# Low-lying dipole response in stable and unstable nuclei

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X. Roca-Maza, G. Pozzi, M.B., K. Mizuyama, G. Colò,
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# Motivations
## Giant Resonances

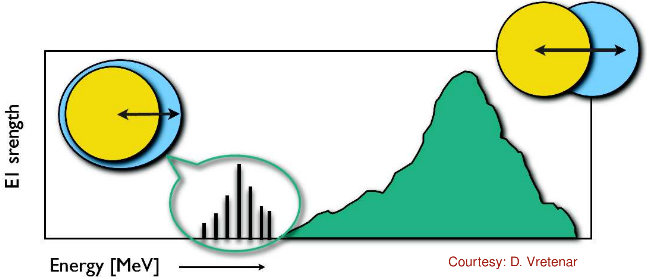
### Giant Resonances

Nuclear collective excitations that are the macroscopic signature of some many-body correlations inside the nucleus.

- Constraints on the parameters of the equation of state of nuclear matter
  - Monopole ⇛ Compressibility $K_0$
  - Dipole ⇛ Symmetry Energy $S(\rho = 0.1\text{fm}^{-3})$
  - Quadrupole ⇛ Effective mass $m^*$
- Nuclear interaction in a given channel
- 60-year-studies on GRs (since 1947), two books
  - P.F. Bortignon, A. Bracco, R.A. Broglia, 1998
  - M.N. Harakeh, A. van der Woude, 2001
- Resonances in exotic nuclei (n – rich)

# Motivations

## Pygmy Dipole Strength (PDS)




Courtesy: D. Vretenar

Low-energy peak in the dipole response of neutron rich nuclei

- due to shell effects, in some models
- has a coherent nature (resonance), in others.

Connection with the slope of the symmetry energy $S(\rho)$ at saturation:

$$L = 3\rho_0 \frac{d}{d\rho} S(\rho)\Big|_{\rho=\rho_0} \ ?$$

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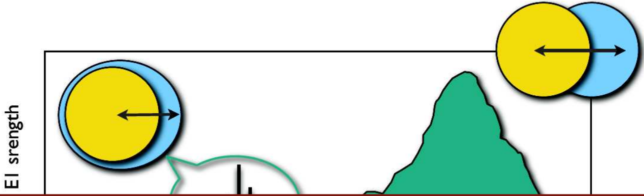


**To have a better understanding of the PDS, we need**

a more exhaustive analysis of its microscopic properties employing different nuclei and a representative set of nuclear interactions

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# List of ingredients

## RPA

- Self-consistent HF+RPA with Skyrme interactions, with different isovector properties.
  - SGII ($L = 37.63$ MeV)
  - SLy5 ($L = 48.27$ MeV)
  - SkI3 ($L = 100.52$ MeV)
- Continuum is discretized. Large basis due to zero range force.
- Three nuclei: $^{68}$Ni, $^{132}$Sn, $^{208}$Pb

### Total Energy and charge radii

| | $^{68}$Ni | | $^{132}$Sn | | $^{208}$Pb | |
|---|---|---|---|---|---|---|
| | $E$ [MeV] | $r_c$ [fm] | $E$ [MeV] | $r_c$ [fm] | $E$ [MeV] | $r_c$ [fm] |
| SGII | 611.048 | 3.808 | 1136.916 | 4.727 | 1667.328 | 5.512 |
| SLy5 | 591.464 | 3.918 | 1104.180 | 4.730 | 1636.336 | 5.507 |
| SkI3 | 604.588 | 3.880 | 1121.076 | 4.701 | 1654.224 | 5.480 |
| Exp. | 590.376 | 3.866 | 1090.32 | – | 1636.336 | 5.501 |

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**We focus in particular on**

- RPA and unperturbed dipole strength.
- the isoscalar or isovector nature.
- the transition densities.
- coherence of p-h contributions.

# RPA

- RPA state: $|\nu\rangle = \sum_{ph} X_{\rm ph}^{(\nu)}|ph^{-1}\rangle + Y_{\rm ph}^{(\nu)}|hp^{-1}\rangle$
- Reduced transition probabilities

  $B(EJ:0\to\nu) = |\langle\nu\|\hat{F}_J\|0\rangle|^2 = \left|\sum_{\rm ph}(X_{\rm ph}^{(\nu)} + Y_{\rm ph}^{(\nu)})\langle p\|\hat{F}_J\|h\rangle\right|^2$
- Strength function

