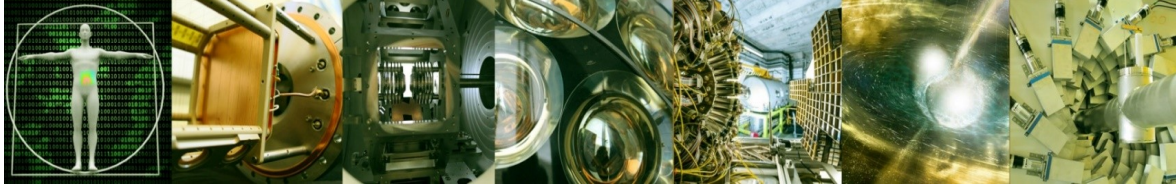

From transport properties to the nuclear equation of state

An experimental survey in the Fermi energy domain

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Laboratoire de Physique Corpusculaire de Caen
Normandie Université , ENSICAEN, CNRS/IN2P3

Outlines

1. From the use of low energy nuclear reactions (dissipative)

2. The nuclear equation of state
   - Phase transitions
   - Empirical parameters
   - Evaluations & uncertainties

3. Panorama of nuclear reactions from B_{coul} up to 100 MeV/nucleon
   - Basic considerations
   - Reaction mechanisms
   - Toward the production of exotic nuclei

4. Path to equilibrium : transport properties in nuclear medium
   - Energy dissipation
   - Isospin transport

5. Improving our knowledge for EOS

6. Experimental tools and some related instrumentation

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Motivations

Why using nuclear reactions @ low energy ?

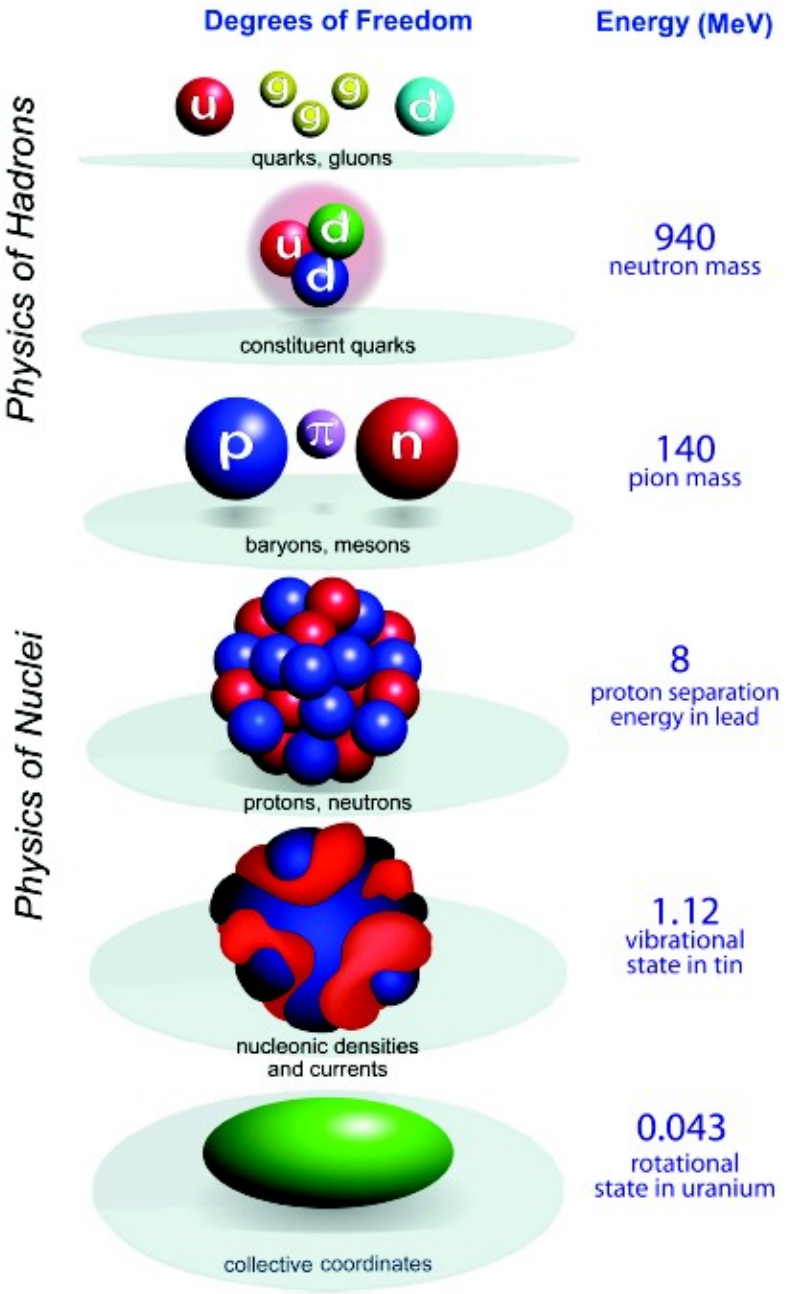
Energy scales in the subatomic world

Depending on scale/energy, systems are described by different **degrees of freedom** and are associated to **different (quasi-)particles**

De Broglie equation (spatial resolution) :

$$\lambda\!\!\!^{-} = \hbar / p$$

E_{inc} (MeV)	$\lambda\!\!\!^{-}$ (fm)
1	8
10	1.5
100	0.5



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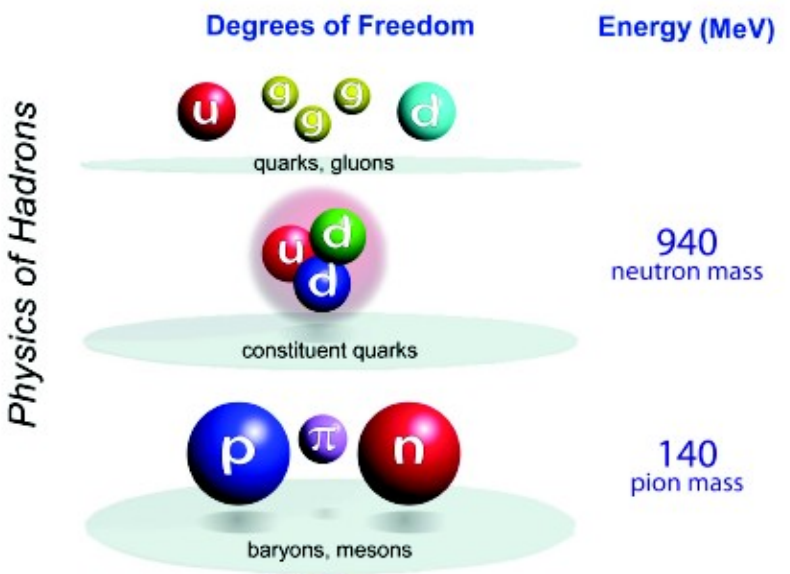
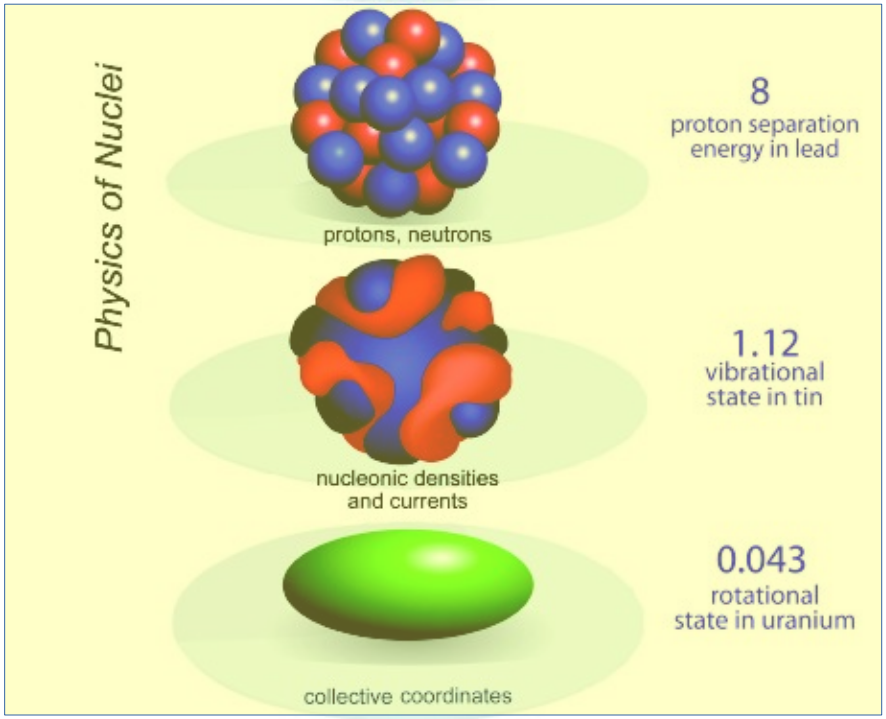
Energy scales in the subatomic world

Depending on scale/energy, systems are described by different **degrees of freedom** and are associated to **different phenomena**



Nuclear physics at low E = nuclear degrees of freedom

- nucleus
- collective phenomena
- excited states
- bulk and surface properties in continuum states

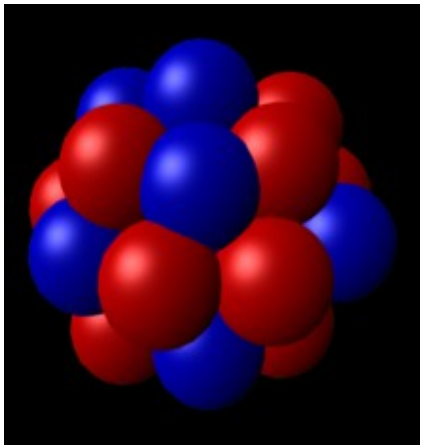


Nuclear reactions
E_{inc} = 5 – 100 MeV/nucleon

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

From nuclei to compact stars

nucleus



Supernova / neutron star

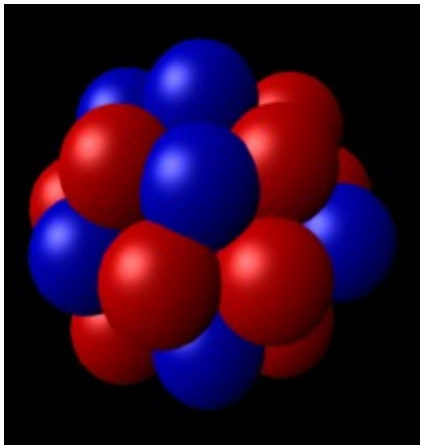
Nucleosynthesis above iron element

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

From nuclei to compact stars

Under pressure !

nucleus



Supernova / neutron star

Nucleosynthesis above iron element

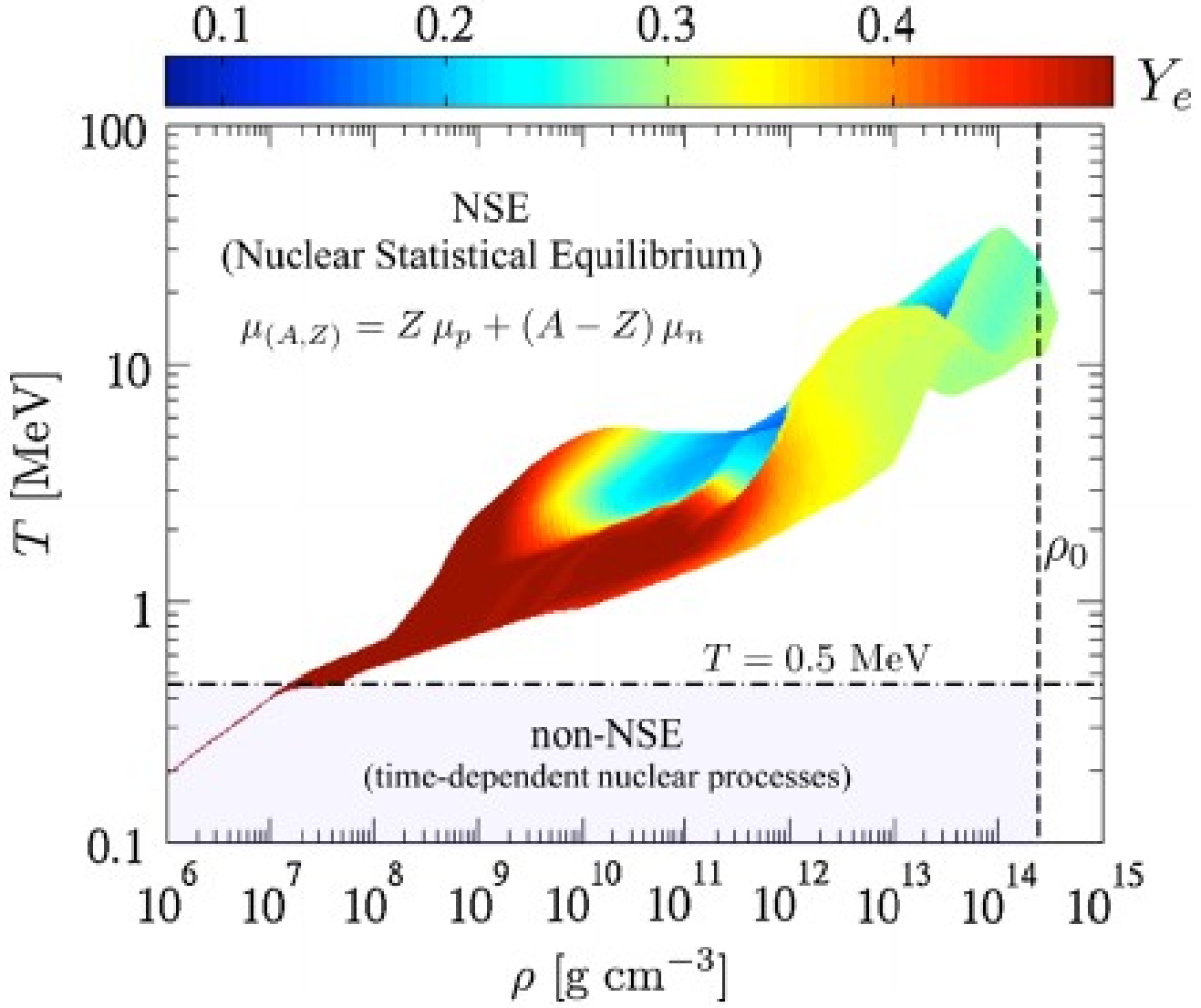
Core Collapse of Supernova : x 10,000,000,000 Sun luminosity ...

NS is governed by the nuclear Equation of State $E(\rho,T,\delta)$

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Domain in the plane (ρ,T)

Temperatures and densities reached during a CCSN simulation within 1s post-bounce



M. Oertel *et al.*, Rev. Mod. Phys. 89, Vol. 1 (2017)

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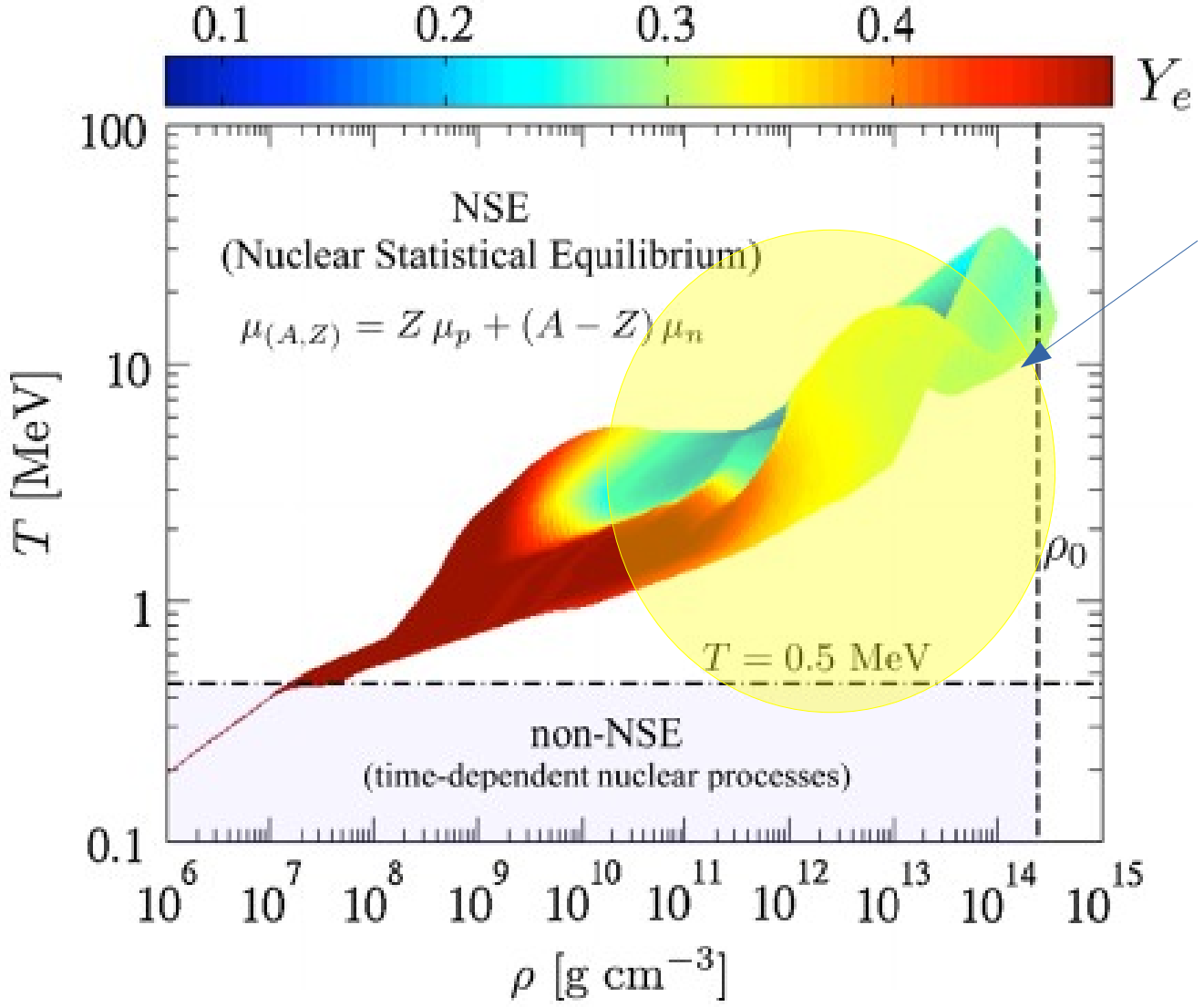


Nuclear reactions

M. Oertel *et al.*, Rev. Mod. Phys. 89, Vol. 1 (2017)

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

(Some of the) Key questions in LE Nuclear Physics

How can we build the atomic nucleus starting from **QCD first principles** and the strong interaction?

Effective interactions and ab-initio models

Nucleus as a **many-body quantum system** : how can we explain and predict the **observed regularities** : magic numbers, collective excitations (GR), deformation, pairing, …?

(No core) shell model and approaches beyond the Mean-Field

How can we describe nuclear matter at very different scales as in nuclei (microscopic) and in compact stars and binary NS mergers (macroscopic)?

Equation of State of nuclear matter / phase transitions

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

The nuclear Equation of state

Equation of State of nuclear mattter

$$E\ (or\ P) = f(\ \rho\ ,\ T\ ,\delta\ )$$

Thermodynamical relation between state variables

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

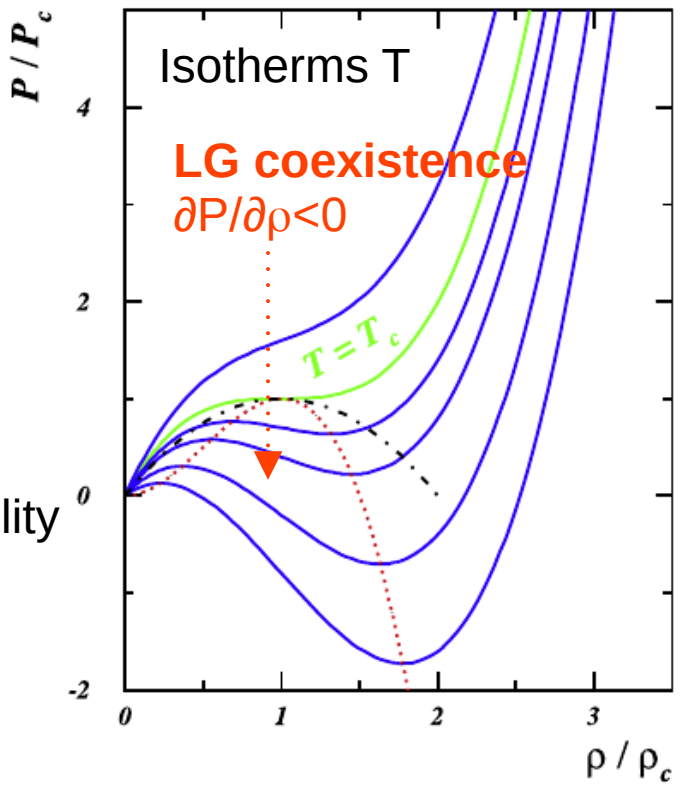
Equation of State of nuclear mattter

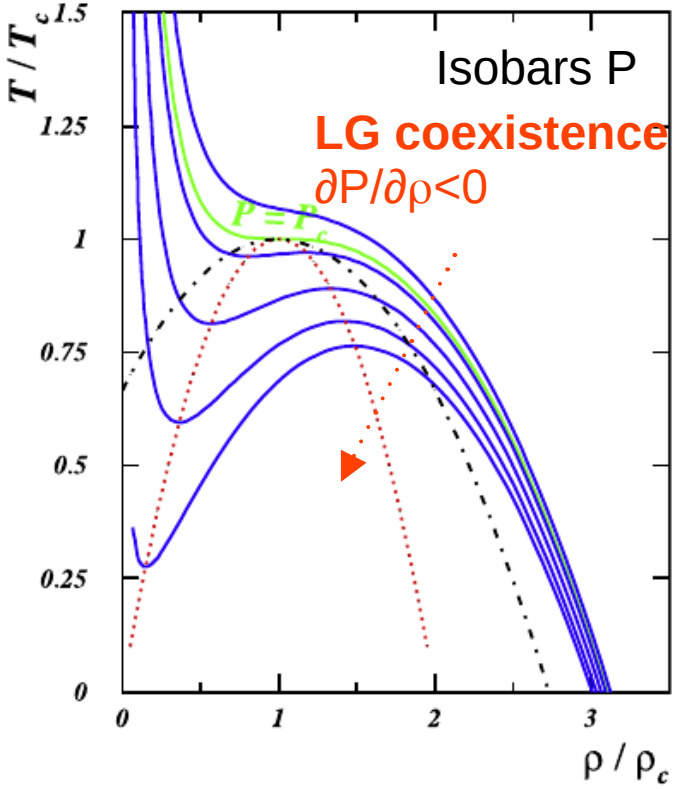
$$E \text{ (or } P) = f(\rho, T, \delta)$$

Thermodynamical relation between state variables

Compressibility

$\partial P/\partial \rho$





Skyrme HF at finite T

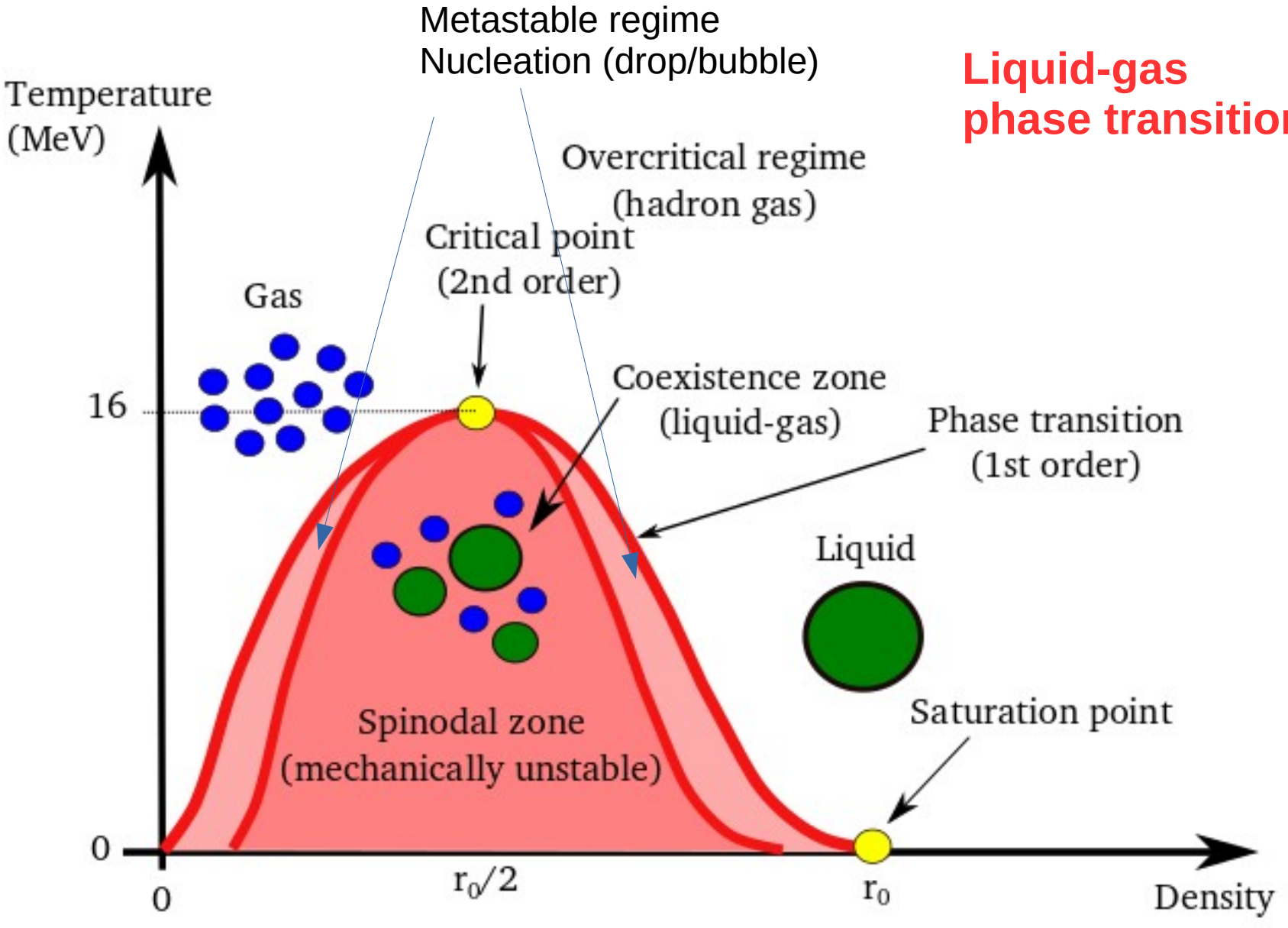
B. Borderie, J. Phys. G: Nucl. Part. Phys. 28 (2002) R217

Pressure : $P(\rho) = \rho^2 (\partial E/\partial \rho)_\rho$

P_c, T_c, ρ_c : **critical point** of the liquid-gas phase transition with T_c = *16-18 MeV*, ρ_c=*0.3-0.5*ρ_{sat}

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Spinodal decomposition : Mean-Field instabilities



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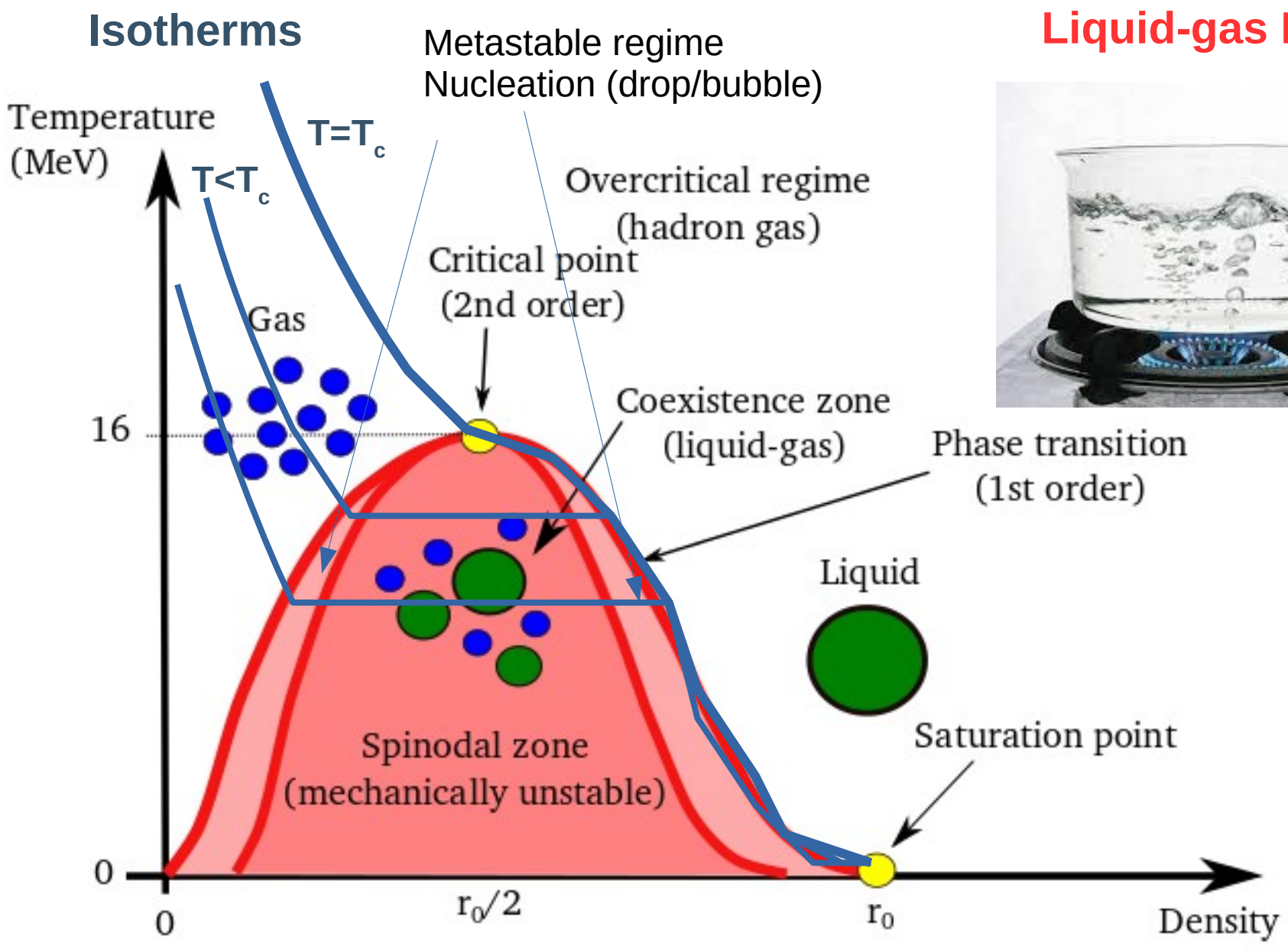

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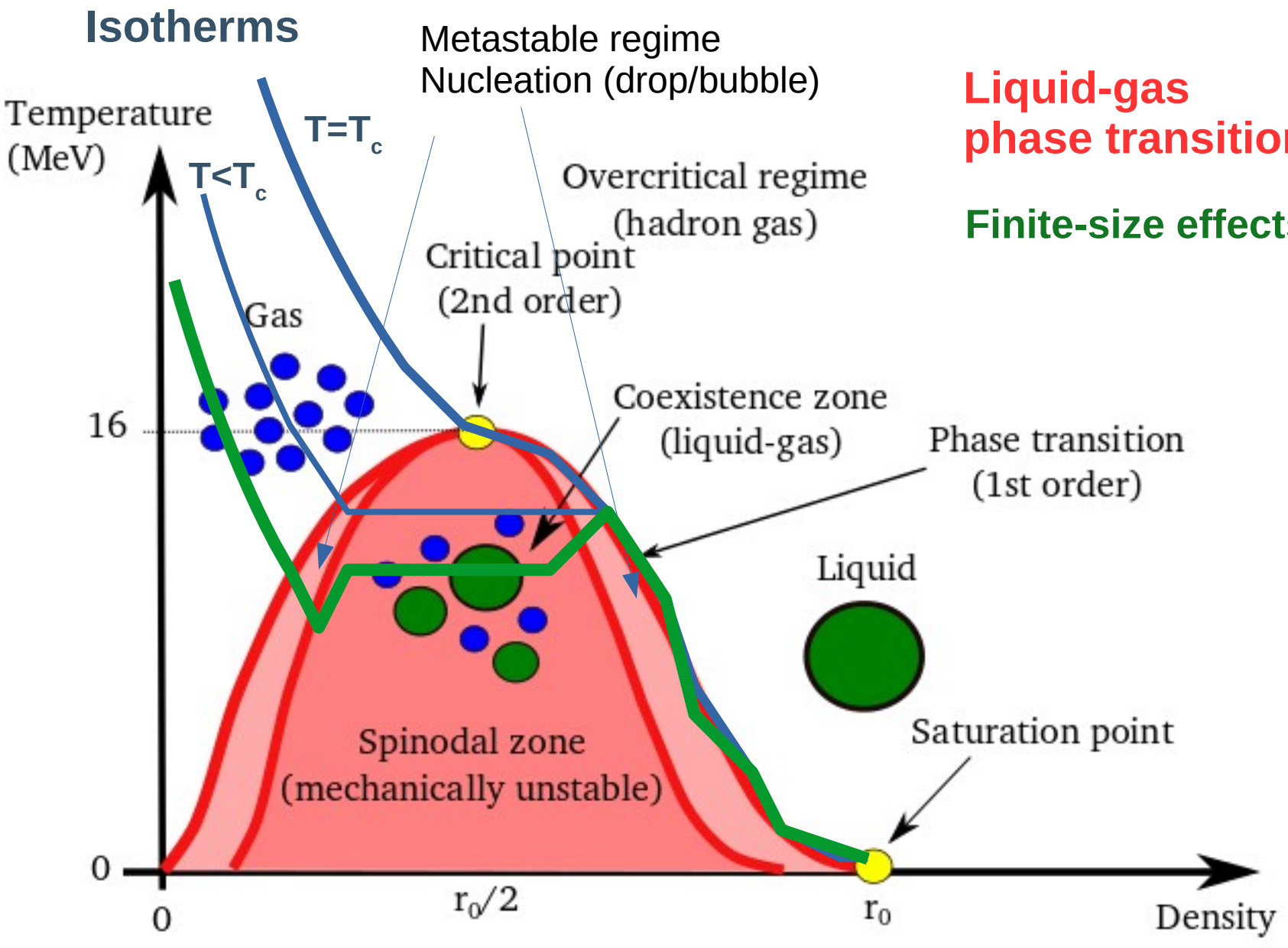
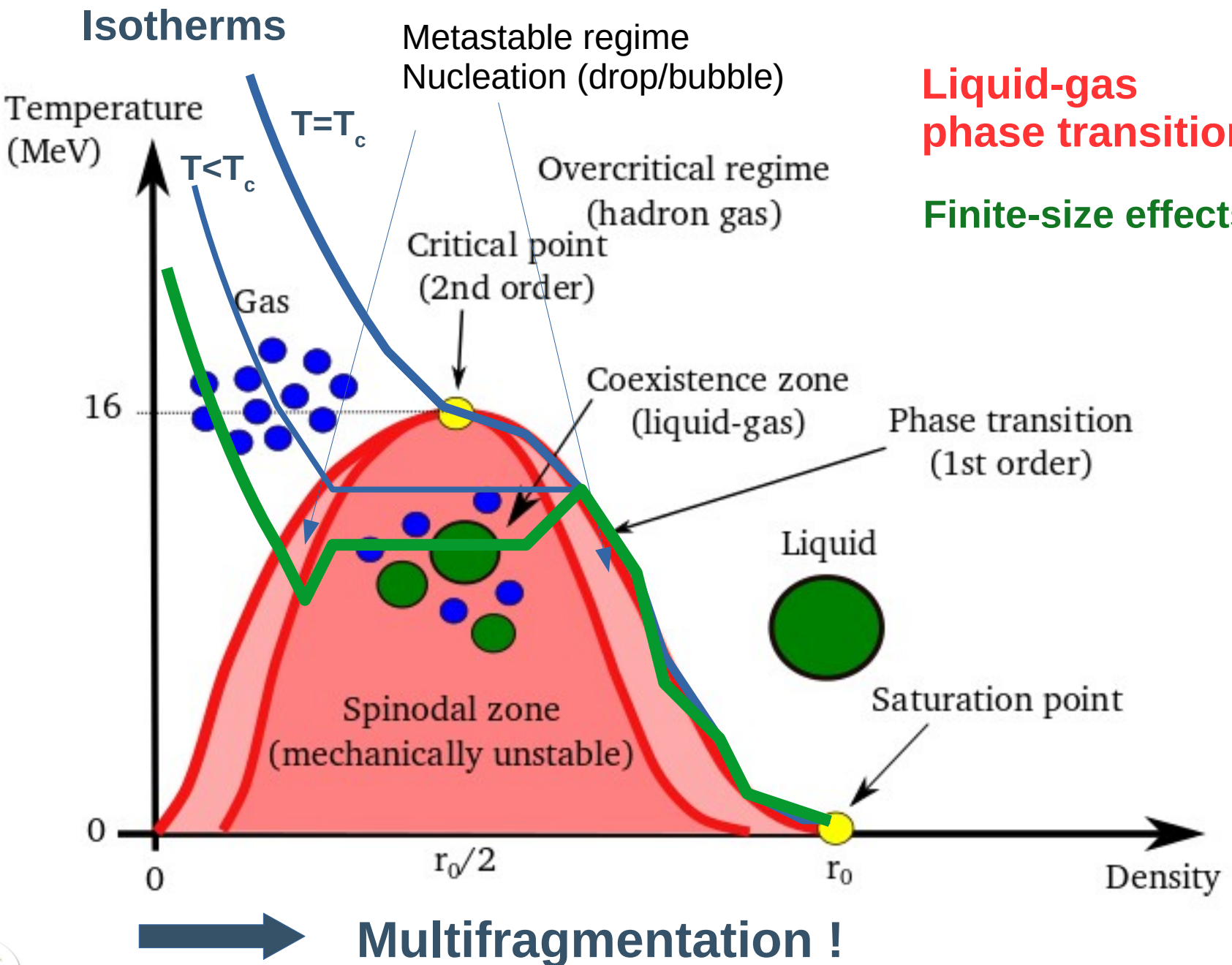


Liquid-gas phase transition

Finite-size effects

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Spinodal decomposition : Mean-Field instabilities



Liquid-gas phase transition

Finite-size effects

Multifragmentation !

