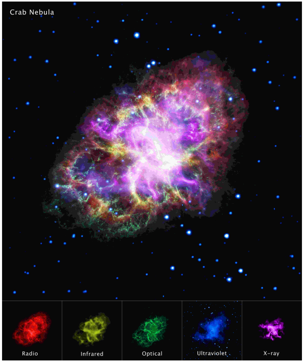
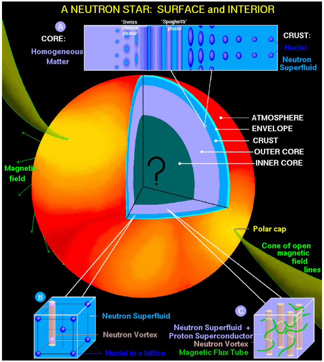
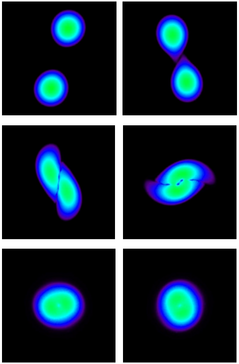
Compact stars and matter at extreme conditions
Part 1: Observations and Theory

Michael Urban (IJCLab, Orsay)

Part 2: Experiments → Francesca Gulminelli's talk

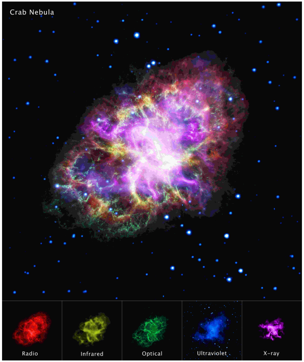


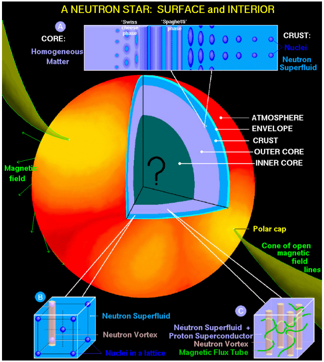


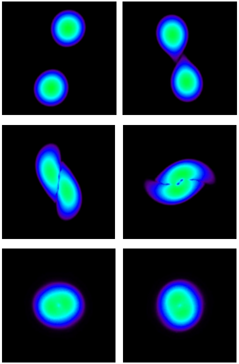


Key questions

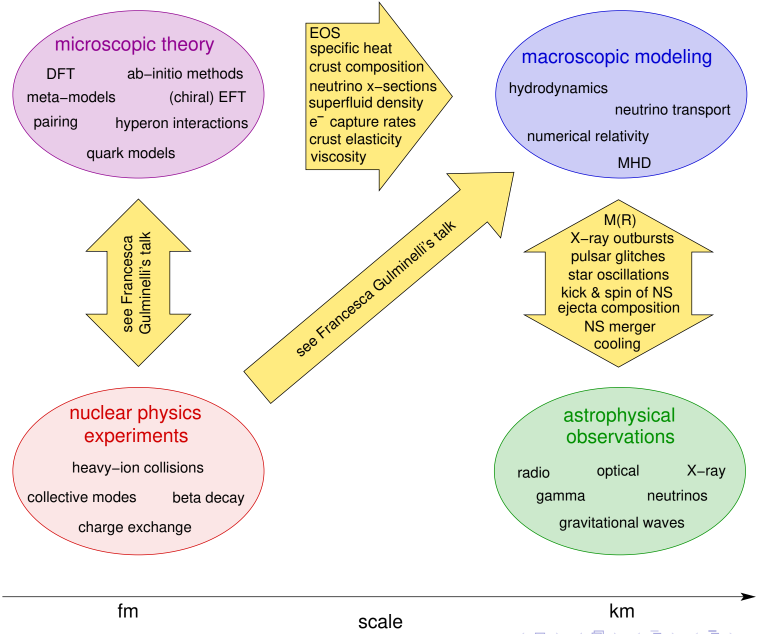
- What are the properties of strongly interacting matter at extreme conditions of density, temperature, and asymmetry?
- How can astrophysical observations constrain these properties?
- How can nuclear physics help to understand core-collapse supernovae, neutron stars, and neutron-star mergers?