  $S(E) = \sum_\nu |\langle\nu\|\hat{F}_J\|0\rangle|^2\delta(E-E_\nu)$
- Operators

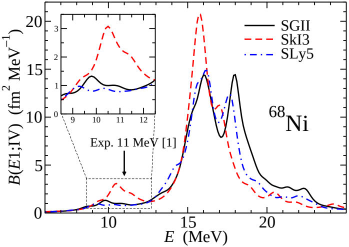
  $\hat{F}_{1M}^{(\rm IV)} = 2\frac{Z}{A}\sum_{n=1}^{N} r_n Y_{1M}(\hat{r}_n) - 2\frac{N}{A}\sum_{p=1}^{Z} r_p Y_{1M}(\hat{r}_p)$

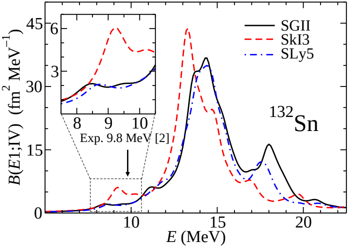
  $\hat{F}_{1M}^{(\rm IS)} = \sum_{i=1}^{A} r_i^3 Y_{1M}(\hat{r}_i)$
- Transition density: nature of excitation (surface - volume, isoscalar - isovector)

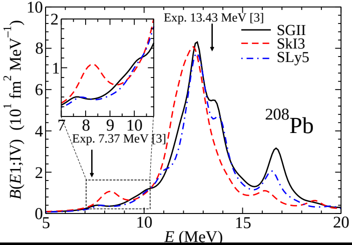
  $\delta\rho_\nu(r) = \frac{1}{\sqrt{2J+1}}\sum_{\rm ph}(X_{\rm ph}^{(\nu)} + Y_{\rm ph}^{(\nu)})\langle p\|Y_J\|h\rangle\frac{u_p(r)u_h(r)}{r^2}$

# Dipole strength functions (IV)

$$\hat{F}^{(IV)}_{1M} = \frac{2Z}{A}\sum_{n=1}^{N} r_n Y_{1M}(\hat{r}_n) - \frac{2N}{A}\sum_{n=1}^{A} r_p Y_{1M}(\hat{r}_p)$$



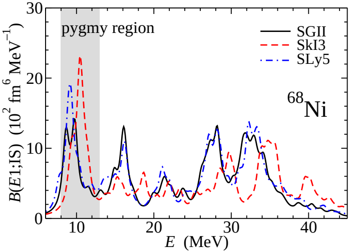

larger $L \rightarrow$ larger PDS peak
A. Carbone *et. al.*, PRC **81**, 041301 (2010).

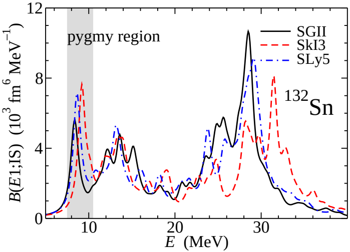
Experiment:

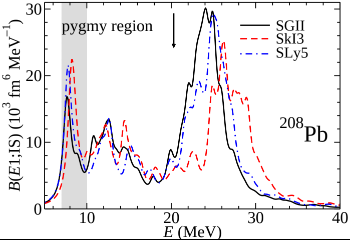
[1] O. Wieland *et. al.*, PRL **102**, 092502 (2009).
[2] P. Adrich *et. al.*, PRL **95**, 132501 (2005).
[3] N. Ryezayeva *et. al.*, PRL **89**, 272502 (2002).

# Dipole strength functions (IS)

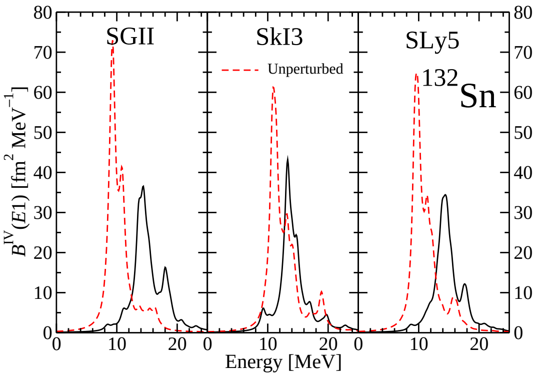
$$\hat{F}^{(IS)}_{1M} = \sum_{i=1}^{A} r_i^3 Y_{1M}(\hat{r}_i)$$



# RPA versus unperturbed strength




| | $E_{PDS}$ [MeV] | $E_{unp}$ [MeV] |
|---|---|---|
| SGII | 8.52 | 9.32 |
| SkI3 | 9.23 | 10.81 |
| SLy5 | 8.64 | 11.41 |