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Equation of State in nuclei

$$E = f(\rho, T, \delta)$$

$\delta = (N-Z)/A$

Astrophysical context (NS)

Nuclear matter :
Bulk properties

Extensive systems
(volume,size)

Pure **neutron matter** (δ=1)

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Terrestrial Labs

Nuclei :
Finite-size effects

Non-extensive systems
(surface, Coulomb)

Asymetric NM
($|\delta|$~0-0.4, E_{sym})

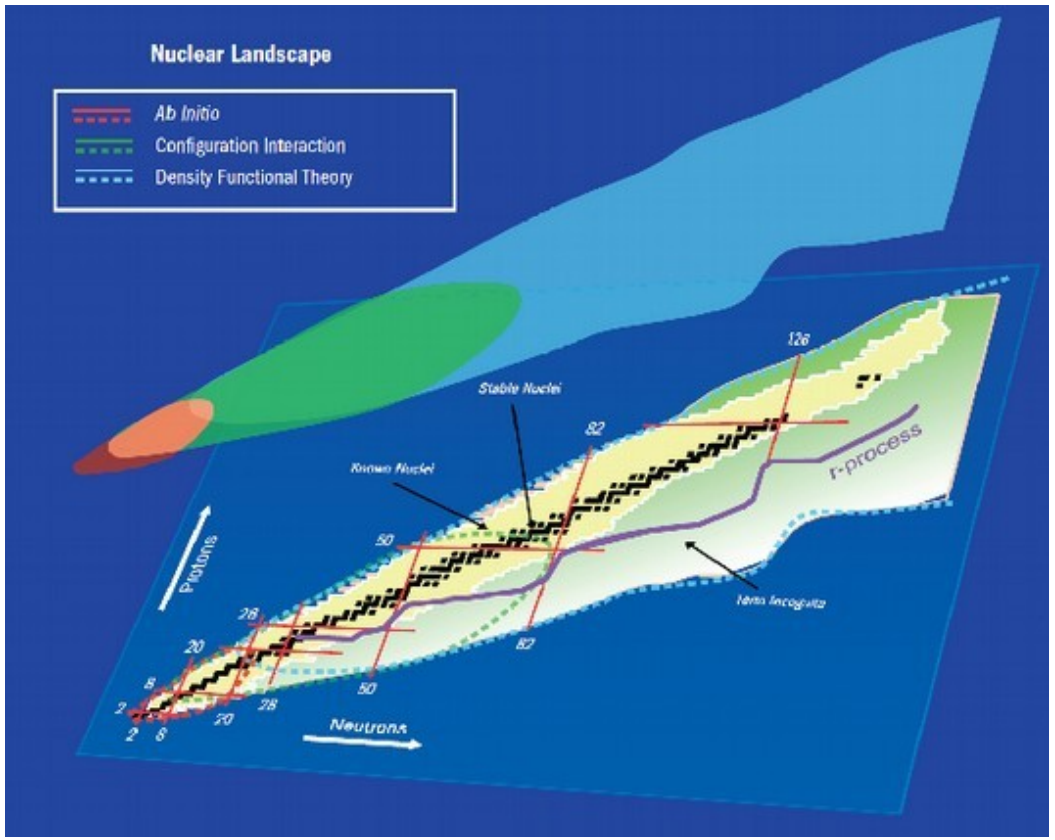
Phase Diagram and **Phase Transitions in finite systems**

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

EoS in Nuclear Physics

Energy-density functionals modelization is probably the best possible framework to understand the properties of medium and heavy nuclei.

Energy-Density Functionals
(HK theorem) : $H_{eff} = E[\rho]$



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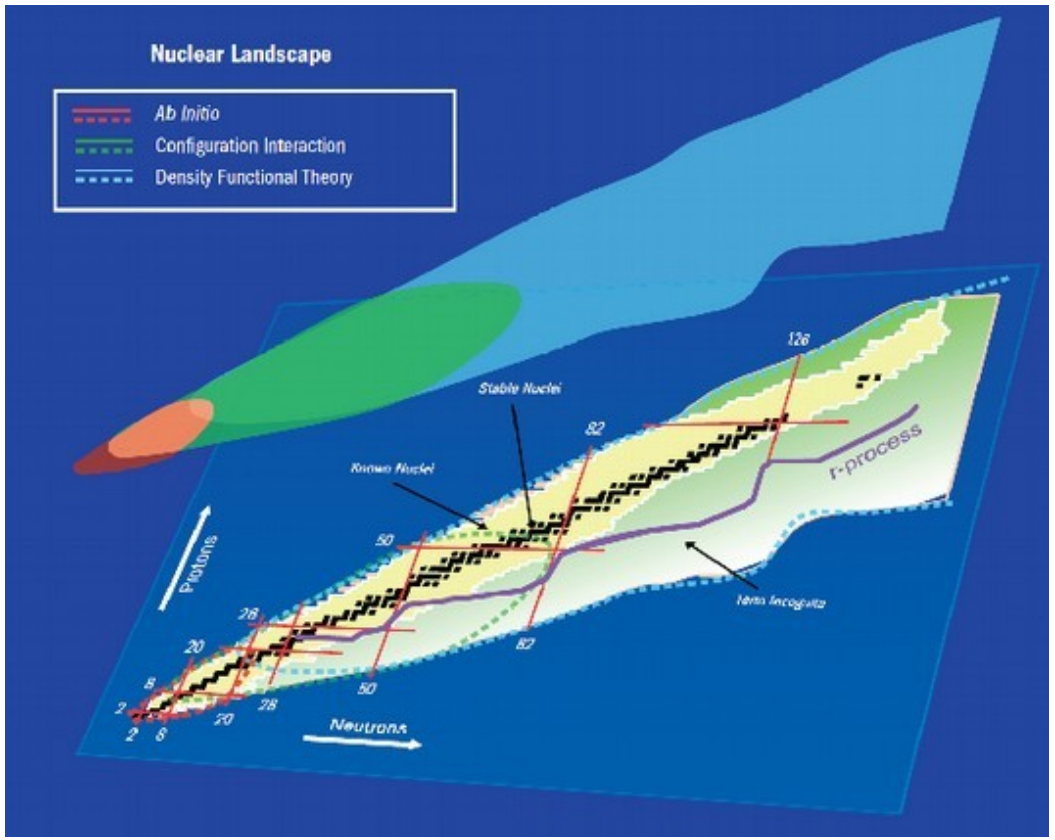

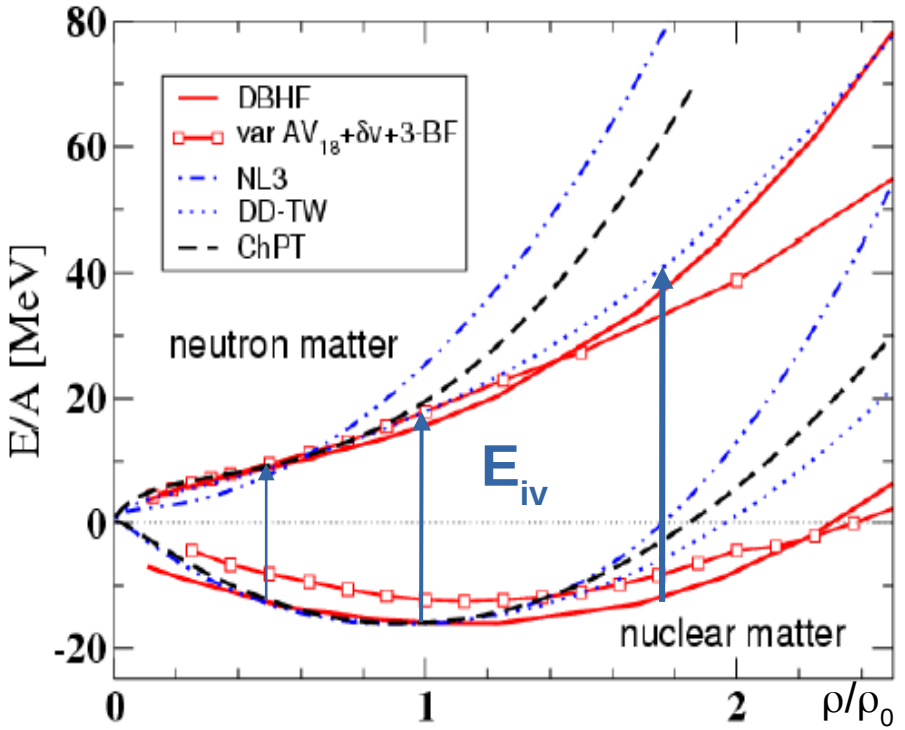

Direct link to *EOS* and Symmetry Energy (isovector term)

E_{iv} **(aka S) = E(ρ,δ=1) – E(ρ,δ=0)**

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

EOS density and isospin dependence

Energy per nucleon in the parabolic (2nd order) approximation is the sum of isoscalar (ρ) and isovector (δ) terms:

Isospin ratio : $\delta=(N-Z)/A$
$\rho_{sat} \approx 0.17$ fm^{-3}

$$E(\rho,\delta) = E_0(\rho) + S(\rho).\delta^2 + O(\delta^4)$$

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Each term (isoscalar and isovector) can be decomposed in **Taylor expansion** (up to the fourth order) in $\chi=(\rho-\rho_0)/3\rho_0$:

$$E_0(\rho) = E_{sat}(\rho_0) + 1/2\ K_0\ \chi^2 + 1/3\ !\ Q_0\ \chi^3 + 1/4\ !\ Z_0\ \chi^4 + O(\delta^5)$$

E_{sat} is the **saturation energy** at $\rho = \rho_0$
K_0 is the **compressibility** (curvature) around ρ_0
Q_0 and Z_0 are the **cubic** and **quartic** terms needed for $\rho >> \rho_0$

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$$S(\rho) = J + L\chi\ + 1/2\ K_{sym}\ \chi^2 + 1/3\ !\ Q_{sym}\ \chi^3 + 1/4\ !\ Z_{sym}\ \chi^4 + O(\chi^5)$$

E_{sat} is the **saturation energy** at $\rho = \rho_{sat}$
K_{sat} is the **compressibility** (curvature) around ρ_{sat}
Q_{sat} and Z_{sat} are the **cubic** and **quartic** terms needed for ρ *far from* ρ_{sat}

J is the **symmetry energy** at $\rho = \rho_{sat}$
L_{sym} is the **slope** (conn. to P) of the symmetry energy around ρ_{sat}
K_{sym} is the **curvature** of the symmetry energy
Q_{sym} and Z_{sym} are the **cubic** and **quartic** terms needed for ρ *far from* ρ_{sat}

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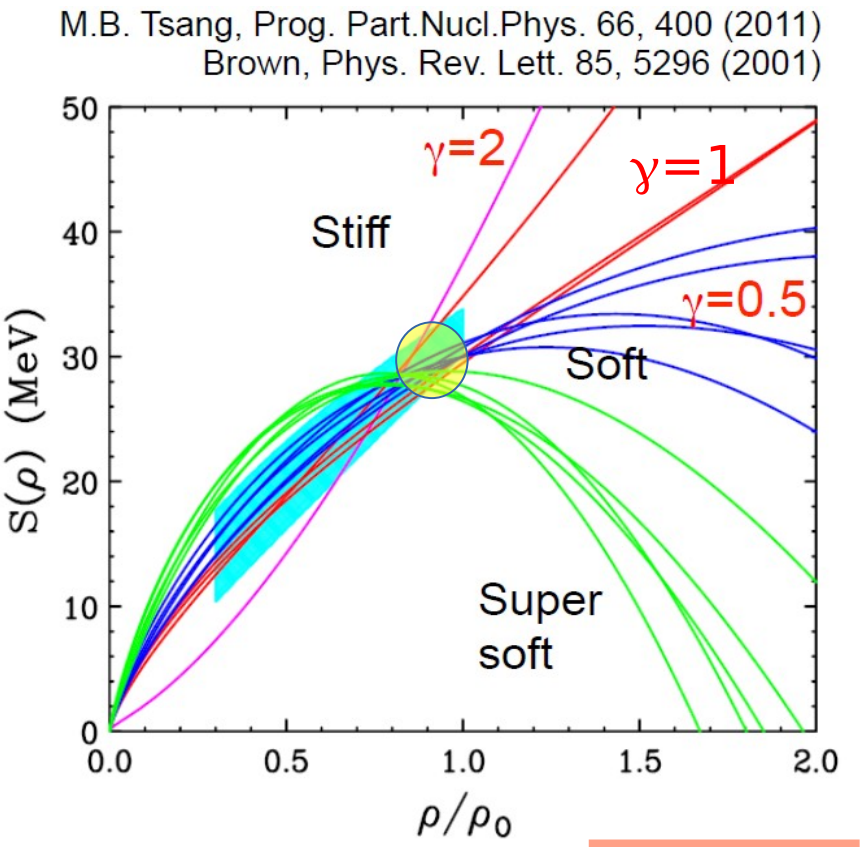
Symmetry Energy and Density Dependence

$$E/A\,(\rho,\delta) = E/A\,(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

- Constraints for **Astrophysics** (NS) and for laboratory experiments
- Needed for **transport models** and nuclear matter studies (Thermodyn.)
- Link to the ***NN* interaction** (isovector) in the nuclear medium



$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

Kinetic (FG) Potential (int.)

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

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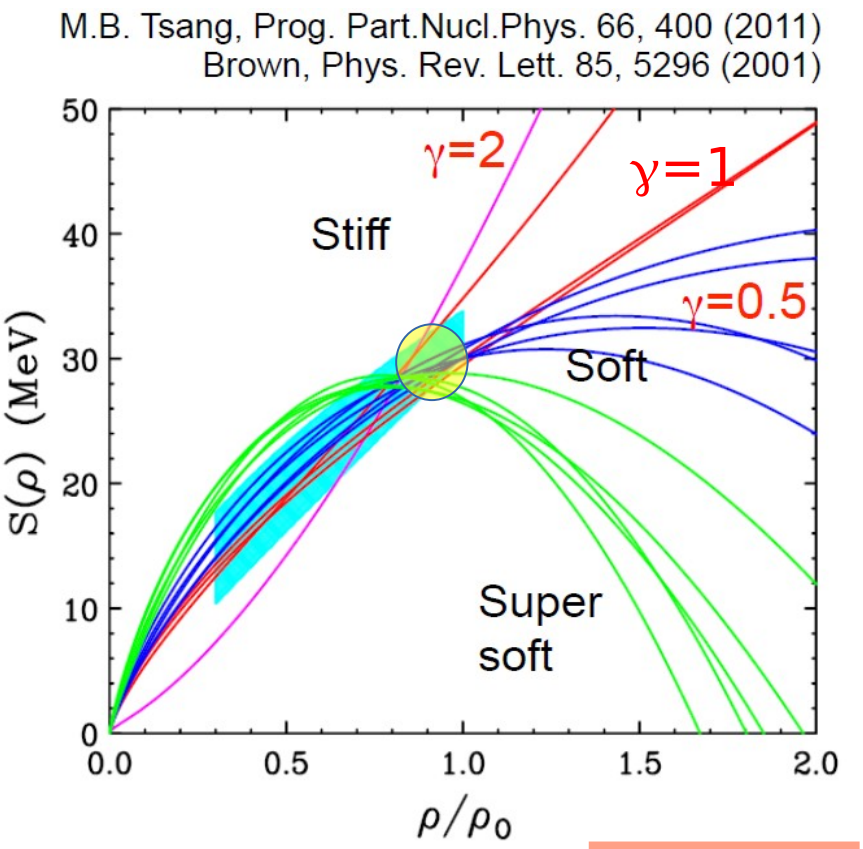
Density dependence of *SE*

Poorly constrained …
Need experimental data !



$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

Kinetic (FG) Potential (int.)

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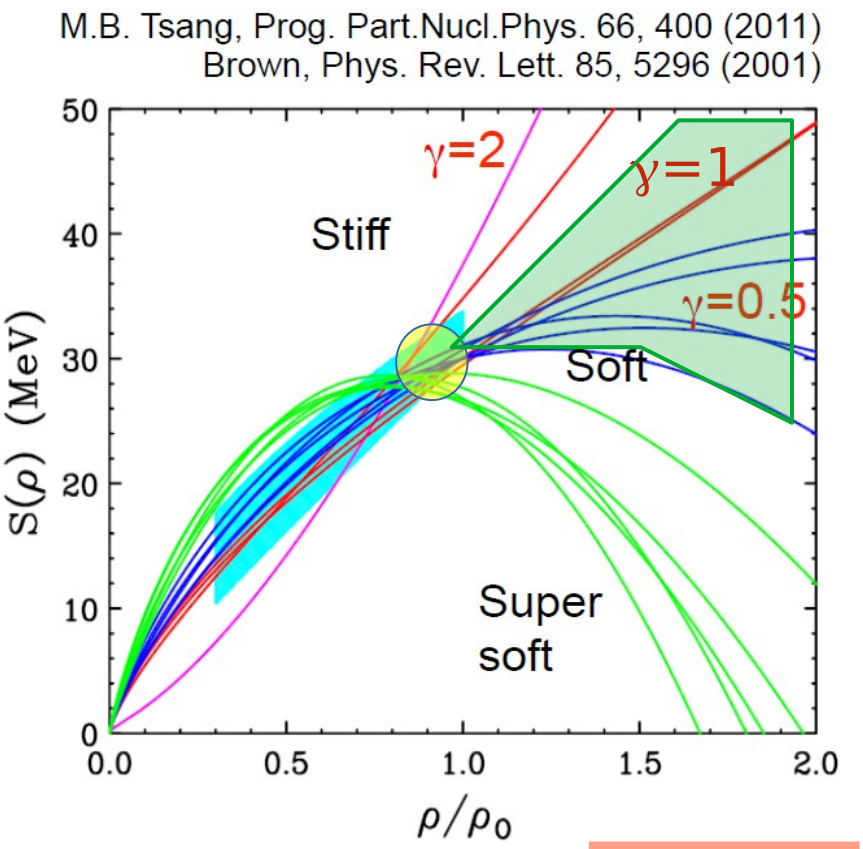

Density dependence of *SE*

$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

Kinetic (FG) Potential (int.)

From Asy-EOS : $\gamma = 0.8 \pm 0.25$

P. Russotto, *et al.*, Phys. Rev. C 94 , 034608 (2016).

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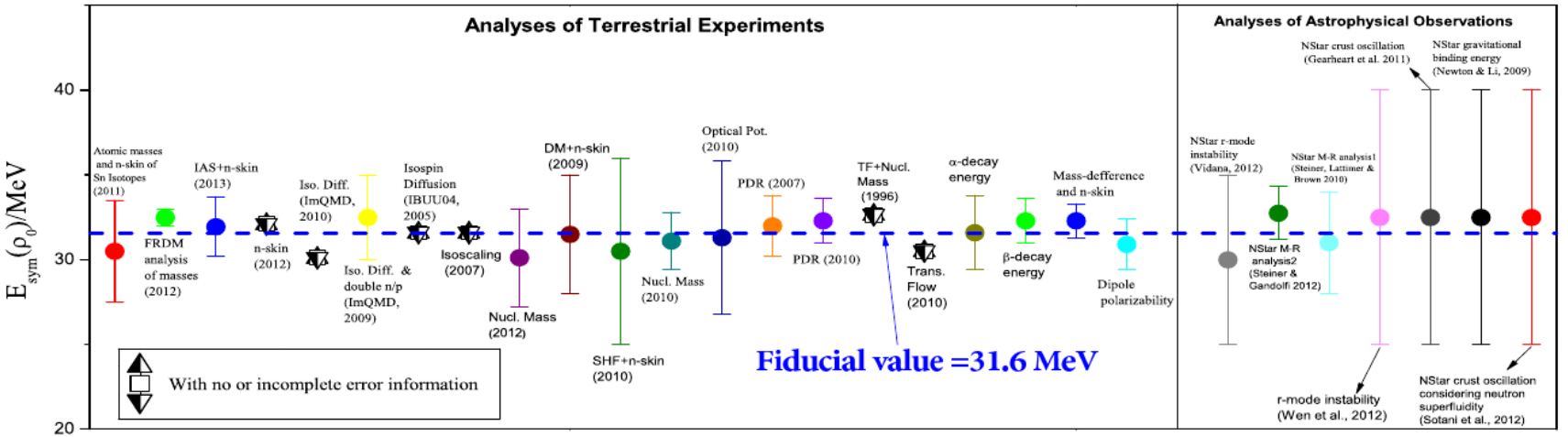
Symmetry Energy around ρ_{sat} (I)

Evaluations for E_{sym}, slope L, curvature K_{sym}, ...

B.A. Li and X. Han, Phys. Lett. B727 (2018) 276



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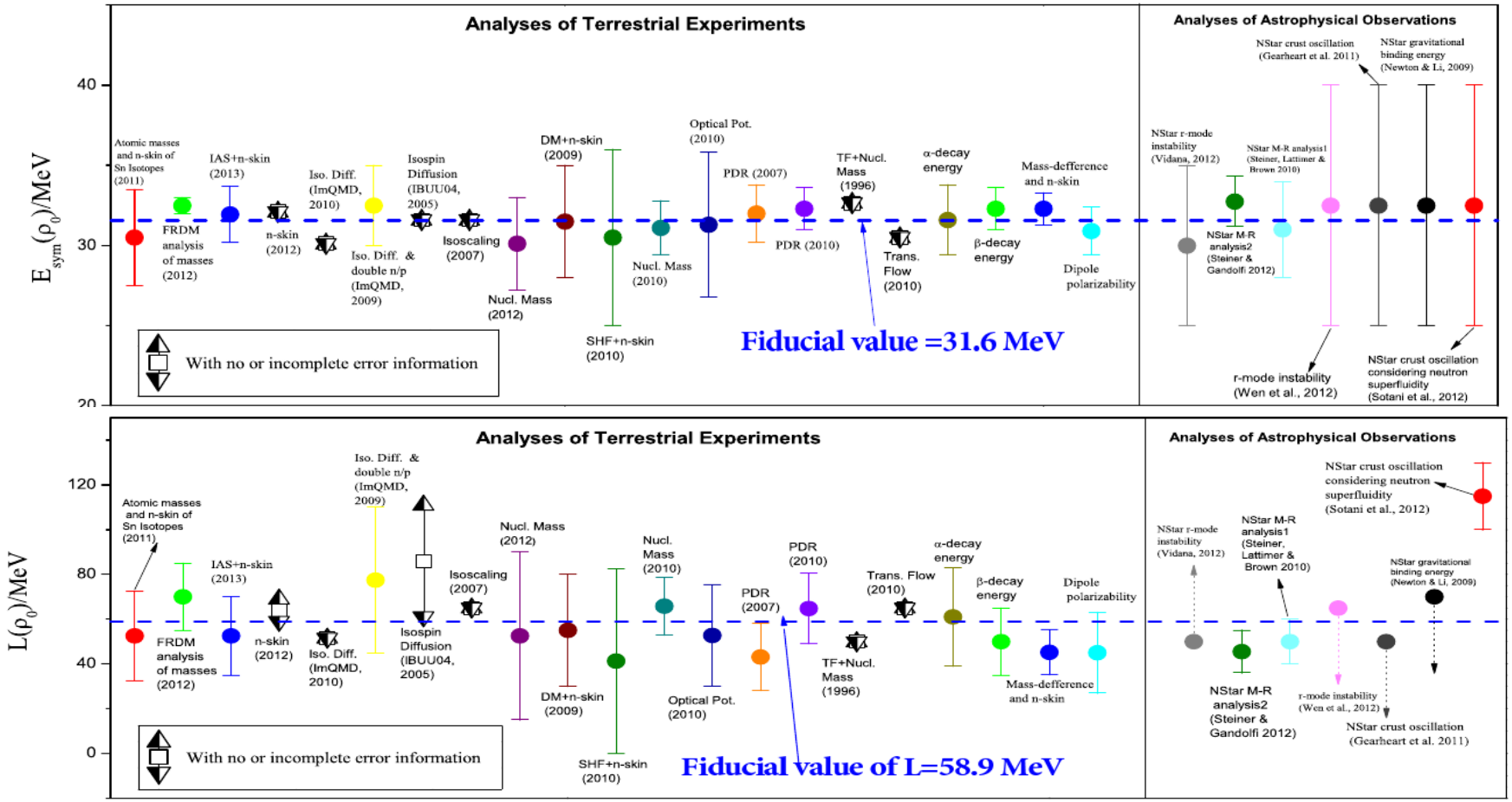

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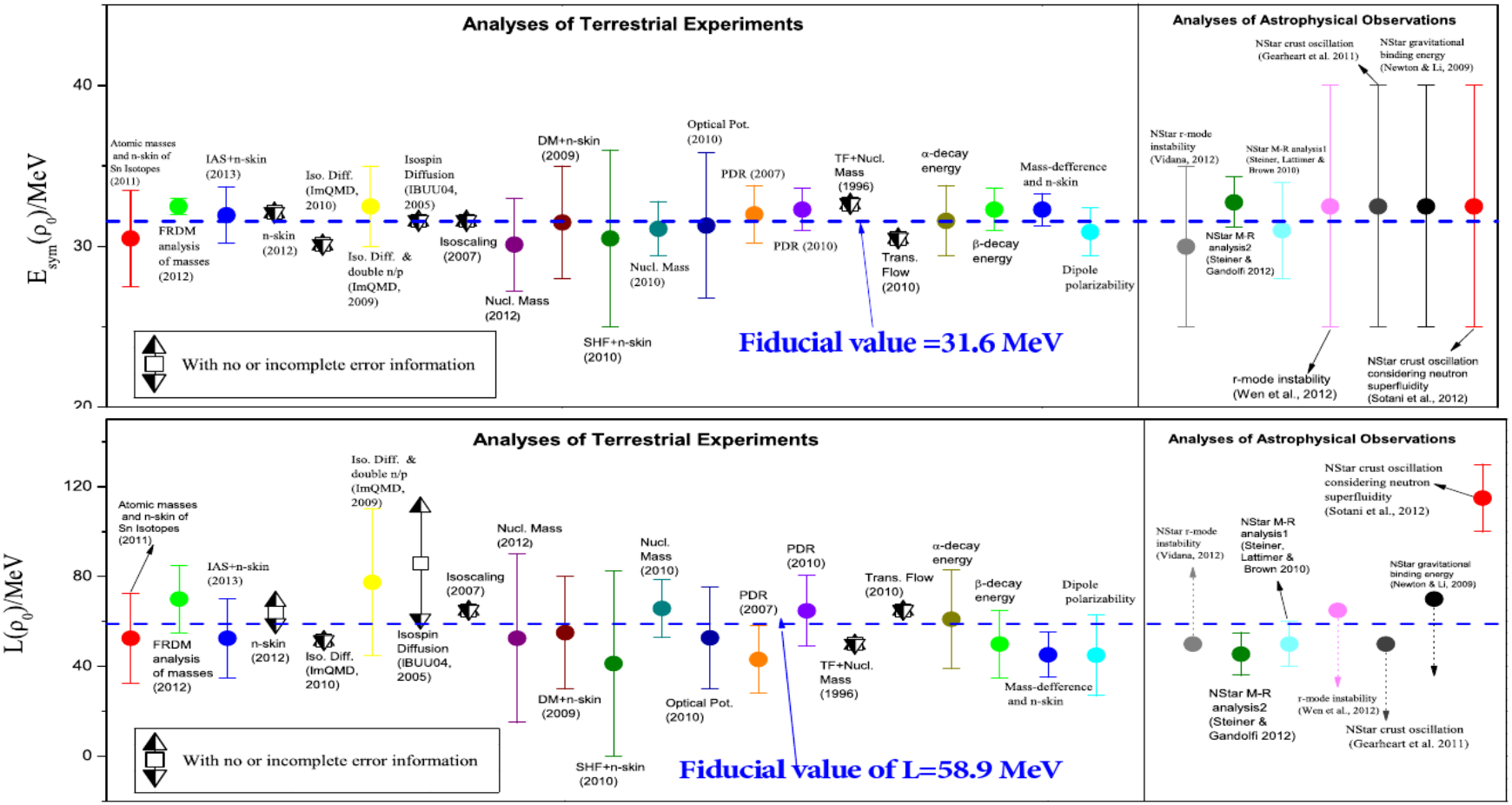

	~1%	~10%		~30%		???				
P_α	E_{sat} MeV	E_{sym} MeV	ρ_0 fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000

J. margueron *et al.*, PRC **97**, 025805 (2018)

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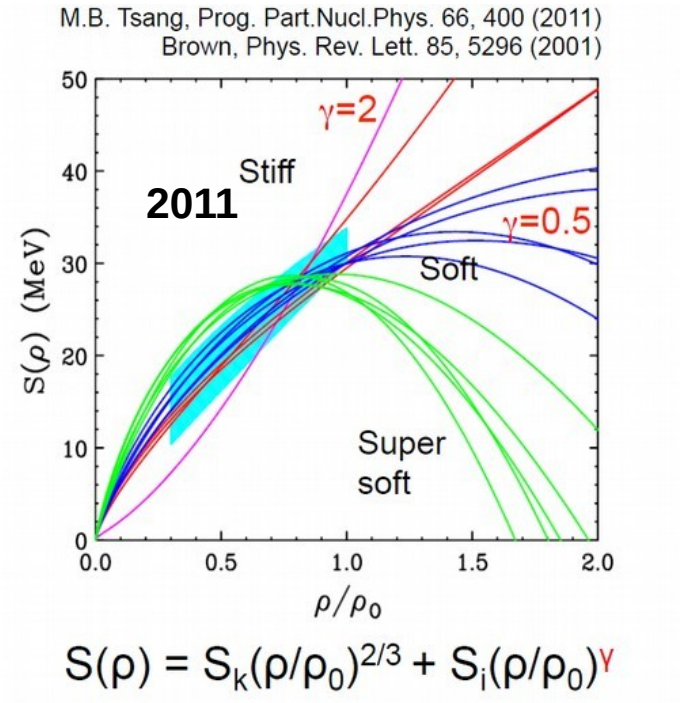
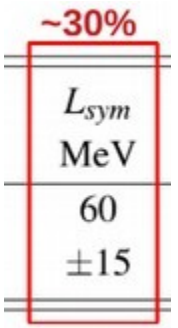
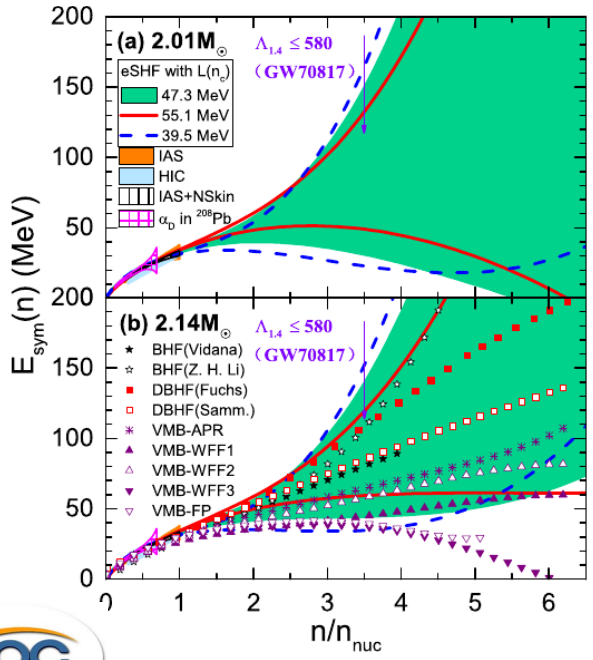
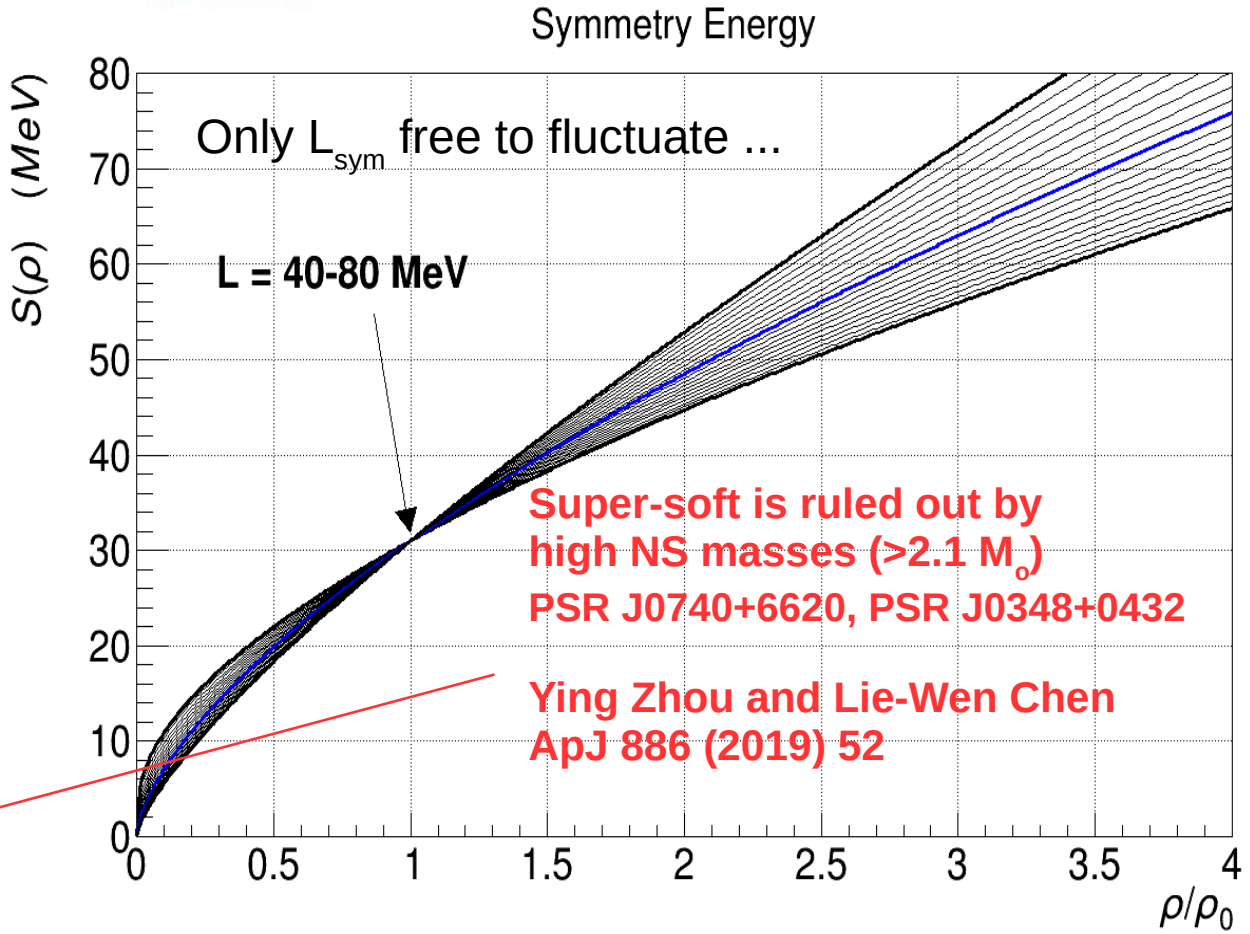
Symmetry Energy around ρ_{sat} (II)





Uncertainties can be reduced but **covariance analysis / Bayesian Inference** is mandatory

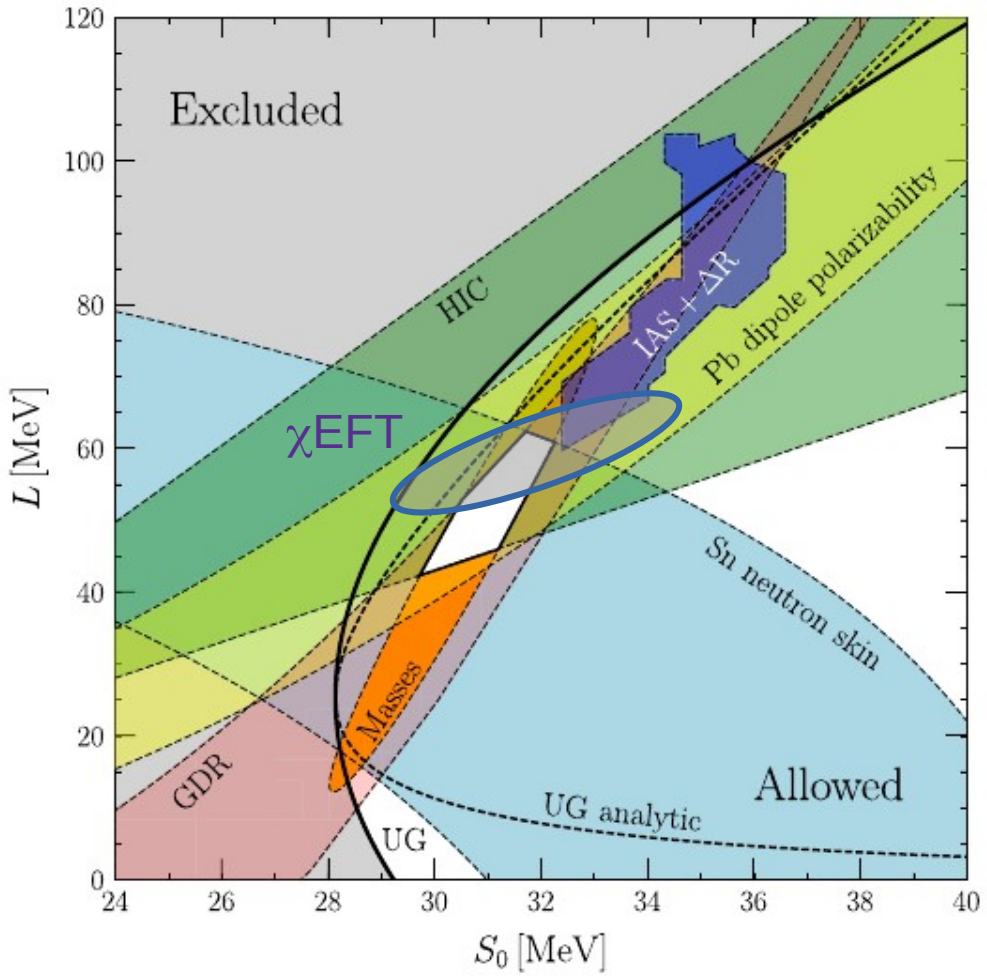




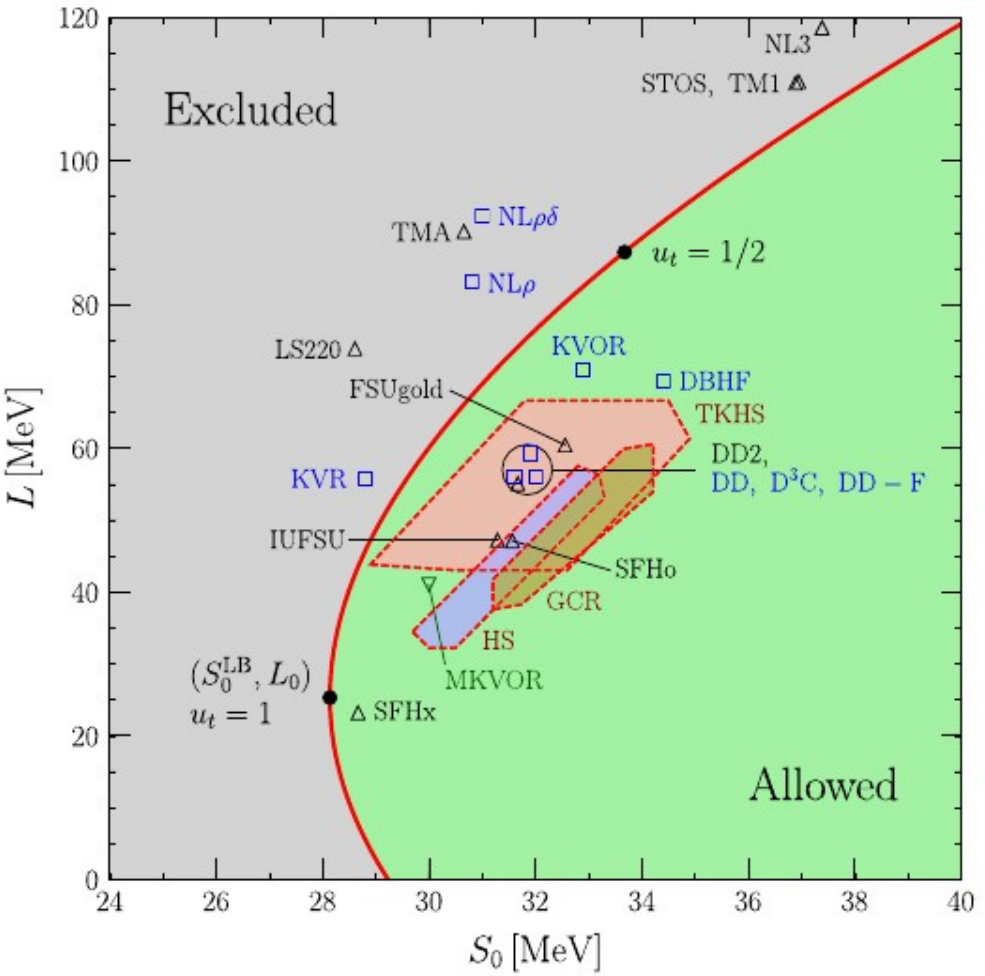
Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Symmetry Energy around ρ_{sat} (III)

