Investigating dense matter using Neutron Star observations

Journée des étudiants

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Plan of the talk

1. From multi-messenger astronomy to dense matter physics
   - Nuclear model theories for Neutron Star interior ...
   - ... and how they compare to observations
2. Unexplained sources in lowly accreting binaries
   - A new approach for the crust
   - Properties of partially accreted crusts
3. Conclusion

From multi-messenger astronomy to dense matter physics

Neutron Stars (NS):

- density $\rightarrow 10^{15}$ g/cm^3
- mass $\sim$ $M_\odot$
- radius $\sim$ 10kms

Structure:

- Crust: lattice state of matter
  - outer crust: up to 10^{11}g/cm^3
  - inner crust: free neutrons outside nuclei
- Core: soup of particles
  - outer core: $npe\mu$ gaz
  - inner core: ?

How is the interior described ?
Equation of State (EoS) : $P(\rho)$

Inner core: different hypothesis

- hyperons
- quark matter ?
- etc.

Calculation techniques:

- Microscopic: *ab-initio* ...
- Phenomenological: Relativistic Mean Field, Skyrme based models...

Equations of State for Neutron Star matter

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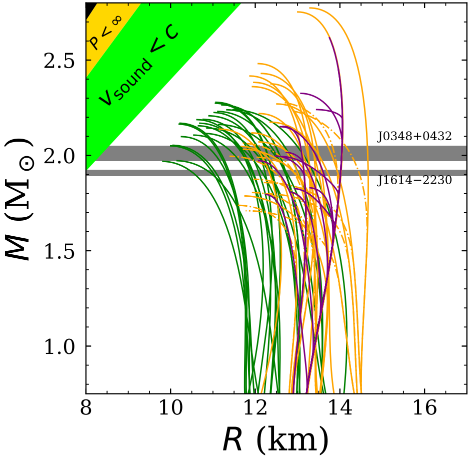
Modelling NS astrophysical properties

... and how they compare to observations

- For cold isolated NS : *Tolman-Oppenheimer-Volkoff*

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

- $\rightarrow M$: $M_{max} \sim 2M_{\odot}$
- $\rightarrow R$: NICER
- $\rightarrow \Lambda$: GW170817
- $\rightarrow I$: still waiting...



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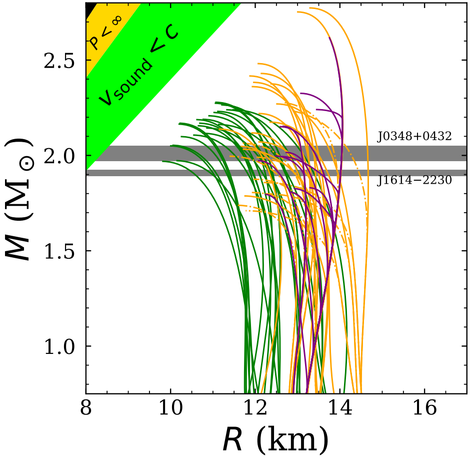

Modelling NS astrophysical properties

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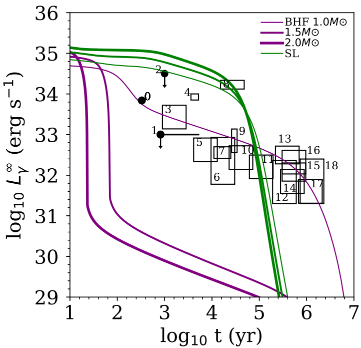
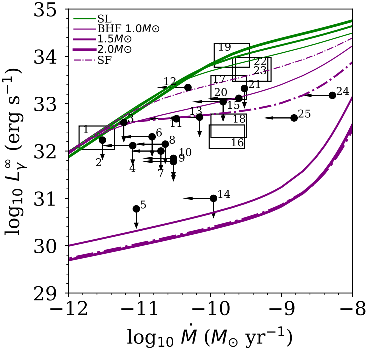
- For accreting NS in binary systems :

$$\frac{\partial}{\partial r}\left(\frac{Kr^2}{\Gamma(r)} e^{\phi} \frac{\partial \mathcal{T}}{\partial r}\right) = r^2 \Gamma(r) e^{\phi} \left(C_V \frac{\partial T}{\partial t} + e^{\phi} \left(Q_\nu - Q_h \right) \right) \quad \rightarrow \quad L^{\infty}_{\nu,\gamma}$$

Study the presence of neutrino emissive processes in NS





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LUTH & CAMK

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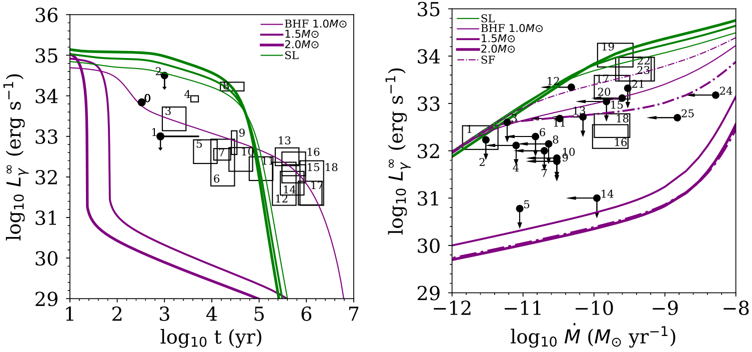

Unexplained sources in lowly accreting binaries

Accreting NS = NS receiving matter from companion

- Accretion → highly luminous 10^{40}erg/s
- Cooling of SQRTs: deep crustal heating [Haensel, Zdunik 1990]
- Directly depends nuclear model

→ SQRTs help us constrain the crust

Fully accreted crust approximation

= Original crust replaced by accreted material

What if that's not valid ?

