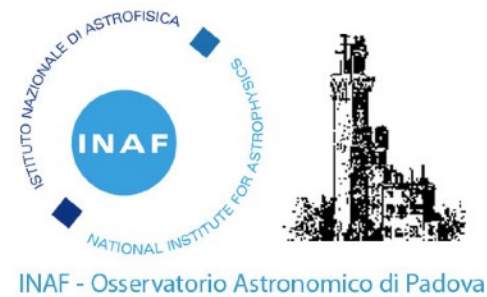


NuMerJet

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



RICCARDO CIOLFI

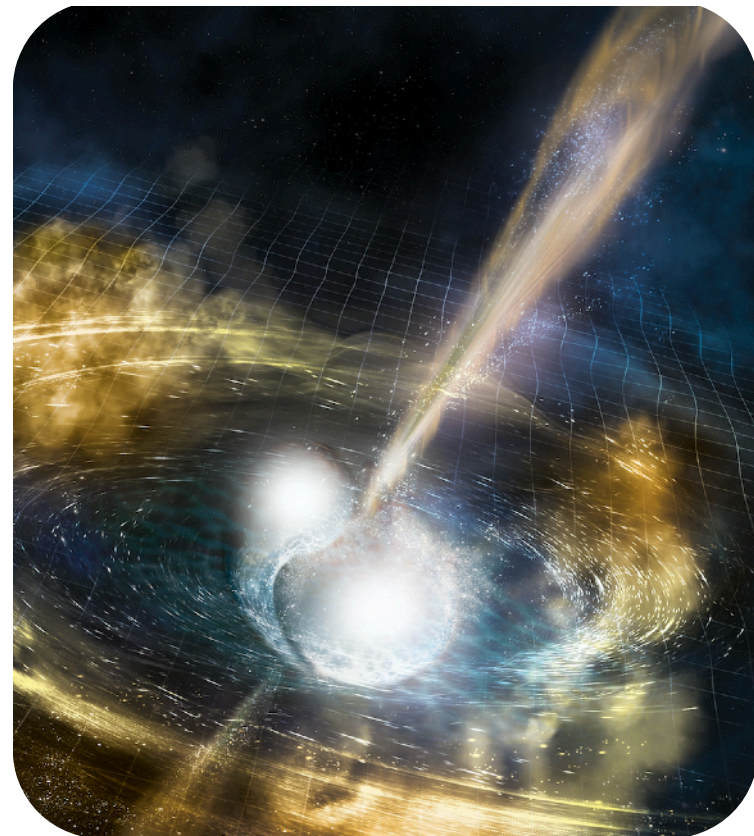
INAF - Osservatorio Astronomico di Padova

INAF - Audizioni 2022 RSN4

10th May 2022

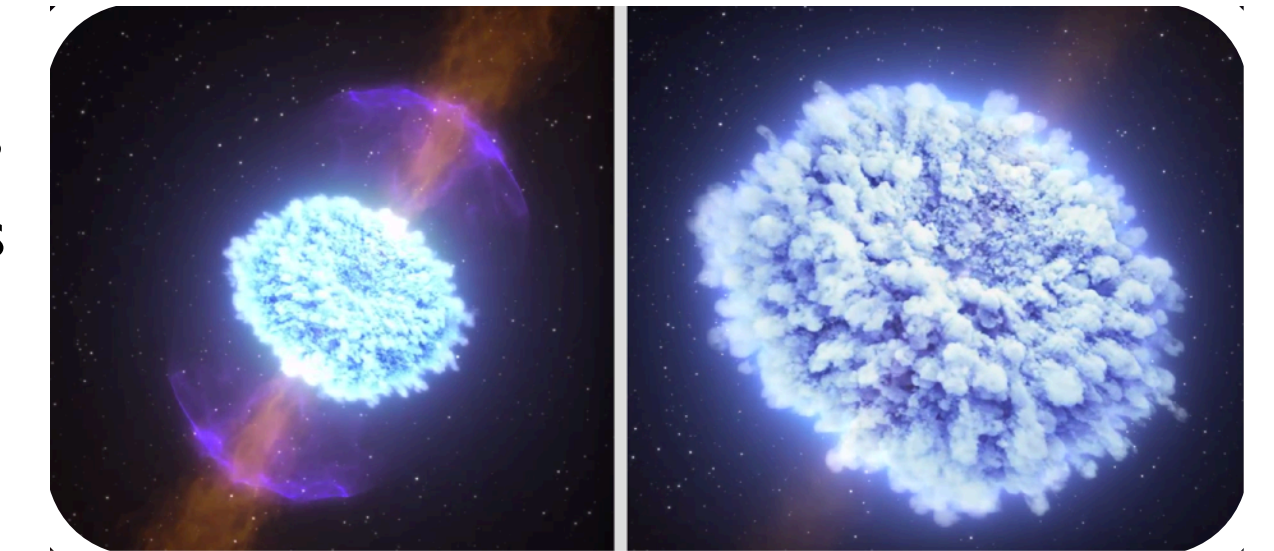
ASTROPHYSICS AND FUNDAMENTAL PHYSICS WITH NS-NS AND NS-BH MERGERS

short gamma-ray bursts



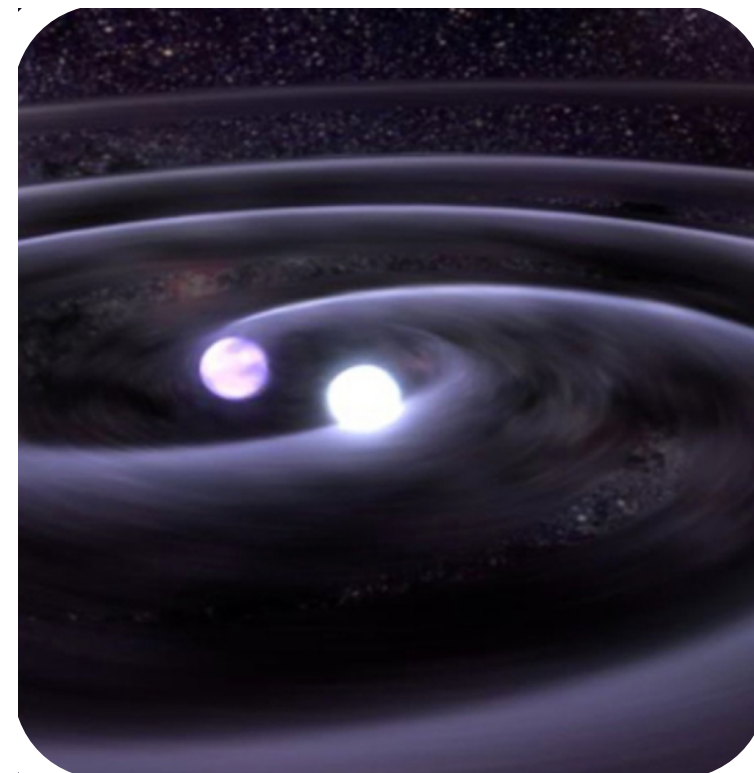
jet formation / central engine
jet breakout and propagation
prompt and afterglow emission
(at different viewing angles)

origin of heavy elements



mass ejection mechanisms
r-process nucleosynthesis
radioactively-powered kilonovae

