

Nuclear Astrophysics at SPES

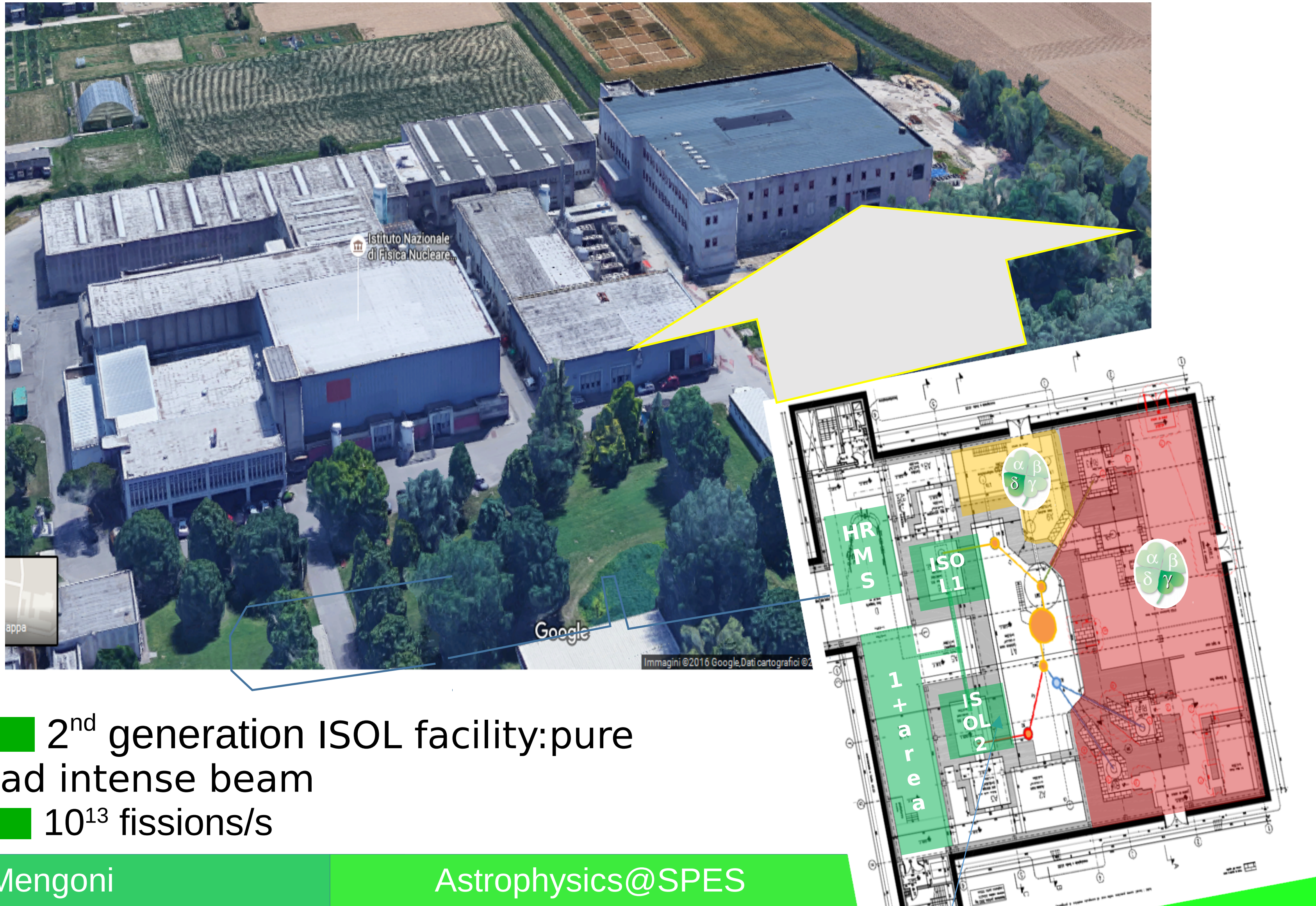
Daniele Mengoni
Università di Padova e INFN

SPES
exotic beams for science

GIANTS, October 5-6, 2017 - Bologna

■ SPES - Infrastructure

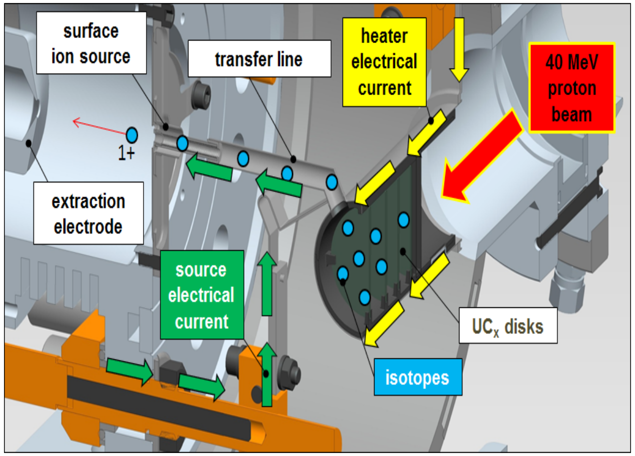
SPES - Layout



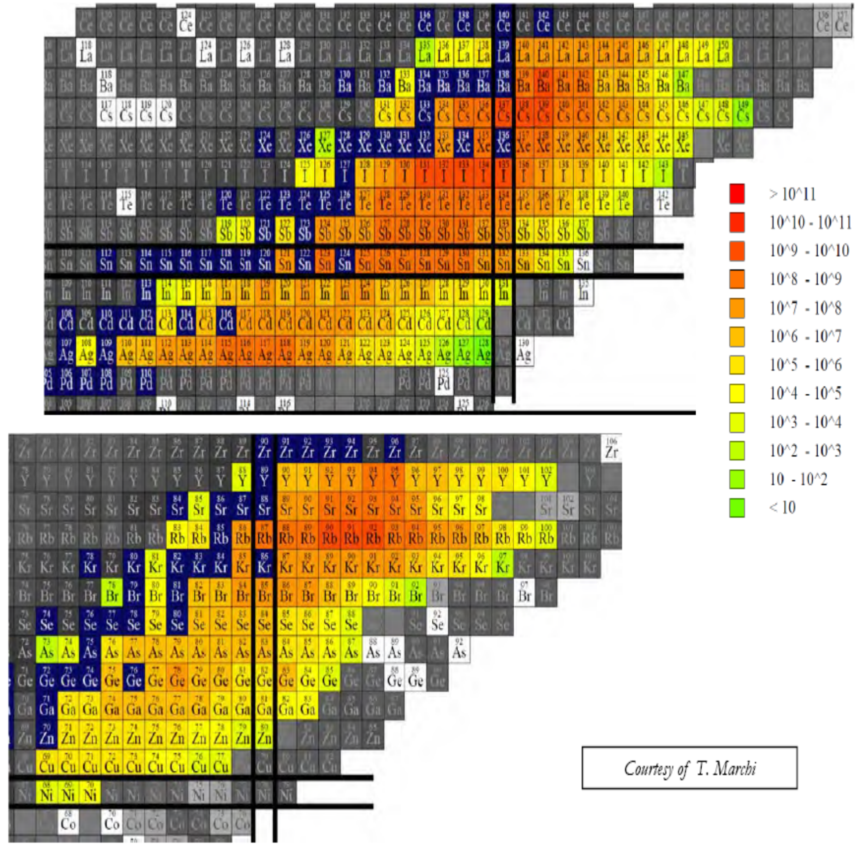
- 2nd generation ISOL facility:pure ad intense beam
- 10^{13} fissions/s

Yield

- UCx Target
  (… + not fissile also foreseen)

