

Multimodal ML techniques for the multimessenger analysis of GWs and GRBs from BNS mergers

Luca Muccillo*, B. Patricelli, E. Cuoco, M. Lenti, F. Di Renzo

*luca.muccillo@unifi.it



UNIVERSITÀ
DEGLI STUDI
FIRENZE

GWsNS - 02 Jul 2026



Multimodal analysis

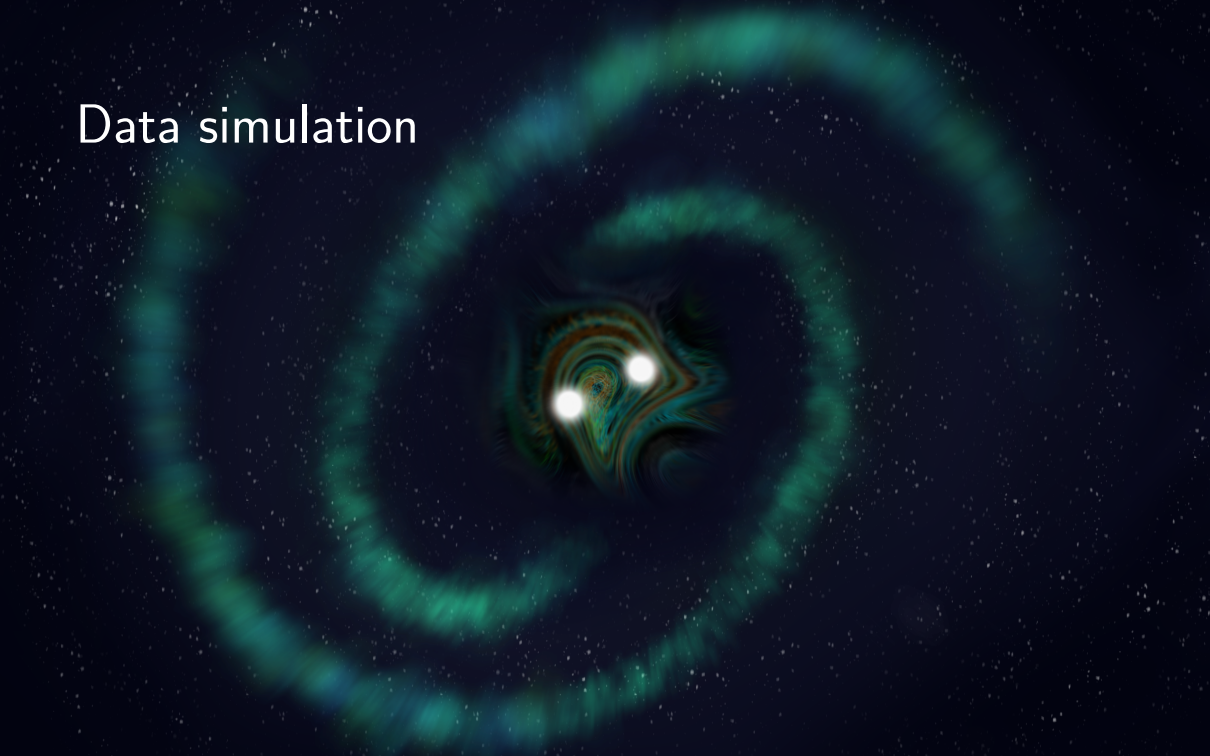
Principle: combine informations from different channels, exploiting their complementarity;

Why Multimodal: characterize the astrophysical event in its entirety using different messengers (Cuoco+2021);

Objective: redshift and inclination angle estimation through the jointly analysis of GW and EM signals;

What's included: GW signals and GRB light curves simulation, deep neural network architecture, nice plots

