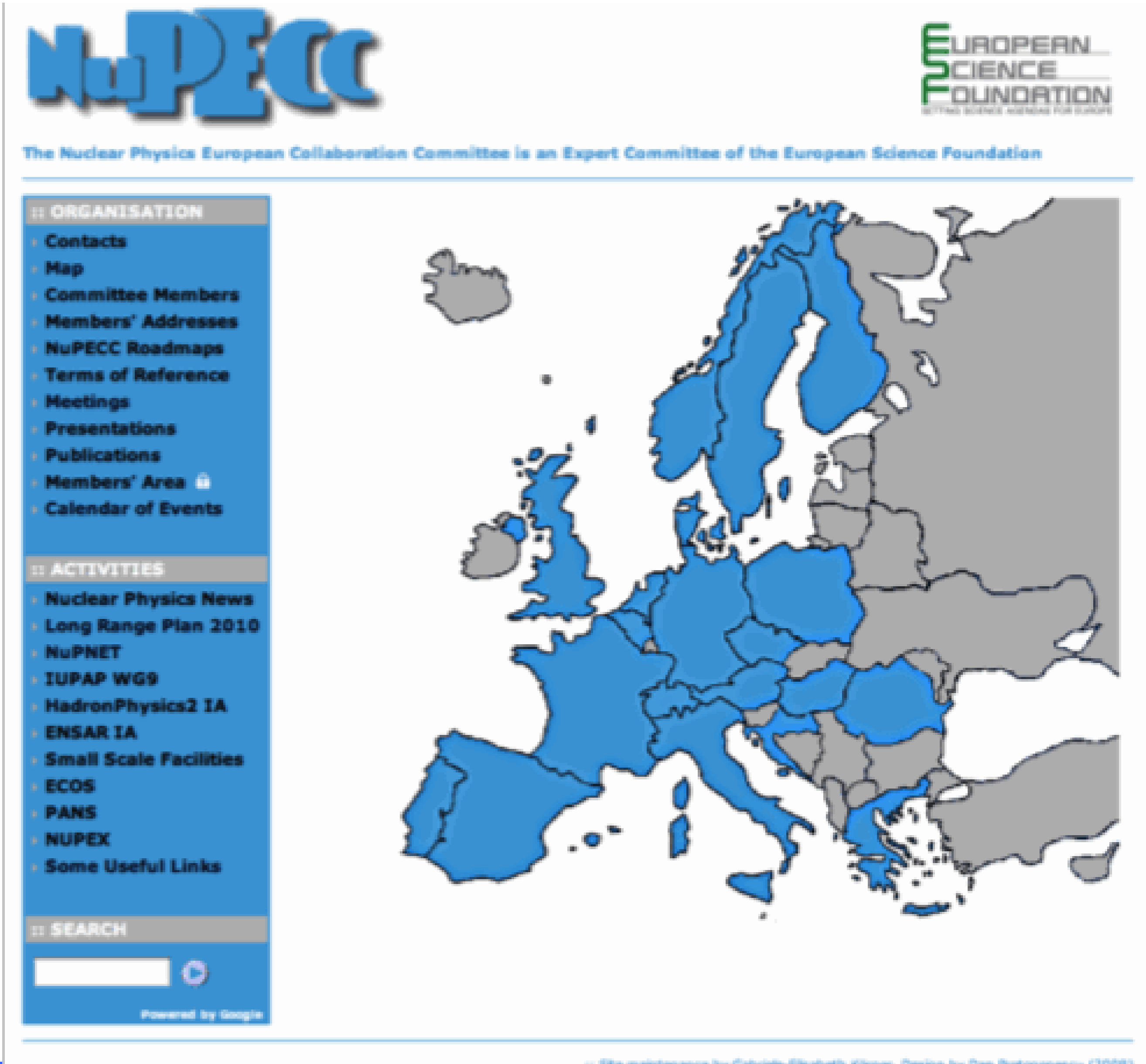
Nuclear astrophysics and the long range plan of NuPECC

Angela Bracco Padova 28 Aprile 2015

GIANTS 2015

Outline

- NuPECC in brief
- The NuPECC long Range plan 2010
- Focus on Nuclear astrophysics
- Future plans



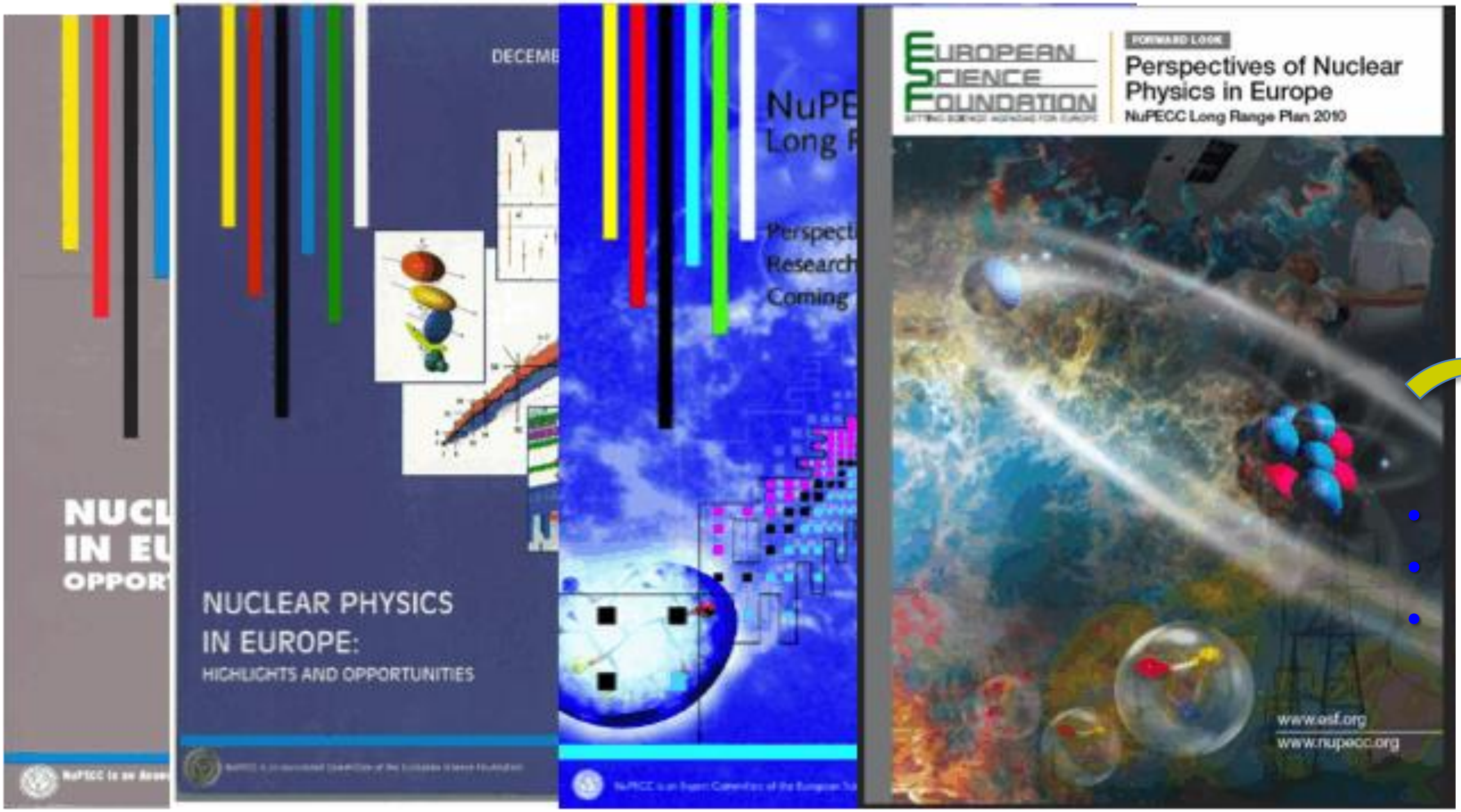
Joint Institute for Nuclear Research Dubna-
Recently joined

exchanges with

- AnPHA
- NSAC
- Canada

+ ALAFNA

Perspectives of Nuclear Physics in Europe



1991 1997 2004 2010

- Volume
- Brochure
- video


LRP 1991
LRP 1997
LRP 2004
LRP 1010
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

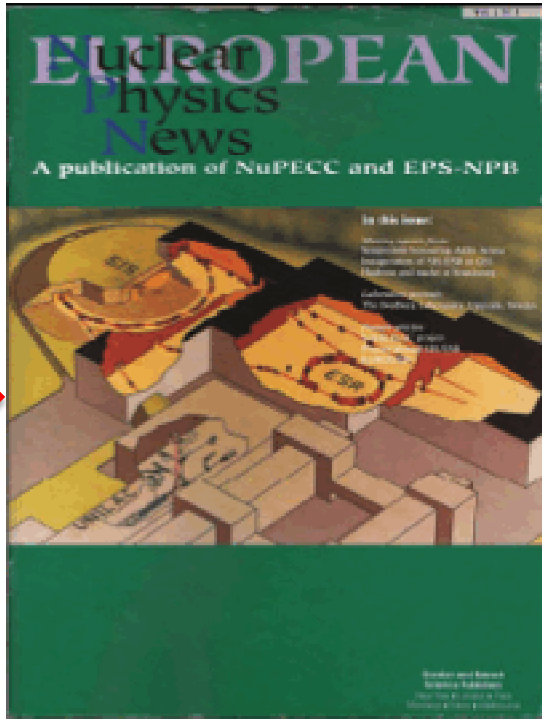
2013- NuPECC
25 year old !

Nuclear Physics News

in December 2015
Issue number 100

NPN four times
per year distributed
worldwide
to 6,000 colleagues

No. 1 –
September 1990



LRP 2010 - Objectives

- **Review** status of the field

- Issue **recommendations** to advance

–The science

–Its applications in Europe

- Develop **action plan (roadmap) for:**

  Building new large-scale Research Infrastructures

  Upgrading existing Nuclear Physics facilities

  Collaborate closely with smaller scale facilities

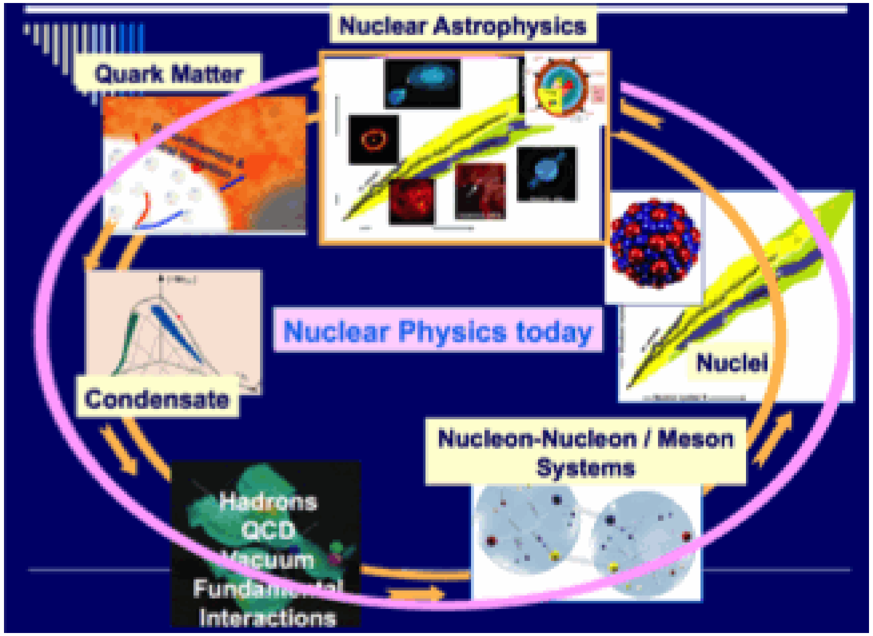
– support **EU FP7 (FP8)** projects (IAs, ERA-net NuPNET)

