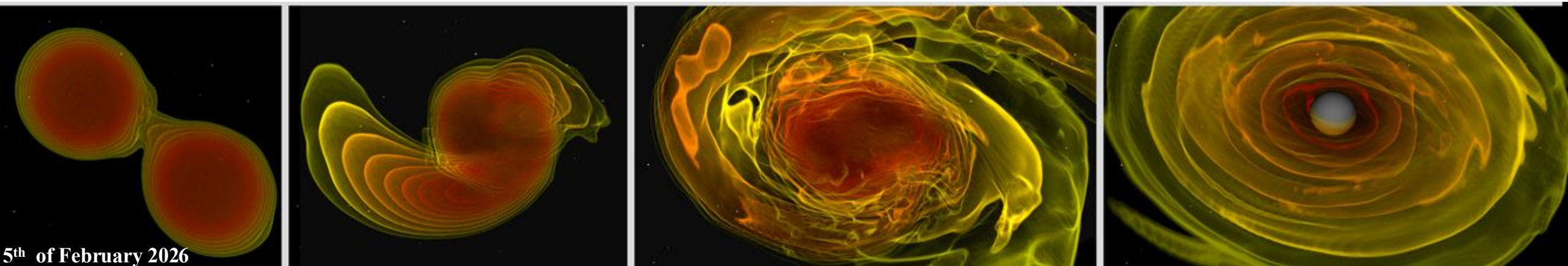
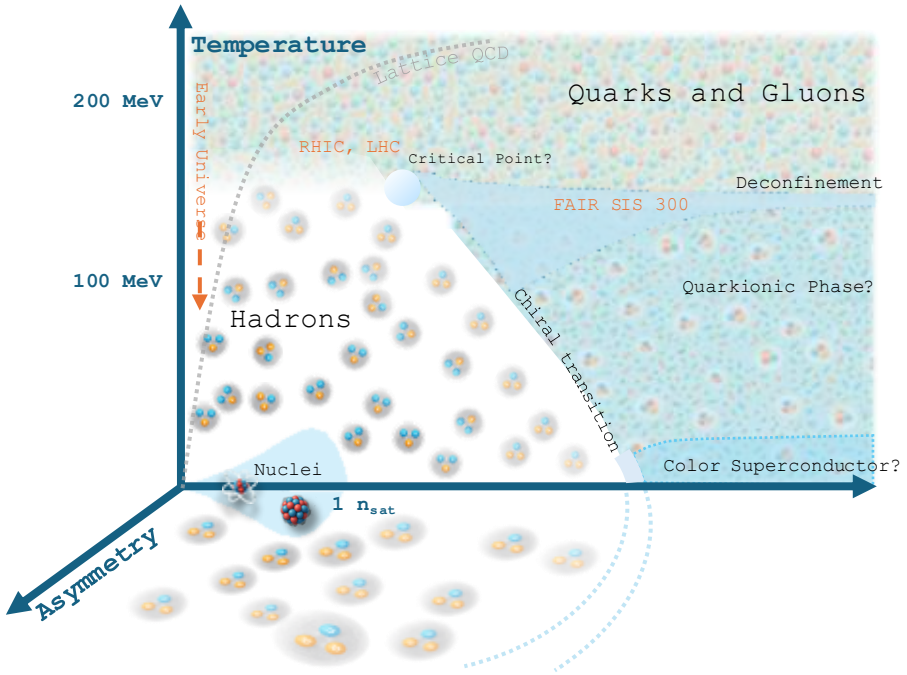
Decoding Neutron Star Mergers:
From Numerical Relativity to Multi-Messenger Inference

Tim Dietrich
University of Potsdam
Max Planck Institute for Gravitational Physics



5th of February 2026

Neutron stars… our astrophysical laboratory



TD et al. 2025, arXiv: 2512.16971

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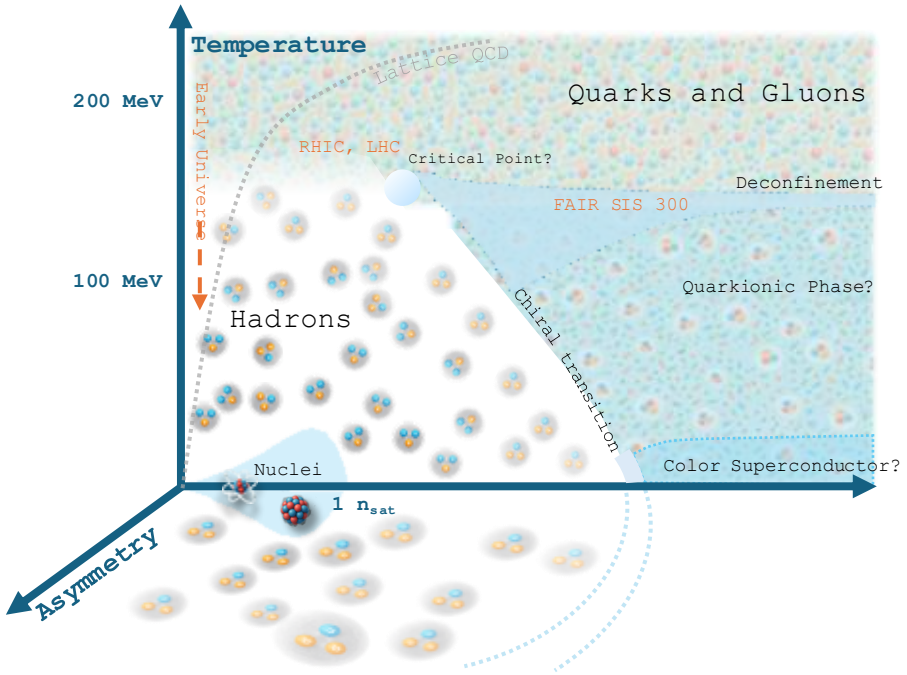

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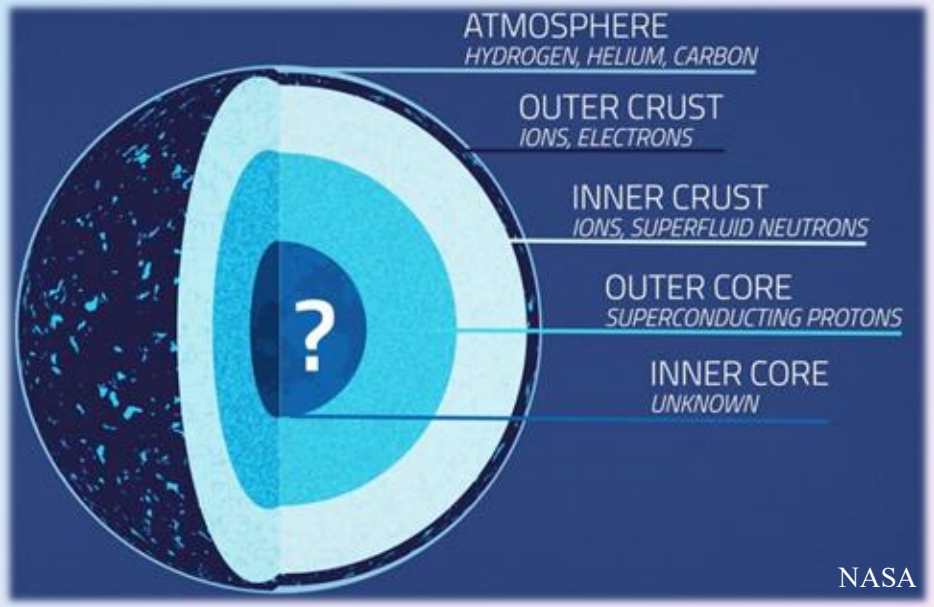
- collapsed core of massive star

- smallest and densest known class of stellar compact objects

- typical size of 12 kilometer and masses between one and two solar masses



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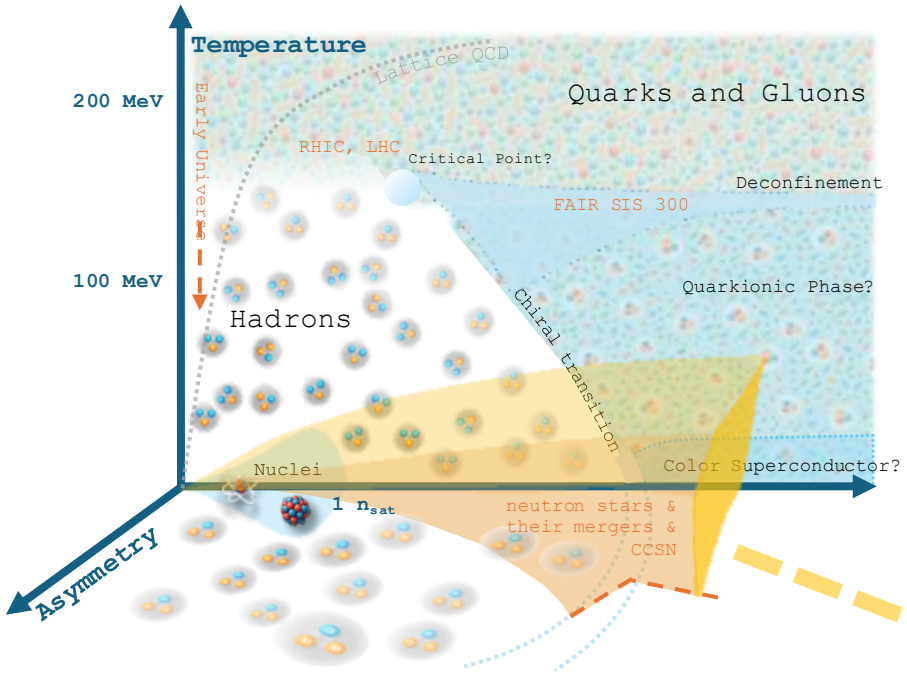

TD et al. 2025, arXiv: 2512.16971

BE CAREFUL: The equation of state is more than simply pressure vs. density

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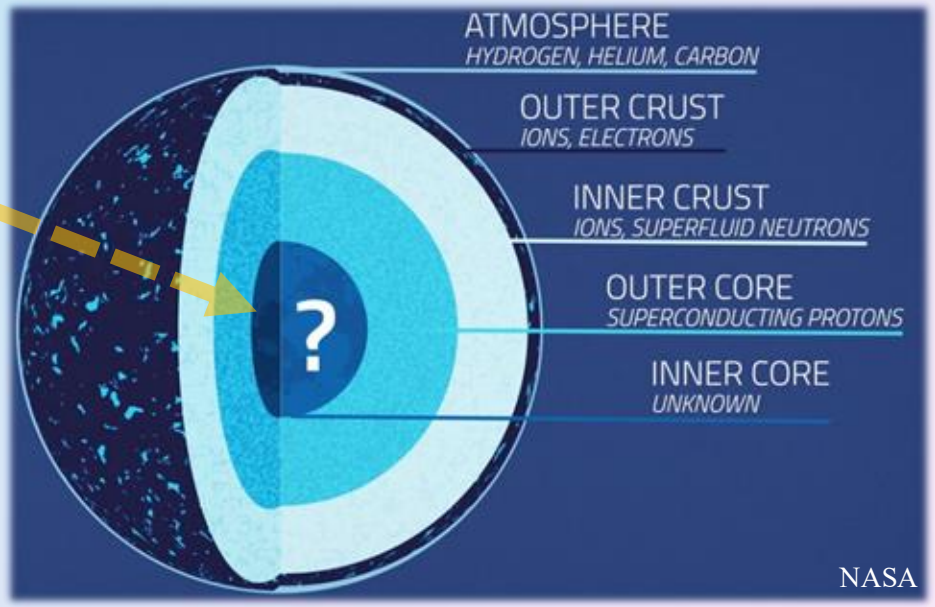

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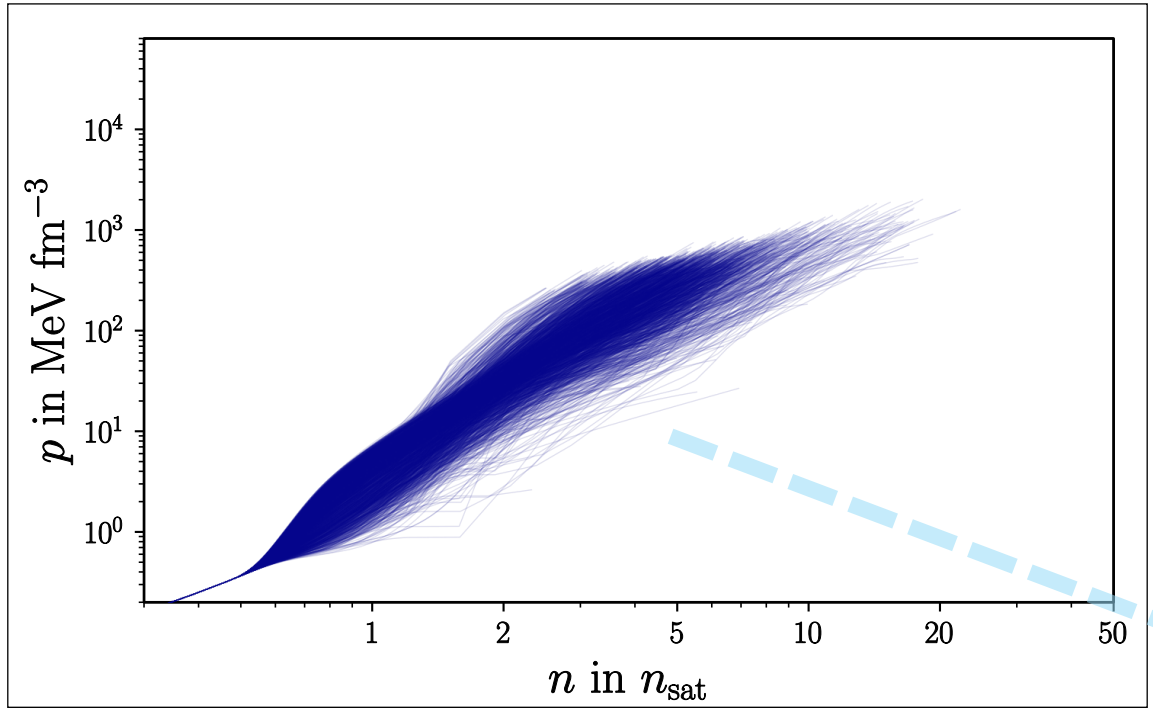

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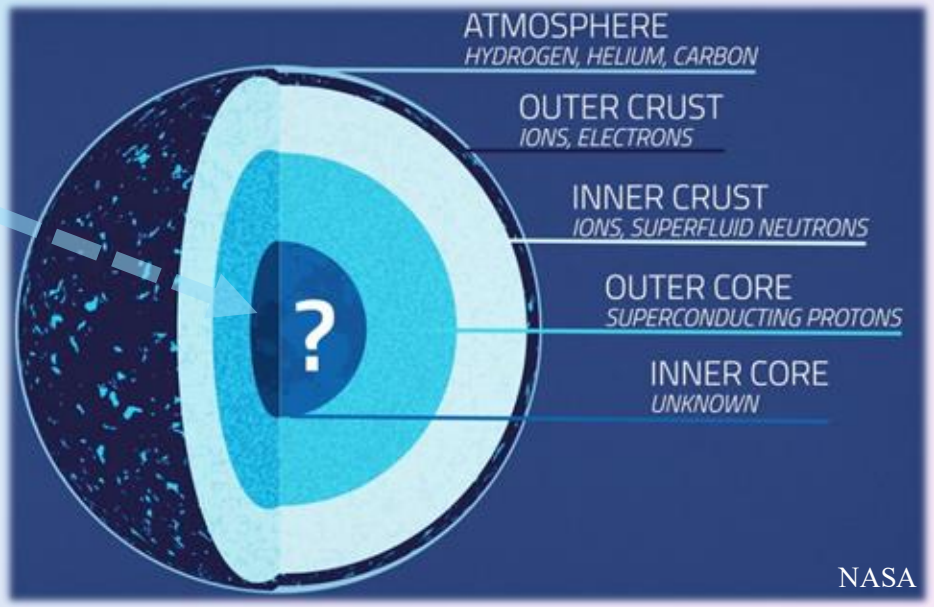
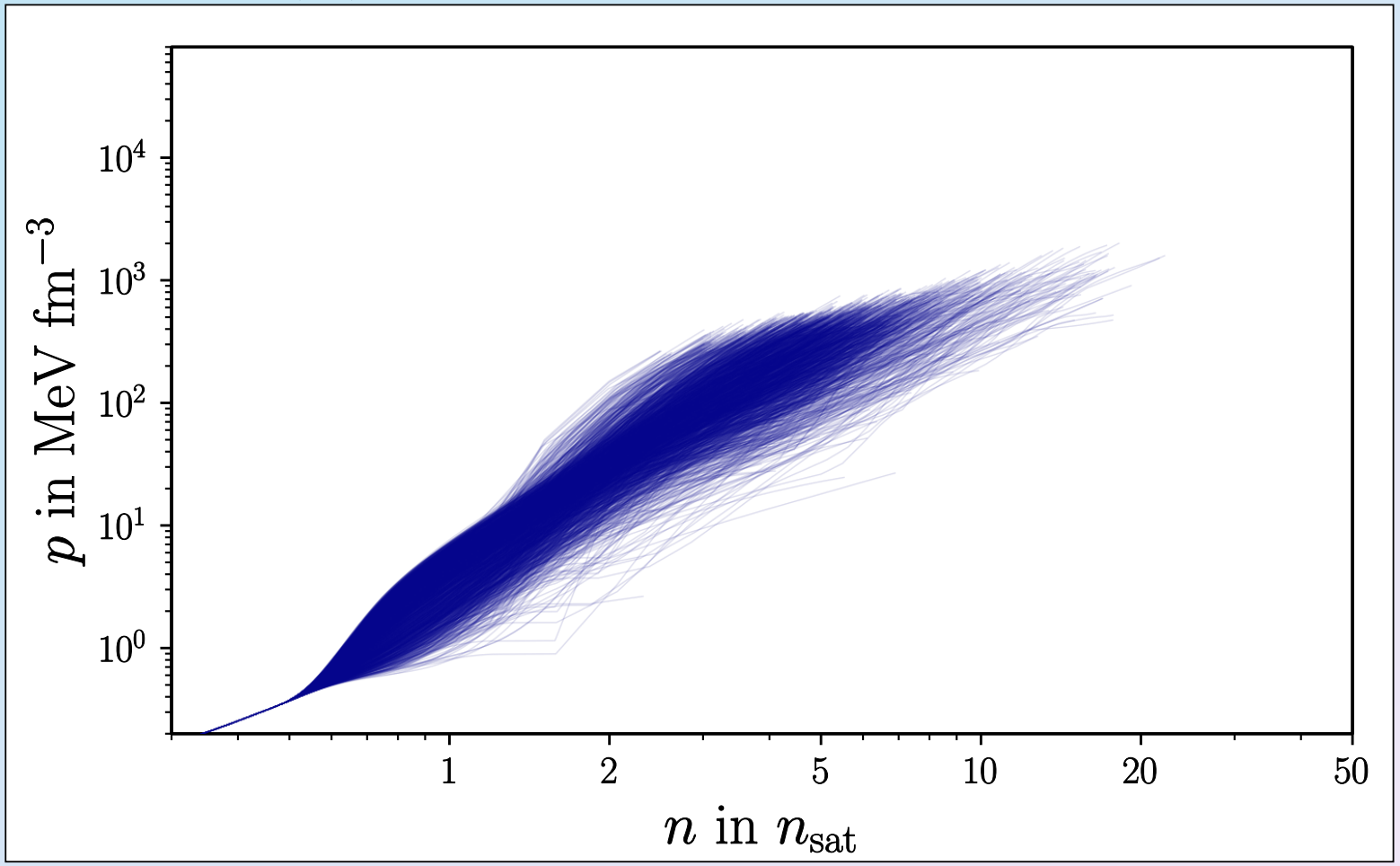
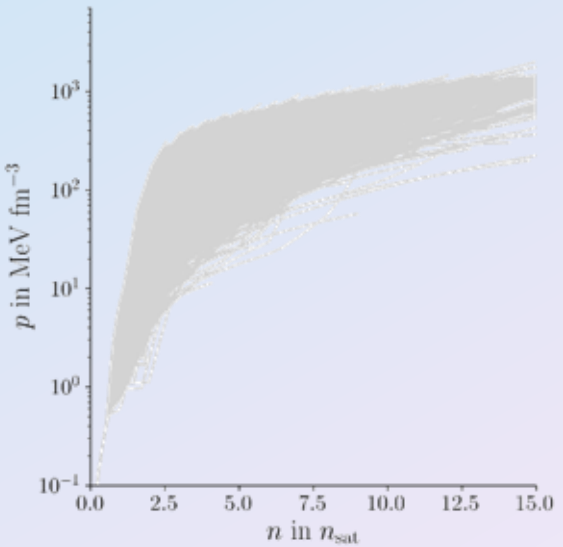
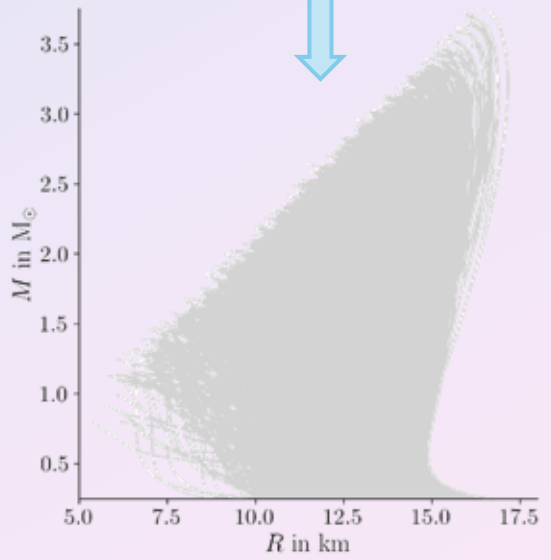


Input from a variety of sources

Koehn et al. 2024, PRX 15 (2025) 2, 021014







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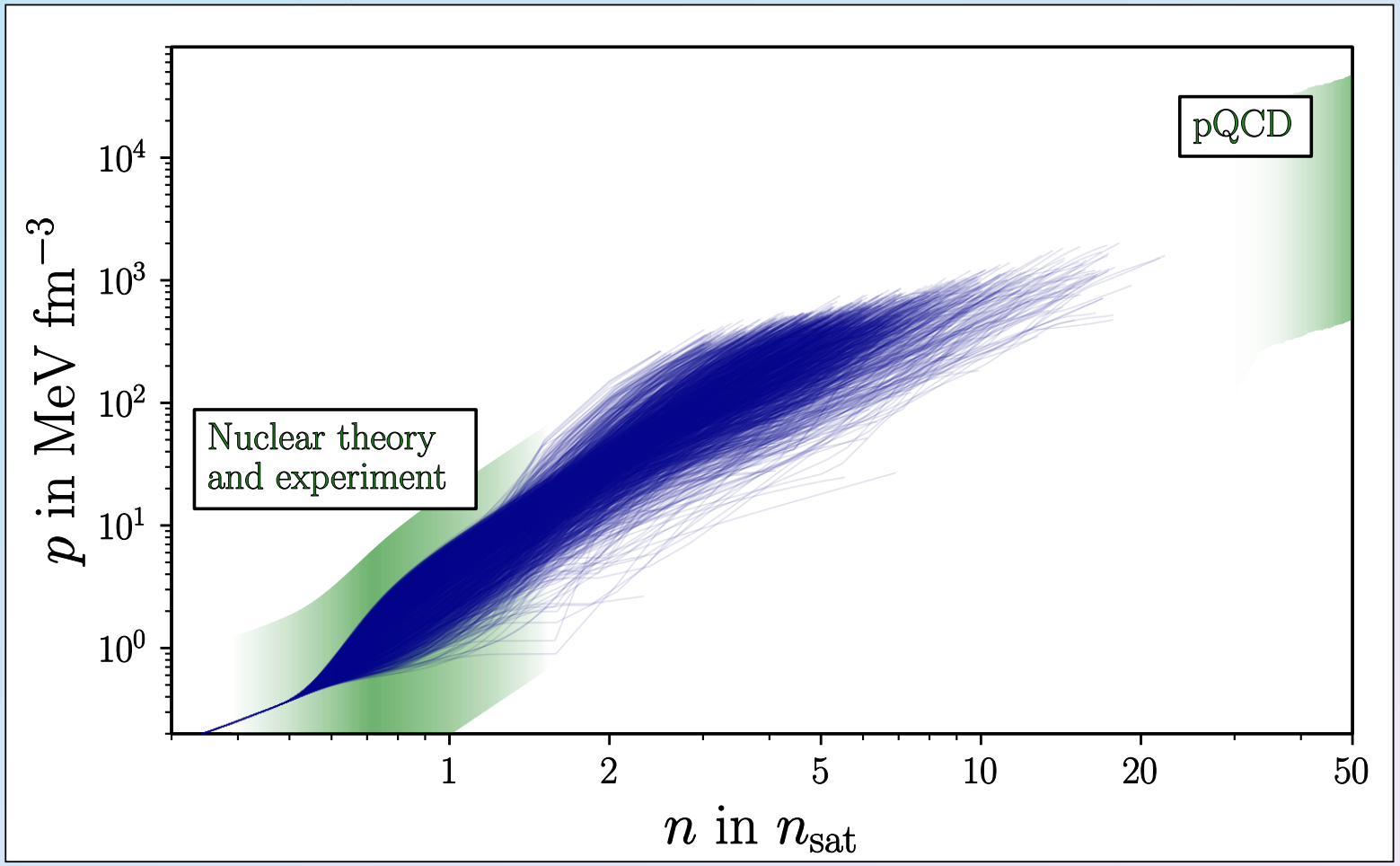
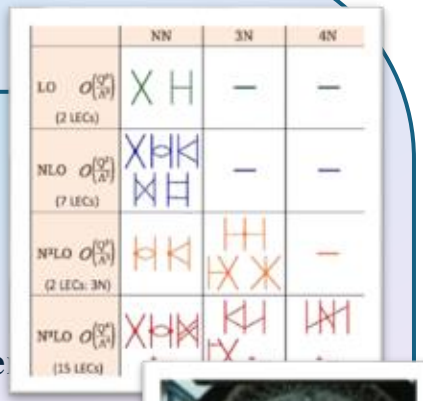


Nuclear Physics

- Chiral EFT
- pQCD
- PREX-II/ CREX
- Pb dipole measureme
- Heavy Ion Collisions
- …



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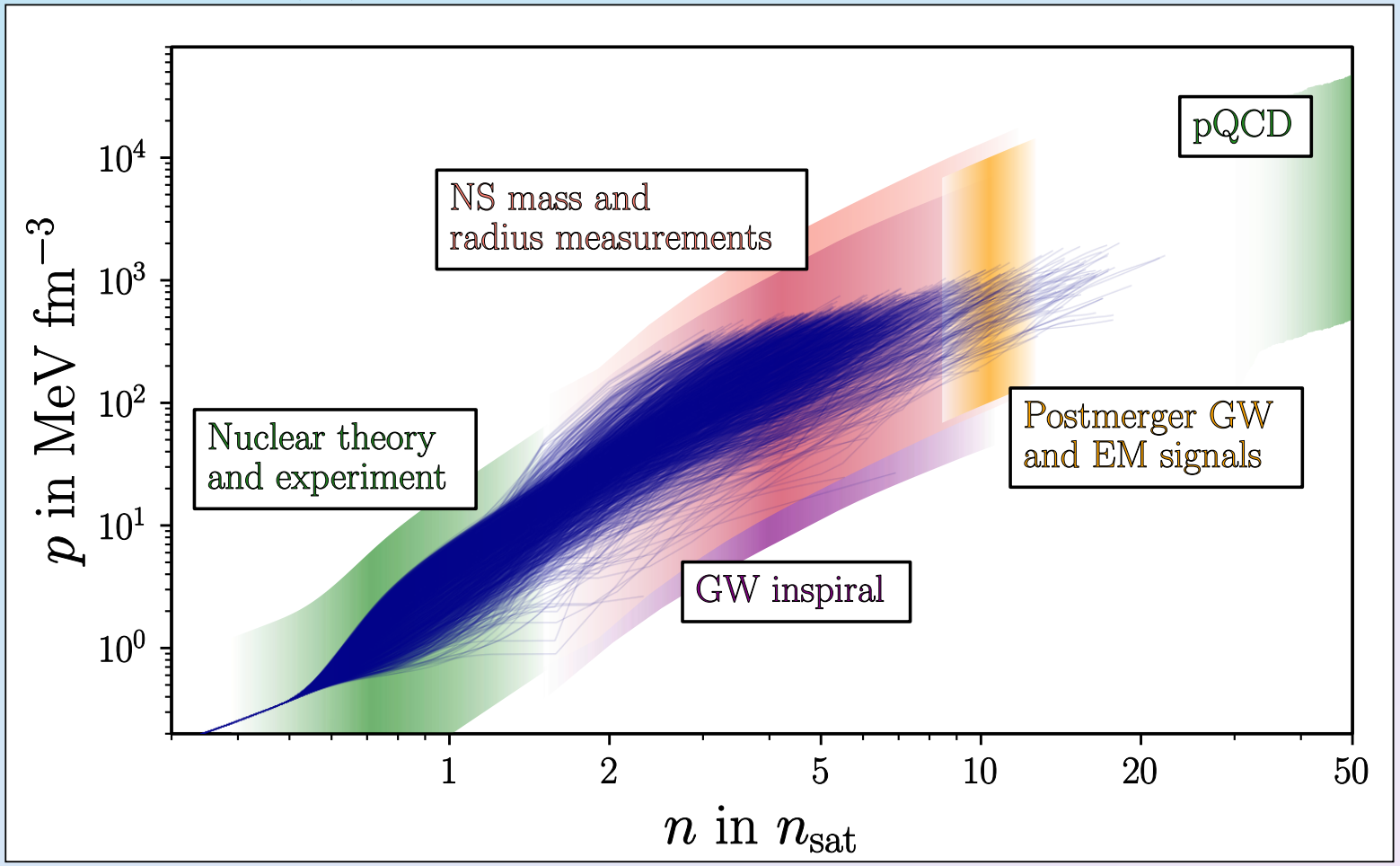

