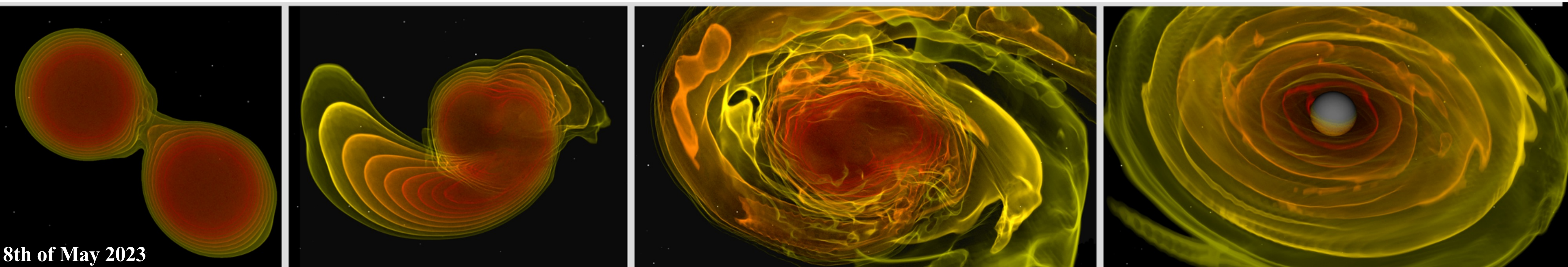
Joint nuclear-physics and multi-messenger astrophysics interpretation of compact binary mergers

Tim Dietrich

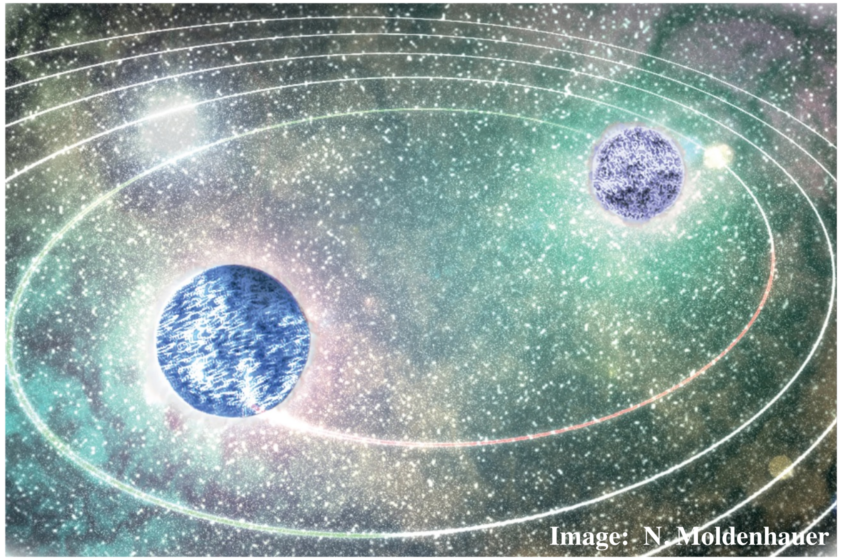
University of Potsdam

Max Planck Institute for Gravitational Physics



8th of May 2023

How to study neutron stars?



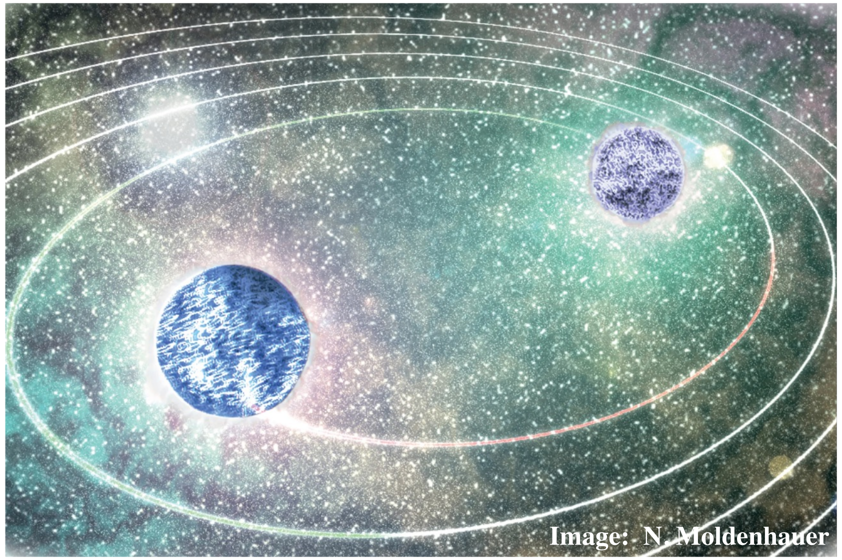
- **X-ray observations** of rotating neutron stars

- **radio measurements** of rotating neutron stars

- Binary mergers:
  - **gravitational waves**

  - **gamma-ray, X-ray, ultraviolet, optical, infrared, radio observations**

How to study neutron stars?



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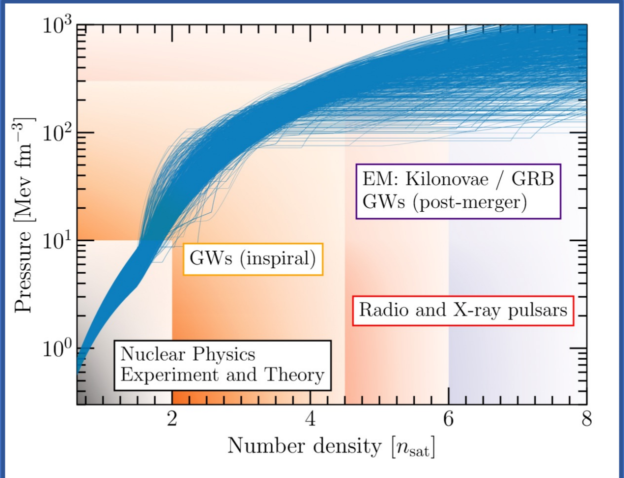
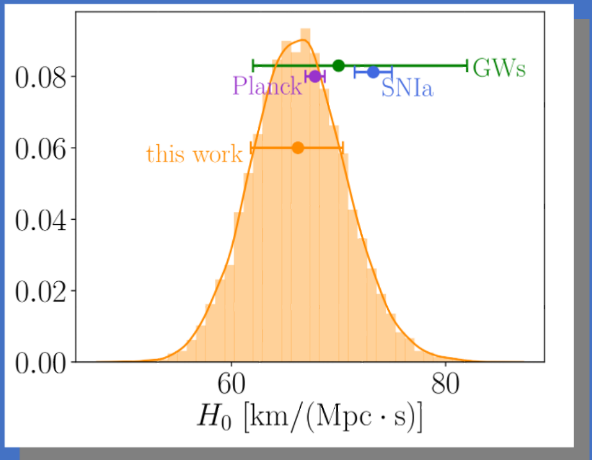
Science cases

Equation of State



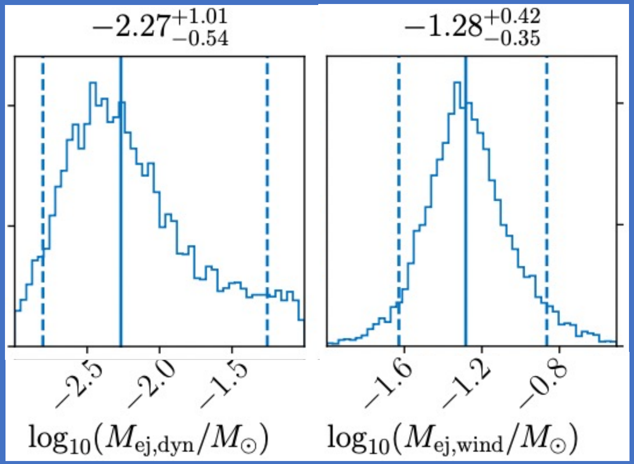
Pang et al., arXiv: 2205.08513

Hubble Constant



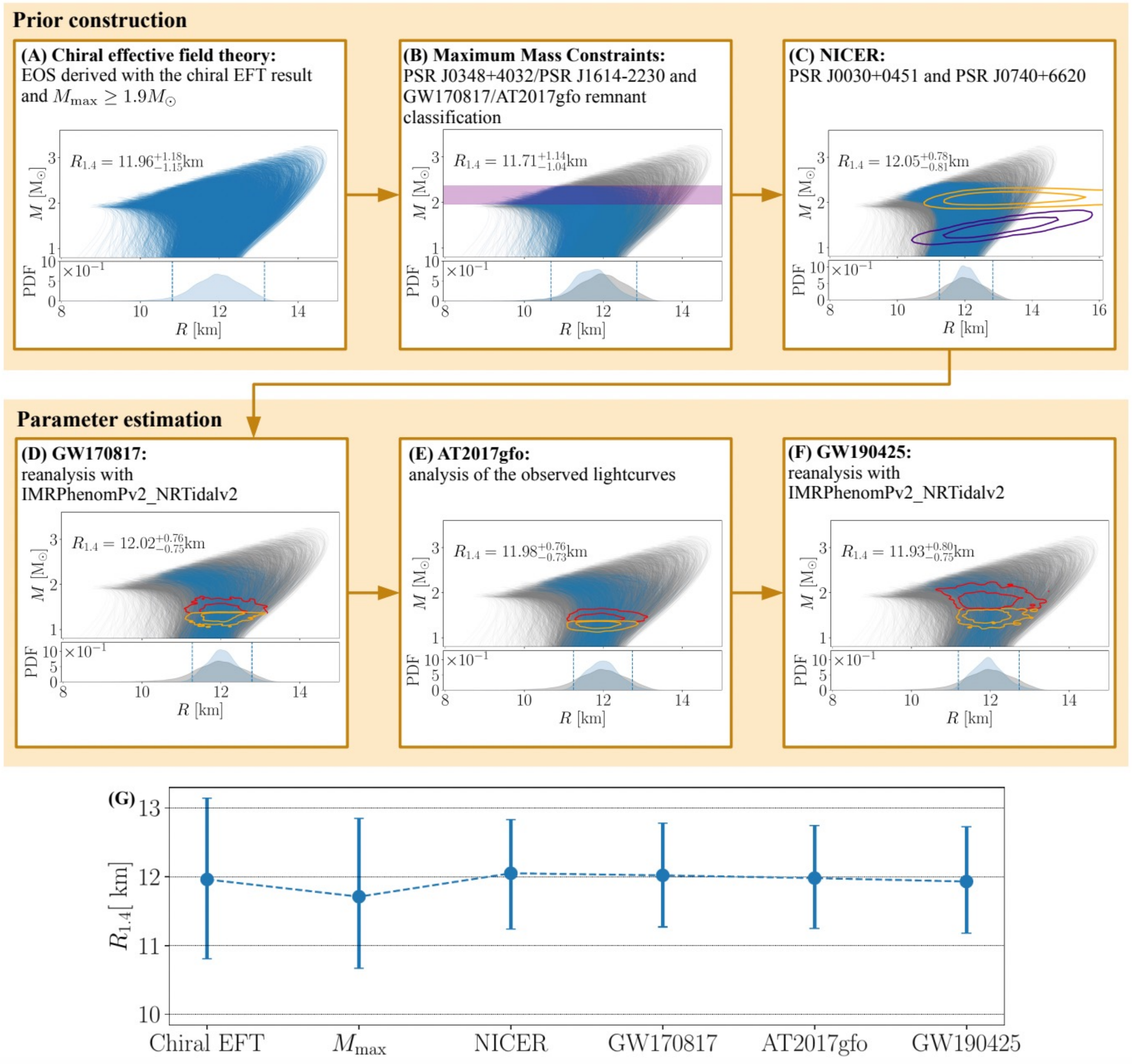
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Heavy element formation

