Nuclear Physics at GANIL

Probing nuclear matter at the extremes

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Profs au GANIL

Part I

Motivations

Describing the nucleus

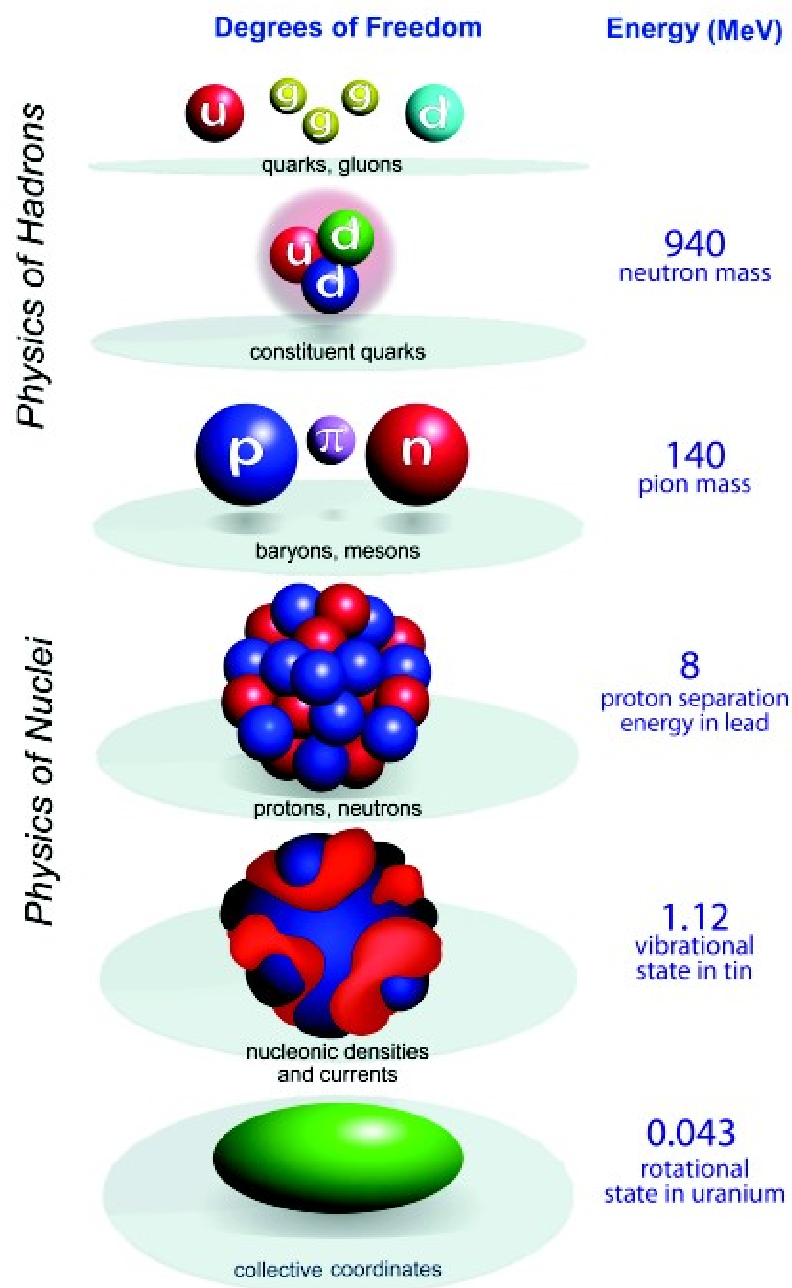
Energy scales in the subatomic world

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

De Broglie equation (spatial resolution) :

$$\lambda = \hbar / p$$

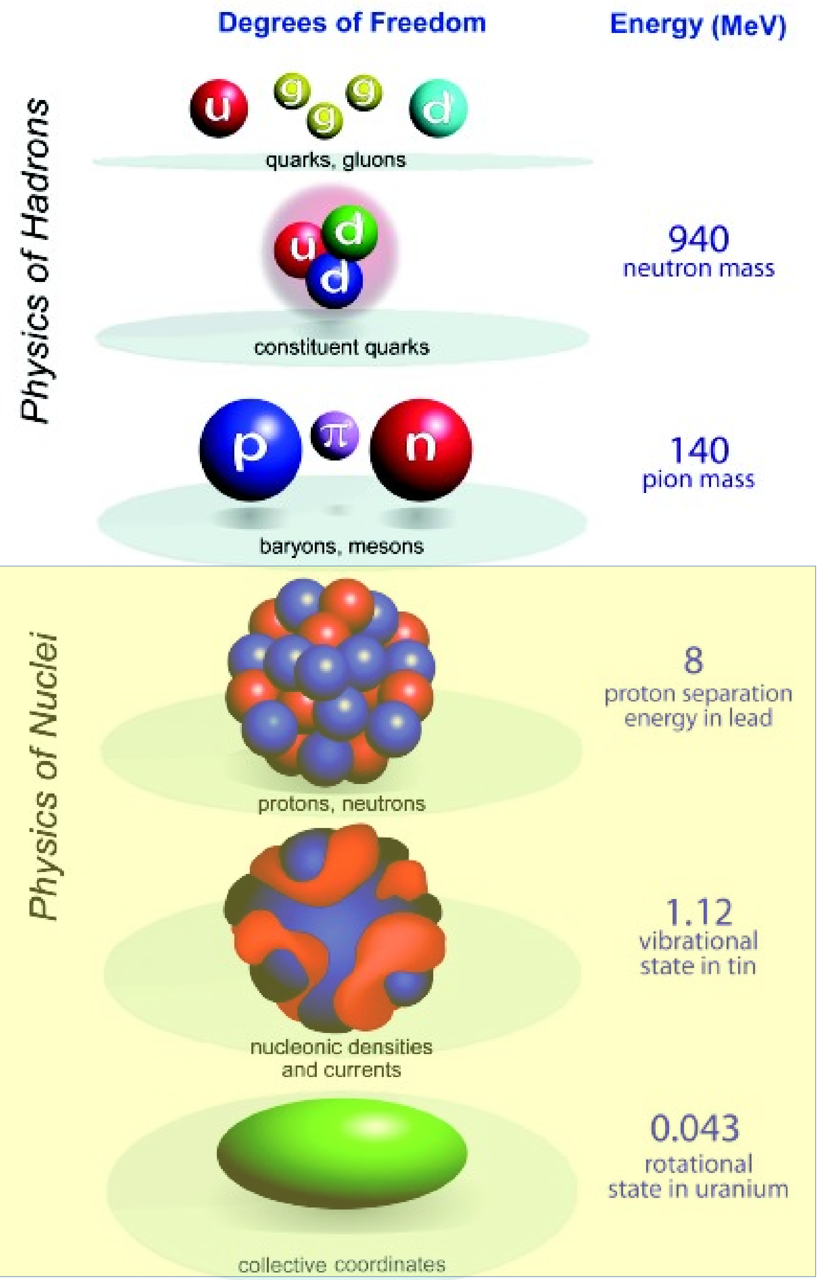
E_{inc} (MeV)	λ (fm)
1	8
10	1.5
100	0.5



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

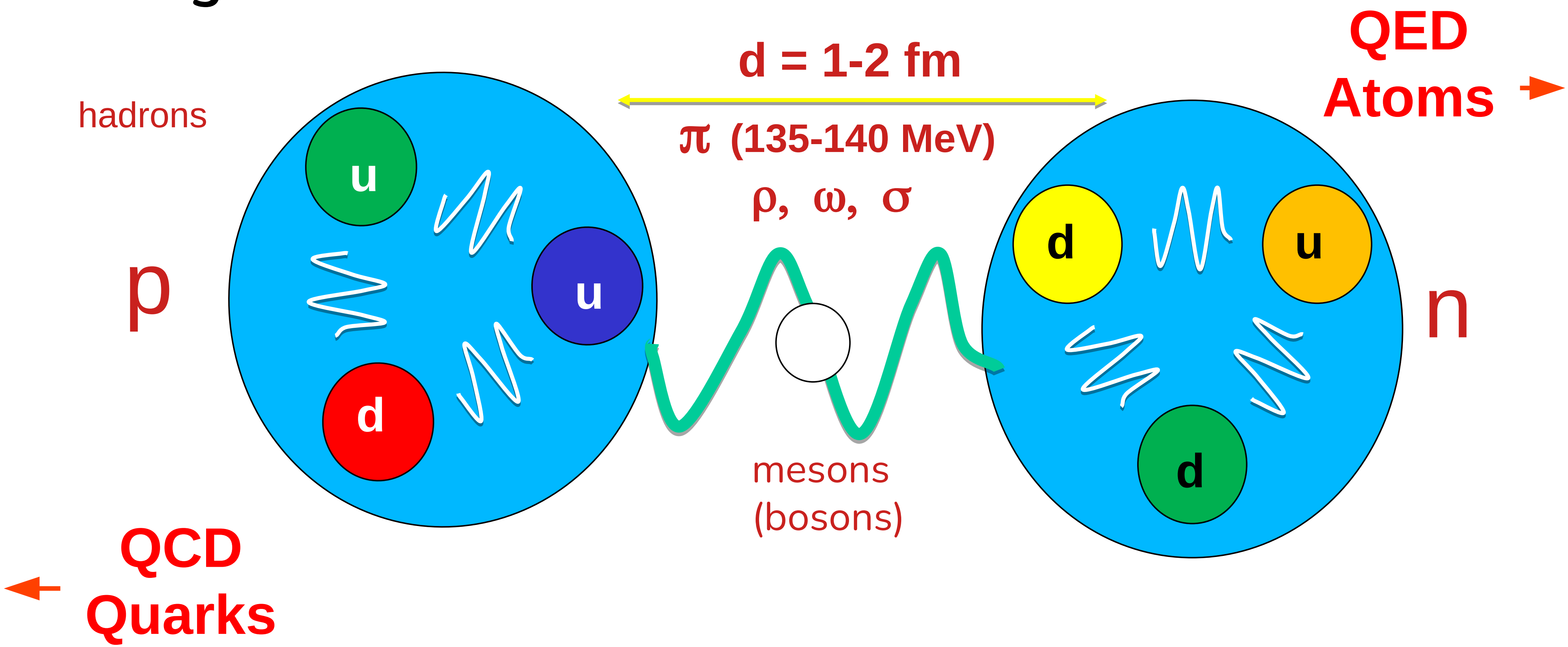
- nucleus
- collective phenomena
- excited states
- bulk and surface properties in continuum states

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

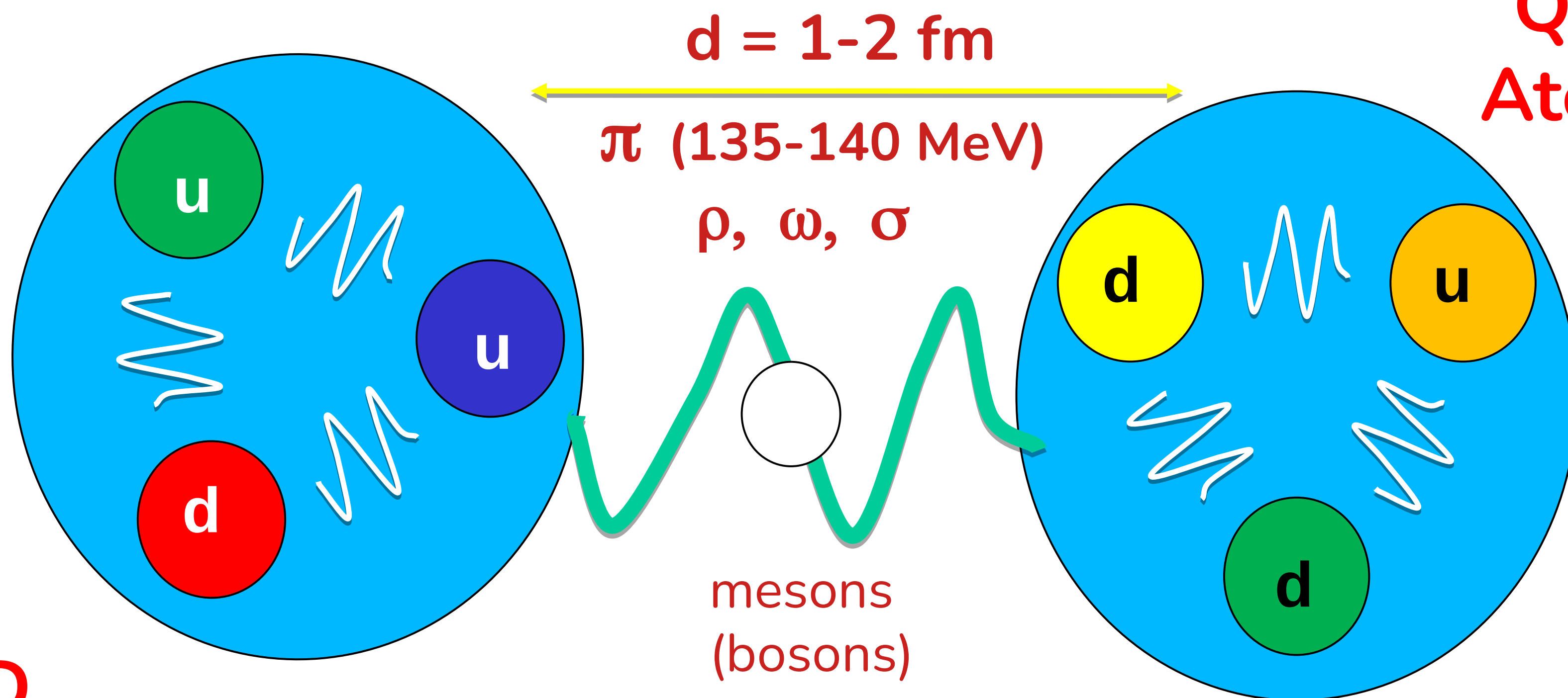


Strong .vs. Nuclear interaction

QED
Atoms →

Hadrons

p

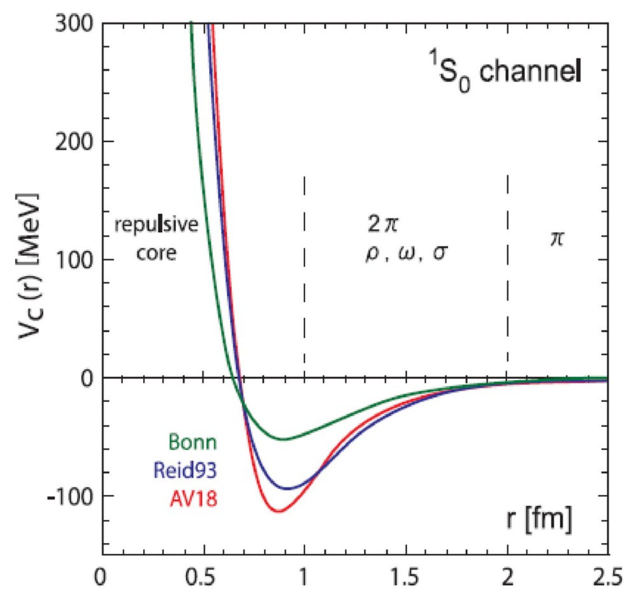


n

← 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

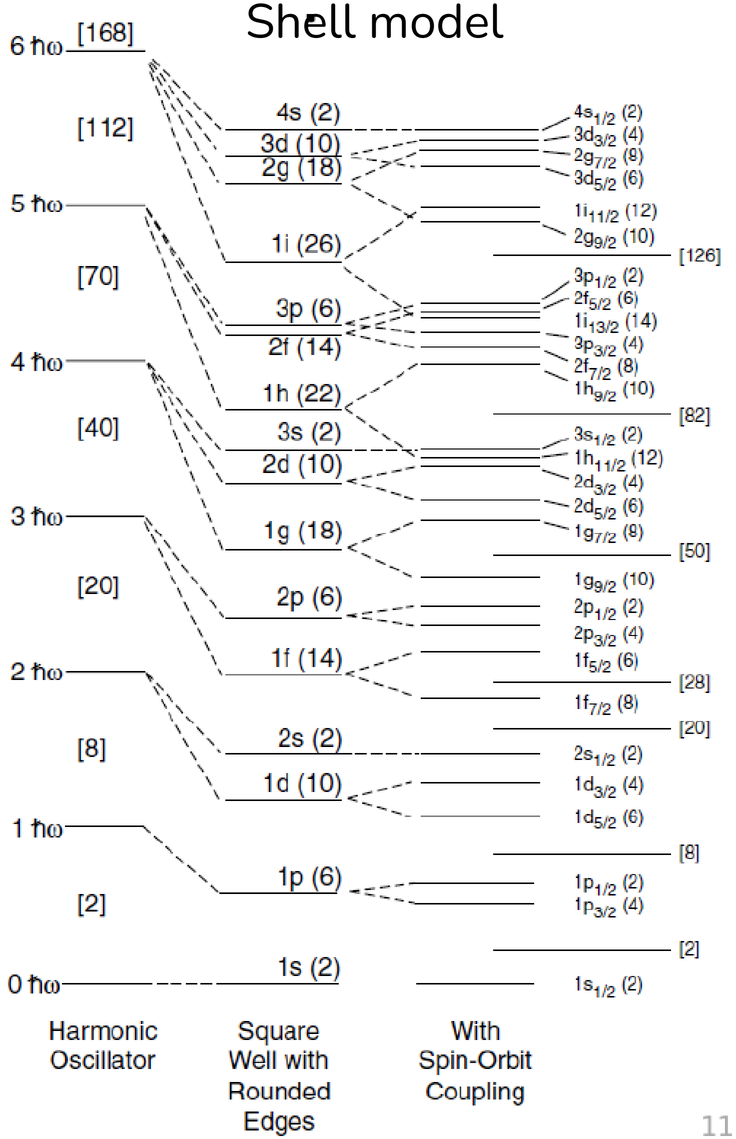


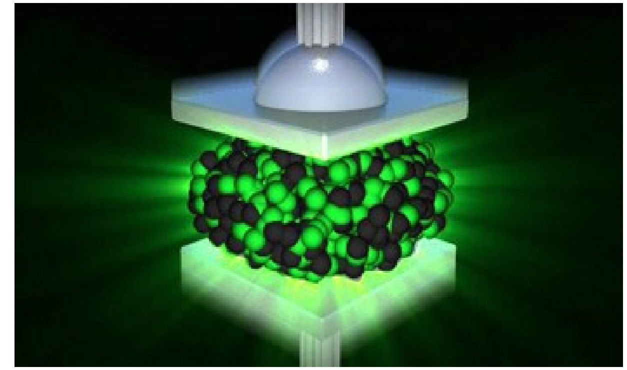
Relevant D.o.F.

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

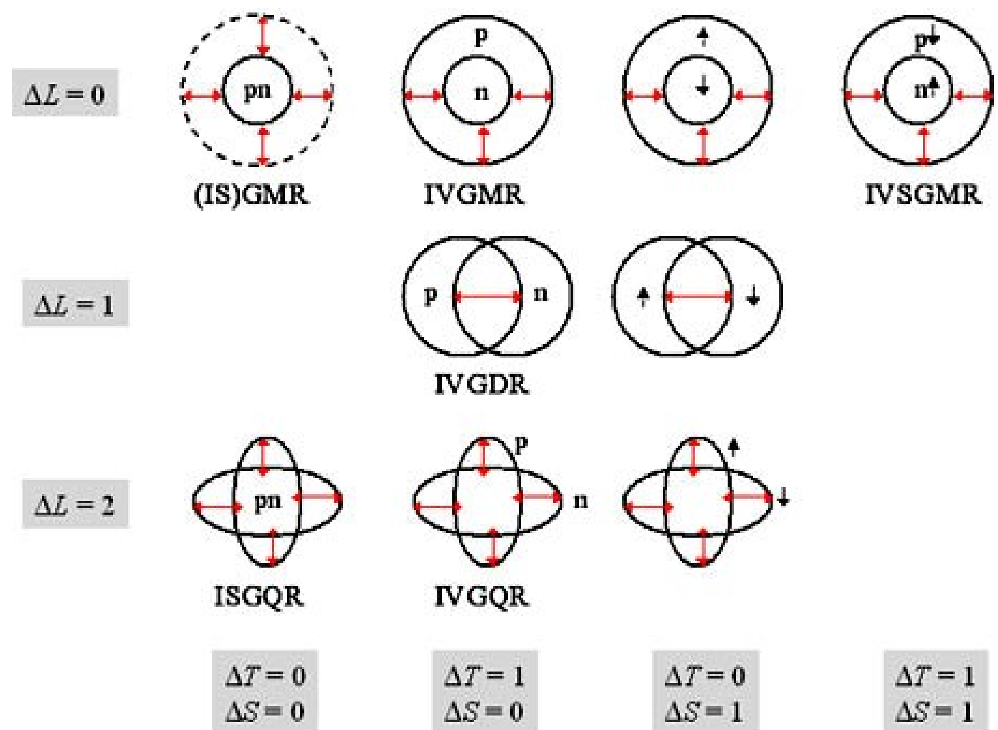
Nucleus at T≈0 : quantum realm

Shell model





Collective excitations
Giant resonances

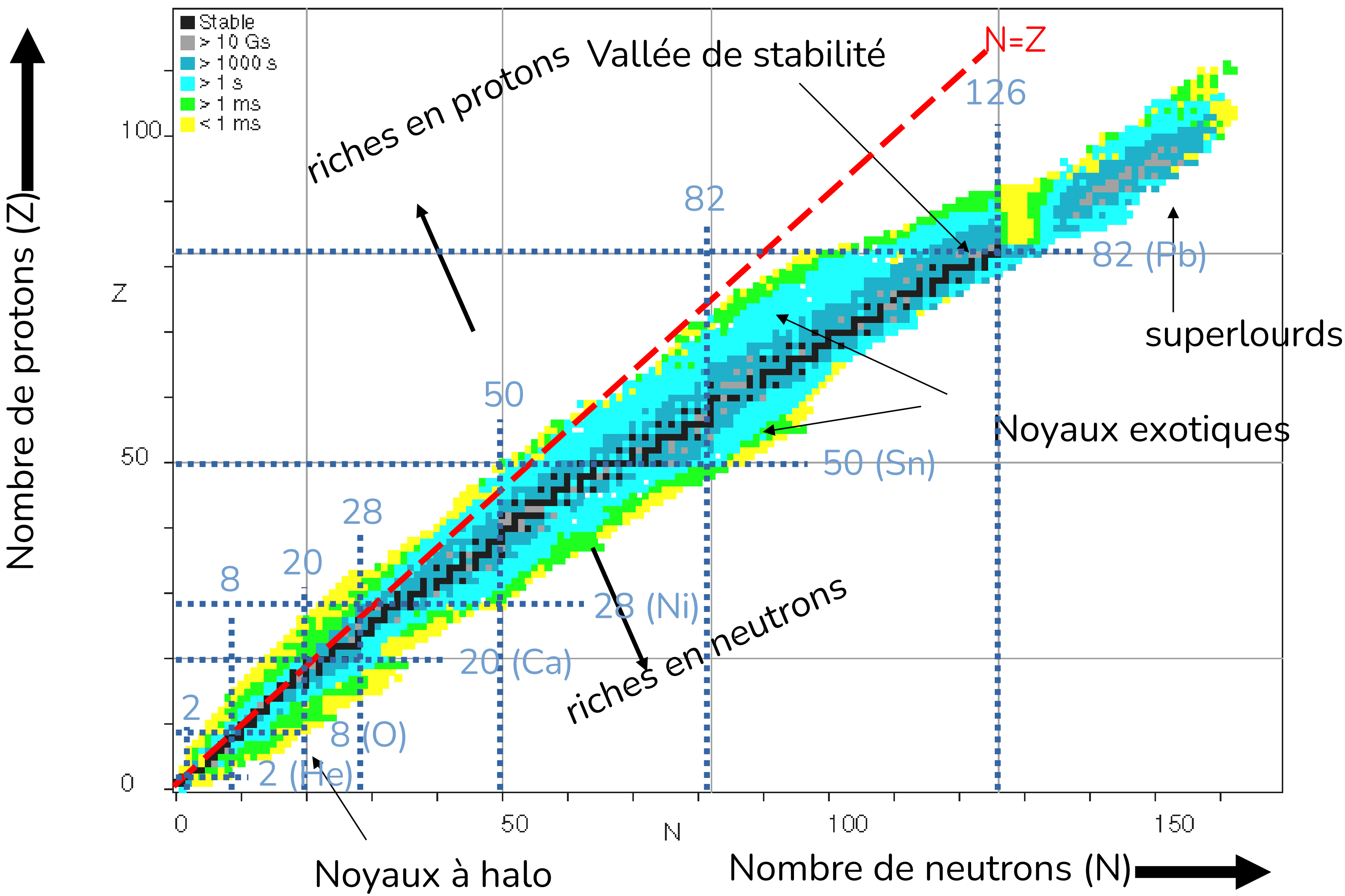


Quantum numbers for nucleon orbitals *n,l,j* : $1s_{1/2}$

Nuclear structure and limits of stability (driplines)

Des noyaux à la carte

Nombres magiques : 2,8,20,28,50,82, 126, ...



Nuclear structure (I)

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

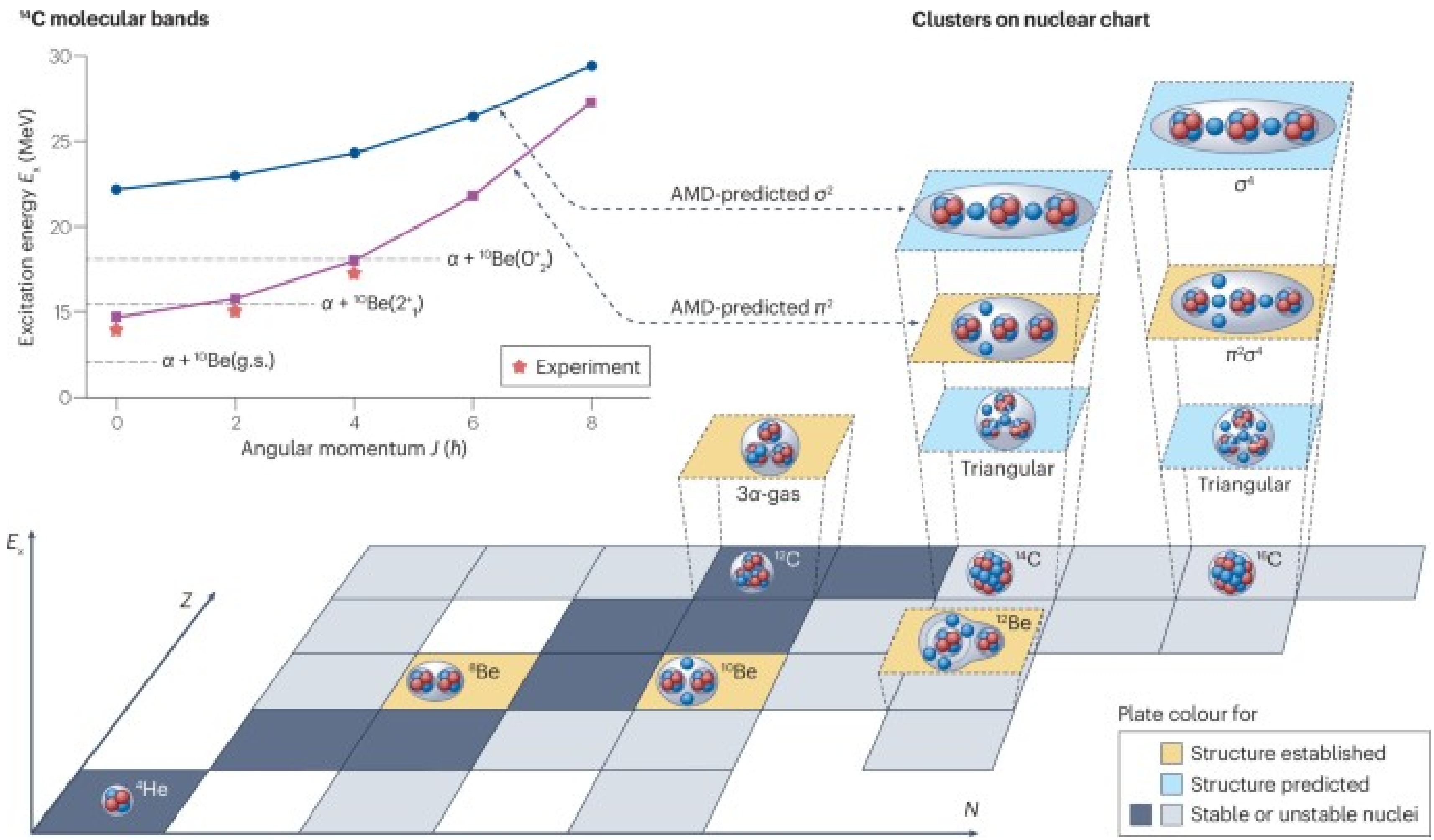
- **new** magic numbers (harmonic shells for exotic nuclei)
- **haloes** nuclei (borromean)
- granular or **molecular** systems (clusters in nuclei)
- nuclear structure for **superheavy** elements (transfermium Z>100)
- **new radioactivities 2p, 2n, clusters** (coupling to continuum)

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)

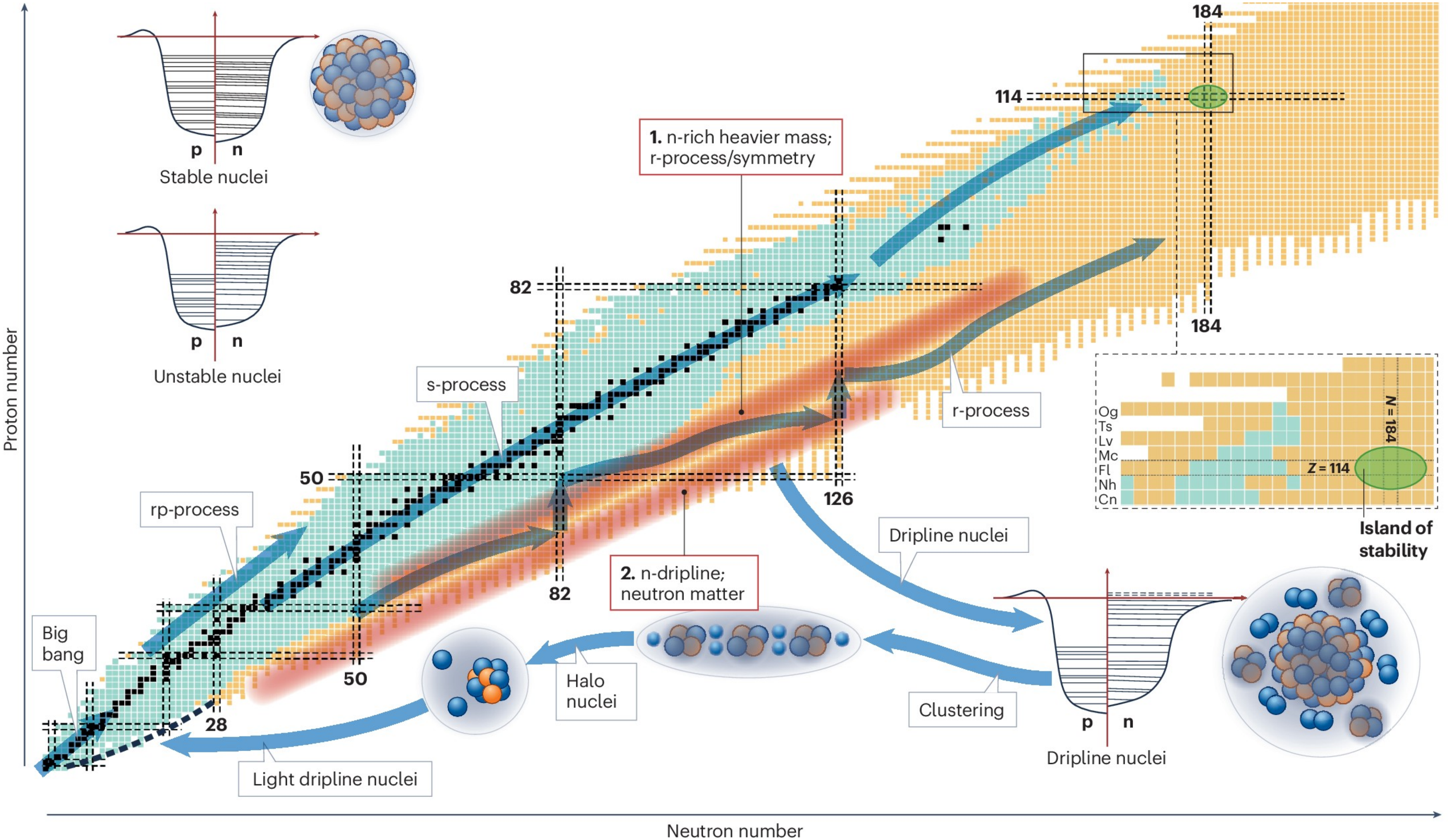
Light Nuclei : Clusters and molecular structure !



