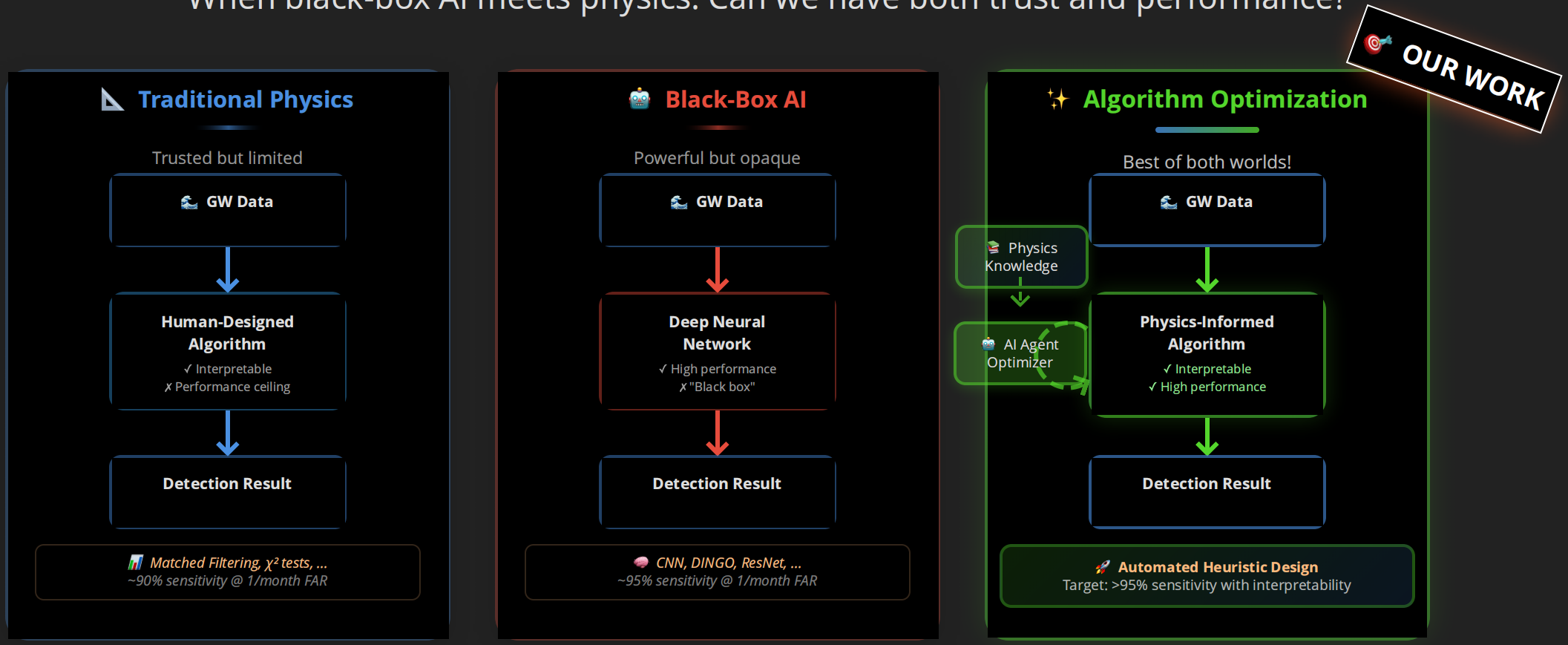
Interpretable AI for Gravitational Wave Detection

When black-box AI meets physics: Can we have both trust and performance?