- Put European Nuclear Physics into **global context**

−NSAC (DoE & NSF) in USA, ANPhA in Asia, ALAFNA in Latin America

−IUPAP and OECD Global Science Forum -

Scientific themes



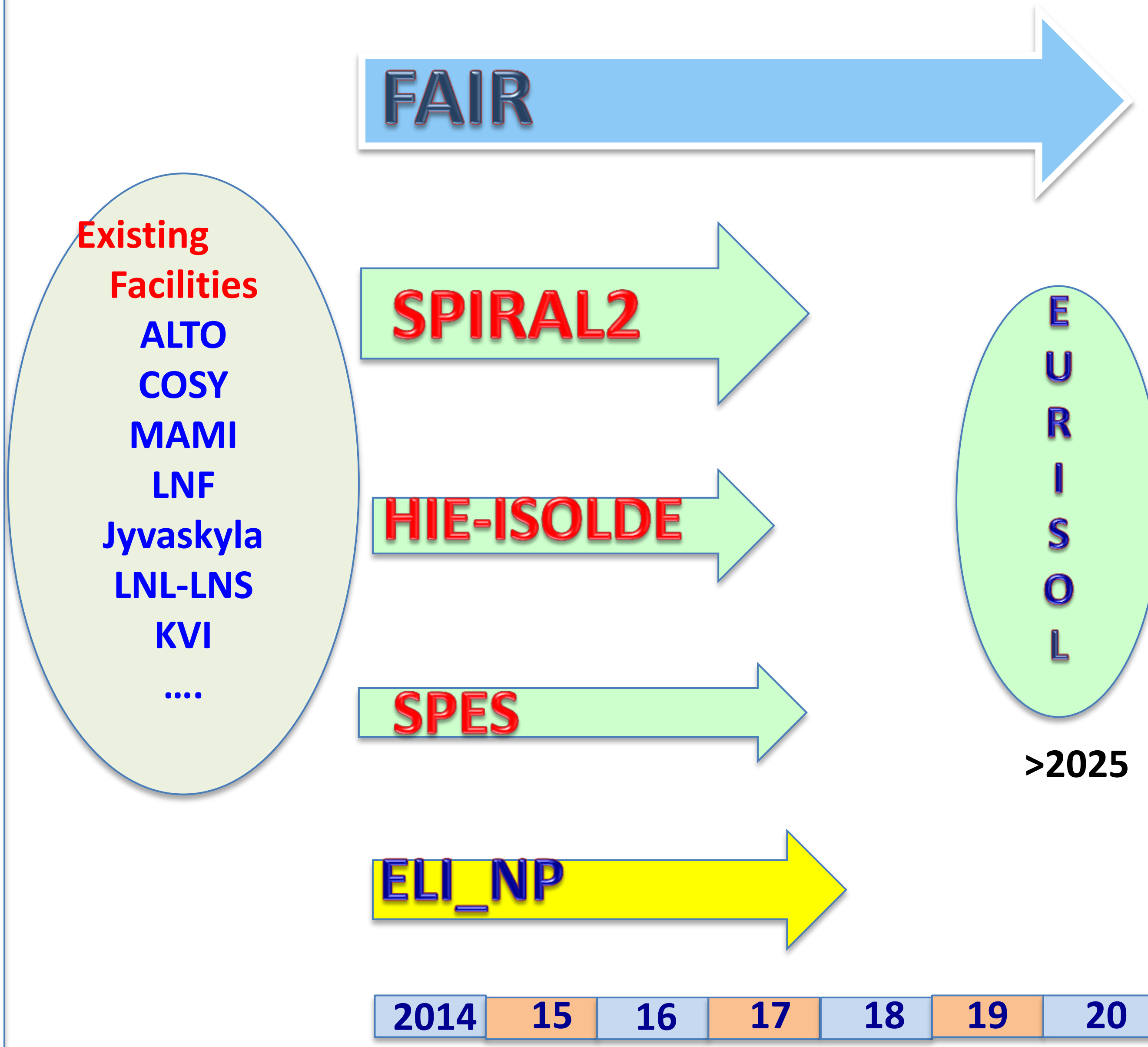
1) Hadron Physics
2) Phases of Strongly Interacting Matter
3) Nuclear Structure & Dynamics
4) Nuclear Astrophysics
5) Fundamental Interactions
6) Nuclear Physics Tools & Applications

One introduction on Facilities + 6 chapters
Summary and reccomandations

NuPECC LRP (2010)

- FAIR and SPIRAL2 (ESFRI)
- HIE-ISOLDE and SPES
- ALICE at CERN
- Existing Laboratories
  + Luna
- Instrumentation (AGATA)
- Theory
- Applications
- New ESFRI fac.

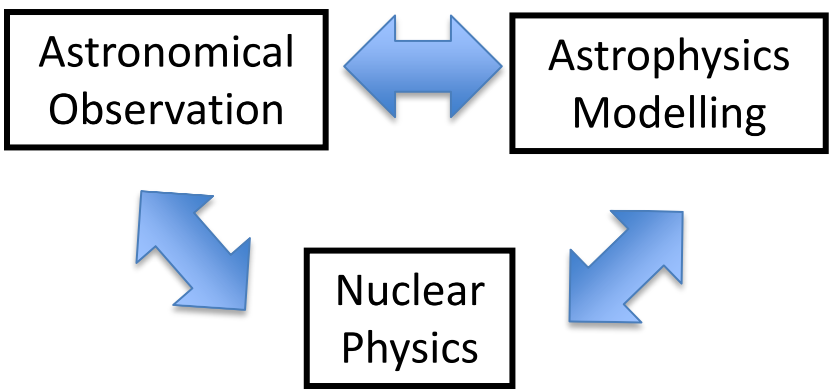
New Facilities and Major upgrades



LRP2010 Nuclear Astrophysics

The Big Bang created only Hydrogen and Helium. All the other elements are created in a continuing cosmic cycle which involves the birth, life and death of starts

An exciting cooperation between sciences



- Nuclear theory – global input for models
- Nuclear experiment – tests of key reaction rates and nuclear structure

Overarching theme – very diverse field

Accelerators: small university based (through underground) to international facilities

Beams: gamma, neutron, particle, radioactive, (neutrino)

Techniques: multi-detector arrays for beta, gamma, neutron, particle, neutrino
spectrometers, traps, low backgrounds, AMS

Theory: masses, lifetimes, decay rates, reaction models, optical potentials
shell model, finite temperature effects, plasma modifications,
screening effects, equation of state, neutrino rates etc.

... nucleosynthesis across the nuclear chart

Where do the chemical elements come from and how did they evolve ?

rp process

powered by protons

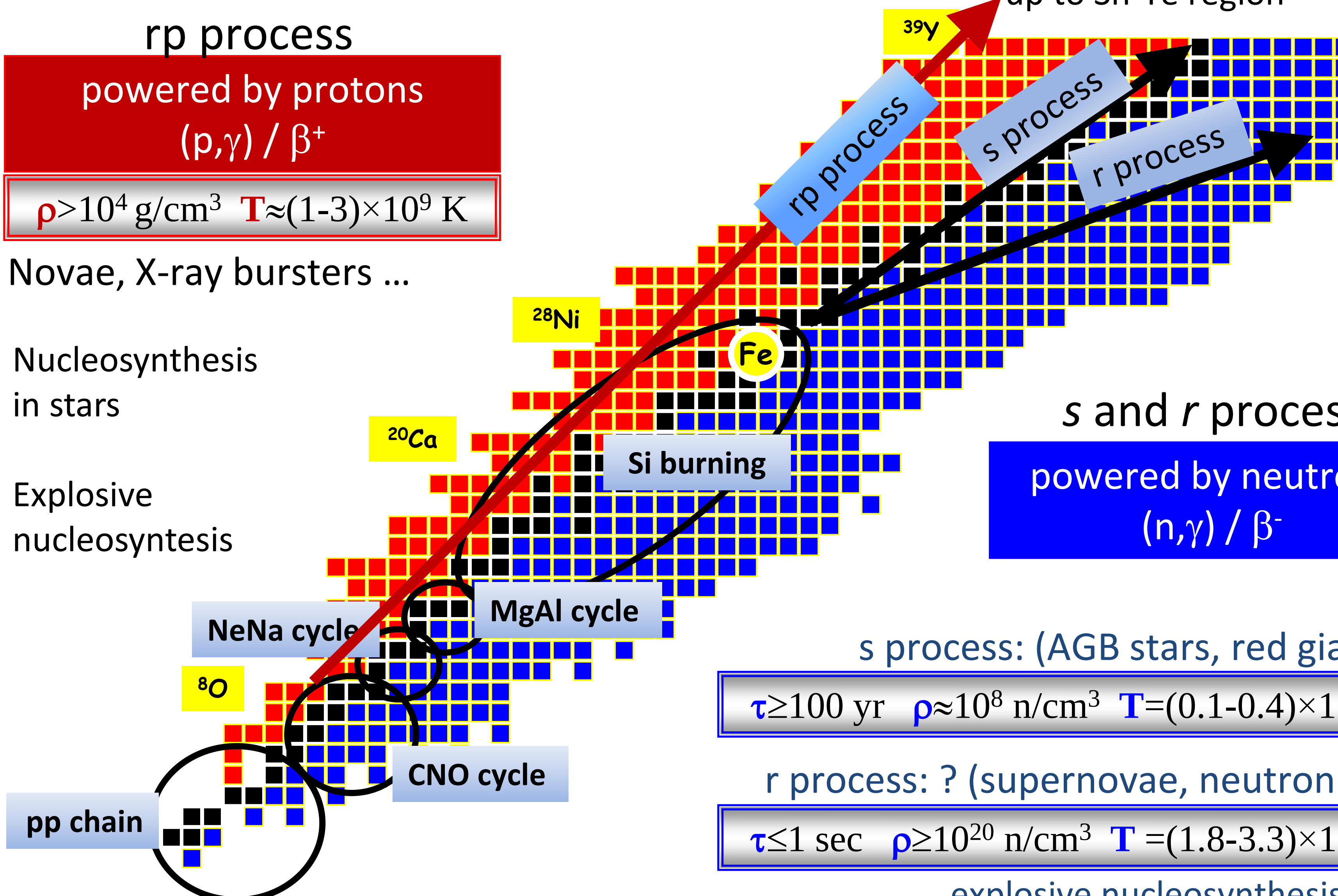
(p,γ) / β^+

$\rho > 10^4$ g/cm^3 T$\approx$(1-3)$\times 10^9$ K

Novae, X-ray bursters …

Nucleosynthesis in stars

Explosive nucleosyntesis



s and *r* processes

powered by neutrons

(n,γ) / β^-

s process: (AGB stars, red giants...)

$\tau \geq 100$ yr $\rho \approx 10^8$ n/cm^3 T=(0.1-0.4)$\times 10^9$ K

r process: ? (supernovae, neutron stars)

$\tau \leq 1$ sec $\rho \geq 10^{20}$ n/cm^3 T =(1.8-3.3)$\times 10^9$ K

explosive nucleosynthesis !!

