Supernova and compact star simulations

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Compact stars & supernovae

- Probes of nuclear matter in extreme conditions that are not reachable in Earth-based experiments
- Powerful sources of gravitational waves
- Central objects in high energy astrophysics

A detailed description of the complex physics requires a numerical approach:

- Large range of densities and temperatures, neutrino interactions
- Intense gravity with significant GR effects
- Relativistic motions, magnetic fields

Numerical models make the link between microscopic calculations (EoSs, neutrino reaction rates, ...) and (astro)physical observable quantities

Compact star & supernova

Isolated neutron stars

Core-collapse supernovae & protoneutron stars

Neutron star mergers

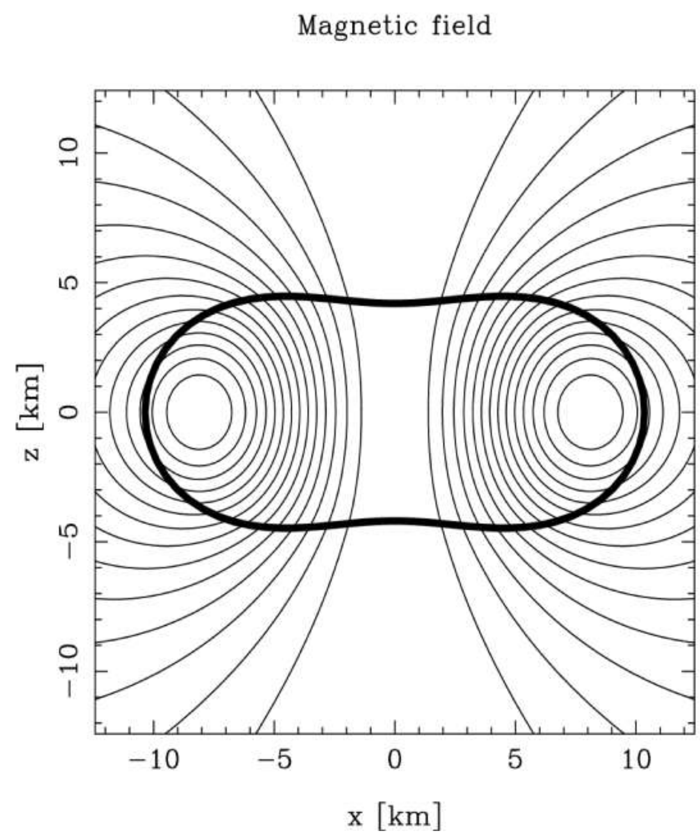
Microphysics input for numerical models

Isolated neutron stars

Numerical library LORENE developed at the Observatoire de Paris (Gourgoulhon et al. 2016, https://lorene.obspm.fr) :

- Spectral methods
- Full GR
- Detailed microphysics models (EOS)

Main developers : Eric Gourgoulhon, Philippe Grandclément, Jean-Alain Marck, Jérôme Novak and Keisuke Taniguchi.