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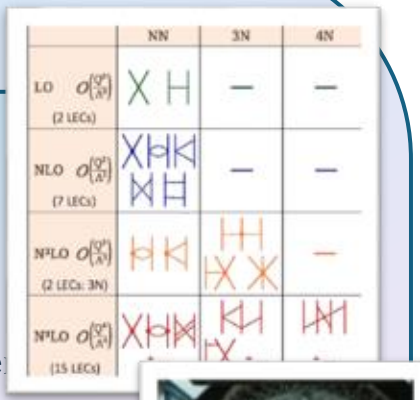
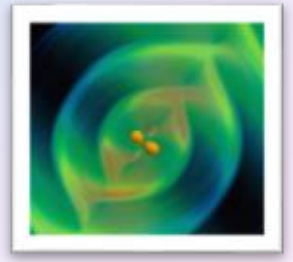


Astrophysics

- Heavy pulsars
- NICER
- HESS object
- qLMXBs
- Thermo-nuclear accretion bursts
- QPOs



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- GW190425
- GRB211211A
- Post-merger constraints from GW170817

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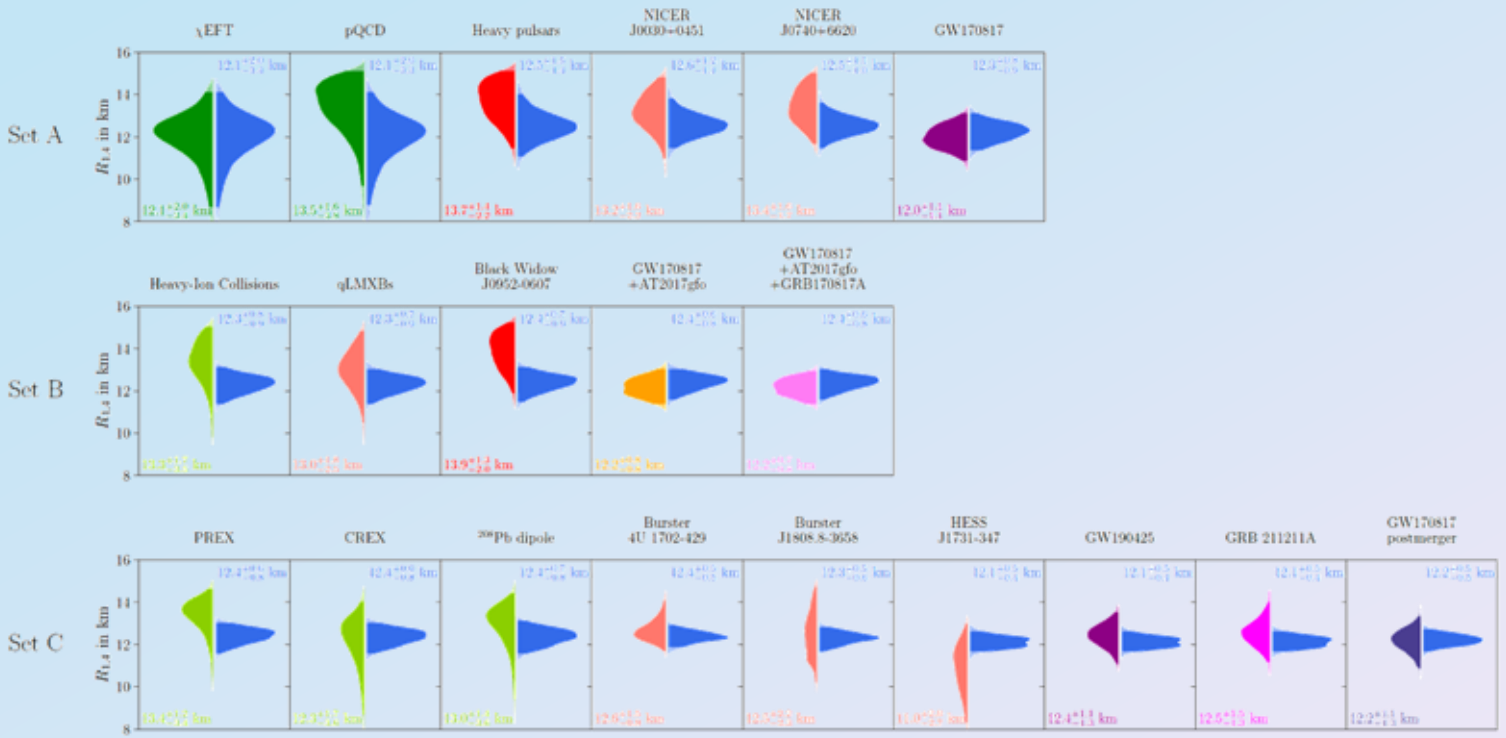

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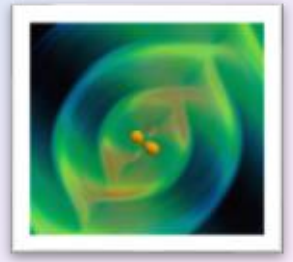

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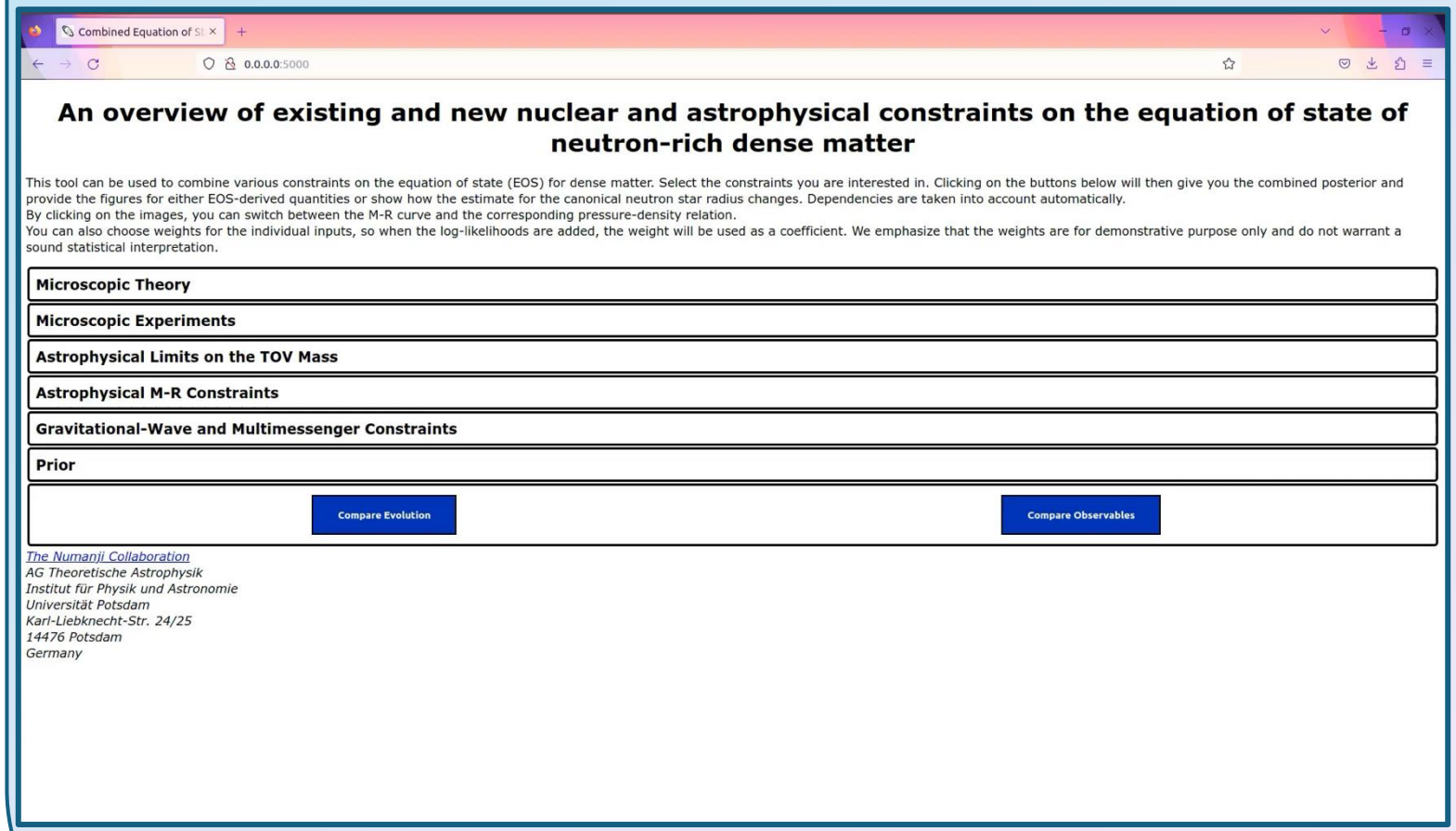

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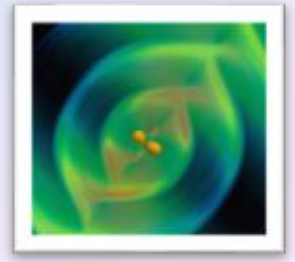

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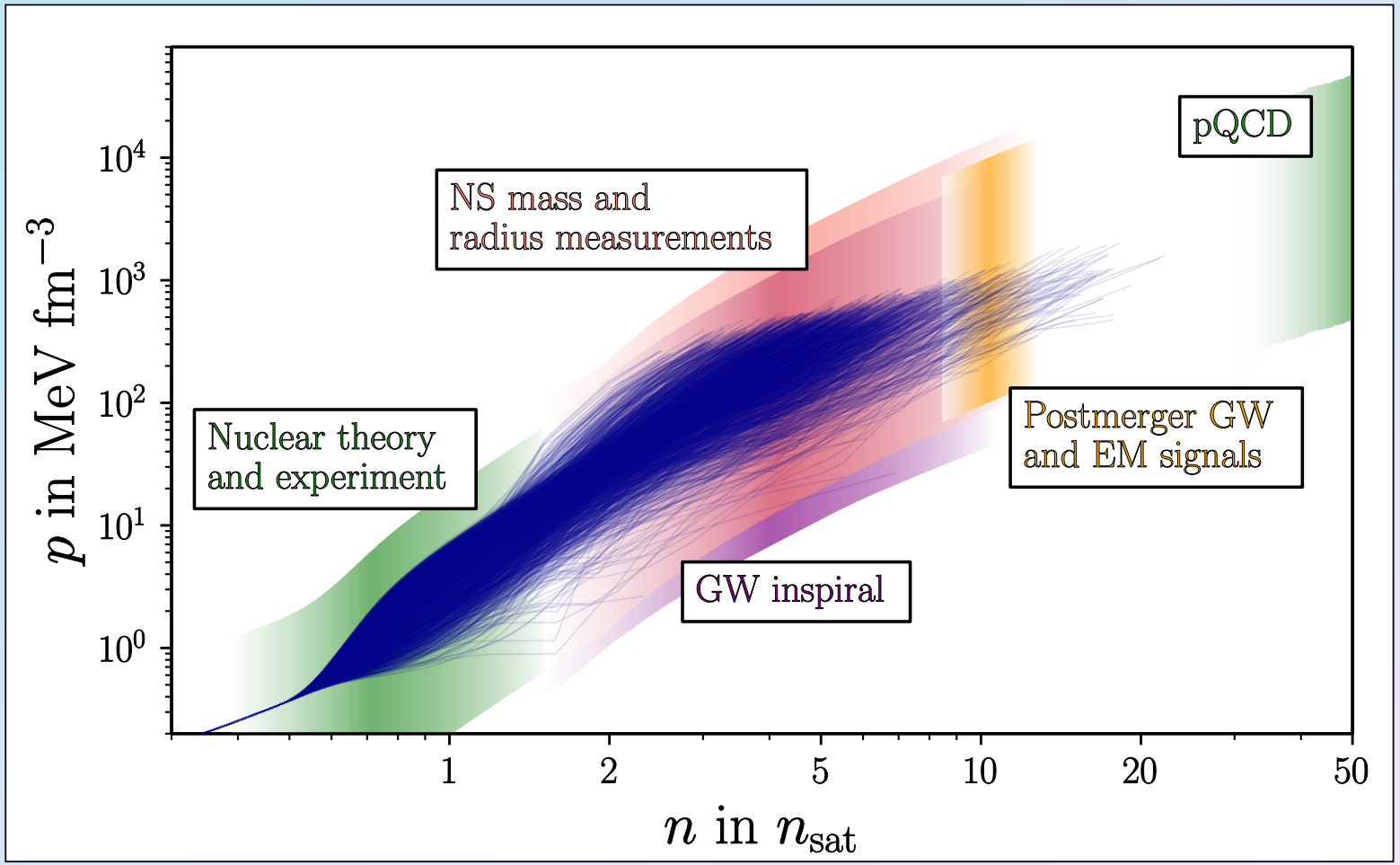

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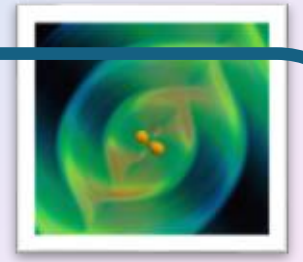

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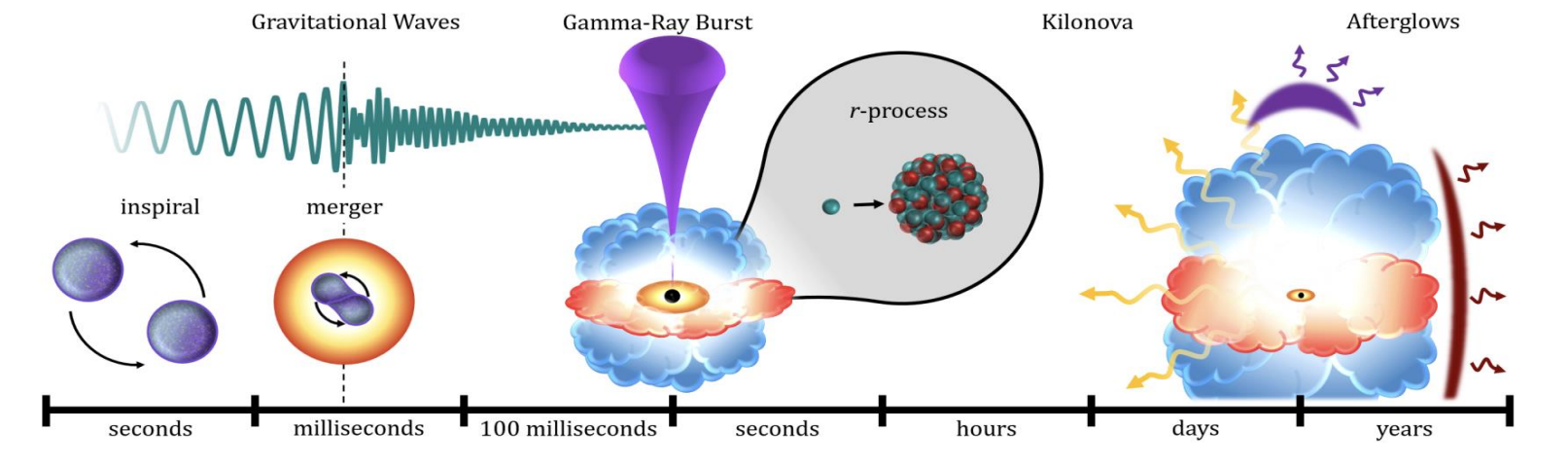
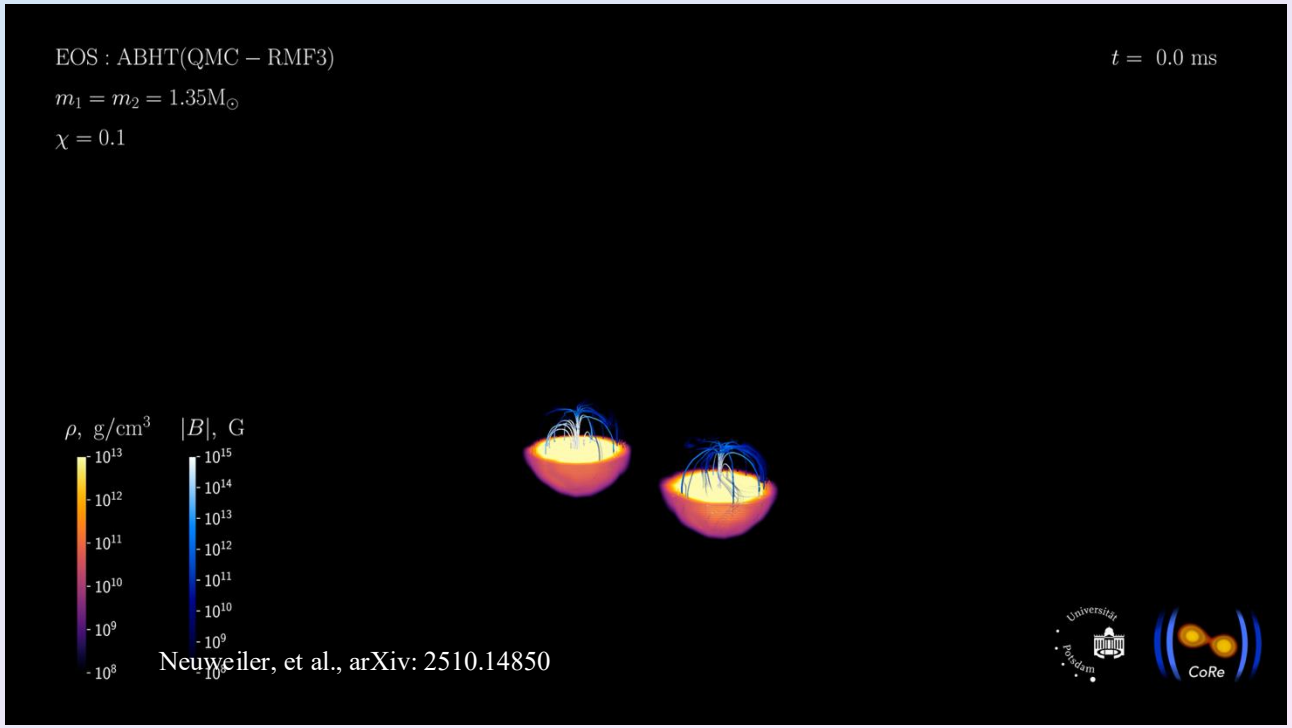
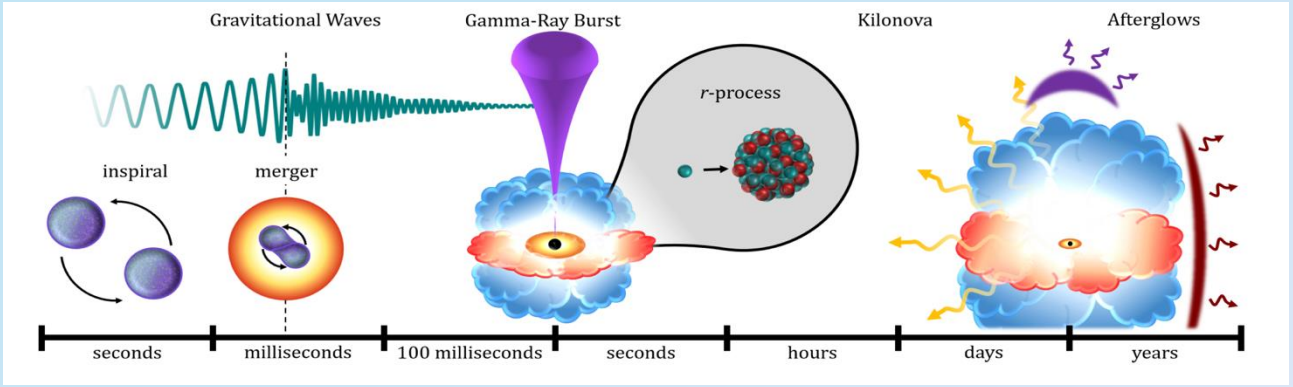


Neuweiler et al., 2510.14850



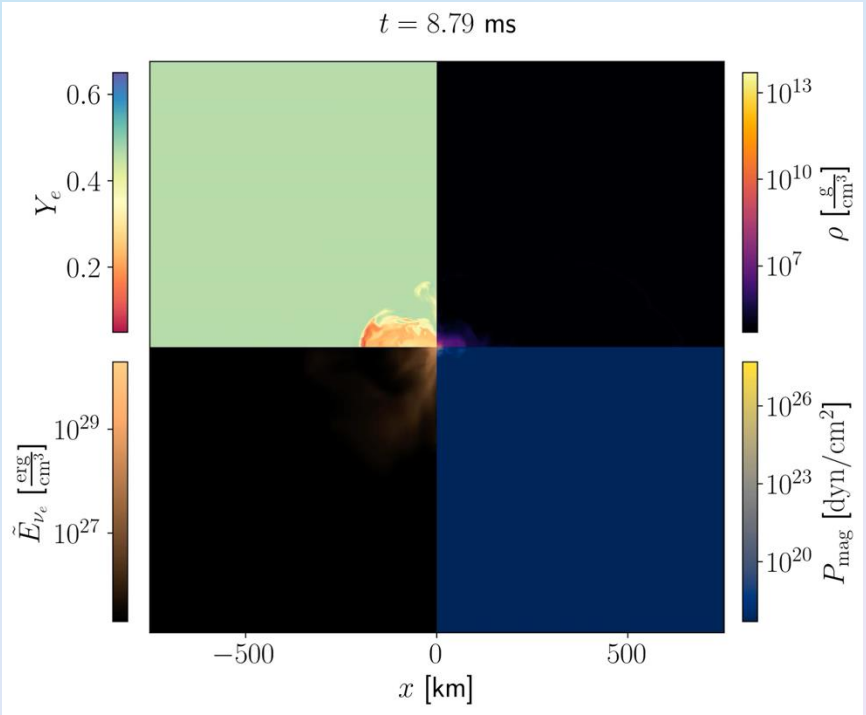
cf. poster of Anna Neuweiler

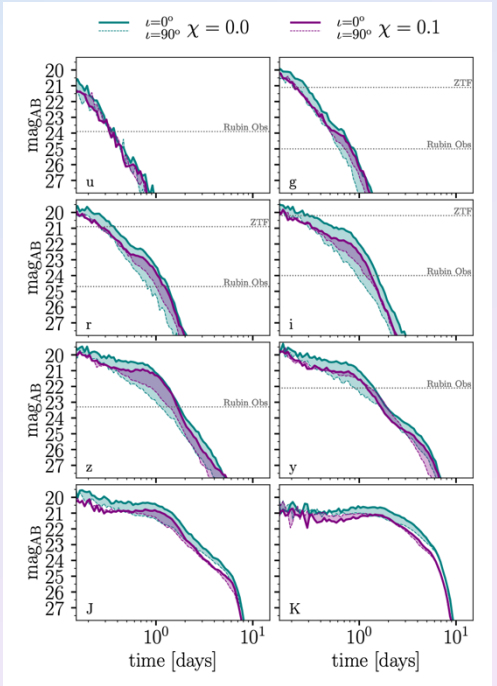


Findings

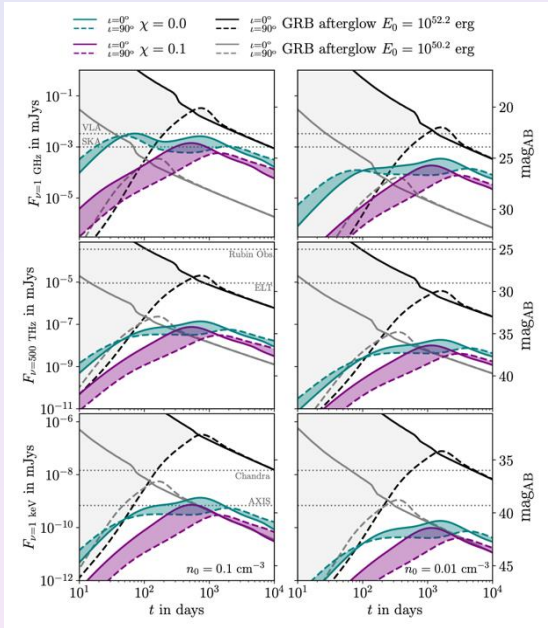
- moderate difference between spinning and non-spinning BNS mergers
- significant difference from idealized geometries generally used to create kilonova grids for data analysis

