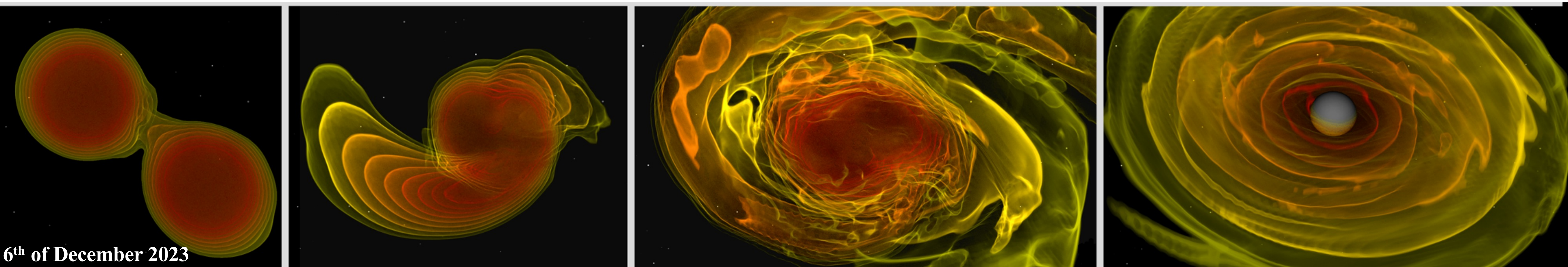
Joint nuclear-physics and multi-messenger astrophysics interpretation of compact binary mergers

Tim Dietrich

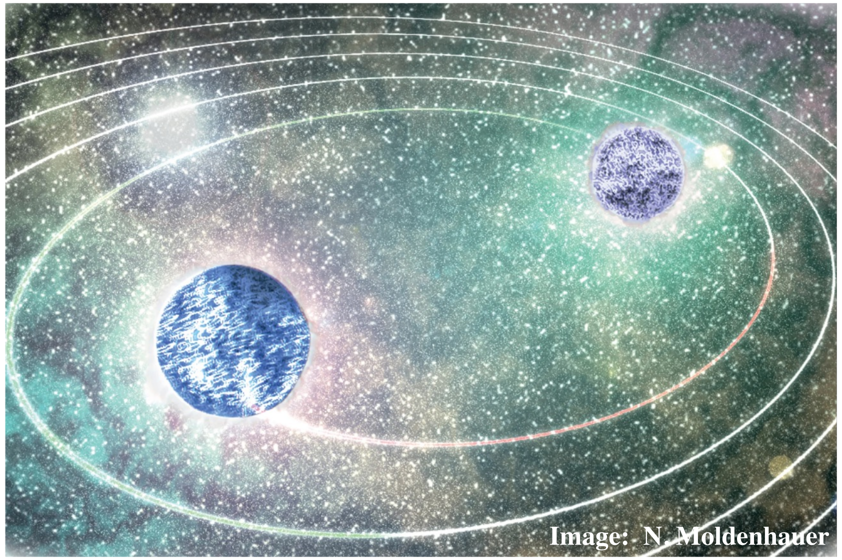
University of Potsdam

Max Planck Institute for Gravitational Physics



6th of December 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**

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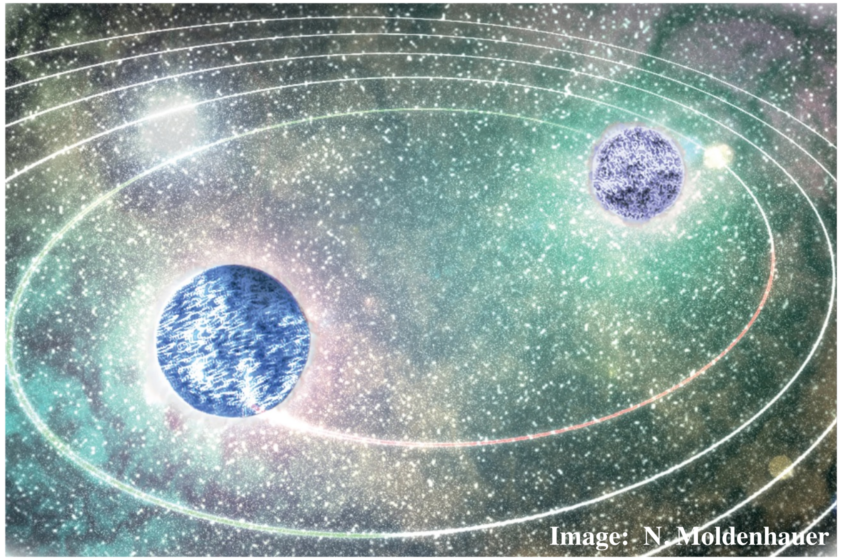

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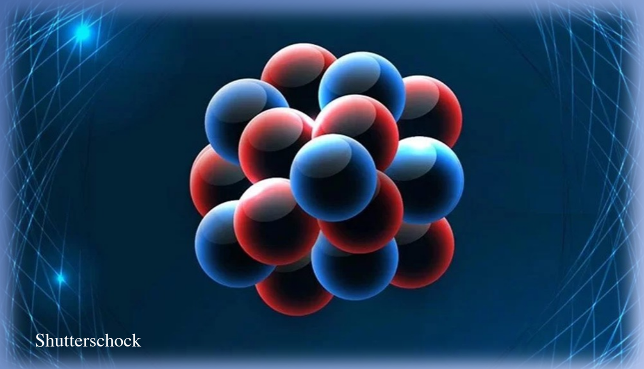
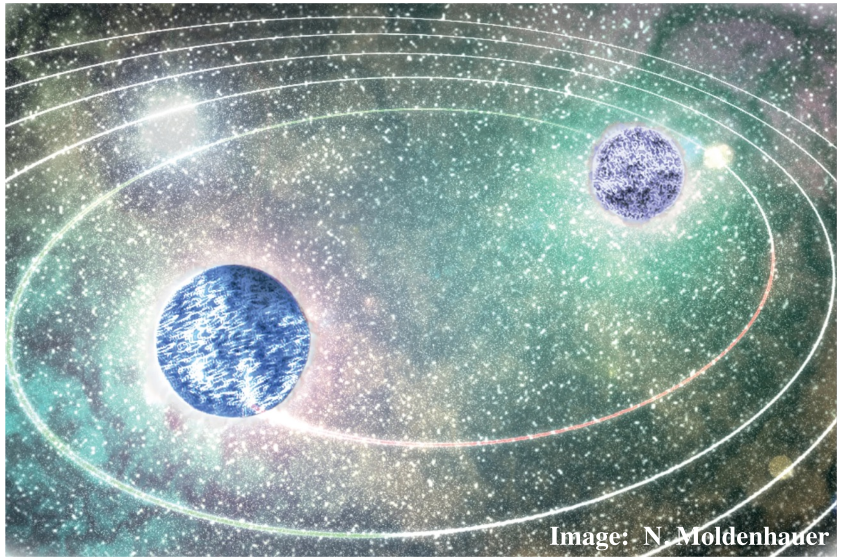
Science cases

State of matter at extreme densities



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

How to study neutron stars?



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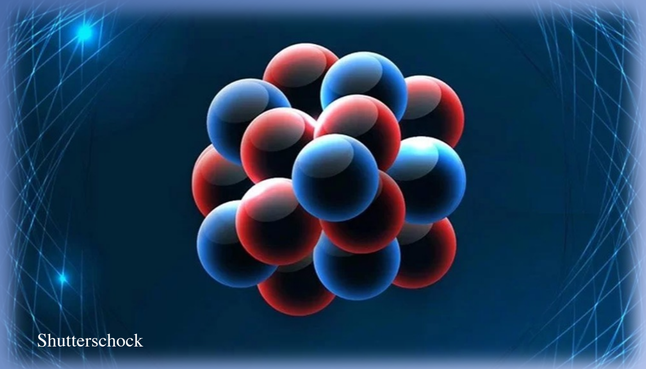

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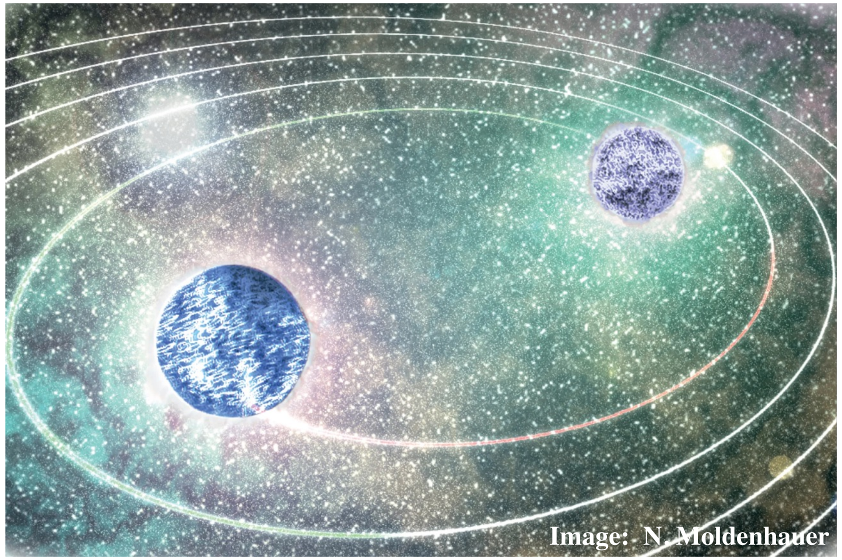
Heavy element production

How to study neutron stars?



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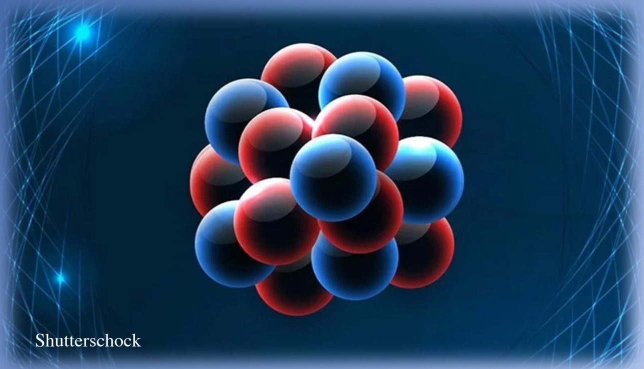
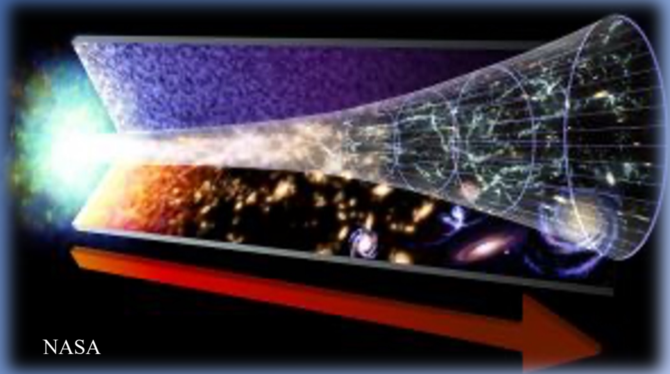


$\mathcal{O}(10^{-15}\mathrm{m})$

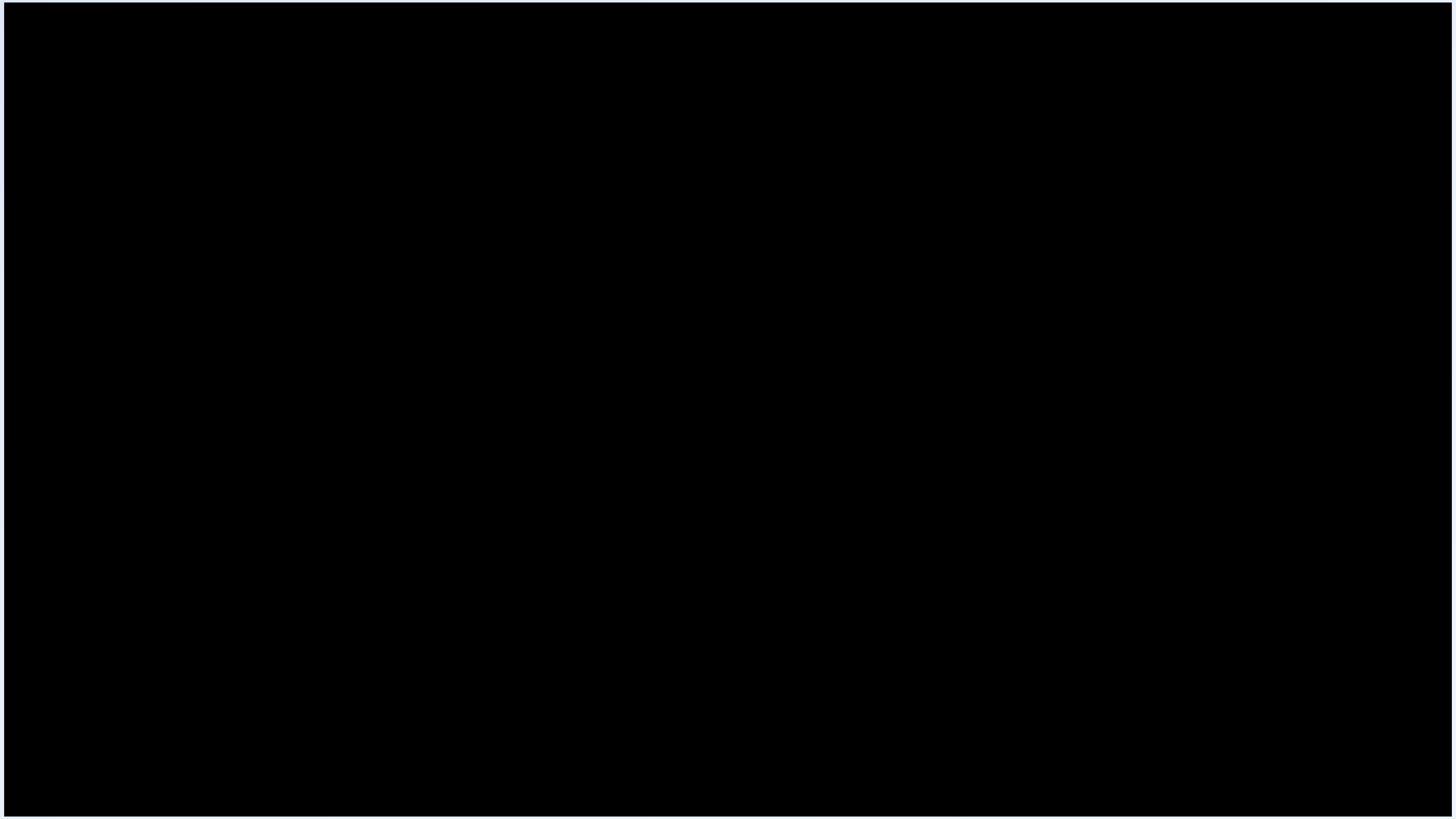
Heavy element production

Expansion rate of our Universe



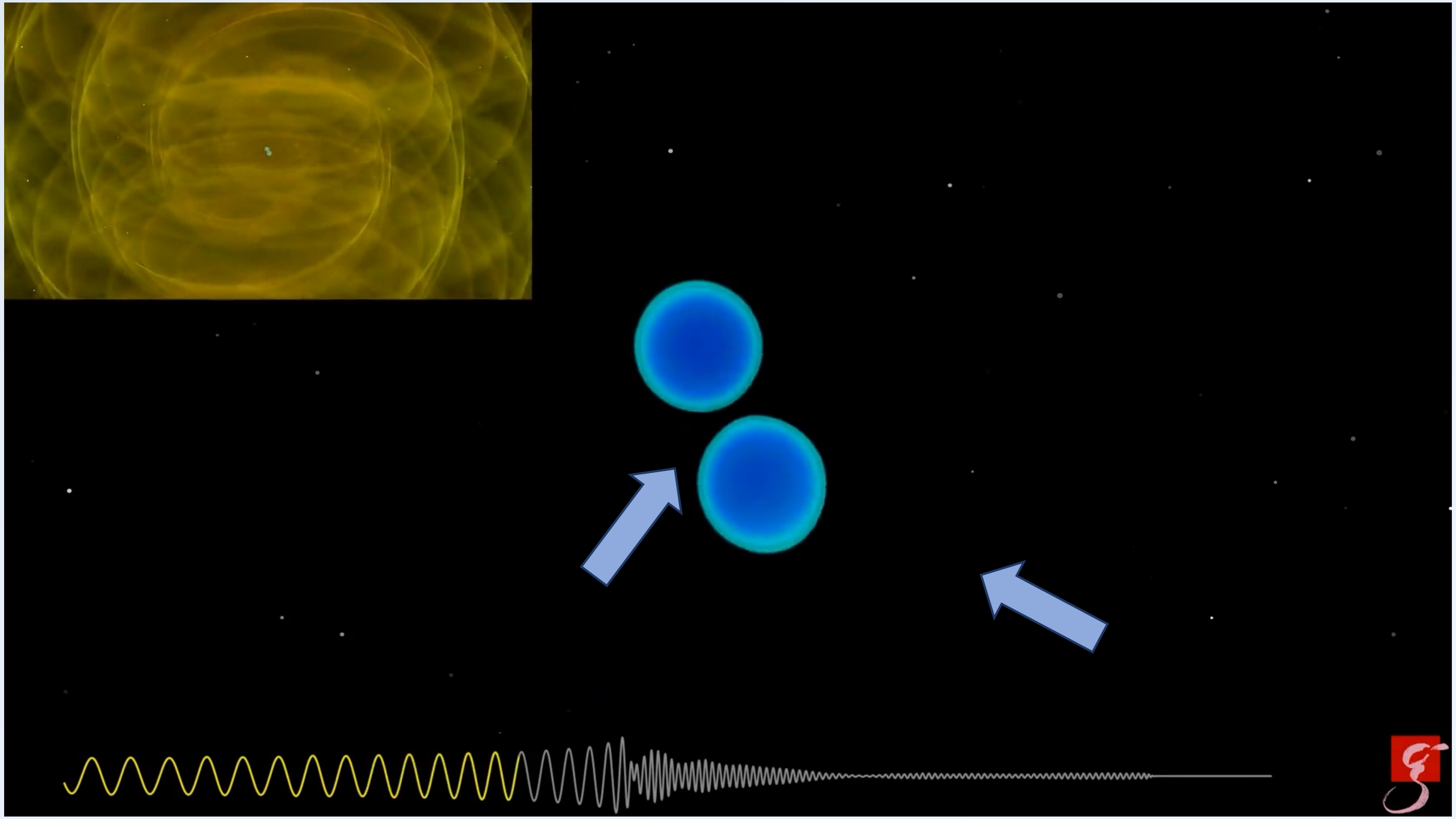
$\mathcal{O}(10^{25}\mathrm{m})$

The Binary Neutron Star Merger Simulation



gravitational wave emission

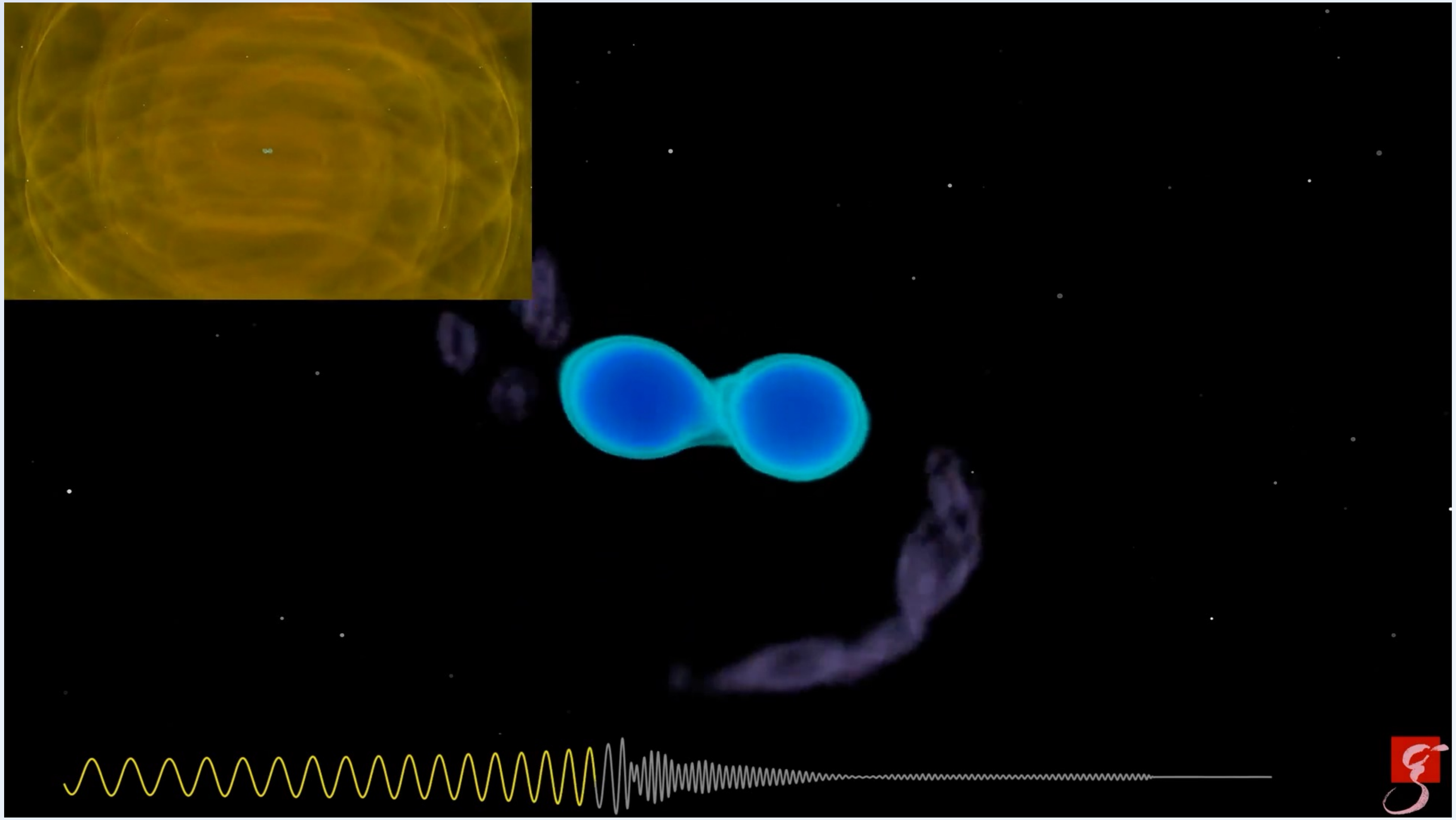
The Binary Neutron Star Merger Simulation



gravitational wave emission

deformation before merger, ejection of material, heavy element production

The Binary Neutron Star Merger Simulation



70 milliseconds

gravitational wave emission

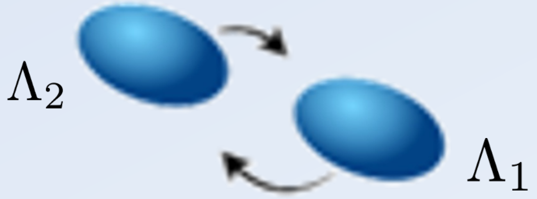
deformation before merger, ejection of material, heavy element production

black hole formation

Gravitational Wave Analysis

GW170817

Λ determines tidal deformability



Gravitational Wave Analysis

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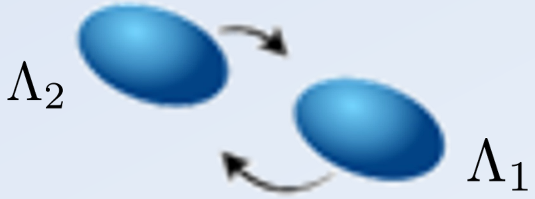

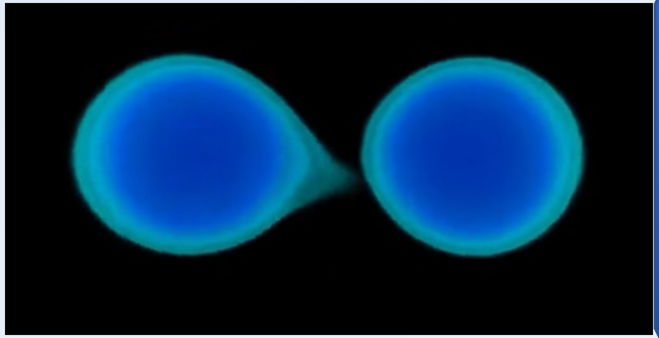

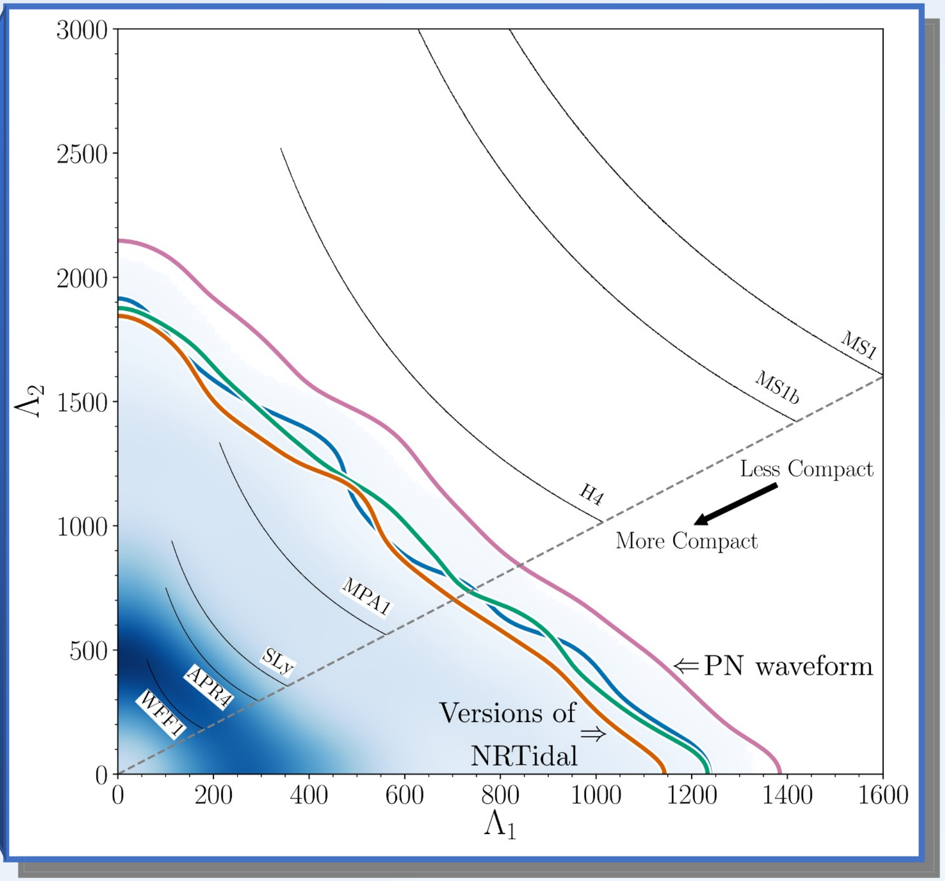

Phys.Rev. X9 (2019) 011001

→ no assumption about the type of the compact object

Gravitational Wave Analysis

GW170817

Assumption: The merging objects were neutron stars

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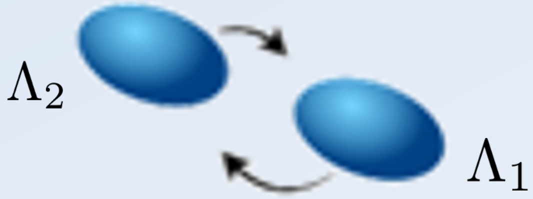
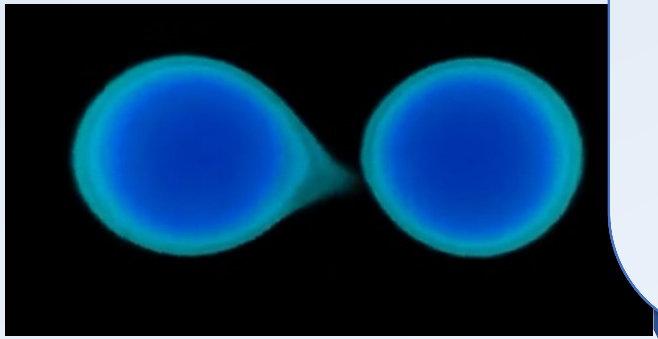
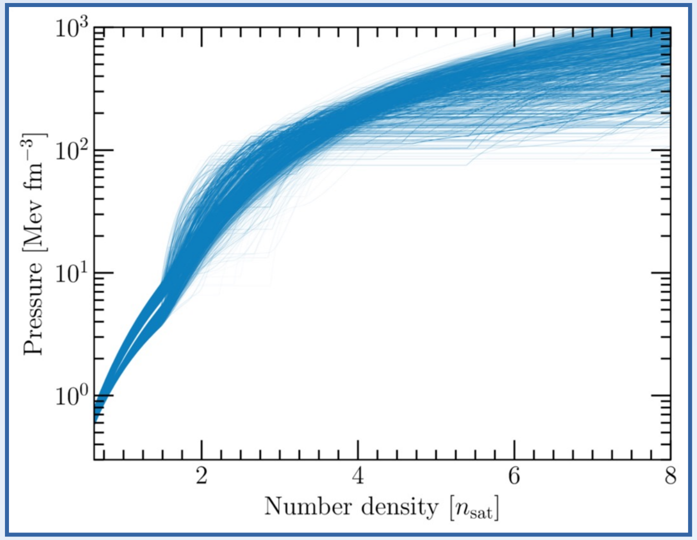
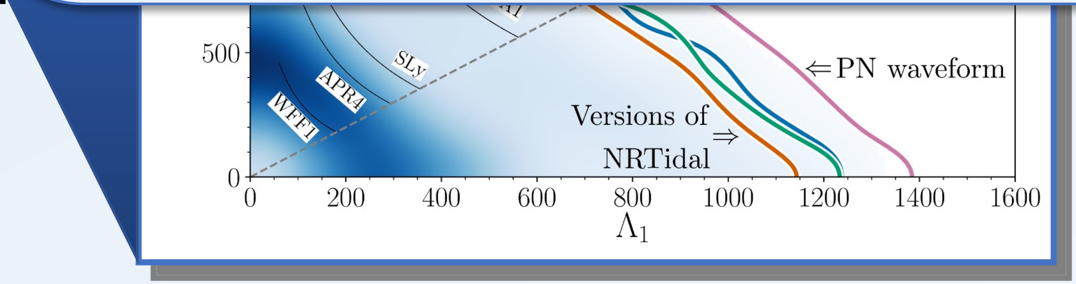






nuclear-physics computations



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Gravitational Wave Analysis

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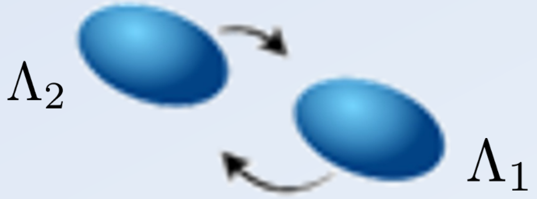