Data simulation

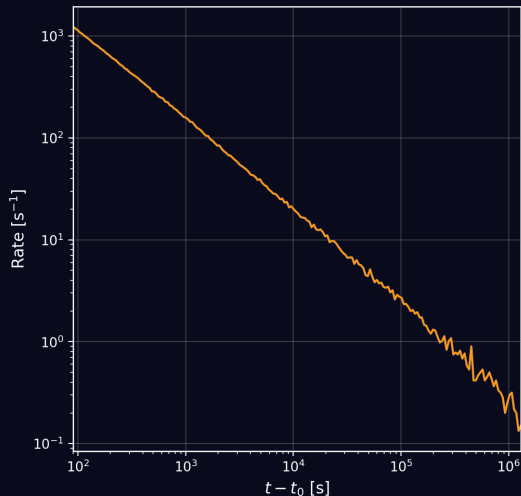


170817-like sources BNS population

- GW params ($m_1 = 1.46 M_\odot$, $m_2 = 1.27 M_\odot$, $\alpha = 3.45$ rad, $\delta = -0.41$ rad) from LVK PE results;
- GRB params ($\theta_{Core} = 0.066$ rad, $\theta_{Wing} = 0.47$ rad, $E_0 = 10^{53}$ erg) from Ryan+2020, assuming a structured jet for the GRB emission;
- redshift z sampled from $U[0.01, 0.1)$, where redshift 0.01 corresponds to $d_L \sim 40$ Mpc;
- maximum inclination of the BNS system fixed to $\iota_{max} = 3.5 \times \theta_{Core}$ (visibility limitations within the observing time considered) $\rightarrow$ sources yielding to both on-axis and off-axis GRBs;
- inclination angle ι sampled from $\cos(\iota) \sim U[\cos(\iota_{max}), 1.0)$.

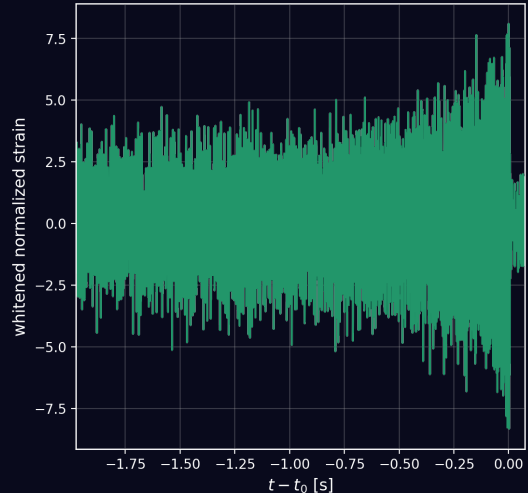
EM simulation

- assume each BNS to be associated with a sGRB;
- simulation of the **afterglow X flux light-curve**, in the time range from 90 s to 15 d after merger time t_0 ;
- taking into account jet structure dependence on the observation angle ι , using `afterglowpy` (Ryan+2020);
- simulation of the observation of this afterglow by the Swift-XRT detector, exploiting the instrument response function.



GW simulation

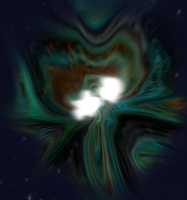
- BNS signals injection to LIGO, Virgo and KAGRA detectors in postO5 era (between O5 and 3G);
- LIGO detectors in the A[#] configuration⁽¹⁾ (~ 500 Mpc BNS range), Virgo and KAGRA in their O5 sensitivity^{2,3} (~ 130 Mpc BNS range);
- waveform adopted: TaylorF2;
- 2s long time-series, sampled at 2048 Hz, whitened through autoregressive model (Cuoco+2001);



⁽¹⁾<https://dcc.ligo.org/LIGO-T2300041/public>

⁽²⁾<https://tds.virgo-gw.eu/?r=25900> ⁽³⁾<https://dcc.ligo.org/LIGO-T2000012/public>

