Detecting the early inspiral of a gravitational-wave signal with convolutional neural networks

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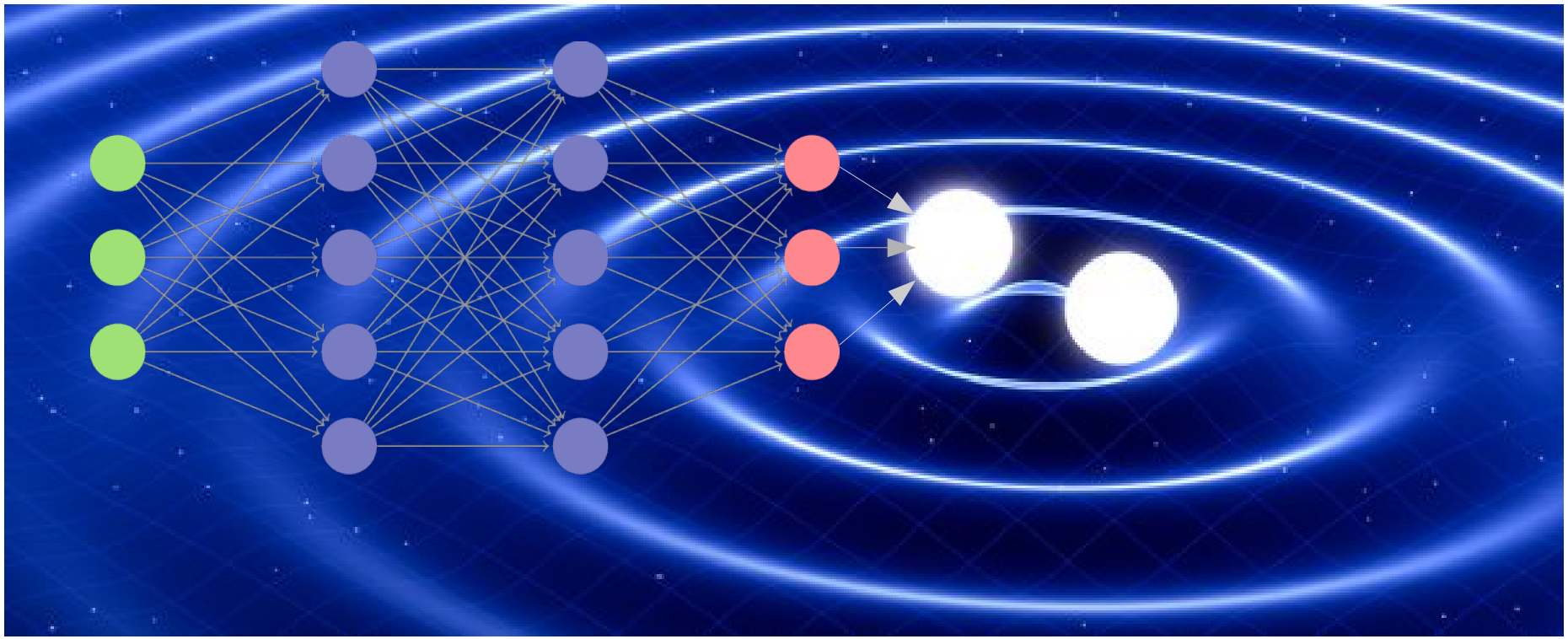
9th Belgian-Dutch Gravitational Waves Meeting



Goals and motivations

Proof of concept

Goal : Detect the early inspiral phase of a BNS with convolutional neural network (CNN)