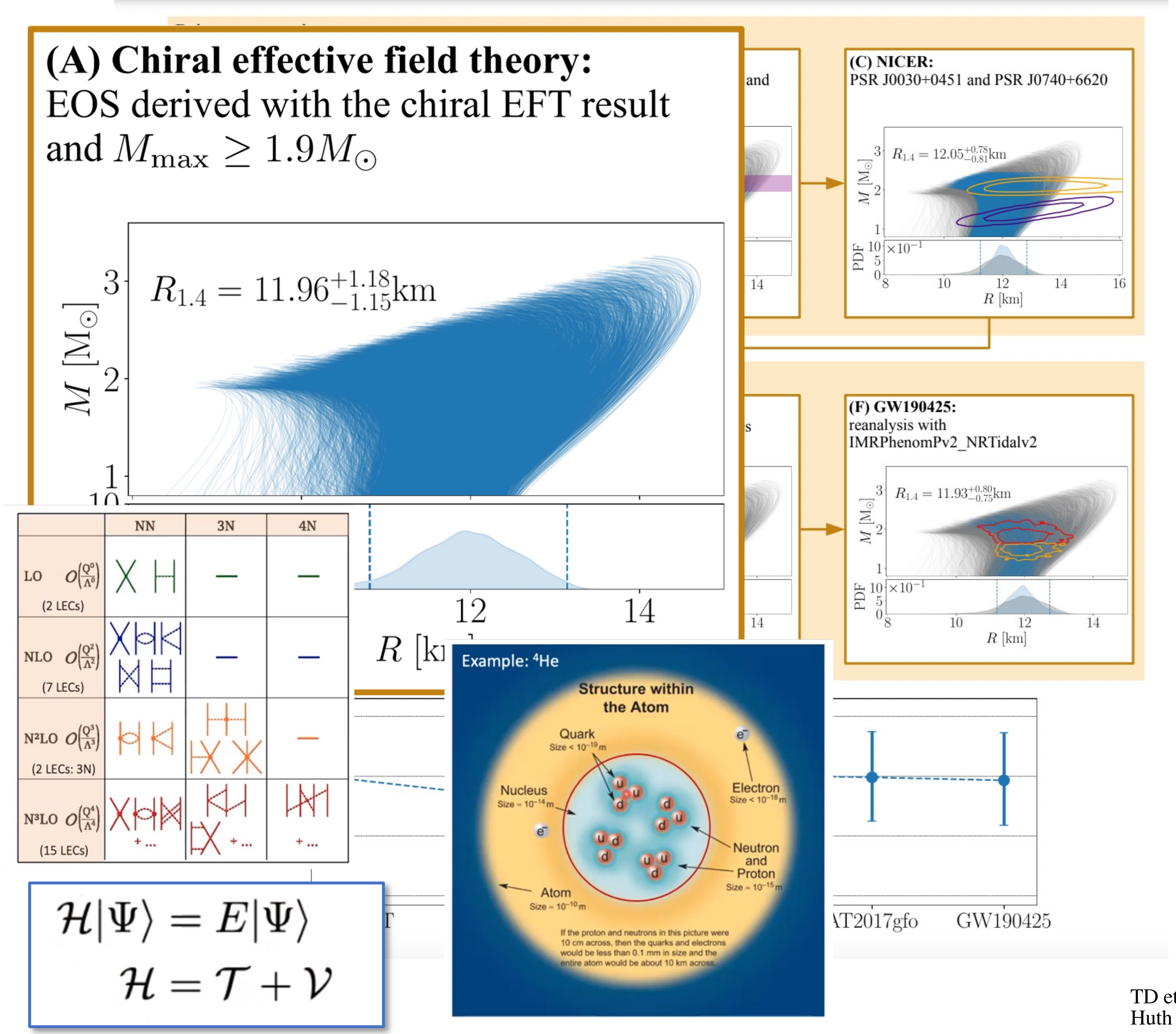


The principle idea:
Multi-Messenger Interpretation of the Equation of State

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



TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., Nature 606 (2022) 276-280



TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
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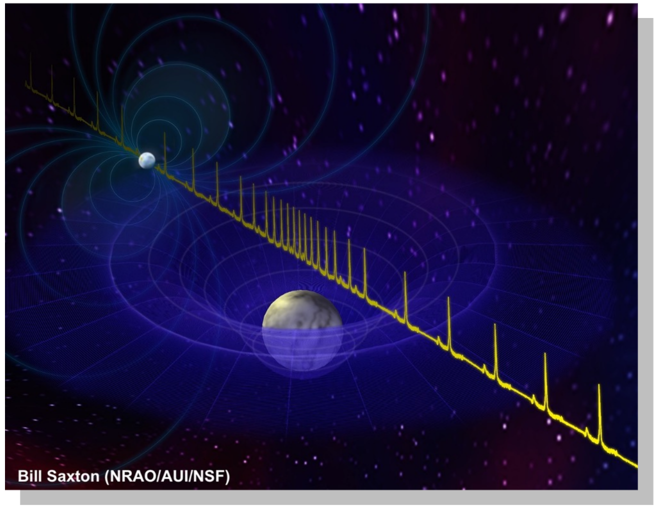
EM Signals – Maximum Neutron Star Mass

lower bound

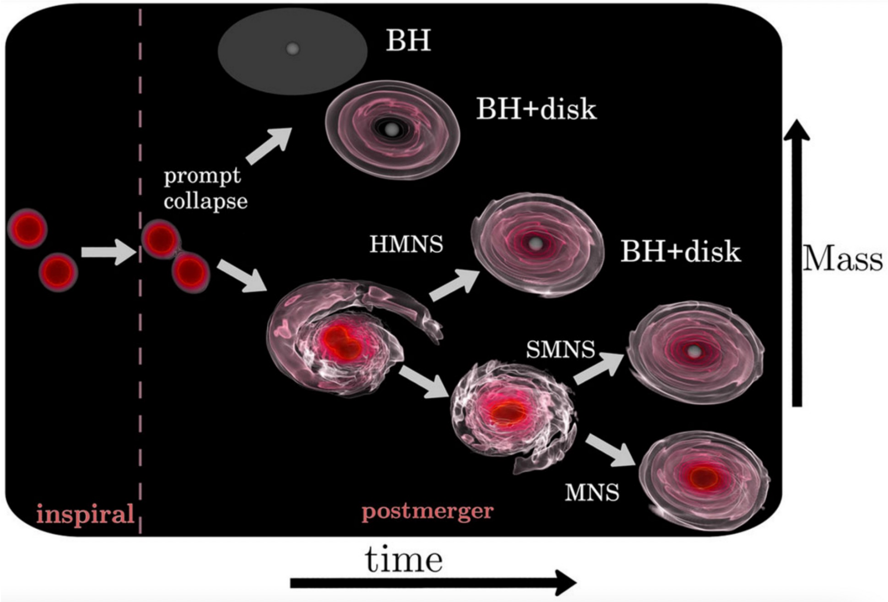
Measurement of massive pulsars through Shapiro time delay



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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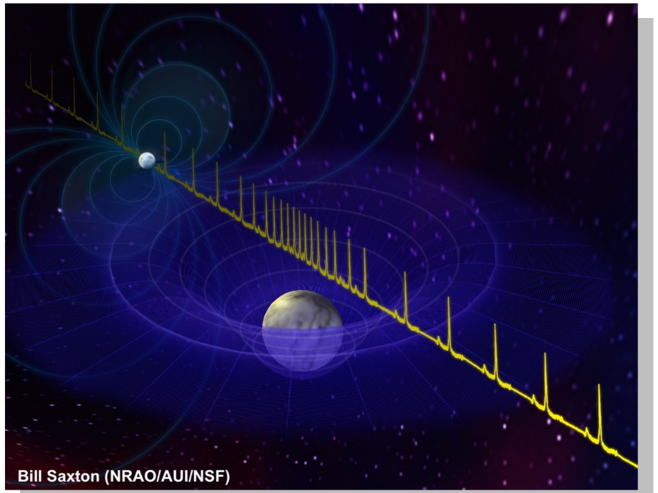

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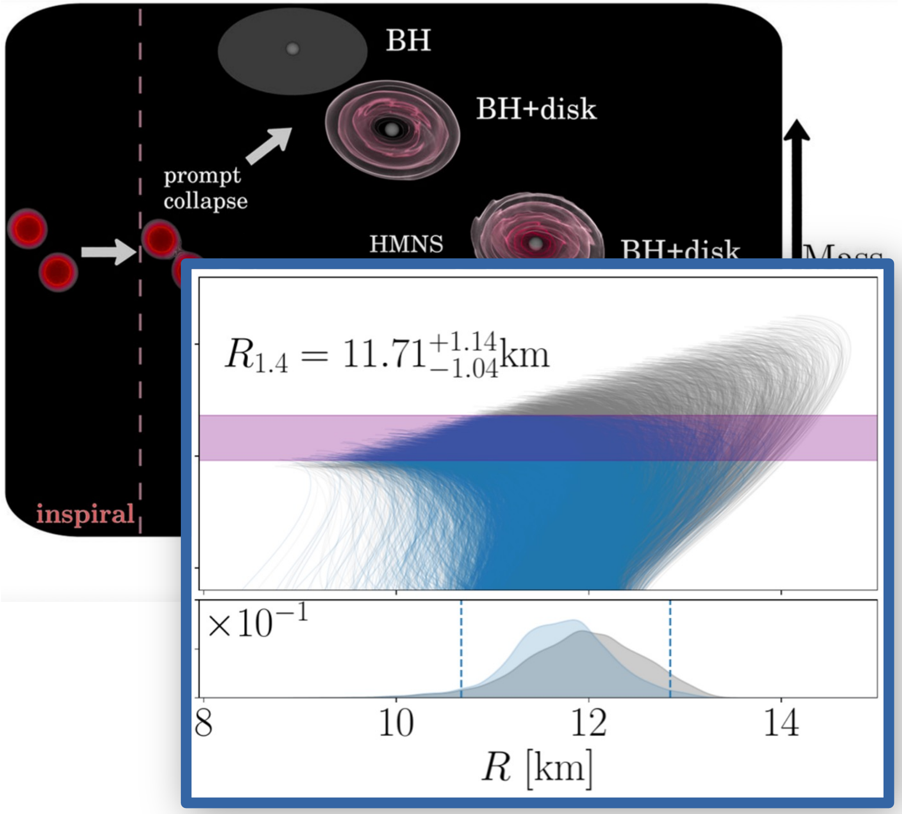
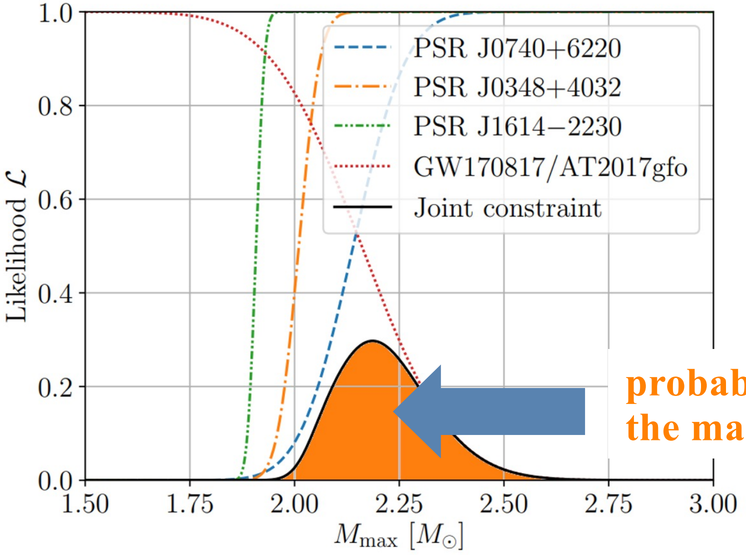
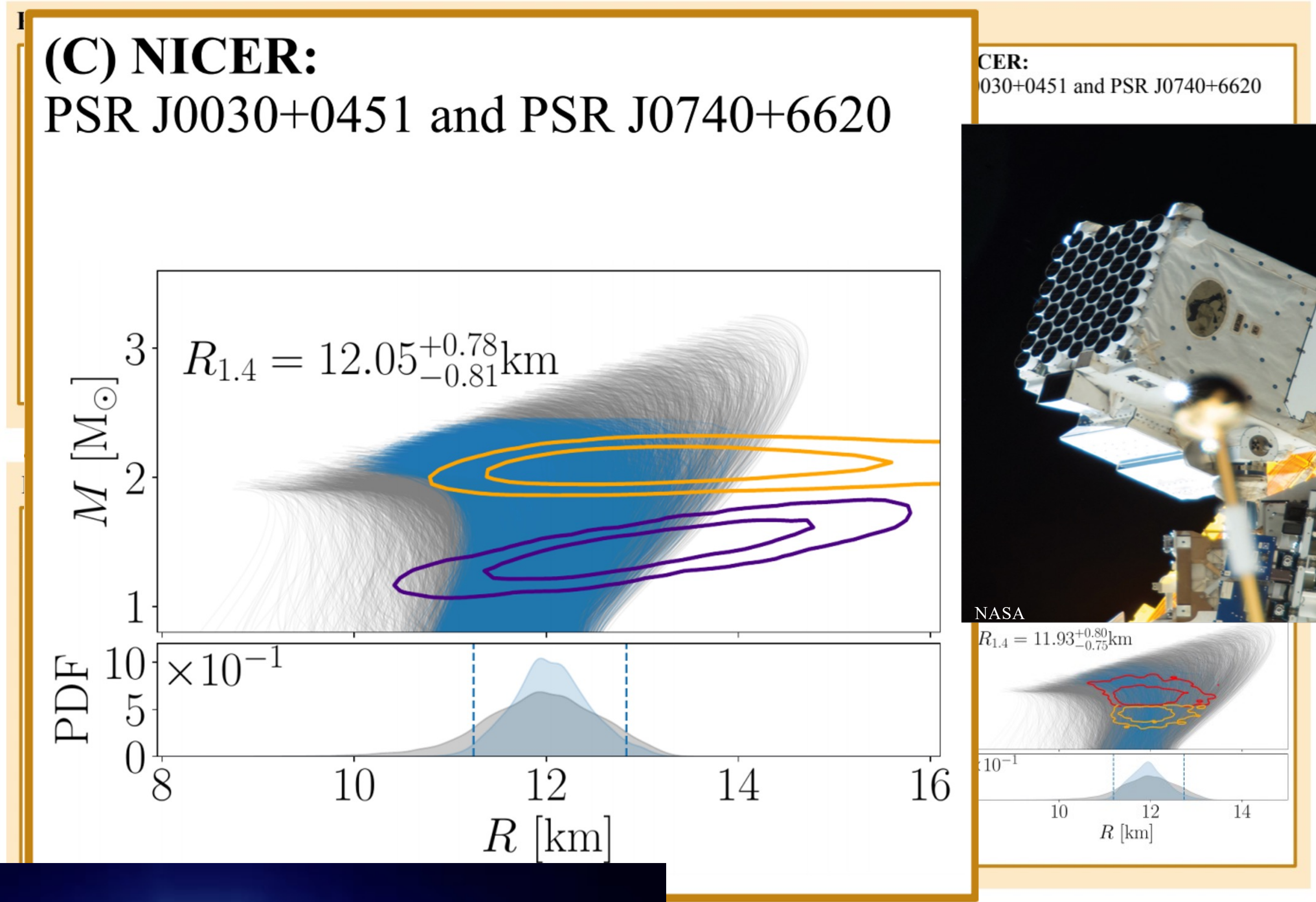
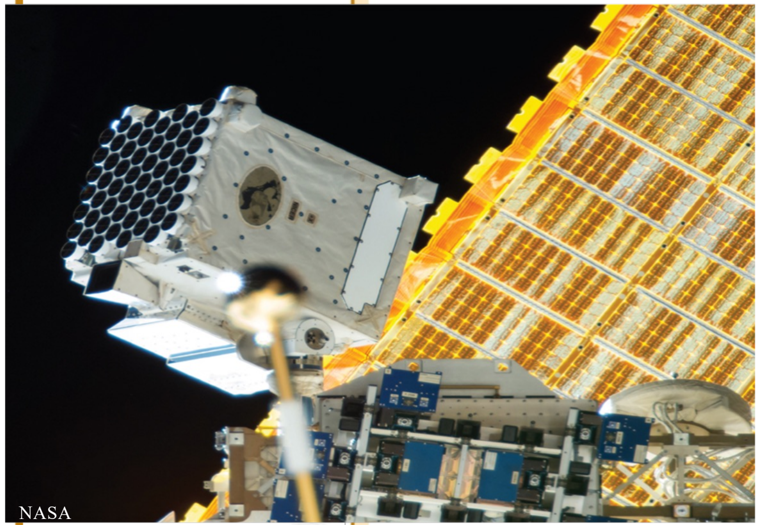


