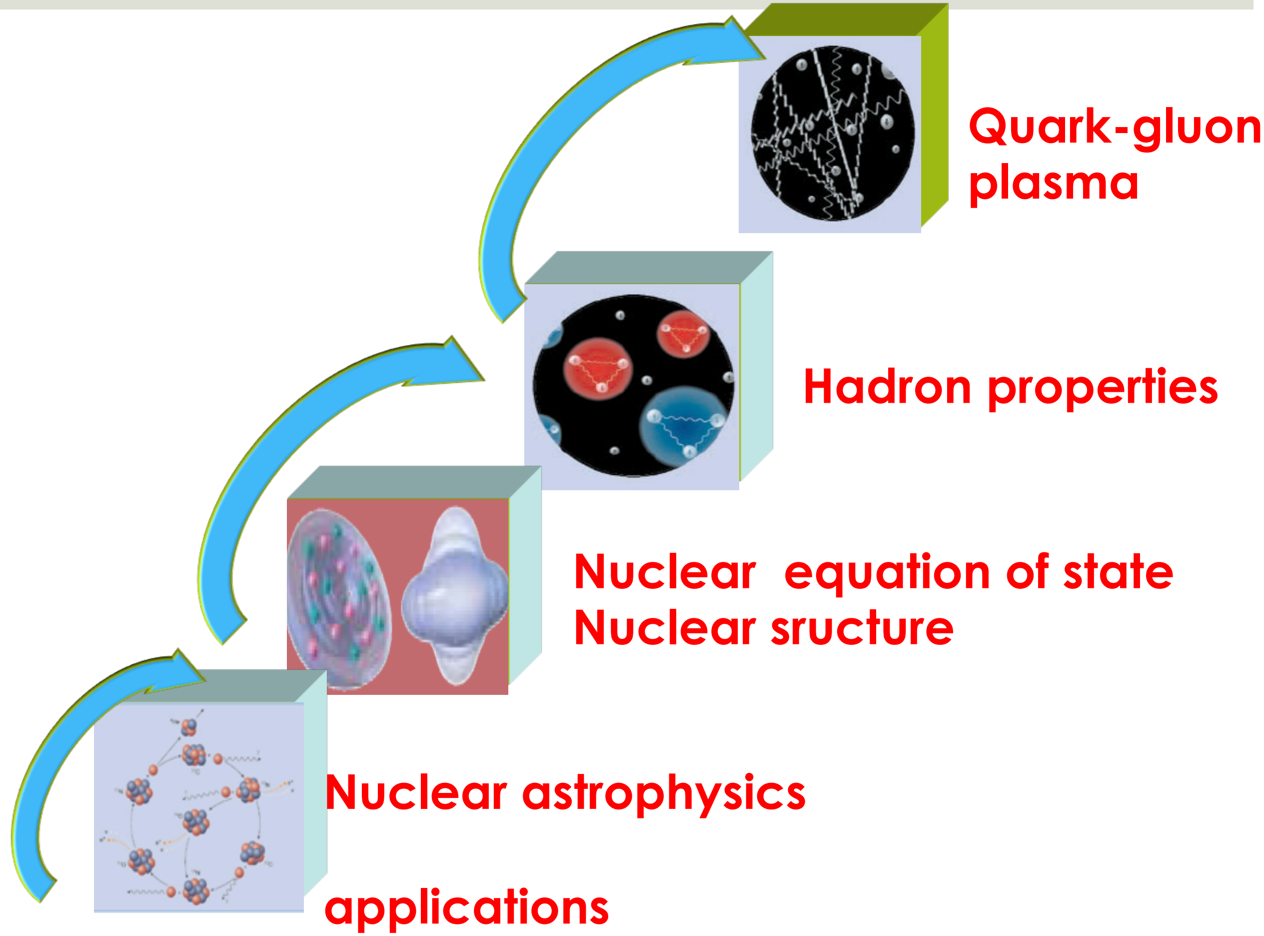
Nucleus Nucleus 2015

21-26 June 2015 *Dipartimento di Fisica ed Astronomia, Università di Catania*

….. some selected highlights since NN2012

Angela Bracco

Università di Milano and INFN



Interlinks of these fields to address questions such as :

- What is the influence of meson and hadron properties in the Quark gluon plasma
- What are the nuclear structure effects influencing the nucleosynthesis and low energy nuclear reactions?

Ultra relativistic heavy ion collisions

From the beginning

the big bang ……

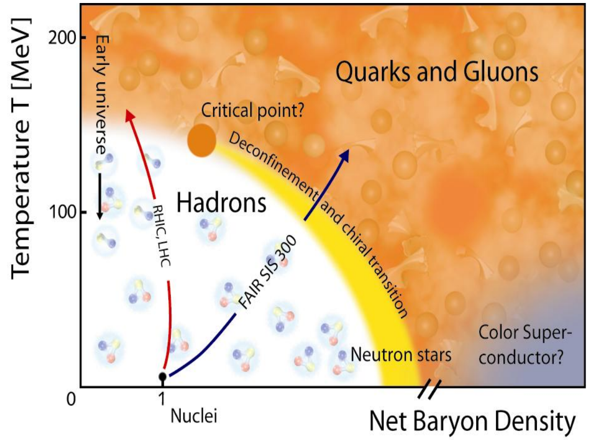
the hot compressed matter and the properties of the hot quark gluon plasma

Heavy ion Collisions : matter under extreme conditions

What do we want to learn from HIC ?

Some results

Future



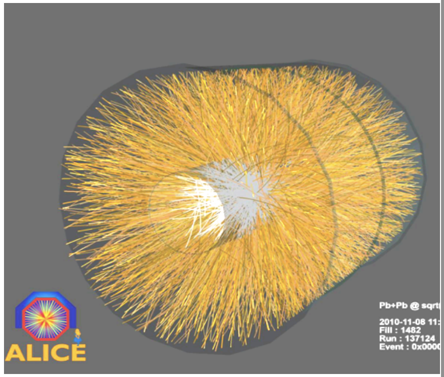
The aim → **Exploring QCD under extreme conditions, where the strong interaction is really strong,**

expectations & predictions :

weakly interacting plasma / ideal gas of (quasi-free) quarks & gluons

partons are **deconfined**
(not bound into composite color neutral hadrons)

chiral symmetry is restored
(partons ≈ massless, vanishing gluon condensate)



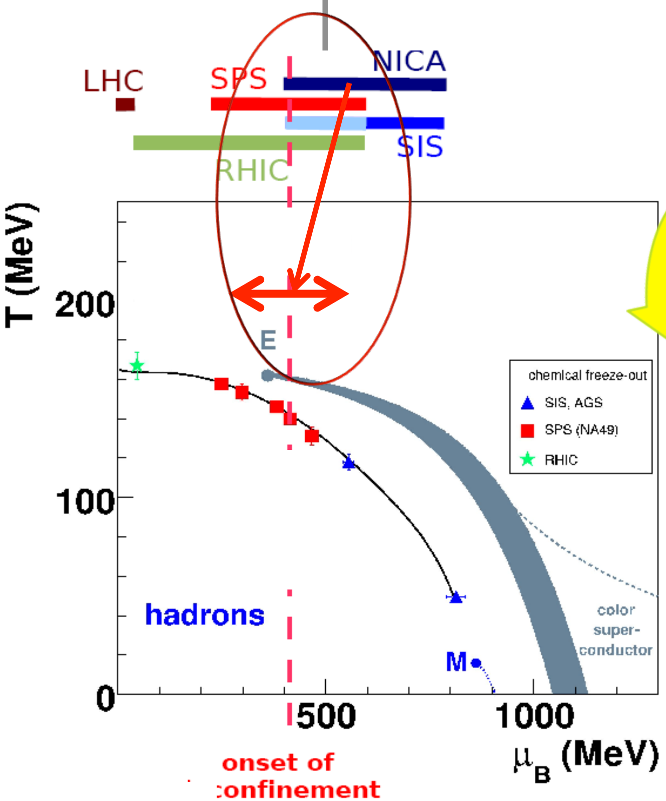
The tools

Relevant degrees of freedom
(and experimental observables) at high T :
ordinary hadrons are not sufficient

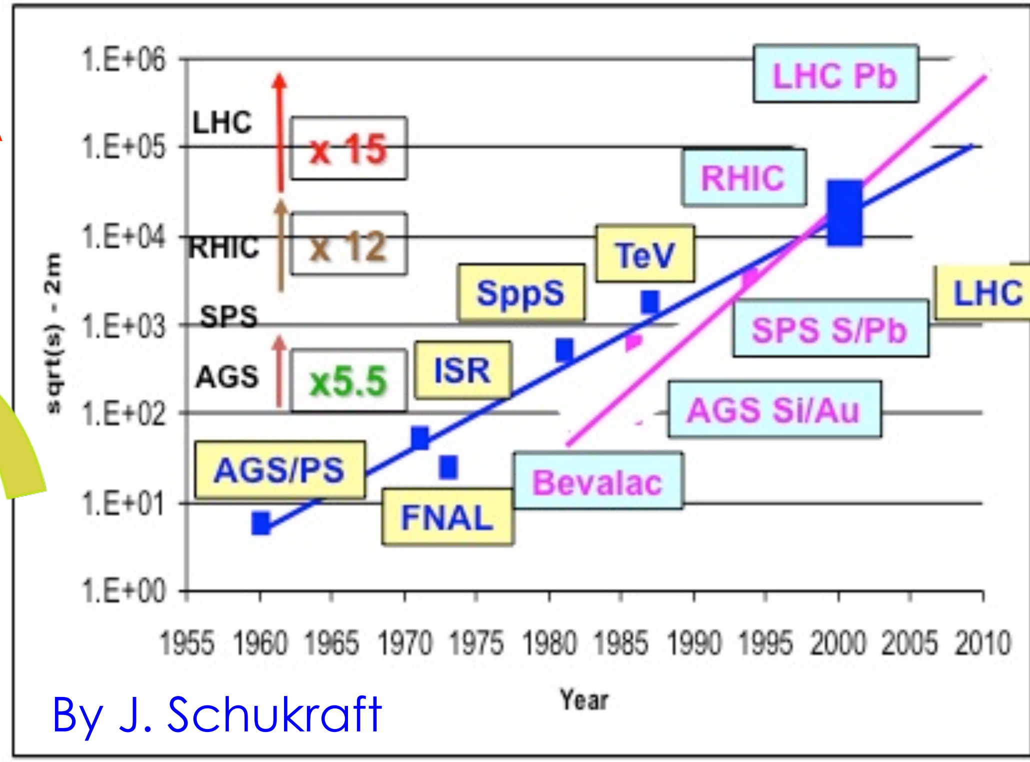
Heavy ion Collisions : matter under extreme conditions

central activity of contemporary **Nuclear Physics**

energy increase by factor 10^4 in ~ 30 years



Total center-of-mass energy versus time



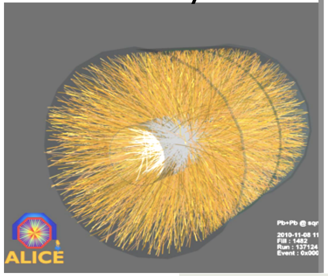
Very strongly interacting, almost perfect liquid' : sQGP

No quasi free gas!!

