

Joint nuclear-physics and multi-messenger astrophysics interpretation of compact binary mergers

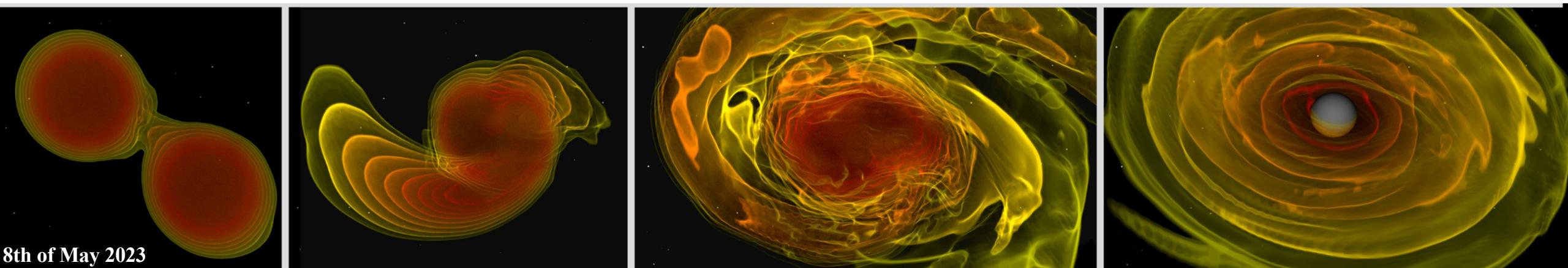


Tim Dietrich

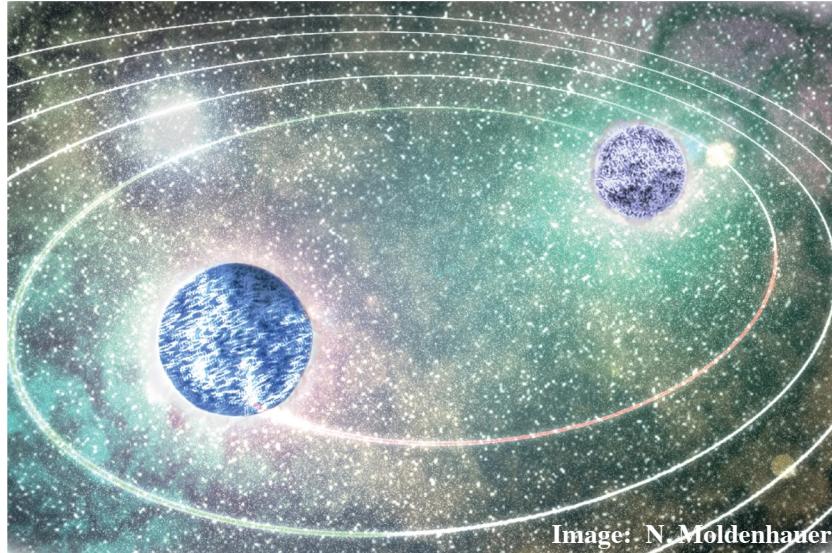
University of Potsdam
Max Planck Institute for Gravitational Physics



Daimler und
Benz Stiftung

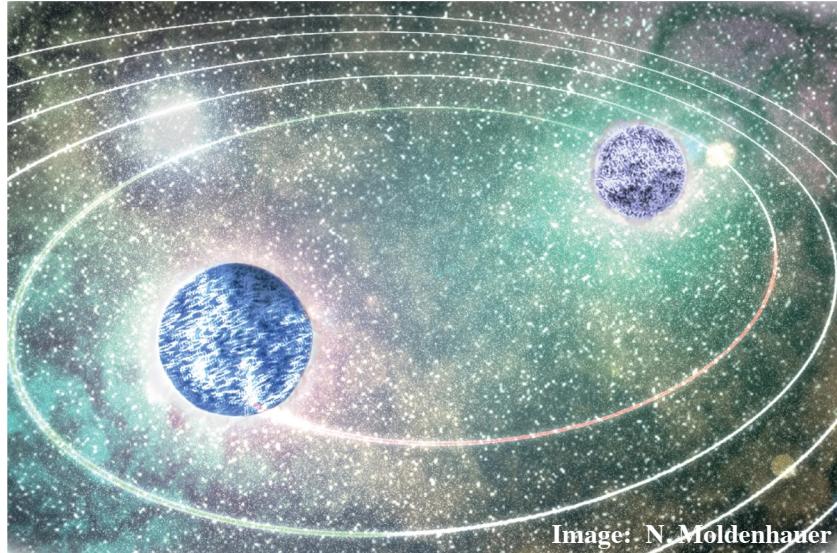


How to study neutron stars?



- **X-ray observations** of rotating neutron stars
- **radio measurements** of rotating neutron stars
- Binary mergers:
 - **gravitational waves**
- **gamma-ray, X-ray, ultraviolet, optical, infrared, radio observations**

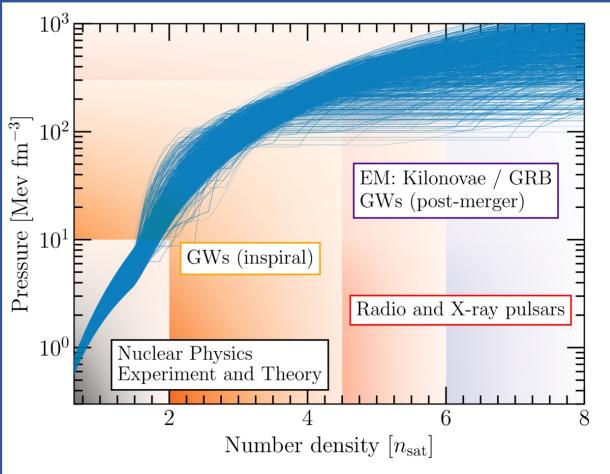
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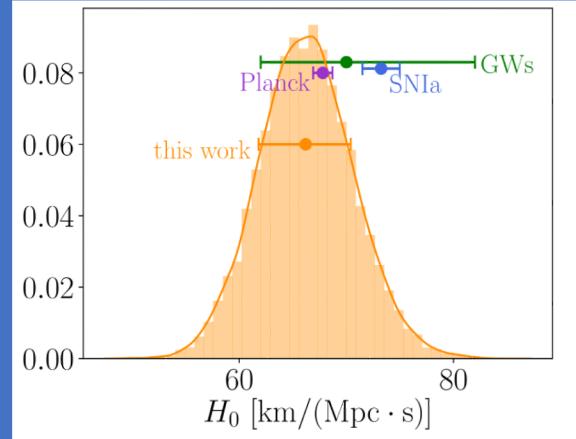
Science cases

Equation of State



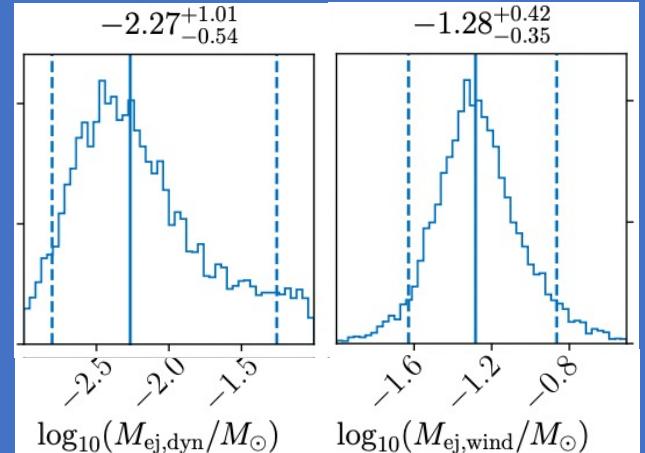
Pang et al., arXiv: 2205.08513

Hubble Constant



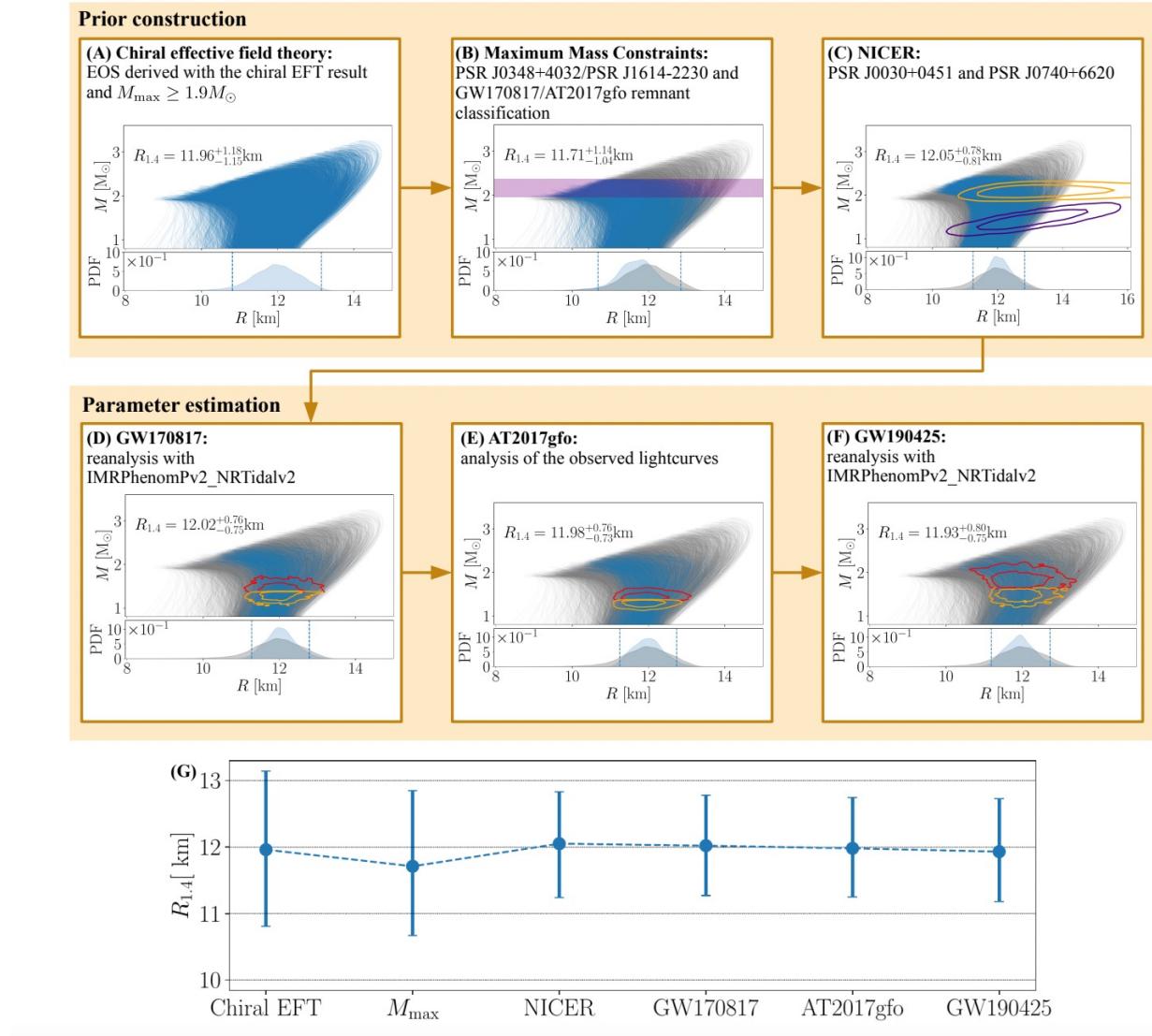
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Heavy element formation

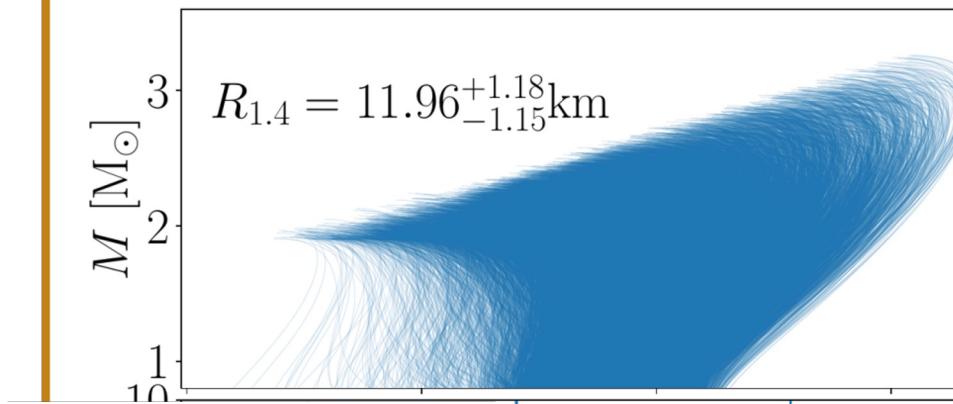


The principle idea: Multi-Messenger Interpretation of the Equation of State

- (initially) multistep procedure
- incorporation of nuclear physics and astrophysics information



