INT program "advances in MC techniques for MB quantum systems", Seattle, August 13, 2018

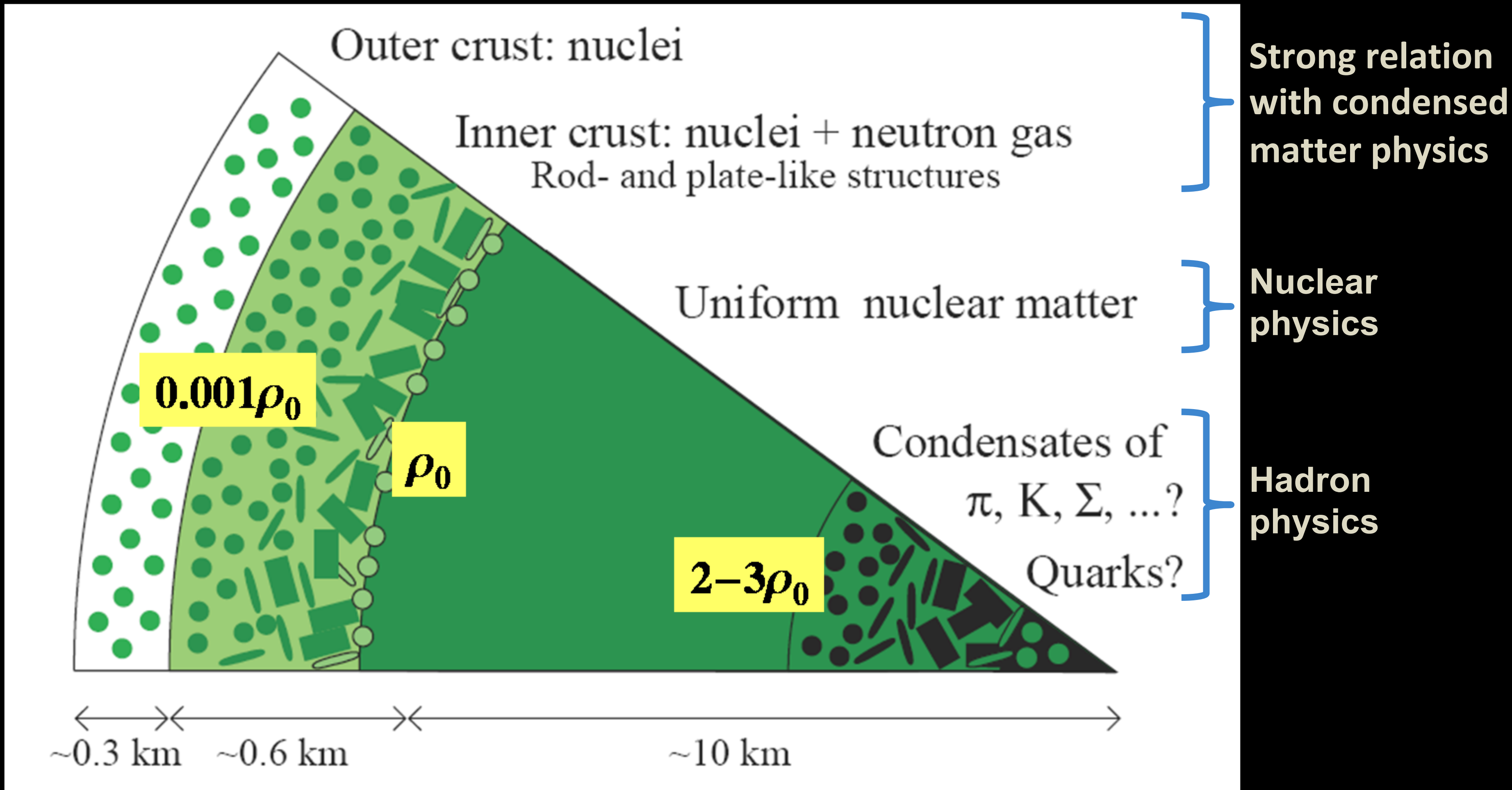
Some open questions in neutron star physics *(with QMC in ambush)*

Jérôme Margueron, IPN Lyon & INT Seattle

- Pairing in non-uniform systems
- Pairing at finite-T and re-entrance phenomenon
- NS mergers, tidal deformability, dense matter EOS

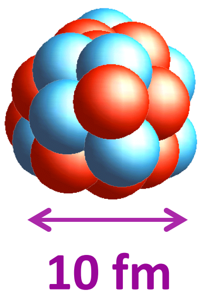
The structure of Neutron stars

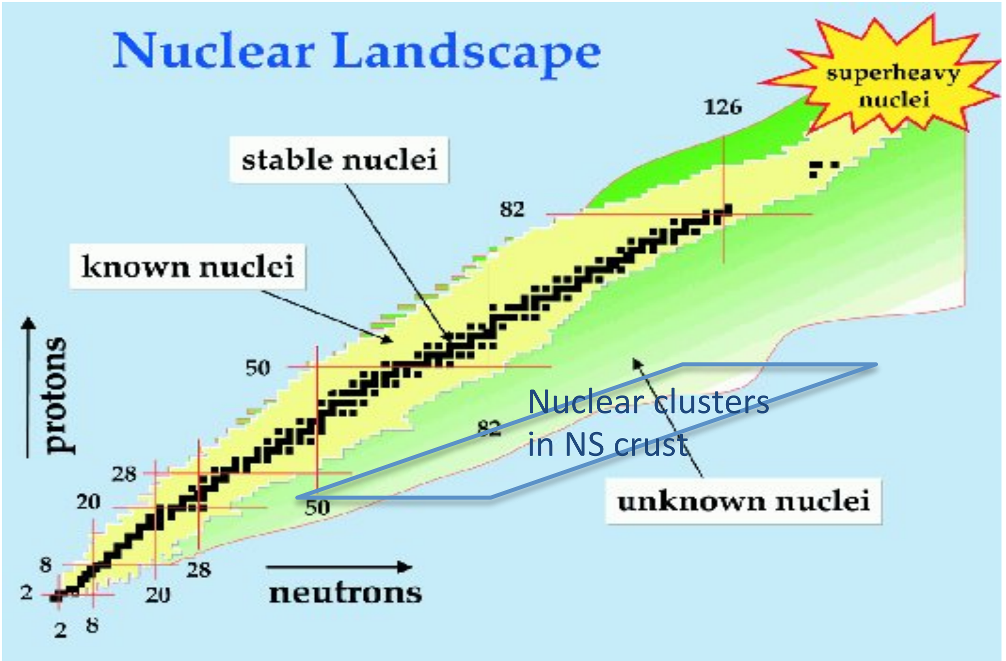
The interior of a neutron star has a complex structure exhibiting various matter configurations:

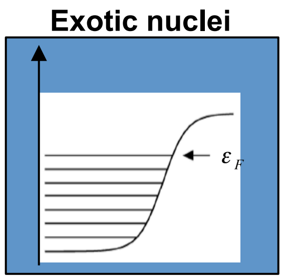


Nuclear physics and neutron star crust

Properties of finite systems:
masses, radii, pairing, evolution of the shells, deformation, collective modes, molecular states, …







Energy Density Functional approach is well suited to explore a large number of neutron rich nuclei.

Energy Density Functional approach

Going towards very N rich nuclei

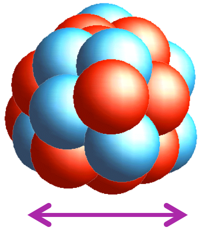
Properties of finite systems:
masses, radii, pairing, evolution of the shells, deformation, collective modes, molecular states, …

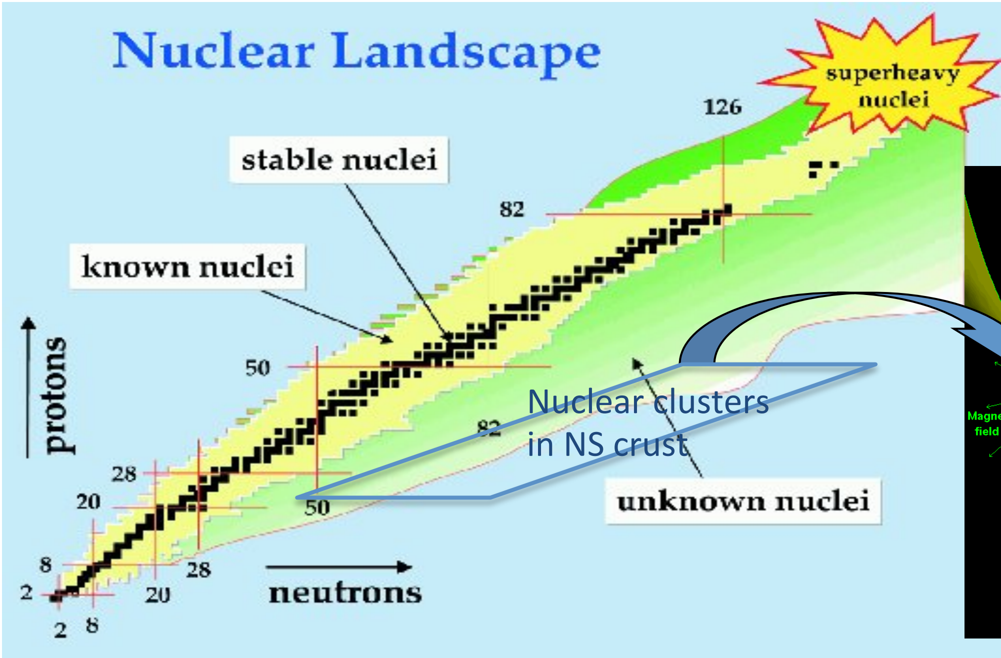
↔

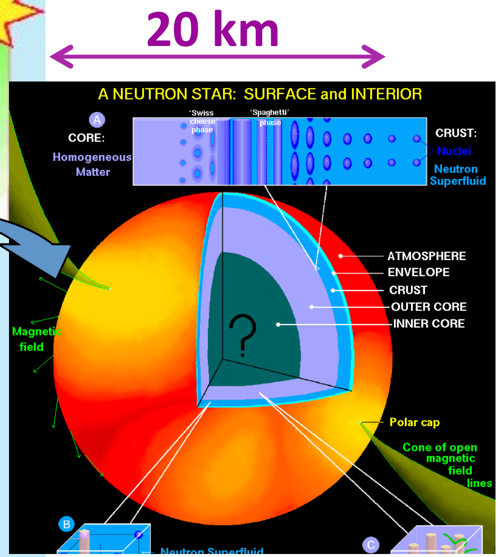
General properties of matter:
incompressibility, symmetry energy equation of state, …

↔

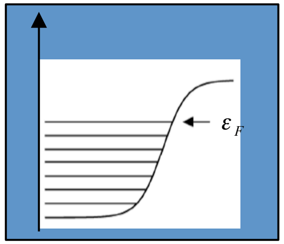
Application to neutron stars and supernovae:
Masses, radii, cooling, Glitches, neutrinos processes, …



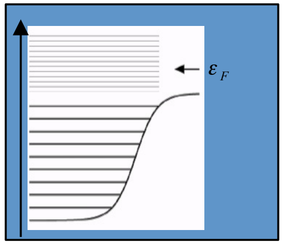




Exotic nuclei



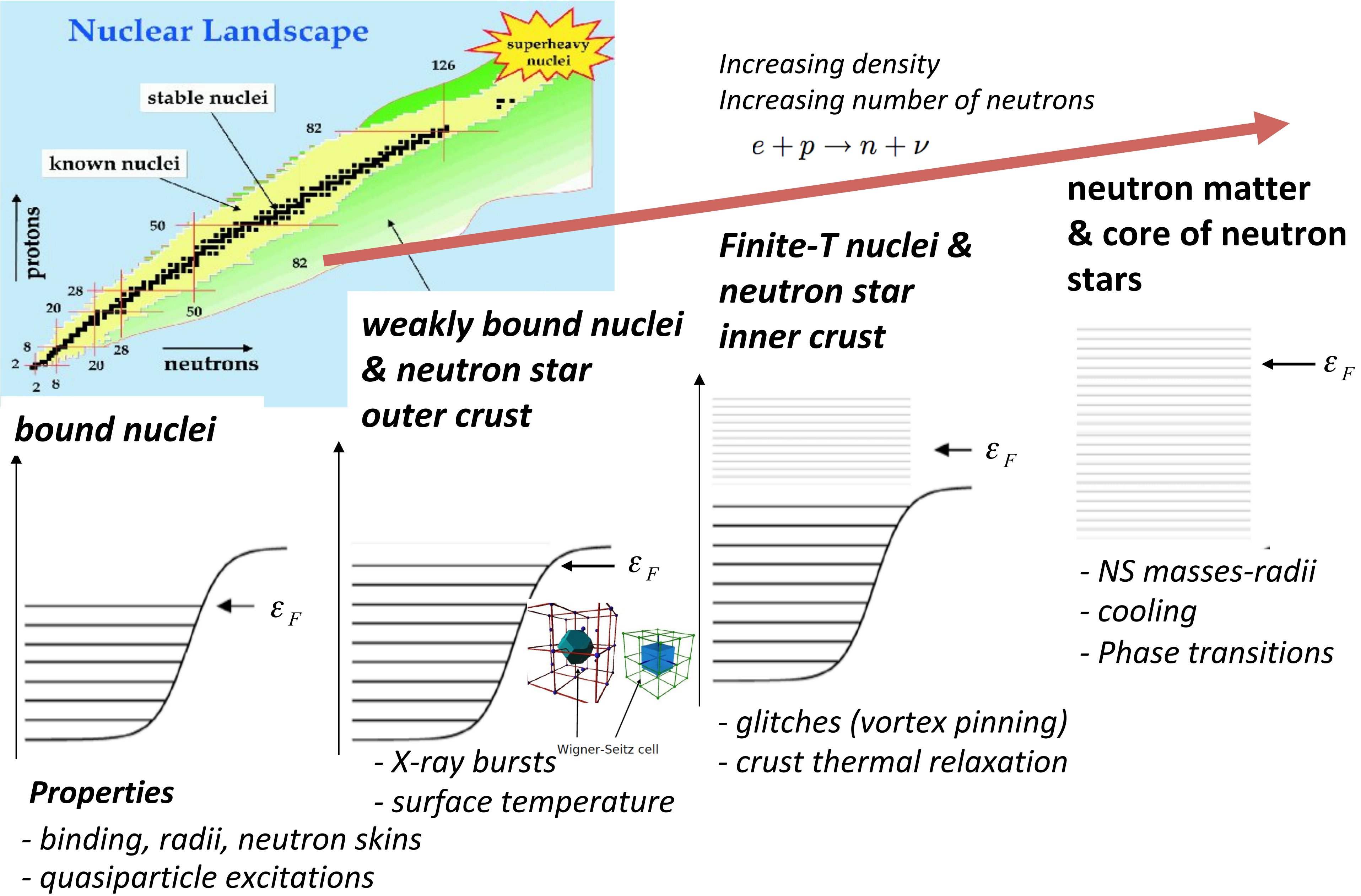
Dilute nuclei



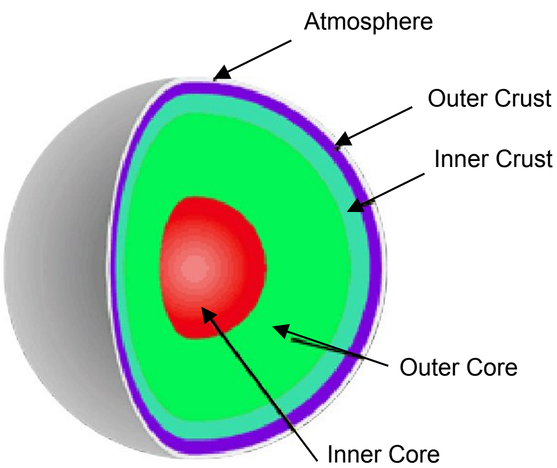
Finite T,
Beyond drip line.