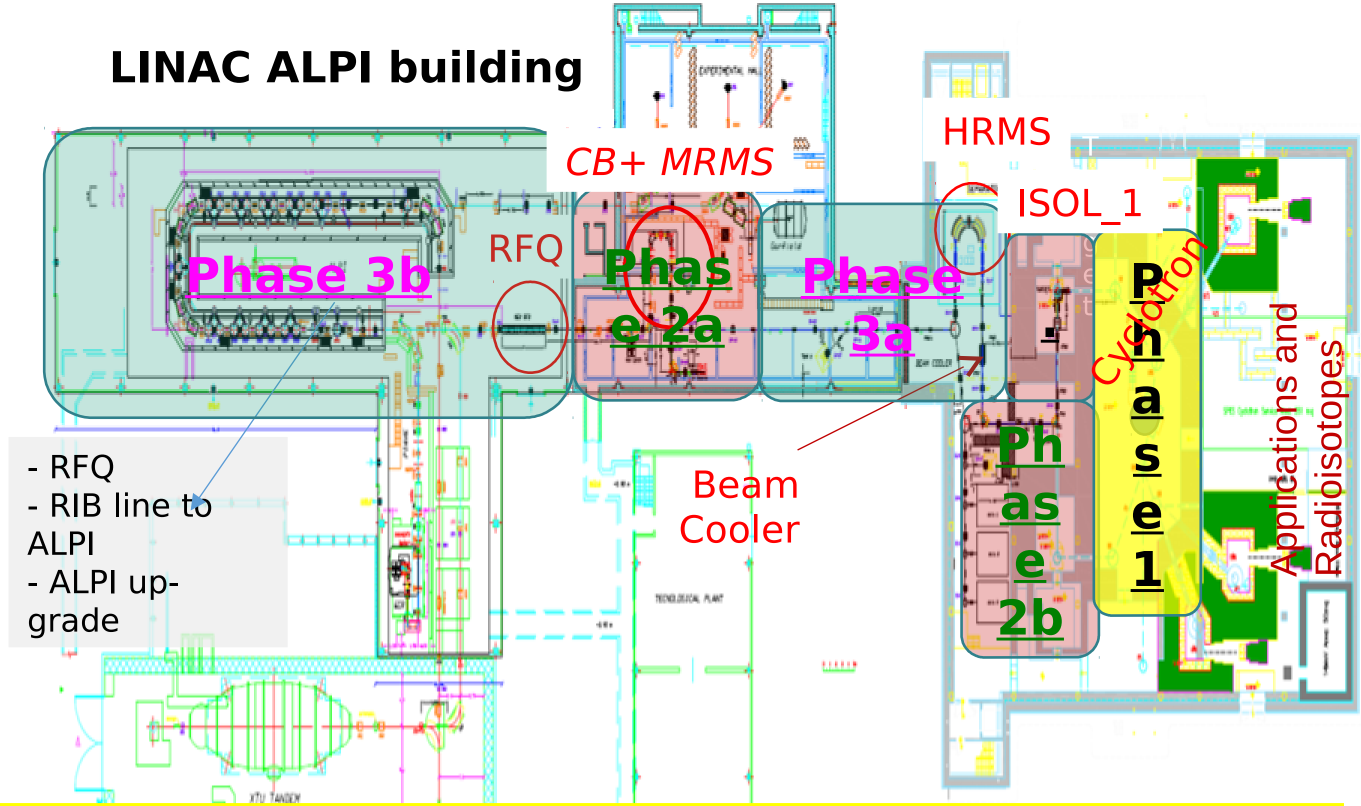


- Expected intensity for reaccelerated beams



- **MCNPX Calculation**
- **BERTINI – ORNL** (FF cross- sections)
- **Release** & **ionization efficiency** in agreement and re-scaled on **HRIBF experimental values** and **currents** (**200µA/5µA**)

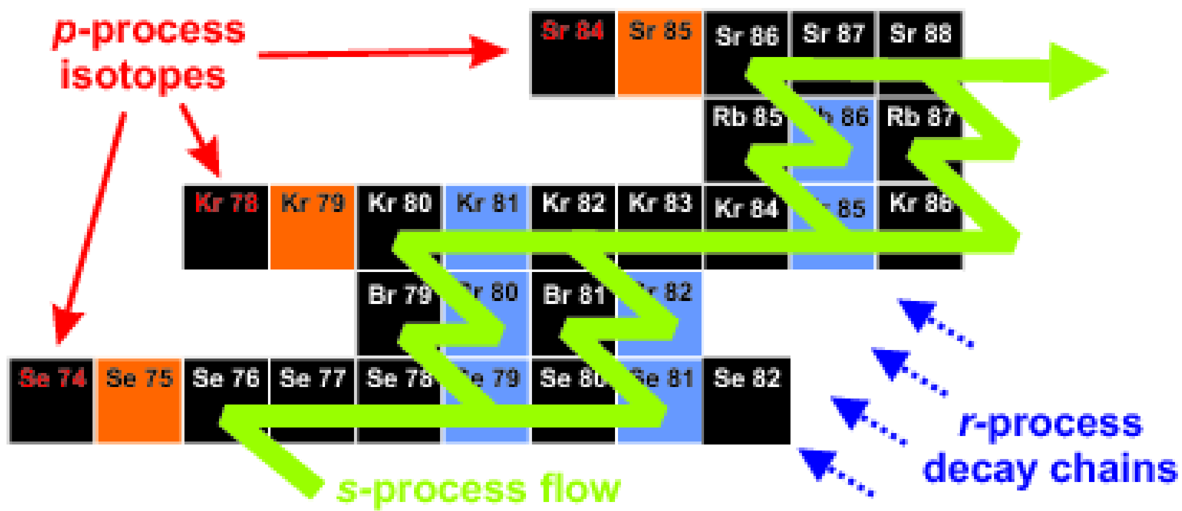
SPES - Timeline



- **Phase 1. 2016** - Building + First operation with the cyclotron
- **Phase 2. 2018-19** - From C.B. to RFQ + SPES target, LRMS, 1+ Beam Lines
- **Phase 3. 2020 – 21 -** HRMS-BeamCooler + RFQ to ALPI

■ SPES – Astrophysics

Fission products @SPES



- β decay faster then n capture
- Neutron density 10^{6-7}n/cm^3
- Branching points: τ and n capture rate of the same order of magnitude
- key reaction: (n,γ)

- n capture faster than β decay
- Neutron density 10^{20} n/cm^3
- Dripline and waiting points: plenty of ... nuclear structure information needed
- τ, masses, energy levels, J^π, s.p. strengths, (n,γ)

- indirect methods for RIB (TH, SR, ANC)

Reactions of interest

s process

- (n,γ):
  - ^{79}Se, ^{81,85}Kr, ^{86}Rb, ^{65}Zn, ^{121}Sn,
  - ^{64}Cu, ^{108}Ag, ^{109}Pd, and ^{123}Sn and many more

➔ collaboration with INFN Pg and INAF Teramo

➔ 2 LoIs presented at the 3rd SPES workshop in 2016

➔ Commissioning tests needed with stable beam

r process

- $^{123,131\text{-}134,131}$In, ^{133}Sb
- Ni, Cu, Zn, Ga, Ge, As

➔ Collaboration with ORNL/Rutgers Univ. (exp) and NSCL (theory)

➔ 2 LoIs presented at the 3rd SPES workshop in 2016

➔ Commissioning tests needed with stable beam

SPES – indirect methods

Techniques for astrophysics

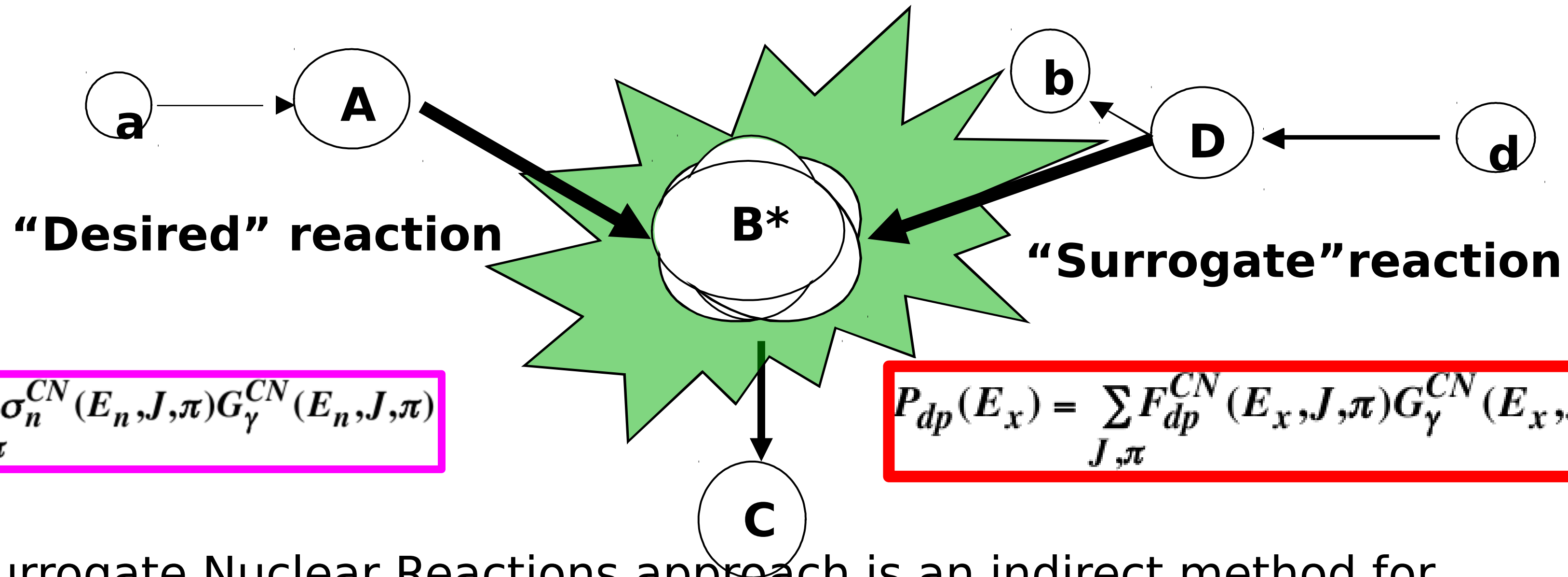
■ DIRECT Techniques: (LUNA, ERNA, DRAGON, ...): .. at relevant (stellar) energy range → low cross section (..pB/keV) but model independent

■ INDIRECT Techniques[(*)]: .. at lab energies (...→ stellar energies) but always model dependent

- ✔Coulomb dissociation
- ✔Transfer reaction
- ✔Breakup of loosely bound nuclei
- ✔Trojan Horse method
- ✔Resonant spectroscopy - γ decay, resonant elastic scattering, etc
- ✔ANC methods
- ✔**Surrogate reaction method (SRM)**