Interplay between micro- and macrophysics



Outline

1. Astrophysical observations

co-authors: Didier Barret[1], Marie-Anne Bizouard[2], Ismaël Cognard[3], Lucas Guillemot[3], Sébastien Guillot[1], Ed Porter[4], David Smith[5], Gilles Theureau[3], Natalie Webb[1]

2. Macroscopic modeling

co-authors: Thierry Foglizzo[6], Jérôme Guilet[6], Jérôme Novak[7]

3. Microscopic theory

co-authors: Guy Chanfray[8], Anthea Fantina[9], Francesca Gulminelli[10], Hubert Hansen[8], Elias Khan[11], Jérôme Margueron[8], Paolo Napolitani[11], Micaela Oertel[7], Rainer Stiele[8]

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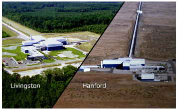
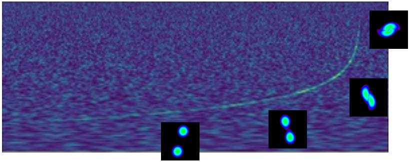
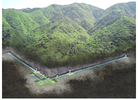
Gravitational waves





- already two neutron-star (NS) mergers detected by LIGO (USA) and Virgo (Italy): GW170817, GW190425
- masses and tidal deformability ($\rightarrow$ masses) of the merging NSs were extracted from GW170817 wave form
- GW170817 was also seen as γ-ray burst and later also in optical, X-ray and radio $\rightarrow$ "multi-messenger astronomy" r-process happens in NS mergers!
- French laboratories involved: APC (Paris), Artemis (Nice), LAPP (Annecy), IJCLab (Orsay)
- recently, LIGO and Virgo improved their sensitivity
- KAGRA (Japan) expected to join LIGO-Virgo network to improve localization of the events



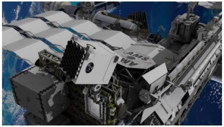
- planned and proposed projects: LIGO India, Cosmic Explorer, Einstein Telescope
- wealth of data on NS mergers expected until 2030!

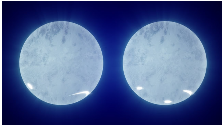
Electromagnetic signals

gamma

- since 2008: Fermi LAT (NASA; in France: CENBG Bordeaux, LPC2E Orléans)
- pulsar searches; pulsar timing: information on B field, age, superfluidity, . . .

X-ray





- since 1999: XMM-Newton (ESA), Chandra (NASA)
- since 2017: NICER (NASA; in France: IRAP Toulouse)
  "Neutron-star Interior Composition ExploreR"
- from 2032: Athena X-IFU (ESA; in France: IRAP, APC)
- measure mass and radius of pulsars ($\longrightarrow$ EOS),
  surface temperature (including "hot spots")

radio

- Nançay Radio Telescope (NRT) and Pulsar Timing Array consortia (EPTA, IPTA)
  $\longrightarrow$ detection of nHz gravitational waves (in France: LPC2E and APC)

- since 2016: MeerKAT (South Africa; in France: LPC2E)
  first phase of planned SKA ("Square kilometer array")
- from $\sim$ 2027: SKA (South Africa and Australia)
- pulsar timing $\rightarrow$ precise mass measurements (binary systems), B field and age,
  coupled with GW detections $\rightarrow$ constraints on oblateness of NSs,
  "glitches" (sudden changes of spin rate) $\rightarrow$ superfluidity

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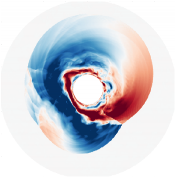
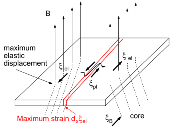
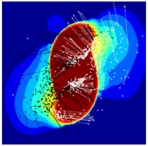
Challenges in macroscopic modeling



