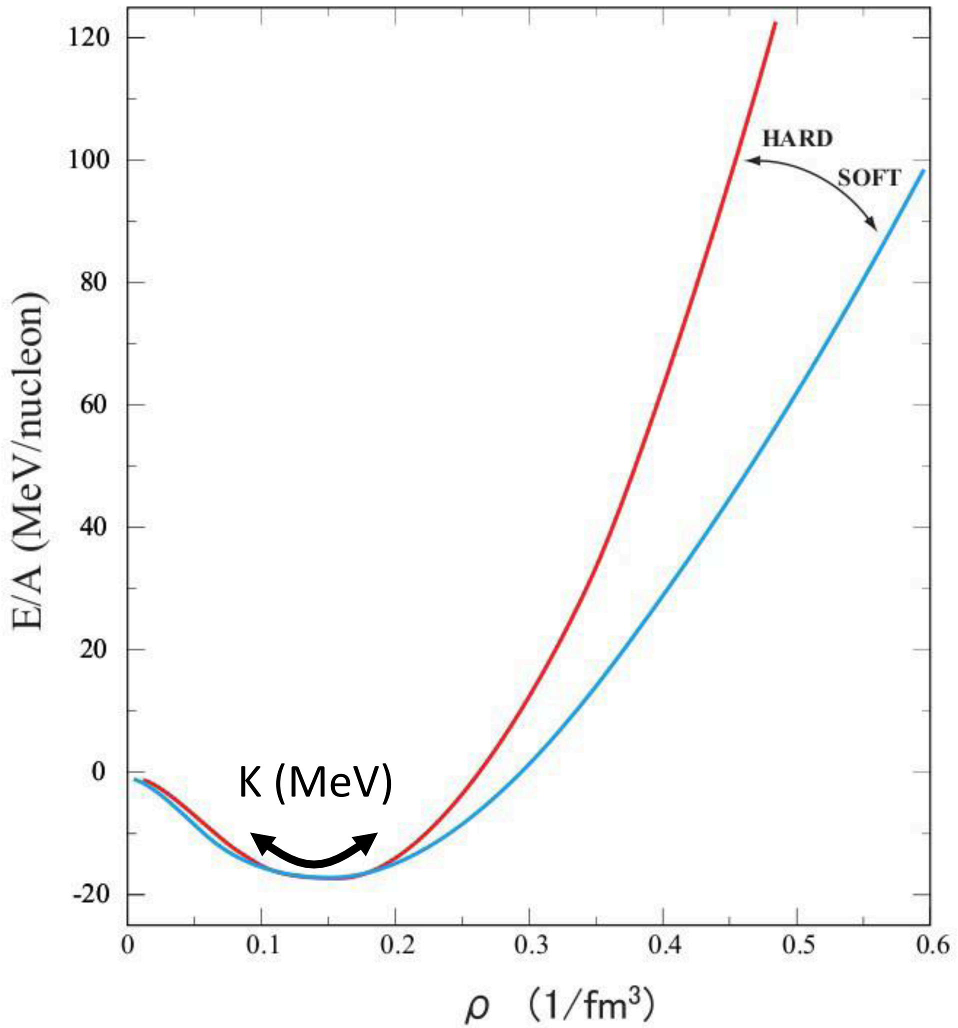
The determination of the nuclear incompressibility

