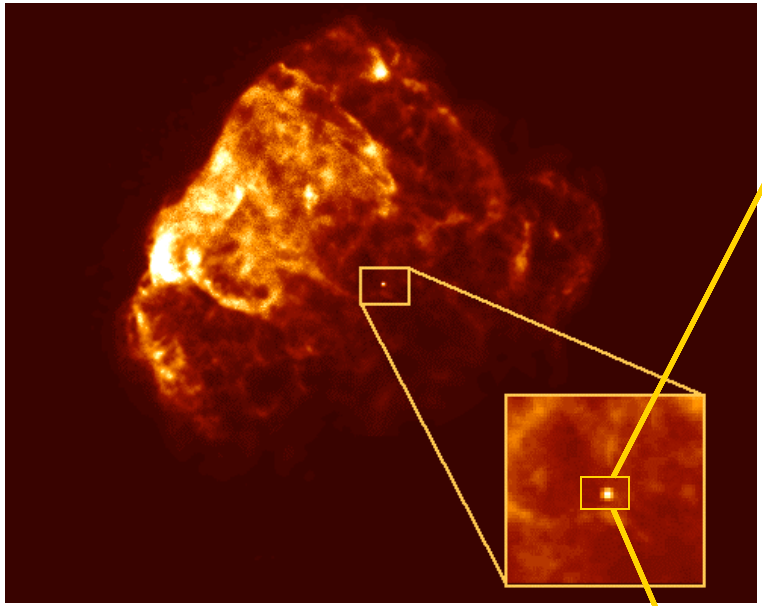
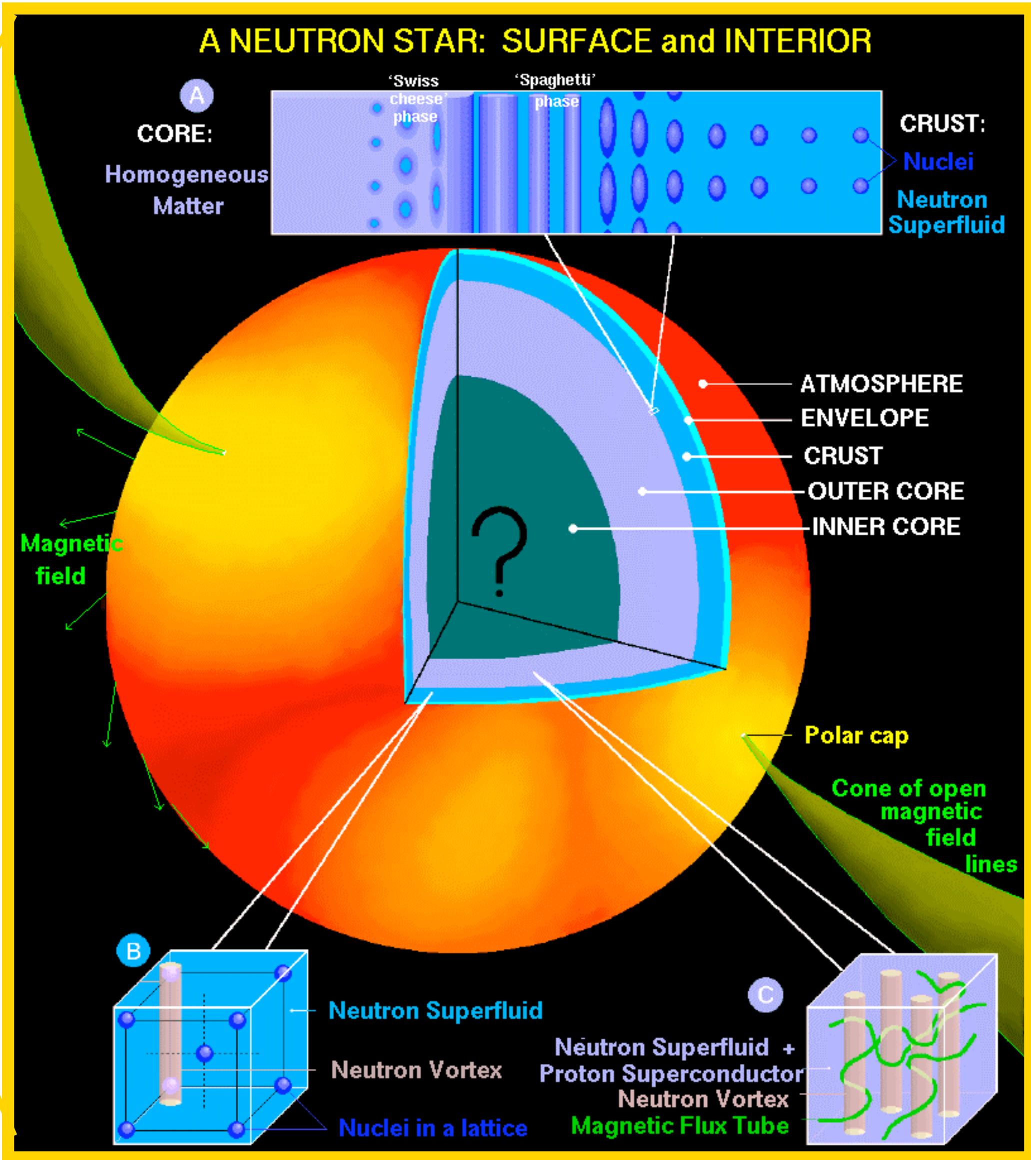
Are there nuclear stucture experiment relevant for neutron stars physics ?





E. Khan

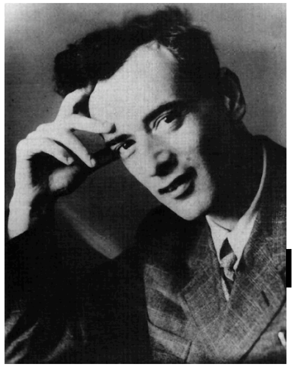
Roadmap

1) Structure of a NS (EOS)

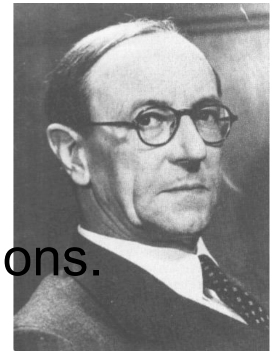
2) Cooling of the NS (Superfluidity, exotic nuclei)

3) Nucleosynthesis in a NS (dripline, E1 strength)

1) Structure of a neutron star



Why Neutron stars ?



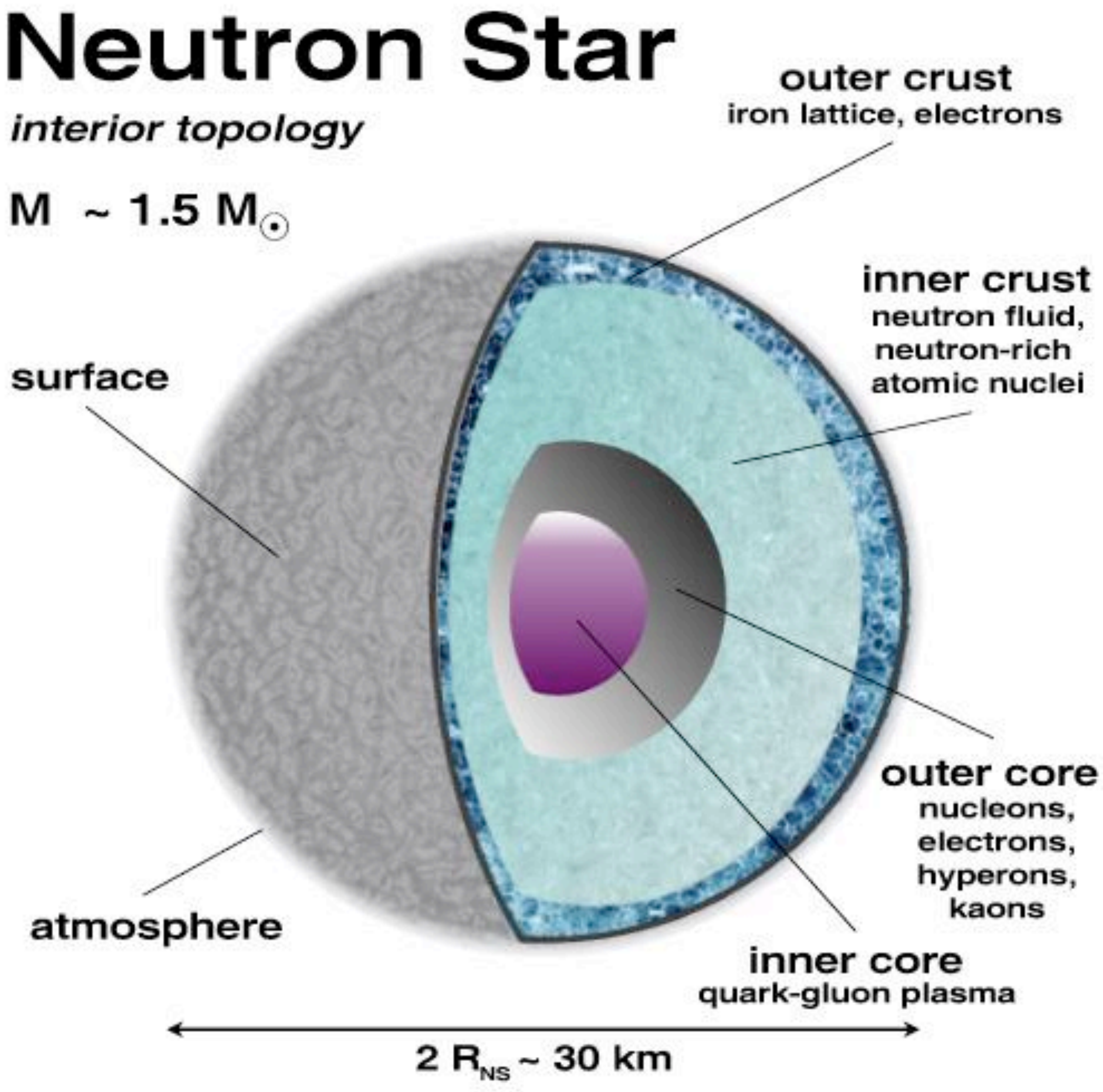
It is the stars, The stars above us govern our conditions.
King Lear

- Landau (1932) : compact object held by the gravity
- Remnant of a core-collapse supernova

- Densiest « active » object (star) of the Universe : emits radio, visible, X, Gamma rays …
- **Pulsars** (1968), **binaries**, **magnetars** (10^{11} T)

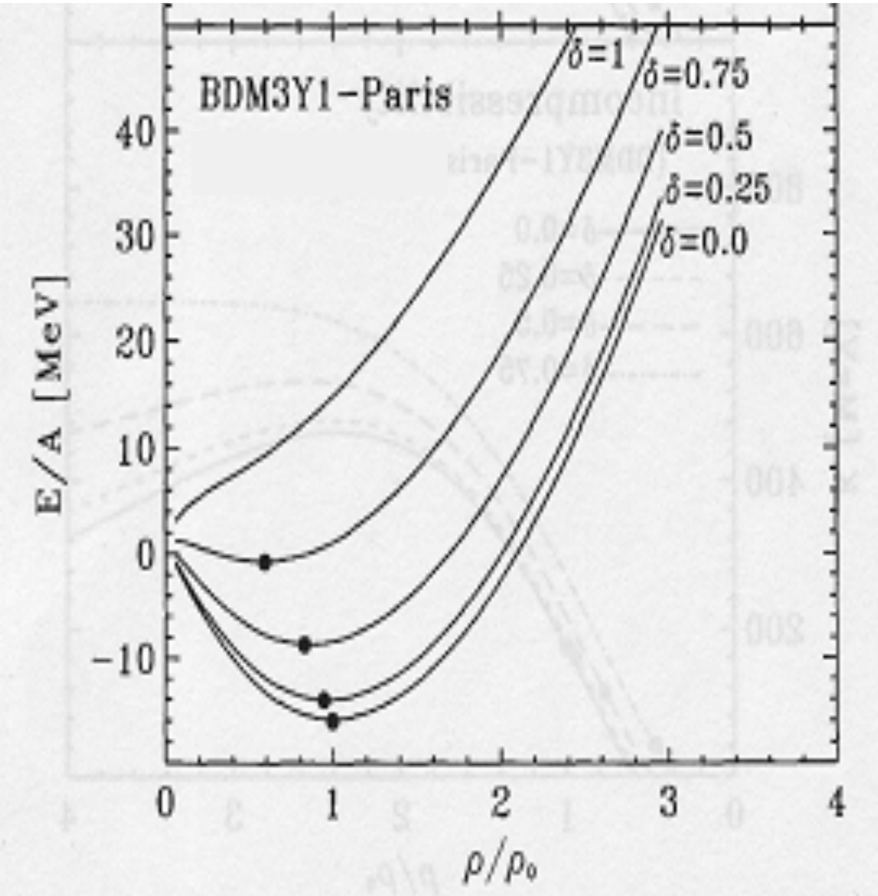
•May be a site for the **r-process**
the acceleration of **ultra high energy cosmic rays** (10^{20} eV)
GRB, …

