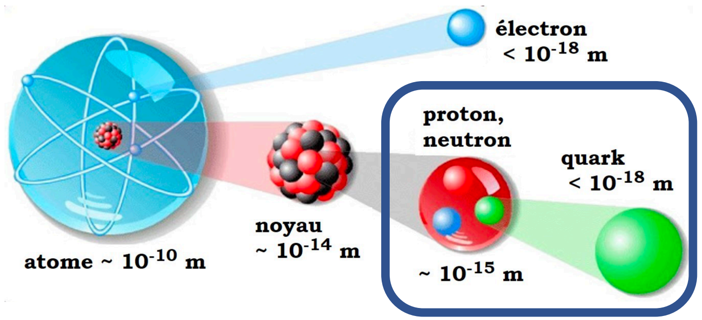
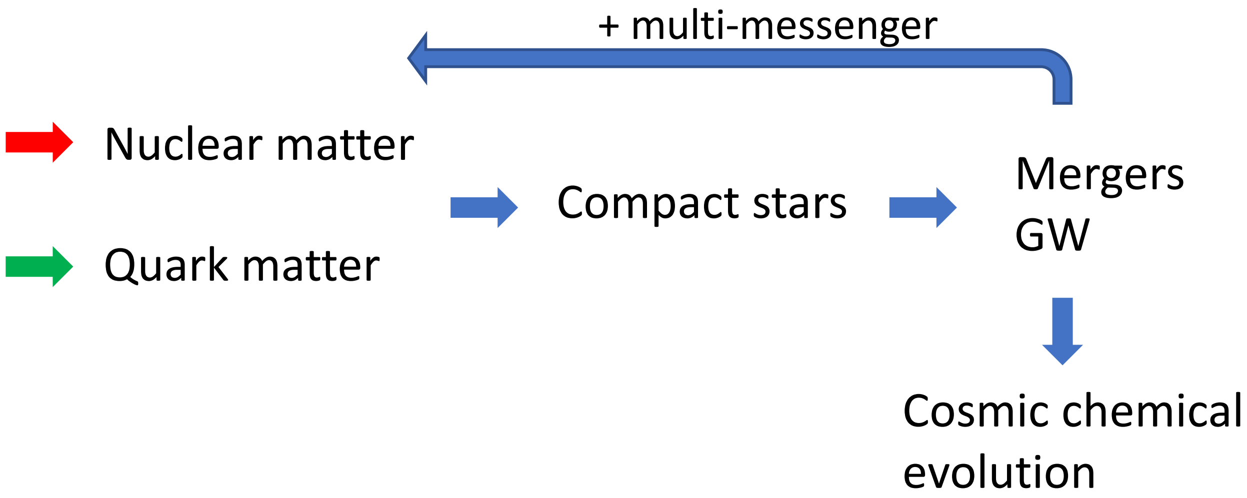
Exercice de prospectives nationales GT04, Annecy, Nov. 12-13, 2019

Probing extreme matter physics with gravitational waves





+ multi-messenger

Nuclear matter

Quark matter

Compact stars

Mergers
GW

Cosmic chemical
evolution

French researchers contributors:

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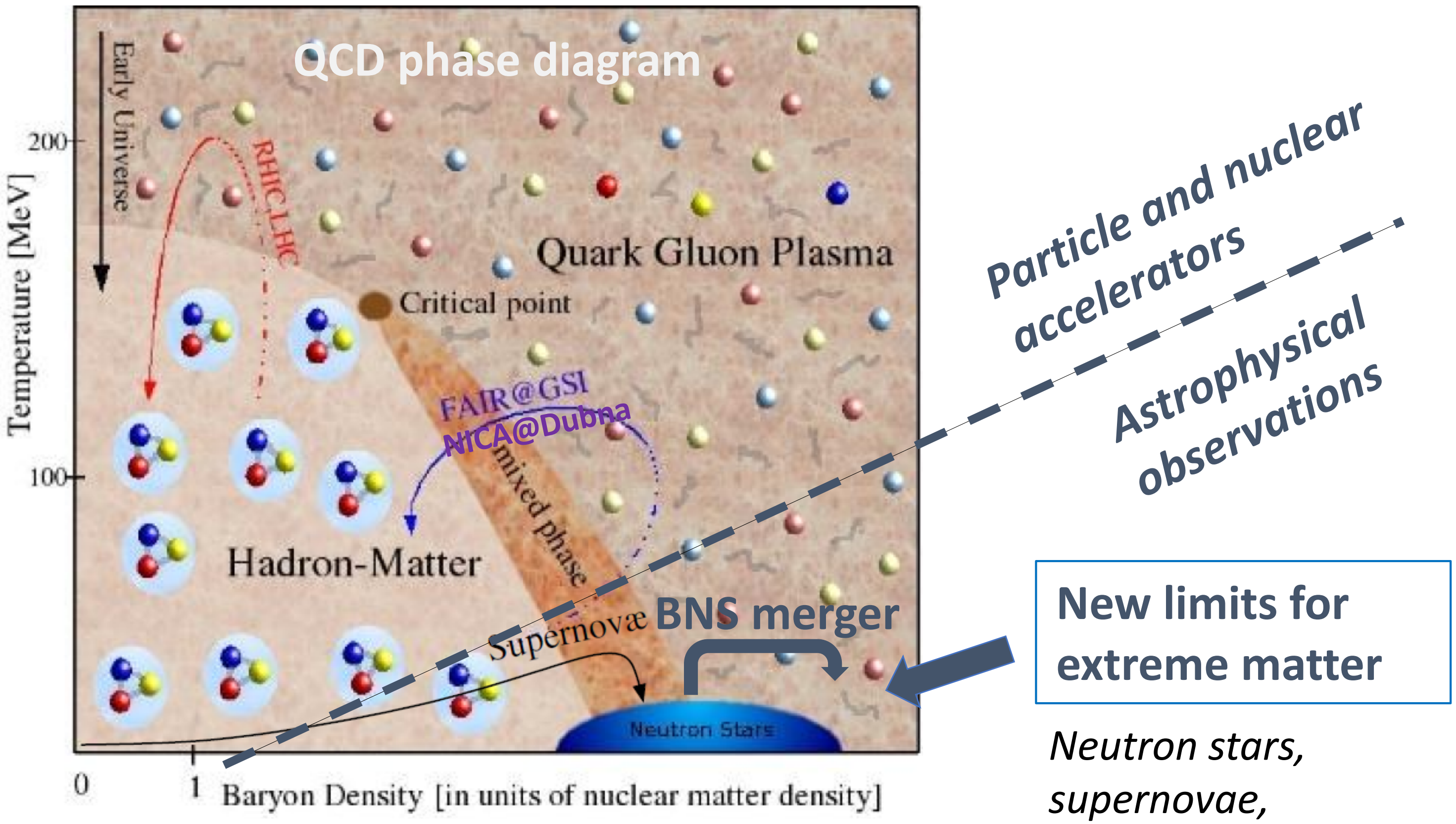
What is the QCD phase diagram? Where are the phase transitions?



Particle and nuclear accelerators

Astrophysical observations

New limits for extreme matter

Neutron stars,
supernovae,
kilonovae…

What is the **nuclear interaction** in dense, isospin asymmetric matter, hot?

