INAF - Osservatorio Astronomico di Padova

Istituto Nazionale di Fisica Nucleare
Sezione di Padova

Ministero degli Affari Esteri
e della Cooperazione Internazionale

Ministero
dell'Università
e della Ricerca

Modelling binary neutron star mergers and GRB jets via numerical simulations

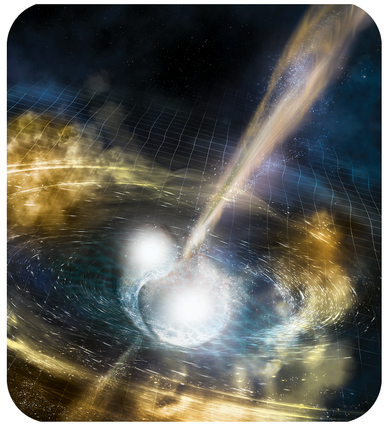
Riccardo CIOLFI, Andrea PAVAN, Matteo PAIS (INAF-OAPd)

Emma DREAS (SISSA), Jay V. KALINANI (RIT)

OAPd days
27th June 2024

Astrophysics and fundamental Physics with BNS mergers

short gamma-ray bursts



jet formation / central engine

jet breakout and propagation

prompt and afterglow emission
(at different viewing angles)

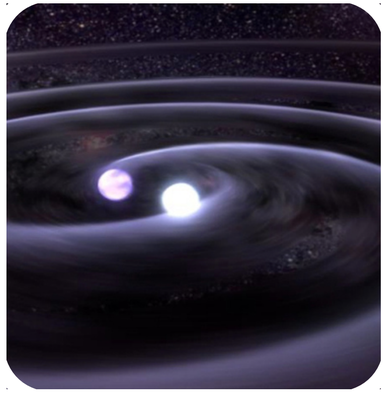
origin of heavy elements

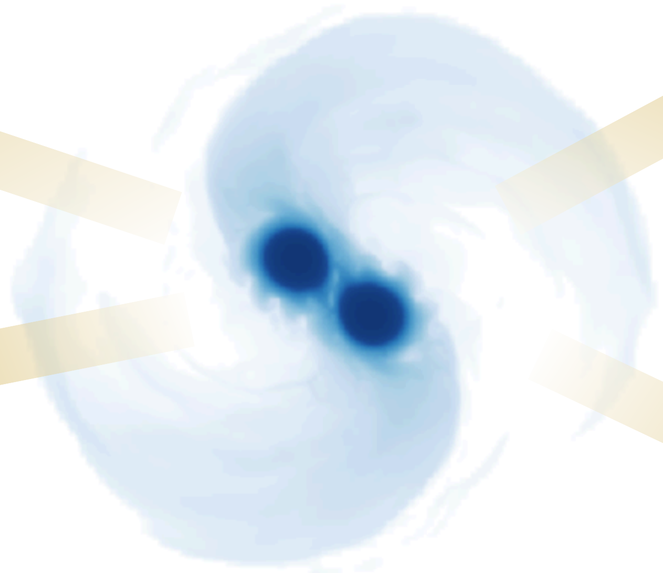
mass ejection mechanisms

r-process nucleosynthesis

radioactively-powered kilonovae

gravitational waves

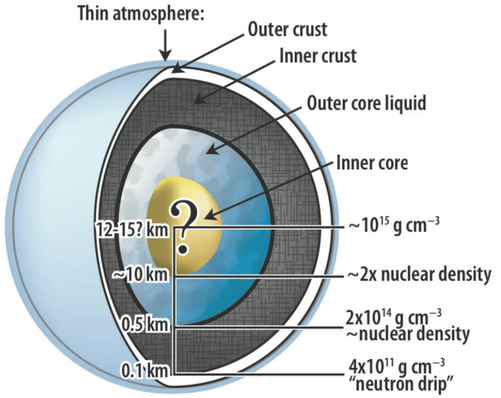




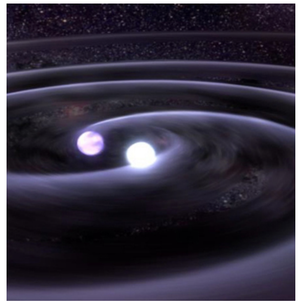
MERGING BINARY NEUTRON STAR SYSTEM

EOS of supranuclear matter

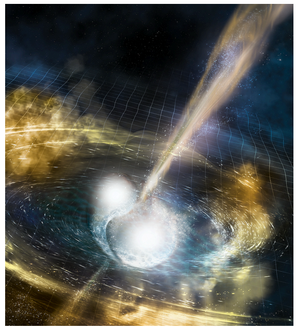
GW and multi-messenger constraints



GW170817: multi-messenger observation of a BNS merger

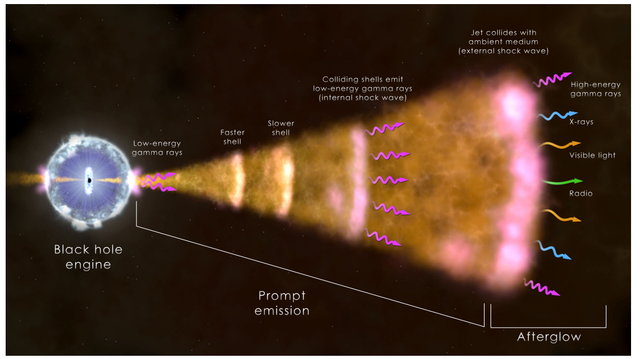


merger
gravitational wave signal



short GRB
GRB 170817A

BNS mergers can launch relativistic jets and produce short GRBs



X-ray afterglow

radio afterglow

t0 +1.7 sec +10.87 hours +9 days +16 days

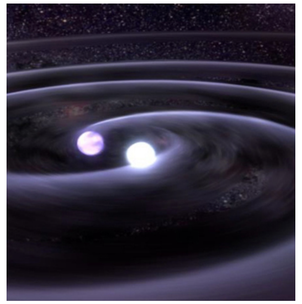
constraints on neutron star EOS and Hubble constant

optical counterpart

kilonova
AT 2017gfo

BNS mergers are ideal sites for r-process nucleosynthesis

GW170817: multi-messenger observation of a BNS merger



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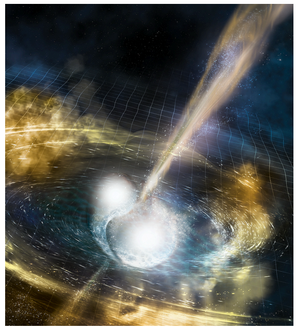