Unexplained source :

IGR J17480 – 2446

→ 11Hz spin

→ not recycled = young star

Hybrid crust = Accreted material + crust compressed

Framework:

- first accretion : original crust is catalyzed
- simple nuclear model : CLDM
- accreted material : Fe^{56}

Beyond the Fully Accreted Crust approximation

A new approach for the crust

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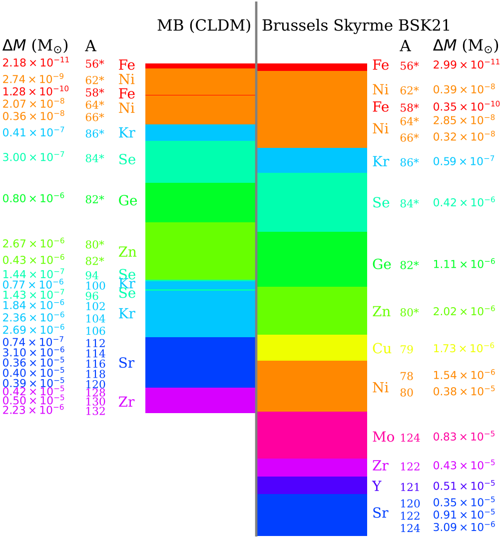

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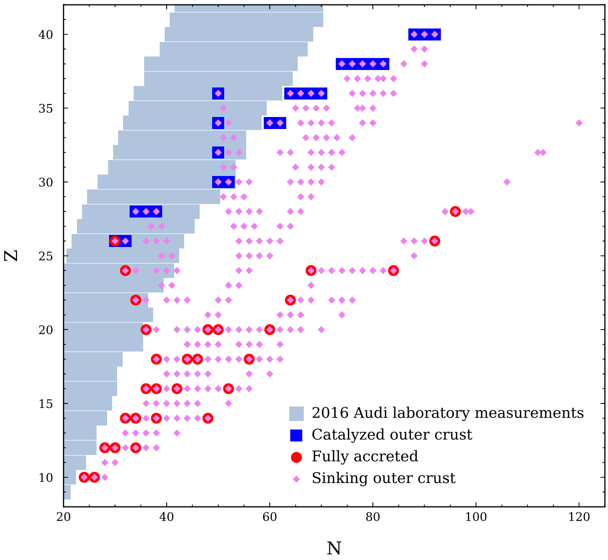
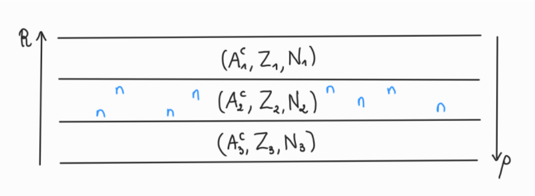


Neutron drip anomaly

Neutron drip = density related + (A_c, Z, N) **dependent**

Alternating shells with and without free neutrons

Happens for $\Delta P = [1 \times 10^{30}; 1.6 \times 10^{30}]$



Do they diffuse ?

Or are they absorbed ?

Does this affect the composition and heat releases ?

Do they pair ?

Potential correction

Properties of partially accreted crusts

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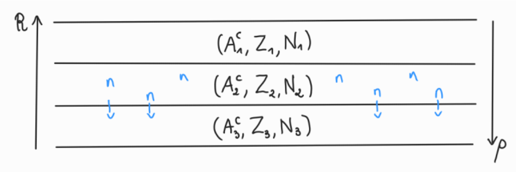

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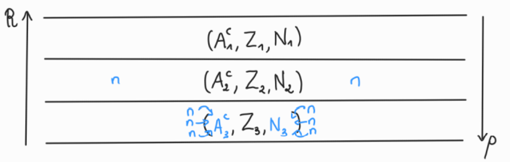

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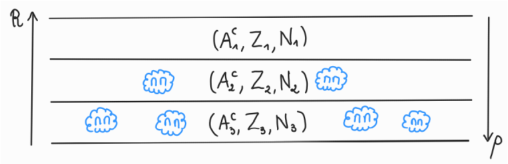

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Conclusion

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- All in all, until we go to higher density in Earth laboratories, NS are the next best laboratory for high density matter we have !
- Modelisation of macroscopic parameters is fully dependent on the treatment of nuclear models
- Need for a correct treatment of the EoS to be able to compare modelisation to observations :
  WARNING be carefully of core-crust bound nuclear models
- Accreting NS are wonderful tests of high density matter because we have many observations
- Partially accreted crusts might experience rearrangement of the shells