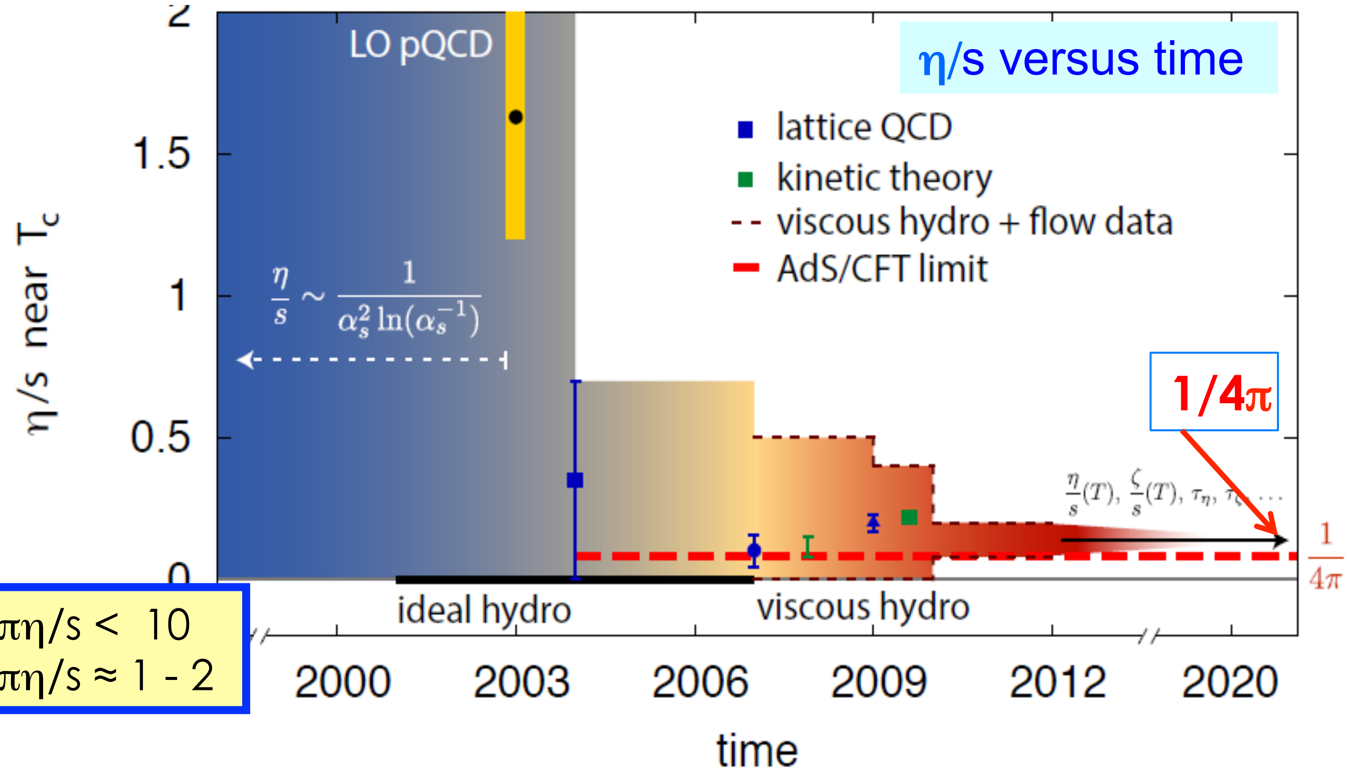
From Collective properties

Future:
What is the dynamics

'Where is the onset ?
size & energy density ?



increasingly precise measurements of **macroscopic properties**
η/S, ξ, q^, e^, D, EoS, c_s,



2004: $4\pi\eta/s < 10$
2014: $4\pi\eta/s \approx 1 - 2$

'Macroscopic' piece of matter with amazing properties

- reaches thermo/hydro equilibrium incredibly fast & in small volumes (< 1 fm)
- tiny viscosity reveals density fluctuations in the initial state, event-by-event !

Heavy ion Collisions : quark deconfinement

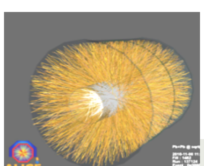
Reconcile:

Perfect Fluid

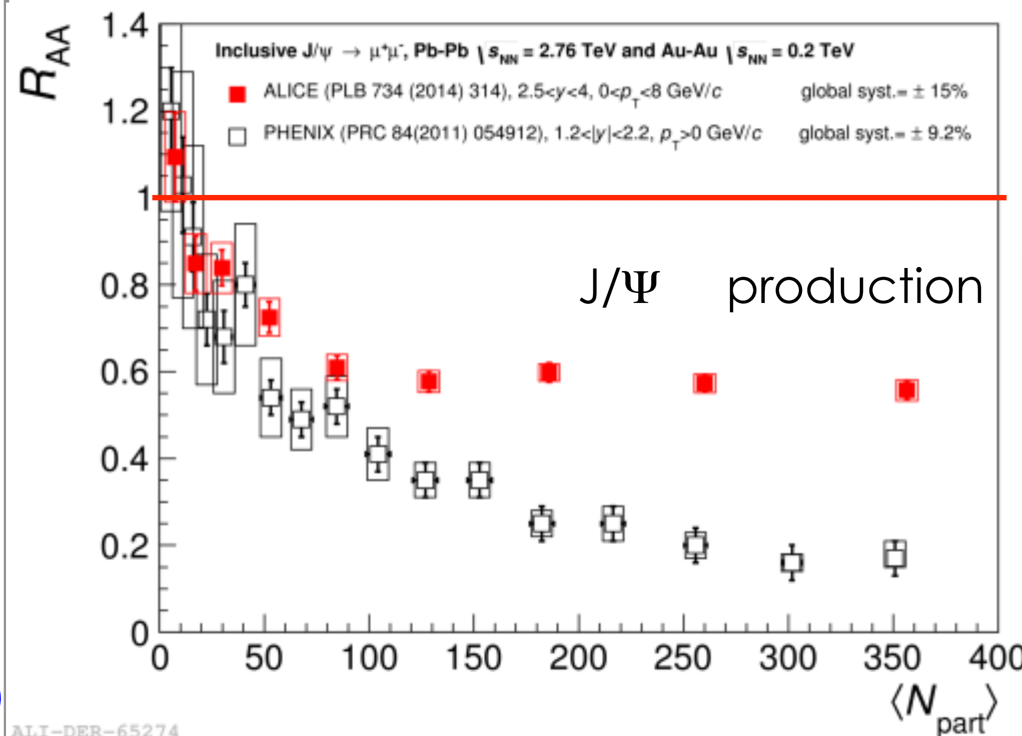
(the relevant dof (particles, excitations, ..) are **NOT free quarks & gluons**

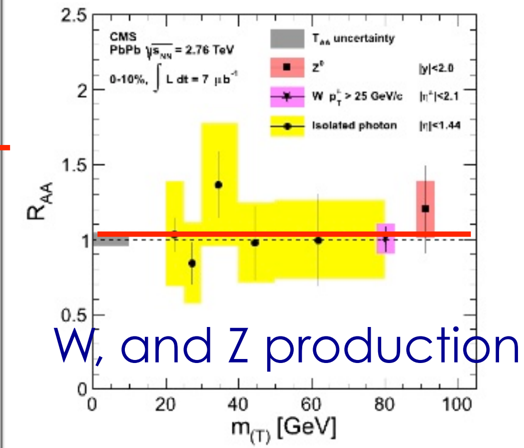
and

Weak coupling (deconfinement) at short distances (from QCD)



good evidence for **deconfinement** (J/Ψ, Υ)
J/Ψ coalescence = **color conductivity**,
Υ suppression = **resonance melting**





→ less suppression than RHIC (PHENIX, $1.2 < y < 2.2$, $p_T > 0$)

→ weaker centrality dependence

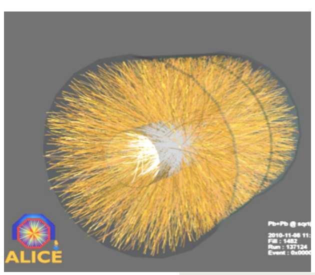
→ new regime c-cbar coalescence?

Heavy ion Collisions : matter under extreme conditions

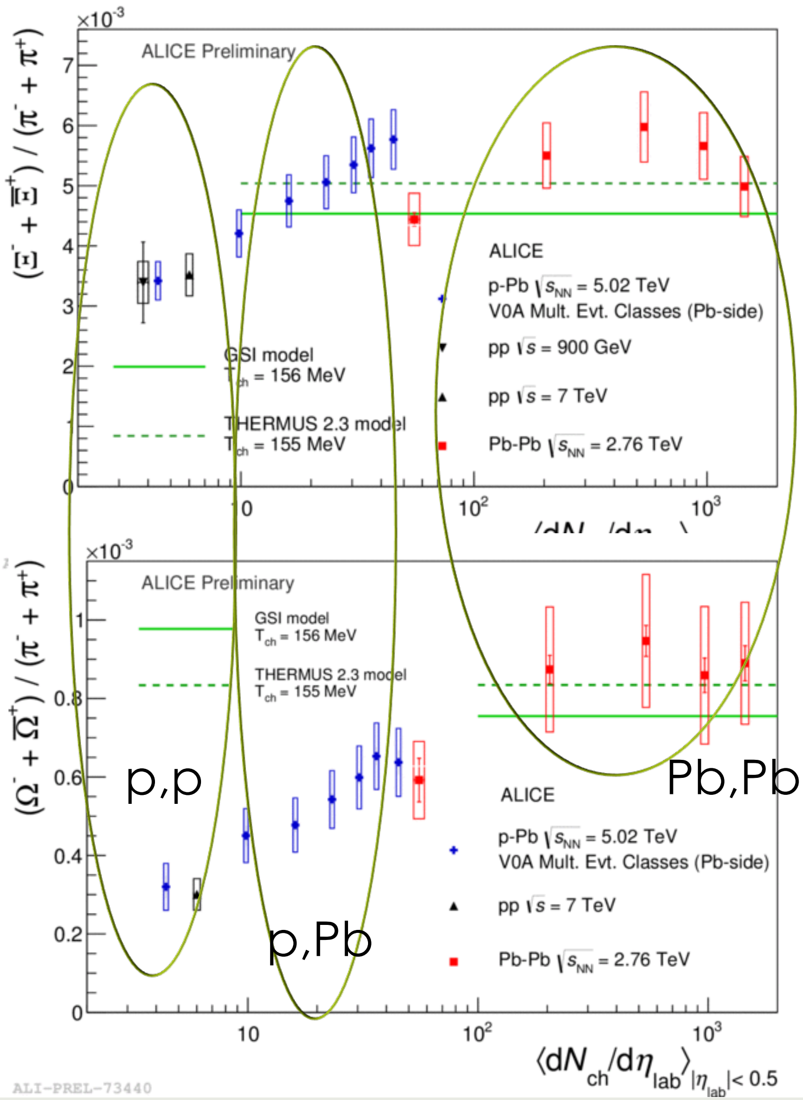
What do we want to learn from HIC ?

Chiral symmetry Restoration ?

Some evidence in low masses (rho) (indirect)



strangeness ???,- Behavior of multi strange barions



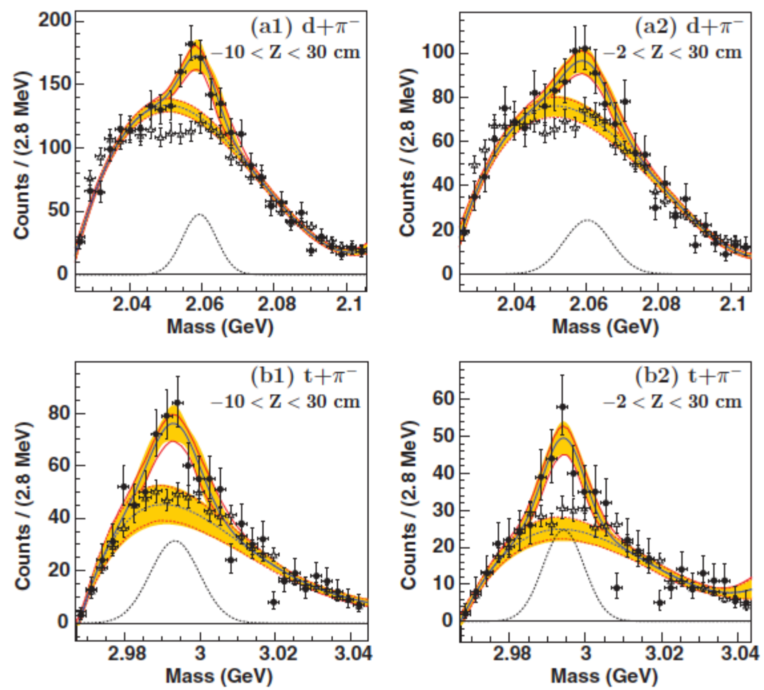
p-Pb smoothly bridges
Ξ , Ω
abundances
from pp to Pb-Pb values!

