Connecting the NEoS to the interplay between fusion and quasi-fission processes in low-energy nuclear reactions

HINPw6 Workshop

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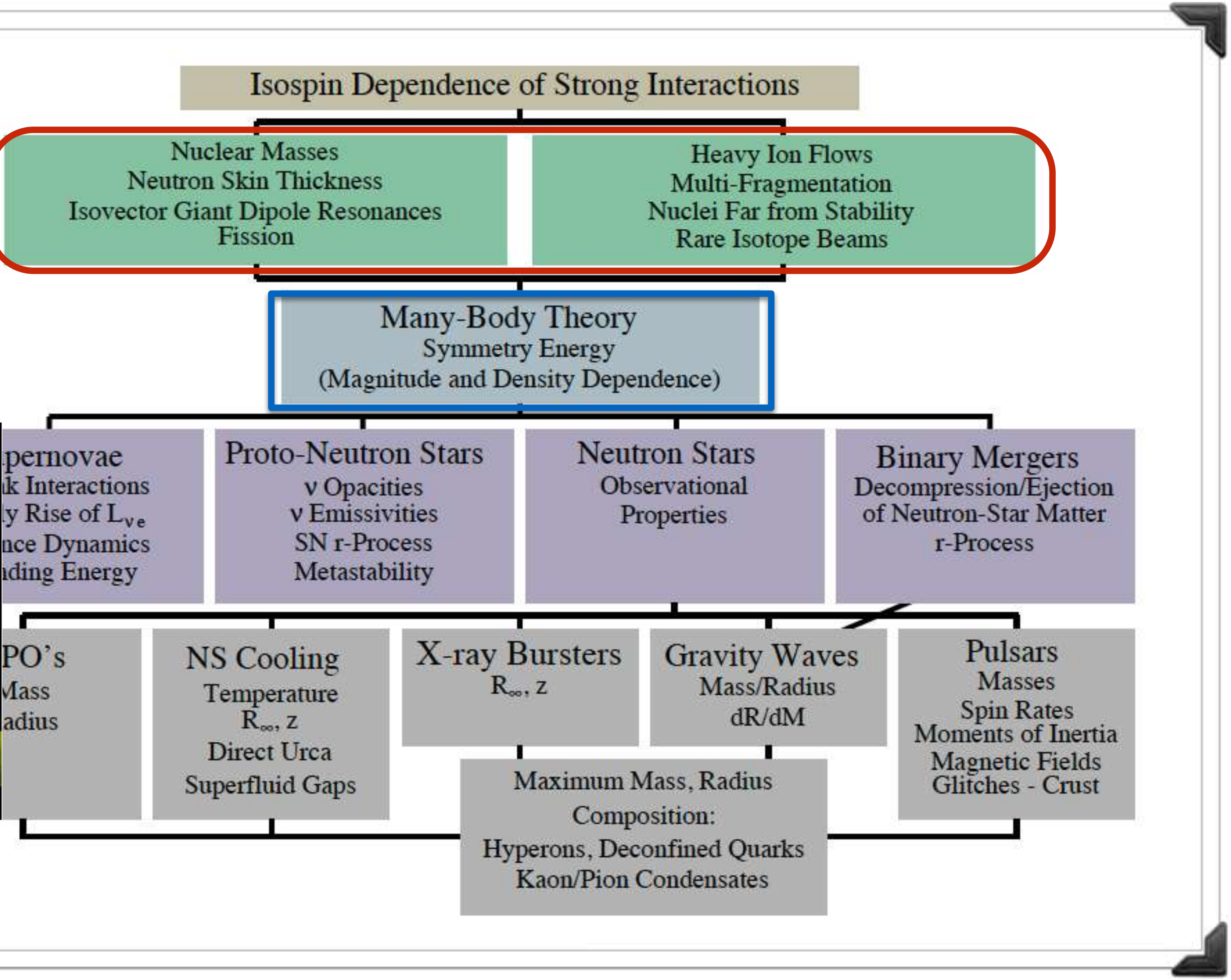
Outline

- Equation of state (EoS) of nuclear matter
- Low-energy (E/A~5-10 MeV/A), reaction mechanisms: from fusion to quasi-fission and deep-inelastic
- The tool: mean-field models (TDHF, Vlasov) and effective interactions
- Sensitivity of selected observables to specific ingredients of the effective interaction
- Conclusions

Equation of State (EoS) is important

EoS



Isospin Dependence of Strong Interactions

Nuclear Masses
Neutron Skin Thickness
Isovector Giant Dipole Resonances
Fission

Heavy Ion Flows
Multi-Fragmentation
Nuclei Far from Stability
Rare Isotope Beams

Many-Body Theory
Symmetry Energy
(Magnitude and Density Dependence)

pernovae
k Interactions
y Rise of $L_{\nu e}$
nce Dynamics
ding Energy

Proto-Neutron Stars
ν Opacities
ν Emissivities
SN r-Process
Metastability

Neutron Stars
Observational
Properties

Binary Mergers
Decompression/Ejection
of Neutron-Star Matter
r-Process

PO's
Mass
adius

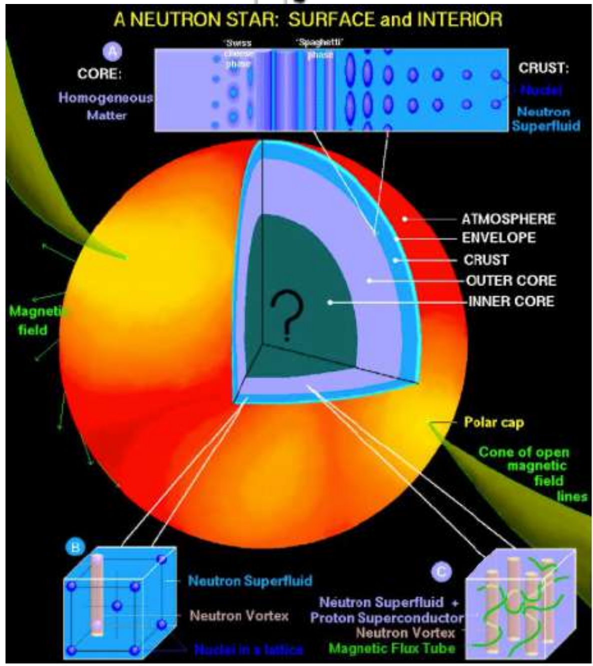
NS Cooling
Temperature
R_∞, z
Direct Urca
Superfluid Gaps

X-ray Bursters
R_∞, z

Gravity Waves
Mass/Radius
dR/dM

Pulsars
Masses
Spin Rates
Moments of Inertia
Magnetic Fields
Glitches - Crust

Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates



A.W. Steiner et al., Phys. Rep. 411, 325 (2005)

Nuclear Density functional theory

- Nuclear DFT has been introduced by **effective Hamiltonians**: by Vautherin and Brink PRC 5, 626 (1972), using the Skyrme model as a vehicle

$$E = \langle \Psi | H | \Psi \rangle \approx \langle \Phi | \hat{H}_{eff}(\hat{\rho}) | \Phi \rangle = E[\hat{\rho}]$$

Based on the philosophy of Bethe, Goldstone, and Brueckner, one has a density dependent interaction in the nuclear interior E(ρ)

At present, the ansatz for E(ρ) is phenomenological:

- Skyrme: non-relativistic, zero range
- Gogny: non-relativistic, finite range (Gaussian)
- CDFT: Covariant density functional theory

courtesy of J. Meng

Skyrme EoS (standard form)

- Effective interaction in standard form

$$
\begin{aligned}
V(\boldsymbol{r}_1,\boldsymbol{r}_2) = {} & t_0\,(1+x_0P_\sigma)\,\delta(\boldsymbol{r}) && \text{central term} \\
& +\frac{1}{2}t_1\,(1+x_1P_\sigma)\left[\boldsymbol{P}'^2\delta(\boldsymbol{r})+\delta(\boldsymbol{r})\boldsymbol{P}^2\right] && \\
& +t_2\,(1+x_2P_\sigma)\,\boldsymbol{P}'\cdot\delta(\boldsymbol{r})\boldsymbol{P} && \text{non-local terms} \\
& +\frac{1}{6}t_3\,(1+x_3P_\sigma)\left[\rho\,(\boldsymbol{R})\right]^\sigma\delta(\boldsymbol{r}) && \text{density-dependent term} \\
& +iW_0\boldsymbol{\sigma}\cdot\left[\boldsymbol{P}'\times\delta(\boldsymbol{r})\boldsymbol{P}\right] && \text{spin–orbit term}\,.
\end{aligned}
$$

$$
\boldsymbol{r}=\boldsymbol{r}_1-\boldsymbol{r}_2\,,\qquad \boldsymbol{R}=\frac{1}{2}\,(\boldsymbol{r}_1+\boldsymbol{r}_2)\;,
$$

$$
\boldsymbol{P}=\frac{1}{2i}\,(\boldsymbol{\nabla}_1-\boldsymbol{\nabla}_2)\;,\qquad \boldsymbol{P}'\ \text{cc of}\ \boldsymbol{P}\ \text{acting on the left}
$$

and

$$
\boldsymbol{\sigma}=\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2\,,\qquad P_\sigma=(1+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\,/2\,.
$$

Modifications can be introduced and are referred as non-standard form.

E. Chabanat et al., NPA 627, 710 (1997), M. Dutra et al. PRC 85, 035201 (2012)

Skyrme EoS (standard form)

- Within the standard form, the total energy density is

$$\mathcal{H} = \mathcal{K} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\mathrm{eff}} + \mathcal{H}_{\mathrm{fin}} + \mathcal{H}_{\mathrm{so}} + \mathcal{H}_{\mathrm{sg}} + \mathcal{H}_{\mathrm{Coul}}$$

where $\mathcal{K} = \frac{\hbar^2}{2m}\tau$ is the kinetic-energy term, $\mathcal{H}_0$ a zero-range term, $\mathcal{H}_3$ the density-dependent term, $\mathcal{H}_{\mathrm{eff}}$ an effective-mass term, $\mathcal{H}_{\mathrm{fin}}$ a finite-range term, $\mathcal{H}_{\mathrm{so}}$ a spin–orbit term and $\mathcal{H}_{\mathrm{sg}}$ a term due to the tensor coupling with spin and gradient.

$$\mathcal{H}_0 = \frac{1}{4} t_0 \left[(2 + x_0)\, \rho^2 - (2x_0 + 1)\left(\rho_{\mathrm{p}}^2 + \rho_{\mathrm{n}}^2\right) \right] ,$$

$$\mathcal{H}_3 = \frac{1}{24} t_3 \rho^\sigma \left[(2 + x_3)\, \rho^2 - (2x_3 + 1)\left(\rho_{\mathrm{p}}^2 + \rho_{\mathrm{n}}^2\right) \right] ,$$

$$\mathcal{H}_{\mathrm{eff}} = \frac{1}{8} \left[t_1 (2 + x_1) + t_2 (2 + x_2) \right] \tau\rho + \frac{1}{8} \left[t_2 (2x_2 + 1) - t_1 (2x_1 + 1) \right] \left(\tau_{\mathrm{p}}\rho_{\mathrm{p}} + \tau_{\mathrm{n}}\rho_{\mathrm{n}} \right) ,$$

$$\mathcal{H}_{\mathrm{fin}} = \frac{1}{32} \left[3t_1 (2 + x_1) - t_2 (2 + x_2) \right] (\nabla\rho)^2 - \frac{1}{32} \left[3t_1 (2x_1 + 1) + t_2 (2x_2 + 1) \right] \left[\left(\nabla\rho_{\mathrm{p}}\right)^2 + \left(\nabla\rho_{\mathrm{n}}\right)^2 \right] ,$$

$$\mathcal{H}_{\mathrm{so}} = \frac{1}{2} W_0 \left[\boldsymbol{J} \cdot \nabla\rho + \boldsymbol{J}_{\mathrm{p}} \cdot \nabla\rho_{\mathrm{p}} + \boldsymbol{J}_{\mathrm{n}} \cdot \nabla\rho_{\mathrm{n}} \right] ,$$

$$\mathcal{H}_{\mathrm{sg}} = -\frac{1}{16} (t_1 x_1 + t_2 x_2)\, \boldsymbol{J}^2 + \frac{1}{16} (t_1 - t_2) \left[\boldsymbol{J}_{\mathrm{p}}^2 + \boldsymbol{J}_{\mathrm{n}}^2 \right] .$$

Nine parameters

$$(t_0, t_1, t_2, t_3, x_0, x_1, x_2, x_3, \sigma)$$

E. Chabanat et al., NPA 627, 710 (1997)

Skyrme EoS

- The total energy density in another form is

$$\boxed{\begin{aligned}\mathcal{E}(\rho) \;=\; & \frac{\hbar^2}{2m}\tau + C_0\rho^2 + D_0\rho_3^2 + C_3\rho^{\sigma+2} + D_3\rho^{\sigma}\rho_3^2 \; + C_{eff}\rho\tau \\ & + D_{eff}\rho_3\tau_3 + C_{surf}(\bigtriangledown\rho)^2 + D_{surf}(\bigtriangledown\rho_3)^2, \qquad (2)\end{aligned}}$$

$$\rho = \rho_n + \rho_p \qquad \rho_3 = \rho_n - \rho_p$$

$$\tau = \tau_n + \tau_p \qquad \tau_3 = \tau_n - \tau_p,$$

with ρ_i and τ_i ($i = p, n$, for protons and neutrons) particles and kinetic energy density, respectively.

$$C_0 = \tfrac{3}{8}t_0,$$

$$D_0 = -\tfrac{1}{8}t_0(2x_0 + 1),$$

$$C_3 = \tfrac{1}{16}t_3,$$

$$D_3 = -\tfrac{1}{48}t_3(2x_3 + 1),$$

$$C_{\text{eff}} = \tfrac{1}{16}[3t_1 + t_2(4x_2 + 5)],$$

$$D_{\text{eff}} = -\tfrac{1}{16}[t_1(2x_1 + 1) - t_2(2x_2 + 1)],$$

$$C_{\text{surf}} = \tfrac{1}{64}[9t_1 - t_2(4x_2 + 5)],$$

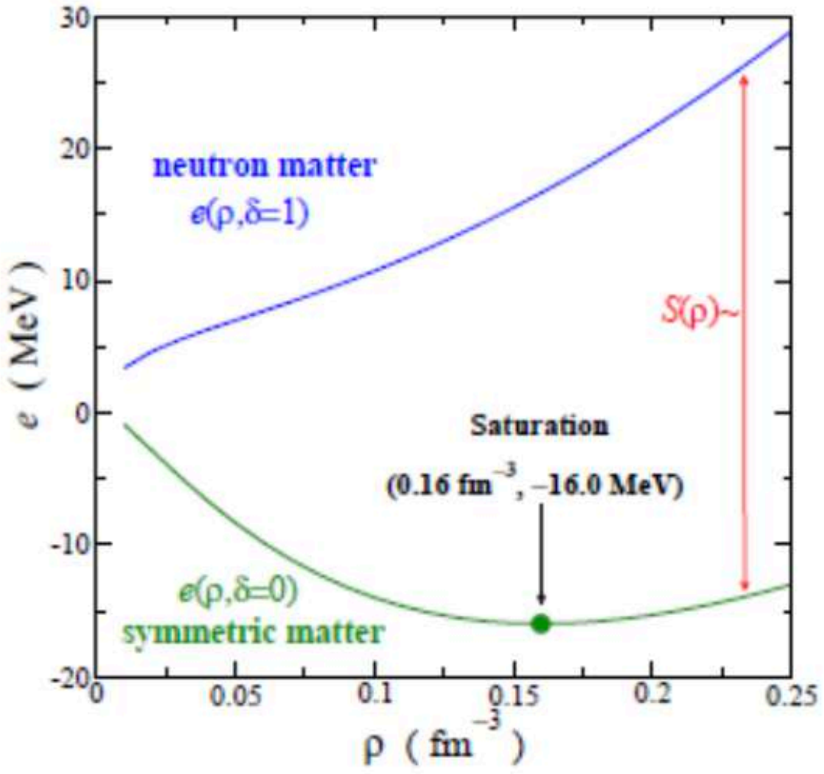
$$D_{\text{surf}} = -\tfrac{1}{64}[3t_1(2x_1 + 1) + t_2(2x_2 + 1)].$$