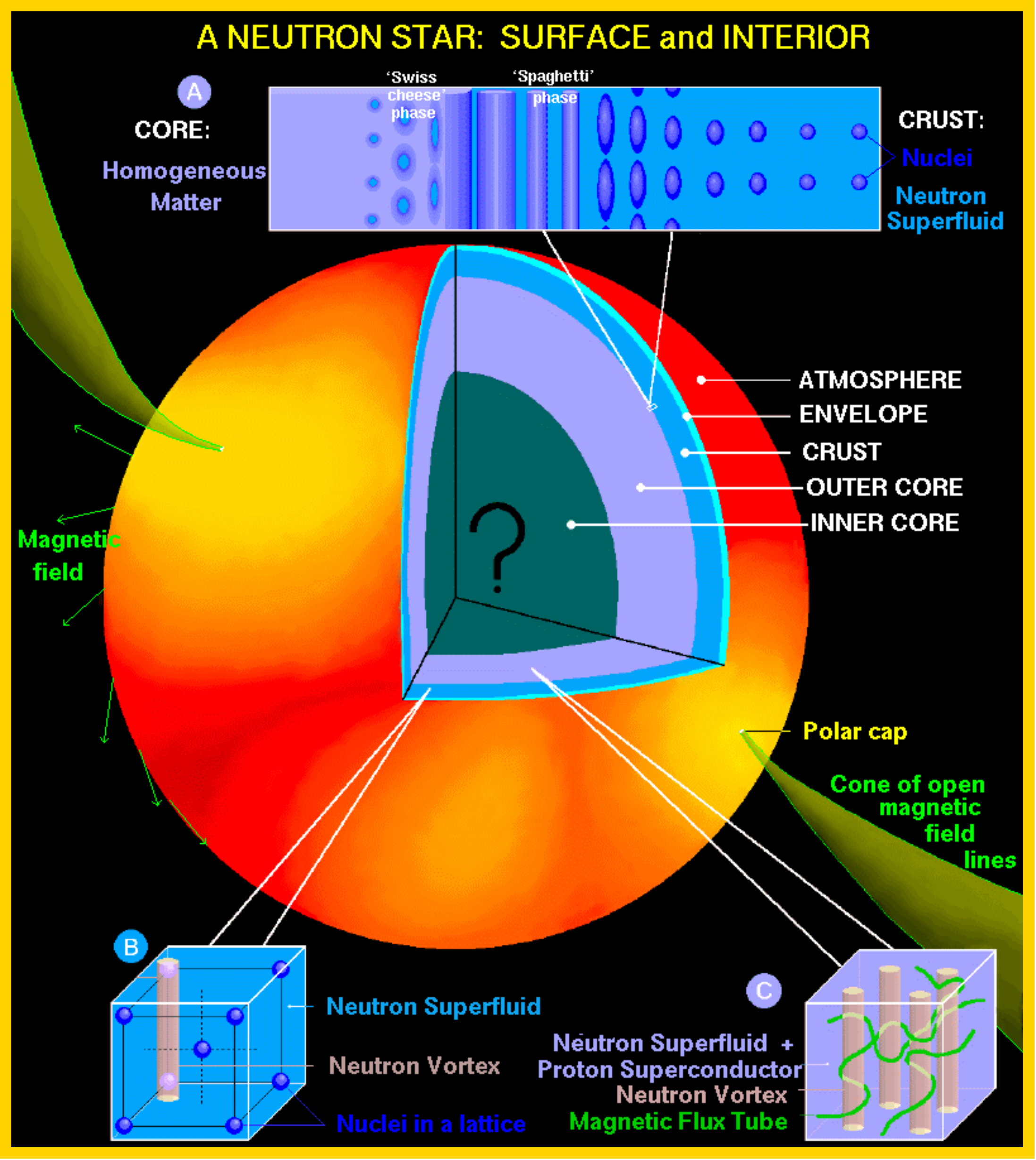
E. Khan

Nuclear incompressiblity

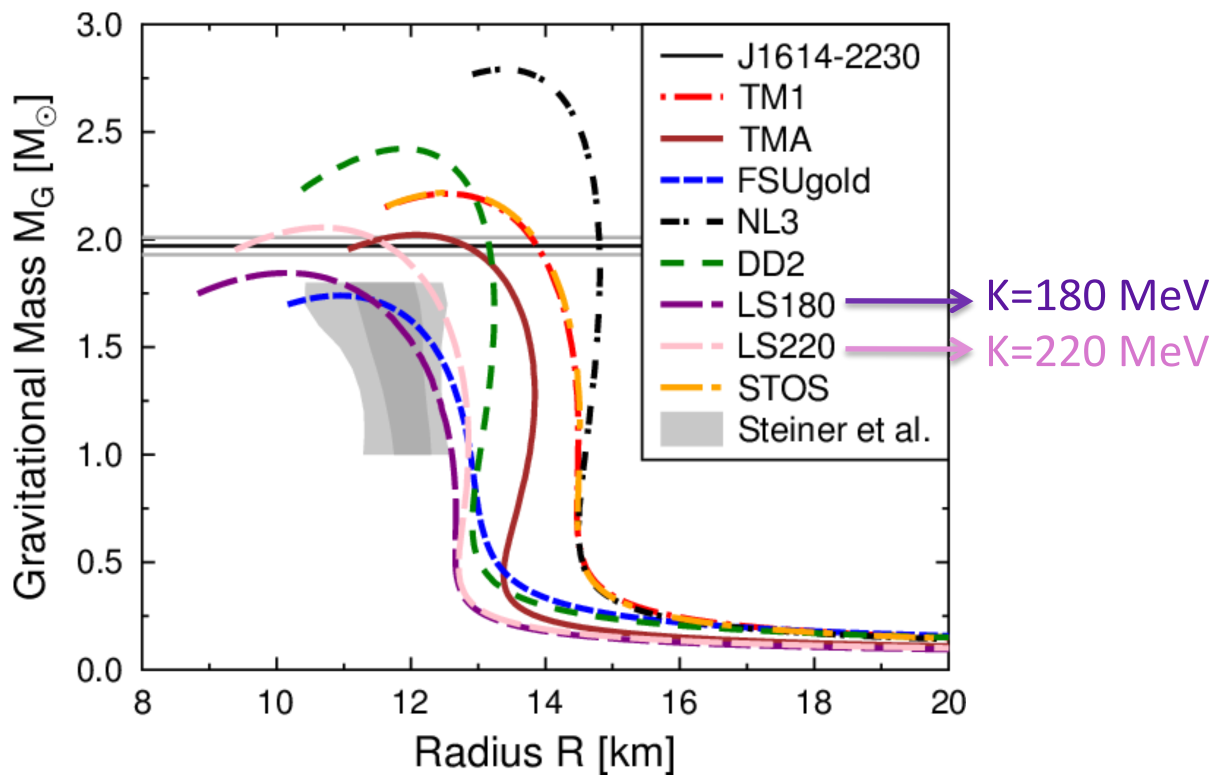
Incompressibility: energy needed to change the density of the nuclear matter around equilibrium



Neutron stars

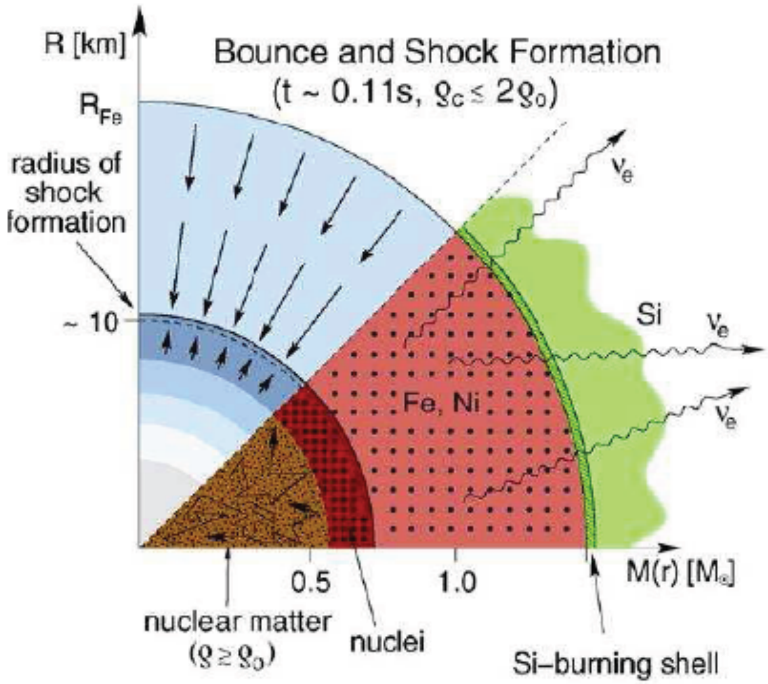


Neutron stars

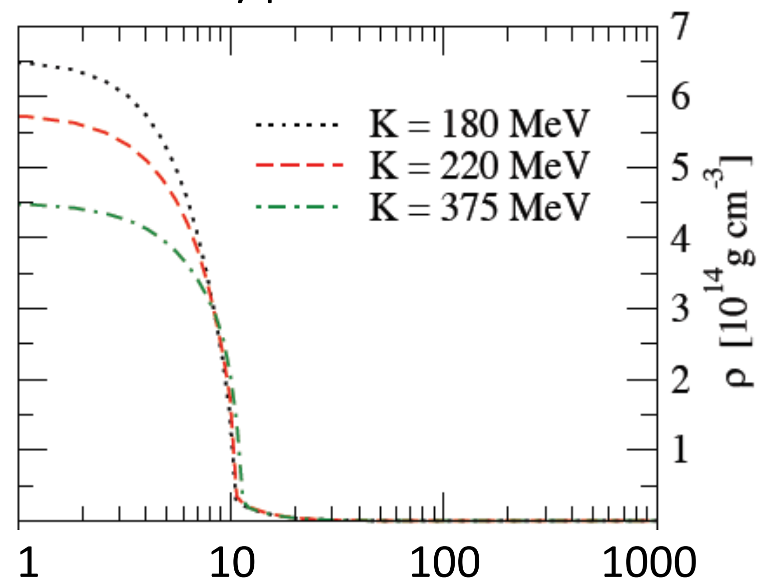


Matthias Hempel
ITP Franckfurt

SuperNovae bounce



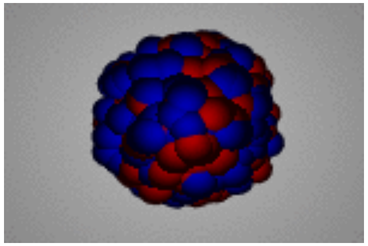
Density profile at bounce

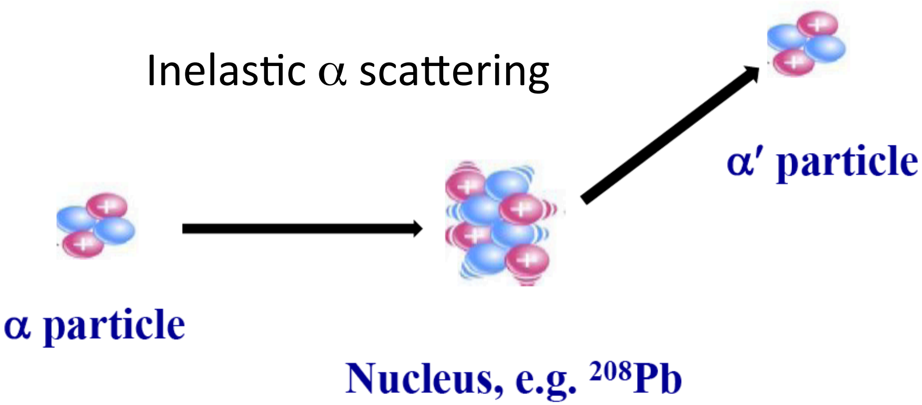


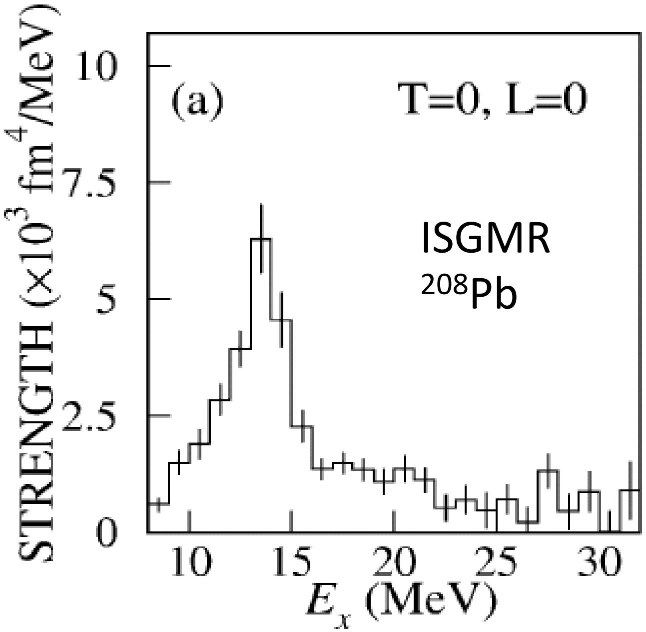
A. Fantina PhD (2010) IPNO-IAA

Method to determine K_∞

- The nucleus exhibits a compression mode (how lucky !): the Giant Monopole Resonance







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

- How to link E_{GMR} to K_∞ ?

