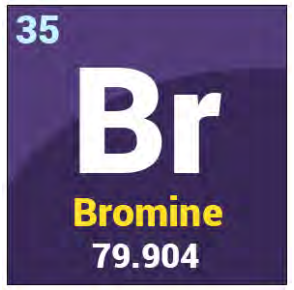
25e Congrès Général
de la Société Française
de Physique

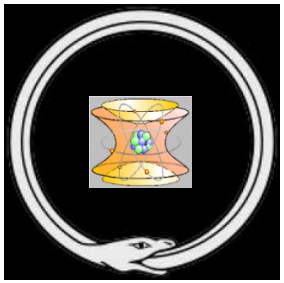
L'origine des éléments

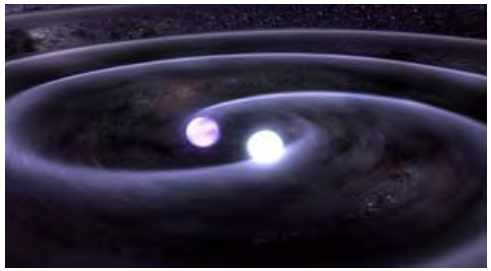
et d'autres implications de la détection des ondes gravitationnelles pour la physique nucléaire

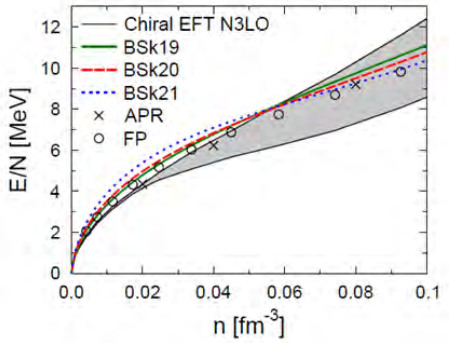
David Lunney – CSNSM (IN2P3/CNRS) – Université de Paris Sud, Orsay

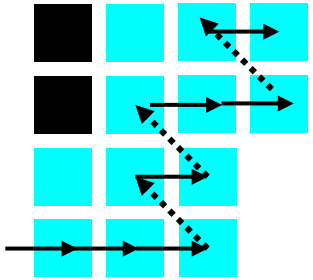
- **Les éléments – le processus *r***
- **GW170817 et son kilonova**
- **Etoiles à neutrons et l'EOS**





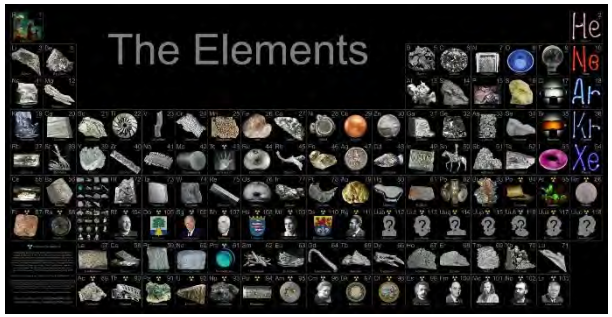


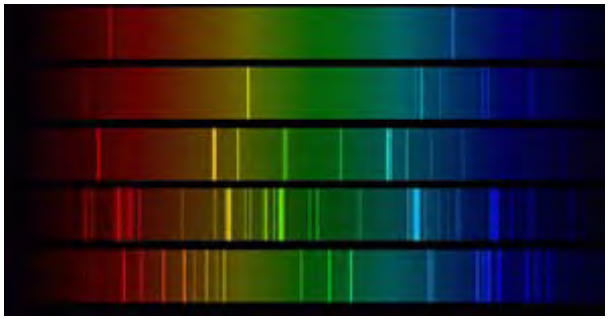




United Nations
Educational, Scientific and
Cultural Organization

International Year
of the Periodic Table
of Chemical Elements





nature
International journal of science

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NEWS FEATURE · 30 JANUARY 2019

Beyond the periodic table

150 years after Mendeleev organized the elements by their characteristics, a special issue explores the enduring influence of this scientific masterpiece.

New elements
Z = 113, 115, 117, 118
(see poster [136] by Z. Favier)

3. How were the heavy elements made?

precise origin
of elements
to uranium
remains a
mystery

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

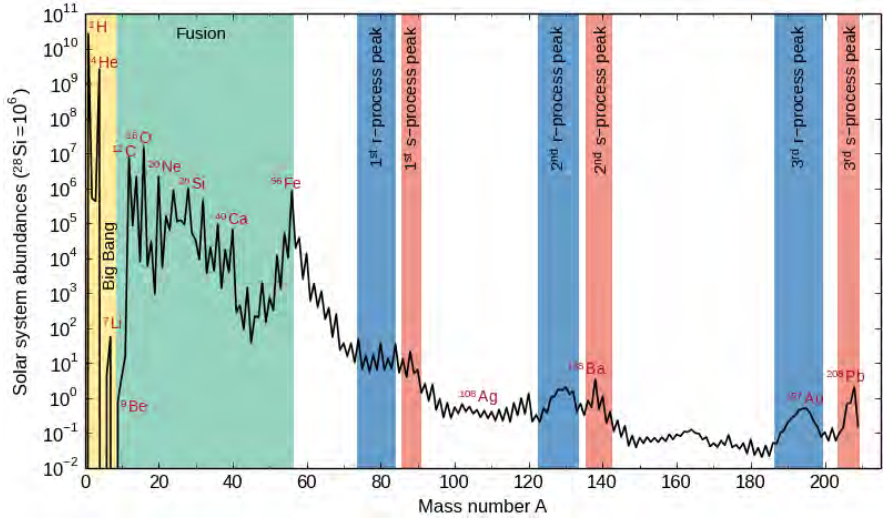
Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

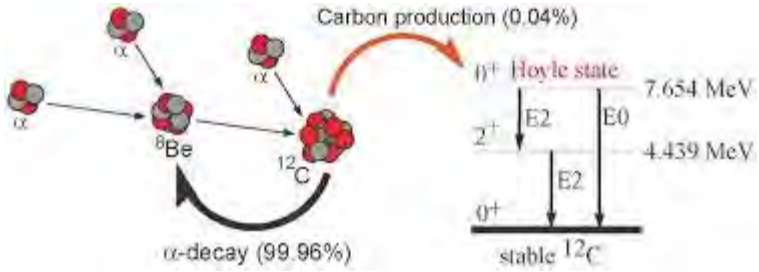
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