Y. Ye, X. Yang, H. Sakurai, and B. Hu, Nature Rev. Physics 7, 21 (2024)

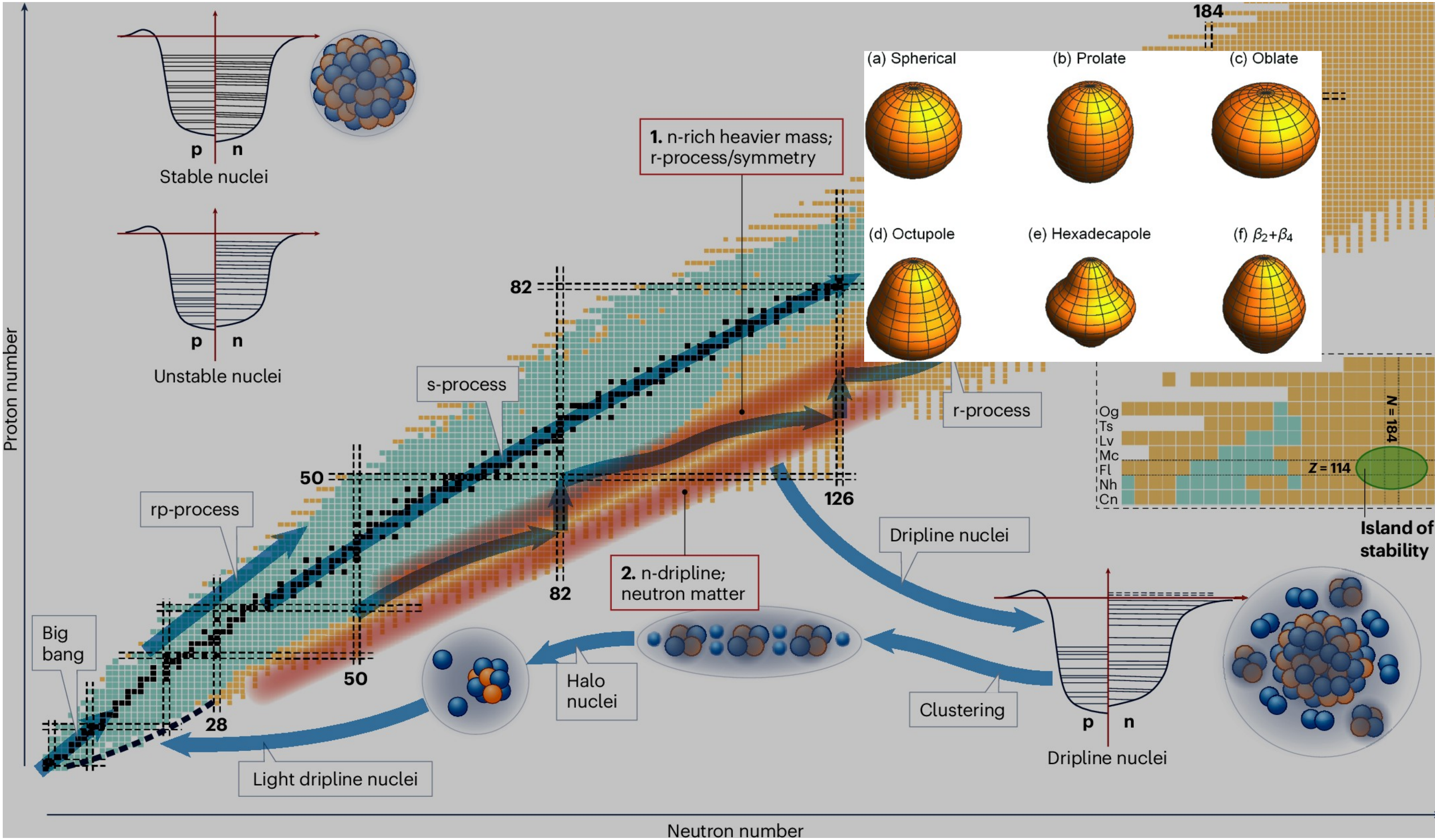
Nuclear structure (III)

Exotic nuclei : toward neutron/proton imbalance



Nuclear structure (V)

Exotic Nuclei : Deformed nuclei and shape coexistence

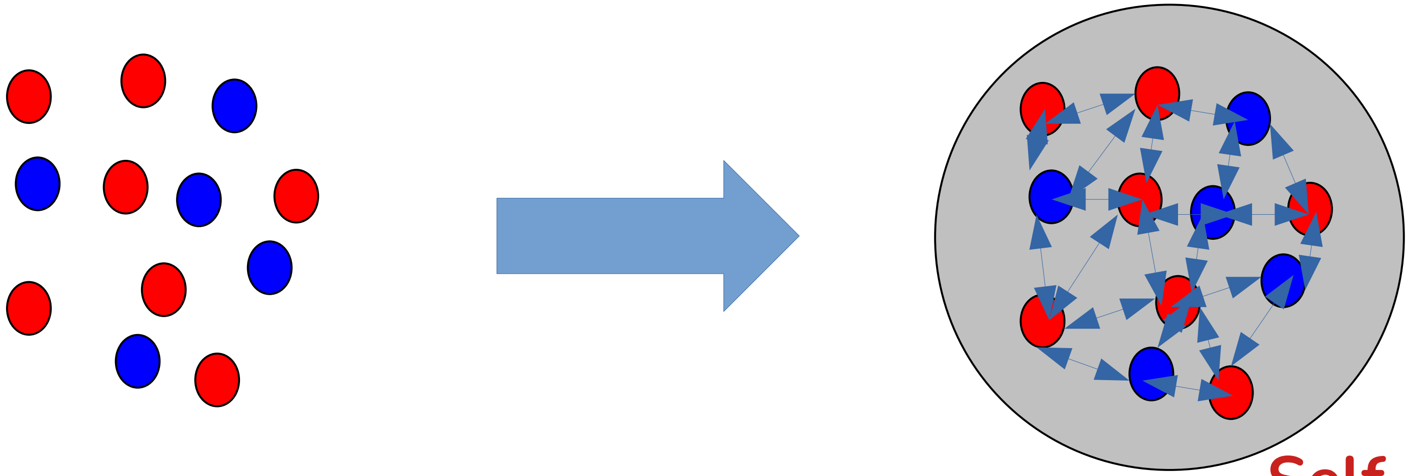


Microscopic description of nuclei : Mean-Field and beyond

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

Free nucleons

nucleus



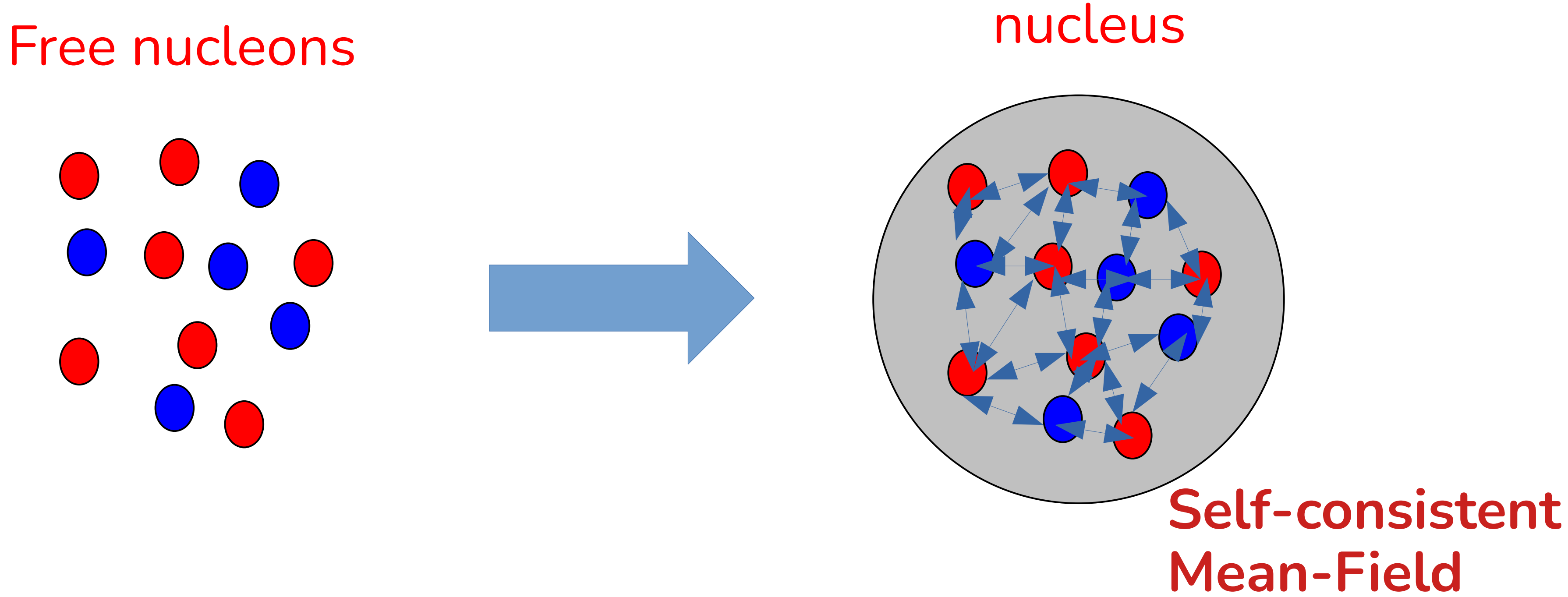
Self-consistent Mean-Field

Bare *NN* interaction

Effective interaction (medium)

Microscopic description of nuclei : Mean-Field and beyond

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



Bare *NN* interaction

Effective interaction (medium)

Macroscopic descrition of nuclei : liquid drop

Bethe & Weisacker formula :

volume surface coulomb asymmetry n/p (isospin)

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

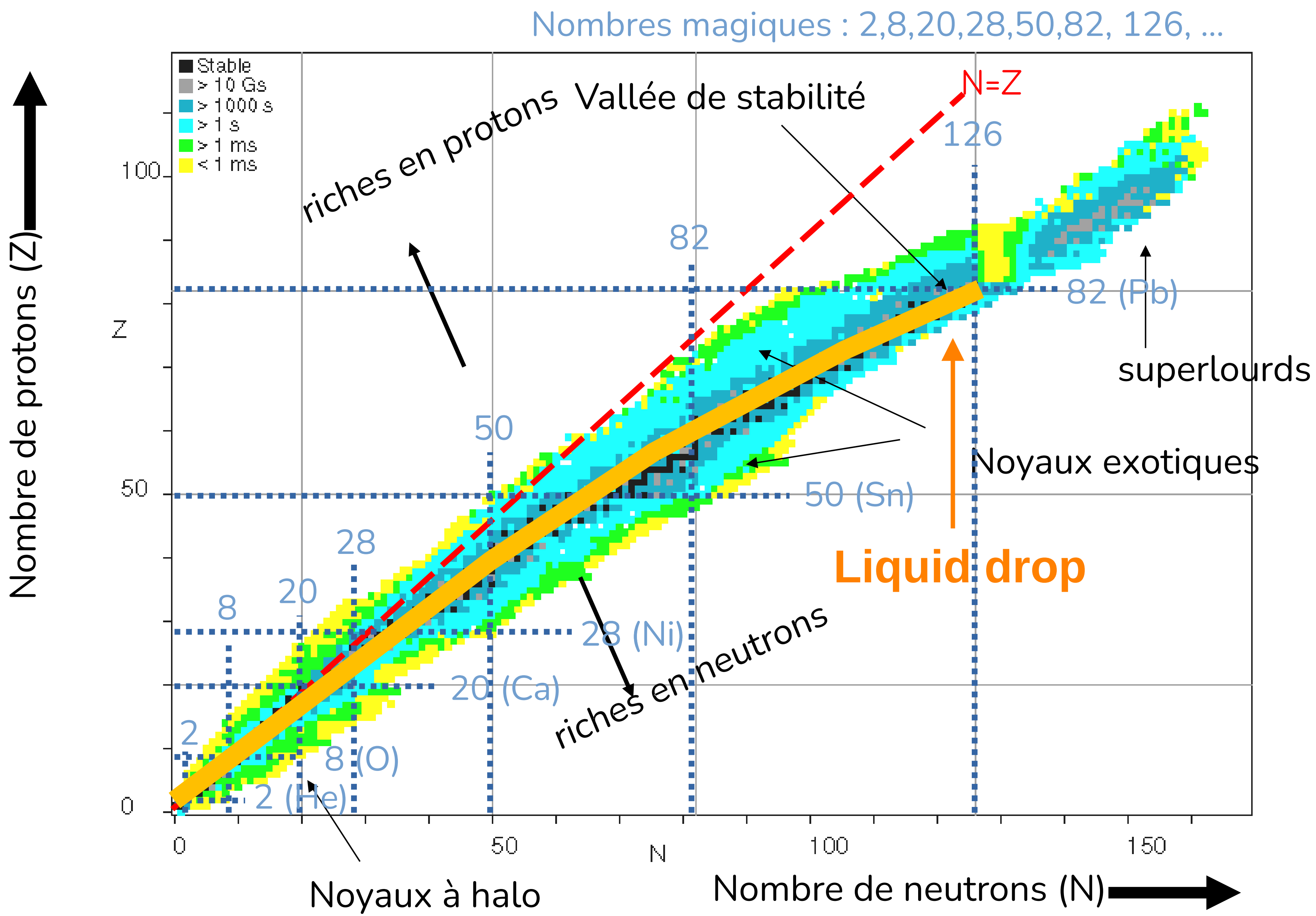
+ shell effects (magic numbers)

+ pairing (nn, pp, np)

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

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

Des noyaux à la carte

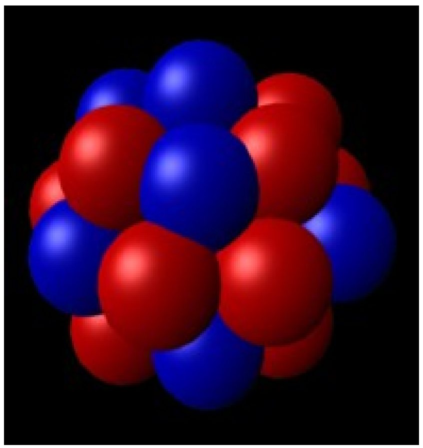


From nuclei to compact stars

Under pressure !

$P = 10^{14}$ g/cm^{-3} = 10^{8} T/cm^{3}

nucleus



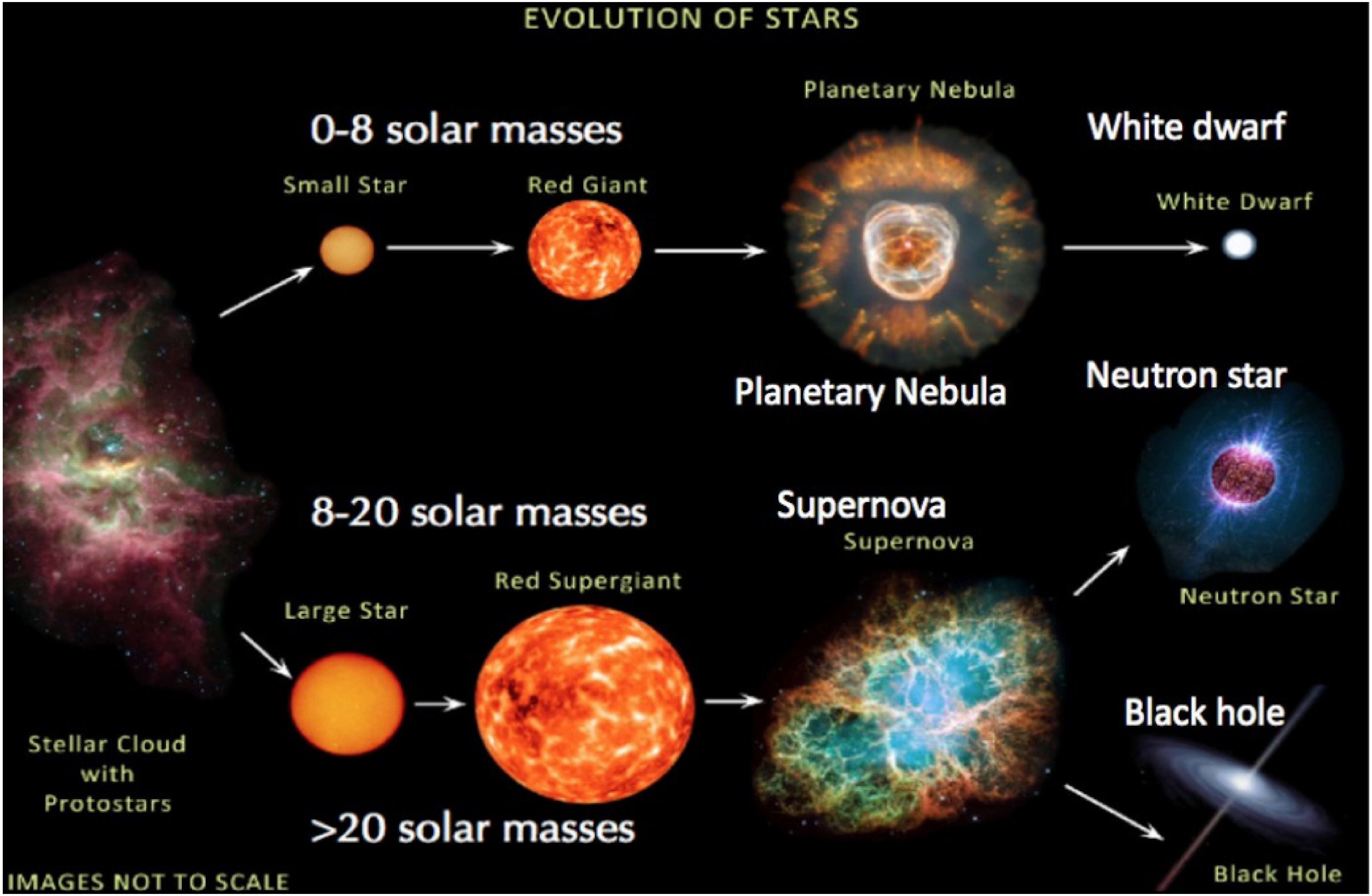
Supernova / neutron star

Nucleosynthesis above iron element

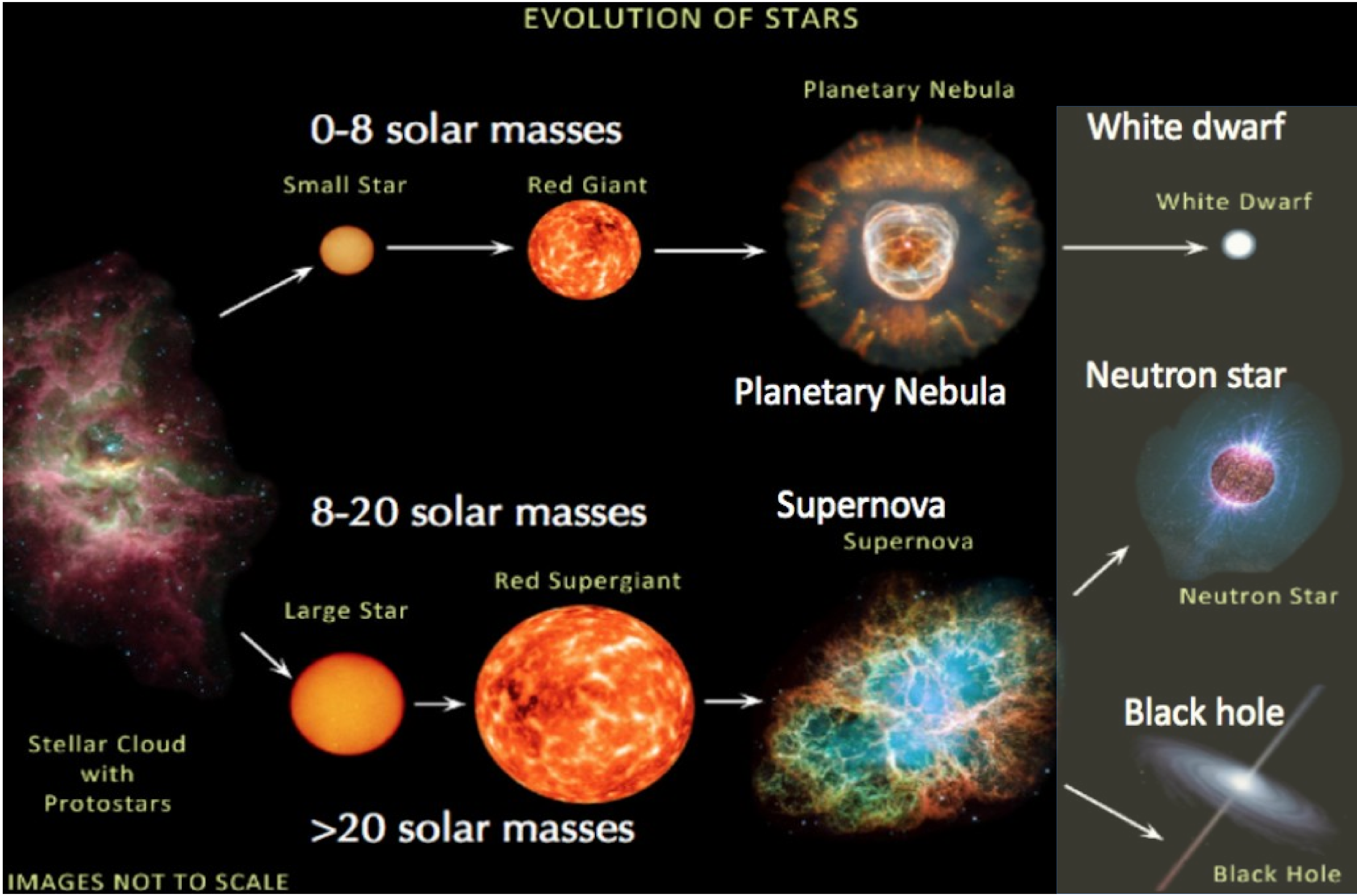
Core Collapse of Supernova : x 10,000,000,000 Sun luminosity ...

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

How a star becomes a neutron star ?



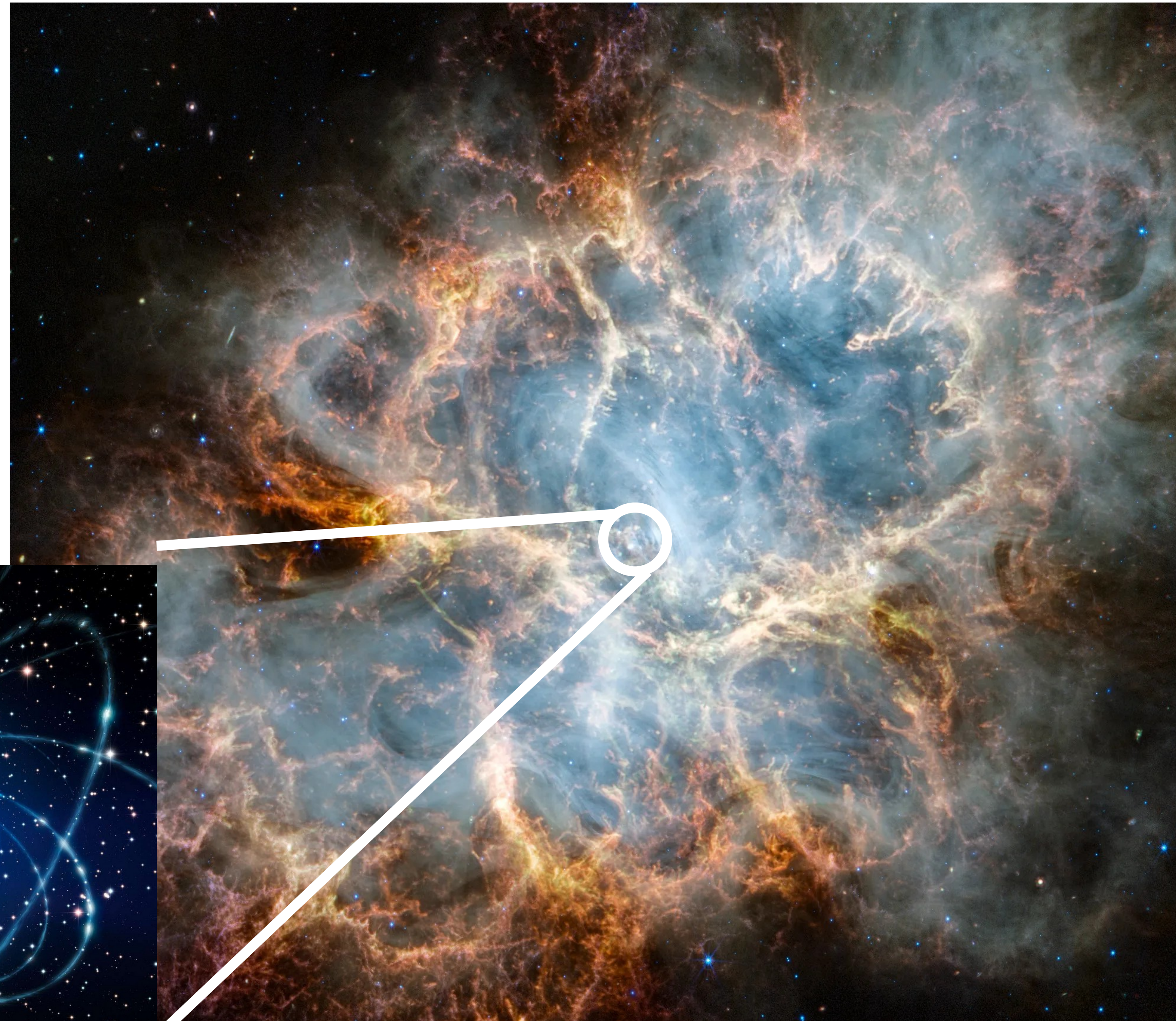
How a star becomes a neutron star ?



Neutron star : a dream for nuclear physicists …

Crab nebula

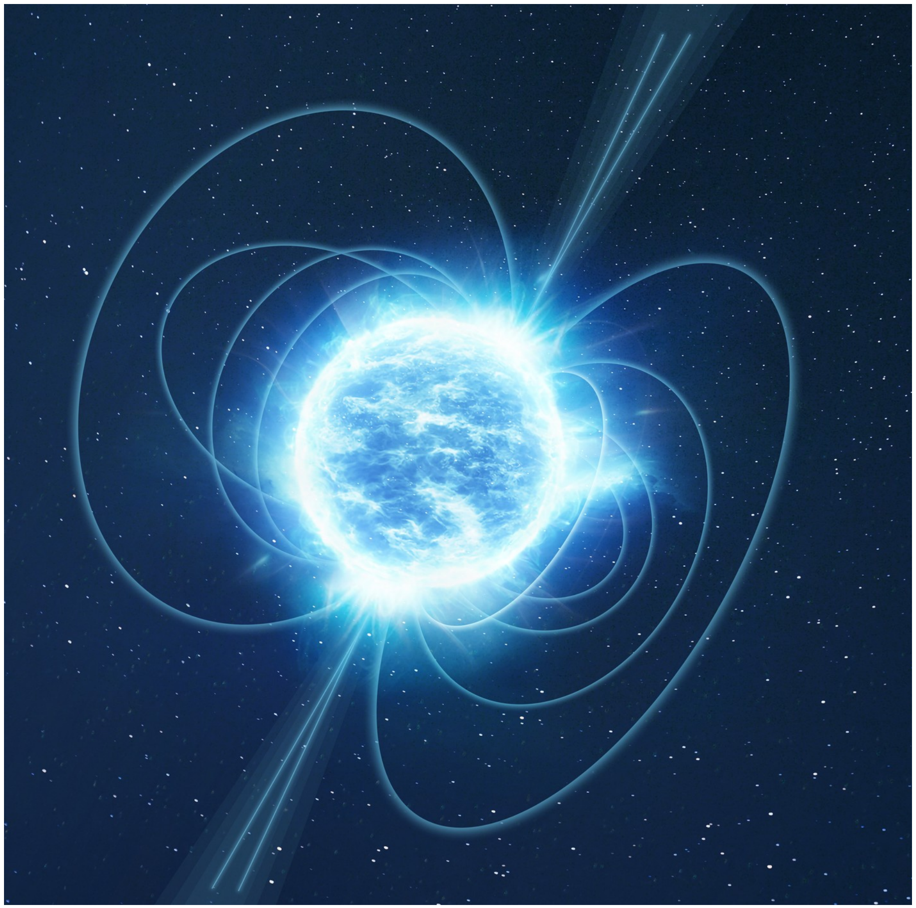
Pulsar at center !

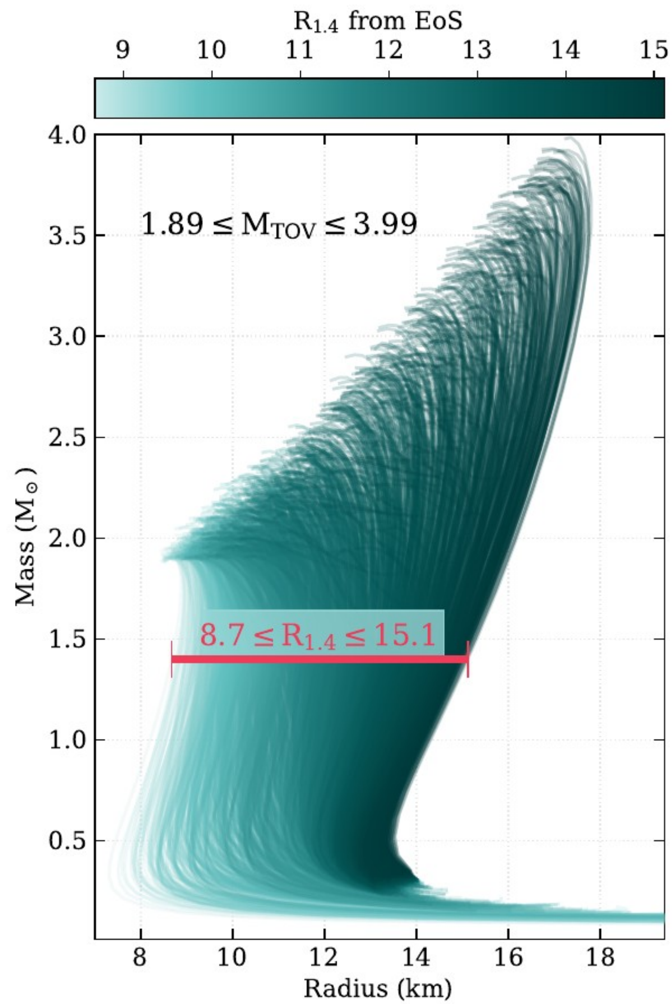


Combined image from James Webb Space Telescope
Credits NASA, ESA, CSA, STScI, T. Temim (Princeton University)

Mass – radius of a neutron star

Mass expressed as solar mass fraction





Different EOSs feature many various profiles !

Goal : try to find the best one…

Size of a big city ~ 10 km !