[(*)]Presentation by M. La Cognata at the last SPES workshop – 2016 LNL

Indirect approach: surrogate approach



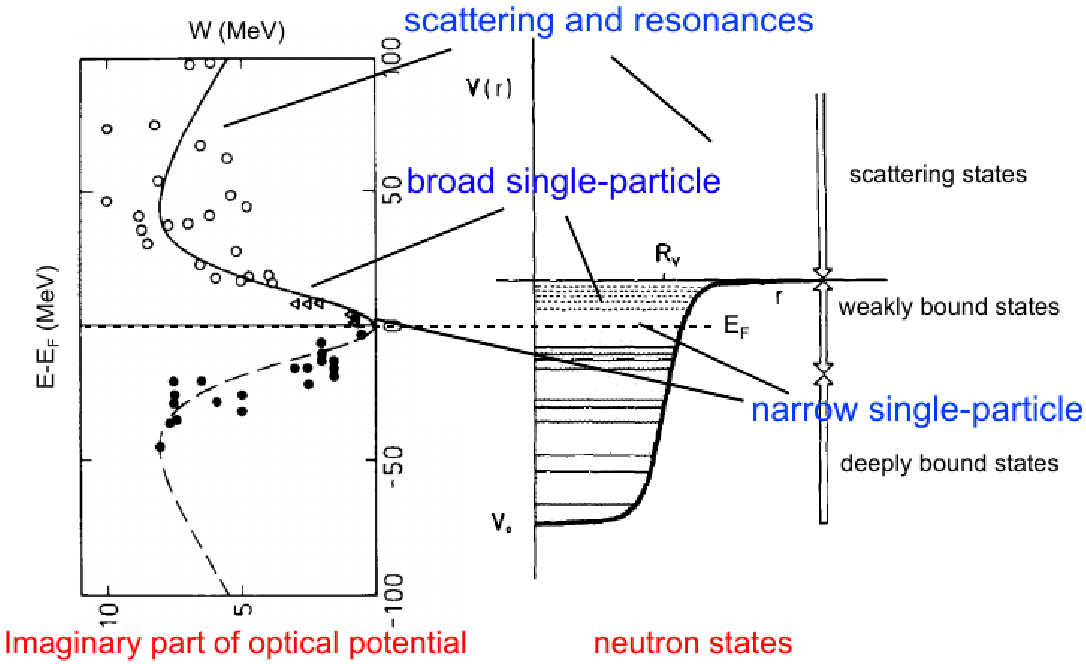
$$\sigma_{n\gamma}(E_n) = \sum_{J,\pi} \sigma_n^{CN}(E_n,J,\pi) G_\gamma^{CN}(E_n,J,\pi)$$

$$P_{dp}(E_x) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi) G_\gamma^{CN}(E_x,J,\pi)$$

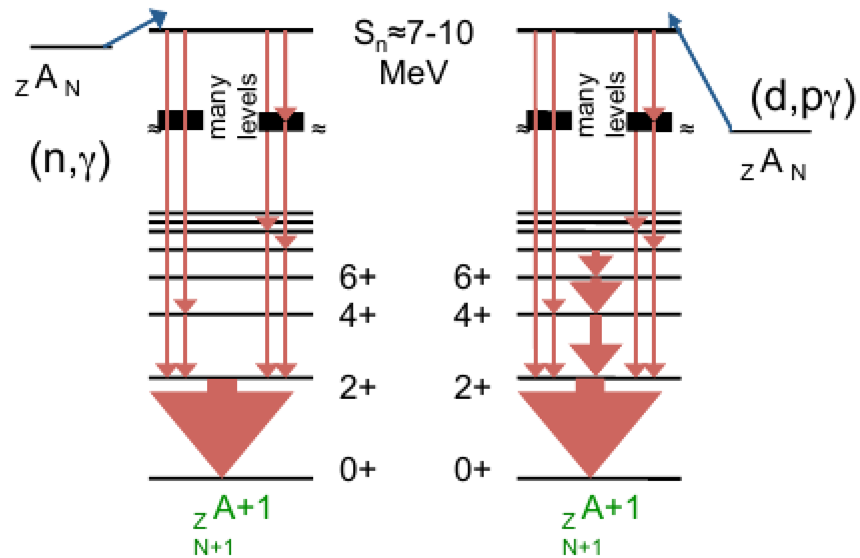
- The Surrogate Nuclear Reactions approach is an indirect method for determining cross section of CN reactions difficult to measure directly.
- Various direct-reaction mechanisms can be employed to create the compound nucleus of interest
- Different “compound-nuclear” decays can be considered

J.E.Escher, J.T.Burke, F.S.Dietrich, N.D.Schielzo, Rev. of Mod. Phys. 84 (2012)

Entry level in the neutron capture

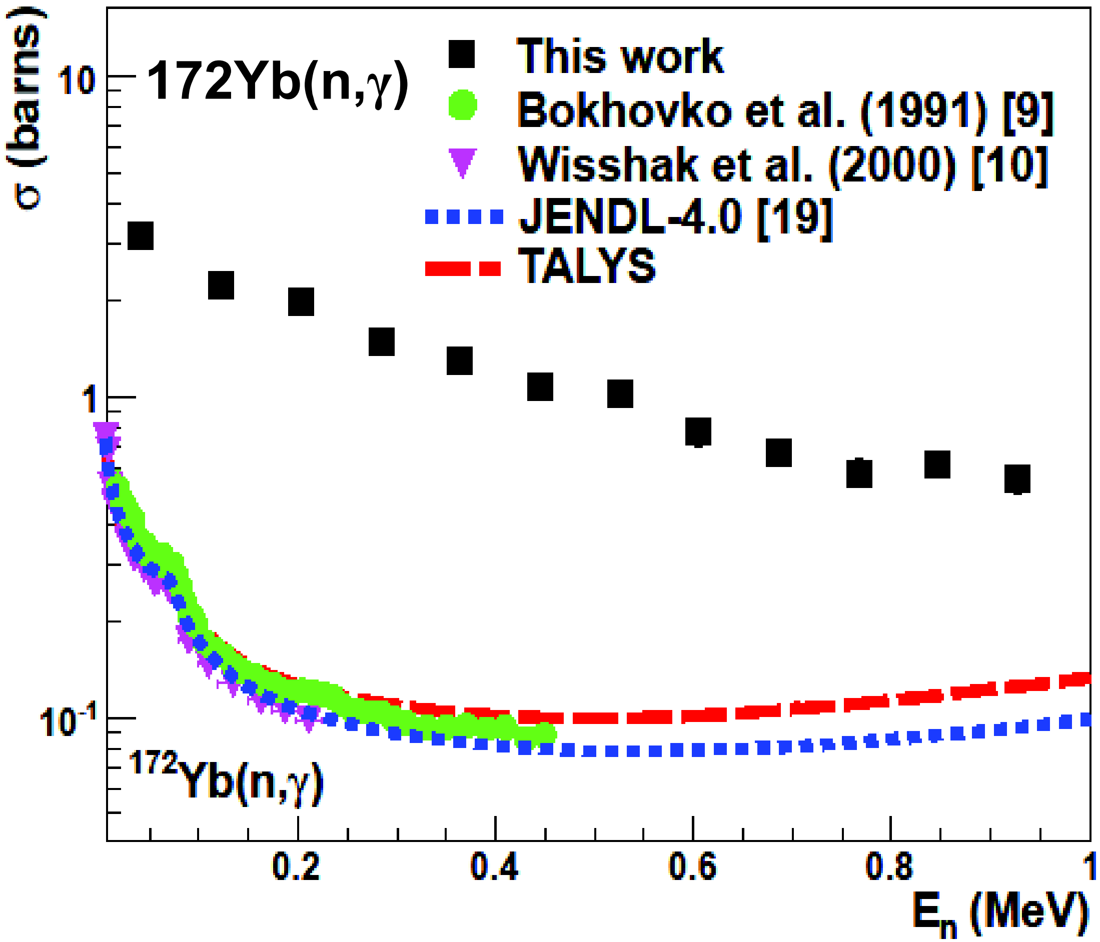


Mahaux, Bortignon, Broglia, Dasso, Phy.Rev.120(1985)1



- Spin distribution generally different from direct and surrogate reaction (*s,p* waves for the neutron). Mitigation still possible in the case of deuteron.
- Compound nucleus or resonances can be formed

benchmarks for (n,γ) cross sections
(3He,4He)