Future planned measurements
Focusing
mainly on heavy quarks
with increased precision!

Heavy ion Collisions at 2GeV/u : strangeness production

^{6}Li +^{12}C invariant mass distributions of d + π **and** t + π

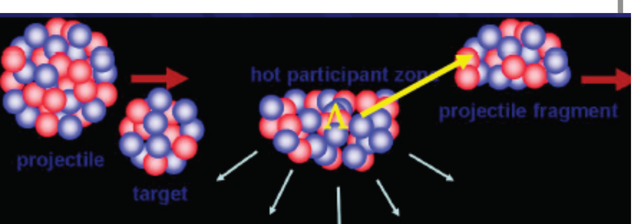
Properties of Λ - n for Neutron stars

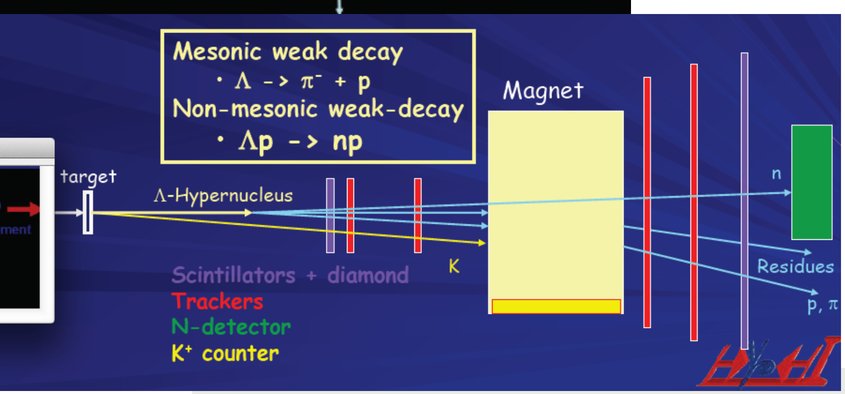


Lifetime estimation of the possible bound states yielding
d + π
t + π

181**+/-**30 ps
and
190**+/-**47 ps

(260 ps lifetime of Lambda)





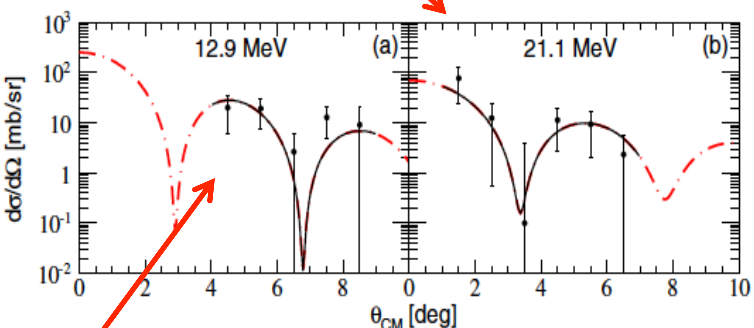
These states may be interpreted as the 2-body and 3-body decay of a neutral bound state :
2 neutrons and a hyperon, $^{3}{}_{\Lambda}$n-

Equation of state of Nuclear matter and neutron stars

EOS :

Constrains from isoscalar modes, as the GMR (nuclear compressibility), heavy ion collisions)

Recent result on ^{68}Ni for the GMR (GANIL- Active target Maya and RIB at 50 MeV/u)

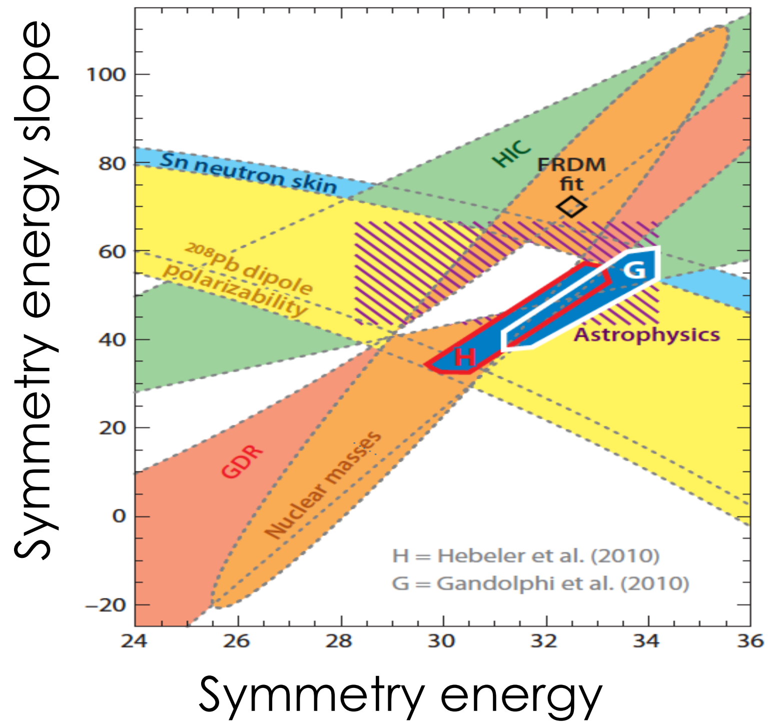


PRL113(2014)032504

Soft mode? compressibility of the skin?

EOS Asymmetric term constrained by :

- Heavy Ion collisions
- Neutron Skin polarizability (GDR and pygmy) P-REX experiments
- Nuclear masses



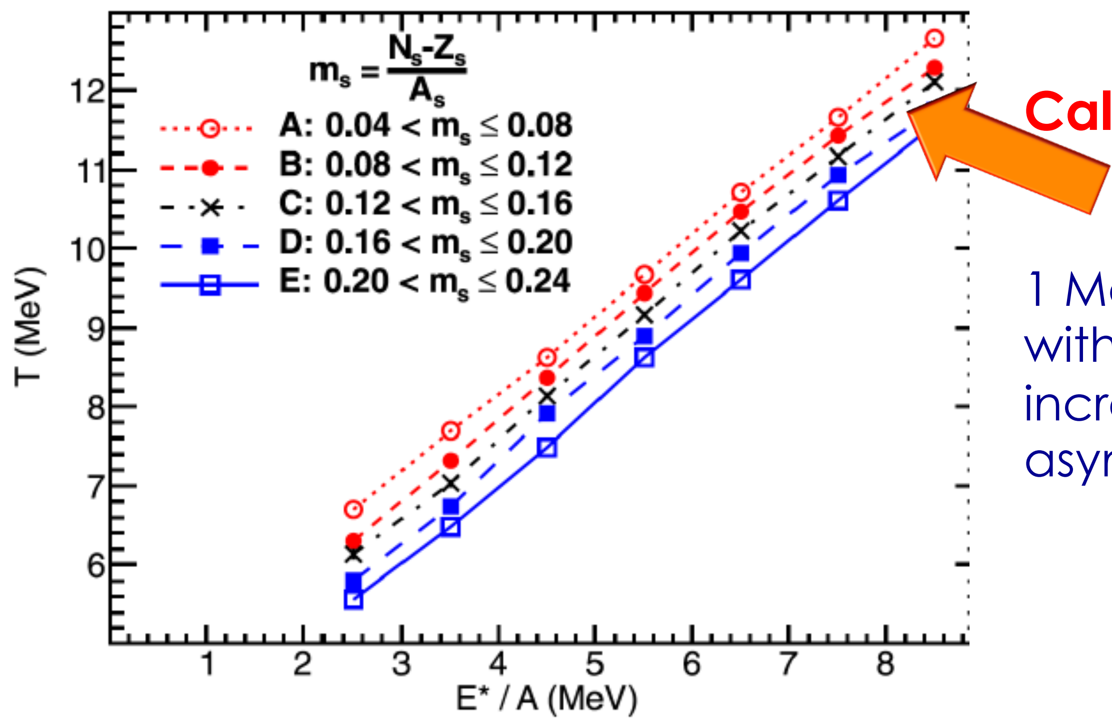
EDF with effective interactions

Heavy ion Collisions and the nuclear equation of state

The EOS,
relationship
between :

Thermodynamic
and
the bulk nuclear
properties

is relevant in
heavy ion
collisions
and
environments of
nucleosynthesis.

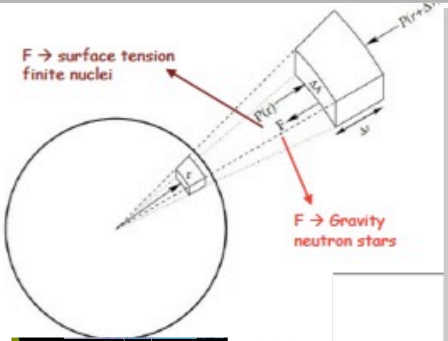


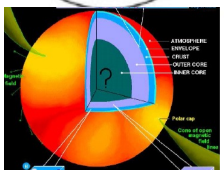
1 MeV decrease
with
increased
asymmetry

Evidence also of effects of **clusterization** on the Low- Density
(see e.g. *J P-G41 (2014)* 075108- (LNL)
and J. P. G . 420(2013) 012087 from LNS)

Equation-of-State :
(see K. Hagel, J.B. Natowitz and G. Roepke, EPJA A 50 39-1 - 39-16 (2014)-
For fluctuation and symmetry energy in nuclear
fragmentation dynamics see M. Colonna, PRL110,042701(2013)

Neutron skin and its properties ….(pygmy-polarizability)

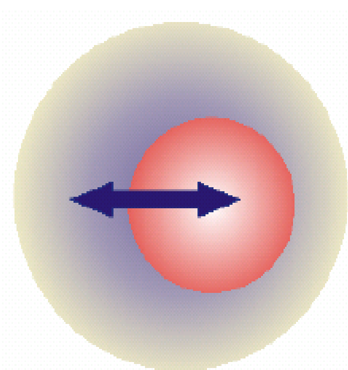




Neutron pressure on neutron Star crust

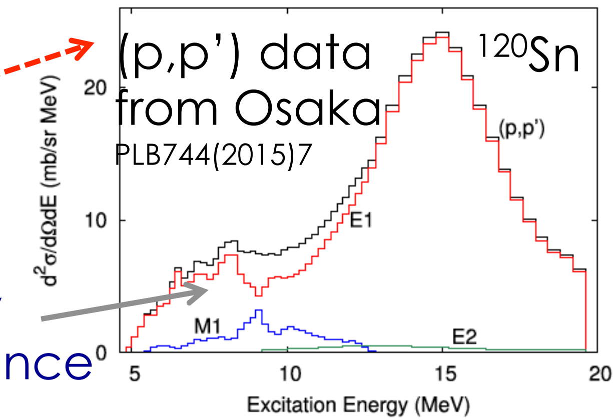
Virtual photon
Excitation of the
dipole response

Low energy part
interpreted as
oscillation of the skin
or excitation of nucleons
in the skin