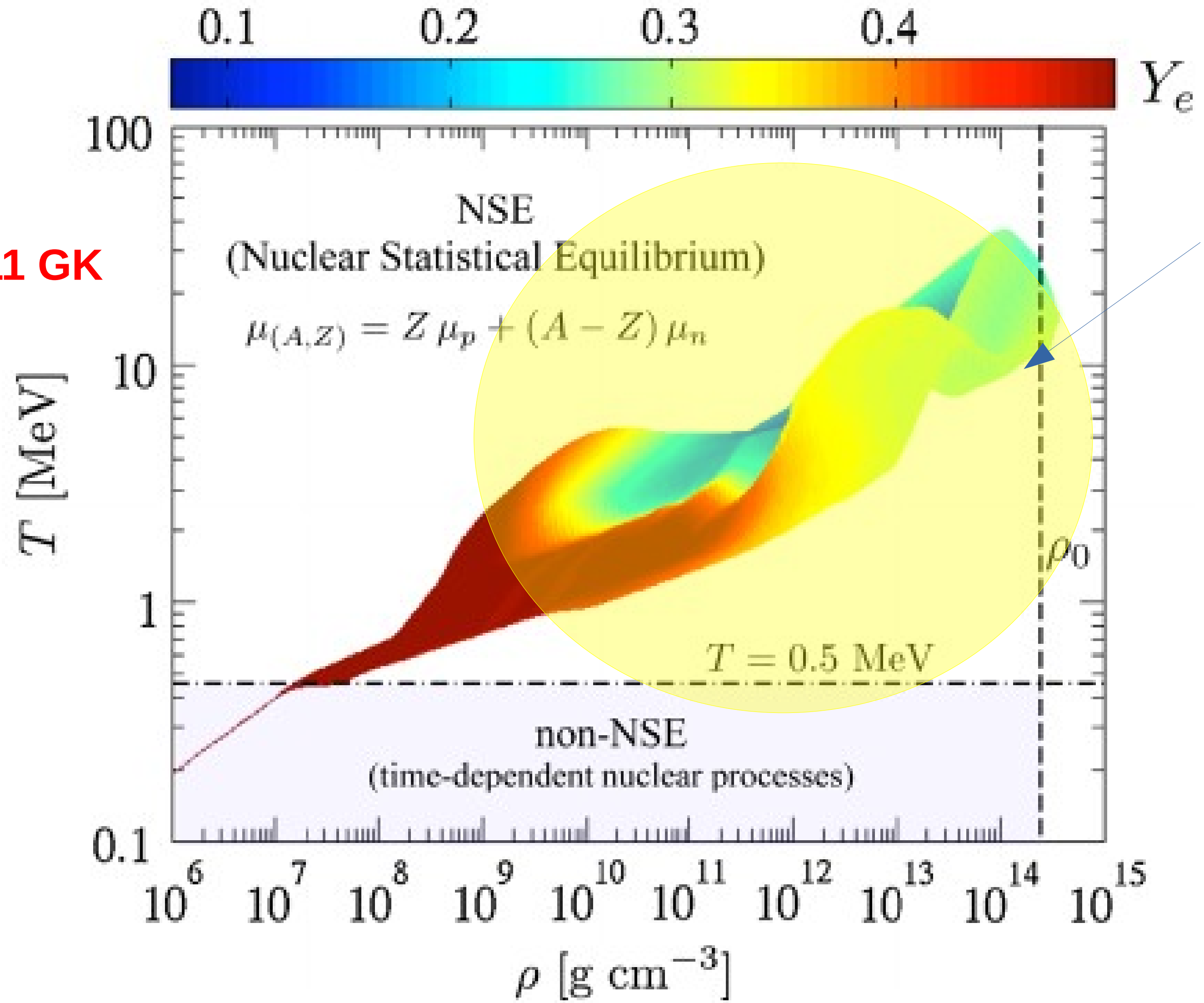
Size of a neutron star

Compared to Vancouver ...

Covered domain in the plane (ρ,T)

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

1 MeV = 11 GK

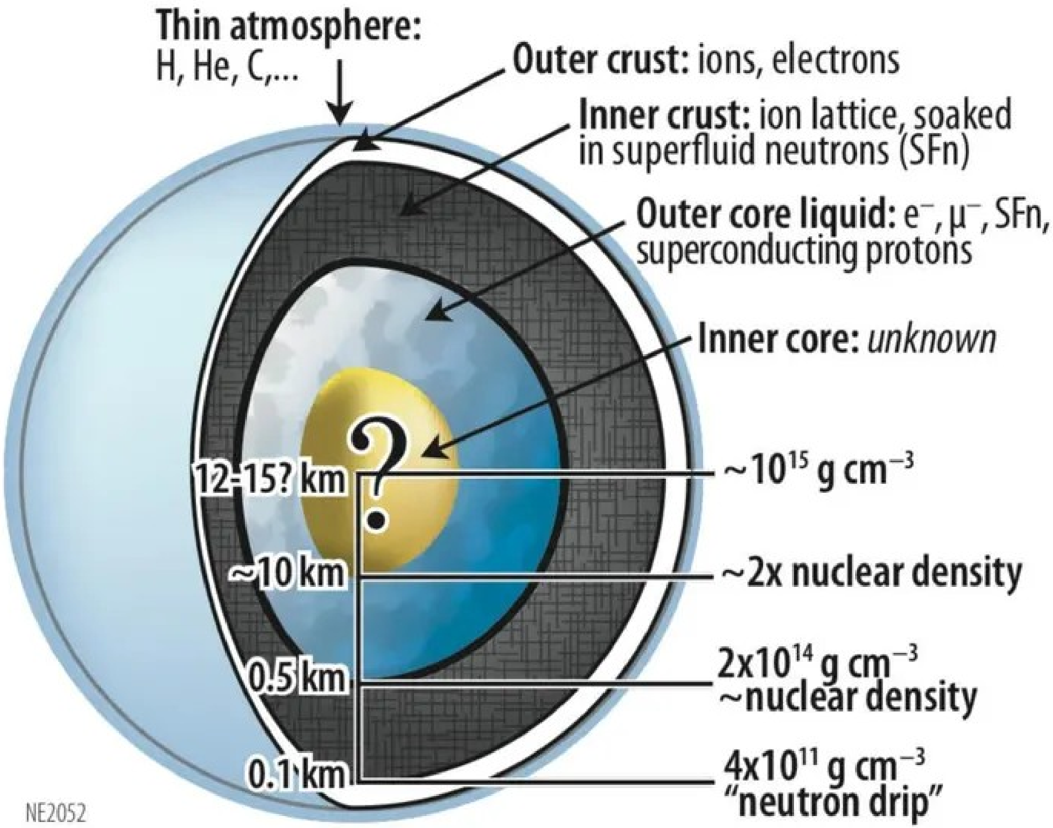


Nuclear reactions @ GANIL ...

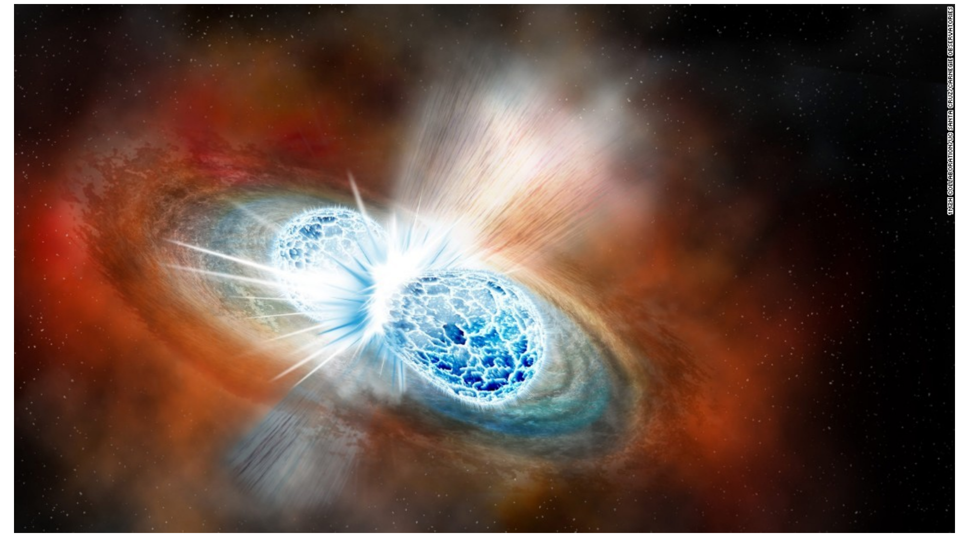
ρ_{nuc} = 10^{14} g.cm^{-3}

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

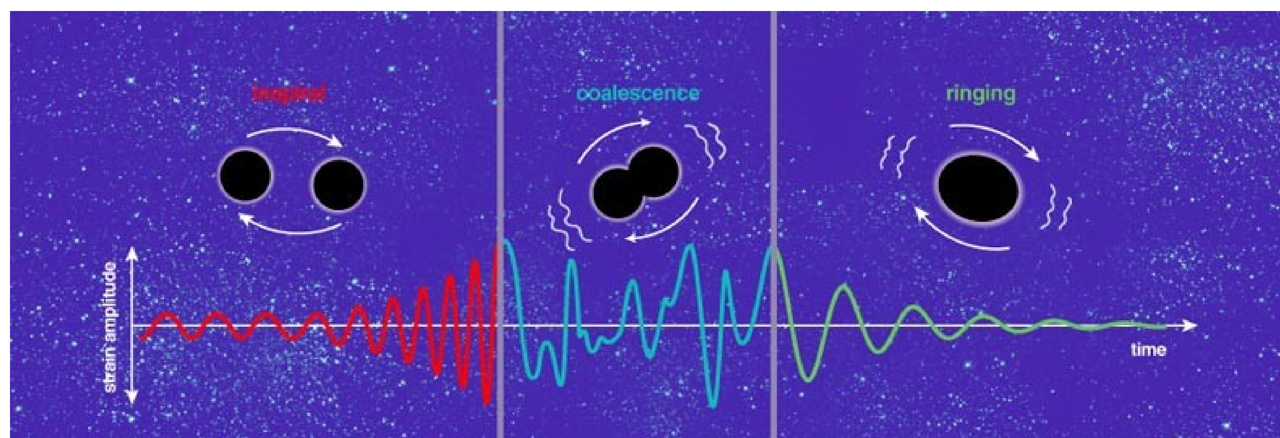
Neutron star : a dream for nuclear physicists …



NS – NS merger



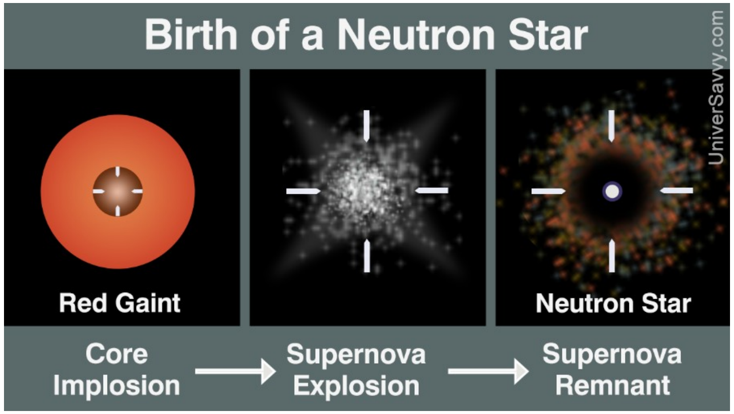
Gravitational waves

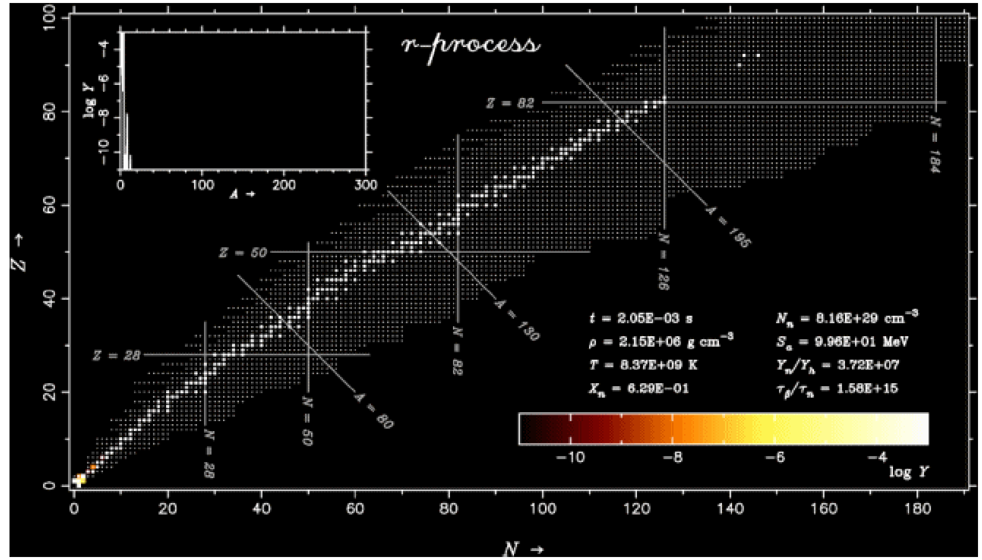


Ligo/Virgo

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)

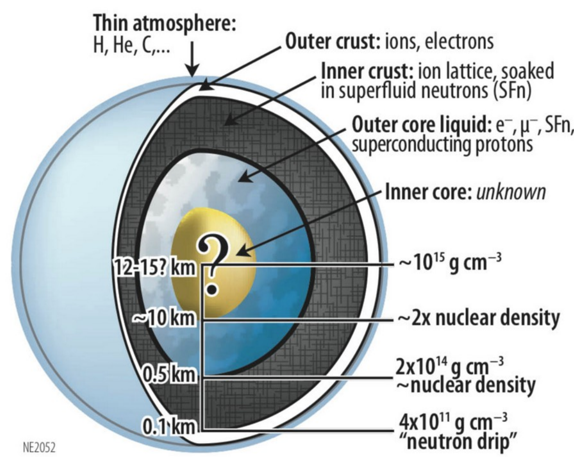
Detection of *GW* and multi-messenger observables (GW170817) considerably reinforces terrestrial *EOS* studies

Core Collapses Sne

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

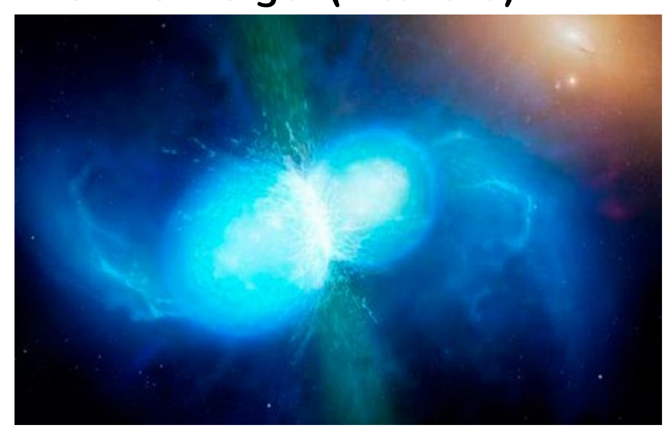
NS structure :

- 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)



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

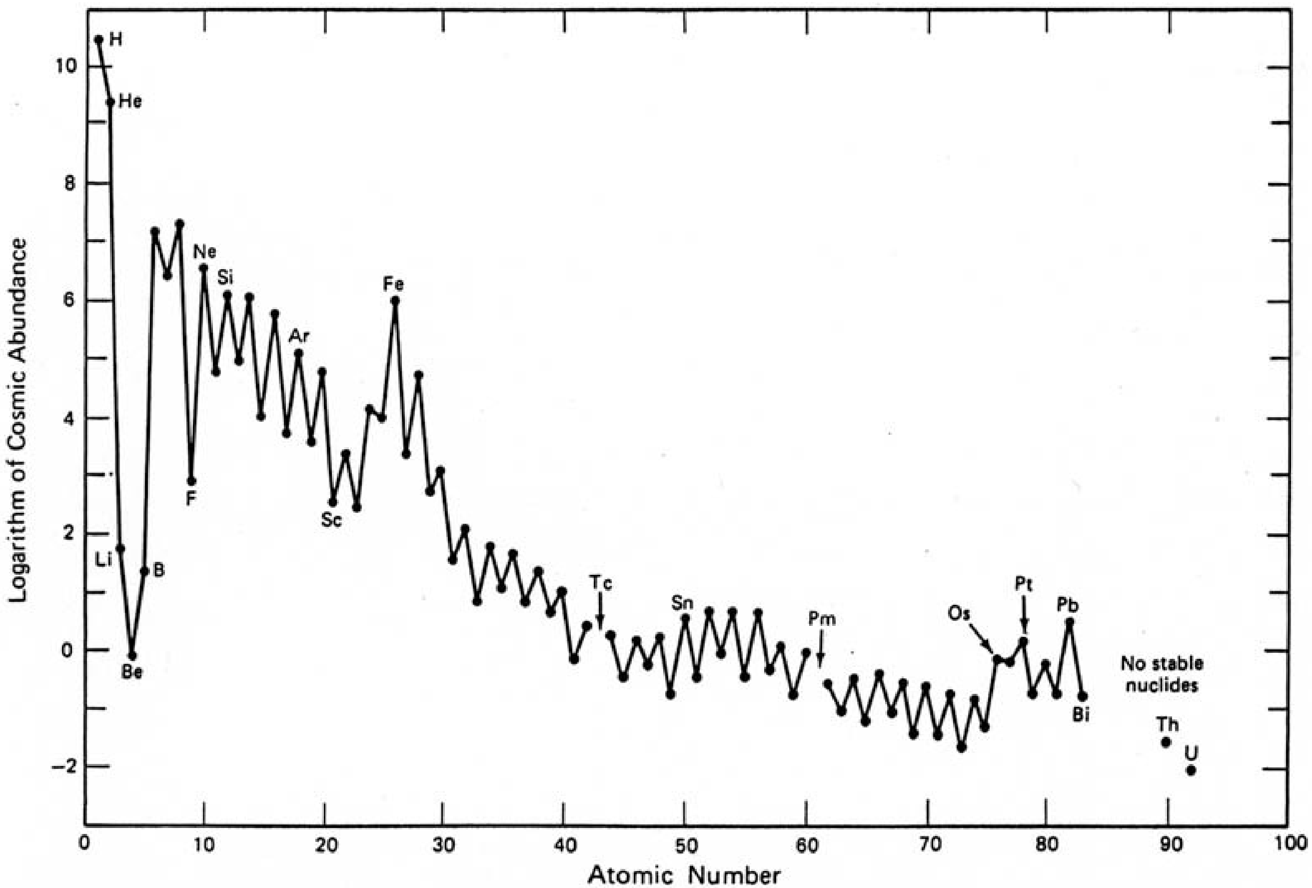
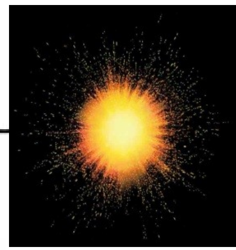


Figure 2.4 Plot of the abundances of the elements in the solar system versus their atomic number. The abundances are expressed as the logarithm of the number of atoms of each element relative to 10^6 atoms of silicon. (Data are listed in Table 2.2 after Anders and Ebihara, 1982.)

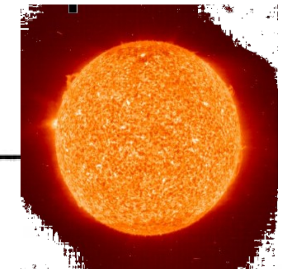
Nucleosynthesis : different origins

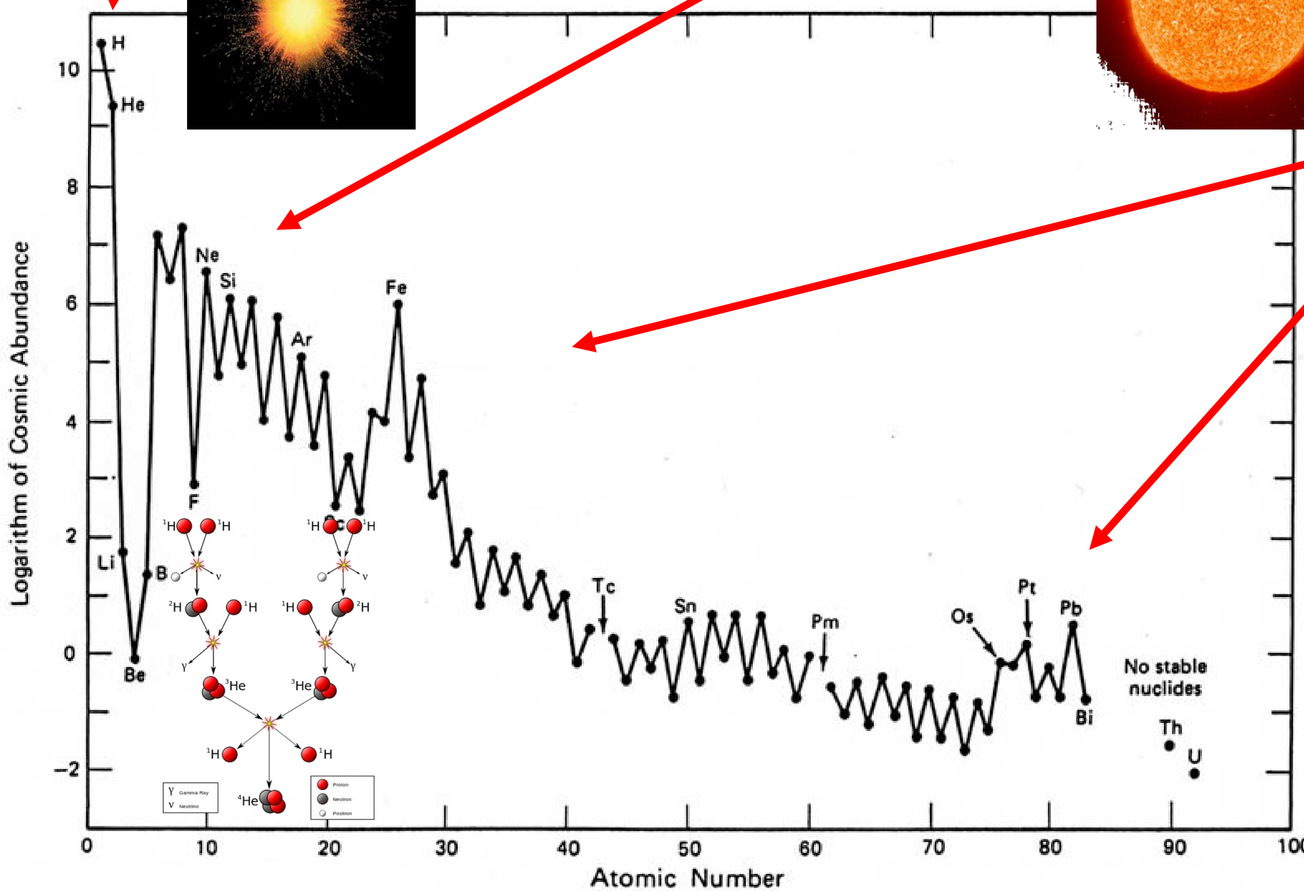
Abundance of elements in the Universe

Primordial Hydrogen (Big Bang) Z=1



Stellar synthesis Z=2-26





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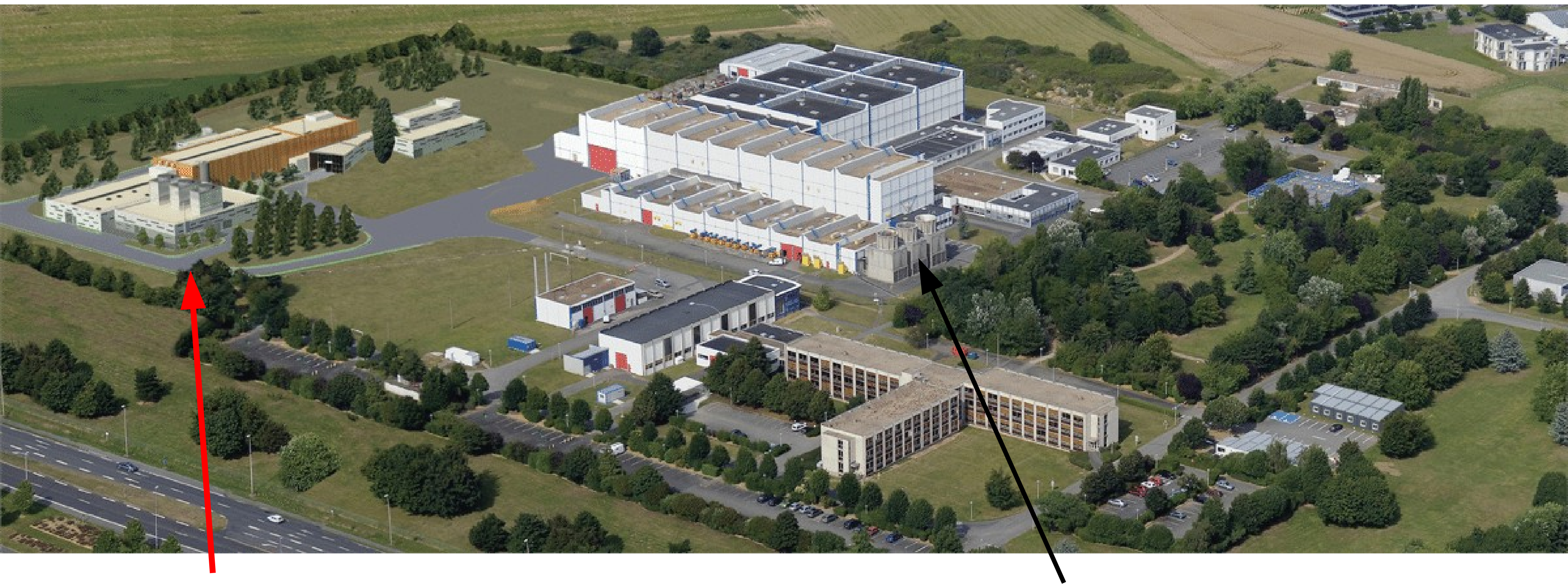
Extra-stellar processes r/s/p-processes in supernovae and NS-NS mergers Z>26

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

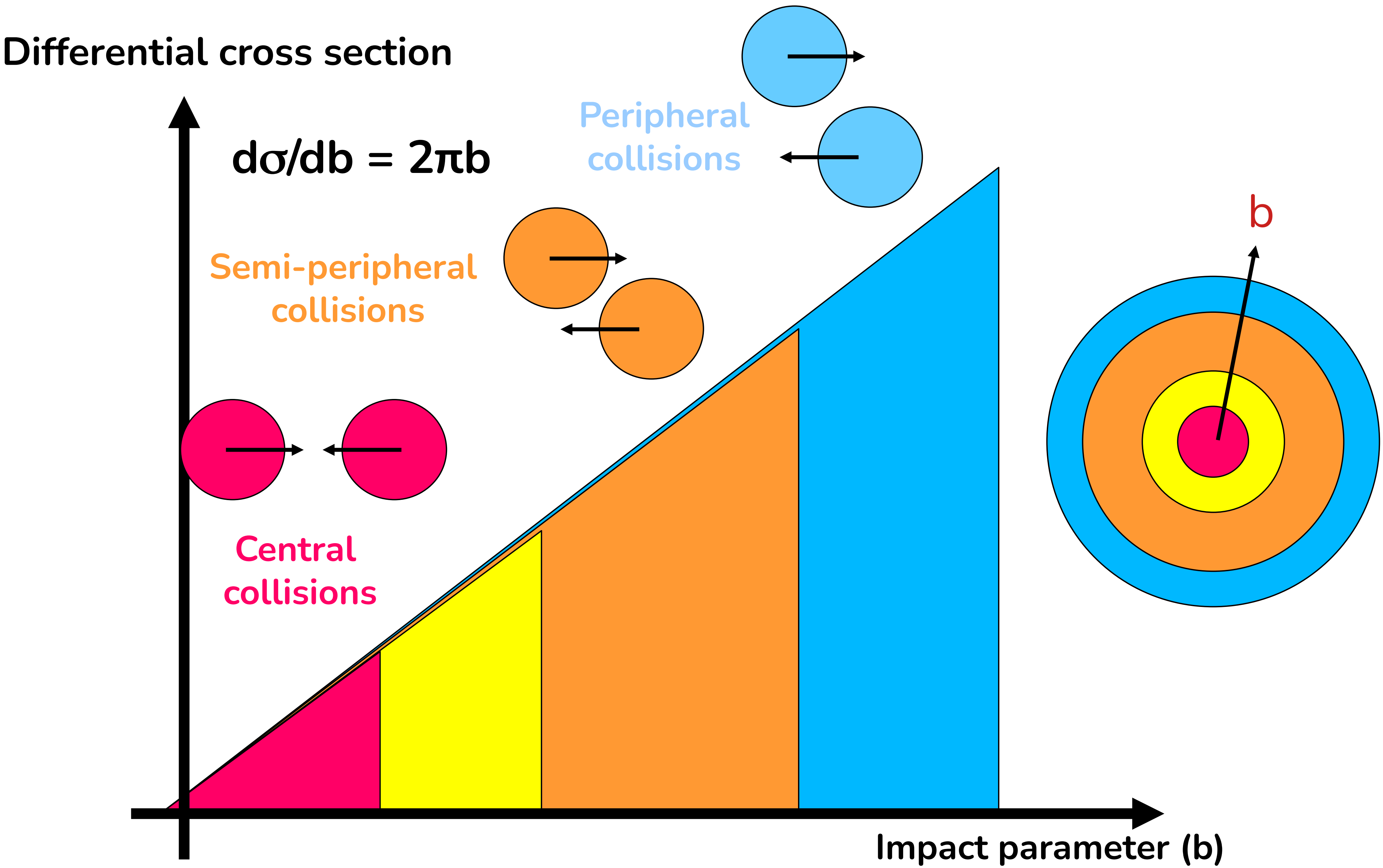
permettent de produire les ions stables ou radioactifs qui seront ensuite mis en faisceaux et accélérés.

End part I

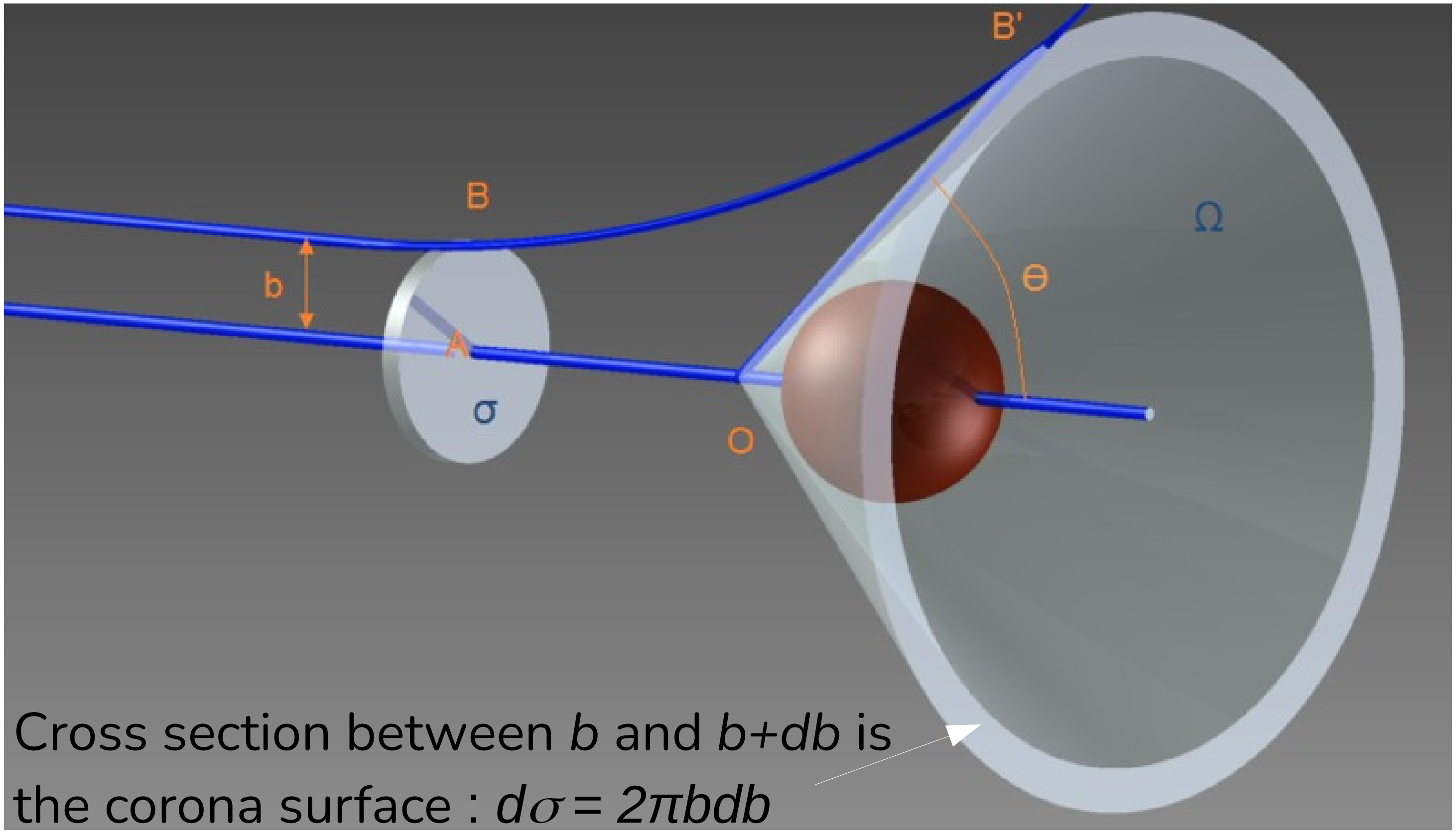
Part II

Some basic concepts of nuclear reactions

Nuclear reactions : playing darts ...