Anatomy


Neutron Star
interior topology
M ~ 1.5 M☉
outer crust
iron lattice, electrons
inner crust
neutron fluid,
neutron-rich
atomic nuclei
surface
outer core
nucleons,
electrons,
hyperons,
kaons
atmosphere
inner core
quark-gluon plasma
2 R_NS ~ 30 km

Equation of state

$$E(\rho,\delta) = E(\rho,0) + a_{sym}(\rho)\delta^2$$

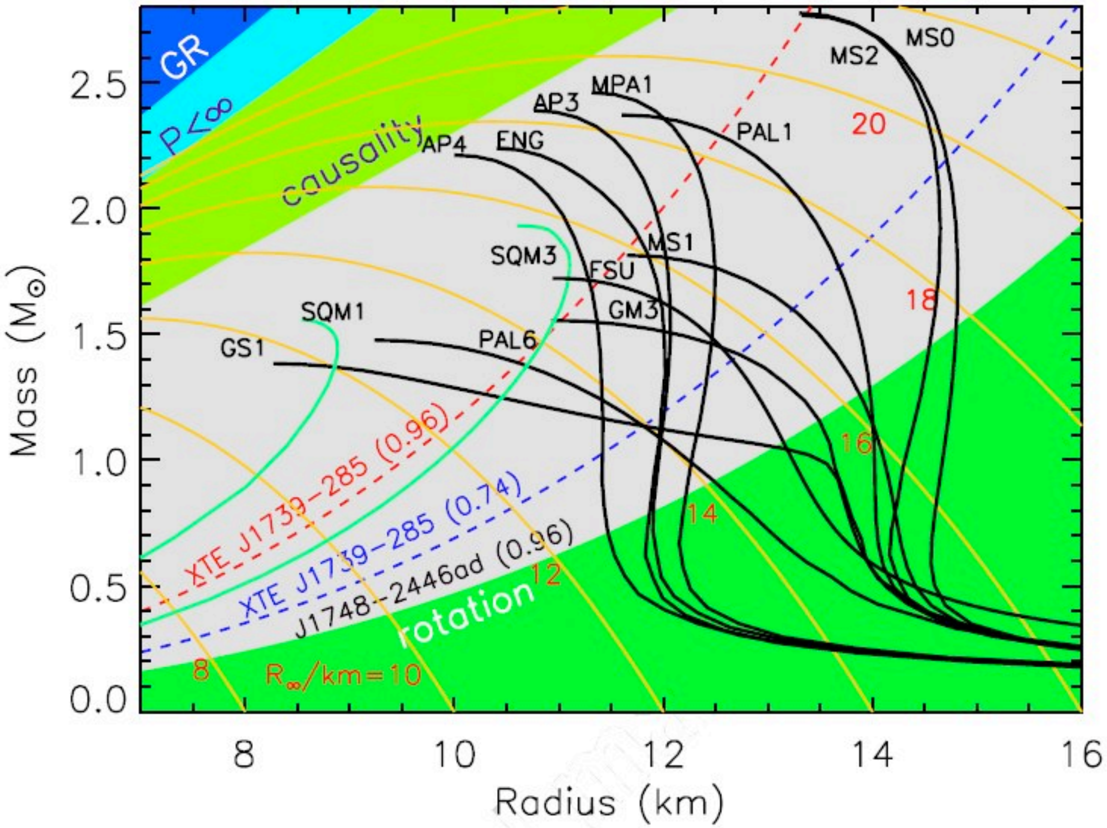


$$\delta = \frac{N-Z}{A}$$

D.T.Khoa *et al.* Nucl. Phys. **A602** (1996) 98

- Densities from $10^{-8}\ \rho_0$ to $3\ \rho_0$
- Isospin asymmetry from 0 to 1

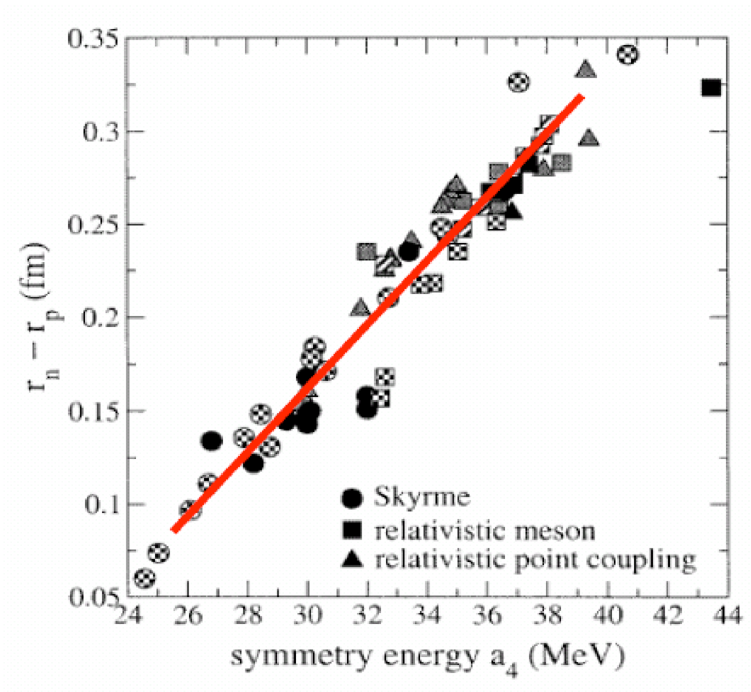
Mass and radius of a neutron star



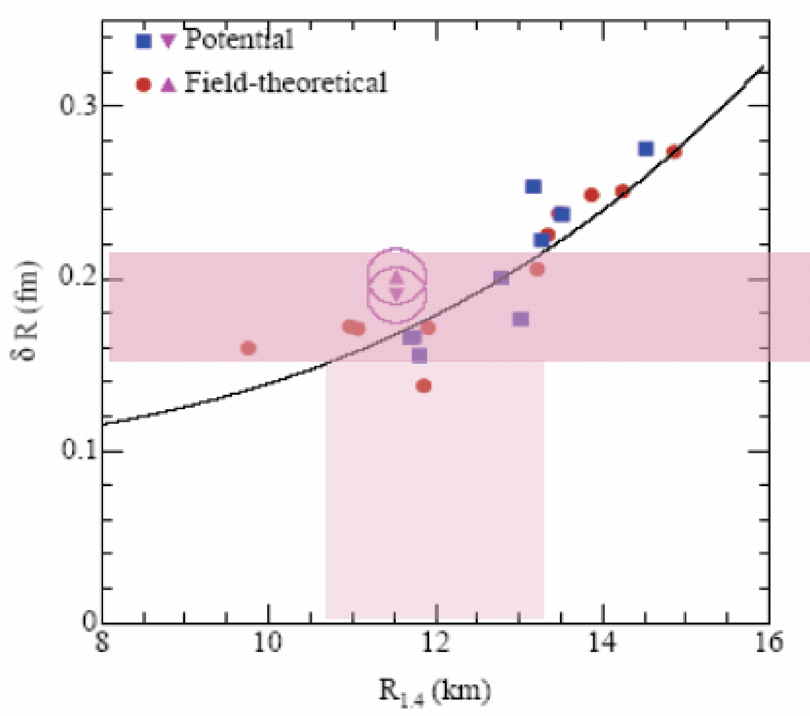
J.M. Lattimer *and M. Prakash.,* Astrop. Jour. **550** (2001) 426

- ~1500 neutrons stars are known
- Typical masse: 1.4 solar mass
- Mass from Kepler law in binary systems (NS+NS)
- Radii from moment of inertia from luminosity and rotation velocity

Neutron skin in ^{208}Pb and symmetry energy

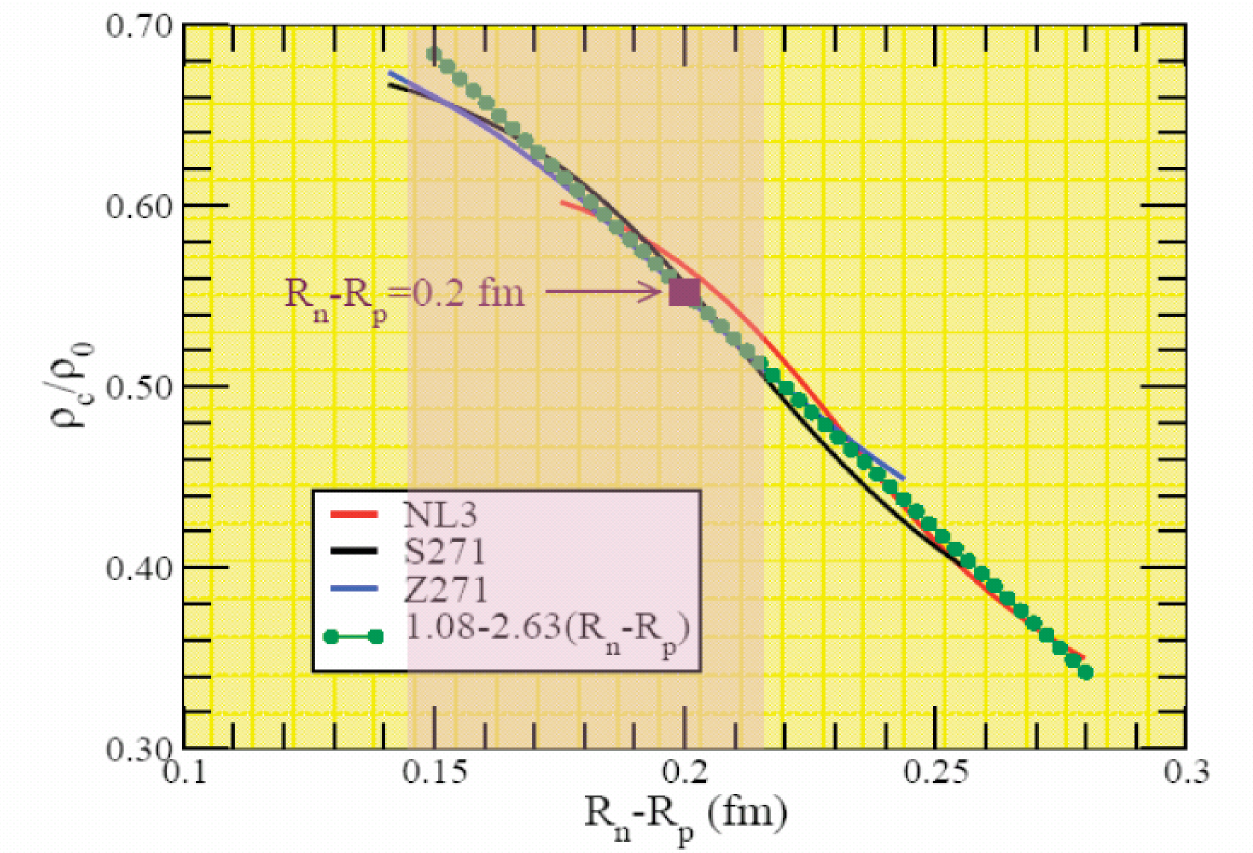


R.J. Furnstahl., NPA. **706** (2002) 85



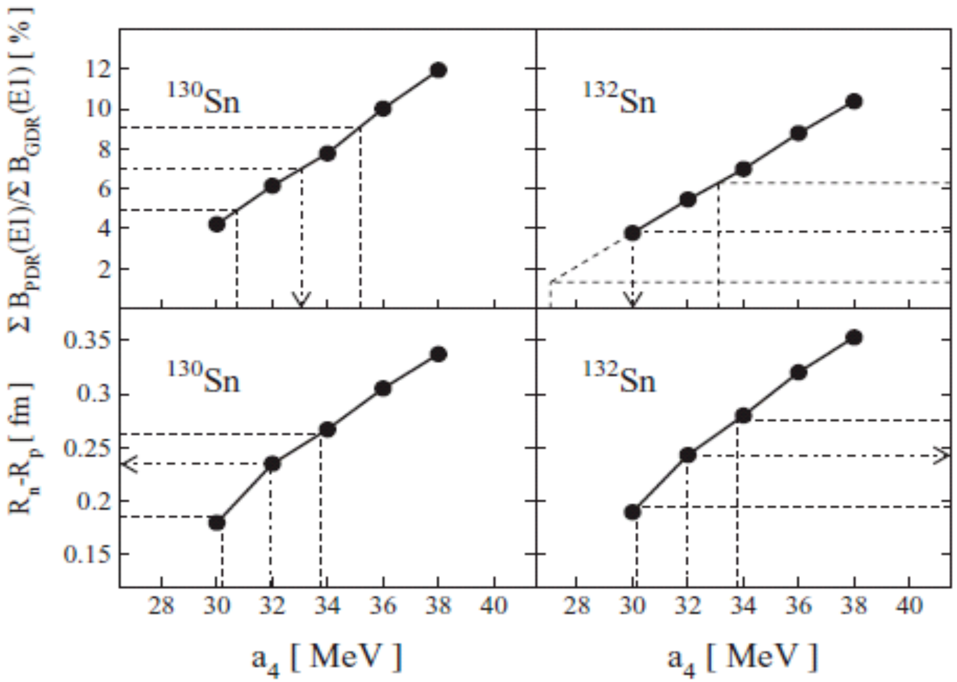
A.W. Steiner et al, Phys. Rep. **411** (2005) 325