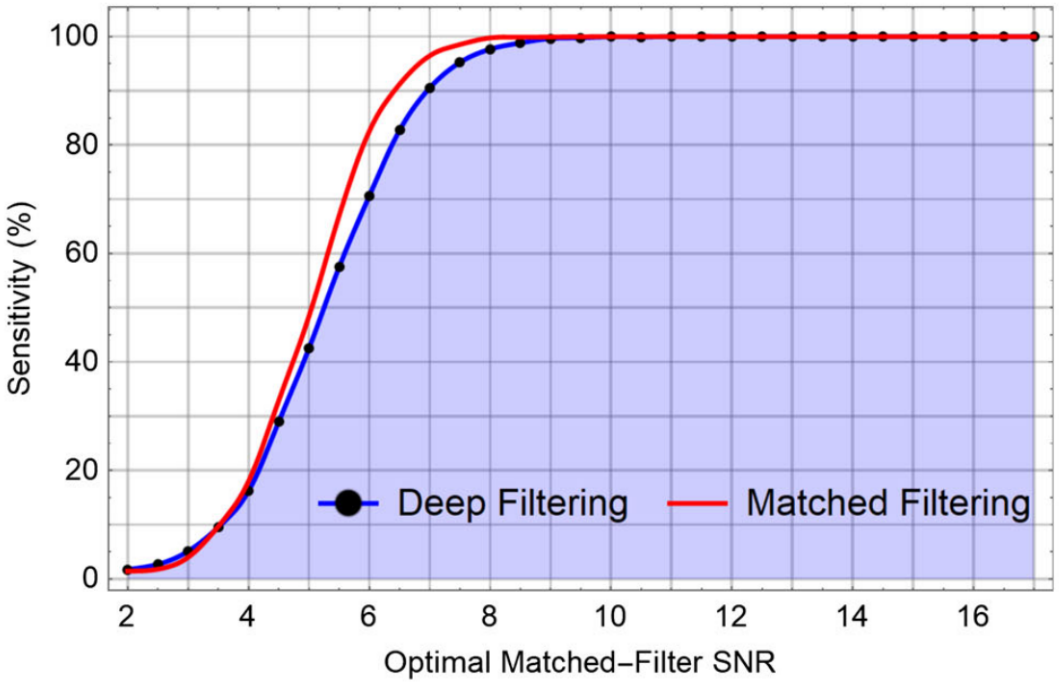
Motivation:
Multi-messenger astronomy
early alert system

Why deep learning ?

- Computationally cheap after the training
- Fast to analyze a data frame
- Does not require a template bank during the search

Previous CNN works

- Several papers using CNN to detect CBC: *arXiv:1711.07966 , arXiv:1711.03121, arXiv:1712.06041*
- Focus on the whole waveform or the merger
- Reach sensitivities similar to matched filtering



Recent paper on pre-merger search:
arXiv:2010.09751, arXiv:2104.09438, arXiv:2104.00594

Matched filtering and pre-merger search

Matched filtering SNR

$$\rho = \left(4\,\mathfrak{Re} \left(\int_{f_{min}}^{f_{max}} \frac{\tilde{d}(f)\tilde{h}^*(f)}{\mathcal{P}(f)} df \right) \right)^{1/2}$$

ρ = signal-to-noise-ratio (SNR)
d = data
h = waveform
f = frequency
P = power spectral density (PSD)

Matched filtering pre-merger

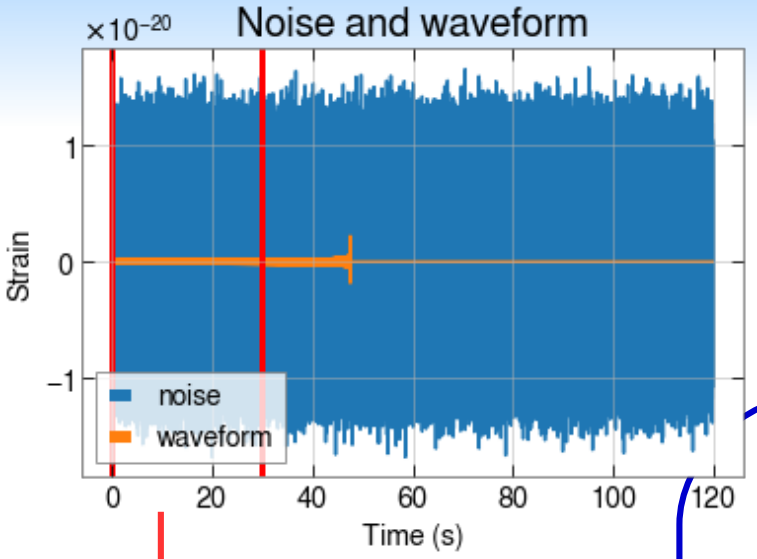
"An early warning system for electromagnetic follow-up of gravitational wave events", *Surabhi Sachdev et al.* arXiv:2008.04288v2

Perform multiple matched filtering searches with different f_{max} (29 Hz, 32 Hz, 38 Hz, 49 Hz, 56 Hz, and 1024 Hz). We will call this partial inspiral SNR (PI SNR).