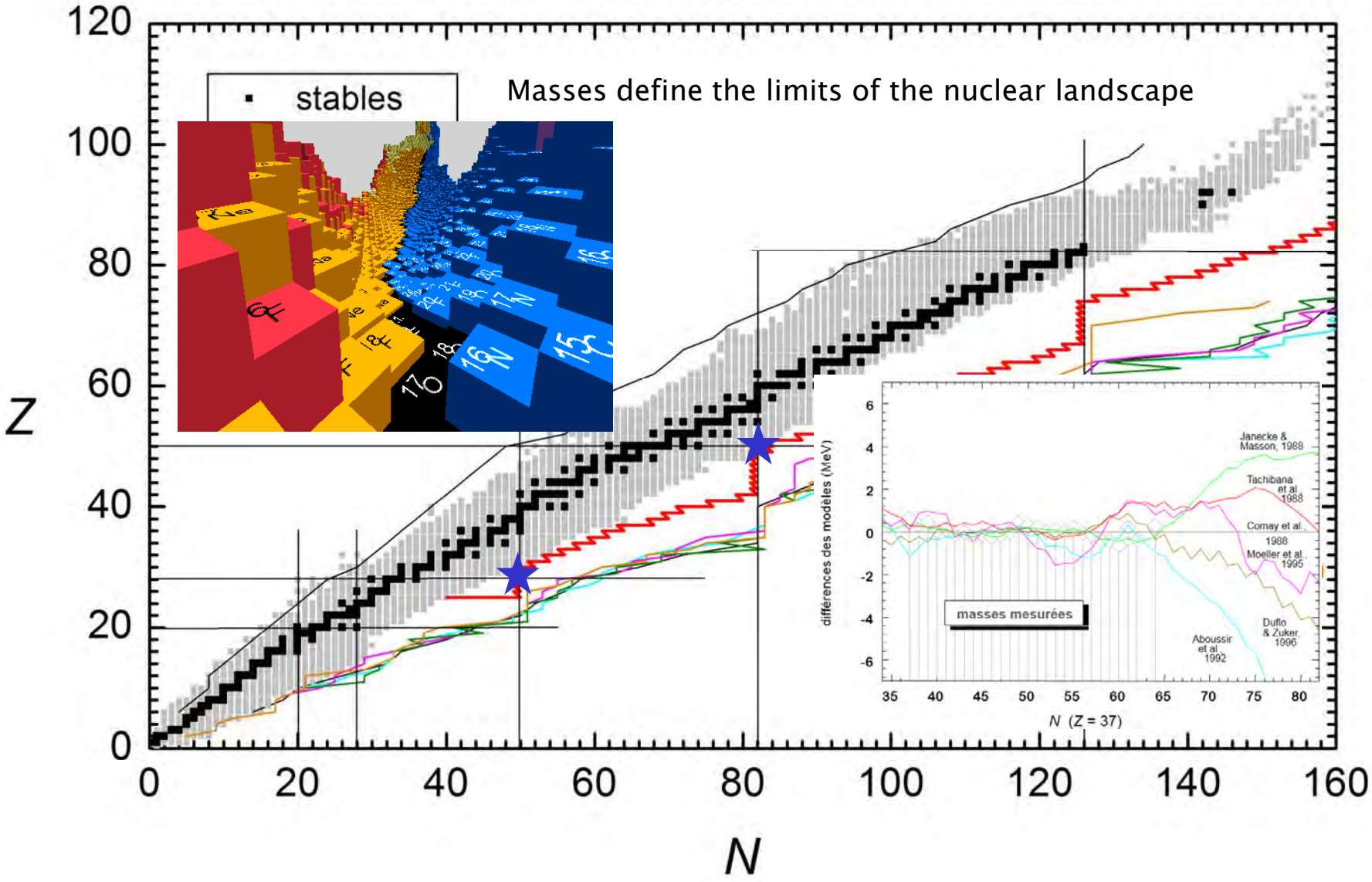
neutron-capture nucleosynthesis:
s process occurs in AGB stars
r process… supernovae? NS mergers?





REVIEWS OF MODERN PHYSICS, VOLUME 89, JANUARY–MARCH 2017

***Colloquium*: Status of α-particle condensate structure of the Hoyle state**


Masses define the limits of the nuclear landscape
stables
Z
N
différences des modèles (MeV)
masses mesurées
Janecke & Masson, 1988
Tachibana et al., 1988
Comay et al., 1988
Moeller et al., 1995
Duflo & Zuker, 1996
Aboussir et al., 1992
N (Z = 37)

stable isotopes
s-process path
r-process path
known masses
β^- decay path

p-isotope
s-isotope
r-isotope

$_{85}$At
$_{84}$Po
$_{83}$Bi
$_{82}$Pb
$_{81}$Tl
$_{80}$Hg
$_{79}$Au
$_{78}$Pt
$_{77}$Ir
$_{76}$Os
$_{75}$Re
$_{74}$W
$_{73}$Ta
$_{72}$Hf
$_{71}$Lu
$_{70}$Yb
$_{69}$Tm
$_{68}$Er

$(Z = 82)$

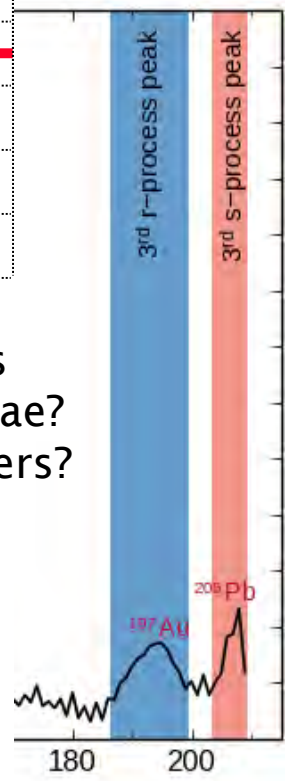
β decay

one / two
β-delayed
neutron decay

neutron number ⟶

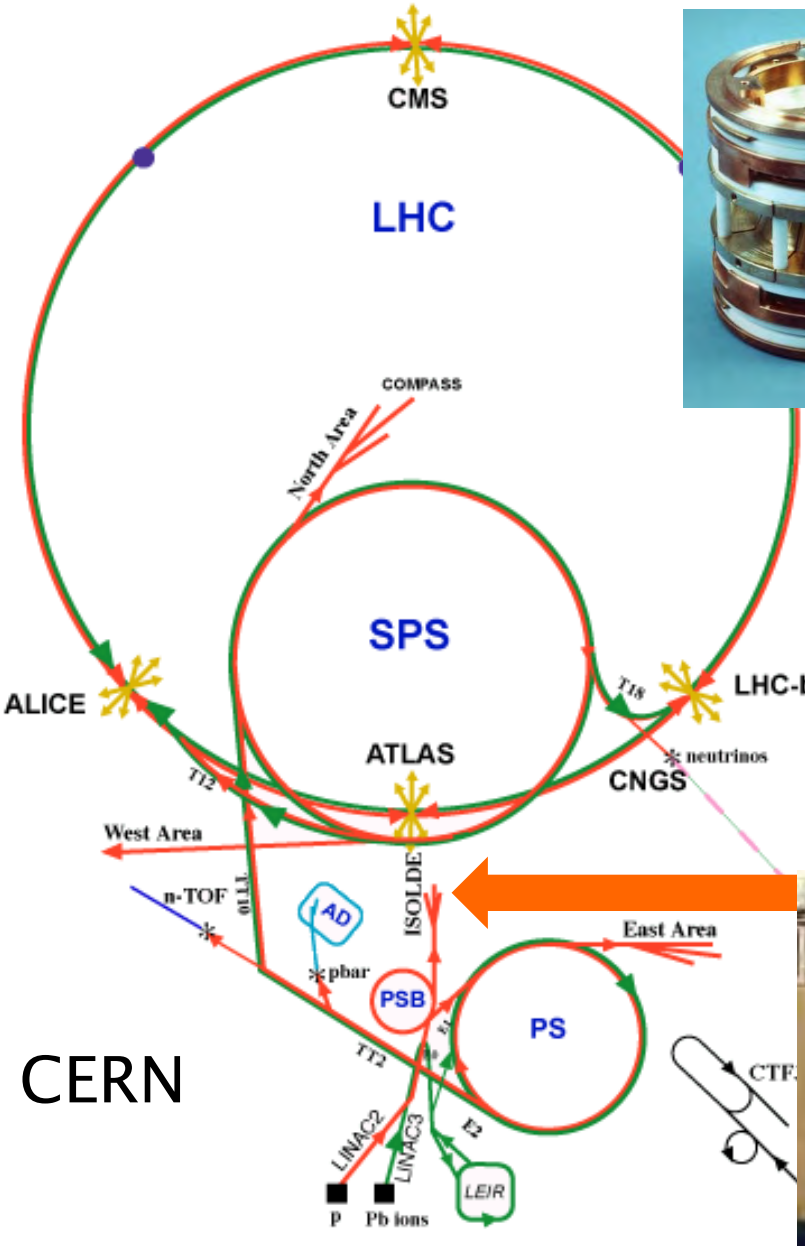
$N = 126$

s : AGB stars
r : supernovae?
NS mergers?
???

