Nuclear Physics at GANIL

Probing nuclear matter at the extremes

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Profs au GANIL

Part I

Motivations

Describing the nucleus

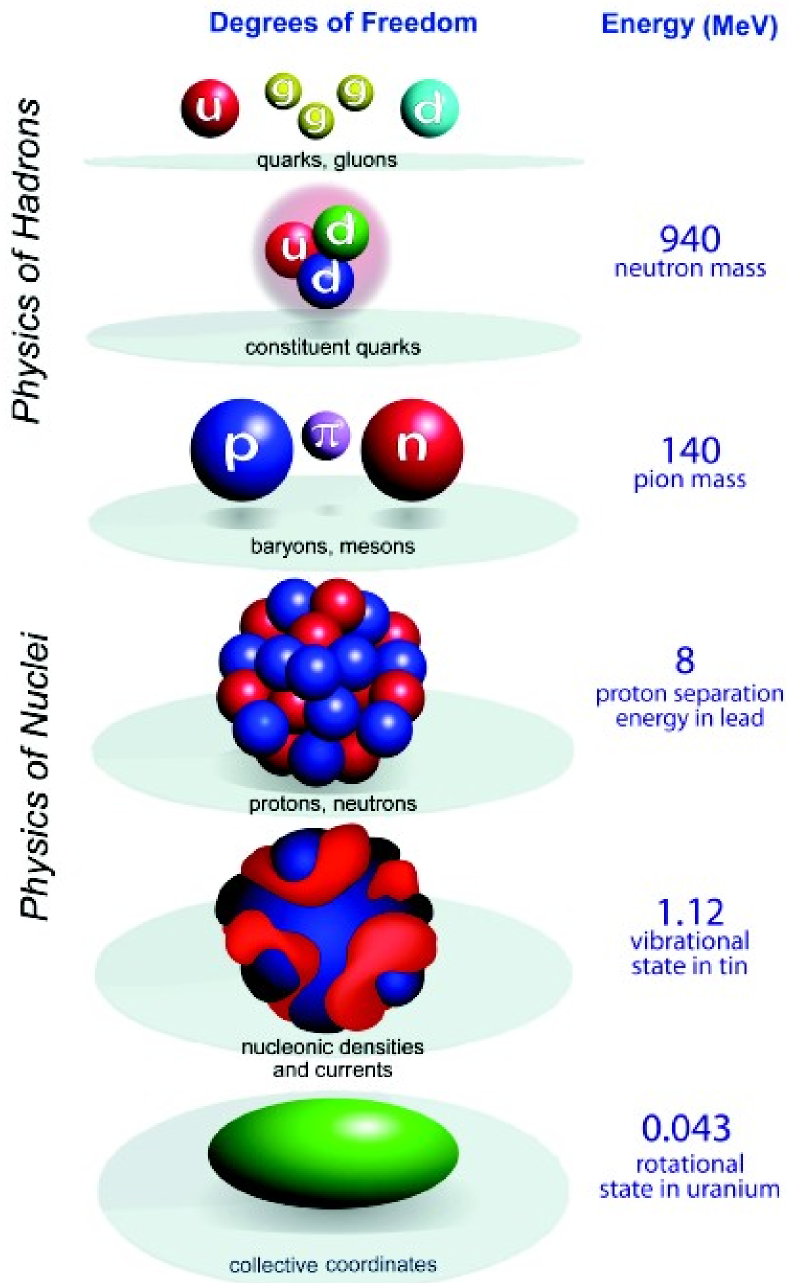
Energy scales in the subatomic world

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

De Broglie equation (spatial resolution) :

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

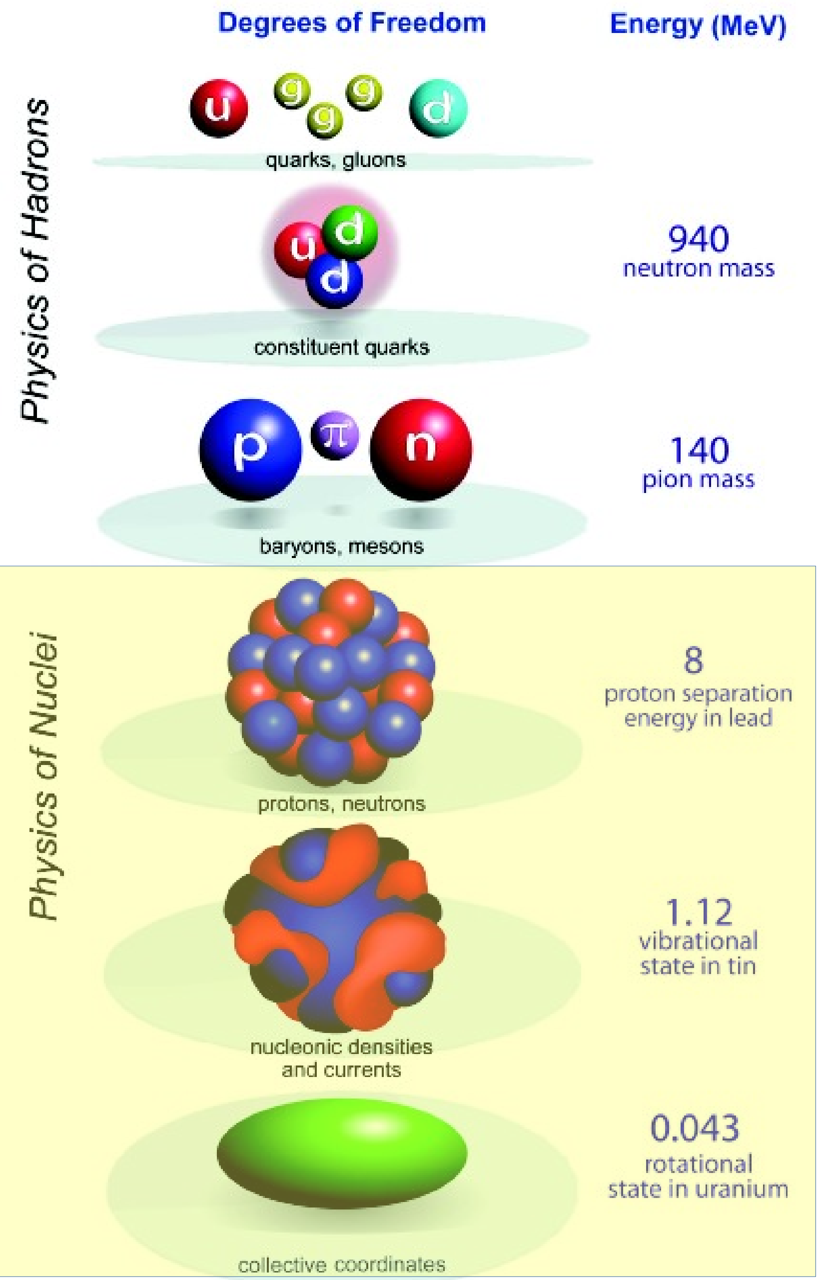
E_{inc} (MeV)	$\lambda\!\!\!^{-}$ (fm)
1	8
10	1.5
100	0.5



1 MeV = 1 méga-électronvolts = 10^6 eV = $1{,}6.10^{-13}$ J

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

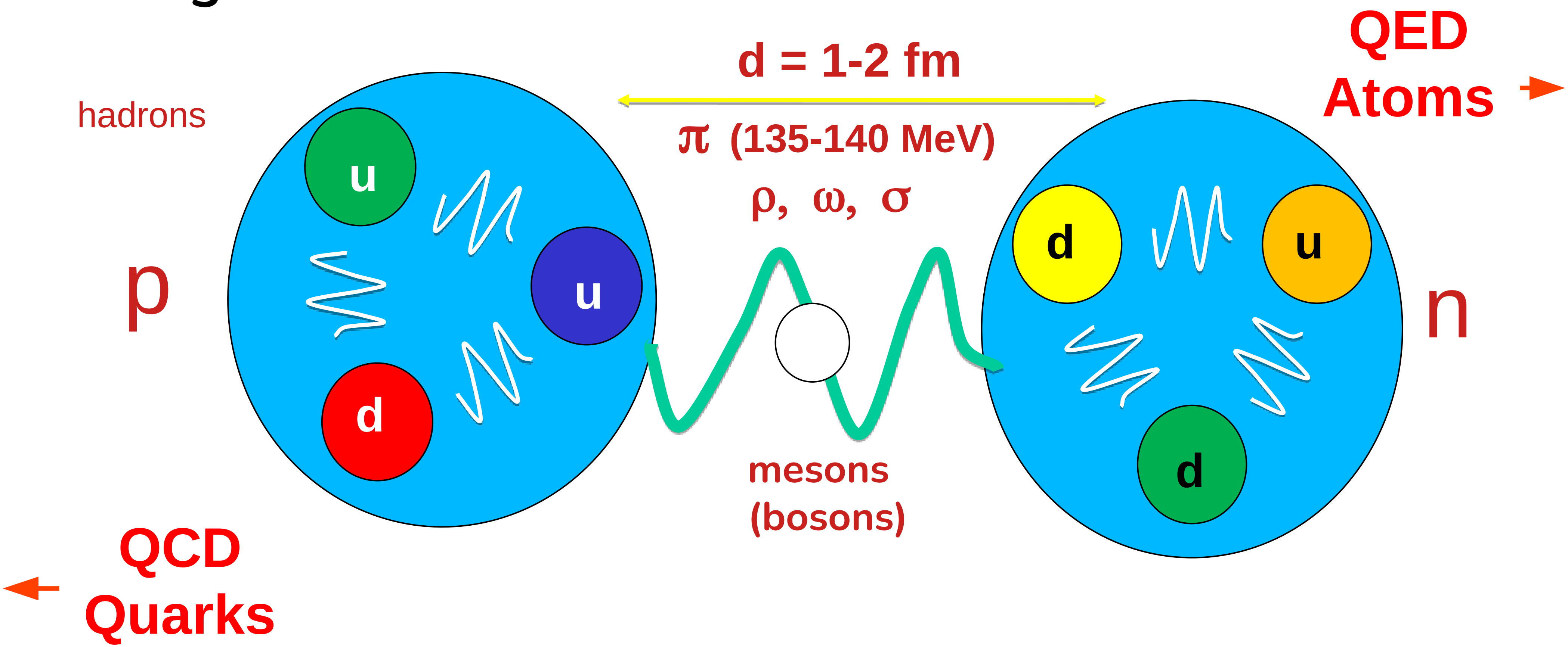
- nucleus
- collective phenomena
- excited states
- bulk and surface properties in continuum states

Nuclear reactions

E_{inc} = 5 – 100 MeV/nucleon

1 MeV = 1 méga-électronvolts = 10^6 eV = $1{,}6.10^{-13}$ J

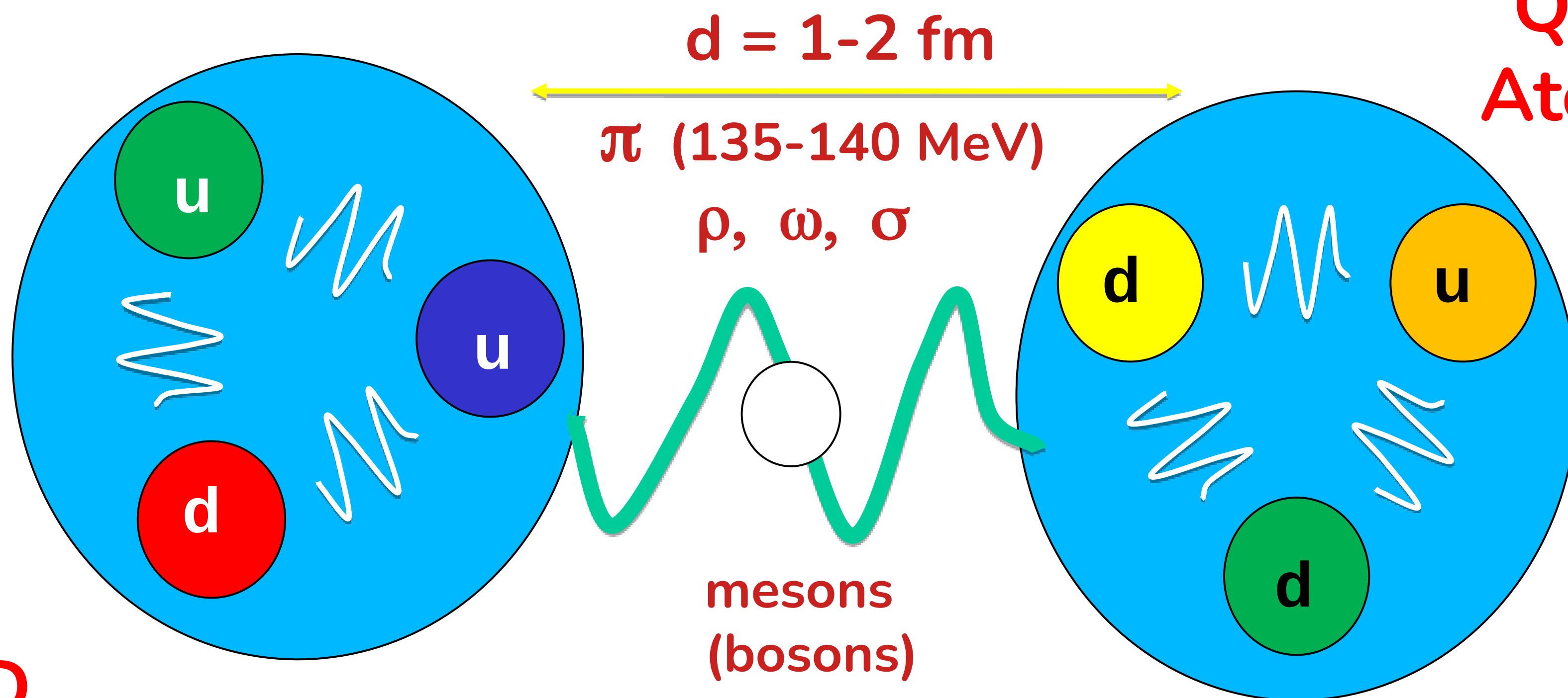
Strong .vs. Nuclear interaction



Strong .vs. Nuclear interaction

Hadrons

p



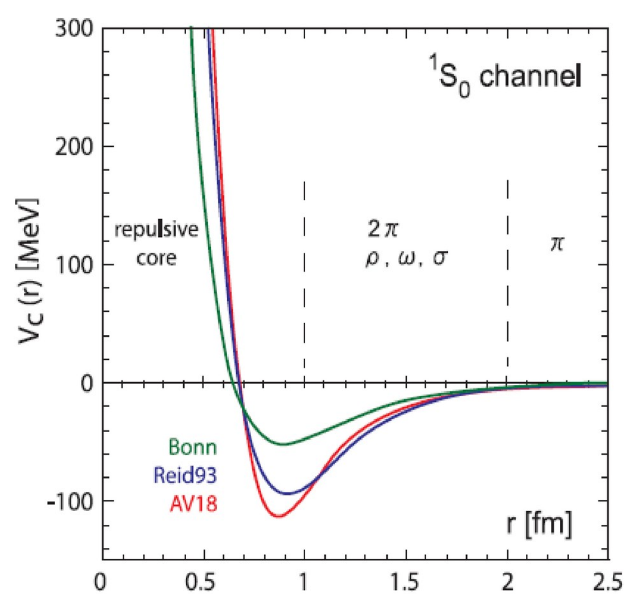
n

QED
Atoms

QCD
Quarks

Nuclear interaction
= long range strong int.
(non perturbative regime)

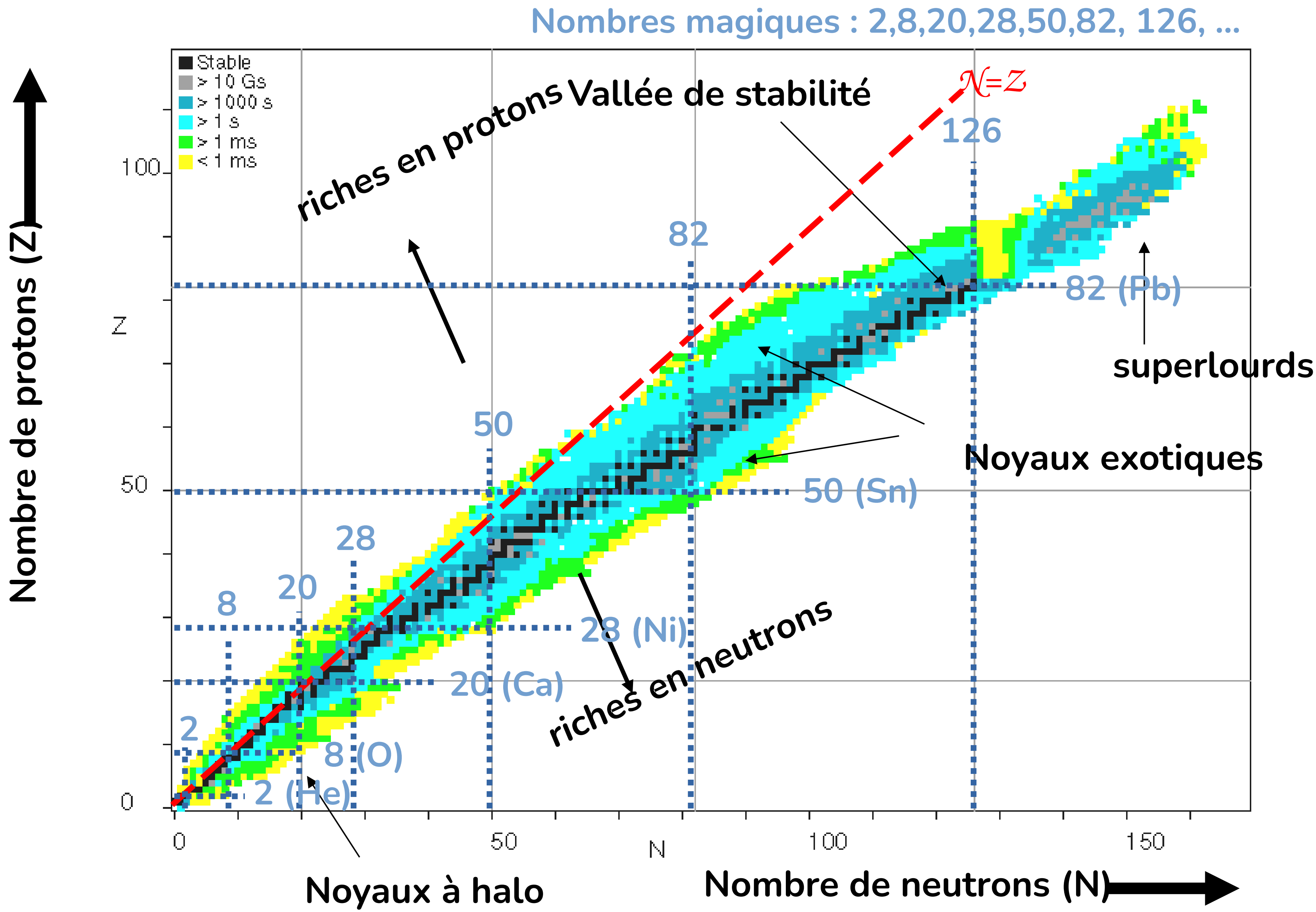
Hard core : r<1 fm
Small range : r ≈ 1 fm
Tensor and isovector: n,p



Relevant D.o.F.

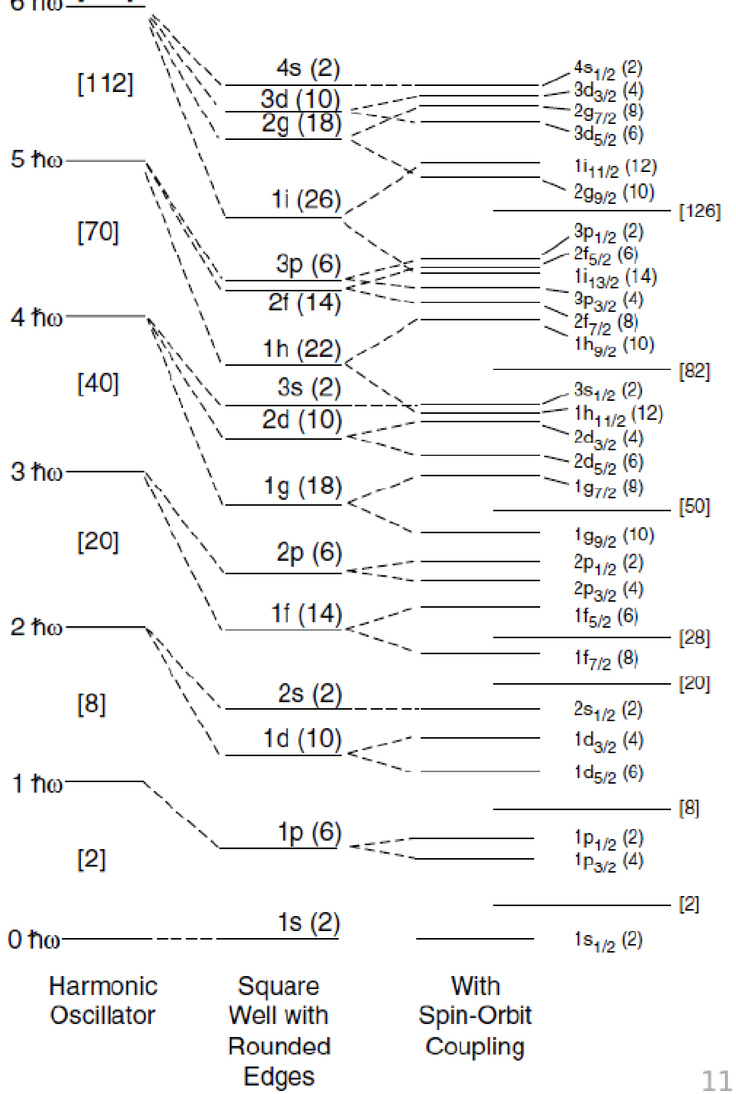
Density $\rho = \rho_n + \rho_p$,
Angular mom. J=L+S
Isospin $I = (\rho_n + \rho_p) / \rho$

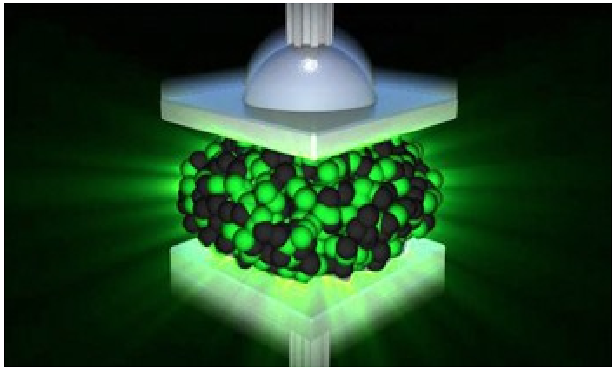
Des noyaux à la carte



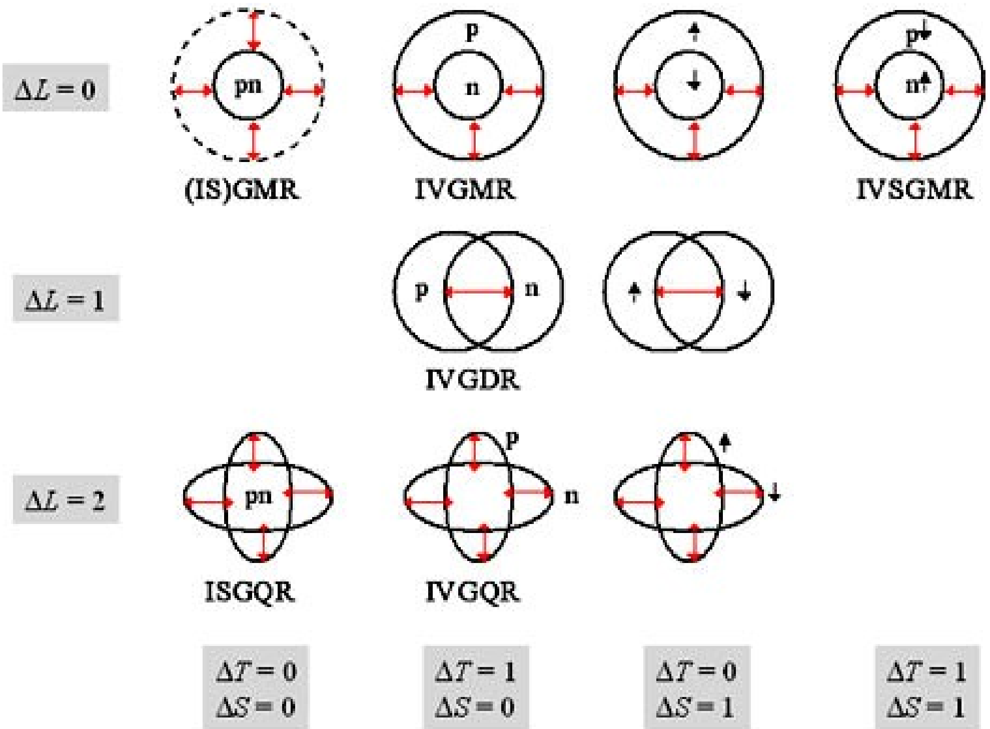
Nucleus at T≈0 : quantum realm

Shell model





Collective excitations
Giant resonances



Quantum numbers for nucleon orbitals n,l,j : $1s_{1/2}$

Nuclear structure and limits of stability (driplines)

Nuclear structure (I)

Thank to the advent of radioactive ion beam facilities, new phenomena have been investigated during the last two decades

- new magic numbers (harmonic shells for exotic nuclei)
- haloes nuclei (borromean)
- granular or molecular systems (clusters in nuclei)
- nuclear structure for superheavy elements (transfermium Z>100)
- new radioactivities 2p, 2n, clusters (coupling to continuum)

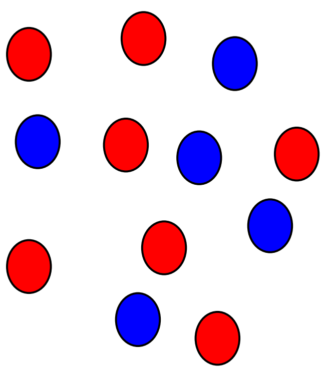
Impact on theories

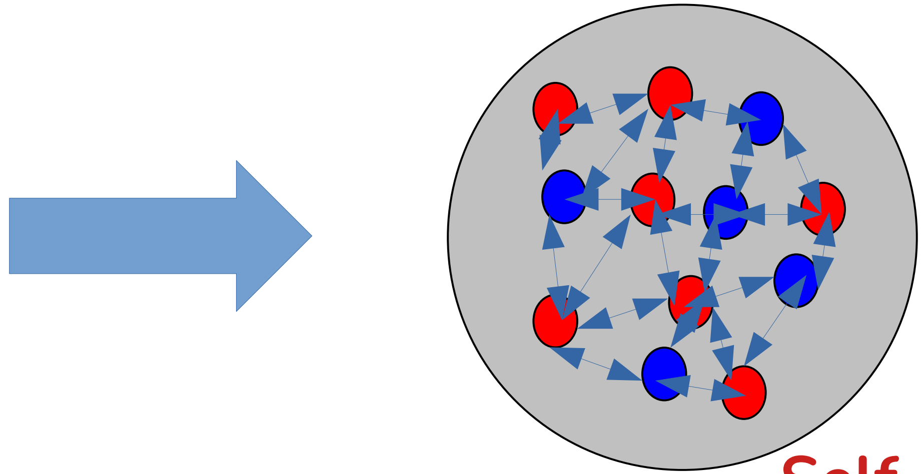
3-body and many-body forces
Isospin (N/Z) dependence
Loosely bound nuclei / coupling to continuum
Correlations : pairing, superfluidity, short range

Nuclear structure (II)

Studying the limits of existence (A,I) of nuclei
What holds together nucleons and to what extend ?

Free nucleons **nucleus**





Self-consistent Mean-Field

Bare *NN* interaction **Effective interaction (medium)**

Nuclear structure (II)

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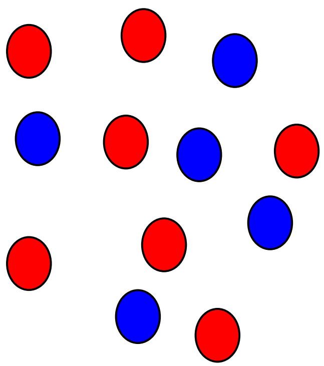
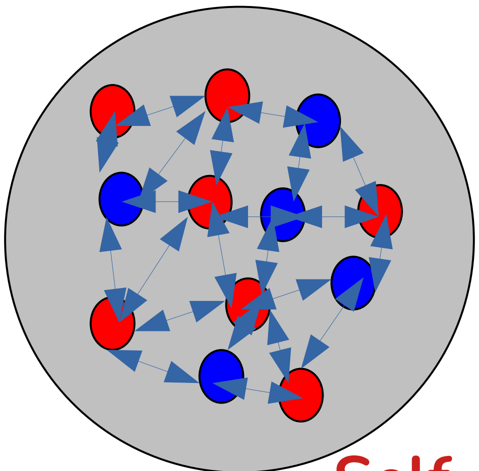
What holds together nucleons and to what extend ?