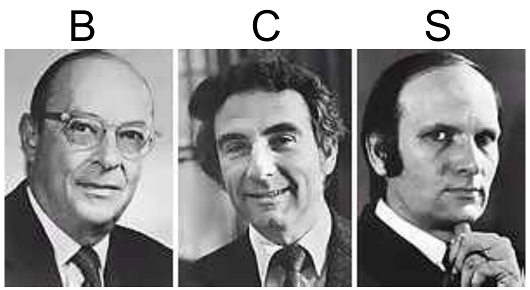
Nuclear matter

From stable nuclei to nuclear matter



Superfluidity in uniform and non-uniform systems

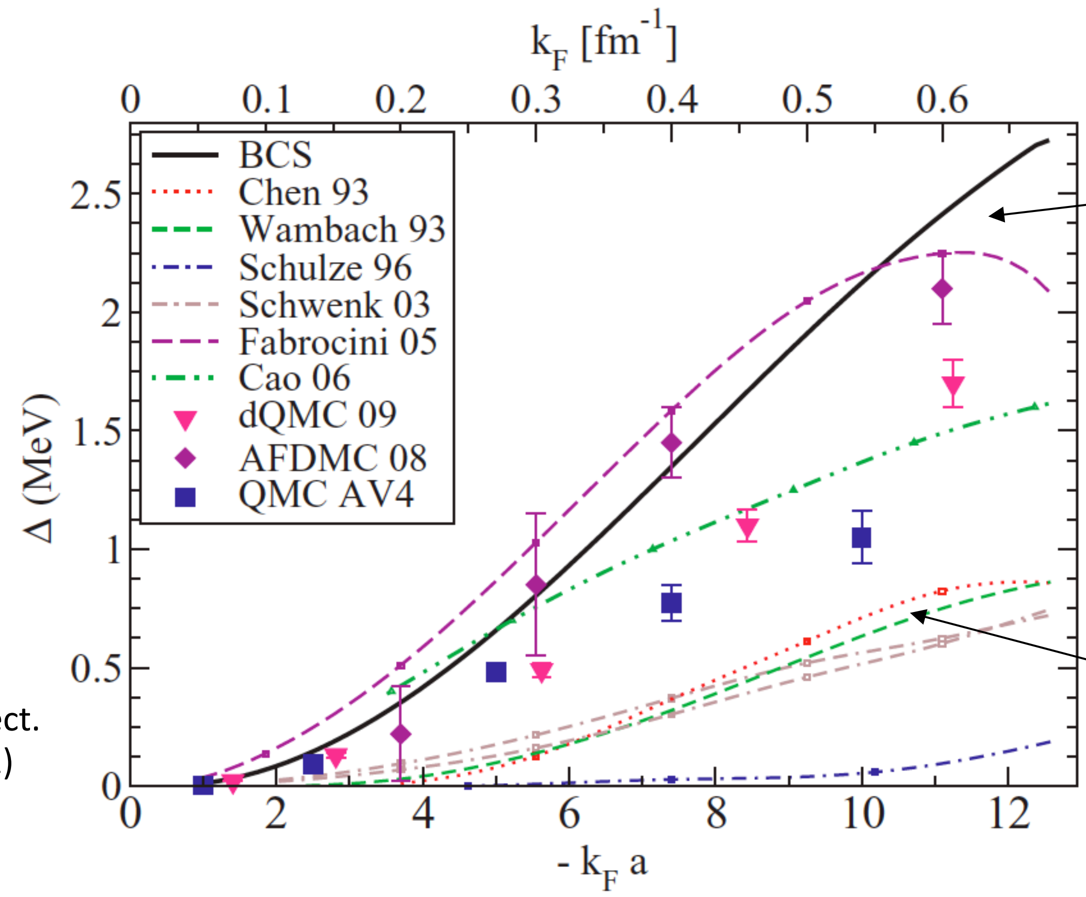




Theory for superfluidity

Pairing gap in neutron matter: comparisons of different approaches

BCS, BCS+polarisation, QMC, AFDMC, ...



BCS

Strong
(max at 3 MeV),

Weak
(max at 1 MeV).

Gezerlis, Carlson, Phys. Rev. C 81 (2010)

Lombardo, Schulze, Lect. Notes Phys. 578 (2001)

In the crust of NS, matter is however not uniform…

Pairing gap in non uniform matter
DFT approach

Ex: Bulgac PRA 2007, Margueron PRC 2008, Chamel NPA 2008, …

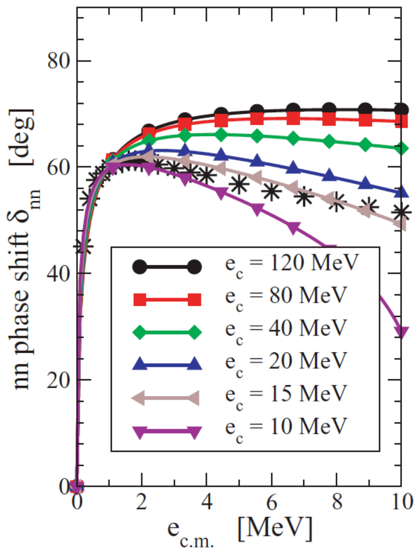
1- Calibrate a pairing functional or interaction / uniform matter results

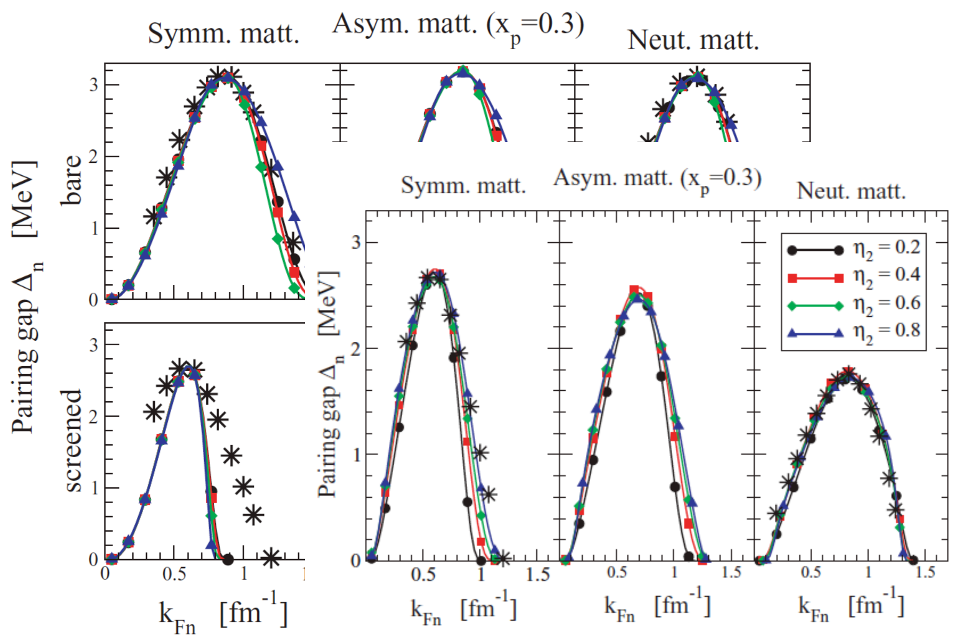
Contact density-dependent pairing interaction:

$$\langle k|v_{nn}|k'\rangle = \frac{1-P_\sigma}{2} v_0\, g[\rho_n,\rho_p]\,\theta(k,k'),$$

Adjust v_0 on NN phase shift ($^1S_0$)

Adjust g[r] on uniform matter predictions

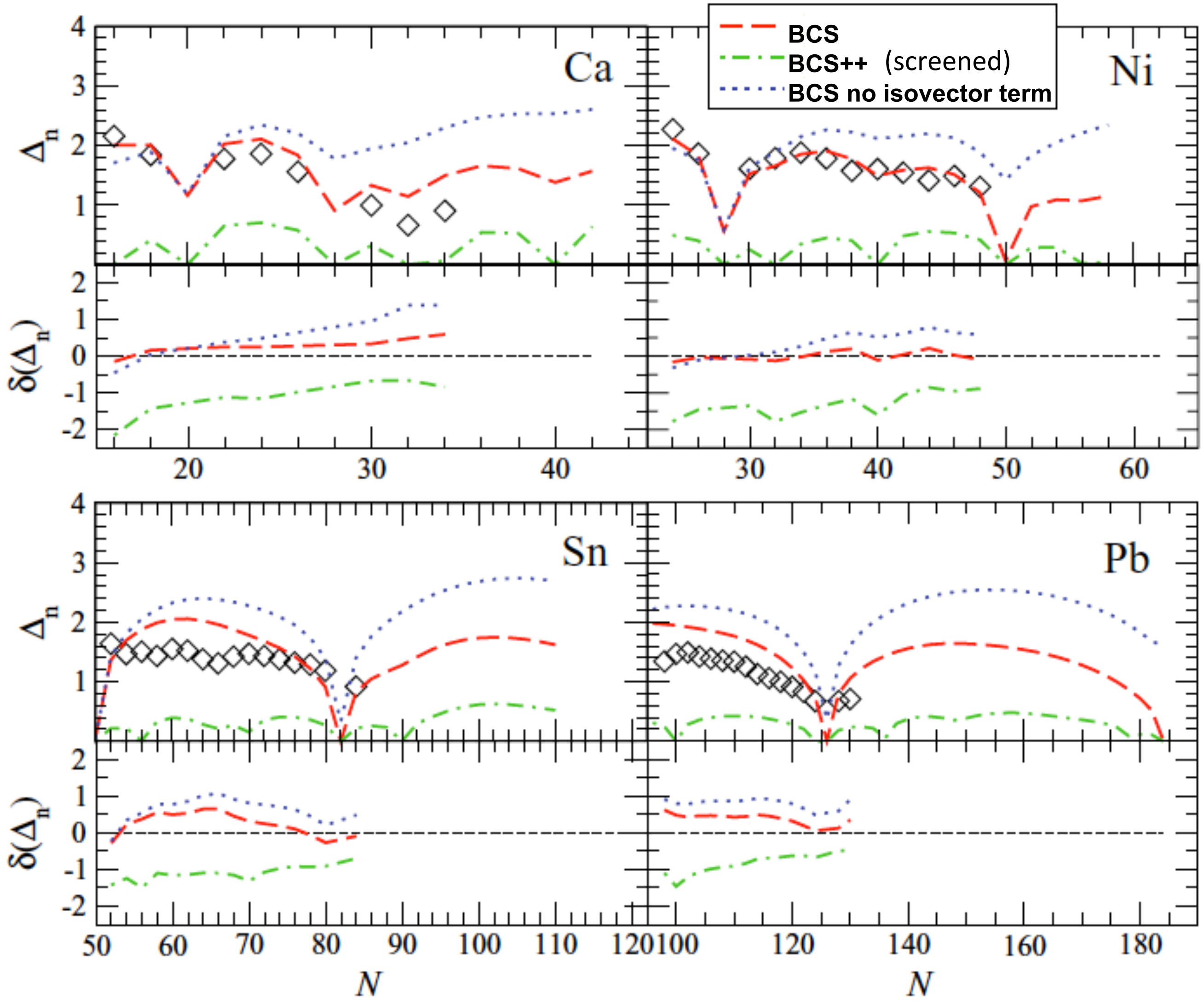




Does condensation energy from QMC and DFT coincide?

2- Solve the pairing in non-uniform matter (Hartree-Fock-Bogoliubov)

Example of semi-magic isotopes

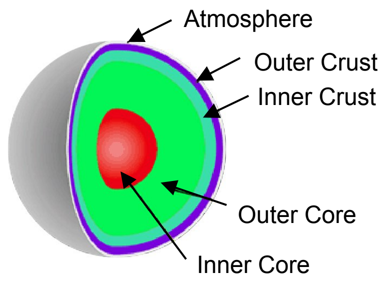


BCS with isovector term reproduce better the isotopic trend.

BCS++ (screened) is too weak.