Ad.R. Raduta et al., EPJA 50, 24 (2014)

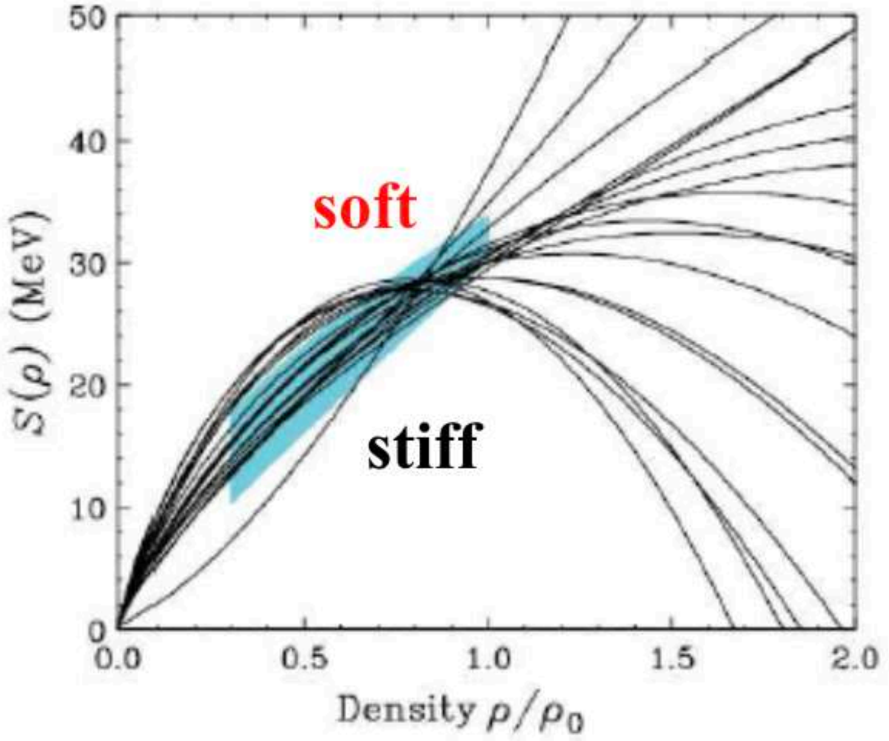
H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)

EoS(T=0) and symmetry energy

Energy per nucleon E/A (MeV)



Symmetry energy E_{sym} (MeV)



poorly known …

predictions of several effective interactions

$$E/A(\rho,\delta) = E/A(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

$$E_{sym}(\rho) = S_0(or\, J) + L\frac{\rho-\rho_0}{3\rho_0} + \cdots$$

- ➢ analogy with **Weizsacker mass formula** for nuclei (symmetry term) !

25 ≤ J ≤ 35 MeV   20 ≤ L ≤ 120 MeV

Associate the nuclear properties with Skyrme EoS

1. Saturation density ρ_0
2. Energy per nucleon $E/A(\rho_0)$
3. Incompressibility K_0
4. Isoscalar effective mass m_S^*
5. Isovector effective mass m_V^*
6. Symmetry energy J
7. Slope of the symmetry energy L
8. isoscalar surface term G_S
9. Isovector surface term G_V

$\rightarrow$ 9

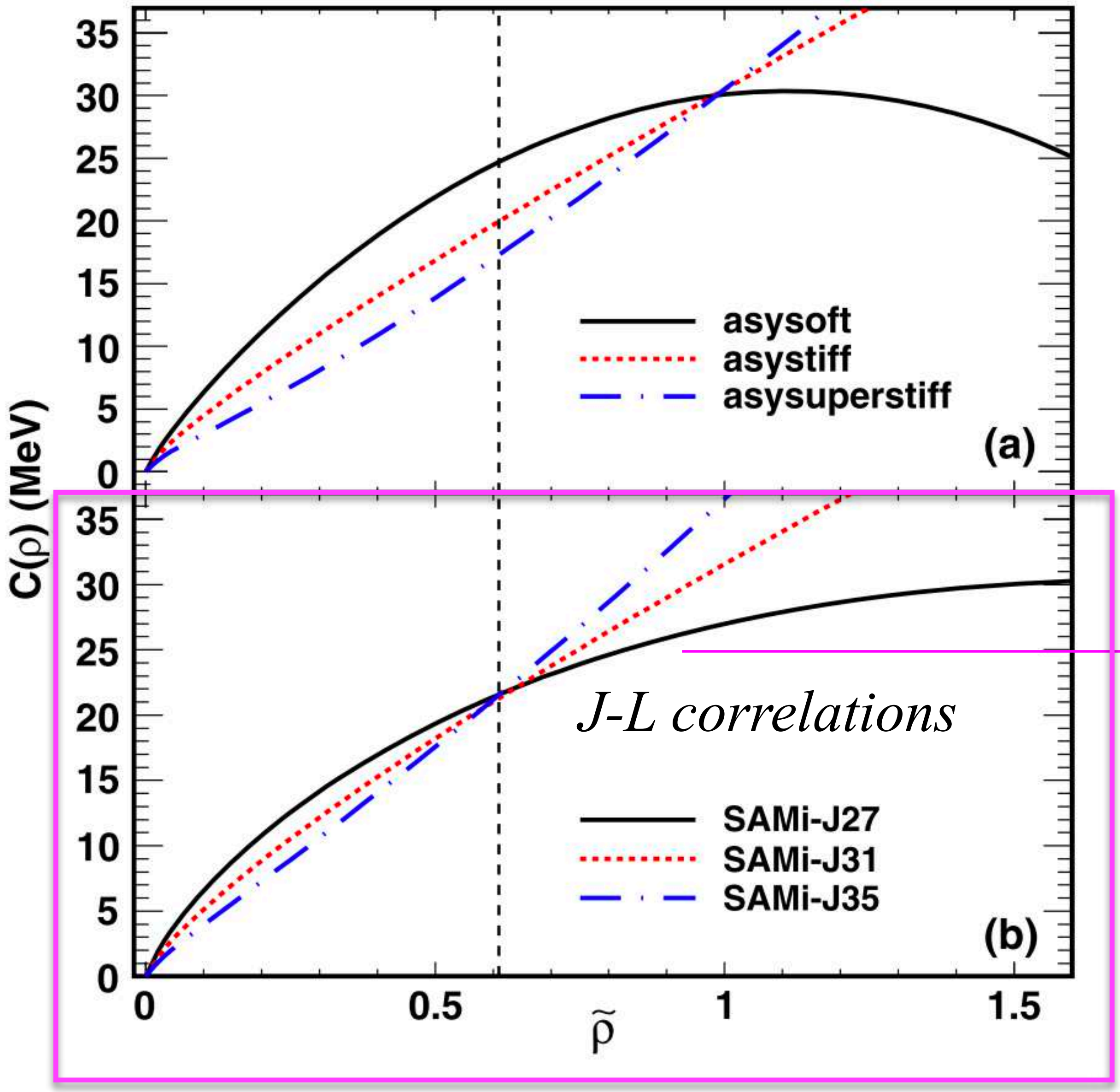
Vs

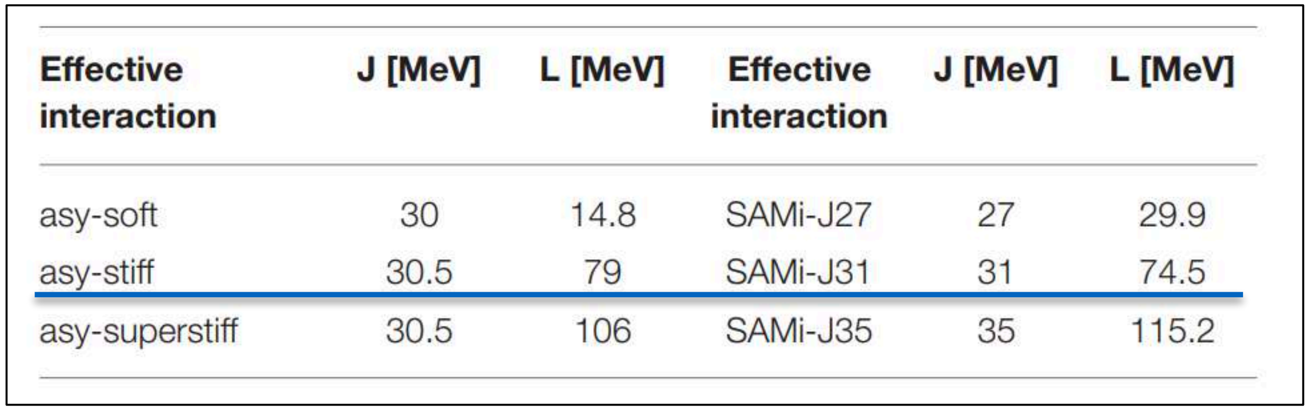
9

The parameters can be determined $(t_0, t_1, t_2, t_3, x_0, x_1, x_2, x_3, \sigma)$

L.W. Chen, C.M. Ko, B.A.Li, J. Xu, PRC 82, 024321 (2010)

Skyrme EoS adopted





Effective interaction	J [MeV]	L [MeV]	Effective interaction	J [MeV]	L [MeV]
asy-soft	30	14.8	SAMi-J27	27	29.9
asy-stiff	30.5	79	SAMi-J31	31	74.5
asy-superstiff	30.5	106	SAMi-J35	35	115.2

SAMi-J:
changing the symmetry energy slope

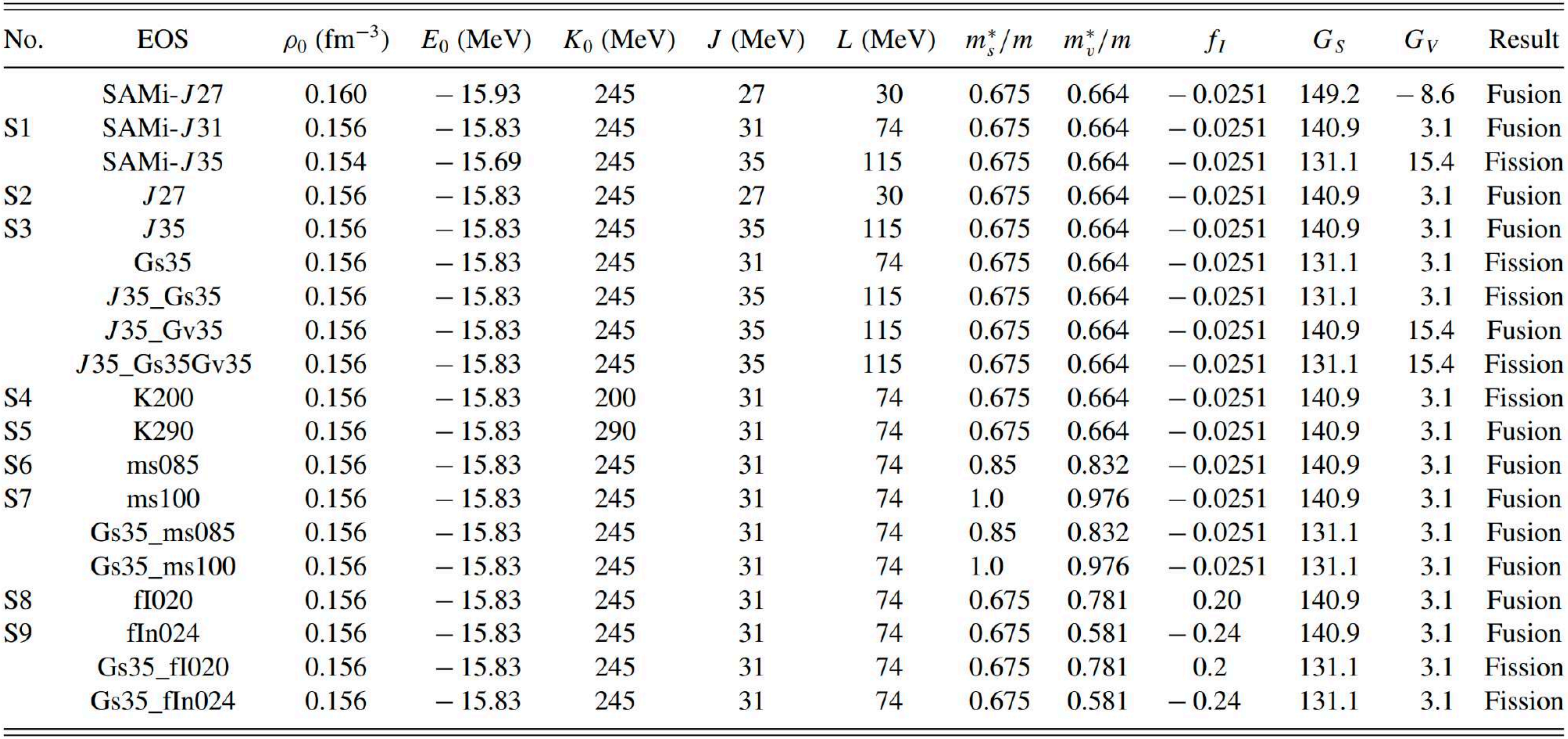
Taking SAMi-J31 as a reference:
consider interactions with different

- symmetry energy
- incompressibility
- effective mass
- n/p effective mass splitting
- surface terms

SAMi-J:
X. Roca-Maza, G. Colò, H. Sagawa, Phys. Rev. C **86**, 031306(R) (2012); X. Roca-Maza *et al.*, Phys. Rev. C **87**, 034301 (2013).