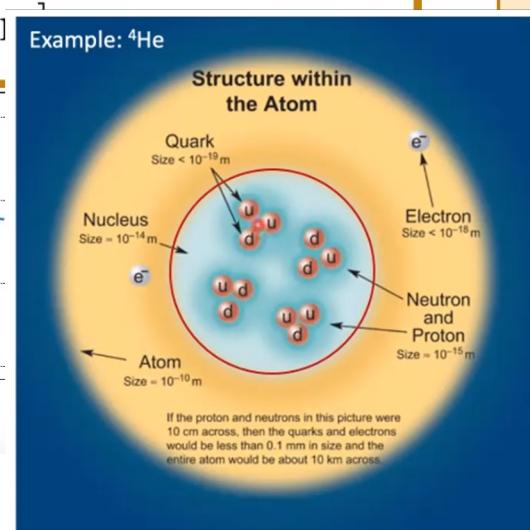
(A) Chiral effective field theory:
EOS derived with the chiral EFT result
and $M_{\max} \geq 1.9M_{\odot}$



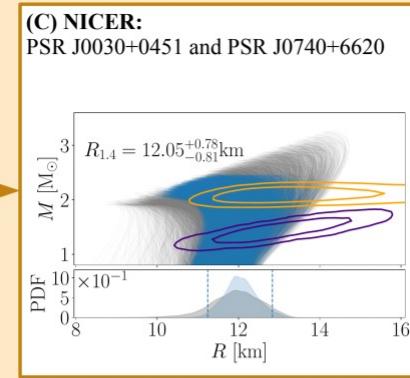
	NN	3N	4N
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$ (2 LECs)	X H	—	—
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$ (7 LECs)	X H X H	—	—
N ² LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$ (2 LECs: 3N)	H H	H H X	—
N ³ LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$ (15 LECs)	X H X H	X H + ...	H H + ...

$$\mathcal{H}|\Psi\rangle = E|\Psi\rangle$$

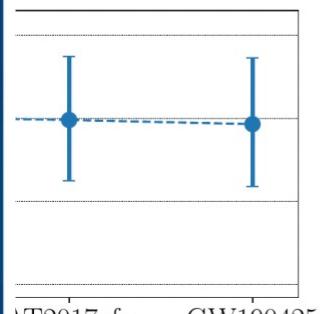
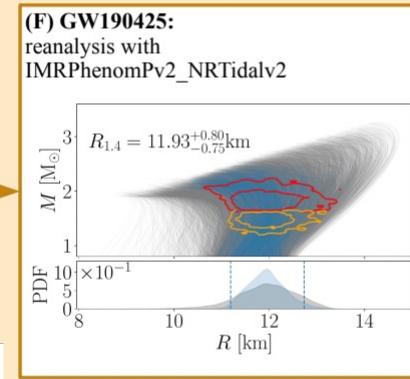
$$\mathcal{H} = \mathcal{T} + \mathcal{V}$$



and



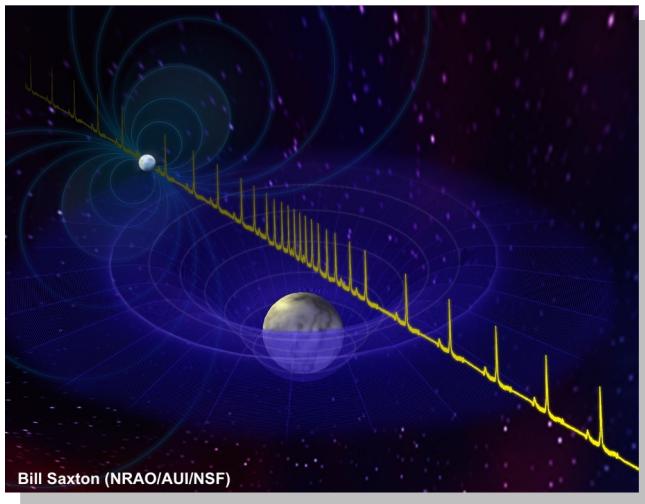
s



EM Signals – Maximum Neutron Star Mass

lower bound

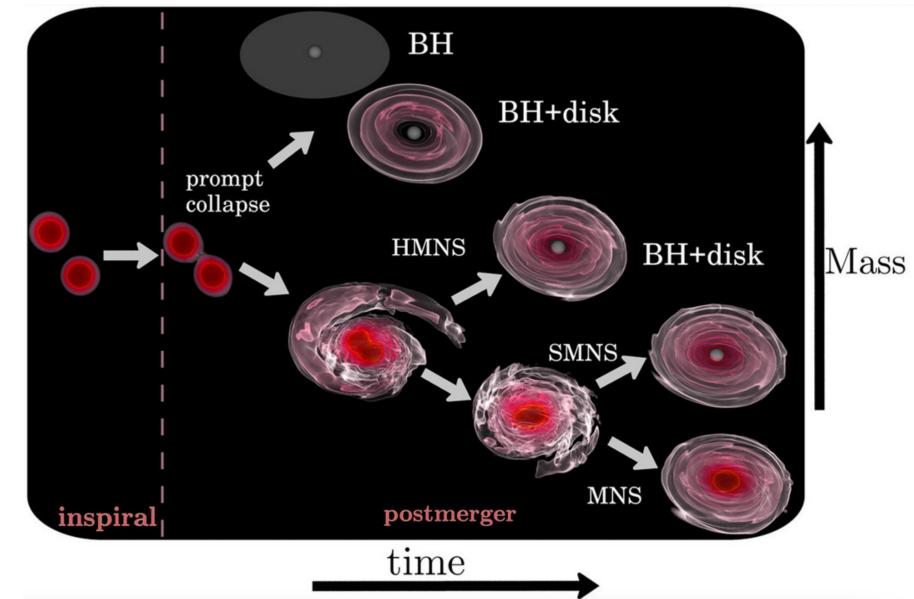
Measurement of massive pulsars through Shapiro time delay



Pulsar	Mass in M_{\odot}
PSR J0740+6620	$2.08^{+0.07}_{-0.07}$
PSR J0348+4032	$2.01^{+0.04}_{-0.04}$
PSR J1614-2230	$1.908^{+0.016}_{-0.016}$

upper bound

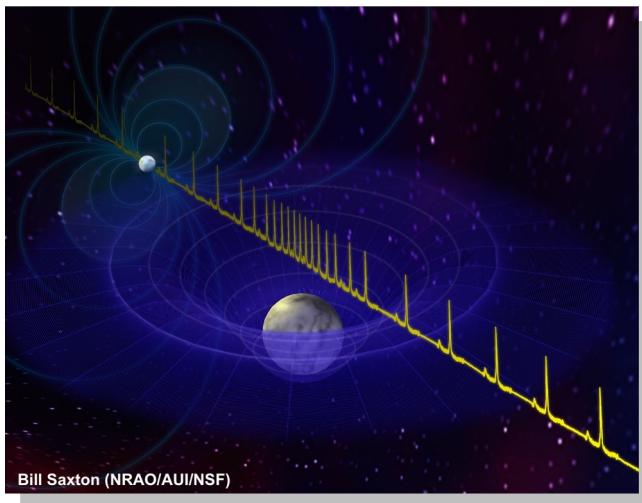
postmerger evolution of GW170817's remnant



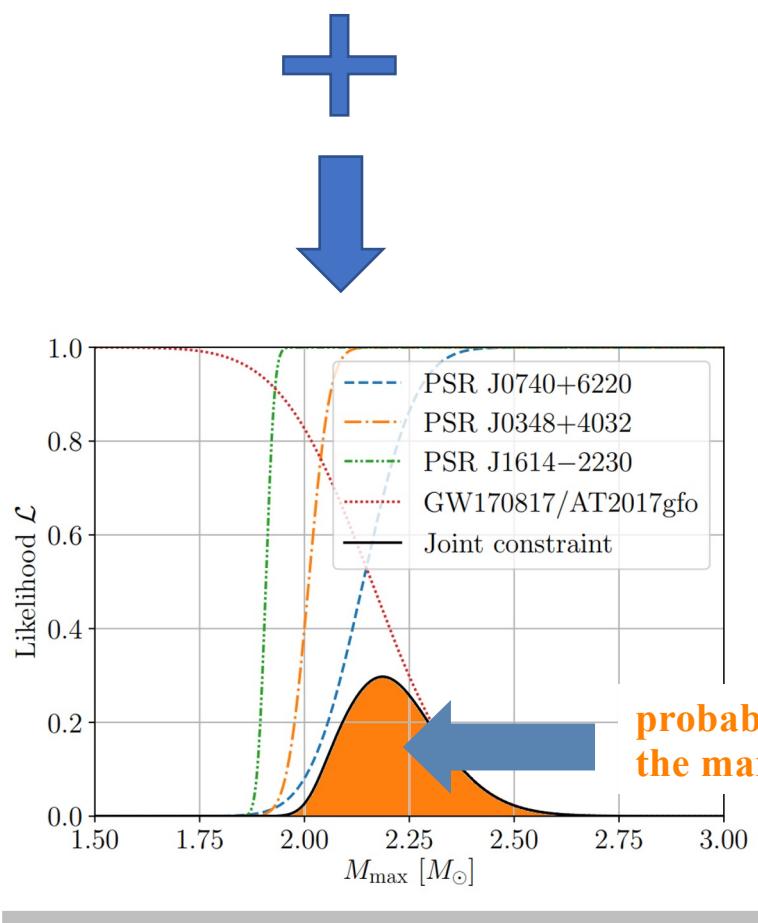
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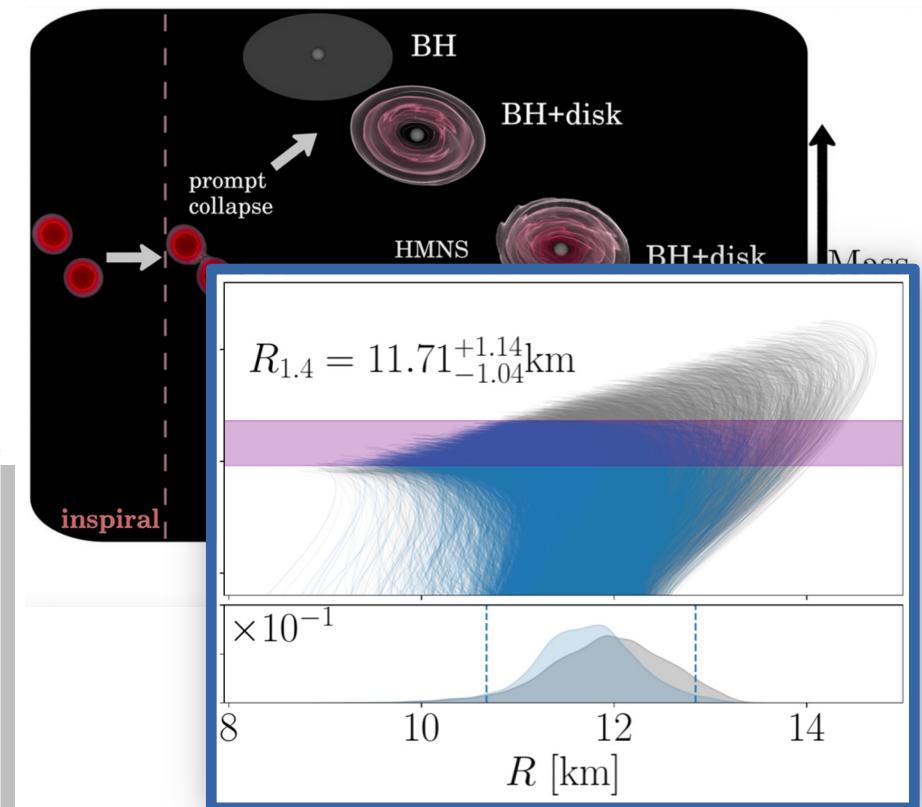


