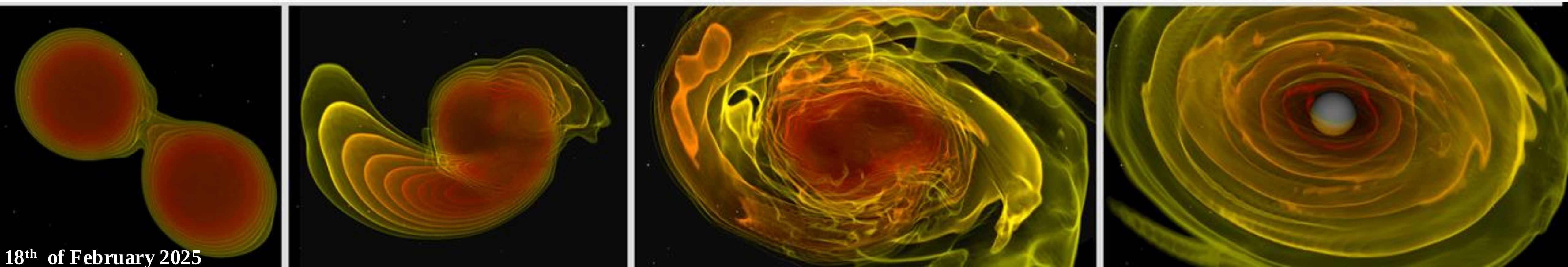
Simulating and Interpreting the Multimessenger Picture of Neutron Star Mergers

Tim Dietrich
University of Potsdam
Max Planck Institute for Gravitational Physics

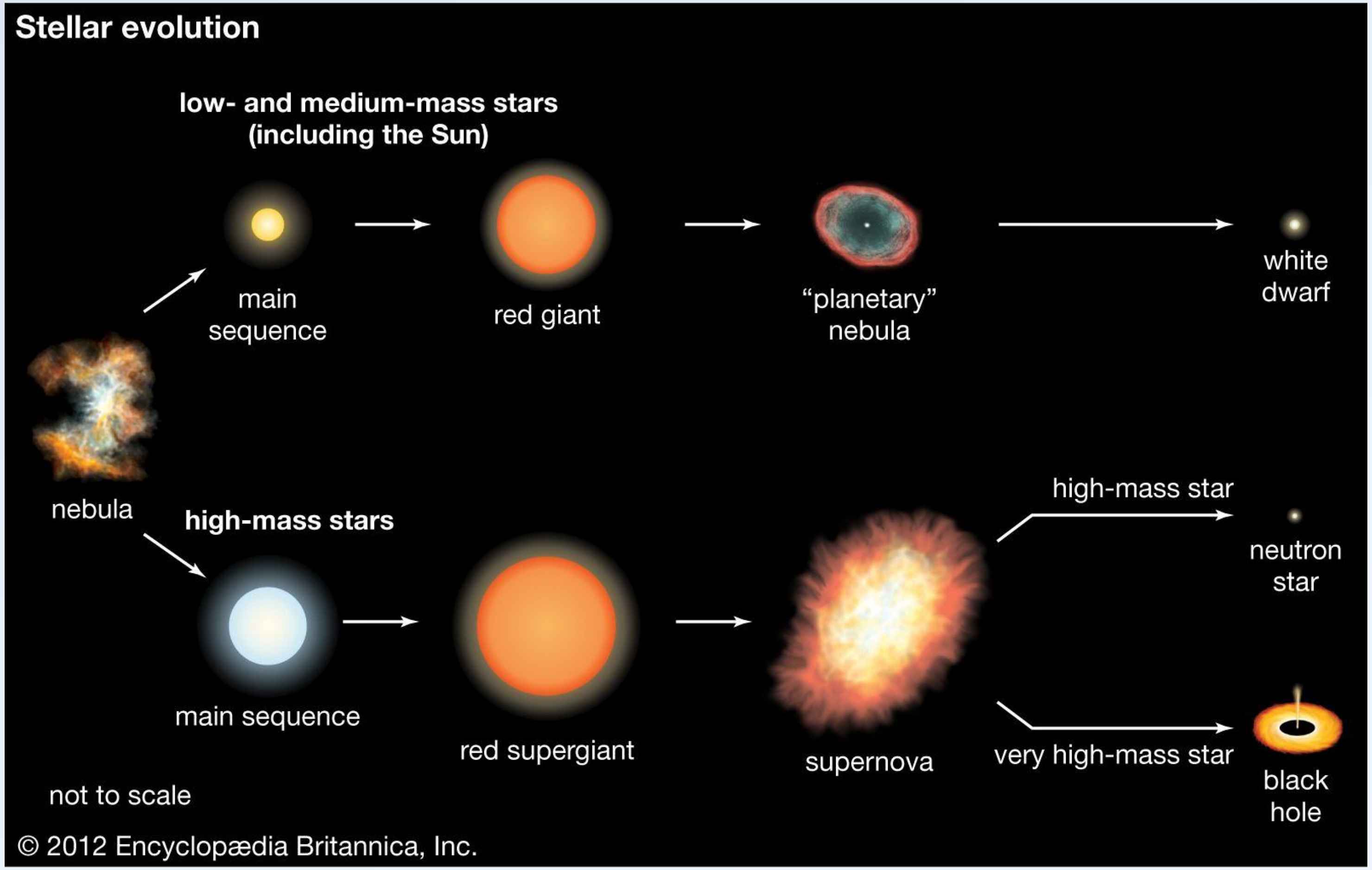


18th of February 2025

Neutron stars…

- collapsed core of a massive star

- smallest and densest known class of stellar compact objects



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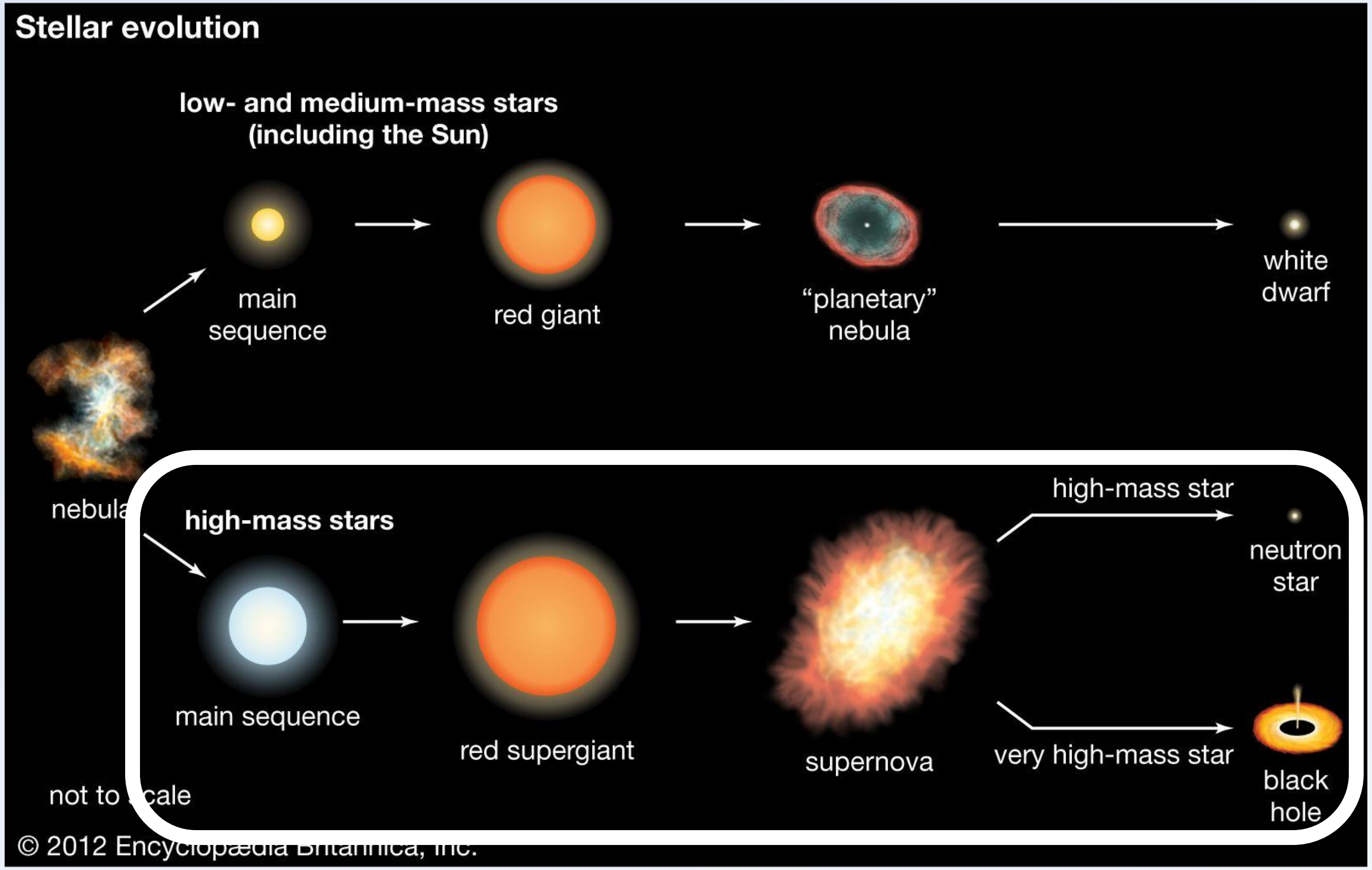

