"Relativité et objets compacts"

Micaela Oertel, on behalf of the ROC team

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CNRS / Observatoire de Paris/ Université de Paris

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What is ROC about ?

"Relativity and compact objects" : scientific interests

- Compact objects : black holes, neutron stars and white dwarfs
  - astrophysical sources of gravitational waves
  - tests of gravitation, alternative theories of gravity
  - properties of ultra-dense and hot matter
- Solutions in classical field theory and gravitation
- Cosmology (structure formation, dark energy, cosmic acceleration)
- Exoplanets and astrometry (Plato, Theia, ...)

Mainly numerical and theoretical modelisation, but strong link to observations

Development of open source numerical tools

- Numerical libraries `LORENE`, `KADATH`
- Ray-tracing code `GYOTO`
- Computer algebra system `SageManifolds`
- Equation of state data base `Compose`

Interaction with the LUTH computer team : S. Auliac, F. Roy, M. Servillat, S. Méné

Composition of the ROC team

Permanent researchers (01/09/2021)

- Jean-Michel Alimi (CNRS, section 17)
- Laura Bernard (CNRS, section 02)
- Éric Gourgoulhon (CNRS, section 17)
- Philippe Grandclément (CNRS, section 02)
- Alexandre Le Tiec (CNRS, section 17)
- Jérôme Novak (CNRS, section 17)
- Micaela Oertel (CNRS, section 02/17)
- Jean Schneider (CNRS, émerite)
- Gilles Theureau (Astronome)

PhD students (01/09/2021)

- Rémy Koskas
- Jordan Nicoules
- Gaël Servignat
- Majd Shalak
- Lami Suleiman (co-tutelle)
- David Trestini (co-tutelle)

Recent PhD defenses

- Aurélien Pascal et Paul Ramond 2021
- Karim Van Aelst 2020

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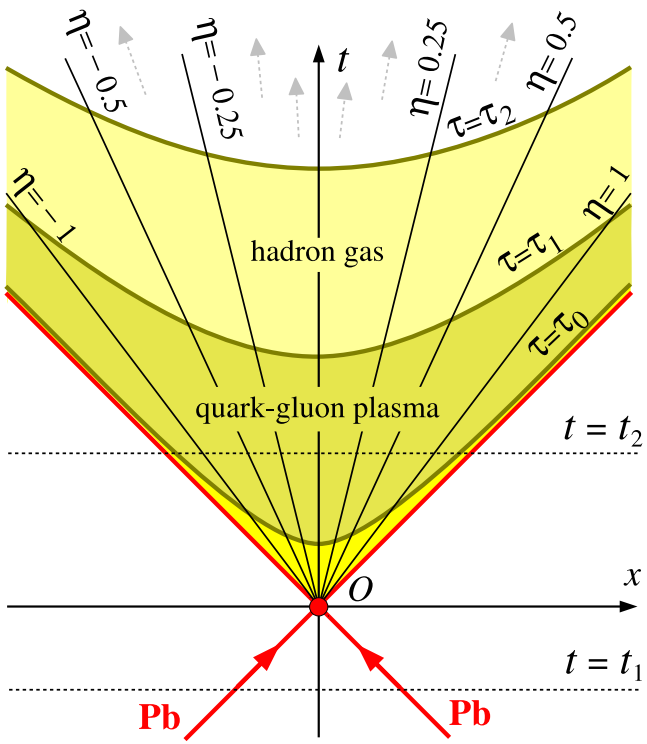
Some recent highlights

Quark-gluon plasma in the gauge/gravity duality



Spacetime diagram of a heavy-ion collision (LHC)

$\tau_0 \simeq 0.2$ fm$/c = 6\ 10^{-25}$ s

$\tau_1 \sim 10\tau_0$

Quark-gluon plasma in heavy-ion collisions (LHC)

strongly coupled plasma behaving as a low-viscosity fluid (non-central collisions $\Longrightarrow$ rotating fluid)

Gauge/gravity duality (holography ; AdS/CFT)

4D strongly-coupled gauge theory $\equiv$ 5D gravitation

Gauge theory : high-temperature QCD

$\approx \mathcal{N} = 4$ supersymmetric Yang-Mills theory

Gravity : 5D Kerr-AdS spacetime (rotating BH)