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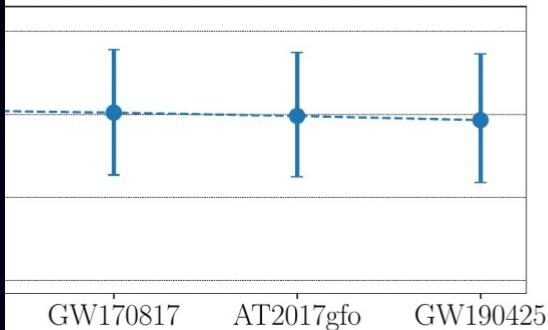
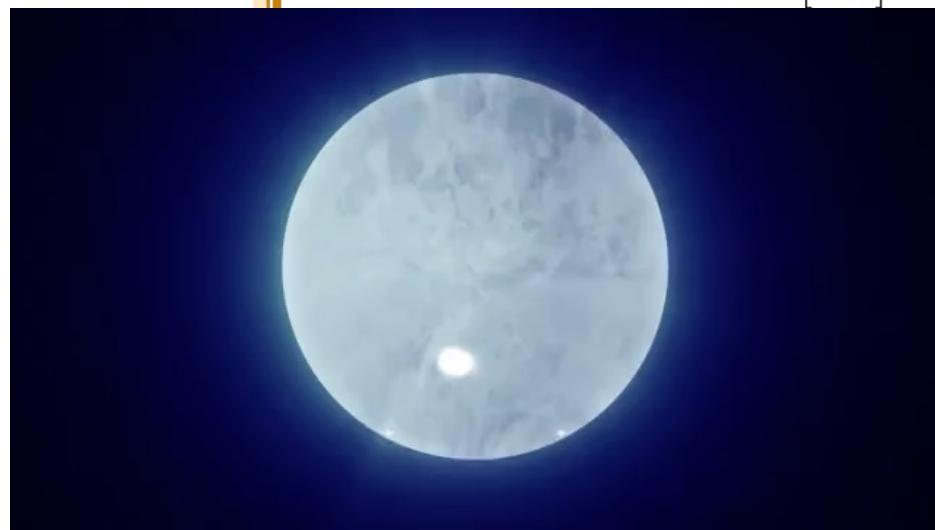
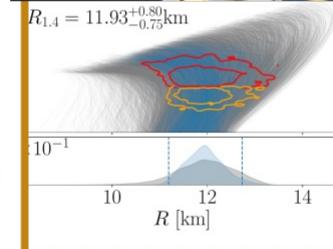
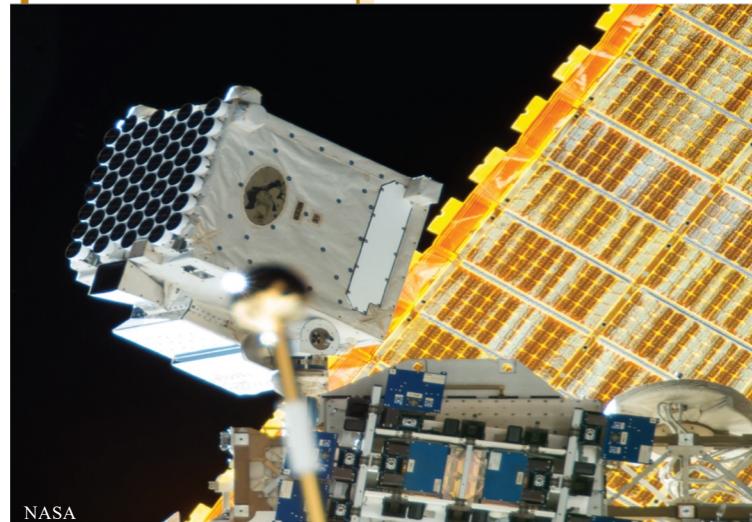
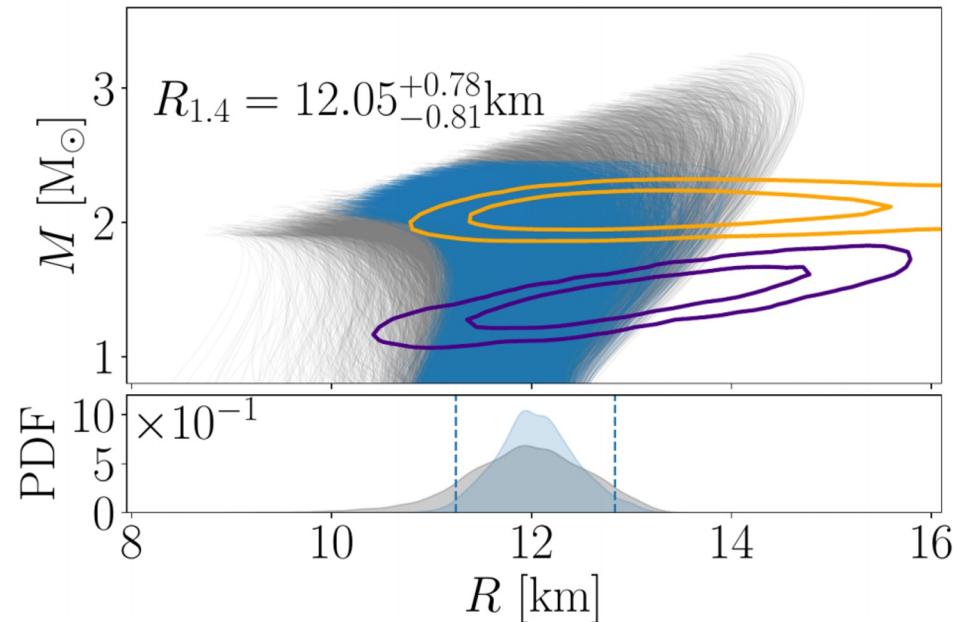
upper bound

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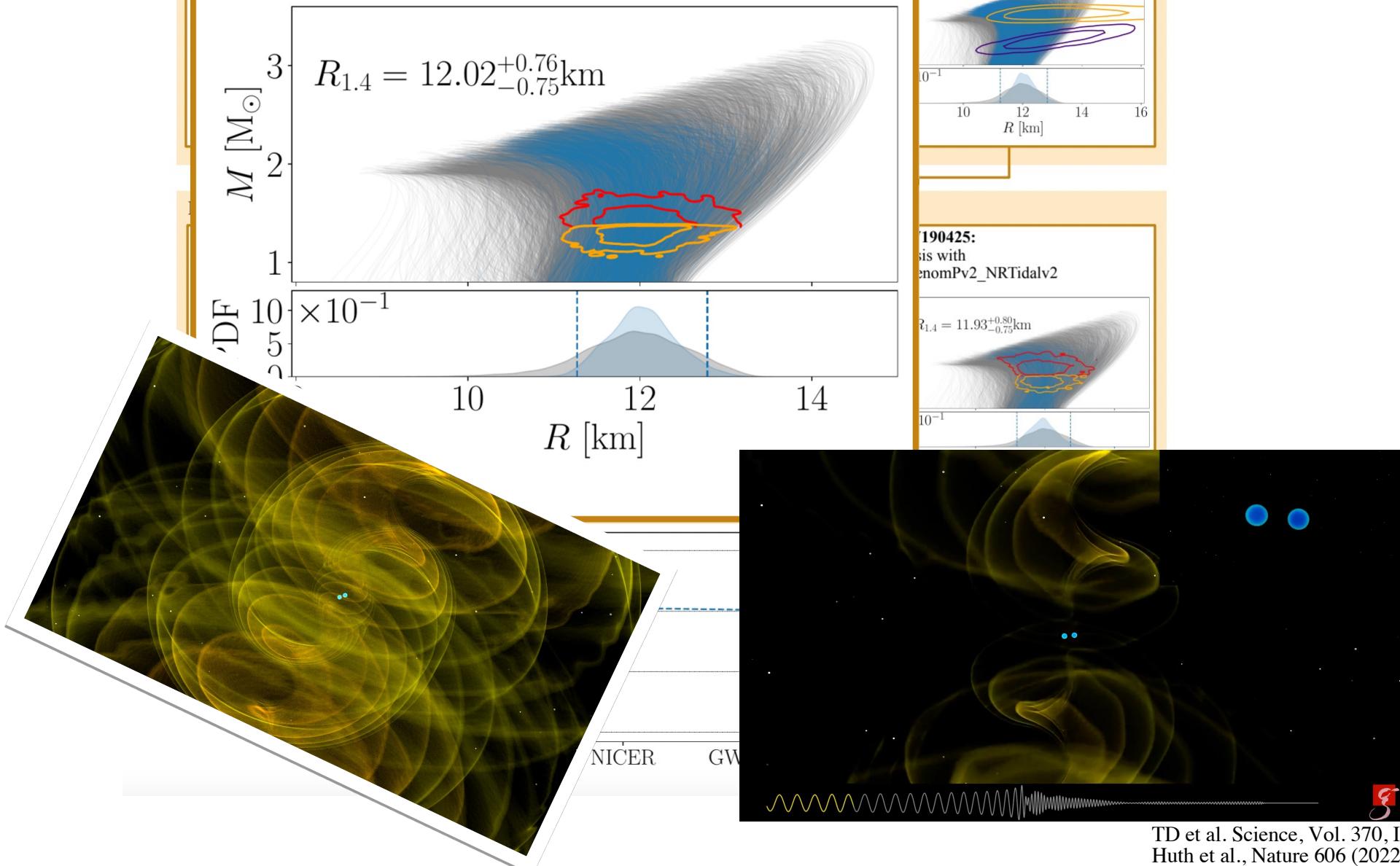