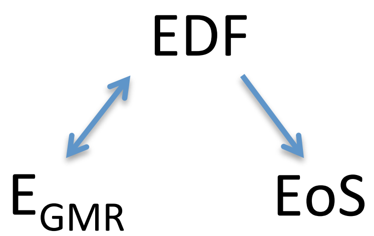
1) Macroscopic method

$$E_{ISGMR} = \sqrt{\frac{\hbar^2 K_A}{m < r^2 >_m}},$$

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

- Limitations : shell effects, data accuracy
- Necessity for a more accurate method

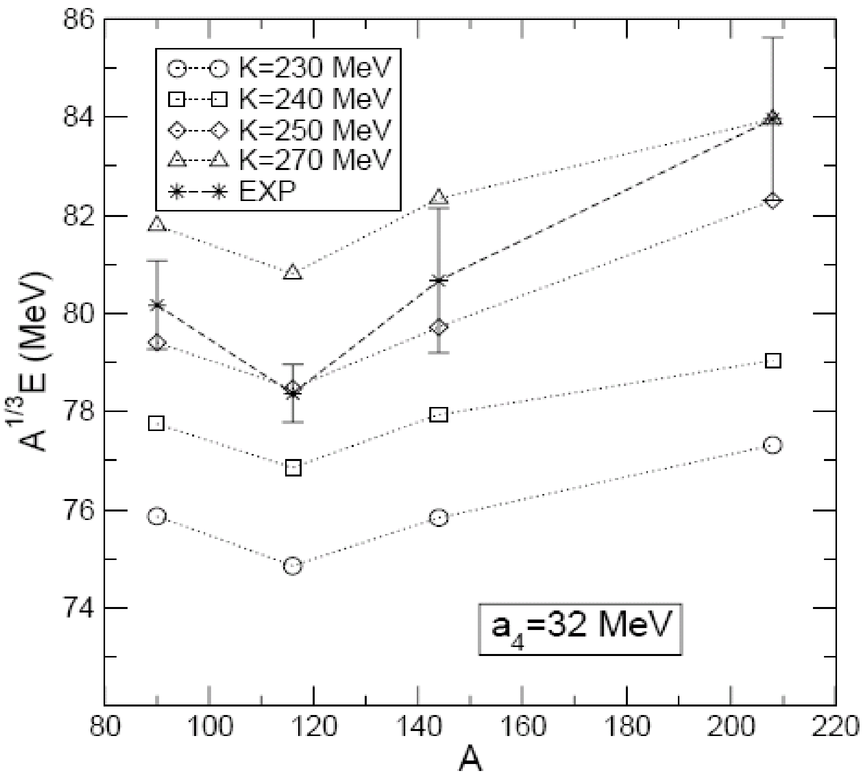
2) Microscopic method



- Nuclear structure models: from EDF to E_{GMR}
- Limitations : all the terms (EoS) have to be correctly predicted at once

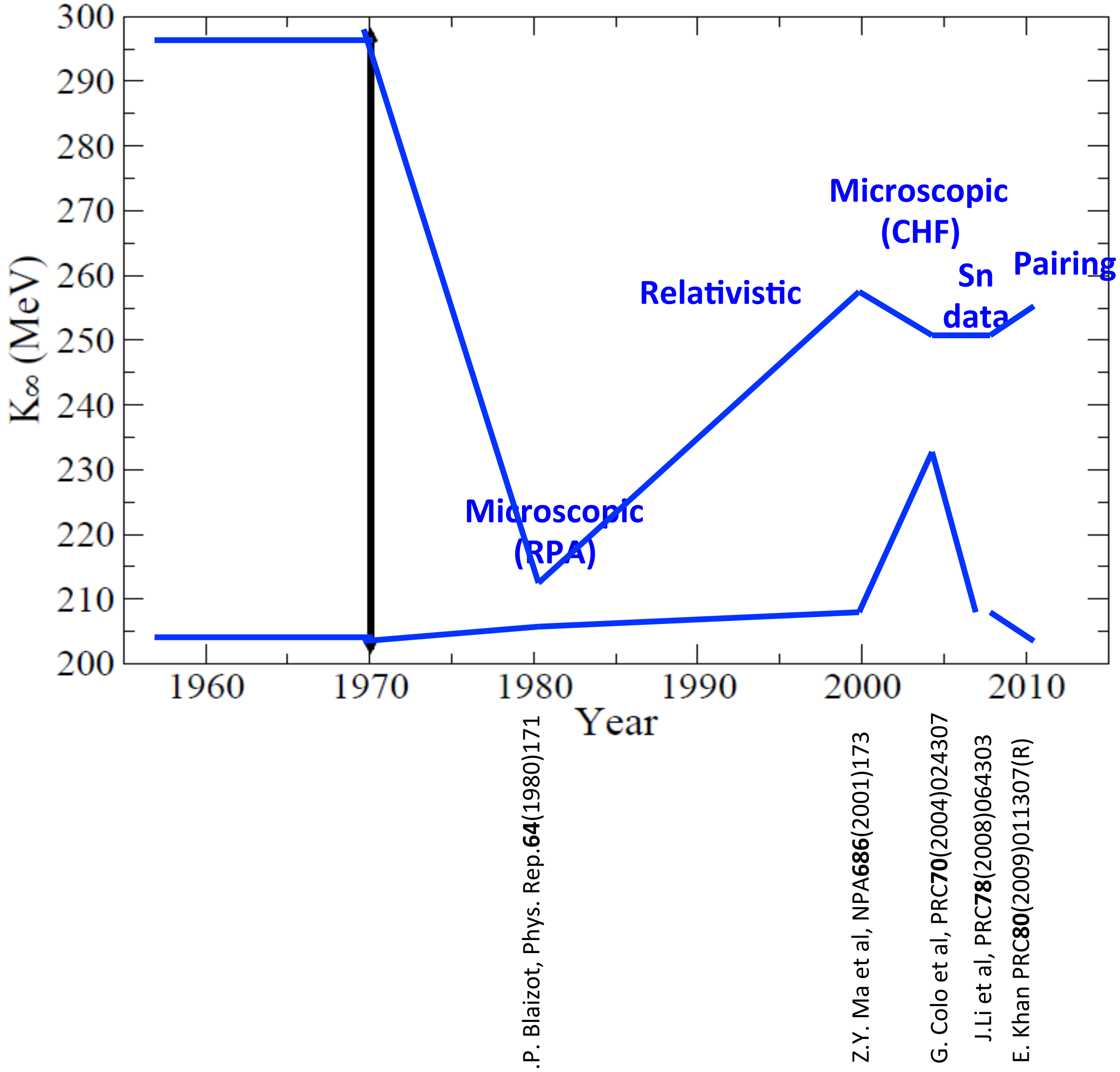
From EDF to E_{GMR}

- HF, RMF, RPA, CHF : the only parameter is the EDF



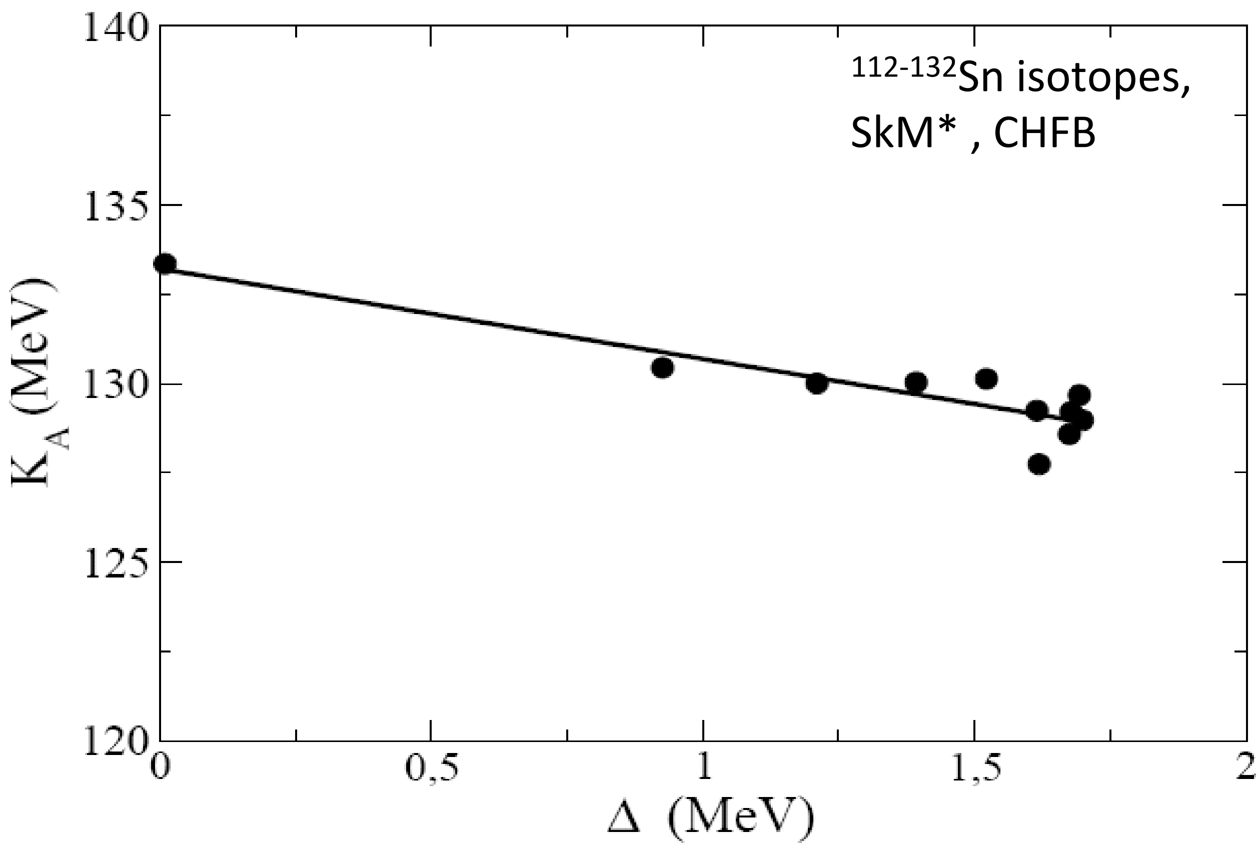
D. Vretenar et al, PRC**68**(2003)024310