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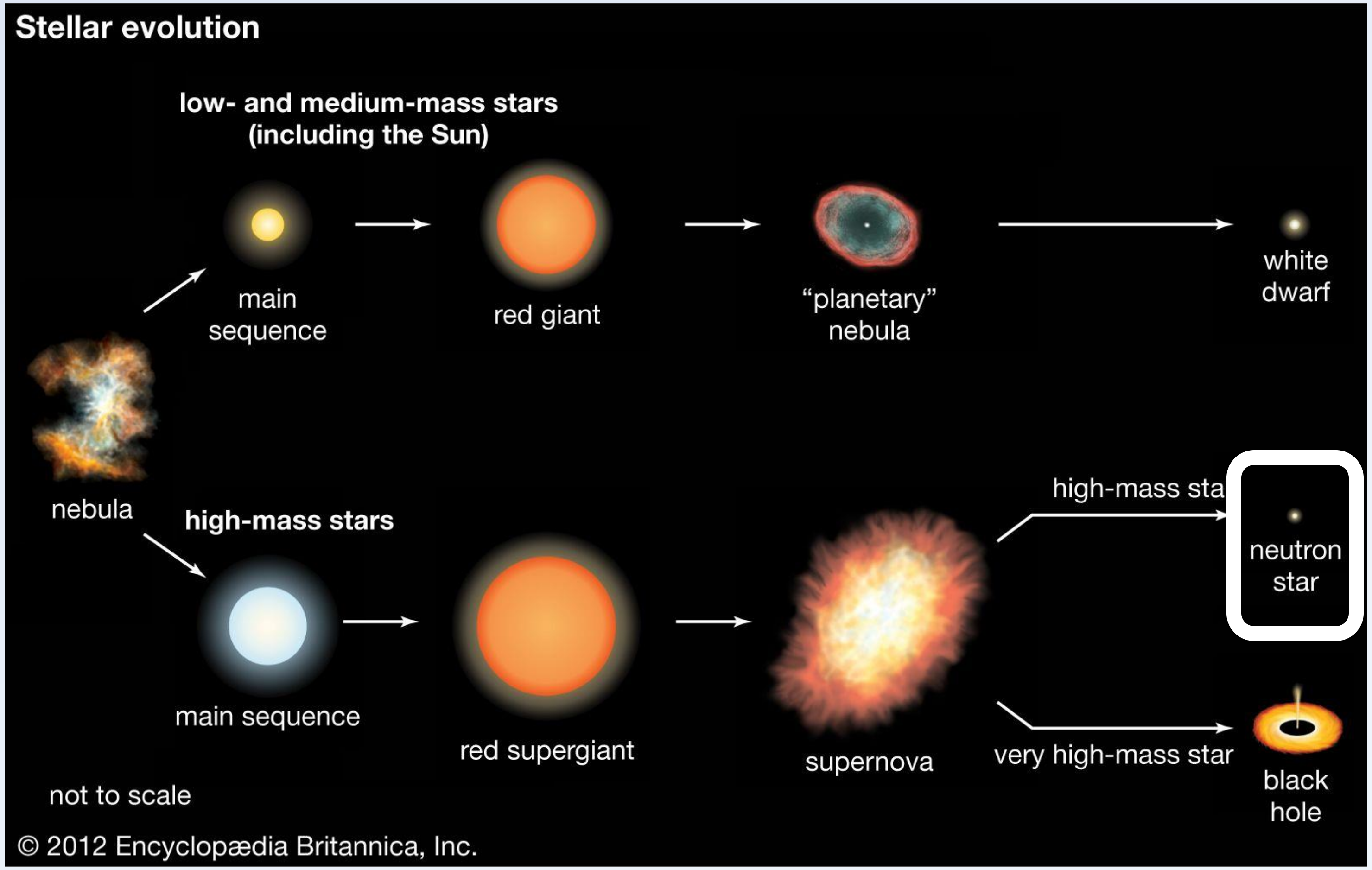

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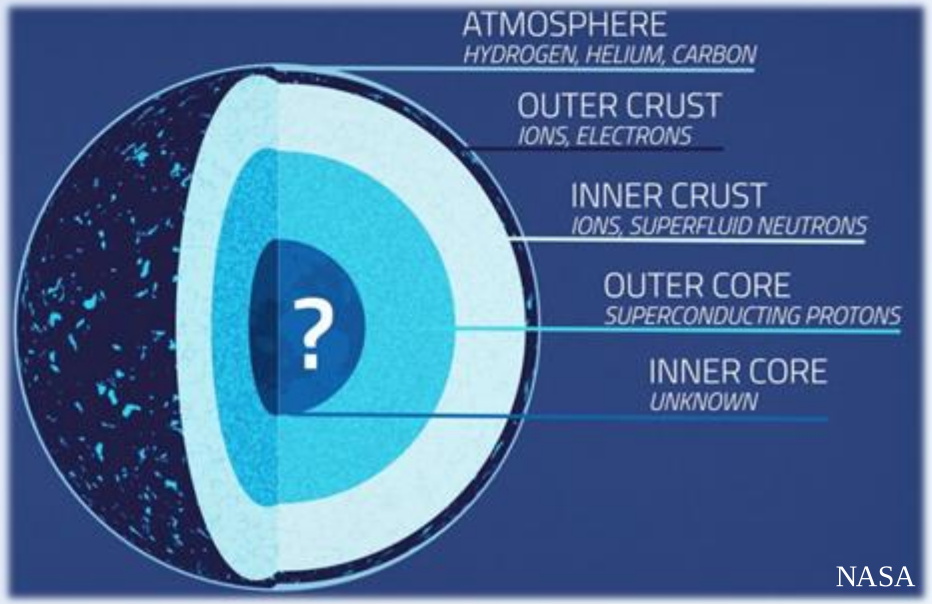
- typical size of 12 kilometer and masses between one and two solar masses



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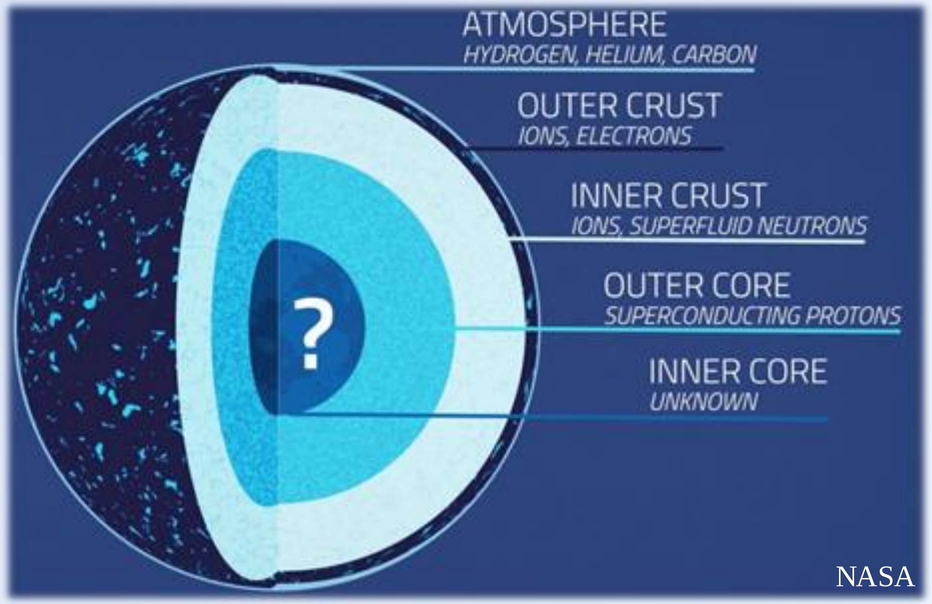
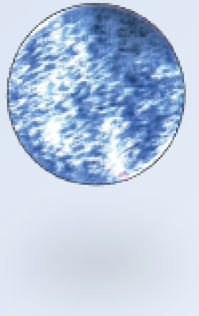


… how to study them?

Single Neutron Stars



- radio pulsars
- through X-ray emission

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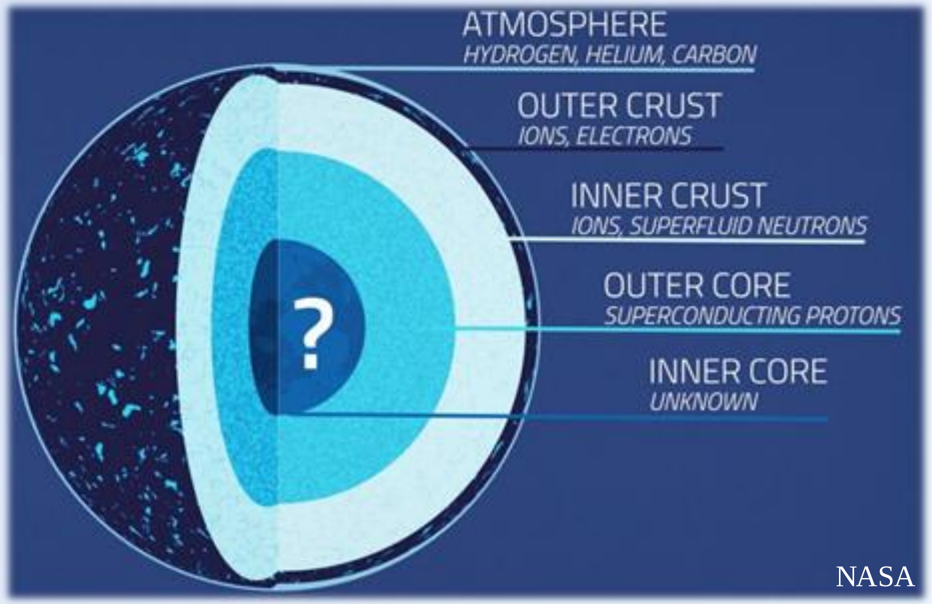