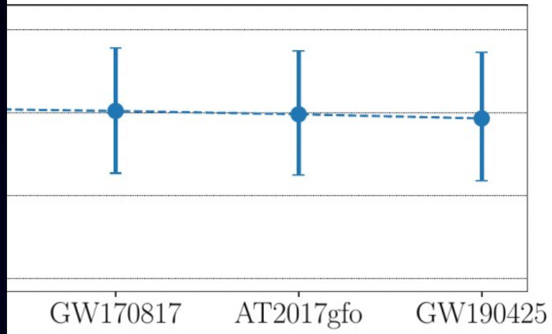


probability distribution for the maximum NS mass

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







NASA

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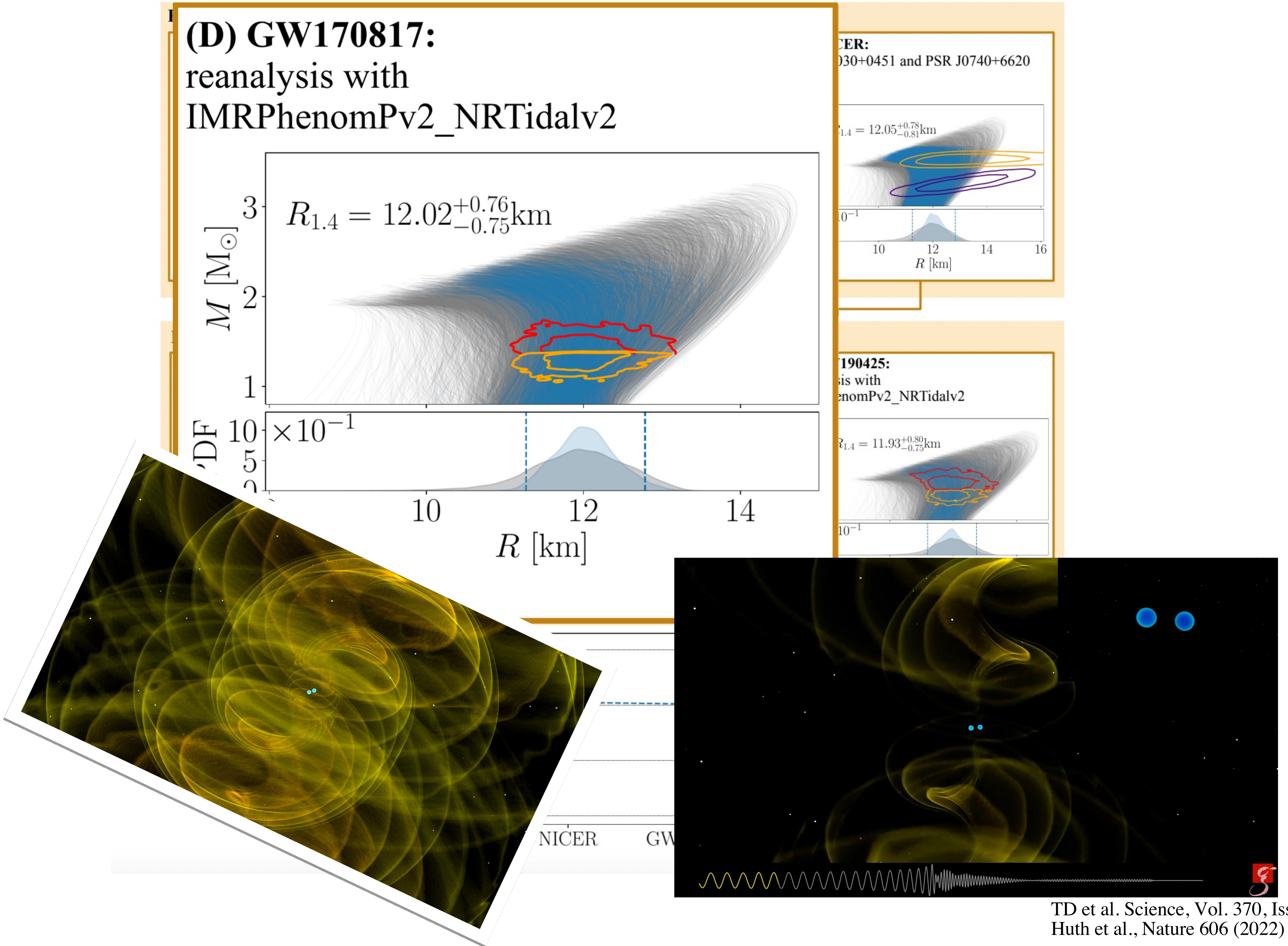
Huth et al., Nature 606 (2022) 276-280



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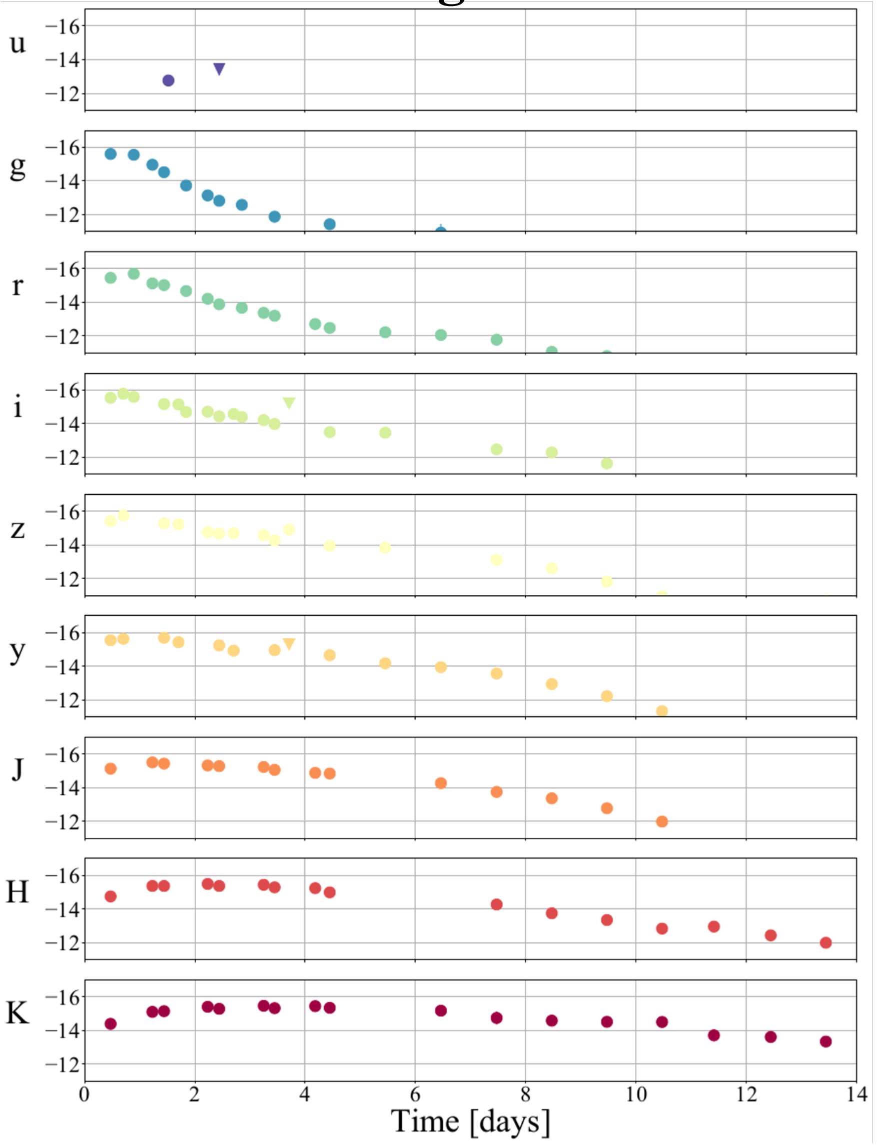
EM Signals – Kilonova

