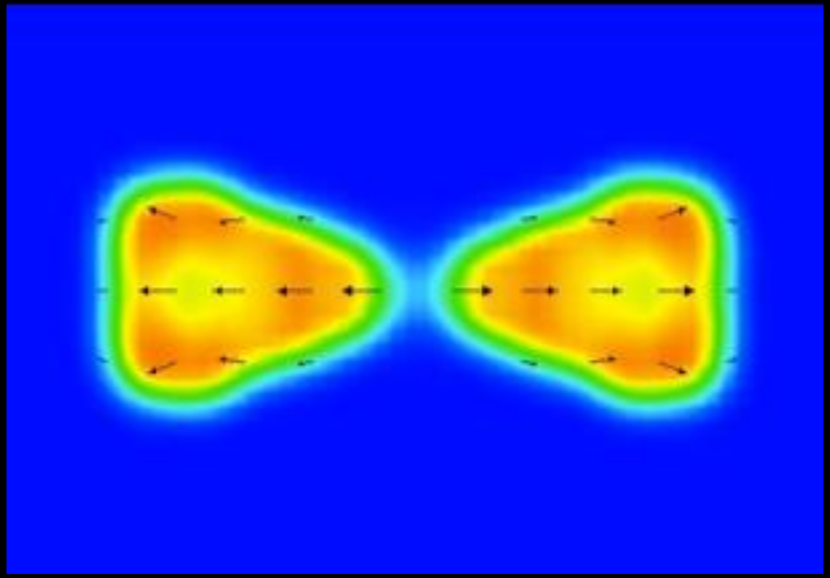
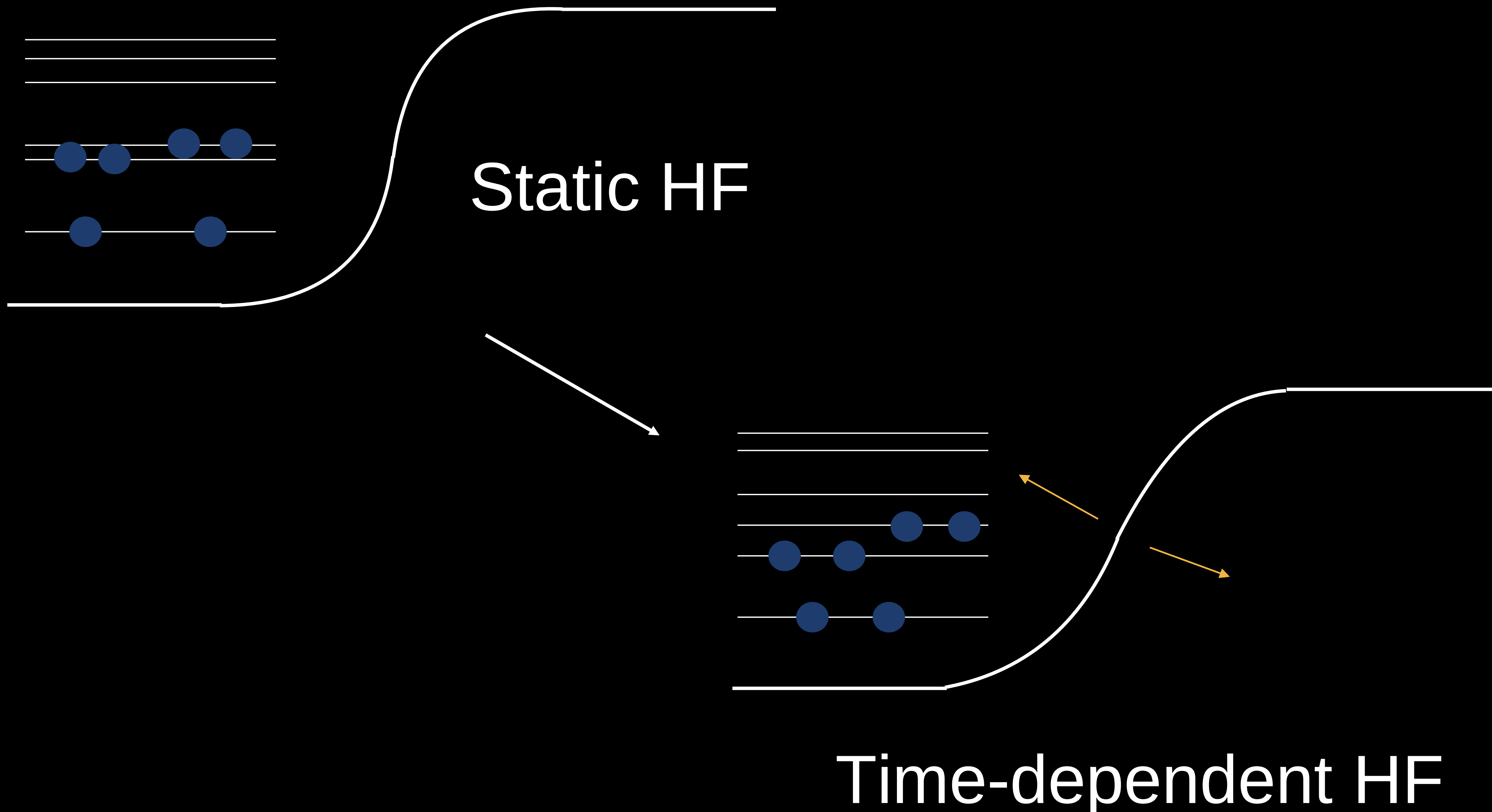
PAUL STEVENSON ☀ UNIVERSITY OF SURREY, UK
NANTES, JANUARY 2015

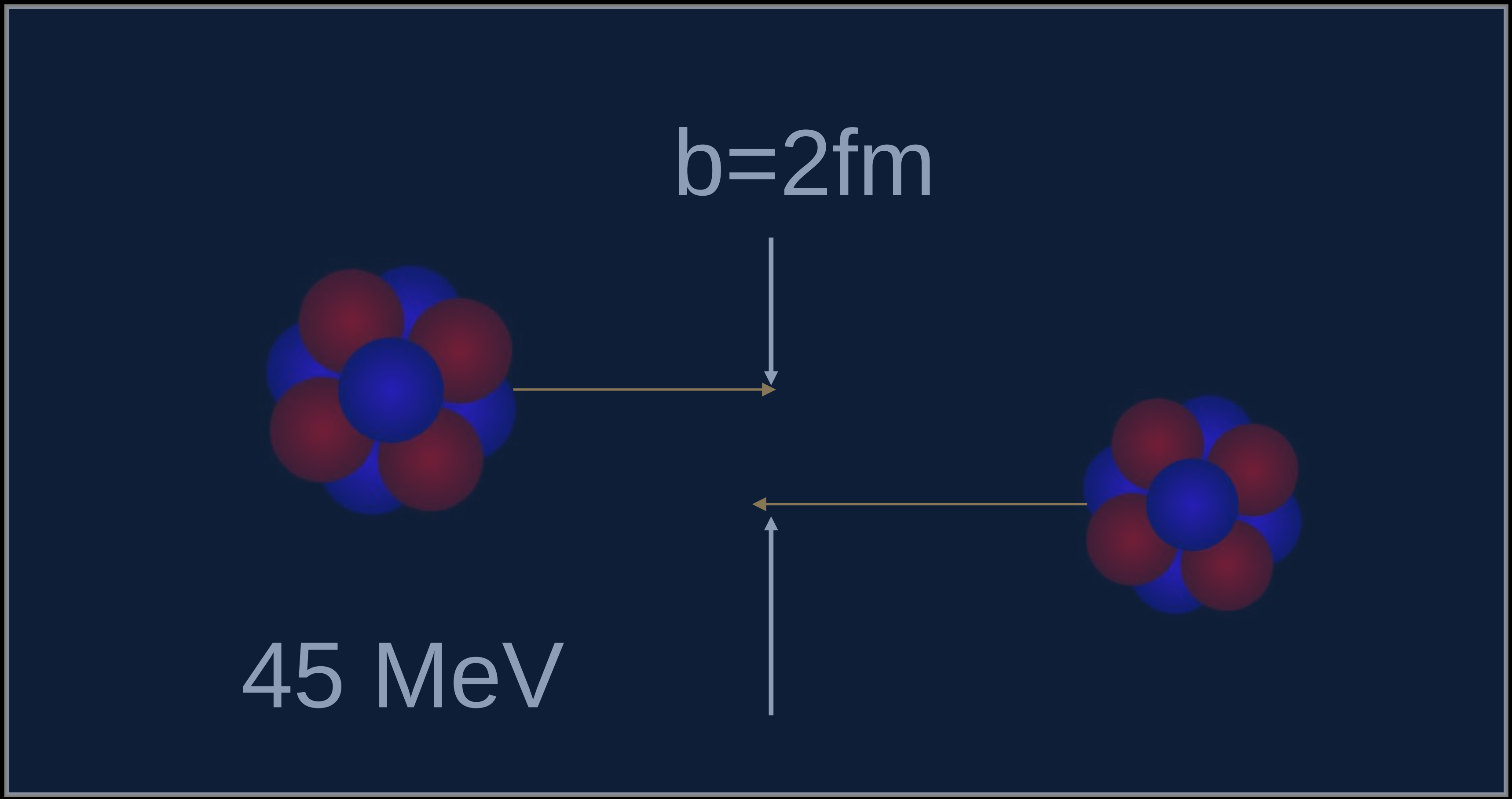
COLLECTIVE MOTION & BETA-DECAY IN TDHF



TIME-DEPENDENT HARTREE-FOCK



EXPERIMENTAL THEORETICAL PHYSICS



Virtual laboratory in which to perform experiments, subject to ass
particular interactions, and space restrictions
-> a kind of semiclassical picture (in collective coordinates)

TDHF CODE SKY3D

- First published general-purpose nuclear TDHF / TDDFT code
- Computer Physics Communications **185**, 2195 (2014)

Computer Physics Communications 185 (2014) 2195–2216

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journal homepage: www.elsevier.com/locate/cpc

ELSEVIER

COMPUTER PHYSICS COMMUNICATIONS

The TDHF code Sky3D☆

CrossMark

J.A. Maruhn[a,*], P.-G. Reinhard[b], P.D. Stevenson[c], A.S. Umar[d]

SKYRME INTERACTION(S)

- T. H. R. Skyrme, Nucl. Phys. 9, 615 (1959)

It is generally believed that the most important part of the two-body interaction can be represented by a contact potential, i.e. by constant $t(\mathbf{k}', \mathbf{k})$; this suggests an expansion in powers of $\mathbf{k}'$ and $\mathbf{k}$. If this expansion is stopped at the quadratic terms only a small number of undetermined coefficients occur, and an attempt can be made to determine these by

$$t_{12} = \delta(\mathbf{r}_1 - \mathbf{r}_2) t(\mathbf{k}', \mathbf{k})$$

$$\begin{aligned} t(\mathbf{k}', \mathbf{k}) = {} & t_0(1 + x_0 P^\sigma) + \tfrac{1}{2} t_1 (1 + x_1 P^\sigma)(\mathbf{k}'^2 + \mathbf{k}^2) \\ & + t_2[1 + x_2(P^\sigma - \tfrac{4}{5})]\mathbf{k}' \cdot \mathbf{k} \\ & + \tfrac{1}{2} T[\boldsymbol{\sigma}_1 \cdot \mathbf{k} \boldsymbol{\sigma}_2 \cdot \mathbf{k} - \tfrac{1}{3} \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \mathbf{k}^2 + \text{conj.}] \\ & + \tfrac{1}{2} U[\boldsymbol{\sigma}_1 \cdot \mathbf{k}' \boldsymbol{\sigma}_2 \cdot \mathbf{k} - \tfrac{1}{3} \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \mathbf{k}' \cdot \mathbf{k} + \text{conj.}] \\ & + V[i(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \mathbf{k}' \times \mathbf{k}], \end{aligned}$$

$$t_{123} = \delta(\mathbf{r}_1 - \mathbf{r}_2)\delta(\mathbf{r}_3 - \mathbf{r}_1) t_3$$