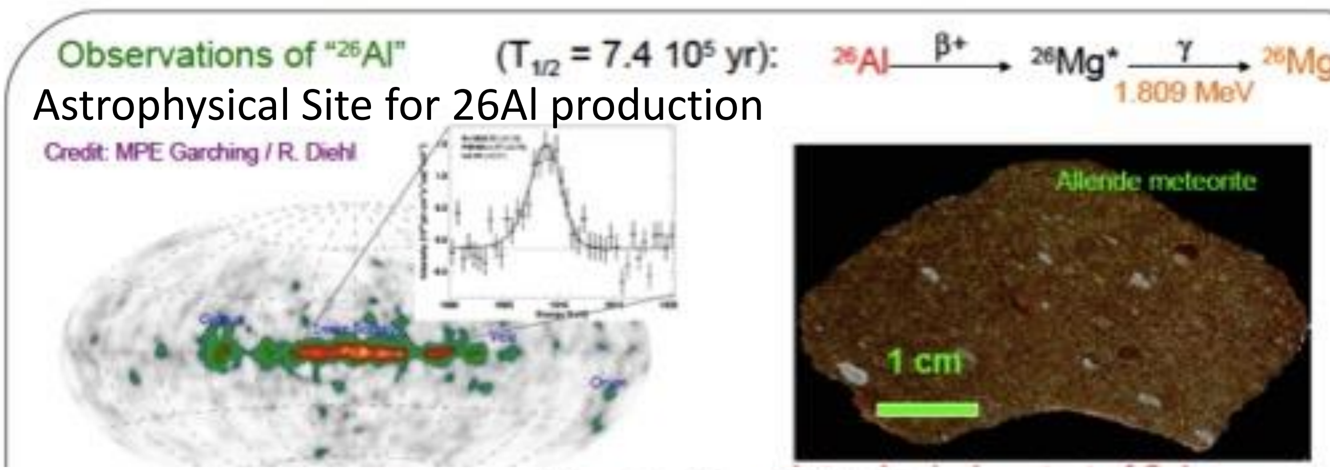
Reactions at low energy induced by charged particles
Stable beams

- Underground Laboratories LUNA has the leadership and will keep it for the next decade (no other underground laboratories have an accelerator at 3-4 MV)

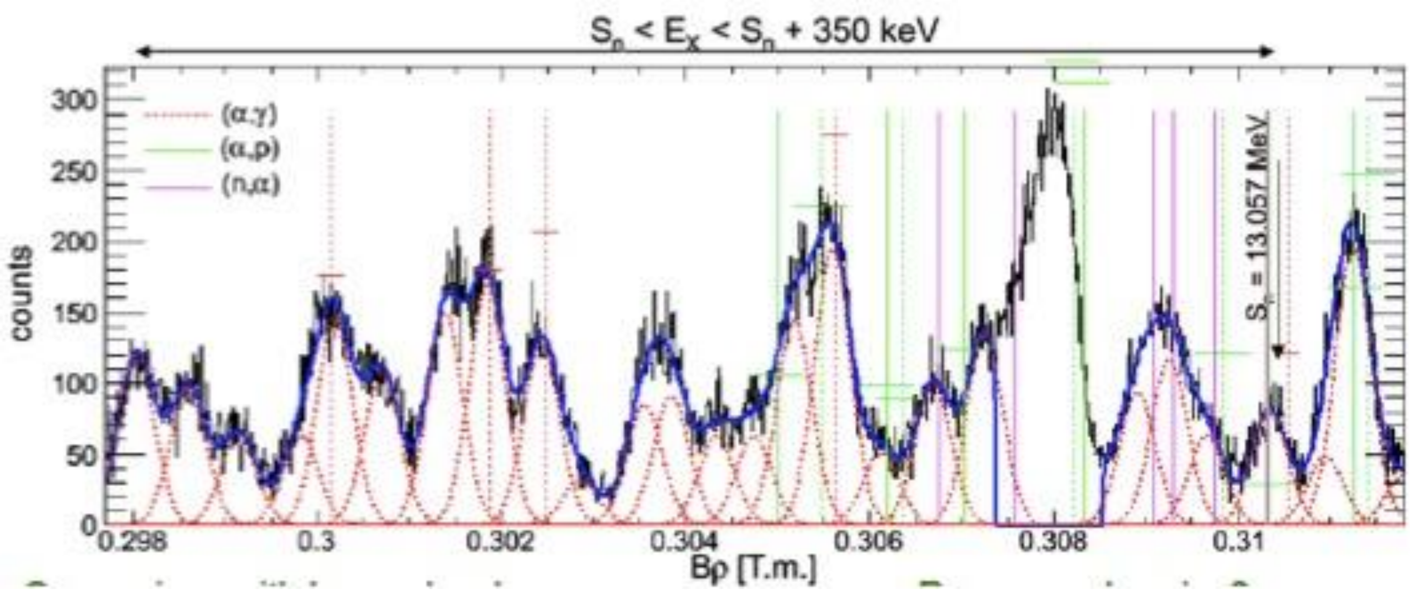
- on ground laboratories are producing excellent results at higher energies with indirect methods

(see CN at LNL,
LNS with trojan horse,
CIRCE (Caserta)
ORSAY- IPNO
ATOMKI
Demokritos (upgrade and a new TANDEM ……..
Croatia
Cologne
……

Selected Nuclear astrophysics activity at IPNO: ^{26}Al Observations and nucleosyntesis

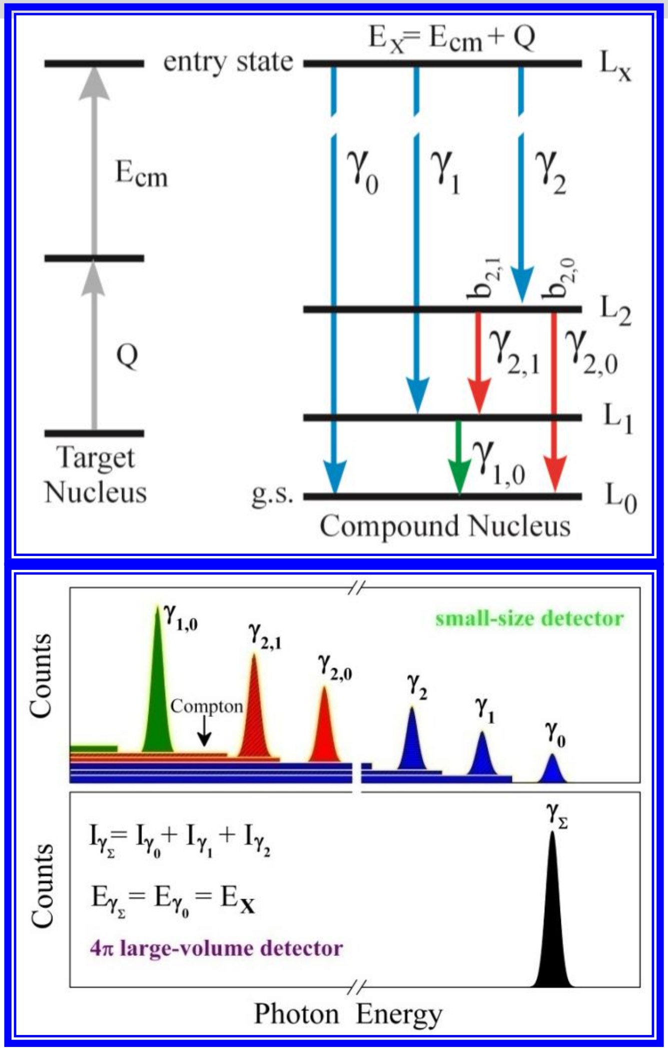


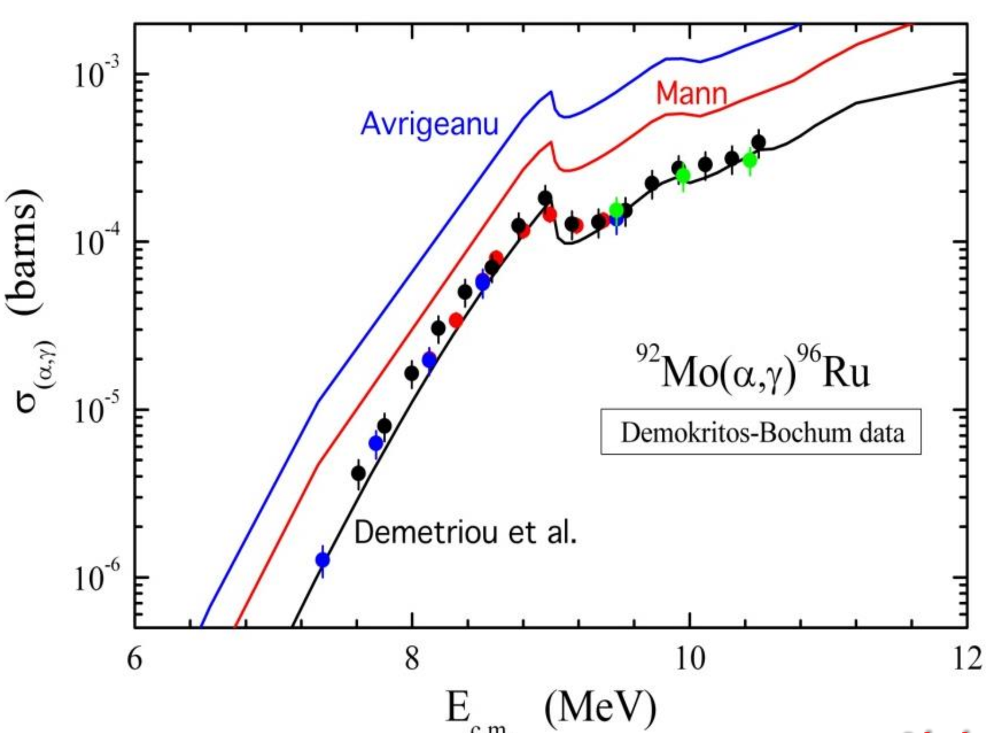
^{26}Al yield depends on ^{26}Al(n,p) and ^{26}Al(n,alpha) reactions



Resonances Above n-binding energy in ^{27}Al

Selected Nuclear astrophysics activity at Demokritos: p-process



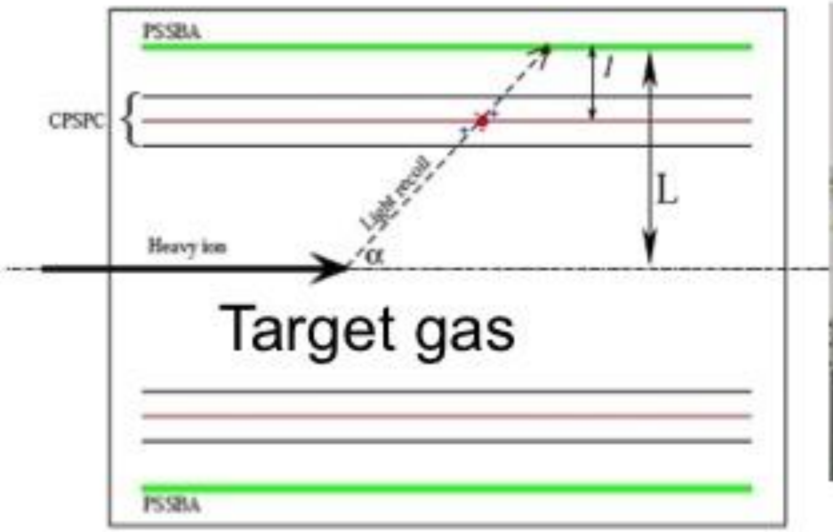


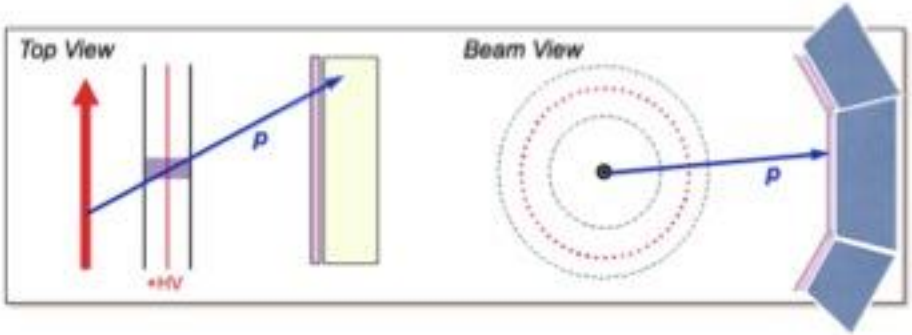
Alpha Optical Model potential

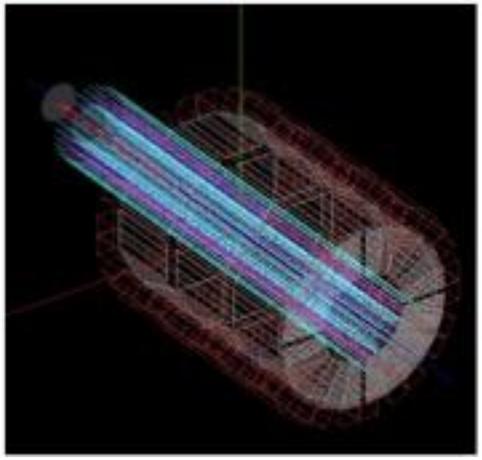
GASP-BGO Ball will be used in the future