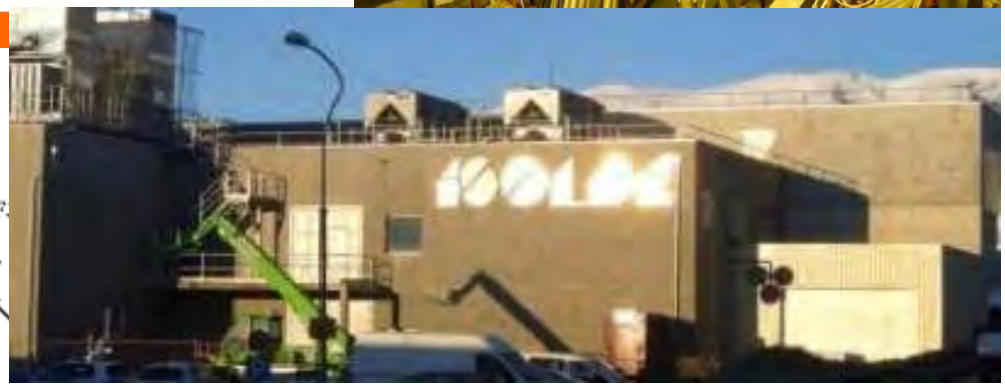


To model *r* process - nuclear physics must provide:
masses, half-lives, spins, energies, fission barriers…

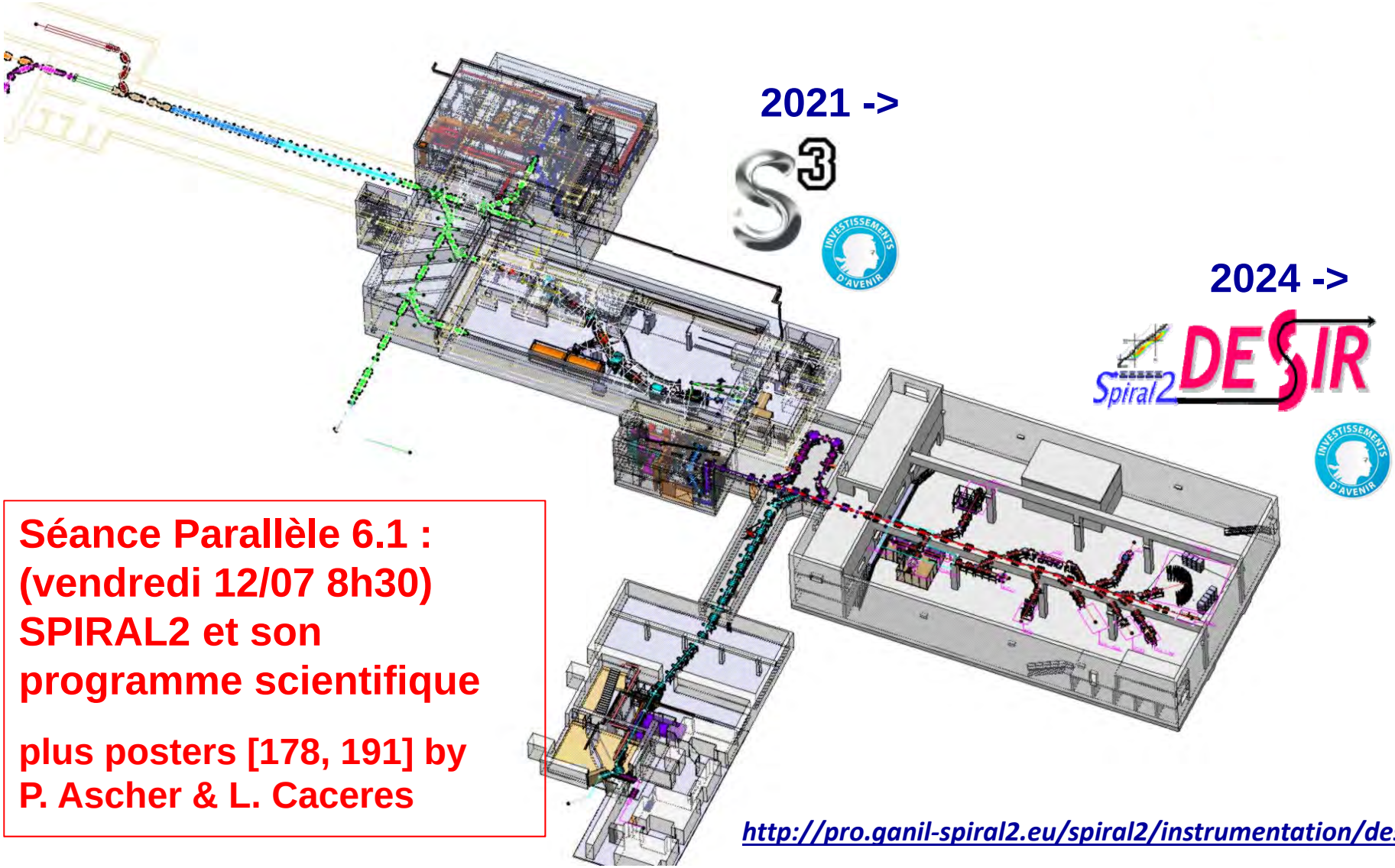
Masses from Penning-trap spectrometer ISOLTRAP (cern.ch\isoltrap) at ISOLDE (cern.ch\isolde)



