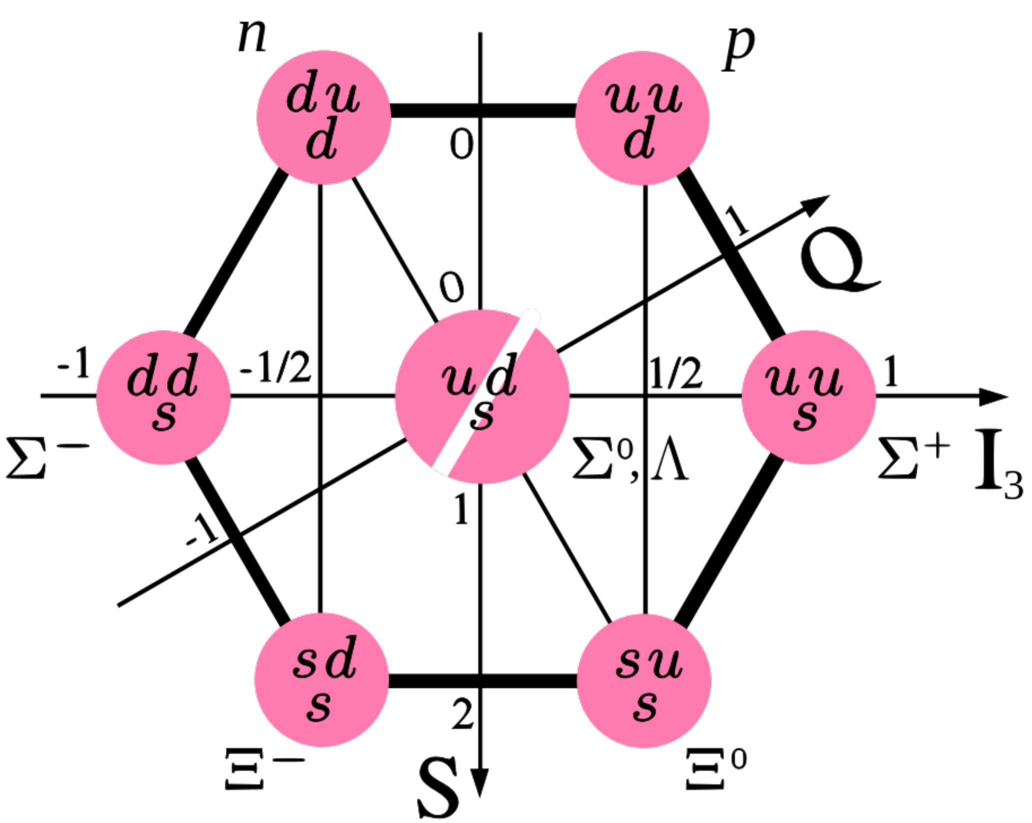
1. Hypernuclei

Hyperons

⊙ **Hyperon:** a baryon containing one, two or three **s** quarks in addition to **u** and **d** quarks

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

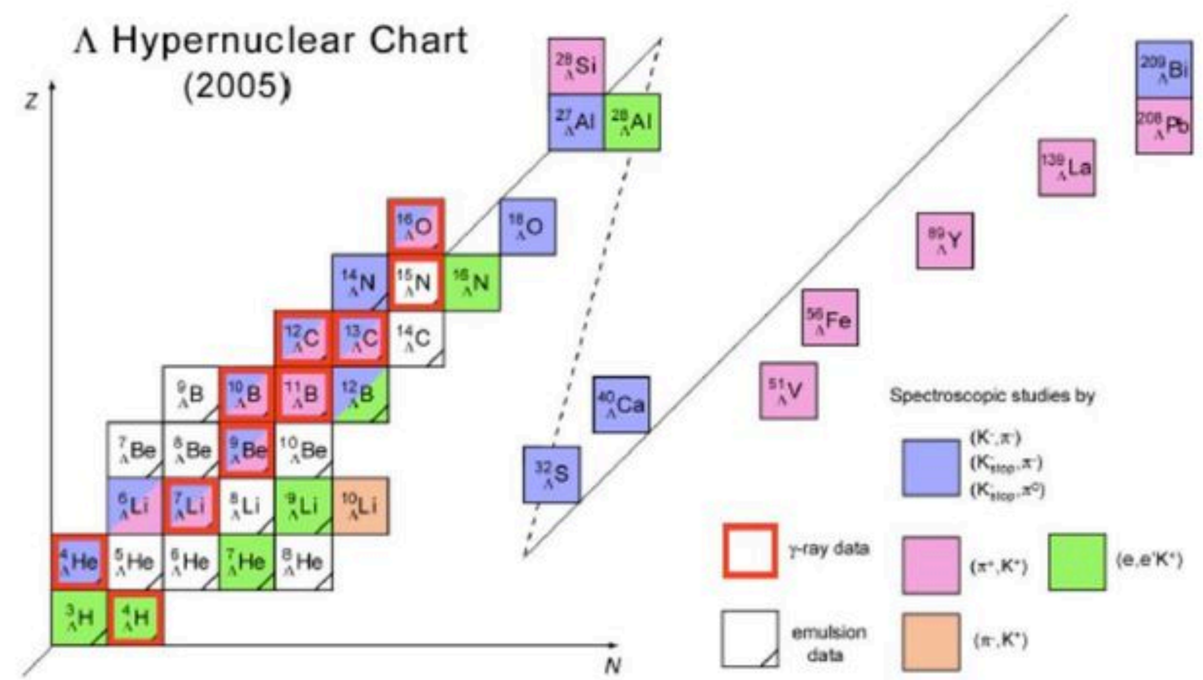


○ Hyperons decay weakly (strangeness conserved by strong and EM interactions)

○ New quantum number: strangeness

Hypernuclei

⦿ **Hypernucleus:** a nucleus with at least one hyperon in addition to protons and neutrons