H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)
H.Zheng, S.Burrello, M.Colonna, V.Baran, PLB 769, 424 (2017)
S.Burrello, M.Colonna, H.Zheng, Frontiers in Physics, Vol. 7, 53 (2019)

Skyrme EoS adopted



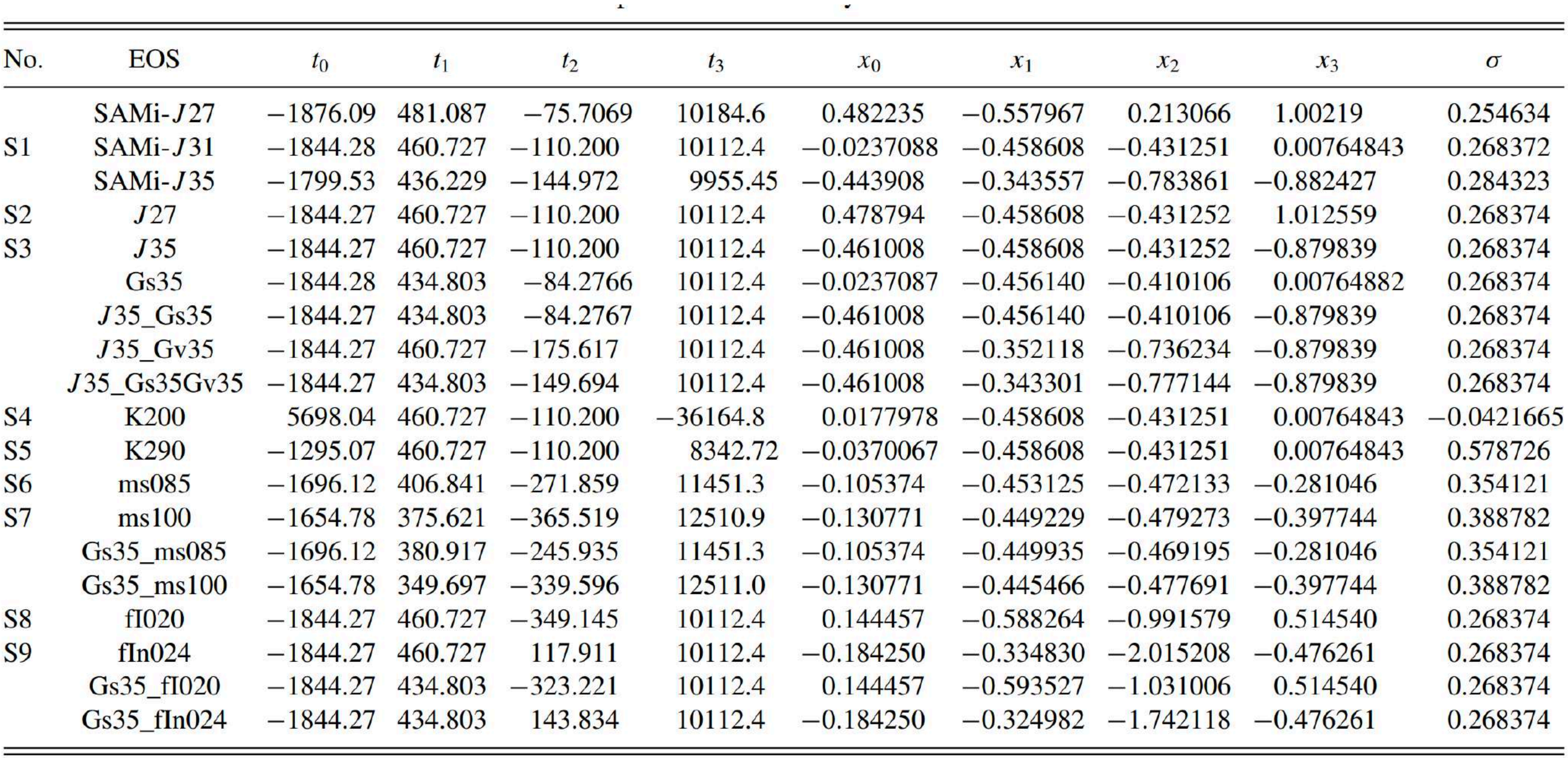
No.	EOS	ρ_0 (fm^{-3})	E_0 (MeV)	K_0 (MeV)	J (MeV)	L (MeV)	m^*_s/m	m^*_v/m	f_I	G_S	G_V	Result
	SAMi-$J27$	0.160	−15.93	245	27	30	0.675	0.664	−0.0251	149.2	−8.6	Fusion
S1	SAMi-$J31$	0.156	−15.83	245	31	74	0.675	0.664	−0.0251	140.9	3.1	Fusion
	SAMi-$J35$	0.154	−15.69	245	35	115	0.675	0.664	−0.0251	131.1	15.4	Fission
S2	$J27$	0.156	−15.83	245	27	30	0.675	0.664	−0.0251	140.9	3.1	Fusion
S3	$J35$	0.156	−15.83	245	35	115	0.675	0.664	−0.0251	140.9	3.1	Fusion
	Gs35	0.156	−15.83	245	31	74	0.675	0.664	−0.0251	131.1	3.1	Fission
	$J35$_Gs35	0.156	−15.83	245	35	115	0.675	0.664	−0.0251	131.1	3.1	Fission
	$J35$_Gv35	0.156	−15.83	245	35	115	0.675	0.664	−0.0251	140.9	15.4	Fusion
	$J35$_Gs35Gv35	0.156	−15.83	245	35	115	0.675	0.664	−0.0251	131.1	15.4	Fission
S4	K200	0.156	−15.83	200	31	74	0.675	0.664	−0.0251	140.9	3.1	Fission
S5	K290	0.156	−15.83	290	31	74	0.675	0.664	−0.0251	140.9	3.1	Fusion
S6	ms085	0.156	−15.83	245	31	74	0.85	0.832	−0.0251	140.9	3.1	Fusion
S7	ms100	0.156	−15.83	245	31	74	1.0	0.976	−0.0251	140.9	3.1	Fusion
	Gs35_ms085	0.156	−15.83	245	31	74	0.85	0.832	−0.0251	131.1	3.1	Fusion
	Gs35_ms100	0.156	−15.83	245	31	74	1.0	0.976	−0.0251	131.1	3.1	Fusion
S8	fI020	0.156	−15.83	245	31	74	0.675	0.781	0.20	140.9	3.1	Fusion
S9	fIn024	0.156	−15.83	245	31	74	0.675	0.581	−0.24	140.9	3.1	Fusion
	Gs35_fI020	0.156	−15.83	245	31	74	0.675	0.781	0.2	131.1	3.1	Fission
	Gs35_fIn024	0.156	−15.83	245	31	74	0.675	0.581	−0.24	131.1	3.1	Fission

The units of G_s and G_V are $MeV\,fm^5$

The EoS name follows the convention that we only label the terms which are different with respect to the ingredients of the SAMi-J31 parametrization.

H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)

Skyrme EoS adopted



No.	EOS	t_0	t_1	t_2	t_3	x_0	x_1	x_2	x_3	σ
	SAMi-*J*27	−1876.09	481.087	−75.7069	10184.6	0.482235	−0.557967	0.213066	1.00219	0.254634
S1	SAMi-*J*31	−1844.28	460.727	−110.200	10112.4	−0.0237088	−0.458608	−0.431251	0.00764843	0.268372
	SAMi-*J*35	−1799.53	436.229	−144.972	9955.45	−0.443908	−0.343557	−0.783861	−0.882427	0.284323
S2	*J*27	−1844.27	460.727	−110.200	10112.4	0.478794	−0.458608	−0.431252	1.012559	0.268374
S3	*J*35	−1844.27	460.727	−110.200	10112.4	−0.461008	−0.458608	−0.431252	−0.879839	0.268374
	Gs35	−1844.28	434.803	−84.2766	10112.4	−0.0237087	−0.456140	−0.410106	0.00764882	0.268374
	*J*35_Gs35	−1844.27	434.803	−84.2767	10112.4	−0.461008	−0.456140	−0.410106	−0.879839	0.268374
	*J*35_Gv35	−1844.27	460.727	−175.617	10112.4	−0.461008	−0.352118	−0.736234	−0.879839	0.268374
	*J*35_Gs35Gv35	−1844.27	434.803	−149.694	10112.4	−0.461008	−0.343301	−0.777144	−0.879839	0.268374
S4	K200	5698.04	460.727	−110.200	−36164.8	0.0177978	−0.458608	−0.431251	0.00764843	−0.0421665
S5	K290	−1295.07	460.727	−110.200	8342.72	−0.0370067	−0.458608	−0.431251	0.00764843	0.578726
S6	ms085	−1696.12	406.841	−271.859	11451.3	−0.105374	−0.453125	−0.472133	−0.281046	0.354121
S7	ms100	−1654.78	375.621	−365.519	12510.9	−0.130771	−0.449229	−0.479273	−0.397744	0.388782
	Gs35_ms085	−1696.12	380.917	−245.935	11451.3	−0.105374	−0.449935	−0.469195	−0.281046	0.354121
	Gs35_ms100	−1654.78	349.697	−339.596	12511.0	−0.130771	−0.445466	−0.477691	−0.397744	0.388782
S8	fI020	−1844.27	460.727	−349.145	10112.4	0.144457	−0.588264	−0.991579	0.514540	0.268374
S9	fIn024	−1844.27	460.727	117.911	10112.4	−0.184250	−0.334830	−2.015208	−0.476261	0.268374
	Gs35_fI020	−1844.27	434.803	−323.221	10112.4	0.144457	−0.593527	−1.031006	0.514540	0.268374
	Gs35_fIn024	−1844.27	434.803	143.834	10112.4	−0.184250	−0.324982	−1.742118	−0.476261	0.268374

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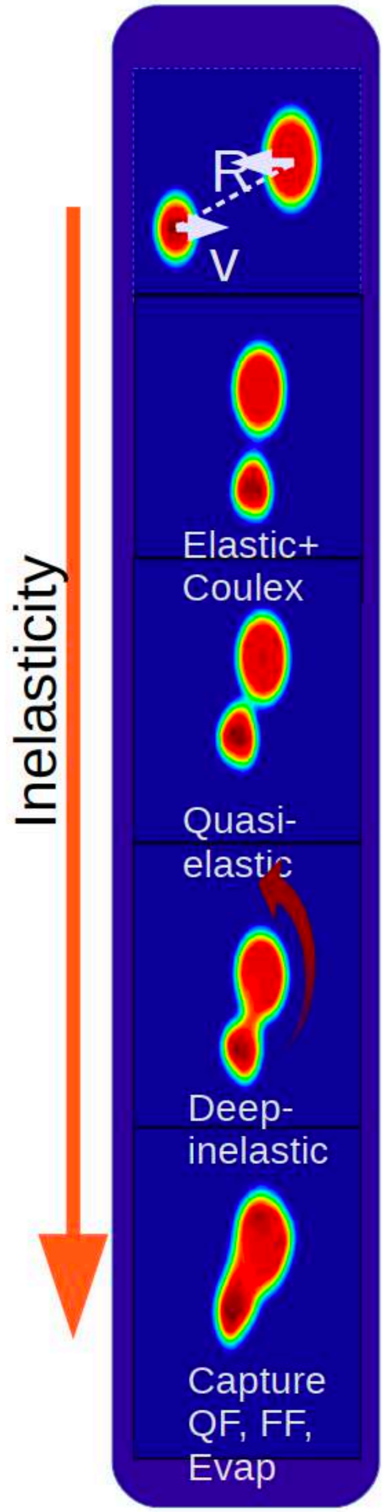
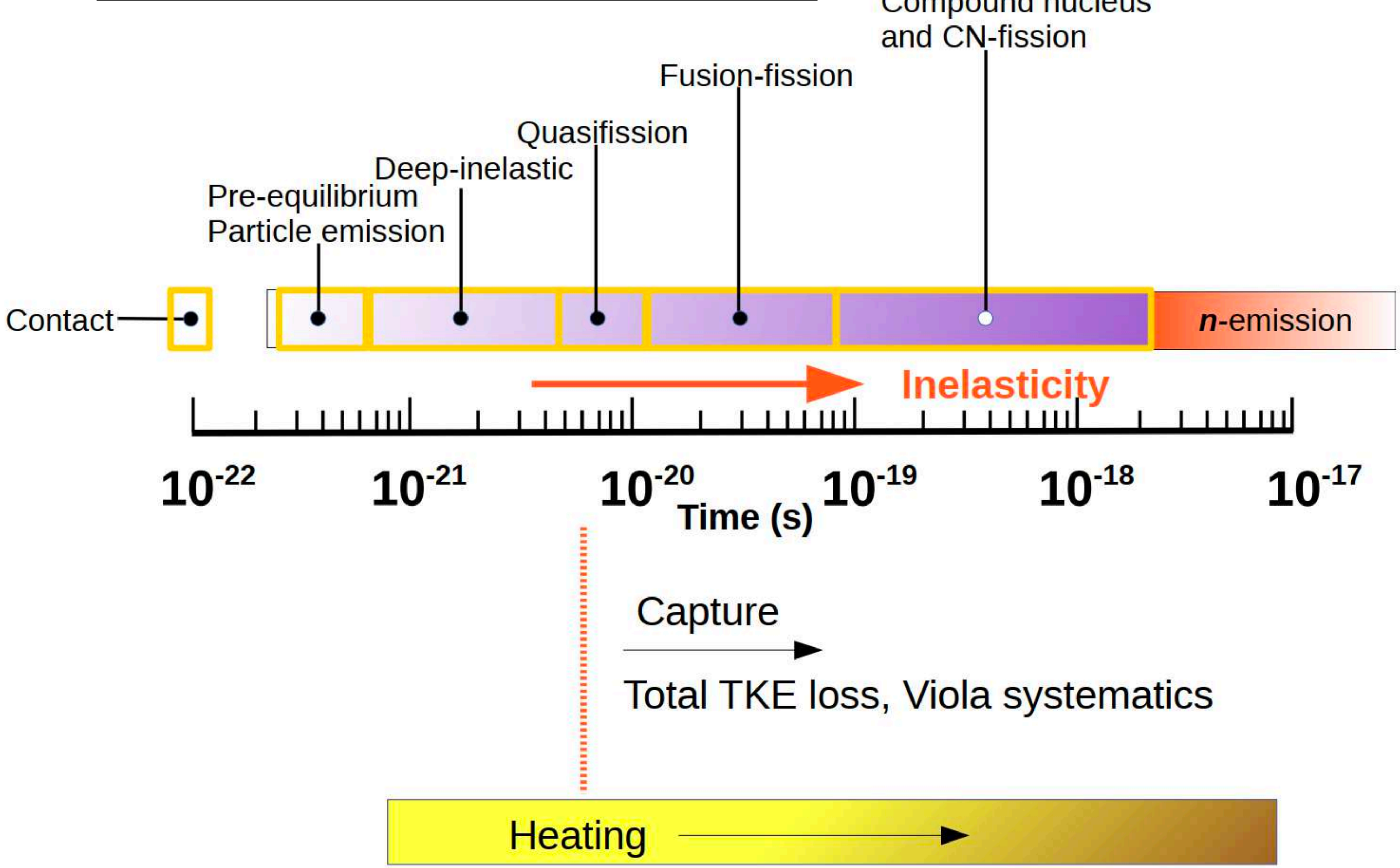
H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)

Inelasticity and time scales at low-energy nuclear reactions

$$1zs = 10^{-21}s = 300fm/c$$



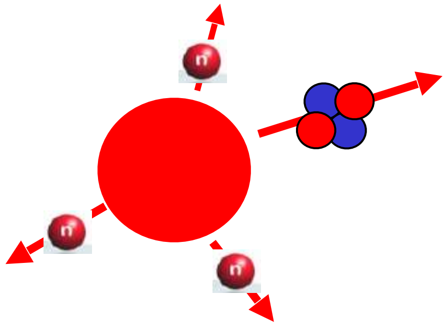


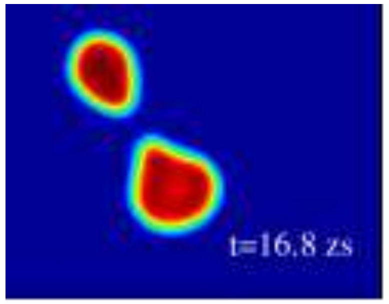
Courtesy of Yu. Ts. Oganessian

Low-energy reaction mechanisms: a study within mean-field models

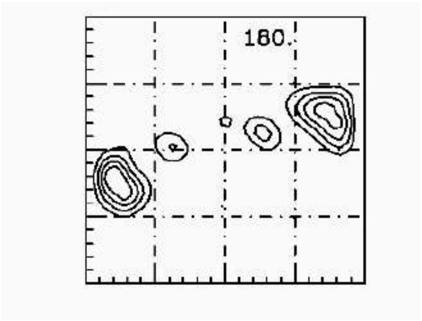
(Fermi energies)

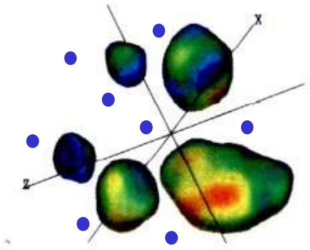
- Fusion vs Quasi-fission or Deep Inelastic
- Charge equilibration





- Fragmentation
- Fragment isotopic composition
- Phase transition





(Beyond) Mean-field models and effective interactions

$$i\hbar\frac{\partial}{\partial t}\hat{\rho}(t) = [H_{eff}[\hat{\rho}],\hat{\rho}(t)] + K(\hat{\rho}) + \delta K(\hat{\rho},\delta\sigma)$$

TDHF

ETDHF

One-body description:

$\hat{\rho}$: the one-body density matrix

Semi-classical approximation

$$\frac{\partial f(\mathbf{r},\mathbf{p},t)}{\partial t} + \{f, H_{eff}\} = k[f] + \delta k$$