Photometric lightcurves



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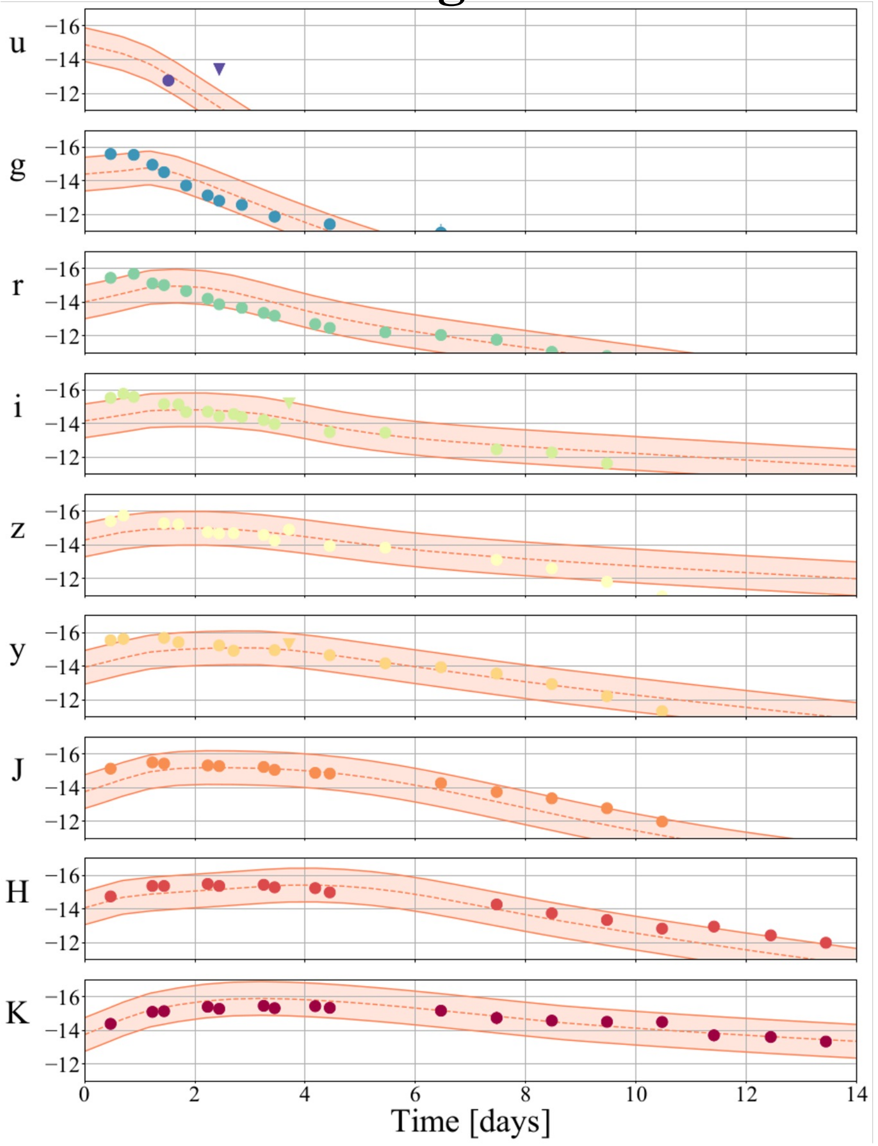
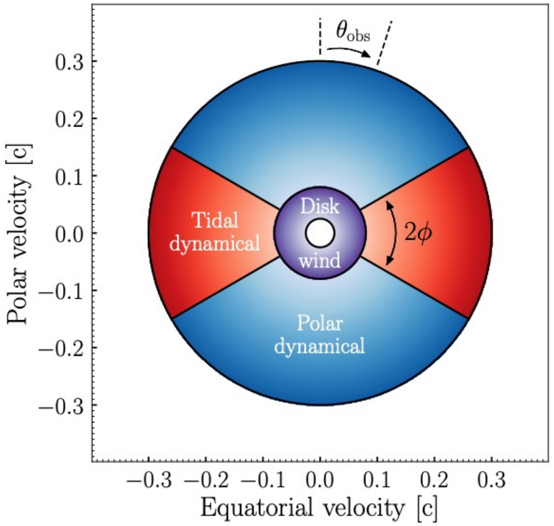
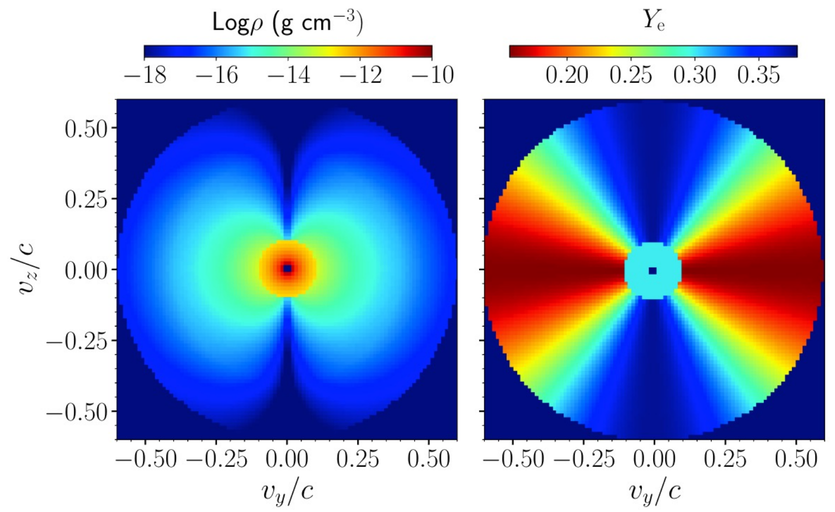






Bulla, MNRAS 520 (2023) 2, 2558-2570

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

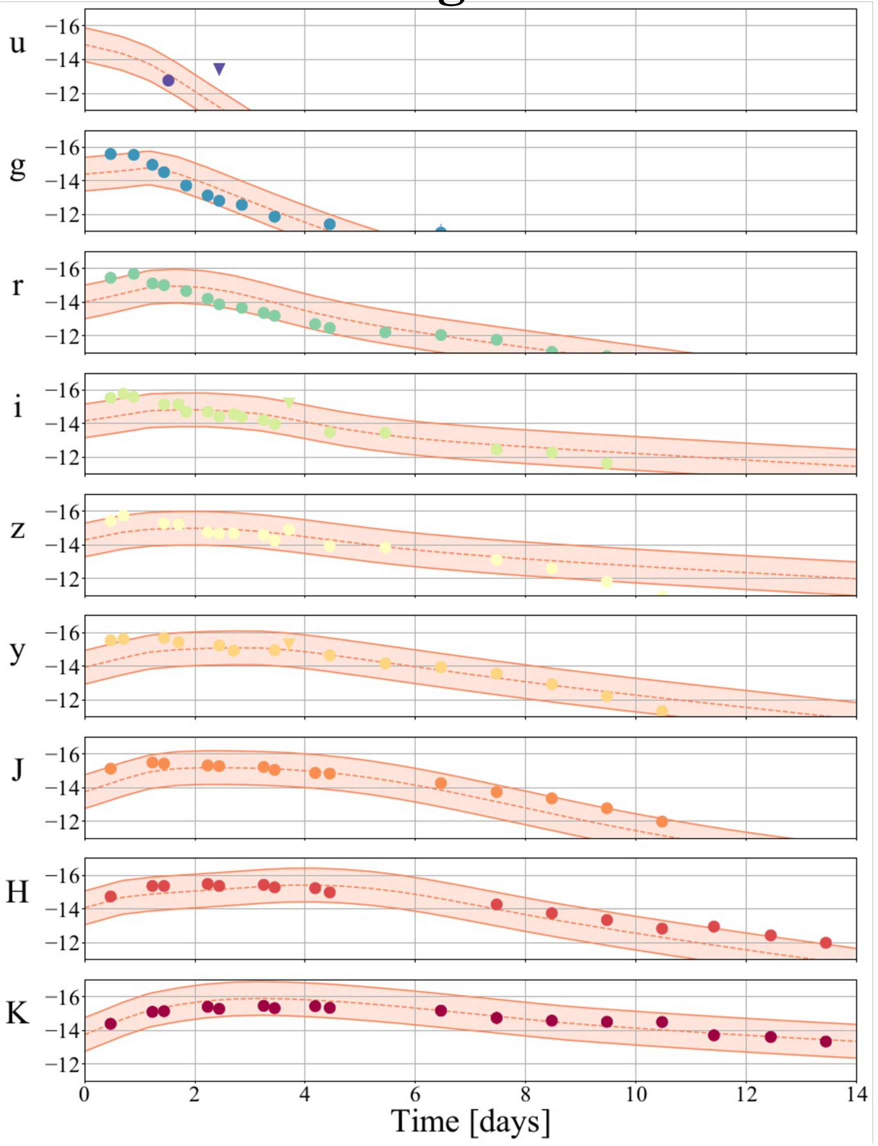
See talk by M. Bulla

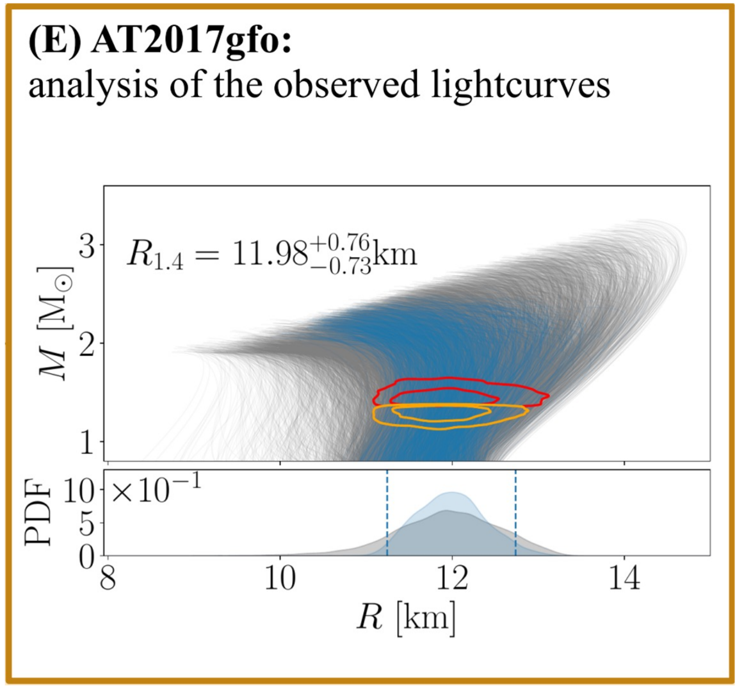
2.) interpolate within this grid through Gaussian process regression or a neural network