Neutron skin in ^{208}Pb and crust



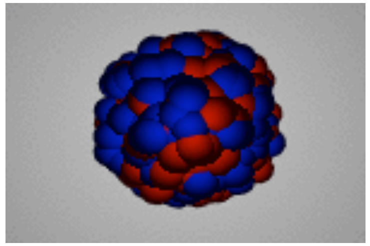
C.J. Horowitz, J. Piekarewicz, Phys. Rev. Lett. **86** (2001) 5647

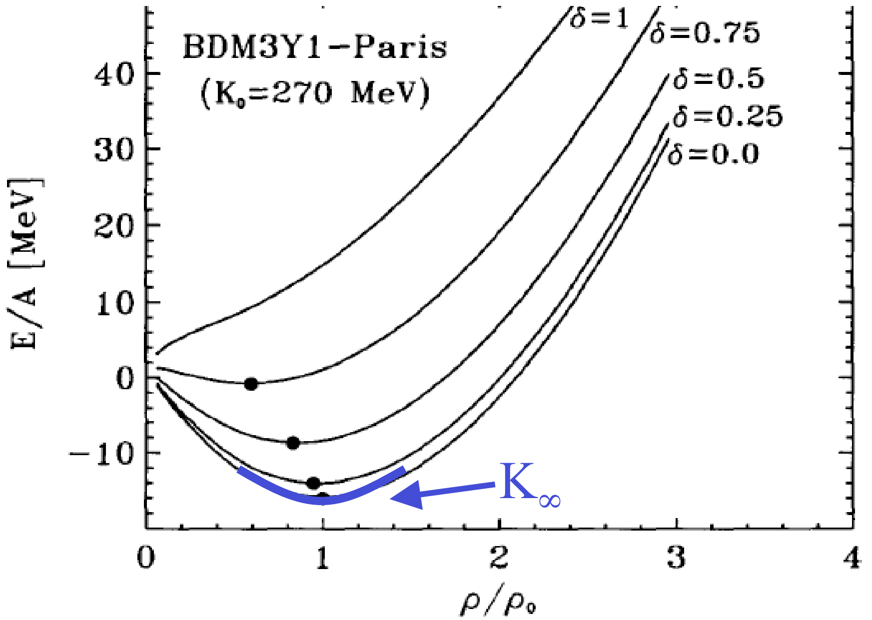
Pygmy modes can help

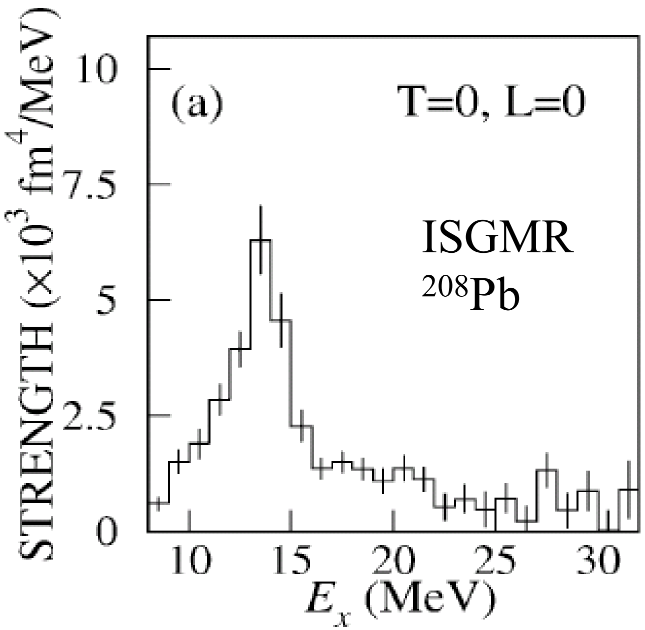


A. Klimkiewicz et al, Phys. Rev. **C76** (2007) 051603(R)

Compression modes in nuclei



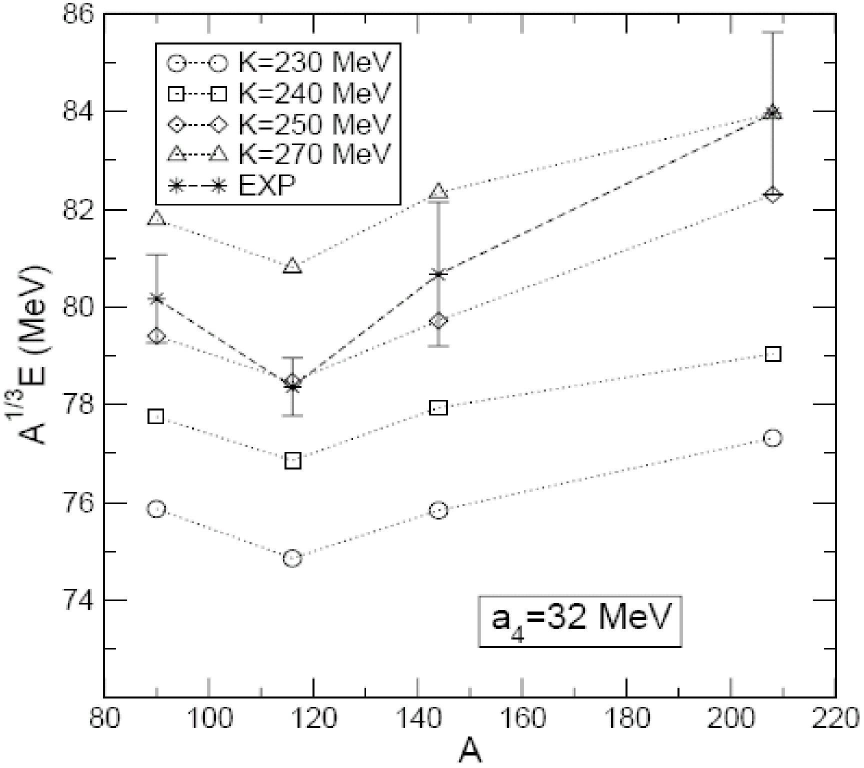




M. Uchida et al., PLB**557**(2003)12

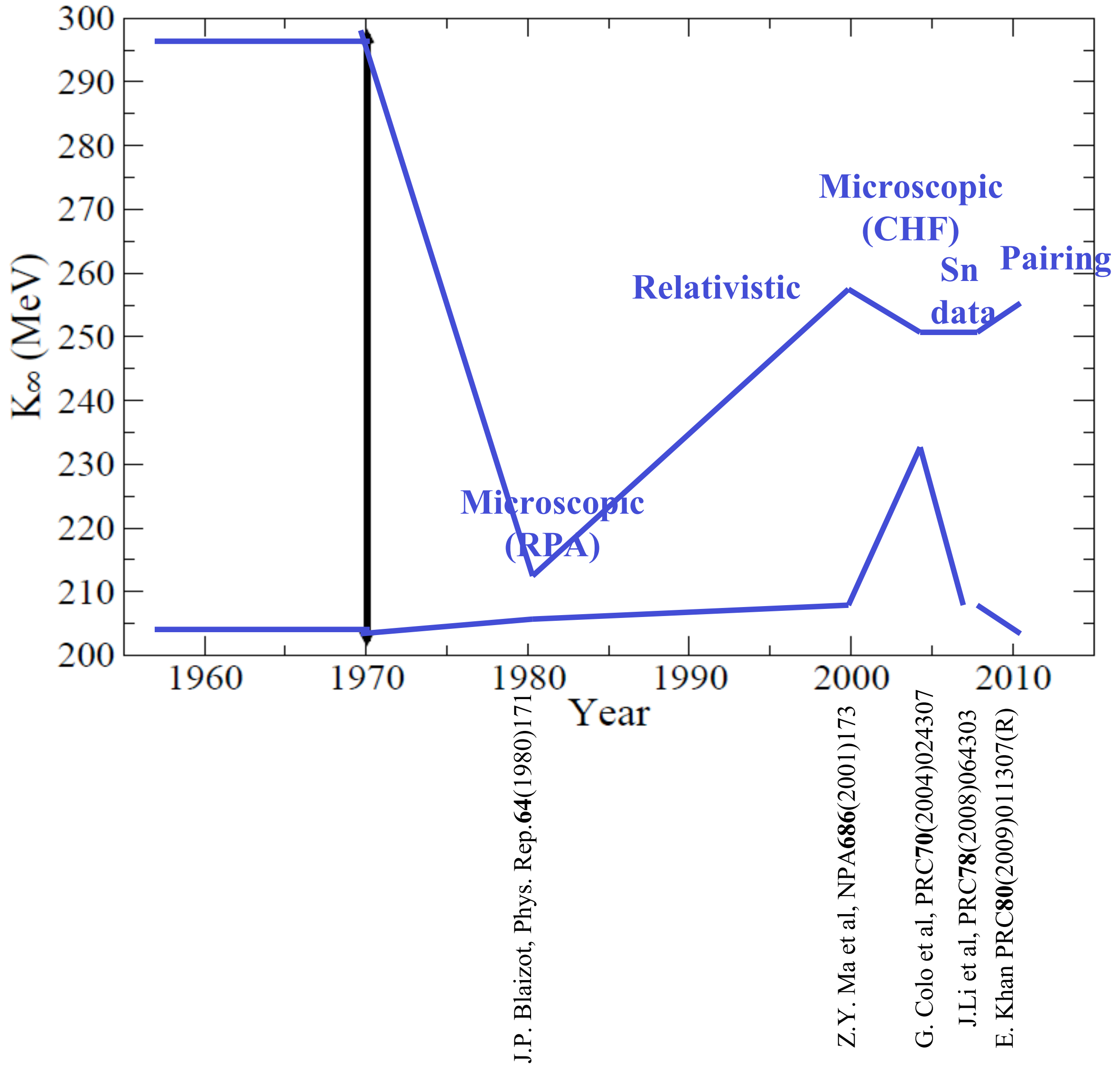
Determination of K_∞

- **Microscopic method**: prediction of the GMR centroid using mean-field approach
- K_∞ from the functionnal describing the GMR data