○ About 40 hypernuclei produced and measured

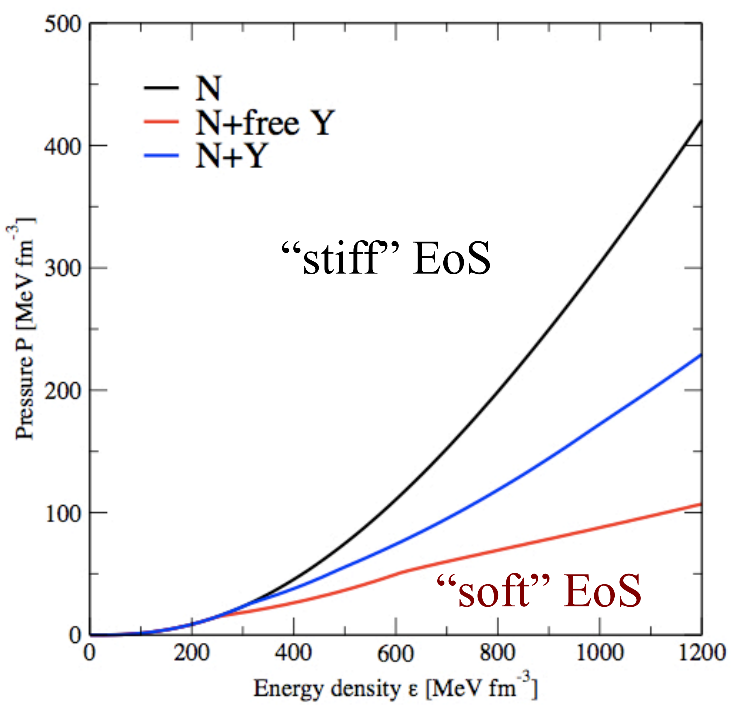
○ Motivation: could give additional insight into standard nuclei

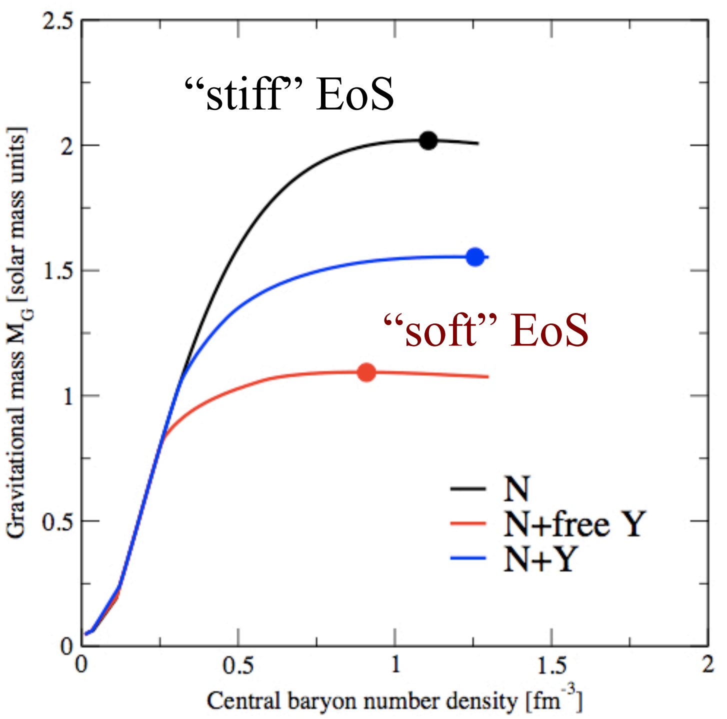
○ Theoretical description: NY and YY interactions not very well known (not to mention 3BFs)

Hyperons in neutron stars

- ⦿ Hyperons could appear in the core of a neutron star
  - ○ Density high enough to make n+n → n + Λ energetically favourable
- ⦿ If hyperons do appear, the EoS is softened → incompatible with experimental observations

  → **Hyperon puzzle**





- ⦿ Possible solutions:
  - ○ Poor knowledge of NY, YY, NNY, NYY, YYY interactions
  - ○ Transition to quark matter in the neutron star interior