I(C) NICER: PSR J0030+0451 and PSR J0740+6620

CER:
030+0451 and PSR J0740+6620

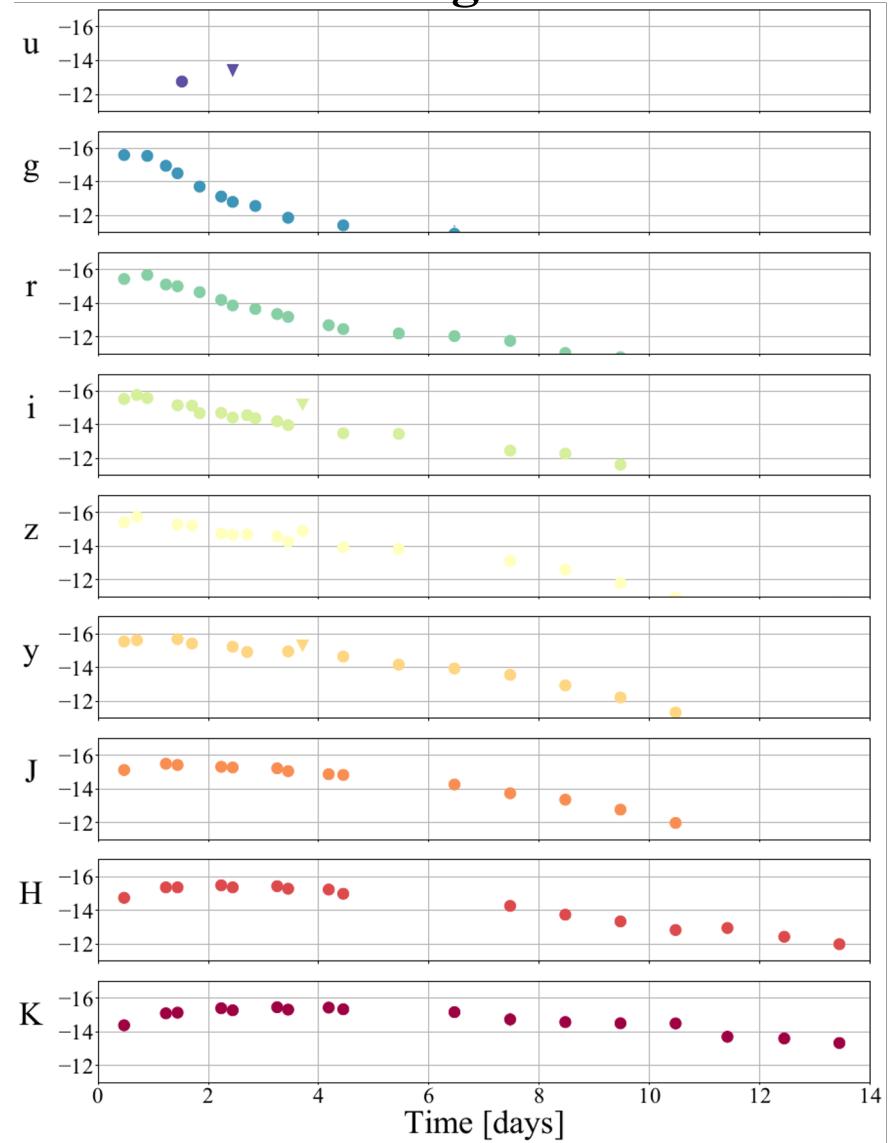


(D) GW170817:
reanalysis with
IMRPhenomPv2_NRTidalv2



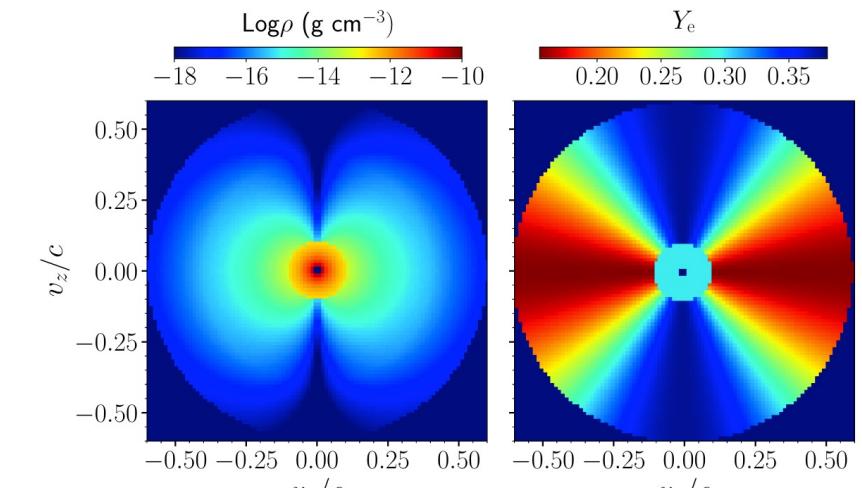
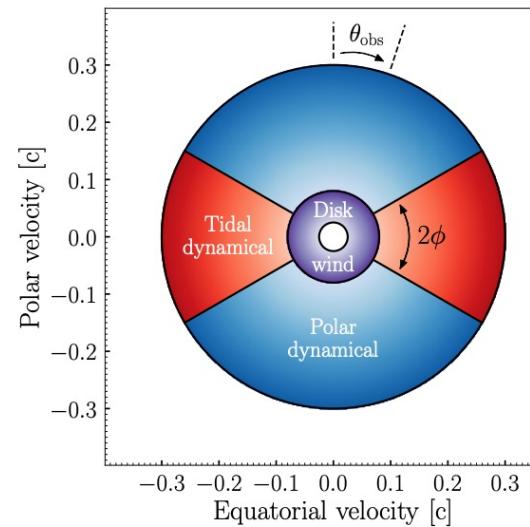
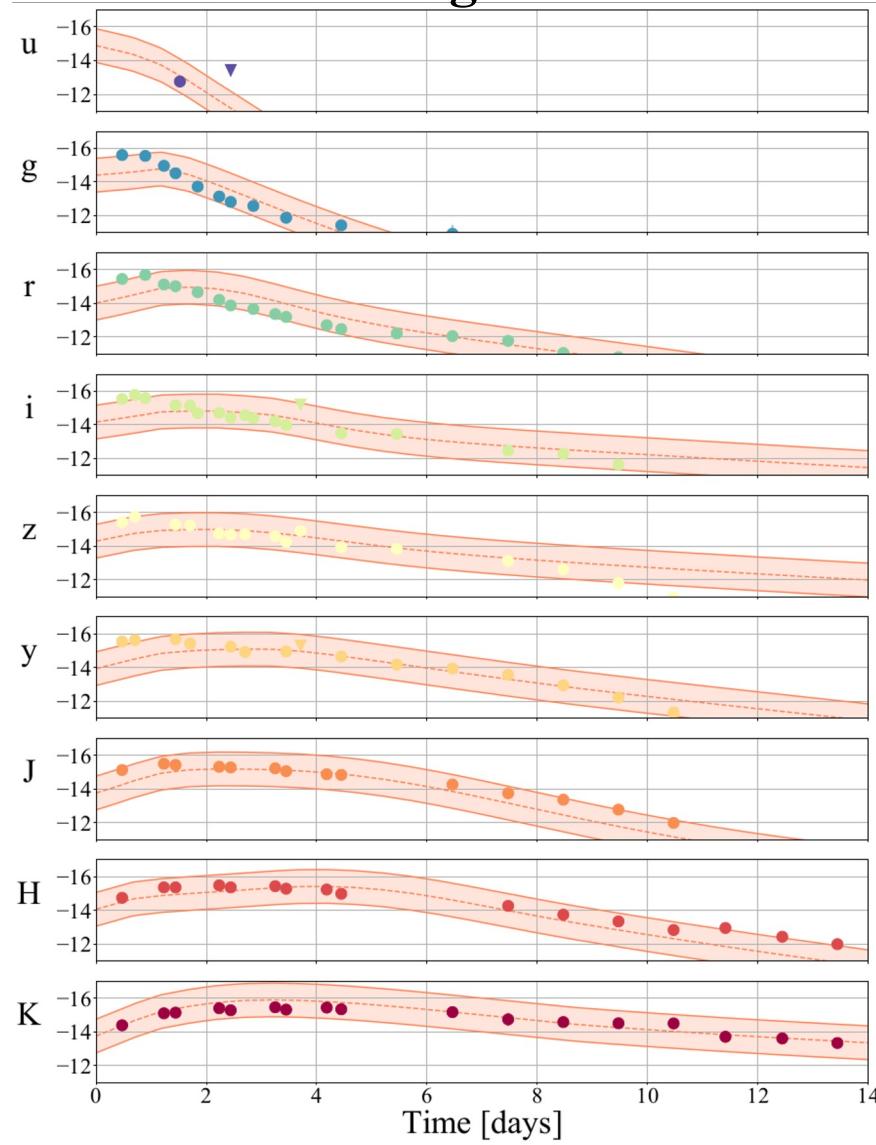
EM Signals – Kilonova

Photometric lightcurves



EM Signals – Kilonova

Photometric lightcurves



Bulla, MNRAS 520 (2023) 2, 2558-2570

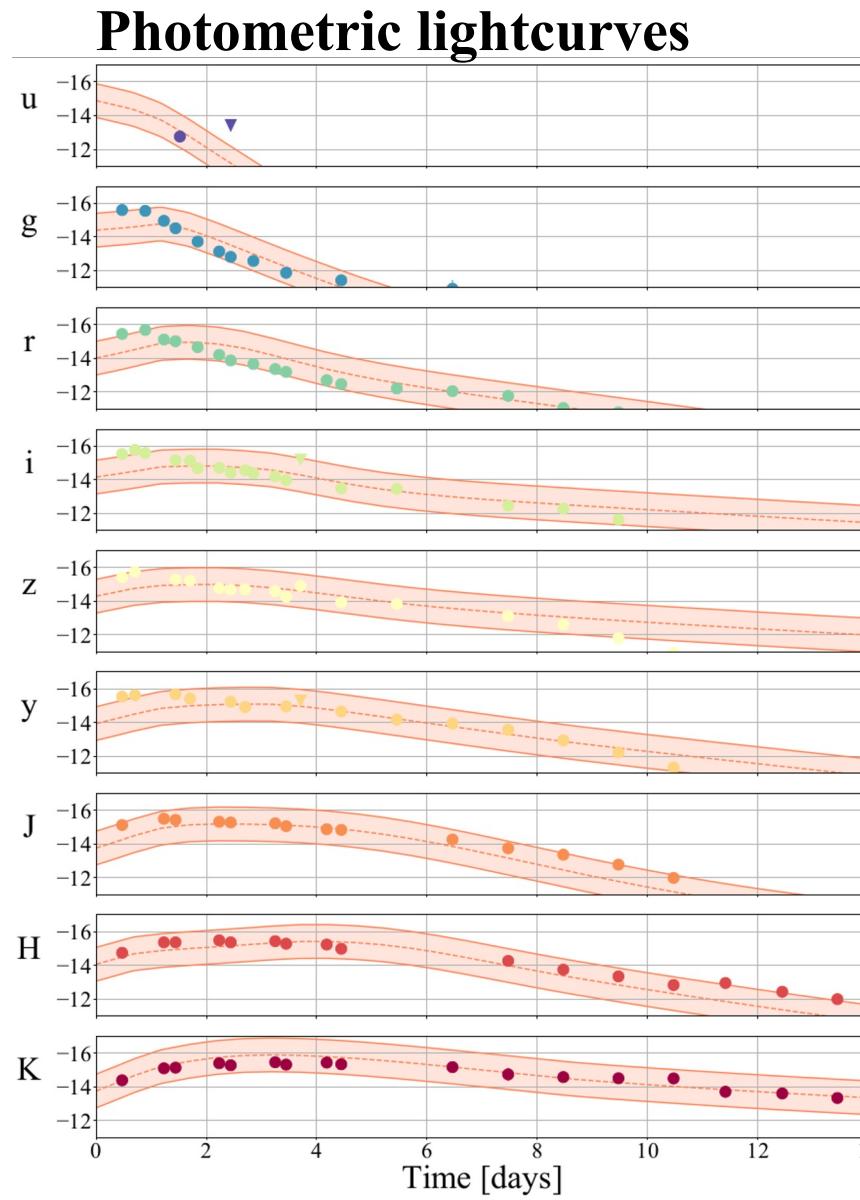
- 1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code

See talk by M. Bulla

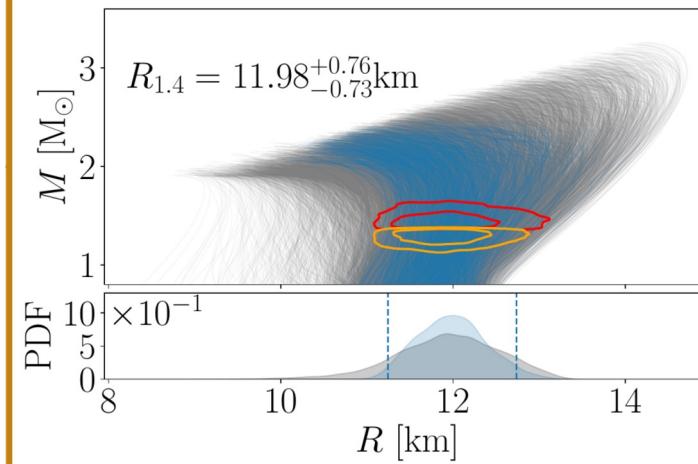
- 2.) interpolate within this grid through Gaussian process regression or a neural network