Cross section in Classical Physics



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

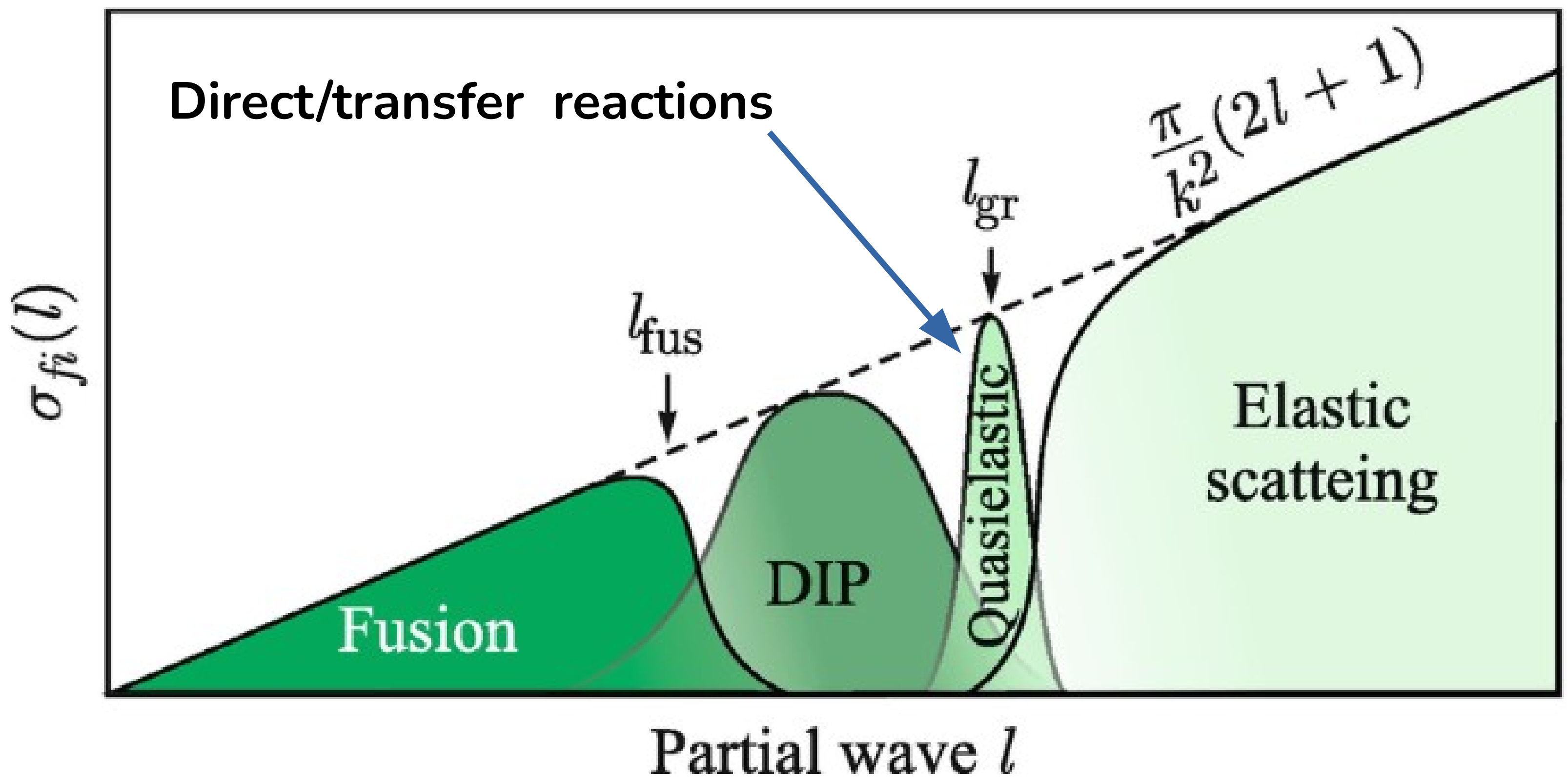
Cross section in Quantum Mechanics : partial waves

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**

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

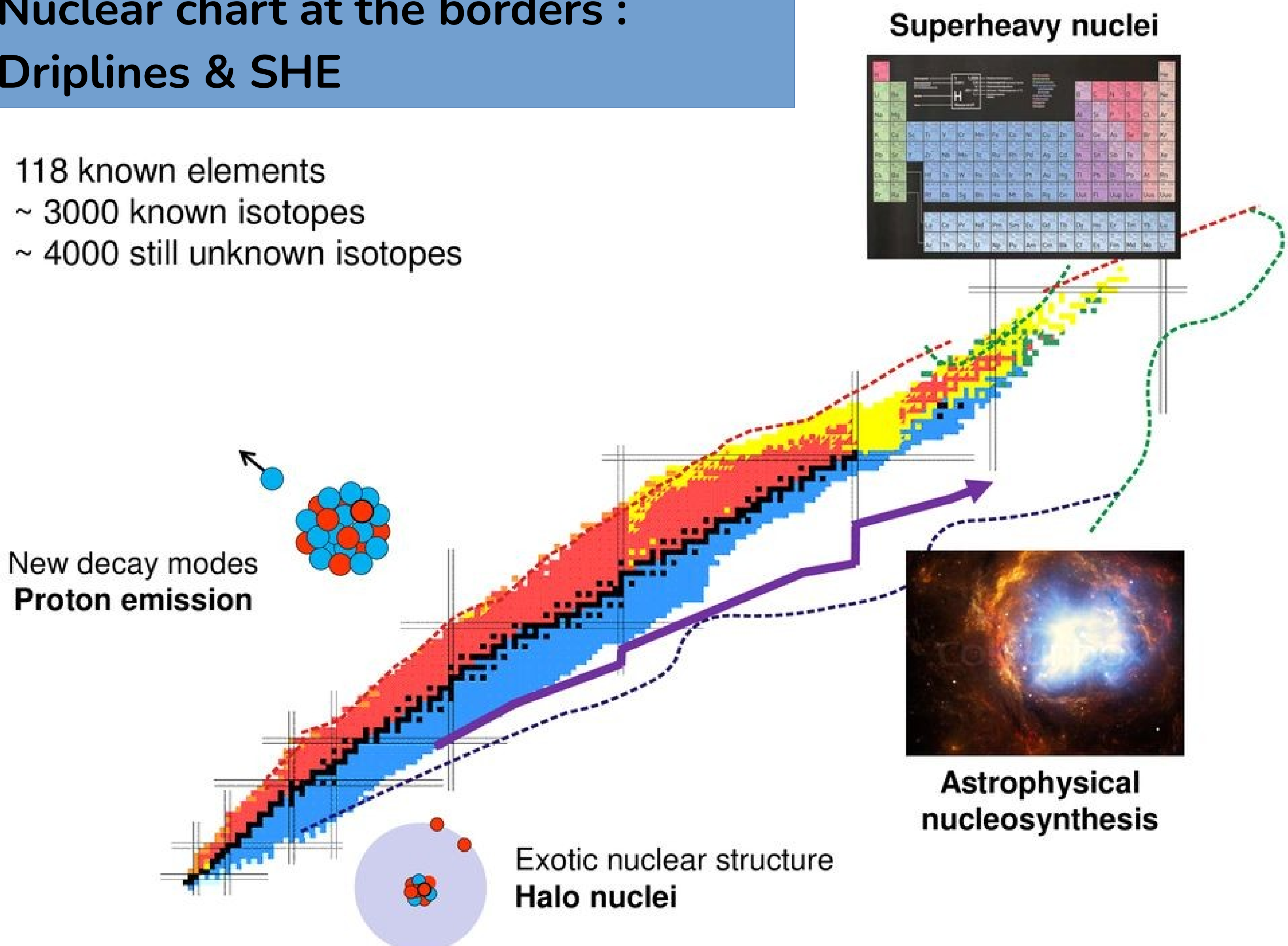
Reaction $\mathcal{F}$ = 10^9 pps	**Cross section**	**Event rate**
Coulomb scattering	100 b	1000 s^{-1}
Deep Inelastic/ Multi-nucleon Transfer	1 b	10 s^{-1}
Central collision (b<1 fm)	50 mb	1 mn^{-1}
Transfer/direct reaction	10 mb	10 hr^{-1}
Fusion reaction	1 mb	1 $week^{-1}$

Nuclear reactions

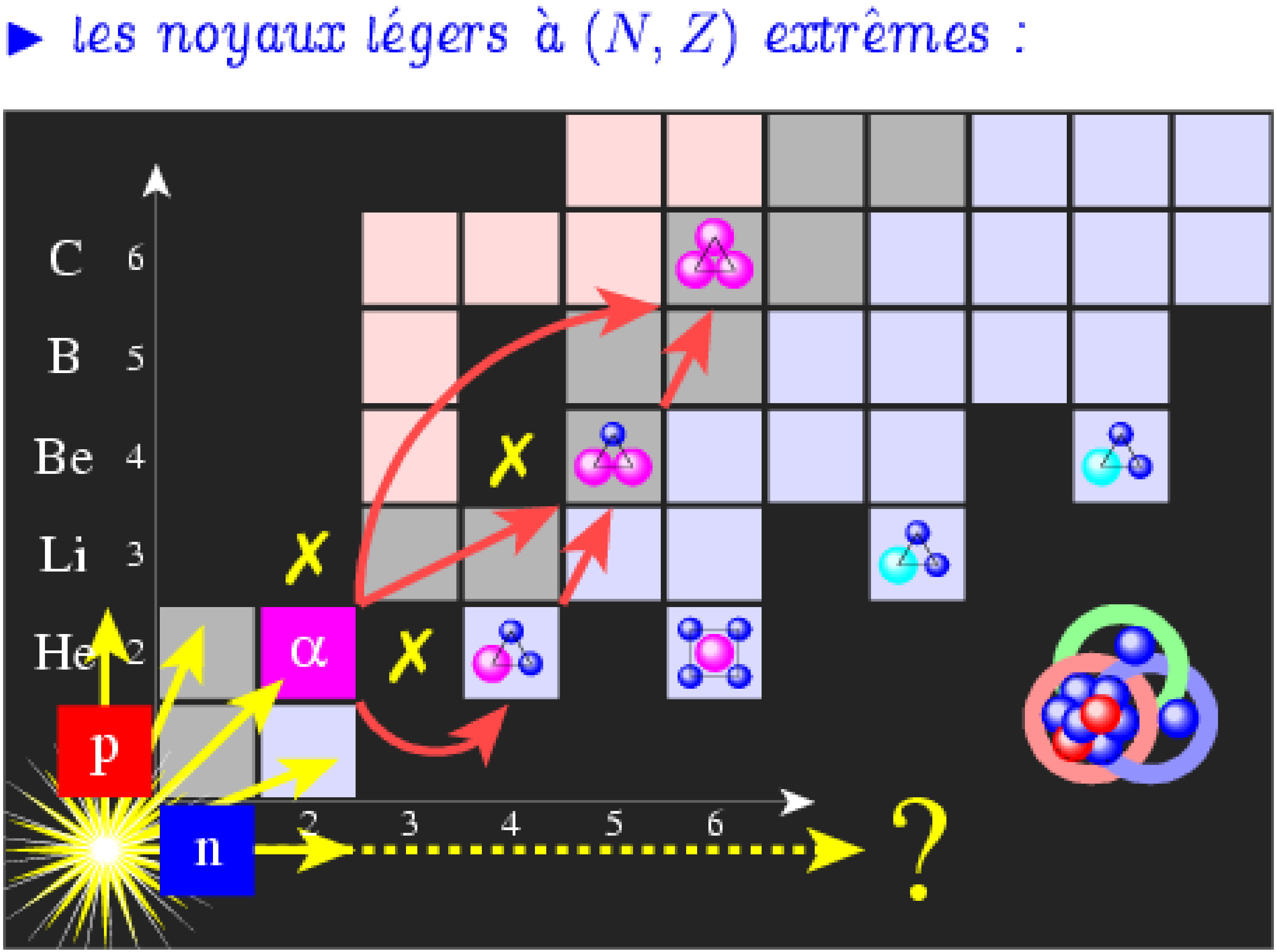
Producing exotic nuclei

Physics cases for nuclear reactions : driplines

Nuclear chart at the borders : Driplines & SHE

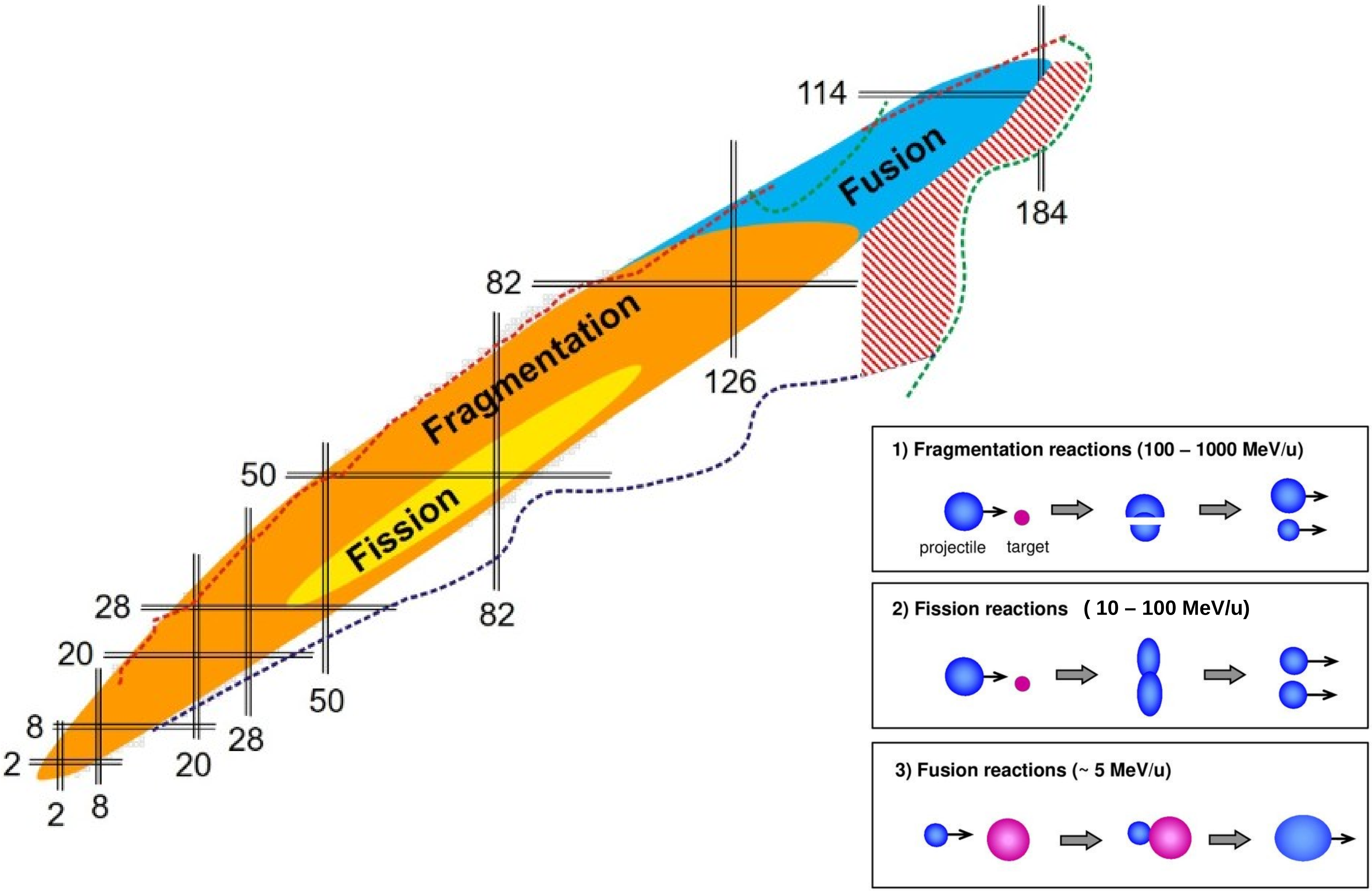


Also Haloes nuclei...

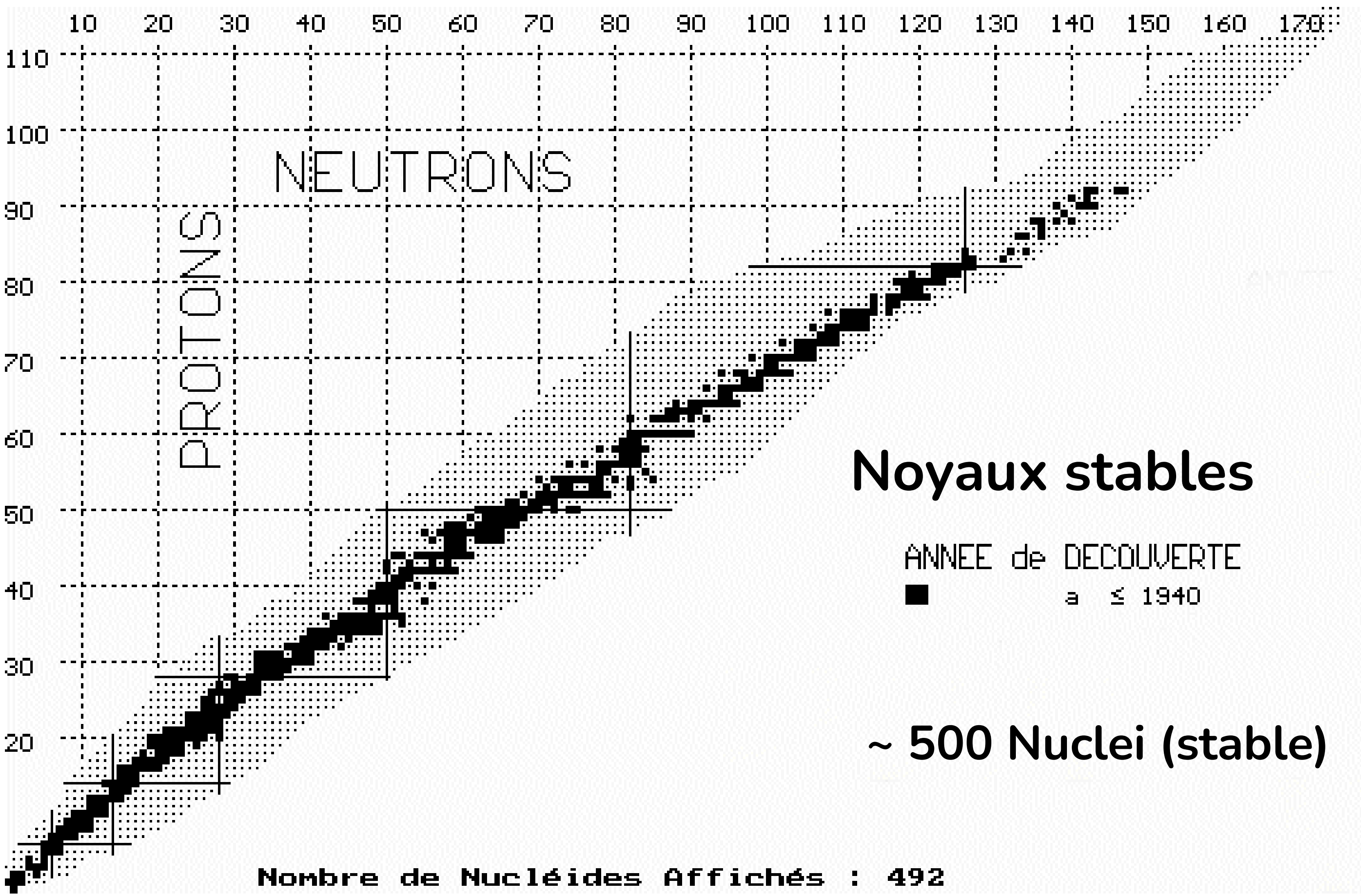


Courtesy Miguel Marques (LPC Caen)

Production of exotic nuclei with HI beams



Known nuclei before WW2

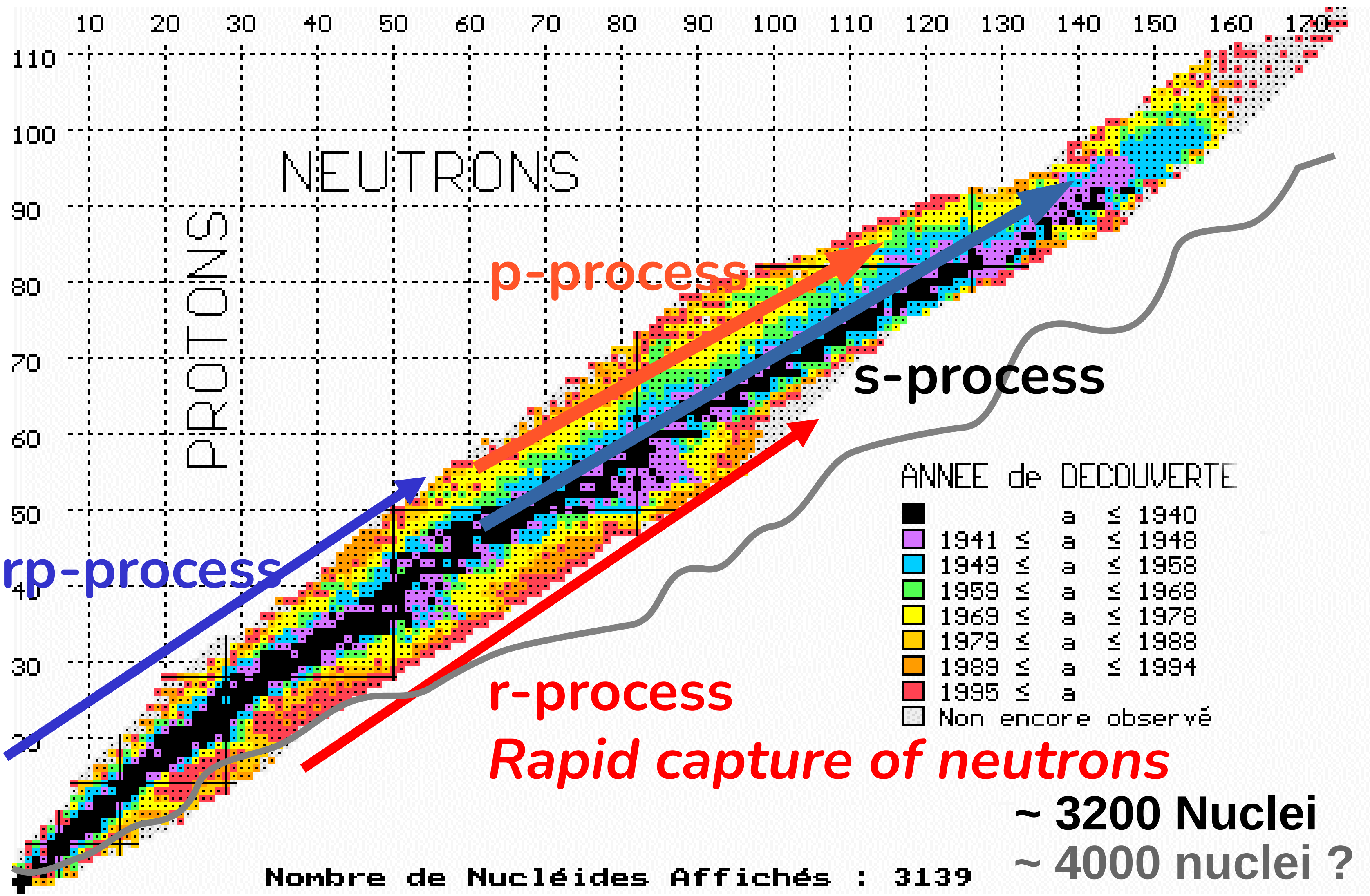


Noyaux stables

~ 500 Nuclei (stable)

Known Nuclei now : astrophysical processes

"Terra Incognita"



Nuclear reactions

Reaction Mechanisms

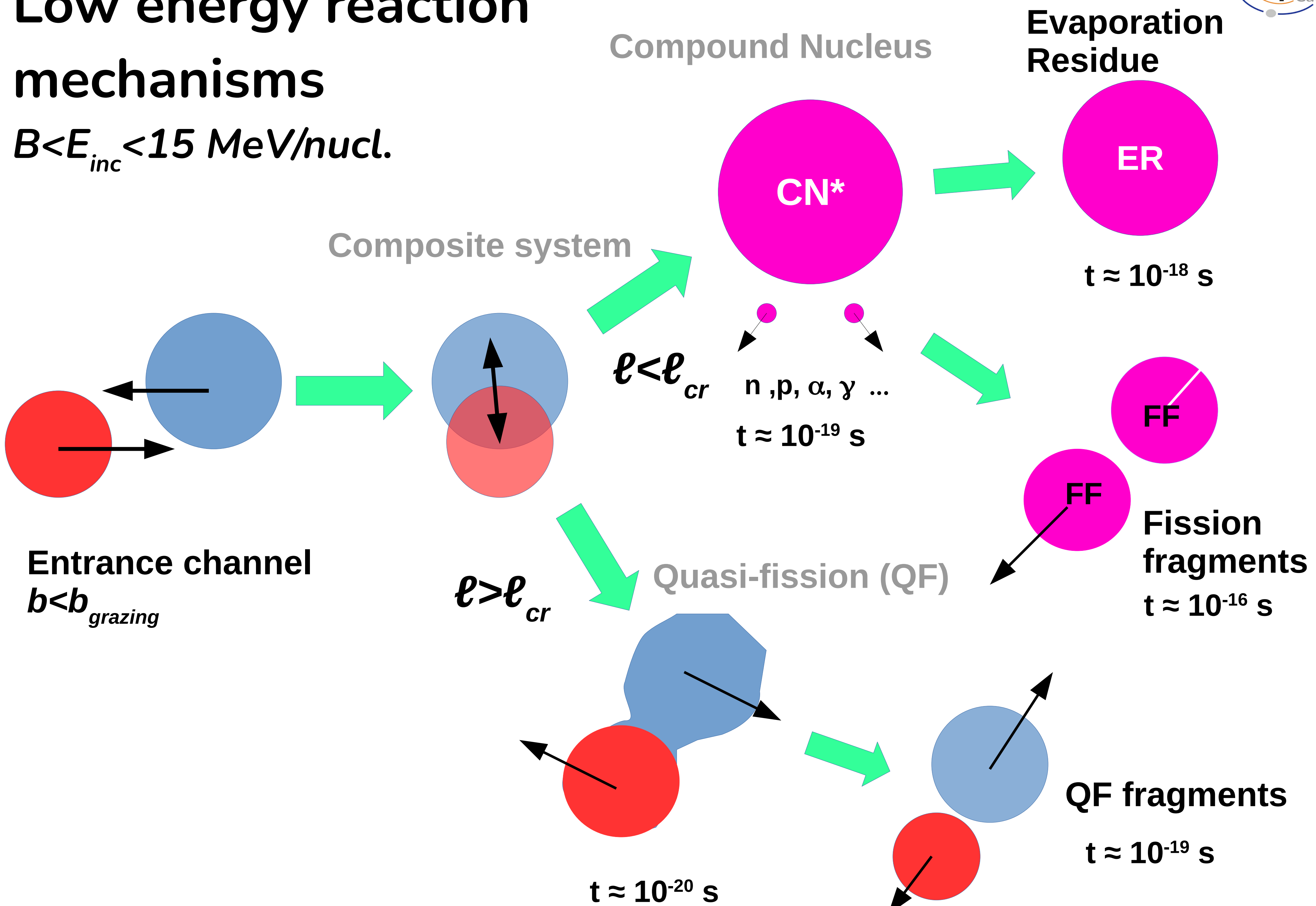
Nuclear reactions

Low incident energy

5 – 15 MeV/nucleon

Low energy reaction mechanisms

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



Nuclear reactions

Fermi incident energy

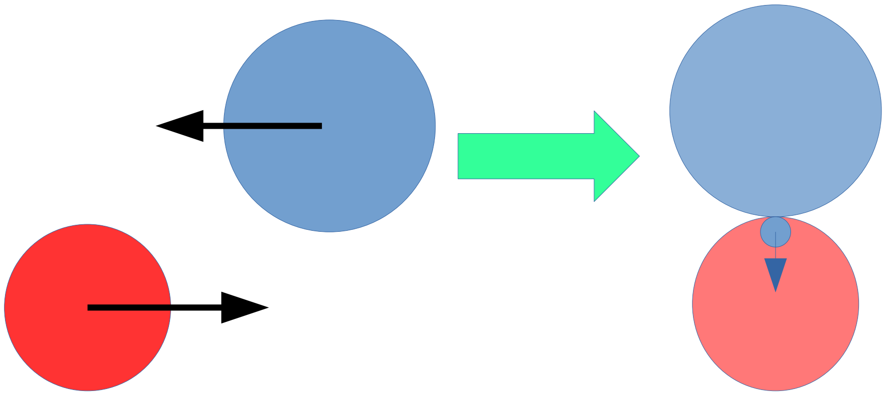
15 – 50 MeV/nucleon

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 :

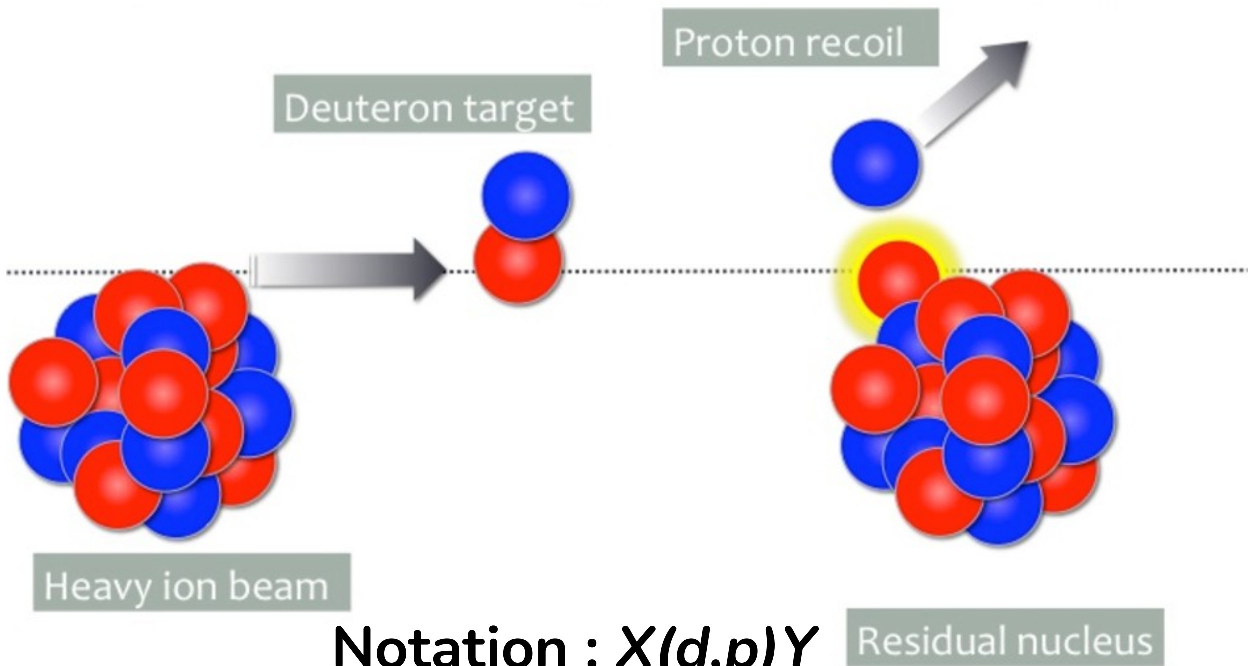
(d,p) : +1n transfer (r-process)
(t,p) : +2n transfer (r-process)
(p,t) : -2n transfer (rp-process)
(^{3}He,d) : +1p transfer (rp-process)
...