D. Vretenar et al, PRC**68**(2003)024310

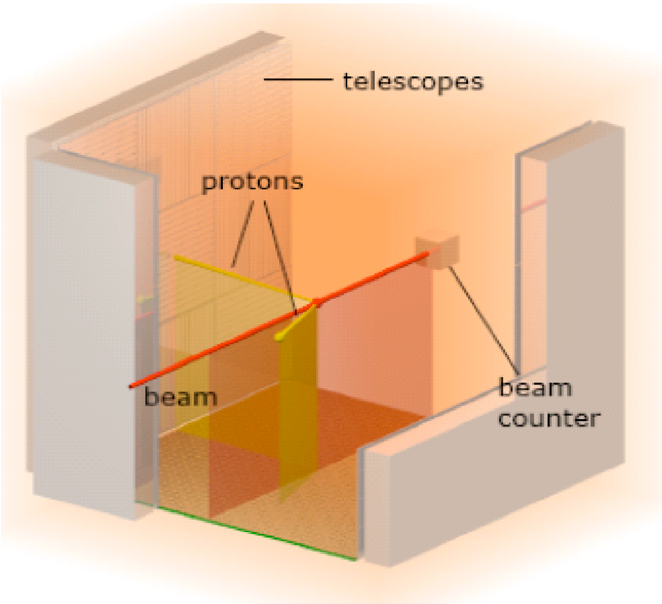
Uncertainties on K_∞

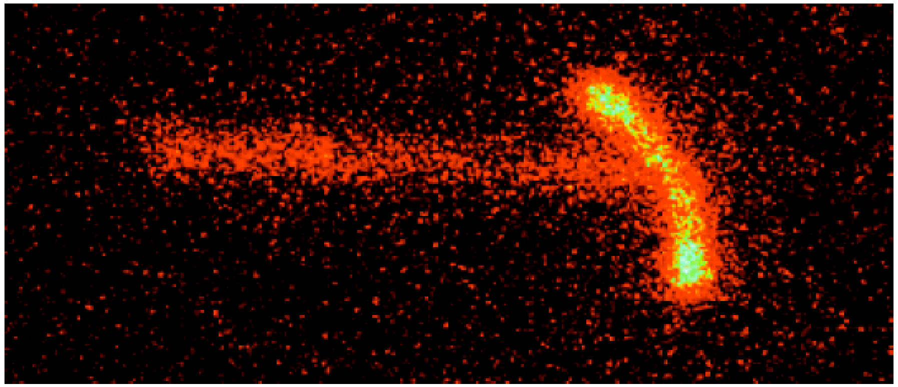


Is the method well defined ?

Physics with active targets

- Low I: closer to the drip-line, resonances, decay
- Low E: GMR   C. Monrozeau et al, Phys. Rev. Lett. **100** (2008) 042501
- TPC: cluster structure, decay