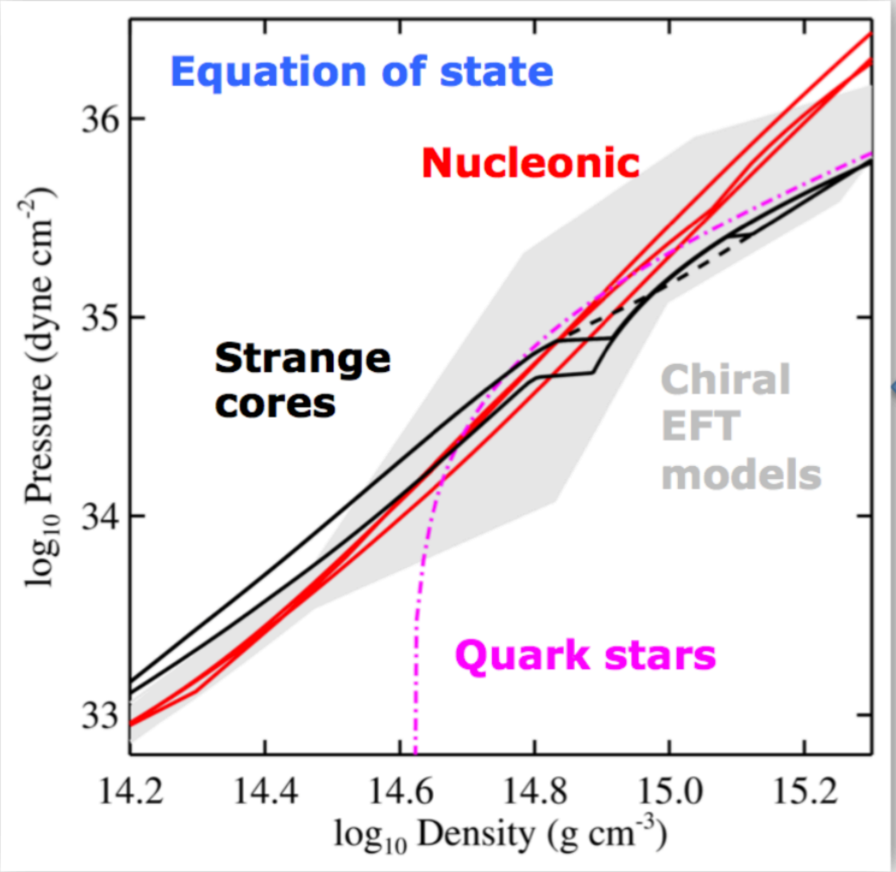
Which **new particles** appear at supra-saturation densities?

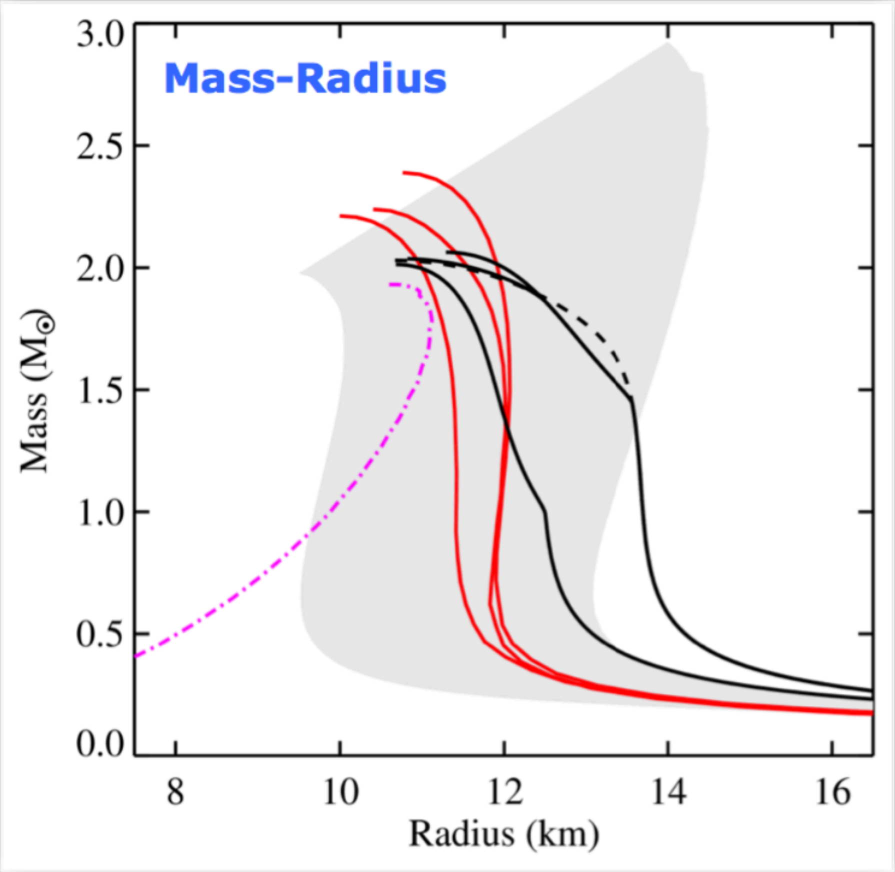
At which density occurs the **deconfinement** from hadrons to quarks and gluons?

How **neutrinos** propagate a d what are the **transport properties** of extreme matter?

Are BNS the main astrophysical site for the **r-process**?

The EoS uncertainties can be mapped into (M,R) uncertainties





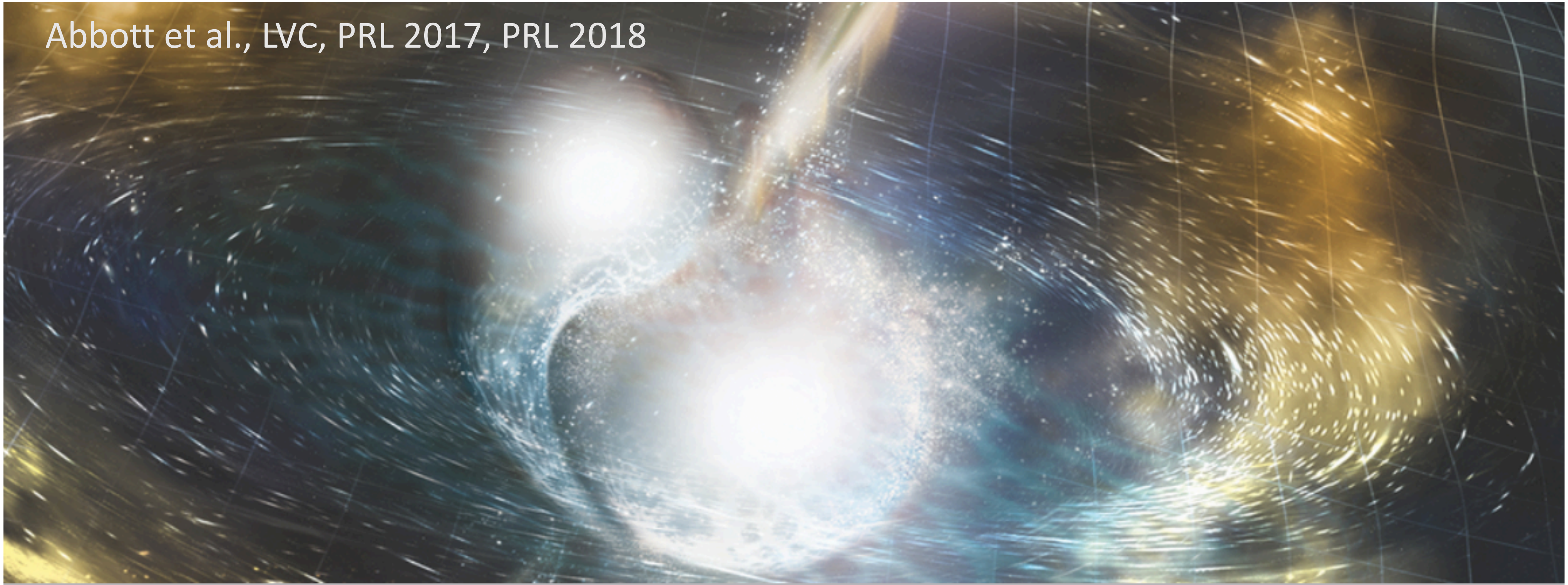
A. Watts et al., PoD (AASKA 14) 043

New data from GW interferometers (LIGO-Virgo): BNS mergers

+ KAGRA, LIGO-India in the near future

+ 3rd generation (2030): cosmic explorer, Einstein Telescope

GW170817: First detection of GW from the merger of two neutron stars (BNS)