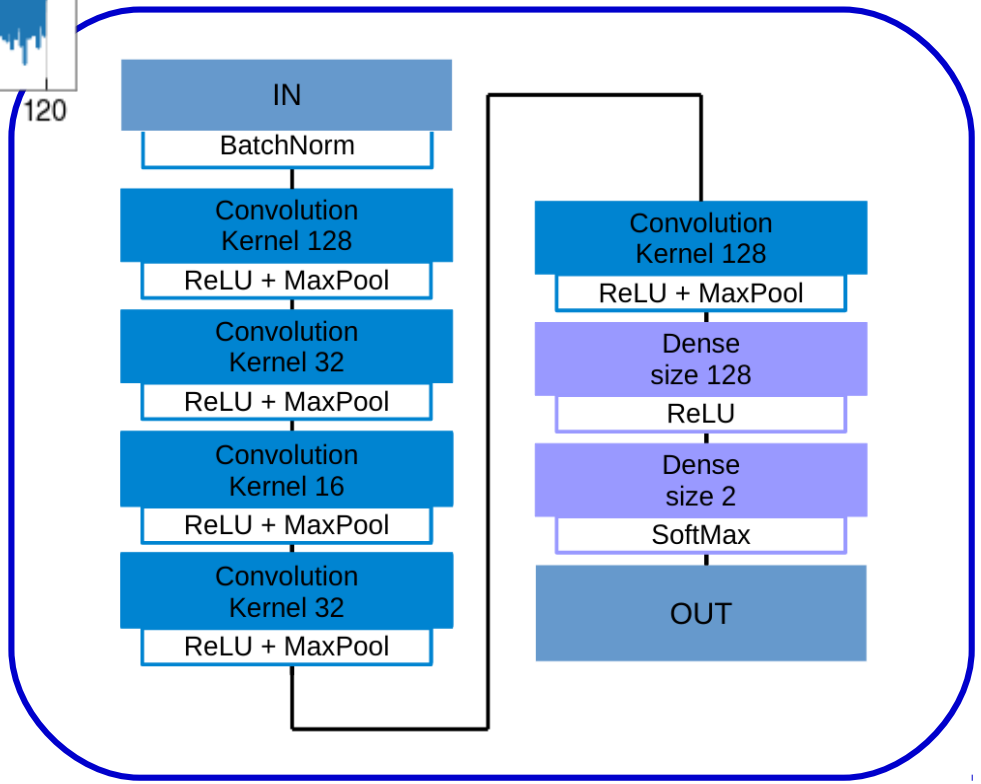
→ Corresponds to search for a fraction of the inspiral

Conclusion: It is possible to detect realistic BNS into design sensitivity noise even for low f_{max}