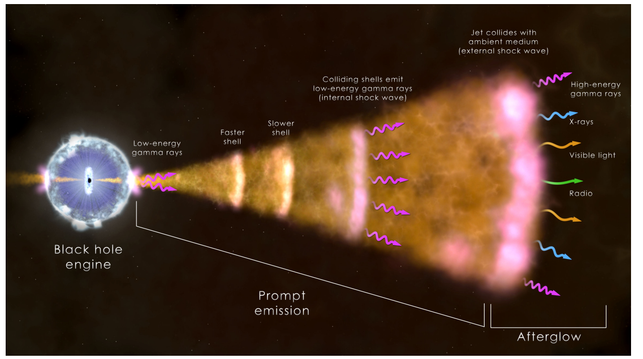
short GRB
GRB 170817A

BNS mergers can launch relativistic jets and produce short GRBs

jet launching mechanism?

jet launching time?

central engine:
neutron star or black hole?



X-ray afterglow

radio afterglow

t0 +1.7 sec +10.87 hours +9 days +16 days

constraints on neutron star EOS and Hubble constant

large uncertainties
also due to incomplete
theoretical scenario

optical counterpart

kilonova
AT 2017gfo

BNS mergers are ideal sites for r-process nucleosynthesis

mass ejection mechanisms?

which ejecta components?

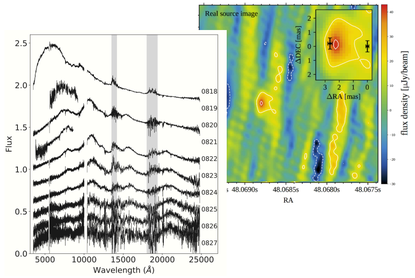
which elements? amount?

Our MAIN GOAL

building a solid theoretical framework for the interpretation of BNS merger events

based on relativistic MHD simulations
of both the merger process and the emerging short GRB jets

complementary to INAF observational effort and leadership
(e.g., 170817 breakthrough papers Pian+2017, Ghirlanda+2019)



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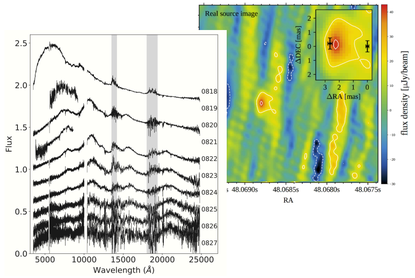


Current group composition

Riccardo Ciolfi
(OAPd)

Andrea Pavan
(postdoc, OAPd)

Matteo Pais
(postdoc, OAPd)

Emma Dreas
(PhD, SISSA)

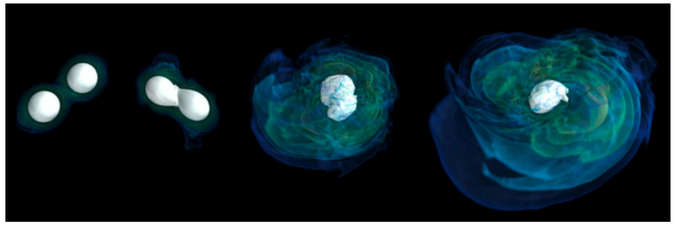
Jay V. Kalinani
(postdoc, RIT)

Key collaborators

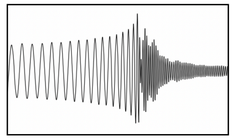
Bruno Giacomazzo (Uni Milano-Bicocca)
Albino Perego (Uni Trento)
Manuela Campanelli (Rochester Inst. Tech.)
Andrea Mignone (Uni Torino)
Om Sharan Salafia (INAF-OAB)

Investigation channels

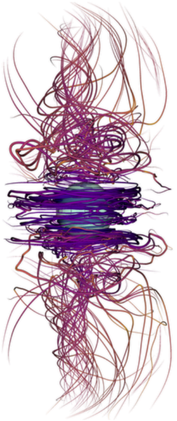
BNS (or NS-BH) mergers
GRMHD simulations



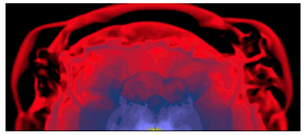
GW signal



magnetic field amplification
and **jet formation**



mass ejection



kilonova modelling

Investigation channels

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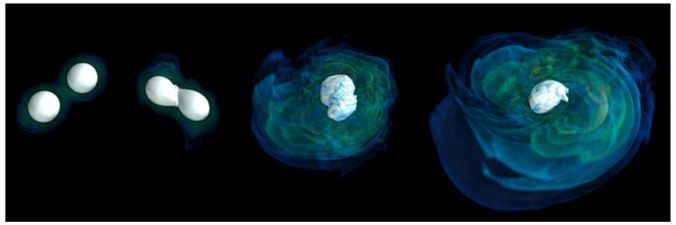

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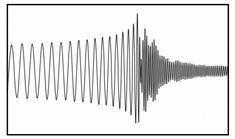

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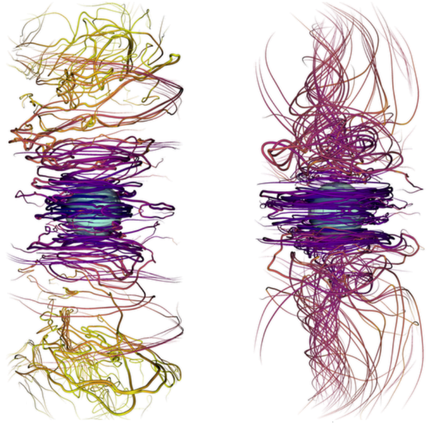