Free nucleons



nucleus



Self-consistent
Mean-Field

Bare *NN* interaction

Effective interaction (medium)

Study of extreme states

- *Density (ρ)*
- *Temperature (T)*
- *Total Spin (J)*
- *Isospin (N/Z)*

Macroscopic descrition of nuclei : liquid drop

Bethe & Weisacker formula :

volume, surface, coulomb, asymmetry n/p (isospin)

$$B = a_v A - a_s A^{2/3} - a_c Z^2/A^{1/3} - a_{sym} (A-2Z)^2/A \ldots$$

+ shell effects (magic numbers)

+ pairing (nn, pp, np)

β-stability valley, B maximum : $\partial B/\partial A = 0$

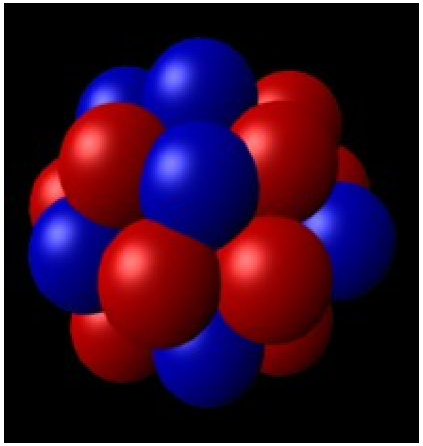
$$Z_{stable} \approx A/2 \left[1+a_c/(4a_{sym})A^{2/3}\right]^{-1}$$

From nucleus to compact stars

Under pressure !

$\rho = 10^6$ T/cm^3

nucleus



Supernova / neutron star

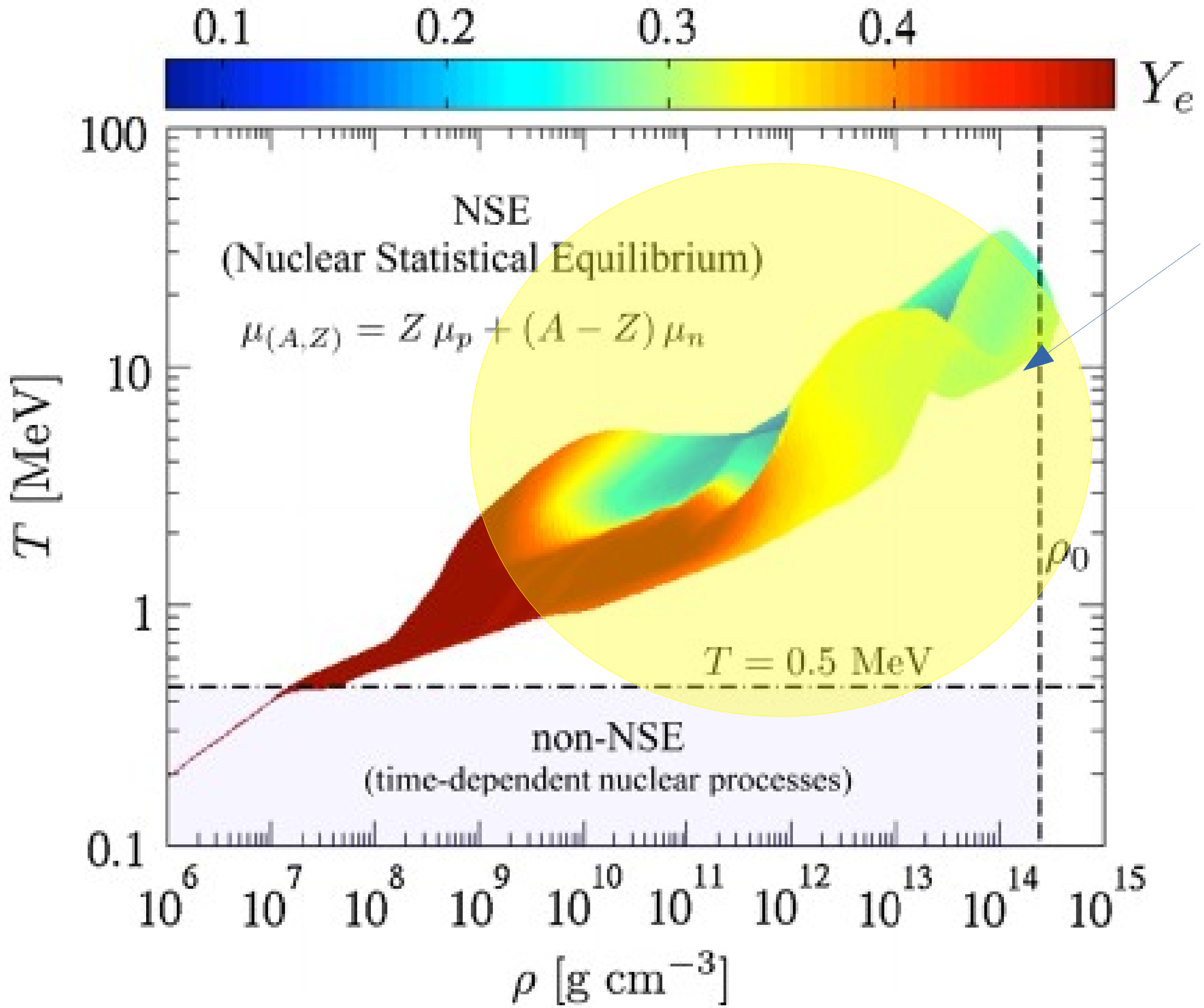
Nucleosynthesis above iron element

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

NS is ruled by the nuclear Equation of State E(ρ, T, δ)

Covered domain in the plane *(ρ,T)*

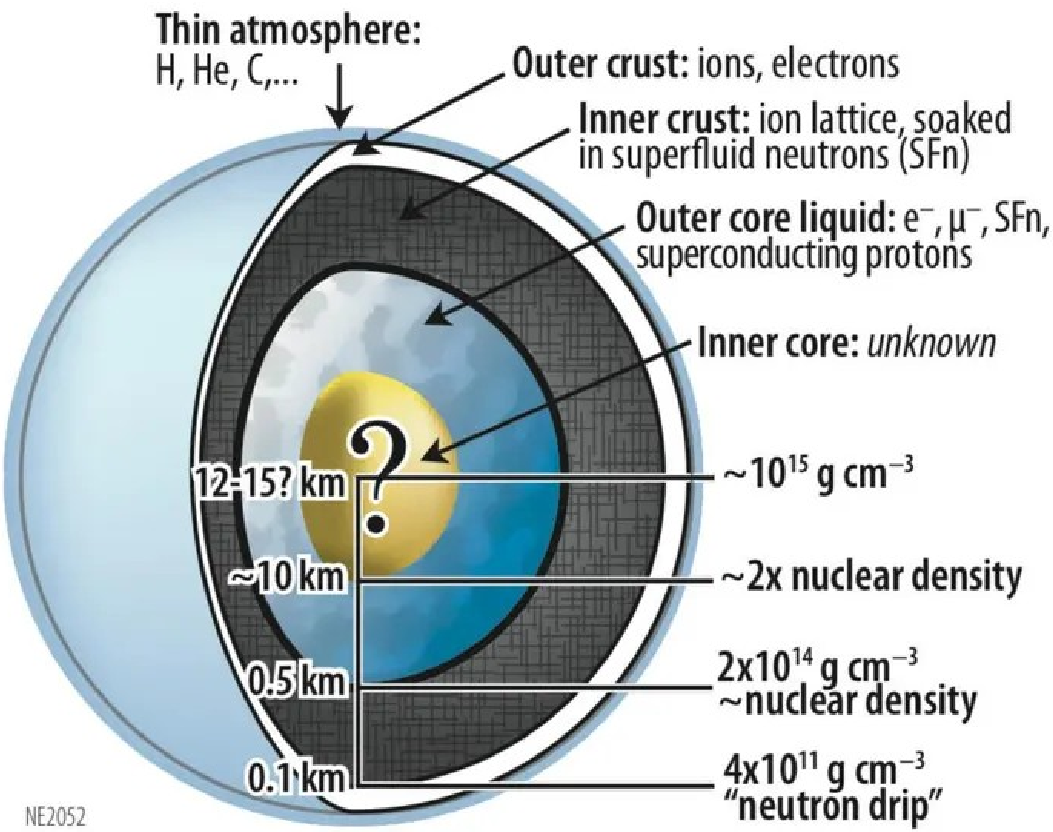
Temperatures and densities reached during a CCSN simulation within 1s post-bounce



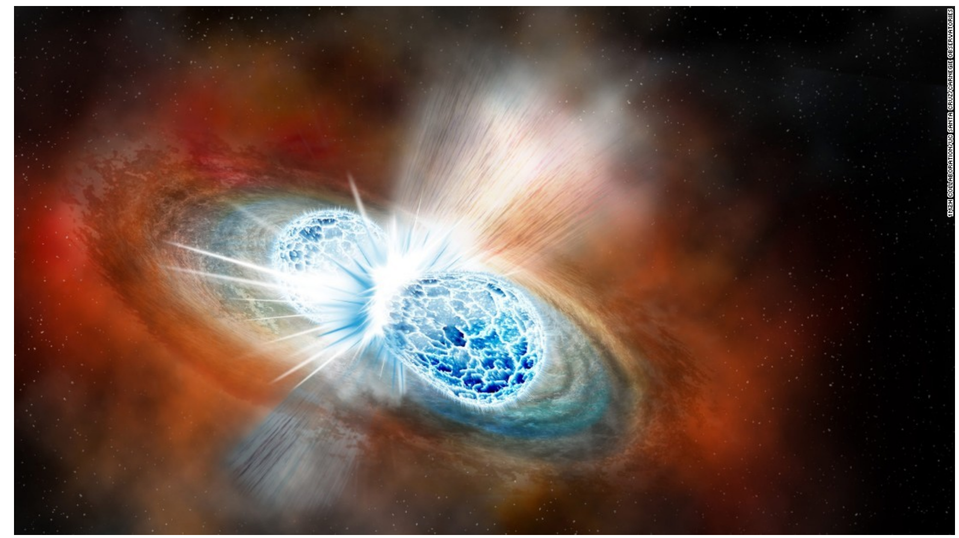
Nuclear reactions @ GANIL ...

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

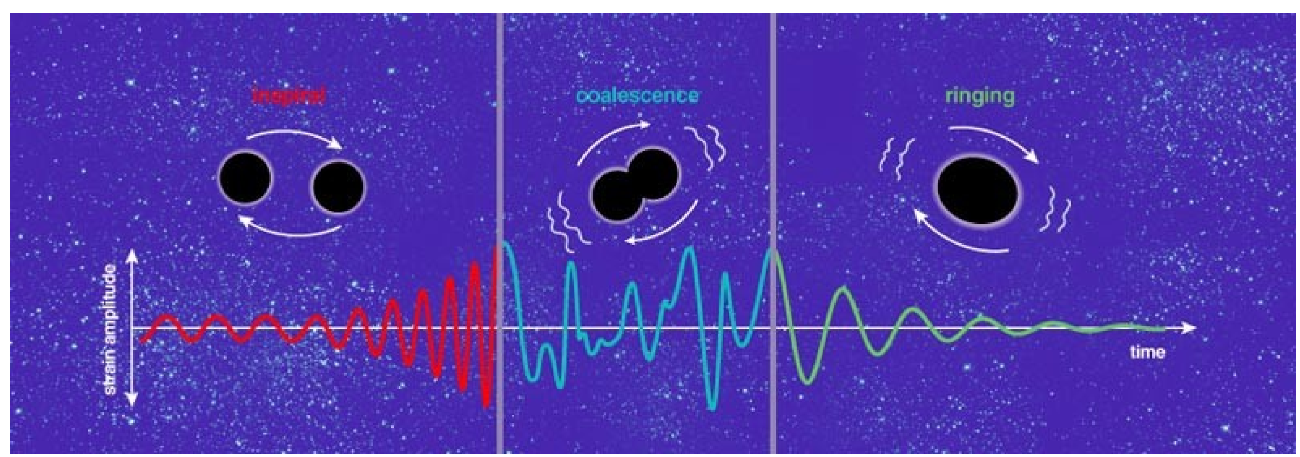
Neutron star : a dream for nuclear physicists …



NS – NS merger



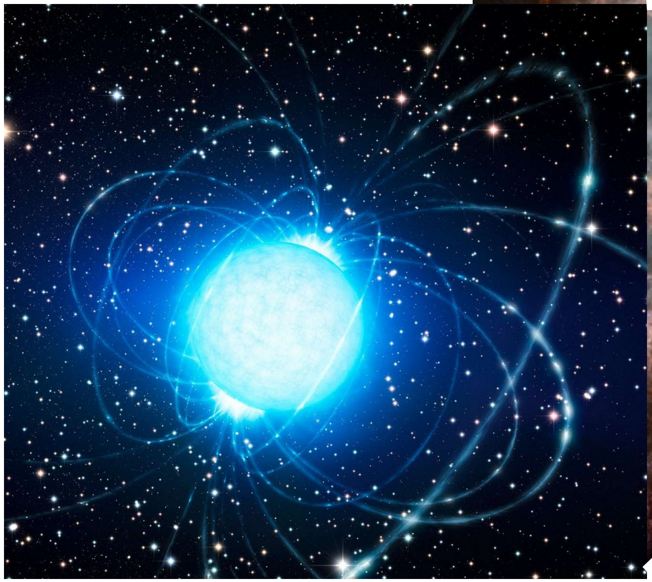
Gravitational waves



Neutron star : a dream for nuclear physicists ...

Crab nebula

Pulsar at center !



Combined image from James Webb Space Telescope
Credits NASA, ESA, CSA, STScI, T. Temim (Princeton University)

Key questions in 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, pairing, drip lines, … ?

Shell model(s) 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 neutron star mergers (macroscopic) ?

Equation of State of nuclear matter / phase transitions

Nucleosynthesis
Where the matter comes from ?

Abundance of elements in the Universe

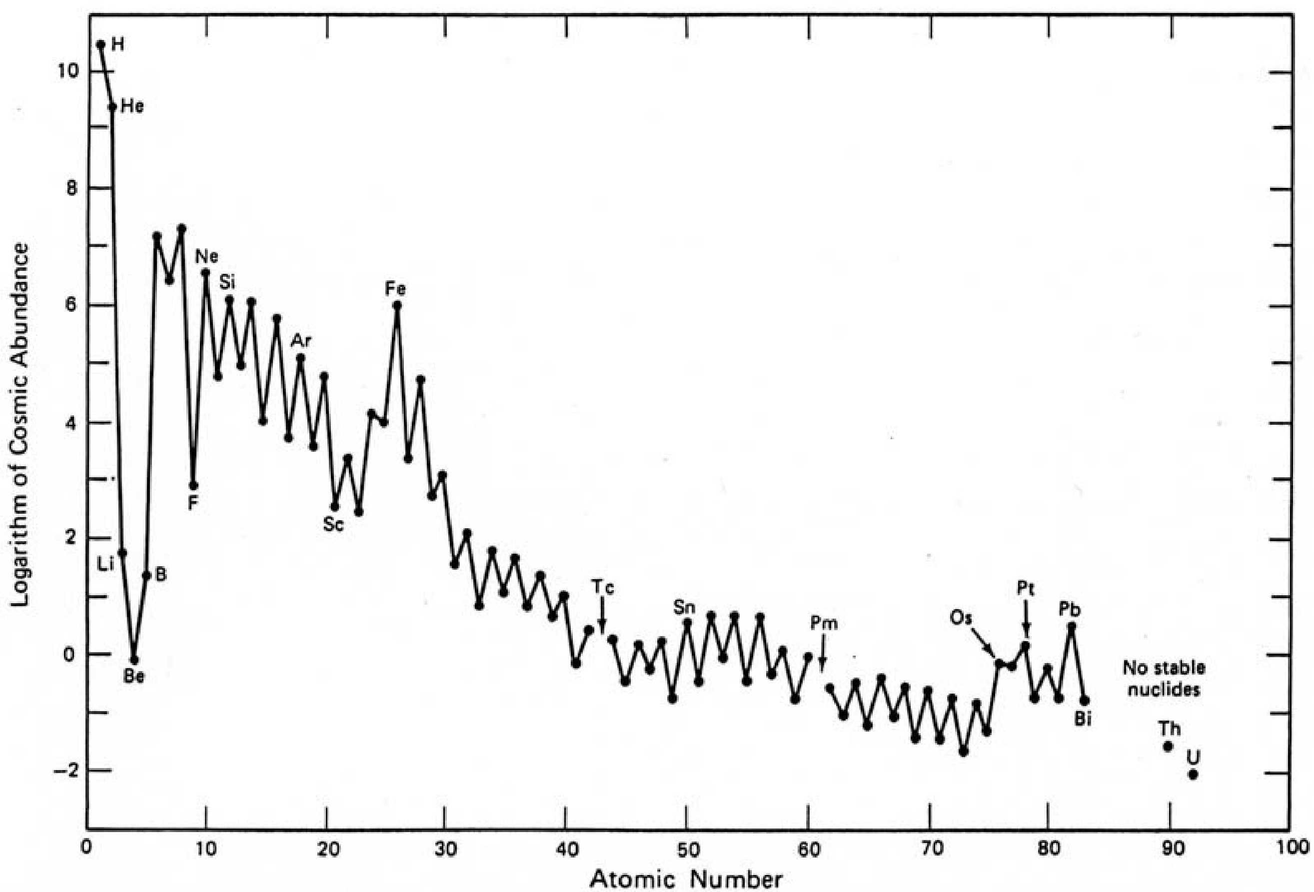


Figure 2.4 Plot of the abundances of the elements in the solar system versus their atomic number. The abundances are expressed as the logarithm of the number of atoms of each element relative to 10^6 atoms of silicon. (Data are listed in Table 2.2 after Anders and Ebihara, 1982.)

Nucleosynthesis : different origins

Abundance
of elements
in the Universe

Stellar synthesis
Z=2-26

Primordial Hydrogen (Big Bang)
Z=1

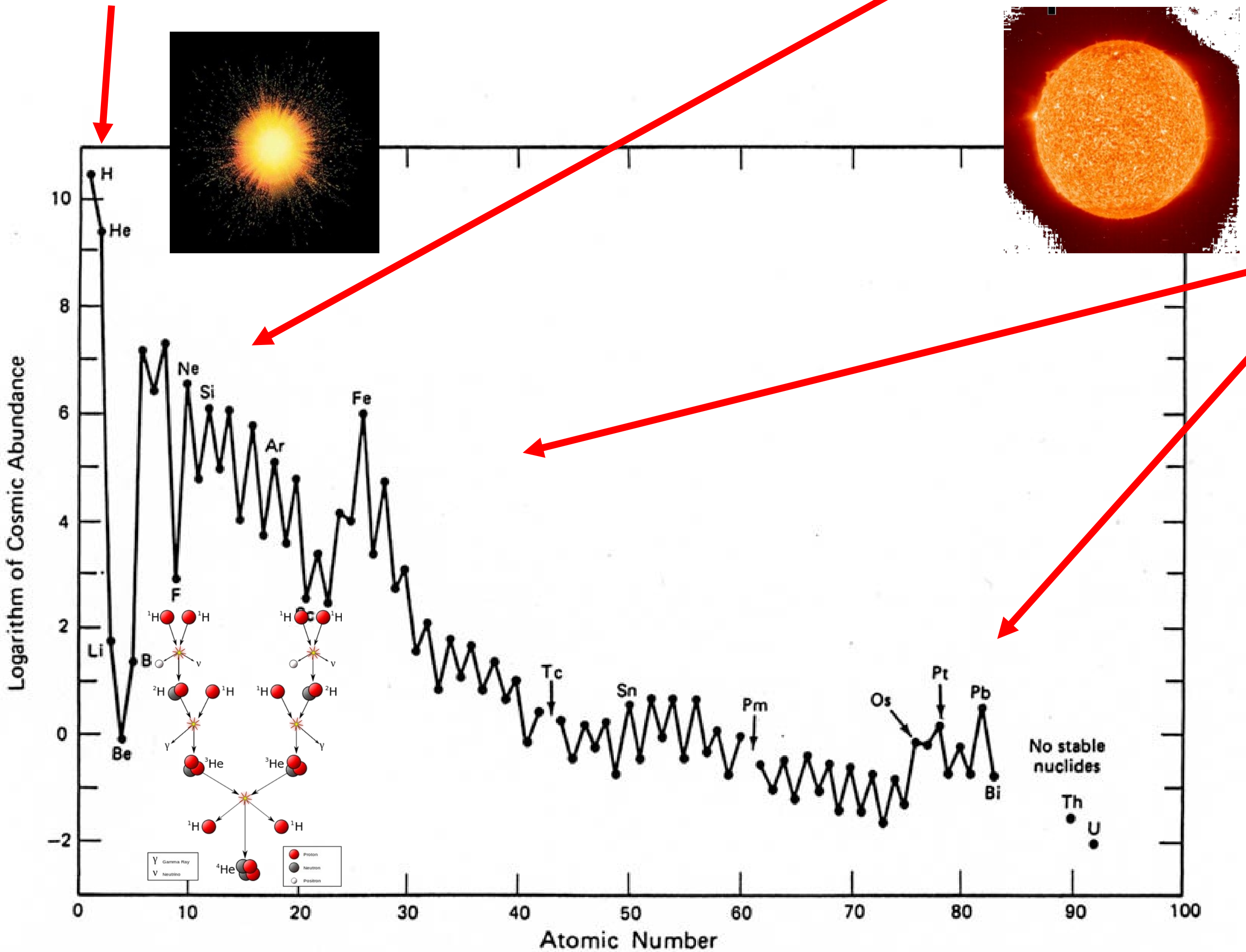
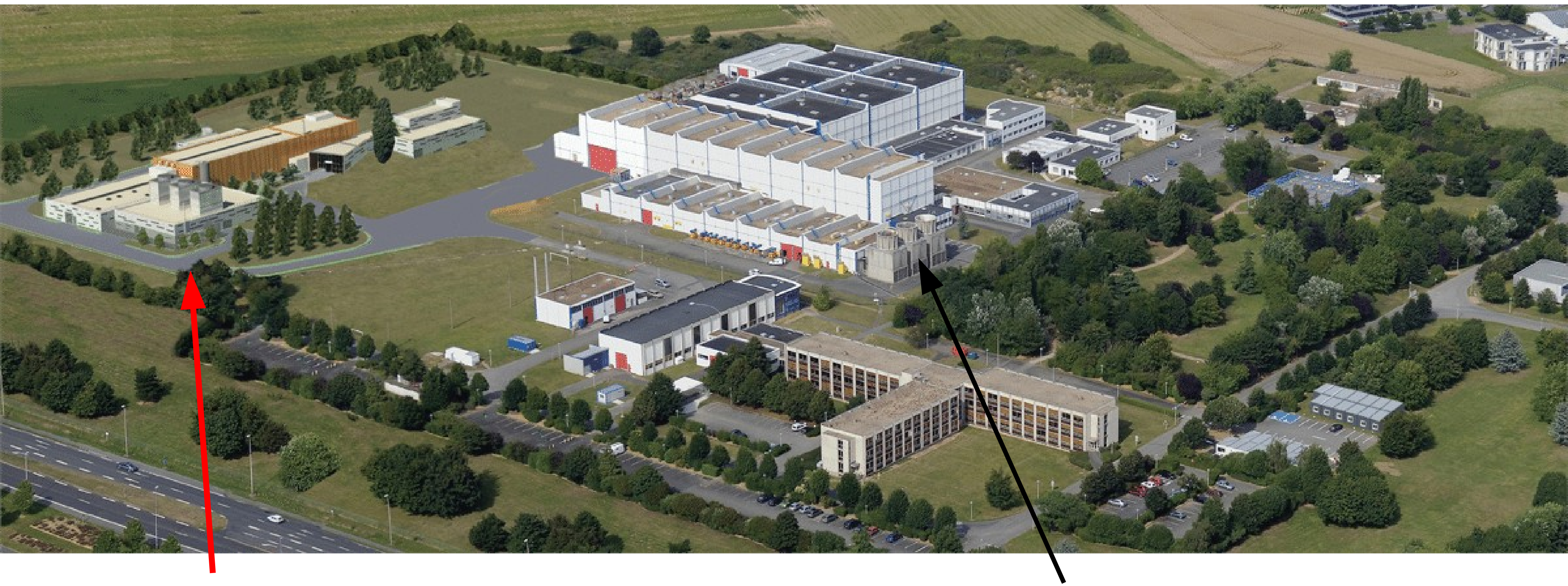


Figure 2.4 Plot of the abundances of the elements in the solar system versus their atomic number. The abundances are expressed as the logarithm of the number of atoms of each element relative to 10^6 atoms of silicon. (Data are listed in Table 2.2 after Anders and Ebihara, 1982.)

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

Terrestrial experiments

At GANIL (Caen, Normandy, France), many teams study heavy ions induced nuclear reactions 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.*

SPIRAL2

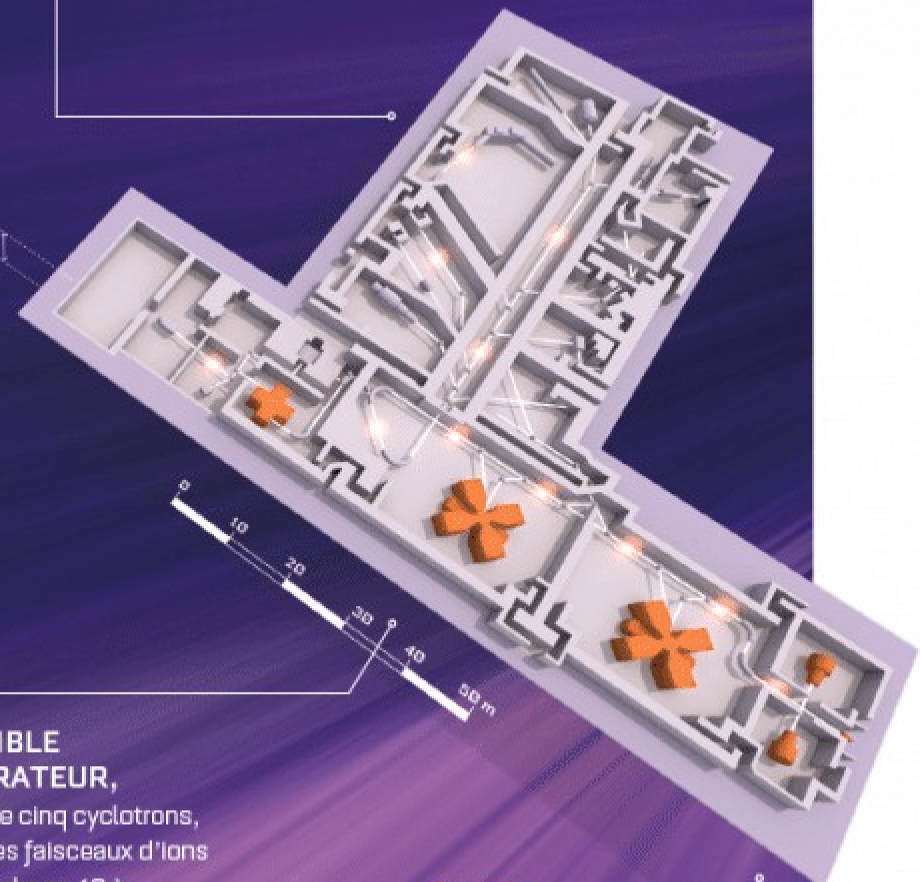
L'ACCÉLÉRATEUR LINÉAIRE SUPRACONDUCTEUR

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.



