Activities of nuclear physics theory at RISP

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Young Ho Song, Panagiota Papakonstantinou

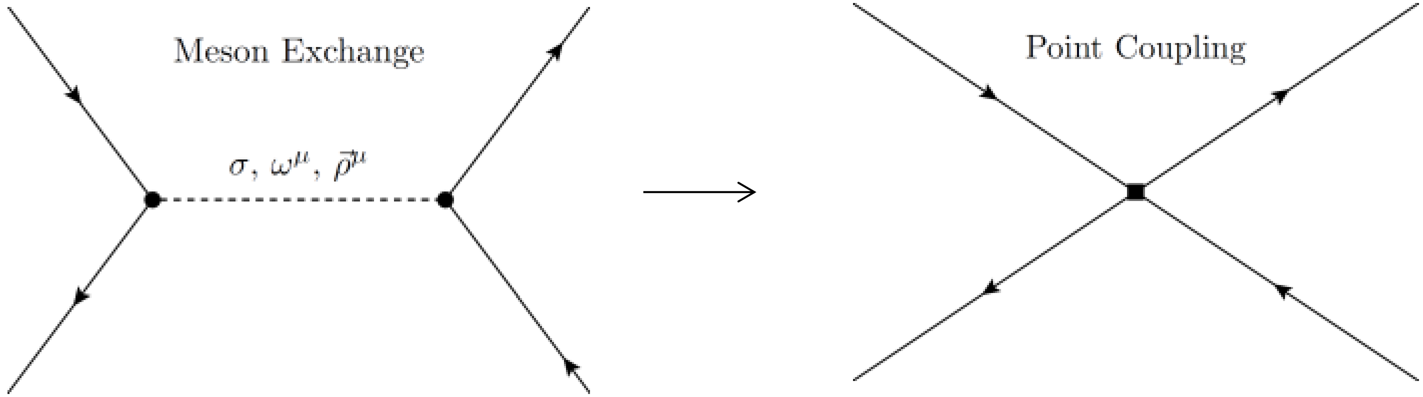
RISP, IBS

Theory activities at RISP

- Boundaries of the nuclear landscape
  - **Covariant density functional theory**
- Production of exotic nuclei and heavy elements
  - Reaction models (**DNS**, …), reactions for astrophysics
- Equation of state of dense matter
  - **New vibrational modes and asymmetric matter**
  - **Symmetry energy of dense matter**
- Neutron stars
- Nuclear structure and reactions from first principles
  - **Ab initio NCSM** …
  - **Unitarily transformed realistic interactions**
- Nuclear transport: **quantum molecular dynamics**
- Chiral effective field theory, **parity doublet model**, ….

Covariant Density Functional Theory

- Nuclear energy density functional has played an important role in the self-consistent description of nuclei
- Simple idea : particle exchange → point coupling



- Successful to describe the properties of finite nuclei, neutron rich nuclei (PC-LA, PC-F1, DD-PC1, PC-PK1)

- Lagrangian density of the point-coupling model

$$\mathcal{L} = \mathcal{L}^{\text{free}} + \mathcal{L}^{\text{4f}} + \mathcal{L}^{\text{der}} + \mathcal{L}^{\text{em}}$$

where

$$\begin{aligned}
\mathcal{L}^{\text{free}} &= \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi\,, \\
\mathcal{L}^{\text{hot}} &= -\frac{1}{3}\beta_S(\bar{\psi}\psi)^3 - \frac{1}{4}(\bar{\psi}\psi)^4 - \frac{1}{4}\gamma_V[(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)]^2\,, \\
\mathcal{L}^{\text{der}} &= -\frac{1}{2}\delta_S\partial_\nu(\bar{\psi}\psi)\partial^\nu(\bar{\psi}\psi) - \frac{1}{2}\delta_V\partial_\nu(\bar{\psi}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\gamma^\mu\psi) \\
&\quad - \frac{1}{2}\delta_{TS}\partial_\nu(\bar{\psi}\vec{\tau}\psi)\partial^\nu(\bar{\psi}\vec{\tau}\psi) - \frac{1}{2}\delta_{TV}\partial_\nu(\bar{\psi}\vec{\tau}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\vec{\tau}\gamma^\mu\psi) \\
\mathcal{L}^{\text{em}} &= -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - e\frac{1-\tau_3}{2}\bar{\psi}\gamma^\mu\psi A_\mu
\end{aligned}$$

- Numerical equations (for finite nuclei) to solve within RCHB forma lism (Relativistic Continuum Hartree Bogoliubov)

$$\sum_\beta \begin{pmatrix} h_{\alpha\beta} - \lambda\delta_{\alpha\beta} & \Delta_{\alpha\beta} \\ -\Delta^*_{\alpha\beta} & -h^*_{\alpha\beta} + \lambda\delta_{\alpha\beta} \end{pmatrix} \begin{pmatrix} U_{\beta\mu} \\ V_{\beta\mu} \end{pmatrix} = E_\mu \begin{pmatrix} U_{\alpha\mu} \\ V_{\alpha\mu} \end{pmatrix}$$

The pairing potential reads,

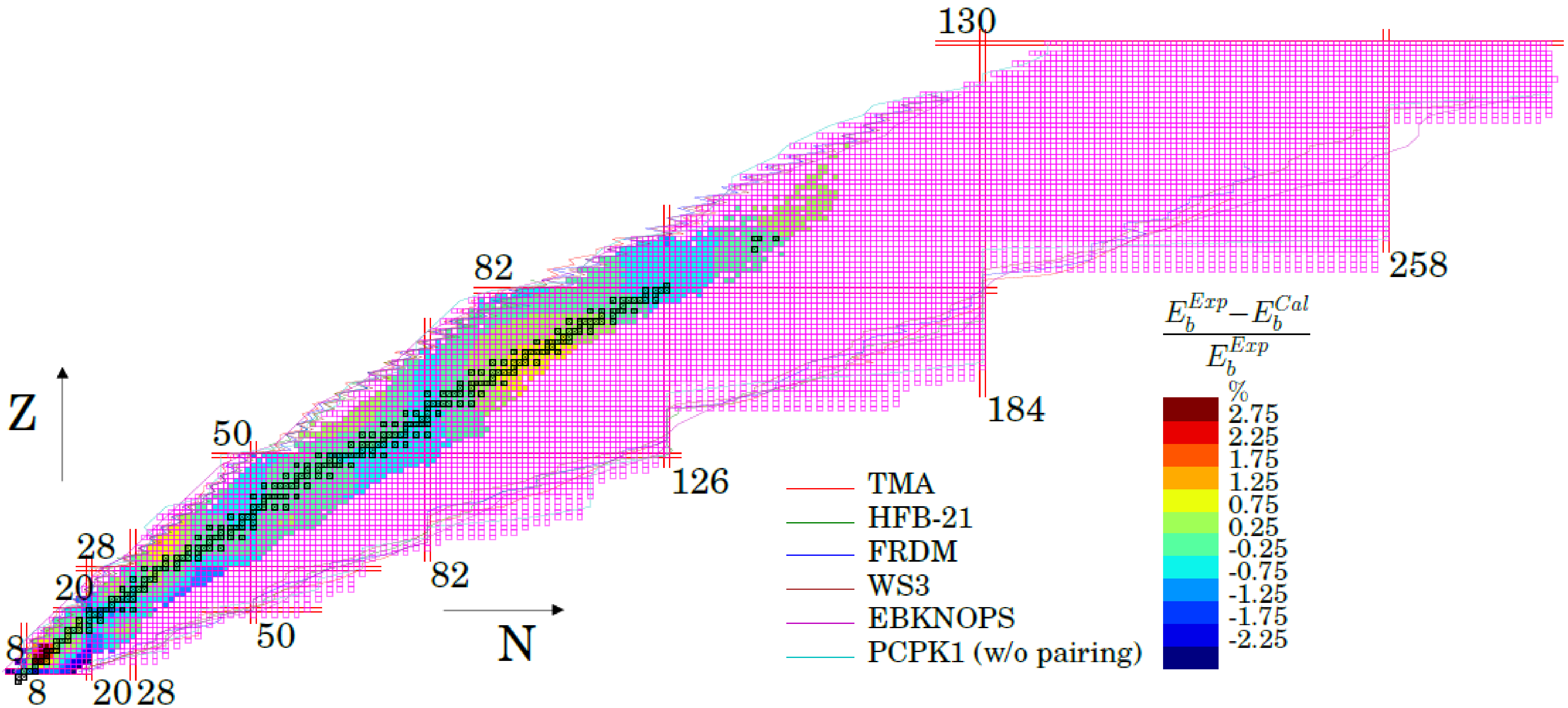
$$\Delta_{kk'}(\mathbf{r},\mathbf{r}') = -\sum_{\tilde{k}\tilde{k'}} \mathbf{V}_{kk',\tilde{k}\tilde{k'}}(\mathbf{r},\mathbf{r}')\kappa_{\tilde{k}\tilde{k'}}(\mathbf{r},\mathbf{r}')$$

with the pairing tensor $\kappa = U^*V^T$ and a density-dependent delta pairing force

$$V^{pp}(\mathbf{r_1},\mathbf{r_2}) = V_0\delta(\mathbf{r_1}-\mathbf{r_2})\frac{1}{4}(1-P^\sigma)(1-\frac{\rho(\mathbf{r_1})}{\rho_0}).$$

V_0 = 685 MeV fm^3: fixed by experimental odd-even mass differences of Ca isotopes, Sn isotopes, N=20 isotones and N=50 isotones.