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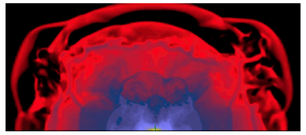
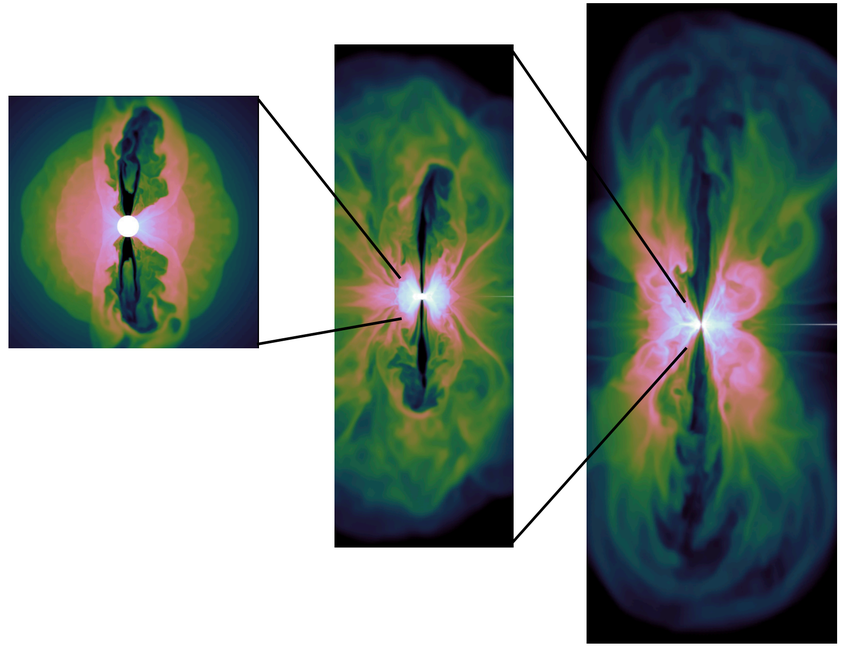


kilonova modelling

short GRB jet propagation
in realistic post-merger environments
relativistic MHD simulations



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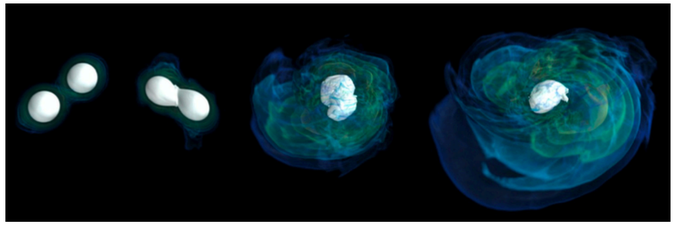

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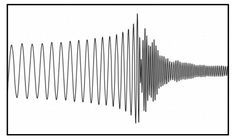

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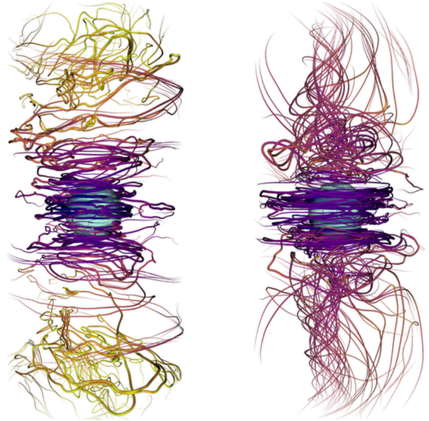

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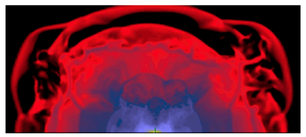

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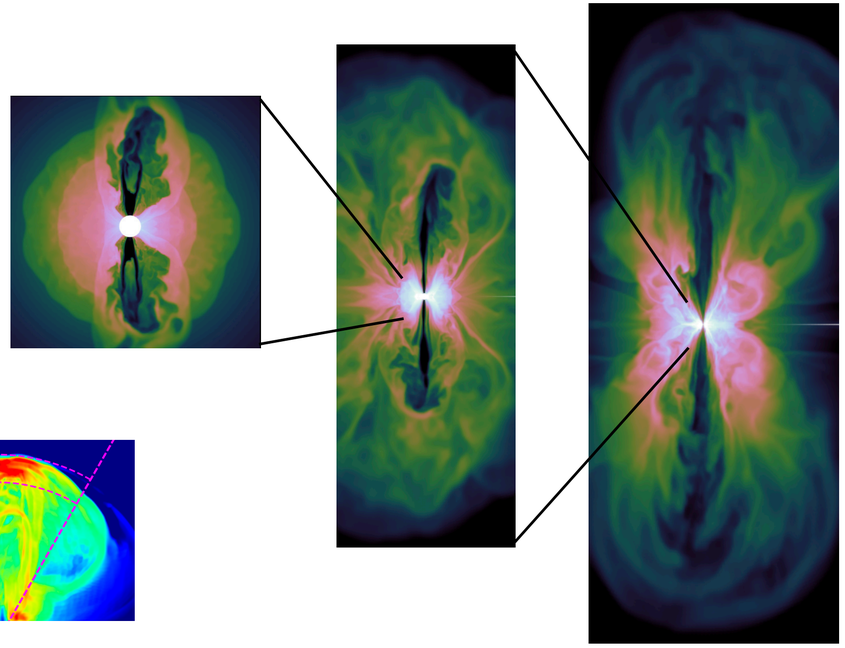
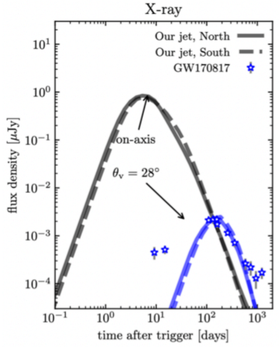
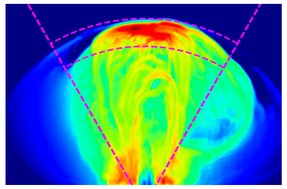