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

EM Signals – Kilonova

Photometric lightcurves





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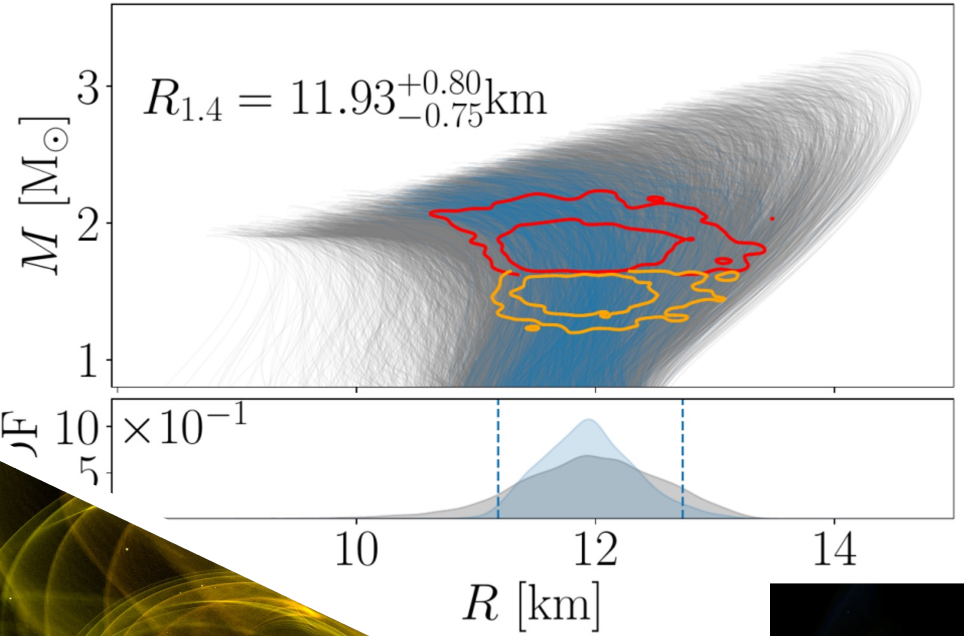
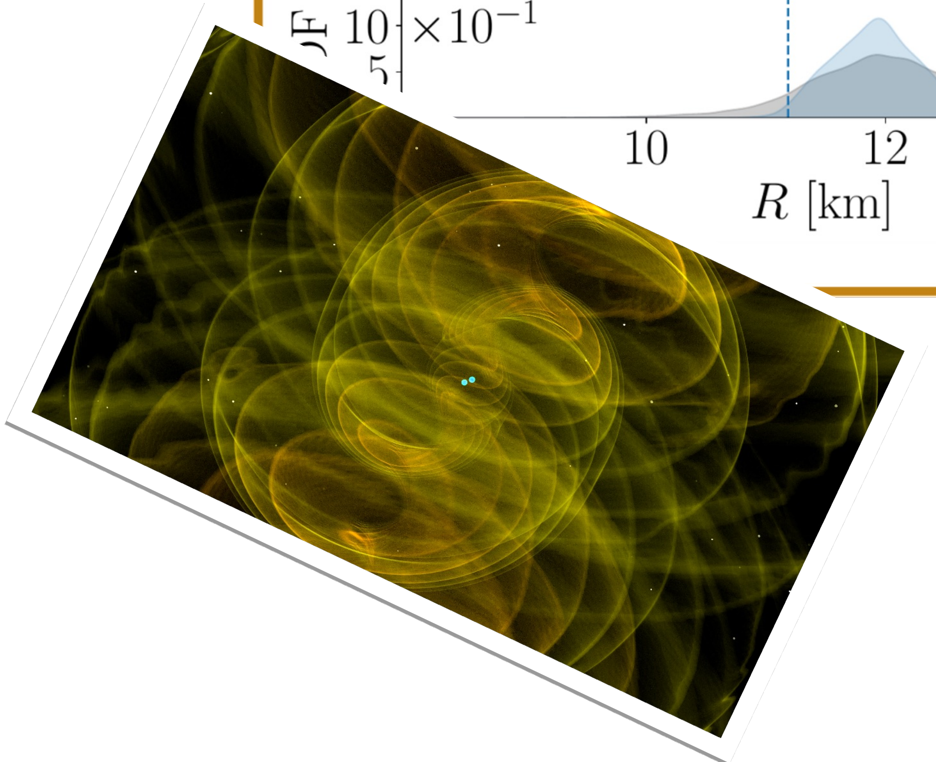
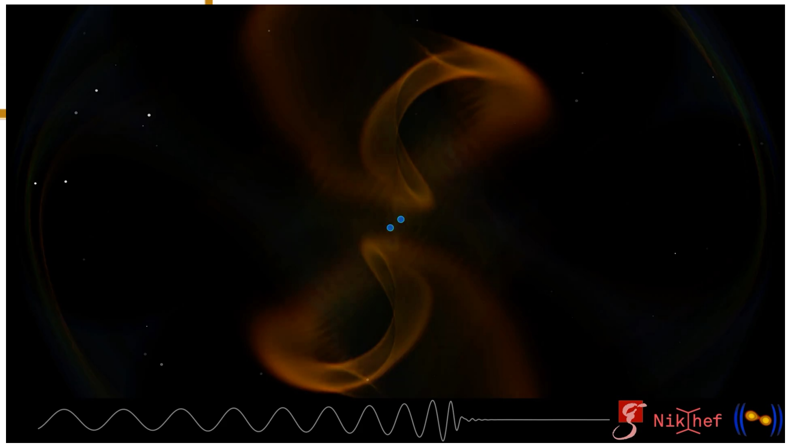
(F) GW190425:
reanalysis with
IMRPhenomPv2_NRTidalv2







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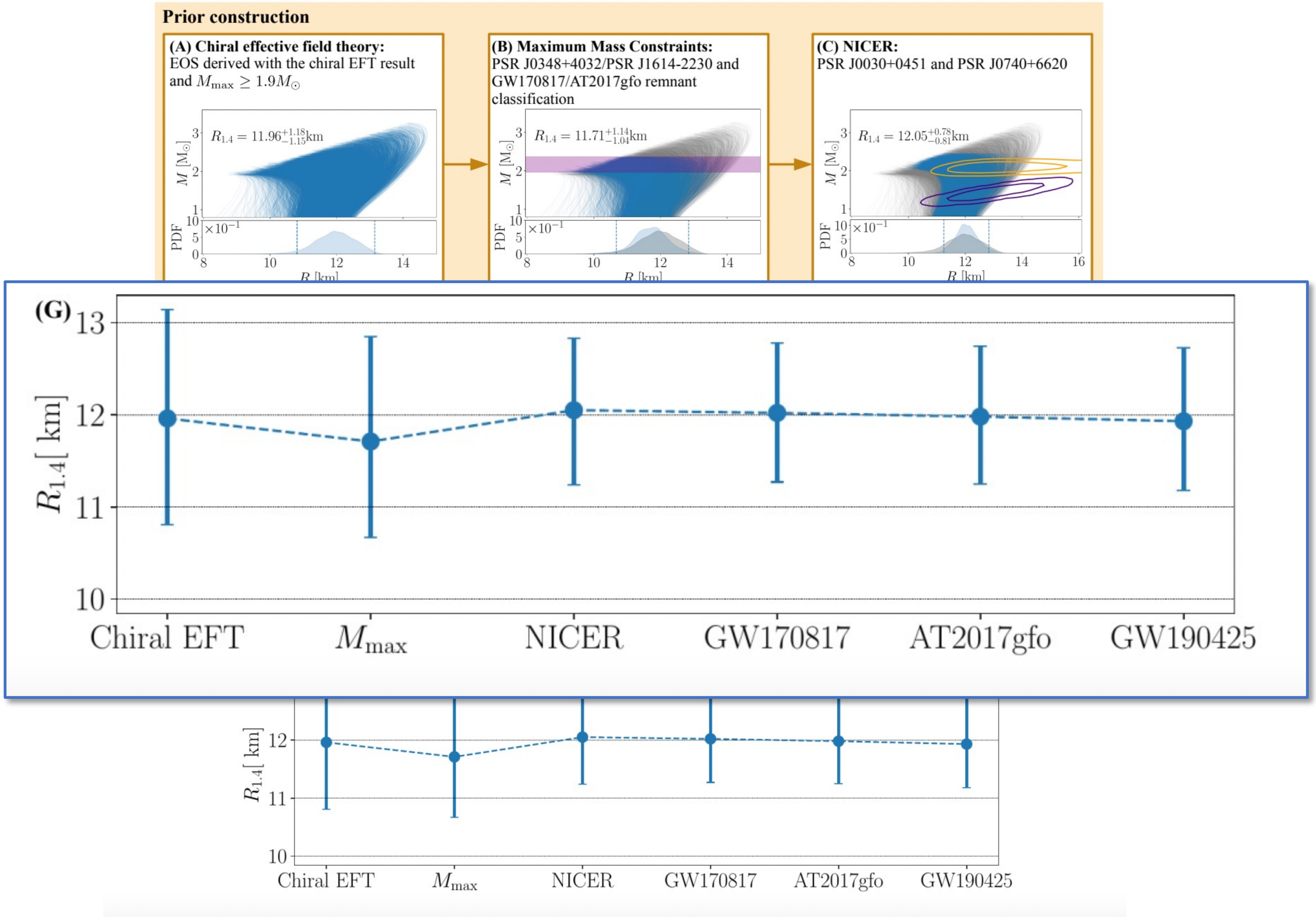
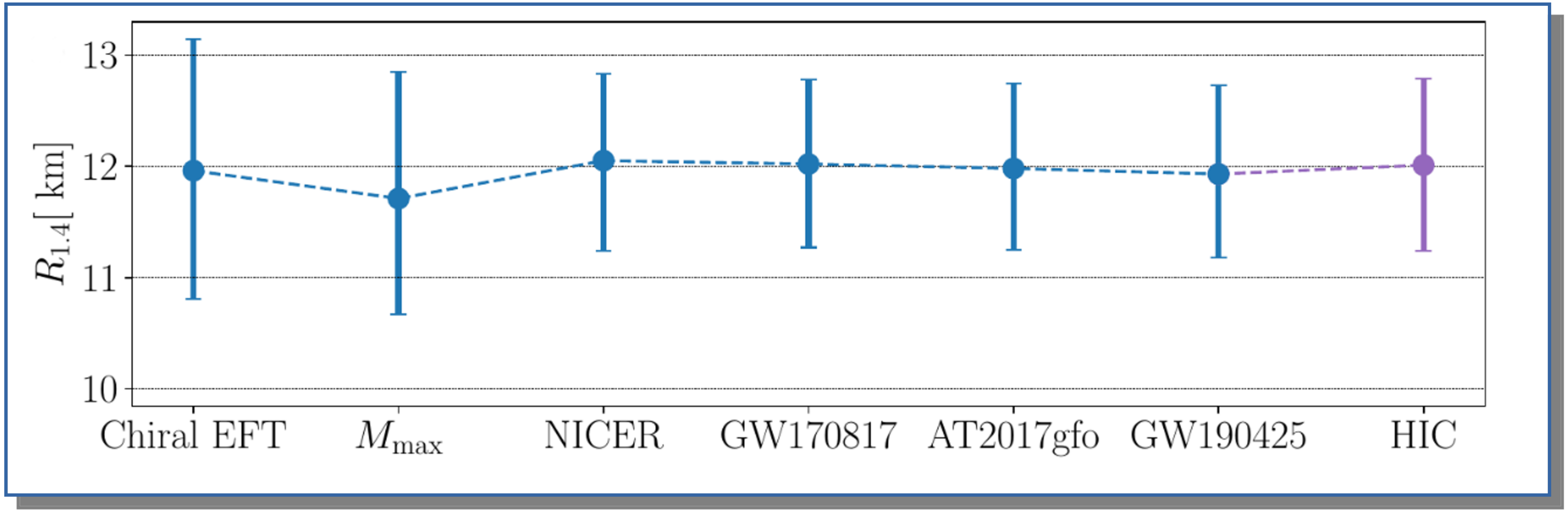


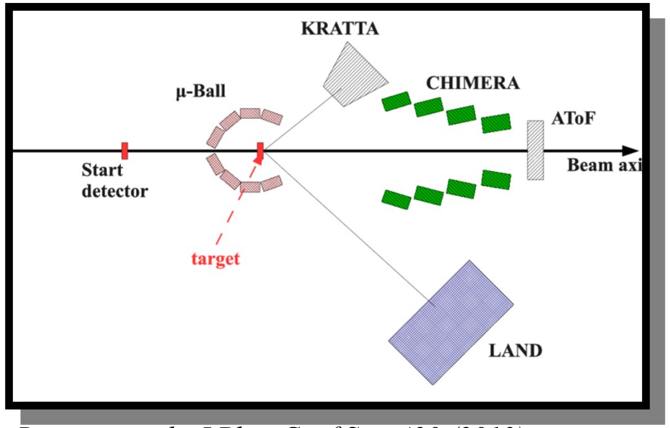
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., Nature 606 (2022) 276-280

Constraints through multi-messenger astronomy and nuclear physics experiments

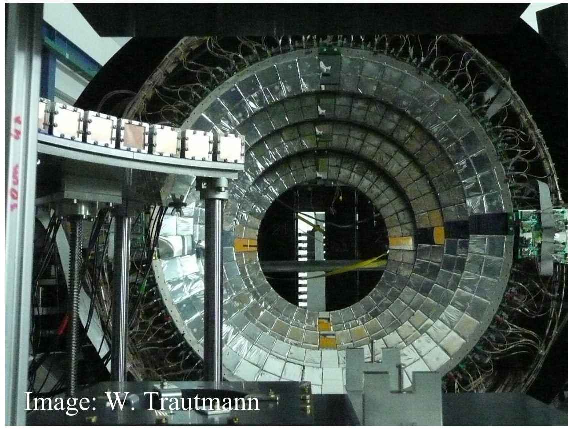
Huth, Pang, et al., Nature 606 (2022) 276-280