CERN



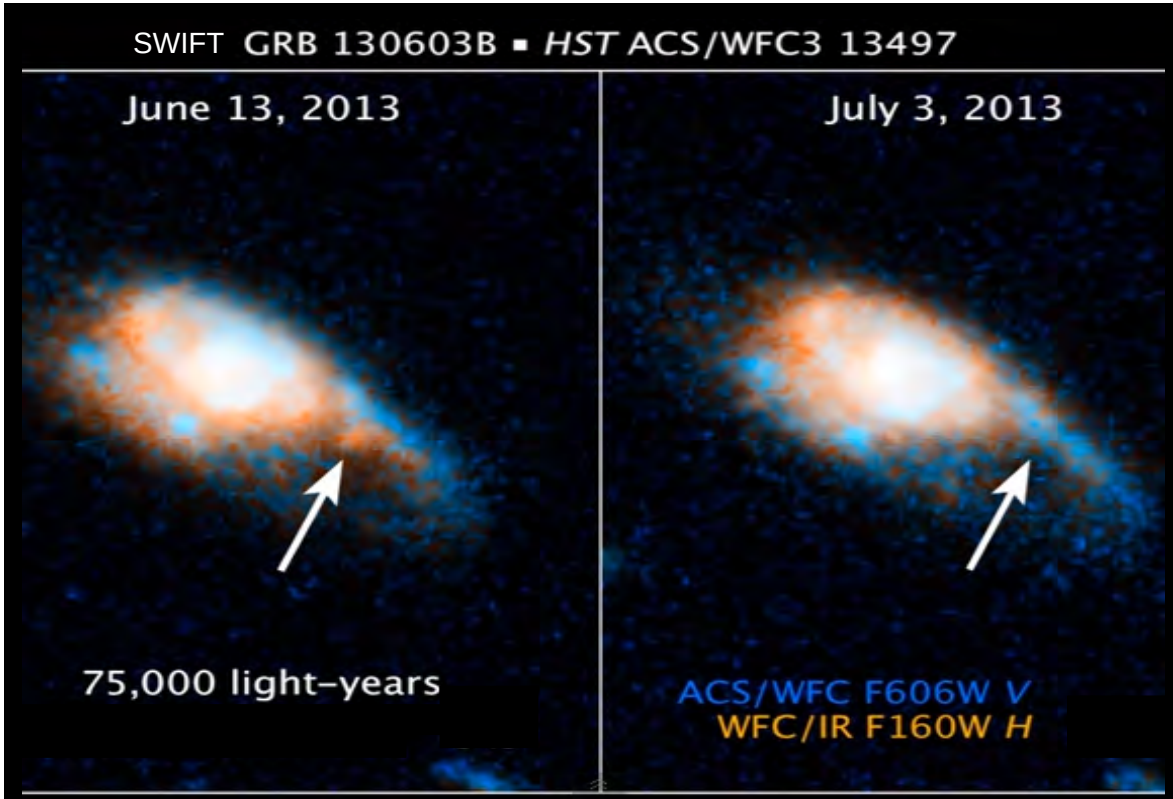
En France, au GANIL (Caen): SPIRAL2



Séance Parallèle 6.1 :
(vendredi 12/07 8h30)
SPIRAL2 et son programme scientifique

plus posters [178, 191] by P. Ascher & L. Caceres

http://pro.ganil-spiral2.eu/spiral2/instrumentation/desir



Gamma-ray burst → detection of a "kilonova"

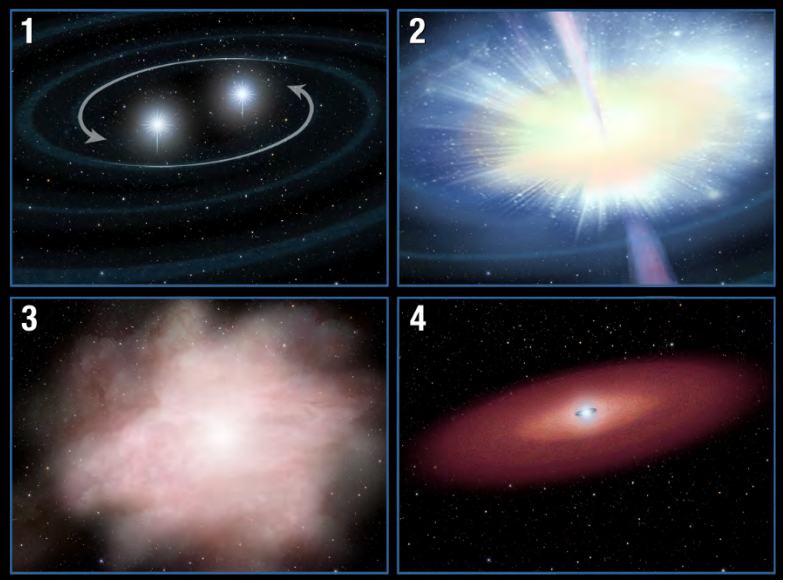
-N.R. Tanvir et al. Nature 500, 537 (2013)

light from decaying radionuclides! (r-process?!)

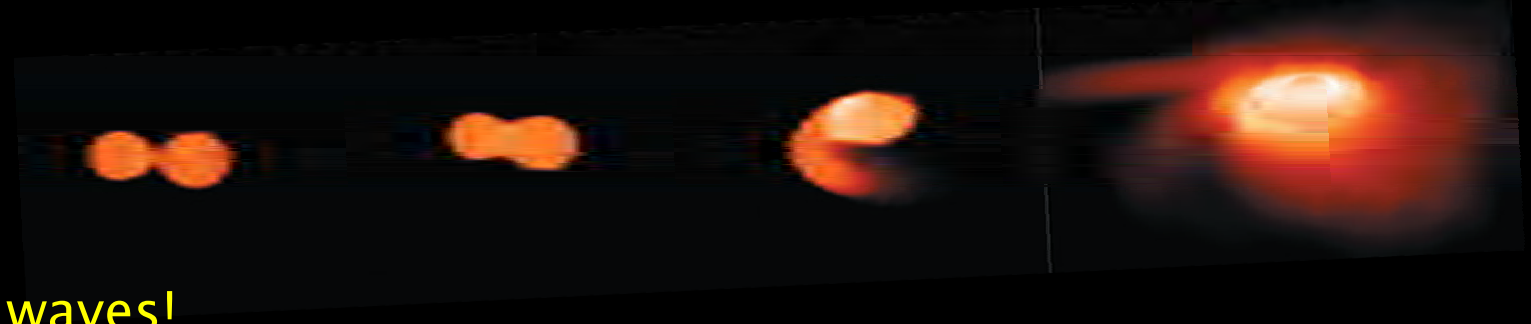
-B.D. Metzger, Liv. Rev. Rel. 20, 3 (2017)

short GRBs → NS mergers (?)

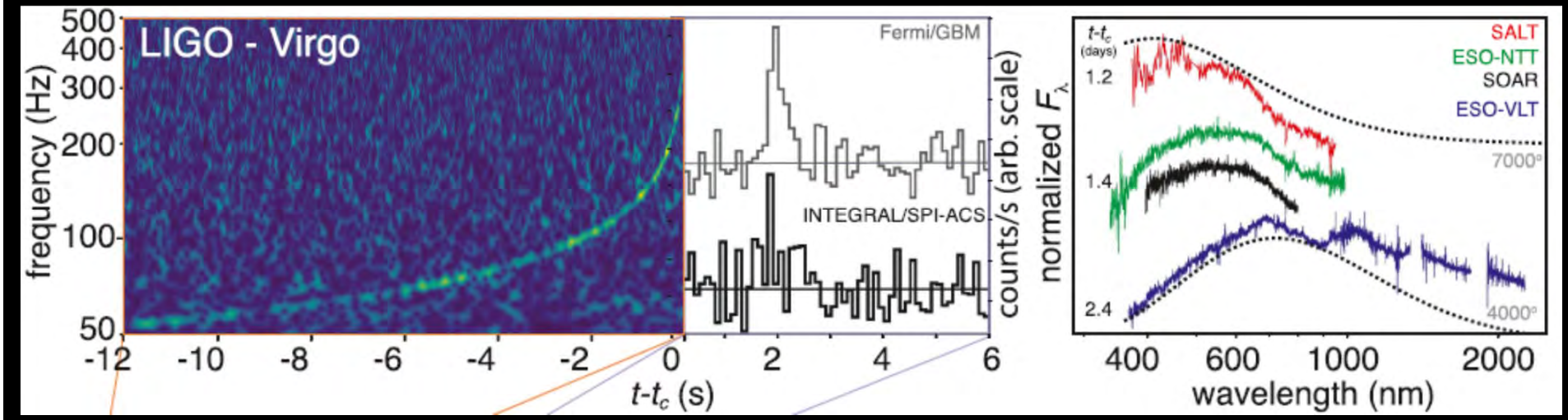
Credit: NASA, ESA, and A. Feild (STScI)