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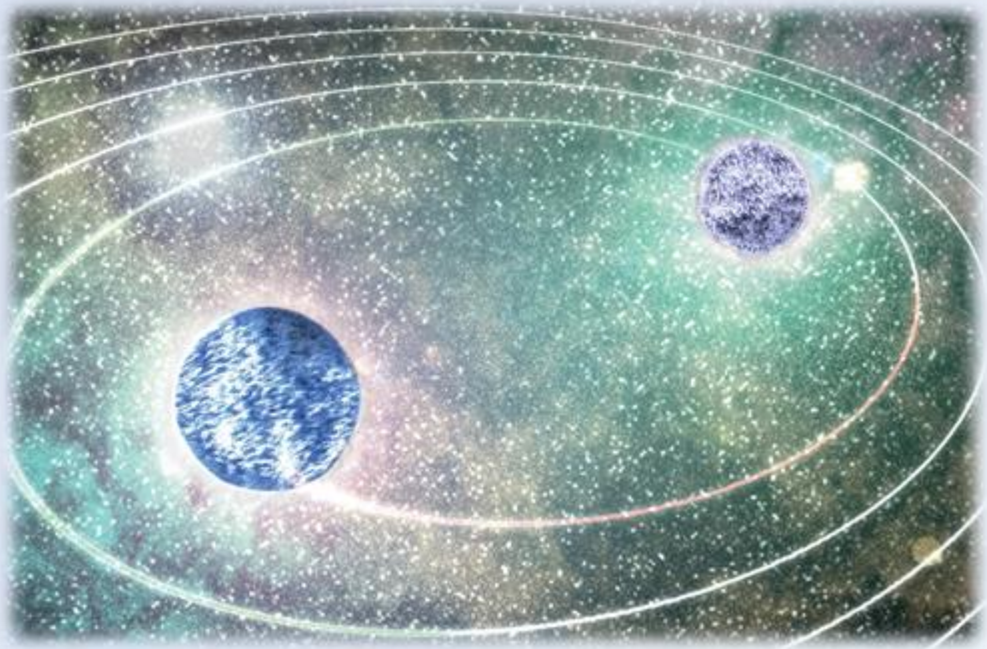
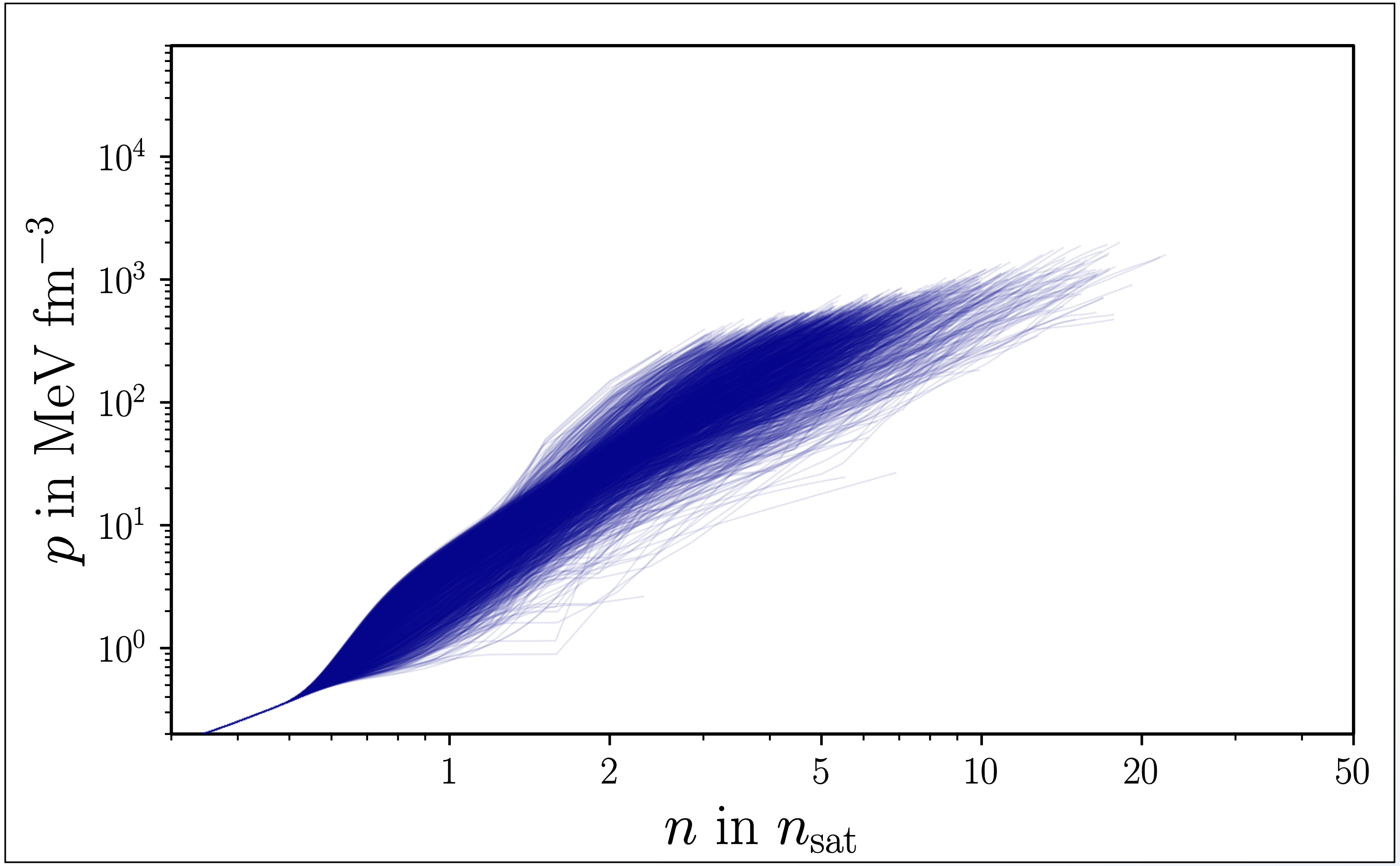
Binary Neutron Stars

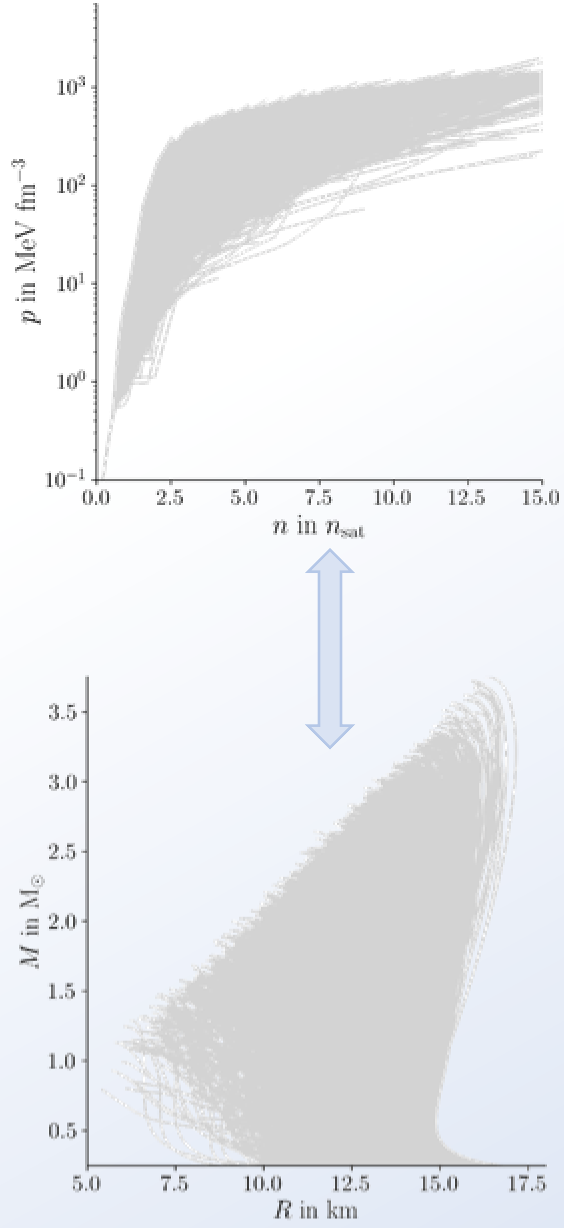


- **gravitational-wave sources**
- **electromagnetic transients**
- **neutrino sources**

Input from a variety of sources:

Koehn et al. 2024, 2402.04172 (accepted in PRX) and PRD 110 (2024) 10, 103015





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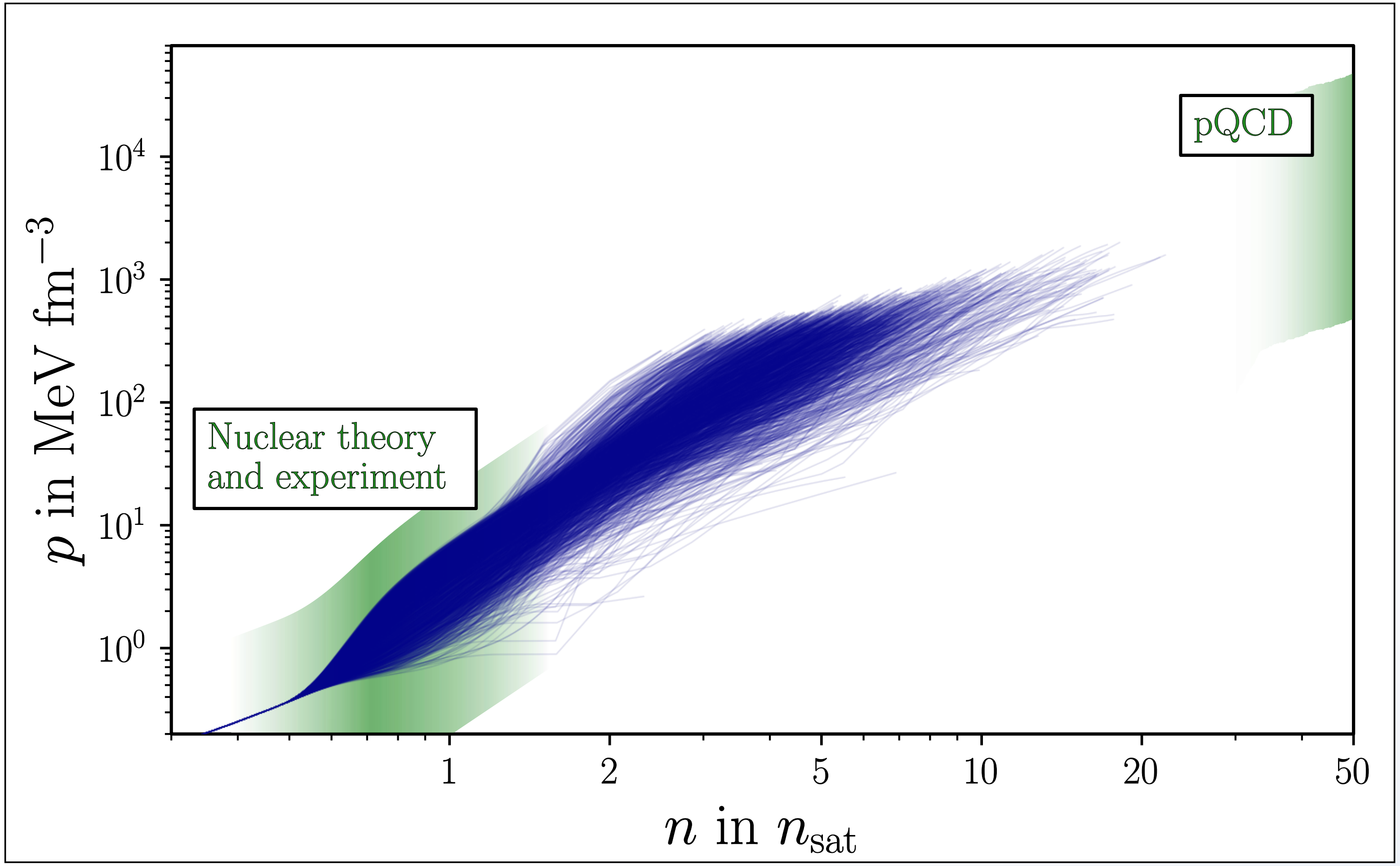
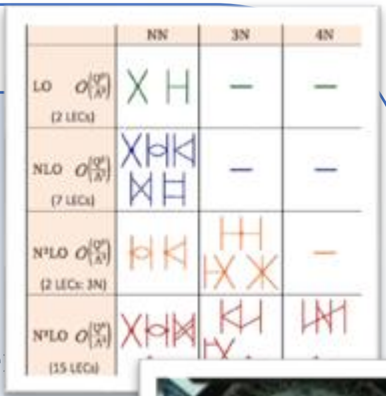


Nuclear Physics

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



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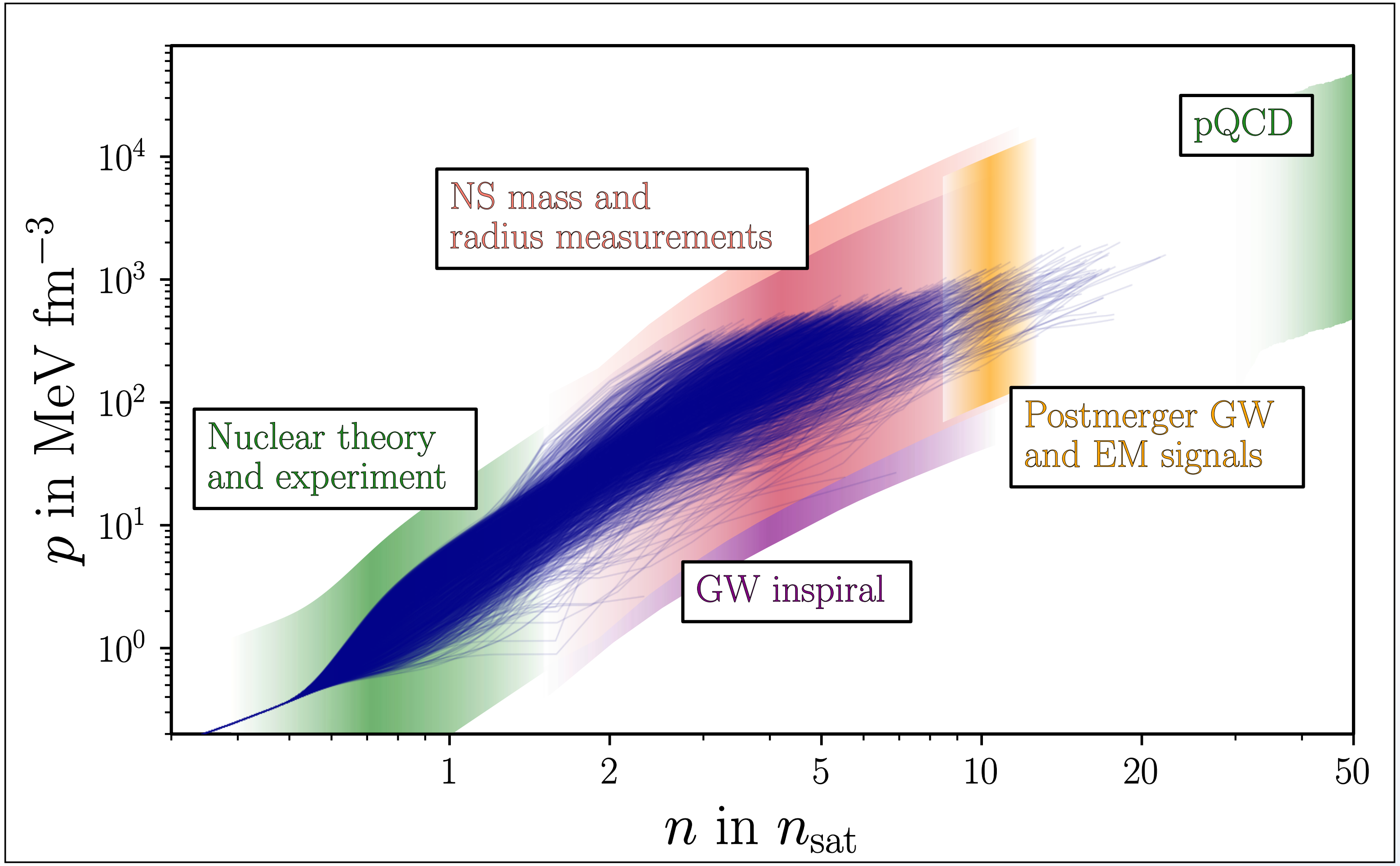

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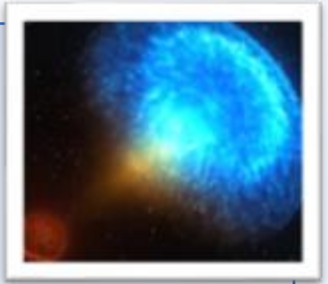
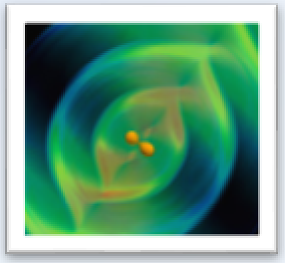