- First mass table using PC-PK1 : 1D code
  - 9035 Bound nuclei from Z=8 to Z=120
  - For 234 exp. known nuclei (Z=8 to Z=22) : σ = 2.23 MeV
  - For 2331 exp. known nuclei (Z=8 to Z=120) : σ = 7.91 MeV



Number of more bound nuclei than FRDM

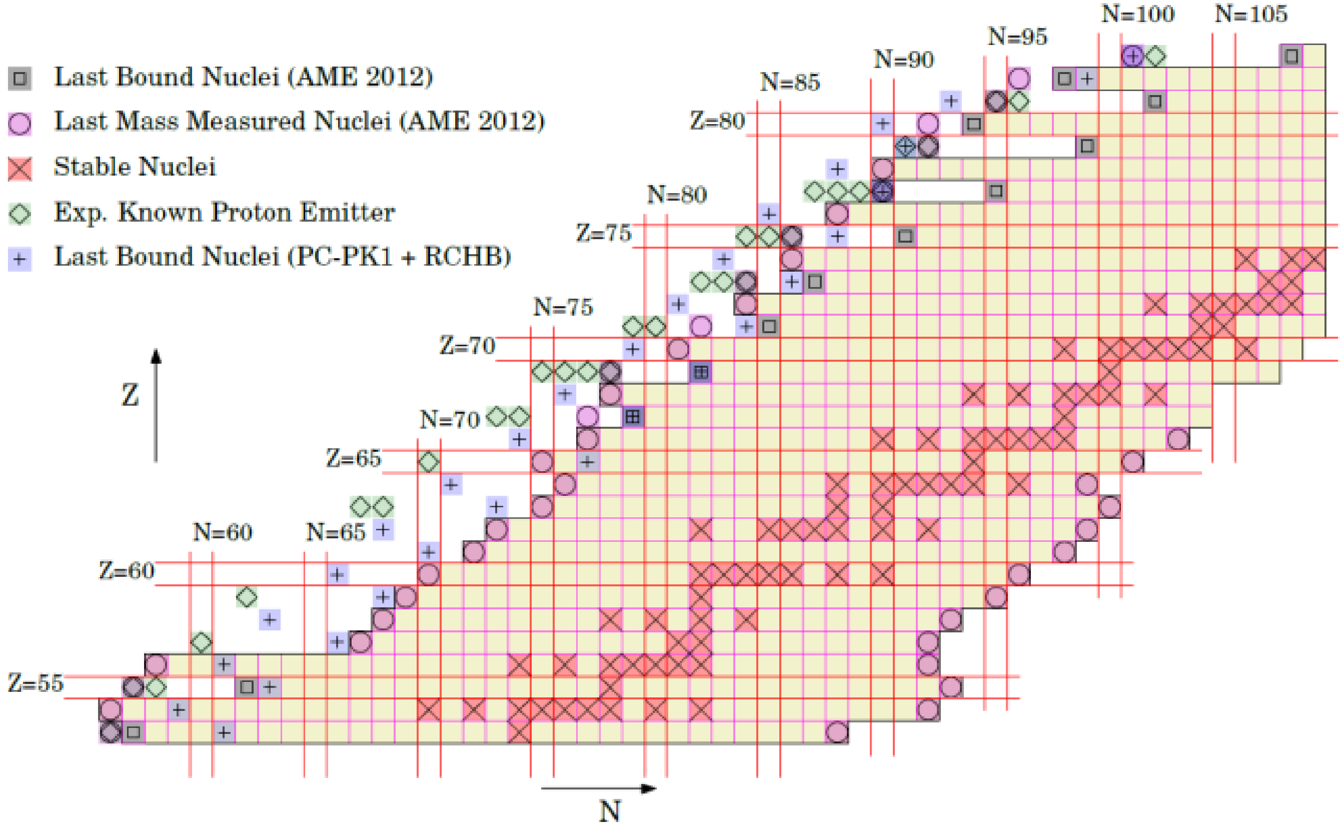
Elt.(Z)	More N	Elt.(Z)	Mor N	Elt.(Z)	More N	Elt.(Z)	More N	Elt.(Z)	More N	Elt.(Z)	More N	Elt.(Z)	More N	Elt.(Z)	More N
O (8)	2	Sc (21)	10	Cu (29)	6	Zr (40)	19	Sb (51)	8	Er (68)	24	Rn (86)	31	Cm (96)	38
Ne (10)	10	Ti (22)	12	Zn (30)	1	Nb (41)	12	Te (52)	2	Tm (69)	26	Fr (87)	29	Bk (97)	38
Na (11)	10	V (23)	10	Ga (31)	1	Mo (42)	12	I (53)	1	Yb (70)	20	Ra (88)	28	Cf (98)	37
Mg (12)	6	Cr (24)	10	Ge (32)	2	Tc (43)	13	Xe (54)	1	Lu (71)	21	Ac (89)	28	Es (99)	35
Al (13)	8	Mn (25)	8	As (33)	1	Ru (44)	10	Pr (59)	20	Hf (72)	21	Th (90)	37	Fm (100)	36
Si (14)	6	Fe (26)	5	Se (34)	6	Rh (45)	11	Nd (60)	16	Ta (73)	19	Pa (91)	43	Md (101)	28
P (15)	8	Co (27)	4	Br (35)	7	Pd (46)	13	Pm (61)	15	W (74)	13	U (92)	39	No (102)	28
S (16)	6	Ni (28)	6	Kr (36)	9	Ag (47)	9	Sm (62)	19	Re (75)	16	Np (93)	38	Lr(103)	28
K (19)	14			Rb (37)	10	Cd (48)	6	Eu (63)	22	Os (76)	6	Pu (94)	44	Rf (104)	24
Ca (20)	10			Sr (38)	14	In (49)	4	Gd (64)	25	Ir (77)	6	Am (95)	45	Db (105)	24
				Y (39)	21	Sn (50)	6	Tb (65)	27	Pt (78)	6				
								Dy (66)	25	Au (79)	2				
								Ho (67)	23	Hg (80)	2				
										Tl (81)	2				

Mostly, due to the proper treatment of pairing correlations in the continuum, the neutron drip line predicted by RCHB theory are more neutron-rich than other mass models; also, our mass table differs from the others (1) functional (PC-PK1, relativistic), (2) symmetry (deformed or spherical), etc.

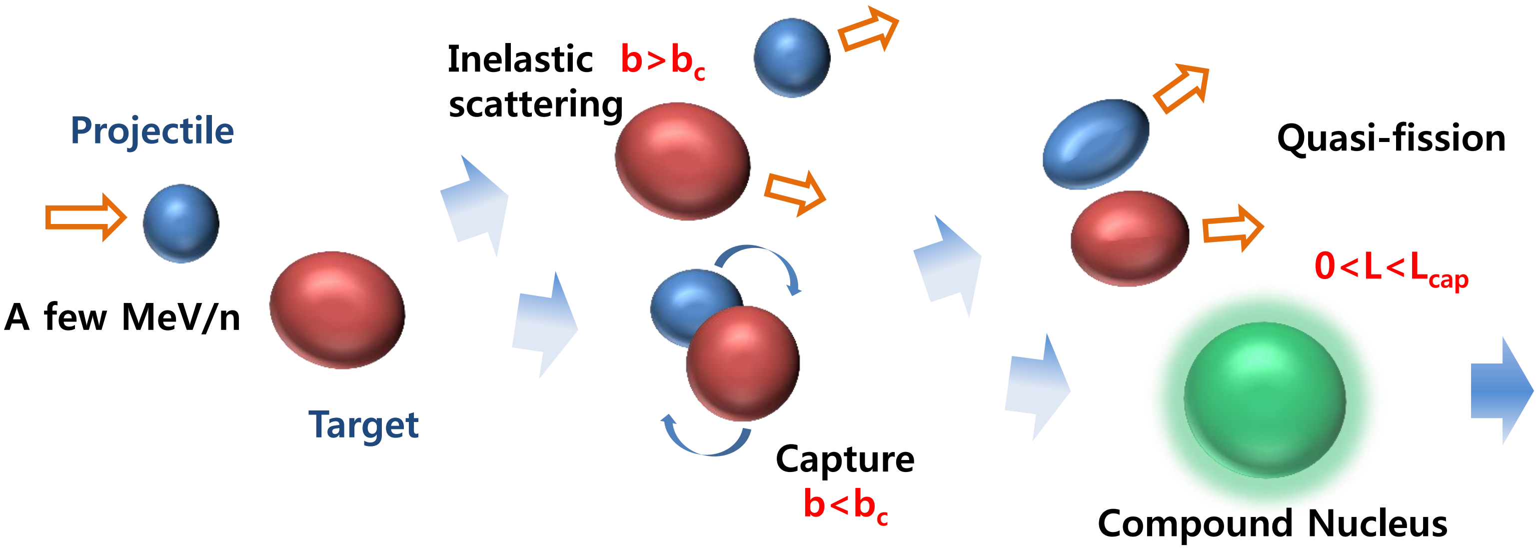
- Application of CDFT (PCPK1)
  - Proton emission phenomena were investigated

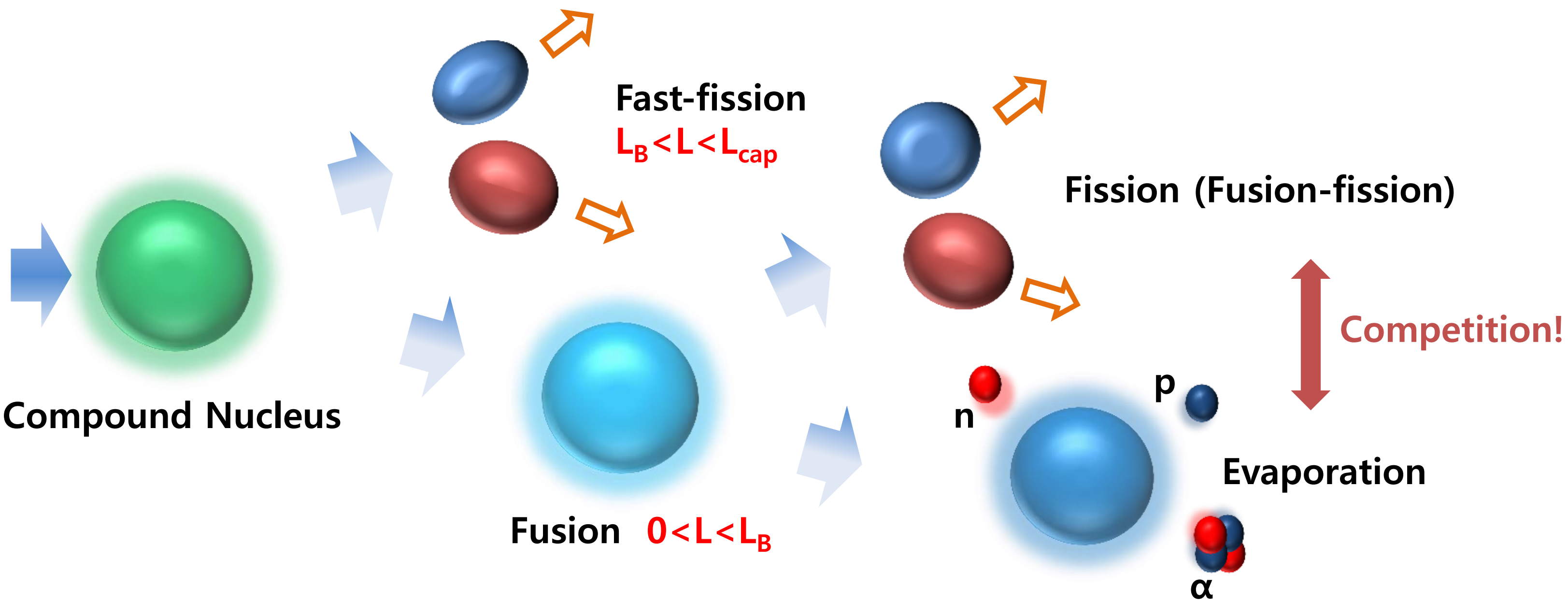
$$(Z, A) \rightarrow (Z-1, A-1) + p + e + \overline{\upsilon}$$

