"Relativity & Compact Objects" team: 2014-2015 report

Jérôme Novak, on behalf of the ROC team

Laboratoire Univers et Théories (LUTH)
CNRS / Observatoire de Paris / Université Paris-Diderot

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What is ROC?

Originally founded by Silvano Bonazzola & Jean-Alain Marck, with interests in:

- relativistic astrophysics,
- gravitational waves,
- numerical relativity,

it has grown and evolved with time.

$\Rightarrow$ 8 permanent researchers, 1 with fixed-term contract & 4 PhD students.

Newer research directions:

- solutions in classical field theory,
- properties of nuclear matter,
- alternative theories of gravity,
- ...

In the last couple of years...

- Microphysics for core-collapse supernovae
- Pulsars and neutron stars
- Hyperons in compact stars
- Gravitational waves
- Compact object binaries
- Rotating boson stars
- Scalar breathers
- SageManifolds *et al.*

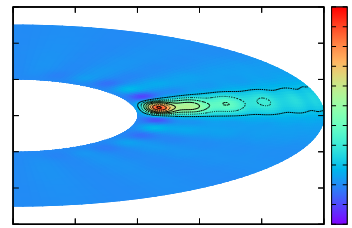
Core-collapse supernovae

S. Bonazzola, I. Cordero-Carrión, J. Novak,
M. Oertel & collaborators

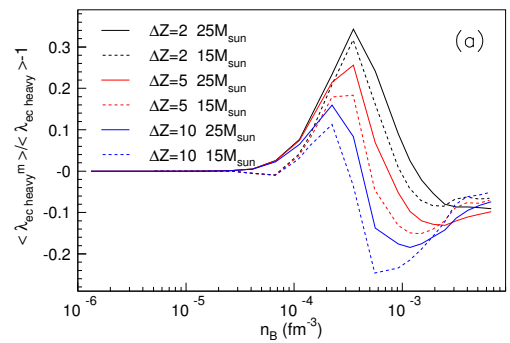
Study of local properties of matter for gravitational collapse of massive stars ($\gtrsim 10 M_\odot$):

$$p^+ + e^- \to n + \nu_e$$

- development of neutrino transport using spectral methods: GR effects taken into account ⇒first proof of principle, able to run on single-CPU in 6D (low resolution)
- study of the influence of the presence of more neutrons in nuclei onto the electron capture rates in core-collapse. Modification of nuclear structure and up to 30% of EC rate ⇒quite important impact on dynamics



Peres et al. (2014)



Raduta et al. (2015)

Hyperons in nuclear matter

M. Oertel & collaborators

Nuclear physics models prediction:

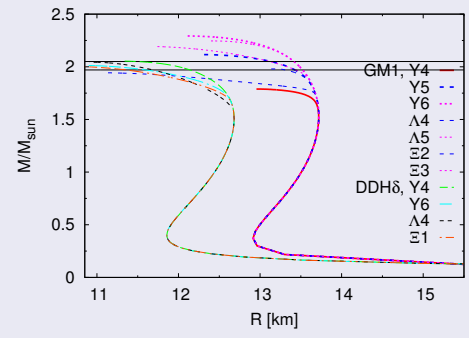
- hyperons appear at $n_B \sim 2 - 3n_0$,
- maximum neutron star masses of $\sim 1.4 M_\odot$

$\Rightarrow$need short-range repulsion to stiffen the equation of state:

- With quark matter appearing early (very early!) enough,

- Modify the interaction
  - In microscopic models (BHF) this seems to be a problem
  - In phenomenological models not difficult
    Here: different RMF models for NS with hyperons
    - Maximum masses above $2M_\odot$
    - Large range of radii for intermediate mass stars
    - Considerable hyperon fraction in NS

Two RMF models with different hyperonic interactions



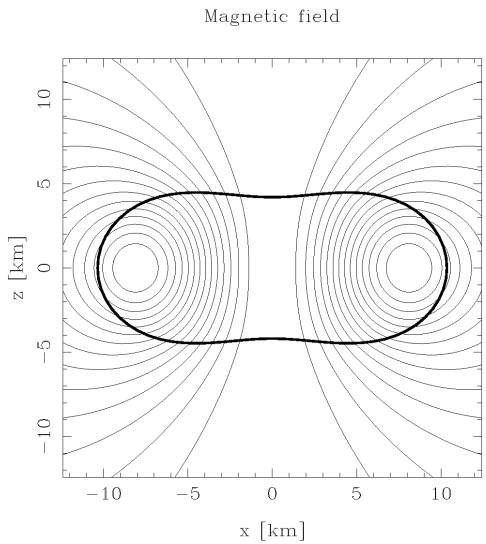
Oertel et al. (2015)

