The determination of incompressibility in nuclei and nuclear matter

1) Incompressibility in nuclei

2) Links with nuclear matter

E. Khan, J. Margueron and I. Vidaña PRL(2012)092501
E. Khan, N. Paar, D. Vretenar, L.-G. Cao, H. Sagawa and G. Colò, PRC87(2013)064311
E. Khan and J. Margueron, PRC88(2013)034319
E. Yüksel, E. Khan and K. Bozkurt, EPJA49(2013)124
M. Vandebrouck et al., to be published in PRL (2014)

E. Khan

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

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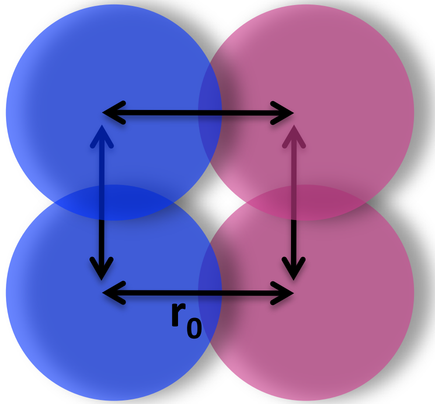
Comprendre le monde, construire l'avenir®

cnrs dépasser les frontières
IN2P3 Les deux infinis

1) Incompressibility in nuclei

Incompressiblity of a finite fermionic system (nucleus with A nucleons)



Incompressibility of the system: $K_A \propto \frac{d^2 E/A}{d\langle r^2 \rangle^2}$