  - 1D spherical, Potential from PC-PK1, WKB approx.
  - More than 80% of data was explained within factor of 2



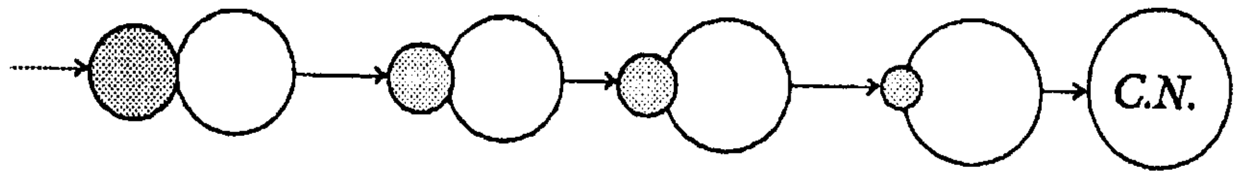
DNS (dinuclear system)



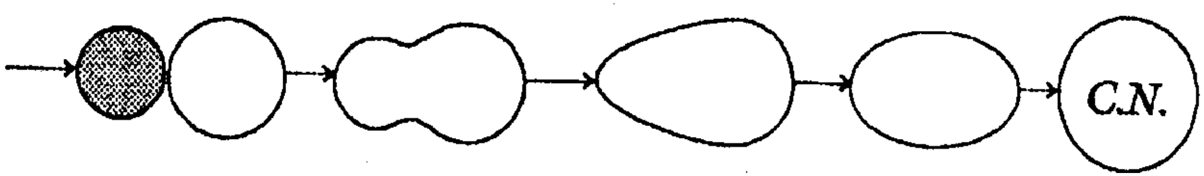


Two distinct ways

<Diabatic way>



<Adiabatic way>



DNS

A configuration of two touching nuclei which keep their individuality. In this framework, the compound nucleus is formed by a series of transfers of nucleons from the light nucleus to the heavy one. Important degrees of freedom are the mass asymmetry η , the relative inter-nuclear distance **R**, deformation (rotation) of the fragments, etc .

$$\eta = (A_1 - A_2)/(A_1 + A_2)$$

The dynamics of the DNS is considered as a combined diffusion in the degrees of freedom of the mass asymmetry η and of the relative distance describing the formation of the compound nucleus and the quasi-fission process (decay of the DNS), respectively.

Fusion in DNS

- Evaporation Residue: $$\sigma_{xn}(E_{\text{c.m.}}) = \sigma_{cap}^{eff}(E_{\text{c.m.}}) P_{CN}(E_{\text{c.m.}}) W_{xn}(E_{\text{c.m.}})$$

- Fusion Probability: $$P_{CN} = \frac{1.25 \exp\left[-(B_{fus}^{*} - B_{qf})/T_{DNS}\right]}{1 + 1.25 \exp\left[-(B_{fus}^{*} - B_{qf})/T_{DNS}\right]}$$

A. S. Zubov, G. G. Adamian, N. V. Antonenko, S. P. Ivanova, W. Scheid (2003)

- Survival Probability: $$W_{sur}(E_{CN}^{*}) = P_{xn}(E_{CN}^{*}) \prod_{i=1}^{x} \frac{\Gamma_n(E_{CN,i}^{*})}{\Gamma_f(E_{CN,i}^{*}) + \Gamma_n(E_{CN,i}^{*})}$$

$$\frac{\Gamma_n}{\Gamma_f} = \frac{4A^{2/3} a_f [E_{CN}^{*} - B_n]}{k a_n (2\sqrt{a_f [E_{CN}^{*} - B_f(E_{CN}^{*})]} - 1)} \times \exp\left[2\sqrt{a_n [E_{CN}^{*} - B_n]} - 2\sqrt{a_f [E_{CN}^{*} - B_f(E_{CN}^{*})]}\right]$$

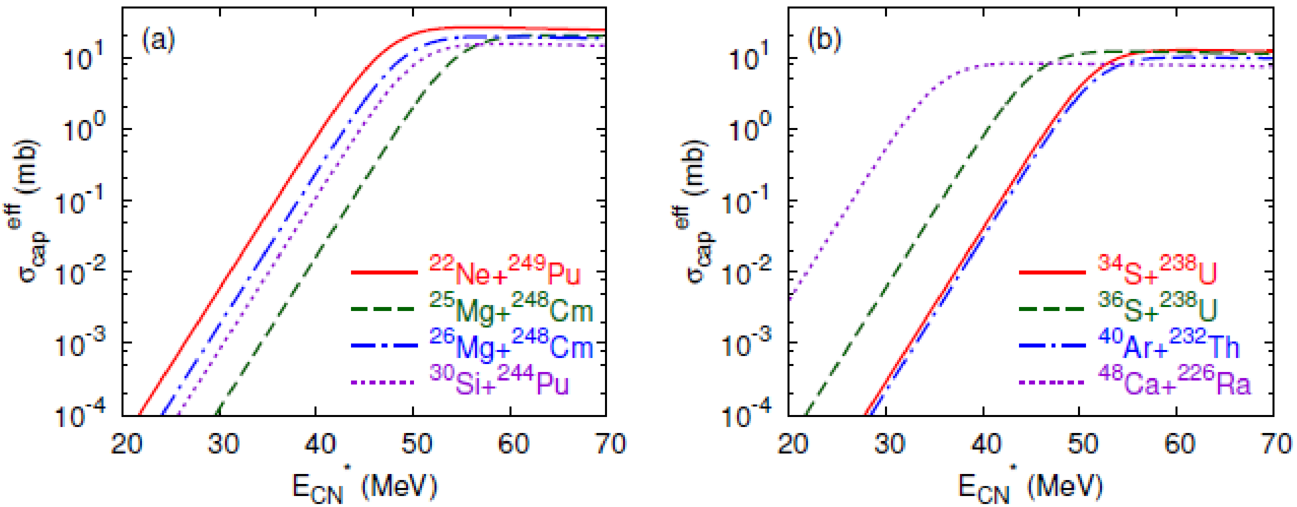
- Effective Capture Cross Section: $\sigma_{cap}^{eff}(E_{\rm c.m.}) = \frac{\pi\hbar^2}{2\mu E_{\rm c.m.}} \sum_{J=0}^{J_{max}} (2J+1) T_J(E_{\rm c.m.})$

- Transmission: $T_J(E_{cm}) = \frac{1}{1+\exp[2\pi\{V_B + \hbar^2 J(J+1)/2\mu R_B^2 - E_{\rm c.m.}\}/\hbar\omega_B]}$

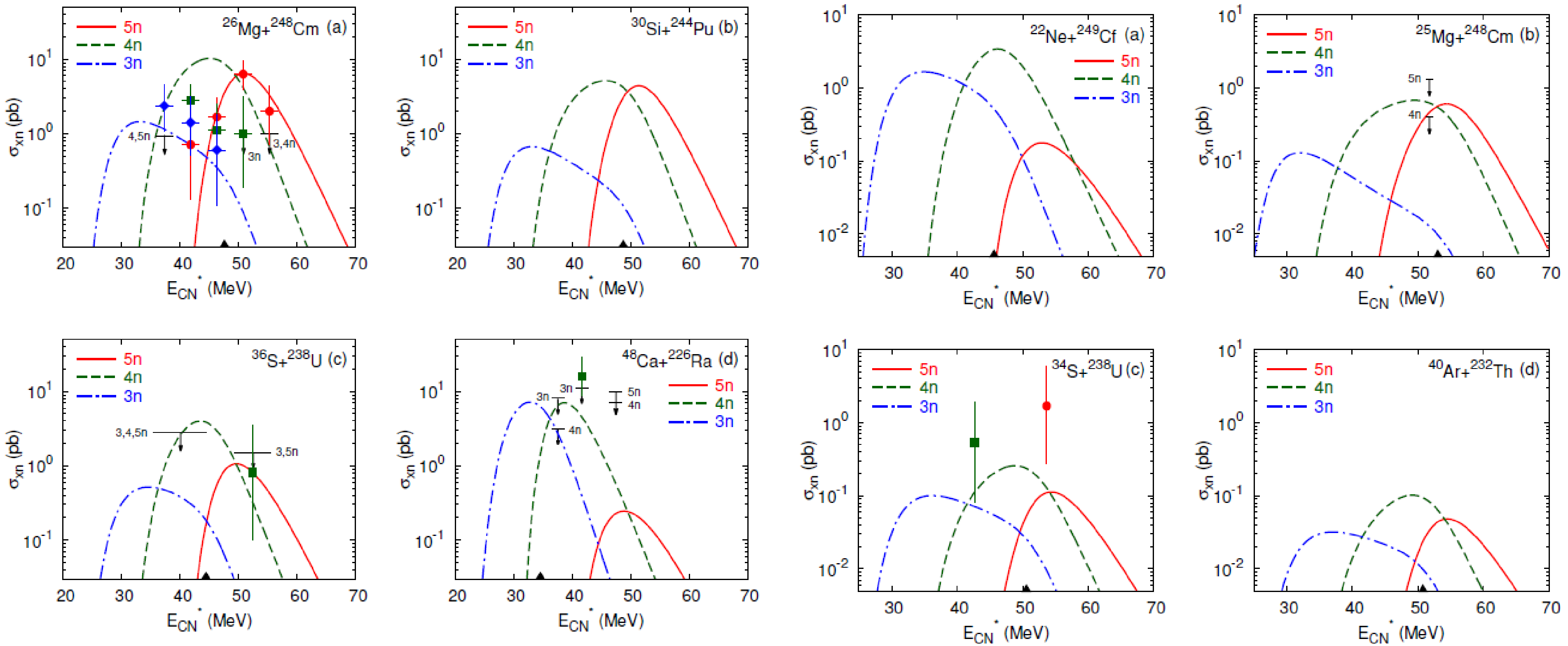
D. L. Hill, J. A. Wheeler (1953)

$$\sigma_{cap}^{eff}(E_{\rm c.m.}) = \frac{\pi\hbar^2 J_{max}^2}{2\mu E_{\rm c.m.}} \left[1 + \frac{\mu_0}{\zeta}\ln(1+\exp[\alpha(V_B - E_{\rm c.m.})]) - \frac{\mu_0}{\zeta}\ln(1+\exp[\alpha(V_B - E_{\rm c.m.}) + \zeta/\mu_0])\right]$$