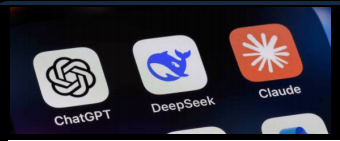


Key Innovation: Agent-based LLMs iteratively optimize physics-based algorithms, creating transparent AI systems that scientists can trust and understand

Presenter: **He Wang**

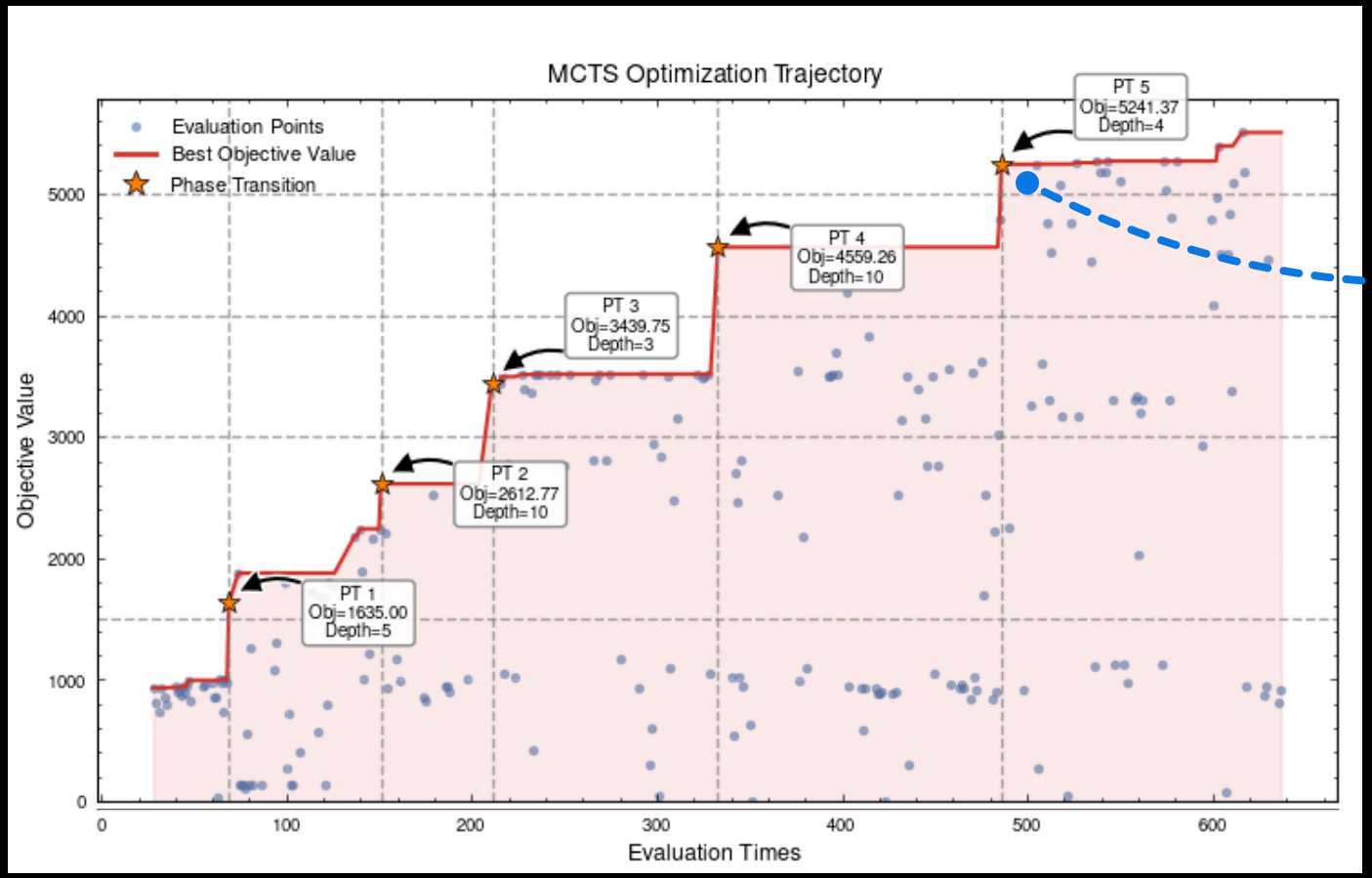
Agent-Based Optimization Framework for GW Detection