Uncertainties on K_∞



K_∞ = 240 ± 30 MeV

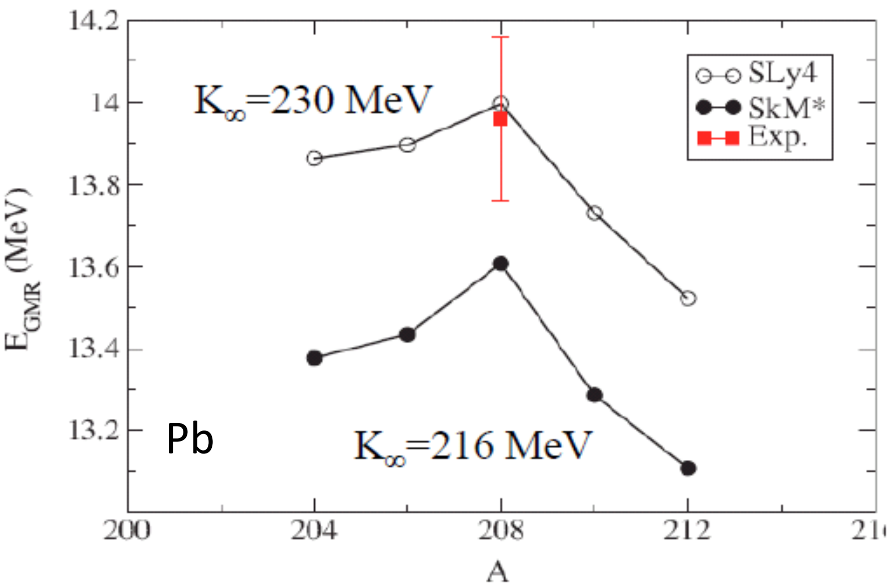
Nuclear incompressibility vs. pairing

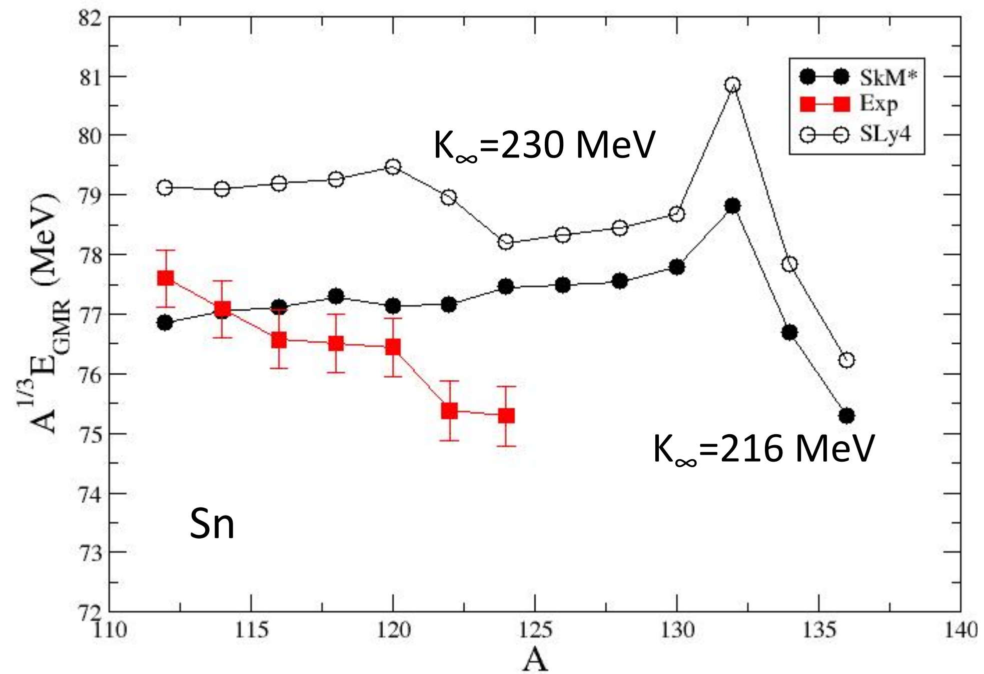


- Cooper pairs favor compressibility
- Incompressibility of **superfluid** nuclear matter: $\mathbf{K_\infty(\Delta)}$

