Nuclear physics aspects of Compact Stars

F.Gulminelli, LPC Caen

Lectures plan

1. **Introduction: dense matter in the universe**
   a. **The sites**
   b. **The signals**
2. Neutron stars and mergers
   a. Observations
   b. Hydrostatics and the EoS
   c. EoS and observables: constraining the parameters
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   a. Phase transitions in dense matter
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   c. The physics of the crust
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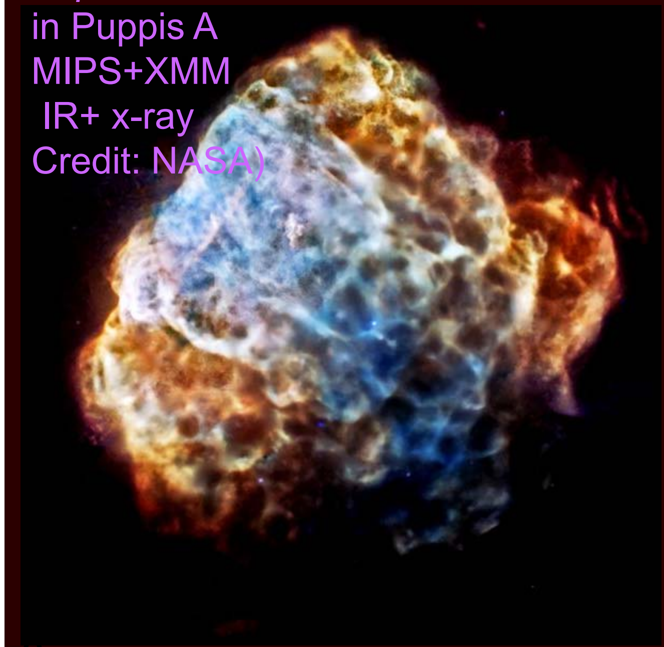
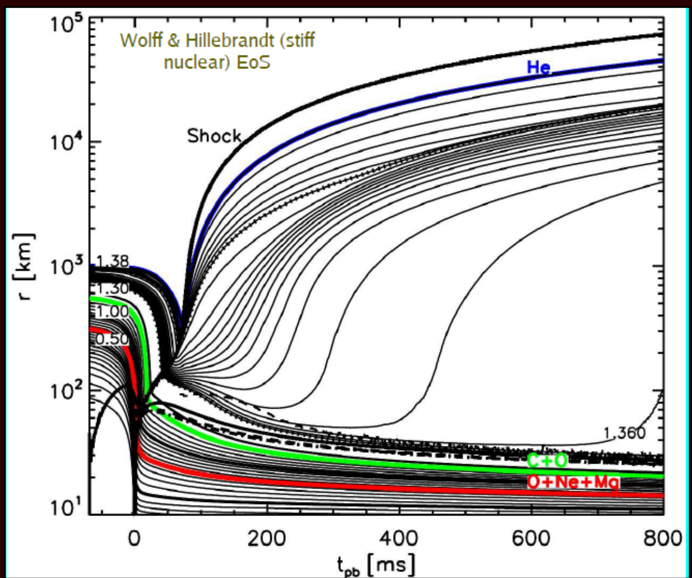
   a. Observations
   b. Modeling supernova explosions
   c. Influence of nuclear physics

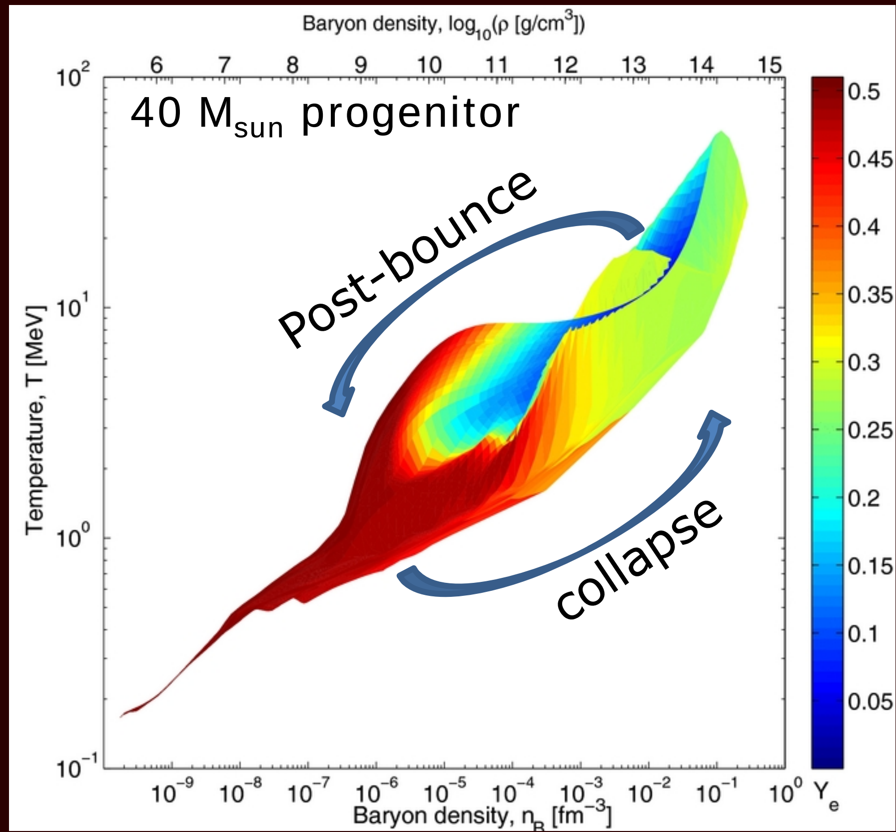
Dense matter in the Universe

Supernova remnant
in Puppis A
MIPS+XMM
IR+ x-ray
Credit: NASA)



F.S.Kitaura et al, *A&A* 450 (06) 345

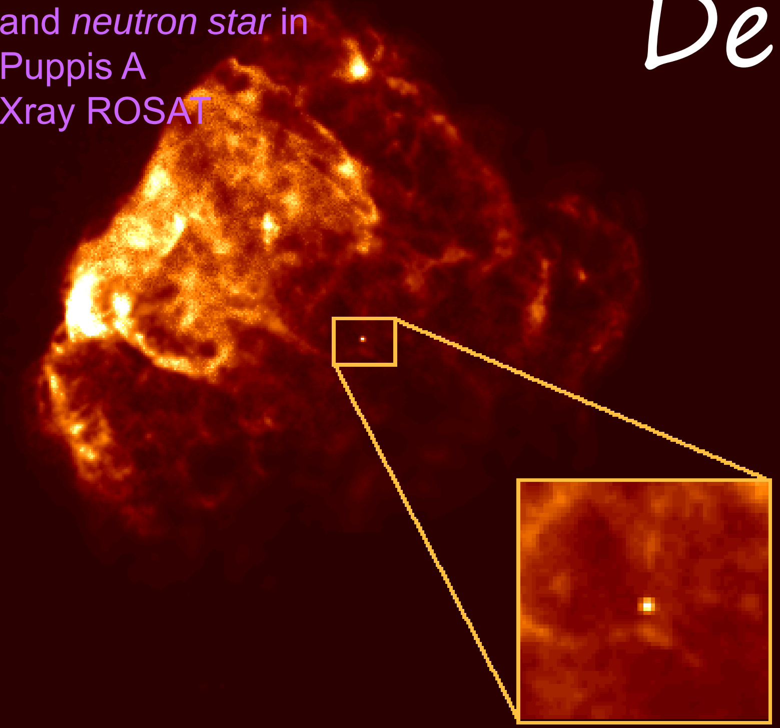


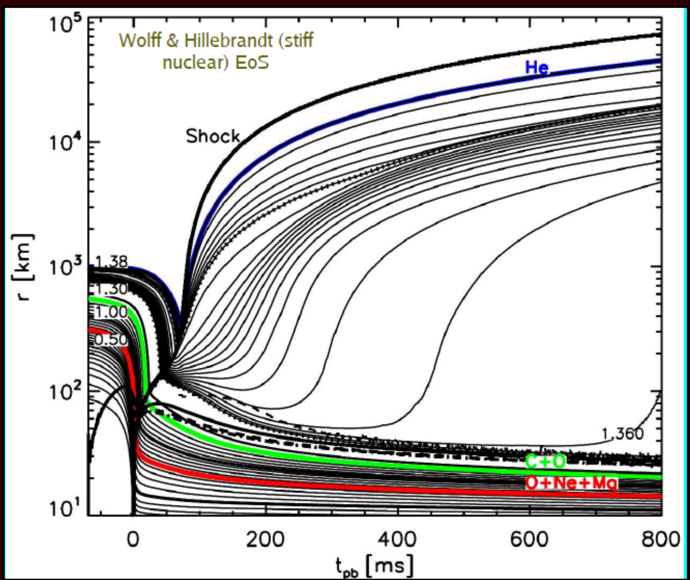


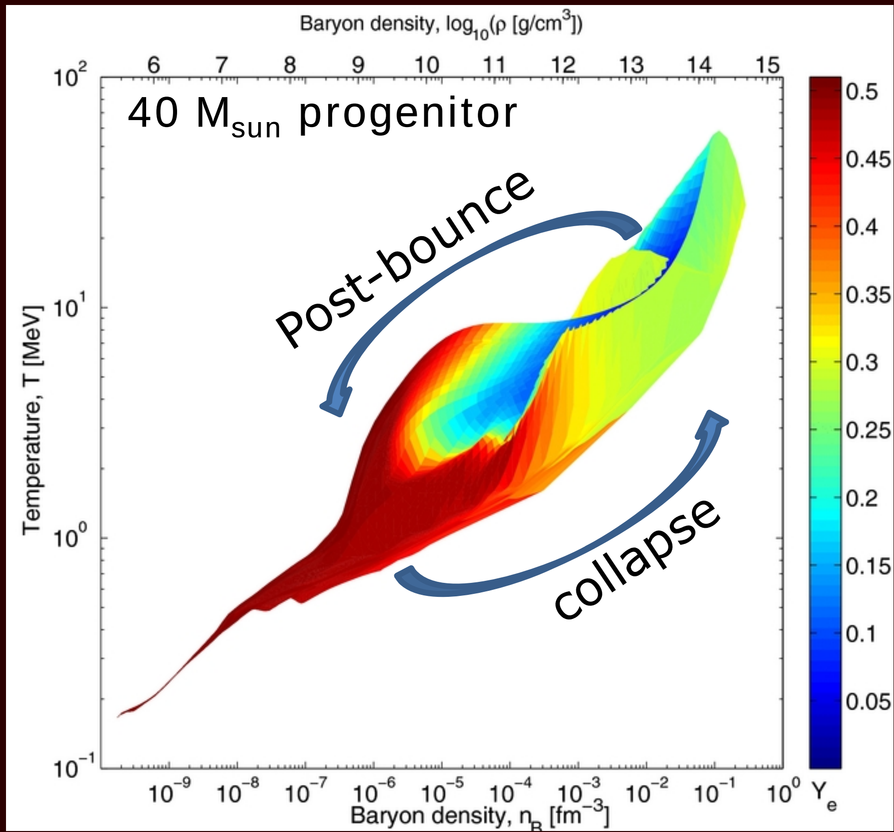
T.Fischer et al, 2011 ApJS **194** 39

Dense matter in the Universe

Supernova remnant and *neutron star* in Puppis A
Xray ROSAT

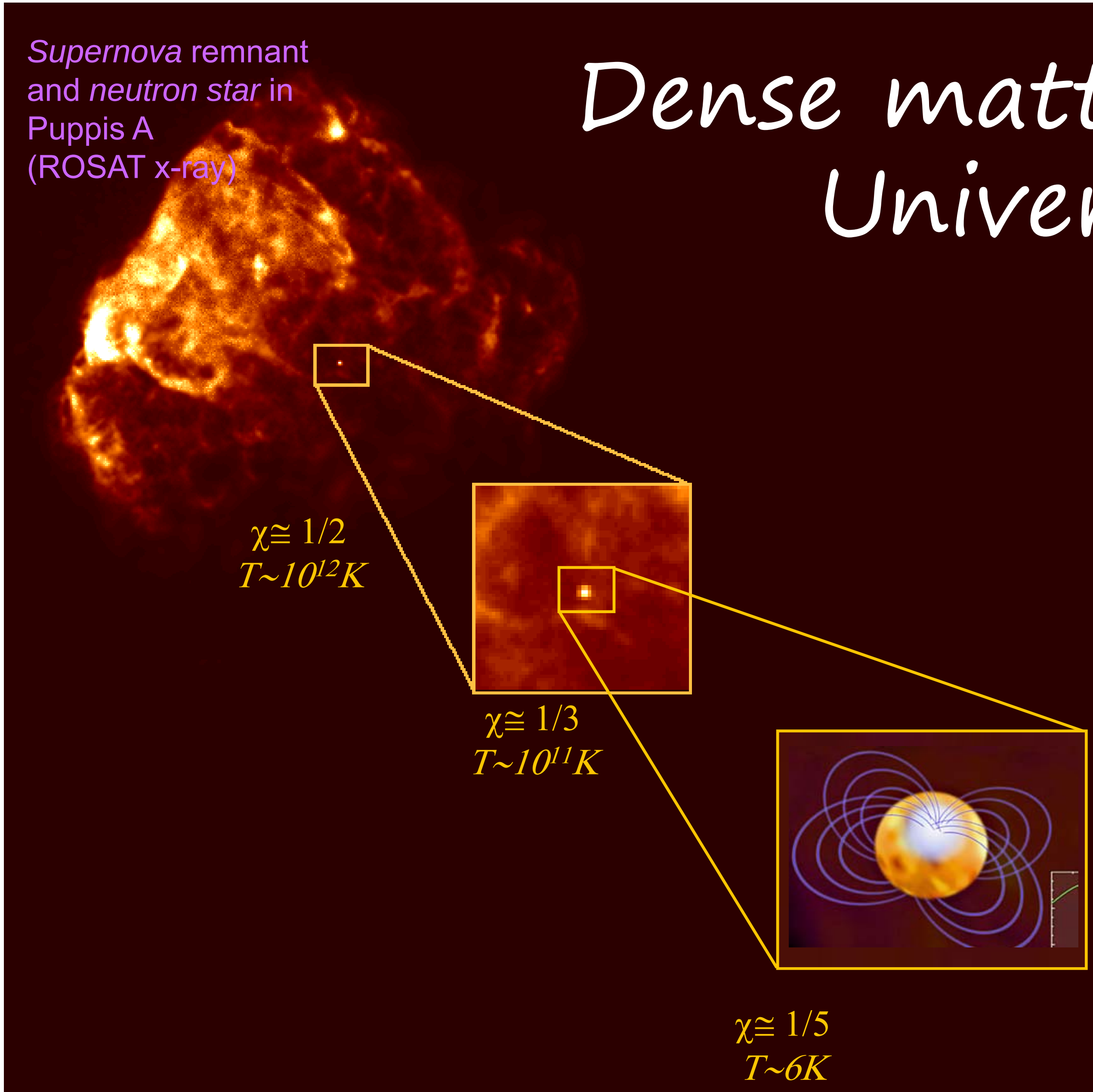


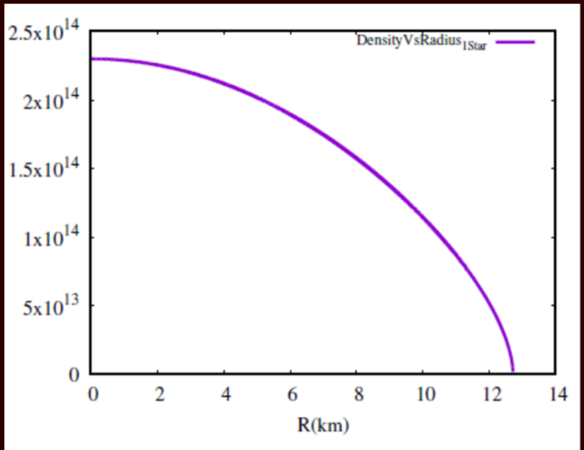




T.Fischer et al, 2011 ApJS **194** 39

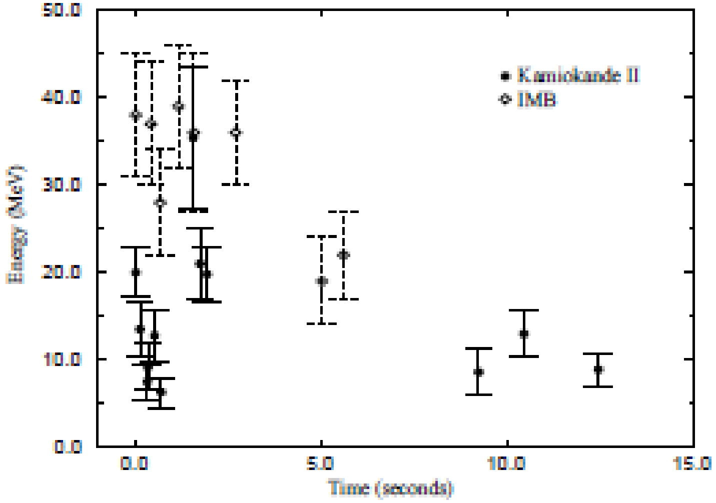
Dense matter in the Universe



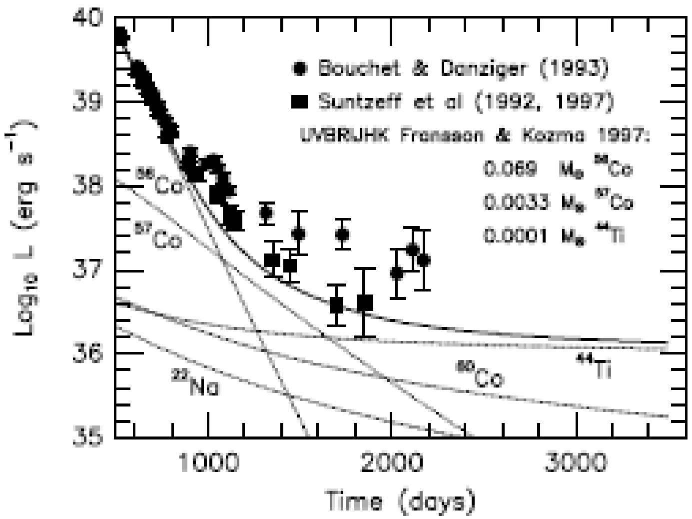


CCSN Signals

neutrinos $E_\nu \approx 2.7 \times 10^{53}$ erg



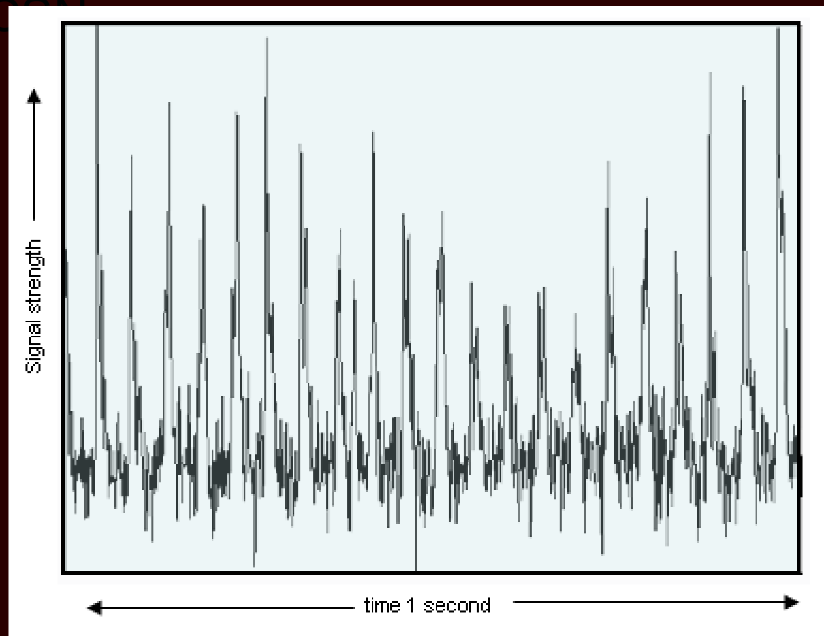
light curve



CCSN

Signals

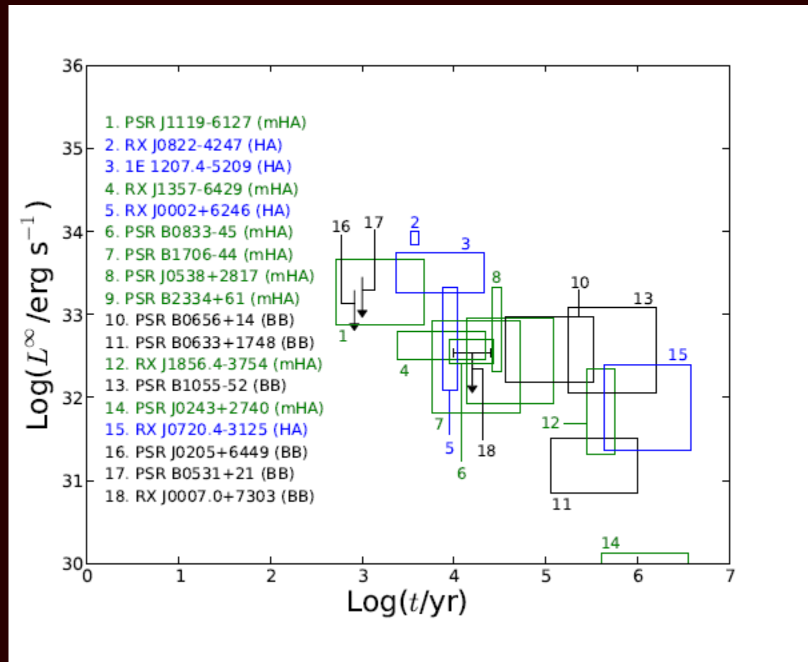
Pulsars



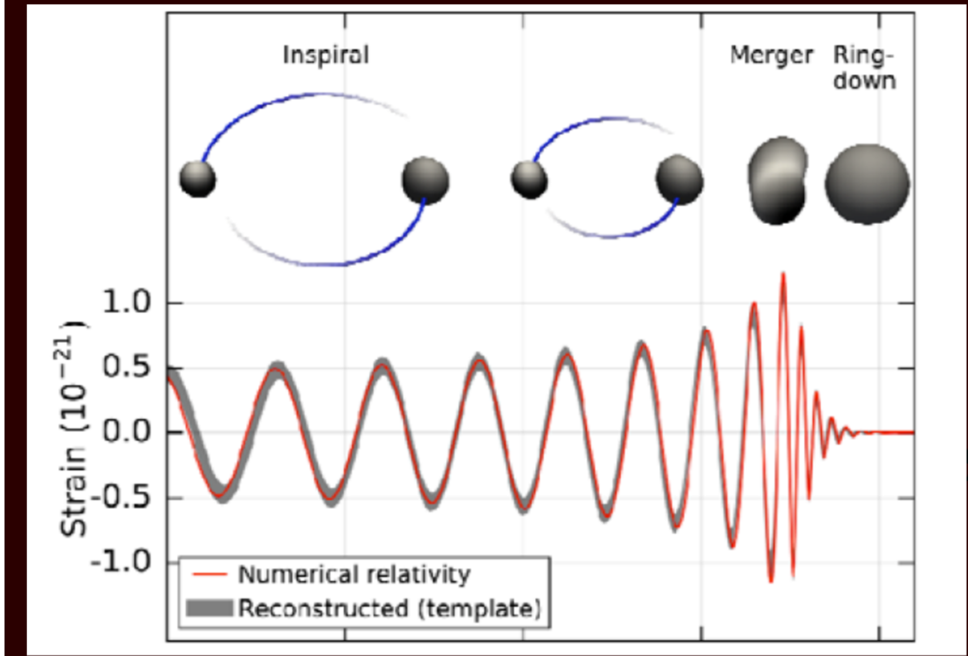
Signals

XR binaries

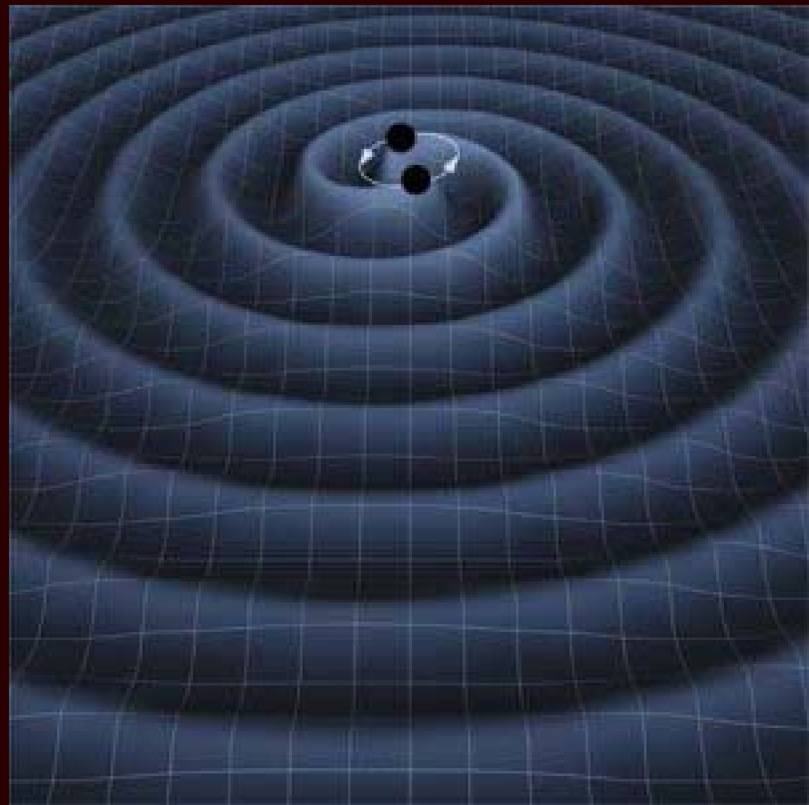
CCSN



Signals

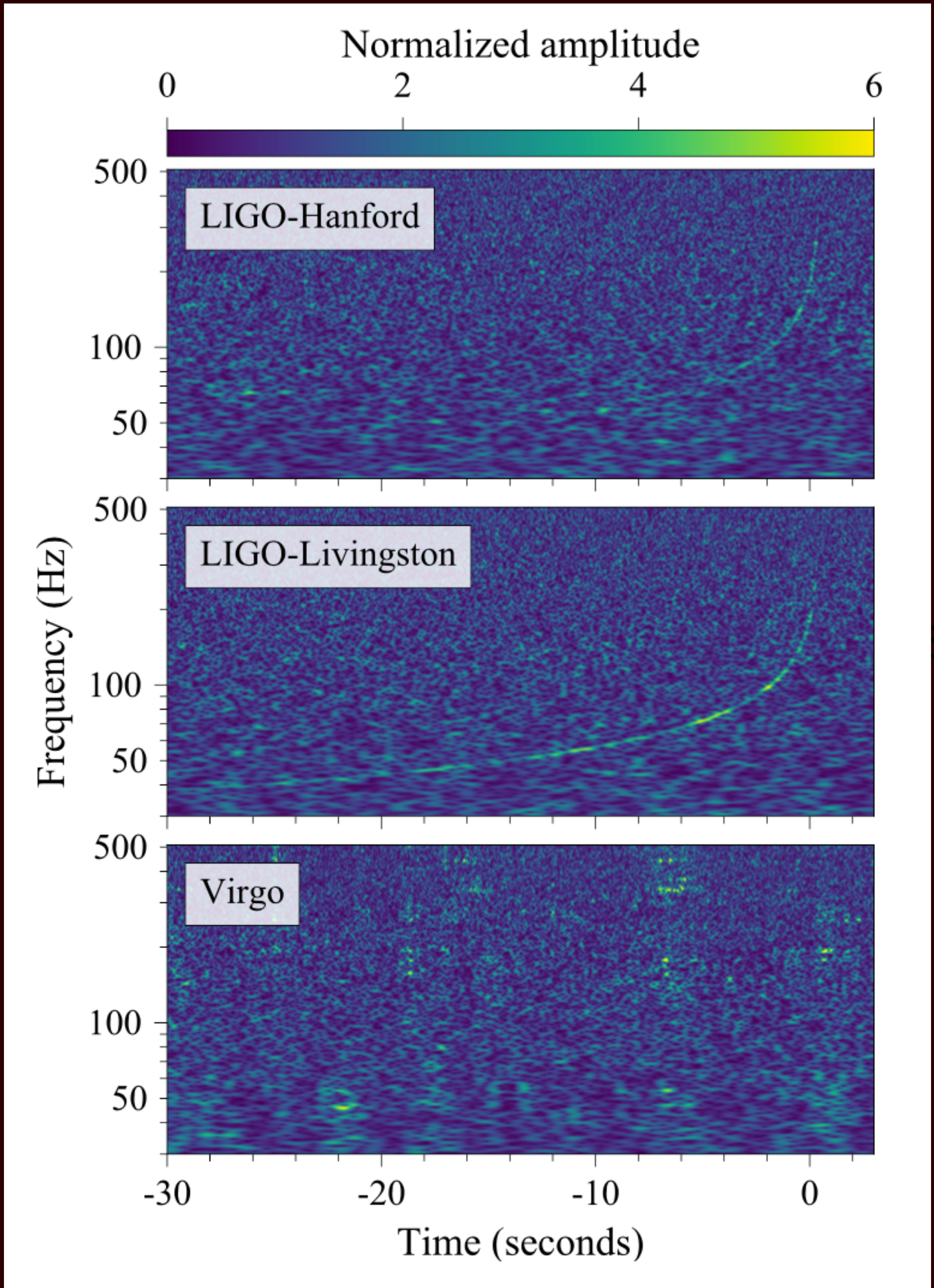


SN



Mergers

Signals



Mergers

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

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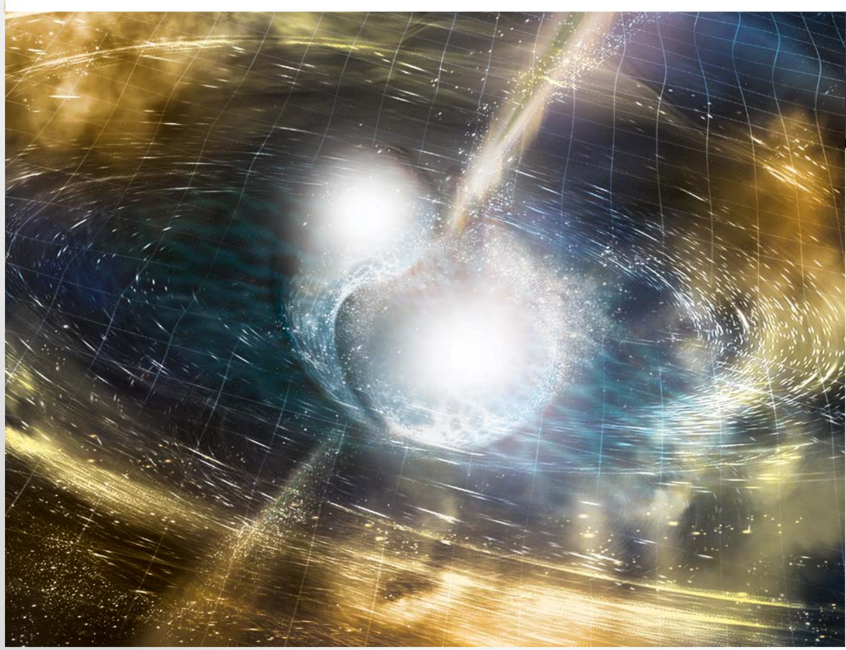
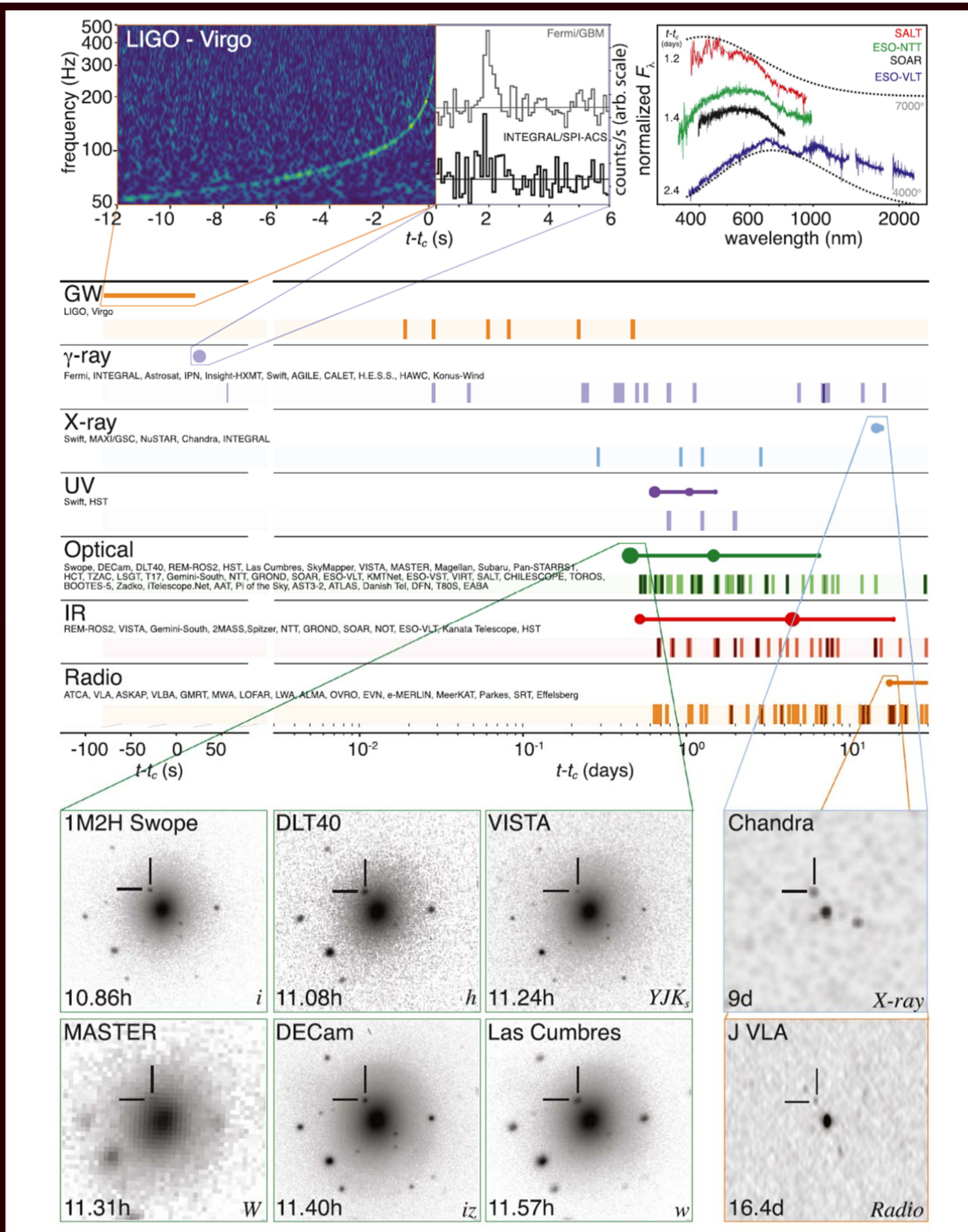


Foundation
Operated by Caltech and MIT

GW170817 Press Release

LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

Discovery marks first cosmic event observed in both gravitational waves and light.

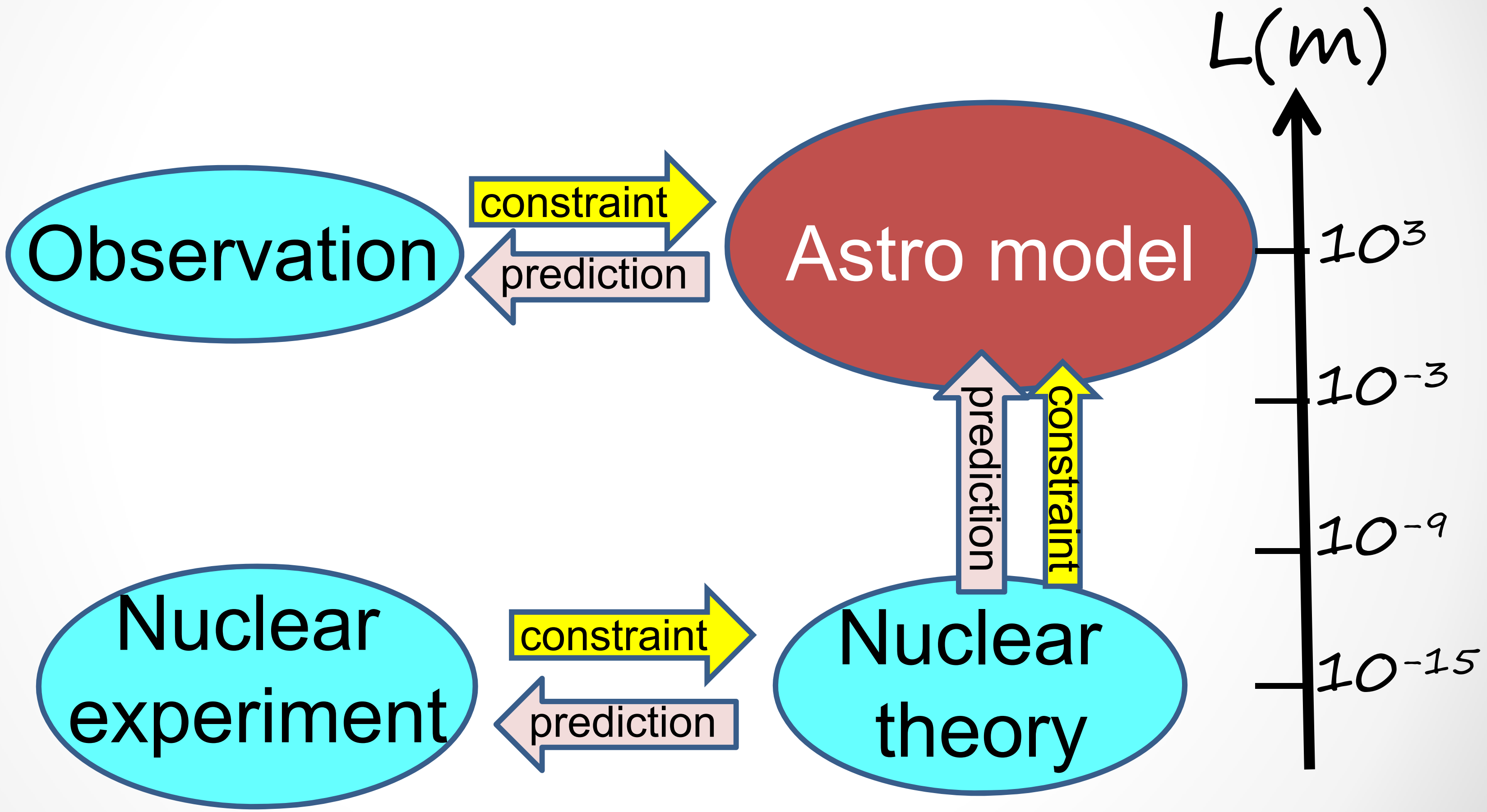


LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)
1M2H Swope
10.86h
DLT40
11.08h
VISTA
11.24h
Chandra
9d
X-ray
MASTER
11.31h
DECam
11.40h
Las Cumbres
11.57h
J VLA
16.4d
Radio

Questions

1. What is the internal structure of the dense matter in neutron stars, supernova cores and mergers? (wide range of T, y_p, ρ !)
2. How does this structure reflect into the observable signals?
3. What can we learn on the underlying nuclear physics?

Jumping across the scales!



