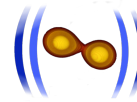


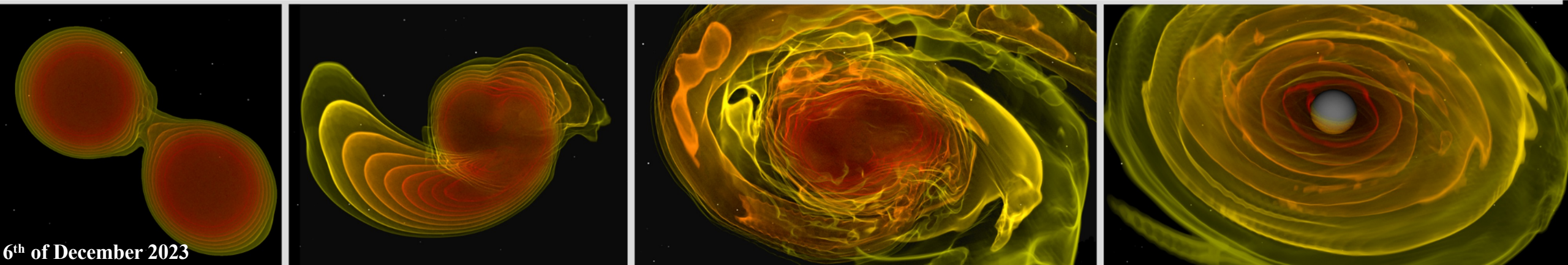
Joint nuclear-physics and multi-messenger astrophysics interpretation of compact binary mergers



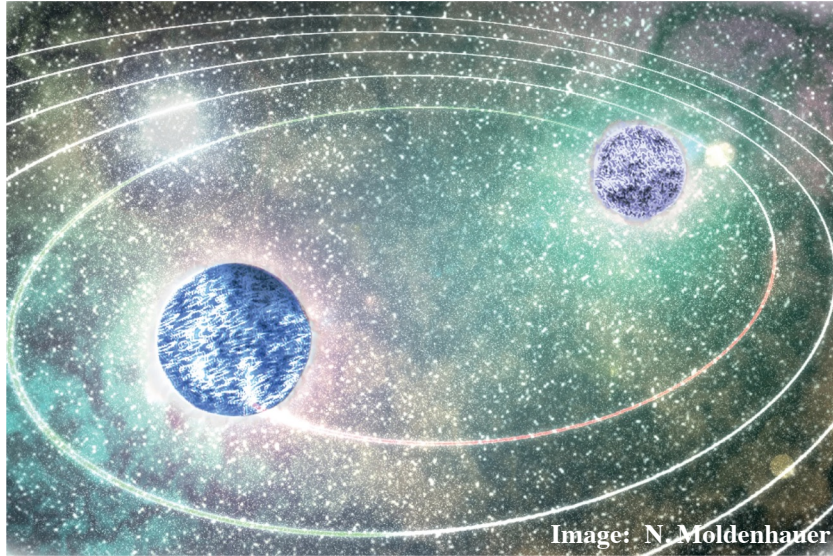
Tim Dietrich
University of Potsdam
Max Planck Institute for Gravitational Physics



Daimler und
Benz Stiftung

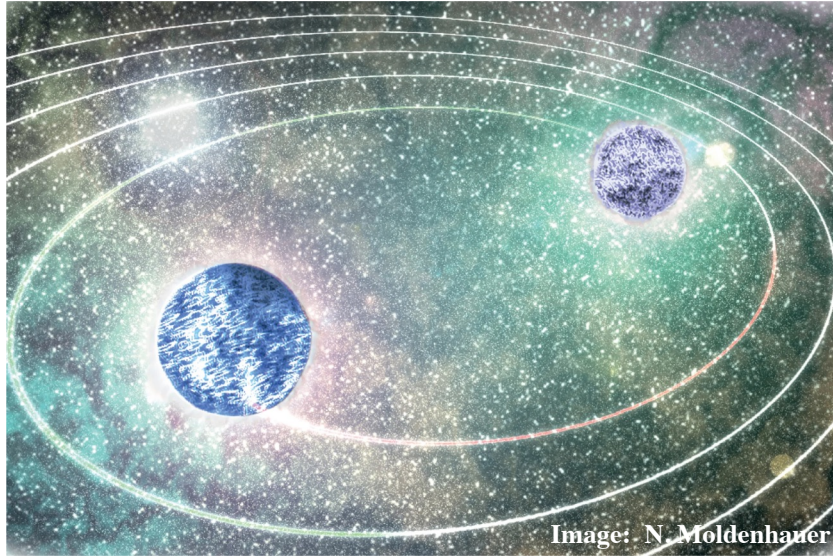


How to study neutron stars?



- **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**

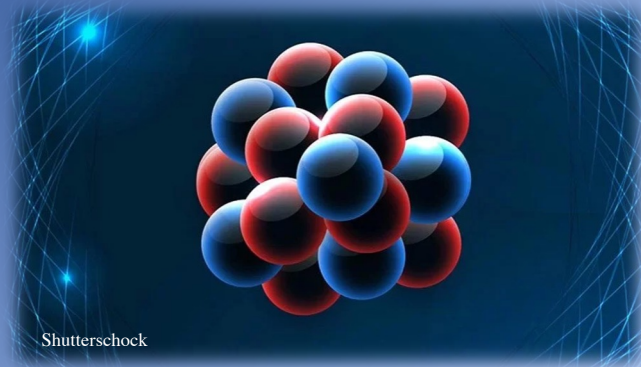
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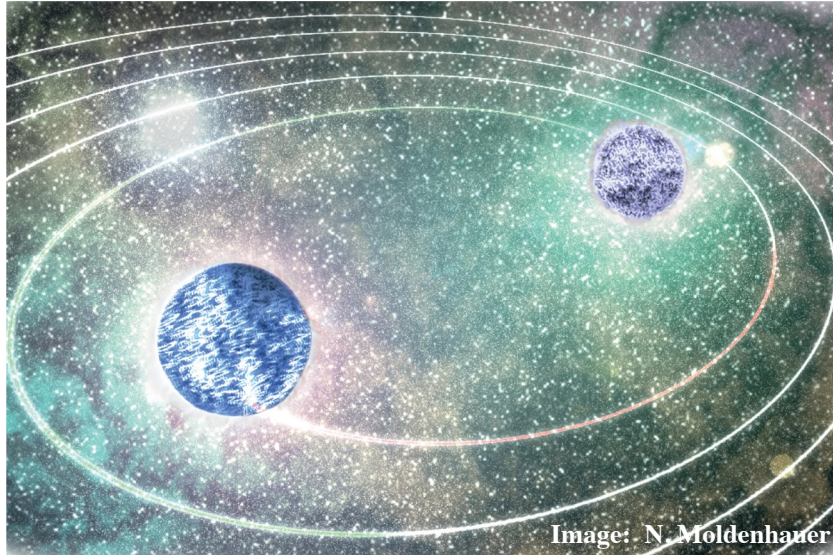
Science cases

State of matter at extreme densities



$\mathcal{O}(10^{-15} \text{ m})$

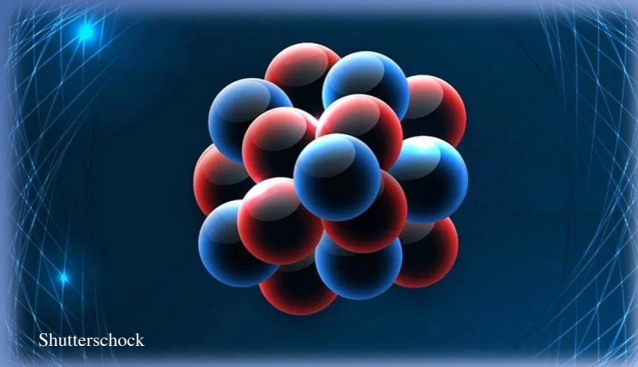
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Heavy element production



How to study neutron stars?

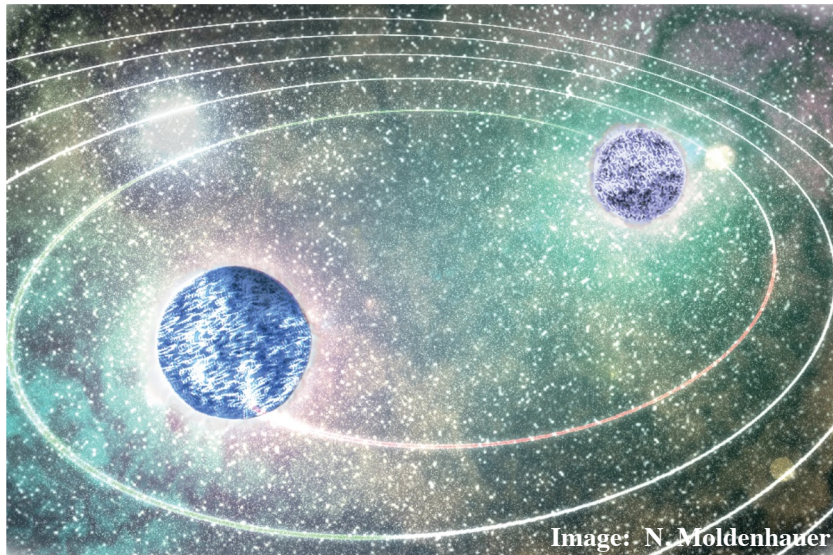
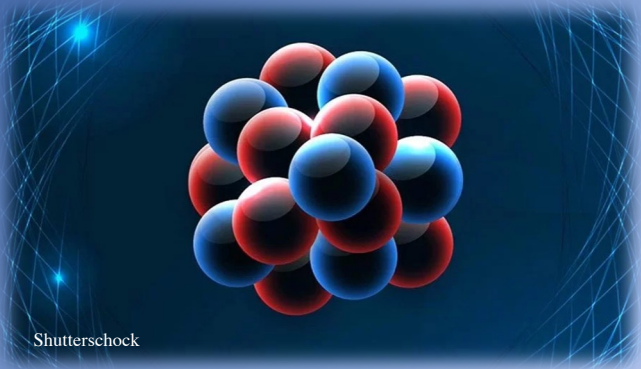


Image: N. Moldenhauer

- **X-ray observations** of rotating neutron stars
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- Binary mergers:
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Science cases

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Shutterschock

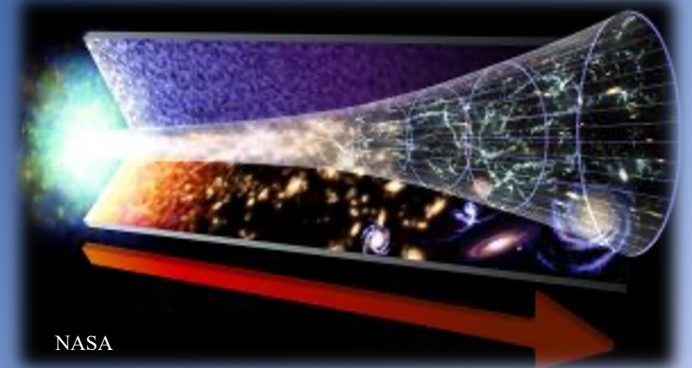
$$\mathcal{O}(10^{-15} \text{ m})$$

Heavy element production



Forbes

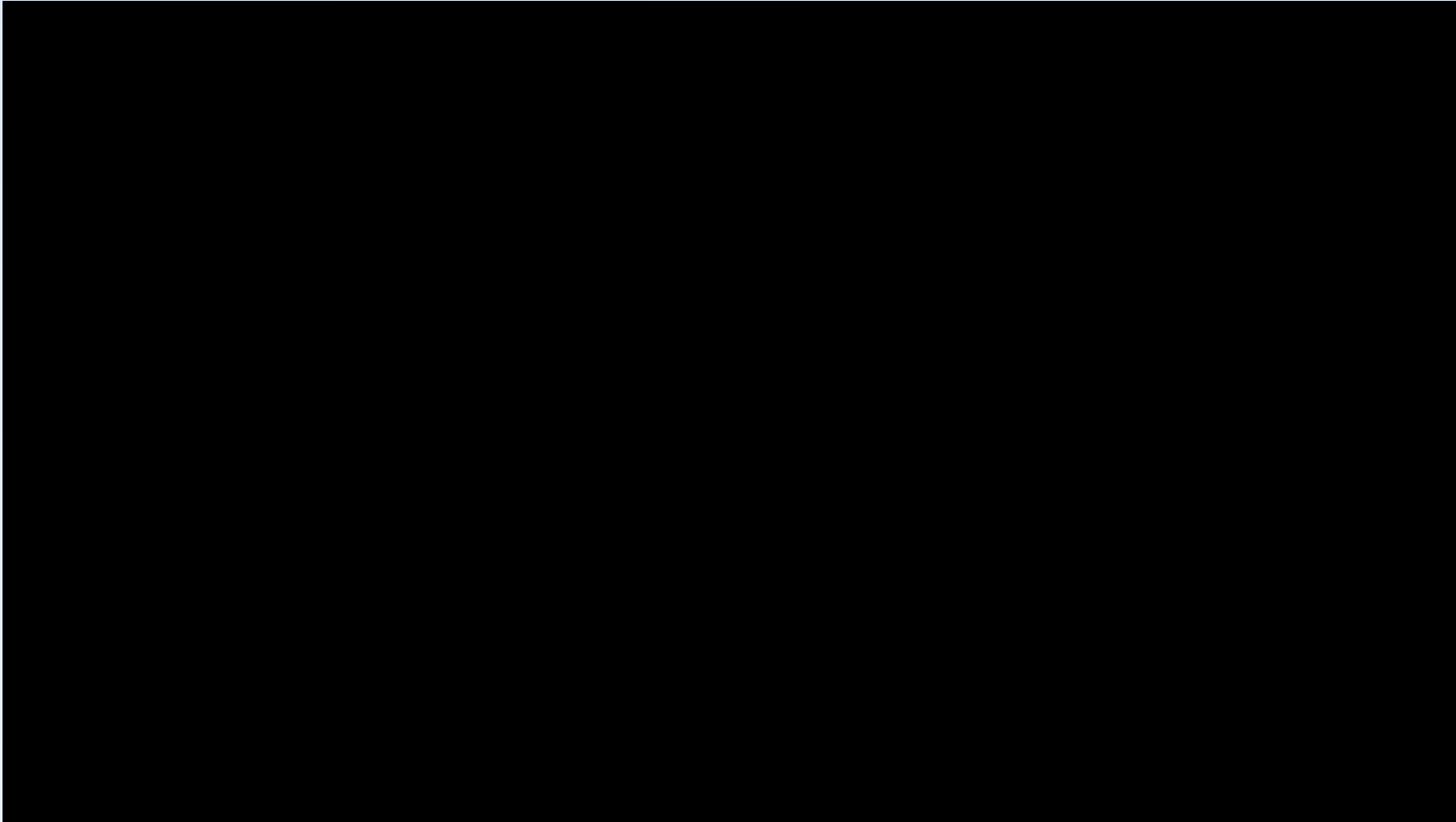
Expansion rate of our Universe



NASA

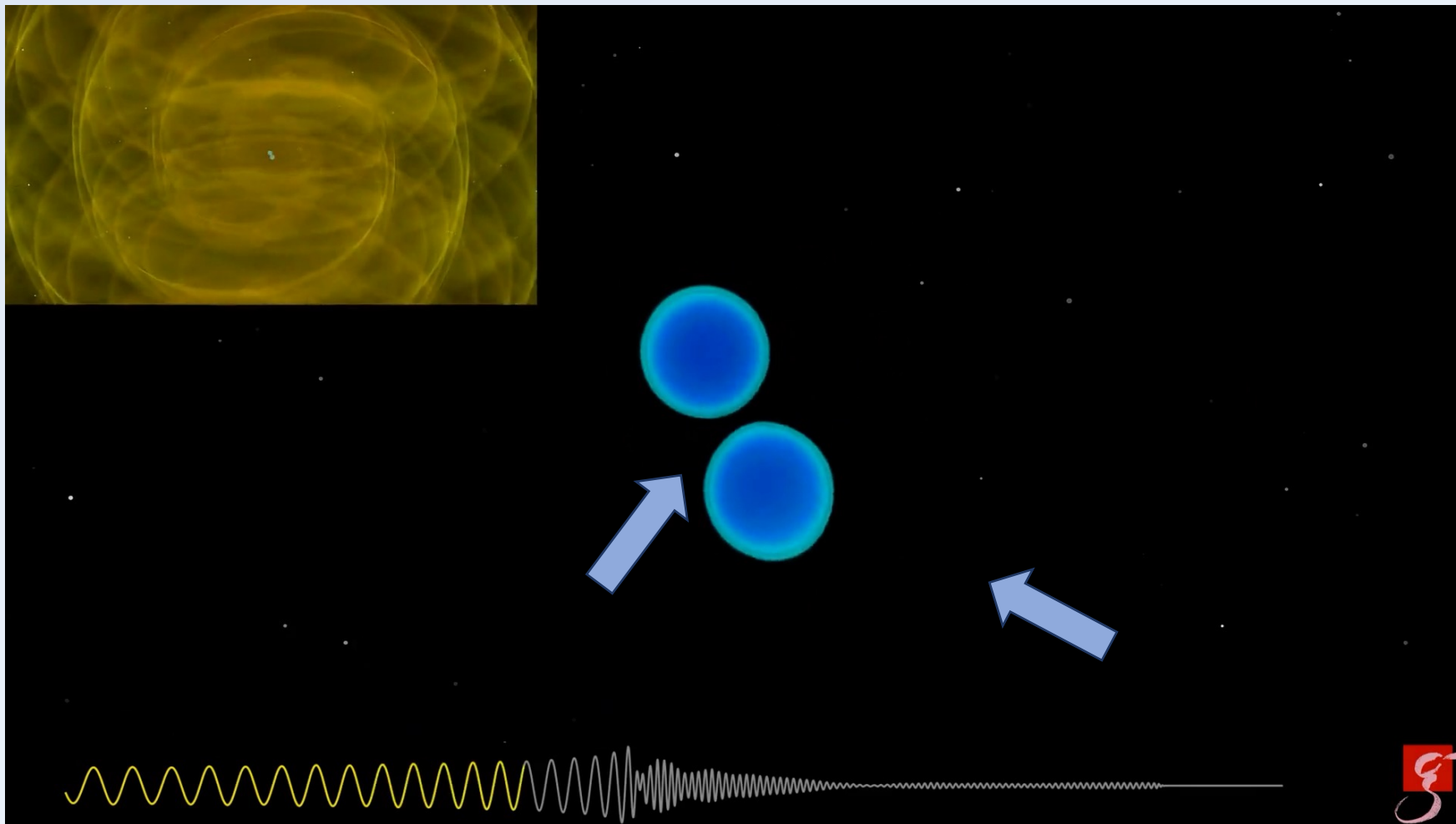
$$\mathcal{O}(10^{25} \text{ m})$$

The Binary Neutron Star Merger Simulation



**gravitational wave
emission**

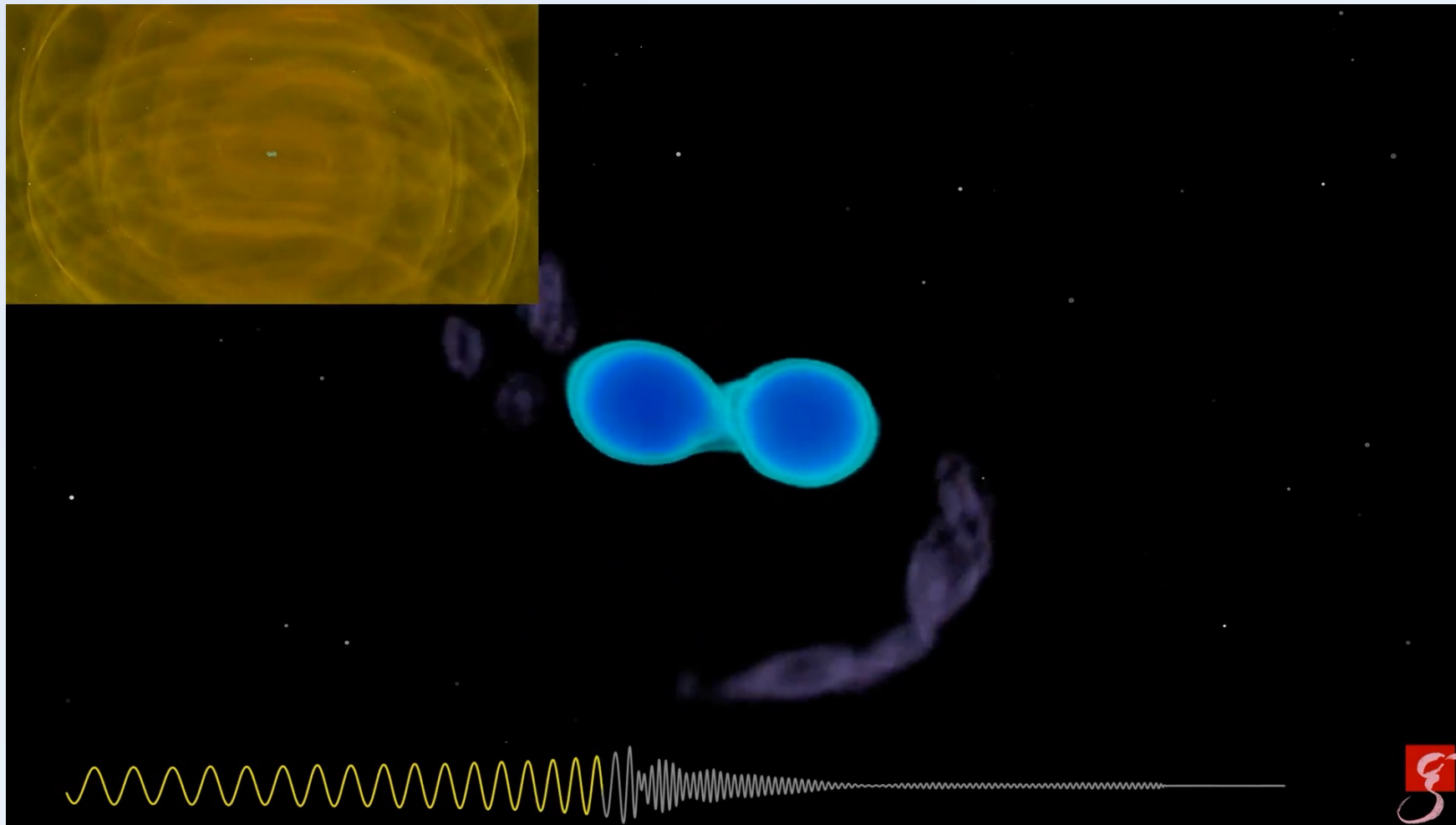
The Binary Neutron Star Merger Simulation



**gravitational wave
emission**

**deformation before
merger, ejection of
material, heavy
element production**

The Binary Neutron Star Merger Simulation



**gravitational wave
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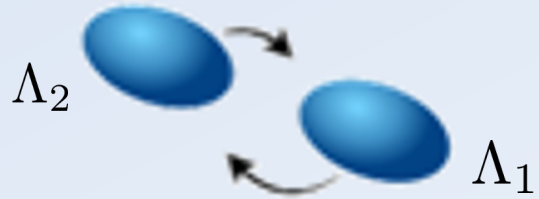
black hole formation

70 milliseconds

Gravitational Wave Analysis

GW170817

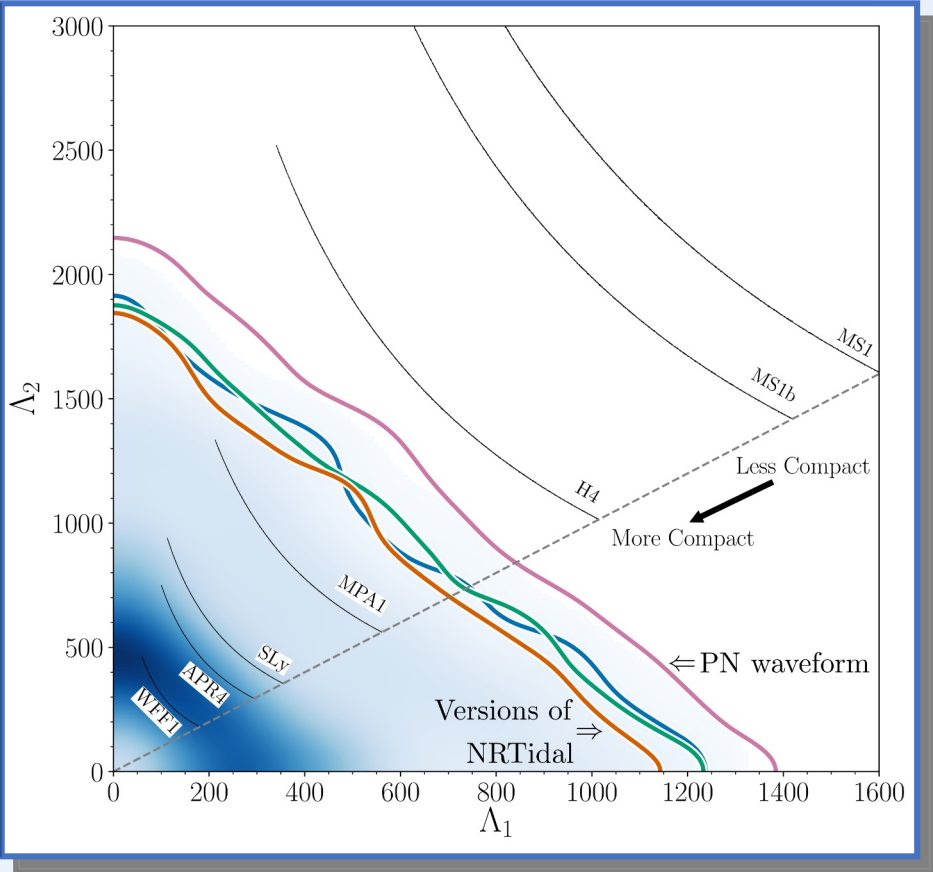
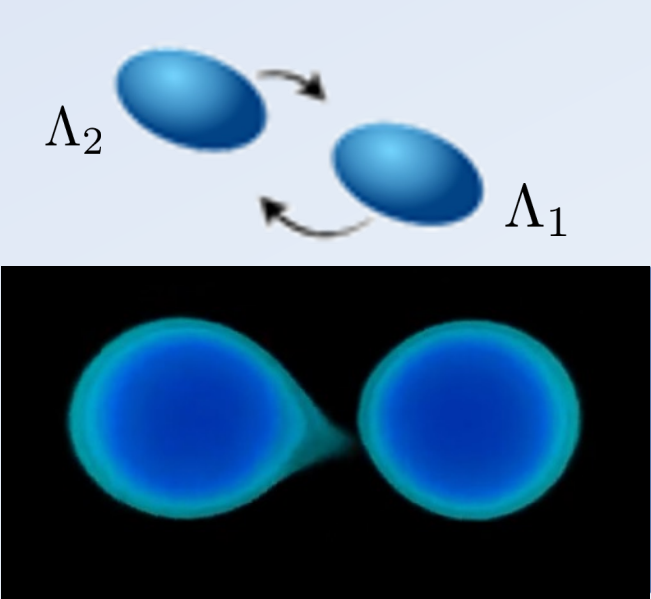
Λ determines tidal deformability



Gravitational Wave Analysis

GW170817

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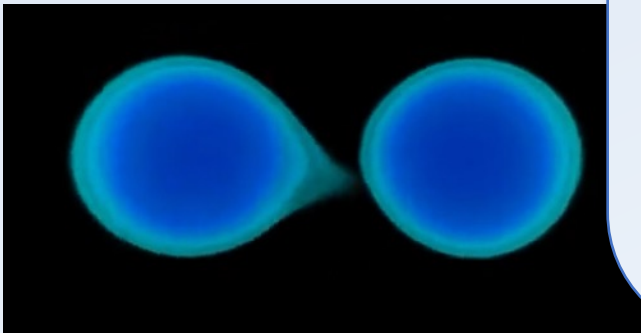
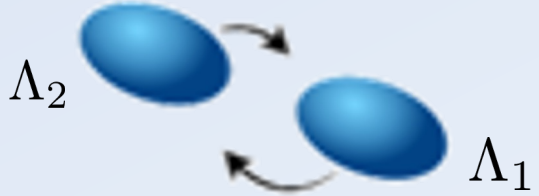


→ no assumption about the type of the compact object

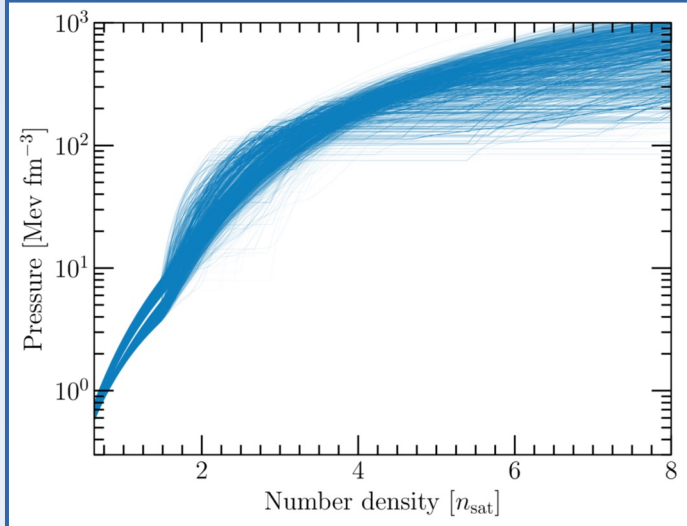
Gravitational Wave Analysis

GW170817

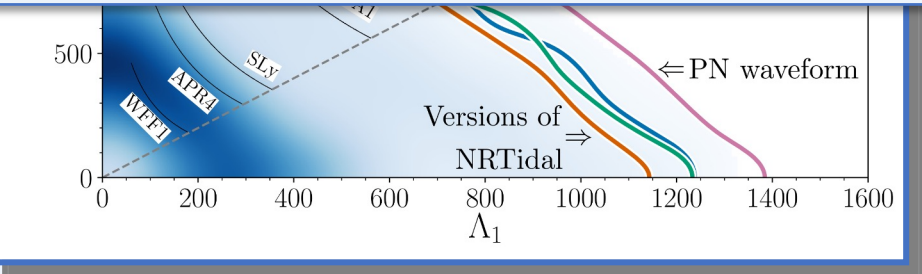
Λ determines tidal deformability



Assumption: The merging objects were neutron stars



nuclear-physics computations

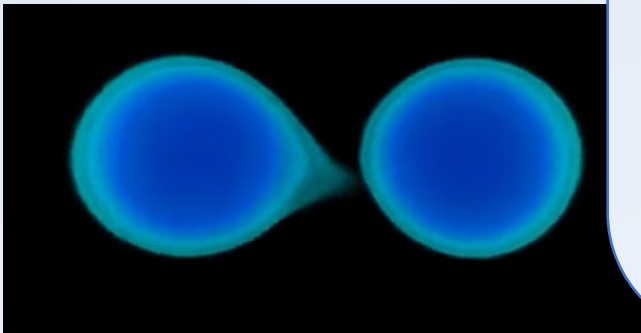
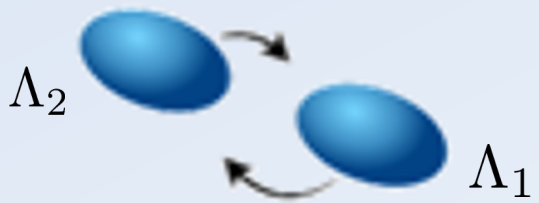