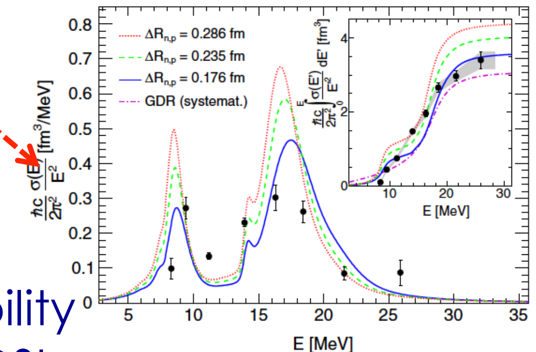


Isospin character of
the pygmy mode
Stringent test to theory

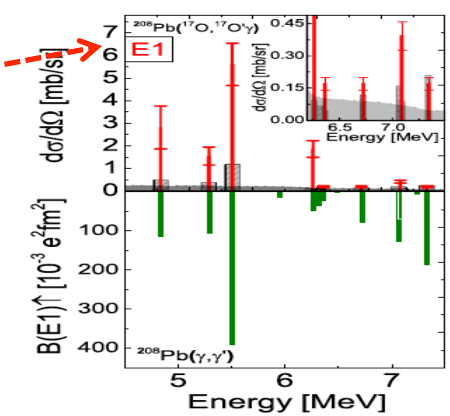
Strength below
binding –affecting
nucleosynthesis in the r-process



Pygmy
resonance

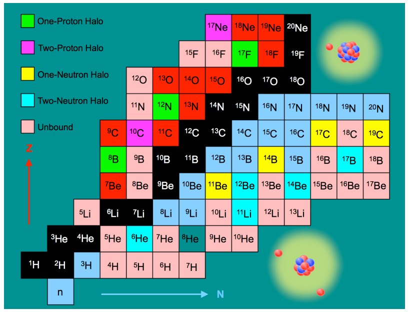


Nuclear
Polarizability
in ^{68}Ni (GSI PRL111(2013)-242503)



^{17}O inelastic
scattering
AGATA at LNL
PRL113(2014)012501

Light nuclei : ab initio calculations 2N and 3N interactions



Quantum montecarlo methds with chiral interactions

To be studied:

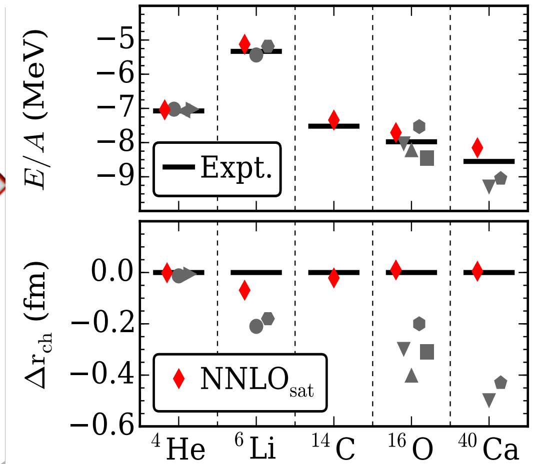
- Halo, radii, skins

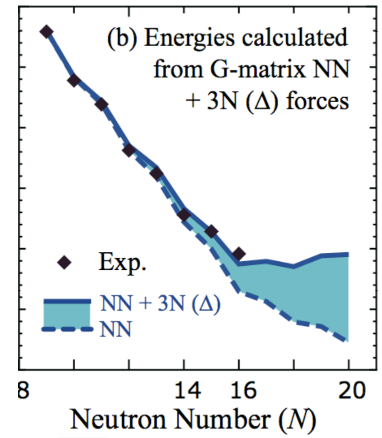
  low energy scattering, break up
  high energy cross sections

- Binding energies (masses)
- The coupling of loosely bound nuclei to the continuum

  g.s and ex. resonances in very short lived b.s. (di-n and di-p decay)

- Excited states of light nuclei
- moments from measurements in traps



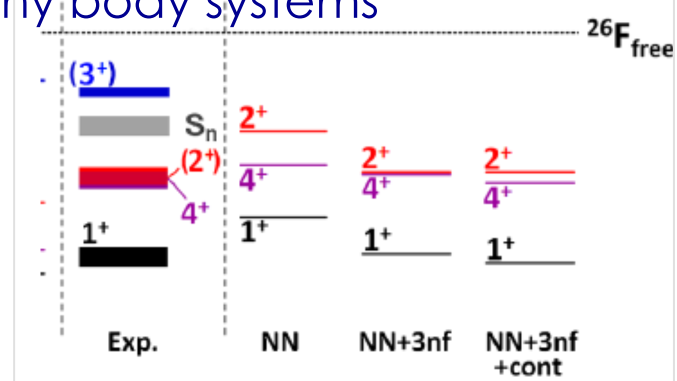


Coupled cluster description of binding energies and radii

Drip line for O A= 24

See e.g:
T. Otsuka et al.PRL105(2010)
G.R. Jansen et al. PRL113(2014)142502

3N int. are needed …..pave the way to many body systems

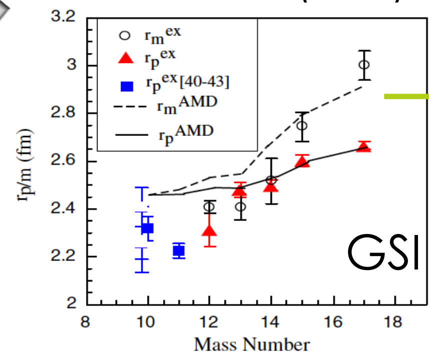


Light nuclei : resonances and the continuum

Halo nuclei , radii

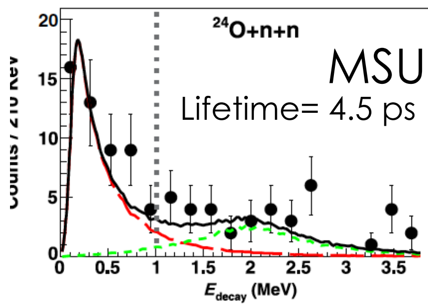
Proton radii from charge changing reaction

PRL113(2014)132501



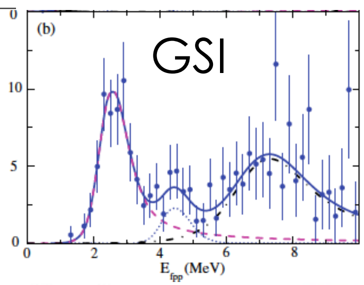
^{26}O n-drip line

PRL113(2014)132501



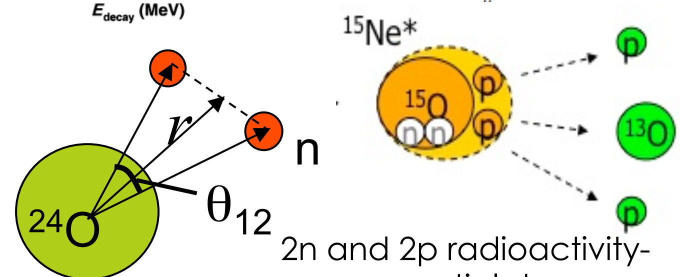
^{15}Ne p-drip line

PRL112(2014)132502



Two neutron decay

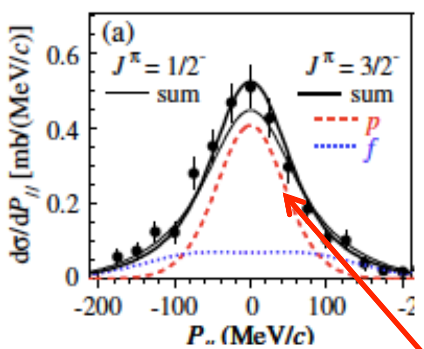
two proton decay



2n and 2p radioactivity-
no sequential decay

the heaviest halo :^{37}Mg
S_n= 0.2 MeV

RIKEN – PRL 112(2014)242501



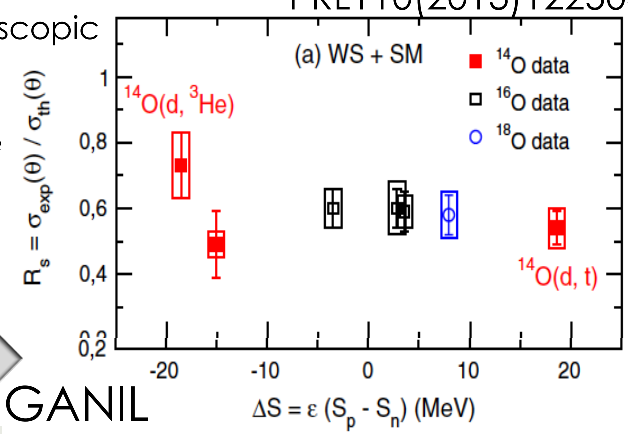
Importance of p-wave
Change of the order level

Spectroscopic factors

^{14}O

PRL110(2013)122503

Spectroscopic factor purity of single particlel



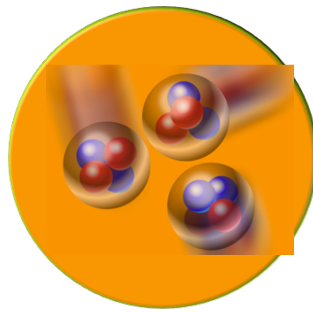
GANIL

Hoyle states ^{12}C

Particular attention to the problem of alpha clustering and of Hoyle states:

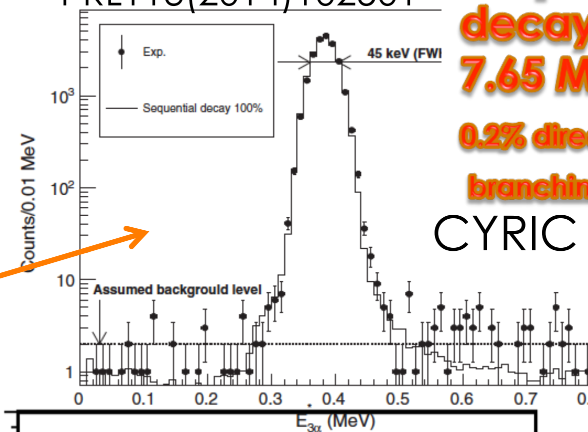
- 3 alpha decay
- Excited bands
- Form factors

^{12}C –
3 alpha cluster



Deduce geometry
Data: spinning of an oblate equilater triangle

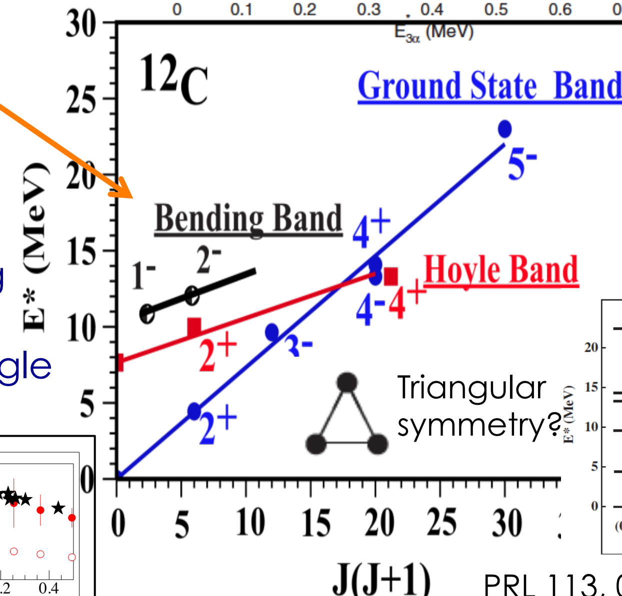
PRL113(2014)102501

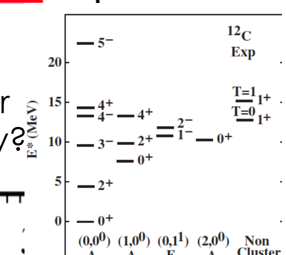


3 alpha decay 7.65 MeV 0^+

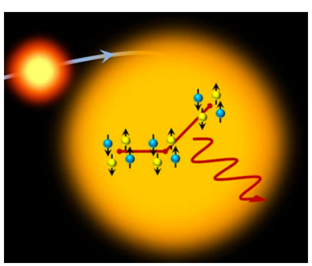
0.2% direct branching

CYRIC



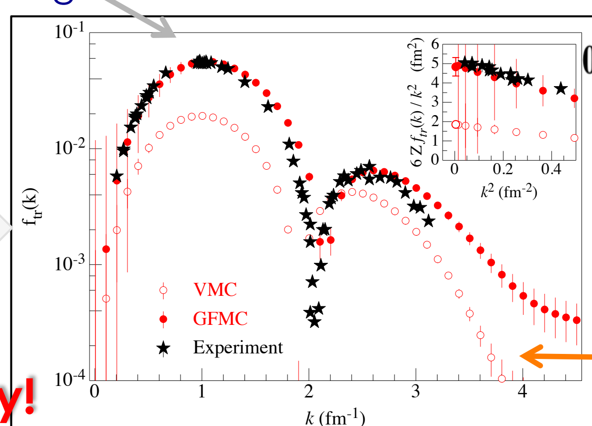


PRL 113, 012502 (2014)
$^{12}C(^4He; 3\alpha)^4He$-
Birmingam



Transition density from elastic scattering data

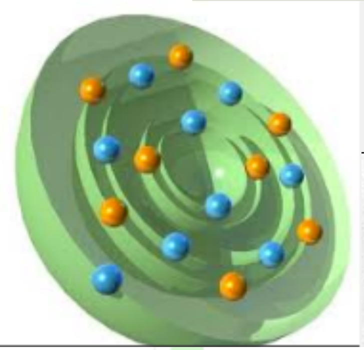
Hoyle state E0 form factor with Quantum Monte Carlo



