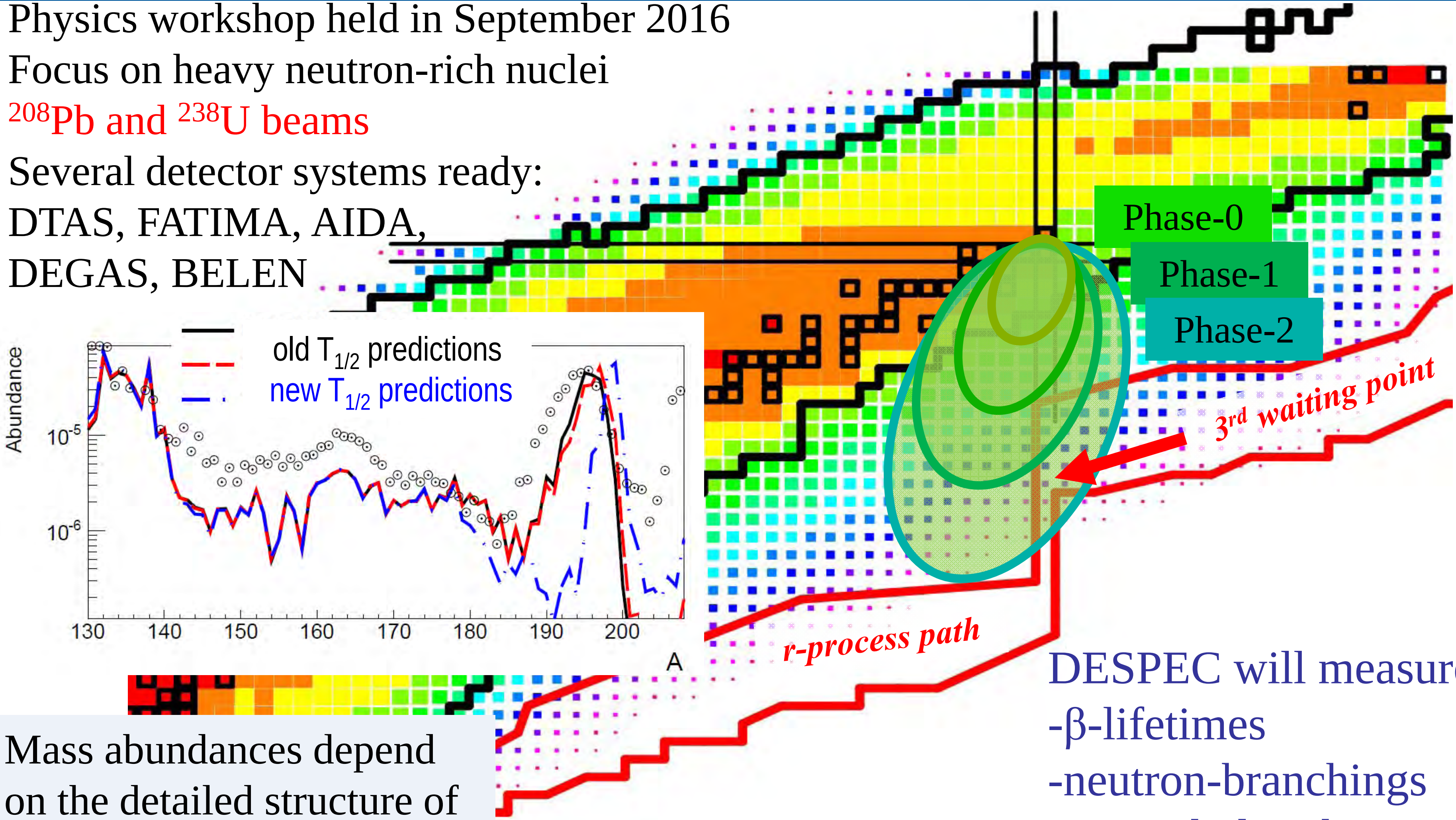
- THM (first meas: $^{18}F(p,\alpha)^{15}O$, EPJ A 52, 24 (2016))
- Reactions: one-nucleon transfer (ANC & Alex, before)
- Breakup of loosely bound nuclei: Coulomb and nuclear
- Decay spectroscopy – for resonances

New facilities:

- FAIR/GSI – recent decision for Phase 0, 1… opens new possibilities
- Spiral2, HIE-ISOLDE, SPES, ELI-NP …

DESPEC in 2018-2020 (Phase 0)

Physics workshop held in September 2016
Focus on heavy neutron-rich nuclei
^{208}Pb and ^{238}U beams
Several detector systems ready:
DTAS, FATIMA, AIDA,
DEGAS, BELEN