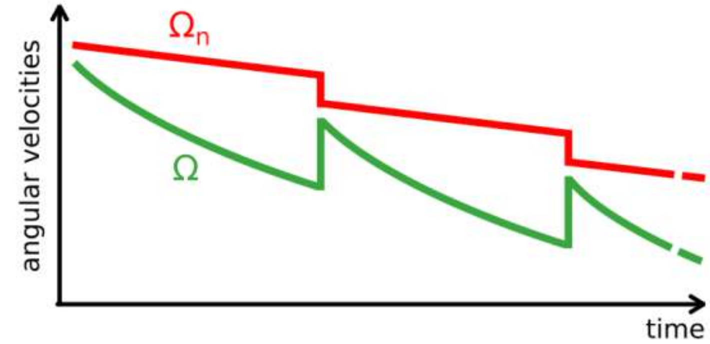
Chatterjee et al. 2015

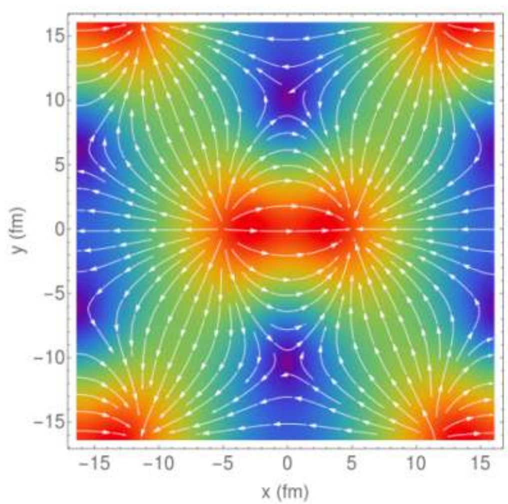
Connecting matter microscopic properties to astrophysical observables

Neutron superfluidity determines glitch rise time

Superfluid hydrodynamics in neutron star crust : local (mesoscopic) models

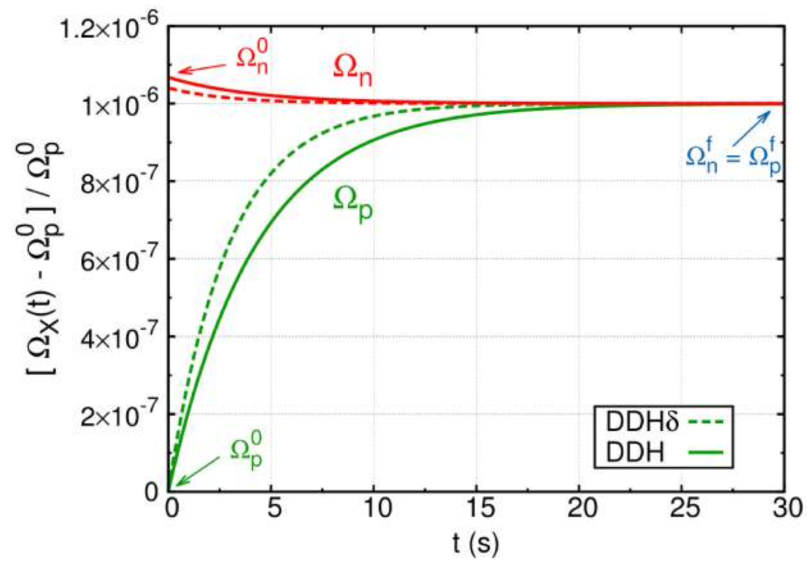
Glitch model





(c) Velocity field ($z = L/4$)

Martin & Urban 2016



Sourie et al. 2017

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Core collapse supernovae: a multi-physics problem

