Probe and Prejudice: *Joint nuclear-physics and multi-messenger constraints on the neutron star equation of state*

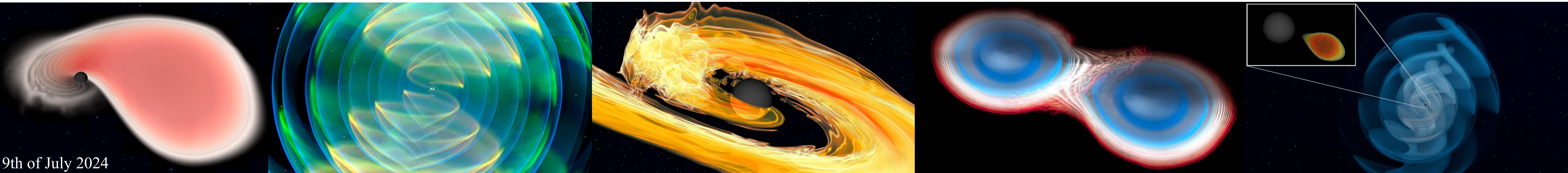
Tim Dietrich

INSTITUTE for NUCLEAR THEORY

INT WORKSHOP INT-24-88W

Inverse Problems and Uncertainty Quantification in Nuclear Physics

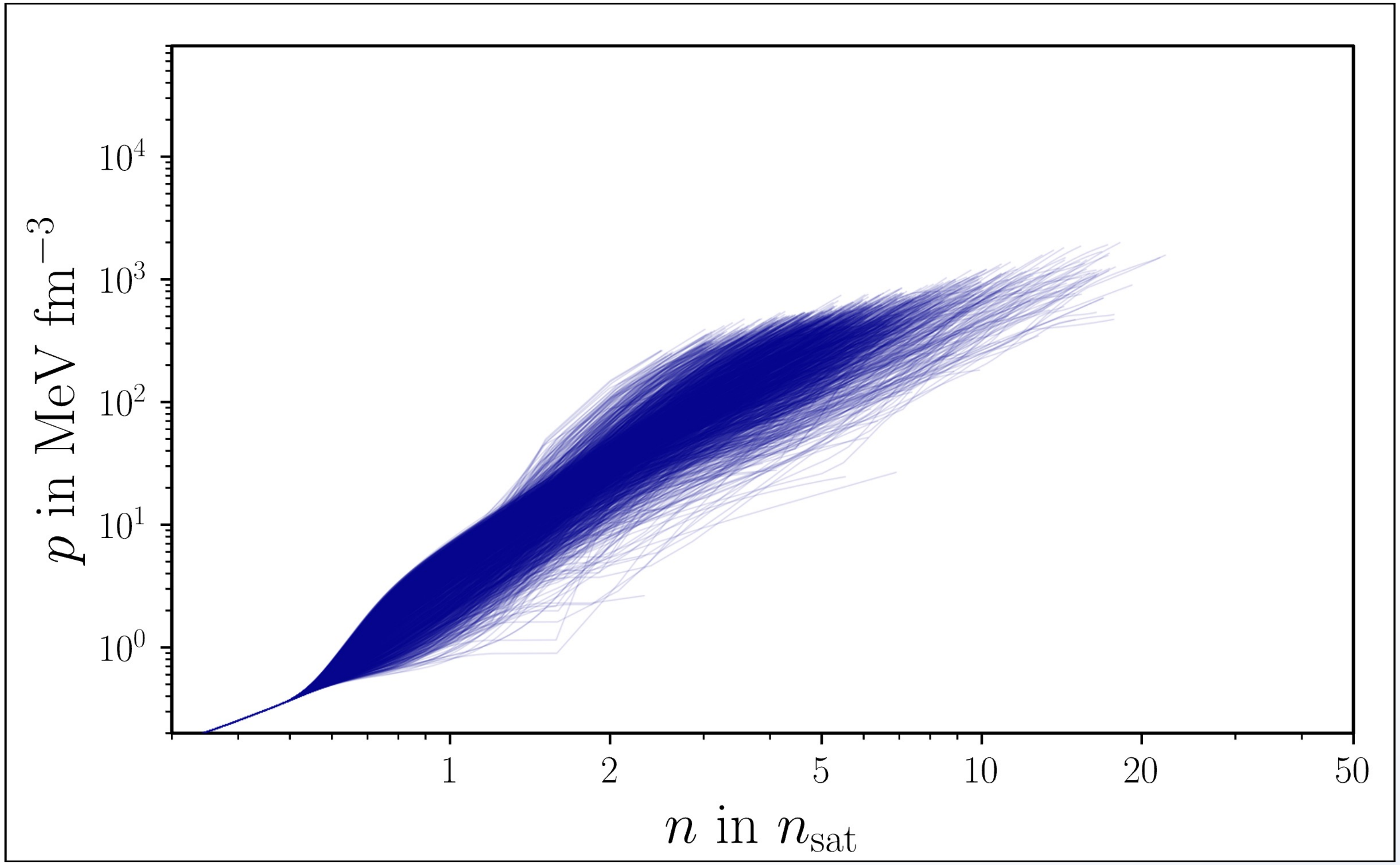
July 8, 2024 - July 12, 2024



9th of July 2024

Input from a variety of sources:

Koehn et al. 2024, 2402.04172



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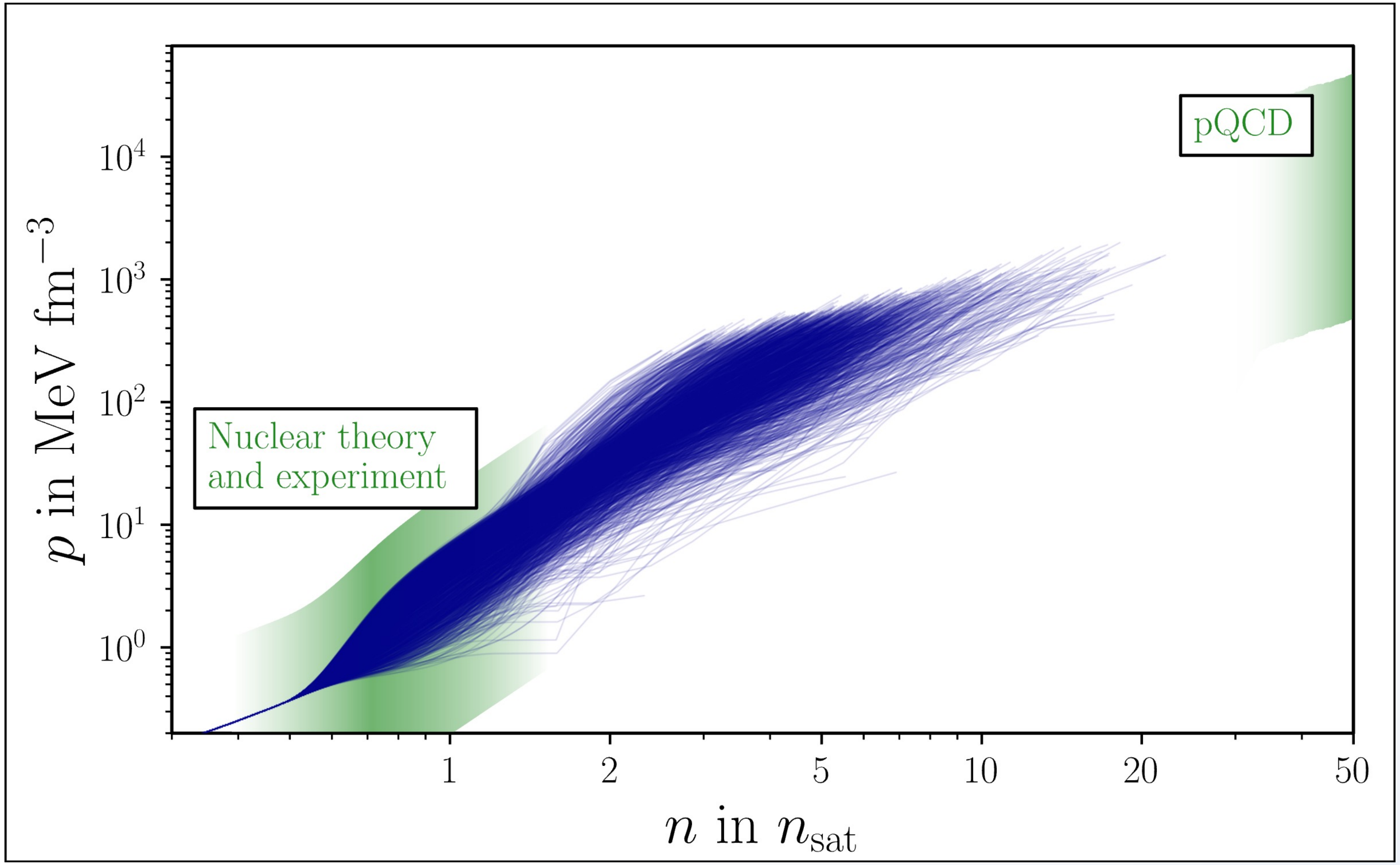
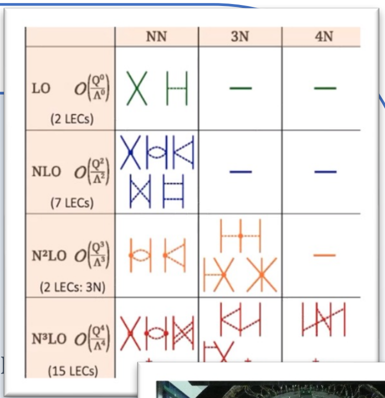
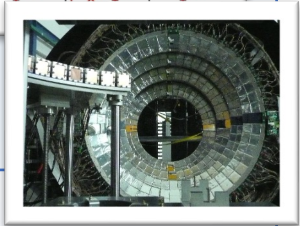


Nuclear Physics

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





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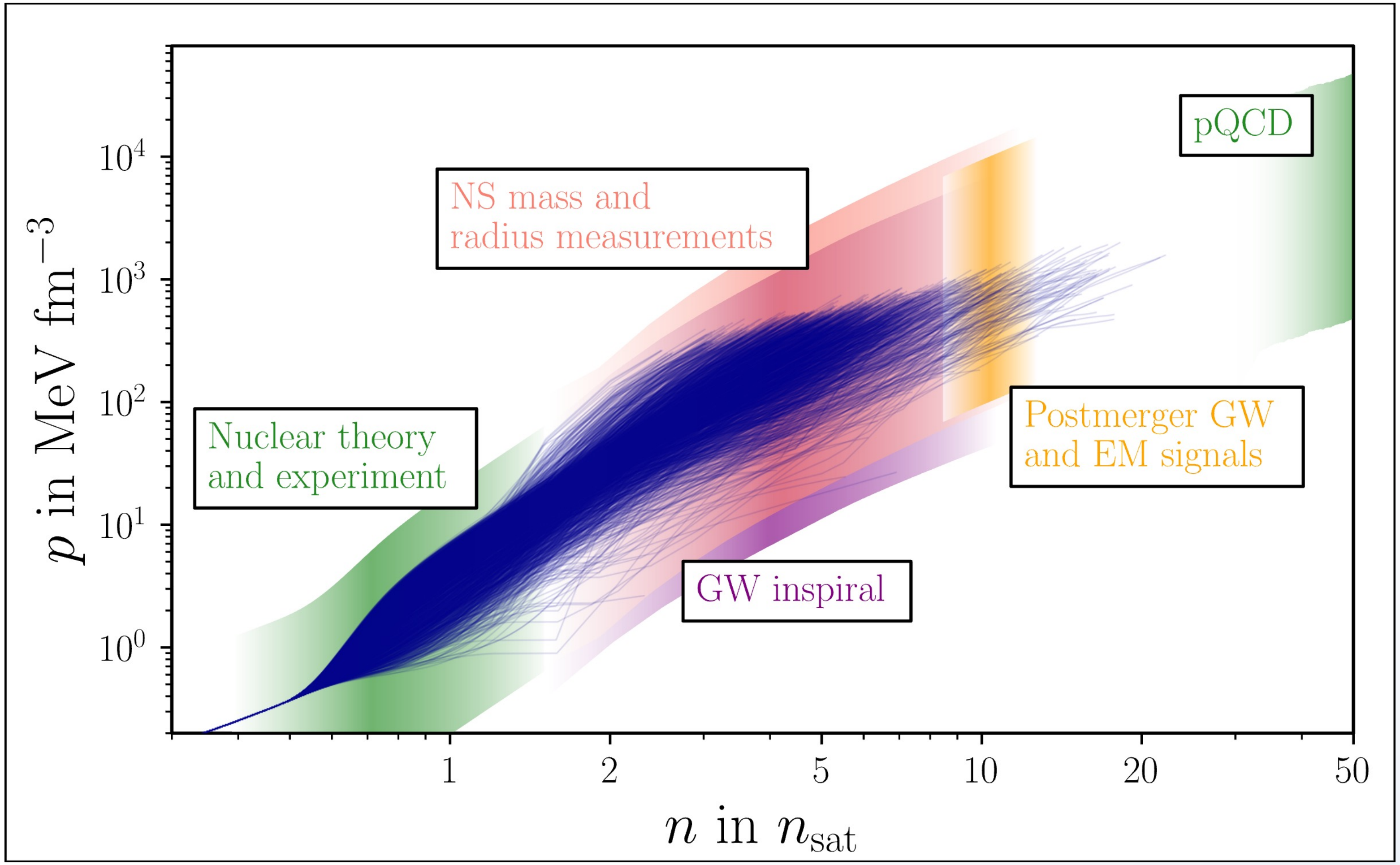
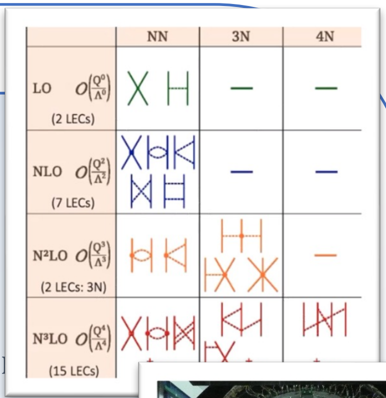


Nuclear Physics



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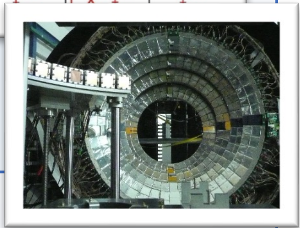
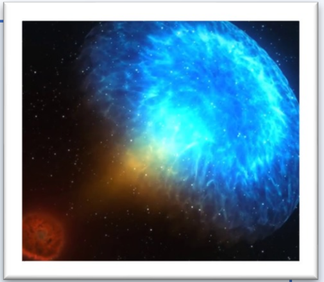
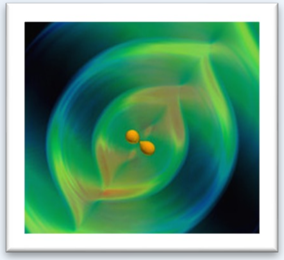


Astrophysics

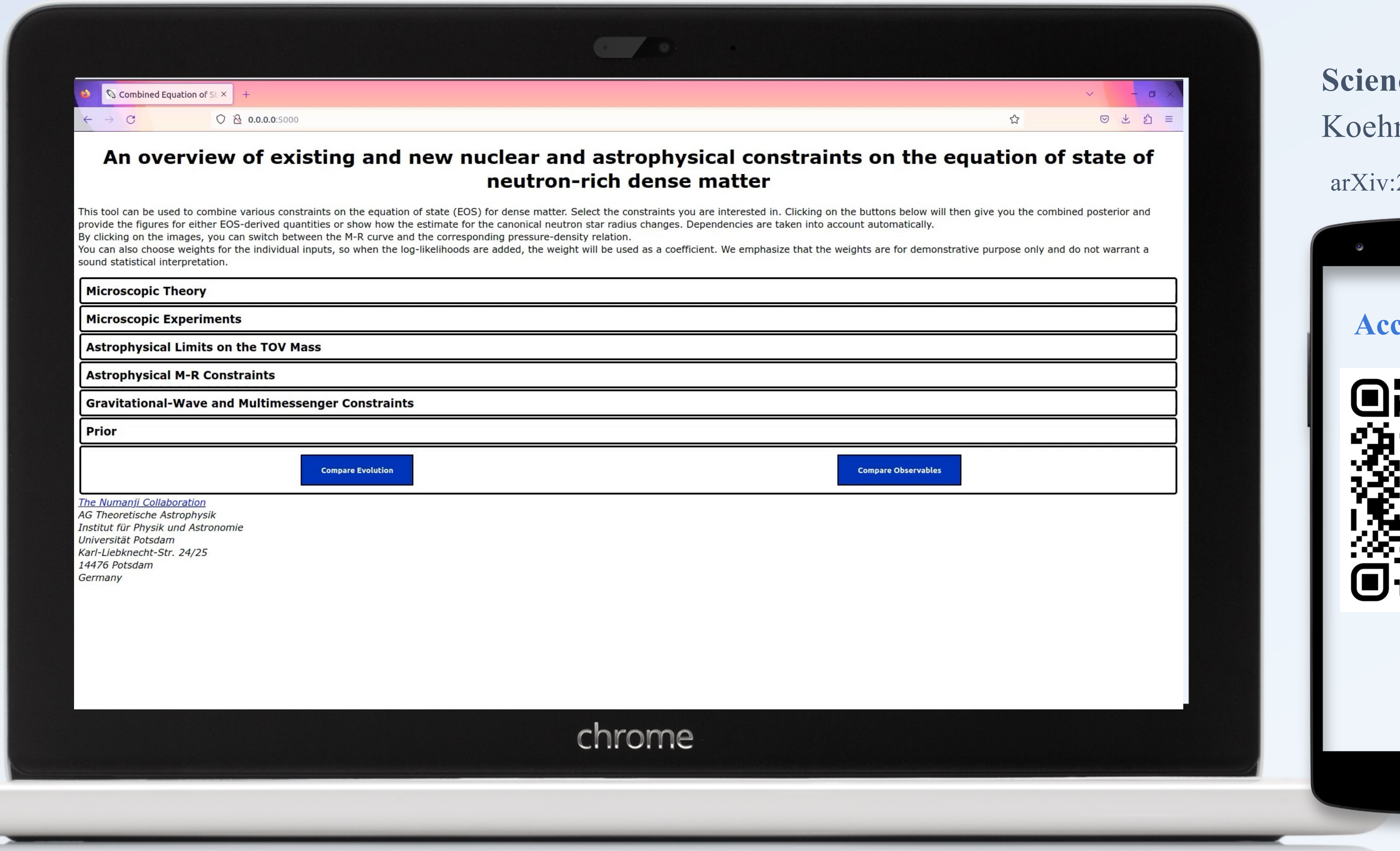


- Heavy pulsars
- NICER
- HESS object
- qLMXBs
- Thermo-nuclear accretion bursts



- GW170817
  + AT2017gfo
  + GRB170817A
- GW190425
- GRB211211A
- Post-merger constraints from GW170817

Combining different constraints on the EOS from different research fields



Science case:

Koehn et al. 2024

arXiv:2402.04172v1

Accessible here:

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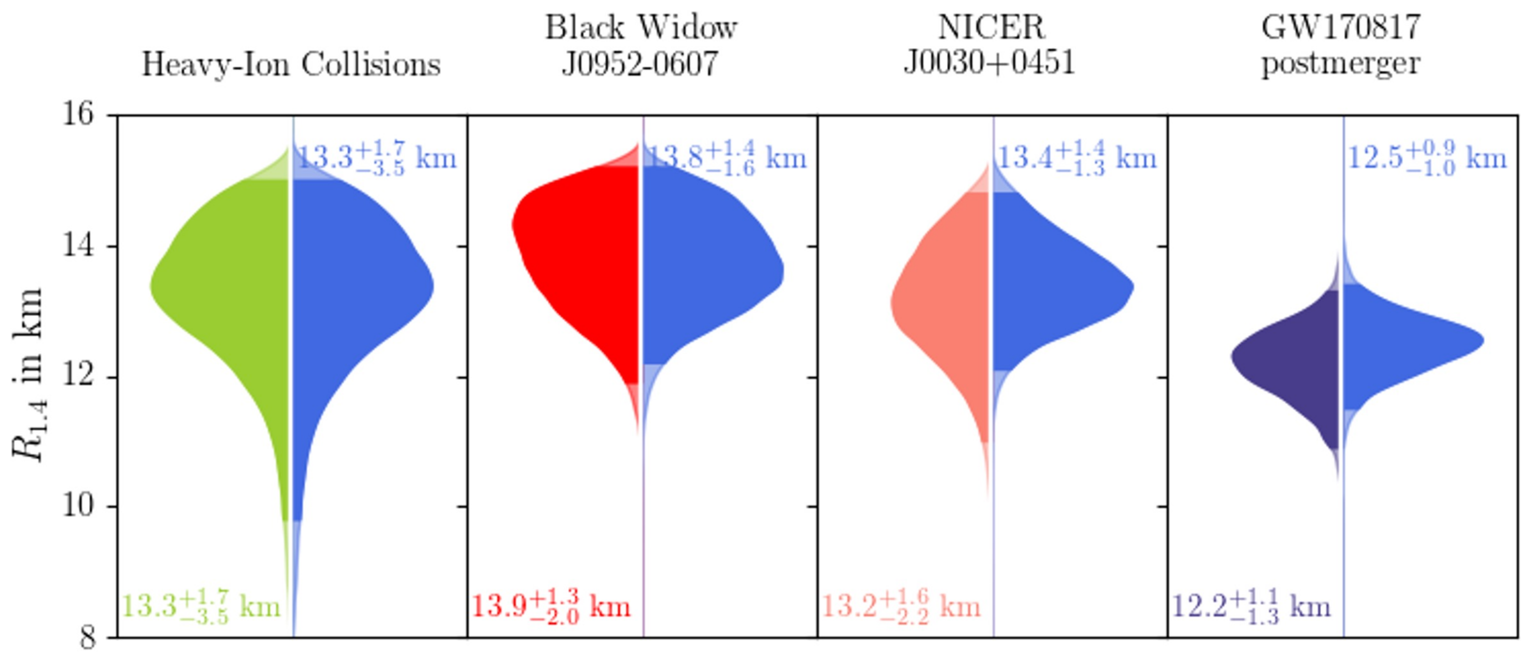