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Neutron Star record list

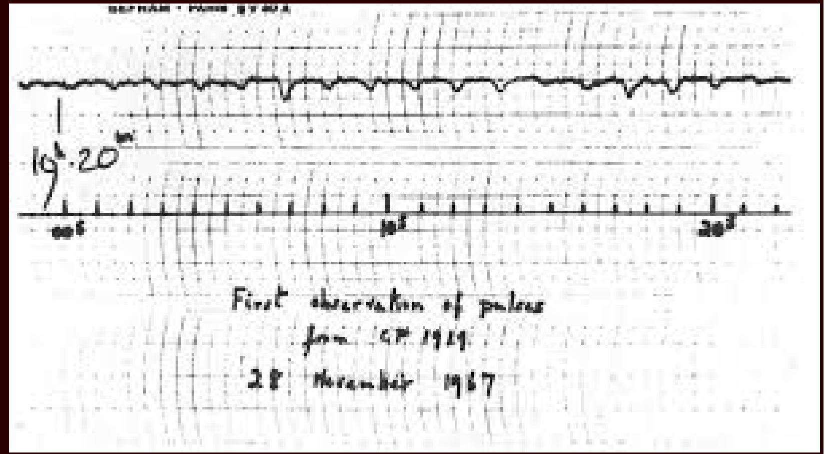
- The densest objects of the universe
  $\rho=10^{14}$g/cm^3
- The objects which spin the fastest
  $\nu=716$ Hz => $v_{equator}=c/4$
- The highest speed of the galaxy
  v=1083 km/s
- The most intense magnetic fields
  $H=10^{14}$ gauss
- The only place after Big-Bang where:
  - Neutrinos can be trapped
  - Quarks can be deconfined

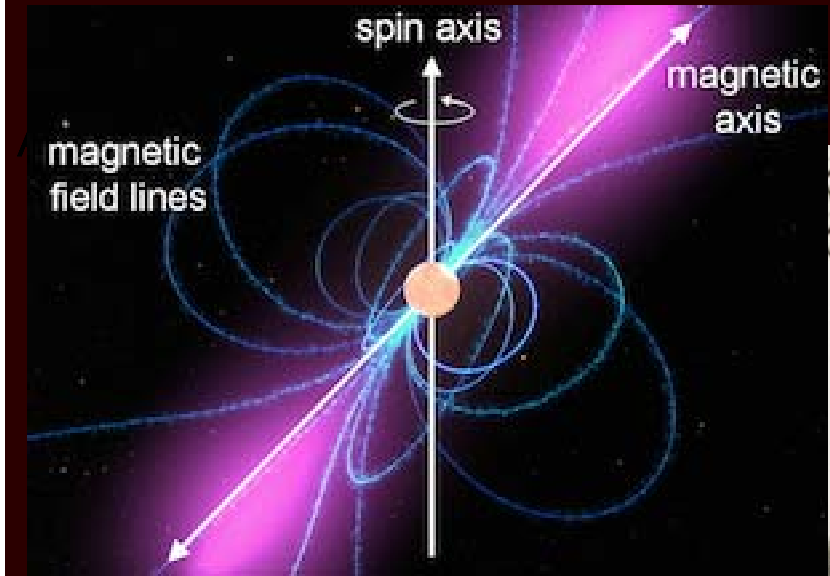
Neutron Star discovery history

- **1934:** prediction W.Baade F.Zwicky
- **1967:** Pulsar discovery Bell&Hewish (Nobel prize)
- **1974:** discovery of binary pulsars
- **1992:** first exo-planet: it orbits around a neutron star!
- **1993**: first evidence of gravitational waves Hulse&Taylor (Nobel prize)
- **1998:** discovery of magnetars
- **2017:** first GW detection from a NS merger LIGO-Virgo (Nobel prize)
- **2017:** first multi-messanger detection of a binary merger

Neutron Stars: the discovery

Jocelyn Bell
& Antony Hewish

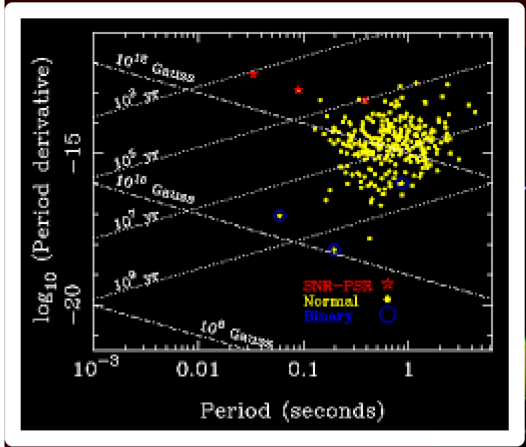


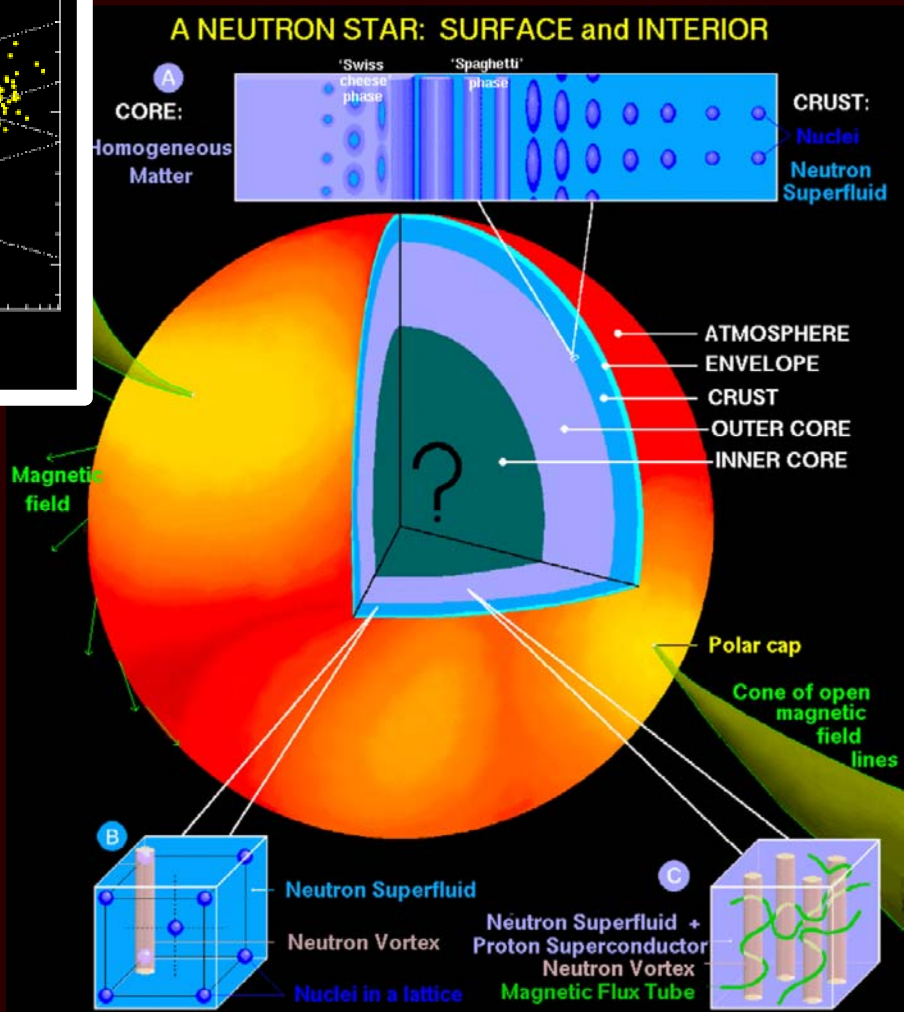


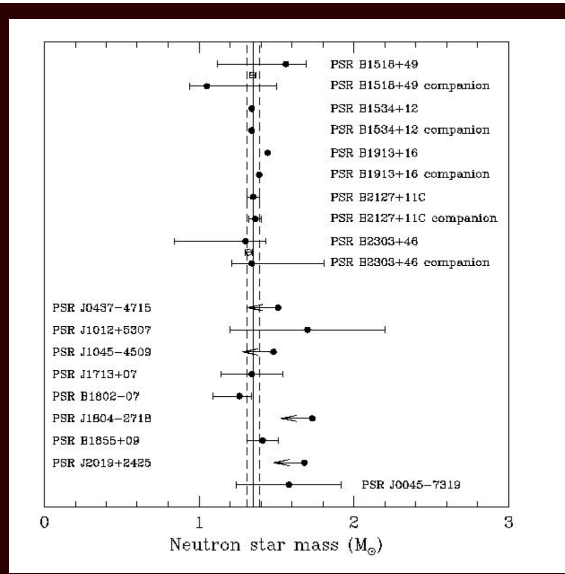
Credit: NASA/Goddard Space Flight Center Conceptual Image Lab

Neutron Stars:

the standard picture







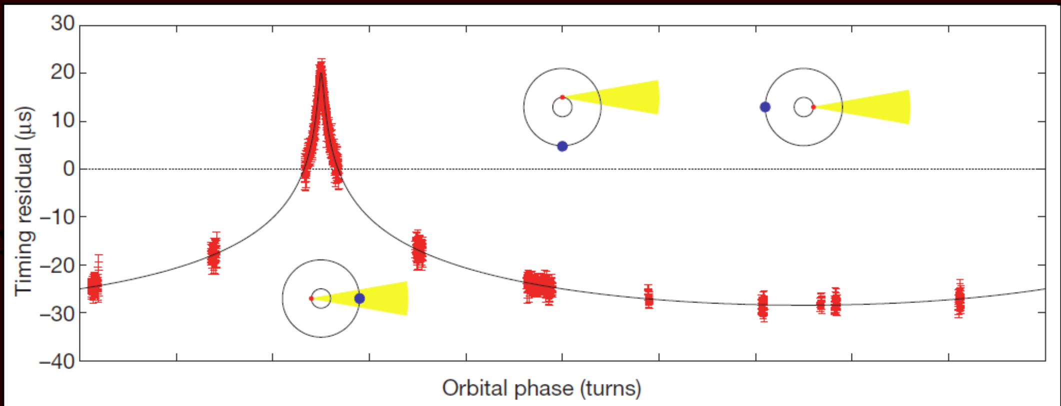
M~1.4 Mo
R~10-15 km
=> $\rho \sim \rho_0$

Picture: D.Page

Today: about 2000 Neutron Stars known in the Milky Way and Large Magellanic Cloud

Neutron Stars: today

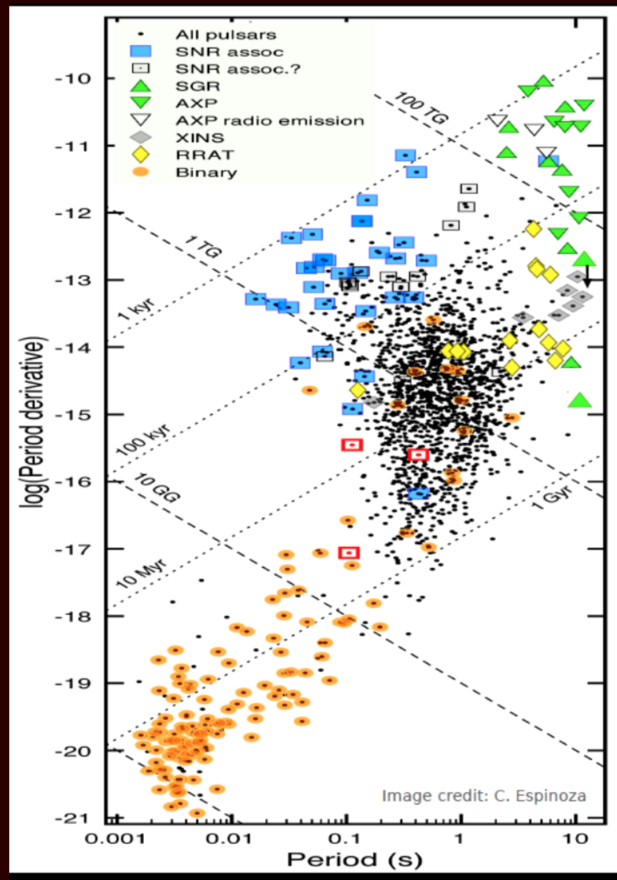
P. Demorest et al., Nature (2010)
M(PSR J1614)=1.97 +/- 0.04
J.Antoniadis et al., Science (2013).
M(PSR J0348)=2.01 +/- 0.04



...supermassive objects: challenge for the strong interaction

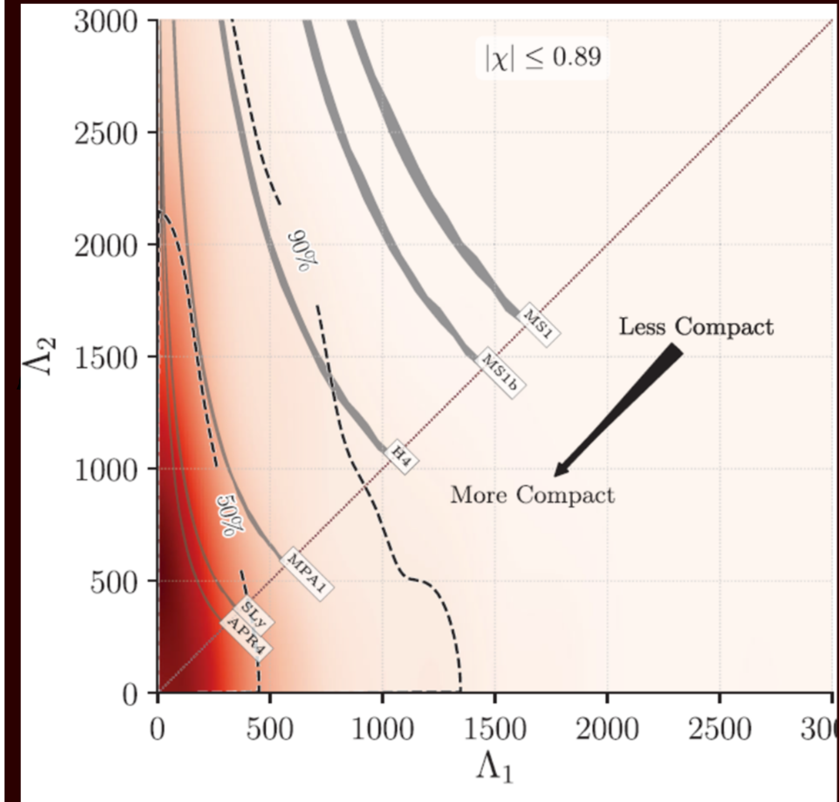
N.Rea et al., ApJ (2013).
B(SGR 0418) = 6x10¹² G

...SGR,pulsar,magnetars: unified picture



Neutron Stars:

today

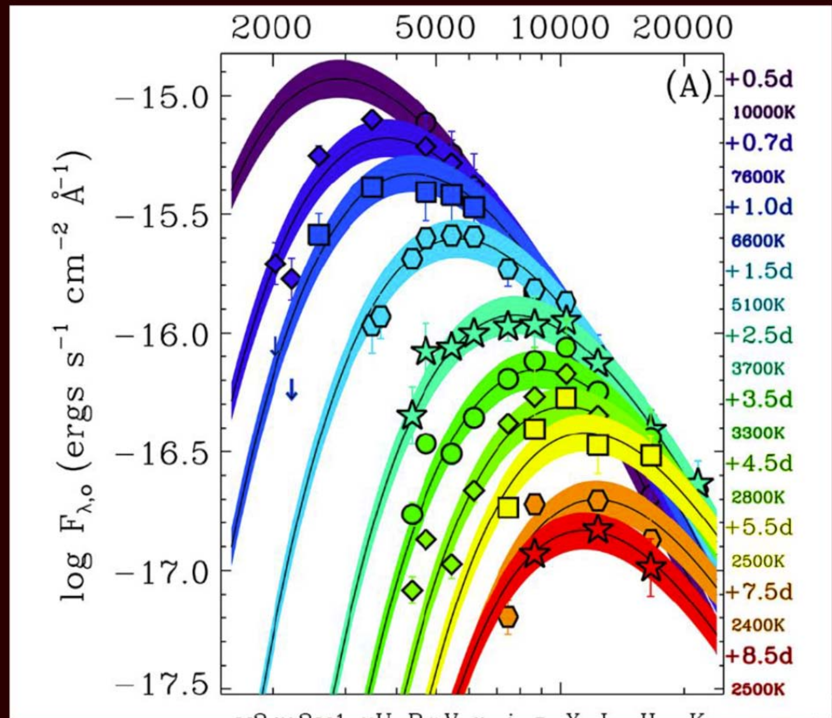


GW170817 in NGC 4993
B.Abbott et al. (LIGO) PRL (2017)

...tidal polarizability: first glance at the internal structure

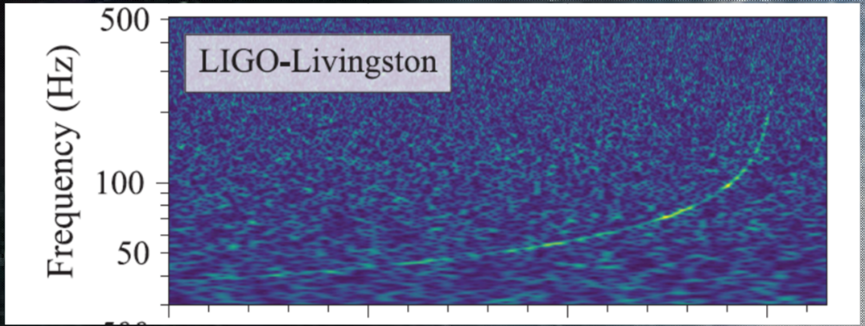
M.Drout et al., Science (2017).

...Light curves: first direct msmt of the r-process



Neutron Stars: tomorrow

What will we learn?



An avenue of quantitative observations from compact objects is ahead

- More binary NS merging
- NS-BH binaries (candidate august 2019)
- Continuous GW from deformed NS/R-modes in young sources
- GW from SN
- NS radii from NICER (2019)

- Nuclear: Equation of state of nuclear matter!

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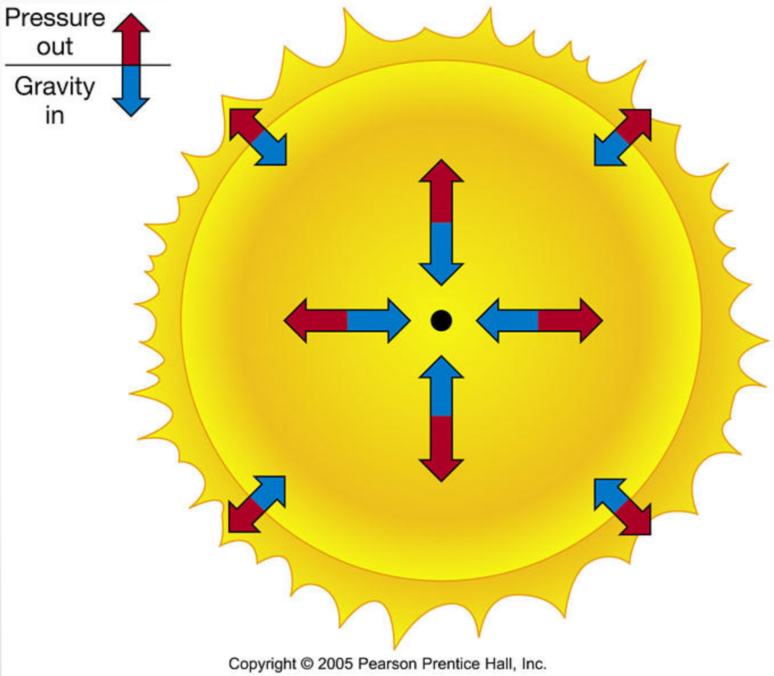
Modelling (Neutron) Stars: hydrostatics

- Self-gravitation => Tolman Oppenheimer Volkoff (1939):

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

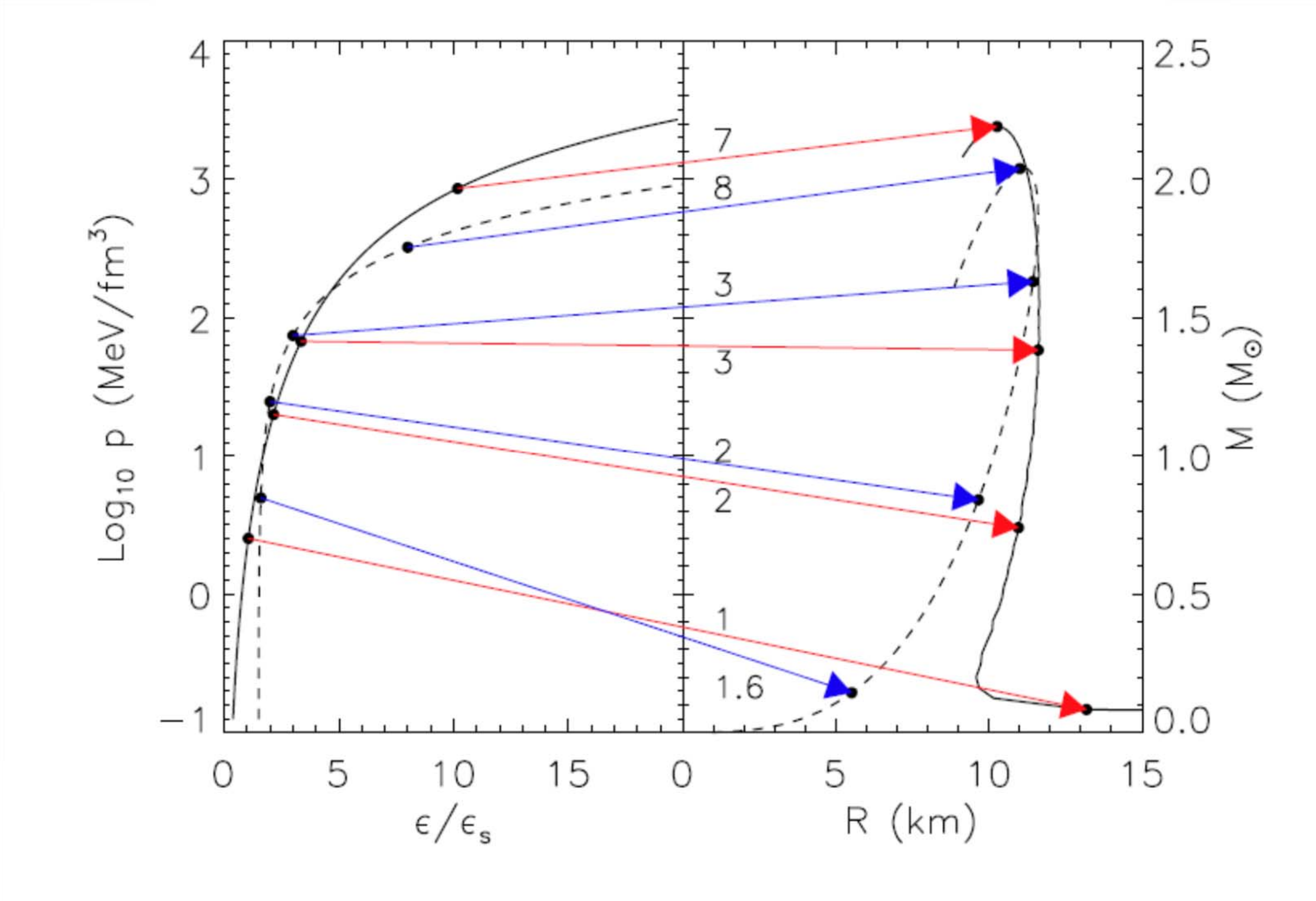


$\forall \rho_c$
R=r(P=0)
M=m(r=R)

Mass and radius

Needs ONLY $P(\rho)$ of NS matter

$P(\rho) \Leftrightarrow M(R)$



- J.Lattimer Ann.Rev.Nucl.Part.Sci 2012

Modelling (Neutron) Stars: hydrostatics

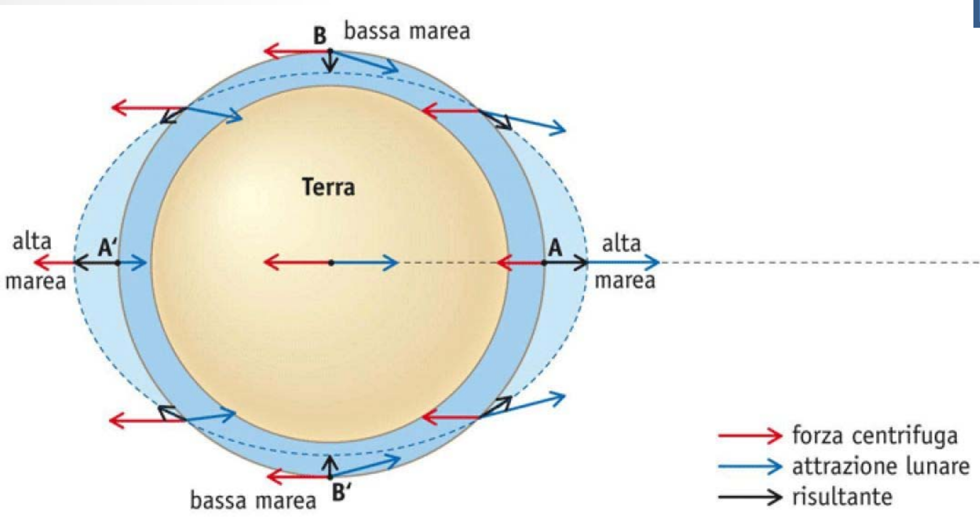
- Influence of a second body => Thorne and Campolattaro (1967):

$$\frac{d^2H(r)}{dr^2} + \frac{dH(r)}{dr}\left[\frac{2}{r} + e^{\lambda(\boldsymbol{P(\rho)})}\left(\frac{2m(r)}{r^2} + 4\pi r\big(\boldsymbol{P(\rho)} - \rho(r)\big)\right)\right] + H(r)Q(\boldsymbol{P(\rho)}) = 0$$

$\forall \rho_c$

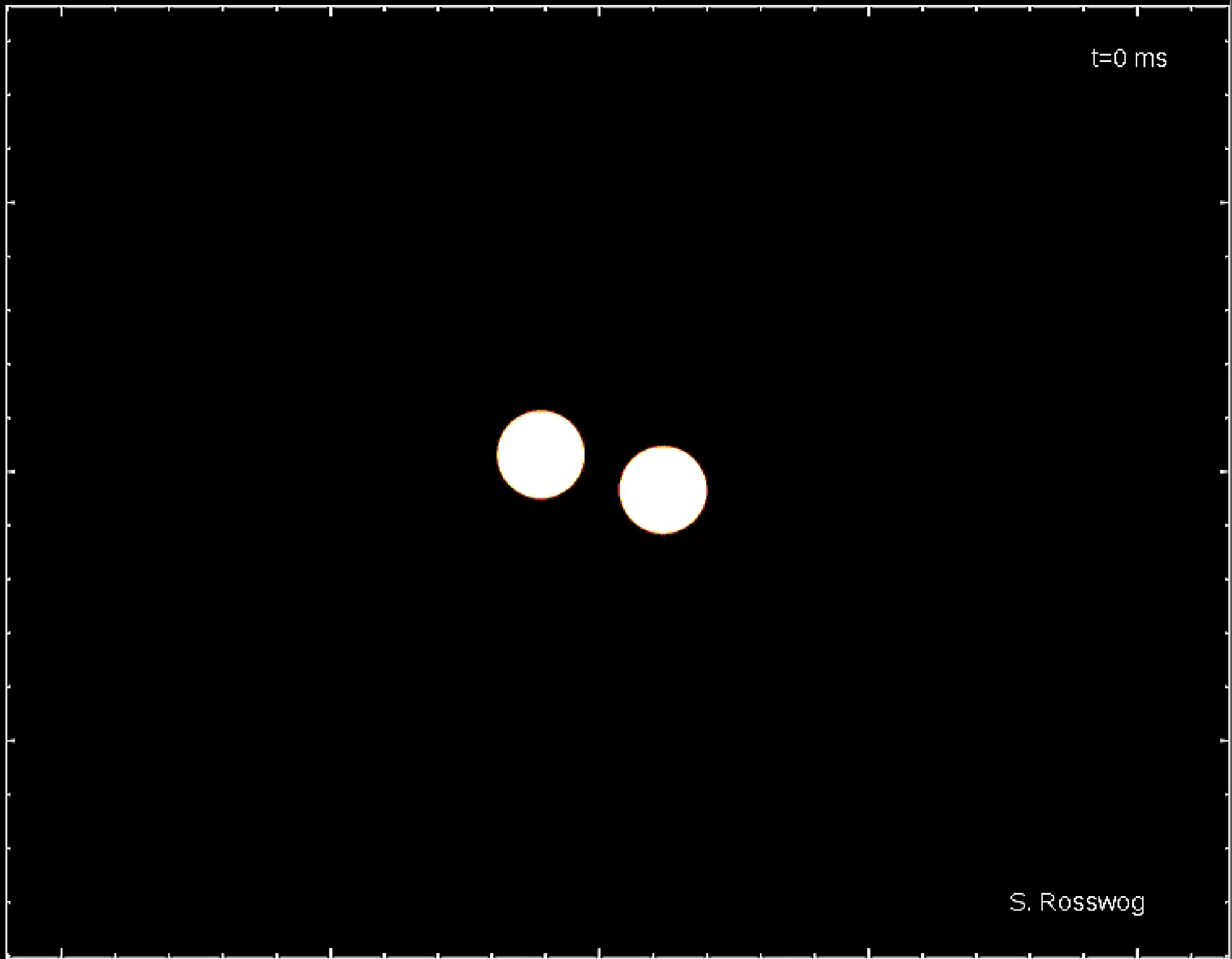
$$\Lambda = \frac{2}{3}k_2\left(\frac{H\prime(r=R)}{H(r=R)}\right)\left(\frac{c^2}{G}\frac{R}{M}\right)^5$$

Tidal polarizability



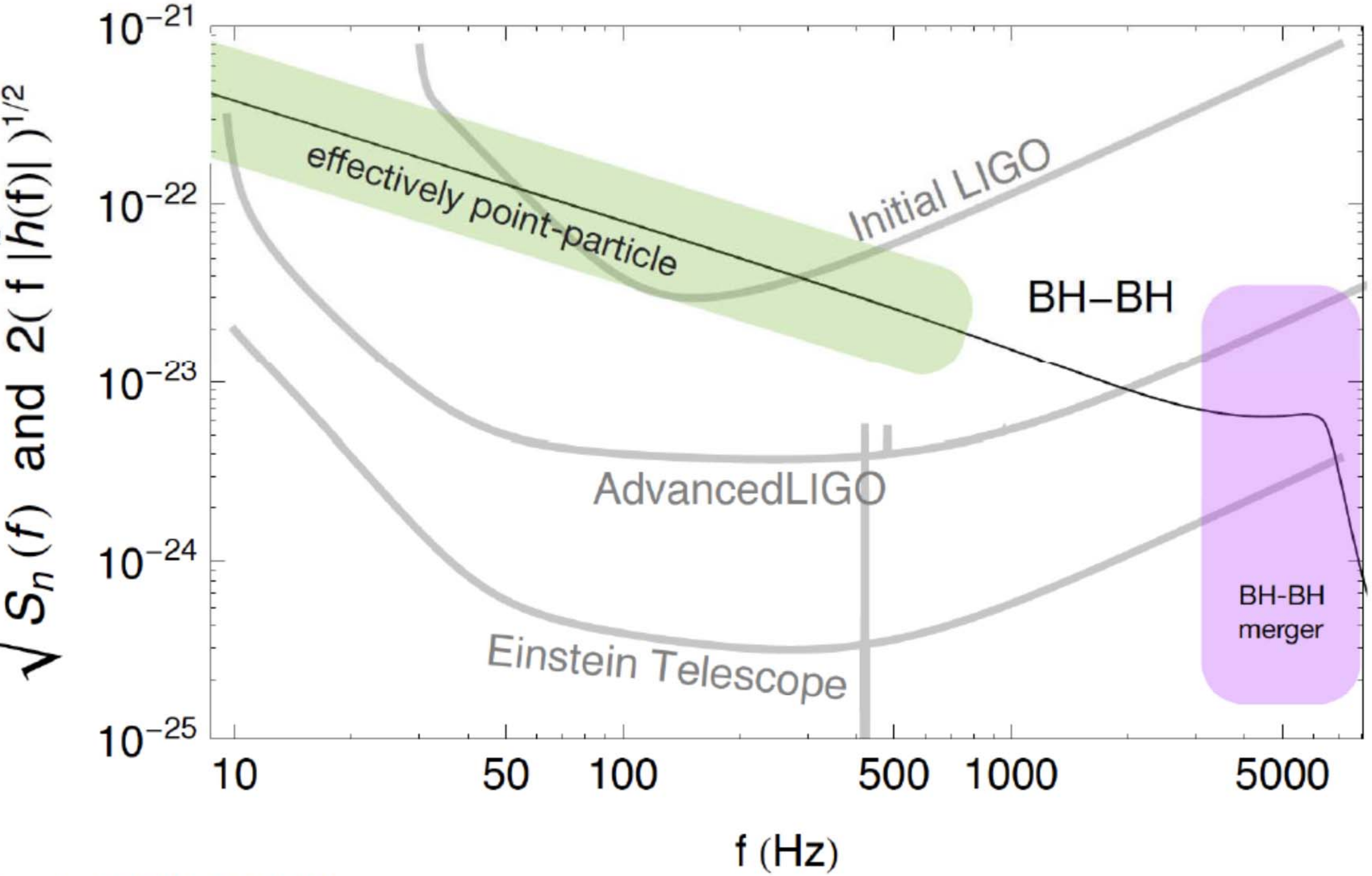
Needs ONLY $P(\rho)$ of NS matter

Modelling NS mergers: hydrodynamics



S. Rosswog, T. Piran and E. Nakar, MNRAS 430, 2585 (2013)
T. Piran, E. Nakar and S. Rosswog, MNRAS 430, 2121 (2013)

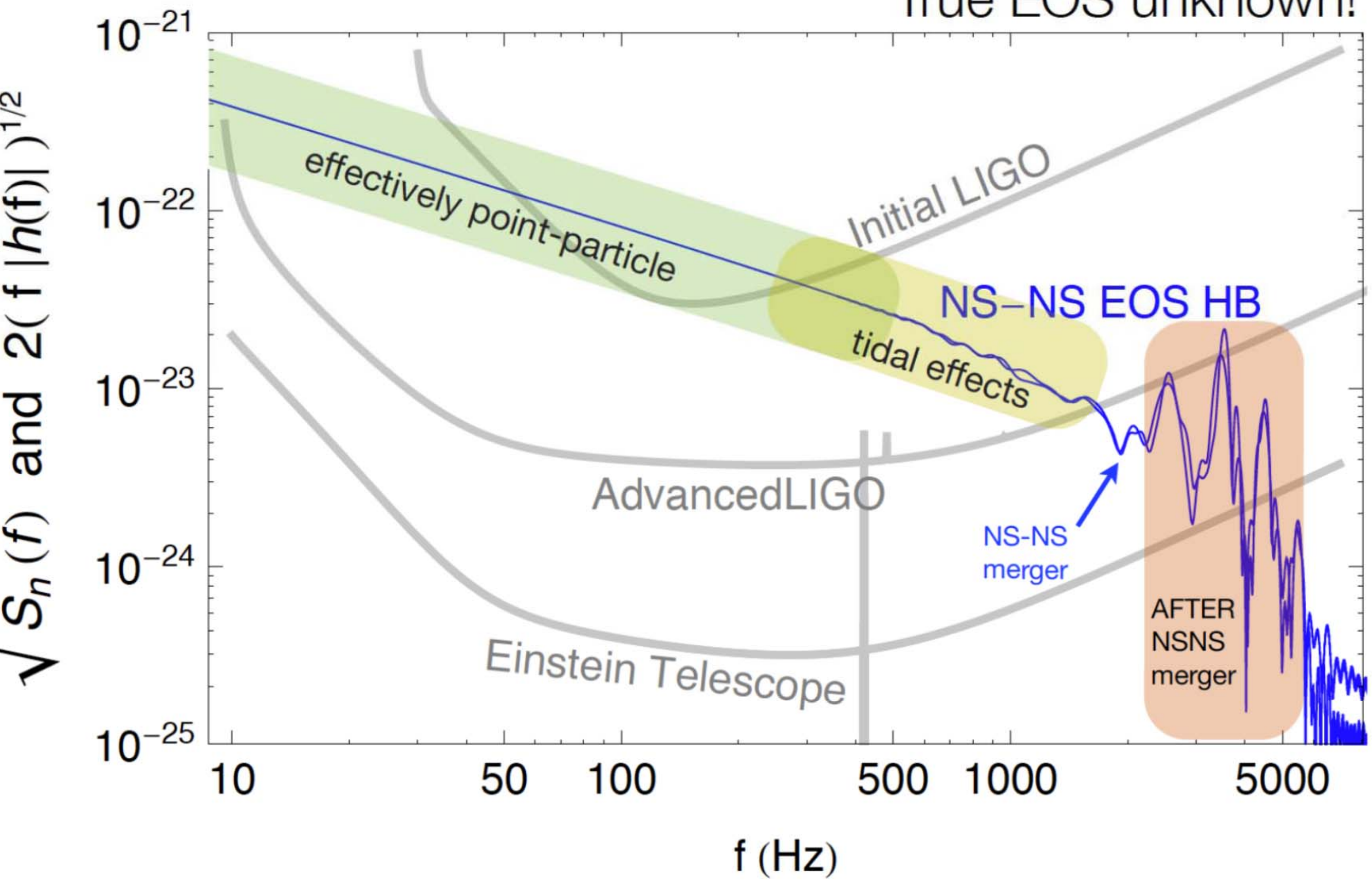
Spectrum of BBH inspiral, scale to 1.35-1.35, 45 Mpc



J. Read, CGWAS 2015

Spectrum of NS-NS inspiral, 1.35-1.35, 45 Mpc

True EOS unknown!



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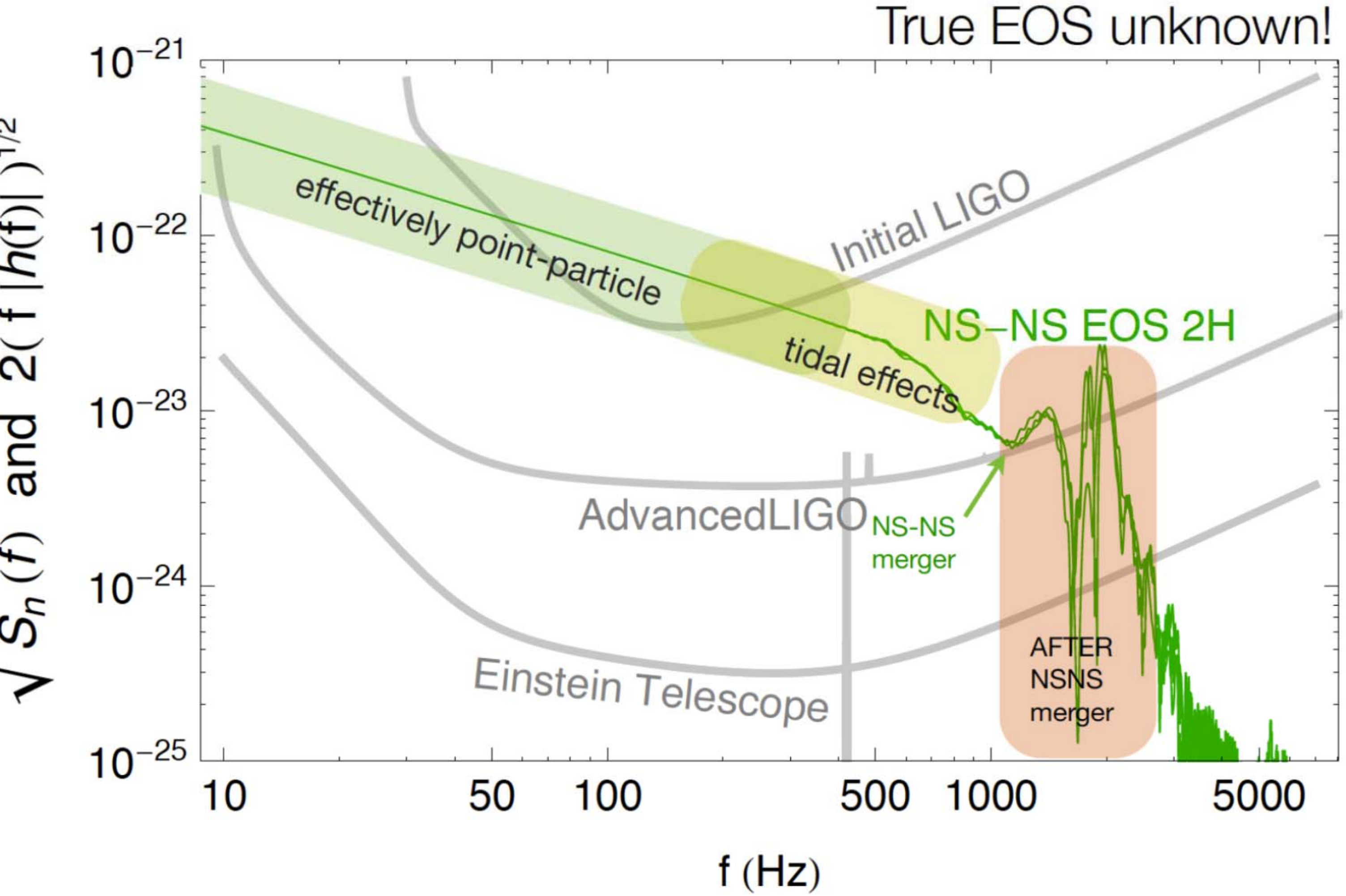
Spectrum of NS-NS inspiral, 1.35-1.35, 45 Mpc



J. Read, CGWAS 2015

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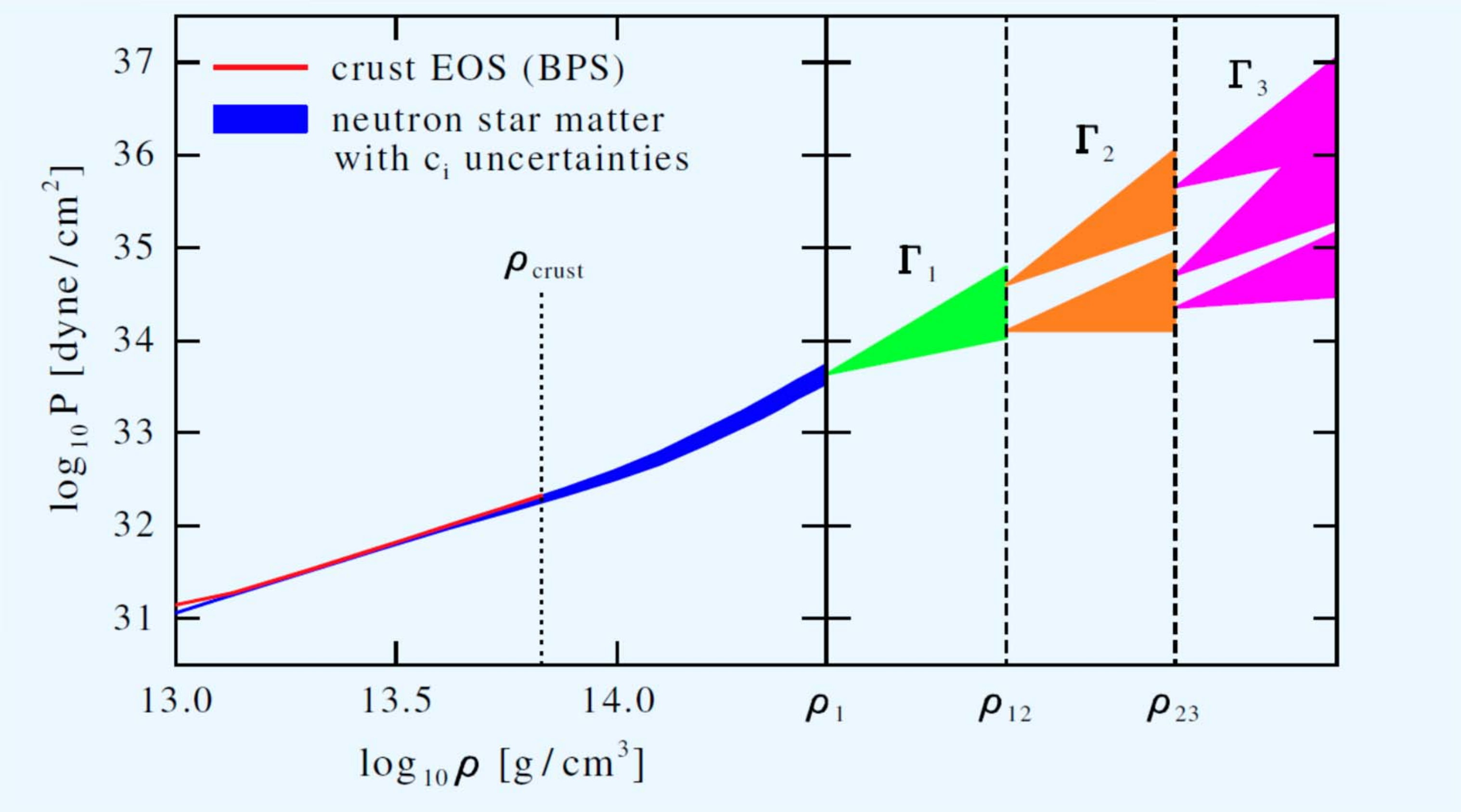
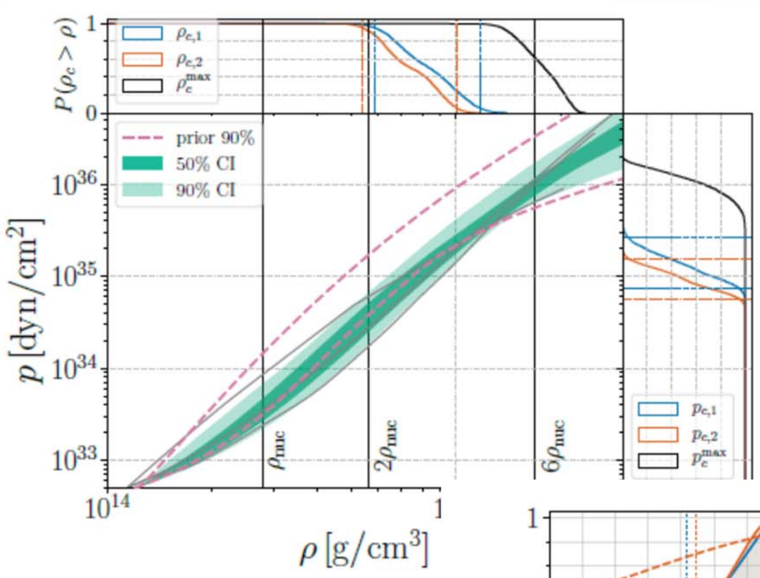
The astrophysicist viewpoint: <O> => P(ρ)



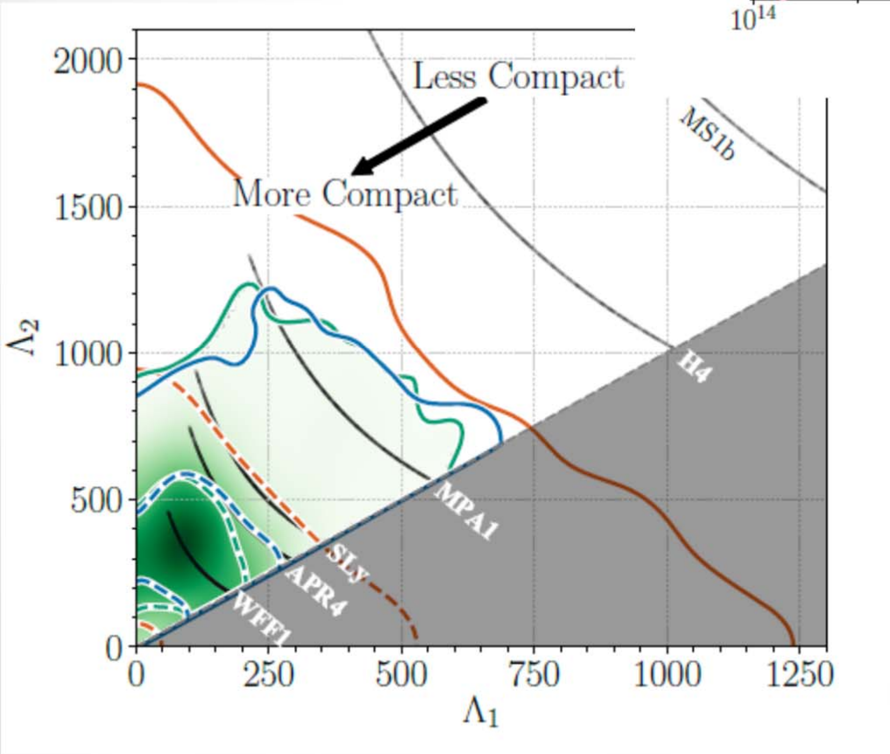
Example: Piecewise polytropic expansion
Steiner Lattimer Brown ApJ 2013