JM, Sagawa, Hagino, PRC 77 (2008)

Application to crust thermal relaxation



<u>Fast cooling of the core:</u>

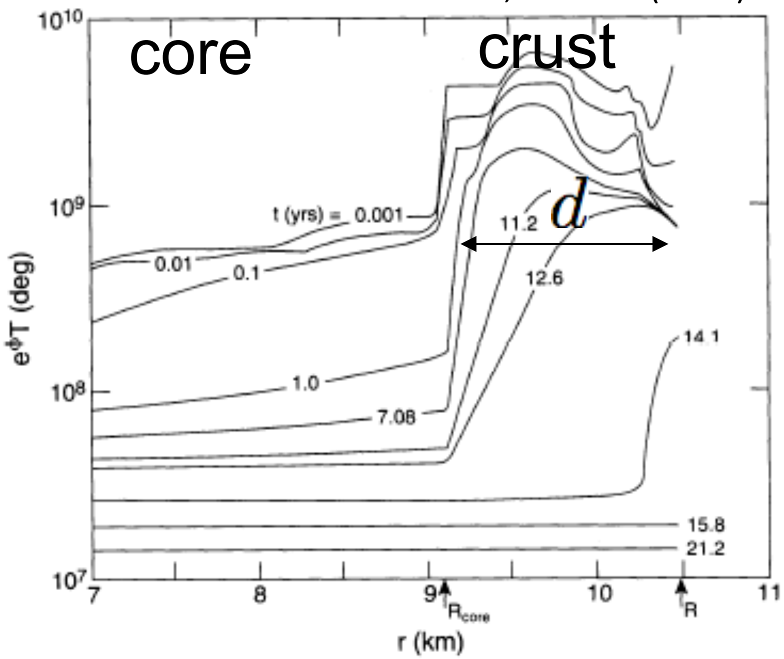
➞ after ~1 year: Tcore << Tcrust~0.5 MeV,

➞ next ~10-100 years: **thermalisation** of the crust:

$$\tau \propto \frac{d^2}{D}$$

with $$D = \frac{K}{\sum_i C_{v,i} \approx C_{v,n}}$$

Lattimer et al., APJ 425 (1994)

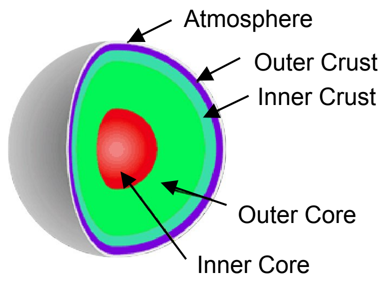


K, conductivity

$C_{v,n}$ neutron specific heat

depend on the cluster structure
in the neutron star crust

Application to crust thermal relaxation



Fast cooling of the core:

→ after ~1 year: Tcore << Tcrust~0.5 MeV,

→ next ~10-100 years: **thermalisation** of the crust:

$$\tau \propto \frac{d^2}{D}$$

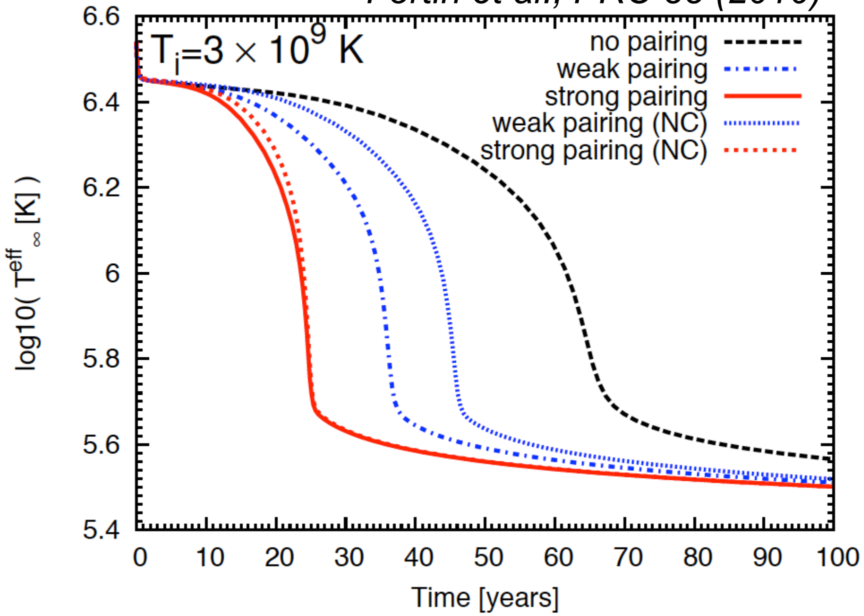
with $$D = \frac{K}{\sum_i C_{v,i} \approx C_{v,n}}$$

K, conductivity

$C_{v,n}$ neutron specific heat

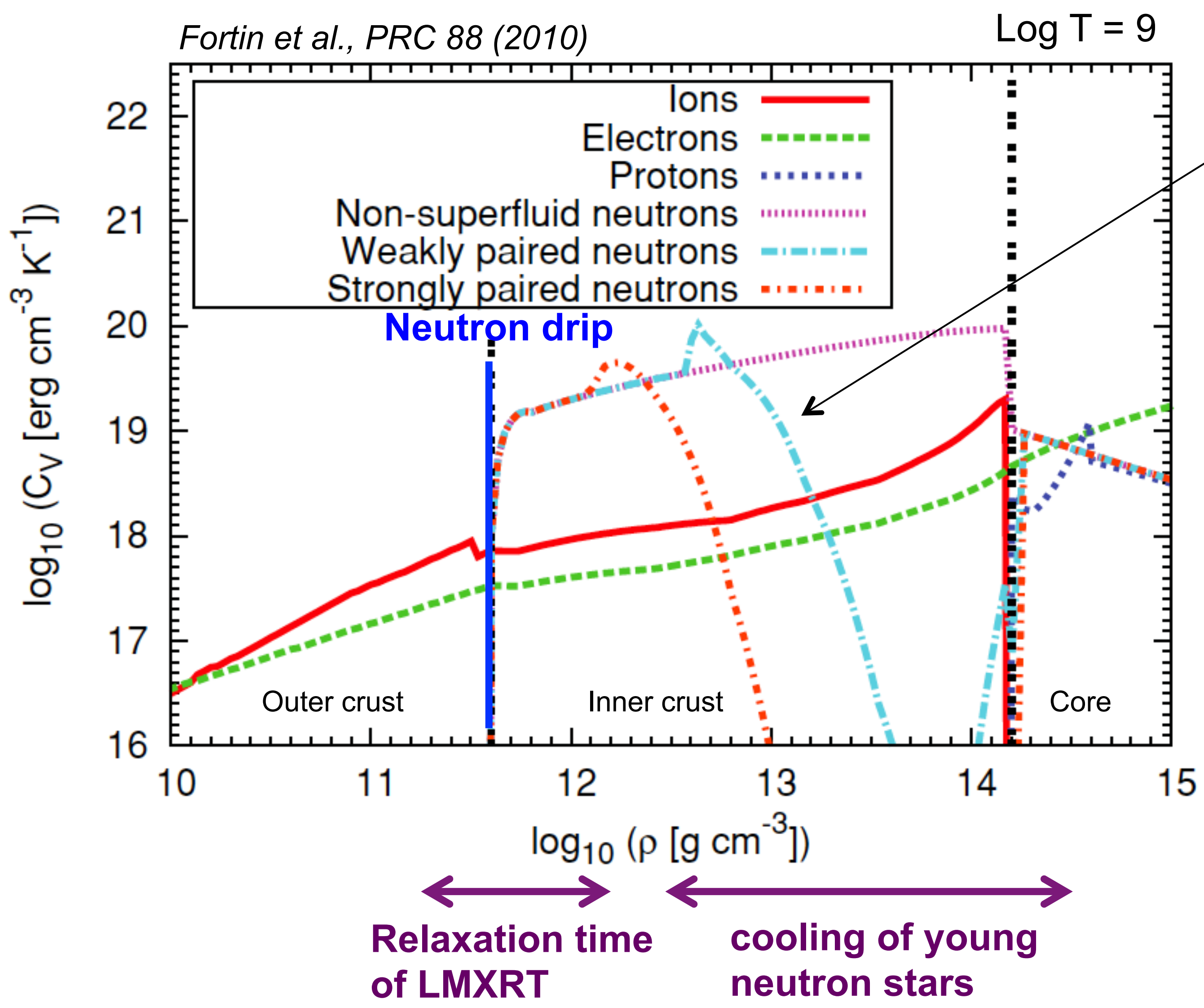
depend on the cluster structure in the neutron star crust

Fortin et al., PRC 88 (2010)



Effect of clusters is larger for weak pairing.

Superfluidity and cooling of neutron stars



Suppression of Cv in the superfluid phase

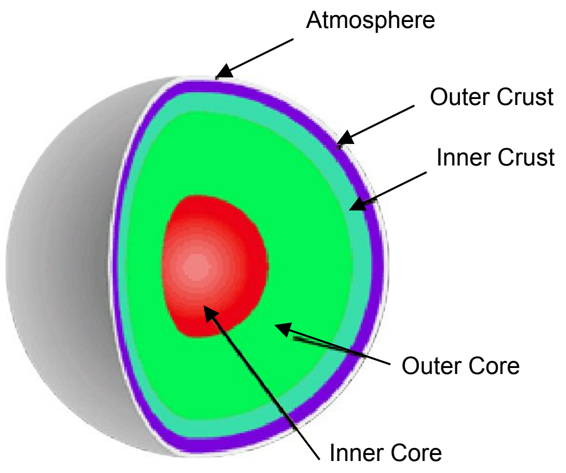
↓

Increase the diffusivity in the crust (D=K/Cv)

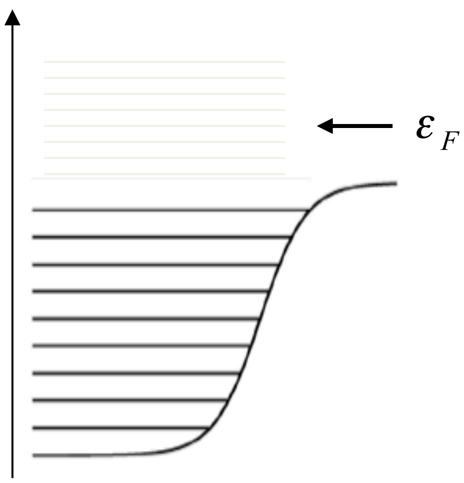
↓

Reduces the thermal relaxation time of the crust (τ=R^2/D)

Finite temperature in non-uniform matter

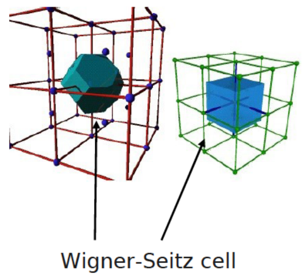


Transition outer / inner crust

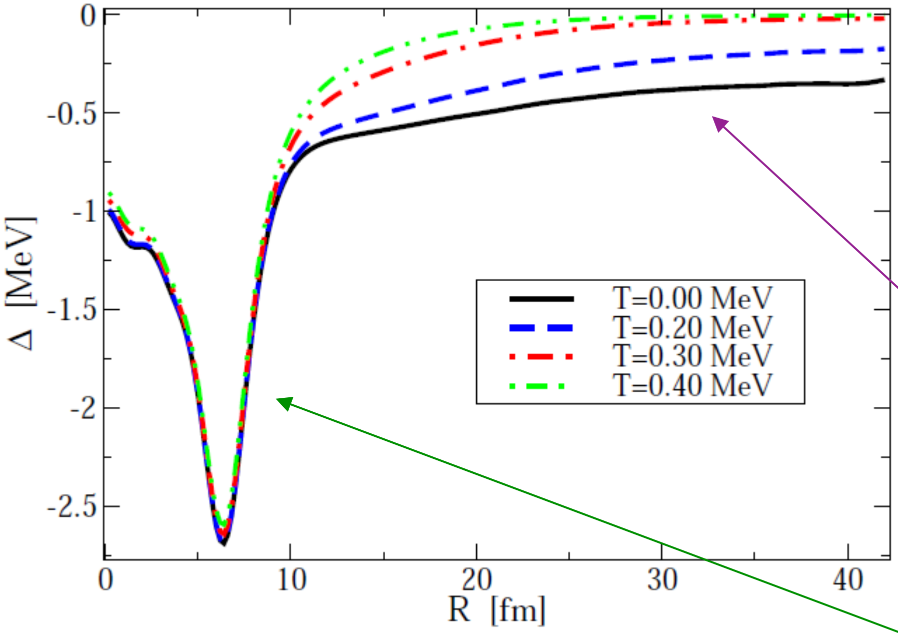


Neutrons specific heat in ^{500}Zr: Cv(T)

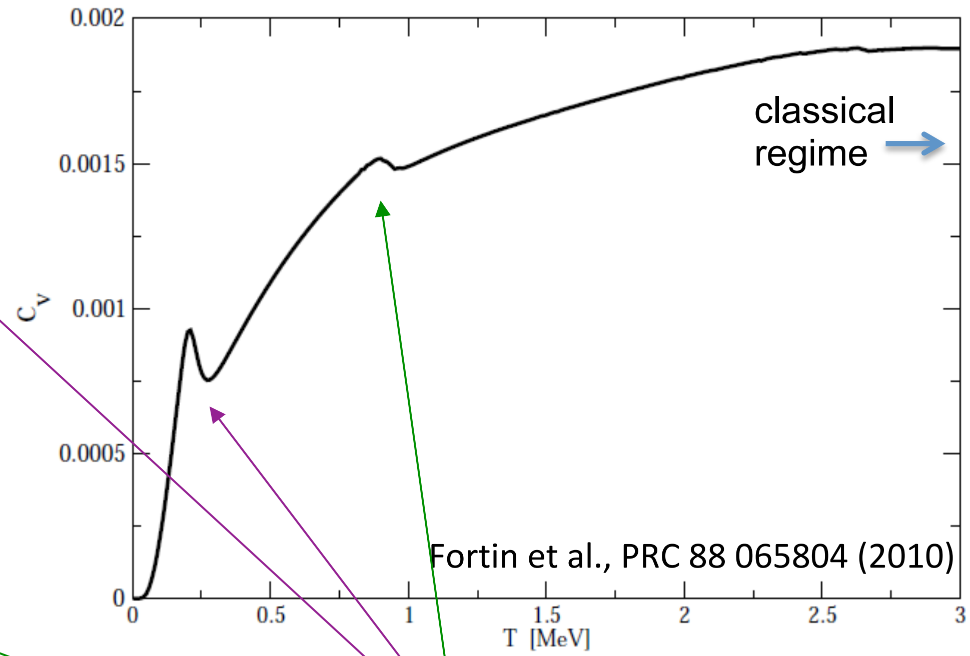
N=460, Z=40



Pairing field profile
at various temperatures:



Neutron specific heat:

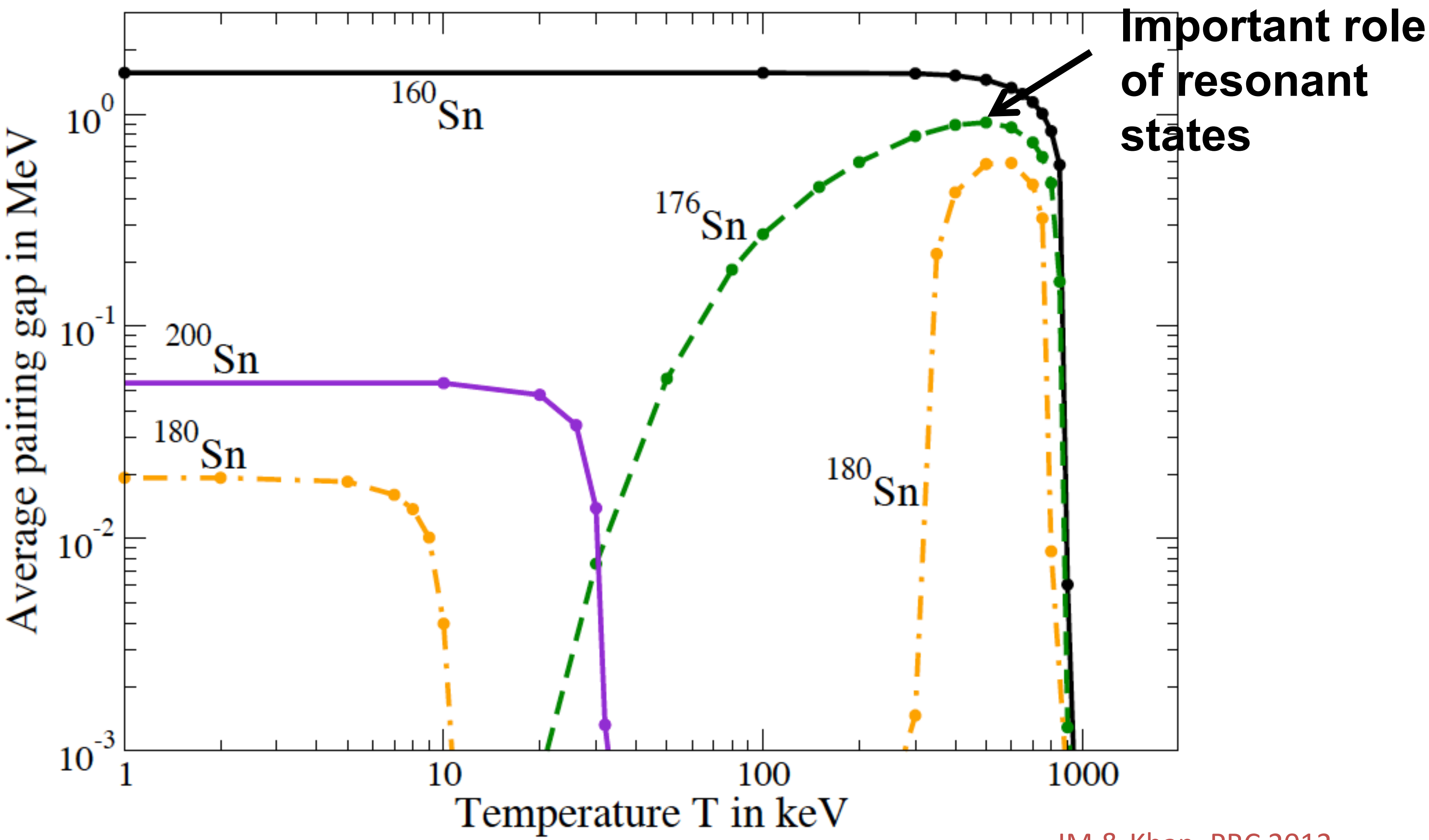


Disappearance of superfluidity:

in the neutron gas

in the cluster

Pairing reentrance in Sn at the drip



JM & Khan, PRC 2012

Temperature populates excited states:

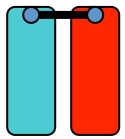
1- kinetic energy cost induces a quenching of pairing,

2- in some cases, pairing occurs among thermally occupied excited states.

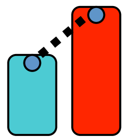
Pairing reentrance phenomenon

Superfluidity is destroyed by increasing the temperature…
But a bit of temperature sometimes helps in restoring superfluidity !

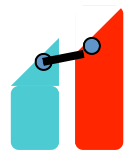
<u>Pairing reentrance in asymmetric systems:</u>



Pairing in symmetric systems



Asymmetry detroys pairing



Temperature in asymmetric systems restore superfluidity

In nuclear matter: pairing in the T=0 (deuteron) channel

Sedrakian, Alm, Lombardo, PRC 55, R582 (1997)

In spin-asymmetric cold atom gas

Castorina, Grasso, Oertel, Urban, Zappala, PRA 72, 025601 (2005)
Chien, Chen, He, Levin, PRL 97, 090402 (2006)

In higly polarized Liquid ^{3}He, ^{4}He

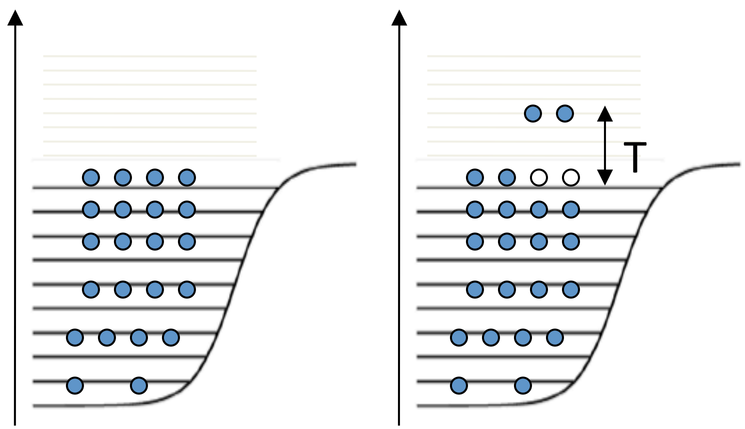
Frossati, Bedell, Wiegers, Vermeulen, PRL 57 (1986)

Pairing in heated rotating nuclei

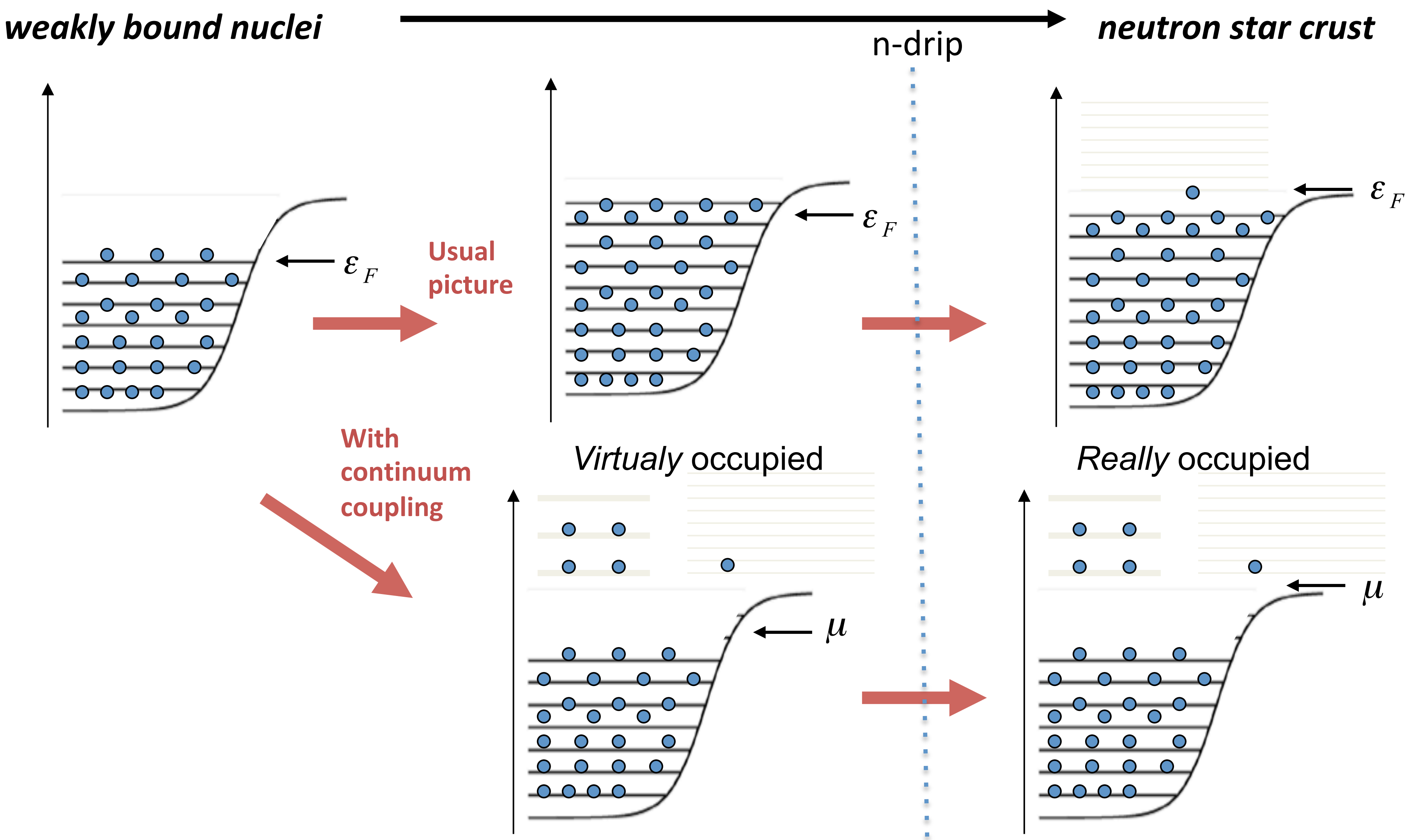
Dean, Langanke, Nam, and Nazarewicz, PRL105, 212504 (2010).

<u>Pairing reentrance in finite systems:</u>

In magic nuclei, the presence of low-energy resonances, populated at low temperature, can help superfluidity to appear. JM, Khan, PRC 2012

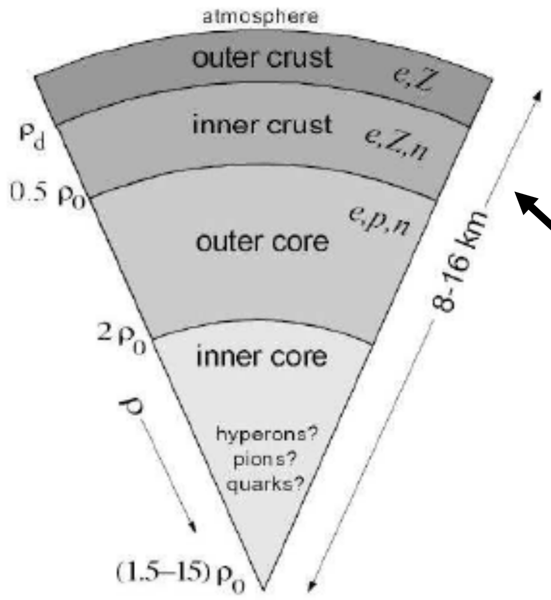


Microscopic picture around the neutron drip

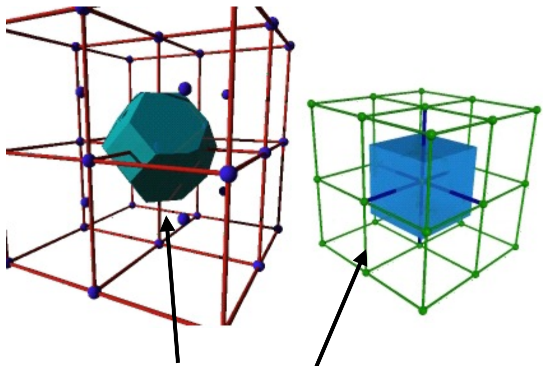


Superfluidy in non-uniform matter

Structure of neutron stars:



The inner crust is made of a lattice of nuclei (cluster) + unbound particles (e, n).



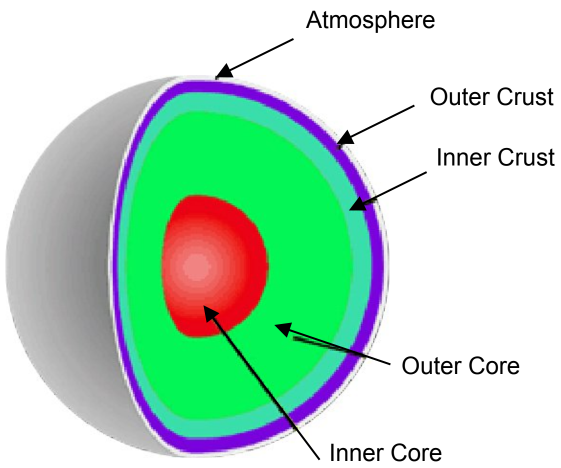
Wigner-Seitz cell

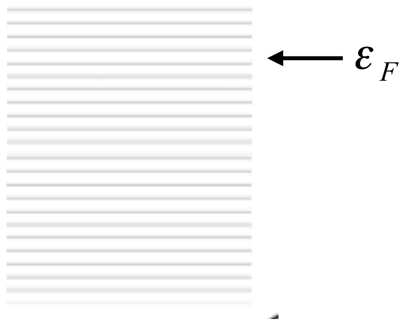
Pairing is acting for:
- clusters,
- unbound neutrons.

We need pairing gaps (and condensation energies):
- at different densities (10^{11} g/cm^3 to 10^{14} g/cm^3),
- temperatures (few 10 keV to ~1 MeV).

Direct QMC in non-uniform matter?