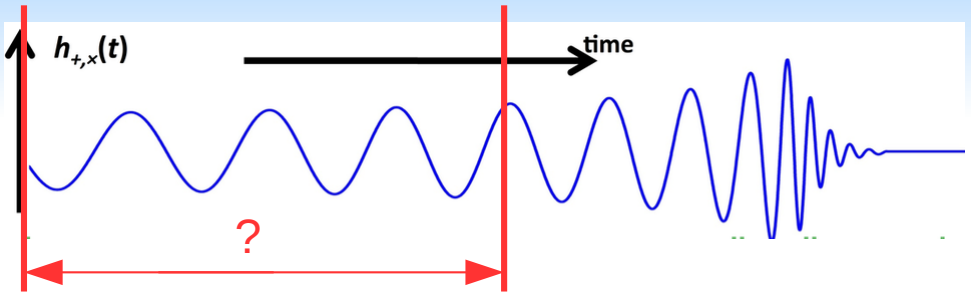
CNN for early detections



Output : [0,1]
If output > Threshold
→ Signal
If output < Threshold
→ Only noise



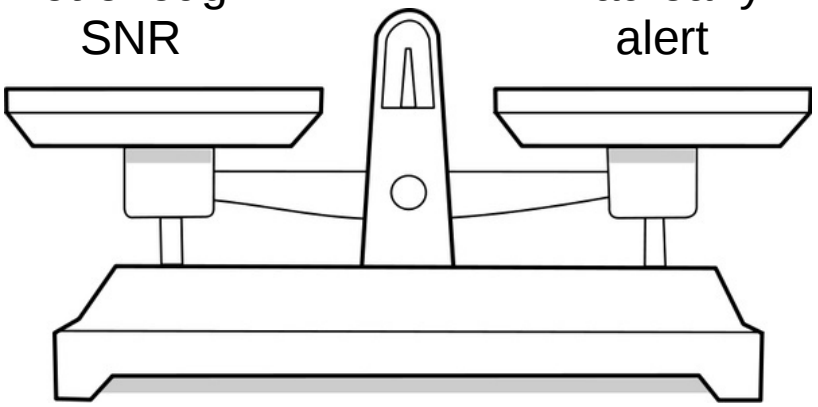
Observable time window



Which inspiral duration to choose?

Too short:
Not enough SNR

Too long:
Bad early alert



Problem : the length of the signal depends of the masses !