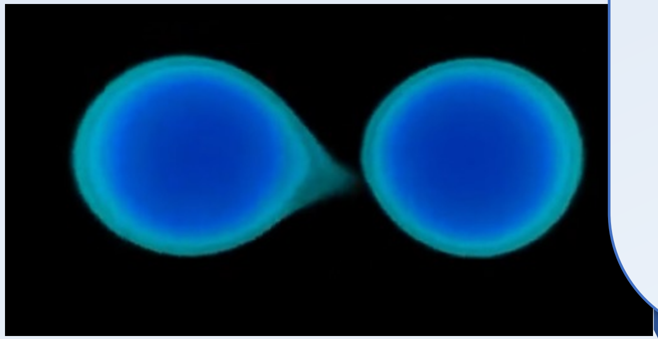

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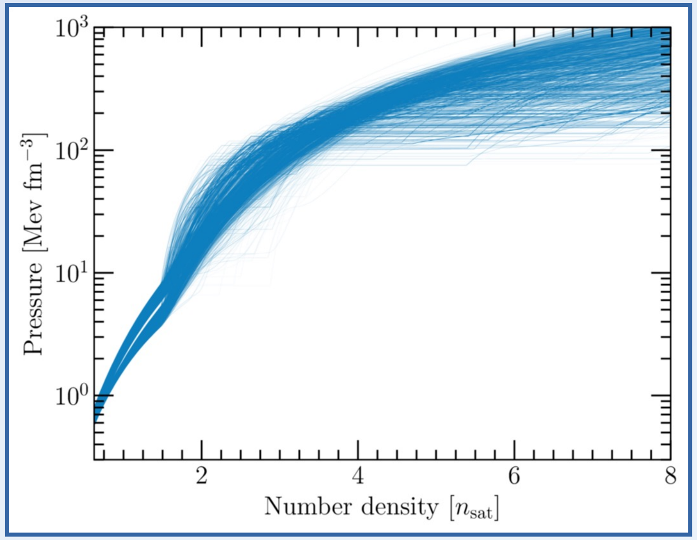

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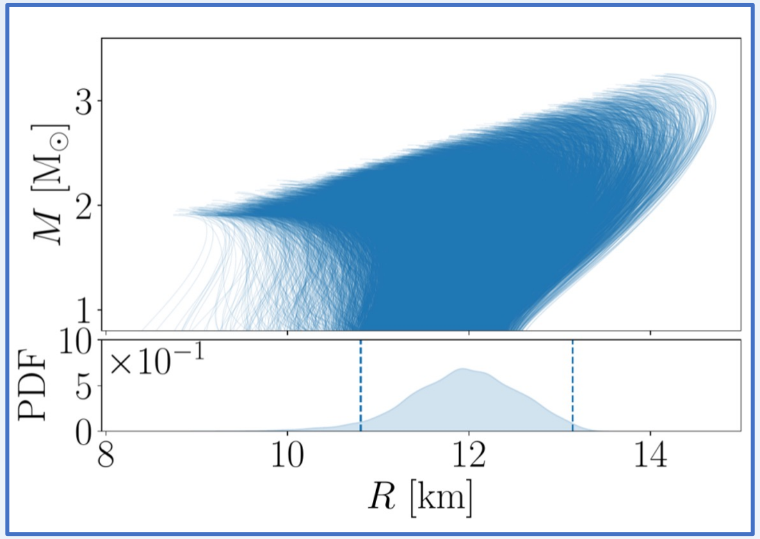

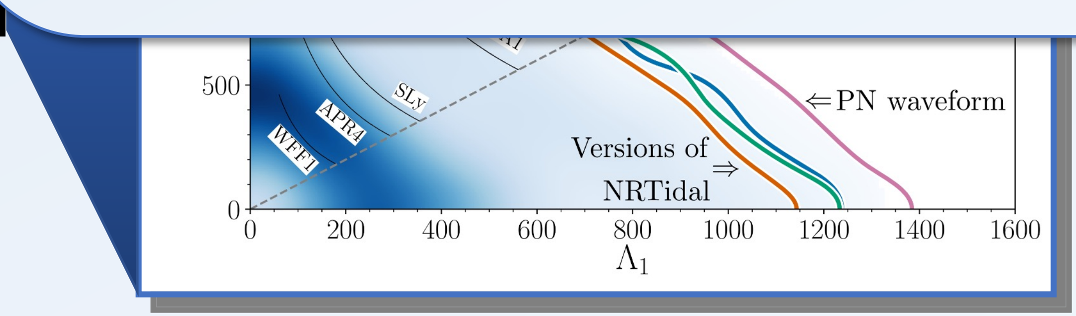

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Gravitational Wave Analysis

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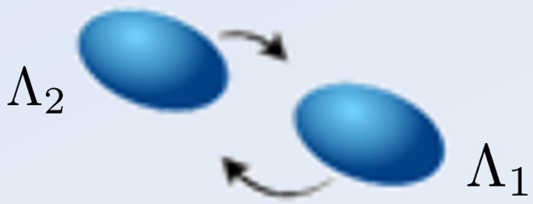

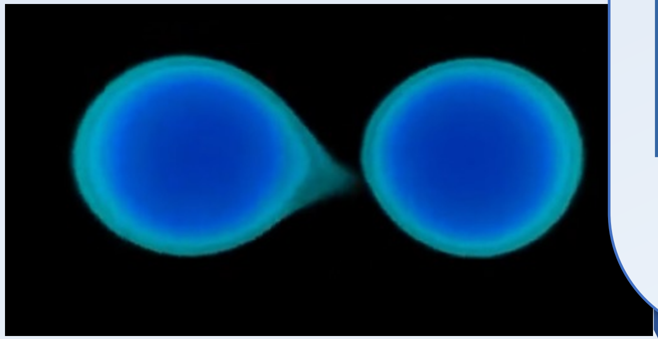

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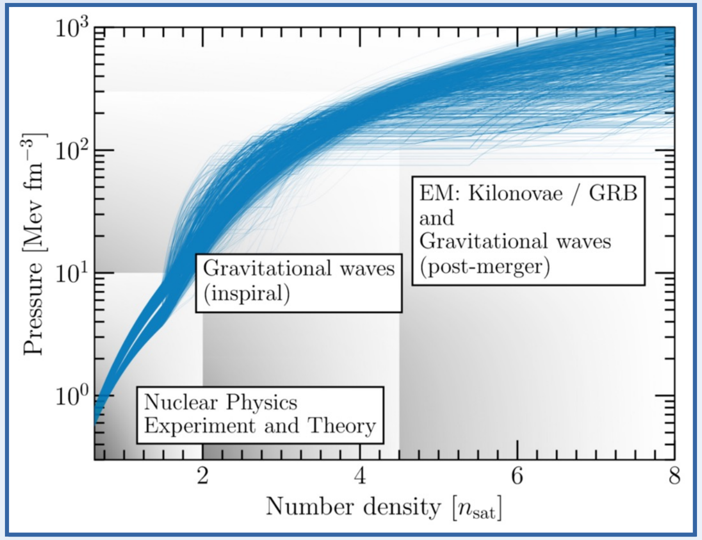

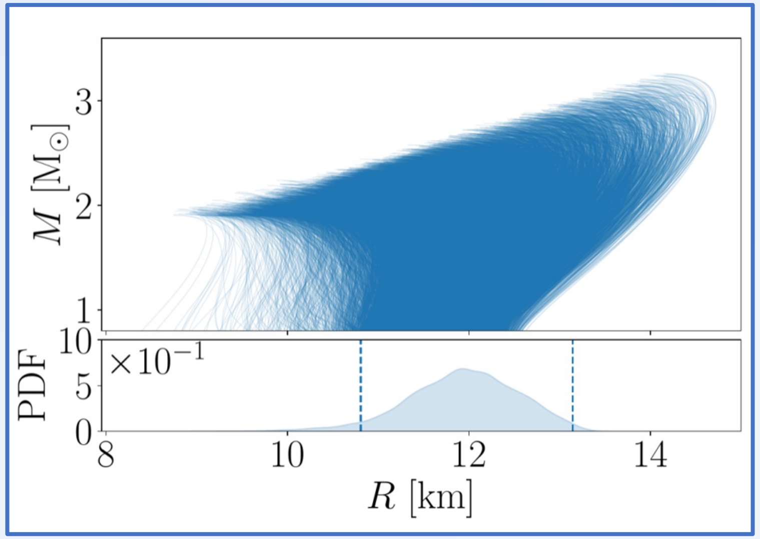

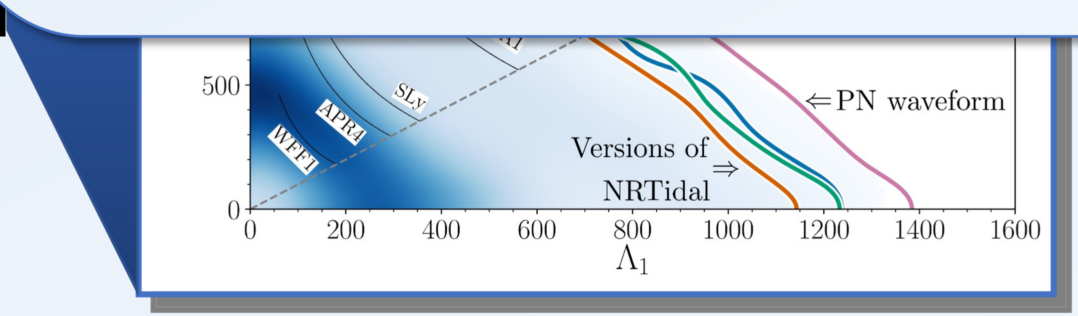

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Gravitational Wave Analysis


RESEARCH | Science

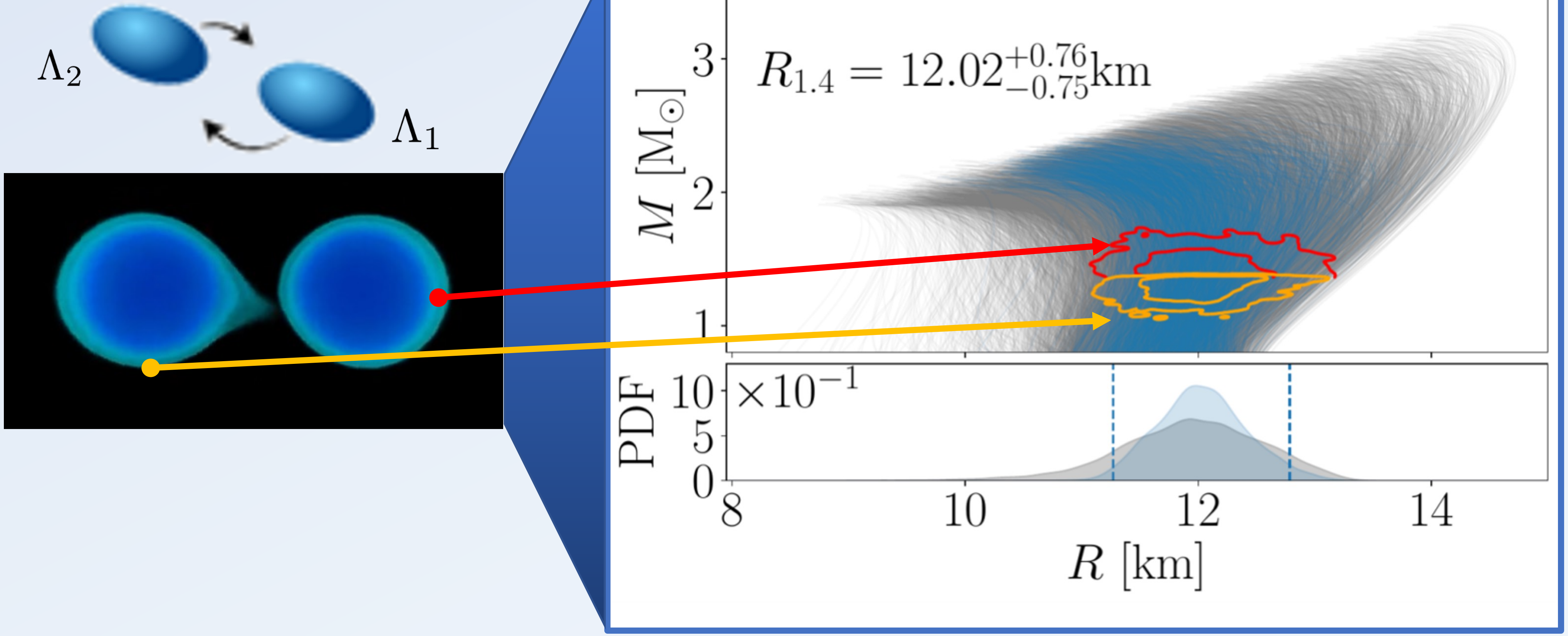
NEUTRON STARS

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

Tim Dietrich[1,2]*, Michael W. Coughlin[3], Peter T. H. Pang[2,4], Mattia Bulla[5], Jack Heinzel[3,6,7], Lina Issa[5,8], Ingo Tews[9], Sarah Antier[10]

GW170817

Λ determines tidal deformability

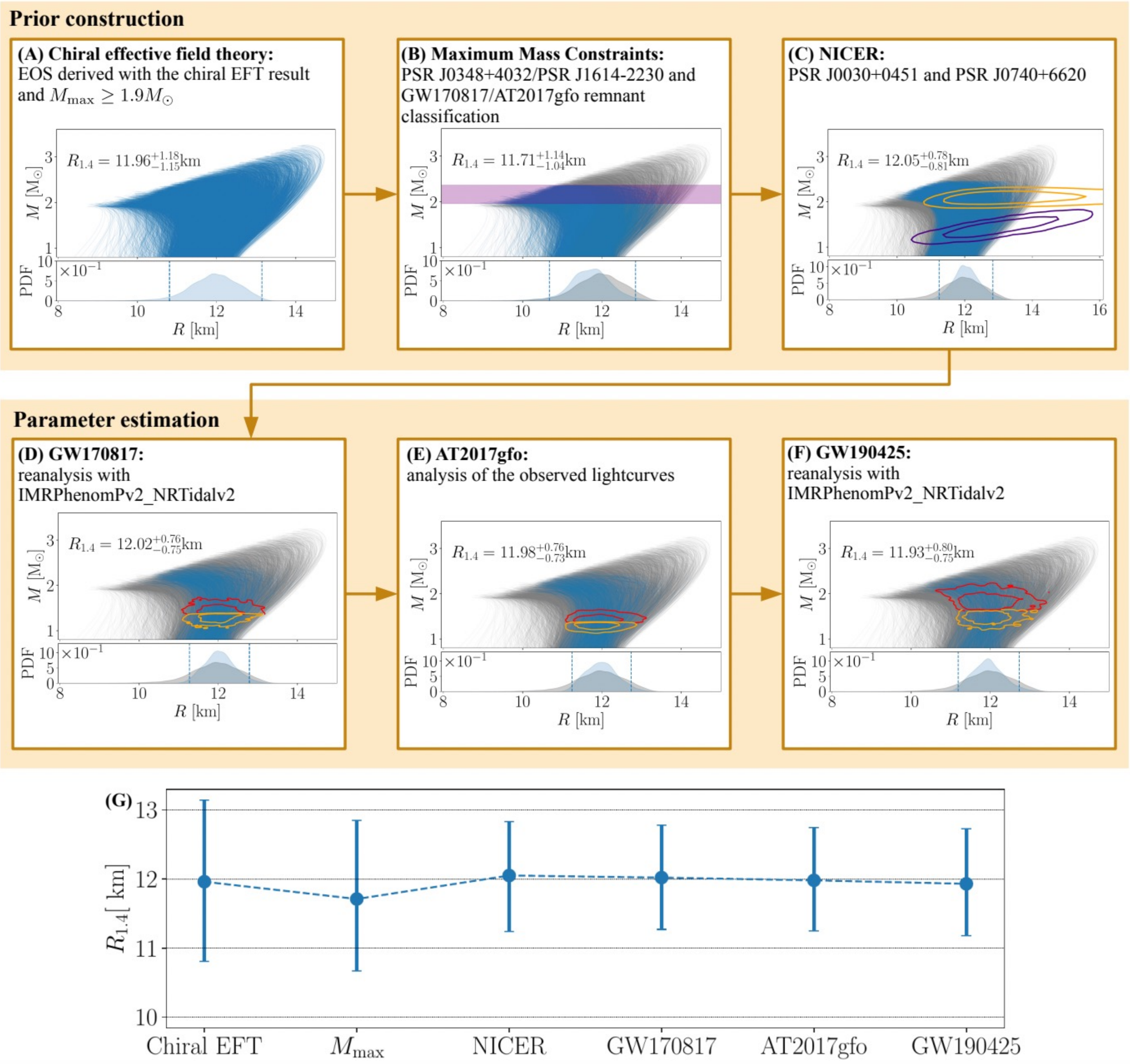


Assumption: The merging objects were neutron stars

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

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

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



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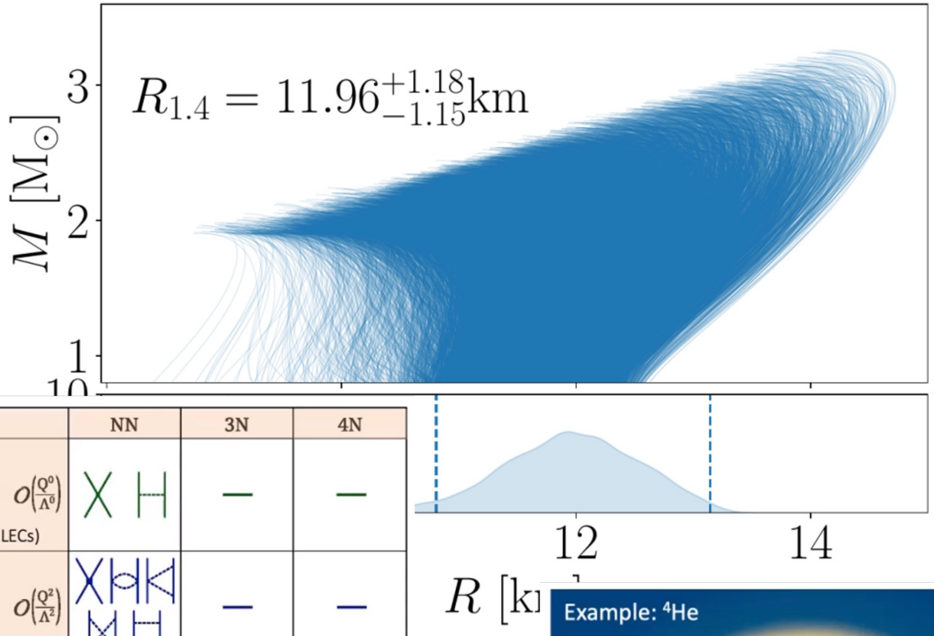
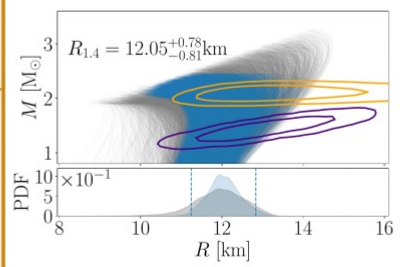
Huth et al., Nature 606 (2022) 276-280

(A) Chiral effective field theory:

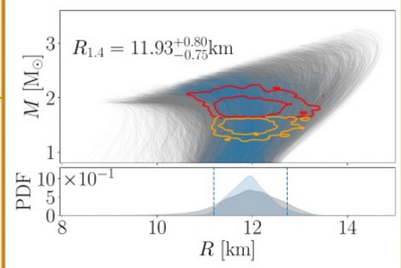
EOS derived with the chiral EFT result and $M_{\max} \geq 1.9 M_{\odot}$

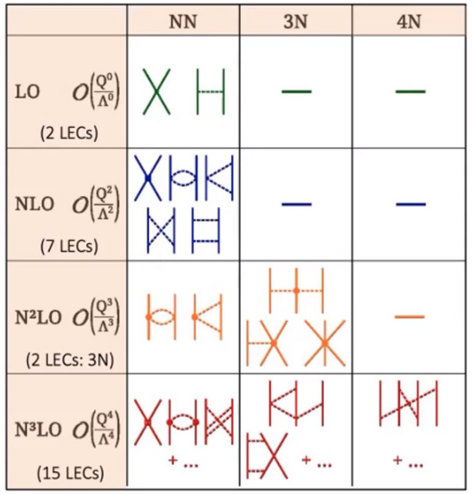


(C) NICER:
PSR J0030+0451 and PSR J0740+6620



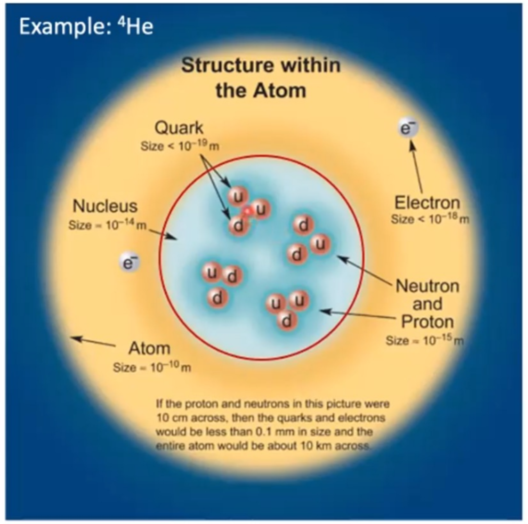
(F) GW190425:
reanalysis with
IMRPhenomPv2_NRTidalv2

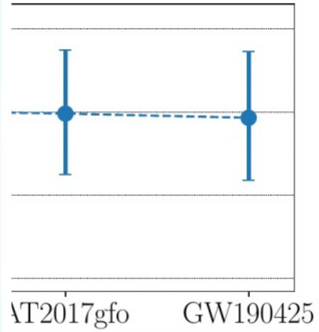




$$\mathcal{H}|\Psi\rangle = E|\Psi\rangle$$

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





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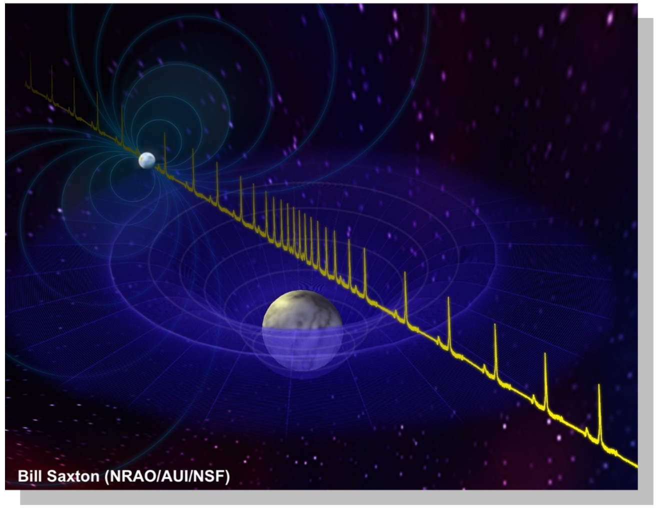
EM Signals – Maximum Neutron Star Mass

lower bound

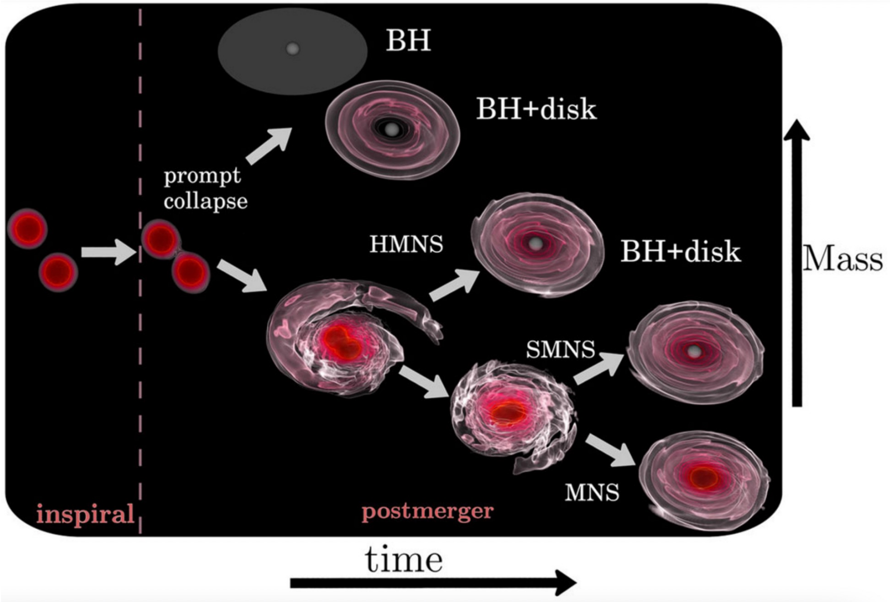
Measurement of massive pulsars through Shapiro time delay



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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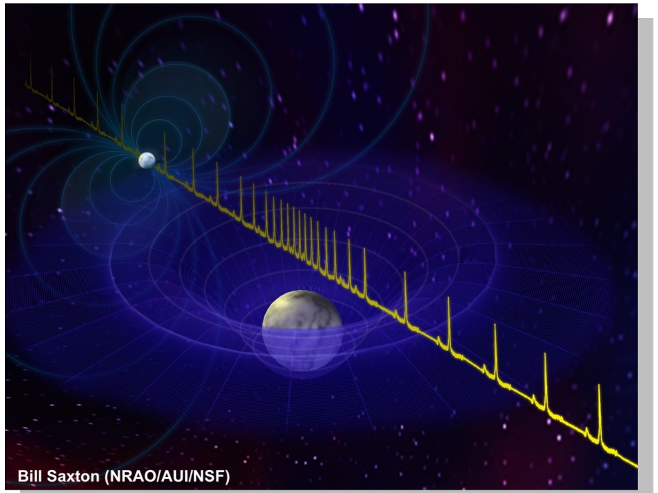