Charged particle reactions for astrophysics with radioactive beams

Array for Nuclear Astrophysics Studies with Exotic Nuclei

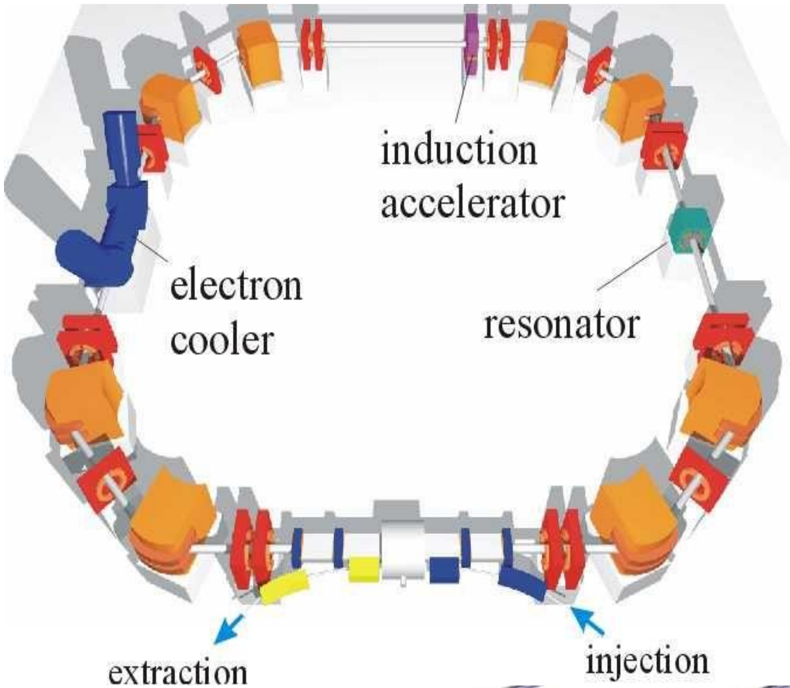


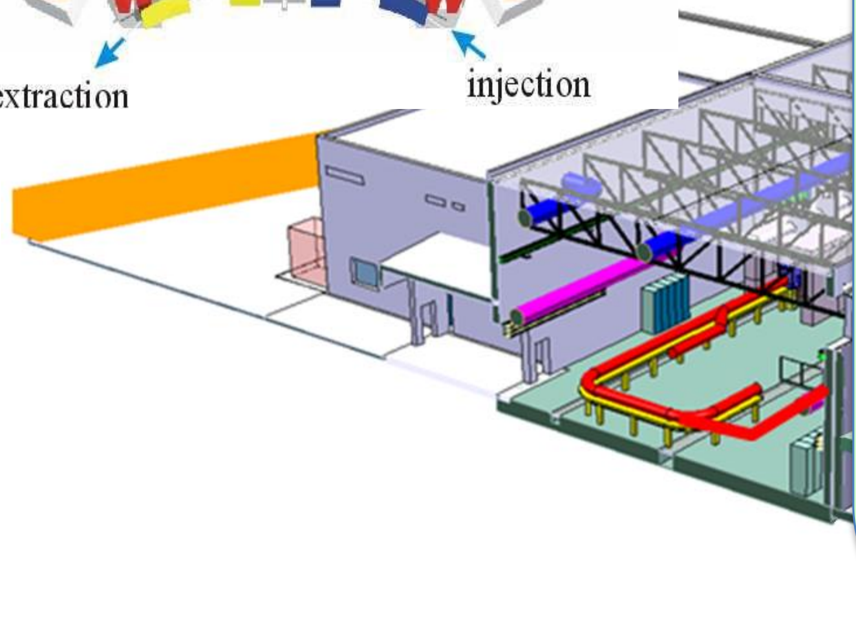




ALSO at MSU and TRIUMF

TSR @ HIE-ISOLDE

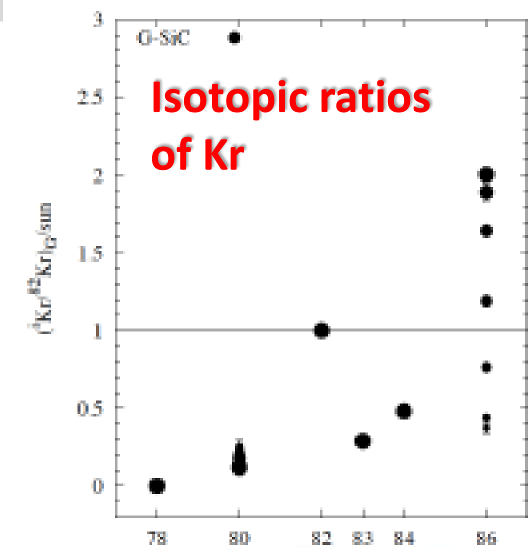




Physics programme

- Astrophysics
  - Capture, transfer reactions
  - ^{7}Be half life
- Atomic physics
  - Effects on half lives
  - Di- electronic recombination
- Nuclear physics
  - Nuclear reactions
  - Isomeric states
  - Halo states
  - Laser spectroscopy
- Neutrino physics

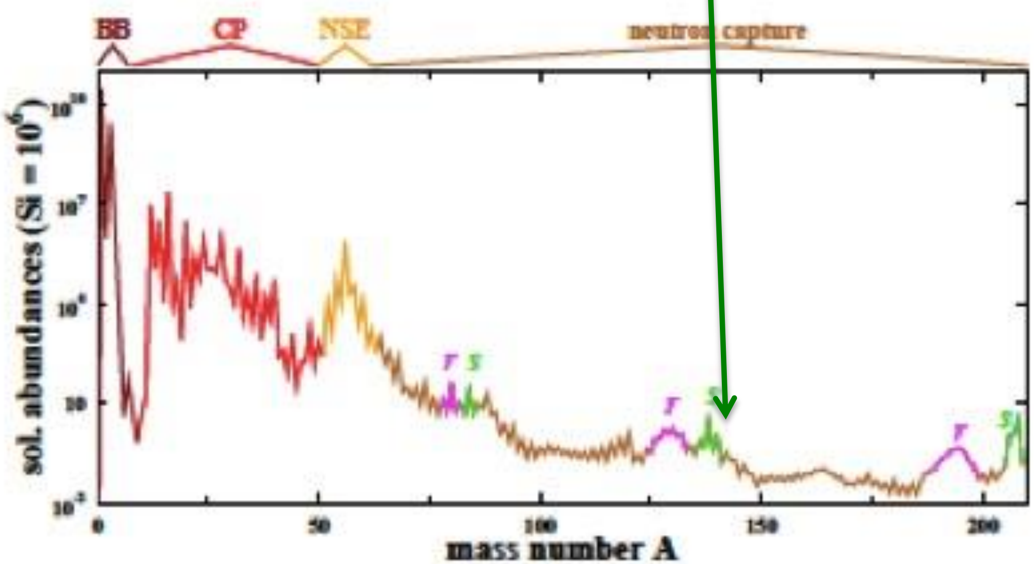
n_tof and neutron probes in other Laboratories

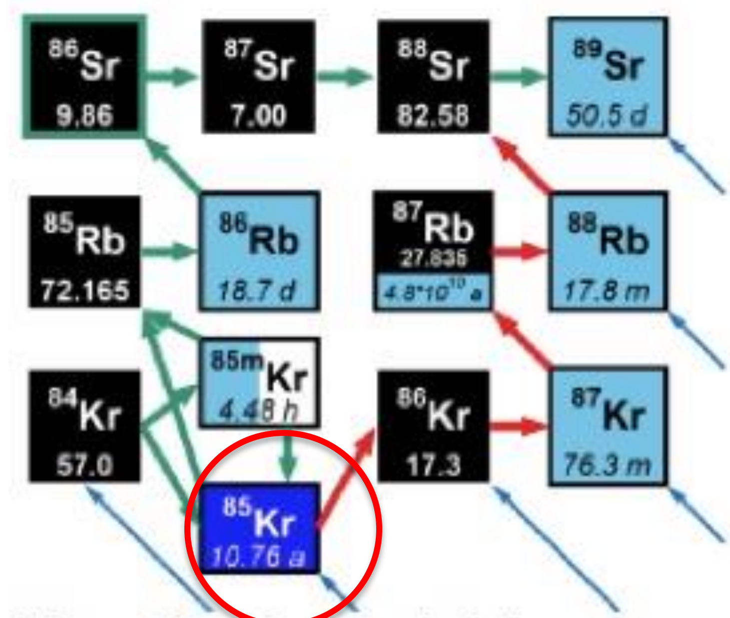


Mainly s-process –

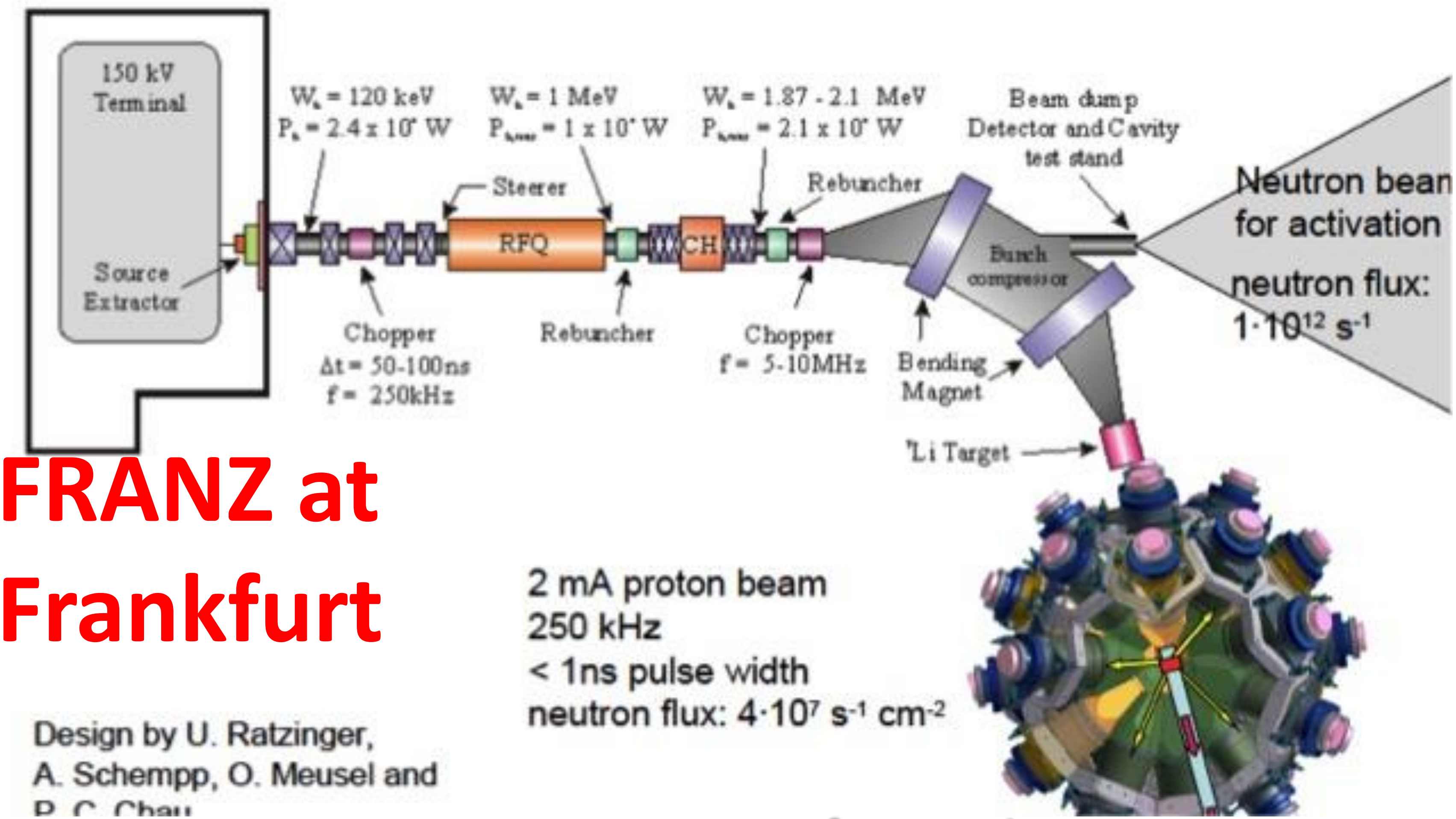
n capture to determine neutron densities in stars from isotopic ratio