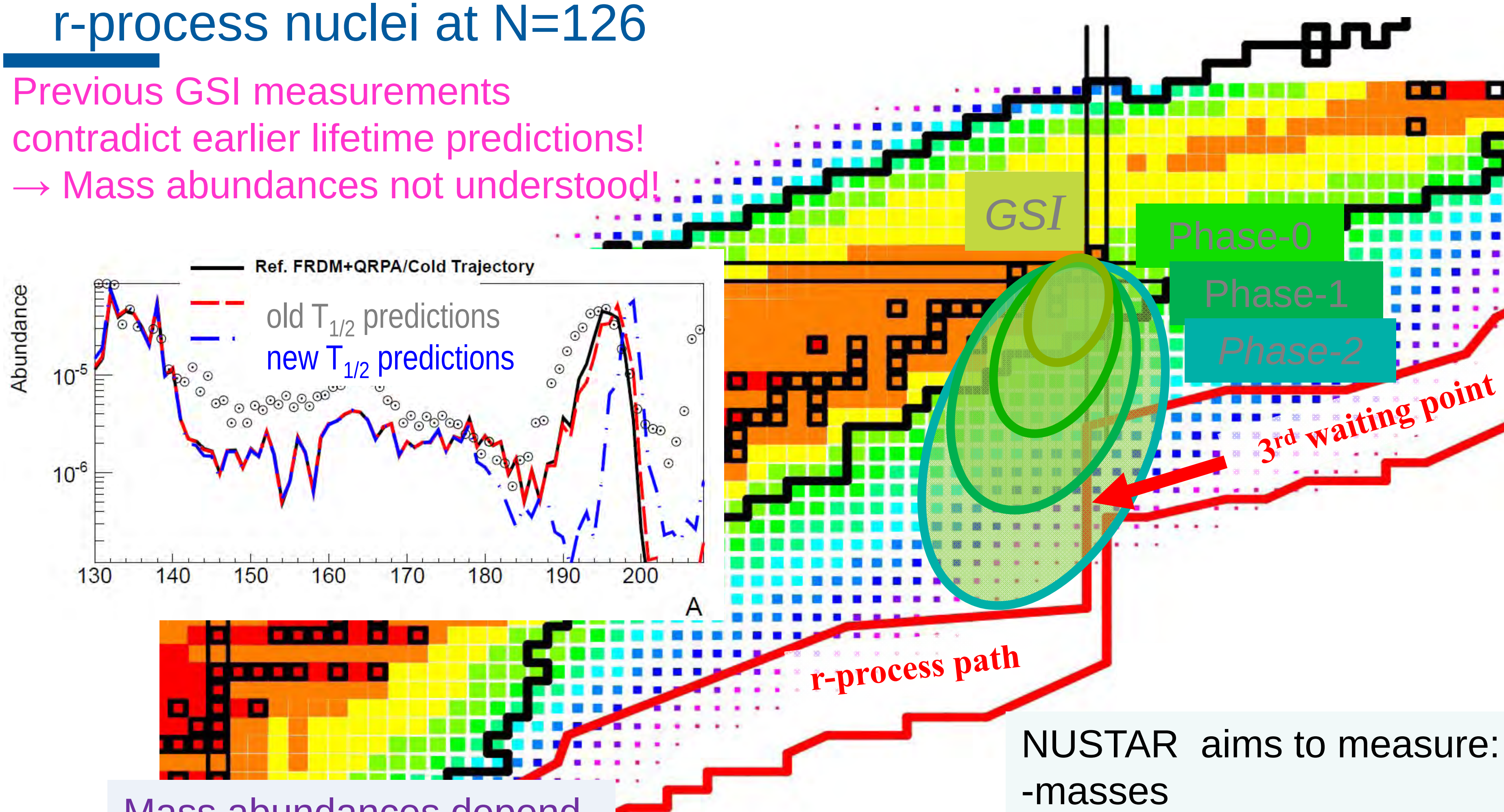


Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

DESPEC will measure
- β-lifetimes
- neutron-branchings
- strength distributions
- level structure

Phase 1 Physics with HISPEC/DESPEC:
r-process nuclei at N=126

Previous GSI measurements contradict earlier lifetime predictions!
→ Mass abundances not understood!



Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

NUSTAR aims to measure:
- masses
- β-lifetimes
- neutron-branchings
- strength distributions
- level structure

FAIR construction site - 2016

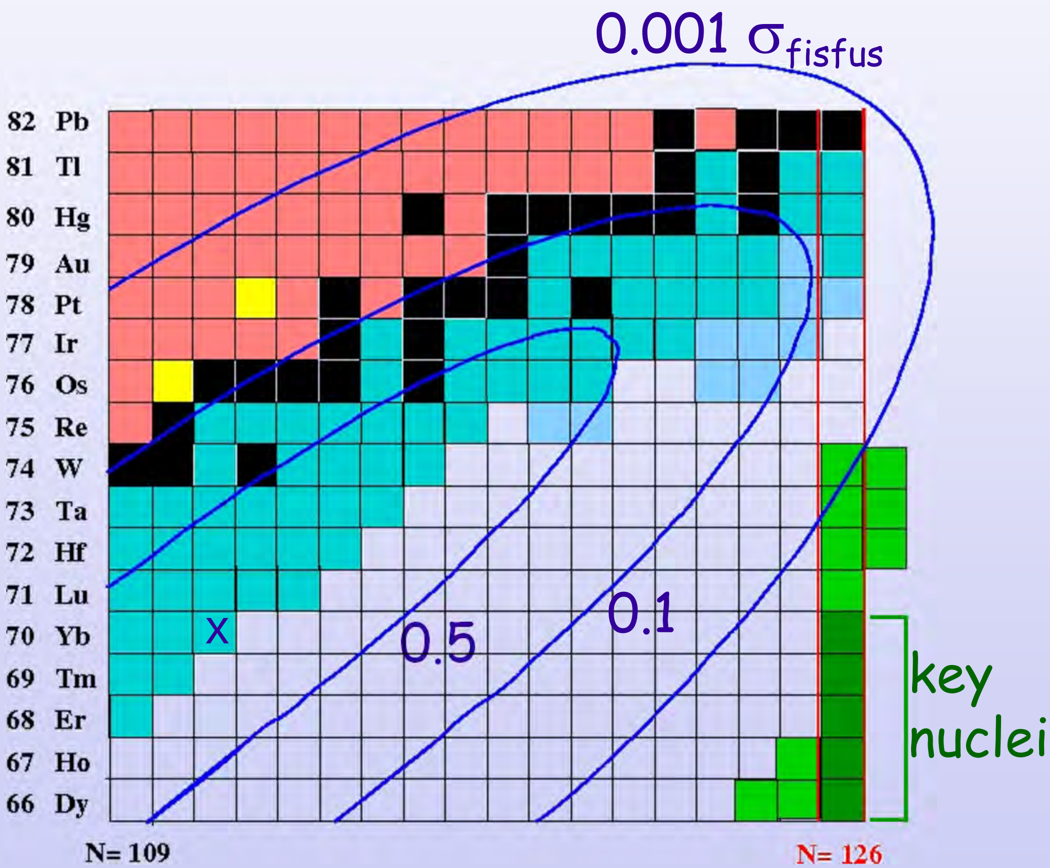
- Others plan to compete:

  ELI-NP Bucharest-Magurele

1. Produce very neutron-rich nuclei with a different method: fission-fusion
2. Stellar plasma

Towards N=126 Waiting Point

- r process path:
  - known isotopes ~15 neutrons away from r-process path (Z≈ 70)