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

EM Signals – Kilonova

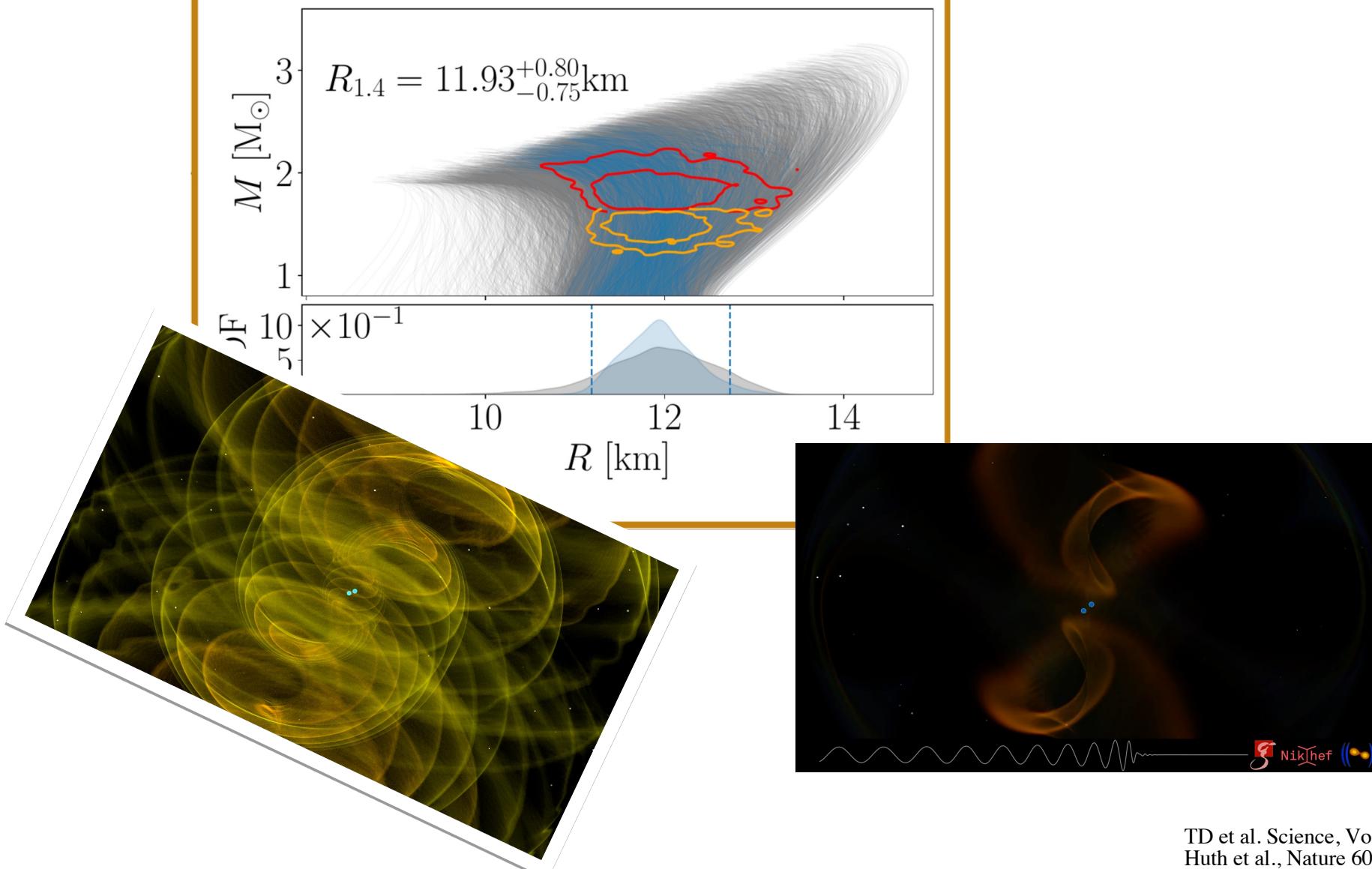


(E) AT2017gfo:
analysis of the observed lightcurves



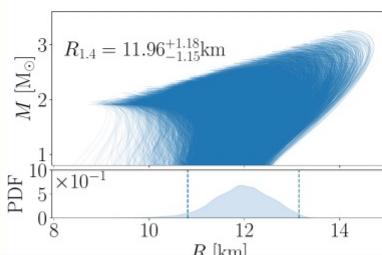
- 2.) interpolate within this grid through Gaussian process regression or a neural network
- 3.) link ejecta properties through numerical-relativity predictions to the binary properties

(F) GW190425:
reanalysis with
IMRPhenomPv2_NRTidalv2

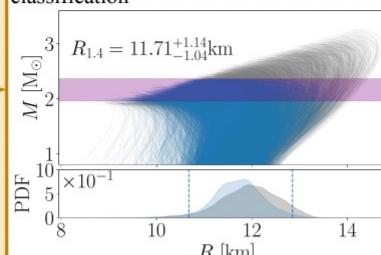


Prior construction

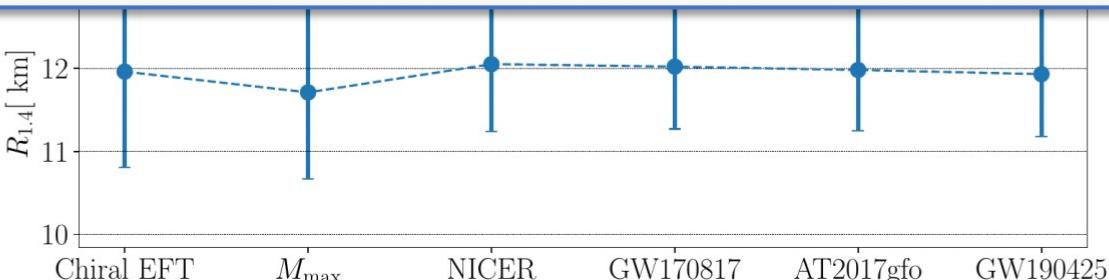
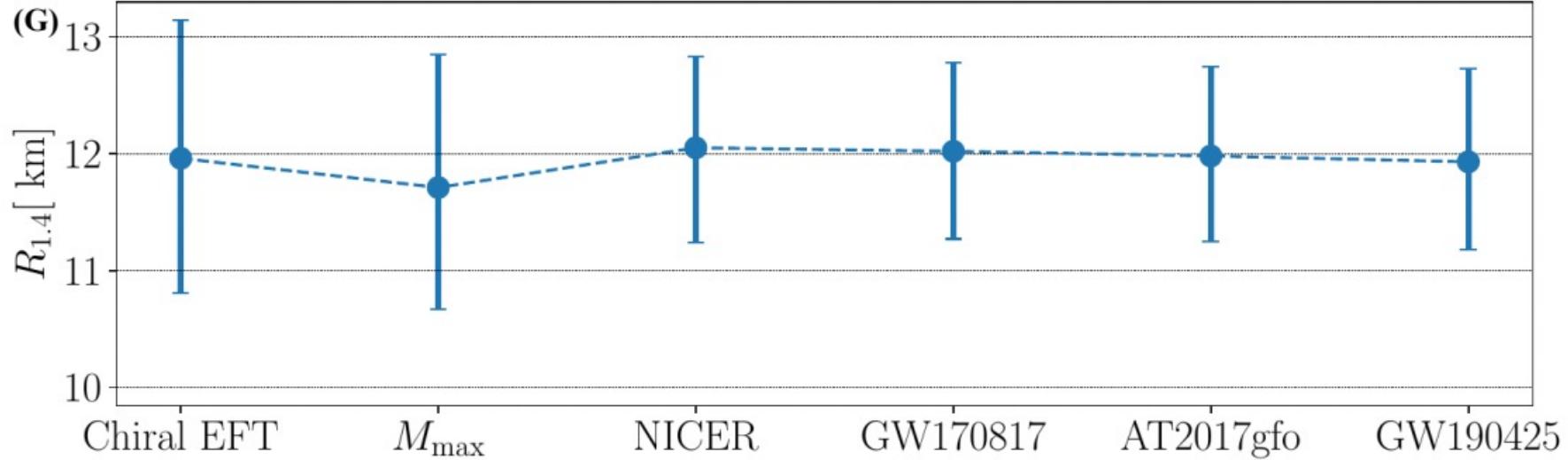
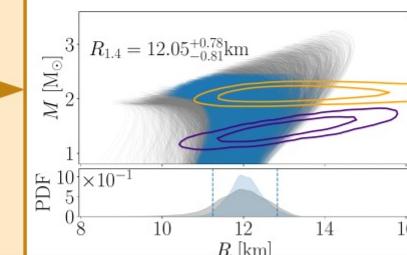
(A) Chiral effective field theory:
EOS derived with the chiral EFT result
and $M_{\max} \geq 1.9M_{\odot}$



(B) Maximum Mass Constraints:
PSR J0348+4032/PSR J1614-2230 and
GW170817/AT2017gfo remnant
classification

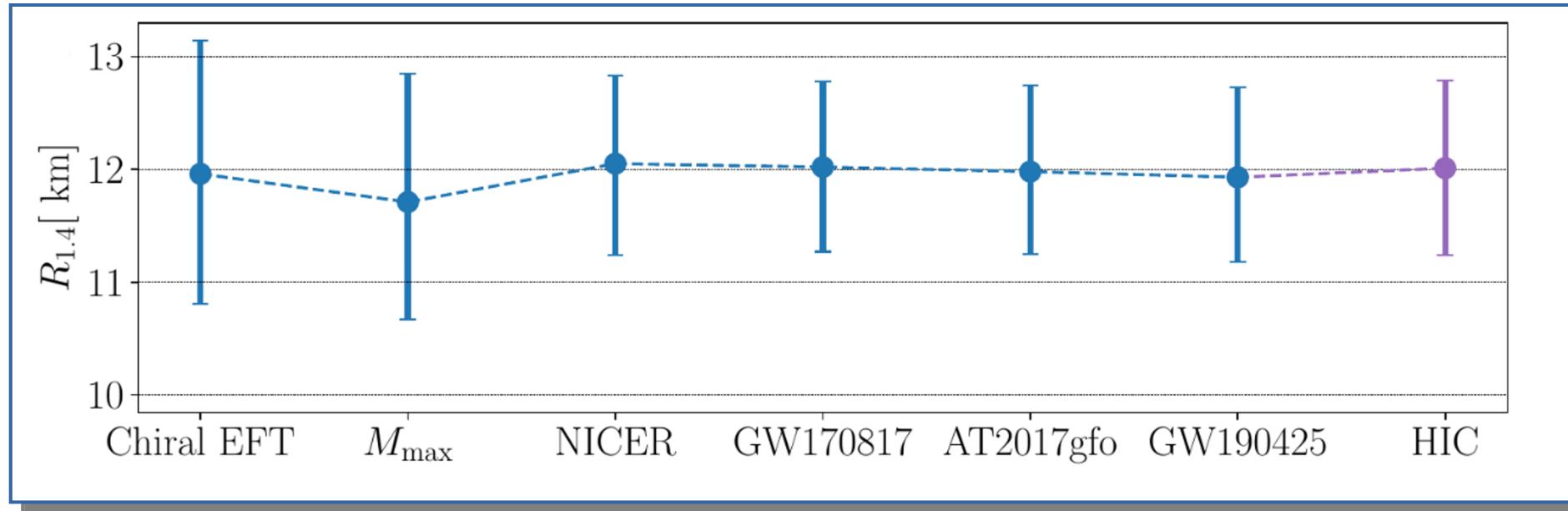


(C) NICER:
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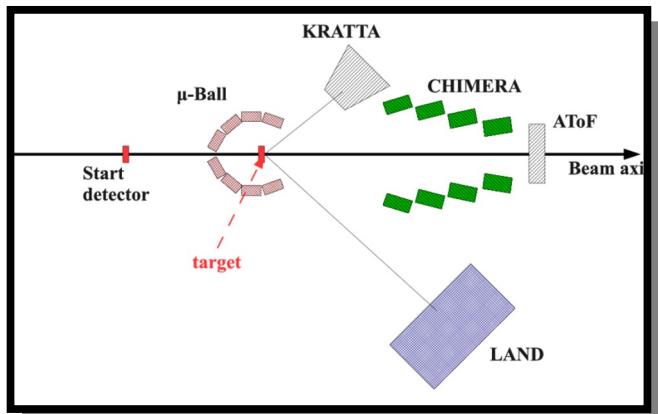


Constraints through multi-messenger astronomy and nuclear physics experiments

Huth, Pang, et al., Nature 606 (2022) 276-280



Huth et al., Nature 606 (2022) 276-280



Russotto et al., J.Phys.Conf.Ser. 420 (2013)

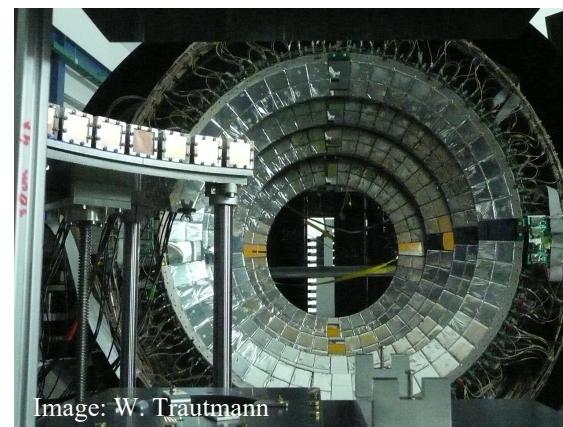


Image: W. Trautmann

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

NMMA: Main Contributions by

University of Potsdam and Max Planck Institute for Gravitational Physics

- computational astrophysics
- gravitational-wave modelling
- multi-messenger data analysis