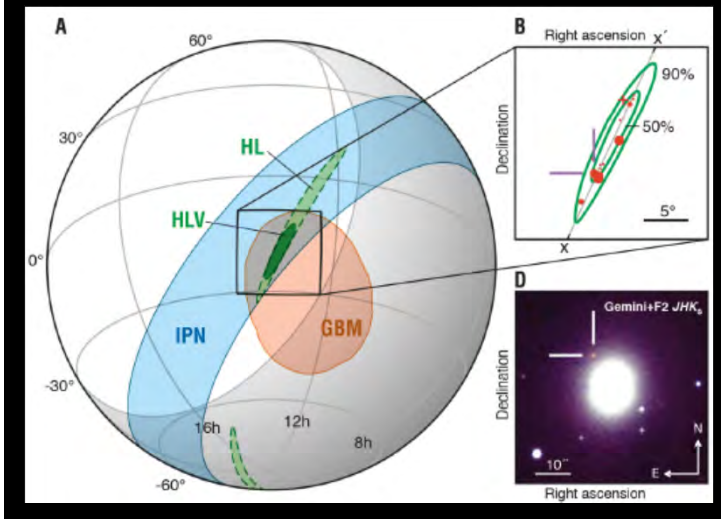


Rosswog, S., Piran, T. & Nakar, E. Mon. Not. R. Astron. Soc. 430, 2585 (2013)



gravitational waves!

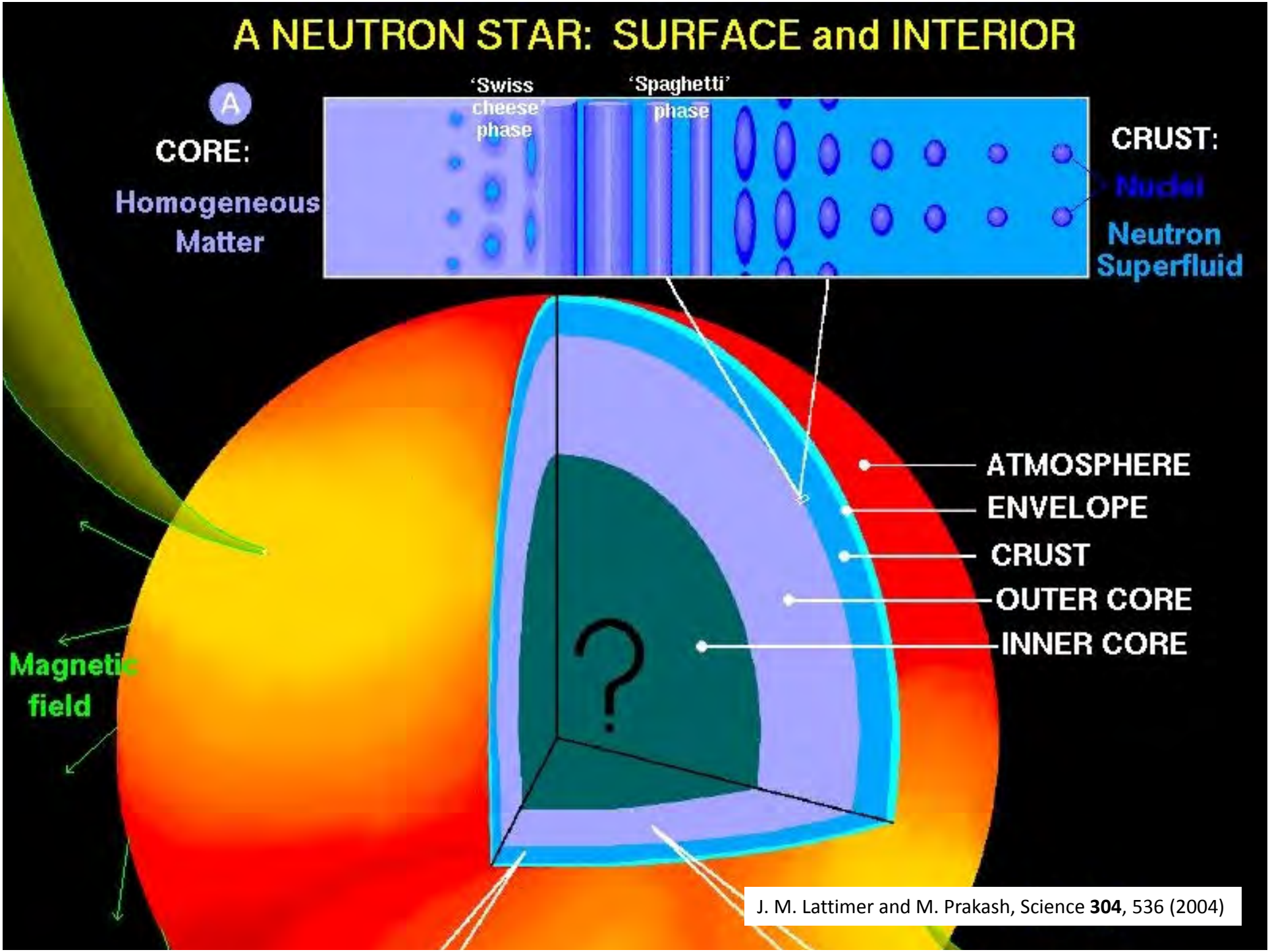




Abbot, B.P. et al., Astrophys. J. Lett. 848, L12 (2017)
Longest astronomer author list ever!

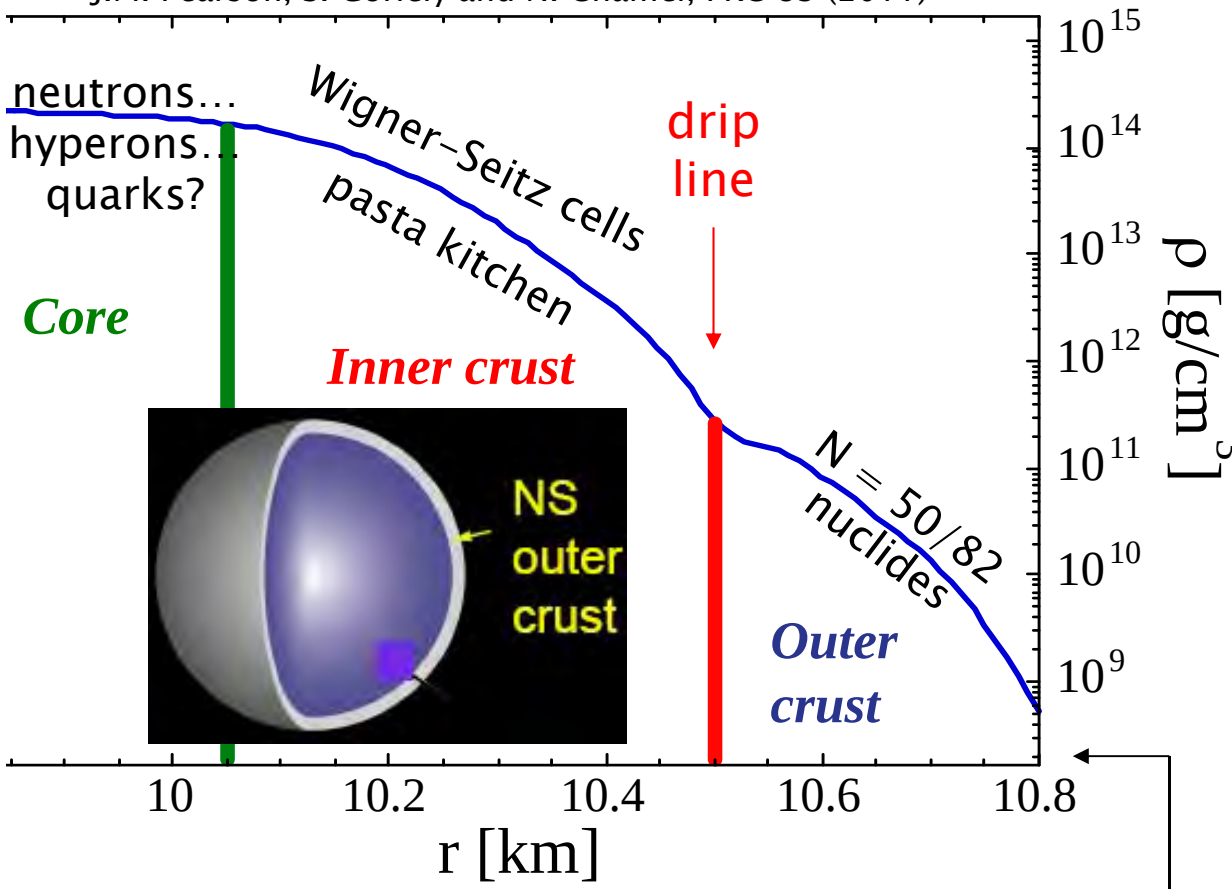
From the Special Issue:
Focus on the Electromagnetic Counterpart of the
Neutron Star Binary Merger GW170817
Astrophys. J. Lett. Oct. 20, 2017
(33 papers!)