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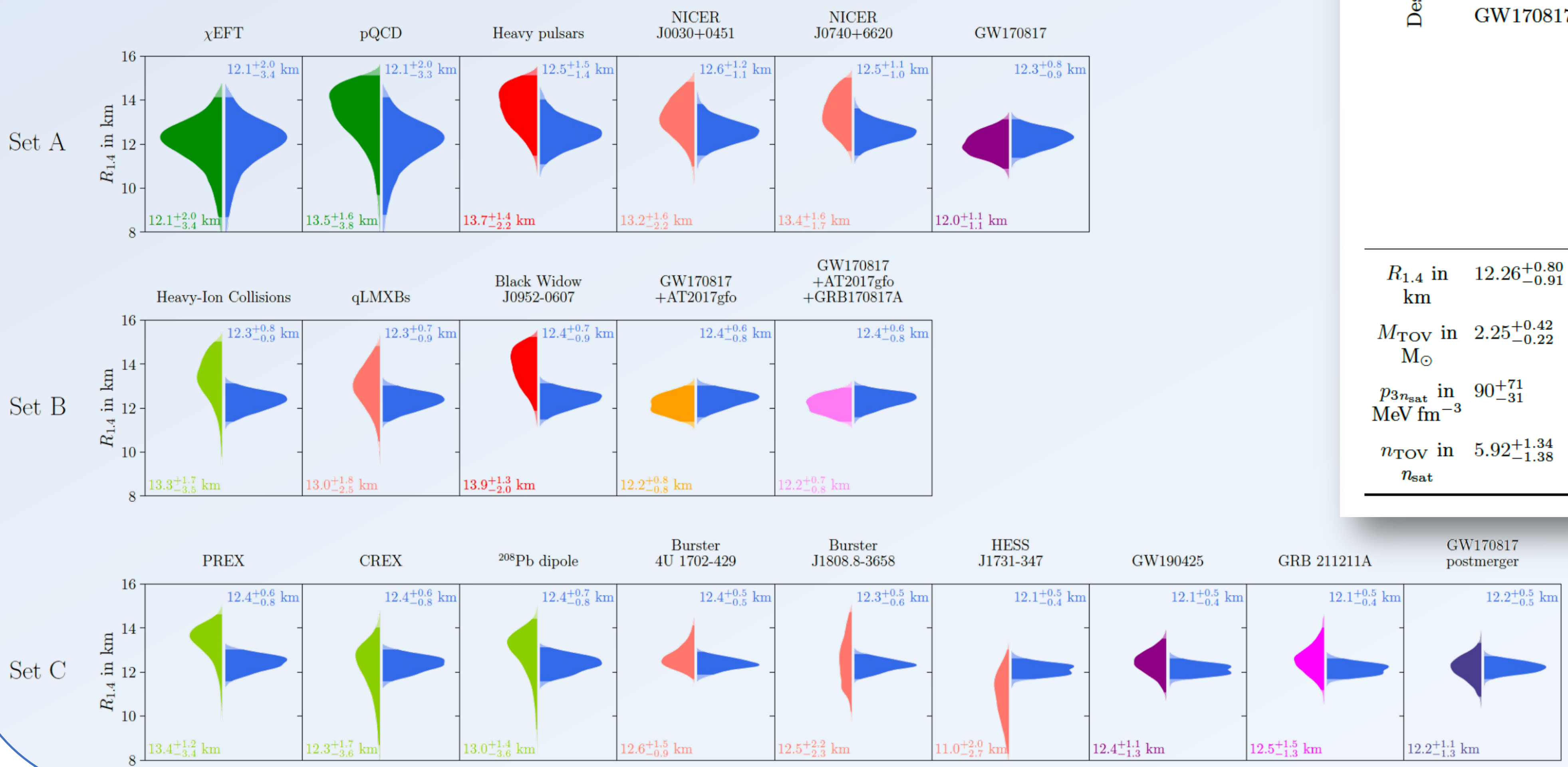

Set	A	B	C
Description	χEFT	Set A	Set B
	pQCD	HIC	PREX-II
	Heavy pulsars	Black Widow J0952-0607	CREX
	NICER J0030+0451	qLMXBs	^{208}Pb dipole
	NICER J0740+6620	GW170817+ KN+GRB	Burster 4U 1702-429
	GW170817		Burster J1808.8-3658
			HESS J1731-347
			GW190425
			GRB211211A
			GW170817 postmerger
$R_{1.4}$ in km	$12.26^{+0.80}_{-0.91}$	$12.41^{+0.57}_{-0.78}$	$12.20^{+0.48}_{-0.50}$
$M_{\rm TOV}$ in $M_\odot$	$2.25^{+0.42}_{-0.22}$	$2.33^{+0.35}_{-0.22}$	$2.30^{+0.08}_{-0.20}$
$p_{3n_{\rm sat}}$ in MeV fm^{-3}	90^{+71}_{-31}	99^{+65}_{-29}	94^{+32}_{-18}
$n_{\rm TOV}$ in $n_{\rm sat}$	$5.92^{+1.34}_{-1.38}$	$5.67^{+1.09}_{-1.09}$	$5.71^{+0.96}_{-0.86}$

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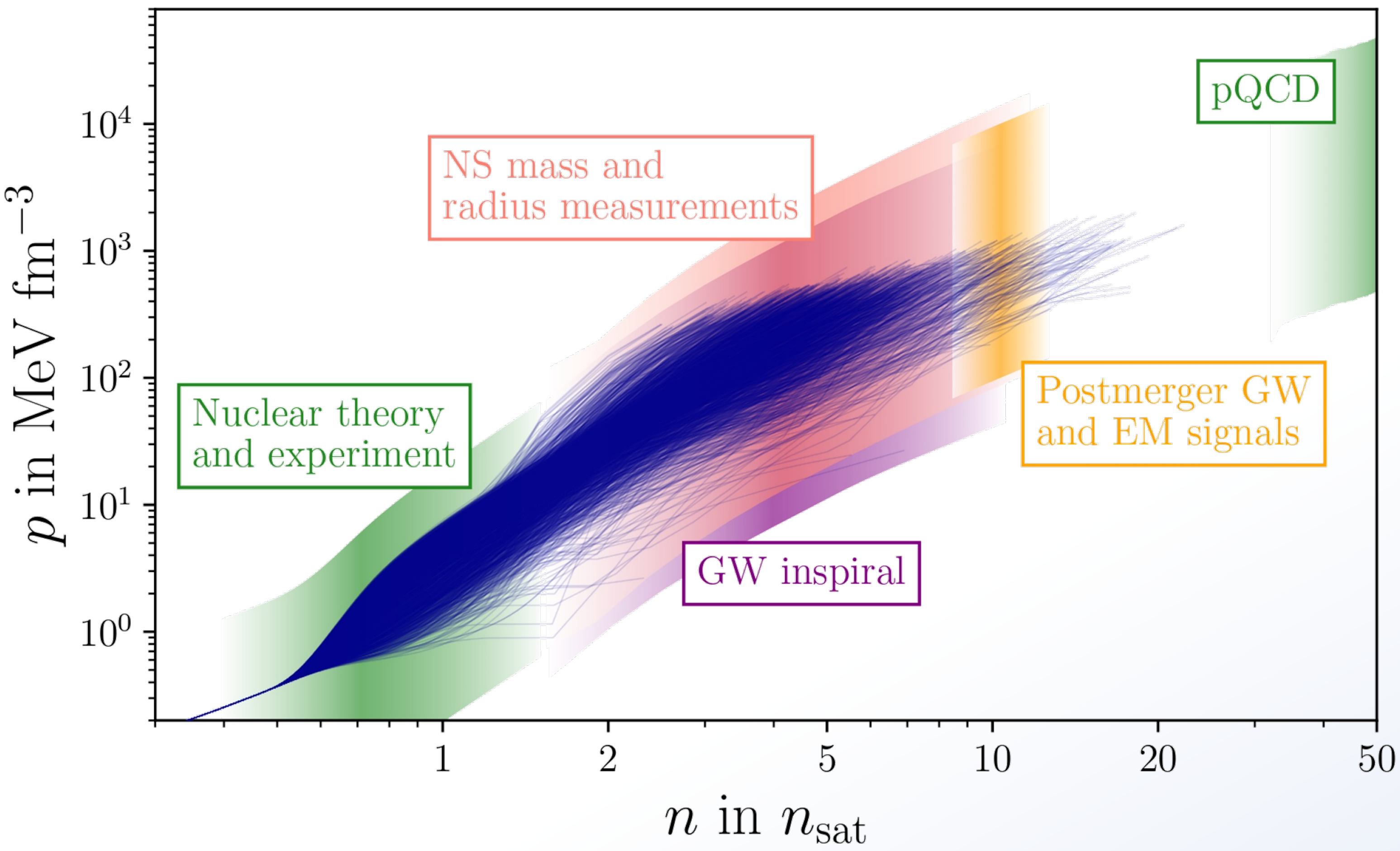
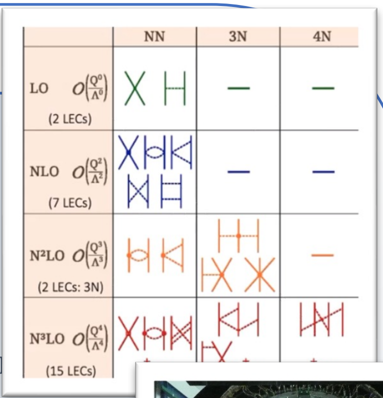


Nuclear Physics



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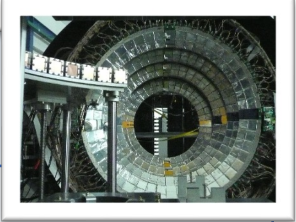
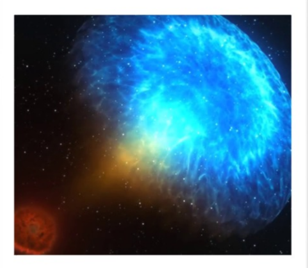


Astrophysics



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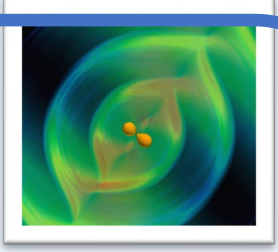

- GW170817
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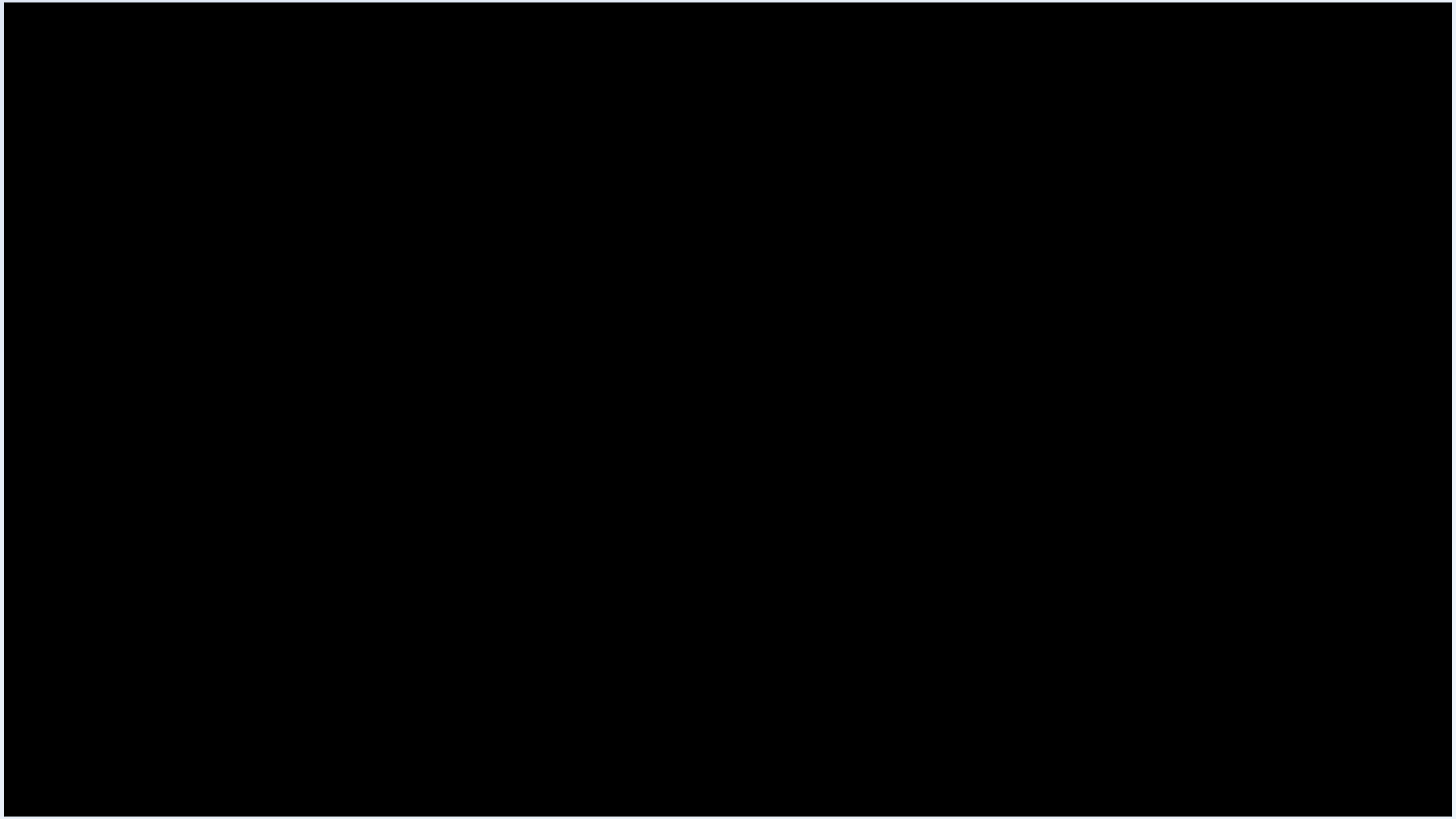
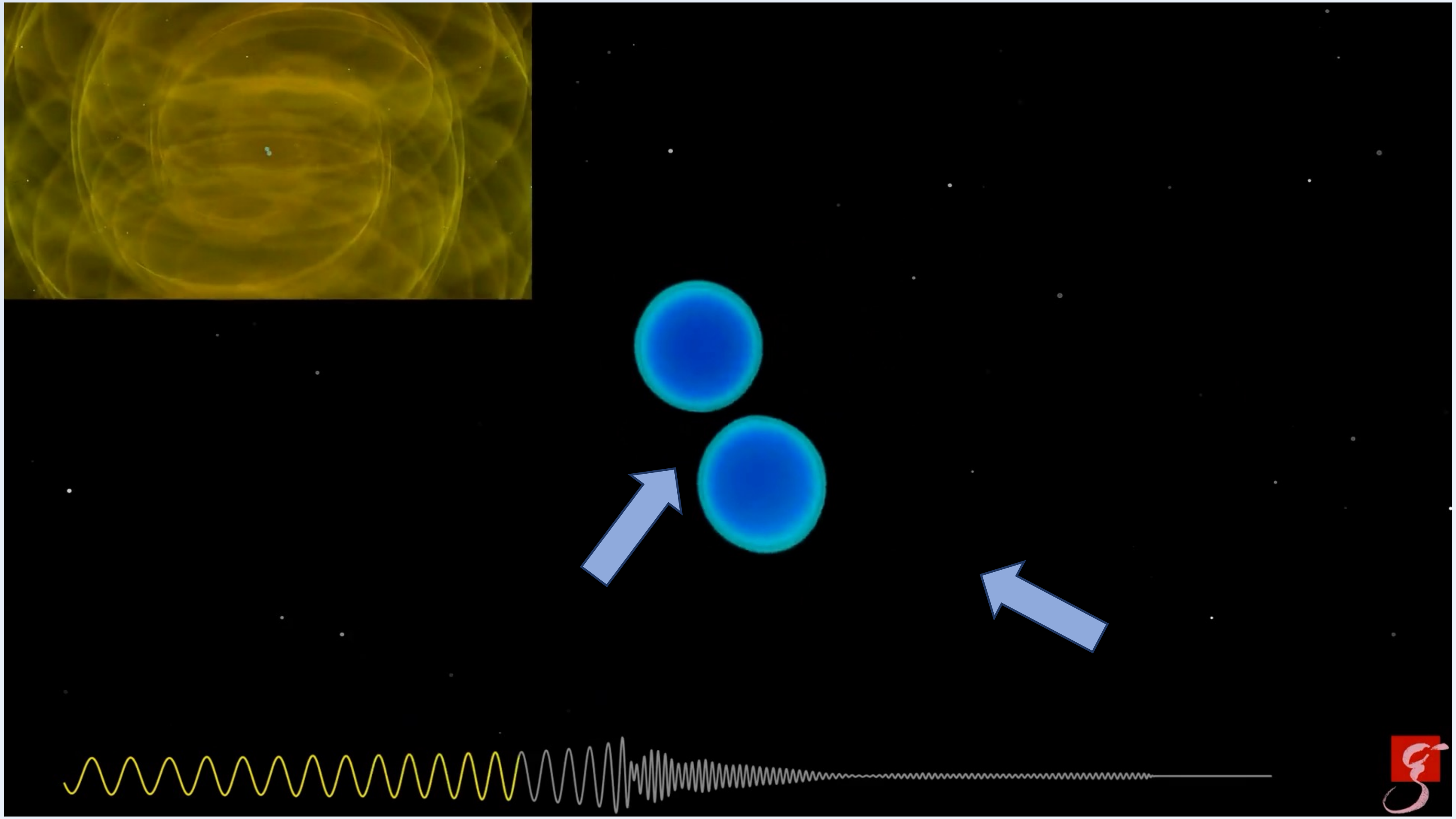
- Post-merger constraints from GW170817

Simulation of GW170817



gravitational wave emission

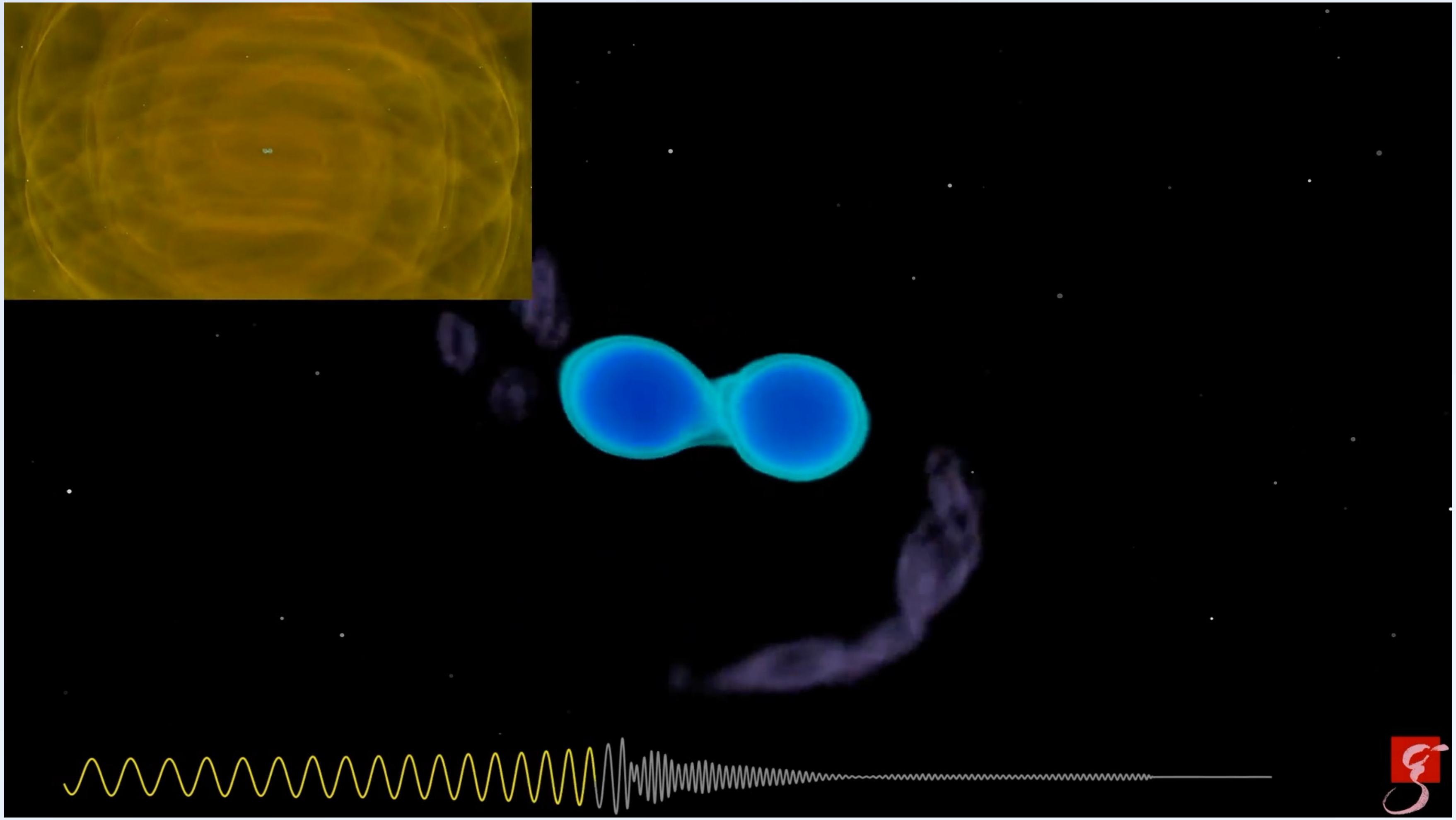
Simulation of GW170817



gravitational wave emission

deformation before merger, ejection of material, heavy element production

Simulation of GW170817



70 milliseconds

gravitational wave emission

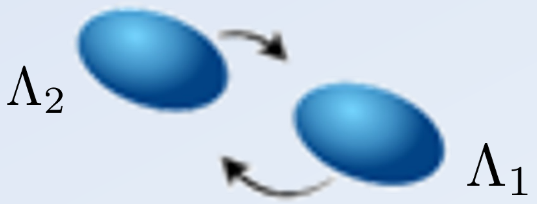
deformation before merger, ejection of material, heavy element production

black hole formation

Gravitational Wave Analysis

GW170817

Λ determines tidal deformability



Gravitational Wave Analysis

GW170817

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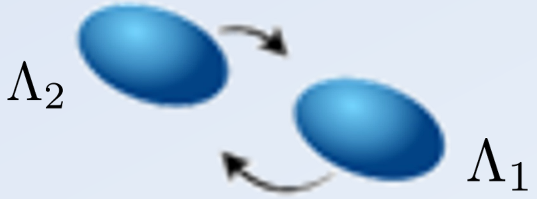