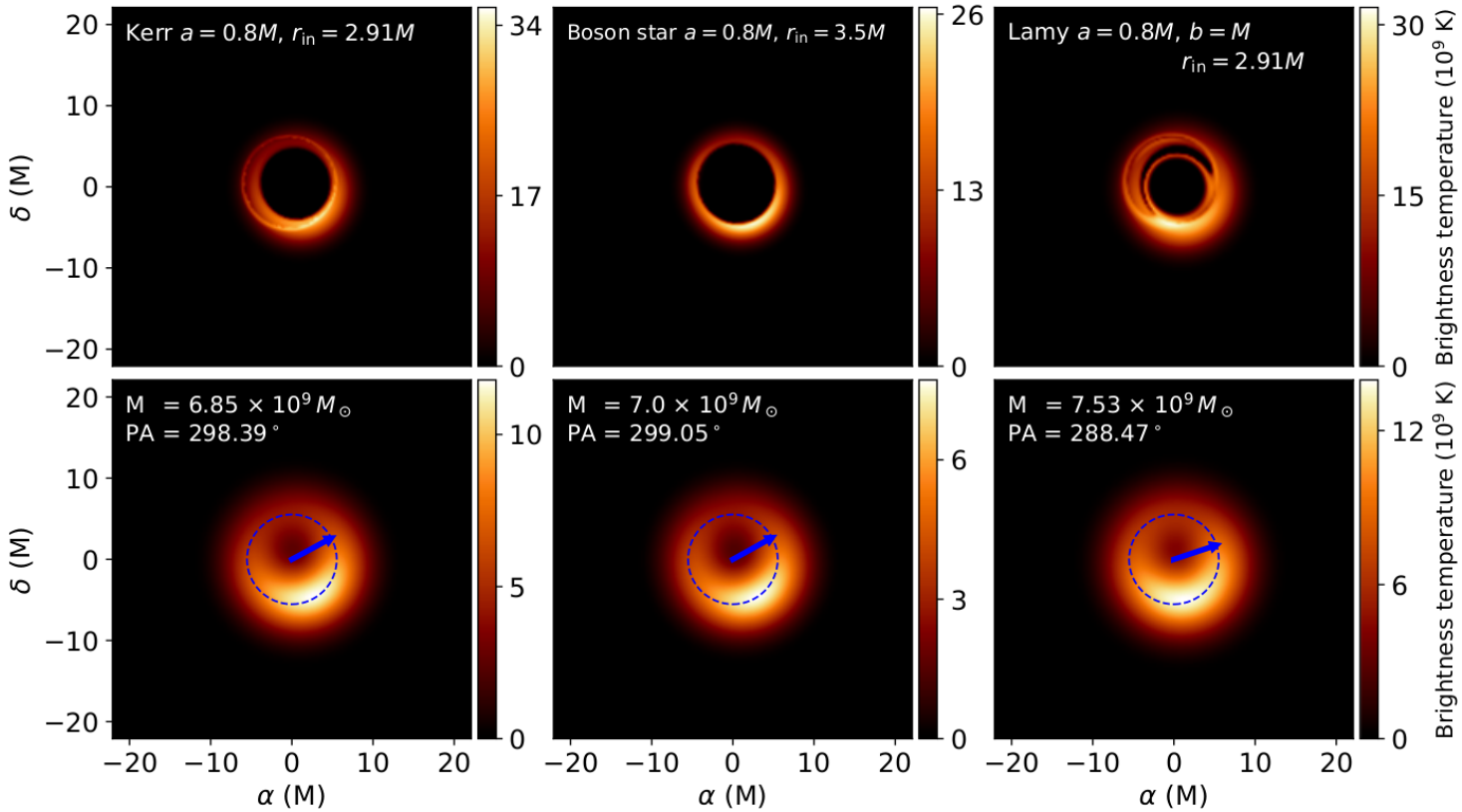
Energy loss of a heavy (b or c) quark

- observed via the phenomenon of *jet quenching*
- computed via the dynamics of a Nambu-Gotto string in Kerr-AdS, using `SageManifolds` tools

[Aref'eva, Golubtsova & Gourgoulhon, JHEP **04(2021)**, 169 (2021)]

[Golubtsova, Gourgoulhon & Usova, Nucl. Phys. B, submitted [arXiv:2107.11672]]

Interpreting the EHT image of the black hole M87*



← computed images

← images blurred at EHT resolution

Images best fitting 2017 EHT data for a geometrically thick and optically thin accretion disk around a Kerr BH, a boson star and a Lamy wormhole.