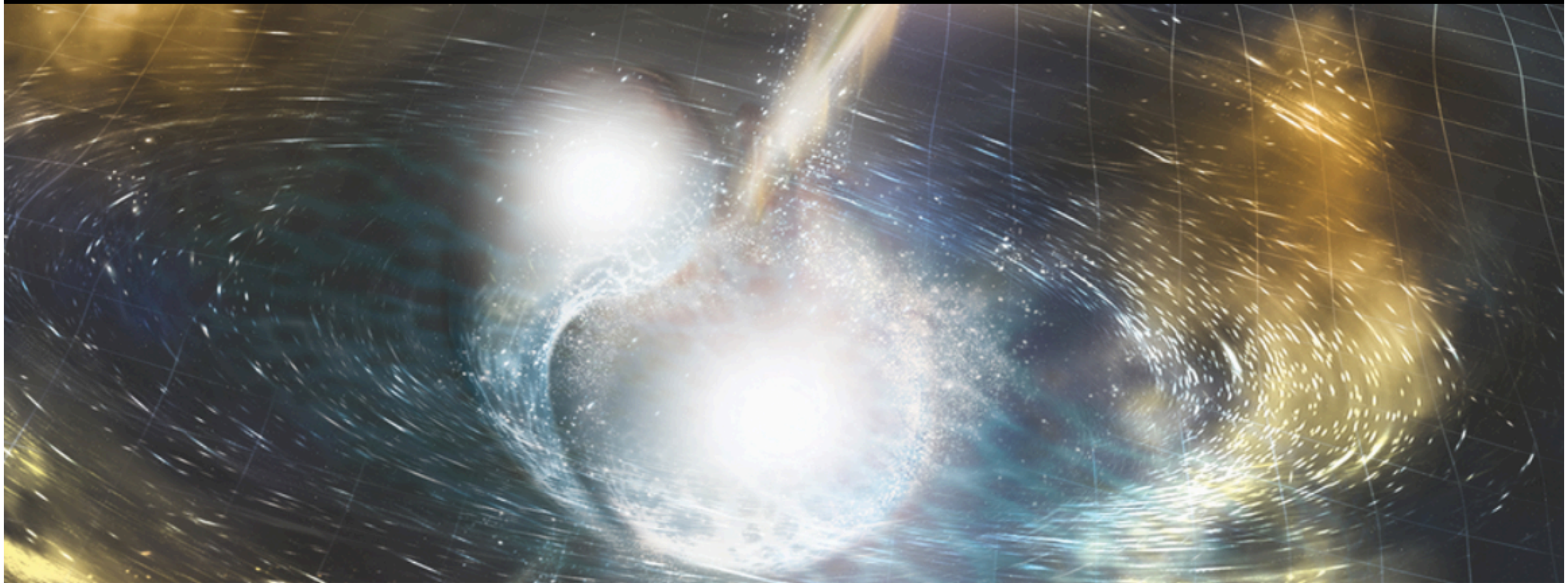
Dense matter EOS





August, 17th 2017 (GW170817)

First detection of GW from the merger of two neutron stars



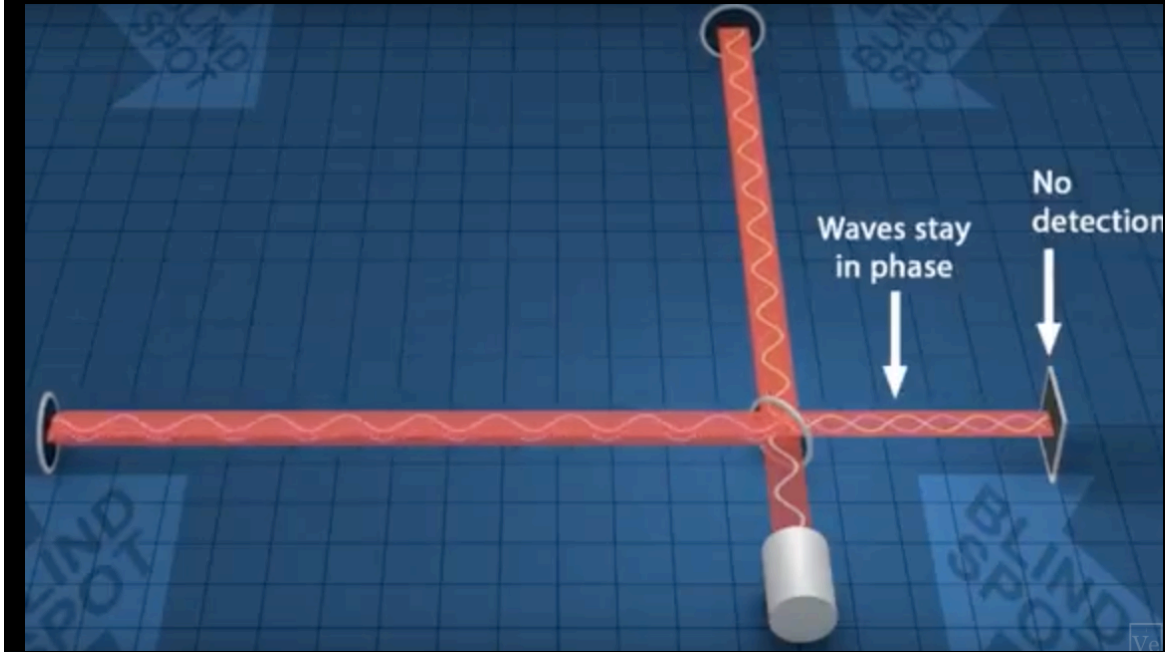
Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

From https://www.ligo.caltech.edu/page/press-release-gw170817

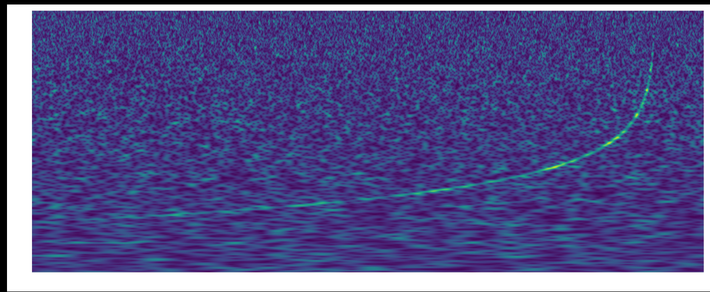
See Abbott et al., the LVC, PRL 2017

Can we learn more about nuclear EOS?

The gravitational wave signal

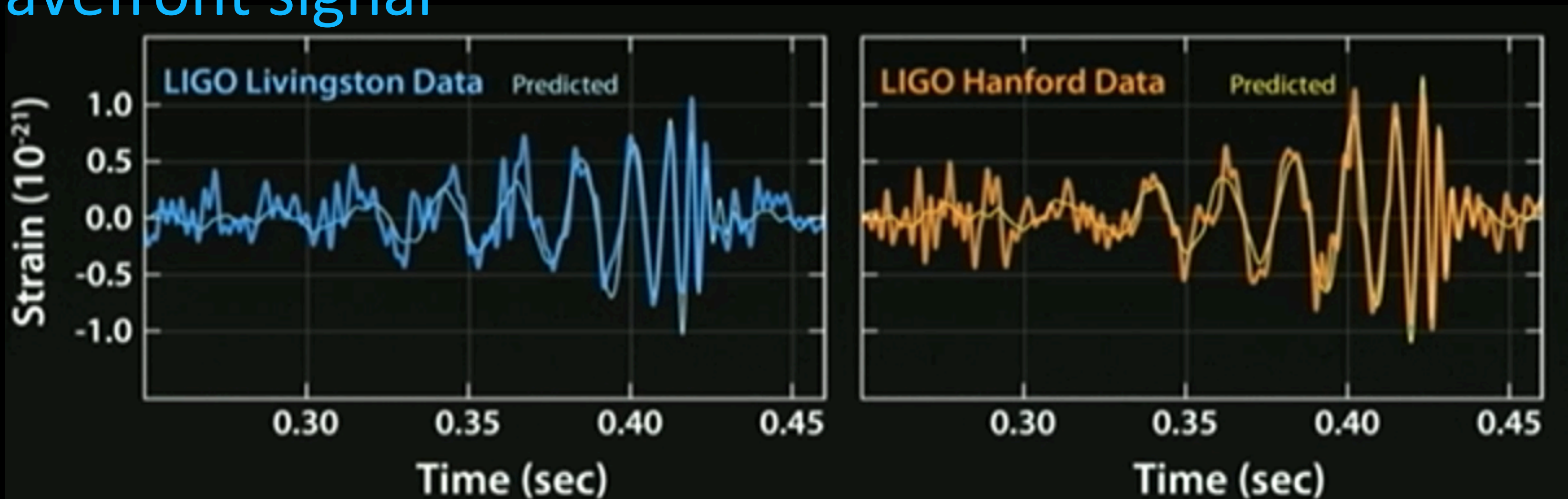


When a GW shakes the interferometer → a chirp!



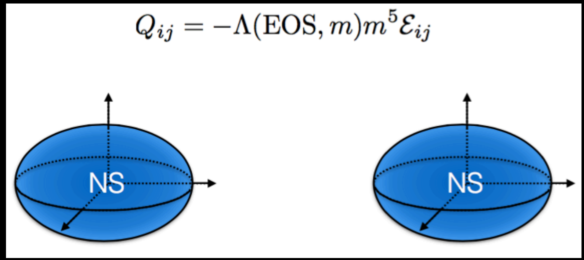
Ear it at https://youtu.be/_SQbaILipjY

The wavefront signal



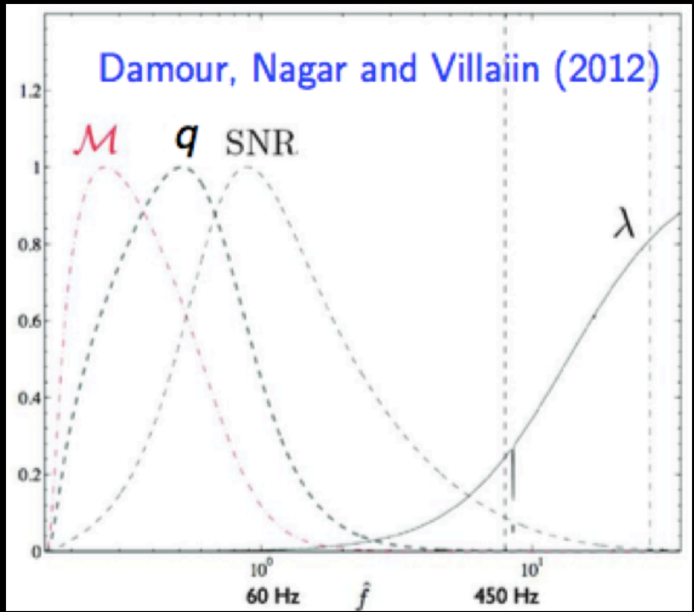
Wavefront & tidal deformability

- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on stiffness of EOS via the tidal deformability Λ:



Post-Newtonian expansion of the wavefront:
Tidal effect enters at 5th order

Hinderer+, PRL 116, 181101 (2016)



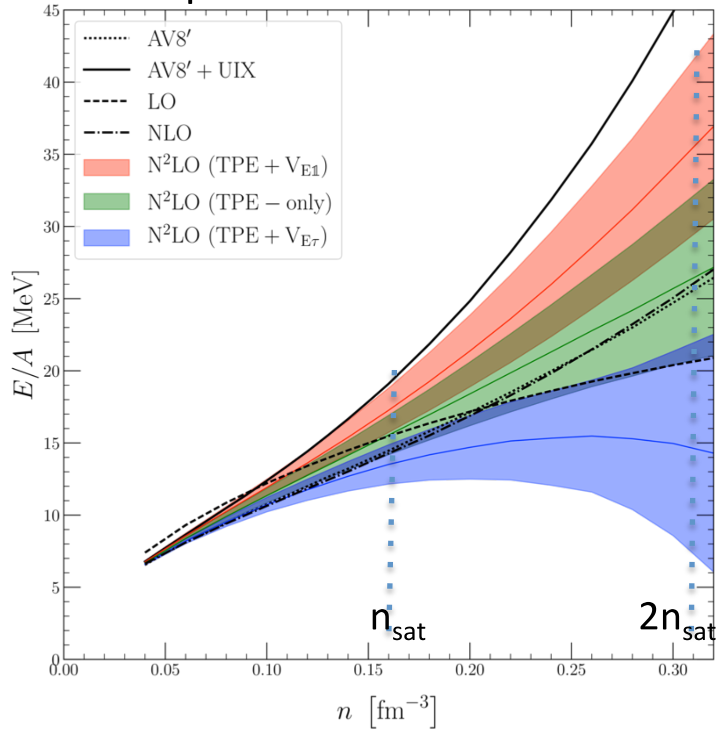
GW170817 : $70 \leq \Lambda \leq 720$

→ What can we learn for the EOS?

Prediction for dense matter EOS

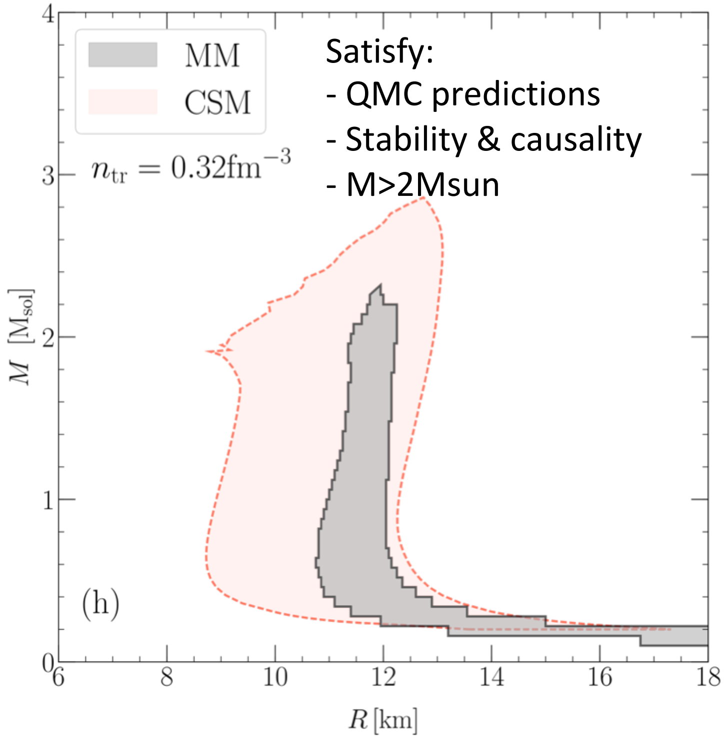
We contrast:
- a meta-model for the nucleonic EOS (minimal model, MM),
- a more general and contains strong first order phase transition (maximal model, CSM).