Abbott et al., LVC, PRL 2017, PRL 2018

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

Tidal deformability

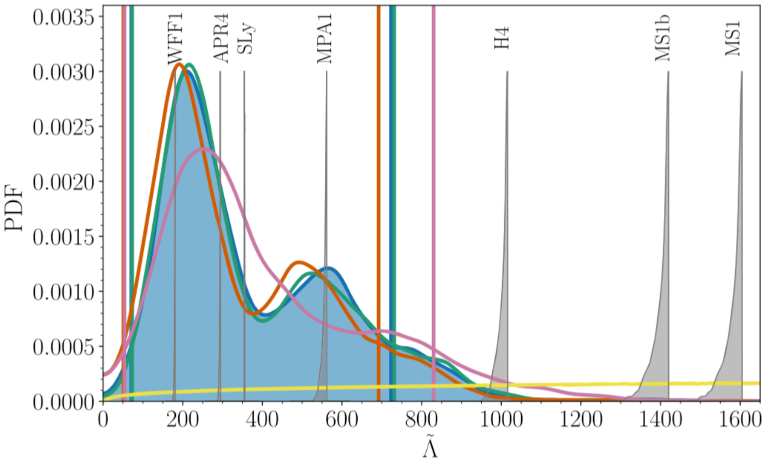
- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability Λ.

$$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$$

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

Hinderer+ 2008, Blanchet, Damour

LVC, Phys. Rev. X 9, 011001 (2019)

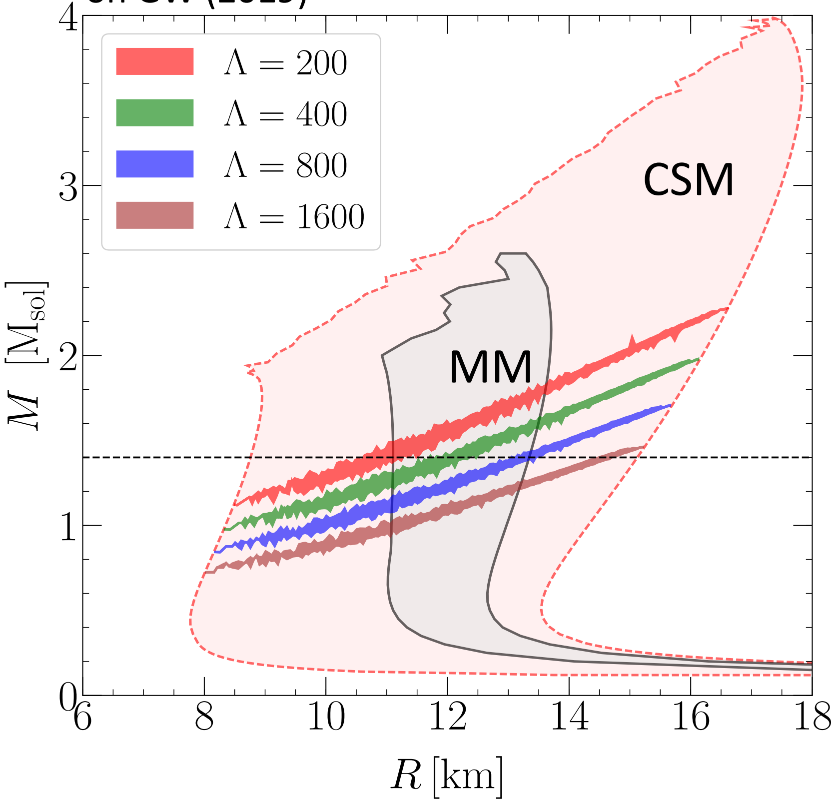


GW170817

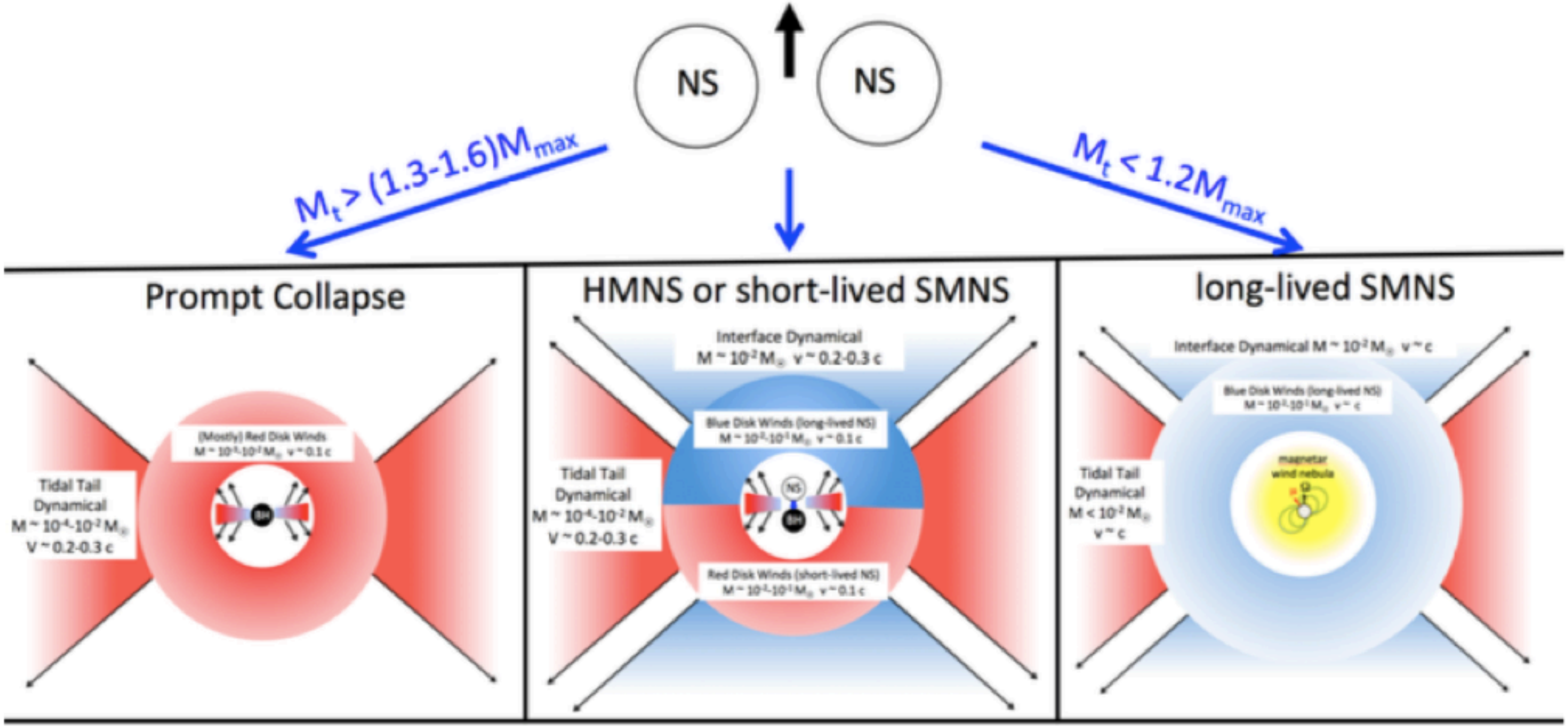
→ 70 ≤ Λ ≤ 720 (90% CL)