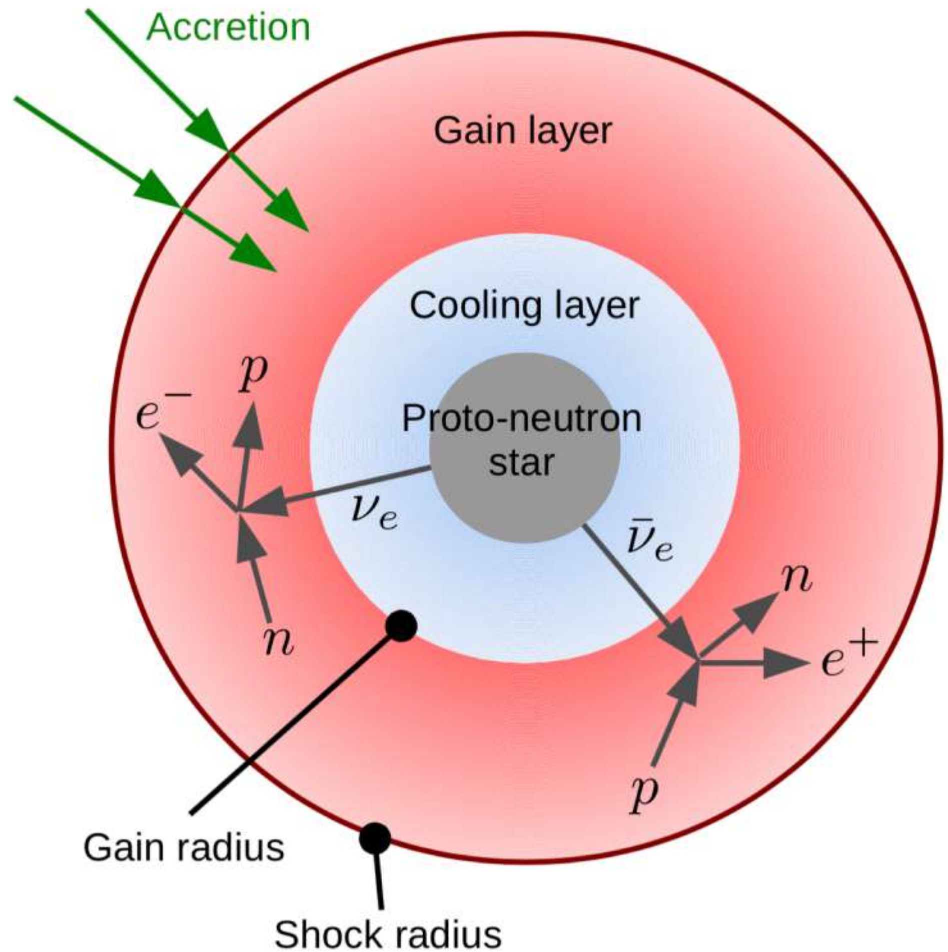
- Neutrino-matter interactions
  sophisticated transport schemes

- Equation of state at ultra-high density and temperatures

- General relativity

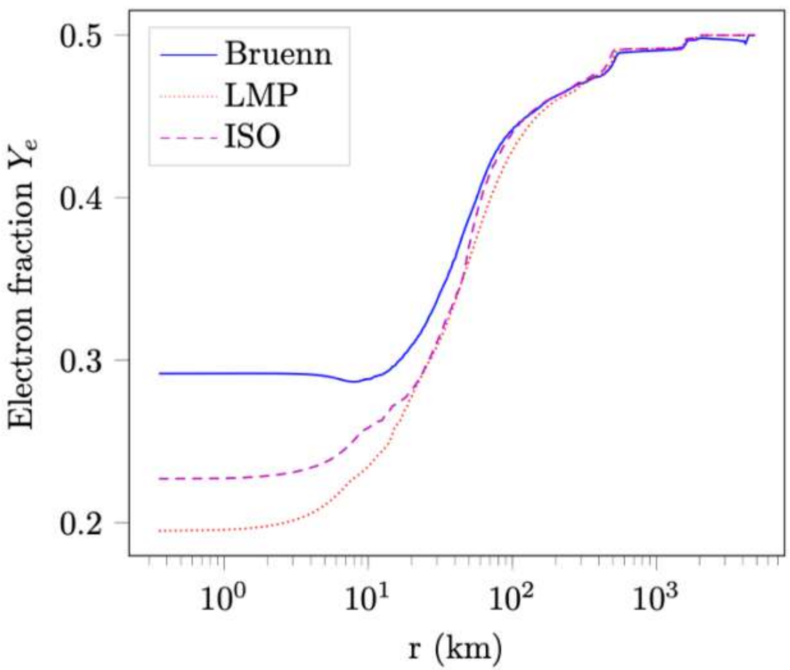
- Multi-dimensional hydrodynamics (instabilities, turbulence..)