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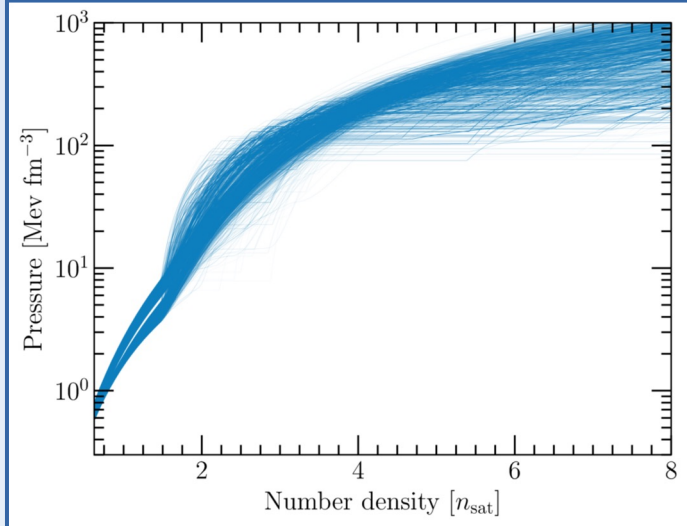
Gravitational Wave Analysis

GW170817

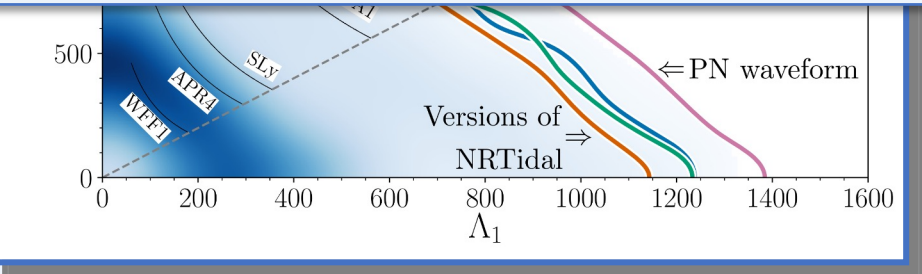
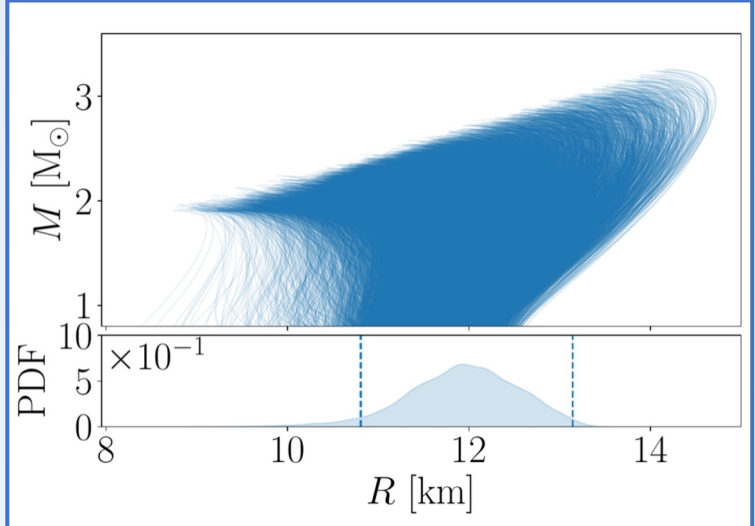
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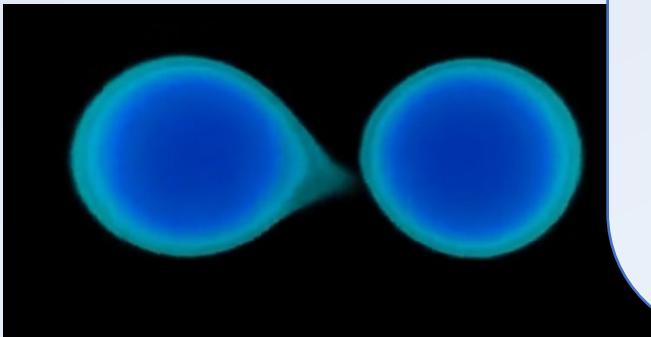
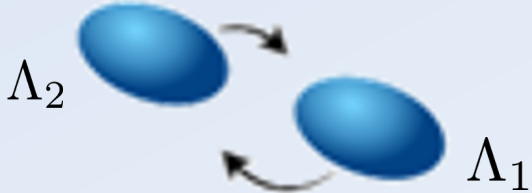


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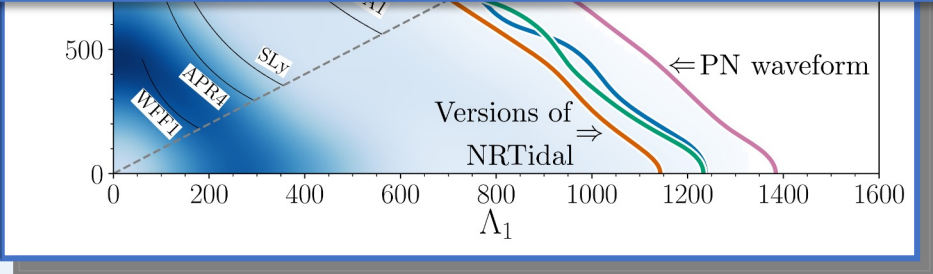
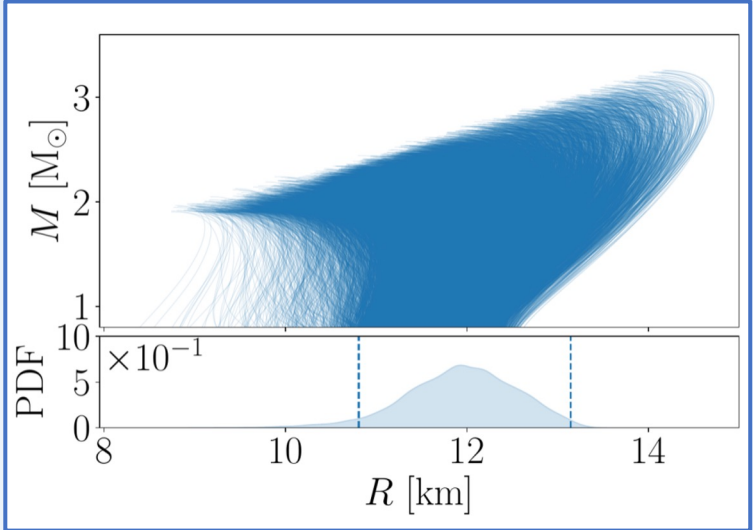
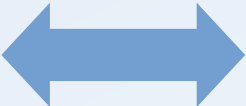
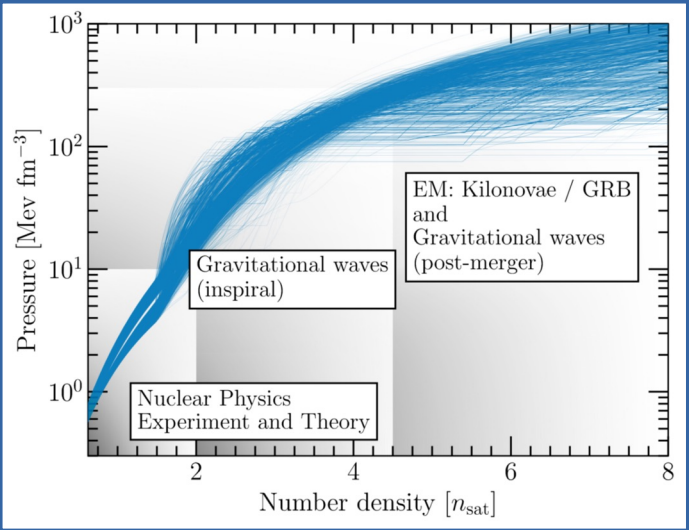
Gravitational Wave Analysis

GW170817

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Gravitational Wave Analysis

RESEARCH

Science

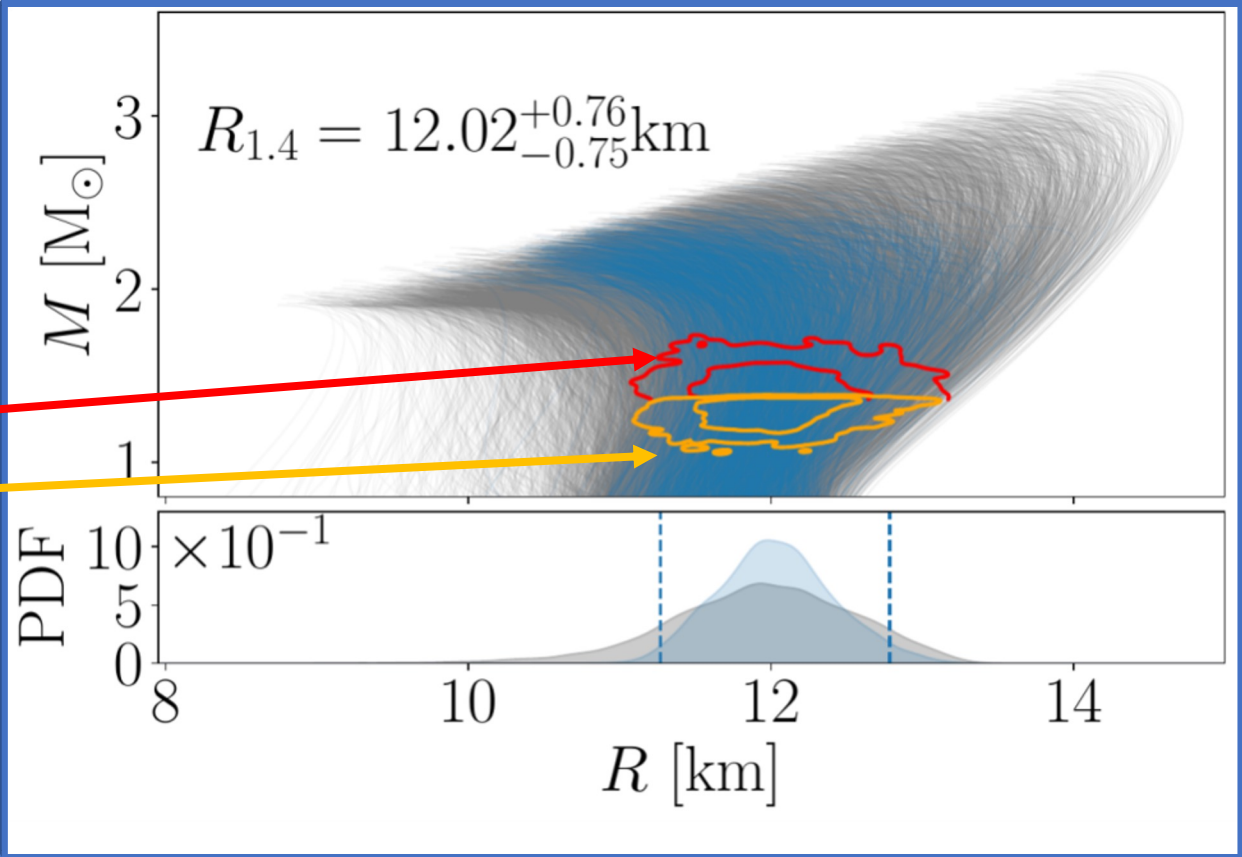
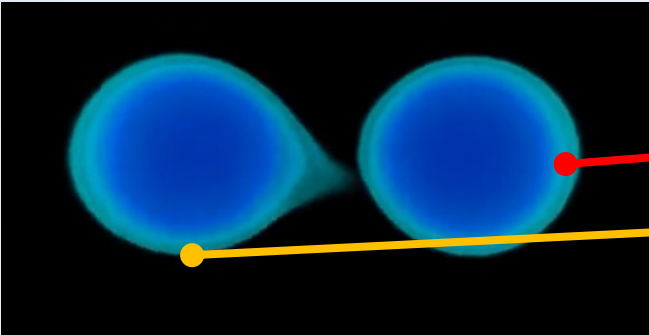
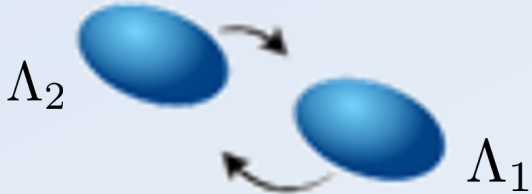
NEUTRON STARS

Multimessenger constraints on the neutron-star equation of state and the Hubble constant

Tim Dietrich^{1,2}, Michael W. Coughlin³, Peter T. H. Pang^{2,4}, Mattia Bulla⁵, Jack Heinezel^{3,6,7}, Lina Issa^{5,8}, Ingo Tews⁹, Sarah Antler¹⁰

GW170817

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Assumption: The merging objects were neutron stars

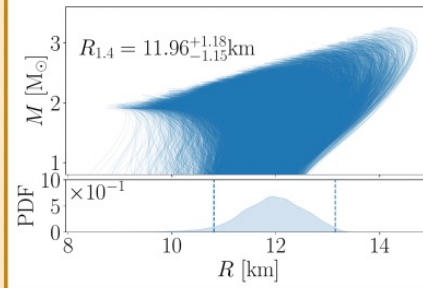
The principle idea: Multi-Messenger Interpretation of the Equation of State

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

Prior construction

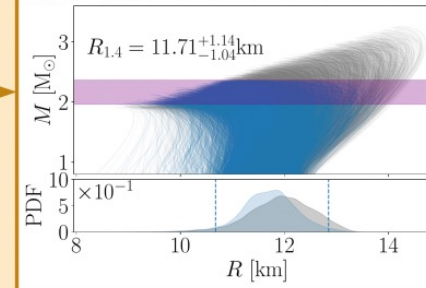
(A) Chiral effective field theory:

EOS derived with the chiral EFT result and $M_{\max} \geq 1.9M_{\odot}$



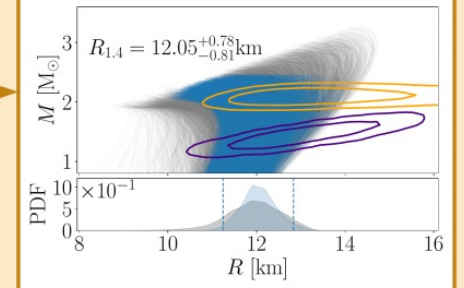
(B) Maximum Mass Constraints:

PSR J0348+4032/PSR J1614-2230 and GW170817/AT2017gfo remnant classification



(C) NICER:

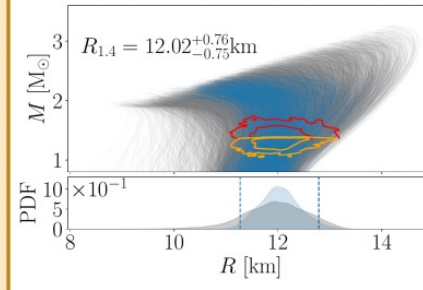
PSR J0030+0451 and PSR J0740+6620



Parameter estimation

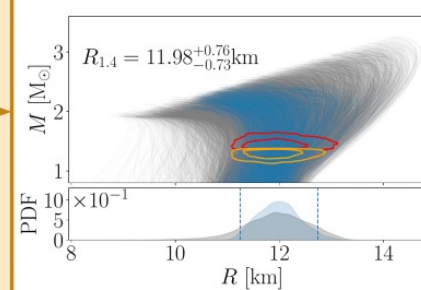
(D) GW170817:

reanalysis with IMRPhenomPv2_NRTidalv2



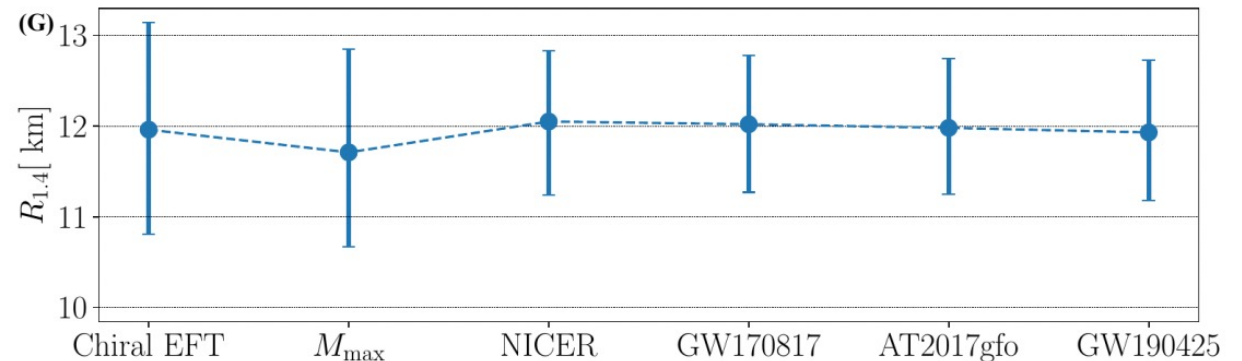
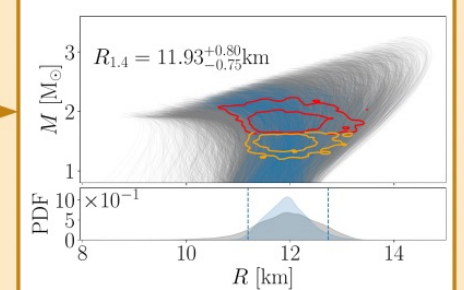
(E) AT2017gfo:

analysis of the observed lightcurves

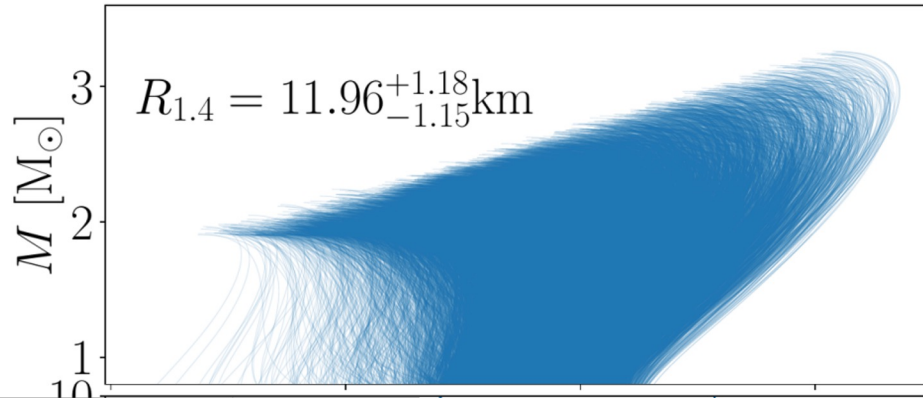


(F) GW190425:

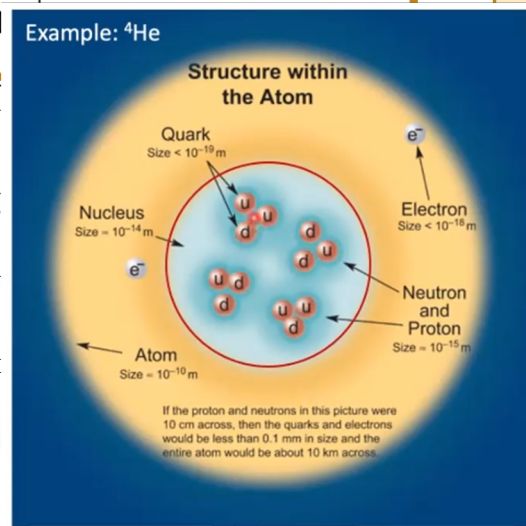
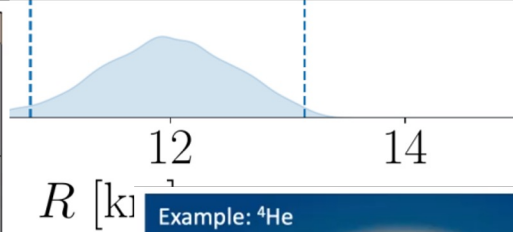
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(A) Chiral effective field theory:
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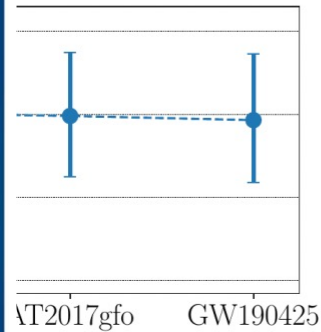
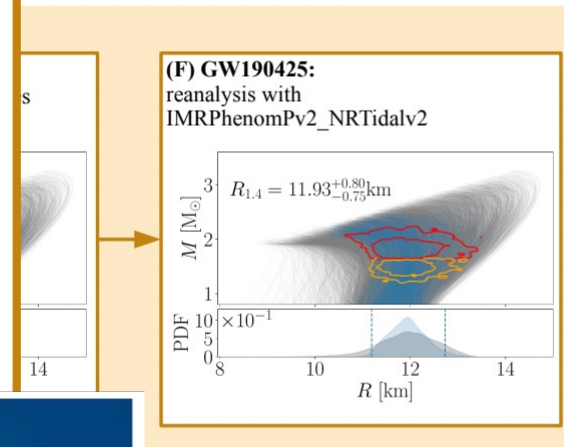
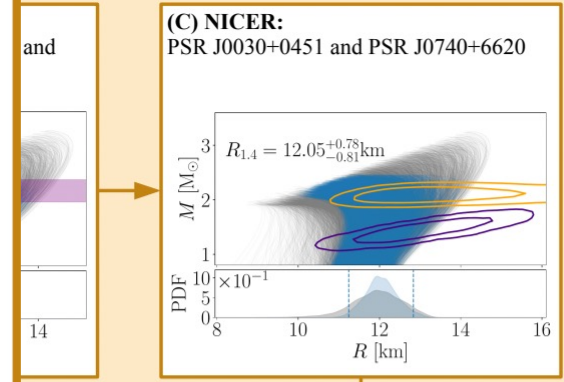


	NN	3N	4N
LO $\mathcal{O}(\frac{Q^0}{\Lambda^0})$ (2 LECs)	X H	-	-
NLO $\mathcal{O}(\frac{Q^2}{\Lambda^2})$ (7 LECs)	X H K X H	-	-
N ² LO $\mathcal{O}(\frac{Q^3}{\Lambda^3})$ (2 LECs: 3N)	H K	H H H X	-
N ³ LO $\mathcal{O}(\frac{Q^4}{\Lambda^4})$ (15 LECs)	X H K + ...	K H H X + ...	H H H H + ...



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

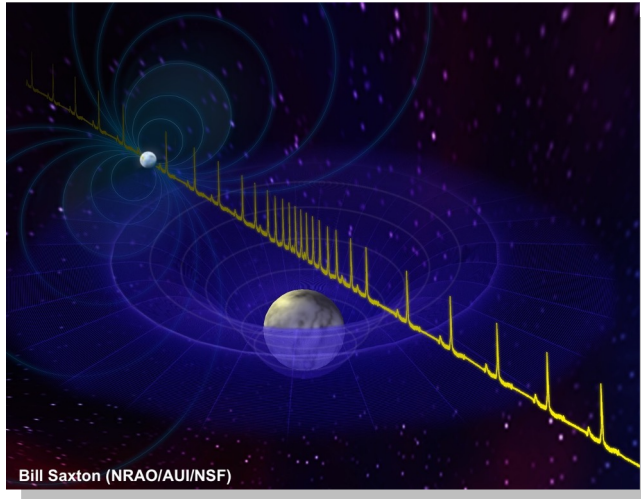
$$\mathcal{H} = \mathcal{T} + \mathcal{V}$$



EM Signals – Maximum Neutron Star Mass

lower bound

Measurement of massive pulsars through Shapiro time delay

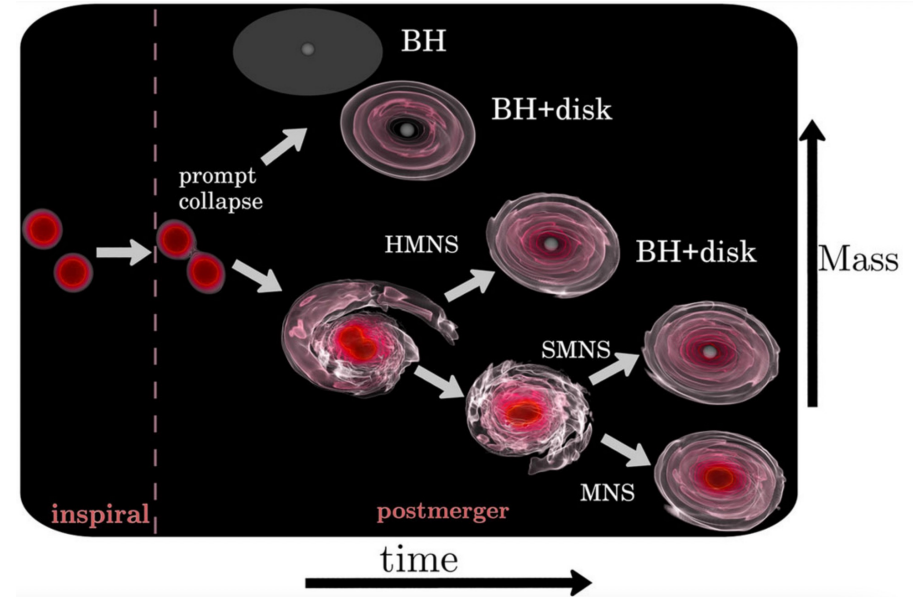


Bill Saxton (NRAO/AUI/NSF)

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

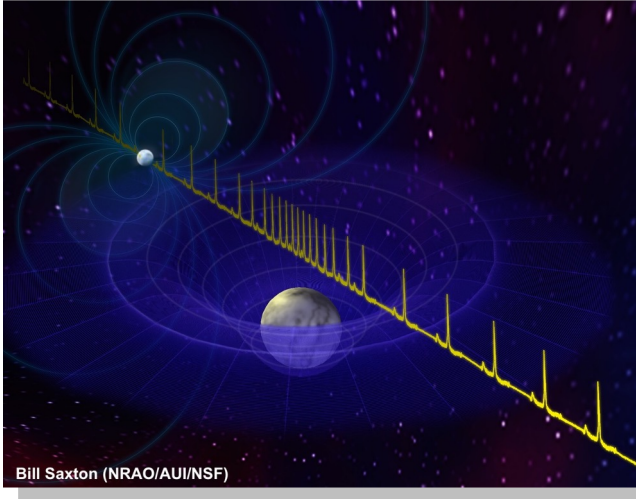
postmerger evolution of GW170817's remnant



EM Signals – Maximum Neutron Star Mass

lower bound

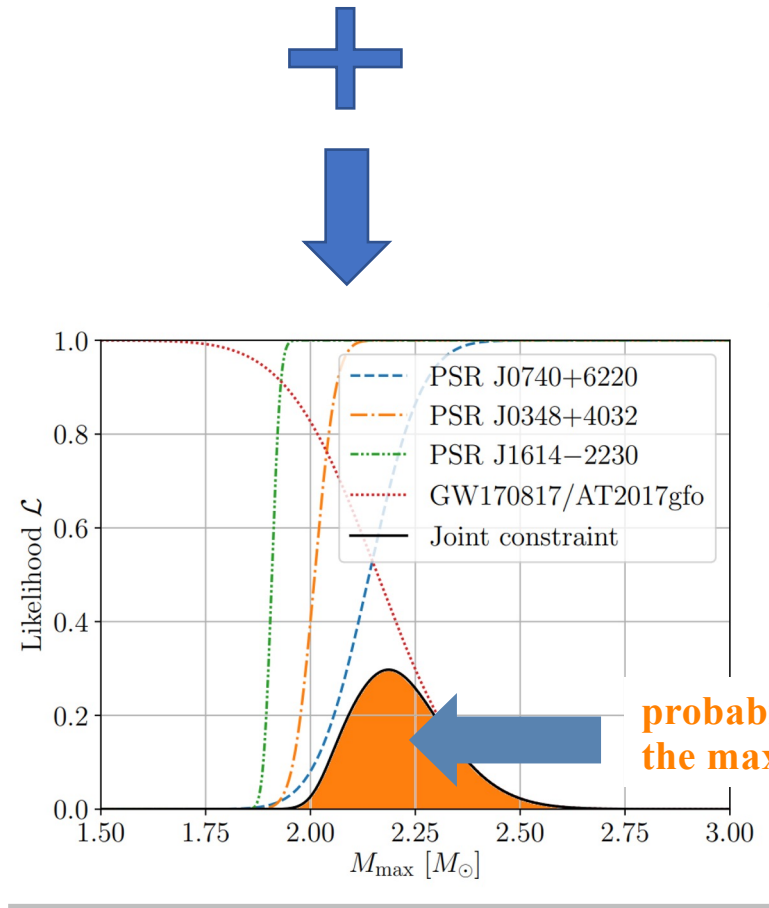
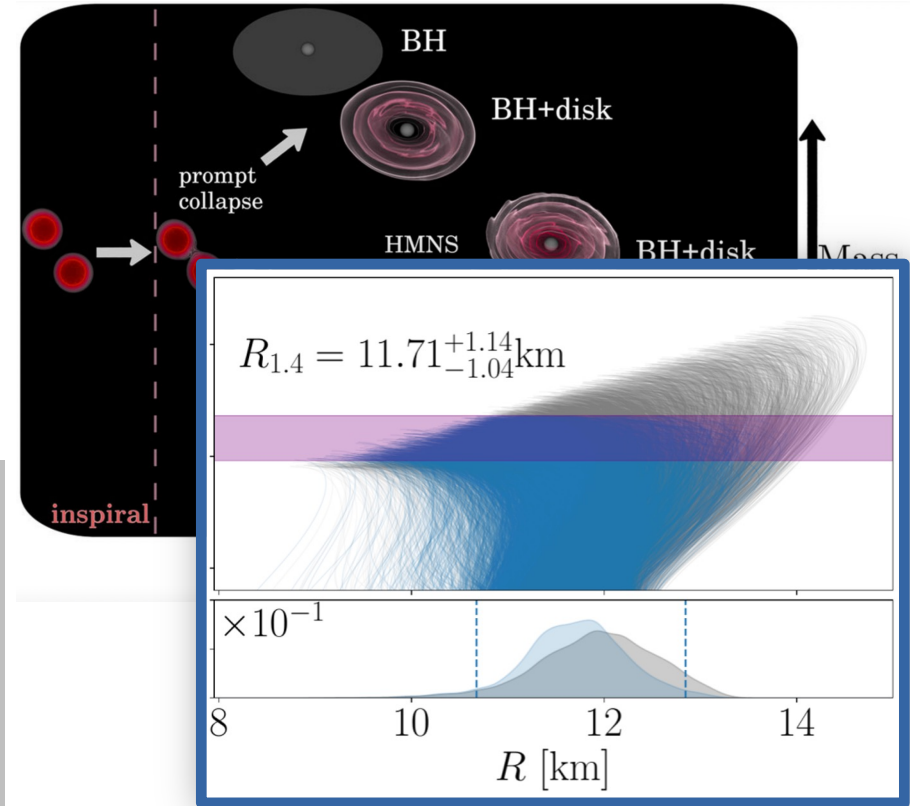
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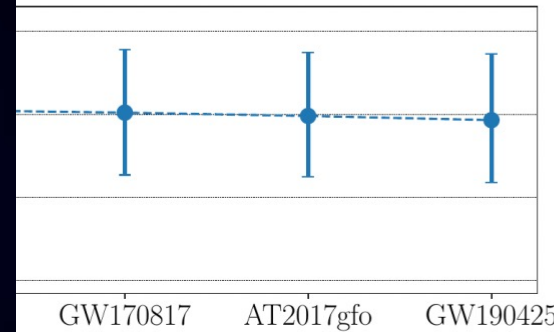
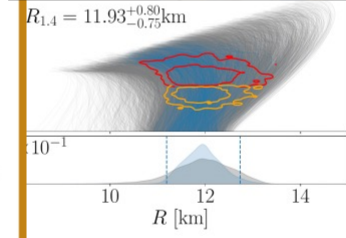
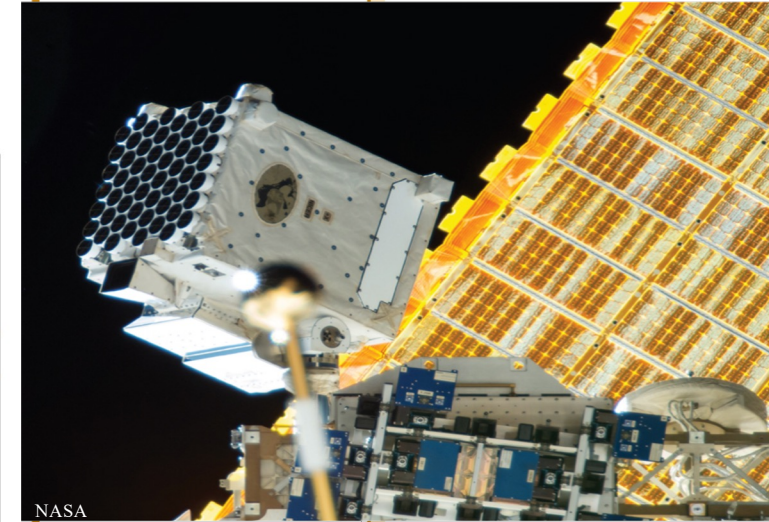
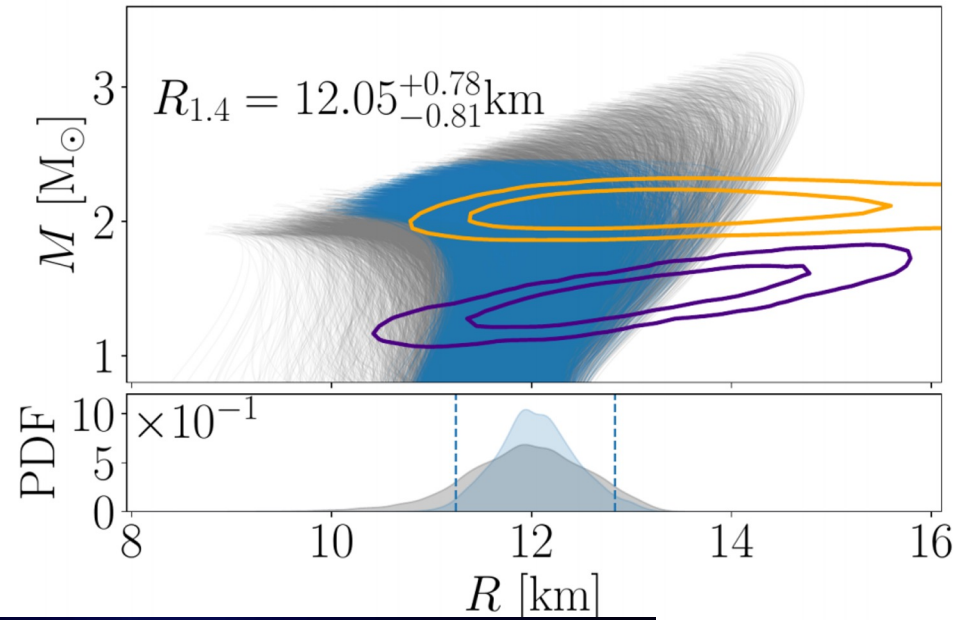
postmerger evolution of GW170817's remnant