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*

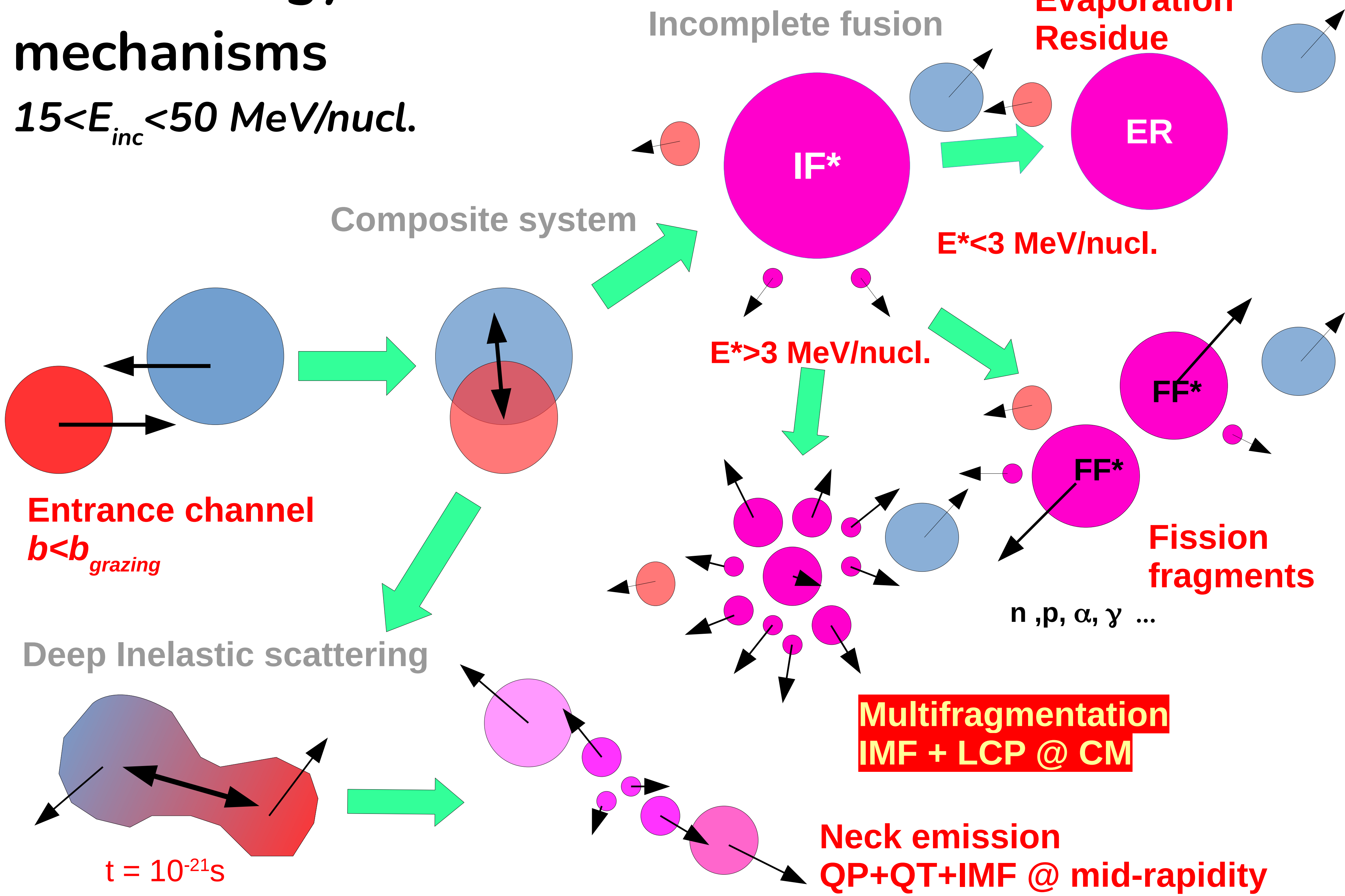
Complete kinematical reconstruction of the reaction / decay
Master the decay process

Limited to few nucleons transfer/pickup
Small excursion toward drip lines

Limited angular momentum selectivity (few $\hbar$)
Few discrete states accessible

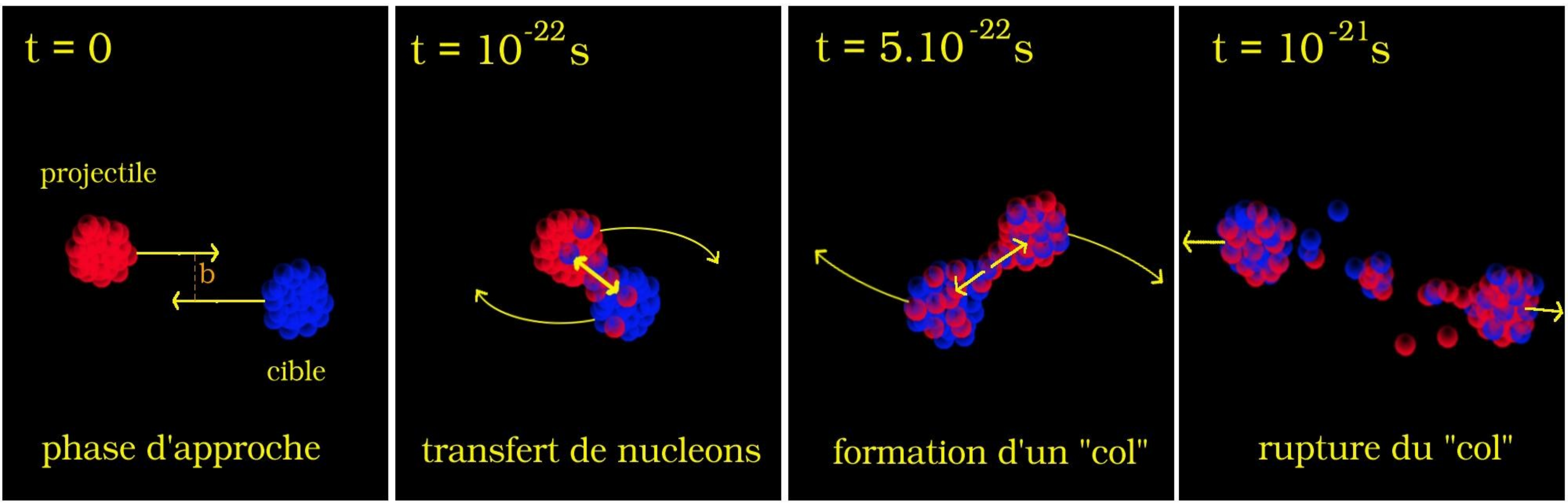
Fermi energy reaction mechanisms

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



Deep Inelastic collisions … toward the limits

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

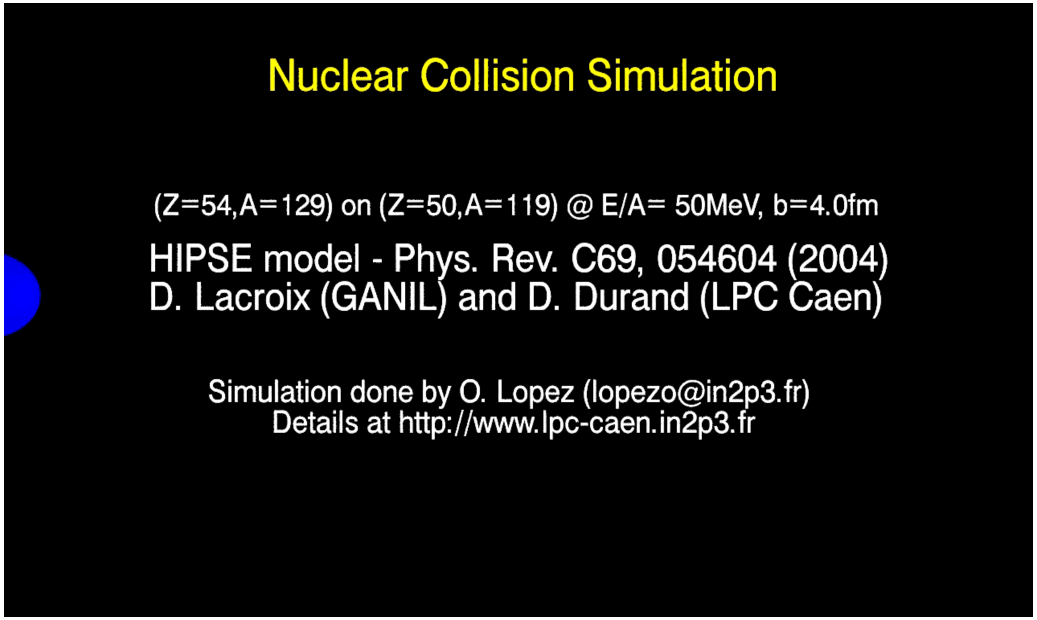


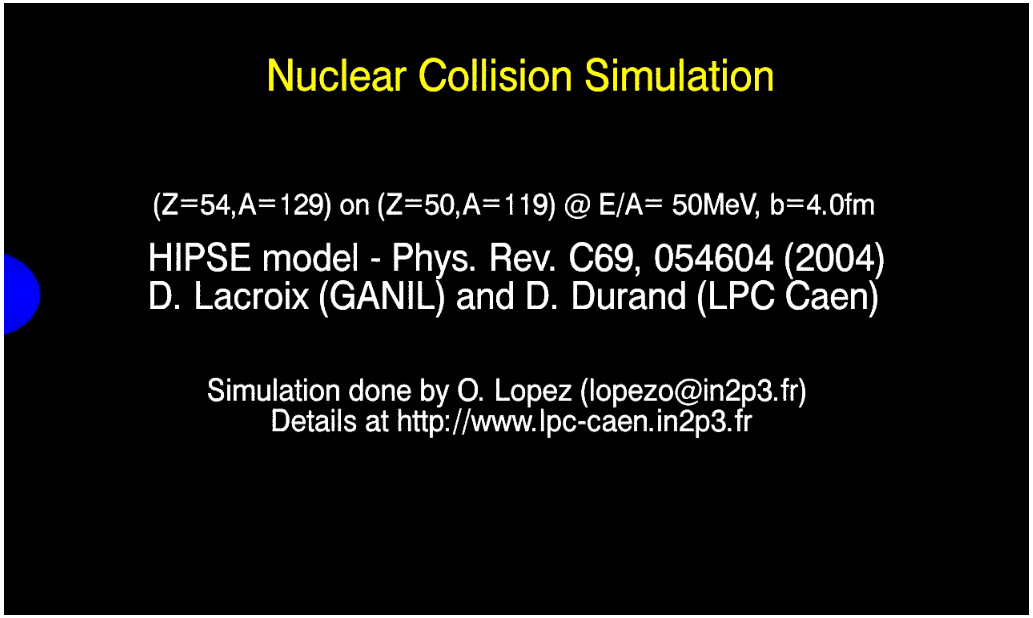
Extreme rotation
10^{23} rpm !

More diluted
$\rho << \rho_0$

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

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





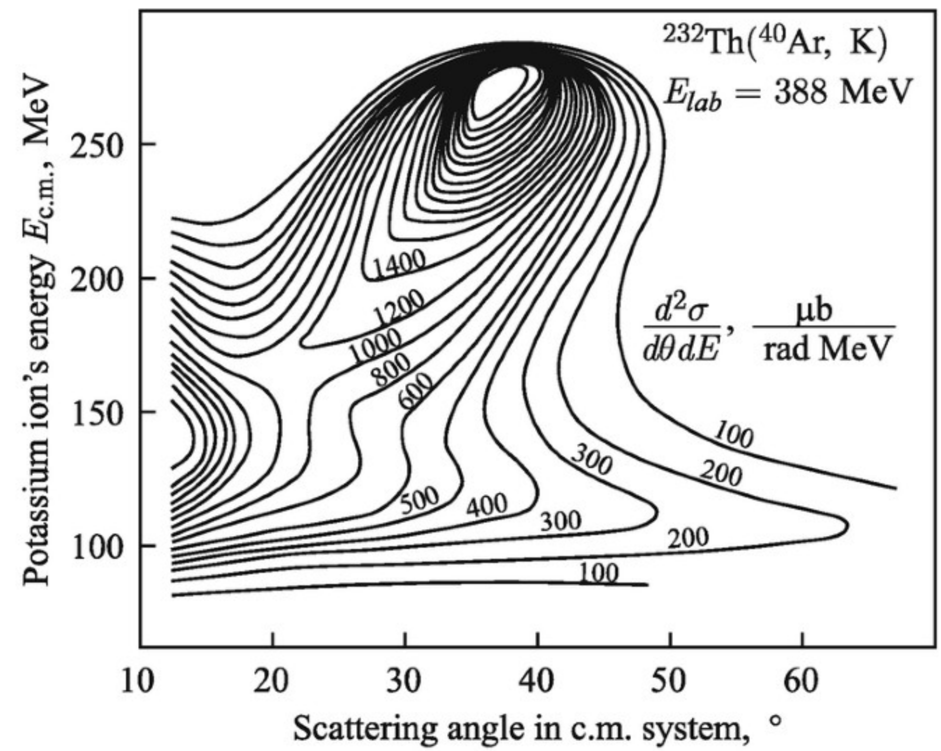
Deep Inelastic Scattering

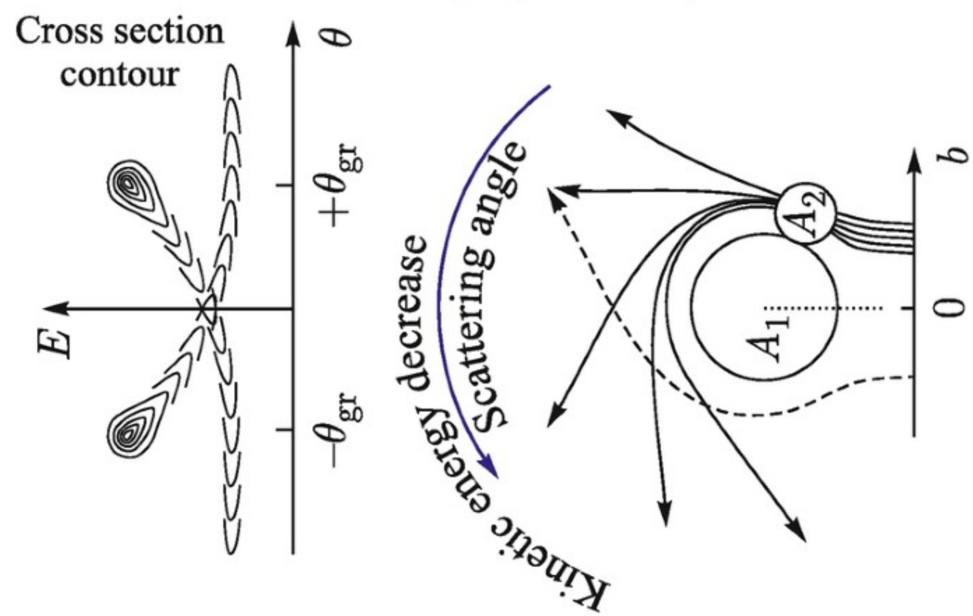
15<E_{inc}<50 MeV/nucl.

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)

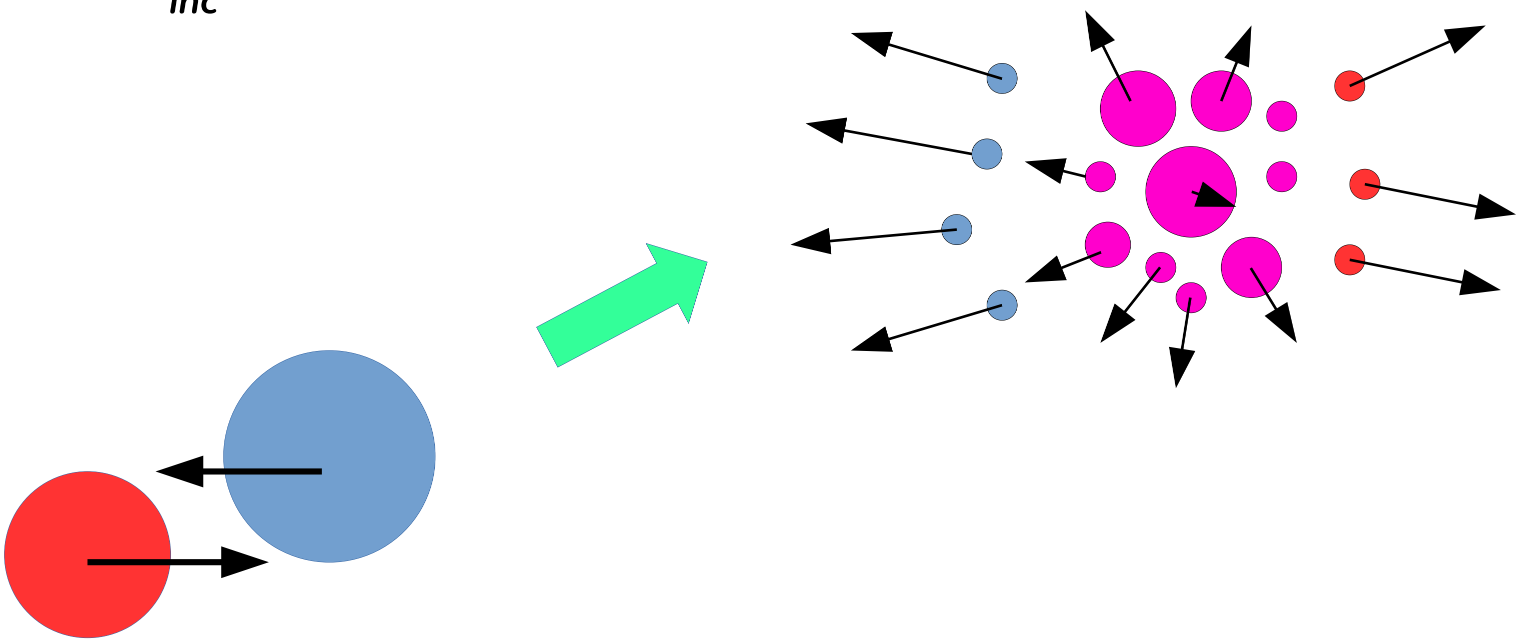
Nuclear reactions

Intermediate incident energy

50 – 100 MeV/nucleon

Intermediate energy reaction mechanisms

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

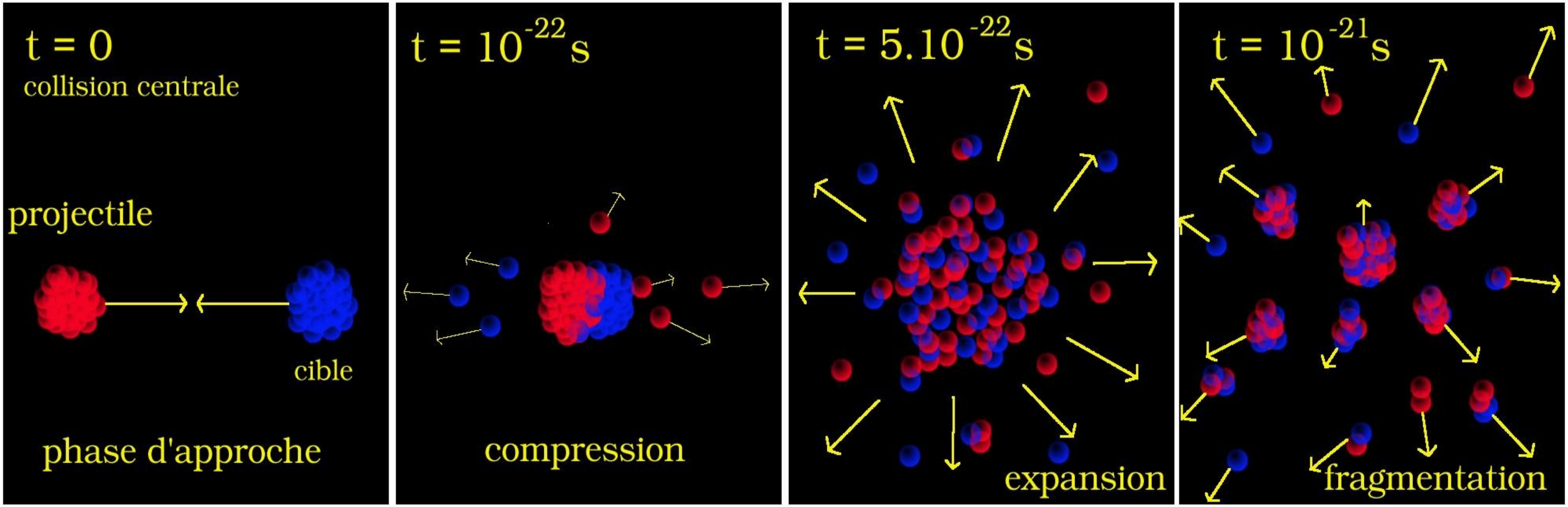


Multifragmentation
IMF + LCP @ CM
***NN* collisions**
(pre-equilibrium)

Entrance channel
$b<b_{grazing}$

Central collisions … Little Big Bang !

Central collision (b=0)