- Magnetic field



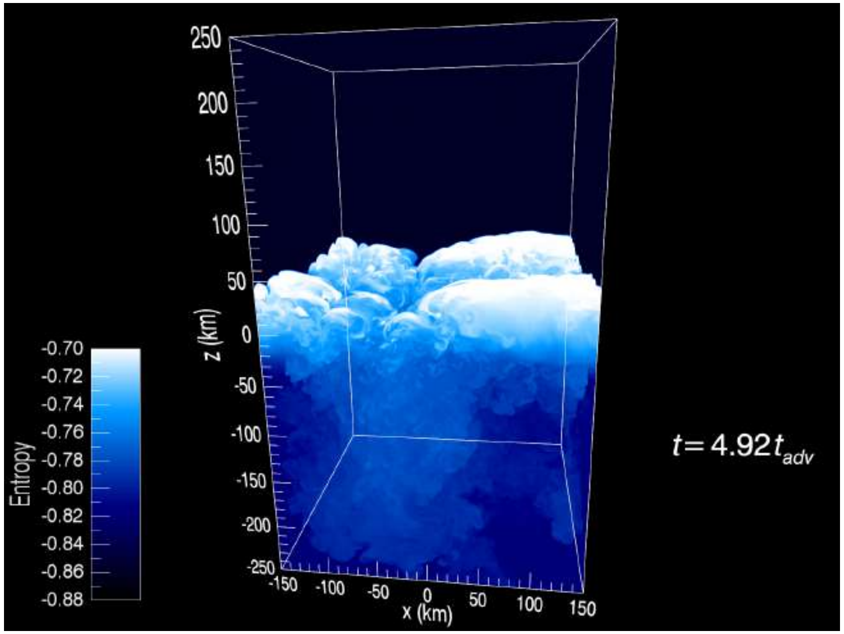
Neutrino-driven supernovae: simplified models

1D models to probe the influence of a microphysics prescription, e.g. electron capture rates, EOS..



Pascal et al. 2020
Codes CoCoNuT, ACCEPT

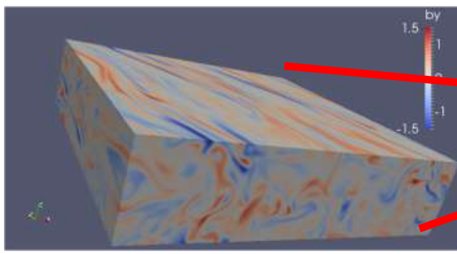
Idealized models to study hydrodynamical instabilities



Kazeroni et al 2018
Code RAMSES

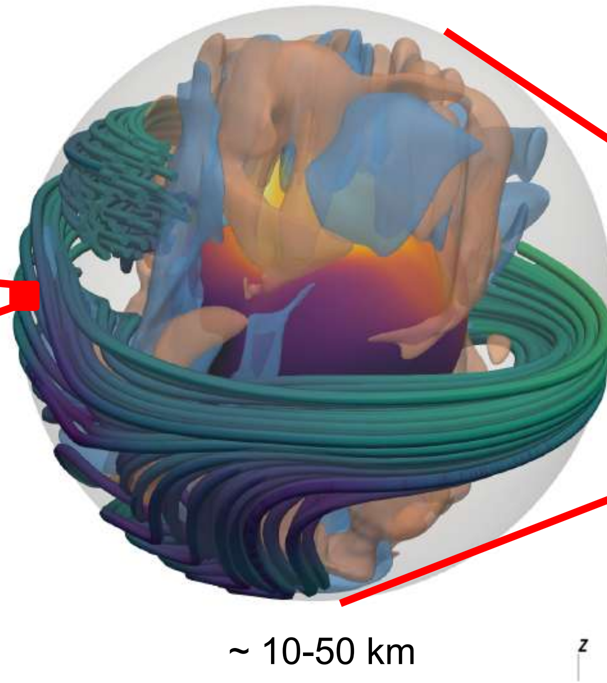
Magnetar as central engine of extreme explosions

Small turbulent scales
Code snoopy
(Lesur & Longaretti 2005)