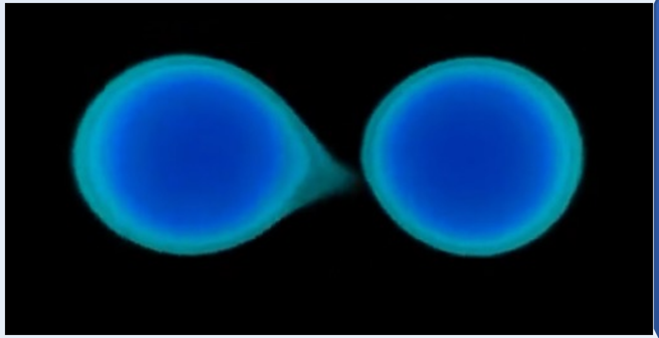

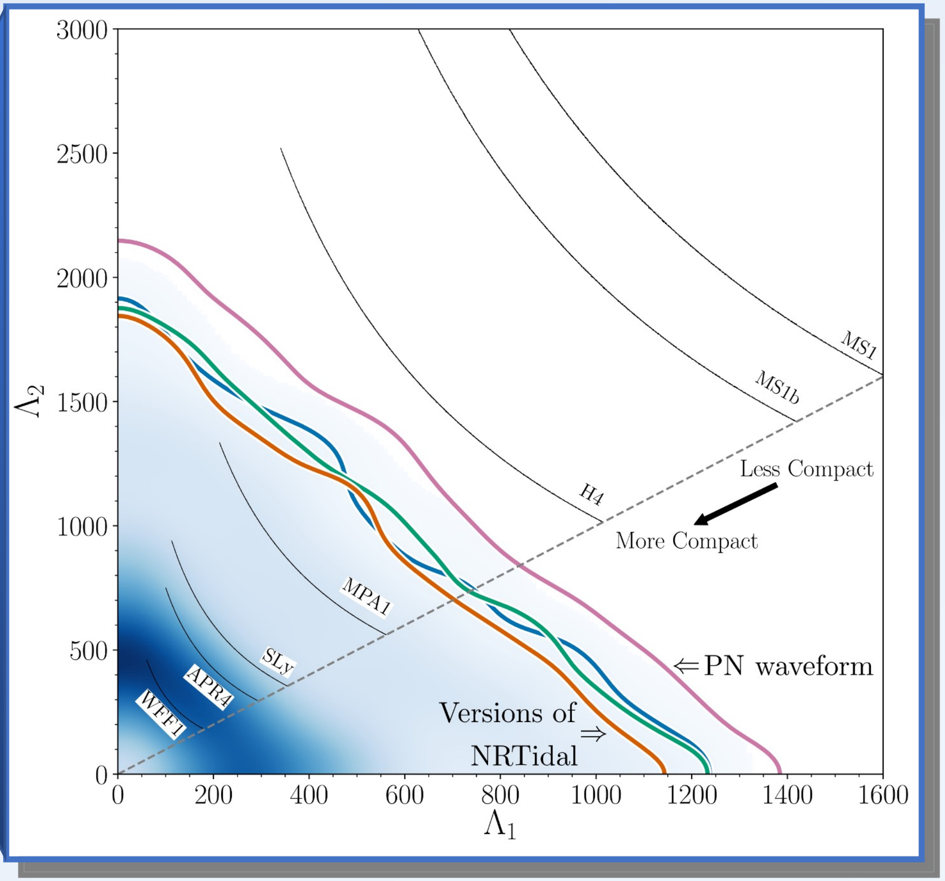

Phys.Rev. X9 (2019) 011001

→ no assumption about the type of the compact object

Gravitational Wave Analysis

GW170817

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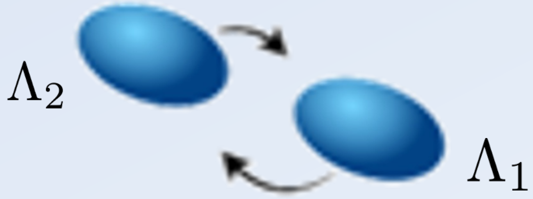
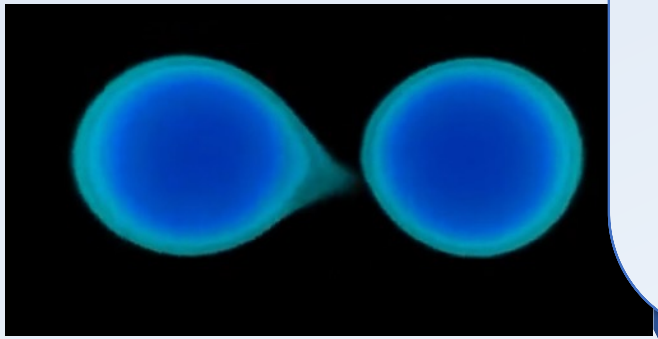
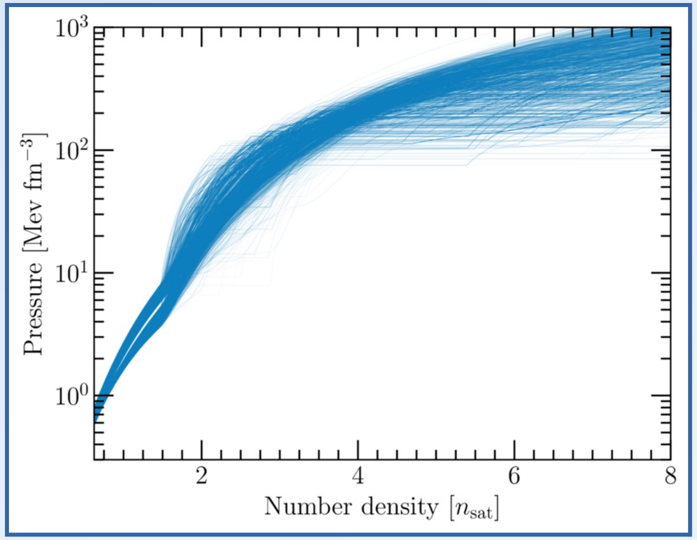
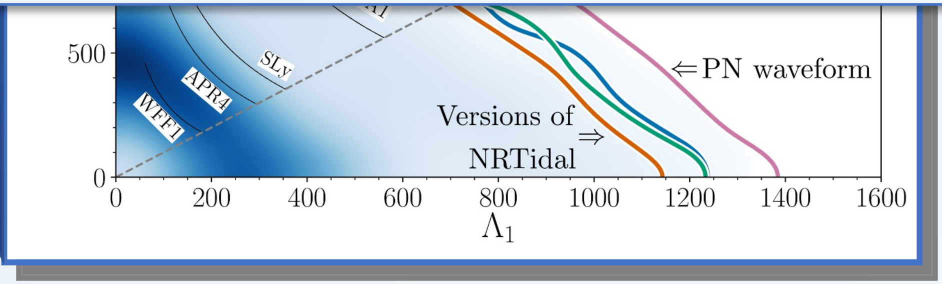




Assumption: The merging objects were neutron stars



nuclear-physics computations



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Gravitational Wave Analysis

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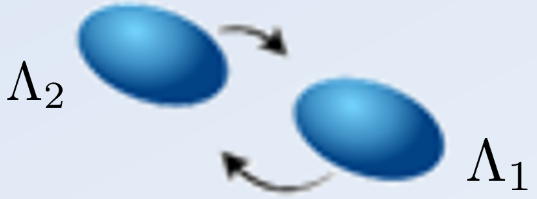

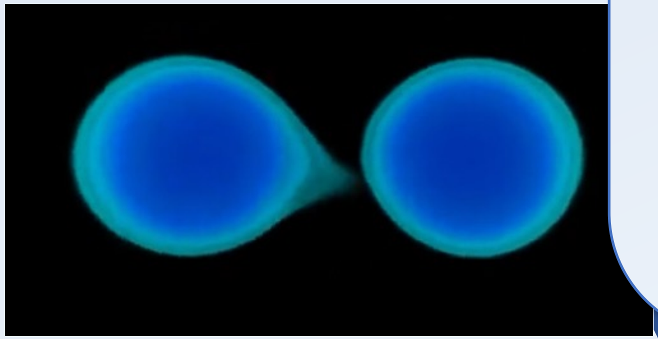

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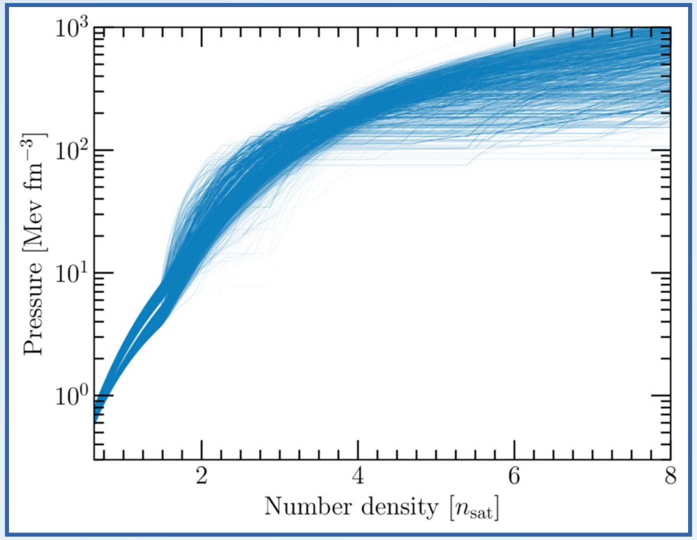

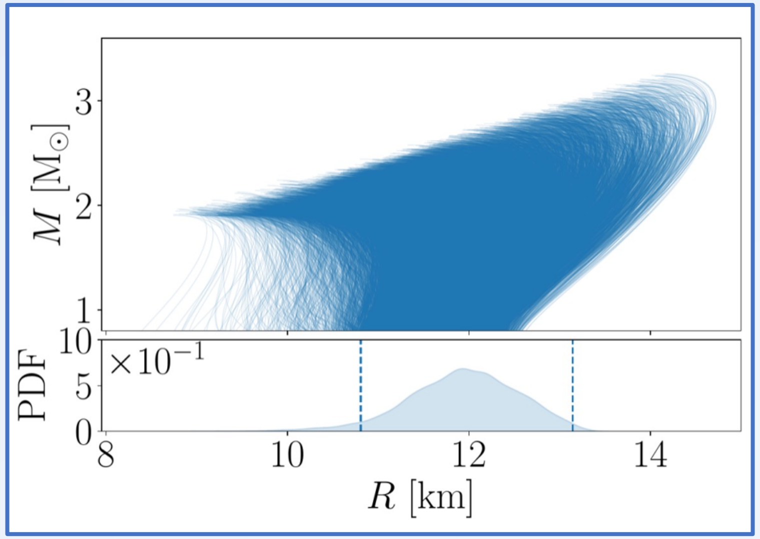

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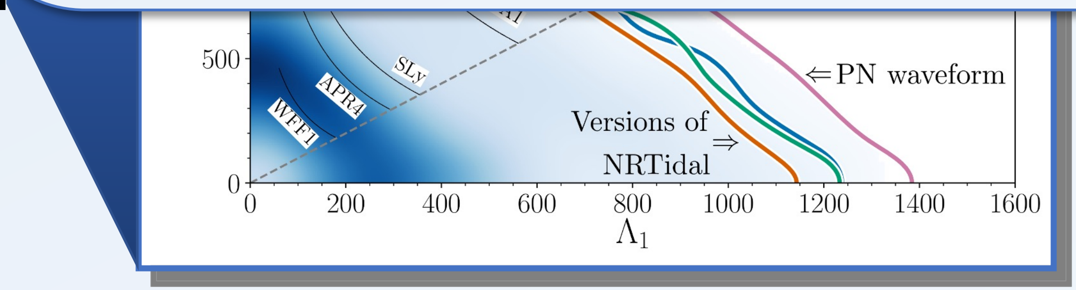

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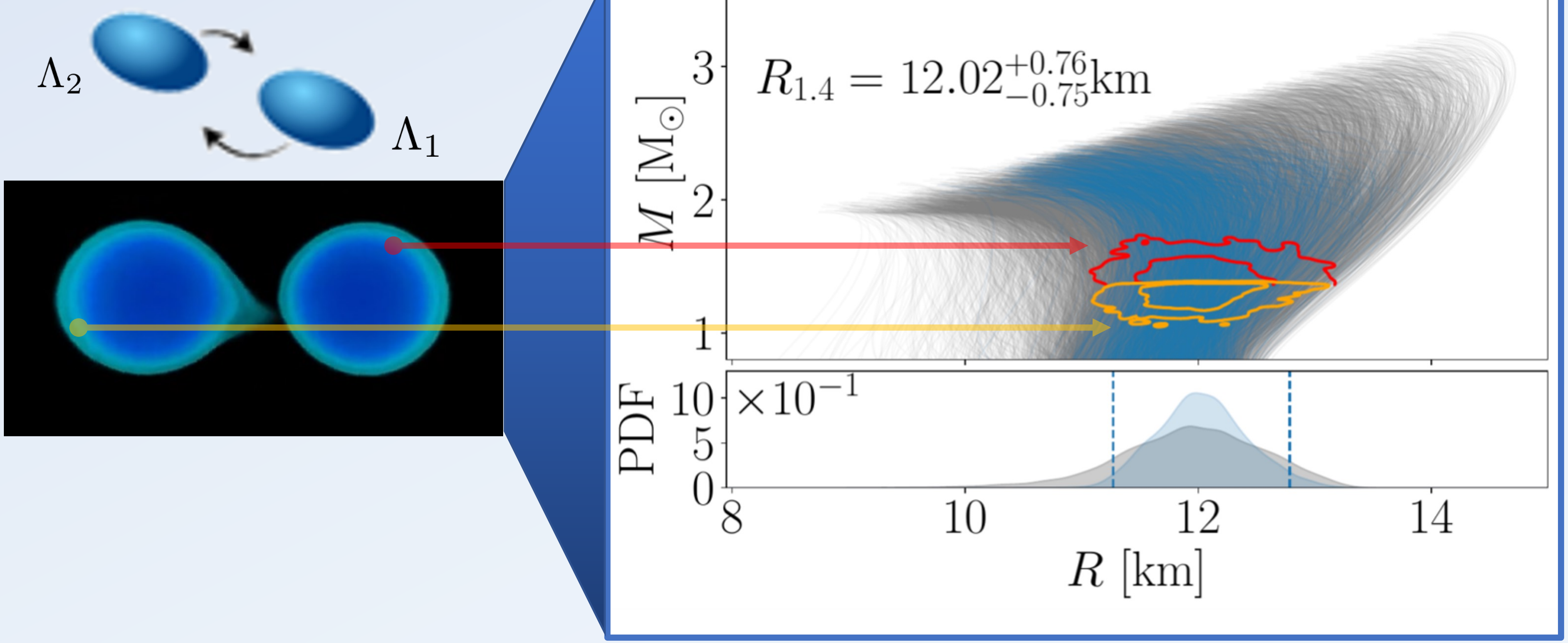
Phys.Rev. X9 (2019) 011001

Gravitational Wave Analysis

GW170817

Λ determines tidal deformability



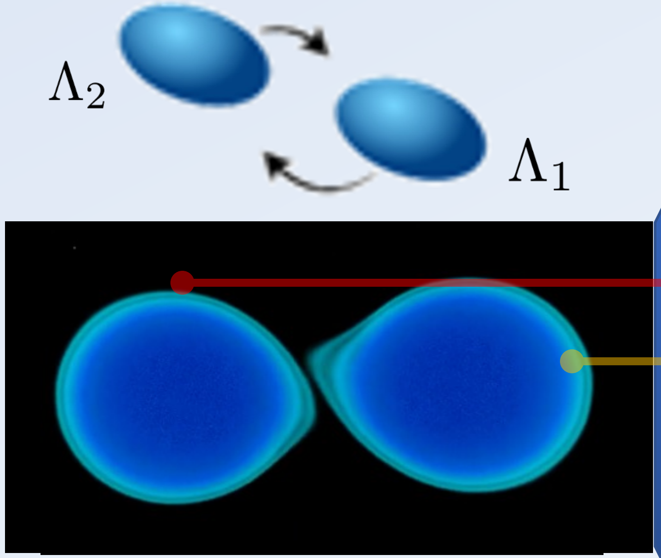
Assumption: The merging objects were neutron stars

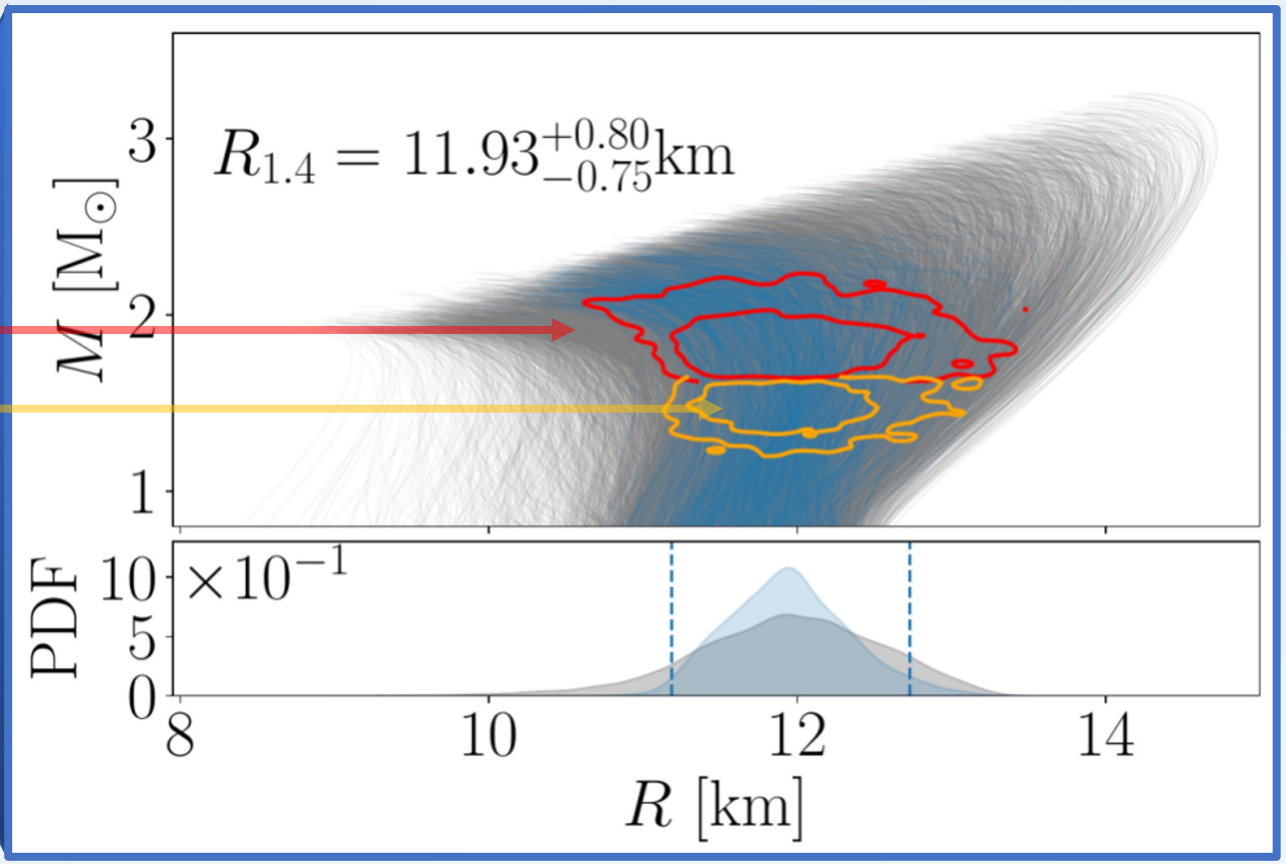
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Gravitational Wave Analysis

GW190425

Λ determines tidal deformability





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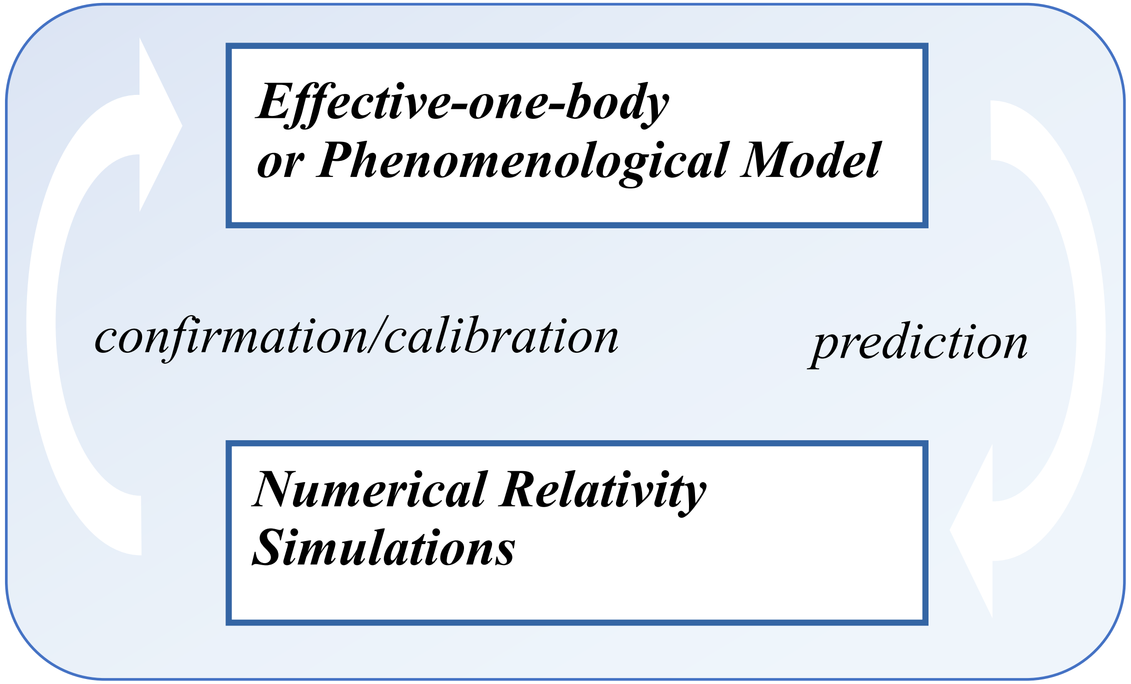
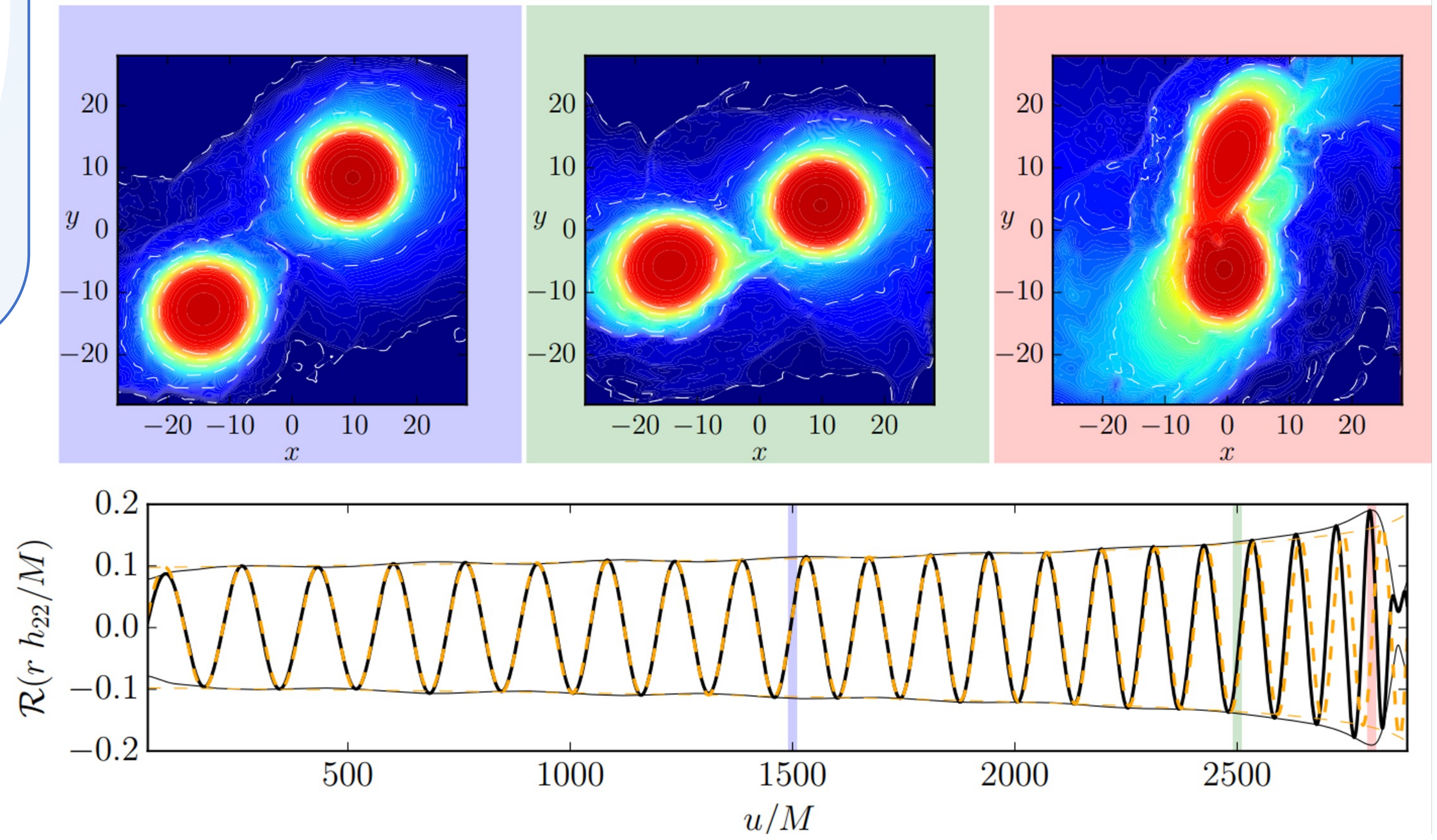
Waveform Model Development through NR simulations