University of Minnesota

- optical and near-infrared observations
- multi-messenger analysis

Observatory of la Côte d'Azur

- optical and near-infrared observations
- multi-messenger analysis

Utrecht University

- gravitational-wave data analysis
- multi-messenger data analysis

University of Ferrara

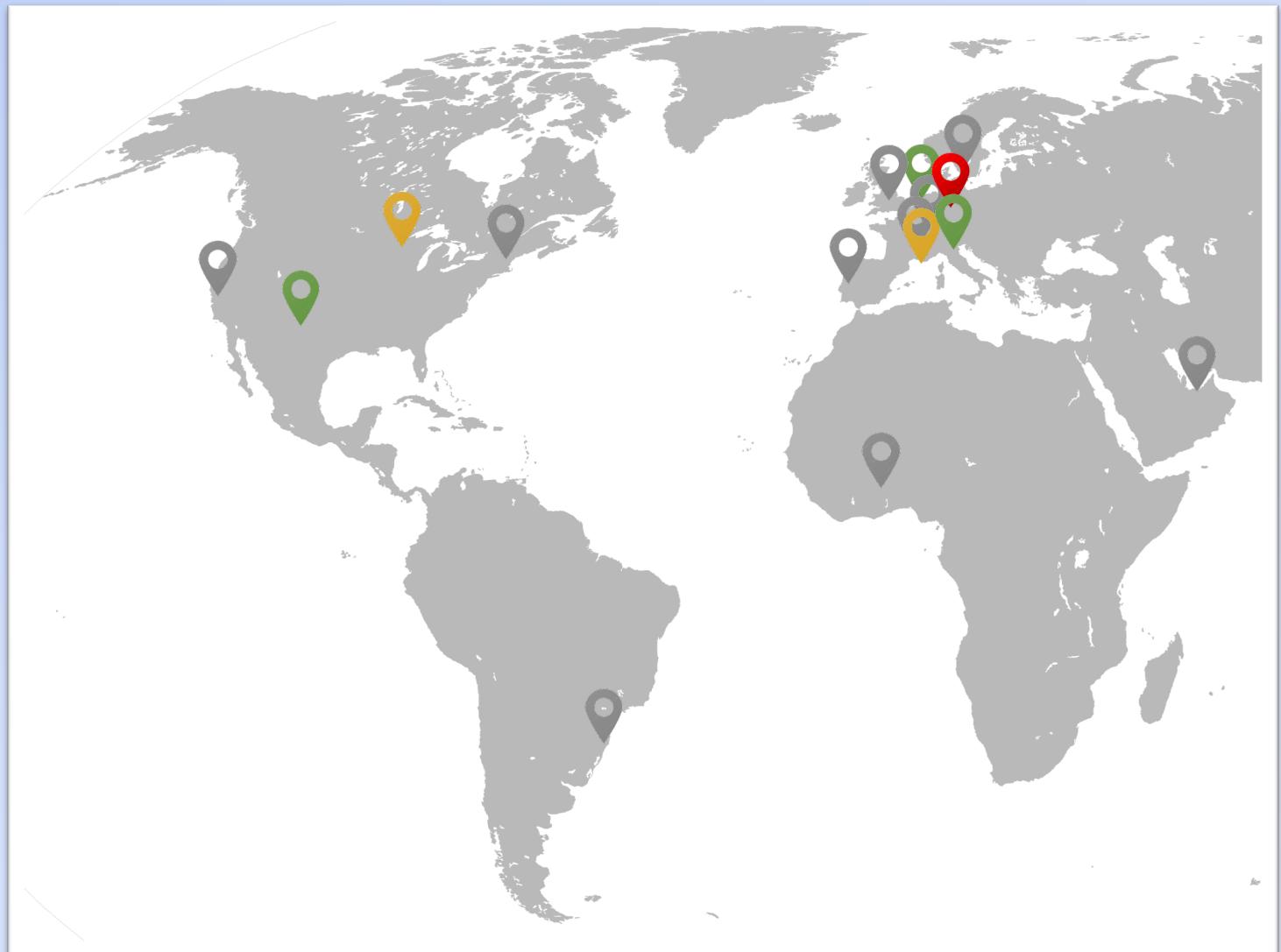
- modelling of electromagnetic signals

Los Alamos National Lab

- nuclear physics

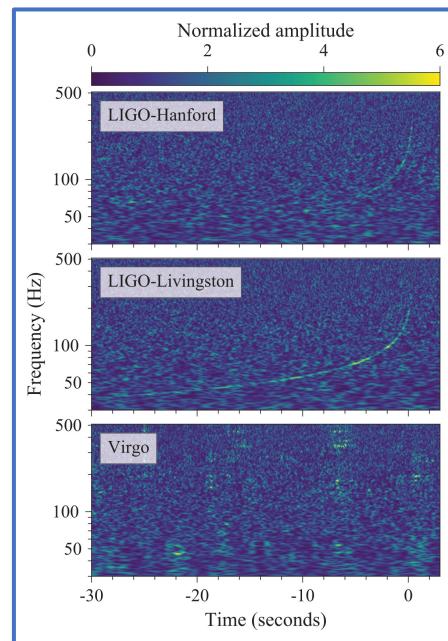
Observations

Theory

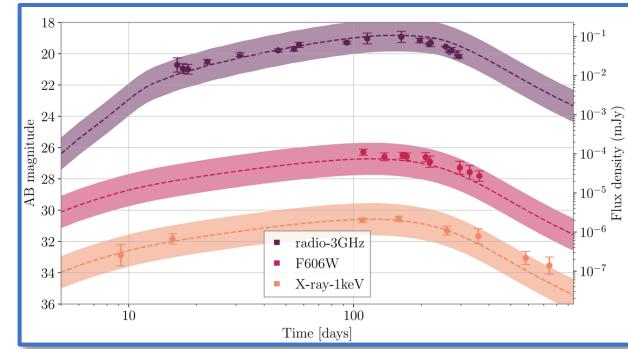


NMMA: Steps towards a nuclear-physics and multi-messenger astrophysics framework

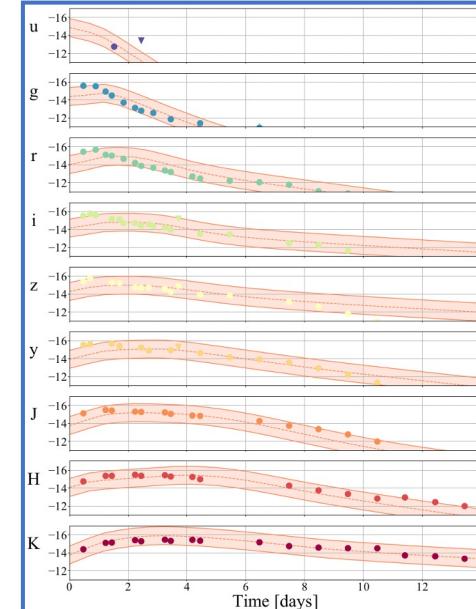
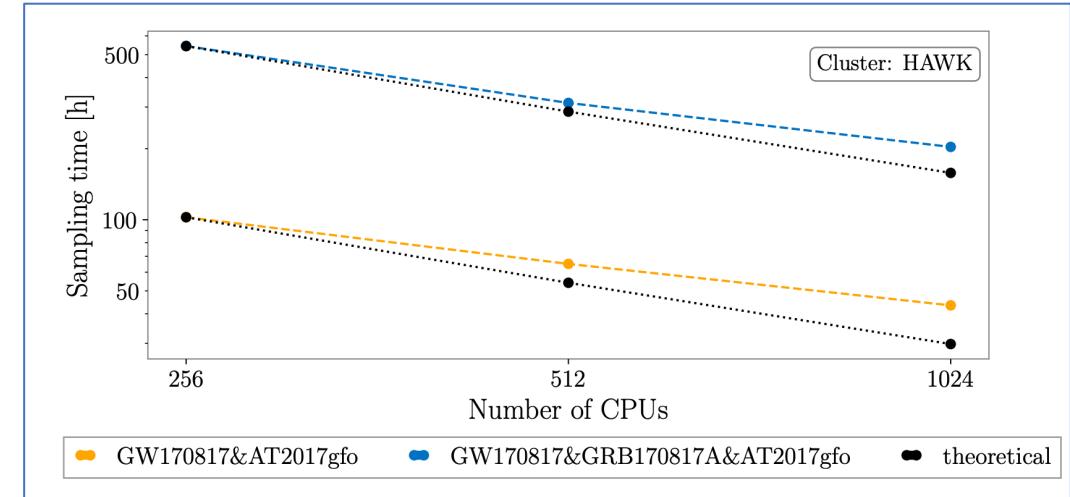
- simultaneous analysis of GW, kilonova, and GRB afterglow
- HPC facilities needed



+



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- simultaneous analysis of GW, kilonova, and GRB afterglow
- HPC facilities needed!

The screenshot shows the GitHub repository page for `nuclear-multimessenger-astronomy / nmma`. The repository has 5 issues, 1 pull request, and 97 commits. The commit history is listed below, showing contributions from `mcoughlin` and others. The repository is public and contains code, projects, wiki, security, and insights.

Commit History:

- mcoughlin Merge branch 'main' of github.com:nuclear-multimessenger-astronomy/nmma 2 months ago
- cache is the wrong name! 4 days ago
- installation file modified 8 days ago
- Add ability to read .dat files 3 days ago
- Merge branch 'main' of github.com:nuclear-multimessenger-astronomy/nmma... 8 days ago
- adding too lims 2 months ago
- Update training documentation 2 months ago
- Update training documentation 3 months ago
- Start basic github work 3 months ago
- Start basic github work 3 months ago
- Fix pre-commit 3 months ago
- First commit 3 months ago
- Update README 2 months ago
- try installing from master 2 months ago
- try installing from master 2 months ago

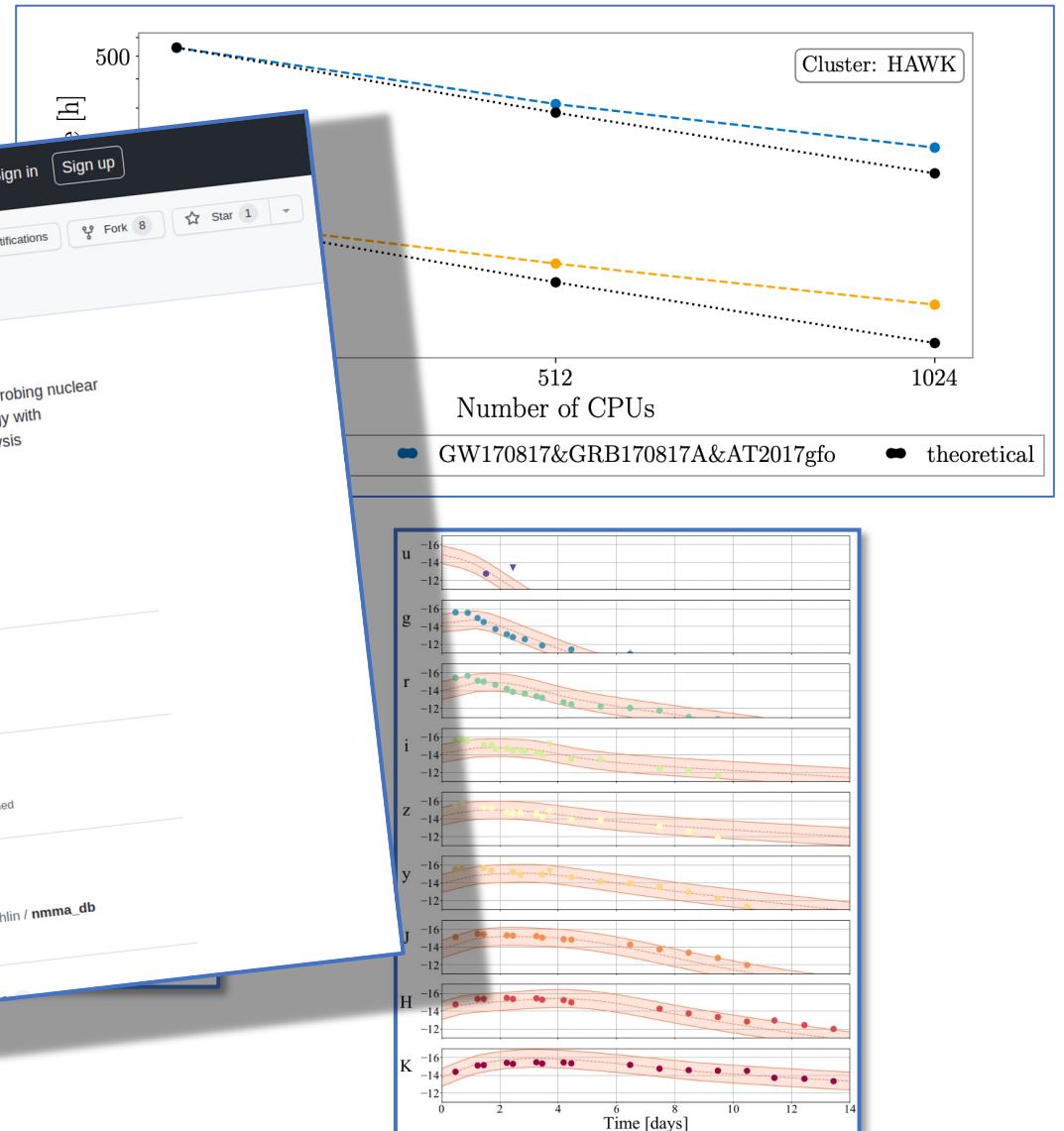
About:
A pythonic library for probing nuclear physics and cosmology with multimessenger analysis