SKYRME AS EDF

$$
\begin{aligned}
\mathcal{E}_{\mathrm{Skyrme}} = \int d^3r \sum_{t=0,1} \Big\{ & C_t^{\rho}[\rho_0]\,\rho_t^2 + C_t^{s}[\rho_0]\,\mathbf{s}_t^2 + C_t^{\Delta\rho}\rho_t\Delta\rho_t + C_t^{\tau}\left(\rho_t\tau_t - \mathbf{j}_t^2\right) \\
& + C_t^{T}\left[\mathbf{s}_t\cdot\mathbf{T}_t - \tfrac{1}{3}(J^{(0)})^2 - \tfrac{1}{2}(J^{(1)})^2 - (J^{(2)})^2\right] + C_t^{\Delta s}\mathbf{s}_t\cdot\Delta\mathbf{s}_t \\
& + C_t^{F}\left[\mathbf{s}_t\cdot\mathbf{F}_t - \tfrac{2}{3}(J^{(0)})^2 + \tfrac{1}{4}(J^{(1)})^2 - \tfrac{1}{2}(J^{(2)})^2\right] + C_t^{\nabla s}(\nabla\cdot\mathbf{s}_t)^2 \\
& + C_t^{\nabla\cdot J}\left(\rho_t\nabla\cdot\mathbf{J}_t + \mathbf{s}_t\cdot\nabla\times\mathbf{j}_t\right)\Big\}
\end{aligned}
$$

$$
\begin{aligned}
\rho(\boldsymbol{r},\boldsymbol{r}') &= \sum_{\sigma,q}\rho_q(\boldsymbol{r}\sigma,\boldsymbol{r}'\sigma) = \sum_{i,\sigma,q}\phi_i^*(\boldsymbol{r}',\sigma,q)\phi_i(\boldsymbol{r},\sigma,q), \\
\boldsymbol{S}(\boldsymbol{r},\boldsymbol{r}') &= \sum_{\sigma,\sigma',q}\rho_q(\boldsymbol{r}\sigma,\boldsymbol{r}'\sigma')\langle\sigma'|\hat{\boldsymbol{\sigma}}|\sigma\rangle = \sum_{i,\sigma,\sigma',q}\phi_i^*(\boldsymbol{r}',\sigma',q)\hat{\boldsymbol{\sigma}}\phi_i(\boldsymbol{r},\sigma,q),
\end{aligned}
$$

$$
\begin{aligned}
\rho(\boldsymbol{r}) &= \rho(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}'=\boldsymbol{r}}, && \text{t-even} \\
\tau(\boldsymbol{r}) &= \boldsymbol{\nabla}\cdot\boldsymbol{\nabla}'\rho(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}'=\boldsymbol{r}}, && \text{t-even} \\
\boldsymbol{S}(\boldsymbol{r}) &= \boldsymbol{S}(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}'=\boldsymbol{r}}, && \text{t-odd} \\
T_\mu(\boldsymbol{r}) &= \boldsymbol{\nabla}\cdot\boldsymbol{\nabla}'S_\mu(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}'=\boldsymbol{r}}, && \text{t-odd} \\
\boldsymbol{j}(\boldsymbol{r}) &= -\frac{i}{2}(\boldsymbol{\nabla}-\boldsymbol{\nabla}')\,\rho(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}'=\boldsymbol{r}}, && \text{t-even} \\
J_{\mu\nu}(\boldsymbol{r}) &= -\frac{i}{2}(\nabla_\mu-\nabla'_\mu)\,S_\nu(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}'=\boldsymbol{r}}, && \text{t-even} \\
F_\mu(\boldsymbol{r}) &= \frac{1}{2}\sum_{\nu=x}^{z}(\nabla_\mu\nabla'_\nu+\nabla'_\mu\nabla_\nu)\,S_\nu(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}'=\boldsymbol{r}}, && \text{t-odd}
\end{aligned}
$$

EDF consists of a series of terms comprised of densities or their derivatives. Parameters determined by fitting to data

RESPONSE FUNCTIONS IN TDHF

- A typical use of TDHF is to start with some external perturbation and watch the response
- Giant resonances are an historically well-studied example
- RPA a more–used method to study GRs from mean-field++ approach
- RPA formally small-amplitude limit to TDHF
- RPA easy for easy cases, hard for hard cases. TDHF about the same for all

TDHF IN PRACTICE FOR GR

Solve formal equation $[\hat{h}(t), \rho(t)] = [\hat{h}_{\mathrm{HF}}[\rho(t)] + \hat{h}_{\mathrm{ext}}(t), \rho(t)] = i\hbar\dot{\rho}$

by starting from static HF solution and applying boost

$\hat{h}_{\mathrm{ext}}(t) = \int \mathrm{d}^3\mathrm{r}\, \rho(r,t) F(r) f(t)$ then evolve in time using operator

$U(t, t+\Delta t) = e^{-i\hat{h}\Delta t/\hbar}$. We follow same F(r) as f^n of time

and take its Fourier transform $S(\omega) = -\frac{1}{\pi} Im \int \mathrm{d}^3\mathrm{r} \frac{\delta\langle F(r,\omega)\rangle}{f(\omega)}$

which is just the Strength Function

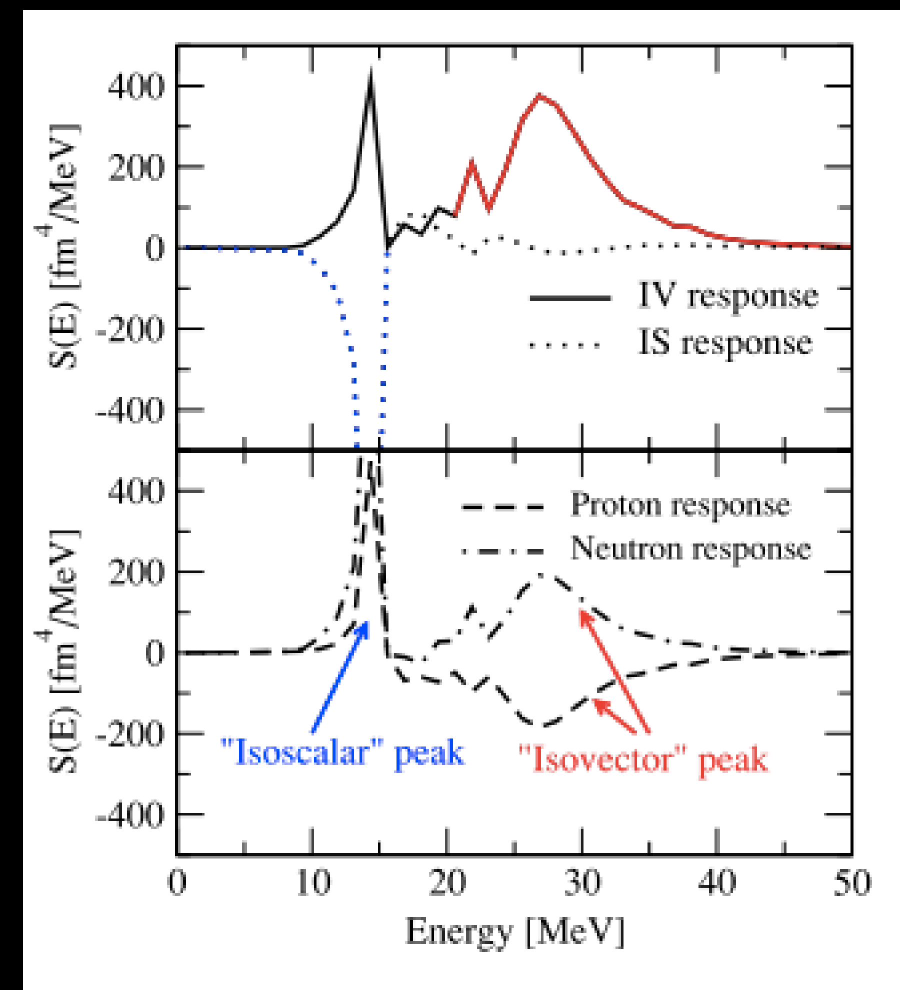
$$S(E) = \sum_\nu |\langle\nu|F|0\rangle|^2 \;\delta(\mathrm{E} - \mathrm{E}_\nu)$$
$$= -\frac{1}{\pi} Im\langle 0|F \frac{1}{\hat{h} - E + i\delta} F|0\rangle$$

ISOSPIN MIXING IN G(M)R

Can kick nucleus with one kind of boost and measure different kind of response;

$$S(E) = \Sigma_\nu \langle 0 | F | \nu\rangle\langle \nu | G | 0\rangle\delta(E-E_\nu)$$

- Strength function measures matrix elements
- Learn about normal modes in isospin sector



Response to IV monopole kick using SkX

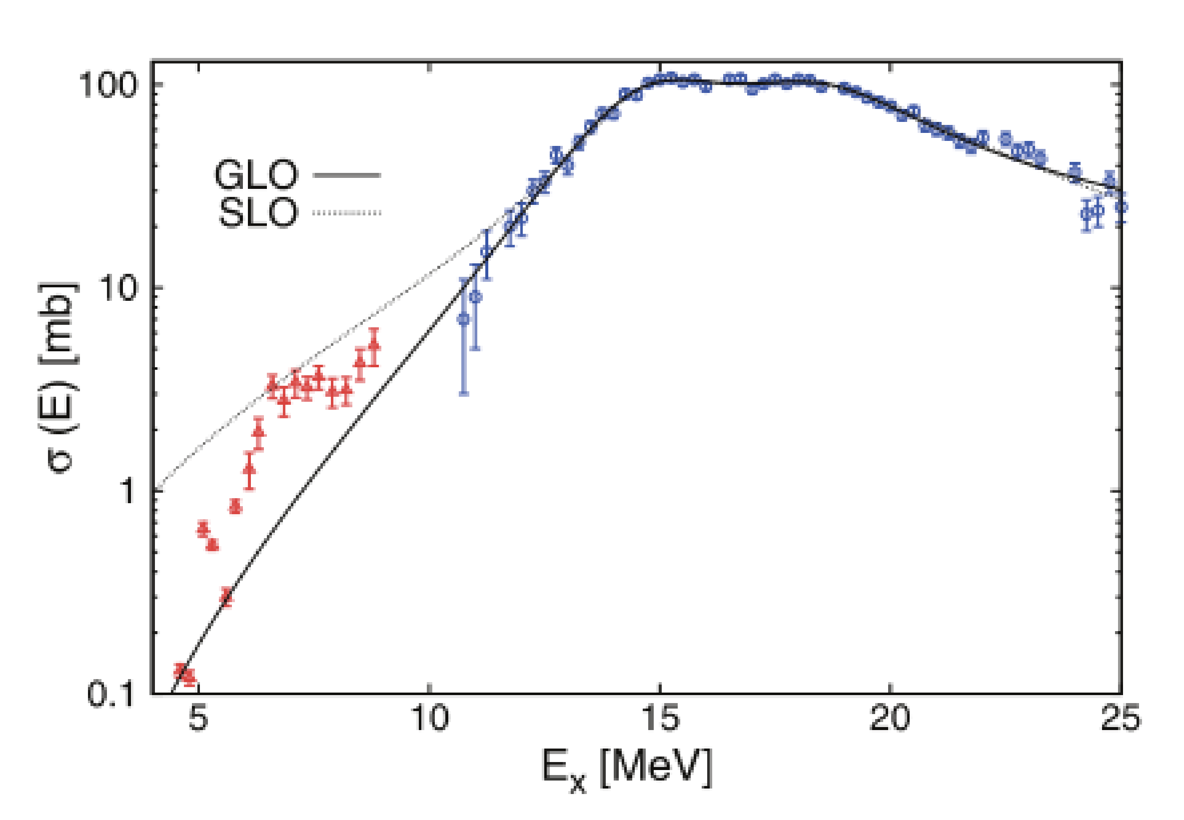
D. Almehed & P. D. Stevenson, J. Phys. G31, S1819 (2005)

STRUCTURE OF THE PYGMY EXCITATION IN SE-76

"*The Electric Dipole Response of* ^{76}*Se Above 4 MeV*", PM Goddard, N Cooper, V Werner, G Rusev, PD Stevenson, A Rios, C Bernards, A Chakraborty, BP Crider, J Glorius, RS Ilieva, JH Kelley, E Kwan, EE Peters, N Pietralla, R Raut, C Romig, D Savran, L Schnorrenberger, MK Smith, K Sonnabend, AP Tonchev, W Tornow, SW Yates, *Phys. Rev. C* **88**, 064308 (2013)

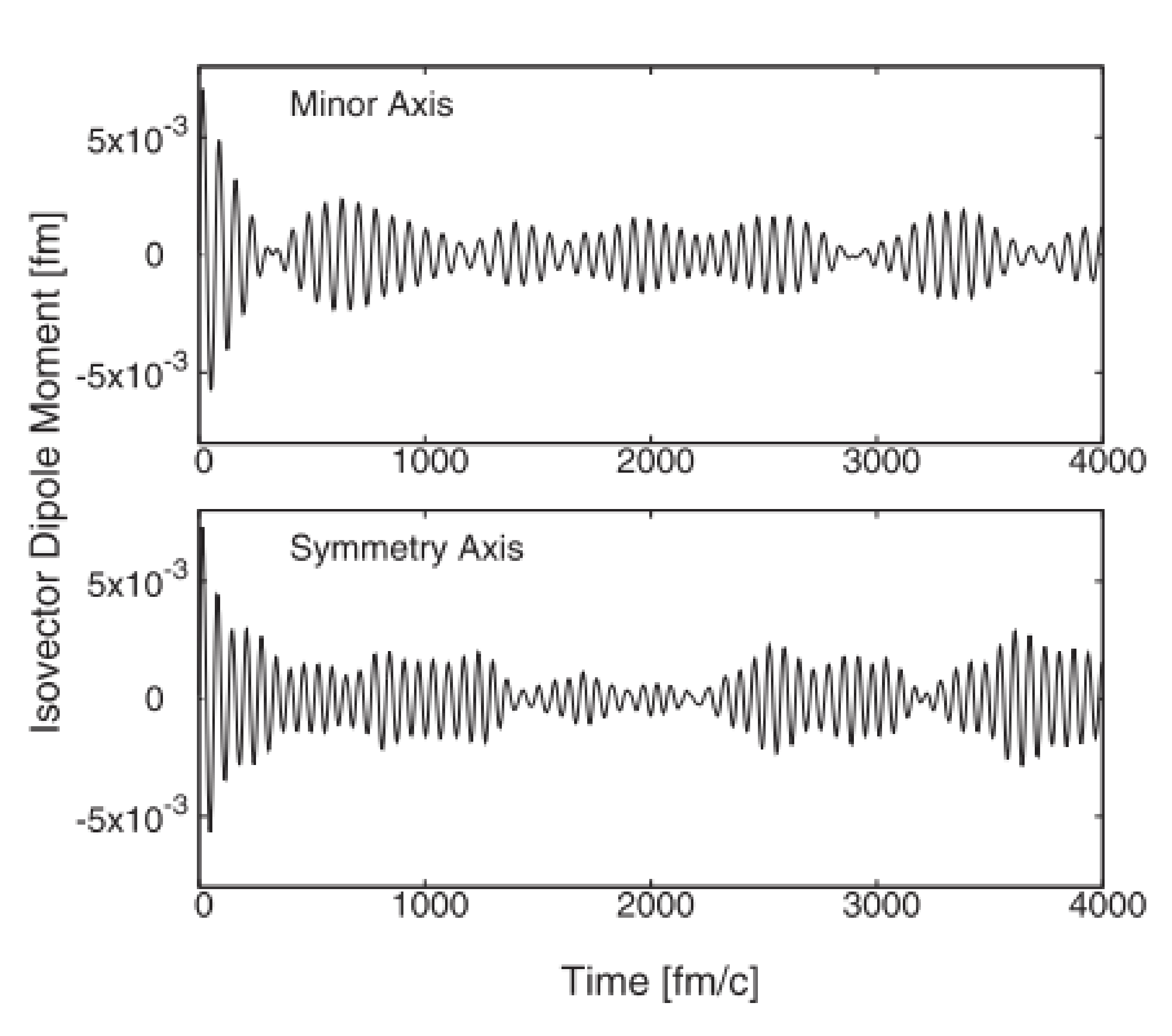
Can be imaginative with external perturbation

polarized photon scattering at HIγS



New data = red triangles
Previous = blue circles, P. Carlos et al., **NPA258**, 365 (1976)
GLO and SLO are two different Lorentzian fits to the old data, extrapolated back to low energy

