Credit: N. Fischer

HYPERION:

a Normalizing Flow based pipeline for the rapid parameter estimation of eccentric Close Encounters

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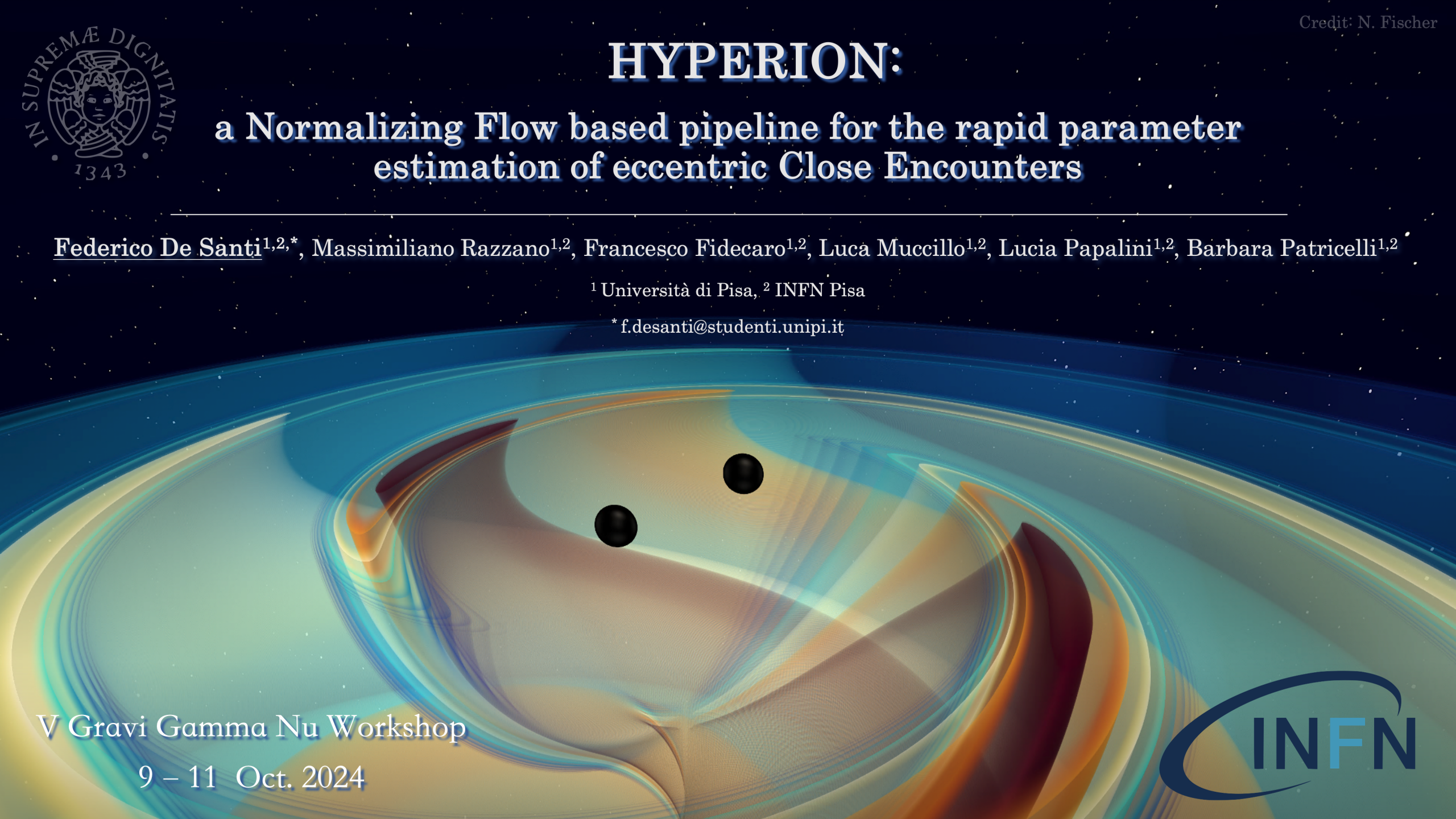
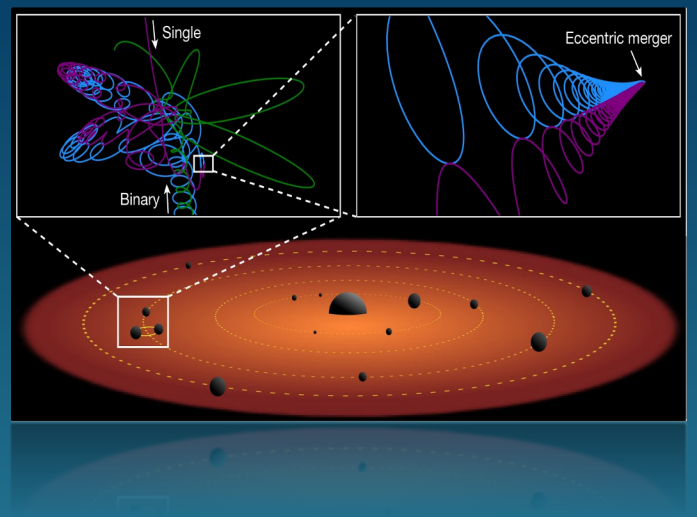