Magnetic field in neutron stars & around pulsars

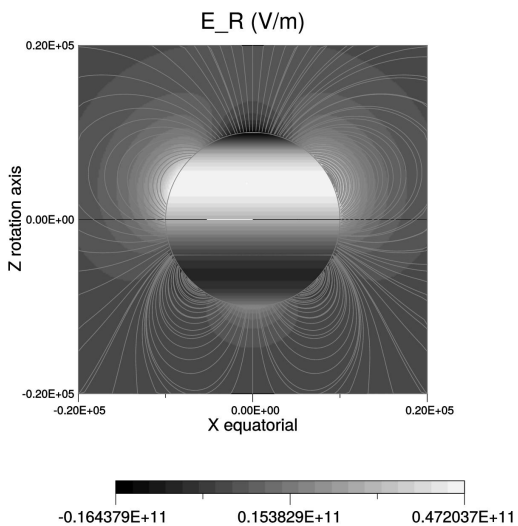
S. Bonazzola, D. Chatterjee, E. Gourgoulhon, J. Novak, M. Oertel & collaborators

New numerical models with magnetic field in neutron stars:

- Mixed poloidal-toroidal magnetic field configurations: formalism & first numerical application in Uryū *et al.* (2014).
- Inclusion of magnetization and magnetic field-dependent equation of state in global models by Chatterjee *et al.* (2015).



Chatterjee et al. (2015)



Bonazzola et al. (2015)

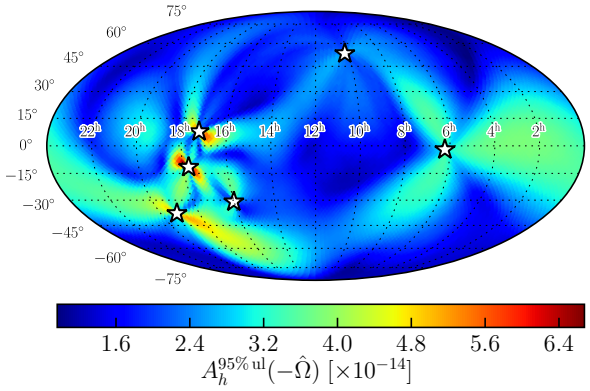
Generalised multipole solution for a rotating star with a magnetic field (Bonazzola *et al.* 2015):

- multipole expansion of electric and magnetic fields around a rotating star (without plasma)
- Explicit form of the solution ⇒current closure in pulsar magnetospheres ?

Pulsar Timing Array

G. Theureau & collaborators

Limits on supermassive black hole binary gravitational wave background from European Pulsar Timing Array



Taylor et al. (2015)

- millisecond pulsars used as probes (clocks) for the detection of nanohertz gravitational waves
- mostly looking at supermassive black hole binaries, which may be few and give anisotropic background

⇒study with more general techniques to take into account possible anisotropy.
⇒strain amplitude for $\ell > 0$ (spherical harmonics) lower than 40% of the monopole value.

Combination with galaxy catalogues?

Compact object binaries

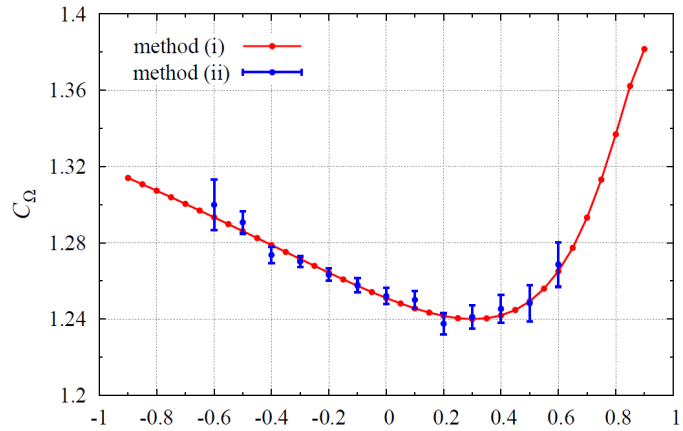
A. Le Tiec & collaborators

Computations of gravitational waveforms need high-accuracy description of the binary orbits.

- Comparison between post-Newtonian and self-force approximations for binary black hole problem.
- Further link perturbative approach / numerical results: unexpectedly good agreement for equal-mass binaries.
- "First law of mechanics" for black hole binaries: fundamental relations between physical quantities allowing for better analytic model (EOB).

Example:

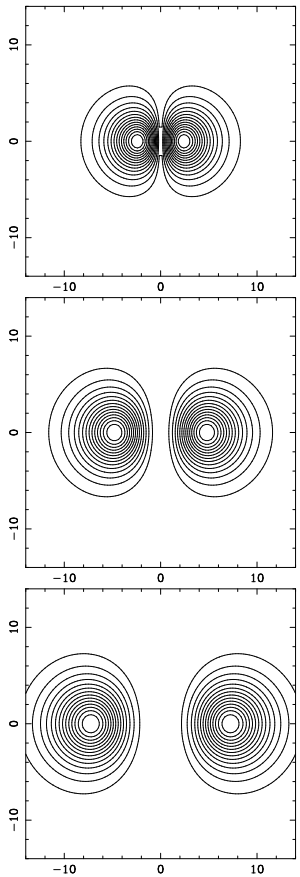
Computation of gravitational self-force for a particle around a Kerr black hole
$\Rightarrow$shift in the frequency of the innermost stable circular orbit.