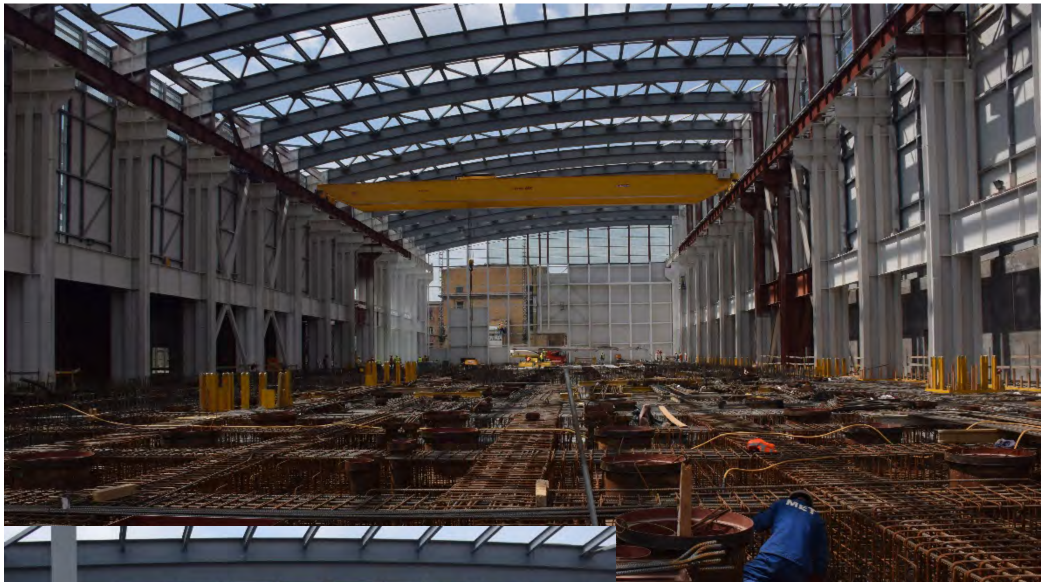
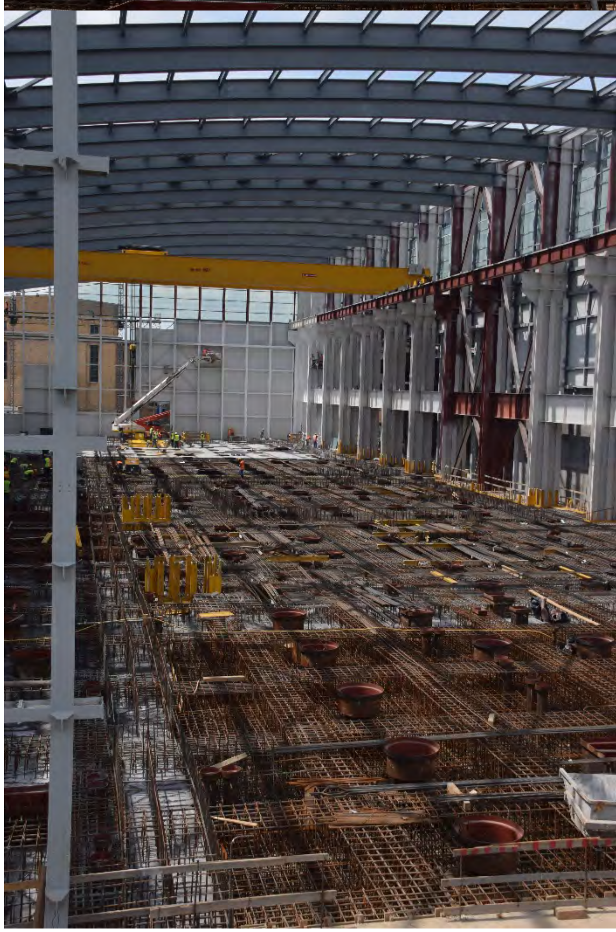


- measure:
  - masses, lifetimes, structure
  - lifetime measurements: already with ~ 10 pps

- visions:
  - test predictions: r process branch to long-lived (~ 10^9 a) superheavies (Z≥110)
    → search in nature ?
  - improve formation predictions for U, Th
  - recycling of fission fragments in r-process loops ?

2. Laser-induced “stellar plasma”?!

- Short-lived plasmas w conditions similar to stellar plasmas?!
  - Characterization
  - Nuclear astrophysics: capture reactions on excited states – very imp for quantitative descr of stellar nucleosynthesis, but out of the range of our current experimental possibilities. Can we…?!!
  - How?! What setups?!