V Gravi Gamma Nu Workshop

9 – 11 Oct. 2024

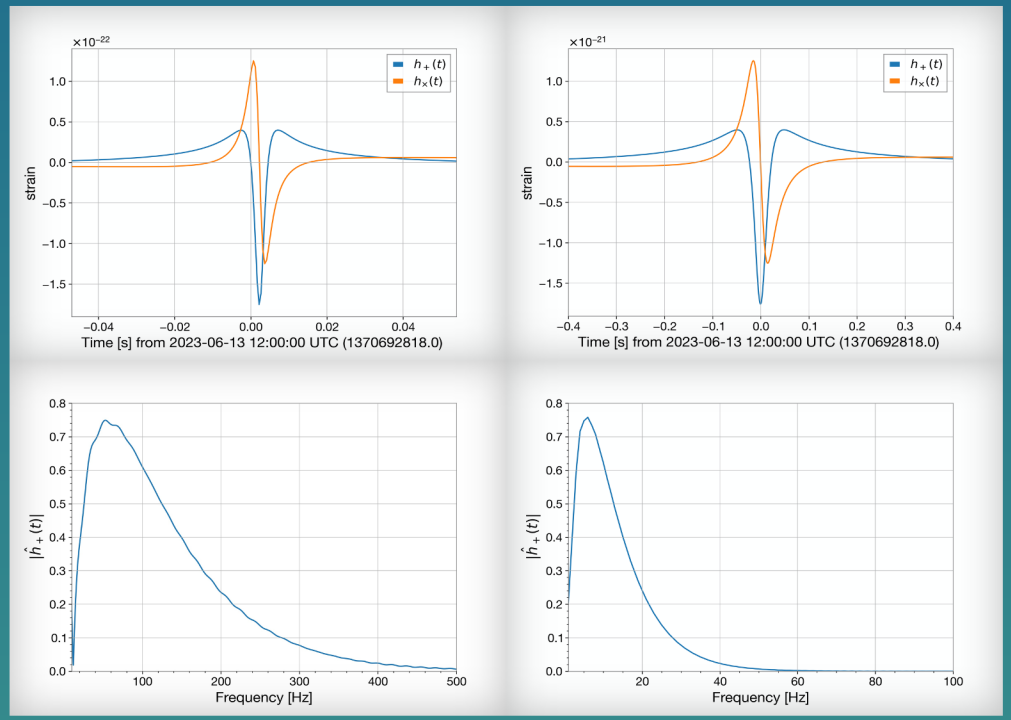
Close Encounters in brief



Samsing J. (2022)