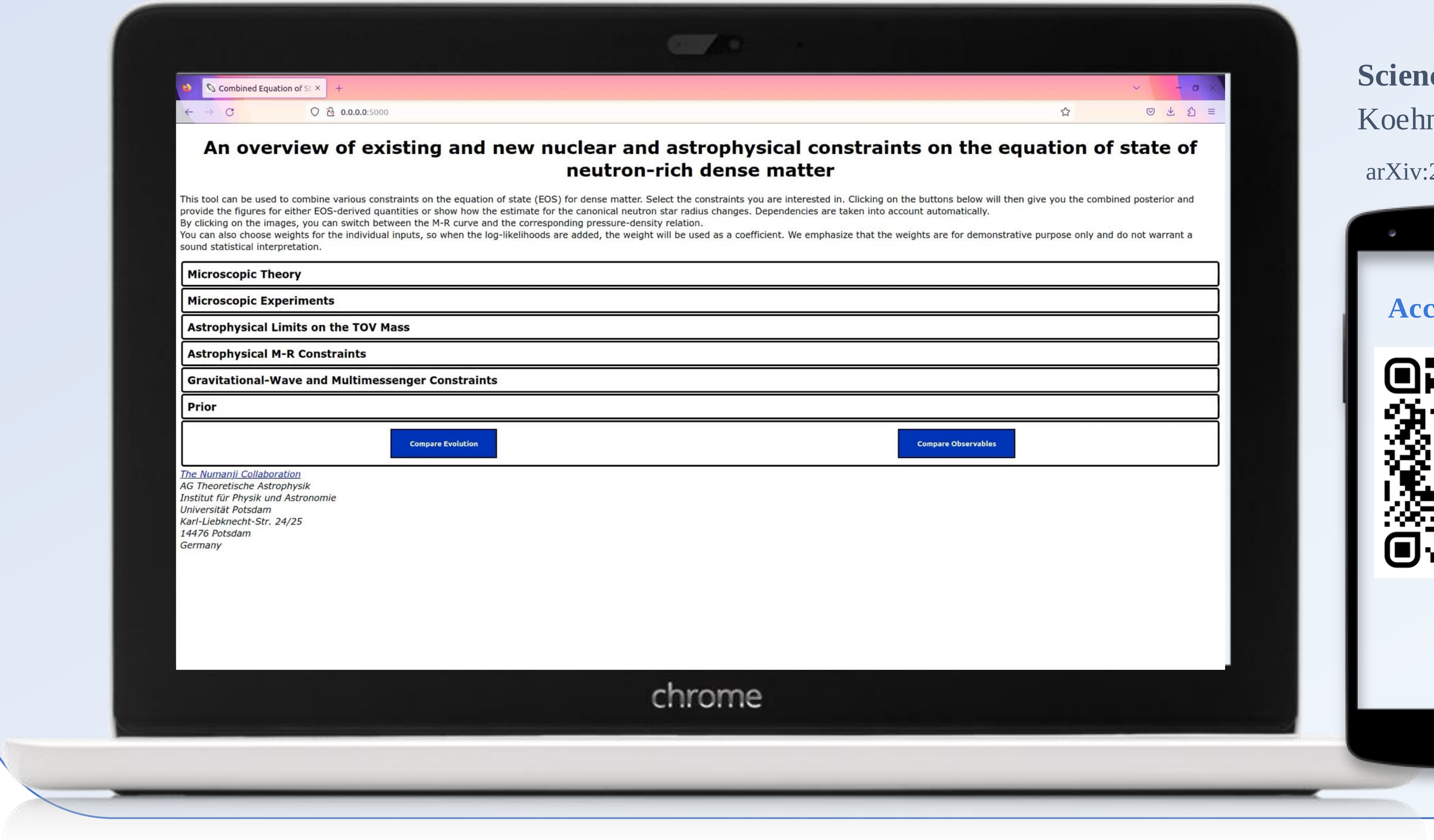
Astrophysics

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



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

Combining different constraints on the EOS from different research fields



Science case:

Koehn et al. 2024

arXiv:2402.04172v1

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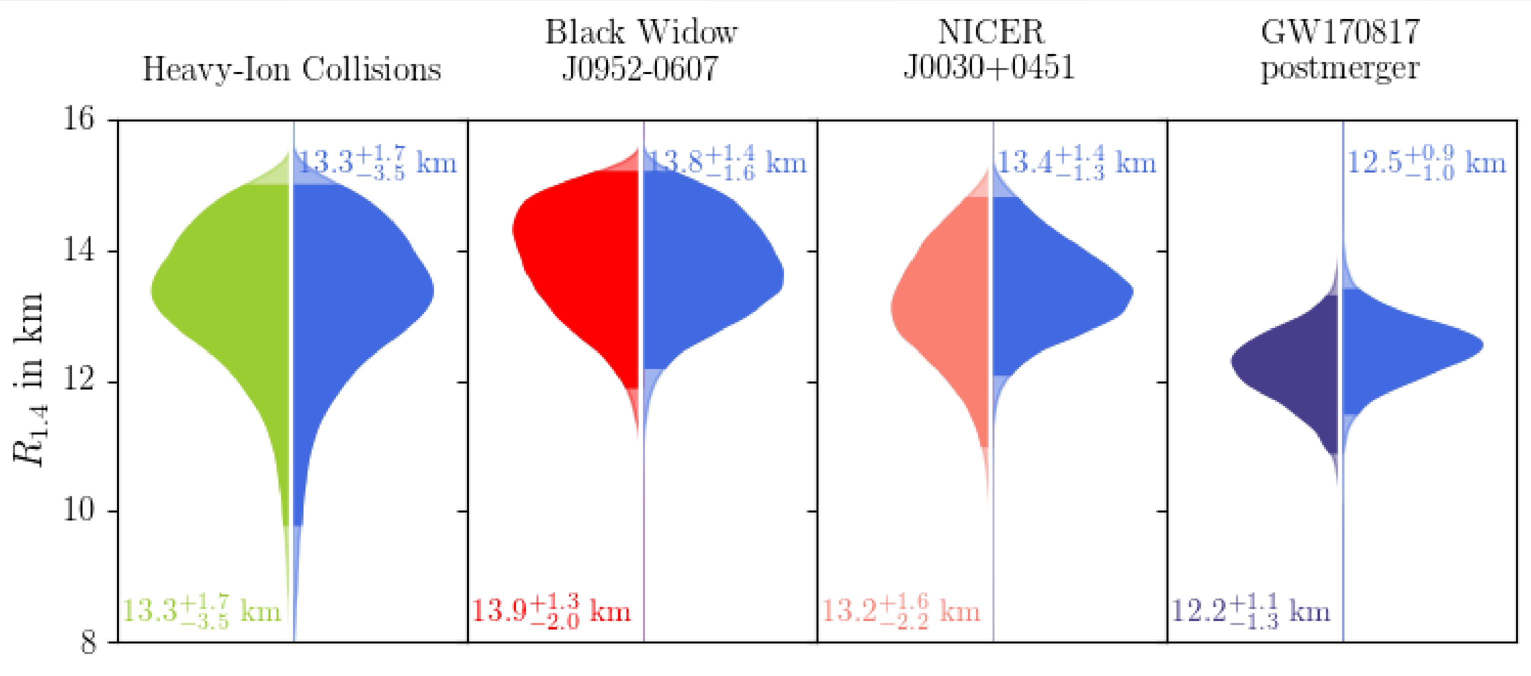

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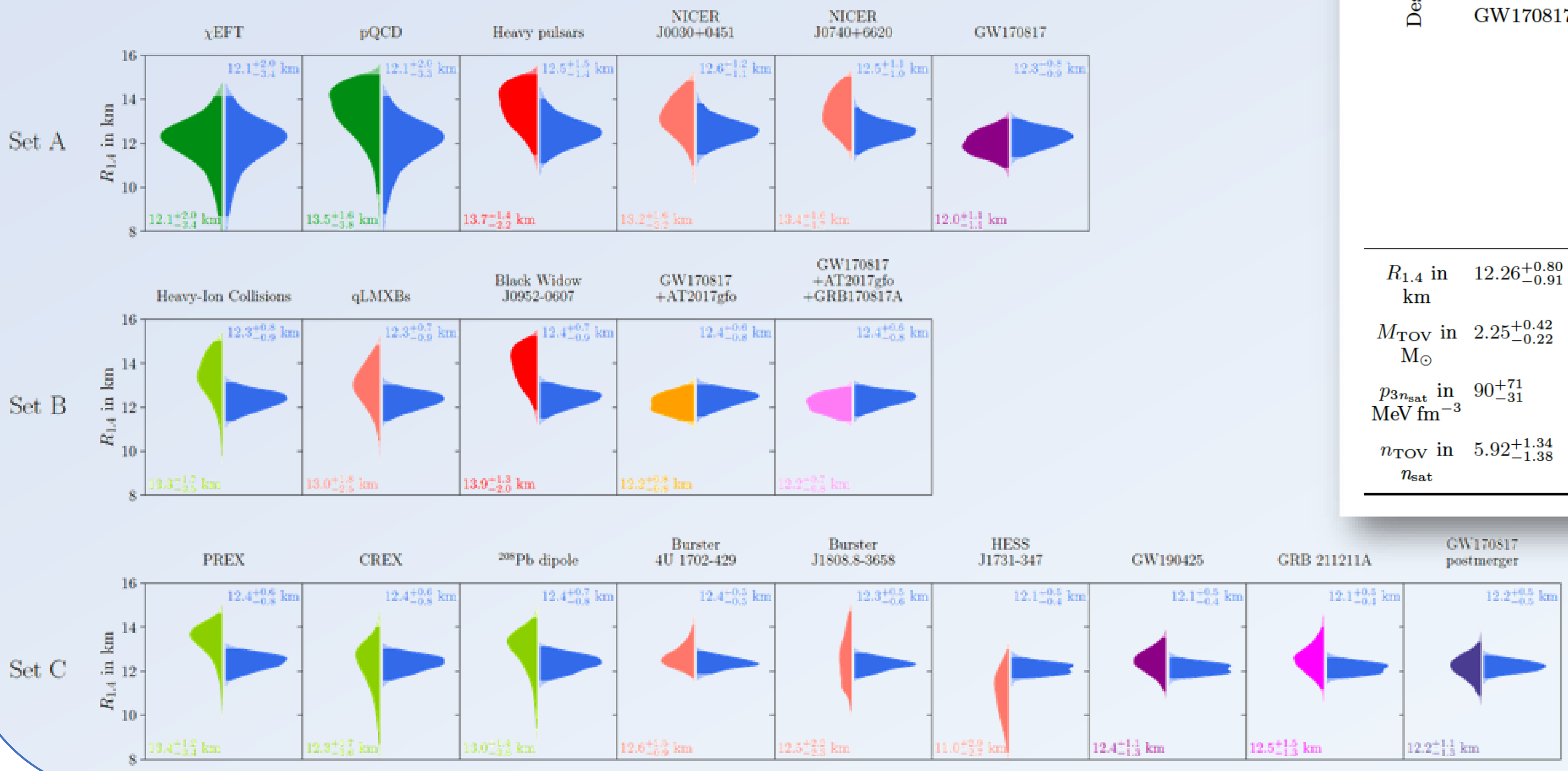