$\Longrightarrow$ better data are required to test the Kerr black hole hypothesis

[Vincent, Wielgus, Abramowicz, Gourgoulhon, Lasota, Paumard & Perrin A&A **646**, A37 (2021)]

Dynamics of compact binaries

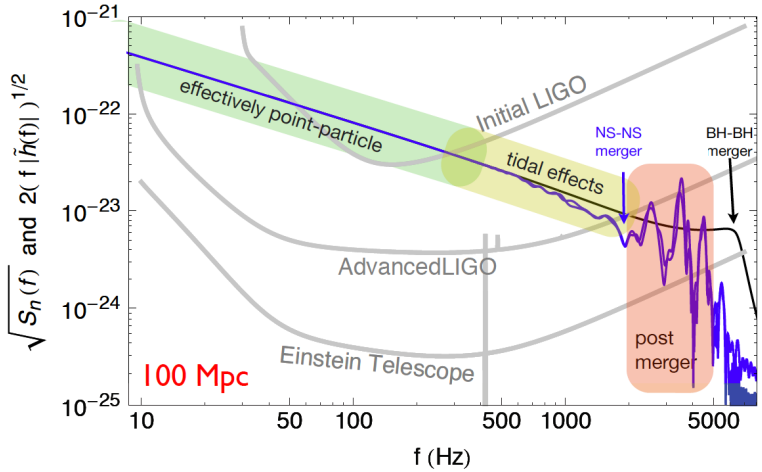
Studies in general relativity and alternative theories

- Post-Newtonian computations to high order → gravitational waveforms

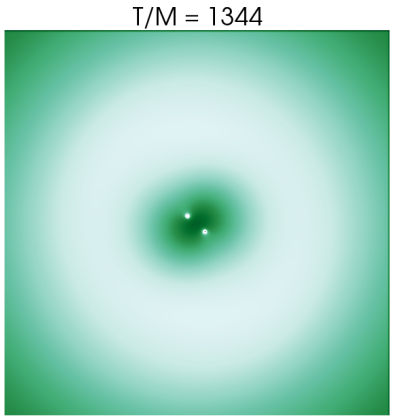
  [Bernard PRD 101 (2020) 021501],

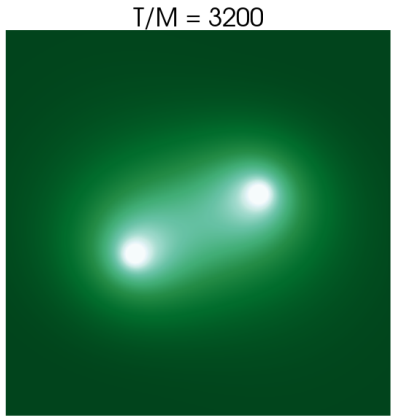
  [Bernard, Blanchet,Trestini, in prep]

- Black holes fall in Love (→ talk by Alexandre Le Tiec)



[ET science case, courtesy J. Read]