Iterative algorithm development guided by physics-informed AI agents



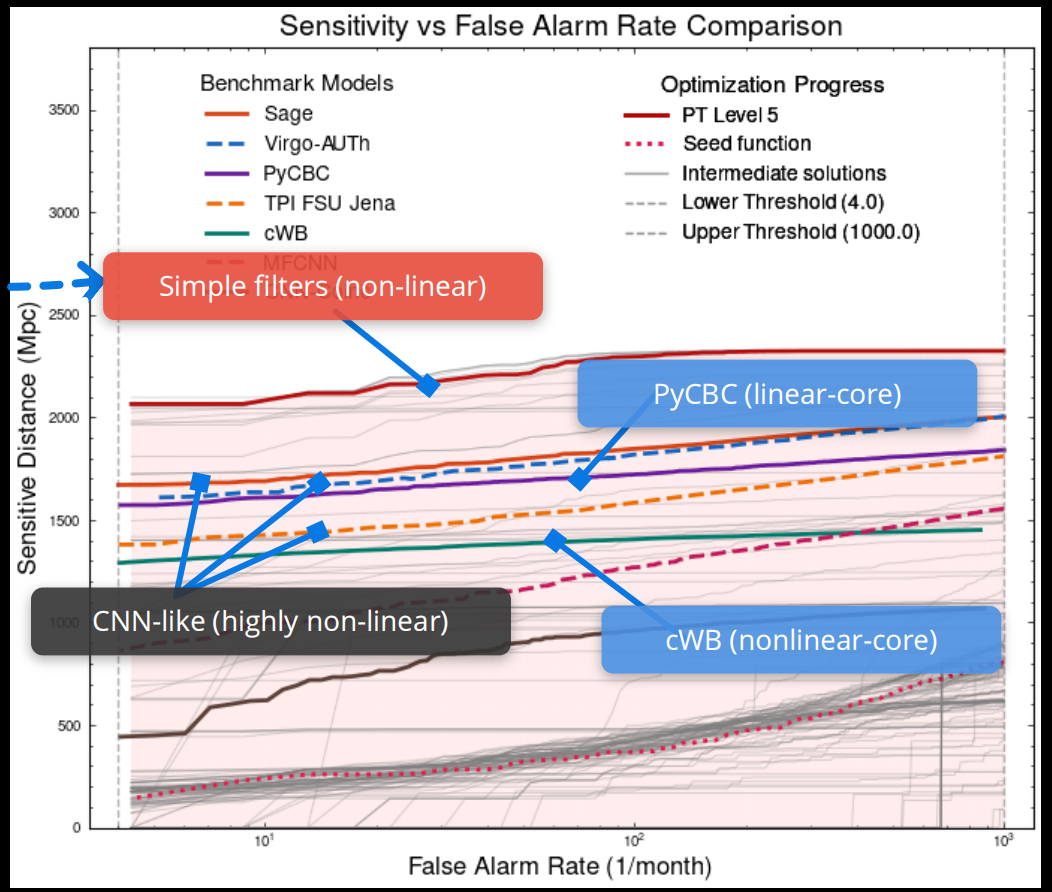
MCTS Optimization Trajectory

Automated exploration of algorithm parameter space



Sensitivity vs False Alarm Rate Comparison

Benchmarking against state-of-the-art methods



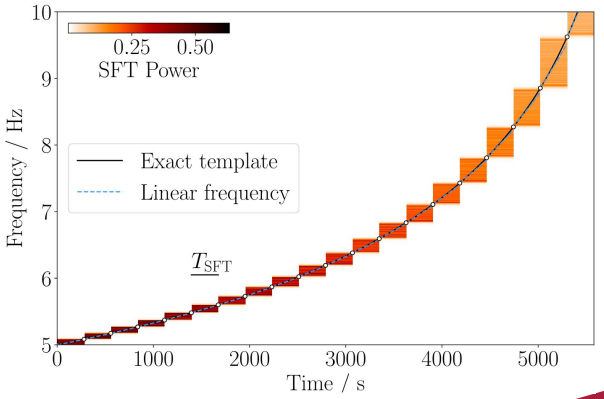
Framework Advantage: Agent-based LLMs navigate complex optimization landscapes, achieving targeted performance improvements while maintaining algorithmic interpretability