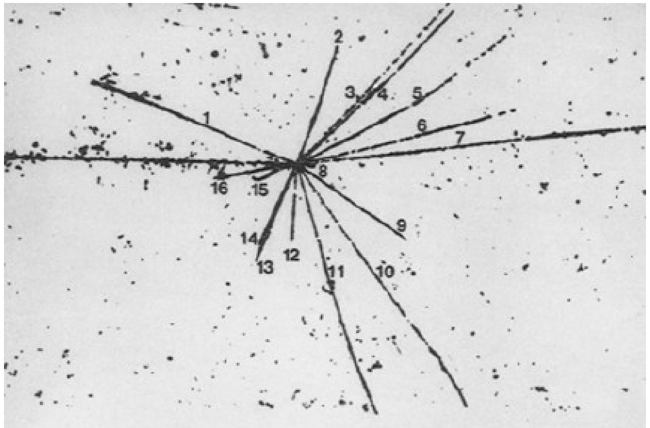


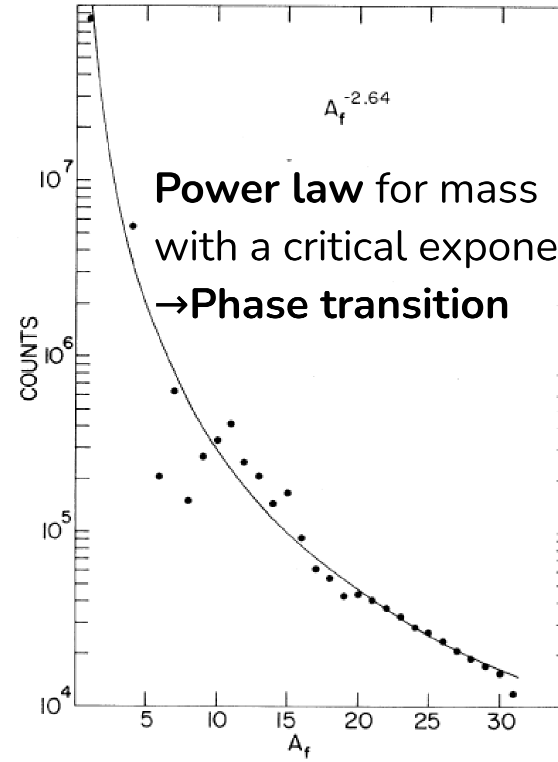
More dense
$\rho / \rho_0 > 2\text{-}3$

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

Fragmented
and diluted
N>10-100

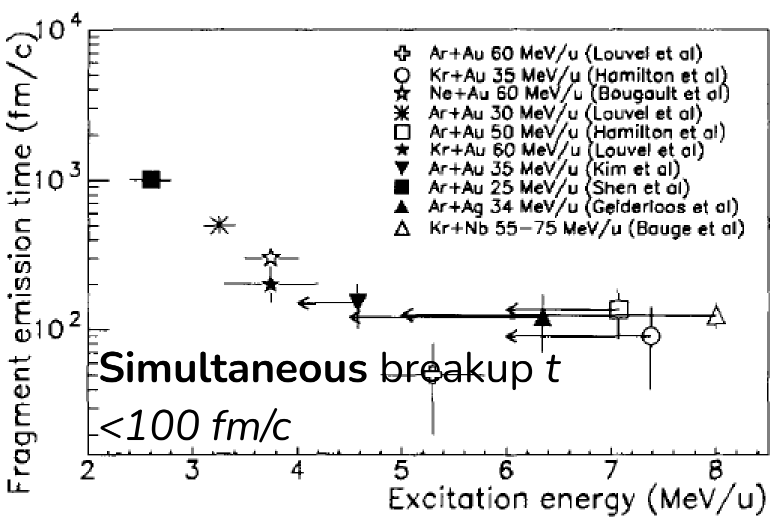
Multifragmentation as Liquid-gas PT



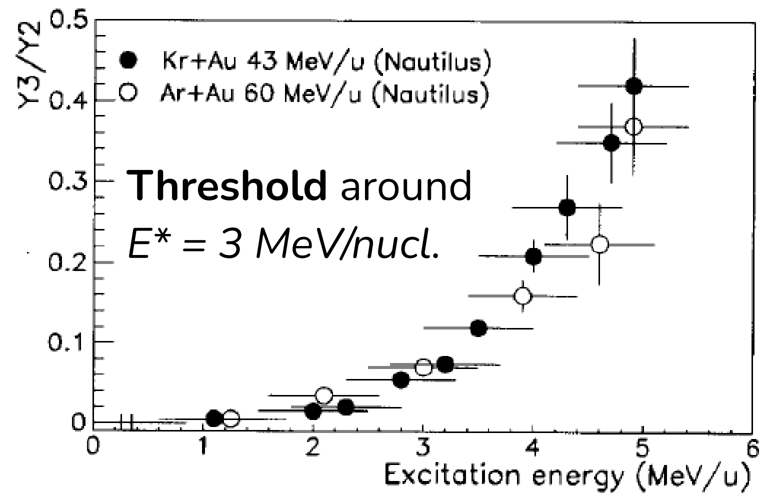


Power law for mass with a critical exponent
→**Phase transition**

Breakup reactions with more than 2 fragments…

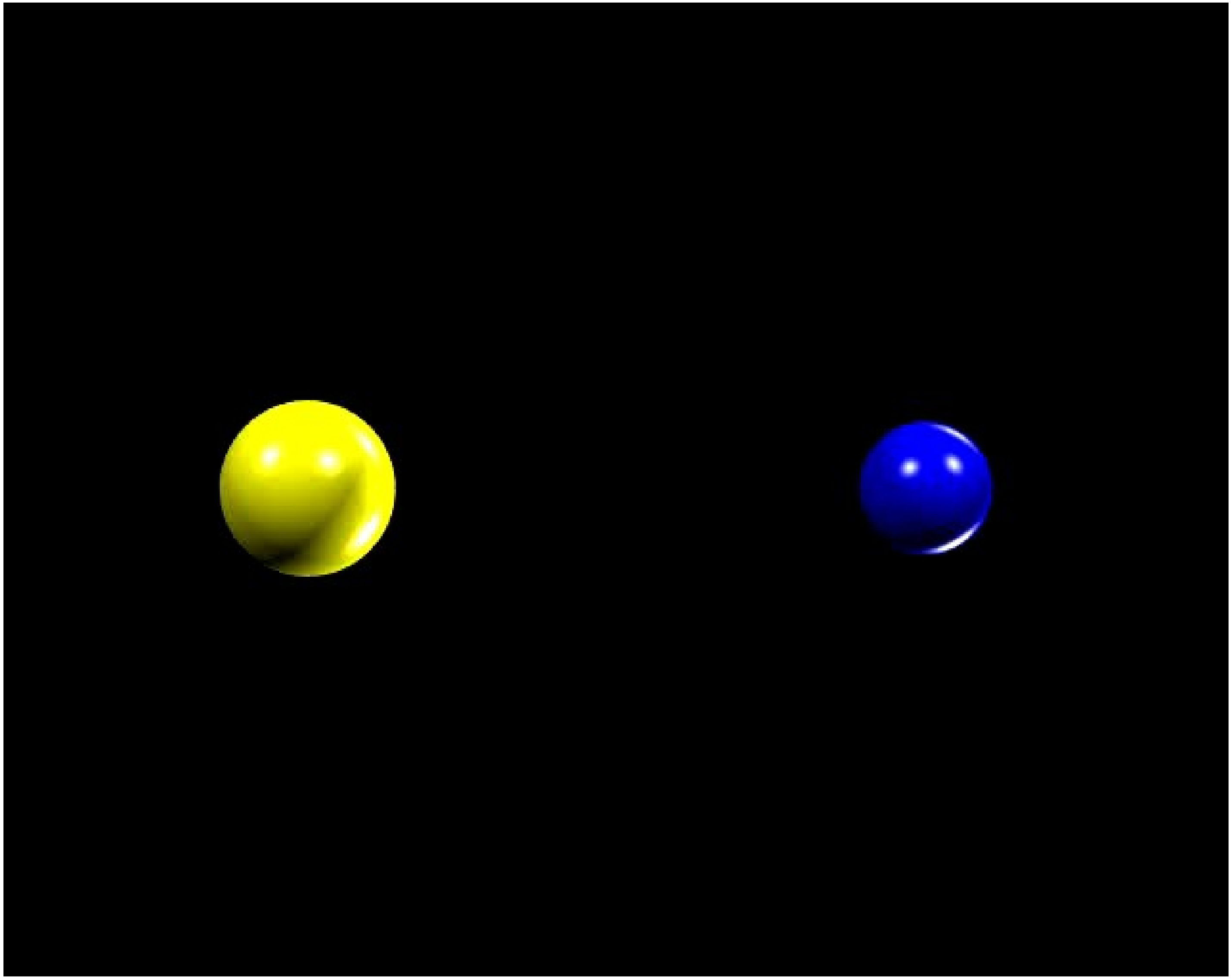


Simultaneous breakup *t* *<100 fm/c*

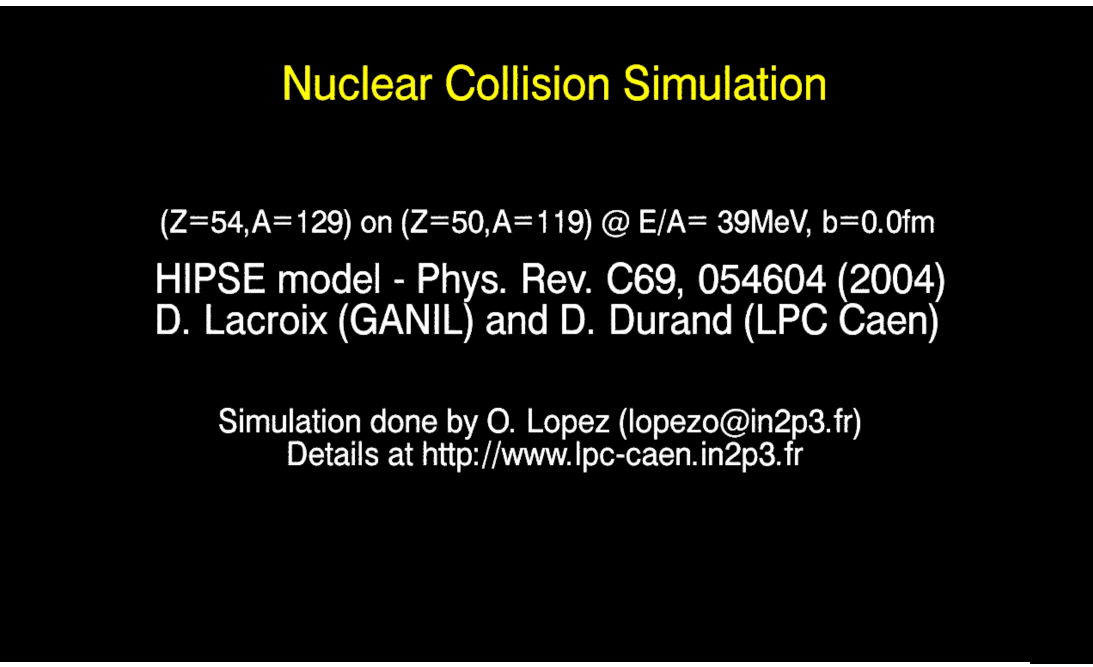


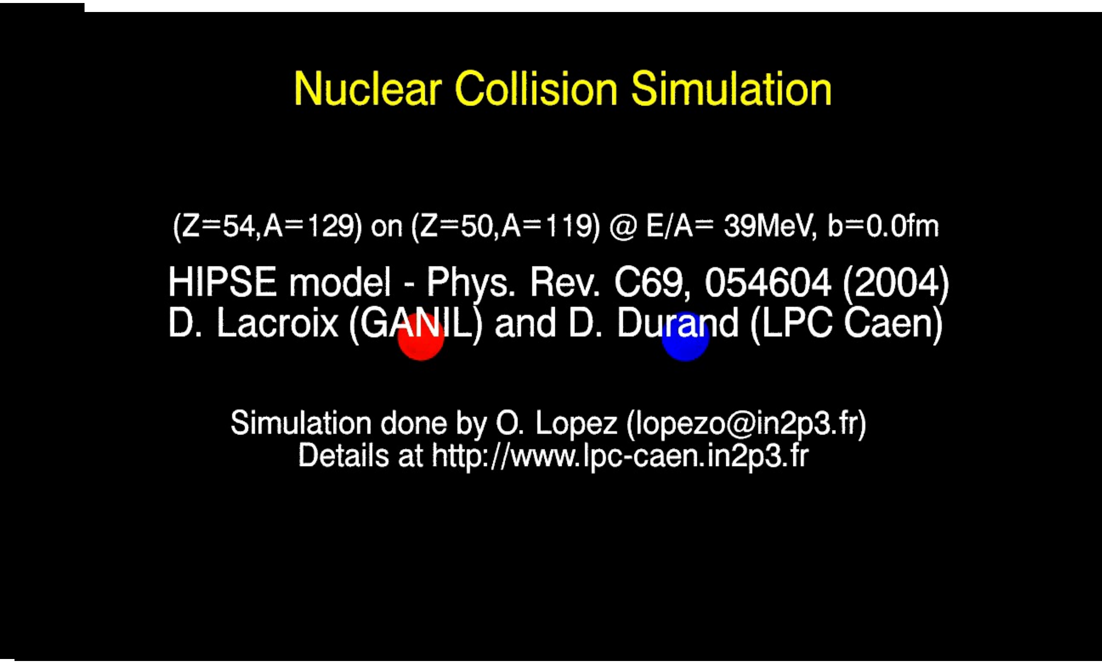
Threshold around *E* = 3 MeV/nucl.*

Multifragmentation



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



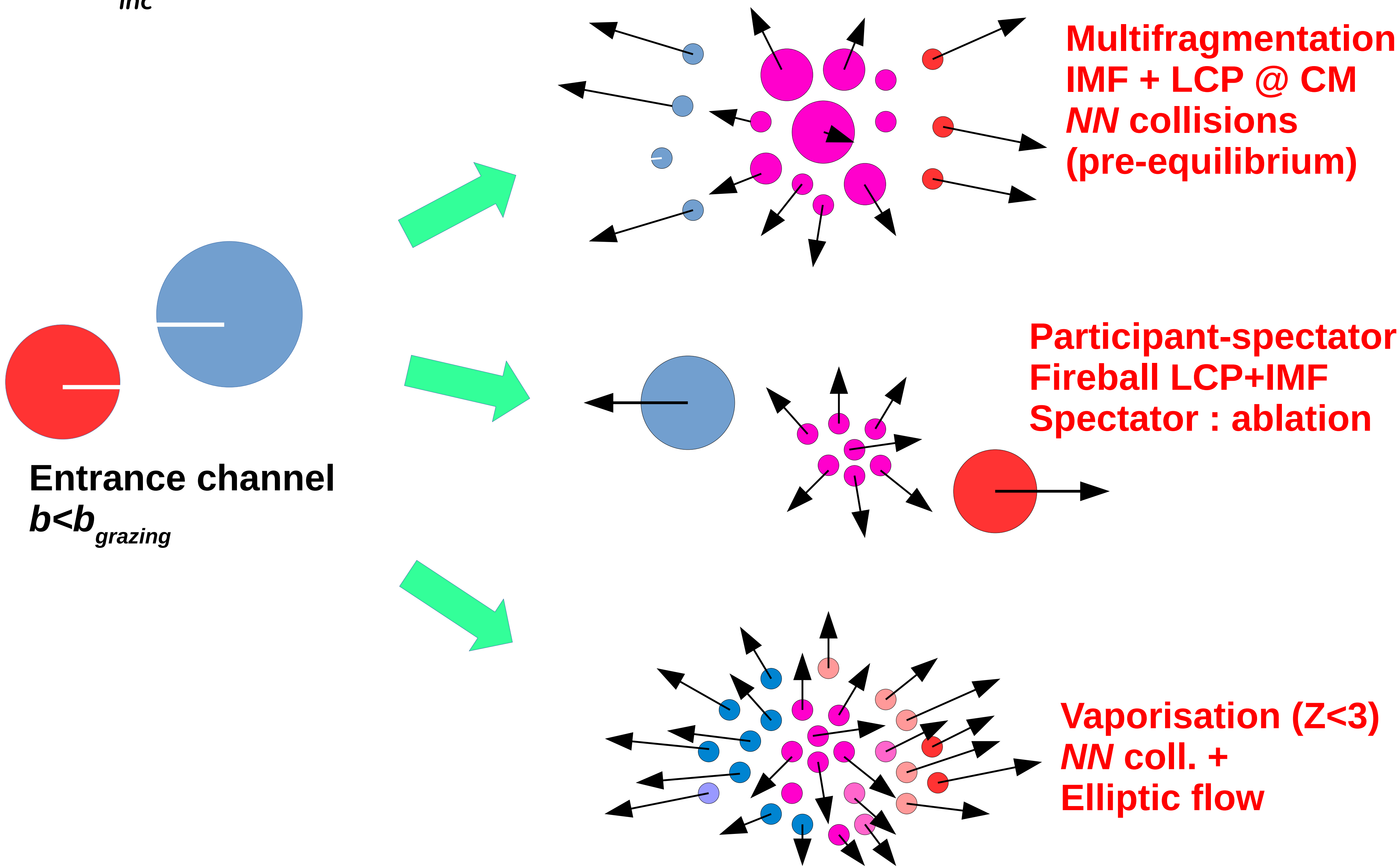


More videos avaialble on this YouTube channel :

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

Intermediate energy reaction mechanisms

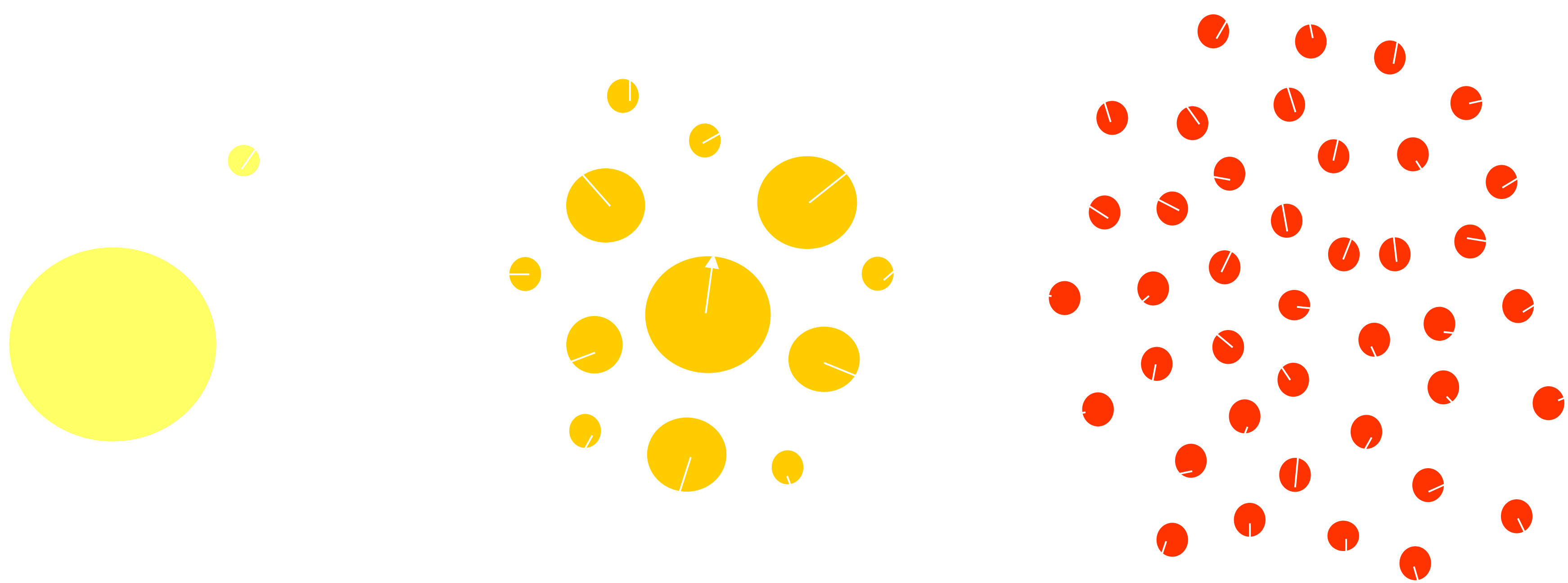
50<E_{inc}<100 MeV/nucl.



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

Evaporation | Multifragmentation | Vaporization

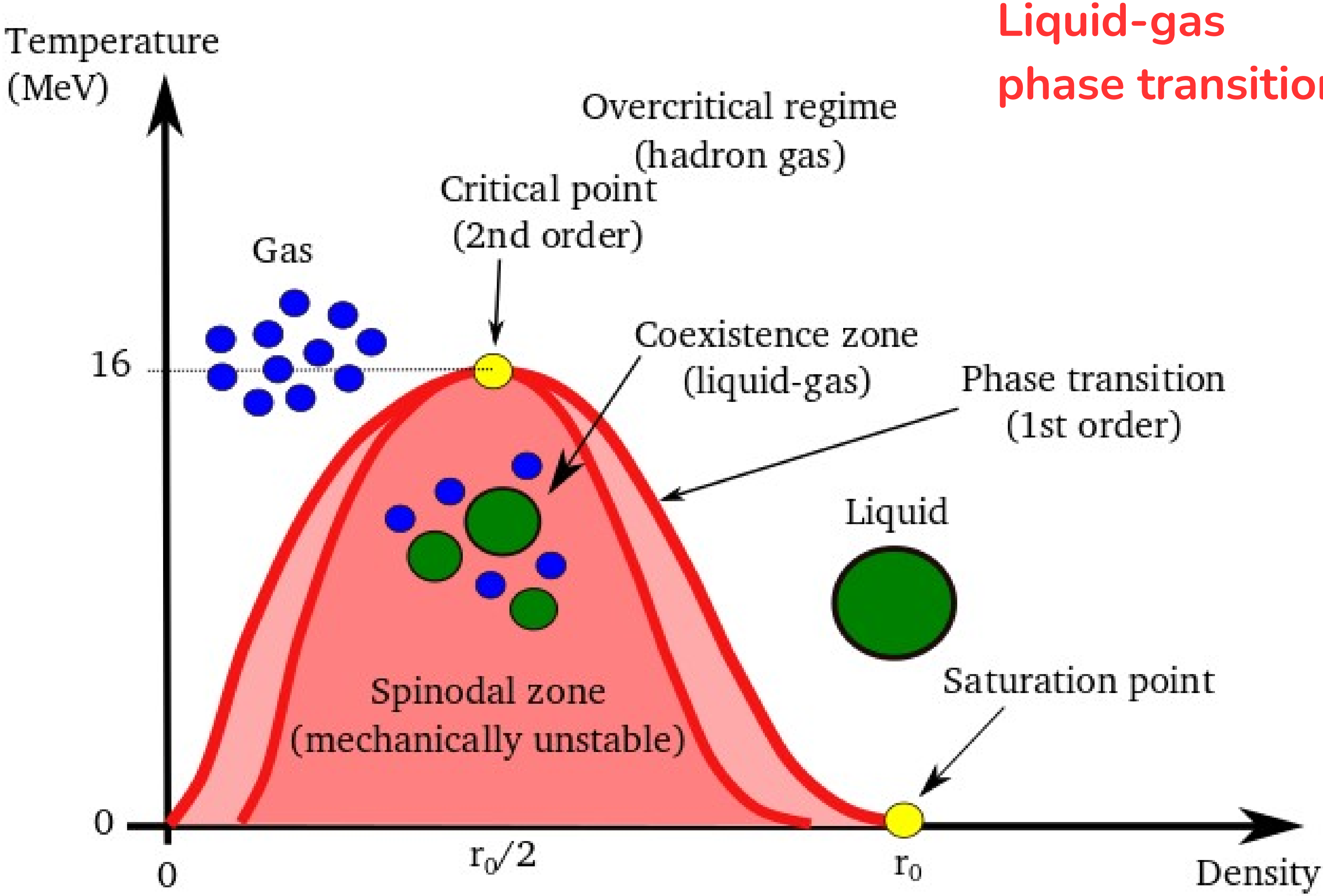
E*/A (MeV)



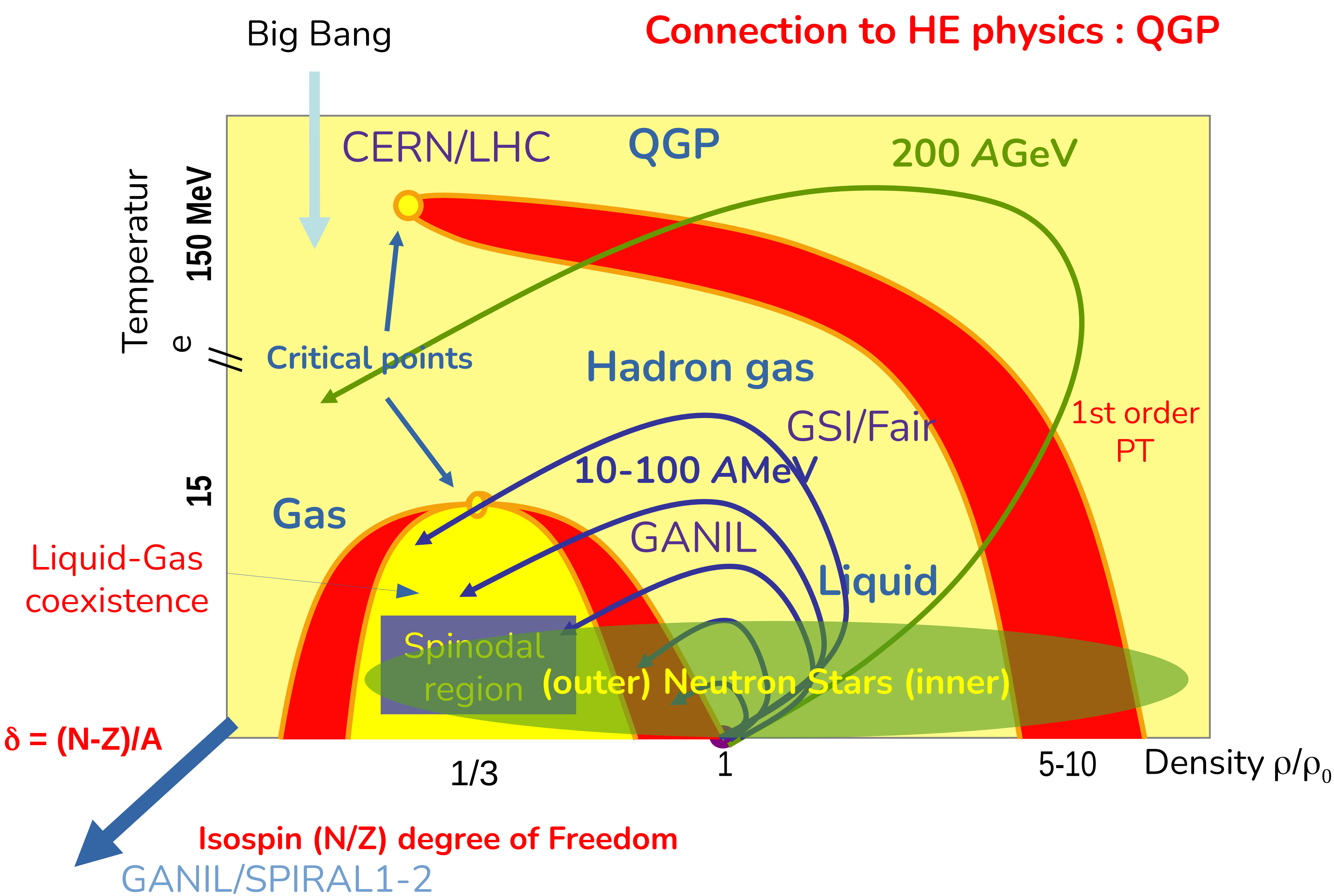
Evaporation	Multifragmentation	Vaporization
$\rho \sim \rho_0$	$\rho < \rho_0$	$\rho << \rho_0$
T < 5 MeV	T= 5-10 MeV	T>10 MeV

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

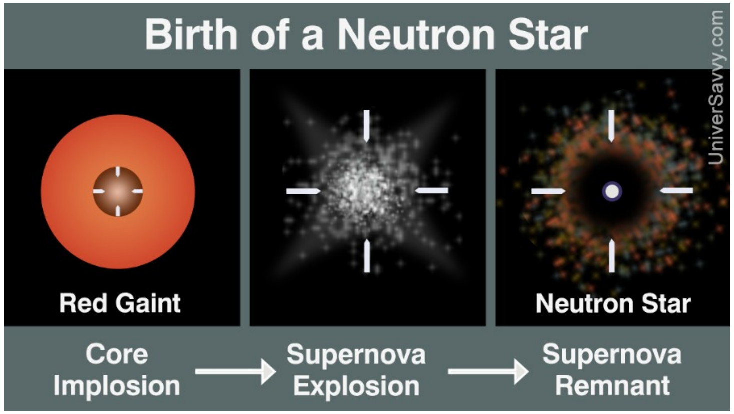
Nova Monocerotis V838, Licorne
May - December 2002
Hubble Telescope (NASA)

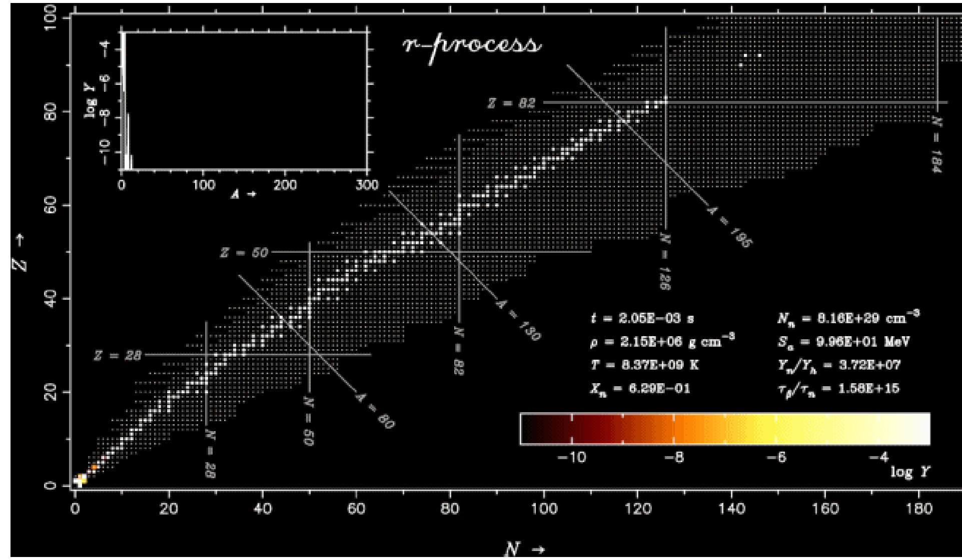
$E = 10^{38}$ J , L x 1000 !

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)

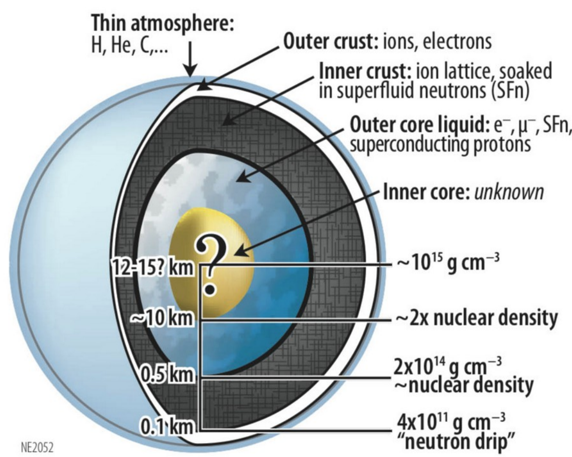
Detection of *GW* and multi-messenger observables (GW170817) considerably reinforces terrestrial *EOS* studies

Core Collapses Sne

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

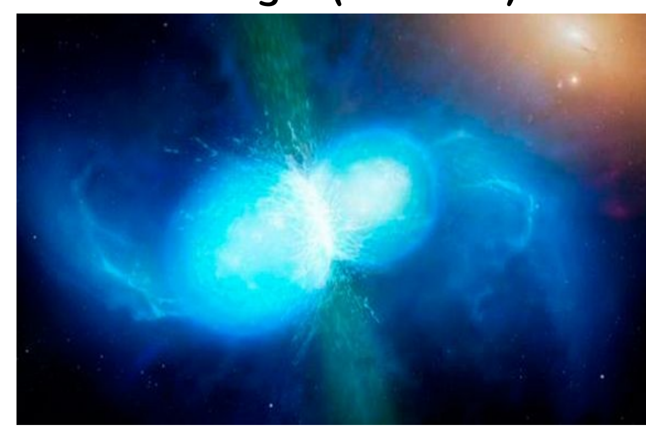
NS structure :

- 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)



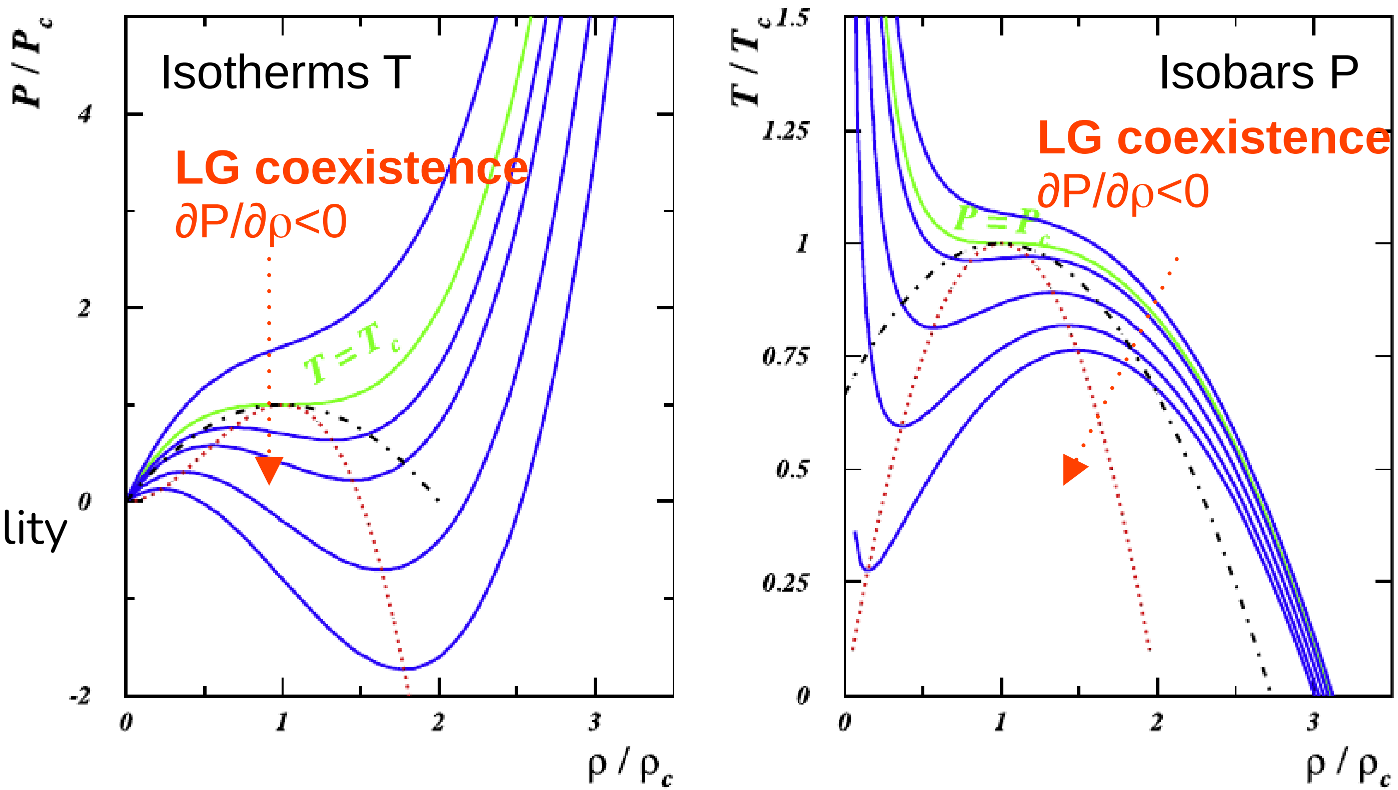
Equation of State of nuclear matter

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

Thermodynamical relation between state variables

Compressibility

$\partial P/\partial \rho$



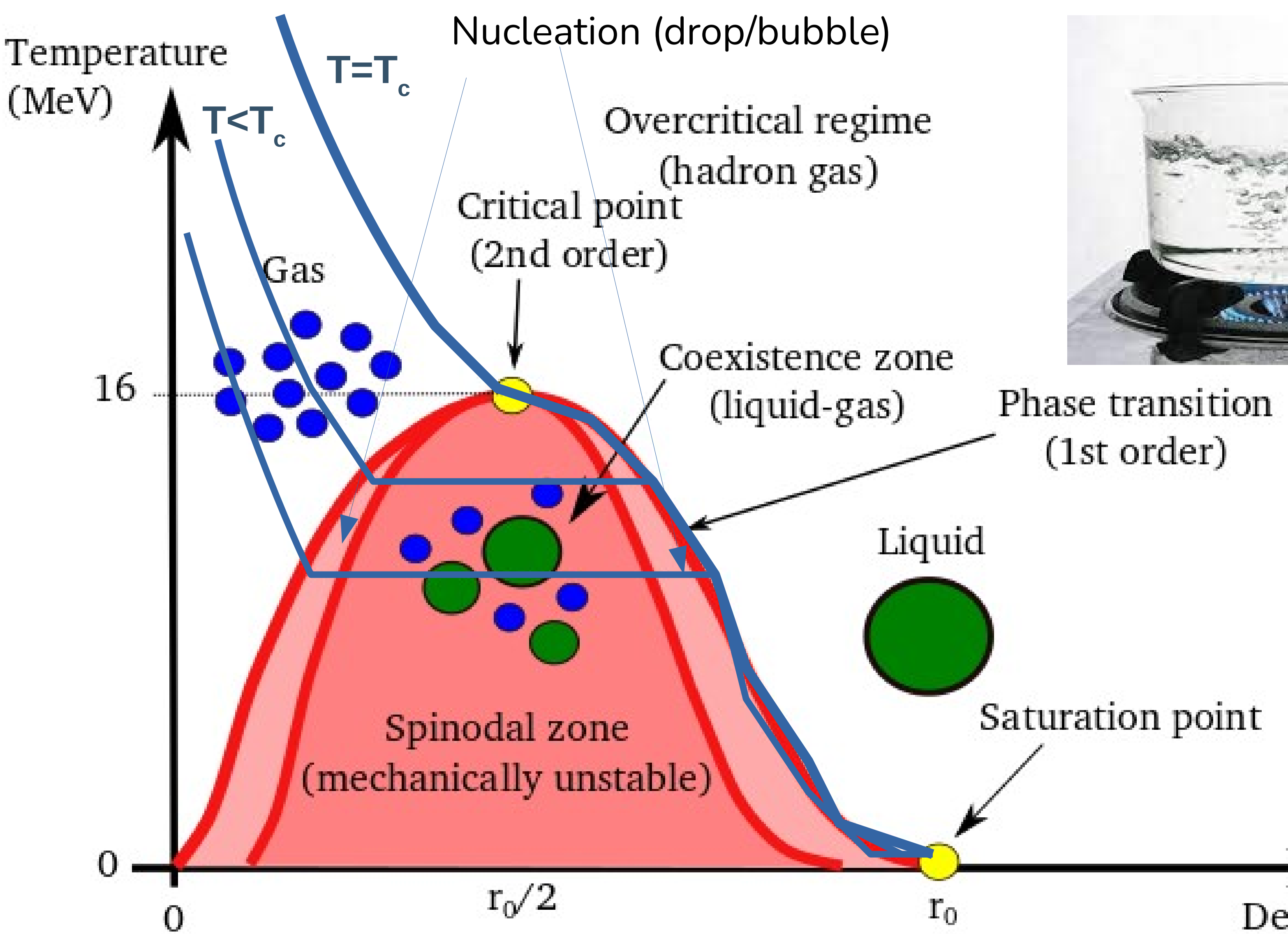
Skyrme HF at finite T

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

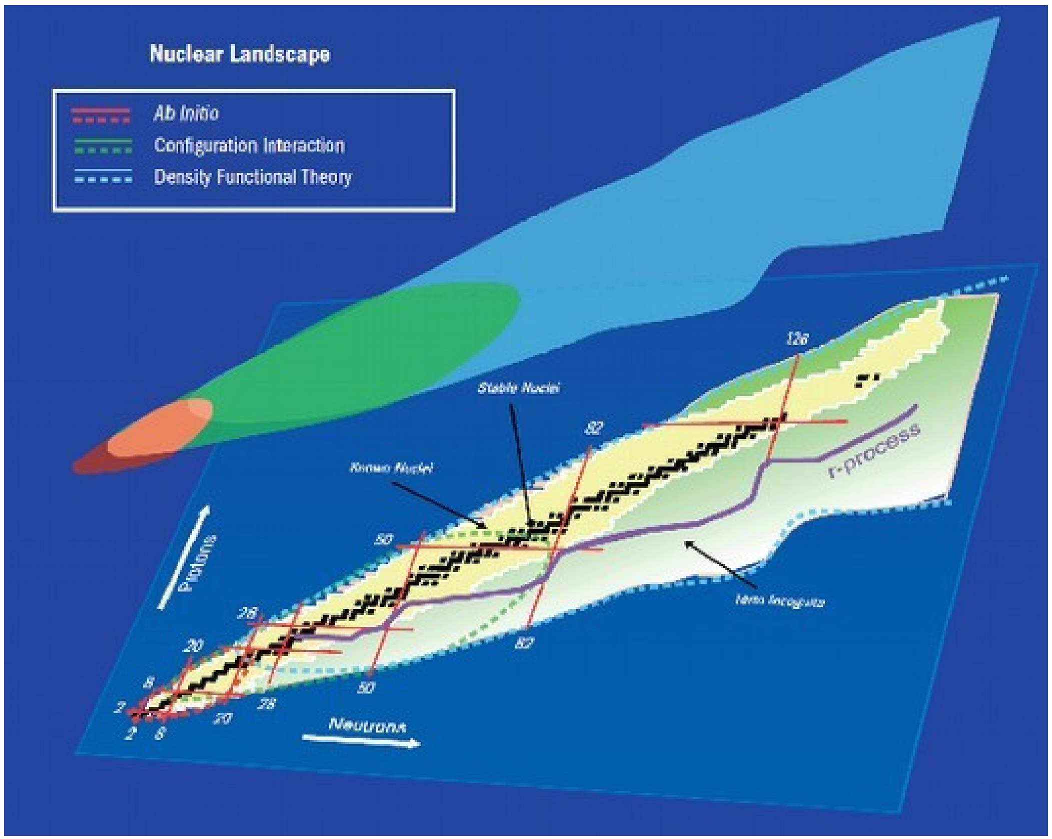
Non-extensive systems
(surface, Coulomb)