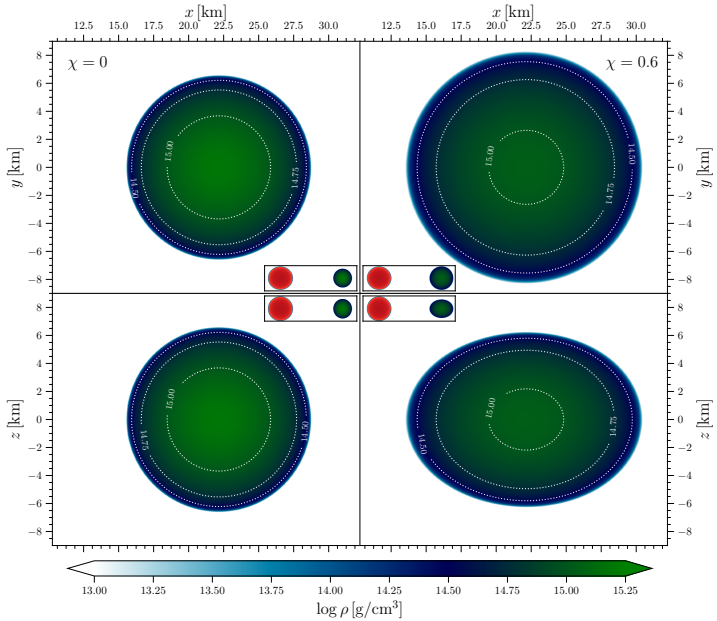


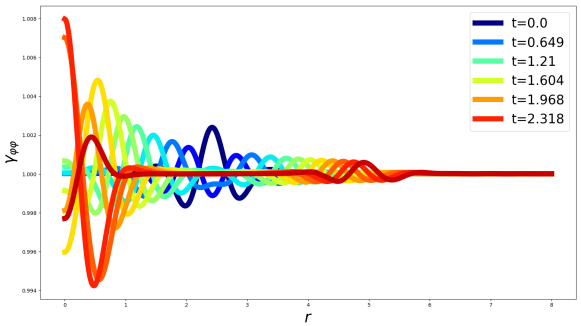
- Evolution of fundamental fields in the vicinity of a compact binary : gravitational molecules

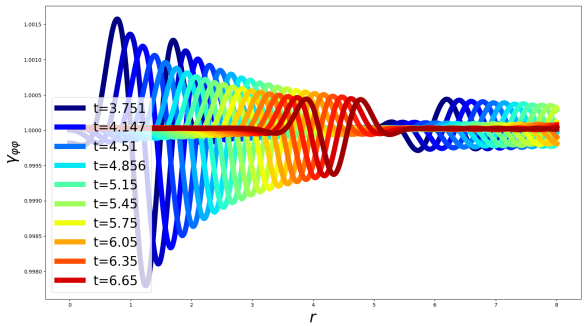
  [Ikeda, Bernard,Cardoso, Zilhão, PRD 103 (2021) 024020]

- Initial data for numerical simulations of binary evolutions
  - LORENE : quasi-equilibrium solutions for all types of binaries, but constraints on masses and spins
  - New public code based on KADATH : unequal mass-spinning binaries

    [Papenfort, Tootle, Grandclément, Most, Rezzolla, PRD 104 (2021) 024057]





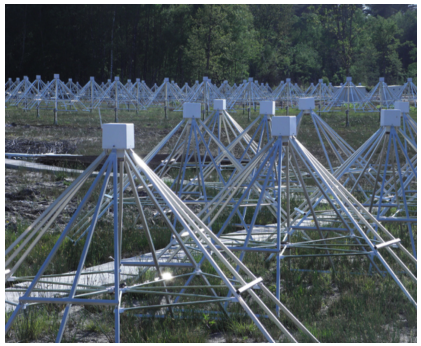


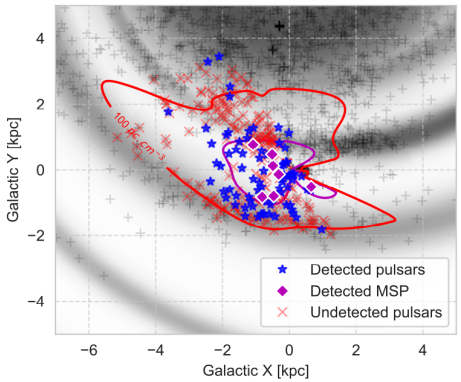
- Modular evolution code in general relativity (and alternative theories)

  [Nicoules, Grandclément, in preparation]

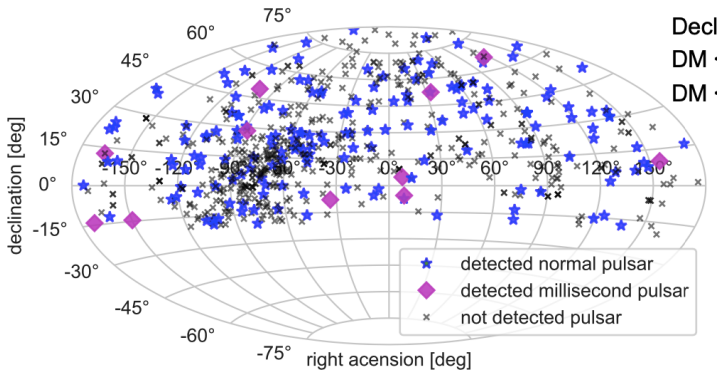
Pulsar studies

Multi-λ studies and constraints on magnetosphere emission models :
search for low frequency emission in known pulsars with NenuFAR (10-85 MHz) and characterisation of the spectral turn-over