**- No low energy peak in the unperturbed response.**

**- Indications that the PDS may show some coherency depending on the model.** (RPA peaks do not coincide in energy with the unperturbed peak)

# Isoscalar or isovector?
## A local criterion

- A state is 70% isoscalar in a given radial range if

$$|\delta\rho_\nu^{(IS)}(r)| > |\delta\rho_\nu^{(IV)}(r)|$$

for at least the 70% of the points in the range [N. Paar *et. al.*, PRL103 (2009) 032502]

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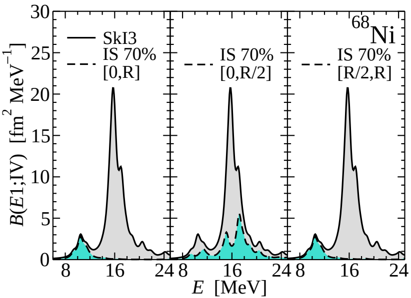
$$B_{IV}(E1) = \sqrt{3}\sum_\nu \left(\frac{2Z}{A}\int drr^3\delta\rho_\nu^n(r) - \frac{2N}{A}\int drr^3\delta\rho_\nu^p(r)\right)$$



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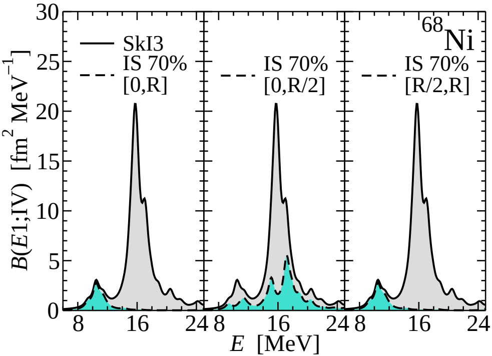


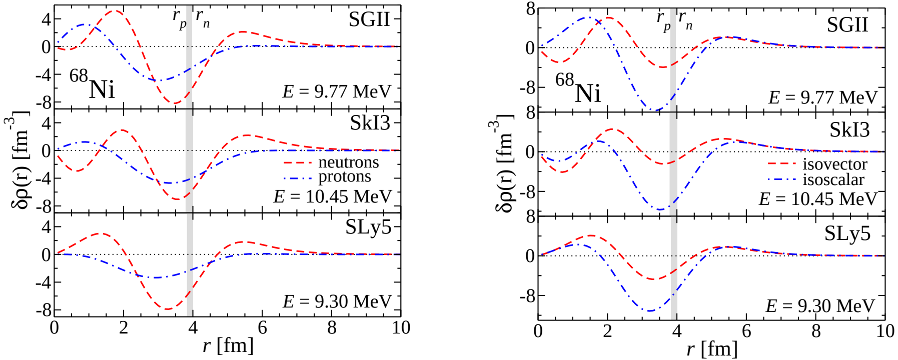

[N. Paar *et. al.*, PRL103 (2009) 032502]

IS nature of the PDS due to outermost nucleons
(neutrons in a neutron-rich nucleus).

# Microscopic analysis of PDS

## Transition densities – $^{68}$Ni

$$\delta\rho_\nu(r) = \frac{1}{\sqrt{2J+1}} \sum_{ph} (X_{ph}^{(\nu)} + Y_{ph}^{(\nu)}) \langle p \| Y_J \| h \rangle \frac{u_p(r)u_h(r)}{r^2}$$

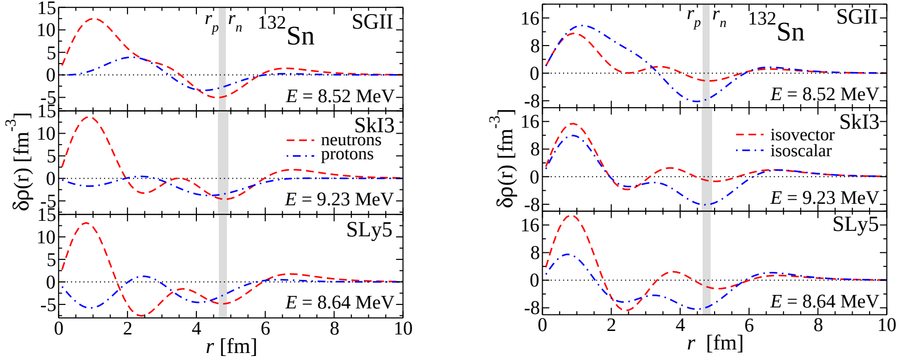



Around the nuclear surface: all models clearly isoscalar.
In the interior: not clear trends. But this part is not quite sensitive to external probes