Pairing and shell effects on the GMR

- Pairing $\Rightarrow$ shell effects on the GMR value



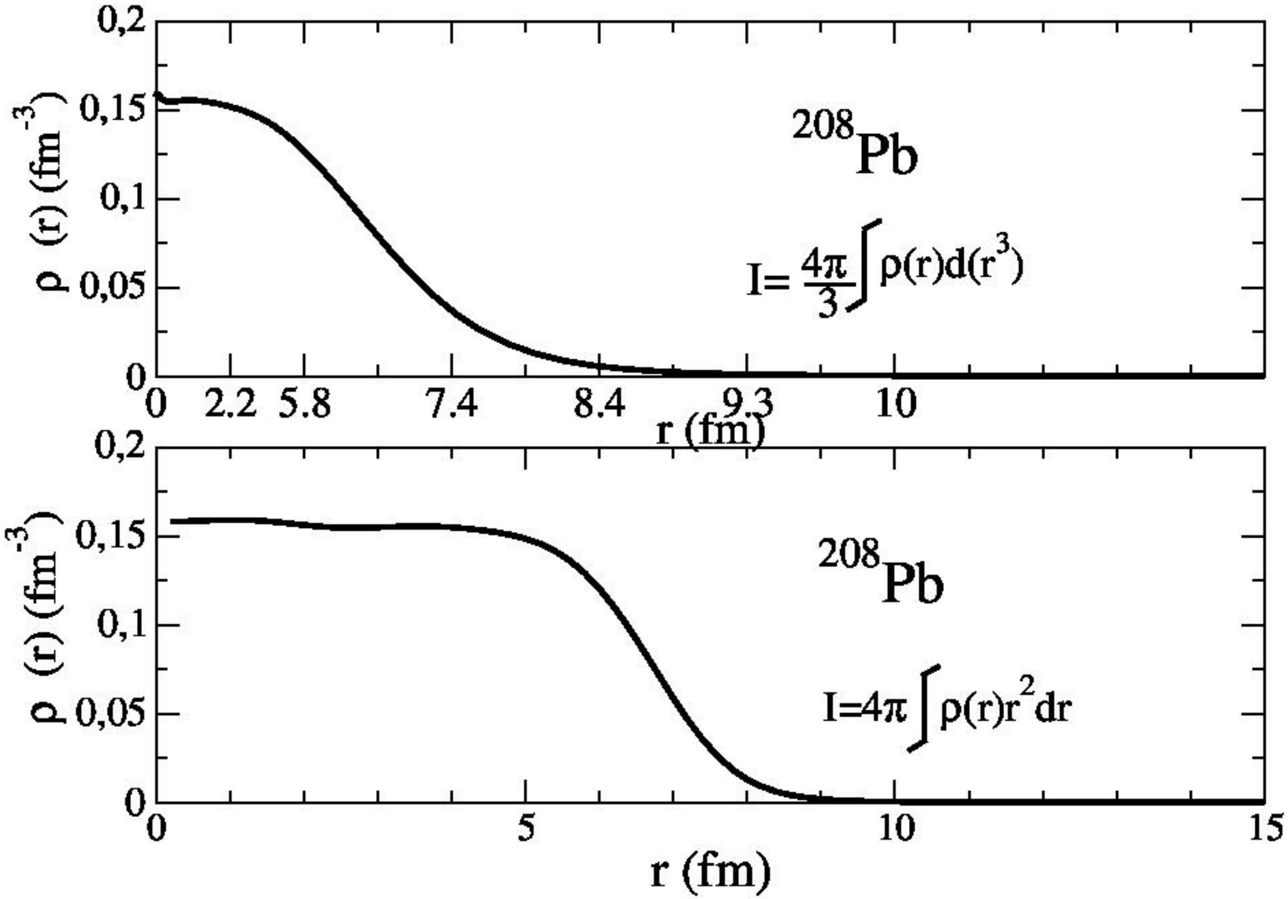


E. Khan, PRC**80**(2009)011307(R)

- Softness of Sn

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

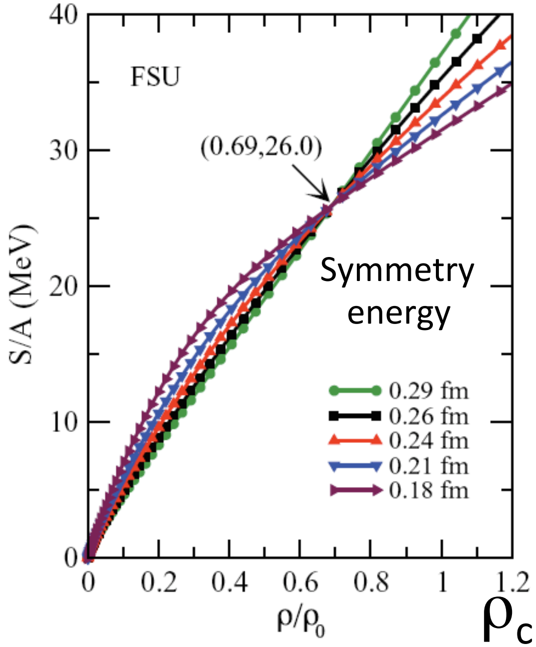
Saturation ?

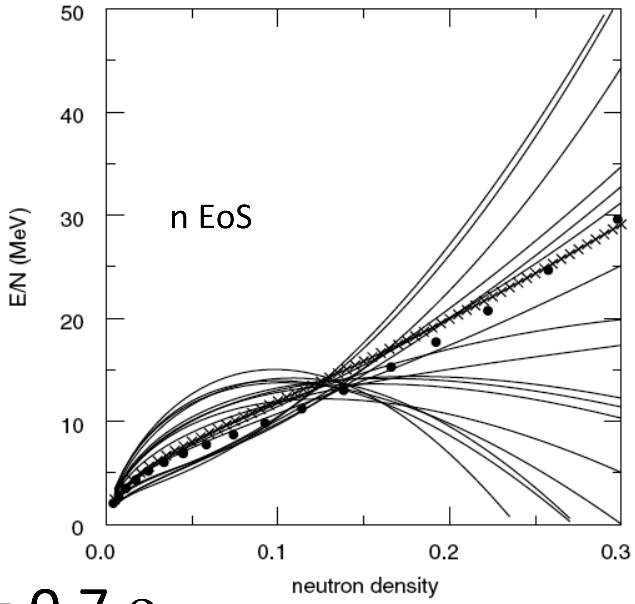


- Surface: 2/3 of nucleons in ^{208}Pb

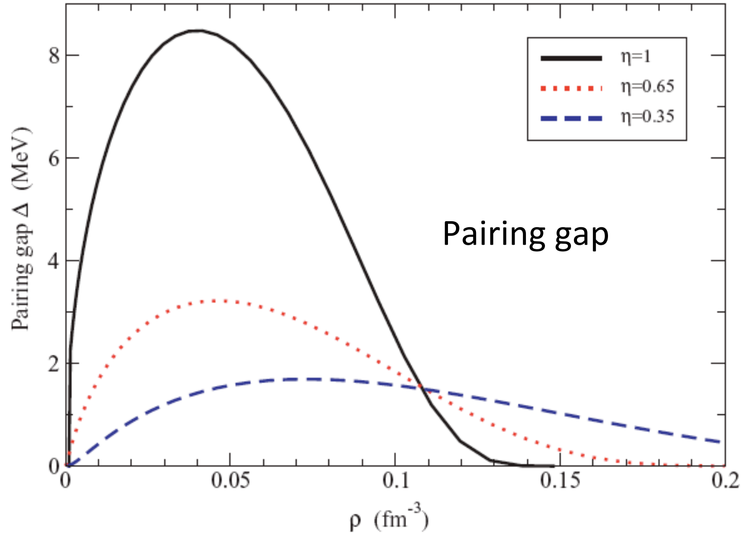
- Saturation density area may not be the most probed