Pulsar census

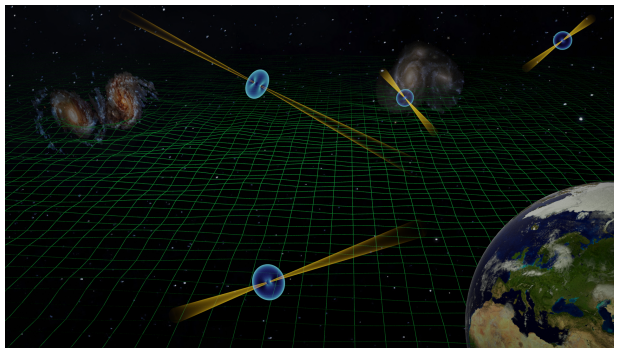


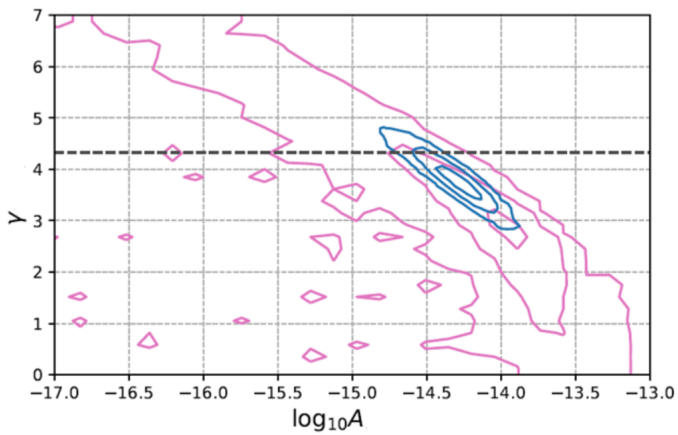
Declination > -20°
DM < 100 pc cm^{-3}
DM < 30 pc cm^{-3} for MSPs

Bondonneau et al. (in prep)

711 pulsars observed ~25 mJy
184 pulsars detected

~100 new detections below 100 MHz





[Chen+, MNRAS 508 (2021) 4970]

Towards the Detection of the nHz gravitational wave background : The European Pulsar Timing Array provides a significant step forward

(Binary) neutron star modelling

GW emission from BNS, BHNS mergers, CCSN, and NS bears information about internal structure and dense matter properties ; possible multi-messenger signal

- New limits on $M_{\rm TOV}$ from GW170817 including finite temperature effects in the EoS

[Khadkikar, Raduta, Oertel, Sedrakian, PRC 103 (2021) 055811]

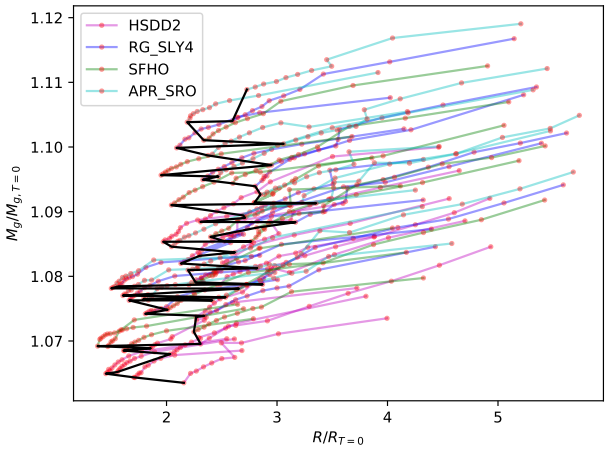
- Proto-neutron star evolution :
  - GW emission allows to determine M and R, but difficult to disentangle different EoS

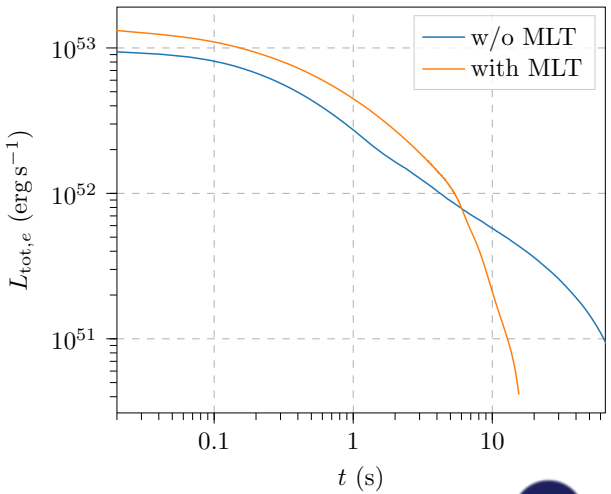
[Préau, Pascal, Novak, Oertel, MNRAS 505 (2021) 939]