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

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

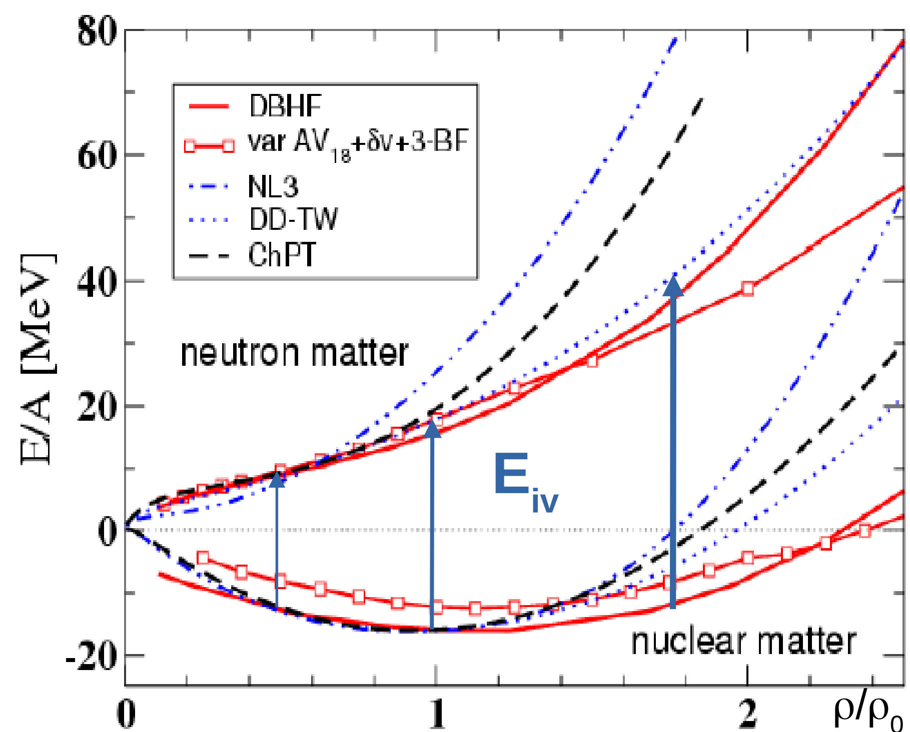
EoS in Nuclear Physics

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 (2^{nd} 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

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

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

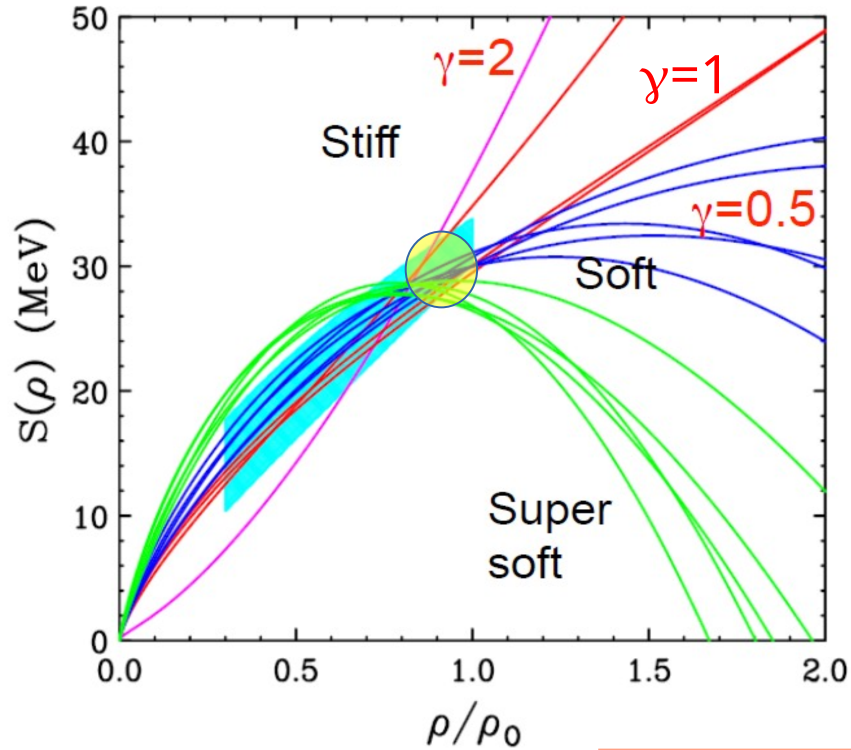
- Constraints for **Astrophysics** (NS) and for laboratory experiments
- Needed for **transport models** and nuclear matter studies (Thermodyn.)
- Link to the ***NN* interaction** (isovector) in the nuclear medium

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)

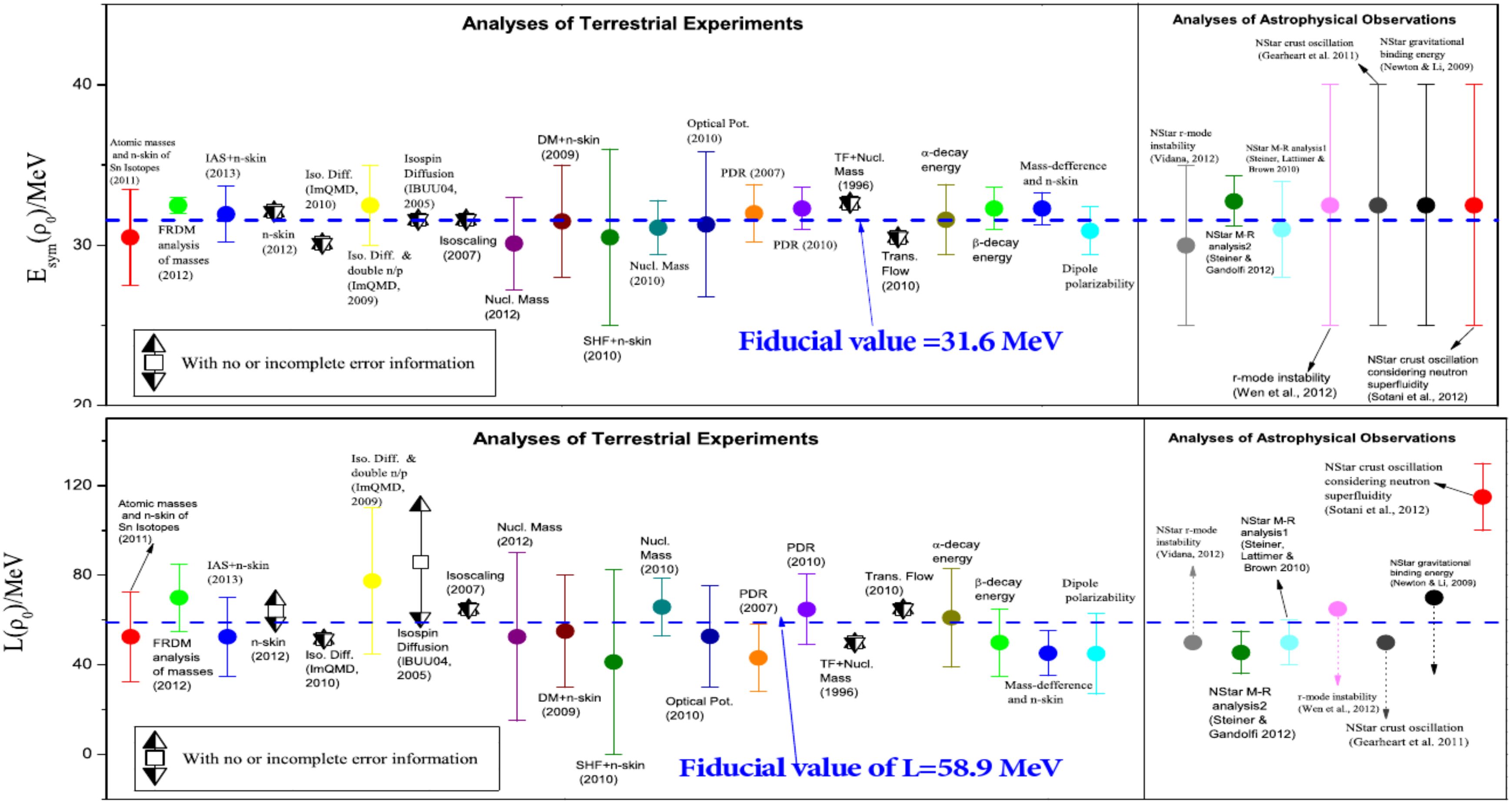


$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

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



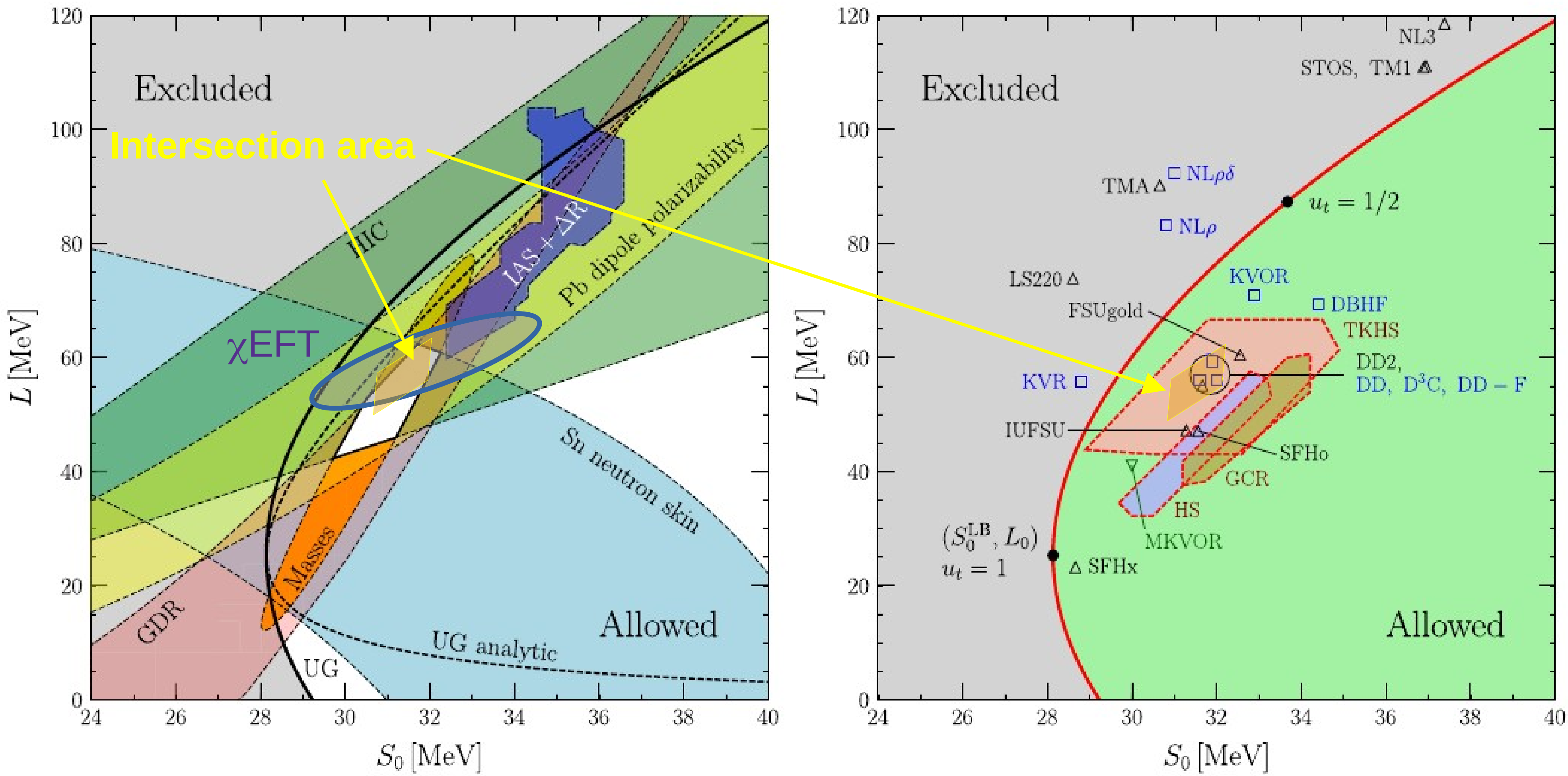
	~1%	~10%		~30%		???				
P_α	E_{sat} MeV	E_{sym} MeV	ρ_0 fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000

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

Symmetry Energy around ρ_0

Experimental constraints

Model predictions

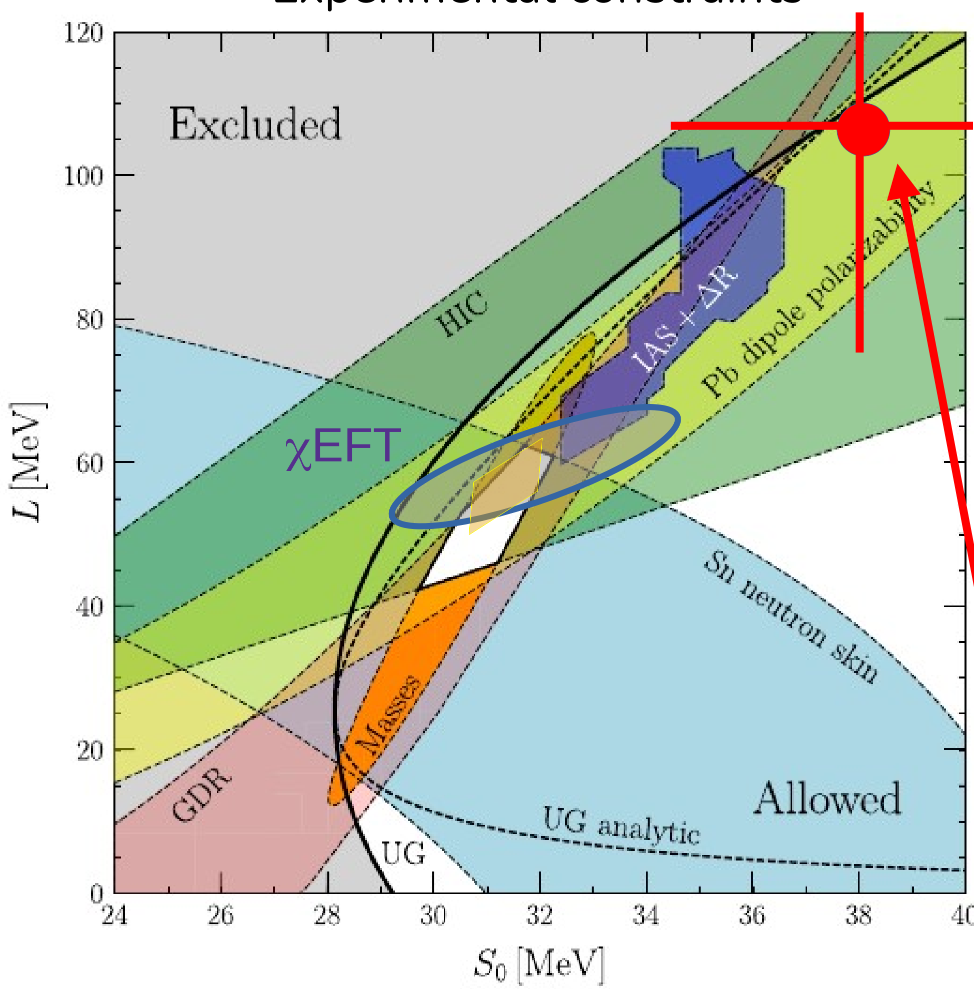


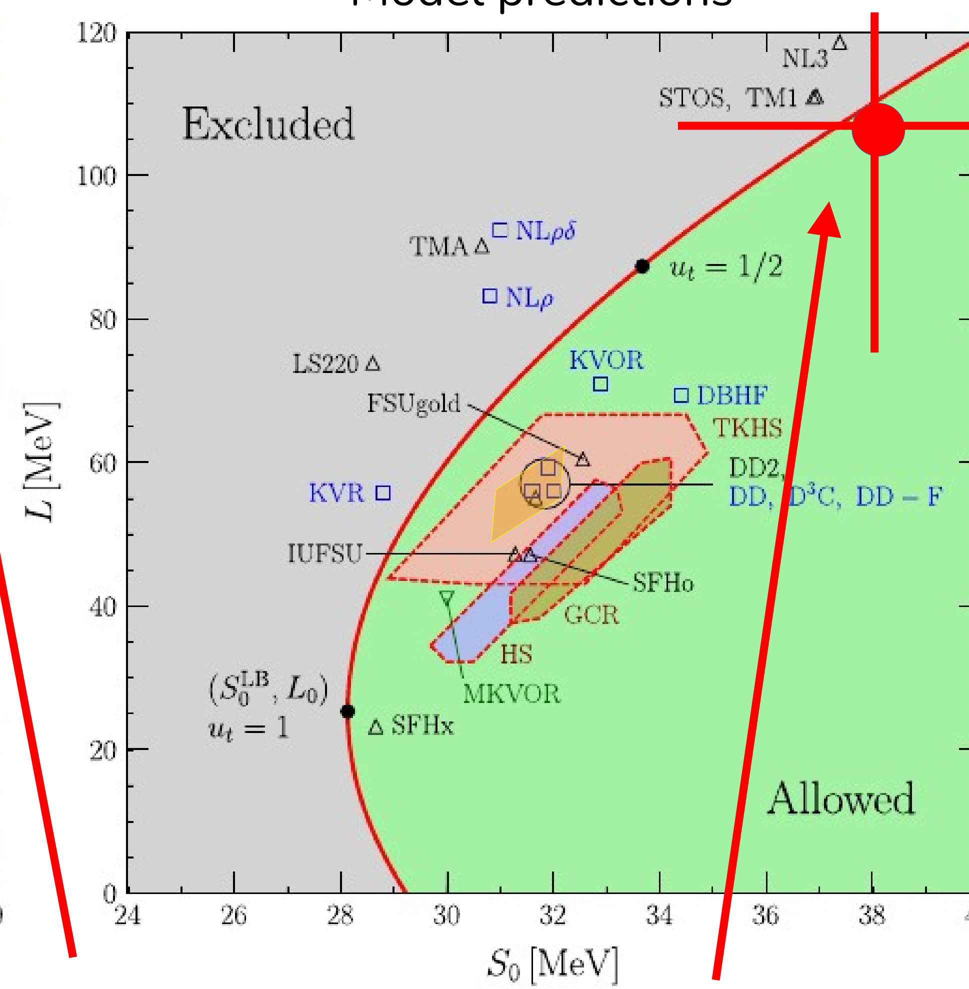
I. Tews *et al.*, Astroph. J. **848** (2017) 105

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





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

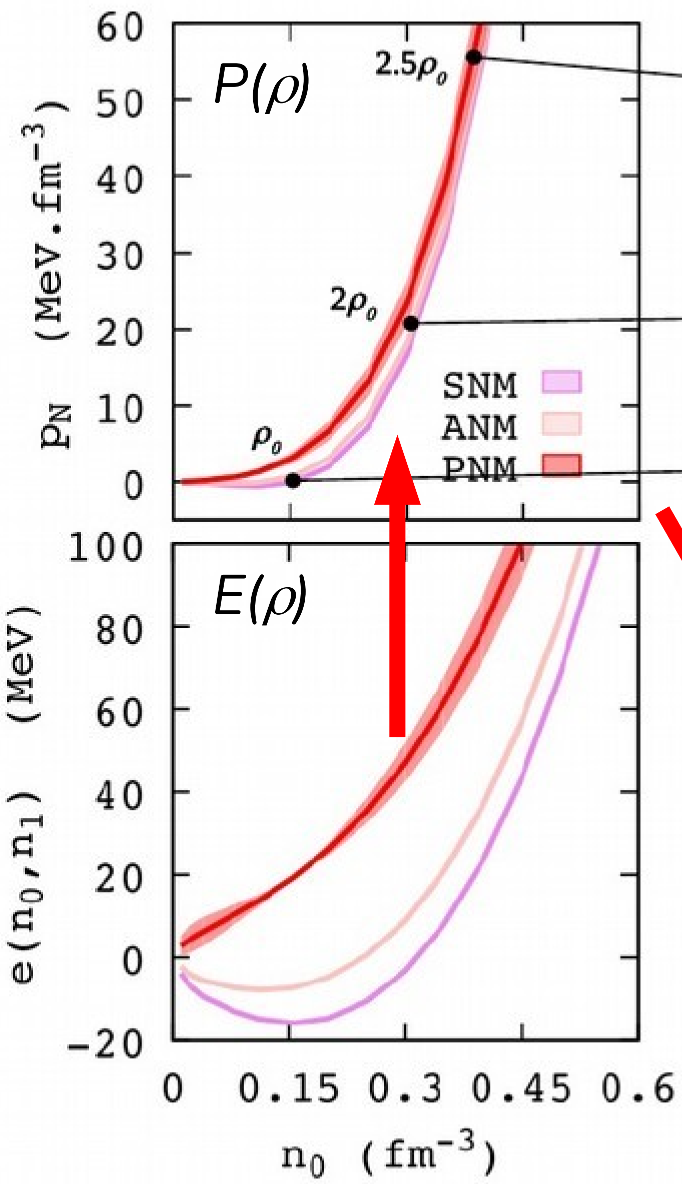
C. Drischler *et al.*, PRL **125** (2020) 202702

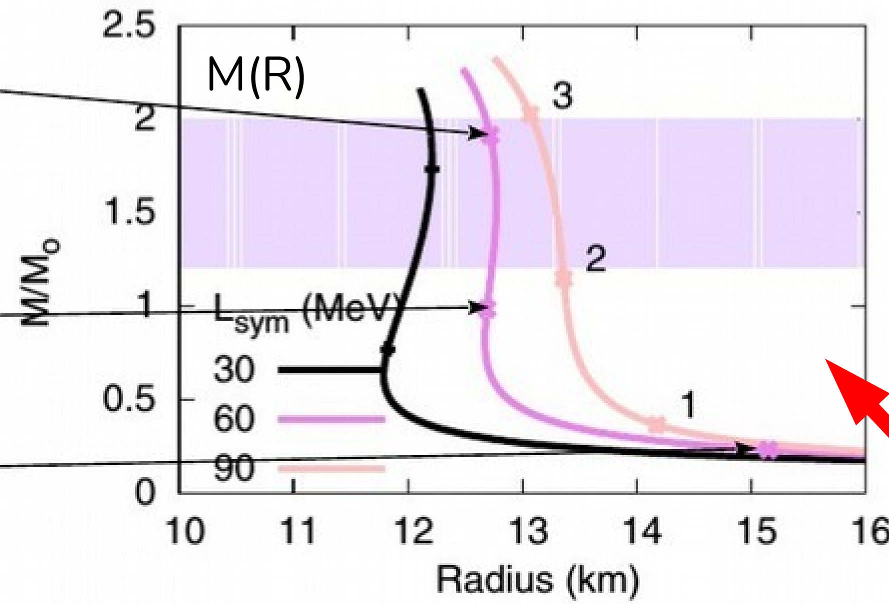
*PREX-2 , B. T. Reed et al., PRL **126** (2021) 172503*

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

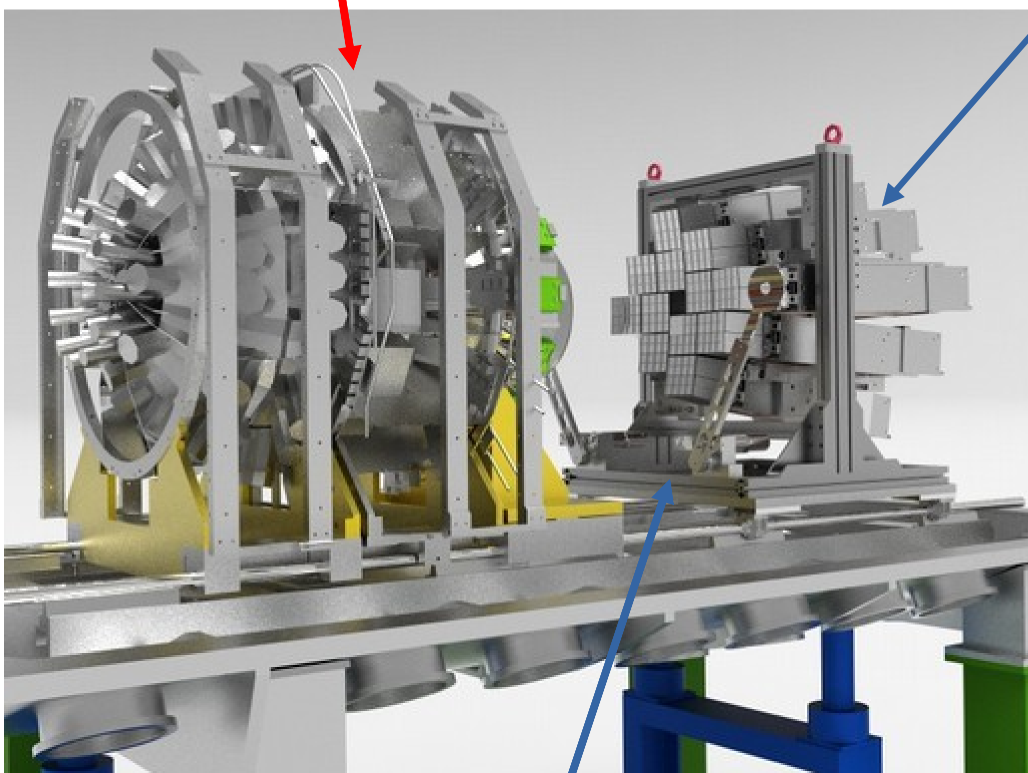
Coupling FAZIA demonstrator with INDRA@GANIL

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

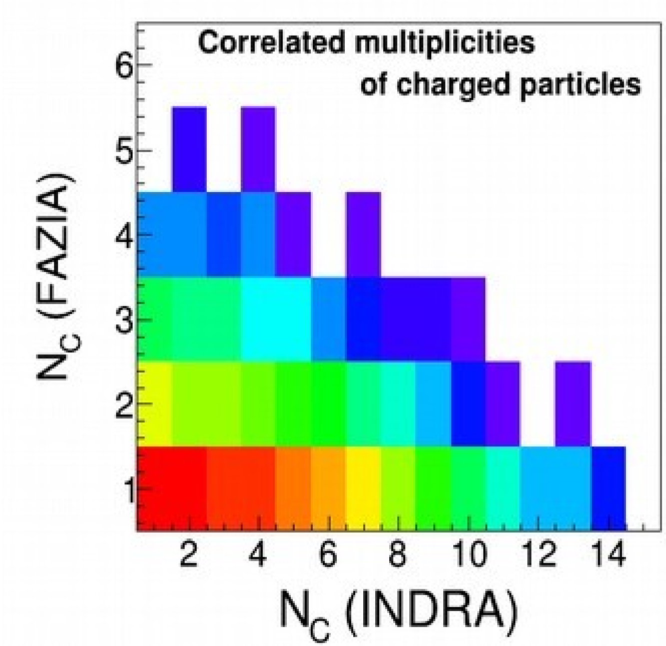
INDRA in *D5*

- \- 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*



Beam Tests in June-July 2018

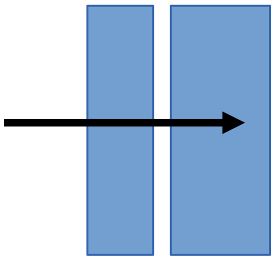


FAZIA demonstrator: *12* blocks of *16* telescopes
192 **High-Quality *Si-Si-CsI*** telescopes
from *2* to *14* deg. + dedicated **Full Digital Electronics**

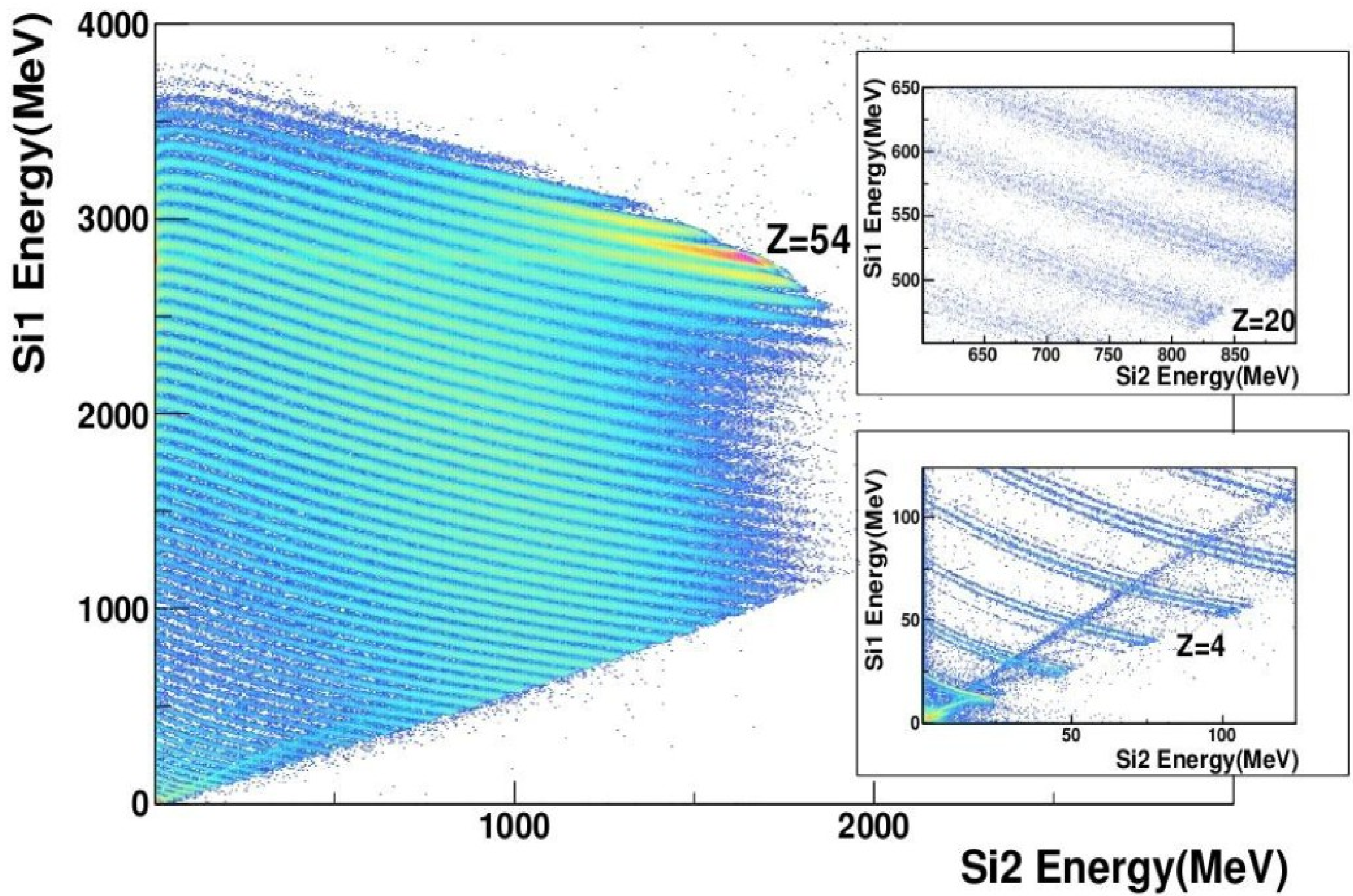
Experiment E789 performed at GANIL in April-May 2019 :