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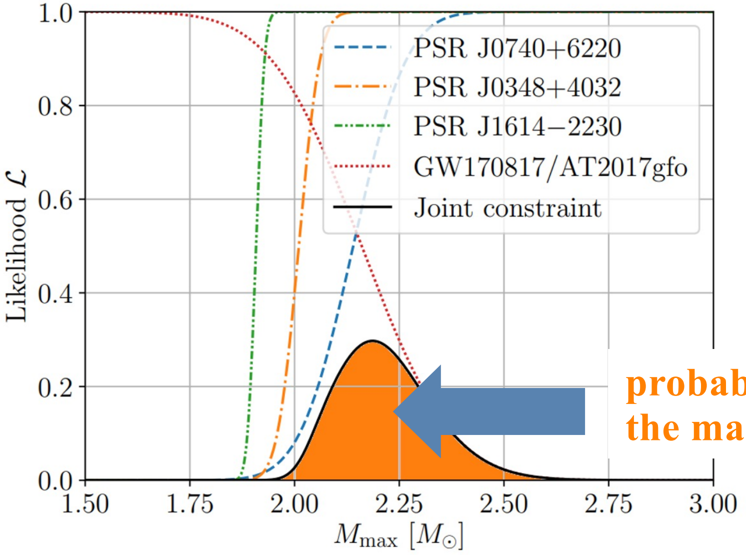
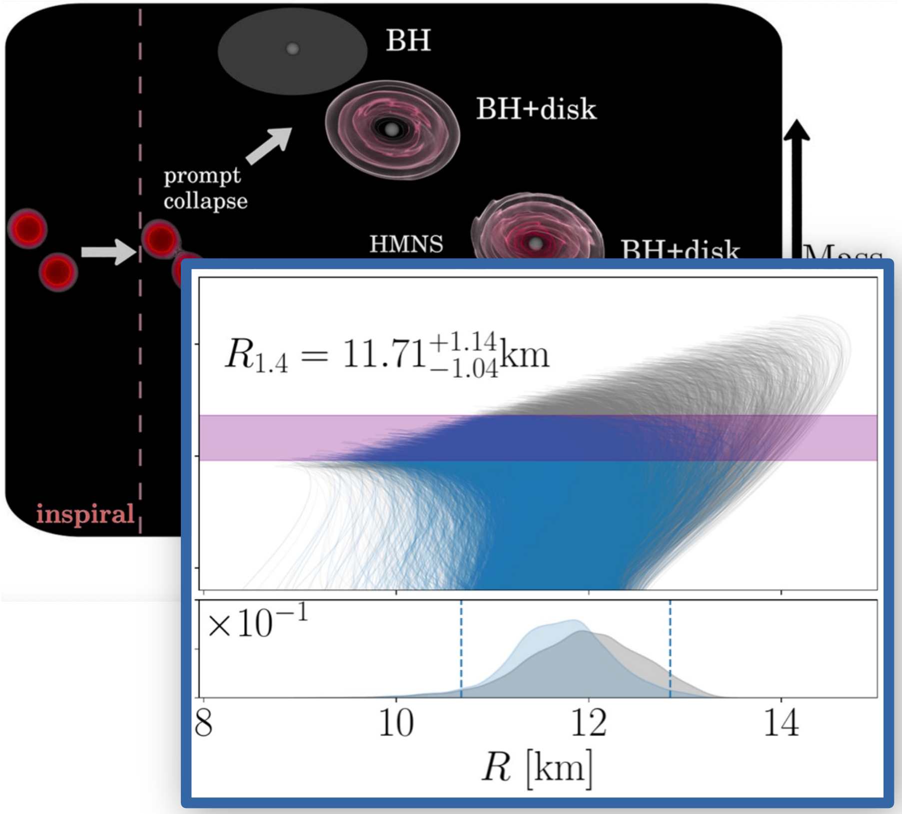


probability distribution for the maximum NS mass

upper bound

postmerger evolution of GW170817's remnant



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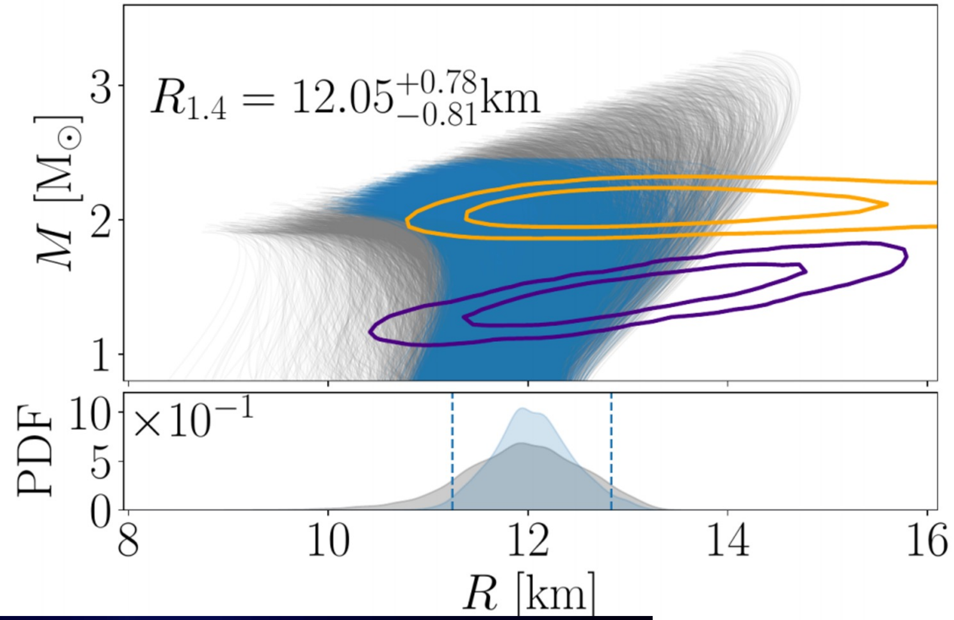
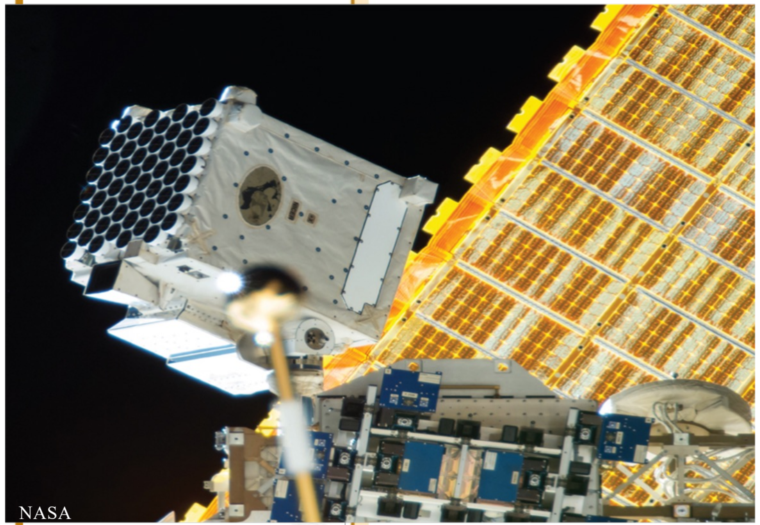
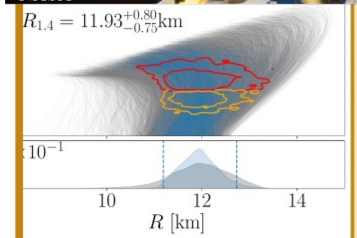
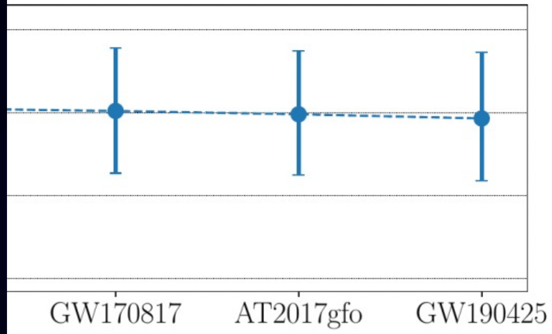


CER:
030+0451 and PSR J0740+6620





NASA



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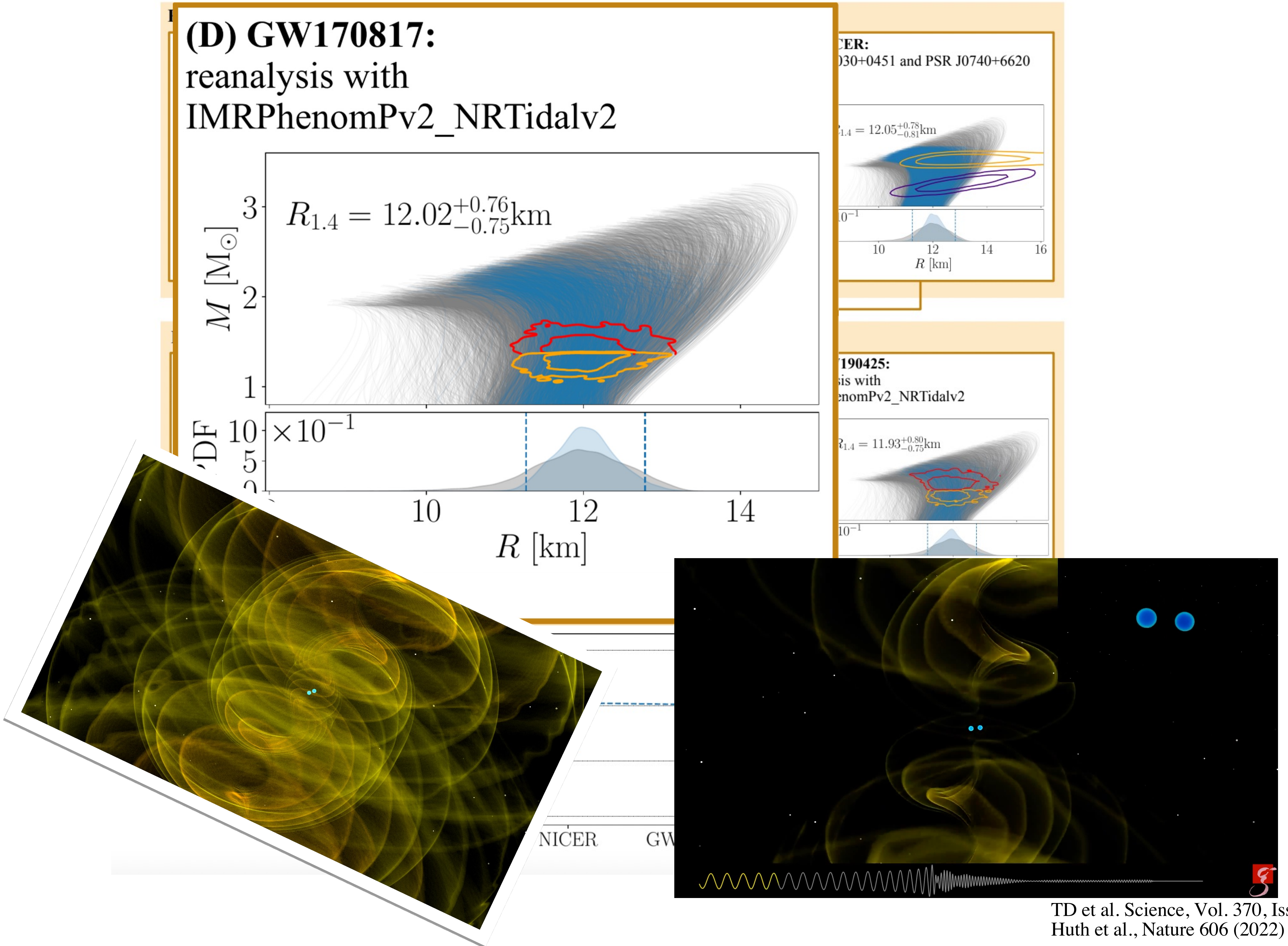

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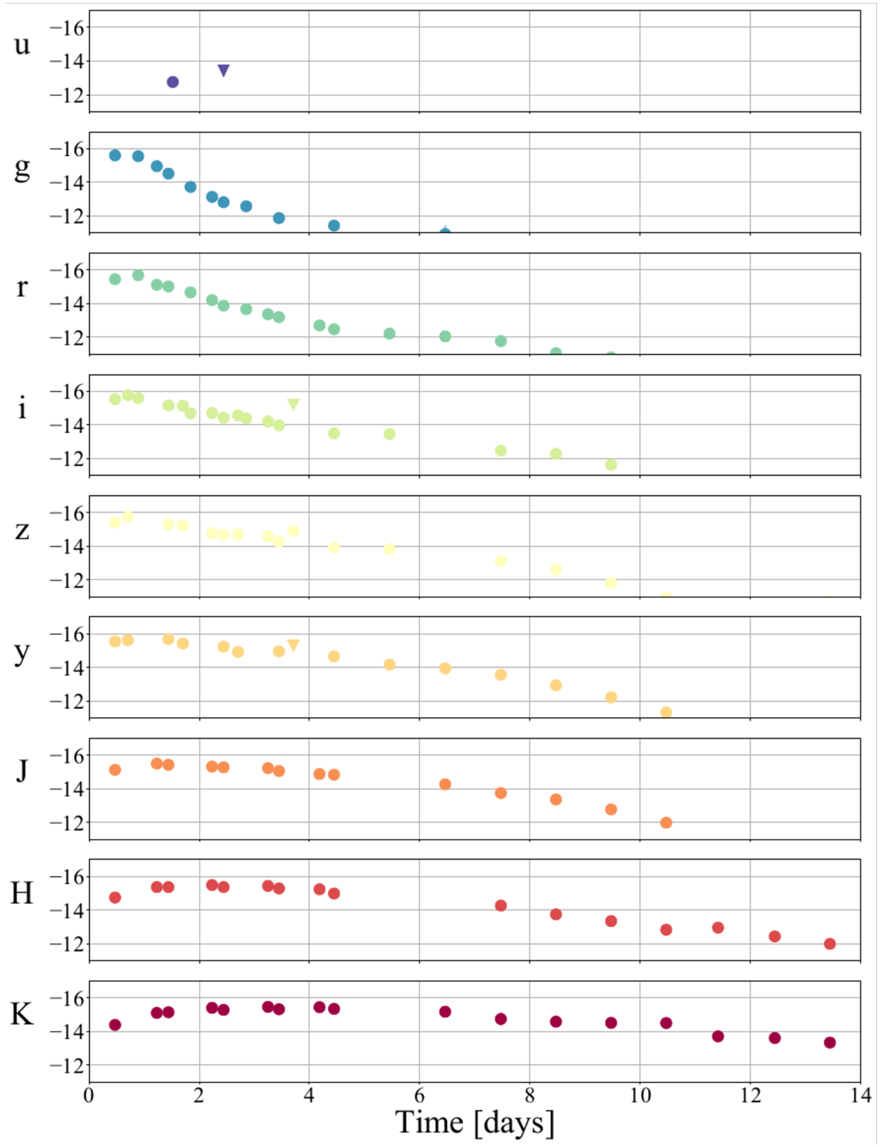
Photometric lightcurves



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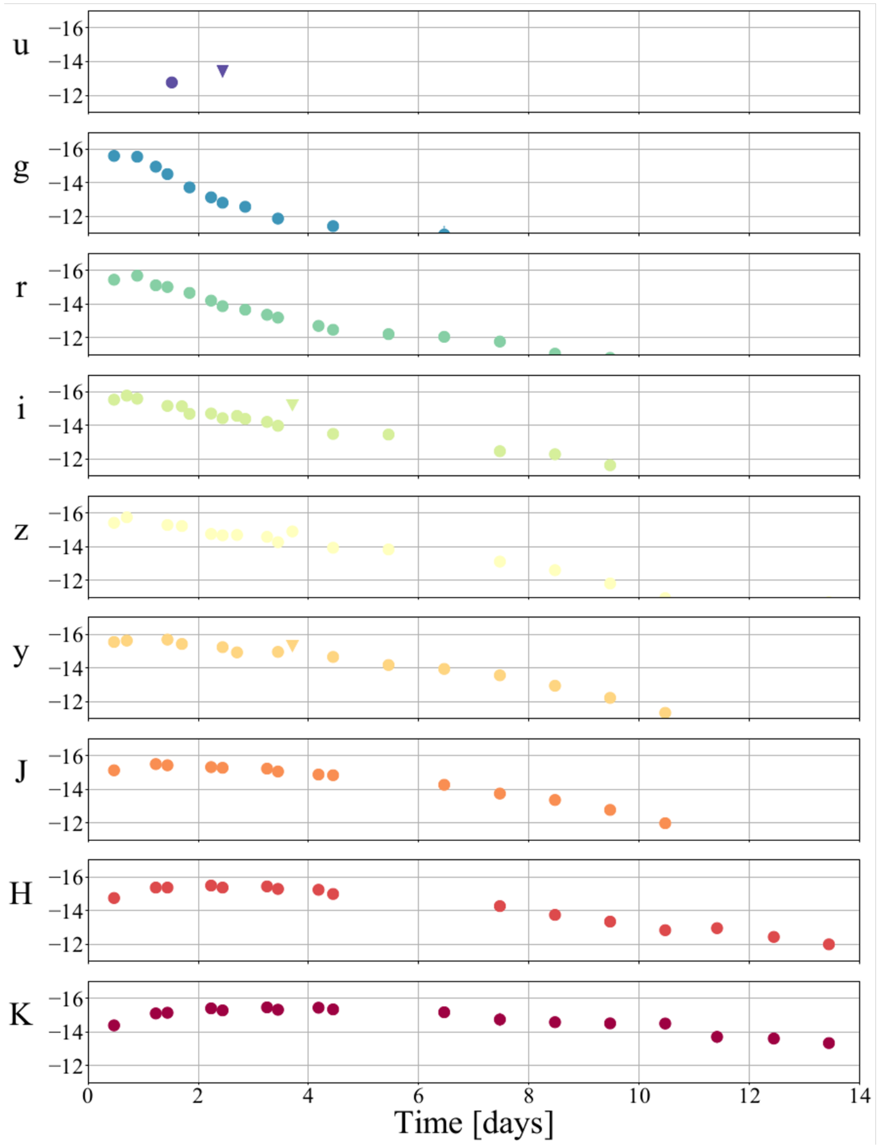
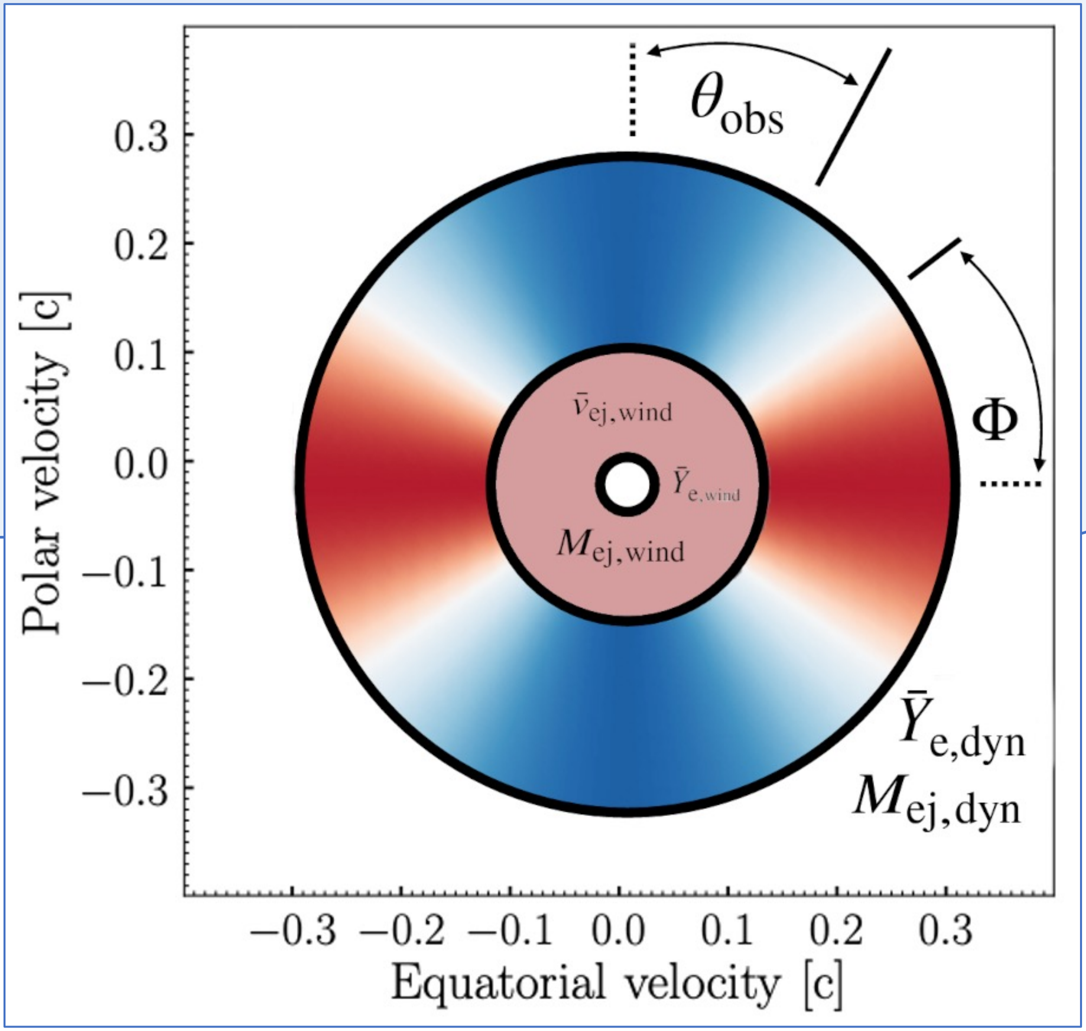


1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code



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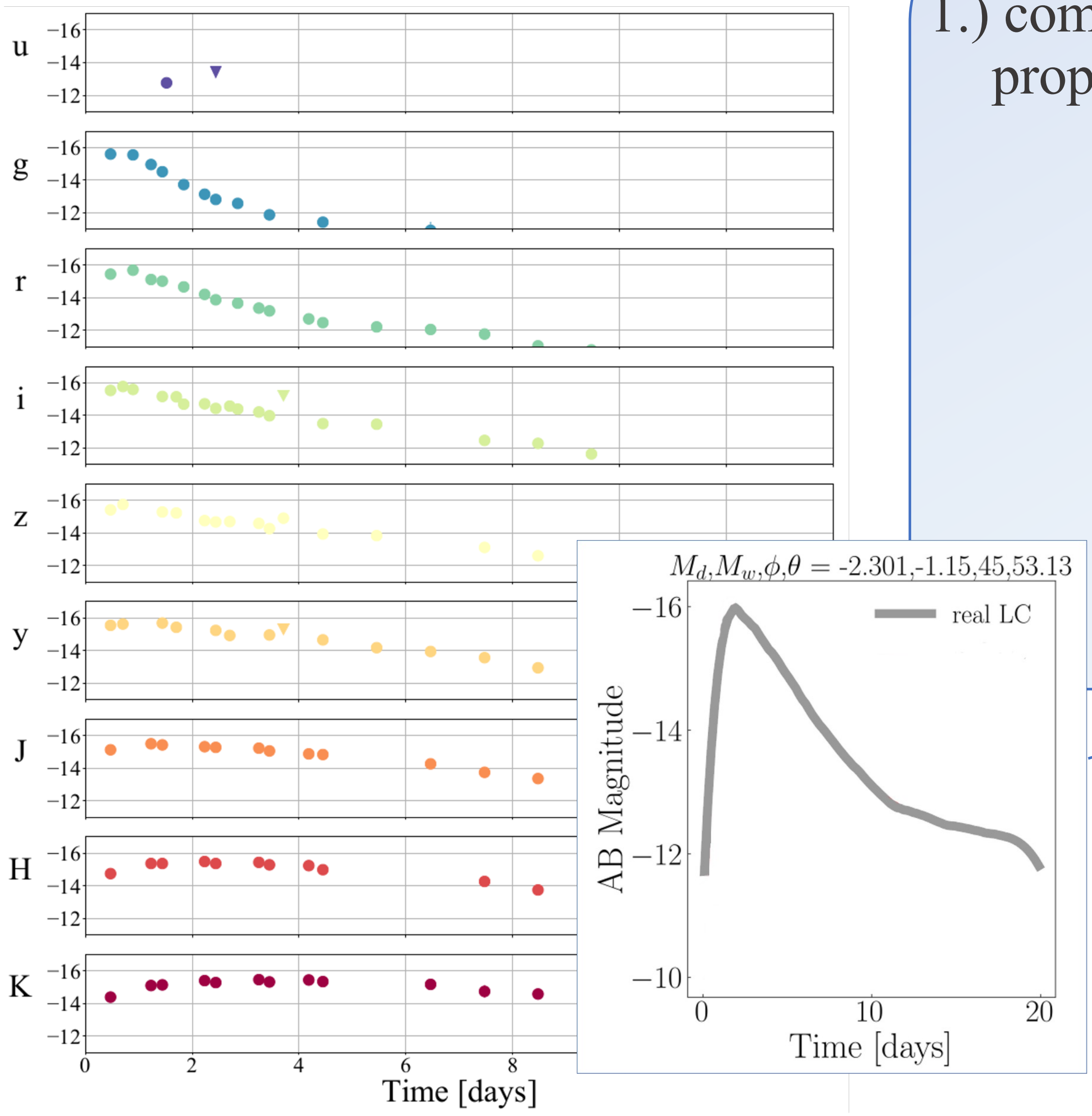

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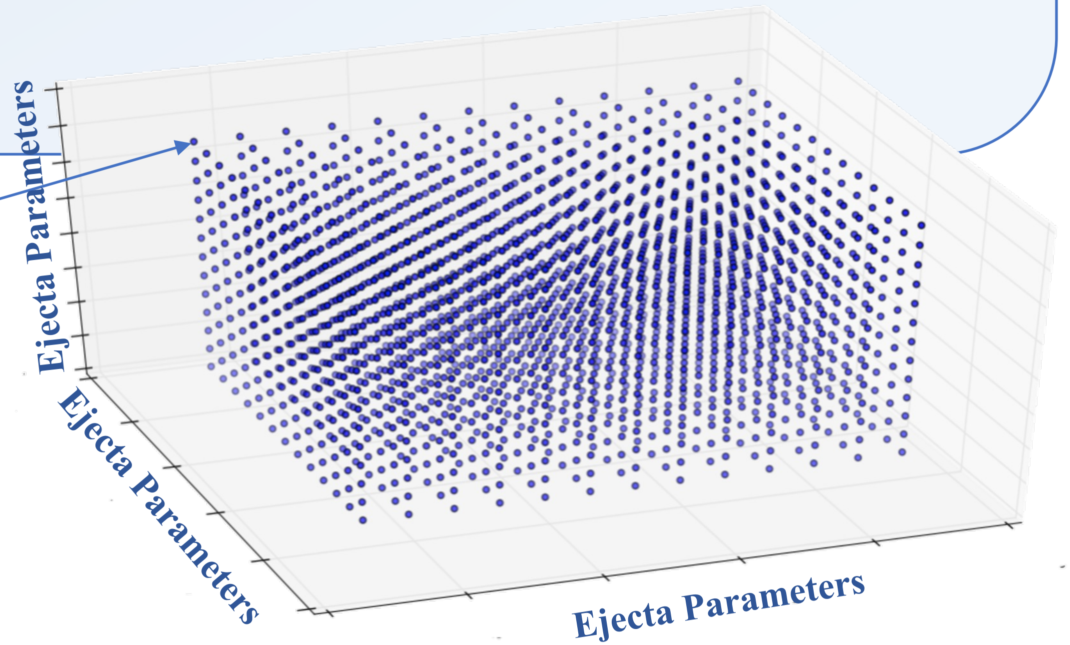

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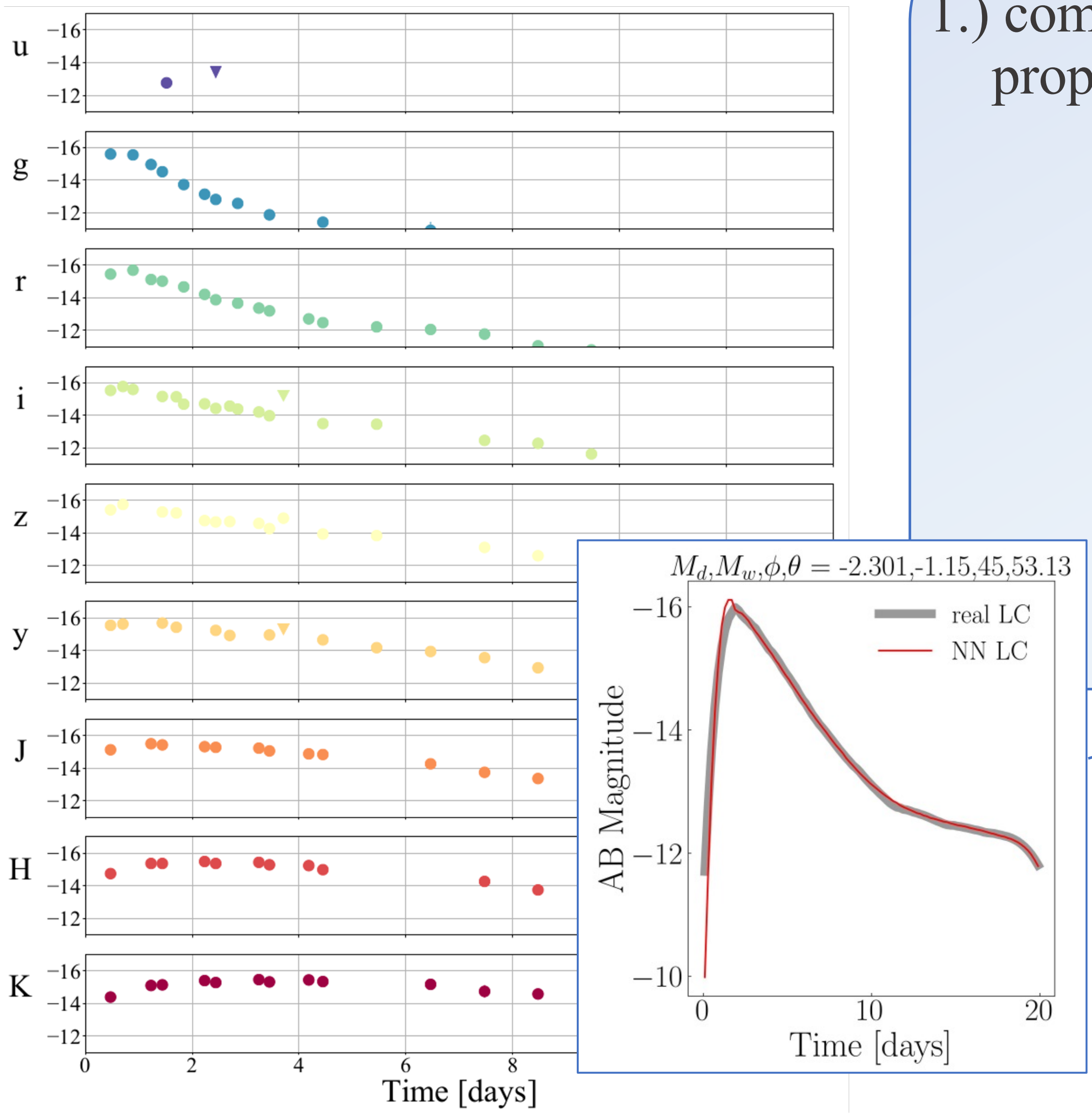