+ jet EM signatures:
afterglow and jet breakout





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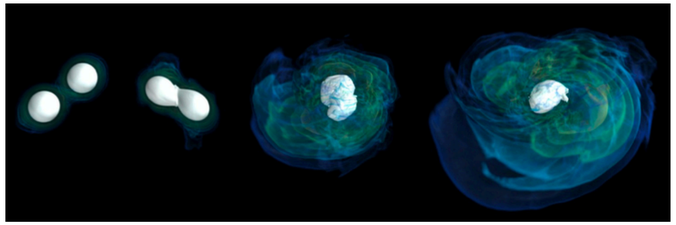

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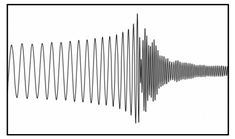

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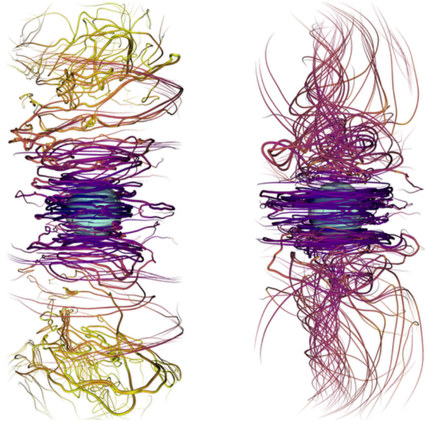

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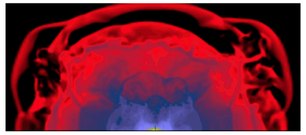

kilonova modelling

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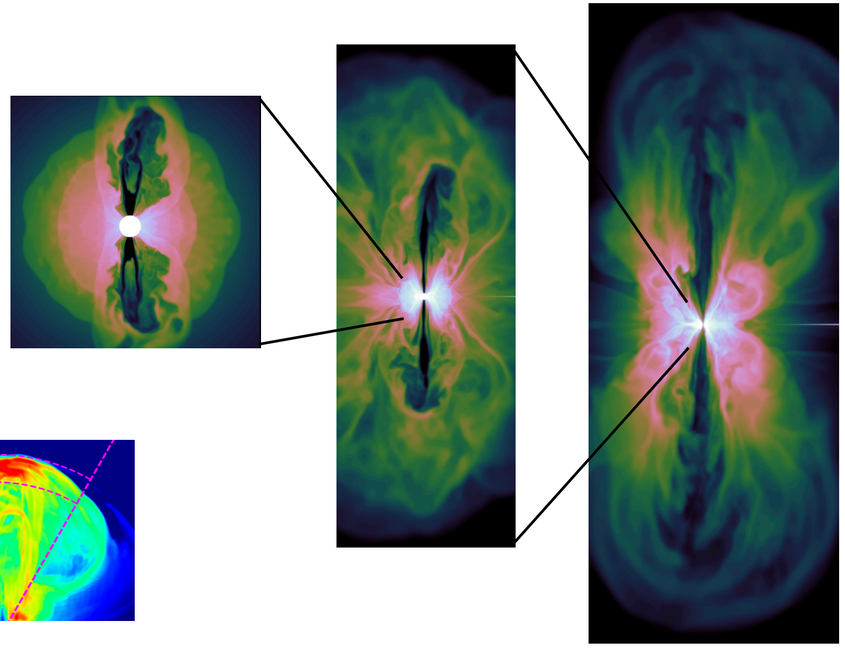

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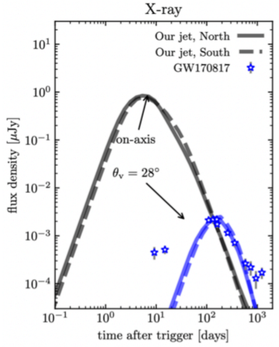
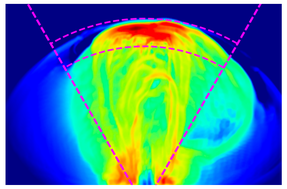
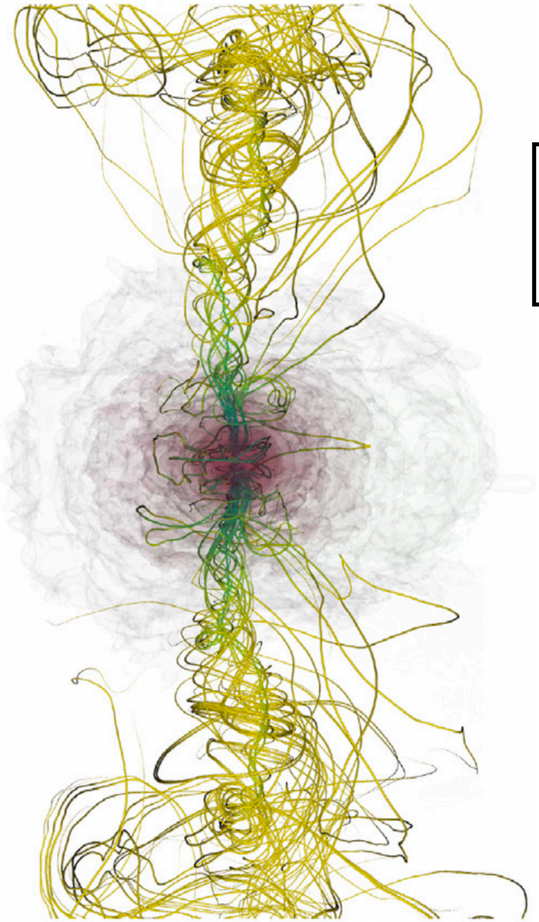