→ +E-M 300 ≤ Λ ≤ 800

Tews, Margueron, Reddy, EPJA special issue on GW (2019)



E-M signal and post-merger GW signal



Margalit & Meitzger ApJ 2017

Kilonova (macronova) AT2017gfo → Mmax = 2.1-2.3 Mo

Rezzolla+ 2018

Global strategy: multi-messenger and multi-physics

Nuclear experiments

CERN (*LHC, NA60, …*)
GANIL,
GSI (*FAIR*),
DUBNA (*NICA*), etc…

Theory for dense matter

Equation of state (*ComPOSE*),
Neutrino diffusion,
Transport coefficients.

Global astrophysical modeling

Neutron stars (*Lorene library, meta-model*),
BH & NS mergers (*Einstein toolkit, WHISKY-THC*),
Kilonova,
Supernova (*COCONUT*),
Galactic chemical evolution.

Observational facilities

GW (*LIGO-Virgo*),
GRB (*FERMI-LAT, XMM Newton*),
E-M (*GRANDMA, ZTF, …*).

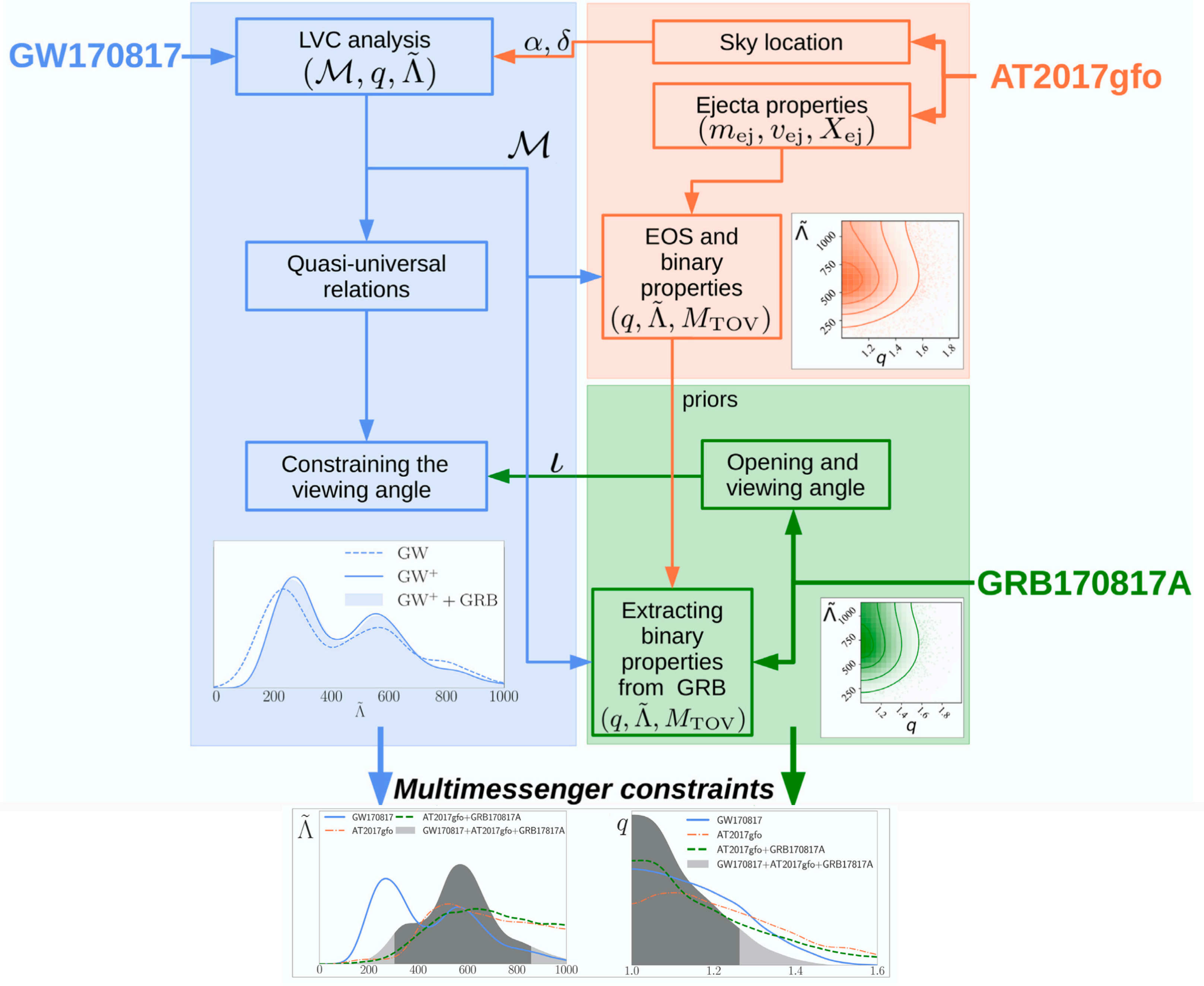
Improved understanding of extreme matter physics

Cross-fertilisation

Improved understanding of astrophysical objects

Richness and complexity of multi-messenger analysis

Coughlin et al. MNRAS 2019



GW170817

LVC analysis $(\mathcal{M}, q, \tilde{\Lambda})$

α, δ

Sky location

AT2017gfo

Ejecta properties $(m_{\rm ej}, v_{\rm ej}, X_{\rm ej})$

$\mathcal{M}$

Quasi-universal relations

EOS and binary properties $(q, \tilde{\Lambda}, M_{\rm TOV})$

priors

Constraining the viewing angle

ι

Opening and viewing angle

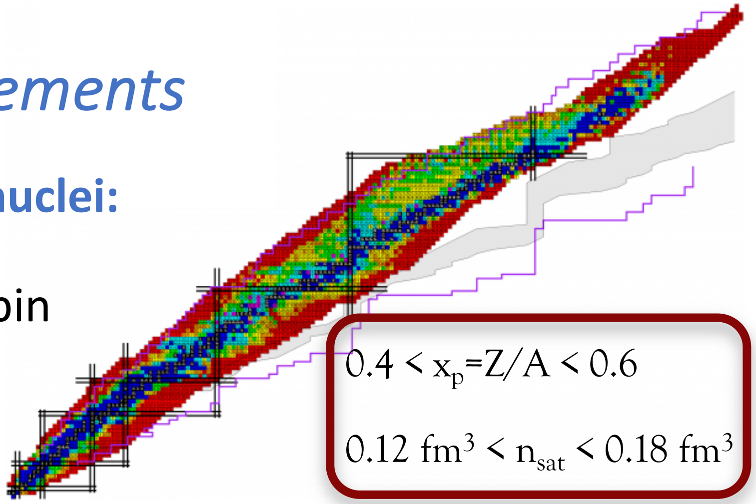
GRB170817A

Extracting binary properties from GRB $(q, \tilde{\Lambda}, M_{\rm TOV})$

Multimessenger constraints

New experimental achievements

Exploration of the nuclear chart with more neutron rich nuclei:



$0.4 < x_p=Z/A < 0.6$

$0.12\ \mathrm{fm}^3 < n_{sat} < 0.18\ \mathrm{fm}^3$

Develop and refine the knowledge of density and isospin asymmetry dependence of the nuclear interaction.