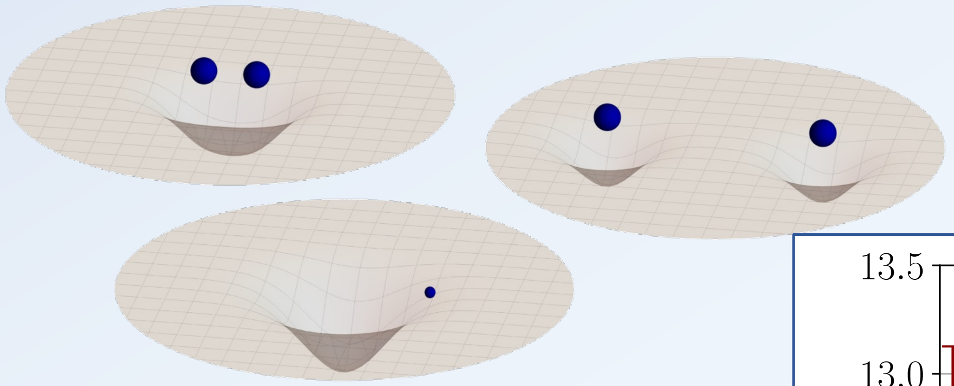


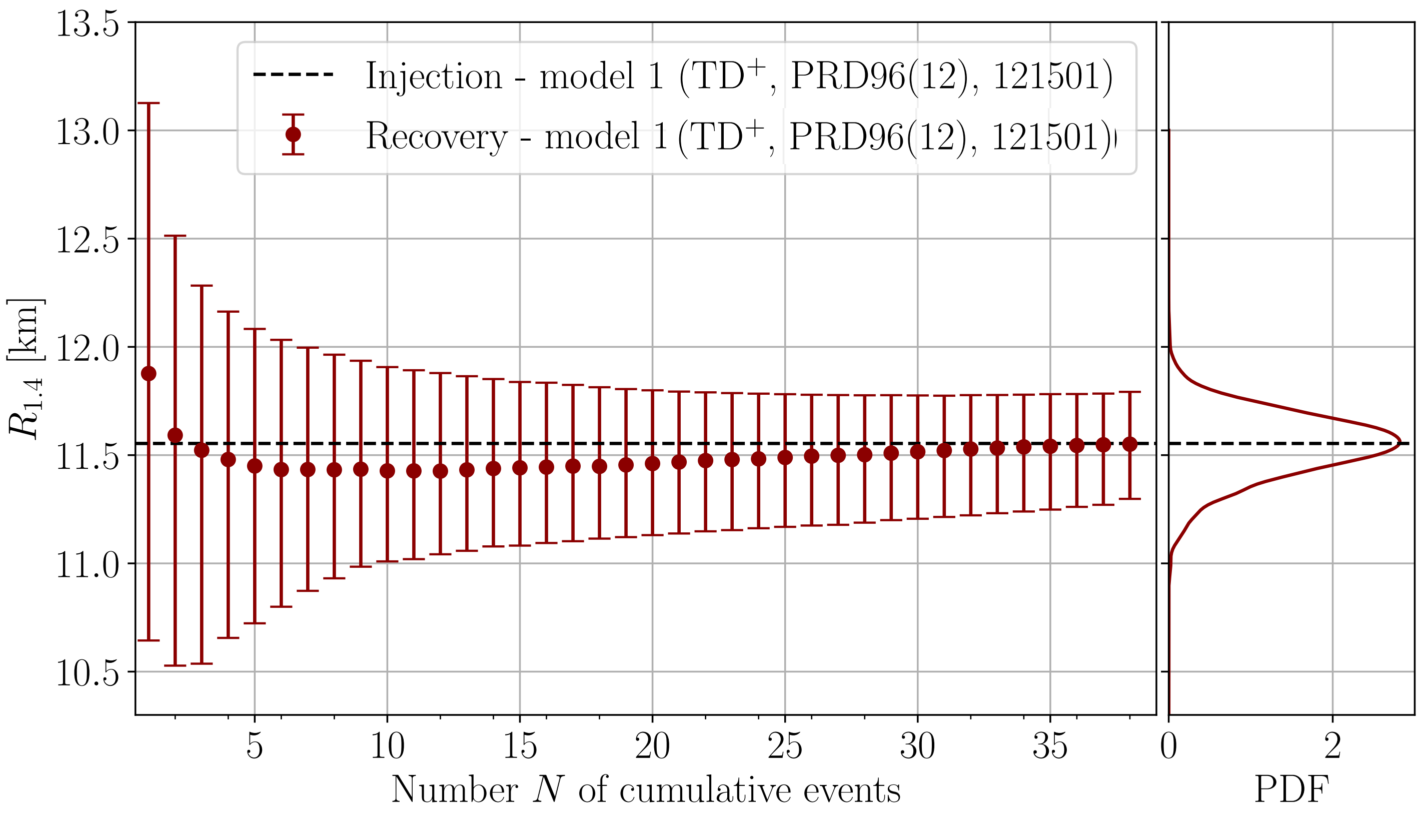


TD & Hinderer, Phys.Rev.D 95 12, 124006

Inspiral waveforms

Various models





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

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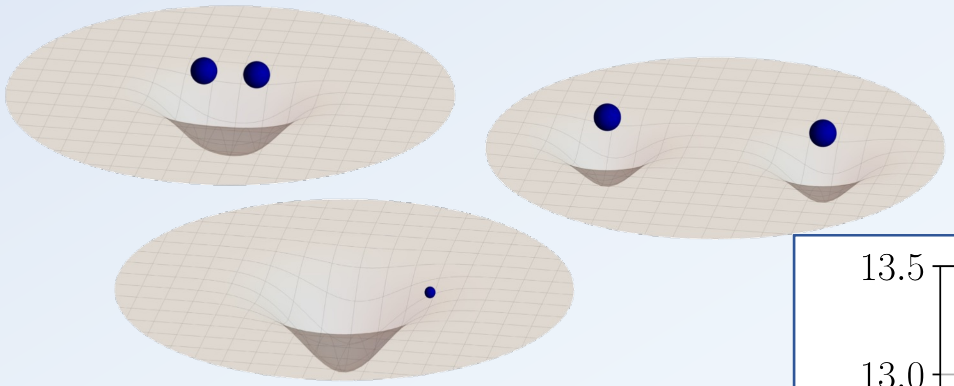

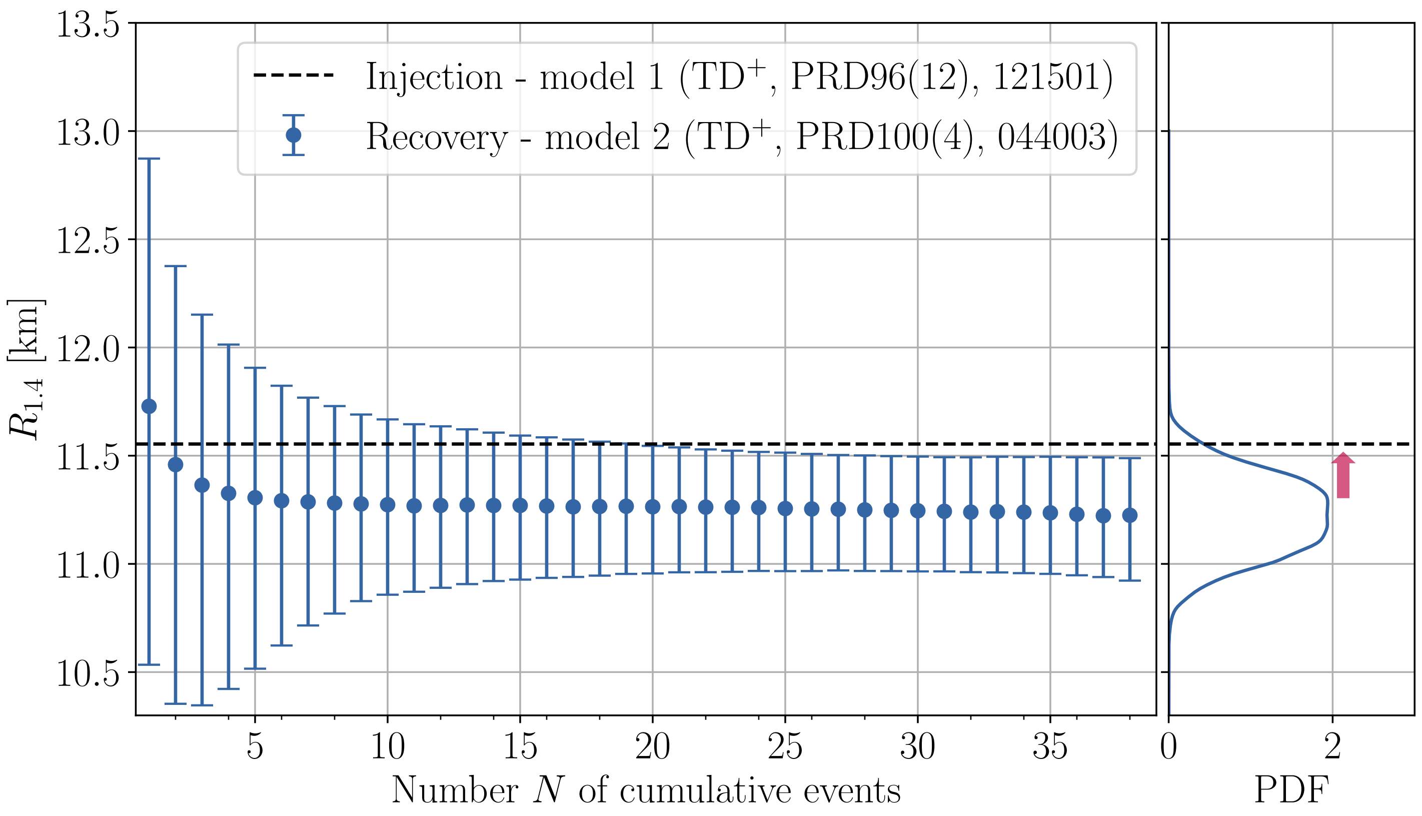

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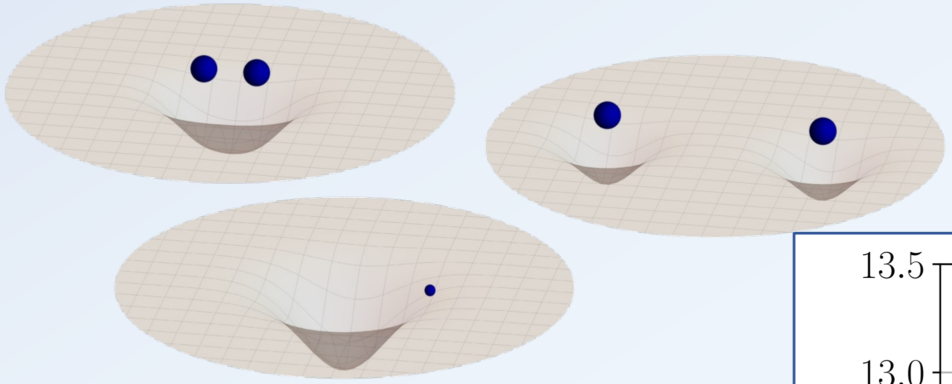
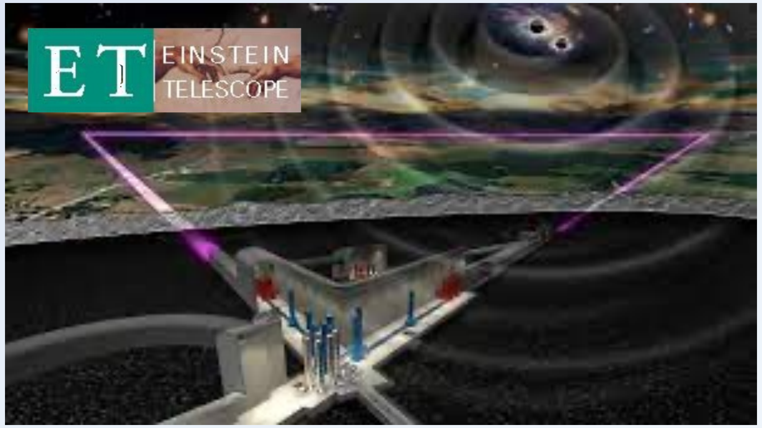
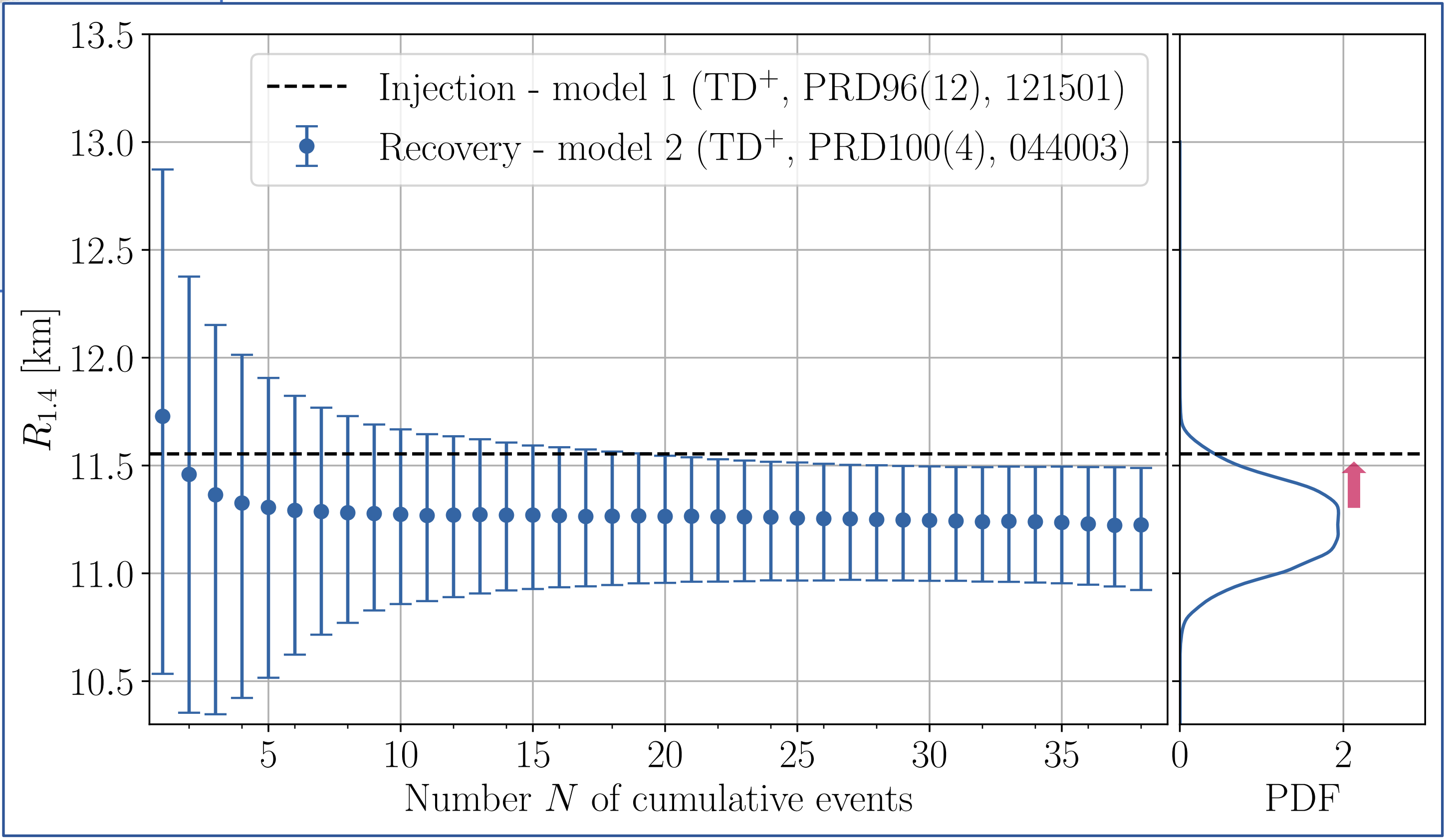


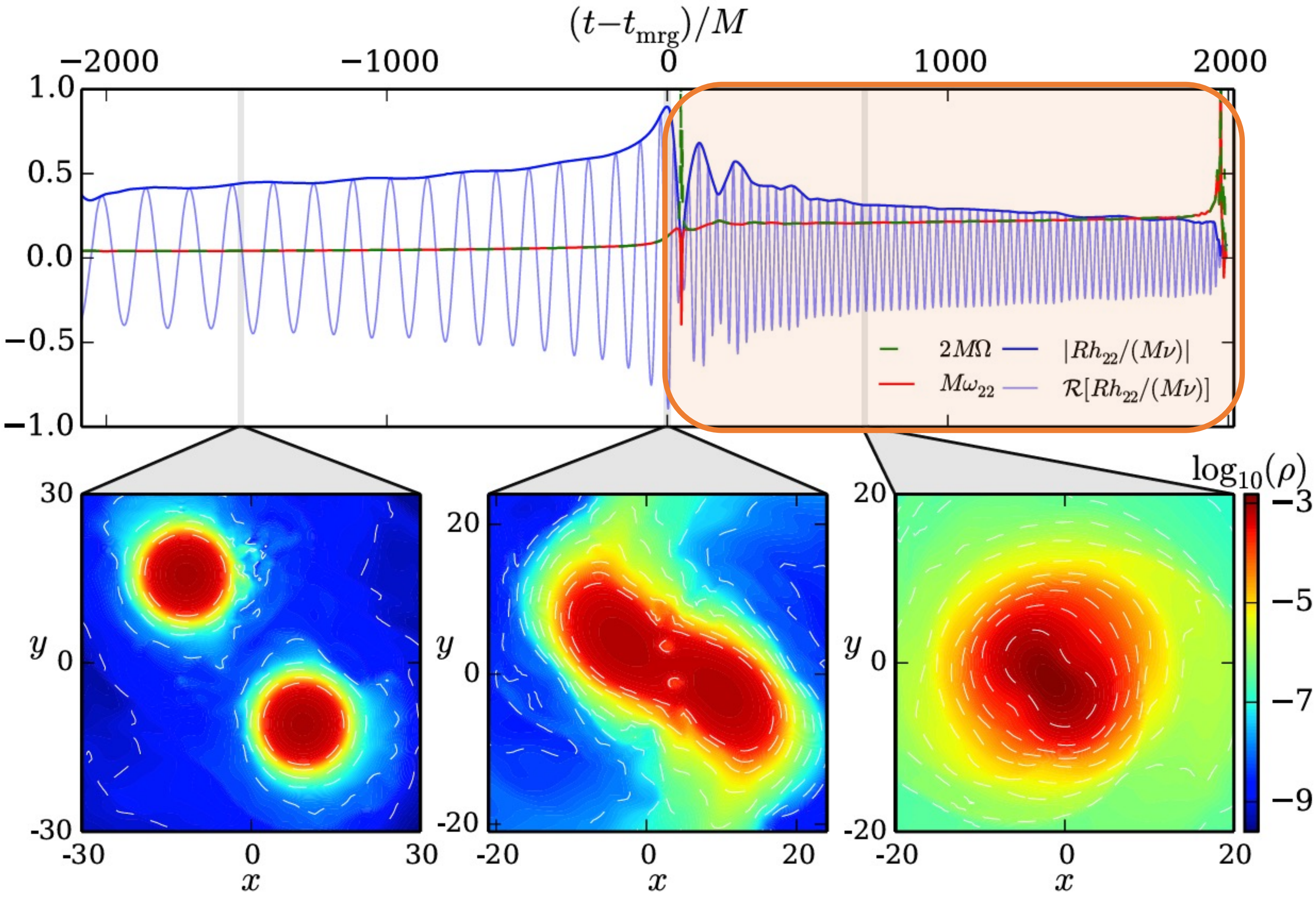


Einstein Telescope



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

What will we be able to learn from the postmerger phase?