Experimental constraints



Model predictions



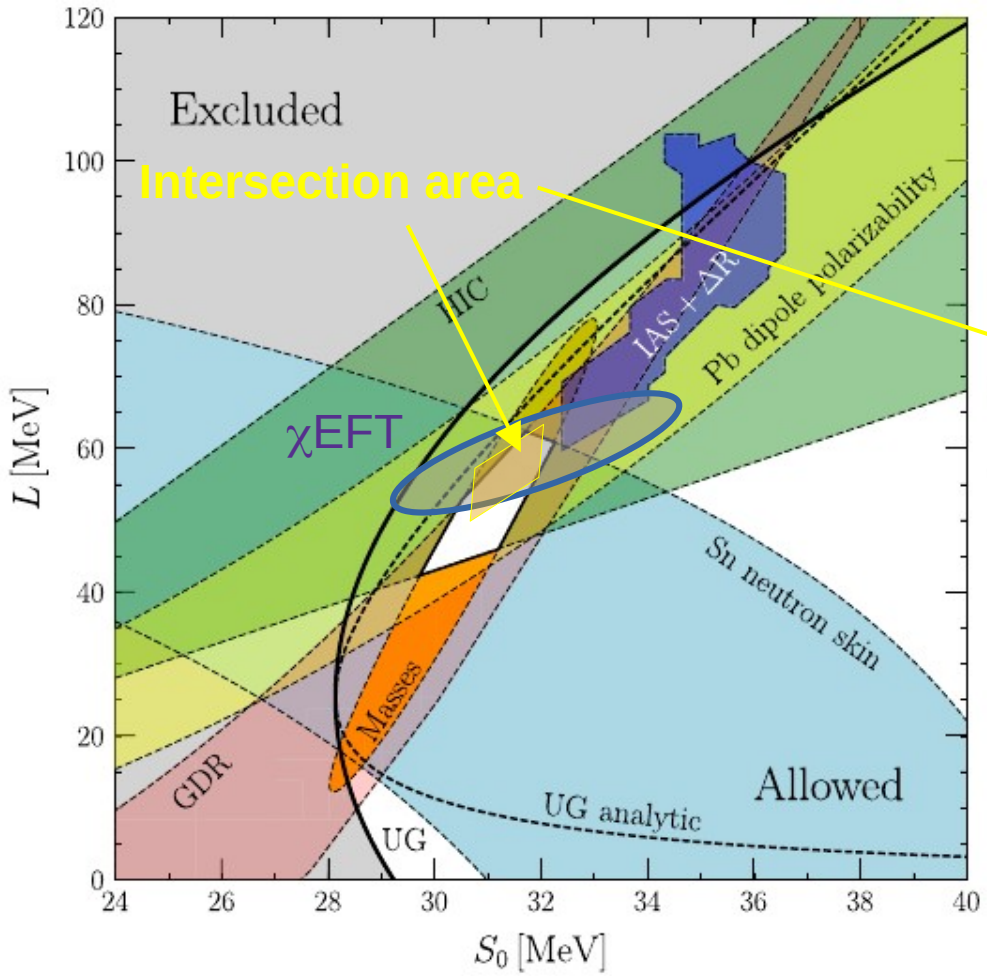
I. Tews *et al.*, Astroph. J. **848** (2017) 105
C. Drischler et al., PRL **125** (2020) 202702

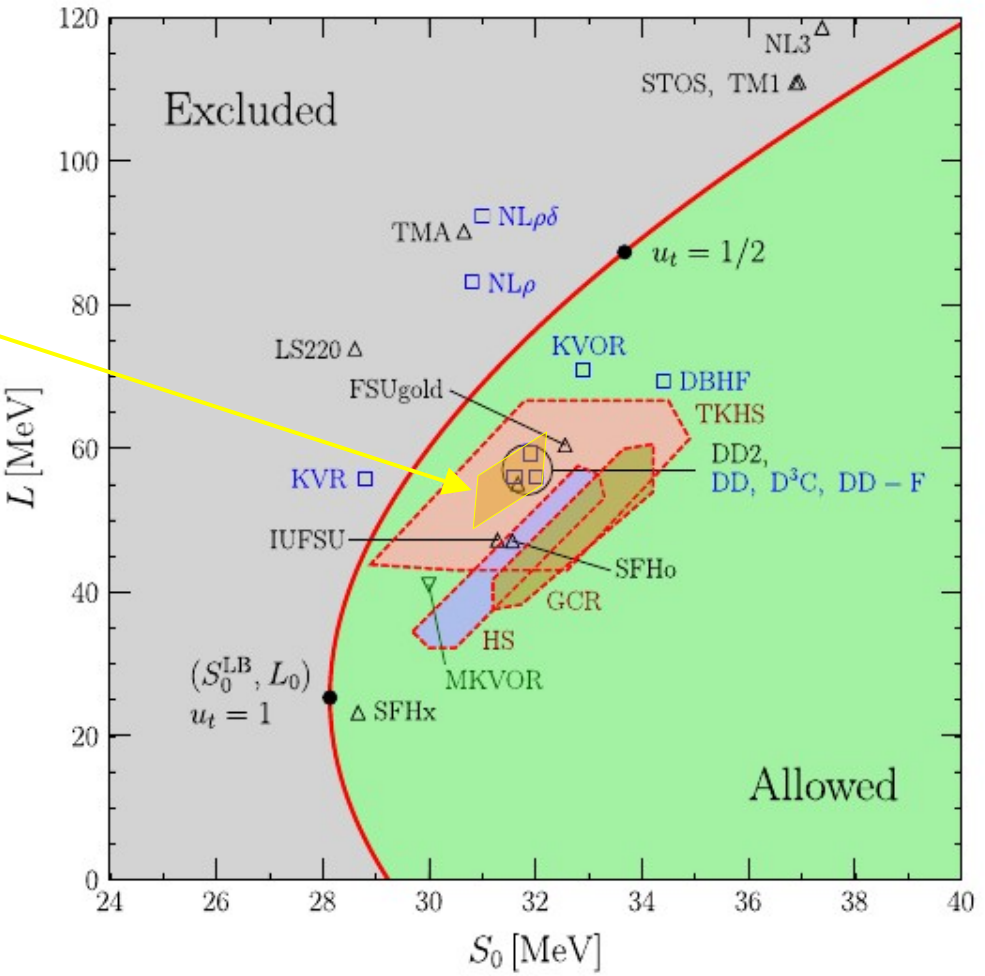
Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Symmetry Energy around ρ_0

Experimental constraints

Model predictions





I. Tews *et al.*, Astroph. J. **848** (2017) 105
C. Drischler *et al.*, PRL **125** (2020) 202702

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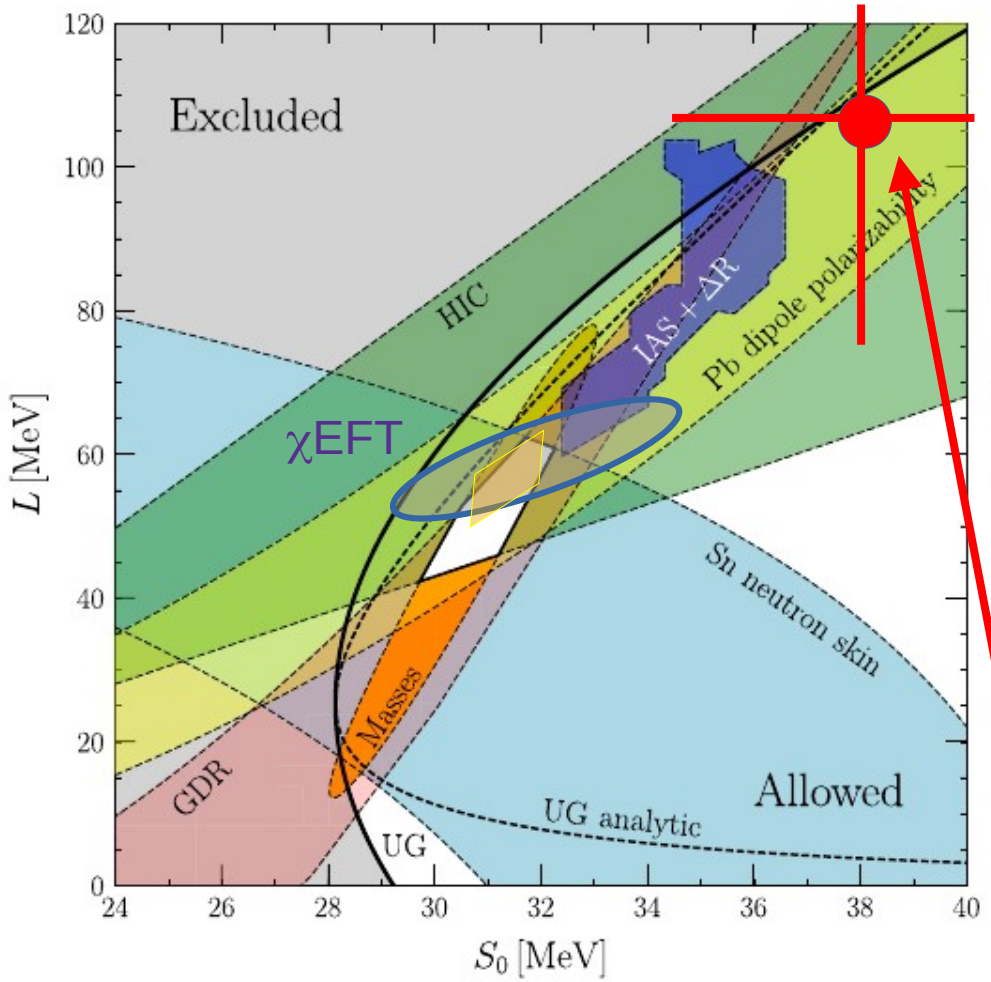
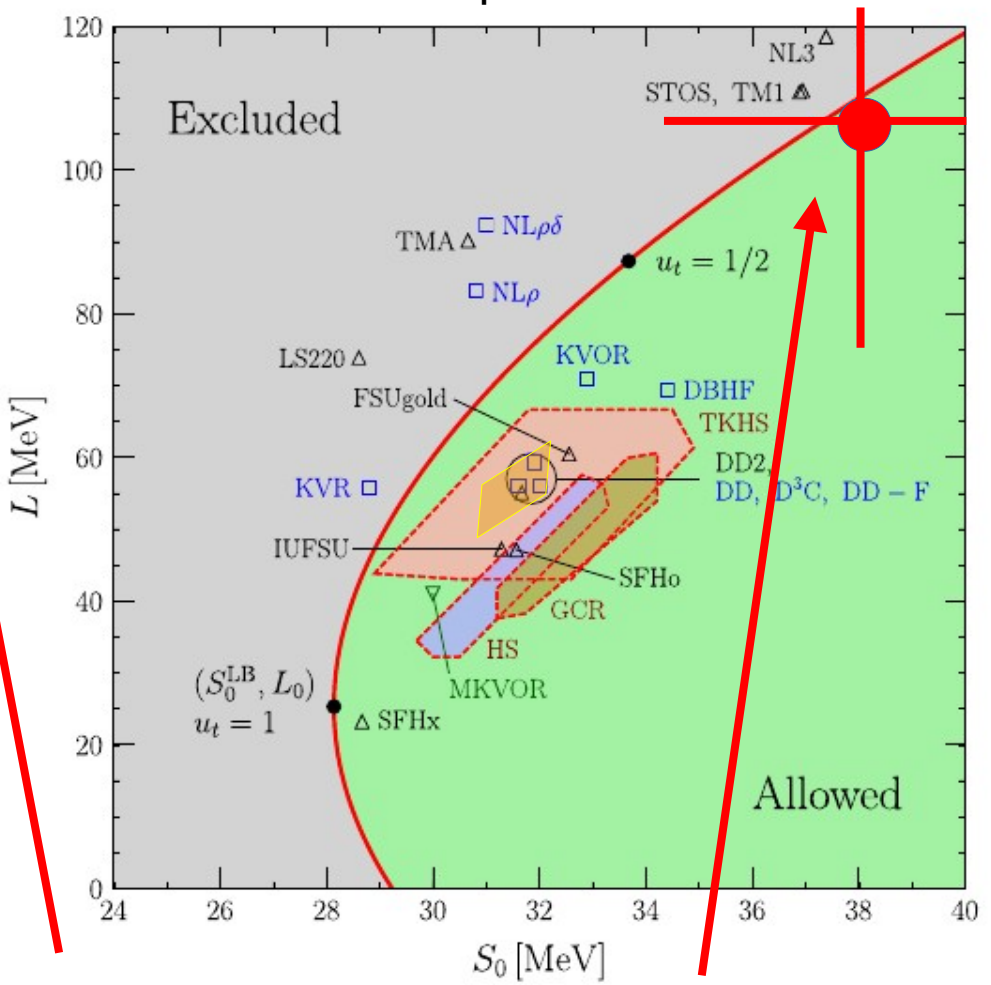
Symmetry Energy around ρ_0 : newcomer in 2021

Tension between PREX-2 and other experimental / theoretical evaluations

Experimental constraints



Model predictions



I. Tews *et al.*, Astroph. J. **848** (2017) 105
C. Drischler *et al.*, PRL **125** (2020) 202702

→ See Chirangi Mondal's poster

*PREX-2 , B. T. Reed et al., PRL **126** (2021) 172503*
S_0 = 38.1 ± 4.7 MeV
L_{sym} = 106 ± 37 MeV

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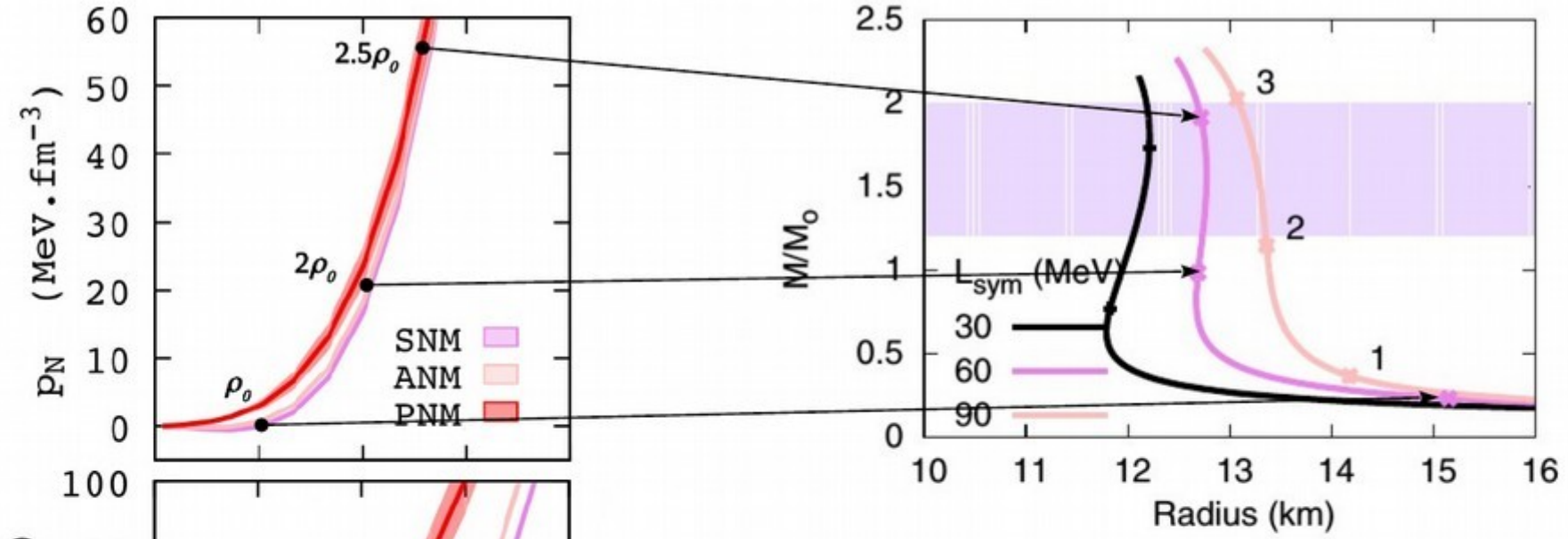
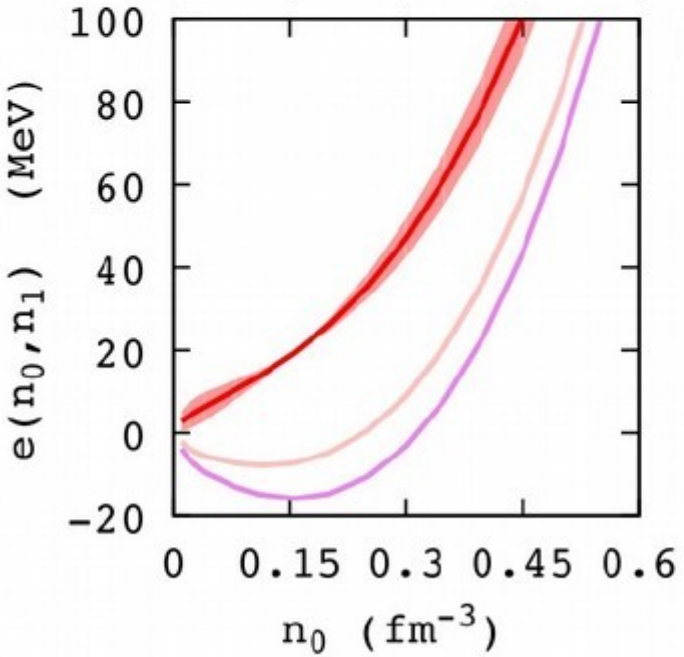
Constraints on Neutron Stars





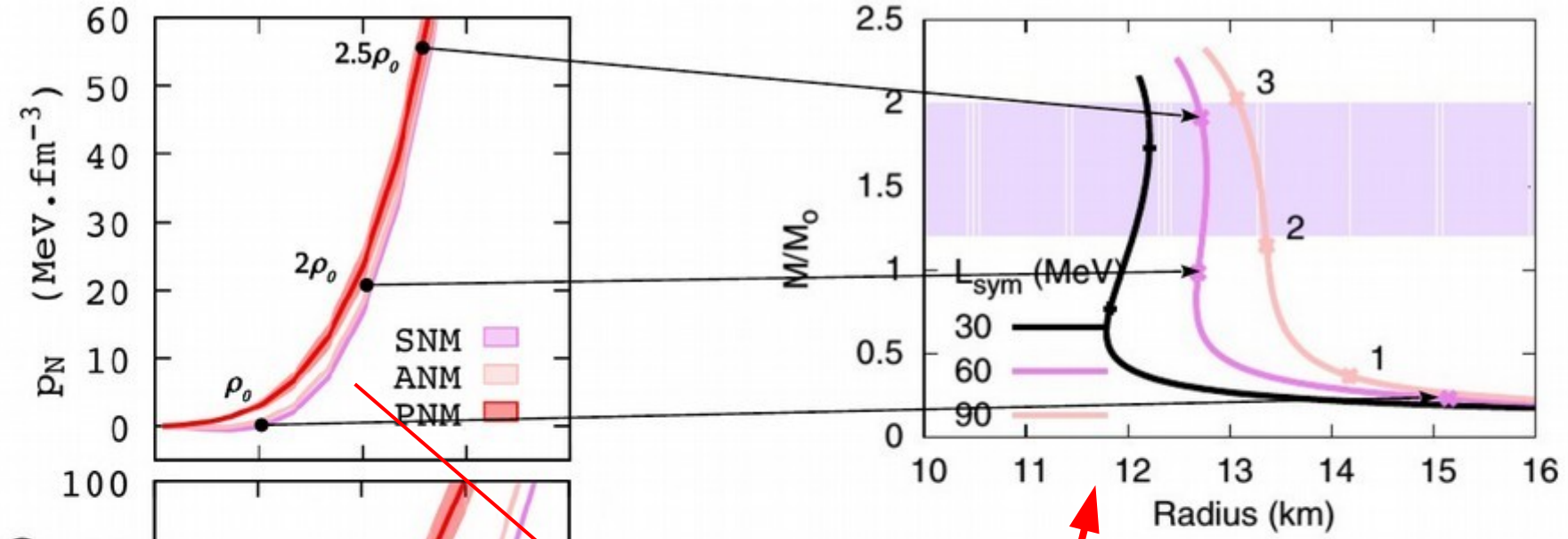
Margueron PRC **97** (2018) 025805
Margueron PRC **97** (2018) 025806

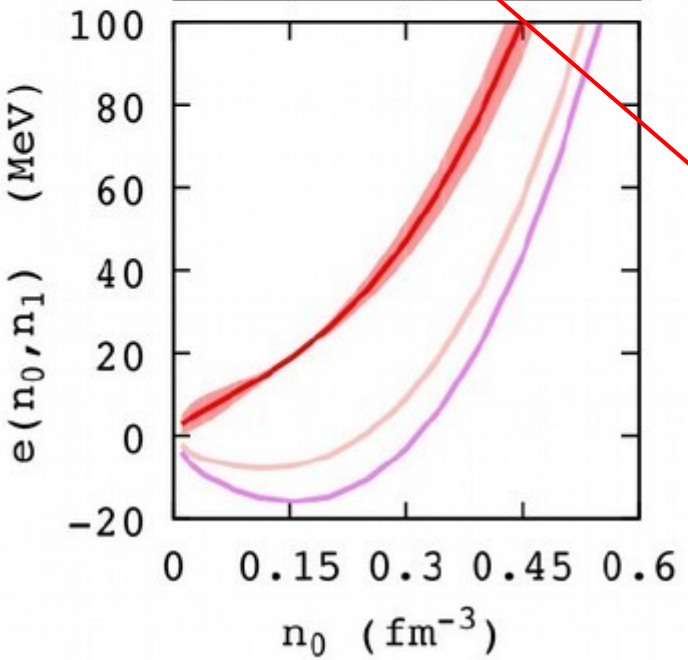
Neutron star radius
Needs the EoS, general relativity, and the sospin content of the system from beta-equilibrium. Mass-radius correlation strongly sensitive to the EoS.

Astrophysical observation
Any neutron star mass-radius measurement would constrain the nuclear EoS.

Also tidal deformability provide a strong constraint
See B. Giacomazzo's lecture

Constraints on Neutron Stars





Margueron PRC **97** (2018) 025805
Margueron PRC **97** (2018) 025806

$$\frac{dP}{dr} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

$$\frac{d\Phi}{dr} = -\frac{1}{\rho c^2}\frac{dP}{dr}\left(1+\frac{P}{\rho c^2}\right)^{-1}$$

$$P = P(\rho)$$

TOV eqs.

Nuclear reactions
at low incident energy

Terrestrial experiments

At GANIL (Caen, Normandy, France), many teams study heavy ions induced nuclear reactions to investigate stable and exotic nuclei properties

GANIL/SPIRAL1

CSS1/CSS2/CIME :

Stable beams (He-U) E_{inc}=*5 – 100 MeV/nucl.*

Radioactive beams E_{inc}=*5 – 15 MeV/nucl.*

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Terrestrial experiments

At GANIL (Caen, Normandy, France), one studies heavy ions induced reactions at low energy to investigate stable and exotic nuclei properties.

SPIRAL2
New *SC-LINAC* :
Intense p,d and HI beams
E_{inc} = *5 – 20 MeV/nucl.*

GANIL/SPIRAL1
CSS1/CSS2/CIME :
Stable beams (He-U) E_{inc}=*5 – 100 MeV/nucl.*
Radioactive beams E_{inc}=*5 – 15 MeV/nucl.*

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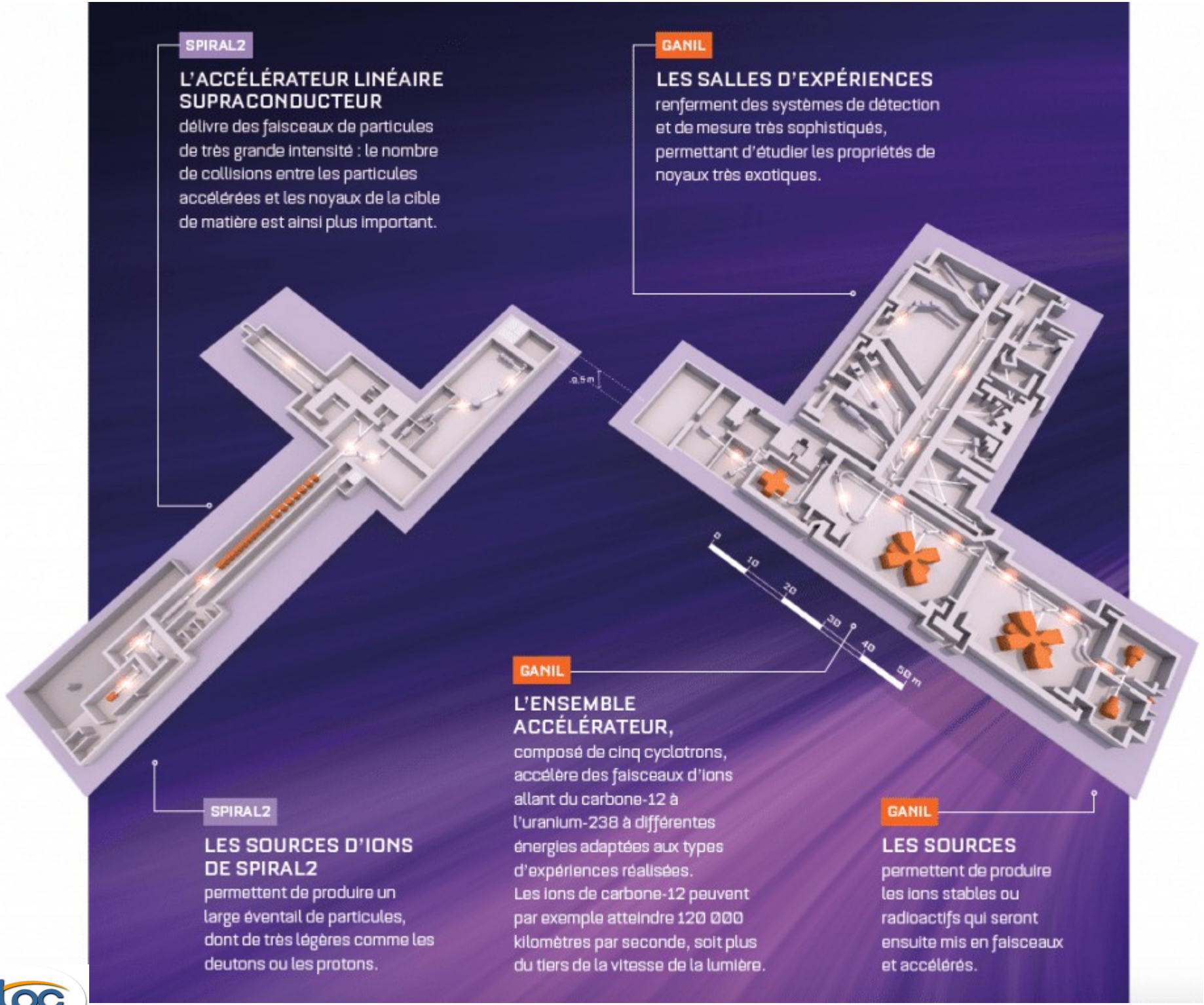
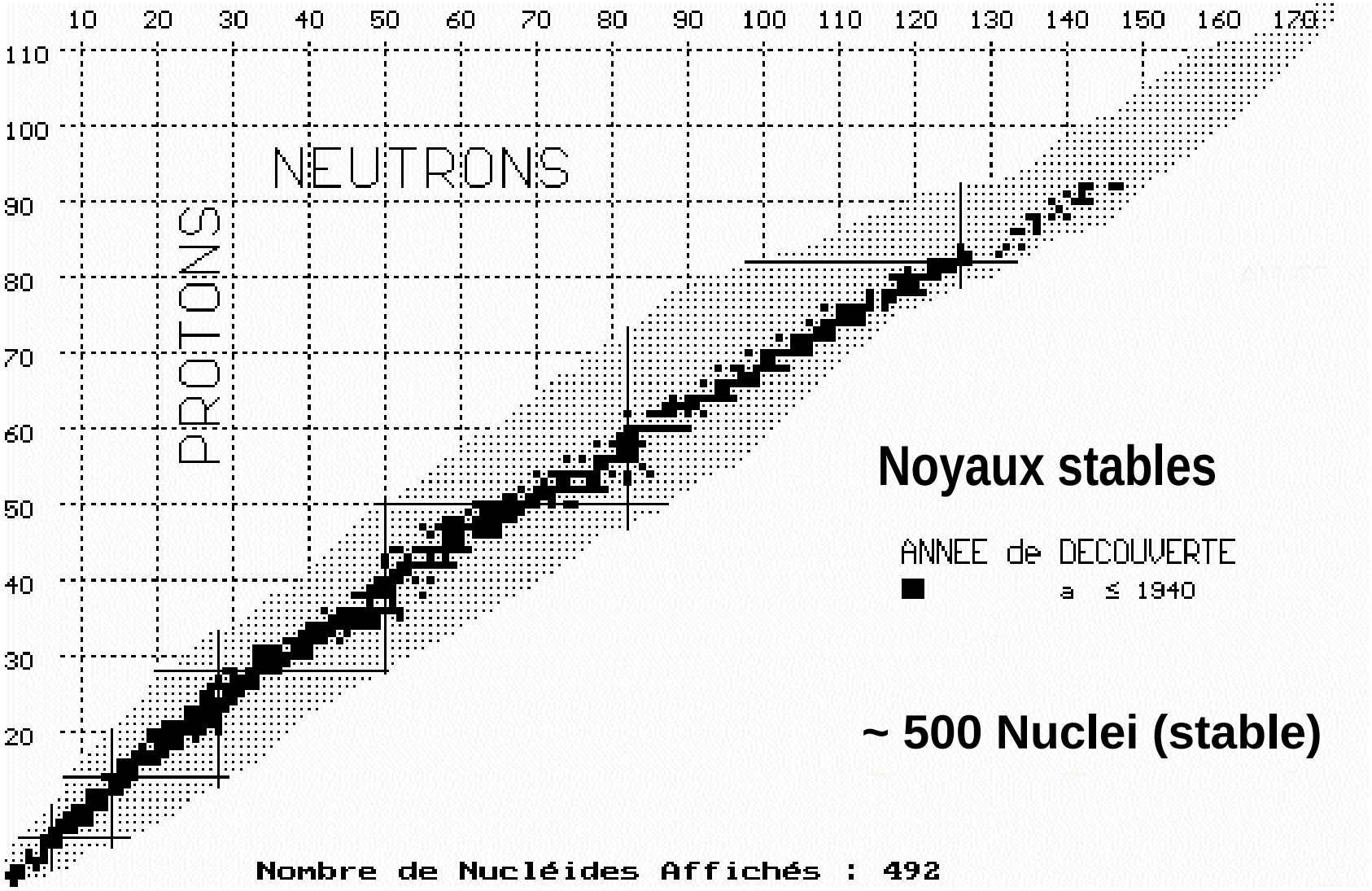

SPIRAL2
L'ACCÉLÉRATEUR LINÉAIRE SUPRACONDUCTEUR
délivre des faisceaux de particules de très grande intensité : le nombre de collisions entre les particules accélérées et les noyaux de la cible de matière est ainsi plus important.
GANIL
LES SALLES D'EXPÉRIENCES
renferment des systèmes de détection et de mesure très sophistiqués, permettant d'étudier les propriétés de noyaux très exotiques.
0,5 m
0
10
20
30
40
50 m
GANIL
L'ENSEMBLE ACCÉLÉRATEUR,
composé de cinq cyclotrons, accélère des faisceaux d'ions allant du carbone-12 à l'uranium-238 à différentes énergies adaptées aux types d'expériences réalisées.
Les ions de carbone-12 peuvent par exemple atteindre 120 000 kilomètres par seconde, soit plus du tiers de la vitesse de la lumière.
SPIRAL2
LES SOURCES D'IONS DE SPIRAL2
permettent de produire un large éventail de particules, dont de très légères comme les deutons ou les protons.
GANIL
LES SOURCES
permettent de produire les ions stables ou radioactifs qui seront ensuite mis en faisceaux et accélérés.

Producing exotic nuclei

Towards the driplines

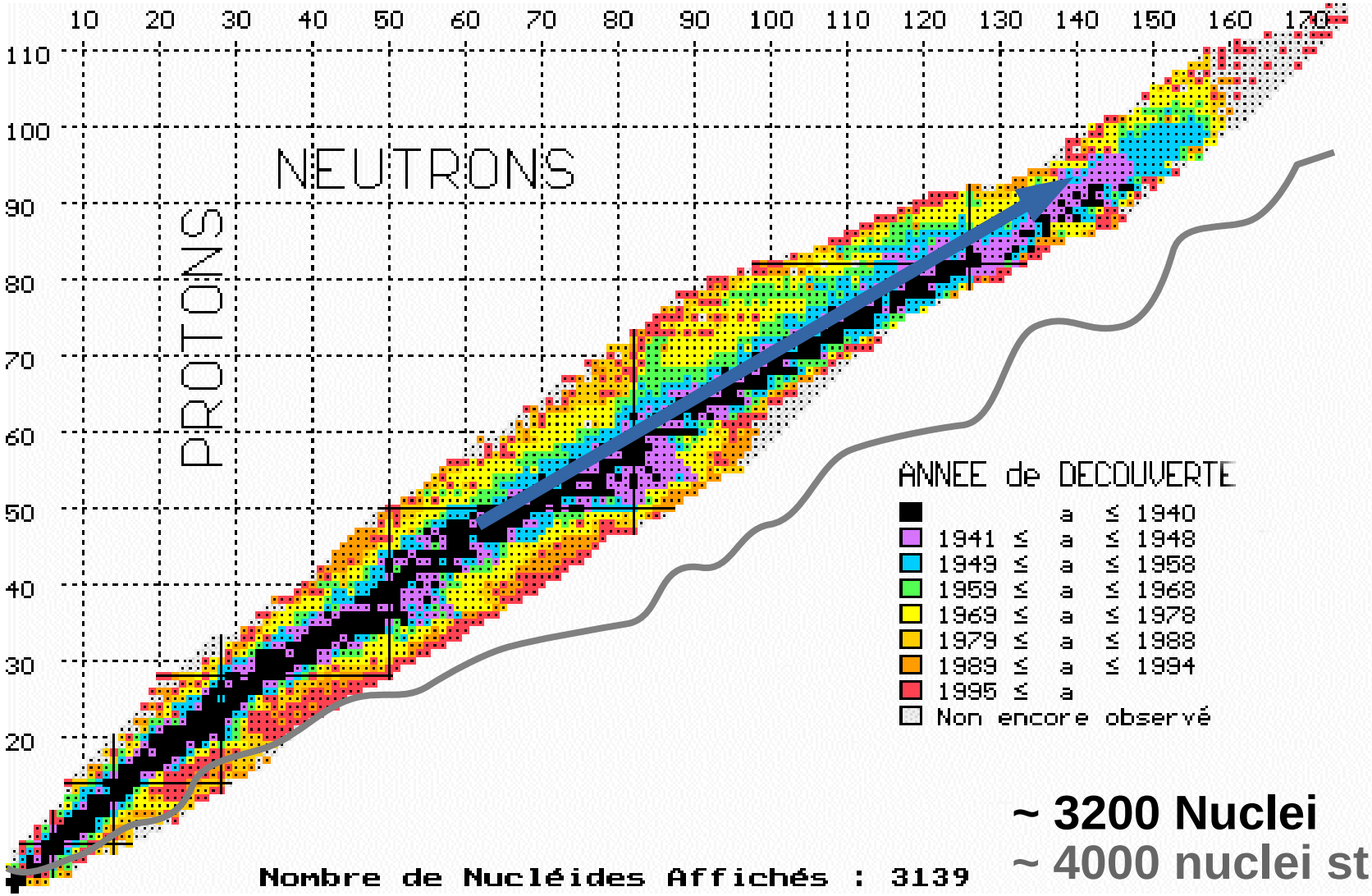
Discovered nuclei before WW II



Known Nuclei nowadays and future

Major outcomes of nuclear physics after 50's

"Terra Incognita"



~ 3200 Nuclei

~ 4000 nuclei still to discover ?