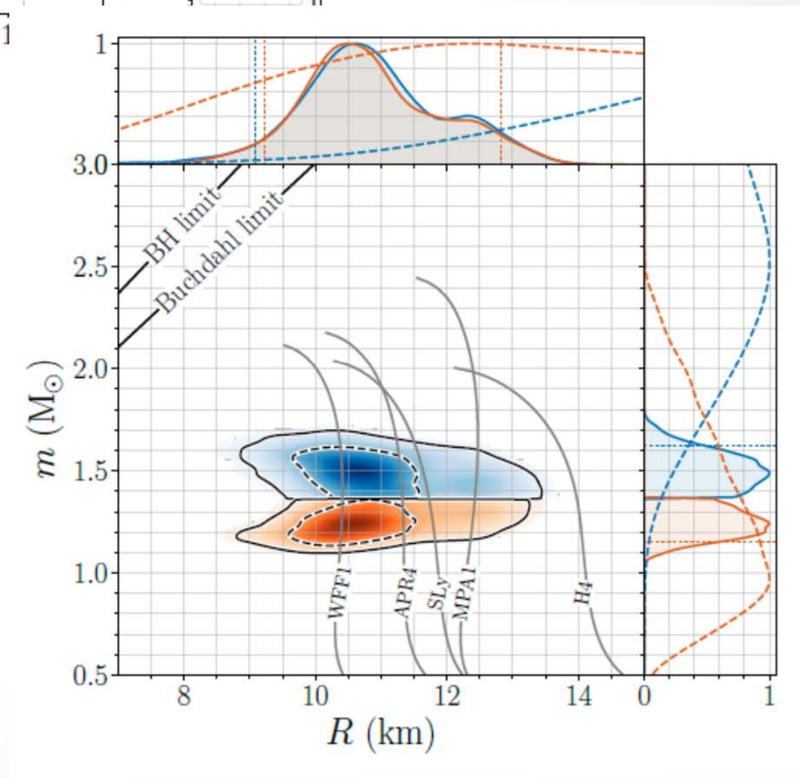
- Recent review: T.E.Riley et al MNRAS 2018

The astrophysicist viewpoint: <O> => P(ρ)



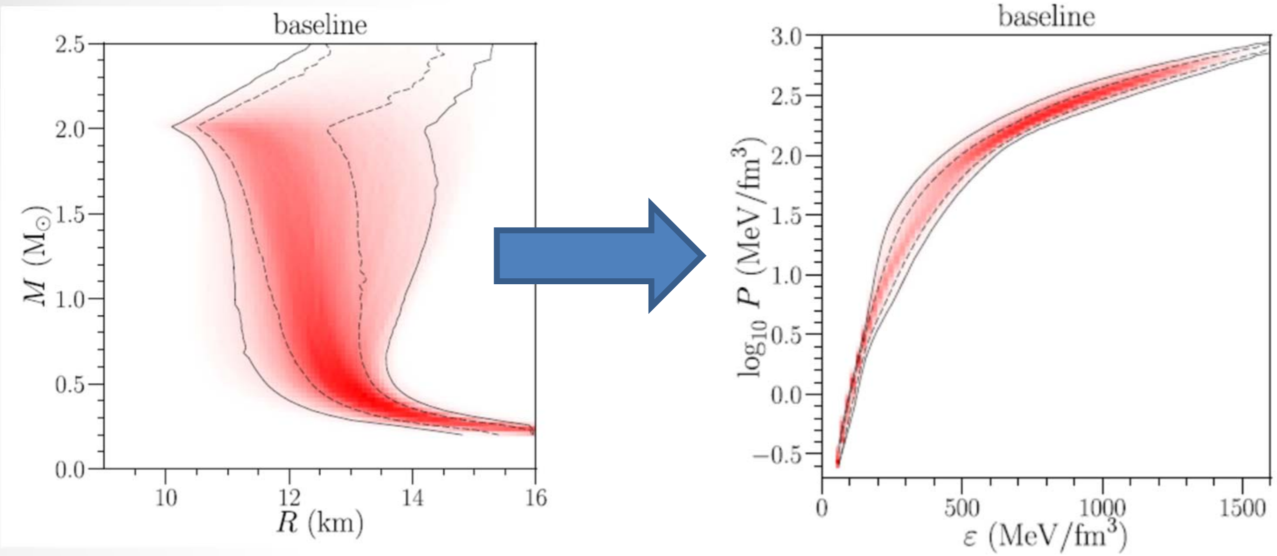
A.Abbott et al, PRL 2018





The astrophysicist viewpoint: <O>=> P(ρ)

A.W.Steiner et al, MNRAS 2018



- (Almost) model independent evaluation of the EoS
- Still, we do not learn much about nuclear physics
- We do not exploit our nuclear physics knowledge either

The nuclear physicist viewpoint: e(ρ) => <O>

- **NS core:** $\rho_q(r) = \rho_q$ ($\forall$ q constituent)

$\Rightarrow \varepsilon_{tot} = \varepsilon_B + \varepsilon_L$ (baryons and leptons decoupled, leptons free FG)

- **Effective single particles:** $e_q(k) = \sqrt{m_q^{*\,2} + k^2} + V_q(\rho_q, \rho_{q'})$

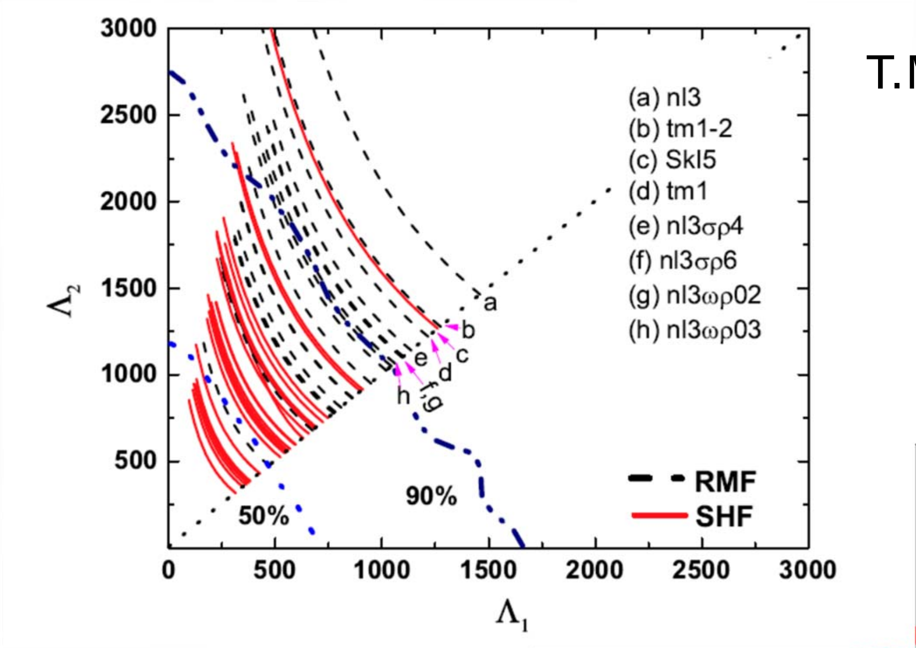
$\Rightarrow m_q^*$, V_q from an effective Hamiltonian (Skyrme, Gogny,M3Y..) or Lagrangian (RMF)

$\Rightarrow$ Coupling constants fitted on nuclear data and/or ab-initio

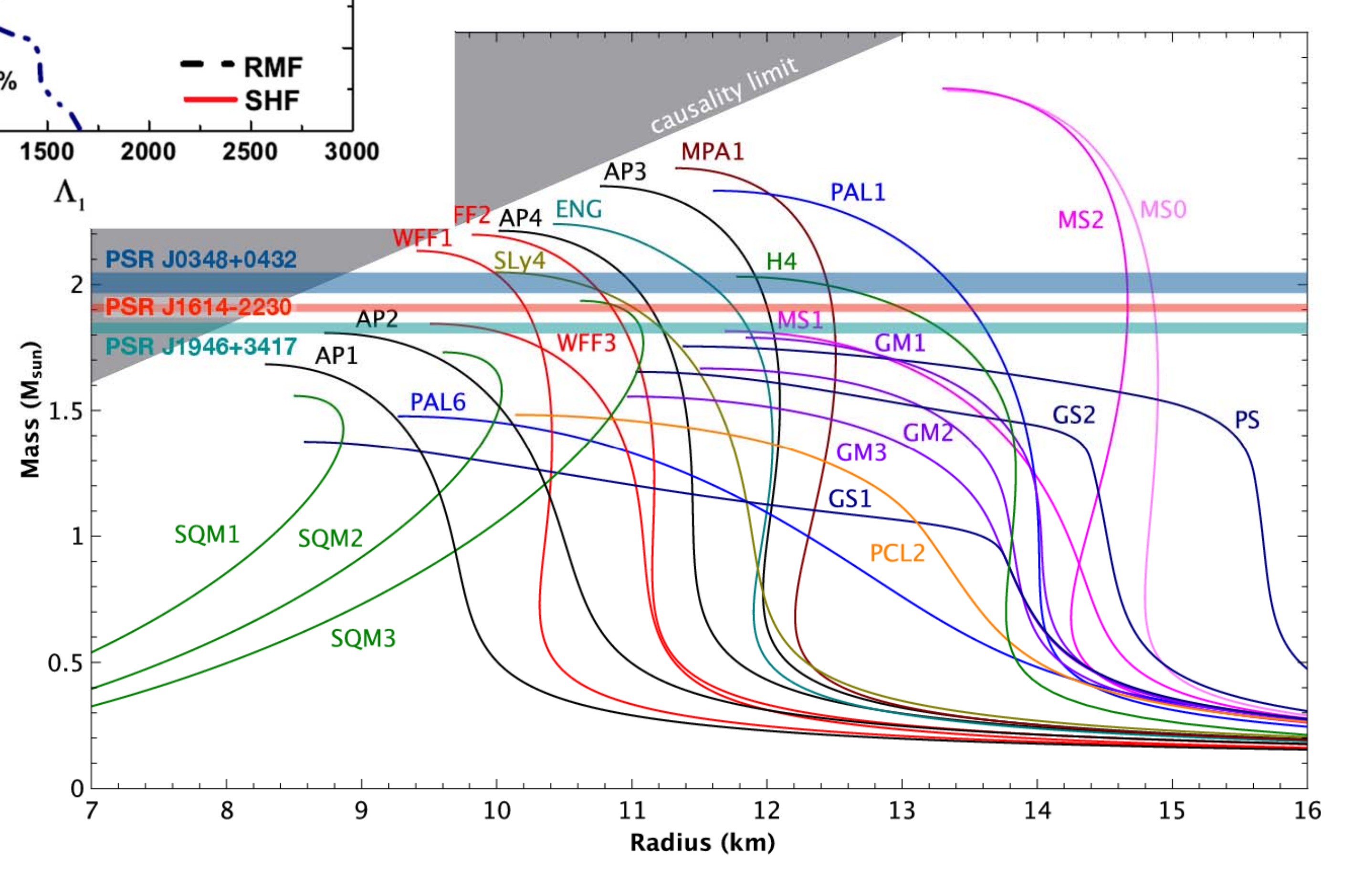
$\Rightarrow e(\rho_B, \rho_L, \rho_S) \quad P(\rho) = -\rho_B^2 \frac{\partial e}{\partial \rho_B}\Big|_{\mu_L=0, \mu_S=0,}$

- **Model dependence: choice of functional form (Lagrangian versus Hamiltonian), fitting protocol, d.o.f. (exotics?) lead to different predictions**

T.Malik ArXiv:180511963



$$\Lambda = \frac{2}{3} k_2 \left(\frac{c^2}{G} \frac{R}{M} \right)^5$$



The nuclear physicist viewpoint: e(ρ) => <O>

- **NS core:** $\rho_q(r) = \rho_q$ (∀ q constituent)

$\Rightarrow \varepsilon_{tot} = \varepsilon_B + \varepsilon_L$ (baryons and leptons decoupled, leptons free FG)

- **« ab-initio » modeling :**

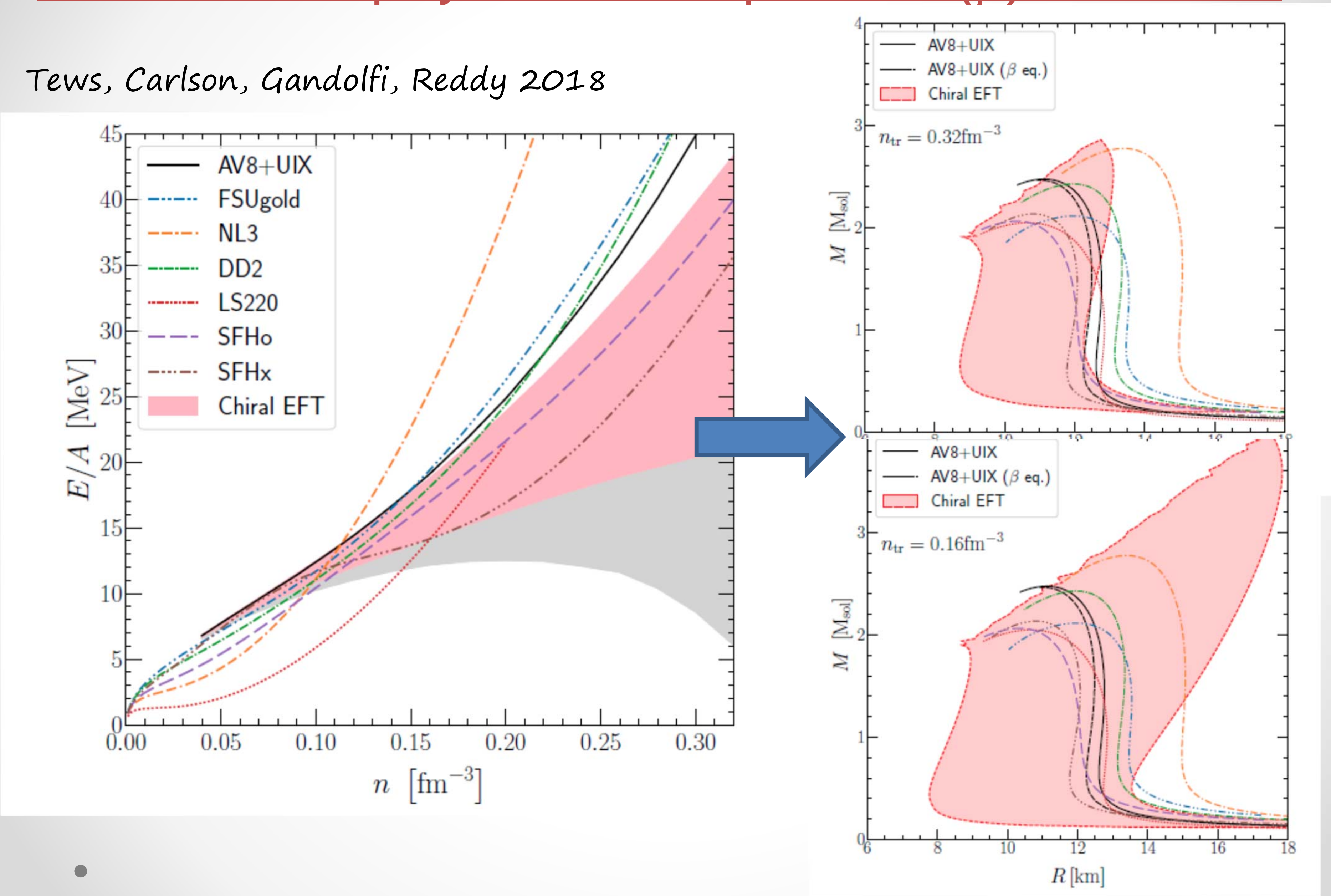
⇒ 2- and 3-body interactions from chiral perturbation theory
⇒ GS from beyond-MF many body techniques (variational, CC,MBPT,QMC...)

⇒ Coupling constants fitted on scattering data and light nuclei
$\Rightarrow e(\rho_n, \rho_p) \quad P(\rho) = -\rho_B^2 \frac{\partial e}{\partial \rho_B}\Big|_{\mu_n - \mu_p = \mu_e,}$

- **Diagrammatic expansion: controlled uncertainties!**
- **Still, power counting&regularization valid only up to ~ 2ρ_0**
- **Extrapolations needed**

The nuclear physicist viewpoint: e(ρ) => <O>

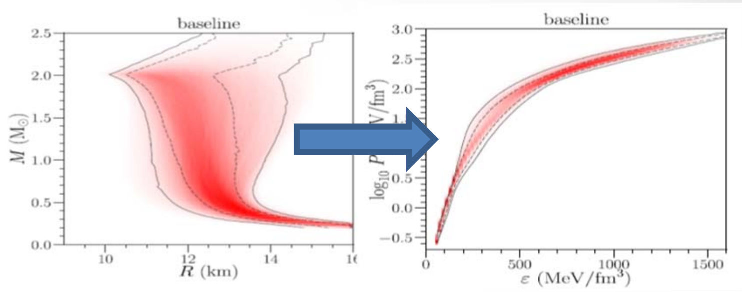
Tews, Carlson, Gandolfi, Reddy 2018



...a brief summary <O>⇔ *P*(ρ)

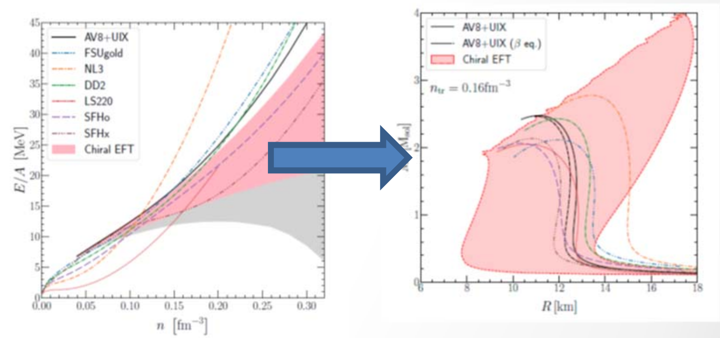
The astrophysicist viewpoint: <O>=> P(ρ)

- (Almost) model independent evaluation of the EoS
- Still, we do not learn much about nuclear physics



The nuclear physicist viewpoint: e(ρ) => <O>

- Controlled dof, hypotheses and approximations, exp data included
- Still, the predictive power is limited



A nuclear-astrophysicist viewpoint: meeting in the middle...

Meta-modeling

A.Steiner et al ApJ 2010
A.Bulgac et al 2016
J.Margueron, R.Casali FG PRC 2018
Y. Lim, J.W. Holt, PRL 2018,PRC 2019

- **Flexible functional** $e(\rho, y_e)$ **able to reproduce existing EDF and interpolate between them** (large parameter space):
- Parameters such that **empirical nuclear physics info** can be included

Taylor expansion around saturation

$$x = \frac{\rho - \rho_0}{\rho_0}$$

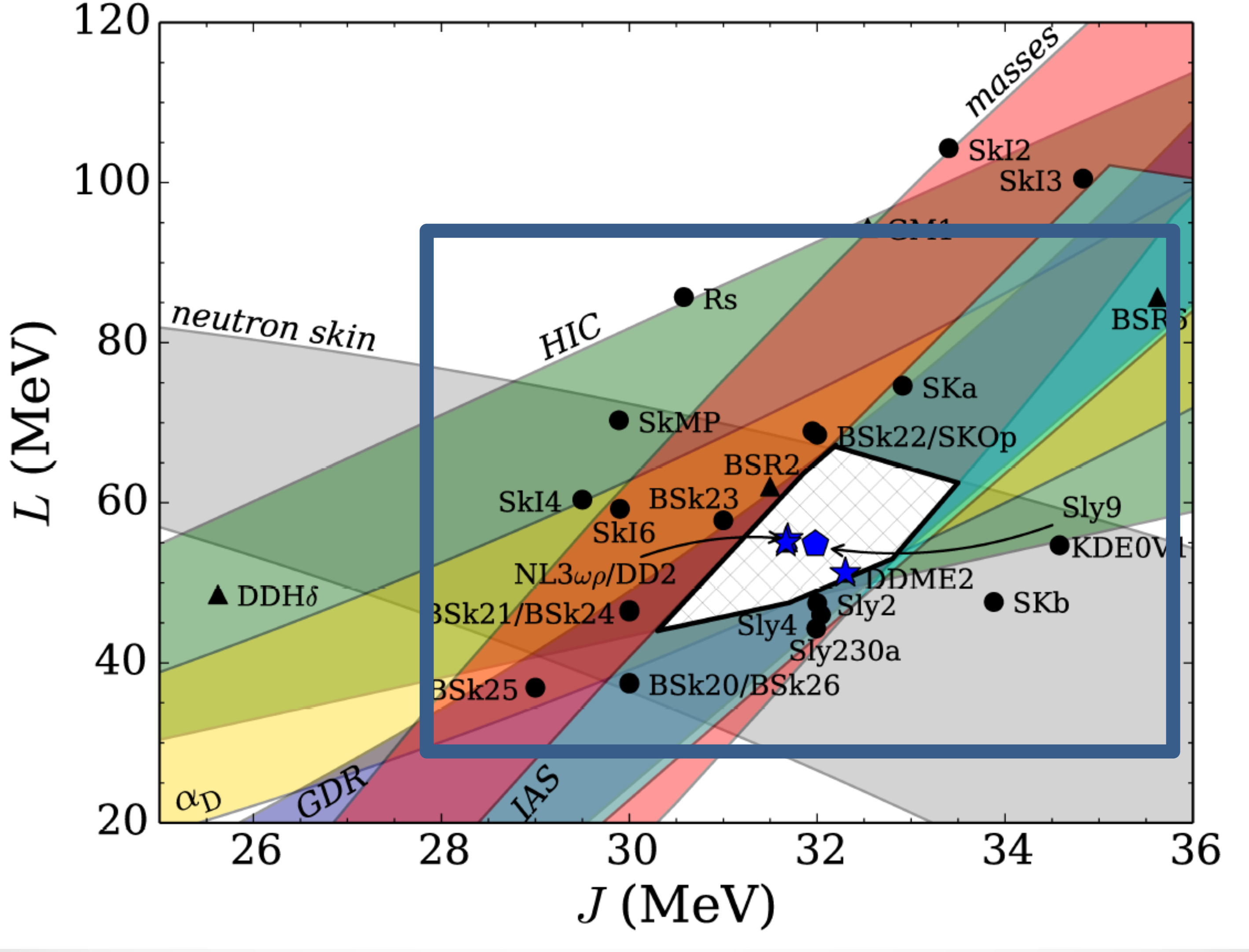
$$e(\rho, y_e) = e_{FG} +$$

$$+\left(\boldsymbol{E_0} + \frac{1}{18}\boldsymbol{K_0}x^2 + ..\right) + \left(\boldsymbol{J_{sym}} + \frac{1}{3}\boldsymbol{L_{sym}}x + \frac{1}{18}\boldsymbol{K_{sym}}x^2 + ..\right)\left(1 - 2\frac{y_e}{\rho}\right)^2$$

- $\vec{X}$ =$(E_0, K_0, J_{sym}, L_{sym}, K_{sym}, m^*, ..)$ EDF⇔parameter set
- $\vec{X}$ = random variable
- Prior $P(\vec{X})$: uncorrelated distribution within empirical uncertainties

Prior parameter distribution: empirical constraints

M.Fortin et al PRC 2016



J.Margueron, R.Casali FG PRC 2018

Nuclear meta-modeling

$\vec{X} = (E_0, K_0, J_{sym}, L_{sym}, K_{sym}, m^*, ..)$ parameter set⇔EDF

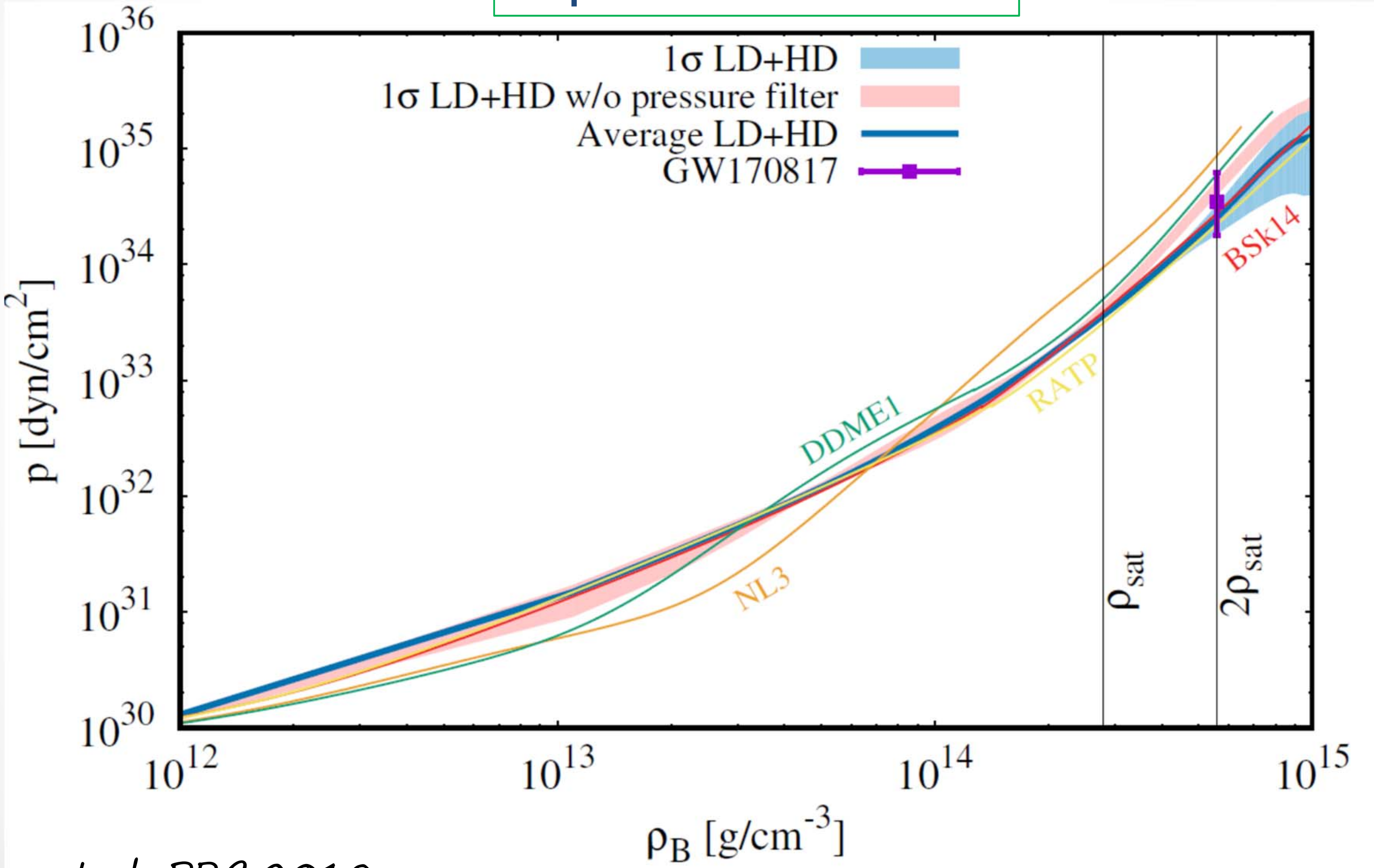
- Bayes theorem: $P(\vec{X}|w) = \frac{P(w|\vec{X})P(\vec{X})}{P(w)}$ ← Prior
- Filters w:
  - ab-initio EoS (LD)
  - NS observation (HD)
  - Nuclear masses

  ……
- Observable calculation: $P(Y|w) = \int d\vec{X}\, Y(\vec{X}) P(\vec{X}|w)$

- **Quantify the reliability of the different EDF**
- **Predict astro observables with controlled uncertainty intervals**

(I) Quantify the reliability of the different EDF

Equation of state



T.Carreau et al, PRC 2019

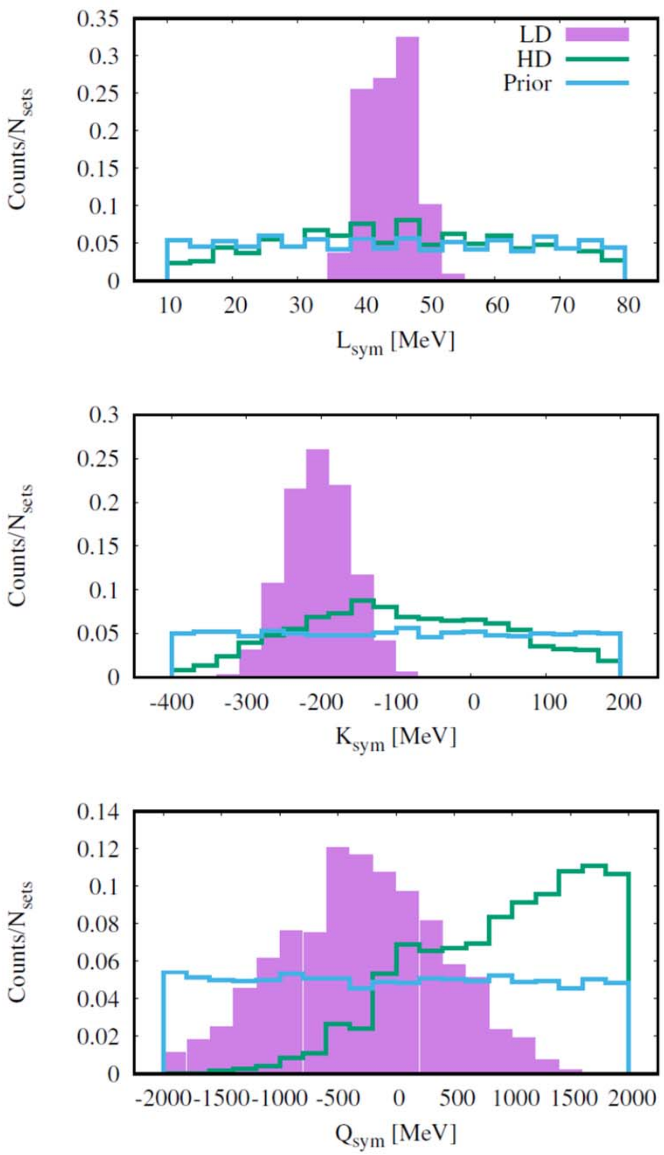
(I) Quantify the reliability of the different EDF

Parameter distribution

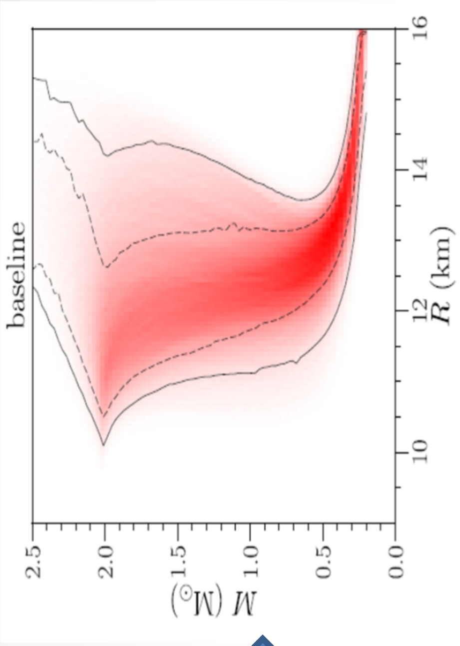
Parameter	Unit	Prior		HD		LD	
		Min	Max	Average	σ	Average	σ
n_{sat}	fm^{-3}	0.15	0.17	0.1600	0.0060	0.1641	0.0049
E_{sat}	MeV	-17	-15	-16.01	0.61	-15.29	0.25
K_{sat}	MeV	190	270	229	24	234	23
Q_{sat}	MeV	-1000	1000	200	535	-31	362
Z_{sat}	MeV	-3000	3000	1038	1233	-146	1728
E_{sym}	MeV	26	38	33.53	3.48	30.71	0.76
L_{sym}	MeV	10	80	45.45	17.97	43.66	3.68
K_{sym}	MeV	-400	200	-92	136	-202	42
Q_{sym}	MeV	-2000	2000	913	740	-253	673
Z_{sym}	MeV	-5000	5000	1463	2216	-114	2868
m^*_{sat}/m		0.6	0.8	0.70	0.06	0.70	0.06
$\Delta m^*_{sat}/m$		0.0	0.2	0.10	0.06	0.10	0.06
b		1	10	5.3	2.7	5.2	2.6

J.Margueron, R.Casali FG PRC 2018

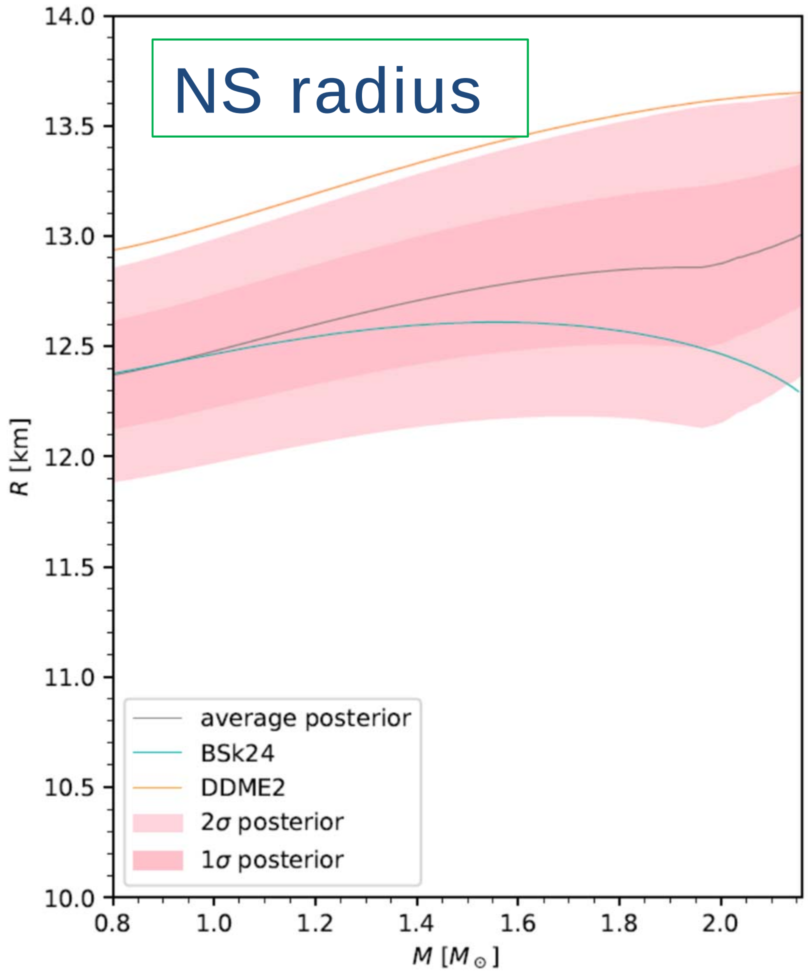
T.Carreau et al, EPJA 2019



(II) Predict astro observables with controlled uncertainties :

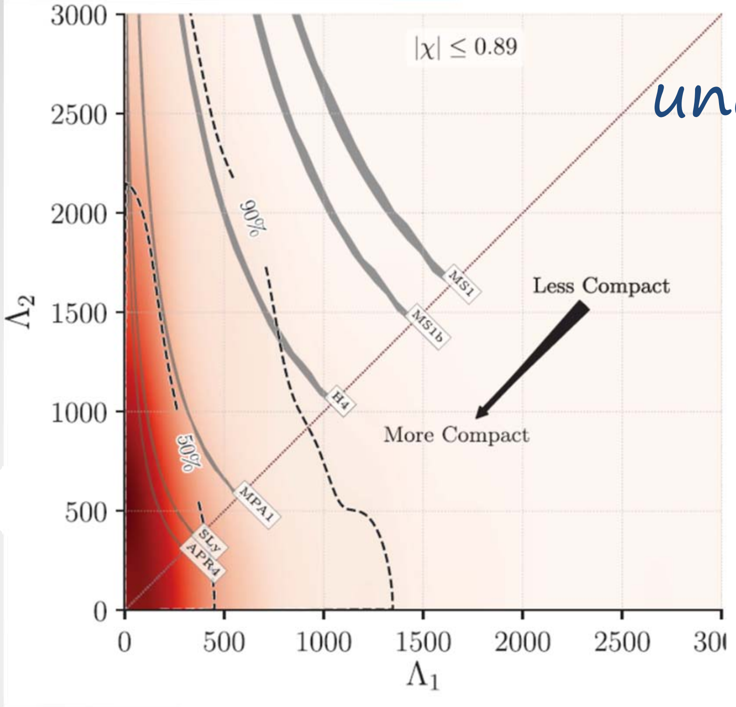


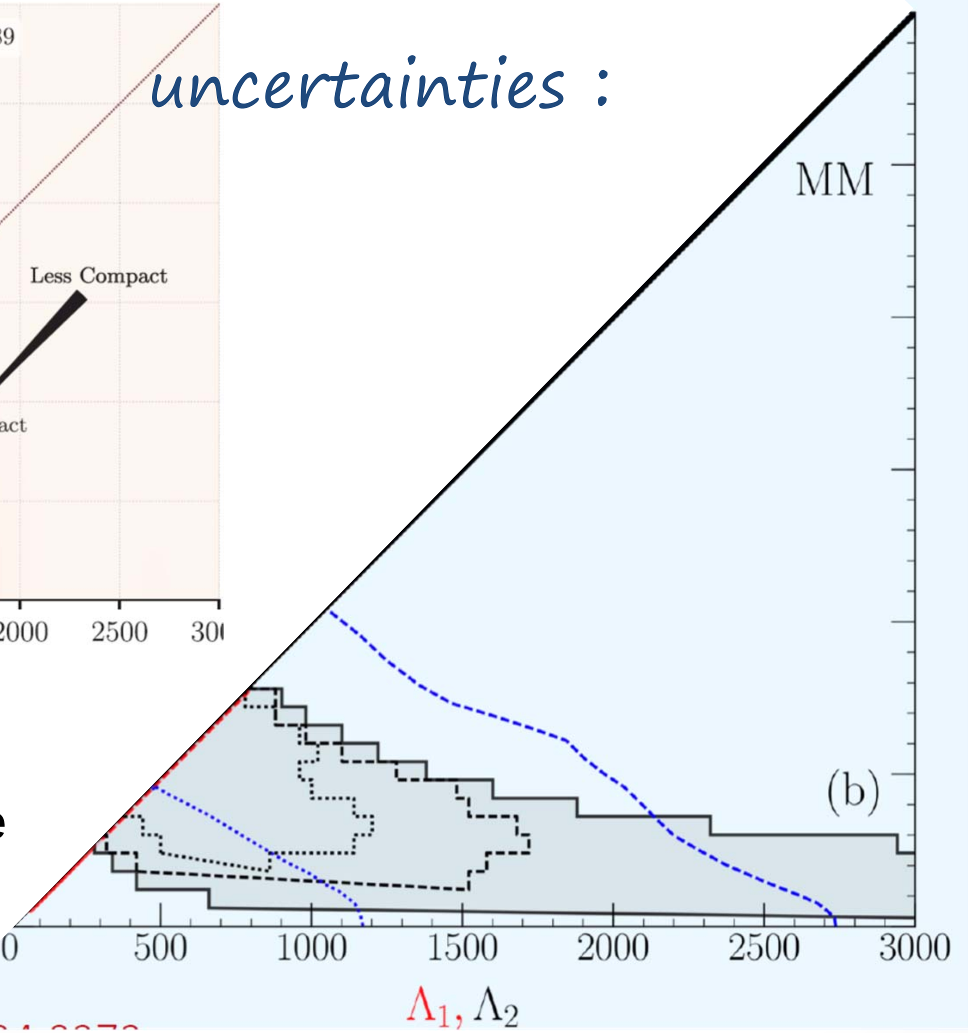
From astro constraints only



Meta-modelling

(II) Predict astro observables with controlled uncertainties :





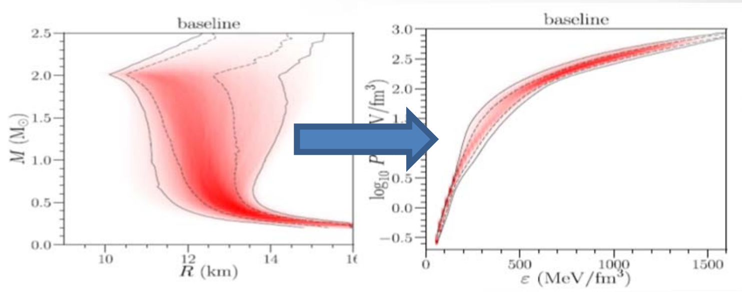
Compatible with GW2017 and more constraining!

I.Tews, J.Margueron, S.Reddy, PRC 2018

...a brief summary

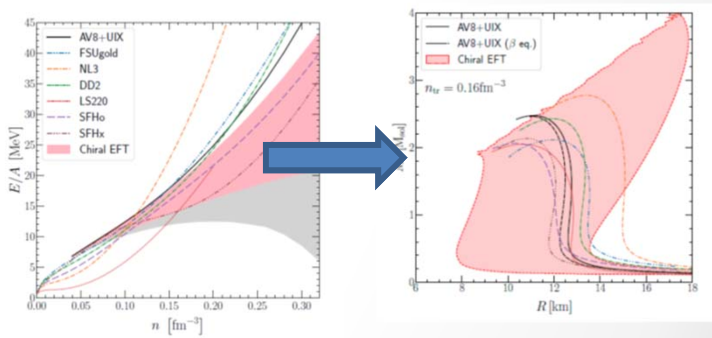
The astrophysicist viewpoint: <O>=> P(ρ)

- (Almost) model independent evaluation of the EoS
- Still, we do not learn much about nuclear physics



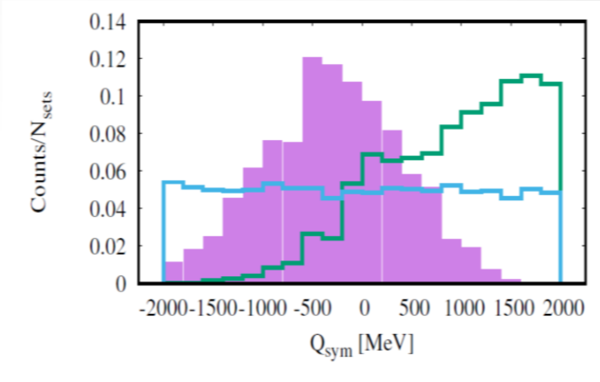
The nuclear physicist viewpoint: e(ρ) => <O>

- Controlled hypotheses and approximations, exp data included
- Still, the predictive power is limited



A nuclear astro-physicist viewpoint: e(ρ) <=> <O>

- Meta-modelling: largely explore the parameter space and build posterior distributions based on nuclear **AND** astrophysical constraints

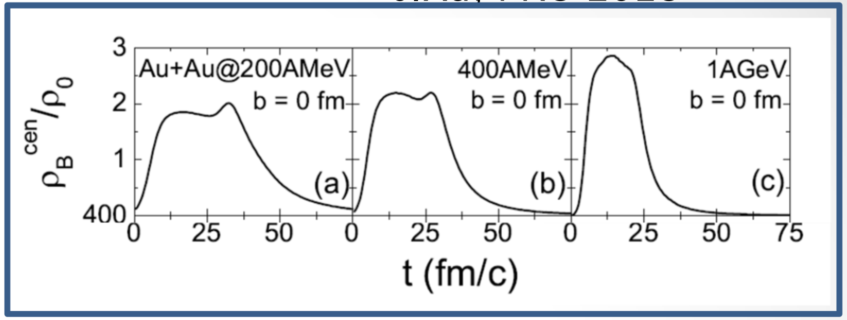


Residual uncertainty: high order parameters => high density EoS

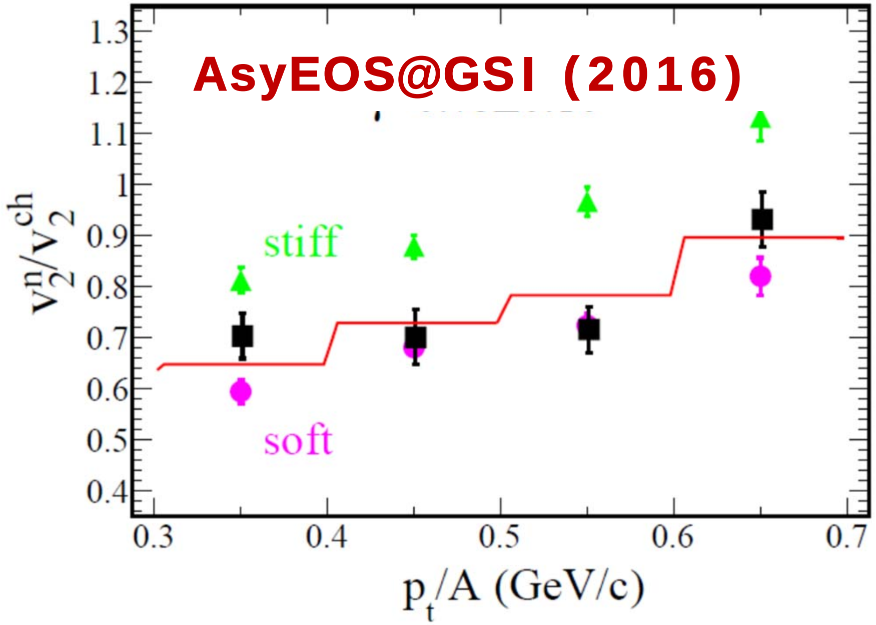
How to further constrain the high density EoS from laboratory data?