Set	A	B	C
Description	χEFT pQCD Heavy pulsars NICER J0030+0451 NICER J0740+6620 GW170817	Set A HIC Black Widow J0952-0607 qLMXBs GW170817+ KN+GRB	Set B PREX-II CREX ^{208}Pb dipole Burster 4U 1702-429 Burster J1808.8-3658 HESS J1731-347 GW190425 GRB211211A GW170817 postmerger
$R_{1.4}$ in km	$12.26^{+0.80}_{-0.91}$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

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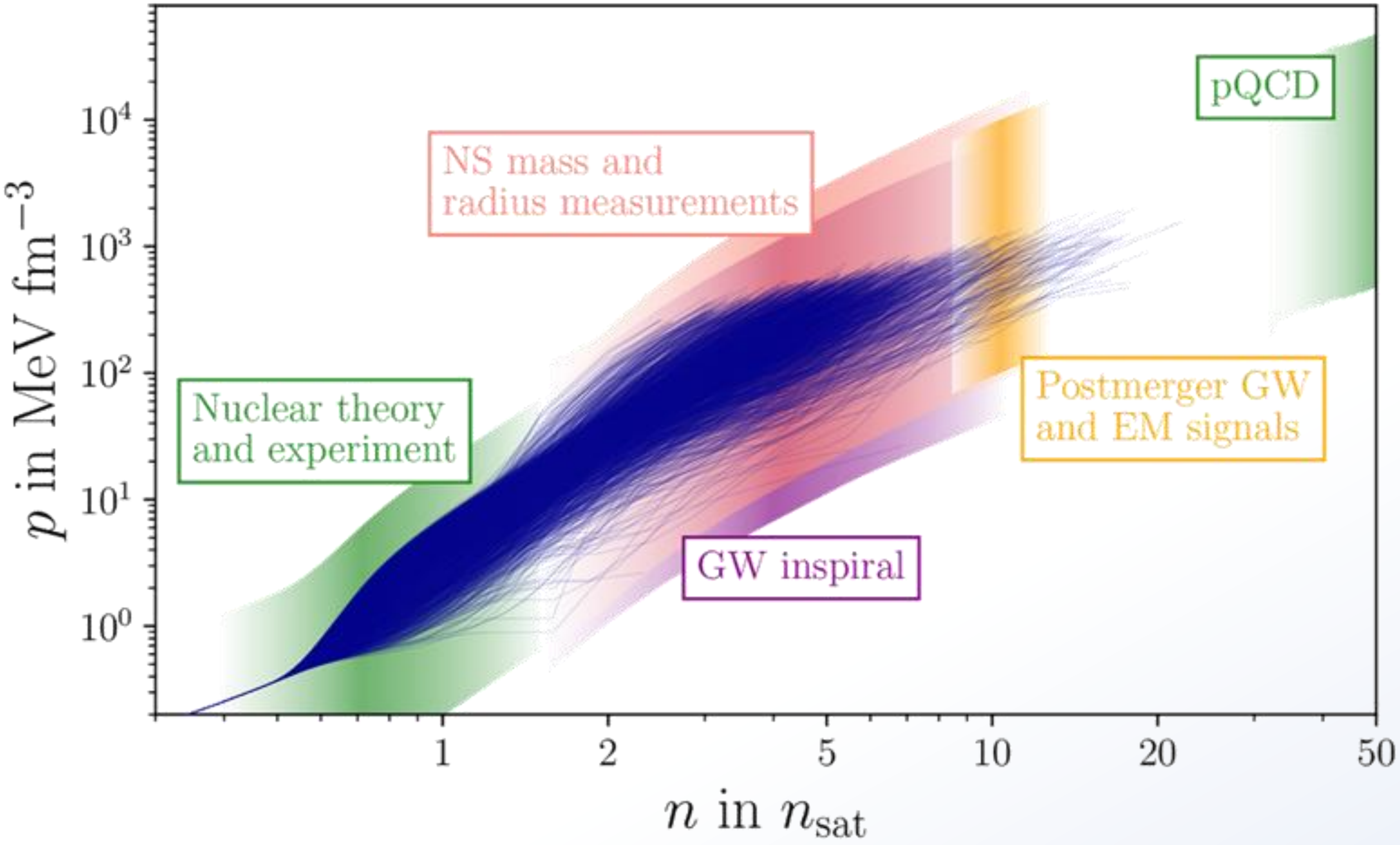
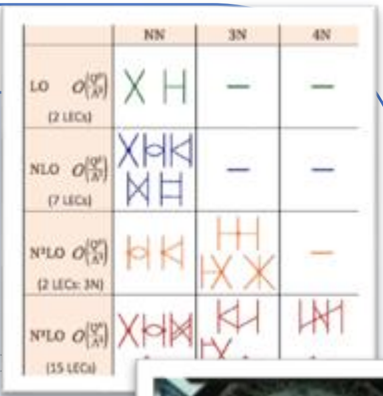
Koehn et al. 2024, 2402.04172



Nuclear Physics



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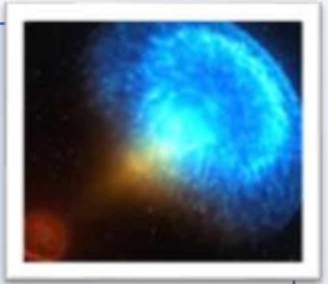

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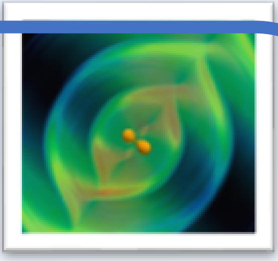

- GW170817
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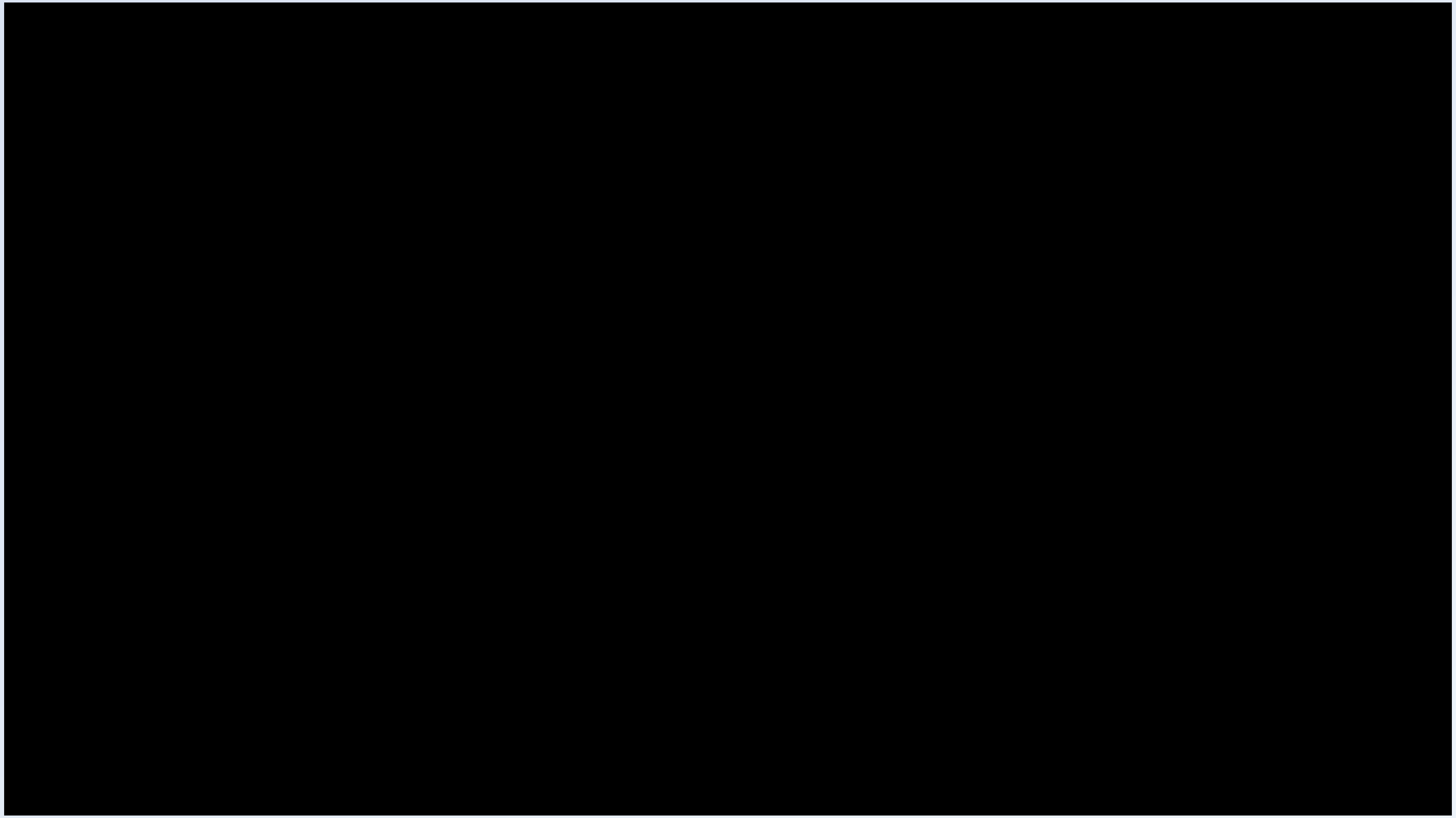
The Binary Neutron Star Merger Simulation