QMC calculations with local chiral potentials



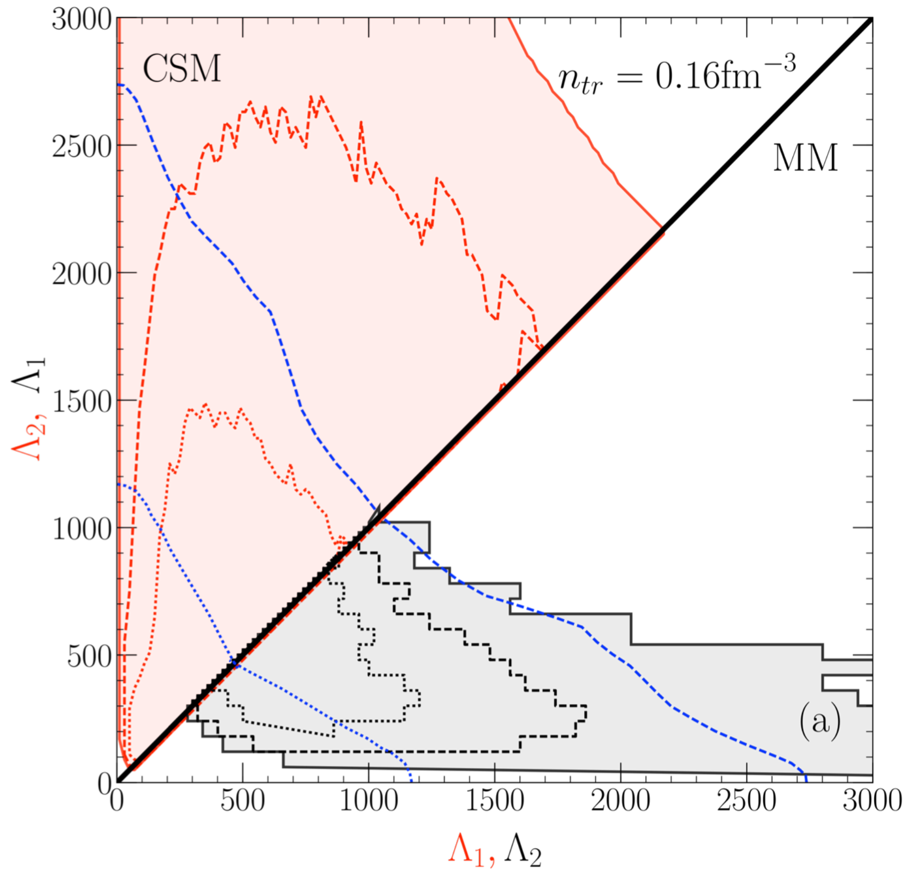
Tews, Carlson, Gandolfi, Reddy, arXiv:1801.01923

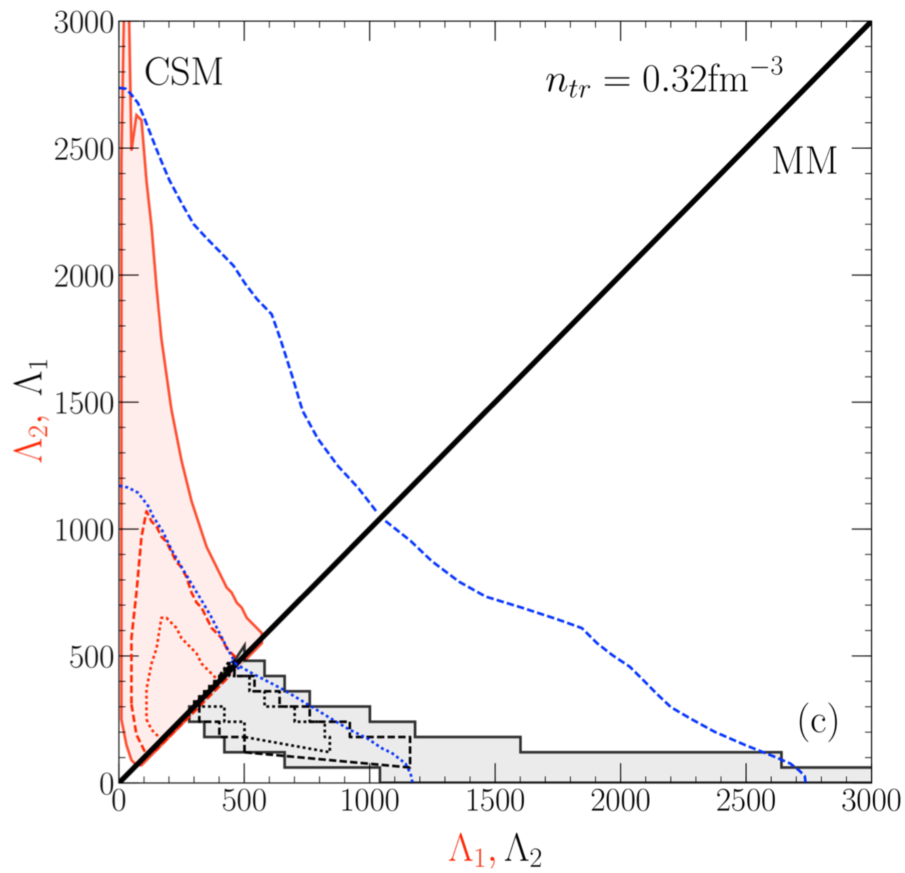
Solution of the non-rotating TOV eqs.



Tews, JM, Reddy, arXiv:1804.0273

CSM versus MM (same constrains)





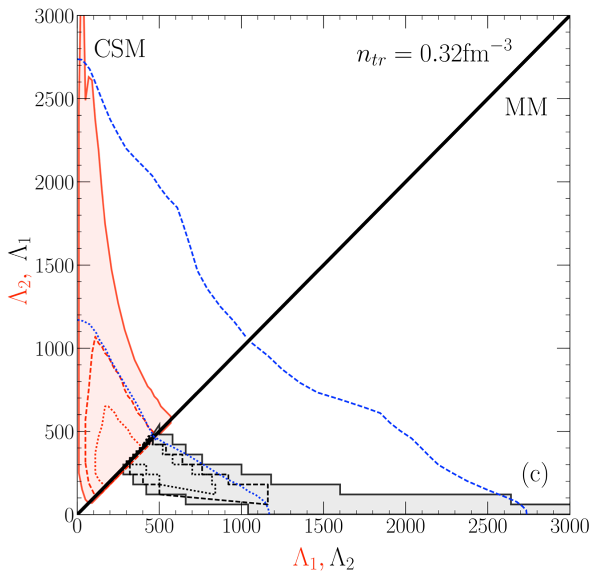
Range of tidal polarizabilities:
CSM: 80 – 570
MM: 260 – 500

Tews, JM, Reddy, arXiv:1804.0273

Prediction for dense matter EOS

- Both MM and CSM can reproduce existing observations.
- More constraints are needed (NICER soon, more GWs, ...)

  + additional observables: cooling, glitches, ...
- Nuclear physics is still more constraining than GW.
- Required GW accuracy to improve our knowledge:



$\Delta\tilde{\Lambda} \approx 300\text{-}400$ → Probe EOS from 1 to $2n_{sat}$

Confirm or rule out nuclear physics

$\Delta\tilde{\Lambda} \approx 100\text{-}200$ → Probe matter composition above $2n_{sat}$

INT program "advances in MC techniques for MB quantum systems", Seattle, August 13, 2018

Some open questions in neutron star physics *(with QMC in ambush)*

Jérôme Margueron, IPN Lyon & INT Seattle

- Pairing in non-uniform systems
- Pairing at finite-T and re-entrance phenomenon
- NS mergers, tidal deformability, dense matter EOS

Conclusions

We addressed:

- Pairing in non-uniform systems
- Pairing at finite-T and re-entrance phenomenon
- NS mergers, tidal deformability, dense matter EOS

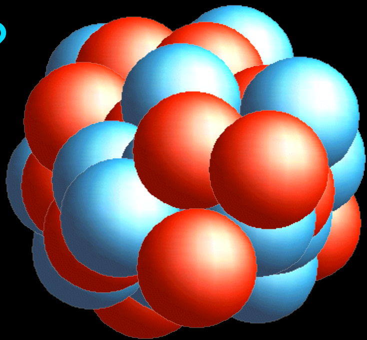
Energy Density Functional could be better constrained by more microscopic approaches (e.g. condensation energy).

Extend the domain of application of QMC to non-uniform systems?

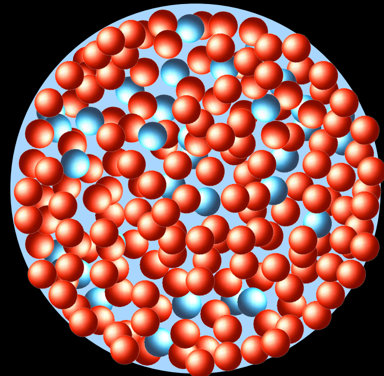
Nuclear Physics and Compact Stars

New methods for astronomy

How to probe nuclear matter properties?



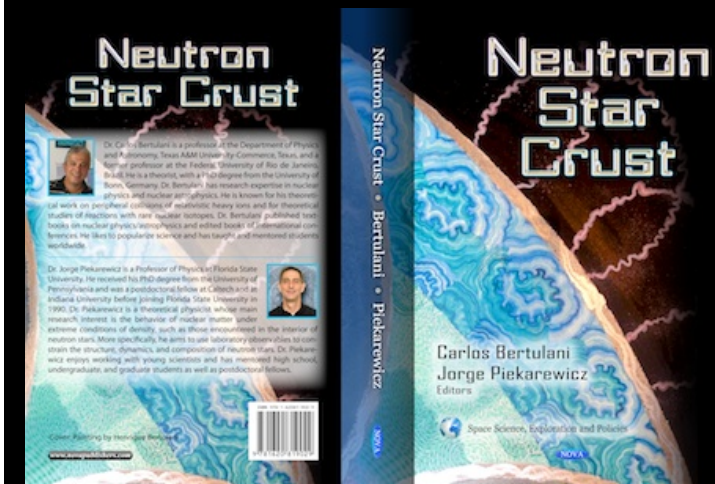
?



What is the role of nuclear physics? How to interpreate the observations?

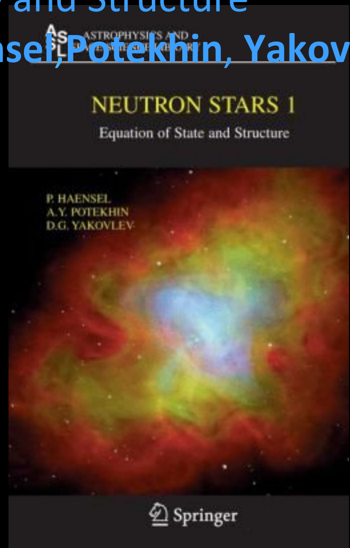
Steiner, Prakash, Lattimer, Ellis, Phys. Rep. 411 (2005) 325
Lattimer and Prakash, Phys. Rep. 442 (2007) 109
B-A Li, Chen, Ko, Phys. Rep. 464 (2008) 113

Topical issue on Nuclear Symmetry Energy.
Guest editors: Bao-An Li, Ramos, Verde, Vidaña



Neutron Star Crust, Bertulani and Piekarewicz, Nova Science

Neutron Stars 1: Equation of State and Structure
Haensel, Potekhin, Yakovlev



What GW170817 tell about dense matter?

The masquerade issue

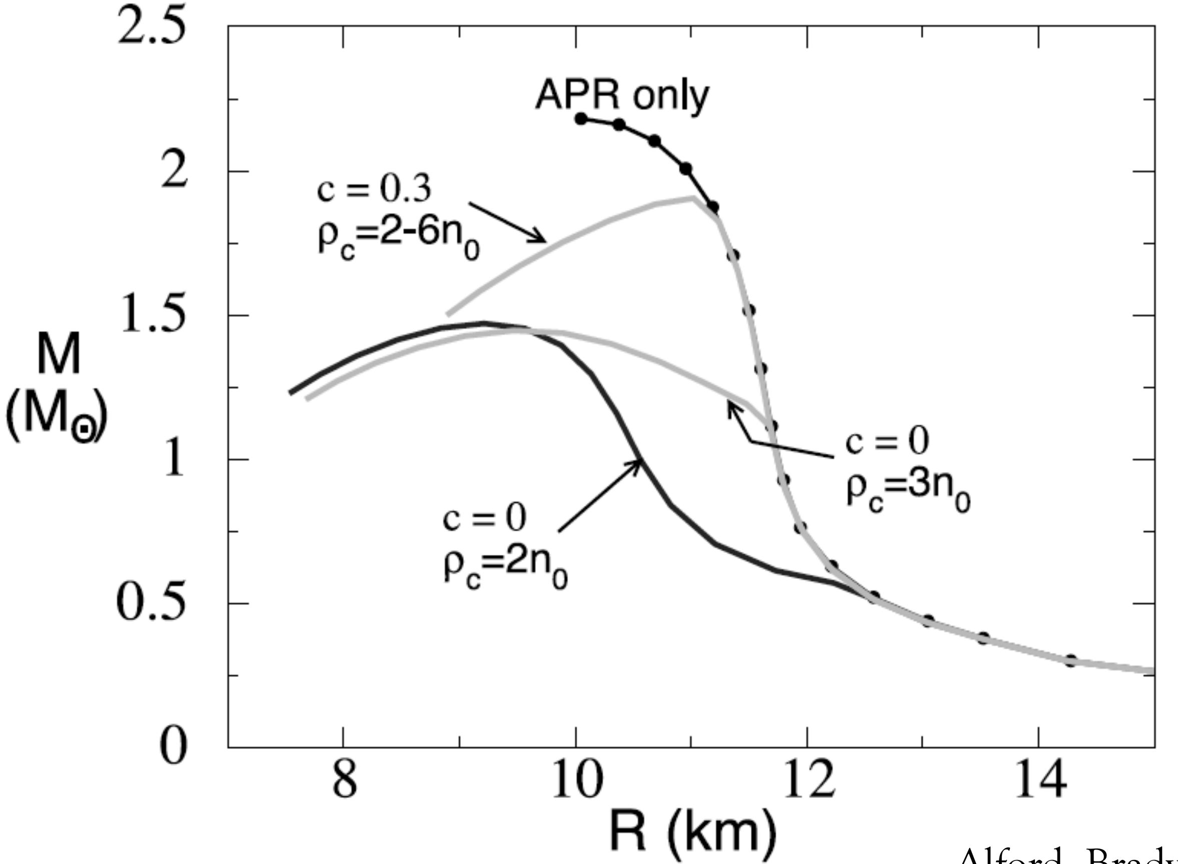
A meta-model for nucleonic EOS (minimal model)

Confronting MM with CSM for GW170817

Tews, JM, Reddy arXiv:1804.0273,
JM, Casali, Gulminelli, PRC 97, 025805 & 025806 (2018)

The masquerade issue

A hybrid star which looks nuclear



Alford, Brady, Paris, Reddy ApJ 2005

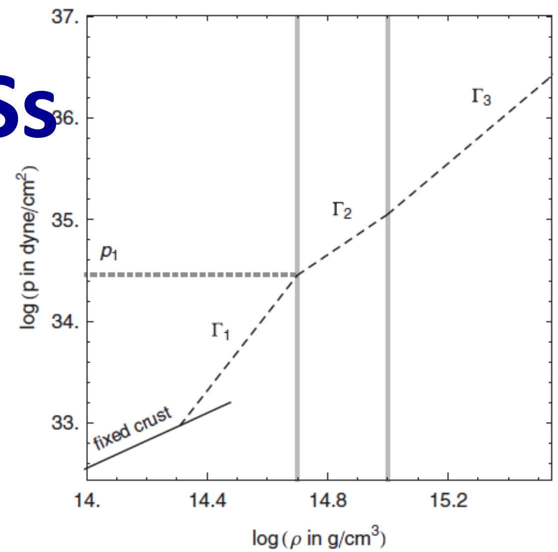
Are we condemned to this ambiguity issue?