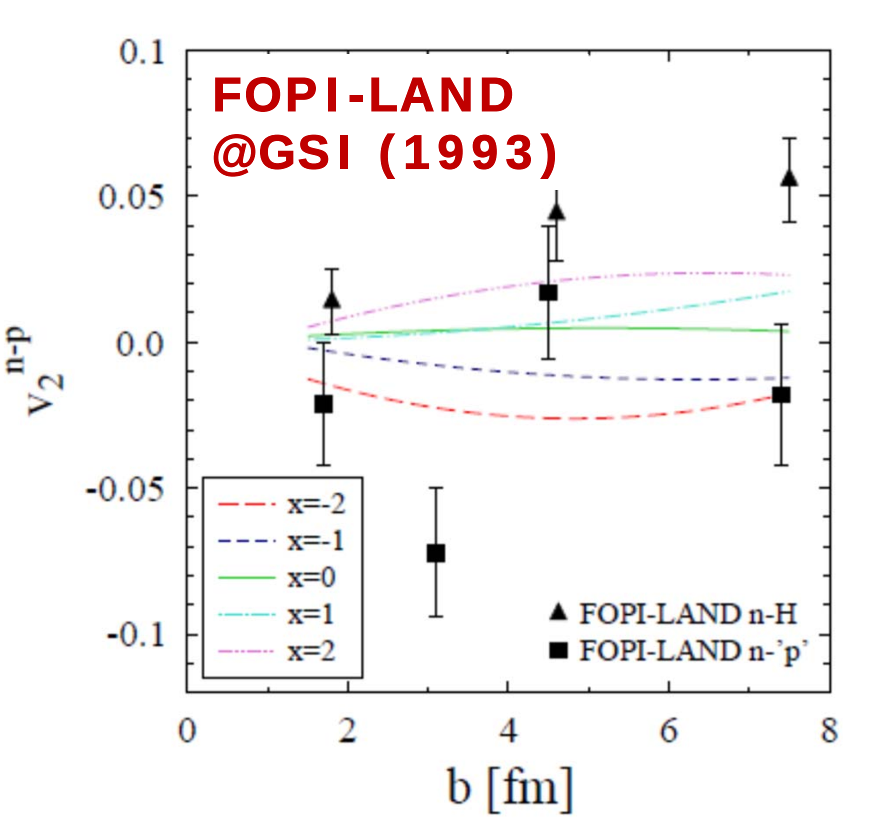
Strategy I: high density constraints

J.Xu, PRC 2013



P.Russotto et al,PRC 2016

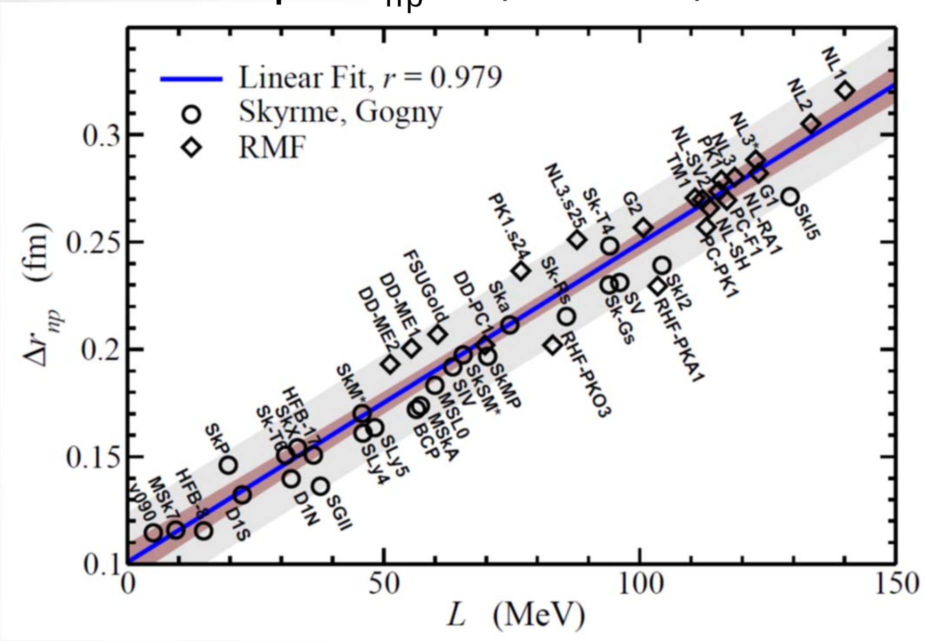




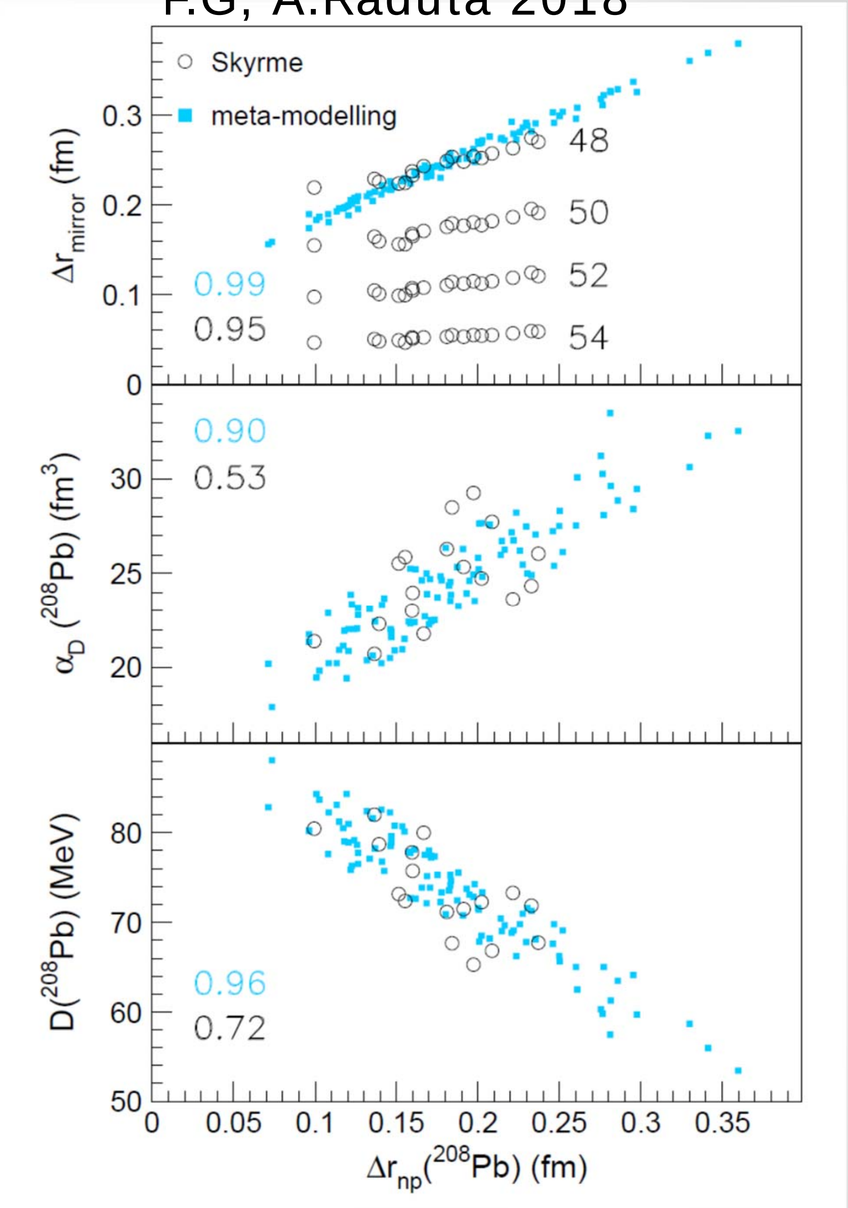
Differential elliptic flow for Au+Au 400 A.MeV

Strategy II: high precision

Exp: Δr_{np}= 0,1318-0,3072

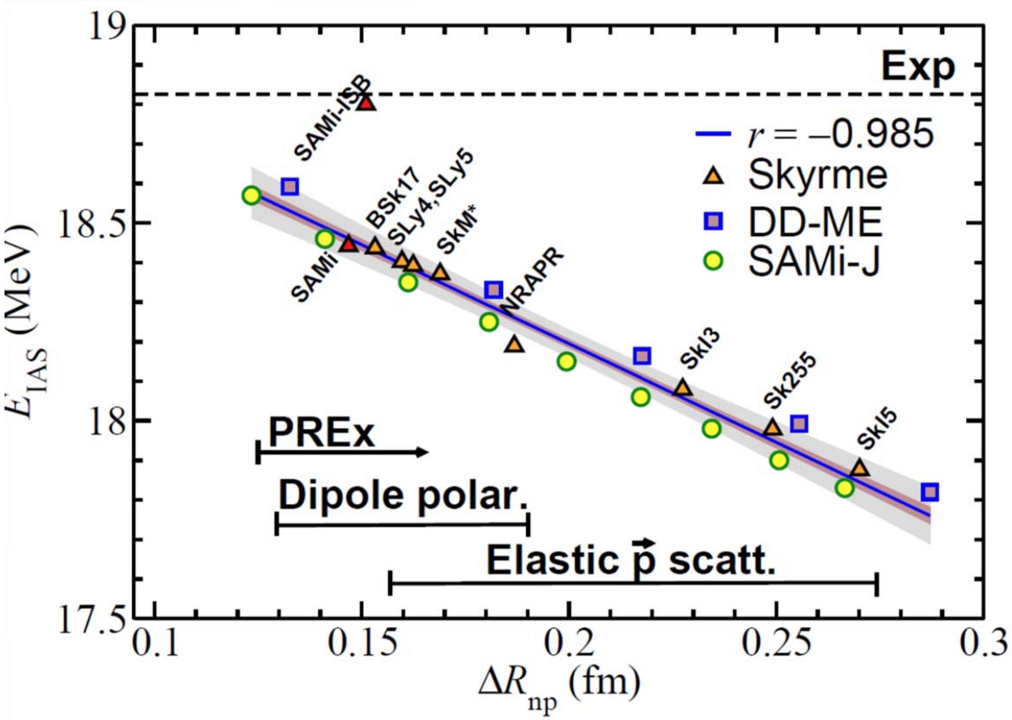


F.G, A.Raduta 2018



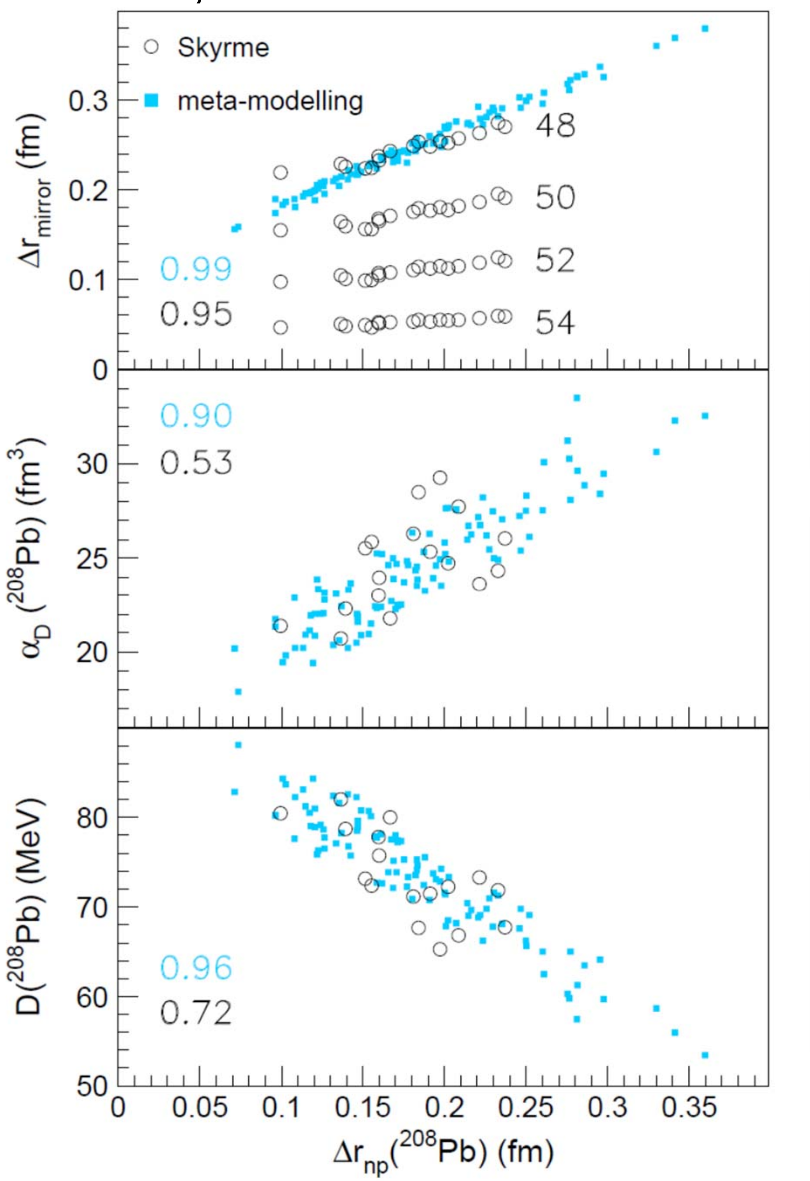
X.Vinas et al 2014
P.G.Reinhard, W.Nazarewicz 2016
D.Chatterjee, F.G. 2017
J.Yang, J.Piekarewicz 2017

Strategy II: high precision



X.Roca-Maza, G.Colo, H.Sagawa 2018

F.G, A.Raduta 2018



- Recent review: X.Roca-Maza, N.Paar Prog.Part.Nuc.Phys.2018

Lectures plan

1. Introduction: dense matter in the universe
   a. The sites
   b. The signals
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   a. Observations
   b. Hydrostatics and the EoS
   c. Constraining the parameters
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   a. **Phase transitions in dense matter**
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   c. The physics of the crust
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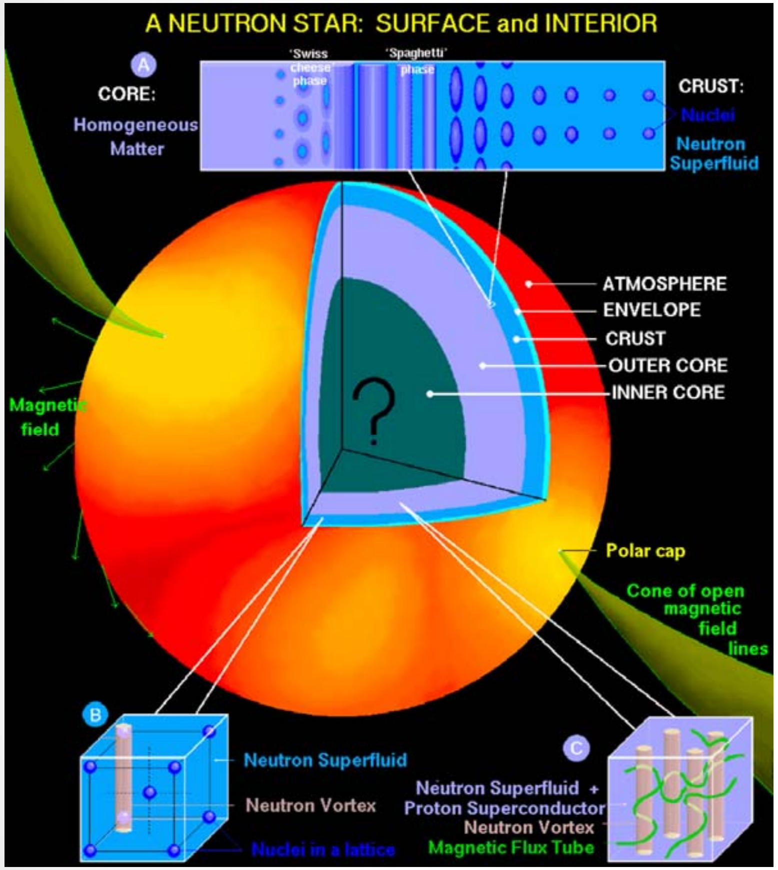
   c. Influence of nuclear physics

Phase transitions in dense matter

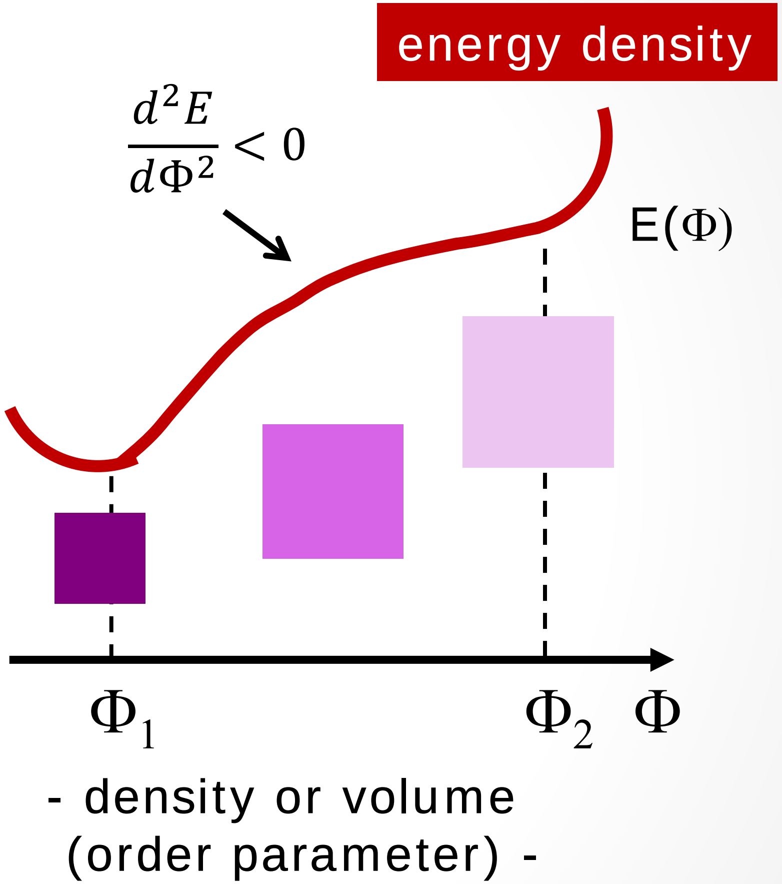


Picture: D.Page

- nuclear data or ab-initio calculations only concern low densities
- Extrapolation suppose that the EoS is an analytic function
- This is not the case if phase transitions occur
- From the core to the crust (S-sF)?
- From the outer to the inner core (sF-QgP)?

Phase transitions: generalities

- Phase transitions are signalled by instability of homogeneous matter towards phase separation
- => Convexity of the energy functional



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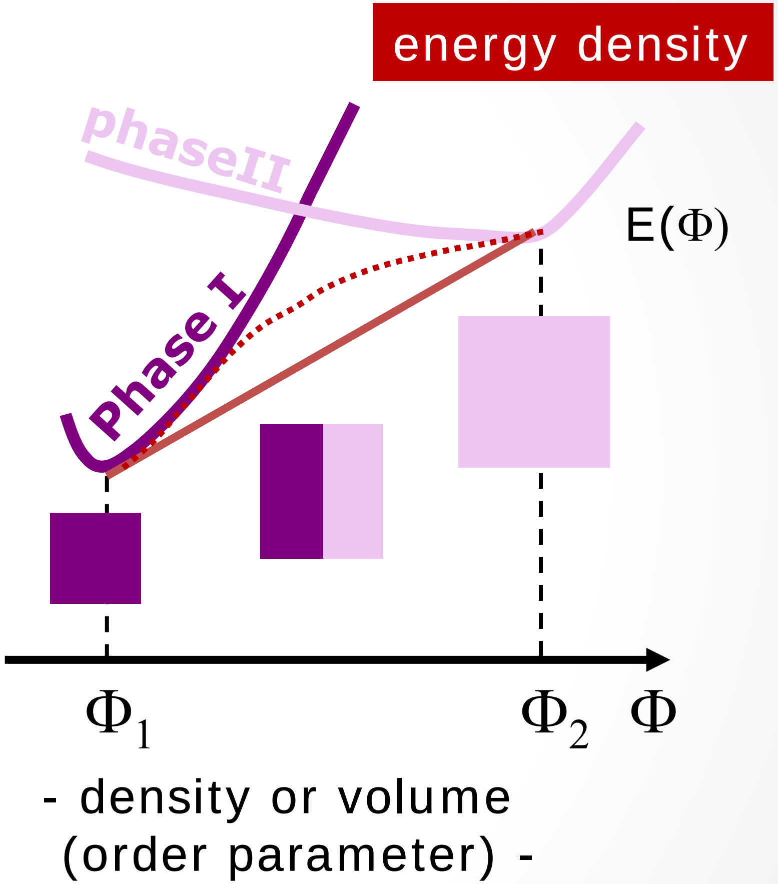

Here: single order parameter (1D space)

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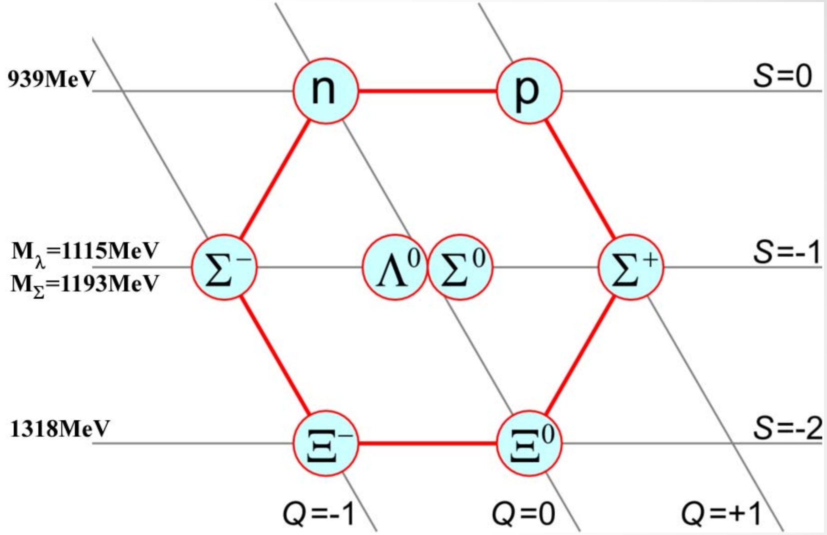
Transitions in the core

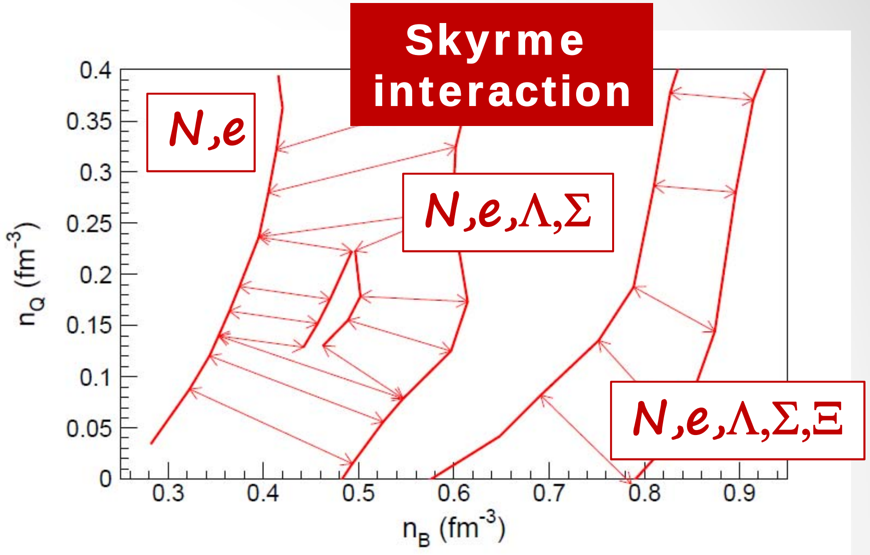
Hadronic matter: the baryon octet



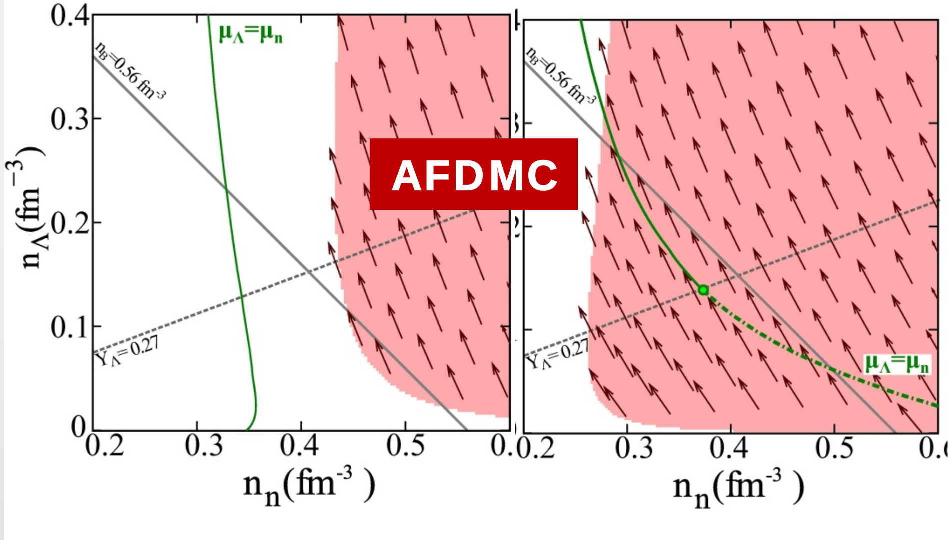
- If $\mu(\rho) > m_Y c^2 + U_Y$, hyperon Y should appear
- **Transition to strange matter?**
- Equilibrium of strong interactions: three densities n_Q, n_B, n_S
- $\frac{d^2E}{d\Phi^2} < 0 \Rightarrow C = \det \frac{\partial^2 E}{\partial n_{ij}}$

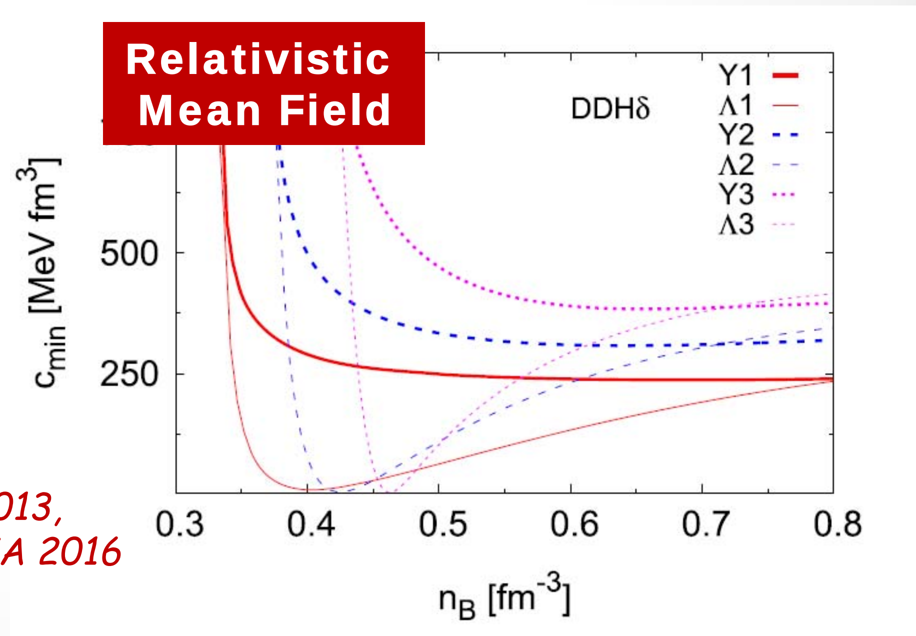
Transitions in the core

- Results are extremely model dependent



J.Torres, F.G.,D.Menezes, PRC 2016



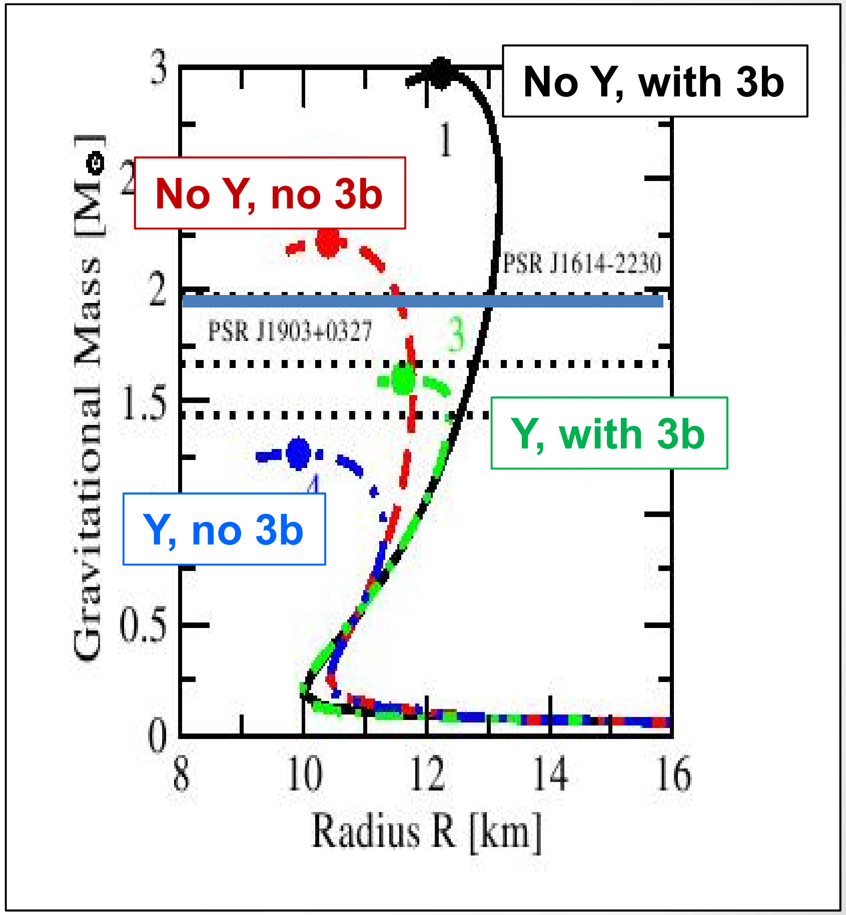


F.G.,A.Raduta and M.Oertel, PRC 2012, PRC 2013, JPhysG 2015, EPJA 2016

-

The hyperon puzzle

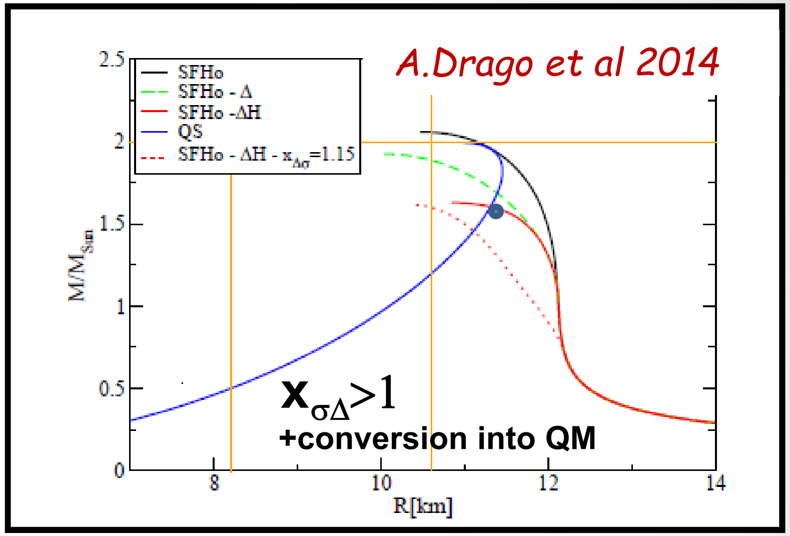
- The highest mass is associated to the highest central density.
- If $\mu(\rho) > m_Y c^2 + U_Y$, hyperon Y should appear
- The appearence of a new degree of freedom softens the EoS=>reduces the mass
- $2M_O$ neutron star should not exist if U_Y is calculated with microscopic BHF based on experimental bare interactions

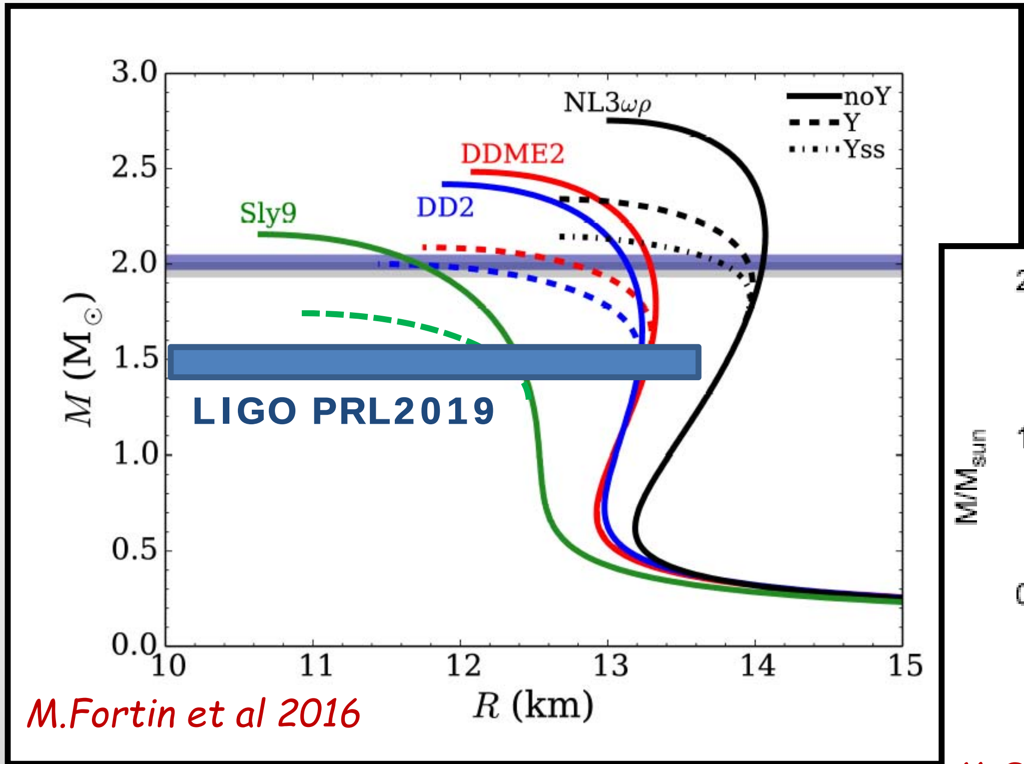


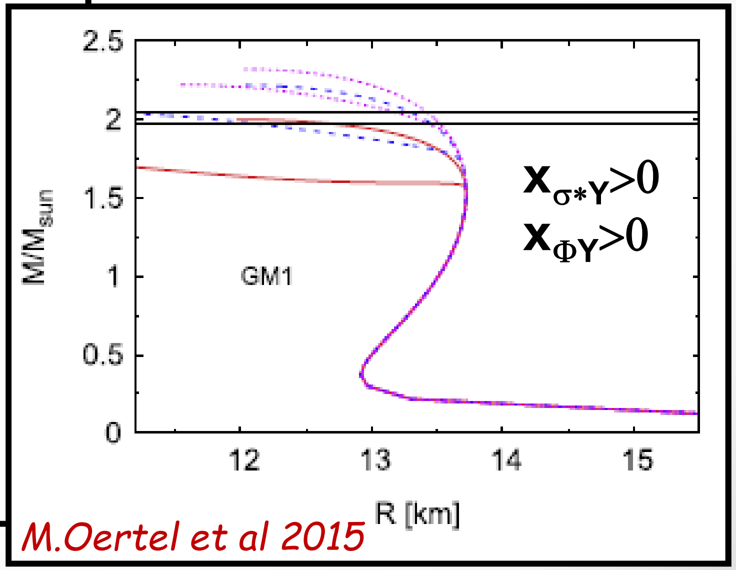
I.Vidana et al, Europhys.Lett.94:11002,2011

The hyperon puzzle: solutions

- Stiffening of the EoS above rho0?
- New strangeness couplings at high density ?
- **Transition to quark matter ?**







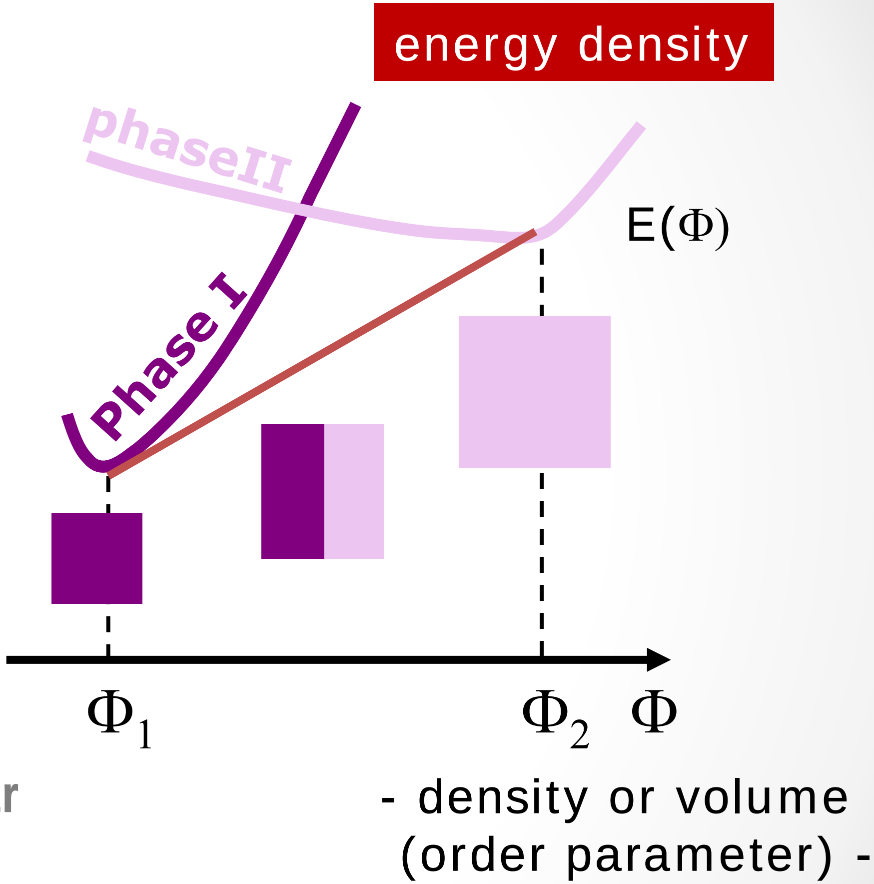
Transitions in the core

Deconfined matter: free quarks u,d,s => $E(n_B,n_S,n_Q)$

- No unified model for confined and deconfined matter
- Effective model (no confinement, no gluons) in the quark phase: MIT, NJL, (P)NJL, QMDD… w/wo color superconductivity (2SC, CFL phases)
- $e_{sdu}(\rho) < e_{had}(\rho)$ => hybrid star
- $\boldsymbol{e_{sdu}(\rho_{eq}) < 930}$ **MeV**

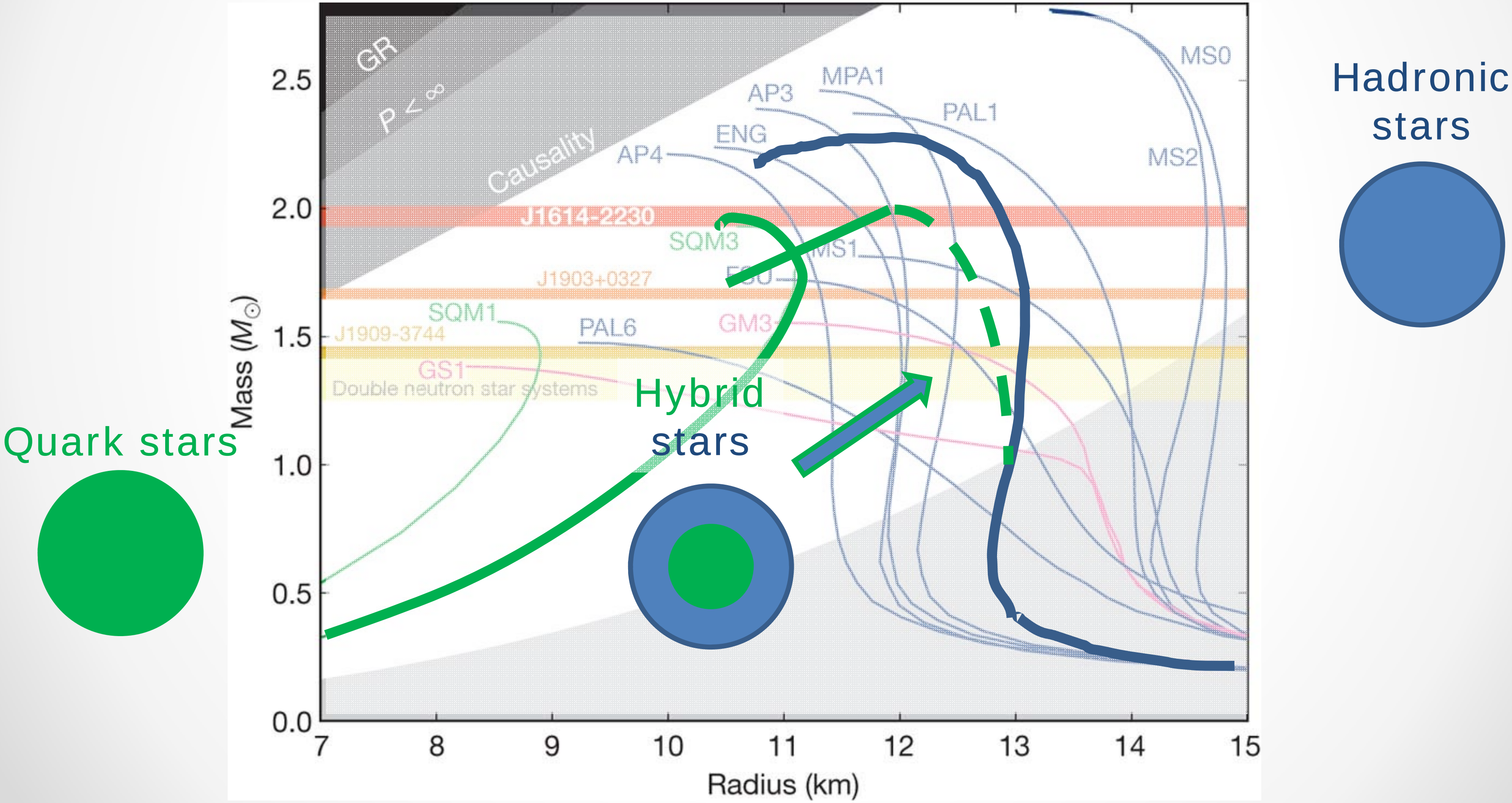
=> Absolutely stable SQM =>quark star

- Results are extremely model dependent

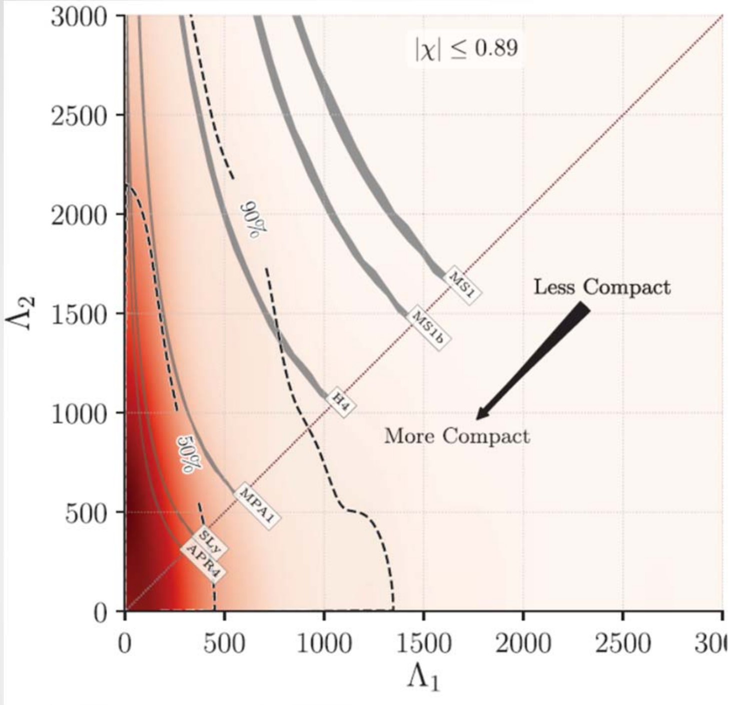


A nice collection of recent results: special issue EPJA 52 (2016)

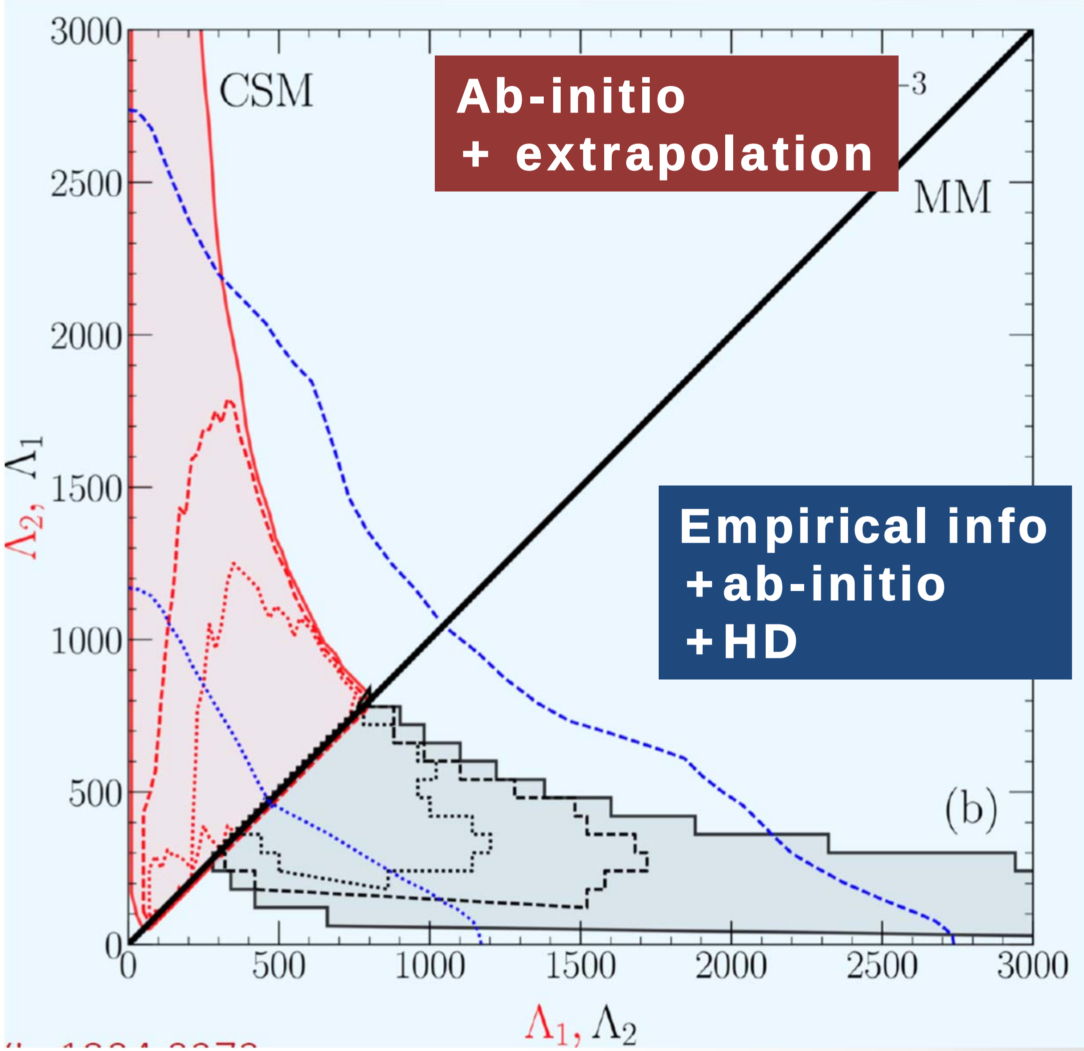
Conclusion: three possible families of neutron stars



Effect of transitions in the core



No more constraining than GW2017!