K. Miernik *et al.*, PRL**99**(2007)192501

2) Cooling of a neutron star

Cooling of a neutron star

•The fraction of proton needed depends on the symmetry energy

$$n \rightarrow p + e^- + \overline{\nu_e},$$

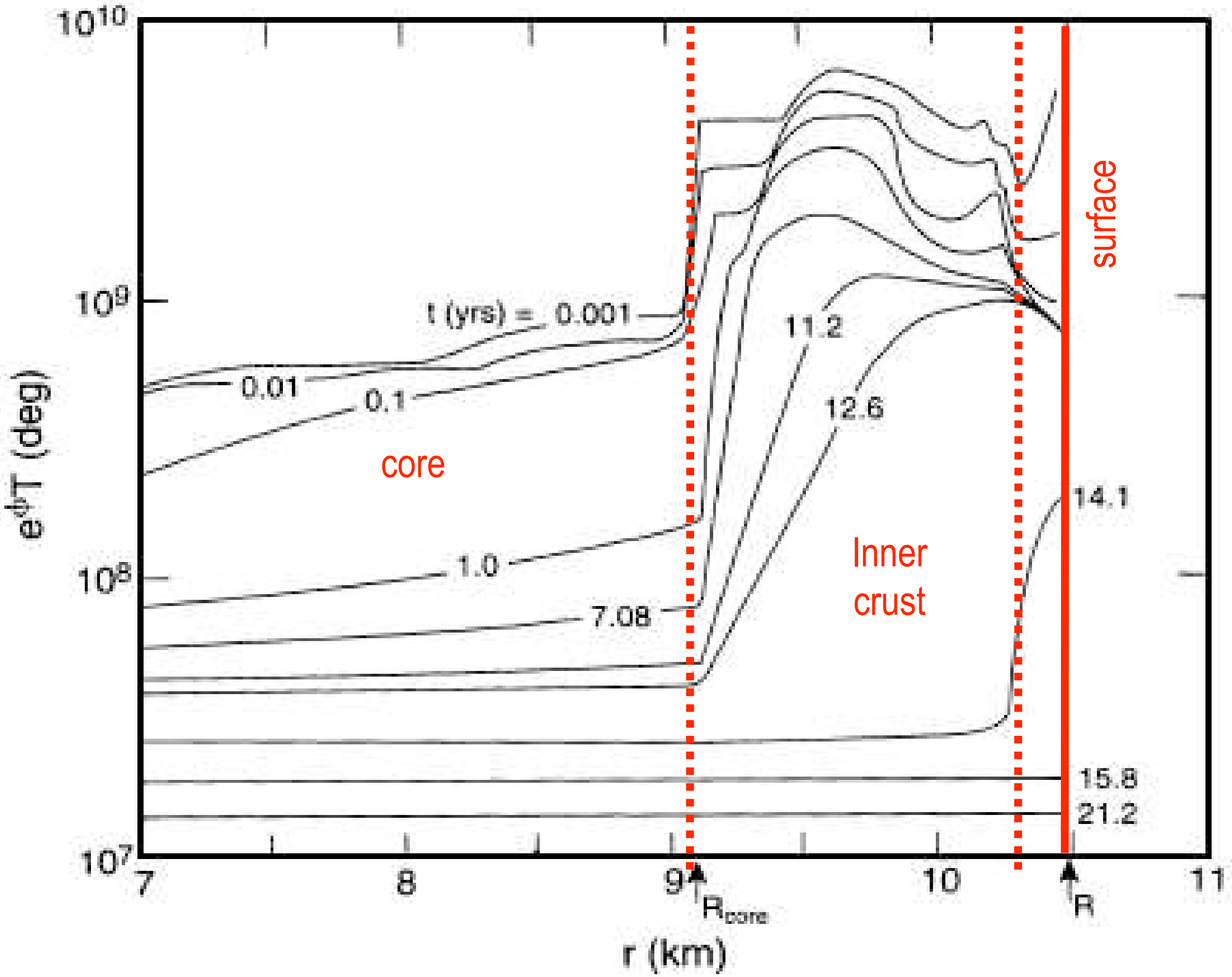
$$e^- + p \rightarrow n + \nu_e.$$

URCA process

$$n + n \rightarrow n + p + e^- + \overline{\nu_e}$$

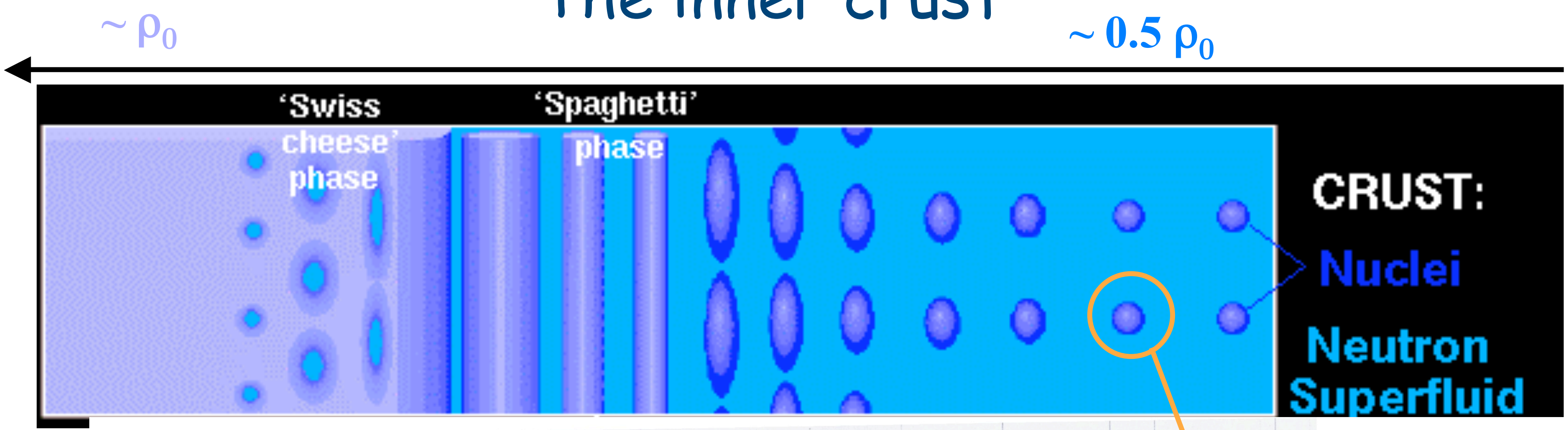
Cooling of a neutron star

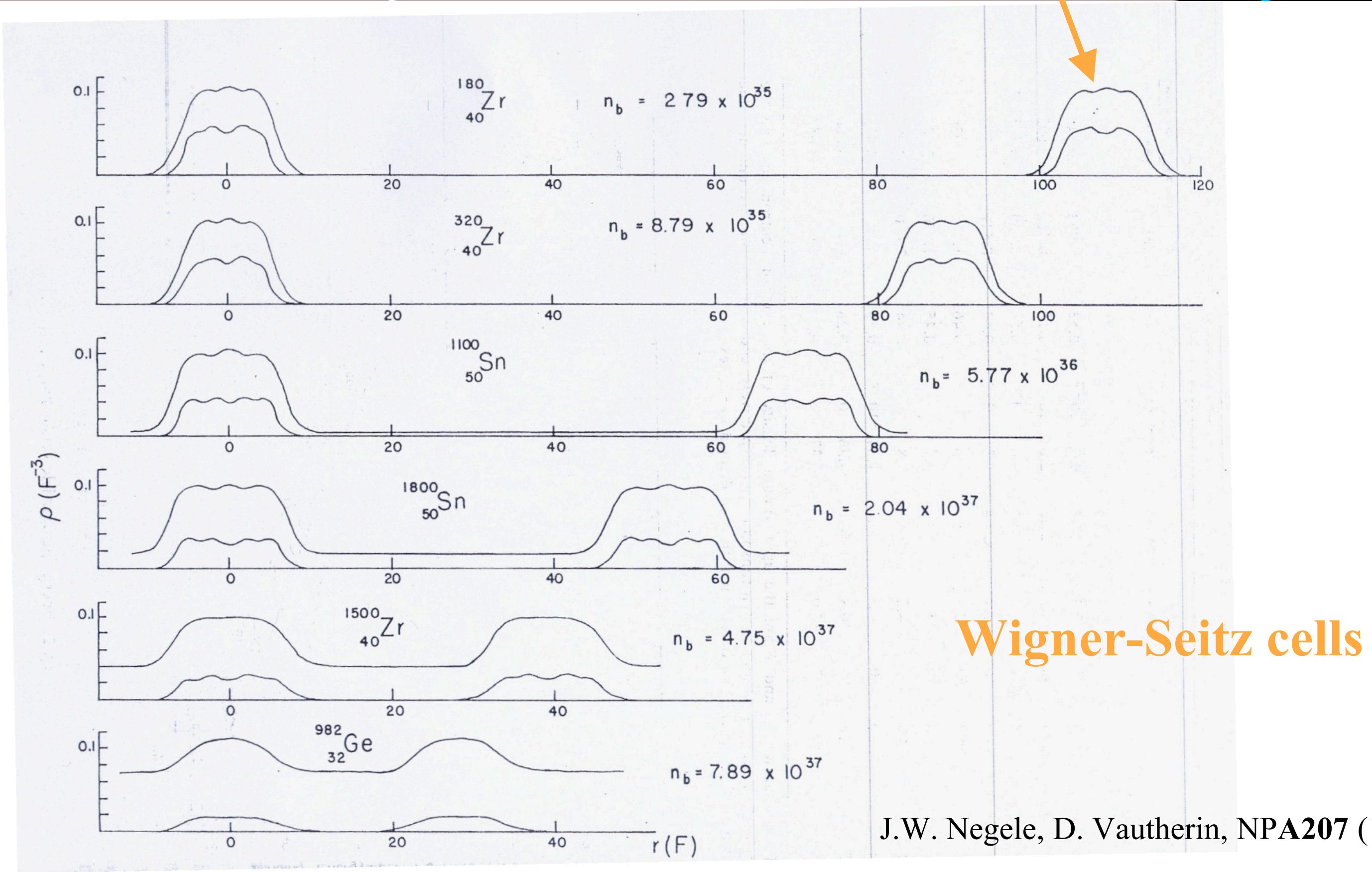
- Cooling time : $t \propto C_V$



J.M. Lattimer *et al.,* Astrop. Jour. **425** (1994) 802

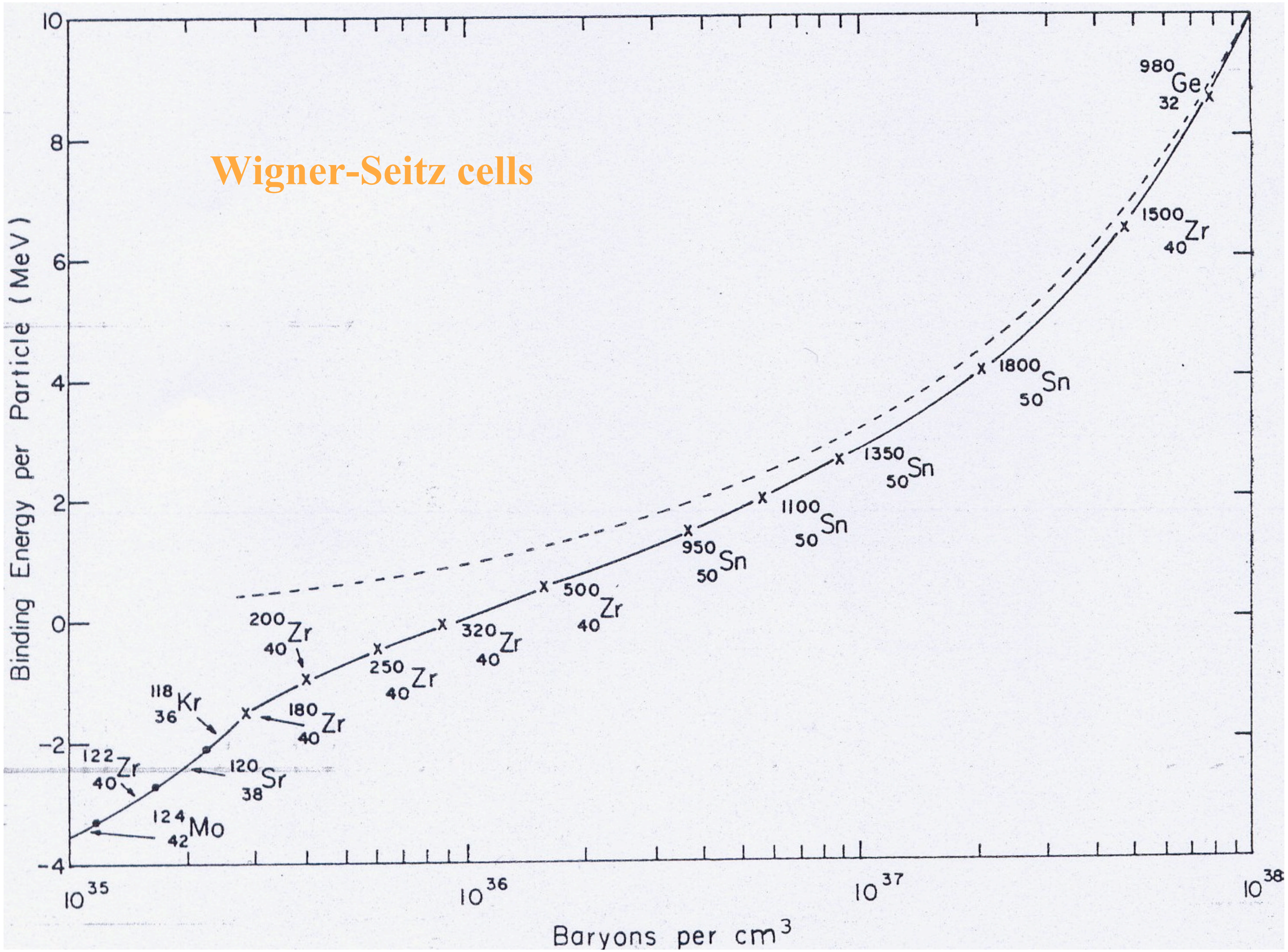
The inner crust



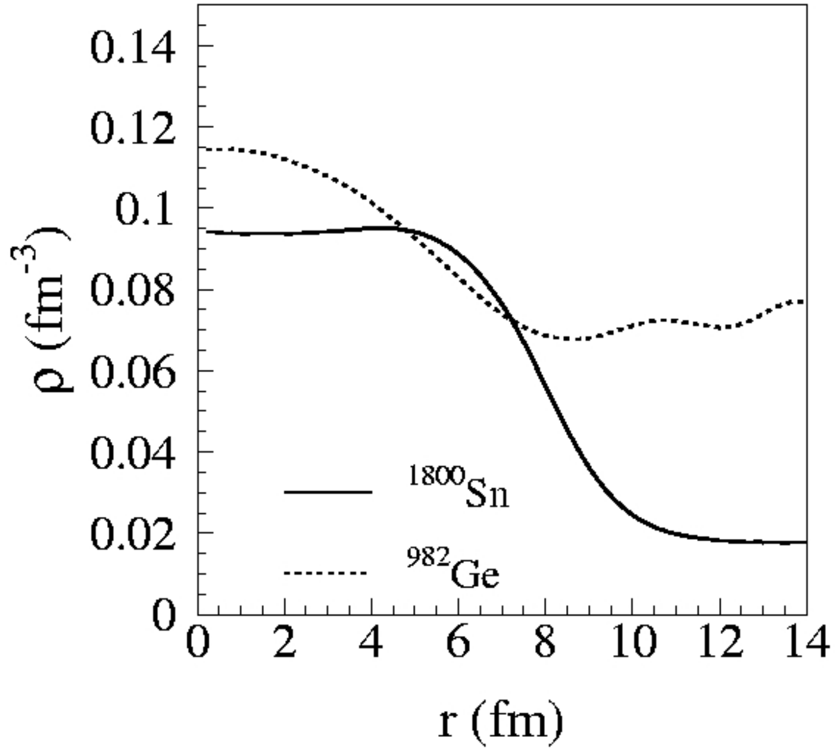


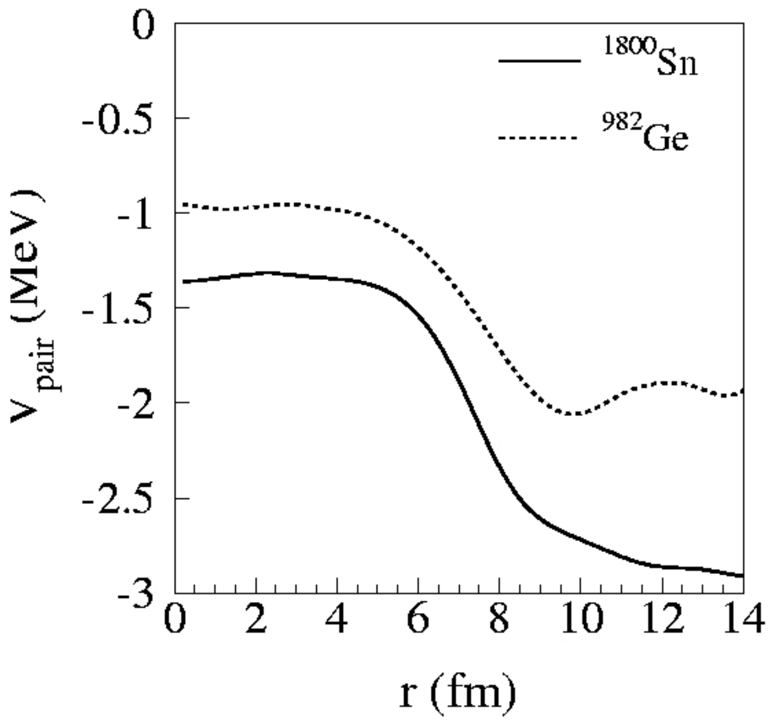
J.W. Negele, D. Vautherin, NP**A207** (1973) 298

Very neutron-rich systems



Pairing in a WS cell



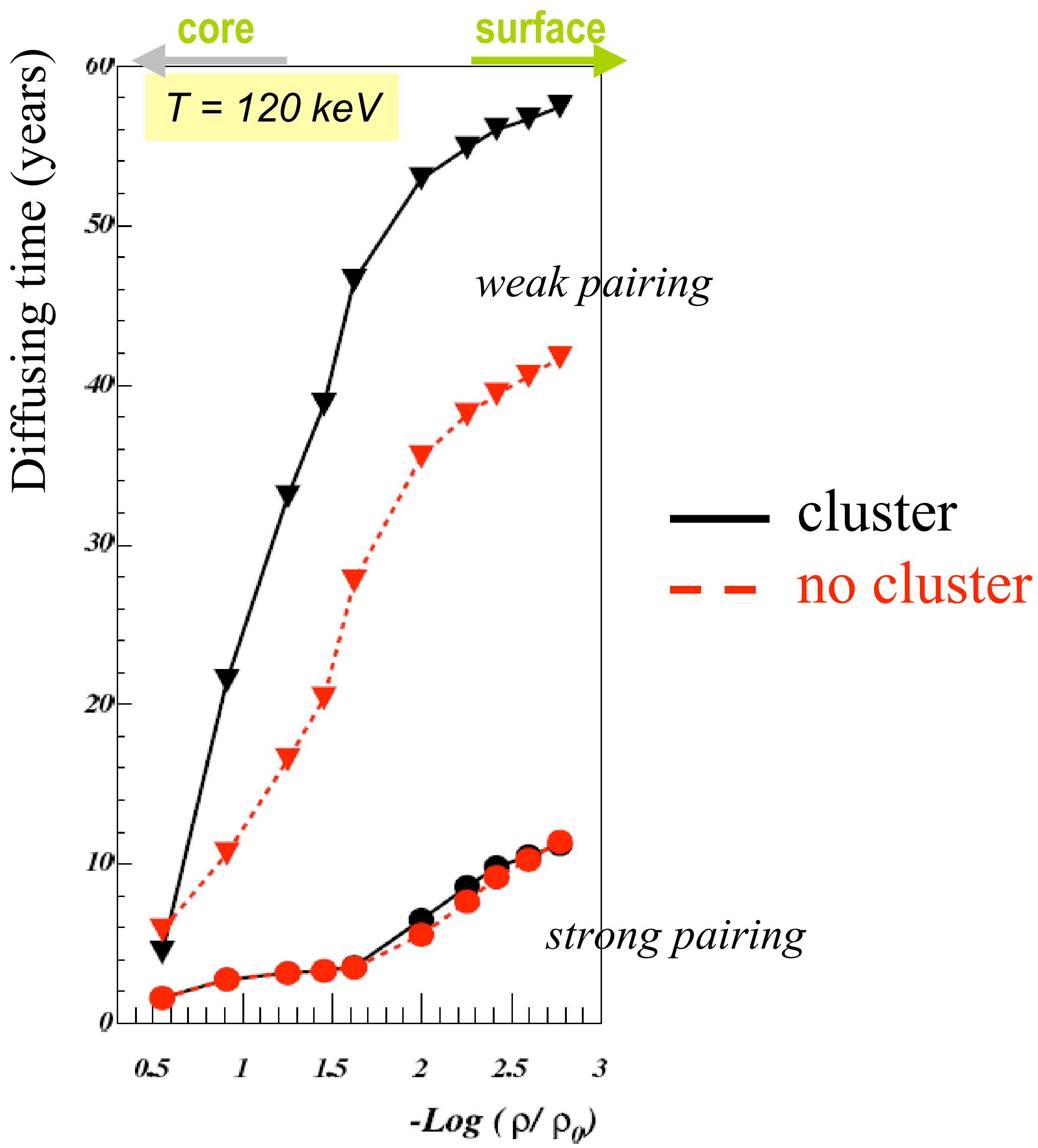


- ^{1800}**Sn** : the pairing field is 2 times larger in the neutron gas than in the cluster
- ^{982}**Ge** : the maximum is located on the cluster surface