$\mu_0 = A_1 A_2/(A_1 + A_2)$ $\alpha = \frac{2\pi}{\hbar\omega_B}$ $\zeta = \frac{\pi\hbar^2 J_{max}^2}{m_0 \hbar\omega_B R_B^2}$

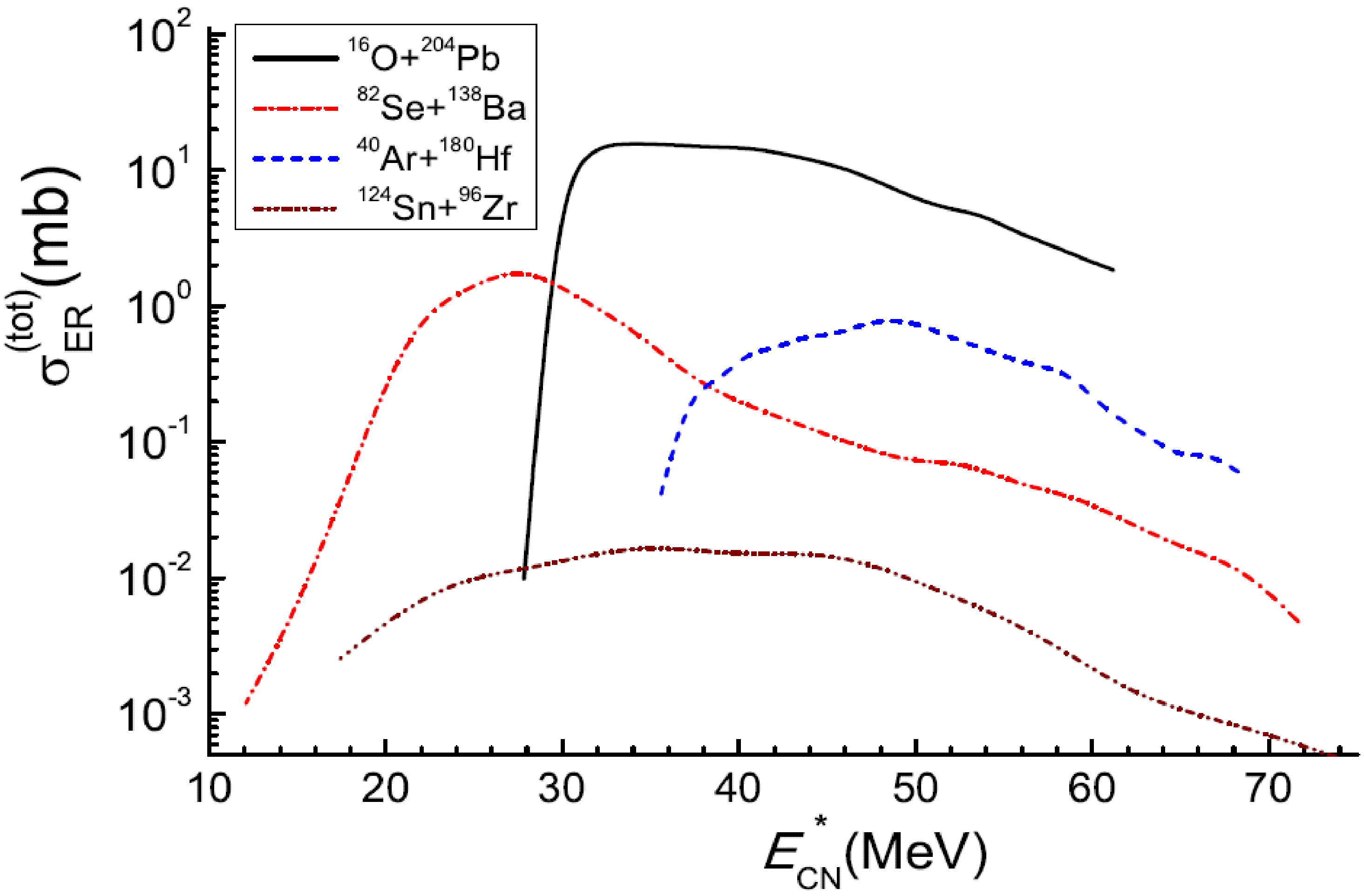


Influence of entrance channel on the production of hassium isotopes



J. Hong, G. G. Adamian, N. V. Antonenko (2015)

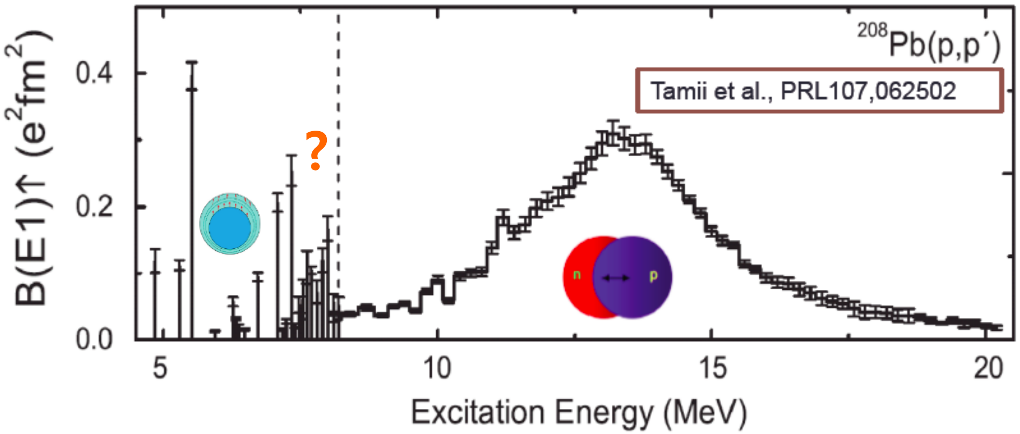
Effects of entrance channels on reactions leading to ^{220}Th compound nucleus

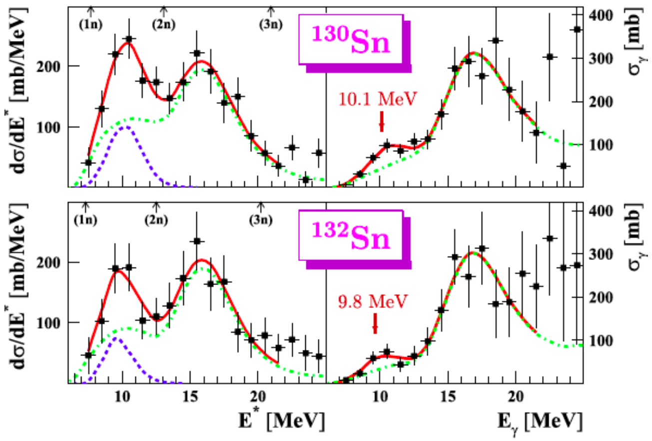


Kyungil Kim, YK, A.K. Nasirov, G. Mandaglio, G. Giardina, Phys.Rev. C91 (2015) 6, 064608

Vibrational modes and asymmetric matter

- Giant and pygmy resonances in ordinary and **exotic nuclei**
- Symmetry energy as a **restoring force**?
- Theory of choice: random-phase approximatio n and extensions





Adrich et al., PRL95

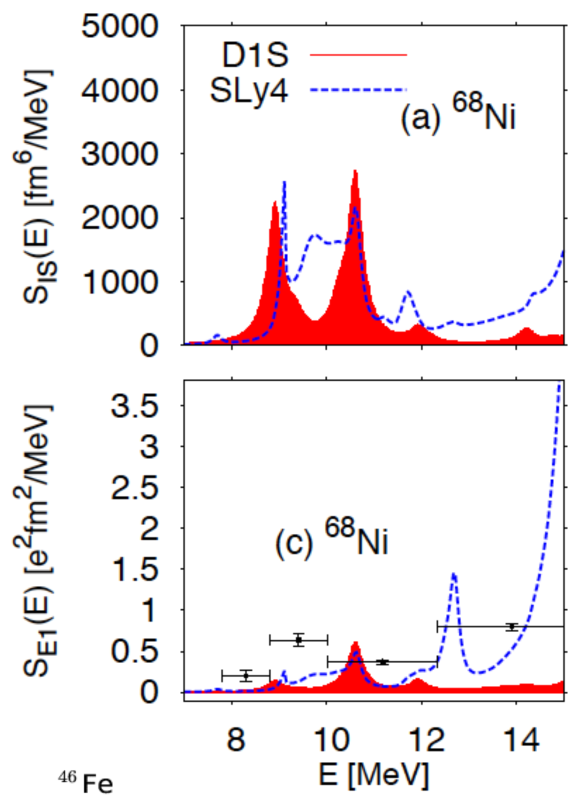
Vibrational modes and asymmetric matter

- Isoscalar and neutron-pygmy resonances in **neutron-rich** Ni isotopes
  - Isoscalar mode coupled with excess neutrons leads to bimodal structure
  - Polarizability, neutron skin, affected by shell structure

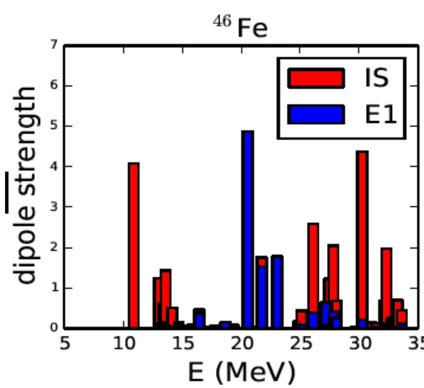
P.Papakonstantinou, H.Hergert, R.Roth, Phys.Rev. C92 (2015) 3, 034311

- Proton pygmy resonances in **loosely bound** N=20 isotones
  - Factors: symmetry energy slope, low separation energy, effective mass
  - Extended wave functions require proper boundary conditions