IV DIPOLE RESPONSE

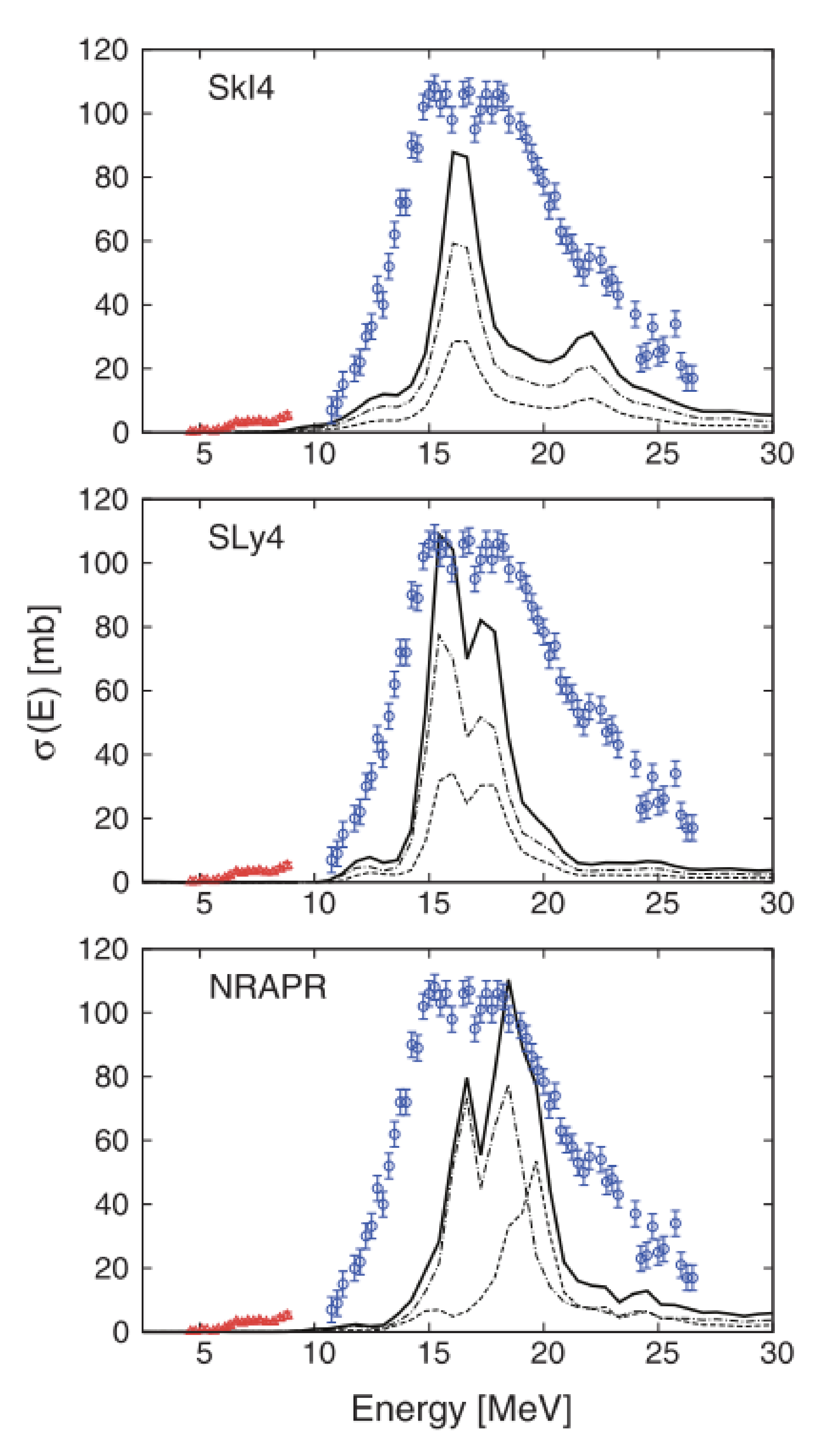


- Isovector dipole boost exp(ik.D) applied to wave functions
- nucleus then relaxes, and oscillates
- deformation gives different oscillation along different axes
- strength function given by Fourier transform

1000 fm/c = $3\text{x}10^{-21}$ s = 3 zs

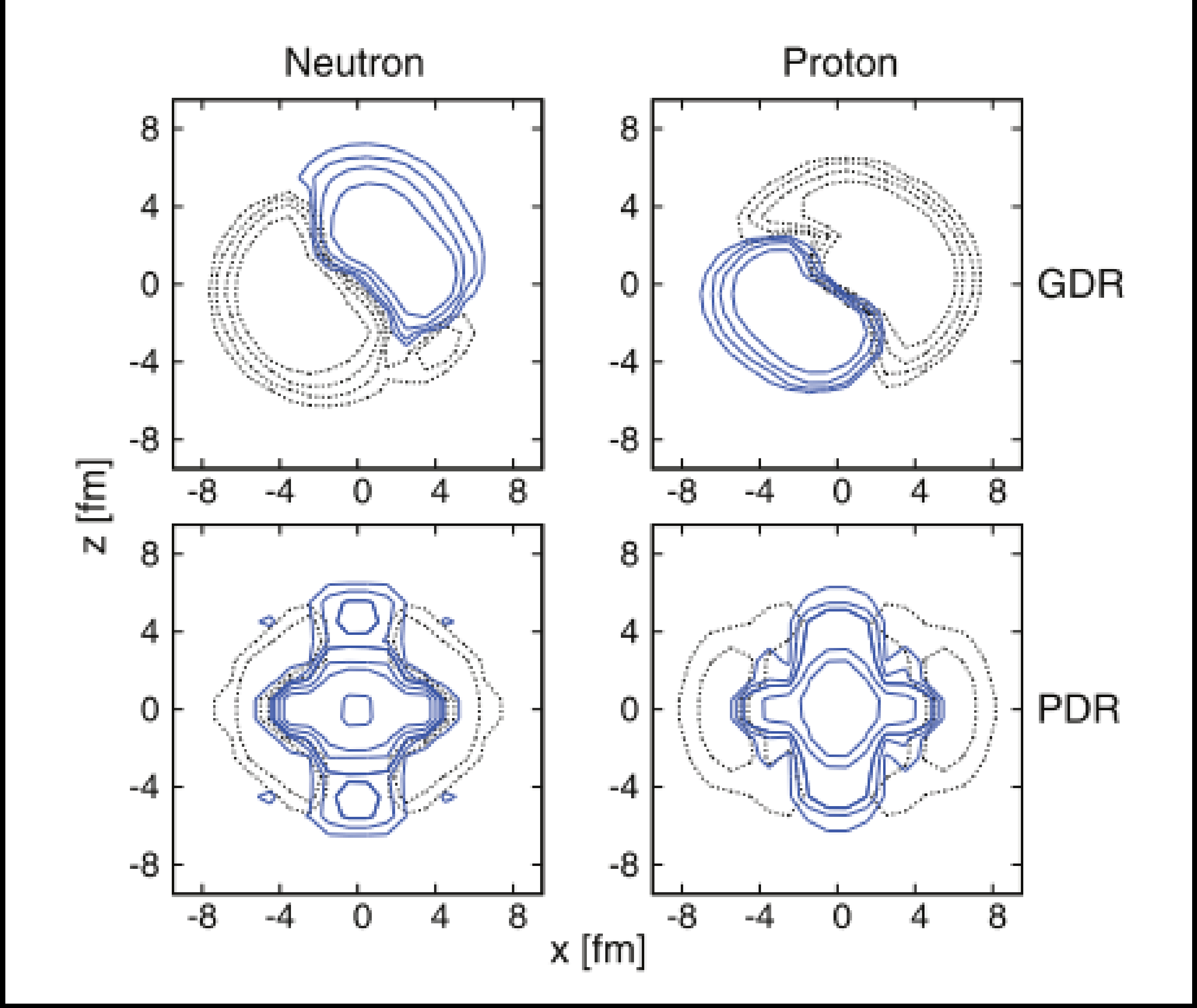
FORCE-DEPENDENCE

- Sample of different Skyrme interactions give results which differ in detail
- no spreading width from higher-order (beyond mean-field) effects
- some structure comes from deformation splitting (evident in NRAPR), some from underling single-particle structure
- GDR region domintates dynamics



DRIVING THE NUCLEUS

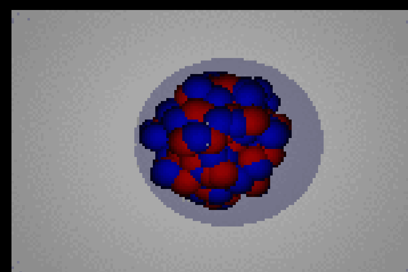
- As an alternative to the broadband instantaneous boost, can drive the nucleus at a frequency corresponding to the energy of interest via E=h*f*.



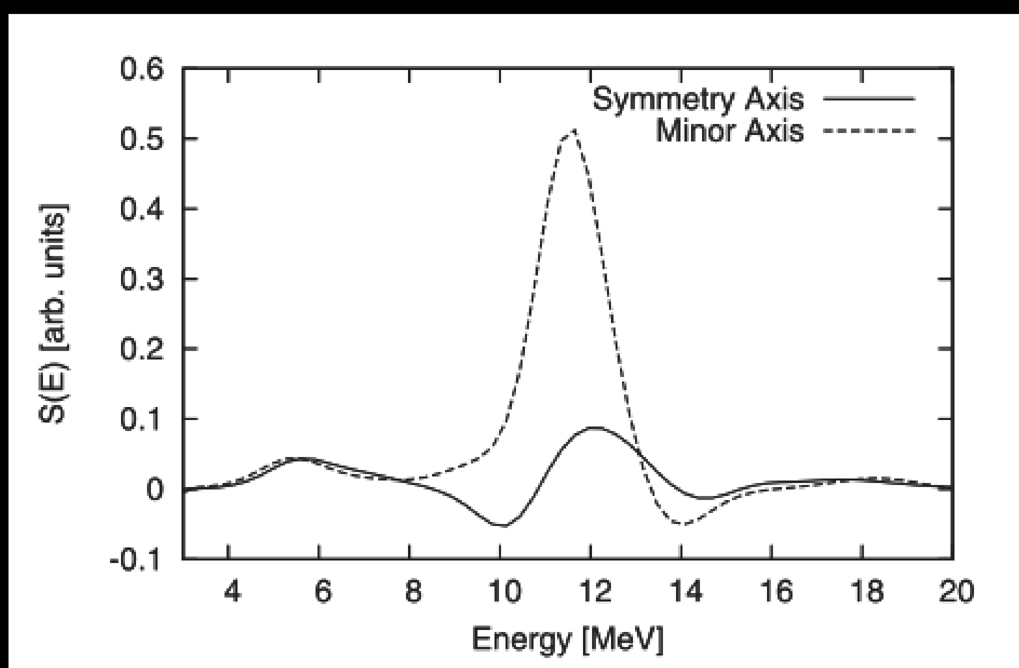
- plots show time-derivative of densities
- at “GDR” energy, clear IV dipole behaviour seen
- when driven at the pygmy peak, a more isoscalar mode is seen, with a surface-core character

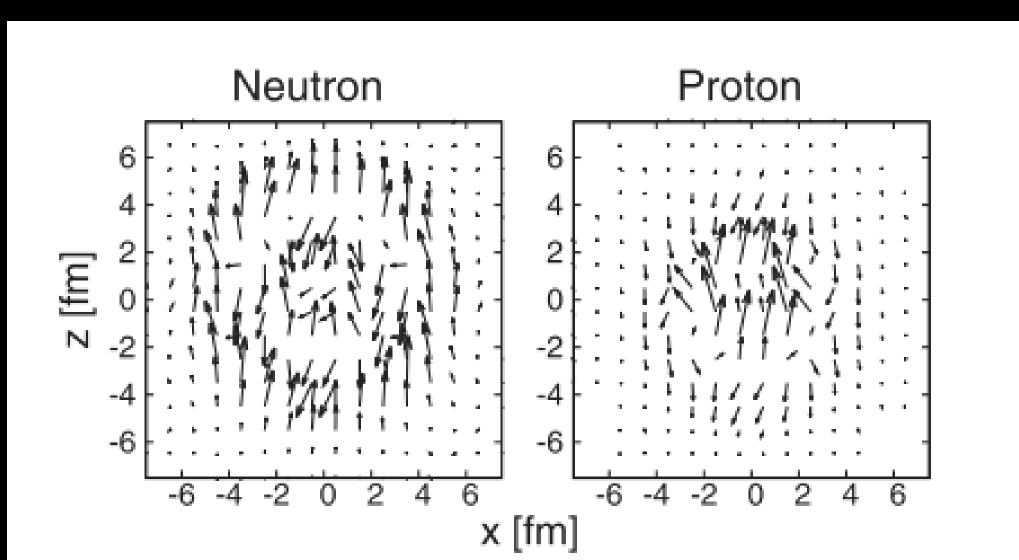
PYGMY KICK

Rather than a normal dipole kick, can construct pygmy kick:



$$\hat{\mathbf{D}}' = \frac{A-\sum v^2}{A}\sum_{i=1}^{\eta}\mathbf{r}_{\mathrm{skin}} - \frac{\sum v^2}{A}\sum_{j=1}^{\zeta}\mathbf{r}_{\mathrm{core}},$$