Neuweiler et al., 2510.14850

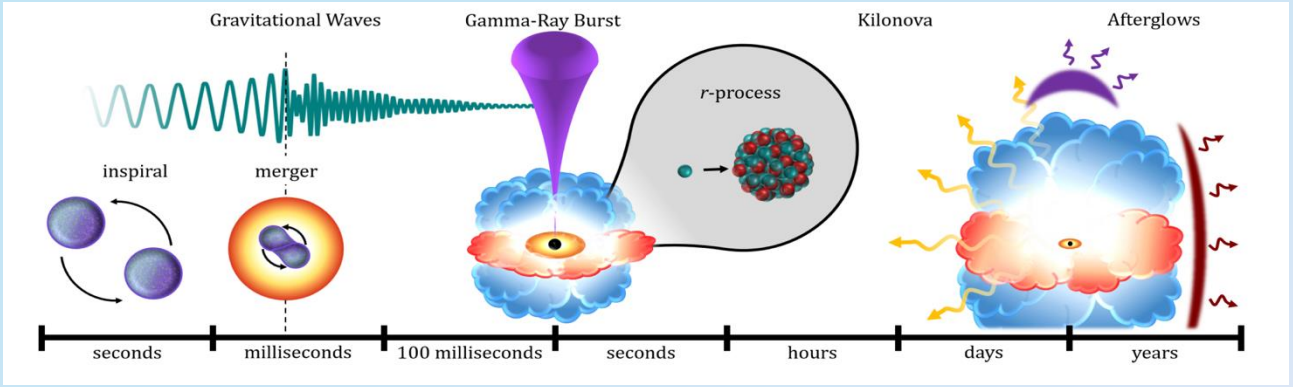




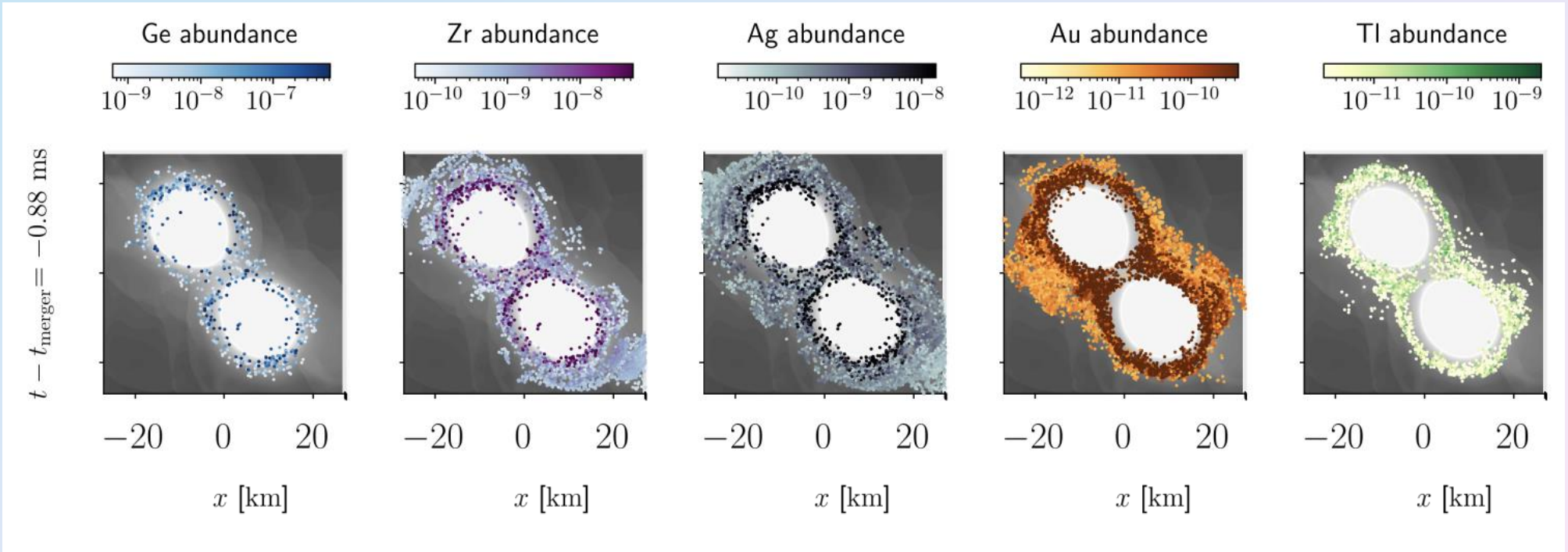
Kilonova



GRB and kilonova afterglow



Treasure maps for BNS mergers



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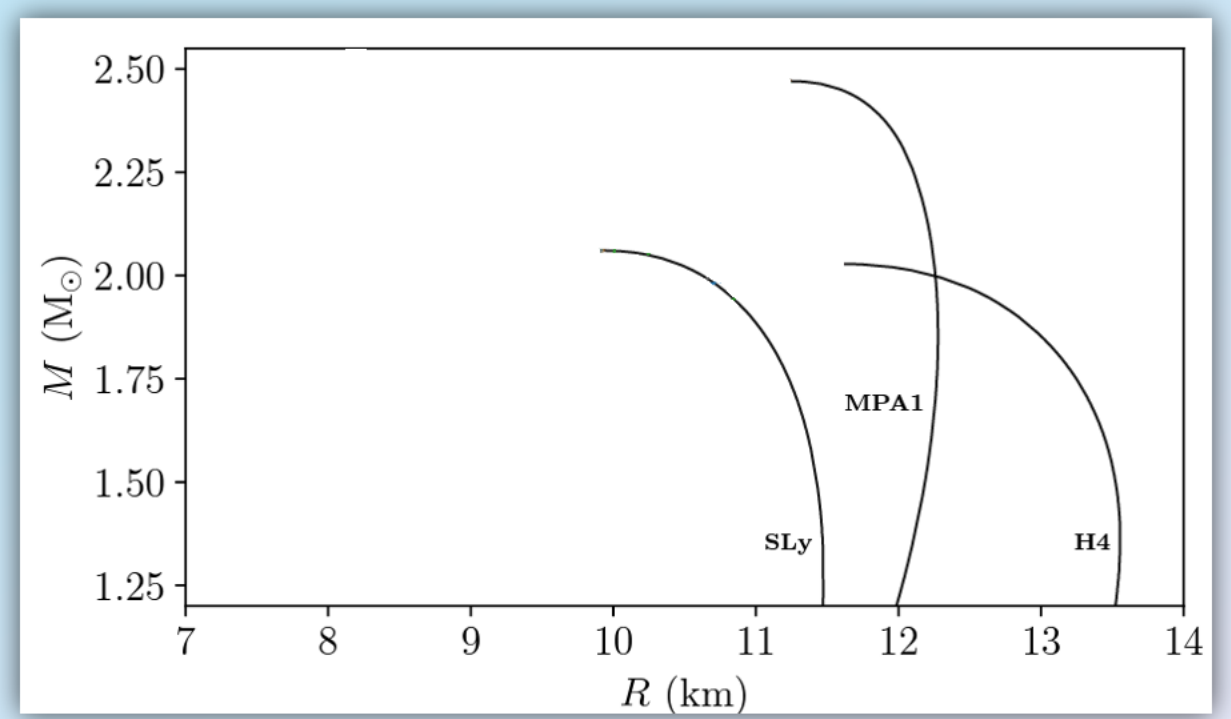
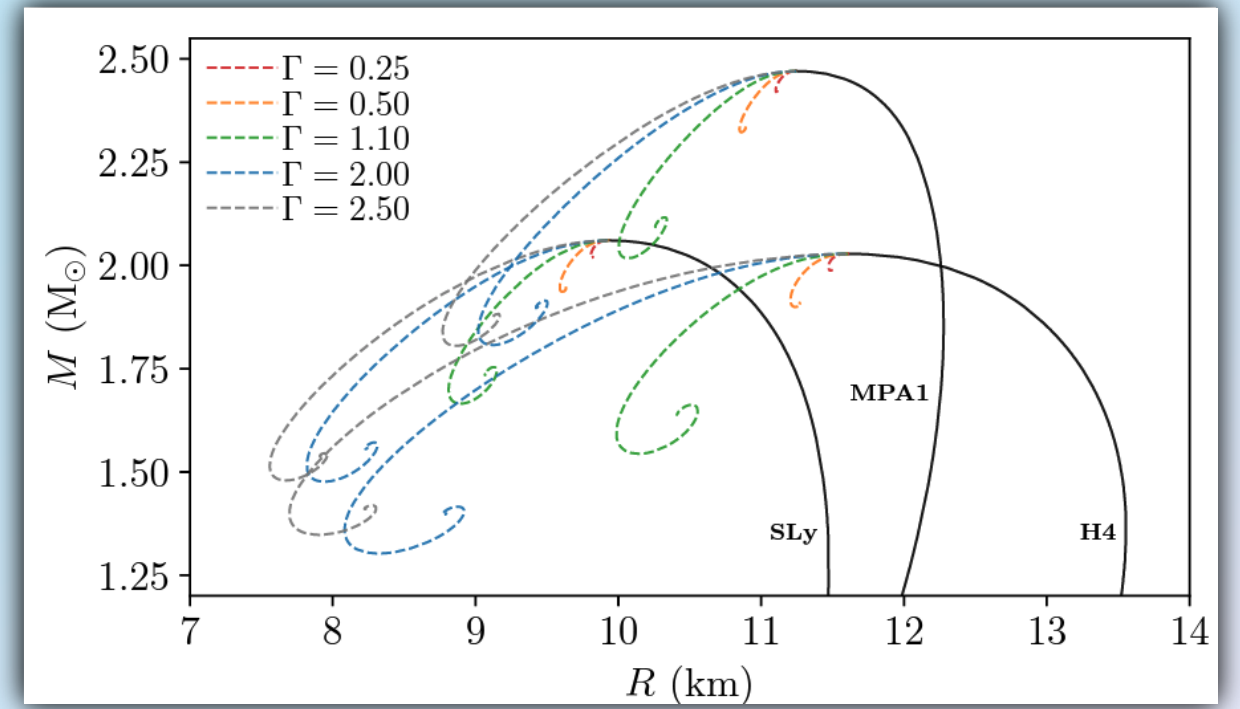
Most extreme densities?



Ujevic et al., APJL 962 (2024) 1, L3

- **Can we test matter above the TOV limit?**

Most extreme densities?



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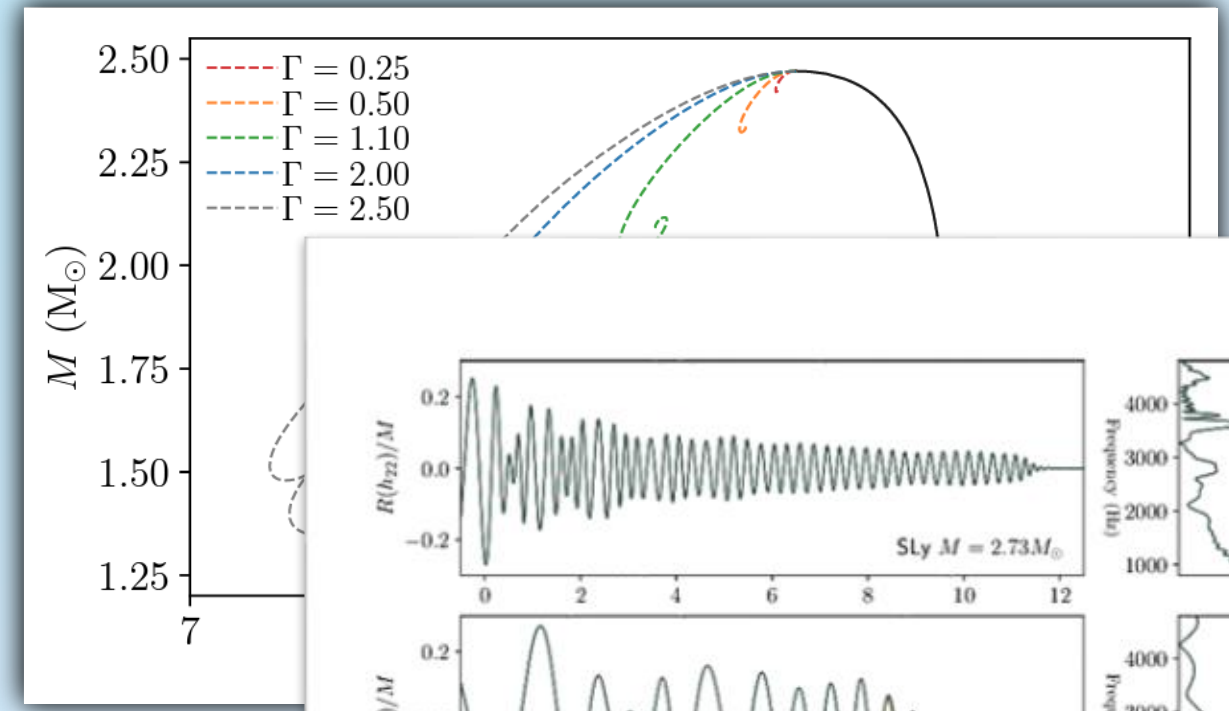


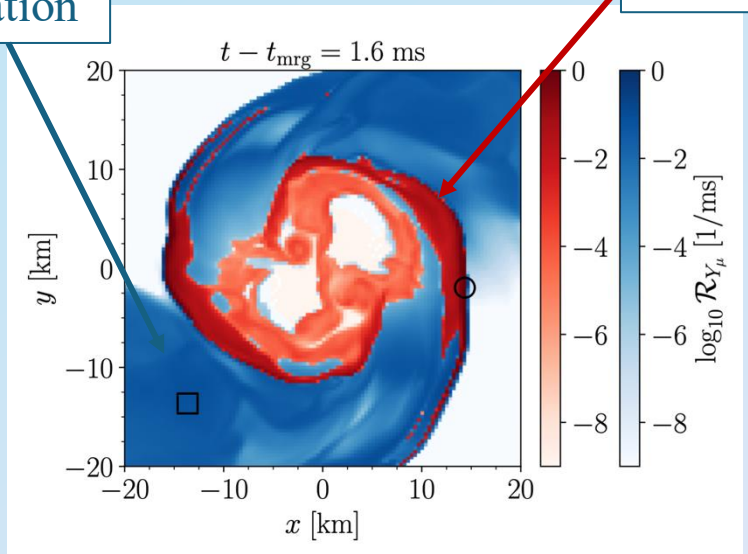
- **Can we test matter above the TOV limit?**

  NO!!

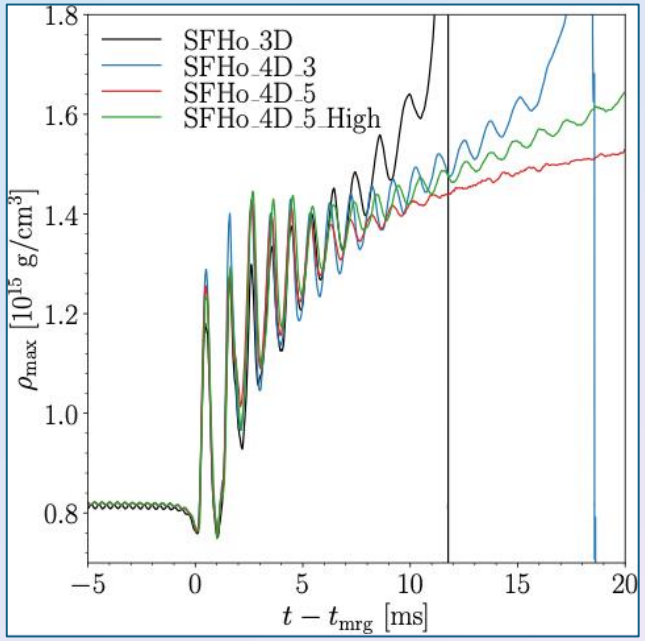
Influence of Muons

demuonization

muonization



Inclusion of muonic neutrinos –
Gieg et al., PRD 112 (2025) 2, 023036



Findings

- inclusion of muons
  - the composition of the ejecta changes
  - the cooling of the remnant is modified
  - the lifetime of the remnant is altered

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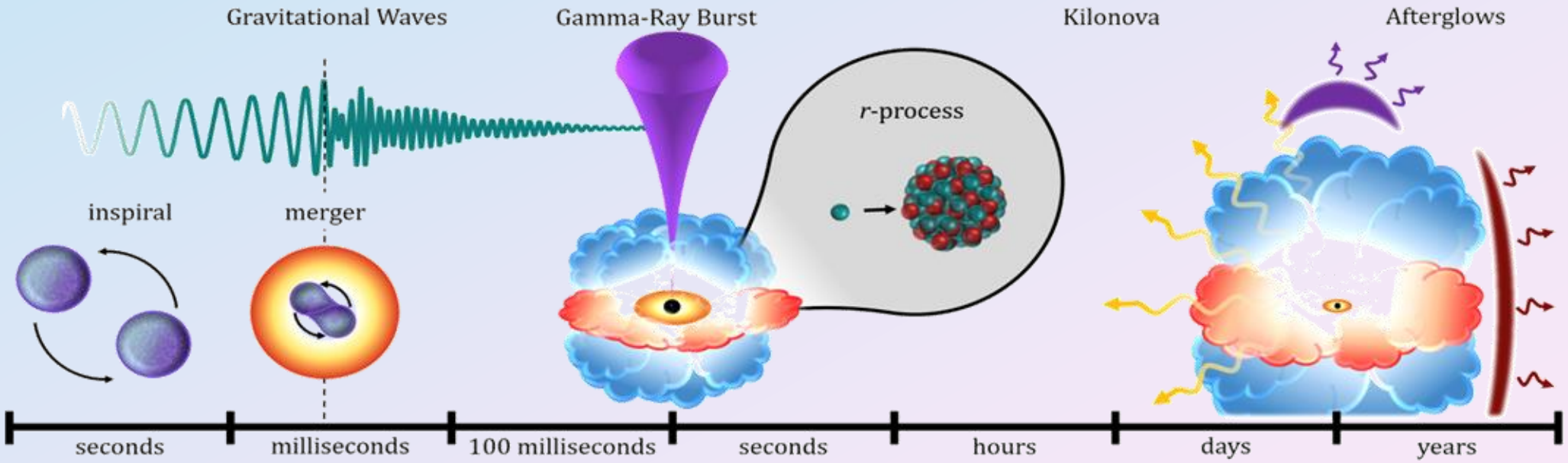
How to move beyond single simulation-based predictions and create general applicable models?



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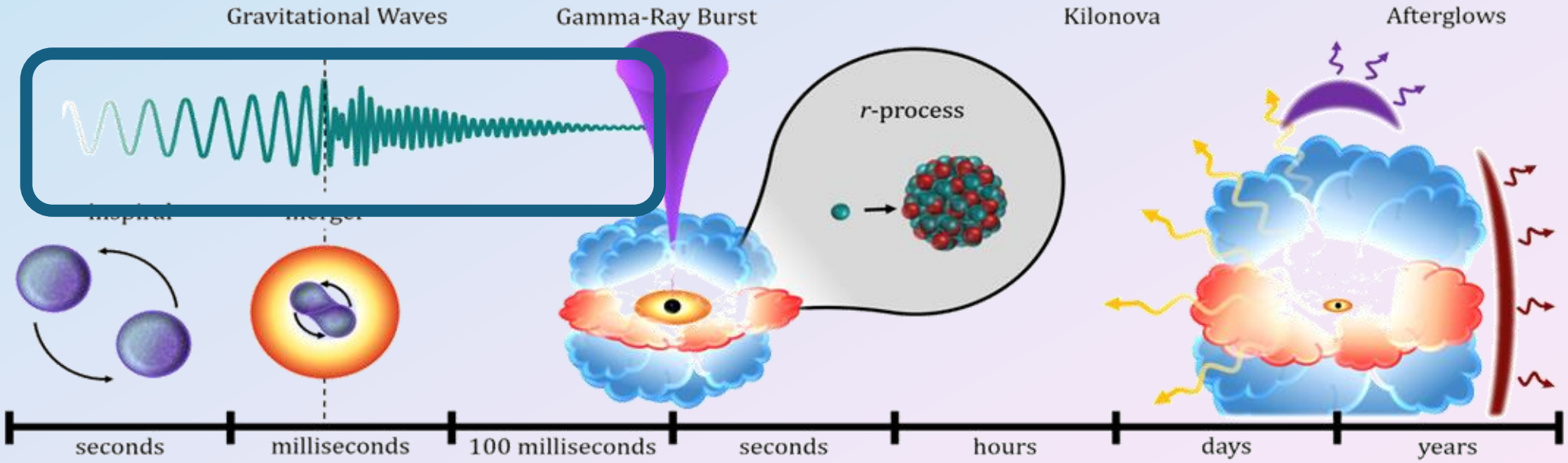
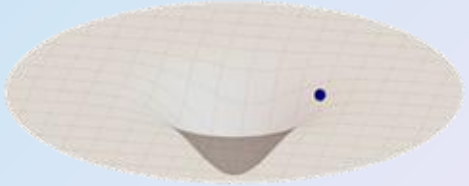


Inspiral waveforms

Various models

Numerical Relativity Simulations

Post-Newtonian Theory



Effective-one-body Formalism

Phenomenological Models

Inspiral waveforms

Various models

Numerical Relativity Simulations

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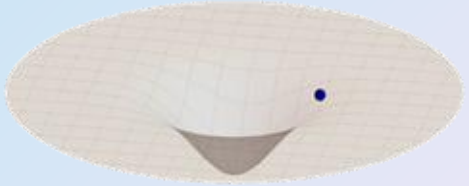

Effective-one-body Formalism

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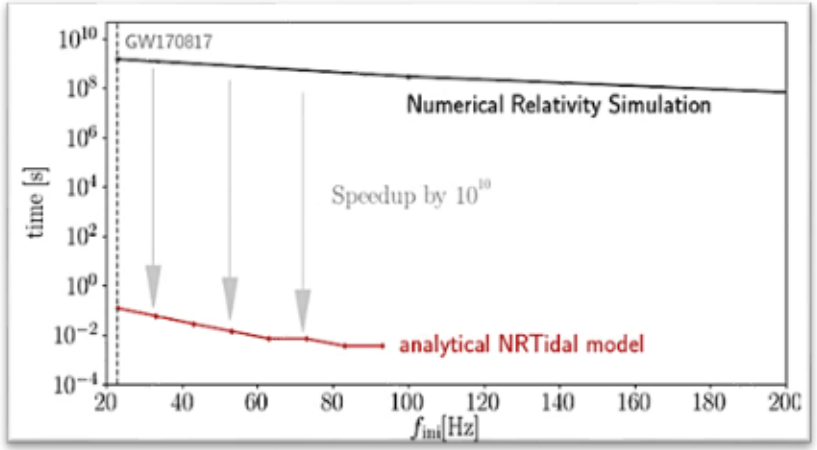
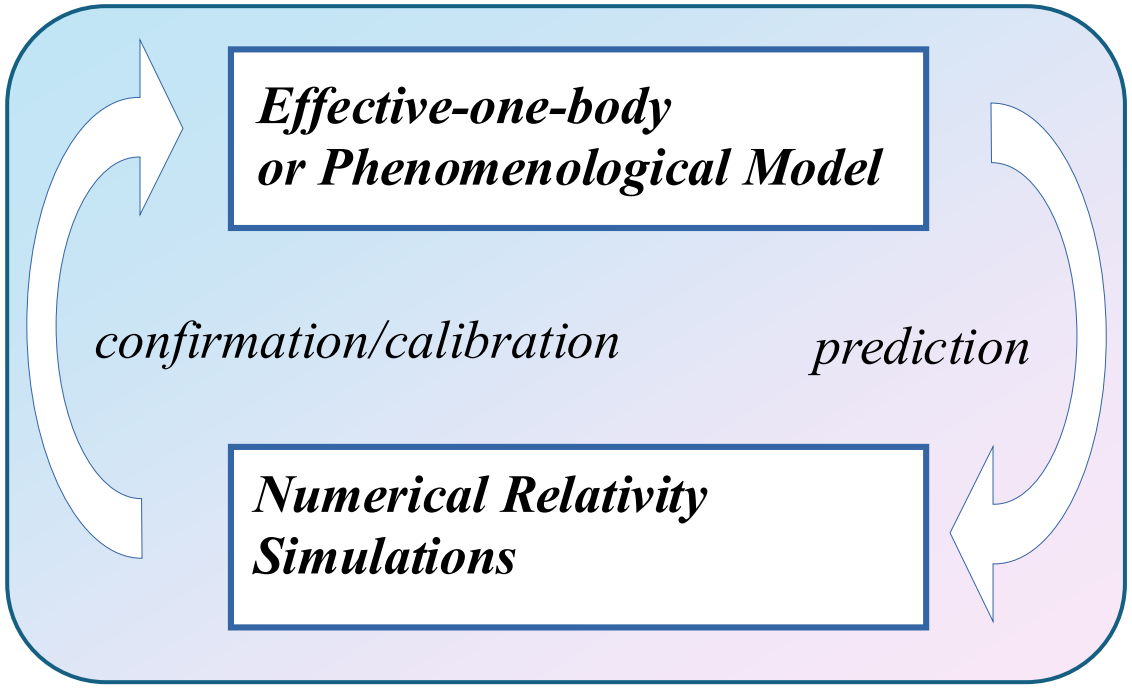


since 2017 ongoing development to model tidal contributions

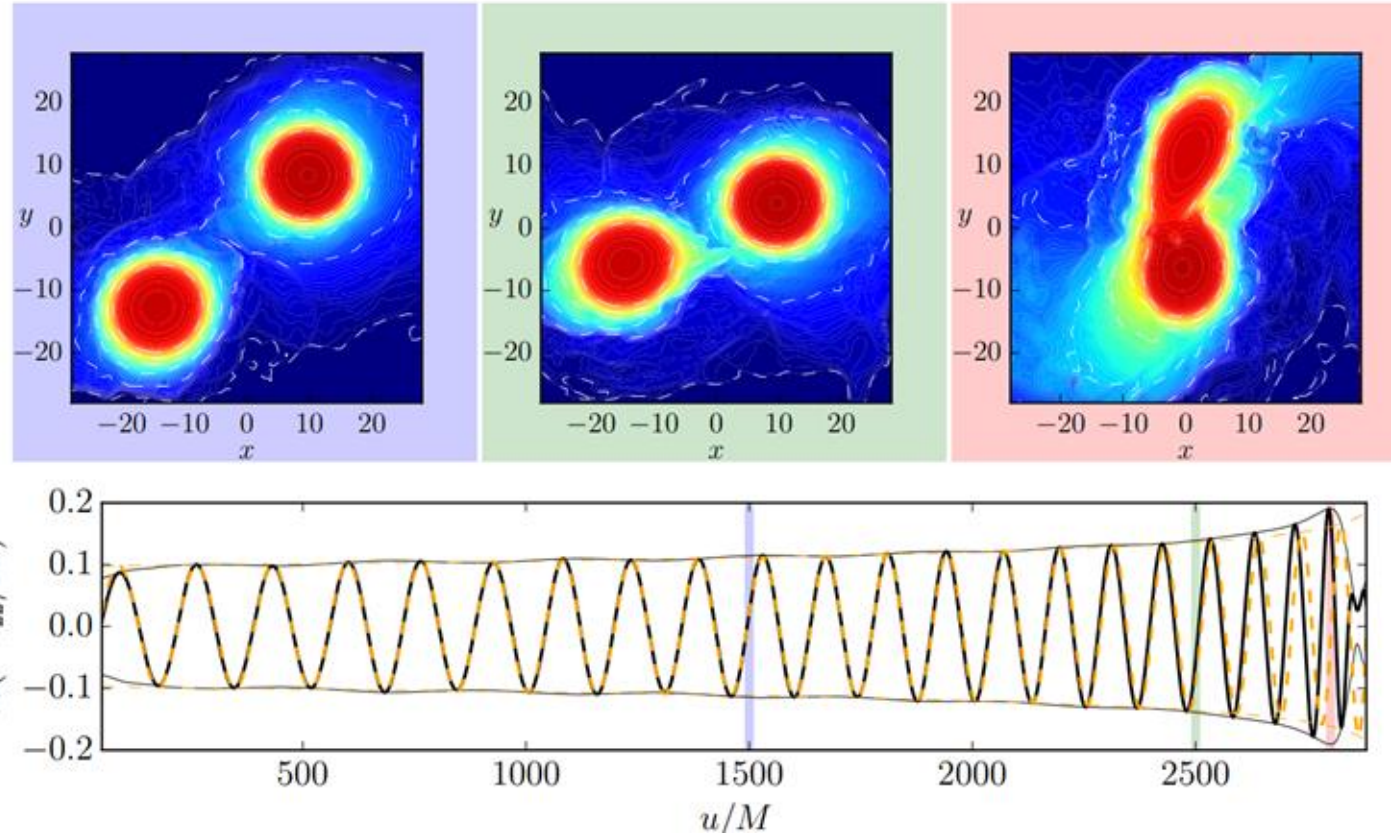
Models:

- NRTidal (2017/2018)
  → used for GW170817 and GW190425
- NRTidalv2 (2019)
- NRTidalv3 (2024) Abac et al., PRD 109 (2024) 2, 024062
- NRTidalv3 with higher modes Abac et al., PRD 112 (2025) 10, 104026

Waveform Model Development through NR simulations



What are the existing challenges on the numerical-relativity side?



TD & Hinderer, PRD 95 12, 124006

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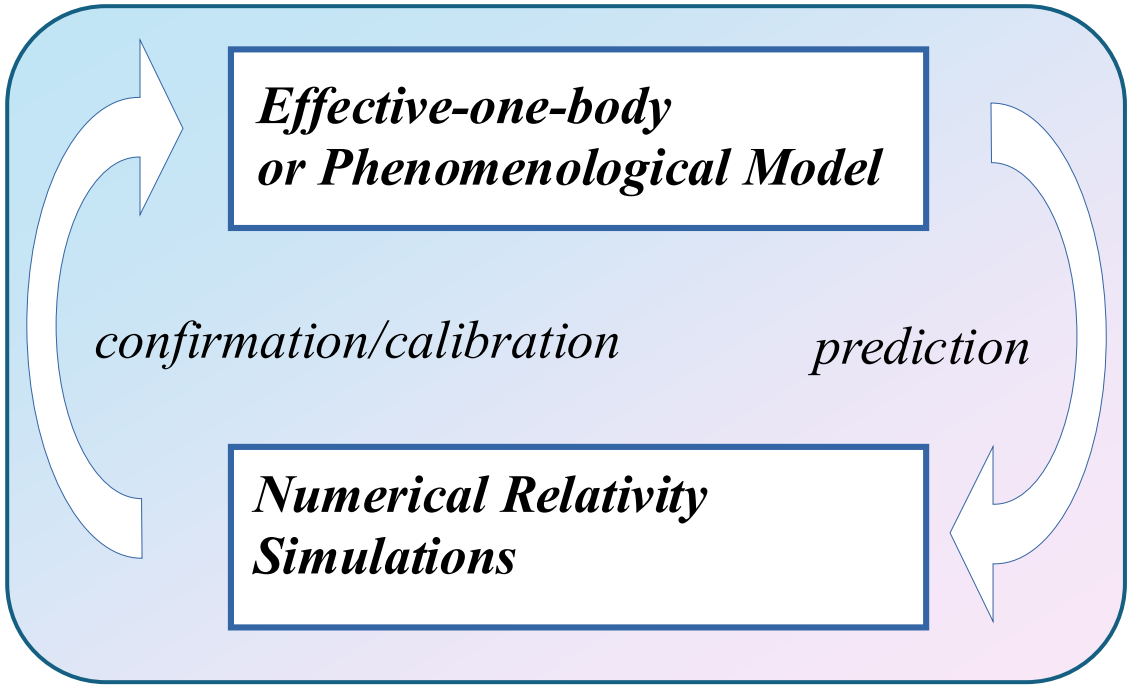

What are the existing challenges on the numerical-relativity side?