Isoyama et al. (2014)

Rotating boson stars

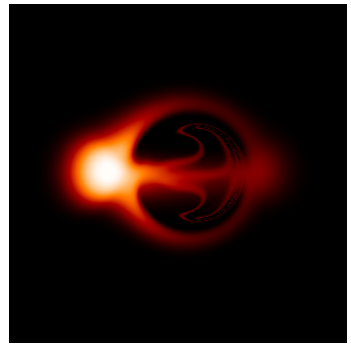
É. Gourgoulhon, Ph. Grandclément, C. Somé & collaborators



Self-gravitating complex scalar field in general relativity:

- Stationarity and axisymmetry of the spacetime.
- Ansatz on the scalar field: $\Phi = \phi\,(r,\theta)\exp\left[i\,(\omega t - k\varphi)\right]$.
- Choice of scalar field potential $V\left(|\Phi|^2\right)$: free field, additional repulsive term or solitonic.

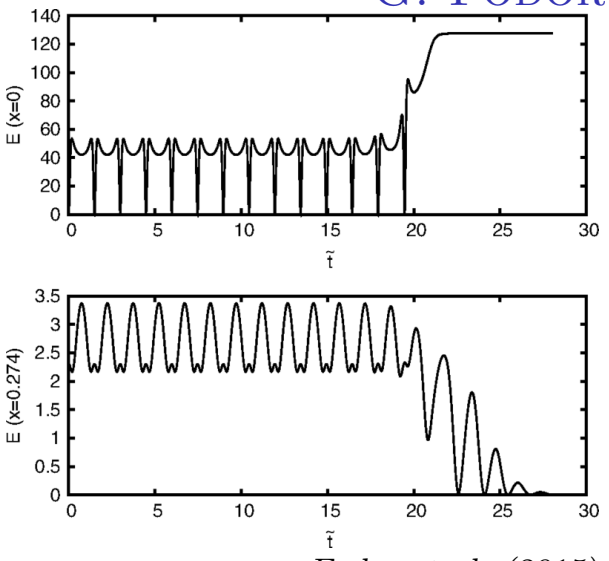
$\Rightarrow$alternative model to black hole for the central region of our Galaxy (tests with GRAVITY);
$\Rightarrow$computation of accretion torus images, to see possible observable differences with black holes



Vincent et al. (2016)

Scalar breathers

G. Fodor, Ph. Grandclément & collaborators



Fodor et al. (2015)

Scalar field soliton-like configuration in anti-de Sitter (AdS) spacetime or self-gravitating asymptotically AdS in D-dimensions.
$\Rightarrow$spatially localized, spherically symmetric & time periodic solutions

"self-gravitating scalar breathers"

- Kadath library: spectral methods both in space and time (Fourier transform), to build initial models
- discrete family of solutions, labelled by their frequency
- time evolution to look for stability $\Rightarrow$unstable branch beyond critical central density

SageManifolds

É. Gourgoulhon & collaborators

- Package used with the mathematics software **SageMath**
- Implements differential geometry and tensor calculus on real differential manifolds of arbitrary dimension.

- Deals with tensor fields and not tensor components: various charts can be used, with corresponding representations of the tensor
- Written in Python under GNU Public License

⇒currently being integrated into SageMath and tensor calculus made parallel (M. Mancini)

⇒new version 0.9, see **http://sagemanifolds.obspm.fr**

Open numerical tools

Everyboby?

Longstanding tradition of opening our numerical projects to the whole community (and beyond):

- LORENE: solving Einstein equation, spectral methods & spherical coordinates; open source and freely downloadable since 2001.
- `Kadath`: inspired from LORENE, more flexible in geometries and physical problems; able to run on 100's of CPUs.
- `Gyoto`: orbits and ray-tracing computations in analytic or numerical GR spacetimes (F.H. Vincent, T. Paumard, LESIA).

CoCoNuT

General relativistic code for core-collapse supernova simulations
⇒parallel version (thanks to that of LORENE) running up to 512 CPUs (F. Roy, P. Cerdá-Durán & J. Novak).

CompOSE

Online database with equations of state tables for astrophysics, nuclear physics, ...
⇒operational and publicly accessible
⇒European effort within *(New)CompStar* frameworks (J.-Y. Giot, T. Klähn, M. Oertel & S. Typel)

All these servers are maintained by LUTH ...
Strong support from the LUTH computer team!

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What's next?

Young researchers

- new member: Jean-Philippe Bruneton ⇒alternative theories of gravity and alternative models to black holes.
- Miguel Marques ⇒rotating, hot neutron star models with realistic equation of state
- Grégoire Martinon ⇒numerical models of self-confined gravitational waves (geons)...Models for dark matter?
- Aurélien Sourie ⇒glitches from superfluid models & gravitational waves from oscillating neutron stars.
- Daniela Pérez ⇒black hole mimickers, avoiding the formation of a singularity.

Collaborations with other teams

- Zakaria Meliani ⇒accretion disks and tori around boson stars.
- ...


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