Charged radius larger than g.s.

Great success for theory!

Nuclear structure - progress on:



Maria Goepper Mayer

Different excitation modes. Their properties need for description:

Theoretical approaches overlap and bridges need to be built between them

- Configuration interactions
- Density Functional Theory
- Dynamical symmetries

Super heavy

beyond p drip line

Far from stability - New shells – and new magic numbers

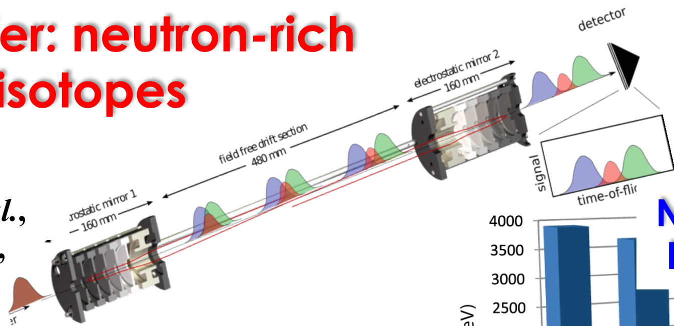
shell disappearance - shell robustness

- Deformation- shape transition Shape coexistance
- Collective effects and particle vibration coupling
- Pairing interaction

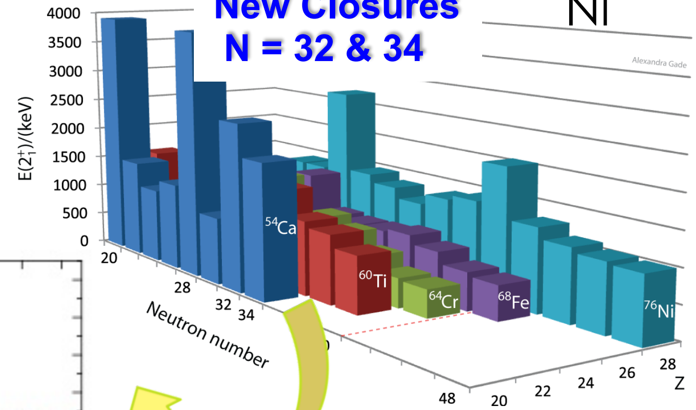
New Shell Closures N = 32 & 34: the Ca – Ni Region

The frontier: neutron-rich calcium isotopes

F. Wienholtz *et al.*, Nature 498, 346 – mass



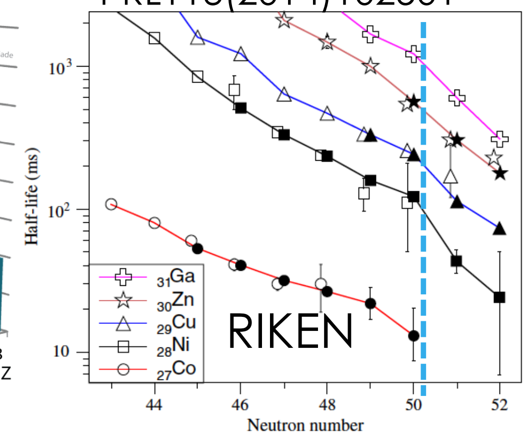
D. Steppenbeck *et al.*, Nature 502, 207 - 2+ state



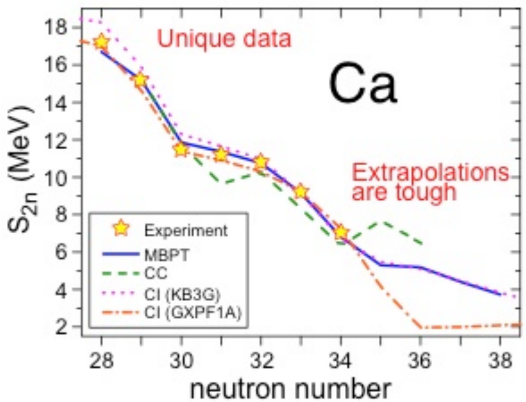
Ni isotopes-Beta decay

Magicity for p and n in ^{78}Ni

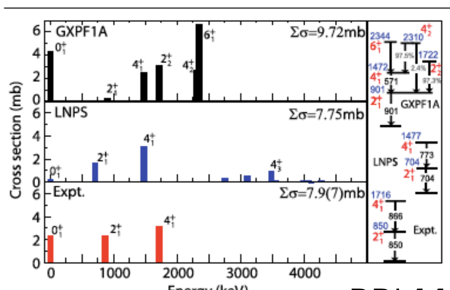
PRL113(2014)102501



where *ab-initio* and DFT meet…



Data on Ti toward ^{60}Ca



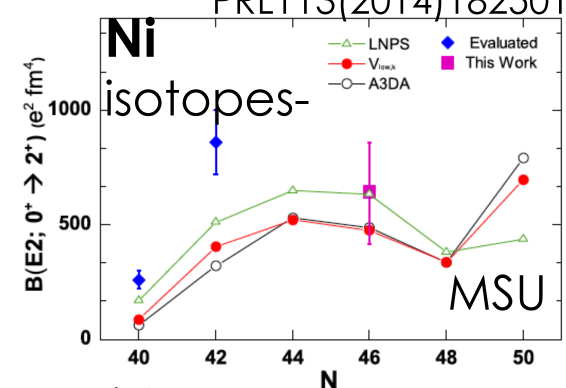
PRL112(2014)112503

And for particle phonon coupling ? They are now included in DFT

(see. e.g. PRL113(2014)252501)

PRL113(2014)182501

Ni isotopes-

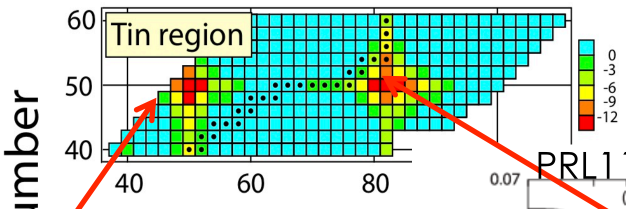


Evidence for neutron excitation

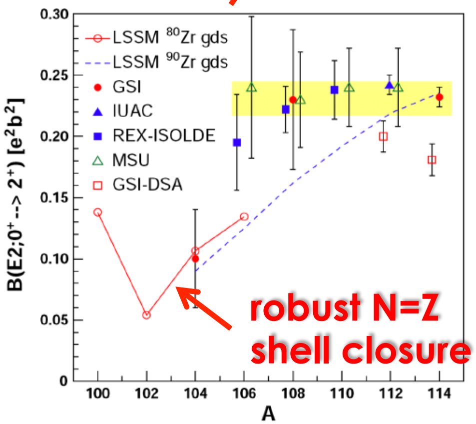
Quenching of shell , and robust shell closure

From ^{100}Sn ^{132}Sn

Shell energy

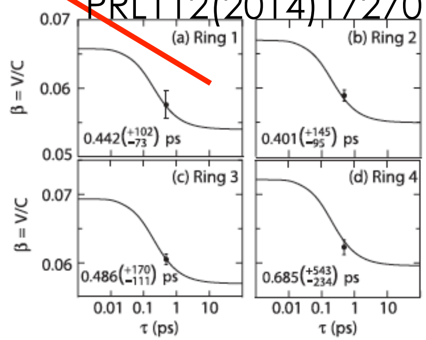


RISING-GSI



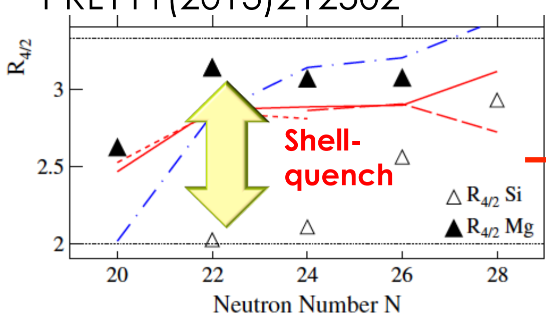
PRL110(2013)172501

PRL112(2014)172701



Shell N=80 in ^{132}Sn
as strong as in ^{208}Pb
Lifetimes and cross sect.
ORNL
Isomers in Cd (RIKEN)
Spin, μ (ISOLDE)

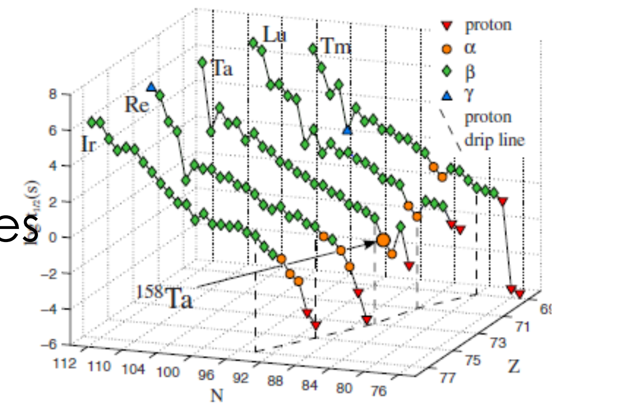
PRL111(2013)212502



Large deformations
for Mg neutron rich
N=

p drip line

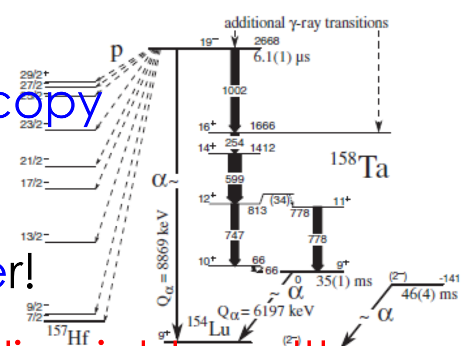
Life
times



PRL112(2014)092501

^{158}Ta is beyond proton drip line
but it has a spin trap- isomer !
(multiparticle nature)
γ and α decay
α decay at high I **Exp. JYFL**

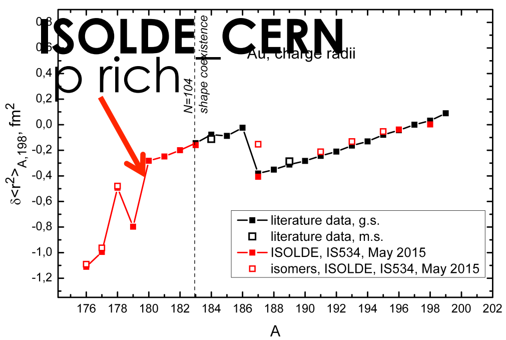
Spectroscopy
done
through
the isomer!