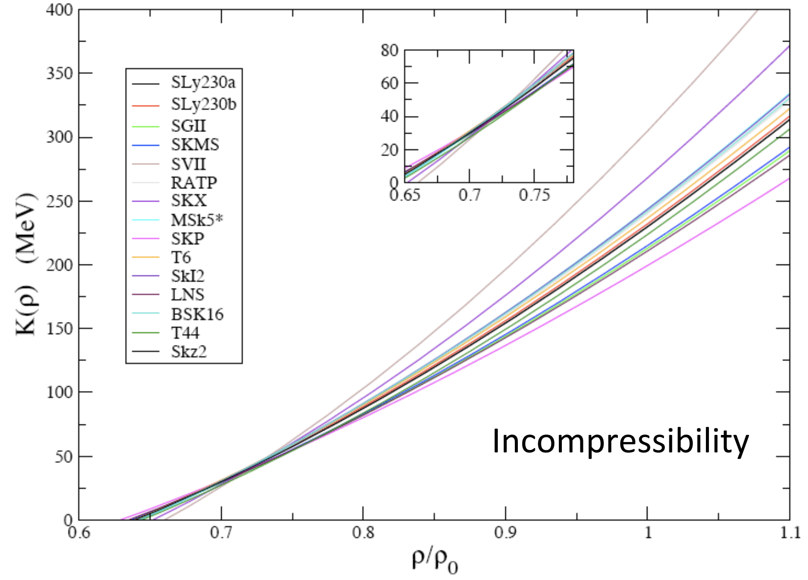
The crossing density





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

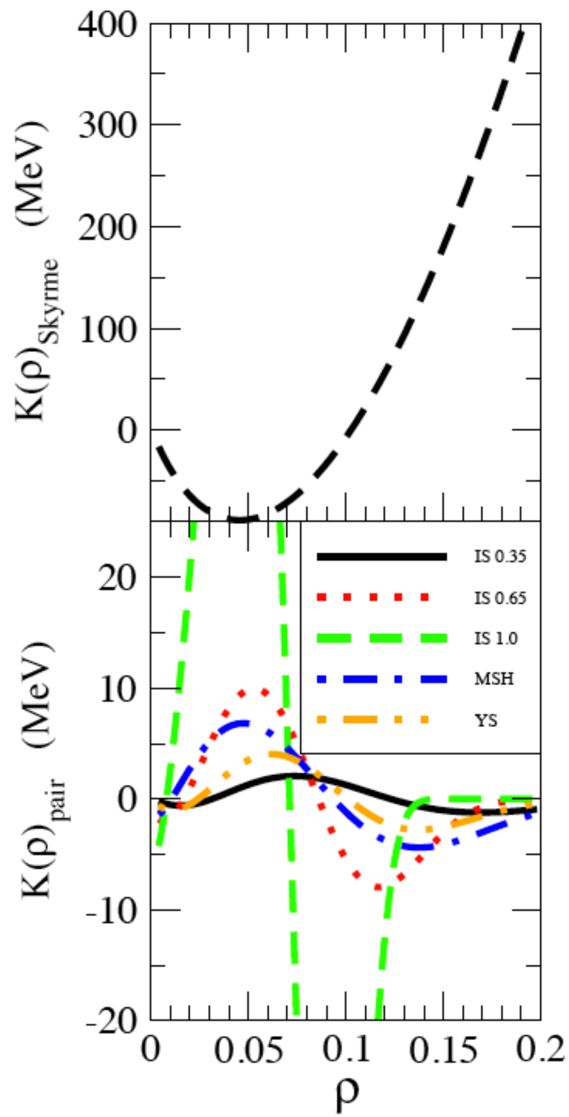




Superfluidity acting on incompressibility

•Explains why superfluidity acts on incompressibility

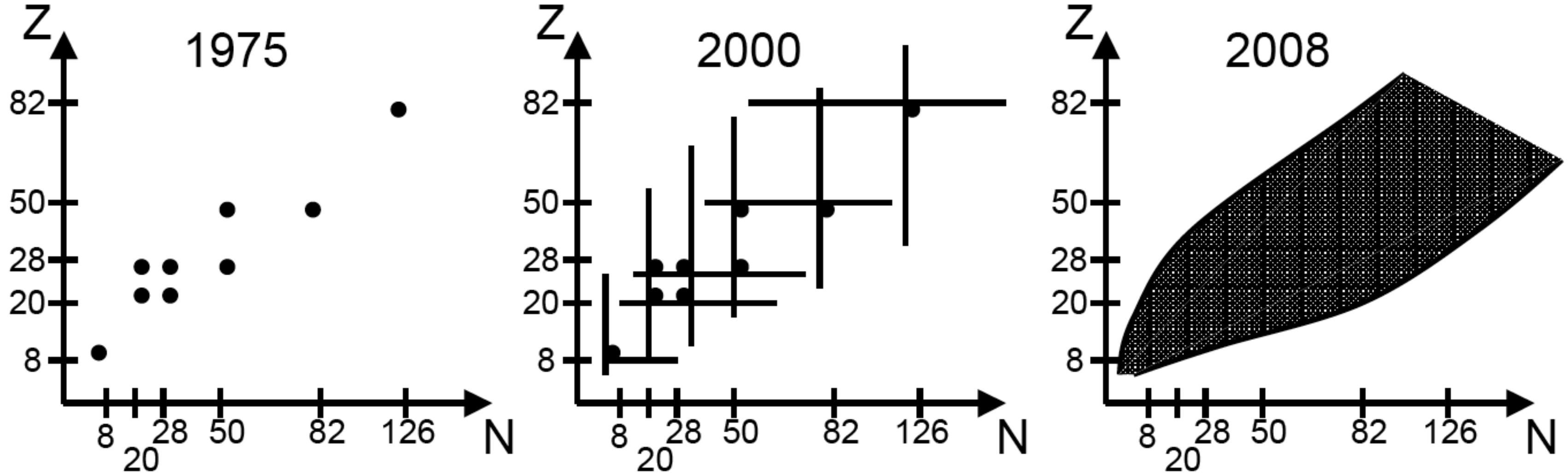
•The microscopic method is necessary



E. Khan et al., PRC**82**(2010)024322

Compressing nuclei
from all over the nuclear chart

Nuclear excitations



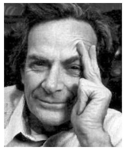
Theory

EDF $\rightarrow$ **E[ρ]**

HK theorem
Skyrme
Gogny

Action

$$S=\int_{t_1}^{t_2} dt \int d\vec{r}\,(i\hbar\Psi^*(\vec{r},t)\partial_t\Psi(\vec{r},t)-E[\rho])$$



Ind. Particles

$$S=i\hbar\sum_{i=1}^{A}\int_{t_1}^{t_2} dt \int d\vec{r}\,(\varphi_i^*(\vec{r},t)\partial_t\varphi_i(\vec{r},t)-E[\rho])$$

Many-body problem

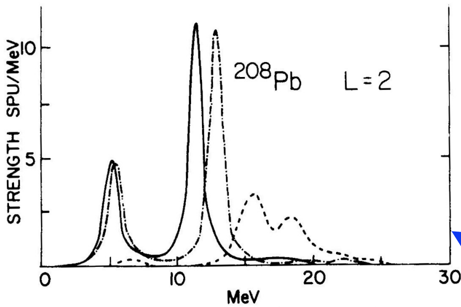
Least action pcple $\delta S=0$

TDHF

$$i\hbar\partial_t\varphi_i=\frac{\delta E[\rho]}{\delta\rho}\varphi_i\widehat{=}h\varphi_i$$

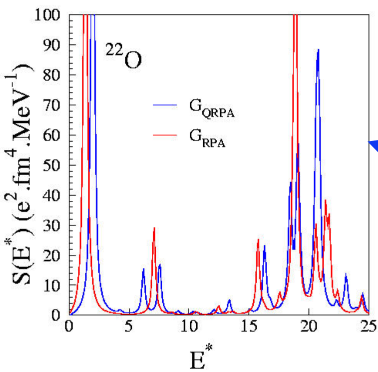
Linear response theory

$$\Pi=\Pi_0+\Pi_0\frac{\delta h}{\delta\rho}\Pi$$



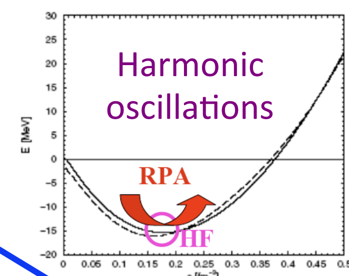
G.F. Bertsch and S.F. Tsai, Phys. Rev. C18 (**1975**) 125

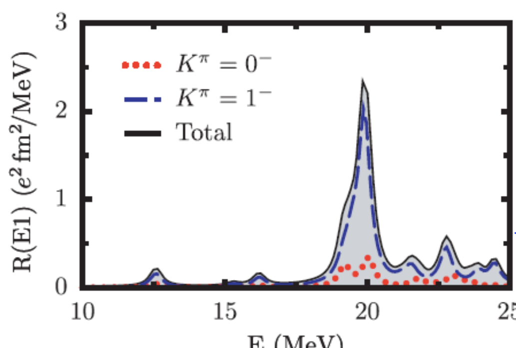
Magic nuclei



E. Khan, Nguyen Van Giai, Phys. Lett. B472 (**2000**) 253

Isotopic chain





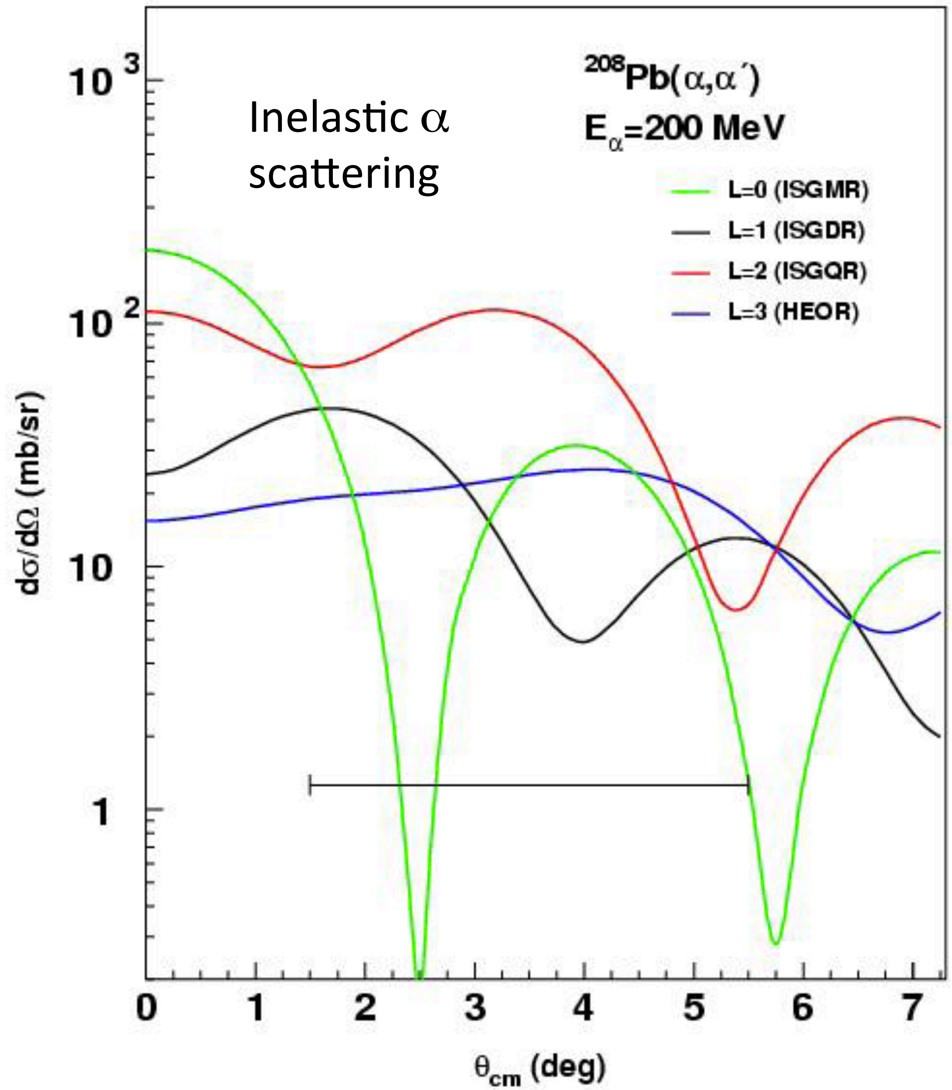
Deformed nuclei

D. Pena Arteaga, P. Ring Phys. Rev. C77(**2008**) 034317

Response function S(E*)