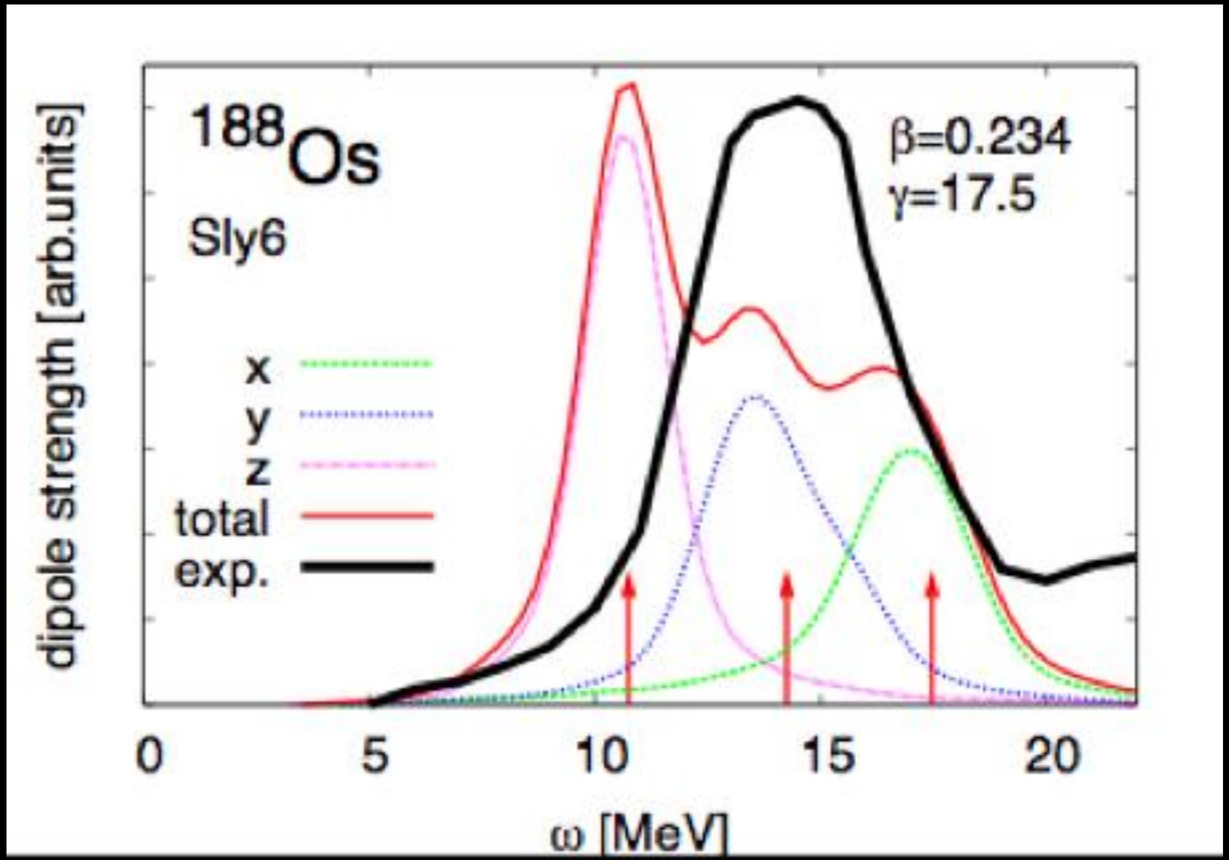
- Now the response is completely in the low energy region.
- See small "spherical" bump at the 4-7 MeV region.
- asymmetric behaviour around 12 MeV
- can we use such ideas to test if β-decay a probe of neutron skin?

PROBE OF TRIAXIALITY

- some Skyrme parameterisations predict static triaxial deformation in some nuclei - e.g. SLy6 in ^{188}Os

- calculated GDR shows strong deformation splitting

- (unlike the observed GDR spectrum!)



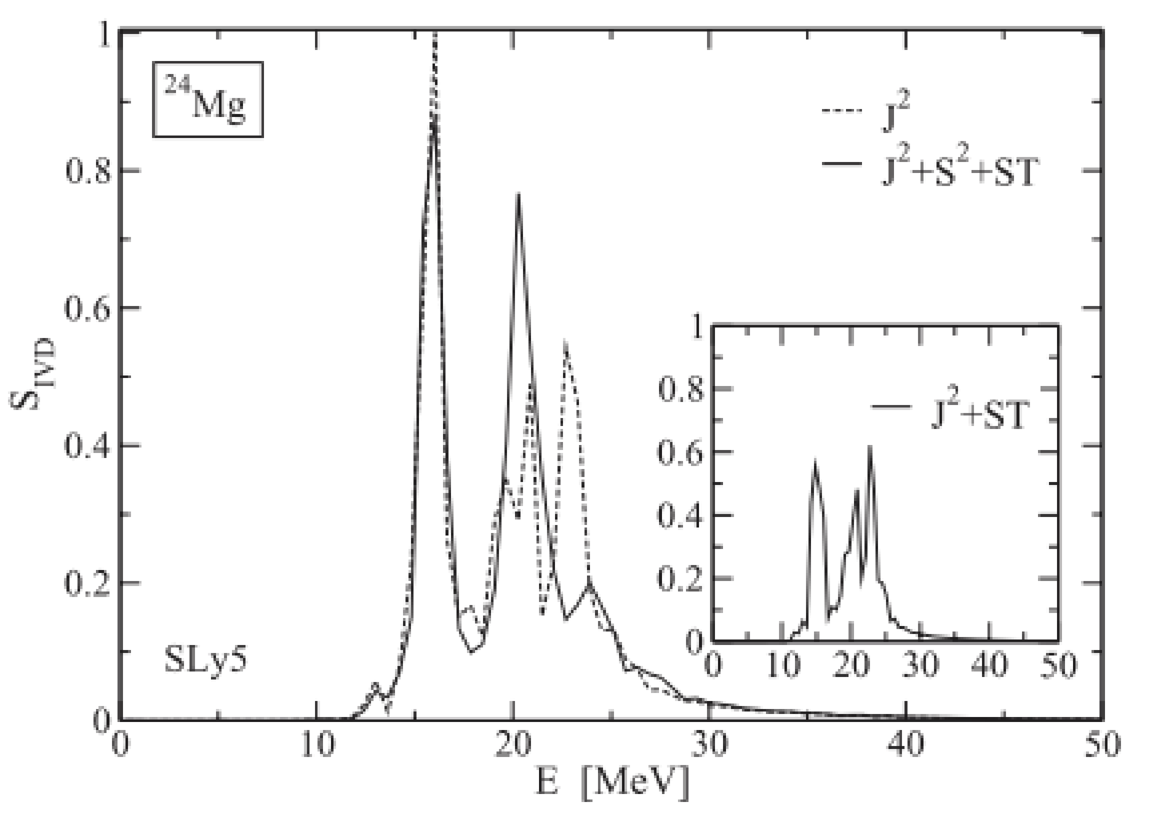
J. A. Maruhn, P.-G. Reinhard, P. D. Stevenson, J. Rikovska Stone and M. R. Strayer, Phys. Rev. **C 71**, 064328 (2005)

TENSOR FORCES & TIME-ODD COMPONENTS

$$
\begin{aligned}
\mathcal{E}_{\text{Skyrme}} = \int d^3r \sum_{t=0,1} \Big\{ & C_t^\rho[\rho_0]\,\rho_t^2 + C_t^s[\rho_0]\,\mathbf{s}_t^2 + C_t^{\Delta\rho}\rho_t\Delta\rho_t + C_t^\tau\left(\rho_t\tau_t - \mathbf{j}_t^2\right) \\
& + C_t^T\left[\mathbf{s}_t\cdot\mathbf{T}_t - \tfrac{1}{3}(J^{(0)})^2 - \tfrac{1}{2}(J^{(1)})^2 - (J^{(2)})^2\right] + C_t^{\Delta s}\mathbf{s}_t\cdot\Delta\mathbf{s}_t \\
& + C_t^F\left[\mathbf{s}_t\cdot\mathbf{F}_t - \tfrac{2}{3}(J^{(0)})^2 + \tfrac{1}{4}(J^{(1)})^2 - \tfrac{1}{2}(J^{(2)})^2\right] + C_t^{\nabla s}(\nabla\cdot\mathbf{s}_t)^2 \\
& + C_t^{\nabla\cdot J}\left(\rho_t\nabla\cdot\mathbf{J}_t + \mathbf{s}_t\cdot\nabla\times\mathbf{j}_t\right)\Big\}
\end{aligned}
$$

- Tensor force contributes to **s**.laps, **s**.**T**, **s**.**F** & J^2 terms
- it is the sole contributor to the **s**.**F** term
- time-odd terms will be important in β-decay. TDHF rarely (if ever) used for odd-mass nuclei.

TIME-ODD EFFECTS IN COLLECTIVE MODES

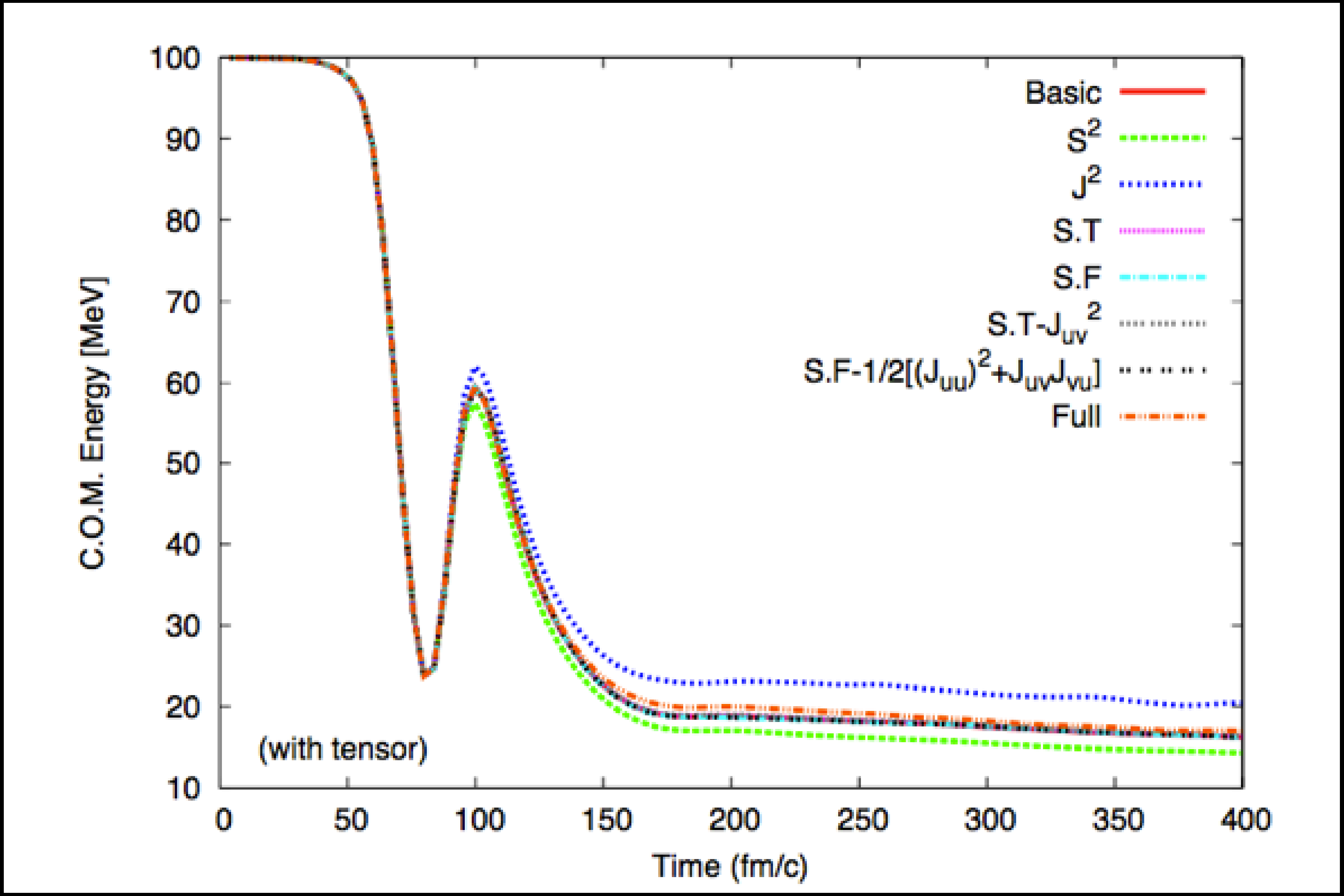


Giant dipole resonance in ^{24}Mg
details of dynamics lead to differences in detail of peak structure & strengths at different energies