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

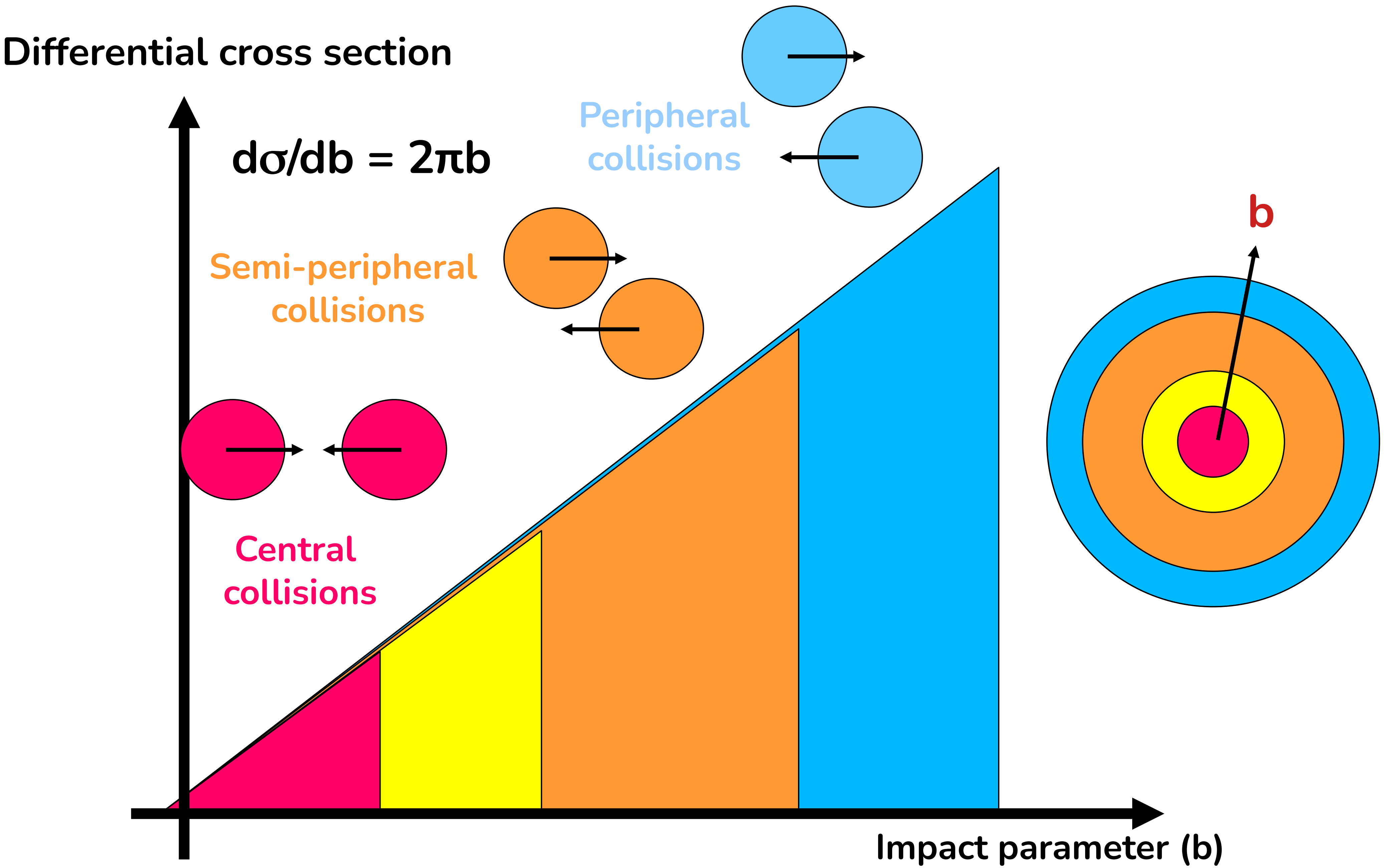
permettent de produire les ions stables ou radioactifs qui seront ensuite mis en faisceaux et accélérés.

End part I

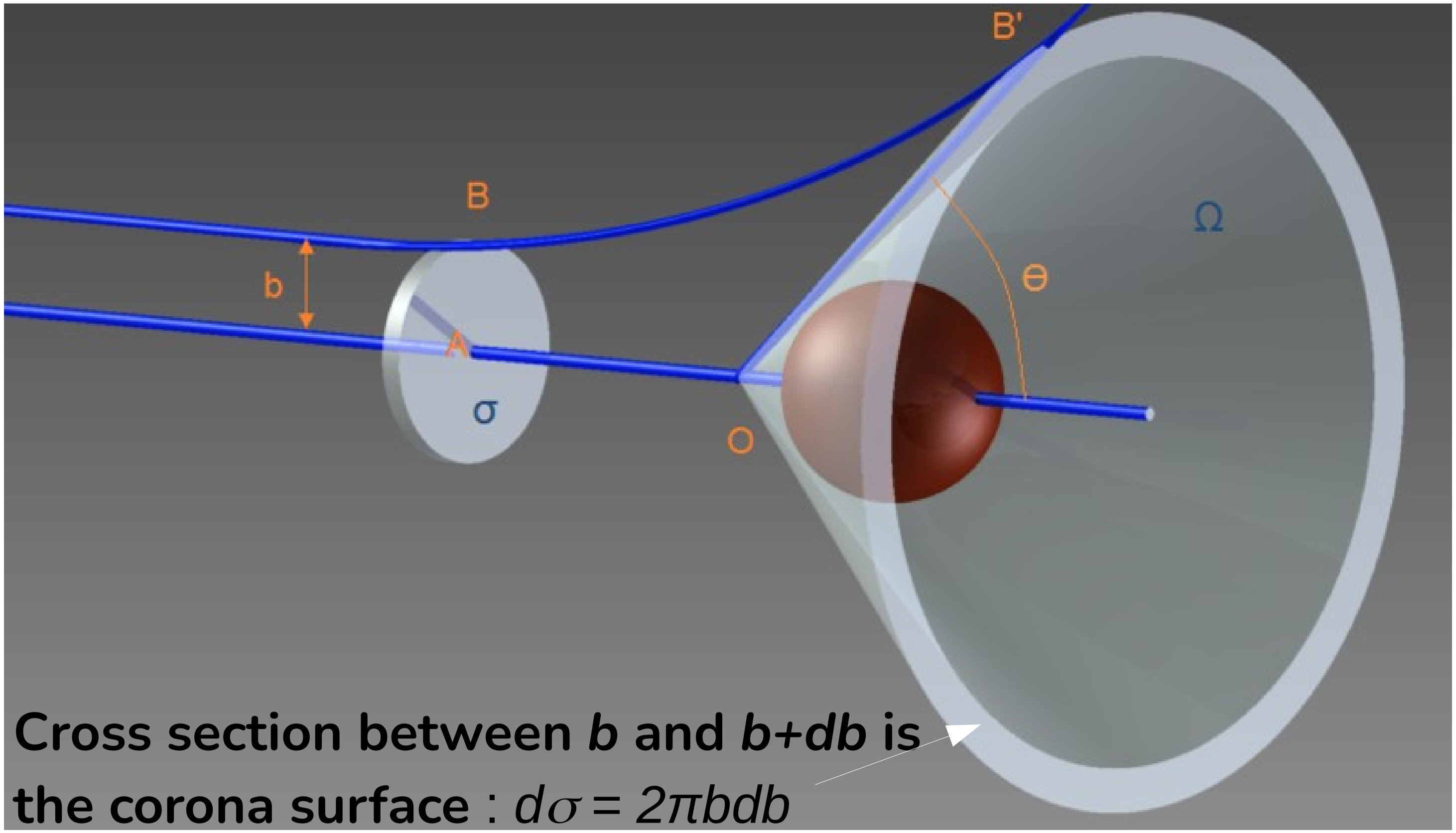
Part II

Some basic concepts of nuclear reactions

Nuclear reactions : playing darts ...



Cross section in Classical Physics



Cross section between *b* and *b+db* is the corona surface : $d\sigma = 2\pi b db$

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 $\sigma_{nuc} = 3{,}142\ b = 3142\ mb$

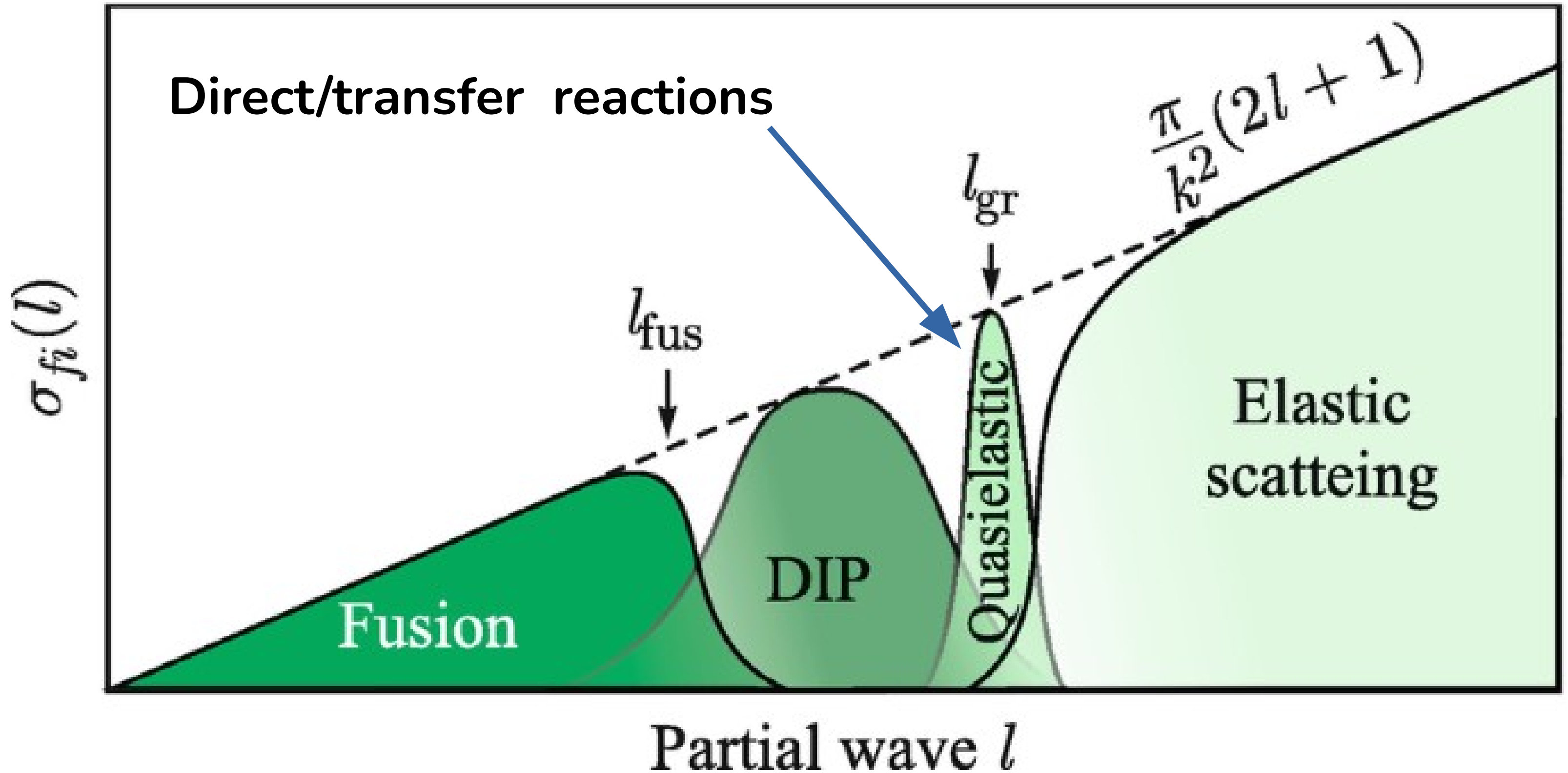
Cross section in Quantum Mechanics : partial waves

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

η_ℓ **=** 0 **for elastic and** $0<\eta_\ell<1$ **for absorption**

Cross section and event rate

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

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

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)**

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^{-1}
Deep Inelastic/ Multi-nucleon Transfer	1 b	10 s^{-1}
Central collision (b<1 fm)	50 mb	1 mn^{-1}
Transfer/direct reaction	10 mb	10 hr^{-1}
Fusion reaction	1 mb	1 $week^{-1}$

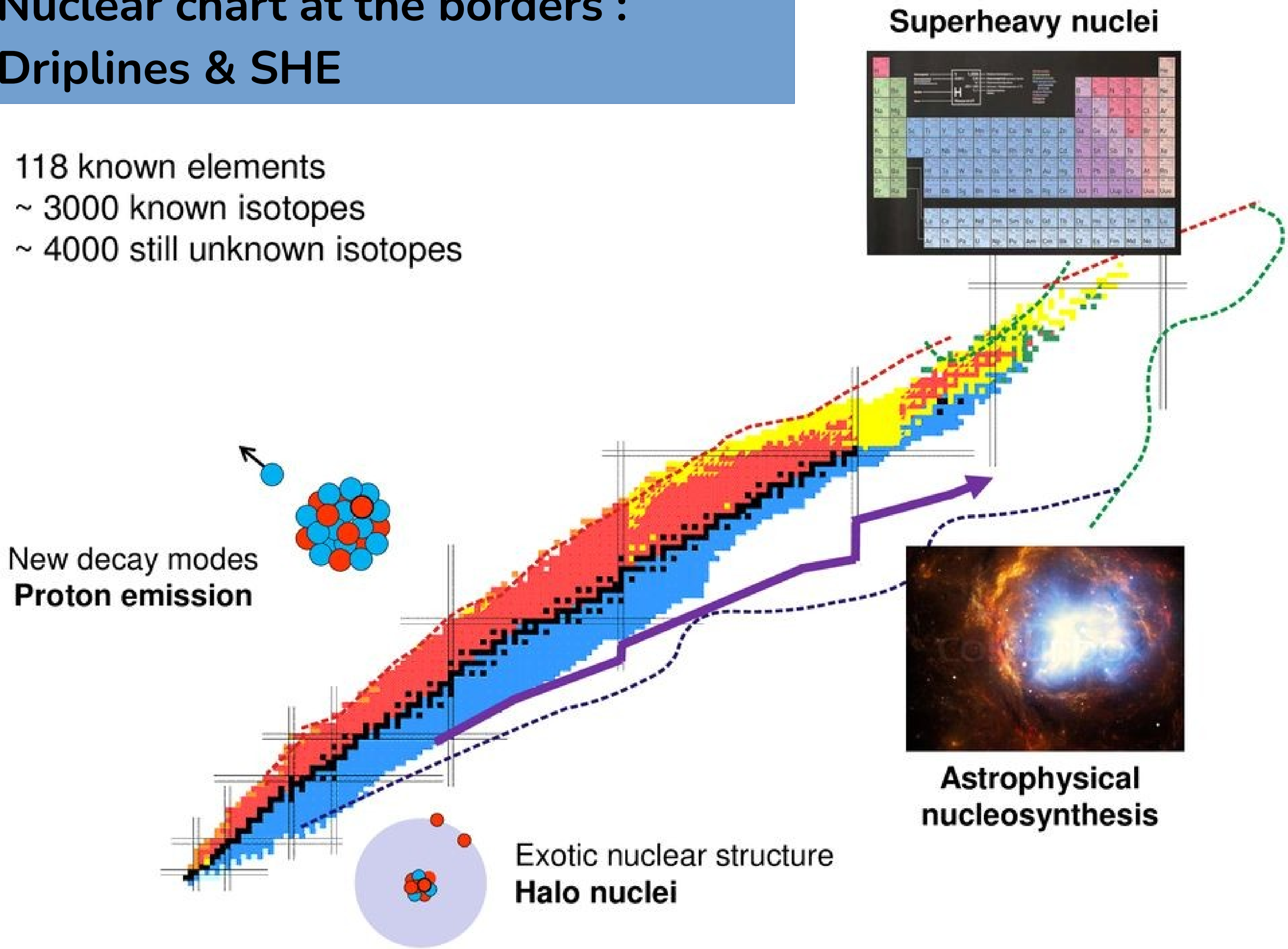
Nuclear reactions

Producing exotic nuclei

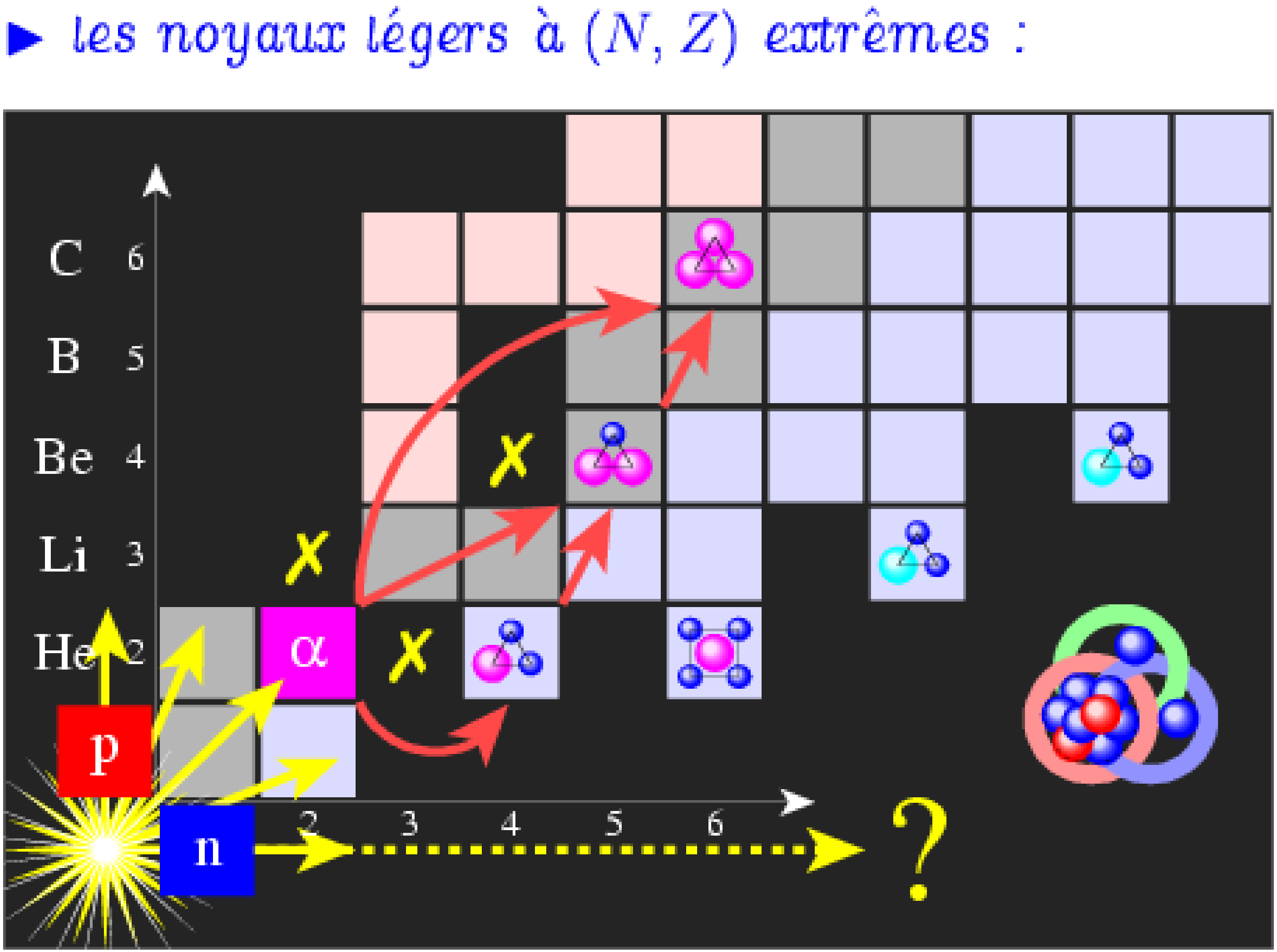
Physics cases for nuclear reactions : driplines

Nuclear chart at the borders : Driplines & SHE

118 known elements
~ 3000 known isotopes
~ 4000 still unknown isotopes

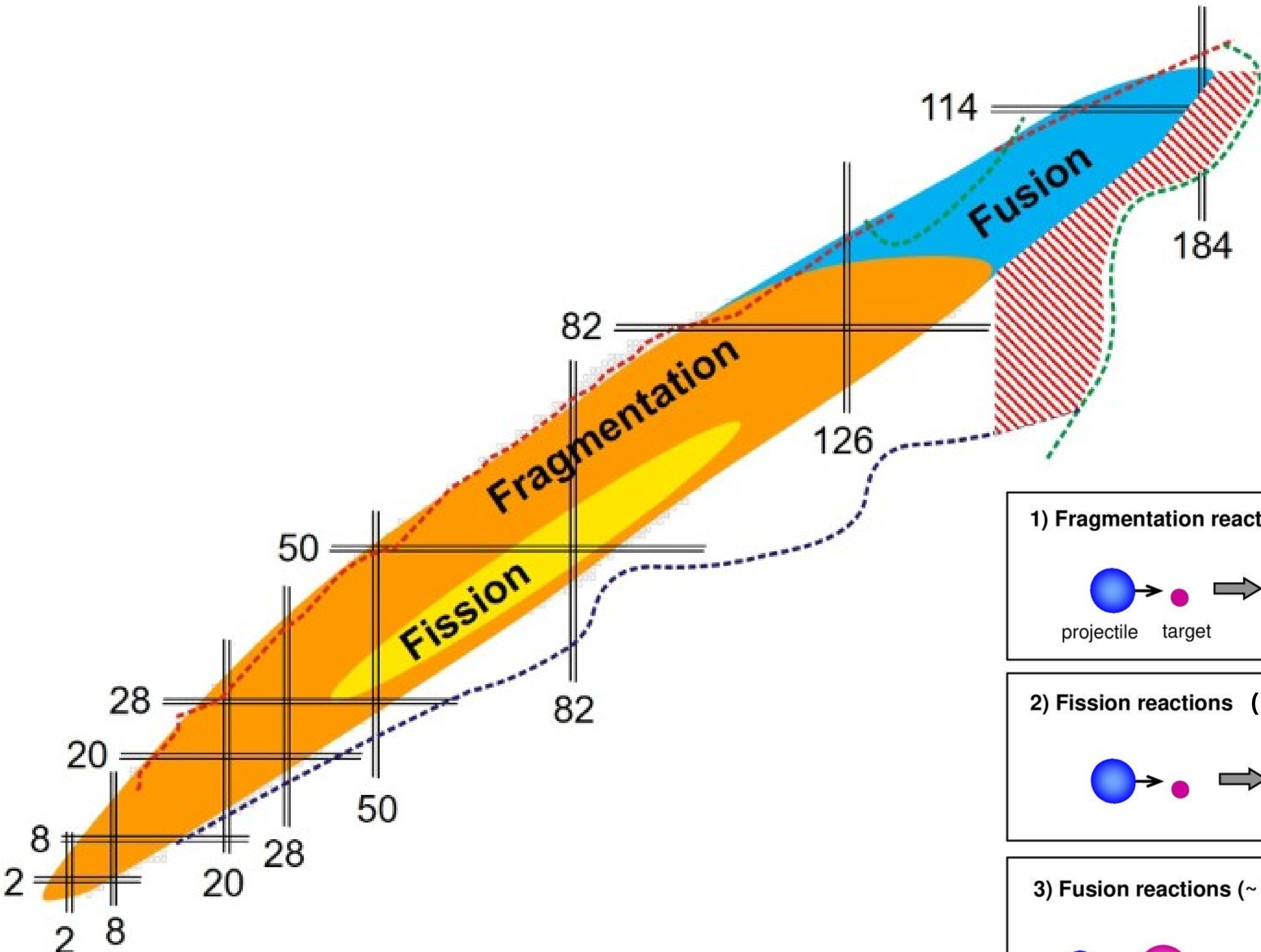


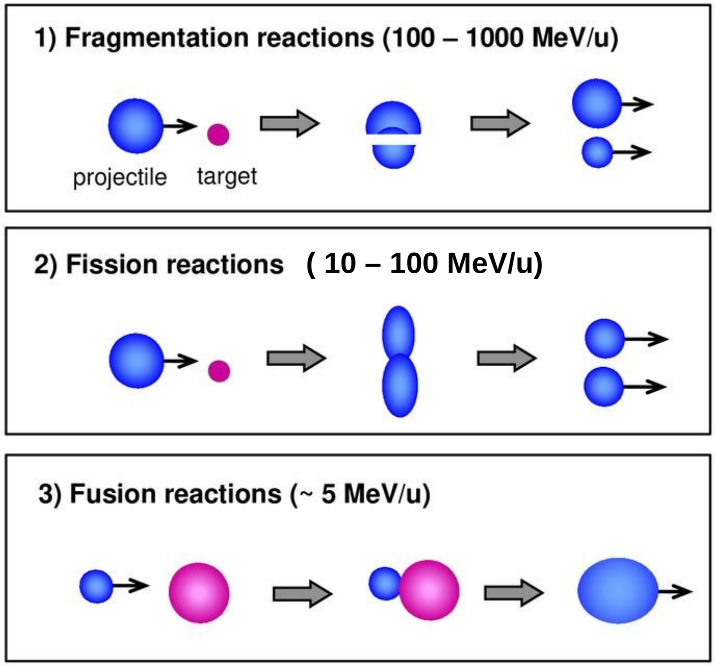
Also Haloes nuclei...



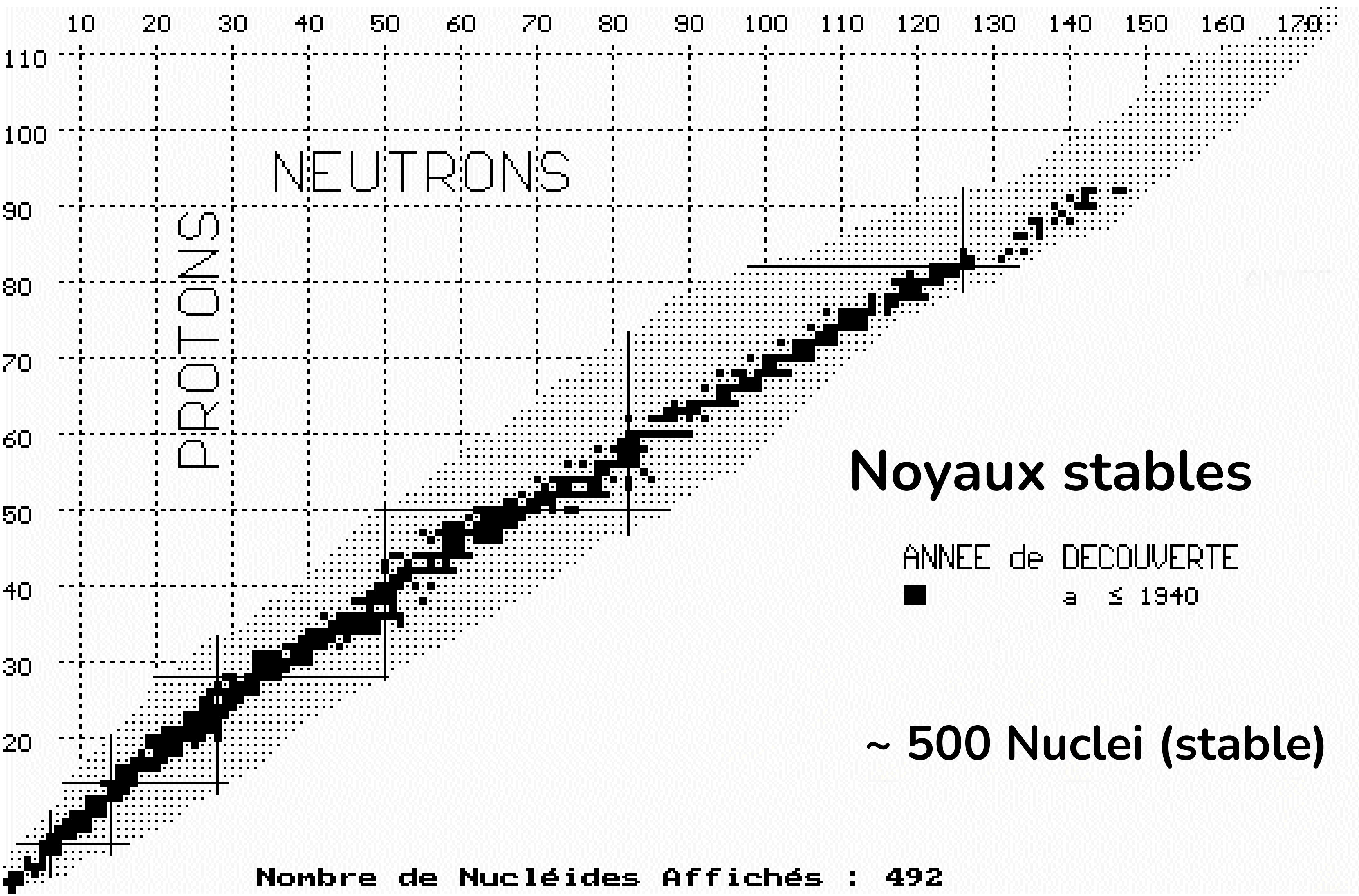
Courtesy Miguel Marques (LPC Caen)