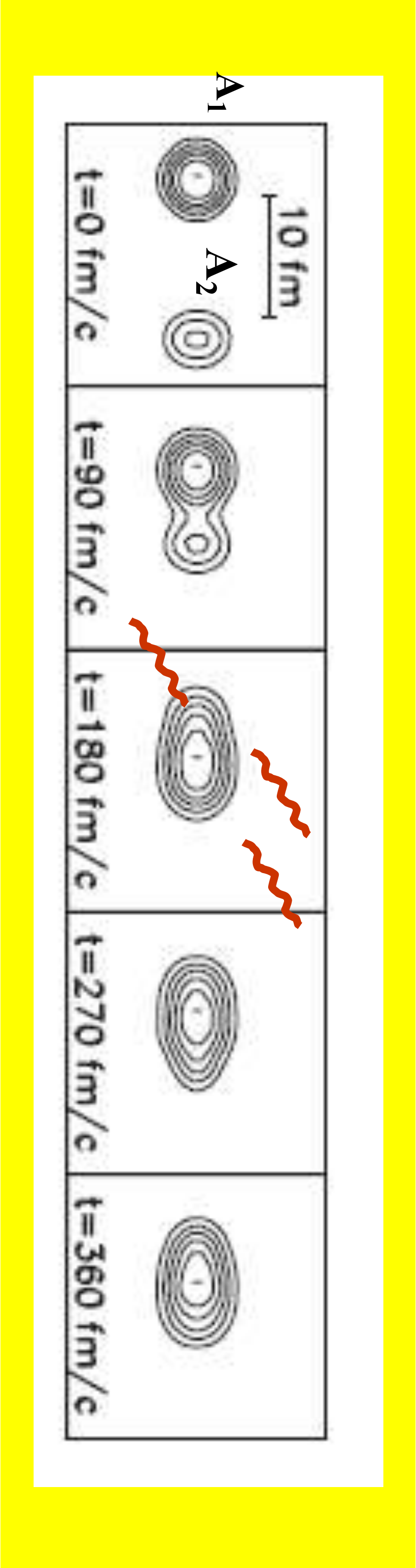
Vlasov

BUU,
Boltzmann-Langevin

H_{eff} : effective Hamiltonian

Residual interaction:
In-medium NN cross-section
2-body correlations, fluctuations

Charge equilibration and dipole oscillations: dependence on the effective interaction

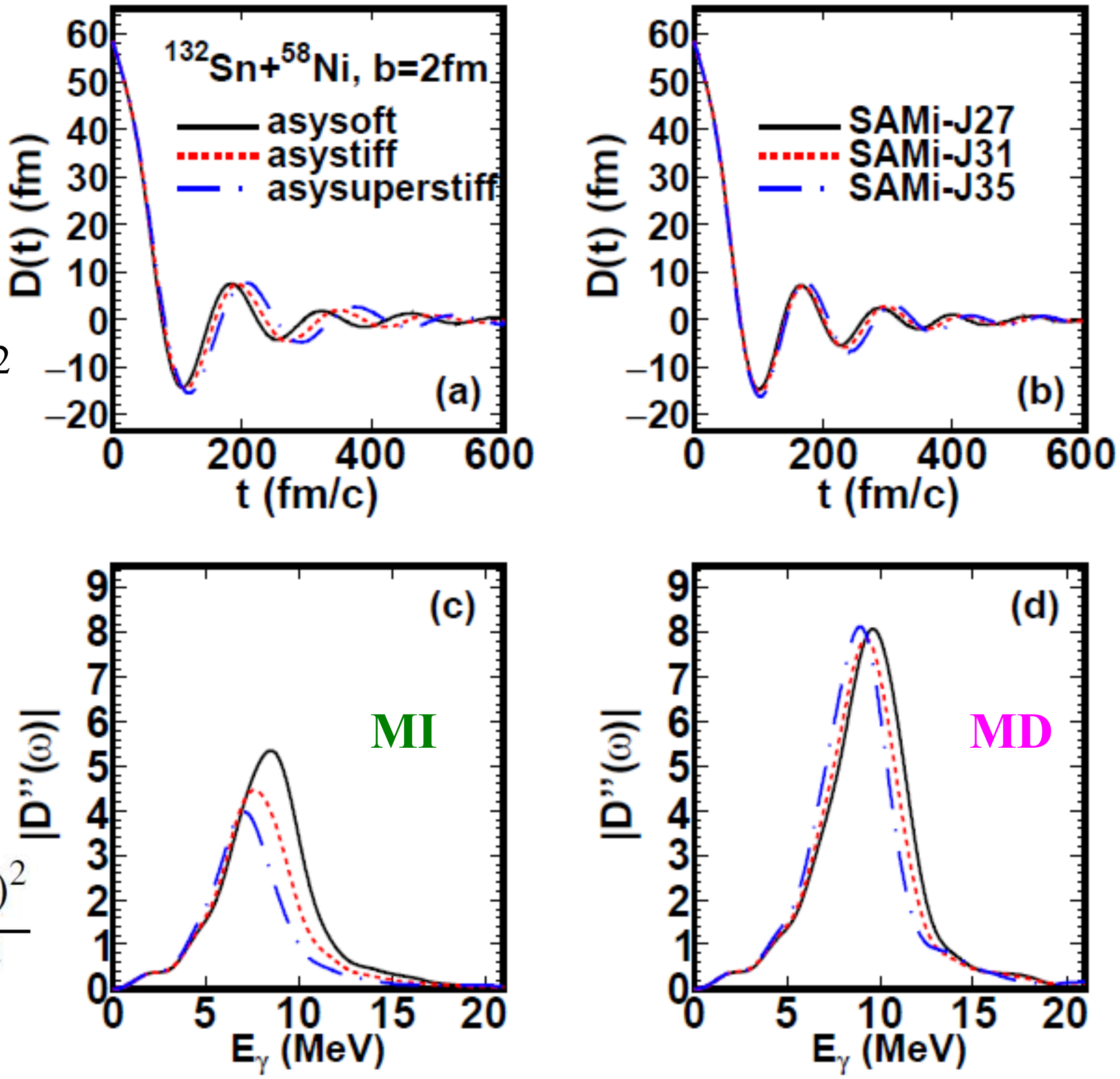


H. Zheng et al. / Physics Letters B 769 (2017) 424–429

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left|D''(\omega)\right|^2$$

$$|D''(\omega)|^2 = \frac{\left(\omega_0^2 + 1/\tau^2\right)^2 D(t_0)^2}{(\omega-\omega_0)^2 + 1/\tau^2}$$

^{132}Sn + ^{58}Ni , E/A = 10 MeV



$$P_\gamma \approx D_0^2 E_{centr}^3 \tau_{coll}$$

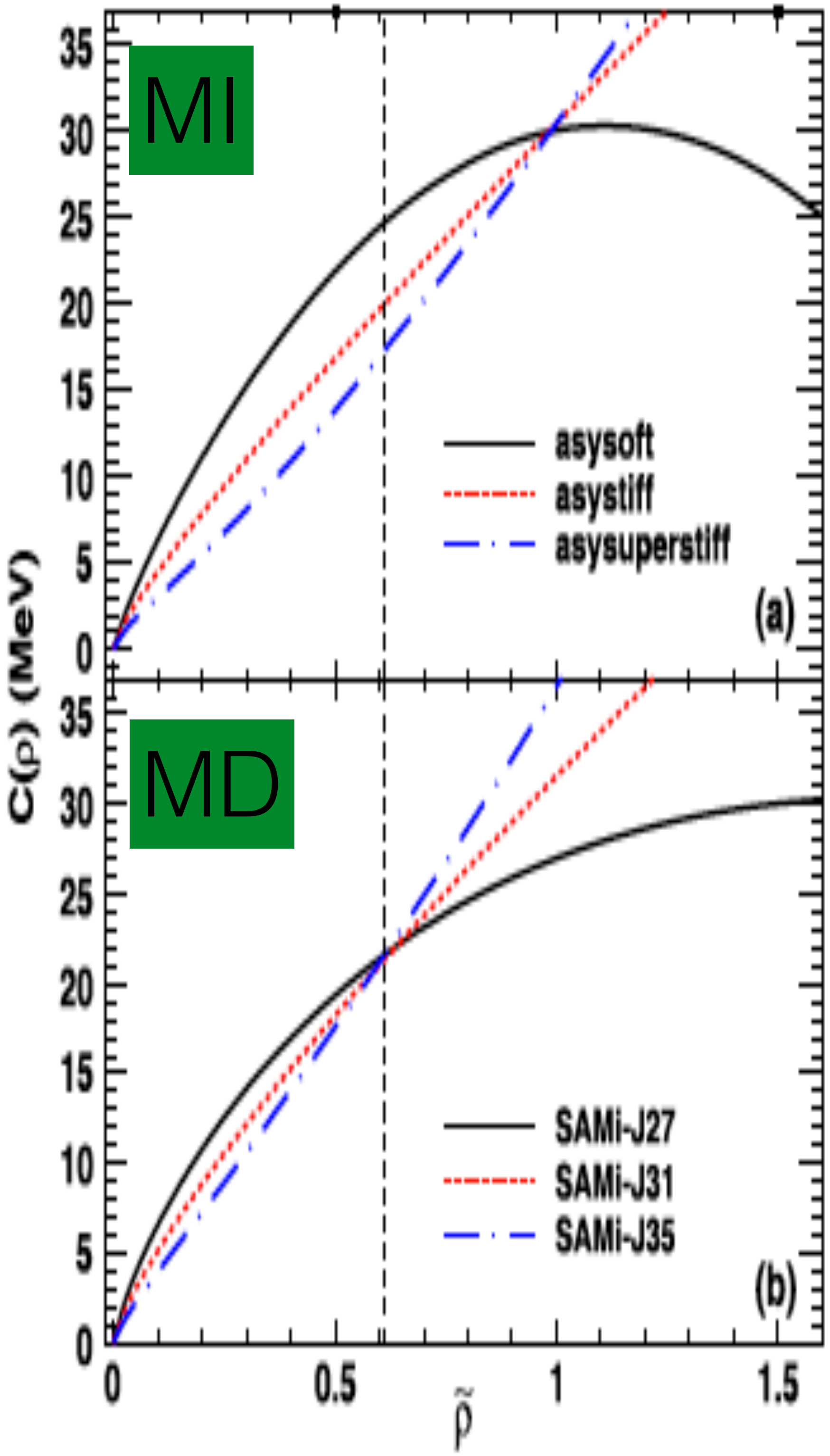
(damped harmonic oscillator)

- The DD emission looks sensitive to E_{sym} at $\rho = 0.6\ \rho_{sat}$

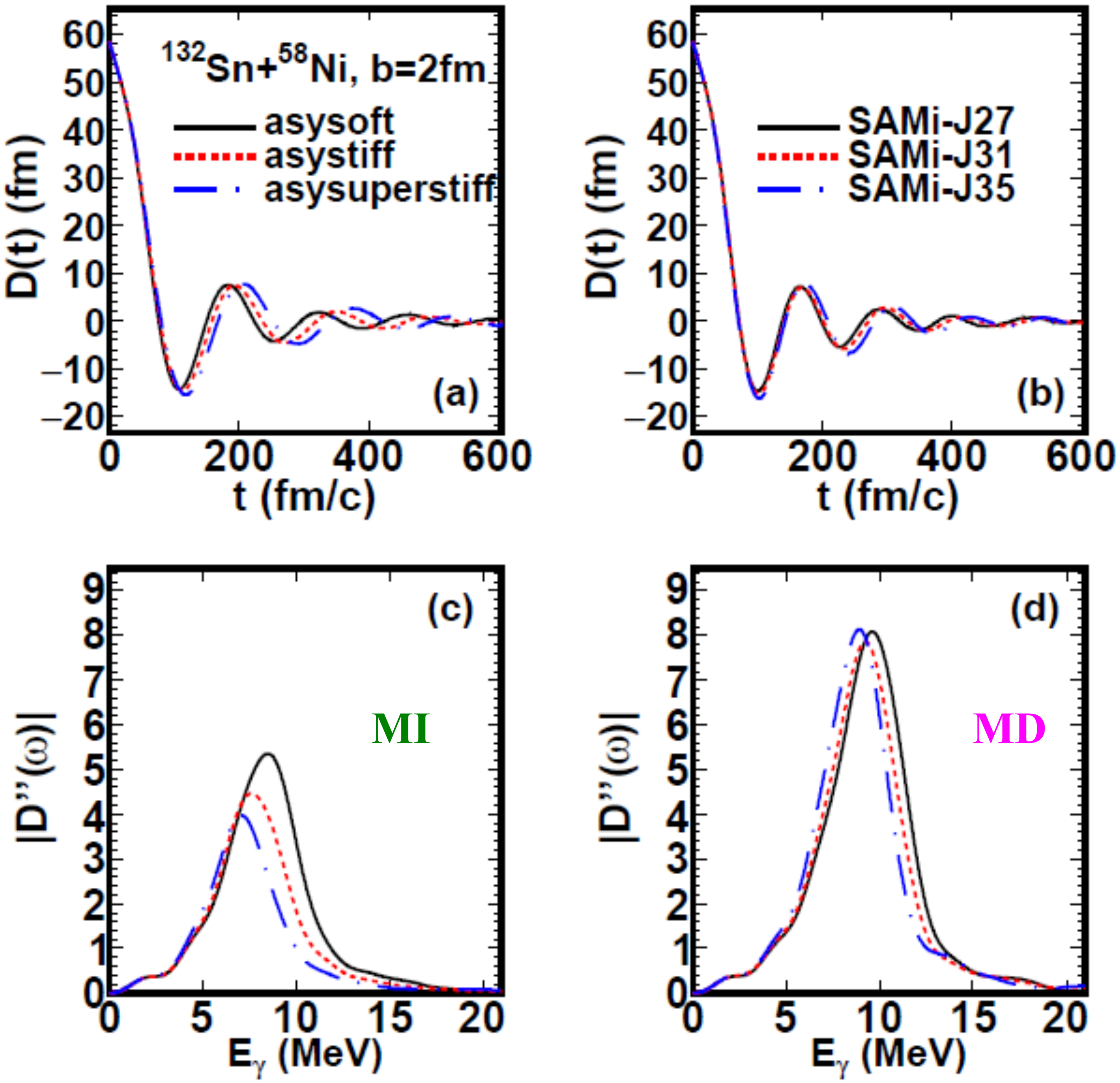
- Larger strength seen in the MD case
- damping connected to n-n collision time (τ_{coll})

The pre-equilibrium dipole strength in ^{132}Sn+^{58}Ni, 10 MeV/A

H. Zheng et al. PLB 769, 424, 2017



^{132}Sn + ^{58}Ni , E/A = 10 MeV



TDHF simulations process

D.Lacroix
IPN-Orsay

Important parameters

Mass/Charge:

Projectile (N_P, Z_P)