end-to-end description
from inspiral to EM signals

Scientific highlights: BNS merger simulations

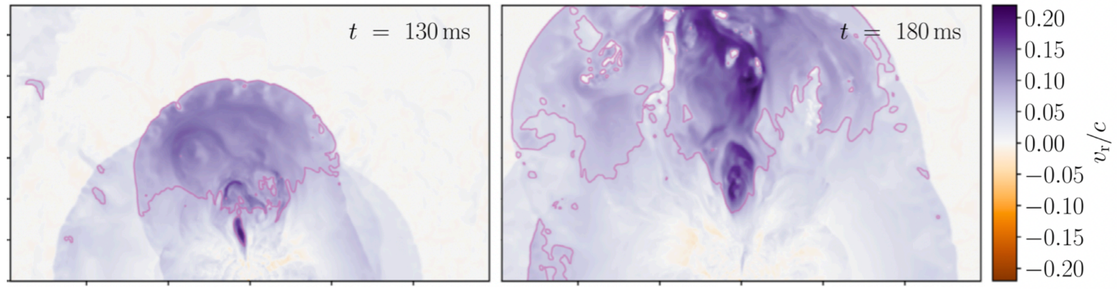
- first systematic investigation of long-lived remnant neutron star scenario in presence of magnetic fields
- at the time, longest GRMHD simulations of magnetized BNS mergers



Ciolfi 2020a
MNRAS Letters

collimated outflow from
massive neutron star remnant

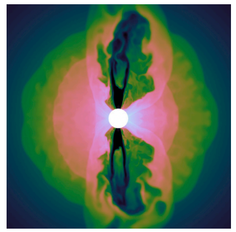
not enough powerful for a short GRB
⟶ BH engine favoured



Ciolfi & Kalinani 2020
ApJ Letters

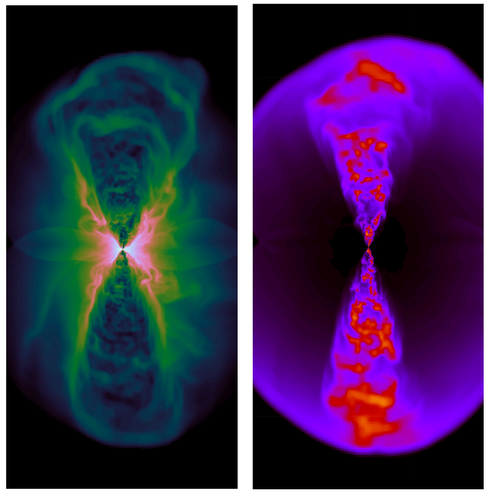
magnetically-driven post-merger
baryon winds are viable
explanation for 2017 blue kilonova

Scientific highlights: short GRB Jet simulations



Pavan+2021
MNRAS

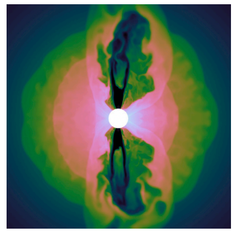
[PLUTO code]



first incipient jet propagation
in environment directly imported
from outcome of BNS merger simulation

- realistic environment makes the difference
- non-axisymmetry of emerging jet

Scientific highlights: short GRB Jet simulations



Pavan+2021
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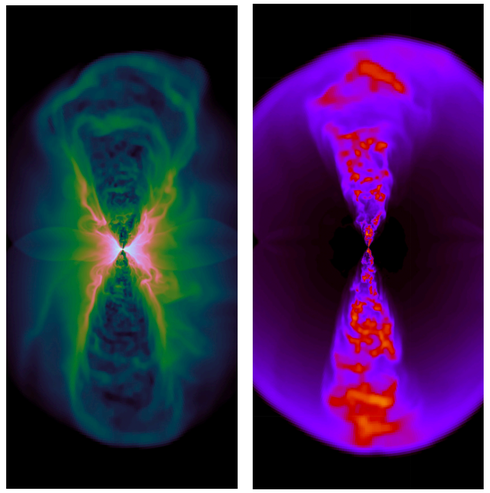

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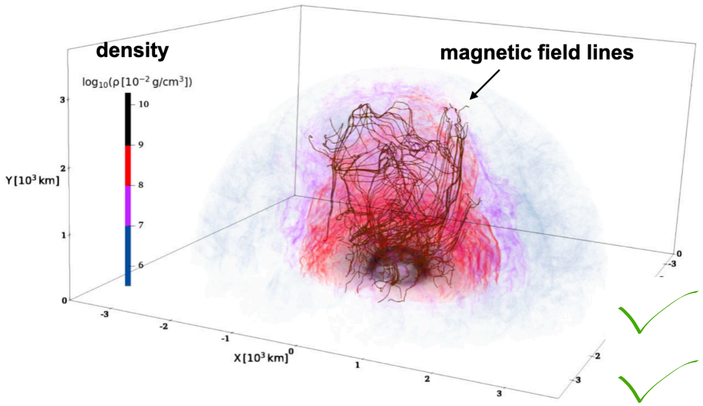
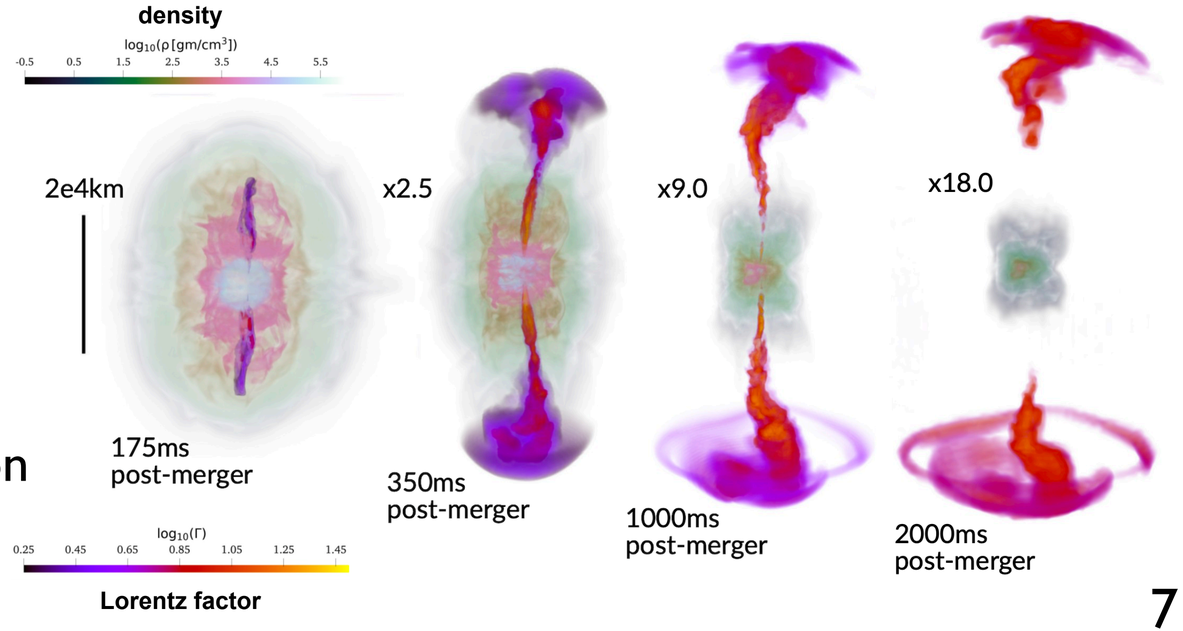