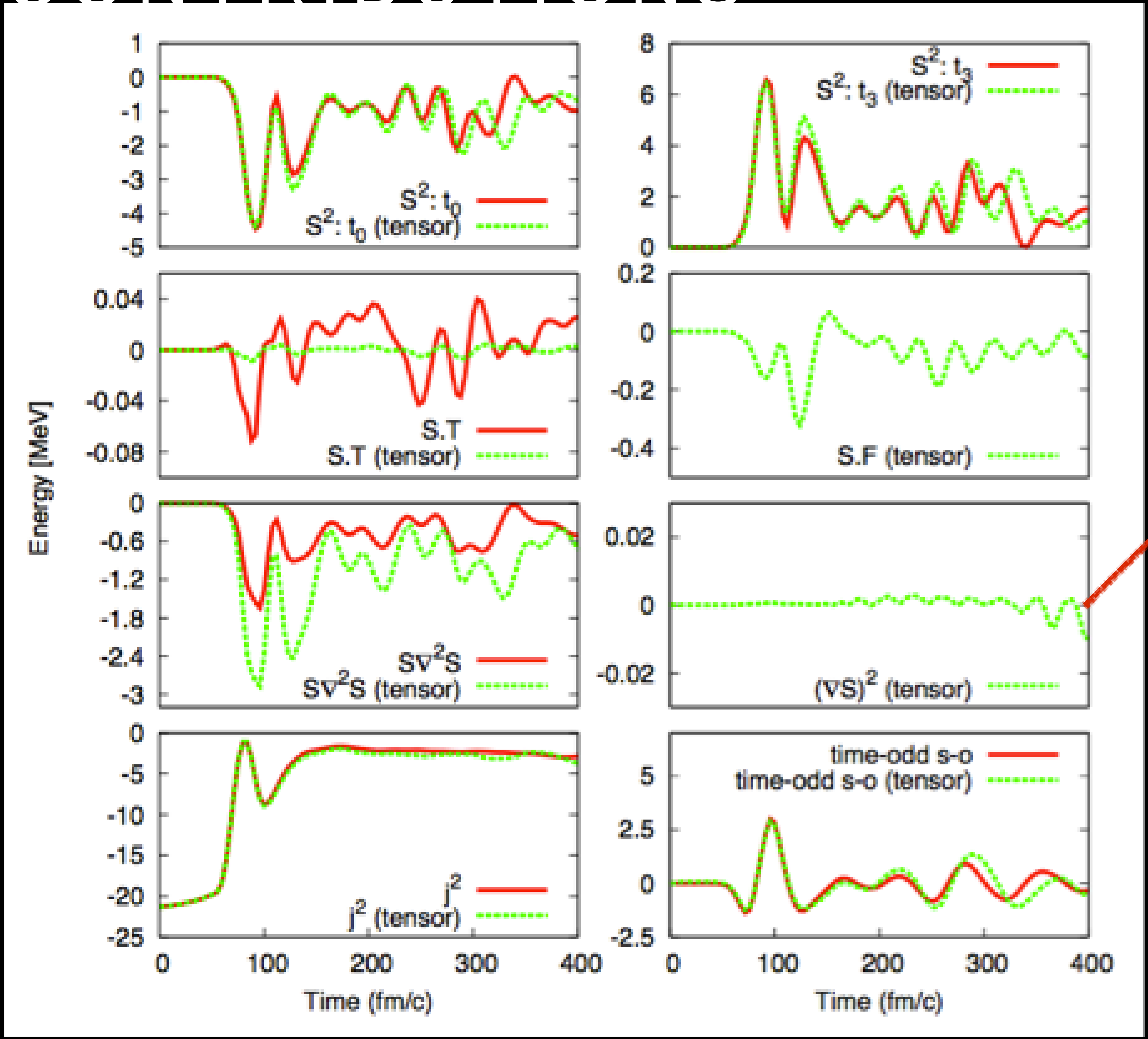
S. Fracasso, E. B. Suckling and P. D. Stevenson, PRC **86**, 044303 (2012)

$^{16}O + ^{16}O$

SLy5 with tensor as in Coló et al, PLB646, 227 (2007)



TIME-ODD DENSITY CONTRIBUTIONS



Stability issues with Skyrme EDF

UPPER FUSION THRESHOLD

Force	Barrier [MeV]	Threshold [MeV]
SkM* (basic)	9	77
SkM* + full t_{odd}	9	73
SLy5 + full t_{odd}	10	68
SLy5 + tensor	10	65
T12	9	60
T14	9	70
T22	9	62
T24	9	71
T46	9	85

E. B. Suckling PhD thesis, Surrey (2011)

BETA-DECAY

- External perturbation operator $\propto \tau_{\pm}$
- cannot use linear response theory(?) – no way of dealing strength of operator towards zero
- in principle existing codes can deal with odd-N/Z nuclei, but not e.g. with pairing.
- Need to think about role of time-odd terms. Usually include only those constrained by Galilean invariance. Other terms are unconstrained in fits.

SUMMARY

- TDHF allows for a range of collective nuclear phenomena to be explored
- Role of effective interaction (can be) important
- Initial boost given to nucleus can be made in creative ways to study nature of collective motion
- β-decay a challenge due to odd-mass, but should be accessible in principle

Thanks: D. Almehed, C. I. Pardi, P. M. Goddard, S. Fracasso, E. Suckling (Surrey), J. A. Maruhn (Frankfurt), P.-G. Reinhard (Erlangen), A. S. Umar (Vanderbilt), M. R. Strayer

OVERVIEW

- I: Mean-field dynamics => TDHF
- II: Nuclear interaction input
- III: Typical kinds of collective motion
- IV: Time-odd fields for ß-decay
- VI: Summary

FUSION CROSS SECTION

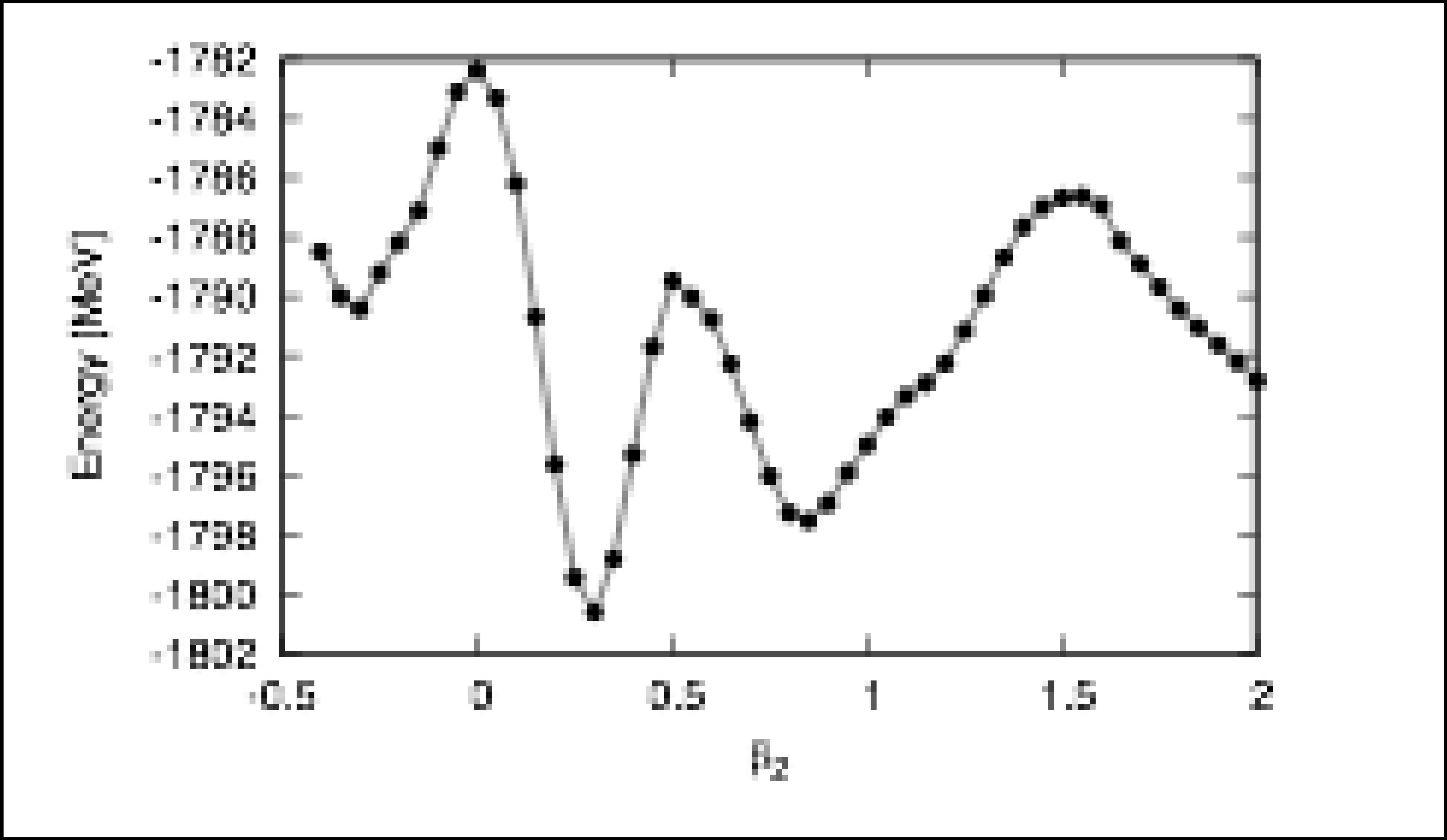
Force	b_{max} (fm)	l_{max} ($\hbar$)	σ_f (mb)
SkM* (full)	6.70	24.26	1388
SLy5 (full)	6.65	24.08	1368
SLy5 (tensor)	6.65	24.08	1368
T_{12}	6.65	24.09	1347
T_{22}	6.65	24.09	1347
T_{24}	6.65	24.09	1347
T_{42}	6.70	24.27	1366
T_{44}	6.70	24.27	1366
Experiment [157]	—	—	1075

^{16}O on ^{16}O @ 34 MeV

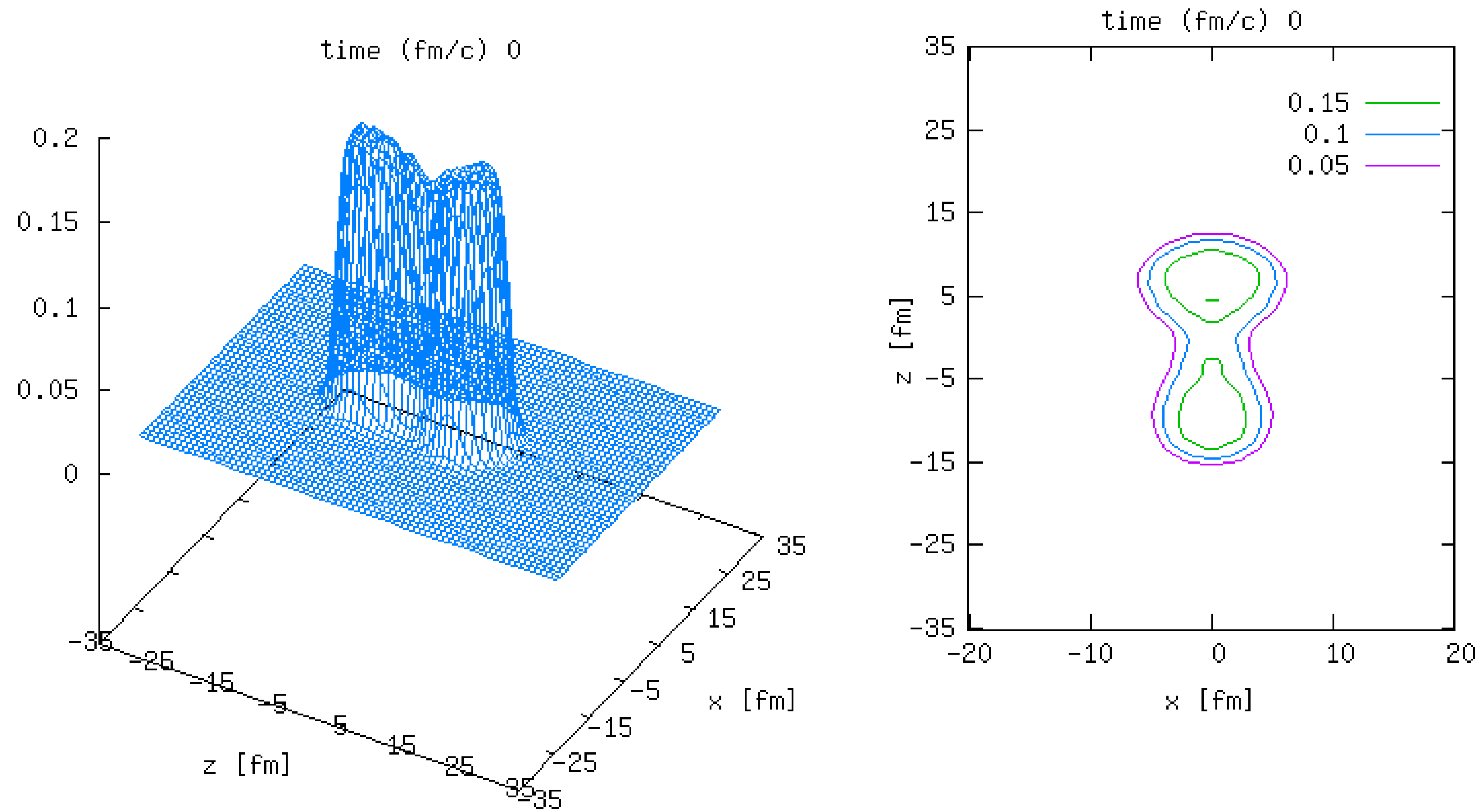
E. B. Suckling PhD thesis, Surrey (2011

[157] R. G. Stokstad, Y. Eisen, D. Pelte, U. Smilansky, and I. Tserruya, *Phys. Rev. Lett.* **41**, 465 (1978).