Neural Network



Network architecture

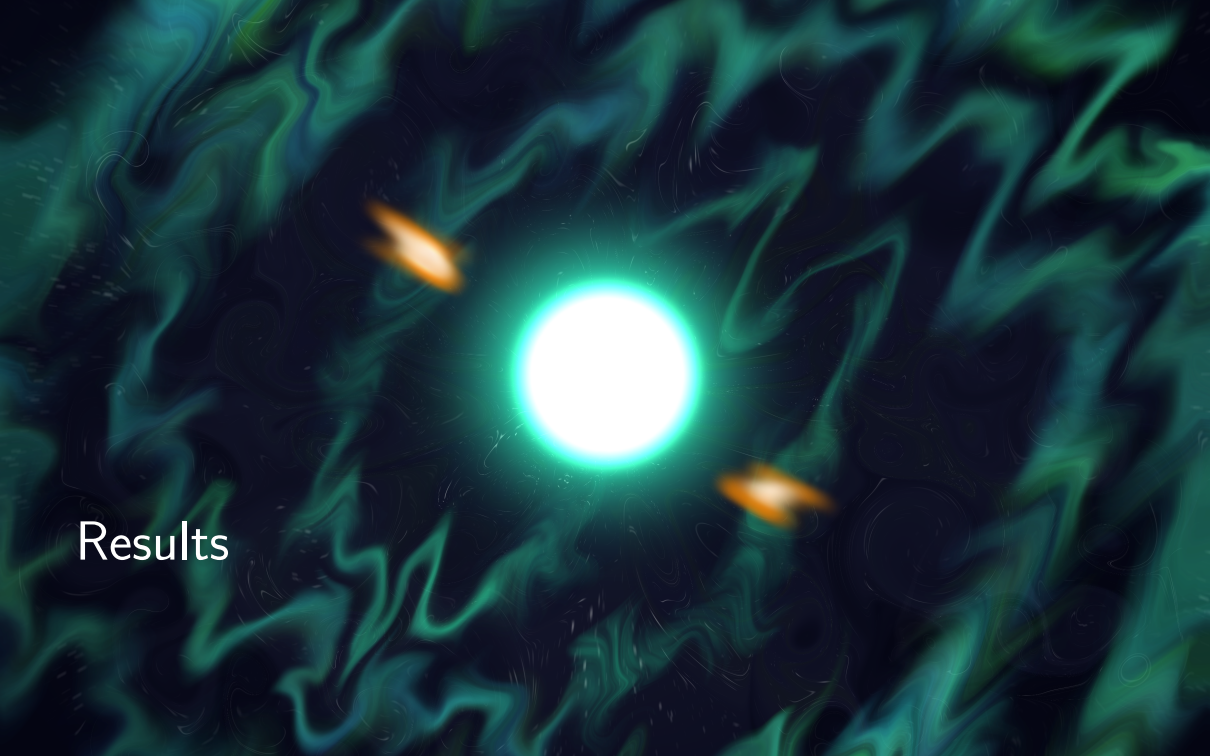
Parallel GW/GRB embedding branches: embedding networks composed by convolutional layers and ELU activations, in order to reduce input dimensionality and extract the first informations

Parallel features extraction stage: ulterior digestion of the branches output, exploiting ResNet-like MLP networks

Final stage: branches concatenation, followed by ResNet-like MLP network, producing bidimensional output for the estimate of z and $\cos(\iota)$