04.07.2016

Nov 2016

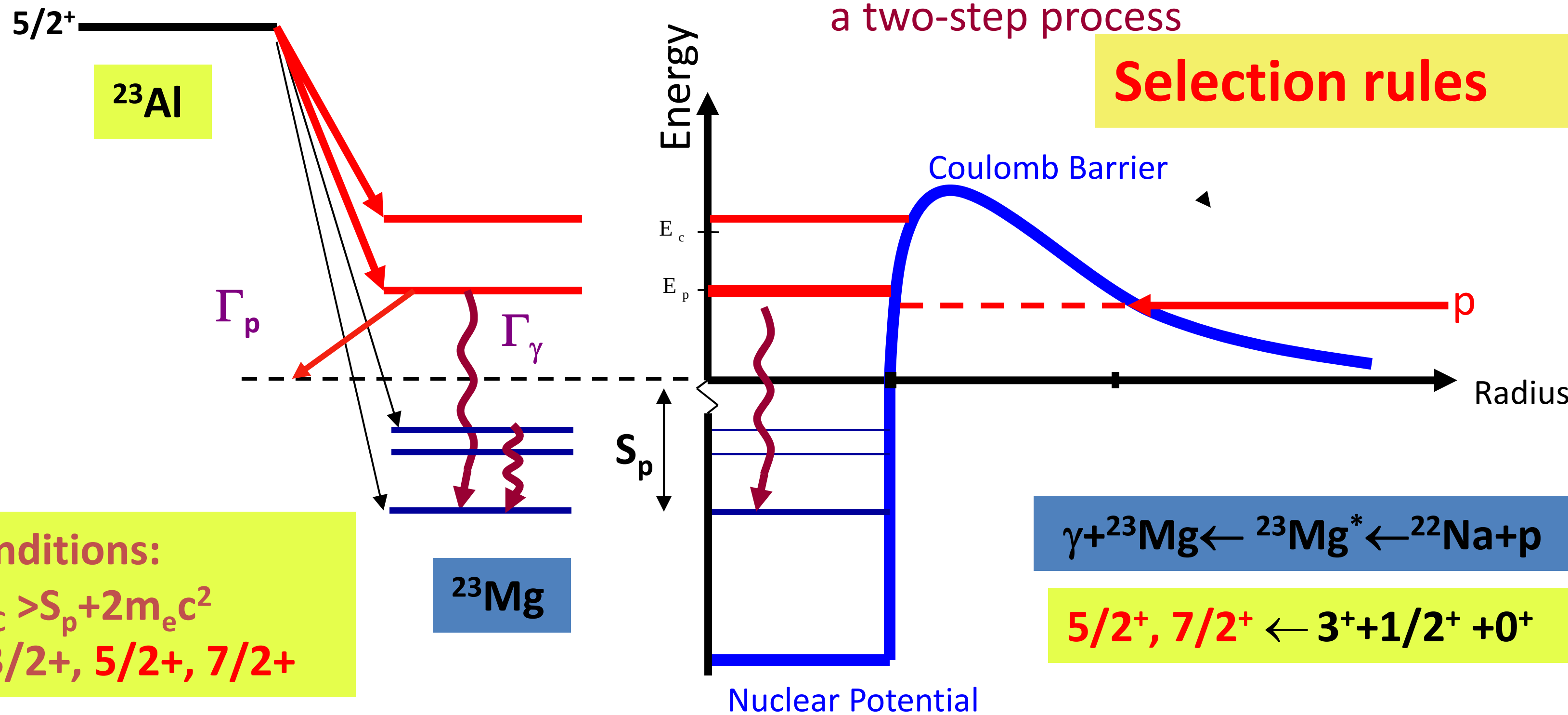
Nov 2016

Decay spectroscopy

Resonant Capture

a two-step process

Selection rules



Conditions:
$Q_{EC} > S_p + 2m_ec^2$
J=3/2+, 5/2+, 7/2+

$\gamma + ^{23}Mg \leftarrow ^{23}Mg^* \leftarrow ^{22}Na + p$

$5/2^+, 7/2^+ \leftarrow 3^+ + 1/2^+ + 0^+$

Same compound system: ^{23}Mg

Resonance strength

Resonant contributions to reaction rate:

$\langle \sigma \upsilon \rangle_{res}$ … $b_\gamma b_p * \Gamma_{tot}$

Lower proton energies most important, but very difficult:

- lower branching
- increased exp difficulties (det windows, background, etc…)

Need energy, J_r and resonance strength

Comparison Si – gas detector

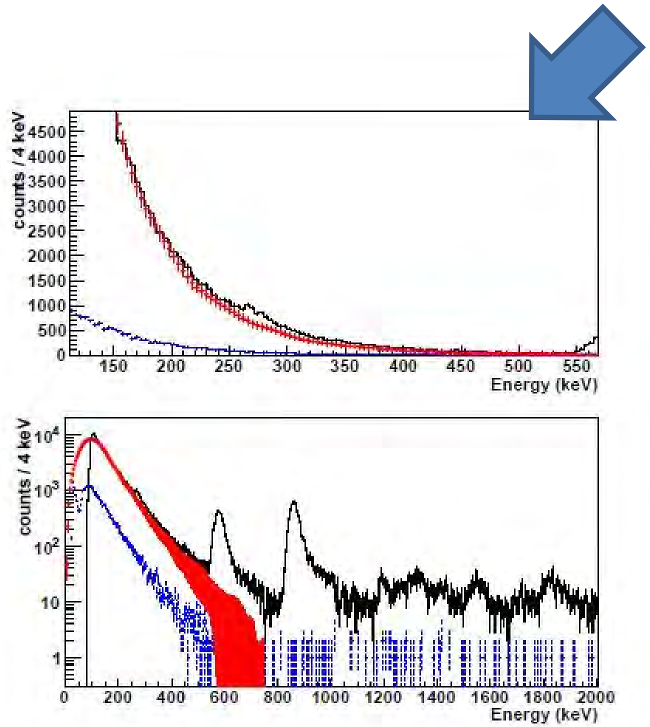
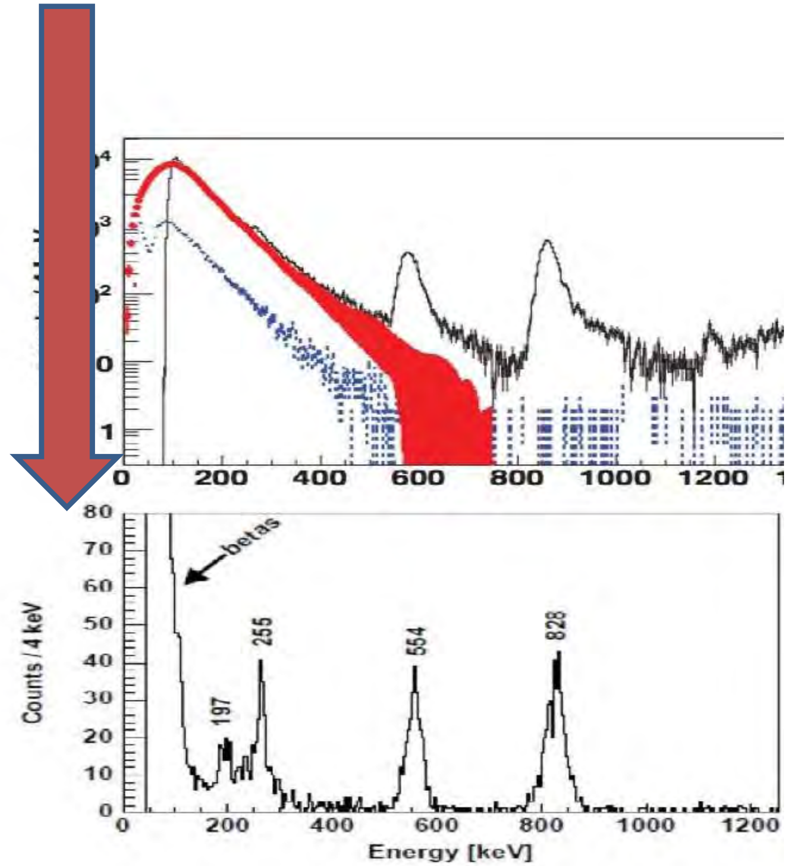
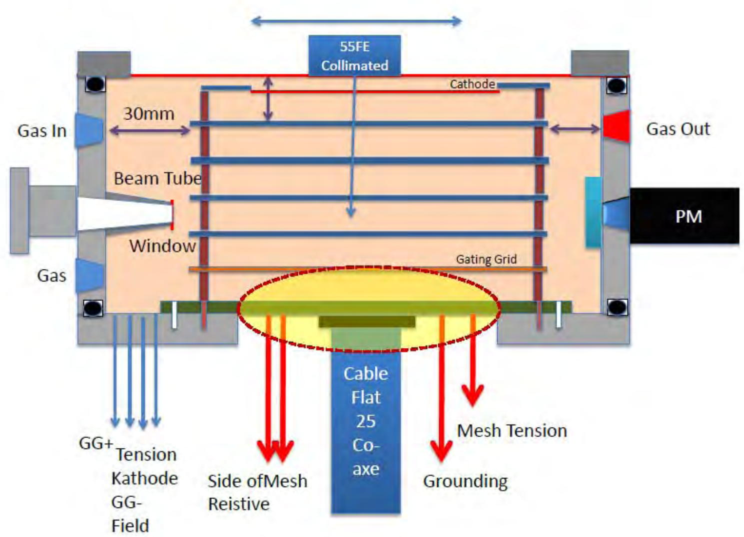