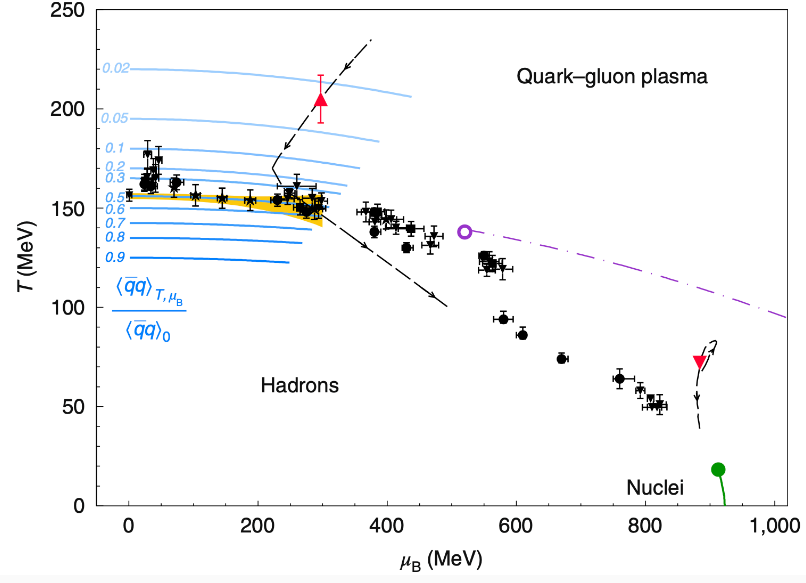
Could be mapped into the nuclear empirical parameters:

Small uncertainties					Large uncertainties					Large uncertainties	
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	$\Delta m^*_{sat}/m$
-15.8	32	0.155	60	230	-100	300	0	-500	-500	0.75	0.1
±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000	±0.1	±0.1

JM, Casali, Gulminelli, PRC 2018

Heavy ion collisions

HADES, Nature phys. 2019



Extreme matter (micro-)physics

Modeling the equation of state:

Main issue: solution of QCD in non-perturbative regime.

- **Agnostic approaches:** no Lagrangian, no matter composition
  Ex.: piece-wise polytropes, sound-speed model, …
- **Semi-agnostic approaches:** no Lagrangian, matter composition
  Ex.: meta-model
- **Phenomenological approaches:** Phenom. Lagrangian, matter composition
  Ex. (nucleon): Skyrme and extensions, Gogny, RMF, RHF, …
  Ex. (quark): PNJL, PQM, …
- **Microscopic approaches:** reproduce NN XS, predict dense matter properties
  Ex. (nucleon): AV16 + 3BF, Nijmegen …
- **QCD based approaches**:
  Ex.: LQCD, chiral EFT (effective field theory), QCD holographic correspondence.

→ Needs interface with global simulations (ex.: ComPOSE library).

Neutrino propagation in hot and dense matter:

Effects of dense matter correlations (mean field and collective modes),
statistical mixing of nuclei, coherent scattering, relativity, weak magnetism, …

→ Needs interface with global simulation (ex.: neutrino tool-kit).

Holographic QCD and neutron star physics

Holographic correspondence: map a strongly coupled quantum field theory (like QCD) to a classical gravitational theory in higher dimensions.

QCD state at finite temperature and density → Higher dimensional black hole geometry

Realistic phenomenological models: V-QCD Kiritsis et al.,2015 - …

- **Zero/finite temperature, zero/finite density phase;**
- **Transport coefficients** (viscosities) **in all phases**
- **Individual baryons** (as in Skyrme model)

→ Can be coupled to ordinary gravity to construct compact object solutions

Can describe quark matter (possibly) present in the core of neutron stars

Challenge: describe state with density of **confined baryonic matter** (neutrons)

Kiritsis, Nitti… in progress

Global astrophysical modeling

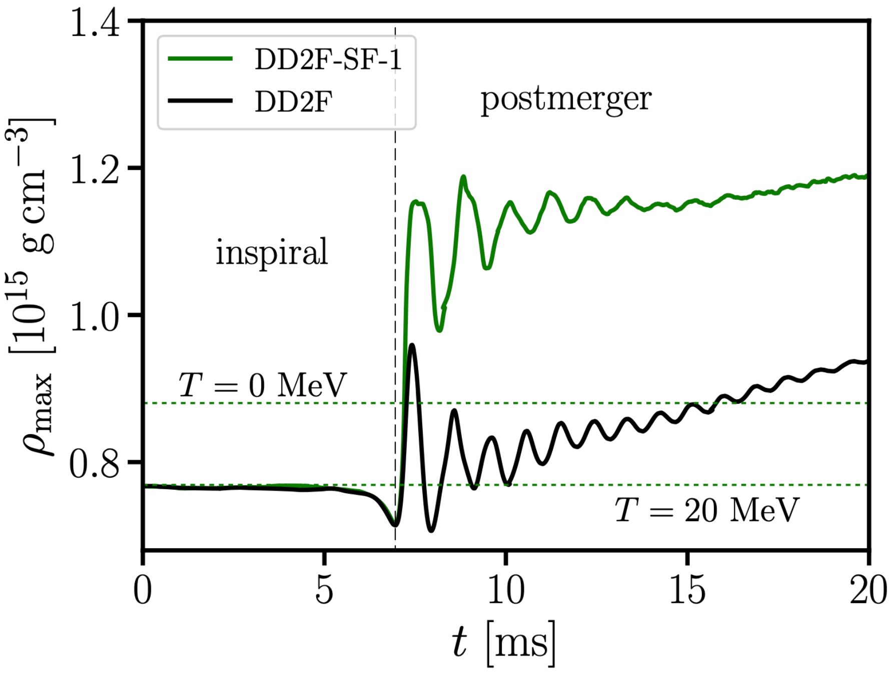
Modeling of dense objects (transient or not):

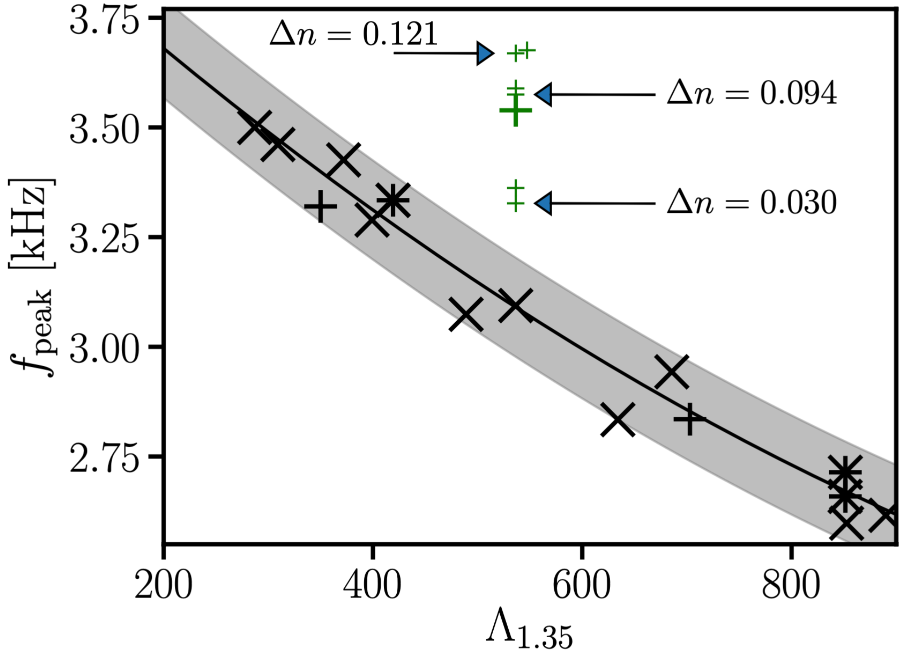
Heat transfer (cooling)
Multi-dimensional features (3d HD)
Transport of matter and neutrinos (multi-group, 1p)
Magnetic field (MHD)