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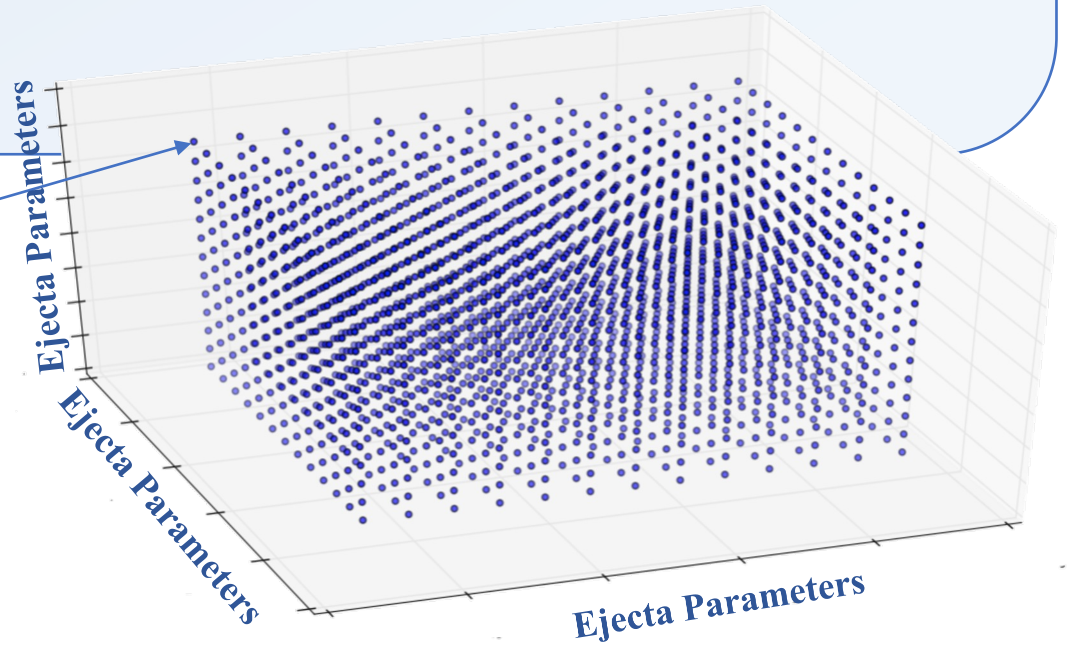
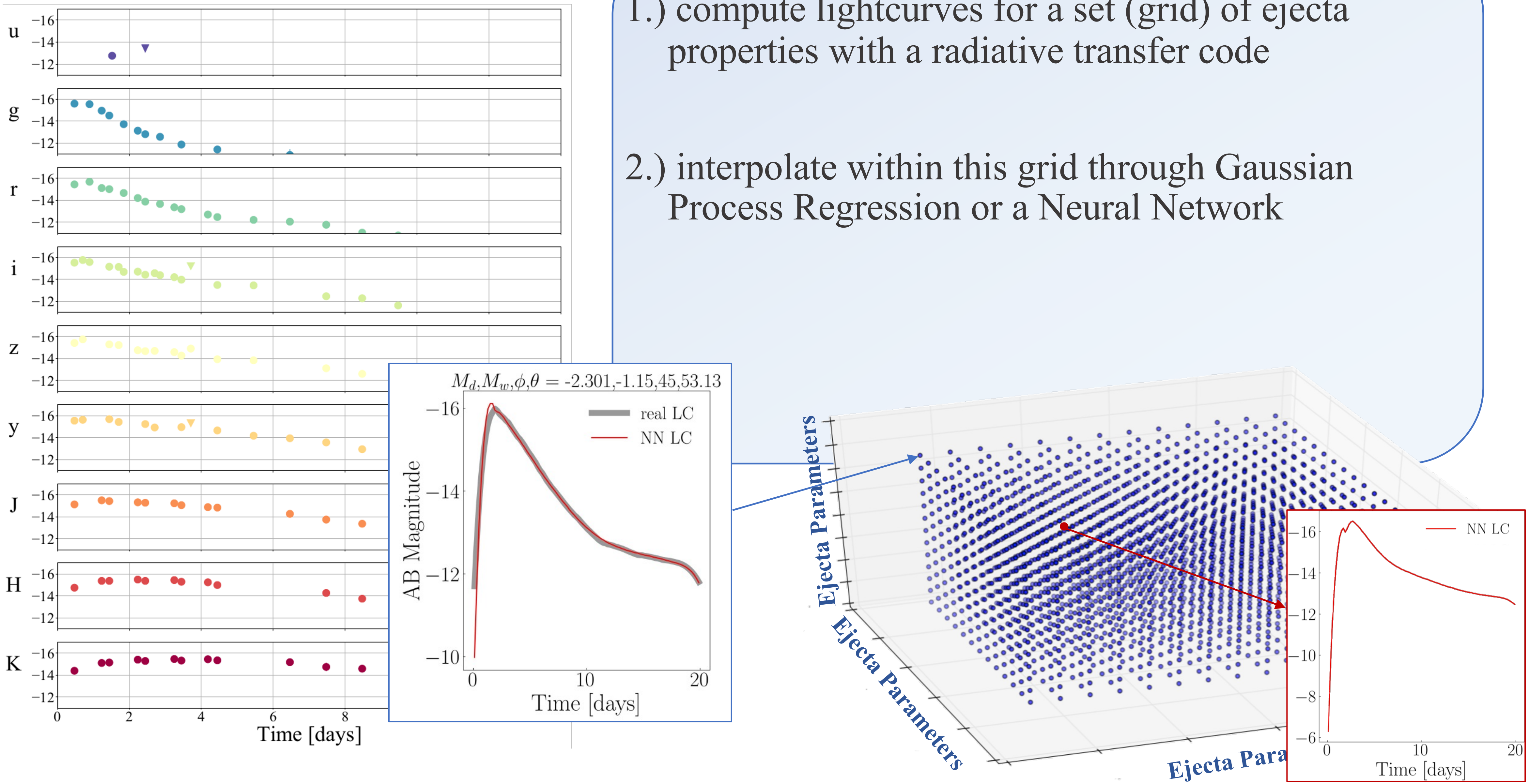


Photometric lightcurves

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



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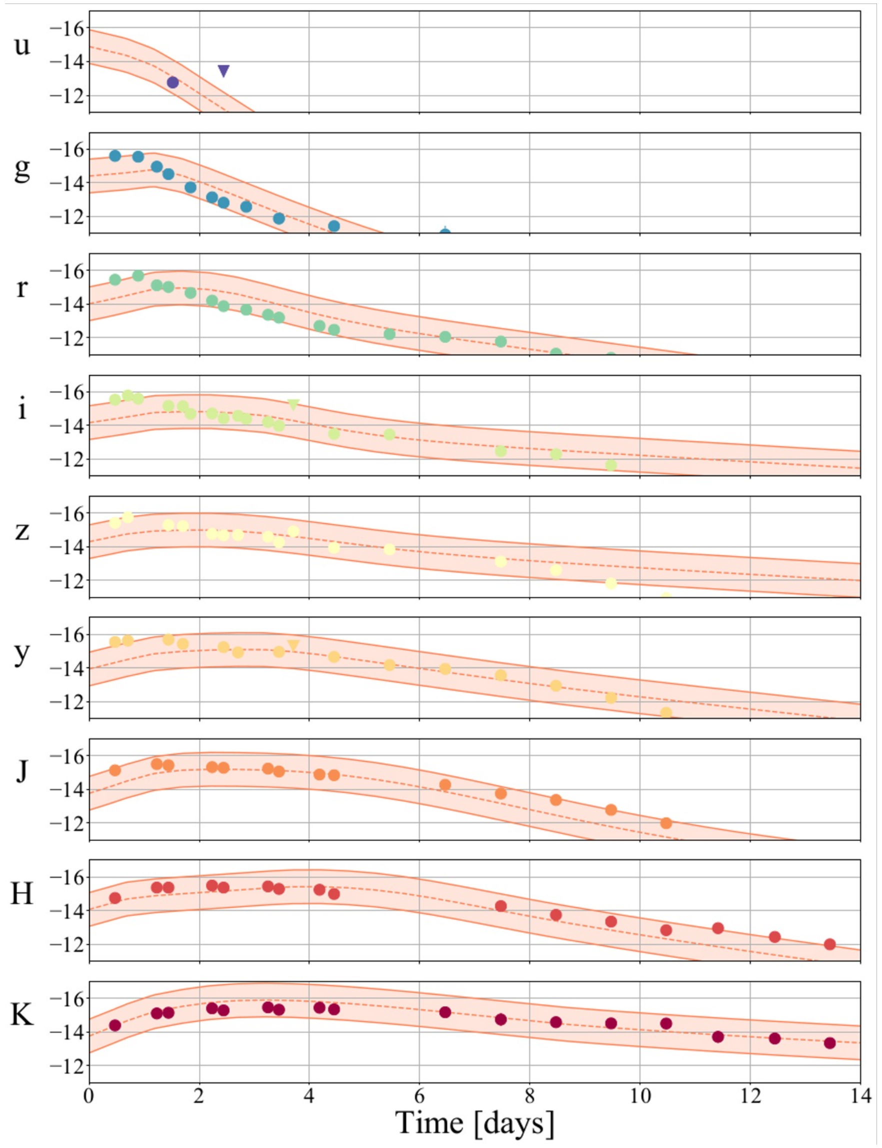

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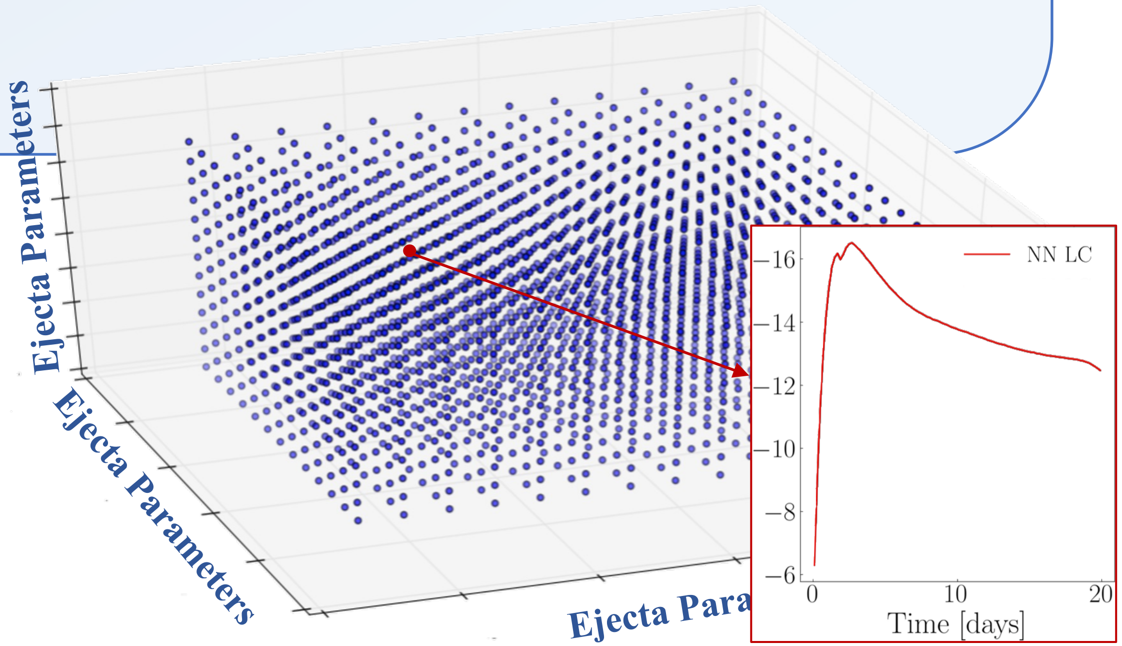

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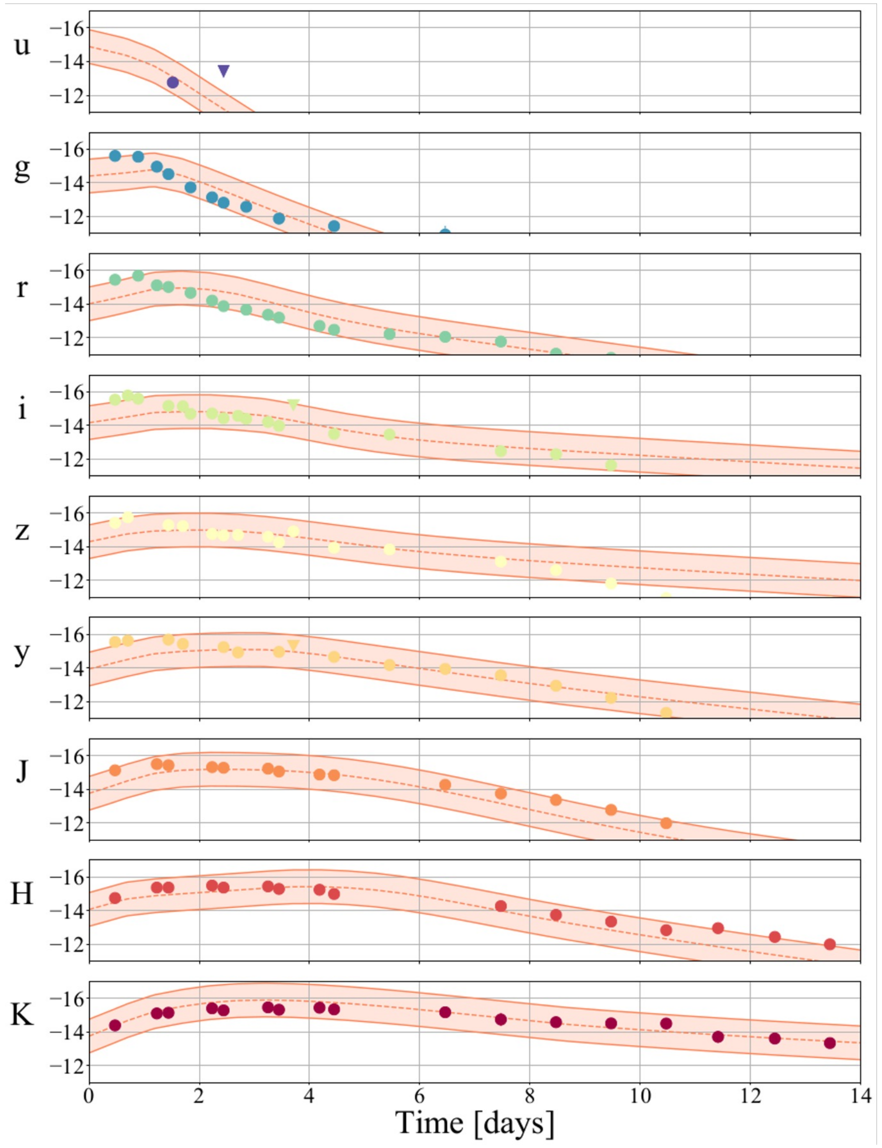

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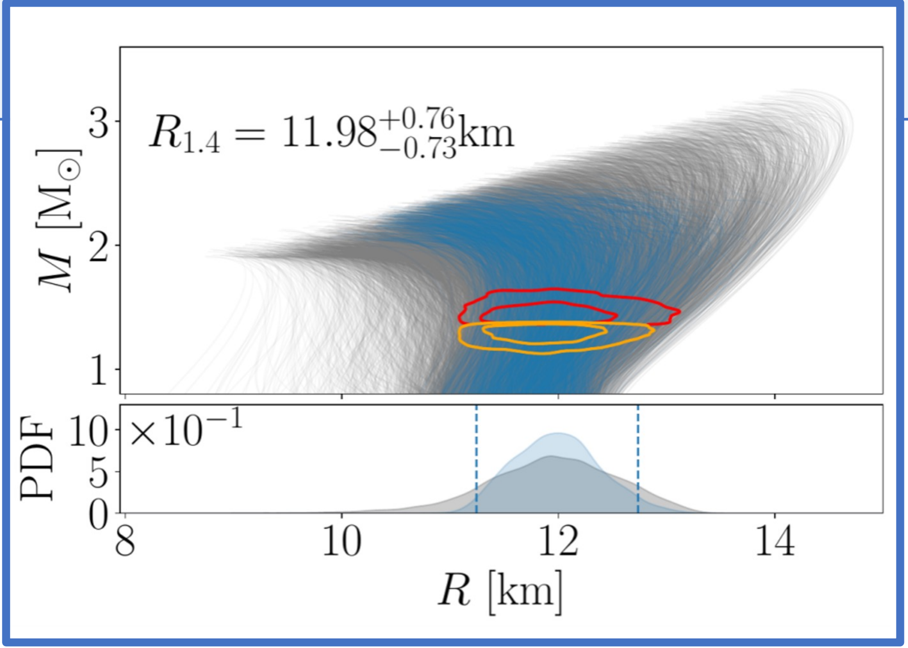
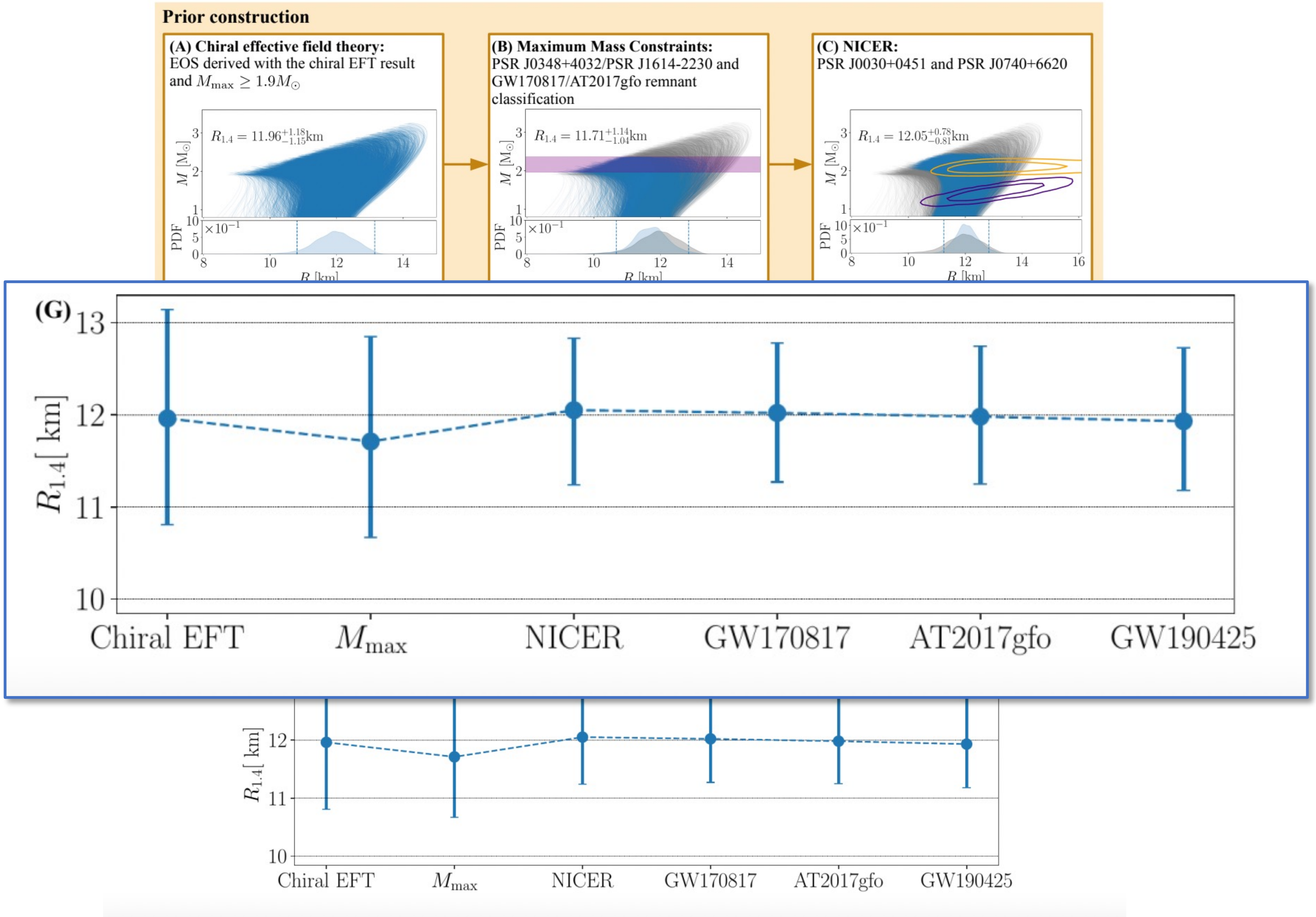
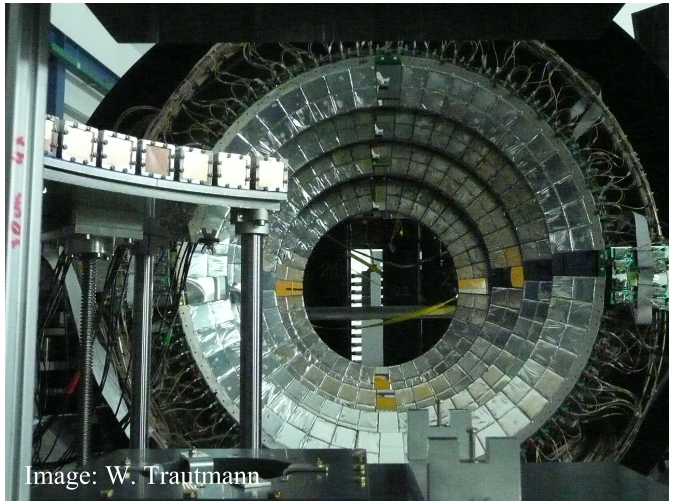
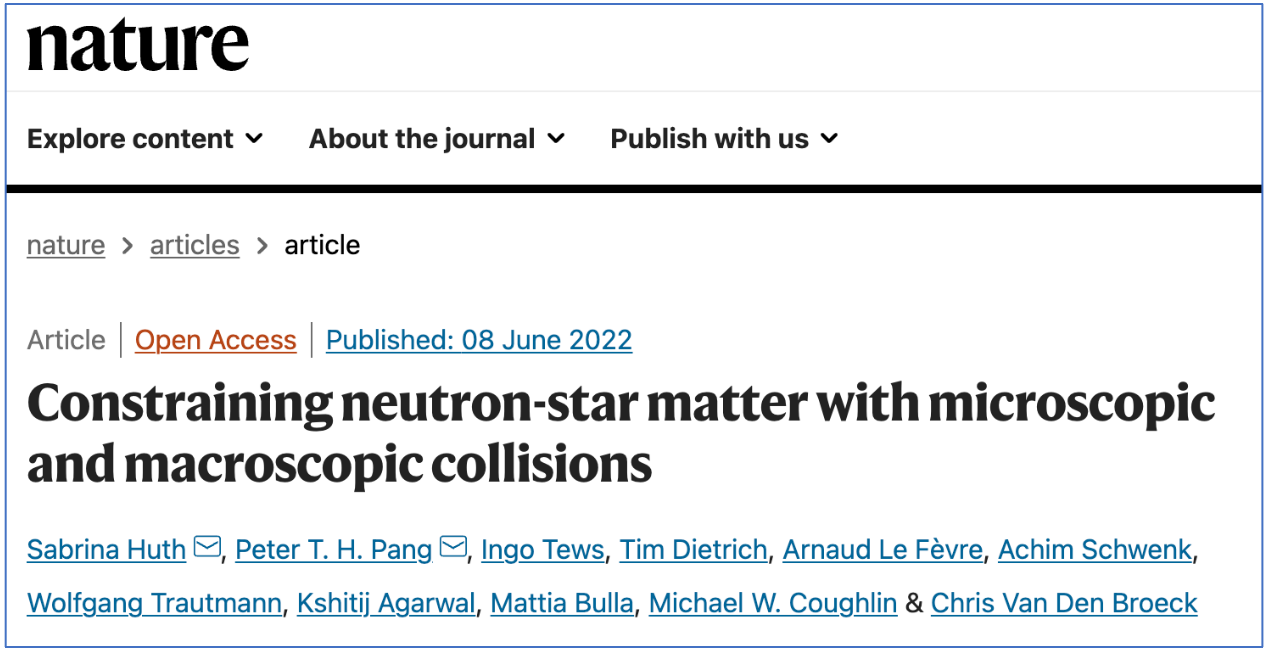
3.) link ejecta properties through numerical-relativity predictions to the binary properties





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

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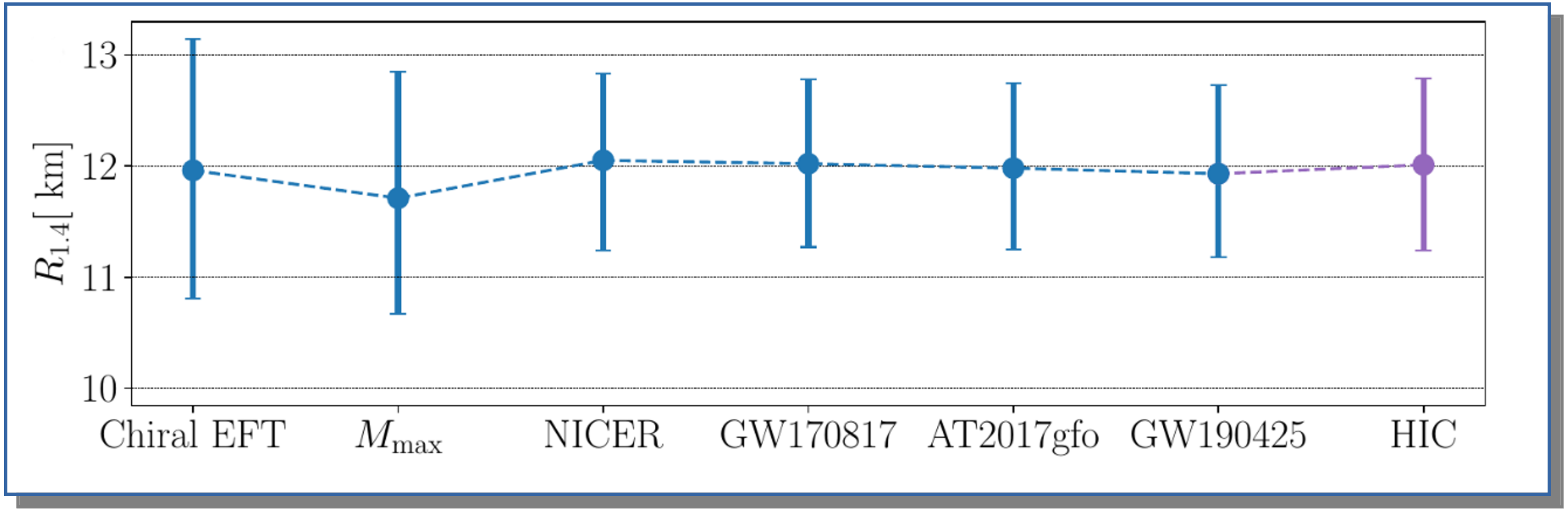
Constraining neutron-star matter with microscopic and macroscopic collisions