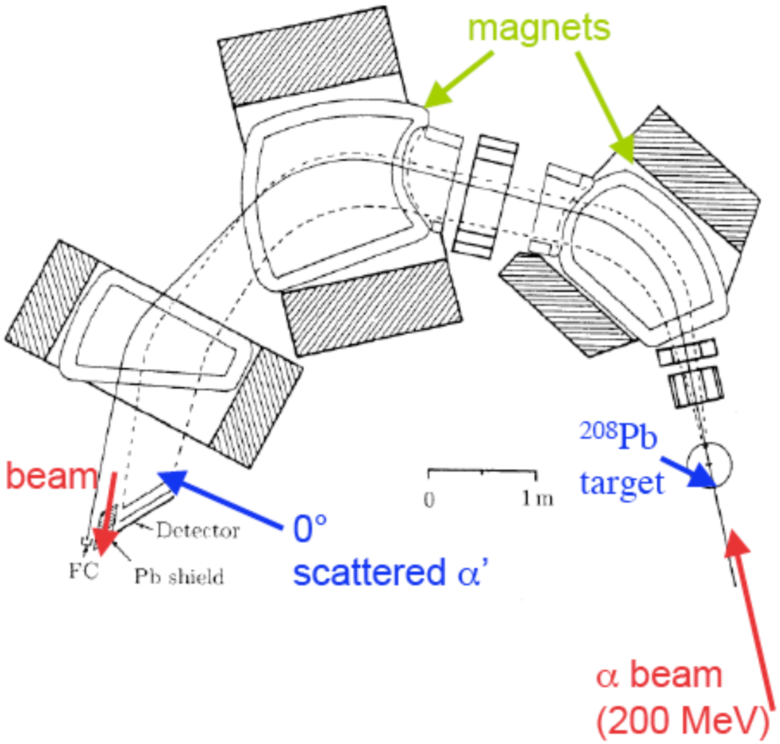
Measurement of E_{GMR}

- Necessity for isotopic chains
- Measurement close to 0 deg. CM
- L separation using the angular distributions