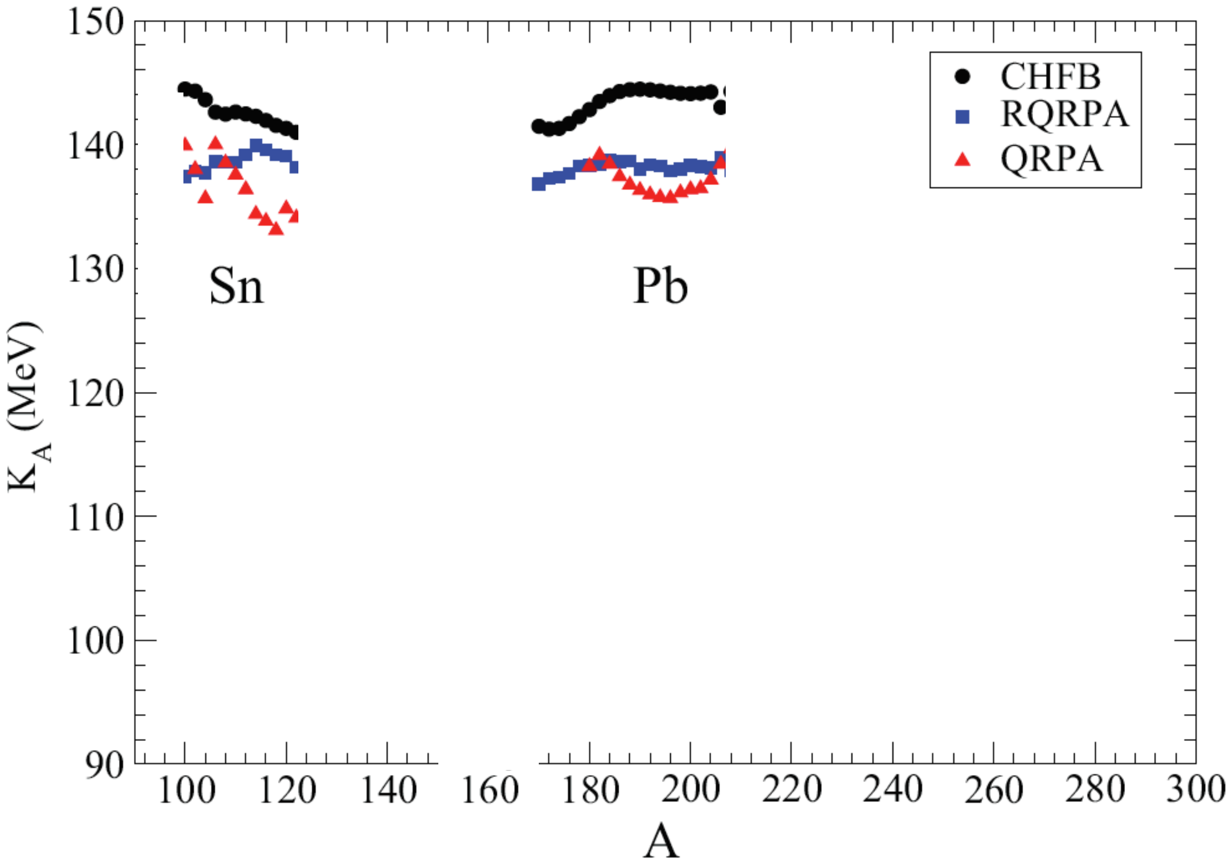
$$E_{GMR} \propto \sqrt{K_A}$$

Zero point kinetic energy: $T_0 = \frac{\hbar^2}{m r_0^2}$

Incompressibility of the system $\simeq$ 5 $*$ Zero point kinetic energy

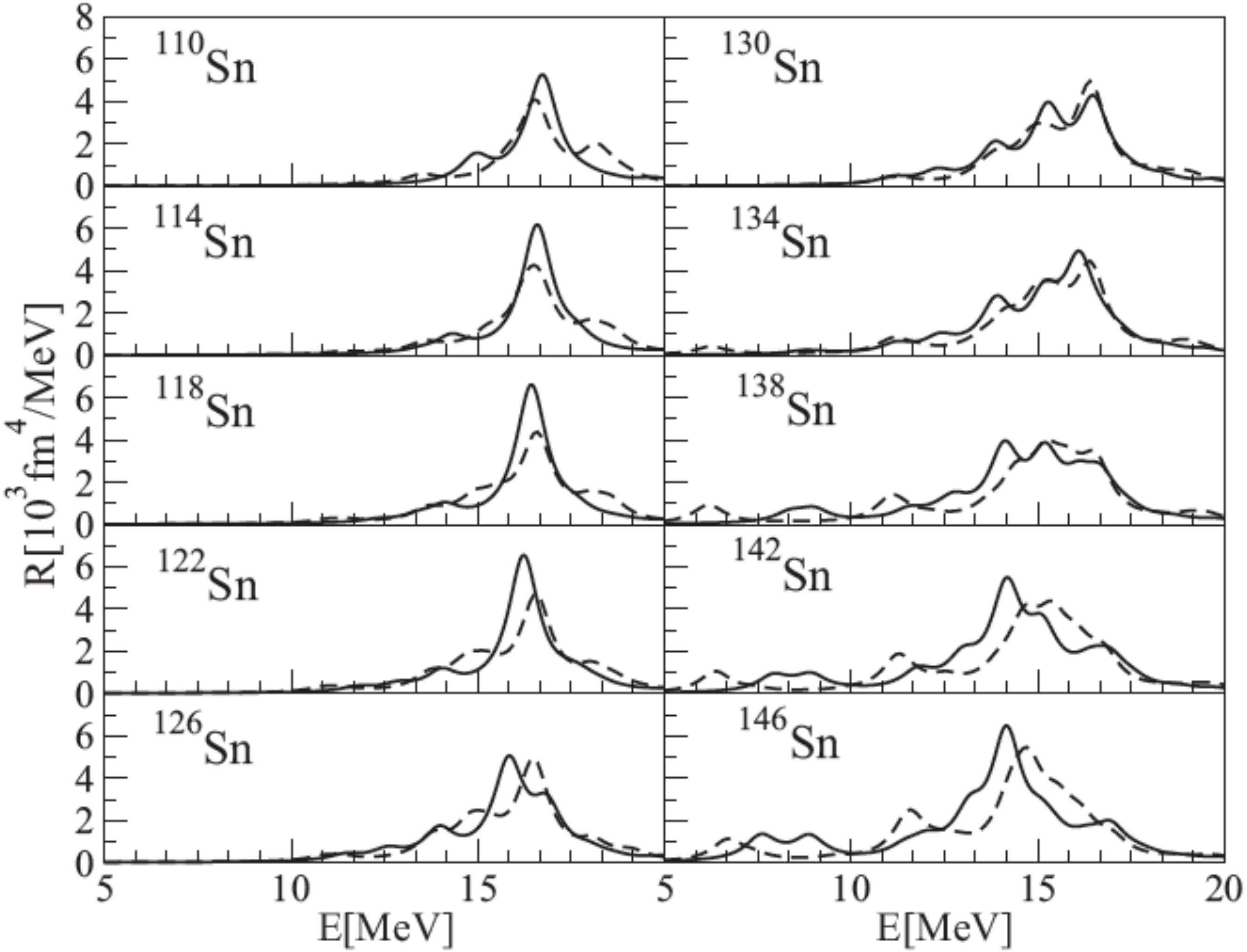
150 MeV $\simeq$ 5 $*$ 30 MeV

Microscopic predictions

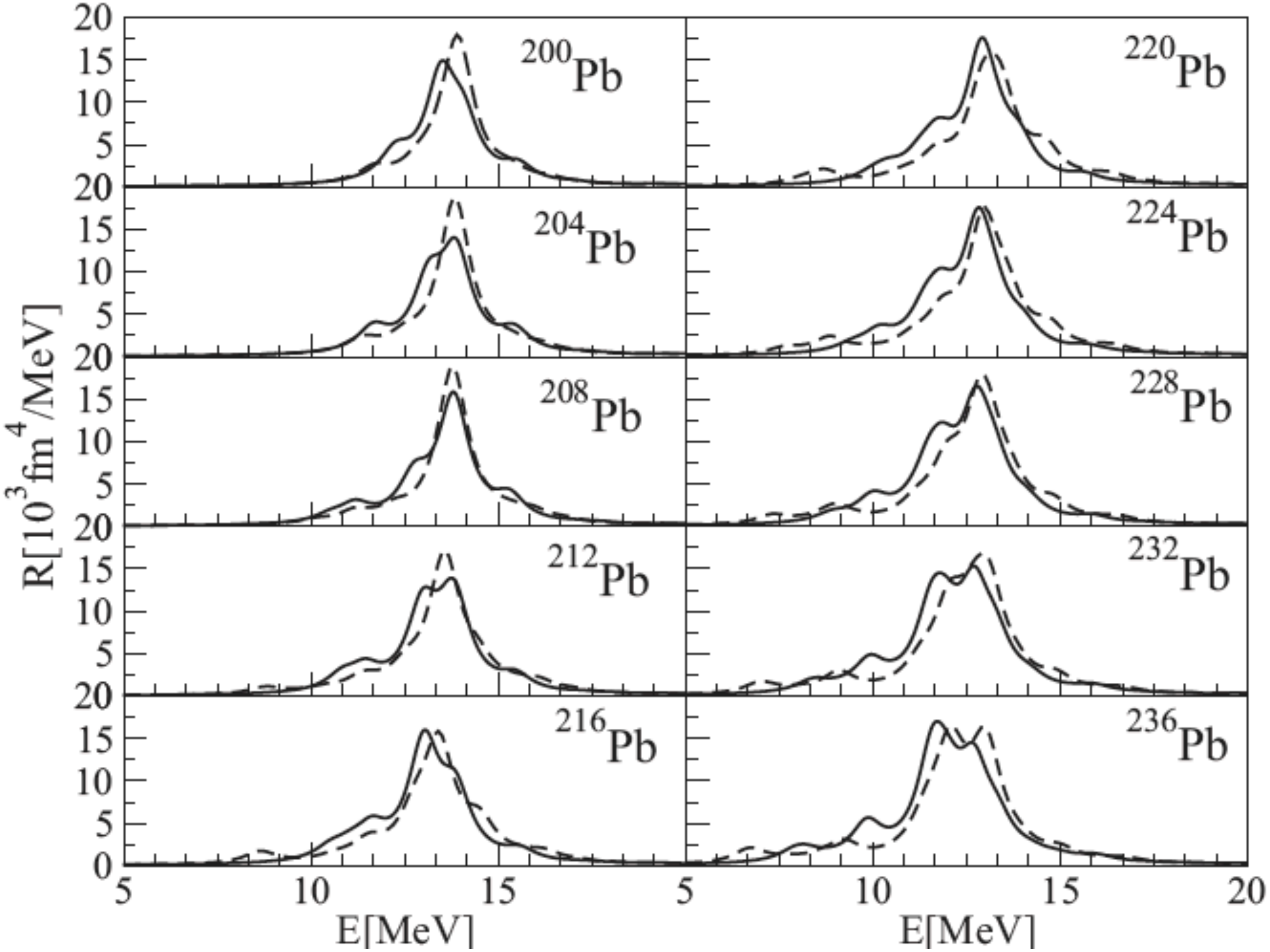


Measurement of the IS monopole strength in unstable Sn and Pb isotopes

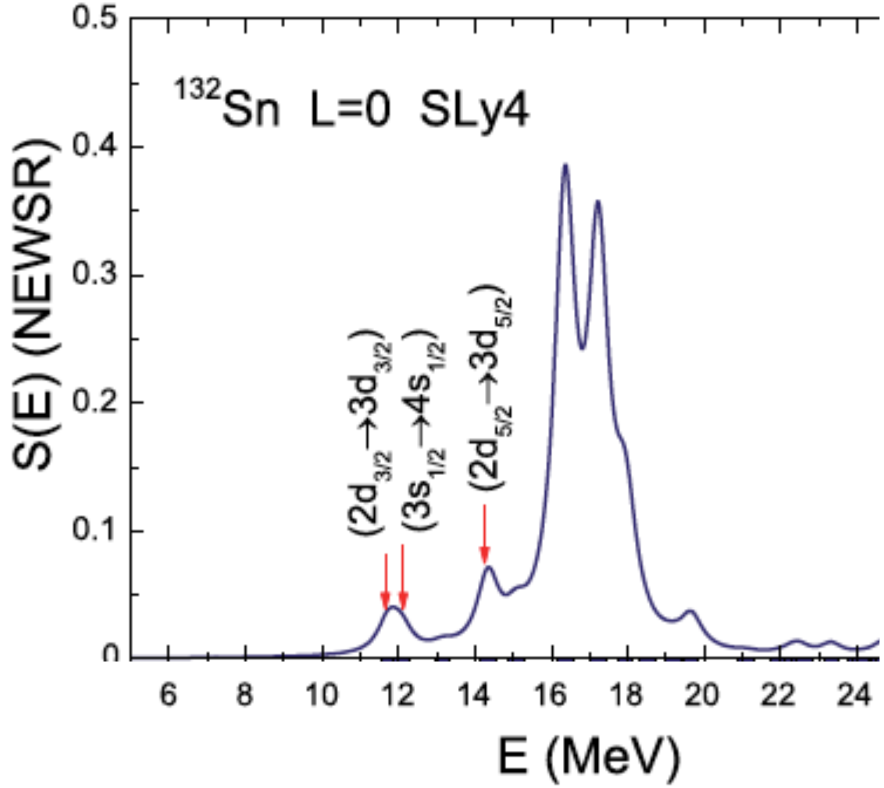
The soft monopole mode

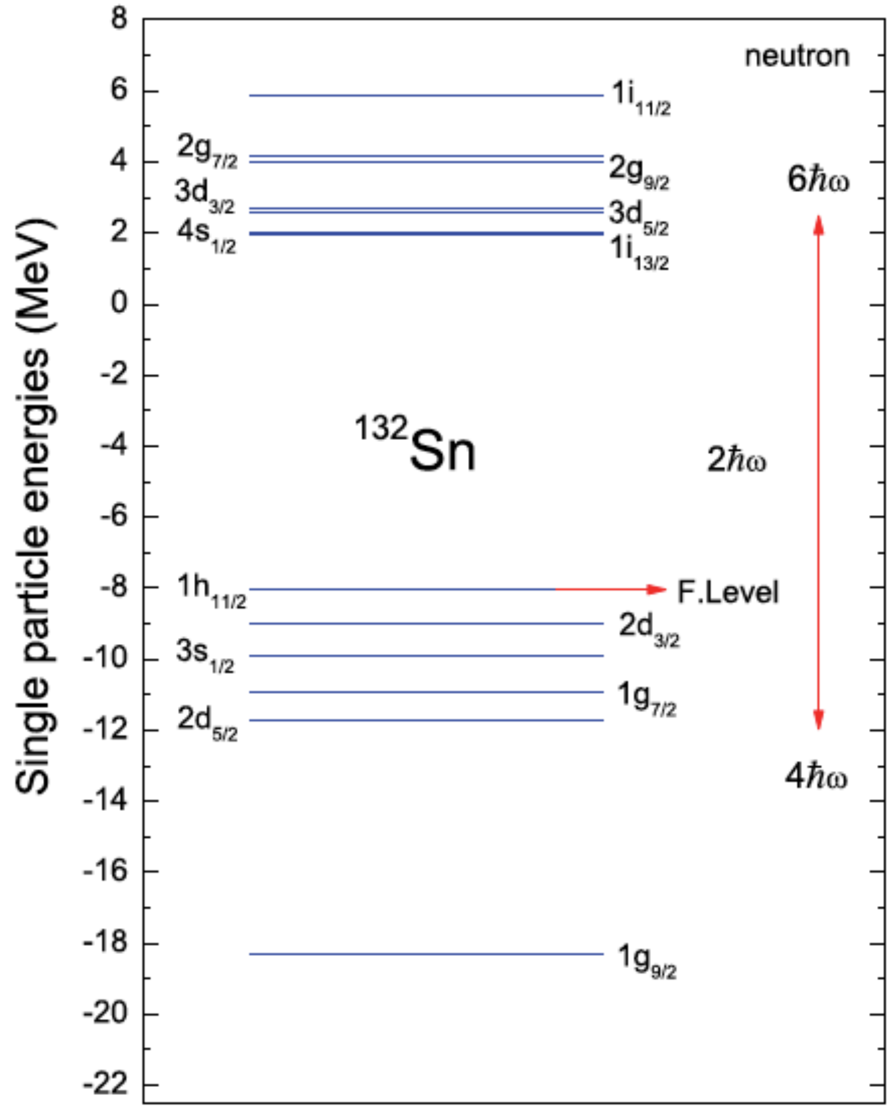


The soft monopole mode



What is the soft monopole mode ?

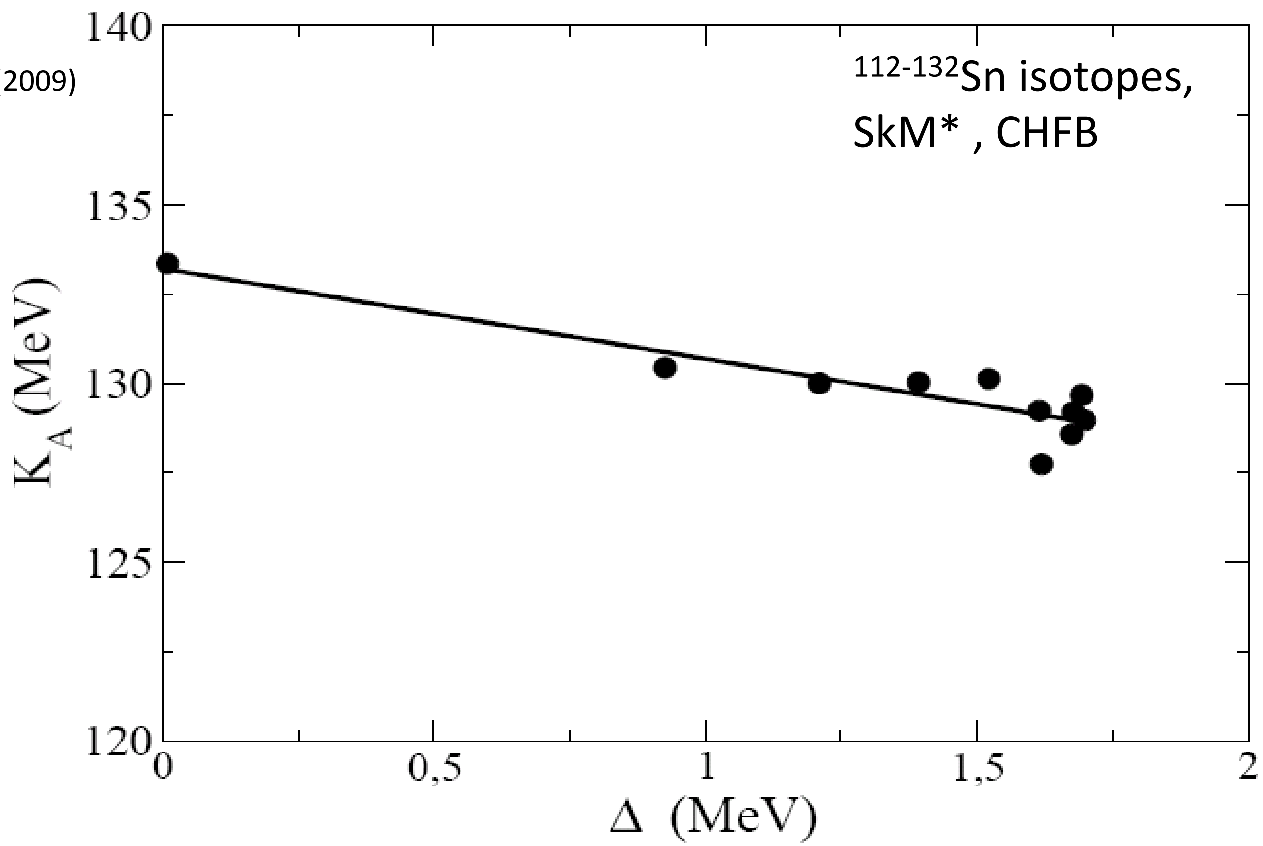




Nuclei incompressibility vs. pairing

Civitarese et al. (1991)
Li, Colò, Meng (2008)
Khan, Margueron, Colò, Hagino, Sagawa (2009)
Li-Gang Cao, Sagawa, Colò (2012)

$$E_{\rm GMR} = \sqrt{\frac{\hbar^2 K_A}{m\langle r^2\rangle}}$$



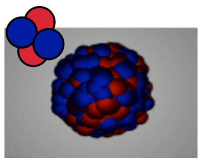
- Cooper pairs favor compressibility
- Incompressibility of **superfluid** nuclear matter: $\mathbf{K_\infty(\Delta)}$

→ Pairing has a small but non negligible effect on the GMR

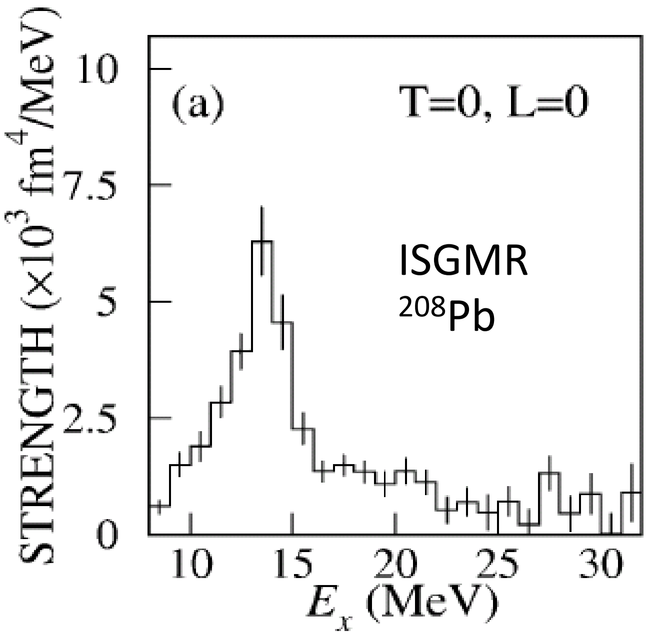
Method to determine K_A

•The nucleus exhibits a collective compression mode (how nice !):
the Giant Monopole Resonance

Inelastic α scattering



Nucleus (e.g. ^{208}Pb)