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



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

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

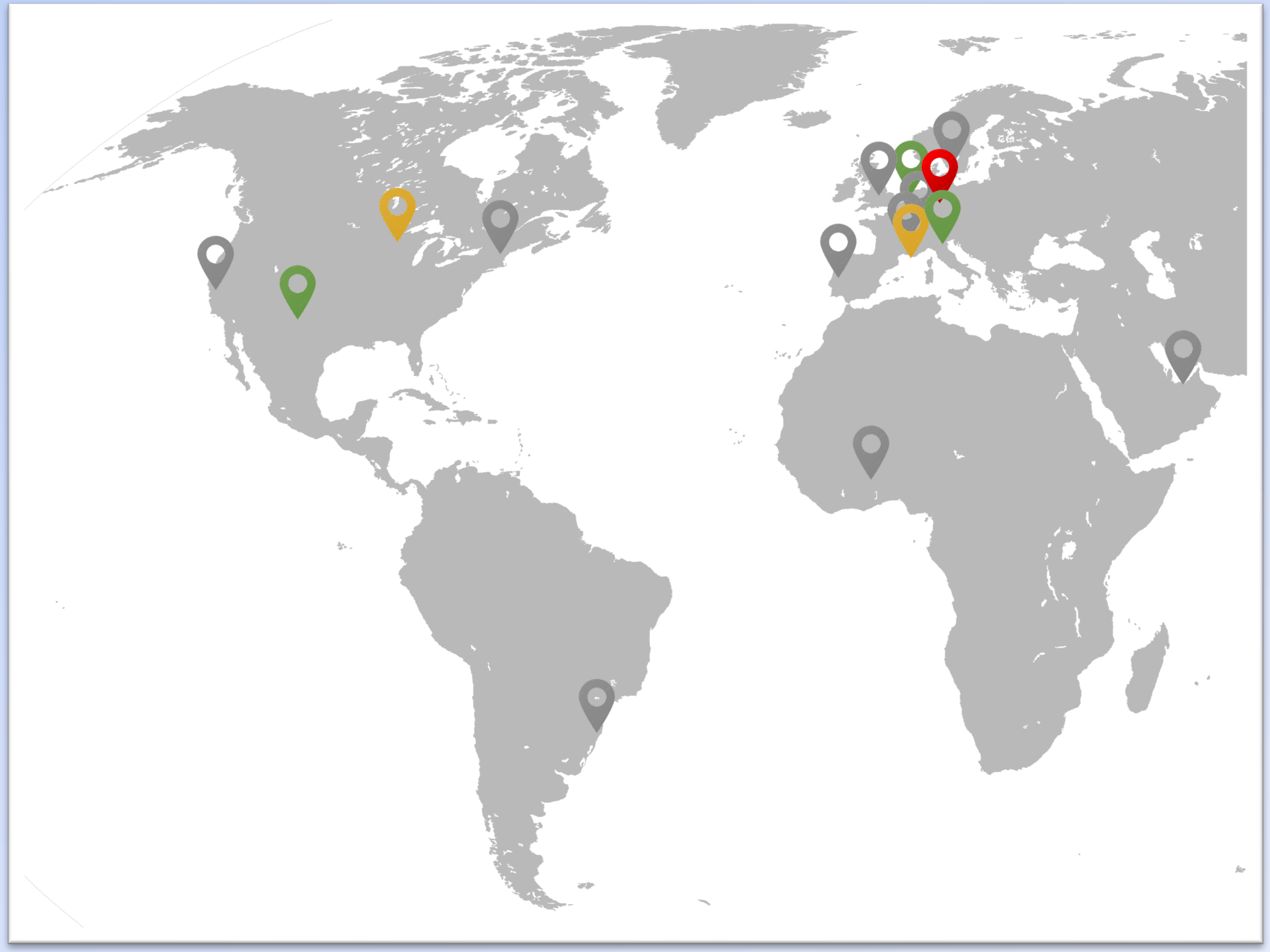
Observations

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

University of Ferrara
- modelling of electromagnetic signals

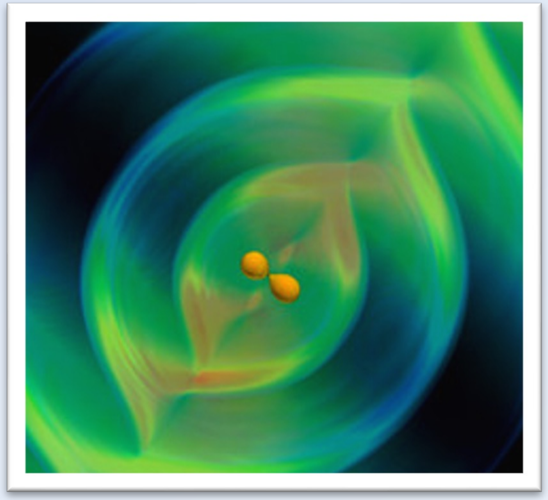
Theory

Los Alamos National Lab
- nuclear physics

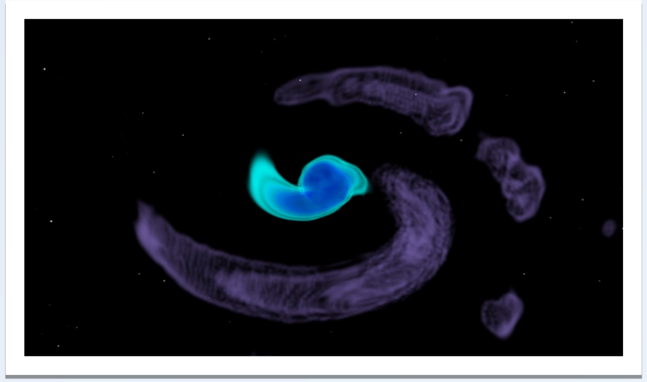


Nuclear Physics and Multi-messenger Astrophysics

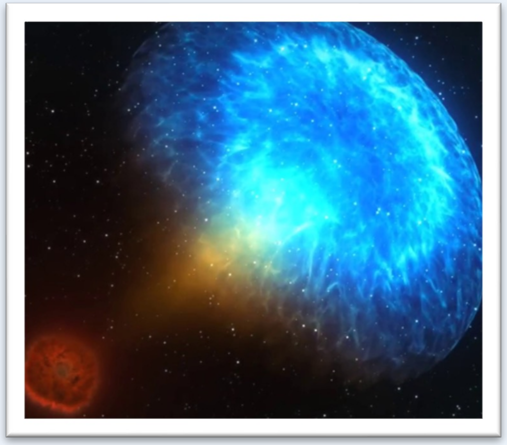
NMMA



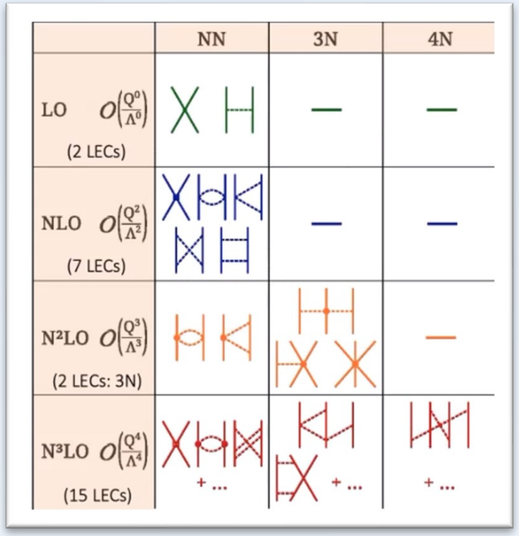
Gravitational Waves



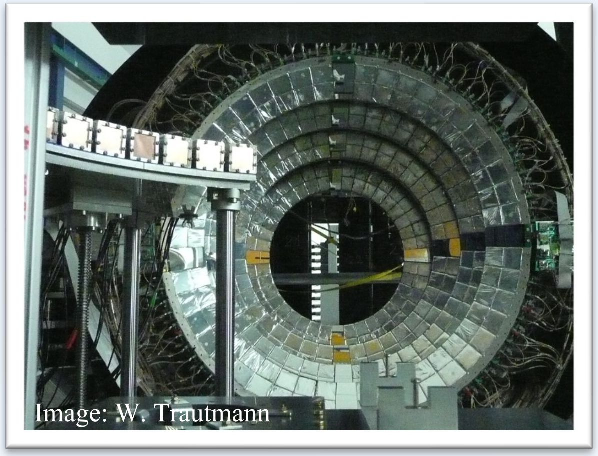
Kilonova



Gamma-ray burst and afterglow



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

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

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

Parameter estimation through Bayes theorem

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

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

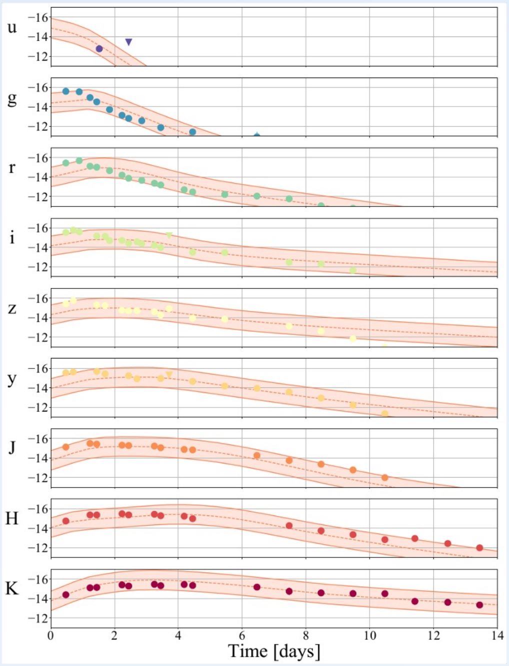
$$\mathcal{L}_{\mathrm{GW}} \propto \exp\left(-\frac{1}{2}\langle d - h(\vec{\theta})|d - h(\vec{\theta})\rangle\right)$$

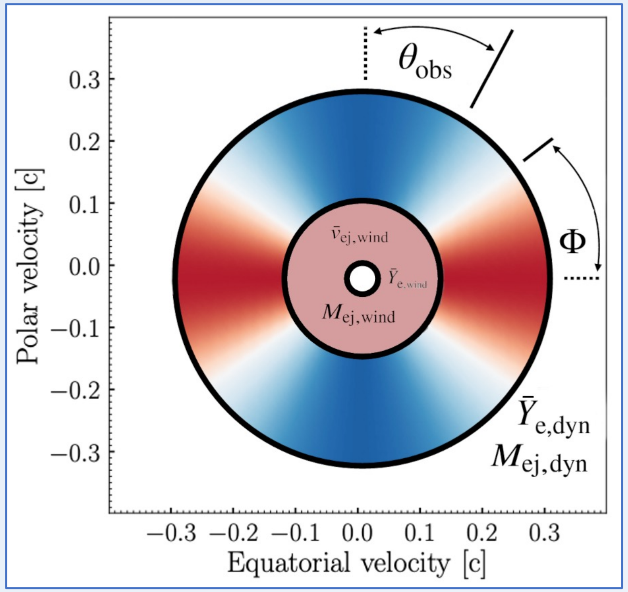
$$\mathcal{L}_{\mathrm{EM}} \propto \exp\left(-\frac{1}{2}\sum_{ij}\left(\frac{m_i^j - m_i^{j,\mathrm{est}}(\vec{\theta})}{\sigma_i^j}\right)^2\right)$$

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

Parameter estimation through Bayes theorem

$\vec{\theta}$





$\mathcal{L}_{\rm EM}$

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

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

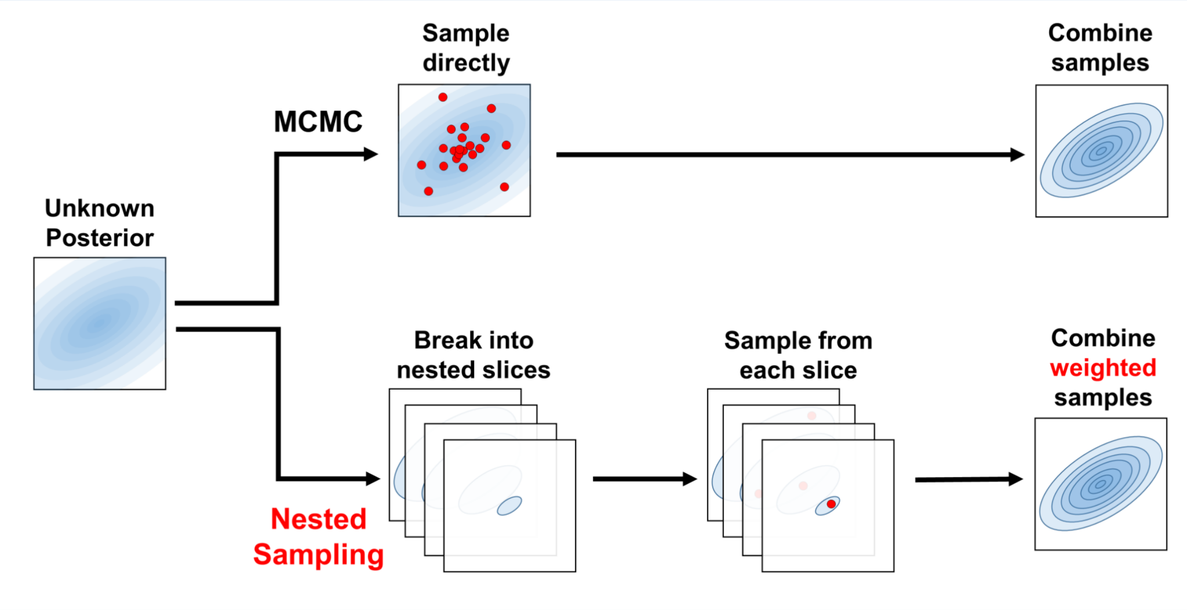
Occam's razor is automatically built in, i.e., if two hypotheses explain the data equally well, the simpler one is preferred

→ **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



https://johannesbuchner.github.io/UltraNest/_static/mcmc-demo/app.html

NMMA Details:

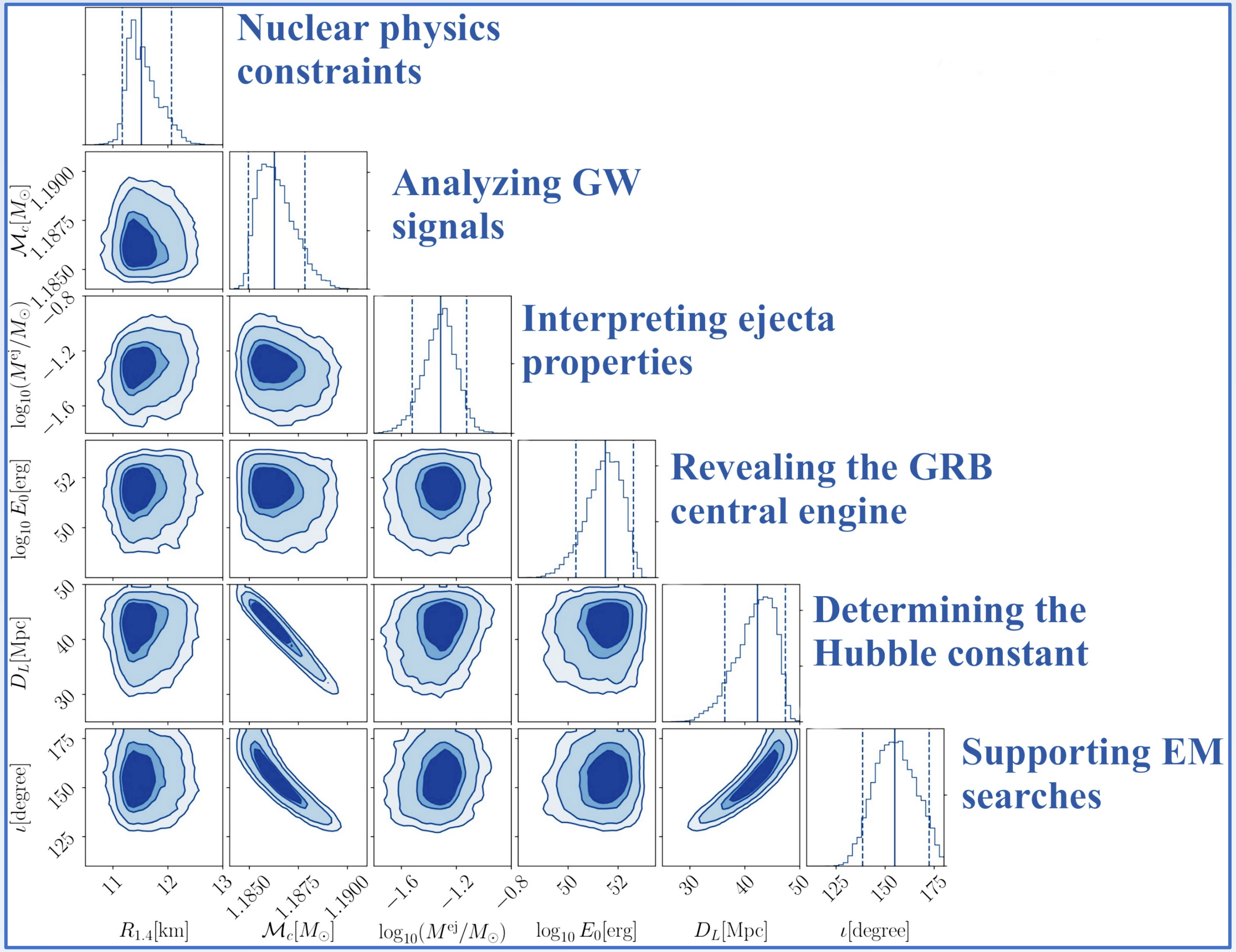
NMMA

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

- **additional astrophysical information**
  - e.g. NICER/pulsar measurements through full posteriors

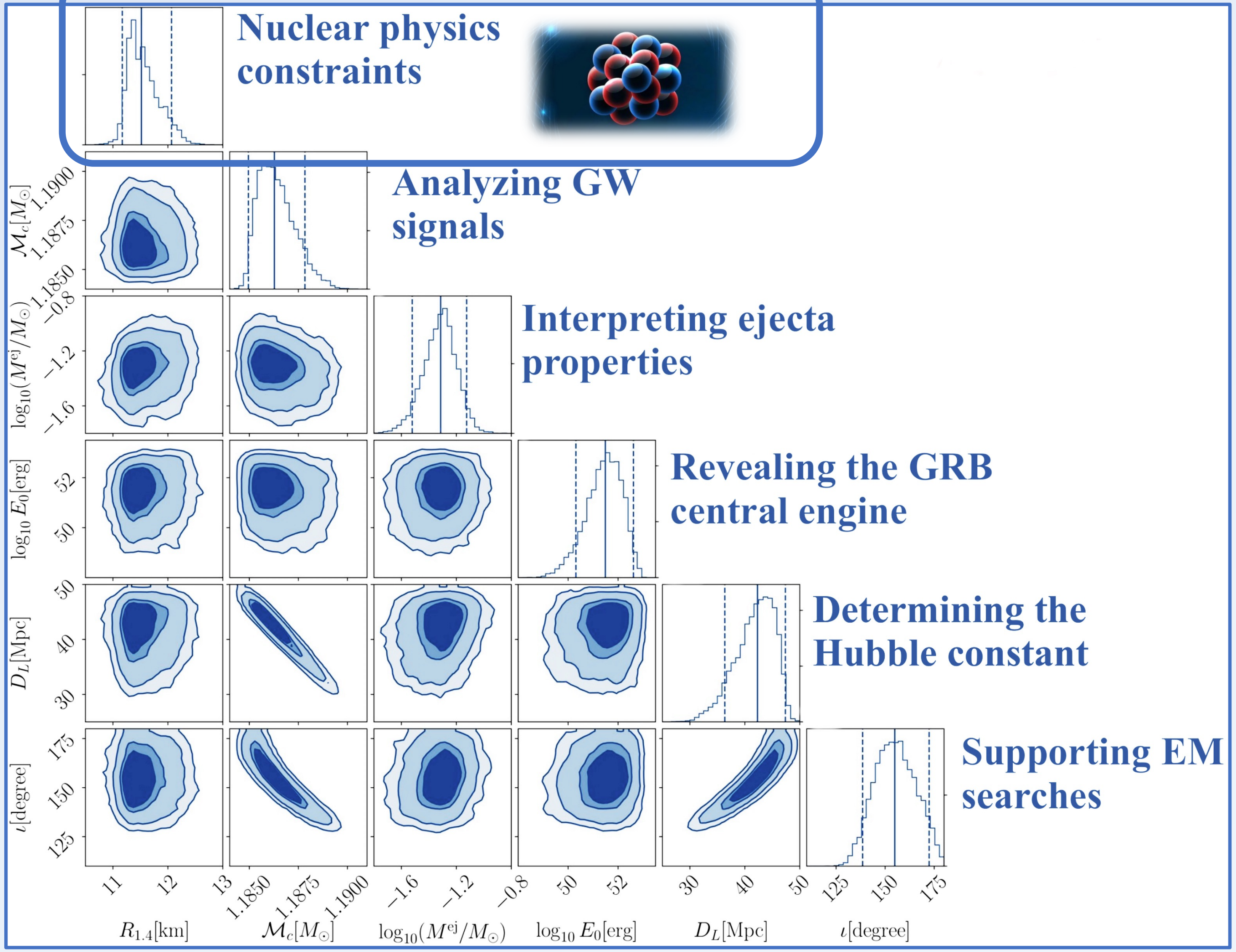
- **GW models employing LALSimulation/sampling through bilby**
- **kilonova models**
  - simple analytic models
  - radiative transfer simulations (POSSIS, Kasen et al.)
- **GRB afterglow:**
  - afterglowpy
  - soon also Pyblastafterglow (Nedora et al.)

Nuclear Physics and Multi-messenger Astrophysics

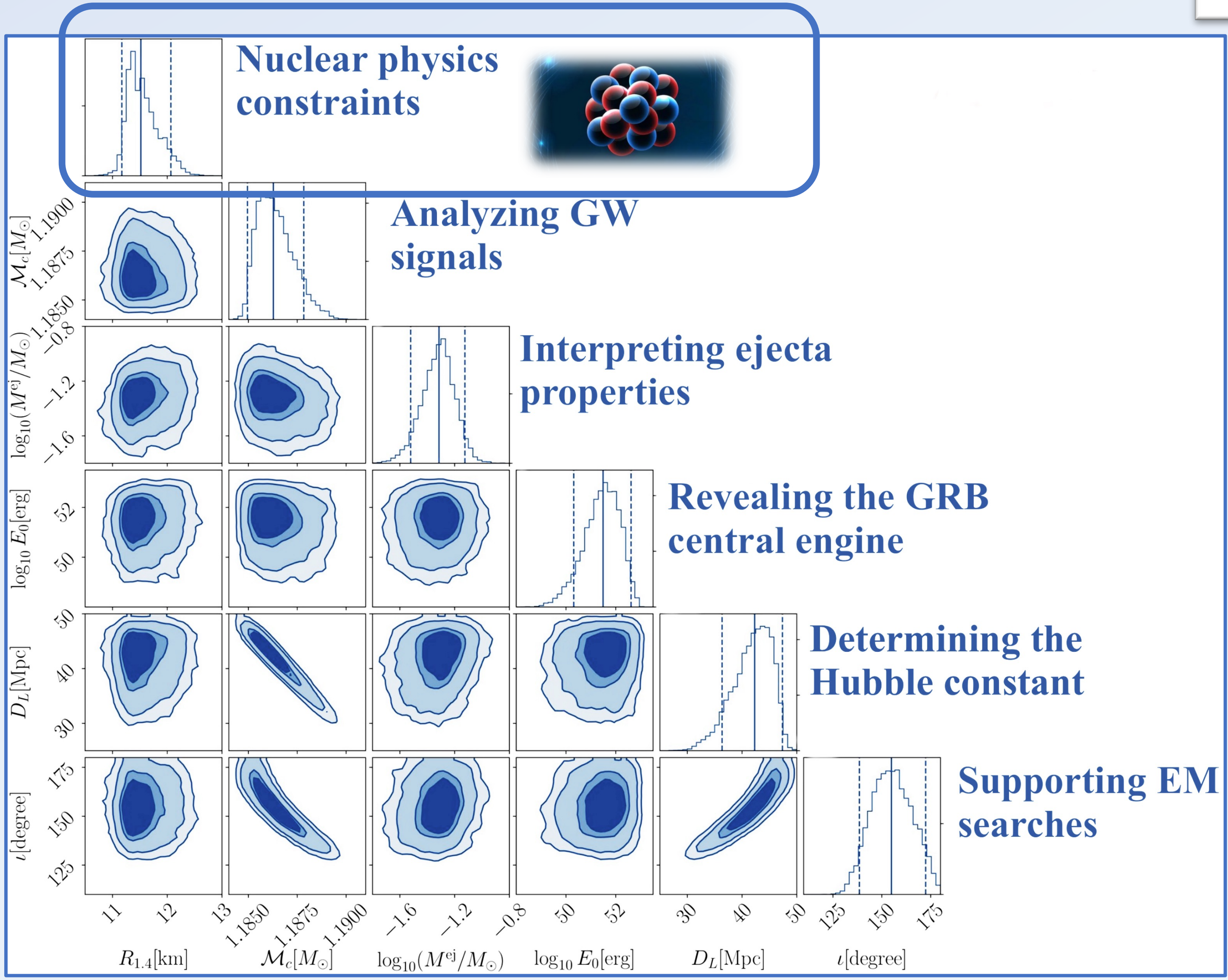


Nuclear Physics and Multi-messenger Astrophysics

NMMA



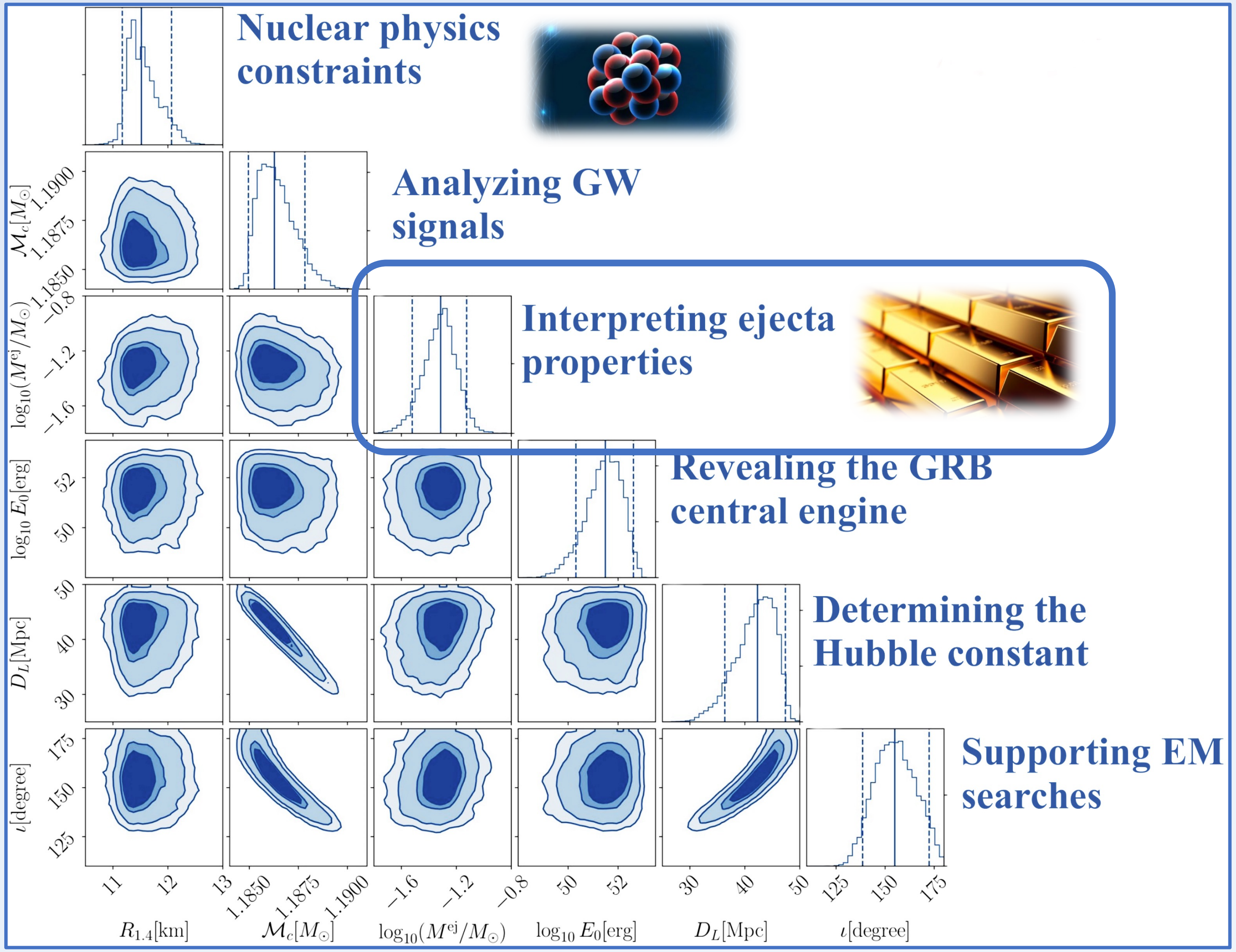
Nuclear Physics and Multi-messenger Astrophysics



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%)

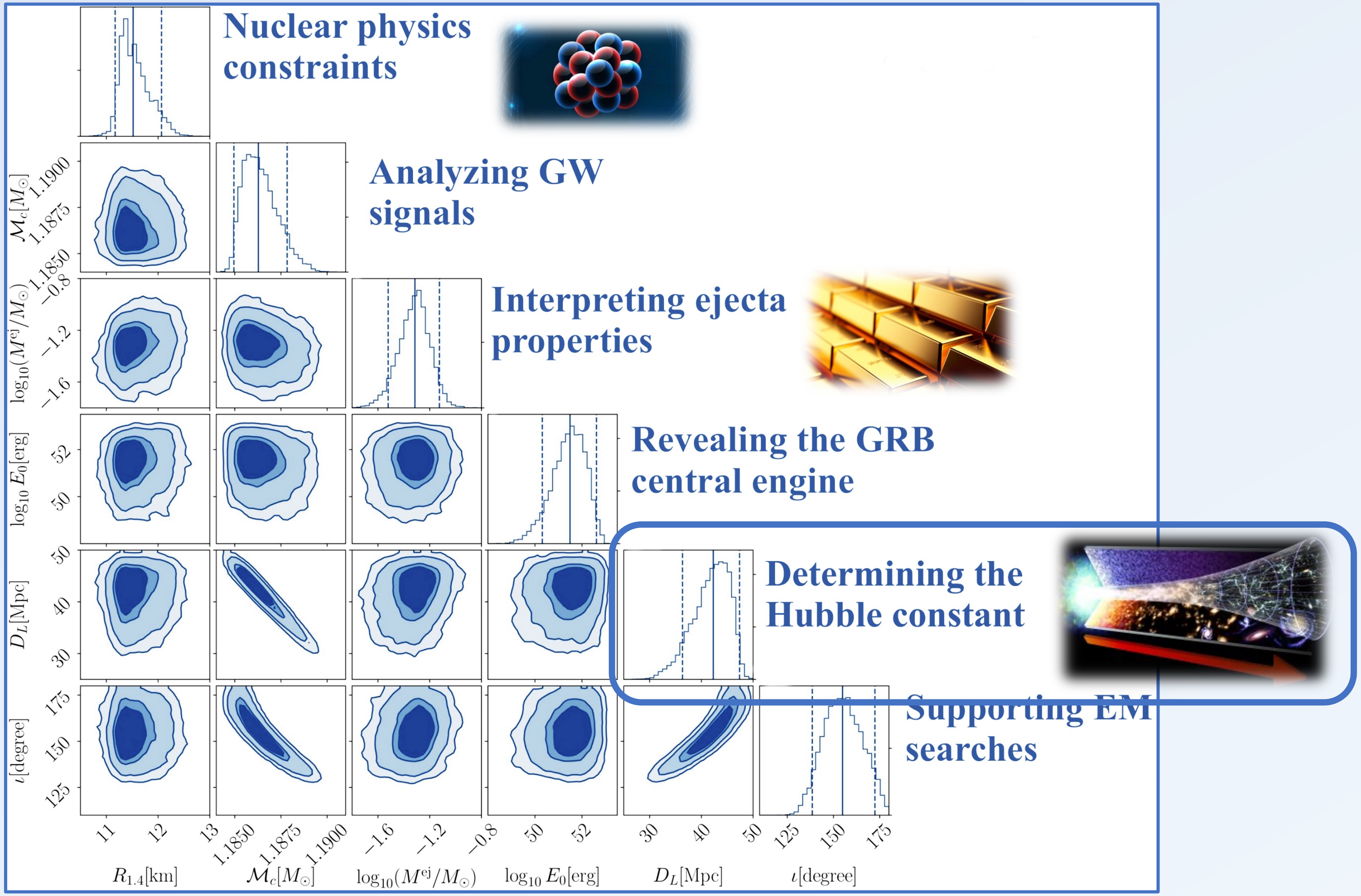
Pang et al., arXiv: 2205.08513
(accepted in Nat. Comm.)