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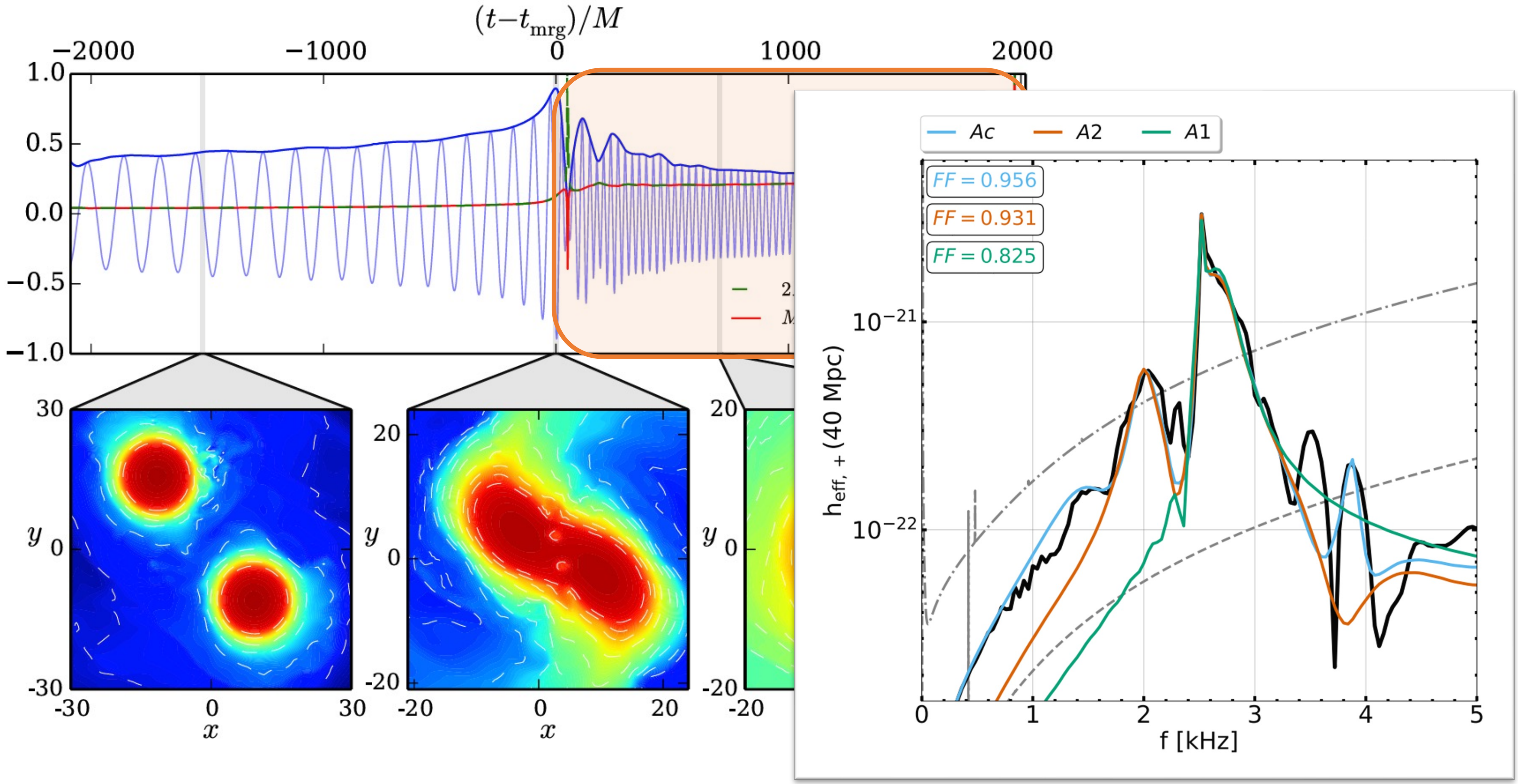
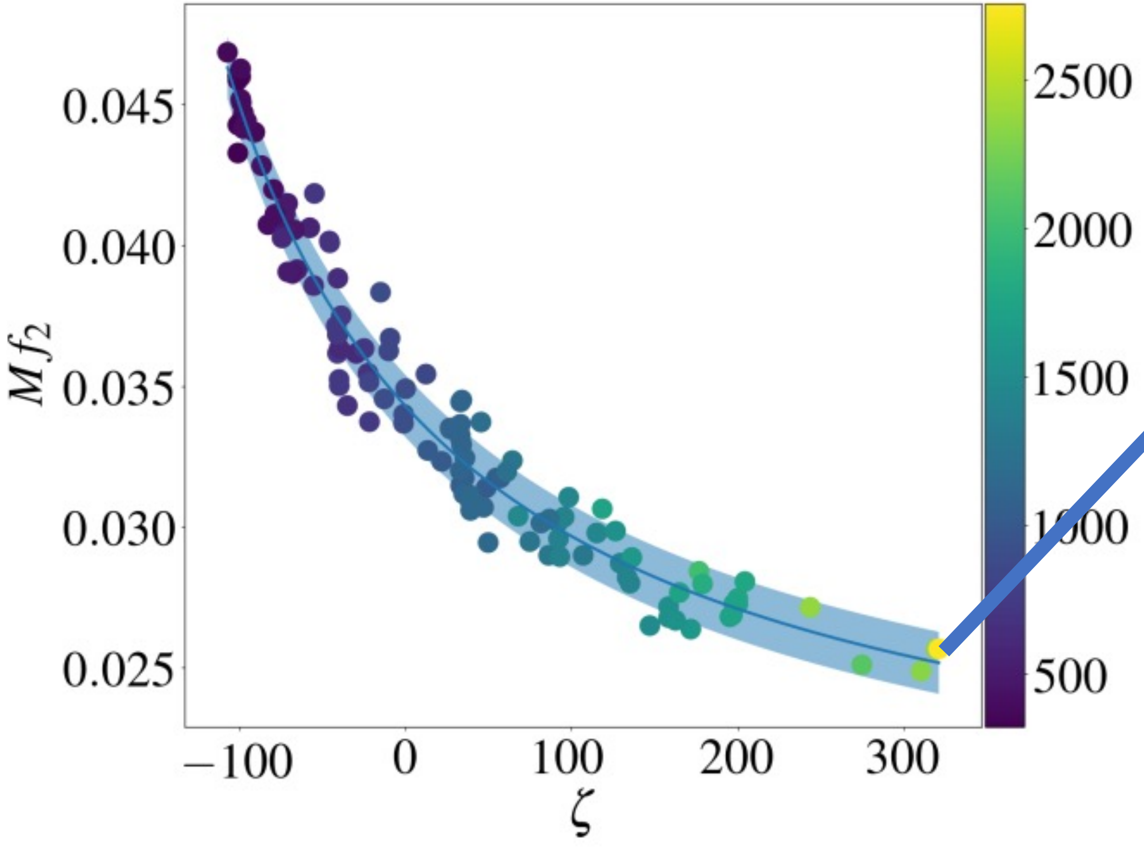


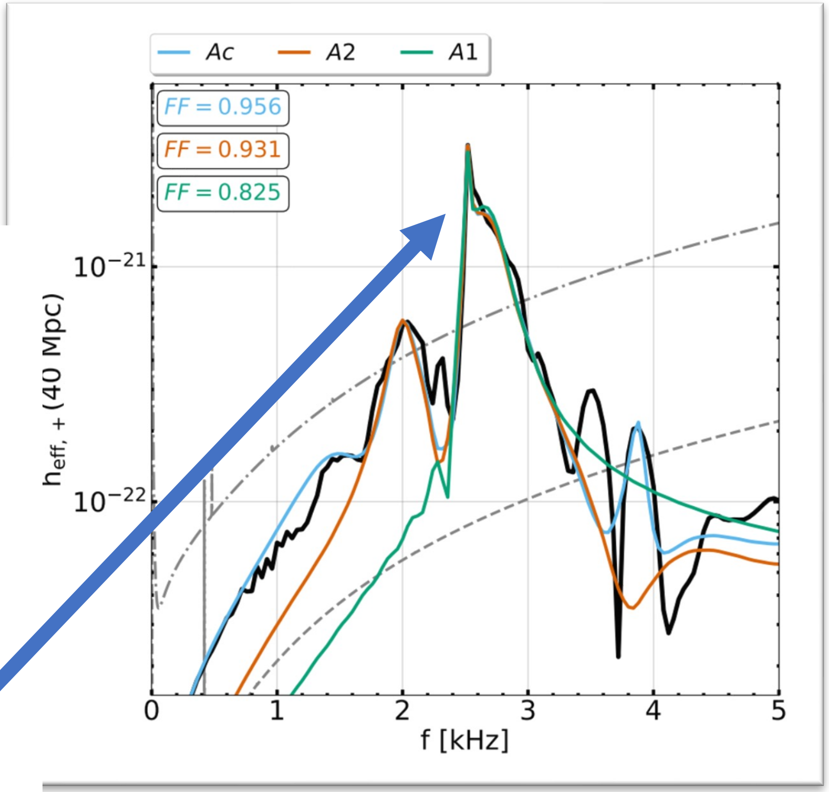
Rezzolla et al., PRD 105, 4, 043020

A relatively complex postmerger spectrum

- numerical-relativity simulations reveal a complex postmerger spectrum



Tsang et al., PRD. 100 (2019) 4, 0440047

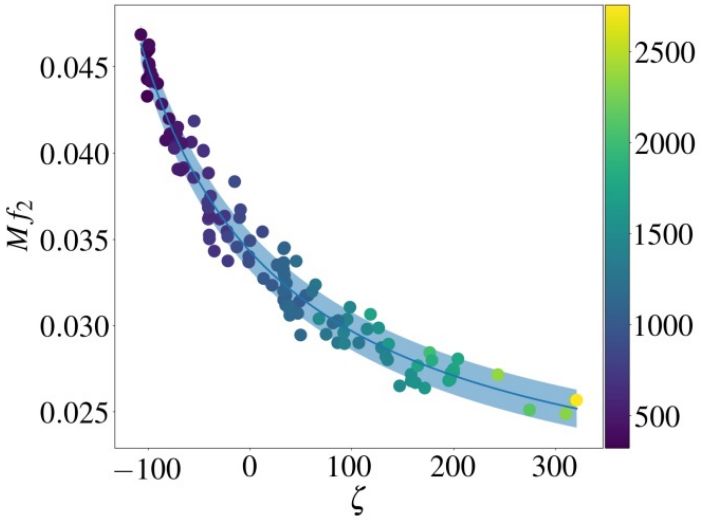


Rezzolla et al., PRD 93, 12, 1244051

$$\zeta = \frac{3}{16}\tilde{\Lambda} + a\frac{M}{M_{\mathrm{TOV}}}$$

Inspiral-merger postmerger consistency checks

- Consistency test employing different numerical-relativity waveforms



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Tsang et al., PRD. 100 (2019) 4, 0440047

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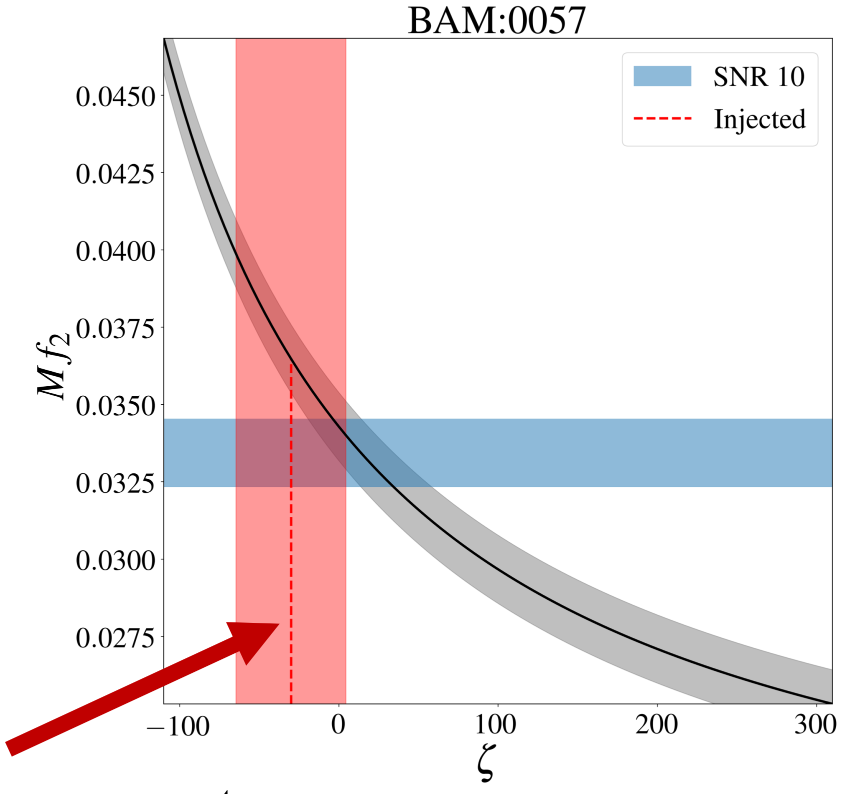
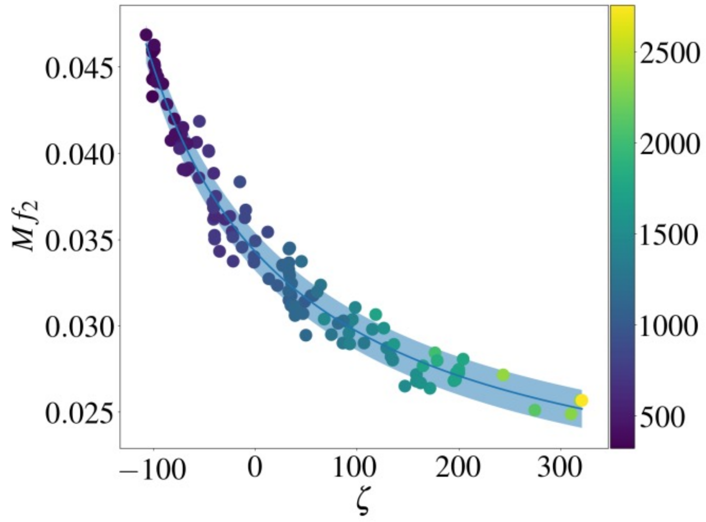


Inspiral measurement



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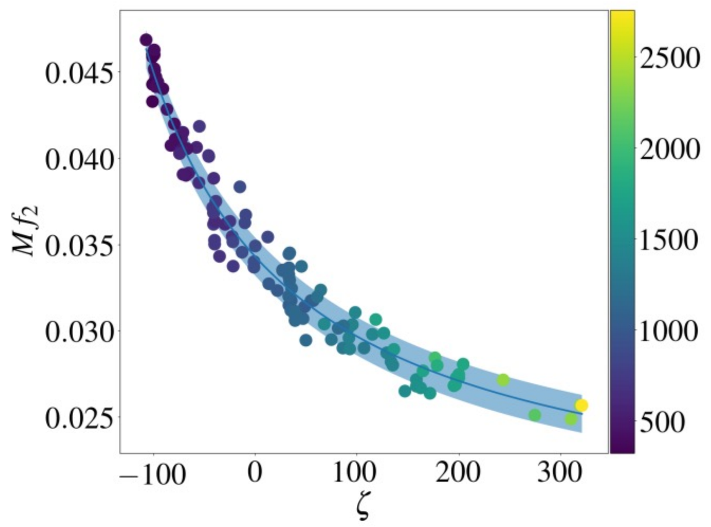

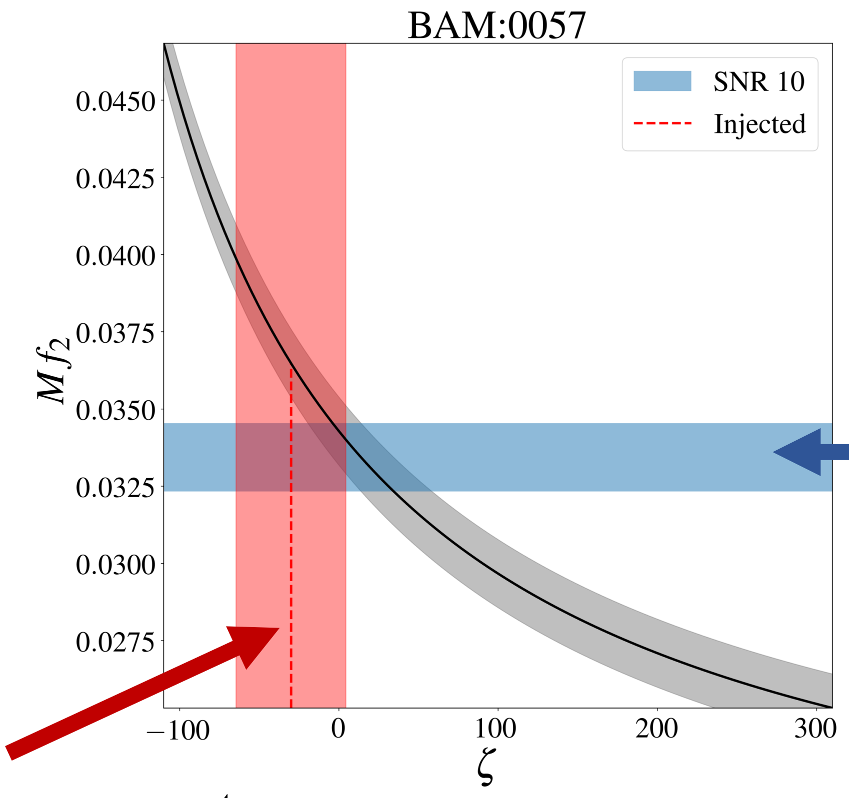

Postmerger measurement of emission frequency

Inspiral measurement

Tsang et al., PRD. 100 (2019) 4, 0440047

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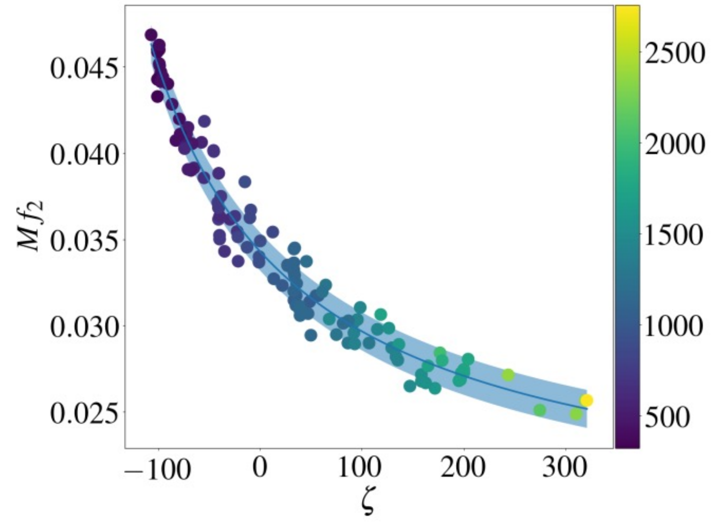
Inspiral-merger postmerger consistency checks



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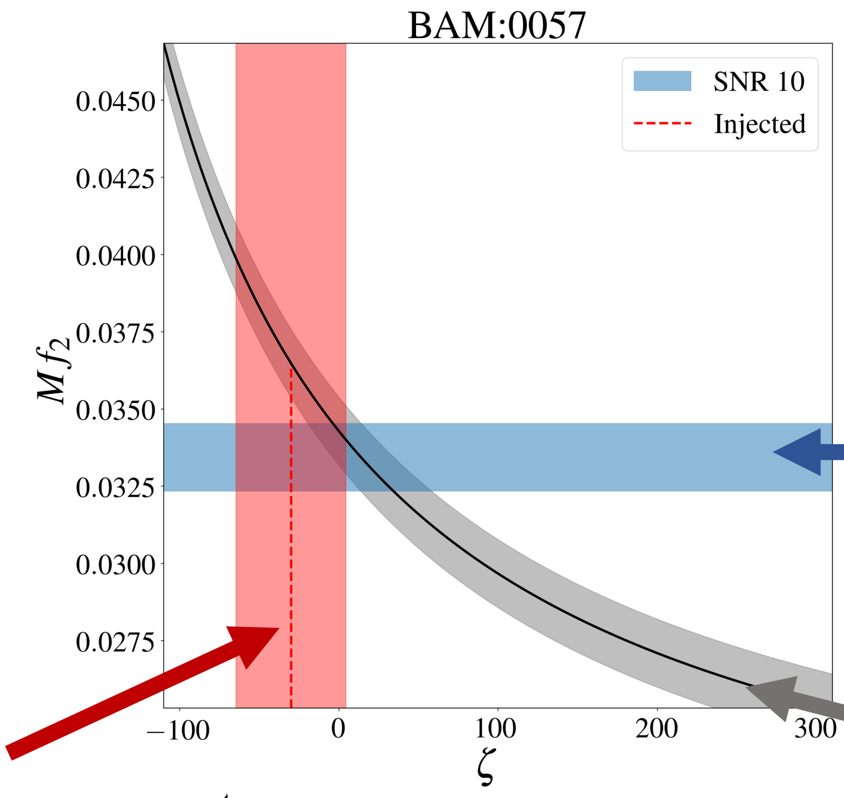

Postmerger measurement of emission frequency

Inspiral measurement

Quasi-universal relation from numerical-relativity simulation

Tsang et al., PRD. 100 (2019) 4, 0440047

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Inspiral-merger postmerger consistency checks

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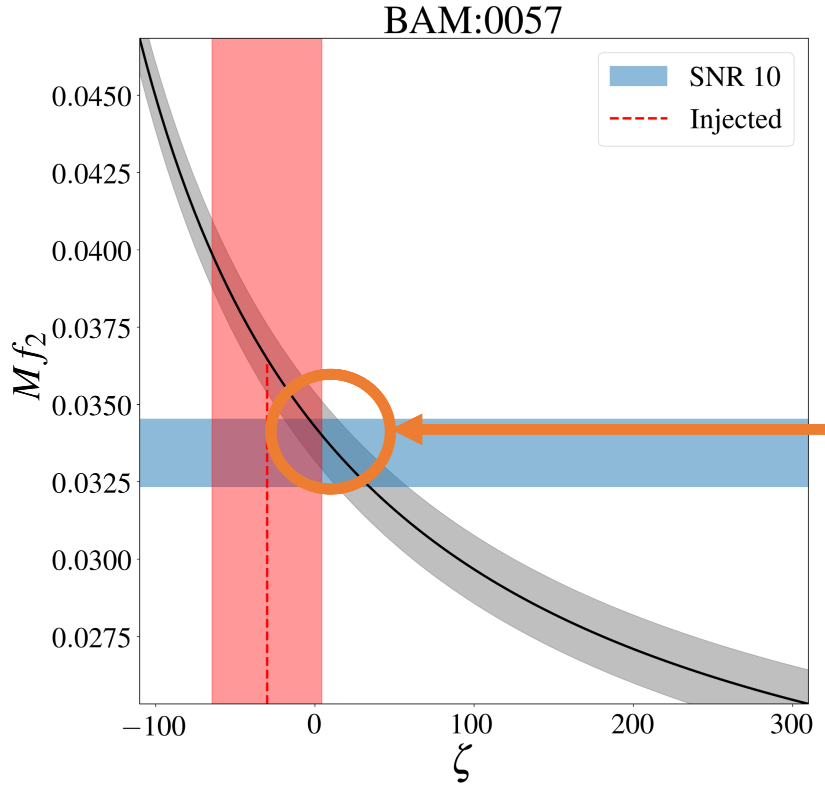
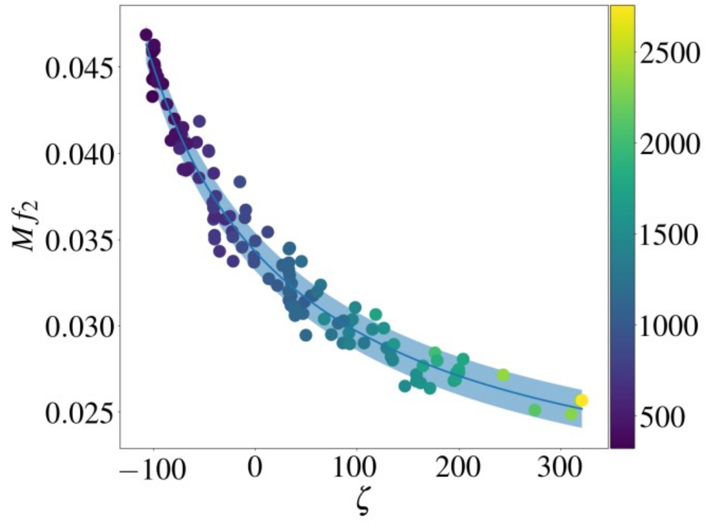