- Coverage of the parameter space
- Accuracy of the obtained simulations (phase error)

Waveform Model Development through NR simulations

Effective-one-body or Phenomenological Model

confirmation/calibration

prediction

Numerical Relativity Simulations

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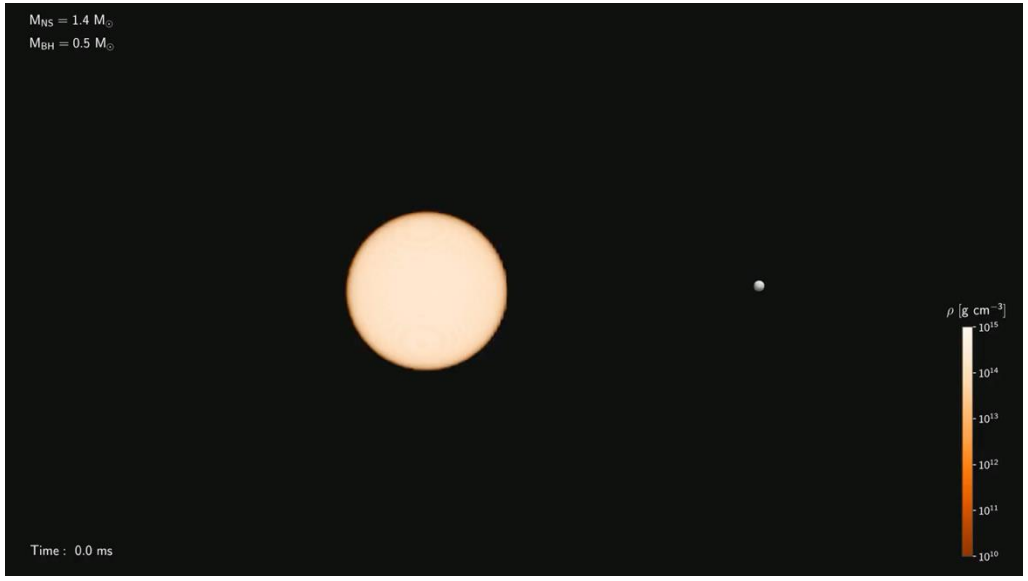
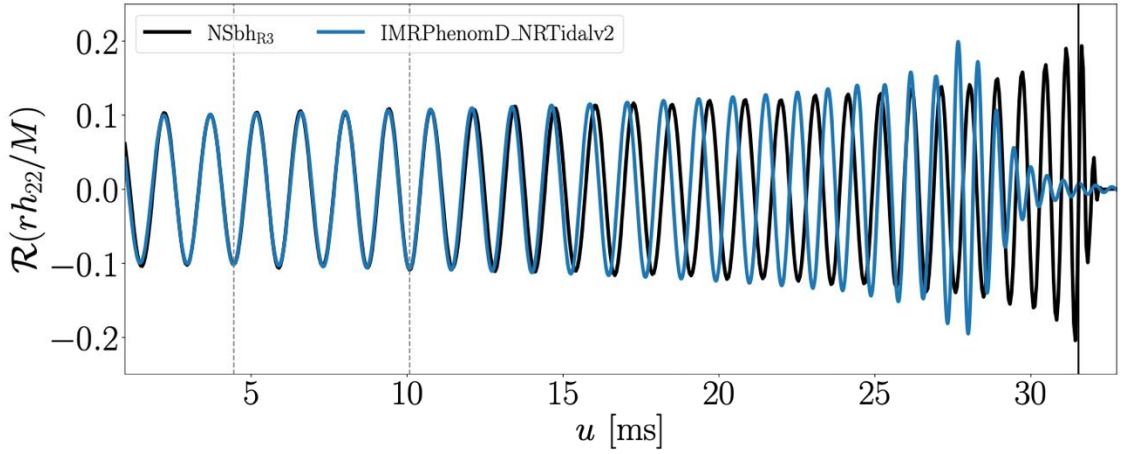


parameter space coverage



Markin et al., Phys.Rev.D 108 (2023) 6, 064025;
see also Markin et al., arXiv:2601.19405

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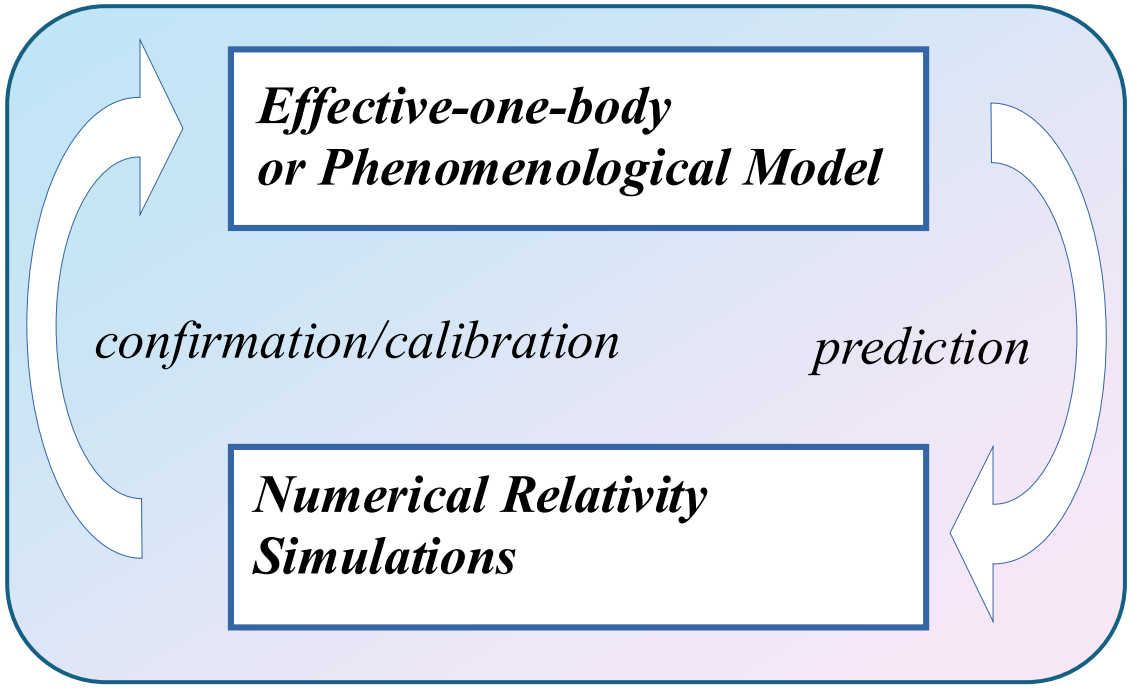

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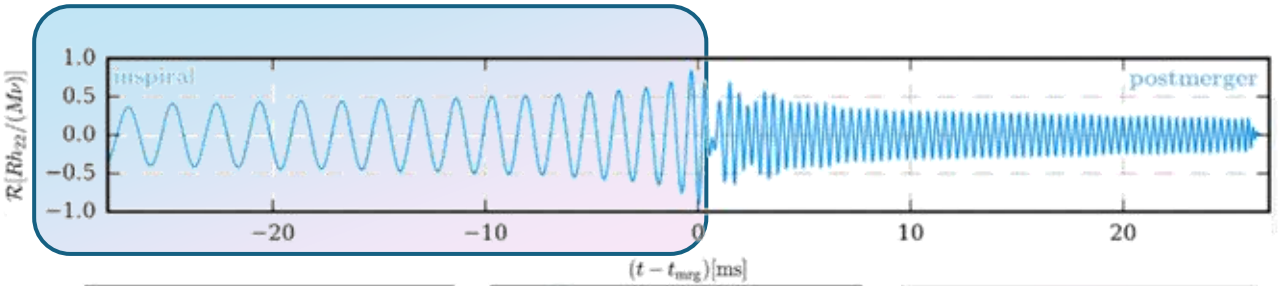
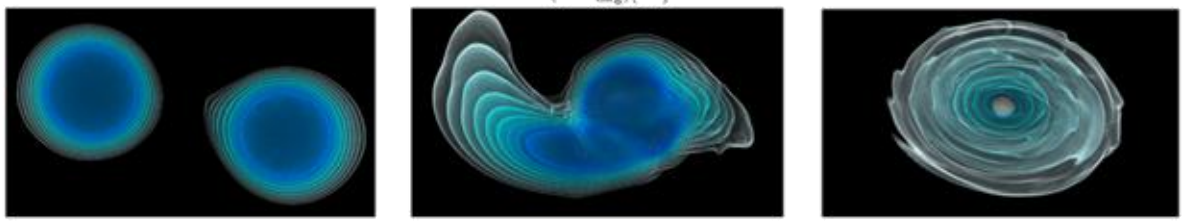




Accuracy of the NR data

Sources of errors (incomplete list):

- numerical discretization

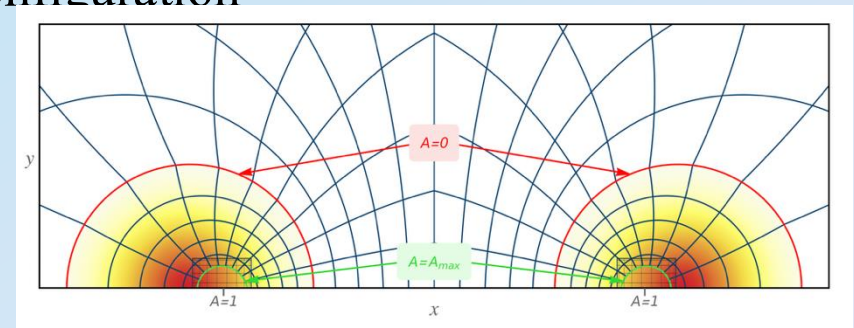
Possible attempts:

- High-order convergence through flux reconstruction in characteristic variables
  Radice et al., *Astron.Astrophys.* 547
  Bernuzzi et al., Phys.Rev.D 94 (2016) 6, 064062
- High-order flux computation
  Most et al., Mon.Not.Roy.Astron.Soc. 490 (2019) 3, 3588-3600
- Usage of entropy limiters
  Giarcilena, Comput.Astrophys.Cosmol. 4 (2017) 1, 3
  Doulis et al., PRD 106 (2022) 2, 02400
- More sophisticated Riemann solvers
  Kiuchi, *Phys.Rev.D* 106 (2022) 12, 124041

Accuracy of the NR data

Sources of errors (incomplete list):

- numerical discretization *Clean convergence order for increasing resolution*
- initial configuration



SGRID by W. Tichy
Phys.Rev.D 92 (2015) 12, 124007

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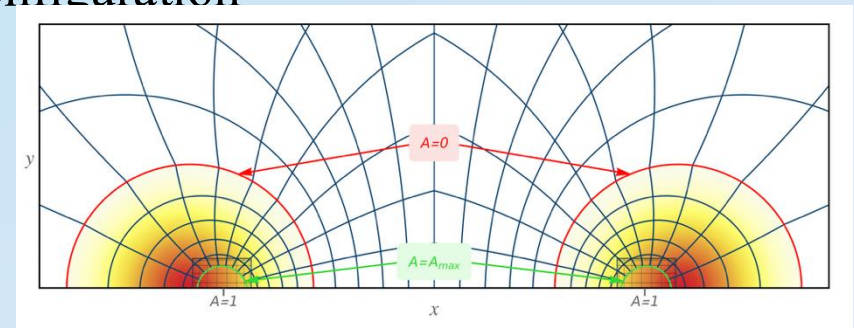
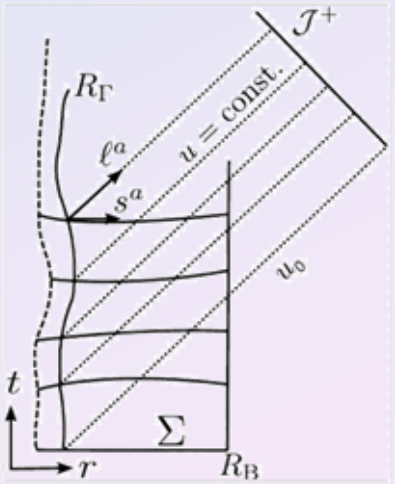


SGRID by W. Tichy
Phys.Rev.D 92 (2015) 12, 124007

- finite extraction radius

$$f(u;r_j) = f_0(u) + \sum_{k=1}^{K} f_k(u) r_j^{-k}$$

$$r\,\psi_{\ell m} = r\,\ddot{h}_{\ell m} + \frac{\ell(\ell+1)}{2r}\, r\,\dot{h}_{\ell m} + \mathcal{O}(r^{-2})$$



C.Reisswig

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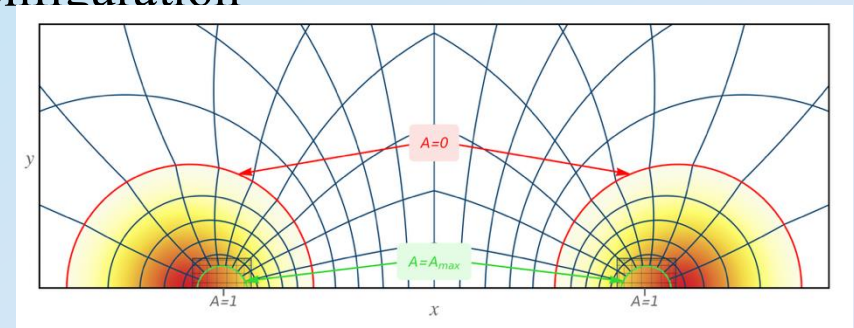

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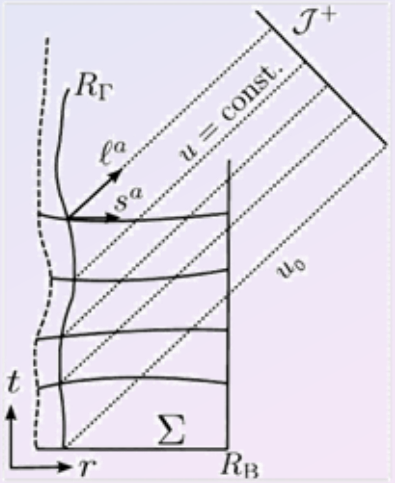
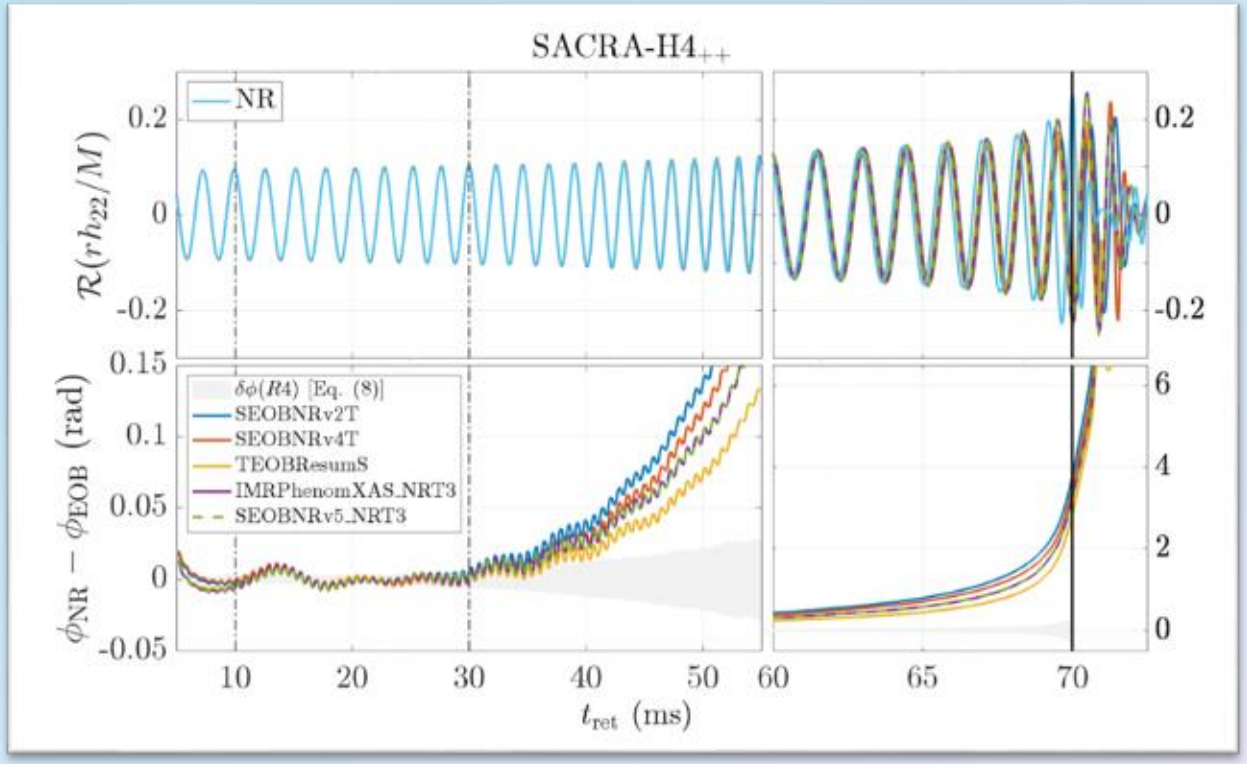


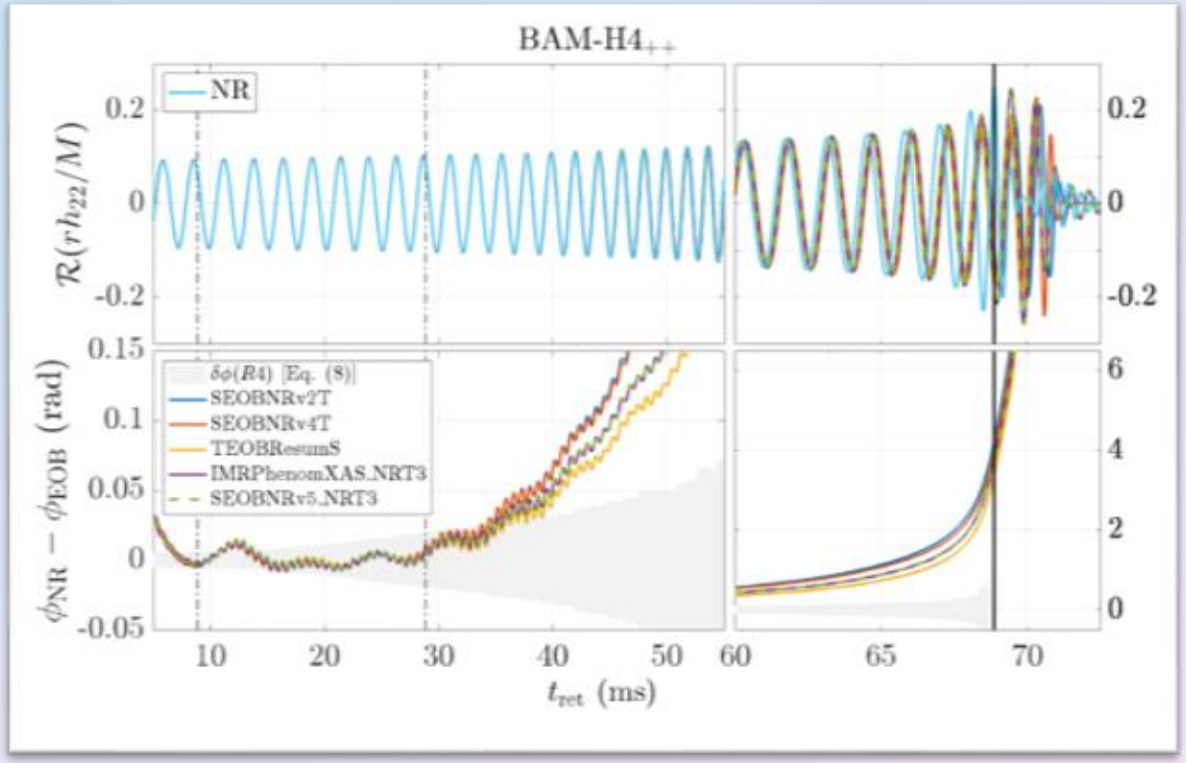
C.Reisswig

- violation of mass conservation, …

Example: high spins and high accuracy

High Spins (dimensionless spin: 0.5)





Kuan et al., arXiv:2506.02115

- Cross-comparison between different codes show consistency between of the parameter space
- Existing waveform models insufficient for high spinning setups

see talk by Kuan

Example: high spins and high accuracy

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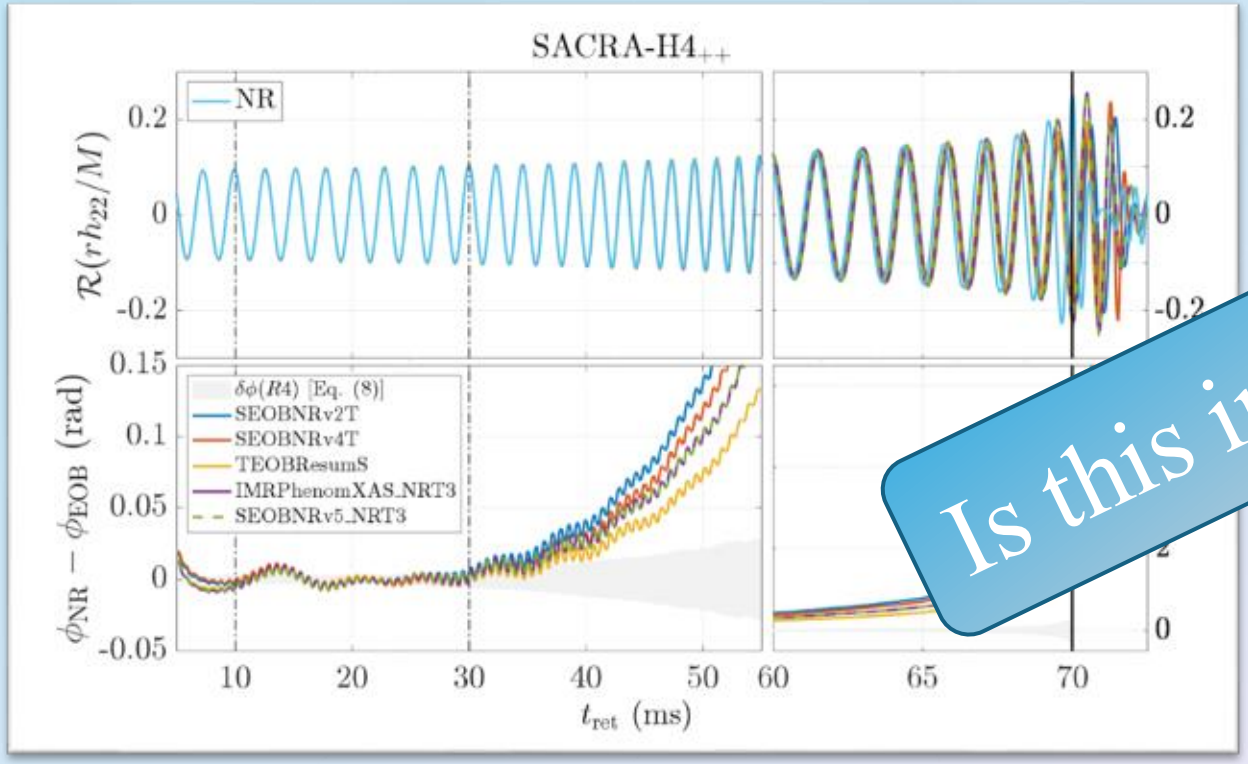
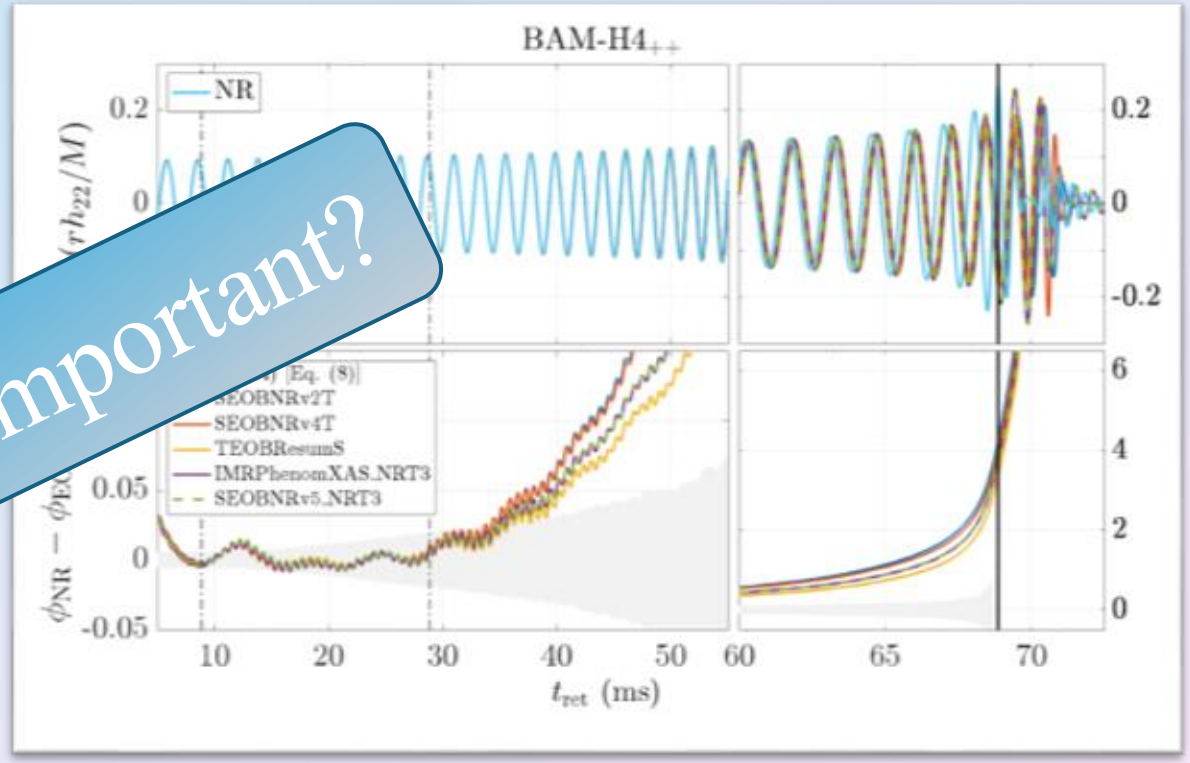




Is this important?