Nuclear Physics and Multi-messenger Astrophysics



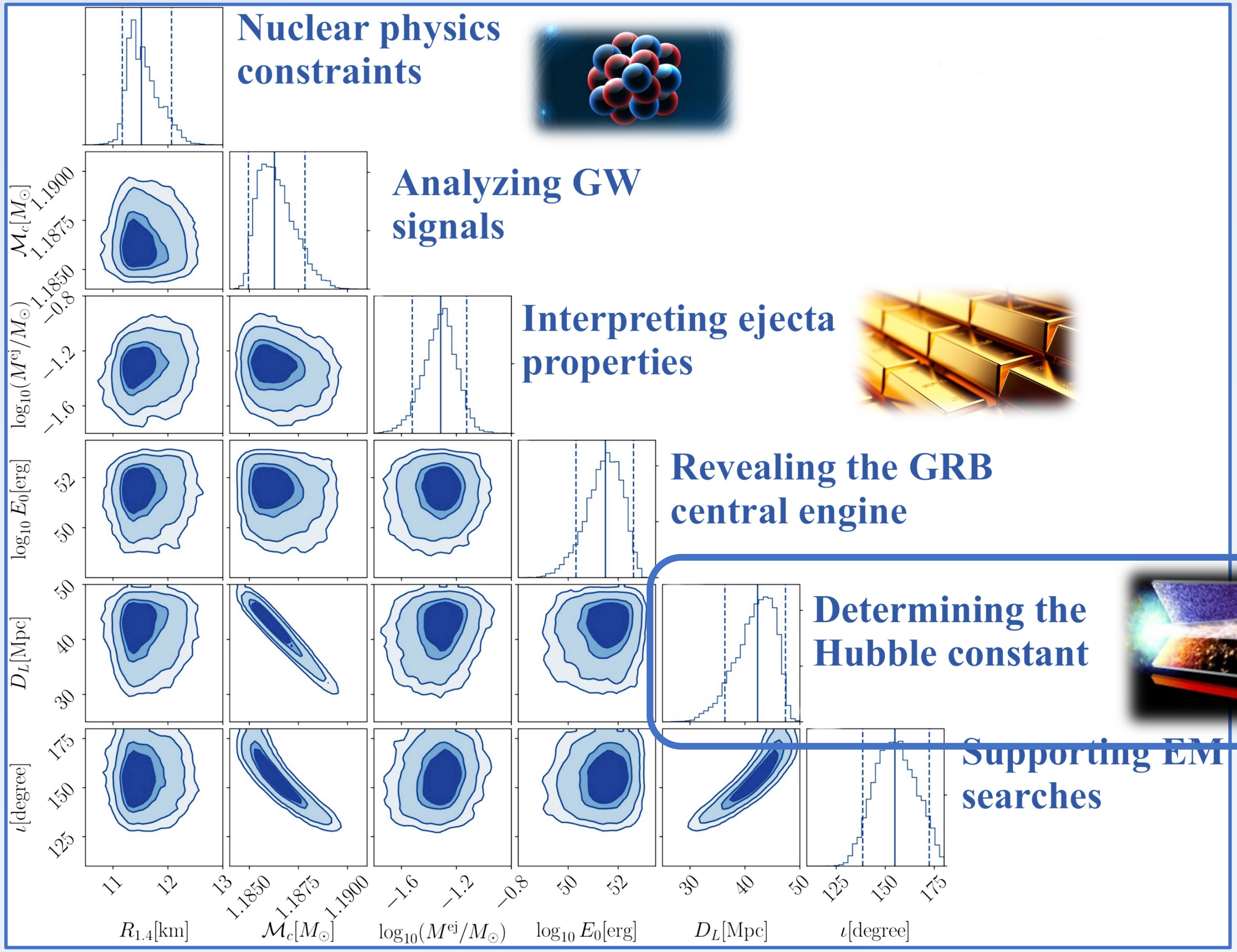
Nuclear Physics and Multi-messenger Astrophysics

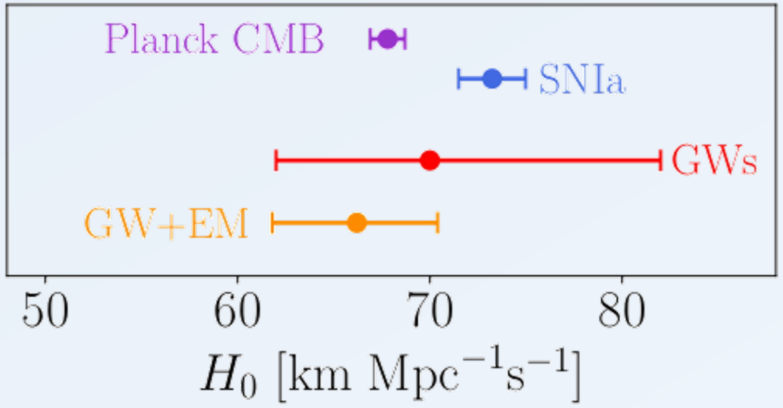
NMMA



Nuclear Physics and Multi-messenger Astrophysics

NMMA



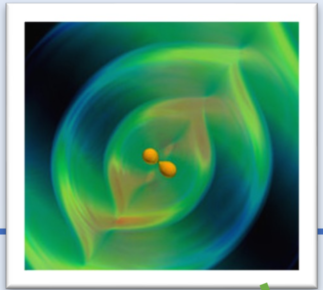


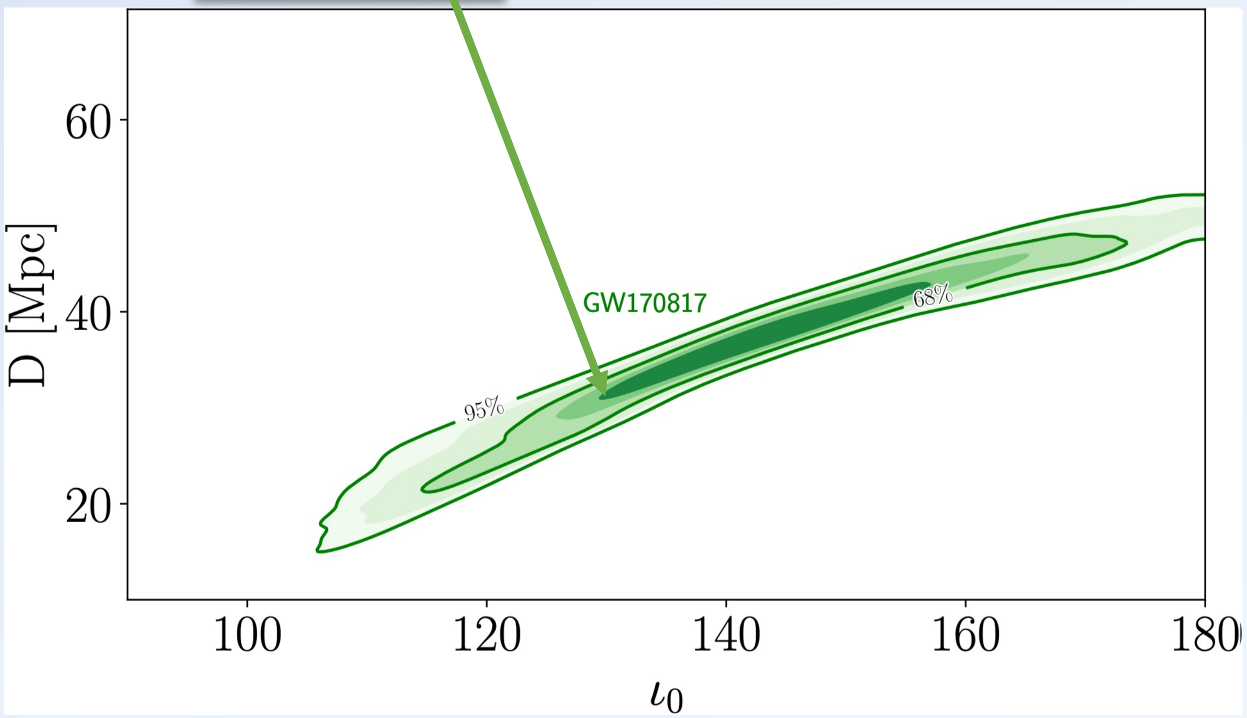
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

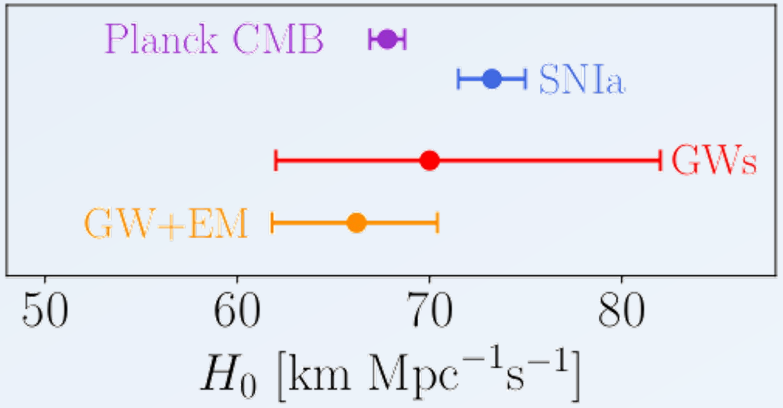
Nuclear Physics and Multi-messenger Astrophysics

NMMA

Gravitational Wave







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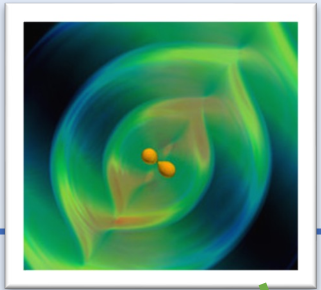
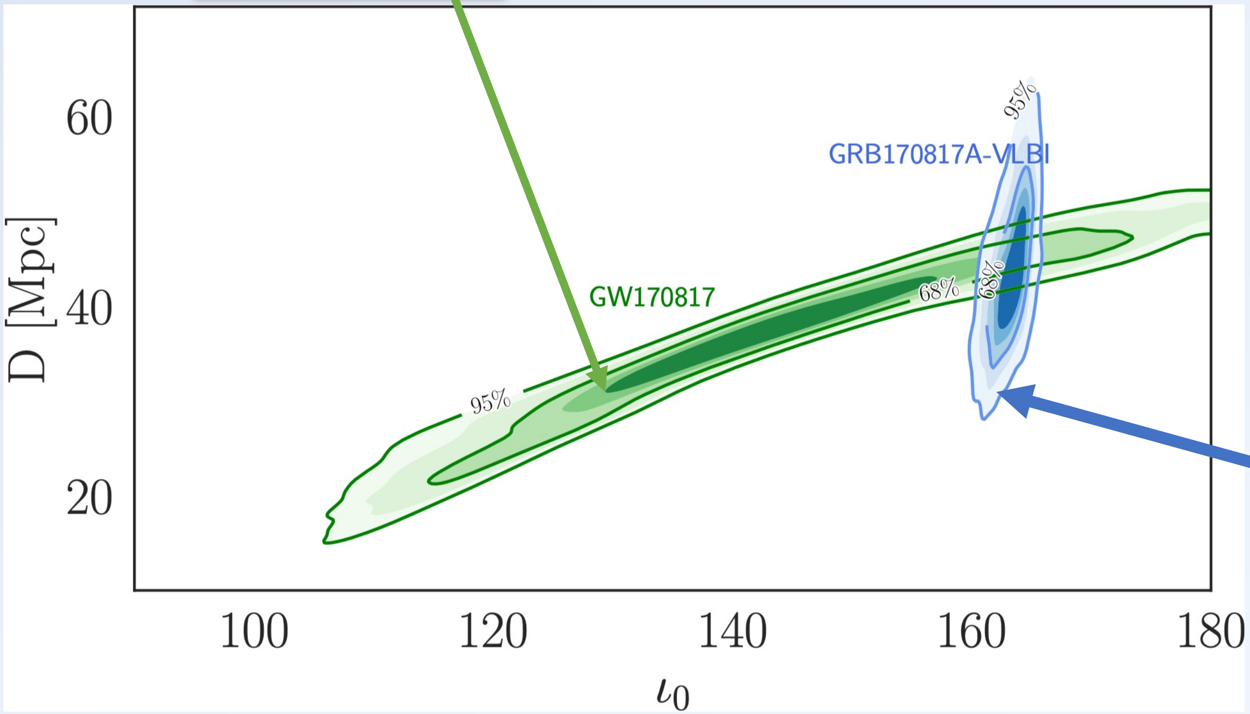
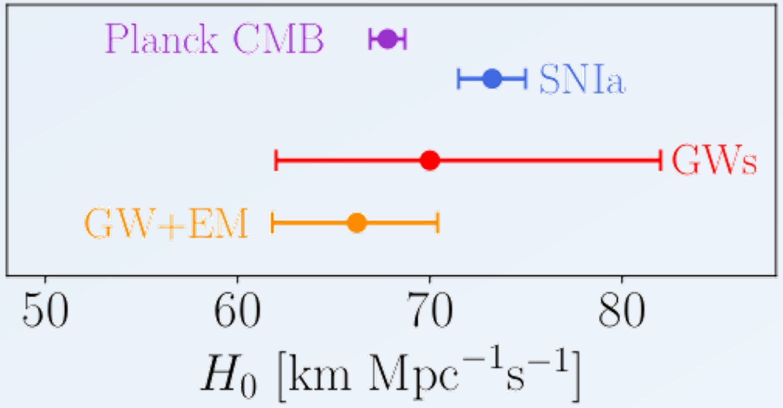
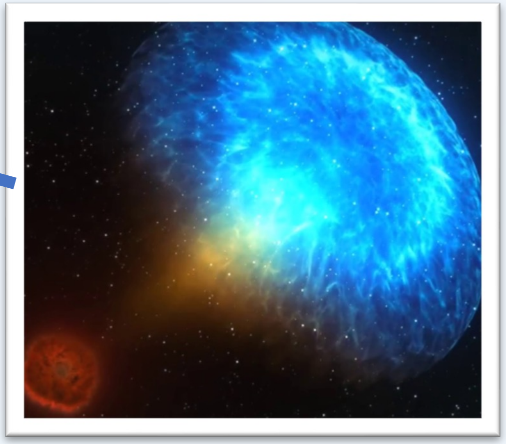






TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

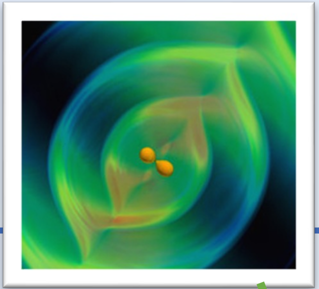
Radio Counterpart



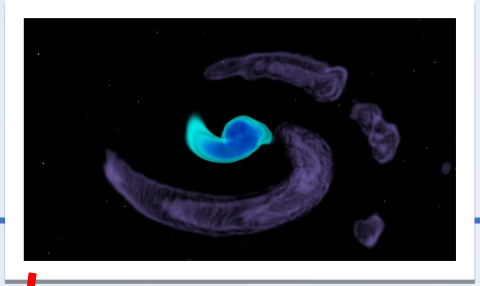
Nuclear Physics and Multi-messenger Astrophysics

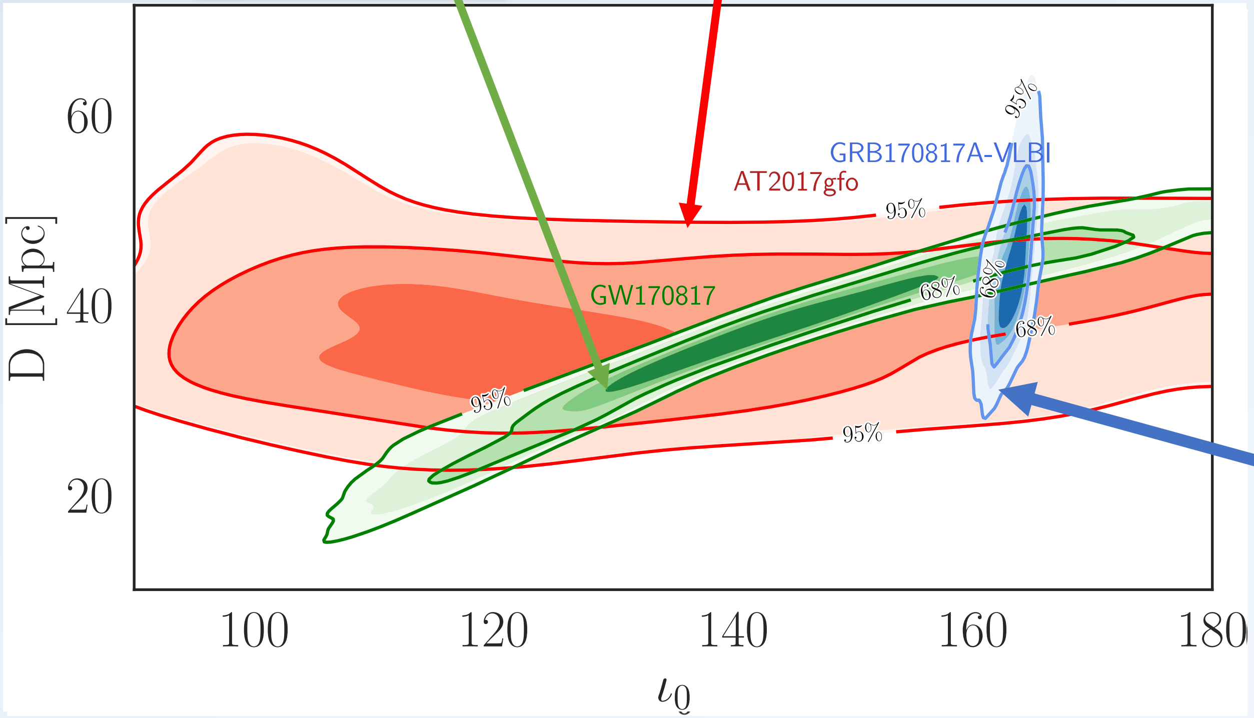
NMMA

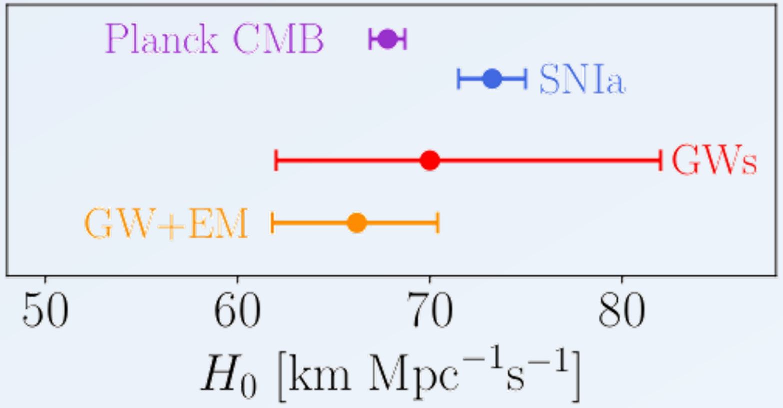
Gravitational Wave



Kilonova







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

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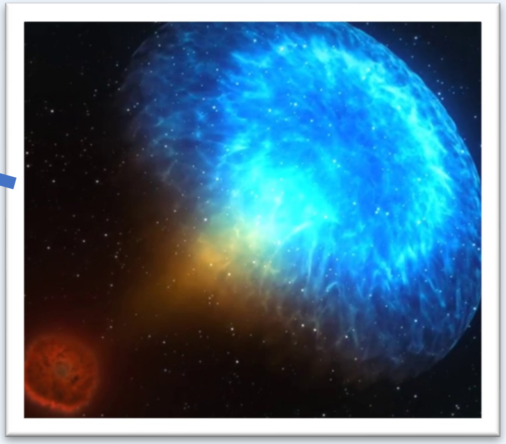
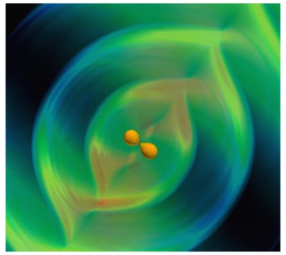


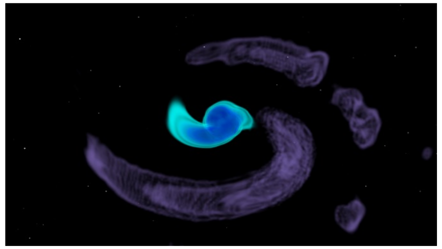
Nuclear Physics and Multi-messenger Astrophysics

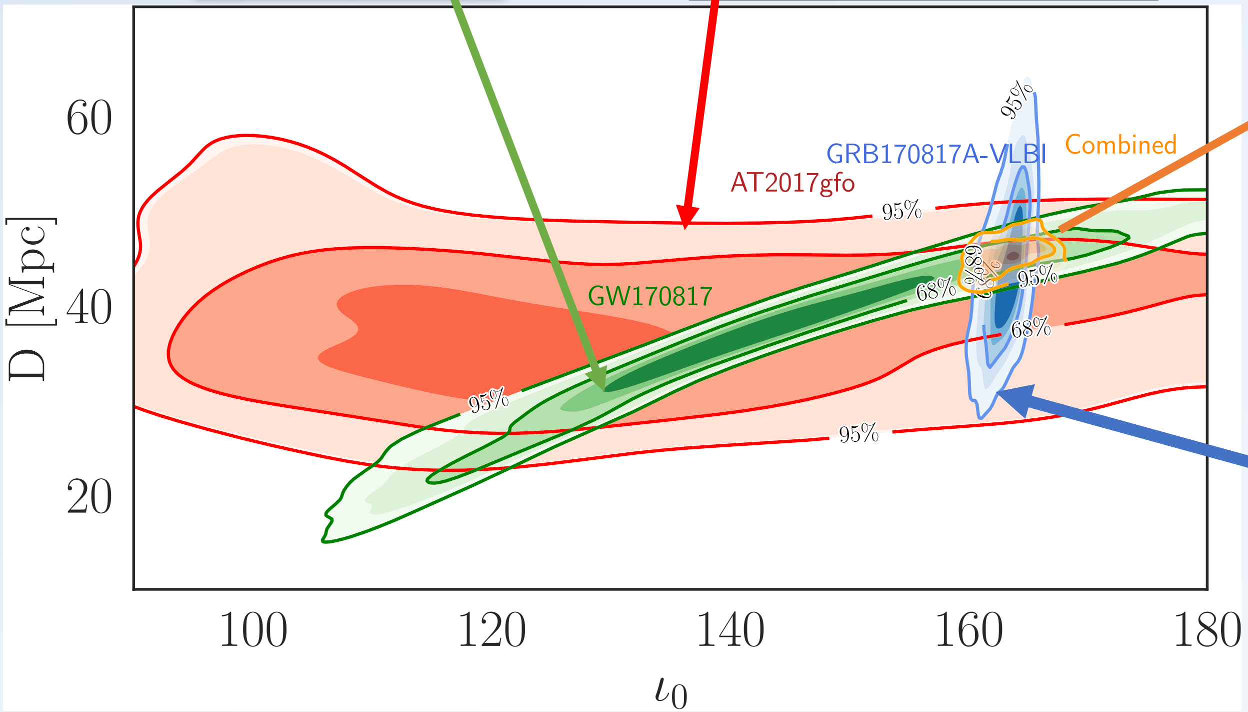
NMMA

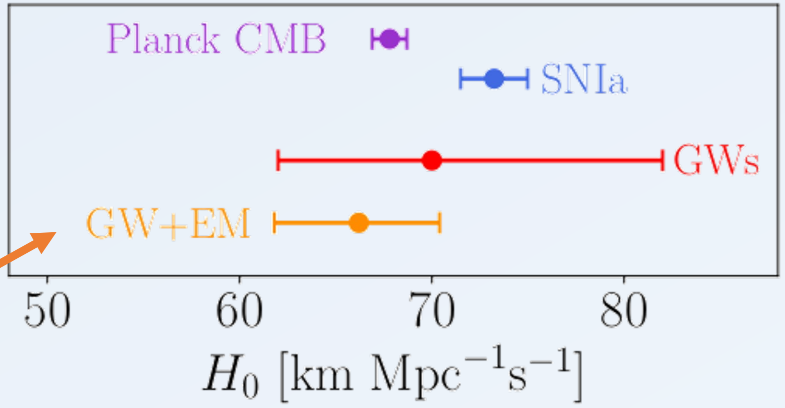
Gravitational Wave



Kilonova







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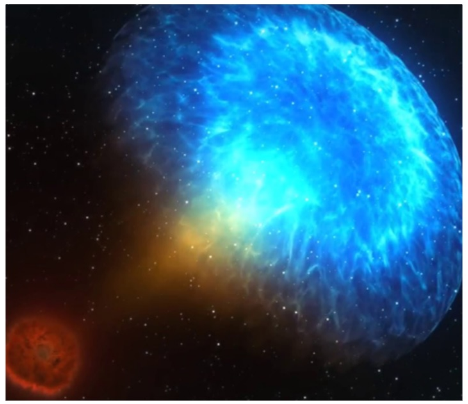
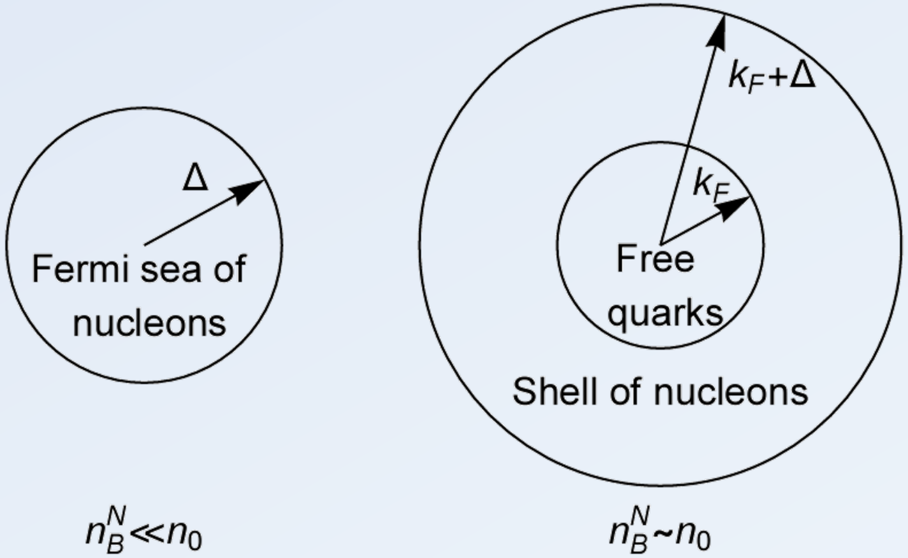
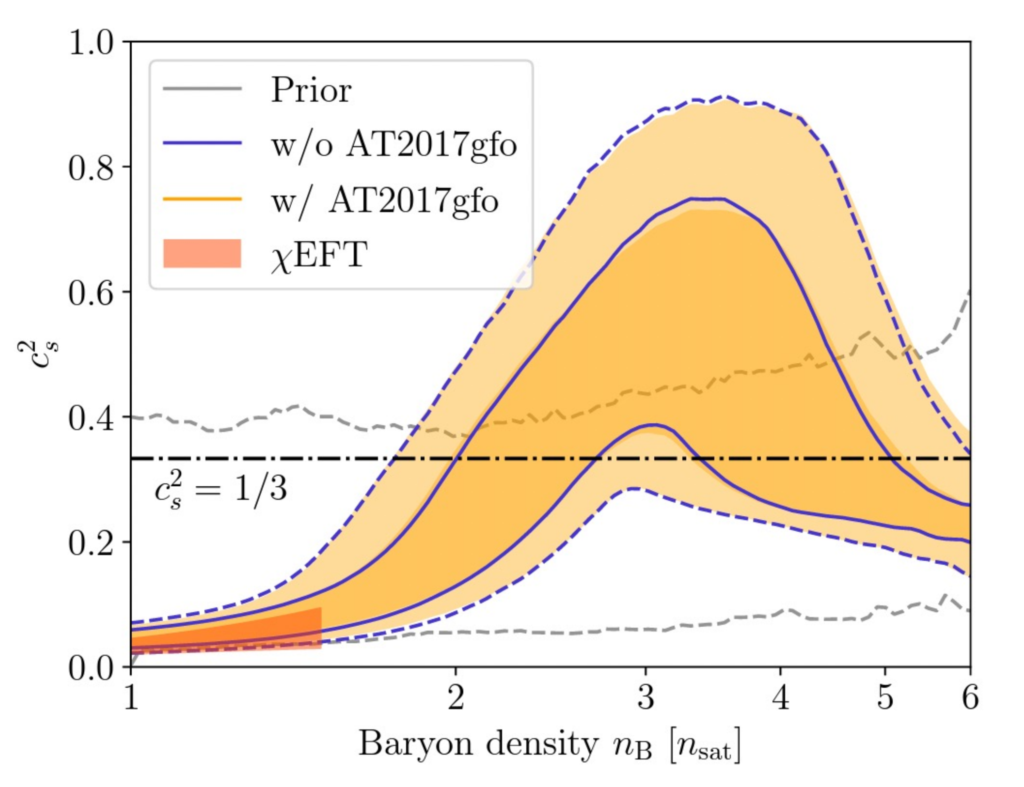
Radio Counterpart