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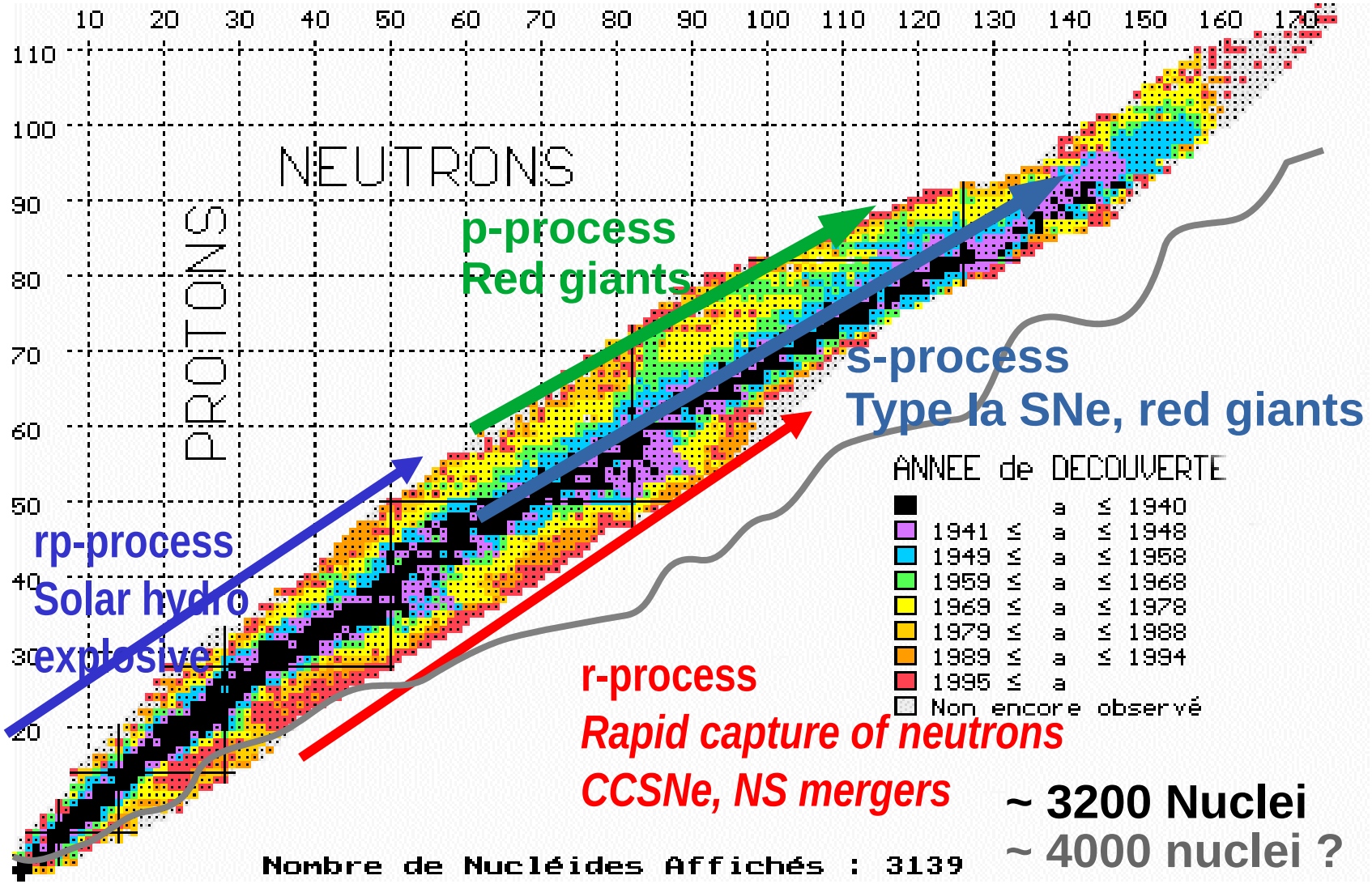
Known Nuclei nowadays and future

“Terra Incognita”



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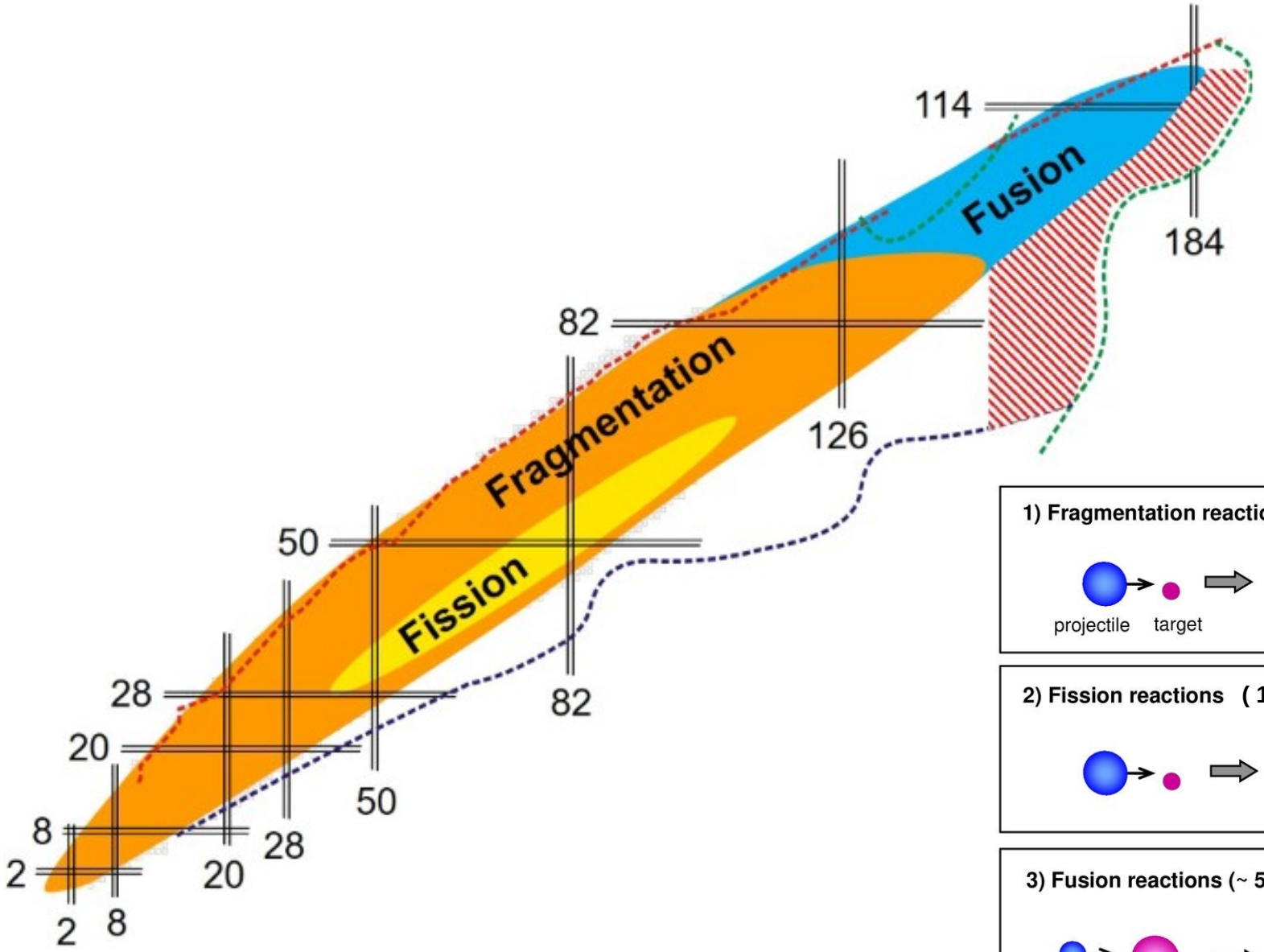
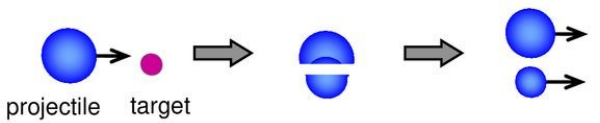
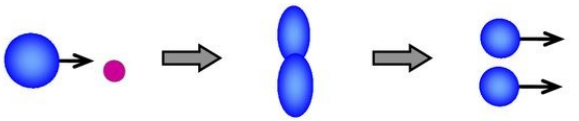
Production of exotic nuclei with HI beams



1) Fragmentation reactions (50 – 1000 MeV/u)



2) Fission reactions (10 – 100 MeV/u)



3) Fusion reactions (~ 5 MeV/u)

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End of lecture I

Outlines

1. From the use of low energy nuclear reactions (dissipative)

2. The nuclear equation of state
   - Phase transitions
   - Empirical parameters
   - Evaluations & uncertainties

3. Toward the production of exotic nuclei

4. Panorama of nuclear reactions from B_{coul} up to 100 MeV/nucleon
   - Basic considerations
   - Reaction mechanisms

5. Path to equilibrium : transport properties in nuclear medium
   - Energy dissipation
   - Isospin transport

6. Improving our knowledge for EOS

7. Experimental tools and some related instrumentation

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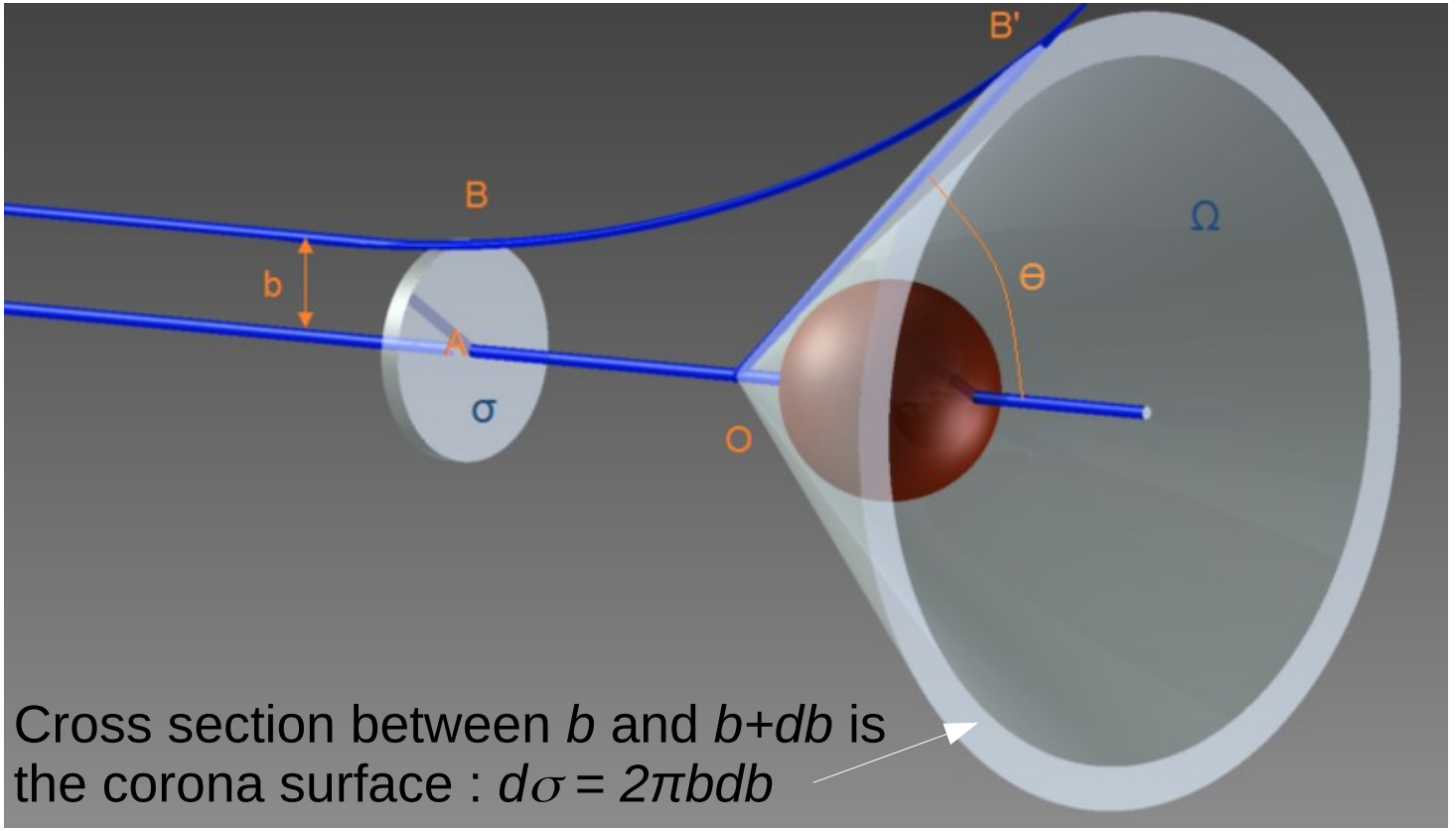
Reaction mechanisms

from Coulomb barrier
up to relativistic energies

Cross section in classical Physics



Integrating over b, we get : $\sigma\ (b) = \pi b^2$

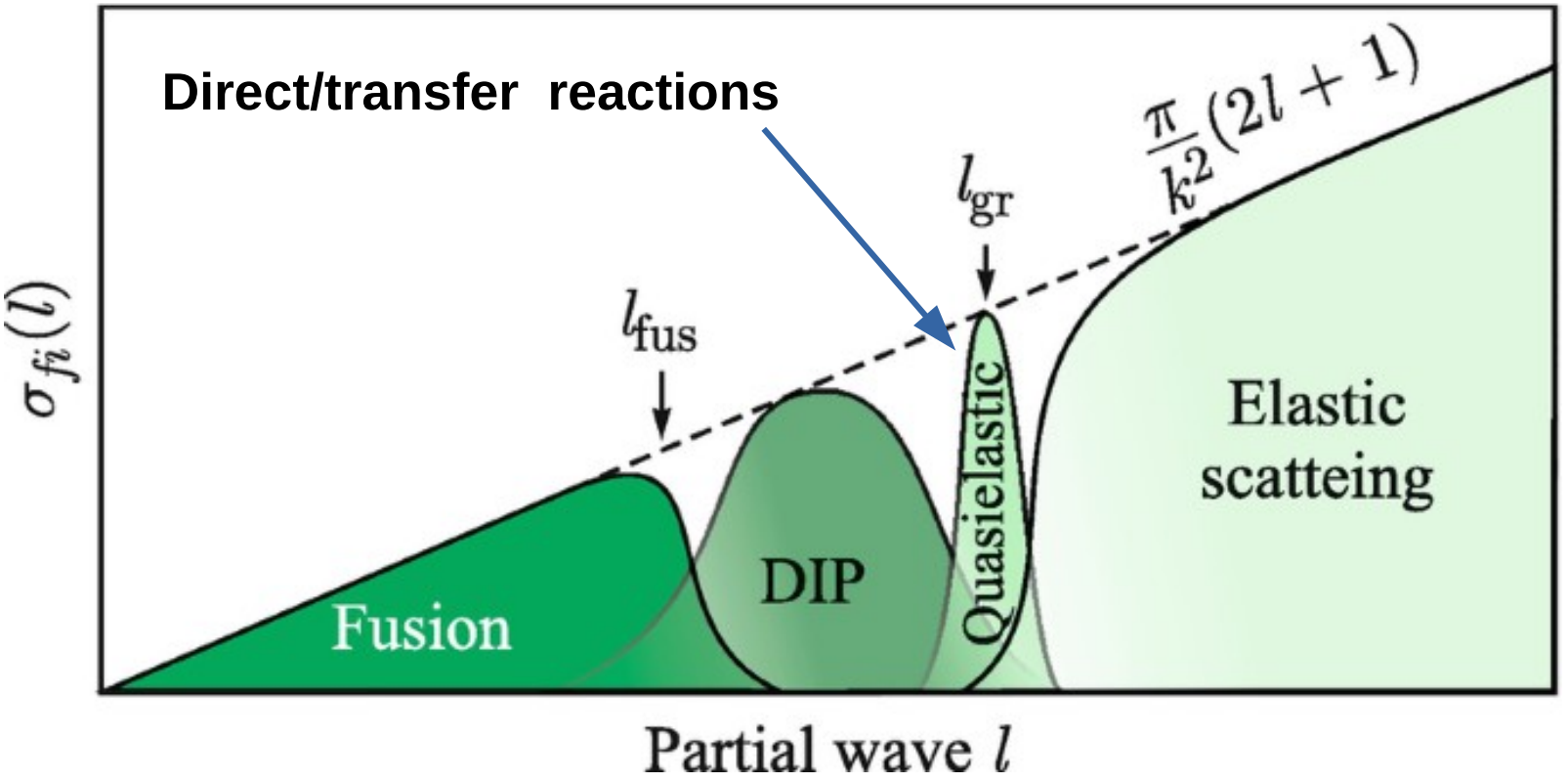
Unit is the barn (b), $1b = 10^{-28} m^2 = 10^{-24} cm^2$

For a typical nuclear reaction between HI, we have $b_{grazing} \approx 10\ fm$, then $\sigma_{nuc} = 3{,}142\ b = 3142\ mb$

Cross section in Quantum Mechanics : partial waves

Total nuclear cross-section
$\sigma_{nuc} = \pi b_{gr}^2 \approx \pi \ell_{gr}(\ell_{gr}+1)\hbar^2/\mu v$

Classical ansatz :
$|\ell| = \sqrt{l(l+1)}\ \hbar = \mu v b$

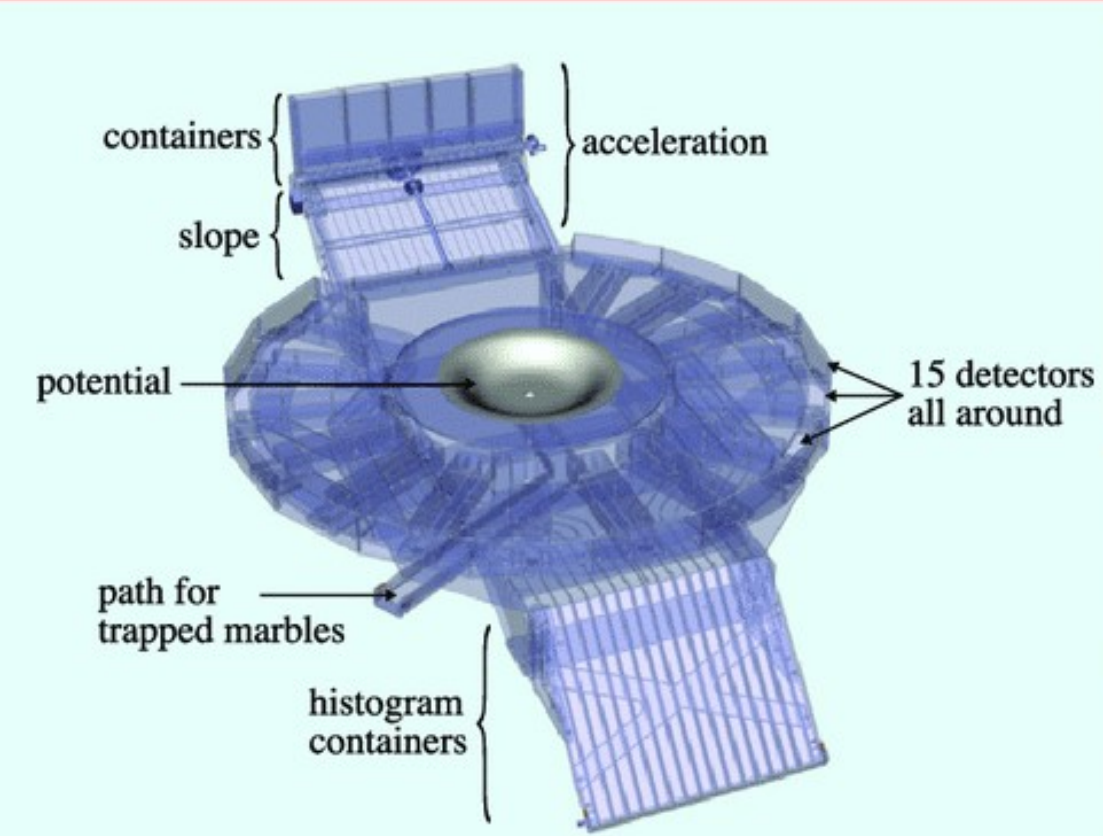


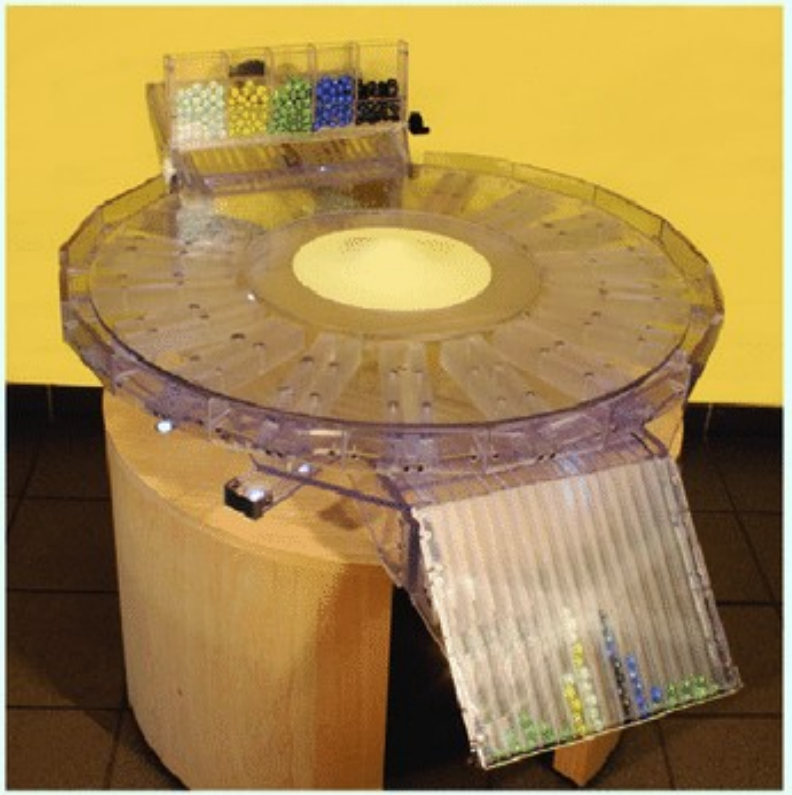
$$\sigma_r = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{\max}}(2\ell+1)(1-\eta_\ell^2)$$

η_ℓ is the **inelasticity coefficient** for partial wave ℓ
$\eta_\ell = 0$ for **elastic** and $0<\eta_\ell<1$ for **absorption**

Rutherford scattering with marble balls : Billotron

https://www.lpc-caen.in2p3.fr/grand-public-rencontrer/le-billotron/





https://youtu.be/_KcK-jS2QQQ

A. Chapon, J. Gibelin, O. Lopez, D. Cussol, D. Dominique Durand, Ph. Desrues, H. Franck De Préaumont, Y. Lemière, J. Perronnel, and J.C. Steckmeyer. *The Billotron: a way to experimentally apprehend the subatomic world*. Physics Education, 50(4):453, 2015. doi: 10.1088/0031-9120/50/4/453. URL http://hal.in2p3.fr/in2p3-01177619.

Ask Julien Gibelin

Cross section and event rate

Event rate E (s^{-1}) for a specific reaction cross section σ_r :

$$E_{reac} = \mathcal{F}\,\rho\,\mathcal{N}\,e\,\sigma_r/A$$

where :

- $\mathcal{F}$ is the incident flux of particles per unit of time (s^{-1})
- ρ is the density of the target material ($g.cm^{-3}$)
- e is the target thickness (cm)
- A is the molar mass of the target material ($g.mol^{-1}$)
- $\mathcal{N}$ = $6.022.10^{23}$ is the Avogadro number
- σ_r is the reaction cross section (cm^{-2})

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Cross section and event rate

Event rate E (s^{-1}) for a specific reaction cross section σ_r :

$$E_{reac} = \mathcal{F} \rho \mathcal{N} e \sigma_r / A$$

Thin target
e=300 μm, Au

Reaction $\mathcal{F}$ = 10^9 pps	Cross section	Event rate
Coulomb scattering	100 b	1000/s
Deep Inelastic/ Multi-nucleon Transfer	1 b	10/s
Central collision (b<1 fm)	50 mb	1/mn
Fusion reaction for SHE	1 μb	1/month

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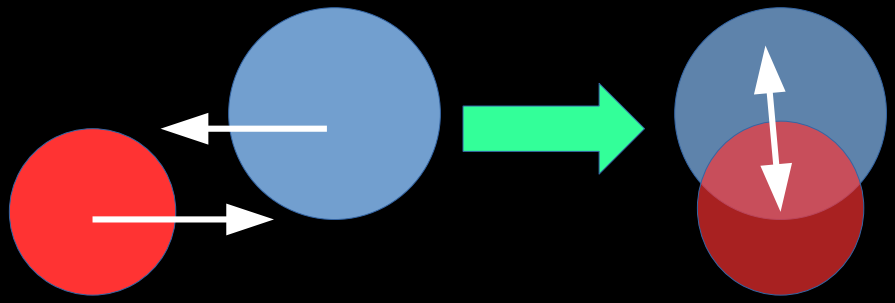
Low energy reaction mechanisms

B<E$_{inc}$<15 MeV/nucl.

Composite system



Entrance channel

b<b$_{grazing}$

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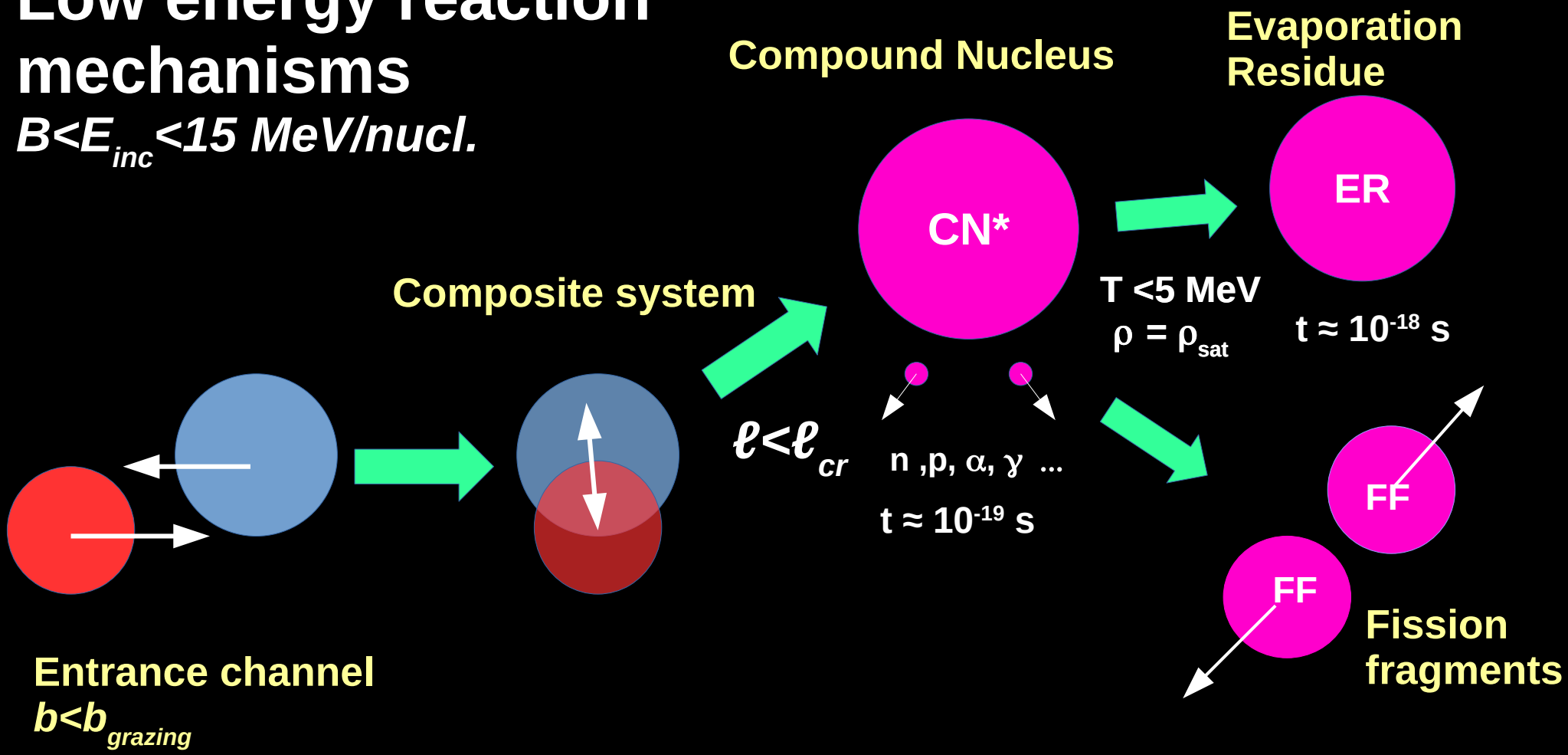
Low energy reaction mechanisms

$B<E_{inc}<15$ MeV/nucl.



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Low energy reaction mechanisms

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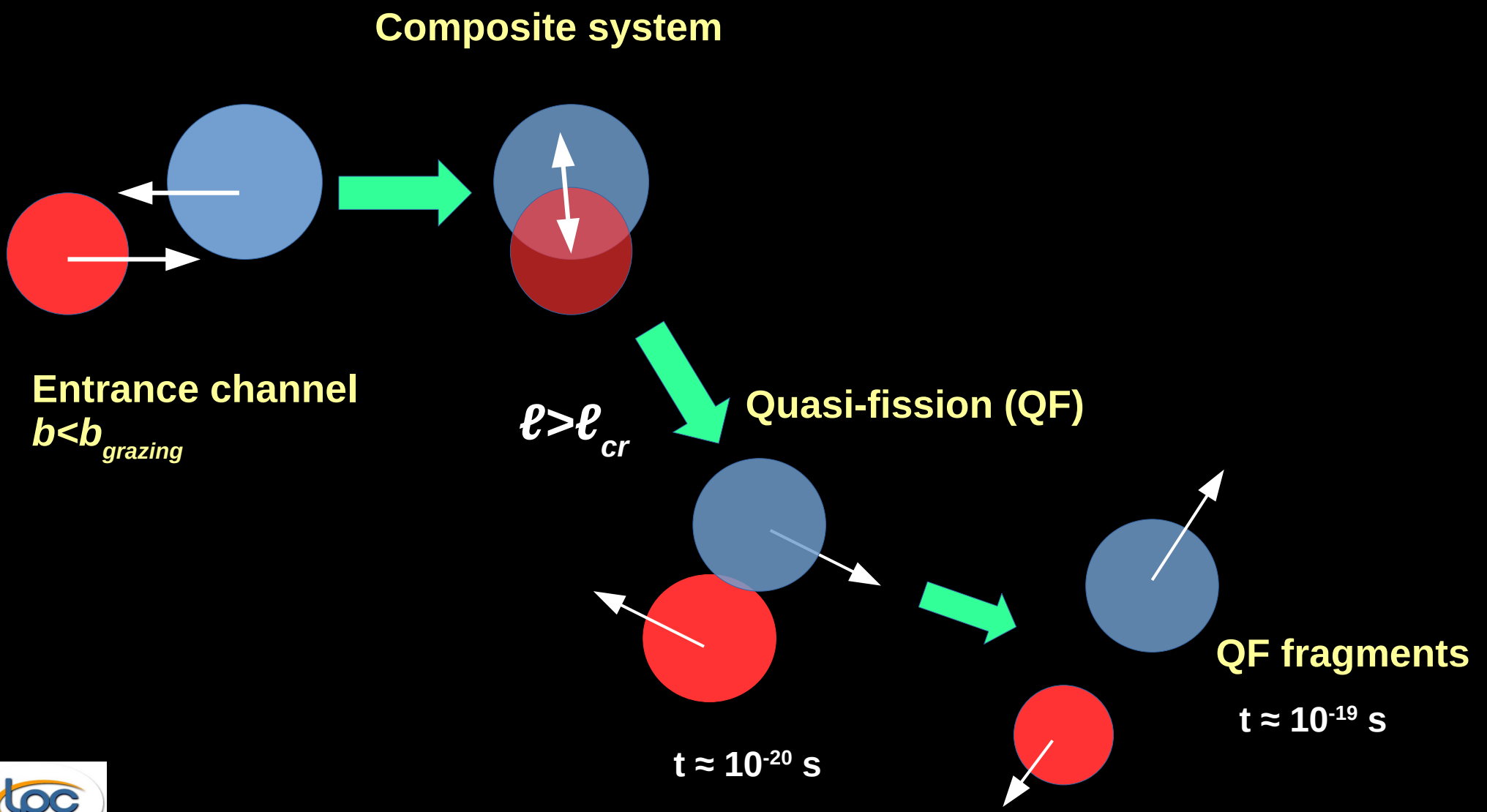

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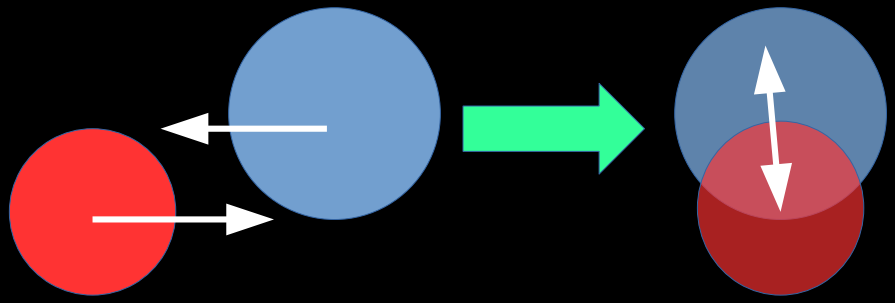
Fermi energy reaction mechanisms

15<E_{inc}<40 MeV/nucl.

Composite system



Entrance channel

b<$b_{grazing}$

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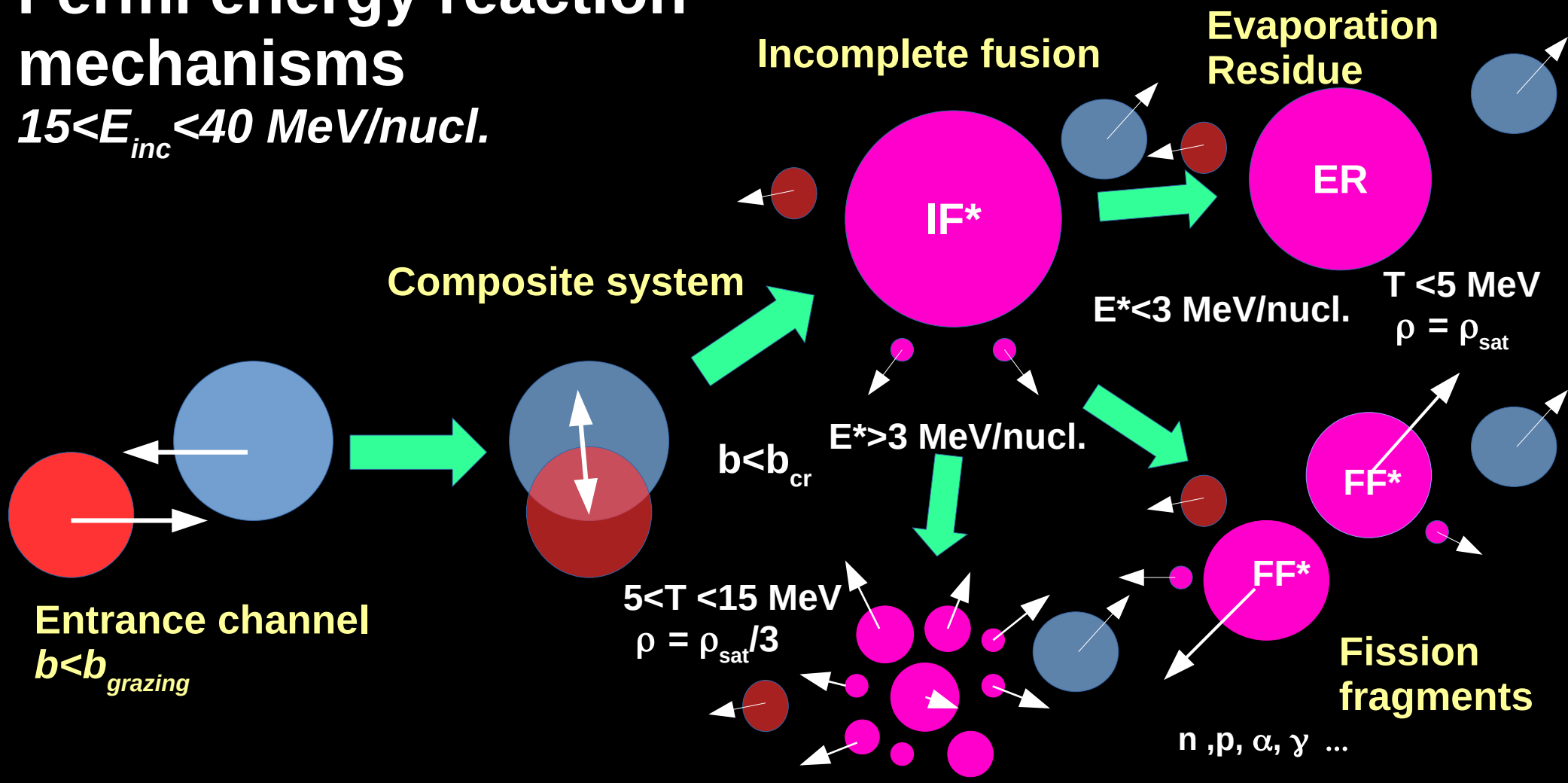
Fermi energy reaction mechanisms

15<E_{inc}<40 MeV/nucl.



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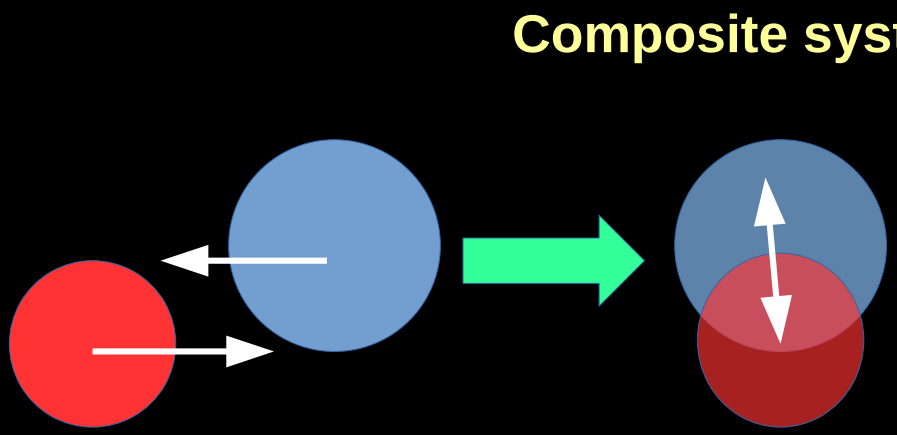
Fermi energy reaction mechanisms

15<E$_{inc}$<40 MeV/nucl.