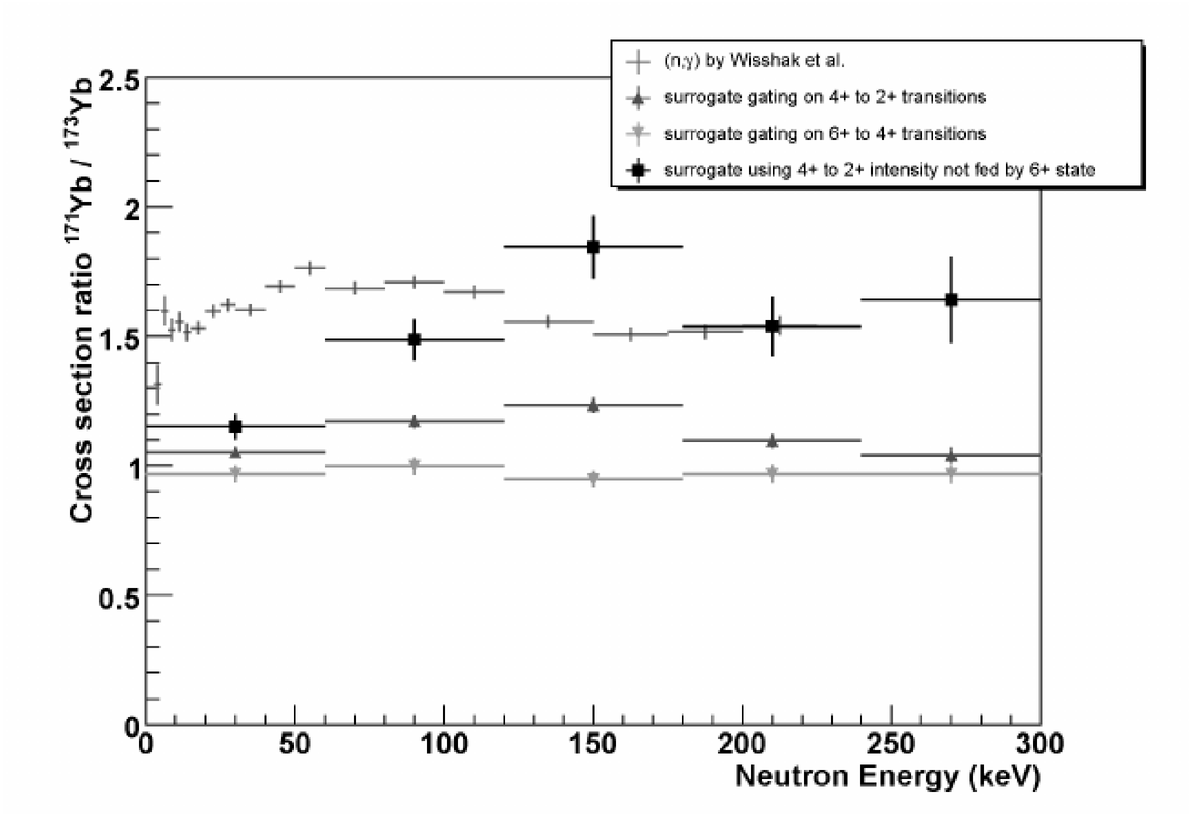
- Disagreement with the measure radiative capture data
- “complex” reaction mechanism

G.Boutoux et al., PLB 712 (2012), 319

(d,p) benchmark for (n,γ) cross sections

171,173Yb(d,pγ)

$$\sigma_{n\gamma}^{WE}(E_n) = \sigma_n^{CN}(E_n) G_\gamma^{CN}(E_n) = \sigma_n^{CN}(E_n) \frac{N(d,p\gamma)}{\varepsilon N(d,p)}$$



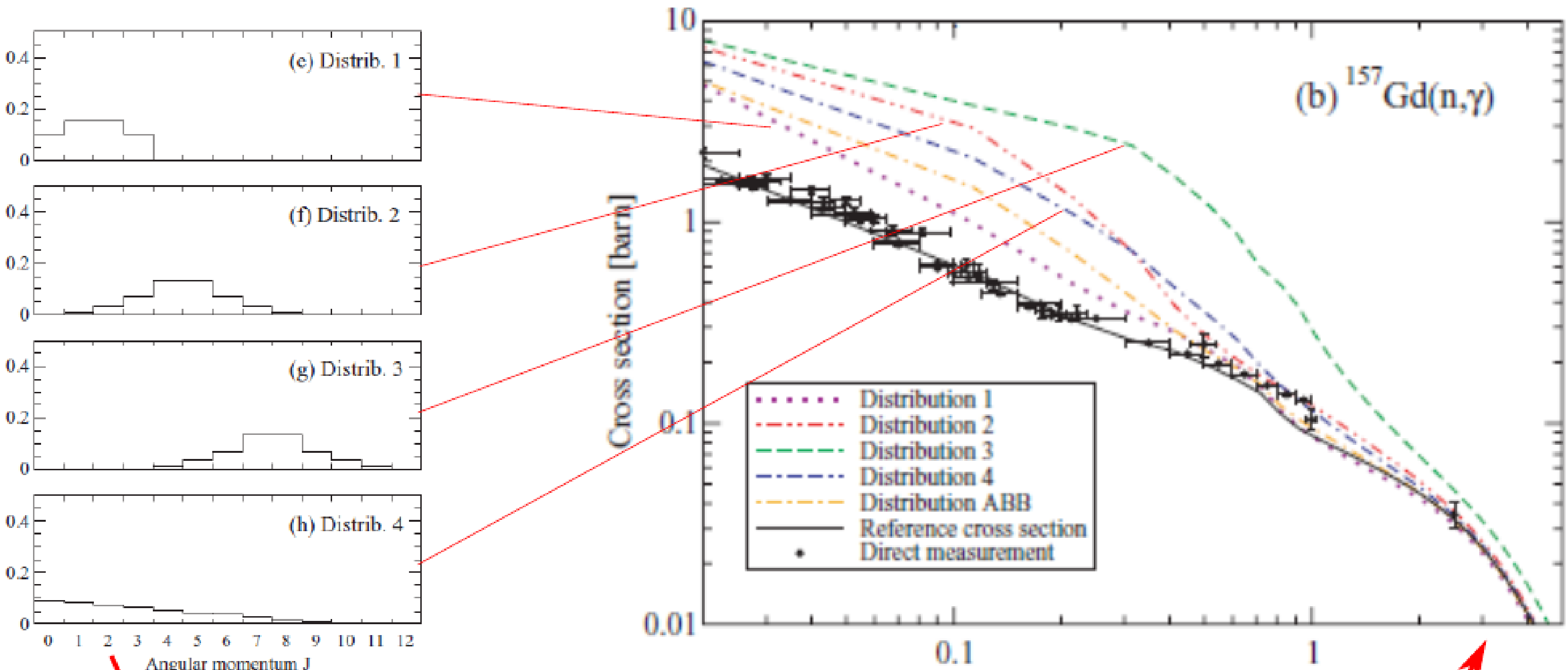
- Spin dependence heavily affects the level of agreement: **from 60% to 15%**
- Different gamma transitions sample different parts of the cascade
- Disregarding the contribution of higher spin states brings the observed spin distribution closer to that of the neutron capture (low l transfer)

A.Ratkiewicz, J.A. Cizewski et al., EPJ Conf 93, 02012 (2015)
R.Hatarick et al., PRC81, 011602(R) (2010)

Weisskopf-Ewing approximation

$$\sigma_{\alpha\chi}(E_a) = \sum_{J,\pi} \sigma_{\alpha}^{\mathrm{CN}}(E_{\mathrm{ex}}, J, \pi) G_{\chi}^{\mathrm{CN}}(E_{\mathrm{ex}}, J, \pi) \xrightarrow{\text{W-E approximation}} \sigma_{\alpha\chi}^{\mathrm{WE}}(E_a) = \sigma_{\alpha}^{\mathrm{CN}}(E_{\mathrm{ex}}) \mathcal{G}_{\chi}^{\mathrm{CN}}(E_{\mathrm{ex}})$$

Weisskopf-Ewing approximation: probability of γ decay independent of J,π



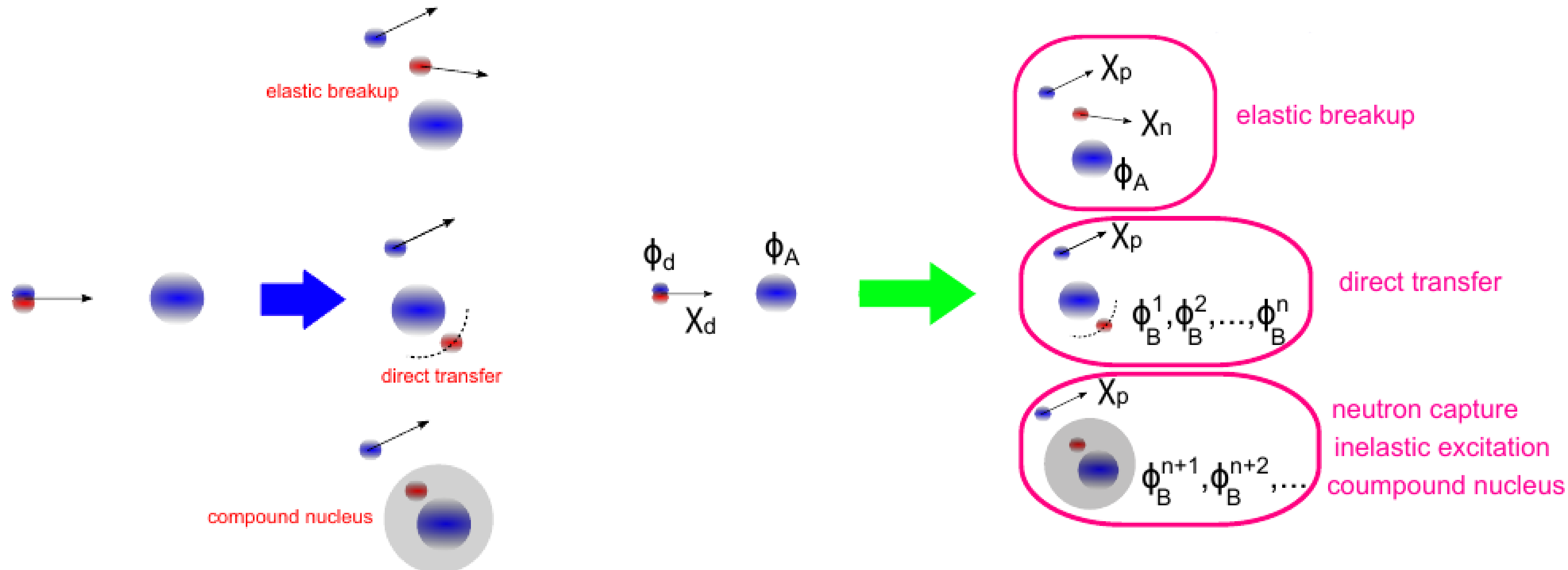
Escher and Dietrich, PRC **81** 024612 (2010)