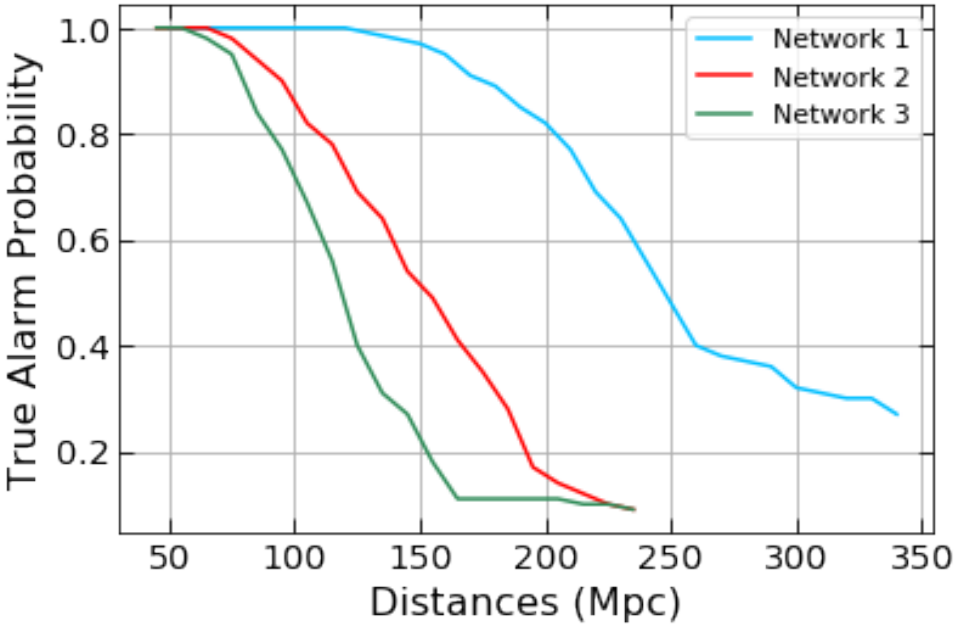
Solution : Multiples categories of BNS

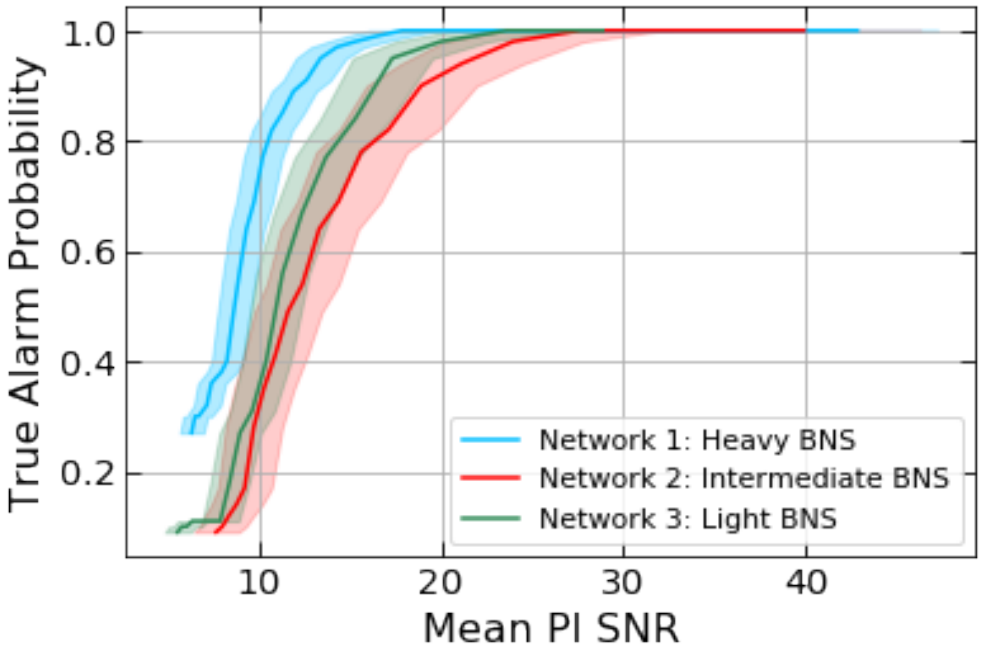
Object	light BNS	intermediate BNS	heavy BNS
$\mathcal{M}_c$ $(M_\odot)$	1.21 - 1.56	1.56 - 2.09	2.09 - 2.61
$m_1 = m_2$ mass range $(M_\odot)$	1.4 - 1.8	1.8 - 2.4	2.4 - 3
f_{low} (Hz)	20	20	20
Duration (s)	160 - 100	100 - 65	65 - 45
OTW (s)	80	50	30
Fraction of signal	0.5 - 0.8	0.5 - 0.77	0.46 - 0.66
Early alert before merger (s)	80 - 20	50 - 15	35 - 15