Ab-initio
+ extrapolation

Empirical info
+ab-initio
+HD

I.Tews, J.Margueron, S.Reddy, PRC 2018

...a brief summary

- The hyperonic component of a NS must be very small for the models to be compatible with NS mass measurements => a microscopic explanation is still missing

J0348+0432

- The possible presence of deconfined matter in the inner core of neutron stars is still not clearly established=> future more precise measurements of the tidal polarizability via GW might allow to conclude

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Phase transitions: generalities

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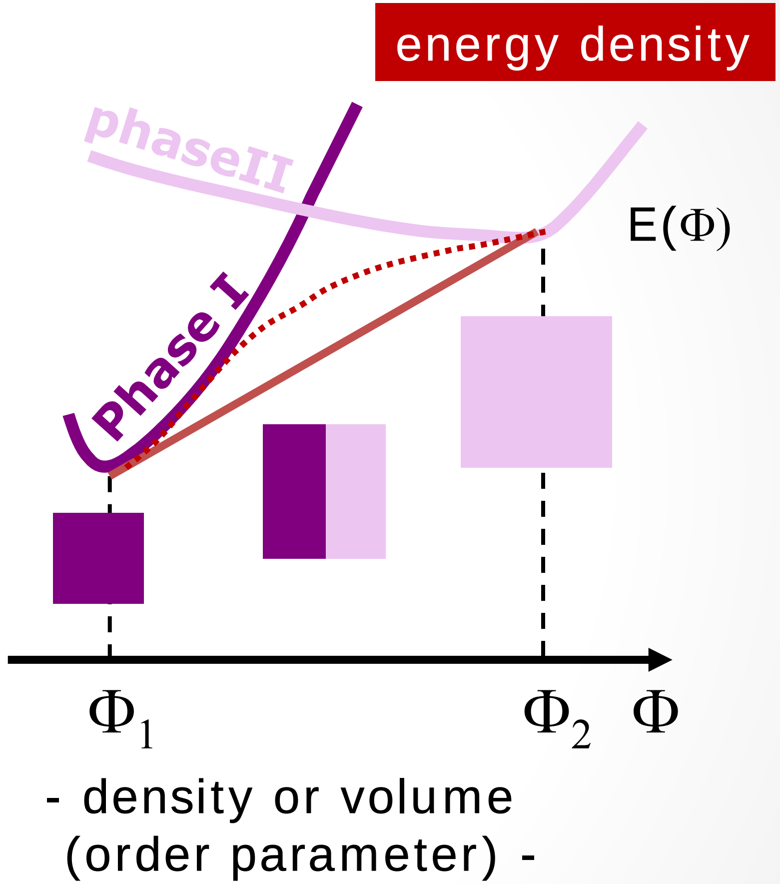
- => Convexity of the energy functional

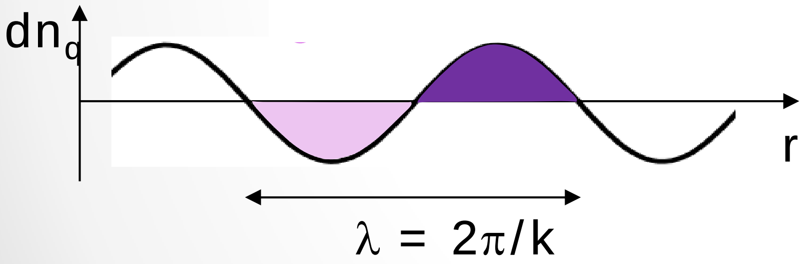


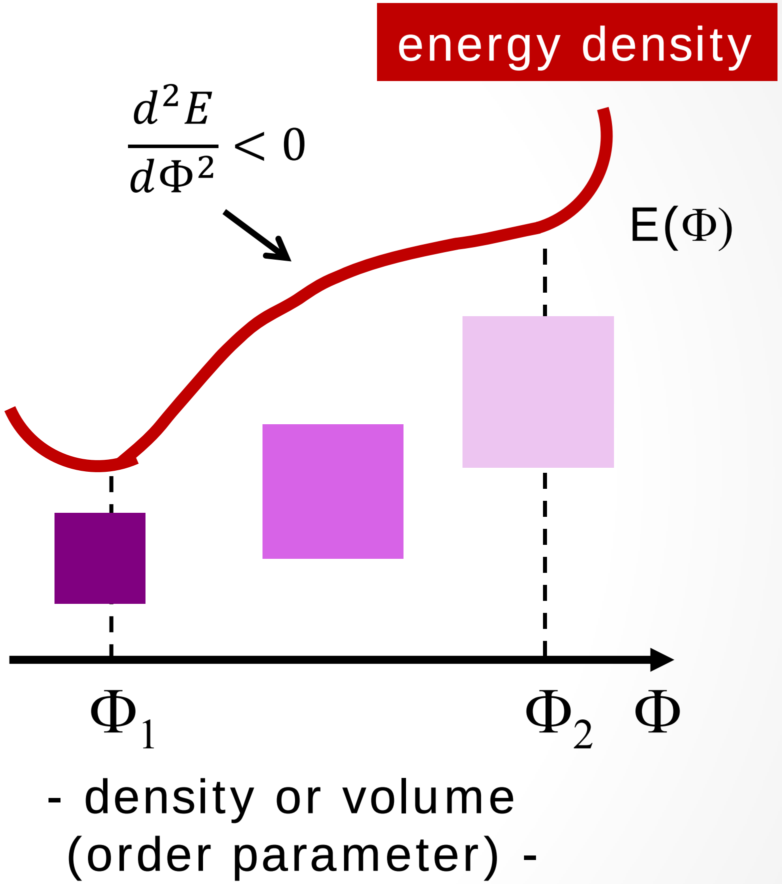
Here: single order parameter (1D space)

Crust-core transition

- (n,p,e) matter:
- $\Phi = \{\delta n_q(k)\}$ q=n,p,e
- $\frac{d^2E}{d\Phi^2} < 0 \Rightarrow$

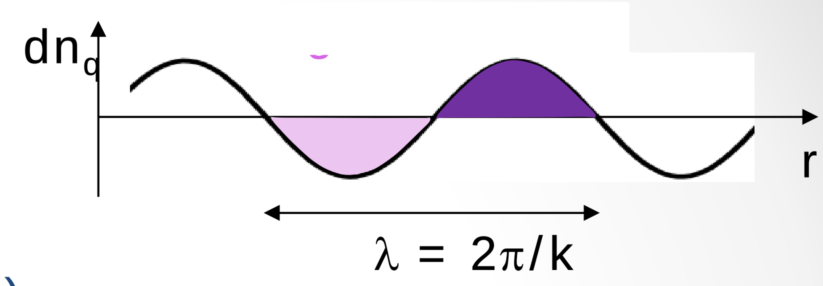
$$C(k) = \det \frac{\partial^2 E}{\partial \delta n_{ij}} < 0$$





Crust-core transition

$$C(k) = \det \frac{\partial^2 E}{\partial \delta n_{ij}} < 0$$



$$C^f_{NMe} = \begin{pmatrix} \partial_{\rho_n}\mu_n & \partial_{\rho_n}\mu_p & 0 \\ \partial_{\rho_p}\mu_n & \partial_{\rho_p}\mu_p & 0 \\ 0 & 0 & \partial_{\rho_e}\mu_e \end{pmatrix}$$

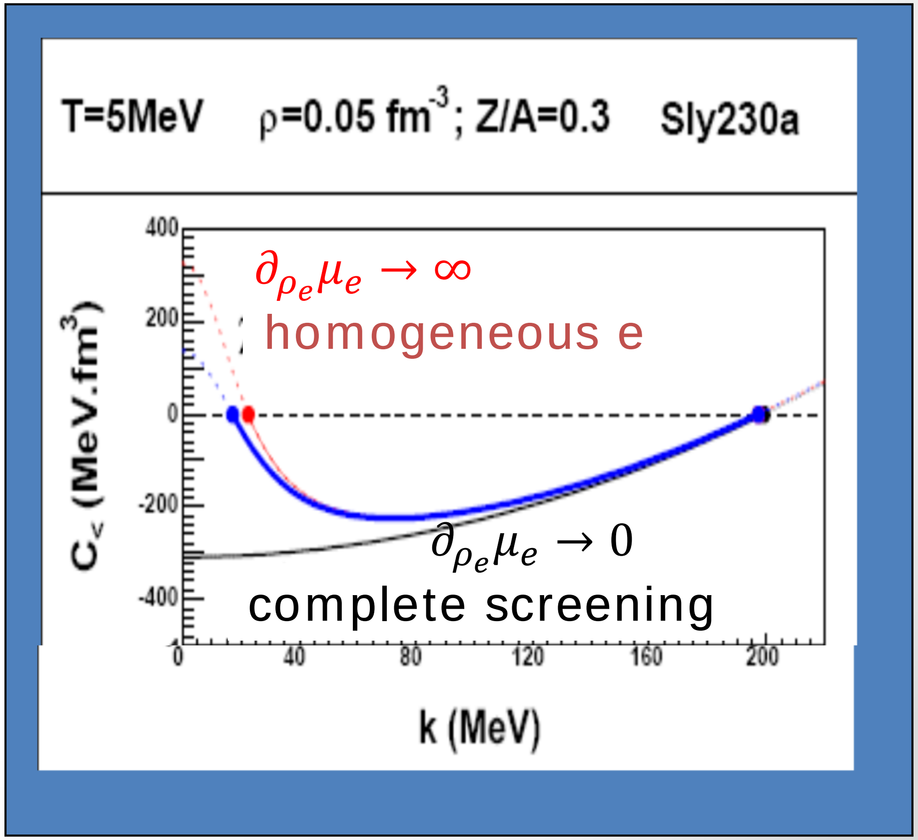
Response to thermal (k=0) fluct.

$$+ \begin{pmatrix} C^f_{nn} & C^f_{np} & 0 \\ C^f_{pn} & C^f_{pp} & 0 \\ 0 & 0 & 0 \end{pmatrix} k^2$$

Surface term

$$+ \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha & -\alpha \\ 0 & -\alpha & \alpha \end{pmatrix} \frac{1}{k^2}$$

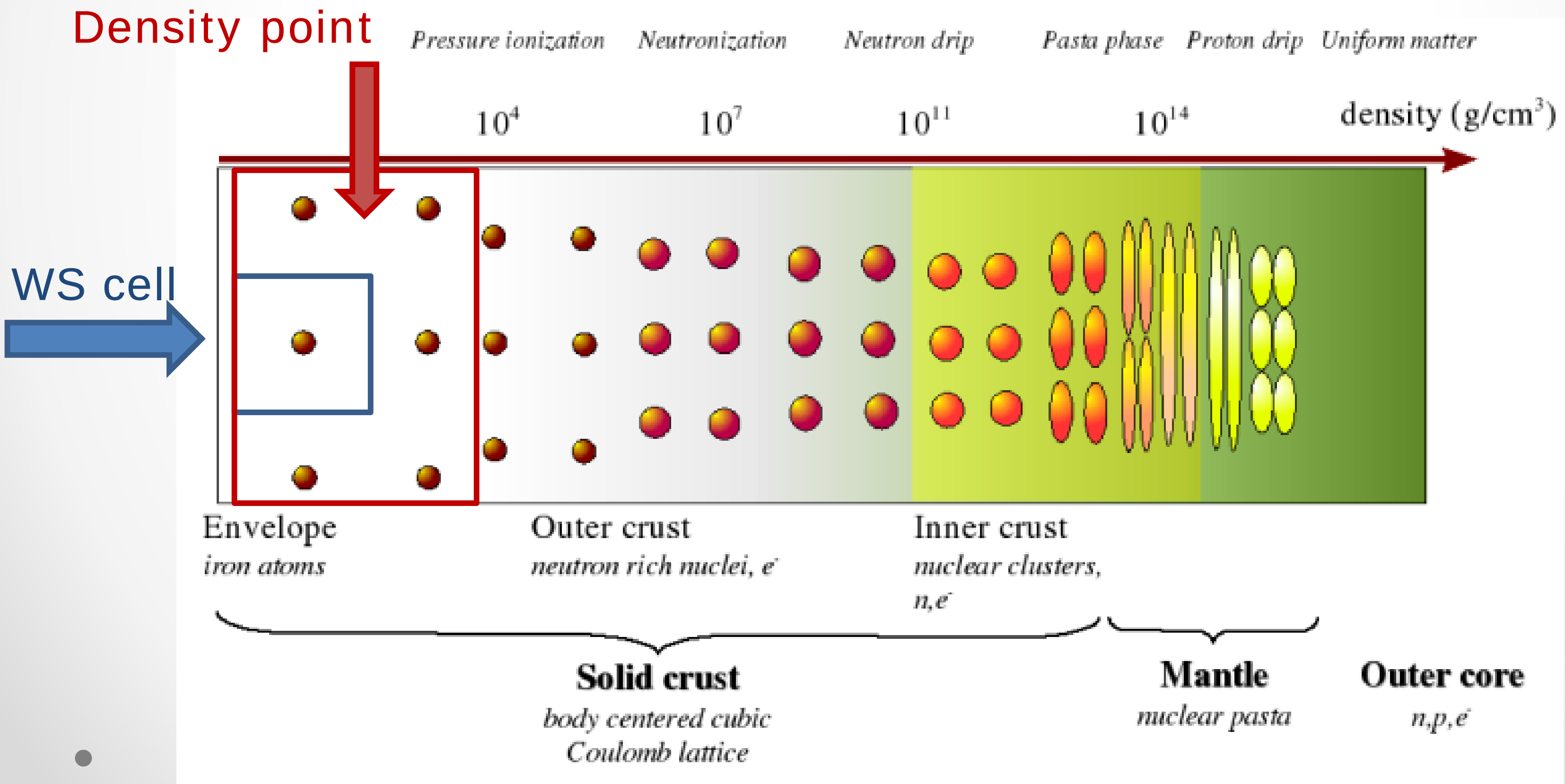
Coulomb term



Stellar matter at $\rho<\rho_0$ is unstable against finite size fluctuations => **cluster formation**

The Wigner-Seitz cell

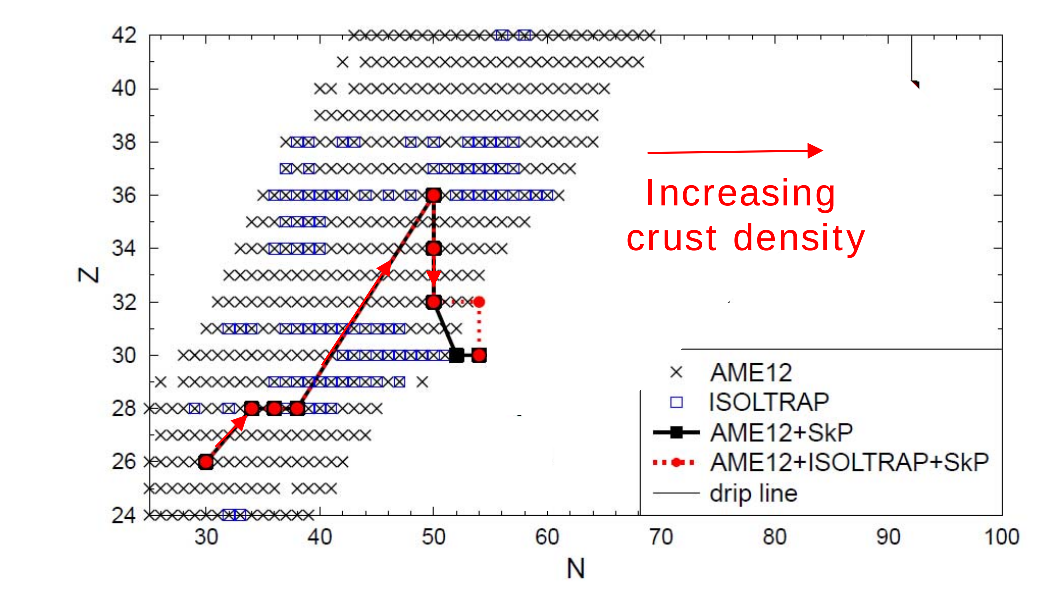
- Below saturation matter is clusterized
- At T=0: solid state: BCC lattice
- Ground state energy density: $\varepsilon(\rho) = \frac{\sum_i E_{WS}}{\sum_i V_{WS}} = \frac{E_{WS}}{V_{WS}}$ =min



Below drip: the outer crust

- $$\varepsilon_{WS}(n_B)=\min_Z\left(\frac{B(N,Z)}{V_{WS}}+\varepsilon_{el}(n_e)+m_p n_p+m_n n_n+\delta\varepsilon_{coul}\right)$$

Only depends on B(N,Z) => the nuclear mass



Kreim *et al.* Int. J. Mass Spectrometry 349, 63 (2013)

Model independent results in the outer crust !

Below drip: the outer crust

- $\varepsilon_{WS}(n_B)=\min\limits_{Z}\left(\frac{B(N,Z)}{V_{WS}}+\varepsilon_{el}(n_e)+m_p n_p+m_n n_n+\delta\varepsilon_{coul}\right)$

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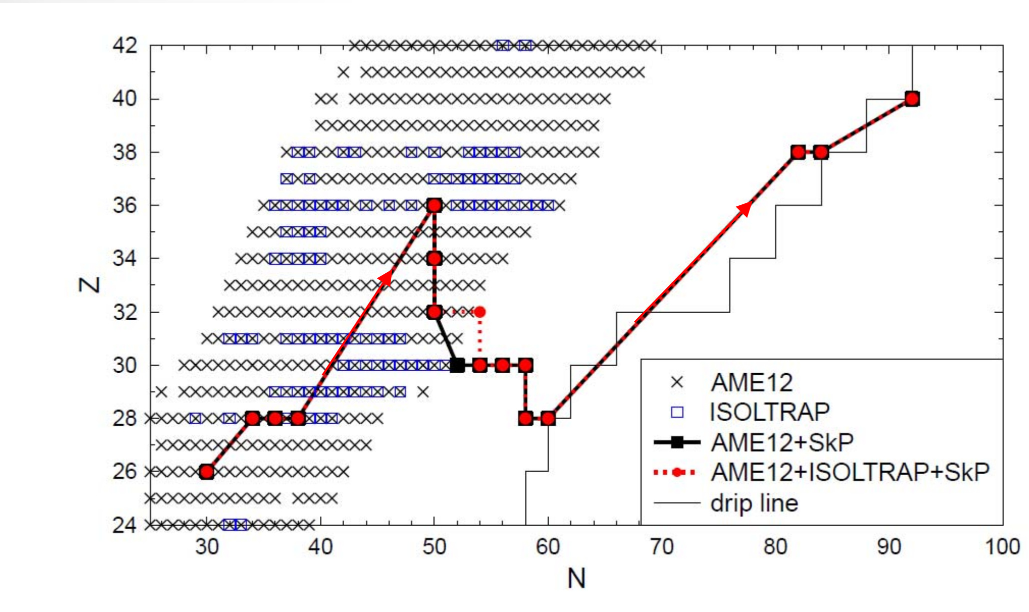
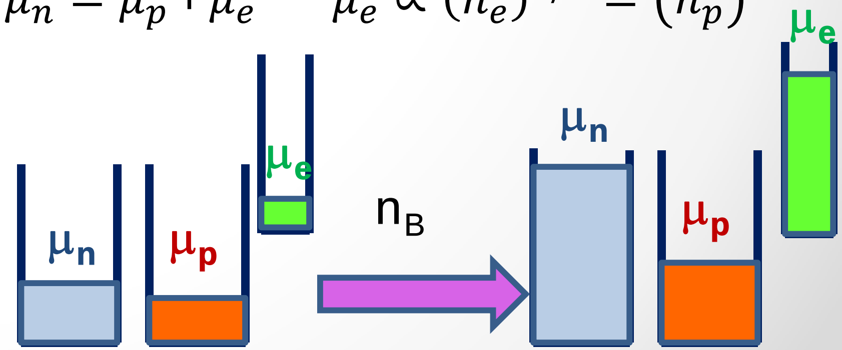


Kreim *et al.* Int. J. Mass Spectrometry 349, 63 (2013)

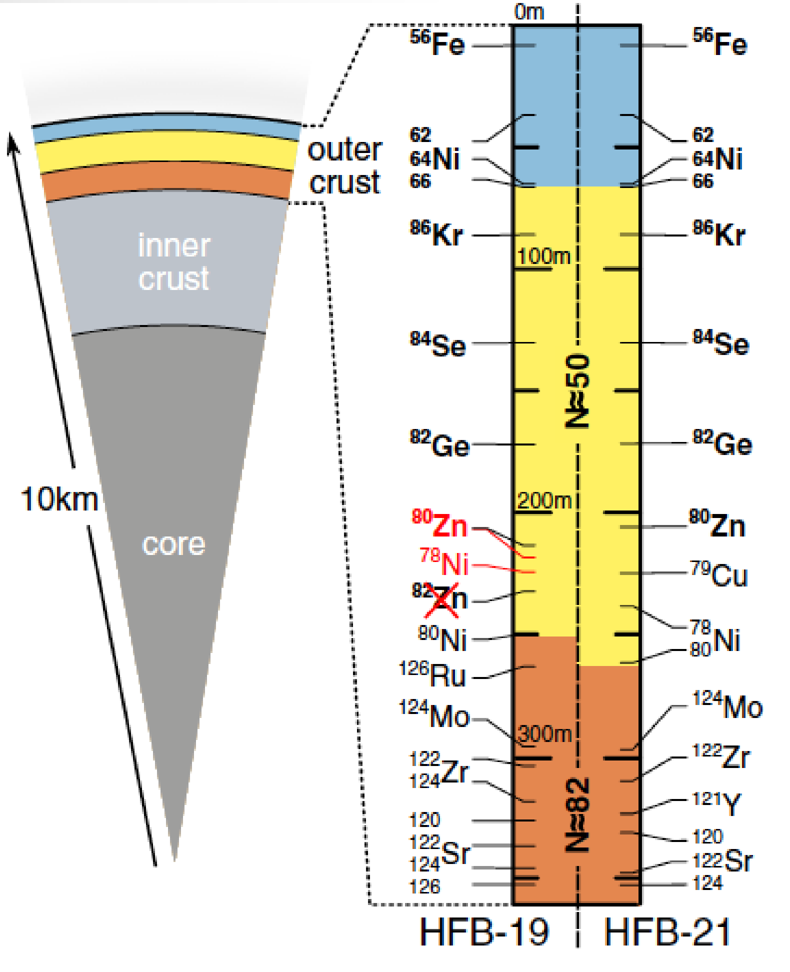
Matter is increasingly n-rich for increasing density

$\Rightarrow$ Model dependence

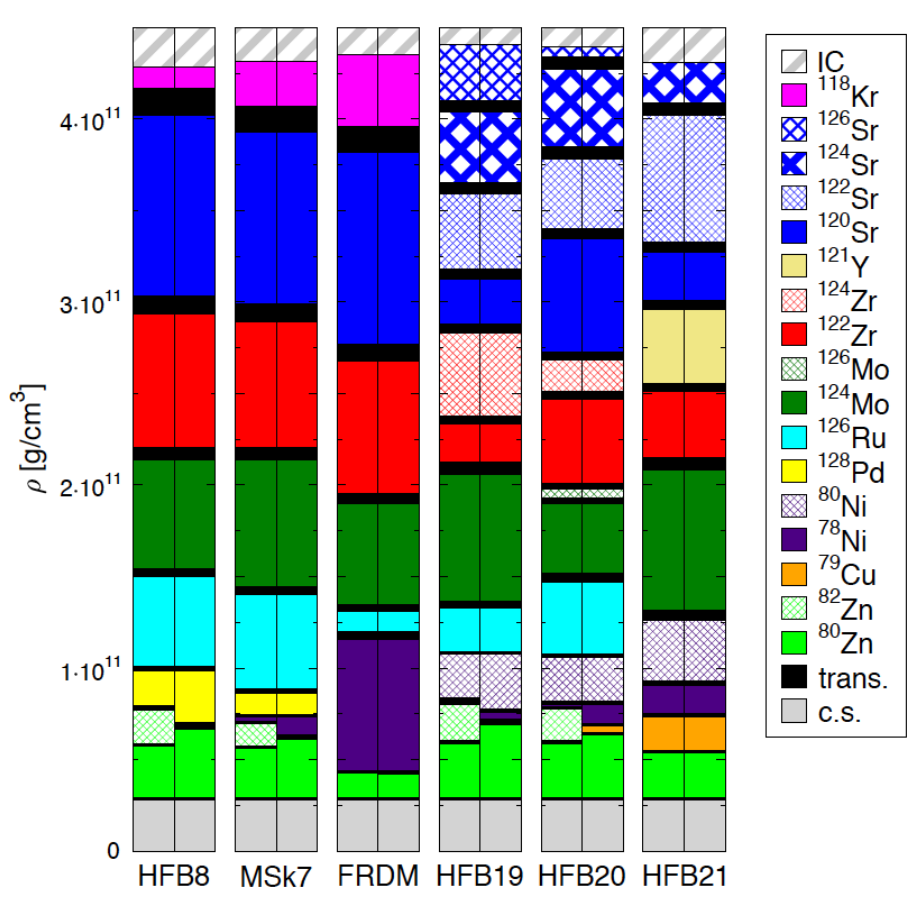
$\mu_n=\mu_p+\mu_e \qquad \mu_e \propto (n_e)^{1/3}=(n_p)^{1/3}$



Below drip: the outer crust



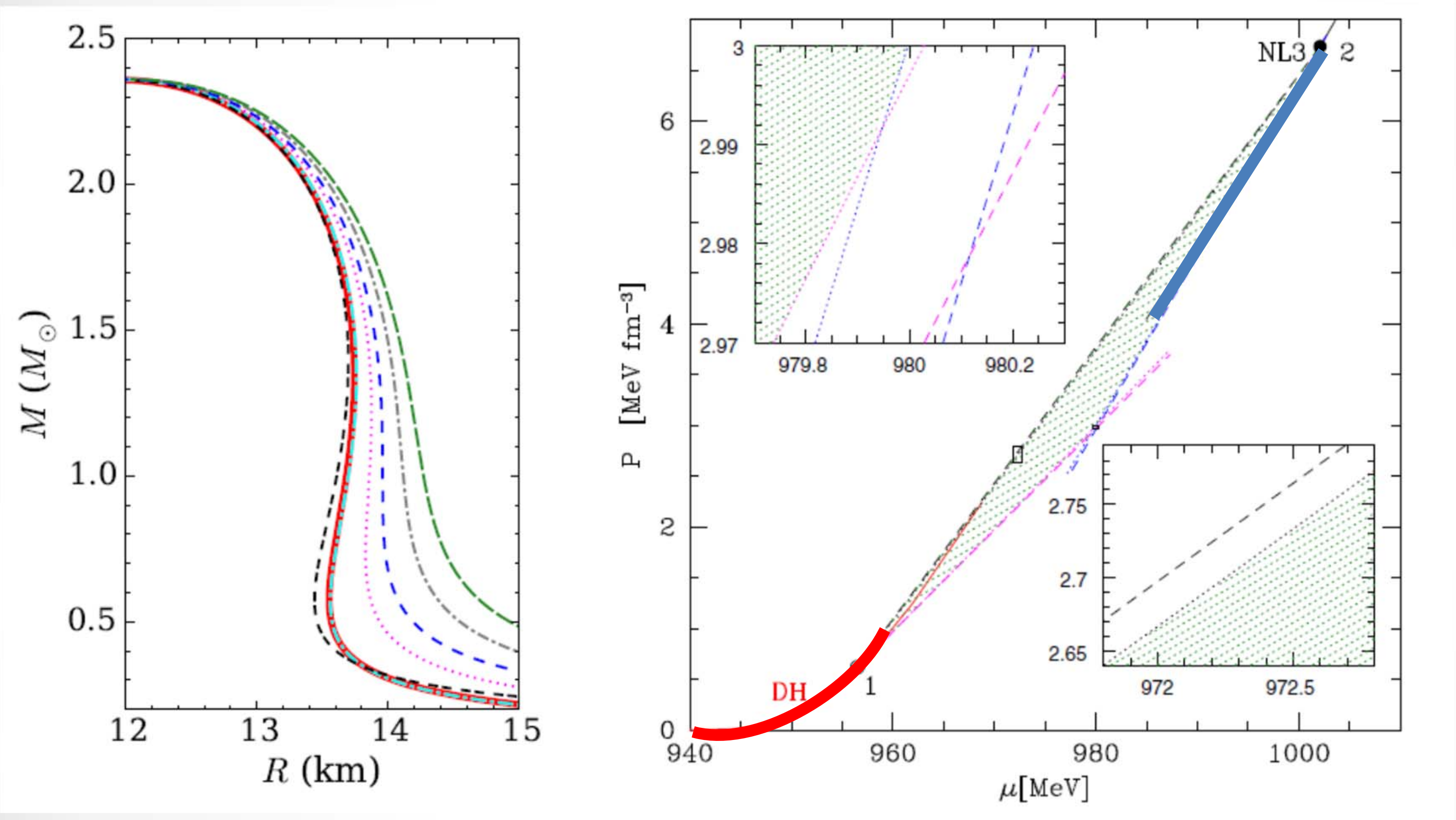
Wolf *et al.*, PRL 110, 041101 (2013)



Kreim *et al.* Int. J. Mass Spectrometry 349, 63 (2013)

Matching Crust and Core

M.Fortin PRC 2016

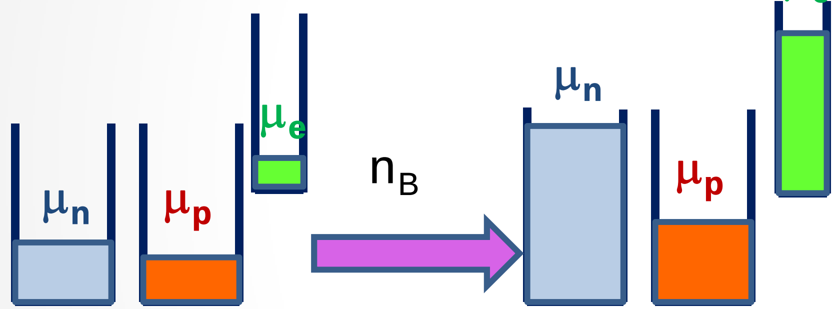


- Need of a unified treatment: same microscopic treatment for the crust and the core

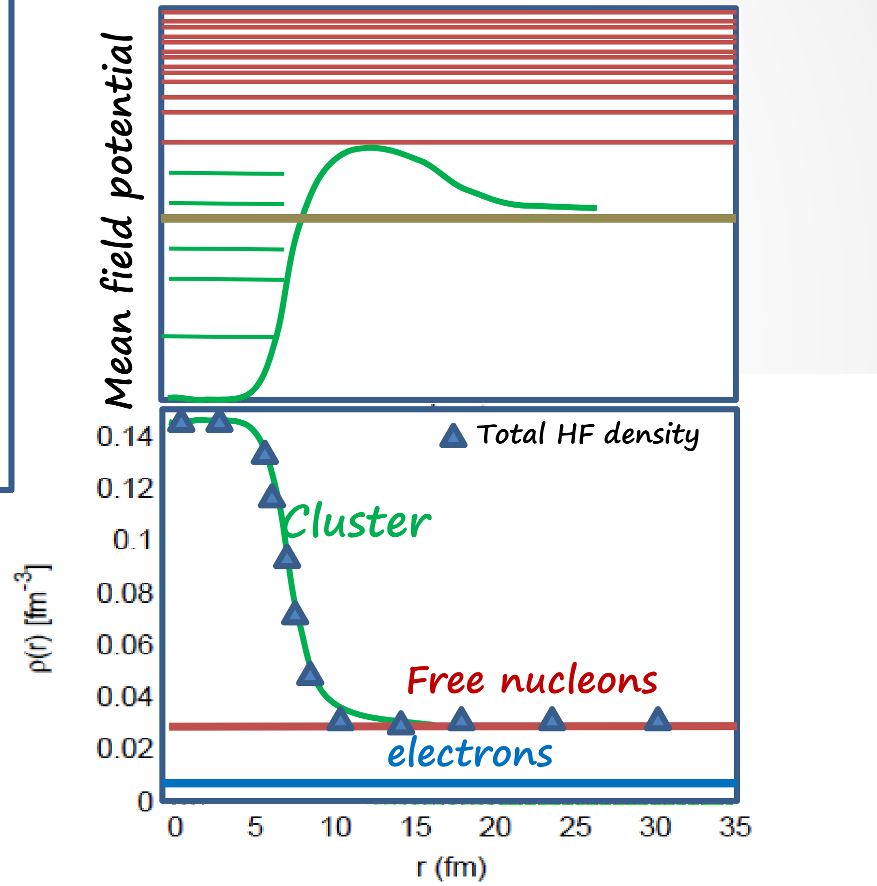
Above drip: the inner crust

Matter is increasingly n-rich for increasing density!

$\mu_n = \mu_p + \mu_e \qquad \mu_e \propto (n_e)^{1/3} = (n_p)^{1/3}$



- In the inner crust, **dripline nuclei** are immersed in the medium of their continuum states: a **neutron superfluid**



P. Papakonstantinou, et al. Phys.Rev.C 88(2013) 045805

Above drip: the inner crust

- The attractive part of the residual interaction leads to pairing correlations
- Channels relevant for neutron star matter: $^1S_0$(nn, $\rho<\rho_0$), $^3P_2$(nn&pp, $\rho>\rho_0$)
- If $\varepsilon_g(n_g)$ is calculated by mean-field models, a pairing contribution must be added
- BCS theory:

$$\varepsilon_{tot}(\rho,\delta) = \varepsilon(\rho,\delta) + \frac{1}{4}\sum_{q=n,p} v_\pi(\rho_q)\tilde{\rho}_q^*\tilde{\rho}_q \qquad \tilde{\rho}_q = 2\frac{\Delta(\rho_q)}{v_\pi(\rho_q)}$$

$$1 = -\frac{v_\pi}{2}\frac{1}{\hbar^3\pi^2}\int_0^{p_{Fq}} dp\, p^2 \frac{1}{\sqrt{\left(\frac{p^2-p_{Fq}^2}{2m^*}\right)^2+\Delta_q^2}}$$

- Effective interaction optimized to reproduce ab-initio calculations of Δ including polarization and screening effects
- Superfluidity and superconductivity negligible for static properties, but essential for cooling and glitches $C_V \propto exp - \Delta/T$

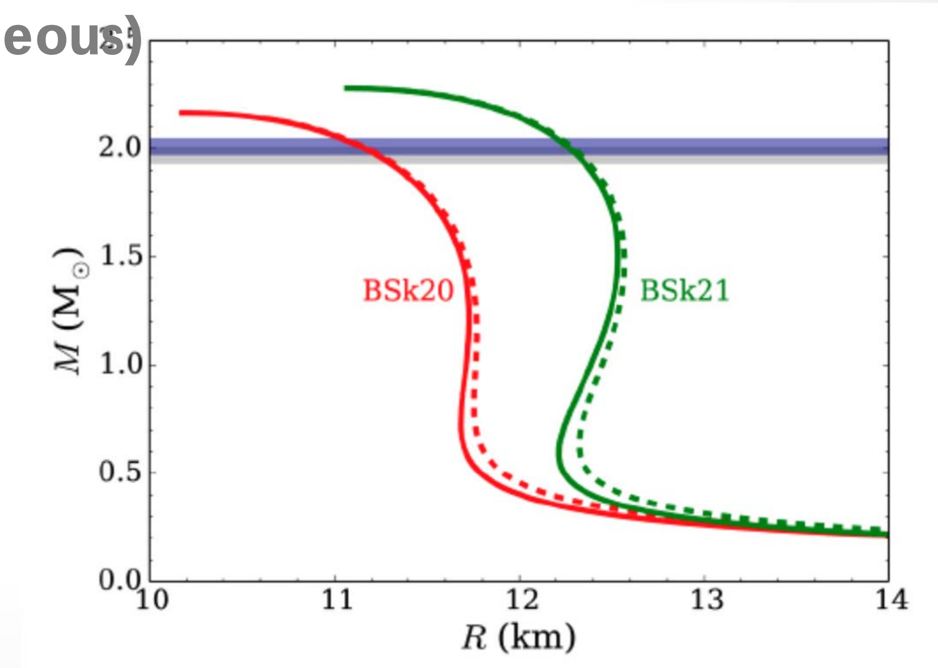
Above drip: the inner crust

$$\varepsilon_{WS}(n_B) = \min_{Z,N,n0,ng,V} \left(\frac{\mathrm{E}(N,Z,n0,ng)}{V_{WS}} + \varepsilon_g(n_g) + \varepsilon_{el}(n_e) + \delta\varepsilon_{coul} \right)$$

- Variational determination of the composition using the same functional for the nucleus and the free neutrons
- Different many body treatments : HFB,ETF,CLDM….
- Transition between crust and core:

e(homogeneous) < e(inhomogeneous)

- The uncertainty due to the many body treatment is << than the error due to the EDF inconsistency



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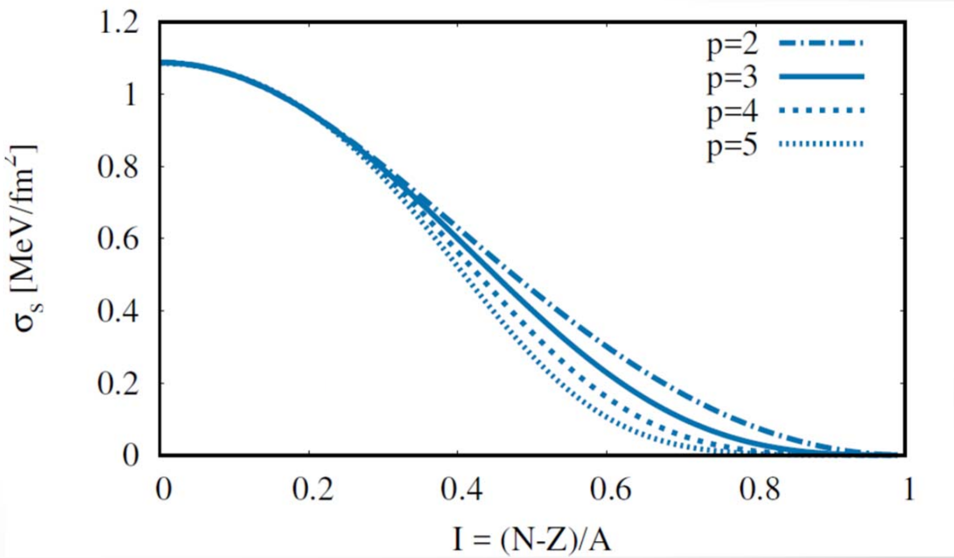
Above drip: the inner crust

$$\varepsilon_{WS}(n_B) = \min_{Z,N,n0,ng,V} \left(\frac{E(N,Z,n0,ng)}{V_{WS}} + \varepsilon_g(n_g) + \varepsilon_{el}(n_e) + \delta\varepsilon_{coul} \right)$$

- Variational determination of the composition using the same functional for the nucleus and the free neutrons
- Different many body treatments : HFB,ETF,CLDM….
- Transition between crust and core:

e(homogeneous) < e(inhomogeneous)

- The energy of inhomogeneous matter depends on the surface tension in addition to the EoS



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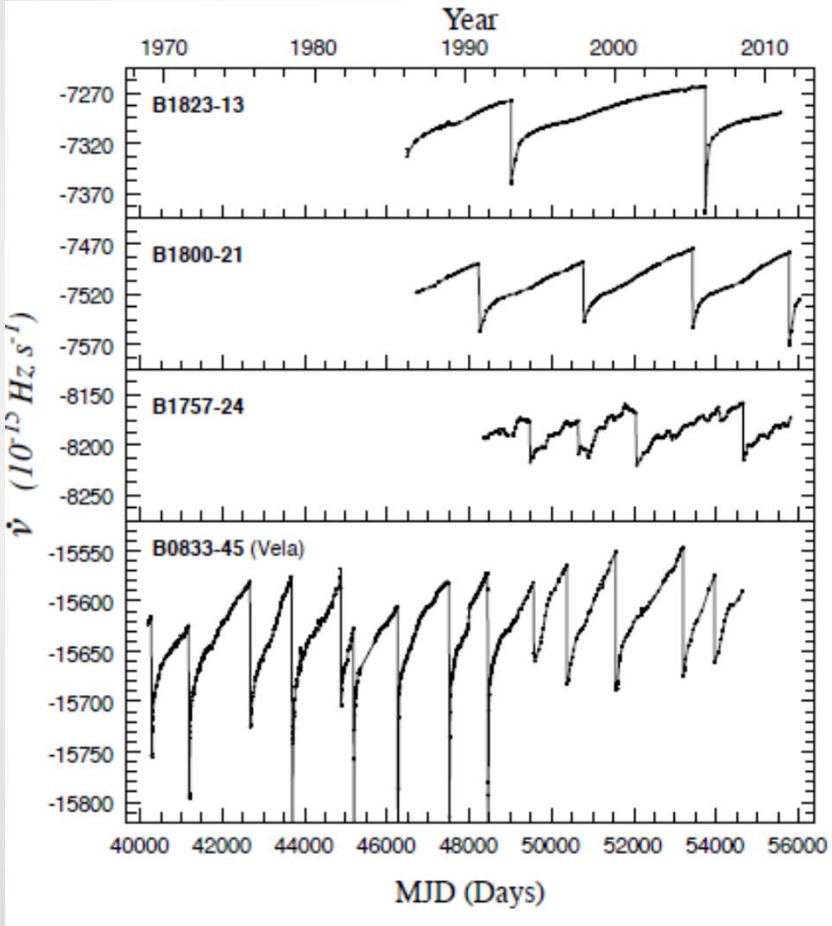
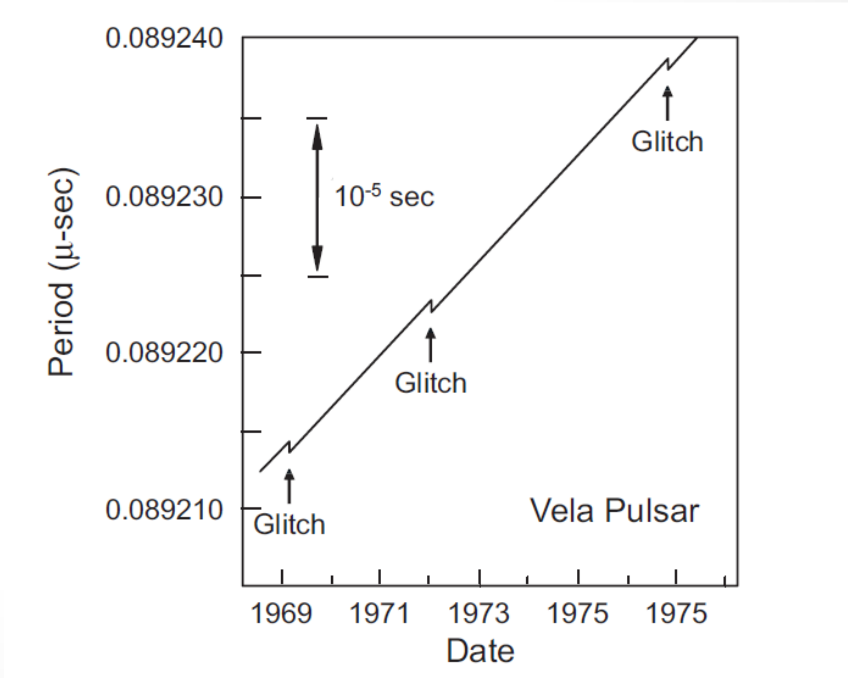
Observable: pulsar glitches