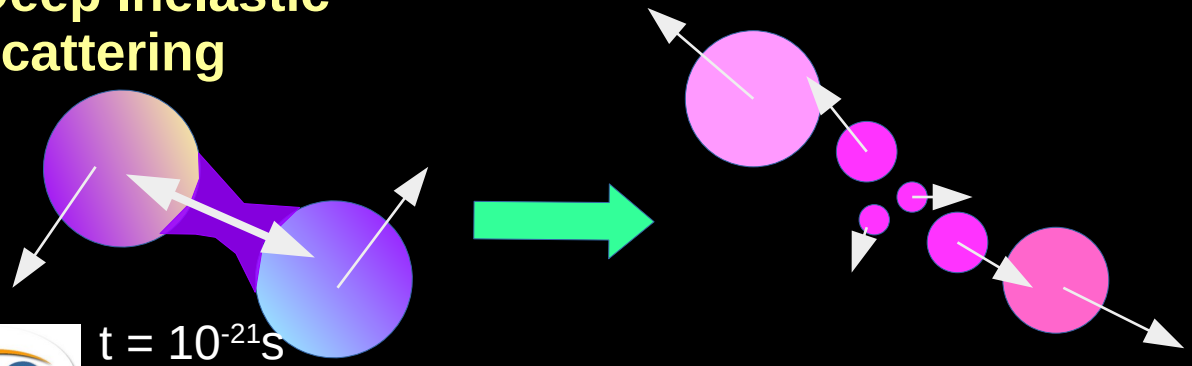


Composite system

Entrance channel
b<b$_{grazing}$

b>b$_{cr}$

Deep Inelastic scattering



t = 10^{-21}s

5<T <15 MeV
ρ = ρ$_{sat}$/10

Neck emission
QP+QT+IMF @ mid-rapidity

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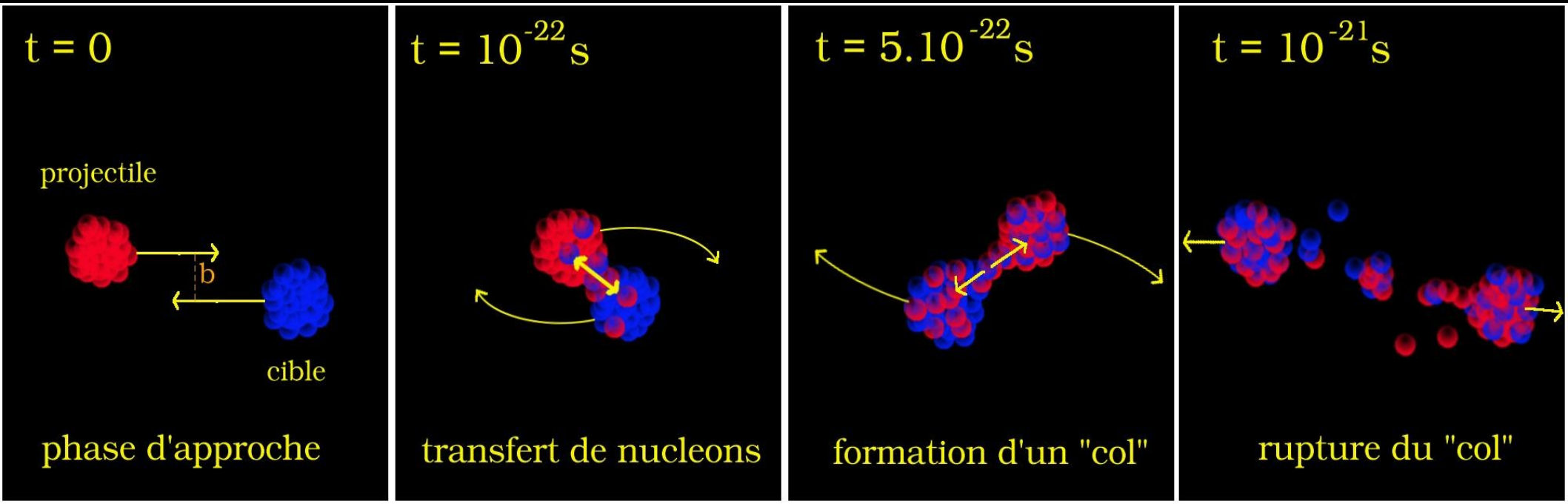
Deep Inelastic collisions ... toward the limits

« semi-peripheral » collision (b=6 fm)



Extreme rotation
10^{23} rpm !

More diluted
$\rho << \rho_0$

More n-rich
(N<<Z, N>>Z)

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Simulation Xe+Sn at 50 MeV/nucleon
b=7 fm

Nuclear Collision Simulation

(Z=54,A=129) on (Z=50,A=119) @ E/A= 50MeV, b=4.0fm

HIPSE model - Phys. Rev. C69, 054604 (2004)
D. Lacroix (GANIL) and D. Durand (LPC Caen)

Simulation done by O. Lopez (lopezo@in2p3.fr)
Details at http://www.lpc-caen.in2p3.fr

Nuclear Collision Simulation

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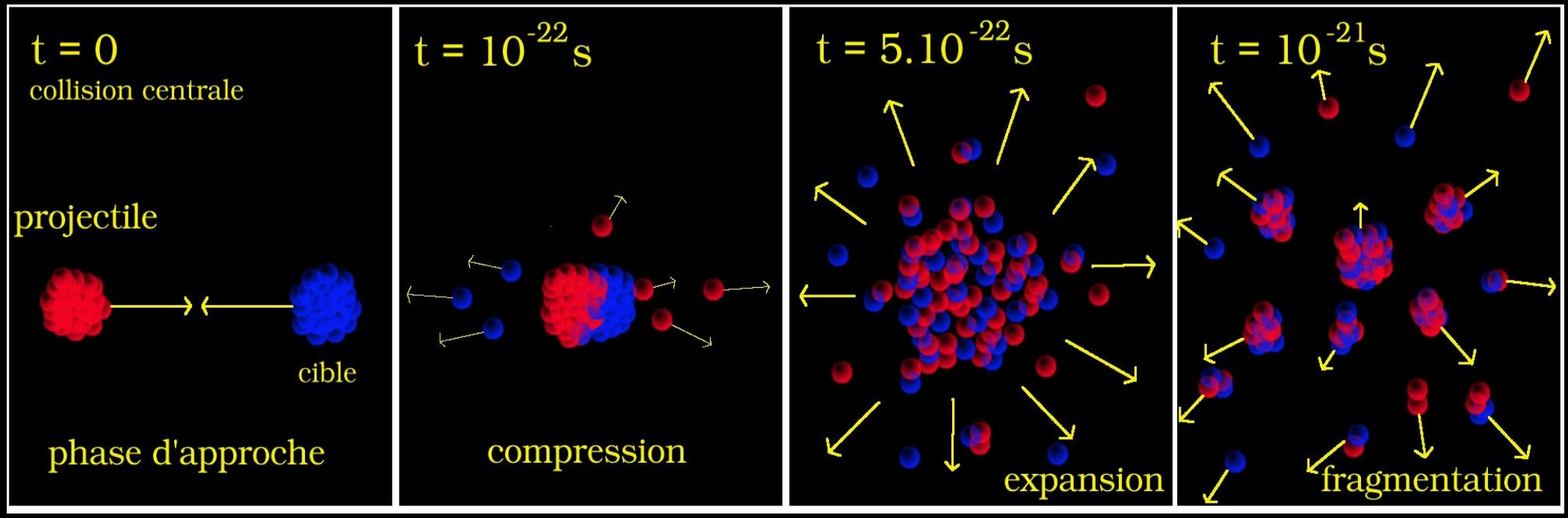
Details at http://www.lpc-caen.in2p3.fr

Central collisions ... Little Big Bang !

Central collision (b=0)



Denser
ρ / ρ_0 >1-3

Hotter
T>5 MeV
1 MeV = 10^{10} K !

Fragmented
and diluted
N>10-100

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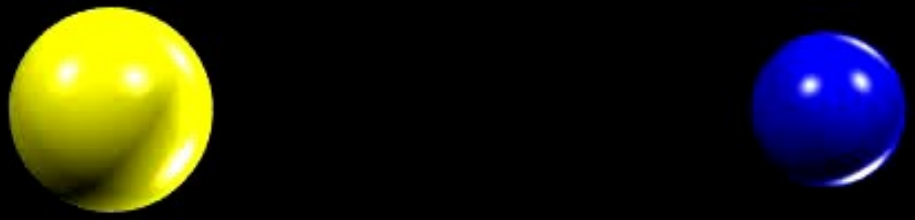
Multifragmentation



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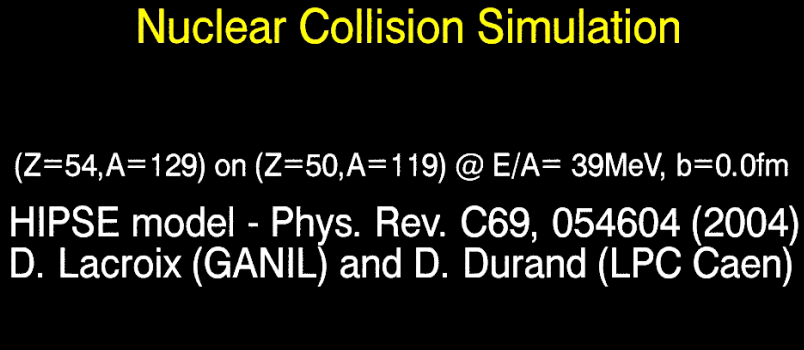
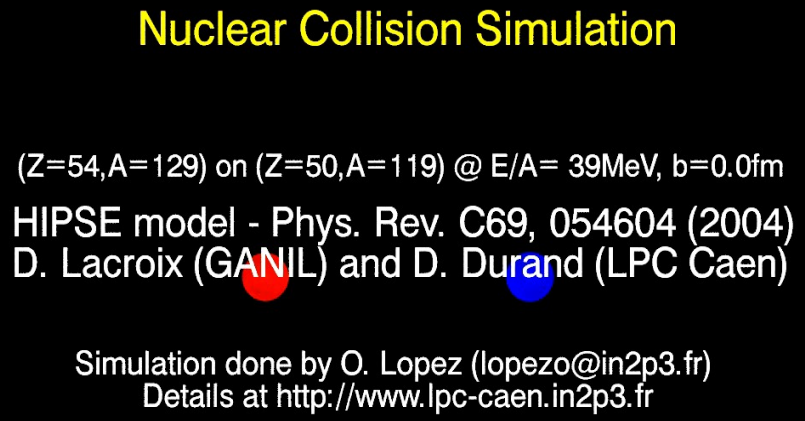
Simulation Xe+Sn at 39 MeV/nucleon b=0 fm

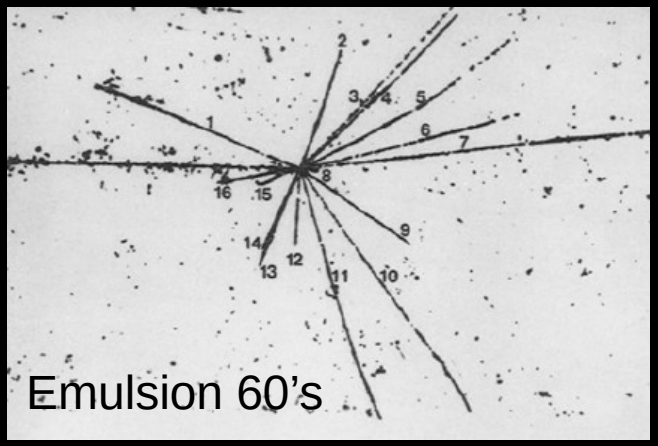




More videos avaialble on this YouTube channel :

https://www.youtube.com/watch?v=azCjJx6REKg

Multifragmentation as Liquid-gas Phase Transition



Breakup reactions with more than 2 fragments...

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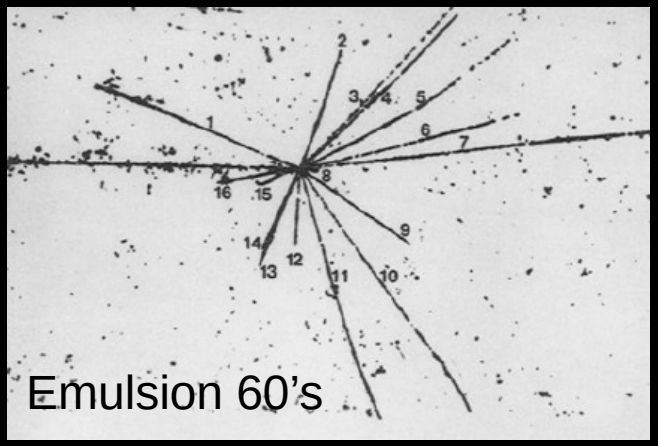
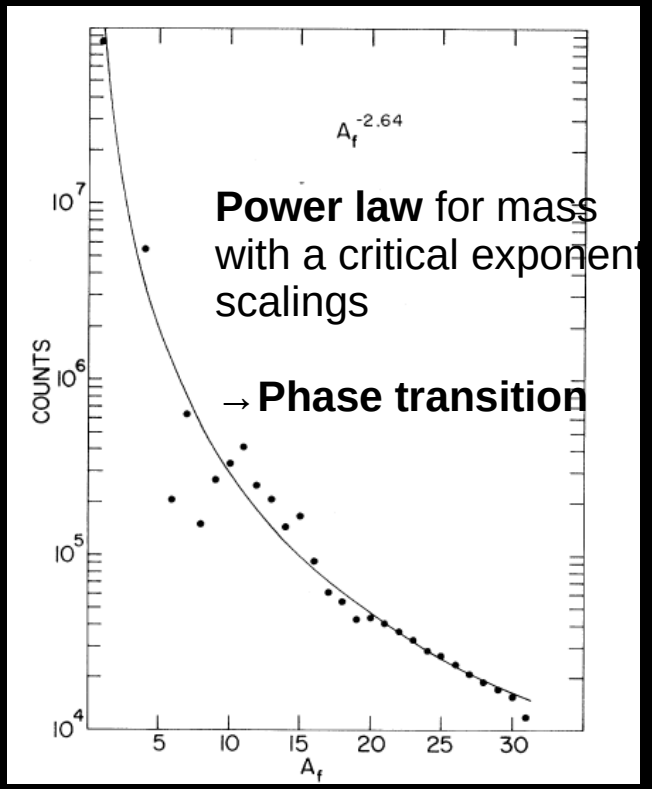
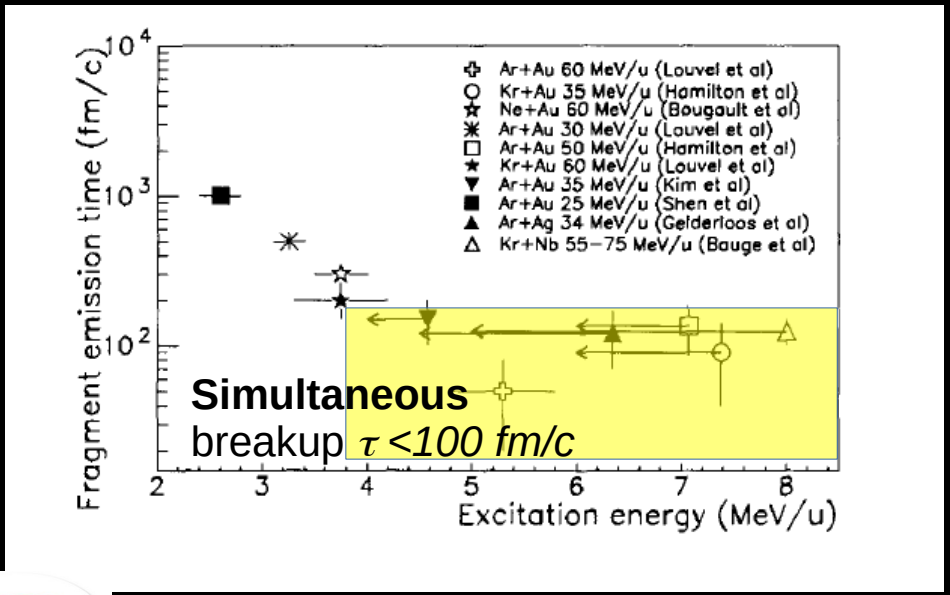
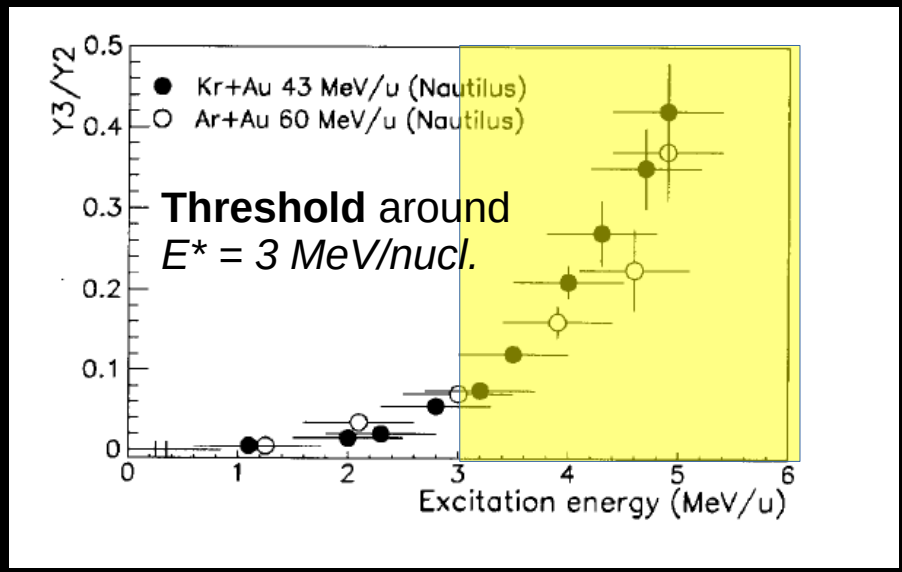
Multifragmentation as Liquid-gas Phase Transition



Breakup reactions with more than 2 fragments...



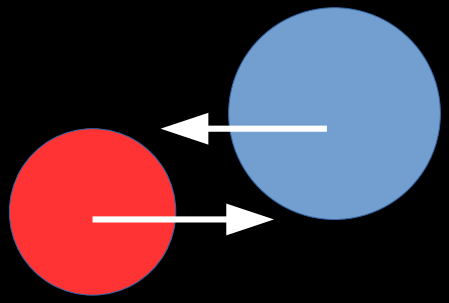




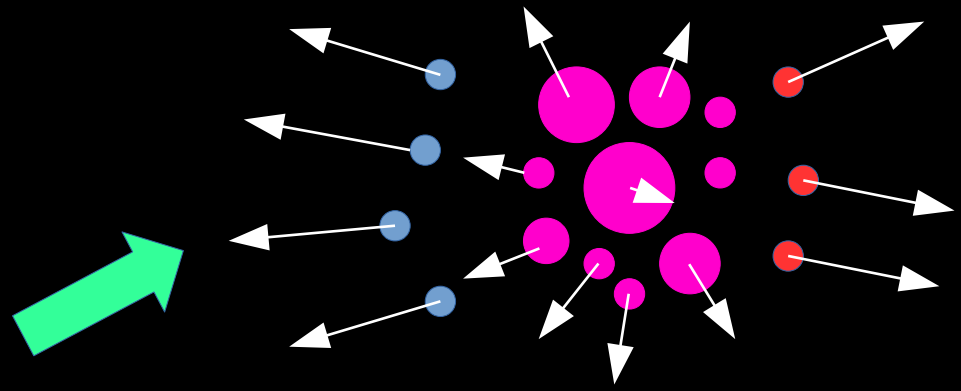
Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Intermediate energy reaction mechanisms

40<E$_{inc}$<150 MeV/nucl.



Entrance channel
b<b$_{grazing}$



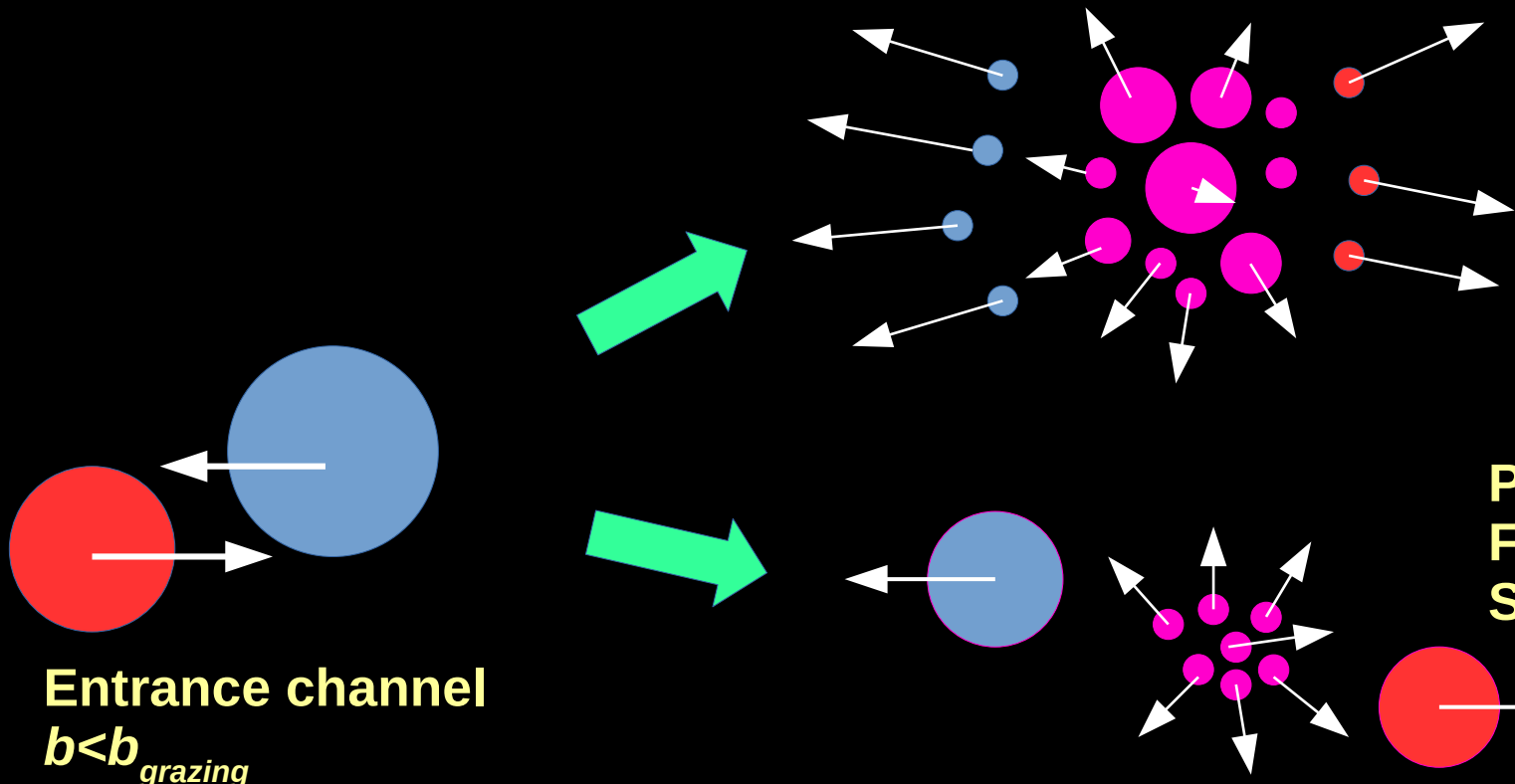
Multifragmentation
IMF + LCP @ CM
***NN* collisions**
(pre-equilibrium)

10<T <20 MeV
ρ = ρ$_{sat}$/3-6

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Intermediate energy reaction mechanisms

40<E$_{inc}$<150 MeV/nucl.



Multifragmentation
IMF + LCP @ CM
***NN* collisions**
(pre-equilibrium)

10<T <20 MeV
ρ = ρ$_{sat}$/3-6

Participant-spectator
Fireball LCP+IMF
Spectator : ablation

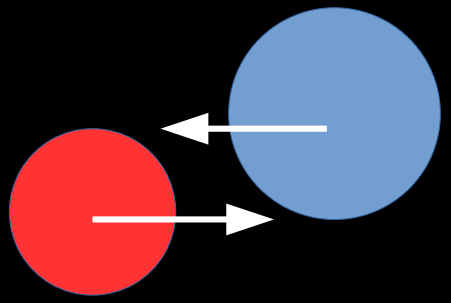
T > 15 MeV
ρ = ρ$_{sat}$/6

Entrance channel
b<b$_{grazing}$

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

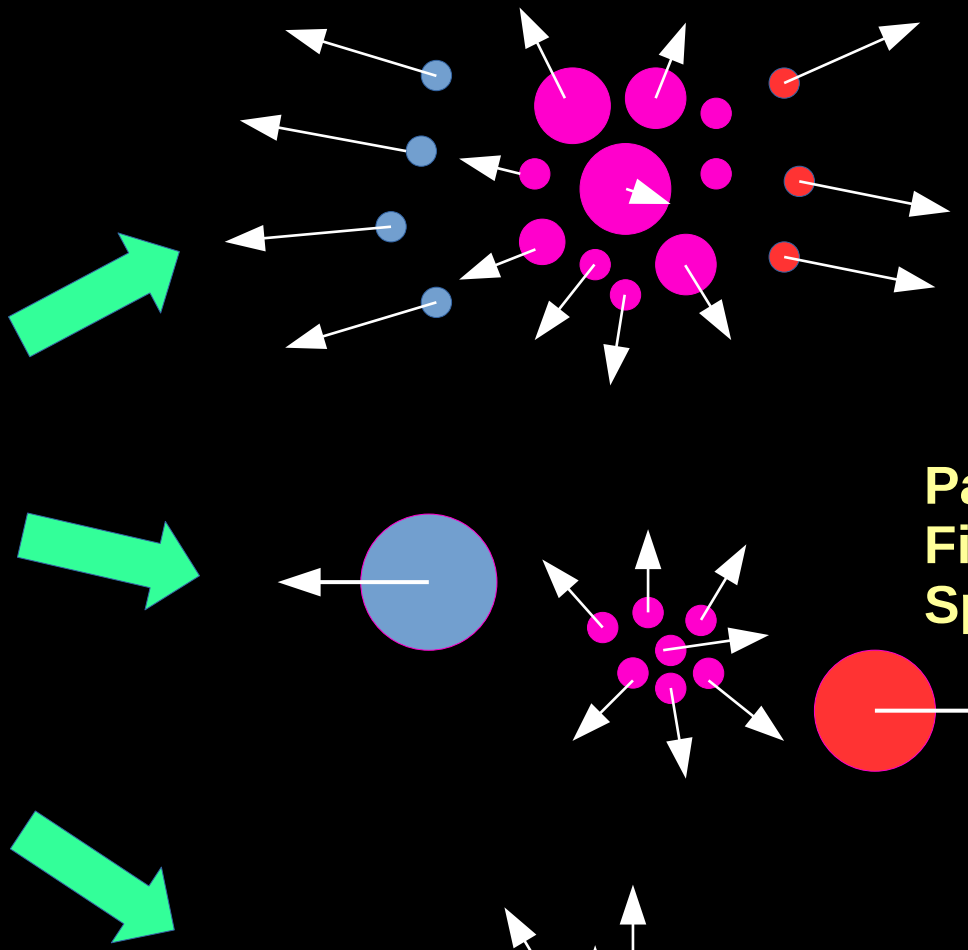
Intermediate energy reaction mechanisms

40<E$_{inc}$<150 MeV/nucl.



Entrance channel

b<b$_{grazing}$



Multifragmentation
IMF + LCP @ CM
***NN* collisions**
(pre-equilibrium)

10<T <20 MeV
ρ = ρ$_{sat}$/3-6

Participant-spectator
Fireball LCP+IMF
Spectator : ablation

T > 15 MeV
ρ = ρ$_{sat}$/6

Vaporisation (Z<3)
***NN* coll. +**
Elliptic flow

T >> 15 MeV
ρ = ρ$_{sat}$/10-100

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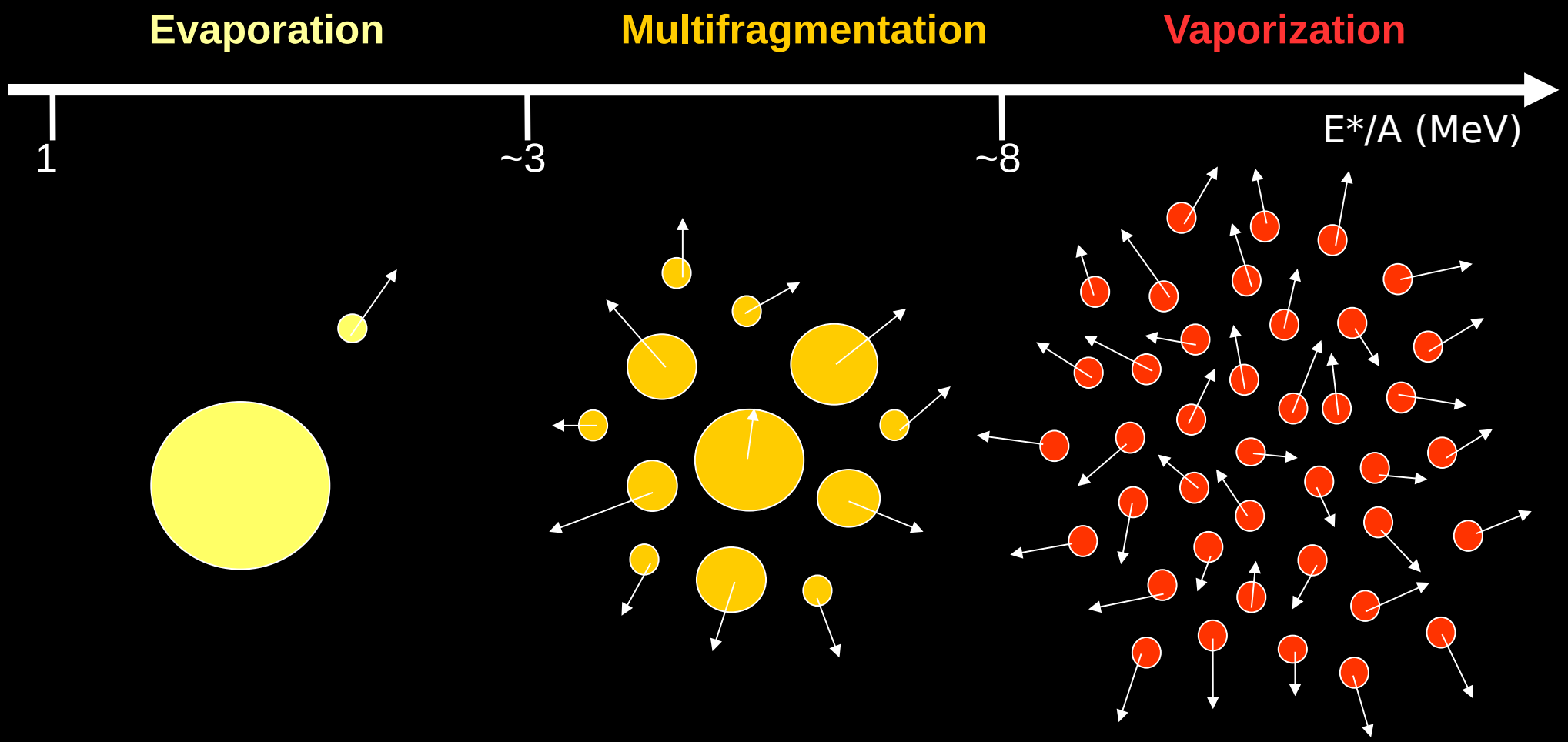
Hot nuclear matter (nuclei) ; from liquid to gas phase



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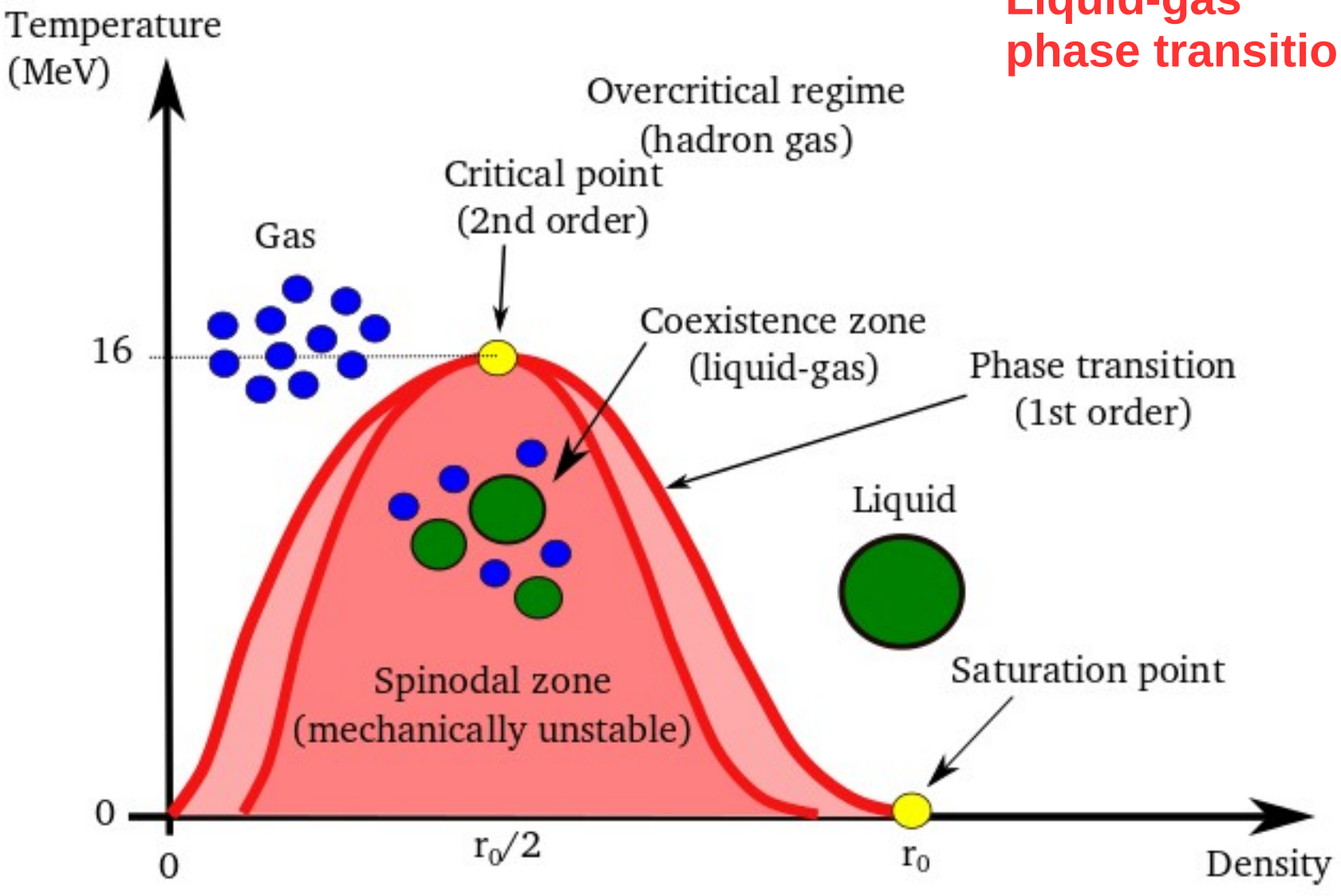
Multifragmentation : Mean-Field density instabilities

Liquid-gas phase transition



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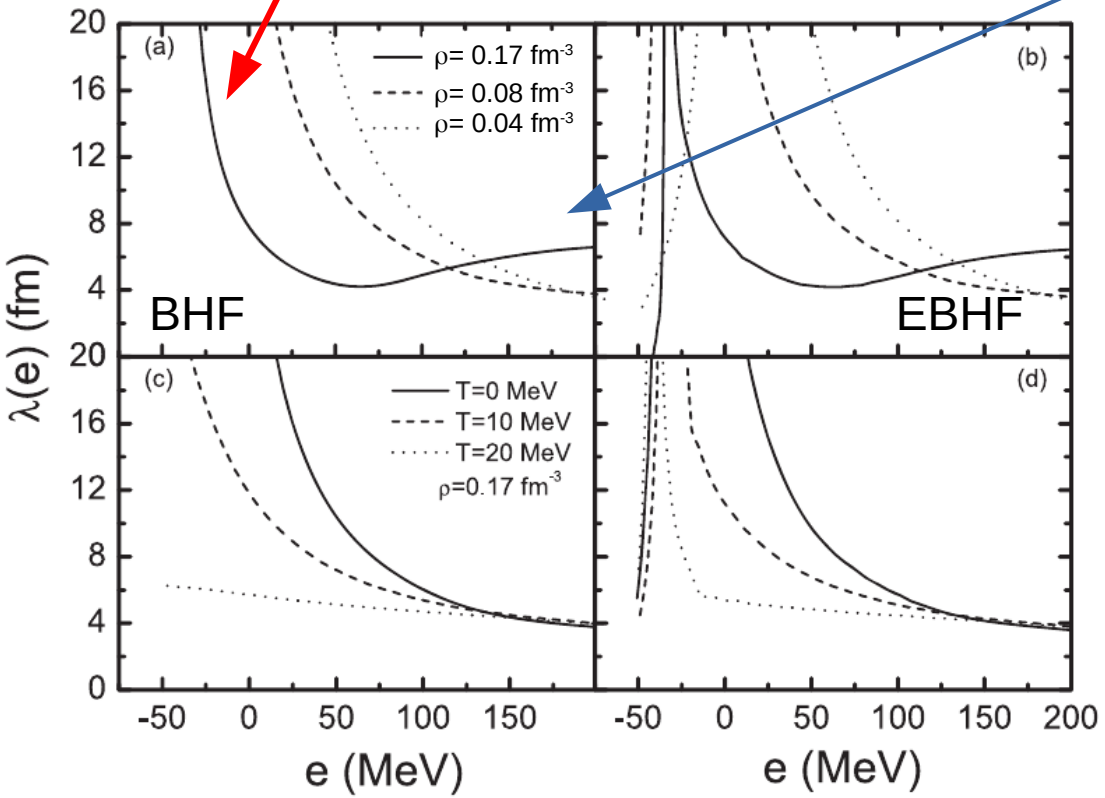
Transport properties

Energy dissipation

Energy dissipation in HIC

Mean Free Path : 2 phenomena coexist

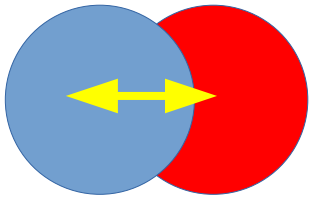
Mean-Field : 1-body dissipation
Prominent for $E_{inc}<E_{Fermi}$



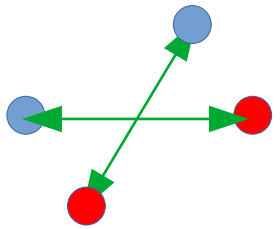
X.J. Bao, *et al.*, J. Phys. G: Nucl. Part. Phys. **41** (2014)