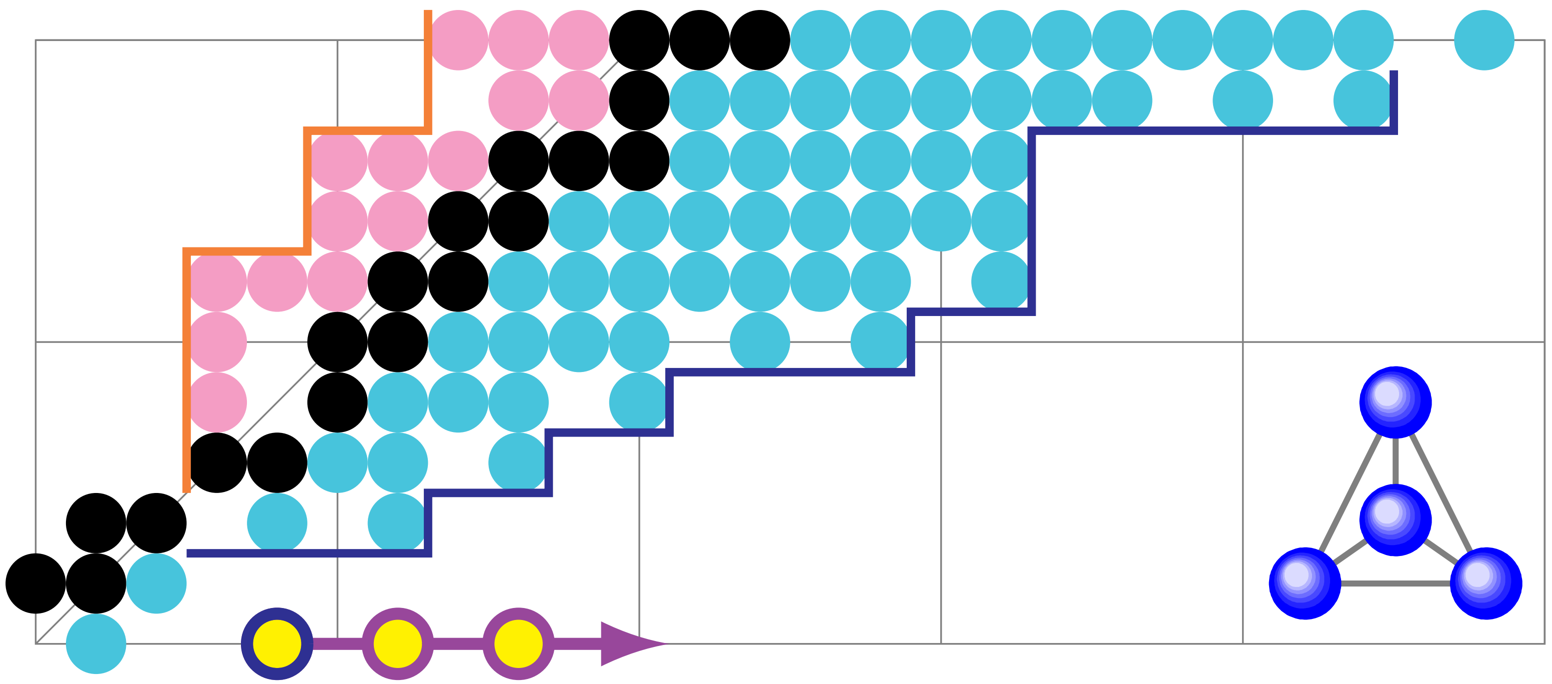
Literature

- A. Gal *et al.*, Rev. Mod. Phys. **88** 035004 (2016) [review]
- D. Lonardoni *et al.*, Phys. Rev. Lett. **114** 092301 (2015)
- L. Contessi *et al.*, Phys. Rev. Lett. **121** 102502 (2018)
- J. Haidenbauer *et al.*, arXiv:1906.11681 (2019)

2. Tetraneutron

Neutral nuclei

⦿ Do **neutral nuclei** exist?



⦿ Candidates

○ Odd-even staggering → even N

○ Not too many neutrons (hard to bring them together) → N=4 (**tetraneutron**)

⦿ Biggest issues

○ Production of very neutron-rich systems

○ Detection of a neutral object

Tetraneutron: experiments

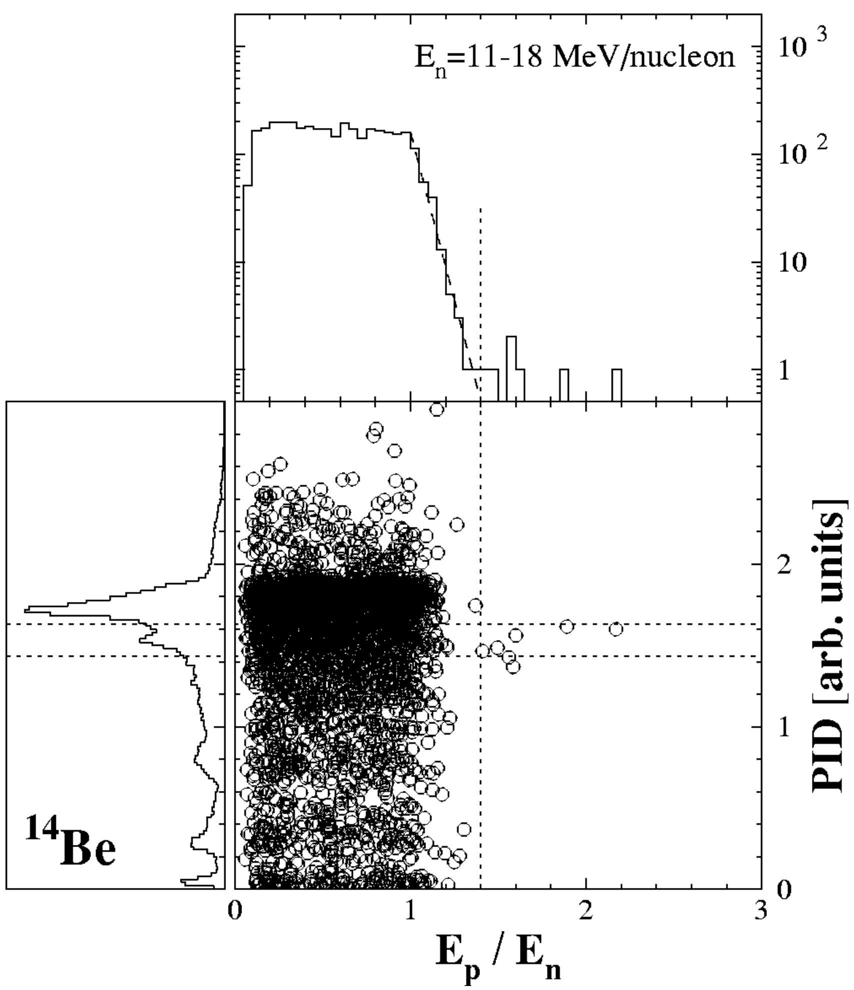
⊙ DEMON experiment @ GANIL, **Caen**

$$^{14}\mathrm{Be} \xrightarrow{(\mathrm{C})} {}^{10}\mathrm{Be} + {}^{4}\mathrm{n} \qquad ('01,'02)$$