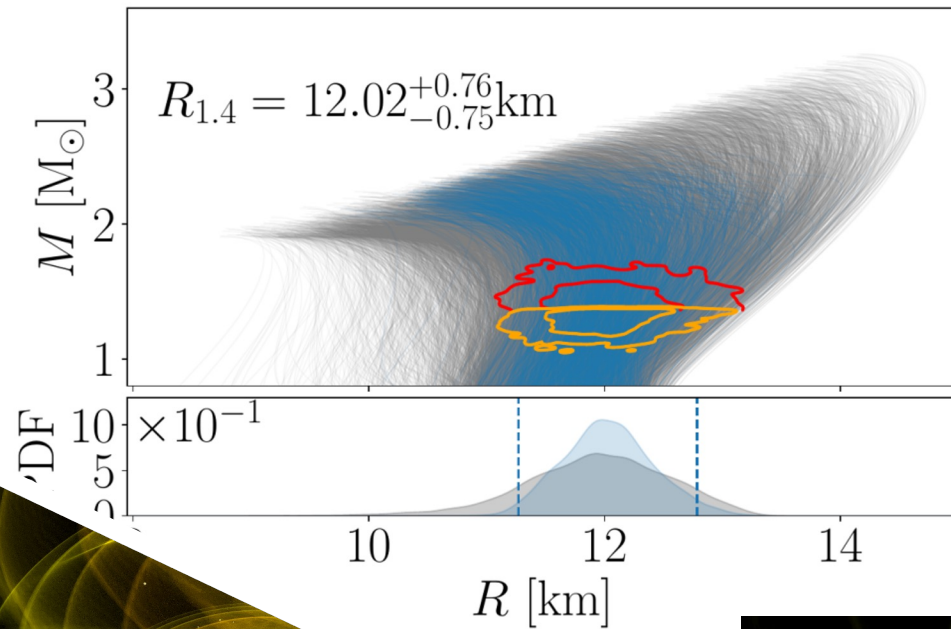
probability distribution for the maximum NS mass

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

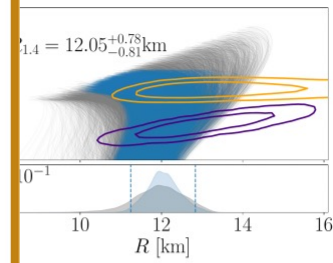
CER:
 030+0451 and PSR J0740+6620



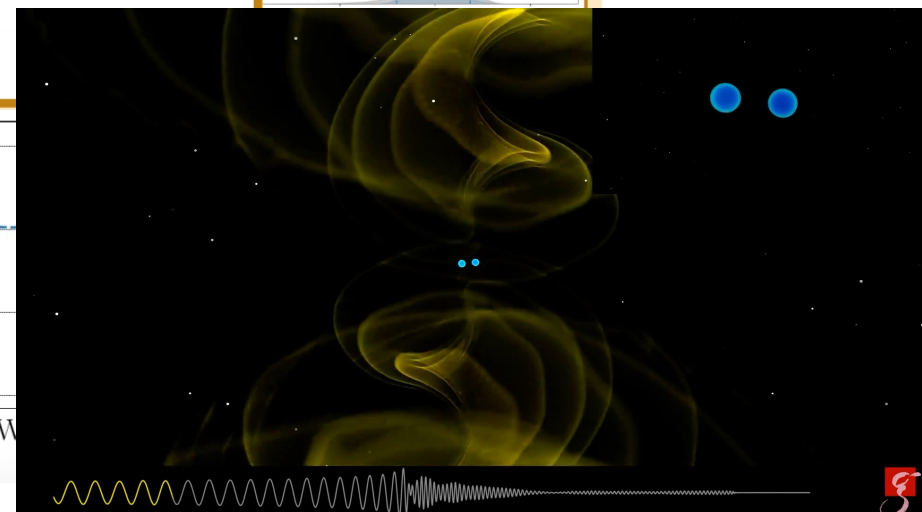
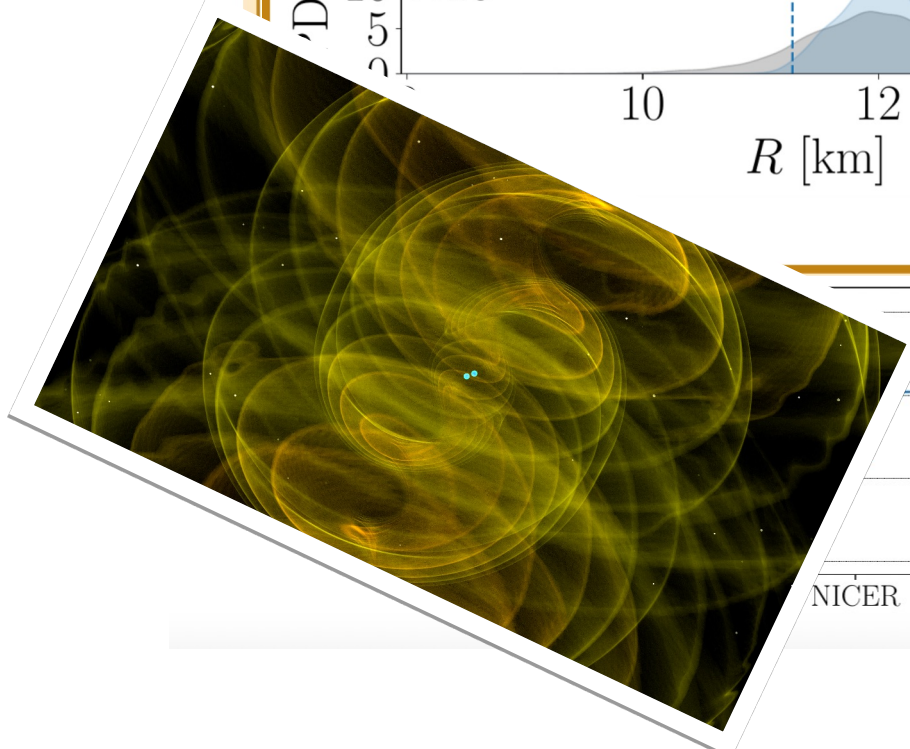
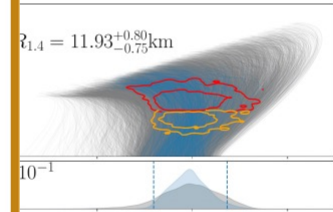
(D) GW170817:
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NICER:
PSR J030+0451 and PSR J0740+6620

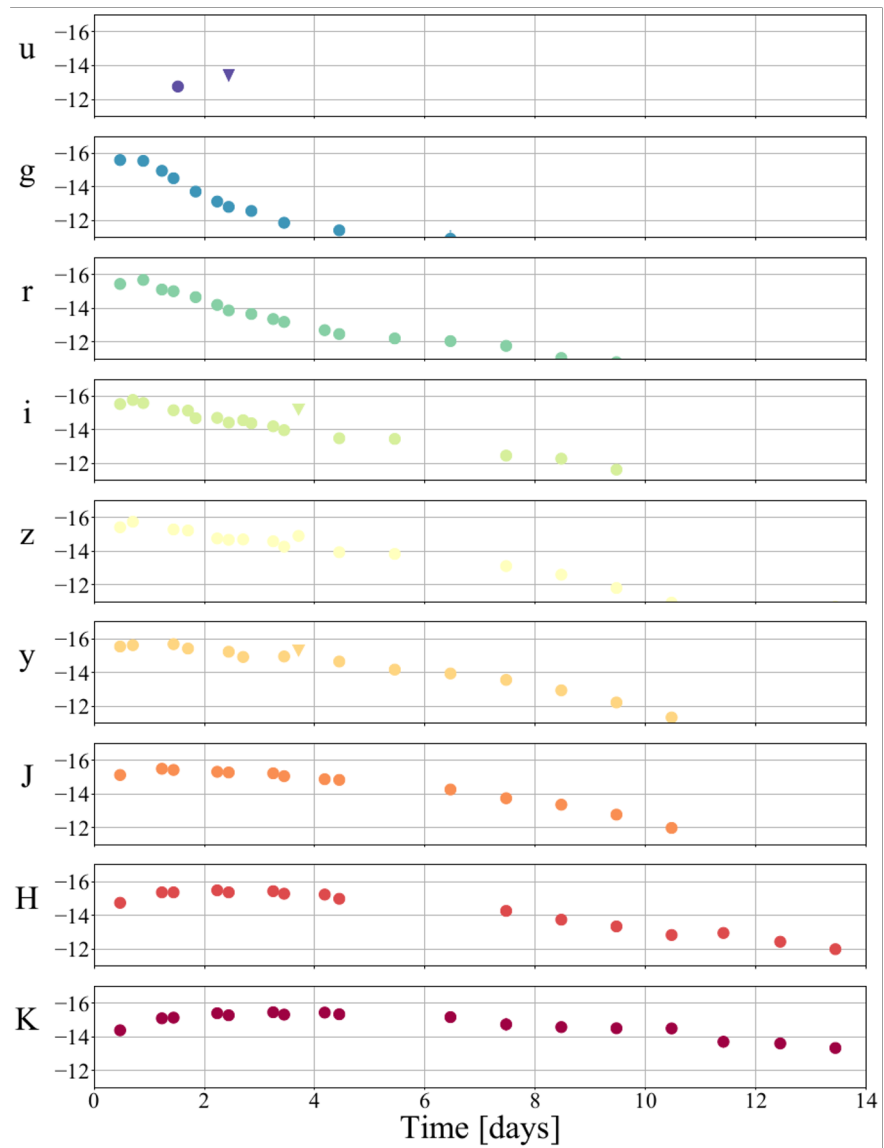


PSR J190425:
reanalysis with
IMRPhenomPv2_NRTidalv2

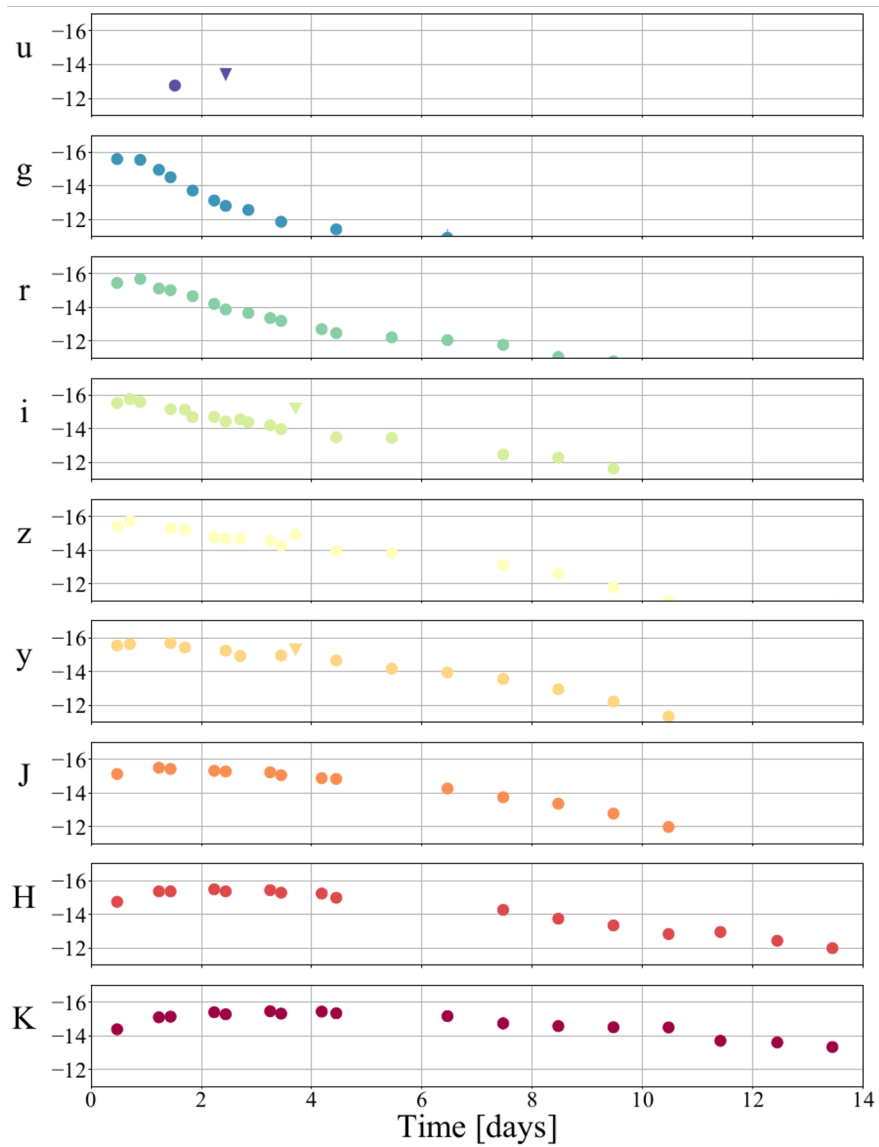


NICER GW

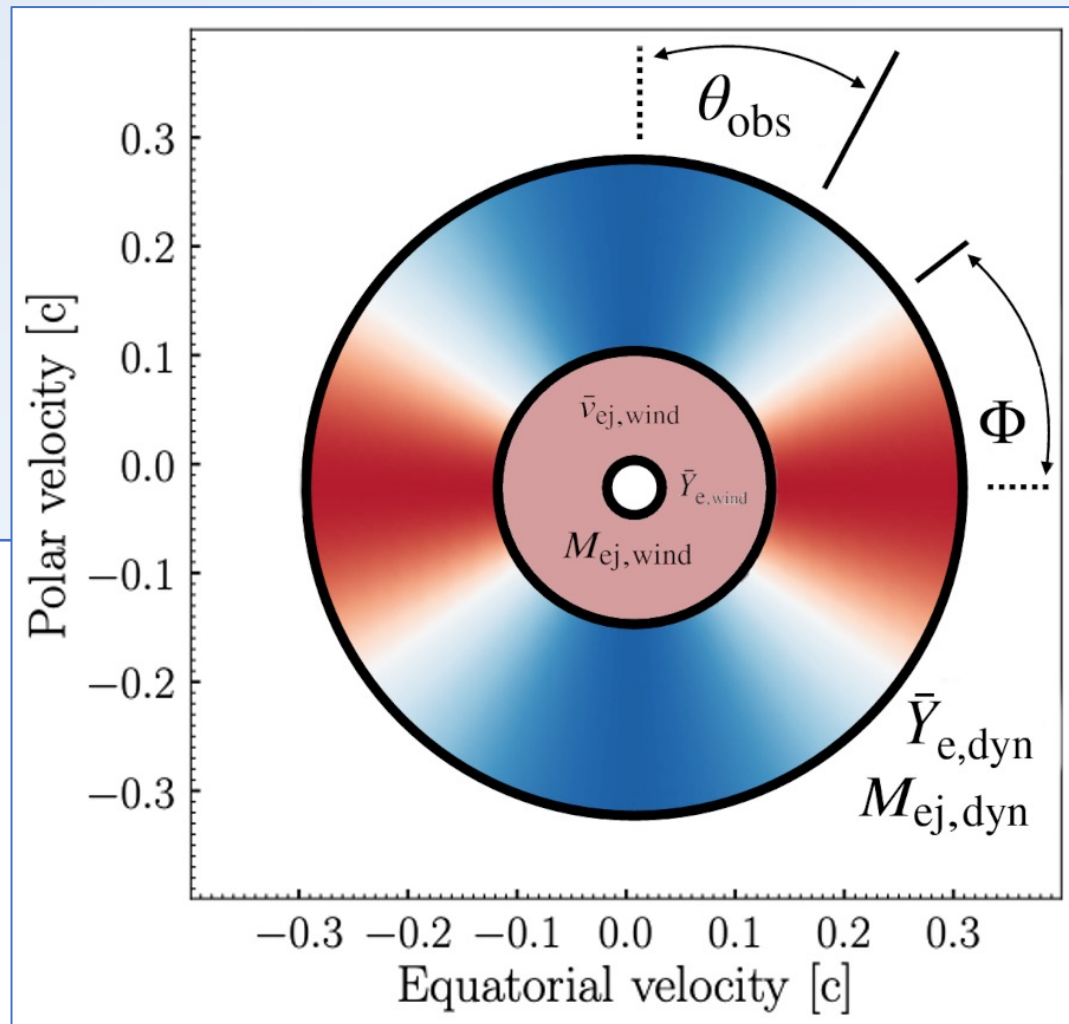
Photometric lightcurves



Photometric lightcurves

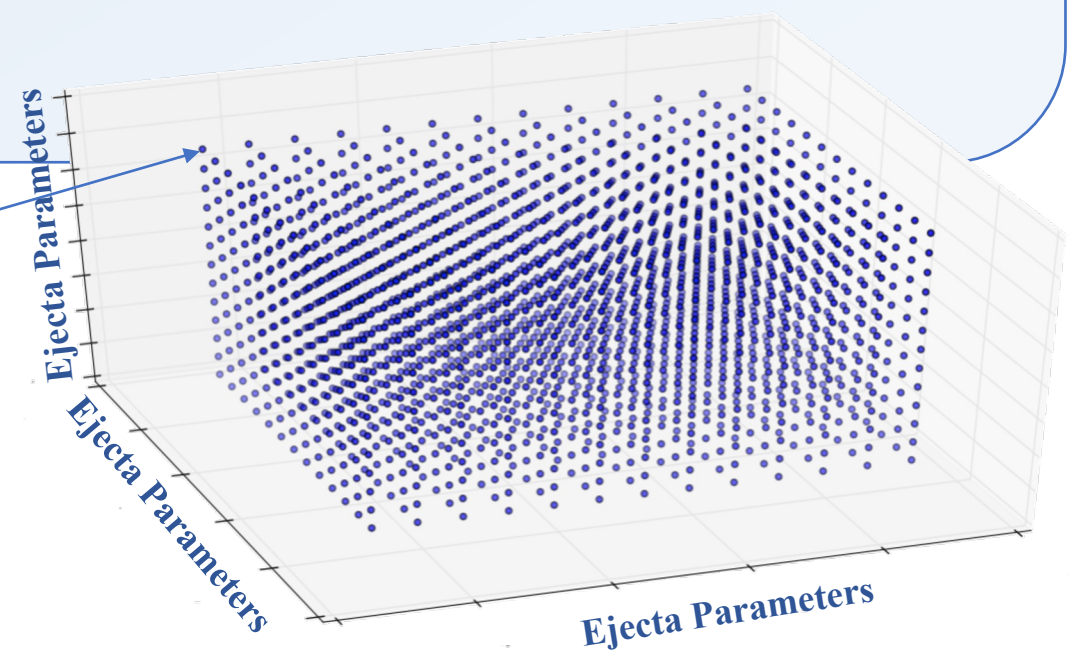
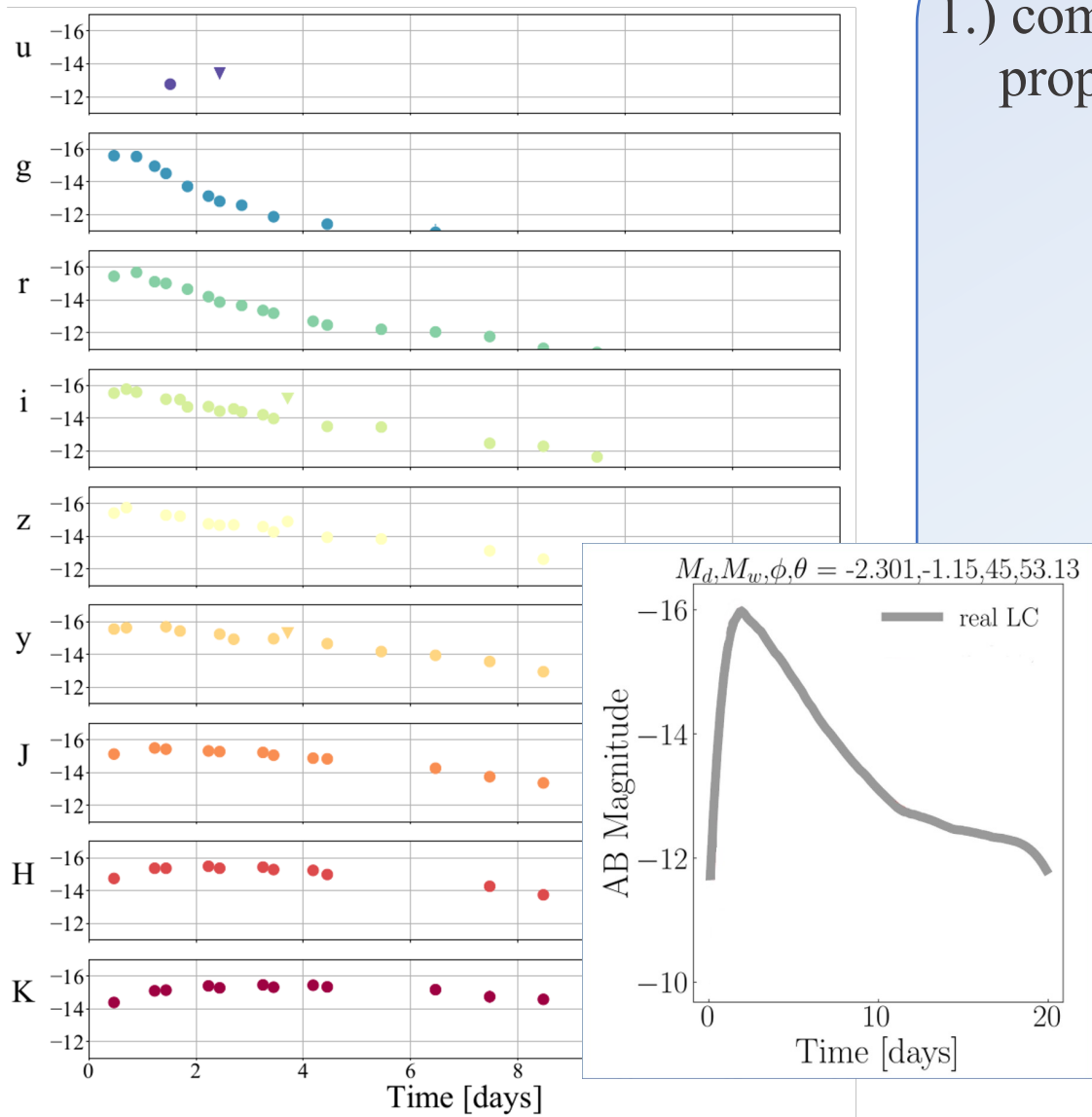


1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code



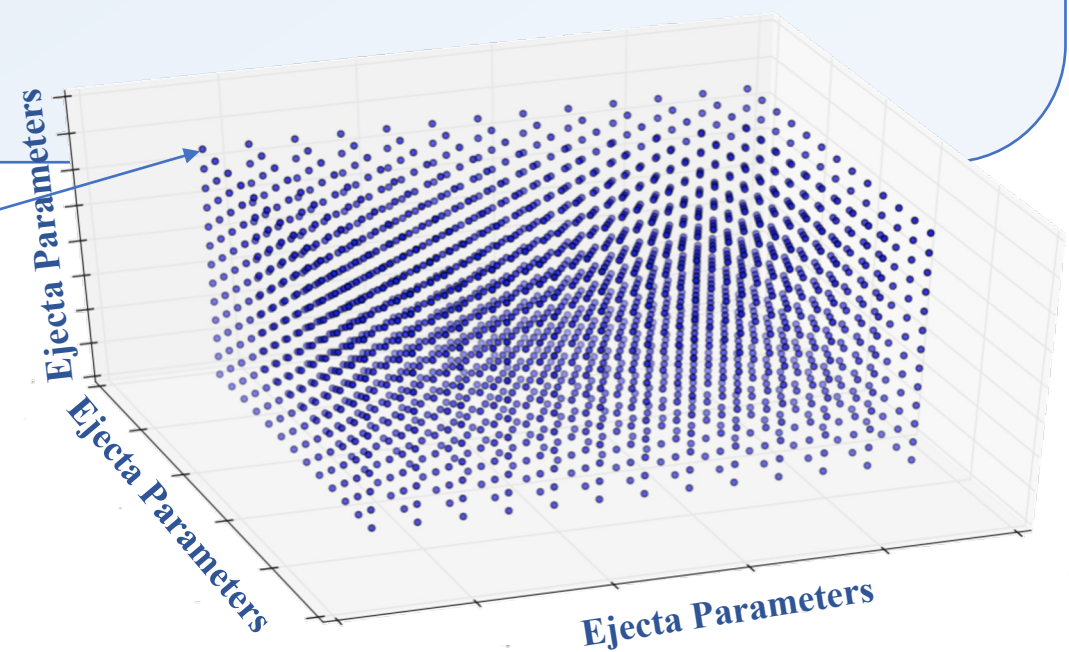
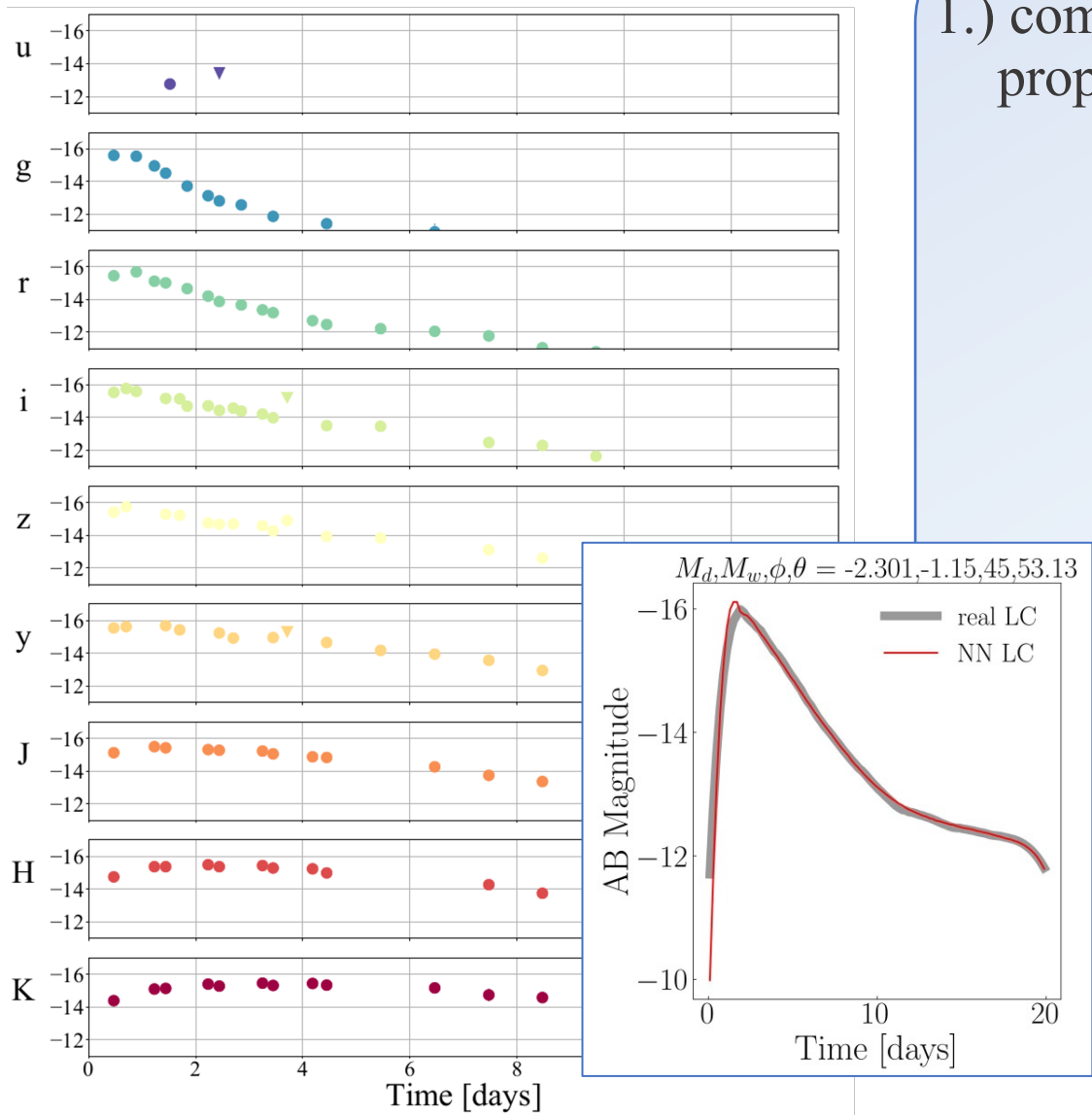
Photometric lightcurves