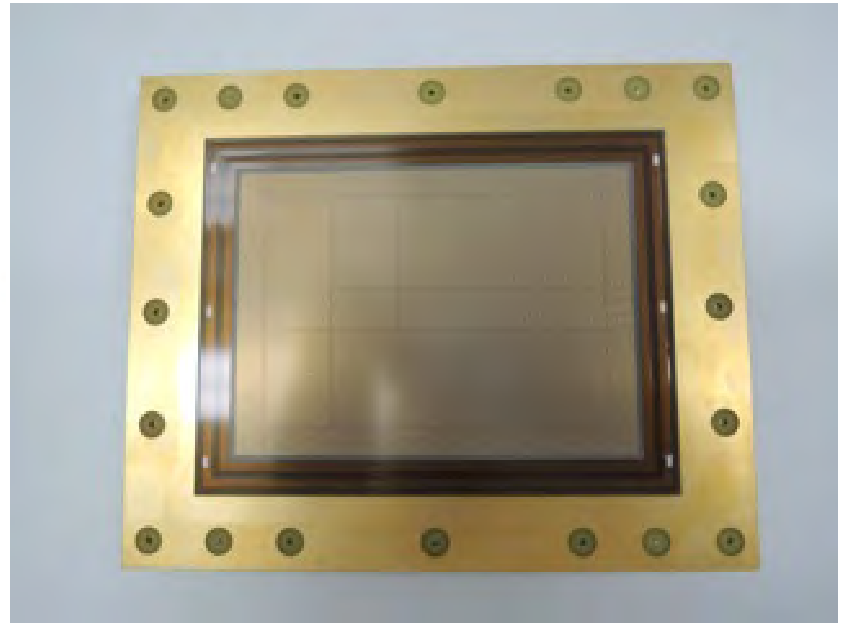
FIG. 7: (Color online) Full collected statistics for the ^{23}Al data (black, solid) and the ^{22}Mg data (blue, dashed). The energy is the total measured decay energy. Smoothed ^{22}Mg spectrum, scaled to match the ^{23}Al spectrum at 150 keV is shown with red dots and corresponding uncertainties. Upper panel shows only the low energy part where the proton group at $\sim$ 270 keV is clearly visible on top of the β background, whereas the lower panel shows the total spectra.



A. Saastamoinen, LT et al, PRC 83 (2011)
E. Pollacco, LT et al., NIM 2014

Design and construction of the micromegas detector for AstroBox2. Measurements, data and nuclear structure calculations

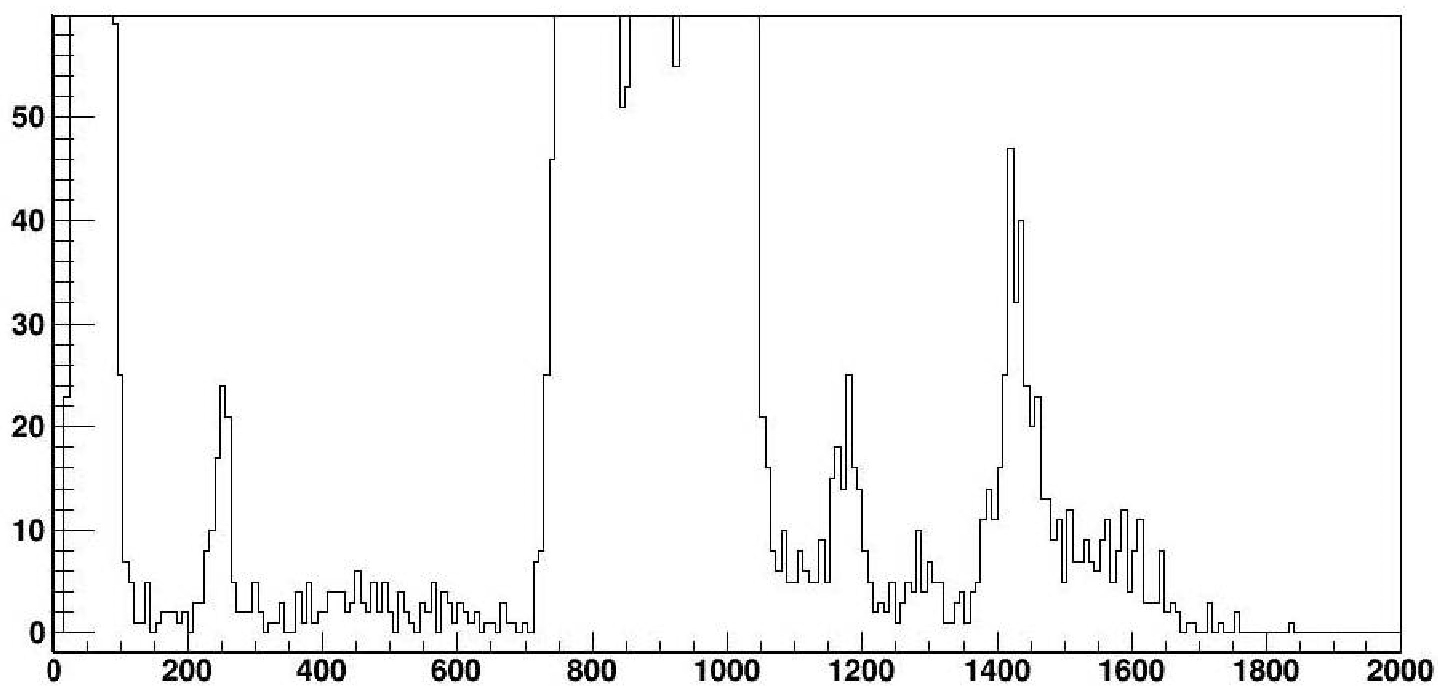




Chamber: design and prod: TAMU
Micromegas: Bucharest, Saclay, CERN
Electronics: Bucharest
Gas (P10) handling: existing at TAMU
Assembly and source tests: Saclay + TAMU
In-beam test and use: Bucharest, Saclay, TAMU