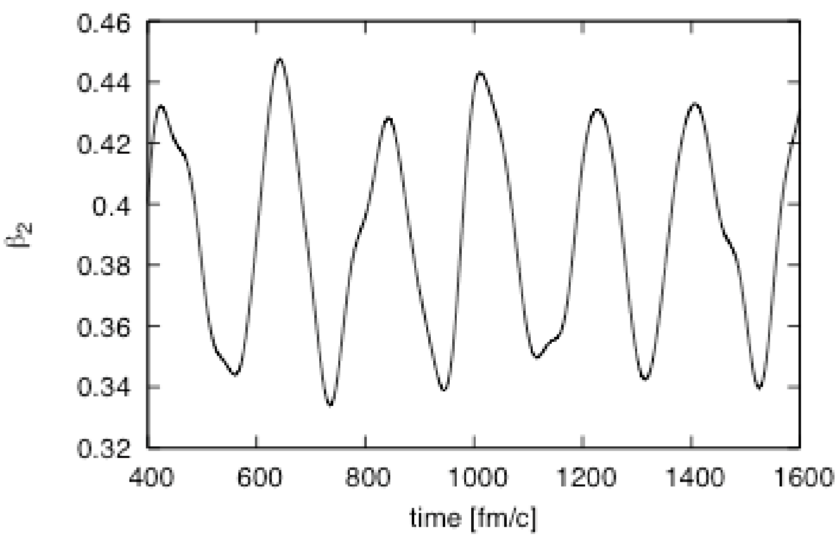
FISSION PU-240



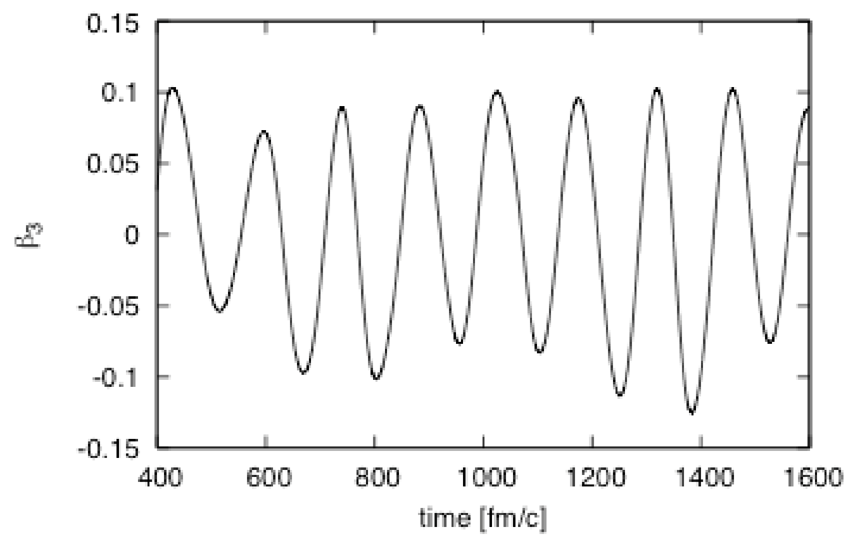
FISSION


time (fm/c) 0
0.2
0.15
0.1
0.05
0
-35
-25
-15
-5
5
15
25
35
z [fm]
35
25
15
5
-5
-15
-25
-35
x [fm]
time (fm/c) 0
0.15
0.1
0.05
35
25
15
5
-5
-15
-25
-35
z [fm]
-20
-10
0
10
20
x [fm]

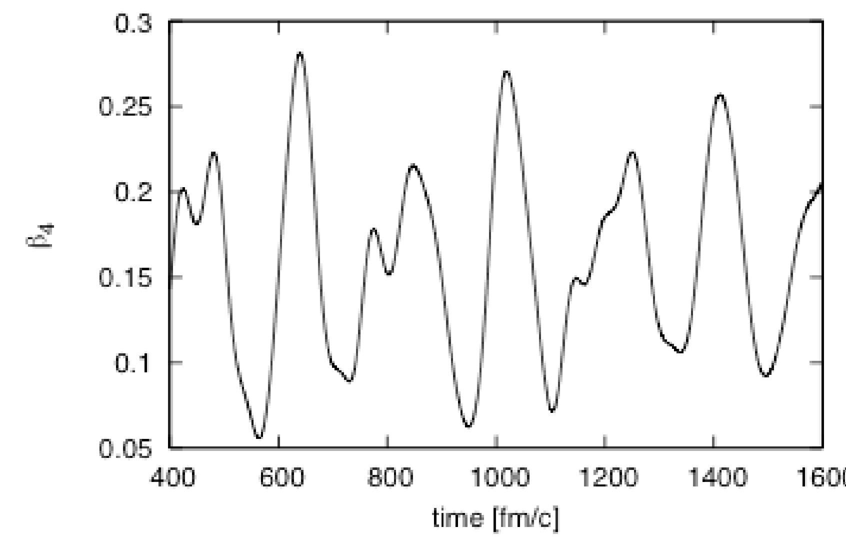
FRAGMENT MODES



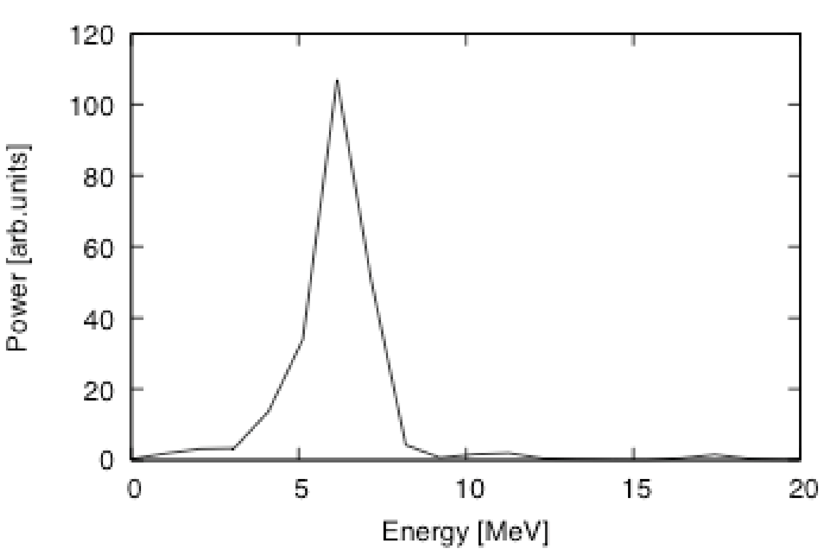
Quadrupole deformation



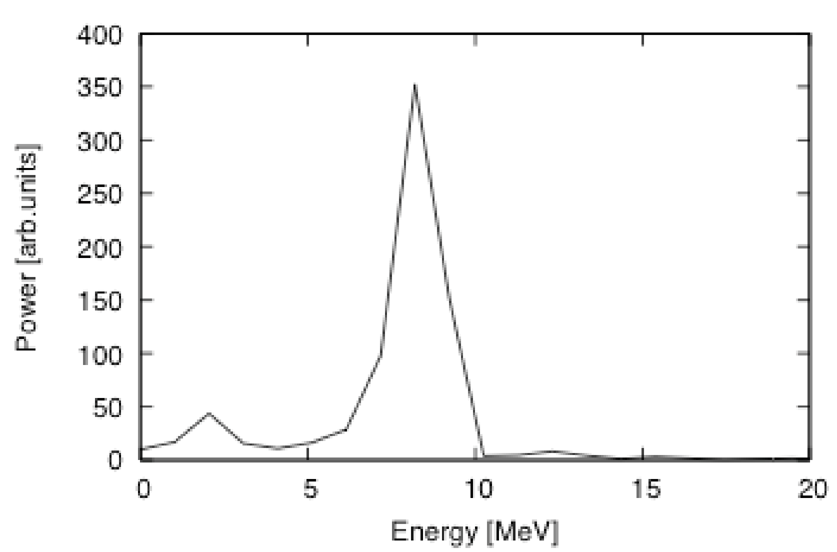
Octupole deformation



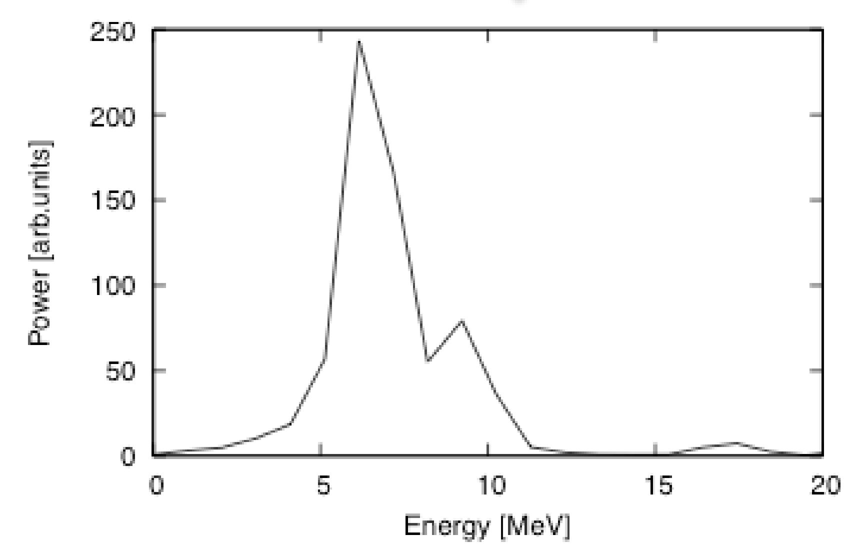
Hexadecapole deformation



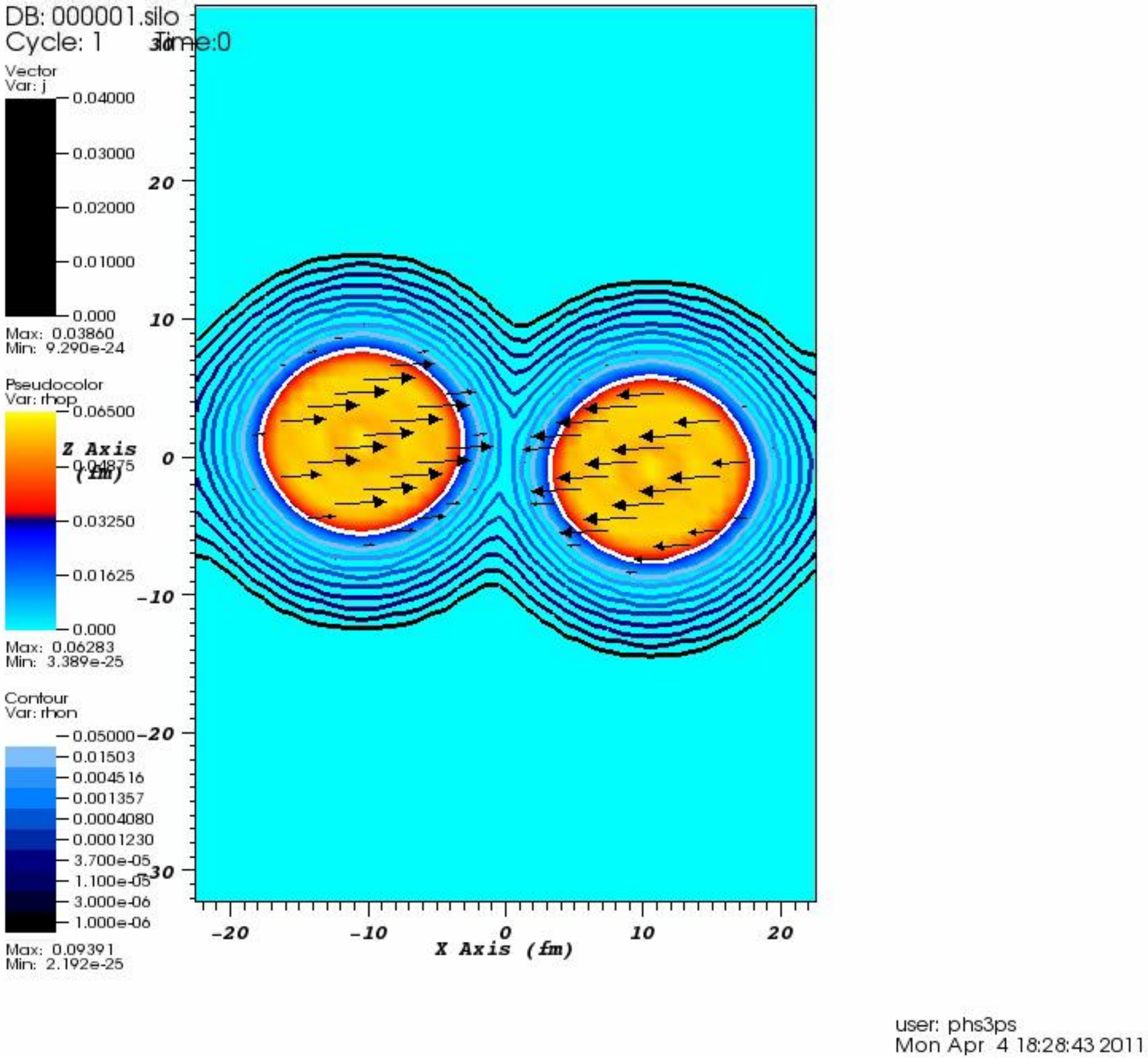
Quadrupole power spectrum



Octopole power spectrum



Hexadecapole power spectrum


DB: 000001.silo
Cycle: 1 Time:0
Vector
Var: j
0.04000
0.03000
0.02000
0.01000
0.000
Max: 0.03860
Min: 9.290e-24
Pseudocolor
Var: rhop
0.06500
0.04875
0.03250
0.01625
0.000
Max: 0.06283
Min: 3.389e-25
Contour
Var: rhon
0.05000
0.01503
0.004516
0.001357
0.0004080
0.0001230
3.700e-05
1.100e-05
3.000e-06
1.000e-06
Max: 0.09391
Min: 2.192e-25
Z Axis (fm)
30
20
10
0
-10
-20
-30
-20
-10
0
10
20
X Axis (fm)
user: phs3ps
Mon Apr 4 18:28:43 2011

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MY ABSTRACT

Mean-field dynamics for giant resonances and fusion reactions
Dr Paul Stevenson, University of Surrey, UK

The energy density functional view of nuclei provides a good description of ground state properites and is linked to the underlying nuclear interactions via the Hartree-Fock (HF) approximation. The extension of HF to dynamical processes via the time-depdendent HF approach allows description of collective nuclear behaviour, including giant resonances and collisions.