# Microscopic analysis of PDS

## Transition densities – $^{132}$Sn

$$\delta\rho_\nu(r) = \frac{1}{\sqrt{2J+1}} \sum_{ph} (X_{ph}^{(\nu)} + Y_{ph}^{(\nu)}) \langle p \| Y_J \| h \rangle \frac{u_p(r) u_h(r)}{r^2}$$



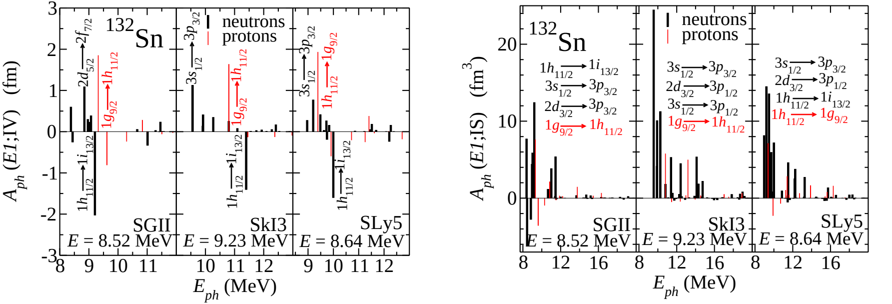

Around the nuclear surface: all models clearly isoscalar.

In the interior: not clear trends. But this part is not quite sensitive to external probes

# Collectivity

## Relevant p-h excitations in the IS and IV dipole response

$$B(E1:0\rightarrow 1^-) = \left|\sum_{ph} A_{ph}(E1)\right|^2 = \left|\sum_{ph}(X^n_{ph}+Y^n_{ph})\langle p\|\hat{F}_1\|h\rangle\right|^2$$




The largest p-h contributions are the same in **IV** and **IS** response:

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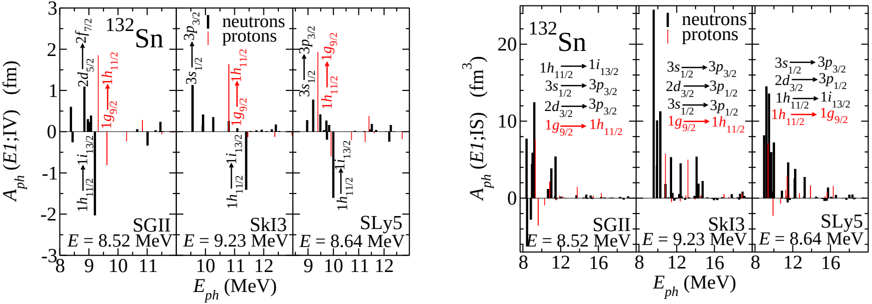
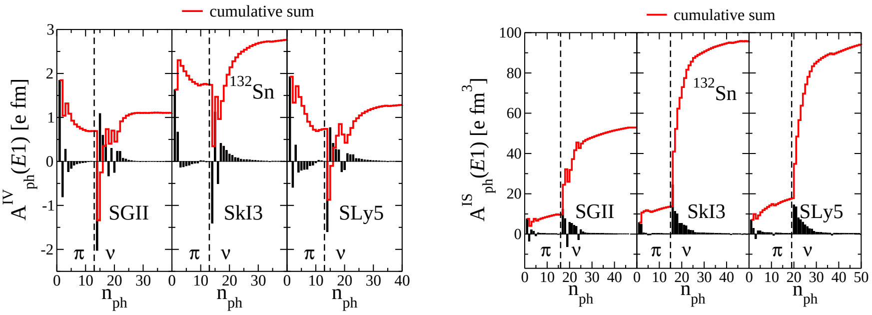



The largest p-h contributions are the same in **IV** and **IS** response:
PDS is one state projected on the two isospin channel.

# Collectivity

## Coherence of the different contributions

$$B(E1:0\rightarrow 1^-) = \left|\sum_{ph} A_{ph}(E1)\right|^2 = \left|\sum_{ph}(X^n_{ph}+Y^n_{ph})\langle p\|\hat{F}_1\|h\rangle\right|^2$$




The largest p-h contributions are:

- coherent in the **IS** channel,
- less coherent in the **IV** channel.

# Conclusions

- Microscopic study of low energy dipole strength in $^{68}$Ni, $^{132}$Sn, $^{208}$Pb using Skyrme-HF+RPA framework.
- **Low-energy peak** in the IS and IV strength for all nuclei and models.
- IV (and IS) peak increases in magnitude with increasing values of $L$ [in agreement with Carbone *et al.*, PRC **81**, 041301(R) (2010) and Vretenar *et al.*, PRC **85**, 044317 (2012)].
- Systematically more collectivity in the **IS** than in the IV transitions
- The low-energy IS response is basically due to the outermost neutrons.