***NN* collisions** : 2-body dissipation
Increasingly important above E_{Fermi}

$$E_{Fermi} \approx 38\ MeV$$



1-body dissipation
below E_{fermi}
MF dissipation



2-body dissipation
above E_{fermi}
Elastic NN collisions

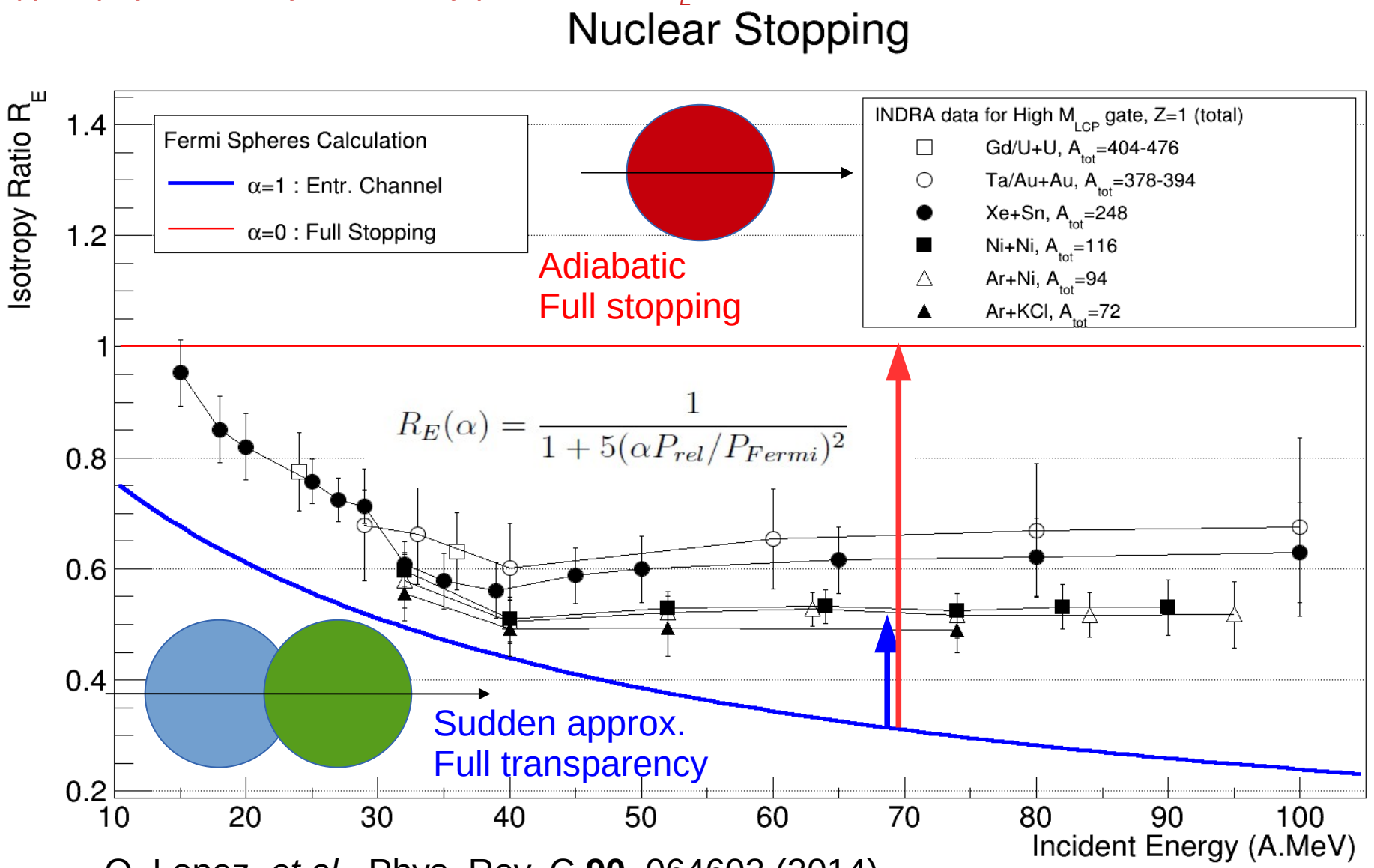
Role of **Pauli blocking** and high-order correlations between nucleons (fermions)
In-medium effects

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Probing *E* dissipation : stopping power in central *HIC*

Isotropy ratio R_E: ratio between **transverse** and **longitudinal** kinetic energies

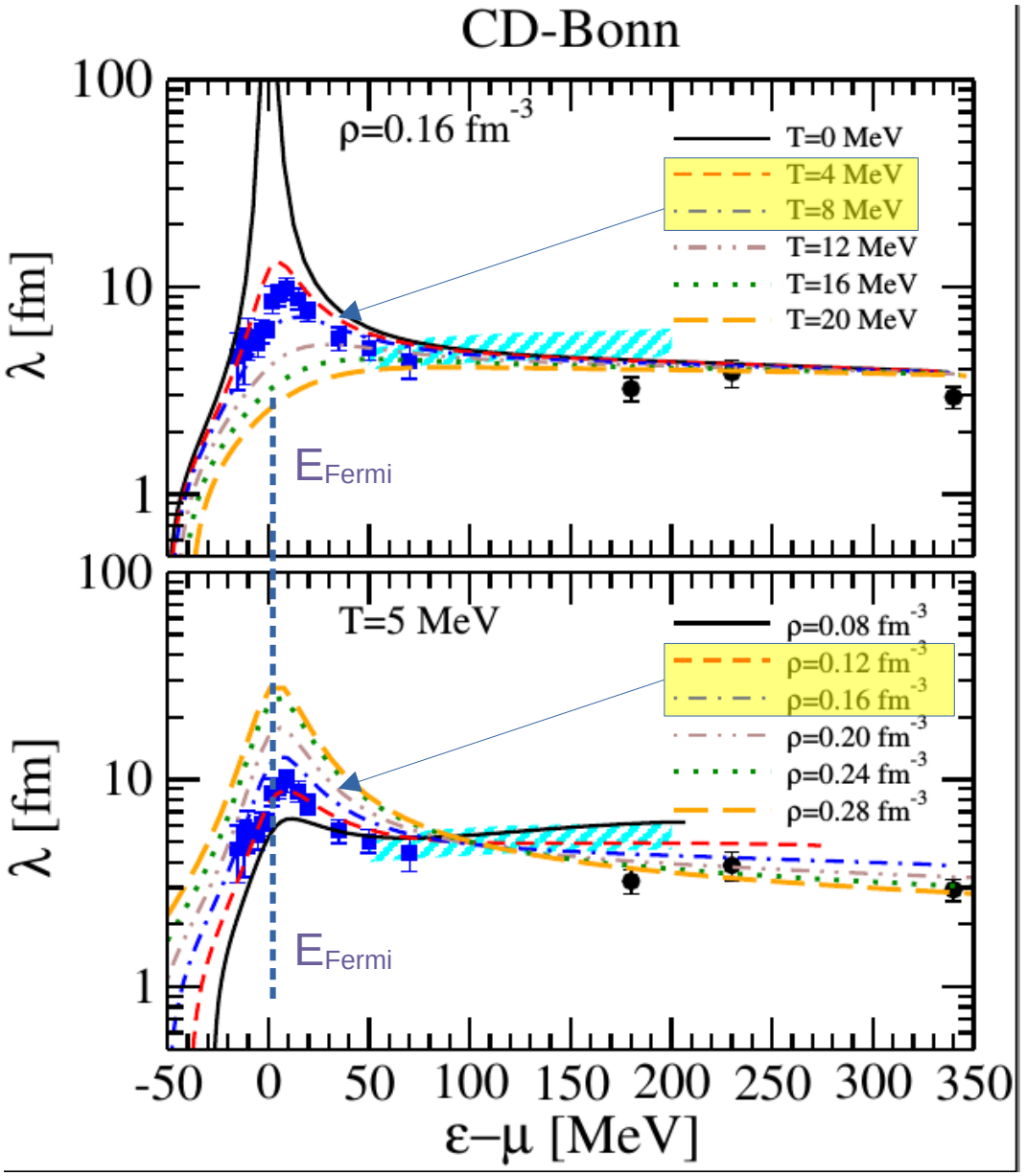
42 (quasi)-symmetric systems, only protons for $<R_E>$



O. Lopez, *et al.*, Phys. Rev. C **90**, 064602 (2014)

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Mean free path and EoS



QFT-SCGF + CD-Bonn int.
A. Rios and V. Soma, *PRL* **108**, 012501 (2016)

- Calculations at $\rho = \rho_{sat}$ for different temperatures

T= 4-8 MeV

- Calculations at ***T=5 MeV*** for different densities

ρ = 0.8-1.2 ρ_{sat}

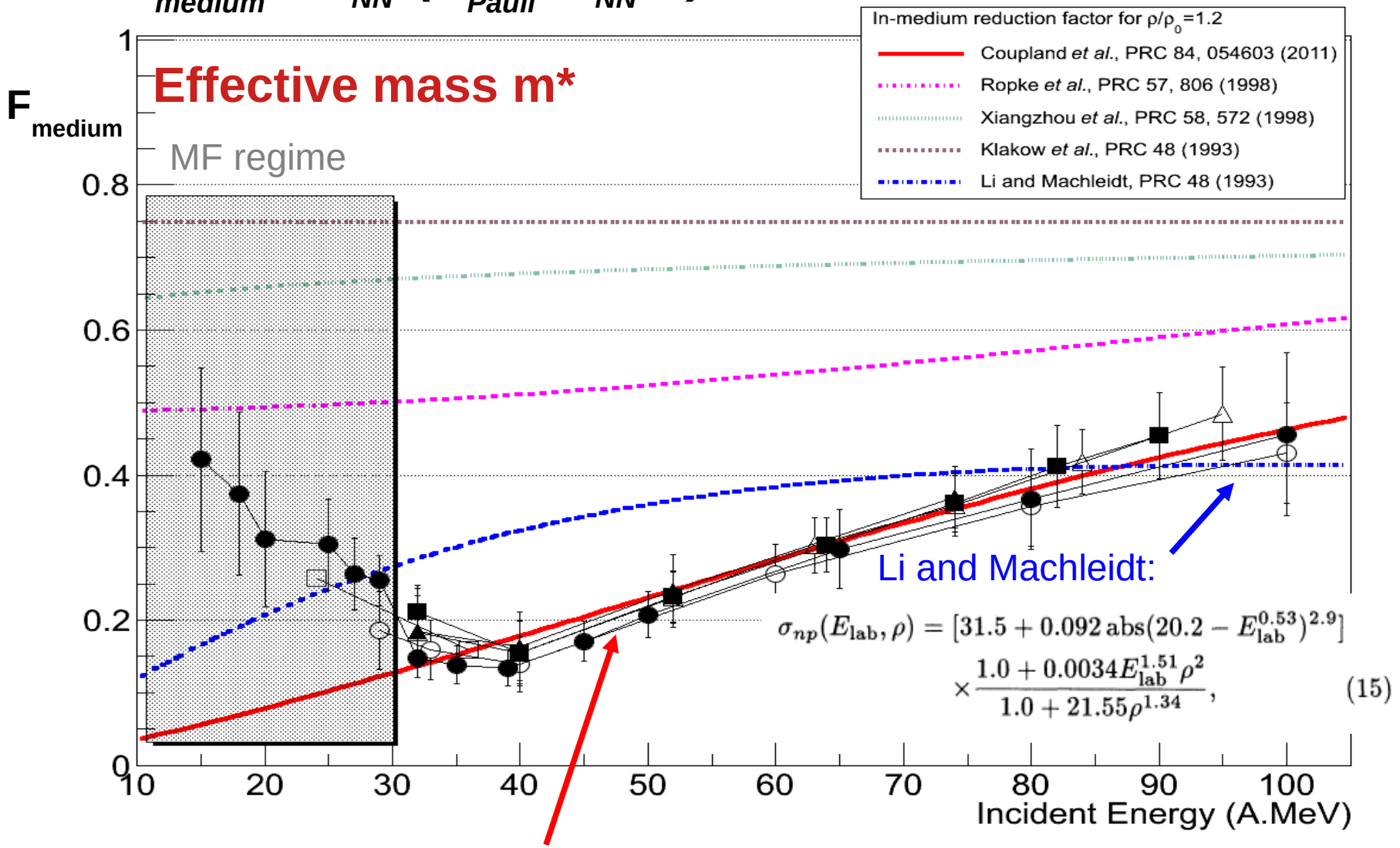
Enhanced sensitivity for $E \approx E_{Fermi}$

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Quenching factor for σ_{nn}* in nuclear medium

$$F_{medium} = \sigma_{NN}^{*}/(P_{Pauli} \cdot \sigma_{NN}^{free})$$

O. Lopez, *et al.*, Phys. Rev. C **90**, 064602 (2014)



Danielewicz (phenom.): $F = \sigma_0 \tanh(\sigma_{free}/\sigma_0)$, with $\sigma_0(mb) = 8.5/\rho^{2/3}$

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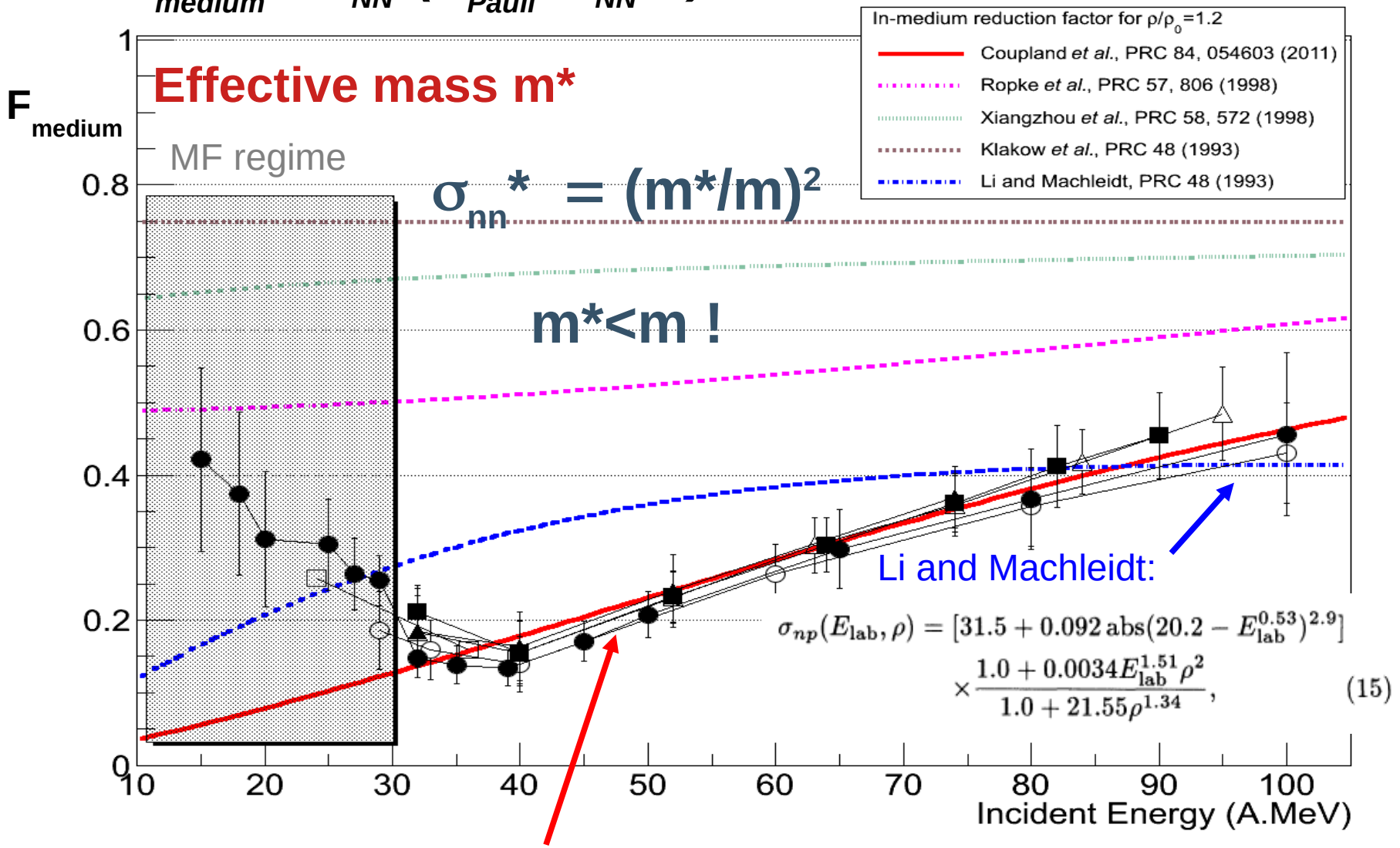
$$F_{medium} = \sigma_{NN}^{*}/(P_{Pauli} \cdot \sigma_{NN}^{free})$$

O. Lopez, *et al.*, Phys. Rev. C **90**, 064602 (2014)



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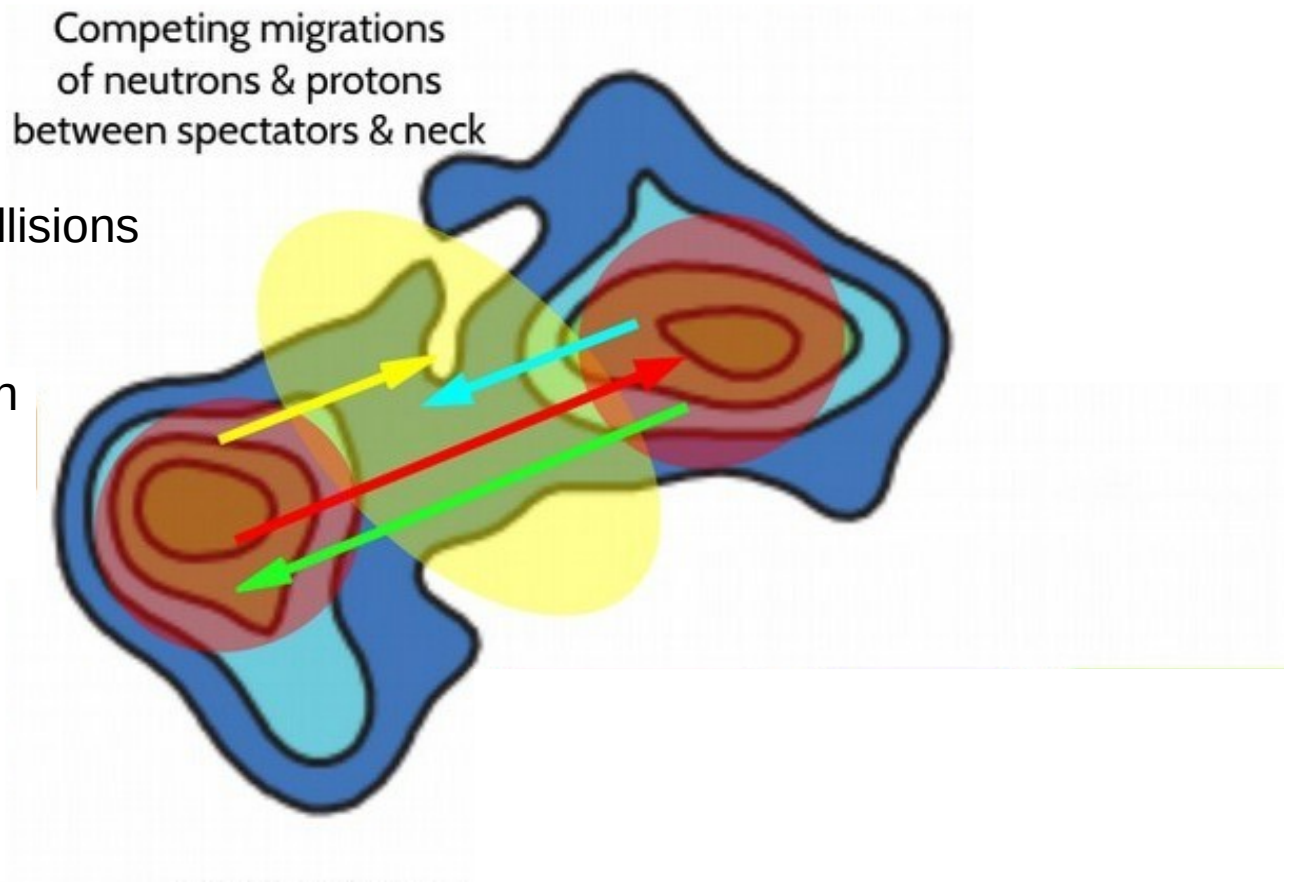
Isospin transport

Density Dependence of E_{sym} : experimental probes

Probing EOS at low density and finite temperature

Isospin transport (flux) :

$$j_n - j_p \propto E_{sym}(\rho)\nabla I - I\left(\frac{\partial E_{sym}}{\partial \rho}\right)\nabla \rho$$



Binary dissipative collisions around **Fermi energy**

Neck and QP formation

Competition between

- **Diffusion** ∇I (QP)
- **Migration** $\nabla \rho$ (neck)

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Density Dependence of E_{sym} : experimental probes

Probing EOS at low density and finite temperature

→ See T. Génard's poster

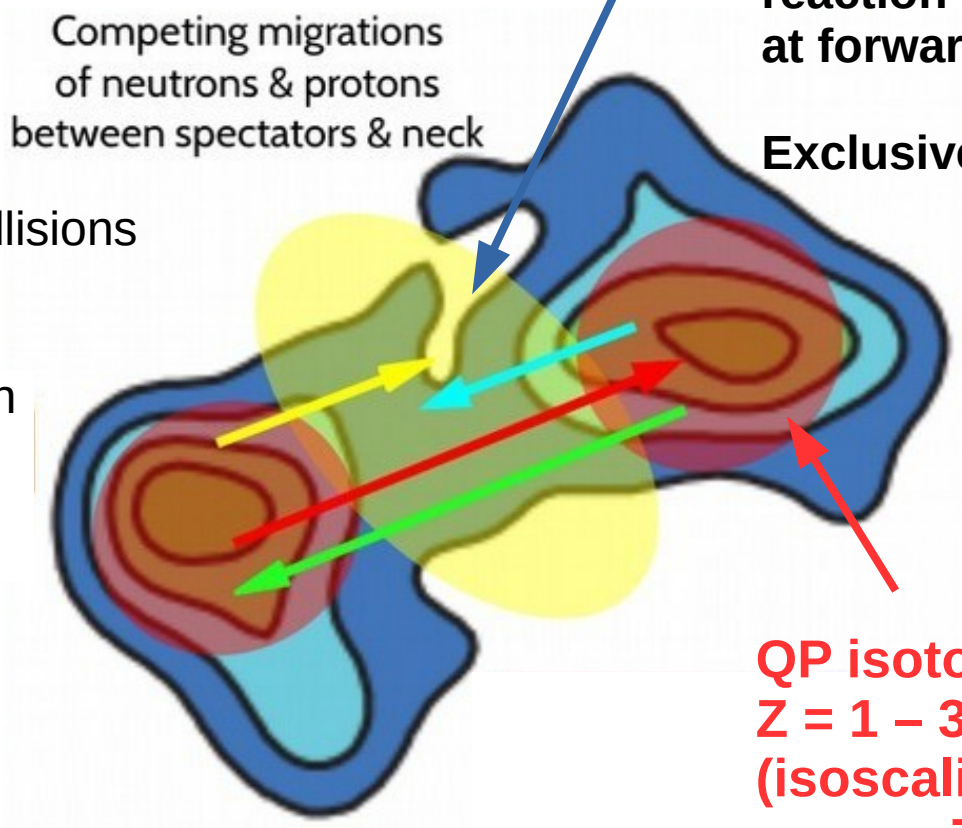
Isospin transport (flux) :

$$j_n - j_p \propto E_{sym}(\rho)\nabla I - I\left(\frac{\partial E_{sym}}{\partial \rho}\right)\nabla \rho$$

Neck isotopic content
Z = 1 – 8, A = 1 – 16 (clusters)
ρ ~ ρ_{sat}/10 , T>>0

Measuring (Z,A) for all reaction products at forward angles :

Exclusive events !



Binary dissipative collisions around **Fermi energy**

Neck and QP formation

Competition between

- **Diffusion** ∇I (QP)
- **Migration** $\nabla \rho$ (neck)

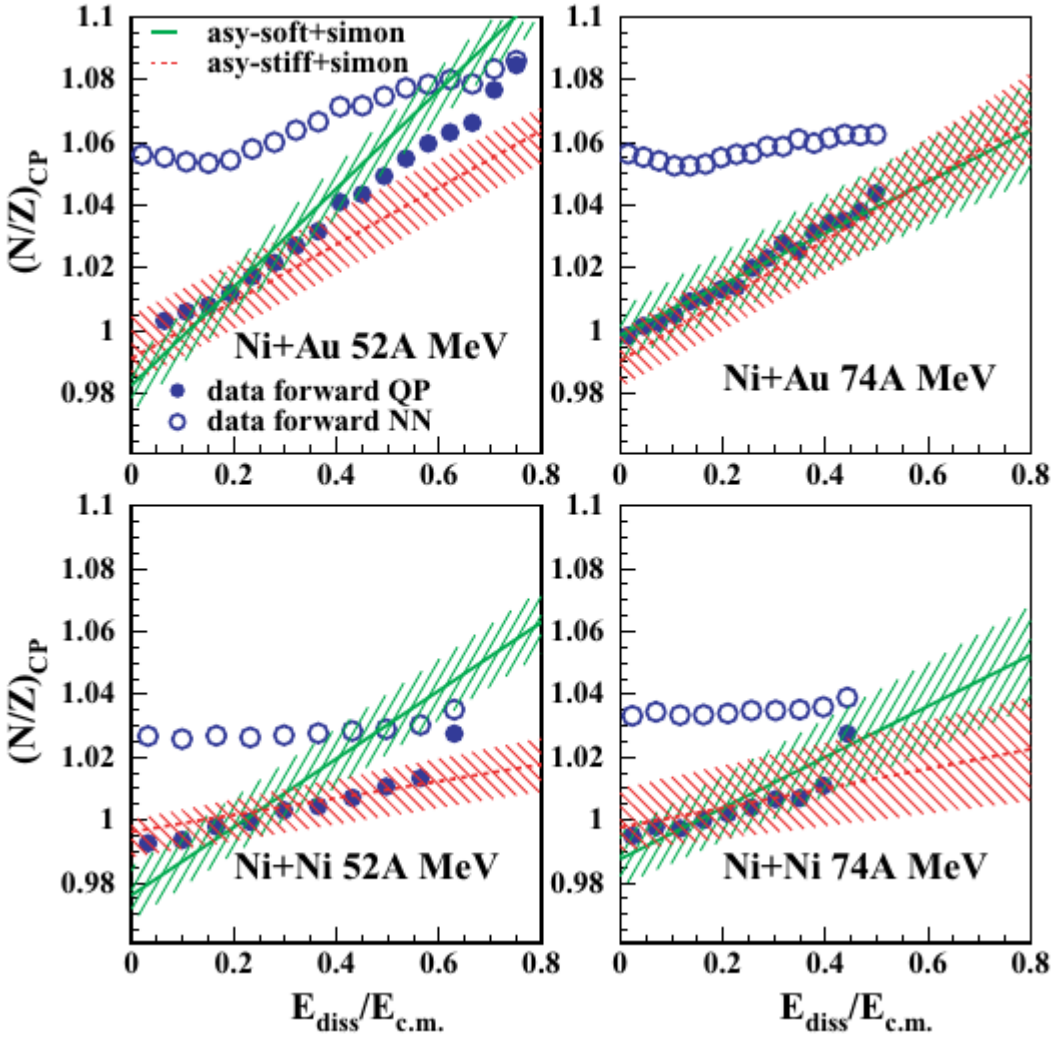
QP isotopic id.
Z = 1 – 30, A = 1 – 50 (isoscaling)
ρ ~ ρ_{sat} , T>0

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Isospin transport for semi-peripheral collisions

Isospin content for Quasi-Projectile

INDRA data, $^{58}Ni+^{58}Ni/^{197}Au$ *at E/A=52,74 MeV*
BNV simulations at *b=5 fm*



- Quasi-Ni neutron-enrichment as a function of dissipation/centrality
- **Moderatly stiff γ=1** better matches
- Isospin equilibration time:

τ_{eq} **= 130 ± 10 fm/c**

From SMF

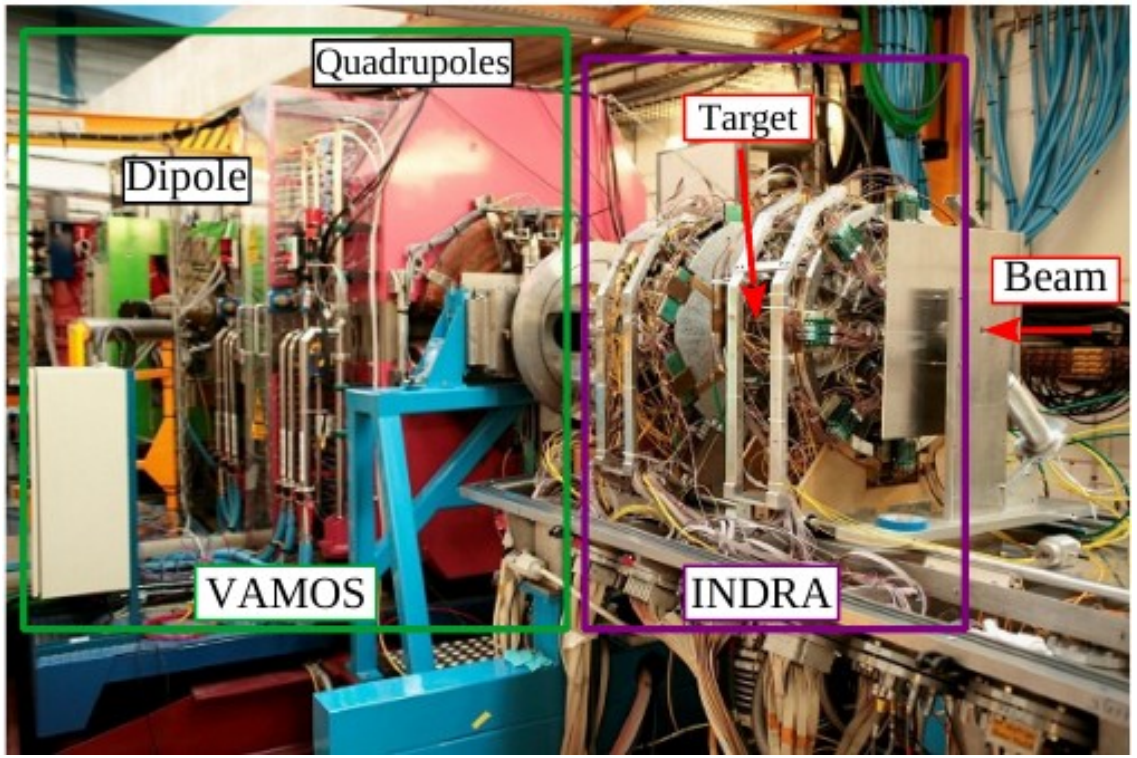
Small sensitivity
Impact parameter mixing

E. Galichet *et al.*, PRC **79**, 064615 (2009)

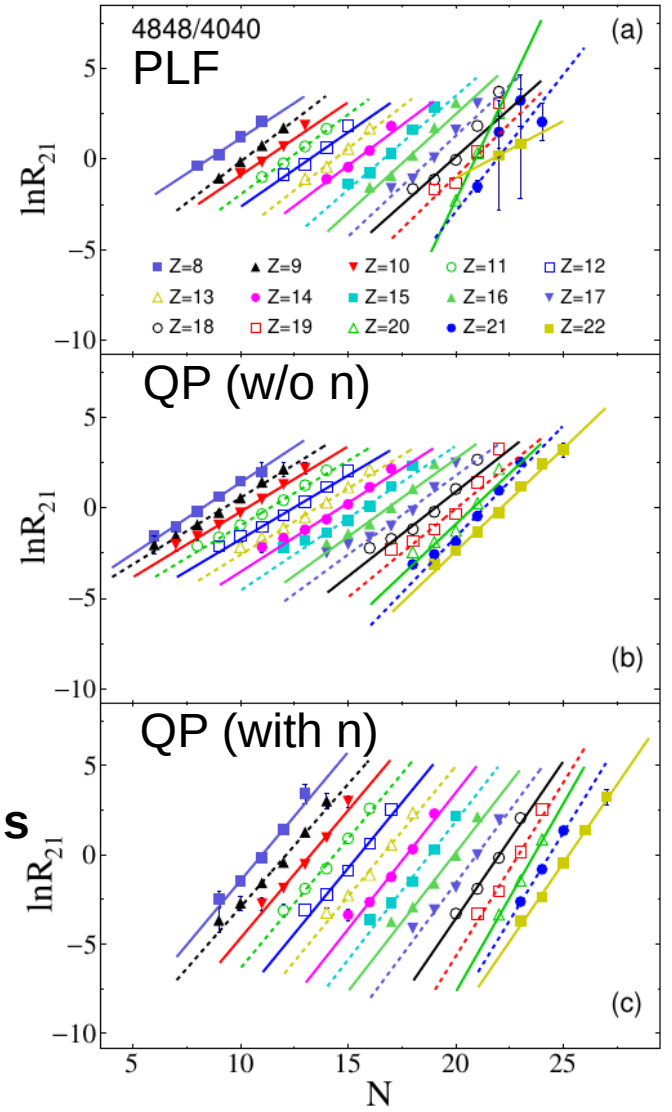
Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Isospin transport for semi-peripheral collisions

INDRA-VAMOS @ GANIL



Isoscaling $^{48}Ca+^{48}Ca$ $^{40}Ca+^{40}Ca$ 35 MeV/nucl.



Importance of QP reconstruction for isoscaling analysis

Need an event-by-event detection

Isoscaling : yield ratio Y of a given specie (N,Z)

$$R_{21}(N,Z) = \frac{Y_{(2)}(N,Z)}{Y_{(1)}(N,Z)} \propto exp\left[\alpha N + \beta Z\right]$$

Q. Fable *et al.*, Phys. Rev. C **106**, 024605 (2022)

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Isospin transport for semi-peripheral collisions

Isoscaling for projectile

Link beween isoscaling α parameter to C_{sym}
in the fragmentation regime and grand-canonical approx.:

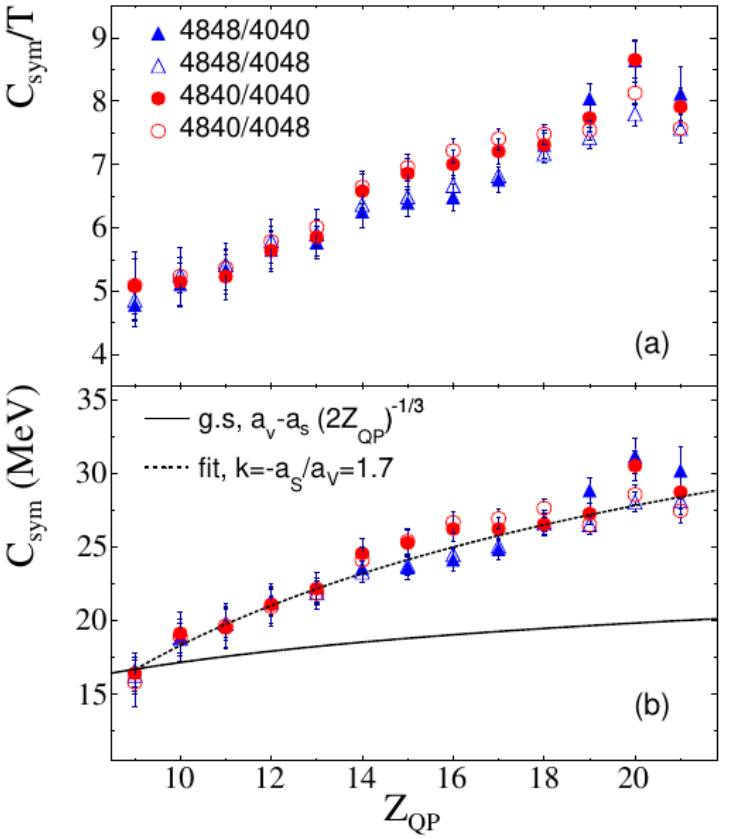
$$\frac{4C_{sym}(Z)}{T} = \frac{\alpha(Z)}{(\frac{Z}{\langle A_1(Z)\rangle})^2 - (\frac{Z}{\langle A_2(Z)\rangle})^2}$$

- C_{sym} can be obtained from isoscaling analysis

- ***AMD*** simulations: ρ / ρ_{sat} **= 0.33-0.84**

- Surface-to-volume ratio: |*as*|/*av* = *1.7*

$$C_{sym}(A) = a_v - a_s A^{-1/3}$$

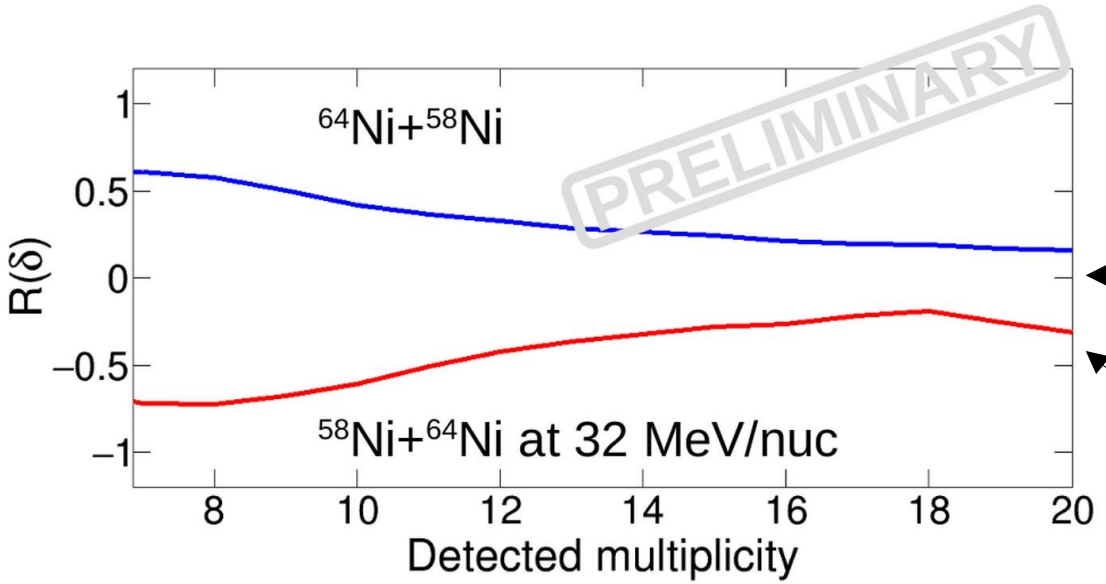


Q. Fable *et al*., Phys. Rev. C **106**, 024605 (2022)

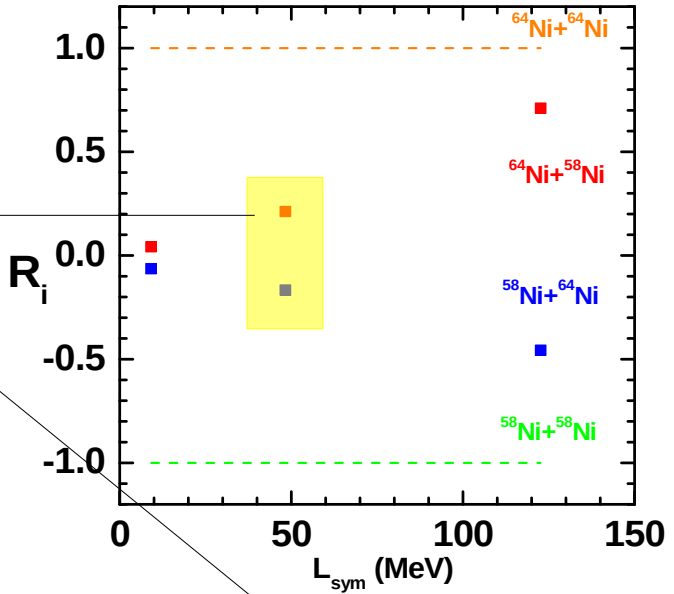
Strong surface contribution : connected to neutron skin ?