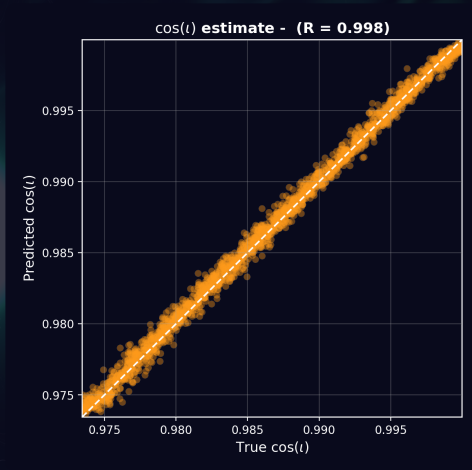
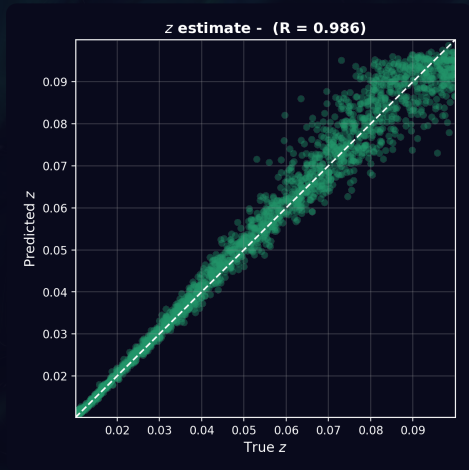
Dataset: Train / Test set: 40k / 10k sources

Training details: Adam optimizer, initial lr=0.001, batch size = 256, MSE loss

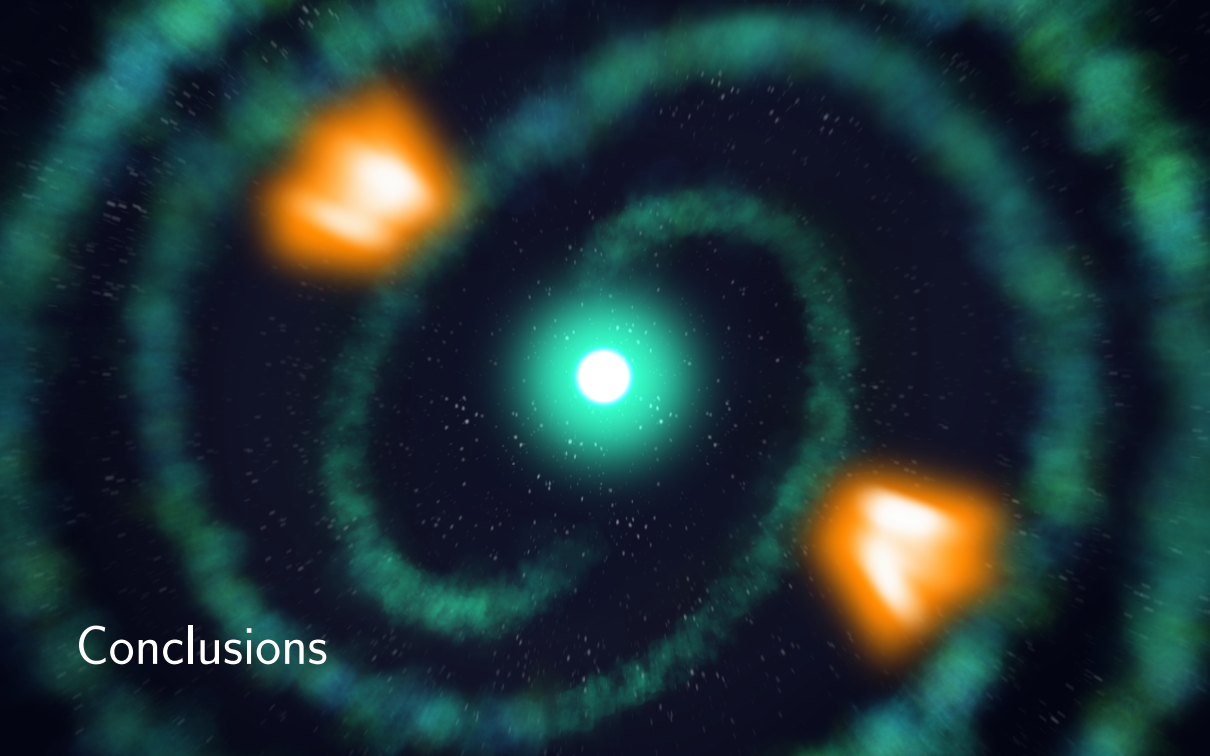
The background of the slide is a dark space filled with a complex, wavy pattern of green and teal colors, resembling a fluid or a gravitational well. In the center of the image is a bright, glowing yellow circle, likely representing a star or a distant galaxy. Two orange, elongated, and slightly blurred shapes, resembling galaxies or nebulae, are positioned on either side of the central yellow circle, one in the upper left and one in the lower right. The word "Results" is written in white, sans-serif font in the lower-left corner of the image.