Latest – Oct 2016, TAMU exp

^{31}Cl beta-delayed proton decay
Texas A&M MARS + Astrobox-2 experiment



E_p [keV]

Theory support

- Theory for indirect methods
- Theory for nuclear data for NS calculations
  - Theory guided extrapolation of systematics
  - Considering excited states involved in stellar processes, but not available experimentally (next 2+2 slides)
- Nucleosynthesis and stellar dynamics calculations (not considered here)

Nuclear Physics for Astrophysics

Indirect methods – measurements at lab energies $\rightarrow$ cross sections at stellar energies

Experiments at 10, … 100, 300 MeV/nucleon to assess cross sections at 10, 100, 300 keV

Indirect methods in NPA with RNB

A. Coulomb dissociation

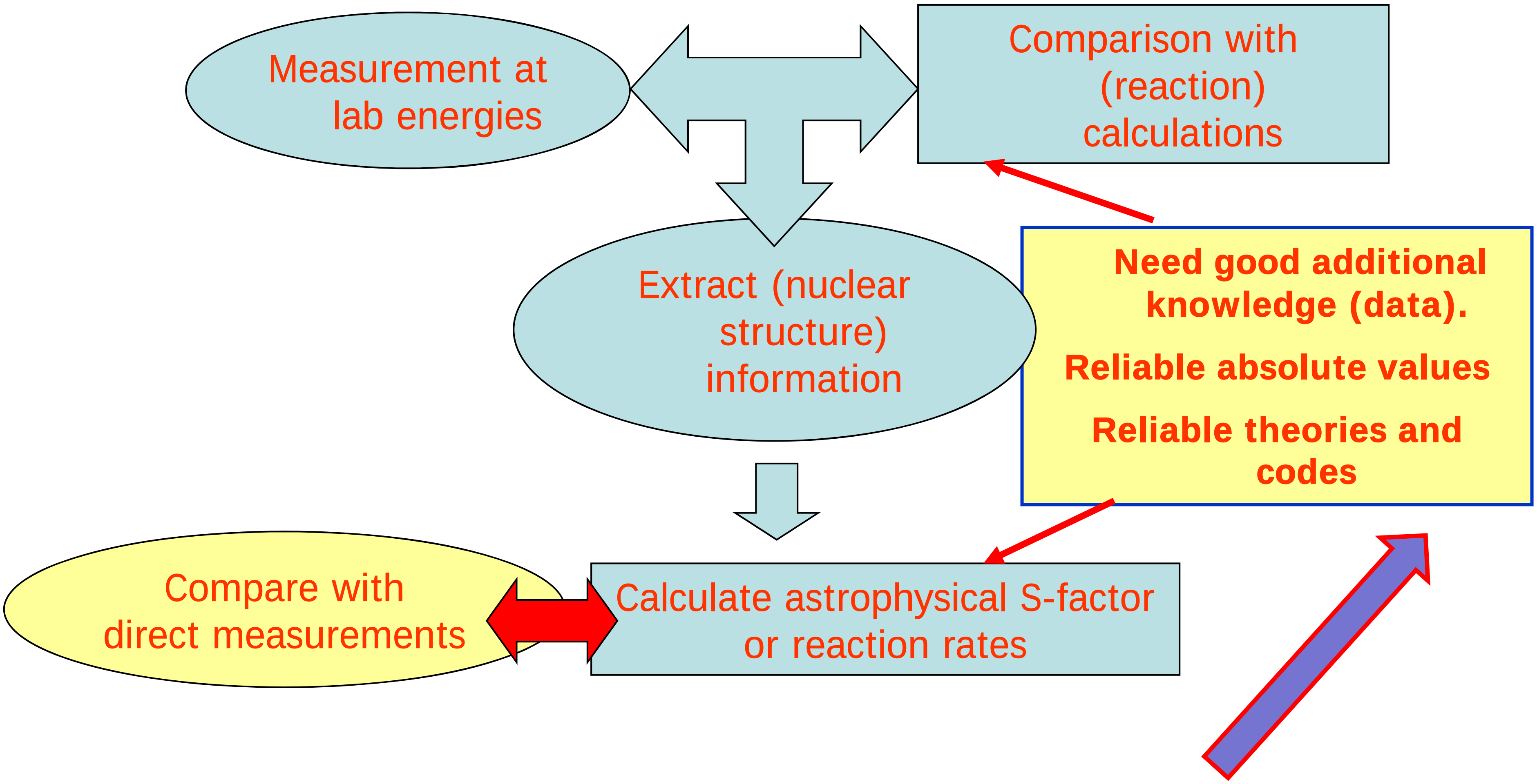
B. Transfer reactions (ANC method)

C. Breakup of loosely bound nuclei

D. Resonance spectroscopy – β-decay, resonant elastic scattering, etc.

E. Trojan Horse Method (non-RNB so far! Just starting …)

Indirect methods for nuclear astrophysics



NUSPRASEN subtask 2.3 plans an workshop on this subject (ECT* ?!)