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

DDSE : toward new probes, isospin imbalance ratio



BUU, b=3 fm
S. Mallik, private comm. (2021)

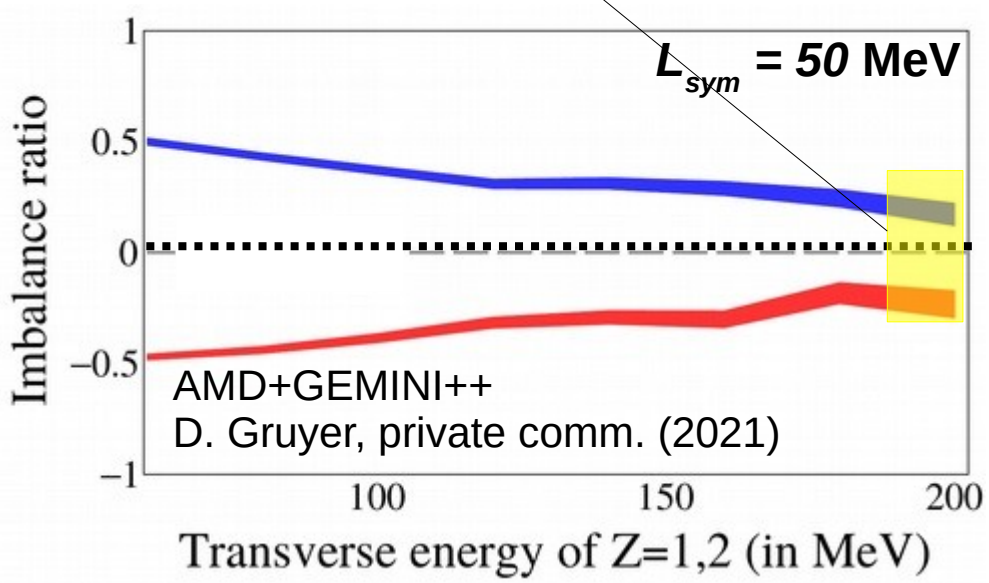


Asy-soft L_{sym}=*50 MeV* better ?

BUT :

Different centrality selections ...

→See J. Lemarié's poster



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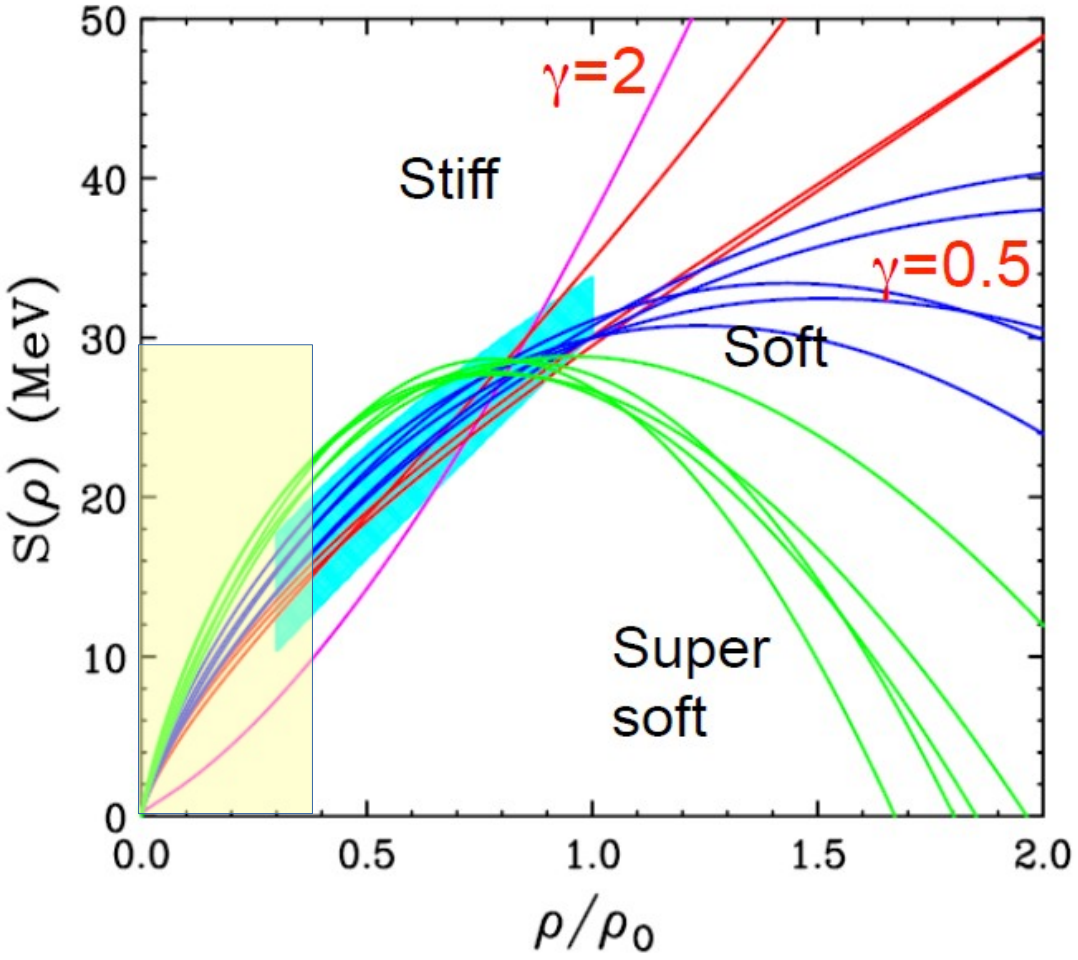
Probing the isovector dependence of EoS

Isospin Physics

Symmetry energy for $\rho \ll \rho_0$

M.B. Tsang, Prog. Part.Nucl.Phys. 66, 400 (2011)
Brown, Phys. Rev. Lett. 85, 5296 (2001)



$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

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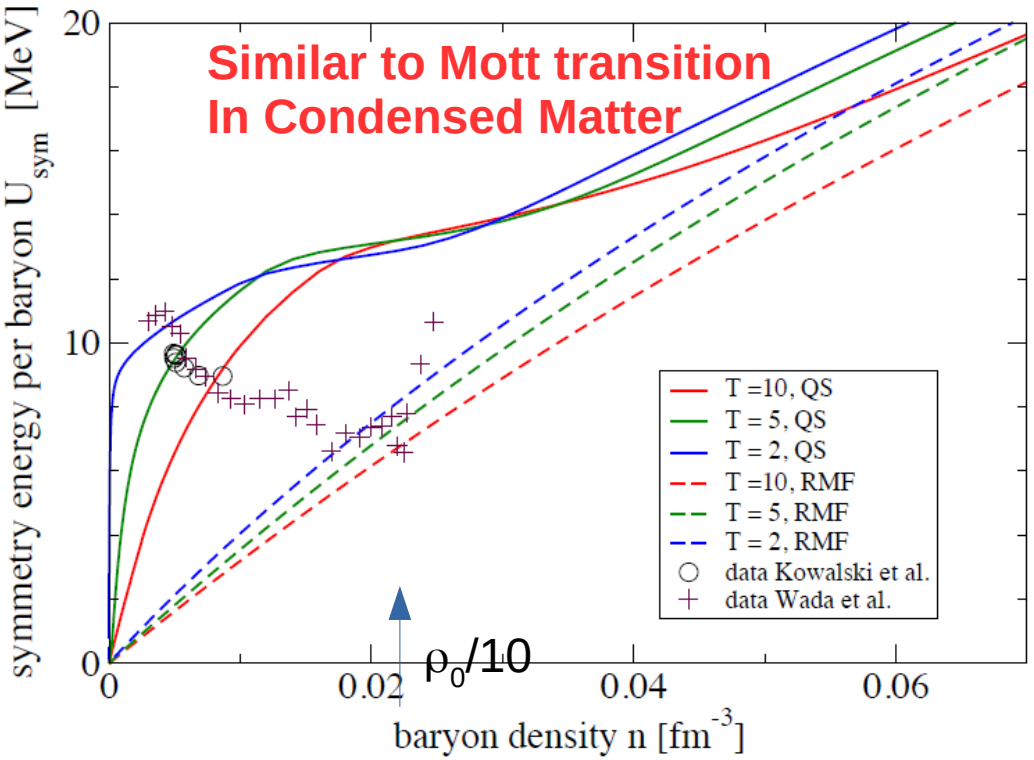
Symmetry energy for $\rho \ll \rho_0$

Prediction for the nuclear EOS : symmetry energy at subsaturation density ($\rho<\rho_0/10$) and finite temperature (*T=1-10 MeV*)



Data versus

- **Relativistic Mean Field** (*RMF* without cluster)

- **Quantum Statistical Model** (*QSM*)

K. Hagel, J.B. Natowitz, G. Röpke
Eur. Phys. Journal A **50** (2014) 39

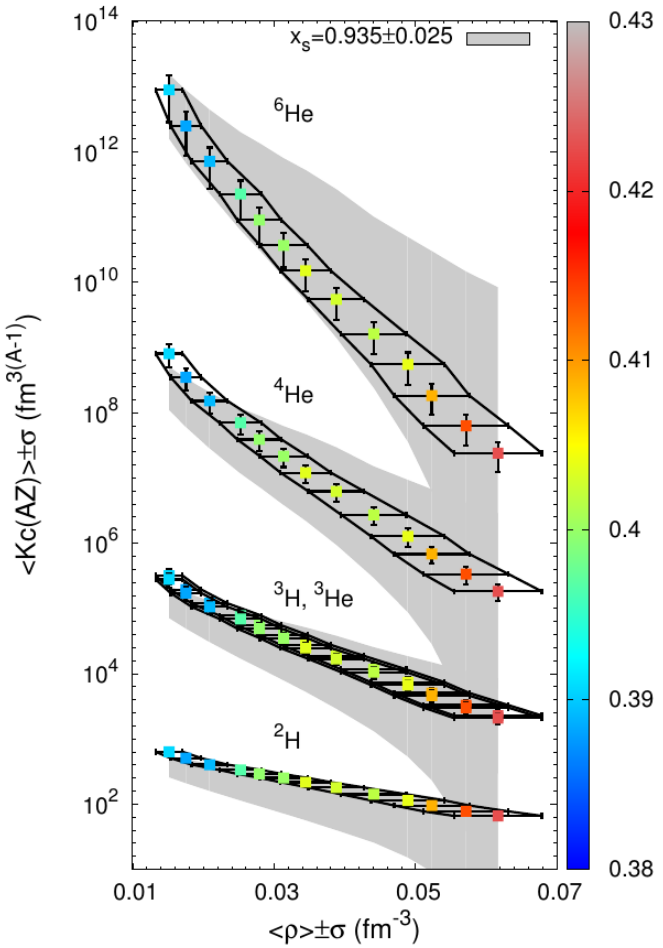
S. Kowalski, *et al.*, PRC **75**, 014601 (2007)
R. Wada, *et al.*, PRC **85**, 064618 (2012)

Relativistic Mean field (no clusters): linear decrease of E_{sym}
QSM : formation of clusters leads to an increase of E_{sym} at (very) low densities

In-medium cluster properties as a function of ρ,*T* and *N/Z*

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

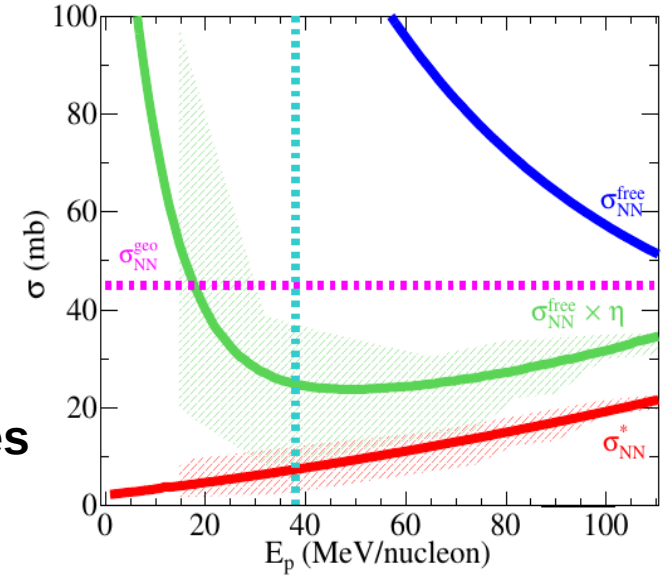
In-medium properties ...



Chemical Equilibrium constants in nuclear medium:
Cluster production at low density
→ **Astrophysics, CCSNe**

H. Pais, R. Bougault *et al.*, Phys. Rev. Lett. 125, 012701 (2020)
R. Bougault, E. Bonnet *et al.*, J. Phys. G 47(2), 025103 (2020)
H. Pais, R. Bougault *et al.*, J. Phys. G 47(10), 025204 (2020)

Experimental determination of σ_{NN}^*:
→ **Transport models, viscosity, effective masses**



M. Henri, O. Lopez *et al.*,
Phys. Rev. C **101**, 064622 (2020)

E818 experiment @ GANIL : ^{36}Ar/^{58}Ni + ^{58}Ni à 74 MeV/nucléon
Performed April-May 2022

→ See A. Rebillard-Soulié's poster

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

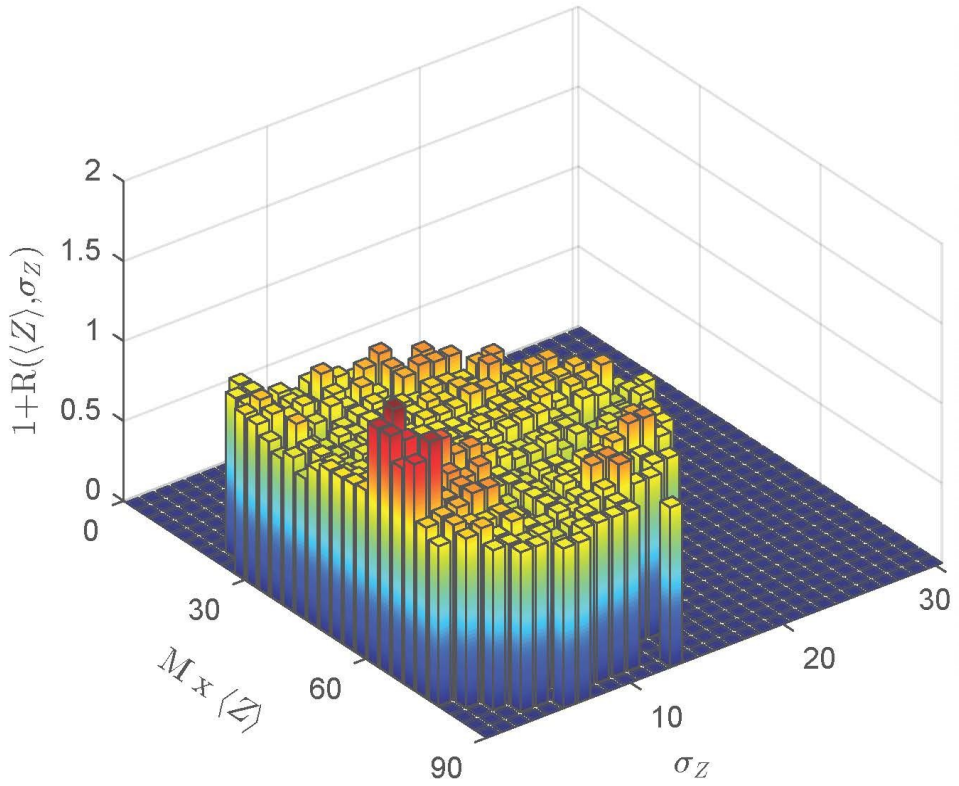
Spinodal decomposition: isoscalar *vs* isovector instabilities

Same analysis done for *central* events

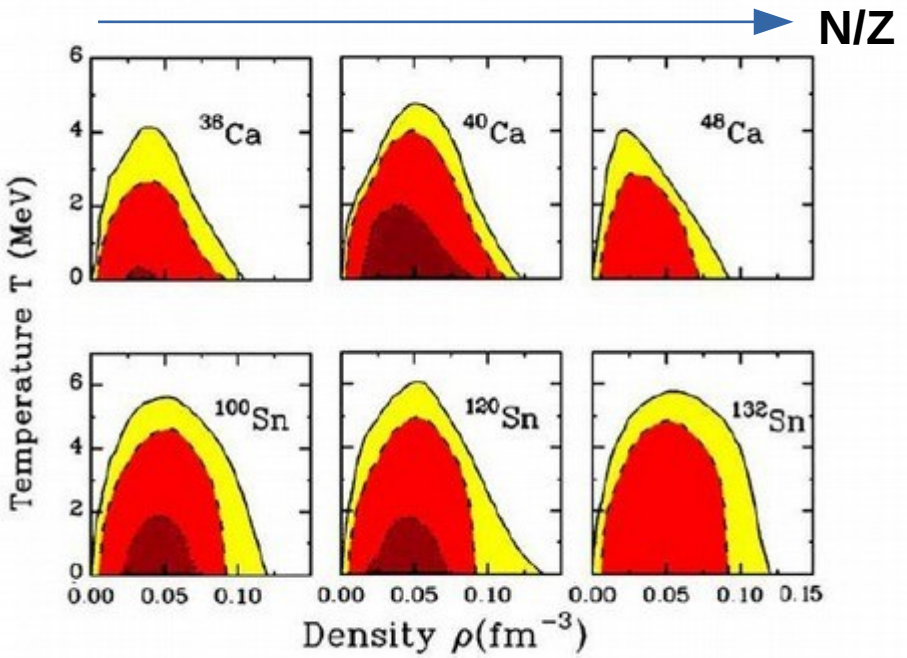
^{124}Xe+^{112}Sn @ 32A,45A MeV
^{136}Xe+^{124}Sn @ 32A,45A MeV

B. Borderie *et al.*
(INDRA Coll.)
PLB 782 (2018)

Spinodal instabilities are indeed reduced in neutron-rich matter !



Spinodal region is reduced



Better with size correlations (A)

- **Equal-sized** fragments are **over-produced**
- Statistical confidence is **largely enhanced** (*10x* statistics) to overcome the **5σ limit** ...

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Experimental tools and instrumentation

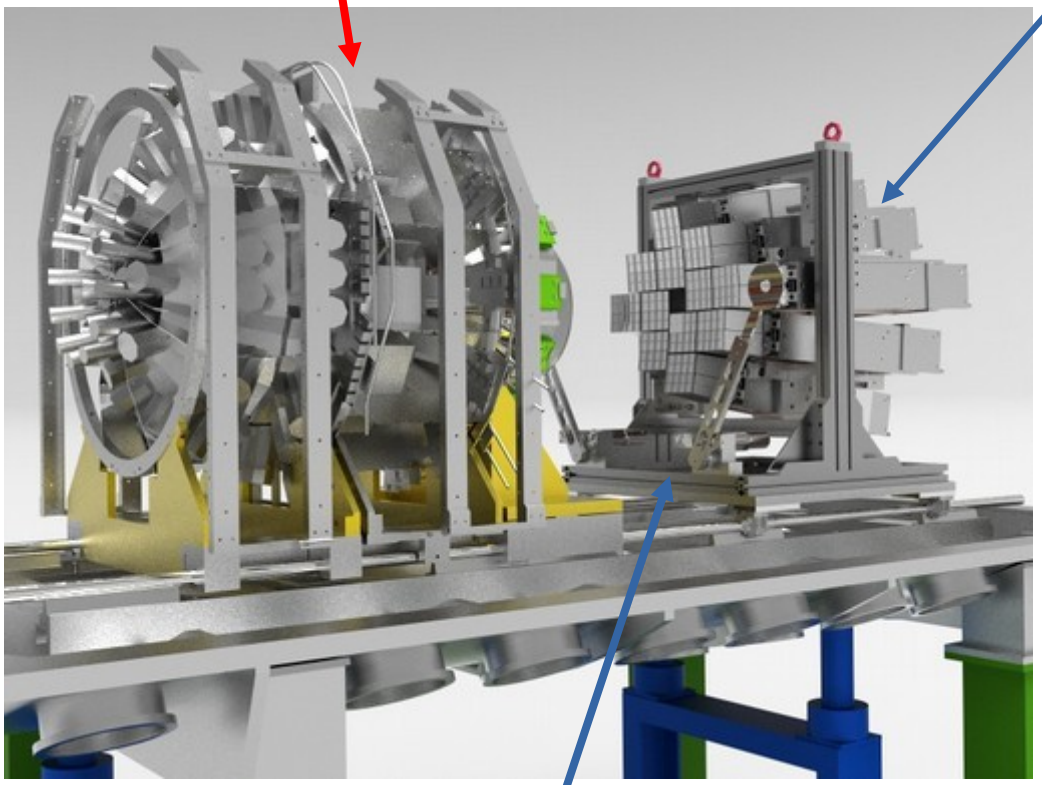
Coupling FAZIA demonstrator with INDRA@GANIL

$^{58/64}$Ni + $^{58/64}$Ni @ 32 and 52 MeV/nucl : E789 performed in 2019

INDRA in *D5*

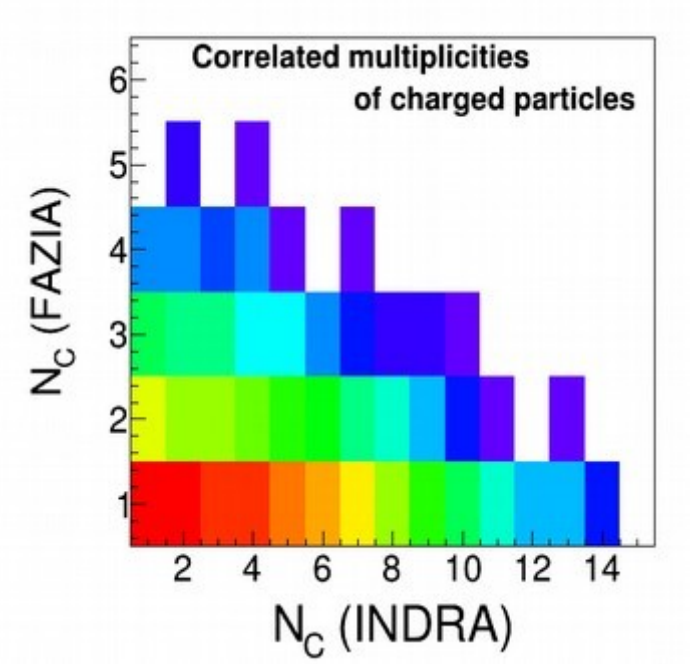
- - 240 detection modules (rings 1,2/3,4/5 removed)
- - 96 Si-CsI from 16 to 45 deg.
- - 144 CsI from 45 to 176 deg.

FAZIA geom. acceptance *82%* (*90%*)
Granularity *x2* as compared to *INDRA*



FAZIA demonstrator: *12* blocks of *16* telescopes
192 **High-Quality *Si-Si-CsI*** telescopes
from *2* to *14* deg. + dedicated **Full Digital Electronics**

Beam Tests in June-July 2018

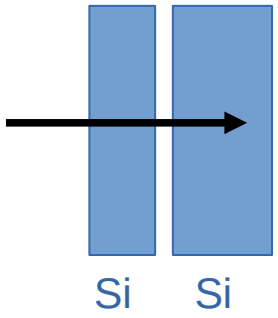


Experiment E789 performed at GANIL in April-May 2019 :

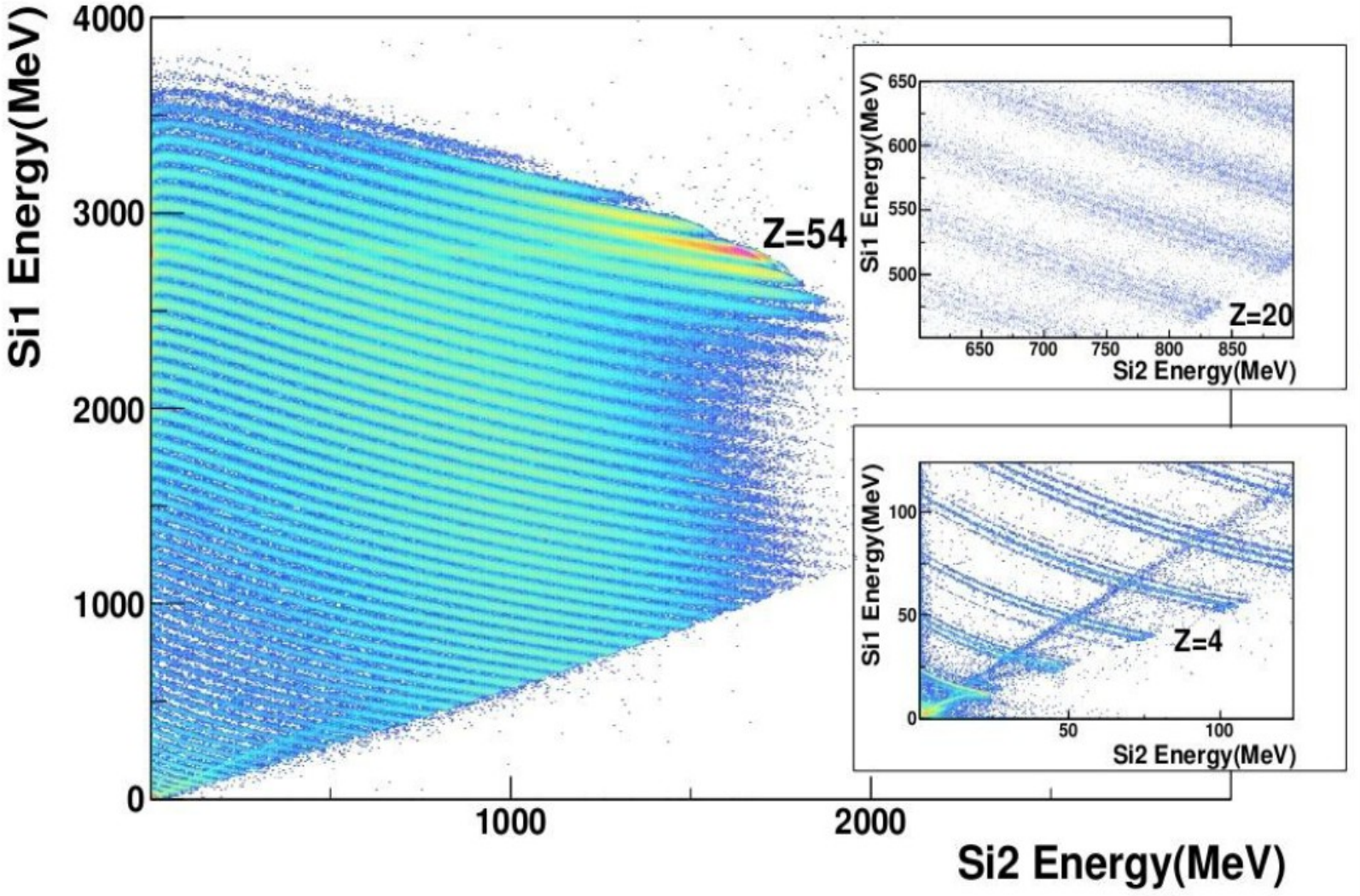
$^{58/64}$Ni+$^{58/64}$Ni @ 32,52 MeV/nucleon

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

FAZIA : *ΔE-E* identification



Some results at the end of phase 1: ΔE(Si1) – E (Si2)

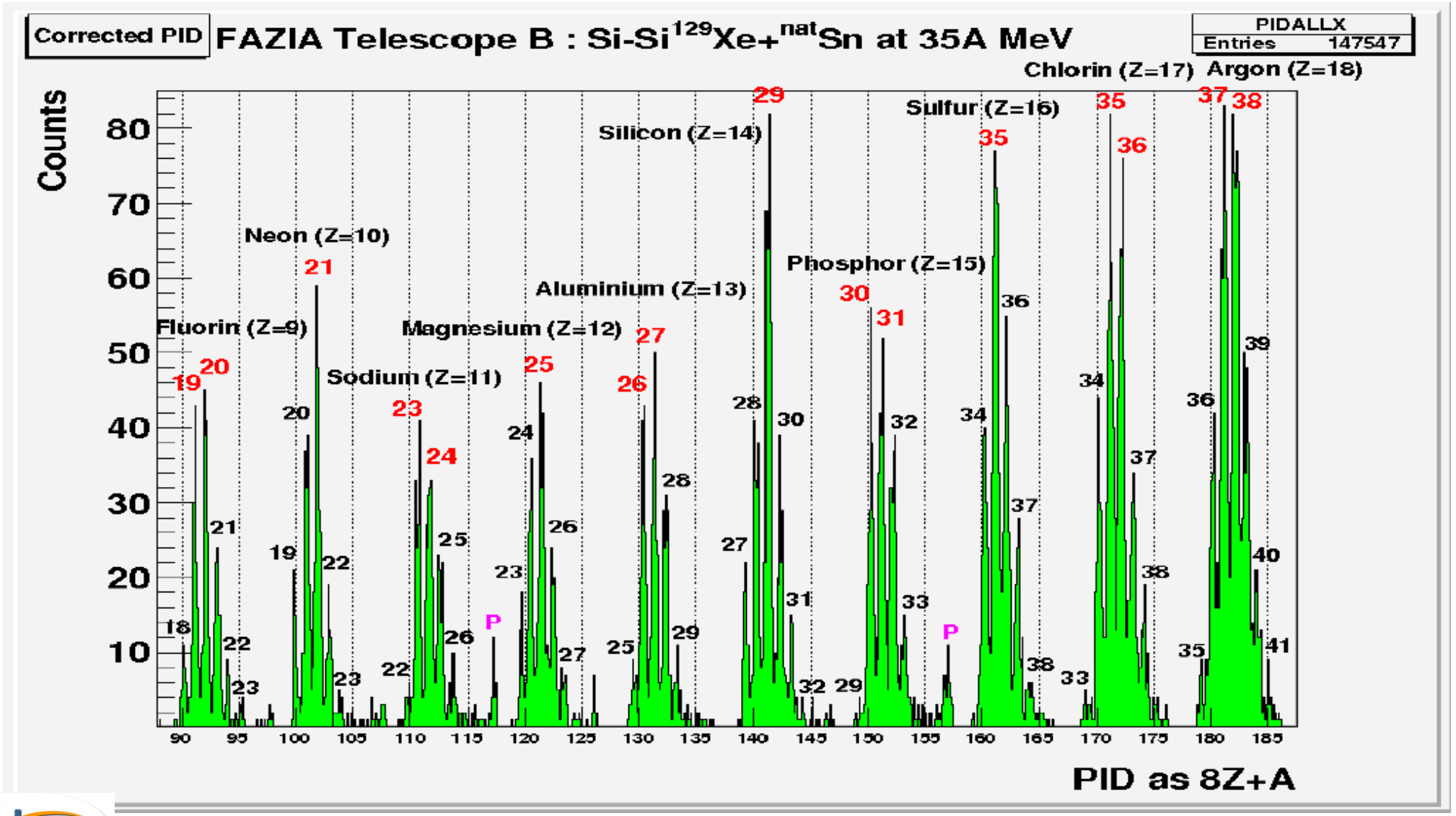


S.Carboni et al., NIMA 664 (2012) 251 **Energy = max of shaped signal (trapezoidal filter)**

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

FAZIA improvements for *ΔE-E* identification

Improving **standard *E-ΔE*** identification method up to ***Z=25-30*** !



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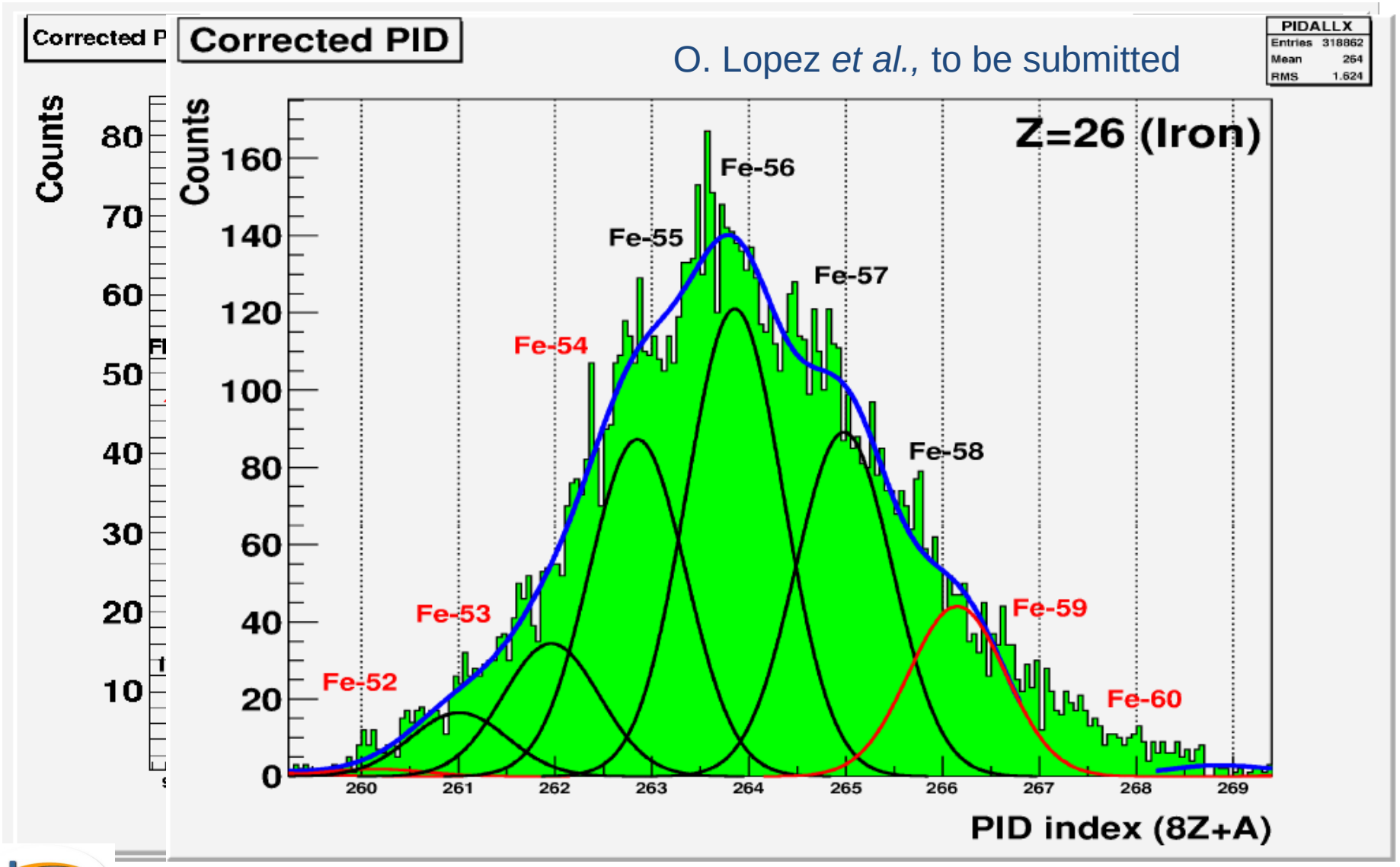
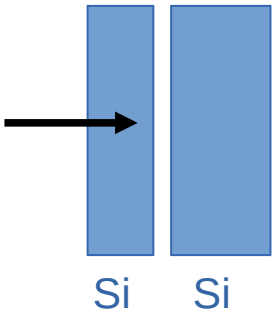
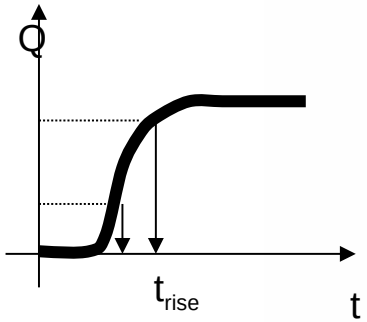


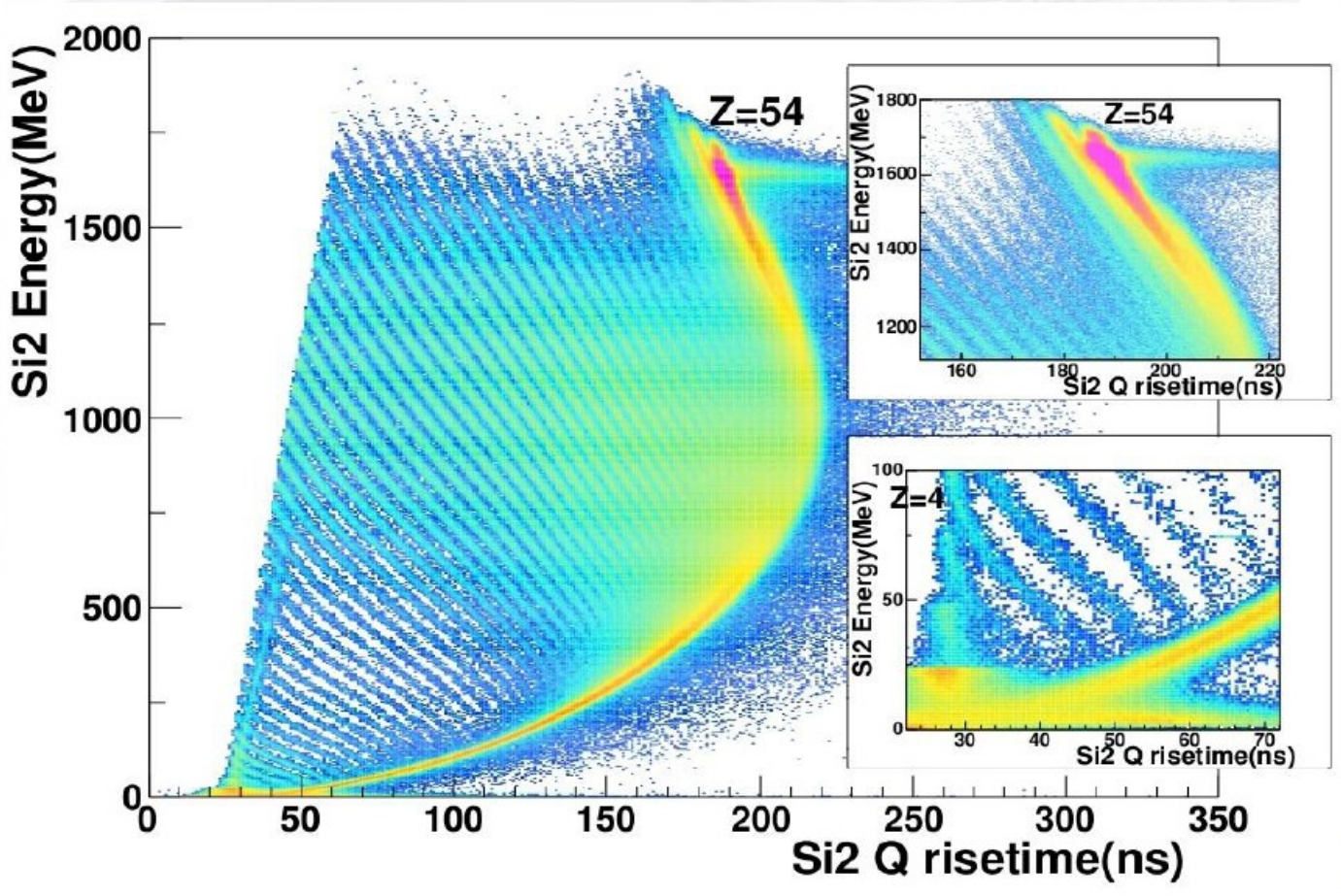
Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