Results

Results



Estimates pretty good!



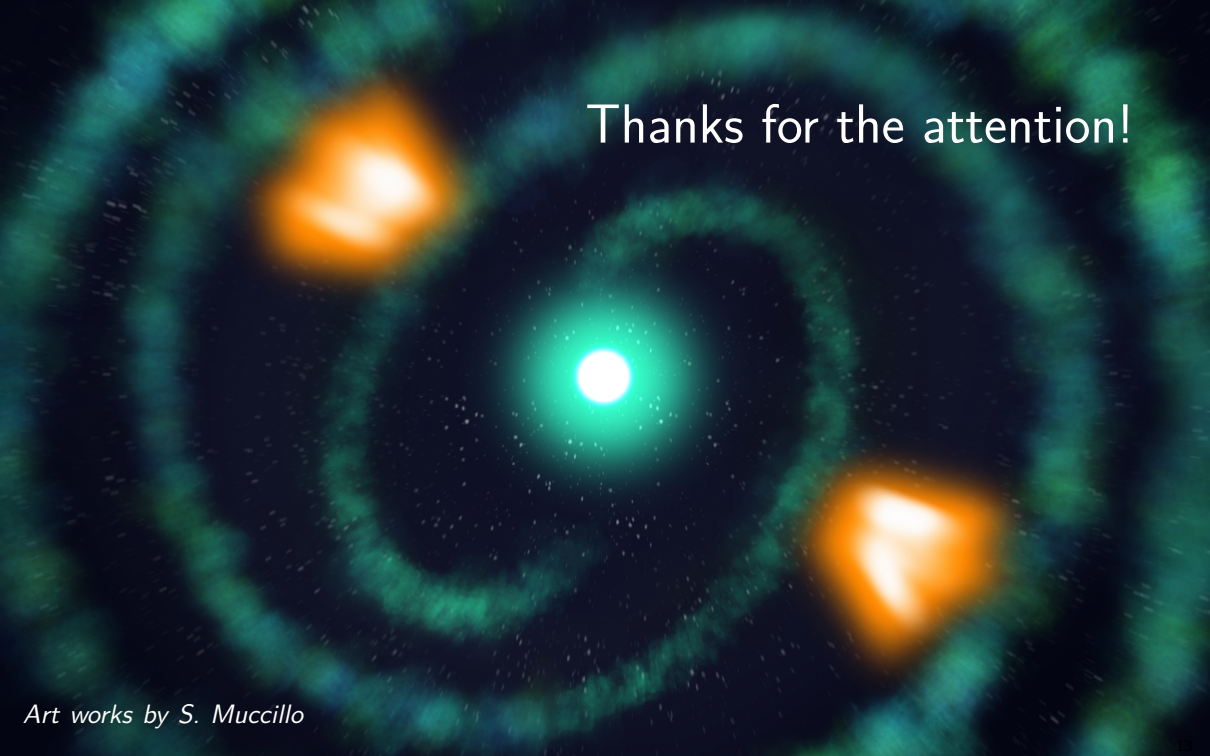
Conclusions

Conclusions

Summary: linear regression as proof of concept for **multimodal analysis**.

Next steps

- update of the network architecture in order to perform parameter estimation over z and $\cos(\iota)$;
- taking into account other parameters of the source, both on the GW and EM side;
- add other interesting messengers (kilonovae, neutrinos, ...);
- adjust network architecture for detection.

A cosmic scene featuring a central bright green star, two orange stars, and green nebulae. The background is dark with scattered white stars.

Thanks for the attention!

Art works by S. Muccillo