Nuclear cosmo-chronometer





Future n facilites for Nuclear Astrophysics



FRANZ at Frankfurt

LENA at LNL

n-capture for rare isotopes,
Radioactive targets and
Small cross sections

LRP2010 Recommendations

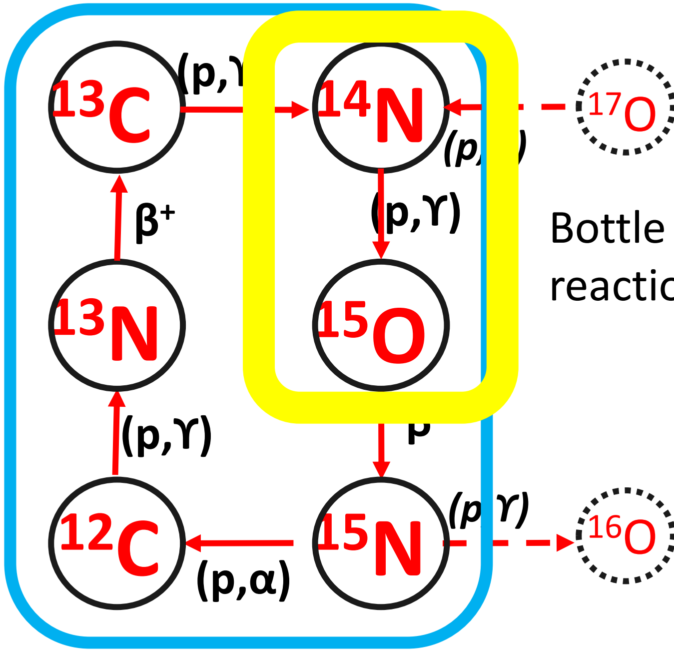
- **Perform Major Upgrades**

  – .....

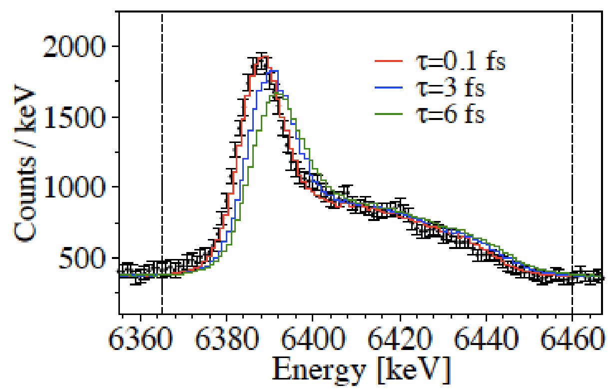
  — AGATA

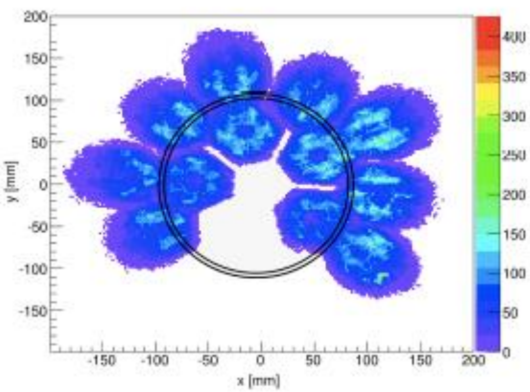
Where are we?

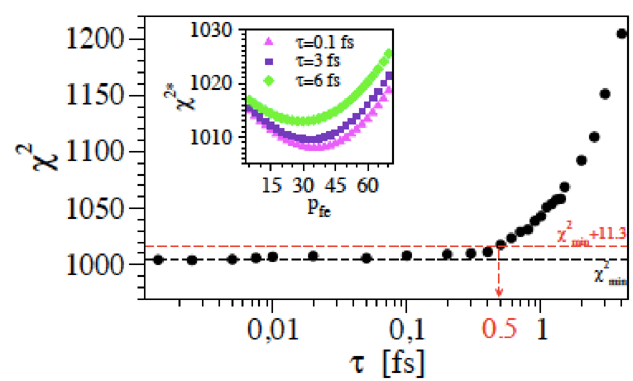
AGATA at LNL : Solar hydrogen burning probed via DSAM lifetime measurement in ^{15}O



Bottle neck reaction in CNO



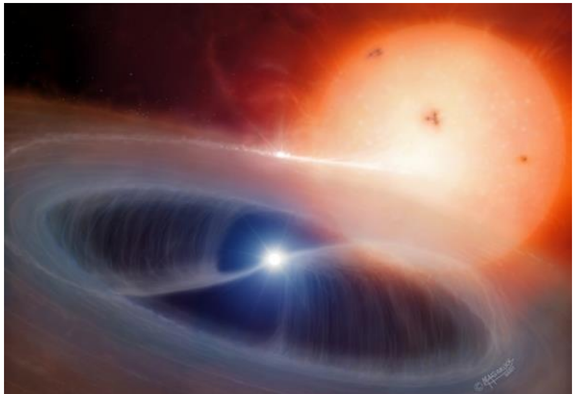




Life time- Radiative width- Measurement
a direct
lower limit on
the formal R-matrix
width and thus on
reaction cross section.

rp-process : reaction flow through ^{56}Ni: Importance of excited states in ^{58}Zn

Type I X-ray burst – the *rp* process

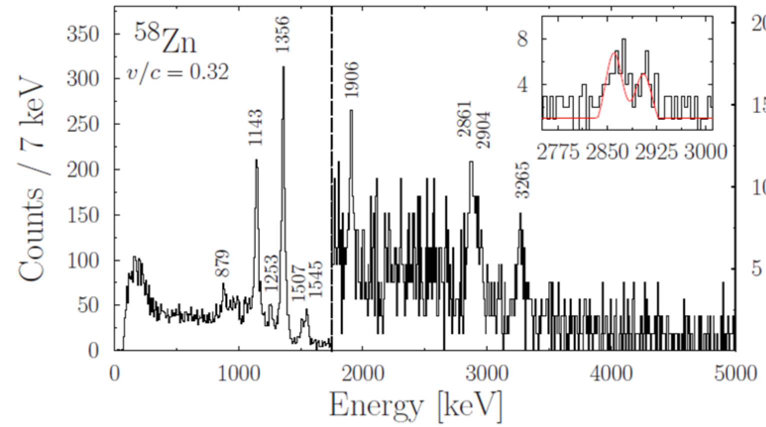


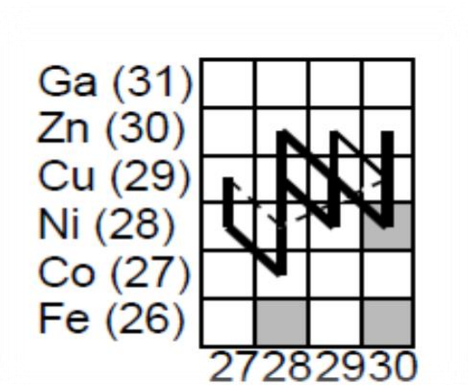
^{57}Cu(p,γ)^{58}Zn among TOP 20 reactions

Spectroscopy of neutron-deficient ^{58}Zn in d(^{57}Cu,^{58}Zn+γ) at 75 MeV/u

Reaction rate dominated by 2^+ resonances

So far: no states measured in ^{58}Zn -> only from theory





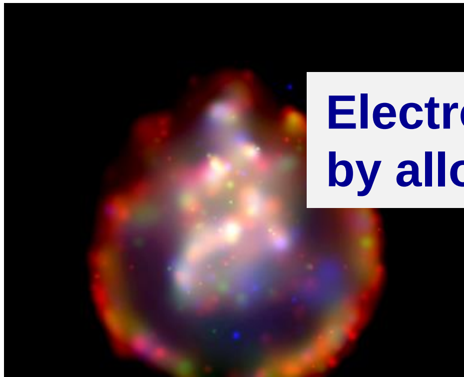
Nuclear reaction flow powers X-ray bursts through important waiting point ^{56}Ni

With GRETINA

From A. Gade- PRL By: Langer,PRL113(2014) 032502.

Nuclear response and supernovae

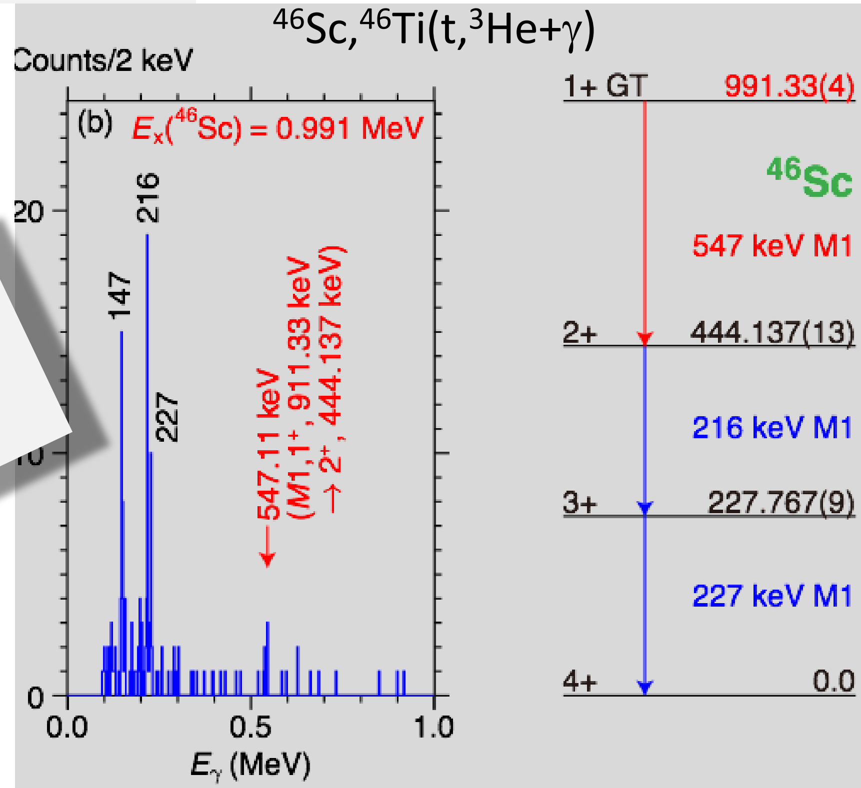
Weak reaction rates in astrophysical phenomena



Core-collapse (Type II) Supernovae

Electron capture dominated by allowed Gamow Teller transition

$$\left(\frac{d\sigma}{d\Omega}\right)_{q=0} = \hat{\sigma} B(GT)$$



continued development of novel tools to obtain high-precision GT strengths from unstable nuclei at present and future RIB facilities

$B(GT)_{0.991}=0.009 \pm 0.005$(experimental) ± 0.003 (systematic)

From Zegers – Langer C. et al PRL113(2014)032502

Importance of Nuclear Deformation for r-process

β-decay half-lives *and* ***neutron emission probabilities***
are different in ***DEFORMED*** *and* ***SPHERICAL*** *nuclei*

Isotope	$T_{1/2}$ [ms] spherical	P_n [%] spherical	$T_{1/2}$ [ms] deformed	P_n [%] deformed	$T_{1/2}$ [ms] experiment	P_n [%] experiment
Ge-85	832	8.3	186	5.4	540(50)	14(3)
Ge-86	627	31.5	177	5.4		
Ge-87	364	33.9	56.7	6.3		
Ge-88	171	69.4	45.8	6.7		
As-86	834	19.4	286	11.7	945(8)	26(7)
As-87	739	46.7	238	82.9	560(110)	17.5(25)
As-88	445	32.1	70.7	41.9		
As-89	218	77.0	63.0	93.3		
As-90	21.1	8.9	22.8	42.5		
As-91	61.1	92.2	33.2	95.7		
Se-89	1646	0.5	137	0.6	410(40)	7.8(25)
Se-90	724	0.6	141	1.1		
Se-91	39.3	0.2	37.6	1.3	270(50)	21(10)
Se-92	137	2.3	62.3	2.7		
Se-93	24.0	14.5	51.6	7.1		
Se-94	39.0	3.7	48.2	23.9		
Br-94	33.4.	14.2	113	56.6	70(20)	68(16)
Br-95	53.2	93.8	70.2	79.1		
Br-96	19.2	31.9	36.7	56.2		
Br-97	20.2	97.2	42.4	92.0		