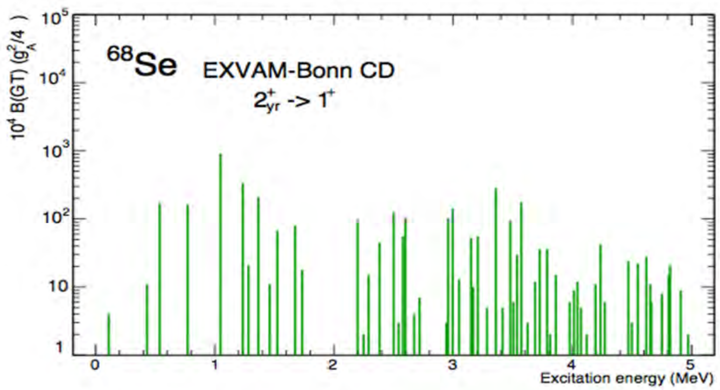
Shape coexistence effects on stellar weak interaction rates for A~70 waiting points

A. Petrovici and O. Andrei, Eur. Phys. J. A 51, 133 (2015)

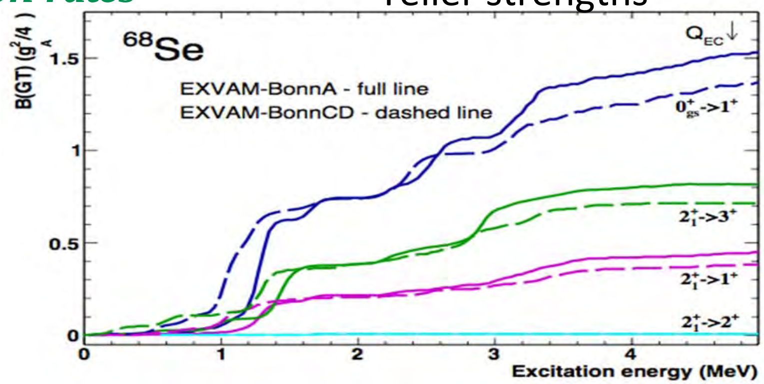
Comprehensive description of structure phenomena and β-decay properties within complex Excited VAMPIR beyond-mean-field model

Effects of shape coexistence in the structure of parents and daughter nuclei on weak interaction rates

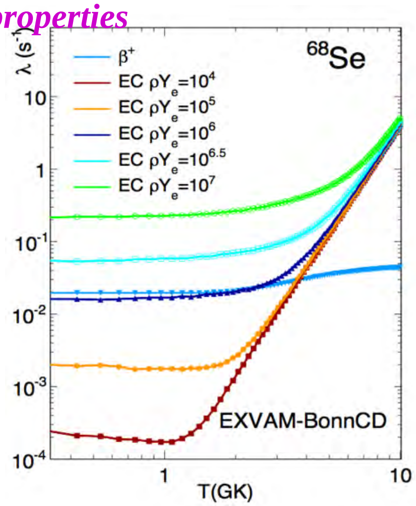
Gamow-Teller strength distribution



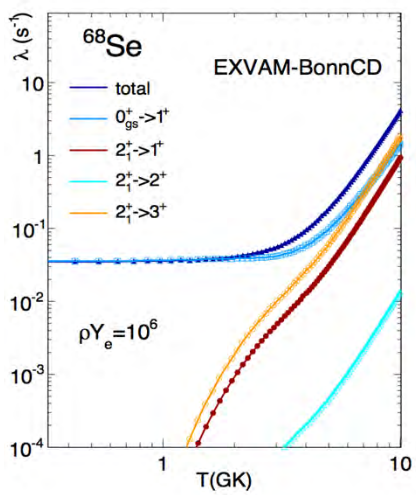
Accumulated Gamow-Teller strengths



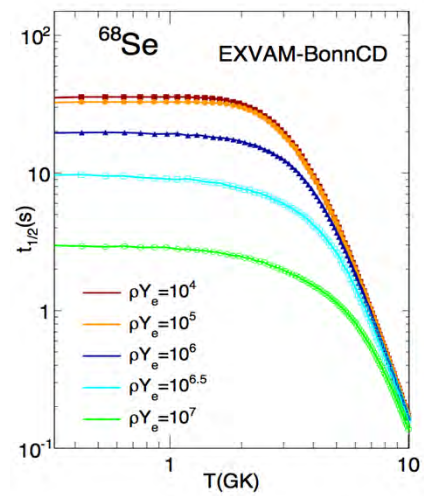
Reliable predictions on stellar weak interaction rates based on self-consistent description of experimentally accessible properties



Continuum electron capture makes a significant contribution



Relevant contribution from low-lying 0^+ and 2^+ states in X-ray burst environment



Prediction: 3 times shorter half-live at T=3GK and $\rho Y_e=10^6$ mol/cm^3 with respect to the terrestrial value

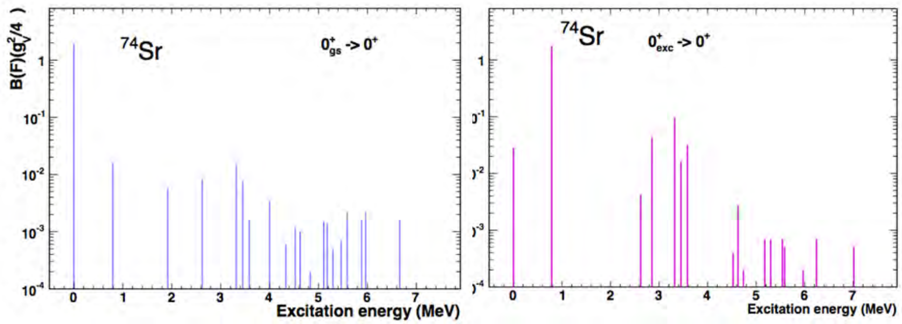
From isospin mixing to stellar weak interaction rates for Z=N+2 medium mass nuclei

complex Excited VAMPIR beyond-mean-field description of shape coexistence effects on terrestrial and stellar weak interaction rates

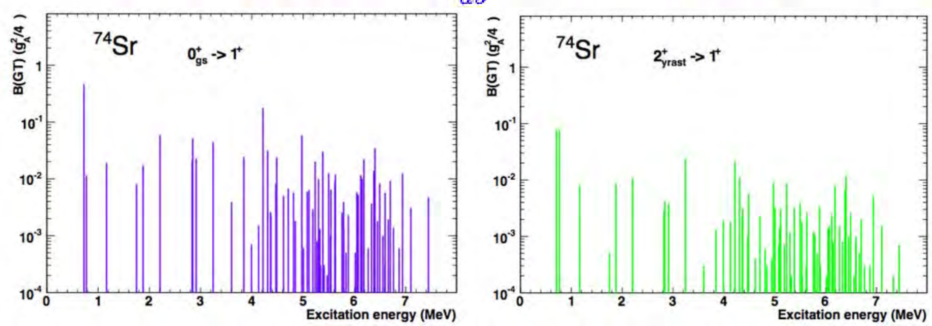
Fermi and Gamow-Teller β-decay are treated on an equal footing

$$M_F \equiv (\xi_f J_f||\hat{1}||\xi_i J_i) = \delta_{J_i J_f} \sum_{ab} M_F(ab)(\xi_f J_f||[c_a^\dagger \tilde{c}_b]_0||\xi_i J_i)$$