Y.Kim, P.Papakonstantinou; arXiv:1509.02259



Data: D.Rossi et al., PRL111,242503

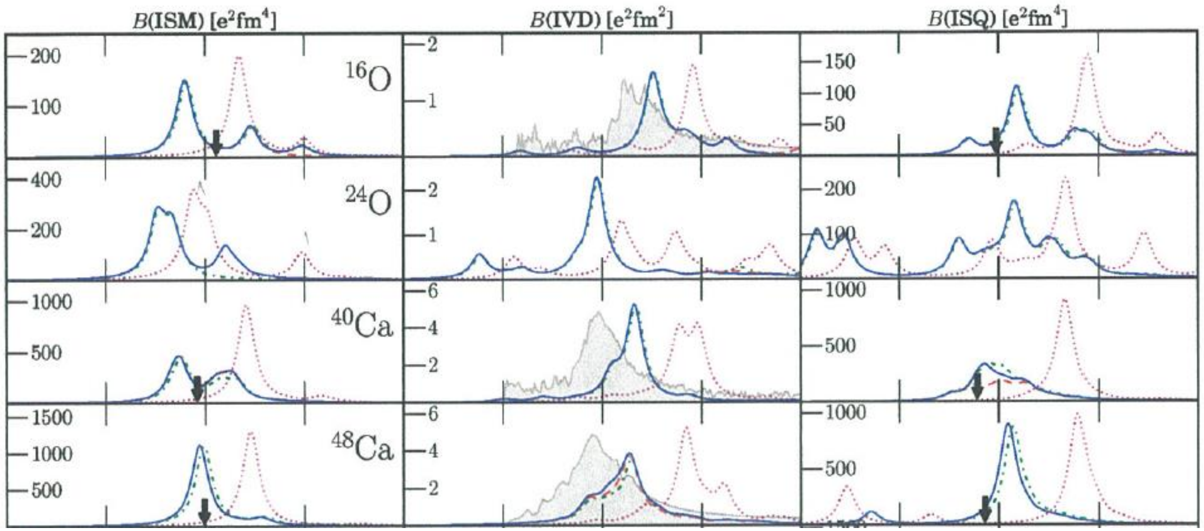


1-2% of TRK
Strongly isoscalar
--
Candidate: ^{46}Fe

Nuclear response “from first principles”

- Realistic nuclear interactions: precise fits (e.g., Argonne V18) or **chiral interactions** – for more predictive power
- Softening through unitary transformations (UCOM, SRG)
- Application to second order: **Second RPA**

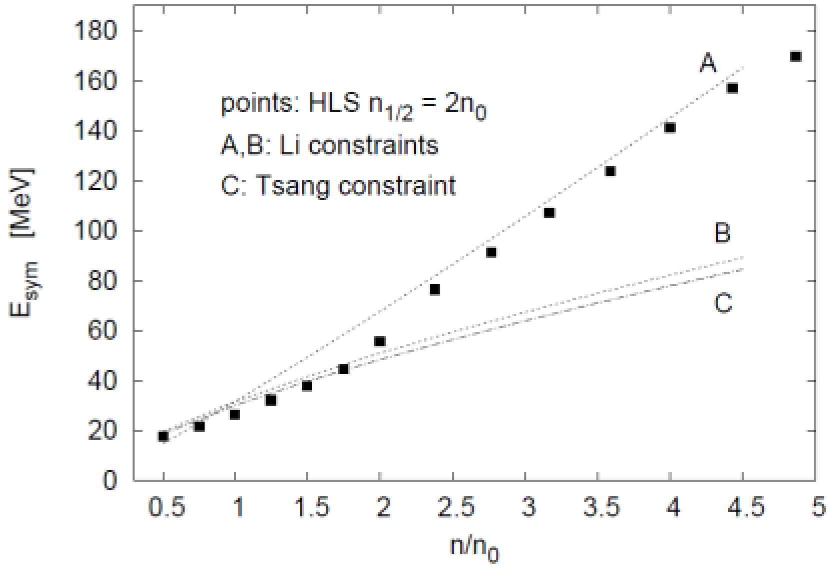
First application of chiral NN+NNN forces to giant resonances



R.Trippel, P.Papakonstantinou, R.Roth; in preparation

Symmetry energy and the nucleon mass

I. Symmetry energy will be soft for low density below ~$2n_0$ while it will be stiff for high density above ~$2n_0$(n_0= 0.16 fm^{-3}).



Li: $E_{sym}(n) \approx 31.6(n/n_0)^{\gamma}$; γ = 0.69(B) – 1.1(A)

Tsang: $E_{sym}(n) = \frac{C_{s,k}}{2}\left(\frac{n}{n_0}\right)^{2/3} + \frac{C_{s,p}}{2}\left(\frac{n}{n_0}\right)^{\gamma_i}$;
$C_{s,k}$ = 25 MeV, $C_{s,p}$ = 35.2 MeV and $\gamma_i \approx$ 0.7(C).

W. G. Paeng, T. T. S. Kuo, H. K. Lee and M. Rho, [arXiv:1508.05210 [hep-ph]

Quantum Molecular Dynamics

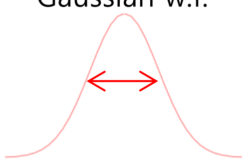
- ***RAON***
  - Exotic beams at low and intermediate energies
    - ✓ Effect of nuclear structure is important in these energies.
    - ✓ Some transport model codes (AMD, CoMD, …) are available, but they are still not good enough to describe rare isotope beam.
    - ✓ Good event generator for RAON is needed for both theoretical and experimental purposes.

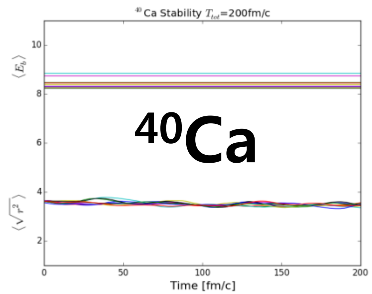
➡ **Transport model** : Model to treat non-equilibrium aspects of the temporal evolution of a collision.

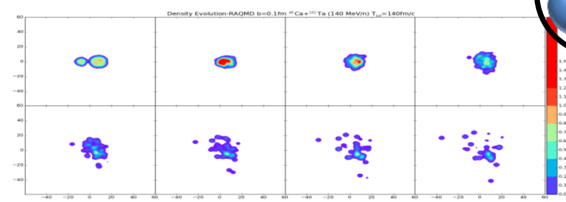
- ***QMD (Quantum Molecular Dynamics) model***
  - ✓ Many-body problem with nucleons
  - ✓ Numerical simulation (event generator)
  - ✓ Early time region in a collision
  - ✓ Different methods with different energies

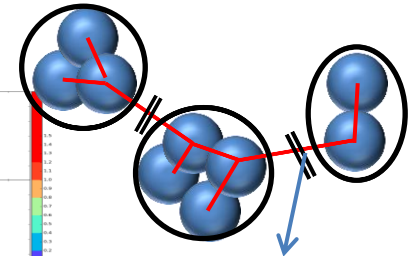
Transport Model

Gaussian w.f.









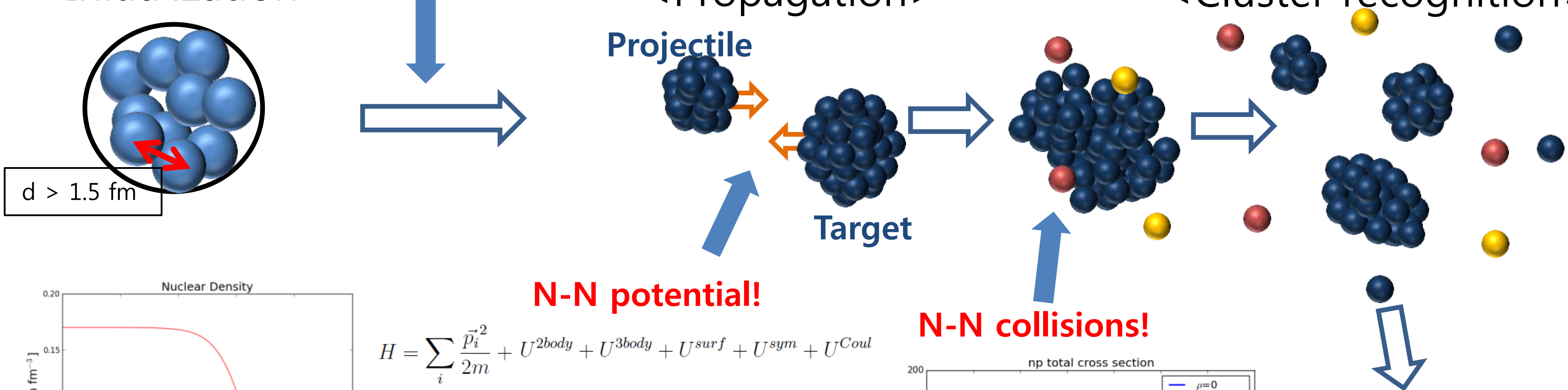
Disconnected if a length is larger than 5 fm.

<Initialization>

Check stability!

<Propagation>

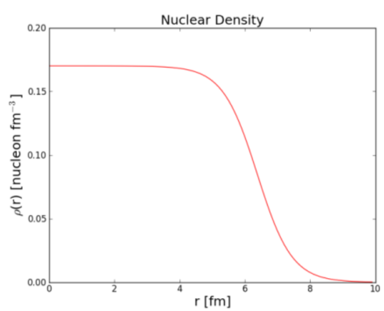
<Cluster recognition>



N-N potential!

N-N collisions!