Are all nucleonic EOS masqueraded by QM? Are all QM masqueraded by nucleonic EOS?

Parametric forms for general EOSs

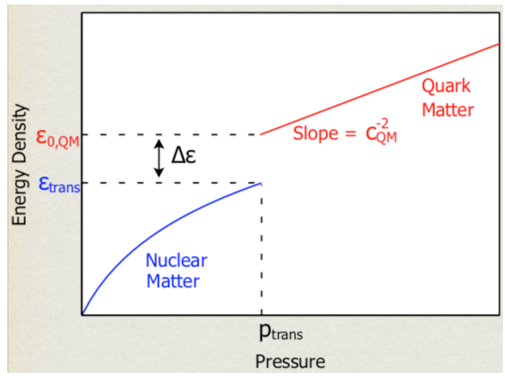
Piecewise polytrope:

3 points: J. Read et al, PRD 2009
5 points: F. Ozel, PRD 2010
Matching pQCD: Kurkela et al., ApJ 2014



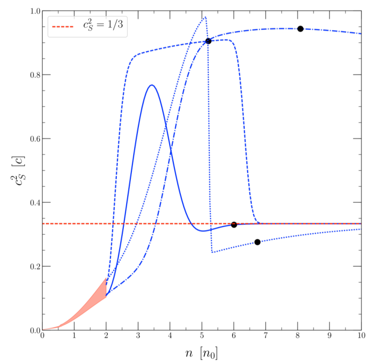
Parametric phase transition:

Zdunik & Haensel 2012,
Alford, Han, Prakash 2013



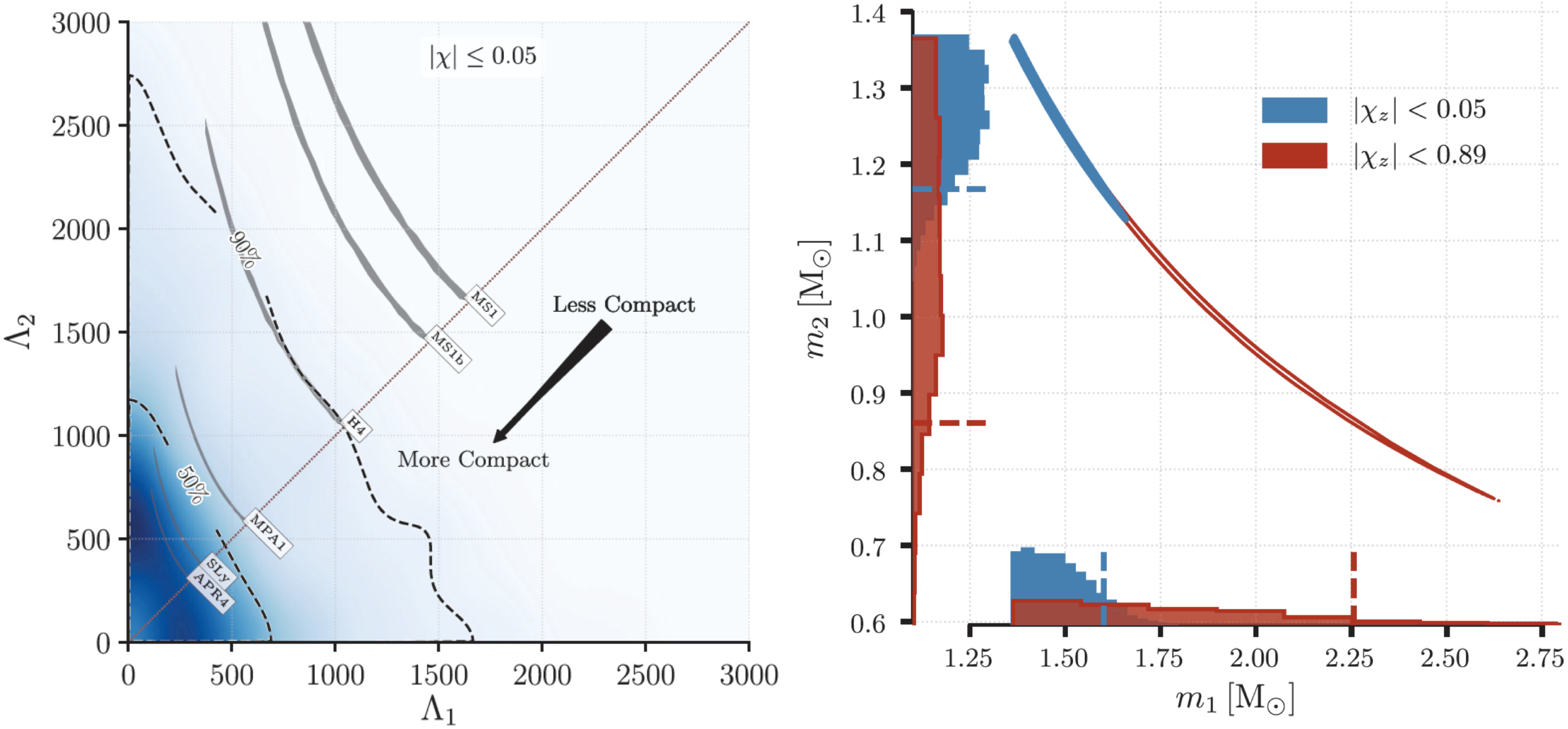
Sound velocity based model (CSM):

Tews, Carlson, Reddy, Gandolfi 2018



All together they set consistant boundaries of all possible EOS.
But they don't say much about matter composition.

Comparison to GW170817 observation



LIGO Virgo collaboration PRL 2017

$\tilde{\Lambda}$=800 → rules out NS with large radii (>13.6km)

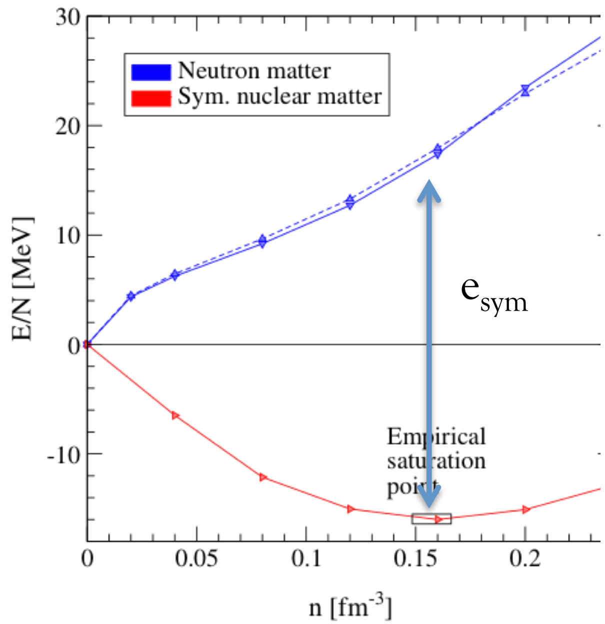
Can GW170817 (or future detection) say something about matter composition?

A minimal model is needed → boundaries for nucleonic EOS.

Towards a generic nucleonic EOS (minimal model)

We use a meta-model for nucleonic EOS which assumes:

- Nuclear potential quadratic in δ (isospin asymmetry),
- The EoS is continuous,
- Satisfies causality and stability



Determined by a set of empirical parameters:

$$e_{sat}(n) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \ldots$$

$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \ldots$$

$$x = (n - n_{sat})/(3n_{sat})$$

A large number of nucleonic EOS can be reproduced by this meta-model (maybe all?).

Prediction boundaries are related to empirical parameters boundaries.

From a detailed analysis of experimental predictions, phenomenological and ab-initio models

Around n_{sat}: $$\frac{E}{A}(n,\delta) \approx e_{sat}(n) + e_{sym}(n)\delta^2 + e_{sym,4}(n)\delta^4 + \ldots$$

with $$e_{sat}(n) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \ldots$$

$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \ldots$$

In the following, we consider the following central values and uncertainties (1σ):

P_α	E_{sat} MeV	E_{sym} MeV	n_{sat} fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV	m^*_{sat}/m	$\Delta m^*_{sat}/m$
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500	0.75	0.1
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000	±0.1	±0.1

Small uncertainties (←→ E_{sat} to K_{sat})

Large uncertainties (←→ K_{sym} to Z_{sym})

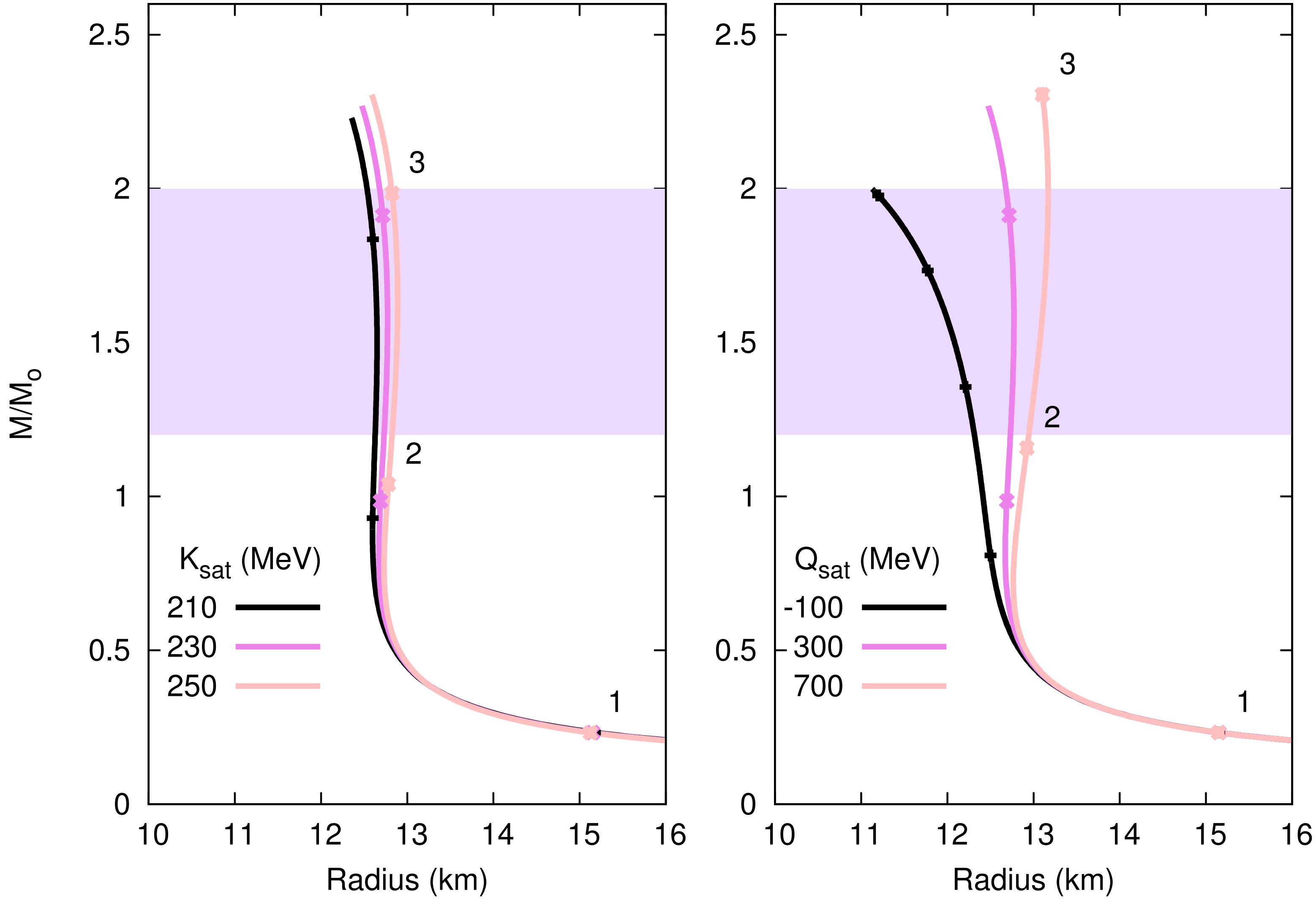
Large uncertainties
No effect on the EOS (←→ m^*_{sat}/m, $\Delta m^*_{sat}/m$)