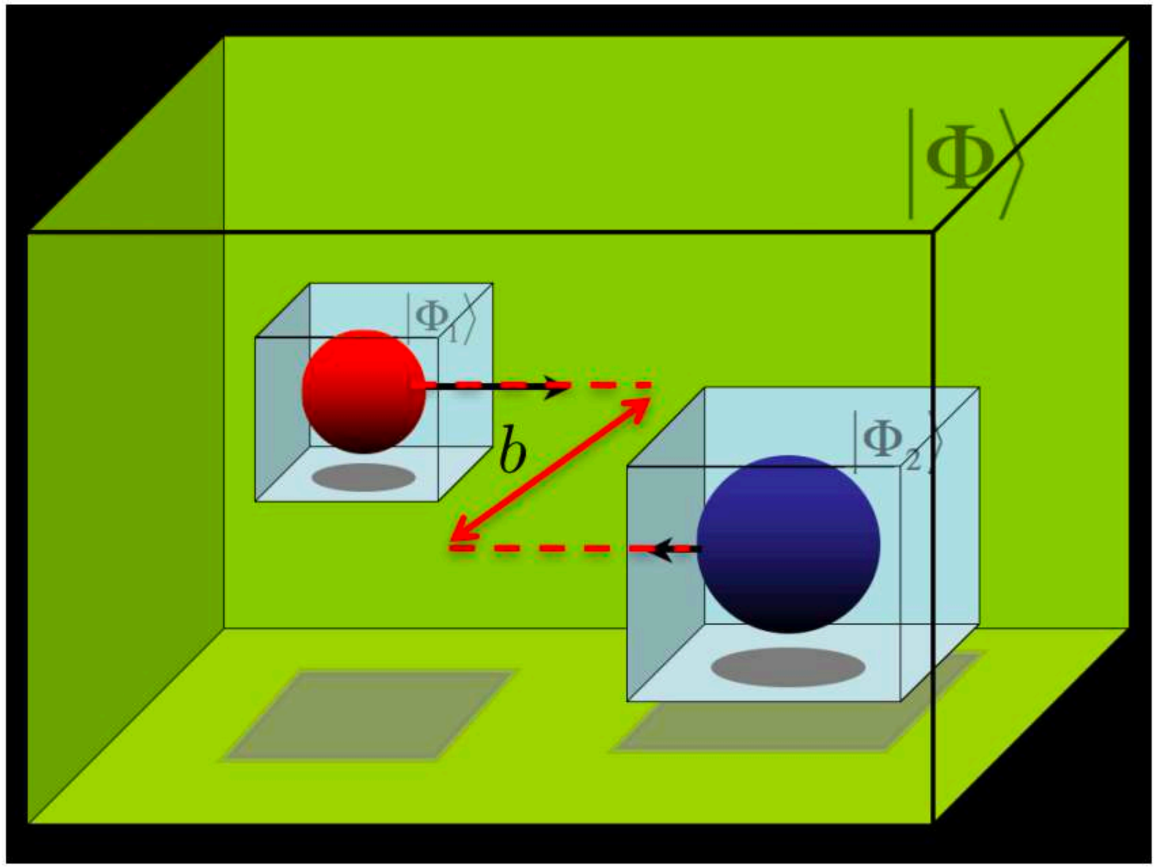
Target (N_T, Z_T)

Impact parameter: b

⇨ $L = r \wedge p = bp_{ini}$

Beam Energy: E_B/A

$$E_B^{Fus} \simeq 5\ MeV.A$$



Step 1

Initialize both nuclei separately

Step 2

Put both in a 3D Mesh (in the c.m.)

Step 3

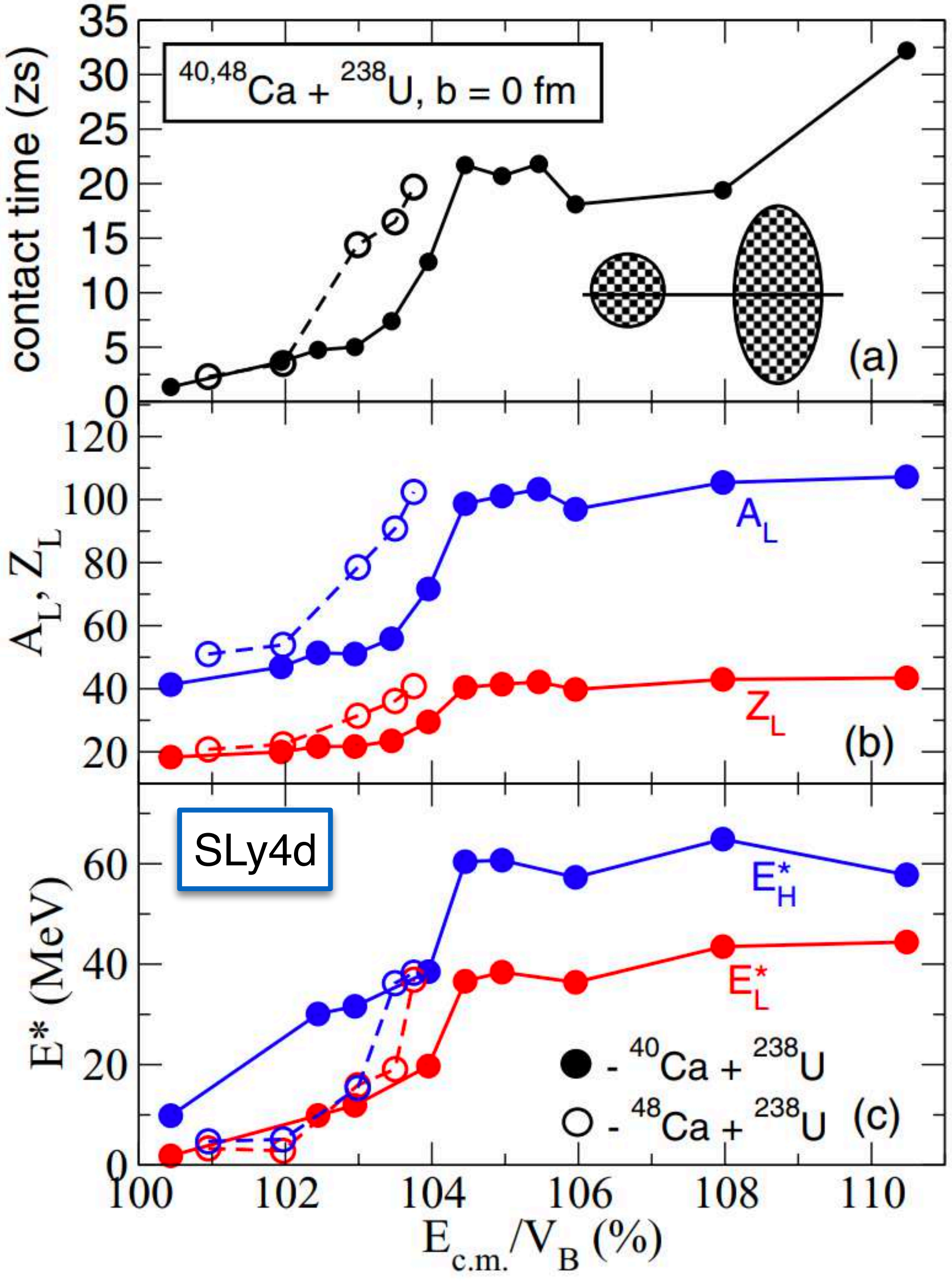
Boost wave-packets $|\phi_\alpha^{T/P}\rangle \rightarrow e^{-ip_{T/P}r/\hbar}|\phi_\alpha^{T/P}\rangle$

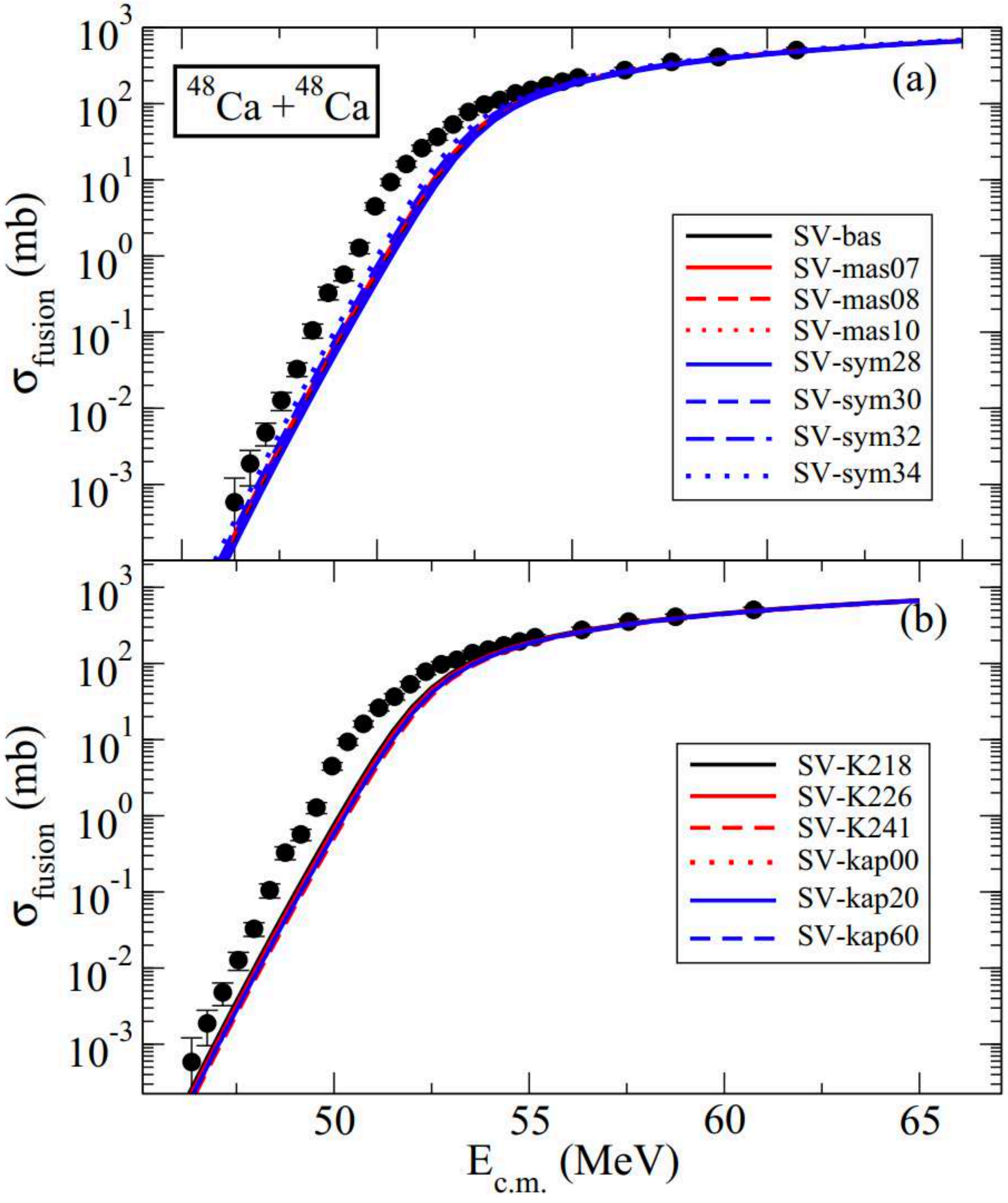
Step 4

Perform evolution

courtesy of D. Lacroix

Fusion vs Quasi-fission: TDHF simulations





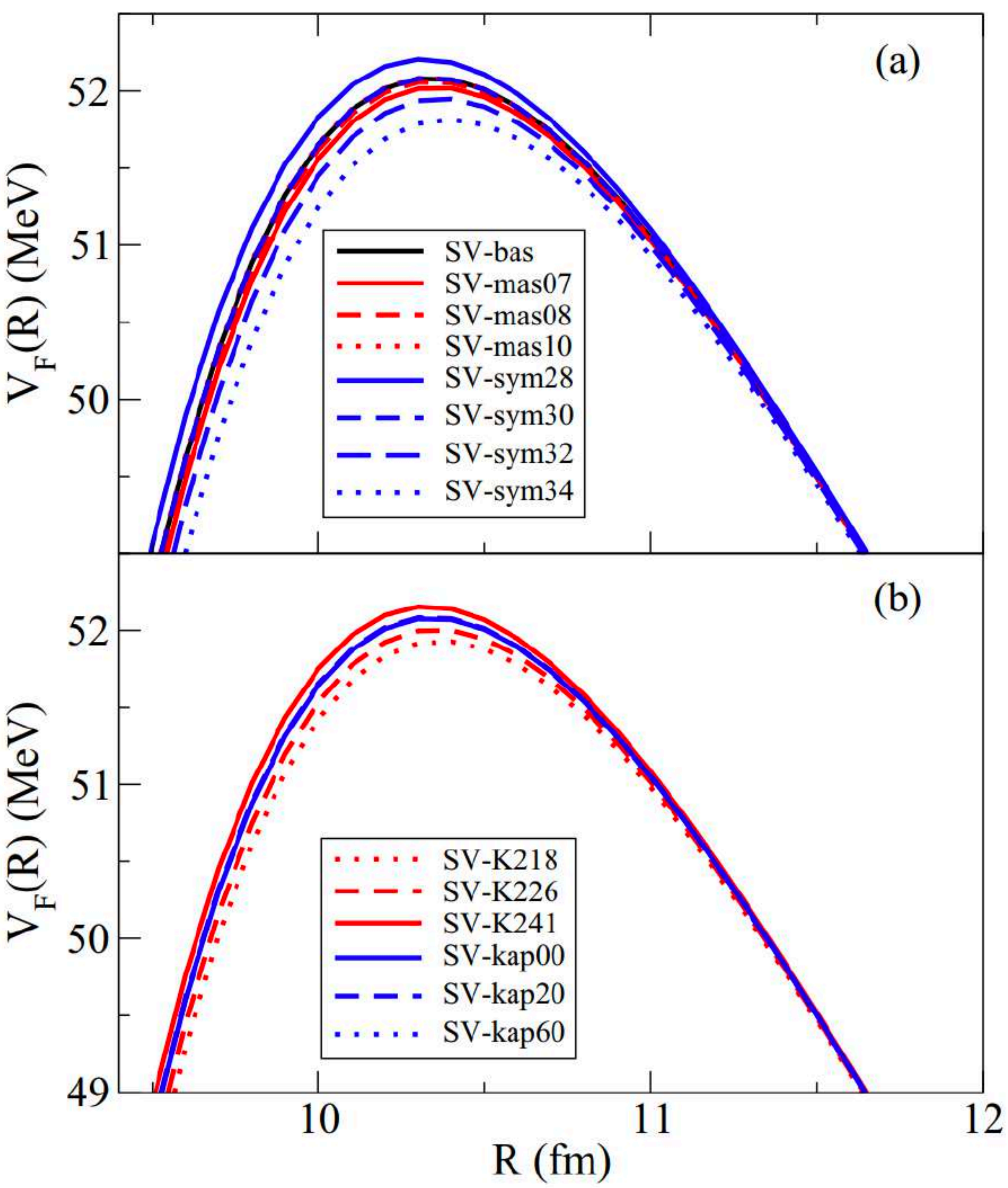
The frozen HF barrier for ^{40}Ca is $V_B = 199.13 MeV$