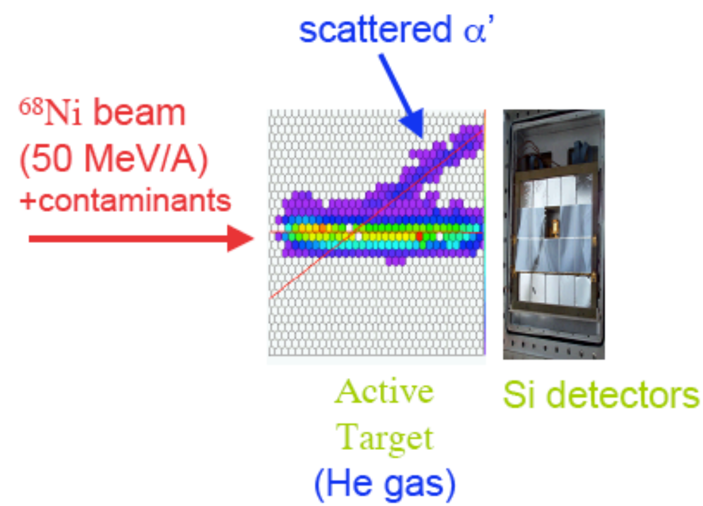


Measurement of E_{GMR}

With stable nuclei



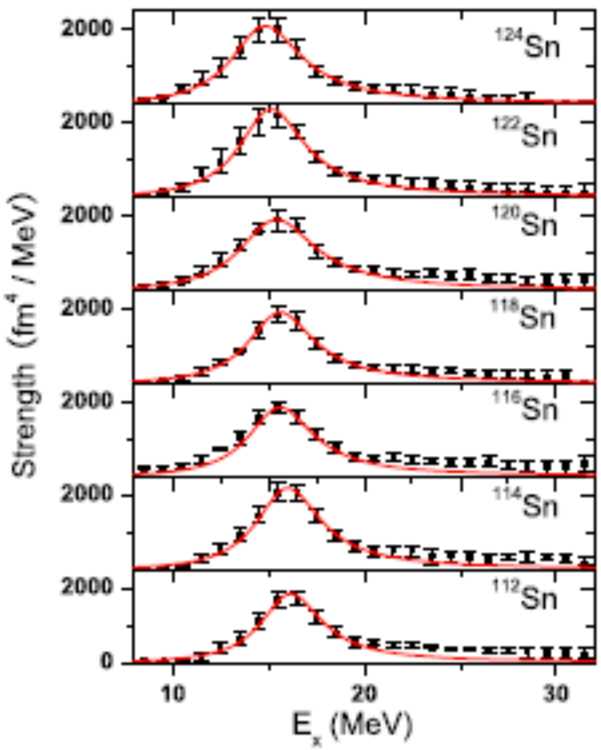
With exotic nuclei



Measurement of E_{GMR}

With stable nuclei

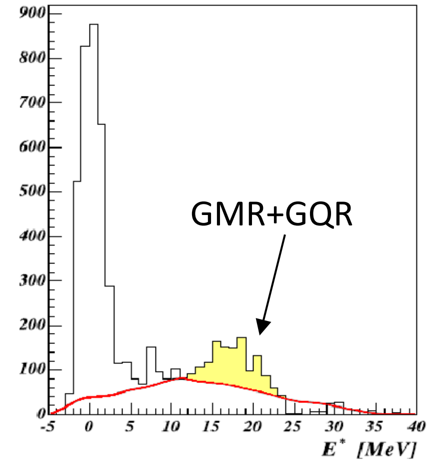
$^{112-124}$Sn

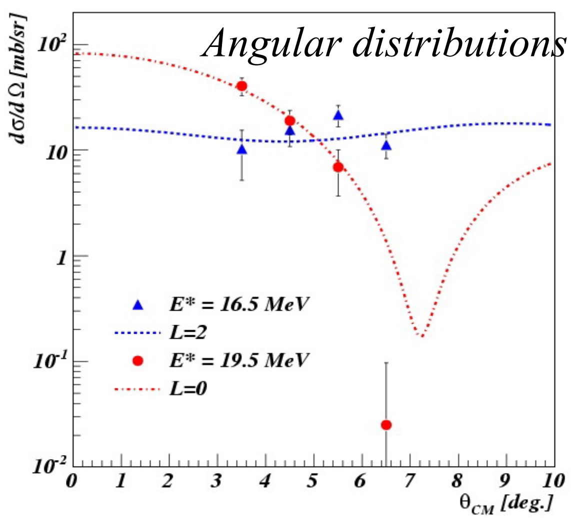


T. Li *et al.*, PRL**99**(2007)162503

With exotic nuclei

^{56,68}Ni



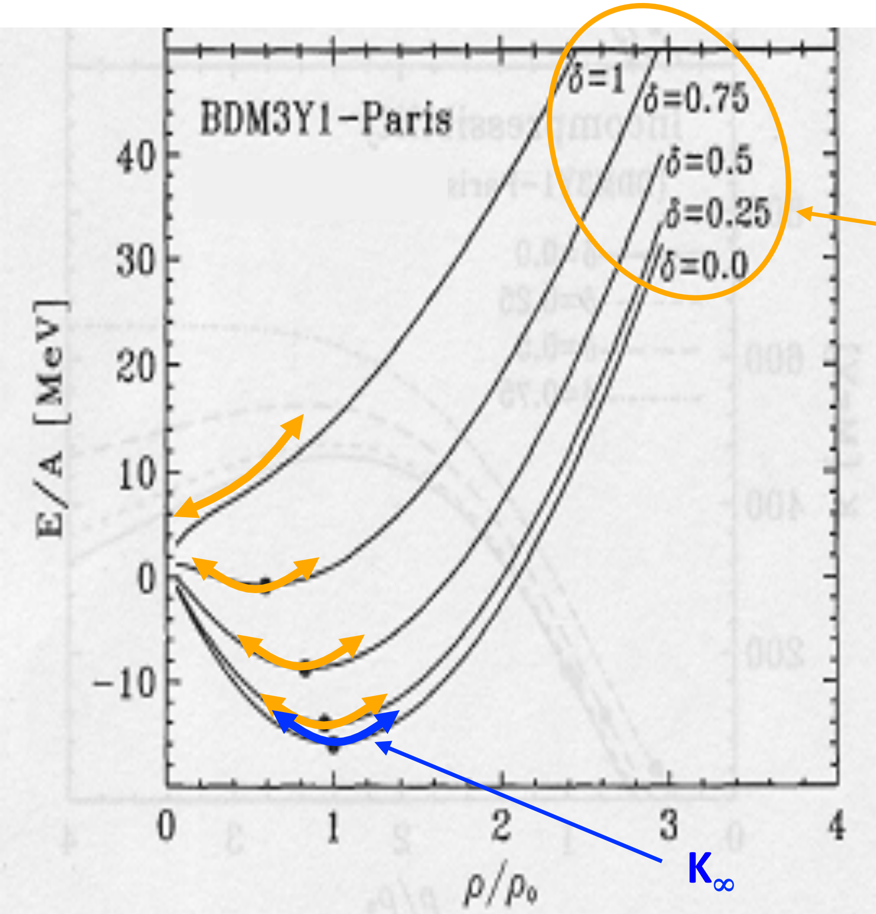


C. Monrozeau *et al.*, PRL**100**(2008)042501

Incompressibility and neutron excess

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

: **density** and **neutron excess** $\delta=(N-Z)/A$



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

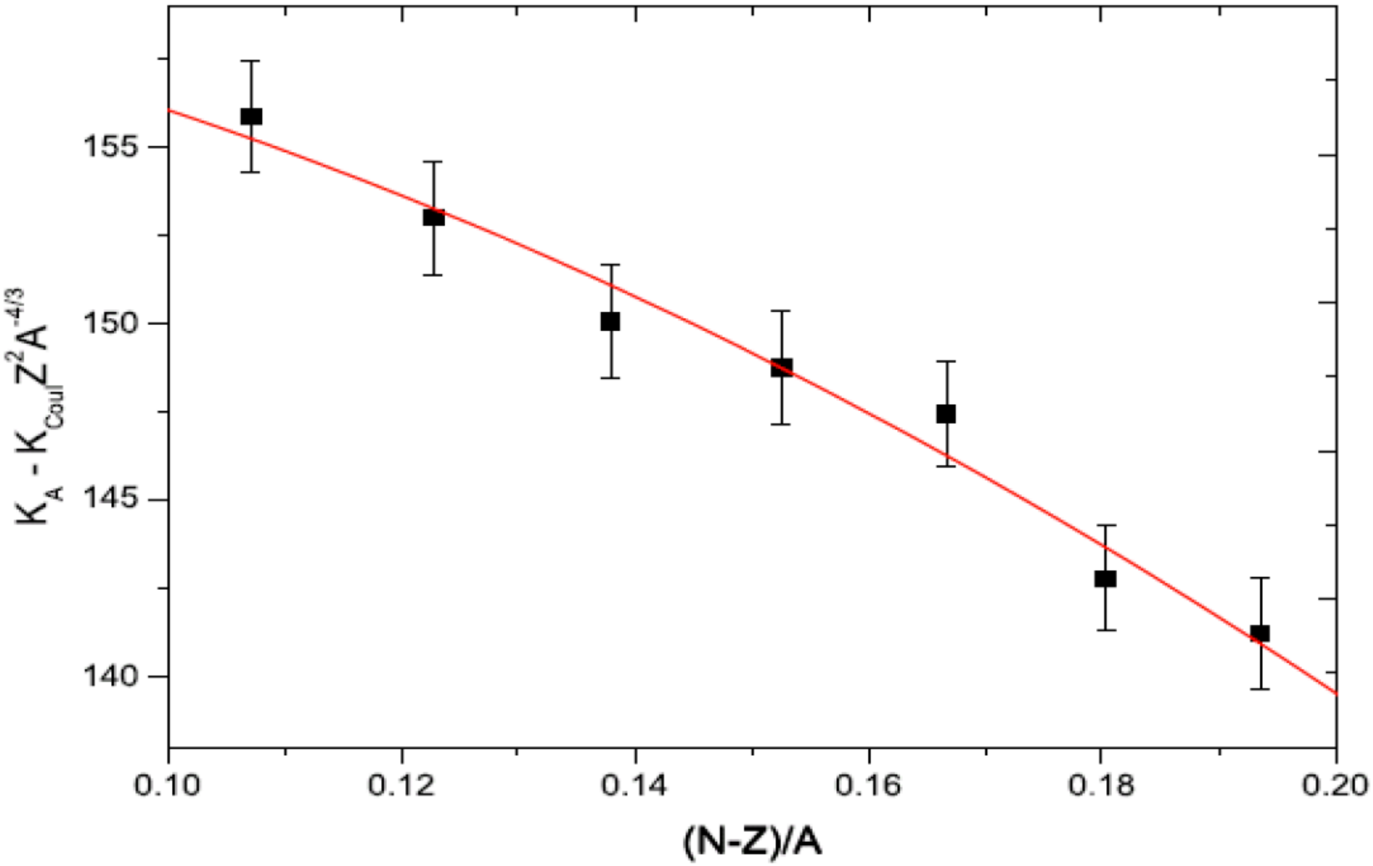
evolution of incompressibility with asymmetry:

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

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

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

Determining the isospin dependence of the incompressibility



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

- K_τ= -550 ± 100 MeV

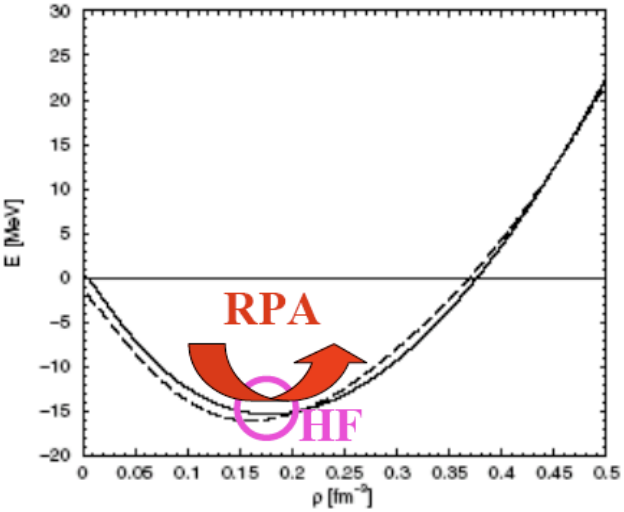
- However the method is macroscopic

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

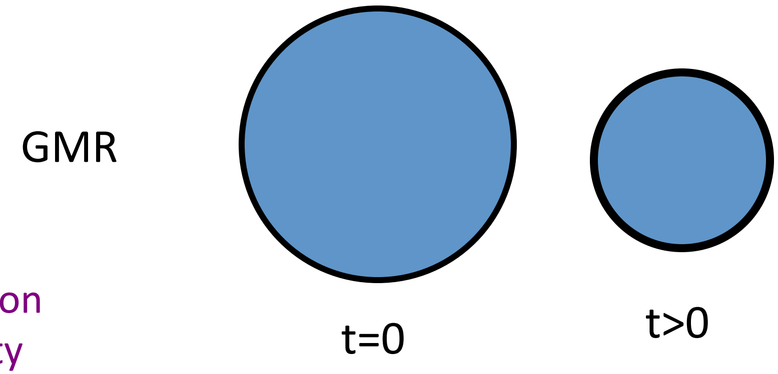
Conclusion

- Nuclear incompressibility has an impact on some astro quantities: neutron stars and SN bounce
- Nuclei have a compression mode : GMR !
- Macro: easy but not very reliable
- Micro: K_∞ = 240 ± 30 MeV
- Status: superfluidity effect, crossing density, Pb vs Sn softness
- Need to measure the GMR in isotopic chains including neutron-rich nuclei
- Isospin dep. of incompressibility : only macro: K_τ= -550 ± 100 MeV
  micro needs more data to constrain the EDF

Picture of a GMR

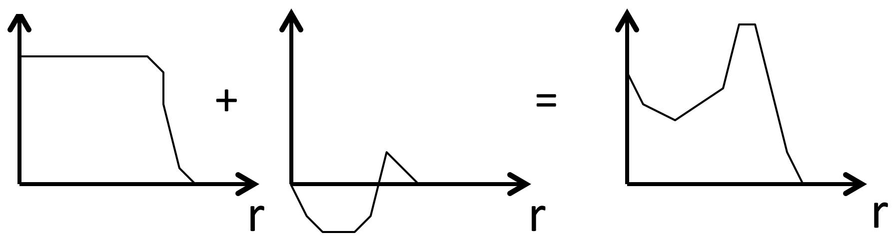


$$\rho(r,t) = \rho(r) + \delta\rho(r) Cos(\omega t)$$



transition density

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



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

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