  - Convection very efficient →clear break in neutrino luminosities

[Pascal, Novak, Oertel, submitted]

- Partially accreted crusts of neutron stars → talk by Lami Suleiman





Physics inspired machine learning techniques in cosmology

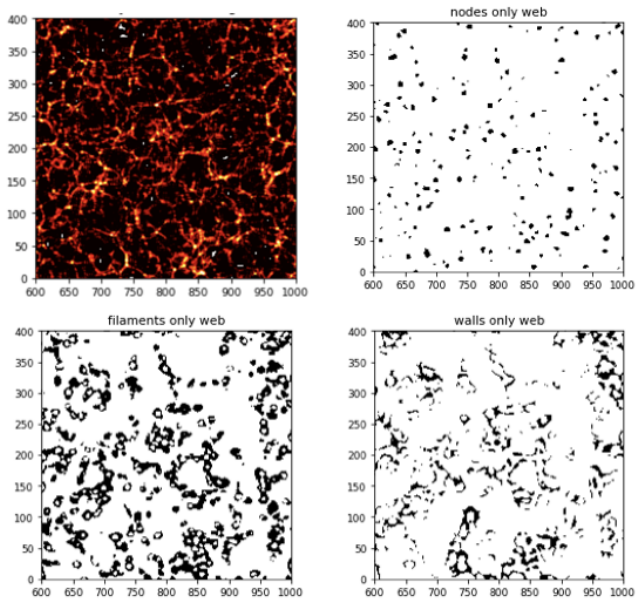
Idea : learning as a substitute for cosmological numerical simulations, exploit the capacity of a program to learn from "data"

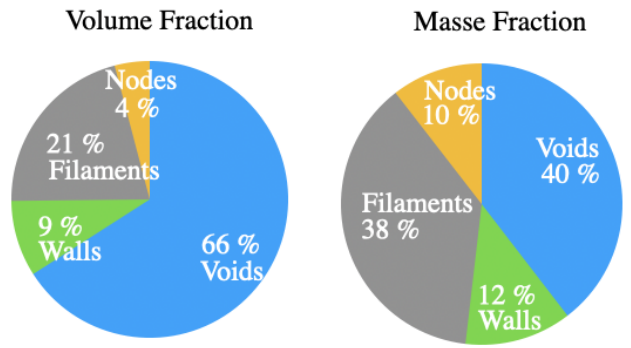
"Data" : observations, experiments, computations, . . .

- Sensitivity of the result according to the input and the learning process
- Applications : [Koskas, Alimi et Alimi, Koskas, in preparation]
  - Possibility to explore the dependence on the formation of the cosmic web on density parameter, theory of gravity, equation of state, . . .
  - Identification of cosmological model from dark matter halos

RPCDM/ΛCDM

	TriAxial	Spherical
Masses	66	63
Masses + Trace(M)	71	65
Masses + a_M+b_M+c_M	71	67
Masses + a_M+b_M+c_M + Trace (V)	73	68
Masses + a_M+b_M+c_M +a_V+b_V+c_V	74	68
Masses + a_M+b_M+c_M + Trace(J)	72	67
Masses + a_M+b_M+c_M + a_J+b_J+c_J	72	68
Masses + a_M+b_M+c_M +a_V+b_V+c_V + a_J+b_J+c_J	74	68
Trace (V)	64	61
Trace(J)	59	57





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Summary

The ROC team

works mainly on the numerical and theoretical modelisation of compact objects and on gravity with a strong link to observations (LISA, ET, Virgo, Gravity, PTA, SKA, ...).
Much effort is devoted to development of open source numerical tools, too.

Future directions :

- Fundamental physics with compact objects and gravitational waves
  - Properties and structure of compact objects (BH, NS, and alternatives)
  - Tests of the theory of gravity
  - Properties of dense nuclear matter
- Implication in GW detectors : Virgo (since 2021), preparation of LISA and ET (horizon 2035), PTA

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