N. Sandulescu, PR**C70** (2004) 025801

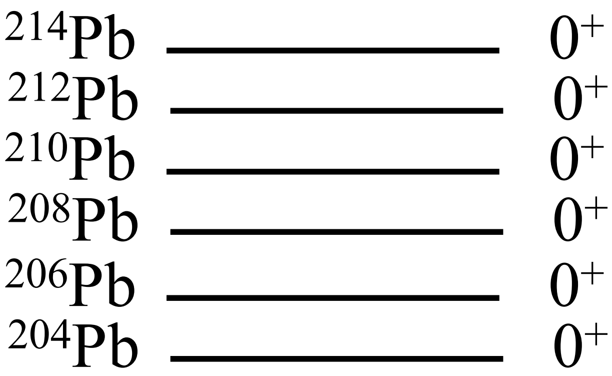
E. Khan, N. Sandulescu, Nguyen Van Giai, PR**C71** (2005) 042801

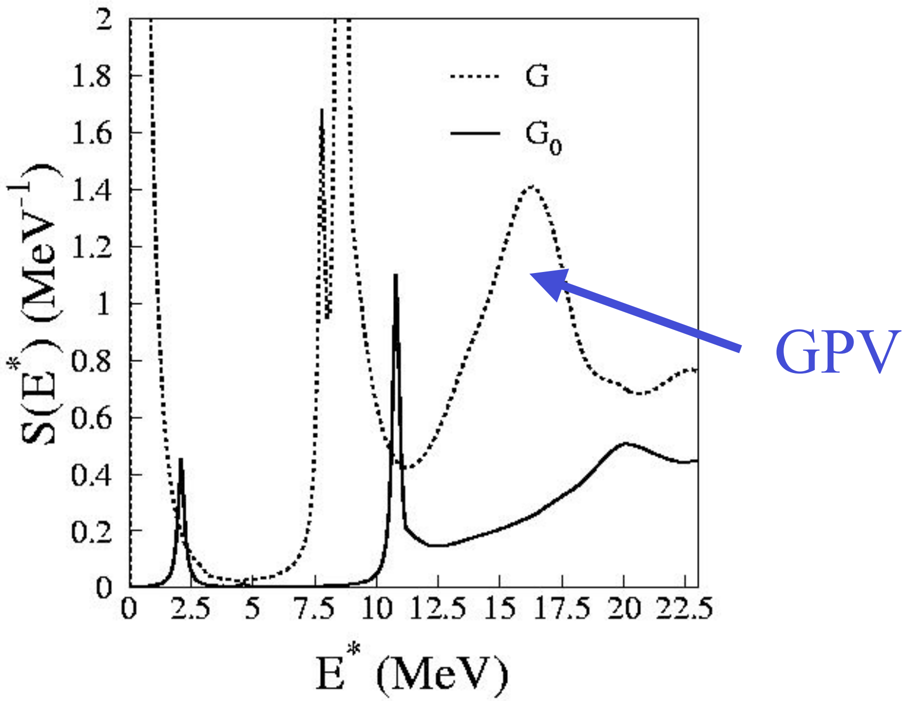
Cooling results



C. Monrozeau, J. Margueron, N. Sandulescu, PR**C75** (2007) 065807

Pairing Vibrations: helps to constrain pairing ?

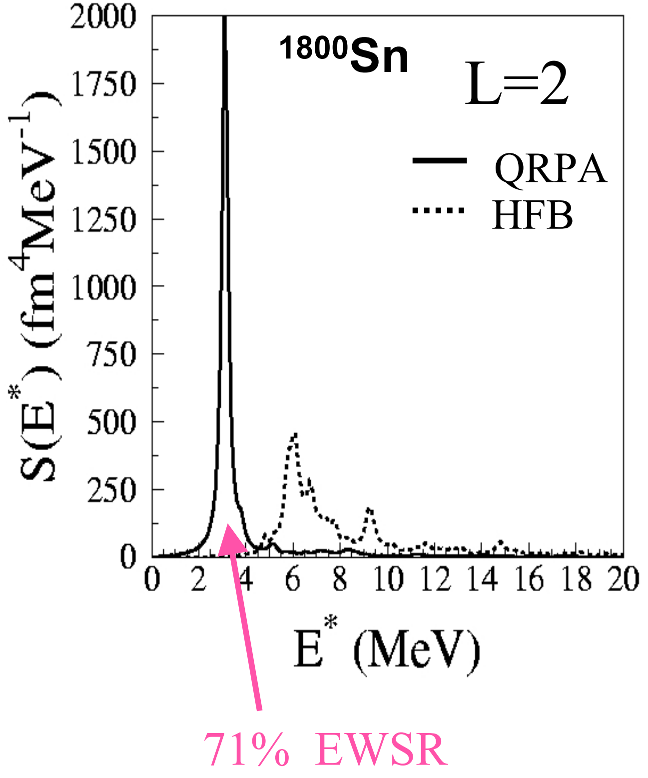


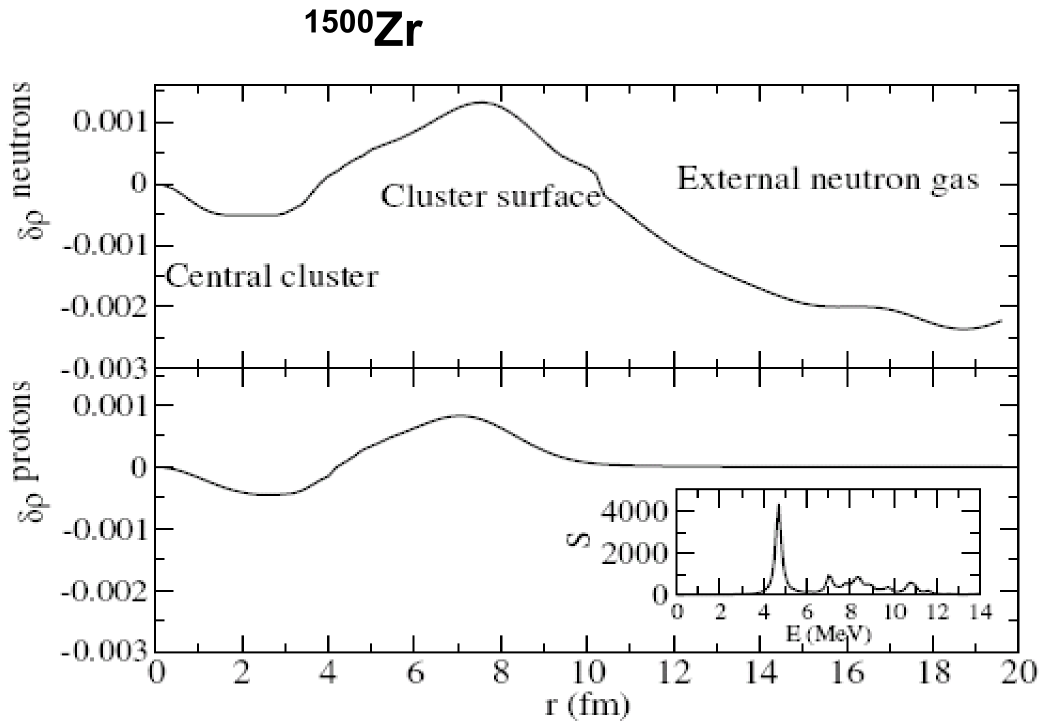


- Two particles 0+ state ~ independent from the remaining part of the nuclei
  → Harmonic vibrations
- Pairing vibrations : L=0, sensitive to the pairing interaction
- Giant Pairing Vibrations : collective mode in the 2n transfer channel analogous to a giant resonance
- Reaction model : 2 particle transfer (sequential, direct, …)