Readme:
MIT License
1 star
1 watching
8 forks

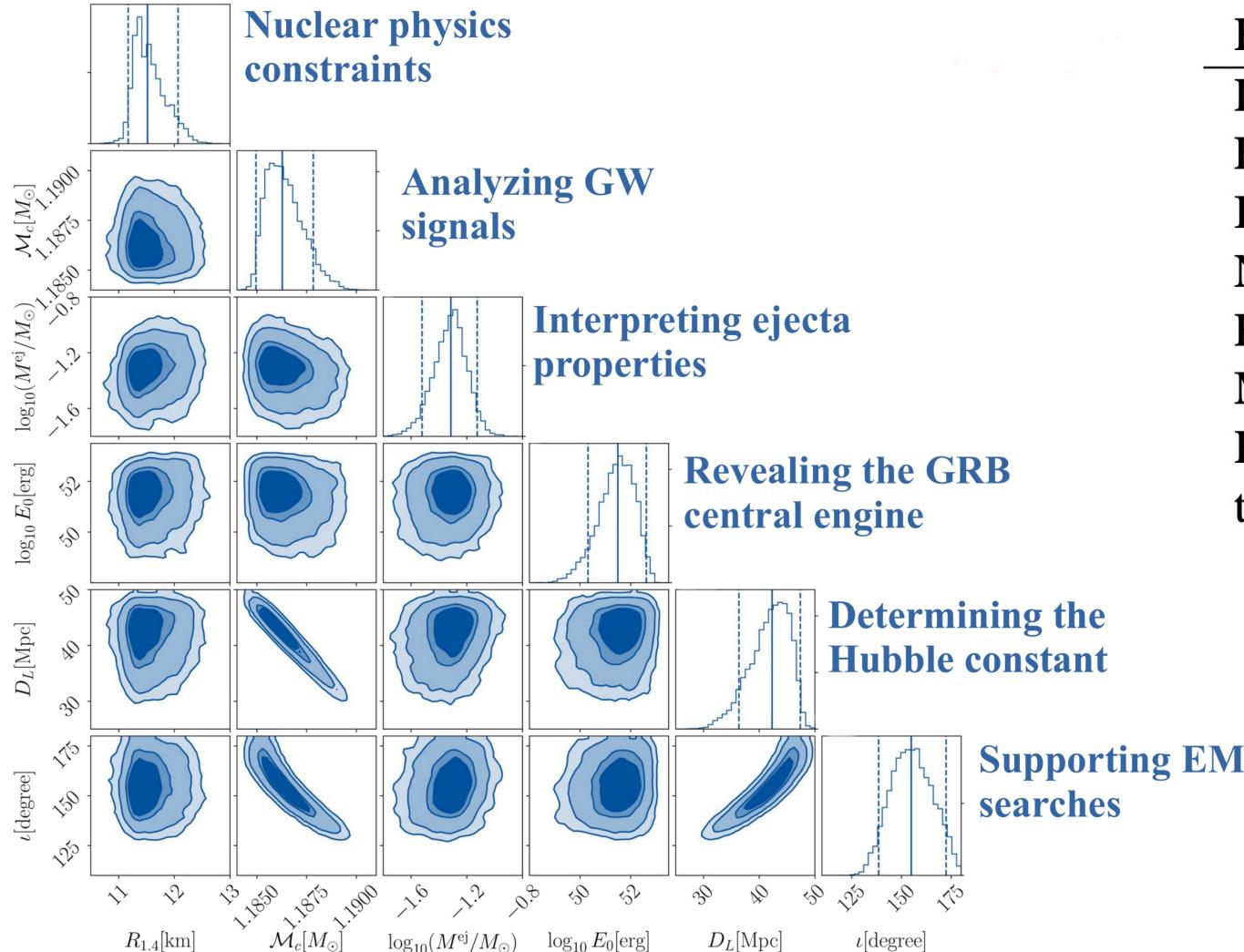
Releases:
No releases published

Packages:
No packages published

Used by:
`@mcoughlin / nmma_db`



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



Reference	$R_{1.4 M_\odot}$ [km]
Dietrich et al. ¹⁵	$11.75^{+0.86}_{-0.81}$ (90%)
Essick et al. ⁵¹	$12.54^{+0.71}_{-0.63}$ (90%)
Breschi et al. ²³	$11.99^{+0.82}_{-0.85}$ (90%)
Nicholl et al. ²⁴	$11.06^{+1.01}_{-0.98}$ (90%)
Raaijmakers et al. ²⁵	$12.18^{+0.56}_{-0.79}$ (95%)
Miller et al. ⁵²	$12.45^{+0.65}_{-0.65}$ (68%)
Huth et al. ¹⁶	$12.01^{+0.78}_{-0.77}$ (90%)
this work [NMMA] ⁵³	$11.98^{+0.35}_{-0.40}$ (90%)

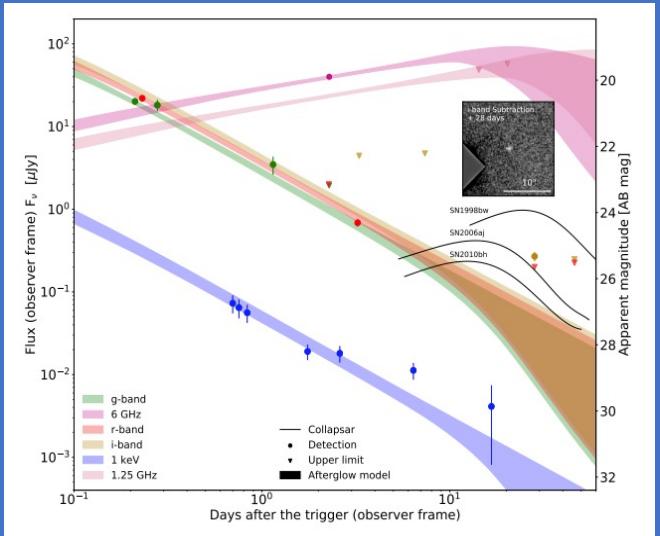
Pang et al., arXiv: 2005.08513

NMMA Details:

- **EOS information**
 - precomputed EOS sets
 - Sampling in tidal deformability/compactness
- **additional astrophysical information**
 - e.g. NICER/pulsar measurements through full posteriors
- **GW models employing LALSimulation/sampling through bilby**
- **kilonova models**
 - simple analytic models
 - radiative transfer simulations (POSSIS, Kasen et al.)
- **GRB afterglow:**
 - afterglowpy
 - soon also Pyblastafterglow (Nedora et al.)

NMMA Applications: Model Selection

GRB 200826A



*shortest long GRB
(no BNS merger, but collapsar)*

NMMA Applications: Model Selection

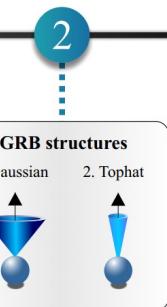
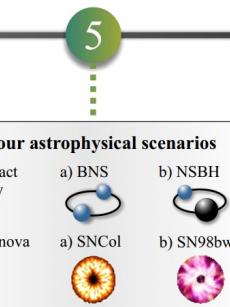
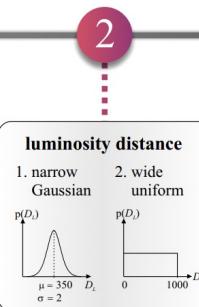
Prior settings

Models

GRB jets

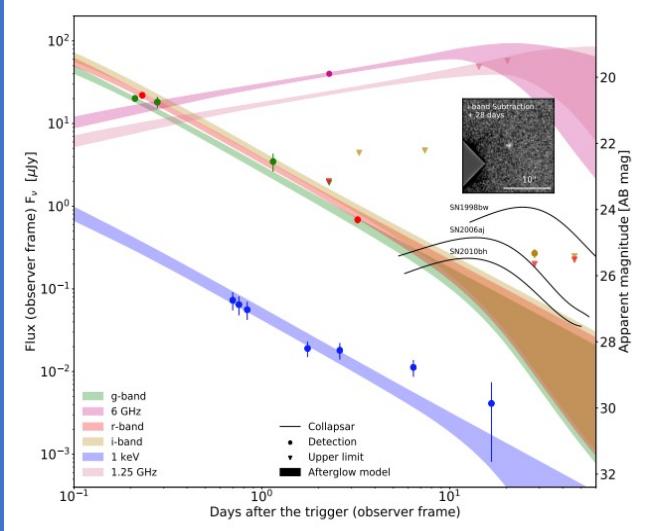
1
Data set

2



20
Simulations

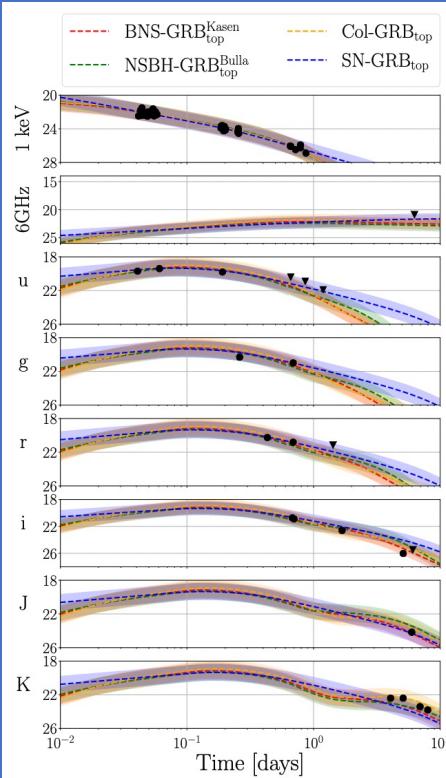
GRB 200826A



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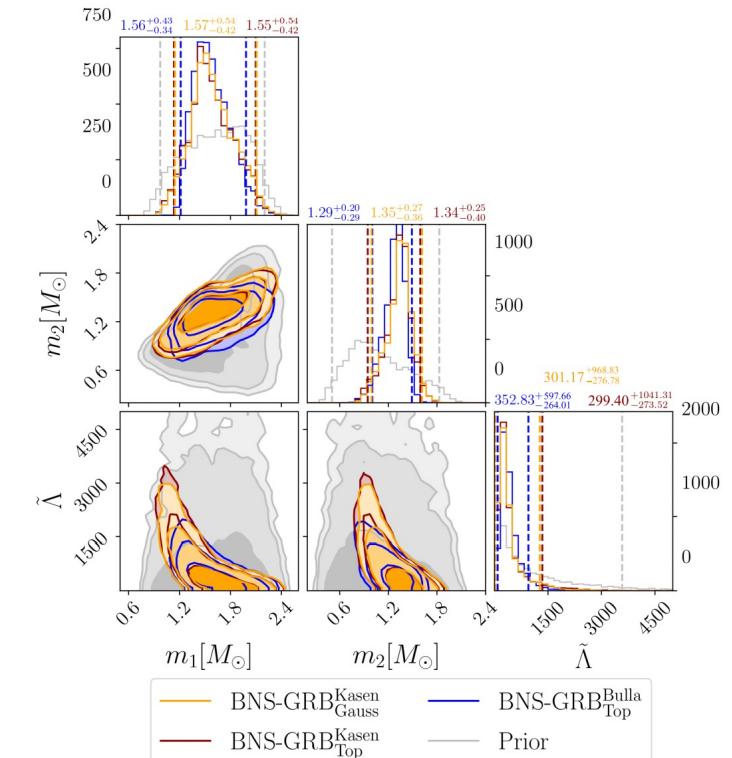
T. Ahumada, et al., Nature Astron. 5 (2021) 9, 917-927