Pavan+2023
MNRAS

- ✓ magnetized environment
- ✓ magnetized rotating jet
- ✓ physically motivated injection prescription

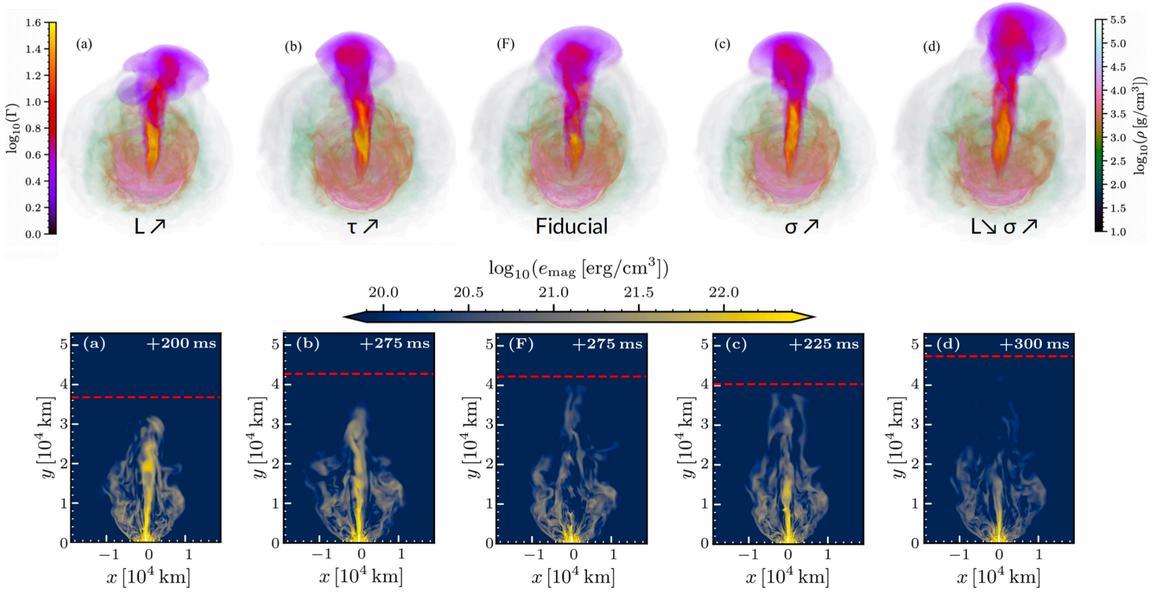


Scientific highlights: from Jet simulations to EM signals

Pavan+
in prep.

first jet parameter exploration with realistic propagation environment

Jet initial power, total injected energy, magnetization, launching time, ..