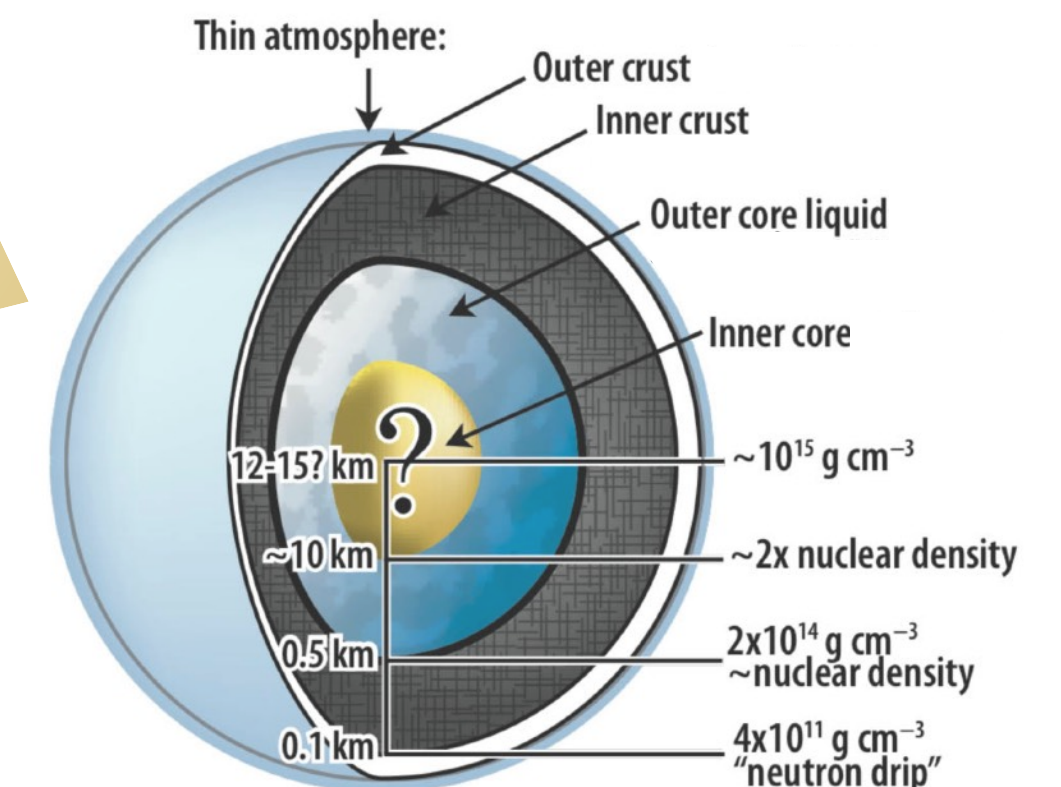
gravitational waves



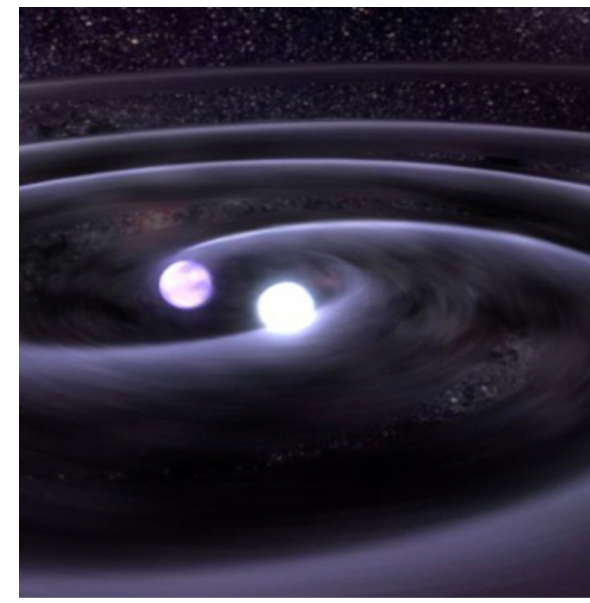
BINARY NEUTRON STAR MERGERS (NEUTRON STAR-BLACK HOLE MERGERS)