GW170817:
landmark event
made more remarkable
by a γ-ray burst and a
kilonova revealing the
r-process site – 60 years after B2FH!


A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
J. M. Lattimer and M. Prakash, Science **304**, 536 (2004)

Neutron-Star density profile

J.M. Pearson, S. Goriely and N. Chamel, PRC 83 (2011)



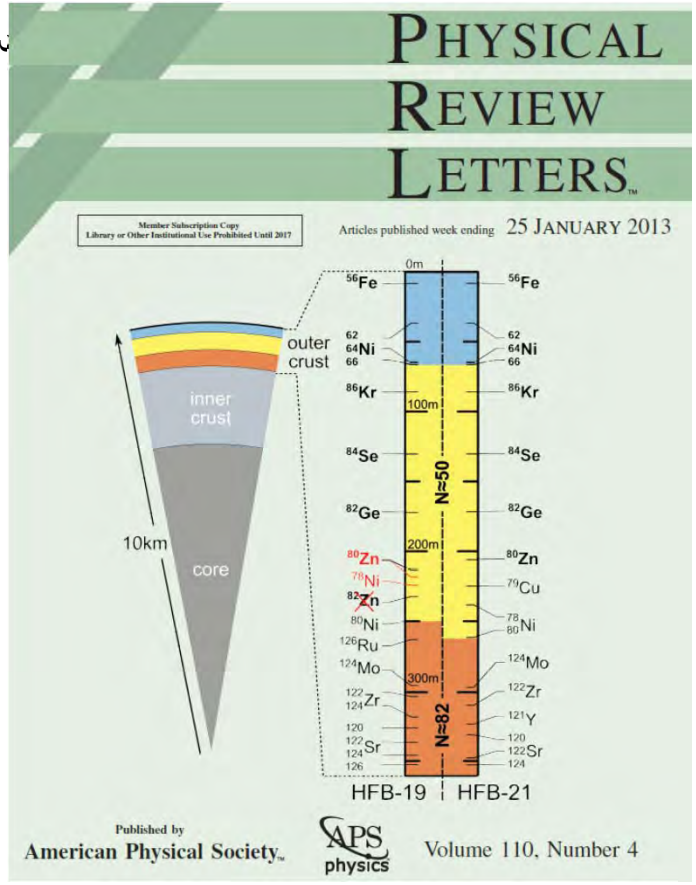
nuclear density:
2×10^8 g/cm^3

See also:
Hempel & Schaffner-Bielich, J. Phys. G (2007)
Gulminelli and Raduta, Phys. Rev. C 92 (2015)
Grams, Giraud, Fantina & Gulminelli, Phys. Rev. C 97 (2018)

Plumbing the depths of a neutron star!

(accretion light curve)

R.N. Wolf & ISOLTRAP Collaboration +
N. Chamel, J.M. Pearson & S. Goriely, PRL (2013)



Brussels interaction for theory combining masses and EOS

pressure/density → TOV
(Tolman Oppenheimer Volkov)

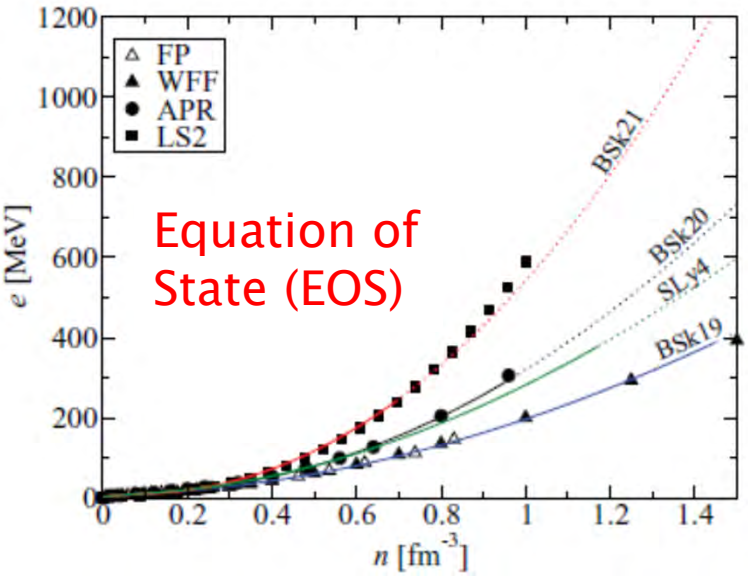
$$\frac{dP}{dr} = -G\frac{\{\mathcal{M}(r) + 4\pi r^3 P(r)/c^2\}\{\mathcal{E}(r) + P(r)\}}{r\{rc^2 - 2G\mathcal{M}(r)\}}$$