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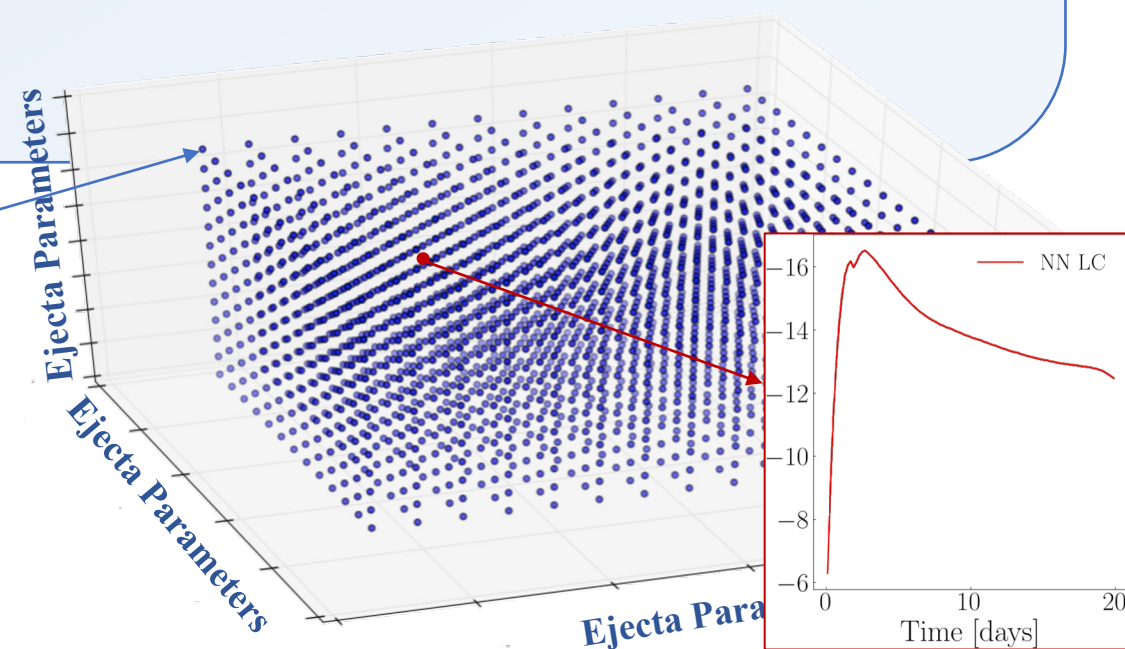
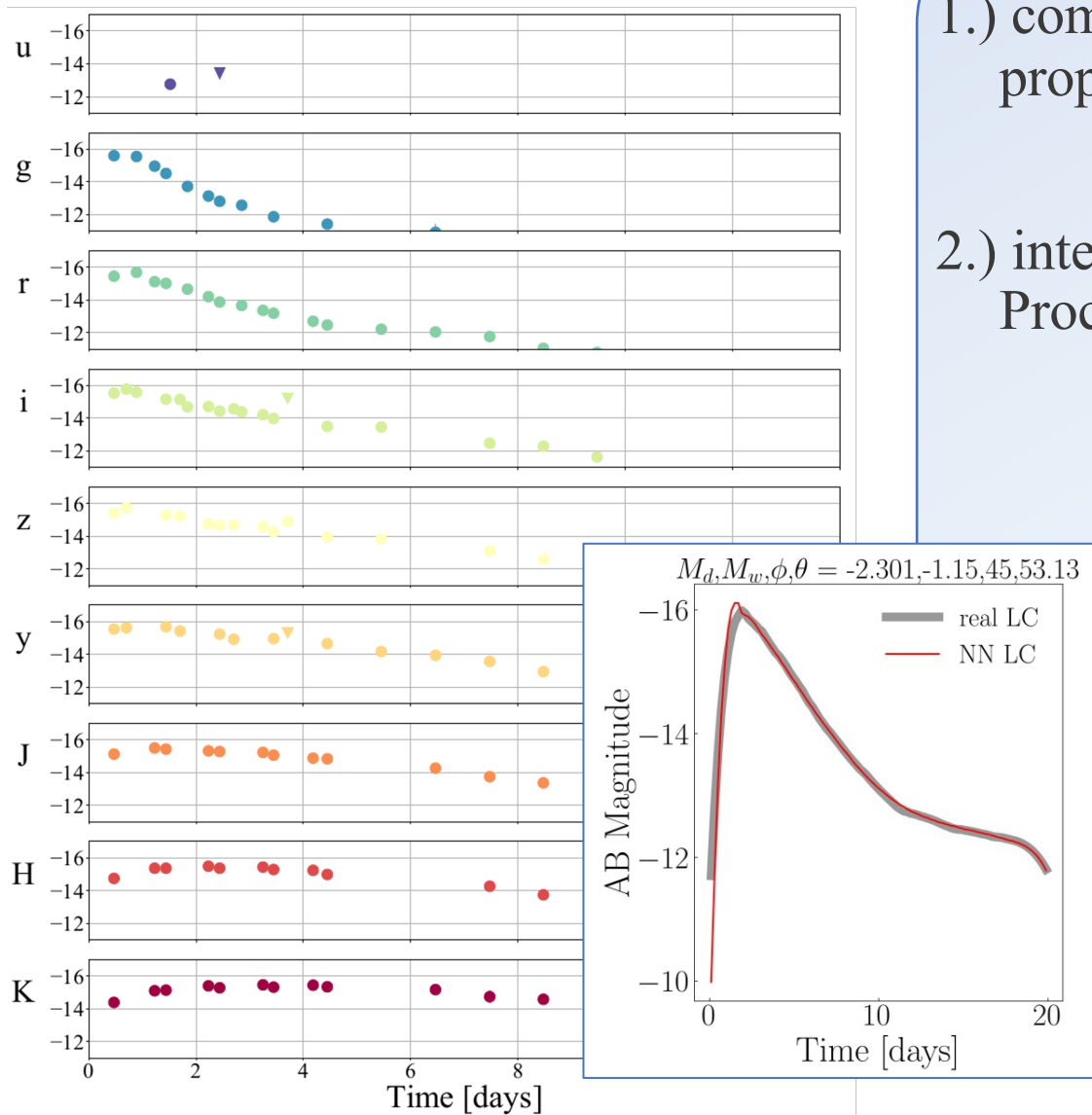
Photometric lightcurves

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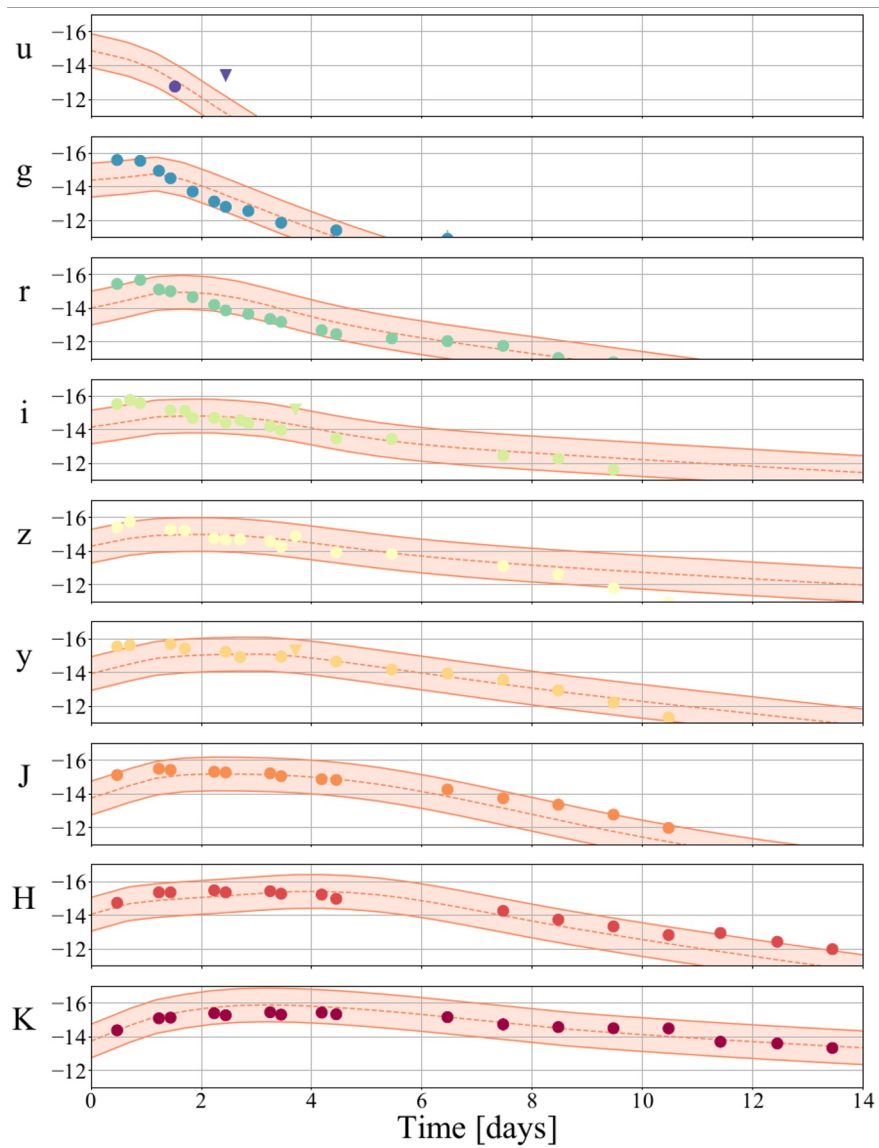


Photometric lightcurves

- 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

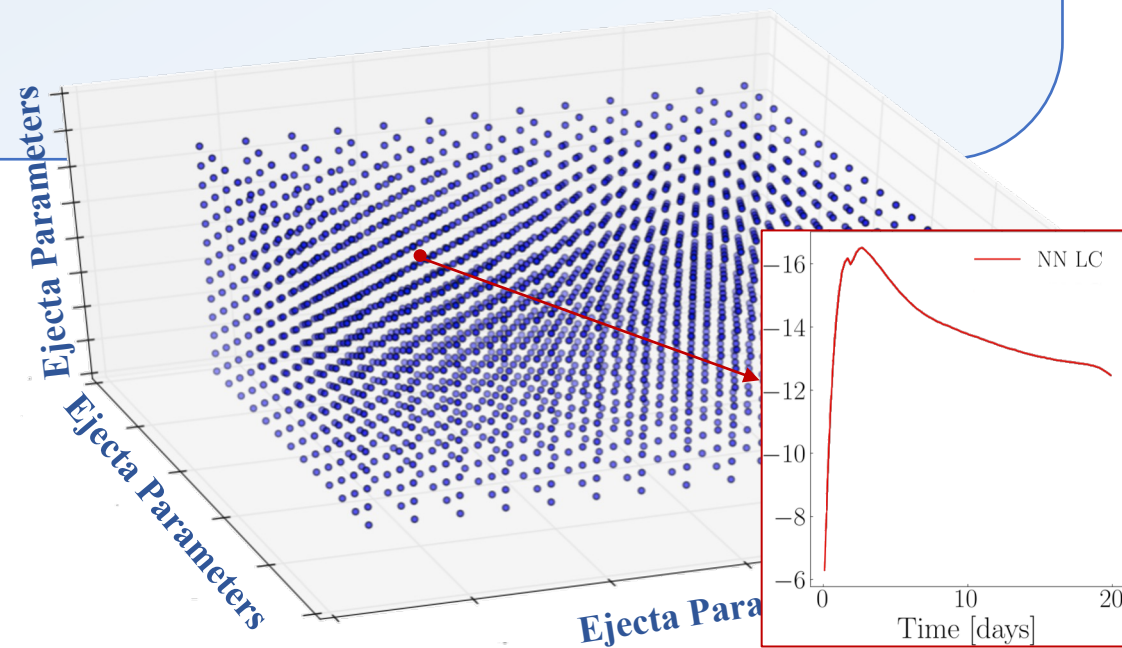


Photometric lightcurves

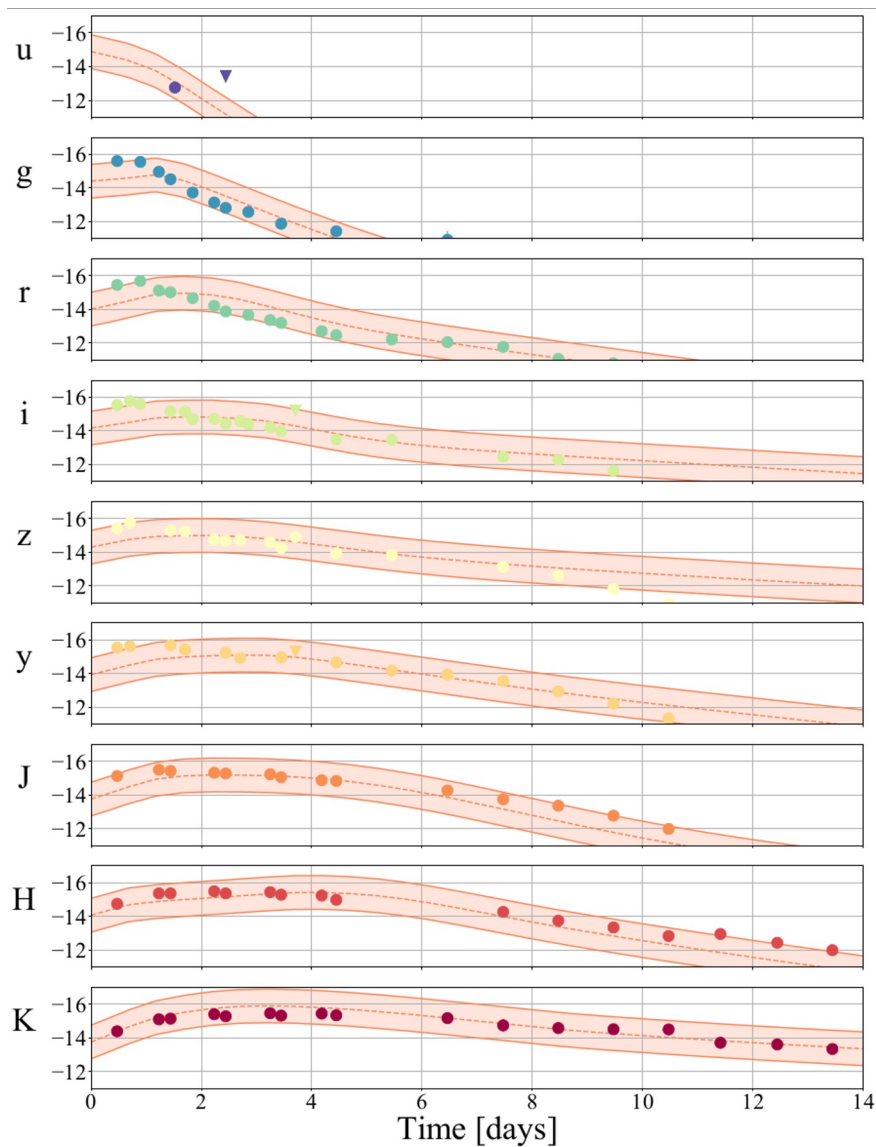


1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code

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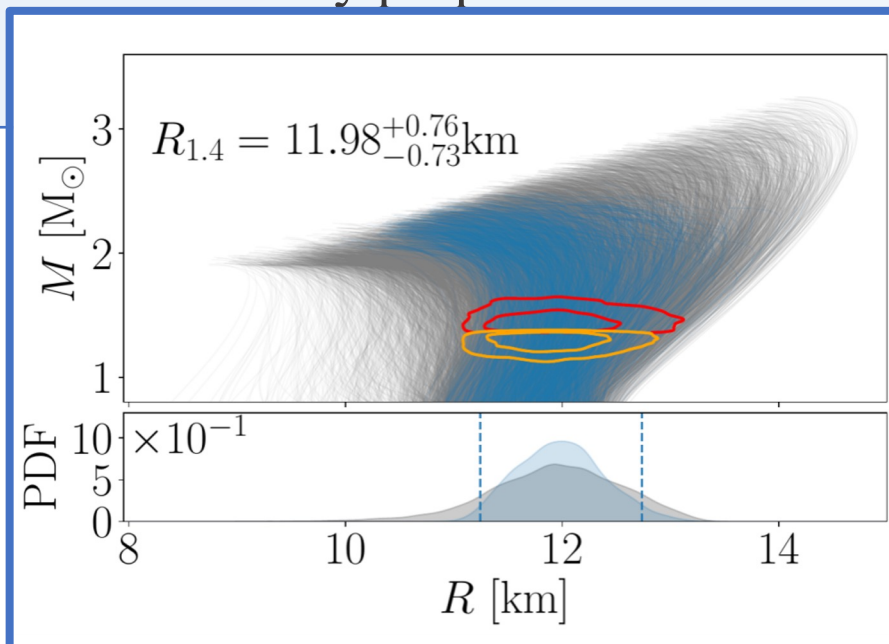
Photometric lightcurves



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

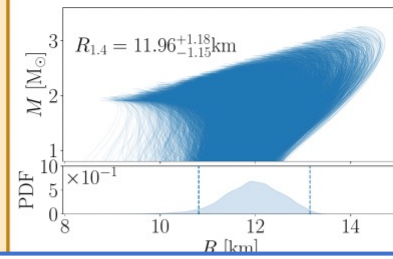
2.) interpolate within this grid through Gaussian Process Regression or a Neural Network

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

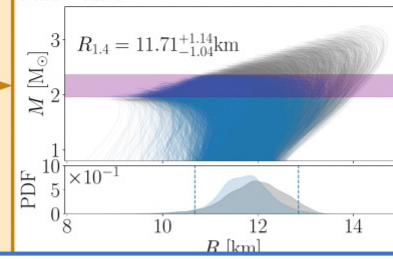


Prior construction

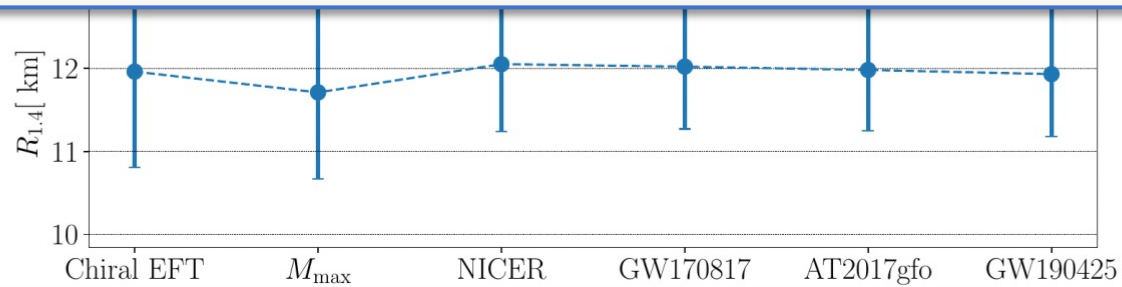
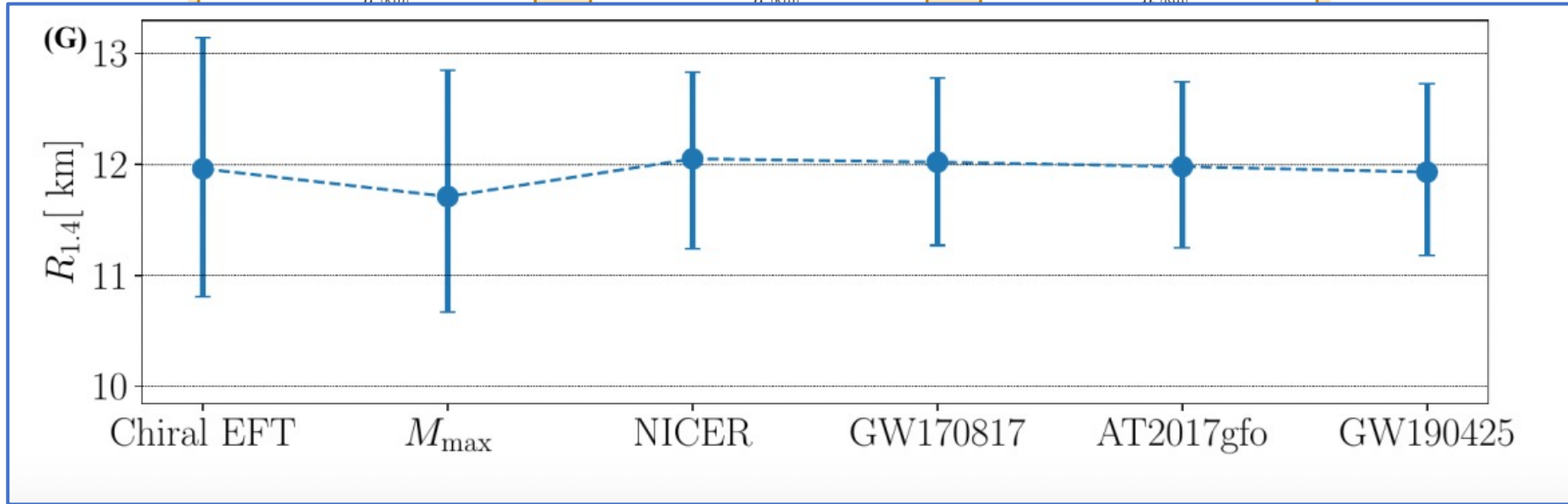
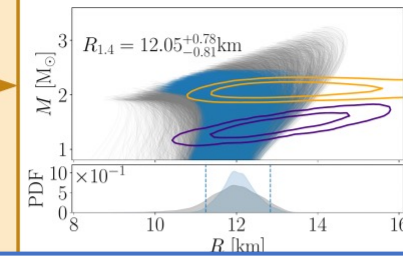
(A) Chiral effective field theory:
EOS derived with the chiral EFT result
and $M_{\max} \geq 1.9M_{\odot}$

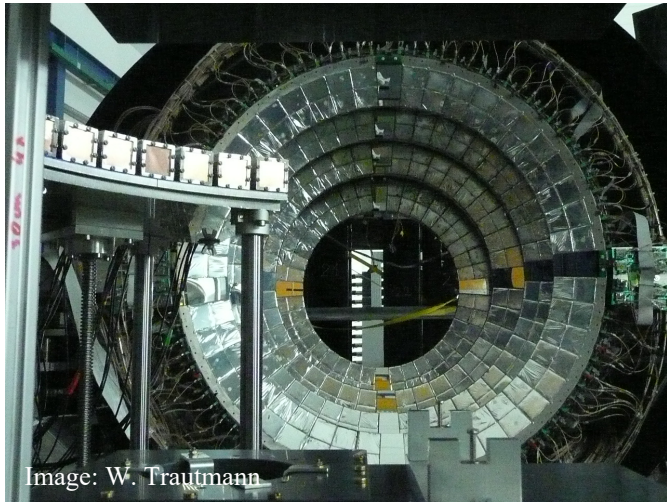


(B) Maximum Mass Constraints:
PSR J0348+4032/PSR J1614-2230 and
GW170817/AT2017gfo remnant
classification



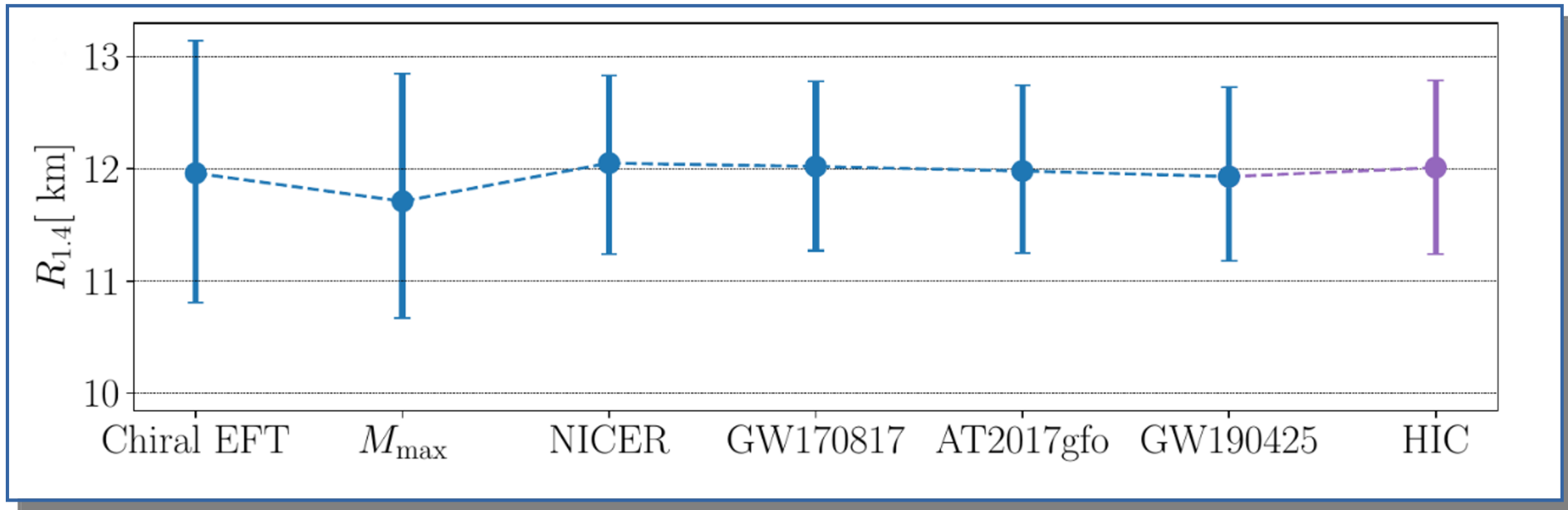
(C) NICER:
PSR J0030+0451 and PSR J0740+6620



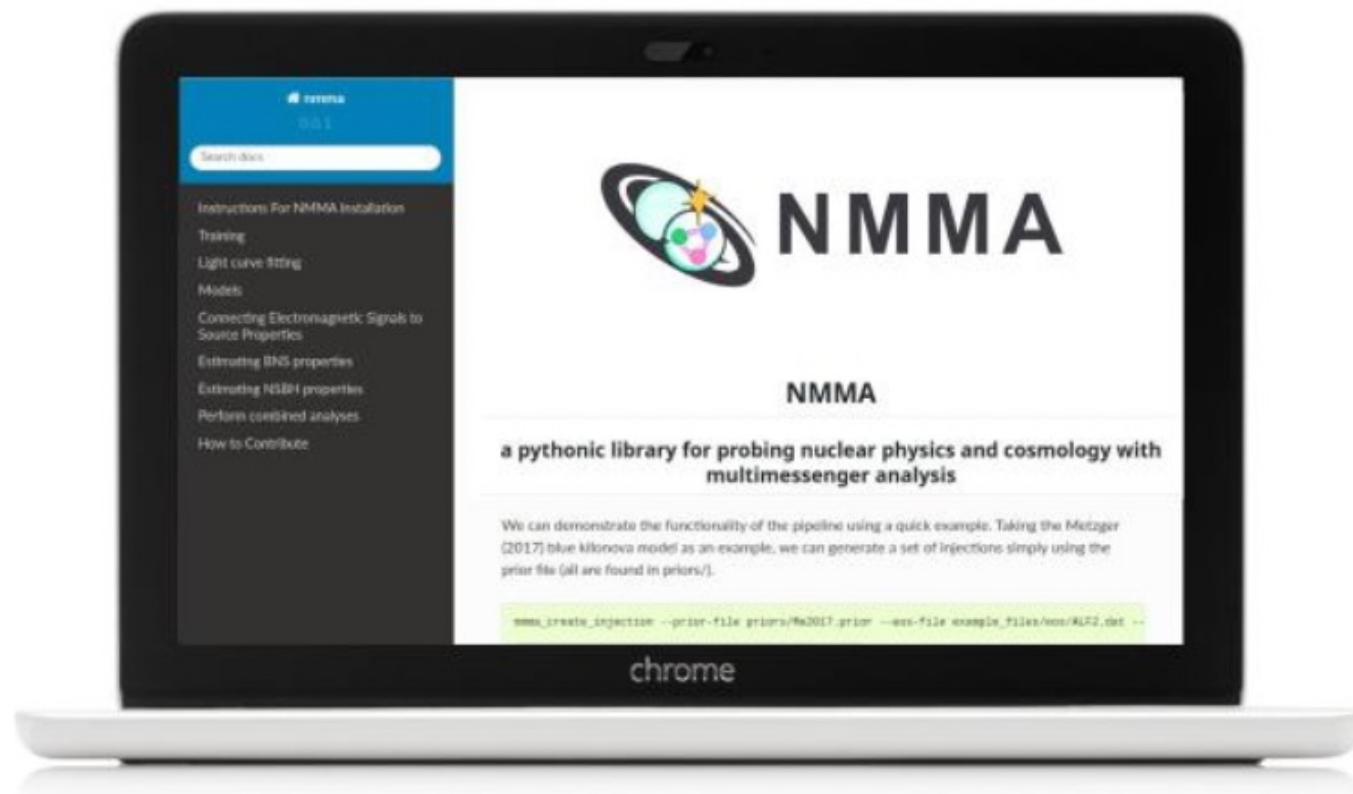


Constraining neutron-star matter with microscopic and macroscopic collisions

[Sabrina Huth](#) , [Peter T. H. Pang](#) , [Ingo Tews](#), [Tim Dietrich](#), [Arnaud Le Fèvre](#), [Achim Schwenk](#), [Wolfgang Trautmann](#), [Kshitij Agarwal](#), [Mattia Bulla](#), [Michael W. Coughlin](#) & [Chris Van Den Broeck](#)