Second de-excitation
: GEMINI, …



$$H = \sum_i \frac{\vec{p}_i^{\,2}}{2m} + U^{2body} + U^{3body} + U^{surf} + U^{sym} + U^{Coul}$$

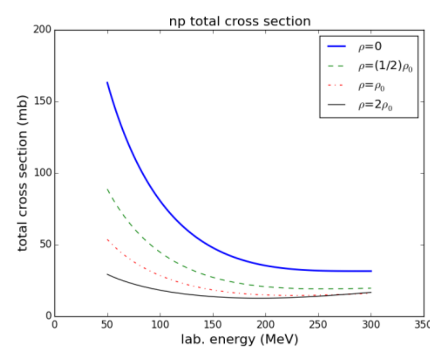
$$U^{2body} = \frac{\alpha}{2\rho_0} \sum_{i,j\neq i} \rho_{ij},$$

$$U^{3body} = \frac{\beta}{\gamma+1} \sum_i \left(\sum_{j\neq i} \frac{\rho_{ij}}{\rho_0} \right)^{\gamma},$$

$$U^{surf} = \frac{g_{surf}}{2\rho_0} \sum_{i,j\neq i} \nabla^2_{r_i}(\rho_{ij}),$$

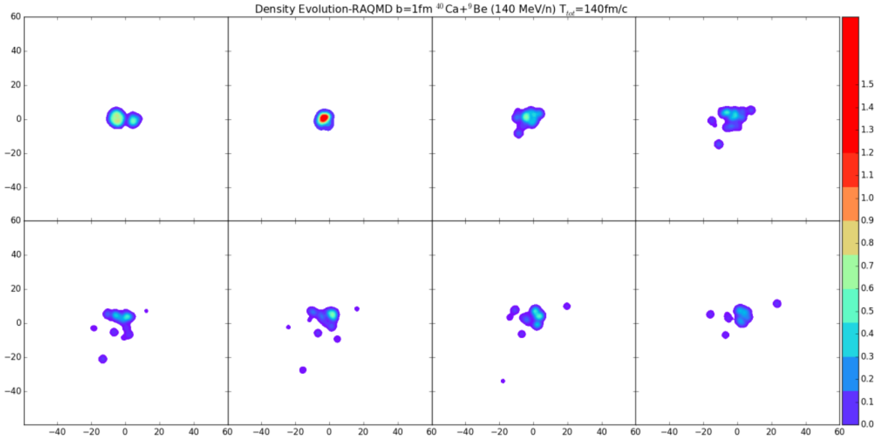
$$U^{sym} = \frac{g_{sym}}{2\rho_0} \sum_{i,j\neq i} [2\delta_{\tau_i\tau_j} - 1]\rho_{ij},$$

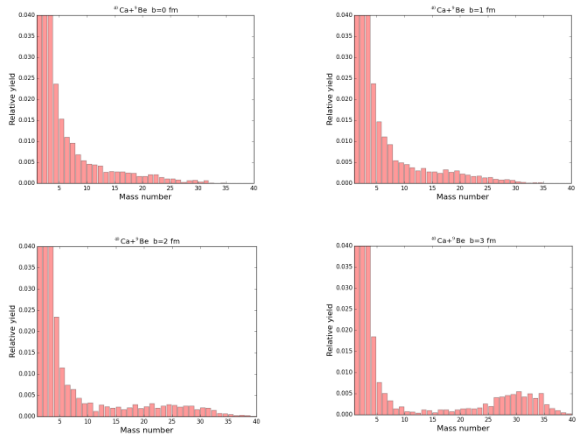
$$U^{Coul} = \frac{e^2}{2} \sum_{i,j\neq i} \frac{1}{|\vec{r}_i - \vec{r}_j|} \mathrm{erf}\left(\frac{|\vec{r}_i - \vec{r}_j|}{2\sigma_r} \right) \quad (i, j \text{ for protons})$$



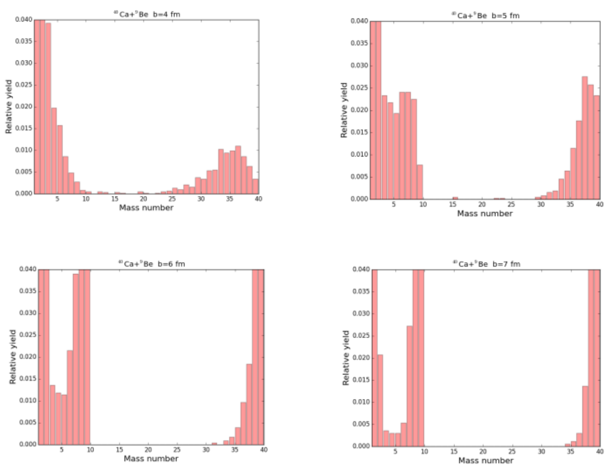
Central and Peripheral Collisions

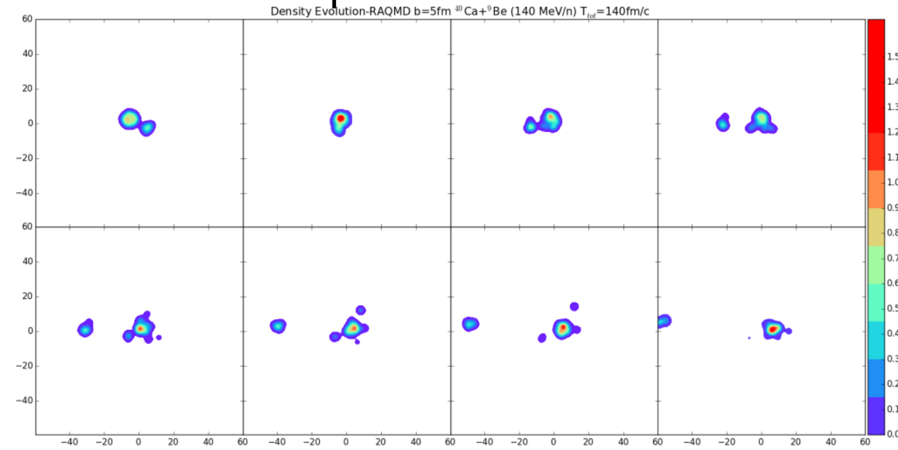
<Central collision>





<Peripheral collision>





Ab initio approaches and interaction

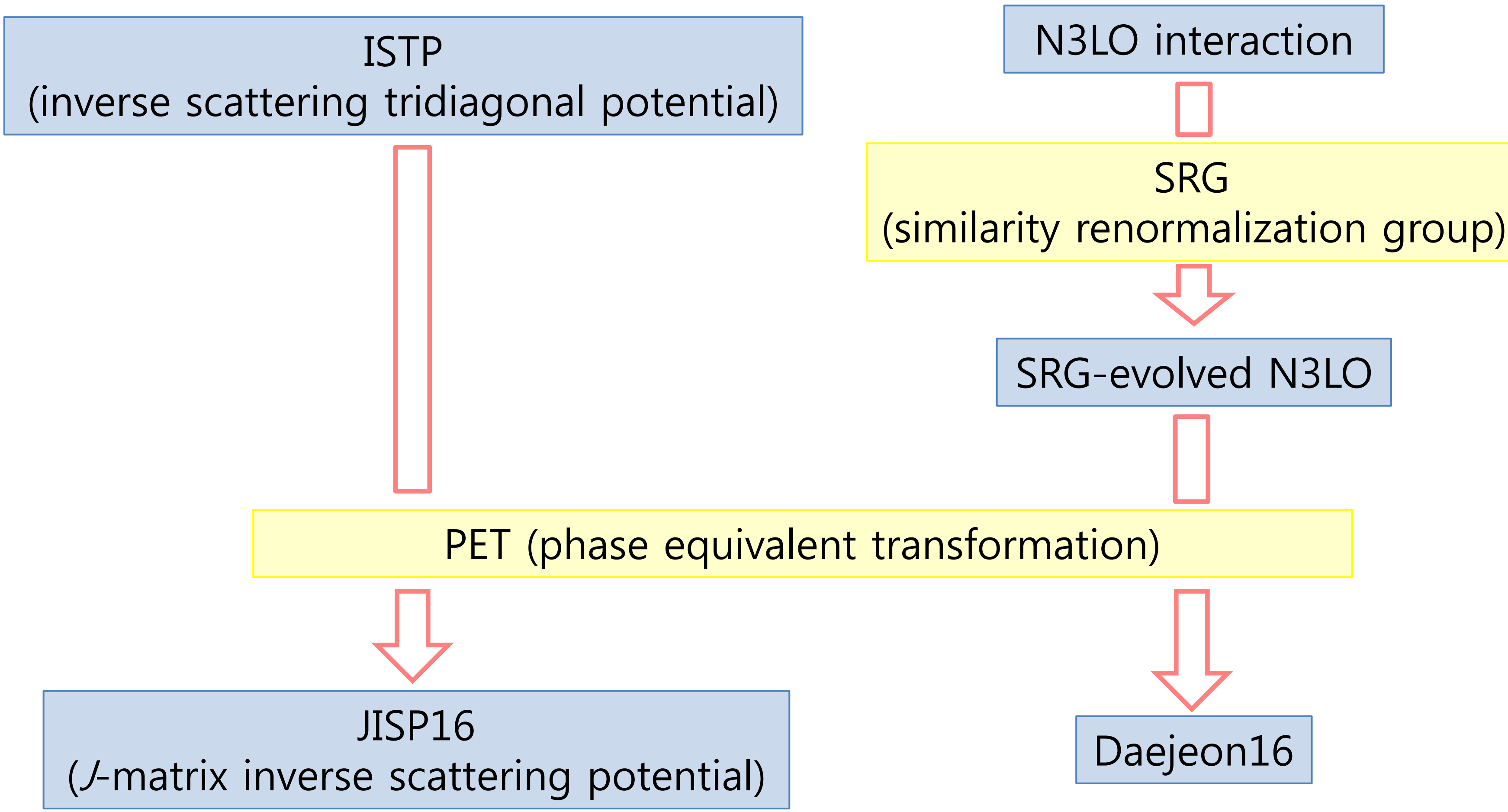
- *ab initio* approaches :

  to understand various nuclei "from first principles" only considering nucleon **interactions**

- Interactions :
  - ➢ Realistic NN interaction comes from meson-exchange(AV18,CD-Bonn), chiral EFT or inverse scattering(JISP16).
  - ➢ 3N forces are also important but need large computing resources.

- **PETs(phase equivalent transformations)** can be helpful to obtain more useful *NN* interactions.