Each category has its own CNN

Performance of the CNNs

Testing the network over 4000 frames

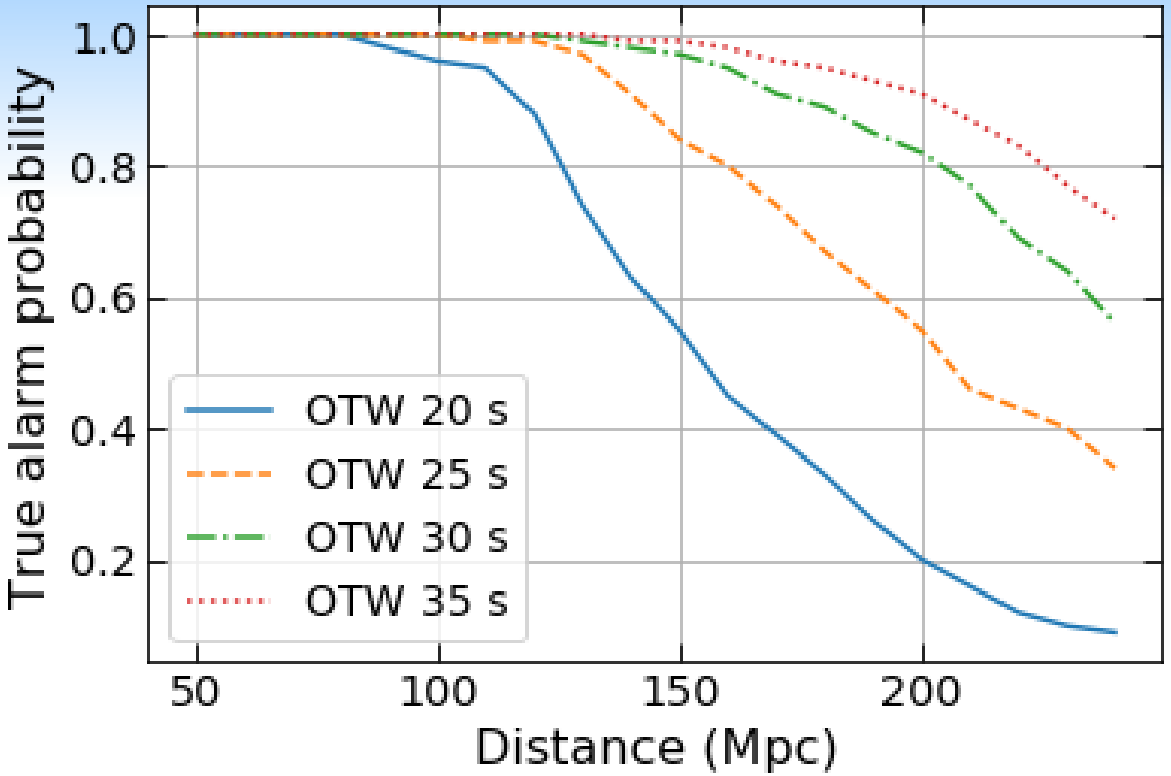




False alarm rate : 1%

PI SNR = Partial inspiral SNR

Influence of the OTW



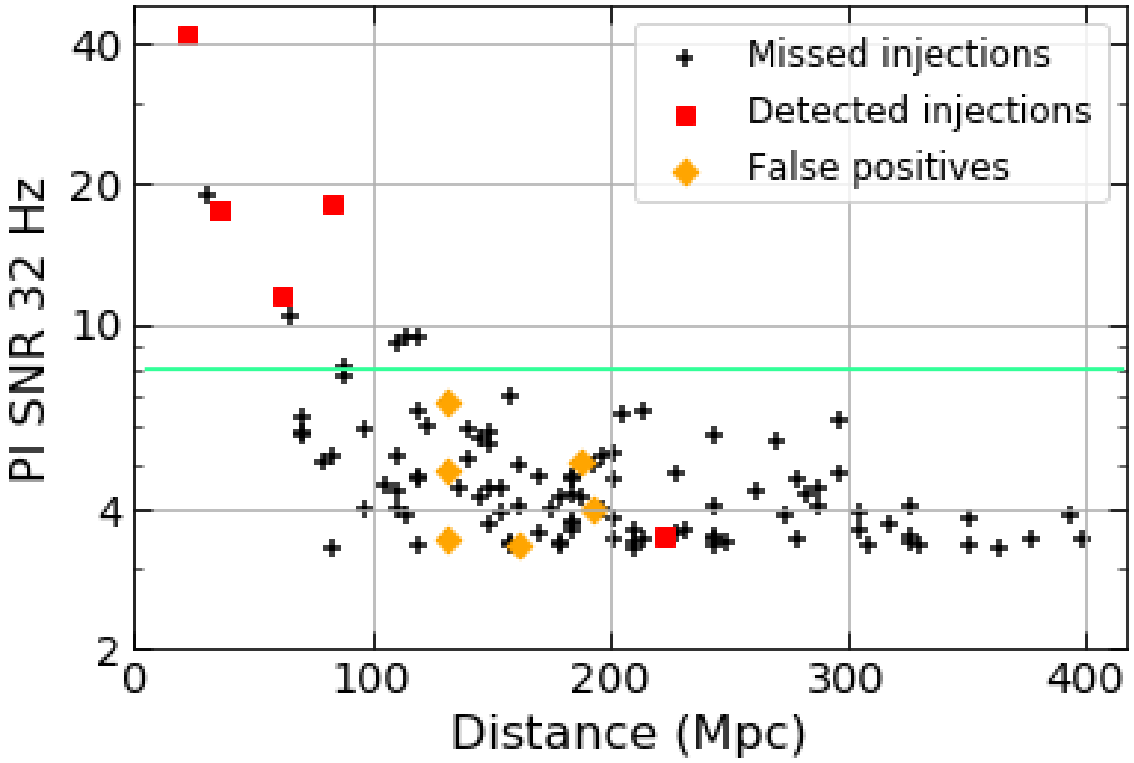
Bigger OTW = better results, but less time before the merger