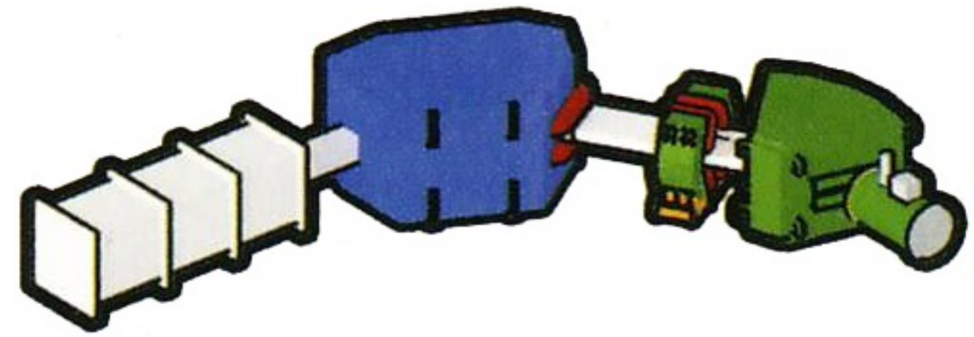
$$^{8}\mathrm{He} \xrightarrow{(\mathrm{C})} {}^{4}\mathrm{He} + {}^{4}\mathrm{n} \qquad ('02)$$

$$^{12/14}\mathrm{Be} \xrightarrow{(\mathrm{C})} \alpha\alpha + {}^{4/6}\mathrm{n} \qquad ('02)$$

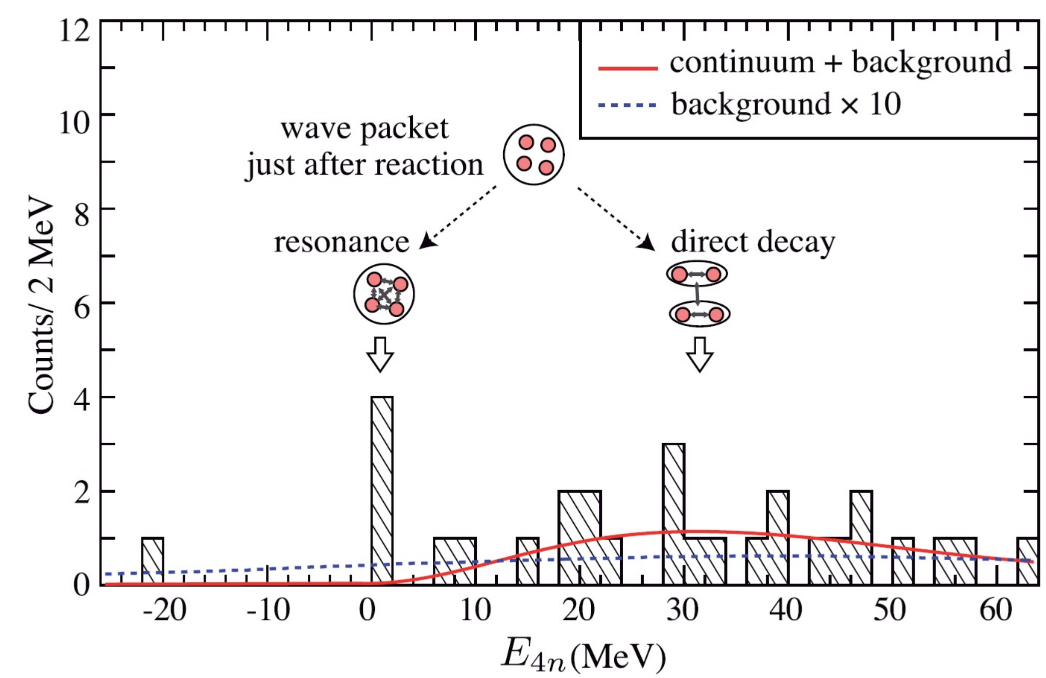
$$^{15}\mathrm{B} \xrightarrow{(\mathrm{C})} {}^{14}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{n} \qquad ('05,'06)$$



⊙ SHARAQ experiment @ RIKEN, **Tokyo**



$$^{4}\mathrm{He}\,({}^{8}\mathrm{He},\alpha\alpha)\,{}^{4}\mathrm{n} \qquad ('12)$$



$\rightarrow$ $\mathrm{E}({}^{4}\mathrm{n}) = 0.8 \pm 1.3$ MeV !