- High eccentricity ($e \sim 1$):
  - $\Rightarrow$ GW emission: Repeated Bursts at each periastron
  - $\Rightarrow v \sim 0.7c \rightarrow$ strong field regime / GR Tests
  - $\Rightarrow$ f-modes excitation in Neutron Stars $\rightarrow$ Equation Of State constraints
  - $\Rightarrow$ Dynamical formation channel $\rightarrow$ Astrophysics
  - $\Rightarrow$ Possible e.m. counterparts $\rightarrow$ Multimessenger Astronomy

Waveform Example with EFB-T model *(Loutrel N. (2020))*



$10\ M_\odot + 10\ M_\odot$ $100\ M_\odot + 100\ M_\odot$

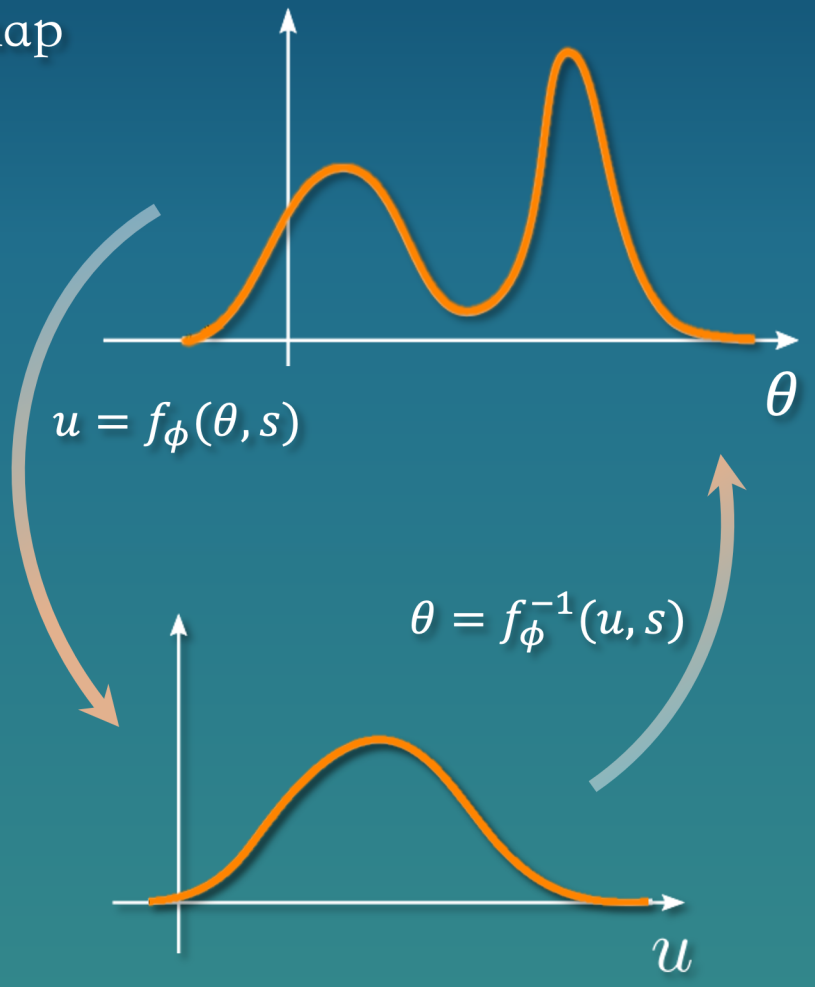
- Challenges for PE and detection:
  - Low SNR with current sensitivities
  - Burst-like signal with small frequency evolution

Normalizing Flows

Papamakarios G. (2019)