The p drip line is blurred!!

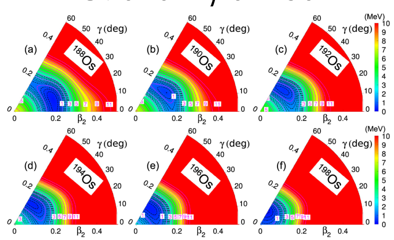
Deformation, collectivity

Evolution of collectivity- rapid shape transitions



Charged Radii of Au isotopes
Hyperfine structure and alpha decay

PRC902014) 021301



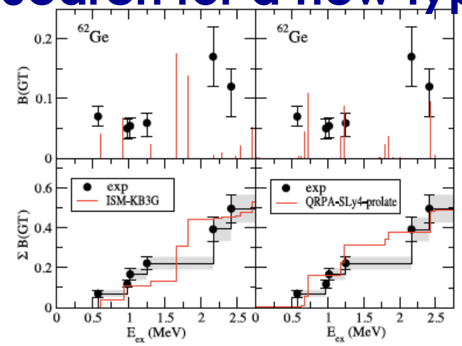
Mapping Shape change
Exp on Os isotopes
Lifetime measured
AGATA at LNL

Motivation for search for a non-zero EDM in ^{225}Ra.

Gaffney *et al.*, Nature 497, 199
Exp at ISOLDE

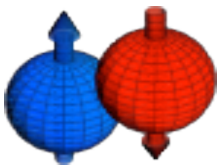
Pairing

Search for a new type of superfuidity

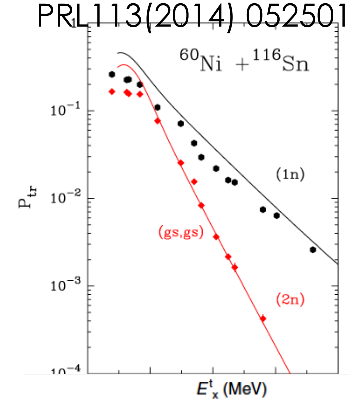


PRL113(2014) 092501

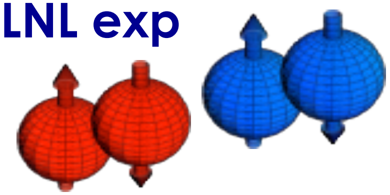
No T= 0 Pairing from Gamow Teller Strength
Rising **GSI**

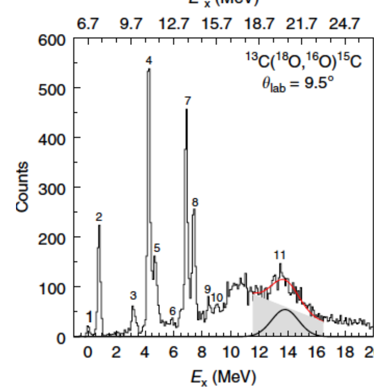


PRL113(2014) 052501



Importance of pairing in the 2n cross section
LNL exp



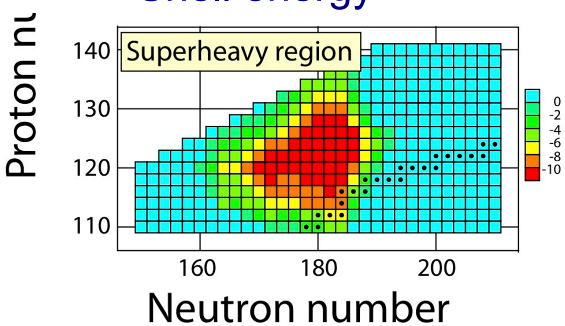


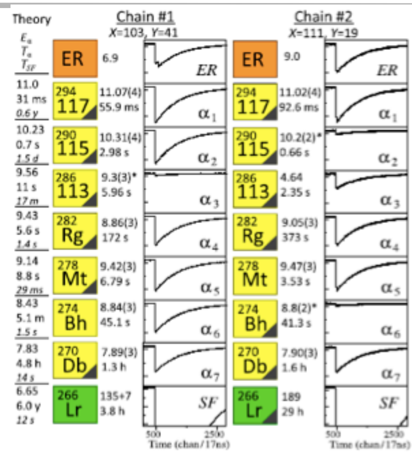
Giant pairing in ^{14,15}C ?
Other cases needed to conclude
nccomms7743 (2015)

LNS experiment

Super-heavy

Shell energy

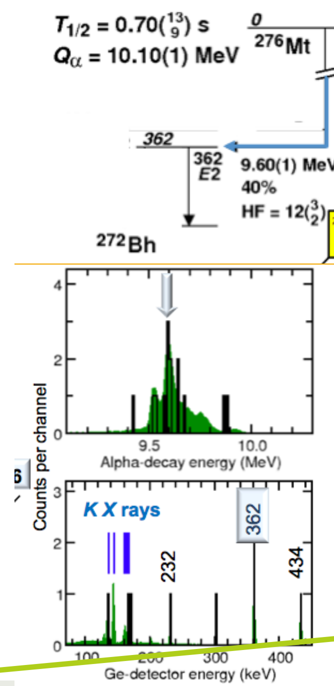




Synthesis ^{48}Ca+^{249}Bk
(Z= 117 fully identified)

PRL 112(2014) 172501
…discovery on 266Lr

Chemistry
(ionization potential)
Nature 520(2015) 209.



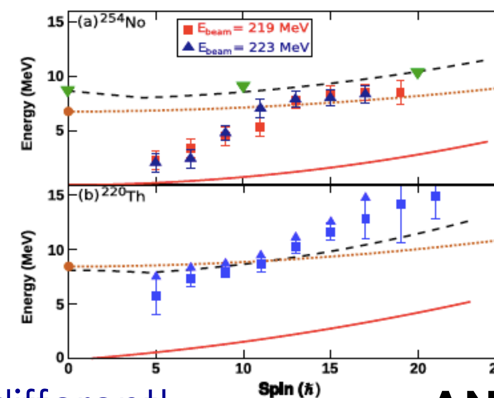
Spectroscopy
of element 115
First leve interpretation
From model
(PRL 111(2013) 112502)

Reactions are studied

Entry point much above yrast !
Fission barrier at 15 h similar to I=0
0.6 MeV different!

How robust are shell in ^{252}No nucleus ?

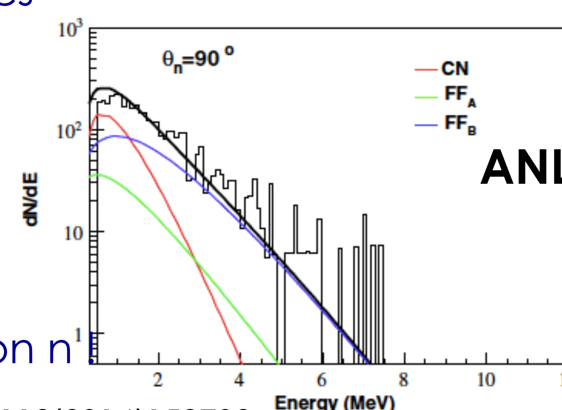
PRL 113(2014) 262505



ANL

Fission dynamics Is needed For super heavy
90% pre-fission n

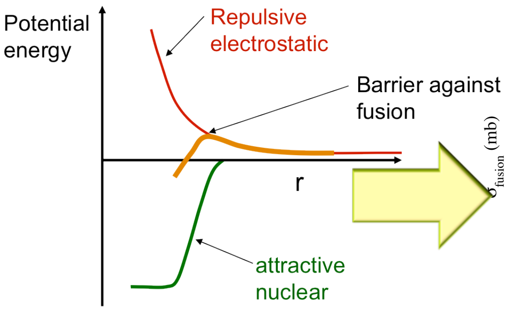
Pre-fission neutron in Z=108

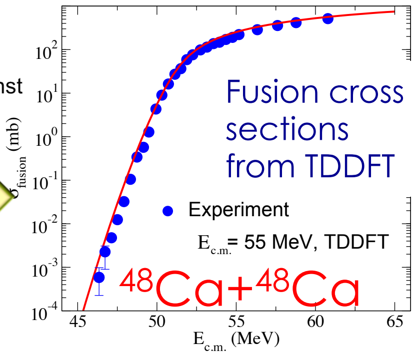


PRL 112(2014)152702 n

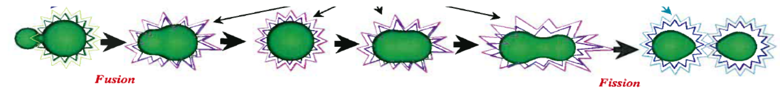
Around the barrier

Reactions   Fusion and fission

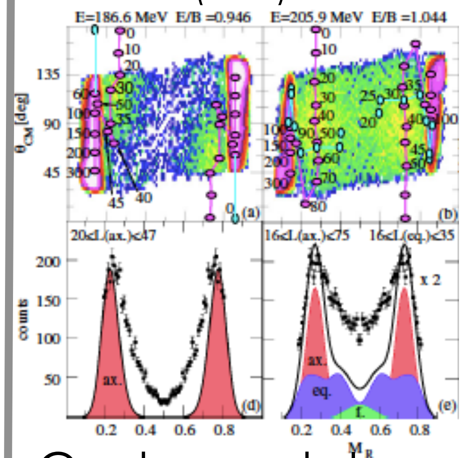




Fusion Hindrance for a Positive-Q-value ^{24}Mg + ^{30}Si
LNL-PRL113(2014)022701



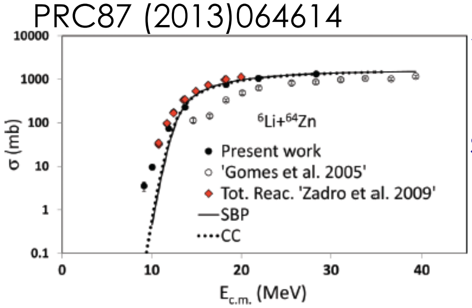
PRL 113(2014)182502



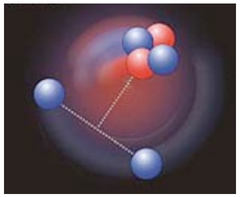
Interplay between orientation of the deformed nucleus and quantum shell

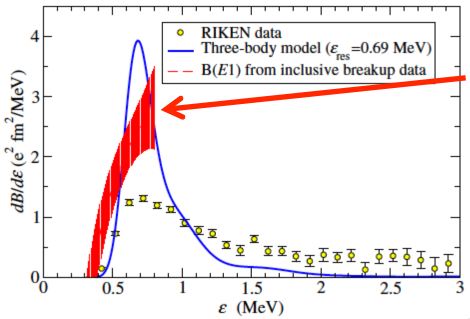
Canberra-data on quasi fission

PRC87 (2013)064614



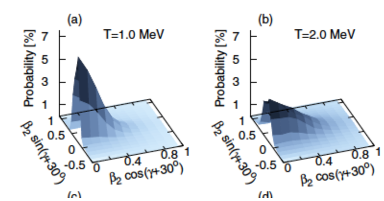
LNS data
Very low- energy
loosely bound and diffuse surface affect the potential
Role of the continuum