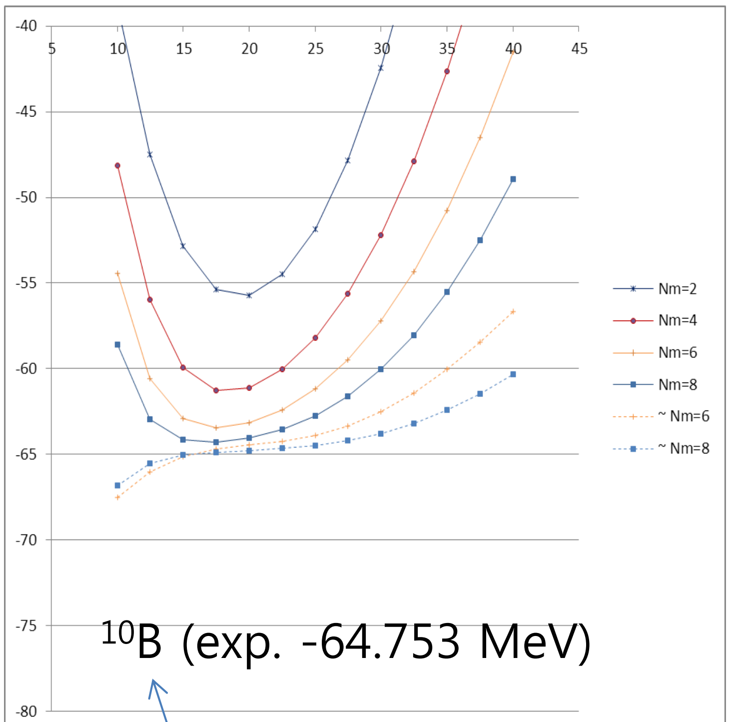
(JISP16 vs) Daejeon16



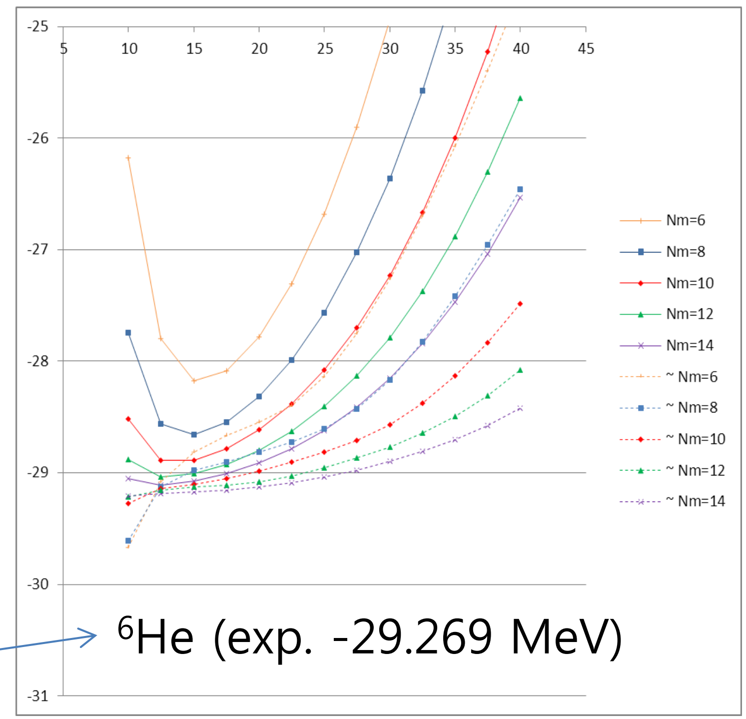
Daejeon16

- Fitted to g.s. energies (including several excited states) of ^{3}H, ^{4}He, ^{6}Li, ^{12}C, ^{16}O and ^{8}He

applicable for various p-shell nuclei !



normal nuclei



exotic nuclei

Parity doublet model

Introduce two nucleon fields that transform in a mirror way under chiral transformations:

$$\mathrm{SU}_L(2) \times \mathrm{SU}(2)_R$$

$$\psi_{1R} \to R\psi_{1R}, \quad \psi_{1L} \to L\psi_{1L},$$
$$\psi_{2R} \to L\psi_{2R}, \quad \psi_{2L} \to R\psi_{2L}.$$

$$m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2)$$
$$= m_0(\bar{\psi}_{2L}\psi_{1R} - \bar{\psi}_{2R}\psi_{1L} - \bar{\psi}_{1L}\psi_{2R} + \bar{\psi}_{1R}\psi_{2L})$$

the decay width $\Gamma_{N\pi}$ for $N^*(1535)\to N+\pi$, $\quad m_0 = 270$ **MeV**

"Linear sigma model with parity doubling," C. E. DeTar and T. Kunihiro, Phys. Rev. D **39**, 2805 (1989)

$$
\begin{aligned}
\mathcal{L} &= \bar{\psi}_1 i\partial\!\!\!/\psi_1 + \bar{\psi}_2 i\partial\!\!\!/\psi_2 + m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2) \\
&\quad + a\bar{\psi}_1(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_1 + b\bar{\psi}_2(\sigma - i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_2
\end{aligned}
$$

$$
m_{N\pm} = \frac{1}{2}\left(\sqrt{(a+b)^2\sigma^2 + 4m_0^2} \mp (a-b)\sigma\right)
$$

The state N+ is the nucleon N(938). while N- is its parity partner conventionally identified with N(1500).

Cf.

$$
\delta\mathcal{L} = -g_\pi\left[\left(i\bar{\psi}\gamma_5\vec{\tau}\psi\right)\vec{\pi} + \left(\bar{\psi}\psi\right)\sigma\right]
$$

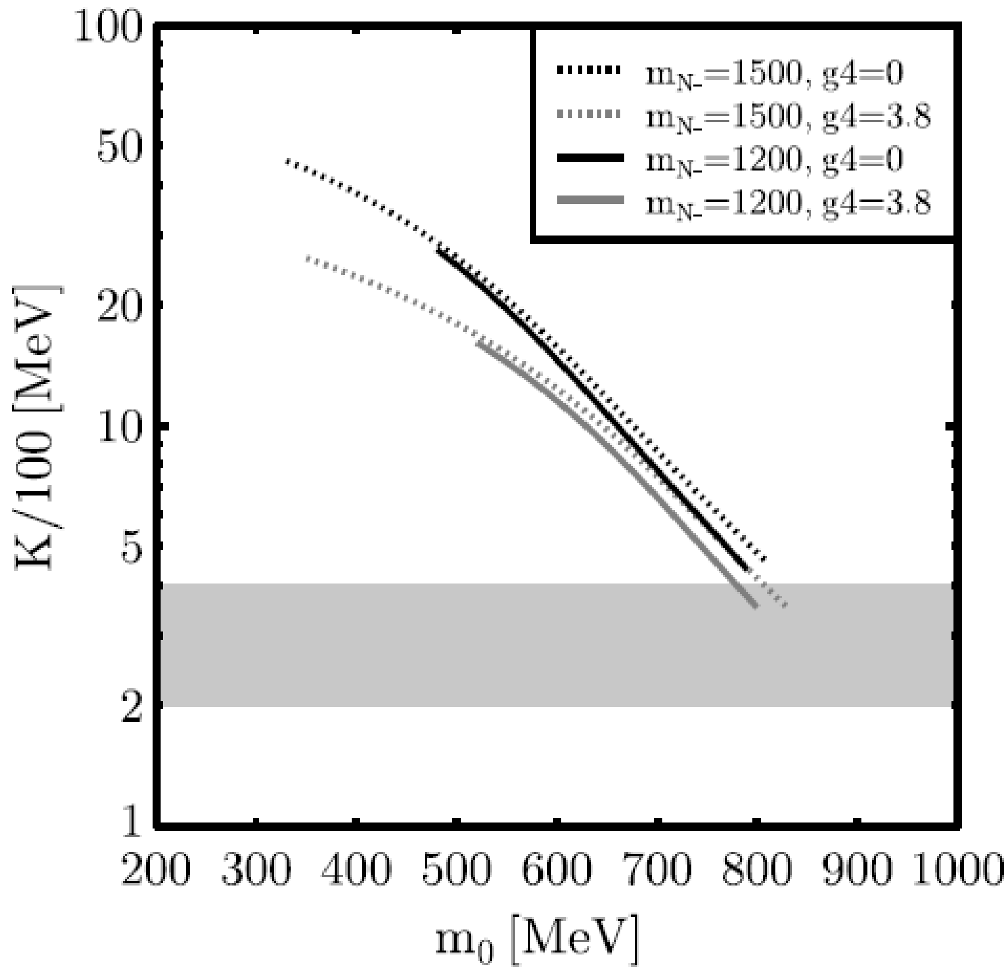
$$
\begin{aligned}
<\sigma> &= \sigma_0 = f_\pi \\
<\pi> &= 0 \\
M_N &= g_\pi\sigma_0 = g_\pi f_\pi
\end{aligned}
$$

Cold, dense nuclear matter in a SU(2) parity doublet model

$$\mathcal{L} = \bar{\psi}_1 i\partial\!\!\!/\psi_1 + \bar{\psi}_2 i\partial\!\!\!/\psi_2 + m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2)$$
$$+ a\bar{\psi}_1(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_1 + b\bar{\psi}_2(\sigma - i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_2$$
$$- g_\omega\bar{\psi}_1\gamma_\mu\omega^\mu\psi_1 - g_\omega\bar{\psi}_2\gamma_\mu\omega^\mu\psi_2 + \mathcal{L}_M,$$

$$\mathcal{L}_M = \frac{1}{2}\partial_\mu\sigma^\mu\partial^\mu\sigma_\mu + \frac{1}{2}\partial_\mu\vec{\pi}^\mu\partial^\mu\vec{\pi}_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + g_4^4(\omega_\mu\omega^\mu)^2$$
$$+ \frac{1}{2}\bar{\mu}^2(\sigma^2 + \vec{\pi}^2) - \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 + \epsilon\sigma,$$

D. Zschiesche, L. Tolos, Jurgen Schaffner-Bielich, Robert D. Pisarski, Phys.Rev. C75 (2007) 055202



If the N' is identified as the $N'(1535)$, the parity doublet model shows a first order phase transition to a chirally restored phase at large densities, $\rho \approx 10\rho_0$, defining the transition by the degeneracy of the masses of the nucleon and the N'. If the mass of the N' is chosen to be 1.2 GeV, then the critical density of the chiral phase transition is lowered to three times normal nuclear matter density,

D. Zschiesche, L. Tolos, Jurgen Schaffner-Bielich, Robert D. Pisarski, Phys.Rev. C75 (2007) 055202

Parity doublet model with HLS

Motivation:

- Lower m_0 ?
- Non-zero isospin density (chemical potential)
- Lower T_c for (chiral) transitions?