M. Uchida, H. Sakaguchi et al., PLB557(2003)12

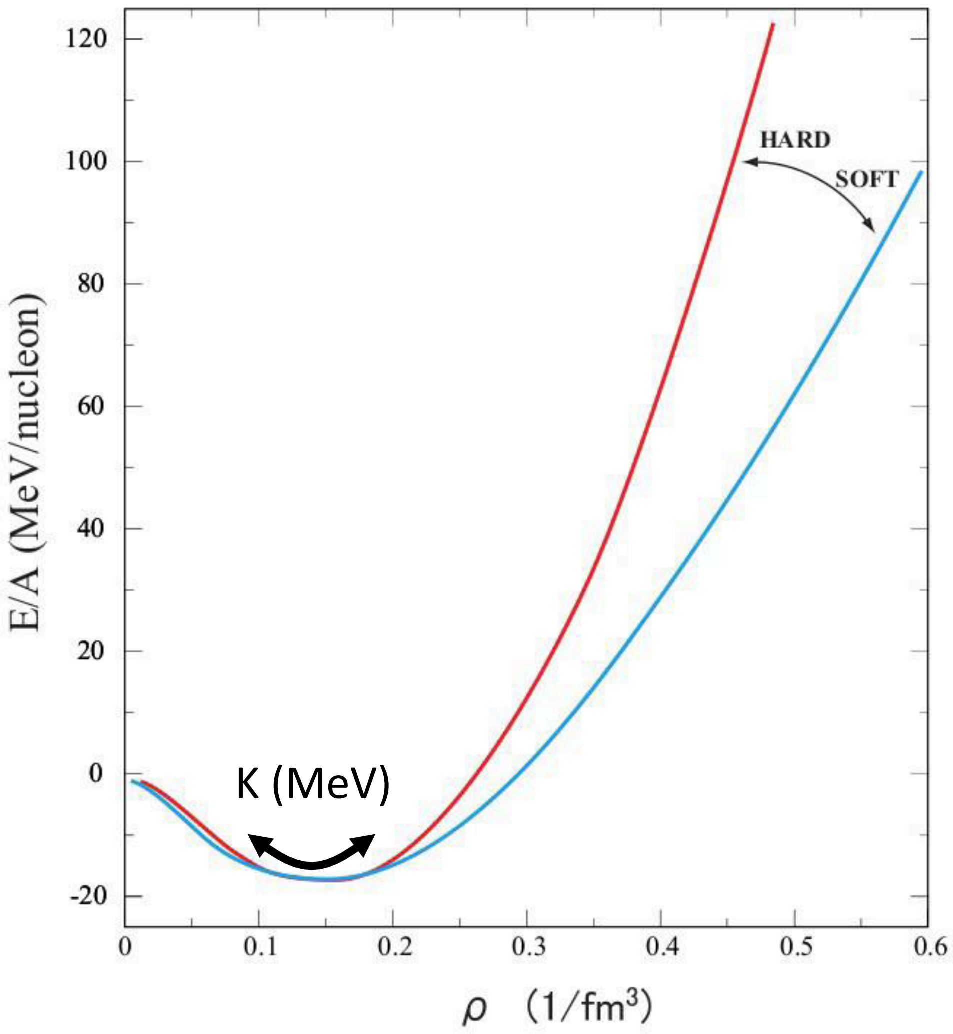
Experimental conerstones

- Is it possible to measure the IS monopole strength neutron-rich exotic nuclei ?
- Is it possible to get experimental clues on a soft monopole mode ?