We present a survey of some recent results with time-dependent approaches; Various properties of giant-resnonace-like modes are explored, including low-lying dipole strength in Se-76 [1], in which a non-multipole excitation is used to pick out "pygmy" strength; Some technical advances leading to a true continuum theory [2]; Results in giant resonances and fusion from exploring tensor terms in the nuclear interaction [3,4].

Some details of a newly-published code allowing such calculations to be performed will also be presented [5]

[1] P. M. Goddard et al., Phys. Rev. C 88, 064308 (2013)
[2] C. I. Pardi and P. D. Stevenson, Phys. Rev. C. 87, 014330 (2013)
[3] S. Fracasso, P. D. Stevenson and E. B. Suckling, Phys. Rev. C 86, 044303 (2012)
[4] P. D. Stevenson, Sara Fracasso and E. B. Suckling, J. Phys. Conf. Ser. 381, 012105 (2012)
[5] J. A. Maruhn, P.-G. Reinhard, P. D. Stevenson and A. S. Umar, accepted for publication in Computer

MANY INTERACTIONS

M. Dutra et al, PRC, 035201 (2012)

TABLE II. Saturation prop
ρ_0 in fm^{-3} and the dimensionle

Model	ρ_0
BSk1 [160]	0.157
BSk2 [161]	0.157
BSk2' [161]	0.157
BSk3 [162]	0.157
BSk4 [163]	0.157
BSk5 [163]	0.157
BSk6 [163]	0.157
BSk7 [163]	0.157
BSk8 [164]	0.159
BSk9 [165]	0.159
BSk10 [166]	0.159
BSk11 [166]	0.159
BSk12 [166]	0.159
BSk13 [166]	0.159
BSk14 [167]	0.159
BSk15 [168]	0.159
BSk16 [169]	0.159
BSk17 [170]	0.159
BSk18 [52]	0.159
BSk19 [130]	0.160
BSk20 [130]	0.160
BSk21 [130]	0.158
E [171]	0.159
Es [171]	0.163
f_- [153]	0.162
f_+ [153]	0.162
f_0 [153]	0.162
FPLyon [172]	0.162
Gs [171]	0.158
GS1 [154]	0.159
GS2 [154]	0.159
GS3 [154]	0.159
GS4 [154]	0.158
GS5 [154]	0.158
GS6 [154]	0.159
GSkI [51]	0.159
GSkII [51]	0.159
KDE [173]	0.164
KDE0v [173]	0.161
KDE0v1 [173]	0.165
LNS [118]	0.175
MSk1 [174]	0.157
MSk2 [174]	0.157
MSk3 [174]	0.157
MSk4 [174]	0.157
MSk5 [174]	0.157
MSk5* [119]	0.156
MSk6 [174]	0.157
MSk7 [175]	0.157
MSk8 [175]	0.157
MSk9 [175]	0.157
MSkA [176]	0.153
MSL0 [101]	0.160
NRAPR [177]	0.161
PRC45 [178]	0.145

Model	ρ_0
RATP [179]	0.160
Rs [171]	0.158
Sefm068 [180]	0.160
Sefm074 [180]	0.160
Sefm081 [180]	0.161
Sefm09 [180]	0.161
Sefm1 [180]	0.161
SGI [181]	0.154
SGII [181]	0.158
SGOI [182]	0.168
SGOII [182]	0.168
SI [27]	0.155
SII [27]	0.148
SIII [183]	0.145
SIII* [184]	0.148
SIV [183]	0.151
SkI' [185]	0.155
SK255 [68]	0.157
SK272 [68]	0.155
SkA [186]	0.155
Ska25s20 [187]	0.161
Ska35s15 [187]	0.158
Ska35s20 [187]	0.158
Ska35s25 [187]	0.158
Ska45s20 [187]	0.156
SkB [186]	0.155
SkI1 [188]	0.160
SkI2 [188]	0.158
SkI3 [188]	0.158
SkI4 [188]	0.160
SkI5 [188]	0.156
SkI6 [189]	0.159
SkM [122]	0.160
SkM* [190]	0.160
SkM1 [191]	0.160
SkMP [192]	0.157
SkO [193]	0.160
SkO' [193]	0.160
SkP [194]	0.163
SKRA [195]	0.159
SkS1 [196]	0.161
SkS2 [196]	0.161
SkS3 [196]	0.161
SkS4 [196]	0.163
SkSC1 [197]	0.161
SkSC2 [197]	0.161
SkSC3 [197]	0.161
SkSC4 [198]	0.161
SkSC4o [199]	0.161
SkSC5 [200]	0.161
SkSC6 [200]	0.161
SkSC10 [200]	0.161
SkSC11 [201]	0.161
SkSC14 [199]	0.161
SkSC15 [199]	0.161
SkSP.1 [119]	0.162
SkT [202]	0.148
SkT1 [113]	0.161

Model	ρ_0
SkT2 [113]	0.161
SkT3 [113]	0.161
SkT4 [113]	0.159
SkT5 [113]	0.164
SkT6 [113]	0.161
SkT7 [113]	0.161
SkT8 [113]	0.161
SkT9 [113]	0.160
SkT1* [113]	0.162
SkT3* [113]	0.162
SkT1a [180]	0.161
SkT2a [180]	0.161
SkT3a [180]	0.161
SkT4a [180]	0.159
SkT5a [180]	0.164
SkT6a [180]	0.161
SkT7a [180]	0.161
SkT8a [180]	0.161
SkT9a [180]	0.160
SkTK [203]	0.168
SKX [204]	0.155
SKXce [204]	0.155
SKXm [204]	0.159
Skxs15 [205]	0.161
Skxs20 [205]	0.162
Skxs25 [205]	0.161
Skz-1 [128]	0.160
Skz0 [128]	0.160
Skz1 [128]	0.160
Skz2 [128]	0.160
Skz3 [128]	0.160
Skz4 [128]	0.160
SLy0 [206]	0.160
SLy1 [206]	0.160
SLy2 [206]	0.161
SLy230a [45]	0.160
SLy230b [45]	0.160
SLy3 [206]	0.160
SLy4 [207]	0.160
SLy5 [207]	0.161
SLy6 [207]	0.159
SLy7 [207]	0.158
SLy8 [206]	0.160
SLy9 [206]	0.151
SLy10 [207]	0.156
SQMC1 [156]	0.137
SQMC2 [156]	0.140
SQMC3 [156]	0.161
SQMC600 [157]	0.174
SQMC650 [157]	0.172
SQMC700 [157]	0.171
SQMC750 [157]	0.171
SSk [51]	0.161
SV [183]	0.155
SV-bas [115]	0.160
SV-min [115]	0.161
SVI [183]	0.143
SVII [184]	0.143

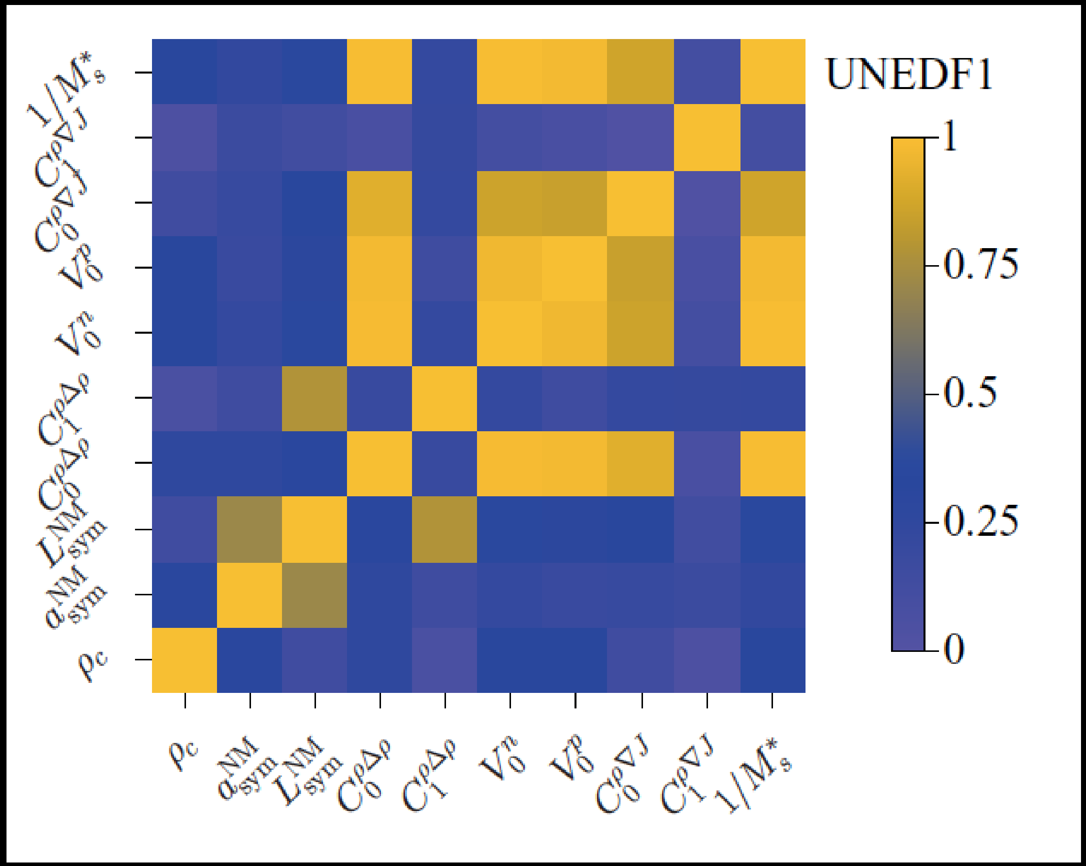
TABLE II. (*Continued.*)

Model	ρ_0	E_0	K_0	K'	J	L	K_{sym}	Q_{sym}	$K_{\tau,v}$	m^*
ZR1a [178]	0.173	−16.99	398.74	−186.01	9.84	−57.61	−471.08	103.34	−98.56	1.00
ZR1b [178]	0.173	−16.99	398.74	−186.01	18.50	−31.62	−471.08	103.34	−266.61	1.00
ZR1c [178]	0.173	−16.99	398.74	−186.01	31.50	7.36	−471.08	103.34	−518.70	1.00
ZR2a [178]	0.173	−16.99	324.78	184.94	1.62	−82.36	−397.29	474.98	49.99	1.00
ZR2b [178]	0.173	−16.99	324.78	184.94	11.95	−51.39	−397.29	474.98	−118.22	1.00
ZR2c [178]	0.173	−16.99	324.78	184.94	27.43	−4.93	−397.29	474.98	−370.53	1.00
ZR3a [178]	0.175	−16.99	198.79	475.65	−138.96	−504.42	−271.89	768.04	1547.69	1.00
ZR3b [178]	0.175	−16.99	198.79	475.65	−100.46	−388.91	−271.89	768.04	1131.04	1.00
ZR3c [178]	0.175	−16.99	198.79	475.65	−42.71	−215.66	−271.89	768.04	506.06	1.00
Zs [171]	0.163	−15.88	233.33	368.95	26.69	−29.38	−401.43	883.05	−271.61	0.78
Zs* [171]	0.162	−15.96	234.87	369.16	28.80	−4.53	−332.64	725.10	−312.58	0.77