- **Key idea:** parametrize an analytical function $f\colon \mathbb{R}^N \to \mathbb{R}^N$ to map GW parameters into a simpler distribution

$$\theta \xrightarrow{f(s)} u \sim \pi(u) = \mathcal{N}(0, \mathbb{I})$$



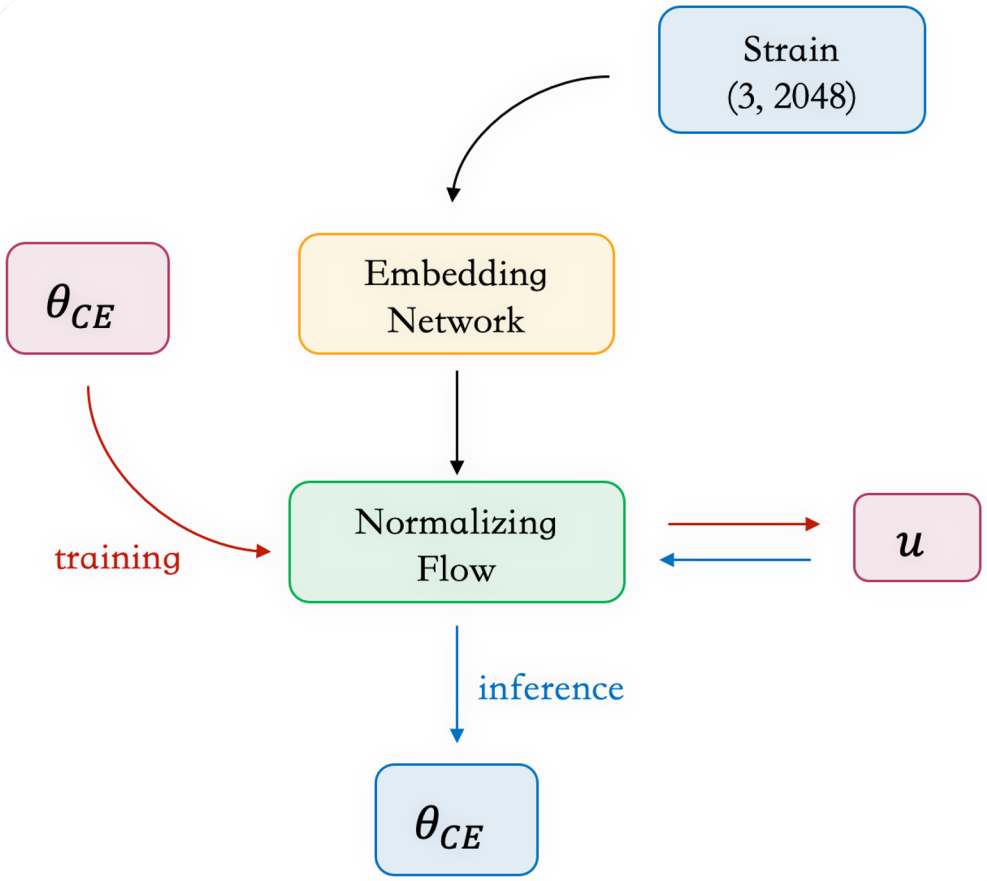
- f must:
  - be invertible and differentiable
  - depend on parameters ϕ ← NN output

$$p(\theta|s) \approx q(\theta|s) = \pi\left(f_\phi(\theta, s)\right) \left|\det J\left(f_\phi(\theta, s)\right)\right|$$

HYPERION: Model Overview

De Santi et al., Phys. Rev. D 109, 102004 (2024)

- **HYP**er fast close **E**ncounte**R** **I**nference from **O**bservations with **N**ormalizing flows



- Developed in Python + PyTorch
- Input: Strain Timeseries
- Output: $\theta_{CE} = \{M, q, e_0, \bar{p}_0, d_L, \delta t_p, \alpha, \delta\}$
- Core modules:
  - Embedding Network: CNN, extracts features
  - Normalizing Flow: coupling layers, reconstructs posterior distribution
  - ~ 180 M parameters