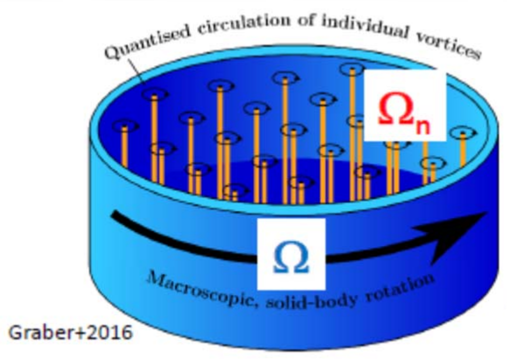
- In some pulsars "glitches" are observed where the spin rate suddenly jumps to a higher value
- Glitches indicate some internal rearrangement has altered the rotation rate by a small amount.
- Great diversity in post glitch behaviors



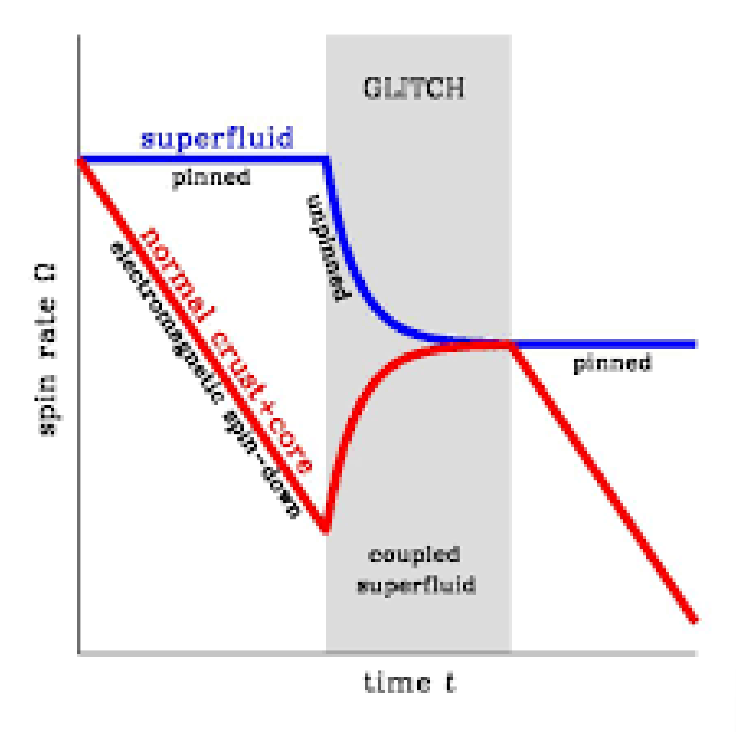
- Figure by C.Espinoza

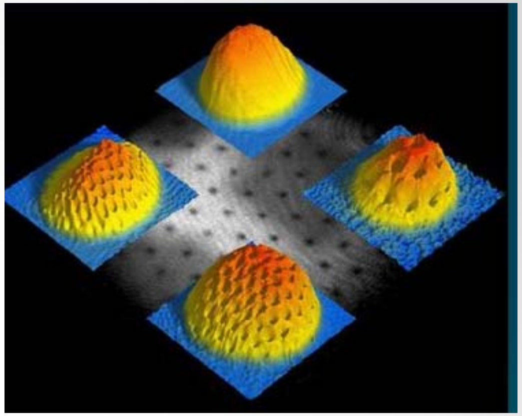
Interpretation

(Anderson &Itoh 1975)



$$\Delta\Omega \propto \Omega_n - \Omega$$

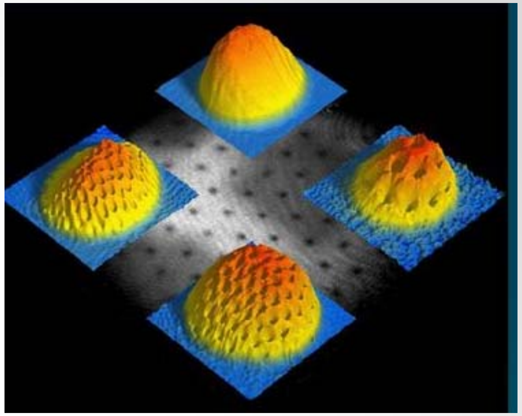


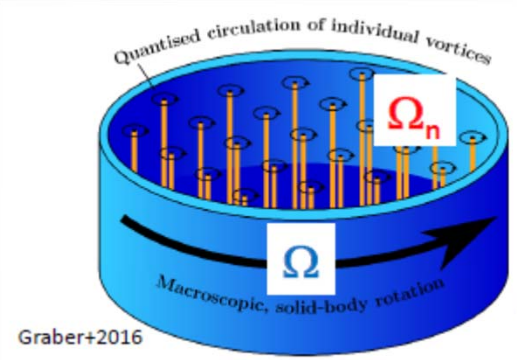


- The crust slows down due to radiation loss
- Vortices move outwards and are pinned to the nuclei in the crust
- Differential lag between the fast vortices and the slower star (crust + core coupled by mutual friction) => crustal stress
- Critical value: sudden unpinning and vortex release
- Angular momentum transfer to the star which spins up

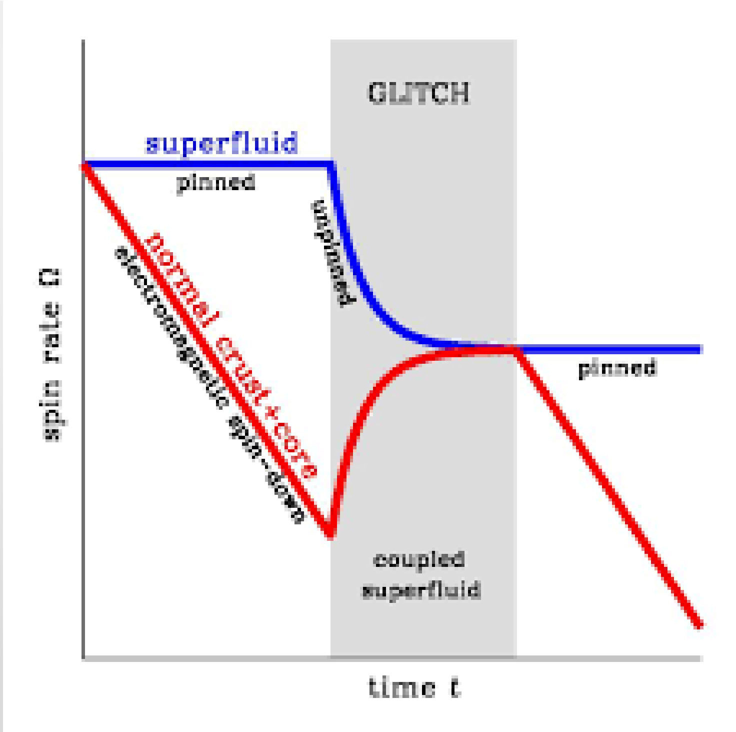
Interpretation

(Anderson &Itoh 1975)



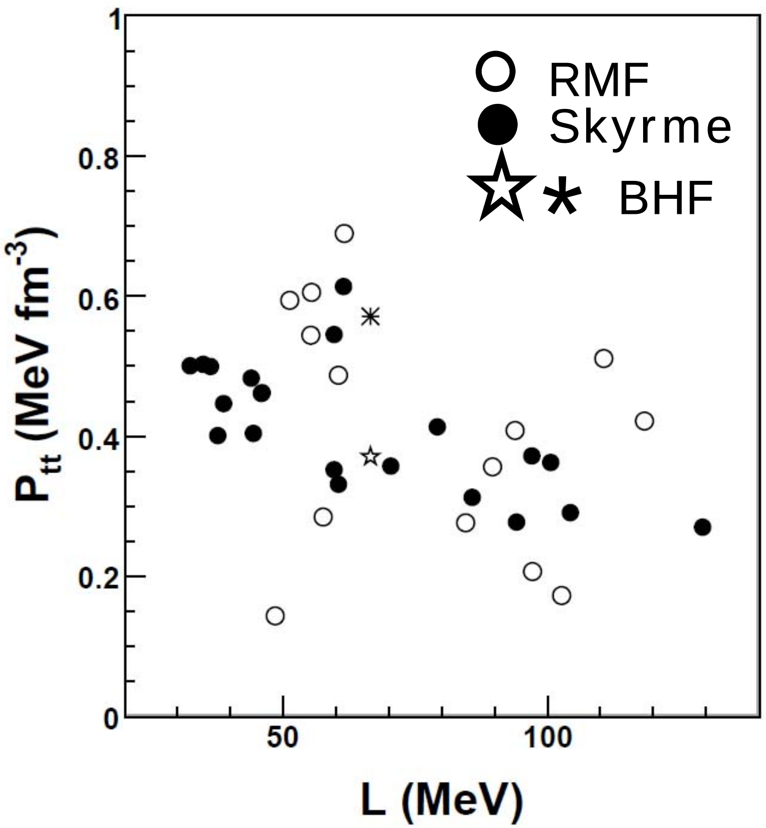


$\Delta\Omega \propto \Omega_n - \Omega$



- The maximum glitch amplitude is proportional to the maximum angular momentum transfer between crust and core
- => to the fractional crust momentum of inertia
- Landau two-fluid model: $I_c/I>0.07$ to explain Vela data

Glitches and CC transition



C.Ducoin et al, PRC 2012

- $I_c/I>0.07$ to explain Vela data

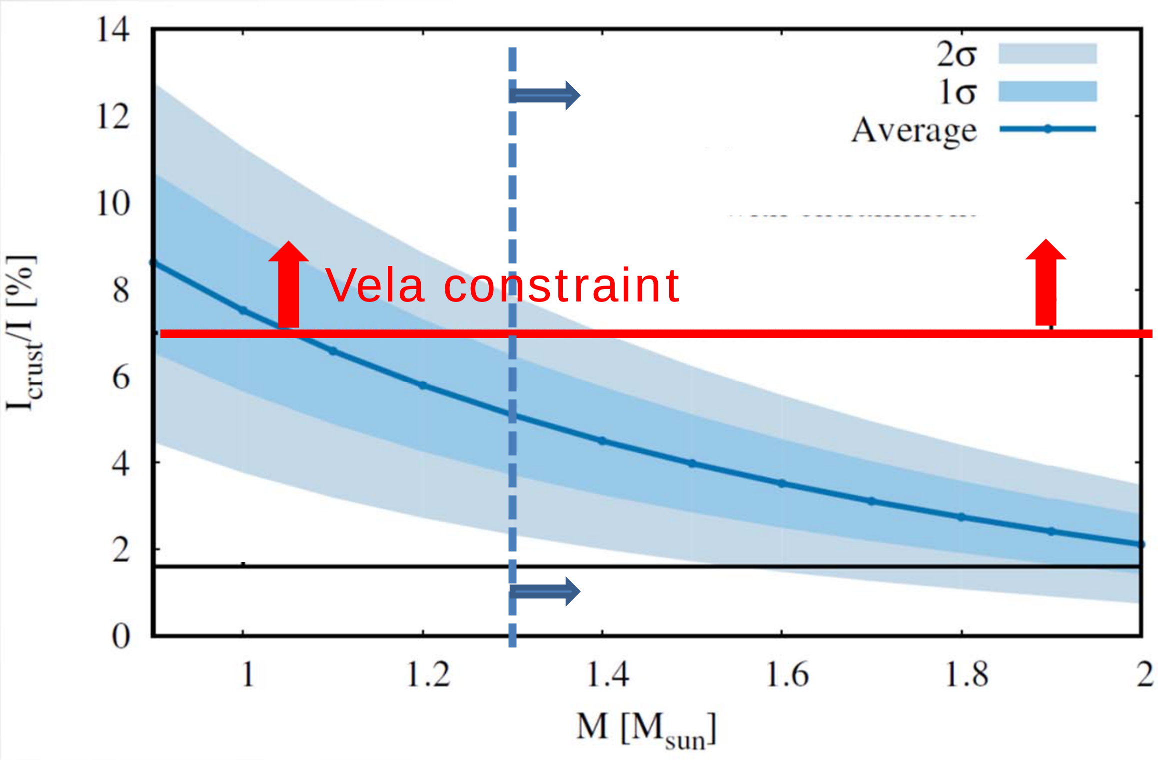
$$I \equiv \frac{J}{\Omega} = \frac{8\pi}{3}\int_0^R r^4 e^{-\nu(r)} \frac{\bar{\omega}(r)}{\Omega} \frac{\left(\mathcal{E}(r)+P(r)\right)}{\sqrt{1-2GM(r)/r}} dr$$

$$I_{\rm crust} = \frac{8\pi}{3}\int_{R_t}^R r^4 e^{-\nu(r)} \tilde{\omega}(r) \frac{\left(\mathcal{E}(r)+P(r)\right)}{\sqrt{1-2GM(r)/r}} dr \ .$$

$\Rightarrow P_t>0.5$ MeV fm^{-3}

Results are extremely model dependent

Crustal moment of inertia: meta-modelling



T.Carreau et al, PRC 2019

- Marginal agreement with the standard glitch model!
- What should we constrain better to have a final answer?

Determine the influential parameters

Correlation between the nuclear parameters
and I_c / I (top) , P_t (bottom)

0.03	-0.20	0.14	-0.06	-0.03	-0.11	-0.24	0.31	0.53	-0.25	-0.02	0.04	-0.02	0.56	0.44	0.58	0.93	0.98	0.94

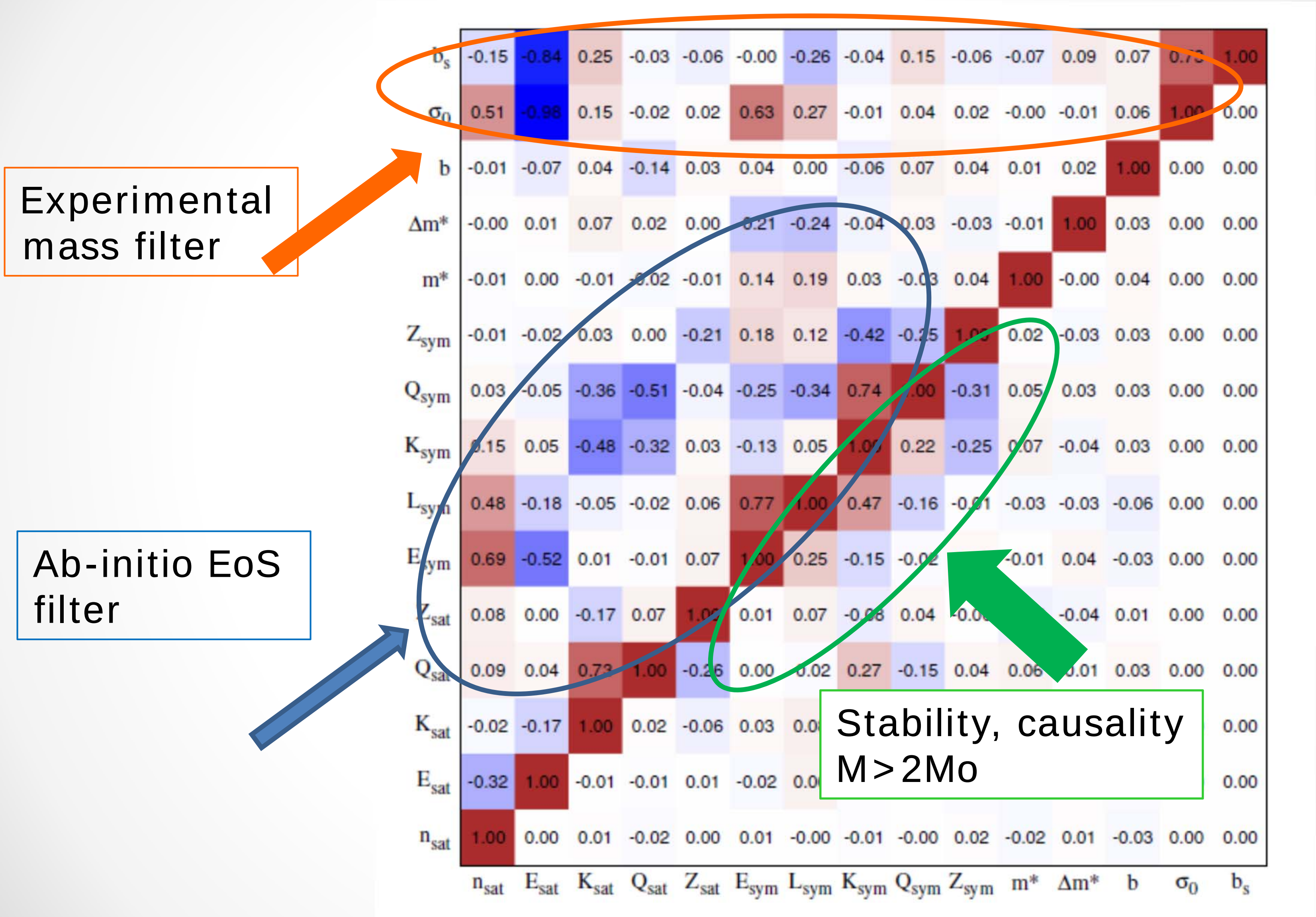
0.06	-0.21	0.09	-0.14	-0.08	-0.07	-0.22	0.24	0.48	-0.28	-0.02	0.05	-0.02	0.60	0.47	0.61	0.97
n_{sat}	E_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}	m^*	Δm^*	b	p	σ_0	b_s	n_t

Bulk parameters

Surface parameters

T.Carreau et al, PRC 2019

Determine the influential constraints

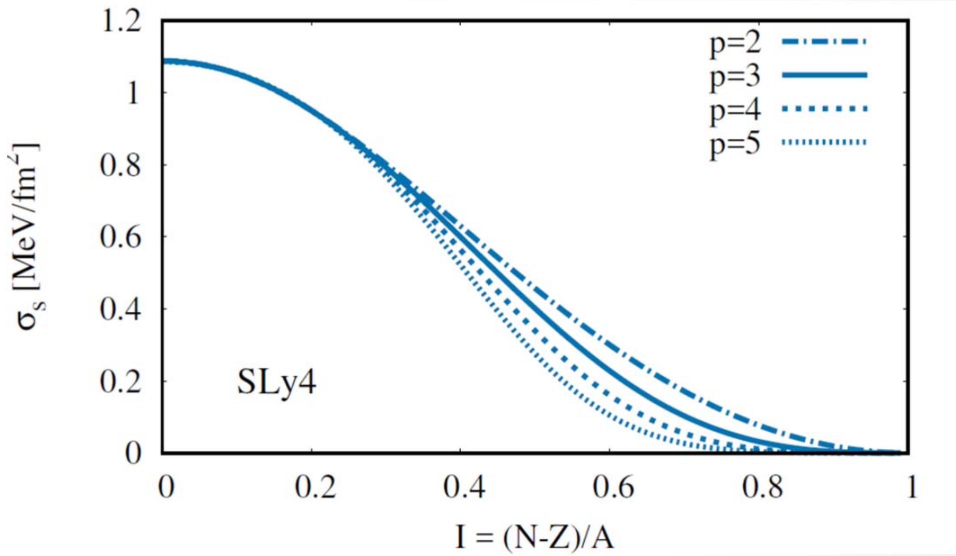


T.Carreau et al, PRC 2019

...a brief summary

- The neutron star crust is a solid BCC lattice of dripline nuclei immersed in a neutron superfluid

- Equation of state modelling requires an unified treatment for the nuclei and the neutrons



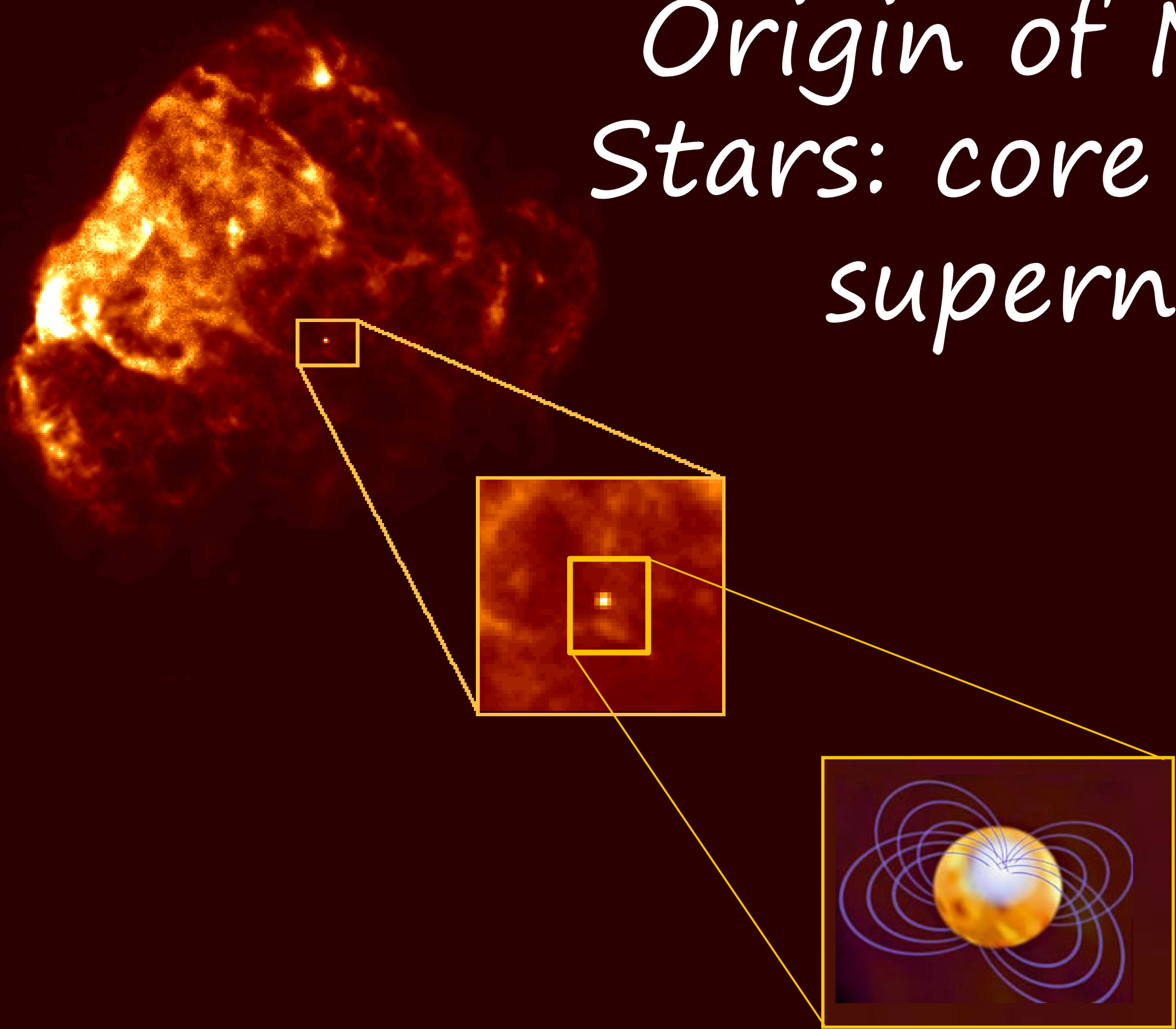
- Pulsar glitches are linked to the dynamic properties of the neutron superfluid (entrainment), and the static properties of the crust (moment of inertia), but the phenomenon is not yet fully understood

- A better understanding of the surface properties of extremely neutron rich nuclei is needed to progress

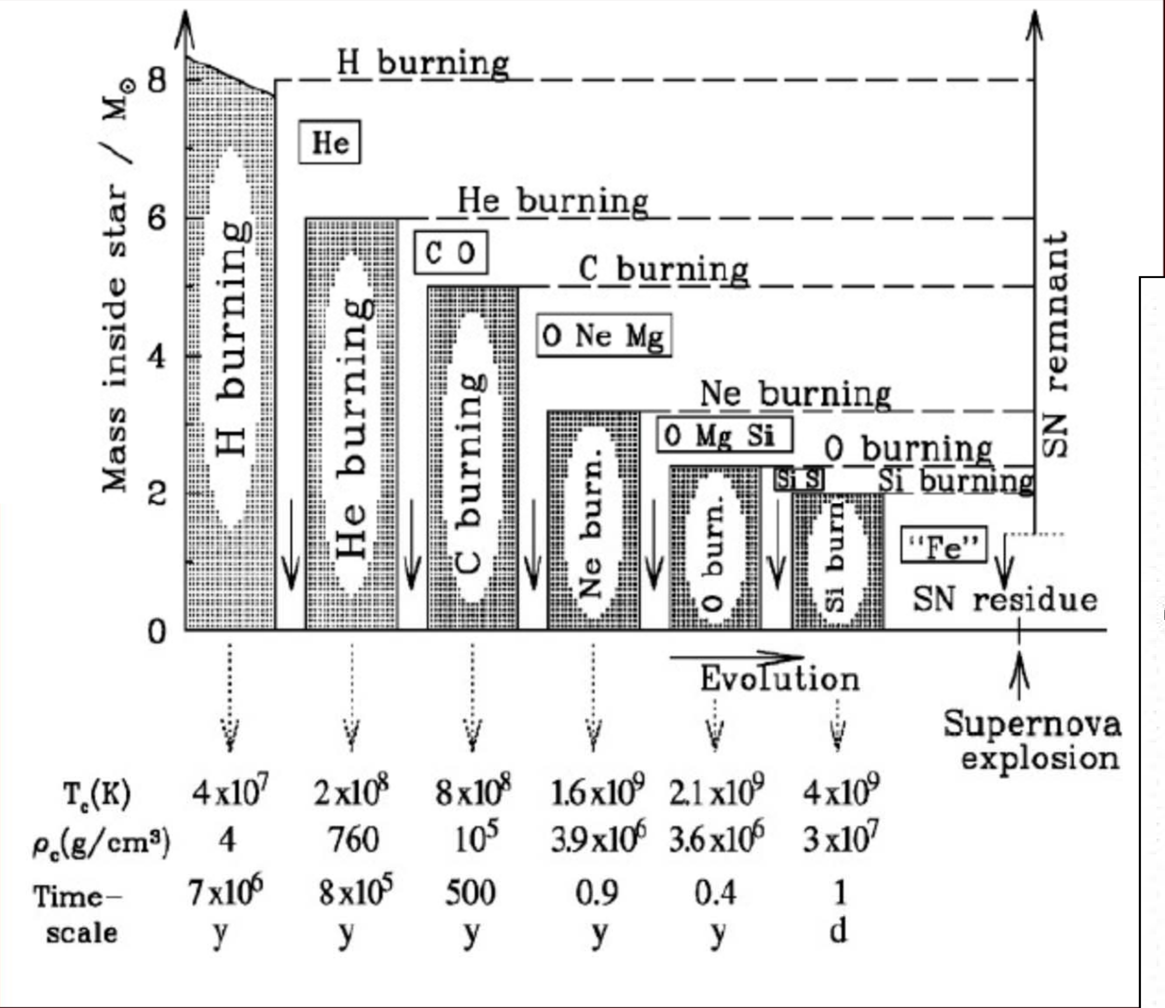
Lectures plan

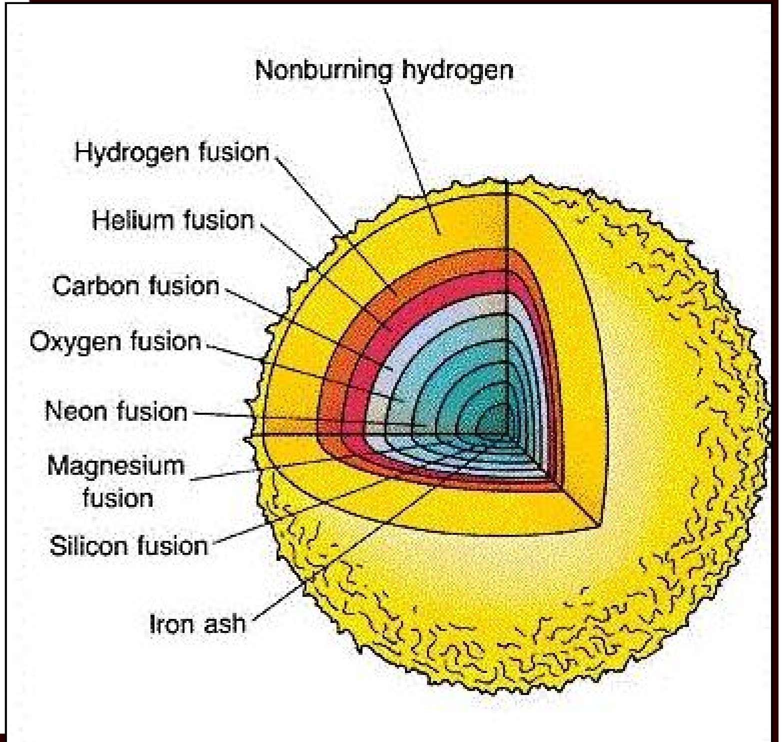
1. Introduction: dense matter in the universe
   a. The sites
   b. The signals
2. Neutron stars and mergers
   a. Observations
   b. Hydrostatics and the EoS
   c. Constraining the parameters
3. Phase transitions and Neutron stars
   a. Phase transitions in dense matter
   b. The physics of the core
   c. The physics of the crust
4. **Core Collapse Supernova**
   a. **Observations**
   b. Modeling supernova explosions
   c. Influence of nuclear physics

Origin of Neutron Stars: core collapse supernova



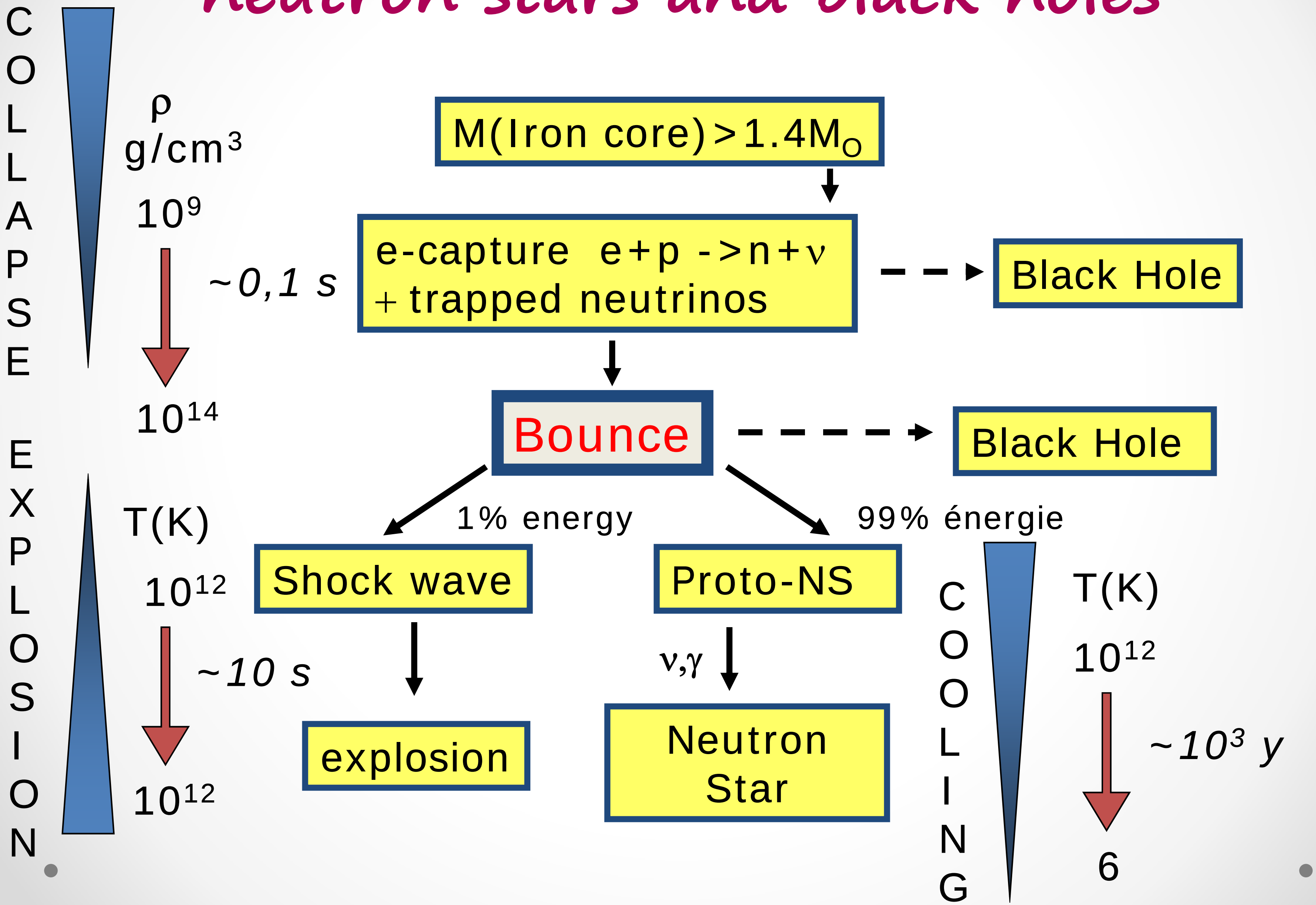
Death of a massive star





Adapted from e-education.psu.edu

From massive stars to supernova, neutron stars and black holes

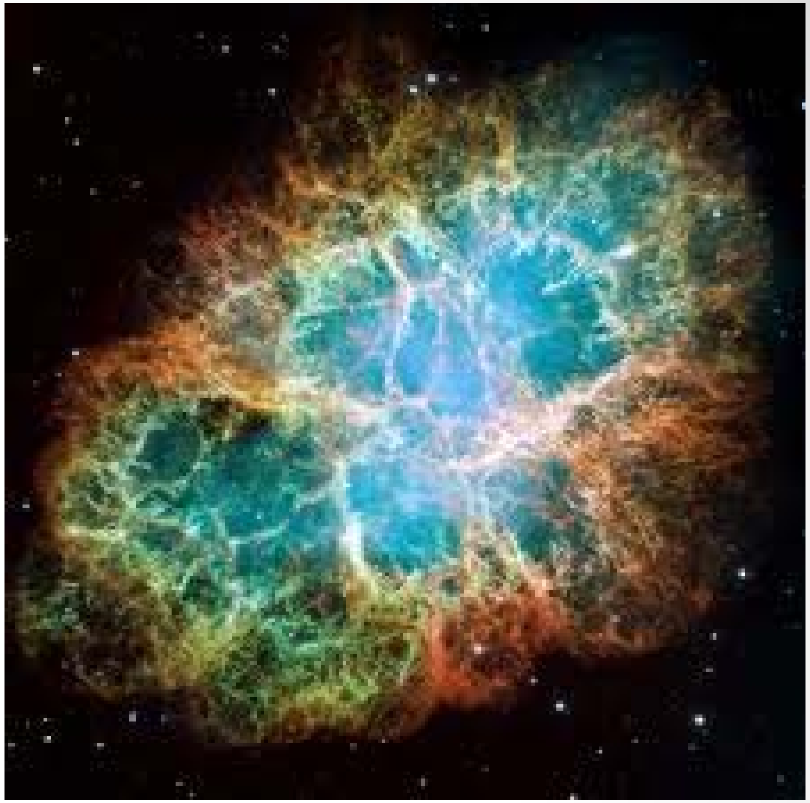


Observations

- 182 First report (China)
- SN1054: Crab (worldwide)
- SN1572: Cassiopea (Tycho Brahe)
- SN1667? CasA
- SN1987A : first observation
  with modern telescopes
- SuperNova Legacy Survey
  (Canada-France-Hawai)
  ~1000 SN de 2005-2008
- Many projects (SDDS, CLASH...)

- 1 SN/50y in our galaxy

Hubble telescope. Credit: NASA

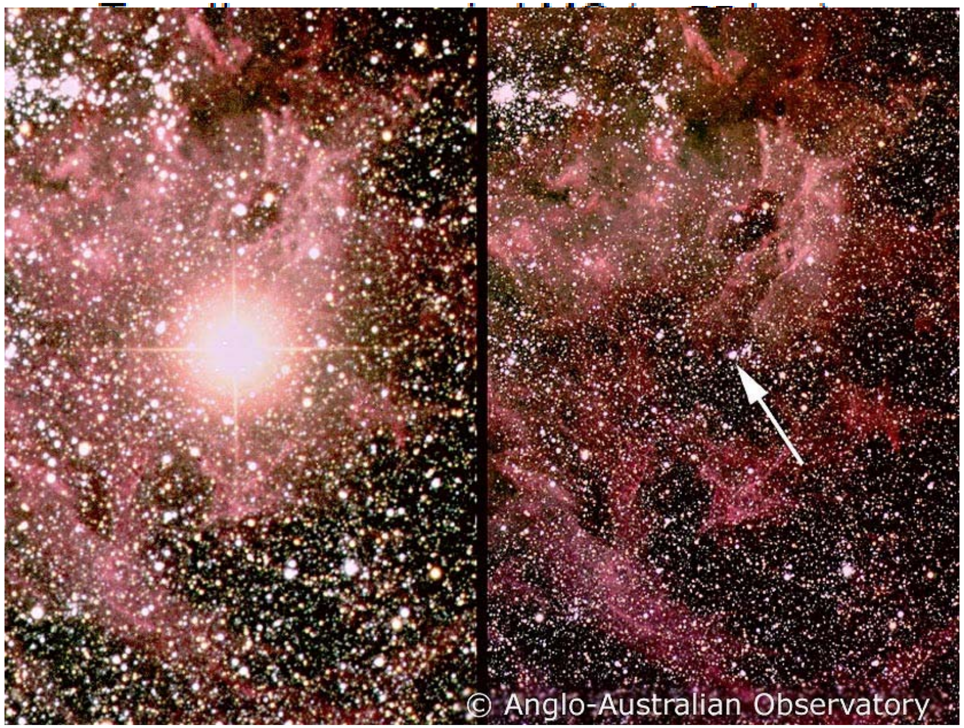


Crab Nebula,
Left over of SN1054 explosion
Reported by arab, chinese and japanese astronomers

Observations

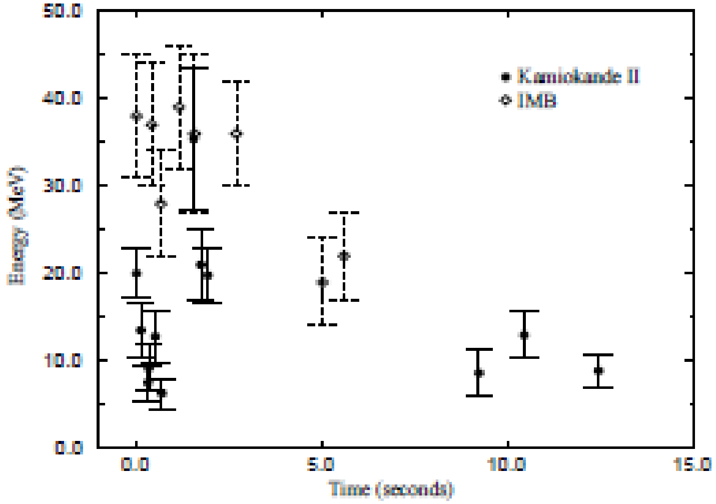
163.000 years ago.....SN1987A

Type II supernova in LMC (~55 kpc)

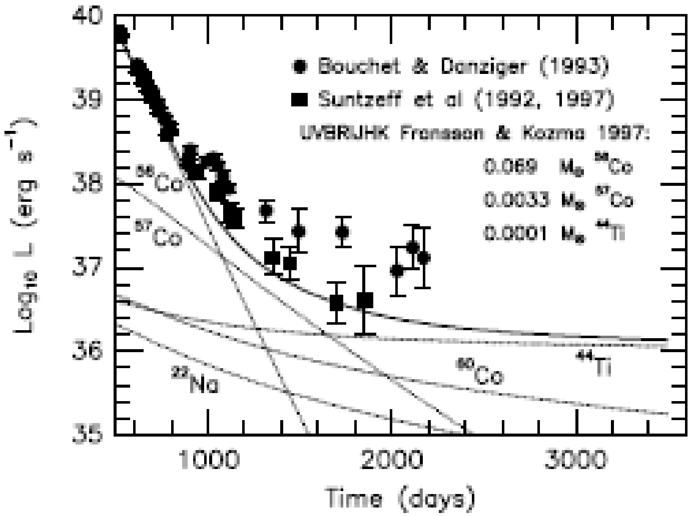


- $E_{\text{grav}} \approx 10^{53}$ erg
- $E_{\text{rad}} \approx 8 \times 10^{49}$ erg
- $E_{\text{kin}} \approx 10^{51}$ erg $= 1$ foe

neutrinos $E_\nu \approx 2.7 \times 10^{53}$ erg



light curve



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CCSN modelling: hydrodynamics in GR

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left[\frac{r^2\alpha}{X}\mathbf{F}(\mathbf{U})\right] = \mathbf{S}(\mathbf{U})$$ (1D)

$$\mathbf{U} = \begin{pmatrix} D \\ S \\ \tau \\ DY_e \end{pmatrix}$$

Density
Linear momentum
Energy
Proton fraction

Conserved quantities

$$\mathbf{F}(\mathbf{U}) = \begin{pmatrix} Dv \\ Sv + P \\ S - Dv \\ DY_e v \end{pmatrix}$$

Fluxes

Source&Sink terms

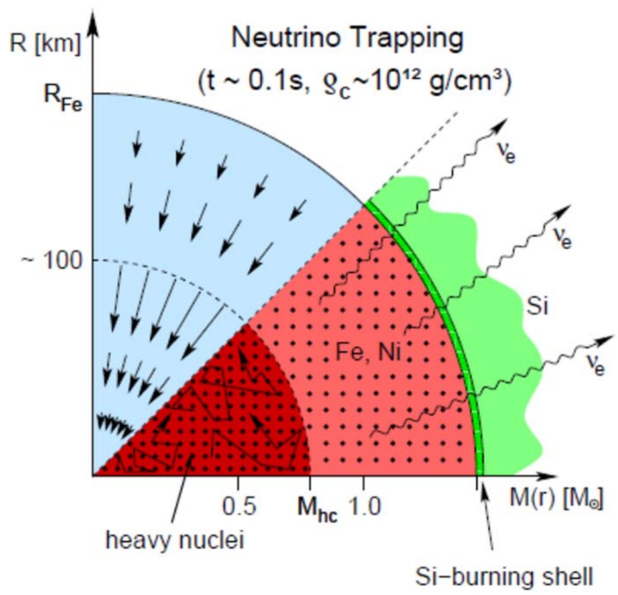
$$\mathbf{S}(\mathbf{U}) = \begin{pmatrix} 0 \\ (Sv - \tau - D)\left(8\alpha X \pi r P + \alpha X \frac{m}{r^2}\right) + \alpha X P \frac{m}{r^2} + \frac{2\alpha P}{Xr} + (vQ_{\nu E} + Q_{\nu M}) \\ Q_{\nu E} + vQ_{\nu M} \\ R_{Y_e} \end{pmatrix},$$