$\tau_{\beta\,SPH} \sim 7 \times \tau_{\beta\,DEF}$

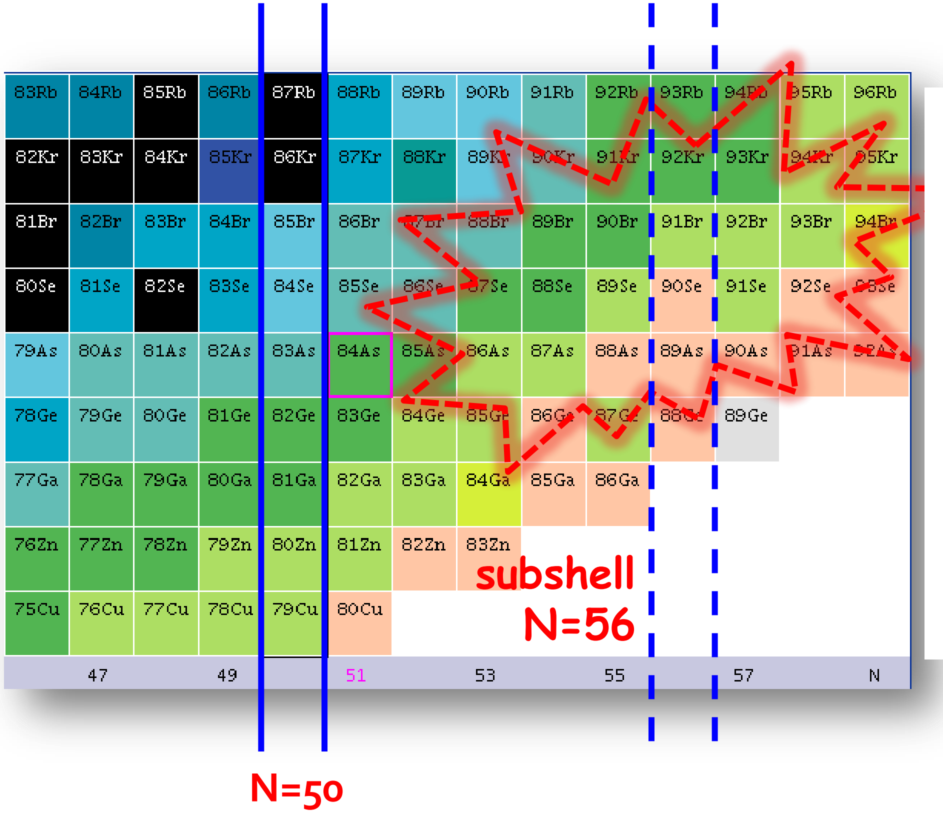
$P_{nSPH} \sim 0.5 \times P_{nDEF}$

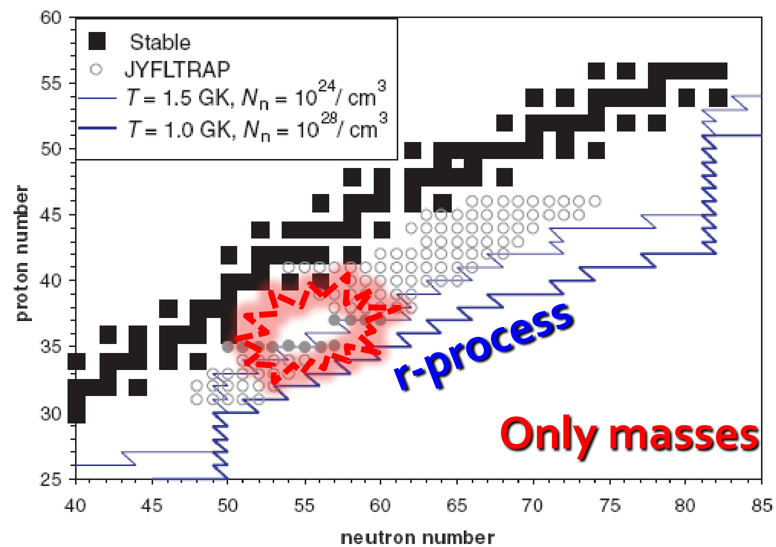
- ***Large uncertainty in r-process location***
- ***difficult to extrapolate to more exotic regions***

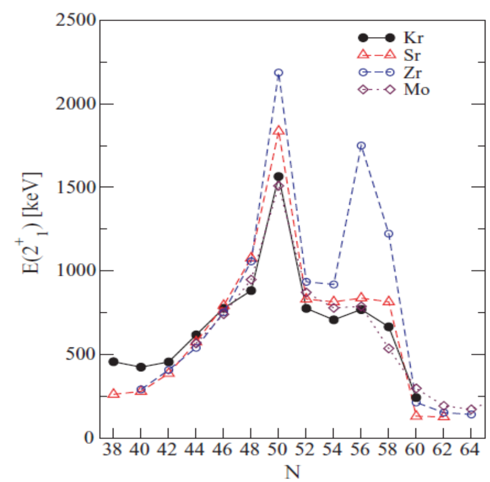
Nuclear Structure studies are needed

P. Moller et al., Phys. Rev. C67, 055802 (2003) and ref. therein.

r-process nuclei beyond N=50

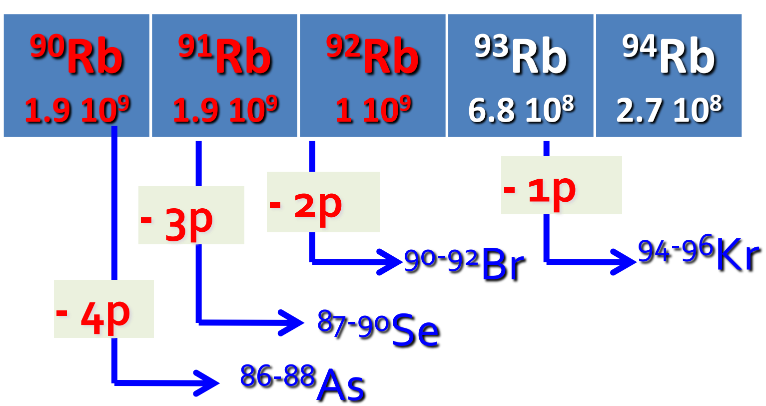






Shape changes with N number

SPES Beams on ^{238}U target



Facilities and Instrumentation needs

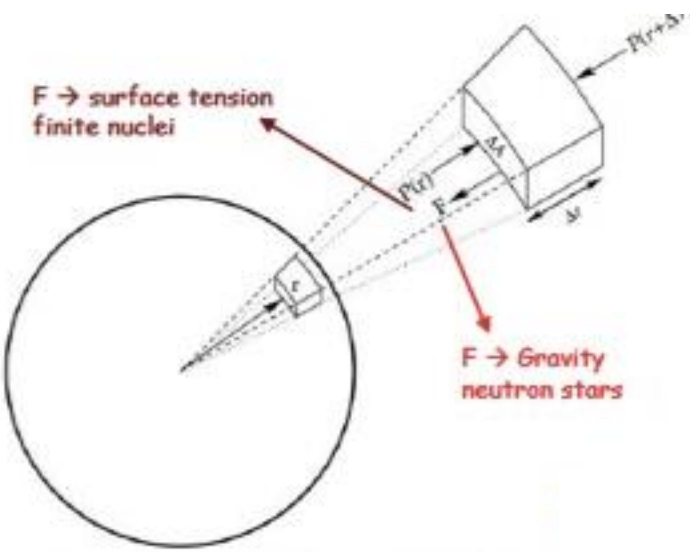
Radioactive beam facilities
for probing stellar explosions

and to understand the nuclear physics aspects of these processes requires a knowledge of nuclei right across the chart of nuclides, including (and indeed mostly) very exotic nuclei

Neutron stars in a laboratory

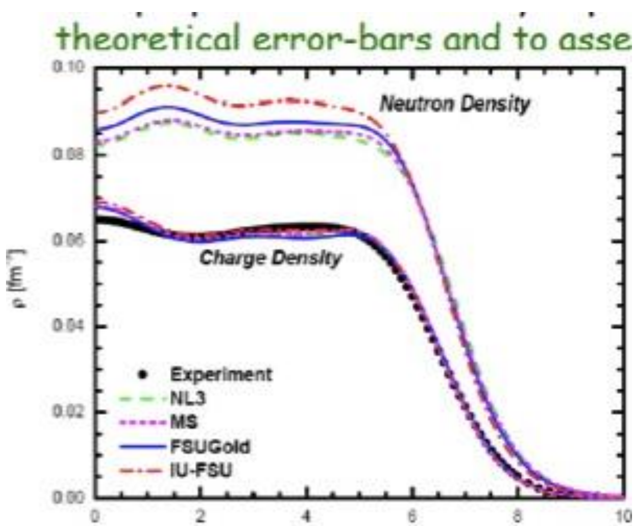
Neutron –rich nuclei
hyperon-hyperon interaction
nuclear matter at high densities

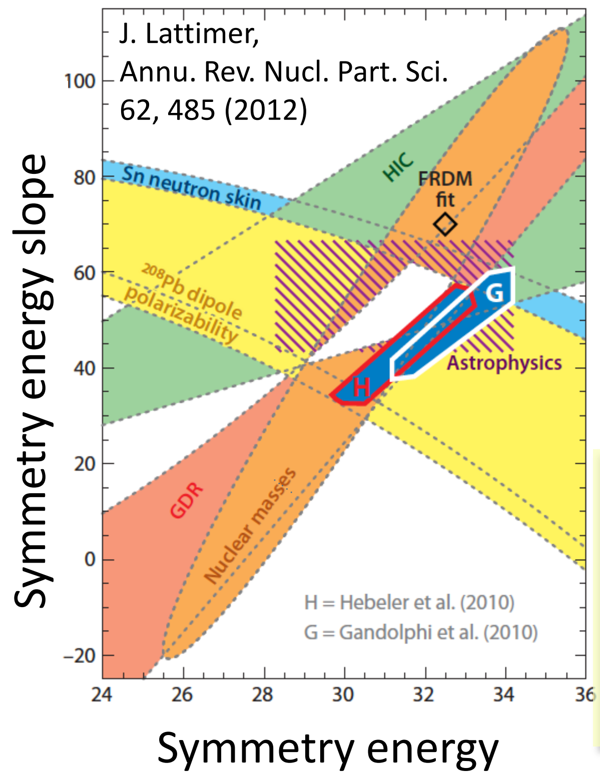
Neutron stars and neutron skin



The same pressure support neutron stars against gravity (similar mass density of nuclei)

Therefore many neutron star properties are sensitive to the pressure of pure neutron matter