$\rightarrow$ $\Gamma({}^{4}\mathrm{n}) < 2.6$ MeV

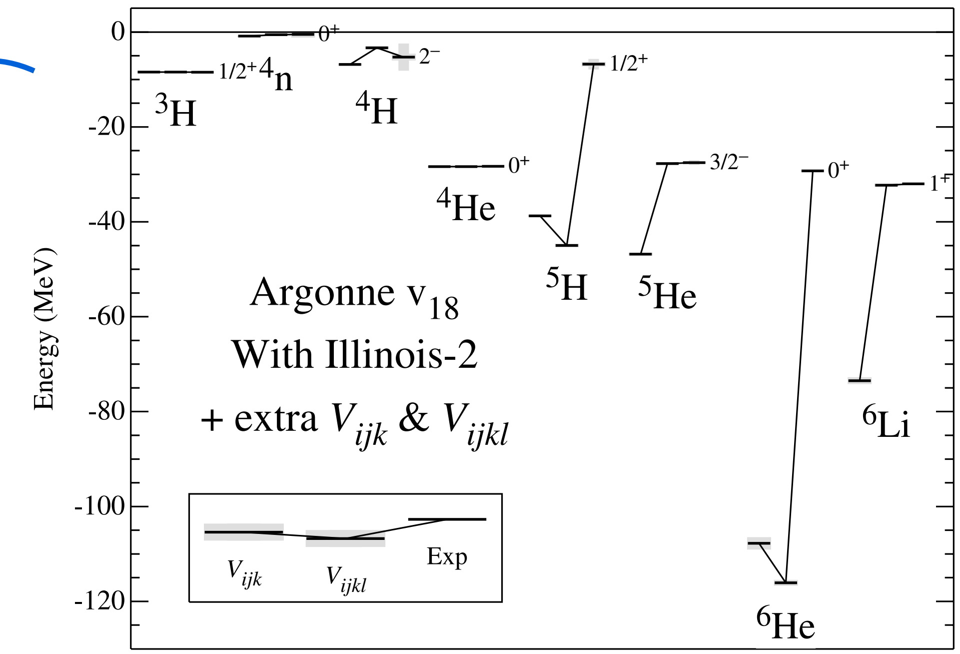
Tetraneutron: theory

- Ab initio calculations: **contradictory results**

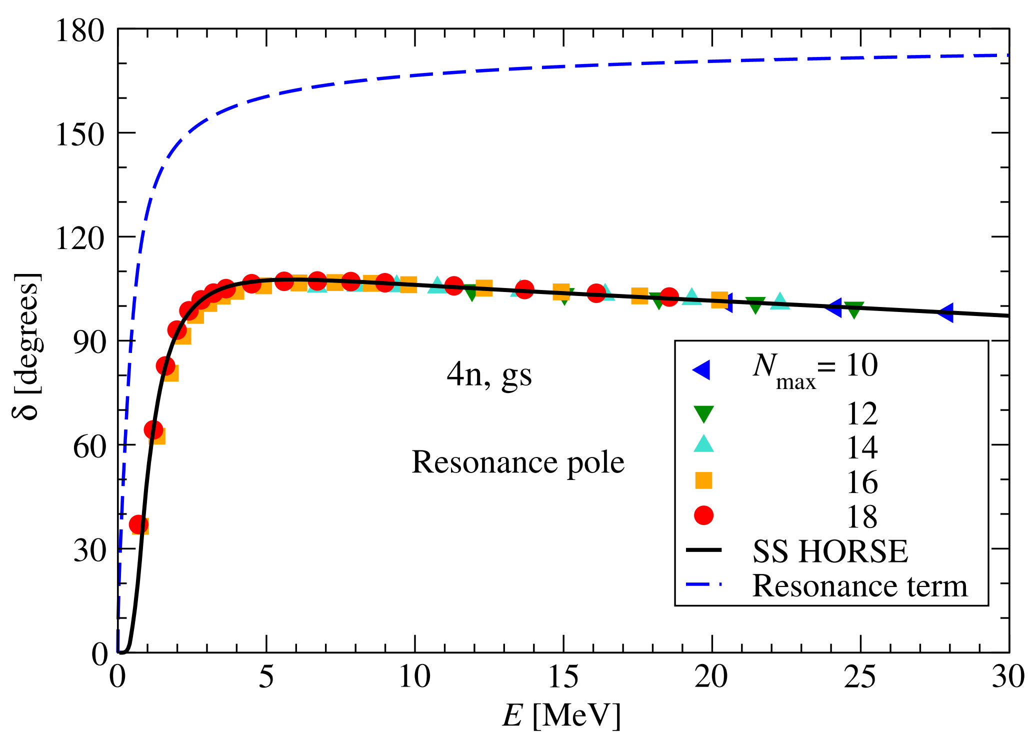
Bound 4n incompatible with other light nuclei

Realistic 3N forces leads to very broad resonance

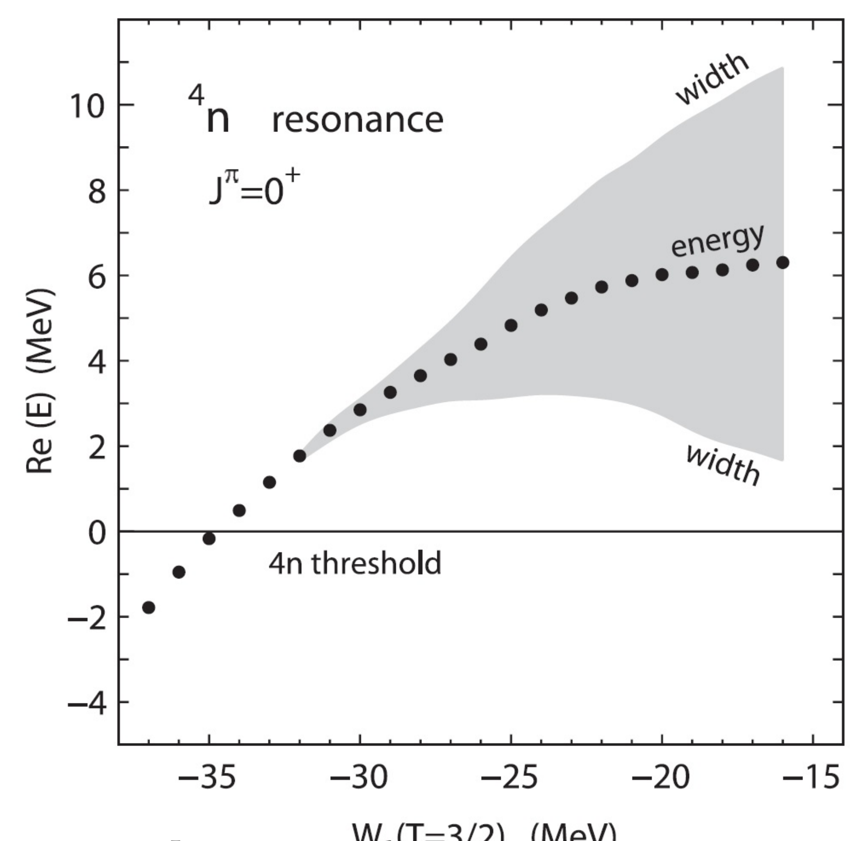
Narrow resonance found at 0.8 MeV



[Pieper 2003]



[Shirokov *et al.* 2016]



[Hiyama *et al.* 2016]