How to analyze long-duration CBC signals

with a time-varying detector response, non-stationary noise, and data gaps

Stop using this!

$$\langle x, h\rangle = 4\,\mathrm{Re}\int_0^\infty \mathrm{d}f\,\frac{\tilde{x}^*(f)\tilde{h}(f)}{S_\mathrm{n}(f)}$$



$$([d,h]) \doteq \Delta f \sum_{\alpha=0}^{N_{\mathrm{SFT}}-1} A_\alpha \Lambda_\alpha e^{i\varphi_\alpha} \mathcal{C}(f_\alpha, \dot{f}_\alpha; \tilde{d}_\alpha)$$

Use Short Fourier Transforms!

Rodrigo Tenorio
rodrigo.tenorio@unimib.it
U. Milano-Bicocca

Tenorio & Gerosa
PRD 111, 104044 (2025)

github.com/rodrigo-tenorio/sfts

Long-duration signals are **hard** to analyze in **frequency domain**.

"2G methods but longer"-approach won't cut it.

SFTs provide **(100–1000)x acceleration and data compression** and **solve all problems** related to **long durations**.

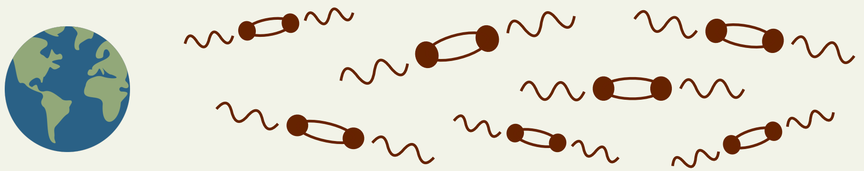
Reconstructing parametric gravitational-wave population fits from nonparametric results without refitting the data

C.M. Fabbri [1, 2], D. Gerosa [1, 3], A. Santini [4], M. Mould [5, 6], A. Toubiana [1, 3], J. Gair [4]

Phys. Rev. D 111 (2025) 104053,
arXiv:2501.17233

Scientific Machine Learning for Gravitational Wave Astronomy **June 2**

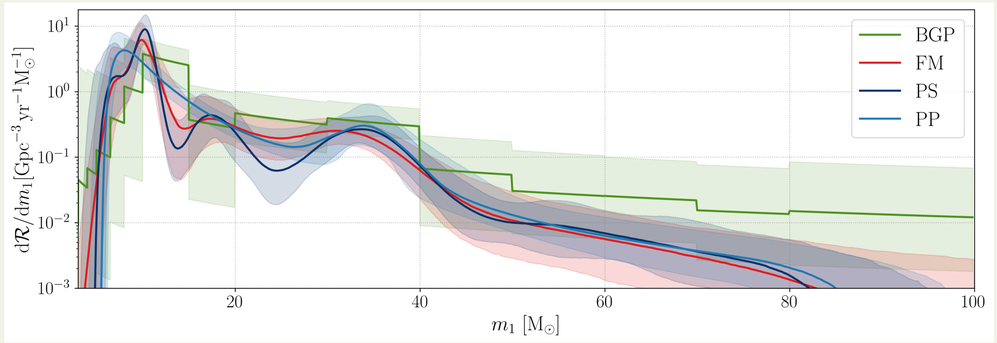
Developing new approaches for population fits



semiparametric & nonparametric	**Population models** parametric	informed by population-synthesis codes

Current approach:

Hierarchical Bayesian inference



Fit the dataset multiple times assuming different population models

Our approach:

Can we obtain multiple population fits analyzing data once?

Assume a flexible, possibly nonparametric model

fit

$p(\gamma \mid d)$

Assume an astrophysical model

fit

$p(\lambda \mid d)$

Can we get $p(\lambda \mid d)$ *without* refitting data?