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



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



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

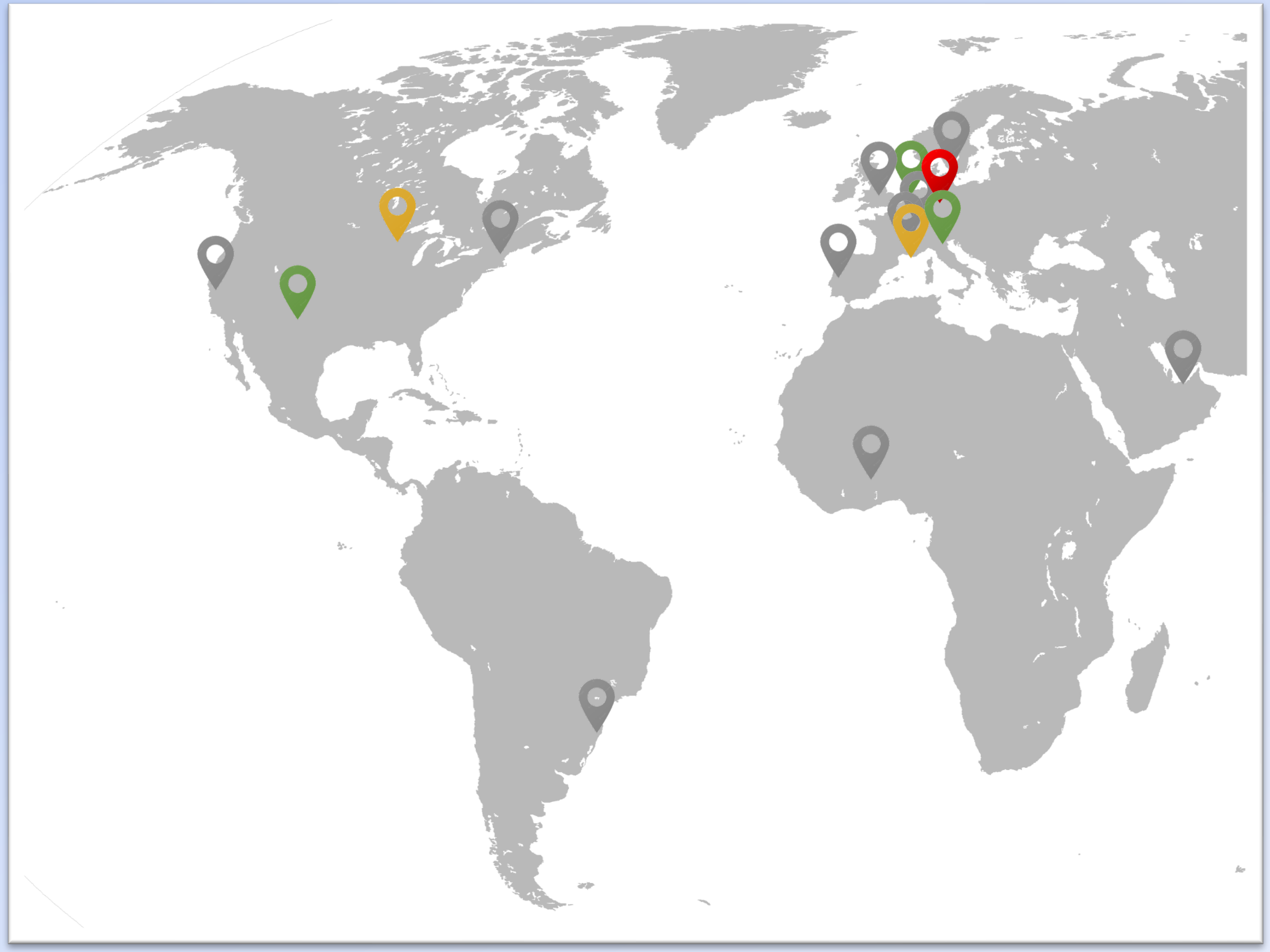
Observations

Utrecht University
- gravitational-wave data analysis
- multi-messenger data analysis

University of Ferrara
- modelling of electromagnetic signals

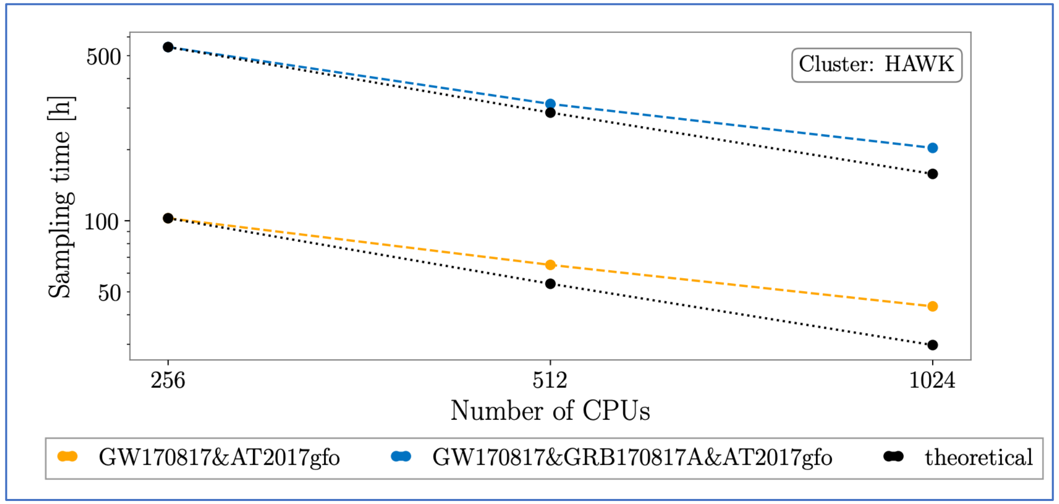
Theory

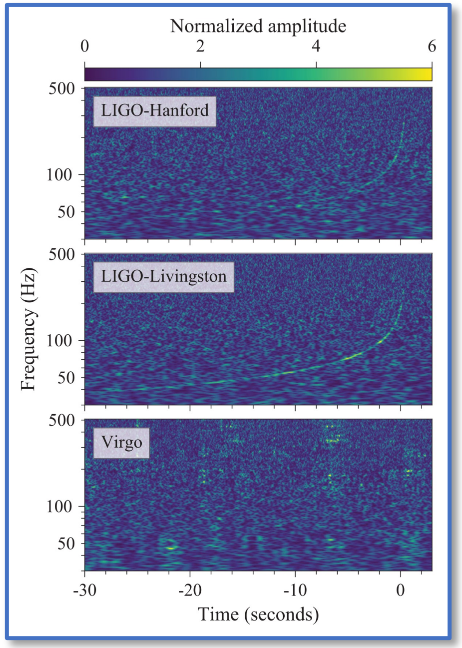
Los Alamos National Lab
- nuclear physics



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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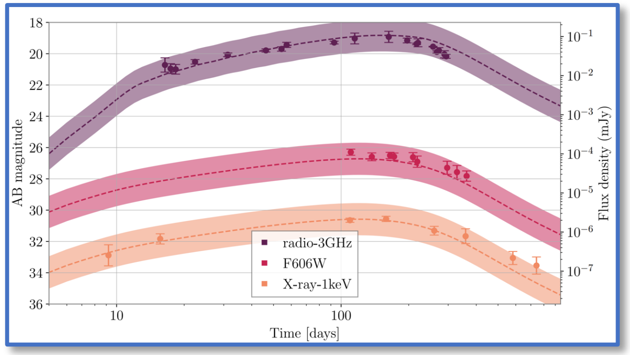

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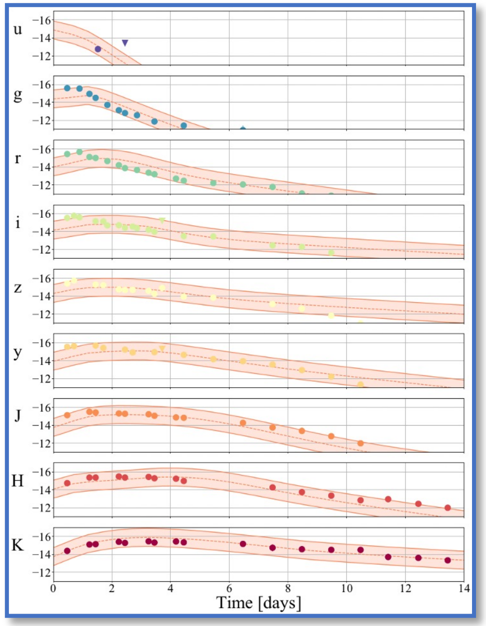

NMMA

github.com/nuclear-multimessenger-astronomy

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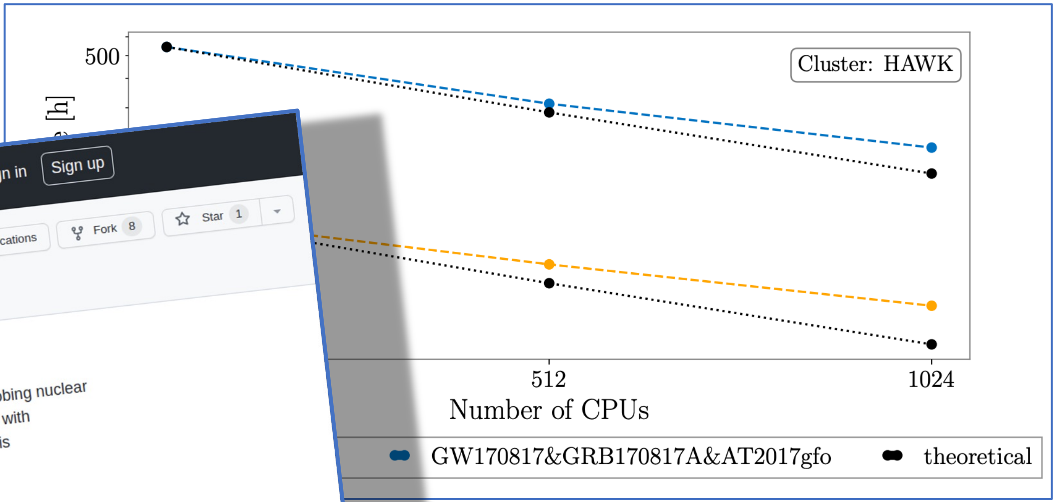