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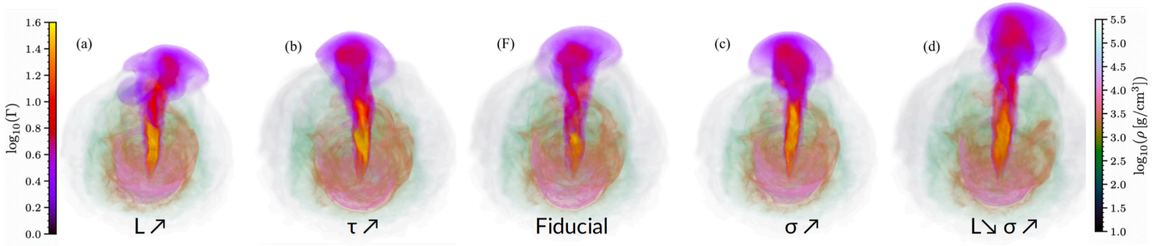
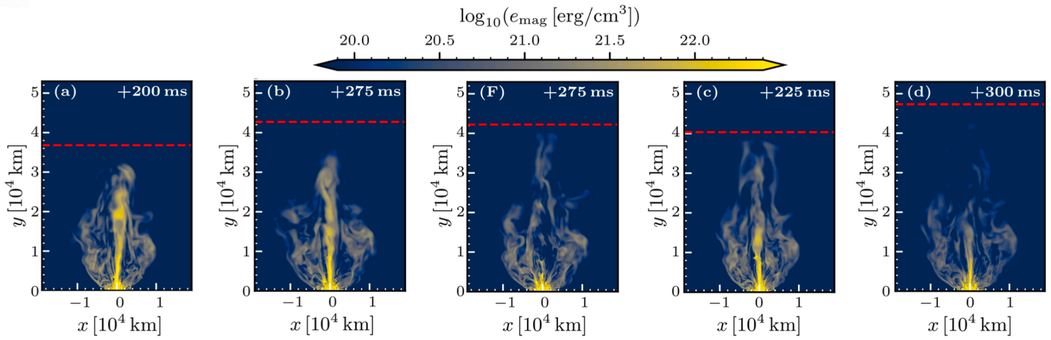
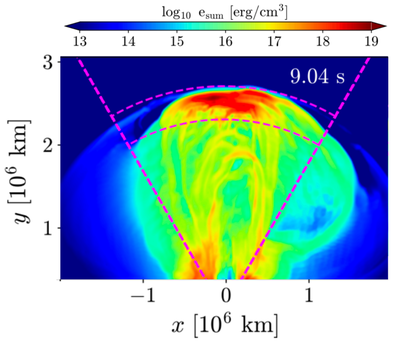
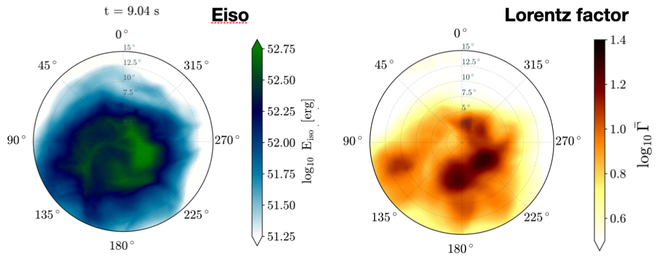




extending 3D jet simulations to a nearly ballistic phase

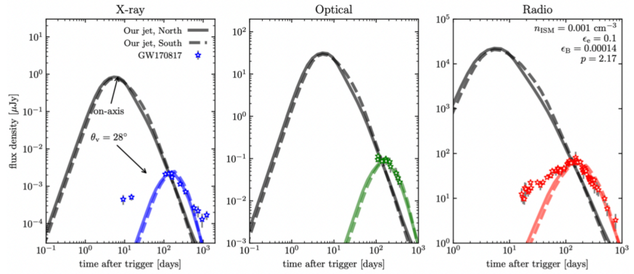
Dreas+
in prep.





see Emma's poster

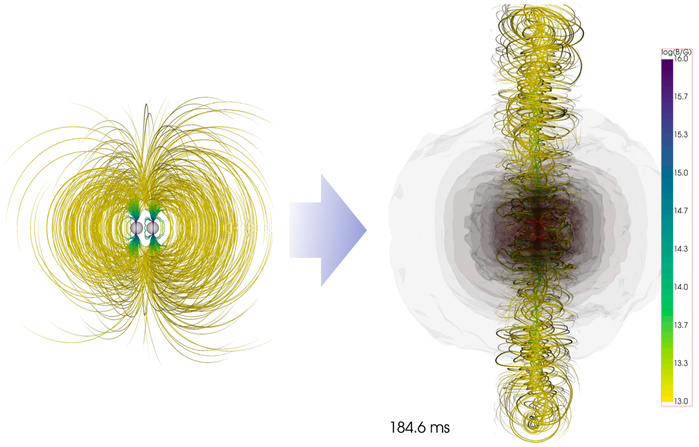
jet afterglow emission

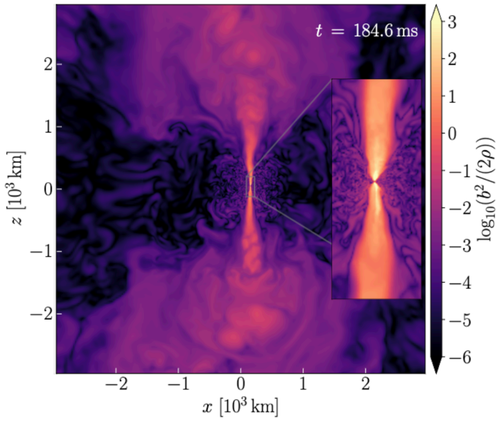


Credits: O.S.Salafia

first approach to prompt emission: opacities and time delay (just started)

Scientific highlights: end-to-end consistent description

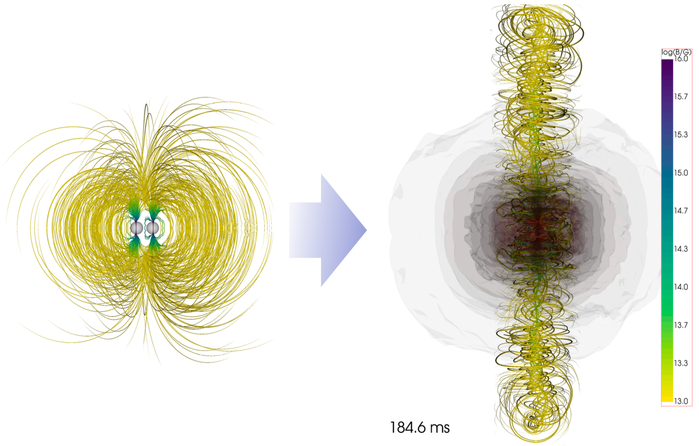


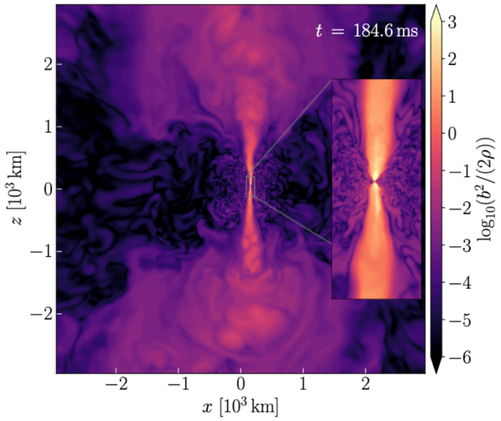


jet-forming BNS merger GRMHD simulation

[Spritz code]