→ Needs expertise in complex MHD
→ Needs HPC

Post-merger GW signal & dense matter phase transition

Bauswein et al. 2019





Global astrophysical modeling

Nucleosynthesis (r-process), neutrino flux, Ye of ejecta

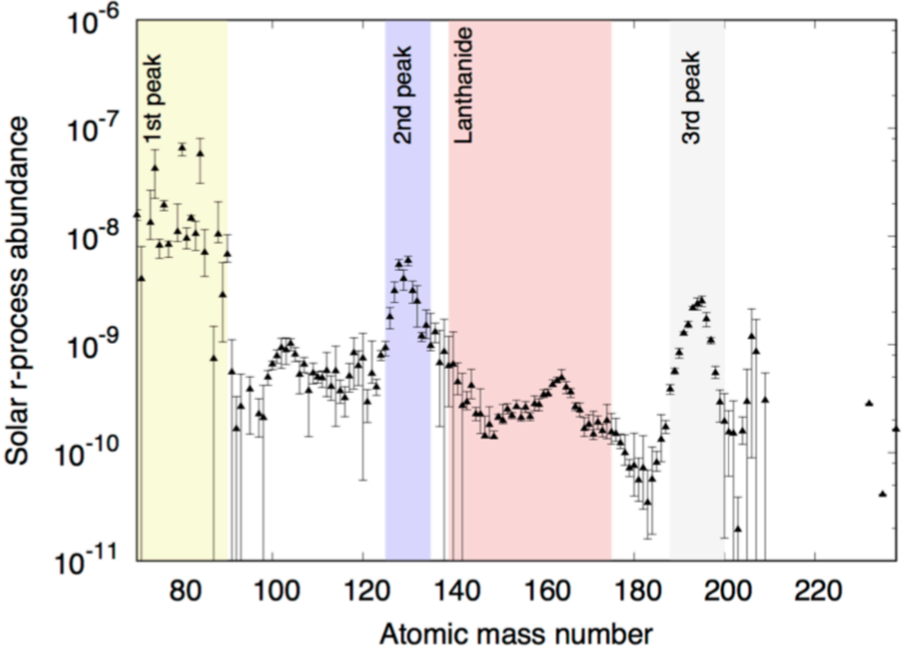
Synthesis of heavy nuclei (above 2nd peak): What are the conditions for the r-process?

In the ejected material:

Ye < 0.25:
- Strong r-process A>130
- Insensitive to details of trajectory

Ye>0.25
- A<130
- Sensitive to details of trajectory

Rosswog+ 2018



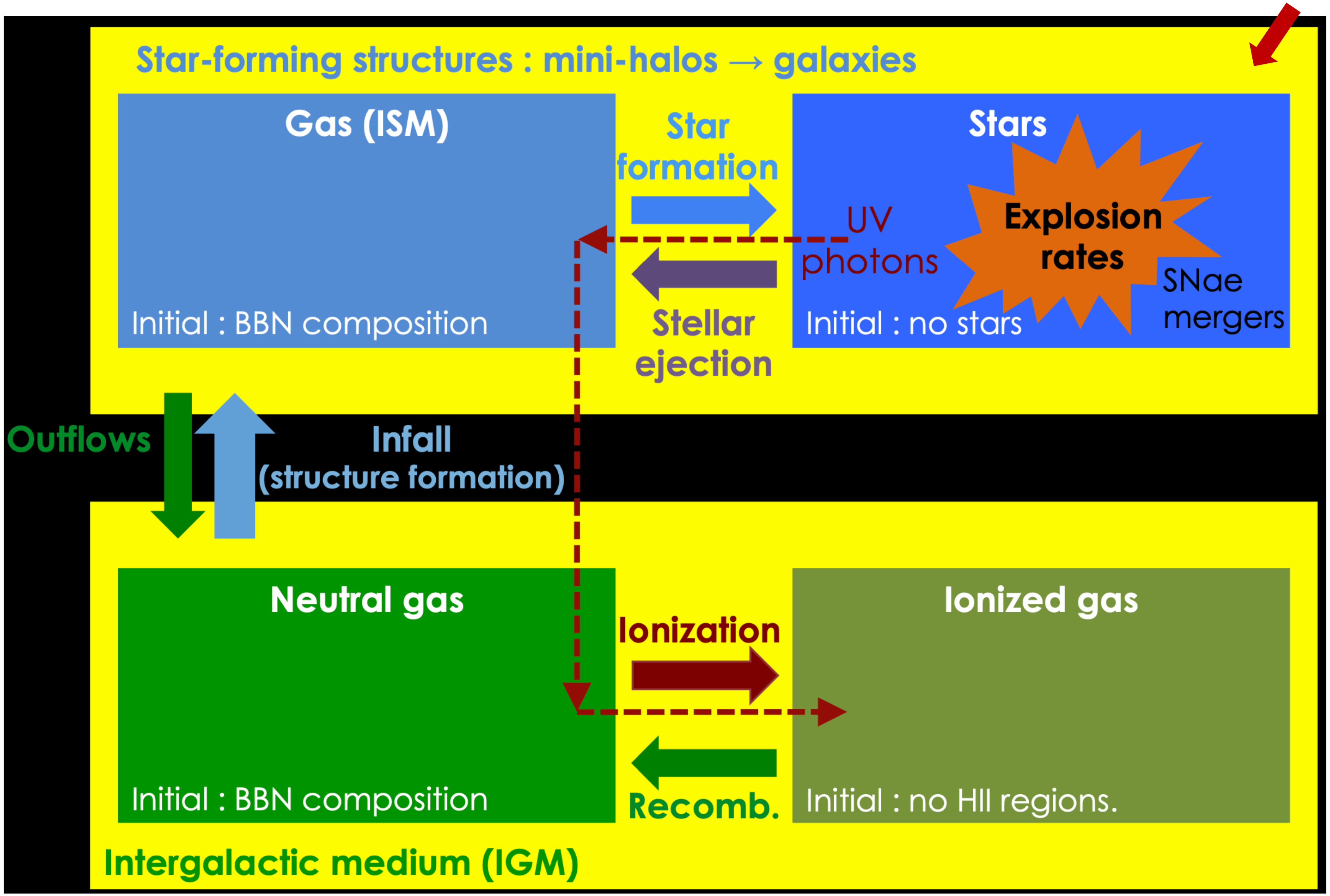
Production of lanthanides (large opacities)
→ redding of the emitted light
→ Impact on the E-M spectra (multi-messenger) observed on Earth

Population studies and observational constraints

Modeling of cosmic chemical evolution:

Population models: event rates and associated chemical evolution
Measurements of r-process element abundances in various sites

BNS rates uncertainties



Star-forming structures : mini-halos → galaxies

Gas (ISM)

Initial : BBN composition

Star formation

Stellar ejection

Stars

UV photons

Explosion rates

SNae mergers

Initial : no stars

Outflows

Infall (structure formation)

Neutral gas

Initial : BBN composition

Ionization

Recomb.