Production of exotic nuclei with HI beams

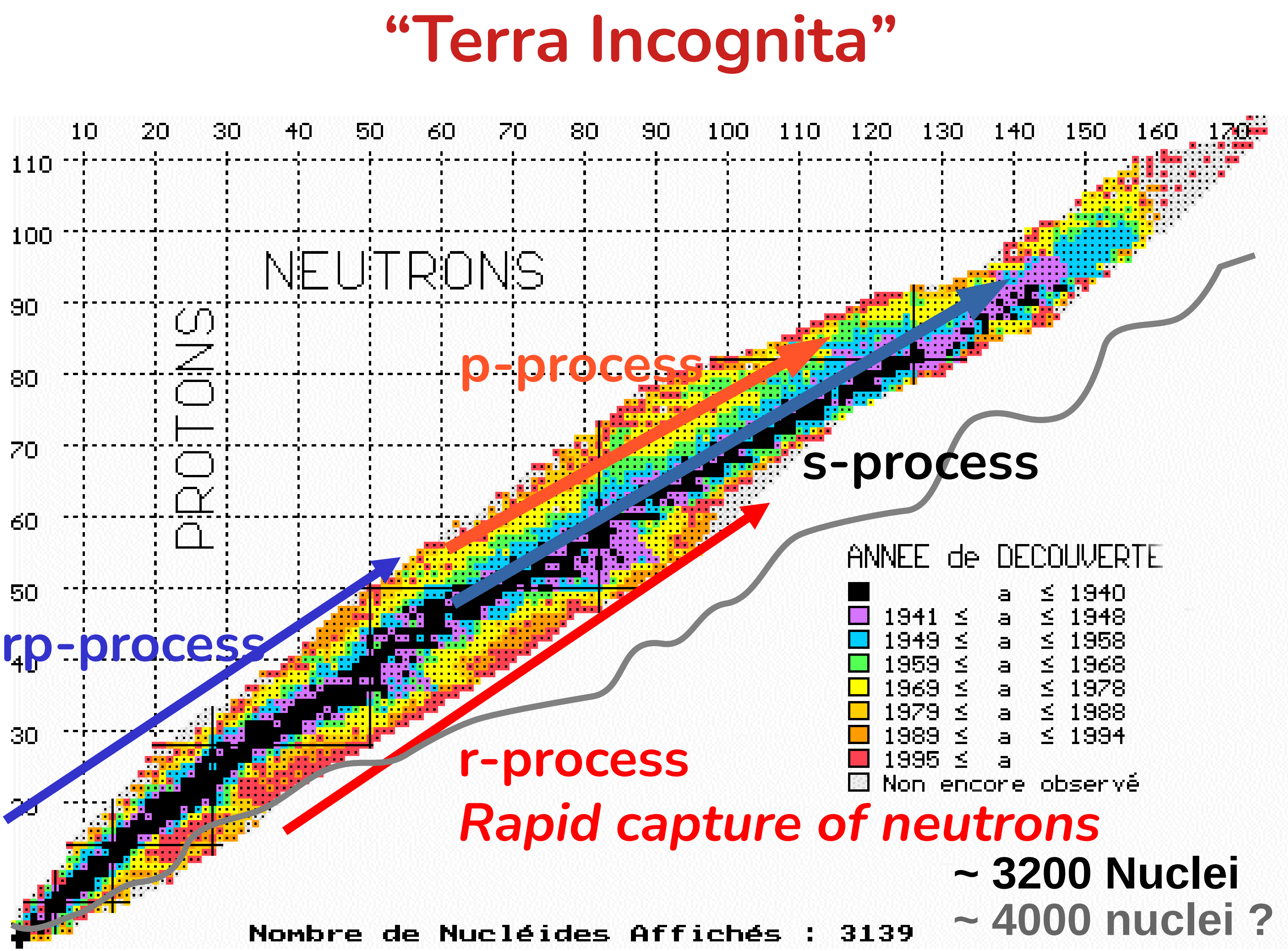




Known nuclei before WW2



Known Nuclei now : astrophysical processes



Nuclear reactions

Reaction Mechanisms

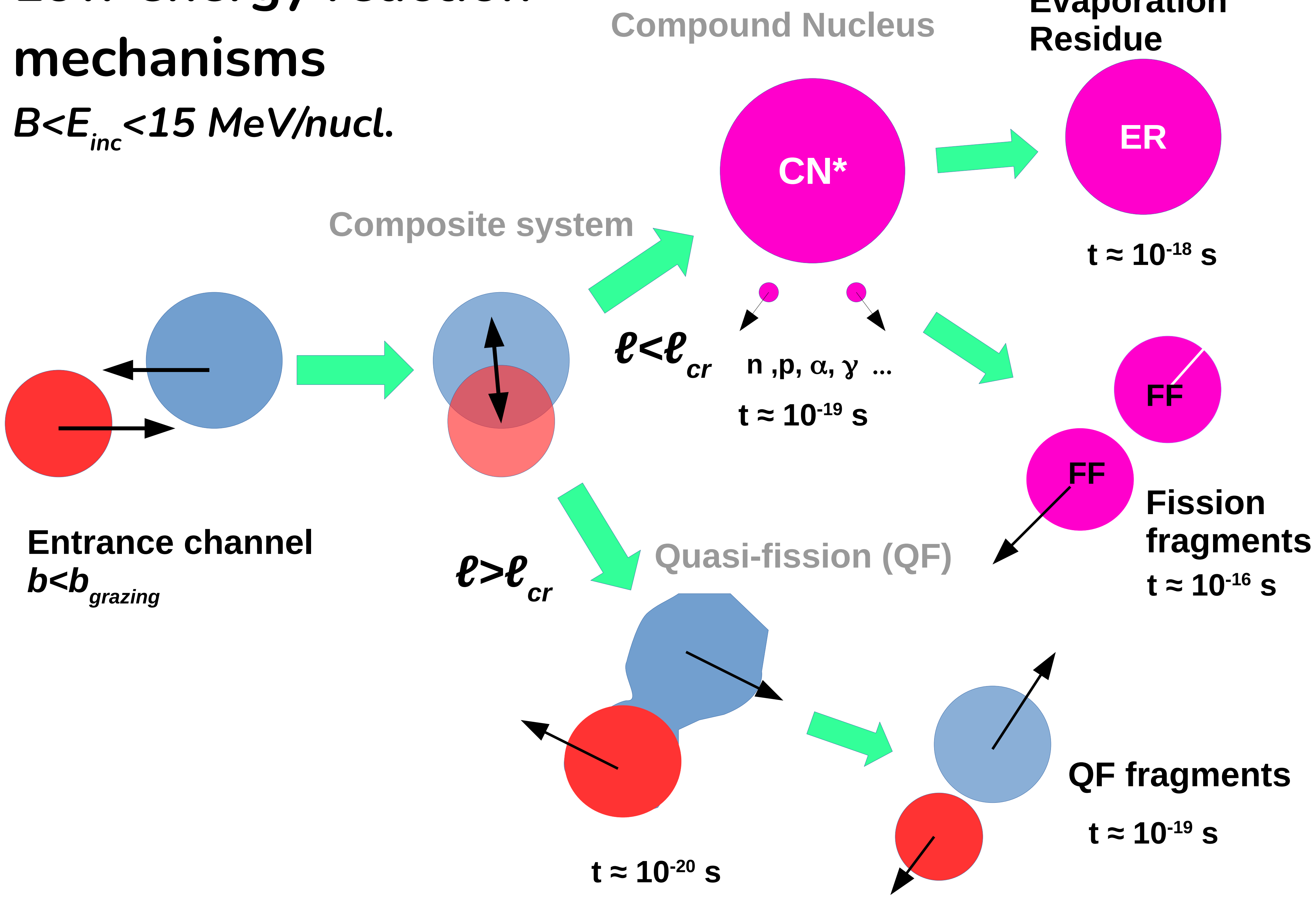
Nuclear reactions

Low incident energy

5 – 15 MeV/nucleon

Low energy reaction mechanisms

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



Nuclear reactions

Fermi incident energy

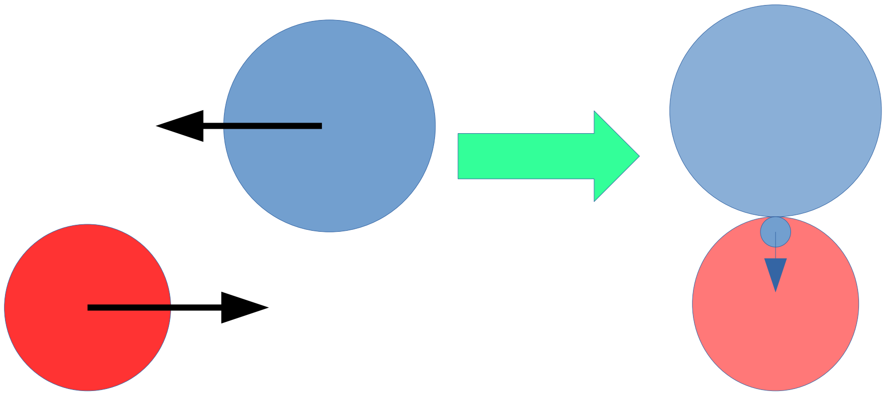
15 – 50 MeV/nucleon

Fermi energy reaction mechanisms

15<E_{inc}<50 MeV/nucl.

Transfer or direct reactions $b \approx b_{grazing}$

Stripping/pick up of nucleon(s)



Entrance channel
$b \approx b_{grazing}$

Examples :

(d,p) : +1n transfer (r-process)
(t,p) : +2n transfer (r-process)
(p,t) : -2n transfer (rp-process)
(^{3}He,d) : +1p transfer (rp-process)
...

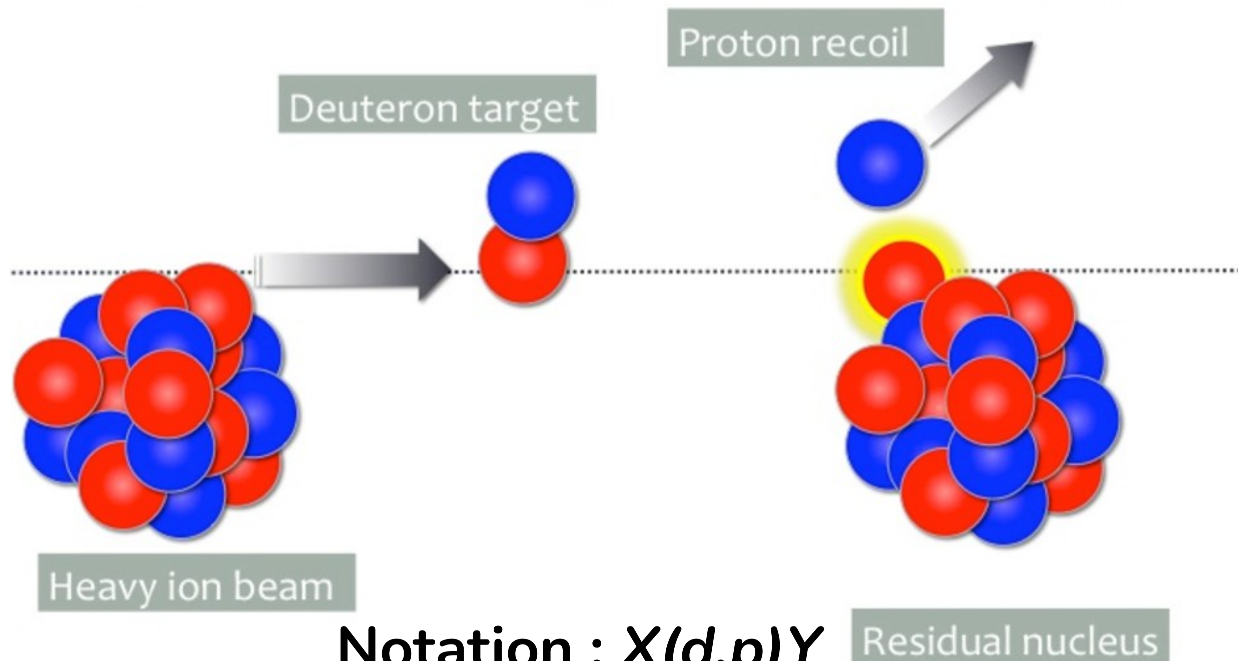
Transfer reactions at low incident energy

E_{inc}<50 MeV/nucl.

Projectile *X(N)* on a deuteron target with the pickup of one neutron to obtain *Y=X(N+1)* →more neutron-rich nucleus

Peripheral collision with $b \approx b_{grazing}$

Sizeable cross section (b)



Notation : *X(d,p)Y*

Complete kinematical reconstruction of the reaction / decay

Master the decay process

Limited to few nucleons transfer/pickup

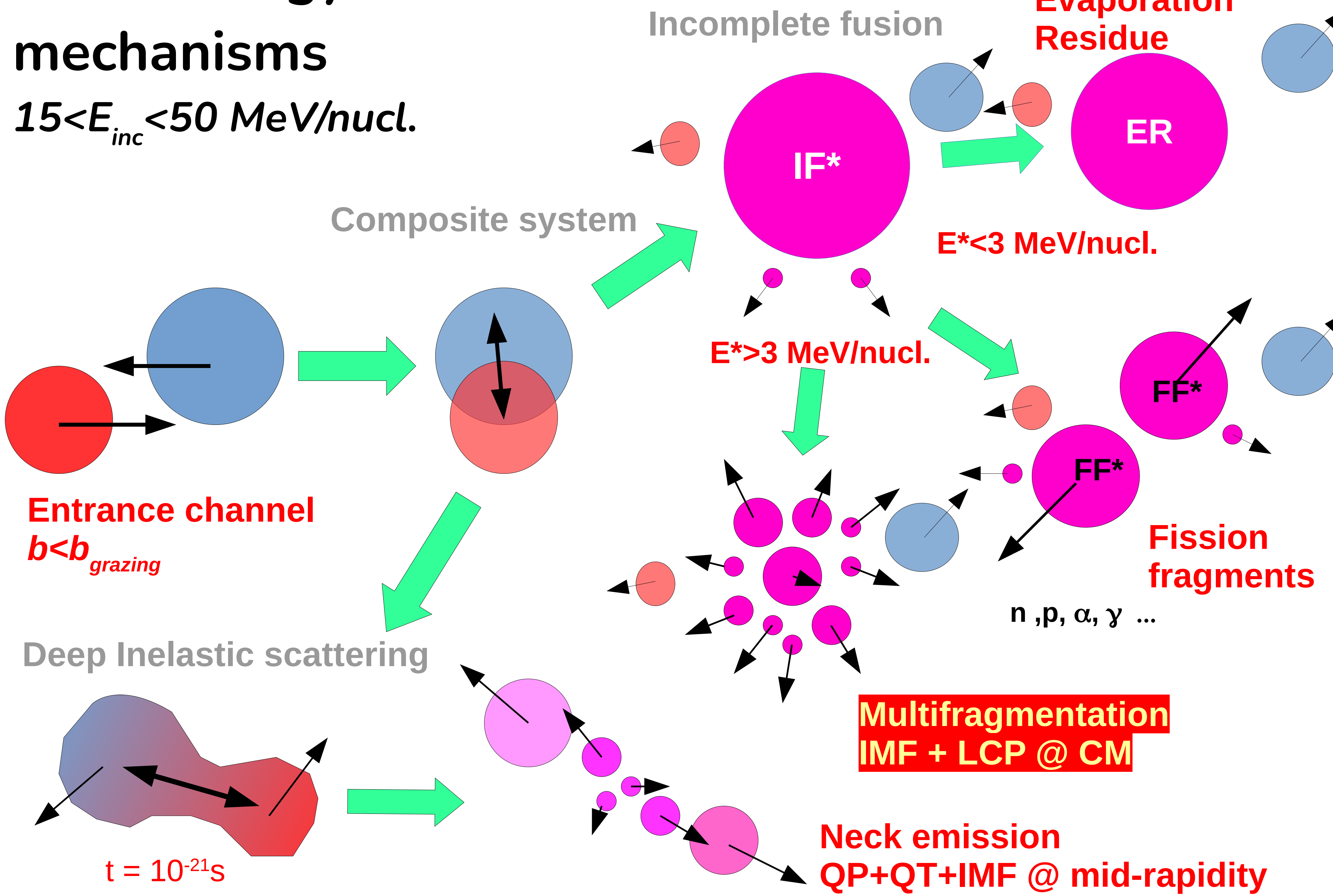
Small excursion toward drip lines

Limited angular momentum selectivity (few $\hbar$)

Few discrete states accessible

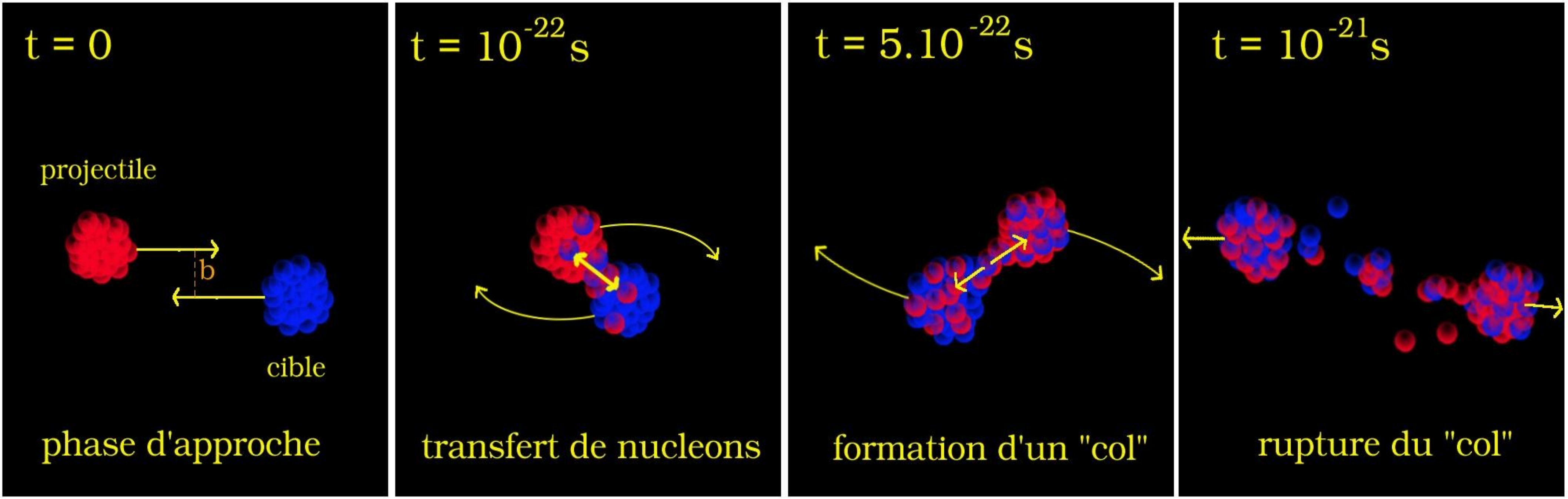
Fermi energy reaction mechanisms

15<E_{inc}<50 MeV/nucl.



Deep Inelastic collisions … toward the limits

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

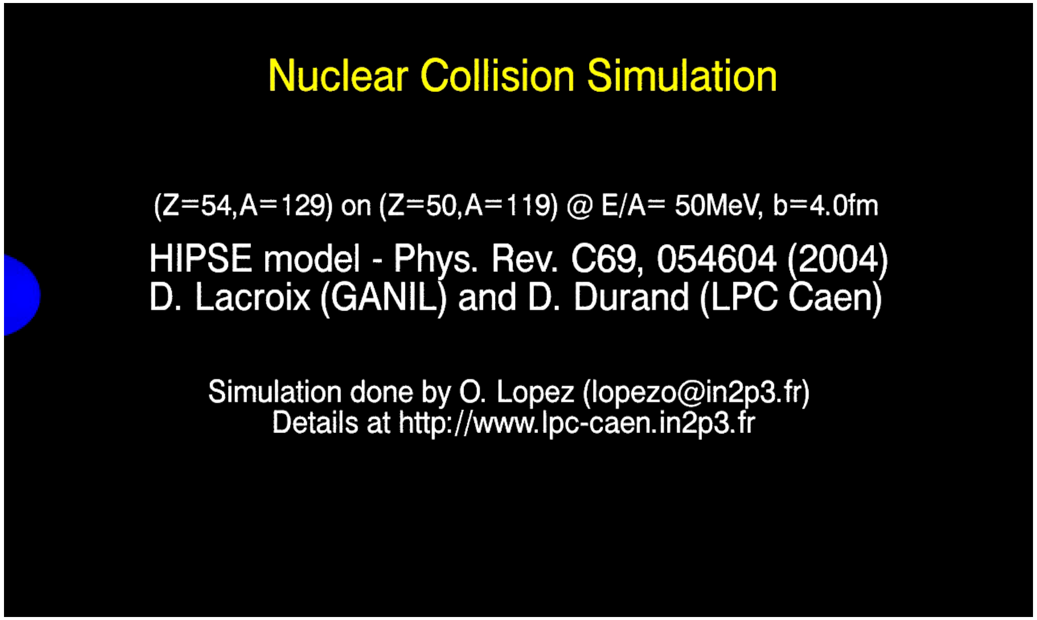


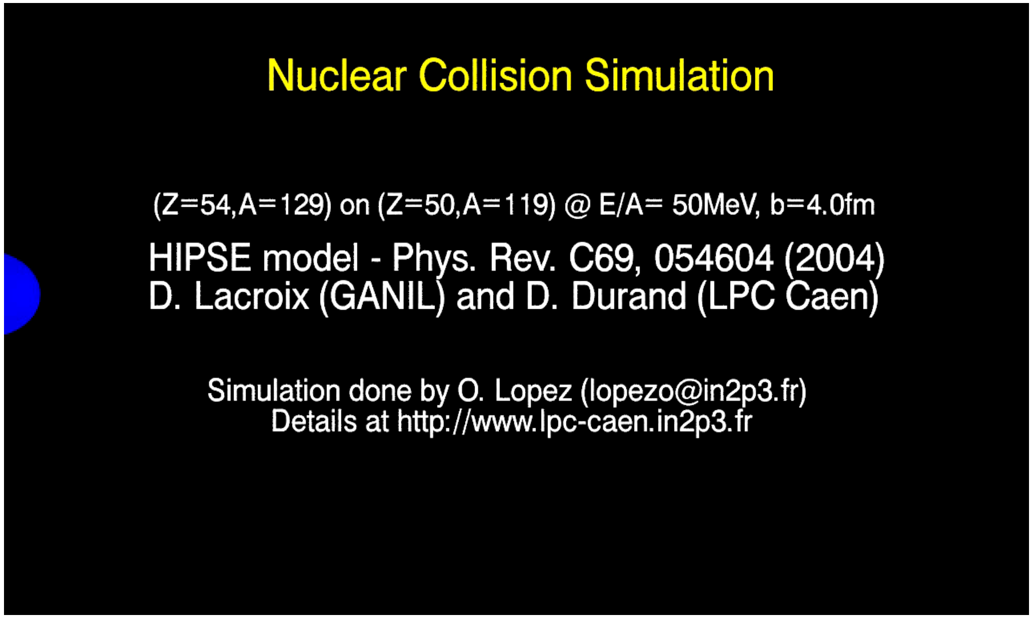
Extreme rotation
10^{23} rpm !

More diluted
$\rho << \rho_0$

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

Simulation Xe+Sn at 39 MeV/nucleon
b=4 fm





Deep Inelastic Scattering

15<E_{inc}<50 MeV/nucl.

Projectile is damped and rotate around the target

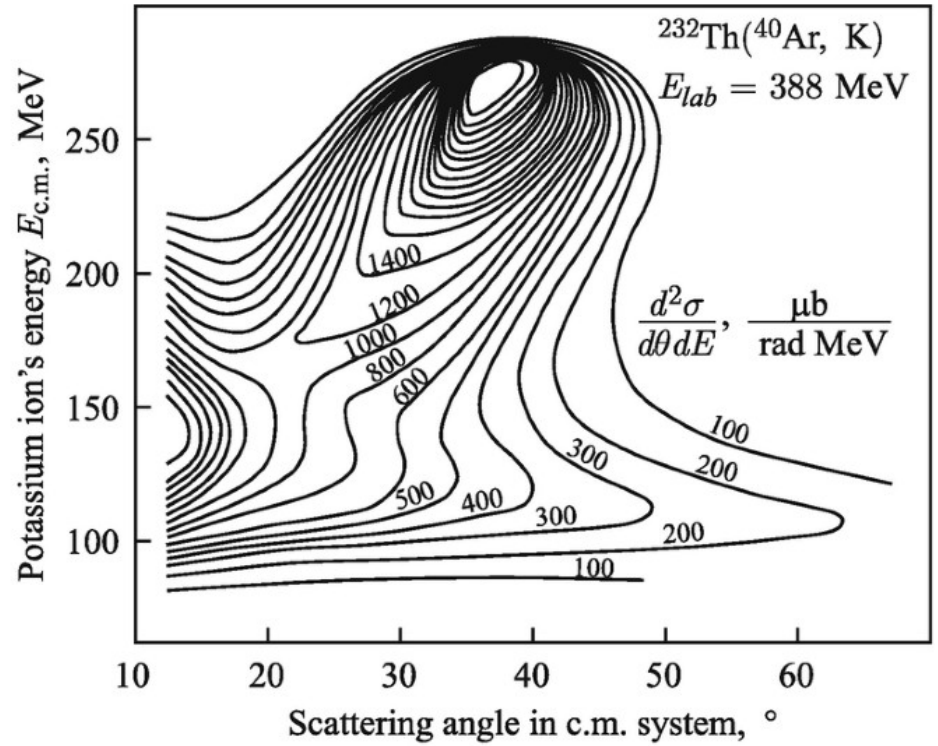
Kinetic energy is associated to the energy dissipation via multi-nucleon transfer (MNT)

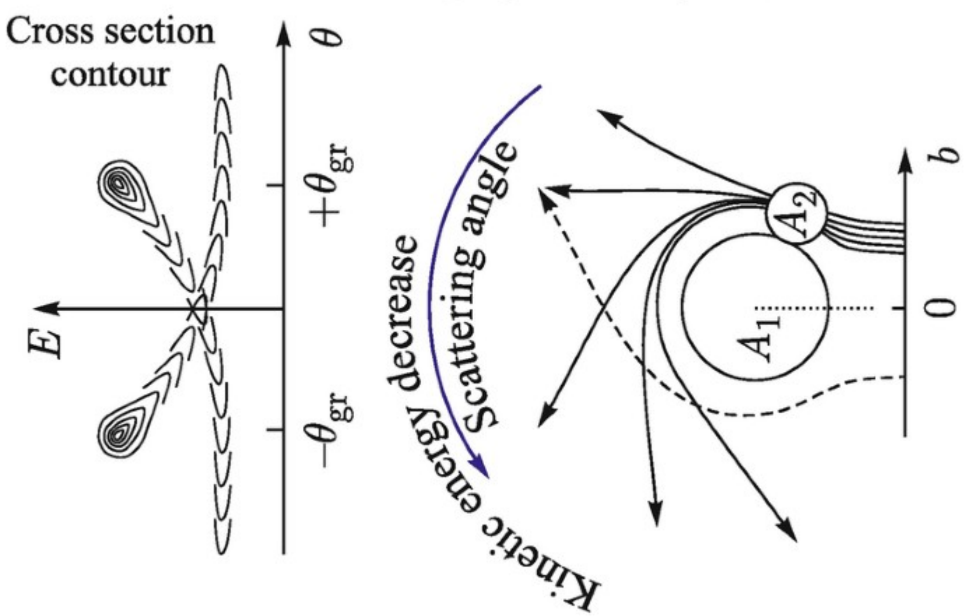
Angle is associated to the timescale of the process

Energy is used to estimate excitation energy

Angle is used as a clock for nuclear timescales

100 fm/c = 10^{-21} s (1 zs)





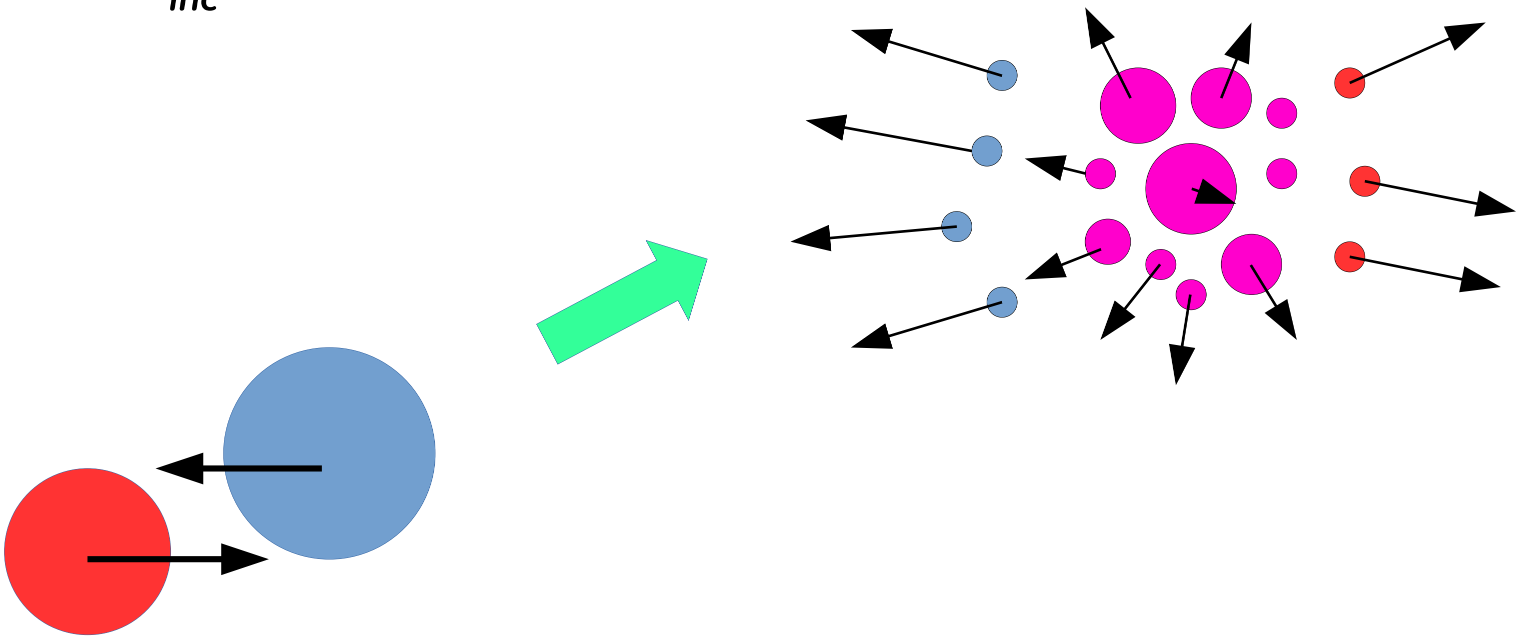
Nuclear reactions

Intermediate incident energy

50 – 100 MeV/nucleon

Intermediate energy reaction mechanisms

50<E_{inc}<100 MeV/nucl.