~ 1-5 km

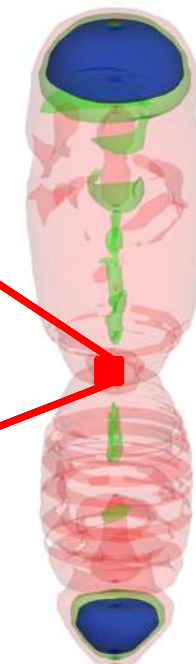
Convective dynamo
MagIC code :
https://github.com/magic-sph/magic



~ 10-50 km

Raynaud et al. 2020

Magnetorotational explosions
Code ALCAR,
Martin Obergaulinger



~ 10^3-10^5 km

Bugli et al. 2020

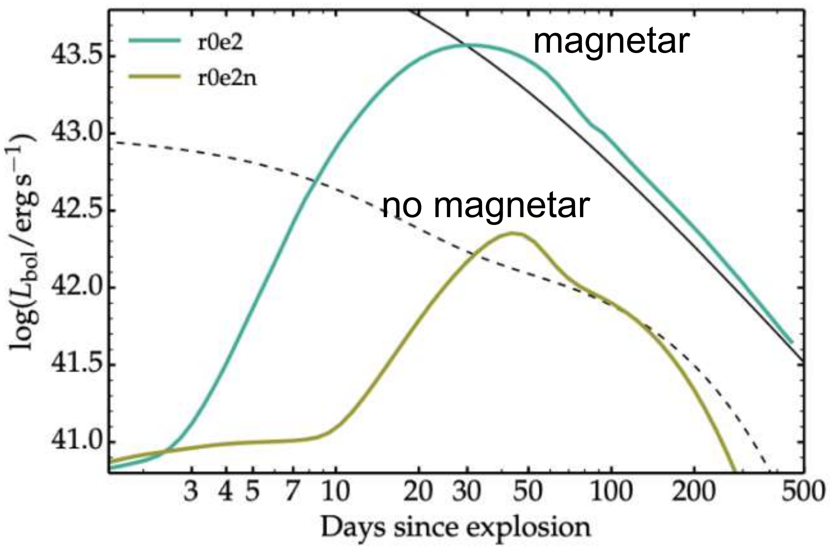
ERC starting grant MagBURST (PI : Jérôme Guilet)

Electromagnetic emission from supernovae

CMFGEN (Hillier & Dessart 2012), a state-of-the-art numerical tool for the modeling of radiative transfer in supernovae

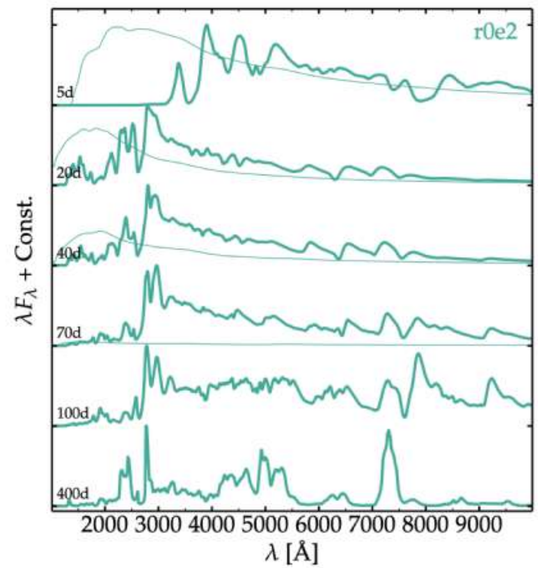
Magnetar-powered superluminous supernovae

Lightcurve

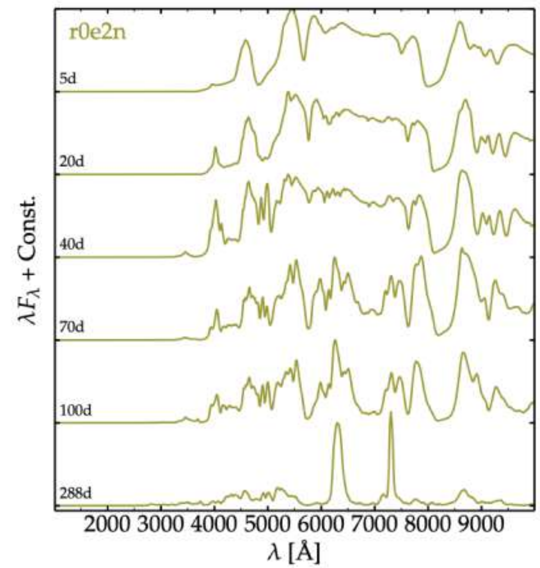


Spectra evolution

magnetar



no magnetar



Dessart (2019)