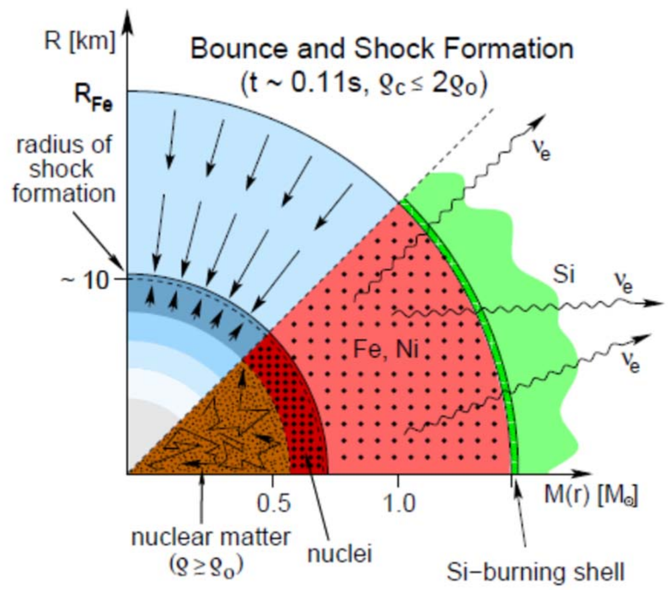
Weak processes in CCSN

$(A,Z) + e^- \rightleftarrows (A,Z-1) + \nu_e$	electron capture on nuclei
$p + e^- \rightleftarrows n + \nu_e$	electron capture on free protons
$\nu + (A,Z) \rightleftarrows \nu + (A,Z)$	elastic scattering on nuclei
$\nu + e^{\pm} \rightleftarrows \nu + e^{\pm}$	inelastic scattering off electrons
$\nu + N \rightleftarrows \nu + N$	elastic scattering on nucleons
$(A,Z) + e^+ \rightleftarrows (A,Z+1) + \bar{\nu}_e$	positron capture on nuclei
$n + e^+ \rightleftarrows p + \bar{\nu}_e$	positron capture on free neutrons
$\nu + (A,Z) \rightleftarrows \nu + (A,Z)^*$	inelastic scattering on nuclei
$(A,Z)^* \rightleftarrows (A,Z) + \nu + \bar{\nu}$	nucleus decay
$N + N \rightleftarrows N + N + \nu + \bar{\nu}$	nucleon nucleon bremsstrahlung
$\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$	$\nu_e\bar{\nu}_e$ annihilation
$e^- + e^+ \rightleftarrows \nu + \bar{\nu}$	e^+e^- annihilation ,

Key microphysics inputs: capture rates and matter composition

Modelling: collapse phase

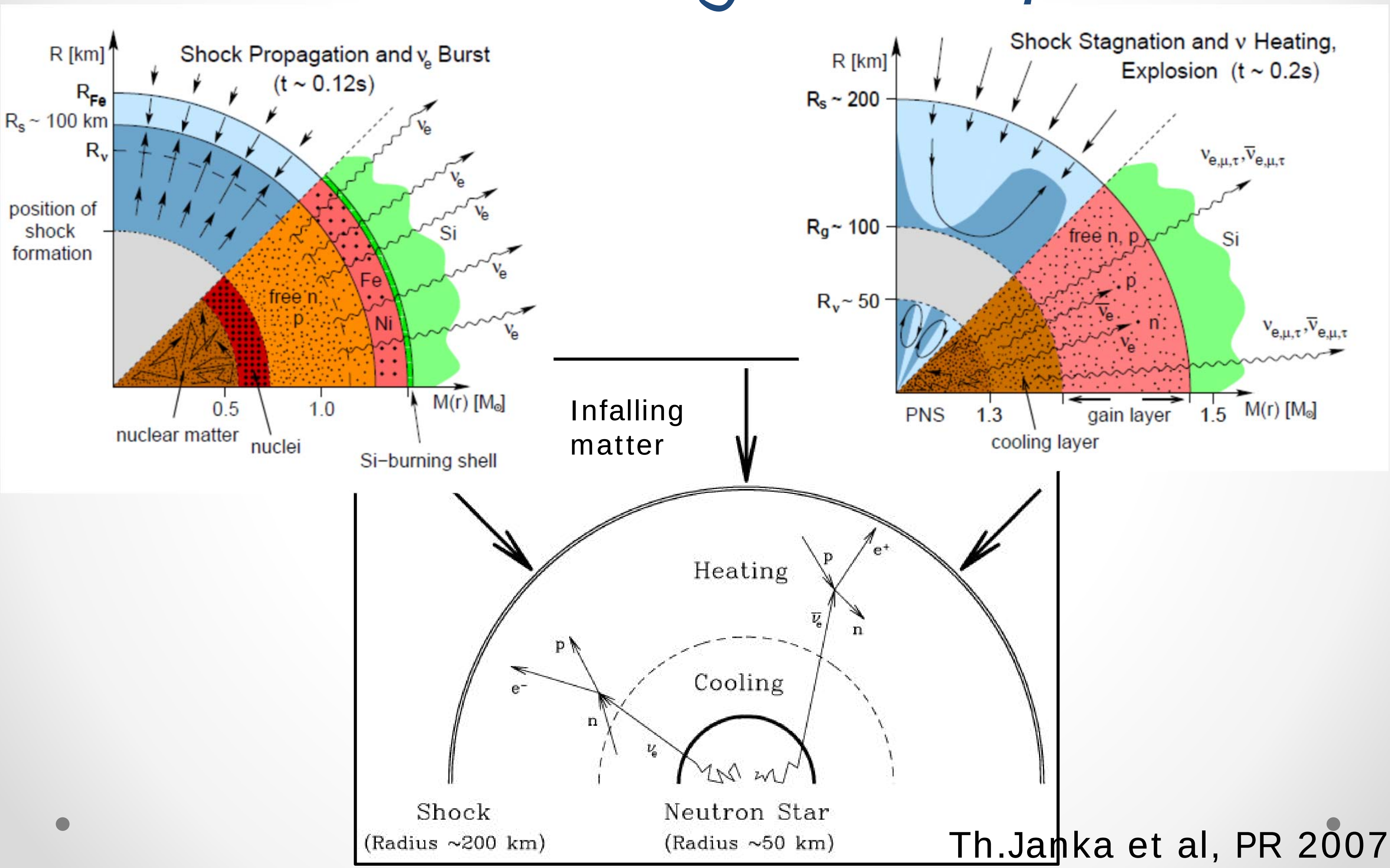




Th.Janka et al, PR 2007

Key microphysics inputs: capture rates on nuclei

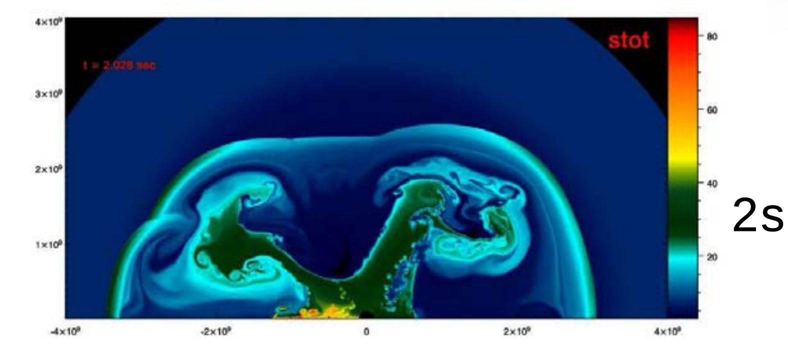
Shock propagation, delayed neutrino heating and explosion



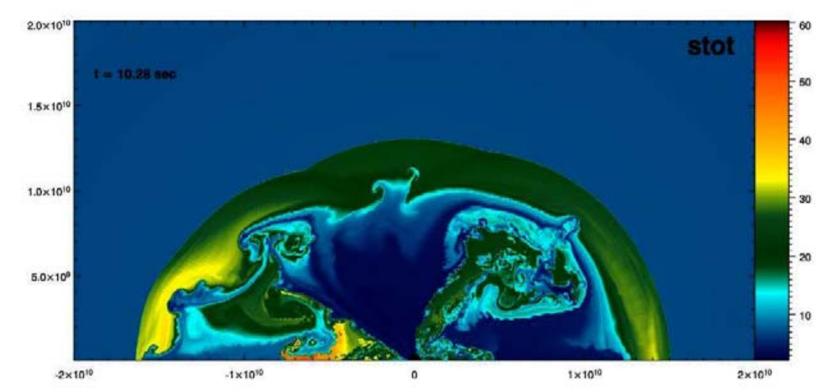
Th.Janka et al, PR 2007

Kifonidis et al., A&A 453 (2005), 661

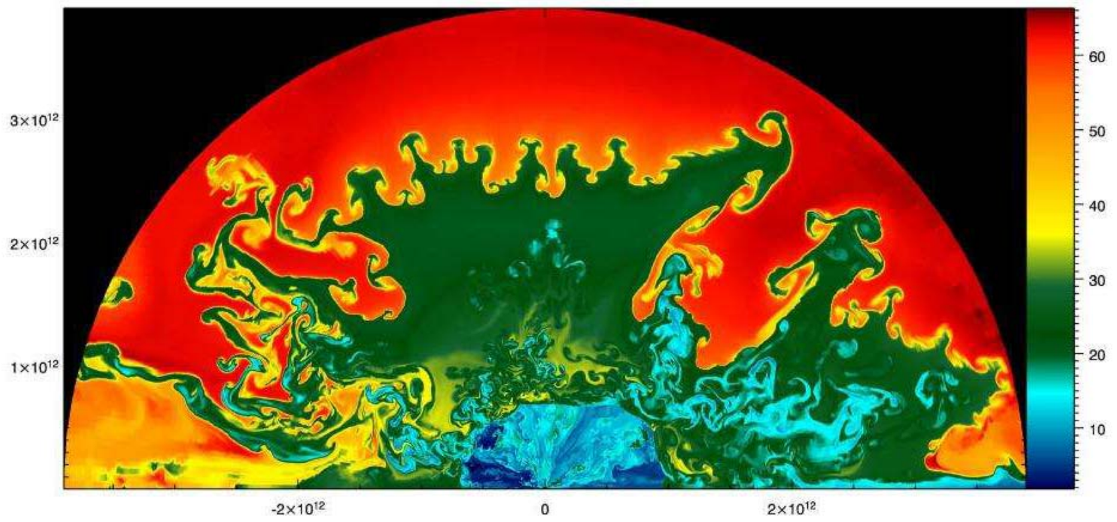
Modelling: a complex multi-scale hydrodynamical problem



2s

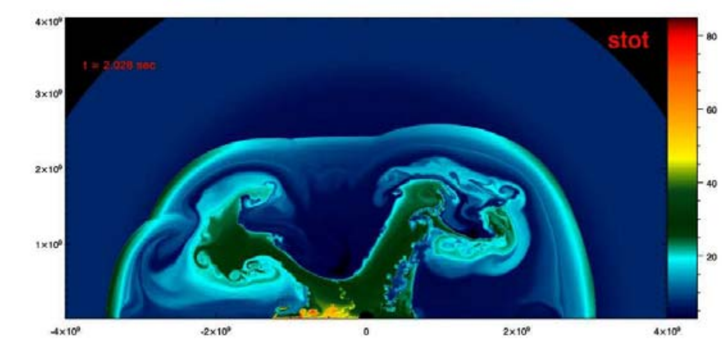


10s



2000s

Kifonidis et al., A&A 453 (2005), 661



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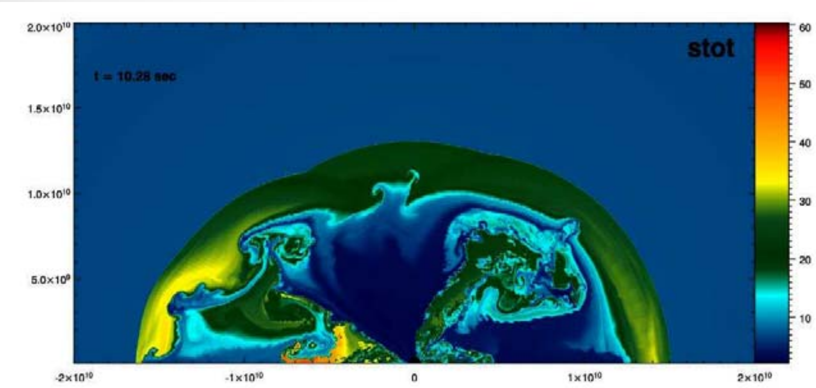
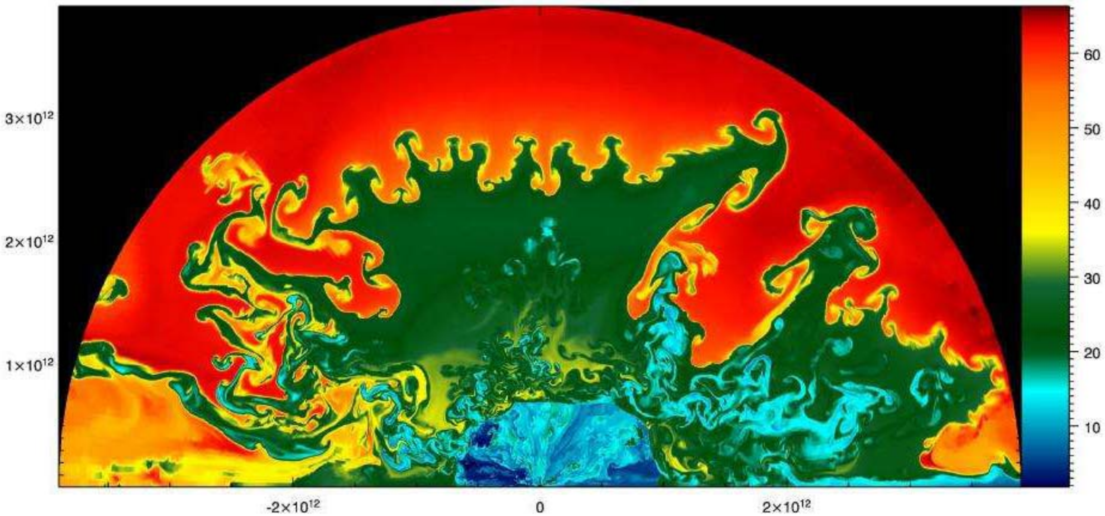
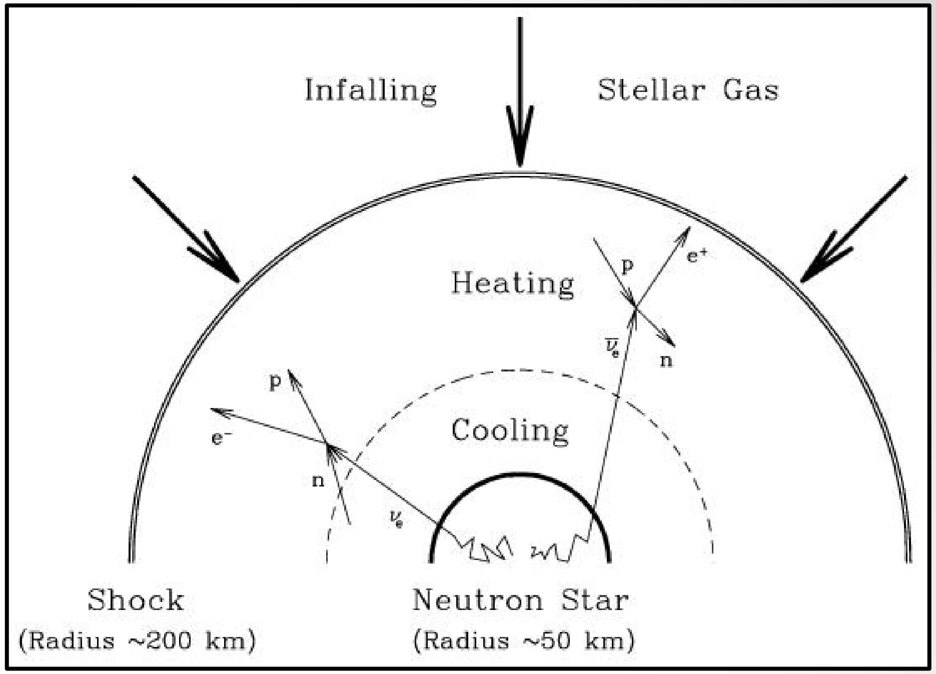


10s



2000s



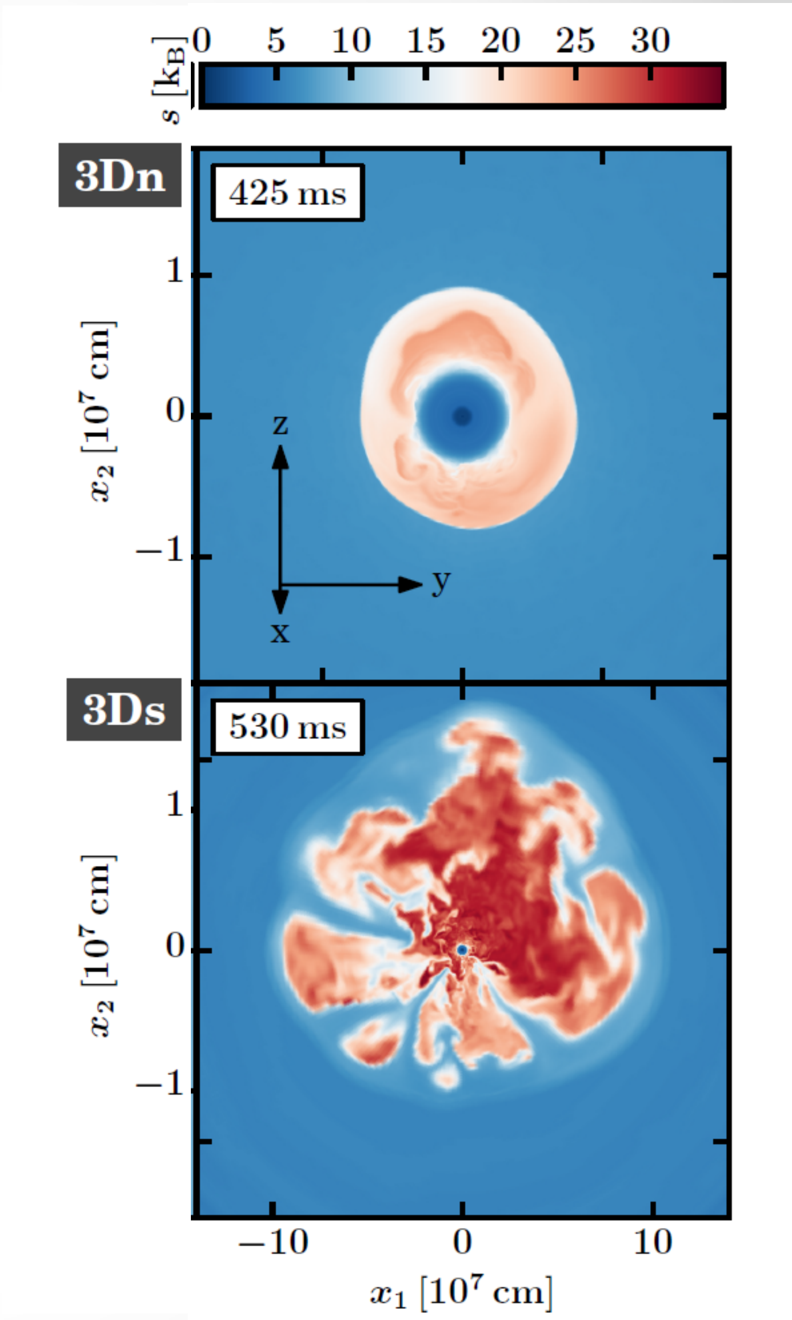
Modelling the explosion phase requires

- Hydro instabilities=> 3D simulations
- Neutrino dynamics in the gain region => matter composition at the neutrinosphere

3D simulations:

explosion

or not explosion?



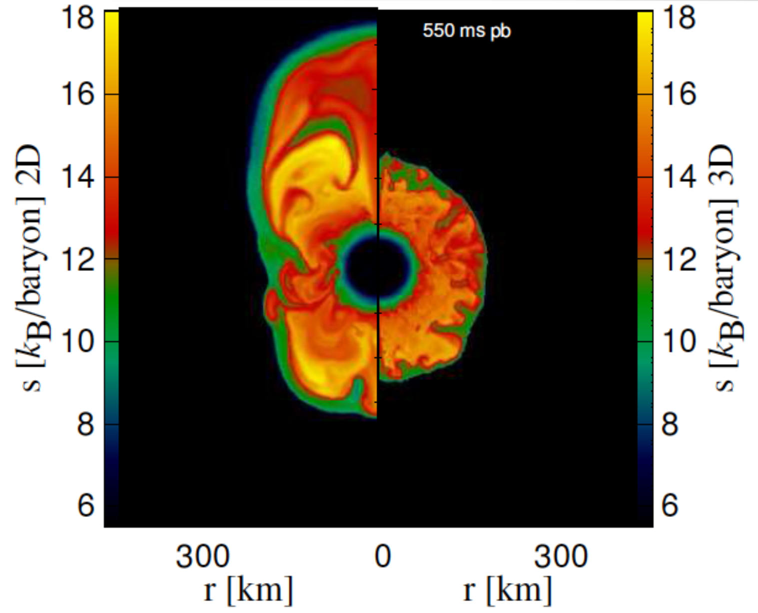
Melson et al. 2015

3D simulations:

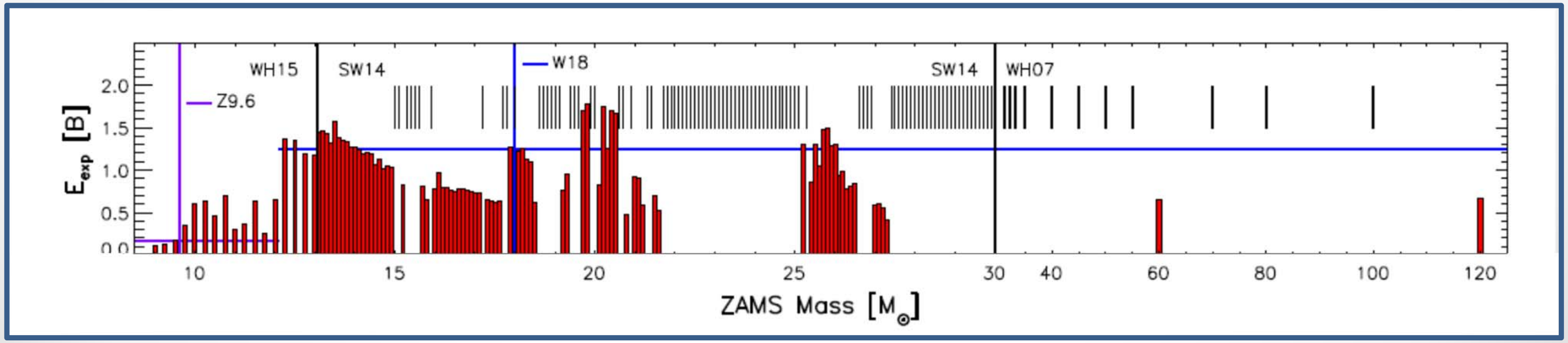
explosion

or not explosion?

Hanke et al 2012



1Bethe=10^{51} erg



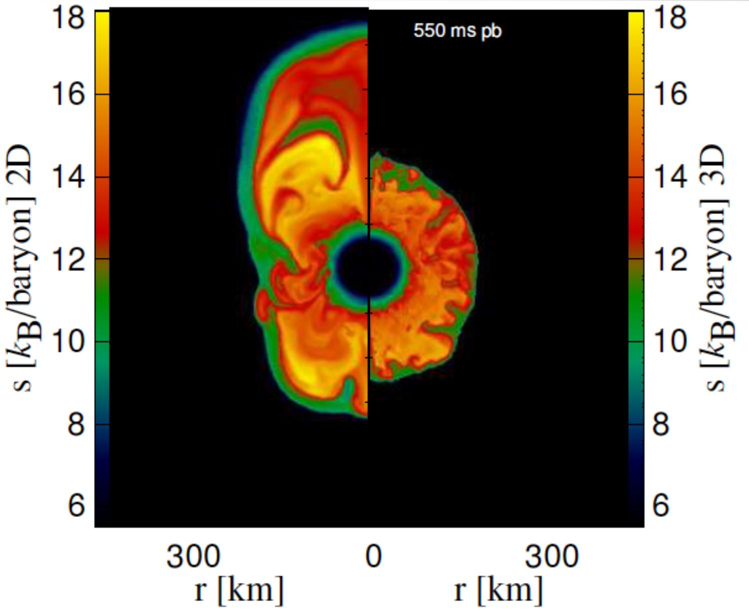
Sukhbold et al 2015

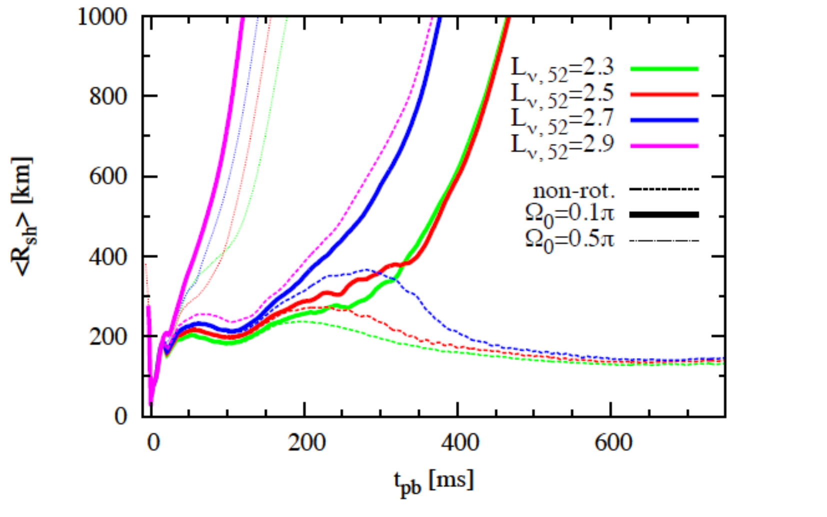
3D simulations:

explosion

or not explosion?

Hanke et al 2012





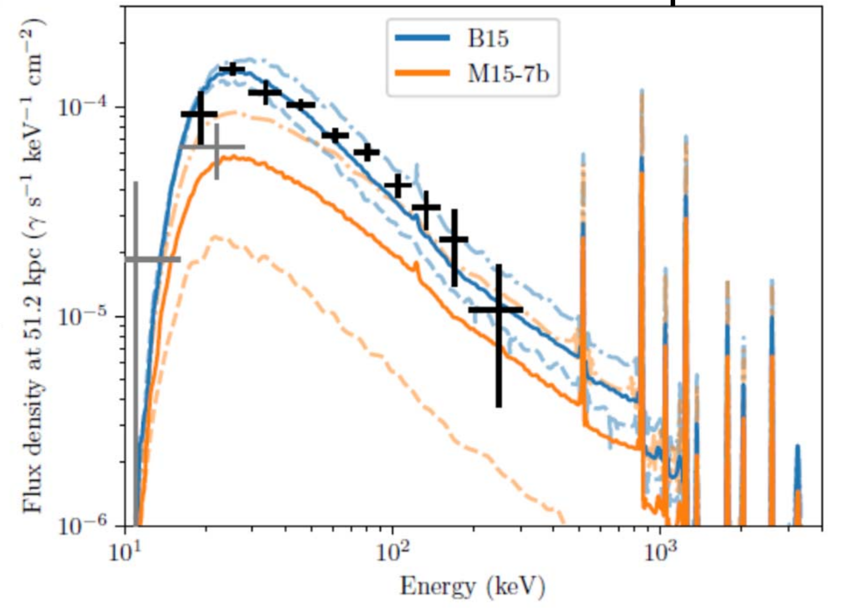
⇒ CRITICAL PHENOMENON

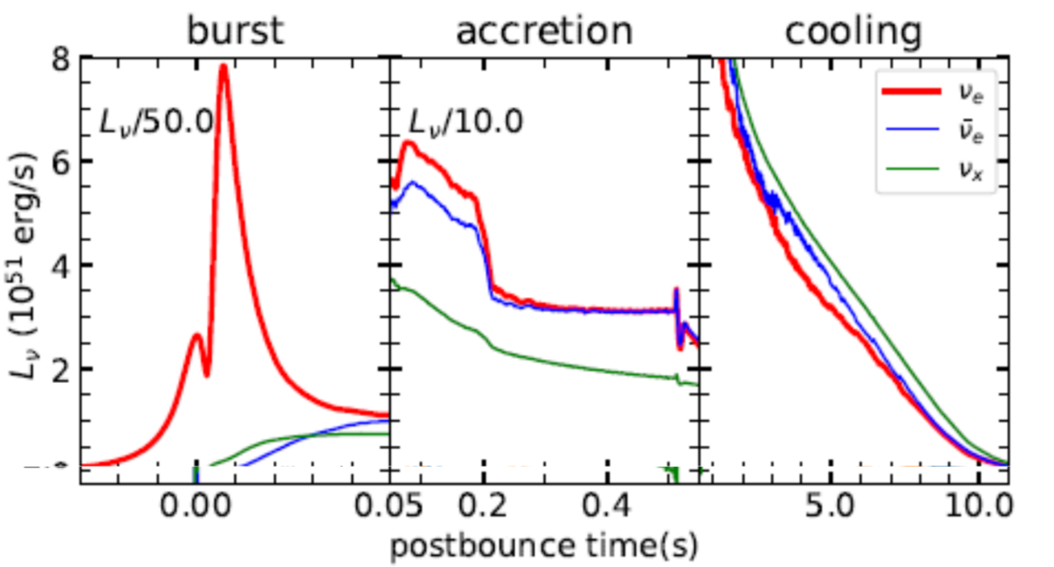
Nakamura et al 2014

Present status

1. SN1987a light spectrum and flux well reproduced by 3D exploding models
2. Predictions for ν spectrum over long times
3. But the ν gain energy is an input parameter
   - Incertainty in the initial of the explosion => col dynamics?
   - Incertainty in the ν dyn the neutrinosphere?

Th.Janka ApJ 2019



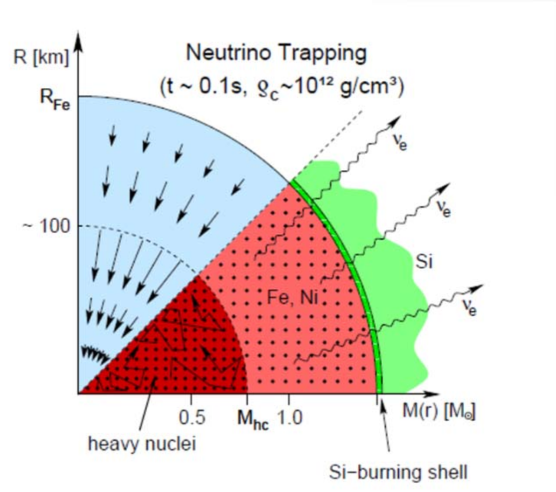


Lectures plan

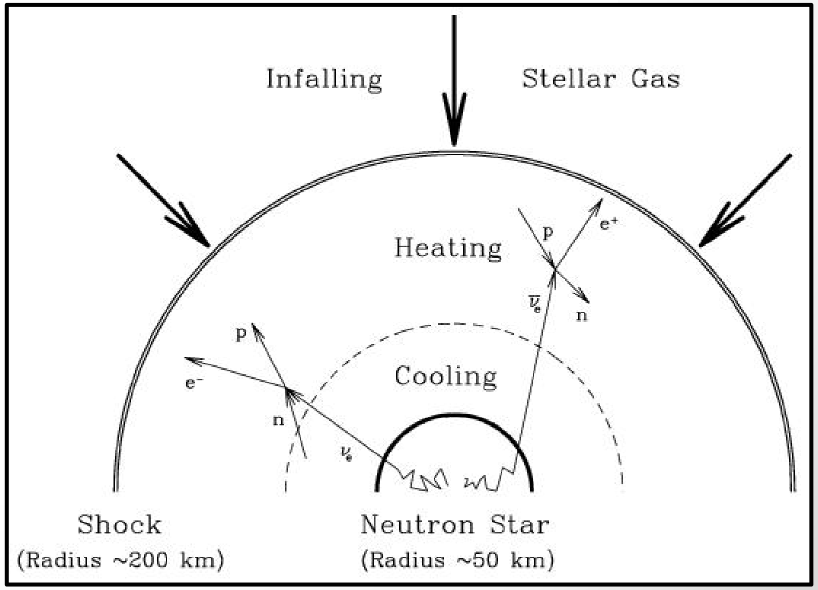
1. Introduction: dense matter in the universe
   a. The sites
   b. The signals
2. Neutron stars and mergers
   a. Observations
   b. Hydrostatics and the EoS
   c. Constraining the parameters
3. Phase transitions and Neutron stars
   a. Phase transitions in dense matter
   b. The physics of the core
   c. The physics of the crust
4. **Core Collapse Supernova**
   a. Observations
   b. Modeling supernova explosions
   c. **Influence of nuclear physics**

CCSN: influence of nuclear physics

- **Core collapse: EC capture on exotic nuclei**



- SN explosion and r-process seeds: matter composition at the neutrinosphere



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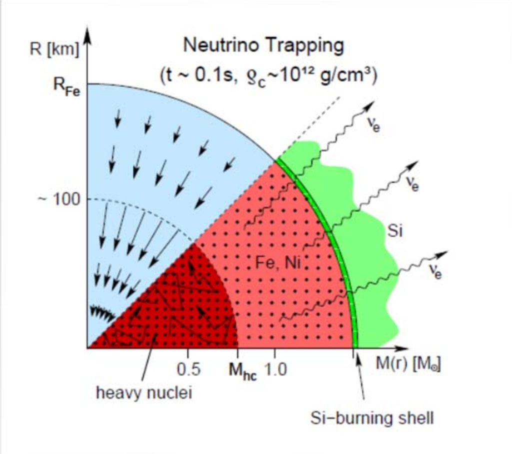
Core collapse and EC rates



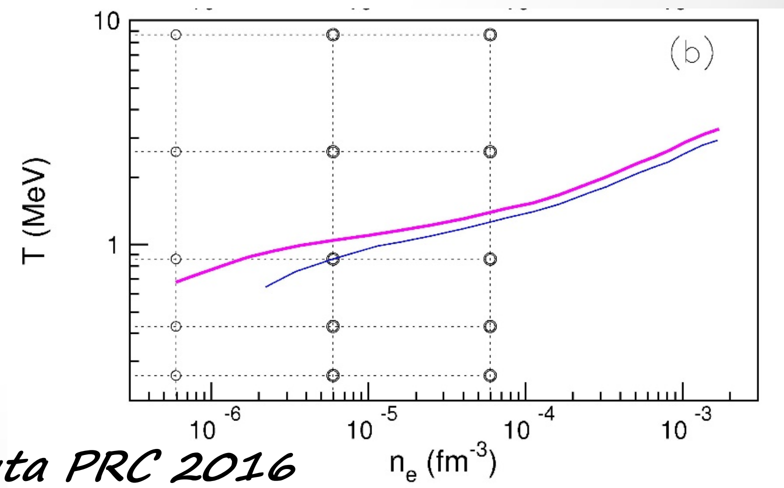
$$(A, Z) + e^- \rightleftarrows (A, Z-1) + \nu_e$$

- EC on exotic nuclei plays a key role during the pre-bounce phase of CCSN

- $$\lambda^{EC}(A,Z) = \frac{ln2}{K}\sum_i \frac{(2J_i+1)e^{-\beta E_i}}{Z_\beta}\sum_j \int_{e_m}^{\infty} de\, f\,(e, Q, \Delta E_{ij})B_{ij}$$

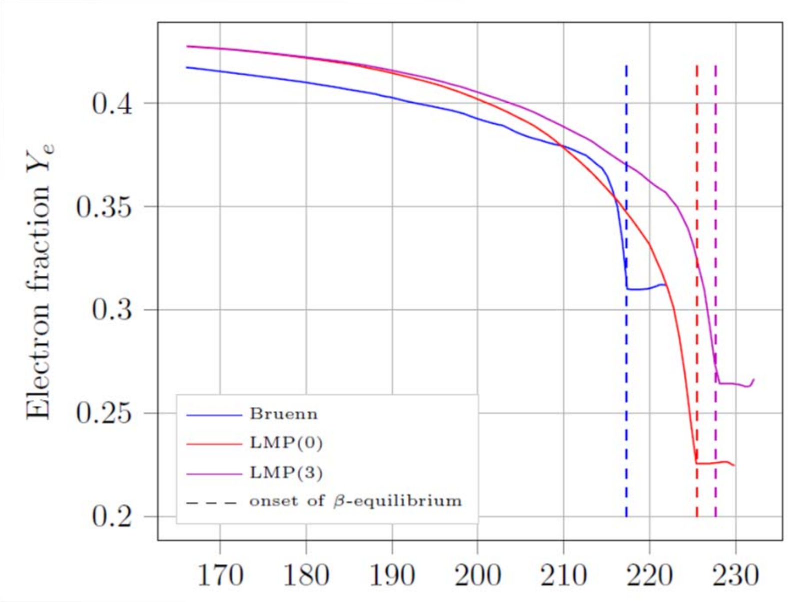
- Microscopic calculations are missing
- Different models for $Q, \Delta E_{ij} B_{ij}$

(Bruenn, LMP, Raduta..)

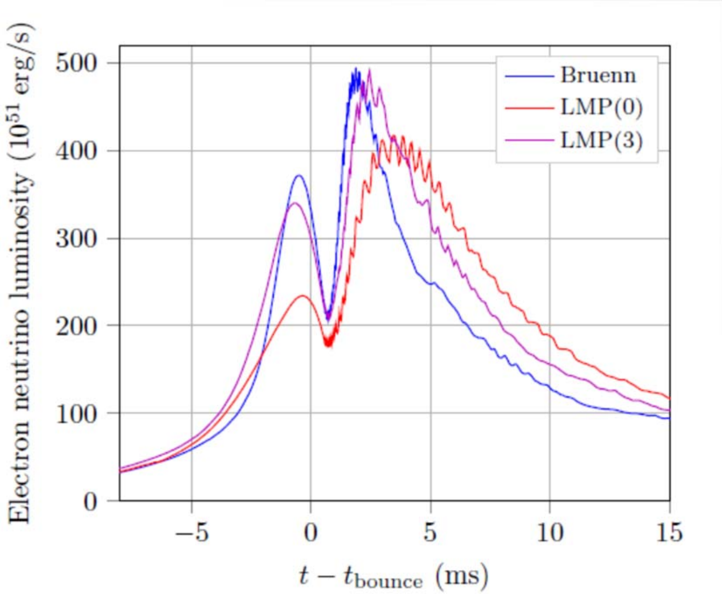


A.Raduta PRC 2016

Effect of the rates on the collapse



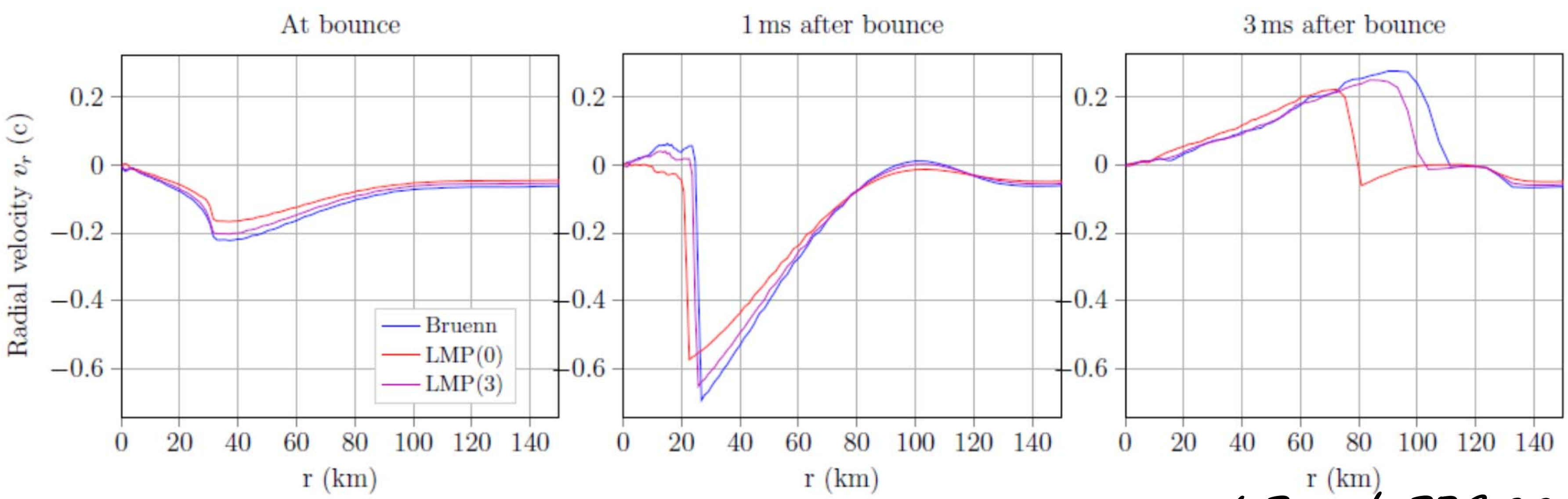
t(ms)



A.Pascal, PRC 2019

- Important effect of the different approx on the e-fraction dynamics
- Leads to a difference $\Delta Y_e/Y_e$=30% => $\Delta M_h/M_h$=30% in the enclosed mass at bounce
- Reflects into the neutrino luminosity

Effect of the rates on the collapse

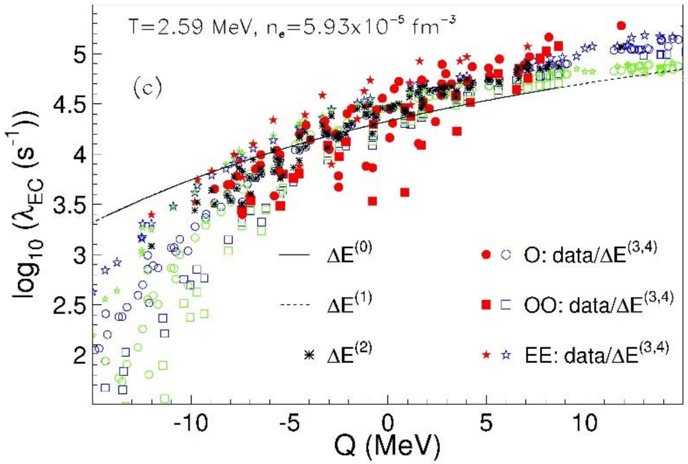


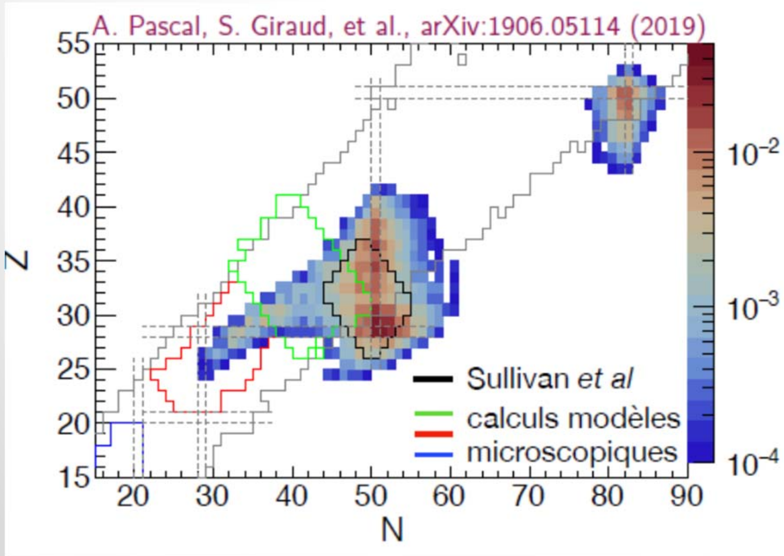
A.Pascal, PRC 2019

- Important effect of the different approx on the e-fraction dynamics
- Leads to a difference $\Delta Y_e/Y_e$=30% => $\Delta M_h/M_h$=30% in the enclosed mass at bounce
- Sizeable effect in the shock propagation after bounce

Which model is correct?