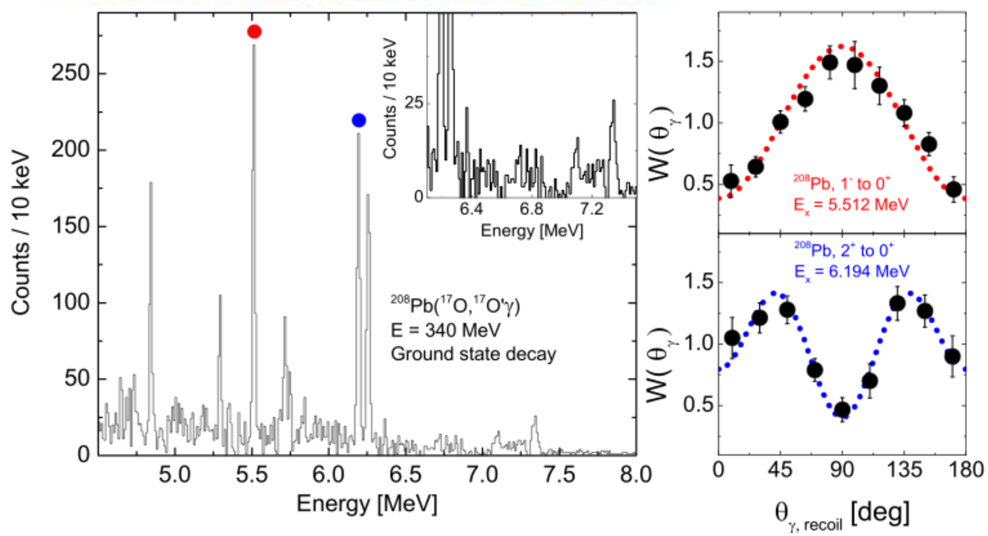


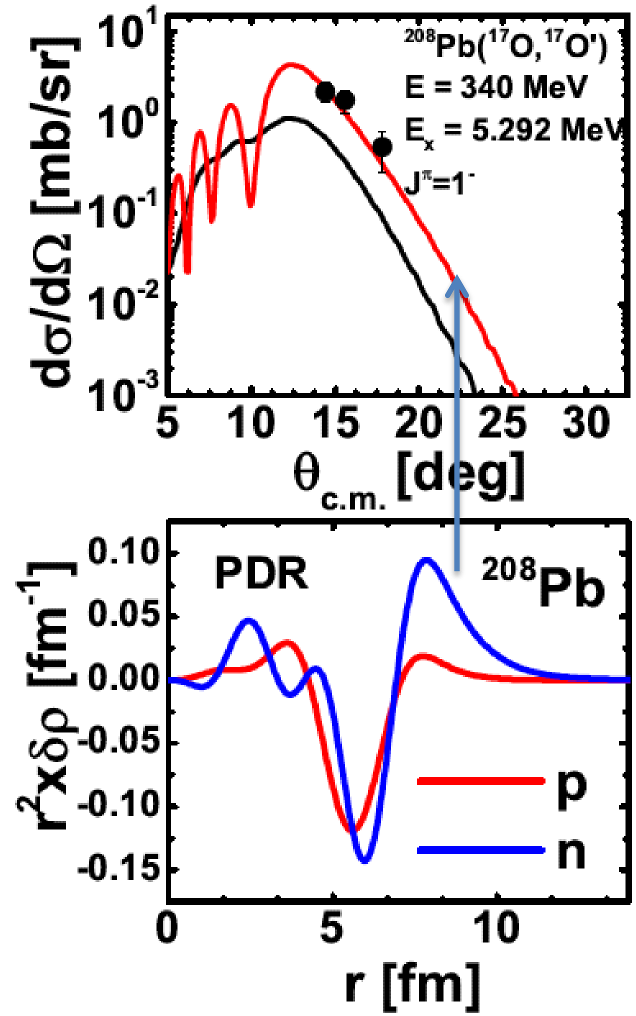


Neutron skin related to symmetry energy in the Equation of state

Experiment:
GSI, Legnaro, Catania, TUD, RCNP, Munich, TAMU, NSCL, GANIL, JLAB, RIBF…

AGATA at LNL: nature of pygmy states
(low energy dipole response)





AGATA data at LNL:
F. Crespi, A. Bracco et al…PRL113(2014)012501

Promote Planning for Future Large-Scale Facilities

–……

–Technical Design Study for intense radioactive beams at ISOL@MYRRHA

–……

–Inclusion of nuclear physics programmes @ ELI and ESS

Where are we?

Future Facilities- NuPECC LRP 2010

- **The inclusion of Nuclear Physics programmes at the multi-purpose facilities ELI and ESS.**

ELI (distributed facility)
ESFRI ROAD MAP
see ESFRI Report 2010

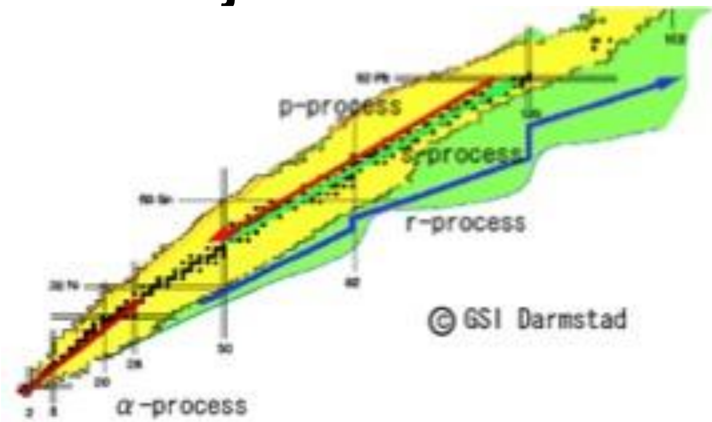
ELI-NP within the Rumanian pillar

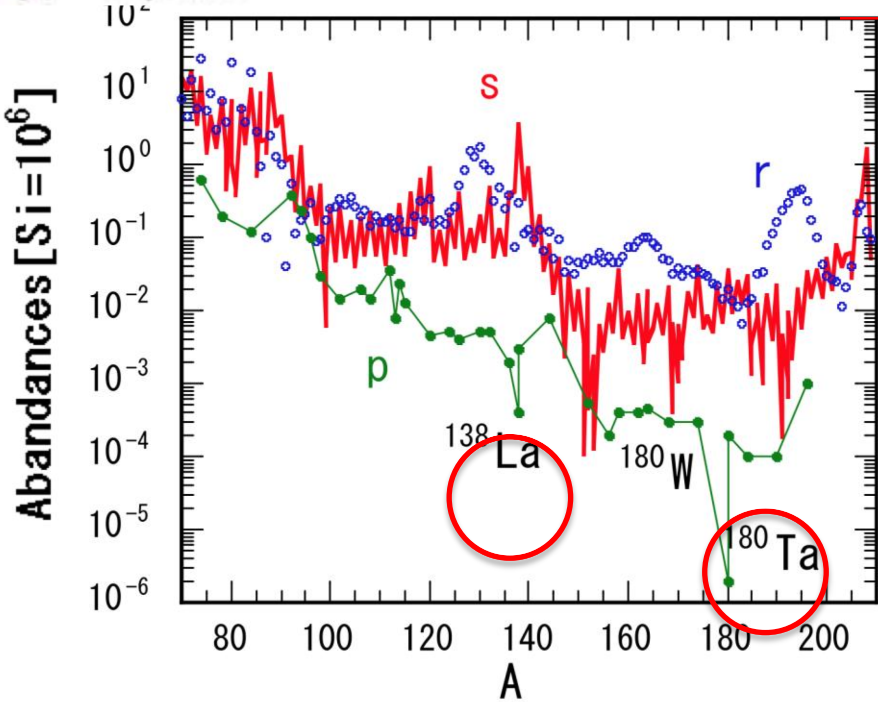
Nuclear Physics

Bucharest-Magurele
National Physics Institutes

P-process nucleosynthesis

Photonuclear reactions play a major role.





35 neutron-deficient rare isotopes

^{180}Ta(γ,n)^{179}Ta

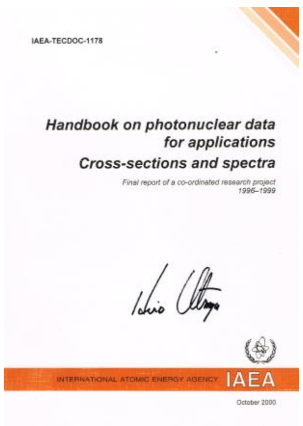
^{138}La(γ,n)^{137}La

Nucleus	Natural abundance (%)	Abundance (10^6 Si) Anders&Grevesse
180Ta	0.012	2.48E-06
190Pt	0.014	0.00017
184Os	0.02	0.000122
156Dy	0.06	0.000221
120Te	0.09	0.0043
124Xe	0.09	0.00571
126Xe	0.09	0.00509
138La	0.09	0.000409
158Dy	0.1	0.000378
132Ba	0.101	0.00453
130Ba	0.106	0.00476
180W	0.12	0.000173
168Yb	0.13	0.000322
162Er	0.14	0.000351
196Hg	0.15	0.00048
174Hf	0.16	0.000249
136Ce	0.185	0.00216
152Gd	0.2	0.00066
138Ce	0.251	0.00284
115Sn	0.34	0.0129
78Kr	0.35	0.153
84Sr	0.56	0.132
114Sn	0.66	0.0252
74Se	0.89	0.55
108Cd	0.89	0.0143
112Sn	0.97	0.0372
102Pd	1.02	0.0142
106Cd	1.25	0.0201
164Er	1.61	0.00404
98Ru	1.87	0.035
144Sm	3.07	0.0008
113In	4.29	0.0079
96Ru	5.54	0.103
94Mo	9.25	0.236
92Mo	14.84	0.378

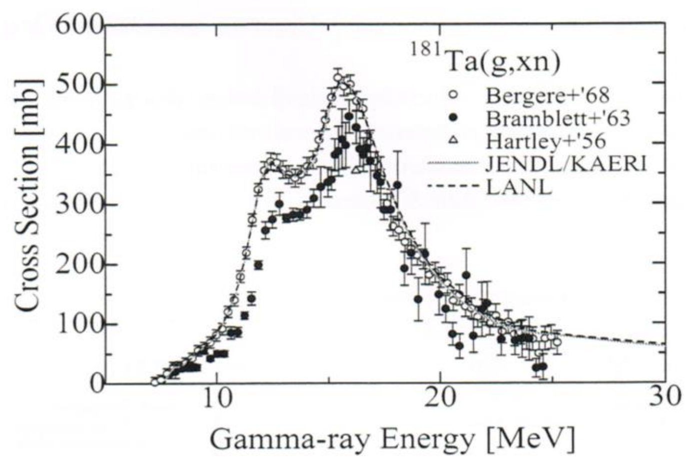
New compilation of photoneutron cross sections as a Coordidated Research Project of IAEA

ATLAS : At. Data and Nucl. Data Tables, 38, 199 (1988)

IAEA-TECDOC-1178 (2000) : Coordinated research project (CRP) 1996-1999



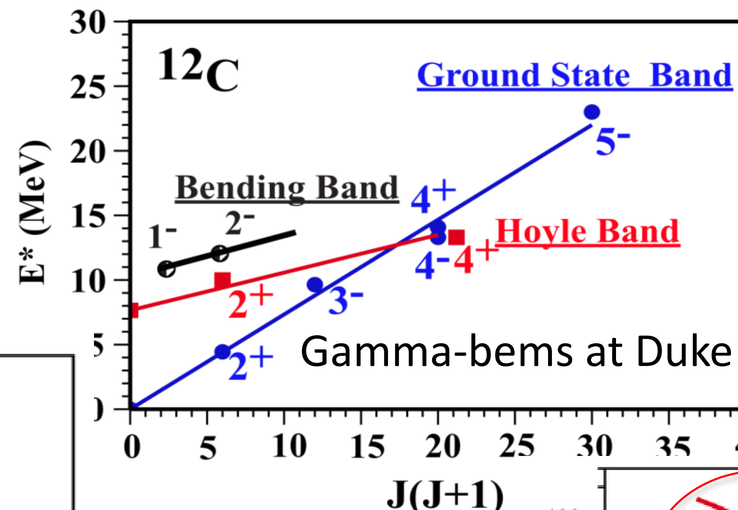
^{181}Ta(γ,xn)



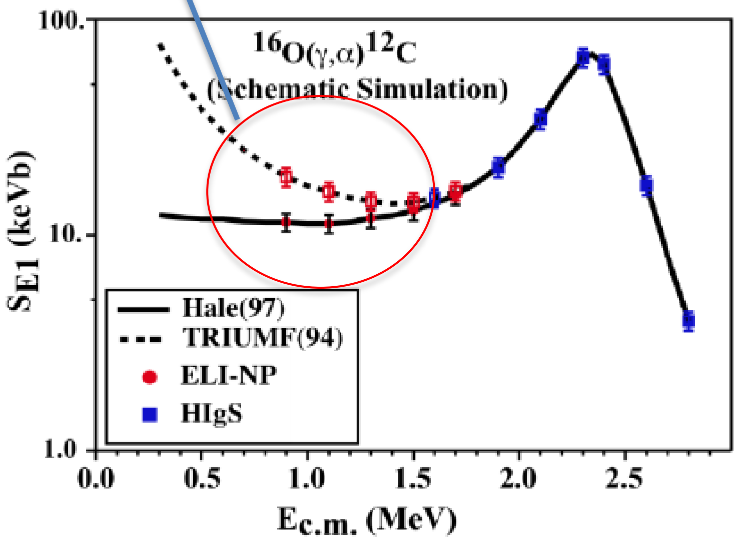
A new CRP of IAEA for <u>an update of IAEA-TECDOC-1178</u> (V. Varlamov) and <u>a new database of the gamma-ray strength function (S. Siem)</u> is proposed by the IAEA scientific officer, <u>P. Dimitriou</u>