A nuclear-physics and multi-messenger astrophysics framework



github.com/nuclear-multimessenger-astronomy

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

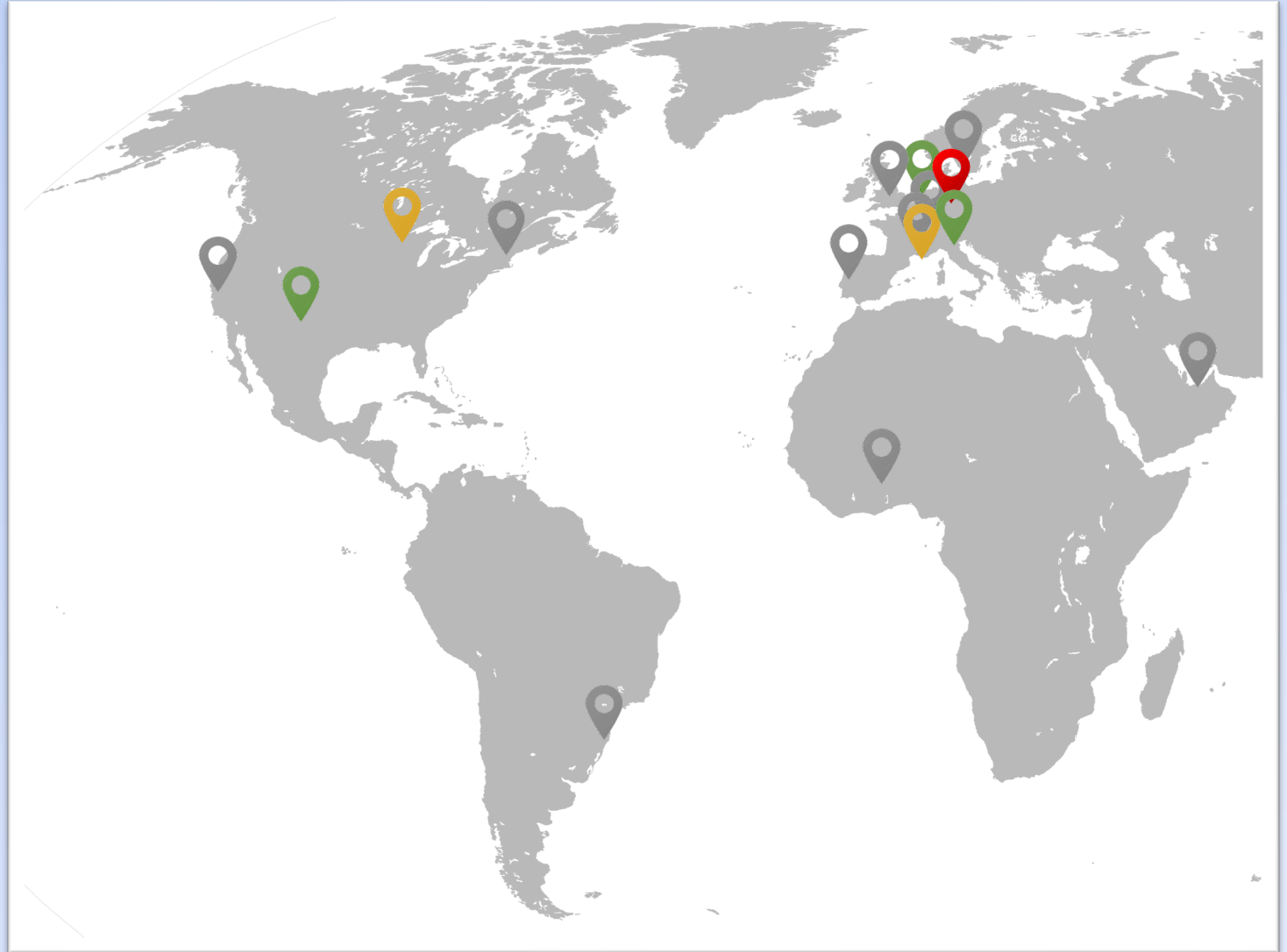
- modelling of electromagnetic signals

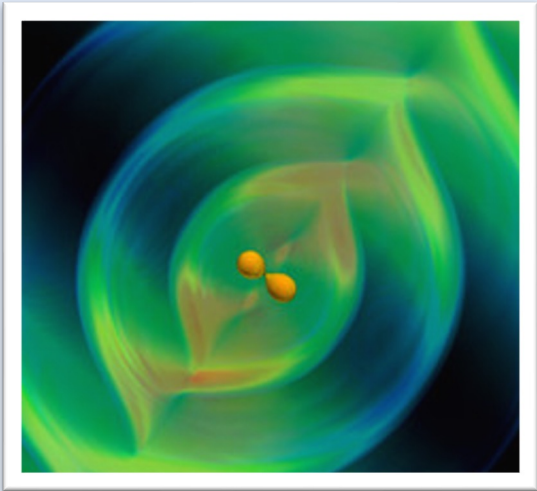
Los Alamos National Lab

- nuclear physics

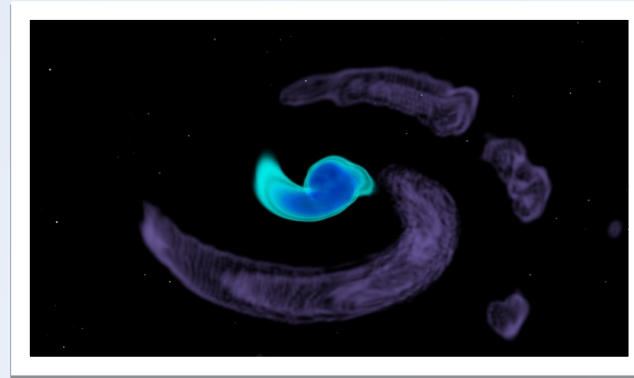
Observations

Theory

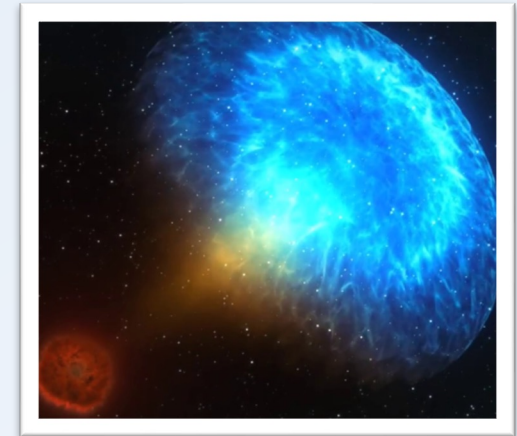




Gravitational Waves



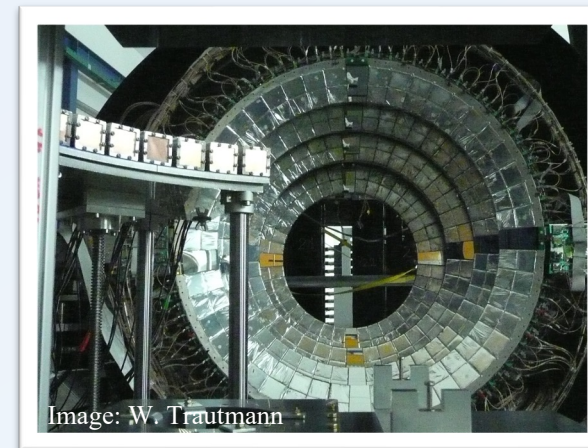
Kilonova



*Gamma-ray burst
and afterglow*

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

Nuclear-Physics Computation



Nuclear-Physics Experiments

Parameter estimation through Bayes theorem

$$p(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

*Probability of the data given
the hypothesis*

Probability of the Hypothesis

$$p(\mathcal{H}|d) = \frac{p(d|\mathcal{H})P(\mathcal{H})}{P(d)}$$

*Probability of the Hypothesis
given the data*

Probability of the data

Parameter estimation through Bayes theorem

$$p(\vec{\theta}|d, \mathcal{H}) = \frac{p(d|\vec{\theta}, \mathcal{H})p(\vec{\theta}|\mathcal{H})}{p(d|\mathcal{H})} \equiv \frac{\mathcal{L}(\vec{\theta})\pi(\vec{\theta})}{\mathcal{Z}(d)}$$

Parameter estimation through Bayes theorem

$$p(\vec{\theta}|d, \mathcal{H}) = \frac{p(d|\vec{\theta}, \mathcal{H})p(\vec{\theta}|\mathcal{H})}{p(d|\mathcal{H})} \equiv \frac{\mathcal{L}(\vec{\theta})\pi(\vec{\theta})}{\mathcal{Z}(d)}$$

$$\mathcal{L}(\vec{\theta}) = \mathcal{L}_{\text{GW}}(\vec{\theta}_{\text{GW}}) \times \mathcal{L}_{\text{EM}}(\vec{\theta}_{\text{EM}})$$

Parameter estimation through Bayes theorem

$$p(\vec{\theta}|d, \mathcal{H}) = \frac{p(d|\vec{\theta}, \mathcal{H})p(\vec{\theta}|\mathcal{H})}{p(d|\mathcal{H})} \equiv \frac{\mathcal{L}(\vec{\theta})\pi(\vec{\theta})}{\mathcal{Z}(d)}$$

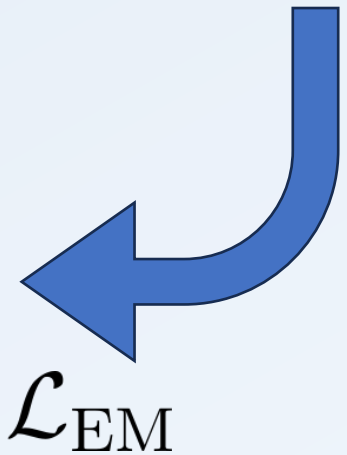
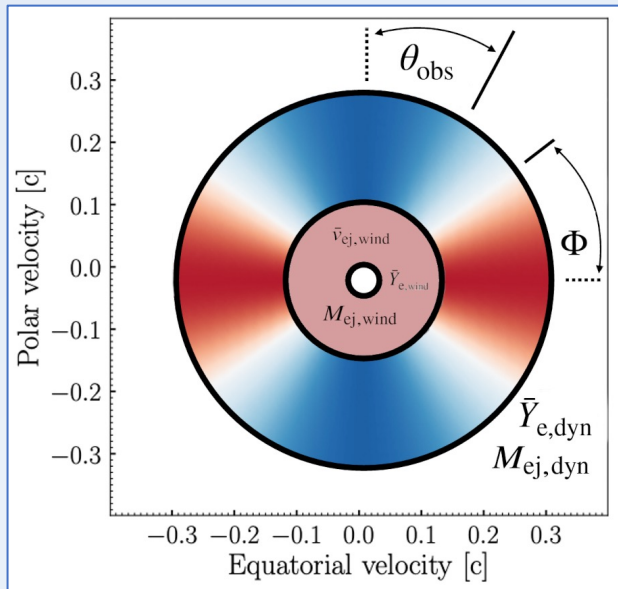
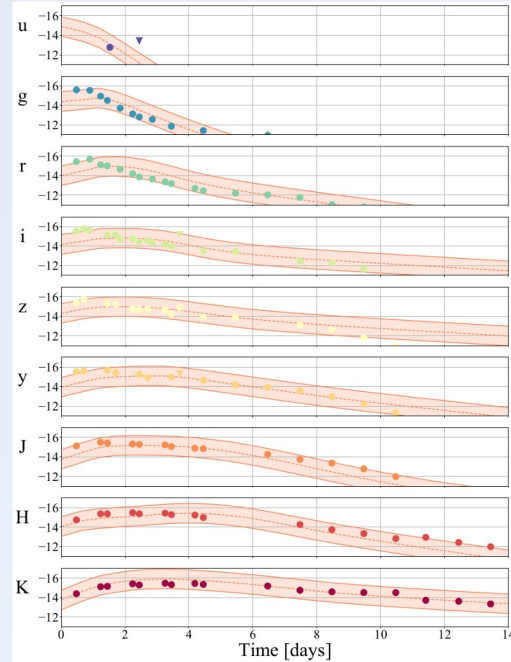
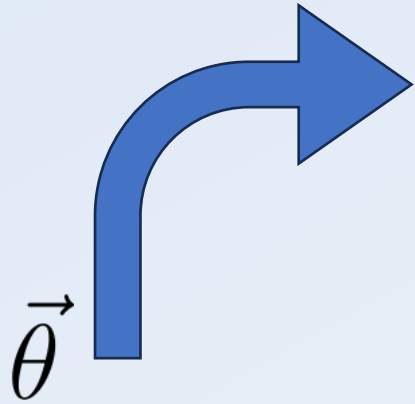
$$\mathcal{L}(\vec{\theta}) = \mathcal{L}_{\text{GW}}(\vec{\theta}_{\text{GW}}) \times \mathcal{L}_{\text{EM}}(\vec{\theta}_{\text{EM}})$$

$$\mathcal{L}_{\text{GW}} \propto \exp\left(-\frac{1}{2}\langle d - h(\vec{\theta})|d - h(\vec{\theta})\rangle\right)$$

$$\mathcal{L}_{\text{EM}} \propto \exp\left(-\frac{1}{2}\sum_{ij}\left(\frac{m_i^j - m_i^{j,\text{est}}(\vec{\theta})}{\sigma_i^j}\right)^2\right)$$

$$\langle a|b\rangle = 4\Re \int_{f_{\text{low}}}^{f_{\text{high}}} \frac{\tilde{a}(f)\tilde{b}^*(f)}{S_n(f)} df$$

Parameter estimation through Bayes theorem



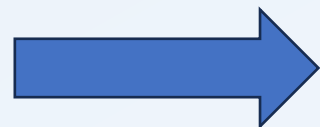
$$\mathcal{L}_{EM} \propto \exp \left(-\frac{1}{2} \sum_{ij} \left(\frac{m_i^j - m_i^{j,est}(\vec{\theta})}{\sigma_i^j} \right)^2 \right)$$

Hypothesis testing through Bayes theorem

$$\frac{p(\mathcal{H}_1|d, I)}{p(\mathcal{H}_2|d, I)} = \frac{p(d|\mathcal{H}_1, I)p(\mathcal{H}_1|I)}{p(d|\mathcal{H}_2, I)p(\mathcal{H}_2|I)}$$
$$\mathcal{O}_2^1 = \mathcal{B}_2^1 \Pi_2^1$$

\mathcal{O}_2^1 :Odds ratio
 \mathcal{B}_2^1 :Bayes factor
 Π_2^1 :Prior odds

Occam's razor is automatically built in, i.e., if two hypotheses explain the data equally well, the simpler one is preferred

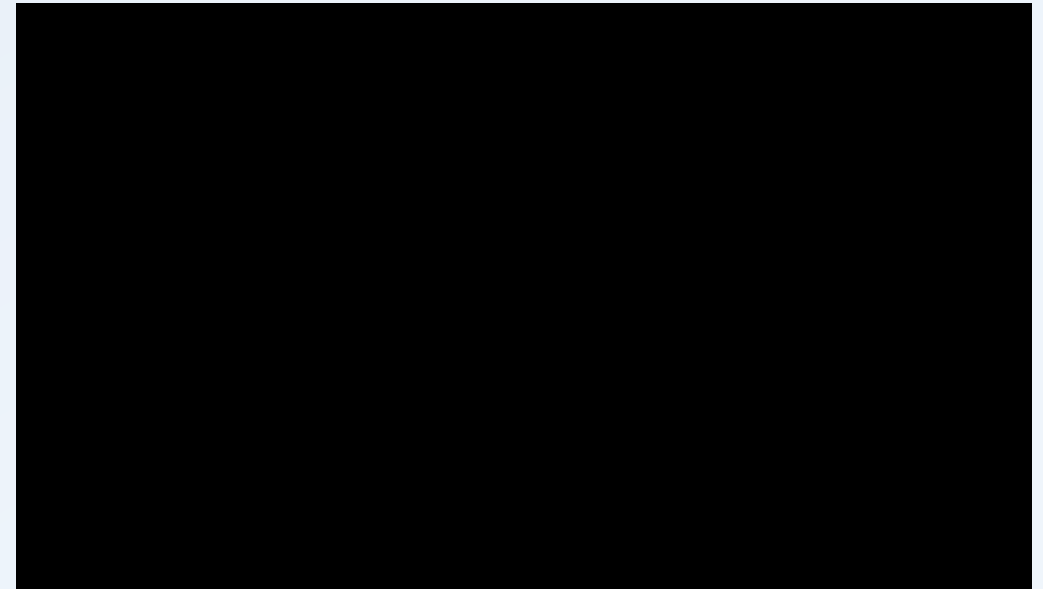
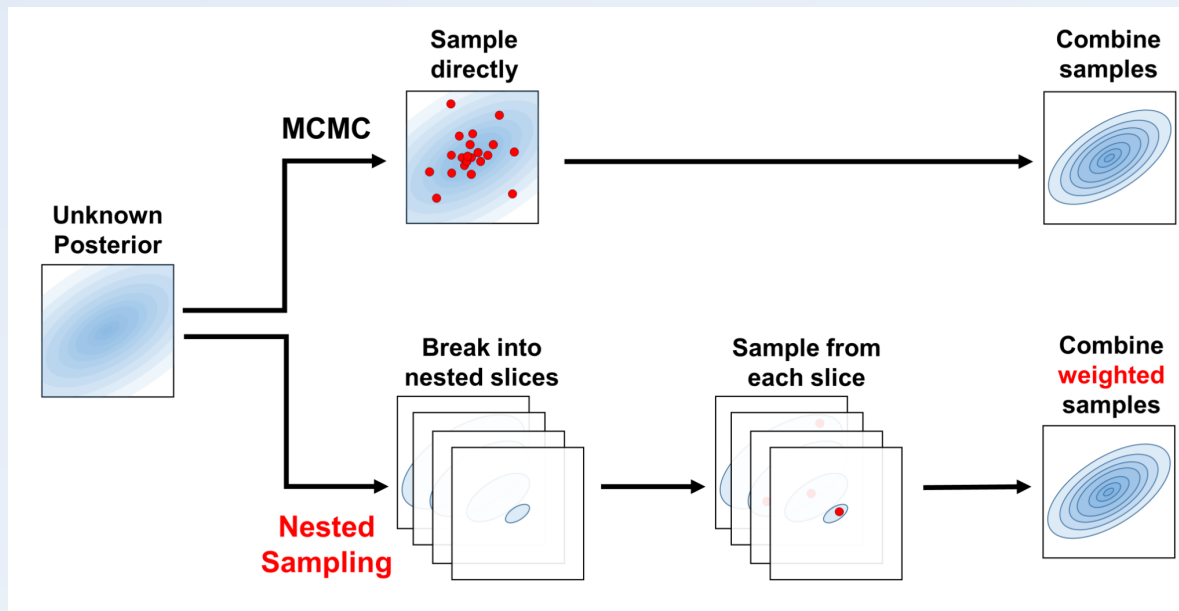


Model selection

Hypothesis testing through Bayes theorem

- Estimate the posterior distribution
 - Sample from the posterior distribution
 - Markov chain Monte Carlo (MCMC)

- Estimate the Bayesian evidence
 - Monte Carlo integration
 - Parallel-tempering MCMC
 - Nested sampling



NMMA Details:



- **EOS information**

- precomputed EOS sets
- Sampling in tidal deformability/compactness

- **additional astrophysical information**

- e.g. NICER/pulsar measurements through full posteriors

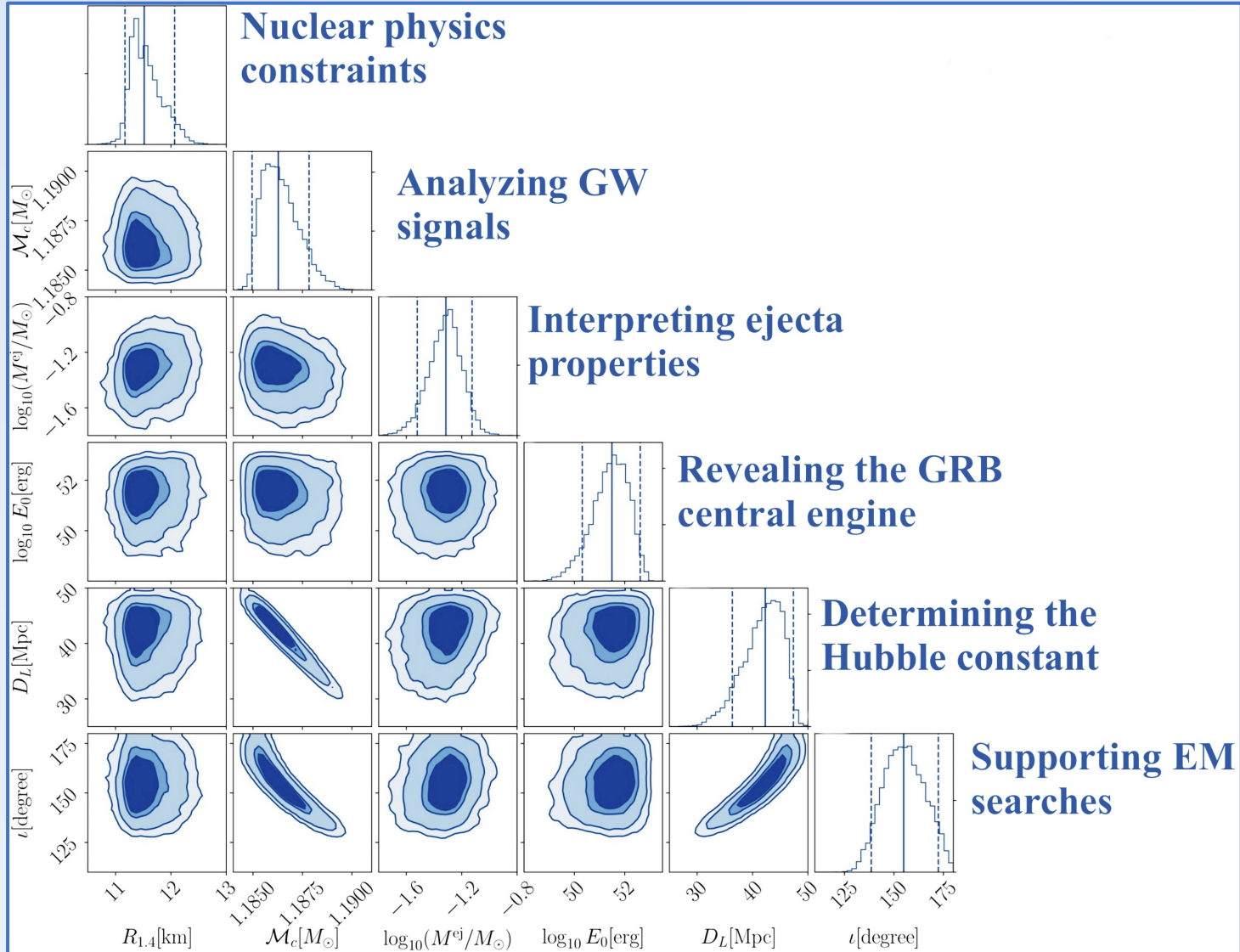
- **GW models employing LALSimulation/sampling through bilby**

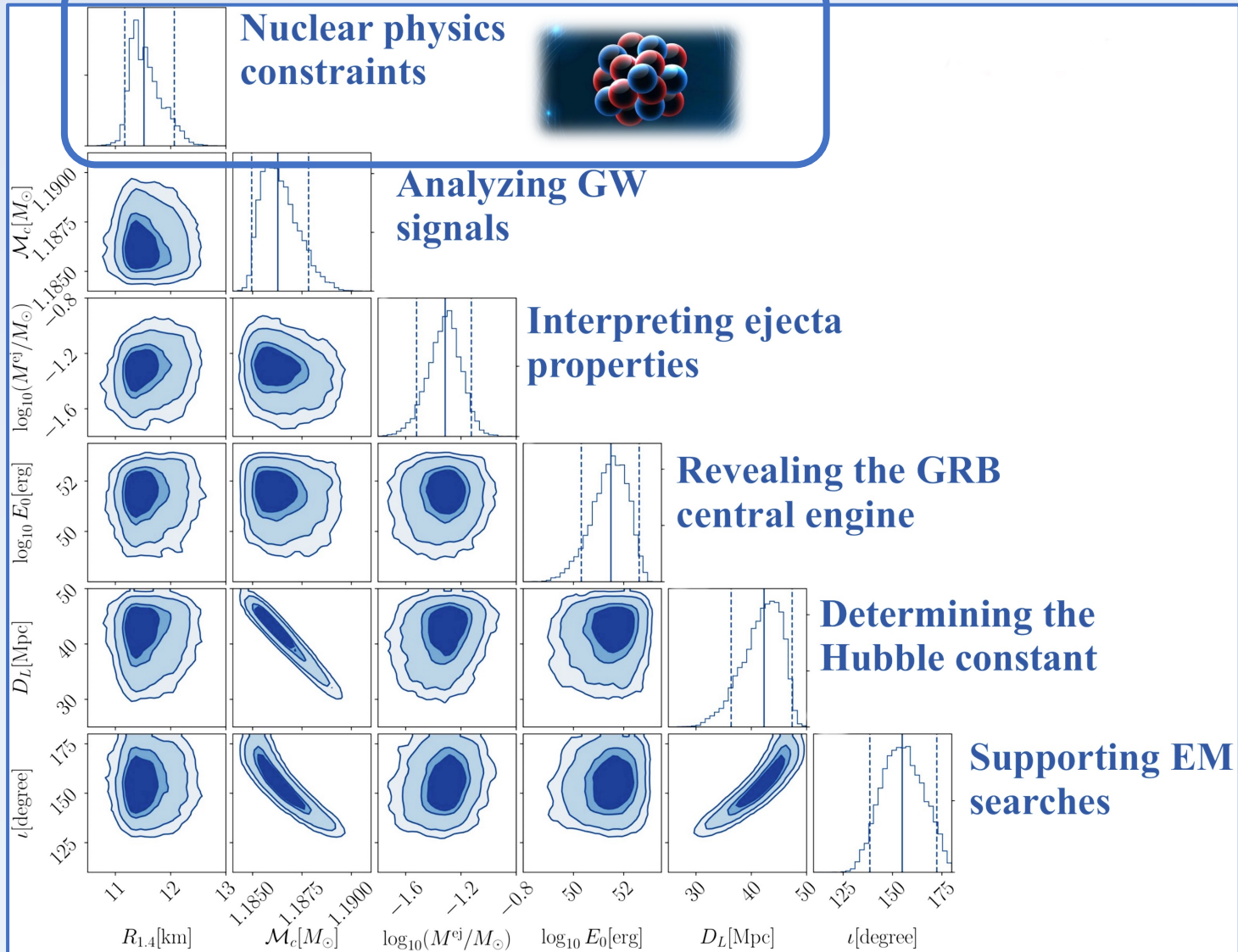
- **kilonova models**

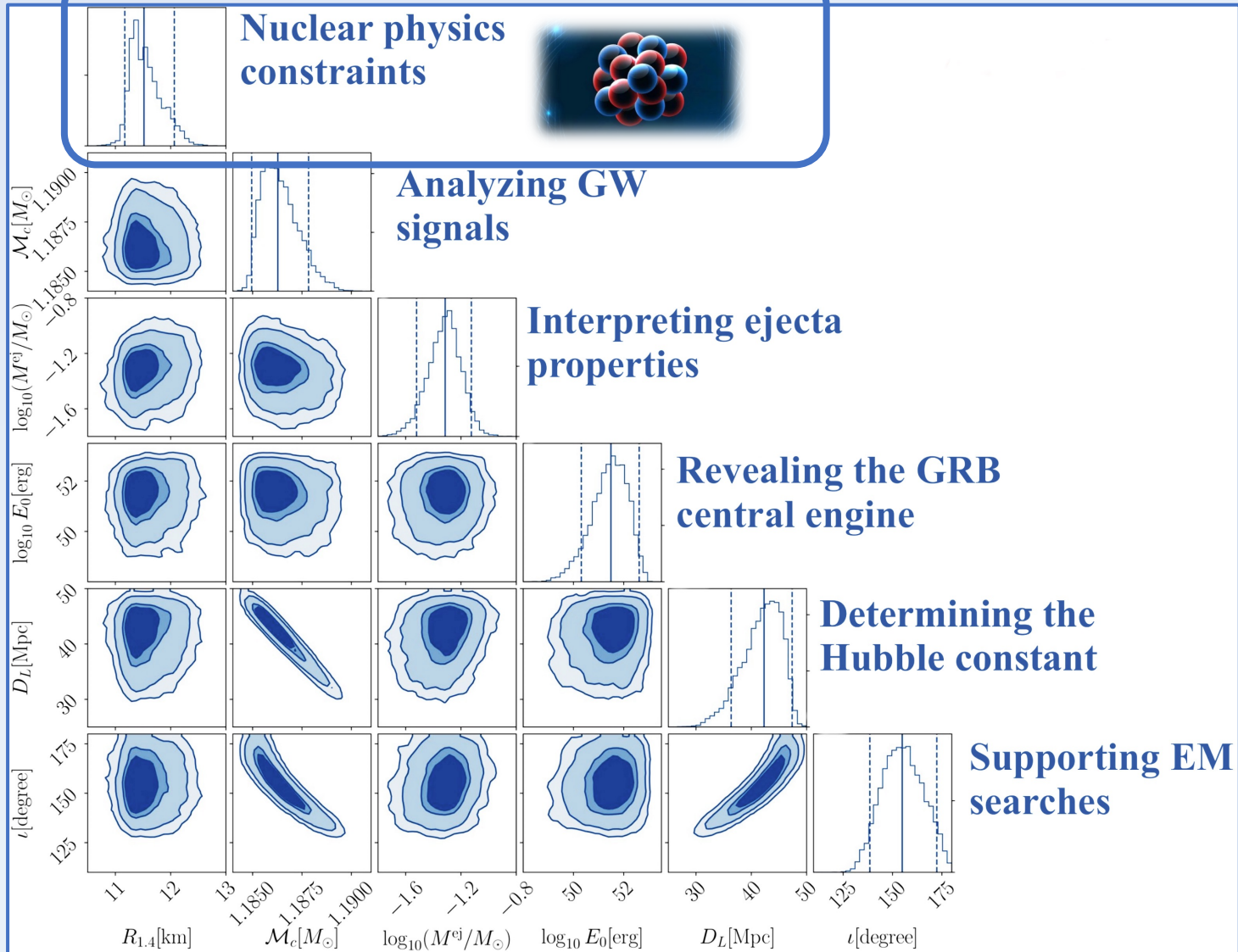
- simple analytic models
- radiative transfer simulations (POSSIS, Kasen et al.)

- **GRB afterglow:**

- afterglowpy
- soon also Pyblastafterglow (Nedora et al.)