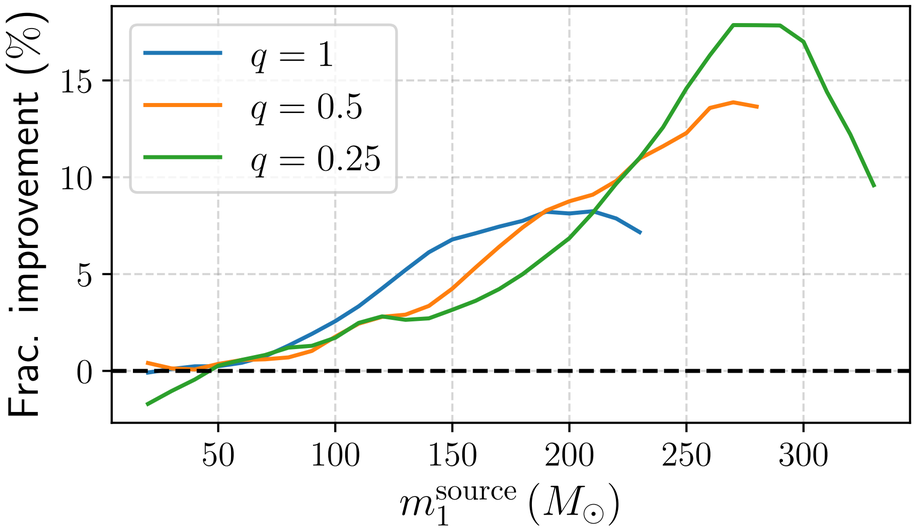
Best of both worlds: combining principled gravitational wave searches with AI/ML

(Jay) Digvijay Wadekar (JHU)

- Combining ML methods with principled matched-filtering based searches can help:

  1. build leaner ML tools which are more robust (w.r.t generalizability, interpretability)
  2. improve upon simplistic analytic assumptions (e.g., noise is Gaussian)

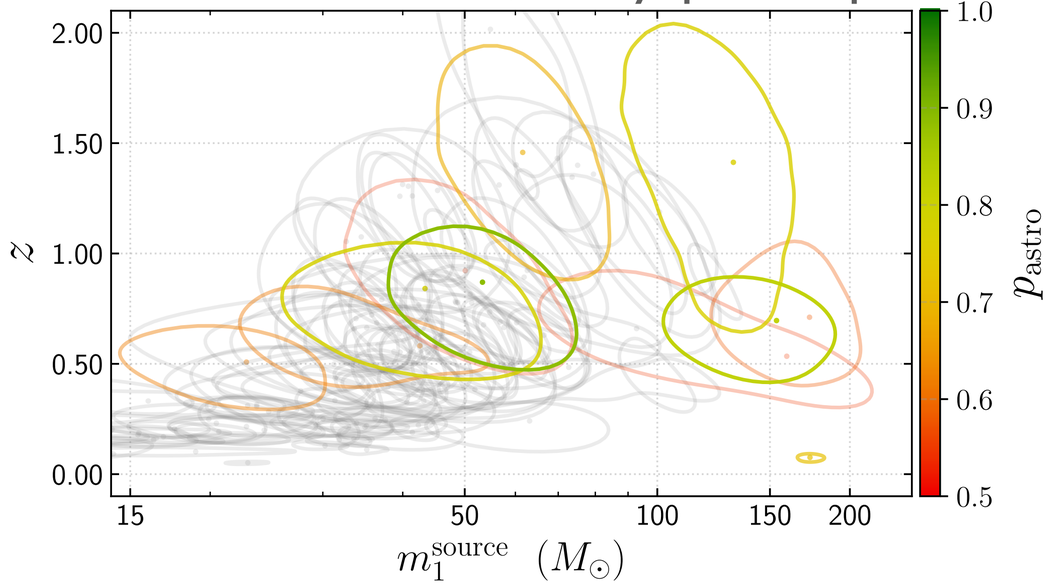
Improvement in VT from neural classifier