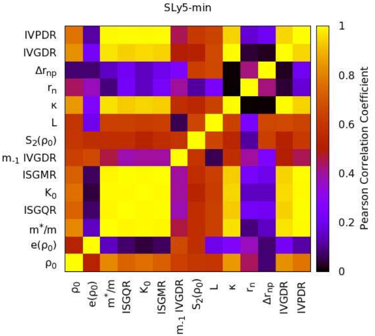
**Therefore,**

- **IS probes** seem to be more suitable for the study of the low-energy dipole response.

# Extra material

# Correlations

- $\chi^2(\boldsymbol{p}) = \sum_{i=1}^{m} \left( \frac{\mathcal{O}_i^{th.}(\boldsymbol{p}) - \mathcal{O}_i^{ref.}}{\Delta \mathcal{O}_i^{ref.}} \right)^2$
- $\chi^2(\boldsymbol{p}) - \chi^2(\boldsymbol{p}_0) \approx \sum_{i,j=1}^{n} (p_i - p_{0i}) \mathcal{M}_{ij} (p_j - p_{0j})$
- $\mathcal{M} \equiv$ curvature matrix ($\propto \partial_{p_i} \partial_{p_j} \chi^2$)
- Given two observables $A$ and $B$, we define the covariance as $\overline{\Delta A \Delta B} = \sum_{i,j} \partial_{p_i} A (\mathcal{M}^{-1})_{ij} \partial_{p_j} B$




- Pearson product-moment correlation coefficient

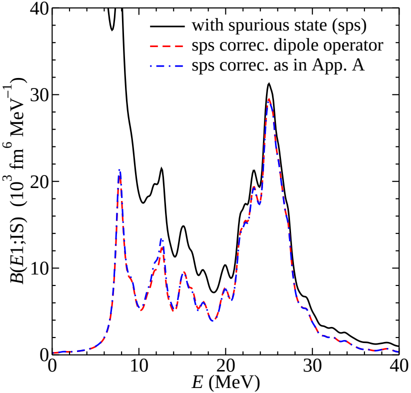
$$c_{AB} = \frac{\overline{\Delta A \Delta B}}{\sqrt{\overline{\Delta A^2} \, \overline{\Delta B^2}}}$$

$|c_{AB}| = 1 \Rightarrow$ fully correlated

$c_{AB} = 0 \Rightarrow$ totally uncorrelated

# Spurious state

Back to Conclusions




- New set of states $\tilde{\nu}$ orthogonal to the spurious state, i.e.

$$\int dr r^2 r(\delta\rho^n_{\tilde{\nu}} + \delta\rho^p_{\tilde{\nu}}) = 0$$

- Equal IV strength with new states

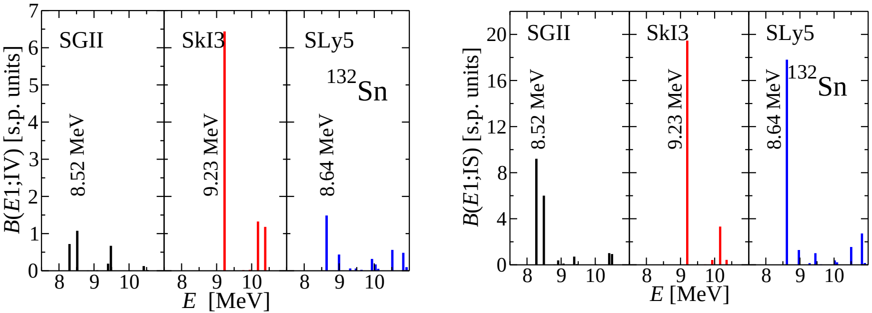
$$\int dr r^2 r(\delta \frac{Z}{A}\rho^n_{\tilde{\nu}} - \frac{N}{A}\delta\rho^p_{\tilde{\nu}}) = \int dr r^2 r(\delta \frac{Z}{A}\rho^n_{\nu} - \frac{N}{A}\delta\rho^p_{\nu})$$

- Assumption (PLB **485**, 362 (2000))

$$\delta\rho^{n,p}_{\tilde{\nu}} = \delta\rho^{n,p}_{\nu} - \alpha^{n,p}\frac{d\rho^{n,p}_{HF}(r)}{dr}$$

# Single particle units

Back to Collectivity




If different p-h states are contributing coherently to the PDS, the most prominent peaks should be clearly larger than one.

# RPA versus unperturbed strength

Back to Unperturbed strength