TABLE I: Determined model parameters for given m_0. Here $m_\omega = 783$ MeV, $m_\rho = 776$ MeV and $\bar{m}\epsilon = m_\pi^2 f_\pi$.

m_0[MeV]	500	600	700	800	900
g_1	15.4	14.8	14.2	13.3	12.3
g_2	8.96	8.43	7.76	6.94	5.92
$g_{\omega NN}$	11.4	9.12	7.31	5.67	3.54
$g_{\rho NN}$	8.05	6.97	7.46	7.75	8.75
$\bar{\mu}$[MeV]	435	434	402	316	109
λ	40.5	39.4	34.5	22.5	4.26
λ_6	16.3	15.4	13.5	8.66	0.607

Note that in free space m_0=(270-500) MeV

slope parameter

m_0[MeV]	L[MeV]
900	75
800	74
700	78
600	78
500	75

S_0=31 MeV

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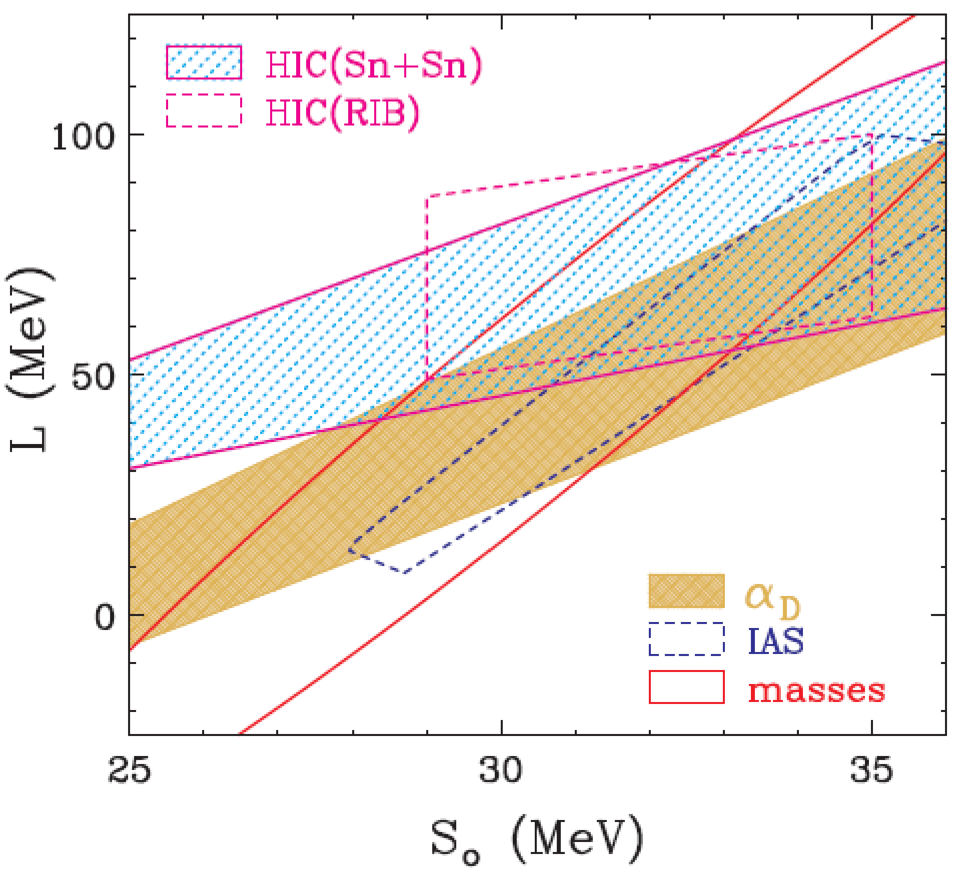
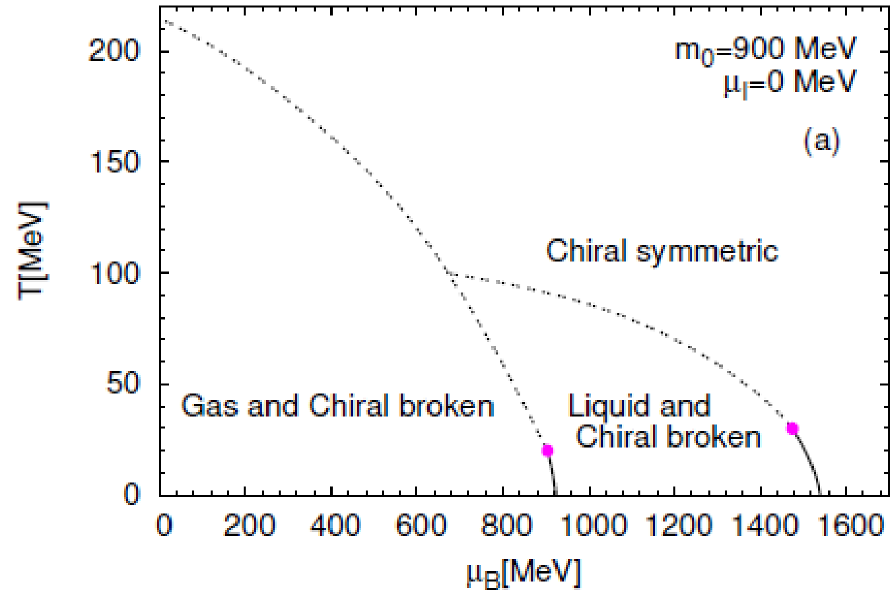
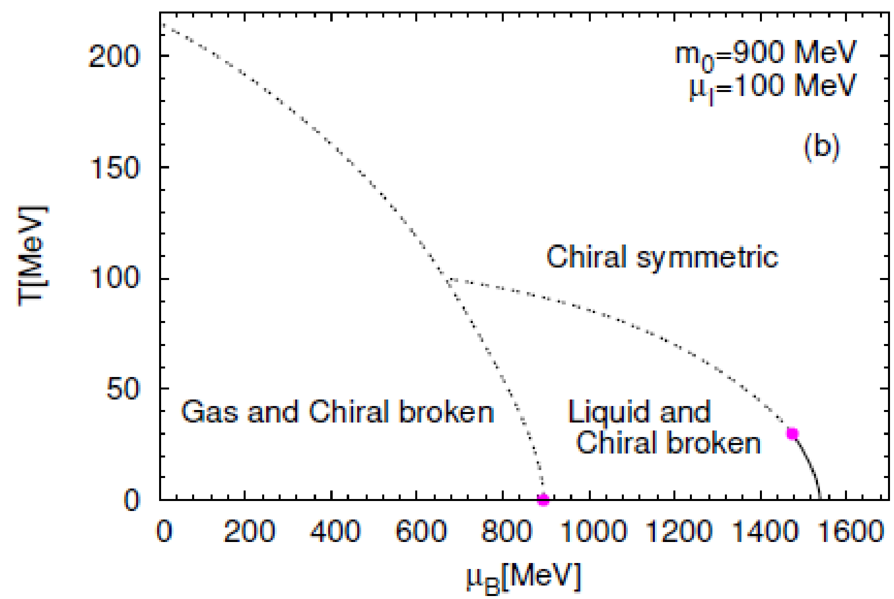


Phase diagrams for m_0 = 900 MeV

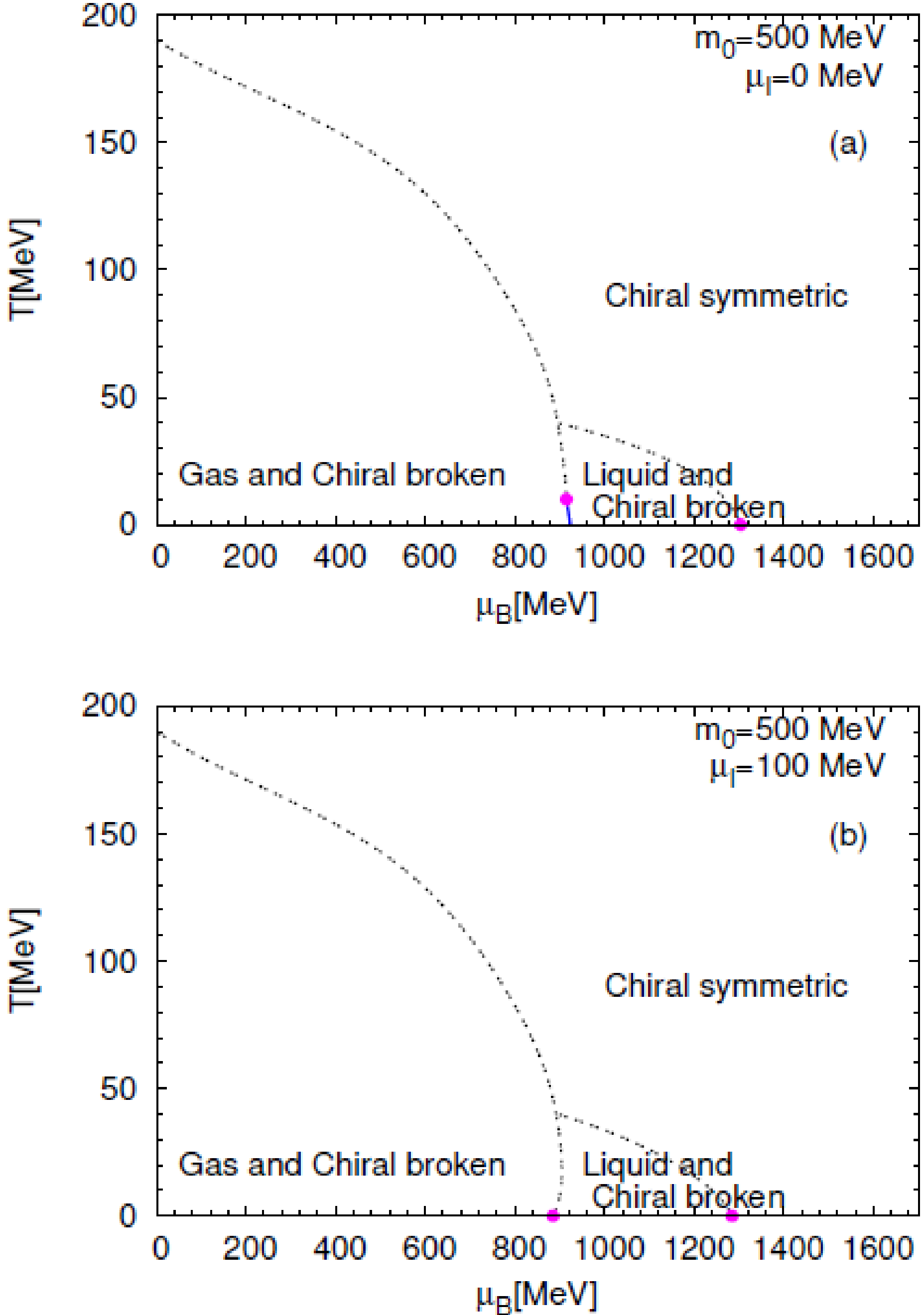


solid: first-order,
dashed: crossover
point: critical point (second order)



LGT: 1st→ 2nd
Critical chemical potential
drops a bit

Phase diagrams for m_0 = 500 MeV



smaller m_0 favors
smaller critical density for
chiral phase transition
both in symmetric and asymmetric
dense matter

Summary

* Boundaries of the nuclear landscape
  Covariant density functional theory
* Production of exotic nuclei and heavy elements
  Reaction models (DNS, …), reactions for astrophysics
* Equation of state of dense matter
  New vibrational modes and asymmetric matter
  Symmetry energy of dense matter
* Neutron stars
* Nuclear structure and reactions from first principles
  Ab initio NCSM …
  Unitarily transformed realistic interactions
* Nuclear transport: quantum molecular dynamics
*Chiral effective field theory, parity doublet model, ….

The key word is international/domestic/theory-experiment collaborations!