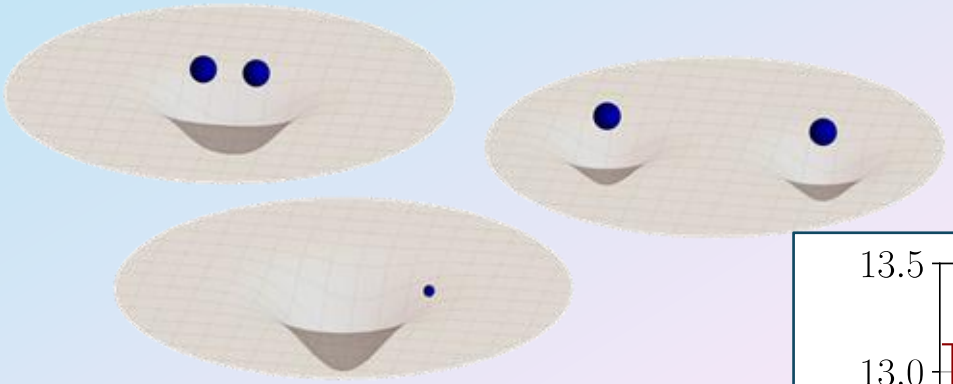
Kuan et al., arXiv:2506.02115

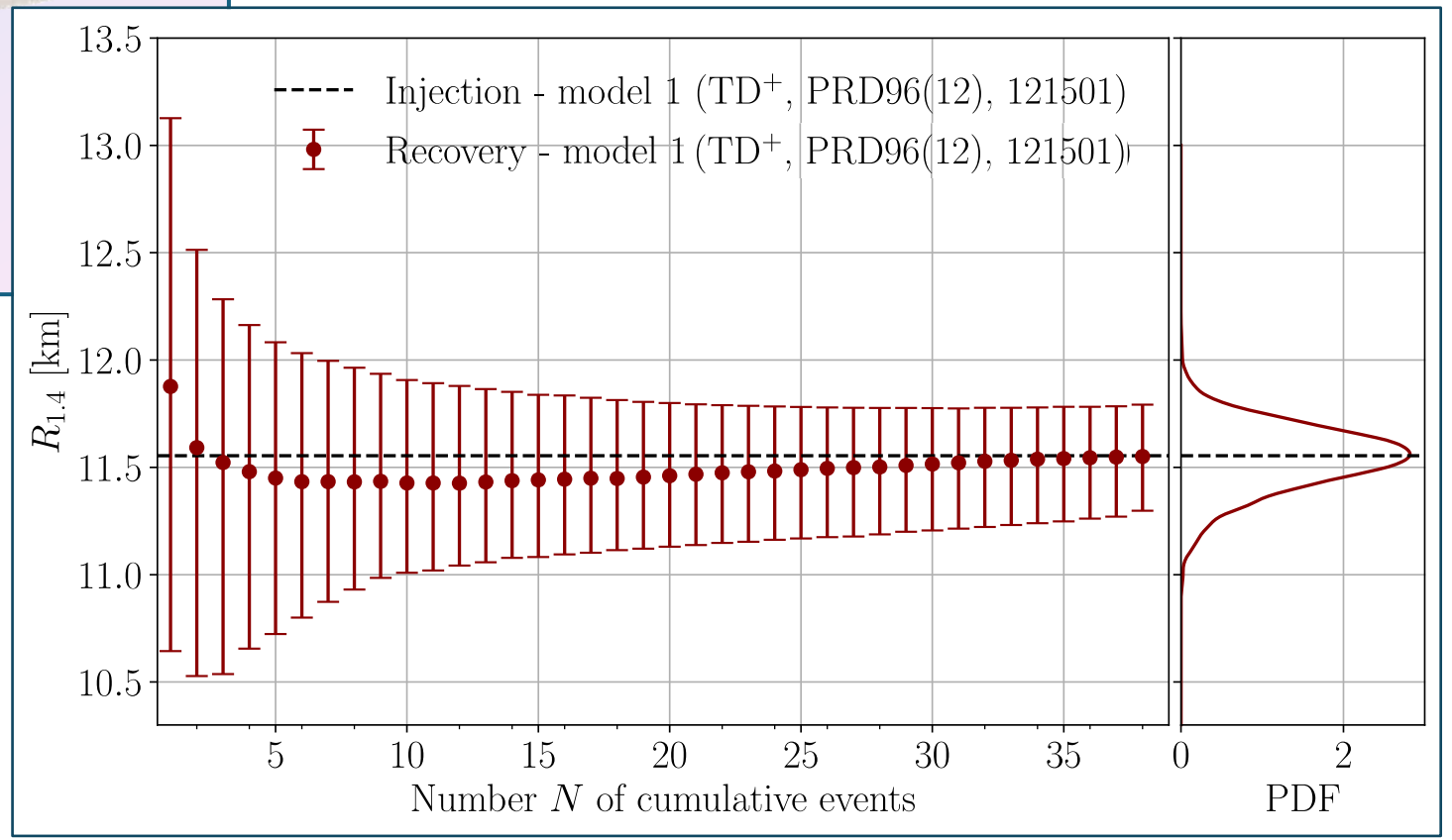
- Cross-comparison between different codes show consistency between of the parameter space
- Existing waveform models insufficient for high spinning setups

see talk by Kuan

Inspiral waveforms

Various models

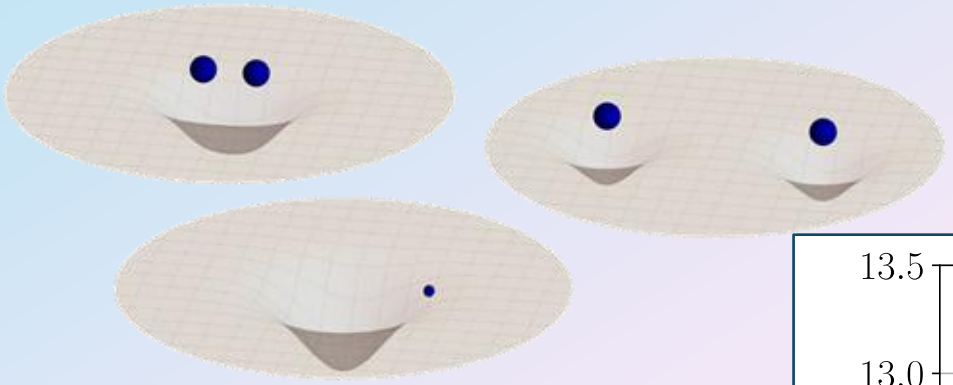


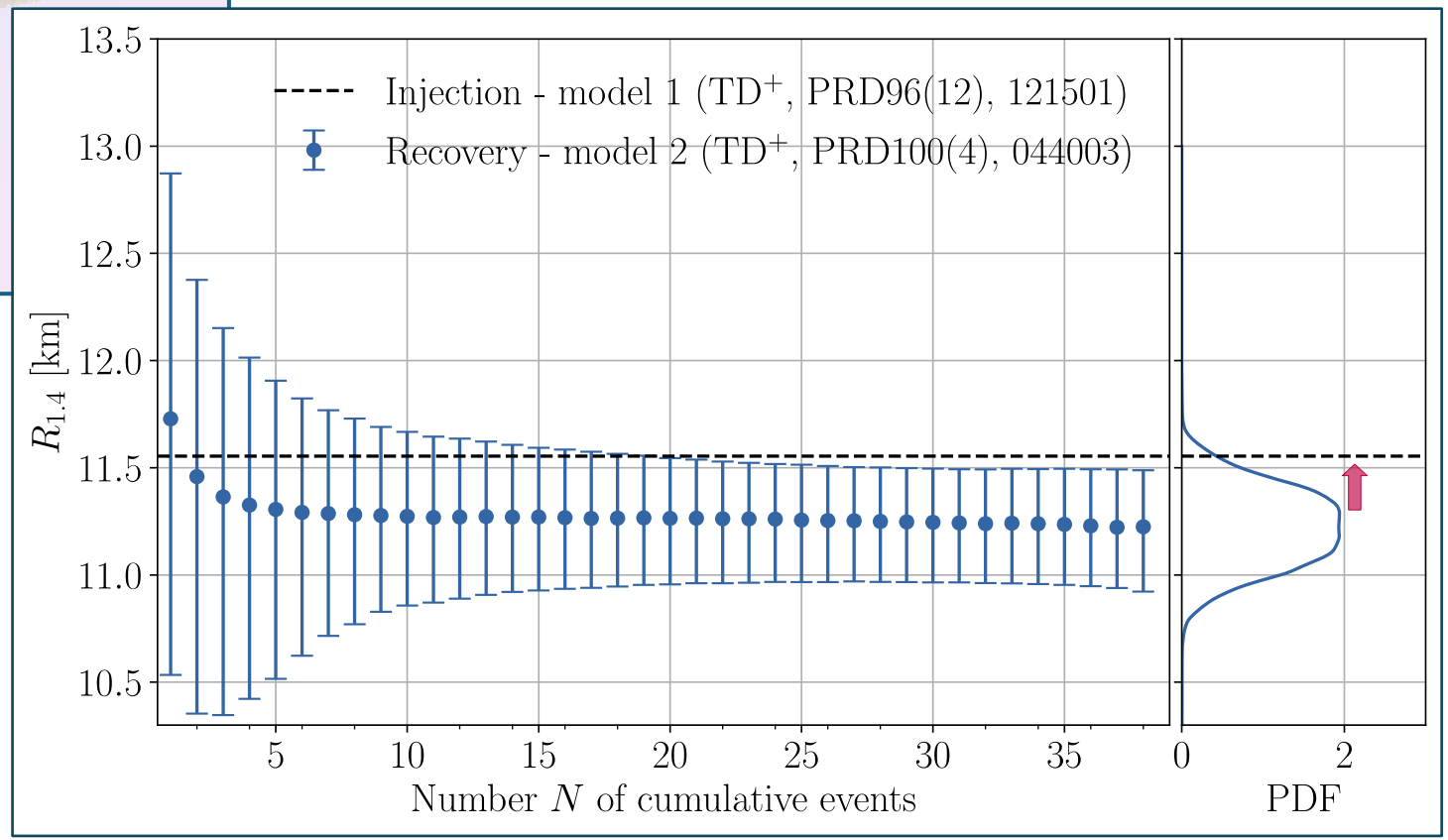


N.Kunert et al., PRD105 (2022) 6, L061301

Inspiral waveforms

Various models





N.Kunert et al., PRD105 (2022) 6, L061301

Inspiral waveforms

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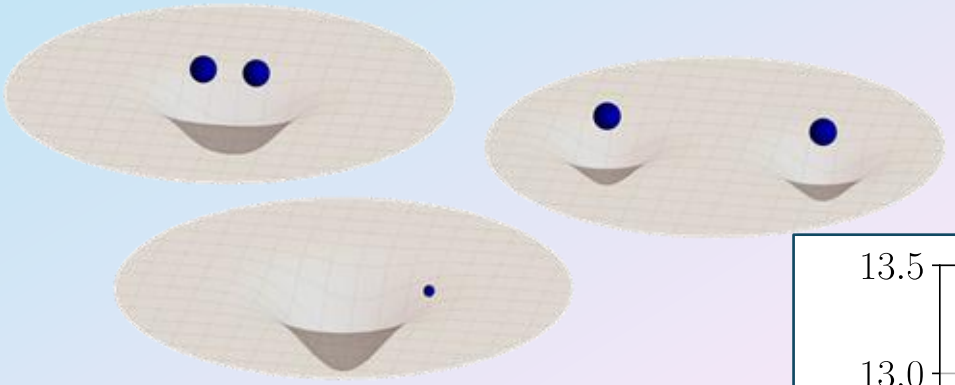
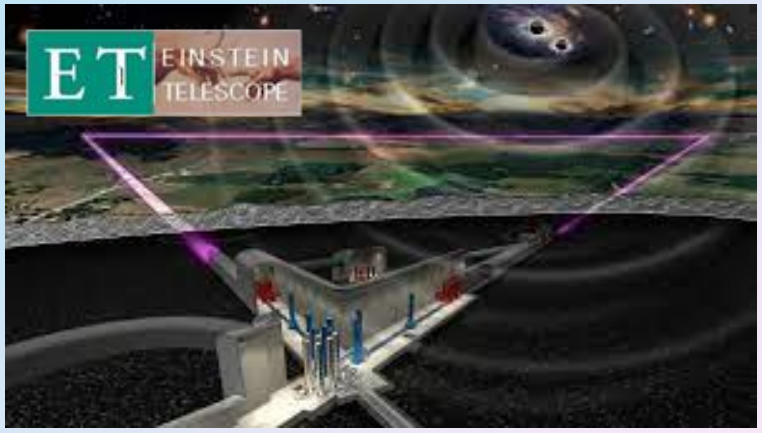
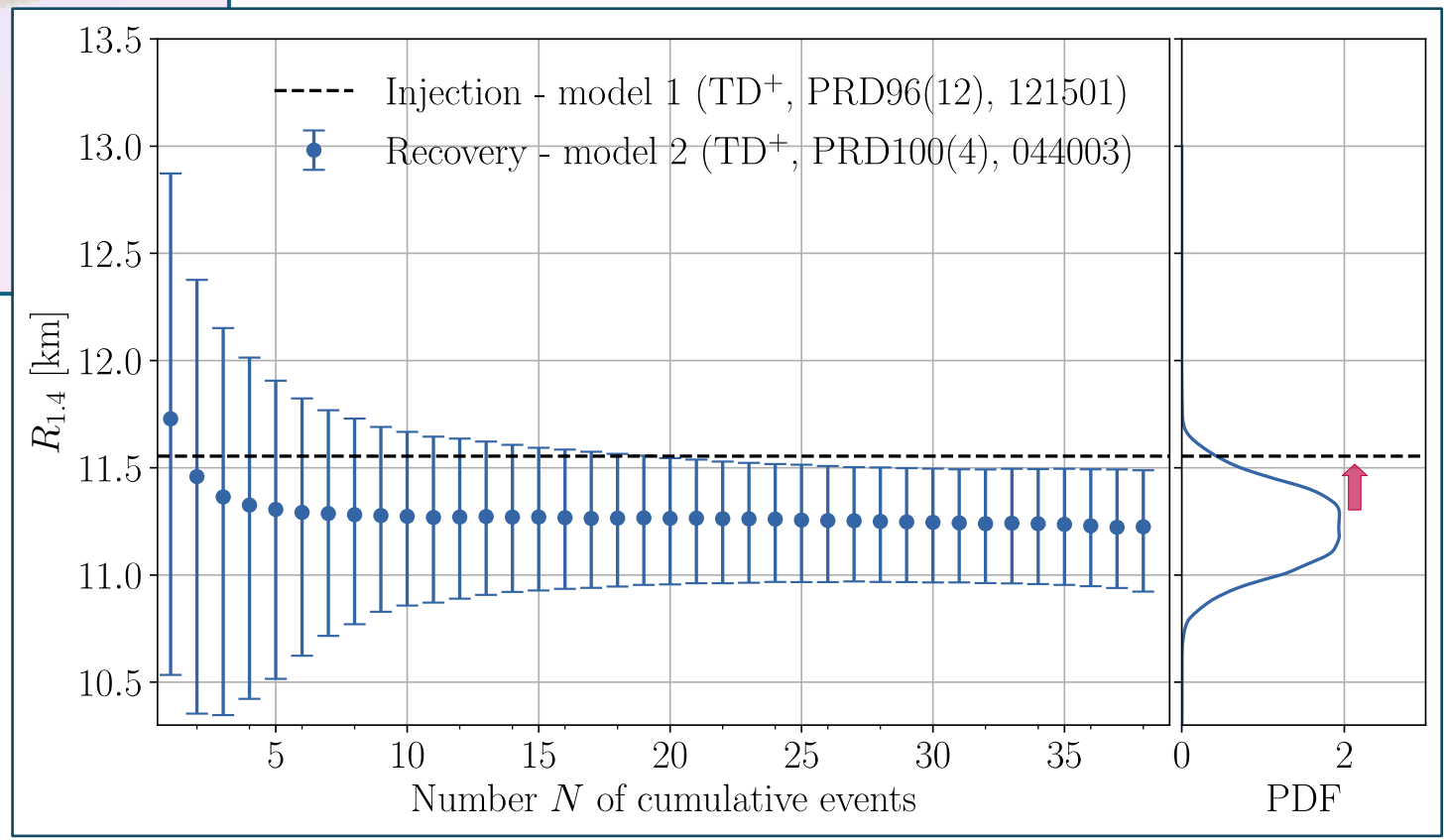


Note: Kunert et al., PRD 110 (2024) 4, 4 shows that Hubble constant measurements show less waveform modelling bias.



Einstein Telescope

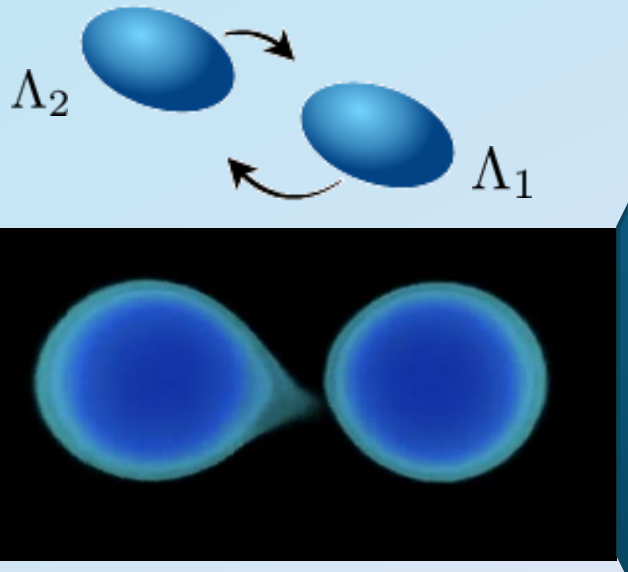


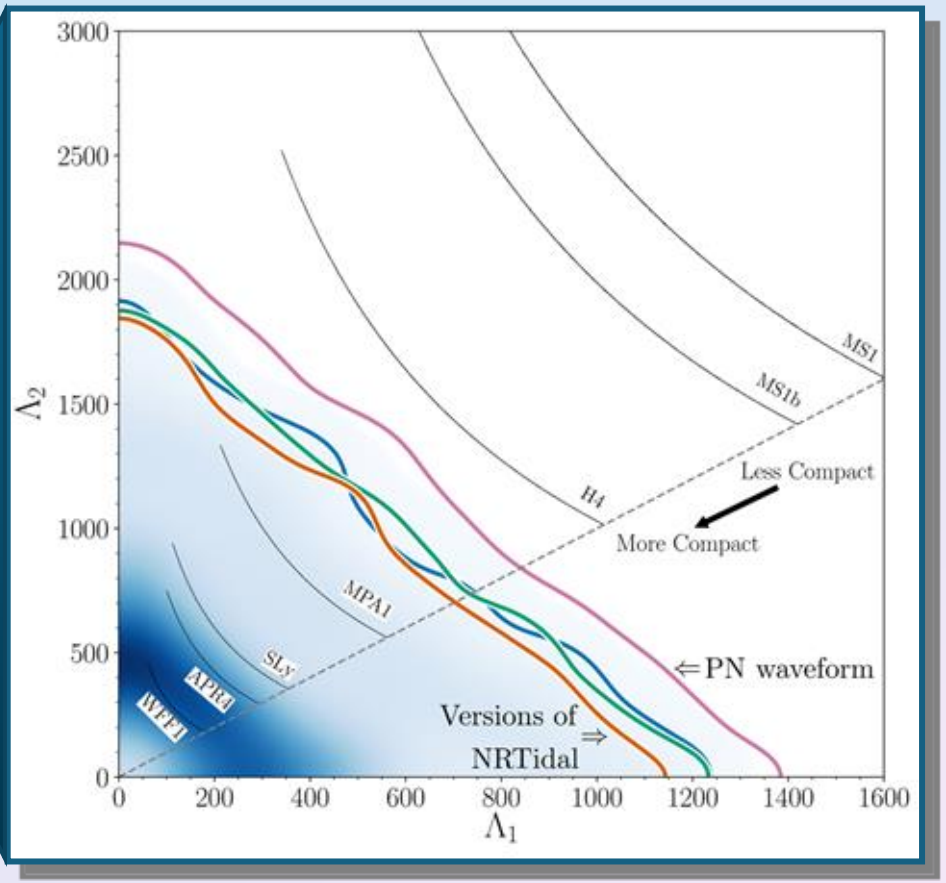
N.Kunert et al., PRD105 (2022) 6, L061301

Gravitational Wave Analysis

GW170817

Λ determines tidal deformability





→ no assumption about the type of the compact object

Phys.Rev. X9 (2019) 011001

Gravitational Wave Analysis

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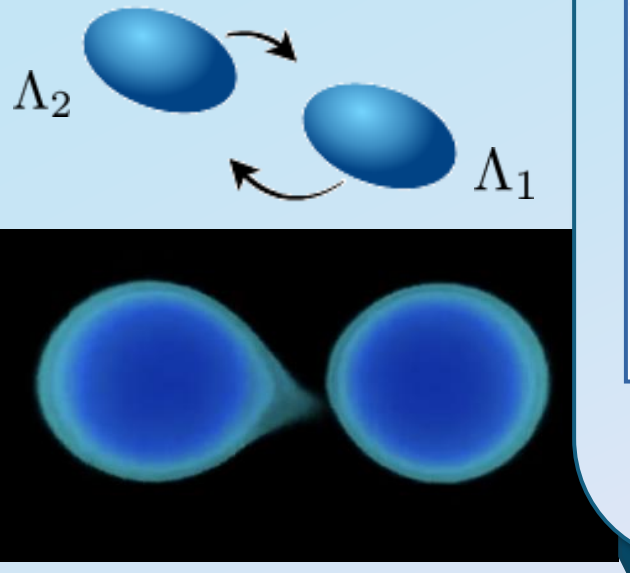
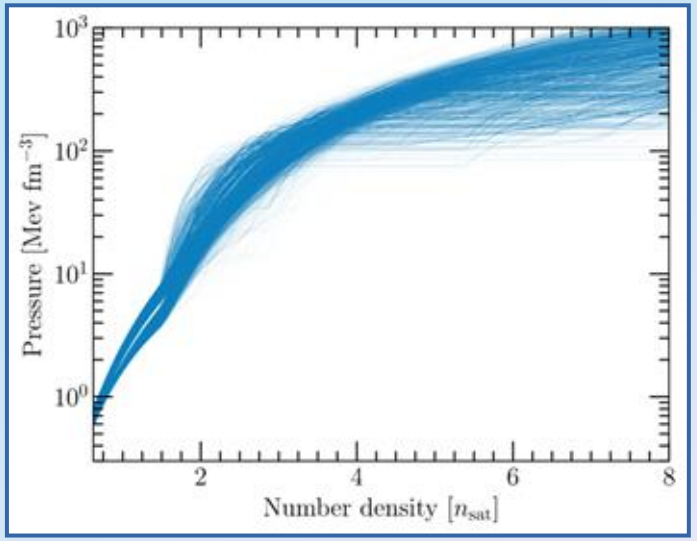
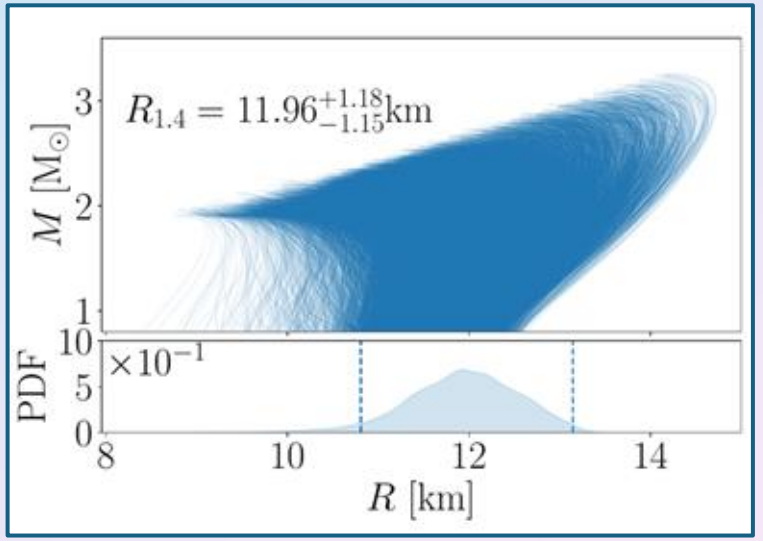
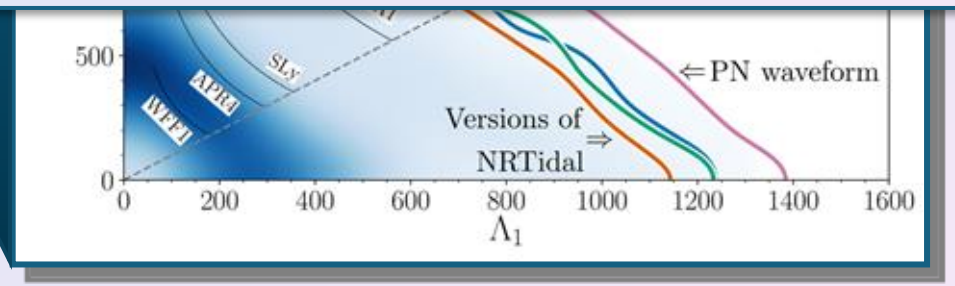


Assumption: The merging objects were neutron stars



nuclear-physics computations





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Phys.Rev. X9 (2019) 011001

Gravitational Wave Analysis

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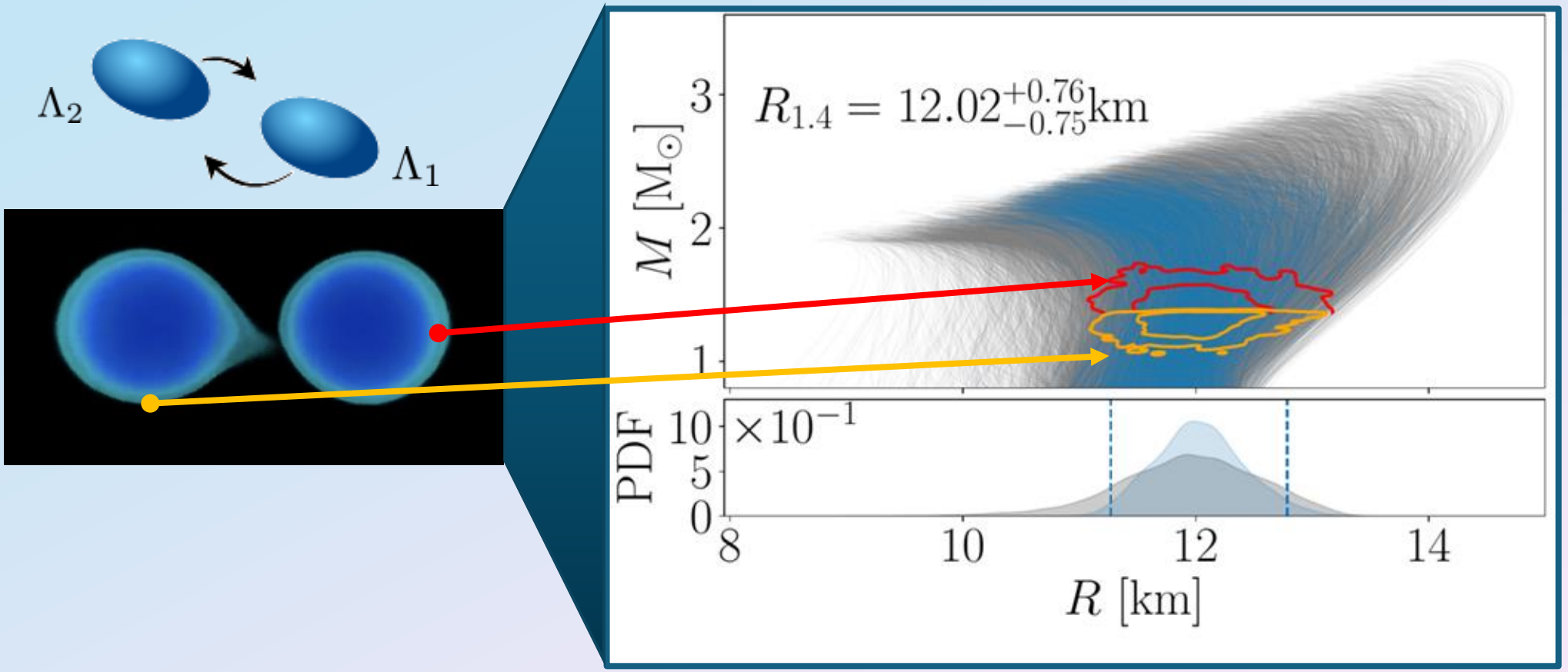


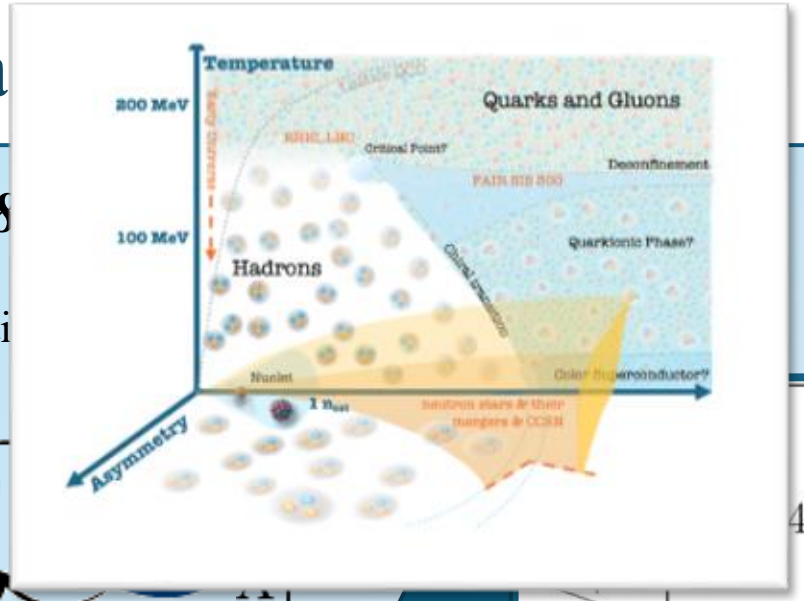
Assumption: The merging objects were neutron stars

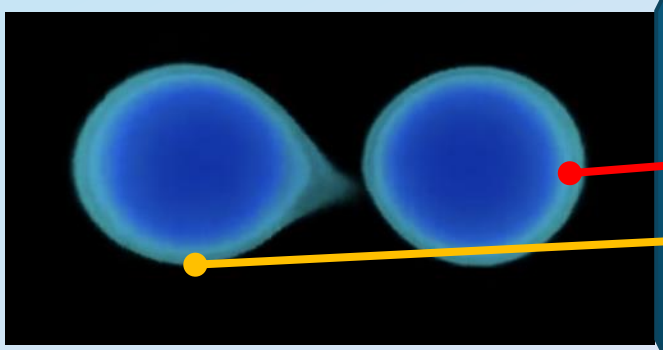
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Gravita

GW1708

Λ determines ti





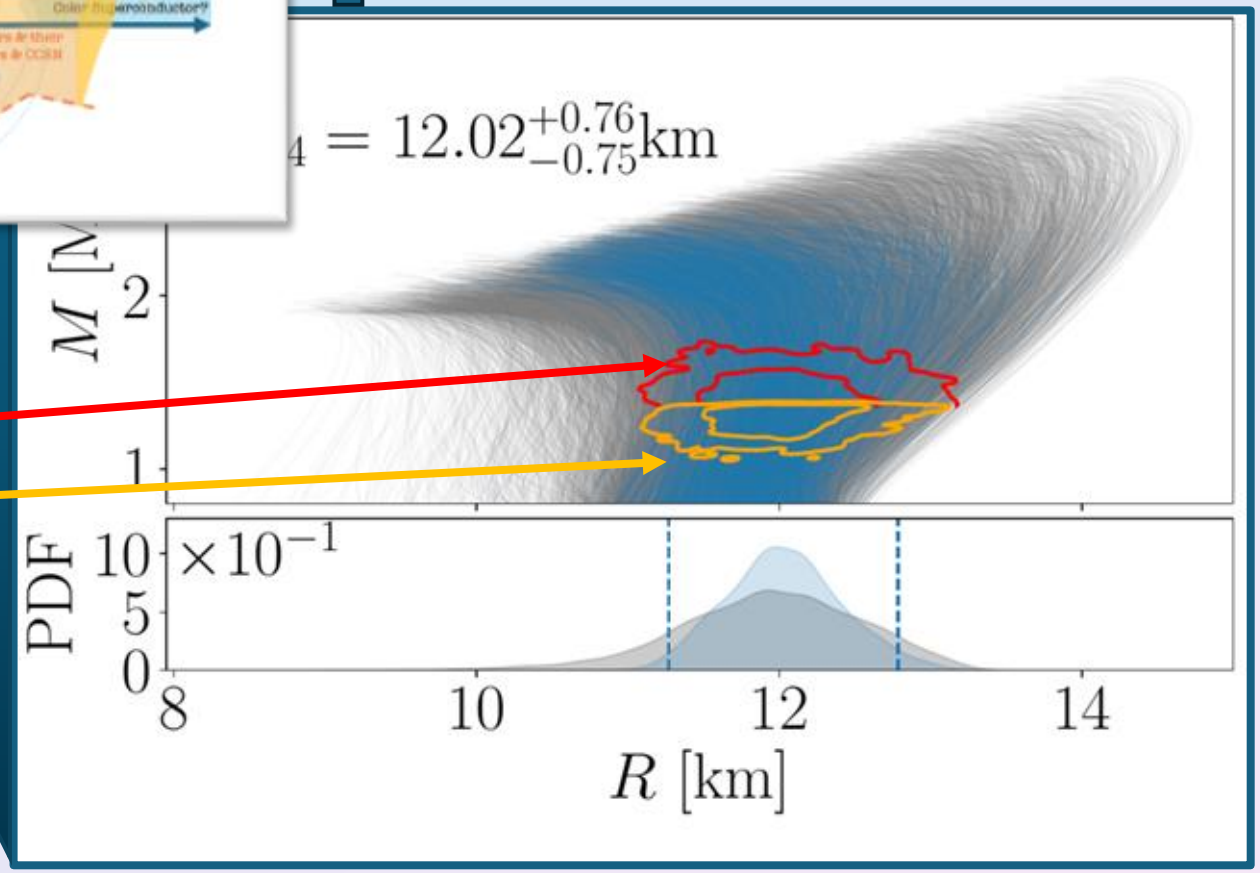
Rose et al. in prep.