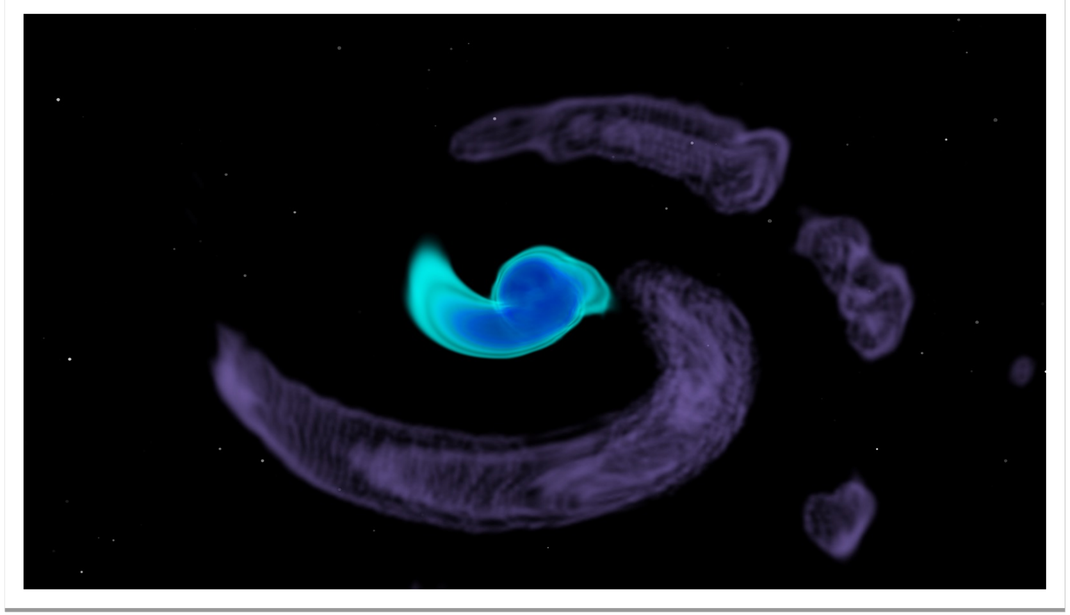
non-consistency could imply:

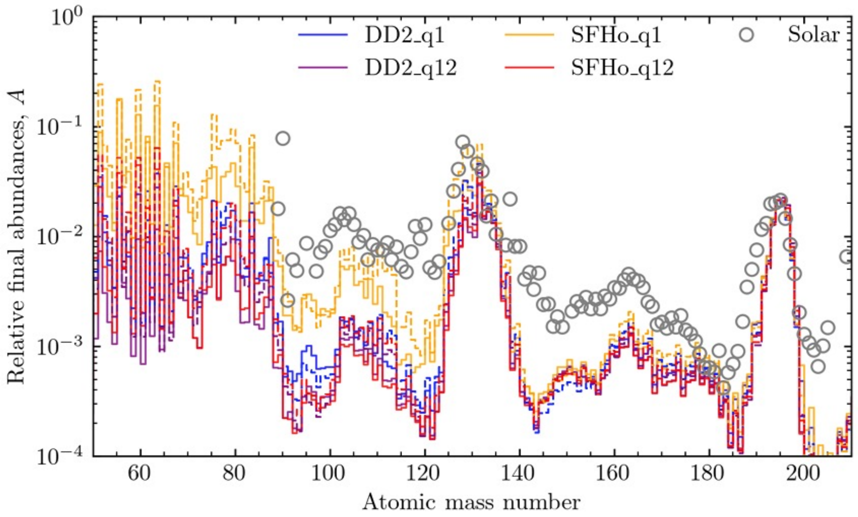
- missing physics in quasi-universal relations
- necessary modification of the nuclear physics description
- violation of general relativity

Tsang et al., PRD. 100 (2019) 4, 0440047

EM Signals – Kilonova (& GRB & GRB Afterglow)

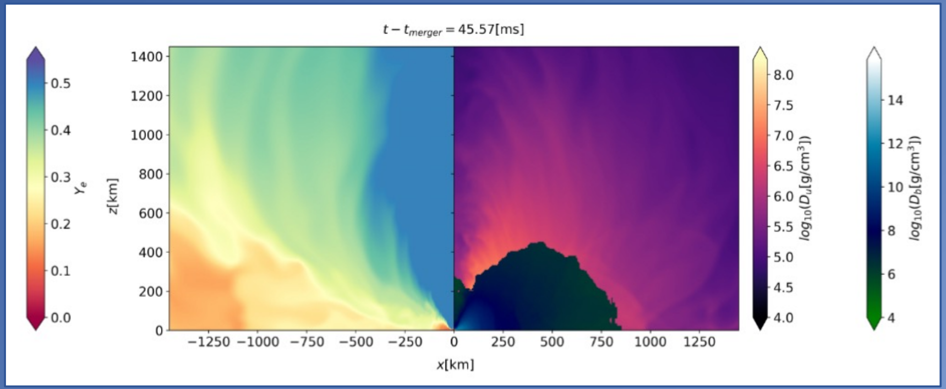
- neutron rich ejecta produce heavy r-process elements
- pseudo-black body radiation from r-process elements
- mergers are major sites for the formation of heavy elements





Schianchi et al., 2307.94572

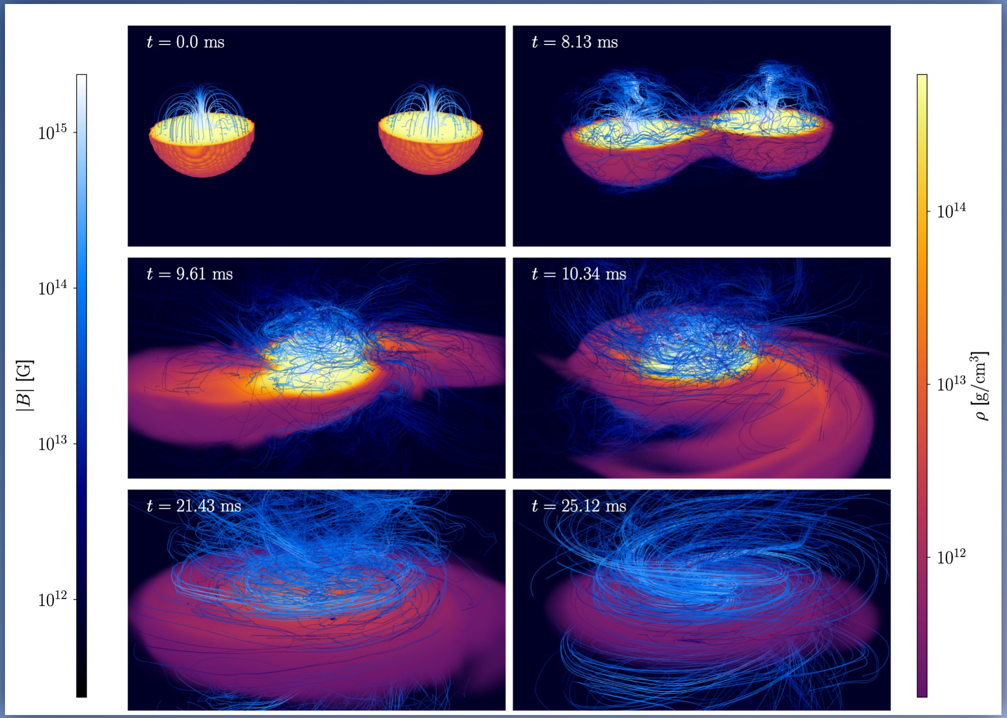
neutrino radiation

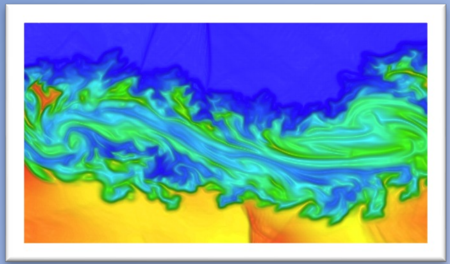


Schianchi et al., PRD 109 (2024) 4, 04412
Gieg et al., Universe 8 (2022) 7, 370

Large Uncertainties regarding our input Physics:

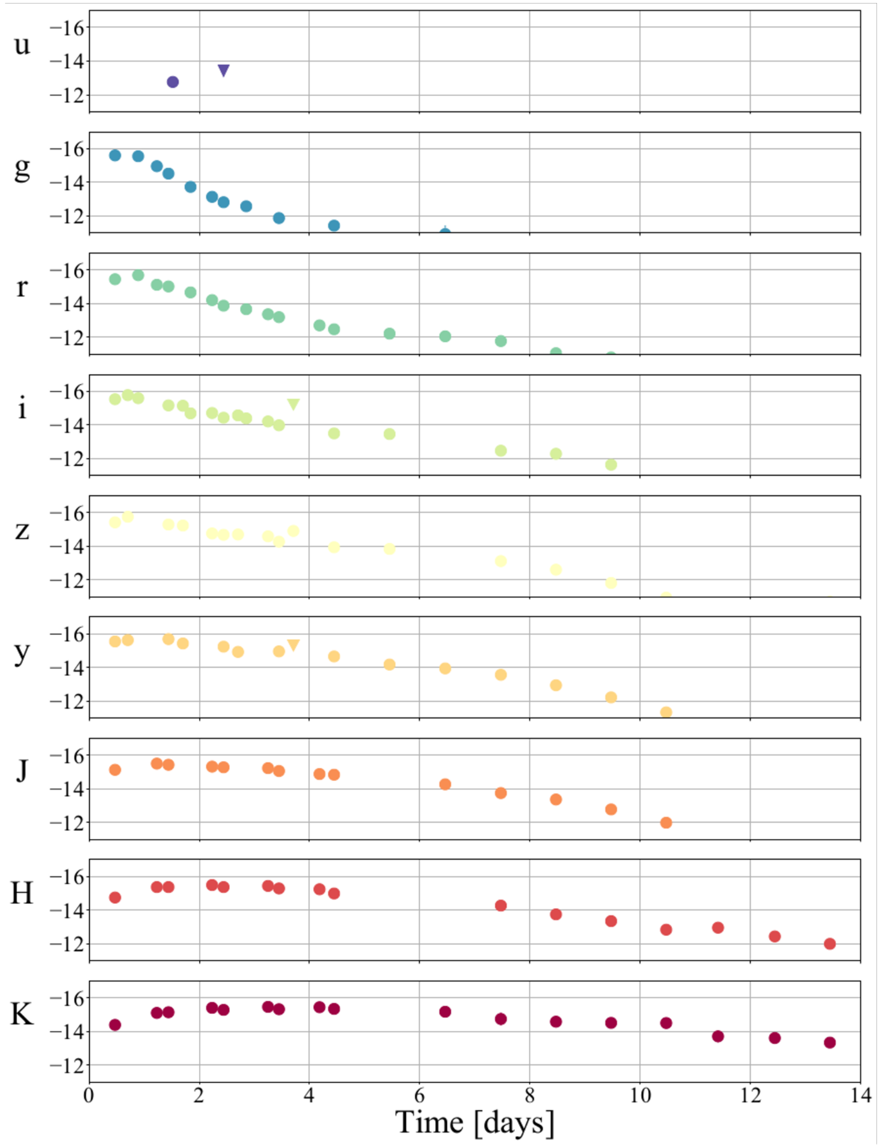
- Neutrino emission
- Magnetic fields
- Turbulences
- …



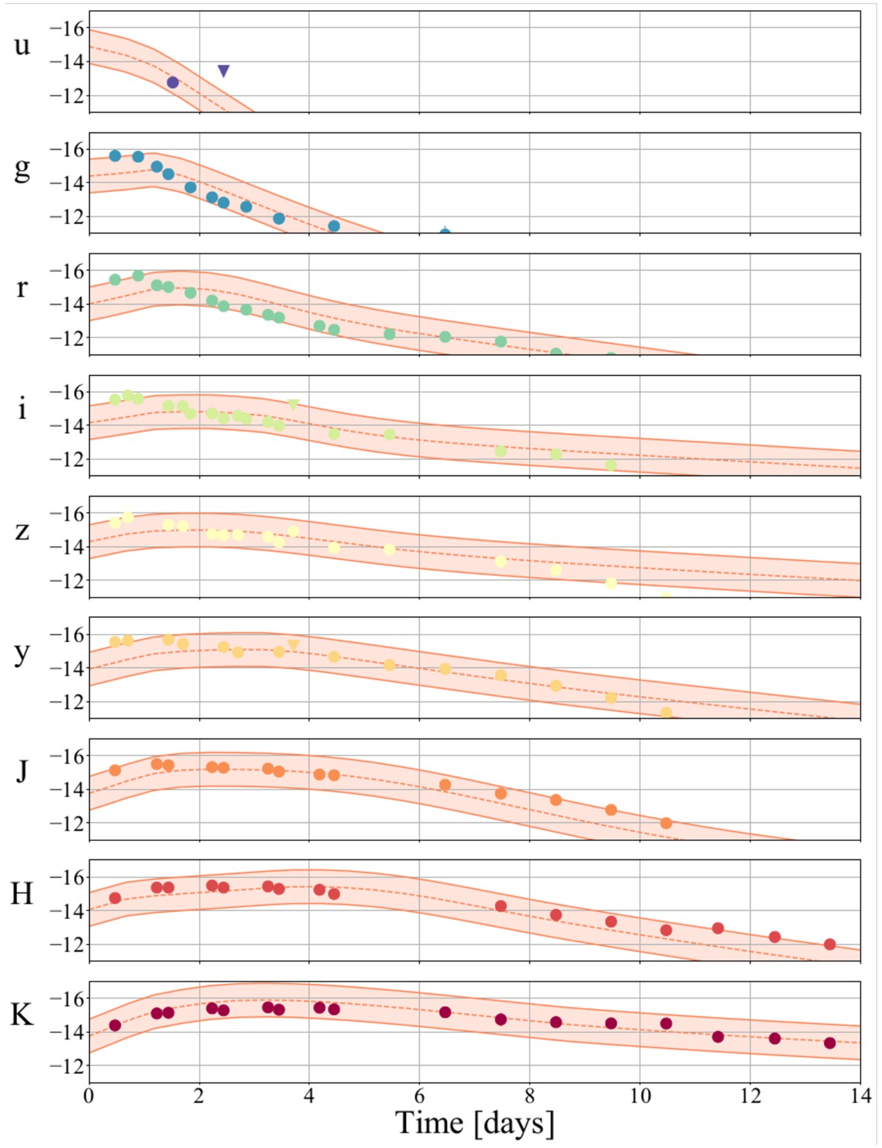


magnetic fields

Photometric lightcurves



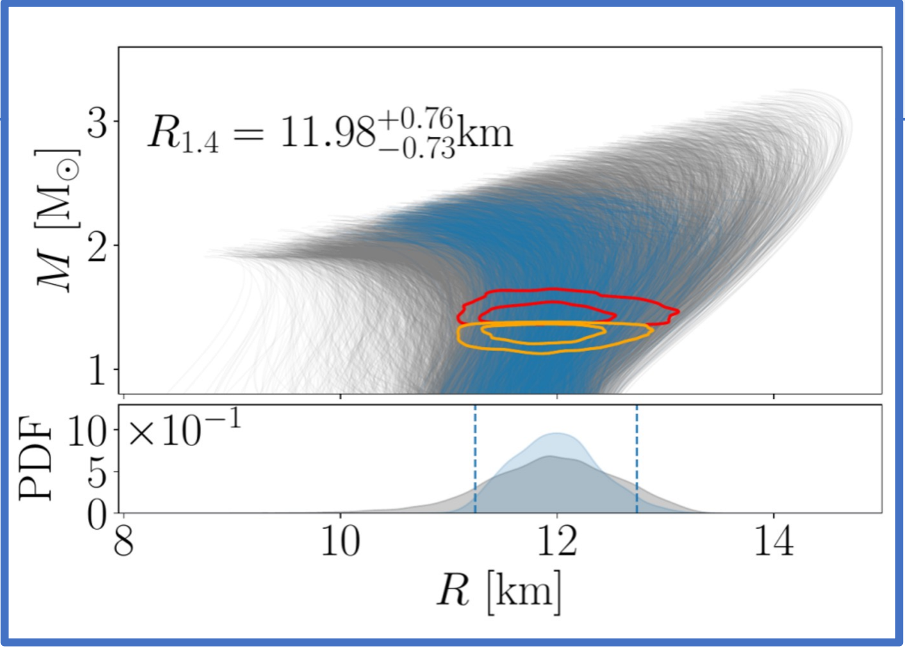
Photometric lightcurves



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

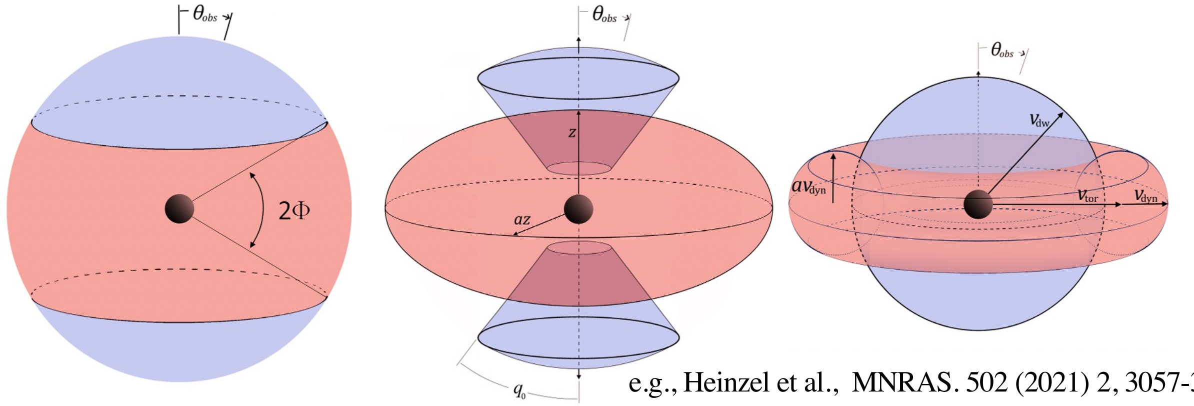


Uncertainties

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

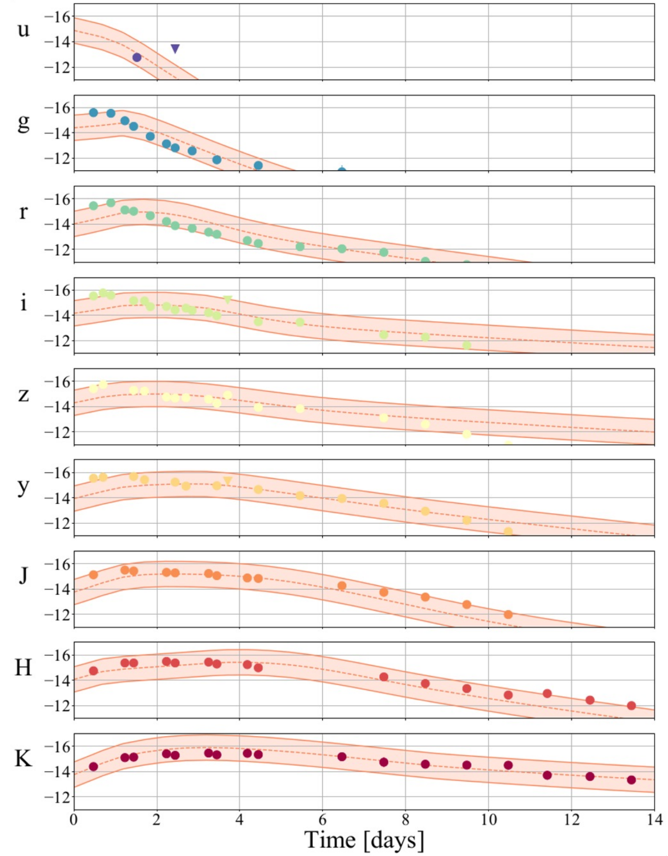
2.) Heating rates depend on the formed elements and ejecta properties