Literature

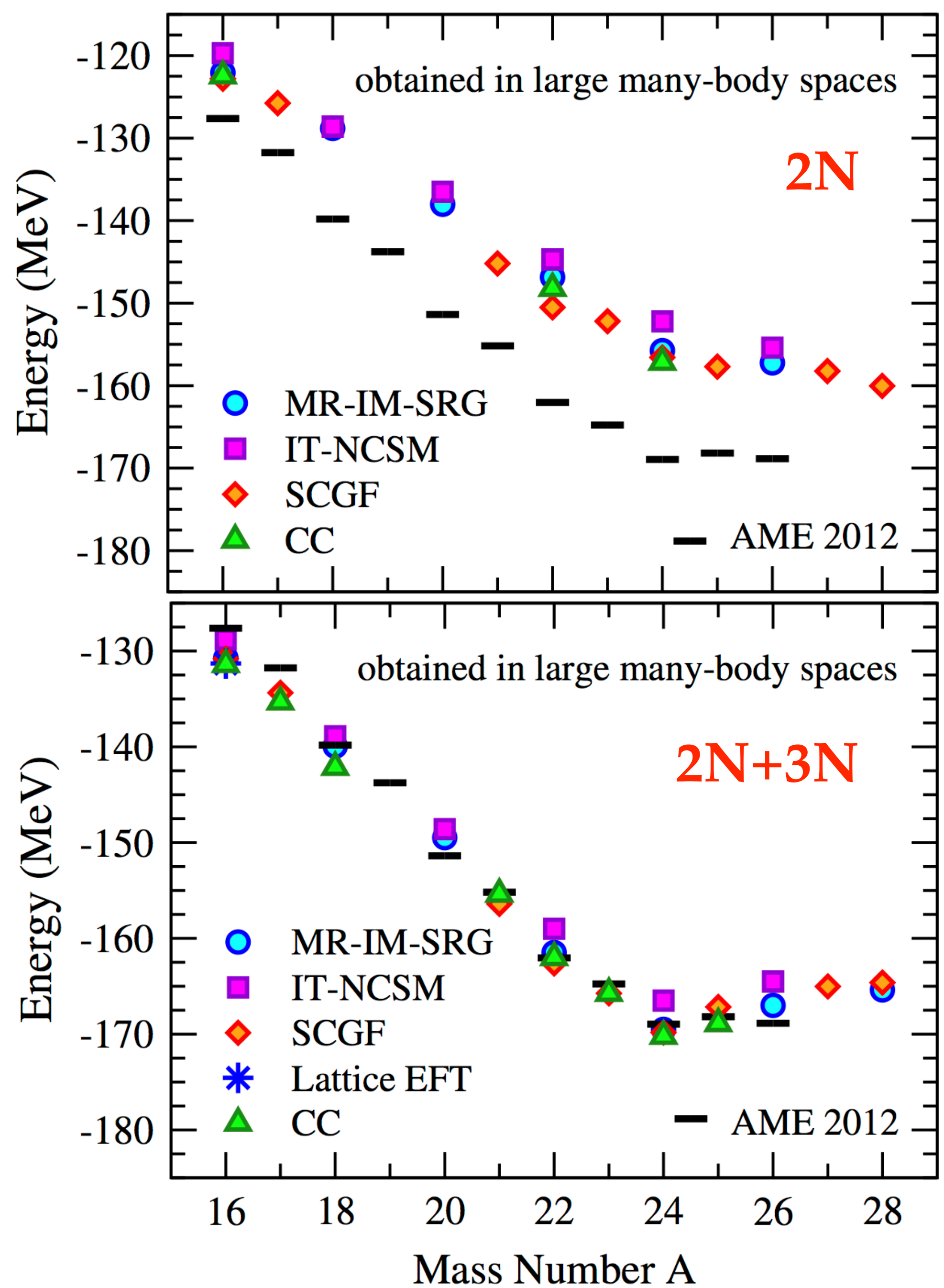
- Experiment
  - F. M. Marques *et al.*, Phys. Rev. C **65** 044006 (2002)
  - K. Kisamori *et al.*, Phys. Rev. Lett. **116** 052501 (2016)

- Theory
  - S. Pieper, Phys. Rev. Lett. **90** 252501 (2003)
  - E. Hiyama *et al.*, Phys. Rev. C **93** 044004 (2016)
  - A. M. Shirokov *et al.*, Phys. Rev. Lett. **117** 182502 (2017)
  - S. Gandolfi *et al.*, Phys. Rev. Lett. **118** 232501 (2017)
  - A. Deltuva and R. Lazauskas, Phys. Rev. Lett. **123** 069201 (2019)

3. Three-nucleon forces

Need for three-nucleon forces

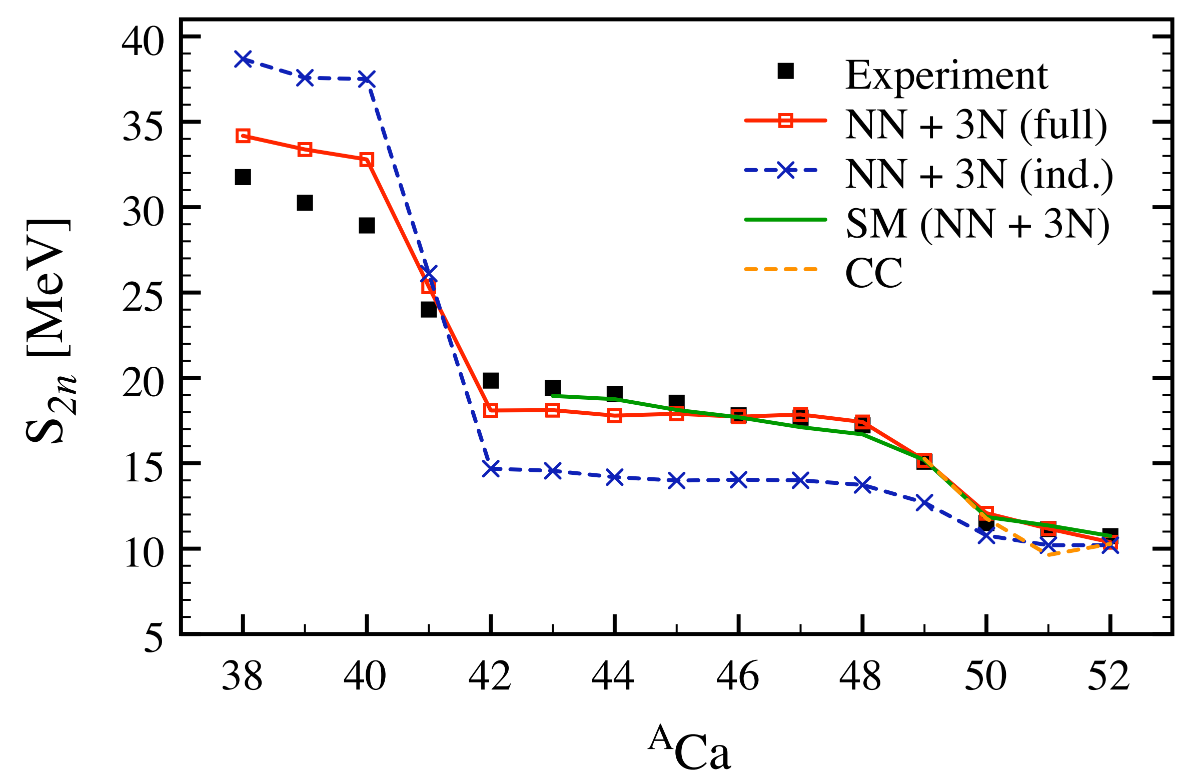
- Three-nucleon forces crucial for a quantitative understanding of nuclear structure