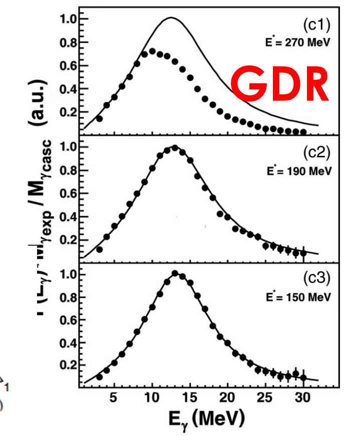




^{11}Li break-up at Coulomb barrier -TRIUMF
(PRL110(2013)142701

Fusion reaction and structure at finite T - LNS
PRC90(2014) 054603

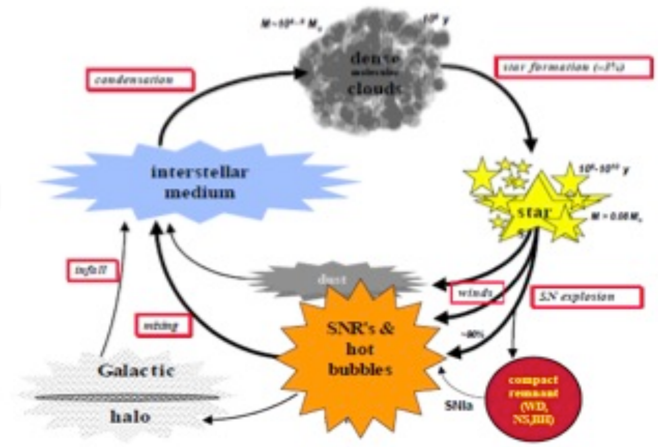


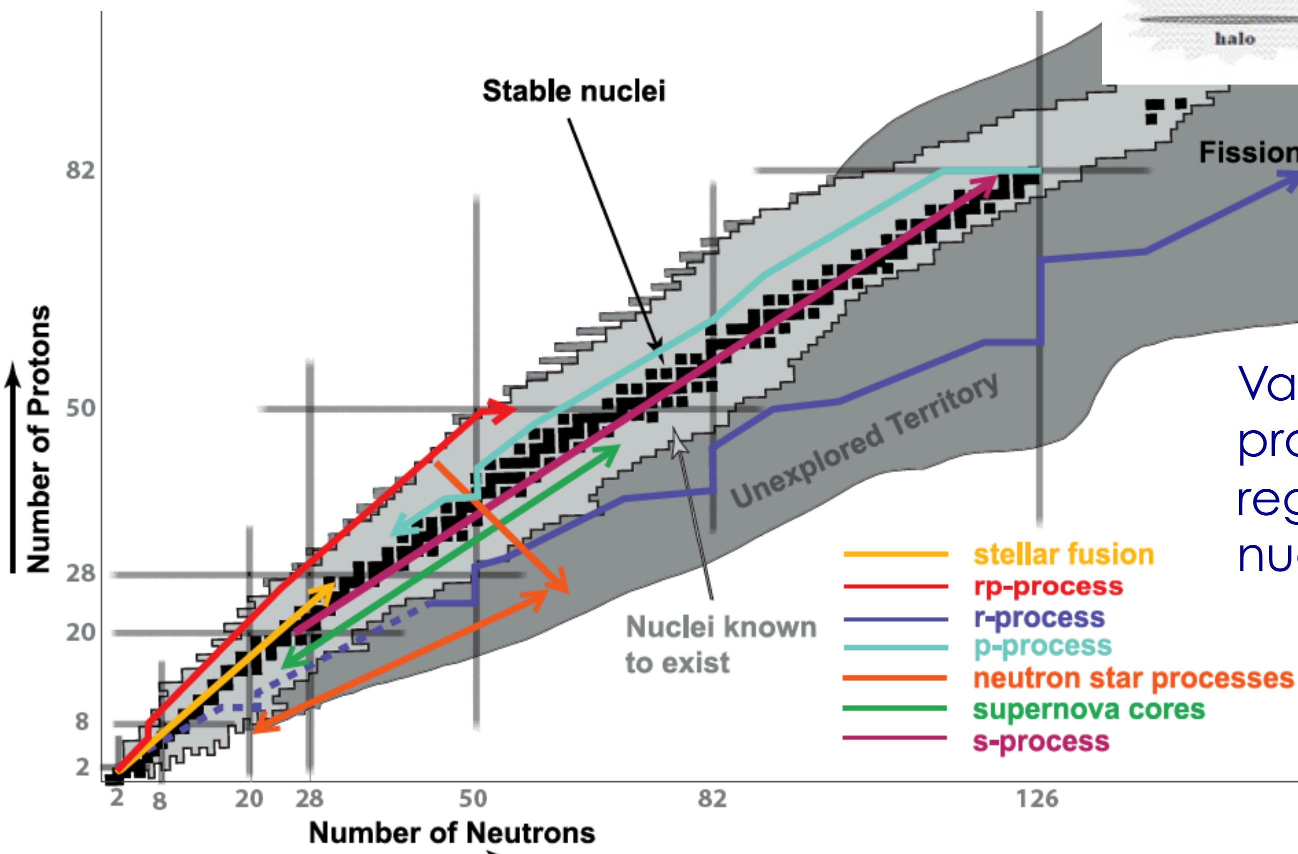


Nuclear landscape and nucleosynthesis

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

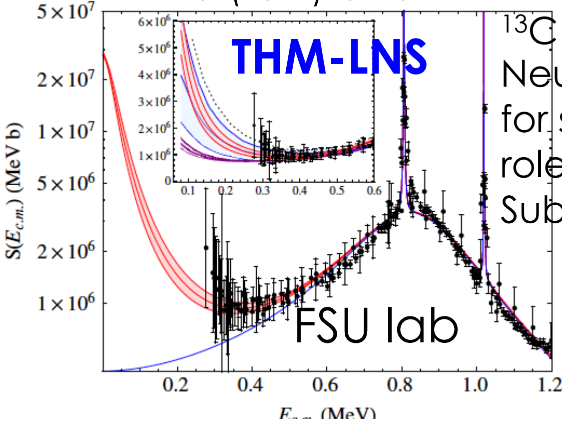




Variuos nucleo-synthesis processes in different regions of the nucleal chart !

Reactions - Cross section measurements for astrophysics

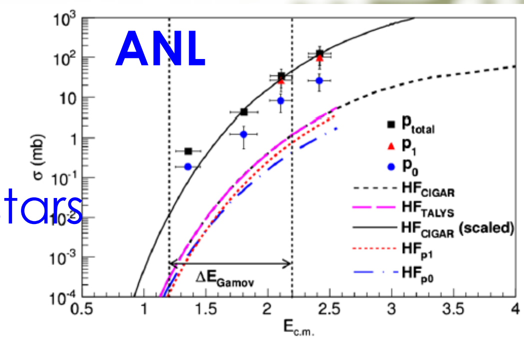
PRL 109(2012)232701



$^{13}C(\alpha,n)^{16}O$
Neutron source for s process
role of 3 keV Subthreshold res

Gamma-ray astronomy
Production of ^{26}Al in massive stars

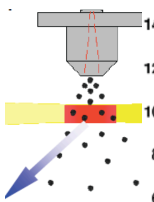
PRL 112(2014) 152701

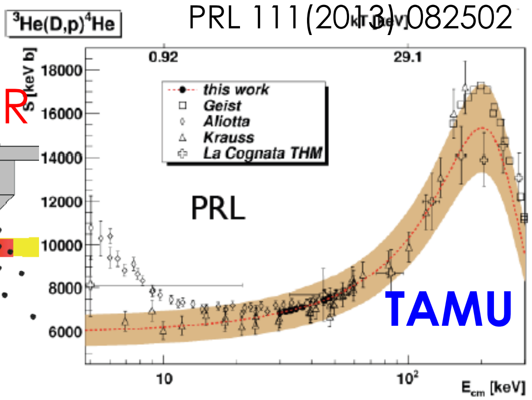


Data= previous calculation X40

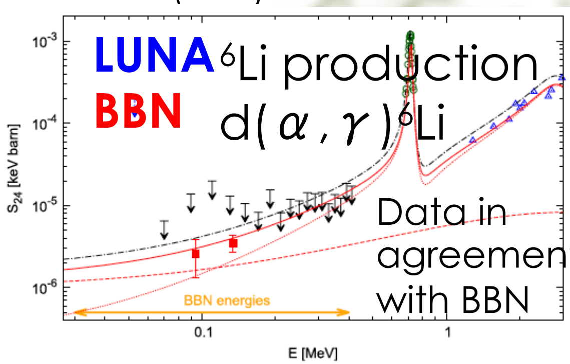
PRL 111(2013)082502

LASER





PRL 113(2014) 042501

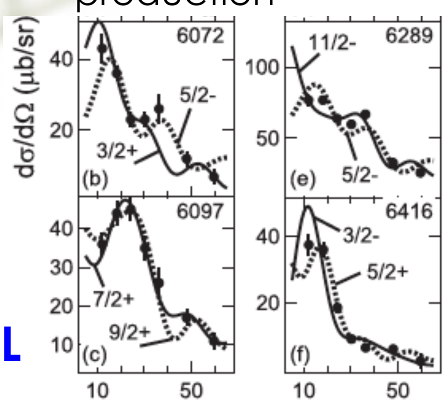


^{6}Li production
$d(\alpha,\gamma)^{6}Li$

Data in agreement with BBN

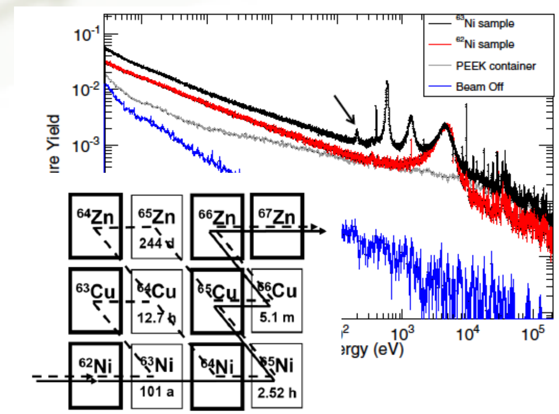
$^{18}F(\alpha,p)^{15}O$
3 new states in ^{19}Ne to exlain rate production

MLL



PRL 110(2013) 032502

n_TOF CERN



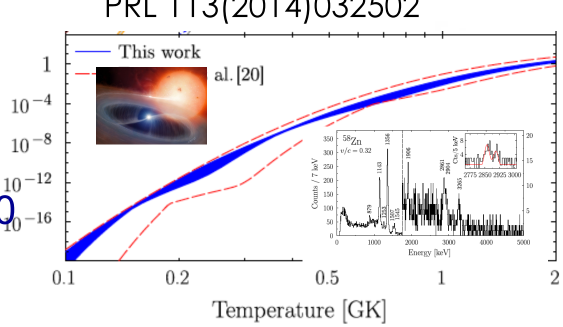
s-process study – isotope ^{67}Zn abundance