NMMA Applications: Constraining Nuclear Parameters

Investigating properties of quarkyonic models



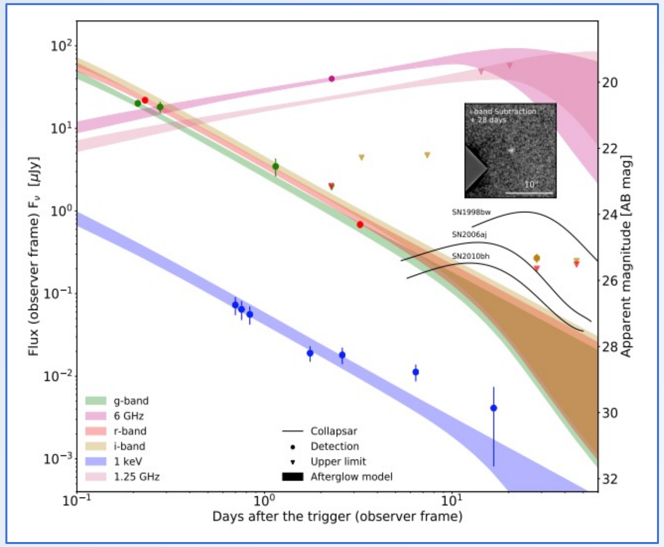


Pang et al., arXiv: 2308.15067

- Clear evidence for speed of sound above the conformal limit

NMMA Applications: Model Selection

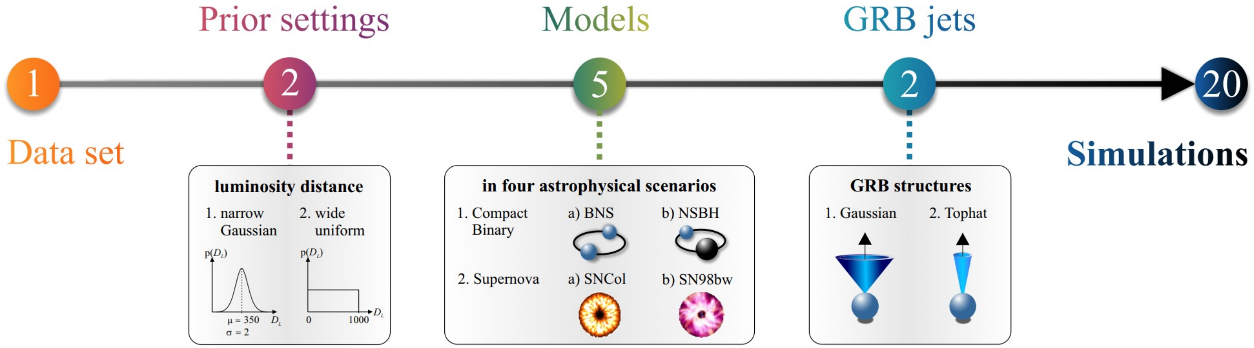
GRB 200826A



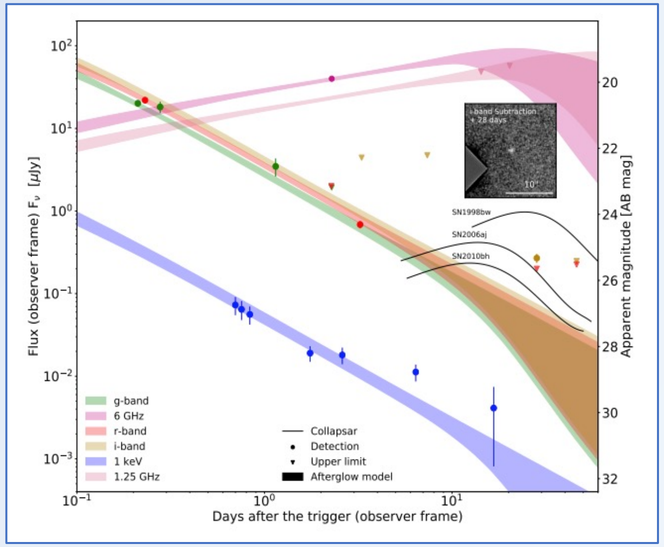
shortest long GRB
(no BNS merger, but collapsar)

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

NMMA Applications: Model Selection



GRB 200826A



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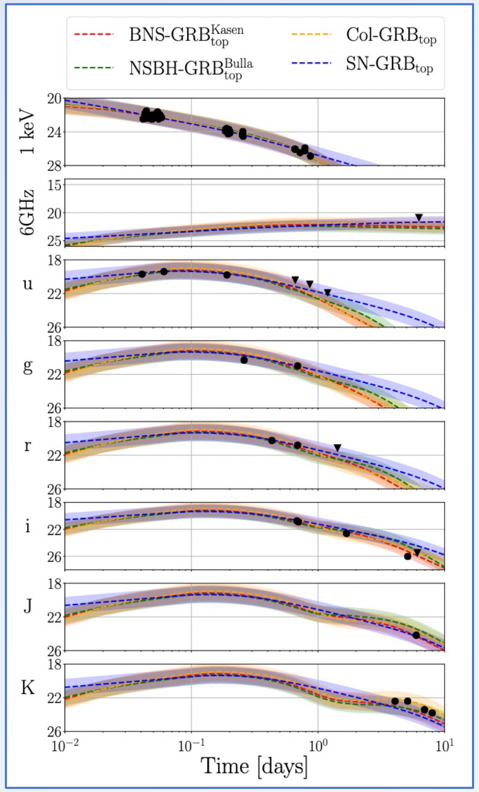
T. Ahumada, et al., Nature Astron. 5 (2021) 9, 917-927

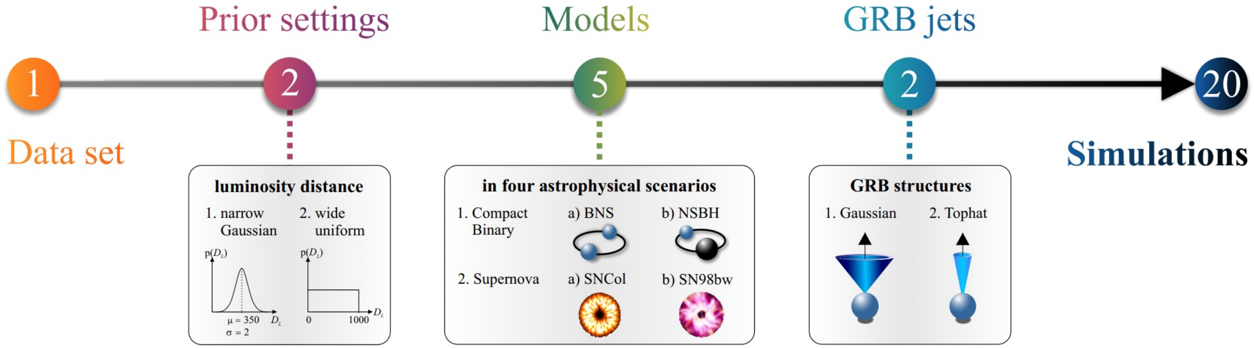
GRB 211211A



potential kilonova due to BNS merger

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

NMMA Applications: Model Selection



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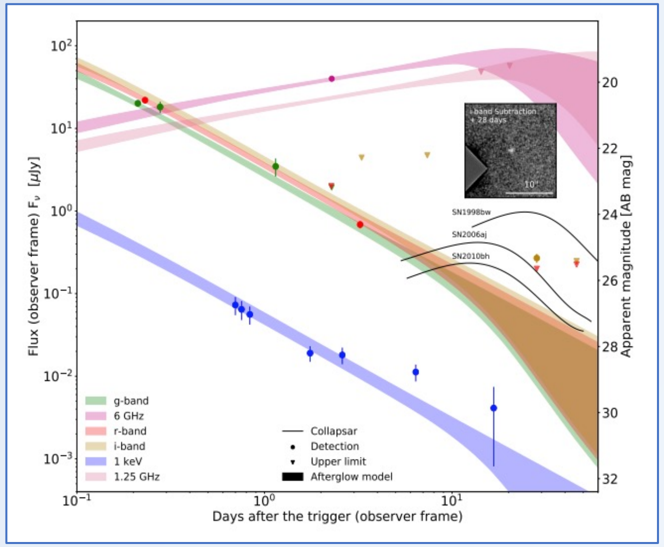

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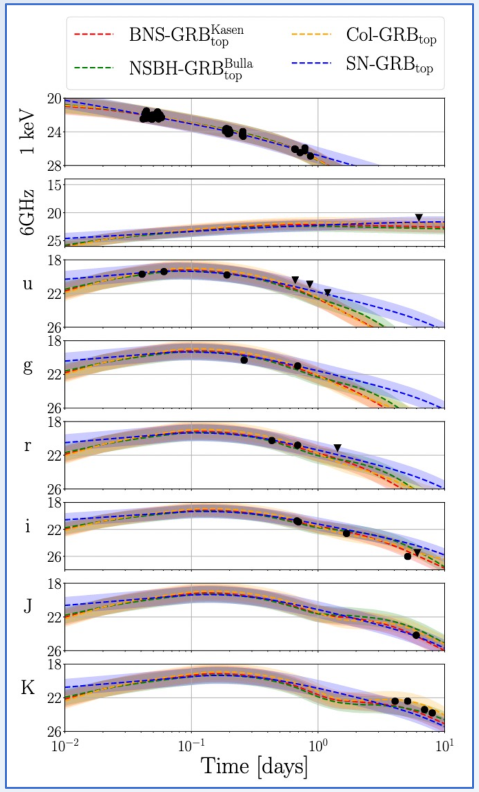
T. Ahumada, et al., Nature Astron. 5 (2021) 9, 917-927

GRB 211211A



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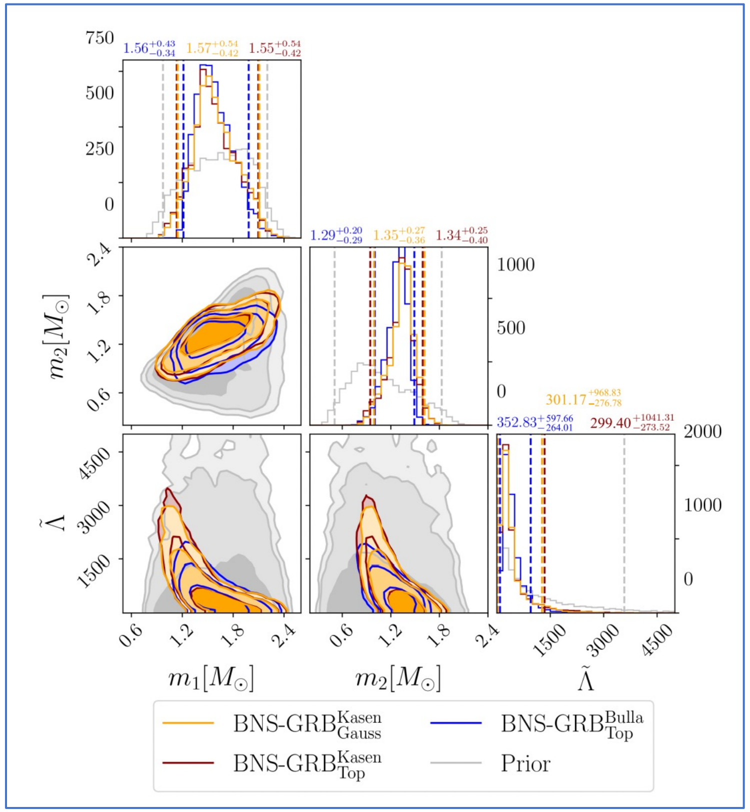
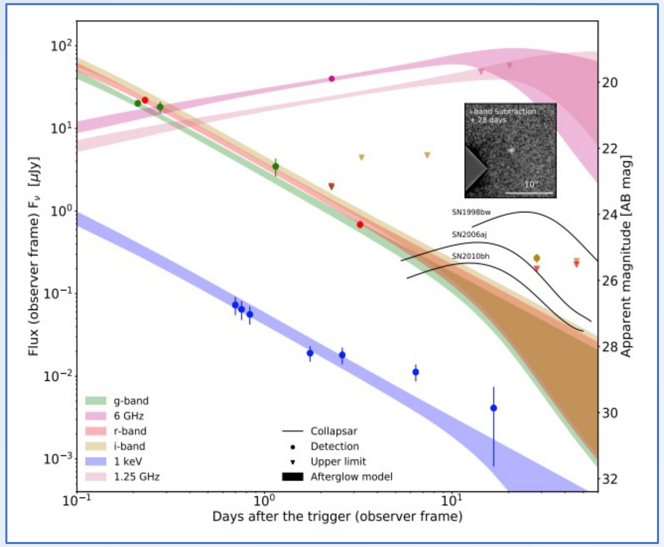
N.Kunert et al., MNRAS 527, 2 (2024)



NMMA Applications: Model Selection

NMMA

GRB 200826A



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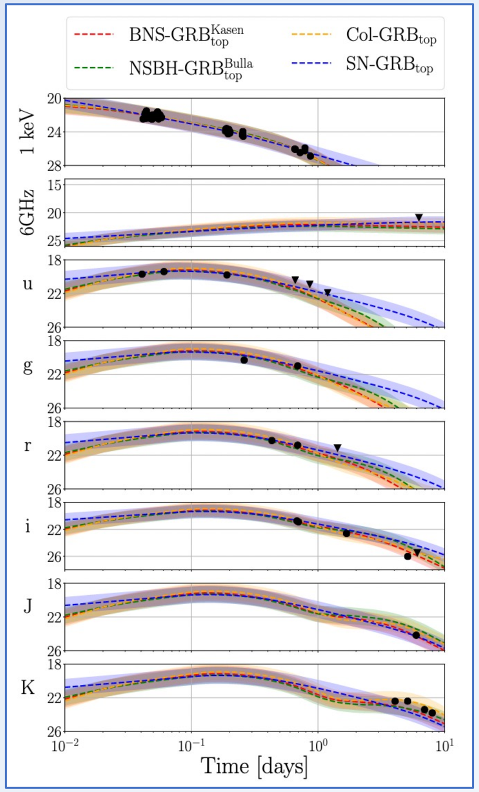
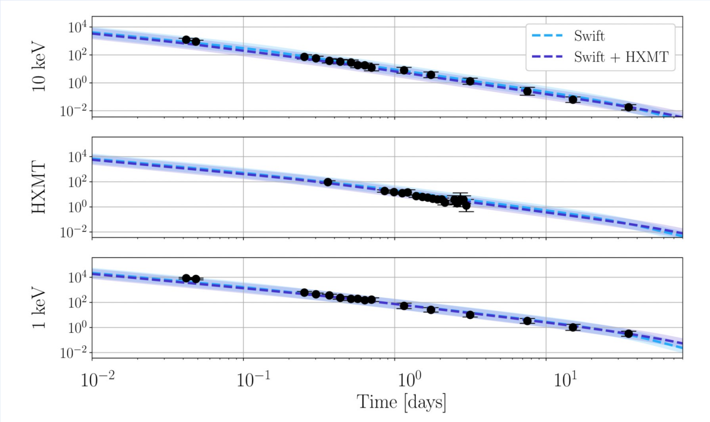


potential kilonova due to BNS merger

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

GRB 221009A



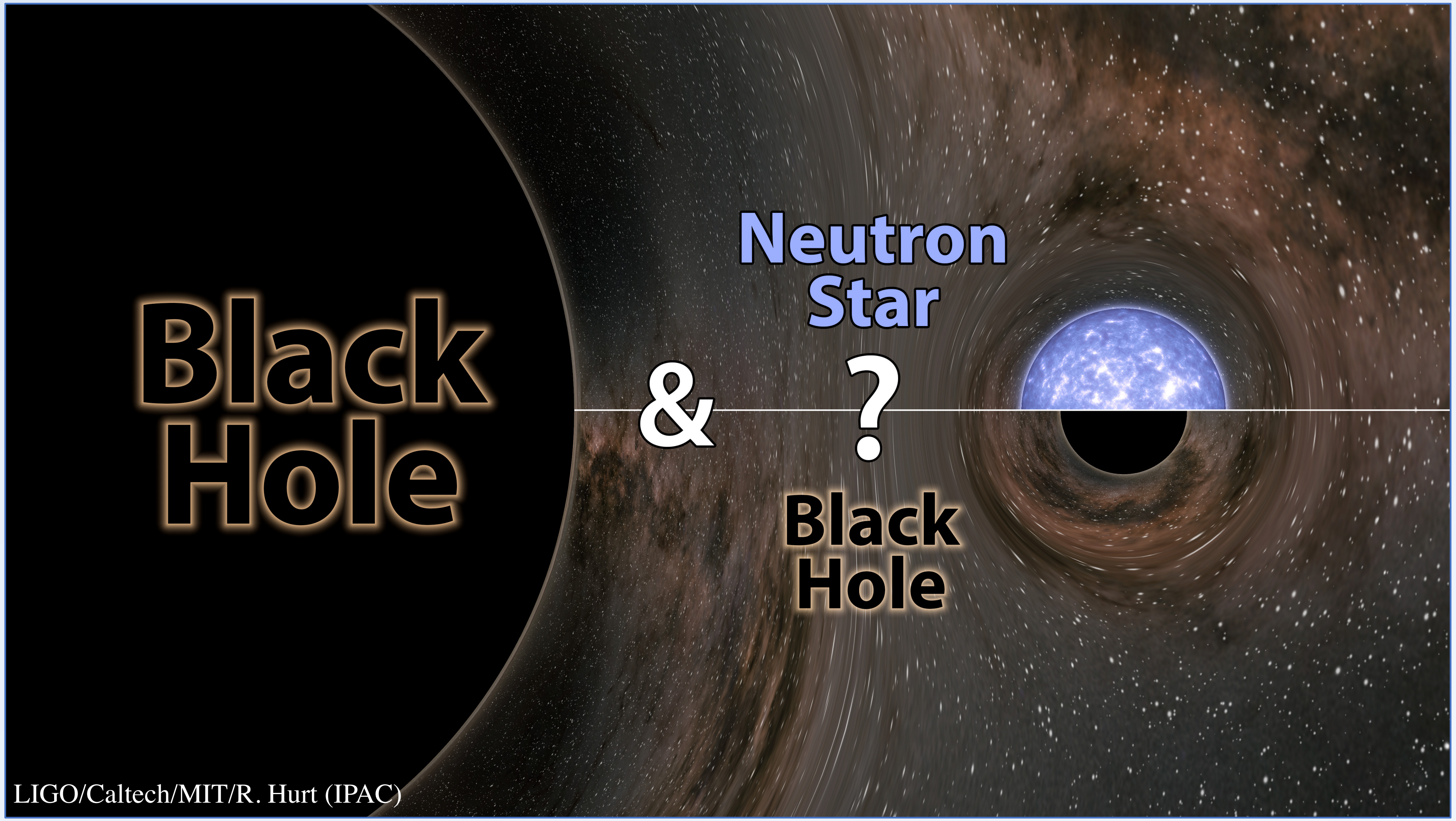
brightest observed GRB to date

GRANDMA analysis

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

NMMA Applications: Model Selection

GW190814

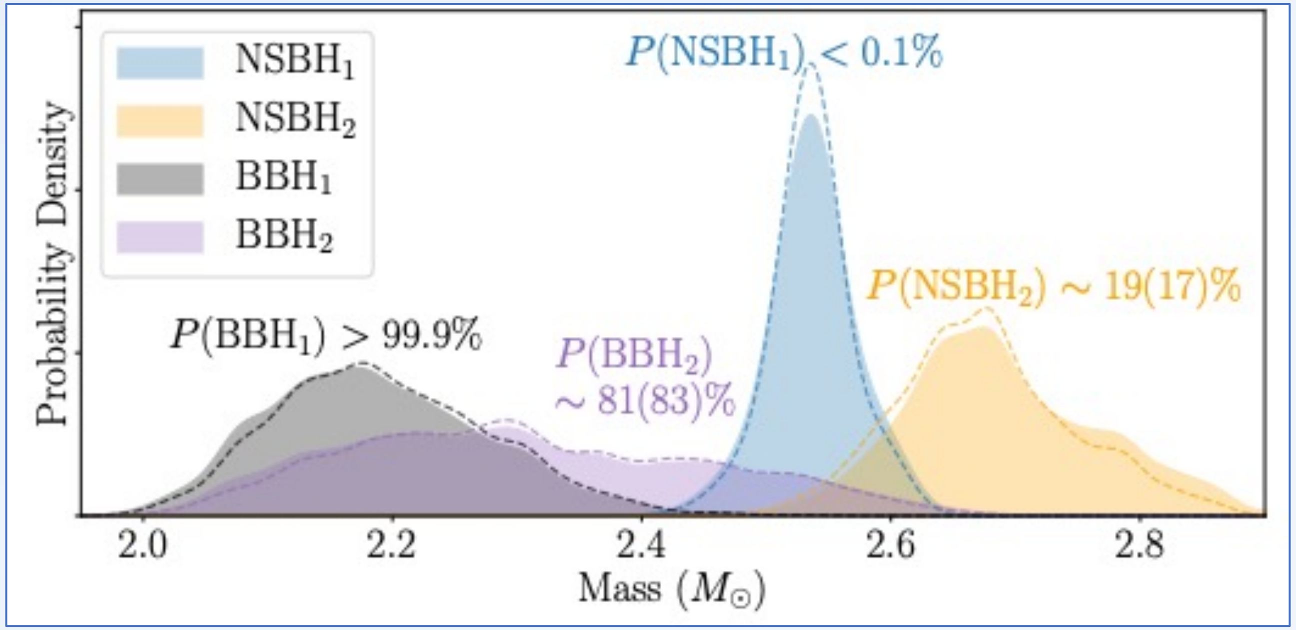


NMMA Applications: Model Selection

GW190814

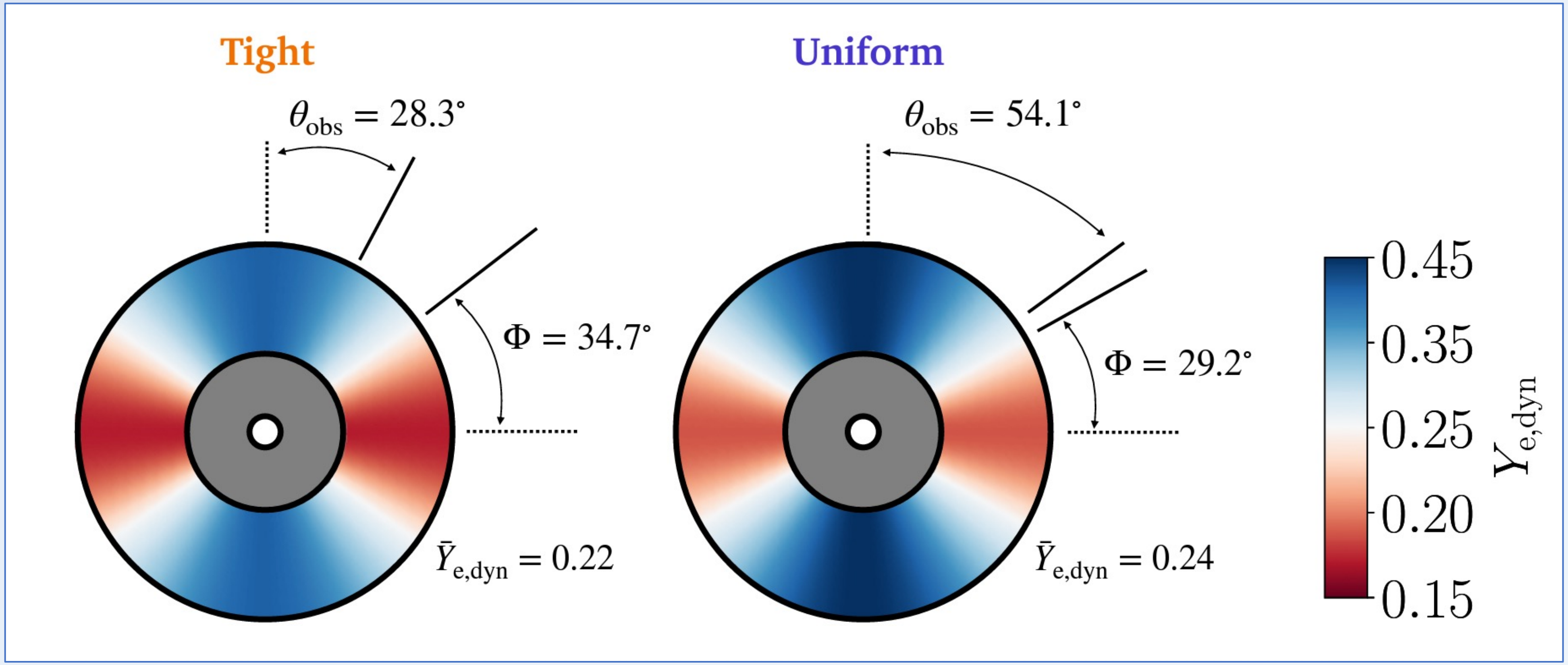
- under the assumption that GW170817 produced a BH, GW190814 was a BBH P(BBH) > 0.999
- relaxing this assumption, it was a BBH P(BBH) ~ 0.83

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



NMMA Applications: Predicting the Chemical Evolution

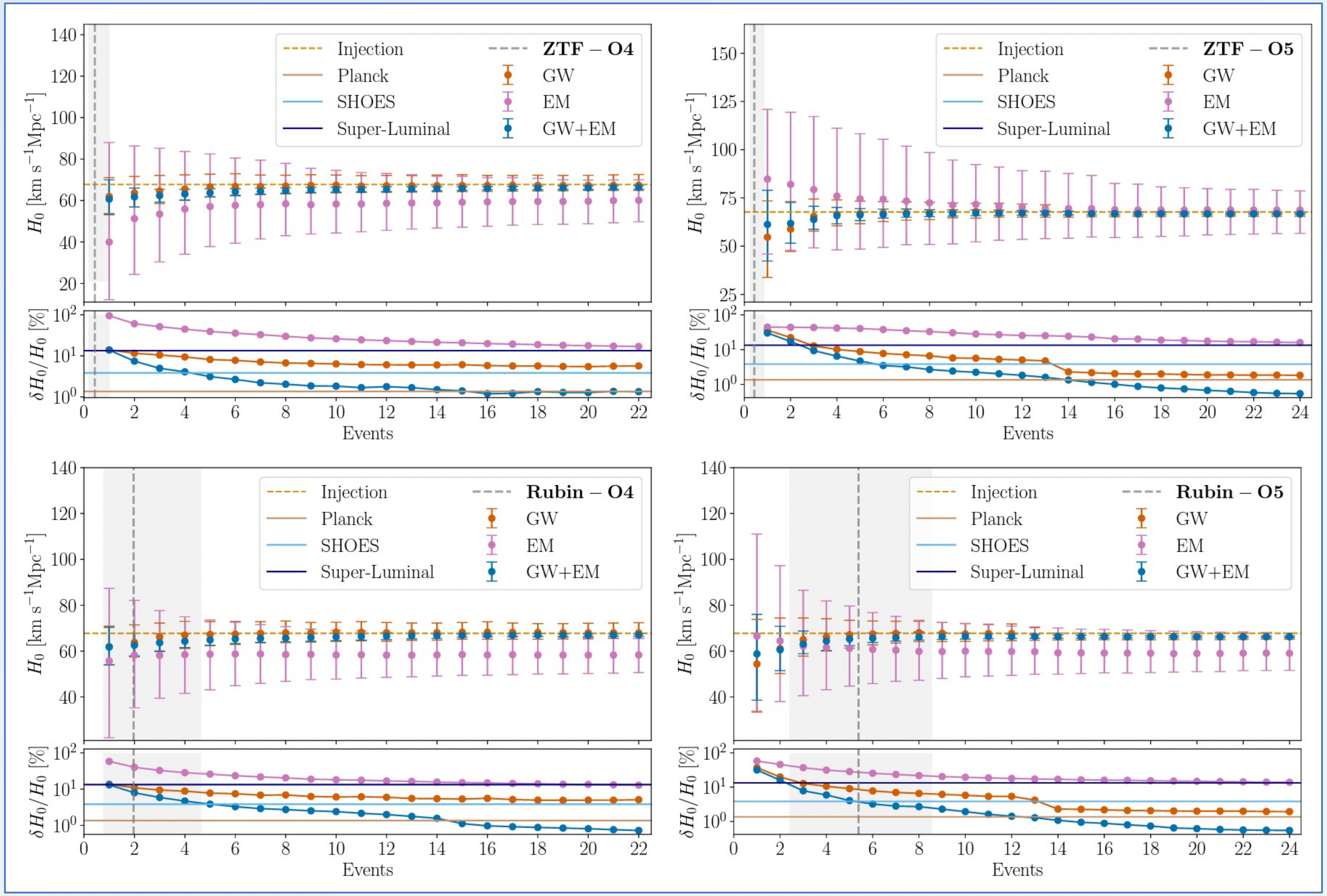
Understanding the composition of material in the mass outflow