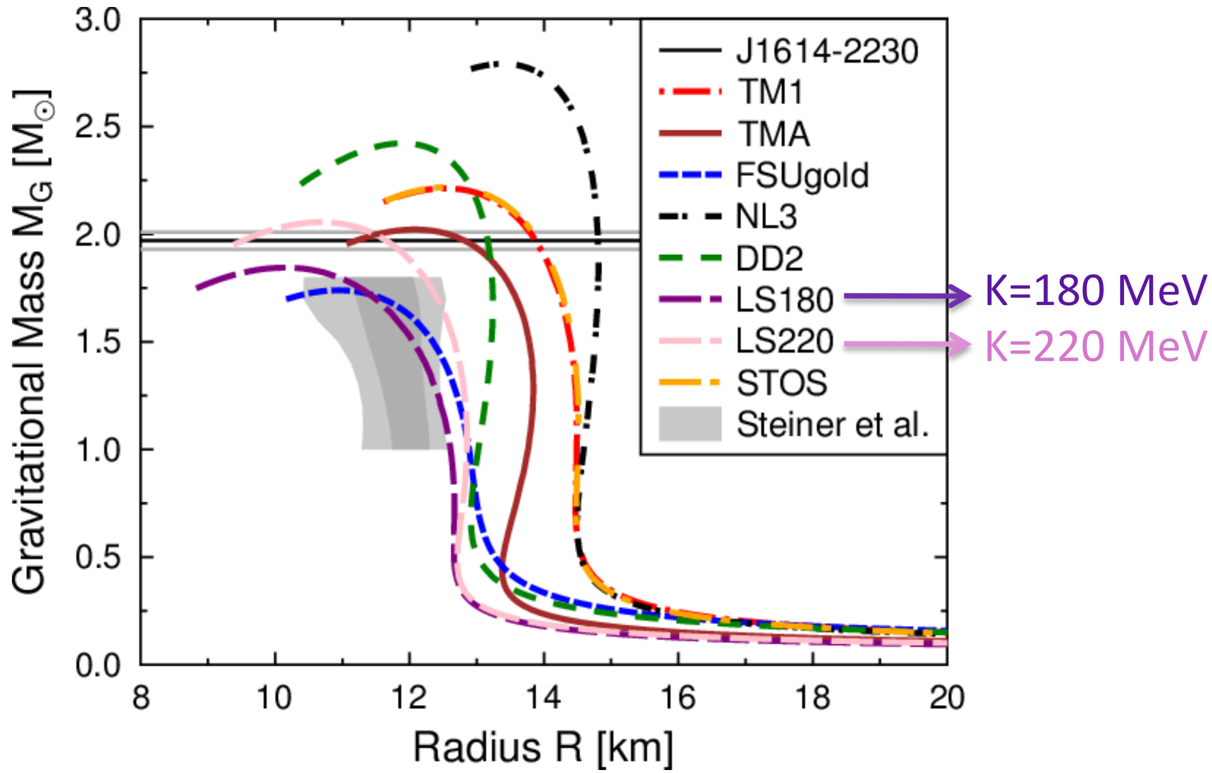
→ See Marine Vandebrouck's talk

2) Links with nuclear matter

Nuclear incompressiblity

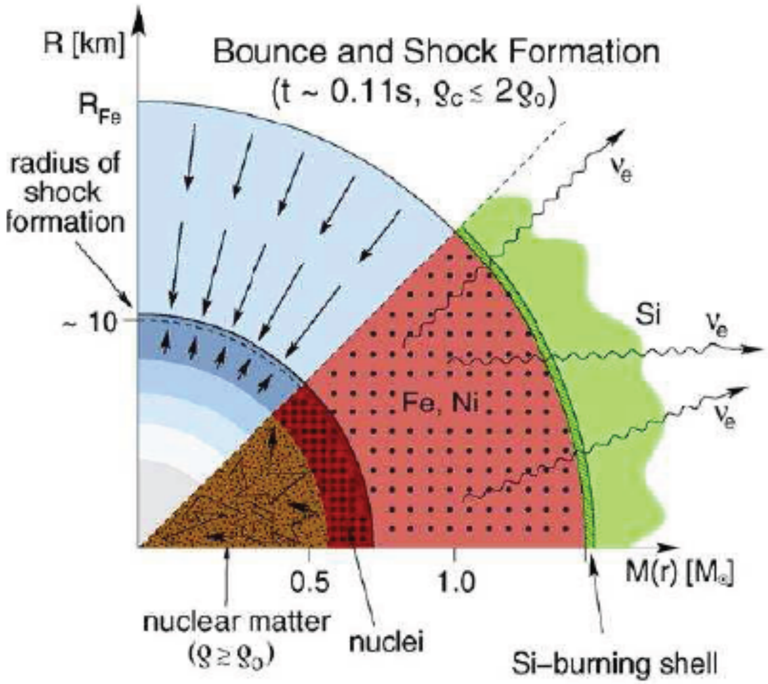


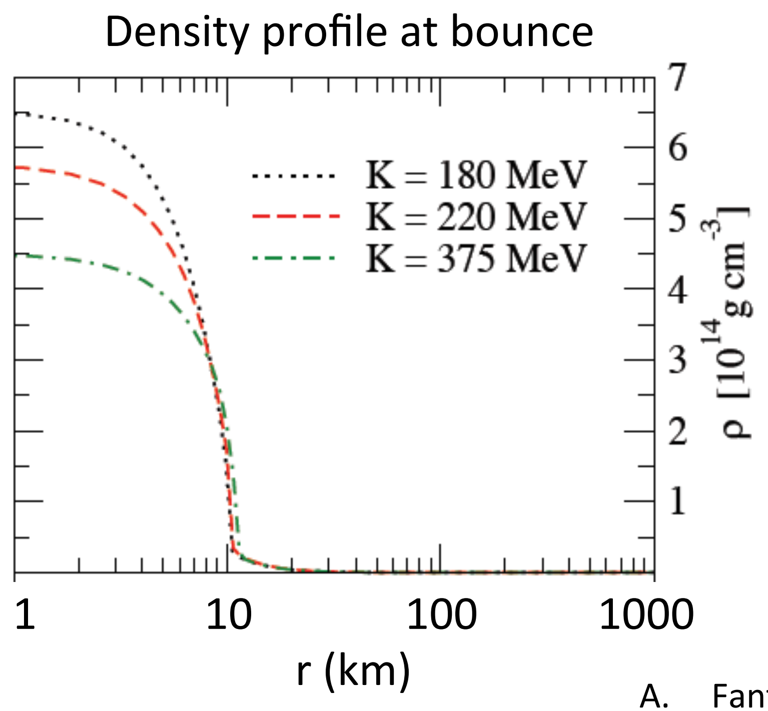
Neutron stars



Matthias Hempel
ITP Franckfurt

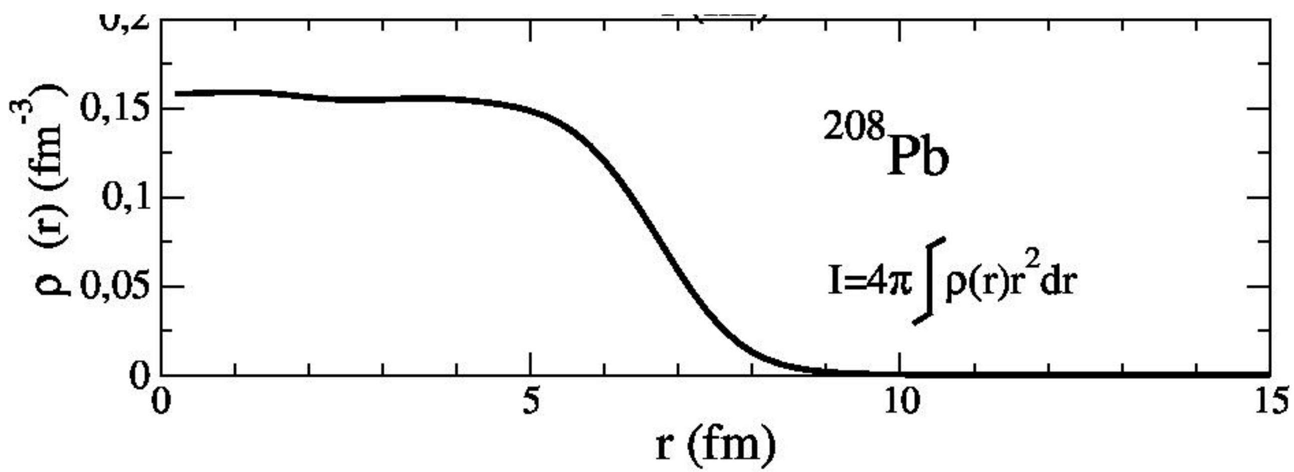
SuperNovae bounce



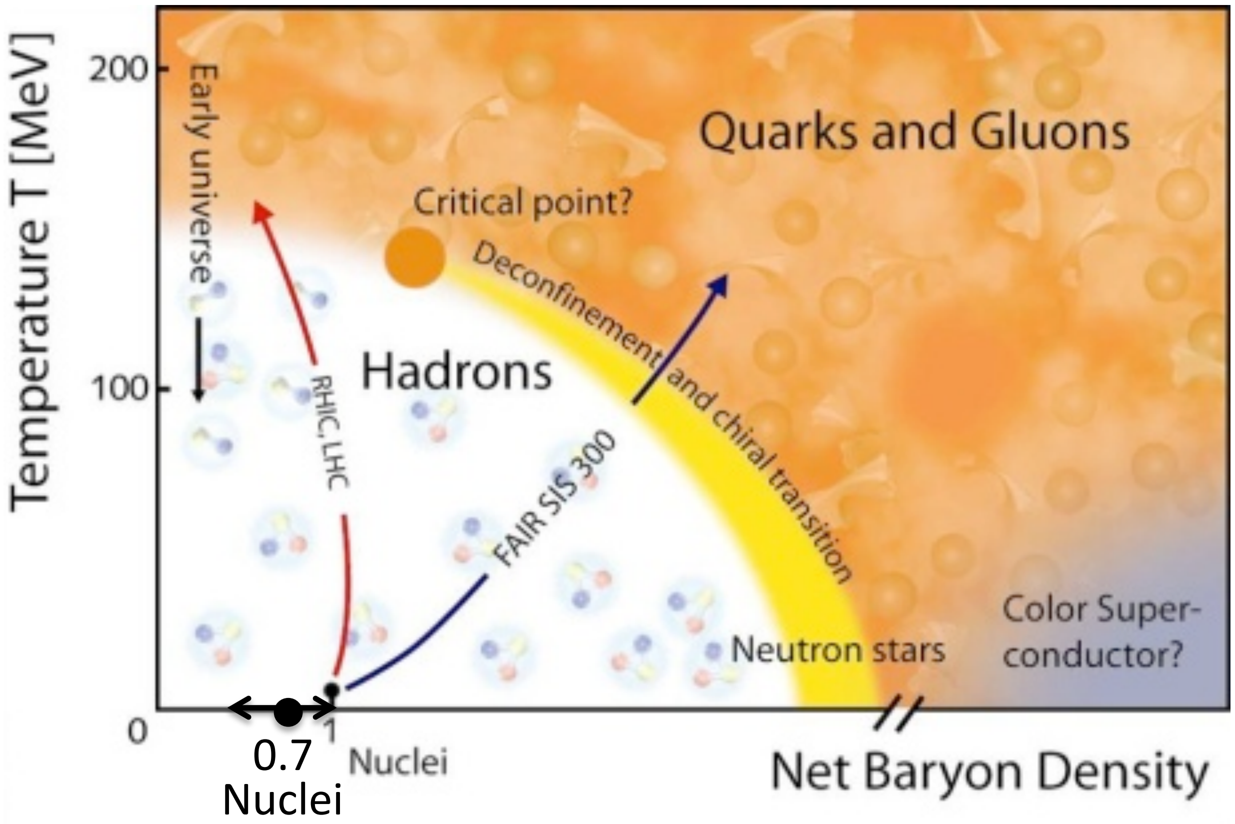


A. Fantina
PhD (2010)
IPNO-IAA

Saturation ?



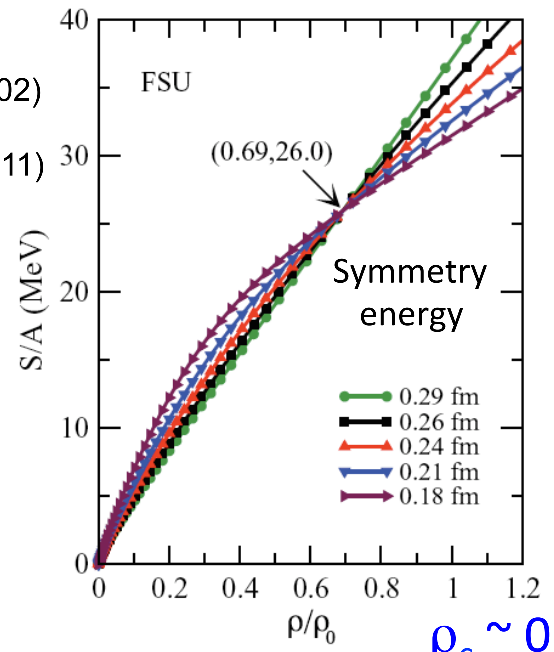
- Surface: 2/3 of nucleons in ^{208}Pb
- Saturation density area may not be the most probed

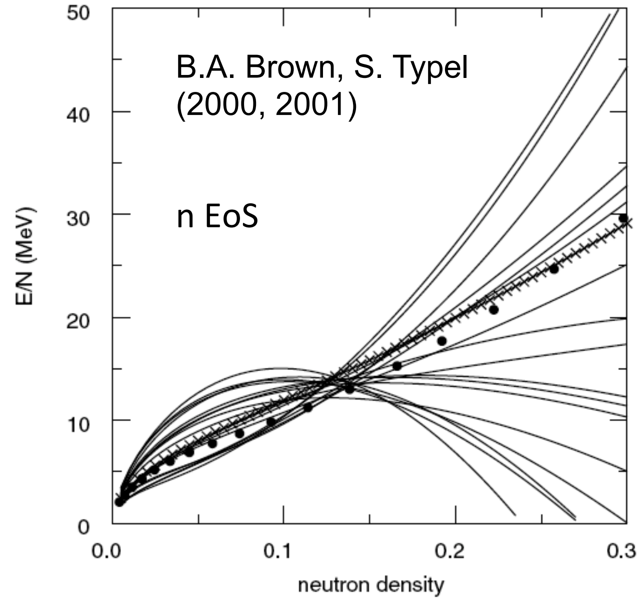


Temperature T [MeV]
200
100
0
Early universe
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
RHIC, LHC
FAIR SIS 300
Neutron stars
Color Super-
conductor?
1
Nuclei
0.7
Nuclei
Net Baryon Density

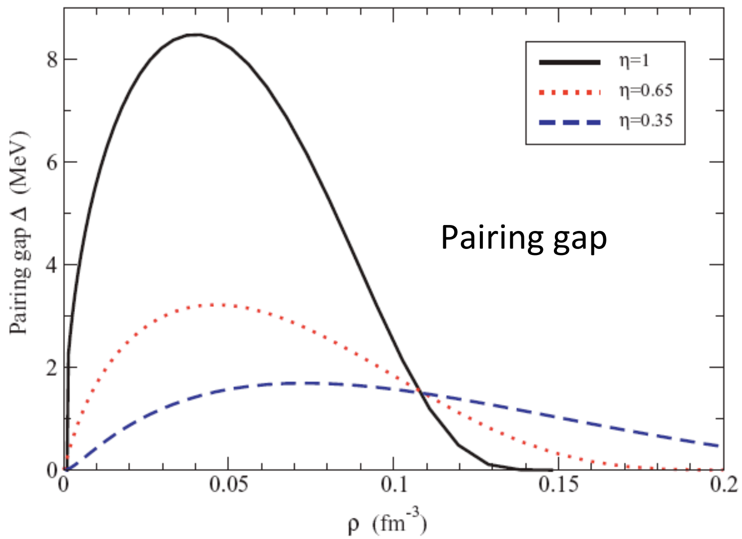
The crossing density

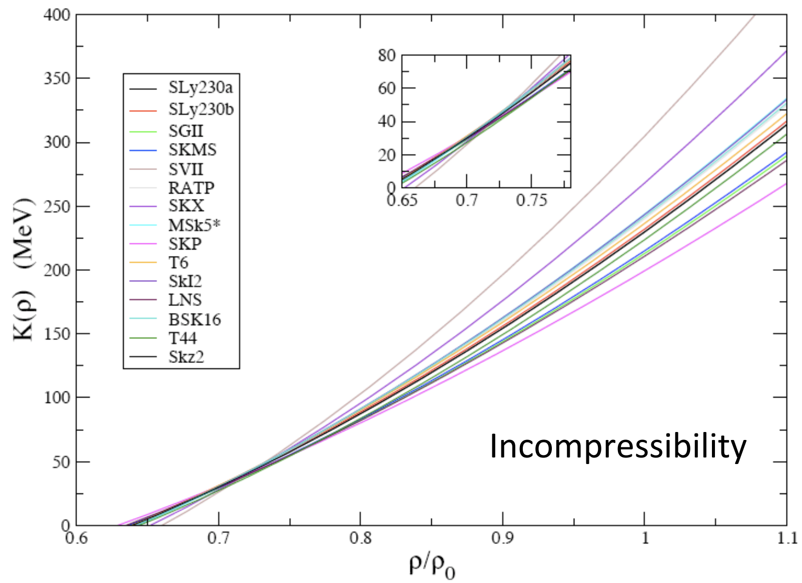
R.J. Furnstahl (2002)
G. Colò (2004)
J. Piekarewicz (2011)





$\rho_c \sim 0.11\ \mathrm{fm}^{-3} = 0.7\ \rho_0$

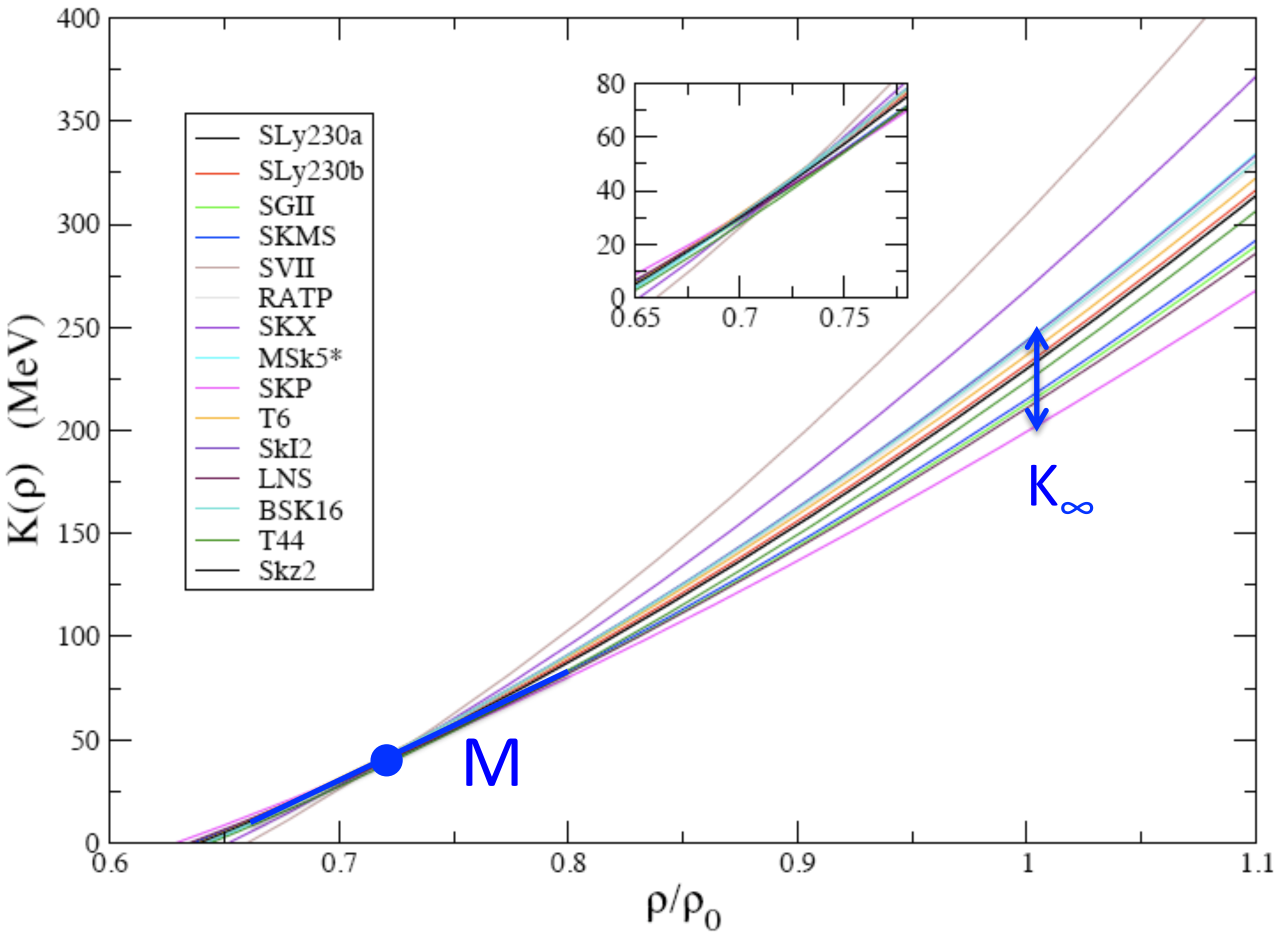




E. Khan, M. Grasso, J. Margueron (2010)

M

$M = 3\rho K'(\rho)|_{\rho=\rho_c}$: third derivative of EoS at the crossing density