- We combine the IAS search pipeline with

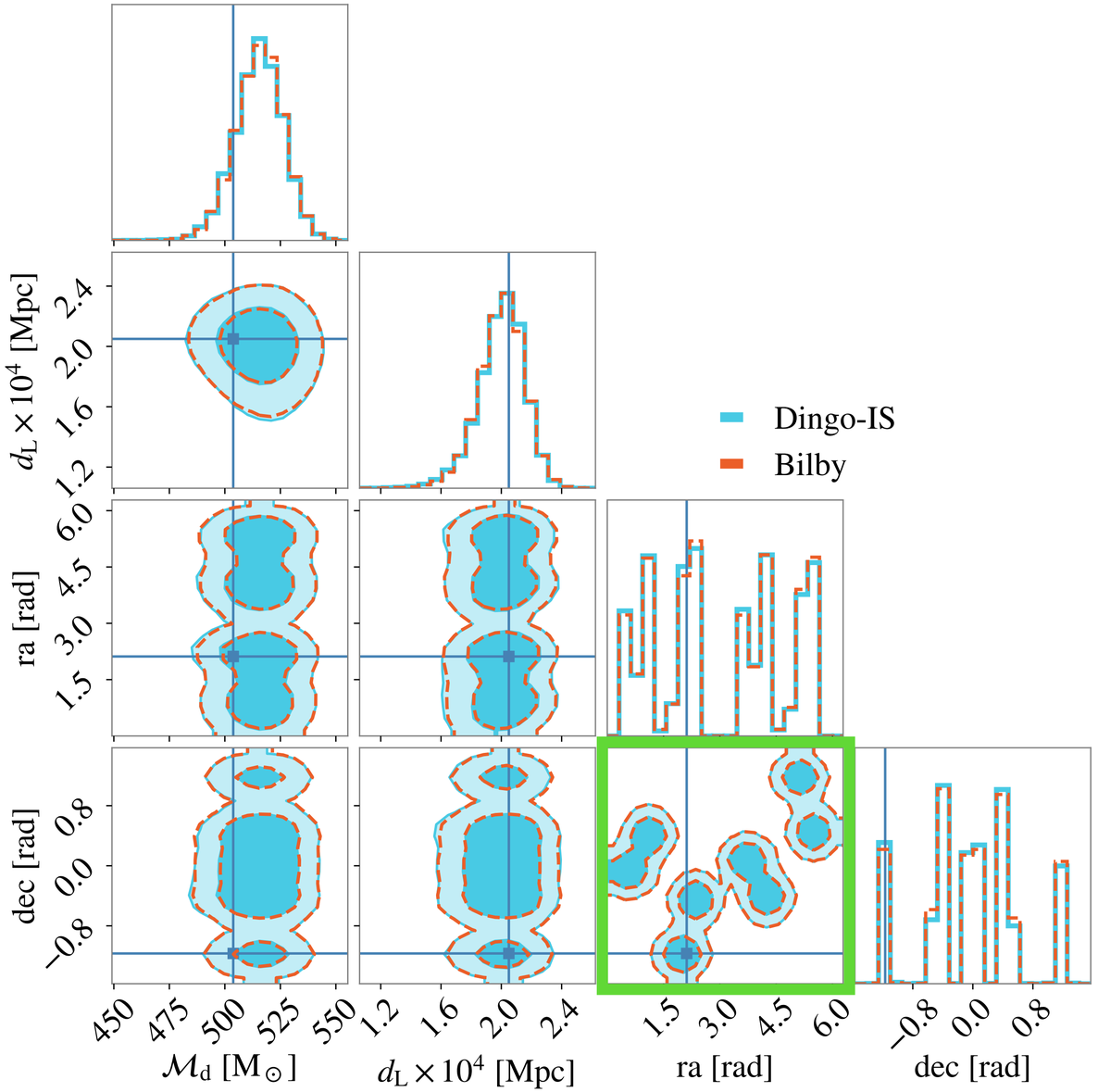
1. Autoencoders / decision trees to build more efficient template banks
2. Neural classifiers for down-weighting noise transients (increases sensitivity volume)
3. Normalizing flows for efficient marginalization over higher harmonics (and precession, eccentricity) d.o.f