Anand et al., 2307.11080

NMMA Applications: Observing scenarios

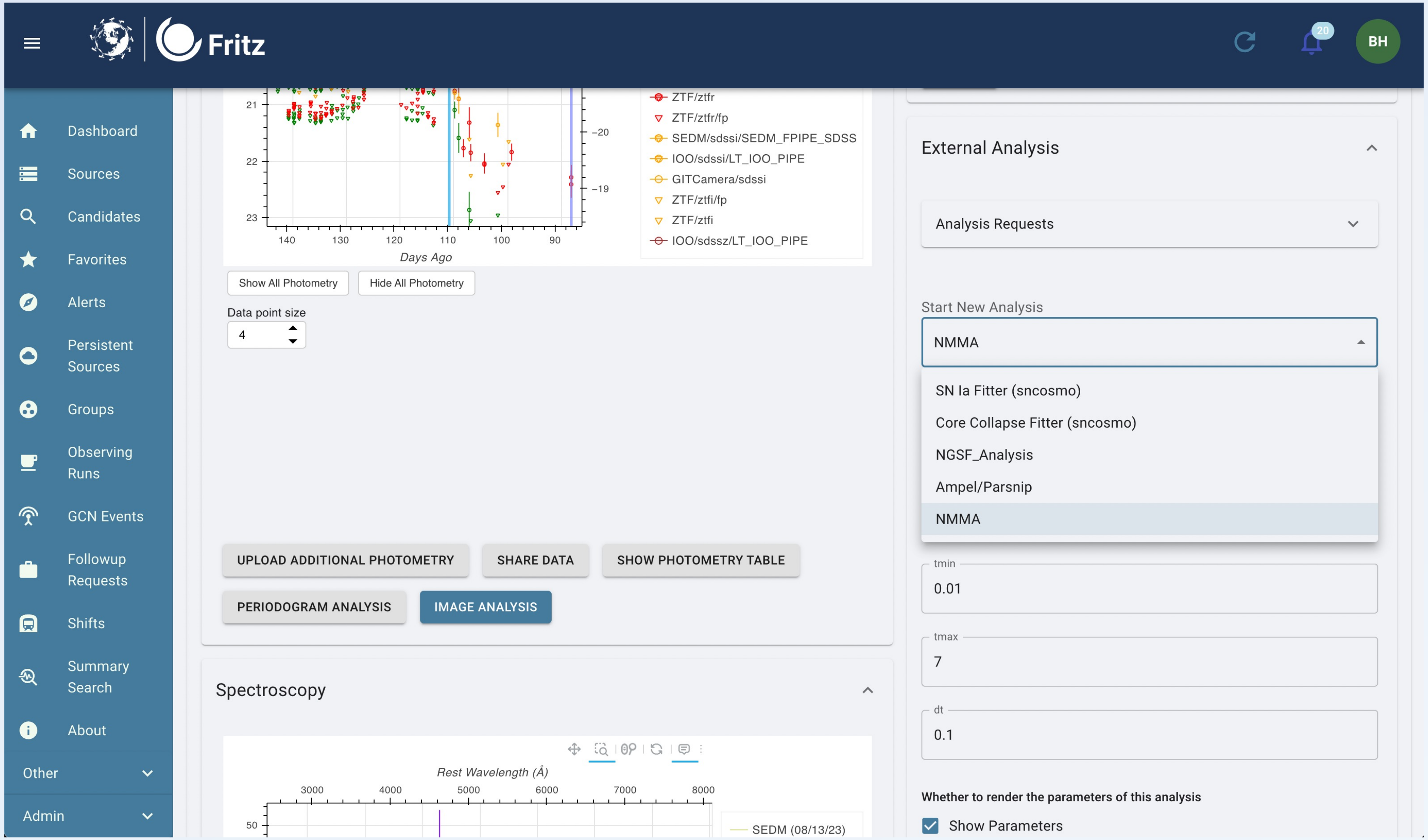
Hubble constraints for future observing runs



Kiendrebeogo et al., APJ 958 (2023) 2, 158

Trigger NMMA Studies directly from fritz

Pick external analysis: NMMA



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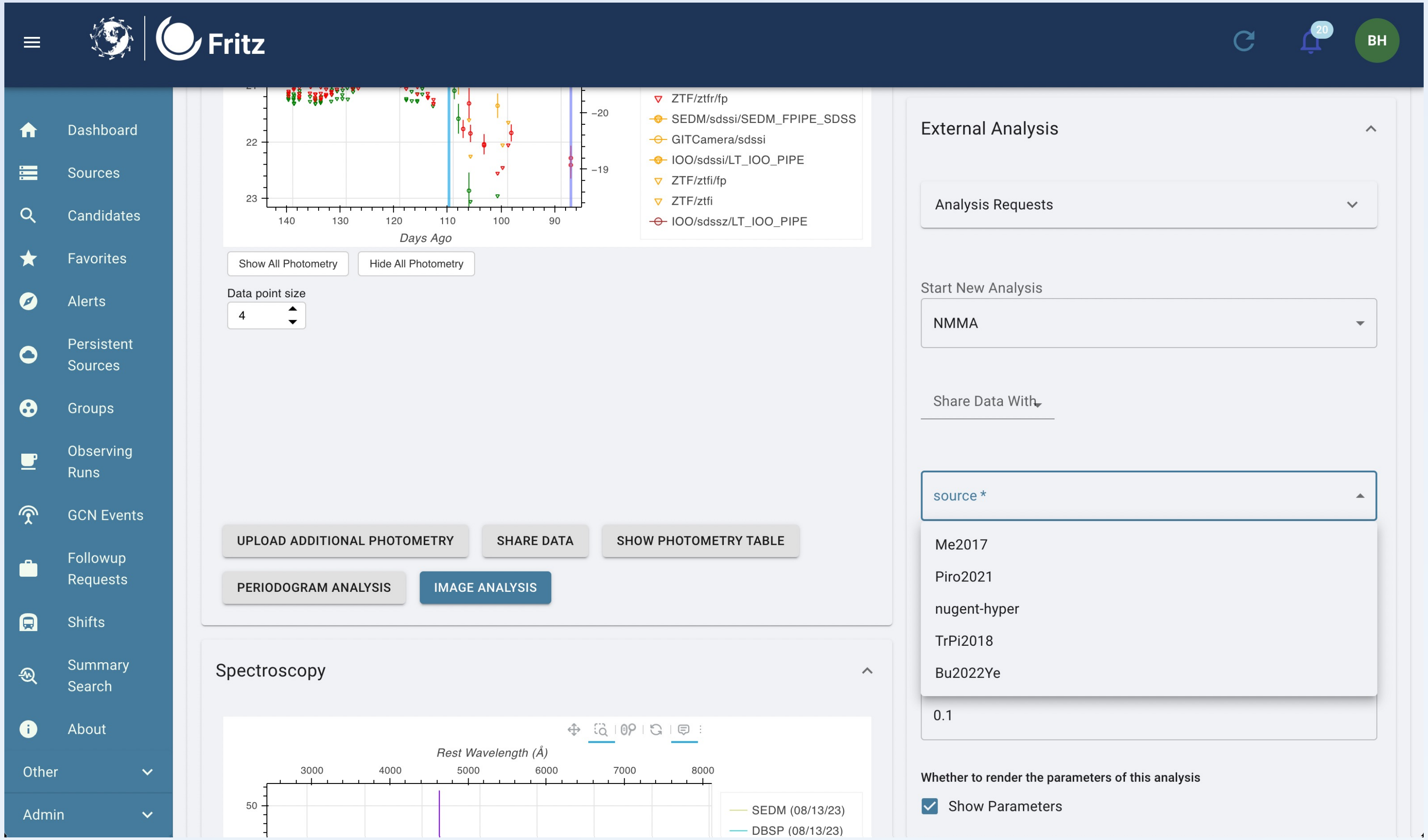
Trigger NMMA Studies directly from fritz

NMMA

Pick your model



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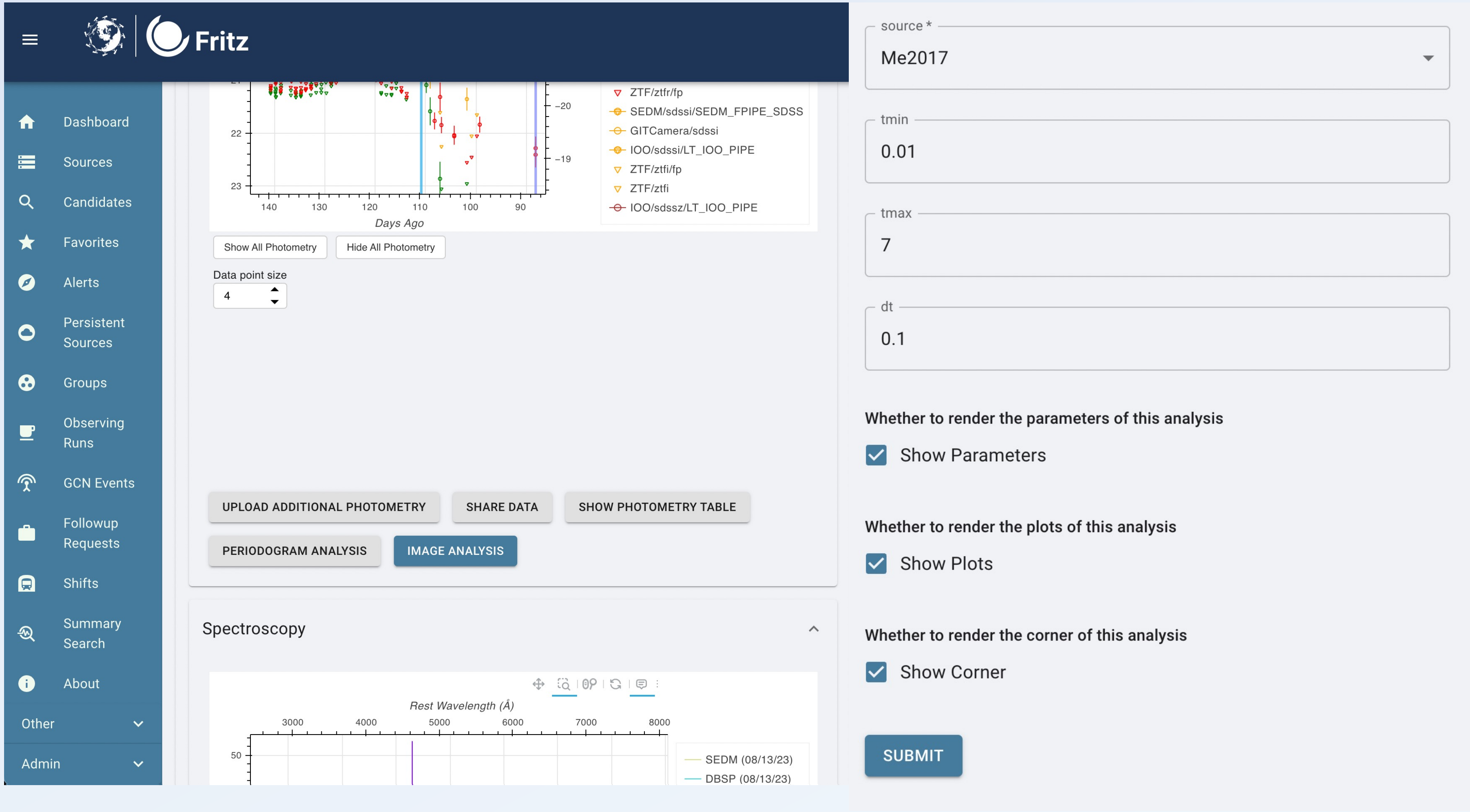
Trigger NMMA Studies directly from fritz

Determine properties for the analysis and submit the run



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Where to find more?

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

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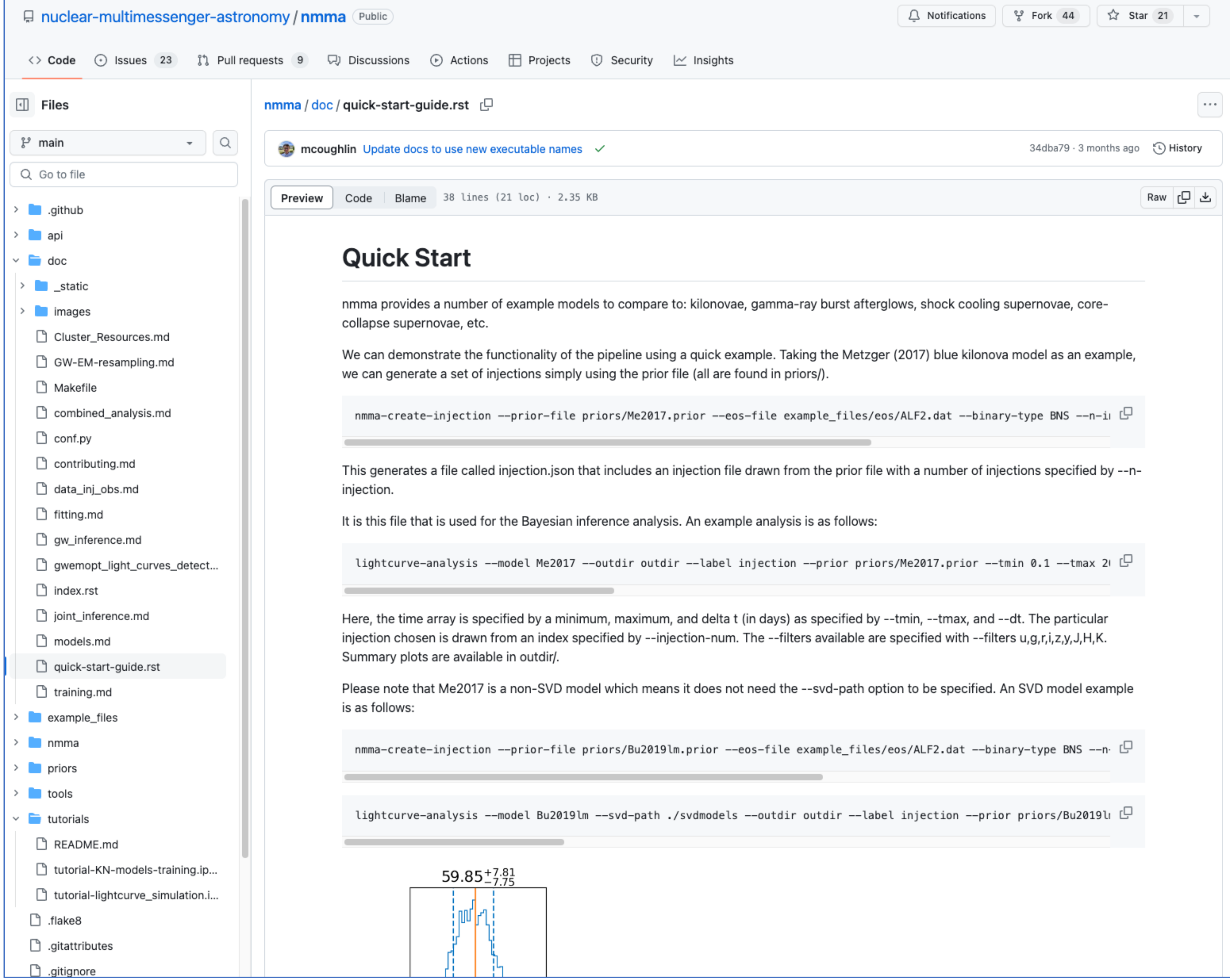
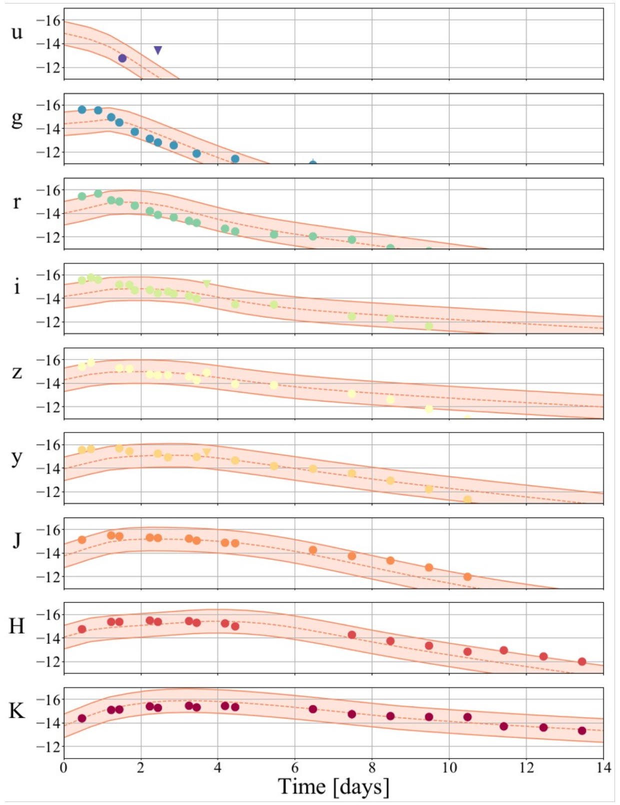


Where to find more?



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='$\\zeta$')
```

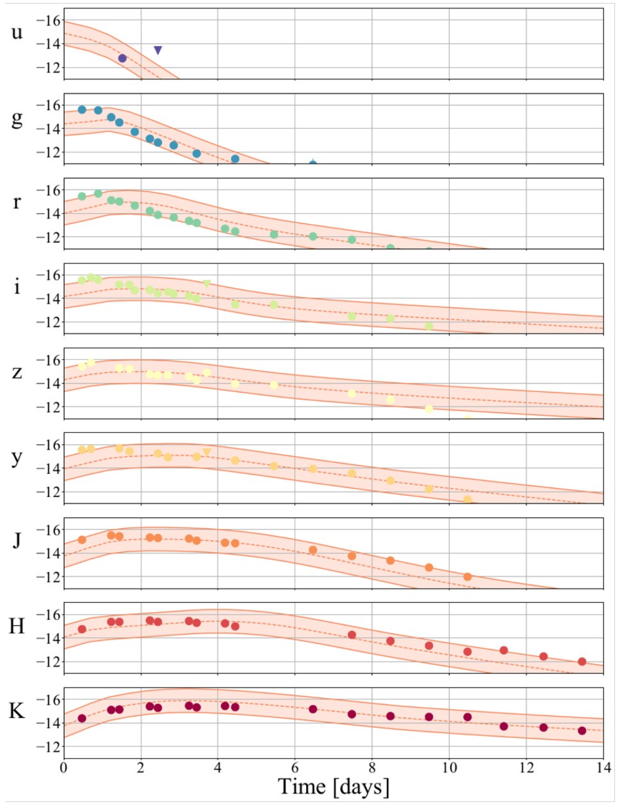
Estimating BNS properties

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.

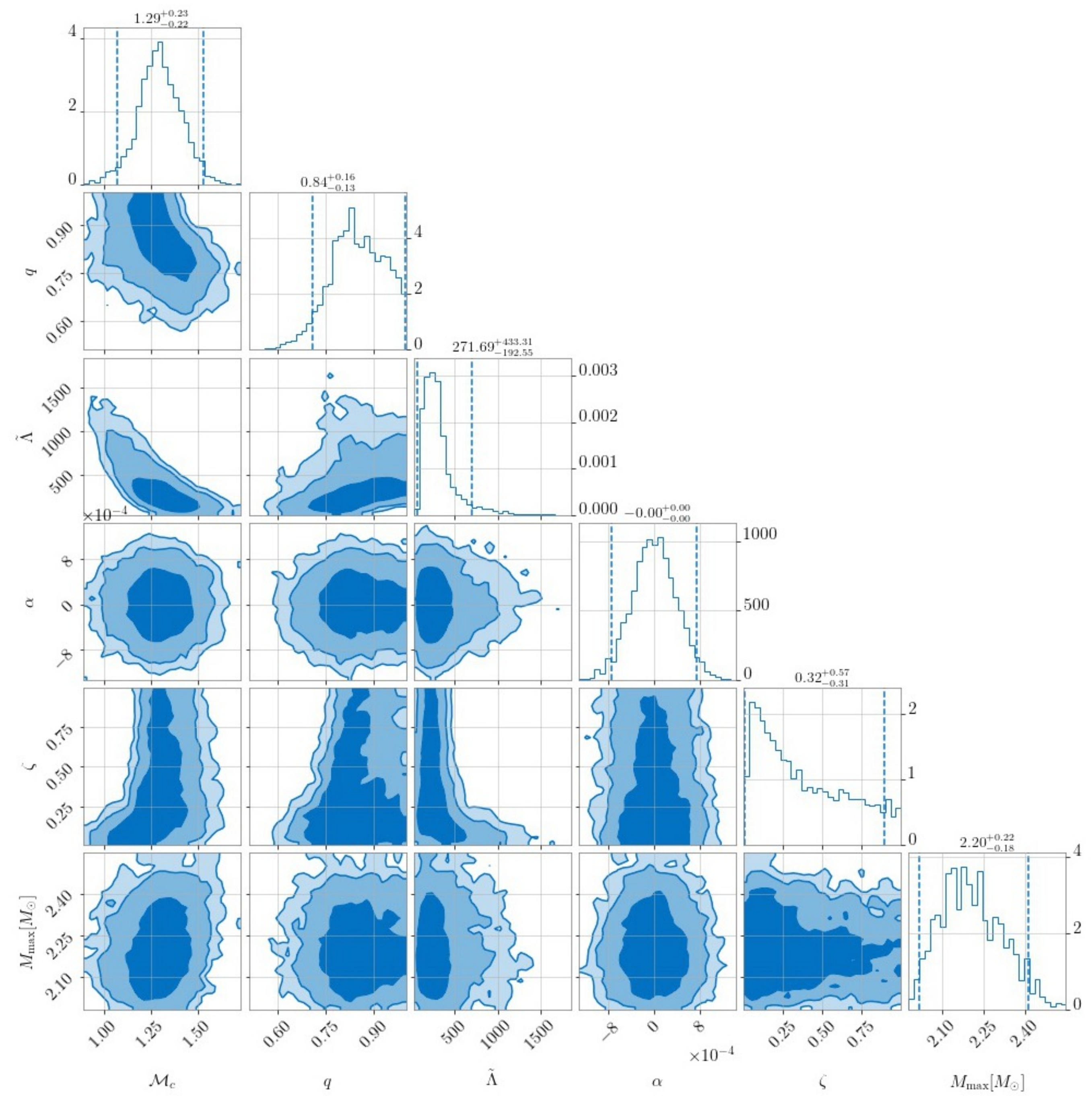
Finally, we can use this command:

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

Where to find more?

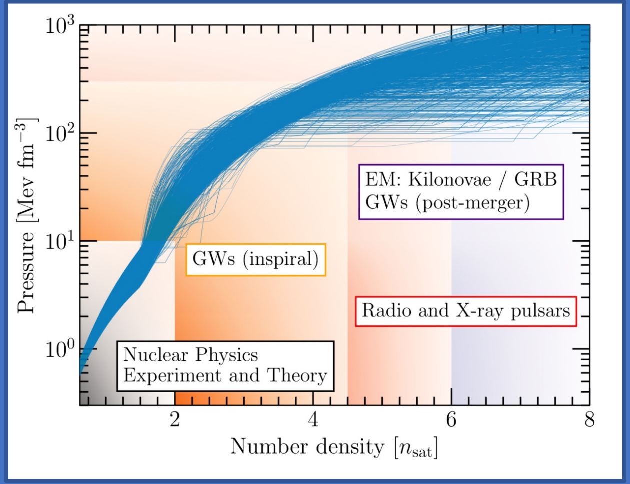


A corner plot is shown below:



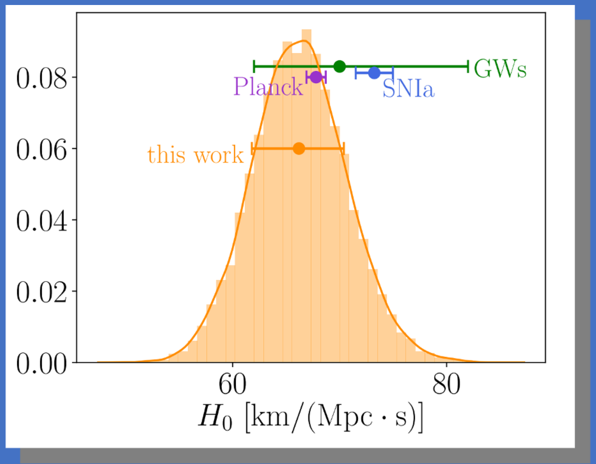
Summary: Multi-messenger Astronomy helps to answer fundamental physics questions

Equation of State



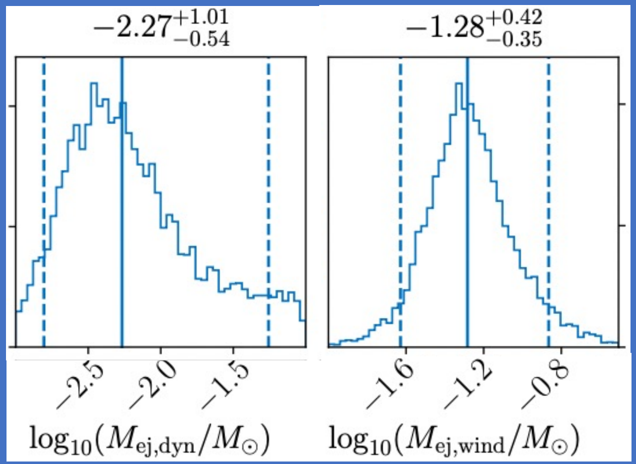
Pang et al., arXiv: 2205.08513

Hubble Constant



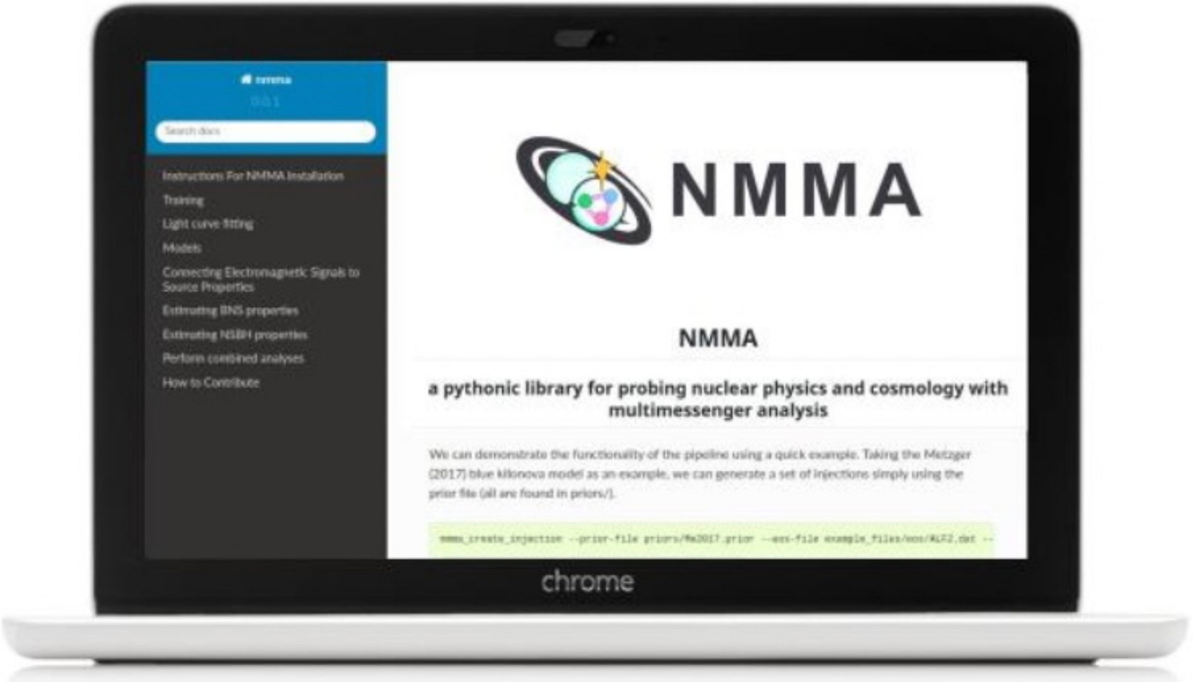
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Heavy element formation



and NMMA is one tool to enable multi-messenger studies, but there is still plenty to do:

- improved models
- more robust sampling
- faster sampling
- ….



Peter T. H. Pang, Michael W. Coughlin, Mattia Bulla, Tim Dietrich, Ingo Tews, Thibeau 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 Jhawar

github.com/nuclear-multimessenger-astronomy