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

FAZIA : ΔE-E identification



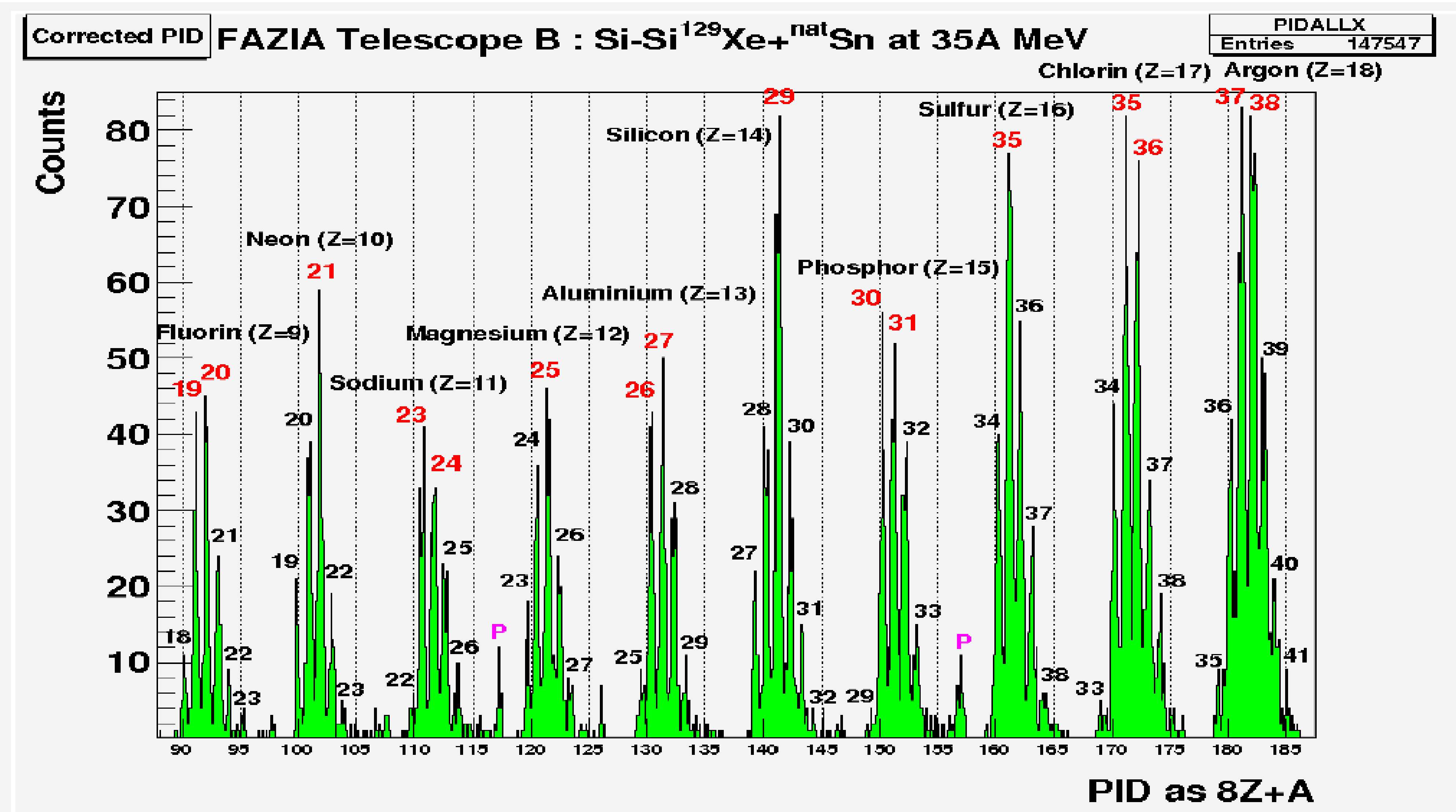
Some results at the end of phase 1: ΔE(Si1) – E (Si2)



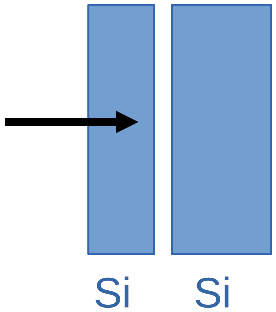
S.Carboni et al., NIMA 664 (2012) 251   *Energy = max of shaped signal (trapezoidal filter)*

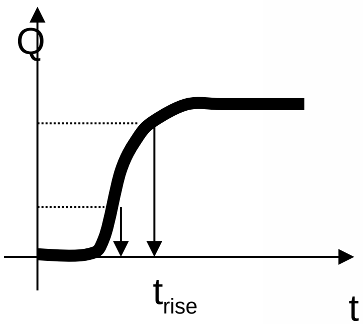
FAZIA improvements for ΔE-E identification

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

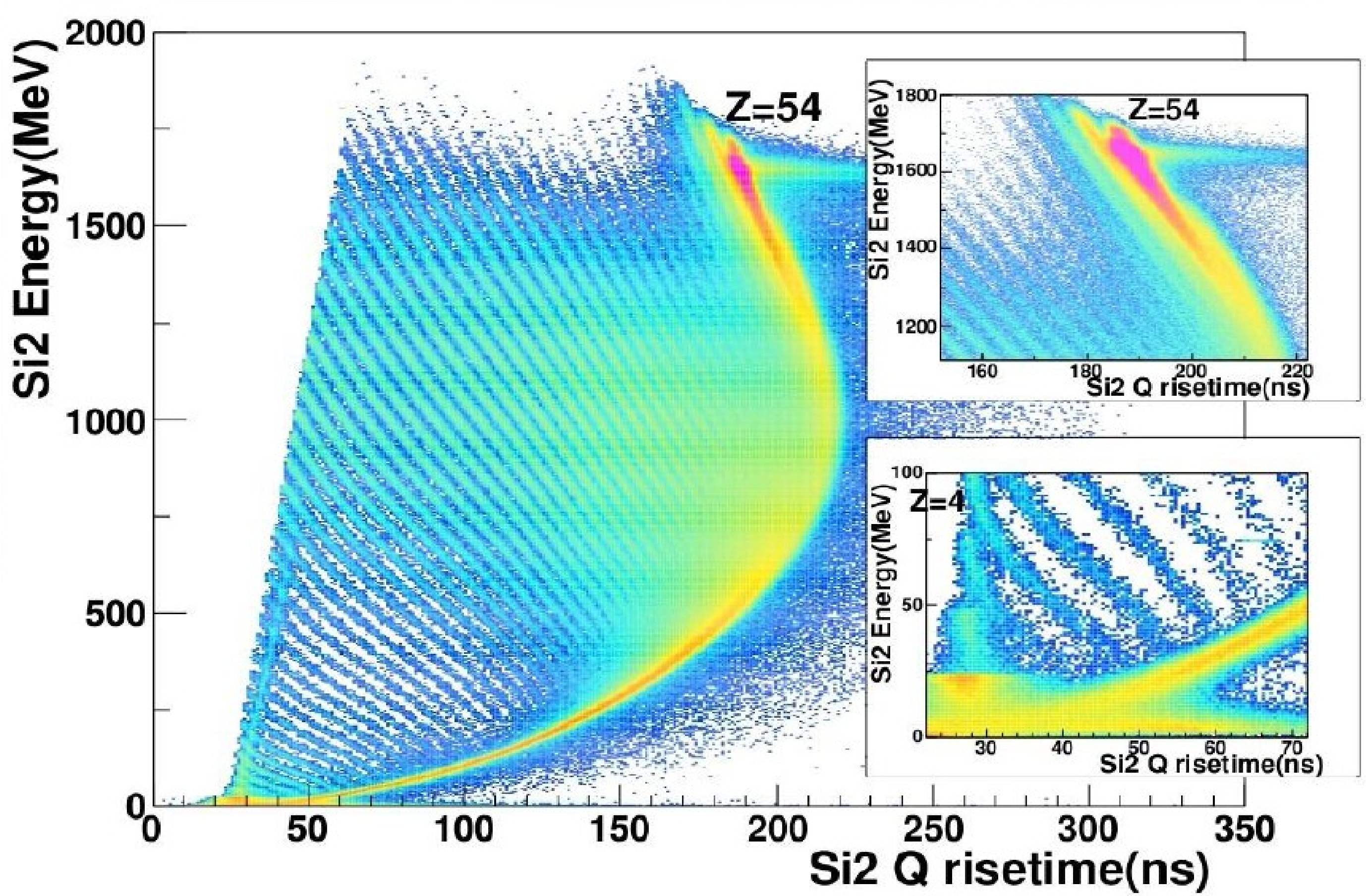


FAZIA : Pulse Shape Analysis



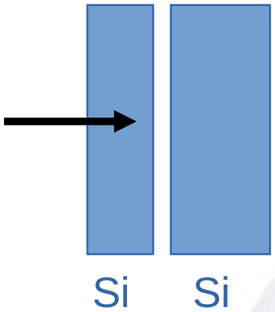


Some results at the end of phase 1:
Pulse Shape Analysis from E – Charge Rise Time



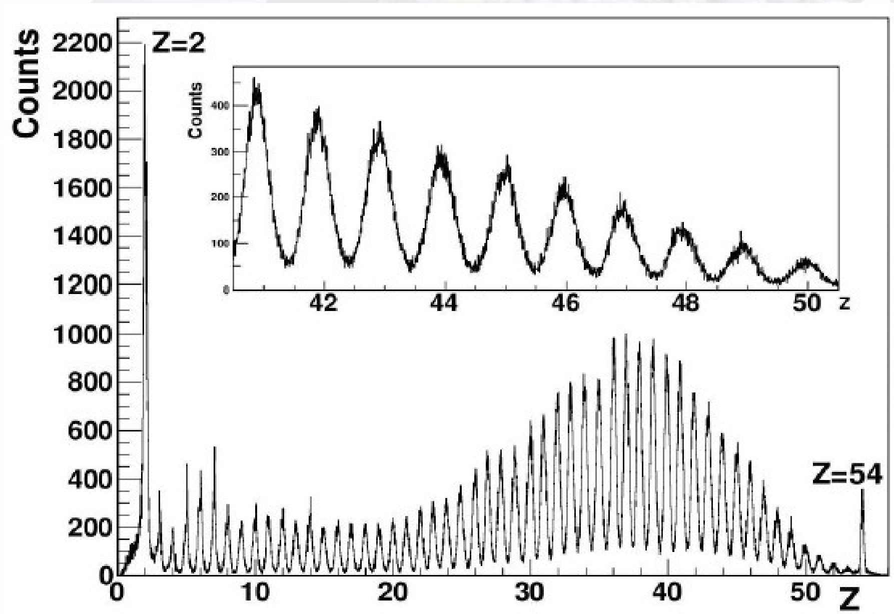
S.Carboni et al., NIMA 664 (2012) 251

FAZIA : Pulse Shape Analysis

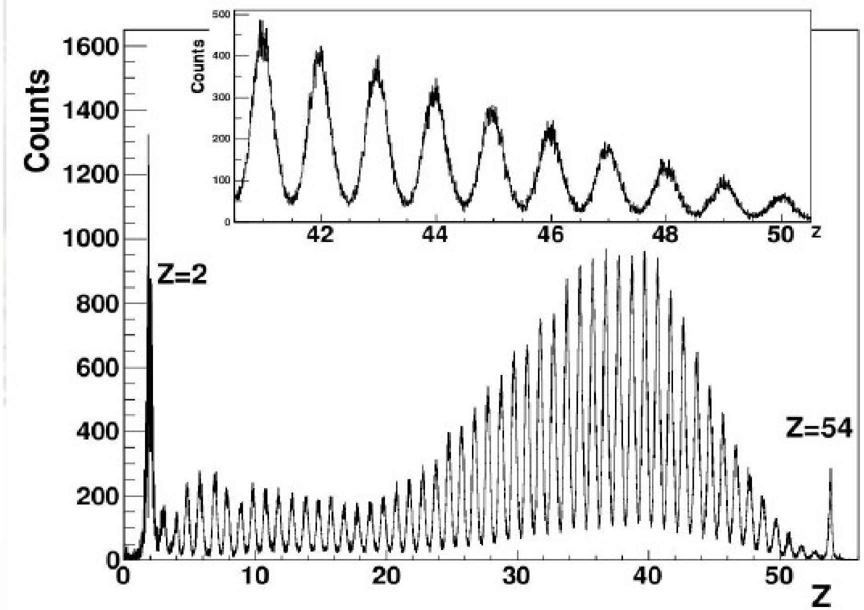


Some results at the end of phase 1:
Particle Identification from Pulse Shape Analysis

Energy vs. charge rise time



Energy vs. maximum of current signal

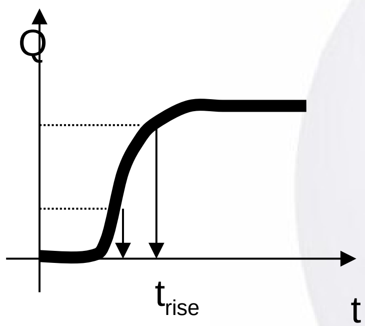


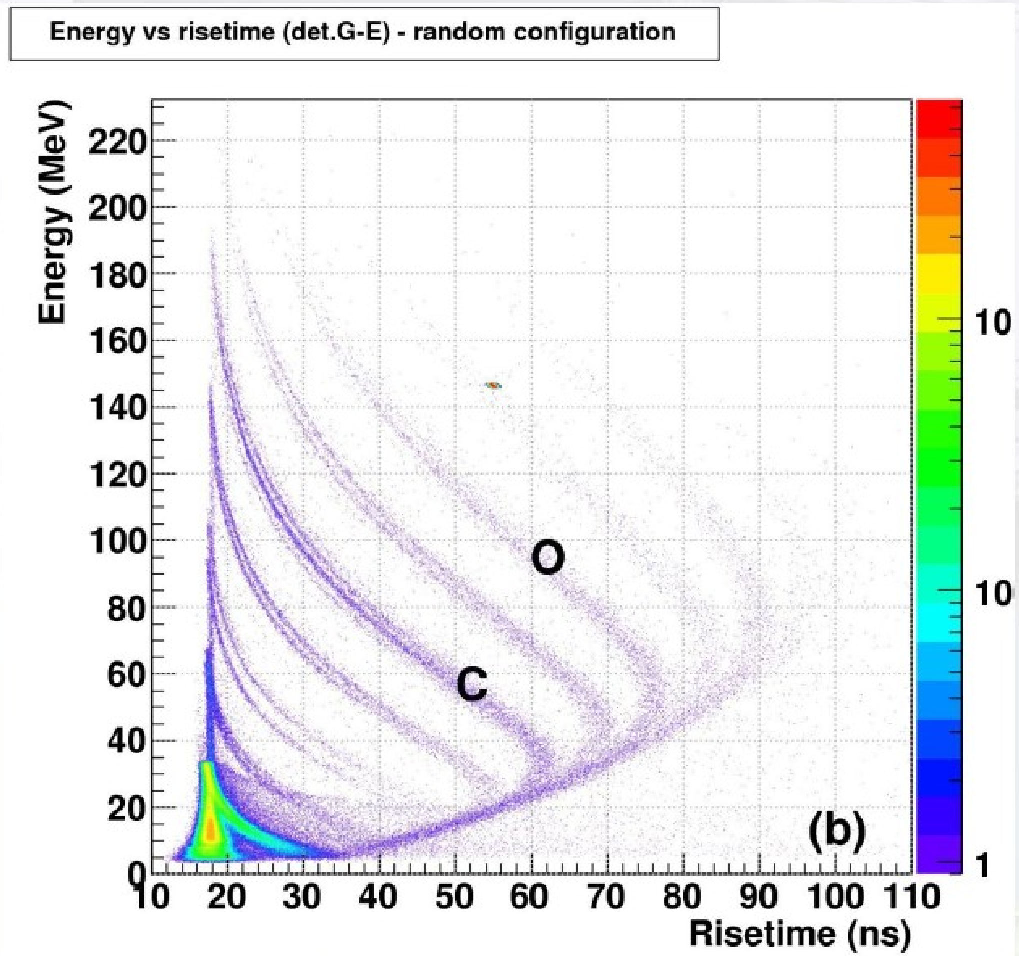
➢ *Z* identification can be achieved in the **first Silicon** detector

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



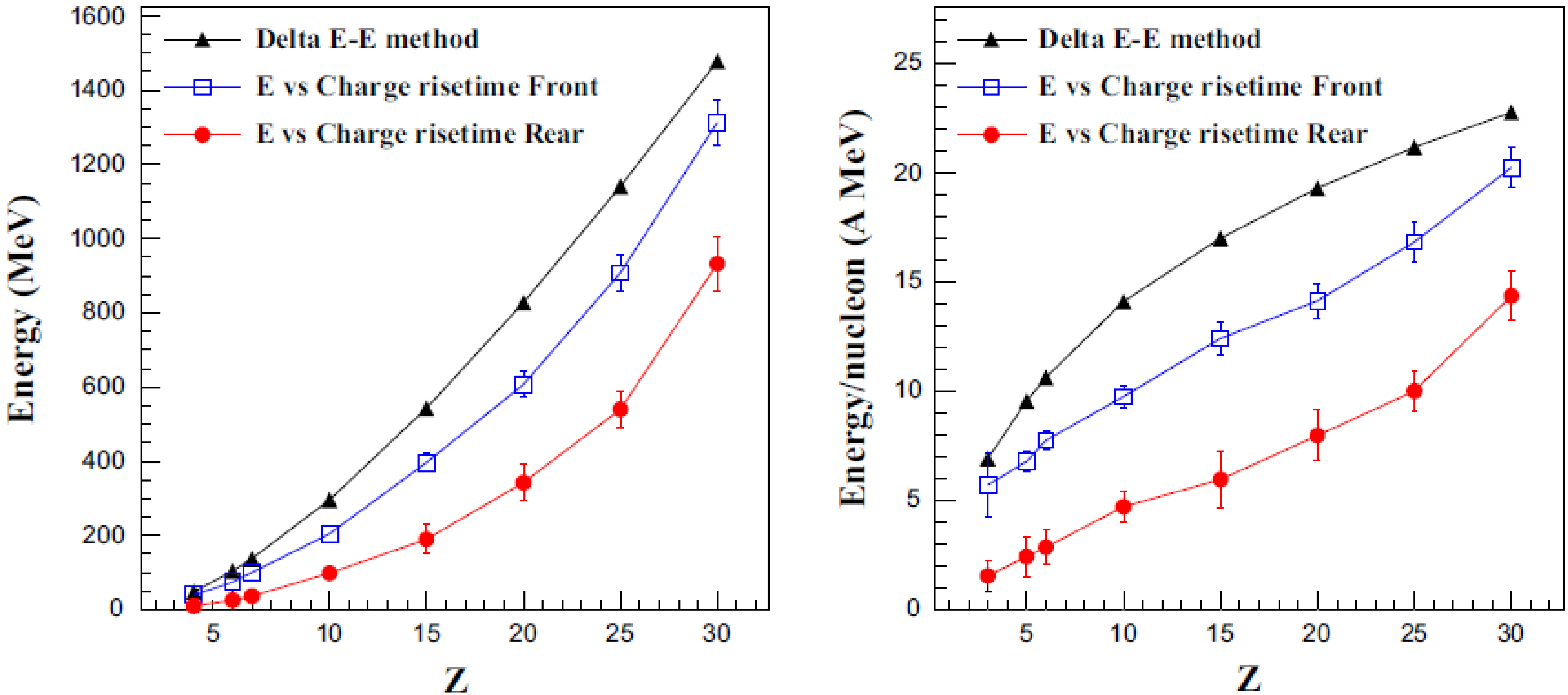


High gain
^{32}S beam@473MeV

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)

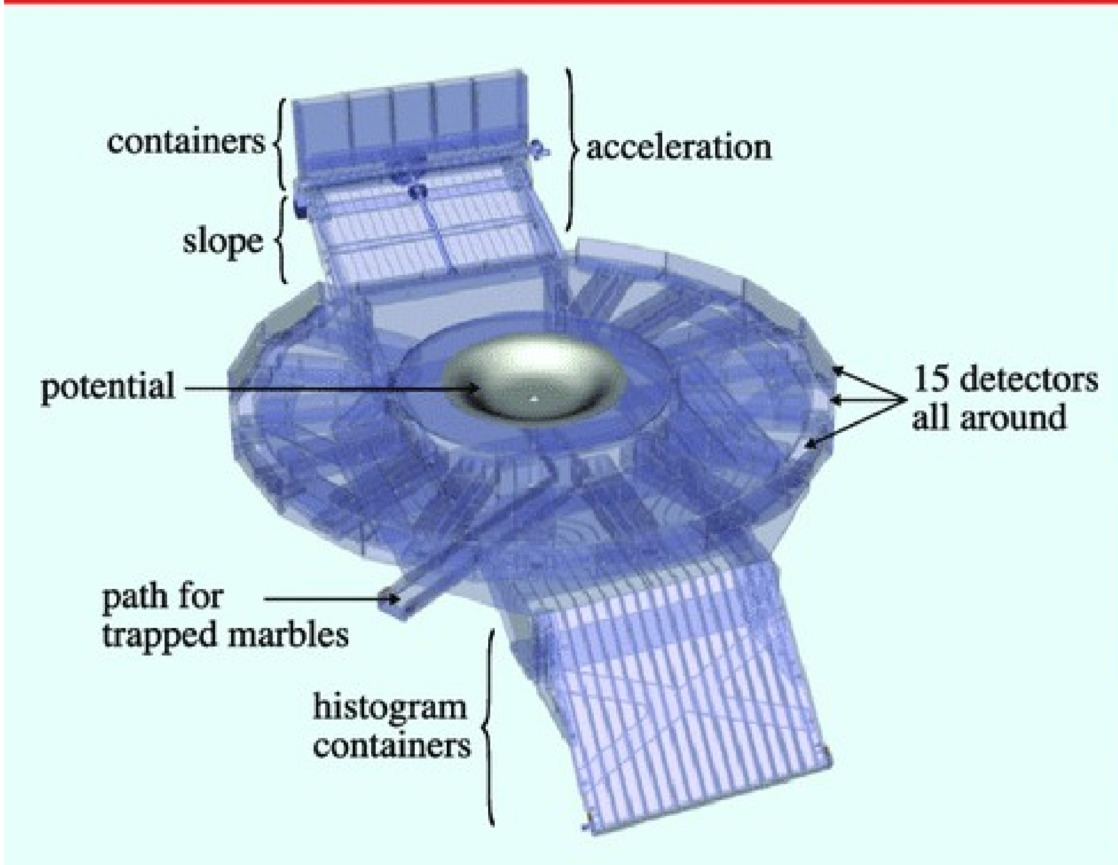
- R. Bougault *et al.* (FAZIA Collaboration) Eur. Phys. J. A 50 (2014) 47

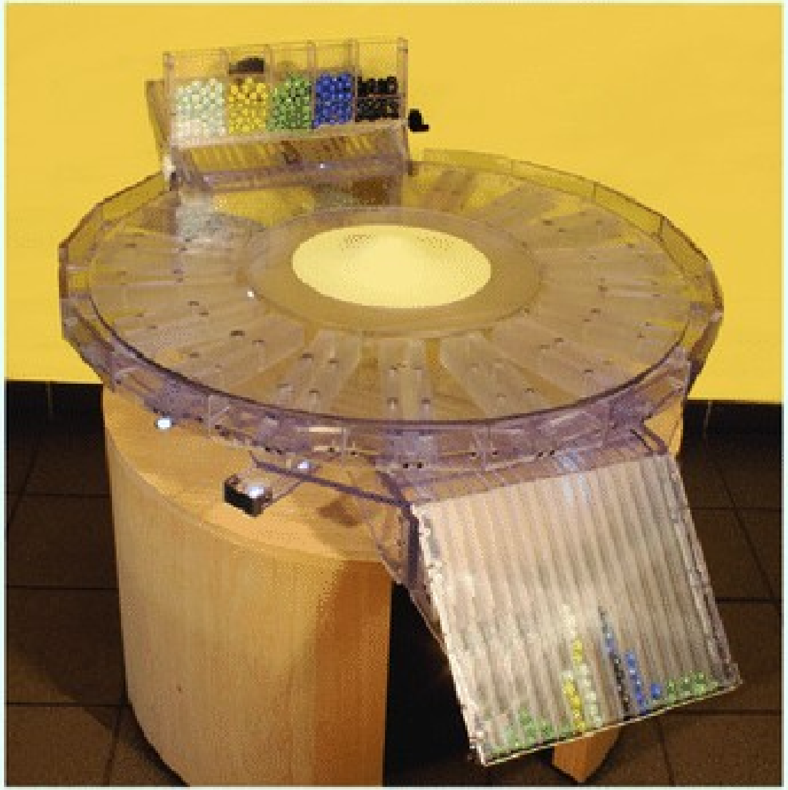
More infos and also scientific outreach contents :

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/



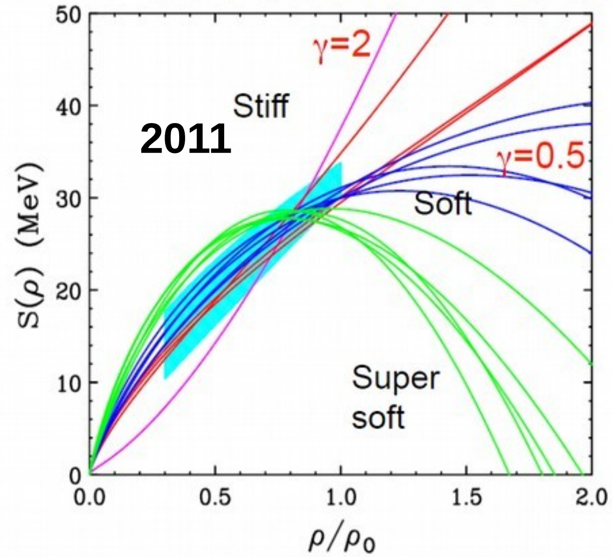


https://youtu.be/_KcK-jS2QQQ

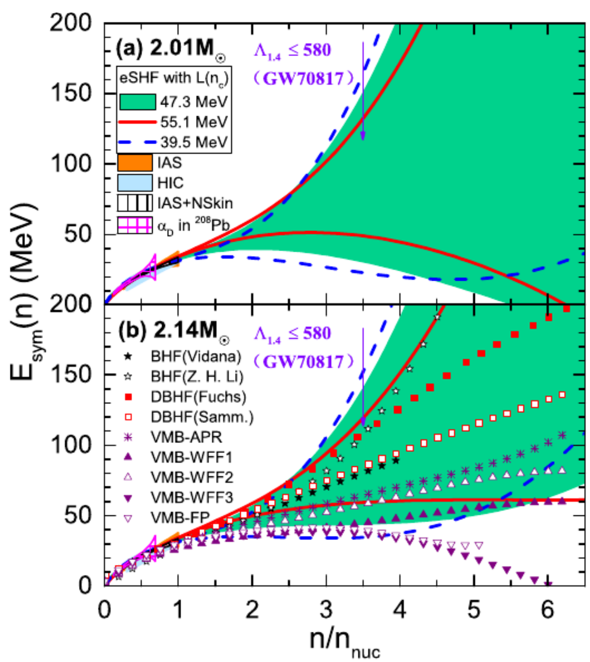
A. Chapon, J. Gibelin, O. Lopez, D. Cussol, D. Dominique Durand, Ph. Desrues, H. Franck De Préaumont, Y. Lemière, J. Perronnel, and J.C. Steckmeyer. *The Billotron: a way to experimentally apprehend the subatomic world*. Physics Education, 50(4):453, 2015. doi: 10.1088/0031-9120/50/4/453. URL http://hal.in2p3.fr/in2p3-01177619.

Symmetry Energy around ρ_0 (II)

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



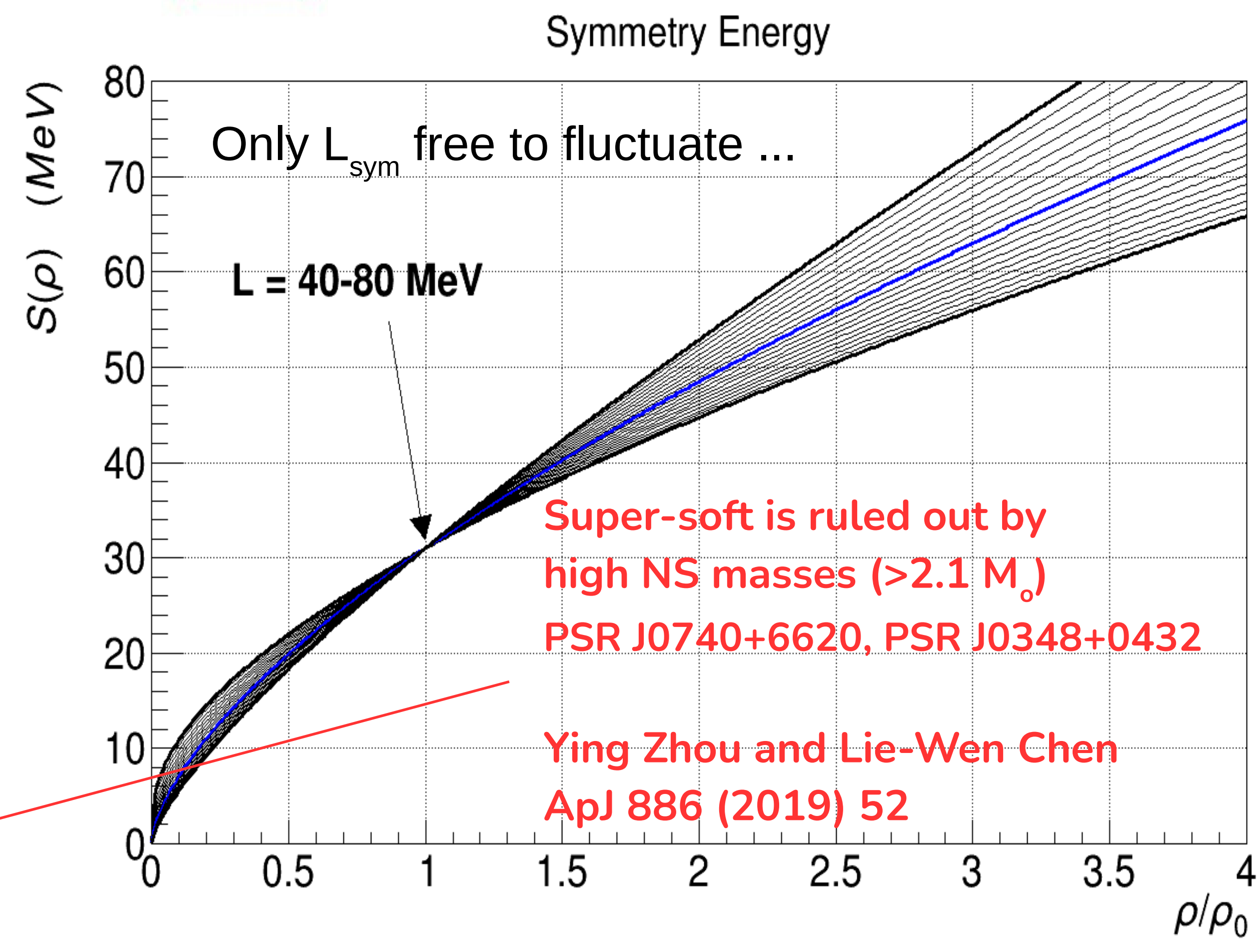
$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$



~30%

L_{sym} MeV
60 ±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