FAZIA : Pulse Shape Analysis



Some results at the end of phase 1:
Pulse Shape Analysis from E – Charge Rise Time

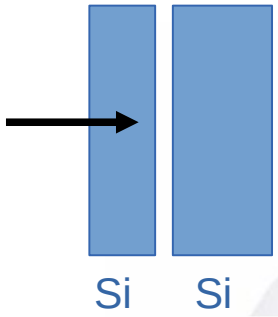




S.Carboni et al., NIMA 664 (2012) 251

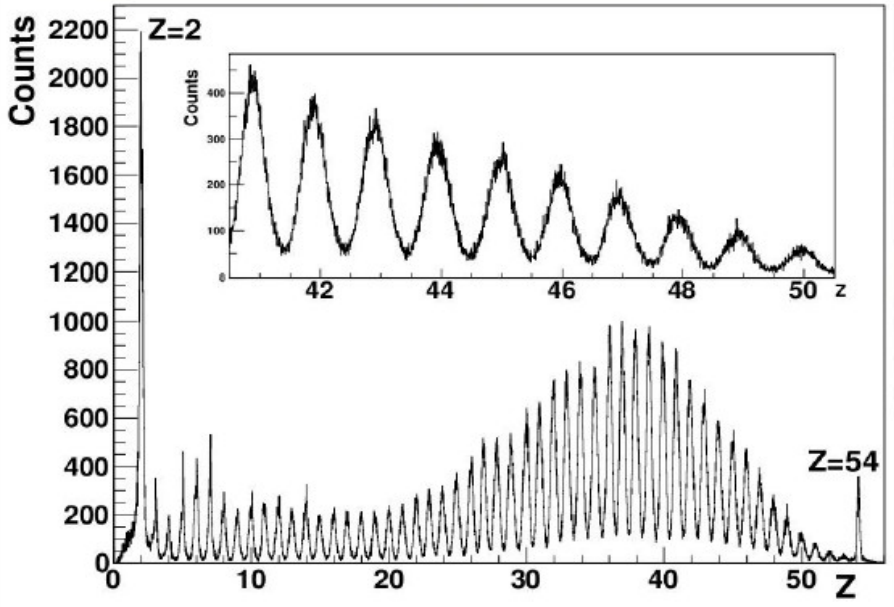
Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

FAZIA : Pulse Shape Analysis

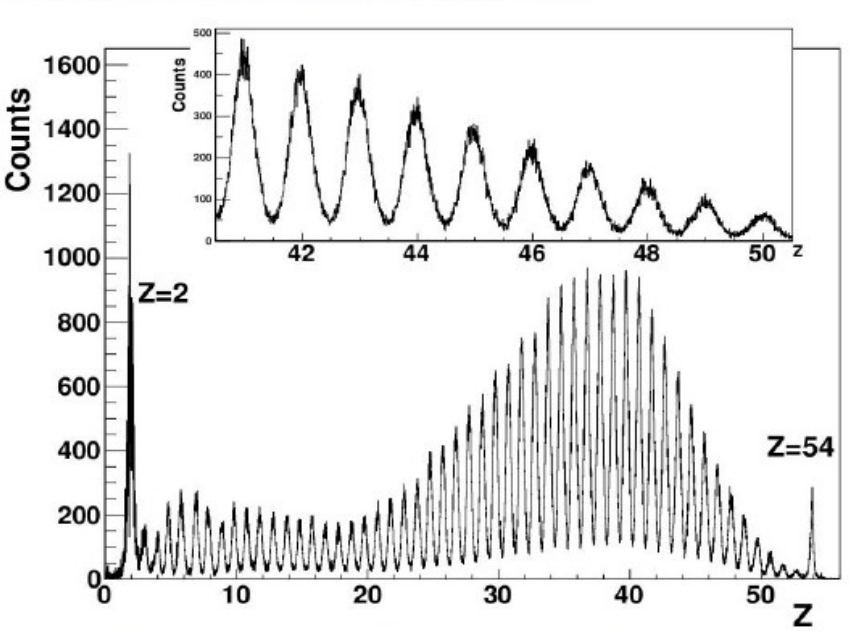


Some results at the end of phase 1: Particle Identification from Pulse Shape Analysis

Energy vs. charge rise time



Energy vs. maximum of current signal



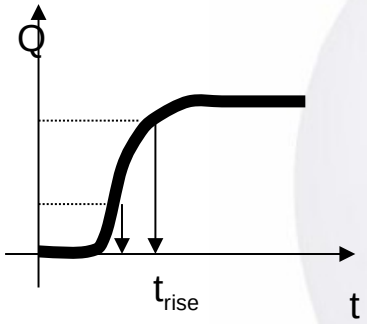
- *Z* identification can be achieved in the **first Silicon** detector

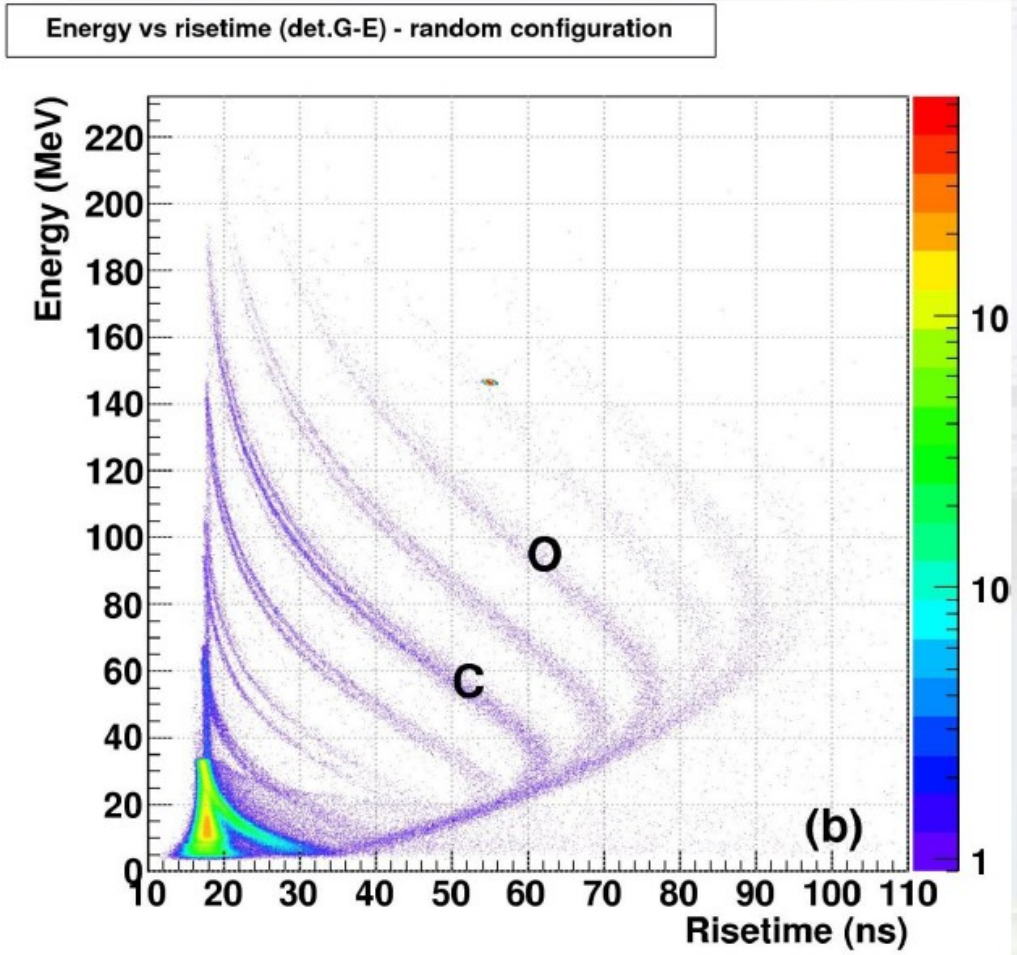
S.Carboni et al., NIMA 664 (2012) 251

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

FAZIA : Pulse Shape Anaysis

Some results at the end of phase 1: Mass resolution from Pulse Shape Analysis Energy vs. charge rise time





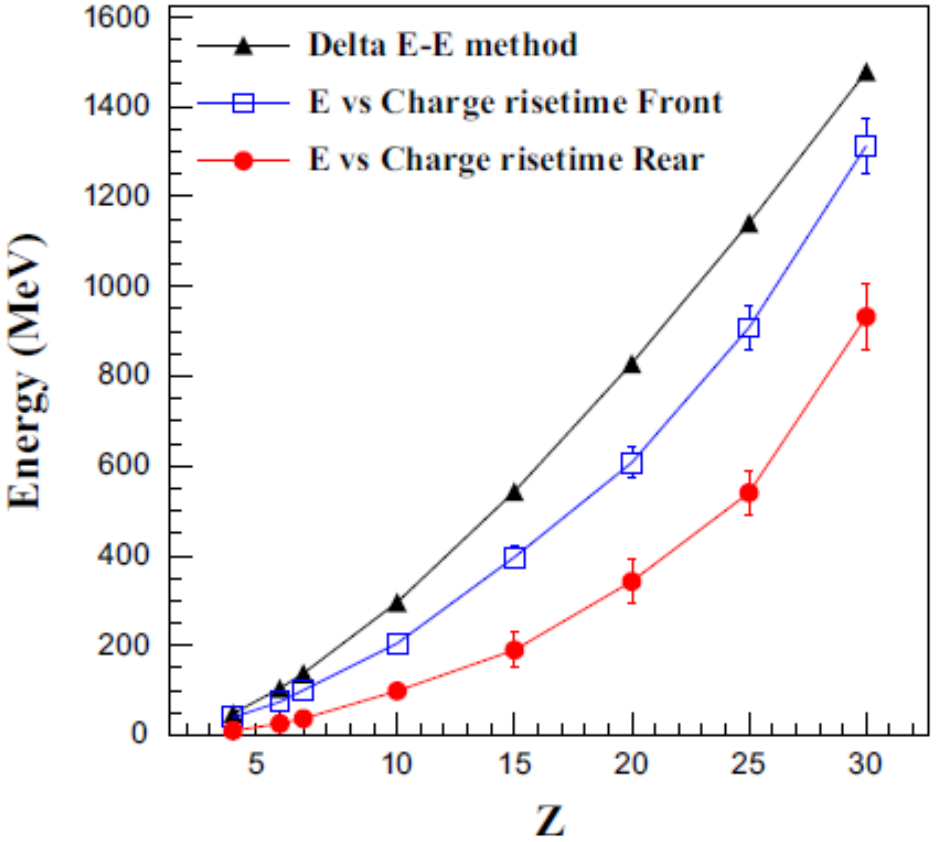
High gain
^{32}S beam@473MeV

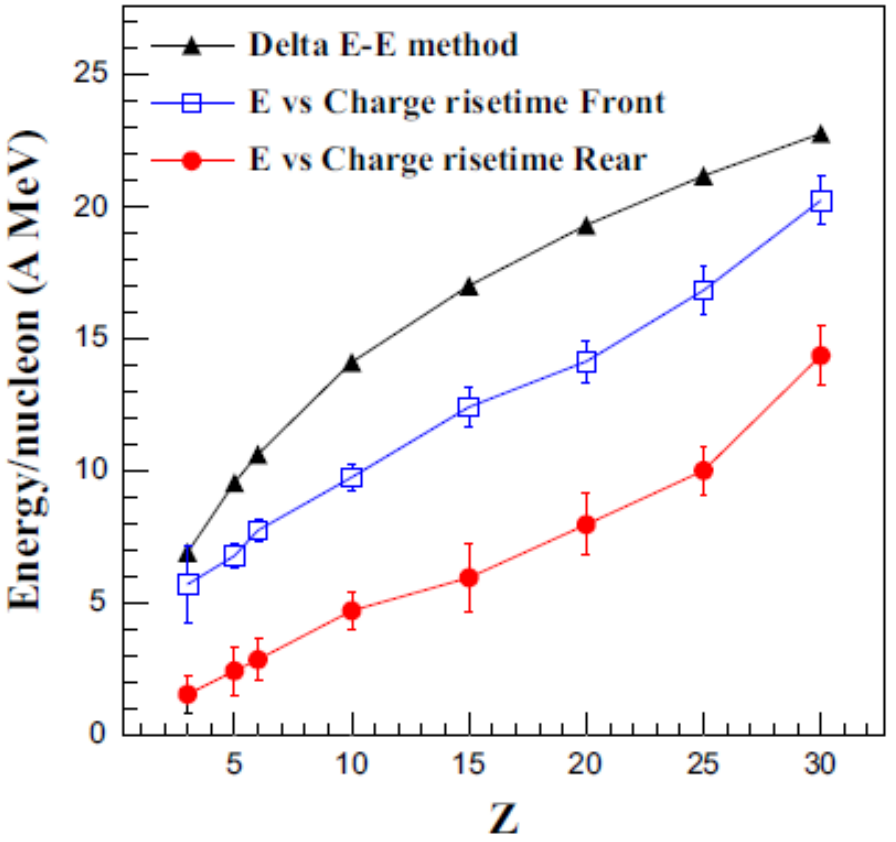
L.Bardelli et al., NIMA 654 (2011) 272

➢ Isotopic identification for **Z=3-8**

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

FAZIA : ID thresholds (Z)





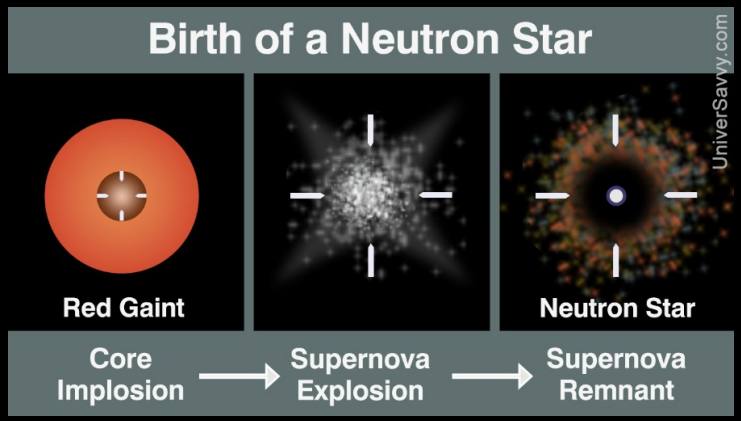
- **Pulse Shape Analysis** lowers significantly the Z (and A) thresholds
- **Rear-side** injection (low Electric Field entrance) is preferred
- **« dead » range** in Silicon is between ***30*** and ***150 μm*** for ***Z=30***

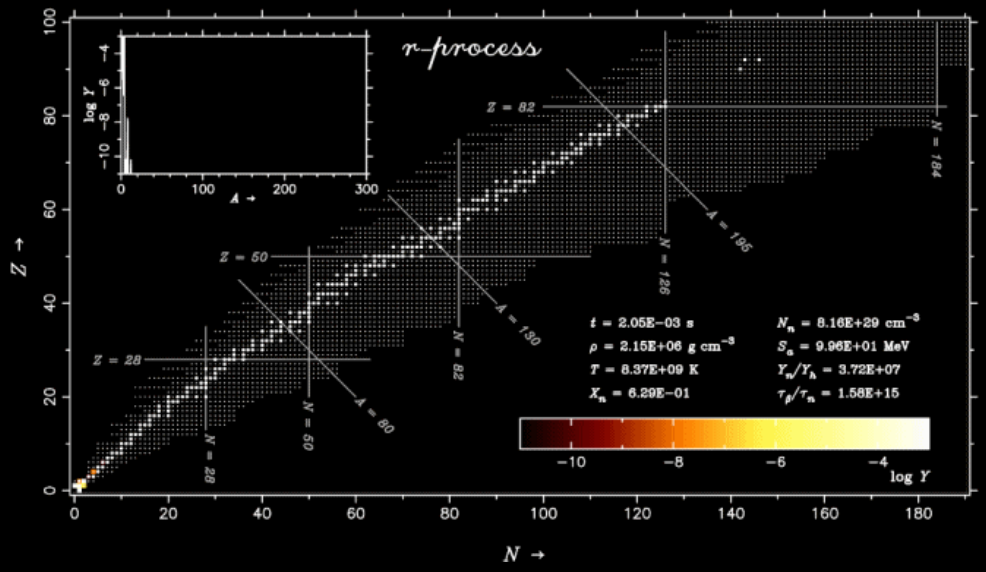
N. Le Neindre *et al.*, NIM A 701(2013) 145–152

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Nuclear *EOS* in Astrophysics

Neutron Stars (*NS*) are unique systems for investigating dense nuclear matter !





B.P. Abbott *et al.* (LIGO/VIRGO),
PRL **116**, 061102 (2016)
PRL **119**, 161101 (2017)

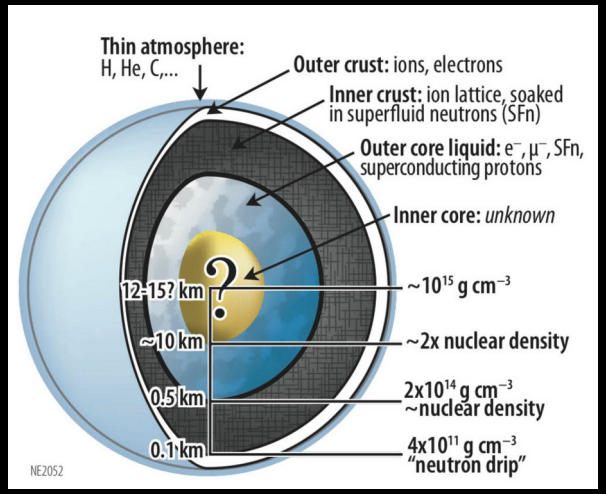
Detection of *GW* and multi-messenger observables (GW170817) considerably reinforces terrestrial *EOS* studies

Core Collapses Sne

- *EoS* (isoscalar/isovector) : **shock waves**
- E_{sym} : ***r*-process** and **nucleosynthesis**
- Cooling : *d-URCA* and **Neutrinosphere** (low density nuclear matter)

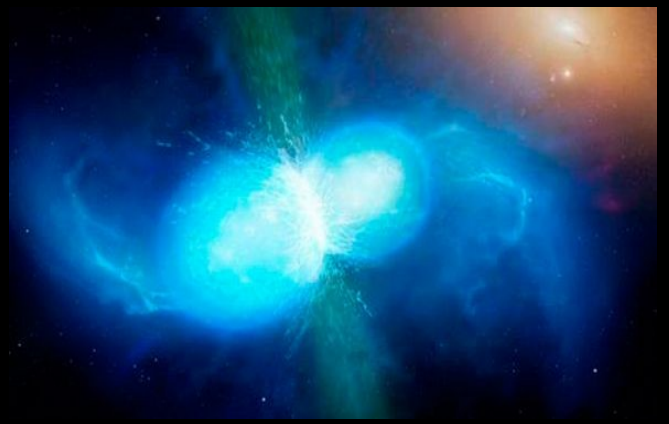
NS structure :

- Crust : **pasta phases** (frustation/**clusters**)
- Crust/Core transition: $\boldsymbol{L,K_{sym}}$
- Core : **hyperons** (strange matter, QCD)



N. Yunes, M. Coleman Miller, and K. Yagi,
Nature Review Physics **4**, 237 (2022)

NS- NS merger (Kilonova)



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Conclusions

Large diversity of reaction mechanisms between 5 – 100 MeV/nucleon

Produce many different nuclear systems :

- in terms of ρ, E^*, T, J, δ
- variety of conditions for the EOS characterization

Allow the production and study of exotic nuclei :

- direct/transfer reactions: probing effective interactions in nuclei, quantum shells
- multi-nucleon transfer and deep inelastic scattering : toward large N/Z excursion
- multifragmentation : phase transitions, order, latent heat and criticality
- complete/incomplete fusion : toward superheavy nuclei

Mimick violent phenomena in Astrophysics of compact objects :

- Core Collapse of Supernovae: CCSNe
- Neutron stars mergers + multi-messenger astrophysics (GW+EM): NS-NS, X-ray bursts
- Stellar and extra-stellar nucleosynthesis: r-, p-,s-processes

Investigate EOS at low density and phase transitions in strongly corr. systems :

- EOS at low densities
- Density and Isospin Instabilities: LG coexistence regions, spinodal decomposition
- finite (nuclei) vs infinite (NS): finite-size effects

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Some references

- D. Durand, B. Tamain, and E. Suraud, *Nuclear Dynamics in the Nucleonic Regime* (Institute of Physics), New York, 2001

- F. Gulminelli, W. Trautmann, S. J. Yennello, and Ph. Chomaz, *Dynamics and thermodynamics with nuclear degrees of freedom*, Eur. Phys. J. A 30, 1 (2006).

- Ph. Chomaz, M. Colonna, and J. Randrup, *Mean-Field instabilities in the Fermi energy regime*, Phys. Rep. 389, 263 (2004)

- B. Borderie *et al.*, Prog. in Part. Sci. and Nucl. Phys. 61, 551 (2008)

- R. Bougault *et al.* (FAZIA Collaboration) Eur. Phys. J. A 50 (2014) 47

More infos and also scientific outreach contents :

https://www.lpc-caen.in2p3.fr/en/lpc-caen/

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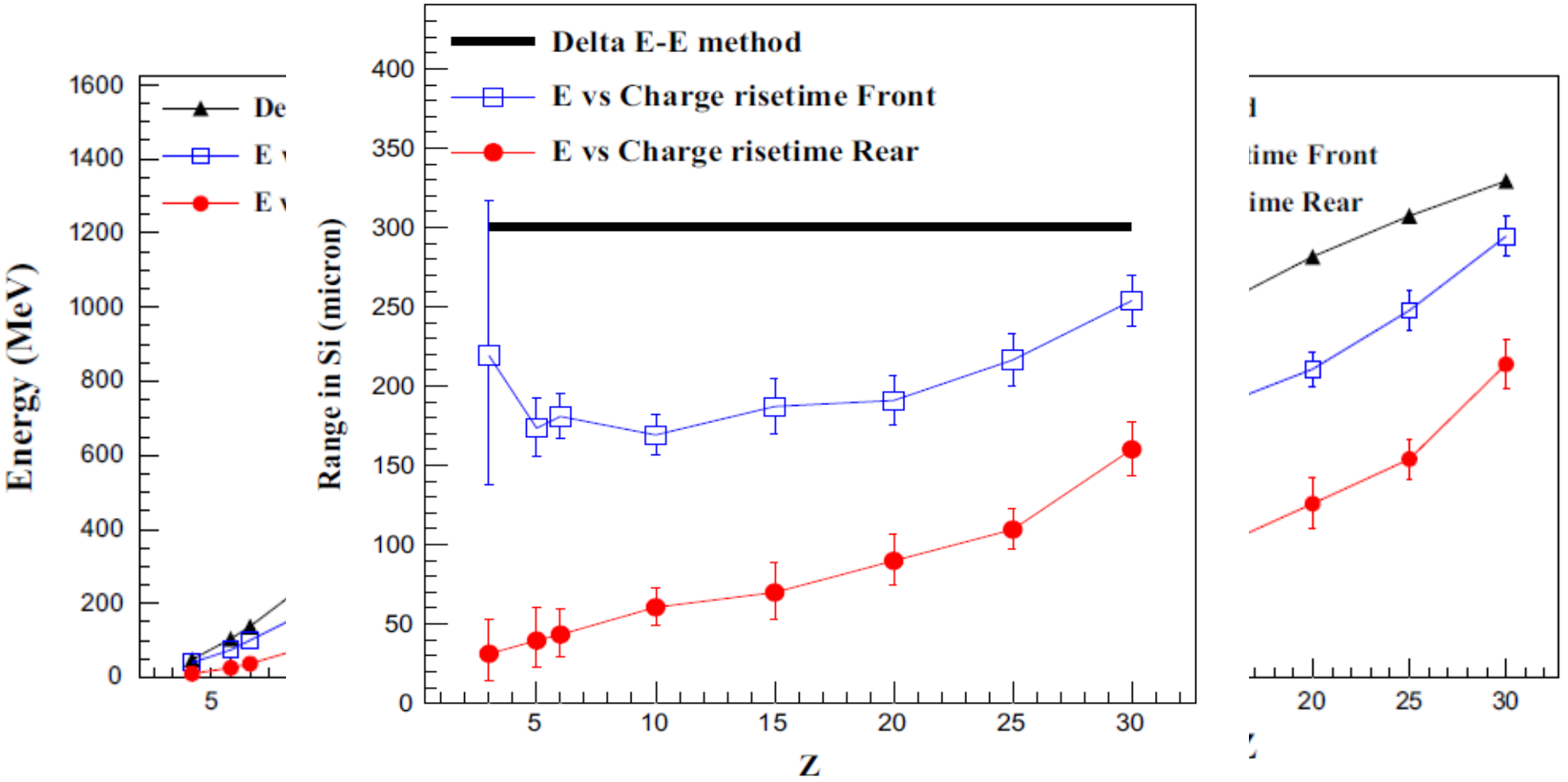
FAZIA : ID thresholds (Z)



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N. Le Neindre *et al.*, NIM A 701(2013) 145–152

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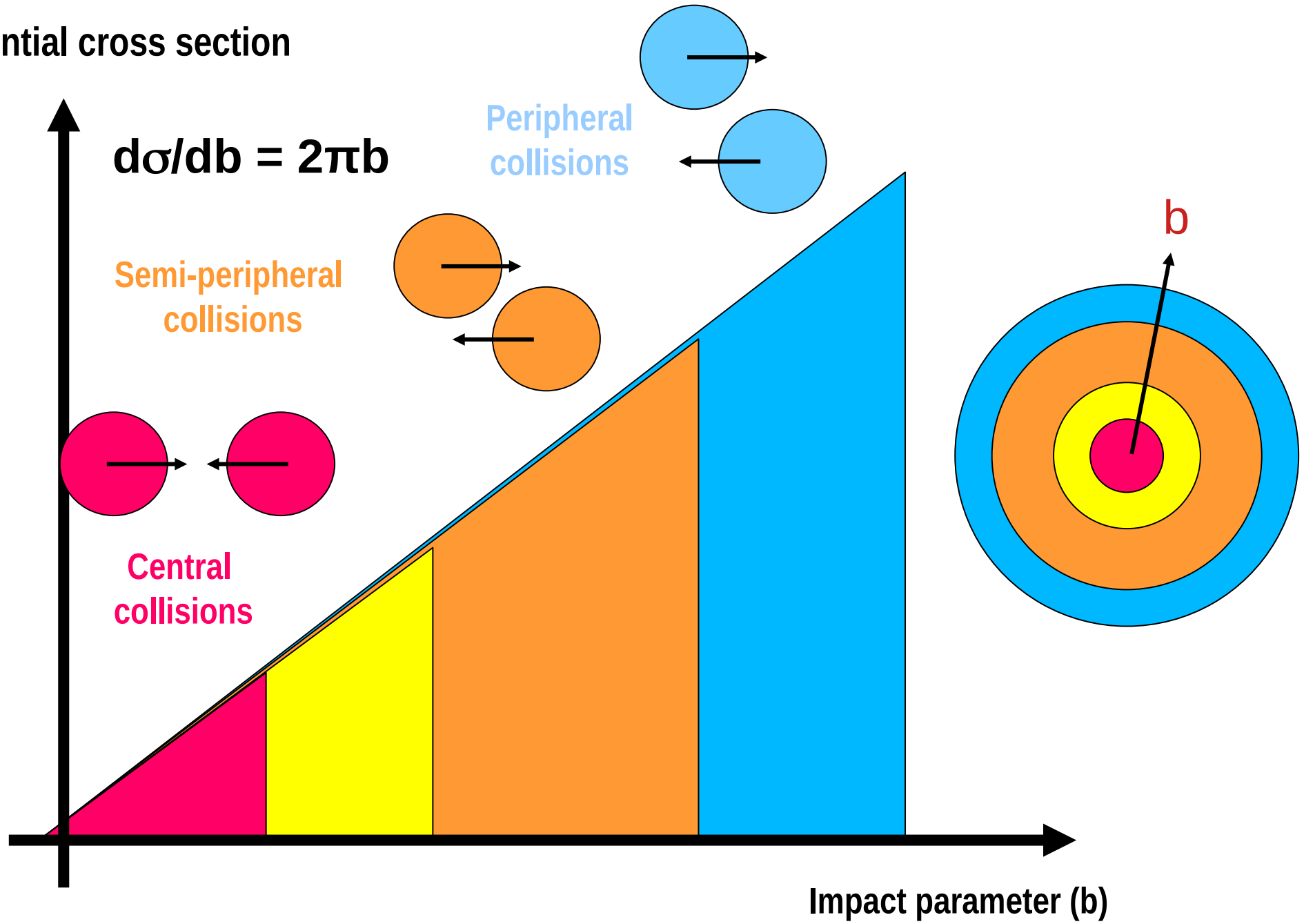
Nuclear reactions : playing darts ...



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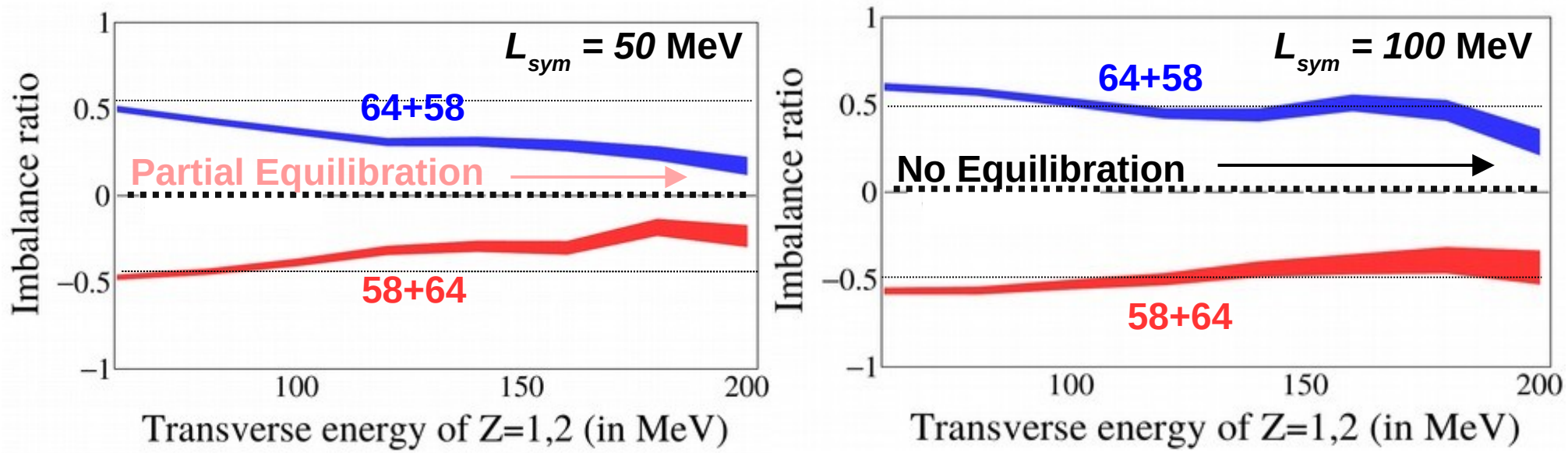
DDSE: toward new probes, isospin imbalance ratio

AMD+GEMINI++ filtered simulations : *2.10⁶* events

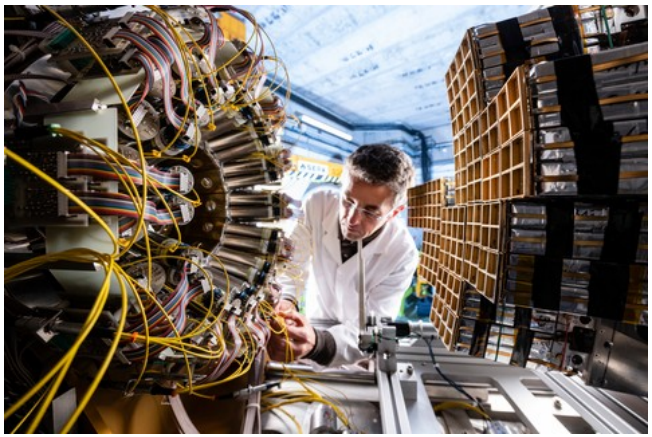
Imbalance ratio ***R*** *for* $\delta_{PLF} = (N_{PLF}-Z_{PLF})/A_{PLF}$

$R_X = (2X-X_1-X_2)/(X_1-X_2)$

^{58,64}Ni + ^{58,64}Ni @ 32A MeV



Transverse energy of *Z=1,2* : measured by INDRA
***N/Z* of *PLF* : measured by FAZIA**



E789 : results coming soon !

→ See J. Lemarié's poster

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End of lecture II

Nucleosynthesis

Abundance
of elements
in the Universe

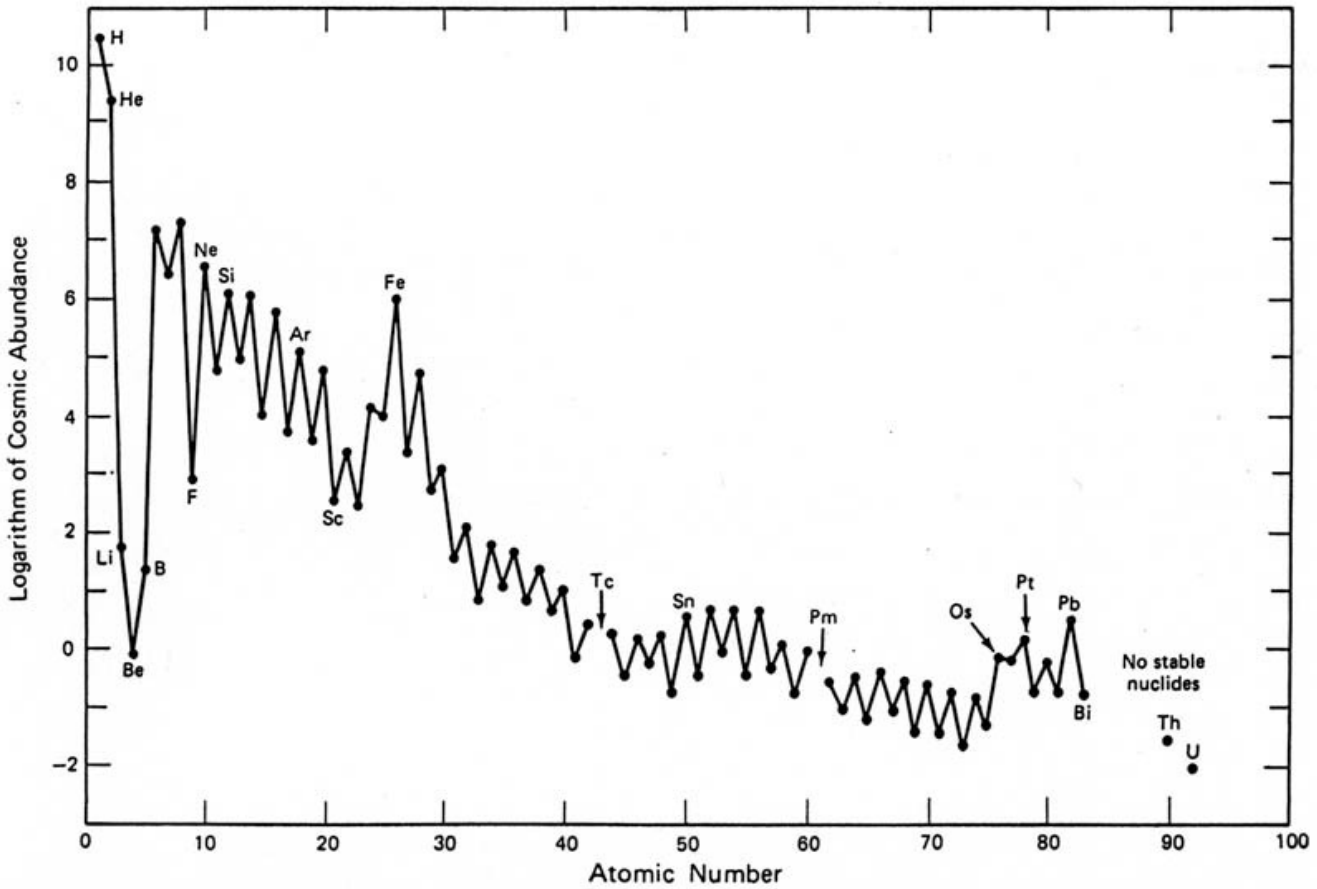


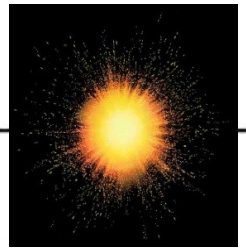
Figure 2.4 Plot of the abundances of the elements in the solar system versus their atomic number. The abundances are expressed as the logarithm of the number of atoms of each element relative to 10^6 atoms of silicon. (Data are listed in Table 2.2 after Anders and Ebihara, 1982.)

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)

Nucleosynthesis : different origins

Abundance
of elements
in the Universe

Primordial Hydrogen (Big Bang)
Z=1



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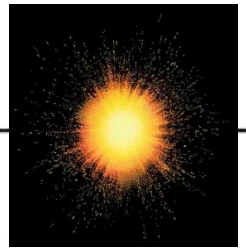
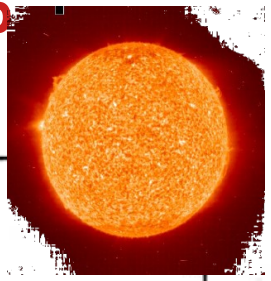
Nucleosynthesis : different origins

Abundance of elements in the Universe

Primordial Hydrogen (Big Bang)
Z=1

Stellar synthesis
Z=2-26





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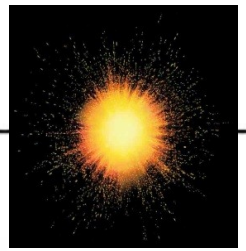

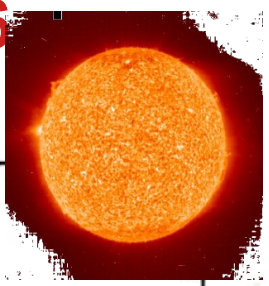

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See S. Goriely

Extra-stellar processes r/s/p-processes in supernovae and NS-NS mergers Z>26

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Novae & Supernovae

$E=10^{44}$ J , L x 10^{10} !!

Nova Monocerotis V838, Licorne
May - December 2002
Hubble Telescope (NASA)

$E = 10^{38}$ J , L x 1000 !

Crab Nebula (M1) - 1054
Hubble Telescope (NASA)

Olivier LOPEZ (lopezo@lpccaen.in2p3.fr)