Direct constraints on nuclear-physics parameters

$$e(n,\delta) = e_{\rm sat}(n) + e_{\rm sym}(n)\delta^2 + \mathcal{O}(\delta^4)$$

$$e_{\rm sat}(n) = E_{\rm sat} + \frac{1}{2}K_{\rm sat}x^2 + \frac{1}{3!}Q_{\rm sat}x^3 + \frac{1}{4!}Z_{\rm sat}x^4 + \dots$$

$$e_{\rm sym}(n) = E_{\rm sym} + L_{\rm sym}x + \frac{1}{2}K_{\rm sym}x^2 + \frac{1}{3!}Q_{\rm sym}x^3 + \frac{1}{4!}Z_{\rm sym}x^4 + \dots$$



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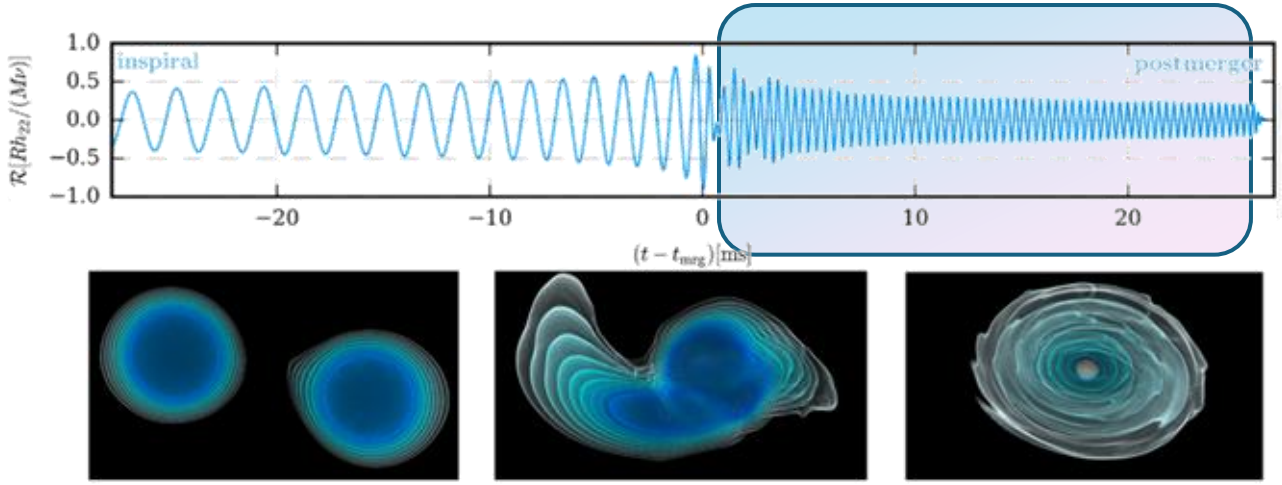
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Waveform Model Development through NR simulations



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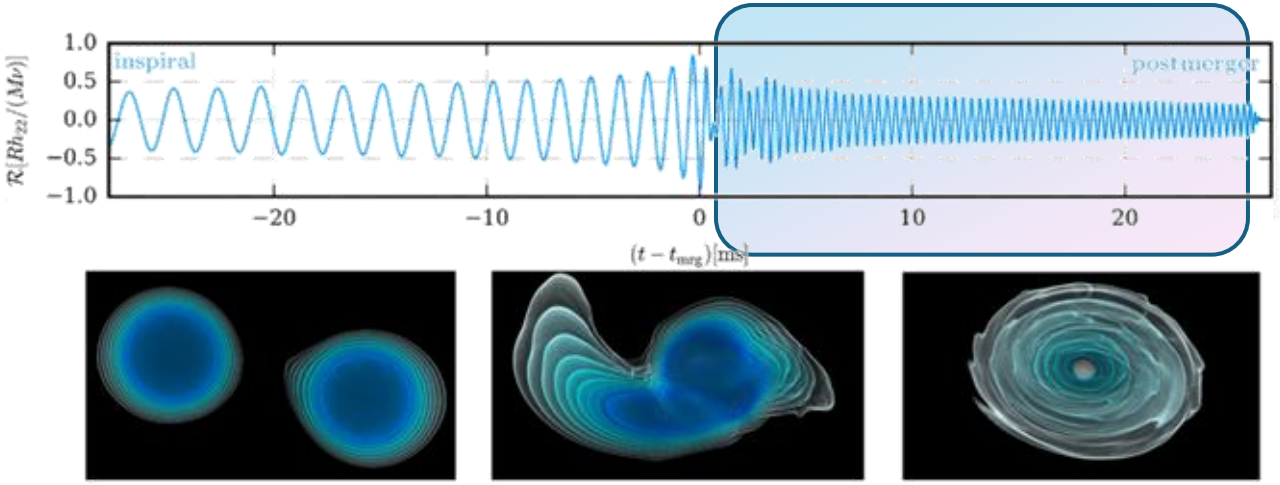
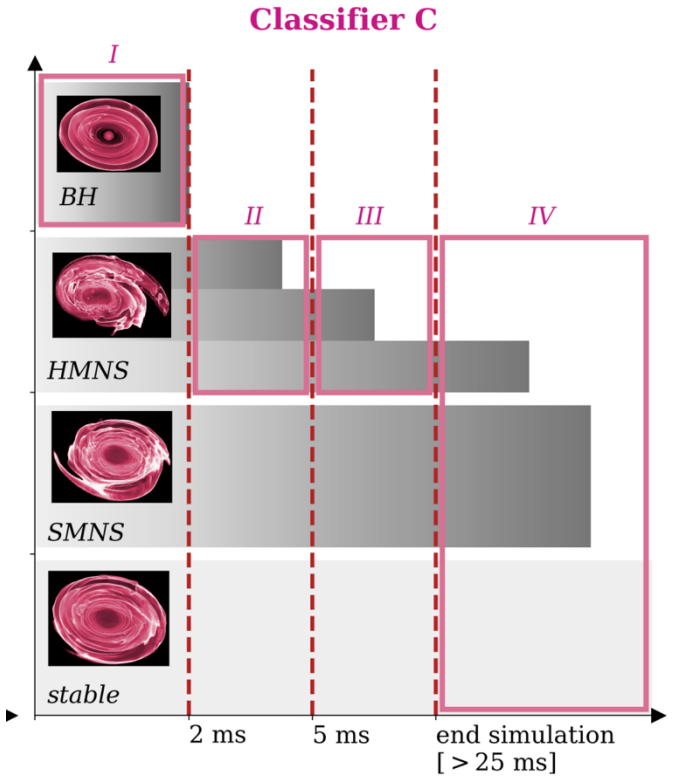


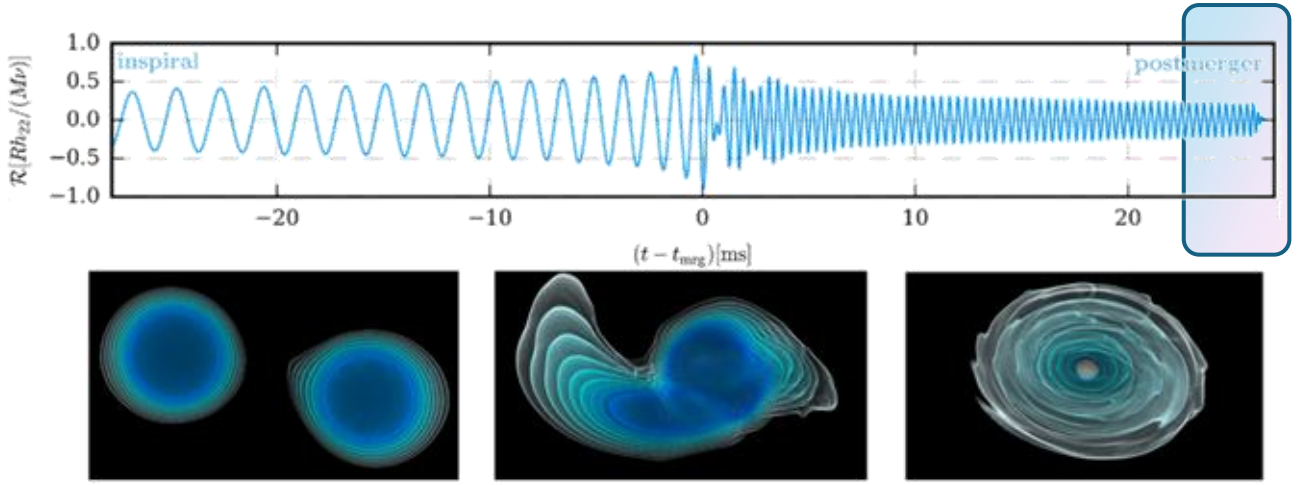


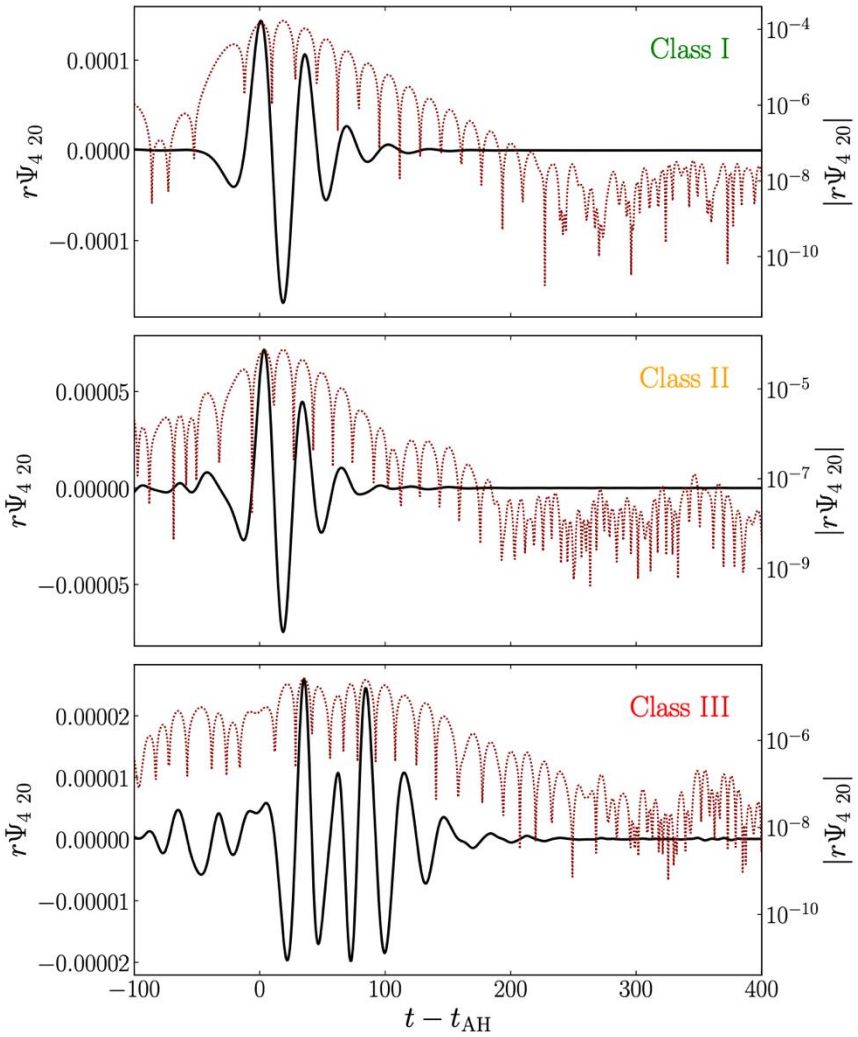
- Prediction of postmerger remnant class based on information from the inspiral (based on numerical-relativity simulation)
- low-latency product to enable counterpart search

Puecher & TD, Phys.Rev.D 110 (2024) 12, 123038

	Classifier A		Classifier B			Classifier C			
	p_{PCBH}	p_{RNS}	p_{PCBH}	p_{HMNS}	p_{NC}	p_{PCBH}	p_{SHORT}	p_{LONG}	p_{NC}
GW170817	39.8%	60.2%	39.7%	57.5%	2.8%	41.7%	15.6%	39.8%	3.7%
GW170817+EoS	9.0%	91.0%	8.8%	90.5%	0.7%	11.6%	38.7%	49.2%	0.5%
GW170817+EoS+KN	0.9%	99.1%	0.9%	98.9%	0.2%	1.3%	42.8%	55.8%	0.2%
GW170817+EoS+KN+GRB	0.1%	99.9%	0.2%	99.5%	0.3%	0.5%	50.8%	48.6%	0.1%
GW190425	59.5%	40.5%	66.2%	7.4%	26.4%	71.9%	0.3%	11.1%	15.7%
GW190425+EoS	98.2%	1.8%	98.6%	0.2%	1.1%	97.3%	0.0%	0.1%	2.5%

Waveform Model Development through NR simulations

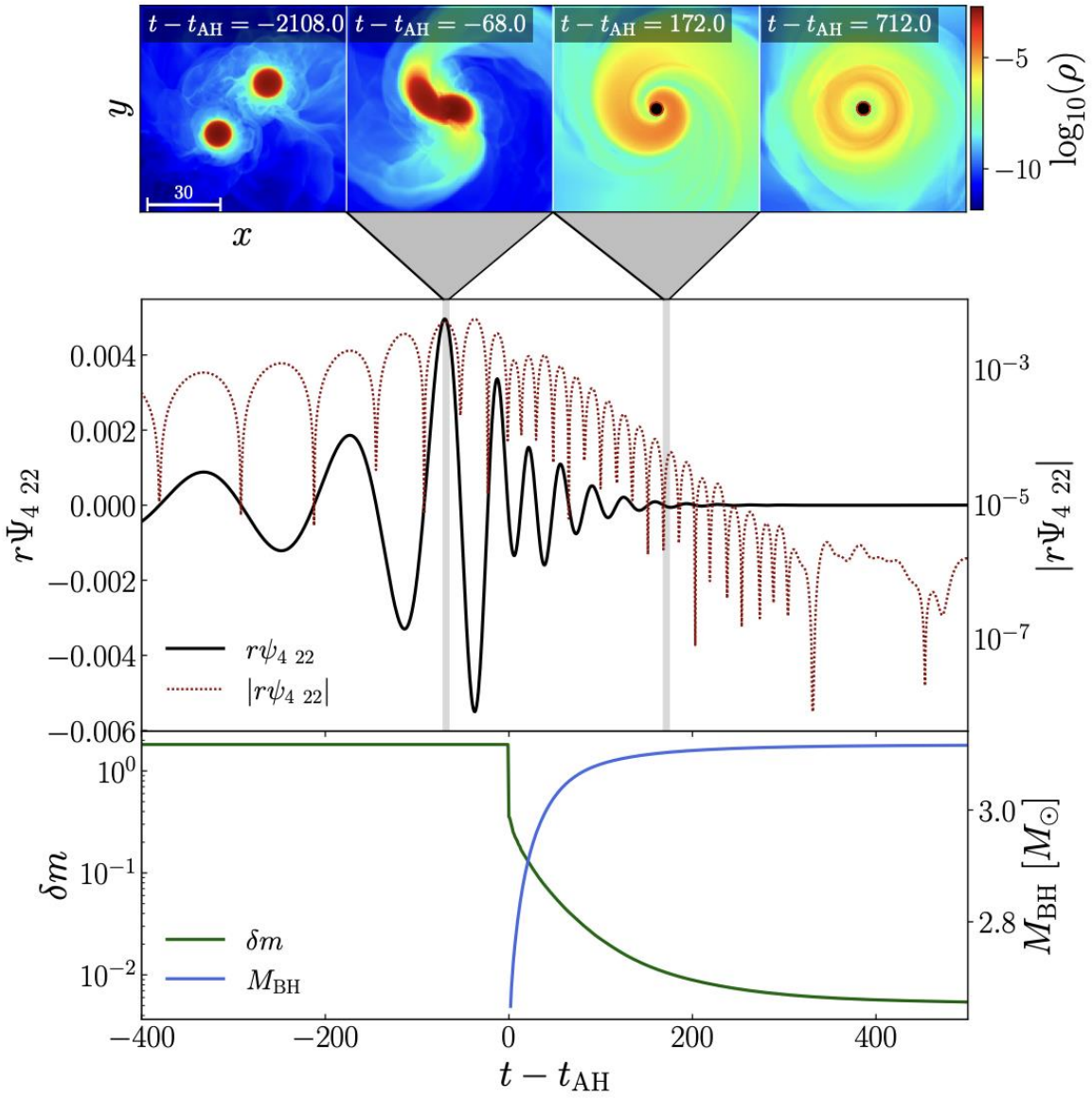


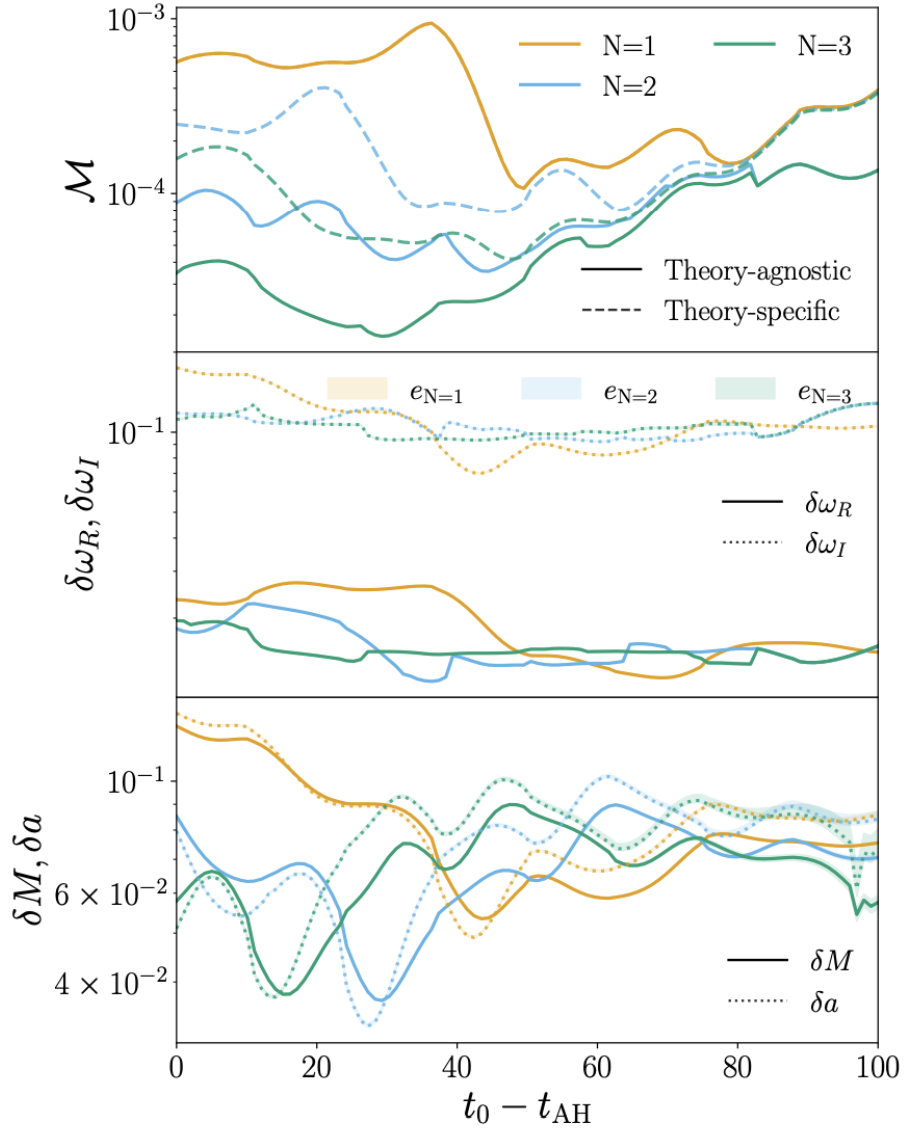


- Classification in 3 classes possible
- Extraction of higher-mode excitations from the simulations is possible, but beyond the dominant mode less robust
- Unlikely to be detected even with 3G

Steppohn et al., Phys.Rev.D 113 (2026) 2, 024011

Waveform Model Development through NR simulations



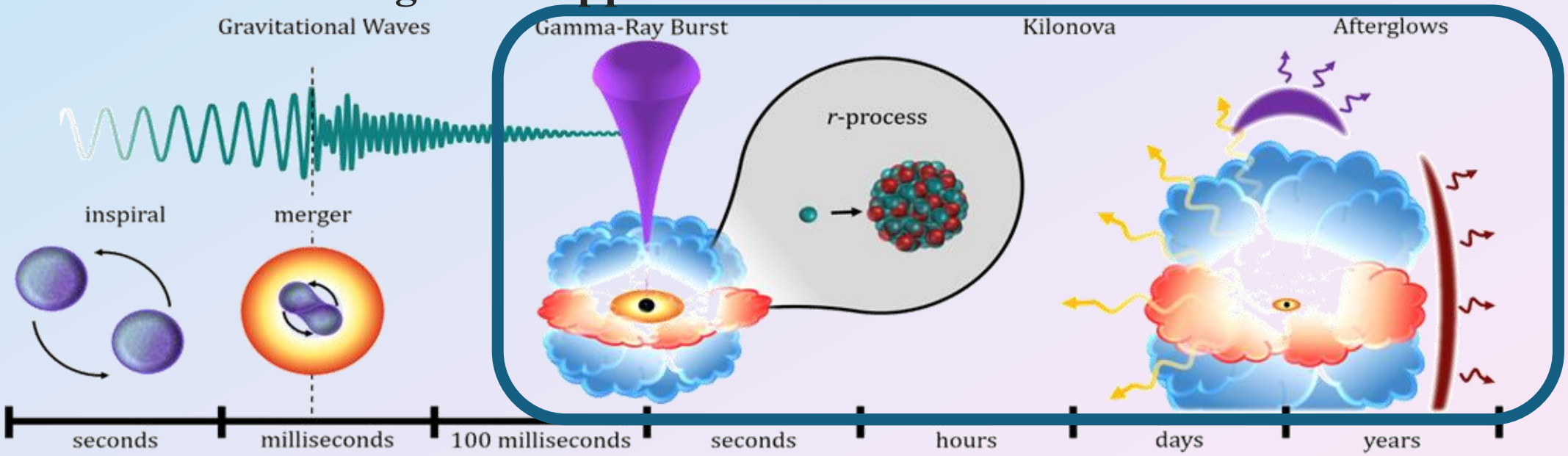


example: unequal mass merger leading to a prompt collapse

Steppohn et al., Phys.Rev.D 113 (2026) 2, 024011

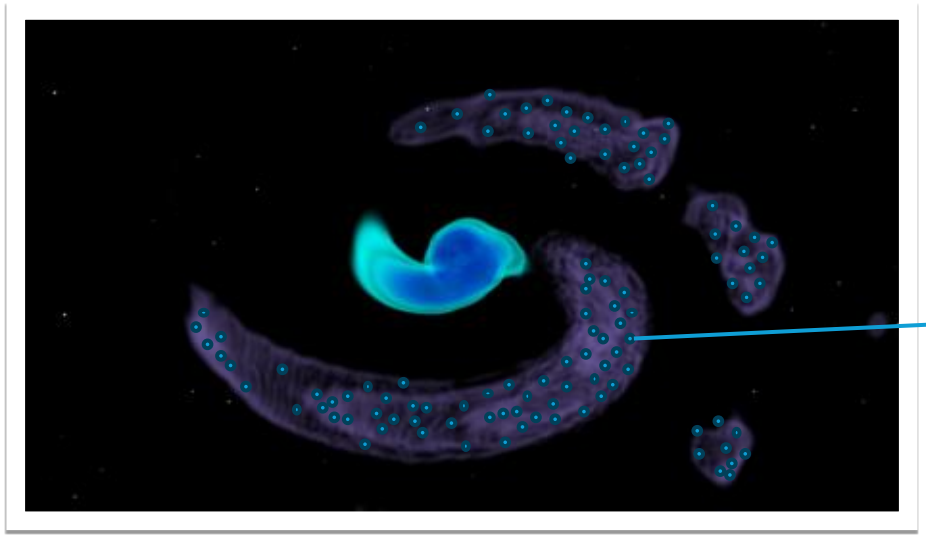
Decoding Neutron Star Mergers:
From Numerical Relativity to Multi-Messenger Inference

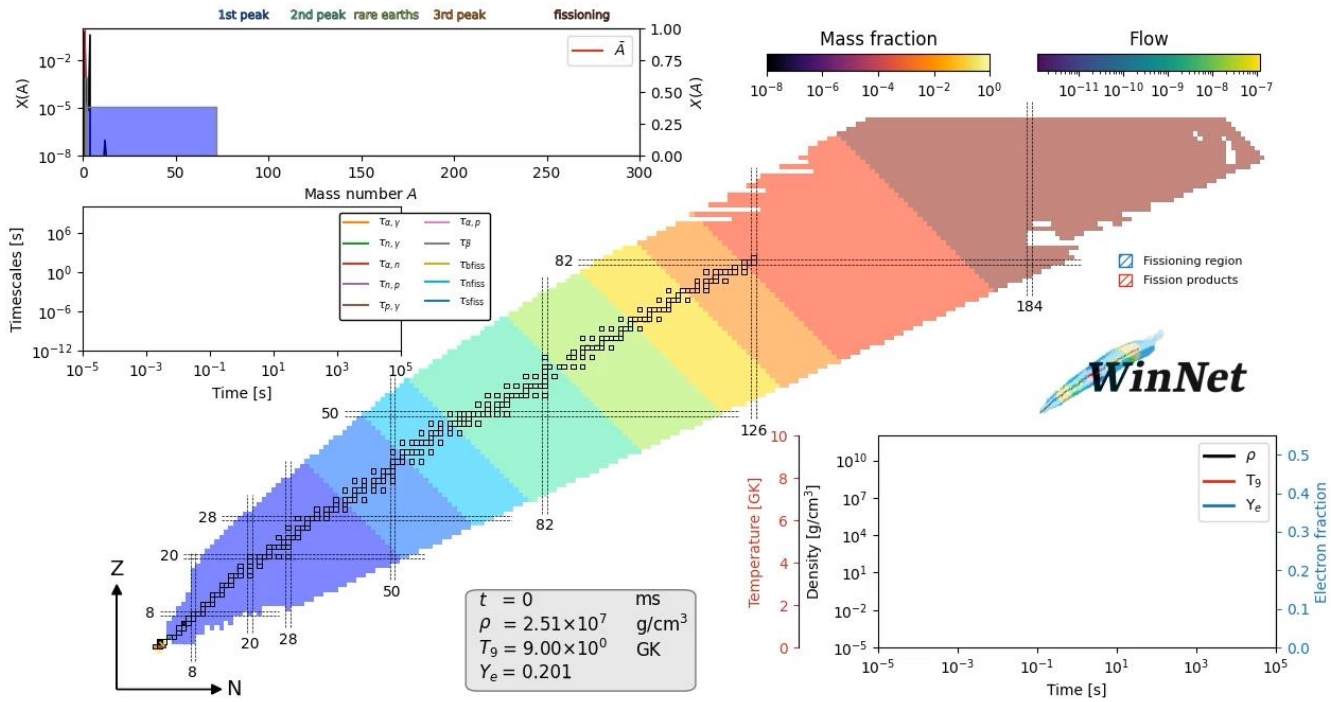
How to move beyond single simulation-based predictions and create general applicable models?