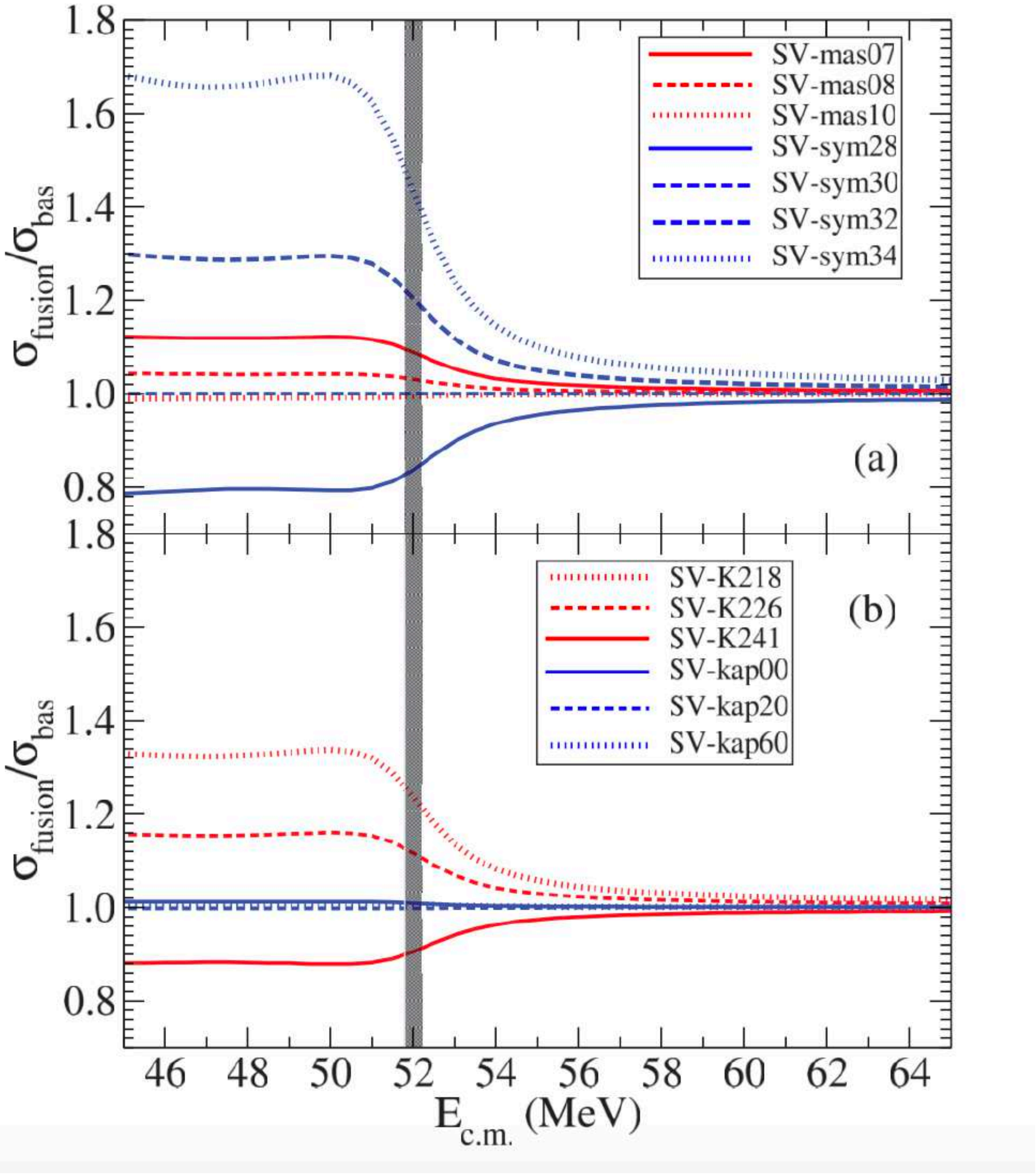
Sensitivity of sub-barrier fusion cross-section to EoS ingredients

V.E.Oberacker, A.S. Umar and C. Simenel, PRC 90, 054605 (2014)

P.-G. Reinhard *et al.* PRC 93, 044618 (2016)

Fusion vs Quasi-fission: TDHF simulations



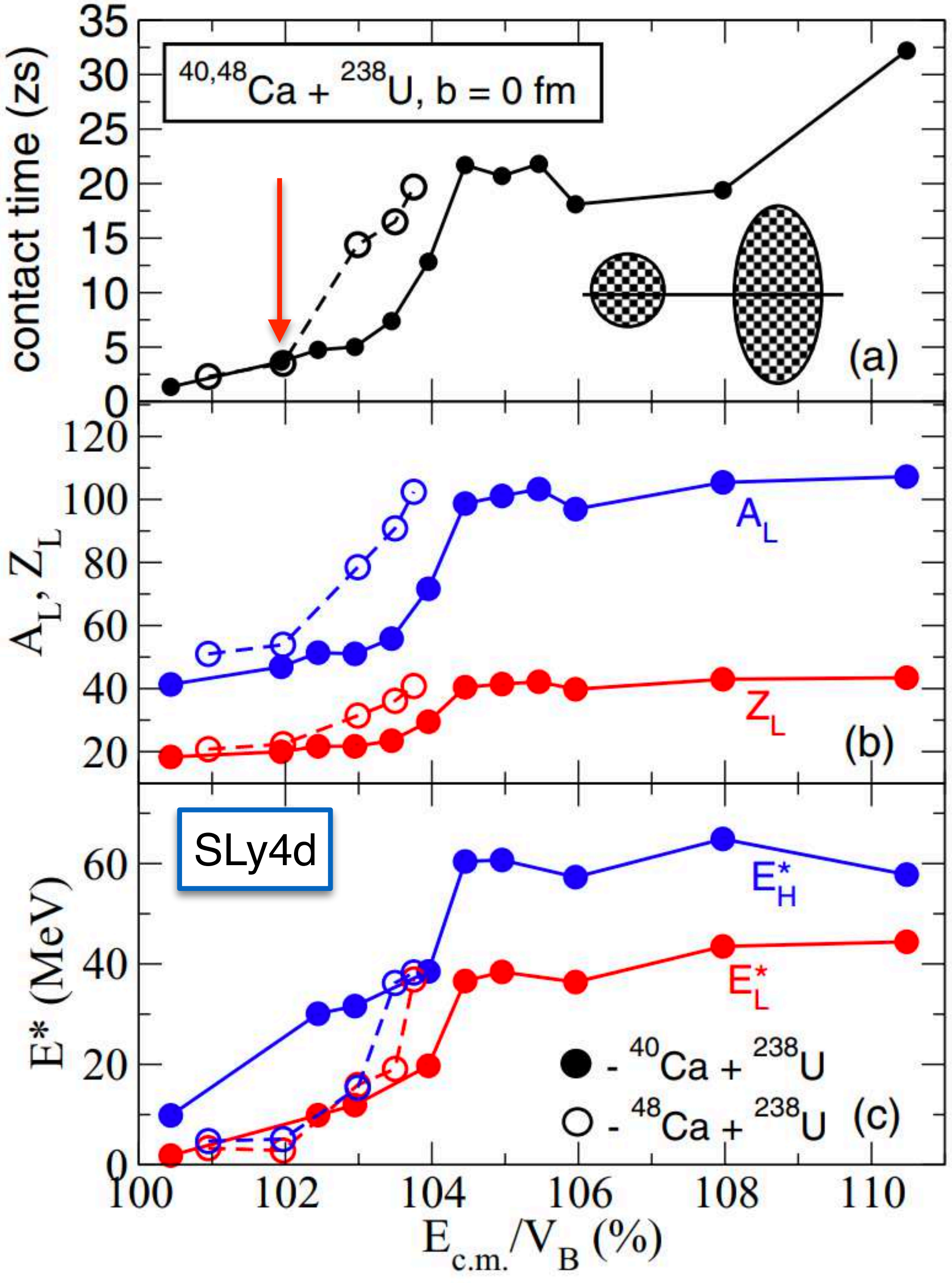


Sensitivity of ion-ion interaction potential to EoS ingredients

Sensitivity of sub-barrier fusion cross-section to EoS ingredients

P.-G. Reinhard *et al.* PRC 93, 044618 (2016)

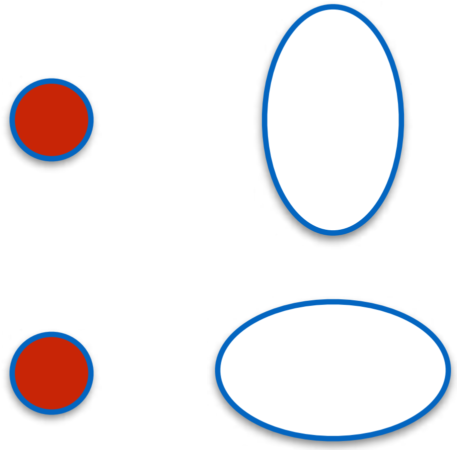
Fusion vs Quasi-fission: TDHF simulations



$\boxed{^{238}U + ^{40}Ca \text{ at } E_{cm} = 203MeV}$

At the threshold between fusion and quasi-fission

^{238}U is deformed:



1) Side

2) Tip

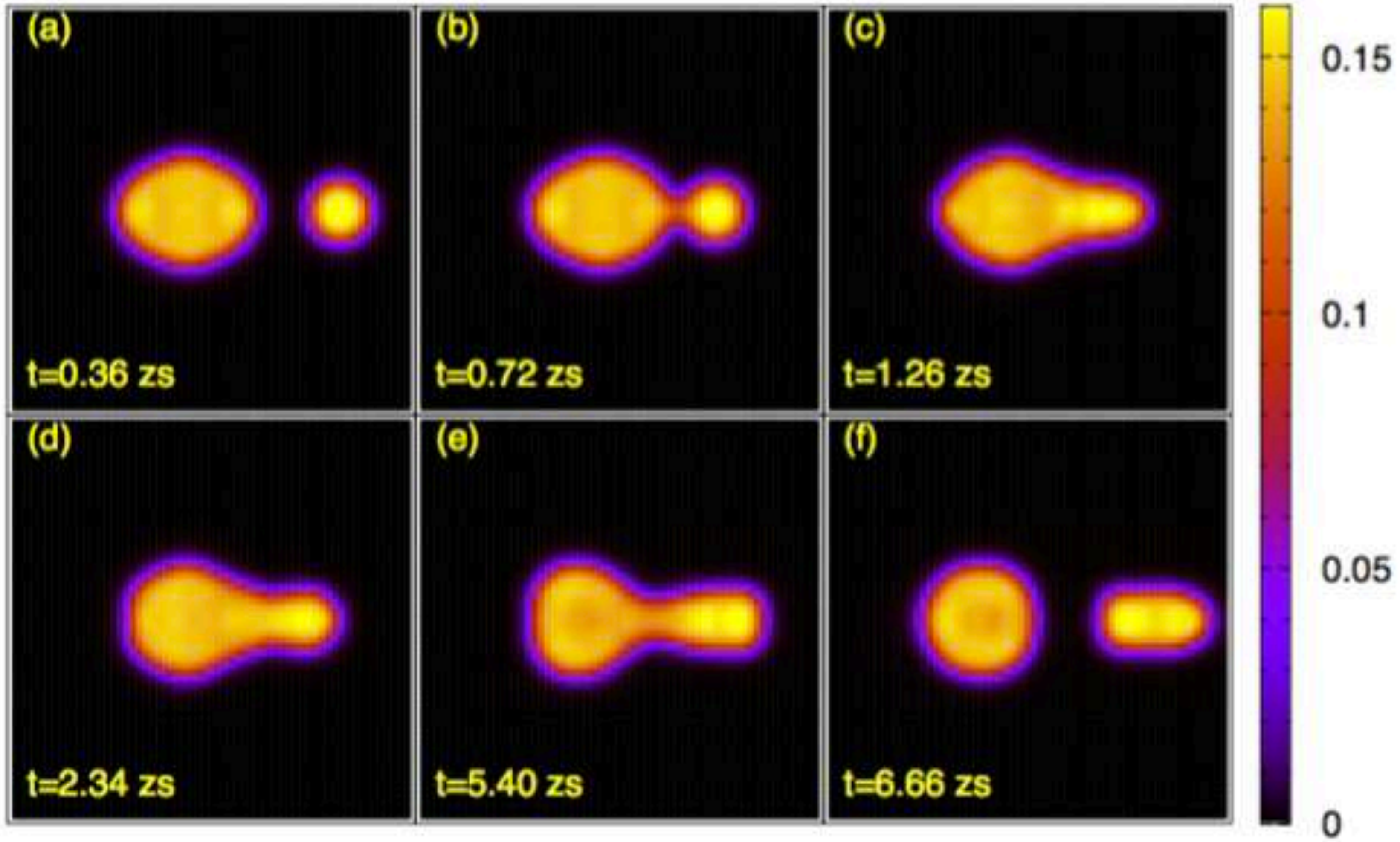
Quasi-fission is observed for the tip configuration

The frozen HF barrier for ^{40}Ca is $V_B = 199.13MeV$

V.E.Oberacker, A.S. Umar and C. Simenel, PRC 90, 054605 (2014)

TDHF simulations

$\boxed{^{238}U + ^{40}Ca \text{ at } E_{cm} = 203 MeV}$



tip collisions: SAMi-J31

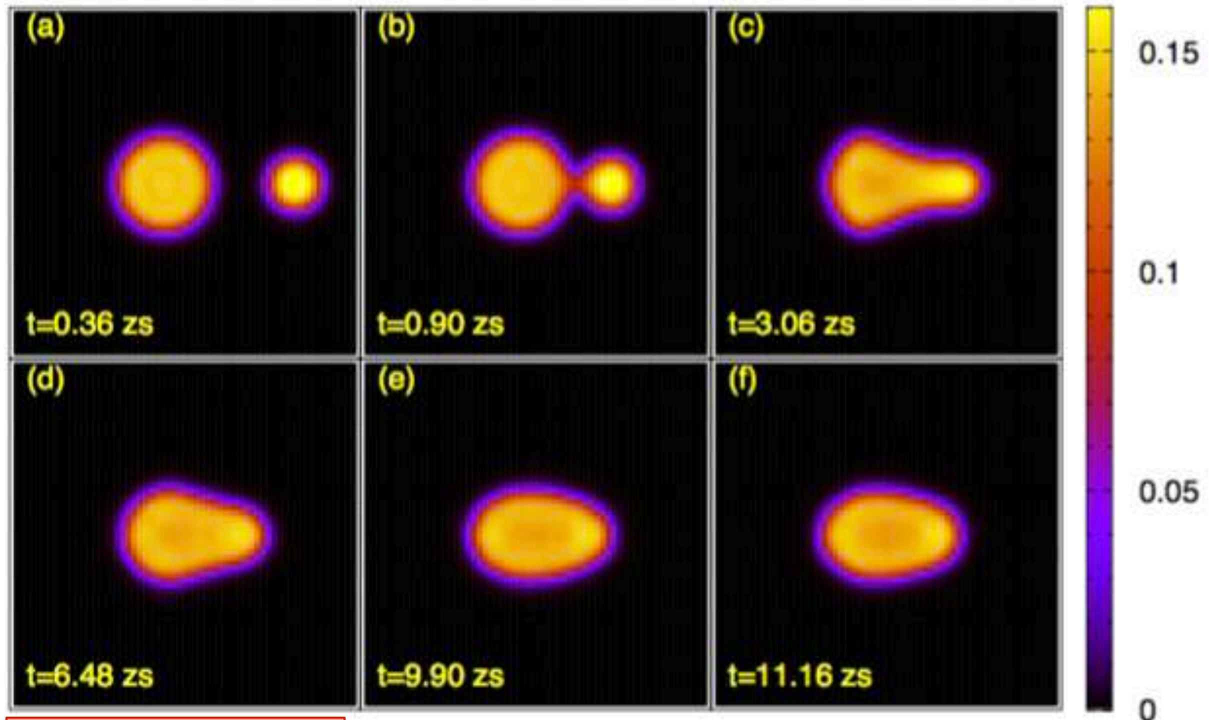
Quadrupole moment evolution

$$\boxed{Q_2(t) = \langle 2x^2 - y^2 - z^2 \rangle}$$

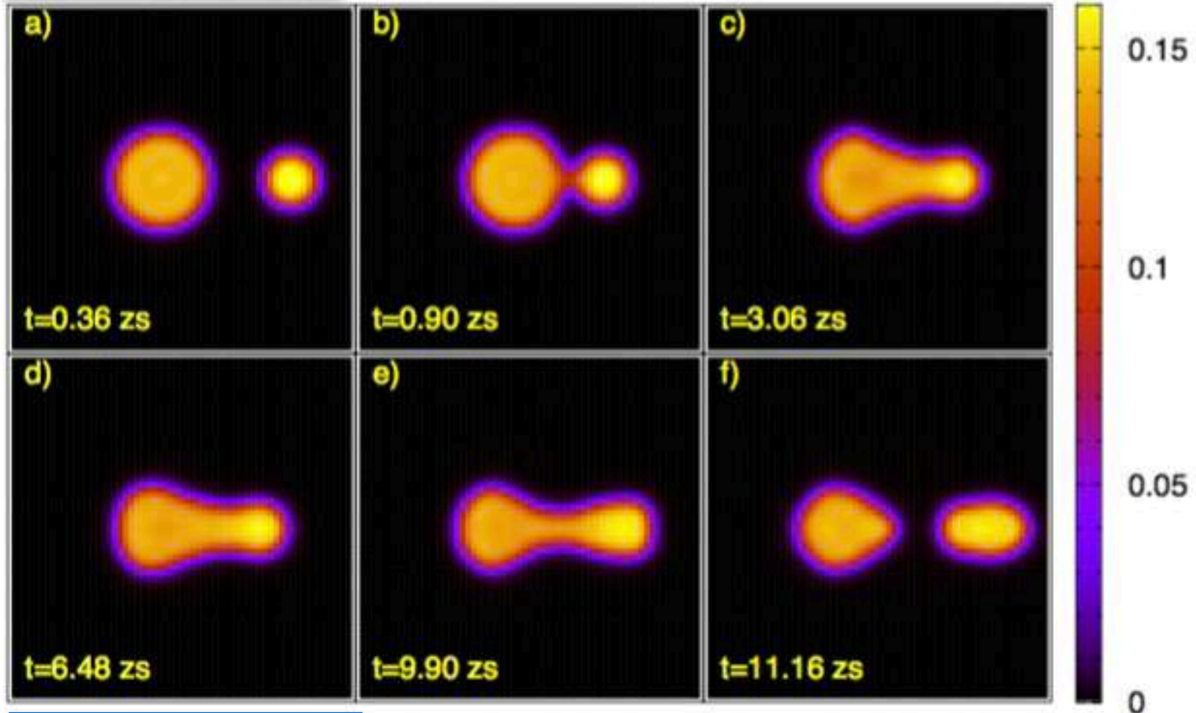
x axis: beam direction

H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)