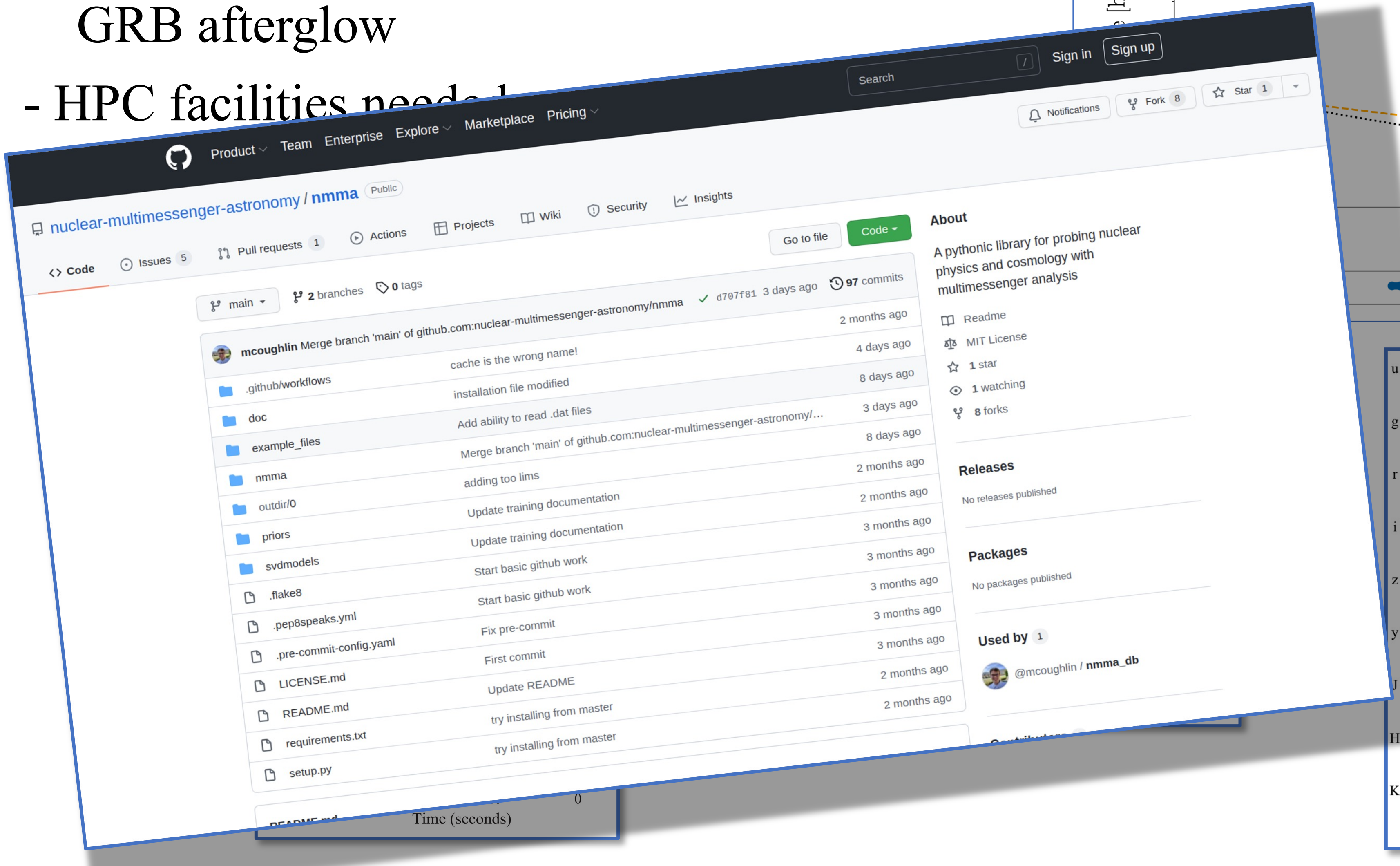

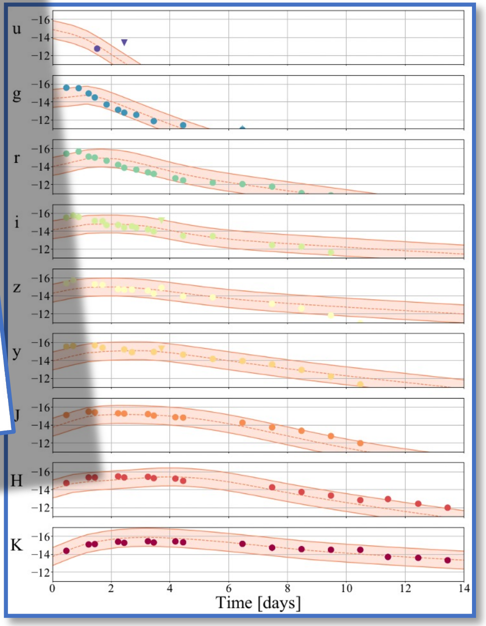

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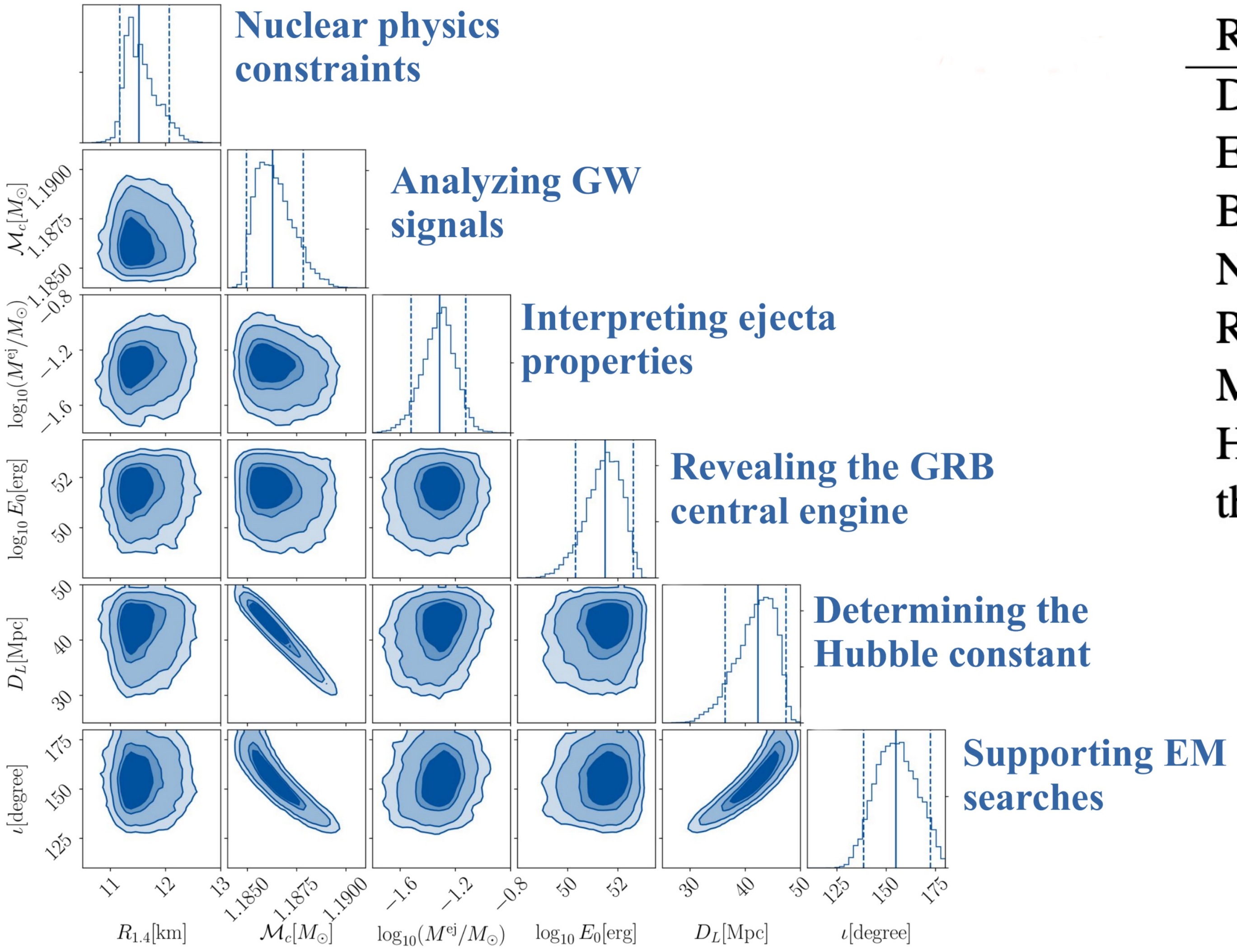


Reference	$R_{1.4M_\odot}$ [km]
Dietrich et al. [15]	$11.75^{+0.86}_{-0.81}$ (90%)
Essick et al. [51]	$12.54^{+0.71}_{-0.63}$ (90%)
Breschi et al. [23]	$11.99^{+0.82}_{-0.85}$ (90%)
Nicholl et al. [24]	$11.06^{+1.01}_{-0.98}$ (90%)
Raaijmakers et al. [25]	$12.18^{+0.56}_{-0.79}$ (95%)
Miller et al. [52]	$12.45^{+0.65}_{-0.65}$ (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:

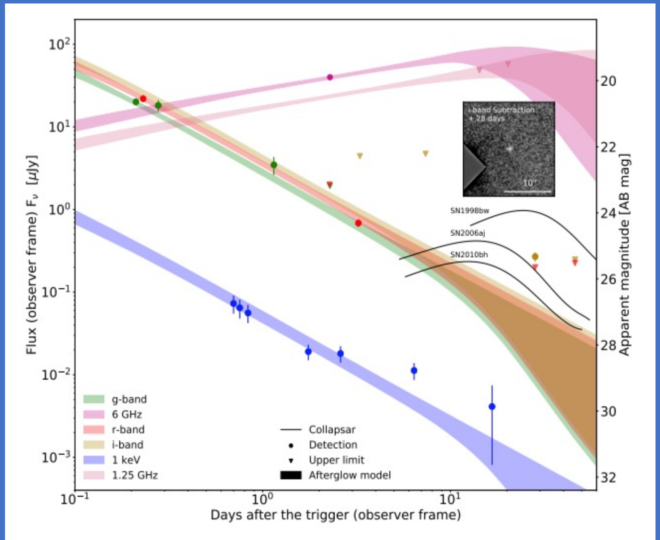
- **EOS information**
  - precomputed EOS sets
  - Sampling in tidal deformability/compactness

- **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

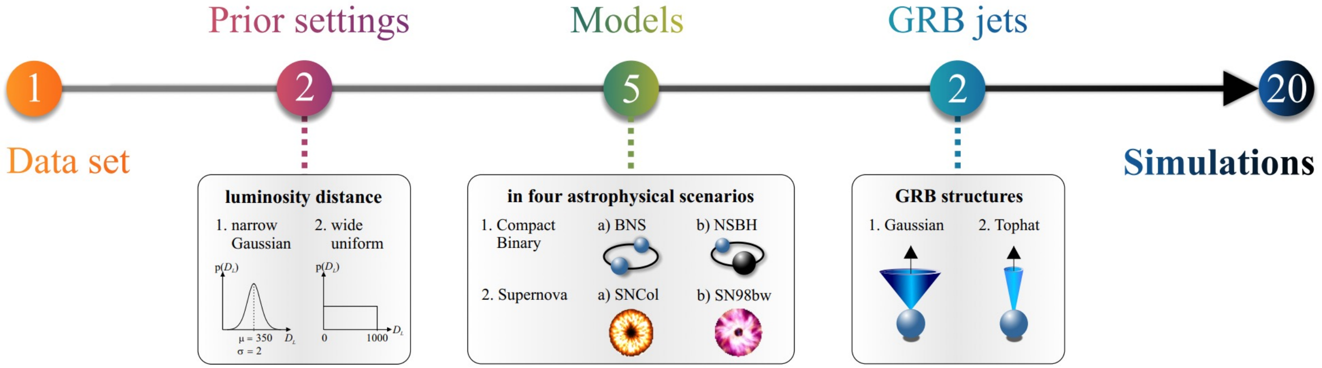
GRB 200826A



shortest long GRB
(no BNS merger, but collapsar)

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

NMMA Applications: Model Selection



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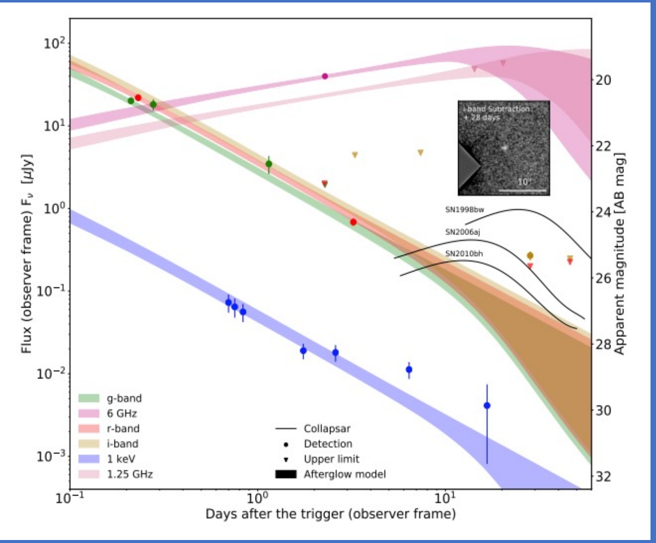

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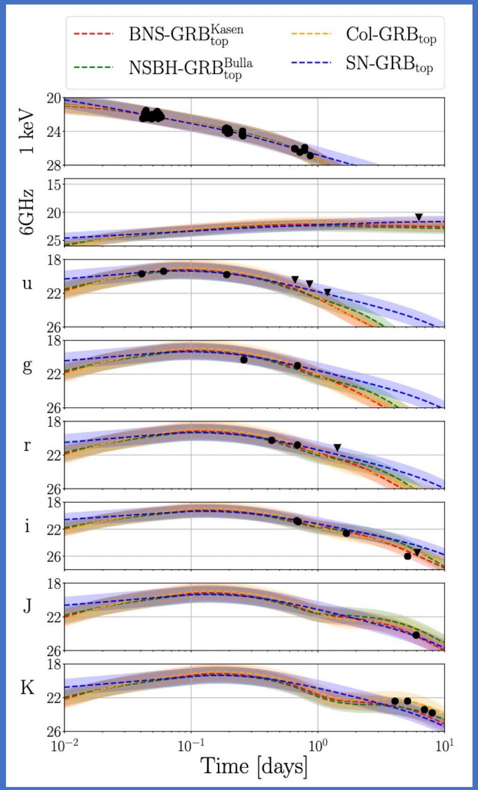
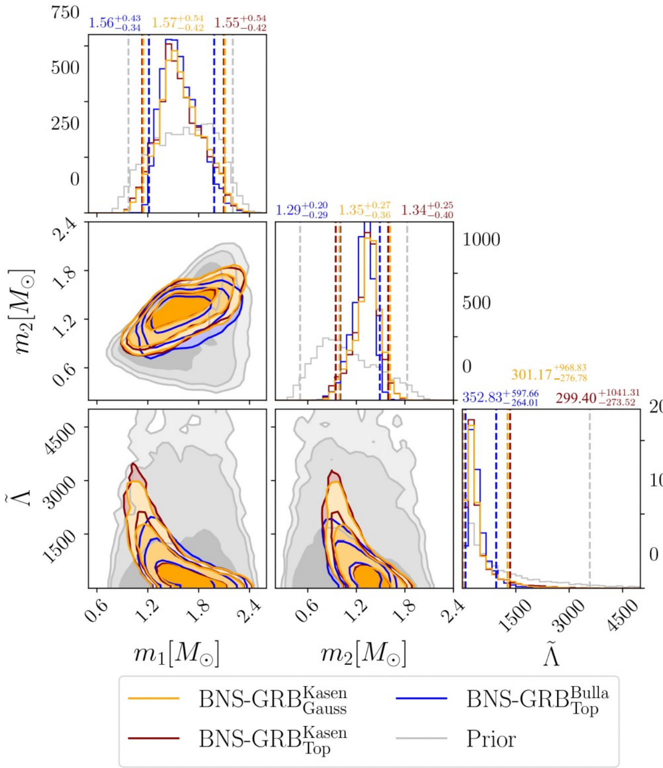
T. Ahumada, et al., Nature Astron. 5 (2021) 9, 917-927