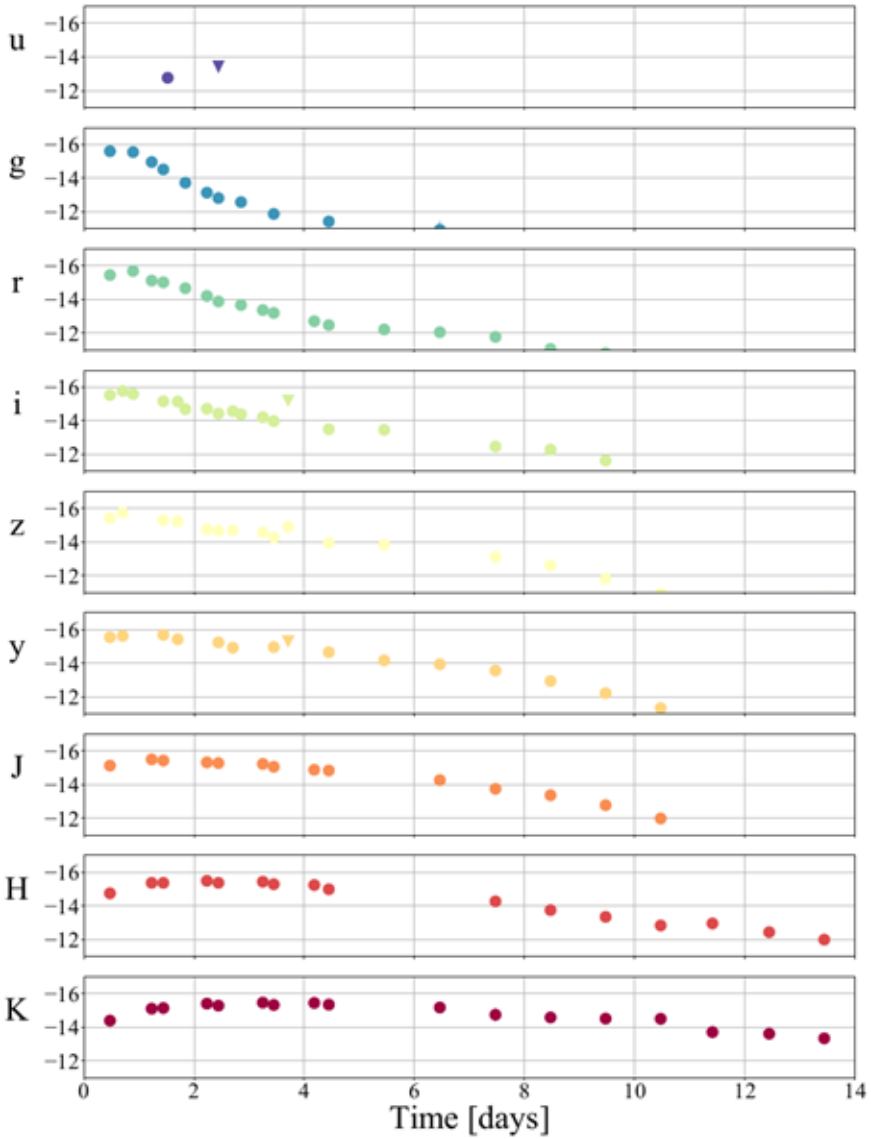
EM Signals – Kilonova

- neutron rich ejecta produce heavy r-process elements
- pseudo-black body radiation from r-process elements
- mergers are major sites for the formation of heavy elements





Photometric lightcurves



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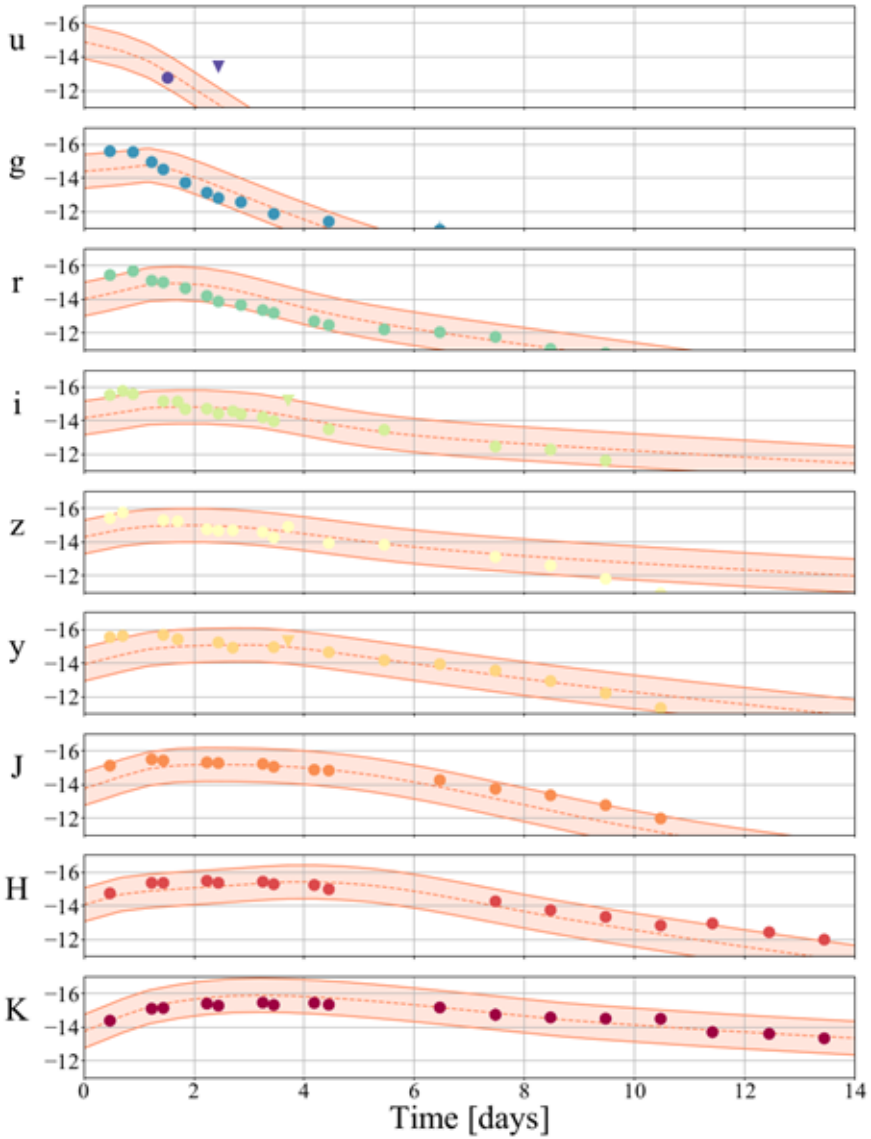

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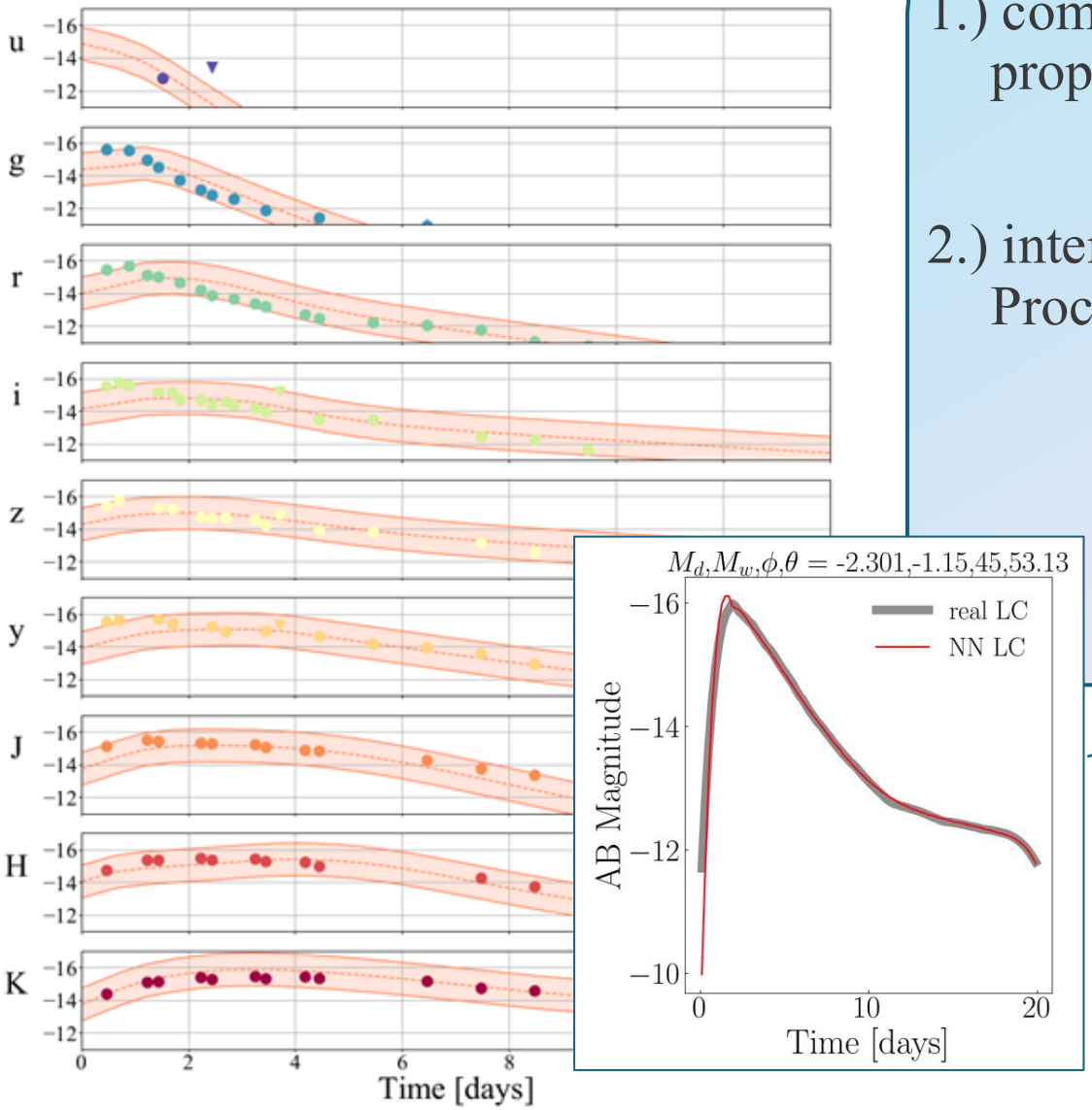
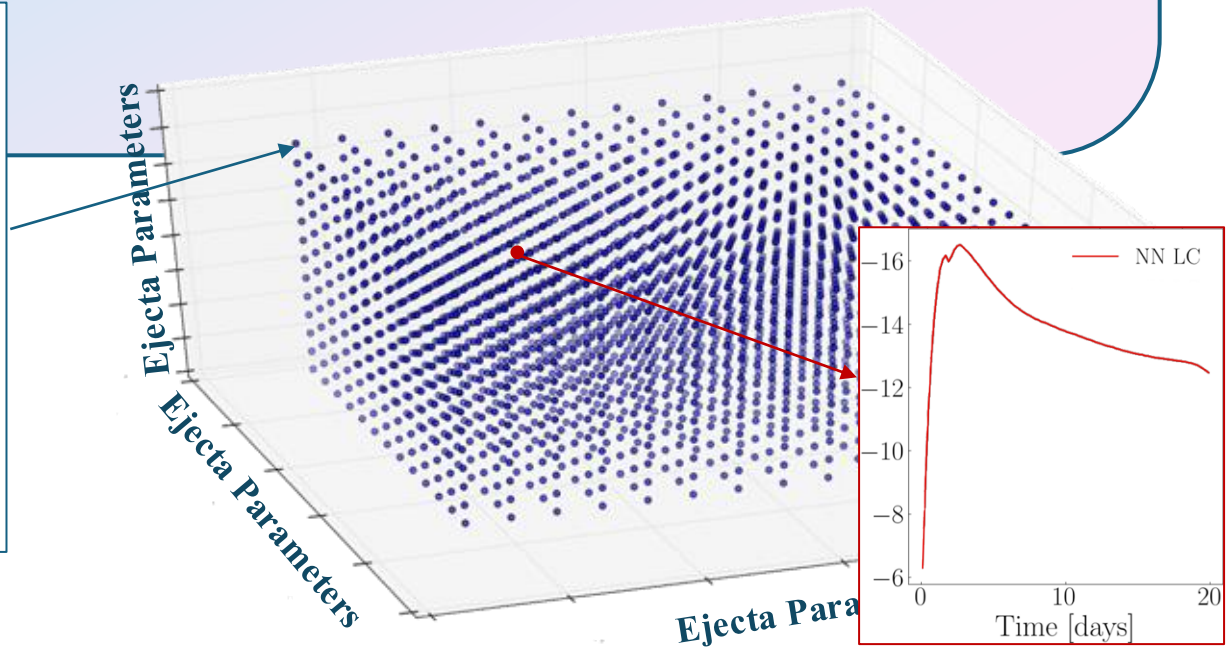


1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code

2.) interpolate within this grid through Gaussian Process Regression or a Neural Network



https://github.com/nuclear-multimessenger-astronomy/fiestaEM

Koehn et al., A&A 704 (2025) A55

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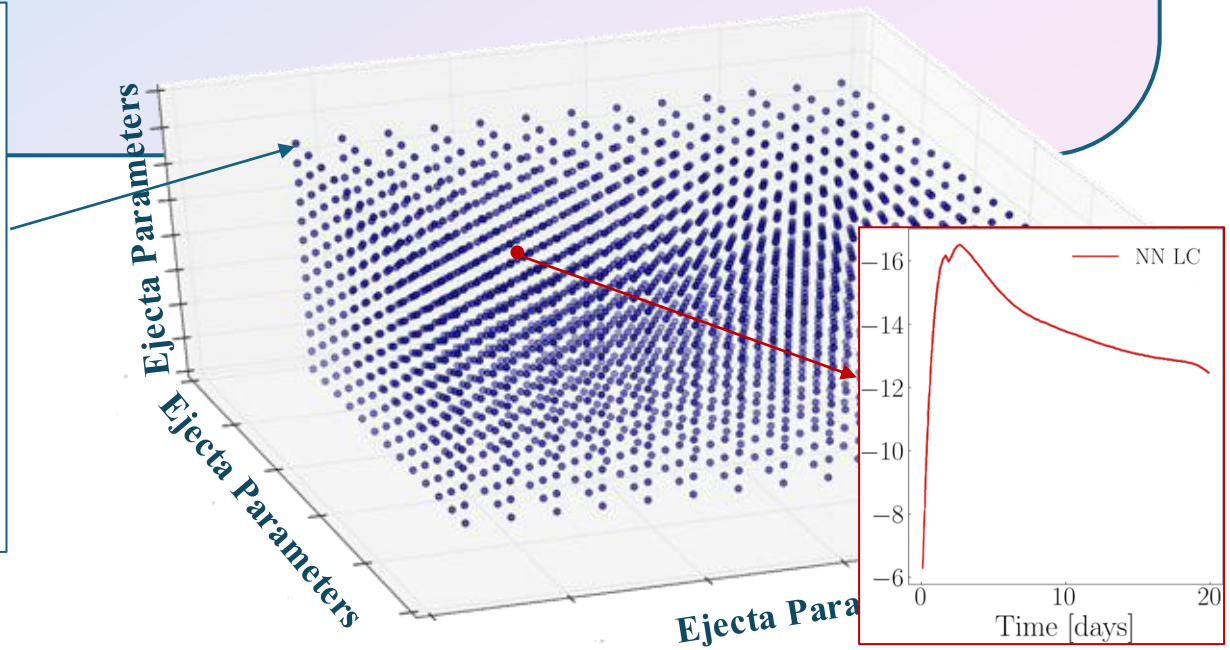
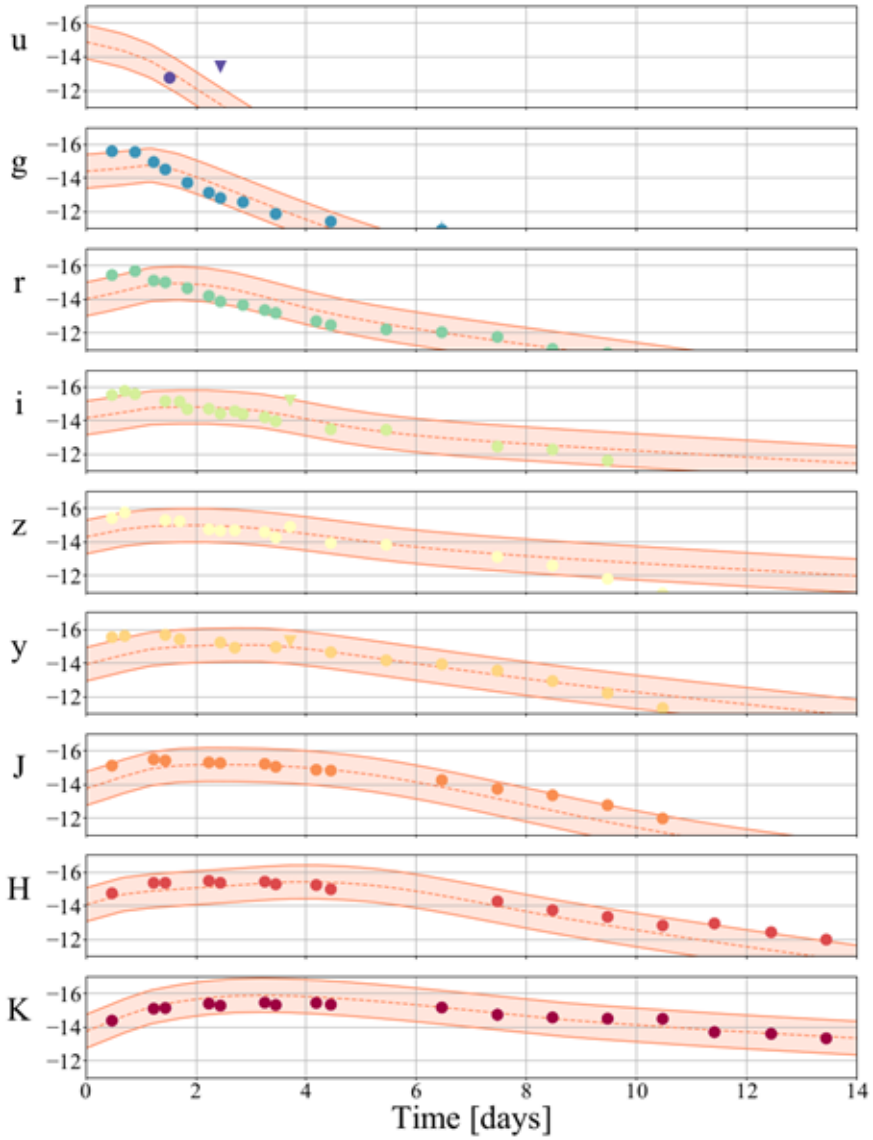


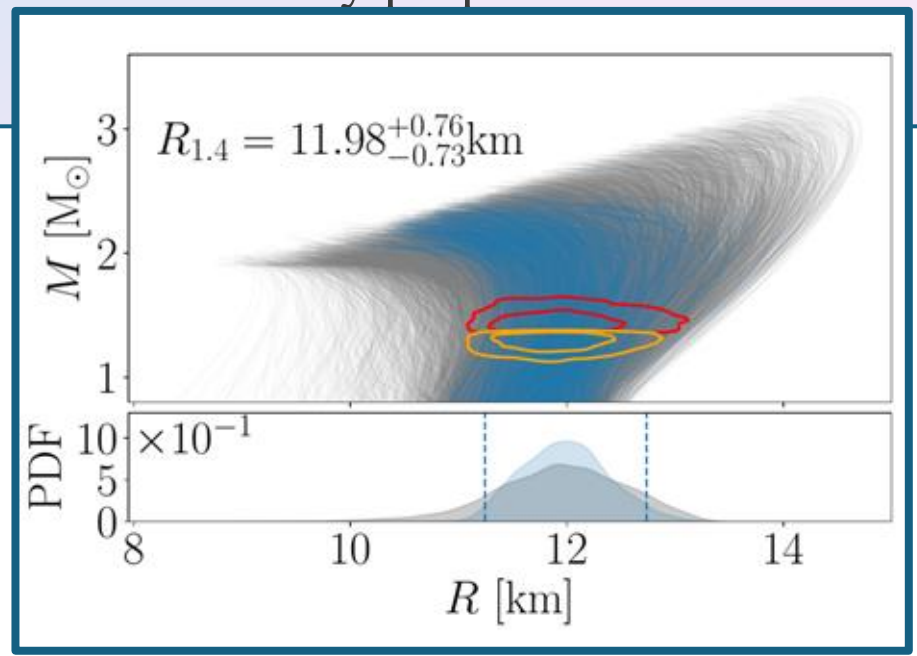
Photometric lightcurves



1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code

2.) interpolate within this grid through Gaussian Process Regression or a Neural Network

3.) link ejecta properties through numerical-relativity predictions to the binary properties

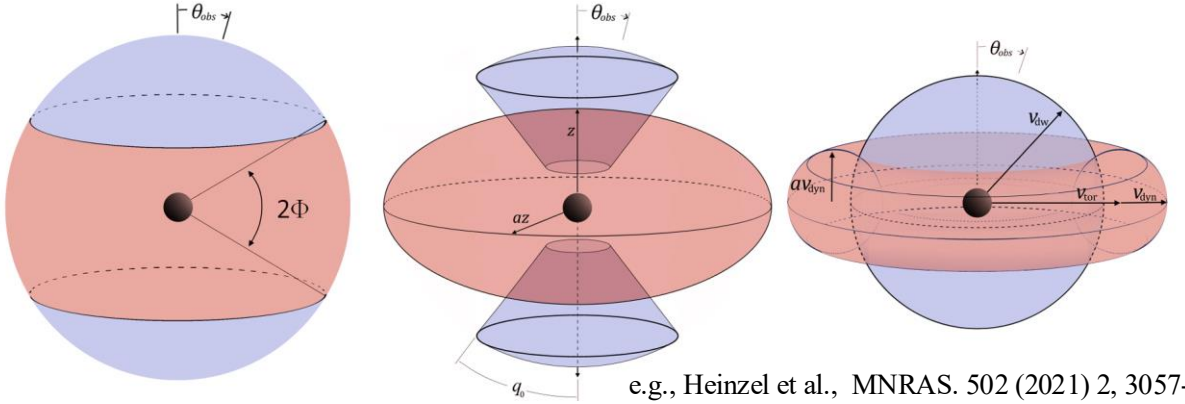


Uncertainties

1.) Knowledge about the outflowing material (mass, velocity, geometry, composition)

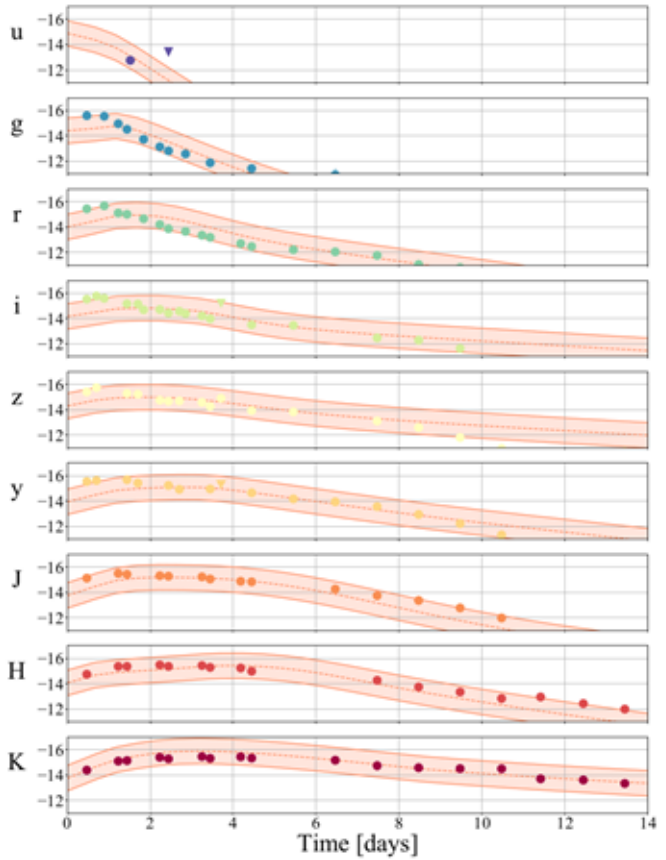
2.) Heating rates depend on the formed elements and ejecta properties

3.) Incomplete knowledge about opacities for complicated elements



e.g., Heinzel et al., MNRAS. 502 (2021) 2, 3057-3065

Cross-code comparisons for numerous geometries and assumptions → estimate on the modelling uncertainty



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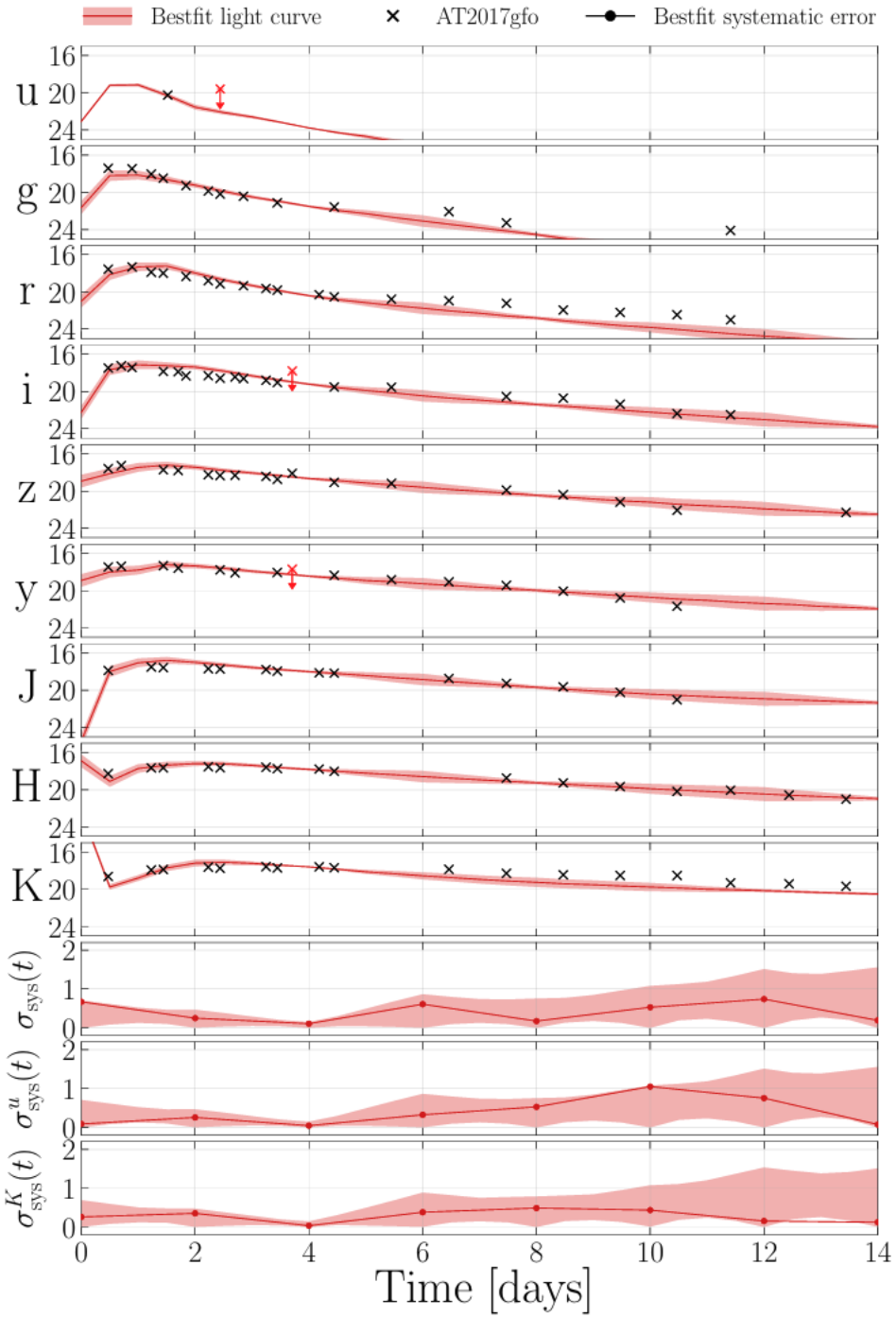
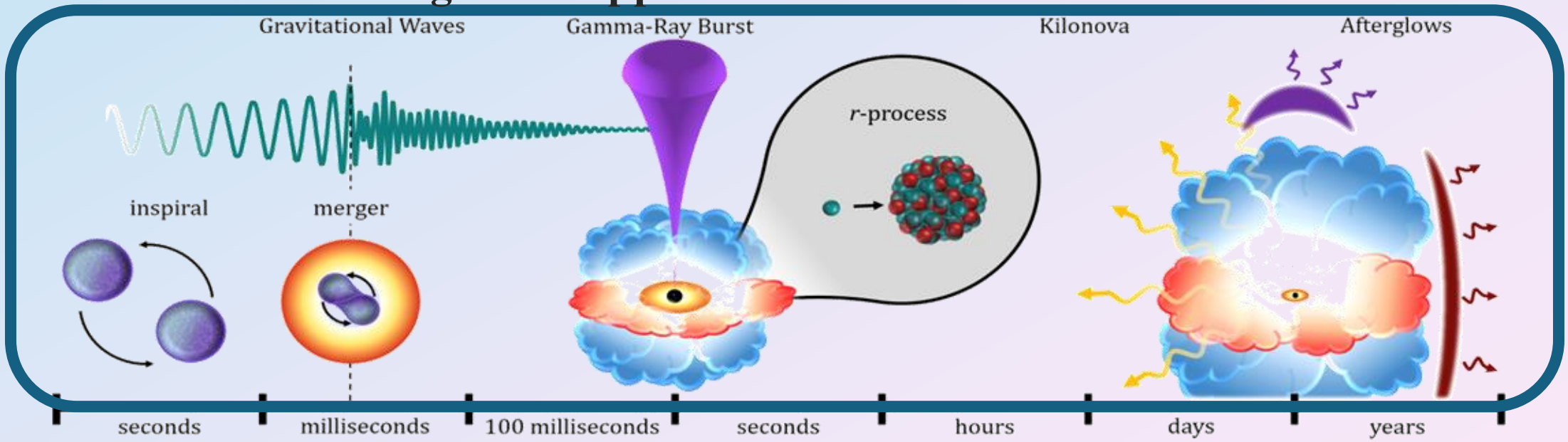
Data-driven approach to determine uncertainties

Jhawar et al., PRD 111 (2025), 4, 043046



Decoding Neutron Star Mergers:
From Numerical Relativity to Multi-Messenger Inference

How to move beyond single simulation-based predictions and create general applicable models?