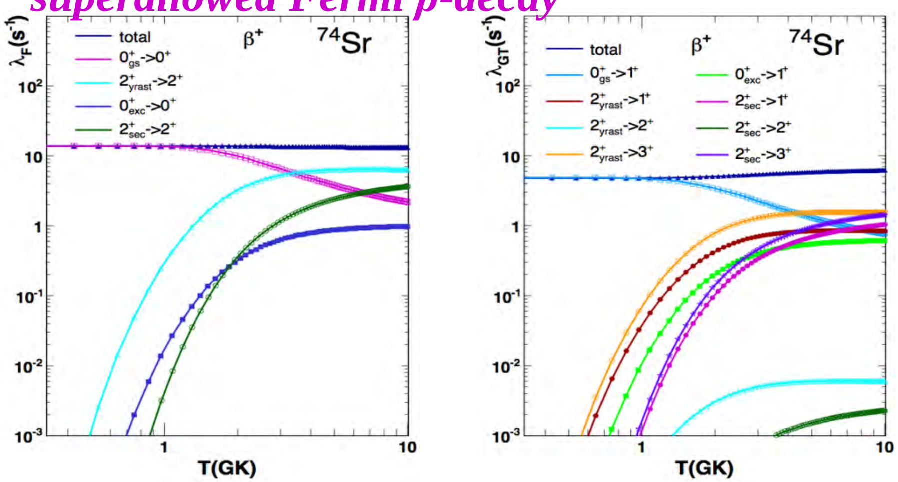
$$M_{GT} \equiv (\xi_f J_f||\hat{\sigma}||\xi_i J_i) = \sum_{ab} M_{GT}(ab)(\xi_f J_f||[c_a^\dagger \tilde{c}_b]_1||\xi_i J_i)$$



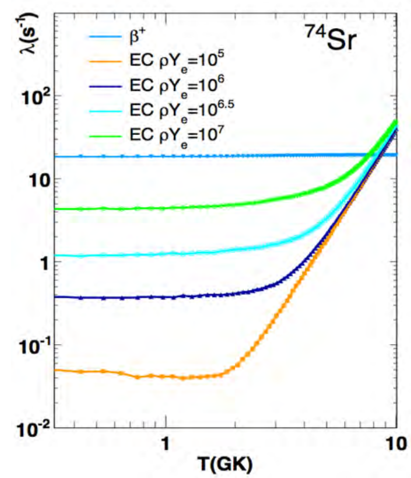
Interplay between isospin-symmetry breaking and shape coexistence effects on superallowed Fermi β-decay



Shape coexistence effects on Gamow-Teller β-decay strength distributions



Decay rates: 75% Fermi and 25% Gamow-Teller contribution



Very small contribution from continuum electron capture in X-ray bursts

A. Petrovici, Phys. Rev. C 91, 014302 (2015), J. Phys. Conf. Ser 724, 012038 (2016); A. Petrovici, and O. Andrei, Phys. Rev. C 92, 064305 (2015)

NUSPRASEN: planned NA activities

Subtask 2.3: Nuclear astrophysics

- Nuclear astrophysics brings the nuclear reactions, which take place in astrophysical environments, into the laboratory. The network will strengthen the collaborations in terms of:
  a) identification, discussion and assessment on the advances of indirect methods, in particular of those using radioactive beams, and
  b) the formation of new collaborations and user groups, mainly attracting students and young scientists through dedicated workshops. The European Network of Nuclear Astrophysics Schools (ENNAS) will be supported.
- c) connect groups and create synergies between nuclear physics for astrophysics, astronomical observations, cosmochemistry, nucleosynthesis calculations, stellar evolution modelling, for mutual benefits

Planned activities (cont'd)

In the framework of nuclear astrophysics activities (subtask 2.3), the following plan exists:

- Support of European Network of Nuclear Physics Schools (ENNAS):
  - Russbach School on Nuclear Astrophysics (in Russbach, Austria) – one week, each year in March: 2016, 2017, 2018, 2019
  - Carpathian Summer School of Physics, Sinaia, Romania – two weeks, every two years: 2016, 2018
  - School on Experimental Nuclear Astrophysics, St. Tecla, Sicily, Italy – 10 days, every two years: 2017 and 2019
- Nuclear astrophysics workshops on specific topics:
  - Workshop on explosive nucleosynthesis – to be organized in Debrecen, Hungary. Tentative time May 2018 (month 27 of ENSAR2). Responsible Zs. Fulop et al.
  - Workshop on Indirect Methods in Nuclear Astrophysics at ECT* - one week, Trento, fall 2017 – early 2018 (by month 24). Organizers L. Trache, A. Bonaccorso, C. Bertulani, Tohru Motobayashi, Zs. Fulop.
- The latter event is considered the relevant milestone as written in the project agreement (report due in month 24).

NA02-NUSPRASEN

News from nuclear astrophysics activities

European Network of Nuclear Astrophysics Schools (ENNAS) - partially supported by NUSPRASEN

- Two NA schools were organized:
  - 13th Russbach School on Nuclear Astrophysics, March 6-12, 2016, Russbach, Austria
    - 60 participants, 33 lectures and 22 short contributions by students
  - Carpathian Summer School of Physics 2016, June 26 – July 9, 2016, Sinaia, Romania

  "Exotic Nuclei and Nuclear/Particle Astrophysics (VI). Physics with small accelerators"

  - 126 participants + … (14 fellowships)
  - 53 lectures and 23 communications
  - 2 days dedicated to ELI-NP sessions
  - School's round table: "JINR @60 and international…"

ENNAS

The organization of the 2017 edition of Russbach school has started

The directors of the 3 ENNASchools coordinate their programs, to offer the community a comprehensive service

- covering together the basic grounds
- but also have specificities and are bridging to the border domains:
    - nuclear structure and astroparticles (CSSP)
    - observational astrophysics and star dynamics (Russbach)
    - nucleosynthesis network calculations and star evolution (St. Tecla)
- we have outlined the program of the NA workshops for the duration of ENSAR2

Thank you for your attention!