A.Raduta PRC 2016

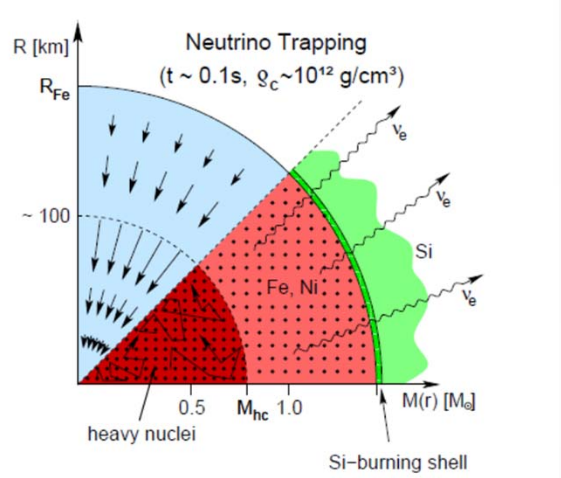




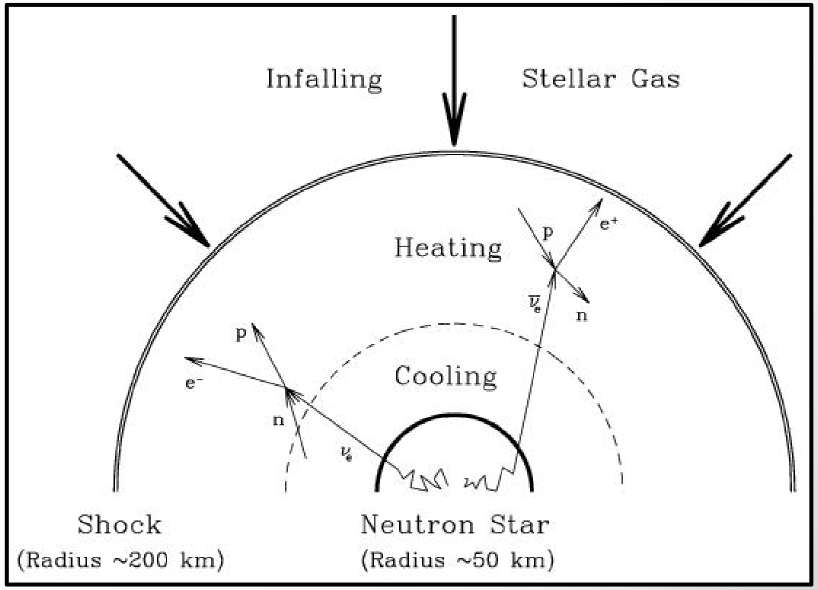
- The differences between the models concern low Q-values where microscopic rates do not exist
- => Need to benchmark on microscopic calculations for some relevant nuclei

CCSN: influence of nuclear physics

- Core collapse: EC capture on exotic nuclei



- **SN explosion and r-process seeds: matter composition at the neutrinosphere**



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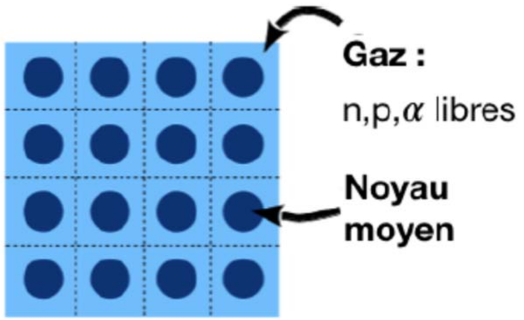
Matter composition at the neutrinosphere

- The energy deposition in the gain region depends on the position of the neutrinosphere
- Coherent scattering off nuclei is the main source of opacity at the neutrinosphere

$$\nu_i + (A,Z) \rightleftarrows \nu_i + (A,Z)$$

- Typical thermo conditions:

  $\rho \sim 0.01\ \mathrm{fm}^{-3}$ $T \sim 5$ MeV



$\Rightarrow$ Composition at finite temperature?

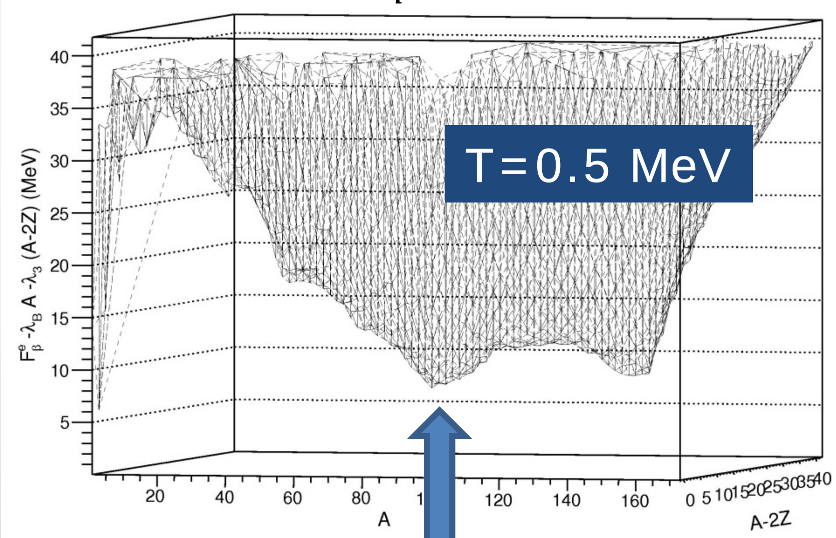
- Standard treatment in SN simulations: the single nucleus approximation => same treatment as for the crust

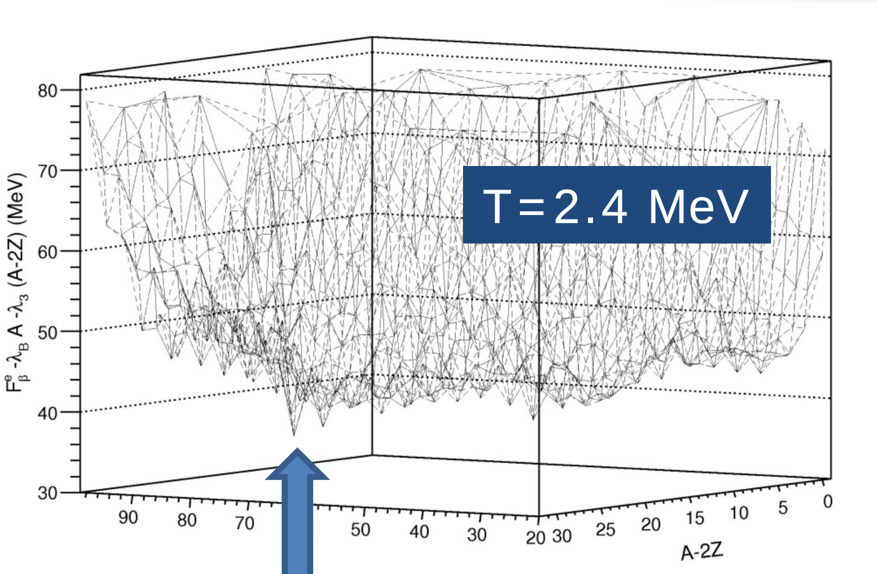
J. M. Lattimer and F. D. Swesty (1991), H. Shen et al (1998).

T>0: the Single Nucleus Approximation

- standard strategy for supernova simulations: minimize the FREE energy density
- It is a very poor treatment of the finite temperature problem.

$\rho_B = 10^{-3} fm^{-3}, Y_p = 0.39$





The absolute minimum is not representative of the free energy landscape

T>0: beyond the SN approximation

- One WS cell

$$d\left(f_{WS}-\mu_n\left(\frac{N_{WS}}{V_{WS}}-n_n\right)-\mu_p\left(\frac{Z_{WS}}{V_{WS}}-n_p\right)\right)=0$$

N,Z,n_{gn},n_{gp} variational variables linked by the strict conservation law in the cell

- Many WS cells

f_{tot}

$$\mathrm{d}\left(T\sum_k p_k ln p_k+\left(E_{tot}-\langle\hat{H}\rangle_V\right)-\mu_n\left(N_{tot}-\langle\hat{N}\rangle_V\right)-\mu_p\left(Z_{tot}-\langle\hat{Z}\rangle_V\right)\right)=0$$

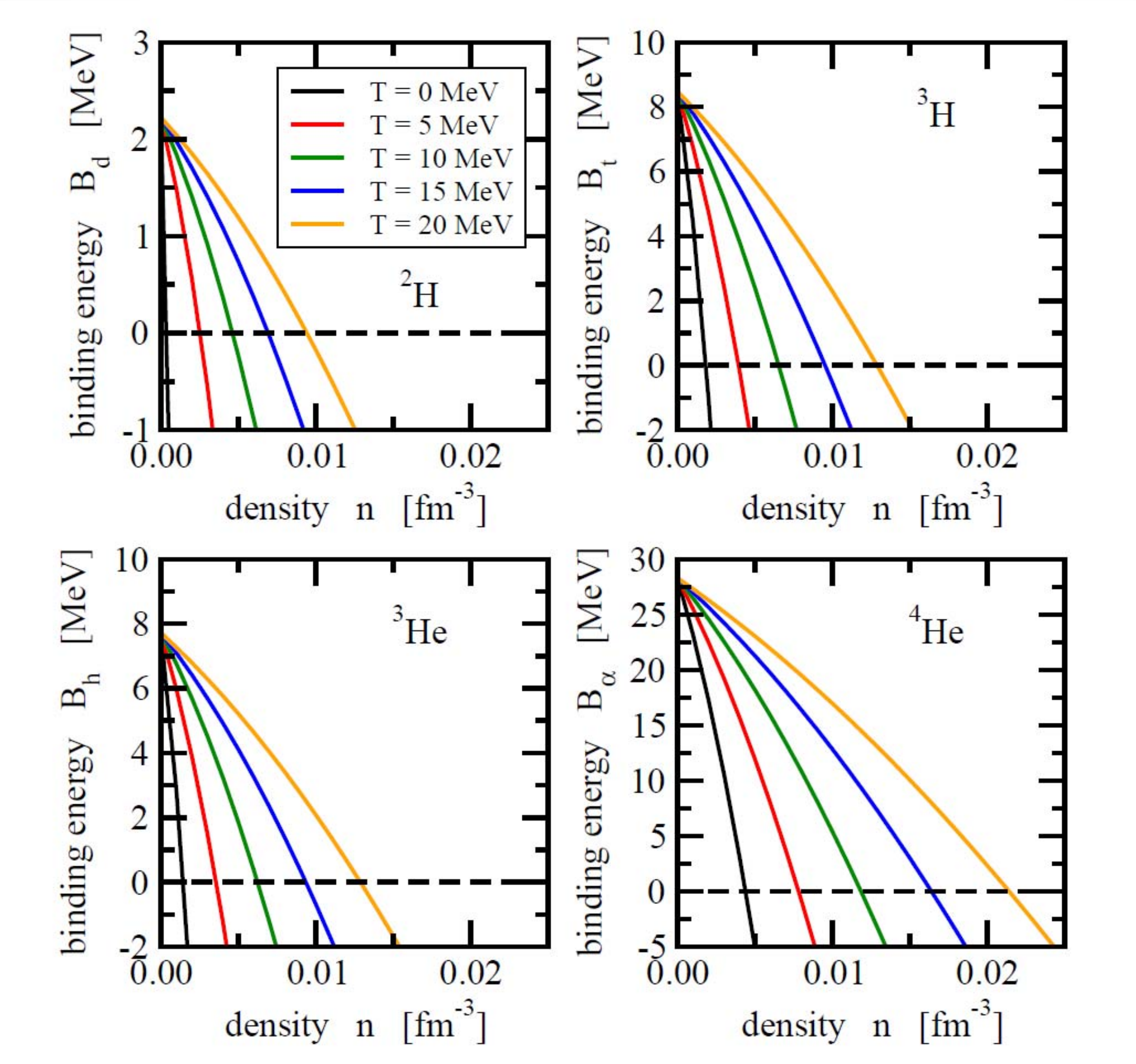
$$k=\left\{n_i^{(k)},N_i,Z_i\ i=1,\dots,N_k;N_{free}^{(k)}Z_{free}^{(k)}\right\}$$

n_i , n_{gn},n_{gp} variational variables linked by the loose conservation law in the cell through the global chemical potential

$$\langle n_{NZ}\rangle=exp-\beta\left(B_m-TS-\mu_nN-\mu_pZ\right)$$

B_m : in-medium modified binding energy

In-medium modified B and the Mott density



S.Typel et al, NPA 2009

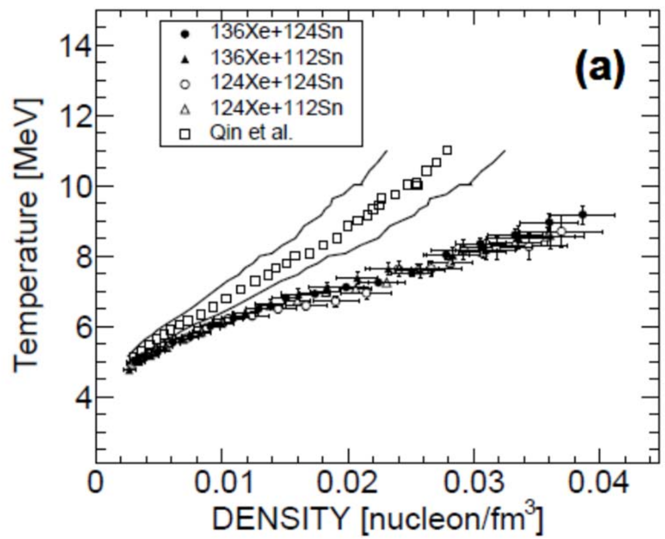
Mott density from experimental data ?

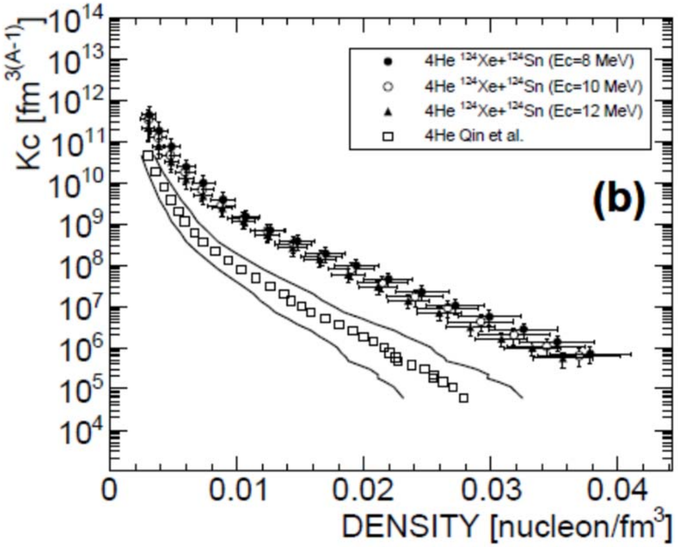
- Chemical constants in multifragmentation experiments

$$K_c(A,Z) = \frac{\rho_{pa}(A,Z)}{\rho_{pa}(1,1)^Z \ \rho_{pa}(1,0)^N}$$

- Different data sets explore different thermo conditions

L.Qin PRL 2012
R.Bougault JPG 2019

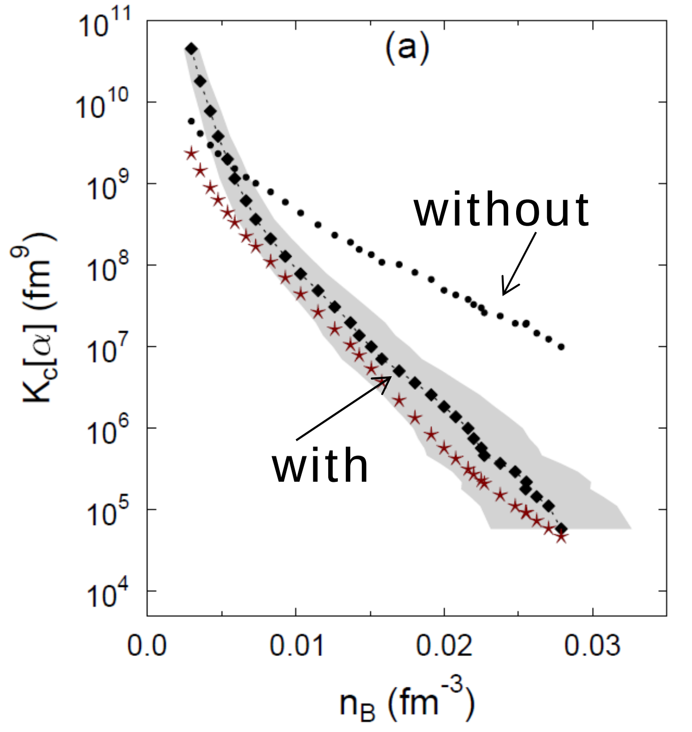




Mott density from experimental data ?

- Chemical constants in multifragmentation experiments
- Different data sets explore different thermo conditions
- Data suggest important corrections

$$K_c(A,Z) = \frac{\rho_{pa}(A,Z)}{\rho_{pa}(1,1)^Z \; \rho_{pa}(1,0)^N}$$



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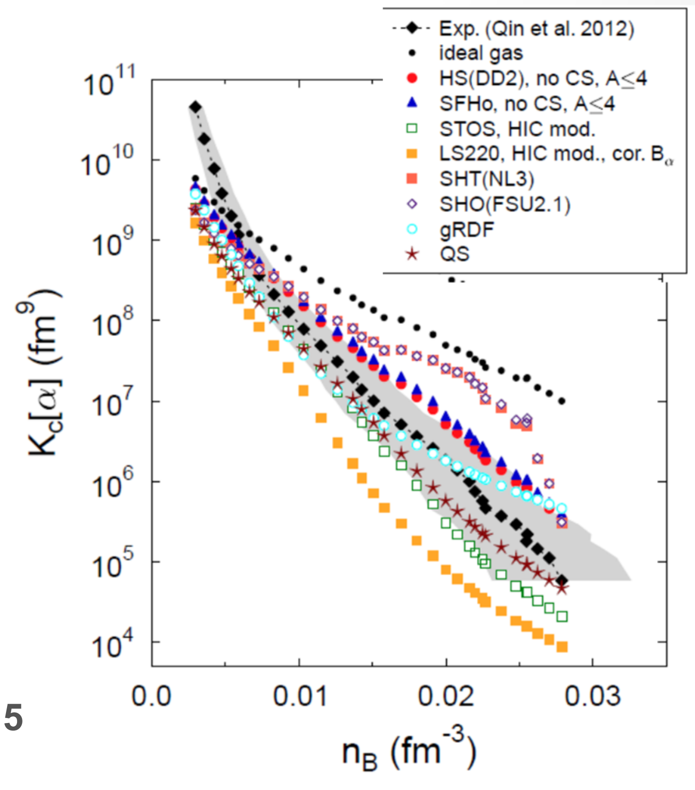
Mott density from experimental data ?

- Chemical constants in multifragmentation experiments
- Different data sets explore different thermo conditions
- Data suggest important corrections
- Wide variation of model predictions
- Model dependence should be addressed
-

$$K_c(A,Z) = \frac{\rho_{pa}(A,Z)}{\rho_{pa}(1,1)^Z \ \rho_{pa}(1,0)^N}$$

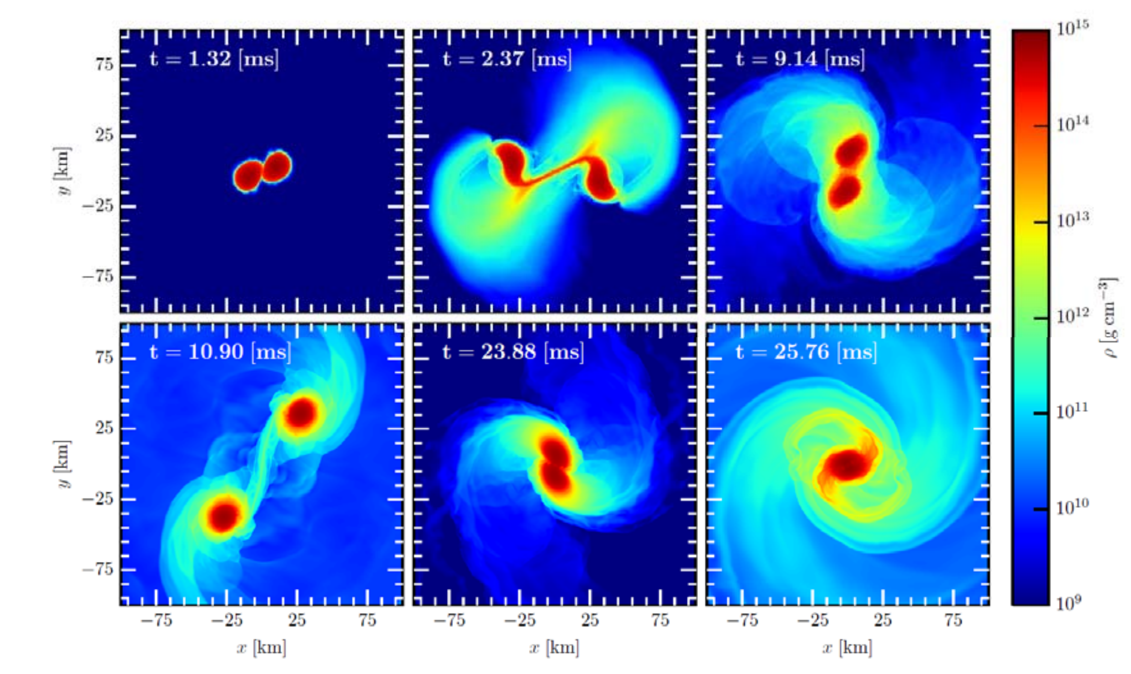


M. Hempel, K.Hagel, et al PRC 2015
H.Pais et al, PRC 2019

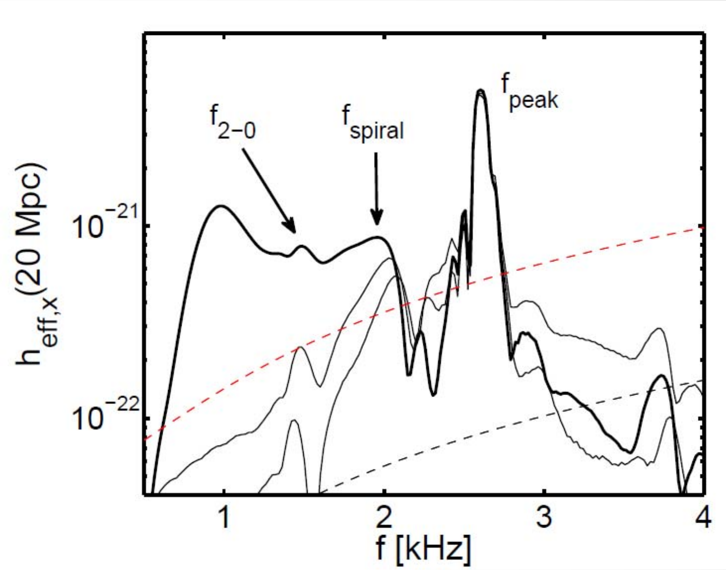
Backup

EoS and GW signals

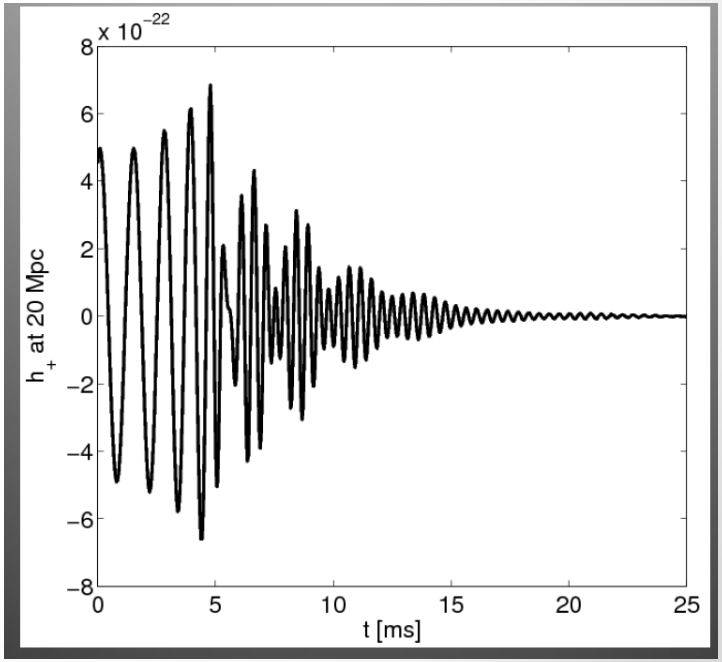
- Post-merger signals (~100-500 Hz)



A.Radice et al ArXiV 1601.02426



A.Bauswein, arXiV:1508.05493



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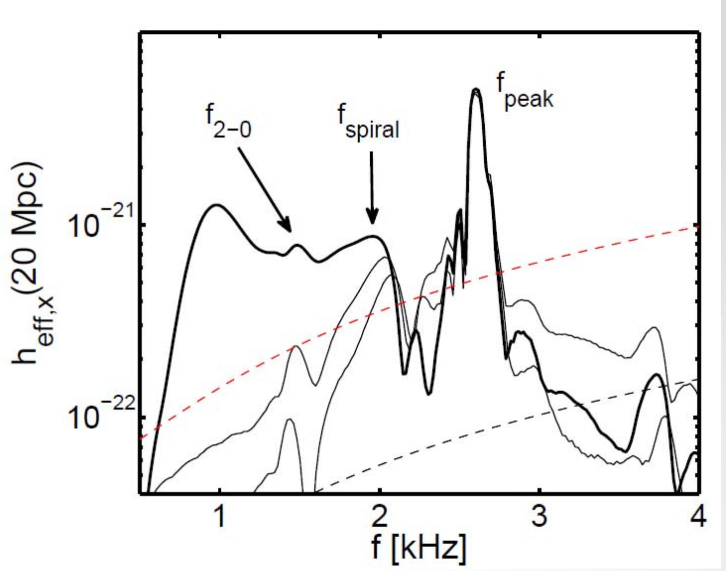
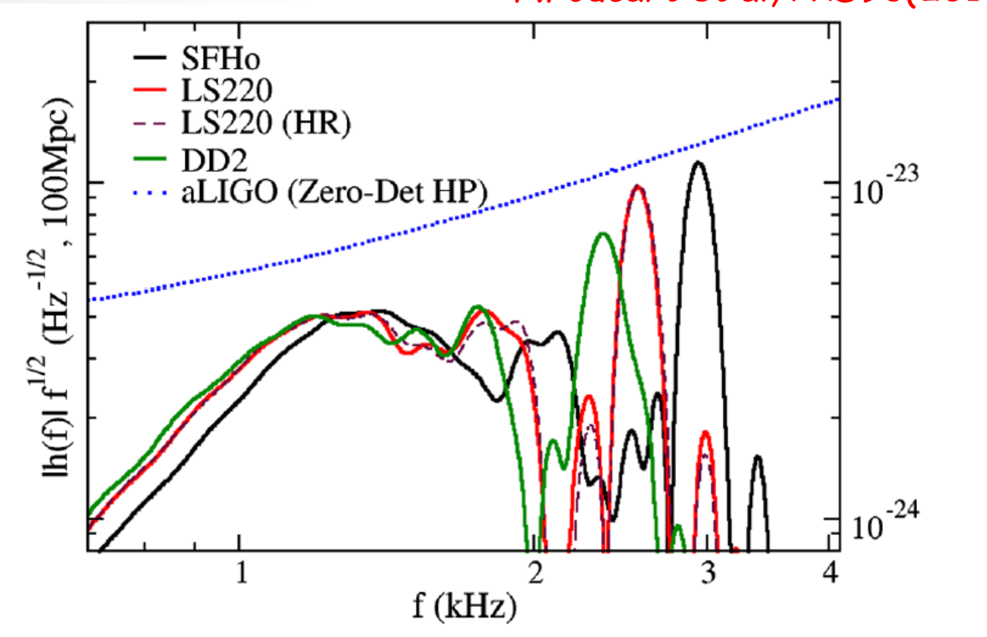
EoS and GW signals

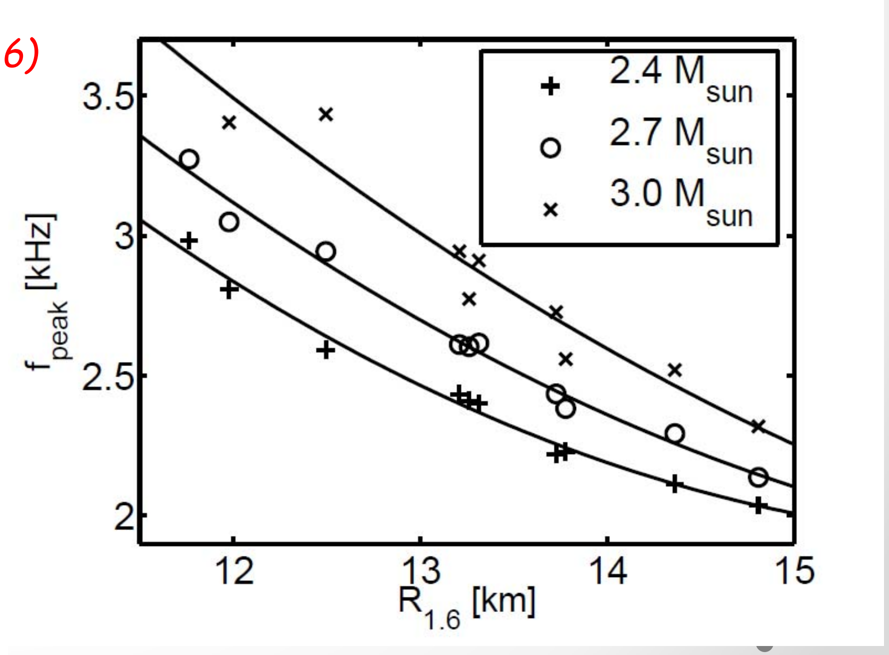
- Post-merger signals (~100-500 Hz)
  - fundamental quadrupole fluid mode (f-peak) of the differentially rotating post-merger remnant
  - Strongly correlated to the radius=>EoS



A.Bauswein, arXiV:1508.05493

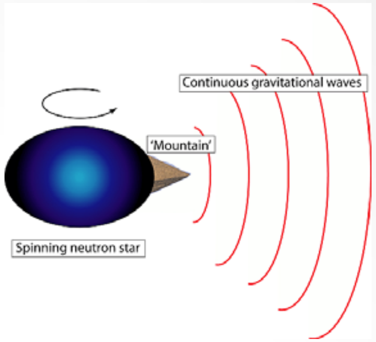
F.Foucart et al, PRD93(2016)

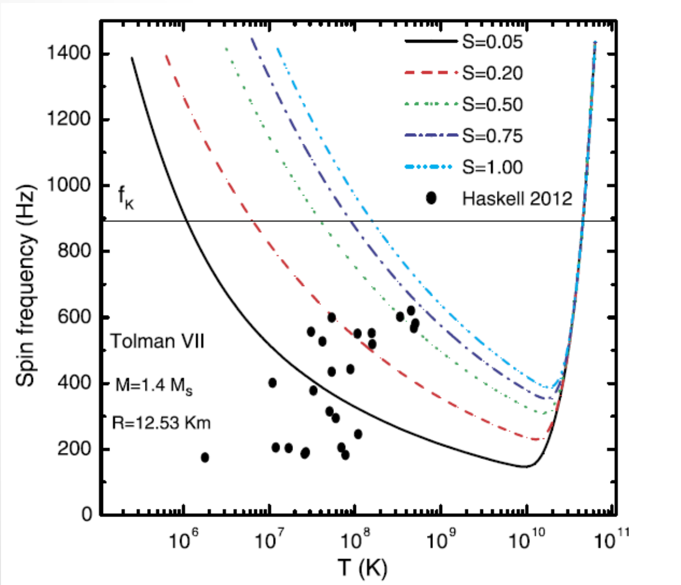




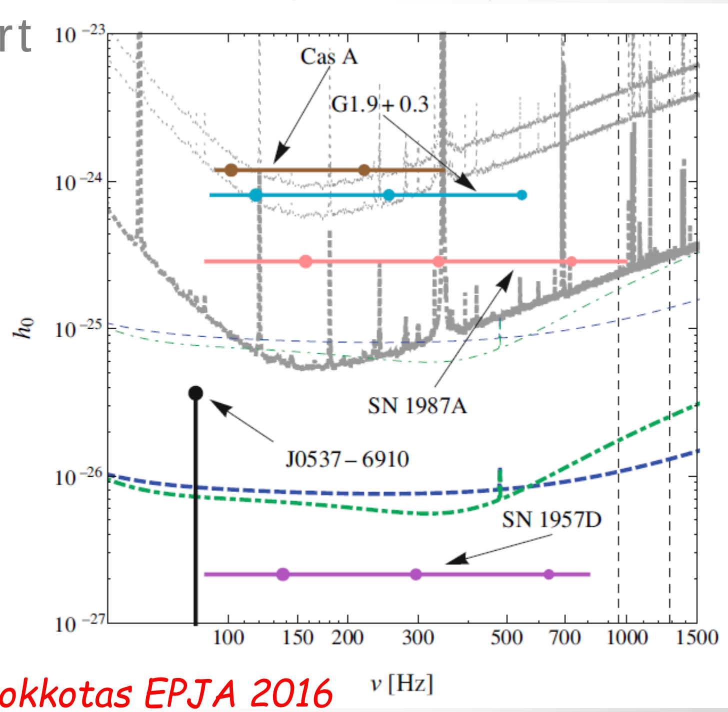
EoS and GW signals

- Spinning NS with asymmetric deformations (~1-10 Hz)
  - Elastic strains in the crust or magnetic fields in the core
  - Too weak for aLIGO and ET
- Unstable r-modes in young sources (~100-500 Hz)
  - Undamped by viscous dissipation if T and ν are high enough
  - Potentially detectable + EM counterpart
  - Very complex modelling





C.C.Moustakidis, Astrophys.Space Sci. 2016



C.D.Kokkotas EPJA 2016

Science

RESEARCH ARTICLES

Cite as: M. R. Drout *et al*., *Science* 10.1126/science.aaq0049 (2017).

Light curves of the neutron star merger GW170817/SSS17a: Implications for r-process nucleosynthesis

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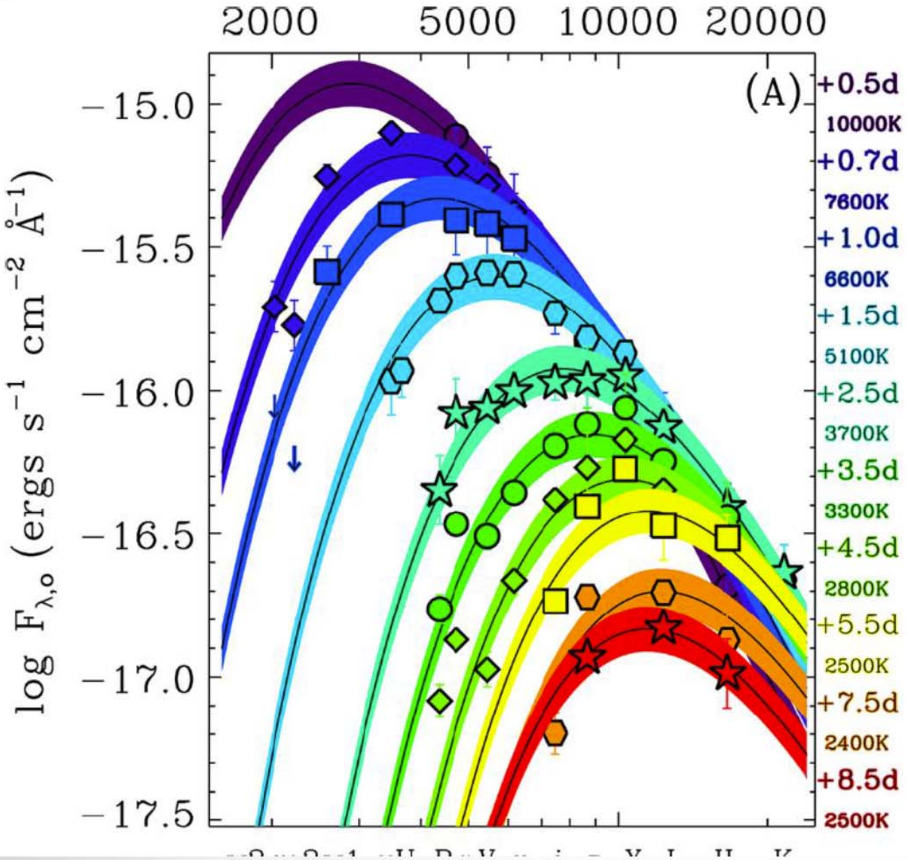


Fig. 3. Evolution of the ultraviolet to near-infrared spectral energy distribution (SED) of SSS17a. (**A**) The vertical axis, log $F_{\lambda,o}$, is the logarithm of the observed flux. Fluxes have been corrected for foreground Milky Way extinction (*33*). Detections are plotted as filled symbols and upper limits for the third epoch (1.0 days post-merger) as downward pointing arrows. Less-constraining upper limits at other epochs are not plotted for clarity. Between 0.5 and 8.5 days after the merger, the peak of the SED shifts from the near-UV (<4500 Å) to the near-IR (>1 μm), and fades by a factor >70. The SED is broadly consistent with a thermal distribution and the colored curves represent best-fitting blackbody models at each epoch. In 24 hours after the discovery of SSS17a, the observed color temperature falls from $\gtrsim$10,000 K to ~5000 K. The epoch and best-fitting blackbody temperature (rounded to 100 K) are listed. SEDs for each epoch are also plotted individually in fig. S2 and described in (*33*). (**B**) Filter transmission functions for the observed photometric bands.

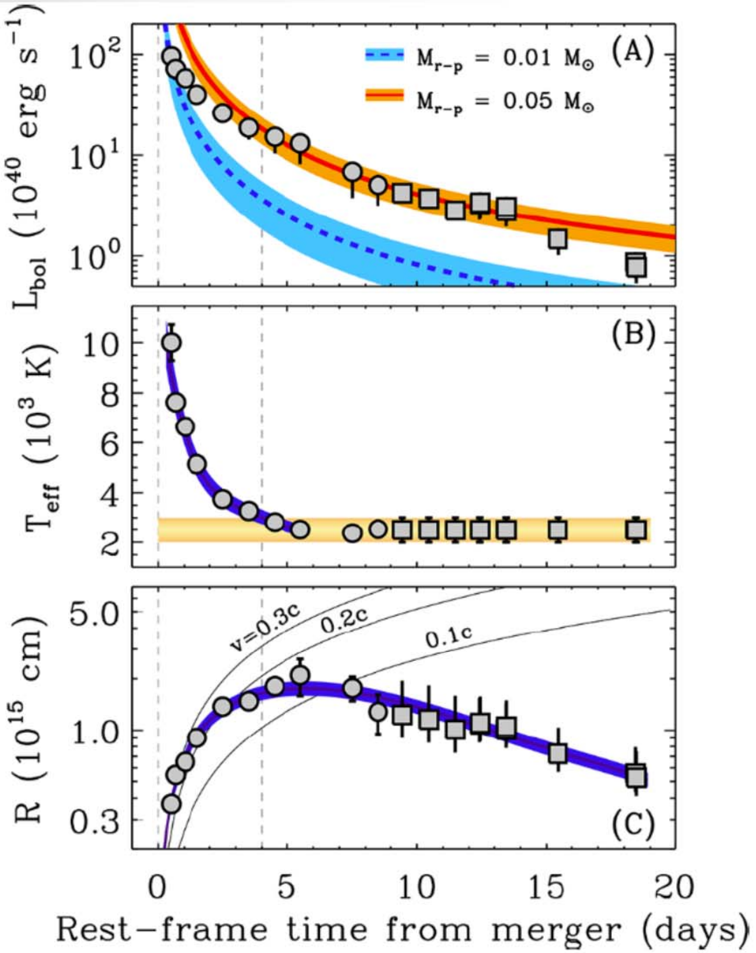


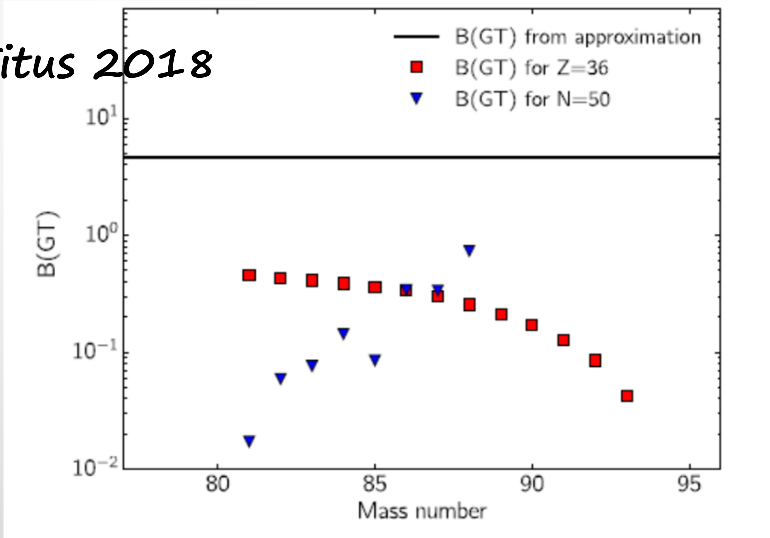
Fig. 4. Physical parameters derived from the ultraviolet to near-infrared SEDs of SSS17. Vertical dashed lines indicate the time of merger and four days post-merger, between which SSS17a undergoes a period of rapid expansion and cooling. (**A**) Pseudo-bolometric light curve evolution; representative r-process radioactive heating curves are also shown. While the initial observed peak is consistent with ~0.01 $M_\odot$ of r-process material (blue curve), this under-predicts the luminosity at later times. Instead, the late-time (>4 day) light curve matches radioactive heating from 0.05 ± 0.02 $M_\odot$ of r-process material (red curves). (**B**) Best-fitting blackbody model temperatures. 11 hours after the merger, SSS17a is consistent with a blackbody of $\gtrsim$10,000 K. Between 4.5 and 8.5 days, the temperature asymptotically approaches ~2500 K — the temperature at which open f-shell lanthanide elements are expected to recombine. Radii and luminosities beyond 8.5 days are computed assuming a temperature of 2500^{+500}_{-1000} K and are plotted as squares. This temperature range is highlighted by the orange horizontal band. (**C**) Best-fitting blackbody model radii. Curved lines represent the radius of material moving at 10%, 20%, and 30% the speed of light. At early times the increase in radius with time implies that the ejecta are expanding relativistically. After ~5 days, the measured radii decrease, likely due to recombination.

EC rates: approximations

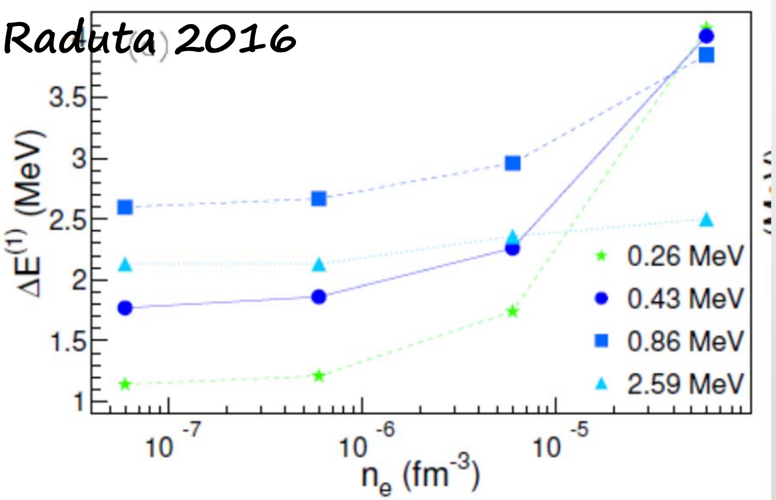
- $\lambda^{EC}(A,Z) = \frac{ln2}{K}\sum_i \frac{(2J_i+1)e^{-\beta E_i}}{Z_\beta}\sum_j \int_{e_m}^{\infty} de\, f\left(e, Q, \Delta E_{ij}\right)B_{ij}$

1. $\Delta E_{ij} = 3;\ Q = \mu_n - \mu_p; B_{ij} = \frac{2}{7}N_p(Z)N_h(N)$ => no capture beyond N=40 *S.W.Bruenn ApJ 1985* **BRUENN**
2. $\Delta E_{ij} = 2.5;\ B_{ij} = 3.6$ *K.Langanke PRL 2003* **LMP(0)**
3. $\Delta E_{ij} = f(I, T, \rho_e);\ B_{ij} = 3.6$ *A.Raduta PRC 2016* **LMP(3)**
   plus odd-even effects fitted from LSSM

R.Titus 2018



A.Raduta 2016



Simulations set-up

- 2 different hydro codes in GR
  - CoCoNuT (spherical symmetry): neutrino loss in FMT scheme
    full NSE from CompOse tables
    J.Novak ASCL 2012
    B.Peres PRD 2013
  - Pons et al., Romero et al.: multigroup leakage
    dynamical EoS calculation
    J.Romero ApJ 1996
    J.Pons ApJ 1999
    A.Fantina PhD 2010
- Progenitors from Woosely et al.

  S.E.Woosley Rev.Mod.Phys.2002
- Benchmark calculation => same results with the different numerical schemes => focus on microphysics only
-