Different J,π → Different cross section for γ emission

Basics of theory from and experimentalist

Gregory Potel Anguilar (NSCL/FRIB) et al, Phys. Rev. C92.034611

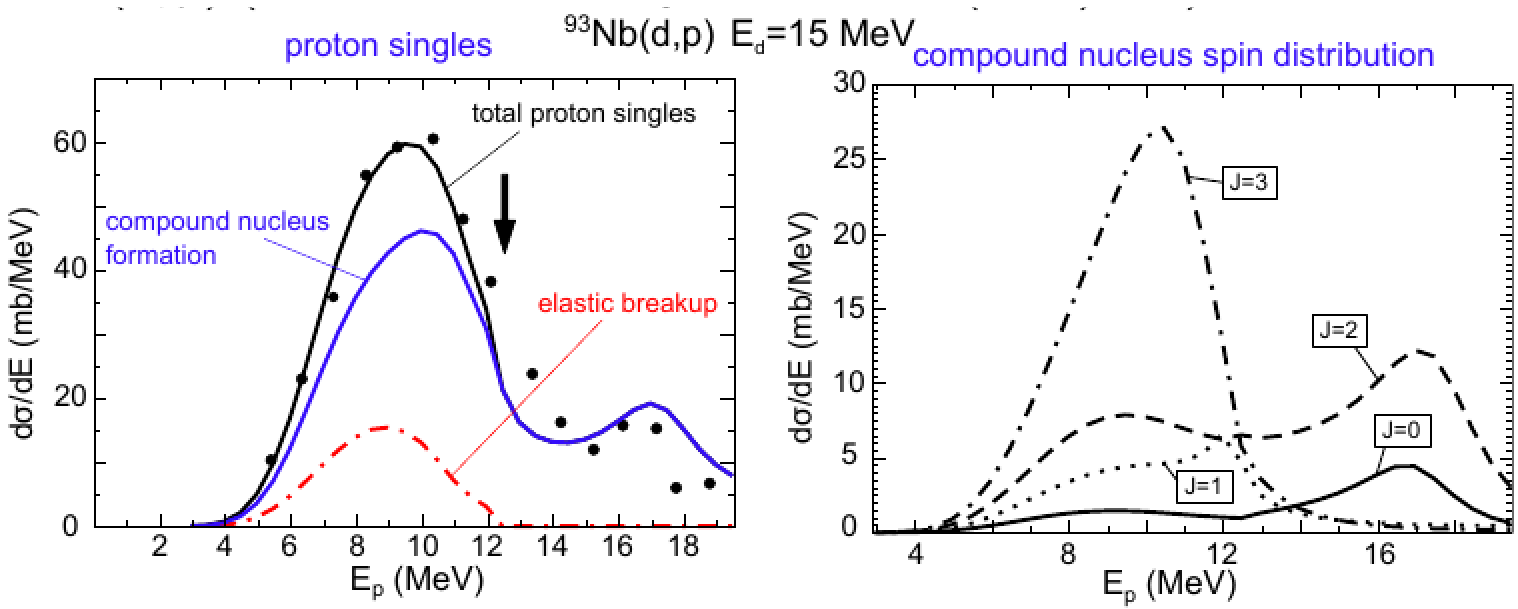
Inclusive deuteron-induced reaction **A+d → B(=A+n)+p**



- Calculation of the spin parity distribution to avoid the WE approximation
- All the final states B need to be calculated

Theory to predict J,π distribution

Gregory Potel Anguilar (NSCL/FRIB) et al, Phys. Rev. C92.034611



- Spin-parity distribution for the compound nucleus
- Contributions from elastic and non elastic breakup disentangled
- Extendable to transfer of light clusters

SPES – LoIs (q^+,1^+)

- Dedicated Nuclear Astrophysics
- Nuclear physics → Nuclear Astrophysics

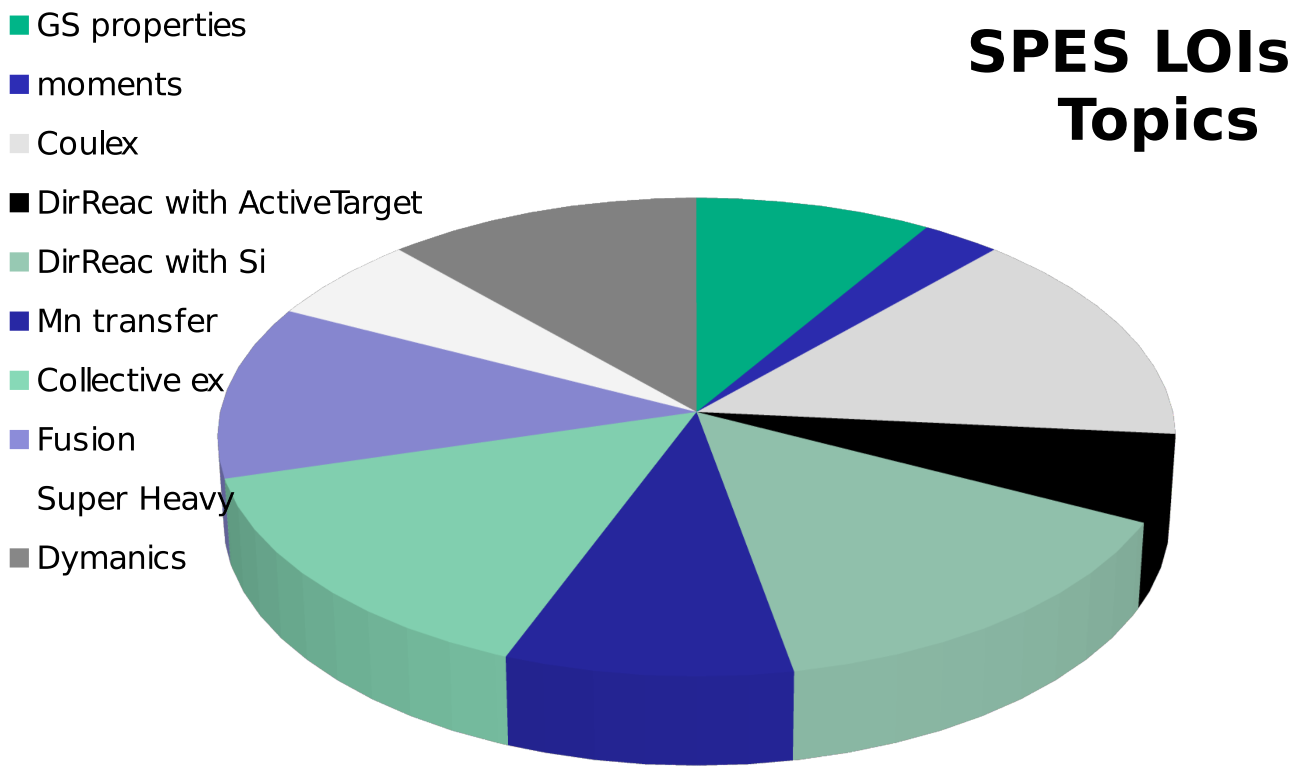
THIRD INTERNATIONAL SPES WORKSHOP

SPES exotic beams for science

OCTOBER 10-12, 2016

LABORATORI NAZIONALI DI LEGNARO (PADOVA), ITALY

46 LoI presented from around the world



Nuclear Astrophysics

- Measurement of the decay characteristics of nuclei around A=90 relevant to the r-process nucleosynthesis [T. Kurtukian-Nieto et al.]
- Letter of Intents for measurements at SPES on beta-decay properties of nuclei belonging to the s-process path [S. Cristallo et al.]
- Study of beta-decay properties of neutron-rich isotopes approaching the r-process path [D. Testov et al.]

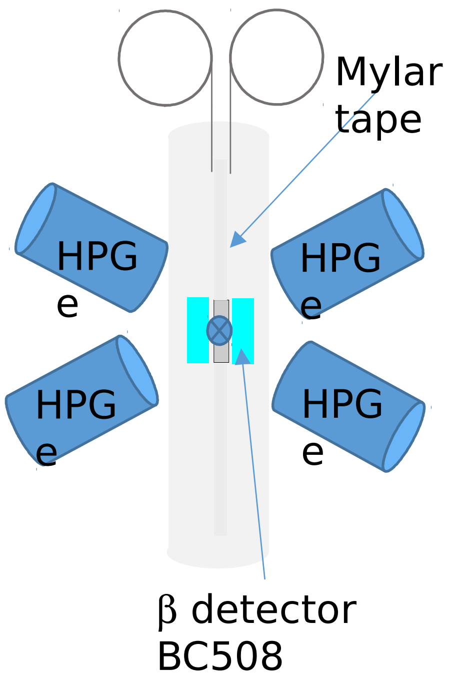
- Measurement of astrophysical relevant reactions induced by alpha, protons and neutrons at the Gamow peak using the Trojan Horse method [M.La Cognata. et al.]
- Direct Reactions at SPES: Shell Evolution and Nuclear Astrophysics around Z~50 and N~82 [D. Mengoni et al.]
- Letter of Intent for transfer reaction measurements at SPES for r-process nucleosynthesis [S.D. Pain et al.]
- Measurements at SPES of n-capture cross sections on radioactive nuclei interesting for s-process nucleosynthesis [O. Trippella et al.]