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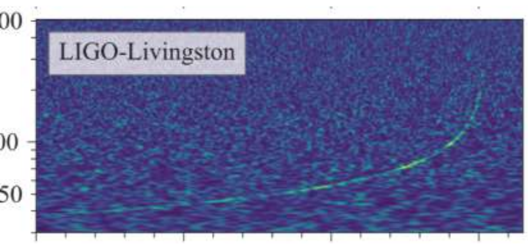
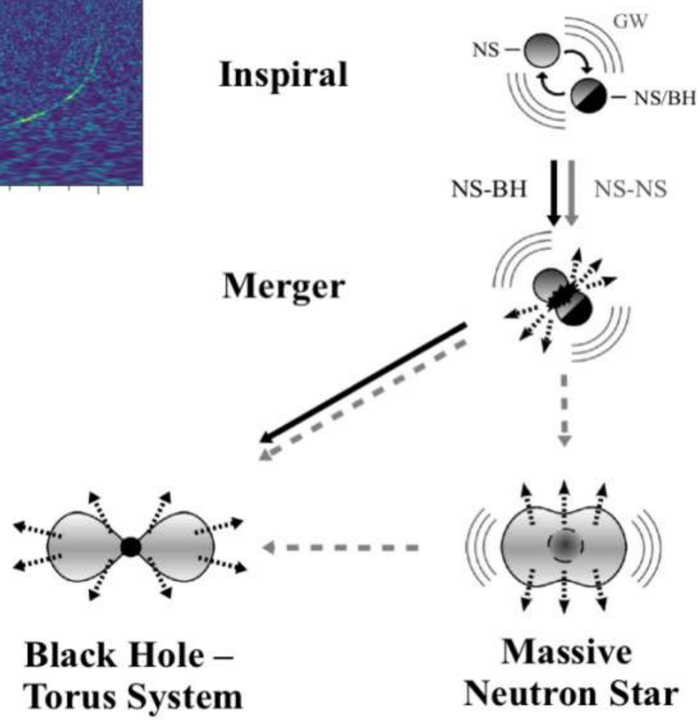
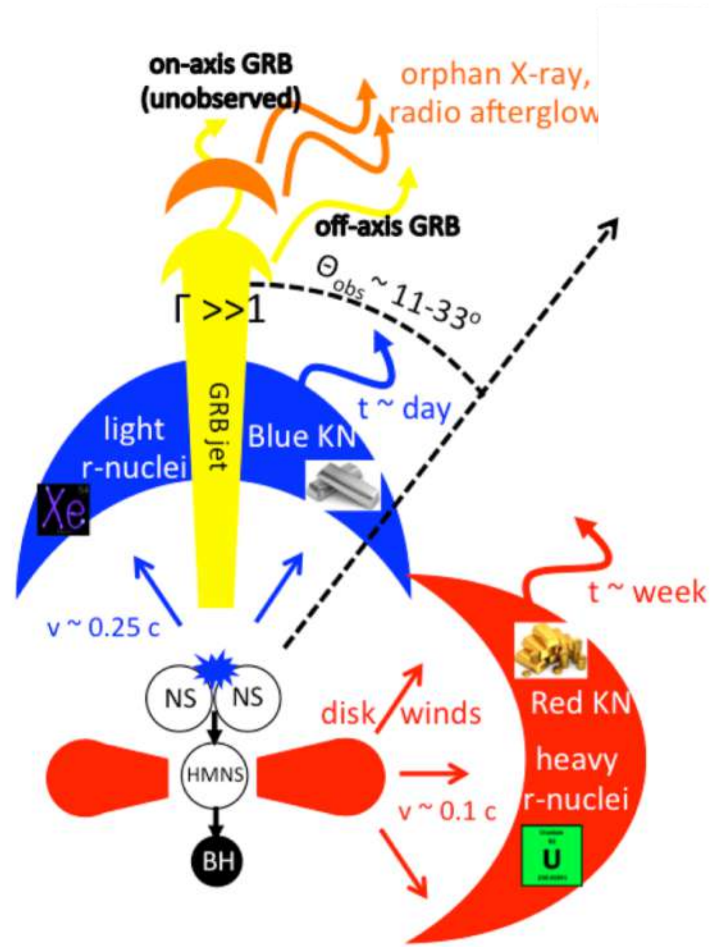
Neutron star mergers in the multimessenger era