[Hebeler *et al.* 2015]

Oxygen dripline

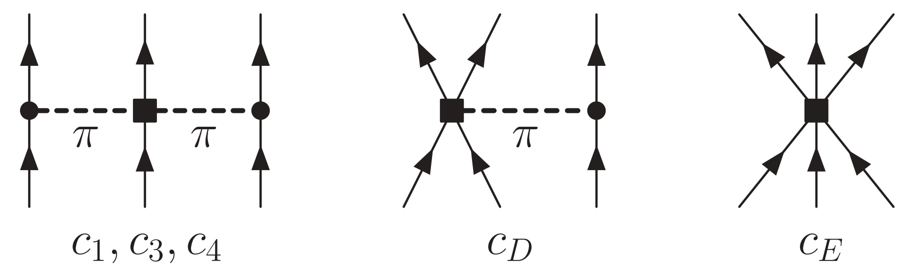
N=20 and N=28 gaps in calcium



[Somà *et al.* 2014]

Three-nucleon forces from EFT

⊙ Lowest-order 3N forces (NNLO)



$$V_c = \frac{1}{2}\left(\frac{g_A}{2f_\pi}\right)^2 \sum_{i\neq j\neq k} \frac{(\boldsymbol{\sigma}_i \cdot \mathbf{q}_i)(\boldsymbol{\sigma}_j \cdot \mathbf{q}_j)}{\left(q_i^2 + m_\pi^2\right)\left(q_j^2 + m_\pi^2\right)} F_{ijk}^{\alpha\beta} \tau_i^\alpha \tau_j^\beta$$

with

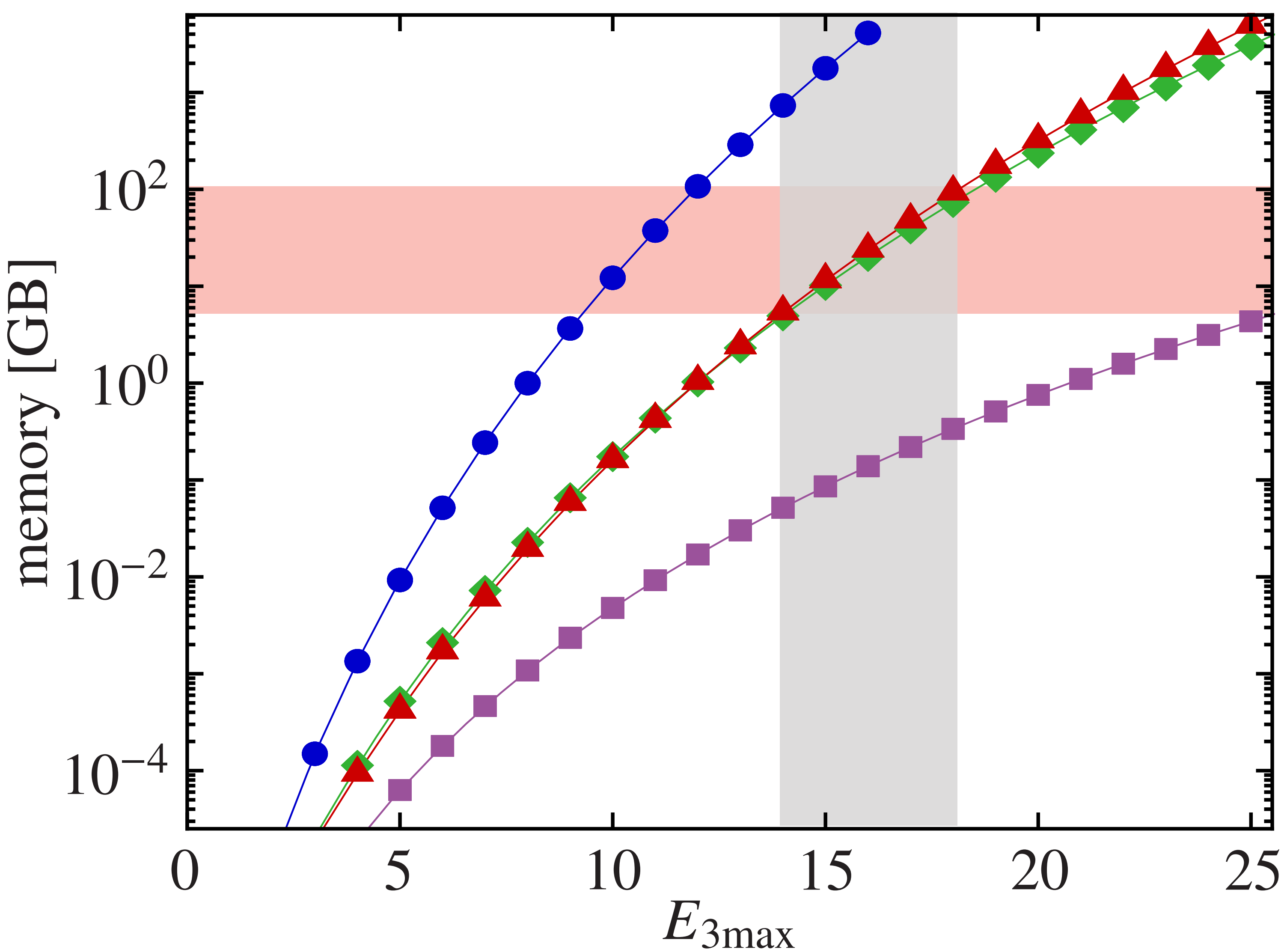
$$F_{ijk}^{\alpha\beta} = \delta^{\alpha\beta}\left[-\frac{4c_1 m_\pi^2}{f_\pi^2} + \frac{2c_3}{f_\pi^2}\mathbf{q}_i \cdot \mathbf{q}_j\right] + \sum_\gamma \frac{c_4}{f_\pi^2}\epsilon^{\alpha\beta\gamma}\tau_k^\gamma \boldsymbol{\sigma}_k \cdot (\mathbf{q}_i \times \mathbf{q}_j)$$