EOS of supranuclear matter

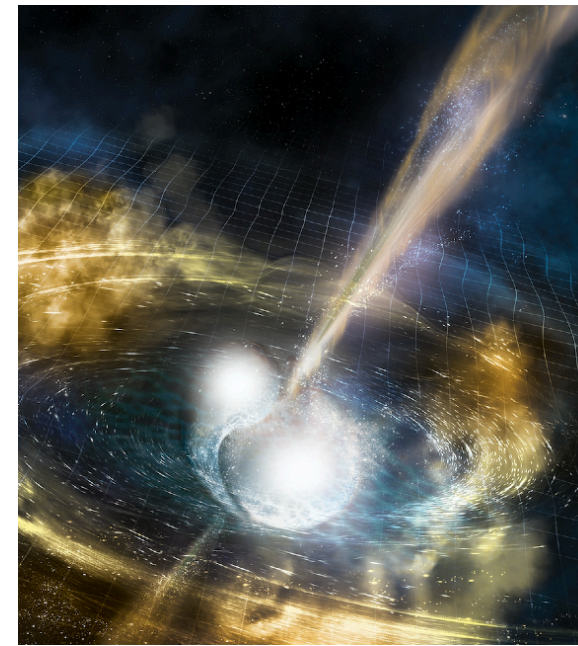
GW and multi-messenger constraints



GW170817: MULTIMESSENGER OBSERVATION OF A BNS MERGER

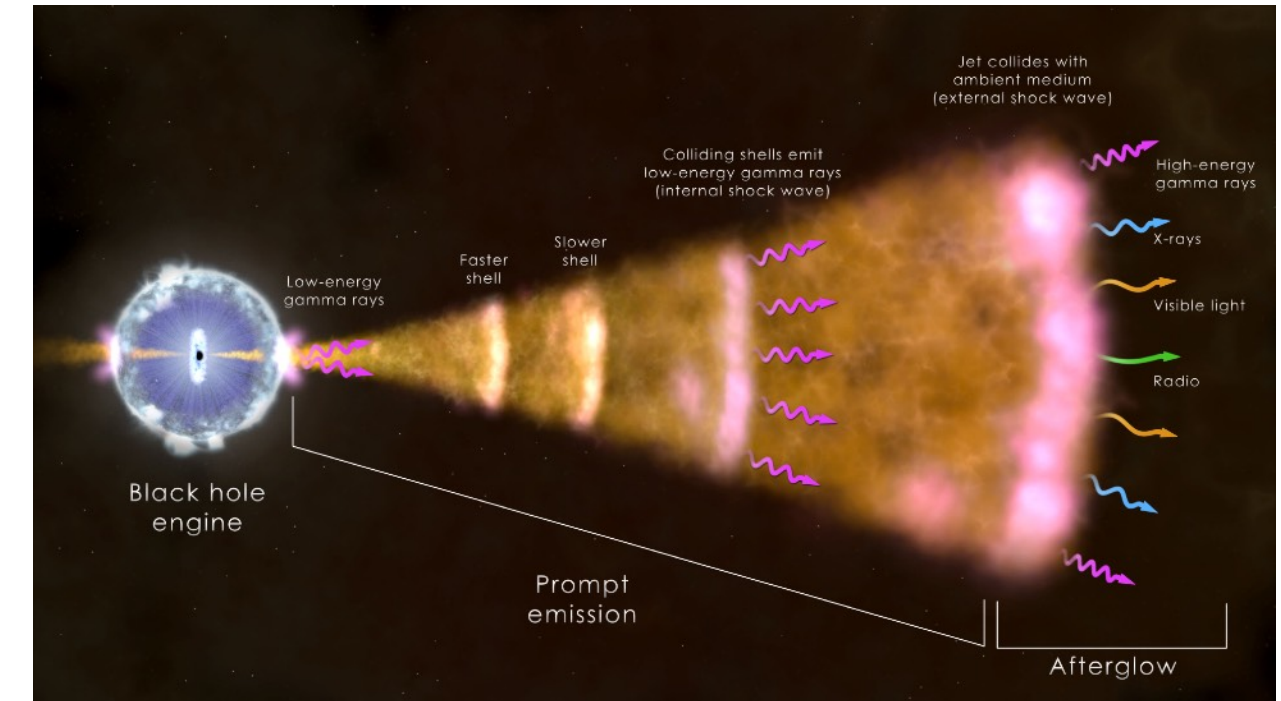


merger
gravitational wave
signal



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

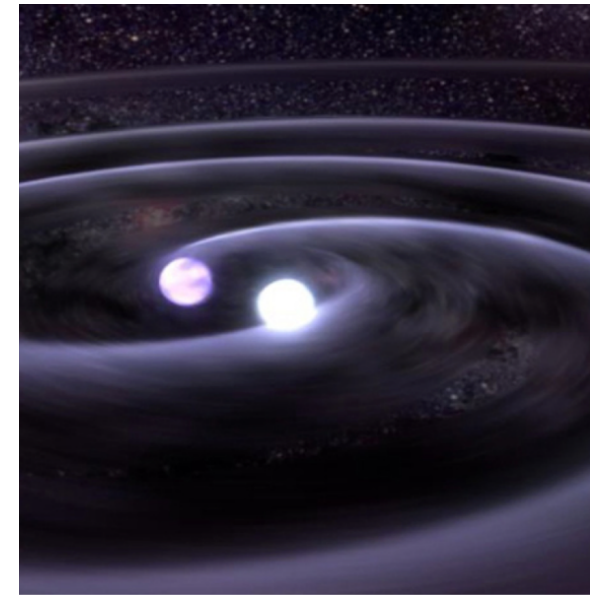
**constraints on
neutron star EOS
and Hubble constant**

optical
counterpart
—
kilonova
AT 2017gfo

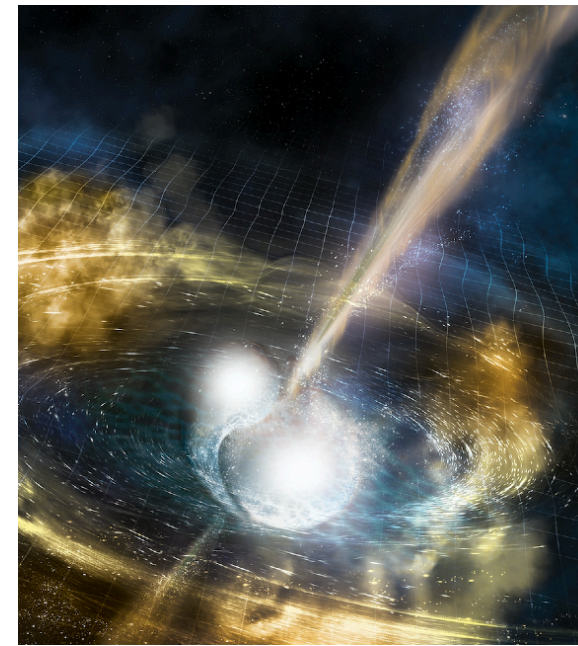


**BNS mergers are ideal sites
for r-process nucleosynthesis**

GW170817: MULTIMESSENGER OBSERVATION OF A BNS MERGER



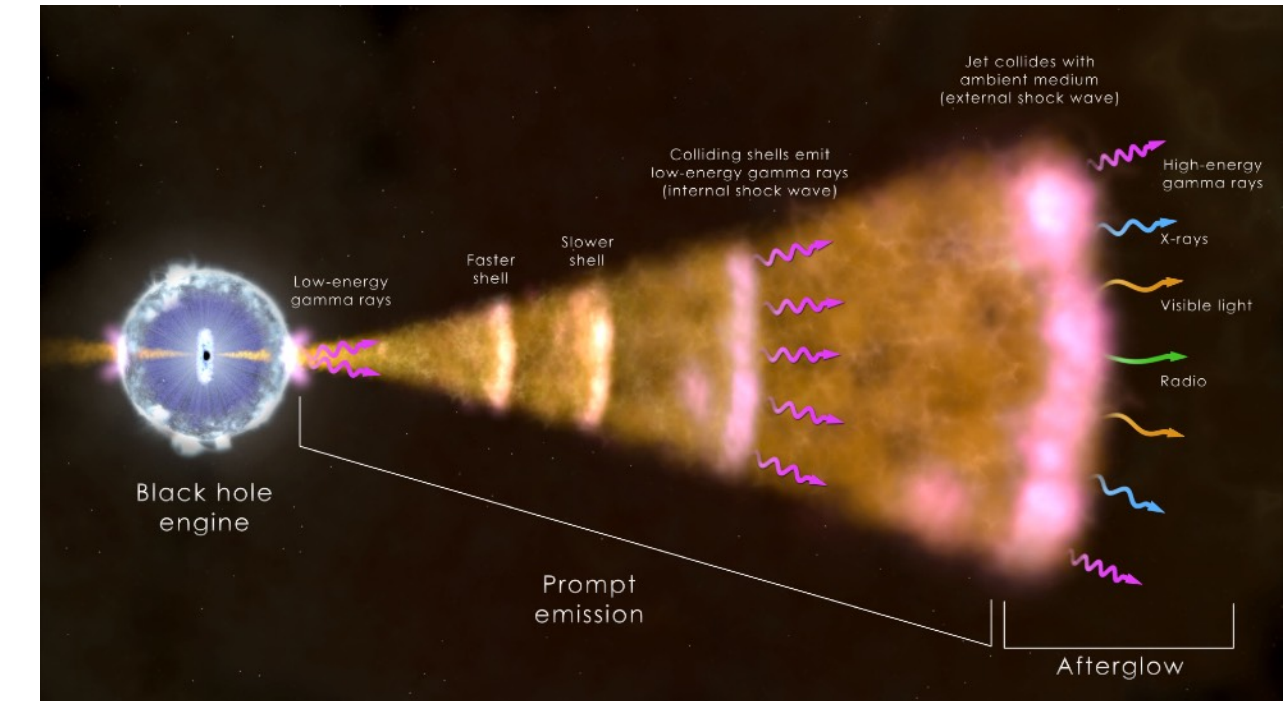
merger
gravitational wave
signal



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?

MAIN GOAL of NuMerJet

**building a solid theoretical framework for the interpretation
of BNS and NS-BH merger events**

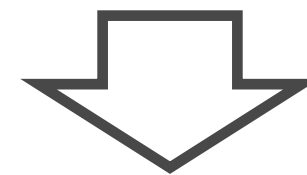
based on relativistic MHD simulations
of both the merger process and the emergence of short GRB jets

MAIN GOAL of NuMerJet

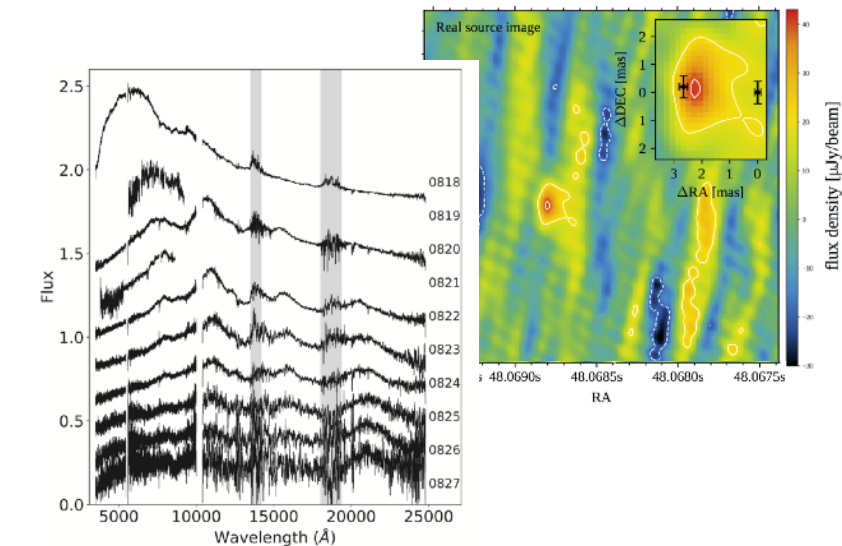
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based on relativistic MHD simulations
of both the merger process and the emergence of short GRB jets