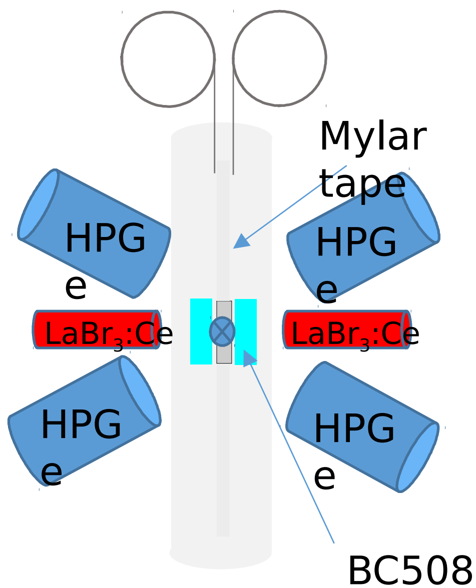
β–decay station

Minimal setup to extract $T_{1/2}$, P_n, β–γ coincidences

Measured quantities: - Time of β emission

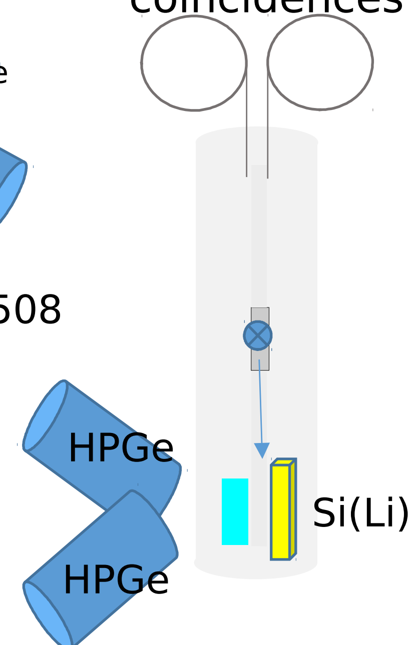
- Energy and Time of γ decay





Fast-timing setup: lifetimes ~ns range

β- γ ($LaBr_3$:Ce)-γ (HPGe) coincidences



Setup for E0 measurements and long-living activity

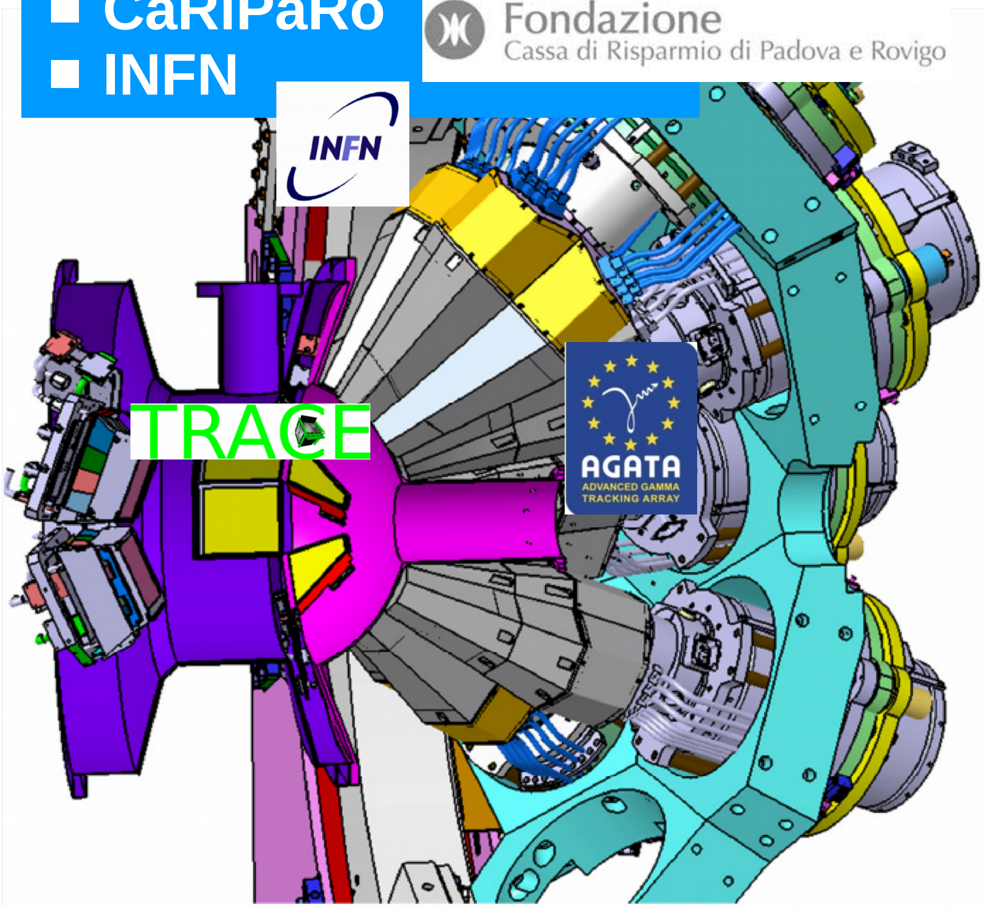
-Additional information: Energy of Conversion electron


Struttura nucleare alla frontiera
Spettroscopia γ a tracciamento
INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro
GSI
GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS
SPES
exotic beams for science

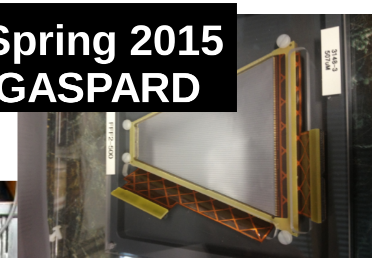
TRACE-MUGAST:

Nuclear structure by detecting light-charged particles

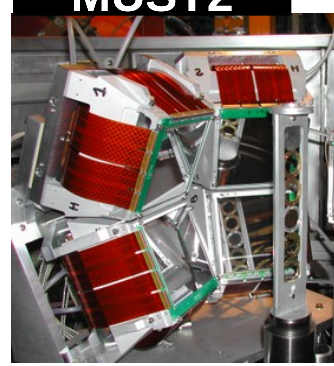
- FIRB 2010-2014
- CaRiPaRo
- INFN



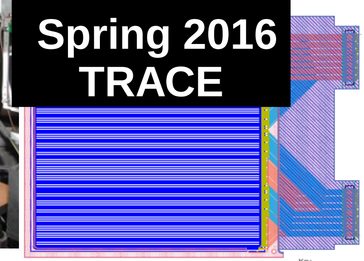
- Science campaign with AGATA at GANIL (>20 physics LoIs/proposals)



Spring 2015
GASPARD

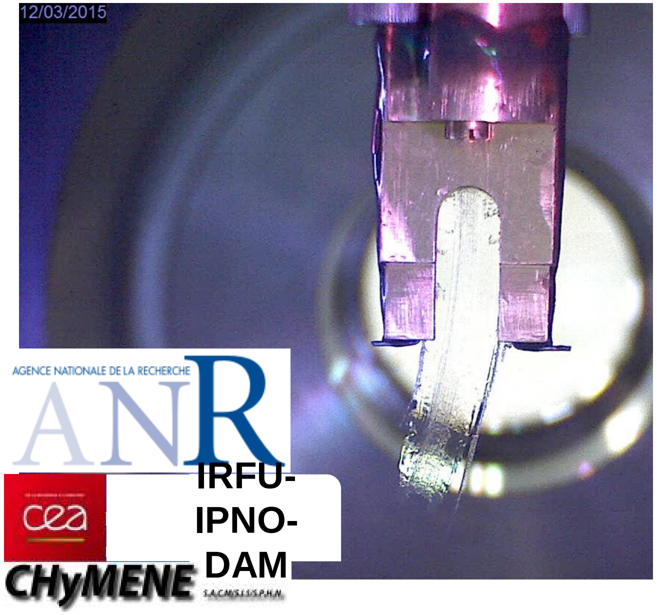


MUST2



Spring 2016
TRACE

Pure targets

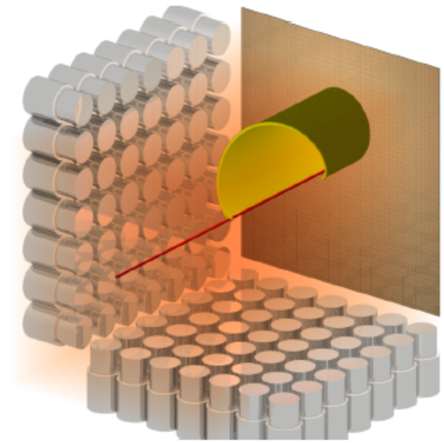


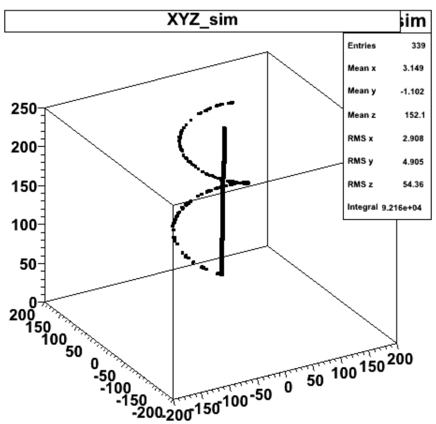
- Hydrogen (h,d) target in a solid phase near triple point (~17K)
- Thickness 50 – 200 µm
- No window - C free
- Continuous flow in vacuum 2-10mm/sec
- Compatible with particle detection

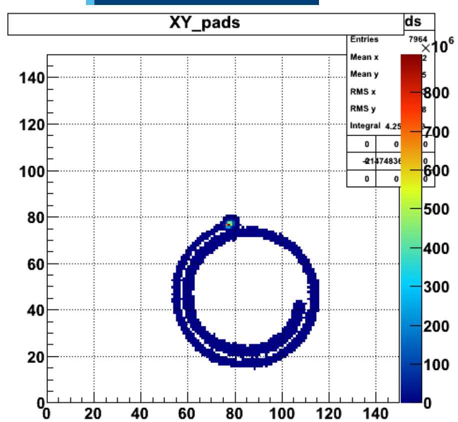
- H, D, ^{3,4}He
- Dense: up to ~**10^{19} nuclei/cm^{2}**
- localized: target size ~ beam spot size, and thin to prevent energy loss and straggling
- windowless
- Cmpativle with particle det.