$$V_D = -\frac{g_A}{8f_\pi^2}\frac{c_D}{f_\pi^2\Lambda_\chi}\sum_{i\neq j\neq k}\frac{\boldsymbol{\sigma}_j \cdot \mathbf{q}_j}{q_j^2 + m_\pi^2}(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)(\boldsymbol{\sigma}_i \cdot \mathbf{q}_j)$$

$$V_E = \frac{c_E}{2f_\pi^4\Lambda_\chi}\sum_{j\neq k}(\boldsymbol{\tau}_j \cdot \boldsymbol{\tau}_k)$$

Scaling of three-nucleon matrix elements

- Storage of full three-body basis is **extremely demanding**
  - Severe truncations on three-body matrix elements typically enforced

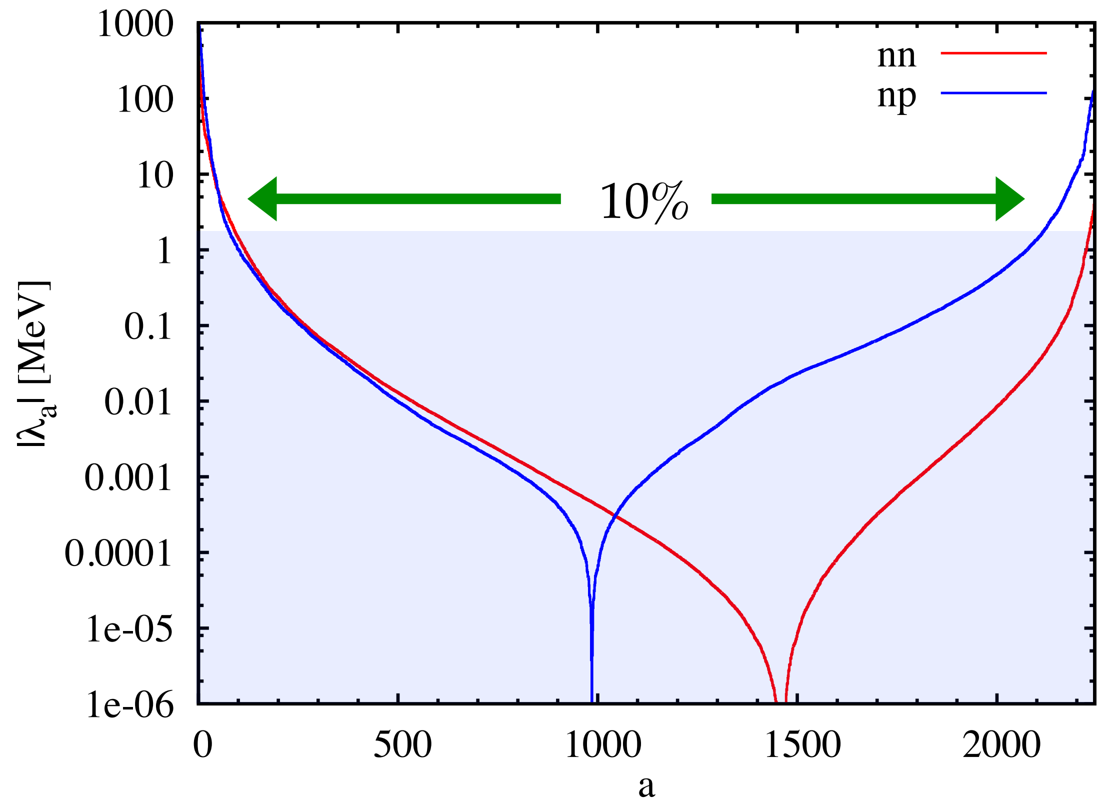


[Roth *et al.* 2014]

Pre-processing techniques

- Ways to pre-process the many-body problem are being developed
  - **Tensor-decomposition techniques**

- **Two-body forces** can be factorised as $v_{ijkl} = \sum_a \lambda_a \, g^a_{ik} \, g^a_{jl}$ (→ Singular Value Decomposition)



[Lesinski 2013]

Gain #1: **size** (→ storage and memory needs)

$$\sum_{kl} v_{ijkl} = \sum_a \lambda_a \sum_k g^a_{ik} \sum_l g^a_{jl}$$

N² m

Gain #2: **CPU speed-up**

(N + N) = **mN**

HF test: → **0.003% error** and **factor 10 speed-up**

- **Higher-order tensors:** exploit techniques from applied maths (e.g. Higher-Order SVD)

[Tichai *et al.* 2019]

Literature

- K. Hebeler *et al.*, Annu. Rev. Nucl. Part. Sci. **65** 457 (2015)
- A. Tichai *et al.*, Eur. Phys. J. A **55** 90 (2019)
- L. de Lathauwer *et al.*, SIAM J. Matrix Anal. Appl. **21** 1253 (2000)