Courtesy of Oliver Just



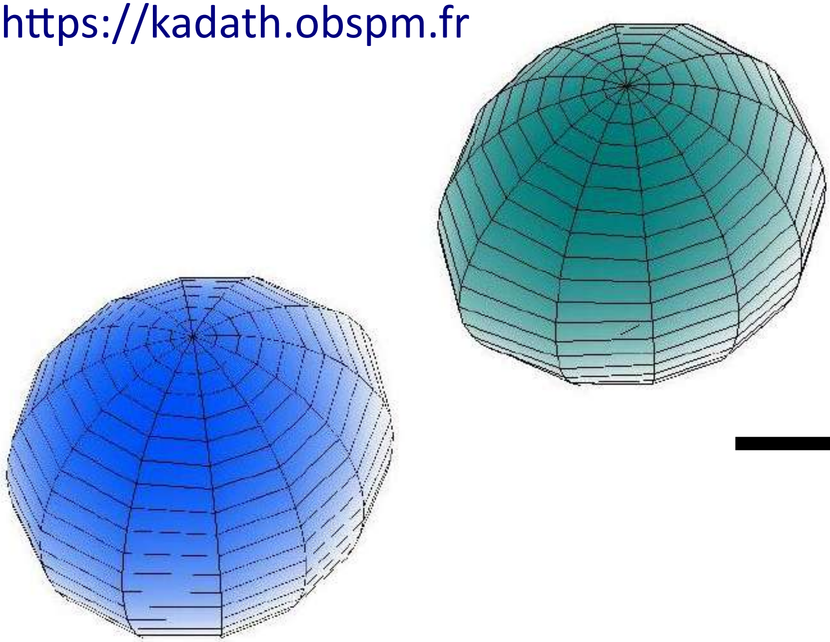
From Metzger (2017)

Neutron star mergers numerical modelling

Initial data computed using the LORENE and KADATH libraries

Grandclément (2010)

https://kadath.obspm.fr



Lack of expertise to simulate the merger itself in the french community

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Microphysics input for numerical models

Microscopic calculations cannot be made on the fly

CompOSE database : https://compose.obspm.fr

Unified format and framework

Community effort supported by COST actions NewCompStar and PHAROS

Alternative : analytic prescriptions of nuclear matter microphysical properties (e.g. the EoS) empirical parameters are constrained by experimental and observational data
Margueron et al (2018)

Conclusion

Very good expertise in simulations of :

- isolated neutron stars,
- instabilities in CCSN and proto-neutron stars,
- astrophysical signals from supernovae,
- link between microphysical and global modeling.

Large observational facilities will give more and more precise constraints:

- supernova electromagnetic signals : SVOM, Vera Rubin Observatory
- neutrino signals : SNEWS network
- gravitational waves : LIGO-Virgo-Kagra, Einstein telescope

High performance computing in the exascale era requires strong support:

- persistent support from computer technicians and engineers
- long term development of complex codes
- complete spectrum of HPC facilities available to researchers