E. Khan, M. Grasso, and J. Margueron, Phys. Rev. C **80**, 044328 (2009)

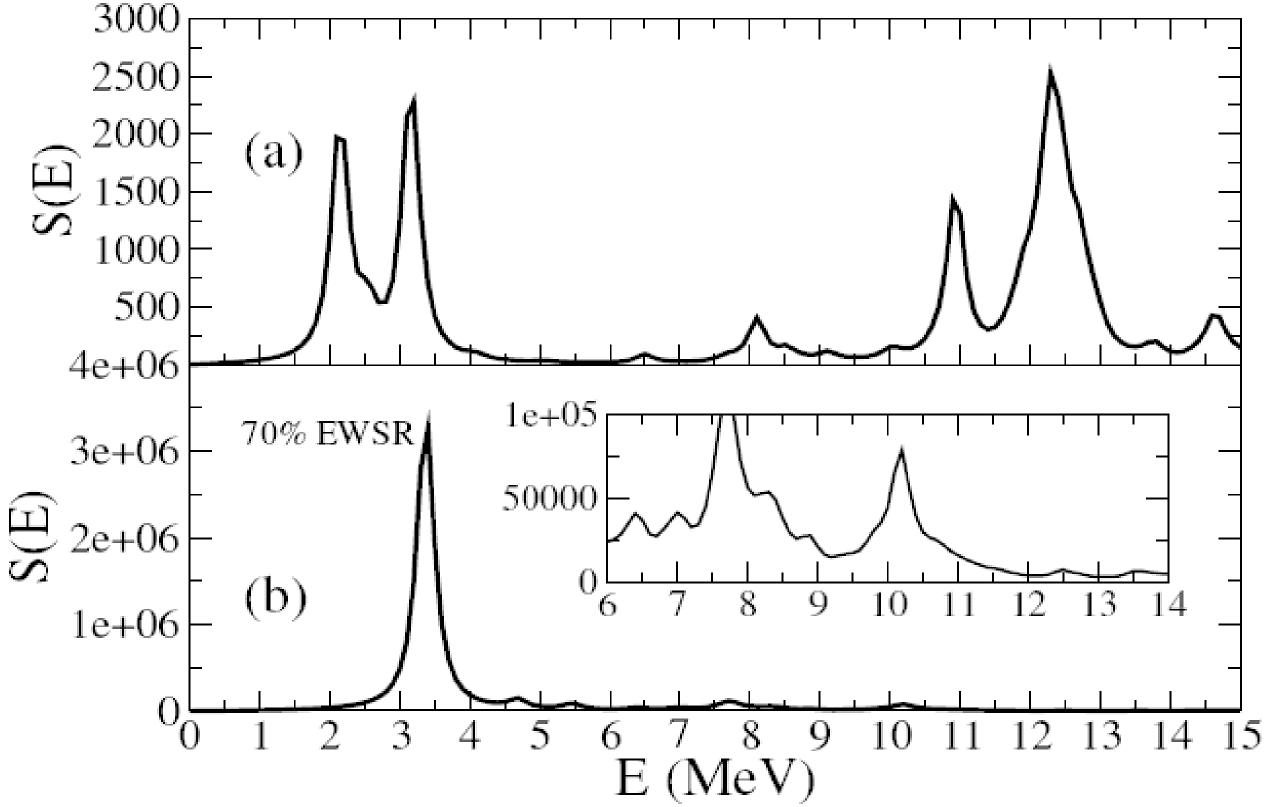
Supergiant resonances





E. Khan, N. Sandulescu, Nguyen Van Giai, PR**C71** (2005) 042801

Low-lying excitations



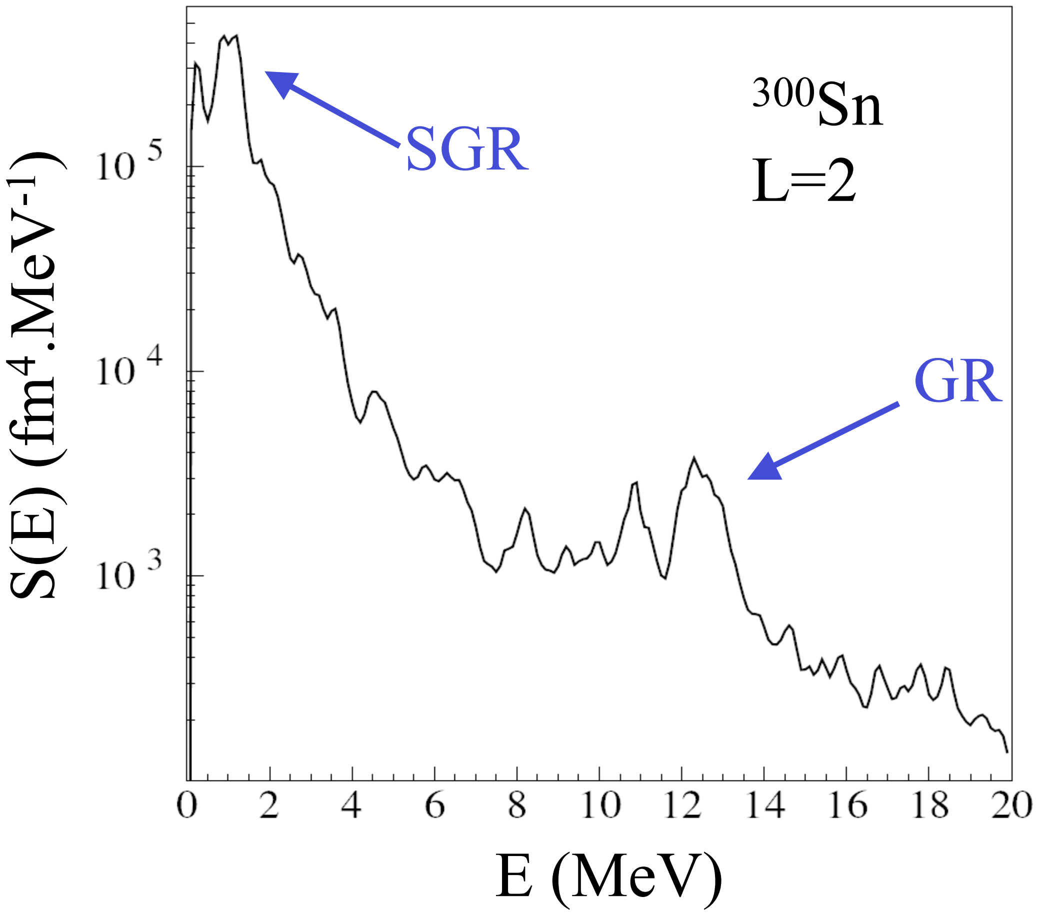
^{122}Zr

^{1500}Zr

M. Grasso, E. Khan and J. Margueron, Nucl. Phys. **A807**, 1 (2008)

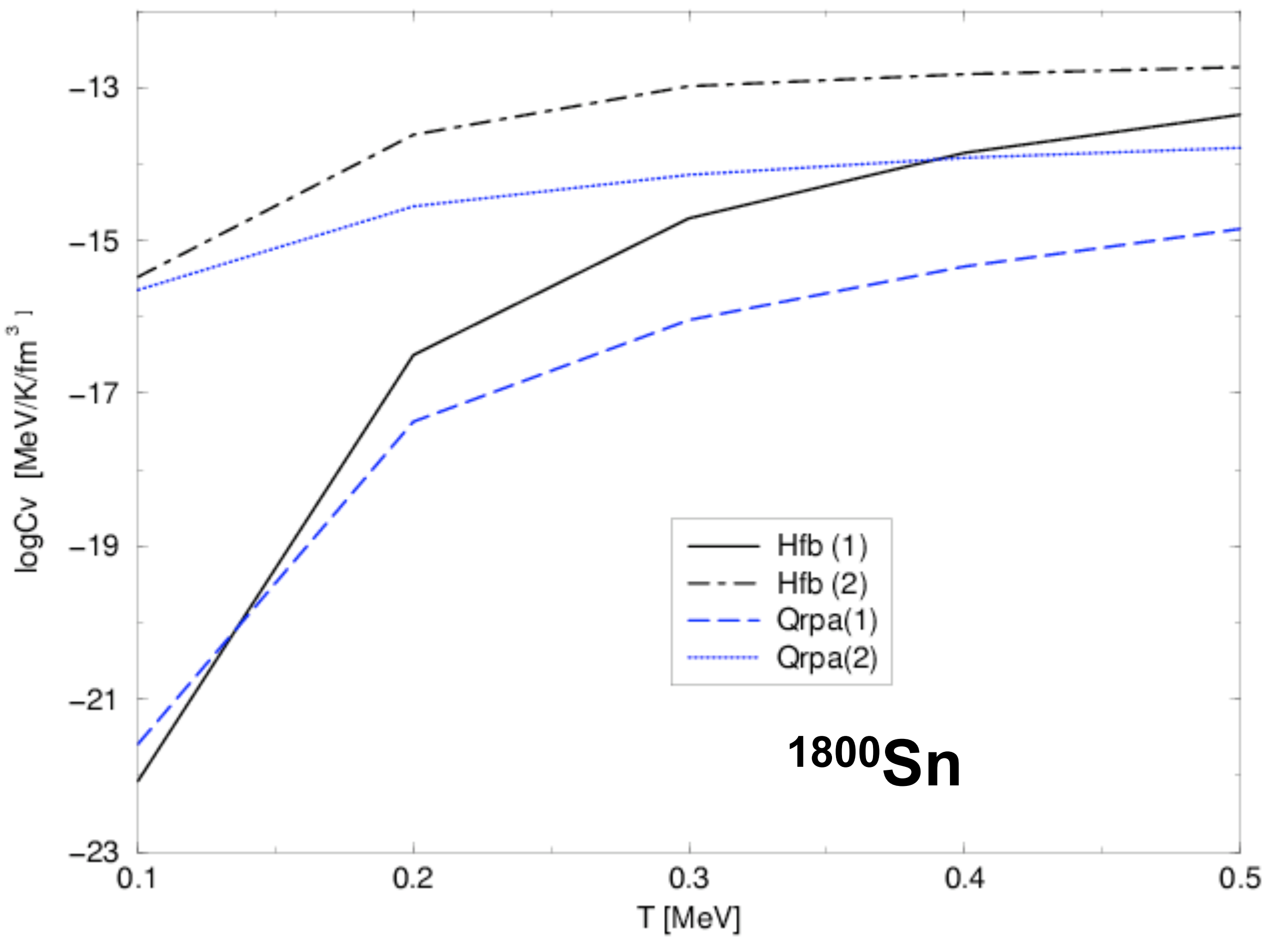
Evolution of the response

- Strong low-lying state already in cells close to the drip-line nuclei
- SGR magnitude is due to the neutron of the gas
- SGR energy position : contribution from the cluster, and pairing effects



Specific heat of the collective response

$$C_V = \frac{1}{T}\frac{\partial S_{coll}}{\partial T}$$



Entropy :

$S_{coll}=S_{QRPA}-S_{HFB}$

L=0 → 4

Experiment proposal

• **Specific heat : spectroscopy of drip-line nuclei drives the excitation spectrum of the Wigner-Seitz cells (low-lying states)**

↓

Coulex or integrated (p,p')
on the most neutron-rich Sn available (^{138}Sn)

Coupling the clusters

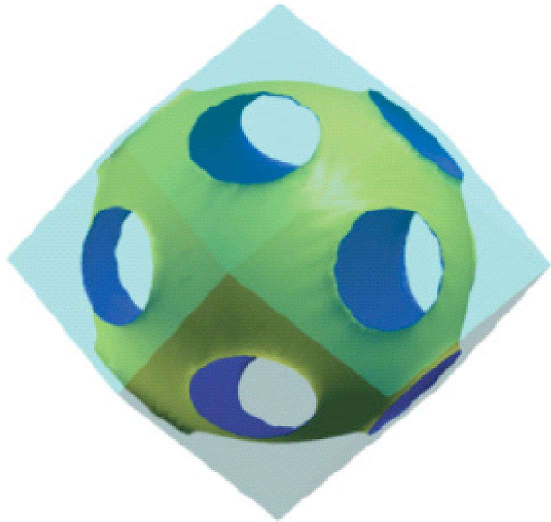
- crystal : clusters in a body-centered cubic lattice

  → band theory (spatial periodicity)

- WS accurate for static properties (n density)
- For dynamics, WS not valid if E< 100 keV

$k < k_{cell}$: no cluster effect

~ homegenous n gas



$k > k_{cell}$: n of the gas diffract on the clusters

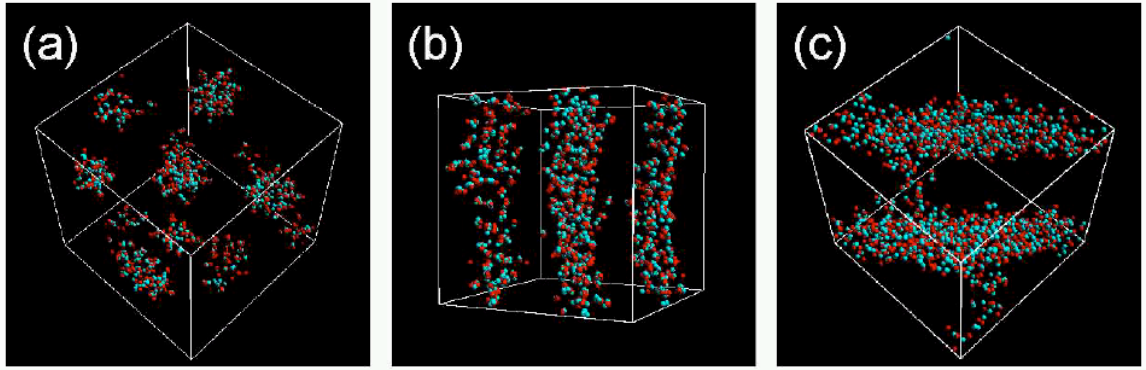
N. Chamel, S. Naimi, E. Khan, J. Margueron, PR**C75** (2007) 055806

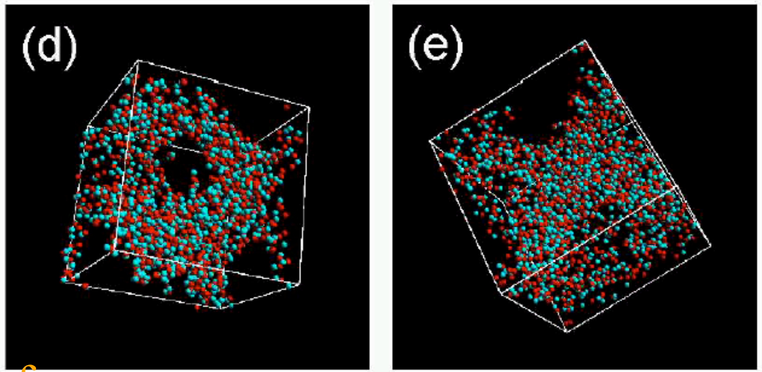
N. Chamel, J. Margueron, E. Khan, PR**C79** (2009) 012801

Molecular dynamics

• Crust/core interface : deformed structures

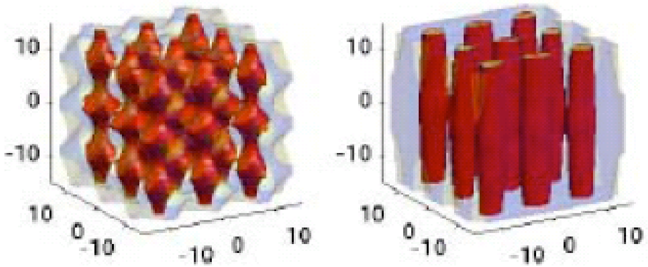
• QMD calculations for pasta phases

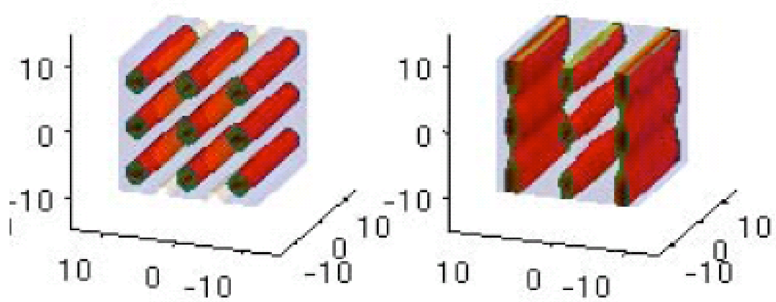




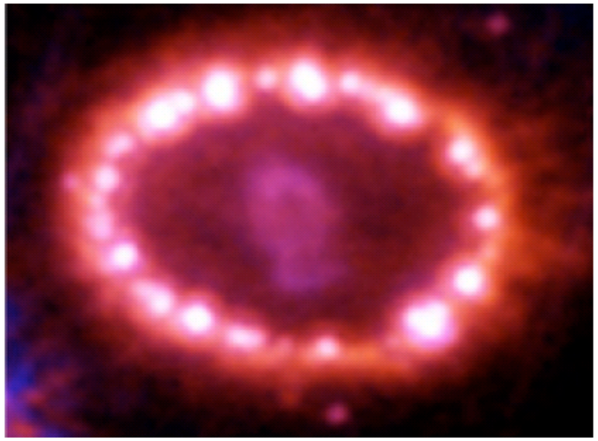
G. Watanabe *et al.*, PR**C66** (2002) 012801