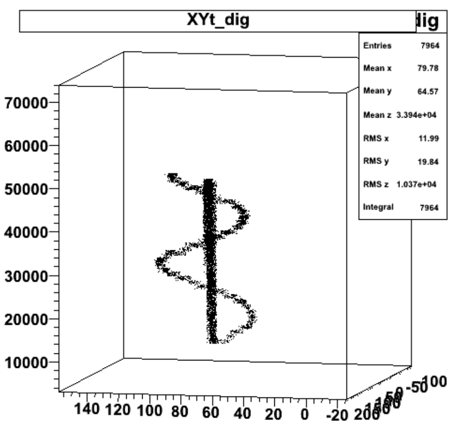
ACTIVE TARGET demonstrator

KU LEUVEN









■ Conclusions

- SPES is a unique opportunity for the nuclear and astrophysics community
- LoIs submitted for key nuclei in the s and r process
- Commissioning run under discussion to check the validity of the surrogate approach
- Ongoing open collaborations: any new idea is much appreciated and very welcome!!

Third International SPES Workshop

SPES exotic beams for science

INFN Istituto Nazionale di Fisica Nucleare

Dipartimento di Fisica e Astronomia Galileo Galilei

October 10-12, 2016

Laboratori Nazionali di Legnaro (Padova), Italy

Under the patronage of

Università degli Studi di Padova

Organizing Committee

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Contact

spes2016@lnl.infn.it
http://agenda.infn.it/event/spes2016

Laboratori Nazionali di Legnaro
Viale dell'Università 2
35020 Legnaro PD - Italy

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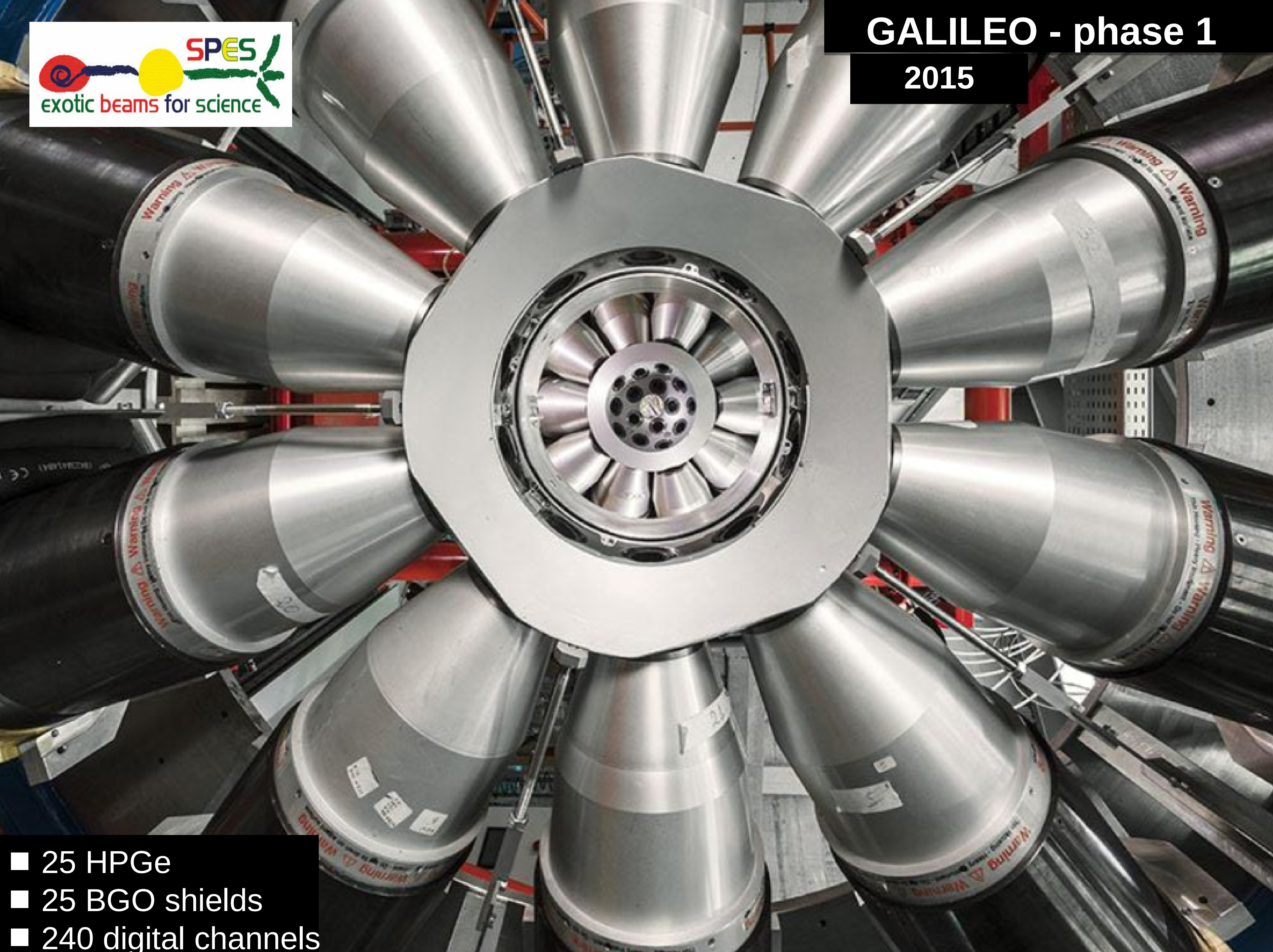