with

$$\frac{d\mathcal{M}}{dr} = 4\pi\mathcal{E}(r)r^2/c^2,$$

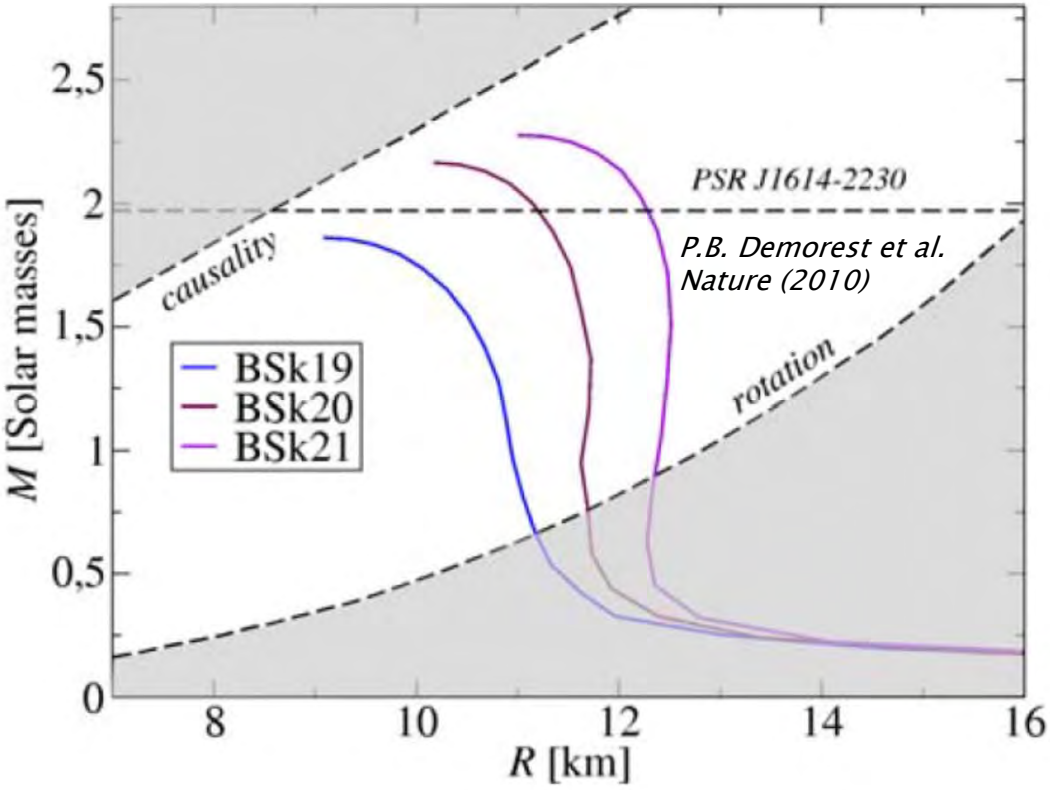
EOS

in which $\mathcal{E}$ denotes the total energy density mass (in the outer crust, $\mathcal{E} \simeq \rho c^2$) and $\mathcal{M}$ is

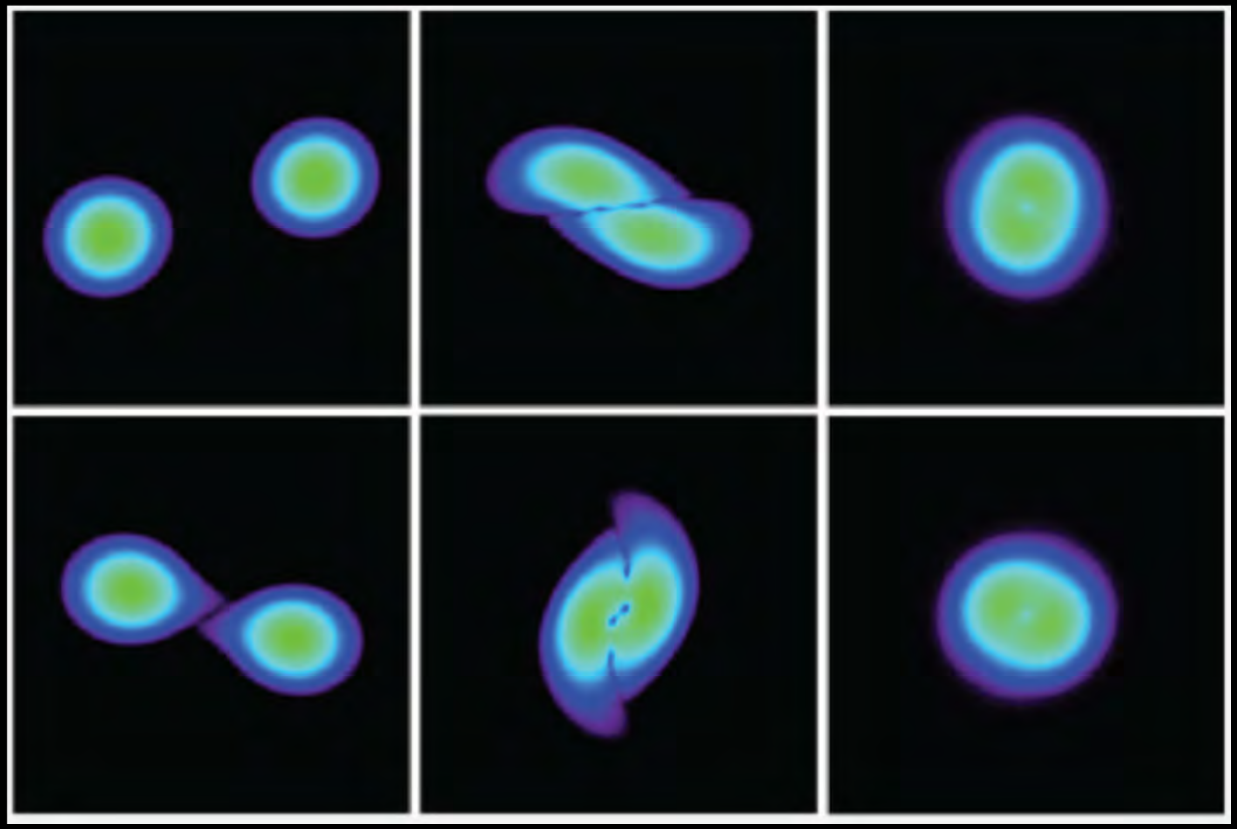


Phenomenological formulations constrained by nuclear physics (masses and scattering experiments)

Mass-radius possibilities constrained by NS mass observations

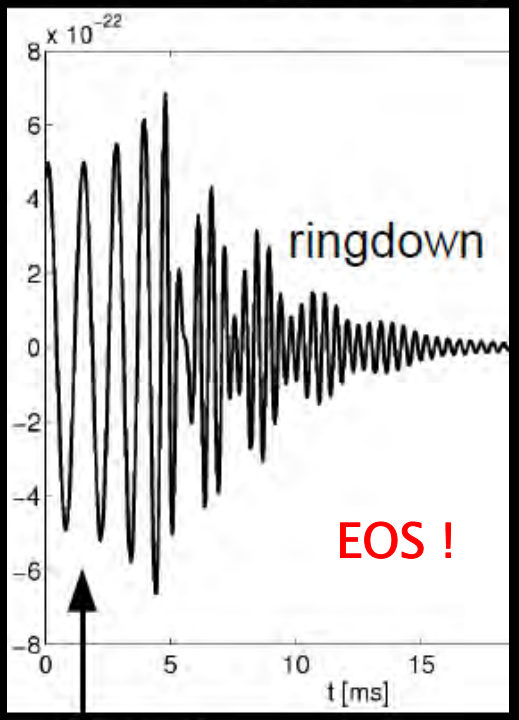


N. Chamel, A.F. Fantina, J.M. Pearson & S. Goriely, PRC 84 (R) (2011)



NS merger simulation: A. Bauswein, H.-Th. Janka

1.35-1.35 M_{sun} , 20 Mp



More bibliography (experts!)


THE CONVERSATION

L'expertise universitaire, l'exigence journalistique

Culture Économie Éducation Environnement International Politique Société Santé Science Mondes francophones

Le mystère de l'or cosmique révélé au cœur des étoiles

20 novembre 2017, 21:46 CET

Étoiles.

Adresse électronique Twitter Facebook Linkedin

D'où provient l'or, ce métal précieux tant convoité ? Comment a-t-il été produit, non sur Terre, mais dans l'Univers ? En août dernier, une unique observation astrophysique nous a enfin donné la clef pour répondre à ces questions. Les résultats de cette recherche ont été publiés le 16 octobre dernier.