Colored: New detections, Gray: prev. reported



Fast and accurate parameter estimation of high-redshift sources with the Einstein Telescope

Filippo Santoliquido,
Jacopo Tissino,
Ulyana Dupletsa,
Jan Harms,
Marica Branchesi,
Manuel Arca Sedda,
Maximilian Dax,
Annalena Kofler,
Stephen R. Green,
Nihar Gupte,
Isobel M. Romero-Shaw,
Emanuele Berti

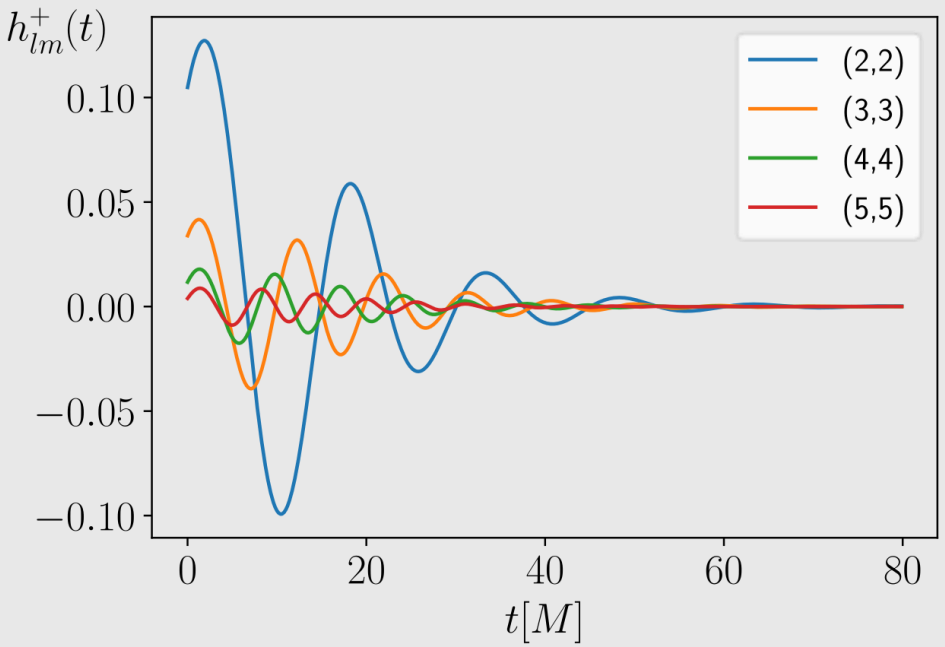


arXiv: 2504.21087

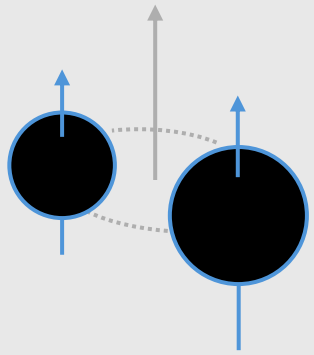
RINGDOWN MODE AMPLITUDES OF PRECESSING BINARY BLACK HOLES

Francesco Nobili, S. Bhagwat, C. Pacilio, D. Gerosa

fnobili@uninsubria.it



- Mode amplitudes depend on merger phase
- Modeling amps
  - Tests of GR
  - RD parameter estimation

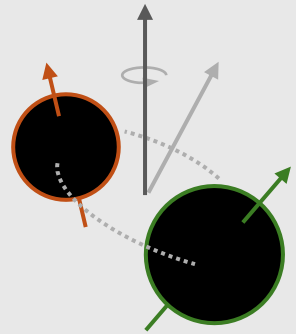


SPIN-ALIGNED

- Simpler: 3D parameter space
- Solid phenom description
- Several models

PRECESSING

- Complex: 7D parameter space
- Only 1 paper on phenom
- no models!



OUR WORK

Amp correlations with BBH physical parameters

models using Gaussian Process Regression