•Dynamic evolution of infinite matter of nuclei leading to self-organised structure





F. Sebille *et al.*, in preparation

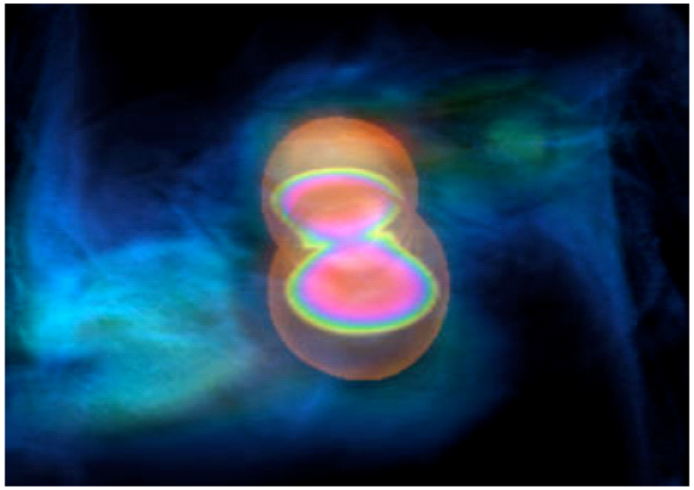


SN1987a

credit : HST

3) Nucleosynthesis in a neutron star

Two Neutron stars merger simulation

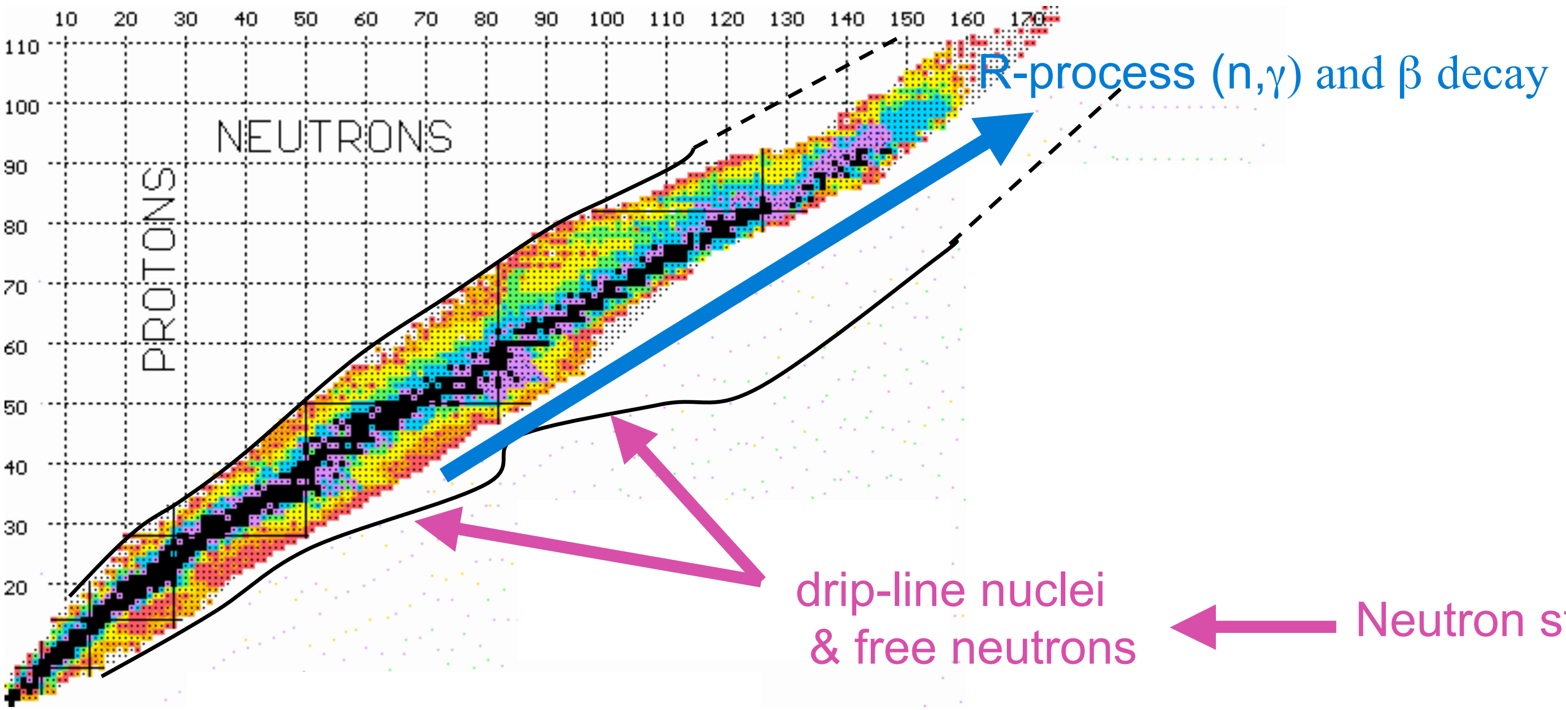


credit : Alan Calder

Astrophysical site ?

1) Core-collapse supernovae

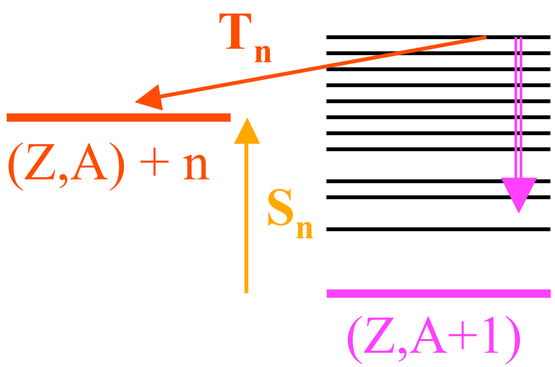
2) Ejection from the neutron star crust



Neutron star crust

The role of dipole strength in (n,γ) rates

•Statistical model of compound nuclear reaction : Hauser-Feshbach



$$T_\gamma = \int_0^{S_n+E_n} T_{E1}(E)\, \rho(E)\, dE$$

Photon transmission coefficient T_γ sensitive to :

- the E1 strength distribution $T_{E1}(E)$
- the level density $\rho(E)$

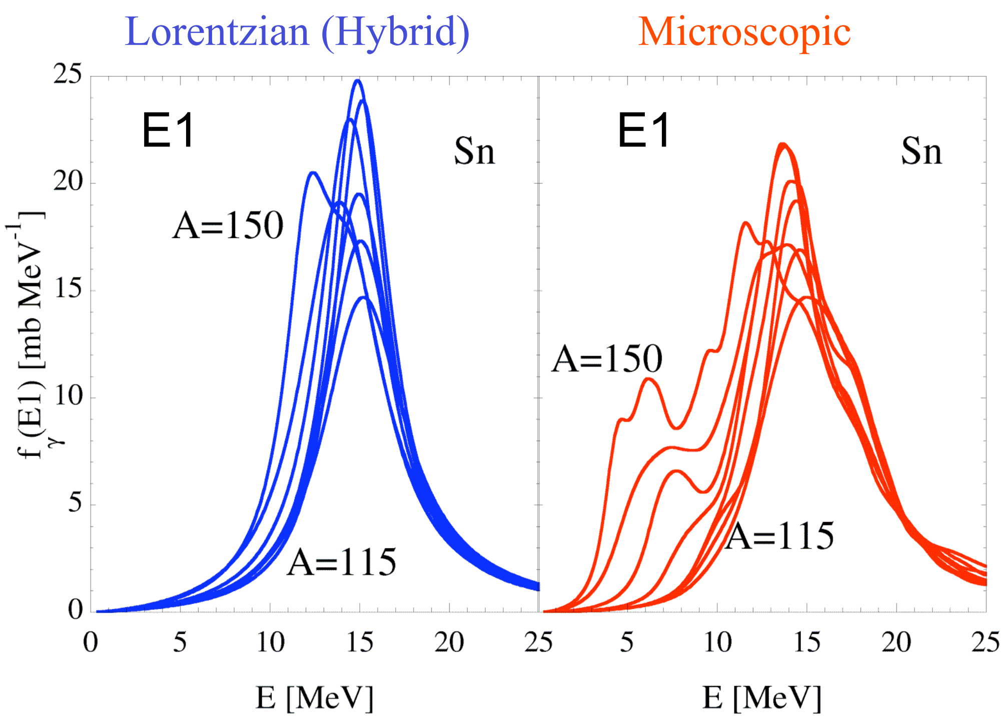
Why using microscopic calculations ?

Phenomenologic

- Fast and simple to use
- Extrapolations ?
- No feedback about nuclear structure

Microscopic

- Efforts consuming ?
- More suited to extrapolate far from stability : neutron skin
- Characterize the n-n interaction on the whole nuclear chart
- Test the model validity on a large scale

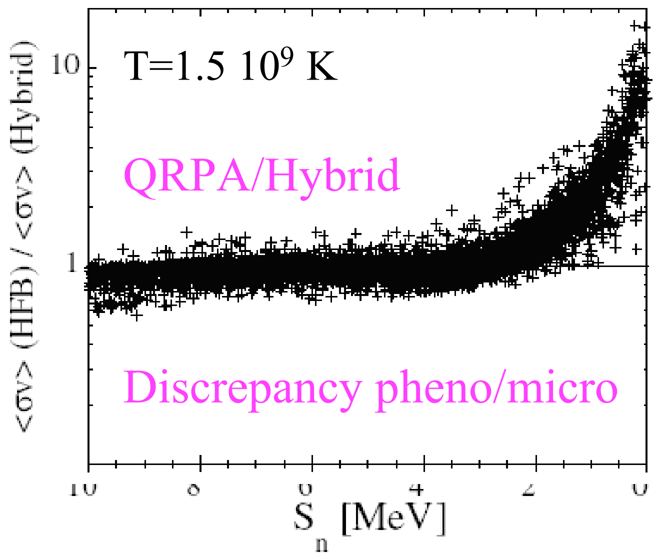


rms on GDR centroids :

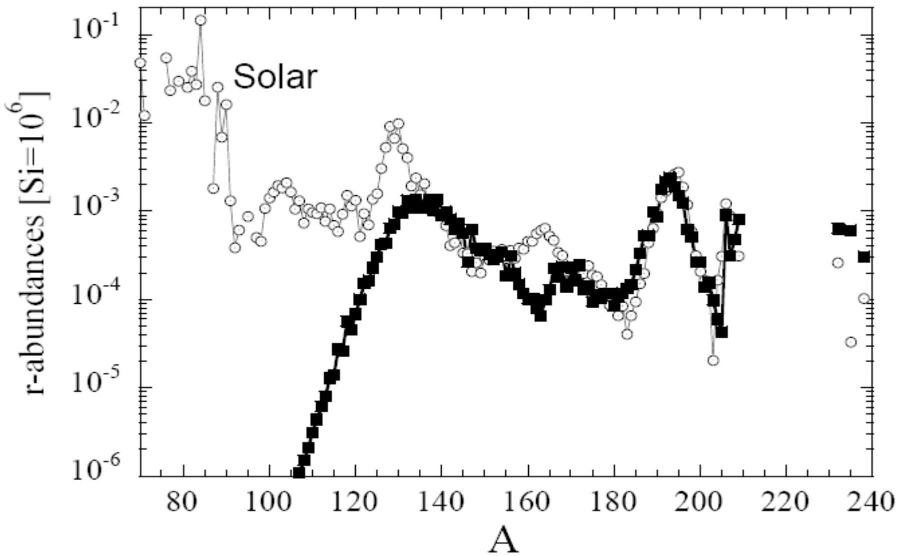
SIII	2267 keV
SGII	573 keV
SLy4	457 keV
MSk7	564 keV
BSk7	485 keV

Astrophysical impact

(n,γ) rates



r-abundance distribution



S. Goriely, E. Khan, M. Samyn, NP**A739** (2004) 331
S. Goriely et al., NP**A758** (2005) 587

Conclusion & outlooks

•There is no nuclear structure experiment directly applied to NS
•There are several experiments usefull to constrain nuclear structure models for NS

• n skin, pygmy response, GMR, pairing (masses, pairing vibrations), Spectroscopy of low-lying states

• Exotic nuclei: neutron rich system (skin) at low density