NMMA: Steps towards a nuclear-physics and multi-messenger astrophysics framework

- simultaneous analysis of GW, kilonova, and GRB afterglow while sampling nuclear physics parameters
- HPC facilities needed or GPU-acceleration required

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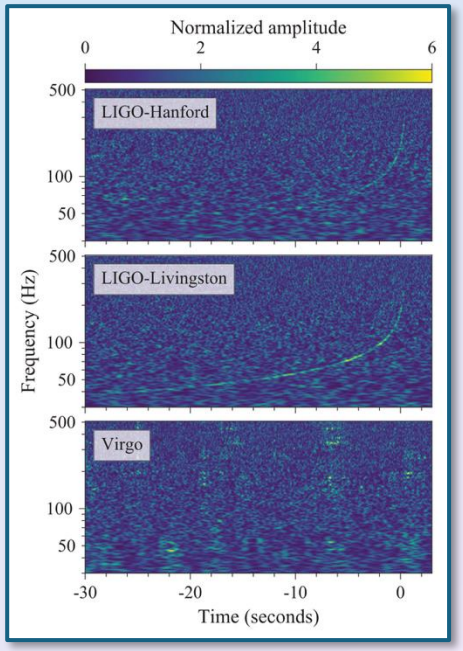

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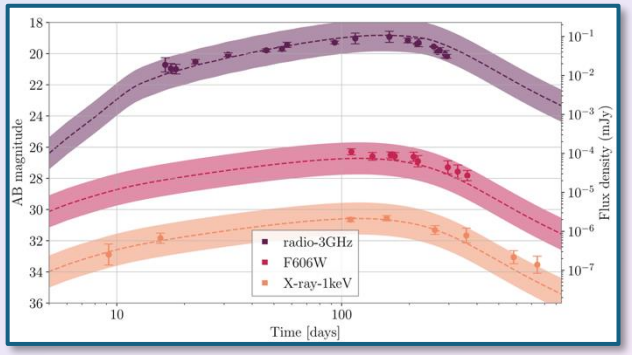

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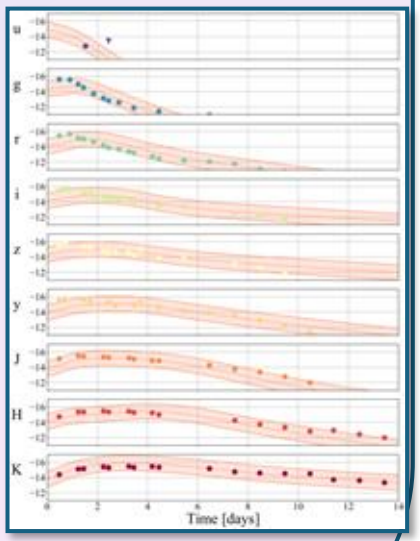
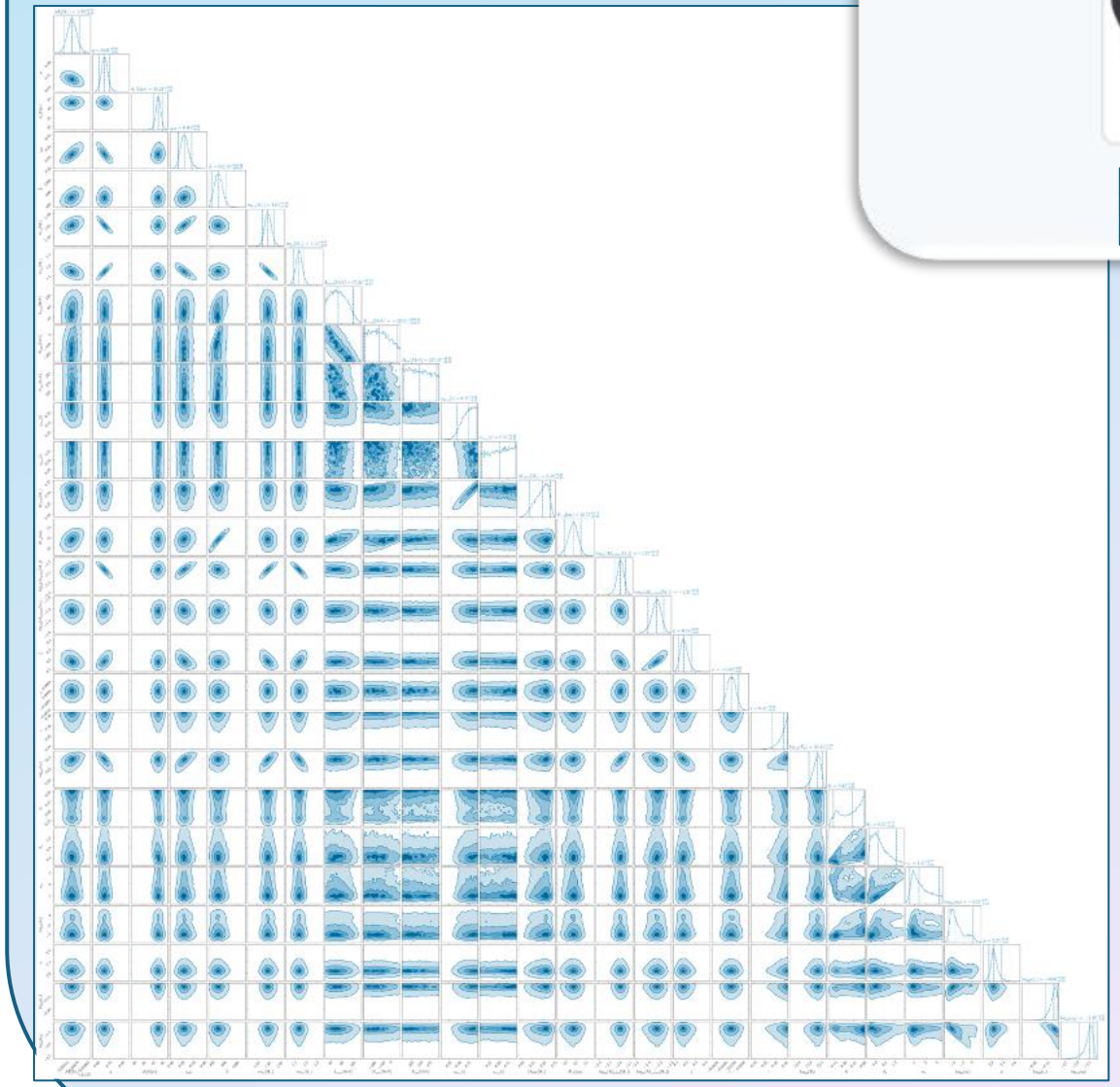




Product Solutions Resources Open Source Enterprise Pricing

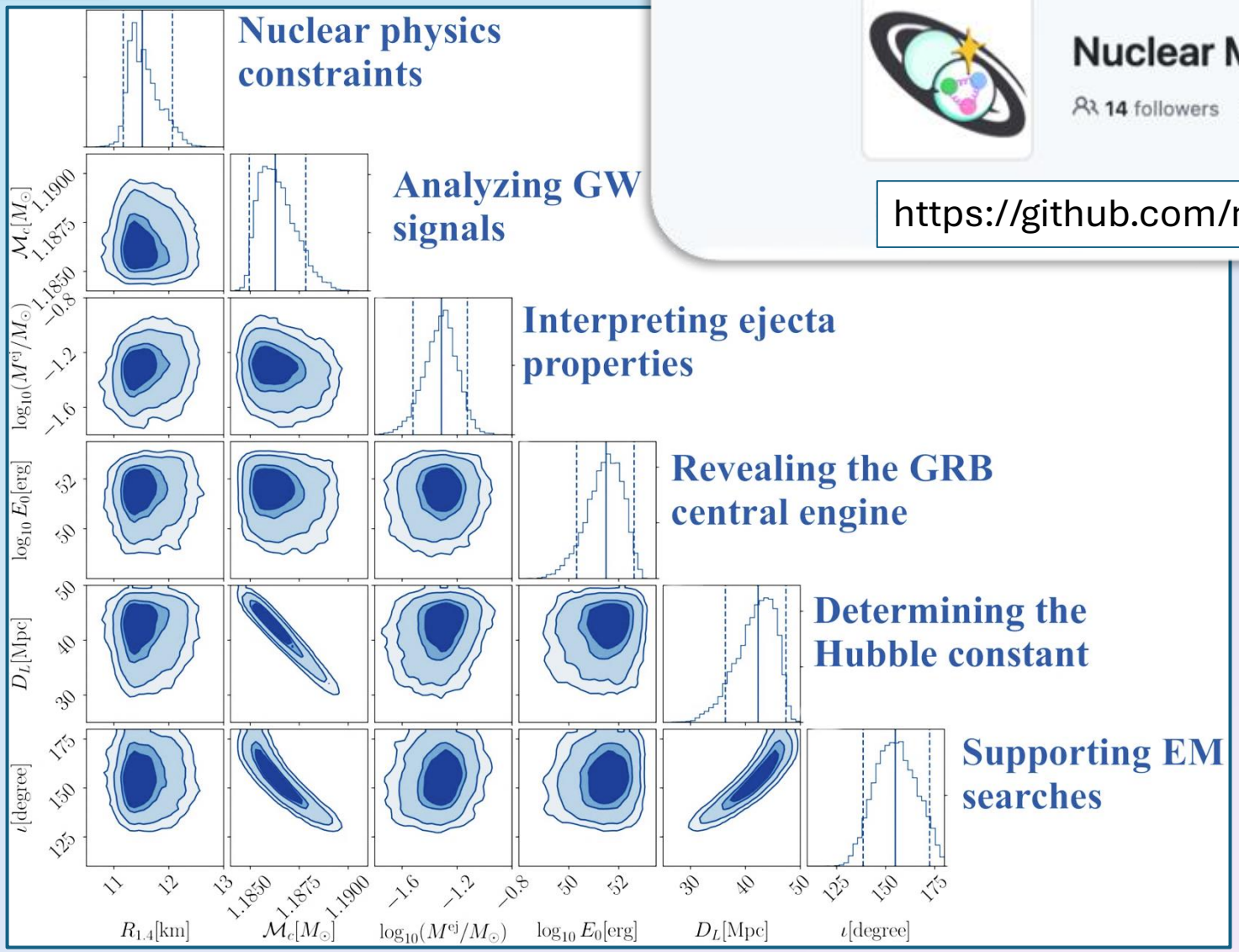
Nuclear Multimessenger Astronomy

14 followers nuclear_multimessenger_astronom...

https://github.com/nuclear-multimessenger-astronomy

Pang et al., Nat. Comm. 14 (2023) 1, 8352

NMMA



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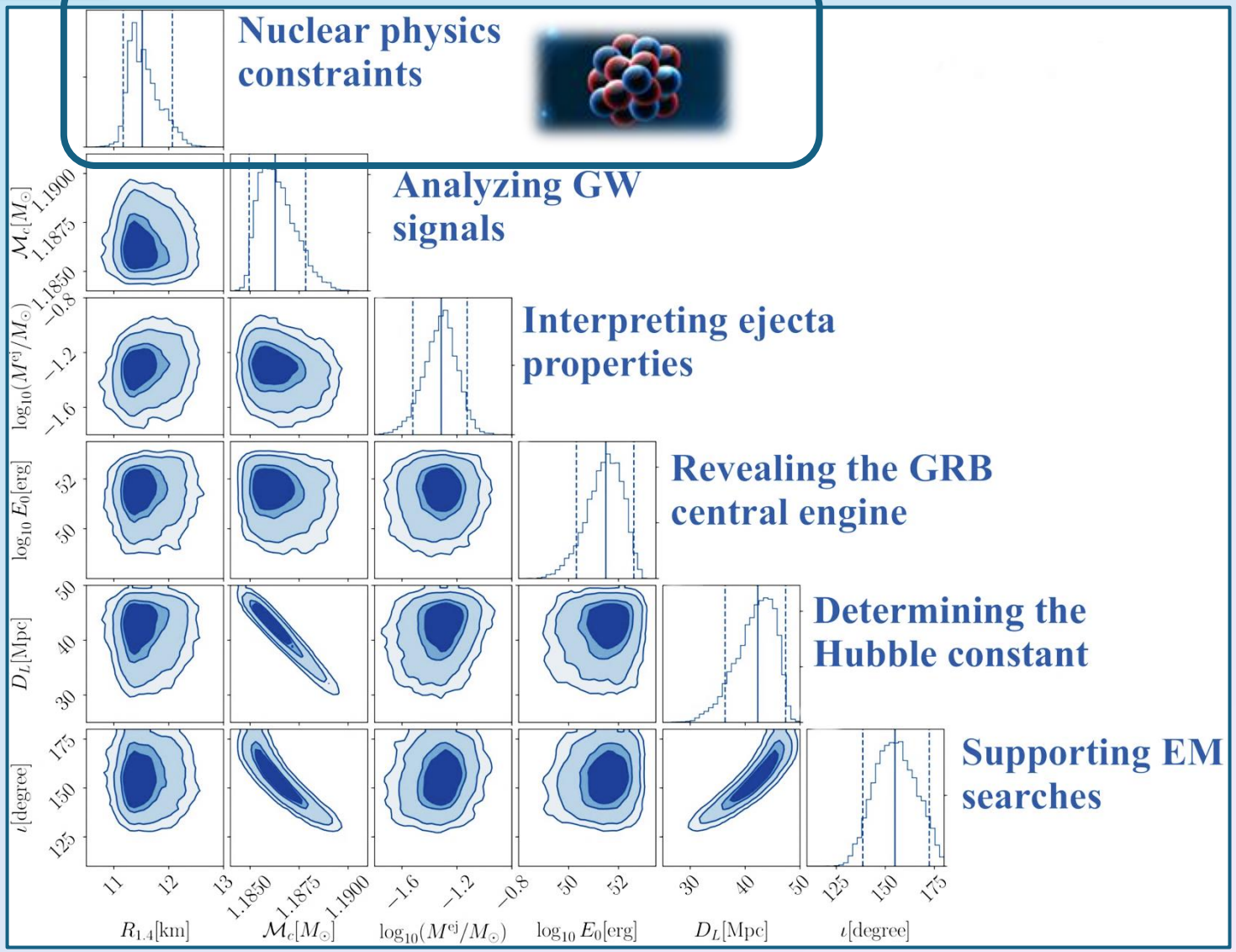
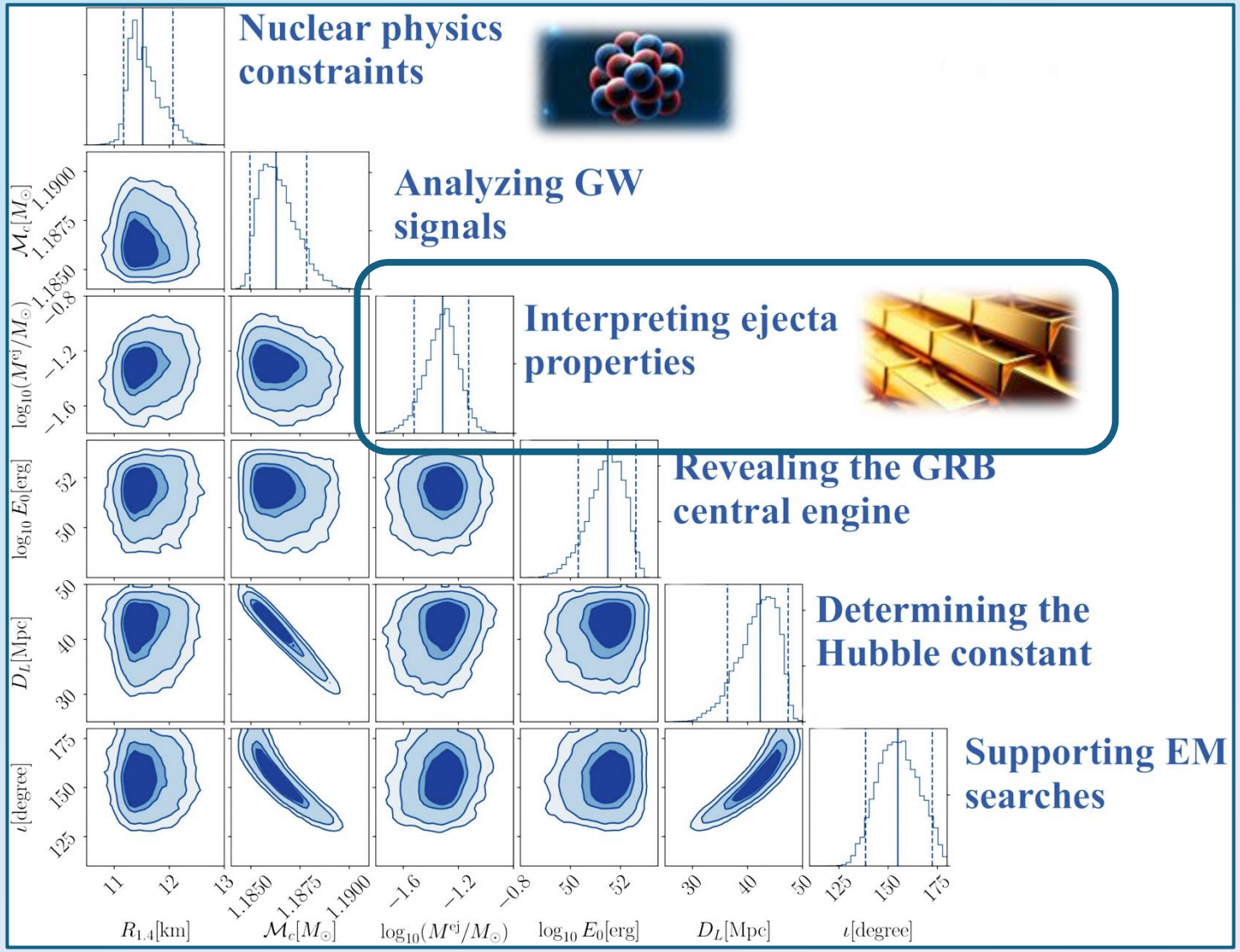

Nuclear physics constraints
Analyzing GW signals
Interpreting ejecta properties
Revealing the GRB central engine
Determining the Hubble constant
Supporting EM searches
$R_{1.4}$[km]
$\mathcal{M}_c[M_\odot]$
$\log_{10}(M^{\rm ej}/M_\odot)$
$\log_{10} E_0$[erg]
D_L[Mpc]
ι[degree]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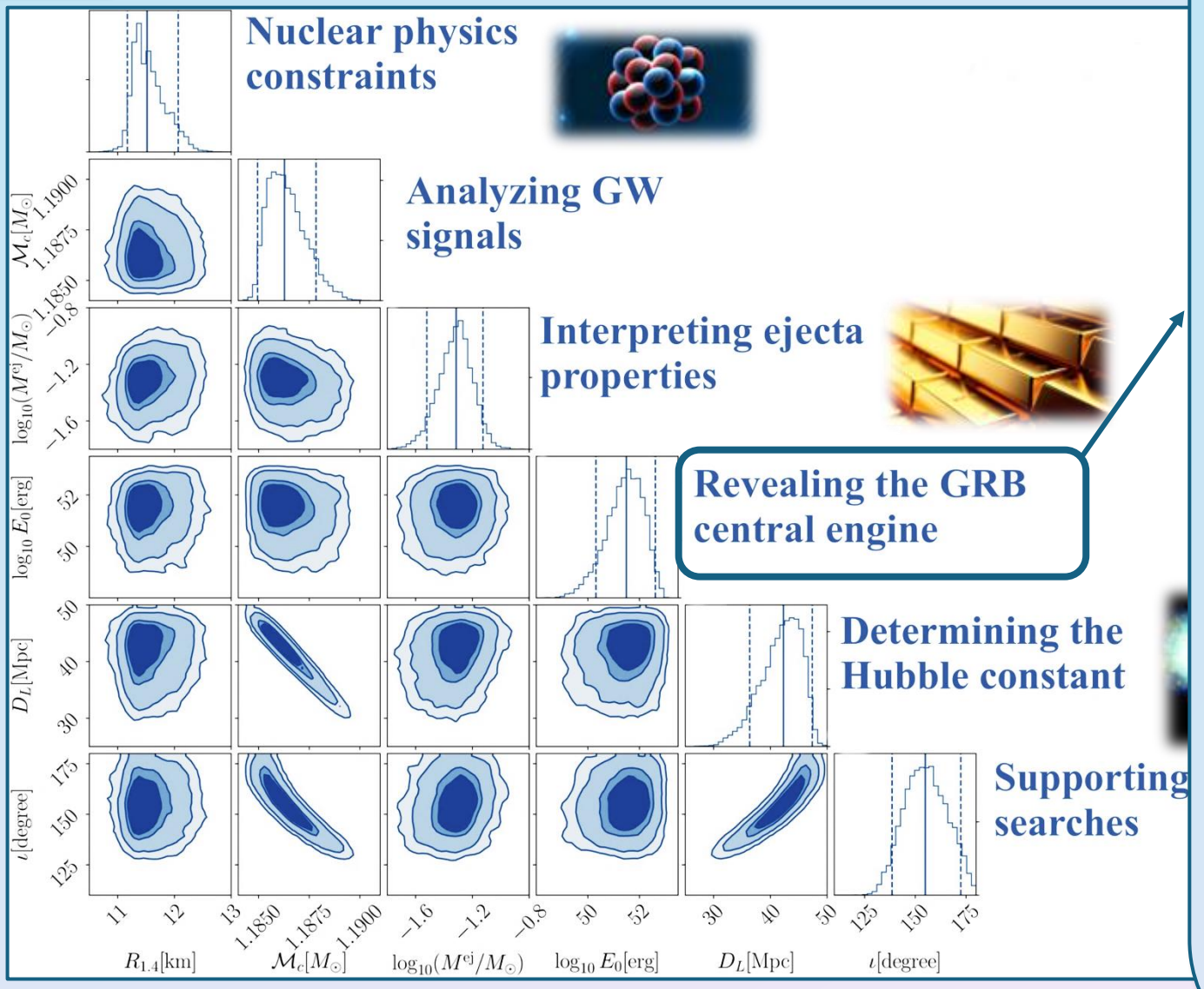
Nuclear Physics and Multi-messenger Astrophysics

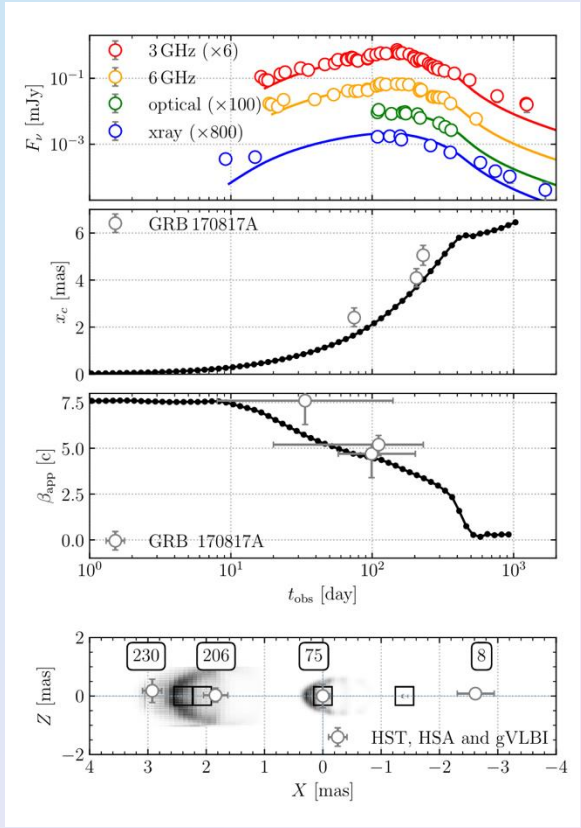


PyBlastAfterglow

https://github.com/vsevolodnedora/PyBlastAfterglowMag

modular publicly available code including

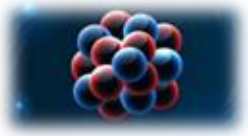
- forward and reverse shock
- lateral spreading and lateral structure
- radiation losses, synchrotron emission, self-absorption, synchrotron self-Compton
- realistic electron distributions, …



Nedora et al., MNRAS 538 (2025),Nedora et al., MNRAS 524 (2023)
Nedora et al., MNRAS 520 (2023), Nedora et al., MNRAS 506 (2021)

Nuclear Physics and Multi-messenger Astrophysics

Nuclear physics constraints



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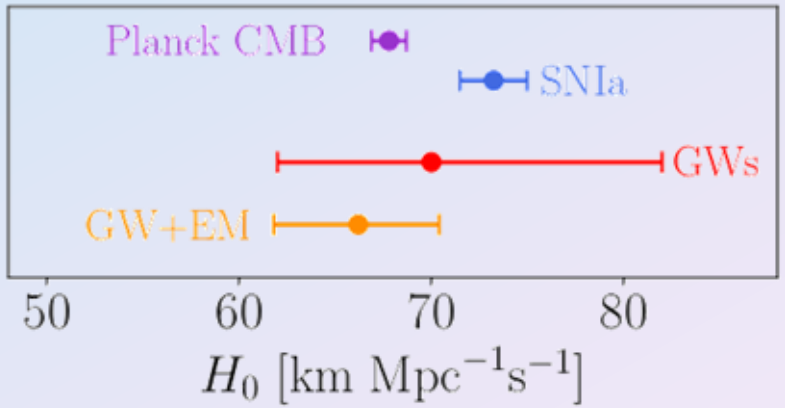


TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Summary

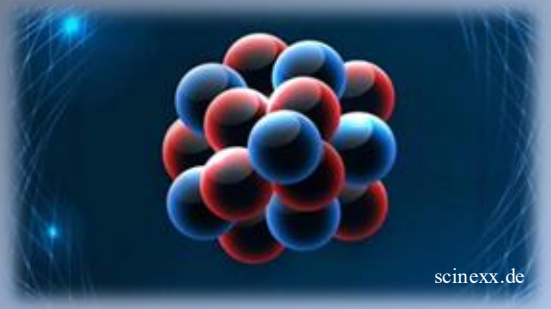
Simulating:
- Numerical Relativity

Modelling:
- Gravitational-Wave Modelling
- Radiative Transfer Simulations
- ….

Data Analysis:
- Bayesian Inference
- Model Selection/Hypothesis testing
- ….

Information about:

Supradense Matter



Chemical Abundances

Universe's Expansion