measurements for astrophysics – via γ-ray spectroscopy

MSU-GRETINA

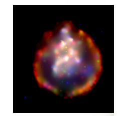
X-ray burst – the *rp* process

PRL 113(2014)032502

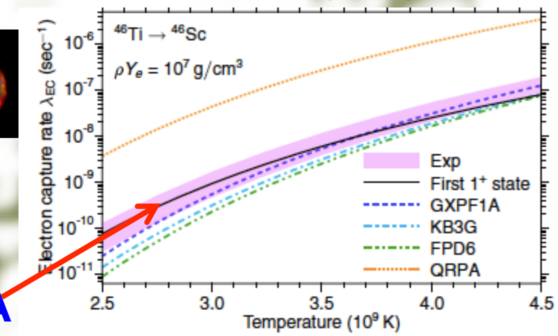


$^{57}Cu(p,\gamma)^{58}Zn$ among TOP 20 reactions

Core-collapse (Type II) Supernovae e-capture dominated by GT



PRL 112(2014) 252501

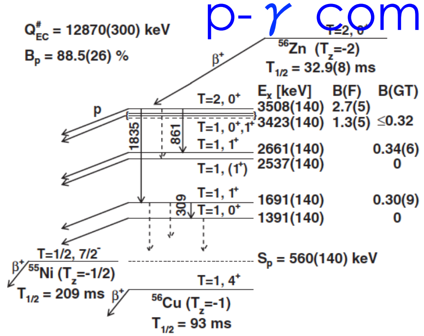


MSU-GRETINA

PRL 112(2014) 222501

GANIL

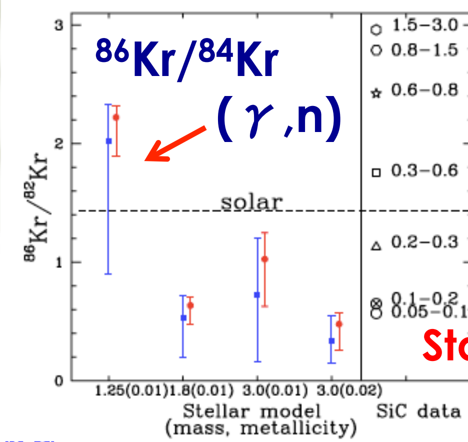
β-delay p-γ competition



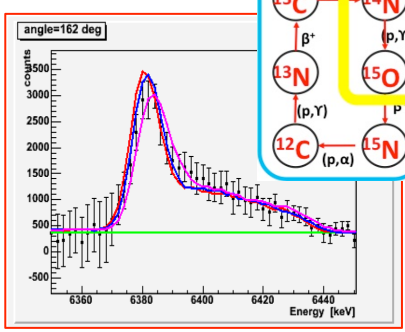
for s-process branching at ^{85}Kr

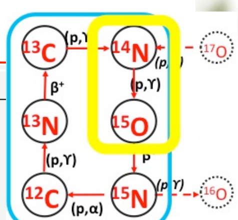
Hiγs lab.

PRL 111(2013)112501



Star dust



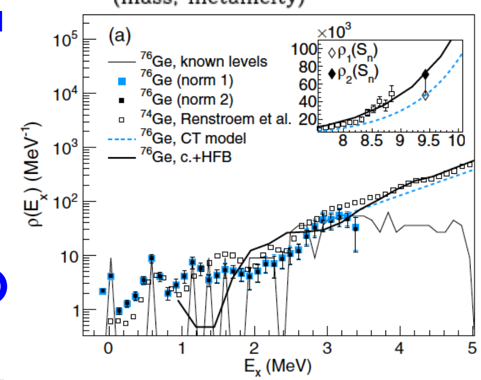


LNL – AGATA

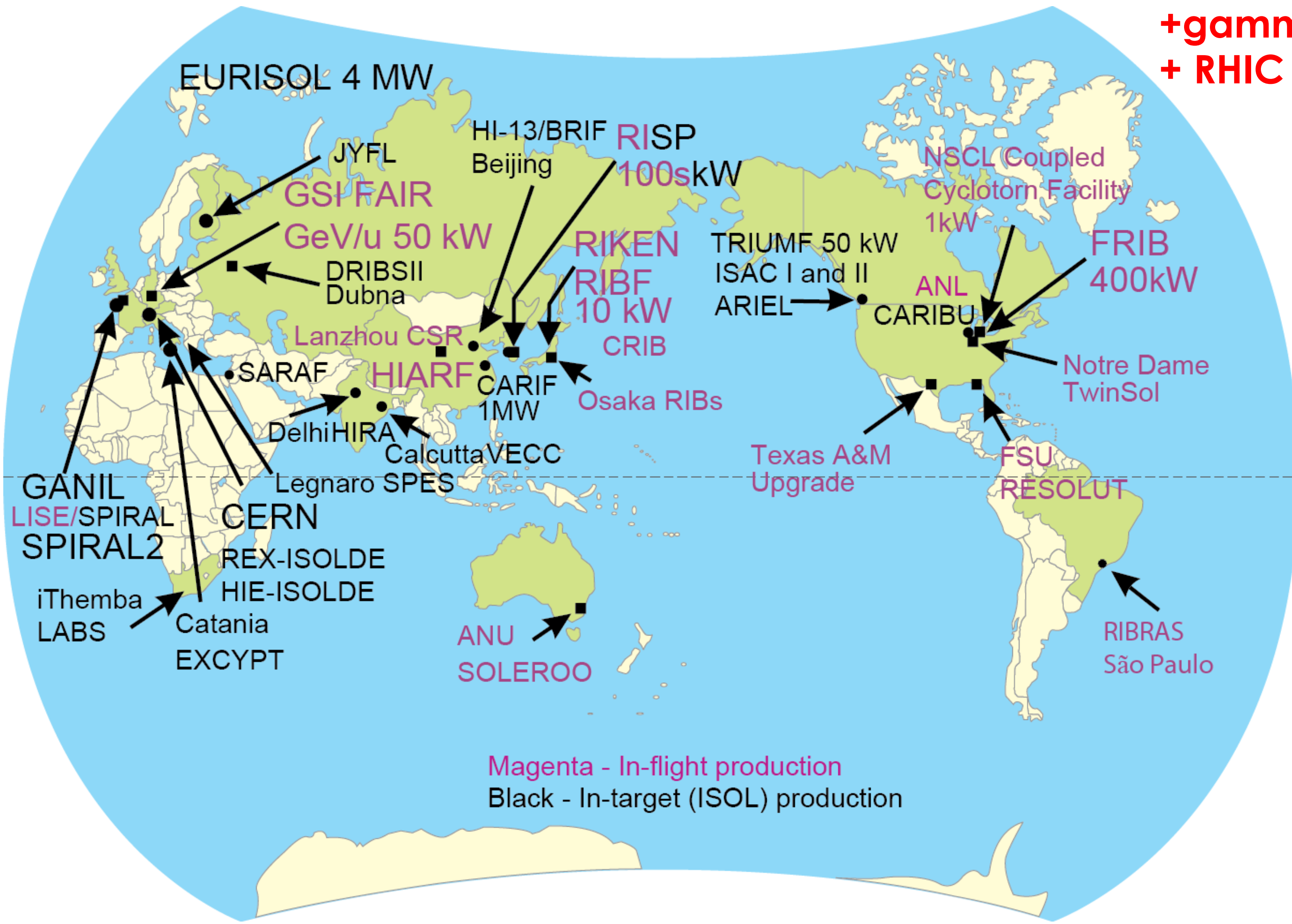
Lifetime γ-ray for bottleneck reaction in CNO

Level density and gamma strength for r- and s - processes

OSLO



Nuclear Physics Laboratories around the world



Major upgrades and new facilities are under construction!

LNL : SPES- CYCLOTRON
for the production of radioactive beams

Main Parameters	
Accelerator Type	Cyclotron AVF 4 sectors
Particle	**Protons (H^- accelerated)**
Energy	**Variable within 30-70 MeV**
Max Current Accelerated	**750 µA** (52 kW max beam power)
Available Beams	**2 beams at the same energy** (upgrade to different energies)
Max Magnetic Field	1.6 Tesla
RF frequency	56 MHz, 4th harmonic mode
Ion Source	Multicusp H^- I=15 mA, Axial Injection
Dimensions	Φ=4.5 m, h=1.5 m
Weight	150 tons

Cyclotron assembled and operated with 700 µA at 1MeV

Applications: in many fields

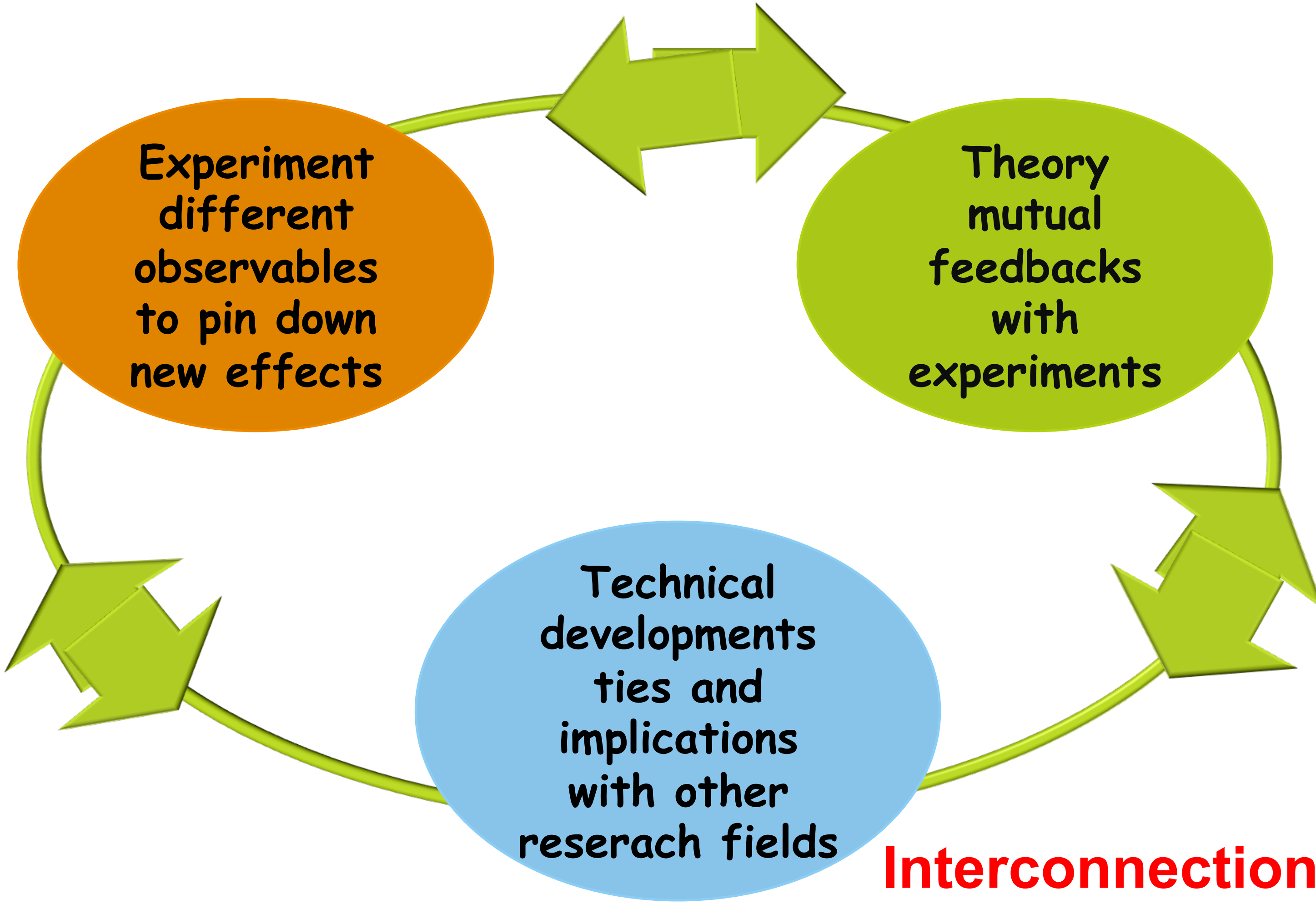
NuPECC Report

Applications in medicine get a great attention

^{149}Tb: targeted alpha therapy. 2014 tests establishing safe usability limits, e.g. kidney damage

^{155}Tb: Very promising results about the effect of Auger electrons for therapy.

Efforts in different directions



Interconnections and mutual inspiration

Final concluding remarks

**My presentation addresses only few of the interesting results
Apologies…. Hope a flavor is givem for a very lively field!!**

For this week we are looking forward for:

- **Presentations of the interesting ongoing work**
- **Discussions for the future plans**
- **Active participation of students and young researchers**

Many thanks to the organizers

and enjoy the NN2015 conference!!!