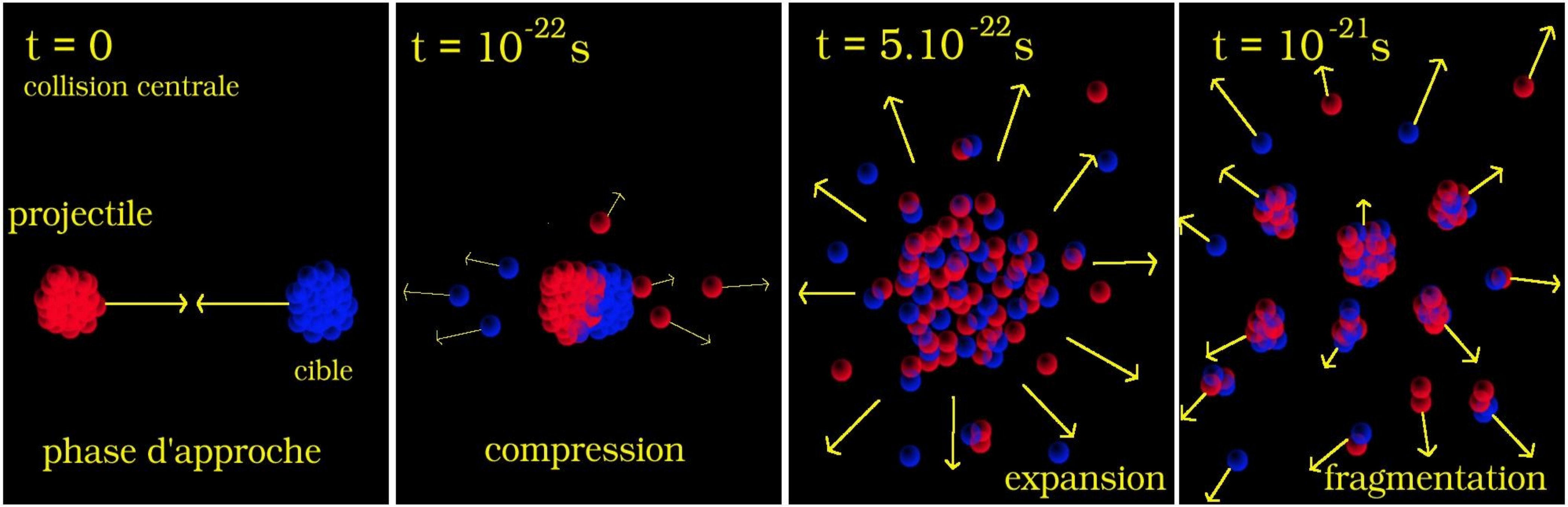


Multifragmentation
IMF + LCP @ CM
***NN* collisions**
(pre-equilibrium)

Entrance channel
b<b$_{grazing}$

Central collisions … Little Big Bang !

Central collision (b=0)

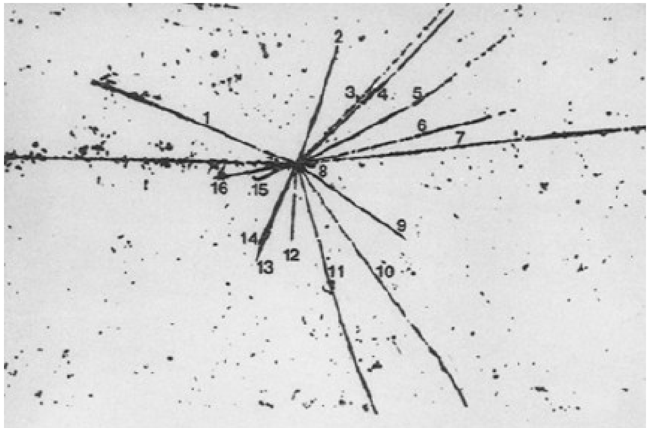


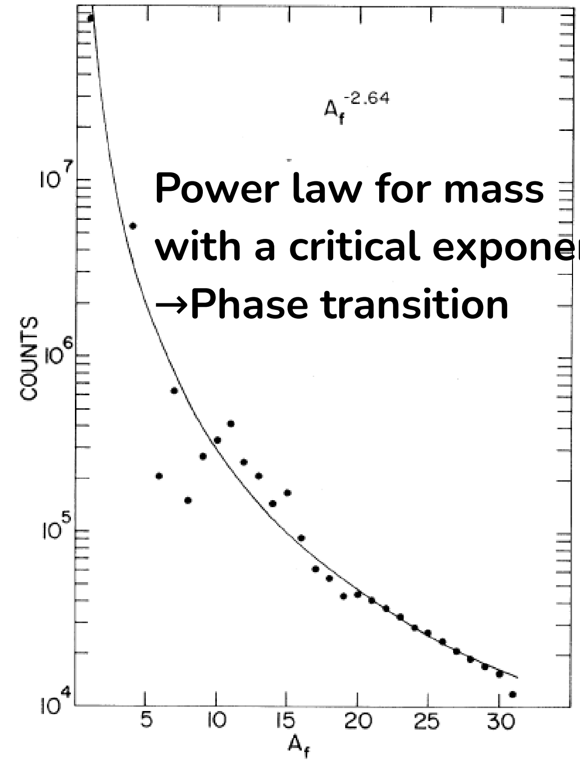
More dense
ρ / ρ_0 >2-3

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

Fragmented and diluted
N>10-100

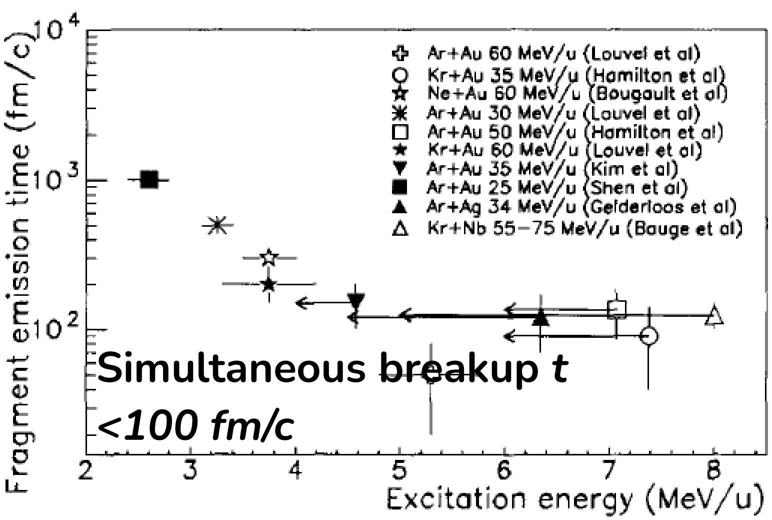
Multifragmentation as Liquid-gas PT



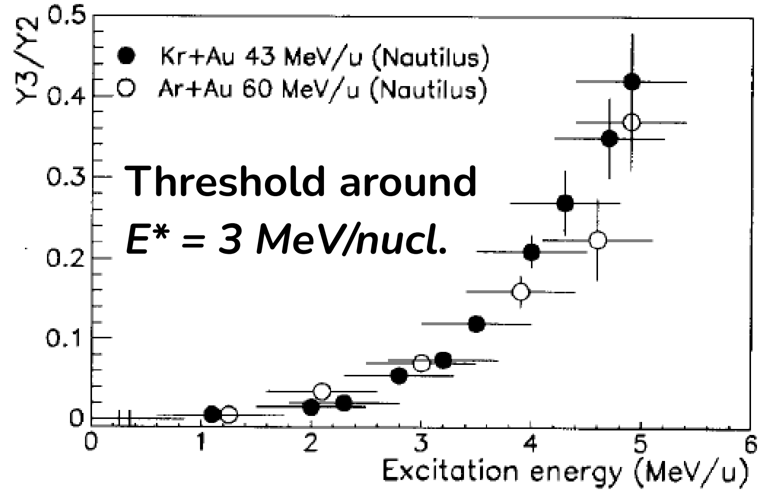


Power law for mass with a critical exponent
→Phase transition

Breakup reactions with more than 2 fragments…

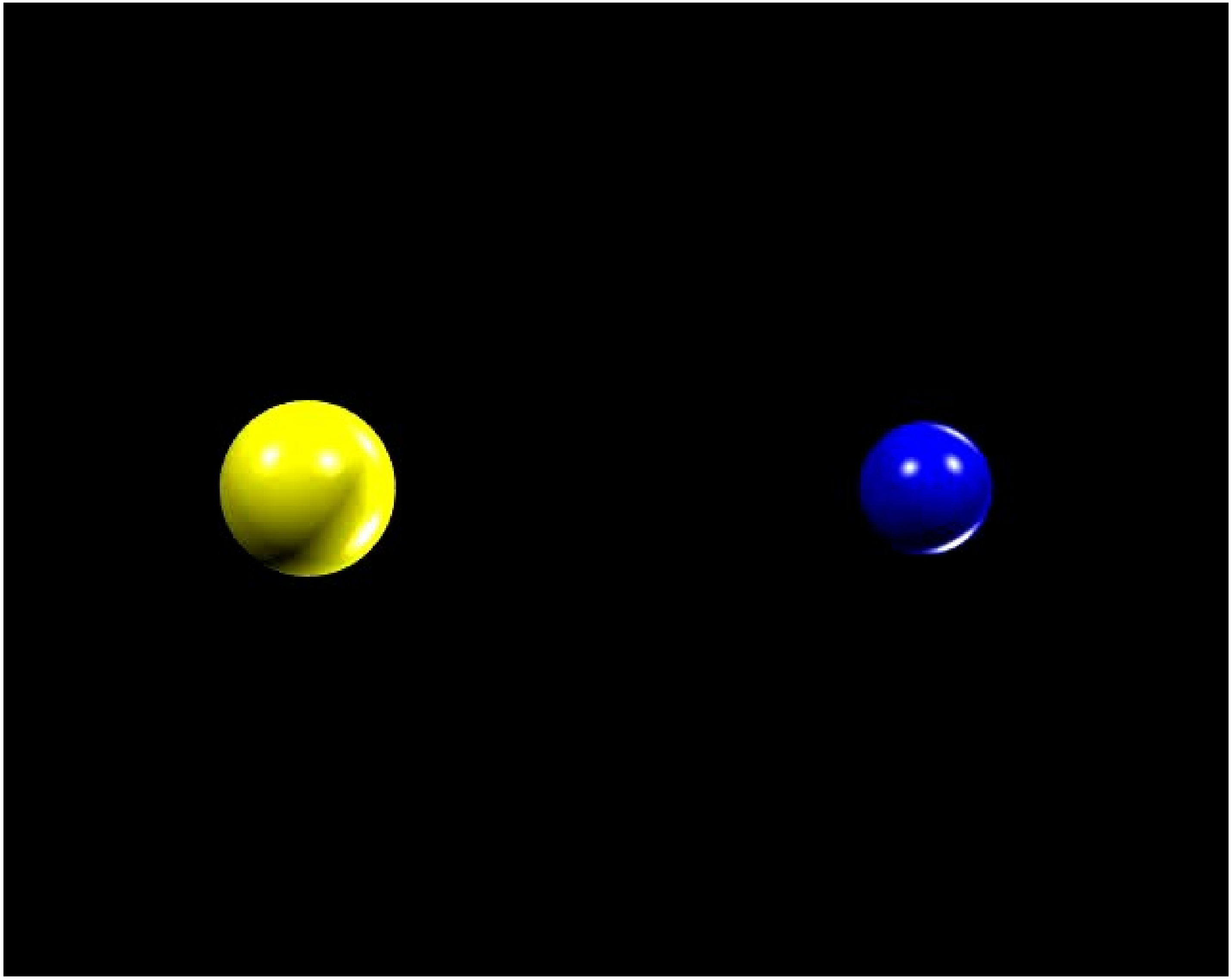


Simultaneous breakup *t* <100 fm/c

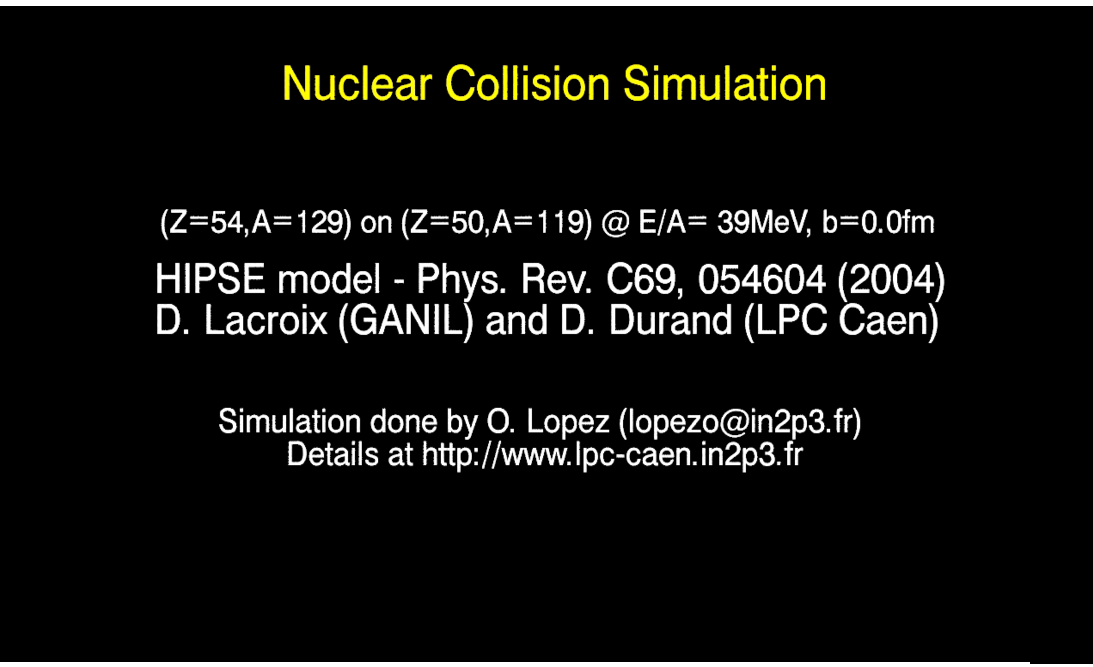


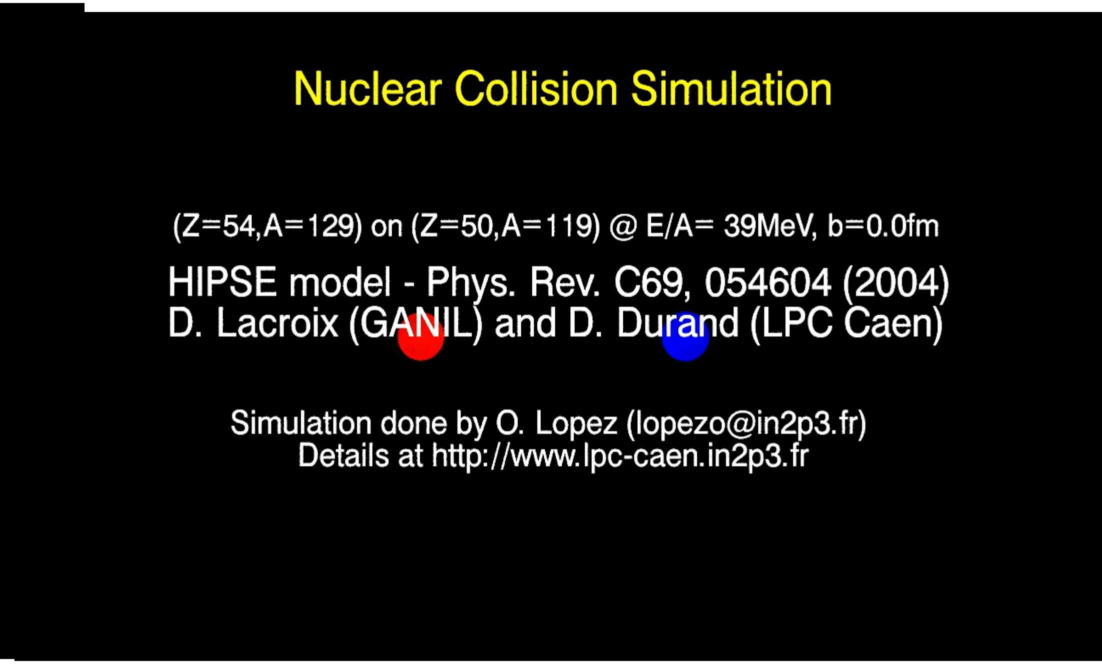
Threshold around *E* = 3 MeV/nucl.*

Multifragmentation



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



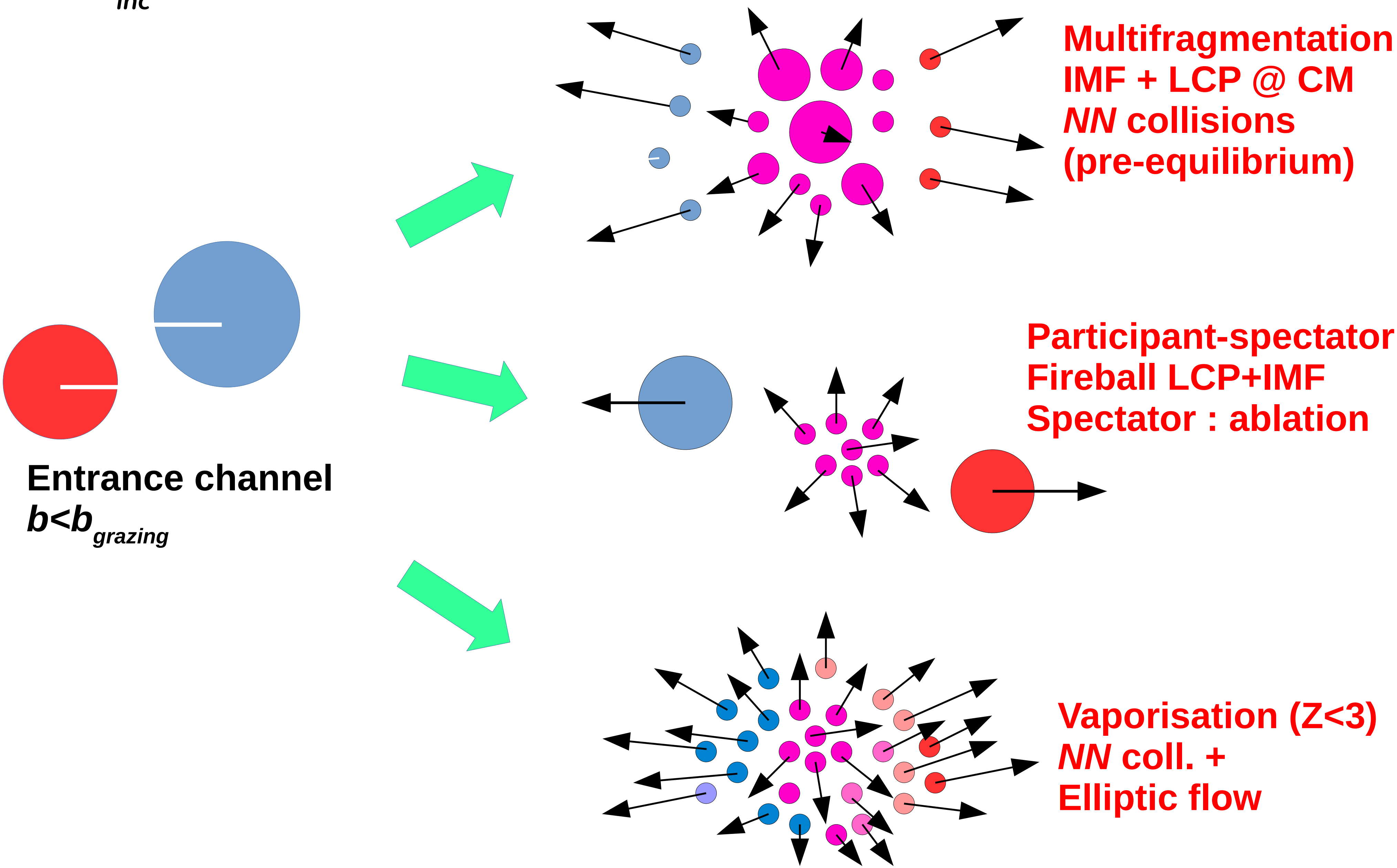


More videos avaialble on this YouTube channel :

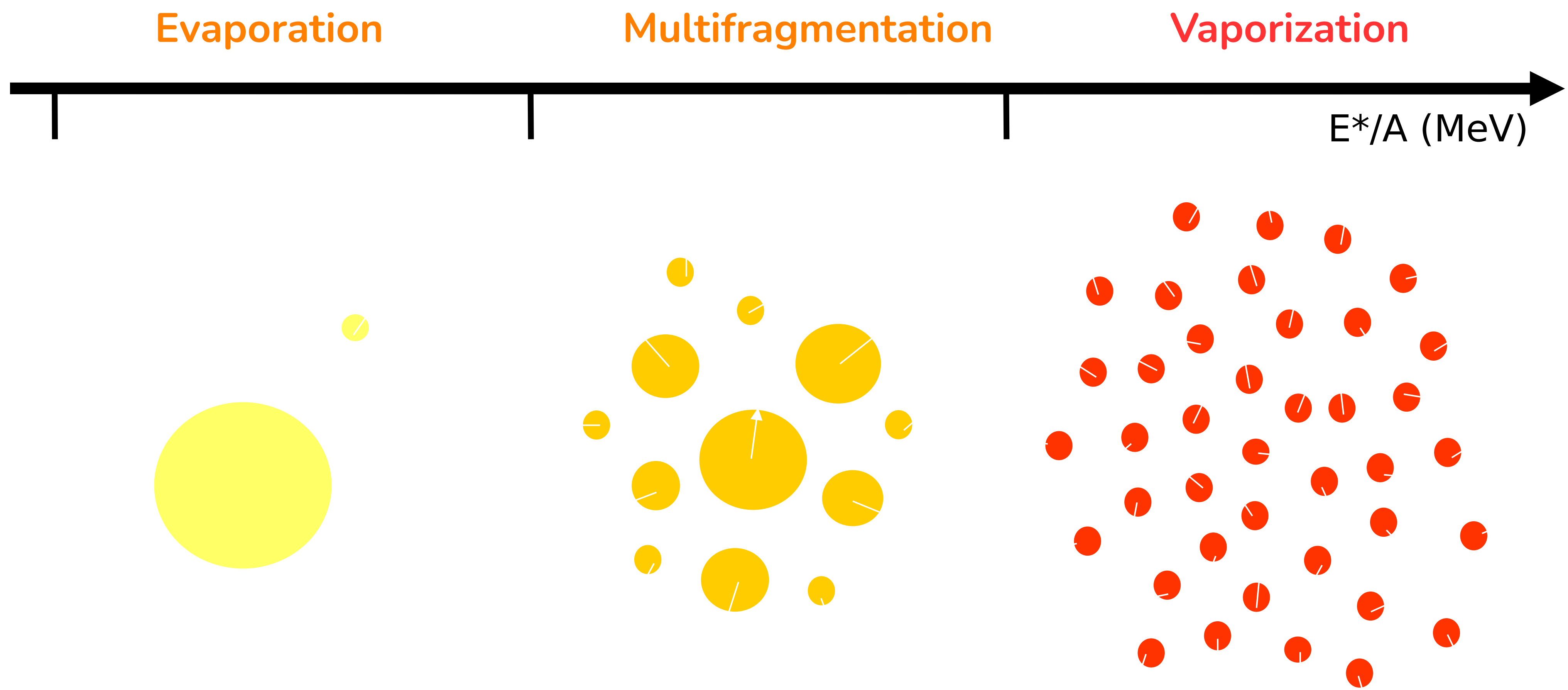
https://www.youtube.com/watch?v=azCjJx6REKg

Intermediate energy reaction mechanisms

50<E_{inc}<100 MeV/nucl.