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



ensuring the best scientific return on the large participation and investment in the relevant
observational programs (GW detectors, optical/IR and radio telescopes, high-energy satellites)

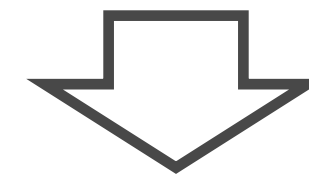


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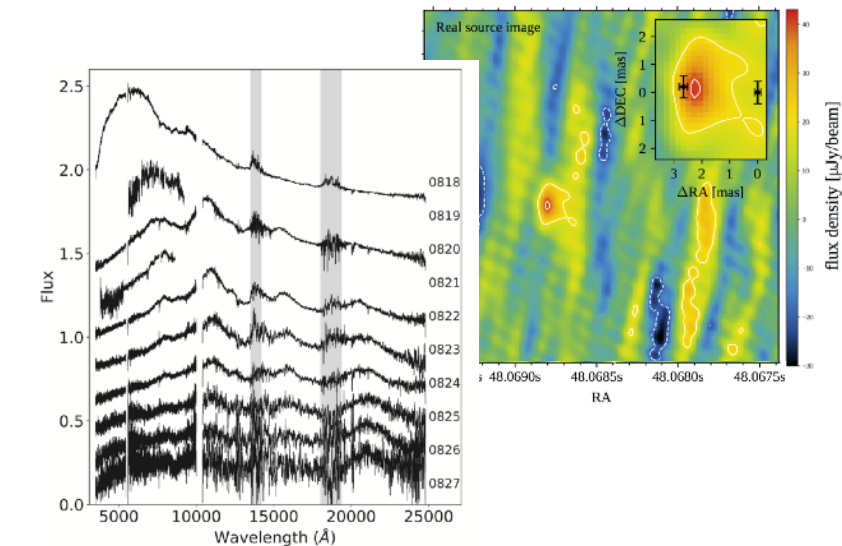
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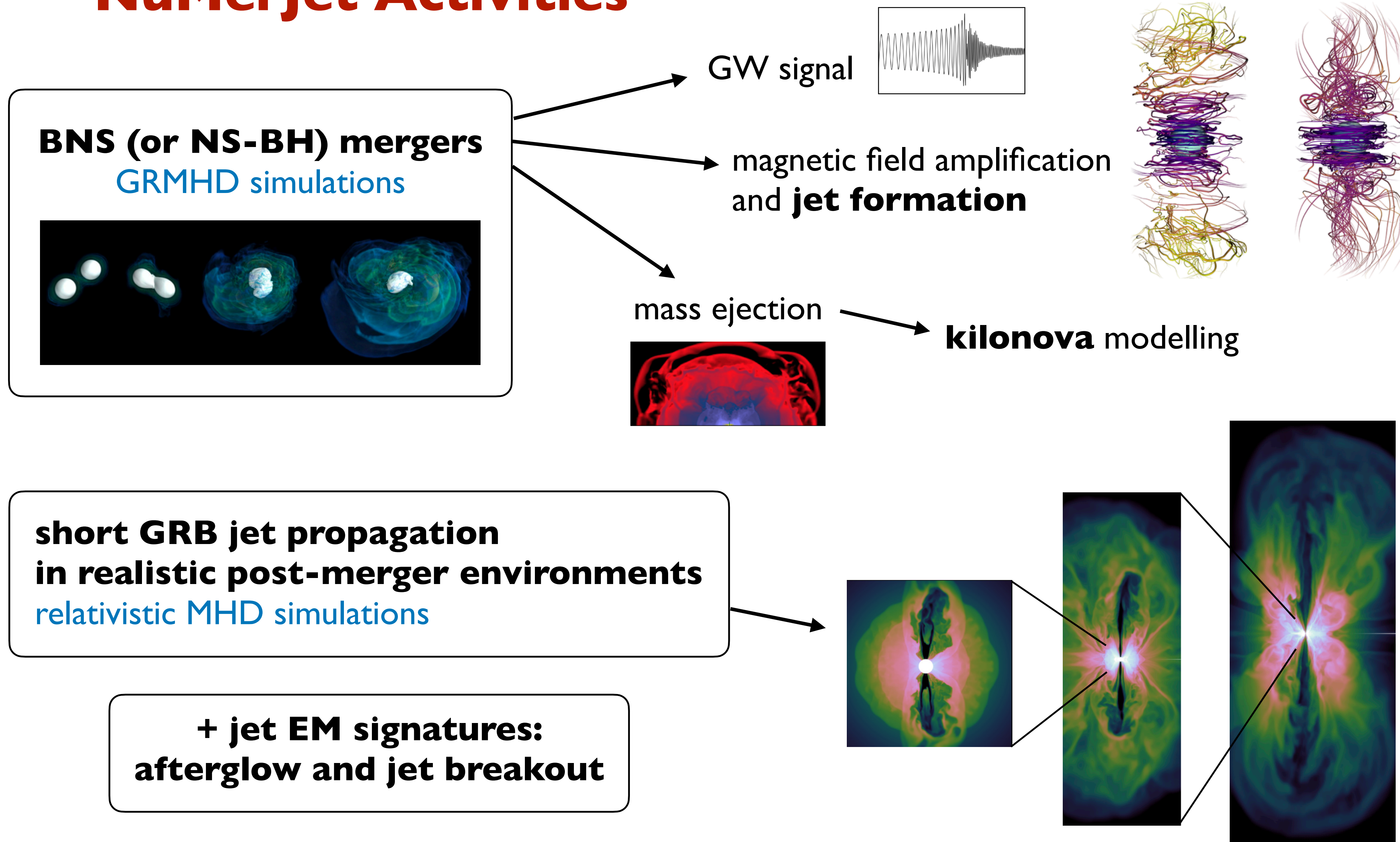