OTW	20s	25s	30s	35s
Time before merger	35s	30s	25s	20s

On a realistic population

Comparison with matched filtering

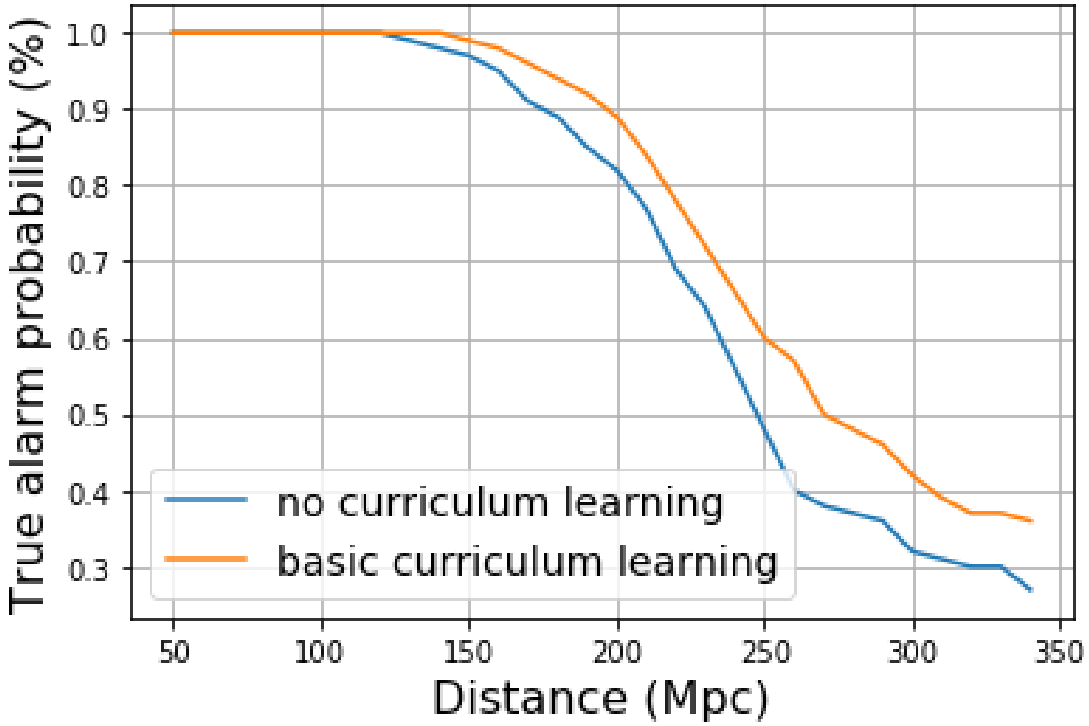
- Simulation of a real BNS population
- Compute the PI SNR
- Usual threshold for matched filtering detection = 8



→ Matched filtering could detect a few more events,
but CNNs are faster: ~0.005s on Nividia GeForce RTX 2070 SUPER GPU

Improvement: curriculum learning

Curriculum learning: train a network on decreasing PI SNR batches



One step curriculum learning: already increases the results.

Improvement: Future prospects

- Implement a more efficient curriculum learning
- Currently only one detector pipeline → upgrade to network (will decrease the FAP)
- Testing on more realistic data
- Include sky localization with neural networks
- Exploring other more exotic architectures

Conclusion

- Gravitational waves are important for MMA
- There is a need to detect the signal before the end of the merger
- Standard technique could be too slow / computationally expensive
- We developed a pipeline to detect the early inspiral phase with CNN
- Performance similar to matched filtering but faster
- Lot of improvements are possible
- Some questions like the sky localization are now under consideration

Our paper on this work: arXiv:2104.00594v1

Thank you for your attention