→ Impact on the nuclear EOS

JM, Casali, Gulminelli, PRC 2018

Impact of the isoscalar empirical parameters

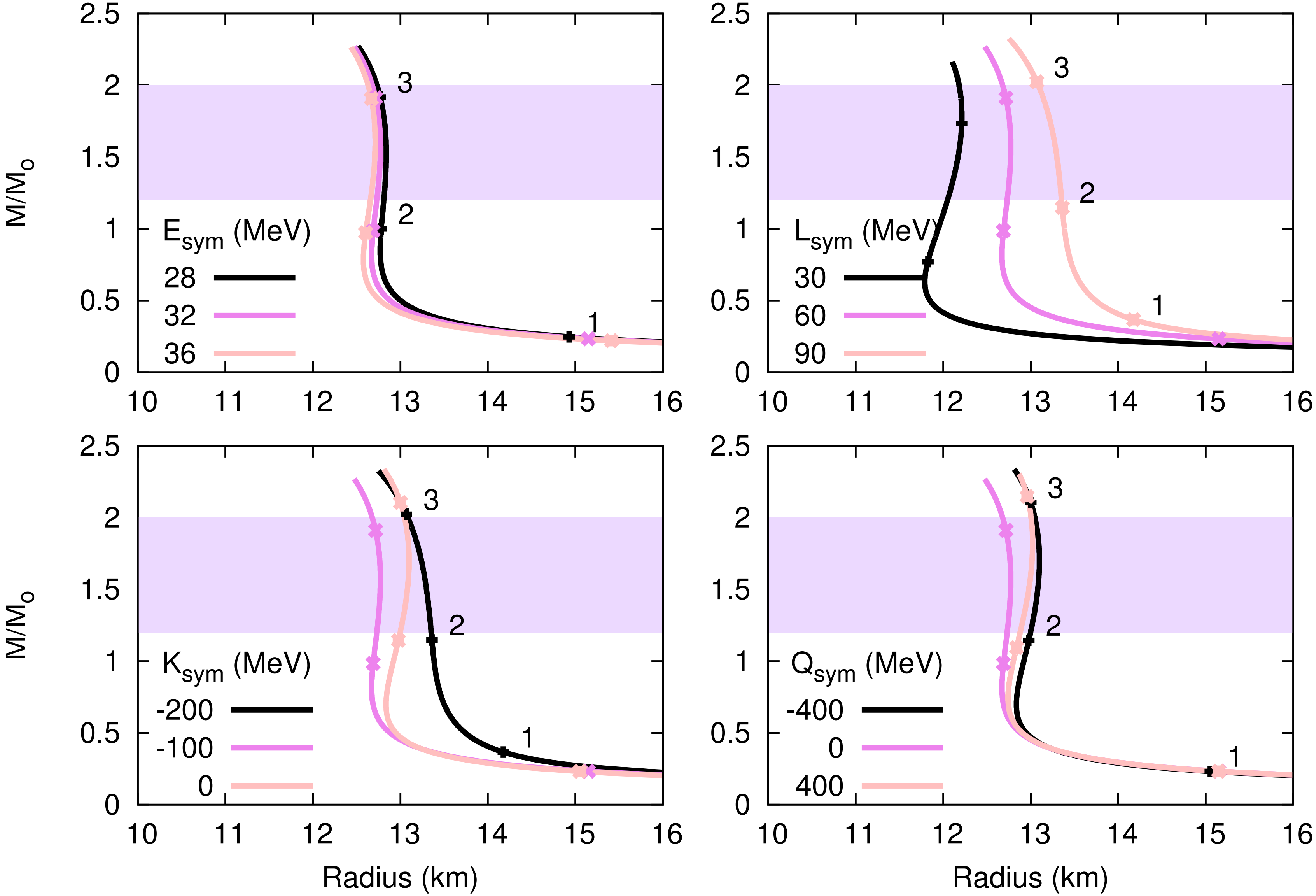
Small impact of these parameters



JM, Casali, Gulminelli, PRC 2018

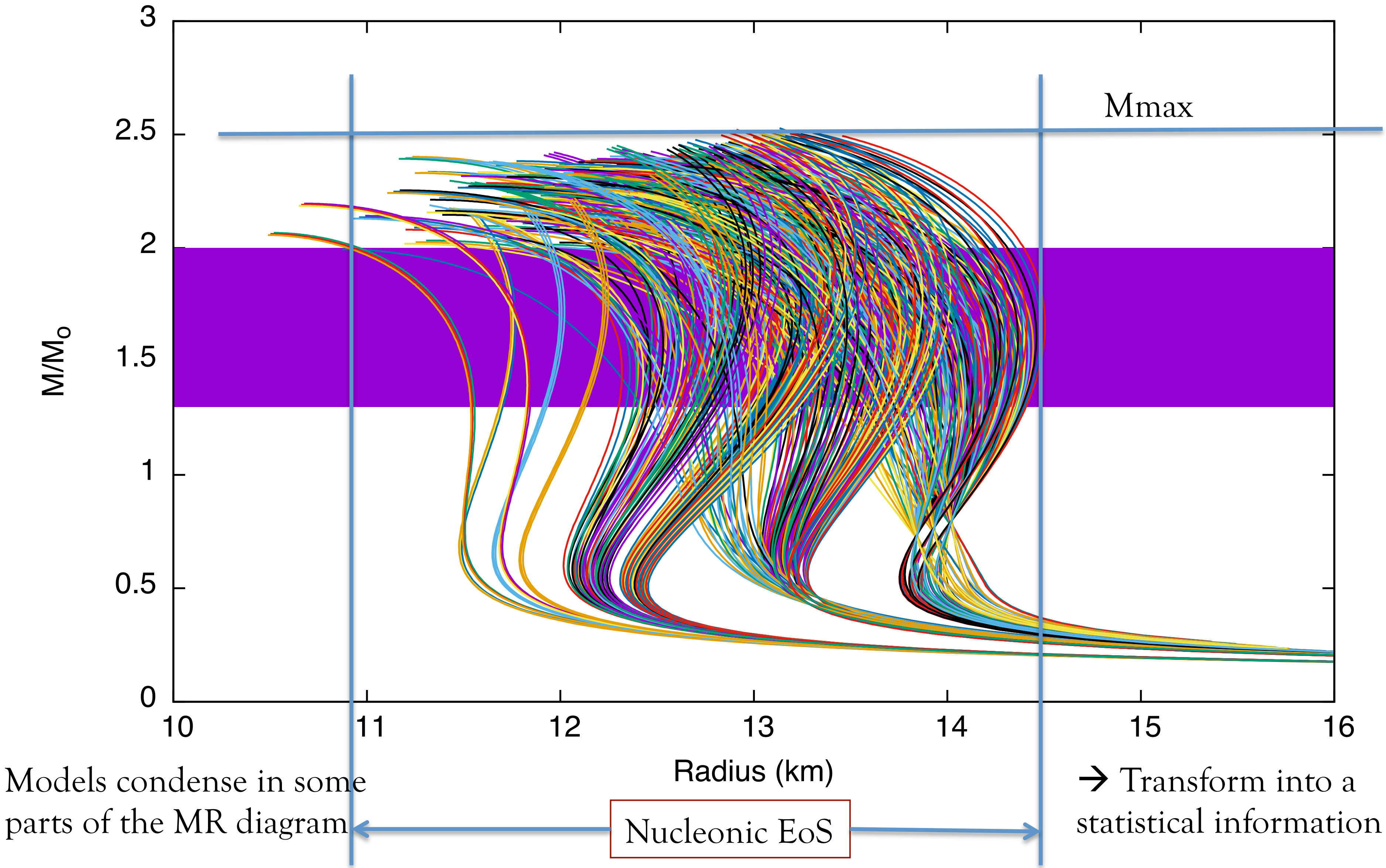
Impact of the isovector empirical parameters

Largest source of uncertainty: Lsym and Ksym

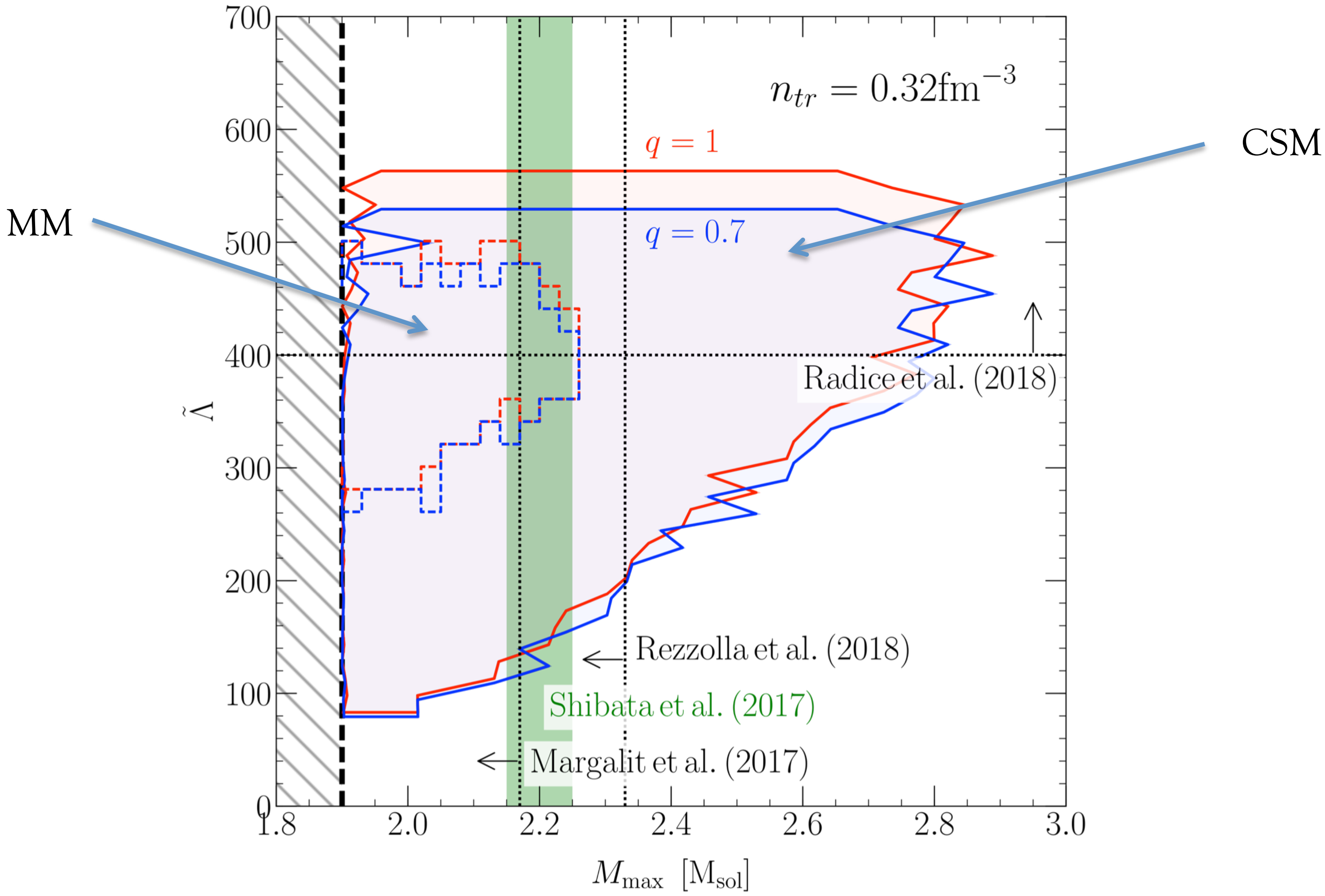


JM, Casali, Gulminelli, PRC 2018

Impact of the “exp” unknown on the Mass/Radius relation



CSM versus MM (same constraints)



Tews, JM, Reddy, arXiv:1804.0273

Tidal deformability

For a single NS:

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

k_2 (love number) depends on the EOS and compactness
k_2 ~ 0.05-0.15 (Hinderer 2008, 2010, Postnikov 2010)

For the binary NS:

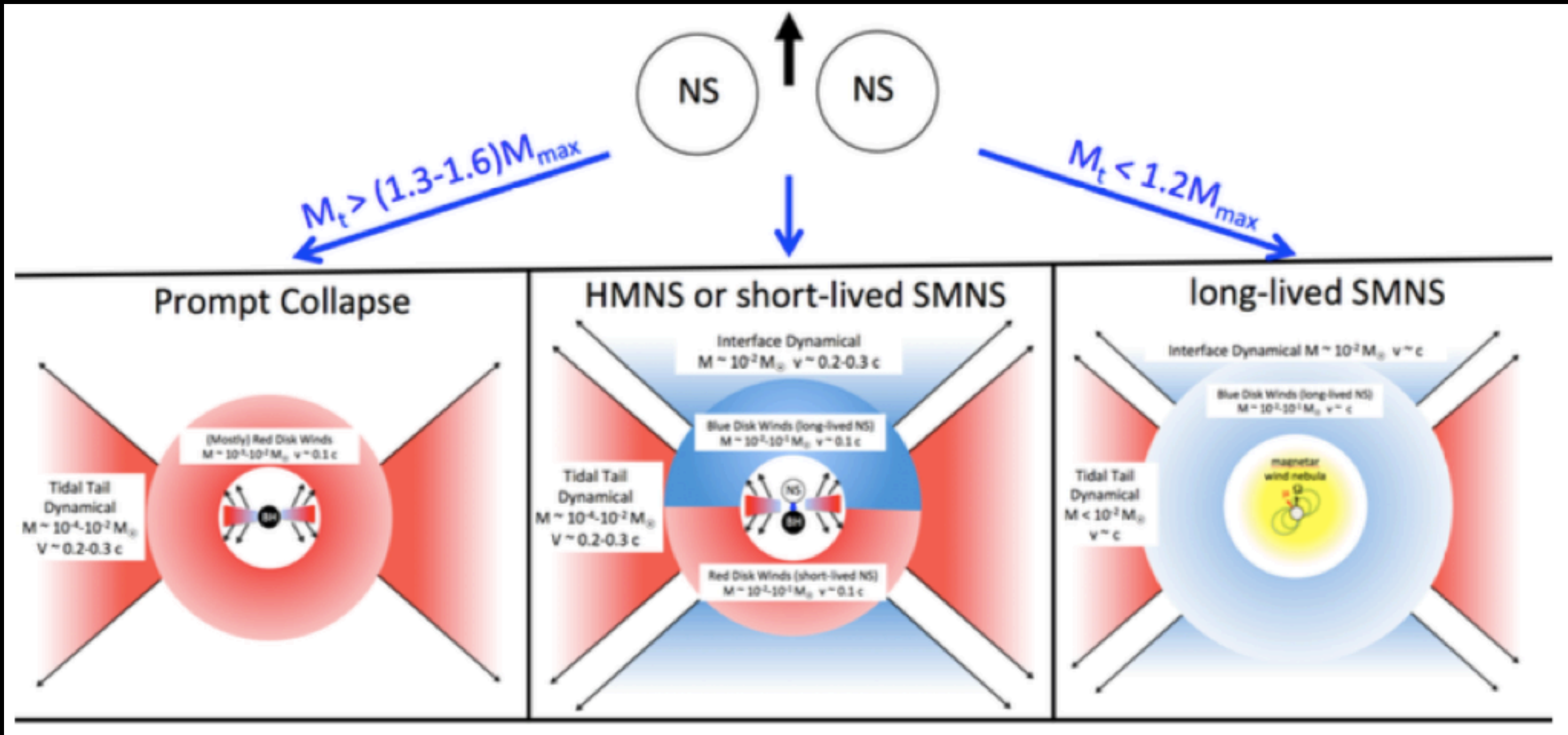
$$\widetilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$$

Tidal interactions lead to accumulated phase shift at high frequencies:

$$\delta\Phi_t = -\frac{117}{256} \frac{(1+q)^4}{q^2} \left(\frac{\pi f_{GW} G \mathcal{M}}{c^3}\right)^{5/3} \widetilde{\Lambda}$$

Kilonova (macronova) AT2017gfo

Interpretation of the EM observations



Mqrgalit & Meitzger, ApJ 2017