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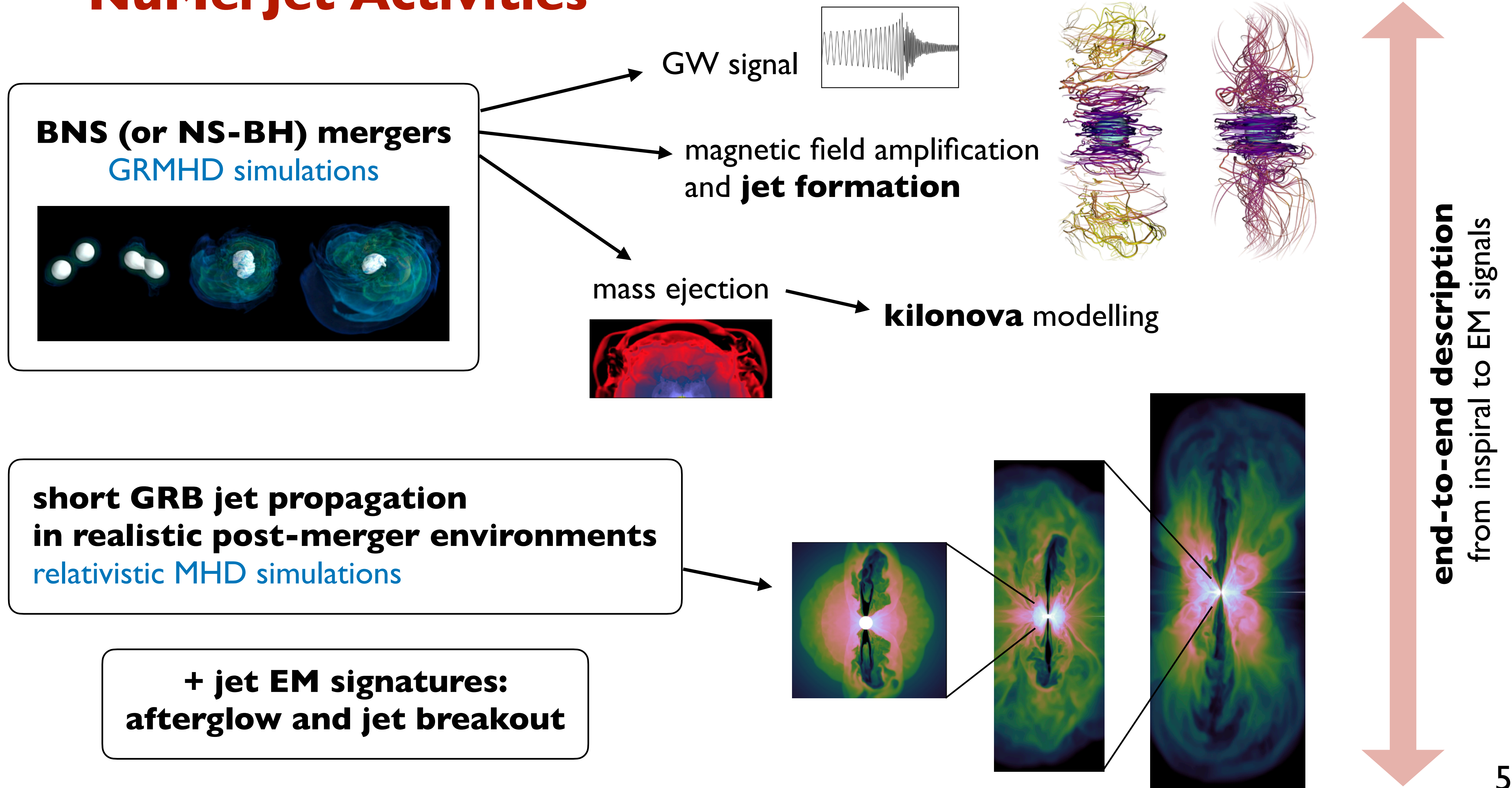


✓ **collecting top national expertise on MHD simulations of these systems**

NuMerJet Activities

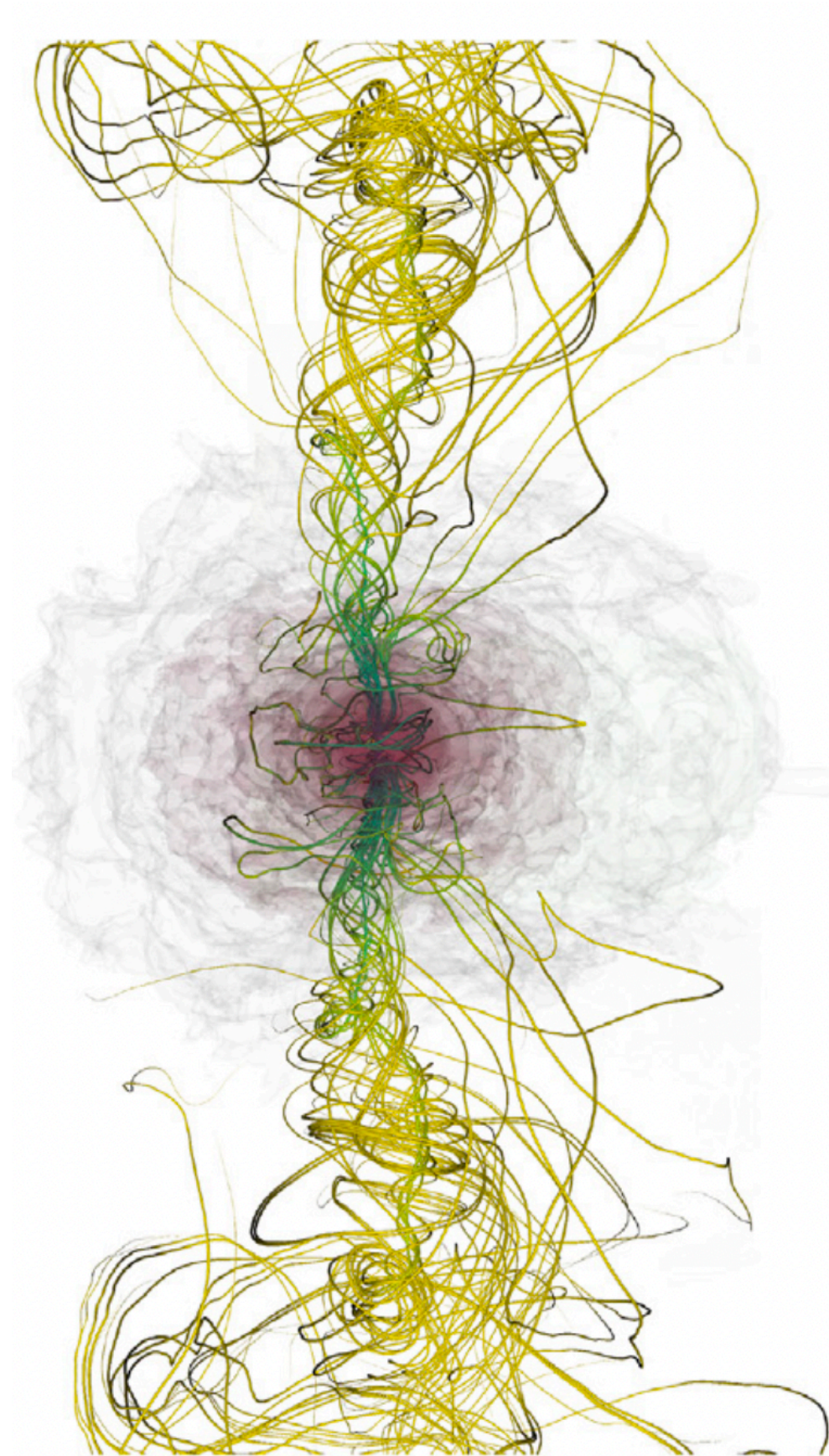


NuMerJet Activities



Scientific highlights: BNS simulations

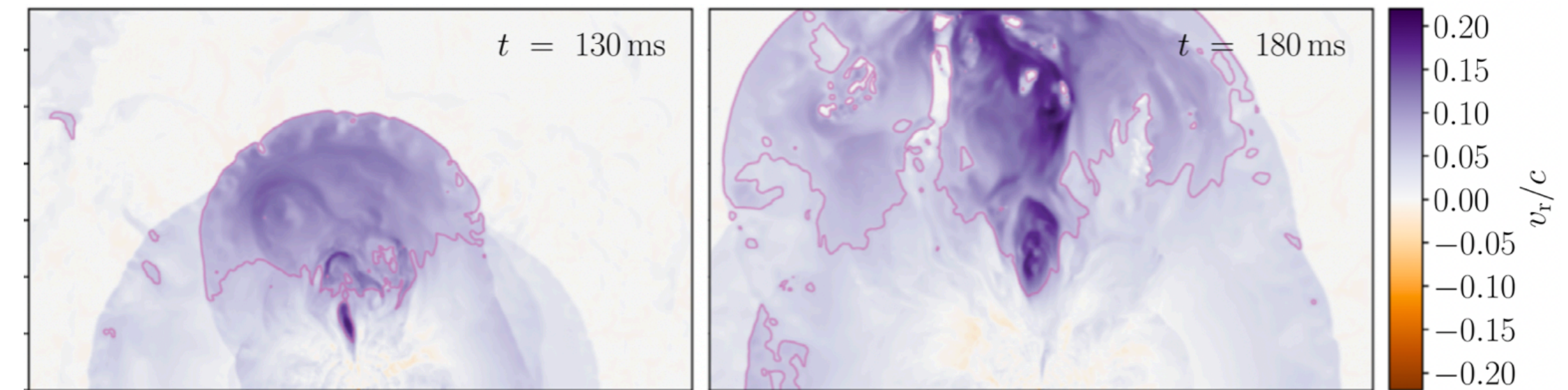
- first systematic investigation of long-lived remnant neutron star scenario in presence of magnetic fields
- longest ever simulations of this type of magnetized BNS mergers