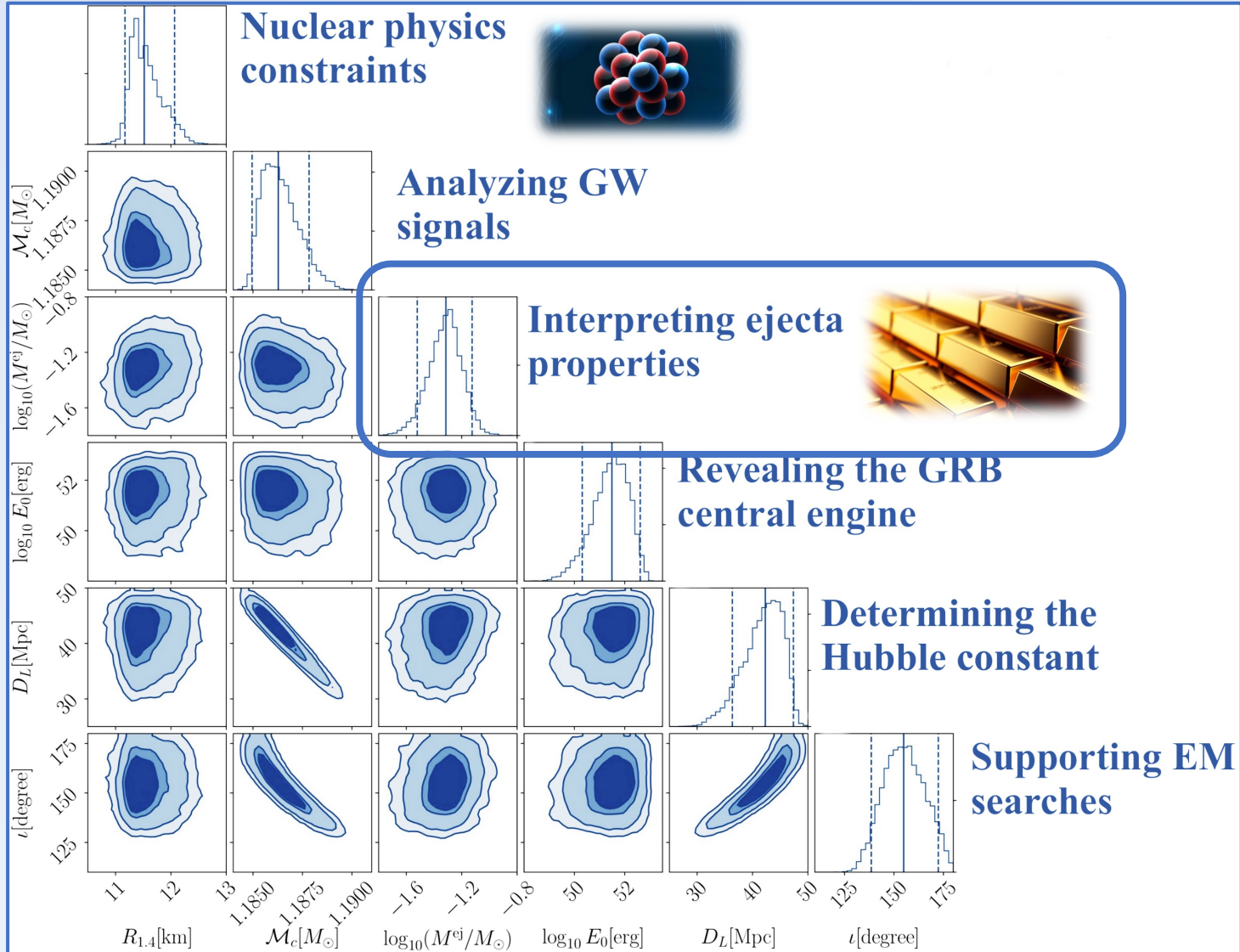


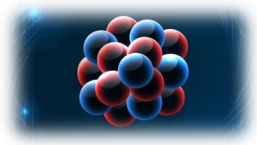
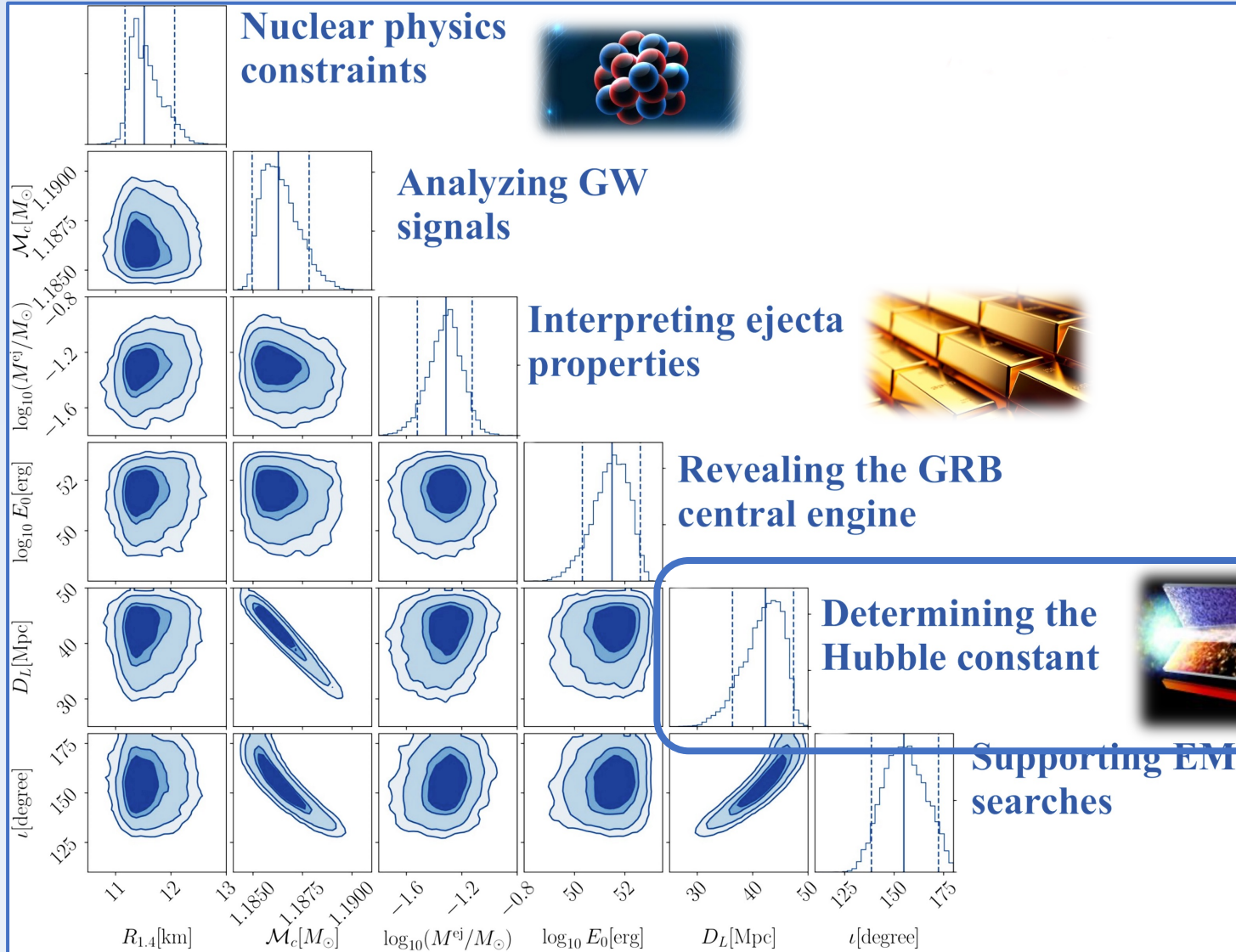


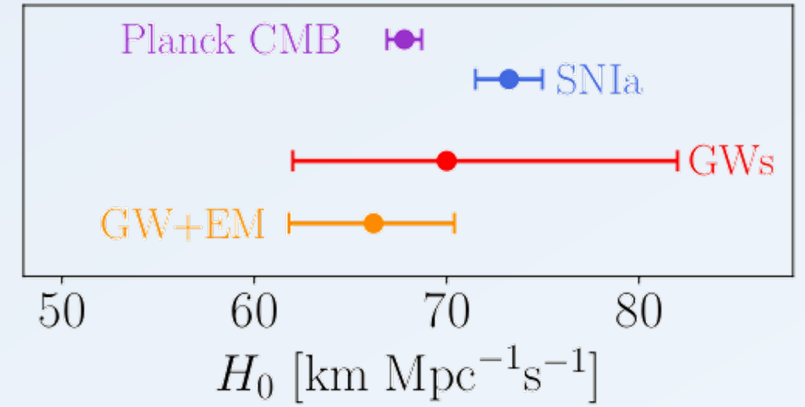
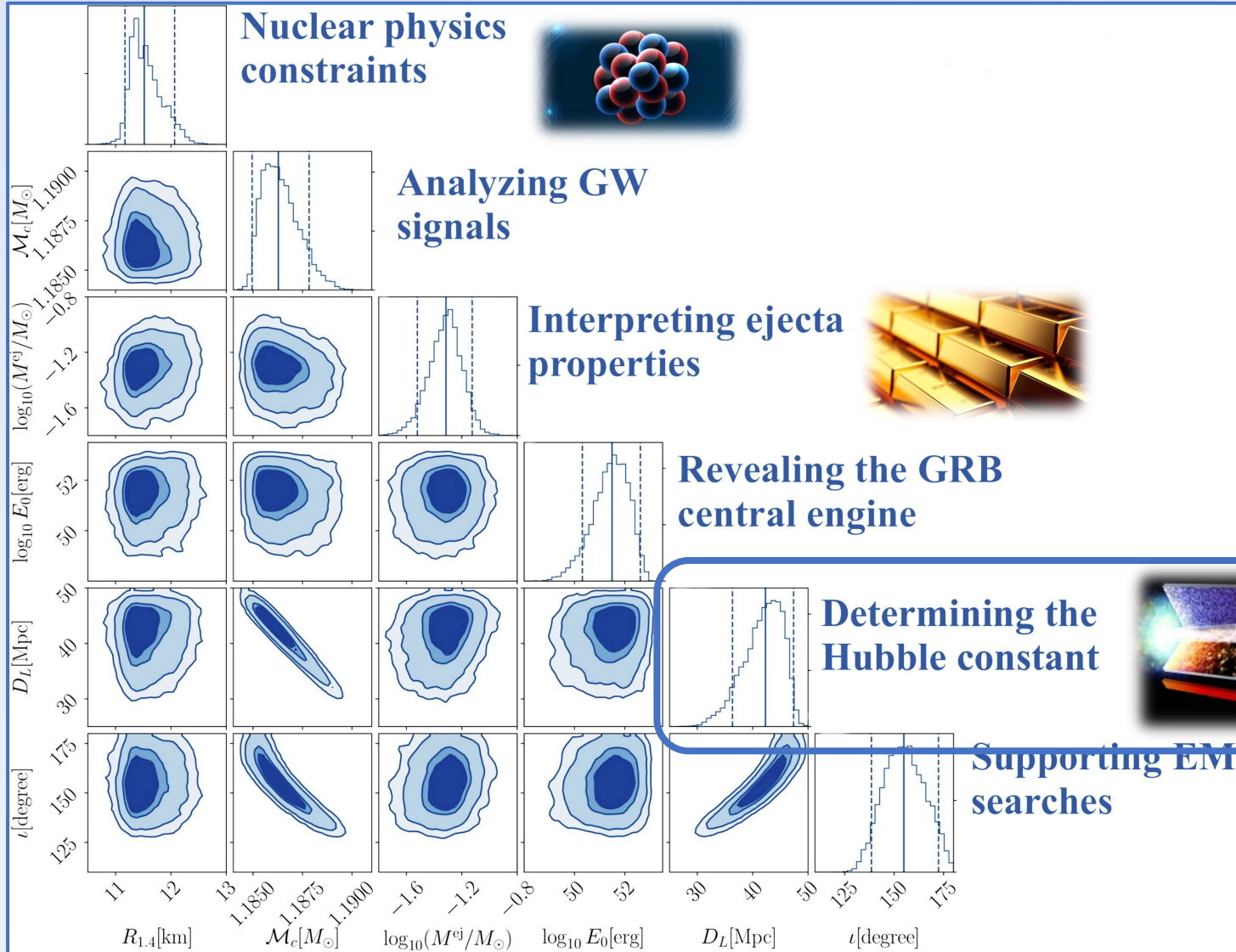


Reference	$R_{1.4M_{\odot}}$ [km]
Dietrich et al. ¹⁵	$11.75^{+0.86}_{-0.81}$ (90%)
Essick et al. ⁵¹	$12.54^{+0.71}_{-0.63}$ (90%)
Breschi et al. ²³	$11.99^{+0.82}_{-0.85}$ (90%)
Nicholl et al. ²⁴	$11.06^{+1.01}_{-0.98}$ (90%)
Raaijmakers et al. ²⁵	$12.18^{+0.56}_{-0.79}$ (95%)
Miller et al. ⁵²	$12.45^{+0.65}_{-0.65}$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

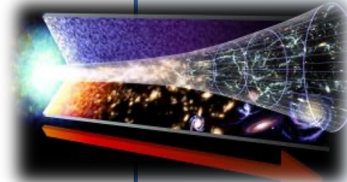
Pang et al., arXiv: 2205.08513
(accepted in Nat. Comm.)



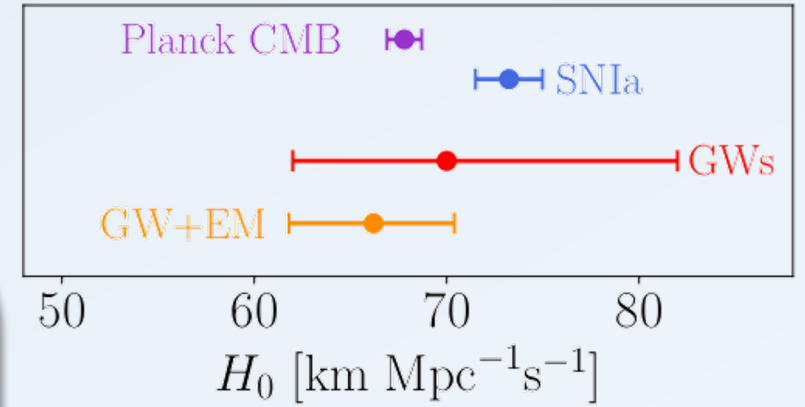
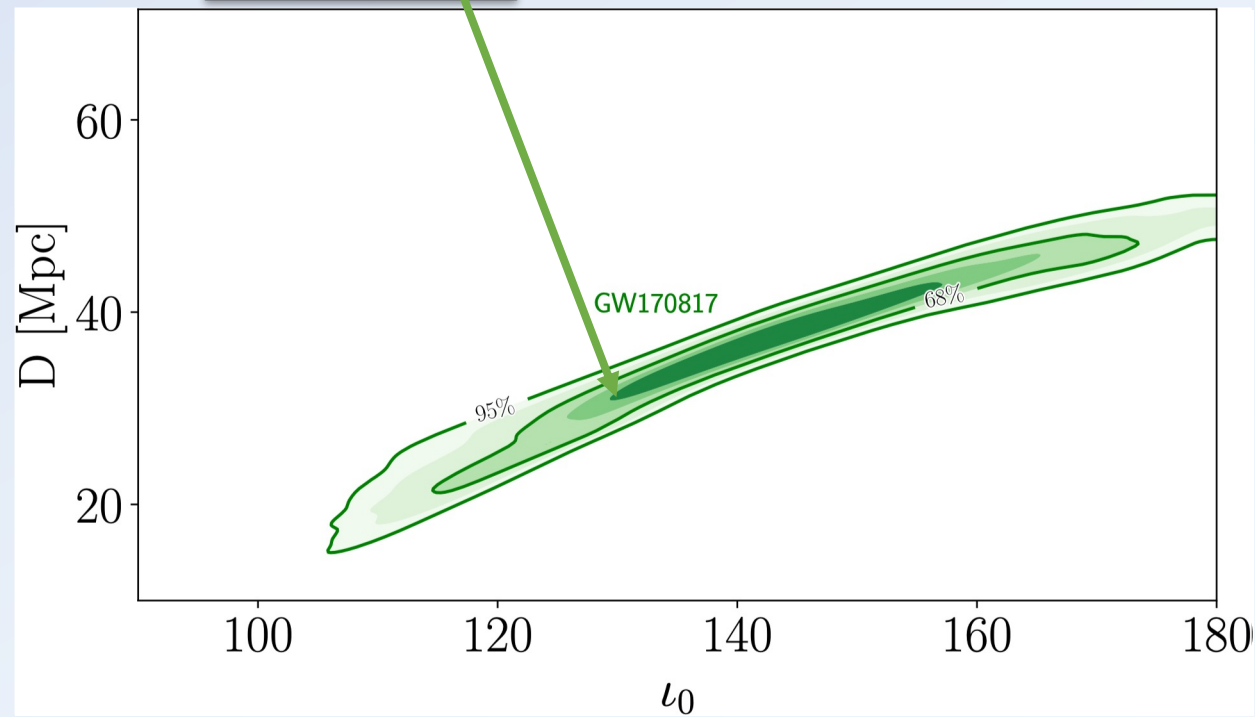
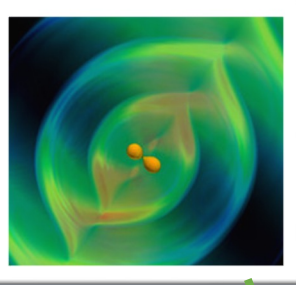




TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

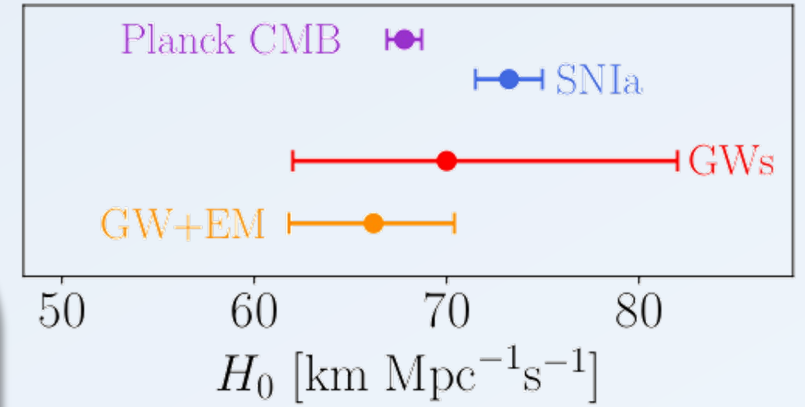
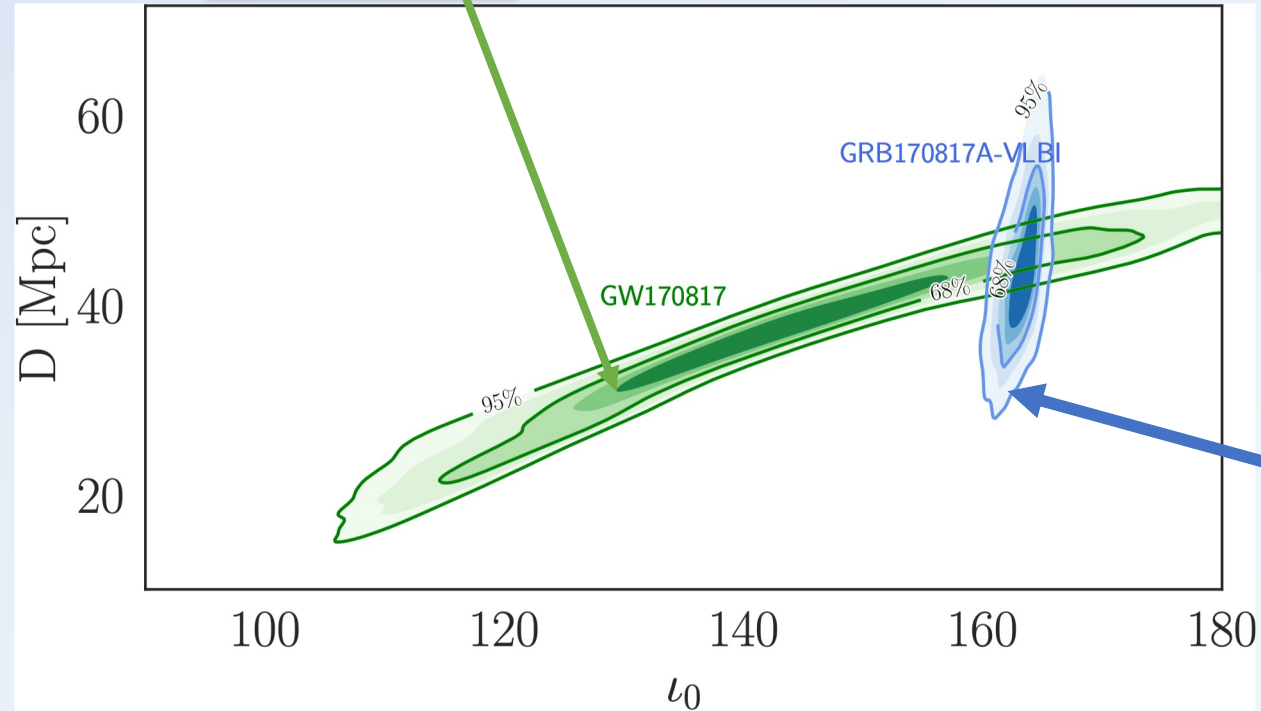
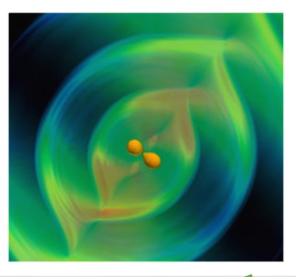


Gravitational Wave



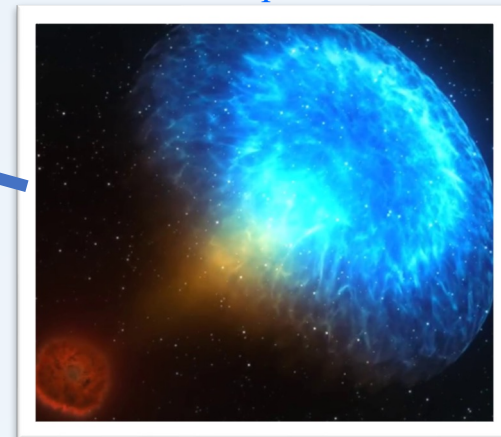
TD et al. *Science*, Vol. 370, Issue 6523, pp. 1450-1453

Gravitational Wave



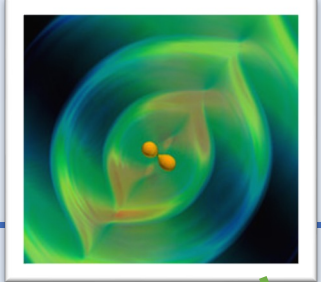
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Radio Counterpart

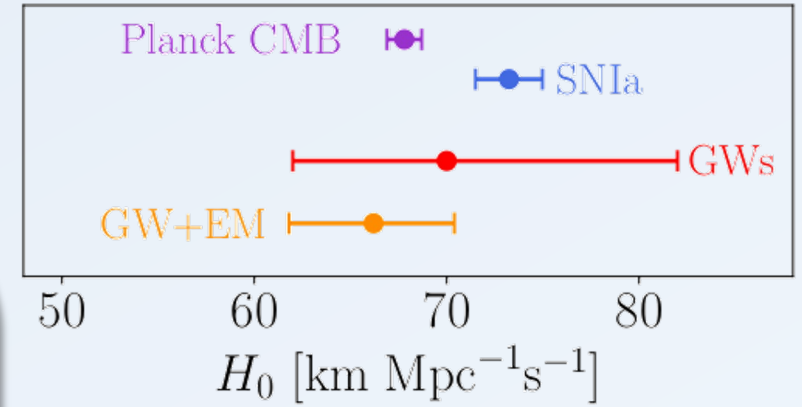
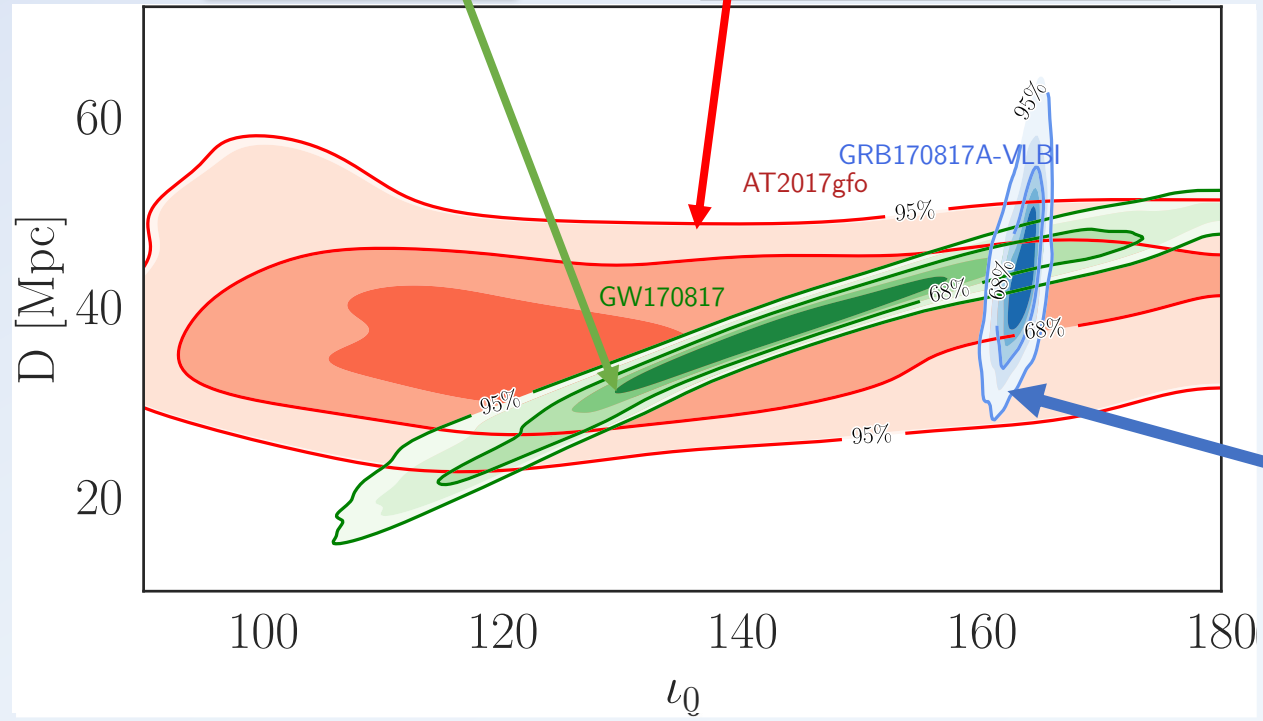
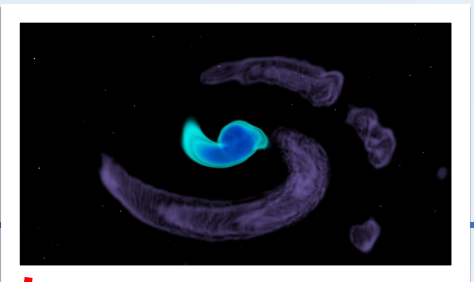




Gravitational Wave

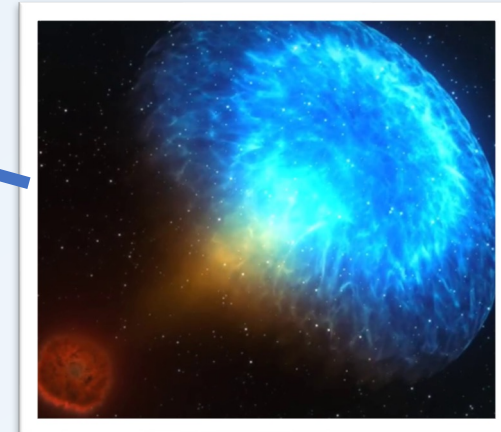


Kilonova

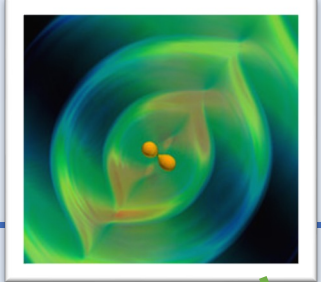


TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

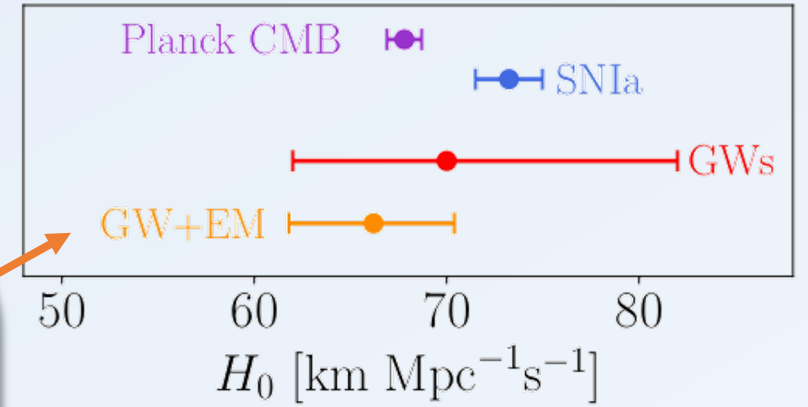
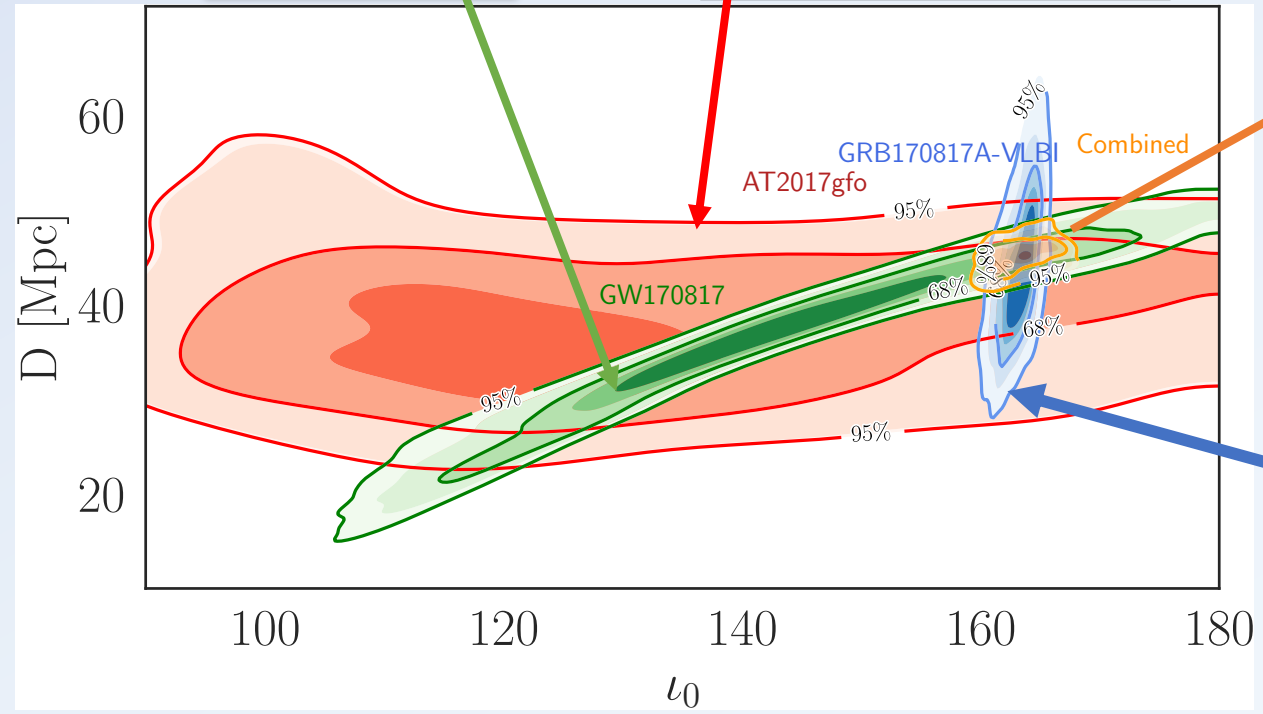
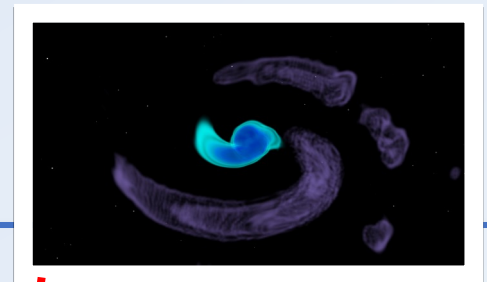
Radio Counterpart