GRB 211211A



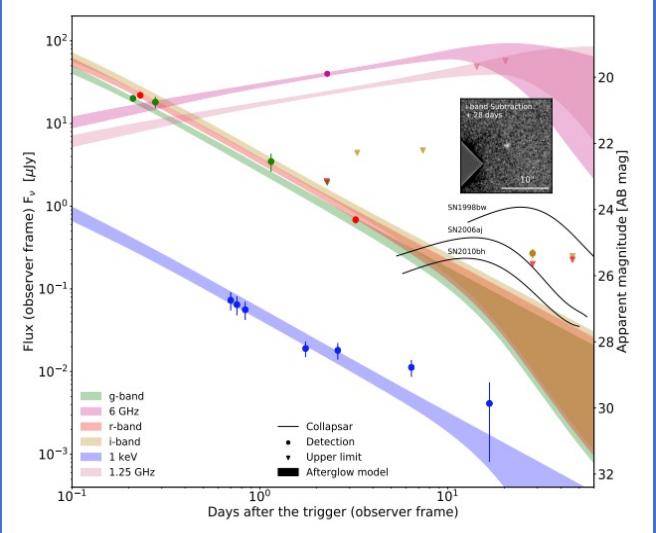
potential kilonova due to BNS merger

N.Kunert et al., arXiv: 2301.02049



NMMA Applications: Model Selection

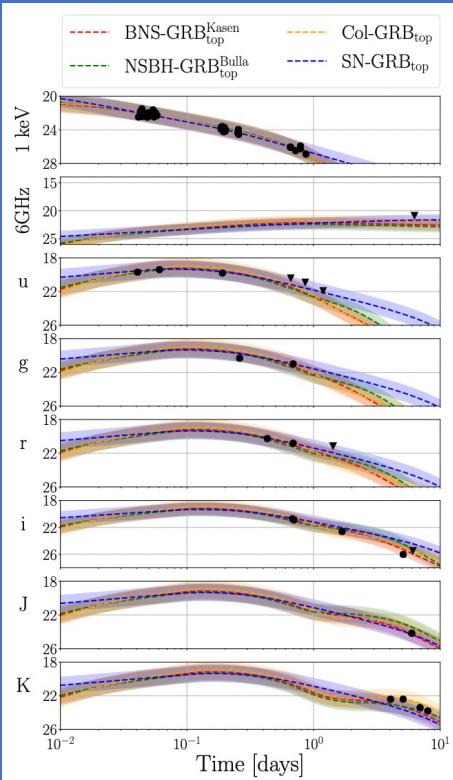
GRB 200826A



shortest long GRB
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T. Ahumada, et al., Nature Astron. 5 (2021) 9, 917-927

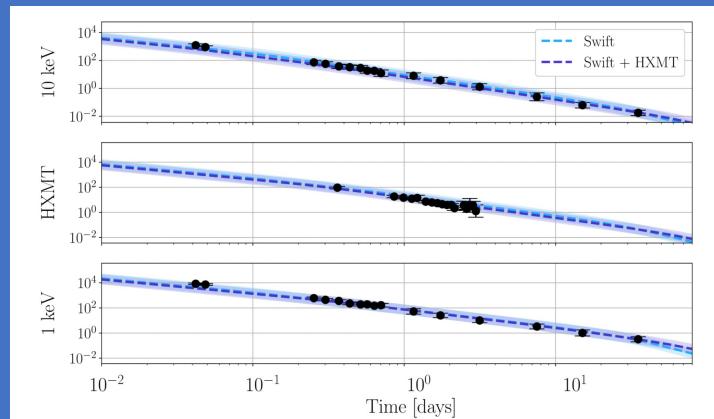
GRB 211211A



potential kilonova due to BNS merger

N.Kunert et al., arXiv: 2301.02049

GRB 221009A



brightest observed GRB to date

GRANDMA analysis;
cf. talk by P.A. Duverne

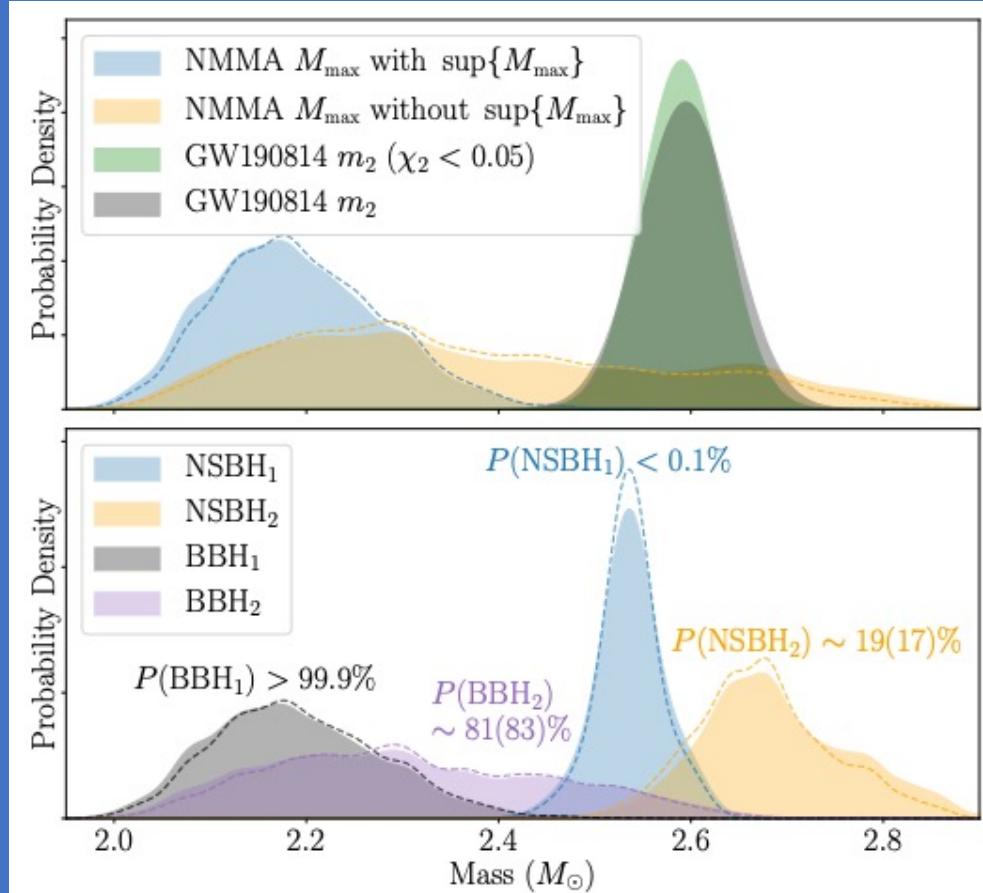
Kann et al., arXiv: 2302.06225

NMMA Applications: Model Selection

GW190814

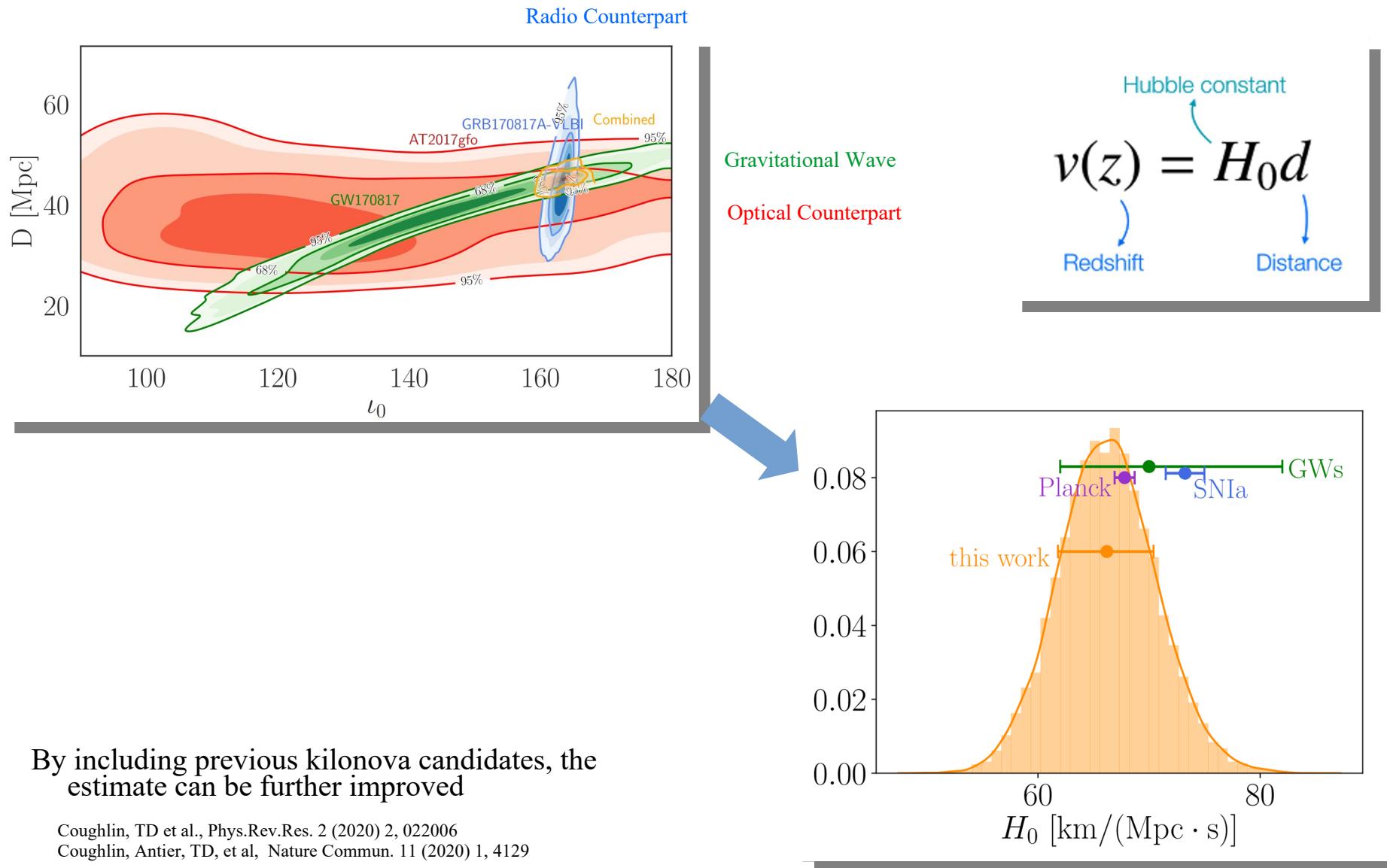
- under the assumption that GW170817 produced a BH, GW190814 was a BBH $P(\text{BBH}) > 0.999$
- relaxing this assumption, it was a BBH $P(\text{BBH}) \sim 0.83$

Maximum mass and posterior distribution



Another Science Target: The Hubble Constant

Hubble constant measurement



Outlook, e.g., the Hubble Constant:

Run	Telescope	BNS	NSBH
EM annual number of detections			
O4	ZTF	$0.43^{+0.58}_{-0.26}$	$0.13^{+0.24}_{-0.11}$
	Rubin	$1.97^{+2.68}_{-1.2}$	$0.03^{+0.06}_{-0.03}$
O5			
	ZTF	$0.43^{+0.44}_{-0.2}$	$0.09^{+0.12}_{-0.06}$
	Rubin	$5.39^{+6.59}_{-2.99}$	$0.43^{+0.59}_{-0.28}$

Kiendrebeogo et al., in prep.