Cioffi 2020a
MNRAS Letters

collimated outflow from
massive neutron star remnant

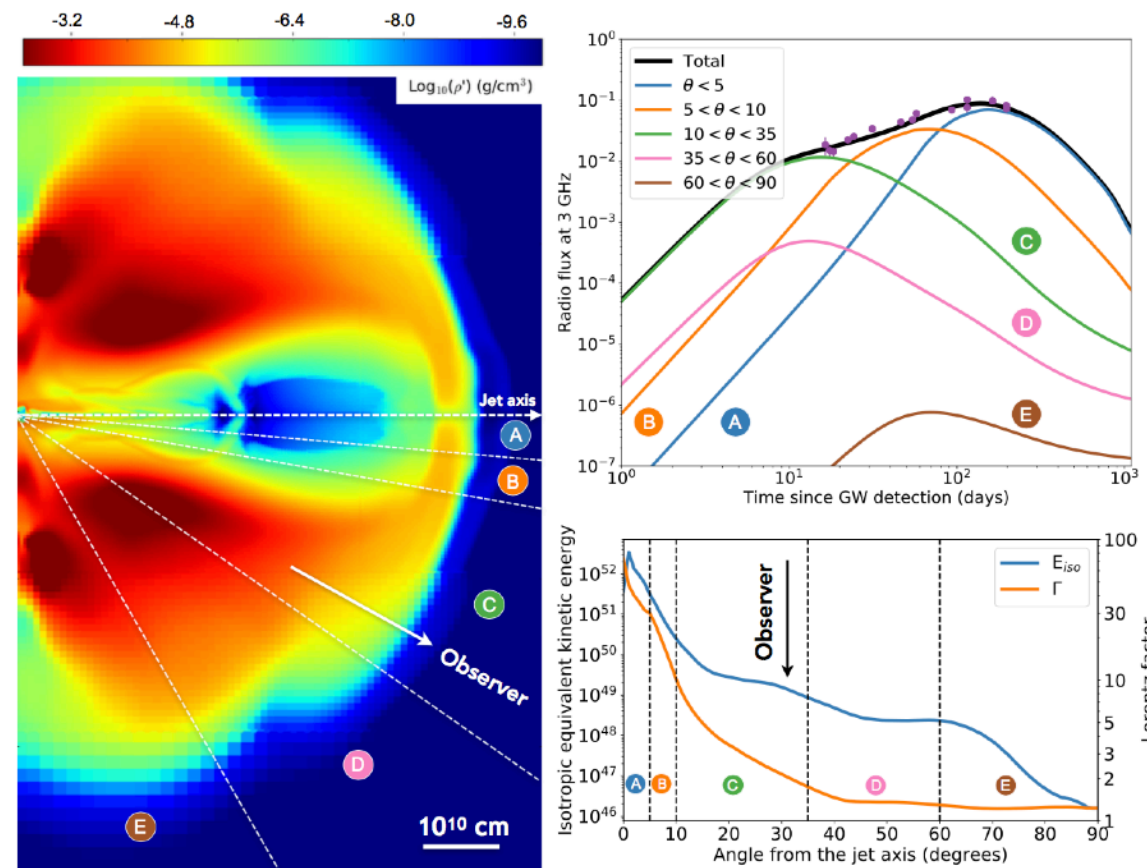
not enough powerful for a short GRB
→ BH engine favoured



Cioffi & Kalinani 2020
ApJ Letters

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

Scientific highlights: short GRB Jet simulations



outcome of hydrodynamic jet simulation used to interpret GRB 170817A prompt and afterglow data

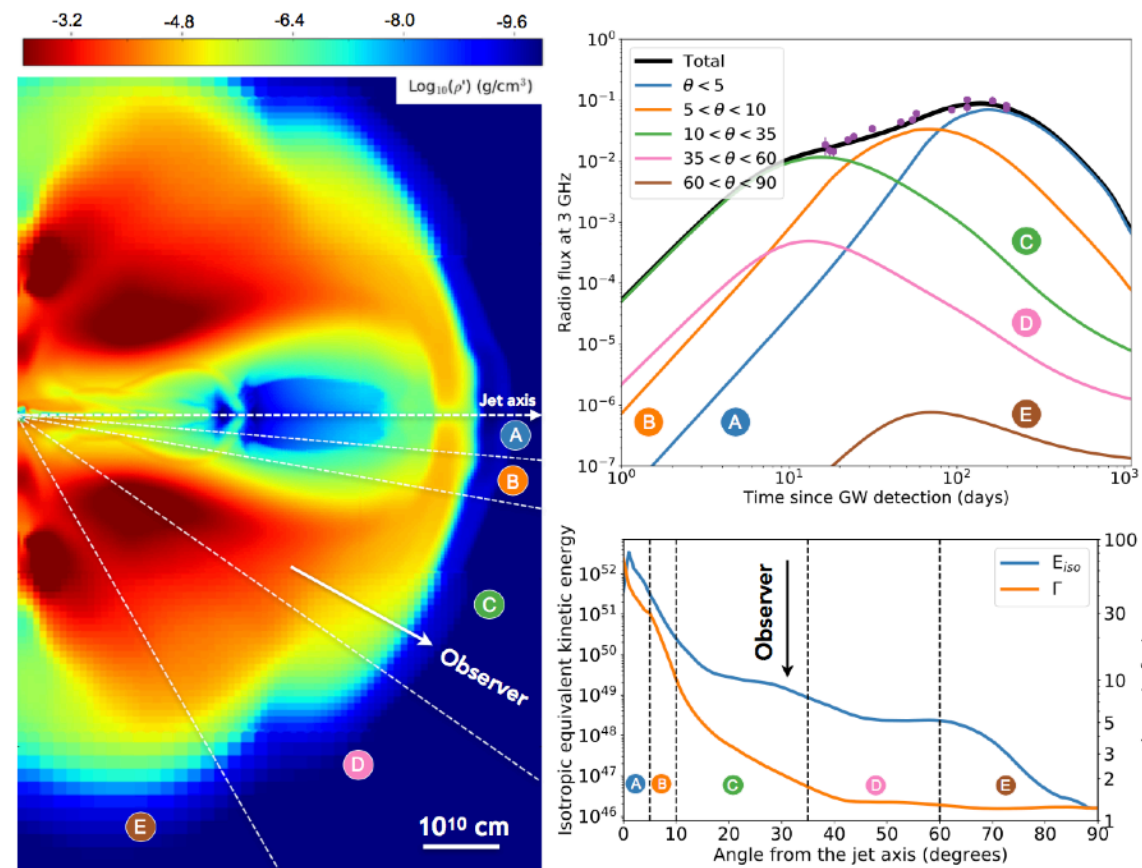
→ viability of canonical short GRB jet seen off-axis
later confirmed via VLBI (Mooley+2018, Ghirlanda+2019)