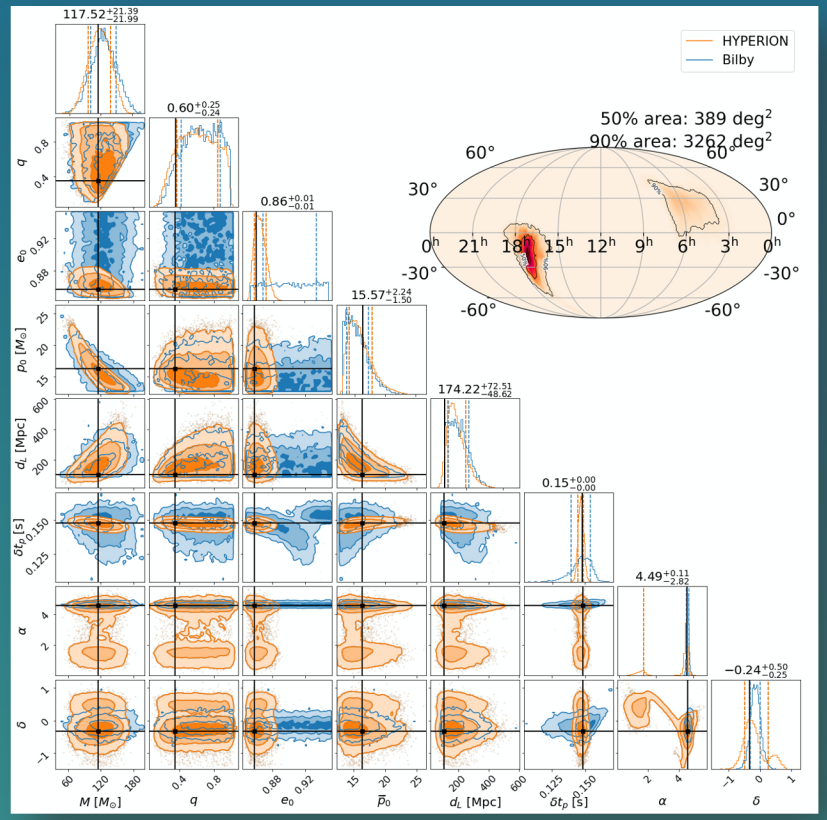
HYPERION Performances

10^4 TIMES FASTER!

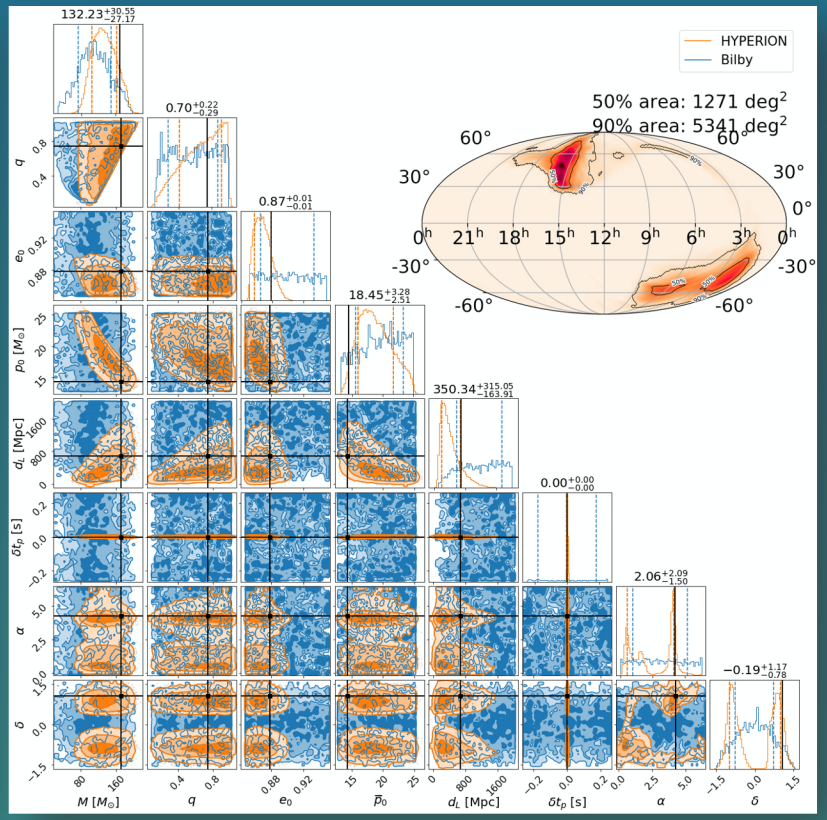
- Comparison with standard PE tools e.g. Bilby: (*Ashton G. et al. (2018)*) :