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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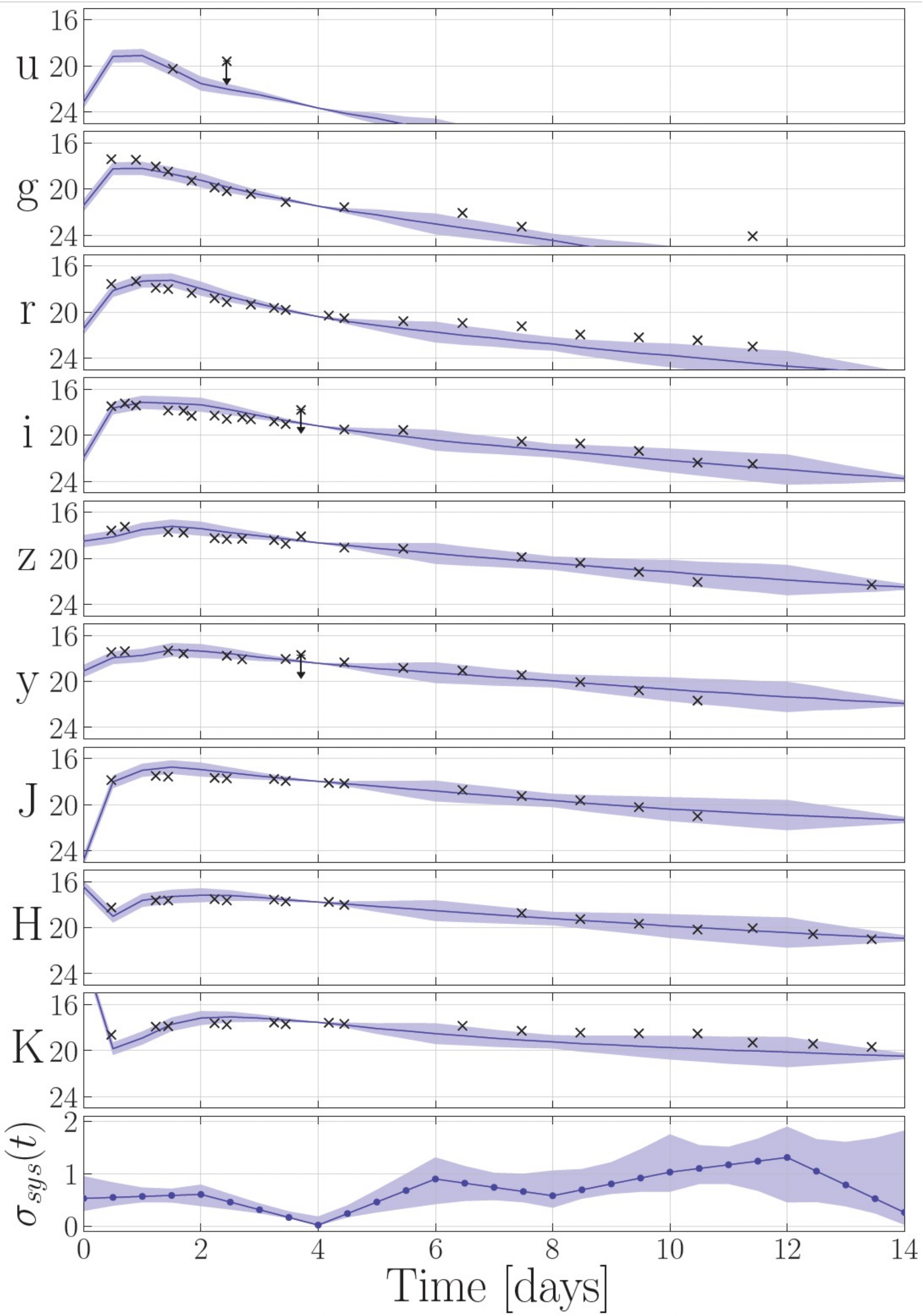
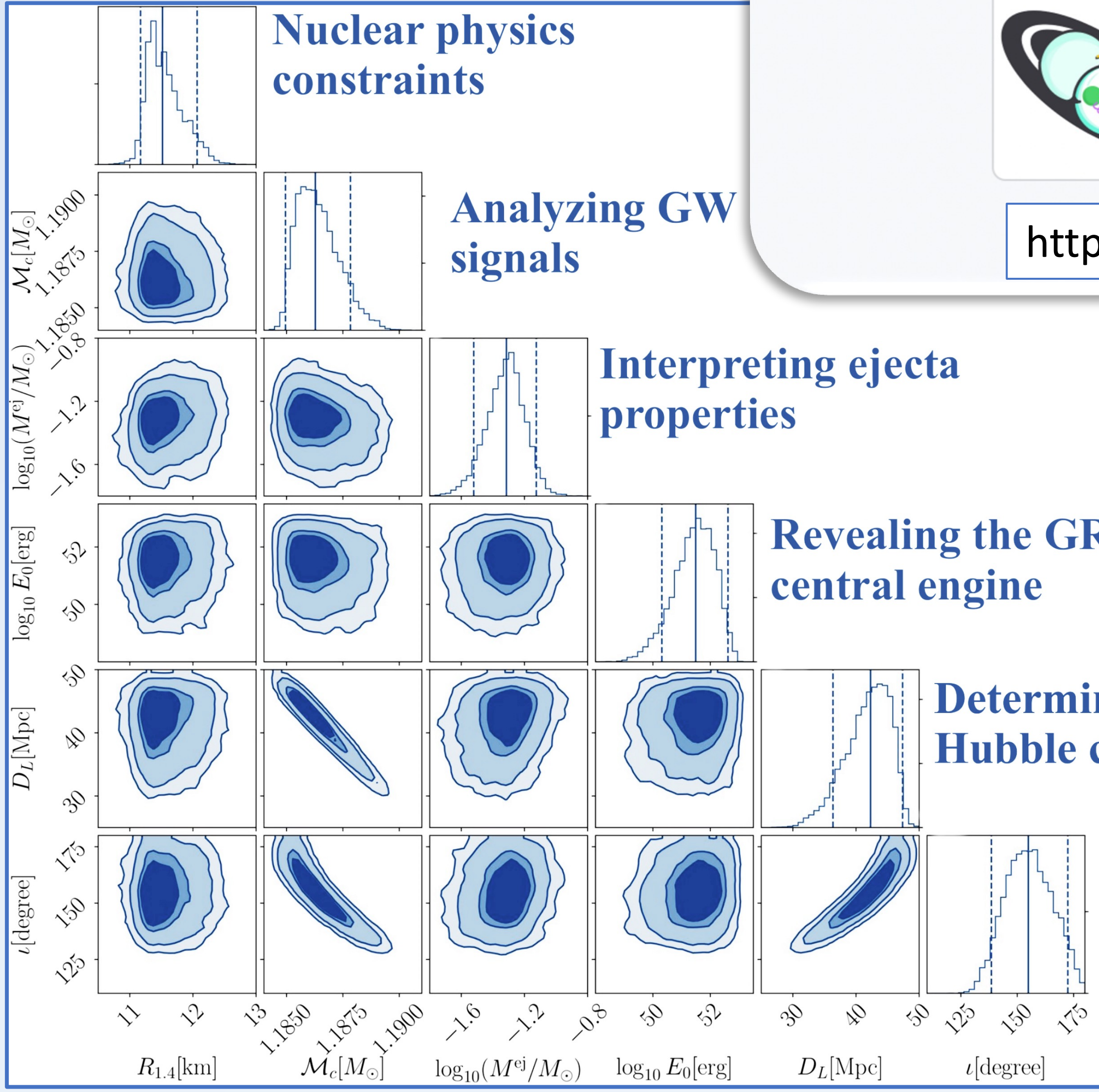


Data-driven approach to determine uncertainties

Jhawar et al. (2024), in prep.



Nuclear physics constraints

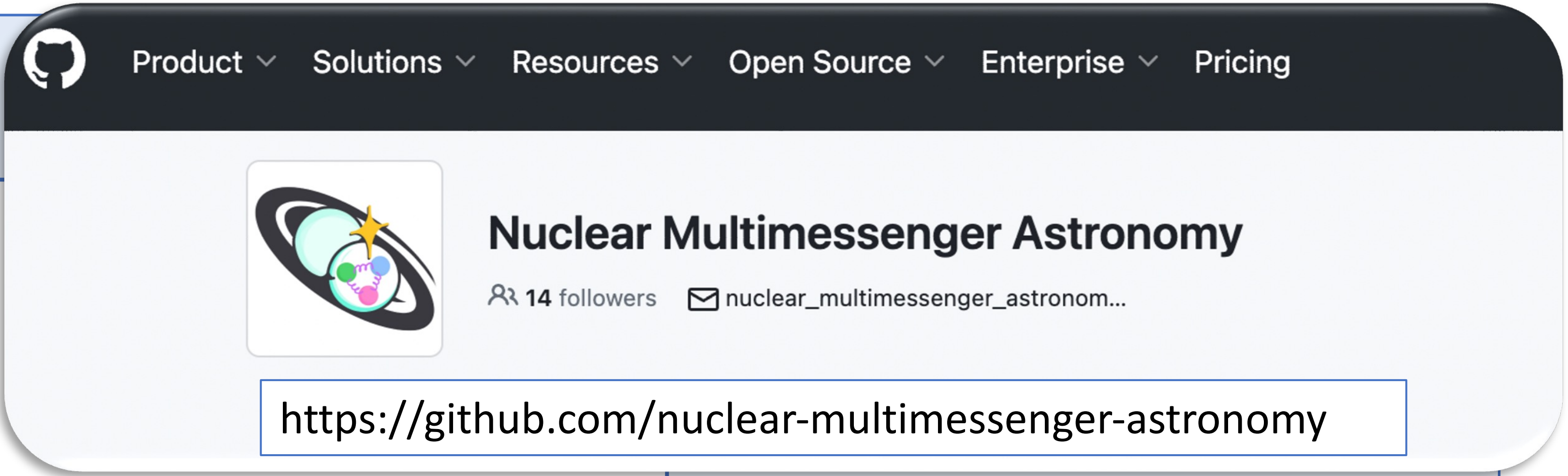
Analyzing GW signals

Interpreting ejecta properties

Revealing the GRB central engine

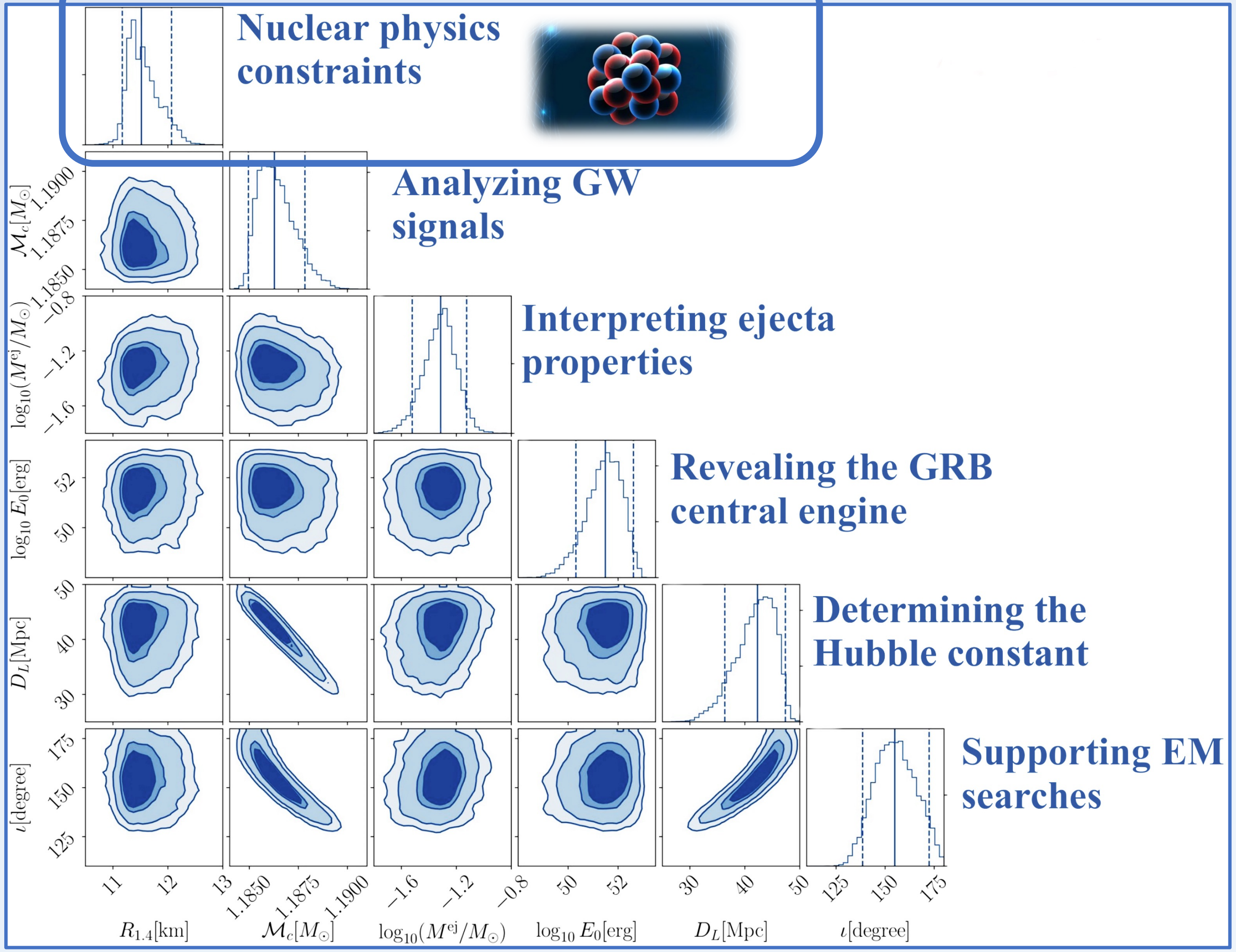
Determining the Hubble constant

Supporting EM searches

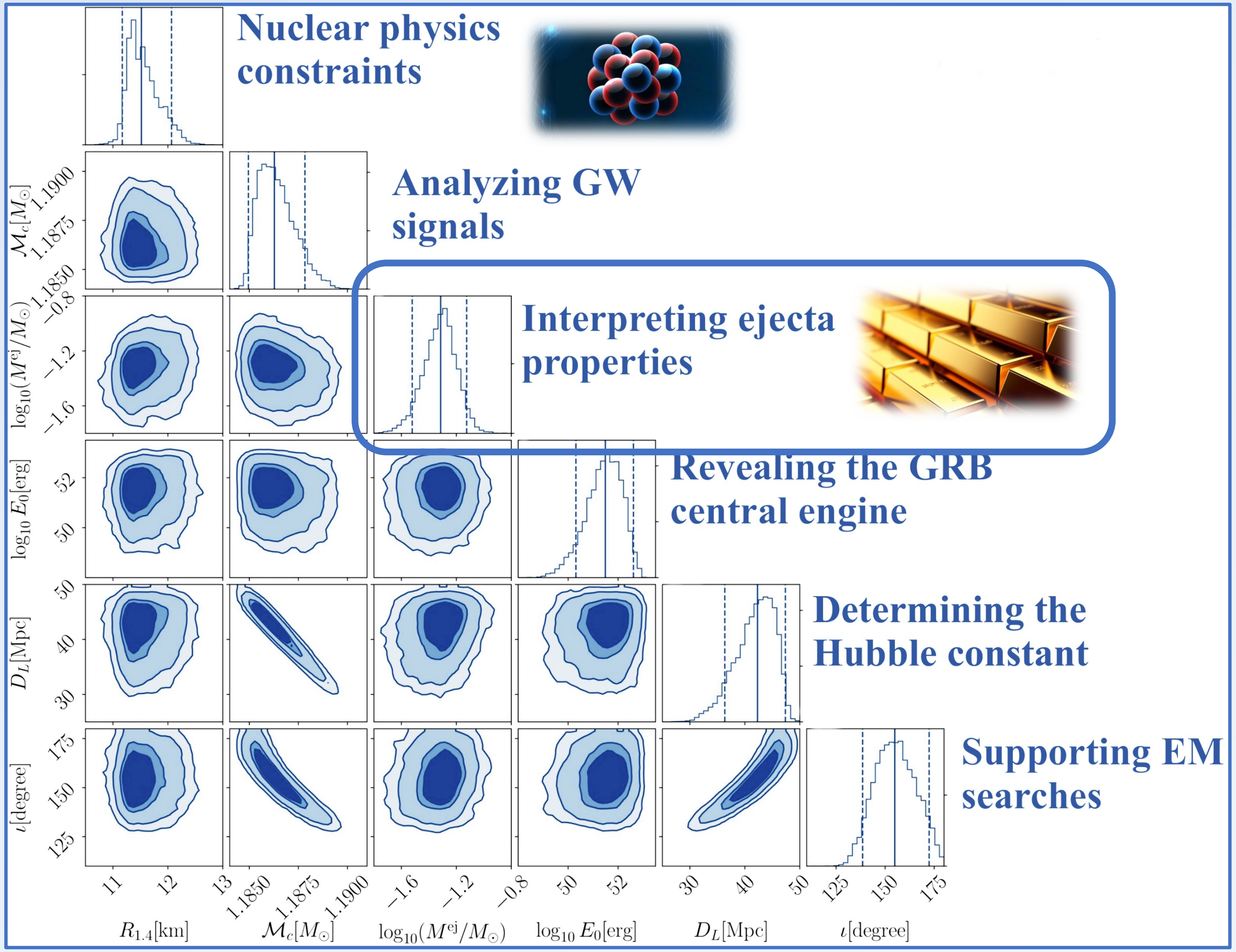


Pang et al., Nat. Comm. 14 (2023) 1, 8352

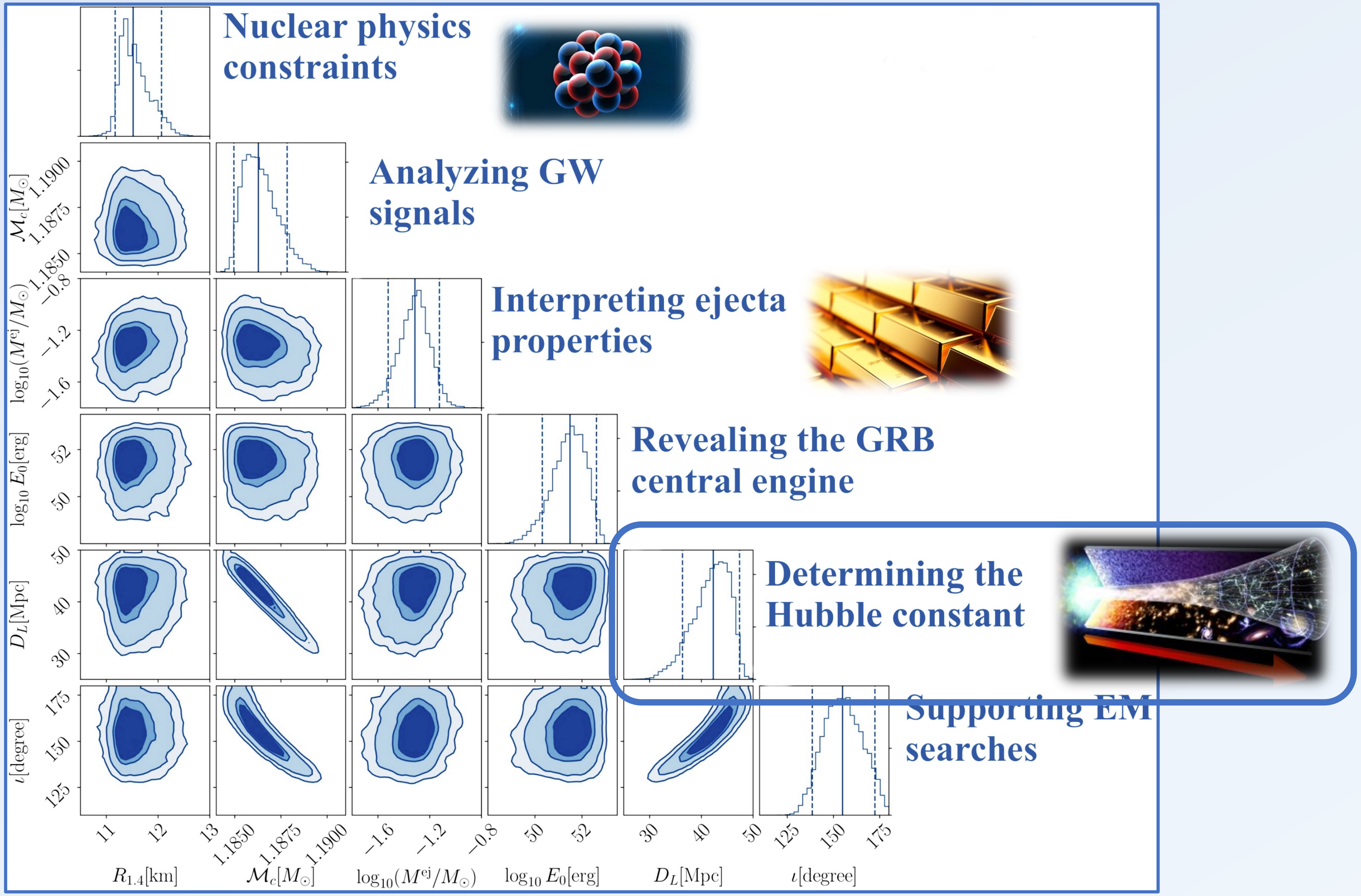
Nuclear Physics and Multi-messenger Astrophysics



Nuclear Physics and Multi-messenger Astrophysics



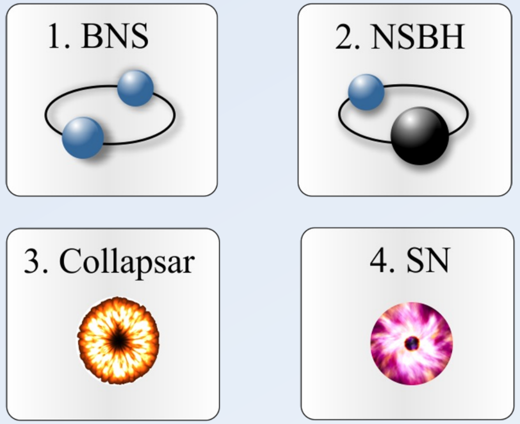
Nuclear Physics and Multi-messenger Astrophysics



Source Classification for GRB211211A

Kunert et al., MNRAS 527 (2024) 2

possible scenarios



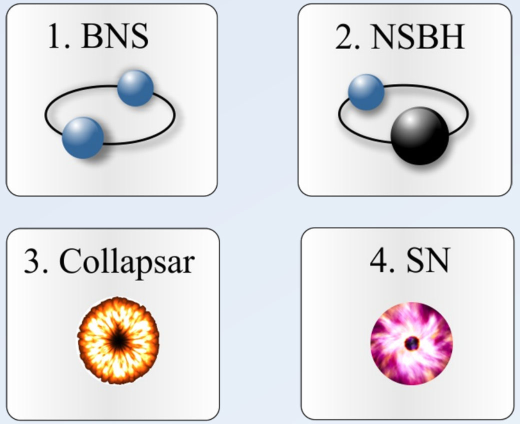
possible GRB jet types

NMMA Applications

Source Classification for GRB211211A

Kunert et al., MNRAS 527 (2024) 2

possible scenarios



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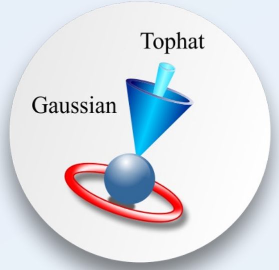


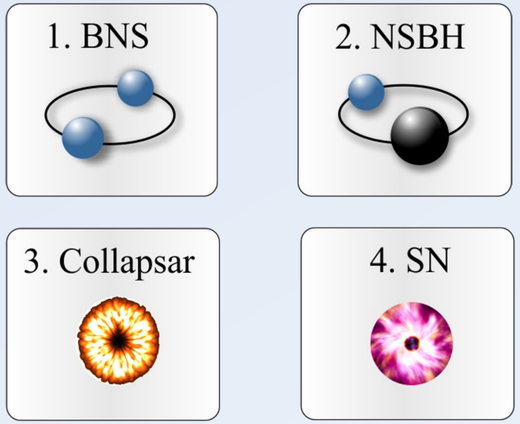
Name	Astrophysical Processes	GRB Jet Structure	Model dimension	Bayes factor $\ln[\mathcal{B}^{1}_{\rm ref}]$
BNS-GRB-$M^{\rm Kasen}_{\rm top}$	Kilonova + GRB	Tophat	11	ref.
BNS-GRB-$M^{\rm Kasen}_{\rm Gauss}$	Kilonova + GRB	Gaussian	12	-1.21 ± 0.12
BNS-GRB-$M^{\rm Bulla}_{\rm top}$	Kilonova + GRB	Tophat	11	-4.51 ± 0.12
BNS-GRB-$M^{\rm Bulla}_{\rm Gauss}$	Kilonova + GRB	Gaussian	12	-6.26 ± 0.12
NSBH-GRB-$M_{\rm top}$	Kilonova + GRB	Tophat	11	-8.41 ± 0.12
NSBH-GRB-$M_{\rm Gauss}$	Kilonova + GRB	Gaussian	12	-10.56 ± 0.12
SNCol-GRB-$M_{\rm top}$	rCCSNe + GRB	Tophat	14	-15.24 ± 0.13
SNCol-GRB-$M_{\rm Gauss}$	rCCSNe + GRB	Gaussian	15	-16.97 ± 0.13
SN98bw-GRB-$M_{\rm top}$	CCSNe + GRB	Tophat	8	-12.66 ± 0.12
SN98bw-GRB-$M_{\rm Gauss}$	CCSNe + GRB	Gaussian	9	-12.59 ± 0.12
GRB-$M_{\rm top}$	GRB	Tophat	8	-12.47 ± 0.12
GRB-$M_{\rm Gauss}$	GRB	Gaussian	9	-12.65 ± 0.12