TDHF simulations



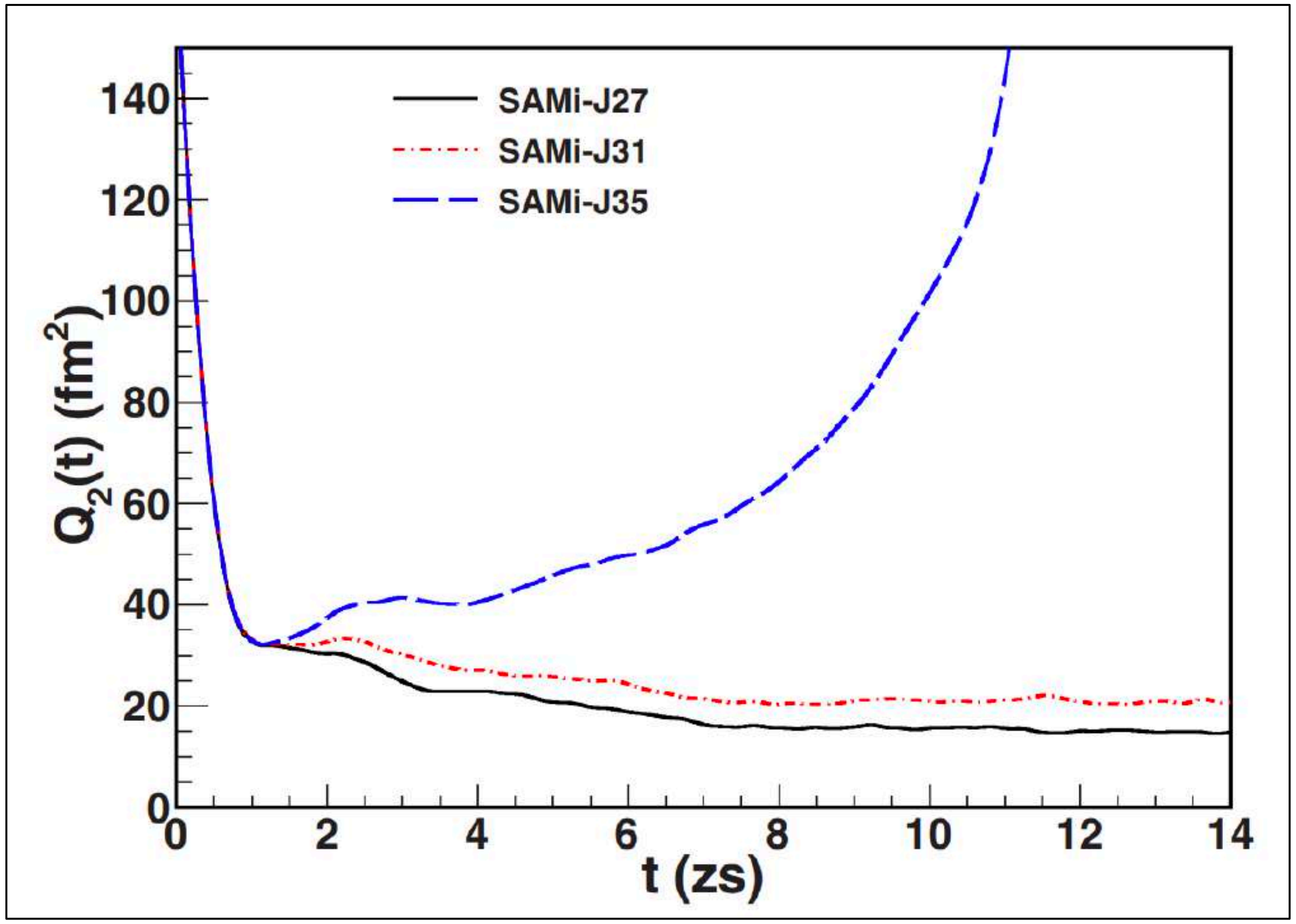
SAMi-J31



SAMi-J35

$^{238}U + ^{40}Ca$ at $E_{cm} = 203 MeV$

Side collisions, b=0 fm



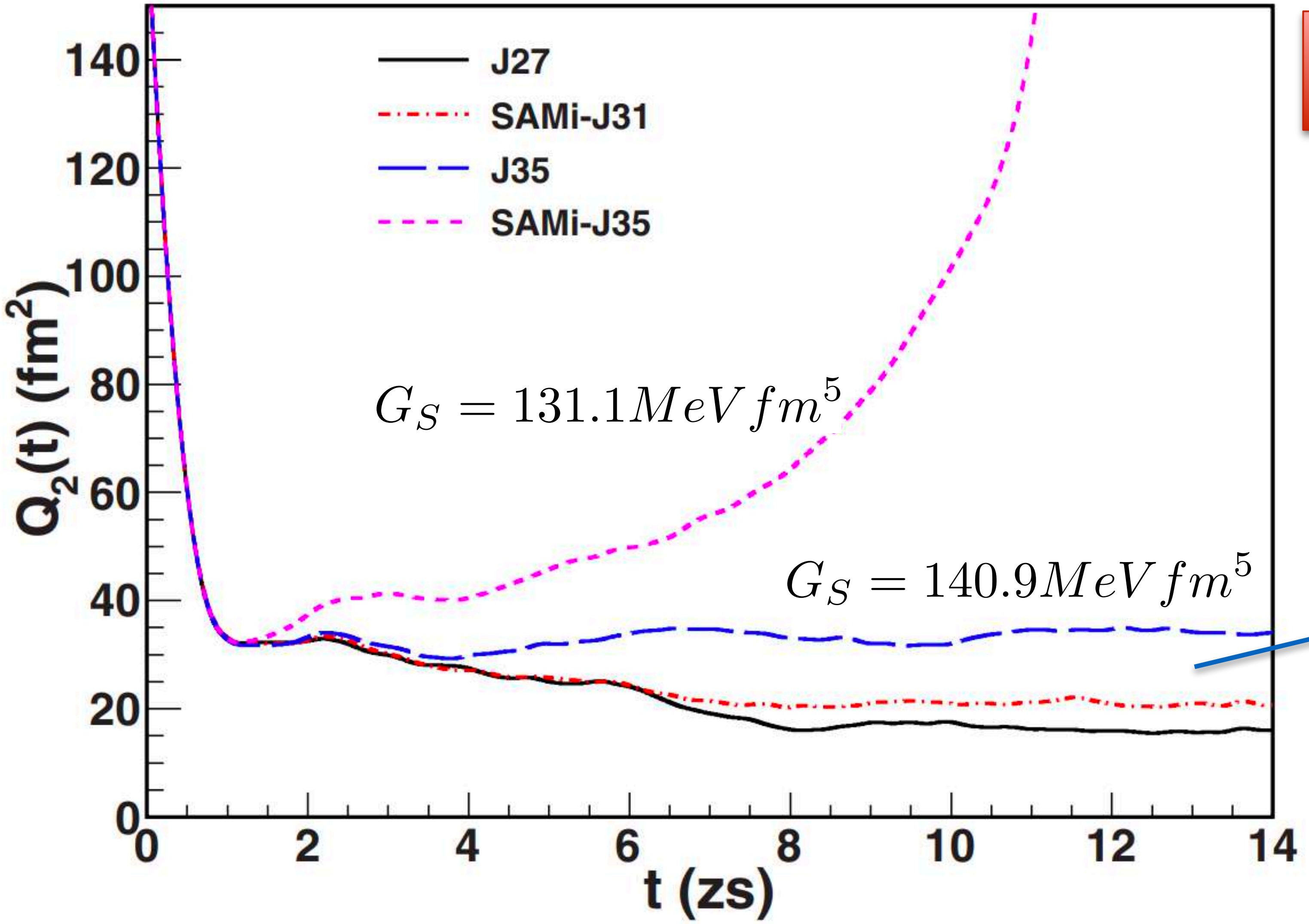
Intuitively, larger L, thicker neutron skin results in quasi-fission

H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)

TDHF simulations

Side collisions, b=0 fm

$^{238}U + ^{40}Ca \text{ at } E_{cm} = 203 MeV$



$G_S = 131.1 MeV fm^5$

$G_S = 140.9 MeV fm^5$

Symmetry energy effects

- J27, SAMi-J31, J35 have the same surface term
- Ordered by the symmetry energy (Symmetry energy effects: associated with neutron skin)

- SAMi-J35 shows different result from J35 (Larger effects are due to the surface term)

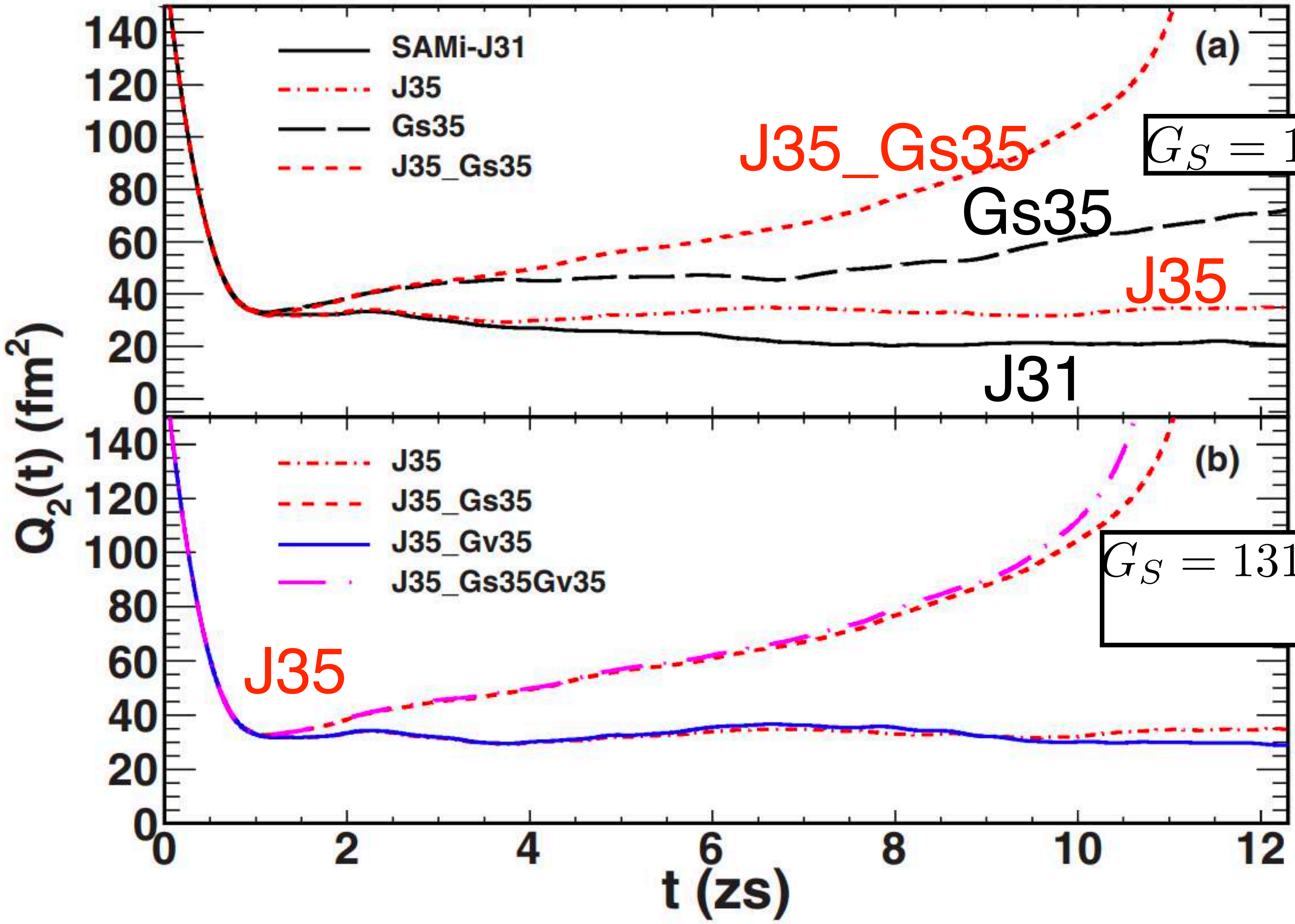
H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)

TDHF simulations

Side collisions, b=0 fm

$\boxed{{}^{238}U + {}^{40}Ca \text{ at } E_{cm} = 203MeV}$

Surface effects



$\boxed{G_S = 131.1 MeV fm^5}$

$\boxed{G_S = 140.9 MeV fm^5}$

$$\boxed{\begin{array}{r} G_S = 131.1 MeV fm^5, G_V = 15.4 MeV fm^5 \\ G_V = 3.1 MeV fm^5 \end{array}}$$

$$\boxed{\begin{array}{r} G_S = 140.9 MeV fm^5, G_V = 15.4 MeV fm^5 \\ G_V = 3.1 MeV fm^5 \end{array}}$$