Lazzati+2018
ApJ Letters

Aspen Institute Italia
Award 2022



Scientific highlights: short GRB Jet simulations

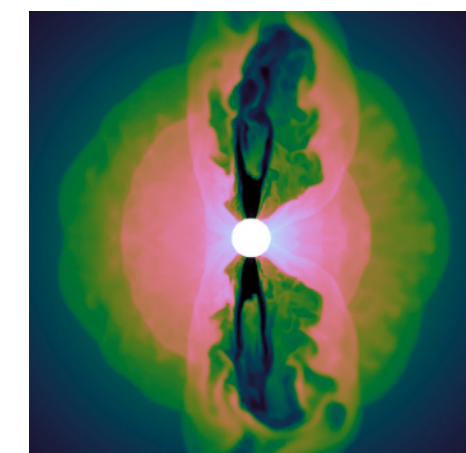


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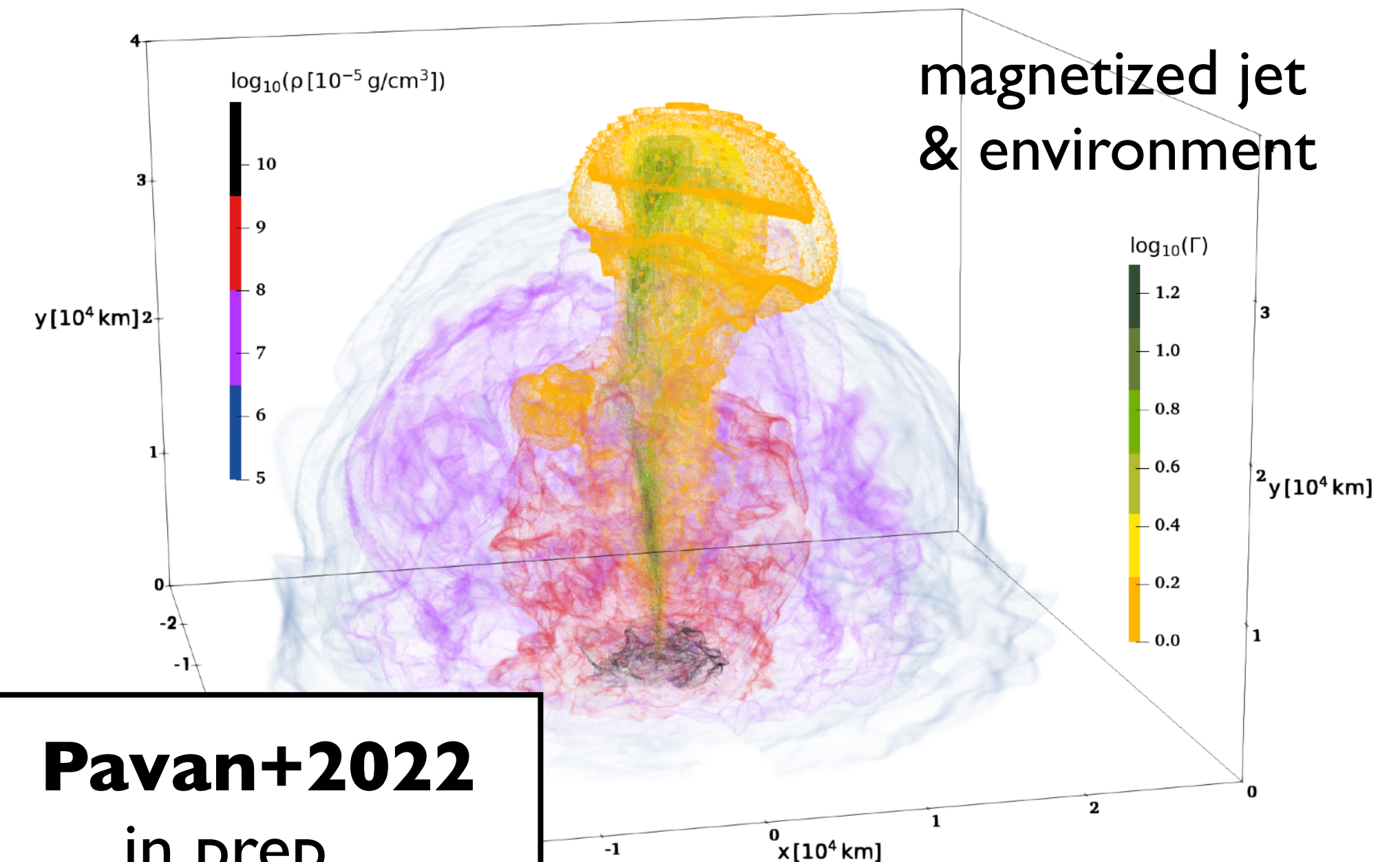
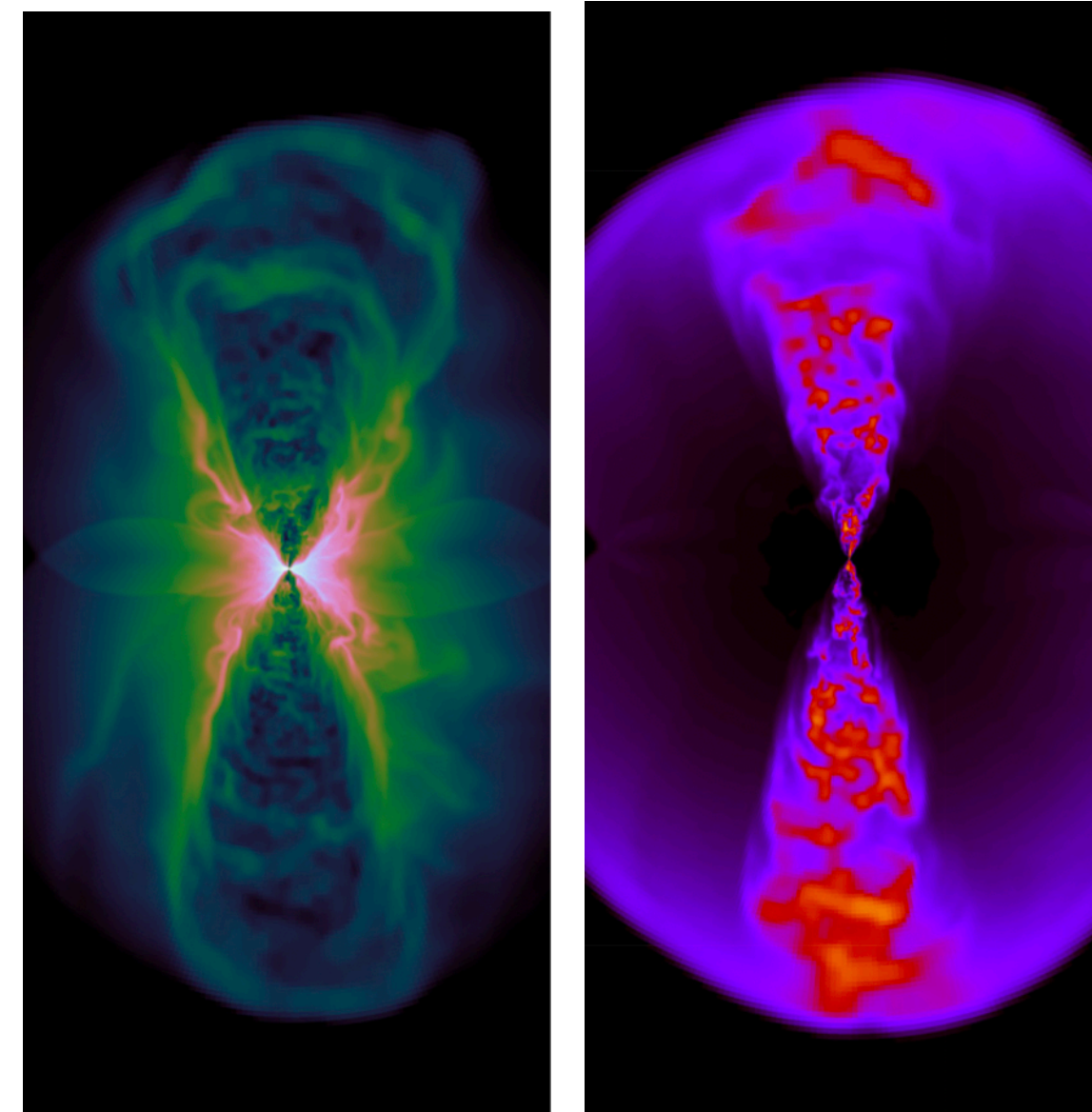
Lazzati+2018
ApJ Letters