Ionized gas

Initial : no HII regions.

Intergalactic medium (IGM)

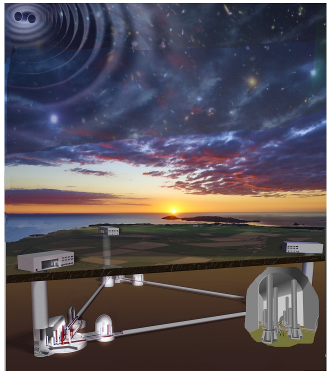
Conclusion and Outlook

Multi-messenger observation: The BNS GW + kilonovae EM signal + GRB + neutrinos.
Variety of GW sources: BNS, BH-NS, CCSN, continuous sources of GW, etc…
Post-merger GW observation: investigation of phase transitions.

French community:

- NS mergers: small and fragmented teams.
- EOS: small and fragmented teams as well.
- Chemical evolution of galaxies: only 1 lab.

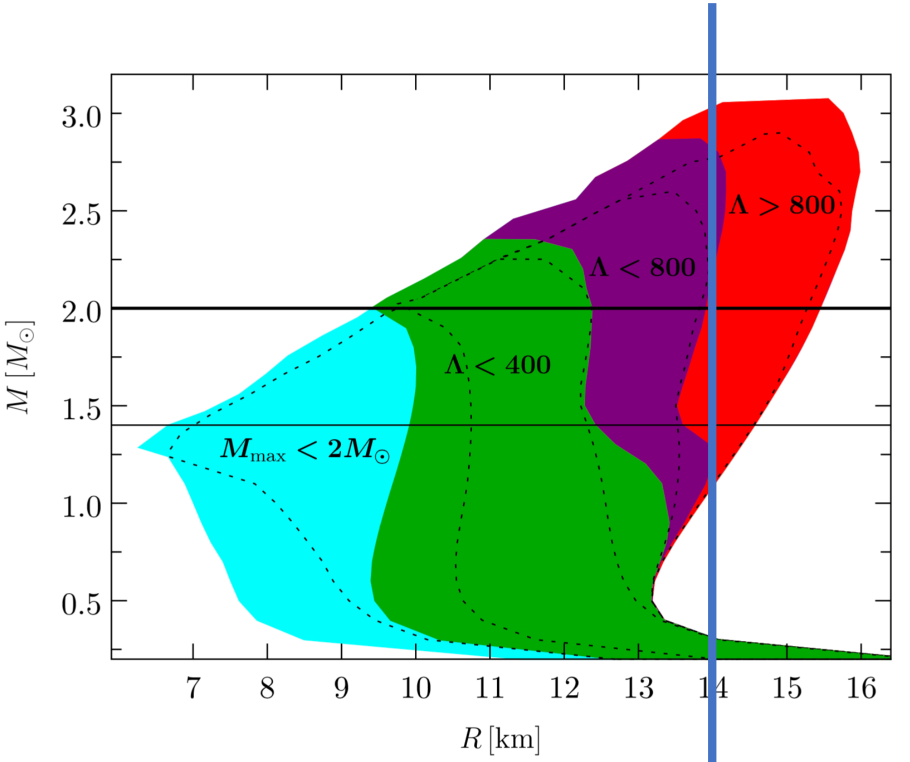
Interdisciplinary research (IN2P3, INP, INSU)
→ needs interdisciplinary CNRS commission.
Fragmented teams
→ needs a strong and coherent national support.
Priority: develop an global modeling of BNS to compare with observations.



Future upgrades and new telescopes:
GW interferometers: upgrades of Virgo → Einstein telescope (2030)
E-M follow-up: GRANDMA, ZTF → LSST

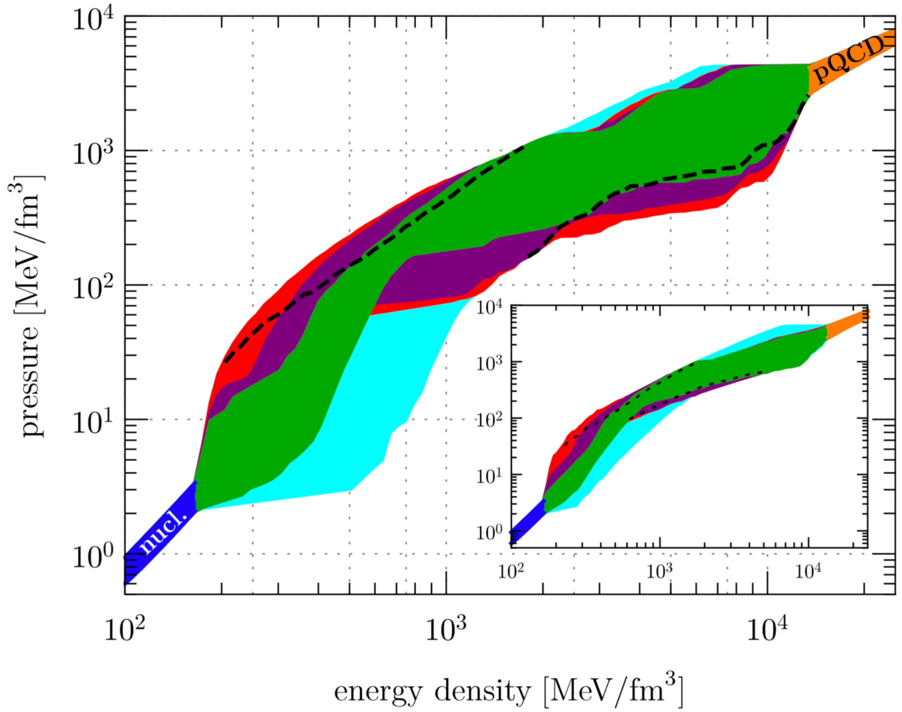
Complementary goals with other contributions:
Neutrino Astrophysics
Understanding the core collapse supernova explosion mechanism.