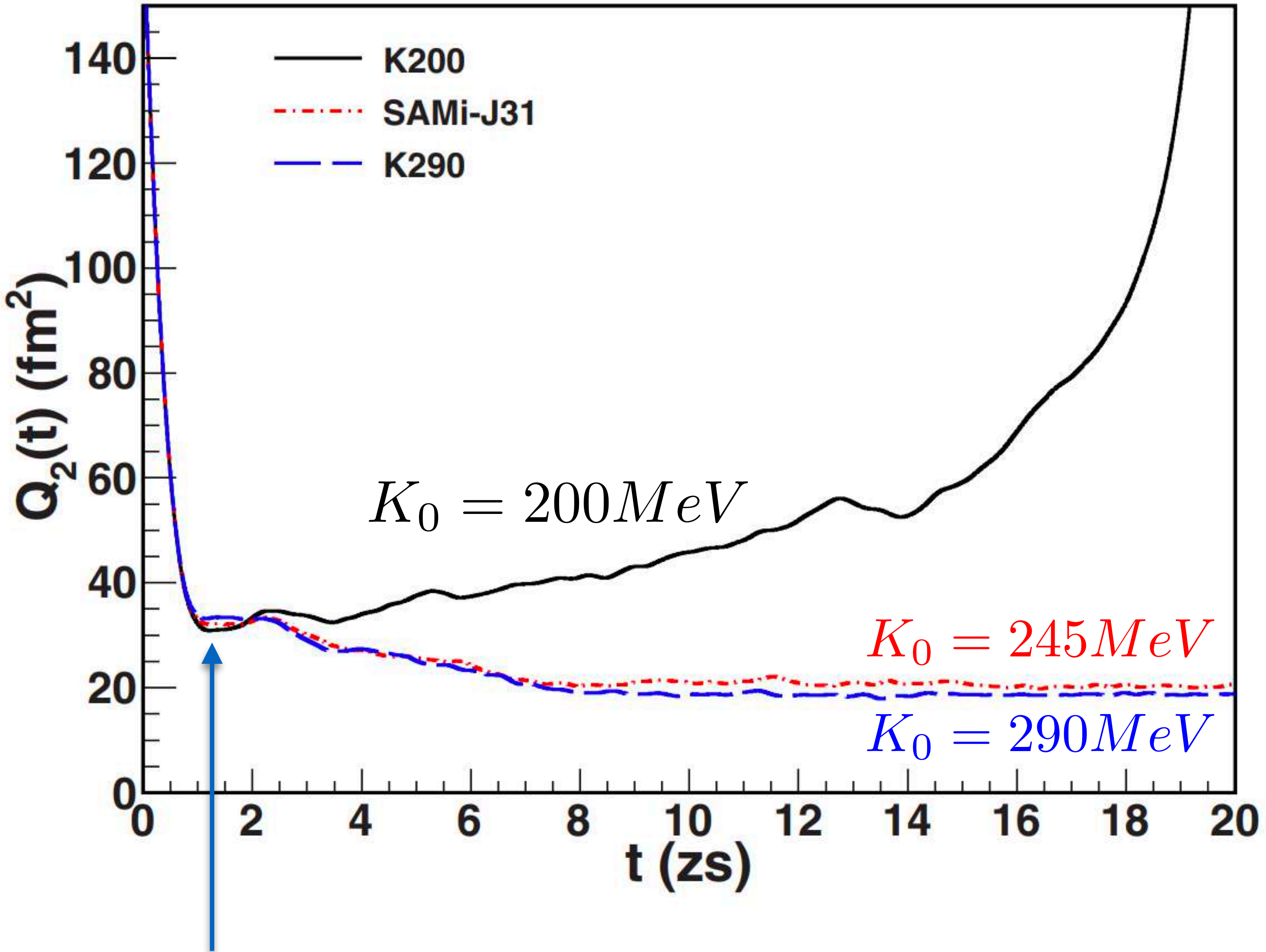
- Isoscalar surface term —> large effect
  (Gs reduced, favor the formation of more elongated configuration)
- Isovector surface term —> tiny effect

H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)

TDHF simulations

Side collisions, b=0 fm

$^{238}U+^{40}Ca$ at $E_{cm}=203MeV$



Incompressibility effects

- Smaller K_0, easier to compress and expand
- Smaller K_0, larger amplitude density oscillations, helps the system to fission

At the compression stage, the smaller K_0 corresponds to the smaller quadrupole moment

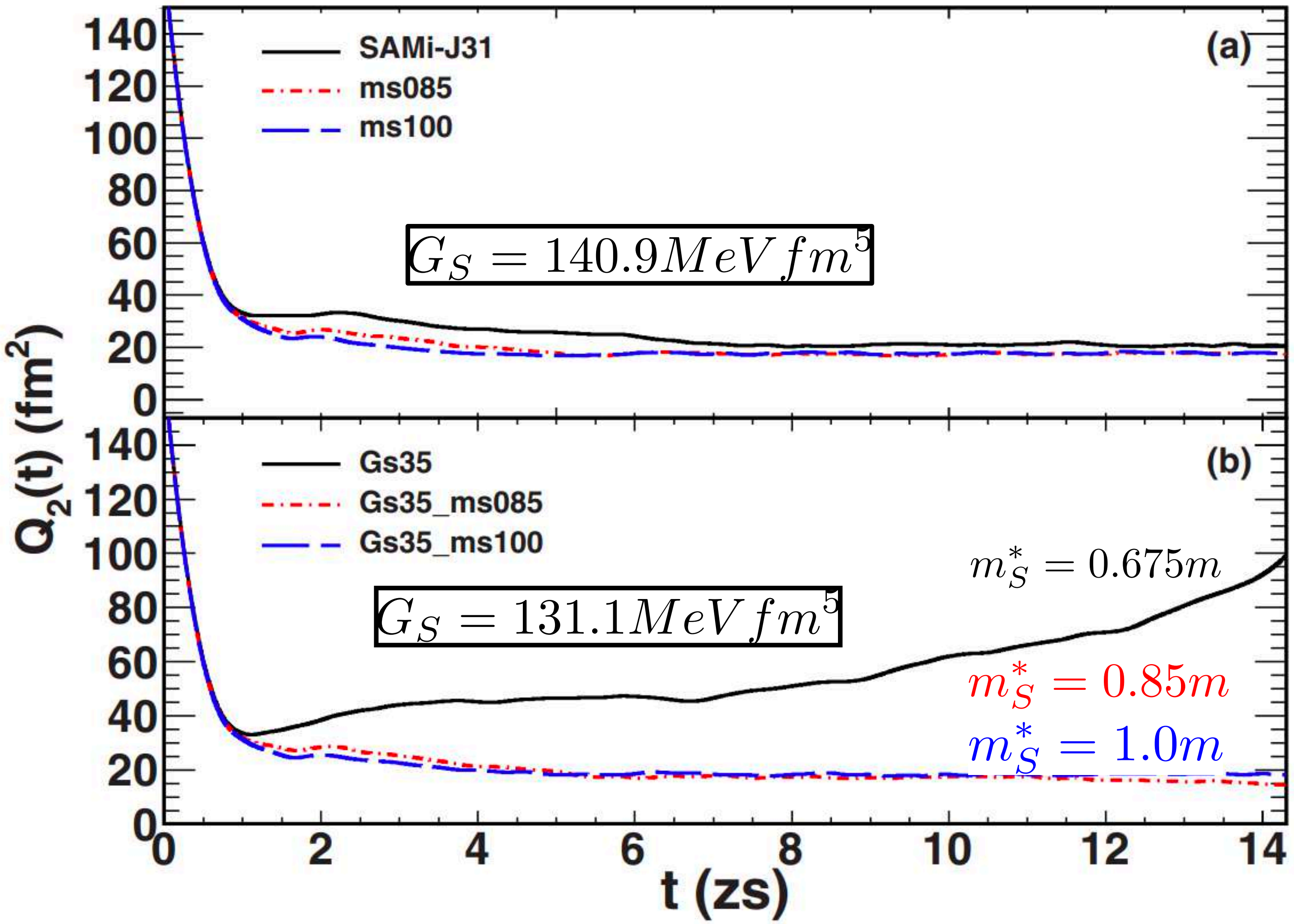
H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)

TDHF simulations

Side collisions, b=0 fm

$^{238}U + ^{40}Ca \text{ at } E_{cm} = 203 MeV$

Isoscalar effective mass



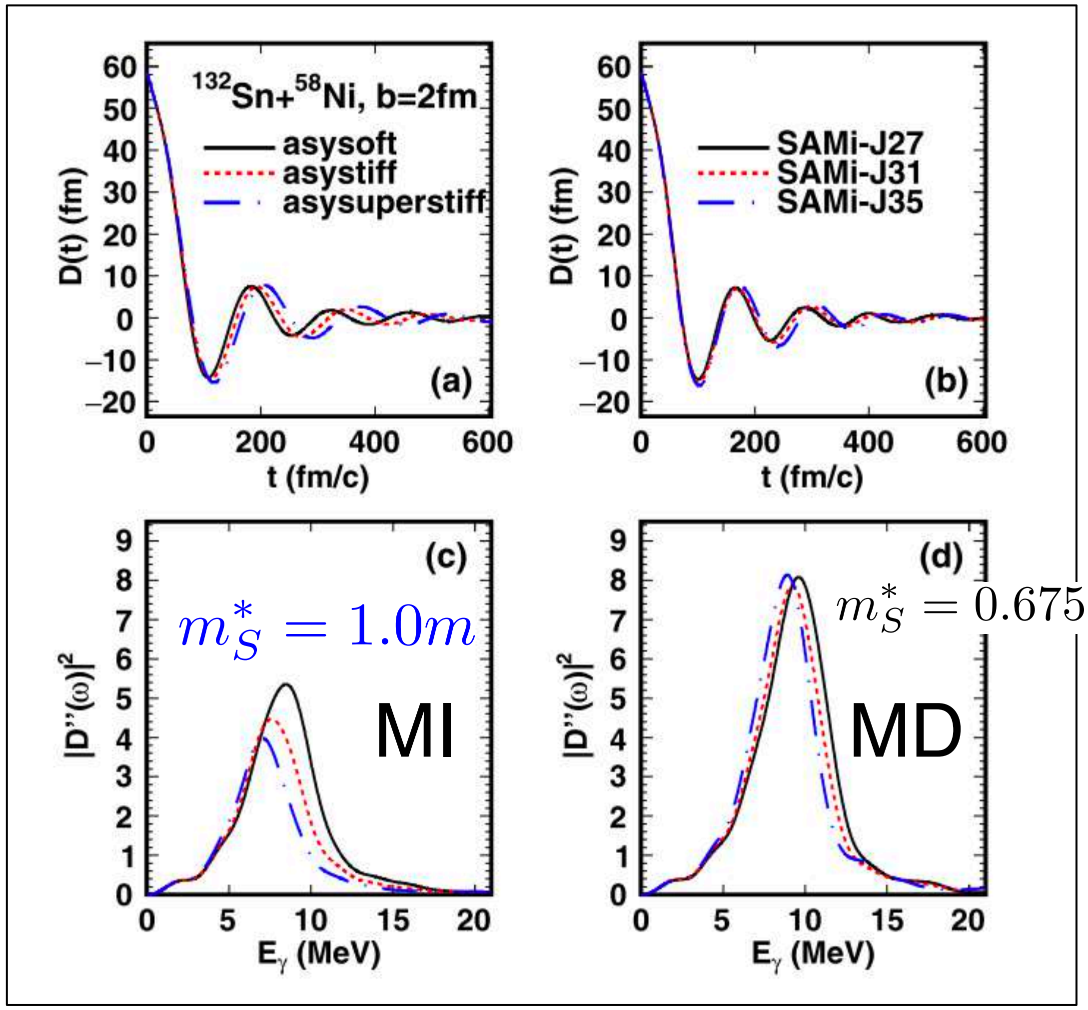
$G_S = 140.9 MeV fm^5$

$G_S = 131.1 MeV fm^5$

$m^*_S = 0.675m$

$m^*_S = 0.85m$

$m^*_S = 1.0m$



$m^*_S = 1.0m$

MI

$m^*_S = 0.675m$

MD

- With increased effective mass, jump from quasi-fission to fusion

H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)
H.Zheng, S.Burrello, M.Colonna, V.Baran, PLB 769, 424 (2017)

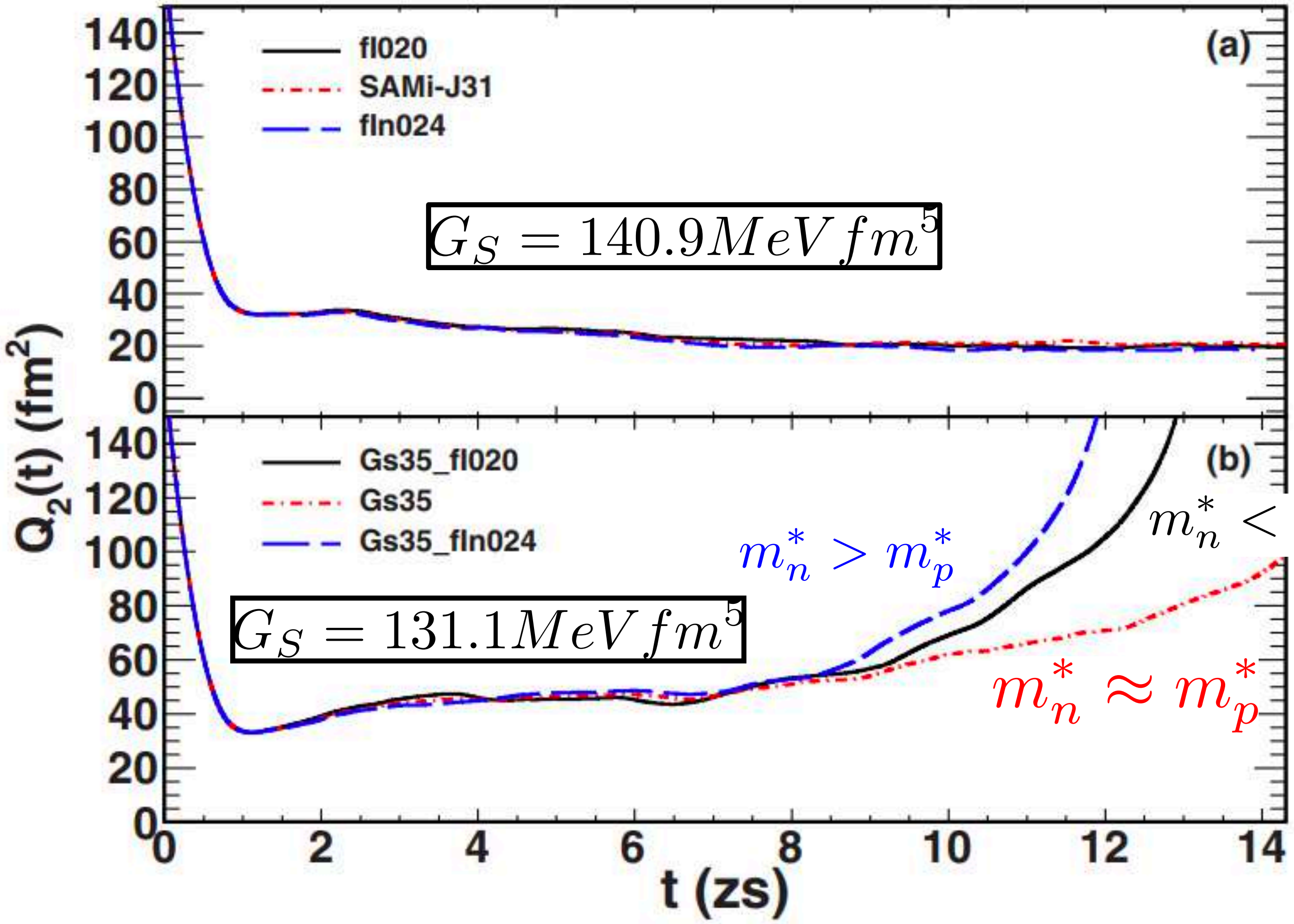
TDHF simulations

Side collisions, b=0 fm

$^{238}U + ^{40}Ca \text{ at } E_{cm} = 203 MeV$

Isovector effective mass

$$f_I = \frac{m}{m_s^*} - \frac{m}{m_v^*}$$



$G_S = 140.9 MeV fm^5$

$G_S = 131.1 MeV fm^5$

$m_n^* > m_p^*$

$m_n^* < m_p^*$

$m_n^* \approx m_p^*$

With increased effective mass splitting faster quasi-fission

- For fI>0, leads to larger neutron repulsion, in addition to symmetry energy
- For fI<0, tends to counterbalance symmetry energy effects but enhance the Coulomb repulsion

H.Zheng, S.Burrello, M.Colonna, D.Lacroix and G.Scamps, PRC 98, 024622 (2018)
Y.X. Zhang, M.B. Tsang and Z.X. Li, PLB 749, 262 (2015)

Conclusions

- Dissipative reactions at low energies open the opportunity to learn about fundamental properties of the nuclear effective interaction of interest also in the astrophysical context

- Competition between fusion and quasi-fission
  In ^{40}Ca + ^{238}U reactions at energies close to the Coulomb barrier an important sensitivity is observed to nuclear EoS properties:
  surface - incompressibility – effective mass – symmetry energy

Thank you
for
your attention