SPES exotic beams for science

GALILEO - phase 1

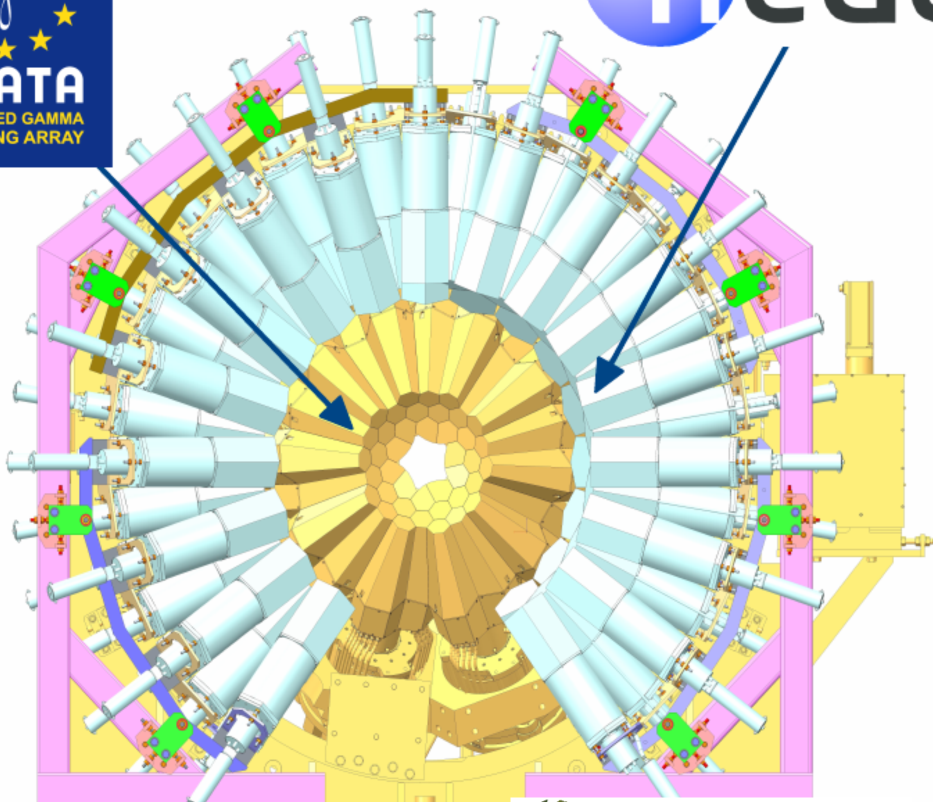
2015

- 25 HPGe
- 25 BGO shields
- 240 digital channels

exotic beams for science SPES

AGATA
ADVANCED GAMMA TRACKING ARRAY

neda



- FIRB 2010-2014
- Spiral2 – Prep.Phase
- INFN

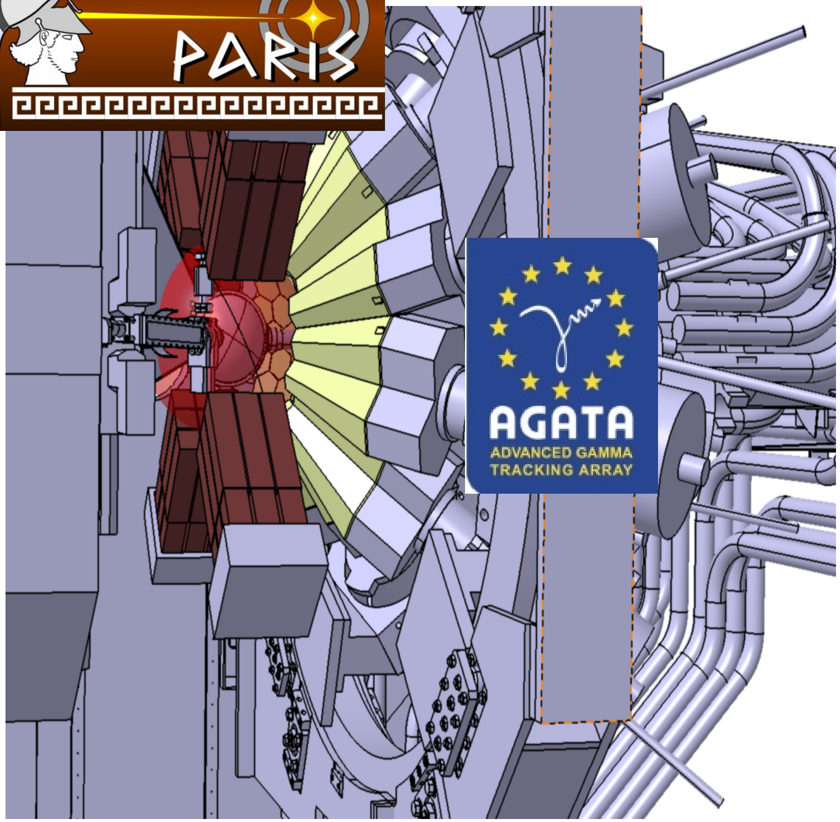
MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

INFN

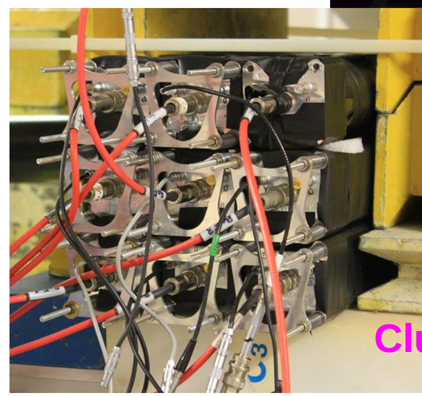
- Science campaign with AGATA at GANIL

GANIL Spiral2 laboratoire commun CEA/DSM CNRS/IN2P3

High-efficiency gamma detectors PARIS, HECTOR+, HELENA



LaBr3@GALILEO



Cluster PARIS

Science campaign

- GANIL: 4 proposals accepted
- Orsay – IPNO : 6 proposals accepted
- 7 LoIs at SPES

				$T_{1/s}$ (s) LIS	I@5μA FEBIAD (cps)	E_{max} (MeV)	SIS			
Be*	7	4	3	4.60E+06	2.E+07 **	9		2		2
Be*	10	4	6		3.E+07 **	13		2		2
F *	17	9	8	6.48E+01	2.E+07 **	15		4		4
F *	18	9	9	6.58E+03	2.E+06 **	14		4		4
Na*	21	11	10	2.25E+01		18	5			
Na*	22	11	11	2.60E+00		17	5			
Mg*	22	12	10	3.86E+00		17		5		4
Mg*	23	12	11	1.13E+01		16		5		4
Al*	24	13	11	2.05E+00		16	1	1		
Al*	25	13	12	7.18E+00	1E+04 **	15	1	1		
Al*	26	13	13	6.35E+00	1E+04 **	15	1	1		
Si*	26	14	12	2.21E+00	1E+03 **	17				4
Si*	27	14	13	4.16E+00	1E+03 **	16				4
P*	29	15	14	4.10E+00		15				4
Cl*	34	17	17	1.53E+00	5E+03 **	15				4

Nuclear physics → Astrophysics

Nuclear physics problem	Astrophysical application
Thermodynamical behavior of hot and deformed n-rich systems (isospin dependence of the nuclear EOS)	Physics of neutron stars and mechanism of explosion of supernovae and X-ray bursts
Superheavy nuclei (existence, lifetime, decay mode)	The r-process is probably halted by fission occurring in the region of unknown heavy nuclei with a large neutron excess
Clustering aspects in N≠Z nuclei	Influence on nucleosynthesis during explosive and quiescent burning stages
Modification of the shell model for N/Z far from stability (e.g. persistence of the N = 82 closure below Z = 50?)	Explosive neutron-capture nucleosynthesis processes
Nuclear spectroscopy, ANC, level energies and spectroscopic factors	Calculation of the reactions rates of processes of astrophysical relevance when measurements are not possible

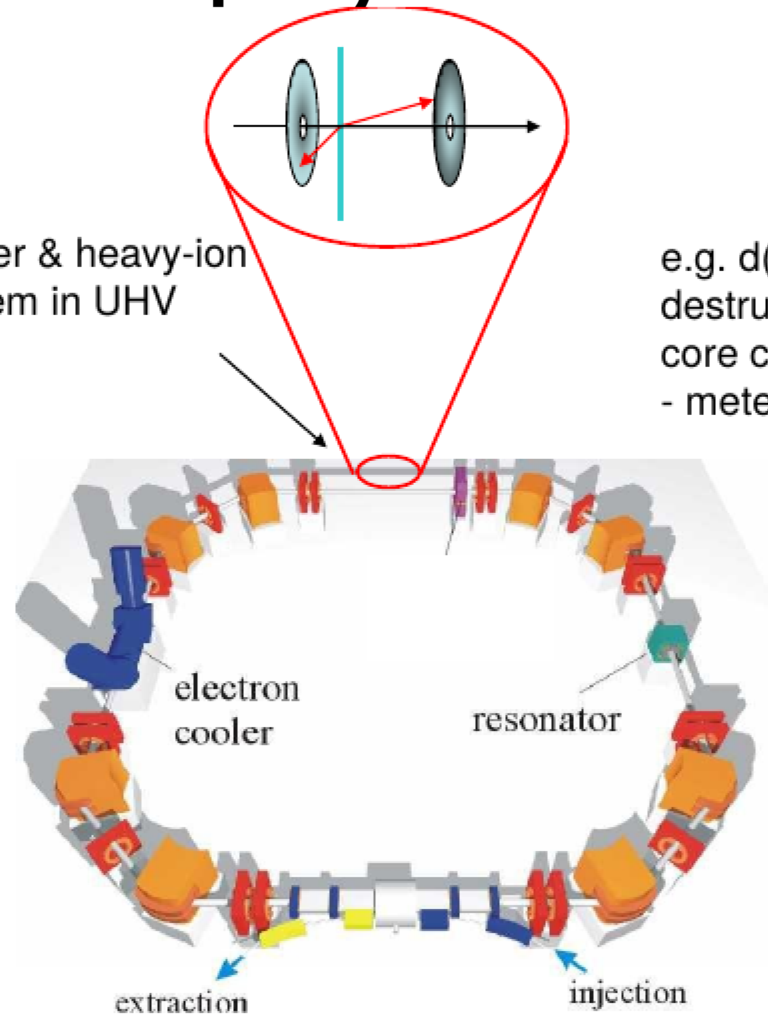
- Lifetime
- Masses
- Energy levels
- J, π
- Spectroscopic factors
- ... nuclear structure

■ SPES^{++} – Future

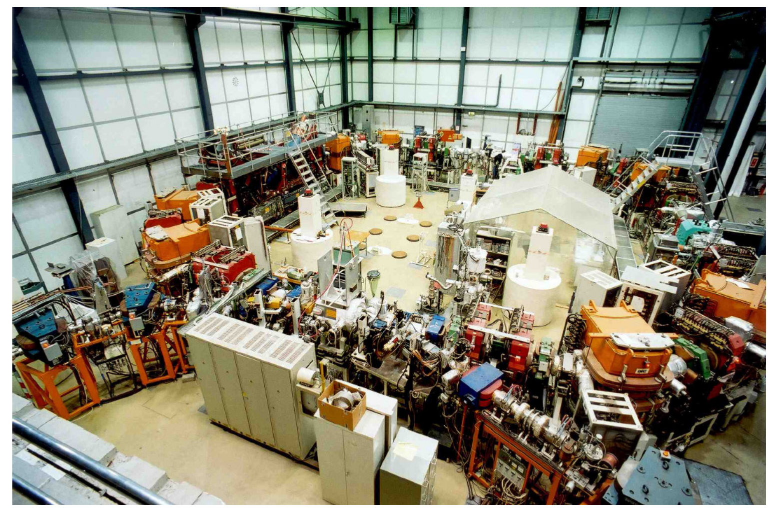
Disclaimer : this is a very personal view

Indirect Studies of Key Astrophysical Resonances

In-ring target chamber & heavy-ion recoil detection system in UHV



e.g. d(^{26m}Al, p)^{27}Al
destruction of ^{26}Al in
core collapse supernovae
- meteoritic abundances



Heidelberg