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



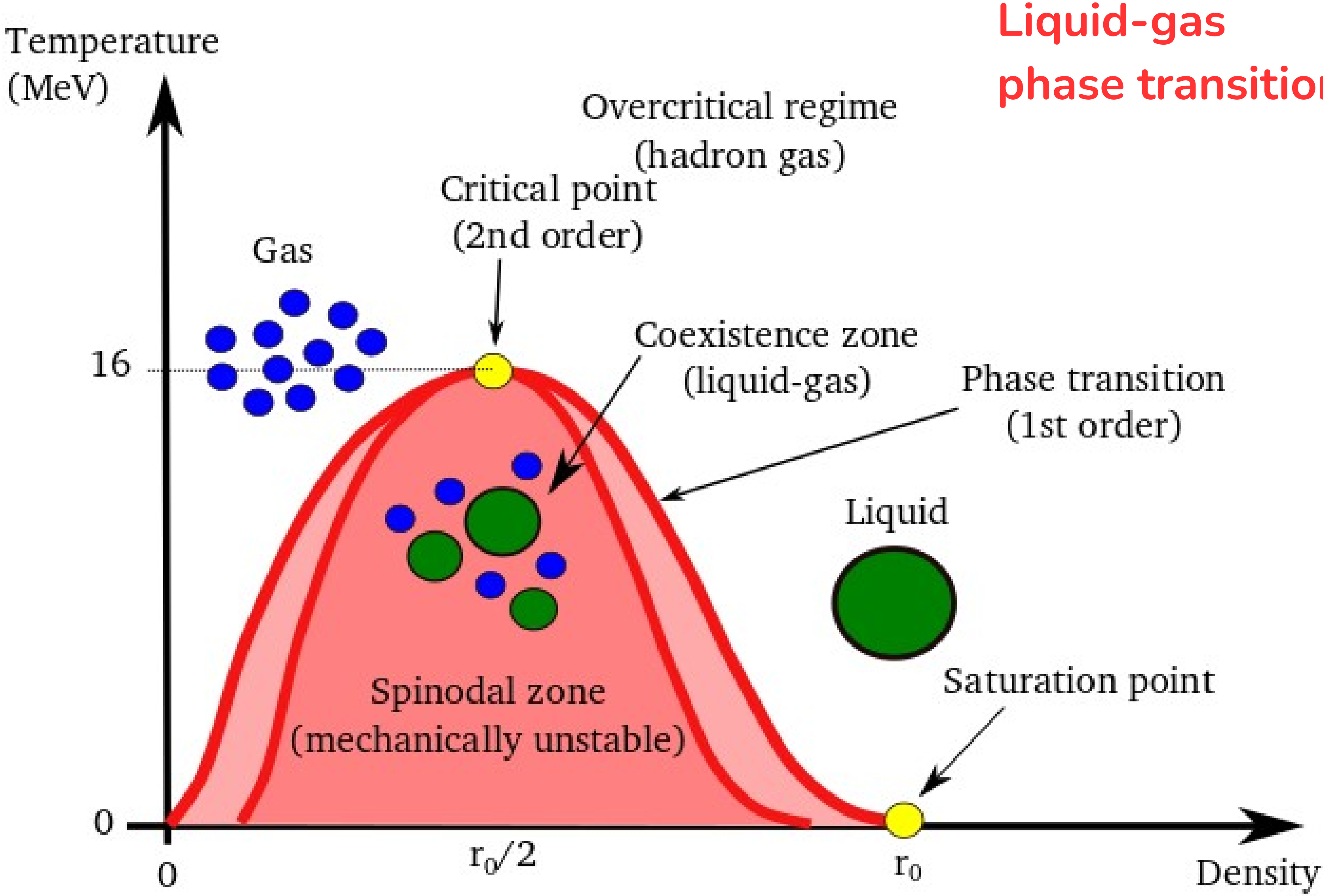
$\rho \sim \rho_0$
T < 5 MeV

$\rho < \rho_0$
T= 5-10 MeV

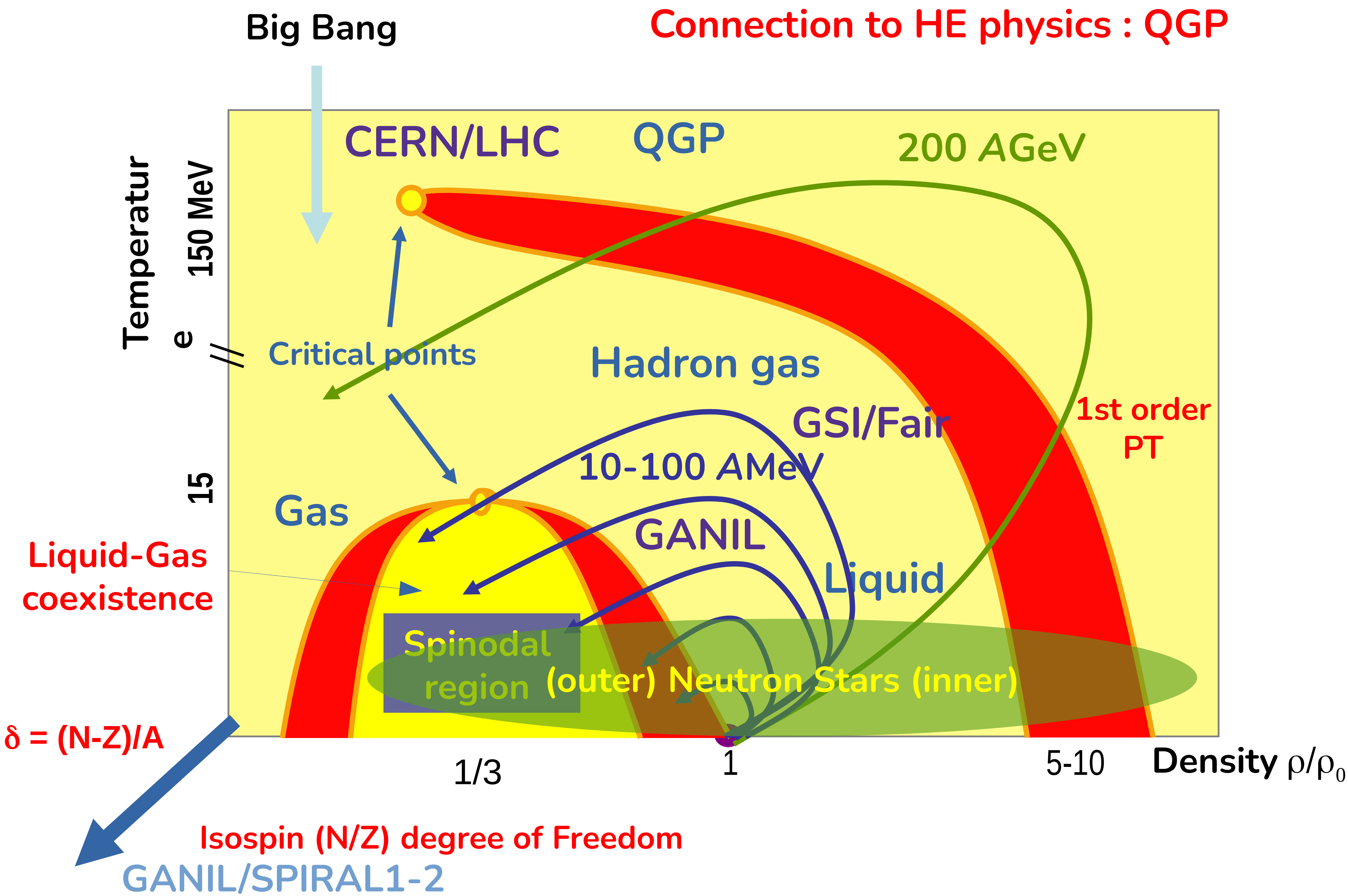
$\rho << \rho_0$
T>10 MeV

Multifragmentation : Mean-Field density instabilities

Liquid-gas phase transition



Phase diagram of Nuclear Matter



End part II

Part III

Nuclei at extremes
Nuclear Equation of state

Novae & Supernovae

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

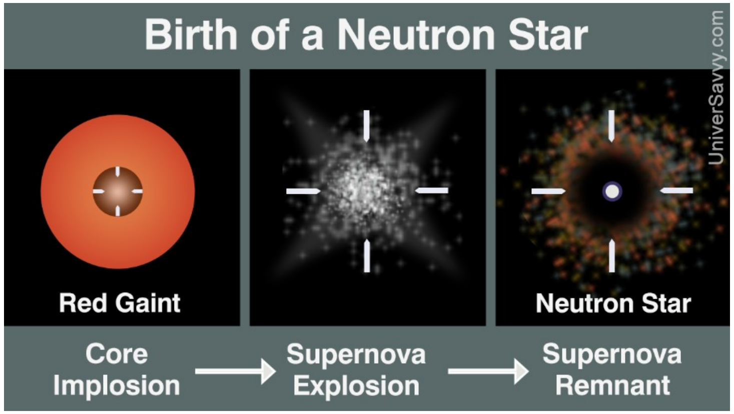
$E = 10^{38}$ J , L x 1000 !

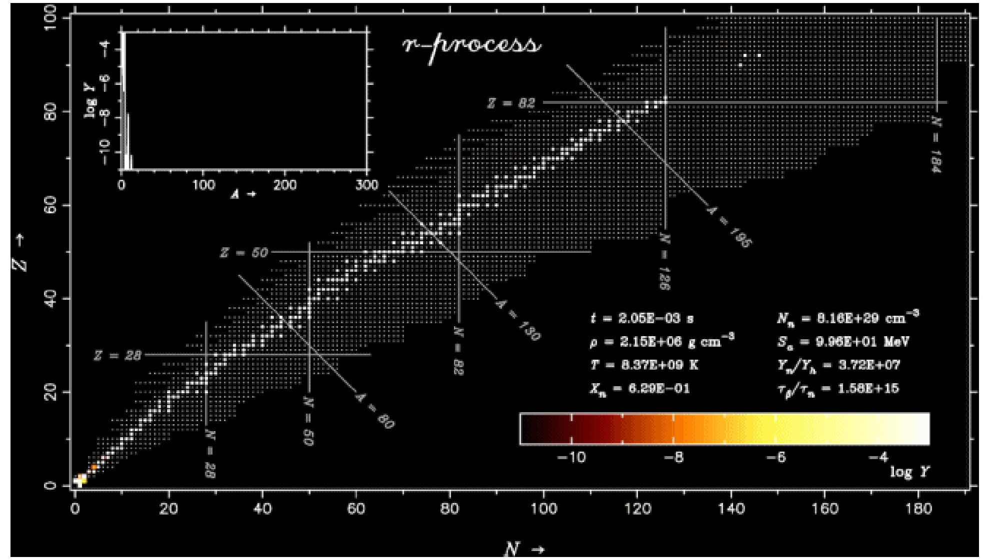
$E=10^{44}$ J , L x 10^{10} !!

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

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)

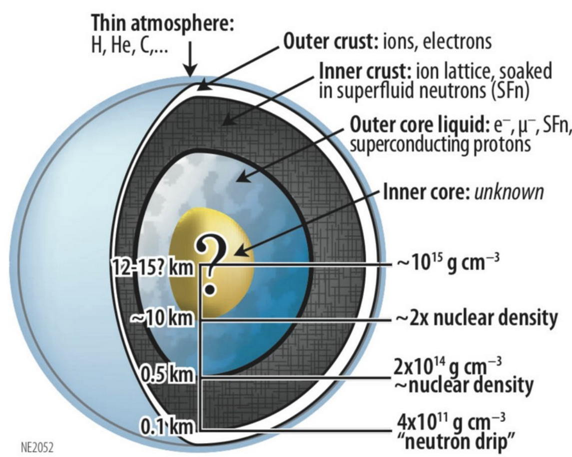
Detection of *GW* and multi-messenger observables (GW170817) considerably reinforces terrestrial *EOS* studies

Core Collapses Sne

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

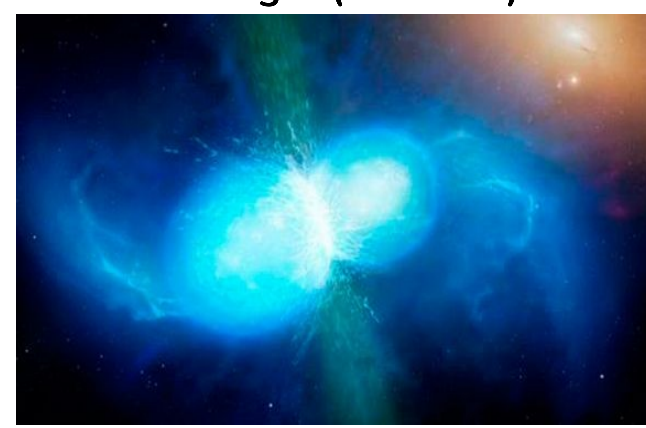
NS structure :

- Crust : pasta phases (frustation/clusters)
- Crust/Core transition: 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)



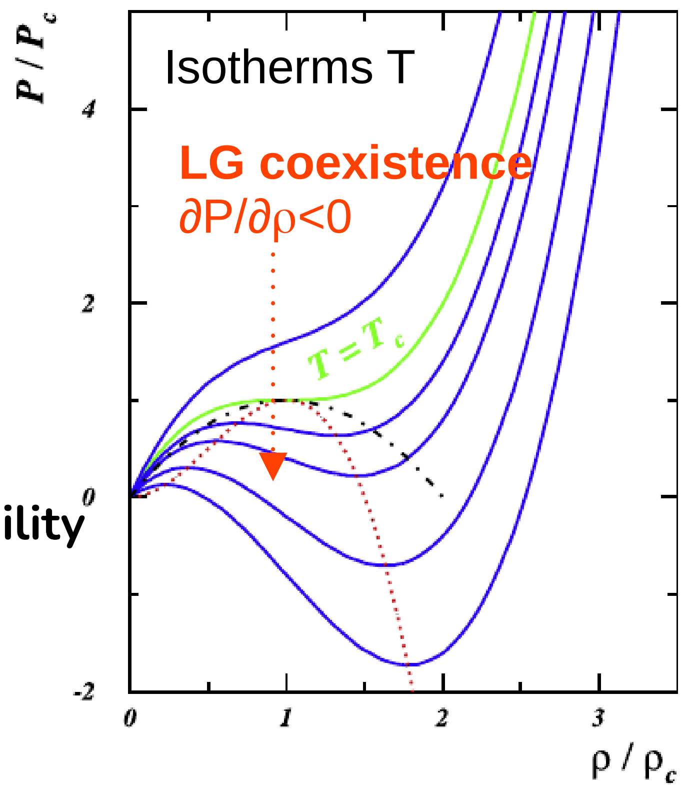
Equation of State of nuclear matter

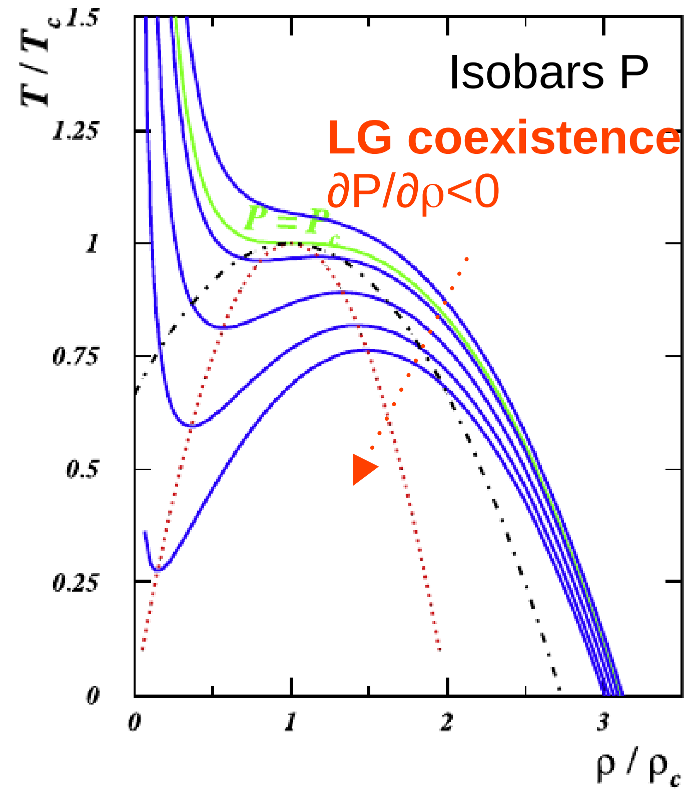
$$E \text{ (or } P) = f(\rho , T , \delta)$$

Thermodynamical relation between state variables

Compressibility

$\partial P/\partial \rho$





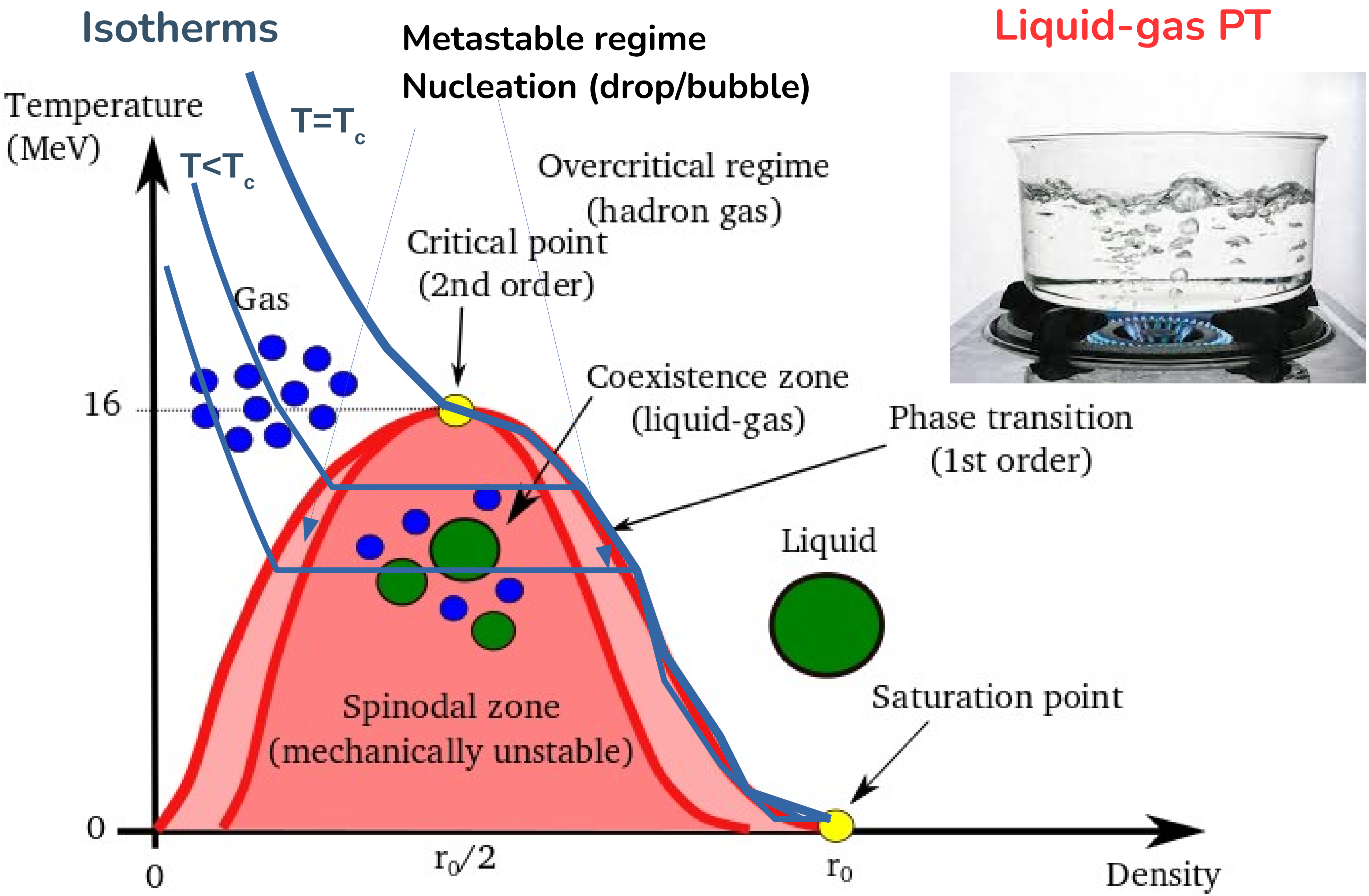
Skyrme HF at finite T

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, r_c **: critical point of the liquid-gas phase transition with** $T_c = 16\text{-}18\ MeV$, $\rho_c = 0.3\text{-}0.5\rho_{sat}$

Spinodal decomposition : Mean-Field instabilities



Liquid-gas PT

Equation of State in nuclei

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

$\delta = (N\text{-}Z)/A$

Astrophysical context (NS)

Nuclear matter :
Bulk properties

Extensive systems
(volume,size)

Pure neutron matter (δ=1)

Terrestrial Labs

Nuclei :
Finite-size effects

Non-extensive systems
(surface, Coulomb)

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

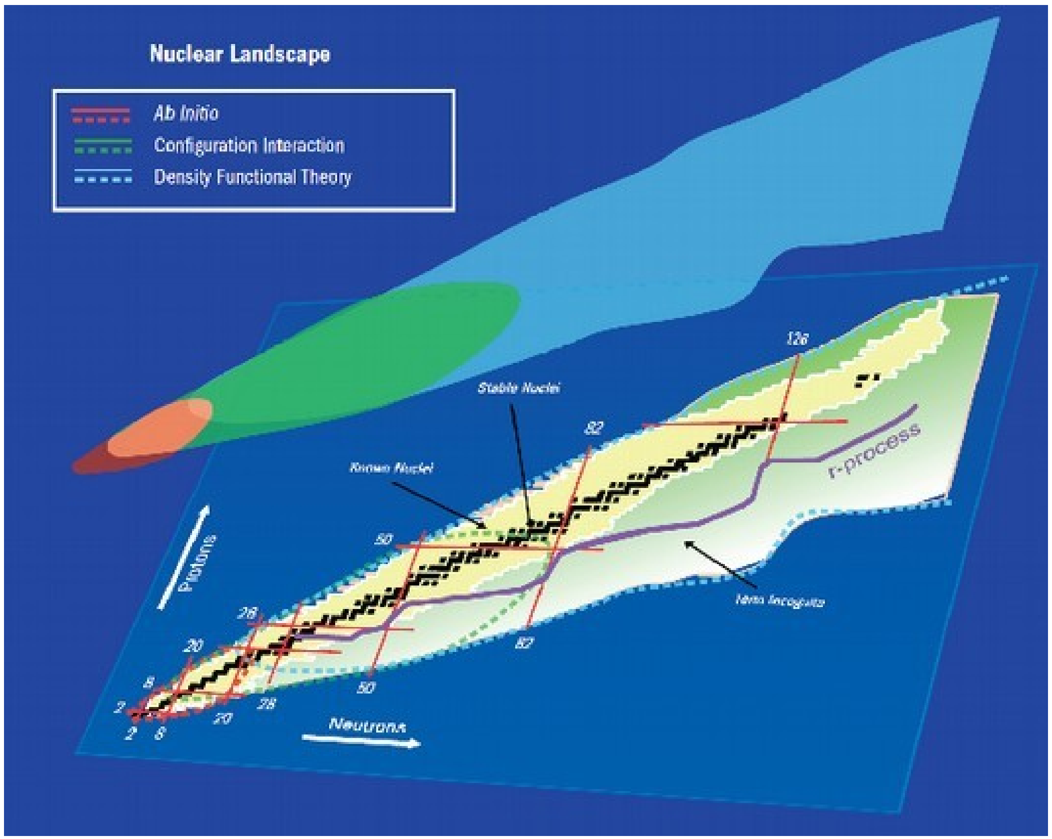
Phase Diagram and Phase Transitions in finite systems

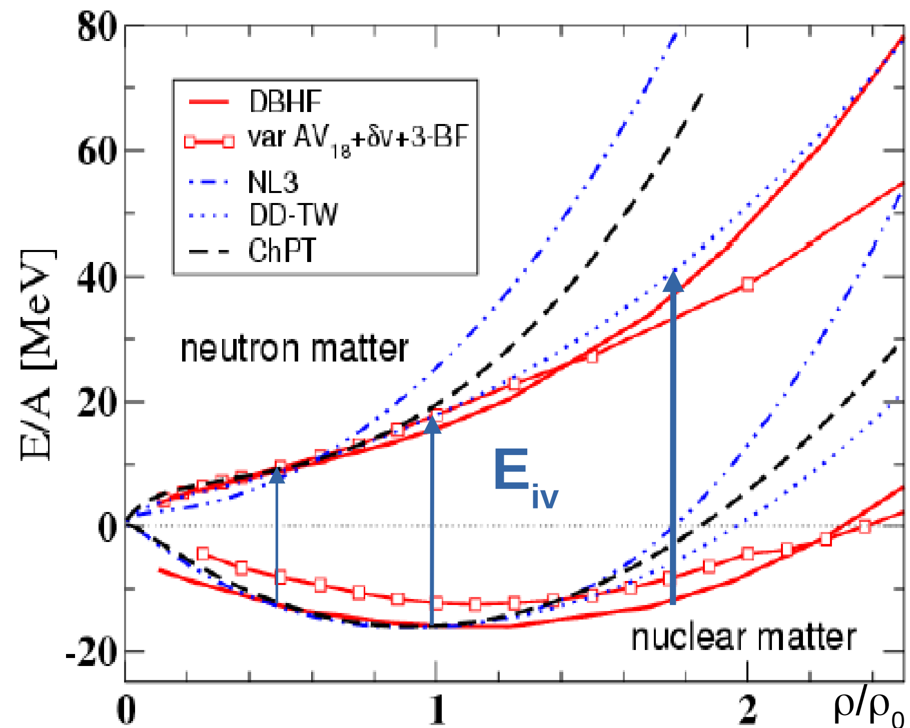
EoS in Nuclear Physics

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

Energy-Density Functionals

(Hohenberg-Kohn theorem) : $H_{eff} = E[\rho]$





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

E_{iv} (aka S) = $E(\rho,\delta=1) - E(\rho,\delta=0)$

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}

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

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

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

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

E_{sat} is the saturation energy at $\rho = \rho_0$

K_0 is the compressibility (curvature) around ρ_0

Q_0 and Z_0 are the cubic and quartic terms needed for ρ *far from* ρ_0

J is the symmetry energy at $\rho = \rho_0$

L_{sym} is the slope (conn. to P) of the symmetry energy around ρ_0

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_0

Symmetry Energy and Density Dependence

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

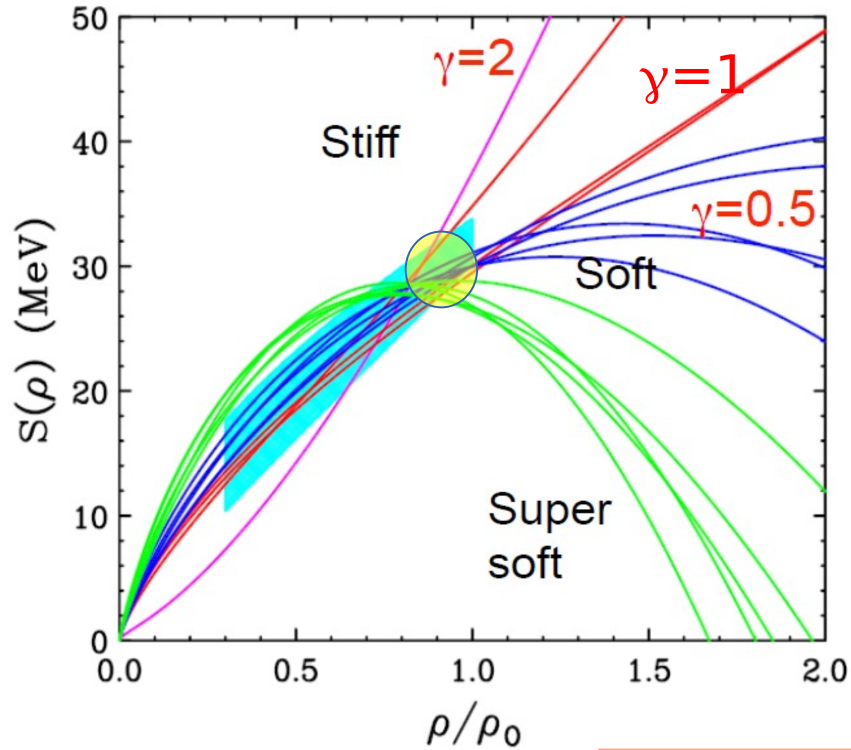
$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

- 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

Density dependence of *SE*

Poorly constrained … Need experimental data !

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

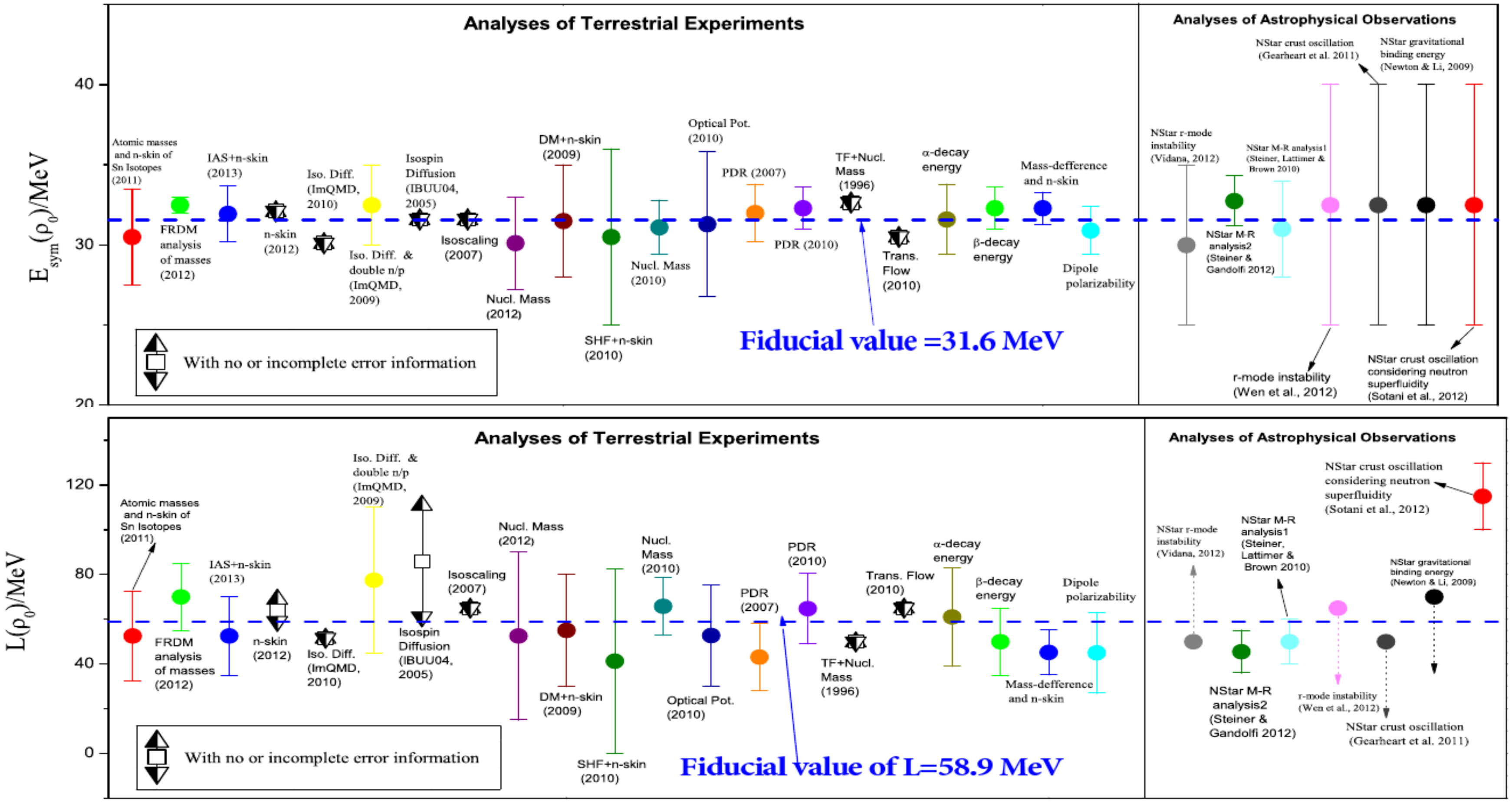


$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

Kinetic (FG) Potential (int.)