Confrontation of polytropic EoS to GW170817



Upper boundary
for R

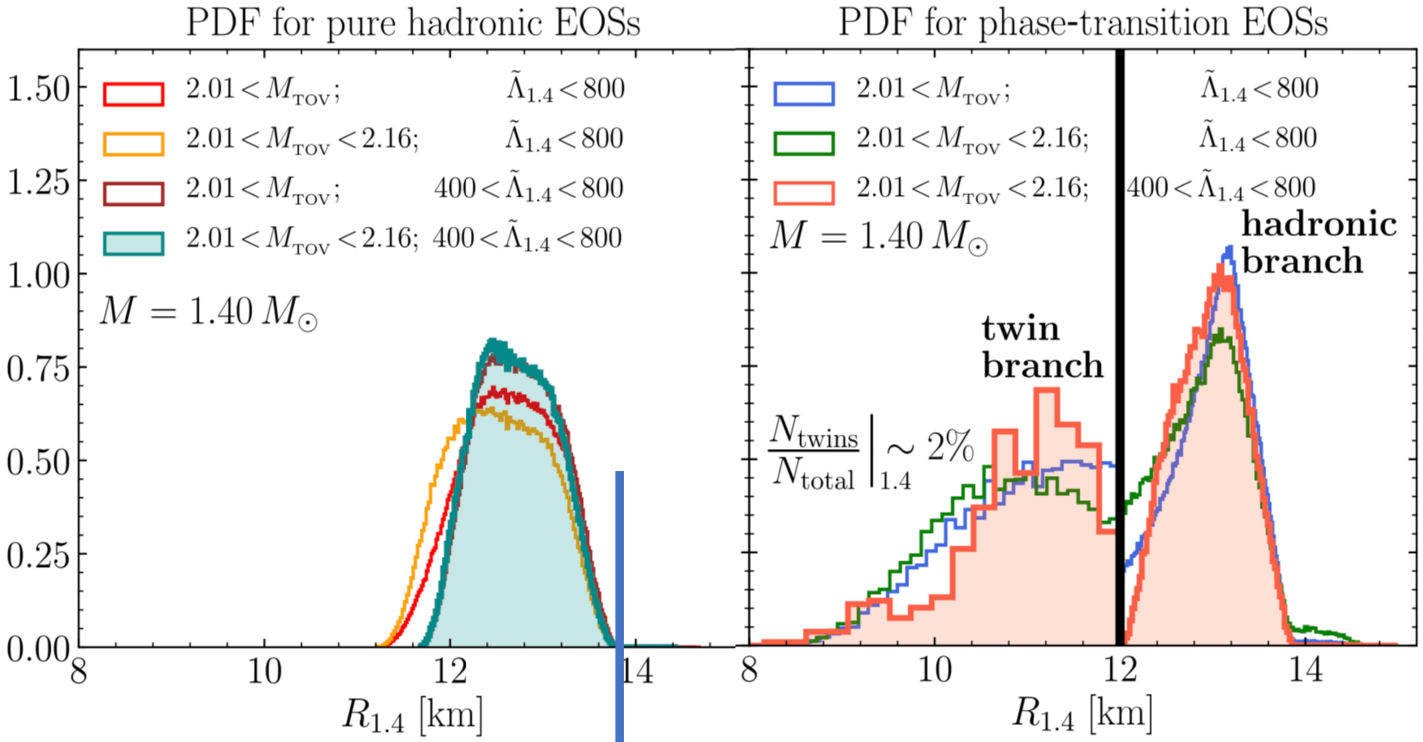
Annala et al., PRL 2018



Boundaries for the EoS

Other: confrontation of relativistic EoS to GW170817

Most et al., PRL 2018



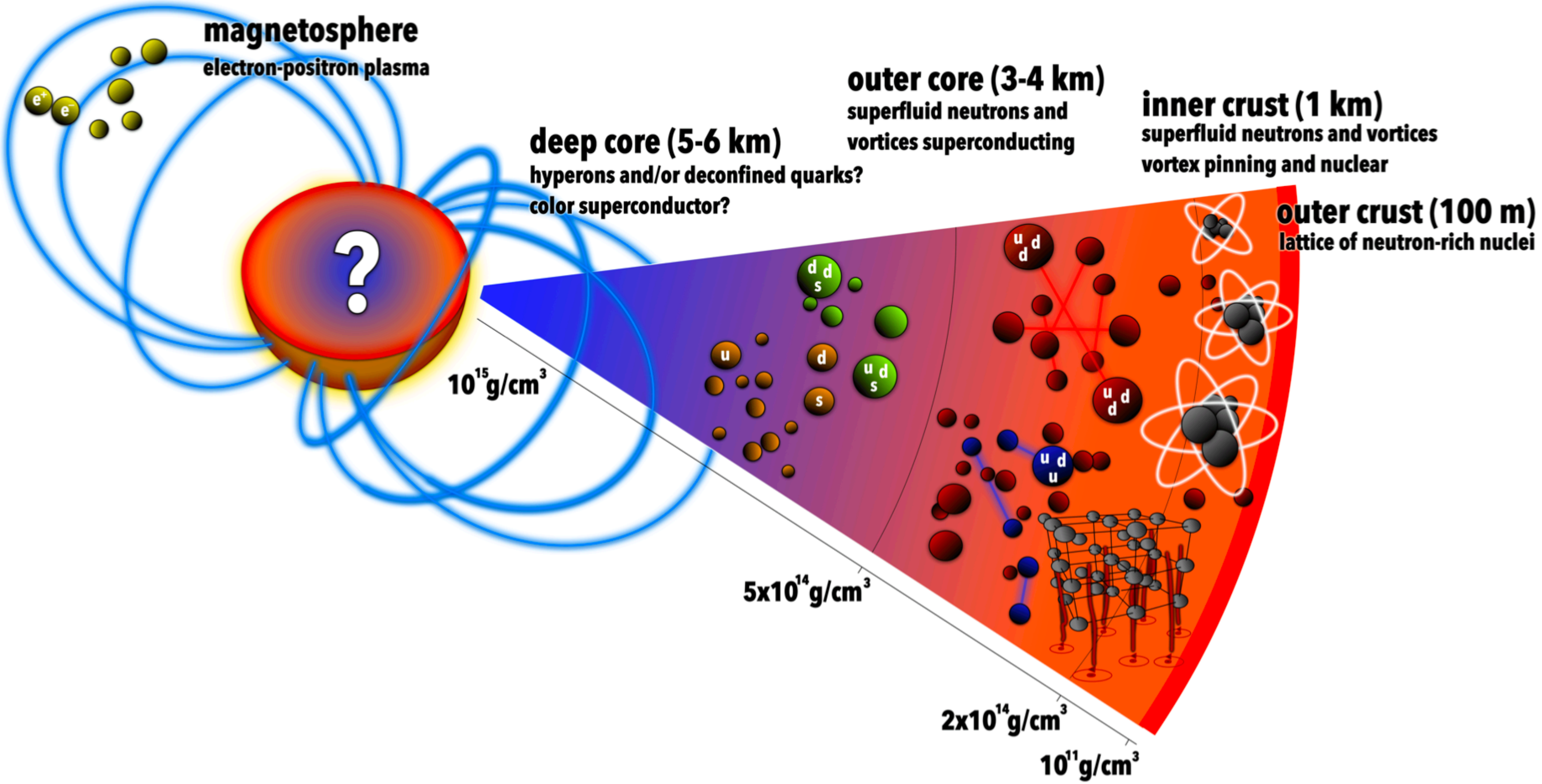
Upper boundary for R

Addressing fundamental questions at the forefront

From the GWIC 3G science-case meeting (oct. 2018, Postdam)
Sanjay Reddy, Neutron Star WG

1. Does matter in NS and NS mergers contain **novel QCD phases** not realized inside nuclei and heavy-ion collisions?
2. Can NS observations guide and validate **theories of nuclei and nuclear matter**?
3. Is there a diversity in the NS population and what are its implications (families)?
4. How do **nuclear** and **neutrino reactions** shape NS mergers dynamics and **nucleosynthesis**?
5. How do the properties of **nuclei far from stabil**ity impact on the electromagnetic emission from NS merger ejecta?
6. Can NSs sustain long-lived large quadrupolar deformations?
7. Do large scale (magneto)hydrodynamic instabilities influence spinning and merging NSs?
8. Can we combine GW and EM signatures to validate multi-physics simulations of BNS and BHNS mergers to predict ejecta, nucleosynthesis, and the gamma-ray burst mechanisms?
9. Can we model and observe post-merger oscillations to reliably constrain dense matter and merger dynamics.
10. Does **dark matter** and **physics beyond the standard model** play a role in NSs and NS mergers?

Neutron star interior structure



A. Watts et al., PoD (AASKA 14) 043