Scientific highlights: end-to-end consistent description

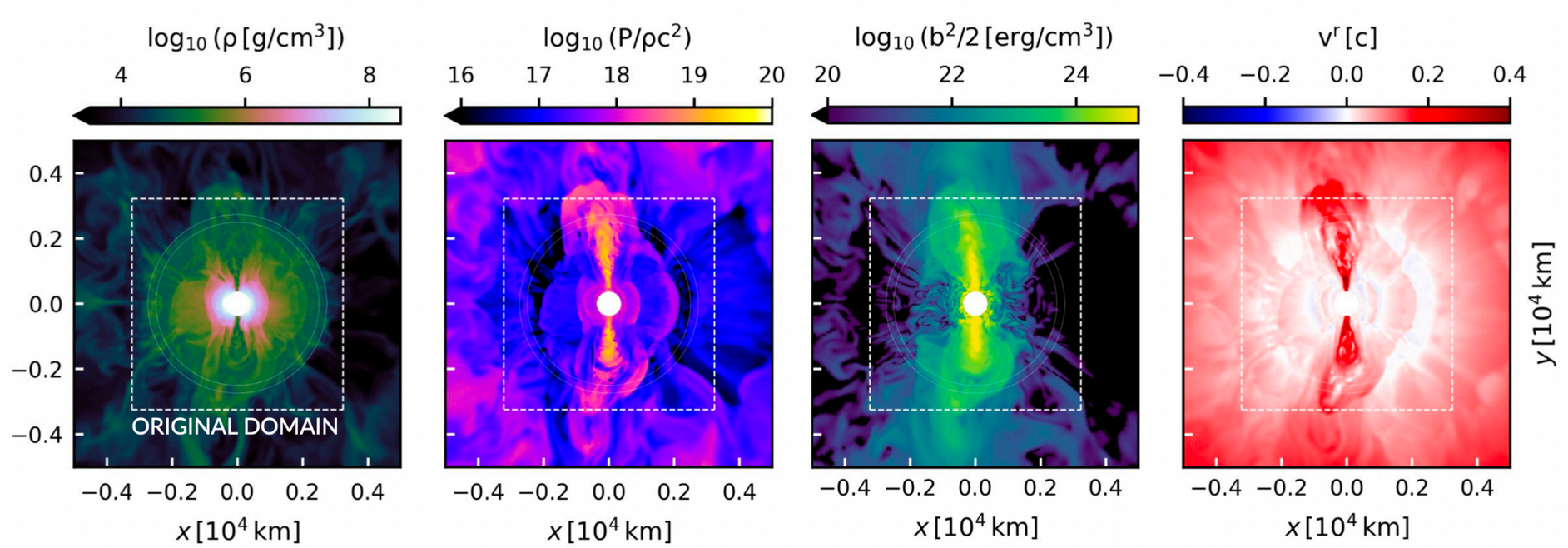




<u>jet-forming BNS merger</u> GRMHD simulation

[Spritz code]

input for large-scale SRMHD jet simulation



PRELIMINARY RESULTS (~150 ms after merger or 100 ms after collapse)

Synergies

EM follow-up campaigns

GRAWITA — **coordinating Theory WG**

INAF GRAWITA

ENGRAVE

ESO ngrave

Ground-based GW detectors

VIRGO (LVK)

VIRGO

EINSTEIN TELESCOPE

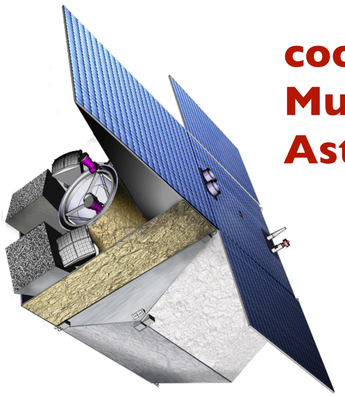
ET ITALY Einstein Telescope

present (2020s) | future (2030s)

GRB mission (ESA finalist M7)

THESEUS

theseus TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



coordinating Multimessenger Astrophysics WG

see also scheda INAF **NuMerJet**

Numerical modelling of binary neutron star and neutron star-black hole mergers, short gamma-ray burst jets, and kilonovae

Synergies

EM follow-up campaigns

GRAWITA — coordinating Theory WG

INAF GraWITA

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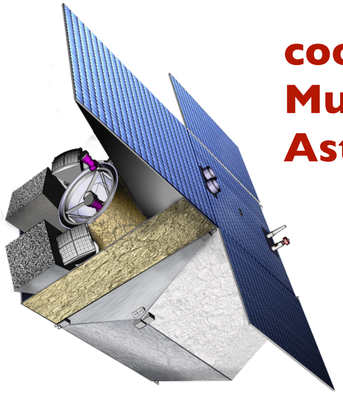

coordinating Multimessenger Astrophysics WG

Resources

GRANTS/FUNDING (as PI)

~450 kEUR

PRIN INAF 2019

MAECI ITA-USA

PRIN MUR 2022

INAF THEORY GRANT

active

(TWICE ERC FINALIST)

COMPUTATIONAL GRANTS (as PI)

~20 awarded projects

~60 Million cpu-hours
(would cost ~1 Million EUR)

including 2 EuroHPC allocations
~ 22 Mcpu-h

TAKE-HOME MESSAGE

- the only INAF group performing relativistic MHD simulations of BNS mergers and short GRB jets
- ambitious goal:
  1) building the first end-to-end consistent description from the inspiralling binary to the final jet in nearly ballistic motion
  2) connecting realistic system dynamics with its EM signatures
- fully complementary to the INAF observational efforts and in strong synergy with Virgo/LVK, GRAWITA, ENGRAVE, and the future Einstein Telescope and THESEUS