Symmetry Energy around ρ_0 (I)

Evaluations for E_{sym}, slope L, curvature K_{sym}, … B.A. Li and X. Han, Phys. Lett. B727 (2018) 276

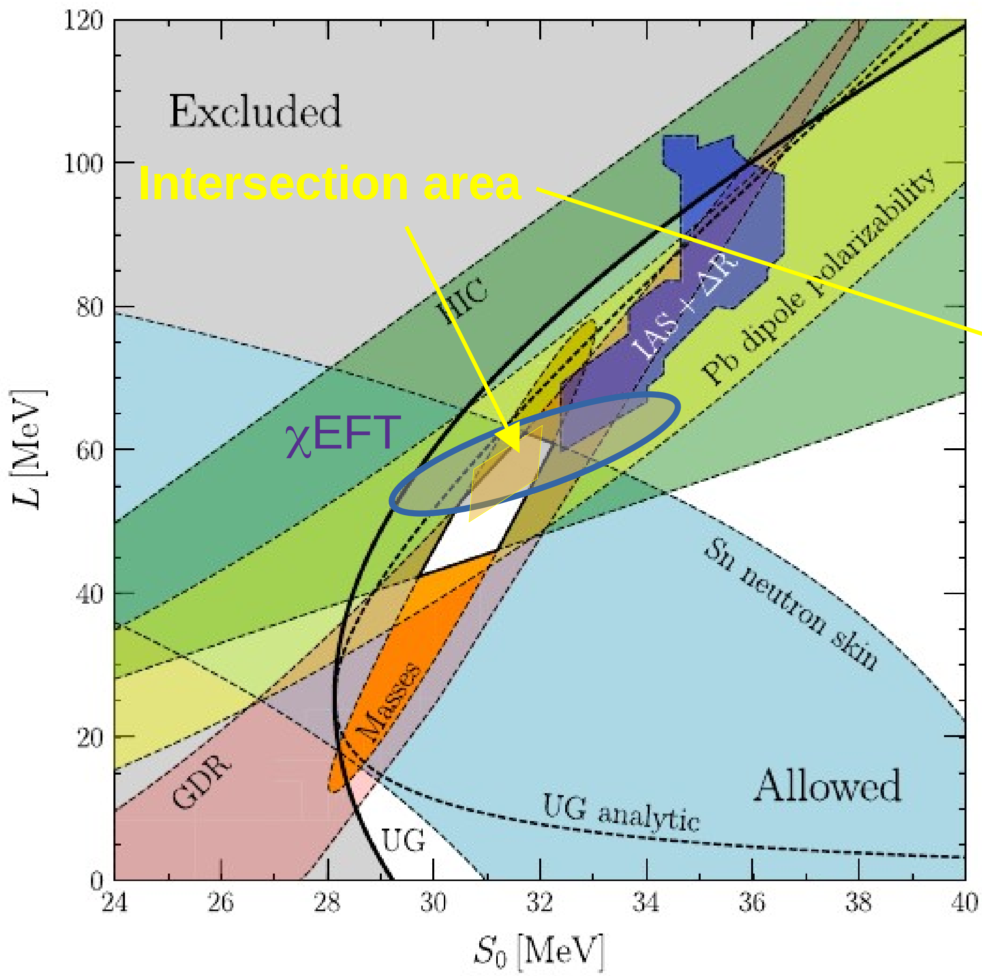


	~1%	~10%		~30%		???				
P_α	E_{sat} MeV	E_{sym} MeV	ρ_0 fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000

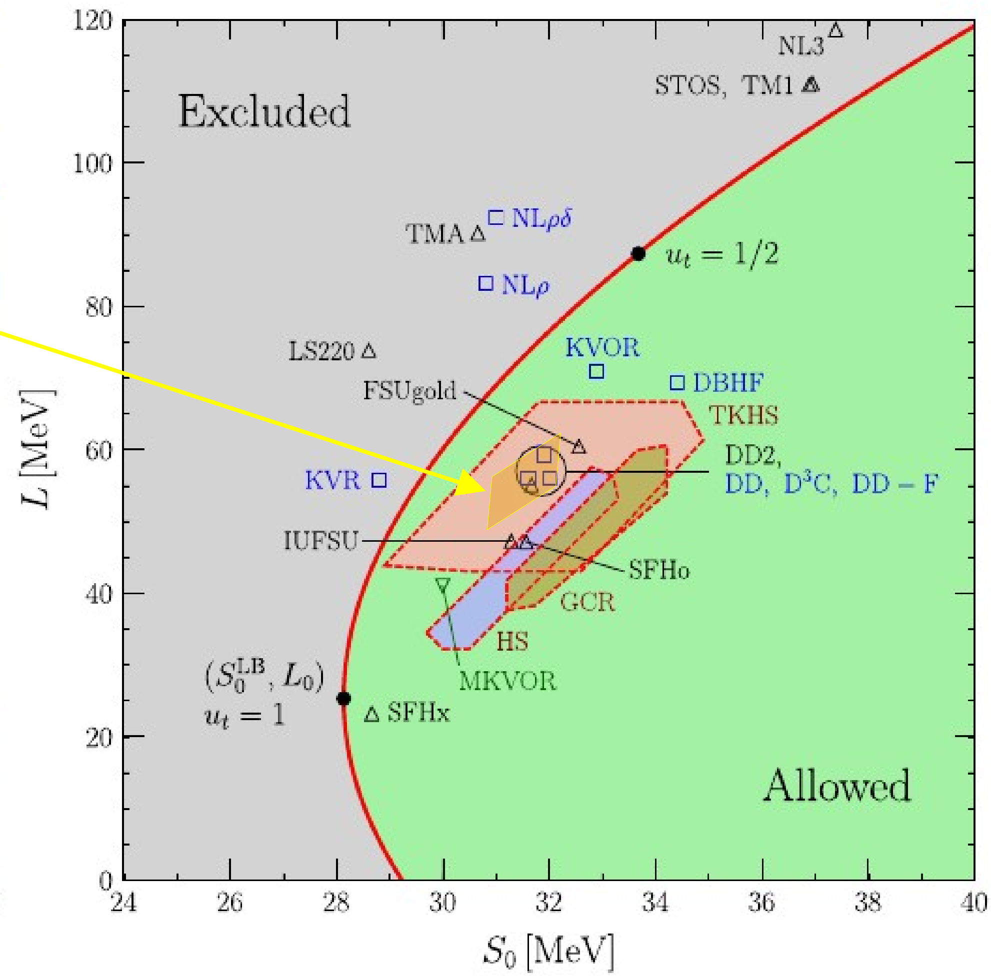
J. margueron *et al.*, PRC 97, 025805 (2020)

Symmetry Energy around ρ_0

Experimental constraints



Model predictions



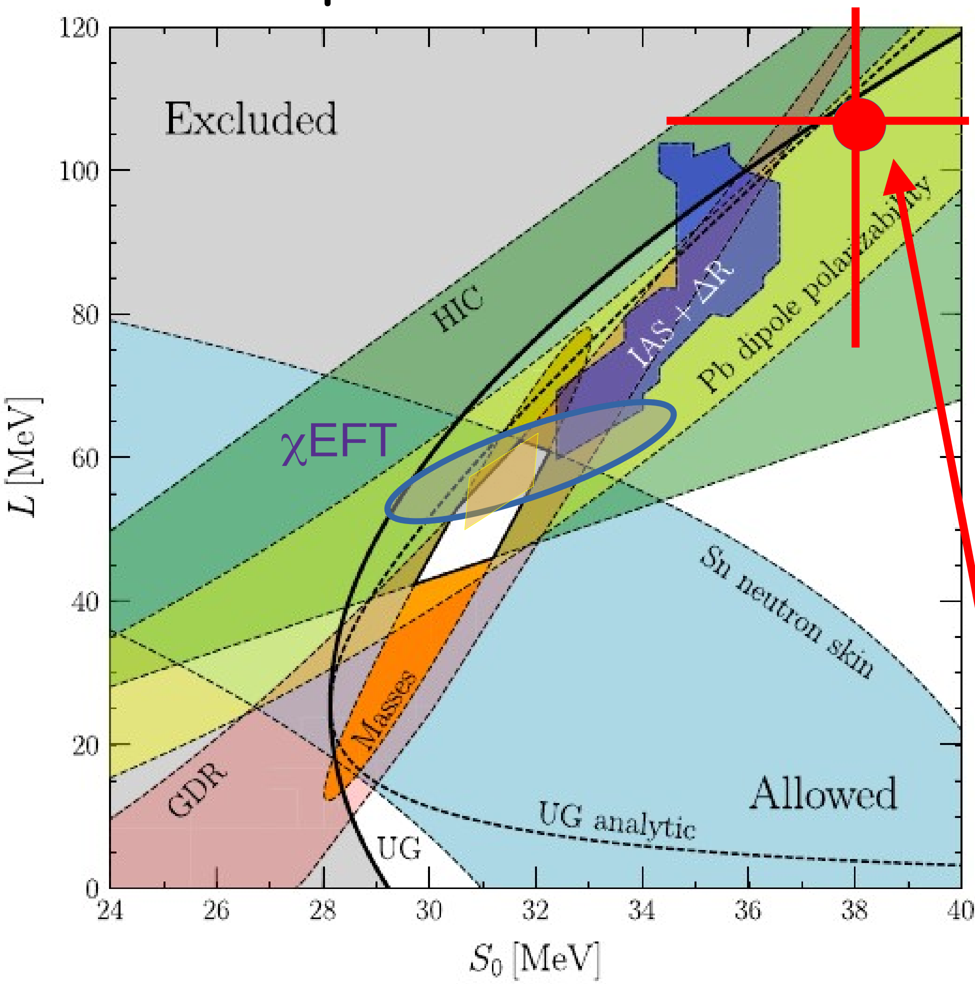
I. Tews *et al.*, Astroph. J. 848 (2017) 105

C. Drischler *et al.*, PRL 125 (2020) 202702

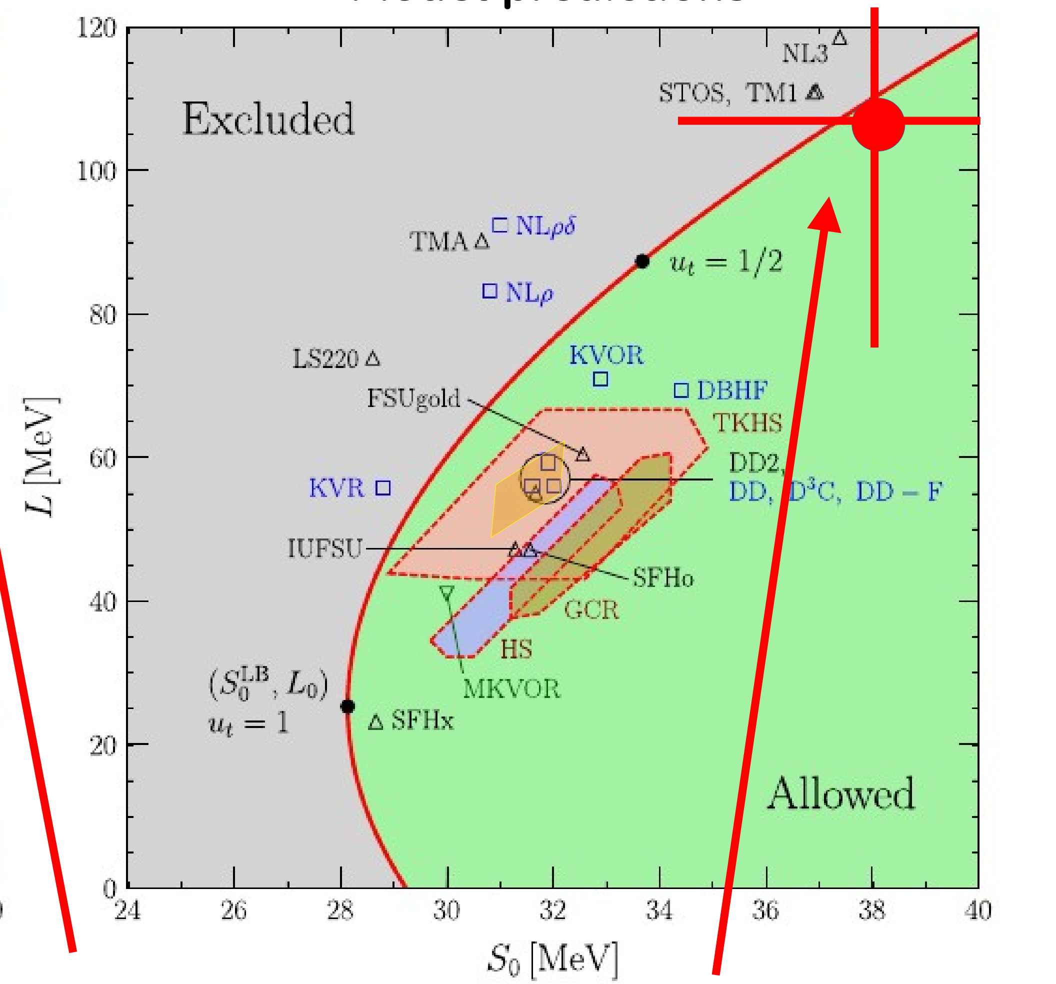
Symmetry Energy around ρ_0 : newcomer in 2021

Tension between PREX-2 and other experimental / theoretical evaluations

Experimental constraints



Model predictions



I. Tews *et al.*, Astroph. J. 848 (2017) 105

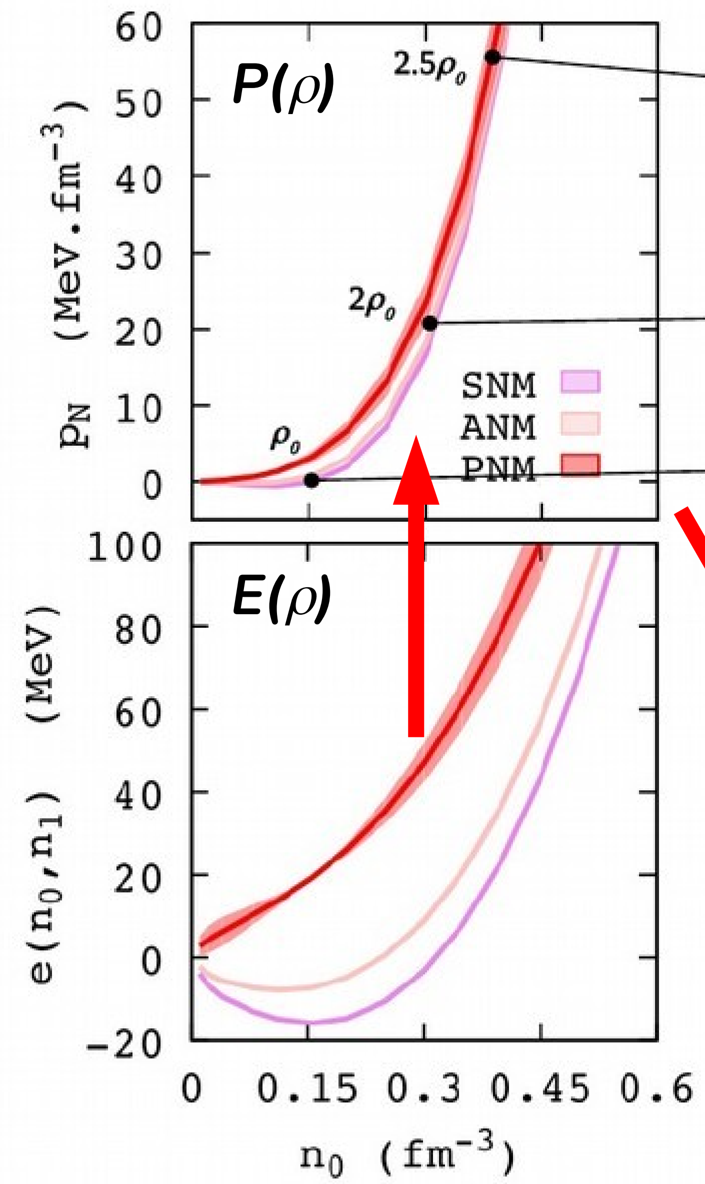
C. Drischler *et al.*, PRL 125 (2020) 202702

PREX-2 , B. T. Reed et al., PRL 126 (2021) 172503

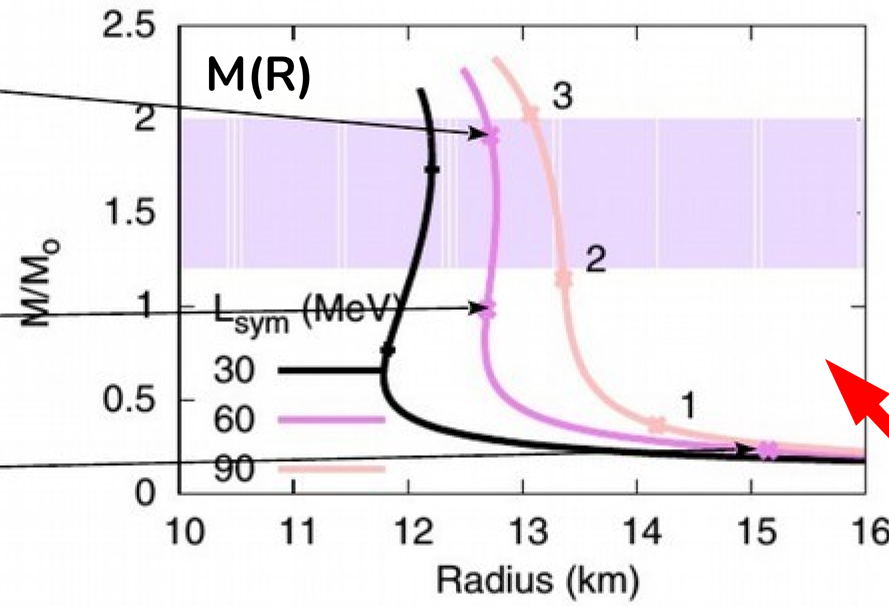
S_0 = 38.1 ± 4.7 MeV

L_{sym} = 106 ± 37 MeV

Constraints on Neutron Stars : link with nuclear EOS



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



From $E(\rho)$, the pressure is $P(\rho) = \partial E(\rho)/\partial\rho$

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

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

Tollman-Openheimer-Volkov Eqs.
General Relativity

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

→ **M(R)**

$$P = P(\rho)$$

Part IV

Some experimental tools and instrumentation

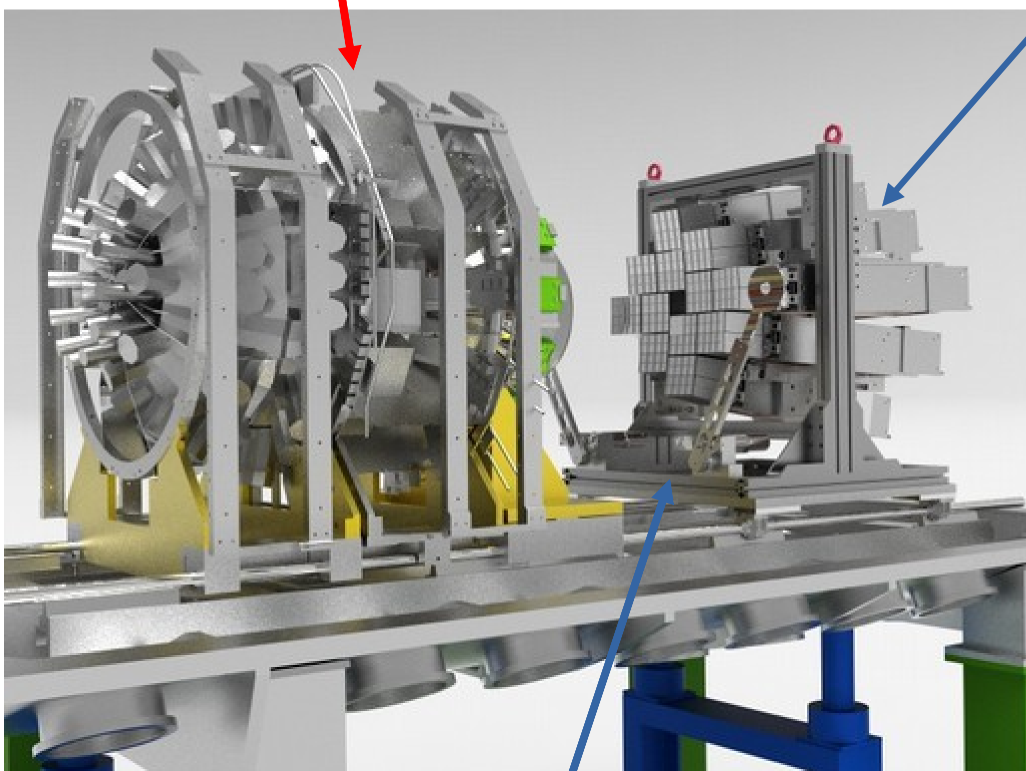
Coupling FAZIA demonstrator with INDRA@GANIL

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

INDRA in *D5*

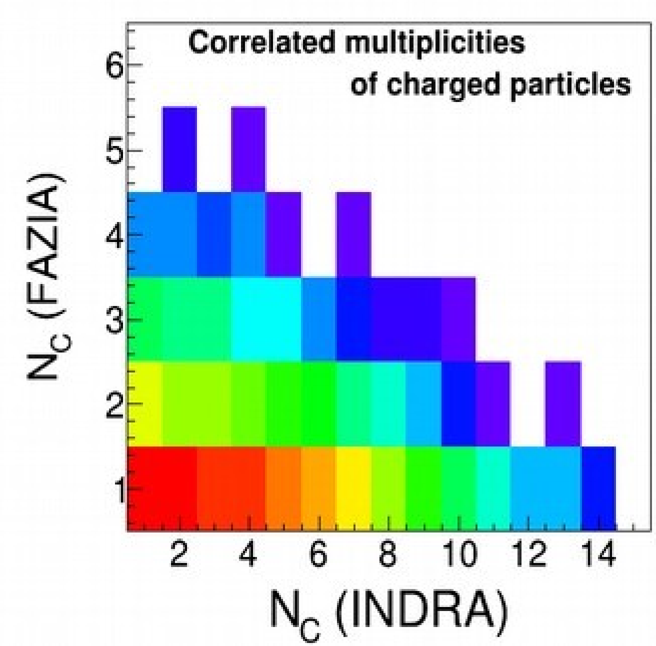
- \- 240 detection modules (rings 1,2/3,4/5 removed)
- \- 96 Si-CsI from 16 to 45 deg.
- \- 144 CsI from 45 to 176 deg.

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

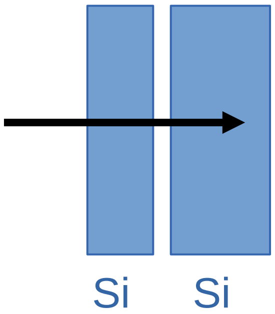


Experiment E789 performed at GANIL in April-May 2019 :

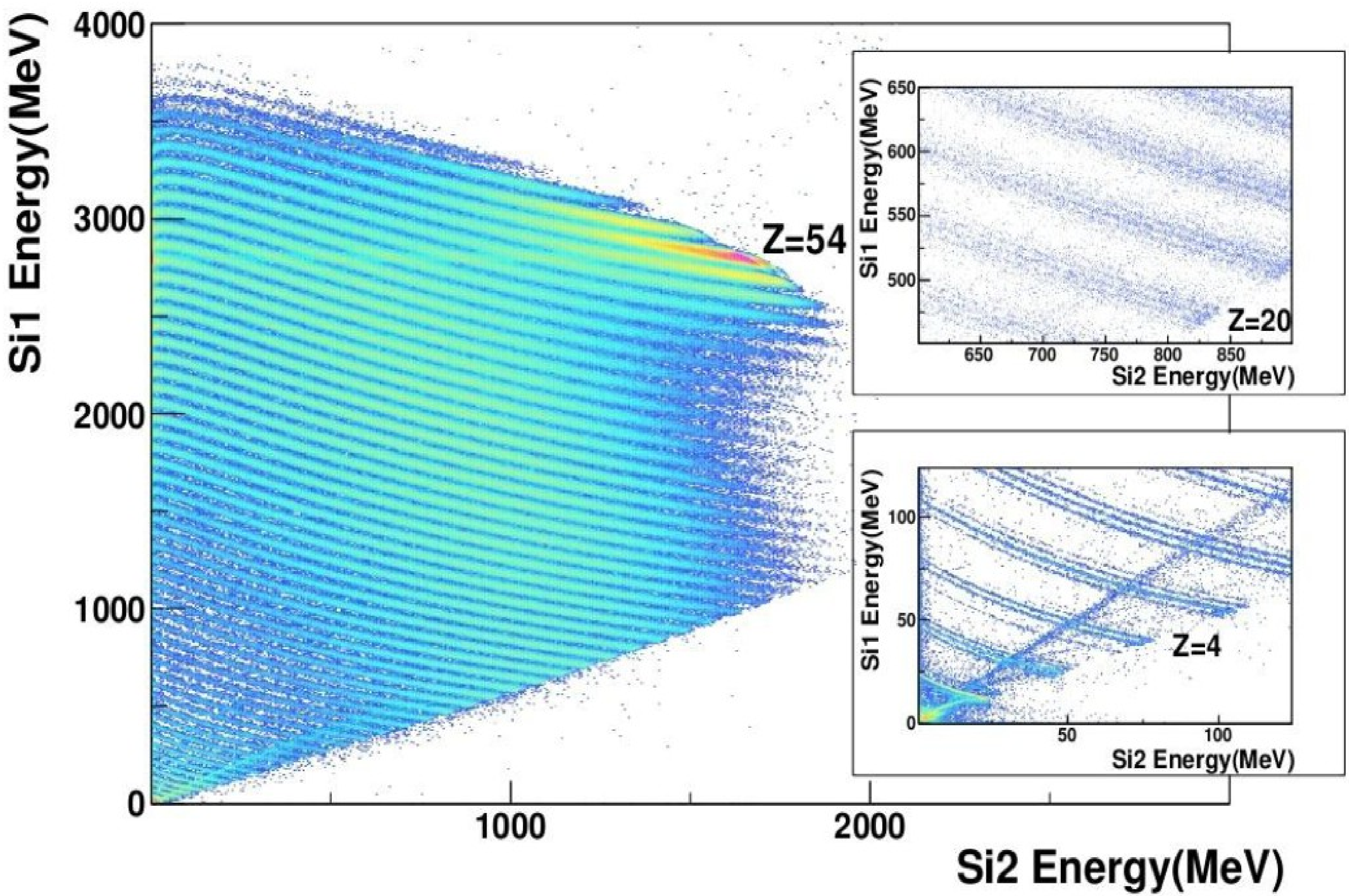
$^{58/64}$Ni+$^{58/64}$Ni @ 32,52 MeV/nucleon

Olivier LOPEZ, LPC Caen (lopezo@in2p3.fr)

FAZIA : °*E-E* identification



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

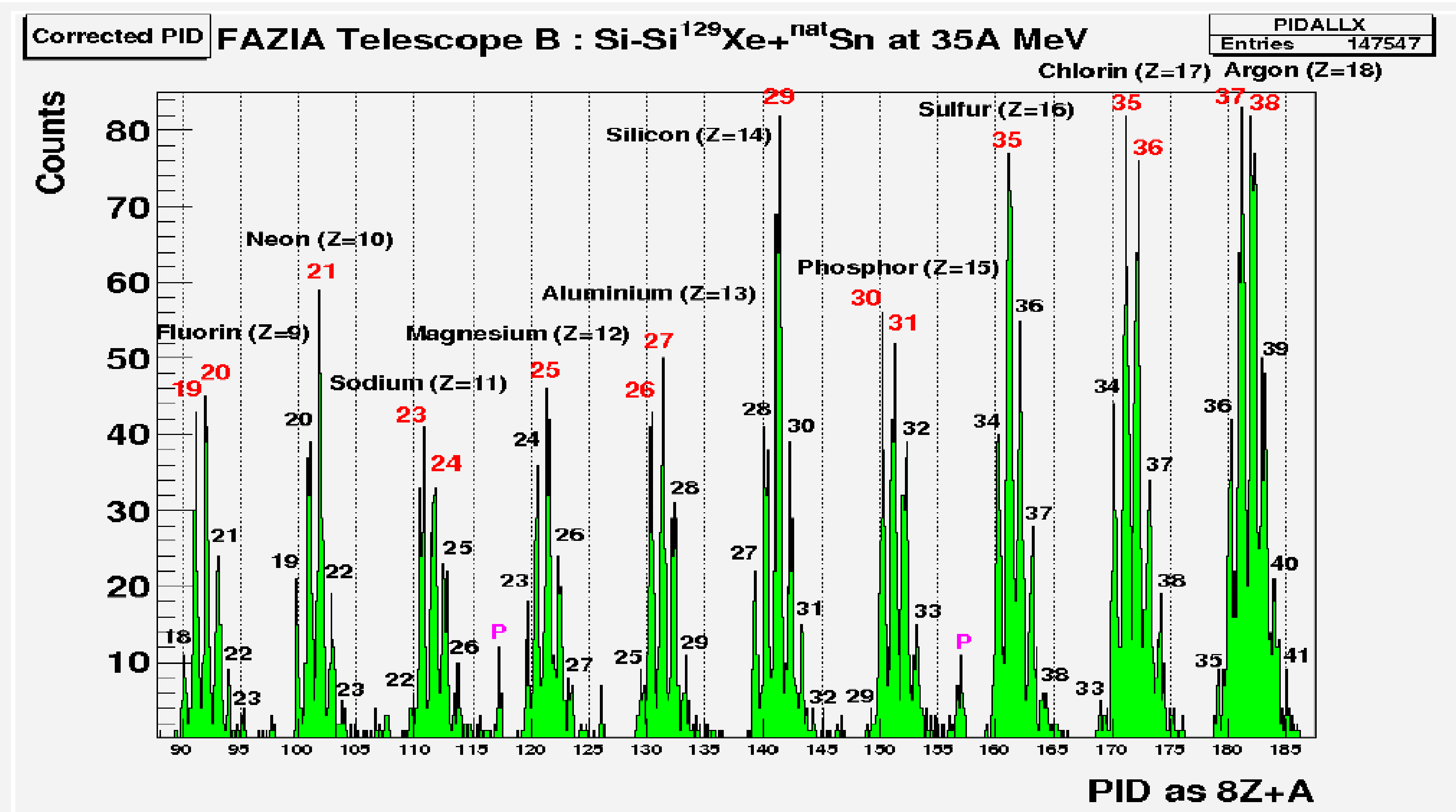


S.Carboni et al., NIMA 664 (2012) 251

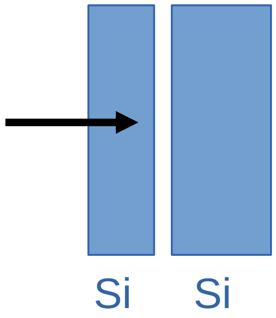
Energy = max of shaped signal (trapezoidal filter)