The Charged Particles with TPC detector

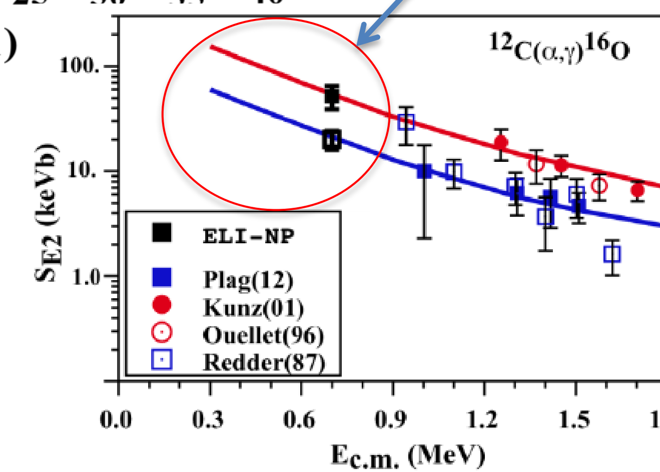
- Nuclear structure – clustering in light nuclei: ^{12}C, ^{16}O;
- Nanodosimetry with γ beams using the eTPC
- Nuclear astrophysics: $^{16}O(\gamma,\alpha)^{12}C$, $^{22}Ne(\gamma,\alpha)^{18}O$, $^{19}F(\gamma,p)^{18}O$, $^{24}Mg(\gamma,\alpha)^{20}Ne$,



Simulations for ELI_NP

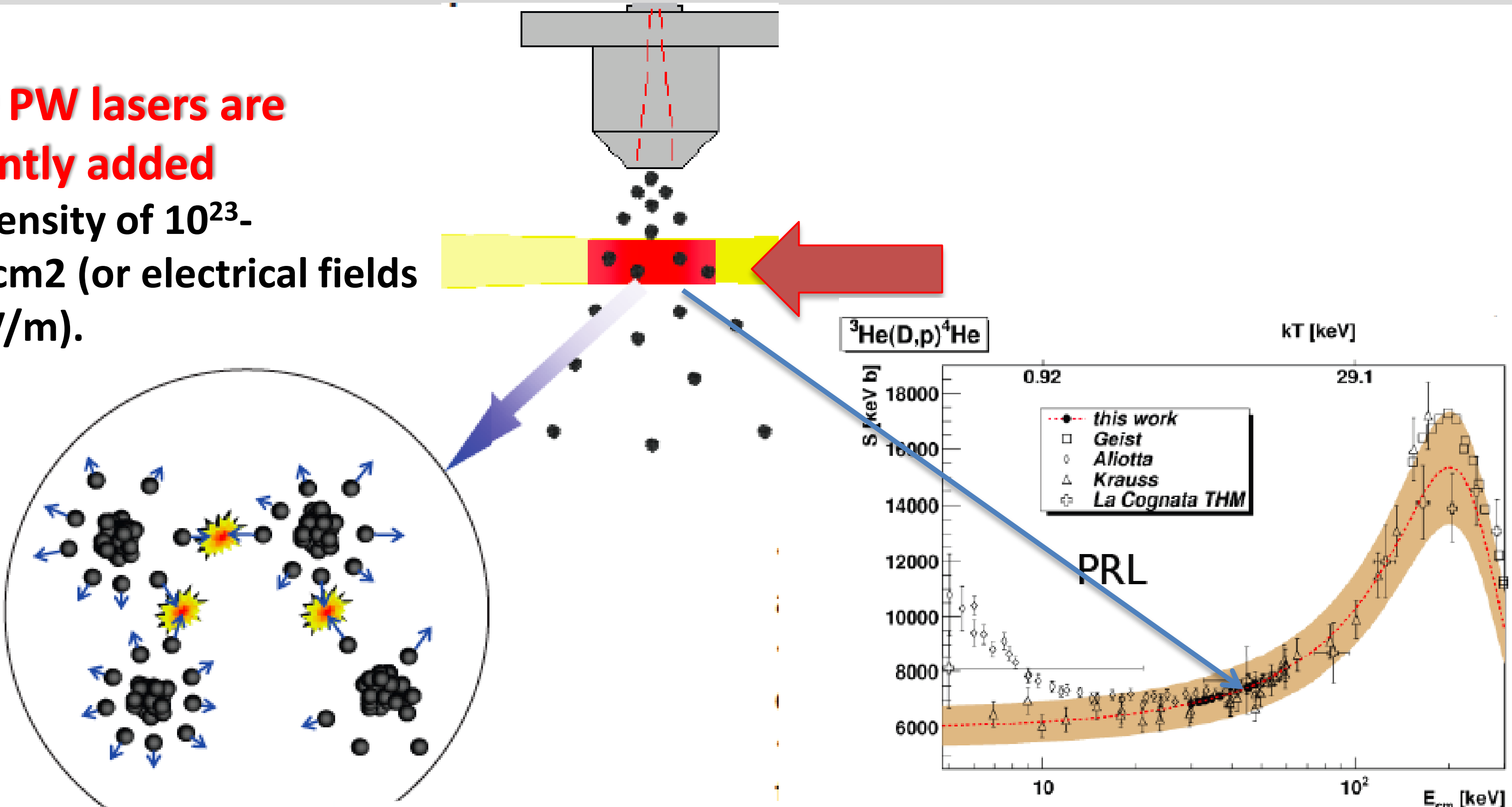


Simulations for ELI_NP



ELI – nuclear reactions in high power LASER

ELI
two 10 PW lasers are coherently added
high intensity of 10^{23}-10^{24}W/cm2 (or electrical fields of 10^{15}V/m).



PHYSICAL REVIEW LETTERS

Measurement of the Plasma Astrophysical S Factor for the ^{3}He(^{2}H, p)^{4}He Reaction in Exploding Molecular Clusters

M. Barbui,[1,*] W. Bang,[2,†] A. Bonasera,[3,1] K. Hagel,[1] K. Schmidt,[1] J. B. Natowitz,[1] R. Burch,[1] G. Giuliani,[1] M. Barbarino,[1] H. Zheng,[1] G. Dyer,[2] H. J. Quevedo,[2] E. Gaul,[2] A. C. Bernstein,[2] M. Donovan,[2] S. Kimura,[4] M. Mazzocco,[5] F. Consoli,[6] R. De Angelis,[6] P. Andreoli,[6] and T. Ditmire[2]

Nuclear astrophysics recommendations (2010)

- **Using radioactive heavy ion beams** for nuclear structure studies far off stability, In-flight at FAIR and (ISOL) techniques at GANIL, CERN and SPES Legnaro

- Improving the capabilities of high intensity stable heavy ion beam facilities and planning for a **new underground accelerator for nuclear structure and astrophysics studies**

- **Improving the support of smaller-scale facilities in Europe** that e.g. vitally support physics projects at the largescale facilities and are of paramount importance for training and education in Nuclear Physics

- Advanced theory methods play a central role → Advancing Reaction Theory and Merging with Structure!

Progress has been made since 2010…….we have to be ready for the next long range plan and push to advance more

It starts this year!!

SPARES

Advances in Theory are Critical

Advancing Reaction Theory and Merging with Structure!

Properties of Neutron Matter and Extremely Neutron Rich Nuclei, from Cluster to Pasta!

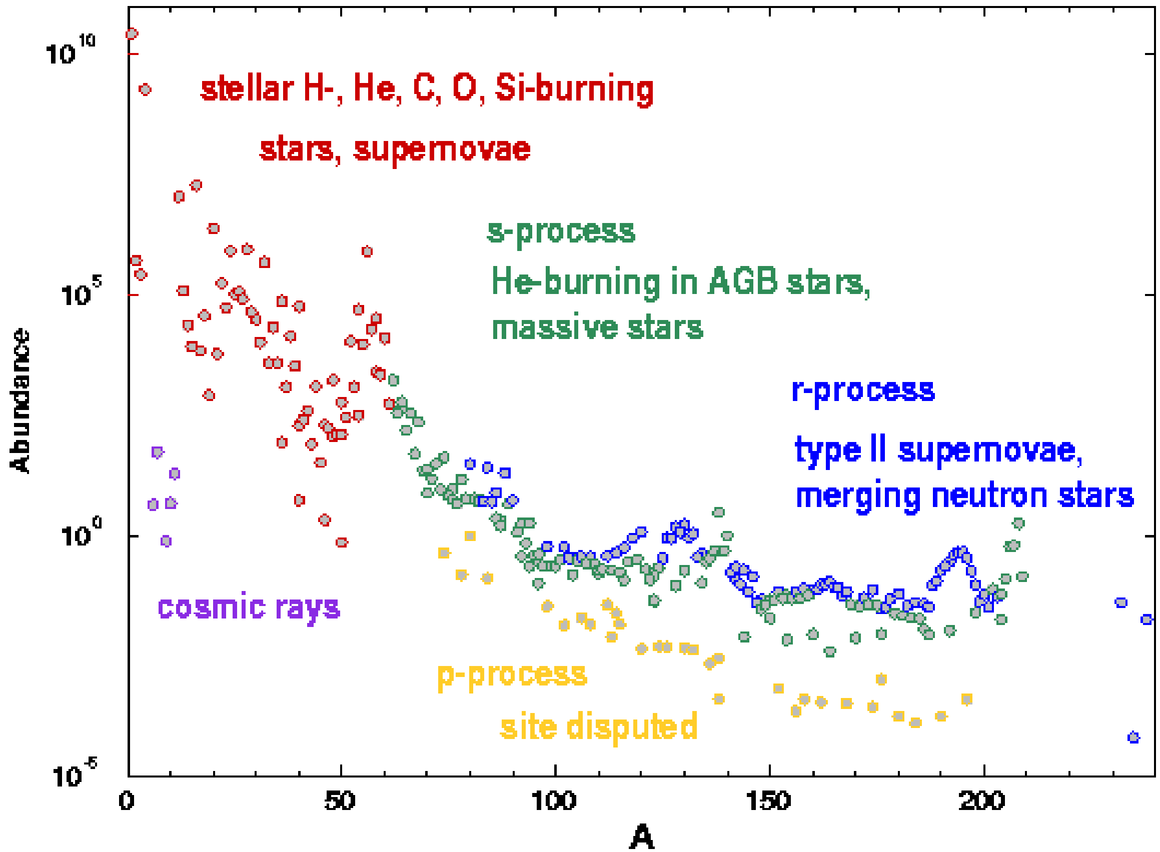
Neutrino Interactions, Signatures & Oscillations

Multi-D Astrophysics and Nuclear Physics Model Simulations

Important cross-cutting themes:

- Astrophysical Model Validation
- Uncertainties need to be quantified
  - Theoretical predictions of nuclear properties and reactions
  - Combining experimental and theoretical information for reaction rates
  - Theoretical predictions of astronomical observables (implementation)
- Computational Physics Opportunities

The different elements are formed in different classes on nucleosynthesis which occur in different astrophysical sites



Big Bang Nucleosynthesis (H, He and small amounts of Li,Be)
Nucleosynthesis in stars (Nuclei up to Fe and about half of heavier elements)
Explosive nucleosynthesis (the rest of the heavy elements)
(Novae, X-ray Bursters, Supernovae...)

Some selected examples and tools

- Low energy reactions induced by charged particles and gamma decay

- neutron induced reactions

- Gamma induced reactions

- Reactions in the plasma (using LASER)

- Reactions, decays and nuclear structure with radioactive beams for astrophysics