Gravitational Wave

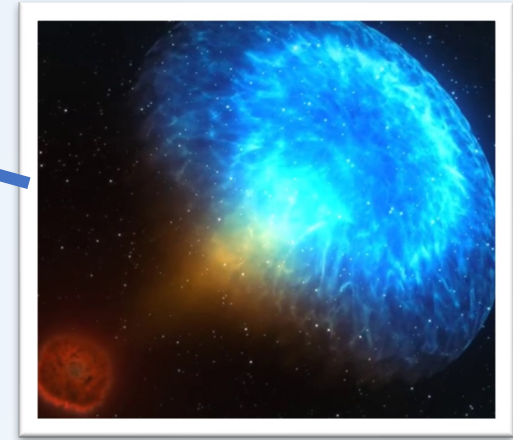


Kilonova



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

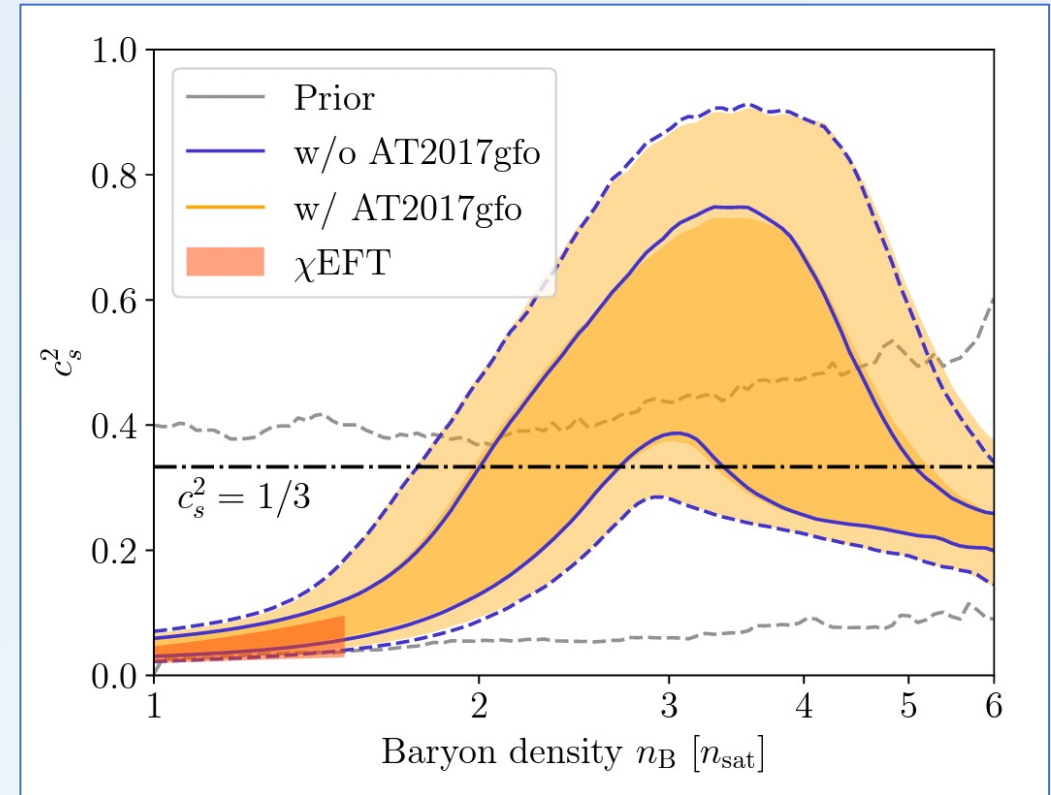
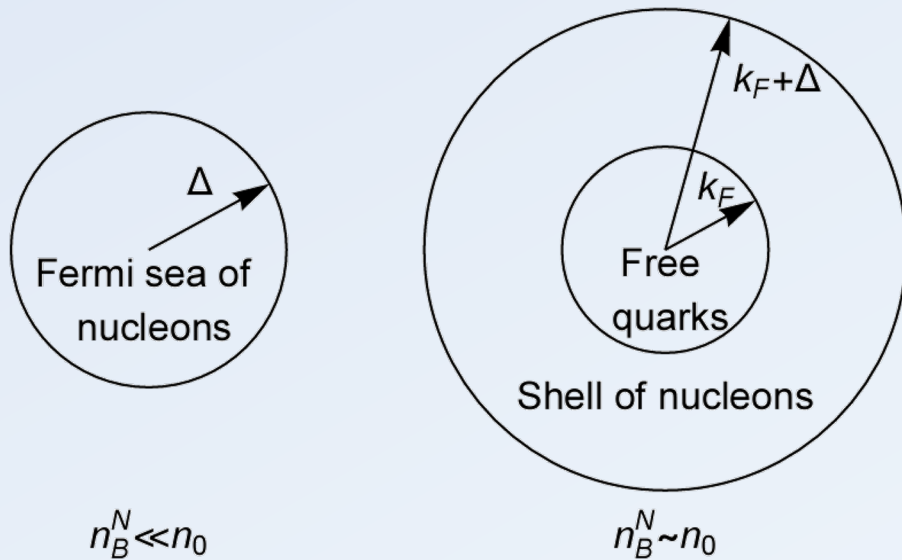
Radio Counterpart



NMMA Applications: Constraining Nuclear Parameters



Investigating properties of quarkyonic models



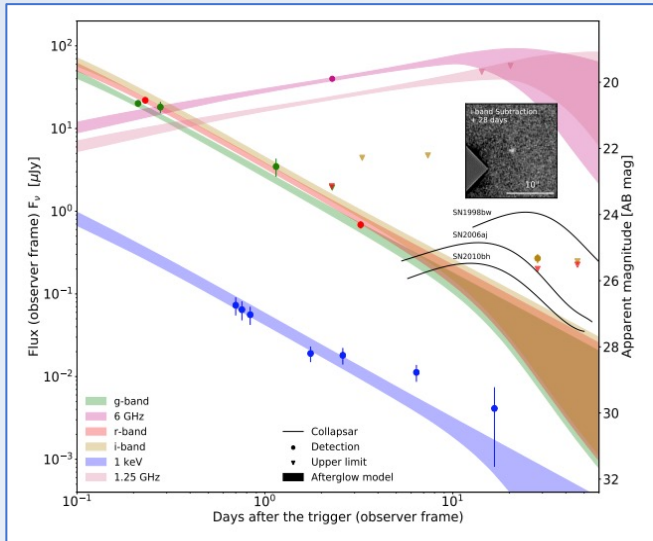
Pang et al., arXiv: 2308.15067

- Clear evidence for speed of sound above the conformal limit

NMMA Applications: Model Selection



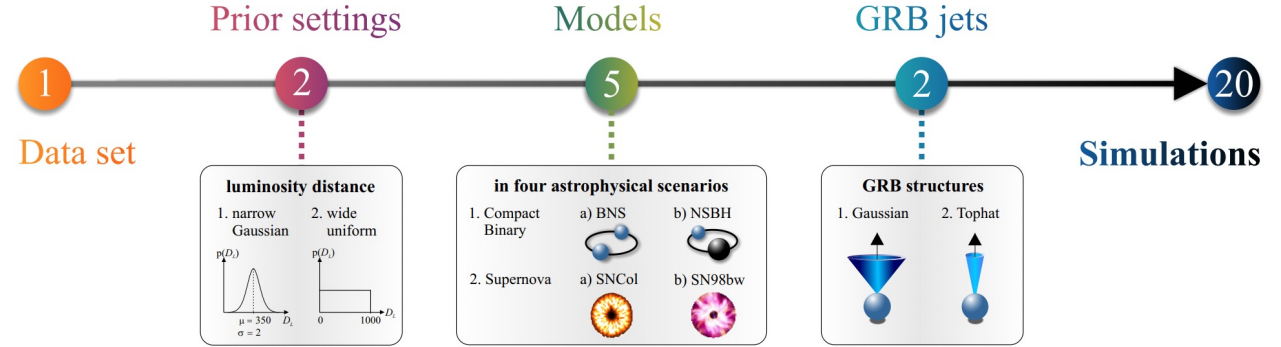
GRB 200826A



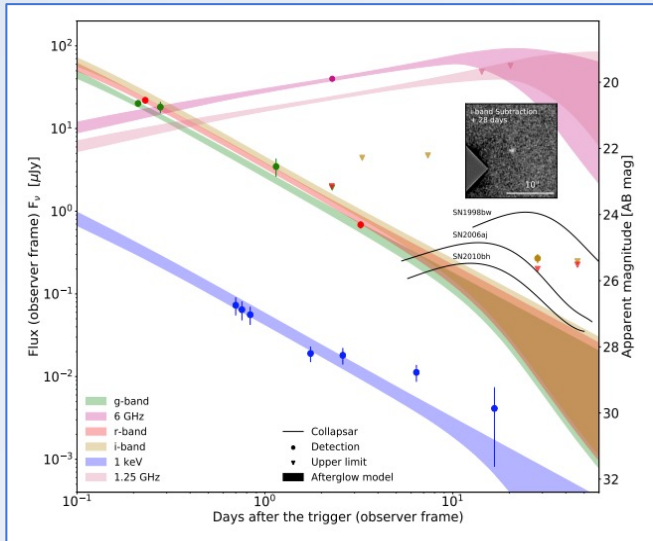
*shortest long GRB
(no BNS merger, but collapsar)*

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

NMMA Applications: Model Selection



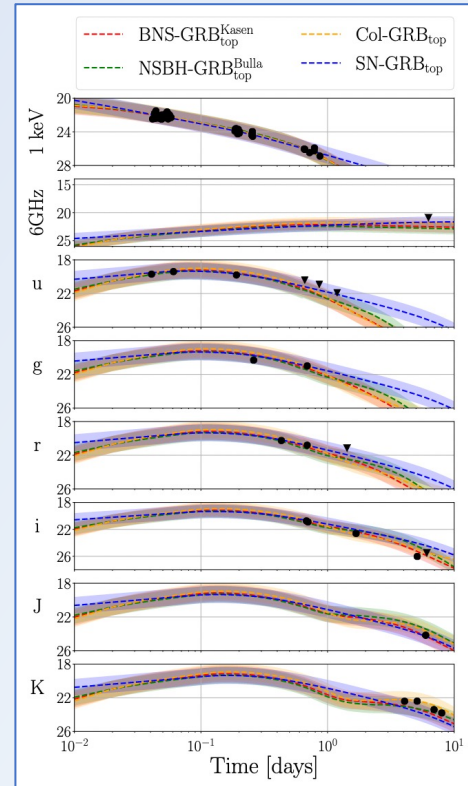
GRB 200826A



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

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

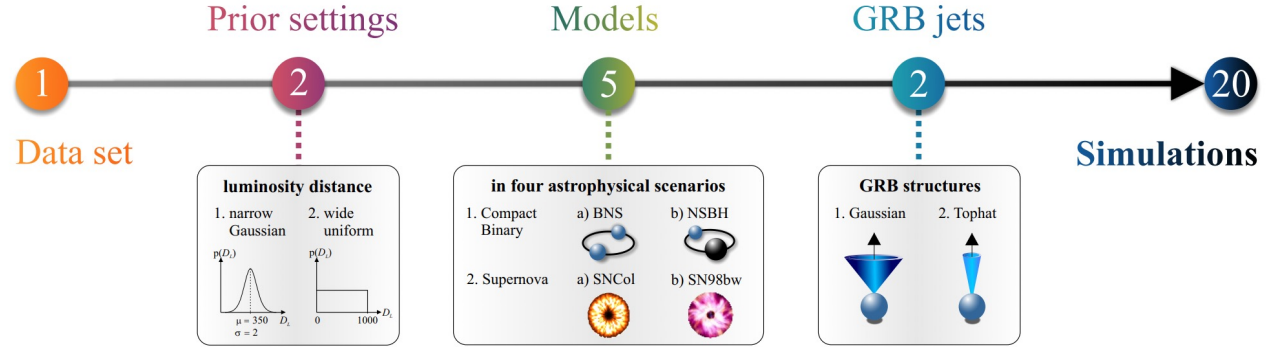
GRB 211211A



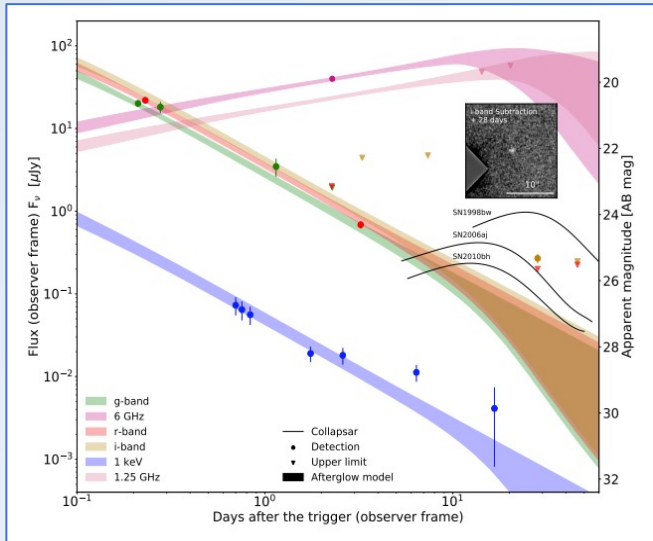
potential kilonova due to BNS merger

N.Kunert et al., MNRAS 527, 2 (2024)

NMMA Applications: Model Selection



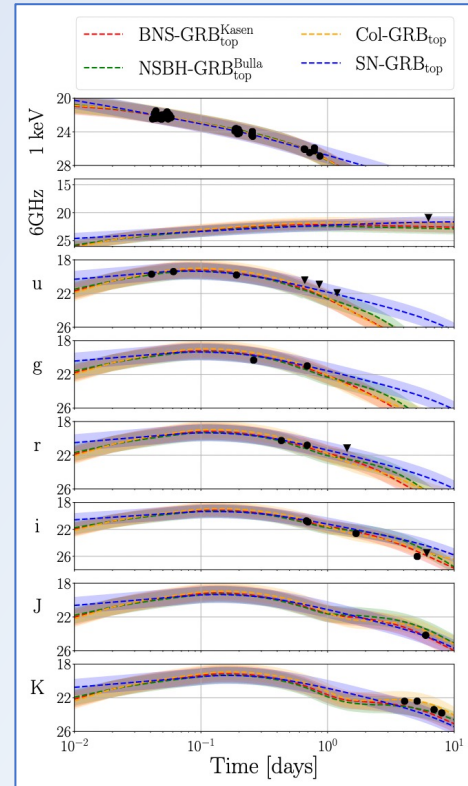
GRB 200826A



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

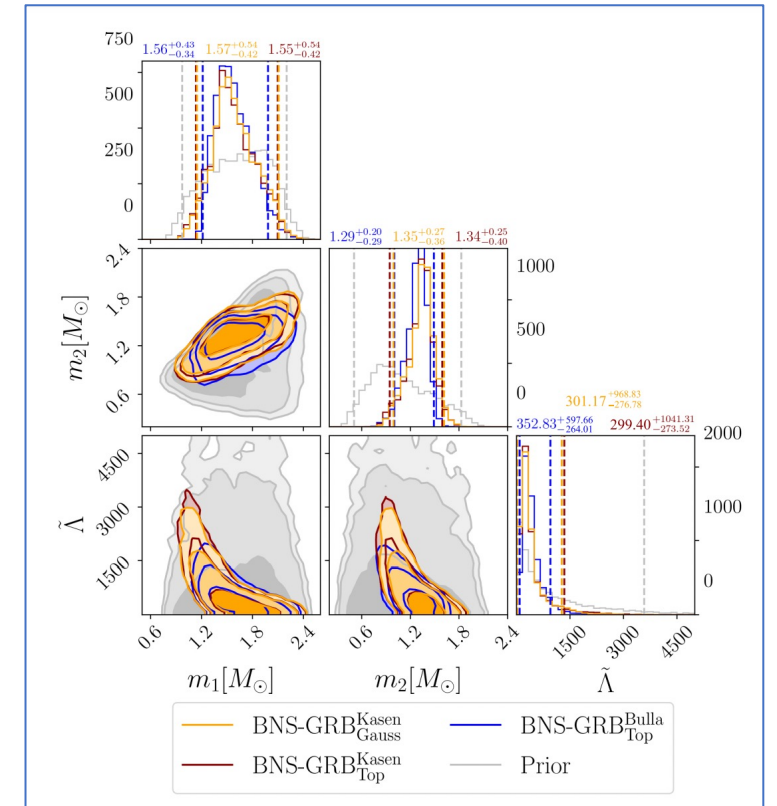
T. Ahumada, et al., Nature Astron. 5 (2021) 9, 917-927

GRB 211211A



potential kilonova due to BNS merger

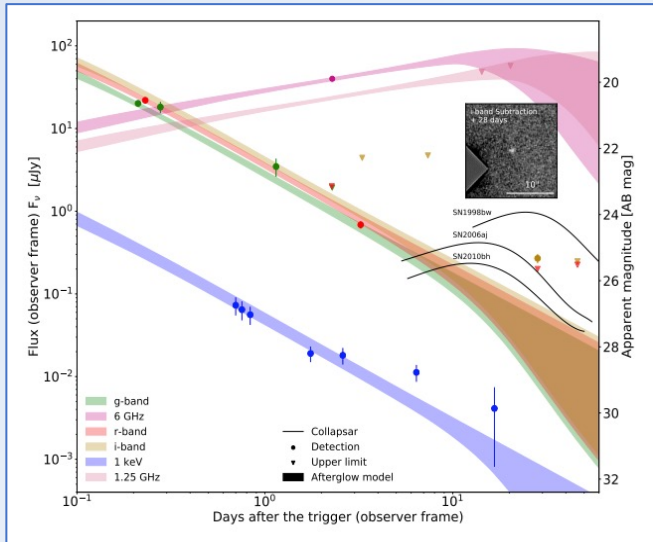
N.Kunert et al., MNRAS 527, 2 (2024)



NMMA Applications: Model Selection



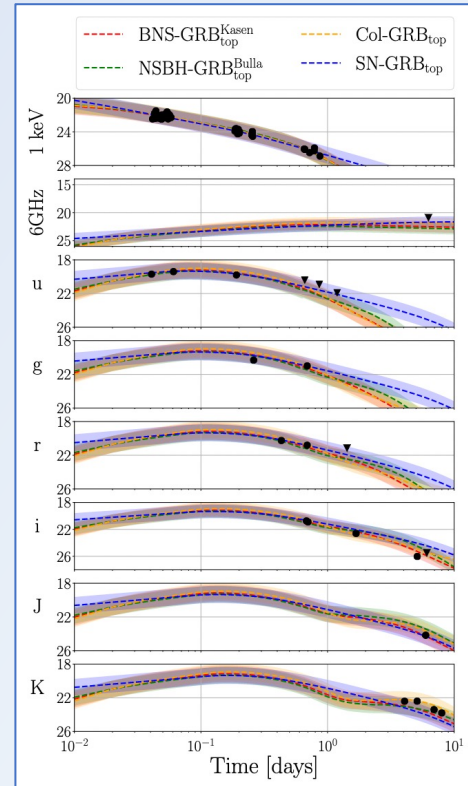
GRB 200826A



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

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

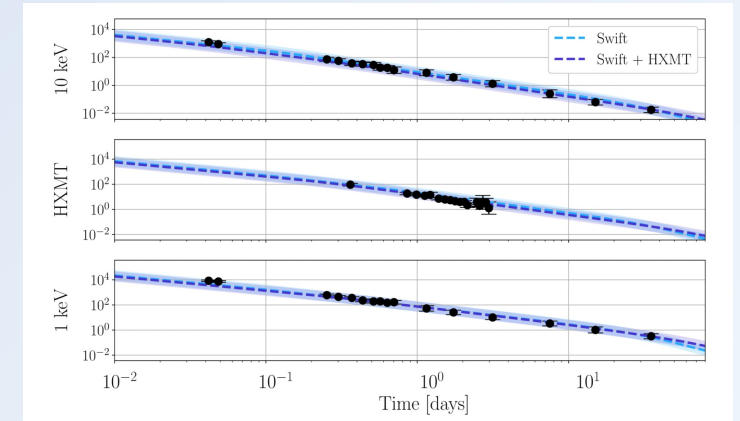
GRB 211211A



potential kilonova due to BNS merger

N.Kunert et al., MNRAS 527, 2 (2024)

GRB 221009A



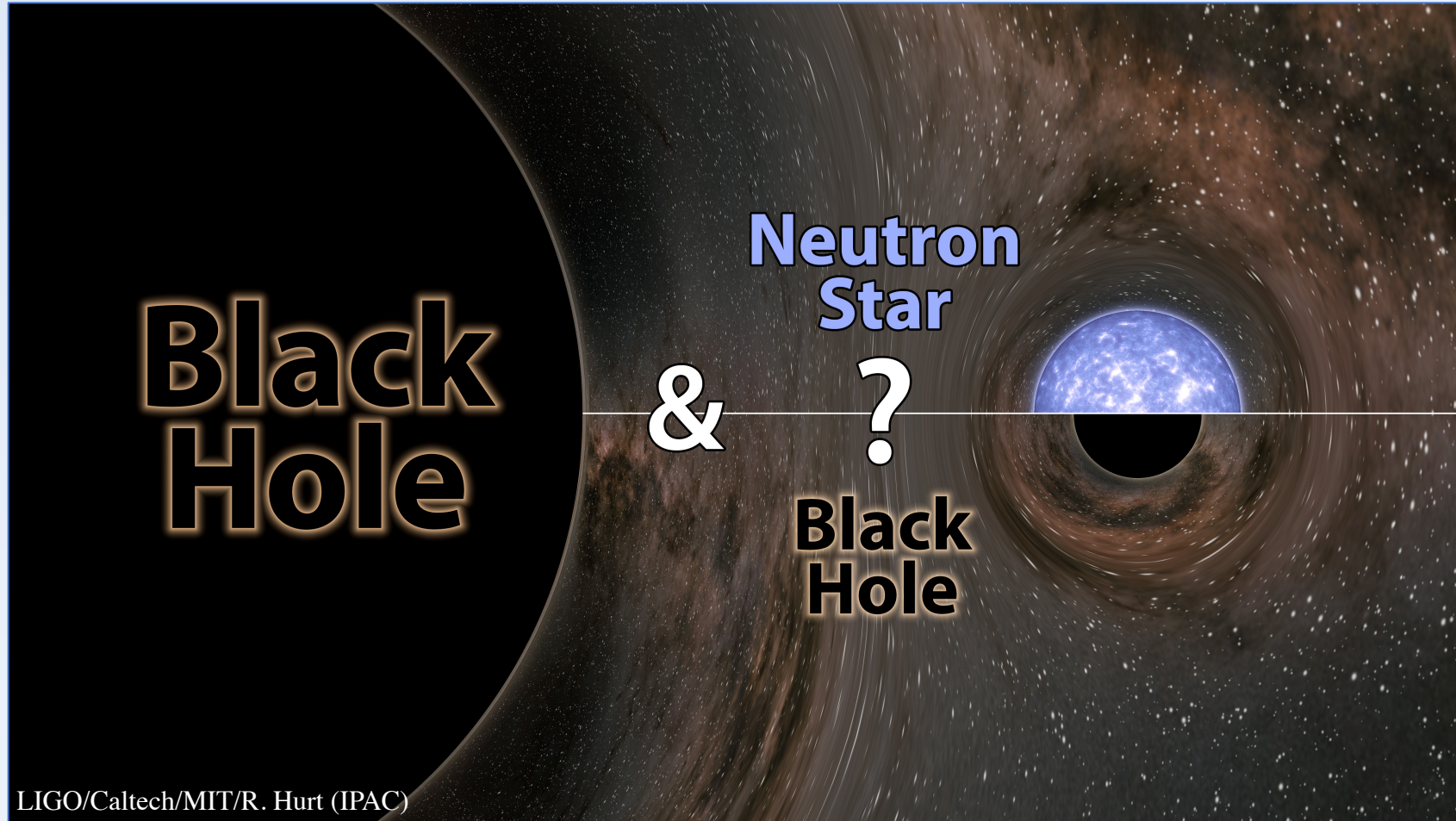
brightest observed GRB to date

GRANDMA analysis

Kann et al., APJL 948 (2023) 2, L12

NMMA Applications: Model Selection

GW190814

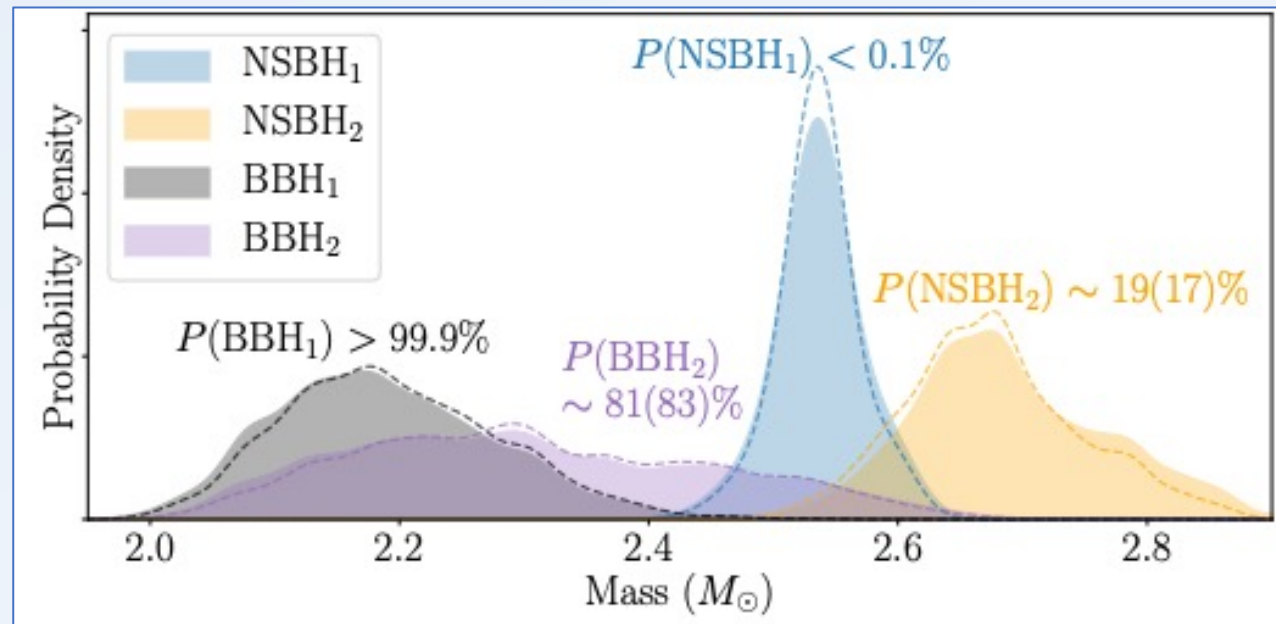


NMMA Applications: Model Selection



GW190814

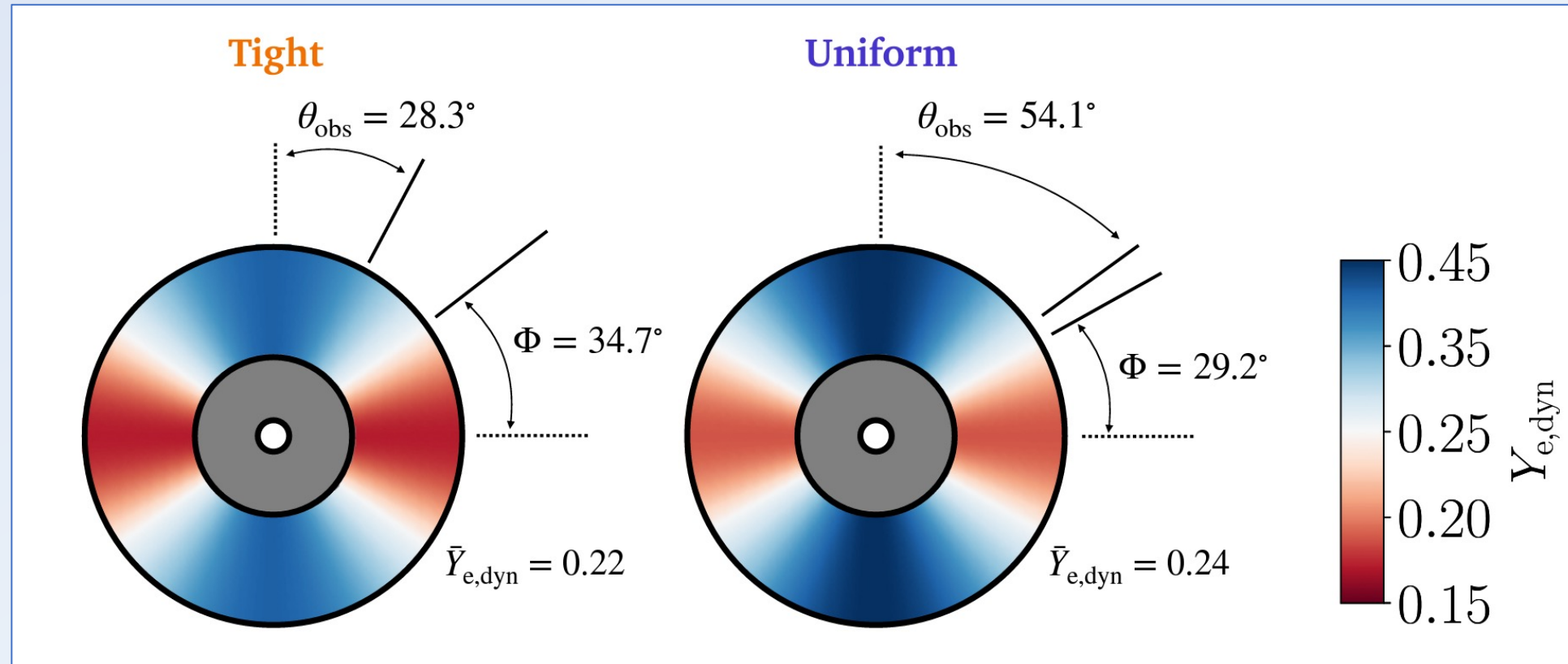
- under the assumption that GW170817 produced a BH, GW190814 was a BBH $P(\text{BBH}) > 0.999$
- relaxing this assumption, it was a BBH $P(\text{BBH}) \sim 0.83$