Aspen Institute Italia
Award 2022



Pavan+2021
MNRAS

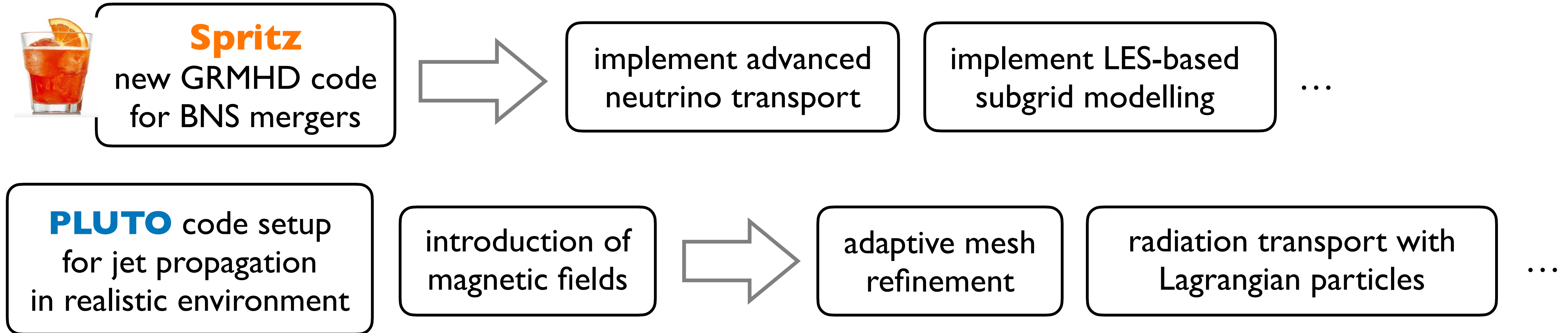
first incipient jet propagation
in environment directly imported
from outcome of BNS merger simulation!



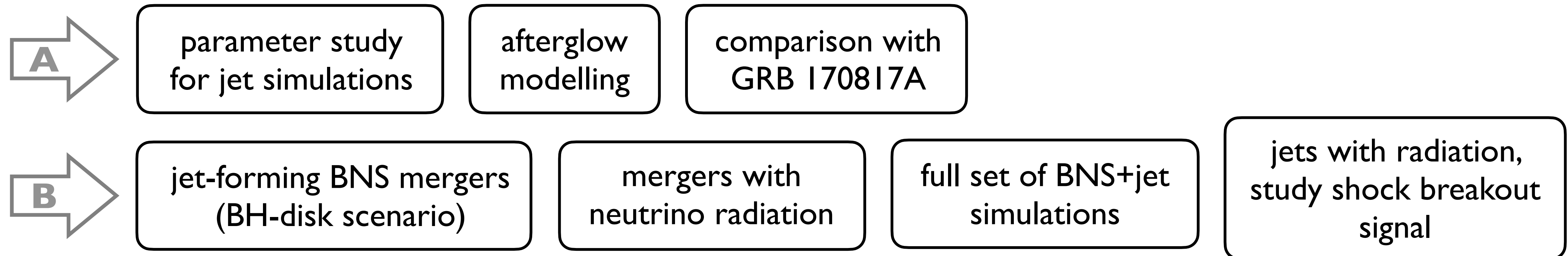
Pavan+2022
in prep.

Workflow / Milestones

CODE DEVELOPMENT / PHYSICAL INGREDIENTS



SCIENTIFIC RESULTS



Team / Expertise

31 Researchers (18 INAF, 13 external) — 6.0 FTE in 2022

MHD SIMULATION EXPERTS

Riccardo Ciolfi (Coord.)
Jay Kalinani
Andrea Pavan
Bruno Giacomazzo
Albino Perego
Andrea Mignone
Claudio Zanni
Luca Del Zanna
Niccolo' Bucciantini
Barbara Olmi

Om Sharan Salafia
Luigi Stella
Cristiano Palomba
Pia Astone
Paola Leaci

0 FTE
members

Elena Pian
Enrico Cappellaro
Marica Branchesi
Gor Oganessian
Samuele Ronchini
Massimo Della Valle
Lorenzo Amati
Enzo Brocato
Stefano Covino
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BNS merger simulations

0 FTE members

Kilonova modelling

Jet simulations

GRB afterglow modelling

GWs from remnant neutron star

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Synergies

VIRGO



12 NuMerJet members
are Virgo members
including
5 with coordination roles

GRAWITA



16 NuMerJet members
are GRAWITA members
including
Brocato PI,
Branchesi, Cappellaro, Palazzi
in Science Board,
Ciolfi coord.WG Theory,
Melandri coord.WG Characteriz.

ENGRAVE



18 NuMerJet members
are ENGRAVE members
including
Branchesi, Brocato, Pian
in Governing Council,
Salafia in Executive Committee,
Perego coord.WG Theory

THESEUS



15 NuMerJet members
are THESEUS members
including
Amati PI,
Ciolfi/Stratta coord.WG
Multimessenger Astrophys.,
Branchesi among coord.
WG synergy

Other connected programs:
GRB@MI, Einstein Telescope, ..

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WG synergy**

strong involvement and coordination roles of NuMerJet members
ensuring direct application of our theoretical framework
in future observations

Other connected programs:
GRB@MI, Einstein Telescope, ..

Criticalities / Resources

I) RESEARCH GRANTS/FUNDING

- mostly used to hire young researchers (postdoc/PhD) —————→ training of a new generation of scientists in the field!
necessary to carry out code development and large sets of simulations
- will need 2-3 or more postdocs and 1 or more PhD within the next 2 years
- past and present applications:

INAF GRANTS (PI Ciolfi)

- PRIN INAF 2019 (assigned ~50kEUR) ✓
- Theory Grant 2022 (also 50kEUR, [pending..](#))

ERC

- finalists: Ciolfi (twice), Giacomazzo, Perego, ..

PRIN MIUR (PI Giacomazzo)

- PRIN 2017 (1st without funding)

PRIN MIUR (PI Ciolfi)

- PRIN 2020 (score 94, funding at 95.7)
- PRIN 2022 (250kEUR, [pending..](#))

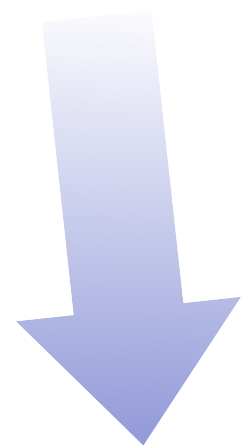
Criticalities / Resources

2) COMPUTATIONAL RESOURCES

- several computational grants awarded every year via CINECA competitive calls
- guaranteed resources via INFN (Teongrav initiative, Giacomazzo national coordinator)

→ order ~10 Million cpu-h per year

- will soon need 2-3 times more



applications at European level
(PRACE, EuroHPC)

ongoing effort..



more resources
within INAF??



Take-home message

NuMerJet — BNS (NS-BH) merger simulations and short GRB jet simulations, combined in a single consistent description (unique of this research team)

- program collects all top experts in Italy on these simulations and the corresponding evolution codes
- attempting to build a direct, unprecedented connection with EM signatures
- fully complementary to the INAF observational efforts and in strong synergy with Virgo, GRAWITA, ENGRAVE, THESEUS
- strengthening INAF leadership in the emerging field of multimessenger astrophysics with GW sources