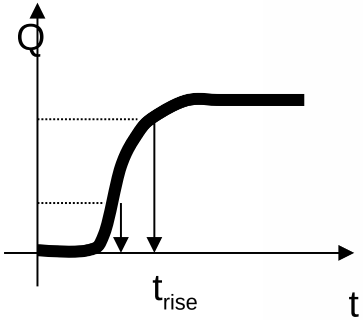
FAZIA improvements for ∆E-E identification

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

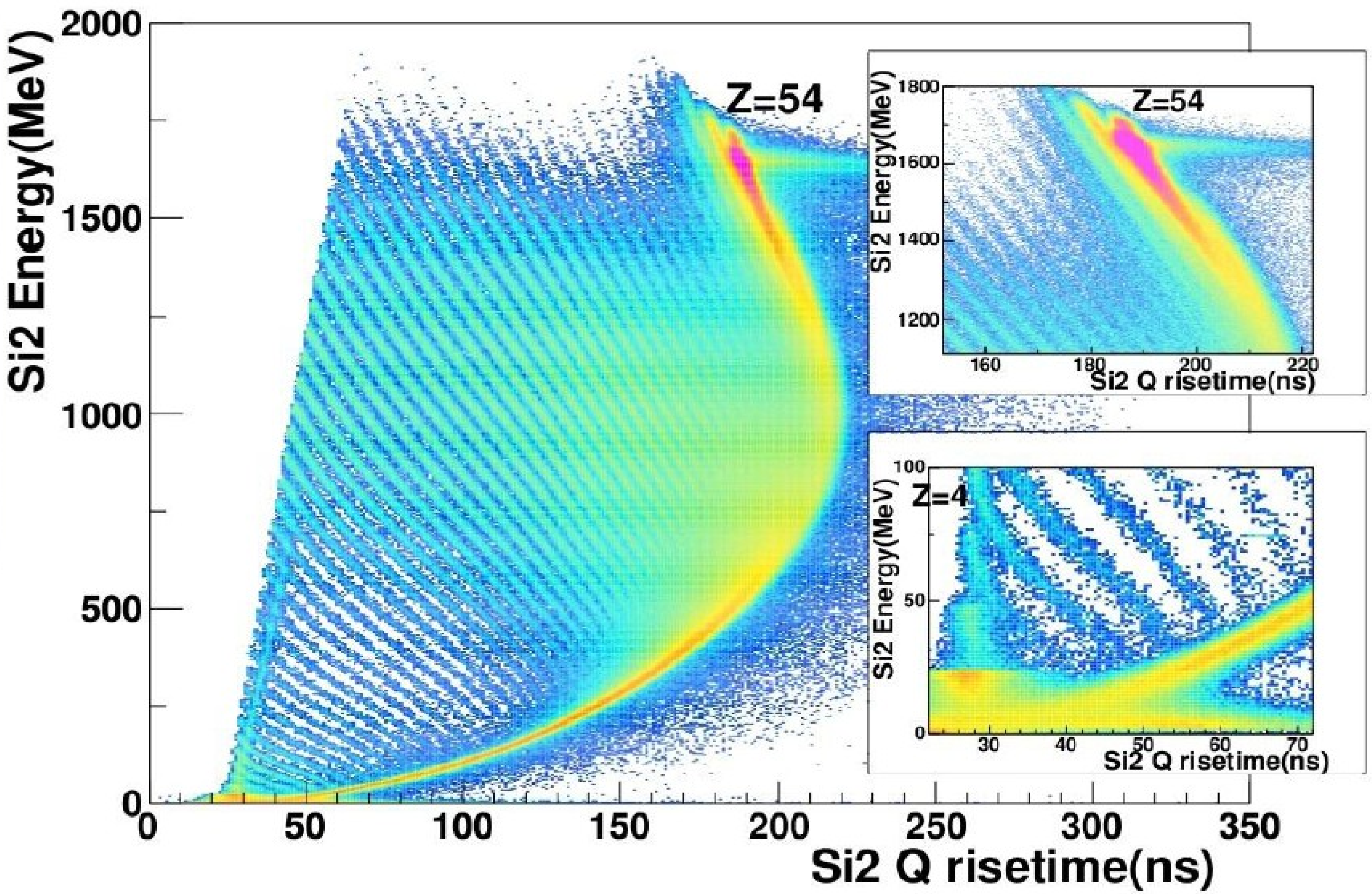


FAZIA : Pulse Shape Analysis



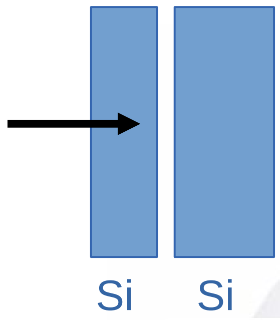


Some results at the end of phase 1:
Pulse Shape Analysis from E – Charge Rise Time



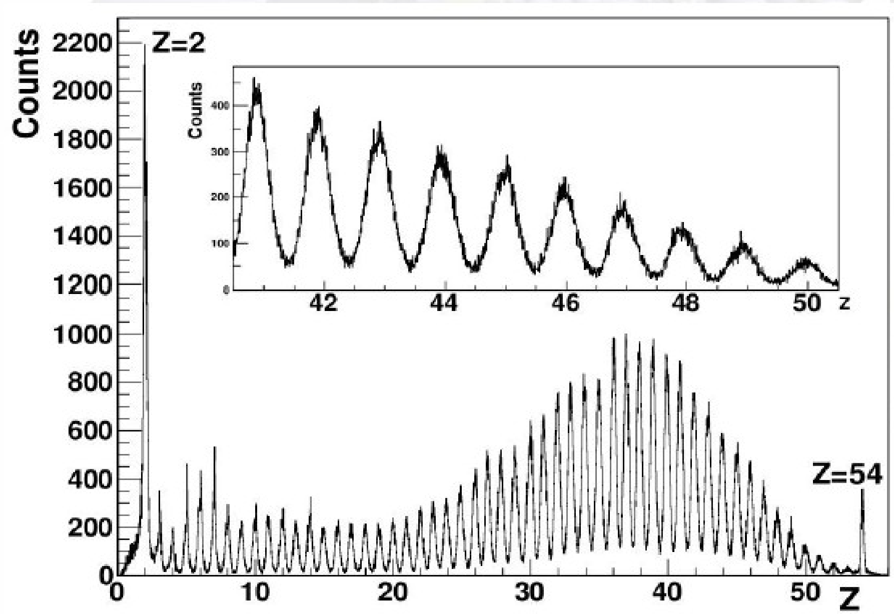
S.Carboni et al., NIMA 664 (2012) 251

FAZIA : Pulse Shape Analysis

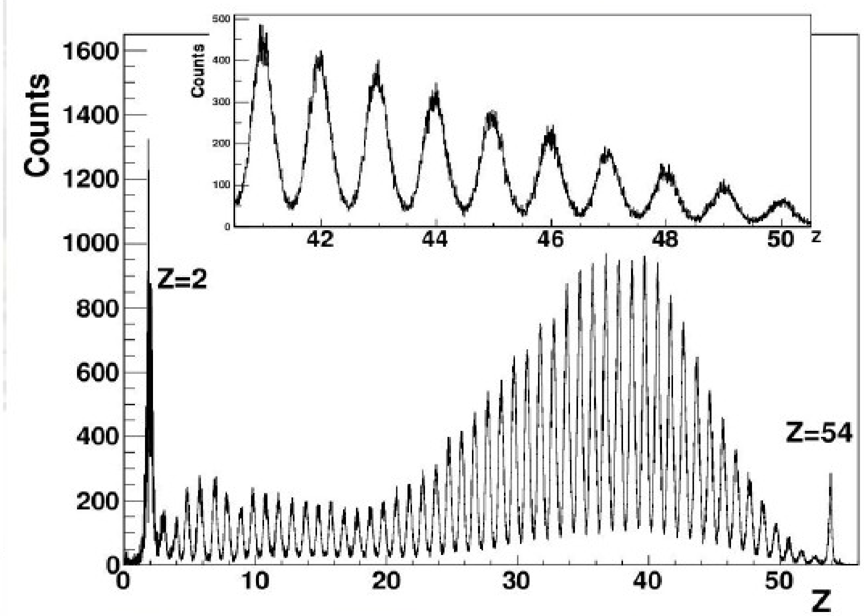


Some results at the end of phase 1: Particle Identification from Pulse Shape Analysis

Energy vs. charge rise time



Energy vs. maximum of current signal

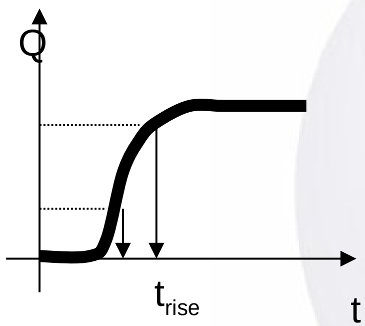


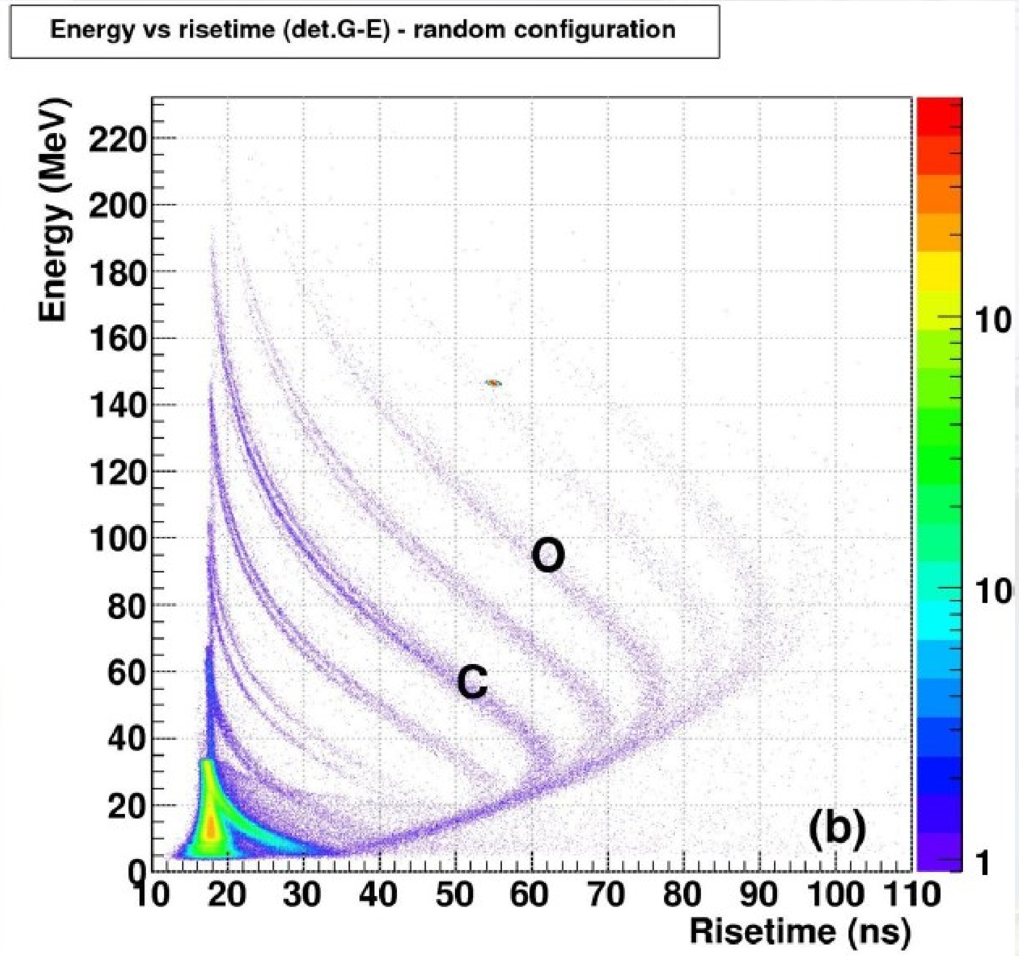
- ➢ Z identification can be achieved in the first Silicon detector

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

FAZIA : Pulse Shape Anaysis

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



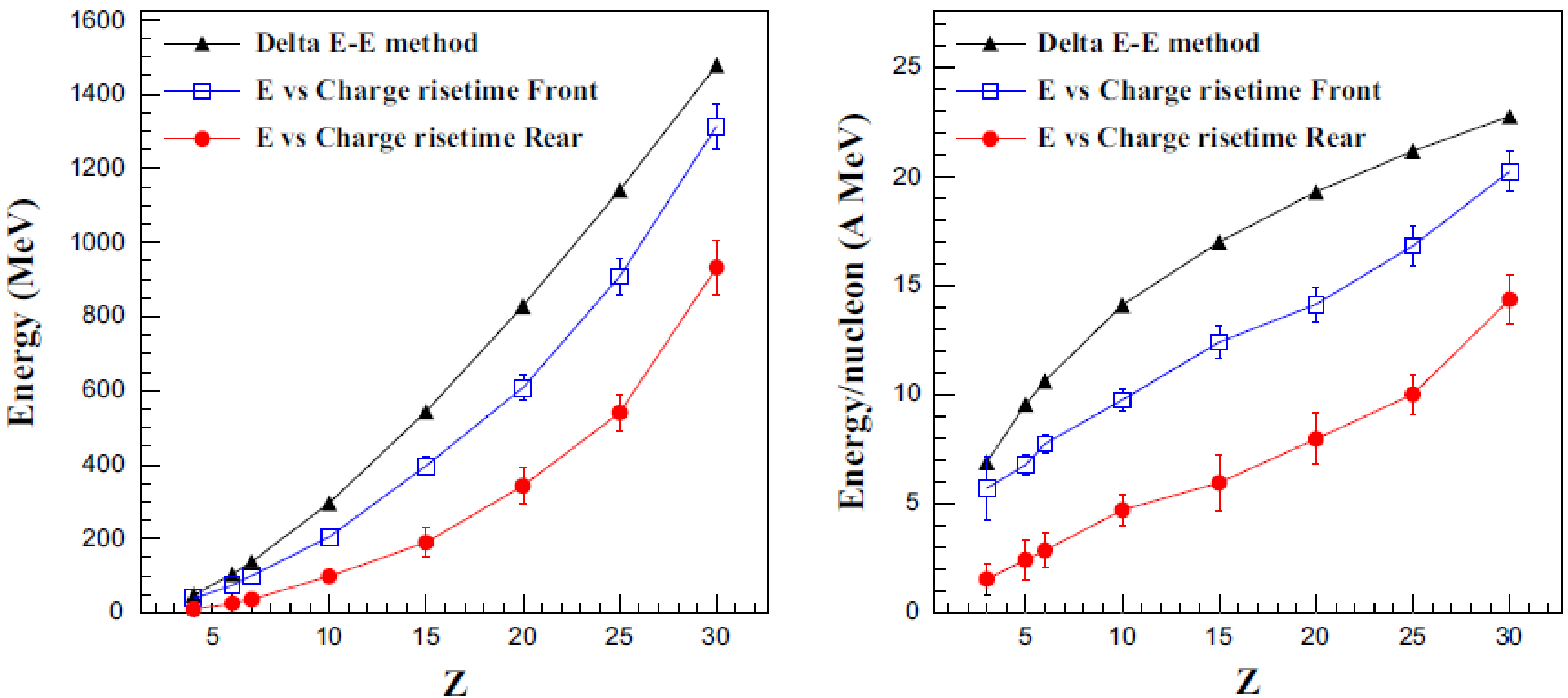


High gain
^{32}S beam@473MeV

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

➢ Isotopic identification for Z=3-8

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

Conclusions

Large diversity of nuclear reactions between 5 – 100 MeV/nucleon

Produce many different nuclear systems :

- in terms of *density* ρ, *excitation energy E*, temperature T, spin J, isospin* δ
- variety of conditions for the **EOS characterization**

Allow the production and study of exotic nuclei :

- direct/transfer reactions: **effective interactions** in nuclei, **quantum shells, continuum**
- multi-nucleon transfer and deep inelastic scattering : toward large N/Z **exotic nuclei**
- multifragmentation : **phase transitions**, order, latent heat and **criticality (universality)**
- 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**

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)

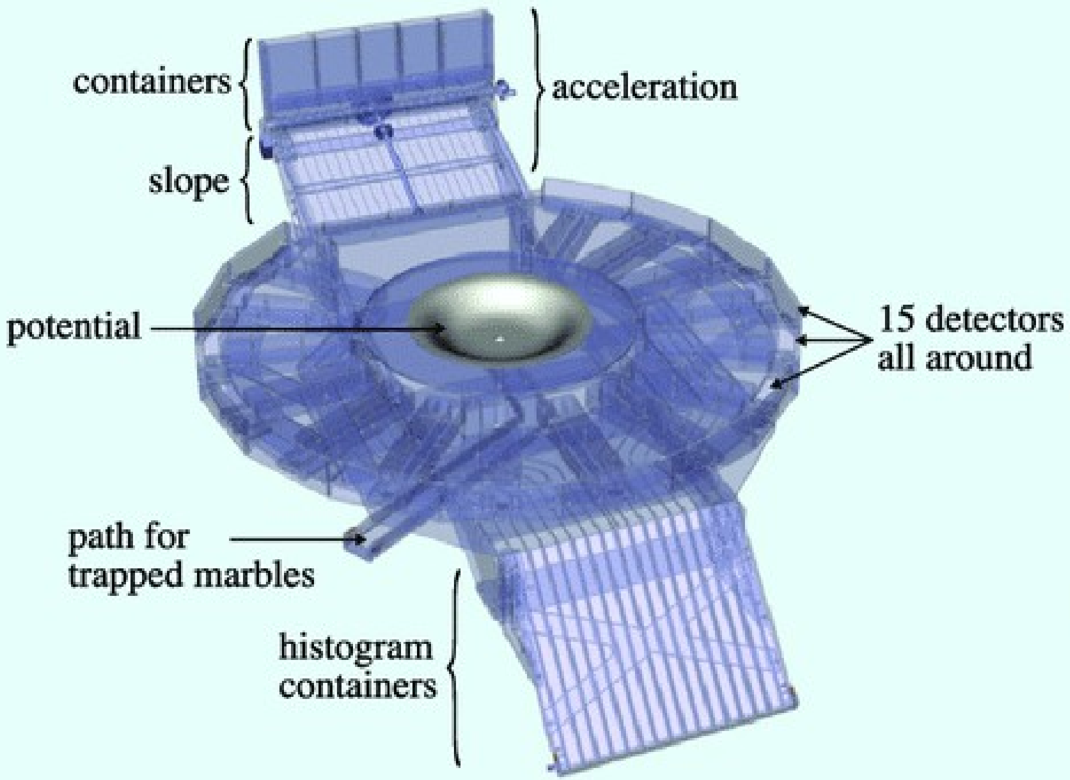
- R. Bougault *et al.* (FAZIA Collaboration) Eur. Phys. J. A 50 (2014) 47

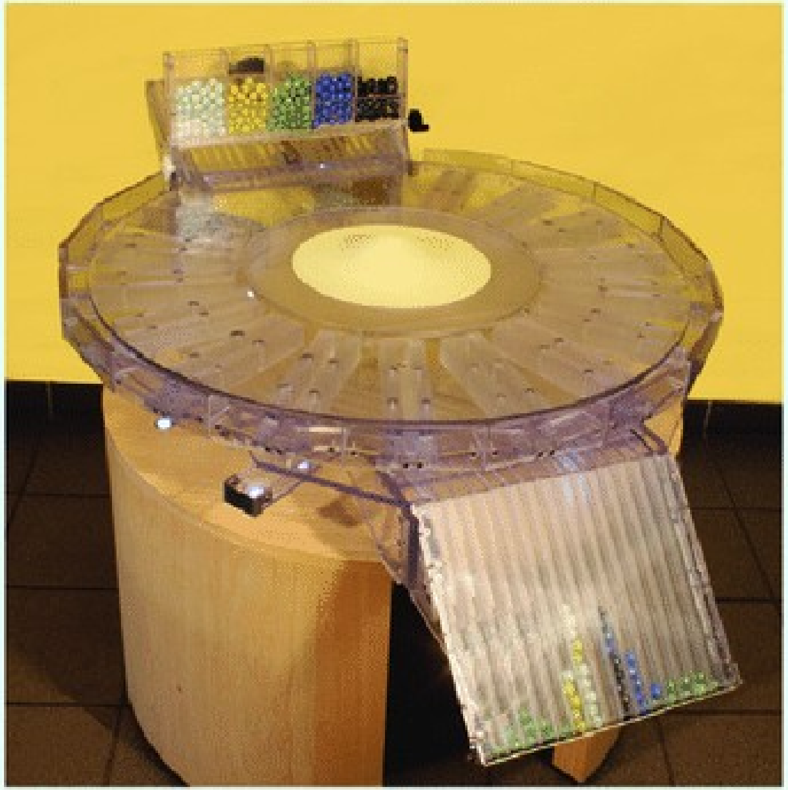
More infos and also scientific outreach contents :

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

Rutherford scattering with marble balls : Billotron

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

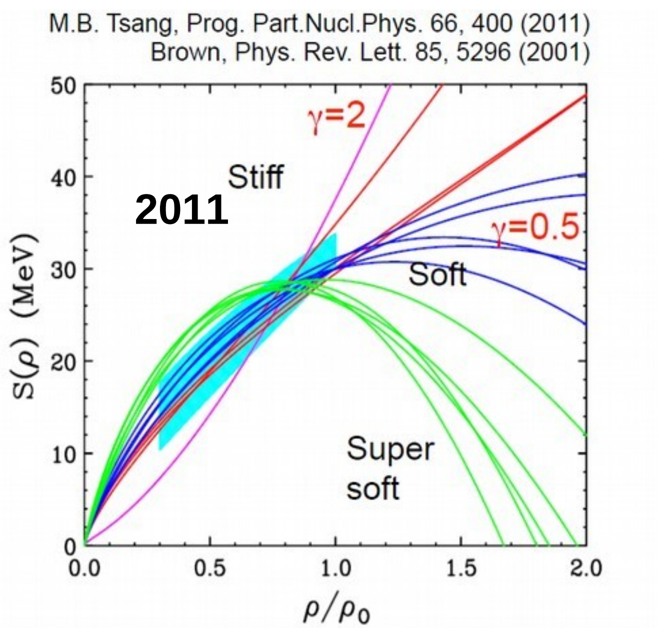




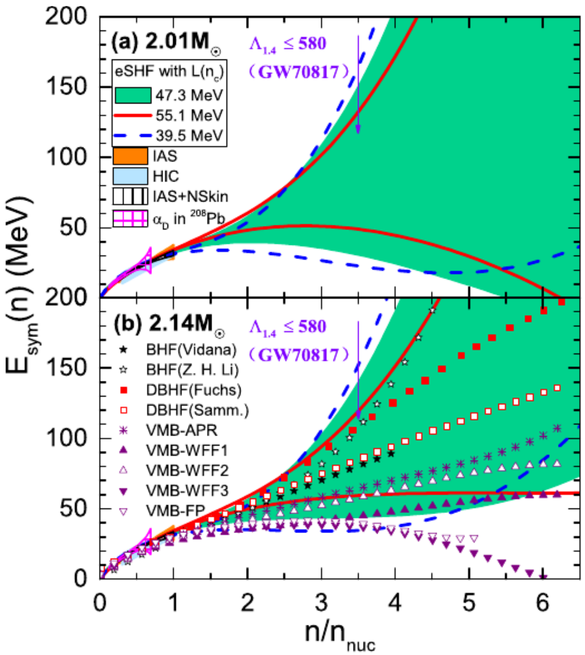
https://youtu.be/_KcK-jS2QQQ

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.

Symmetry Energy around ρ_0 (II)



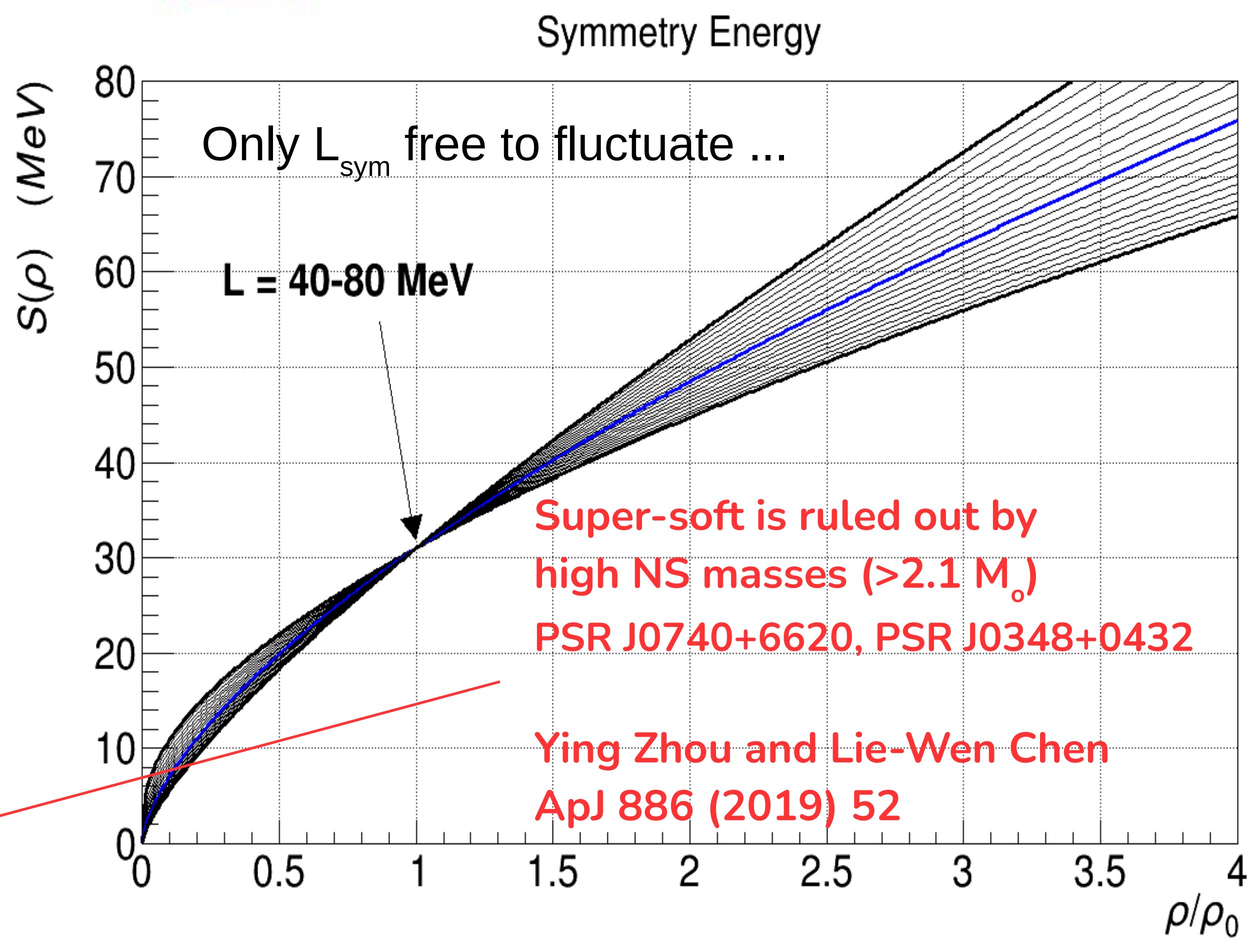
$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$



~30%

L_{sym} MeV
60 $\pm$15

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



Super-soft is ruled out by high NS masses (>2.1 M_o)
PSR J0740+6620, PSR J0348+0432

Ying Zhou and Lie-Wen Chen
ApJ 886 (2019) 52