	Posterior samples	Inference time
Bilby	~ 5×10^3	~ 10 h
HYPERION (CPU)	5×10^4	~ 16 s
HYPERION (GPU)	5×10^4	~ 0.5 s

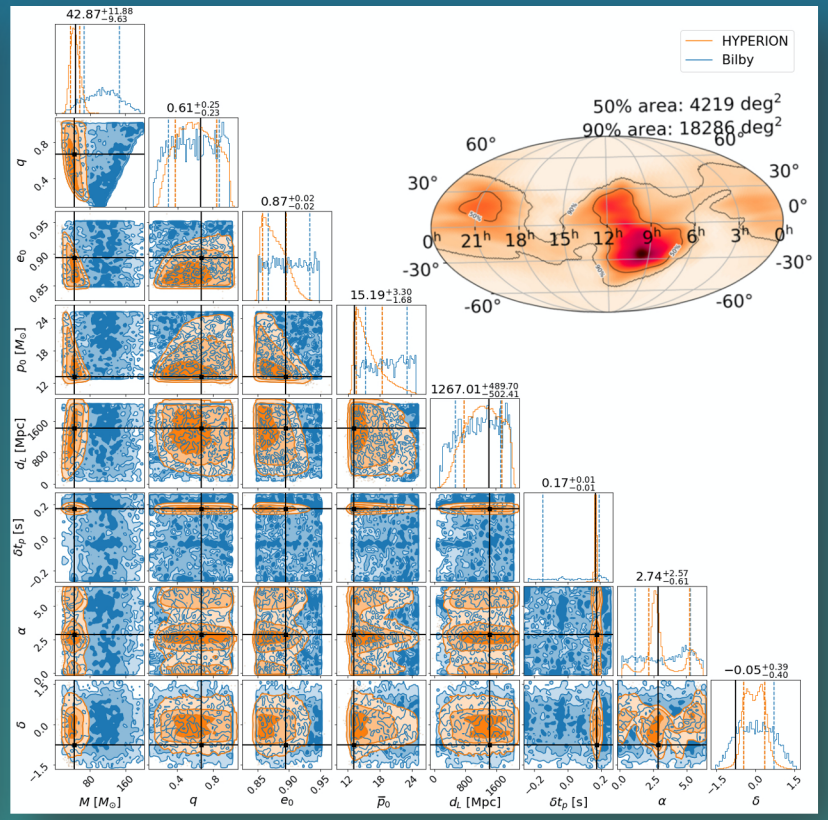
- SNR ≃ 30



- SNR ≃ 12



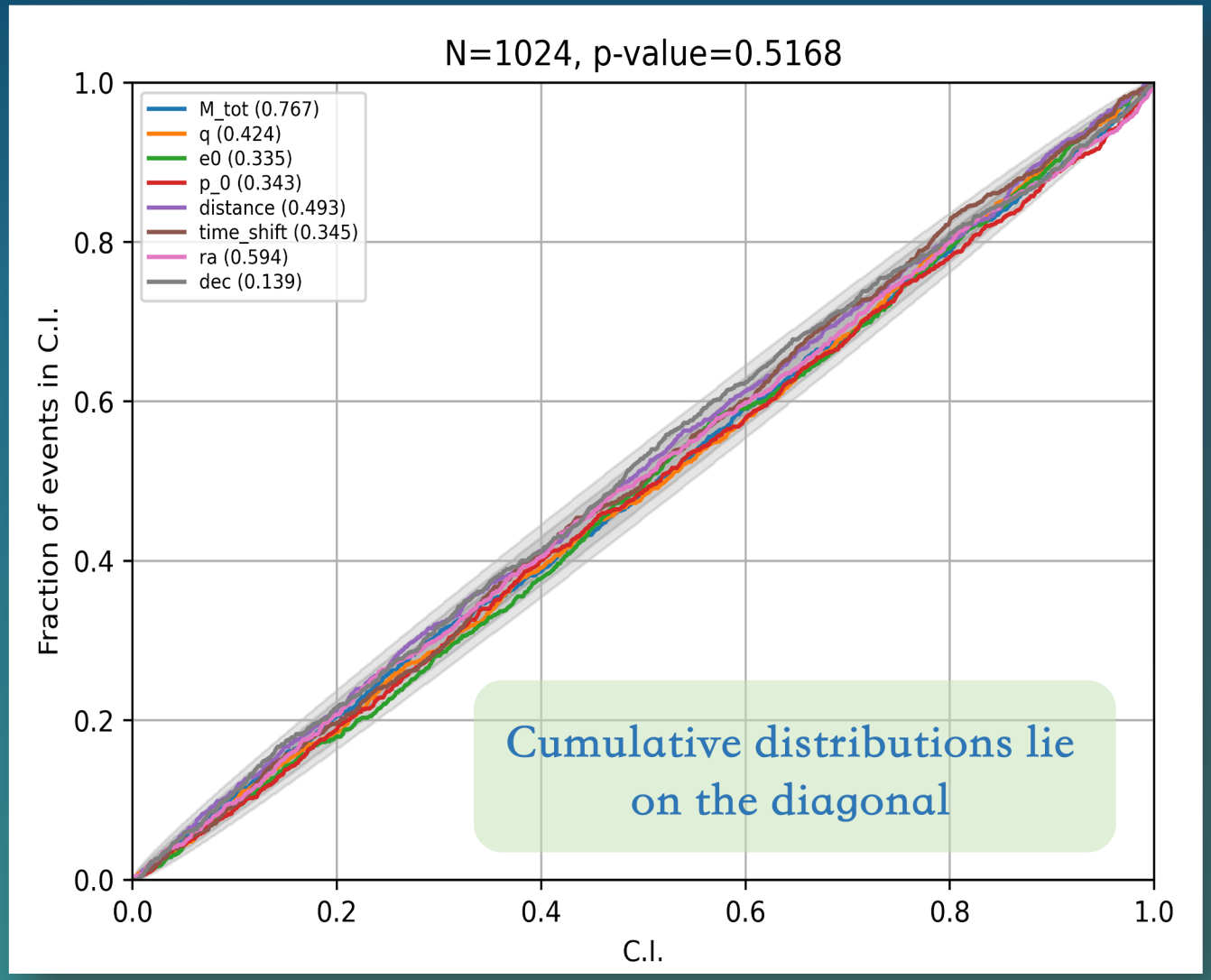
- SNR ≃ 6



HYPERION Performances

1. Obtain posterior for 1024 events from the test dataset
2. For each parameter compute the percentile score of the true value in the marginalized posterior
3. Take the cumulative distributions
4. Kolmogorov-Smirnov Test (95%)

➢ Promising approach on simulations



Conclusion & Future prospects

- Normalizing Flows for Close Encounters :
  - CEs are interesting but challenging sources
  - Likelihood – free approach
  - $\sim 10^4$ times faster than traditional methods → low latency → e.m. follow-up
  - To our knowledge, first application to CE
  - Method paper: *De Santi et al., Phys. Rev. D 109, 102004 (2024)*

- Future work :
  - Test detection capabilities on real data
  - Perform systematic searches over O3

Thank you for the attention!

If you're curious about this work, please come and chat!