Model										
SV-K218 [115]										
SV-K226 [115]										
SV-K241 [115]										
SV-kap00 [115]										
SV-kap02 [115]										
SV-kap06 [115]										
SV-mas07 [115]										
SV-mas08 [115]										
SV-mas10 [115]										
SV-sym28 [115]										
SV-sym32 [115]										
SV-sym34 [115]										
SV-tls [115]										
T [171]	0.161	−15.93	235.66	382.44	28.35	27.18	−206.76	462.91	−325.76	1.00
T11 [152]	0.161	−16.01	230.01	365.75	32.00	49.46	−108.76	486.98	−326.88	0.70
T12 [152]	0.161	−16.00	230.01	365.11	32.00	49.38	−108.75	488.50	−326.63	0.70
T13 [152]	0.161	−16.00	230.01	364.78	32.00	49.53	−108.06	487.57	−326.69	0.70
T14 [152]	0.161	−15.99	230.01	364.48	32.00	49.48	−108.12	488.35	−326.57	0.70
T15 [152]	0.161	−16.01	230.01	365.32	32.00	49.65	−107.91	485.83	−326.95	0.70
T16 [152]	0.161	−16.01	230.01	365.68	32.00	49.45	−108.75	487.24	−326.83	0.70
T21 [152]	0.161	−16.03	230.01	366.49	32.00	49.77	−108.03	483.25	−327.37	0.70
T22 [152]	0.161	−16.02	230.01	365.95	32.00	49.57	−108.50	485.74	−327.04	0.70
T23 [152]	0.161	−16.01	230.01	365.63	32.00	49.59	−108.27	485.95	−326.97	0.70
T24 [152]	0.161	−16.01	230.01	365.37	32.00	49.85	−107.22	484.00	−327.14	0.70
T25 [152]	0.161	−15.99	230.01	364.24	32.00	49.12	−109.21	491.85	−326.16	0.70
T26 [152]	0.161	−15.98	230.01	363.48	32.00	48.76	−110.15	495.92	−325.64	0.70
T31 [152]	0.161	−16.02	230.01	366.28	32.00	49.75	−108.00	483.82	−327.27	0.70
T32 [152]	0.161	−16.03	230.01	366.39	32.00	50.28	−106.20	478.97	−327.80	0.70
T33 [152]	0.161	−16.02	230.01	366.10	32.00	49.66	−108.23	484.88	−327.13	0.70
T34 [152]	0.161	−16.02	230.01	366.28	32.00	50.10	−106.81	480.71	−327.60	0.70
T35 [152]	0.161	−16.00	230.01	364.84	32.00	49.59	−107.85	487.05	−326.74	0.70
T36 [152]	0.161	−15.99	230.01	364.51	32.00	49.05	−109.62	491.98	−326.20	0.70
T41 [152]	0.162	−16.06	230.01	368.36	32.00	50.60	−106.02	473.67	−328.60	0.70
T42 [152]	0.162	−16.05	230.01	368.04	32.00	50.70	−105.51	473.28	−328.59	0.70
T43 [152]	0.162	−16.04	230.01	367.39	32.00	50.57	−105.66	475.23	−328.31	0.70
T44 [152]	0.161	−16.02	230.01	365.91	32.00	50.05	−106.76	481.62	−327.45	0.70
T45 [152]	0.161	−16.02	230.01	366.10	32.00	49.66	−108.24	484.73	−327.16	0.70
T46 [152]	0.161	−16.00	230.01	364.75	32.00	49.93	−106.59	484.25	−327.00	0.70
T51 [152]	0.162	−16.05	230.01	367.96	32.00	50.69	−105.52	473.55	−328.55	0.70
T52 [152]	0.161	−16.06	230.01	368.07	32.00	50.68	−105.55	473.55	−328.55	0.70
T53 [152]	0.161	−16.02	230.01	366.21	32.00	50.03	−106.99	481.50	−327.50	0.70
T54 [152]	0.161	−16.03	230.01	366.73	32.00	50.27	−106.36	478.71	−327.85	0.70
T55 [152]	0.161	−16.03	230.01	366.66	32.00	50.24	−106.49	479.02	−327.83	0.70
T56 [152]	0.161	−16.01	230.01	365.26	32.00	50.13	−106.19	481.83	−327.34	0.70
T61 [152]	0.162	−16.07	230.01	368.76	32.00	50.79	−105.56	471.67	−328.85	0.71
T62 [152]	0.162	−16.07	230.01	368.93	32.00	50.33	−107.25	475.46	−328.49	0.71
T63 [152]	0.162	−16.06	230.01	368.30	32.00	51.07	−104.36	469.72	−329.00	0.70
T64 [152]	0.162	−16.03	230.01	366.74	32.00	50.49	−105.65	476.73	−328.08	0.70
T65 [152]	0.162	−16.04	230.01	367.37	32.00	50.50	−105.90	475.82	−328.25	0.70
T66 [152]	0.161	−16.02	230.01	366.04	32.00	50.30	−105.96	479.25	−327.72	0.70
v070 [208]	0.157	−15.78	230.99	384.93	27.98	−3.45	−361.15	591.72	−346.20	1.05
v075 [208]	0.157	−15.80	231.29	385.51	28.00	−0.31	−341.88	587.67	−340.52	1.05
v080 [208]	0.157	−15.79	231.17	385.26	28.00	2.23	−325.61	585.53	−335.29	1.05
v090 [208]	0.157	−15.79	231.17	385.26	28.00	5.04	−304.26	593.46	−326.10	1.05
v100 [208]	0.157	−15.79	231.17	385.26	28.00	8.73	−281.39	588.25	−319.22	1.05
v105 [208]	0.157	−15.79	231.17	385.26	28.00	7.08	−284.51	611.85	−315.20	1.05
v110 [208]	0.157	−15.79	231.17	385.26	28.00	7.51	−279.62	617.86	−312.19	1.05
Z [171]	0.159	−15.97	330.30	64.98	26.82	−49.70	−657.85	495.24	−369.43	0.84

NUCLEAR MATTER

- Nuclear matter is ideal testing ground for in-medium interactions
- (mean field) wave functions can be written down
- nuclear matter properties correlate strongly with giant resonances:
    - K_0, K_τ from GMR
    - m_s^* from GQR
    - m_v^* from GDR
    - + asymmetry form many IV modes



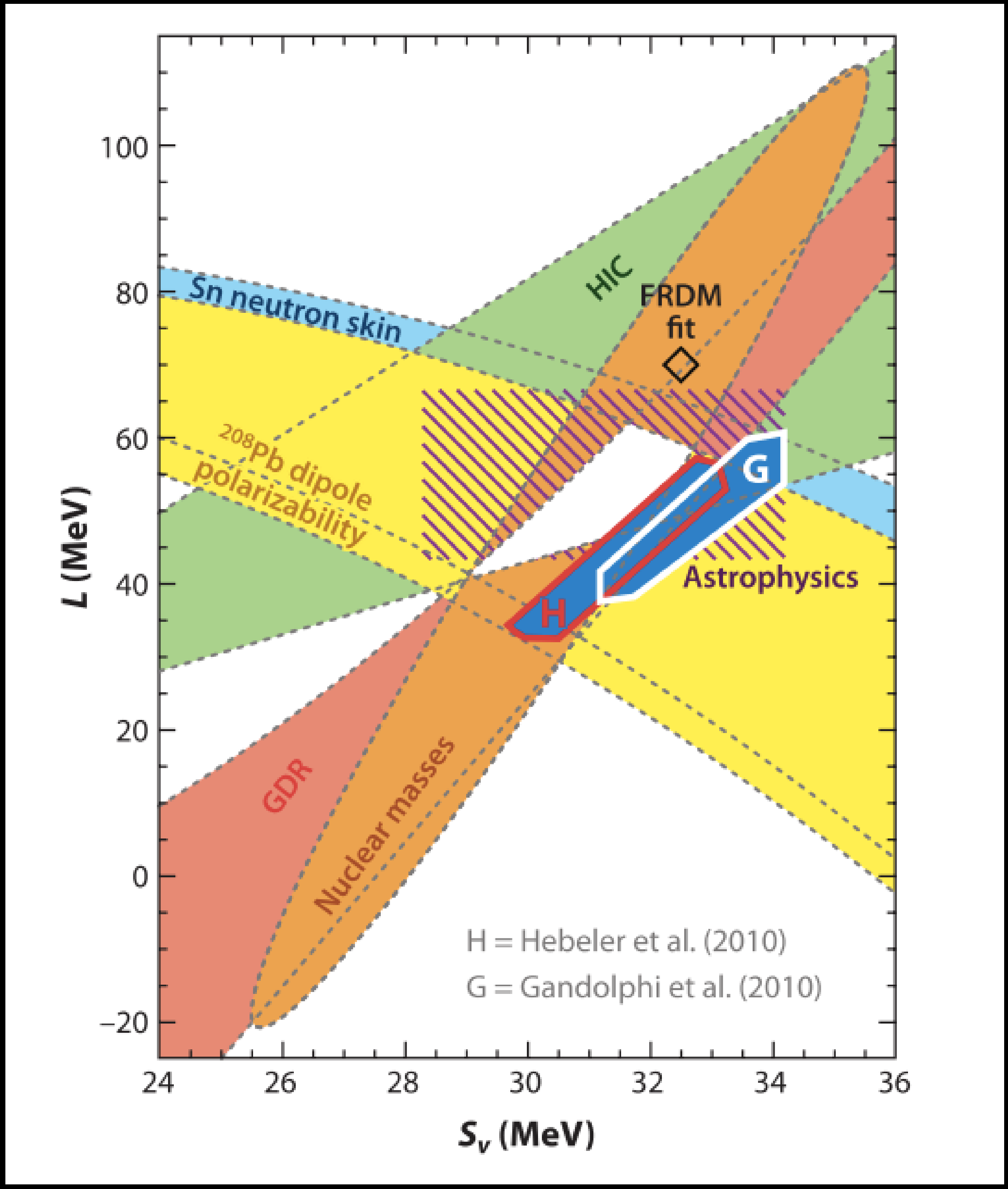
Kortelainen et al, PRC85, 024304 (2012)

NEUTRON STARS

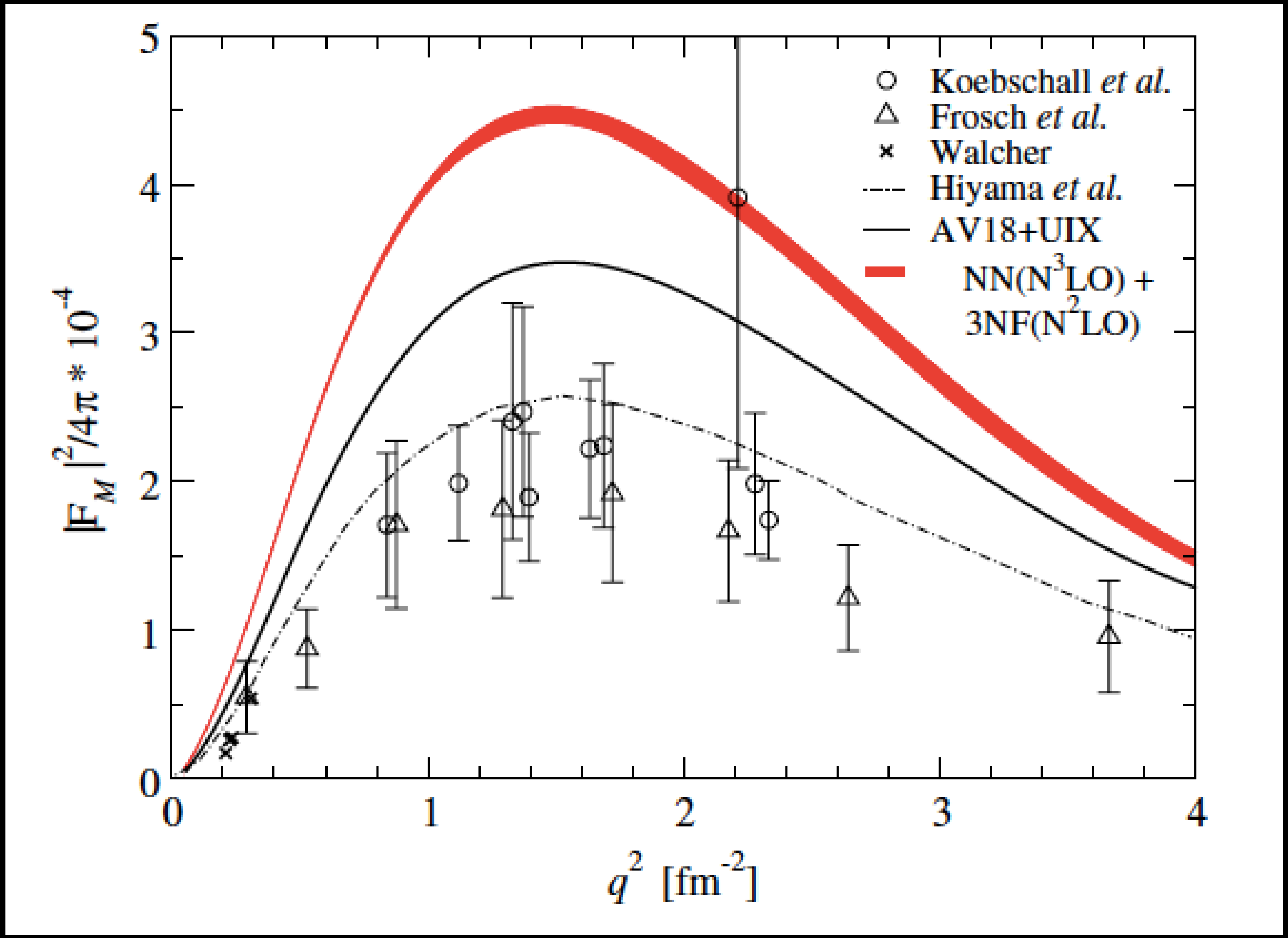
Giant resonances are of interest to compact star astrophysicists

Strong correlations between GDR and S(ρ). Nuclear EoS is key input to neutron star calculations

Plot from J. Lattimer, Annu. Rev. Nucl. Part. Sci. **62**, 485 (2012) based on work of L. Trippa, G. Colò and E. Vigezzi, Phys. Rev. **C 77**, 061304(R) (2008)



NUCLEAR INTERACTIONS



Despite the talk title, I won’t cover nuclear interactions in their full glory - but giant resonances are now within reach of some ab initio approaches

Theoretical and experimental transition form factors, from Sonia Bacca, Nir Barnea, Winfried Leidemann and Giuseppina Orlandini, Phys. Rev. Lett. 110, 042503 (2013)

TENSOR TERMS FOR GR