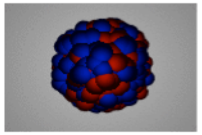


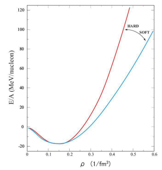
Microscopic method

$$V = \int d\mathbf{r} \sum_{T=0,1} \Big[C_T^{\rho}\rho_T^2 + C_T^{\Delta\rho}\rho_T\Delta\rho_T + C_T^{\tau}\rho_T\tau_T + C_T^{\mathbb{J}}\mathbb{J}_T^2 + C_T^{\nabla J}\rho_T\boldsymbol{\nabla}\cdot\mathbf{J}_T + C_T^{s}\mathbf{s}_T^2 + C_T^{\Delta s}\mathbf{s}_T\cdot\Delta\mathbf{s}_T - C_T^{\mathbb{J}}\mathbf{s}_T\cdot\mathbf{T}_T + C_T^{\nabla s}(\boldsymbol{\nabla}\cdot\mathbf{s}_T)^2 - C_T^{\tau}\mathbf{j}_T^2 + C_T^{\nabla J}\mathbf{s}_T\cdot\boldsymbol{\nabla}\times\mathbf{j}_T \Big]$$

EDF

E_{GMR} ⟷ EDF → EoS

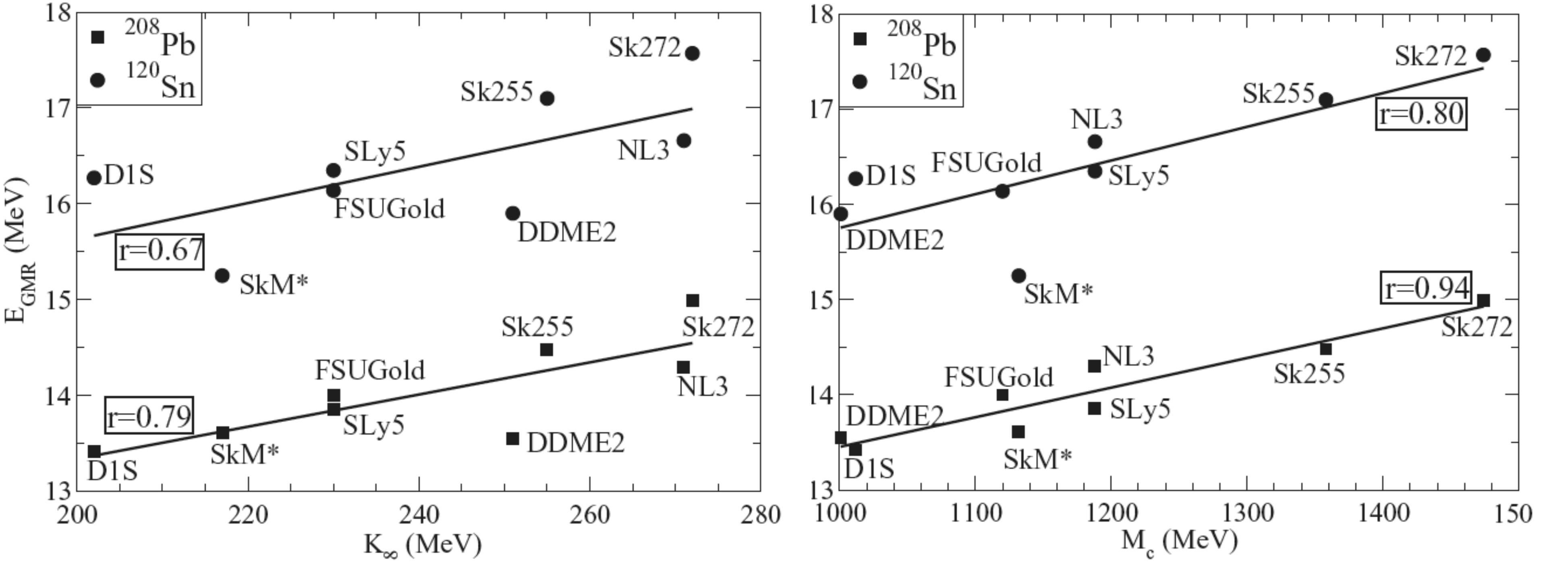




- Nuclear structure models: from EDF to E_{GMR}

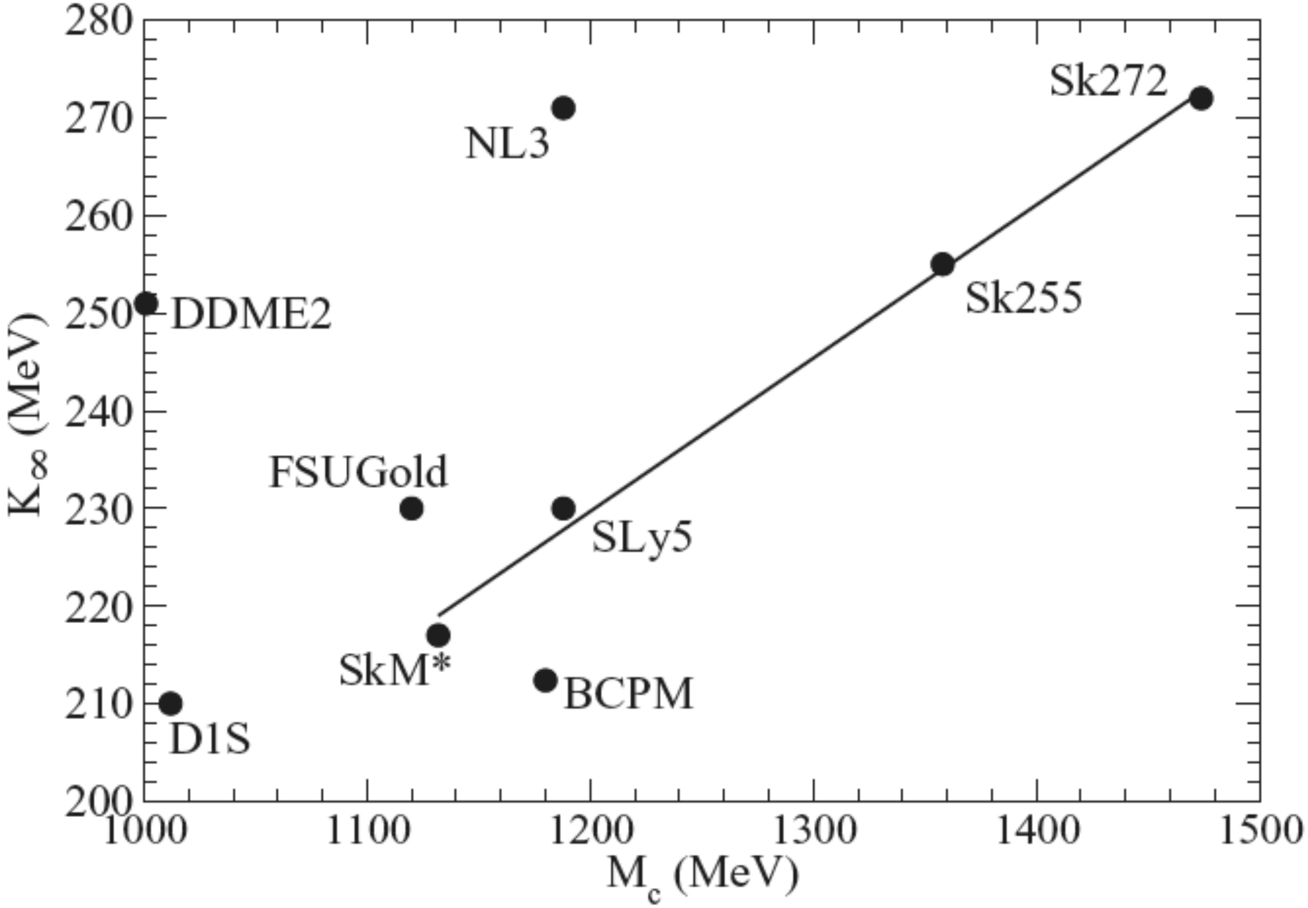
- Limitations : all the terms (EoS) have to be correctly predicted at once

From the GMR to nuclear matter



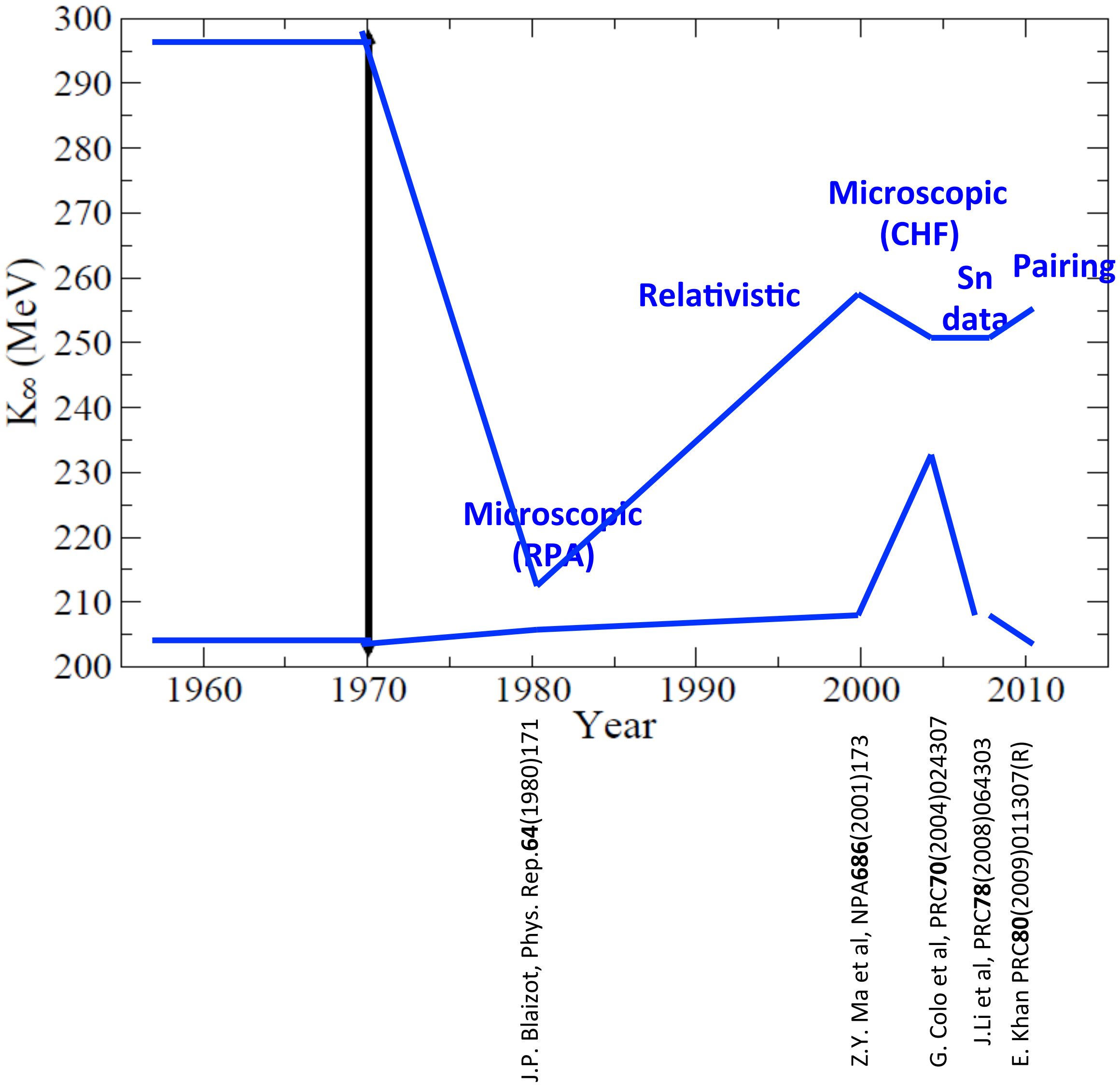
M_c better constrained by the data than K_∞