NMMA Applications

Source Classification for GRB211211A

Kunert et al., MNRAS 527 (2024) 2

possible scenarios



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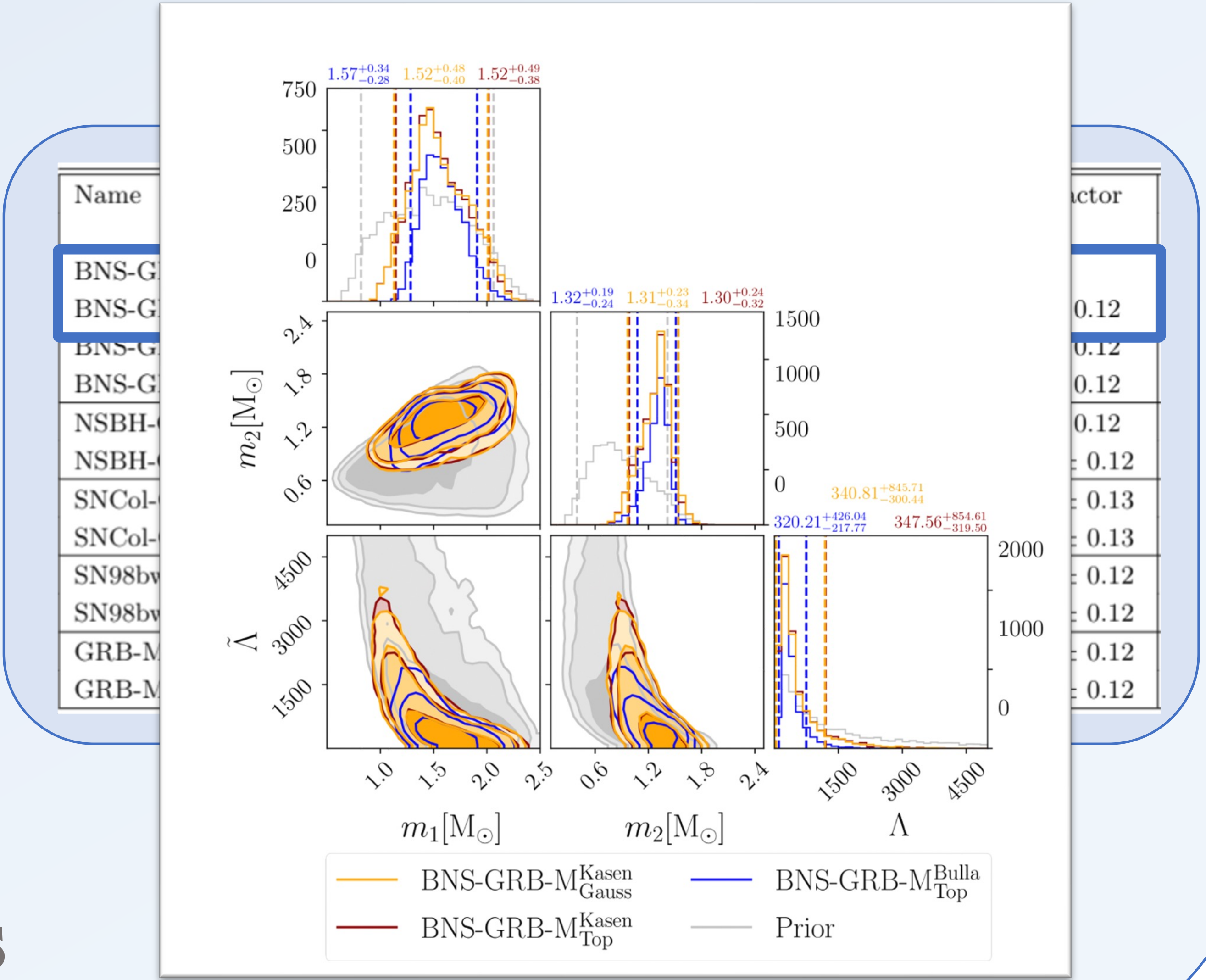
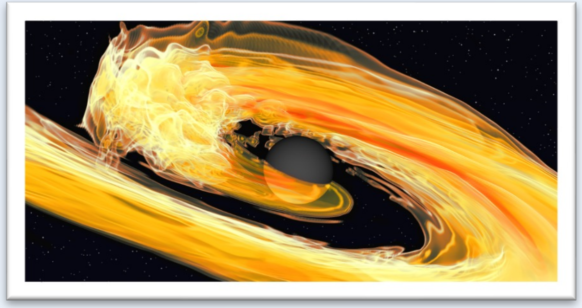


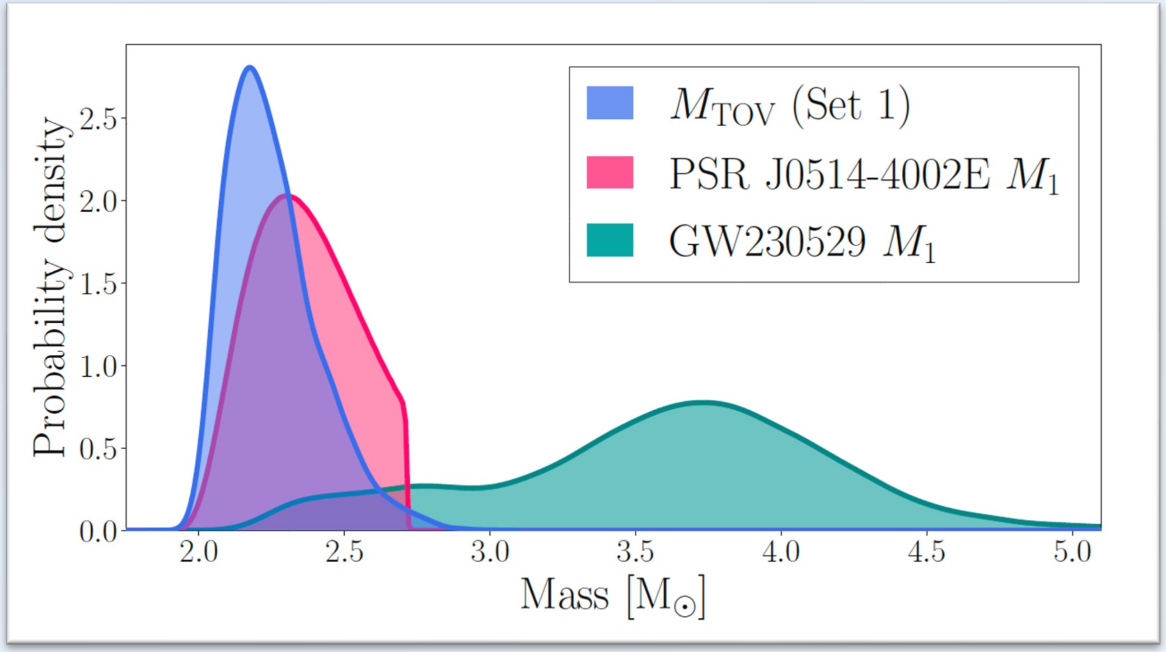
Applications

Source Classification for PSR J0514+4002E & GW230529

Koehn et al., 2024, in prep.



Recent detections of sources with "mass-gap" components



NMMA Applications

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Koehn et al., 2024, in prep.

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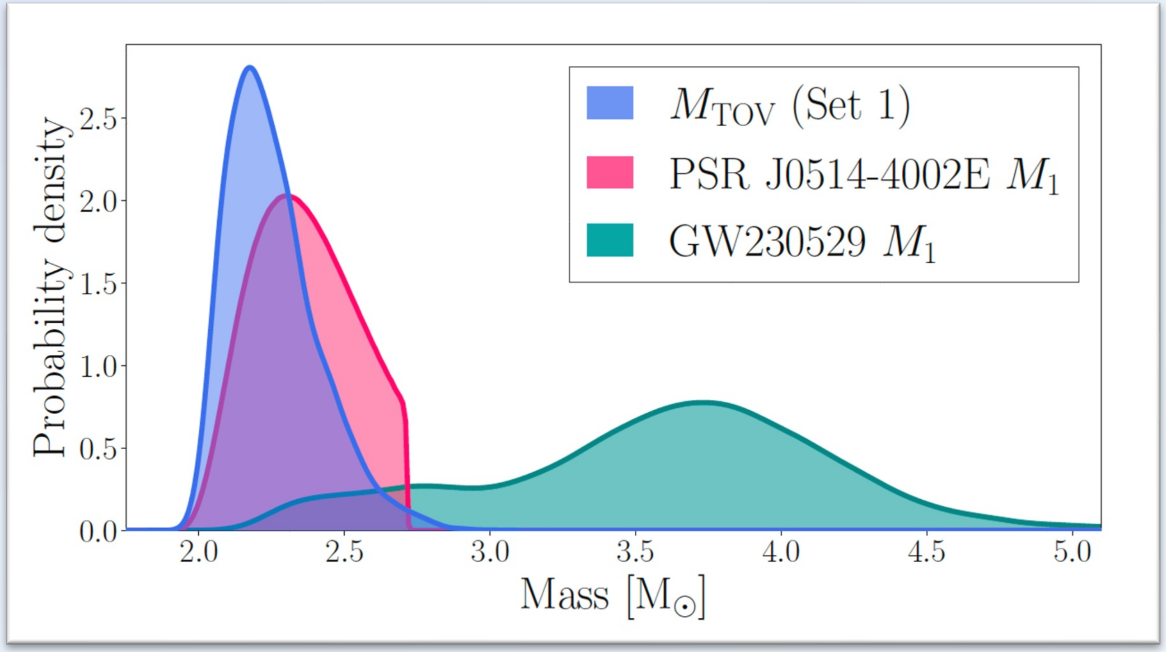
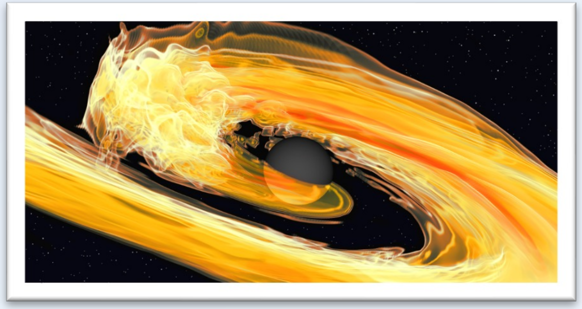




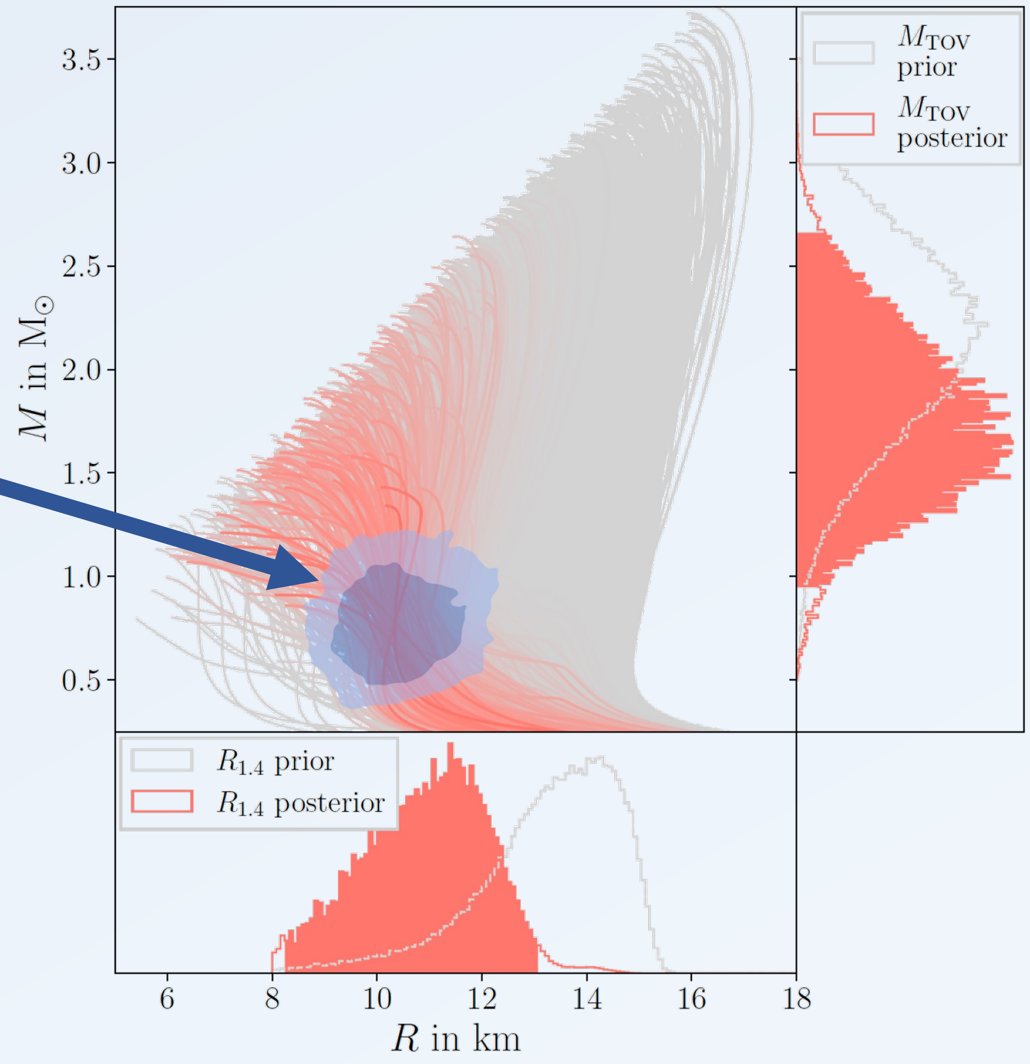
Object			Set 1	Set 2	Set 3
PSR J0514 -4002E	$M_2 > 1.17\,\mathrm{M}_\odot$		31%	34%	3.1%
	M_2 unconstrained		24%	26%	1.9%
	$M_2 \sim P^{\mathrm{gal}}(M_{\mathrm{PSR}})$		15%	8.1%	1.6%
GW230529	default prior	w/o spin	1.6%	1.3%	0.02%
		w/ spin	3.9%	3.9%	0.82%
	PDB prior	w/o spin	8.1%	6.9%	0.36%
		w/ spin	17%	17%	1.7%

Probability of the individual companions class

Applications

Outlier Classification, e.g., HESS J1731-347

- **Measurement of the X–ray spectrum of HESS J1731-347 by** ***Doroshenko et al., 2022 Nat. Astro 6, 1444***

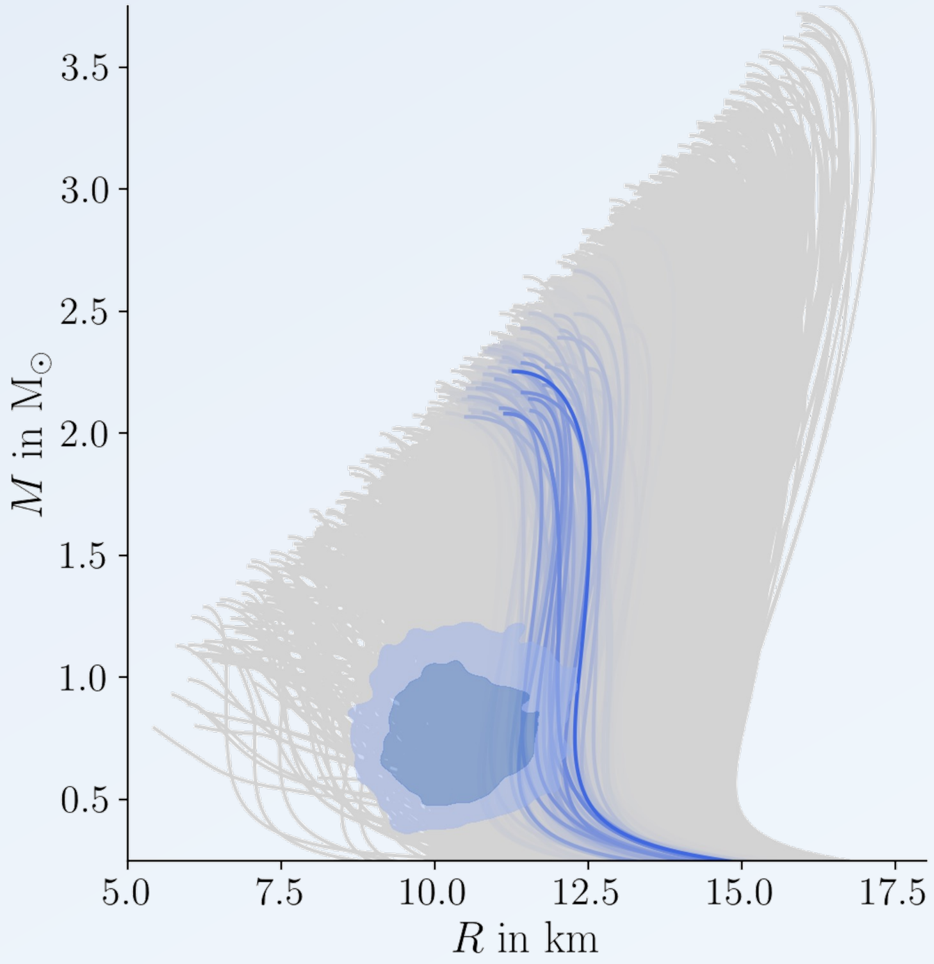


NMMA **Applications**

Outlier Classification, e.g., HESS J1731-347

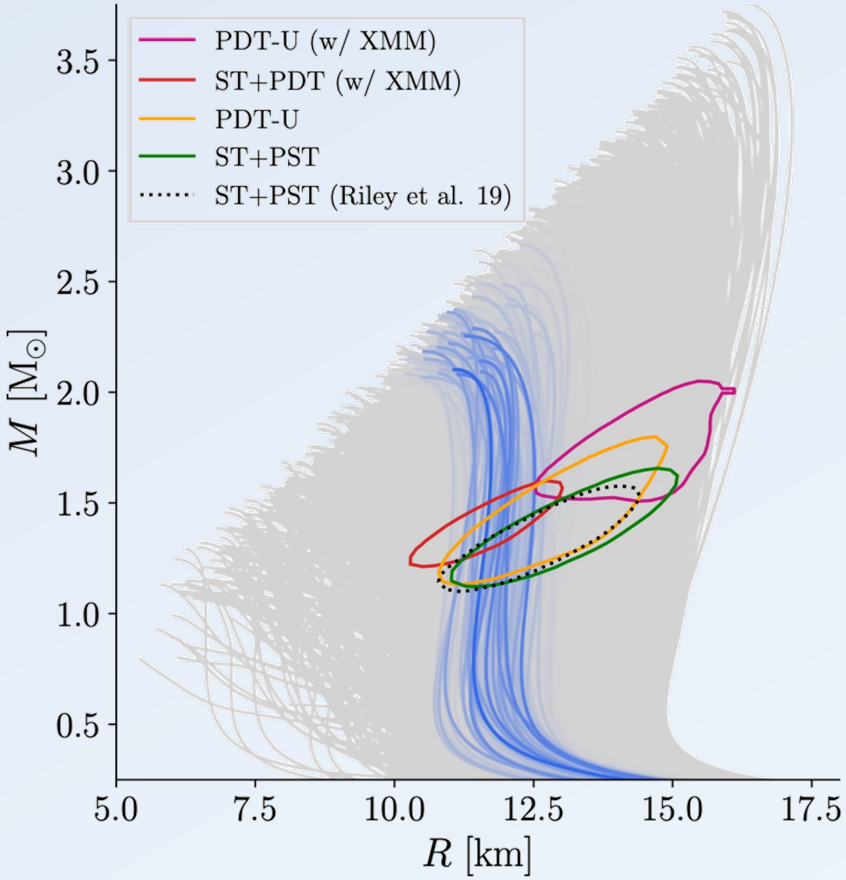
- **Measurement of the –ray spectrum of HESS J1731-347 by *Doroshenko et al., 2022 Nat. Astro 6, 1444***

- **Noticeable disagreement between other derived multi-messenger constraints and the HESS measurement**



NMMA **Applications**

Outlier of NICER Models

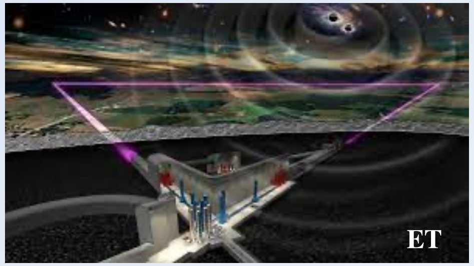


- **Analysis complementary to the Bayes Factors provided in *Vinciguerra et al., APJ 961, 62 (2024)***
- **Some indication that most of the presented results are less preferred than the original analysis**

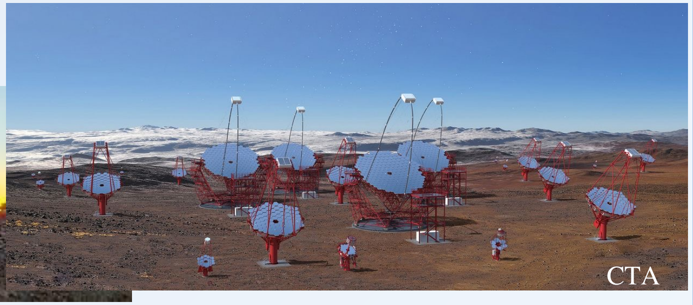
NMMA **Applications**

Science Summary and Outlook

Gravitational Waves



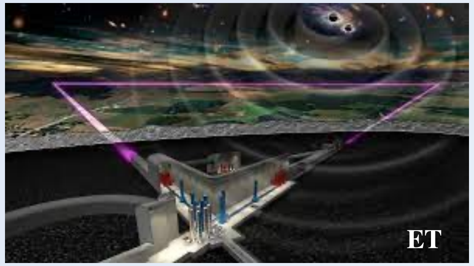
Electromagnetic Signals



… neutrino detectors, nuclear physics facilities, ….

Science Summary and Outlook

Gravitational Waves



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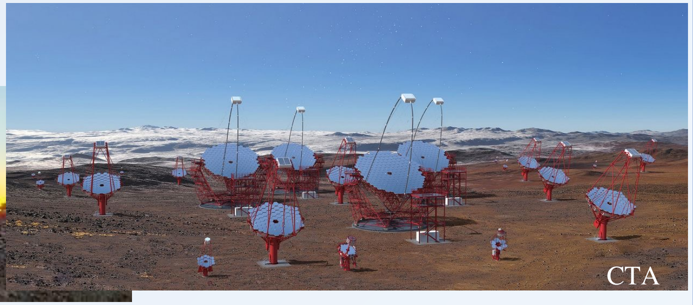

… neutrino detectors, nuclear physics facilities, ….

- Astrophysical constraints provide important information that is currently not accessible for nuclear-physics computations and experiments
- Systematic Biases for Gravitational-wave studies smaller than statistical uncertainties
- Kilonova and other EM modelling of BNS/BHNS mergers subject of large uncertainties *-investigations ongoing-*
- Combined set of information can help to tighten constrain, but also to point towards outliers/new physics