NMMA Applications: Predicting the Chemical Evolution



Understanding the composition of material in the mass outflow

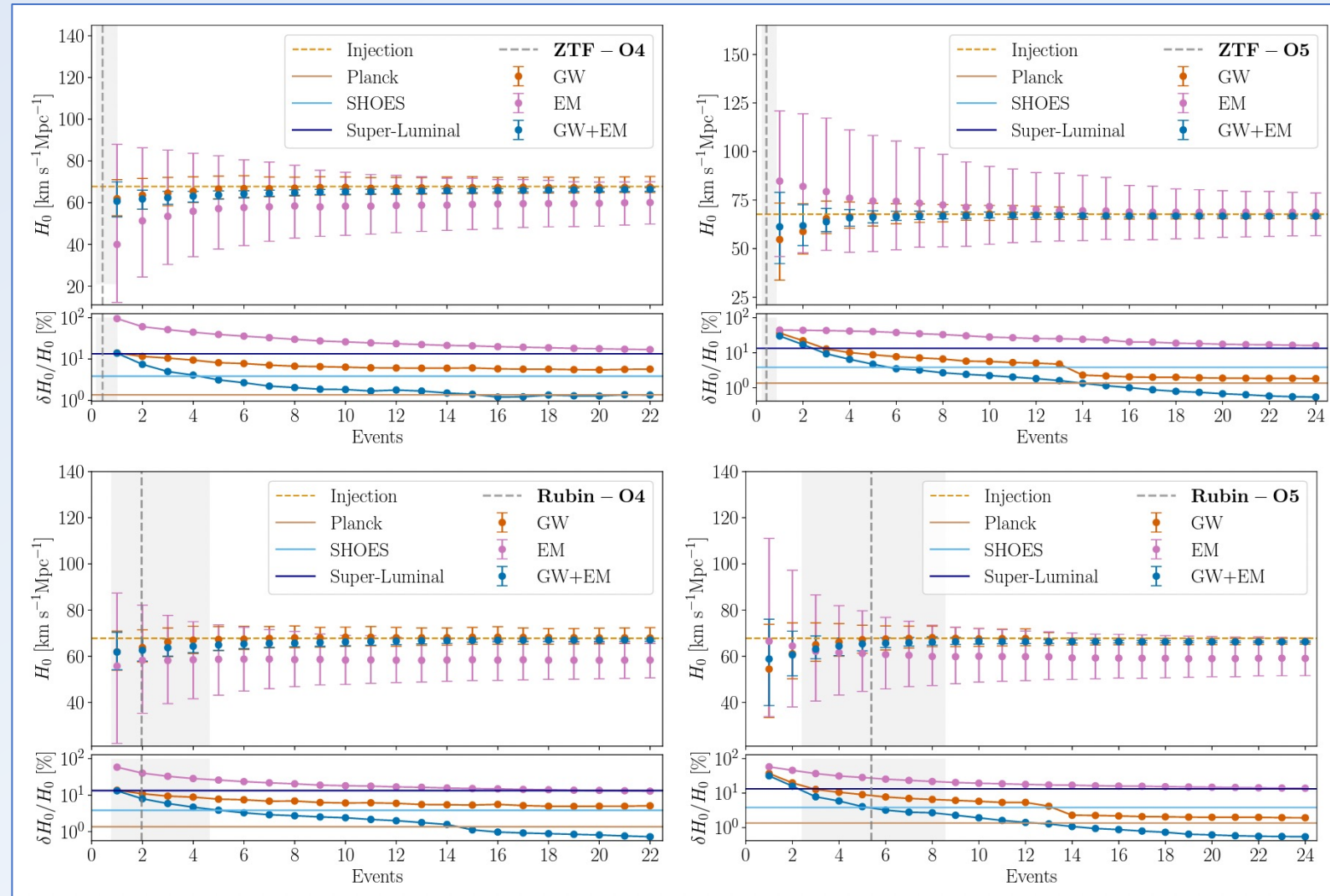


Anand et al., 2307.11080

NMMA Applications: Observing scenarios

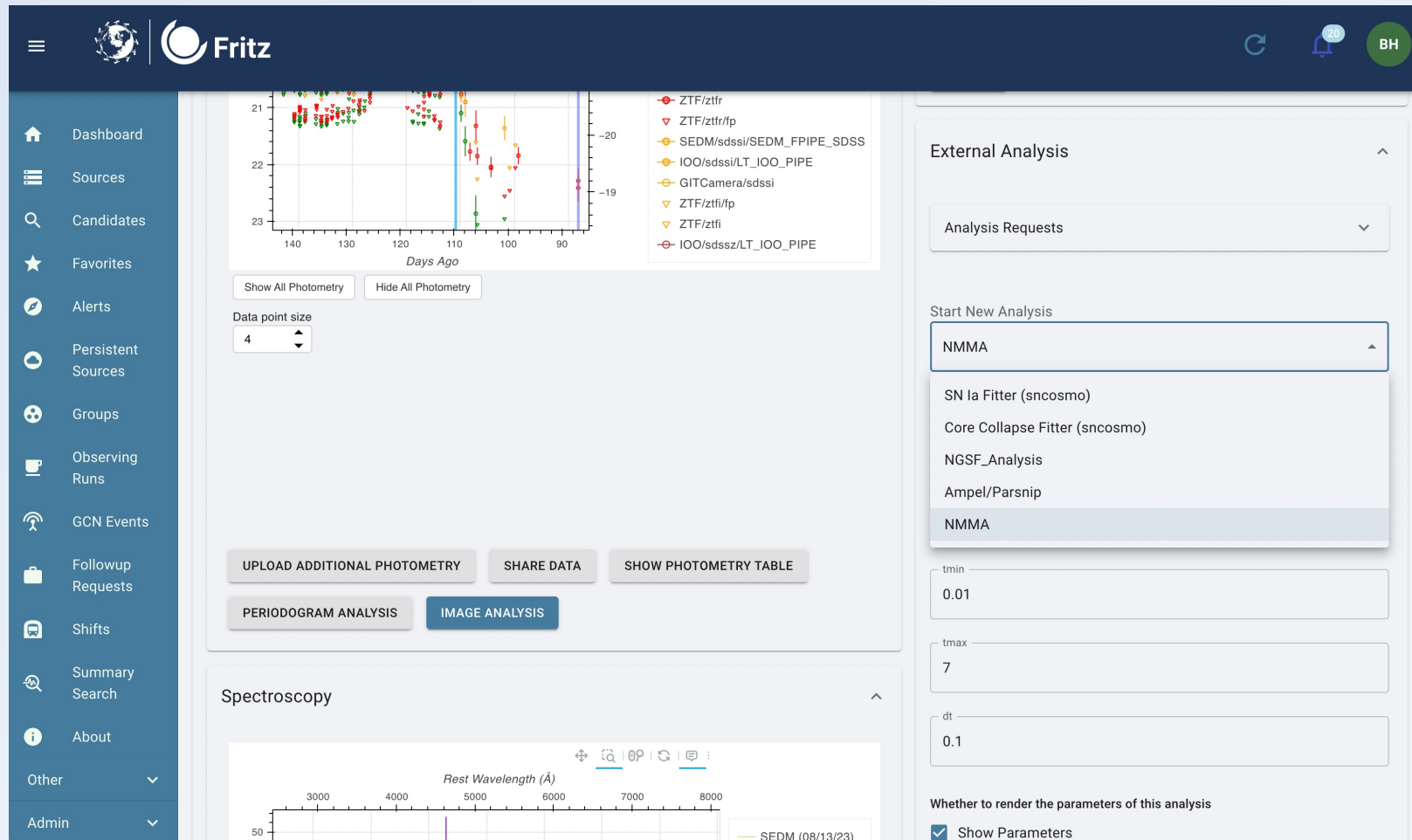


Hubble constraints
for future observing
runs



Trigger NMMA Studies directly from fritz

Pick external analysis: NMMA

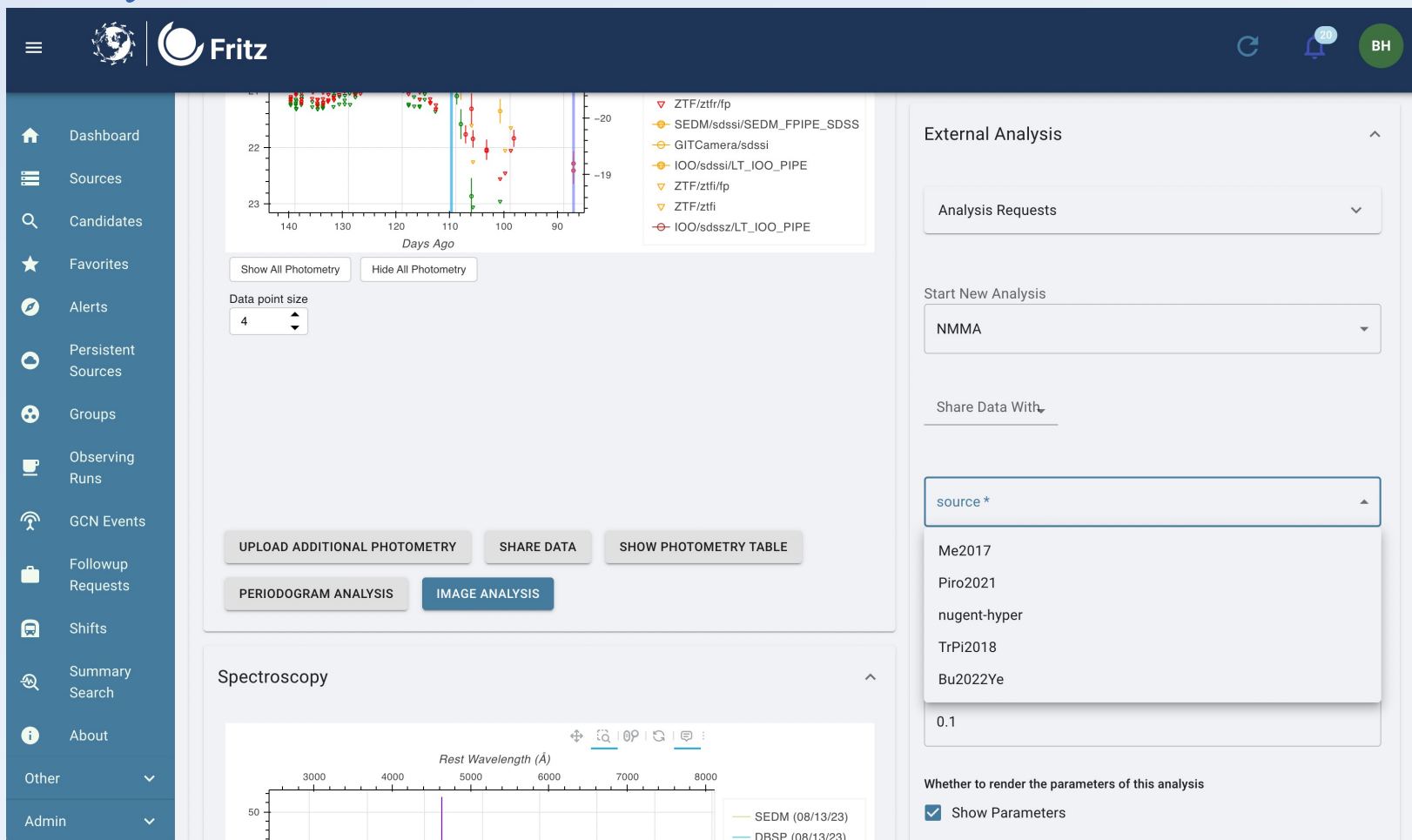


The screenshot shows the Fritz web interface. On the left is a navigation sidebar with options like Dashboard, Sources, Candidates, Favorites, Alerts, Persistent Sources, Groups, Observing Runs, GCN Events, Followup Requests, Shifts, Summary Search, and About. The main content area is divided into several sections:

- Photometry Plot:** A scatter plot showing magnitude (y-axis, 21 to 23) versus Days Ago (x-axis, 140 to 90). Data points are color-coded by source type. A legend on the right lists sources like ZTF/ztr, ZTF/ztr/fp, SEDM/sdssi/SEDM_FPIPE_SDSS, etc. Below the plot are buttons for "Show All Photometry", "Hide All Photometry", and a "Data point size" dropdown set to 4.
- Analysis Actions:** A row of buttons including "UPLOAD ADDITIONAL PHOTOMETRY", "SHARE DATA", "SHOW PHOTOMETRY TABLE", "PERIODOGRAM ANALYSIS", and "IMAGE ANALYSIS".
- Spectroscopy:** A section at the bottom with a plot of Rest Wavelength (Å) from 3000 to 8000. A single data point is visible at approximately 4000 Å, labeled "SEDM (08/13/23)".
- External Analysis Panel:** A sidebar on the right titled "External Analysis" containing:
 - "Analysis Requests" dropdown.
 - "Start New Analysis" dropdown menu with "NMMA" selected.
 - Input fields for "tmin" (0.01), "tmax" (7), and "dt" (0.1).
 - A checkbox "Whether to render the parameters of this analysis" which is checked, labeled "Show Parameters".

Trigger NMMA Studies directly from fritz

Pick your model




The screenshot displays the Fritz web interface. On the left is a navigation sidebar with options: Dashboard, Sources, Candidates, Favorites, Alerts, Persistent Sources, Groups, Observing Runs, GCN Events, Followup Requests, Shifts, Summary Search, About, Other, and Admin. The main content area is divided into three sections:

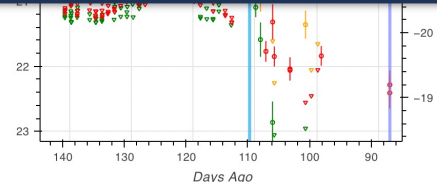
- Photometry Plot:** A scatter plot showing magnitude (y-axis, 22 to 23) versus Days Ago (x-axis, 140 to 90). Data points are color-coded by source. A legend on the right lists sources: ZTF/ztf/tp, SEDM/sdssi/SEDM_FPIPE_SDSS, GiTCamera/sdssi, IOO/sdssi/LT_IOO_PIPE, ZTF/ztf/tp, ZTF/ztf/i, and IOO/sdssi/LT_IOO_PIPE. Below the plot are buttons for 'Show All Photometry', 'Hide All Photometry', and a 'Data point size' dropdown set to 4. At the bottom of this section are buttons for 'UPLOAD ADDITIONAL PHOTOMETRY', 'SHARE DATA', 'SHOW PHOTOMETRY TABLE', 'PERIODOGRAM ANALYSIS', and 'IMAGE ANALYSIS'.
- Spectroscopy Plot:** A plot showing Rest Wavelength (Å) on the x-axis (3000 to 8000) versus flux on the y-axis (50). Two spectral lines are visible, labeled 'SEDM (08/13/23)' and 'DBSP (08/13/23)'.
- External Analysis Panel:** A sidebar on the right titled 'External Analysis'. It contains:
 - 'Analysis Requests' dropdown.
 - 'Start New Analysis' dropdown set to 'NMMA'.
 - 'Share Data With' dropdown.
 - A search box containing 'source *' with a dropdown menu listing: Me2017, Piro2021, nugent-hyper, TrPi2018, Bu2022Ye, and 0.1.
 - 'Whether to render the parameters of this analysis' section with a checked checkbox for 'Show Parameters'.

Trigger NMMA Studies directly from fritz

Determine properties for the analysis and submit the run

☰


- 🏠 Dashboard
- ☰ Sources
- 🔍 Candidates
- ★ Favorites
- 🔔 Alerts
- 🔄 Persistent Sources
- 🗑️ Groups
- 📄 Observing Runs
- 📡 GCN Events
- 📁 Followup Requests
- 🚗 Shifts
- 🔎 Summary Search
- 👤 About
- Other ▾
- Admin ▾



Show All Photometry Hide All Photometry

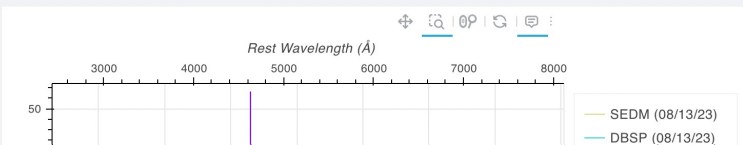
Data point size: 4

- ▼ ZTF/ztf/rfp
- SEDM/sdssi/SEDM_FPIPE_SDSS
- GiTCamera/sdssi
- IOO/sdssi/LT_IOO_PIPE
- ▼ ZTF/ztf/rfp
- ▼ ZTF/ztf/i
- IOO/sdssz/LT_IOO_PIPE

UPLOAD ADDITIONAL PHOTOMETRY
SHARE DATA
SHOW PHOTOMETRY TABLE

PERIODOGRAM ANALYSIS
IMAGE ANALYSIS

Spectroscopy



— SEDM (08/13/23)
— DBSP (08/13/23)

source*
Me2017

tmin
0.01

tmax
7

dt
0.1

Whether to render the parameters of this analysis

Show Parameters

Whether to render the plots of this analysis

Show Plots

Whether to render the corner of this analysis

Show Corner

SUBMIT

Where to find more?

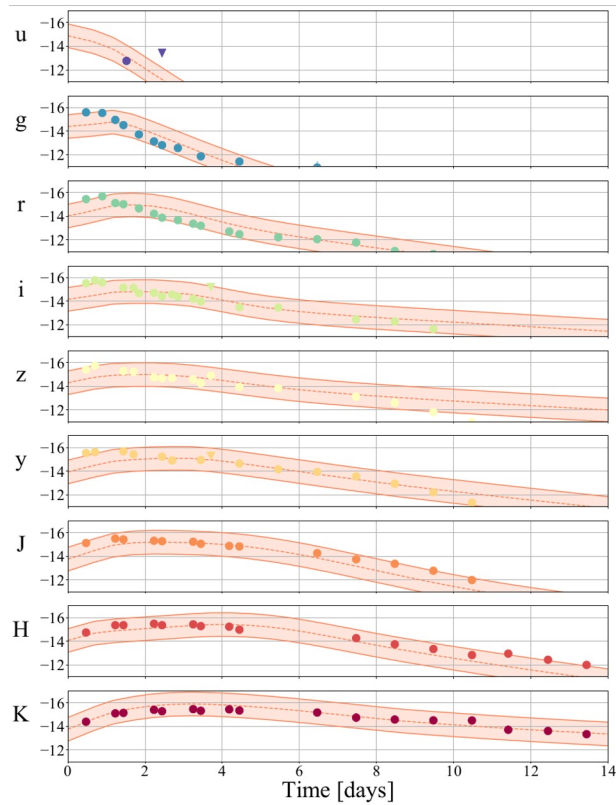
- Weekly NMMA calls to discuss progress and problems
- Discussion about issues and problems on git
- Documentation on git

Where to find more?

- Weekly NMMA calls to discuss progress and problems
- Discussion about issues and problems on git
- Documentation on git

The screenshot shows the GitHub interface for the repository `nuclear-multimessenger-astronomy/nmma`. The left sidebar displays the file tree with the `quick-start-guide.rst` file selected. The main content area shows the file's preview, which includes a commit message by `mcoughlin` and the title `Quick Start`. The text in the preview explains that `nmma` provides example models and demonstrates how to generate injections using a quick example. It includes two code blocks: one for `nmma-create-injection` and one for `lightcurve-analysis`. At the bottom, there is a plot showing a distribution with a central value of $59.85^{+7.81}_{-7.75}$.

Where to find more?



Connecting Electromagnetic signals to Binary Source Properties

In NMMA, it is possible to use the results from GW inferences together with kilonova inferences or joint KN+GRB afterglow inferences to get estimates on the binary properties. A binary system can be a binary neutron star (BNS) merger or a neutron-star-black-hole (NSBH) merger. We can connect observed electromagnetic signals to potential source properties via phenomenological relations, i.e., via fits based on numerical-relativity relations, see [\(Pang et al. 2022\)](#) and Refs. therein for further details.

For estimating the source properties, the following input files are required:

- `EMsamples` - is the posterior sample file from a previous Bayesian inference (e.g. Kilonova+GRB inference) on electromagnetic (EM) signals,
- `EMprior` - is the prior file that was used for the EM inference
- `EOS` - number of equation of state files which will be used in the resampling
- `EOSpath` - path to the folder of all EOS files
- `GWsamples` - some fiducial randomly generated posterior samples for masses, chirp mass, mass ratio, luminosity distance, and EOS samples,
- `GWprior` - a prior file for gravitational wave sources

The prior file from the EM inference needs to be supplemented by two additional parameters α and ζ that are used in the numerical fit expressions that link the disk, wind and total ejecta masses:

```
alpha = Gaussian(mu=0., sigma=4e-4, name='alpha', latex_label='$\alpha$')
zeta = Uniform(minimum=0., maximum=1.0, name='ratio_zeta', latex_label='$\zeta$')
```

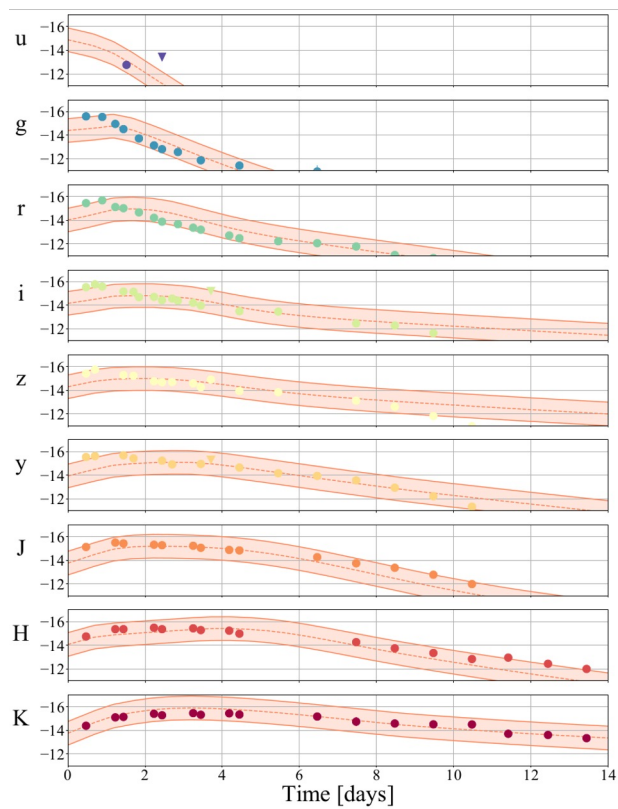
Estimating BNS properties

Here, we take the observed gamma-ray burst [GRB211211A](#) as an example and assume that associated electromagnetic signals originated from a BNS merger. For this signal, a joint inference (kilonova + GRB) can be carried out and will provide you with the required `EMsamples`. For the `GWsamples` input file, we need to generate some fiducial dummy GW samples. A script for the generation can be found [here](#). The GW sample generation is based on the EOS set `15nsat_cse_uniform_R14` which can be found on [Zenodo](#). The `EMprior` file is the same as used for the KN+GRB inference (see [priors](#)) and the `GWprior` file should be adjusted to the `GWsamples`.

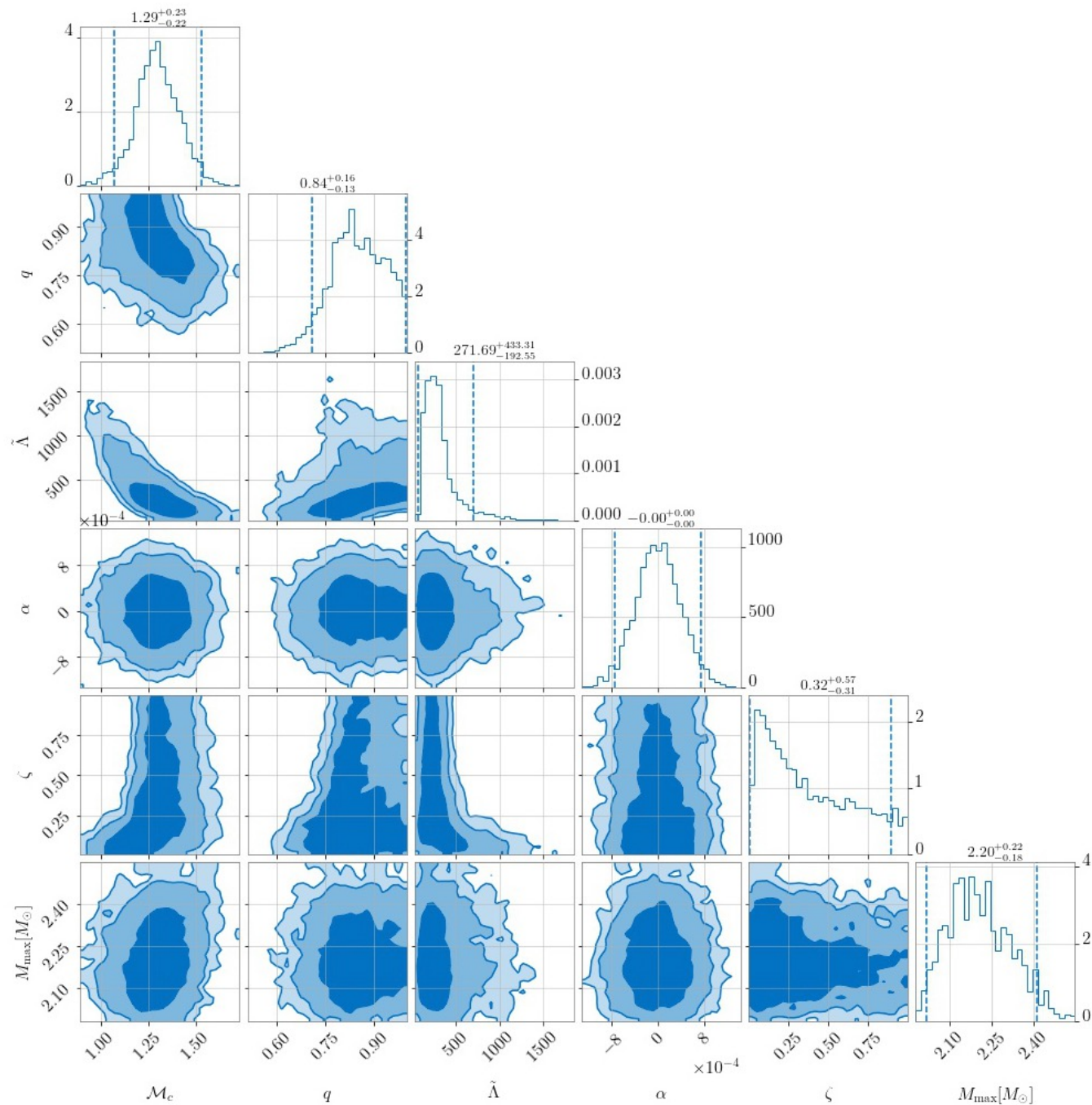
Finally, we can use this command:

```
gwem-resampling --outdir outdir --GWsamples example_files/tools/gwem_resampling/GWsamples.dat --GWprior priors/GWBNS
```

Where to find more?

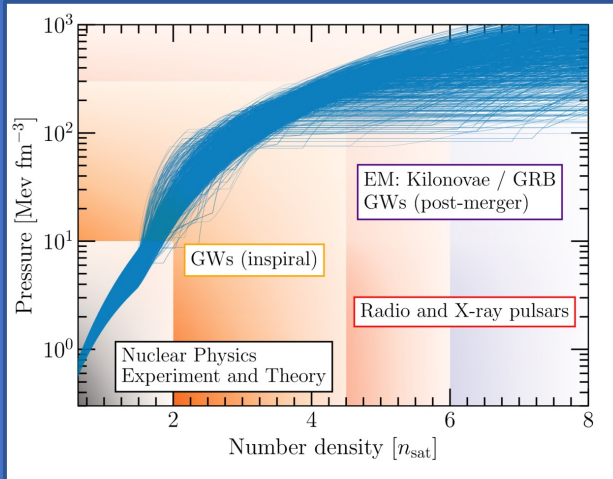


A corner plot is shown below:



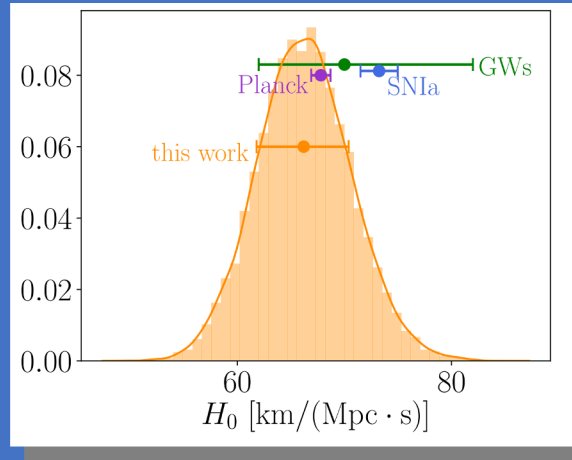
Summary: Multi-messenger Astronomy helps to answer fundamental physics questions

Equation of State



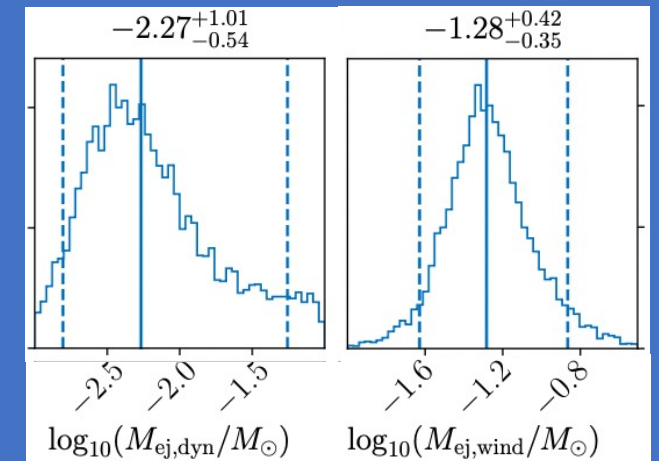
Pang et al., arXiv: 2205.08513

Hubble Constant



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

Heavy element formation



and



still plenty to do:

is one tool to enable multi-messenger studies, but there is

- improved models
- more robust sampling
- faster sampling
-



Peter T. H. Pang, Michael W. Coughlin, Mattia Bulla, Tim Dietrich, Ingo Tews, Thibbeau Wouters, Tyler Barna, Brendan, King, Mouza Almualla,, Weizmann Kiendrebeogo, Nina Kunert, Gargi Mansingh, Brandon Reed, Nidharika Sravan, Andrew Toivon, Sarah Antier, Robert O. Vandenberg, Jack Heinzeln, Vsevolod Nedora, Pouyan Salehi, Ritwik Sharma, Chris Van den Broeck, Rahul Somasundaram, Shraya Anand, Thomas Hussenot-Desenonges, Theophile Jegou du Laz, Anna Neuweiler, Ivan Markin, Hauke Koehn, Henrik Rose, Edoardo Giangrandi, Sahil Jhavar

github.com/nuclear-multimessenger-astronomy