The reason for dispersed K_∞ values



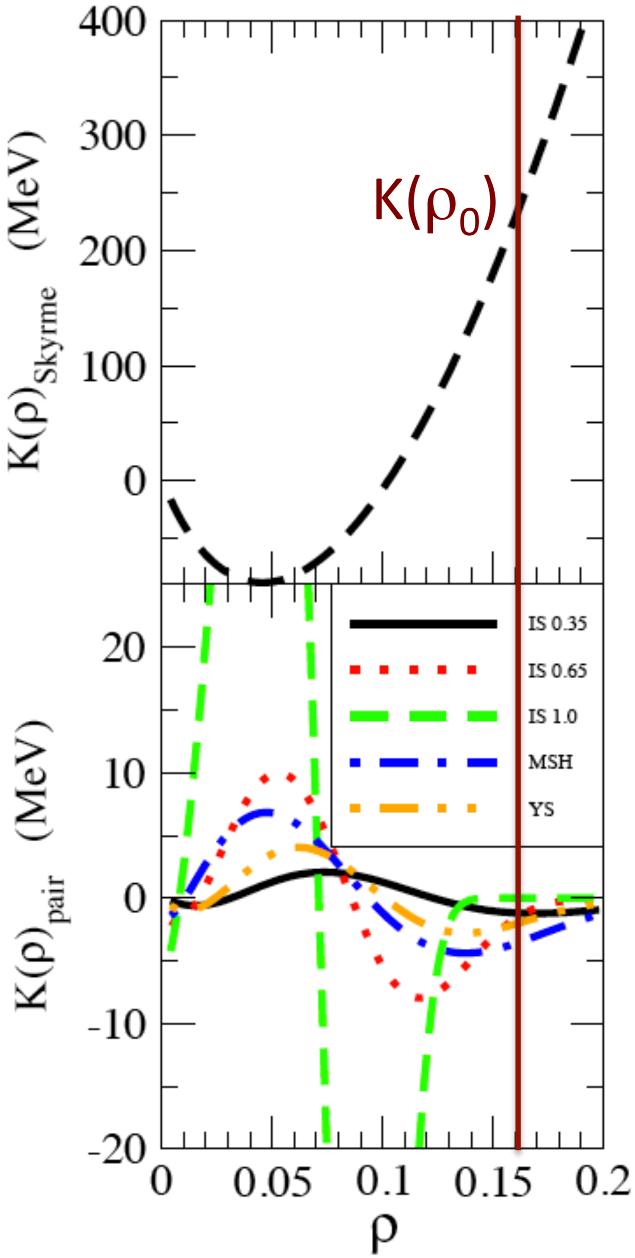
Lack of constraints on the density dependence of the EDF generates dispersion of K_∞

Uncertainties on K_∞



$K_\infty = 240 \pm 30$ MeV

Origin of the pairing effect



Density dependence of K

E. Khan, J. Margueron, G. Colò, K. Hagino, H. Sagawa, PRC82(2010)024322

Some clues on N vs. Z asymmetry

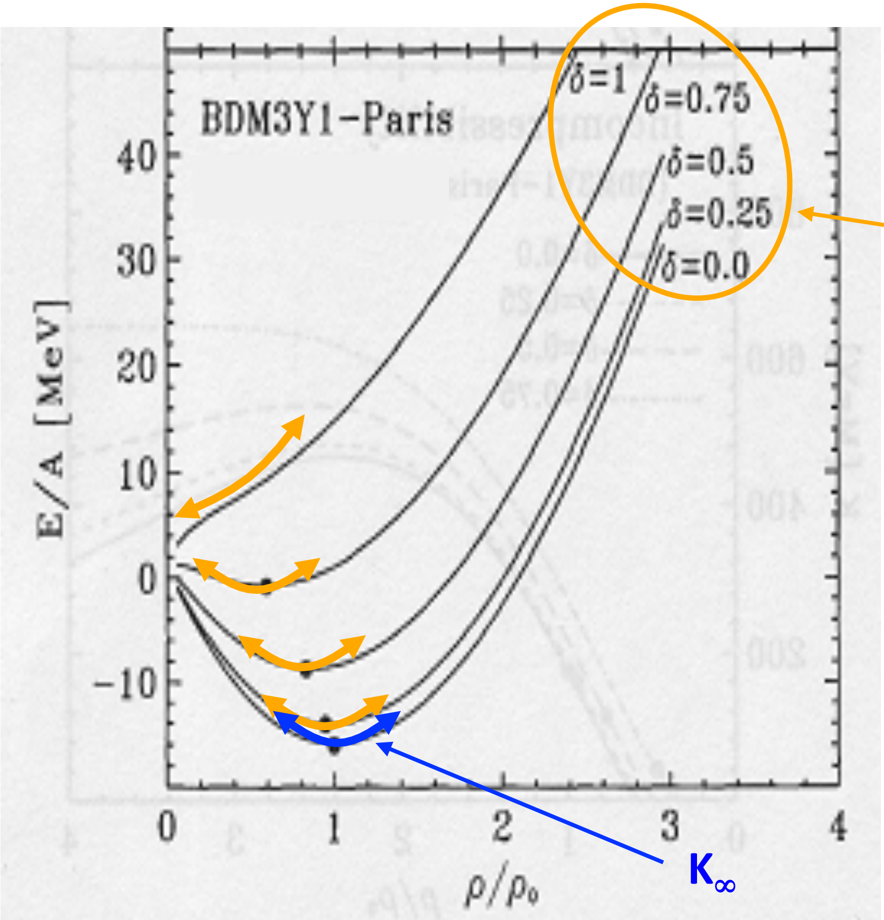
$$E(\rho,\delta) = E(\rho,0) + a_{sym}(\rho)\delta^2$$

: **density** and **neutron excess**

δ=(N-Z)/A

δ(^{100}Sn)=0
δ(^{132}Sn)=0.24
δ(^{208}Pb)=0.21

δ(^{180}Sn)=0.44



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

evolution of incompressibility with asymmetry:

$$K(\rho,\delta) \sim \frac{1}{2}\frac{\partial^2 E(\rho,\delta)}{\partial \rho^2}$$

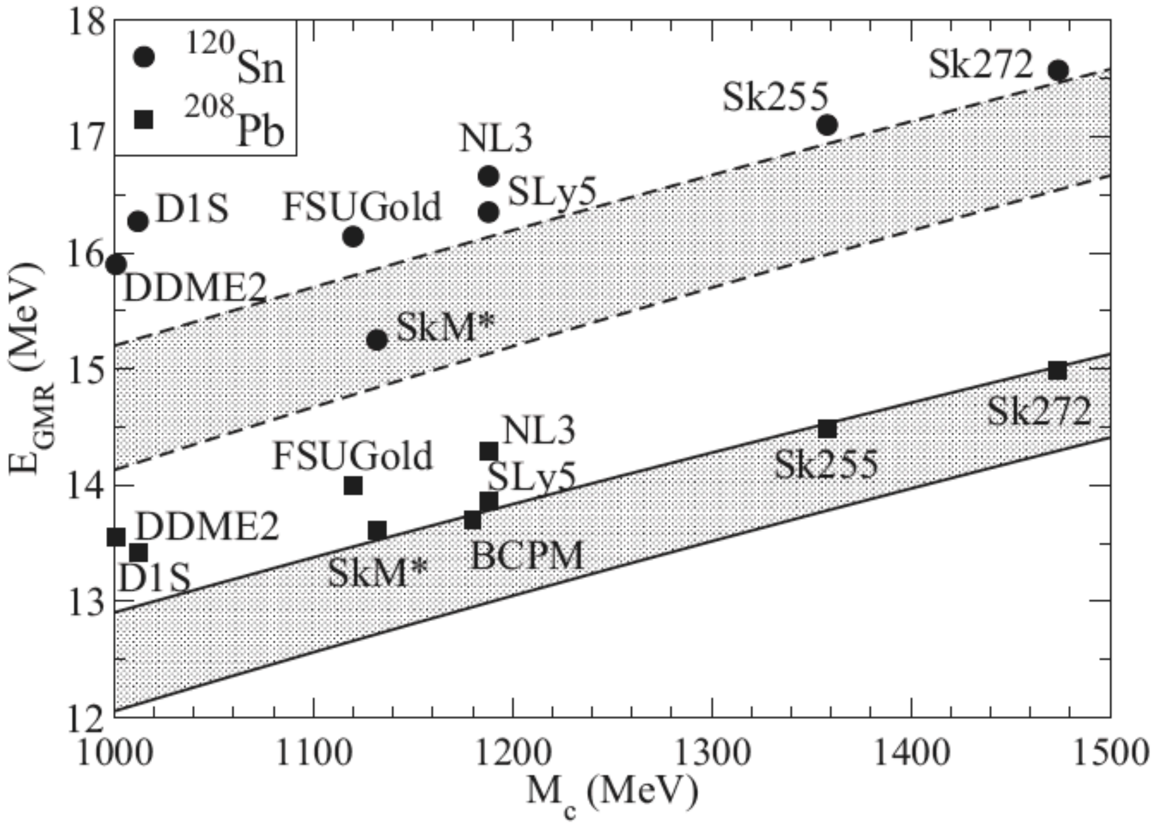
$$= K(\rho) + K_{sym}(\rho)\delta^2$$

$$K_{sym} = \frac{1}{4}\frac{\partial^4 E(\rho,\delta)}{\partial \rho^2 \partial \delta^2}\bigg|_{\rho=\rho_0,\delta=0}$$