Auteur

Jérôme Margueron

Chercheur en astrophysique nucléaire, University of Washington


REVIEWS OF MODERN PHYSICS

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Equations of state for supernovae and compact stars

M. Oertel, M. Hempel, T. Klähn, and S. Typel

Rev. Mod. Phys. **89**, 015007 – Published 15 March 2017

LUTH-Observatoire de Paris, Meudon


PHYSICAL REVIEW C

covering nuclear physics

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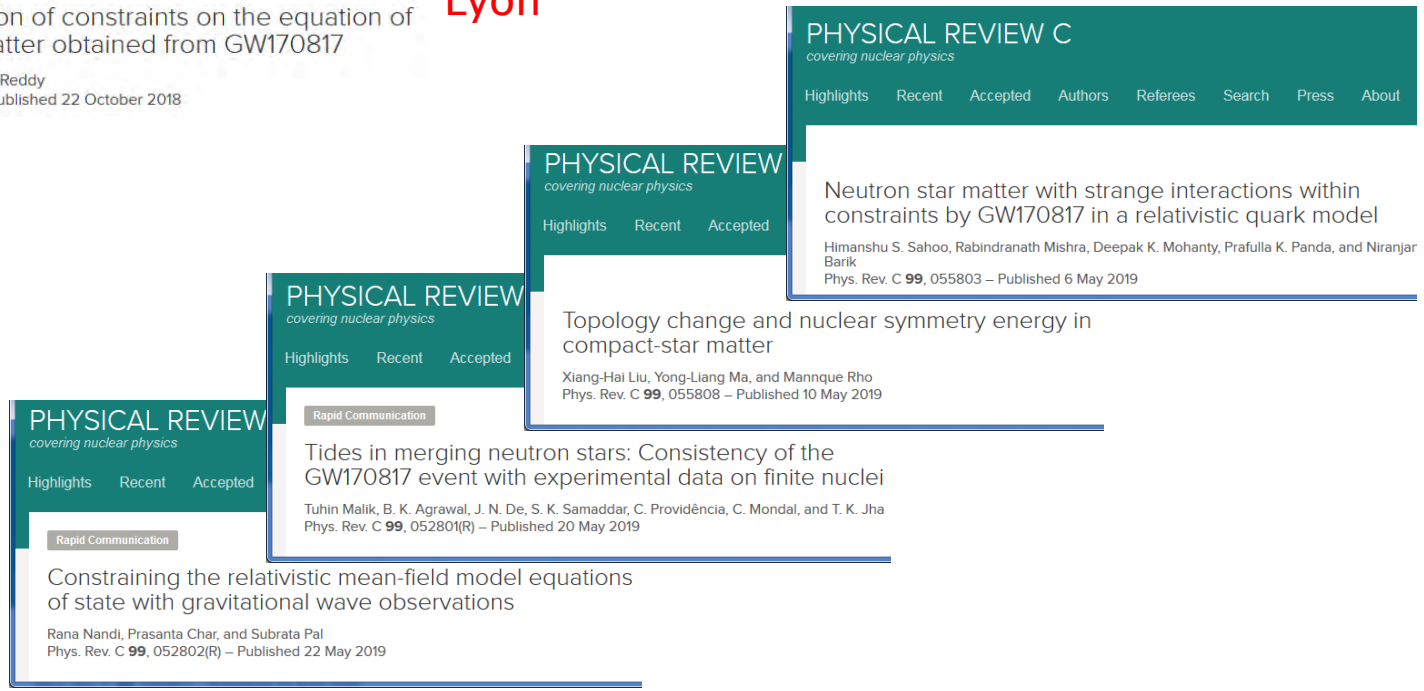
Editors' Suggestion

Critical examination of constraints on the equation of state of dense matter obtained from GW170817

I. Tews, J. Margueron, and S. Reddy

Phys. Rev. C **98**, 045804 – Published 22 October 2018

Laboratoire 2 Infinies, (ex-IPN) Lyon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covering nuclear physics

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Neutron star matter with strange interactions within constraints by GW170817 in a relativistic quark model

Himanshu S. Sahoo, Rabindranath Mishra, Deepak K. Mohanty, Prafulla K. Panda, and Niranjar Barik

Phys. Rev. C **99**, 055803 – Published 6 May 2019

PHYSICAL REVIEW

covering nuclear physics

Highlights Recent Accepted

Topology change and nuclear symmetry energy in compact-star matter

Xiang-Hai Liu, Yong-Liang Ma, and Mannque Rho

Phys. Rev. C **99**, 055808 – Published 10 May 2019

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covering nuclear physics

Highlights Recent Accepted

Rapid Communication

Tides in merging neutron stars: Consistency of the GW170817 event with experimental data on finite nuclei

Tuhin Malik, B. K. Agrawal, J. N. De, S. K. Samaddar, C. Providência, C. Mondal, and T. K. Jha

Phys. Rev. C **99**, 052801(R) – Published 20 May 2019

PHYSICAL REVIEW

covering nuclear physics

Highlights Recent Accepted

Rapid Communication

Constraining the relativistic mean-field model equations of state with gravitational wave observations

Rana Nandi, Prasanta Char, and Subrata Pal

Phys. Rev. C **99**, 052802(R) – Published 22 May 2019

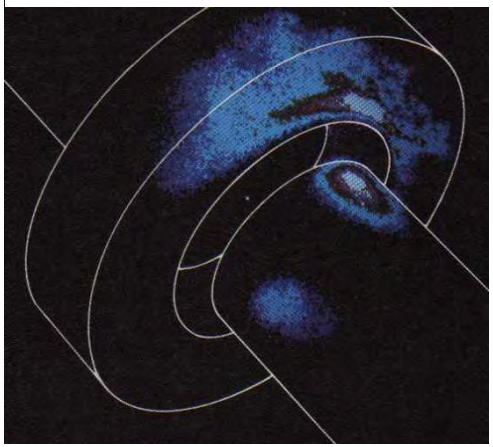
L'origine des éléments

et d'autres implications de la détection des ondes gravitationnelles pour la physique nucléaire

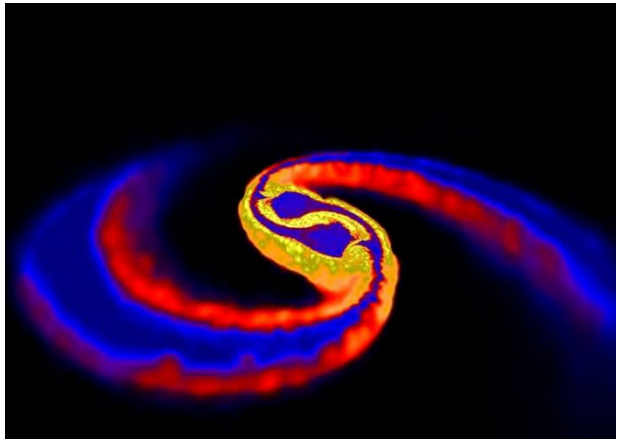
GW170817: 60 years after B2FH (1957) !
More GW results already (maybe NS-BH) !

Important links to nuclear physics (masses and EOS)
See parallel session 6.1 (Fri. 8h30) – SPIRAL2 & associated physics (including talk by M. Henri on measuring the EOS!)

Infinitely small…



…to infinitely large!



Outreach efforts