- supernova explosions: towards ab-initio 3D simulations with realistic equations of state (EOS) and neutrino interactions (instabilities destroy initial spherical symmetry $\leftrightarrow$ kick and spin of neutron star)
- modeling of the magnetic field (formation of magnetars, superluminous explosions, hypernovae. . .)
- neutron stars: include properties and dynamics of the crust:
  - elasticity for oscillations ($\leftrightarrow$ GW observations)
  - coupling with B field for magnetar bursts
  - superfluidity for pulsar glitches





- NS mergers: include viscosity, B field, ν transport with realistic microphysics input (viscosity, ν cross sections)
- Later stages of the merger (kilonova) depend on microphysics input for ejecta composition and r-process rates
- general trend: make simulations more realistic by using better microphysics input $\longrightarrow$ nuclear physicists should provide their results in a form that is easy to use

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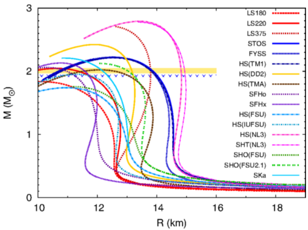
Equation of state (EOS)

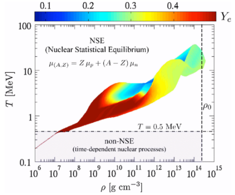


cold neutron stars ($T = 0$, β equilibrium)

- EOS provides $M(R)$ relationship
  (and tidal deformability, observable in GW signal)
- crust: inhomogeneous
  (neutron-rich nuclei or clusters in neutron gas)
  $\longrightarrow$ need consistent EOS for crust and core!
- up to $\simeq \rho_0$: towards ab-initio description based on realistic NN and 3N interactions
- outer core above ρ_0: meta-modeling in terms of few parameters
  (such as compressibility, symmetry energy and its density dependence, etc.)
- inner core: hyperons (repulsive hyperon interaction, constraints from hypernuclei?), quarks (lattice QCD not applicable $\longrightarrow$ effective quark models)

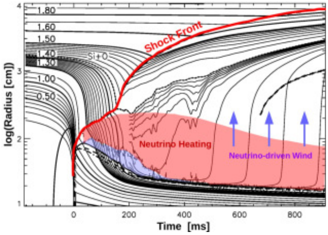
supernovae, binary NS mergers

- need EOS at finite temperature up to ~ 100 MeV and out of β equilibrium
- different phase transitions: astrophysical signals?
- facilitate use of microscopic EOS by macroscopic modelers
  (e.g., COMPOSE data base)



Microscopic input for dynamical evolution

- viscosity: important input for hydrodynamic simulations
- electroweak cross sections:
  - e^- capture rates and ν cross sections needed in supernova simulations
  - ejecta composition of binary NS mergers depends on ν reactions
  - ν emission is the most efficient cooling mechanism in NSs



  - nuclear many-body effects strongly modify ν cross sections in dense matter
- superfluidity:
  - crust (and maybe also core) superfluidity responsible for pulsar glitches (reduction of superfluid density in the crust through entrainment effect?)
  - density dependence of pairing gap (s and p wave) related to NS cooling (e.g. $\nu\bar{\nu}$ pair emission in the pair-breaking and formation process)
- results should be provided to macroscopic modelers in a form that is easy to use

Conclusions

- Exchange (i.e., in both directions!) between micro- and macrophysics
- Observations rely on big instruments. IN2P3 contributes to Virgo, Fermi, and future Athena X-IFU
- To relate astrophysical observations to nuclear physics results (and vice versa), detailed simulations of the macroscopic phenomena are necessary. In France, very few people (only from CEA and INSU) work in this field. IN2P3 should reinforce this activity which allows to give more importance and visibility to the (theoretical and experimental) nuclear-physics results.
- Microscopic theory: not very large but strong and internationally visible community in several IN2P3 and non-IN2P3 labs. Reinforcement is needed since plenty of very diverse questions have to be addressed.
- Topic is closely related to other contributions in GT02: "nucleosynthesis" and "experiments for compact stars", as well as to contributions in GT03 "hadronic physics" (hot and dense matter) and in GT04 "astroparticles" (gravitational waves, X-ray astronomy, etc.)