Conclusions

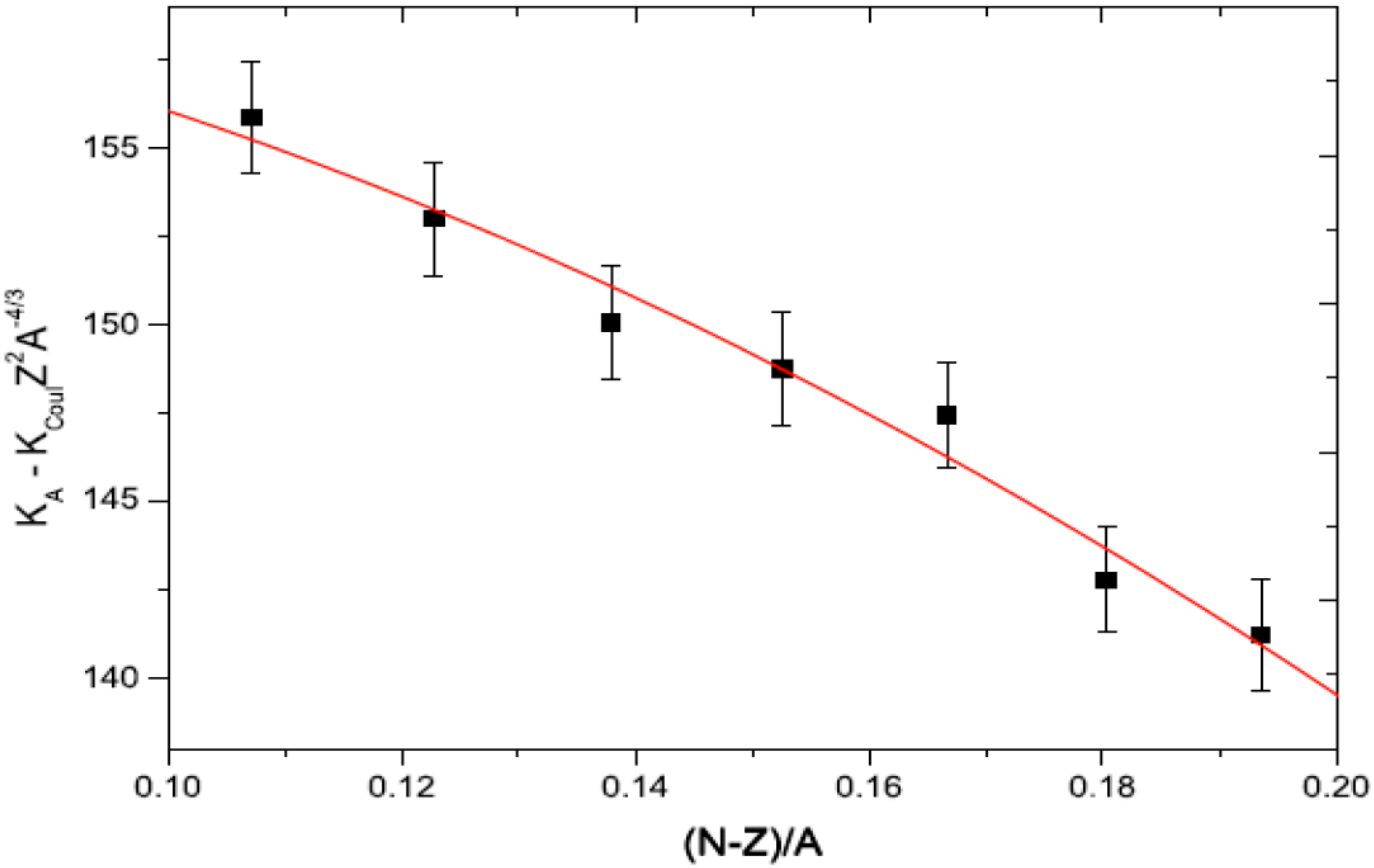
- Incompressibility in nuclei originates from the ZPE
- Concomitant exp. and theo. Indications for a soft monopole mode
- Measurement of the IS L=0 in ^{132}Sn, $^{210,212}Pb$
- The GMR measurement constrains Mc before Kinf
- The density dep. of the EDF is critical to better constrain Kinf.
- Far beyond 132Sn to grasp the isospin dep. of nuclear incompressibility

Analytical $E_{GMR}(M_c)$



$$E_{\rm GMR} = \frac{\hbar}{R}\left\{\frac{20\pi}{3mA}\int_{\rho_0/2}^{\rho_0}\left[a\ln\left(\frac{\rho_0}{\rho}-1\right)+R\right]^2\left(\frac{M_c\rho}{3\rho_c}-\frac{M_c}{3}+K_c\right)\frac{a}{1-\rho/\rho_0}\frac{\rho_0^2}{\rho^2}{\rm d}\rho+\frac{5K_{\rm Coul}}{3m}Z^2A^{-4/3}\right\}^{1/2}$$

Determining the isospin dependence of the incompressibility



T. Li *et al.*, PRL**99**(2007)162503

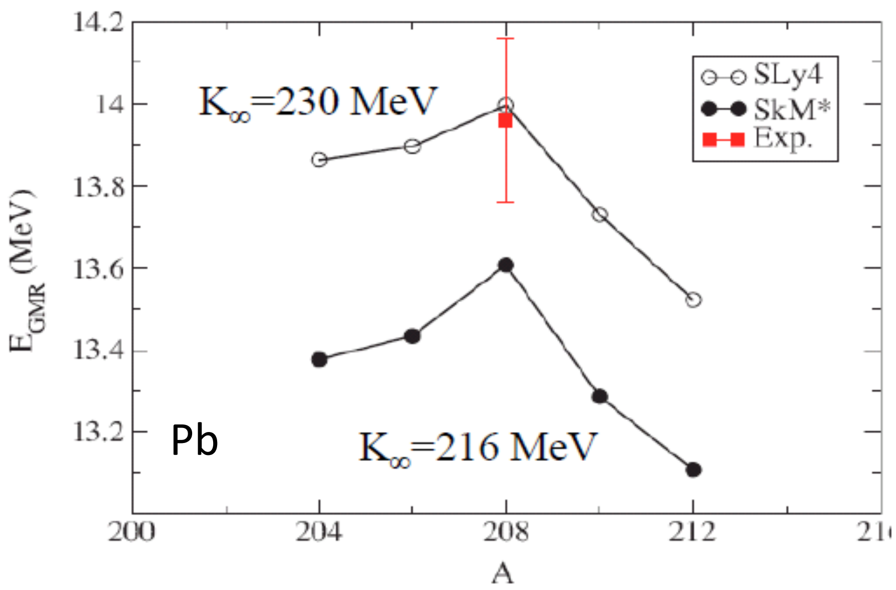
- K_τ= -550 ± 100 MeV

- However the method is macroscopic

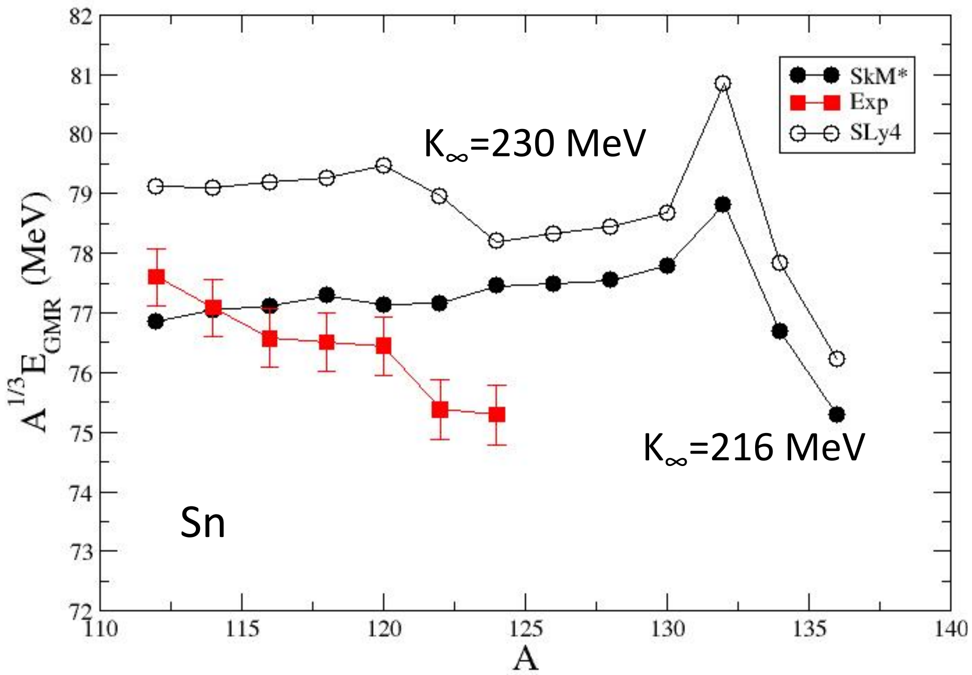
$$K_A = K_\infty + K_{surf} A^{-1/3} + K_\tau \delta^2 + K_{Coul} \frac{Z^2}{A^{4/3}},$$