GRB 211211A



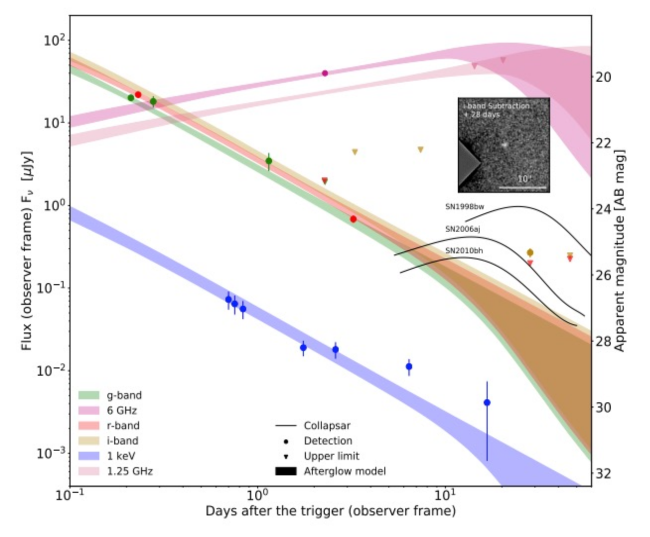
potential kilonova due to BNS merger

N.Kunert et al., arXiv: 2301.02049



NMMA Applications: Model Selection

GRB 200826A



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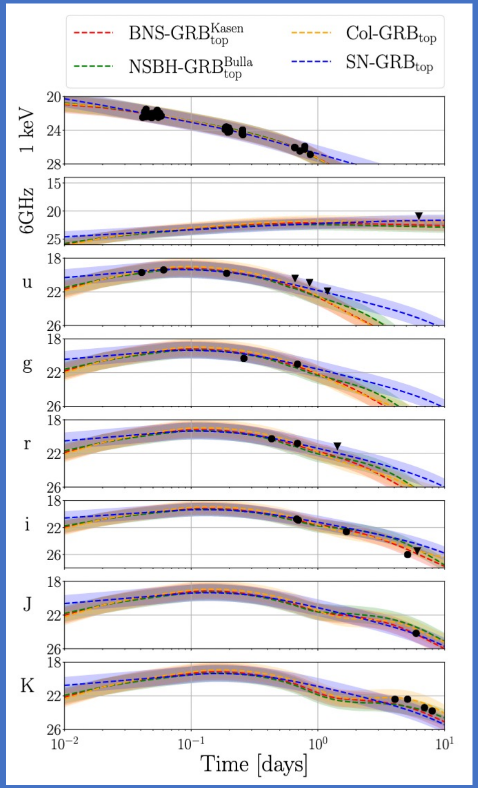
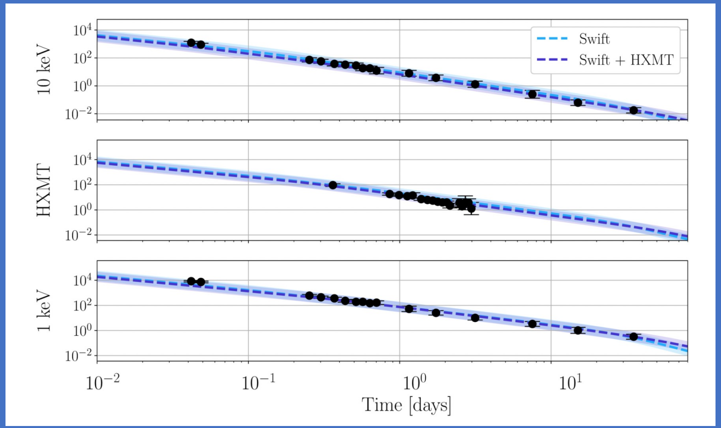
GRB 211211A



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

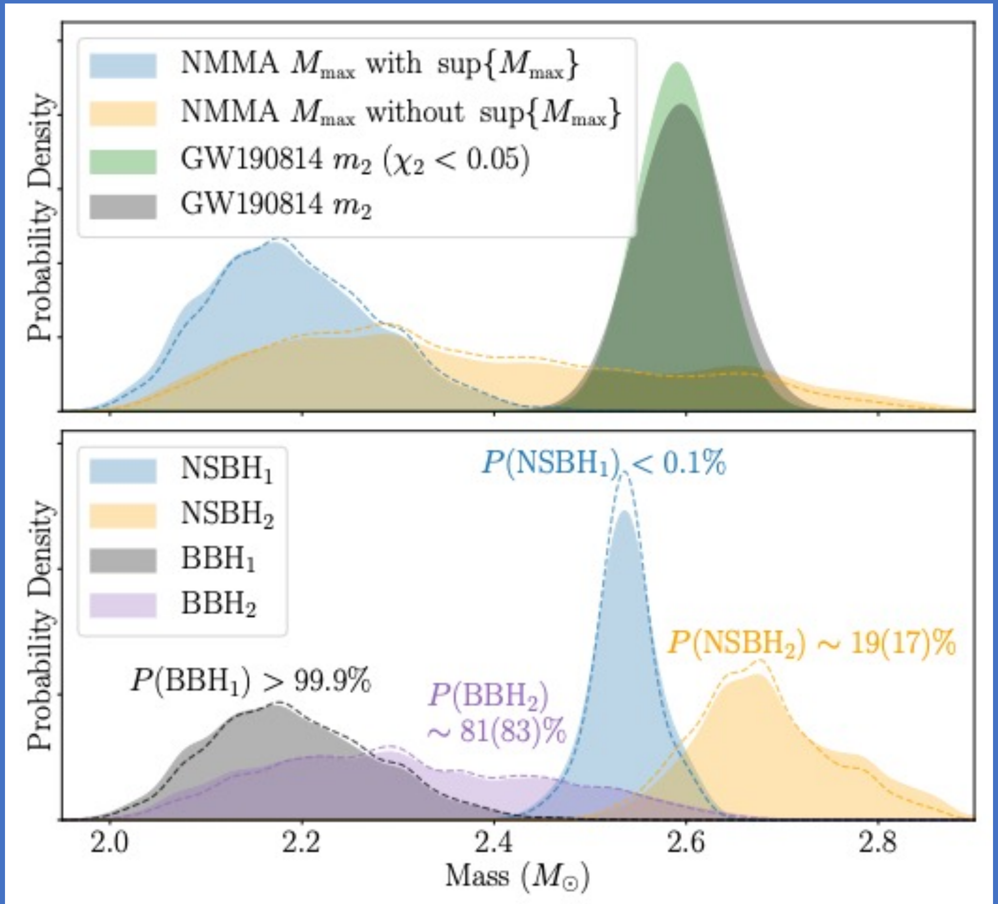
Kann et al., arXiv: 2302.06225

NMMA Applications: Model Selection

GW190814

- under the assumption that GW170817 produced a BH, GW190814 was a BBH P(BBH) > 0.999
- relaxing this assumption, it was a BBH P(BBH) ~ 0.83

Maximum mass and posterior distribution



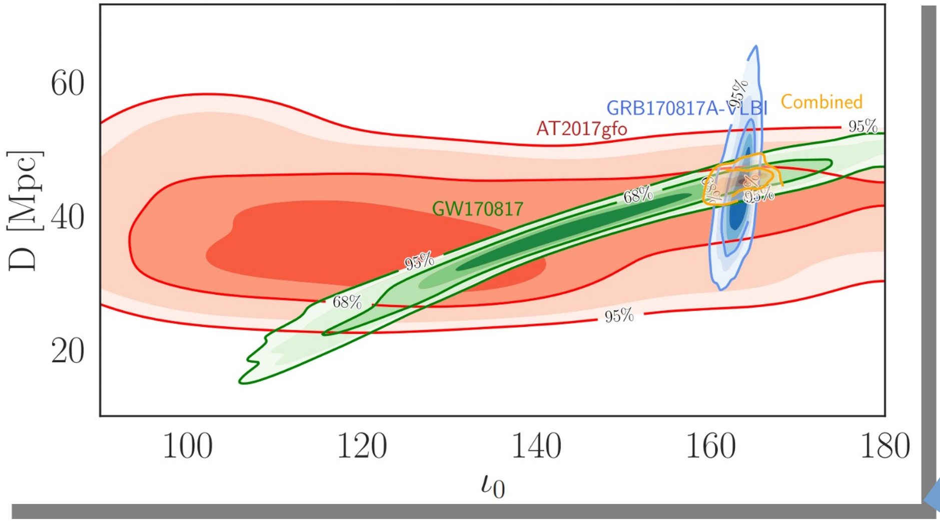
source classification

Tews et al., APJL 908 (2021) 1, L1

Another Science Target: The Hubble Constant

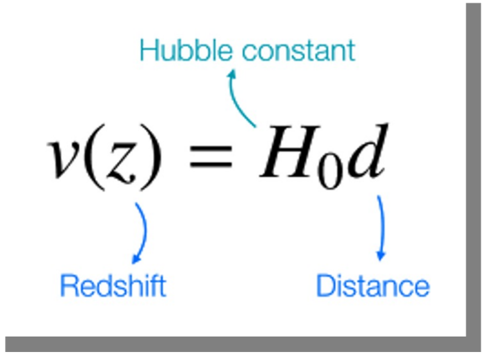
Hubble constant measurement

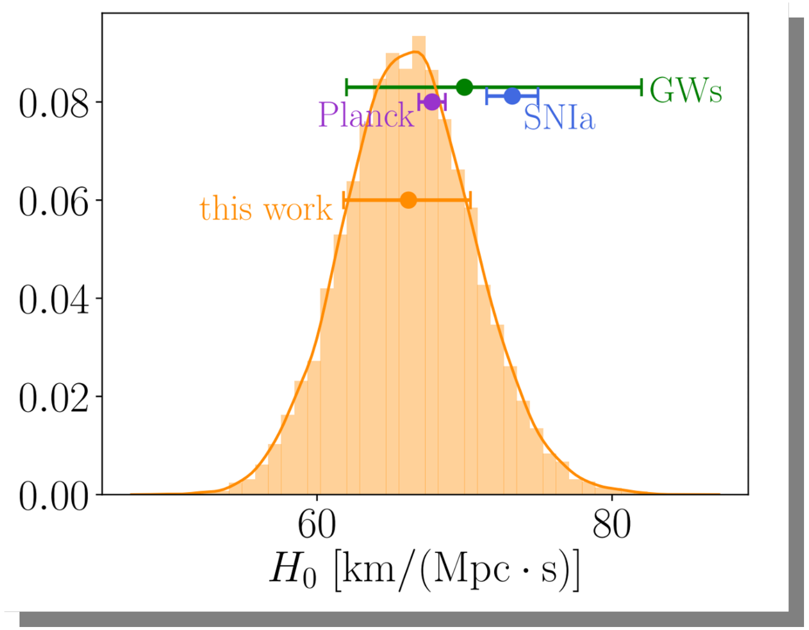
Radio Counterpart



Gravitational Wave

Optical Counterpart





By including previous kilonova candidates, the estimate can be further improved

Coughlin, TD et al., Phys.Rev.Res. 2 (2020) 2, 022006
Coughlin, Antier, TD, et al, Nature Commun. 11 (2020) 1, 4129

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

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.