Pairing and shell effects on the GMR

•Pairing ⇒ shell effects on the GMR value



E. Khan, PRC**80**(2009)057302

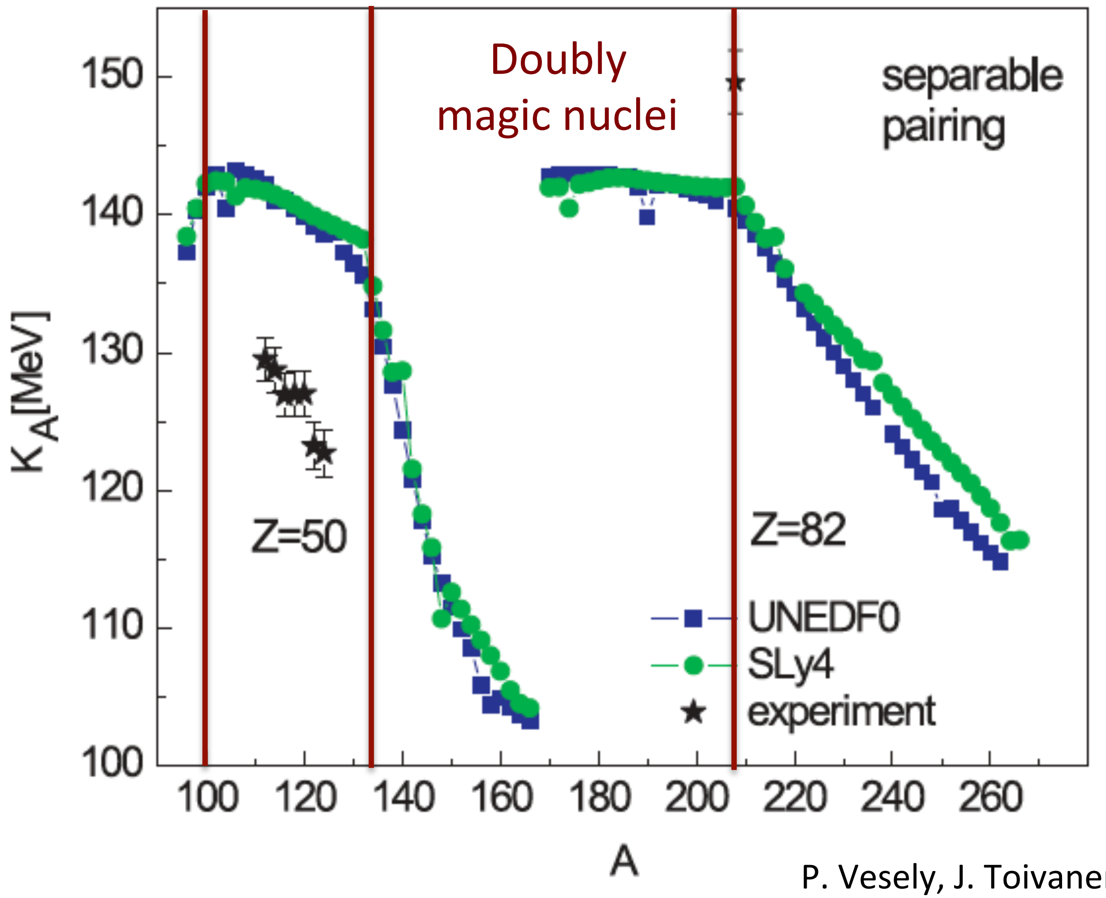


E. Khan, PRC**80**(2009)011307(R)

•Softness of Sn

•Necessity to measure isotopic chains, including unstable neutron-rich nuclei

The shell effect on the GMR

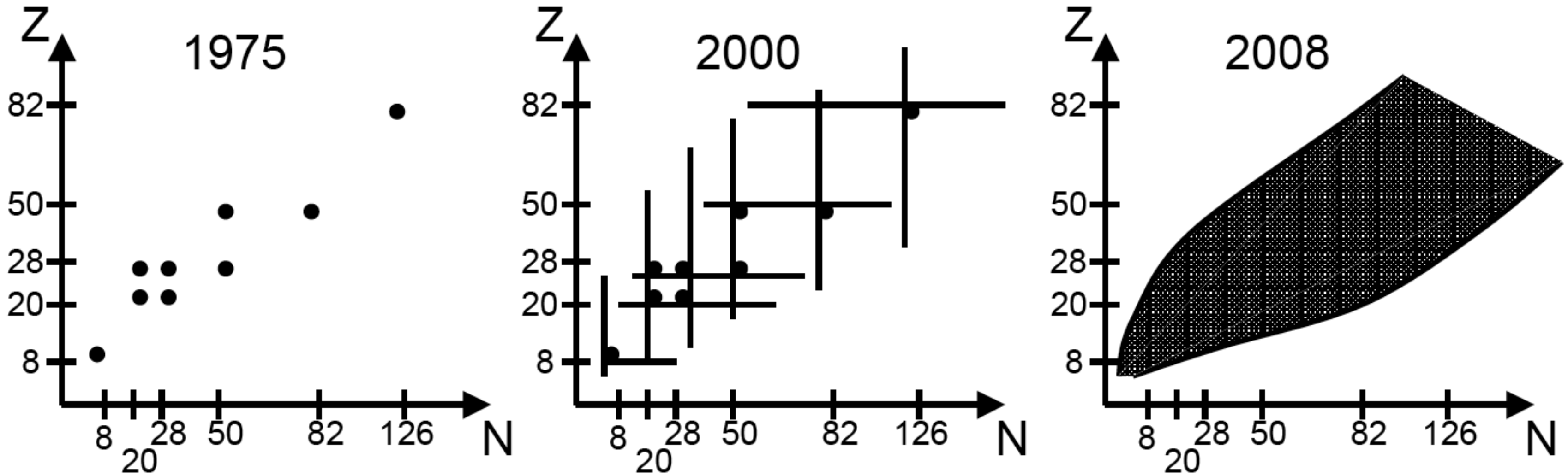


P. Vesely, J. Toivanen, B.G. Carlsson, J. Dobaczewski, N. Michel, A. Pastore, PRC86(2012)024303

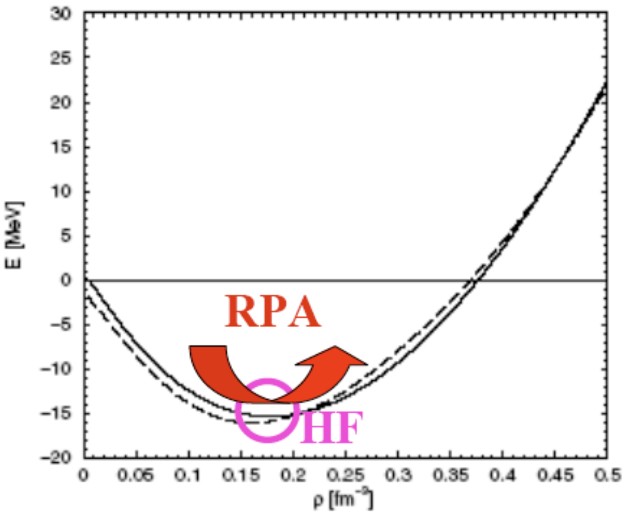
→ shell effects (MEM ?)

Pairing and shell effects not enough to explain Pb/Sn difference on K_∞

Nuclear excitations

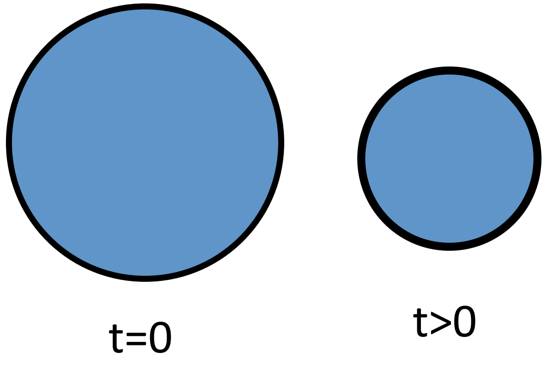


Picture of a GMR



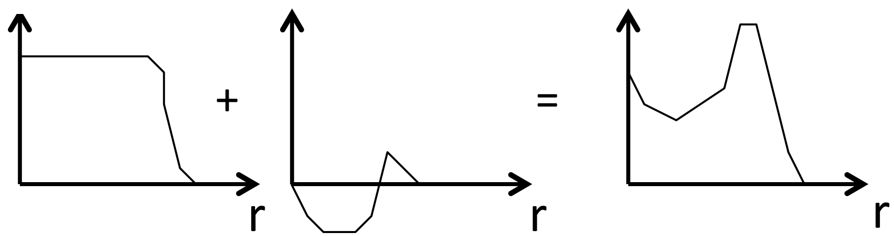
$$\rho(r,t) = \rho(r) + \delta\rho(r)Cos(\omega t)$$

GMR



transition density

$$\rho(r) \quad + \quad \delta\rho(r) = \rho(r,0)$$

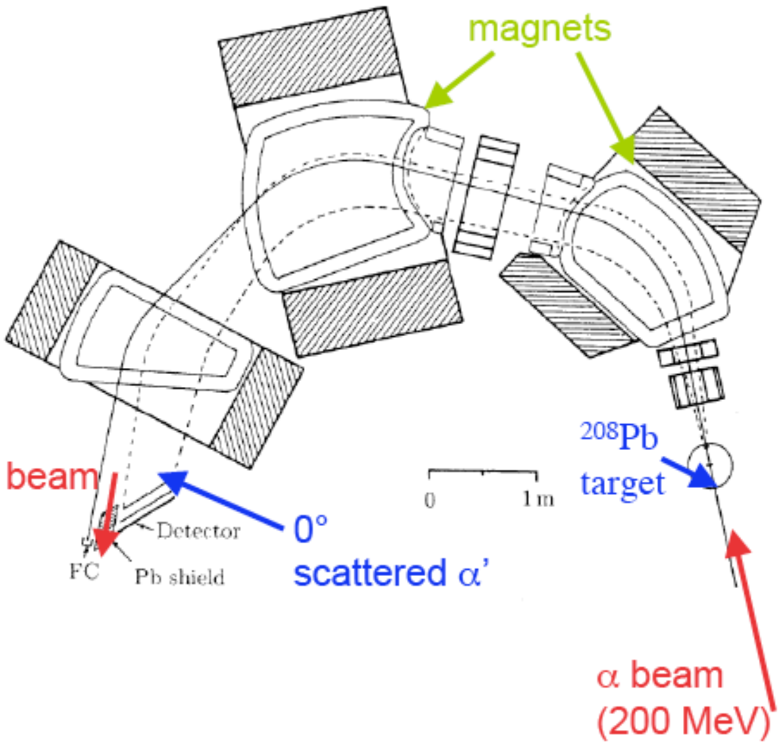


- GR are collective (many ph pairs involved)
- Small amplitude vibration: $\delta\rho \ll \rho$

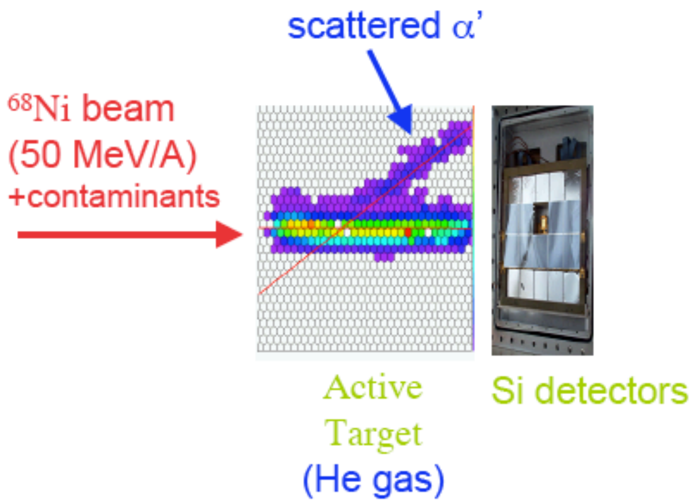
$$\delta\rho(r) = \sum_{mi}(X_{mi} - Y_{mi})\phi_i^*(r)\phi_m(r)$$

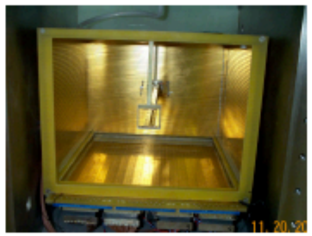
Measurement of IS monopole modes

With stable nuclei

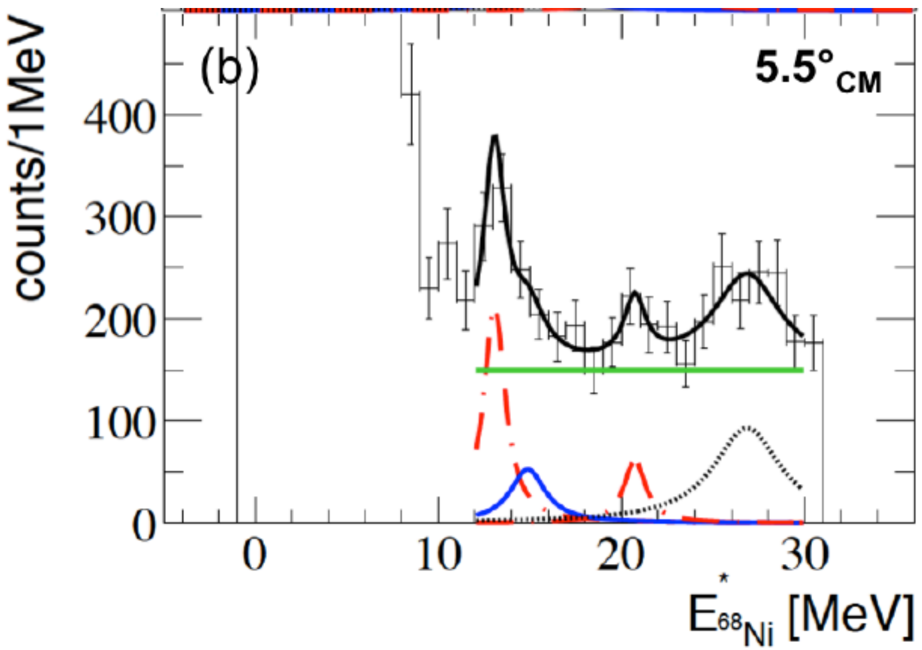


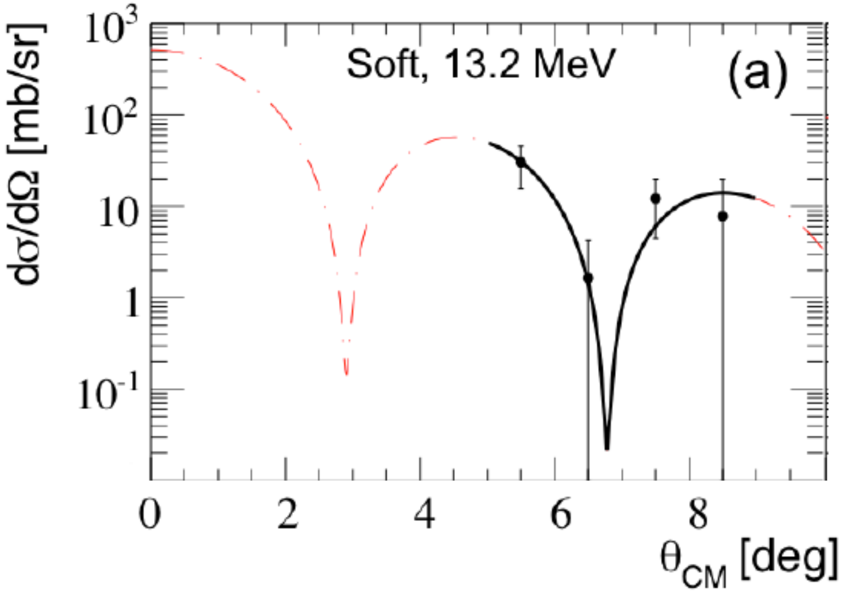
With exotic nuclei





Is the soft monopole mode detected ?





Exp. collaboration

M. Vandebrouck[1], J. Gibelin[2], E. Khan[1], N.L. Achouri[2], H. Baba[3], D. Beaumel[1], Y. Blumenfeld[1], M. Caamaño[4], L. Caceres[5], F. Delaunay[2], B. Fernandez-Dominguez[4], U. Garg[6], G.F. Grinyer[5], M.N. Harakeh[7], N. Kalantar[7], W. Mittig[8], R. Raabe[9], T. Roger[9,5], P. Roussel-Chomaz[10], H. Savajols[5], O. Sorlin[5], C. Stodel[5], D. Suzuki[8,1], J.C. Thomas[5].

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+ G. Colò (Milano) and N. Keeley (Warsaw) for theo. predictions of the angular distributions