gravitational wave emission

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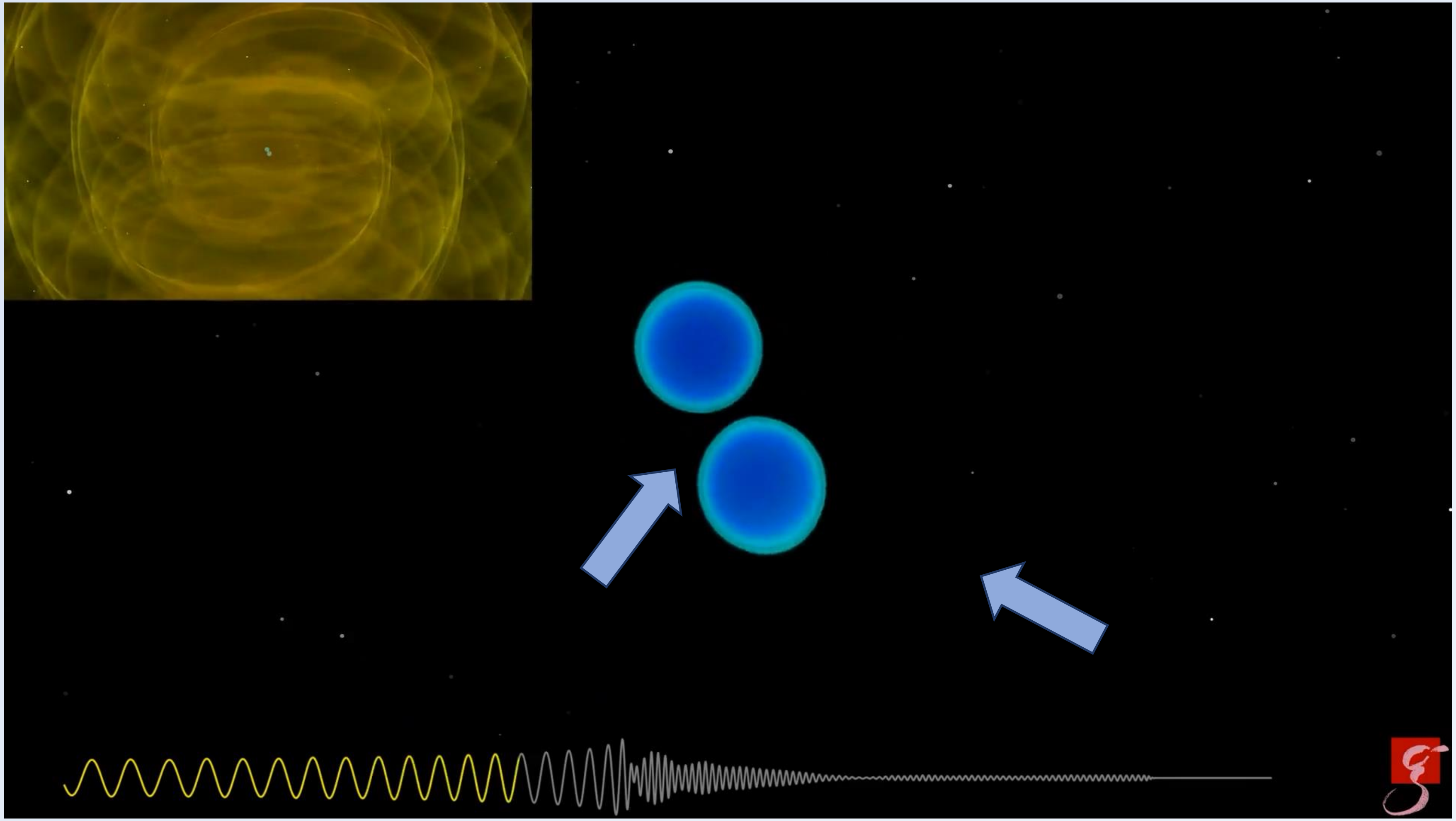
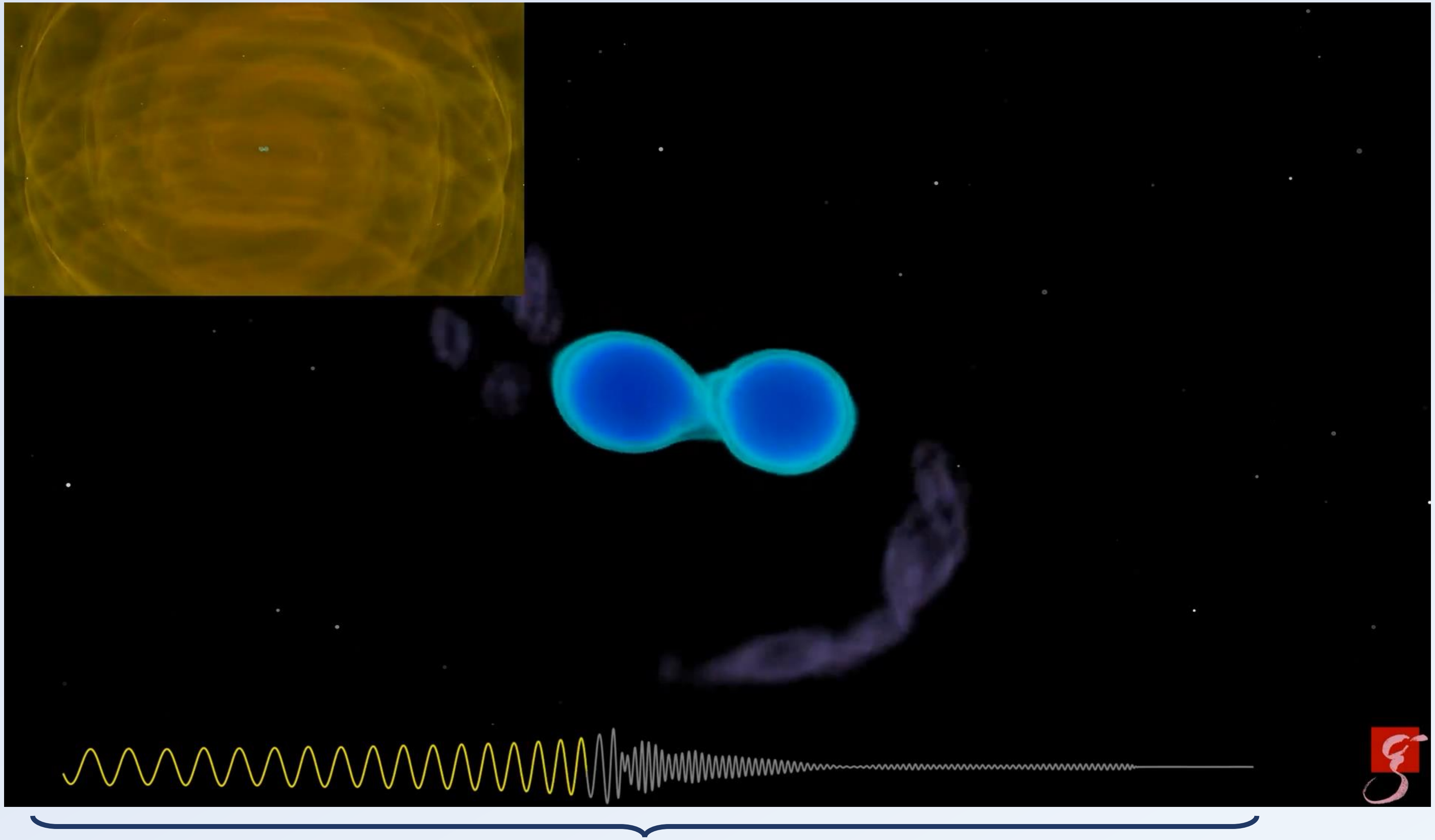


gravitational wave emission

deformation before merger, ejection of material, heavy element production

The Binary Neutron Star Merger Simulation

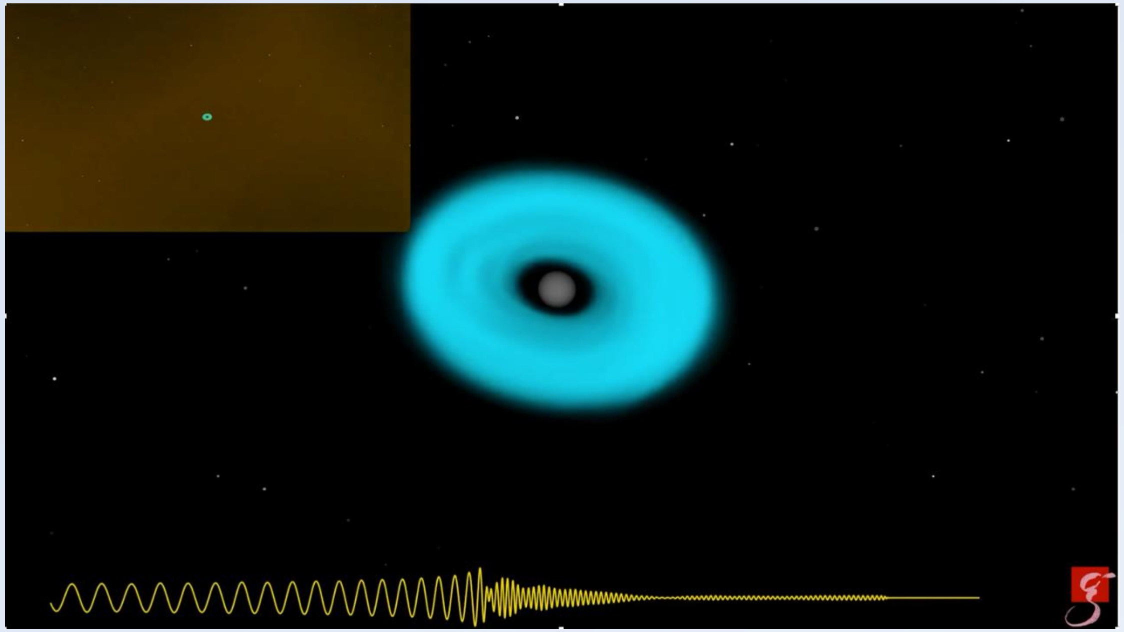


70 milliseconds

gravitational wave emission

deformation before merger, ejection of material, heavy element production

black hole formation



Theoretical Framework:

- well-posedness of PDEs
- advantageous properties

$$
\begin{aligned}
\partial_t \chi &= \frac{2}{3}\chi\left(\alpha(\hat{K}+2\Theta) - D_i\beta^i\right),\\
\partial_t \tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij} + \beta^k\partial_k\tilde{\gamma}_{ij} + 2\tilde{\gamma}_{k(i}\partial_{j)}\beta^k - \frac{2}{3}\tilde{\gamma}_{ij}\partial_k\beta^k,\\
\partial_t \hat{K} &= -D^iD_i\alpha + \alpha\left(\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}(\hat{K}+2\Theta)^2\right)\\
&\quad + 4\pi\alpha(S+E) + \beta^k\partial_k\hat{K} + \alpha\kappa_1(1-\kappa_2)\Theta,\\
\partial_t \tilde{A}_{ij} &= \chi\left(-D_iD_j\alpha + \alpha\left({}^{(3)}R_{ij} - 8\pi S_{ij}\right)\right)^{TF} + \alpha\left((\hat{K}+2\Theta)\tilde{A}_{ij} - 2\tilde{A}^k{}_j\tilde{A}_{kj}\right)\\
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\end{aligned}
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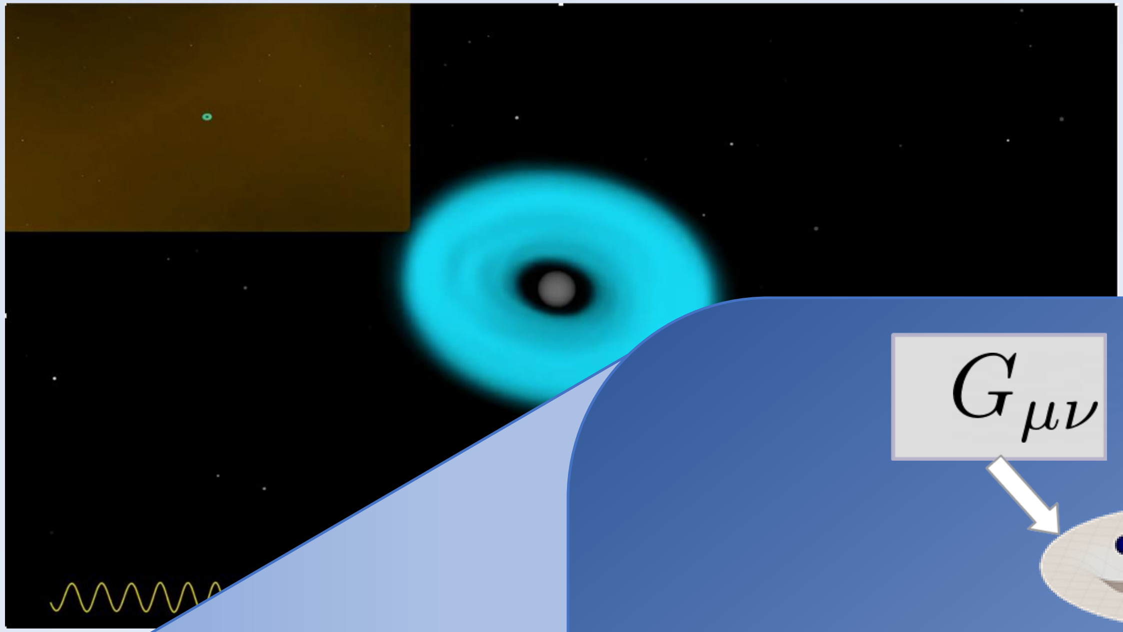

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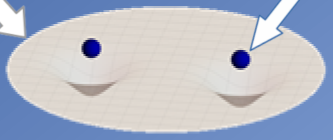
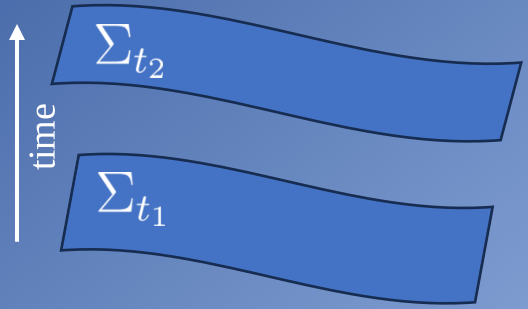
\end{aligned}
$$

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

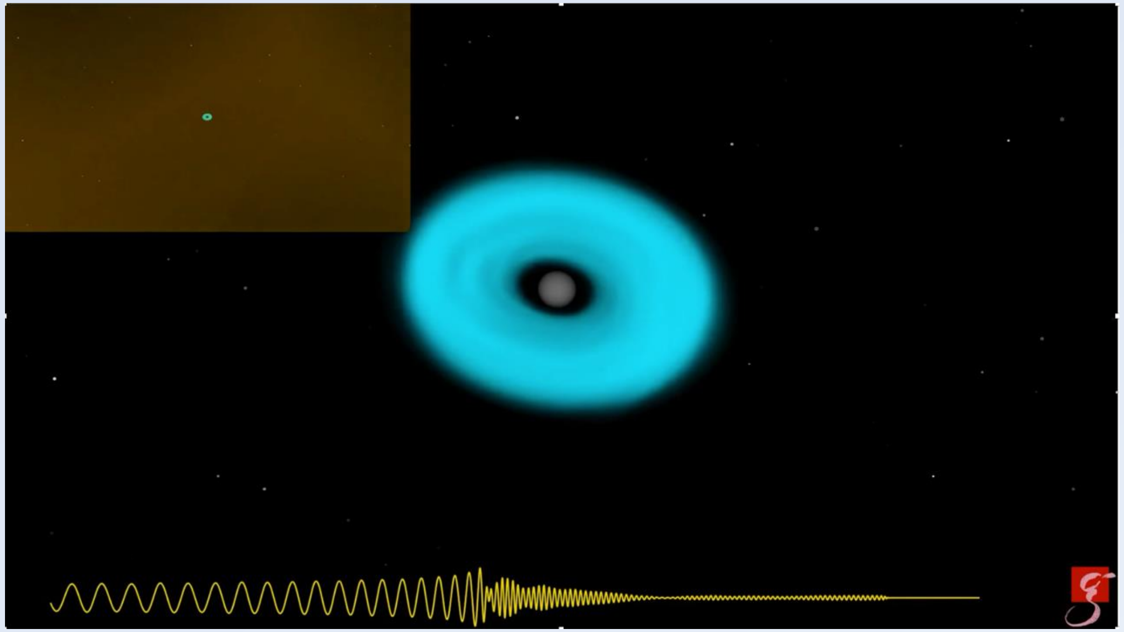




3+1-decomposition

$$\partial_t\mathbf{u} = \mathbf{A}(\mathbf{u})\mathbf{u}+\mathbf{v}$$

Reformulating as initial value boundary problem



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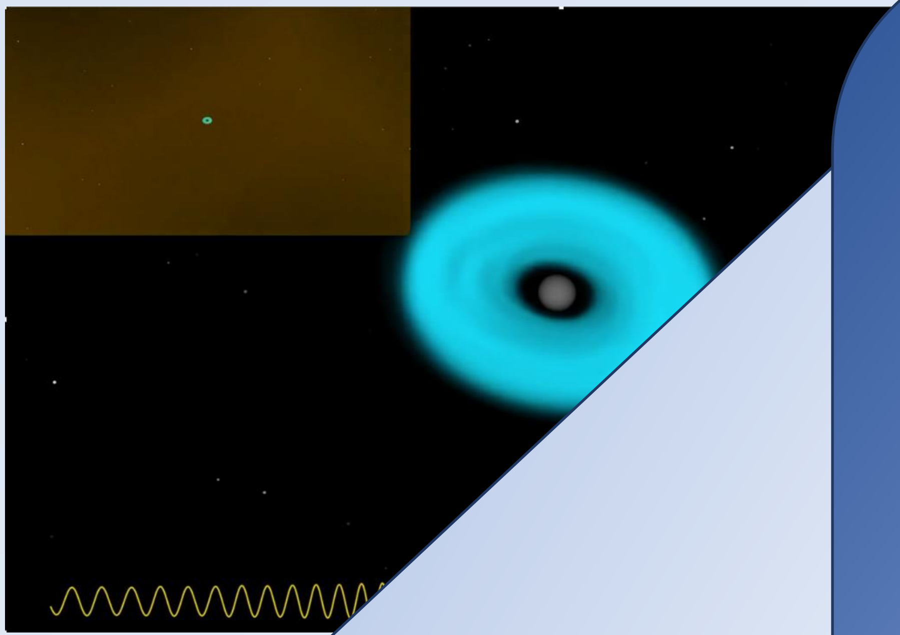
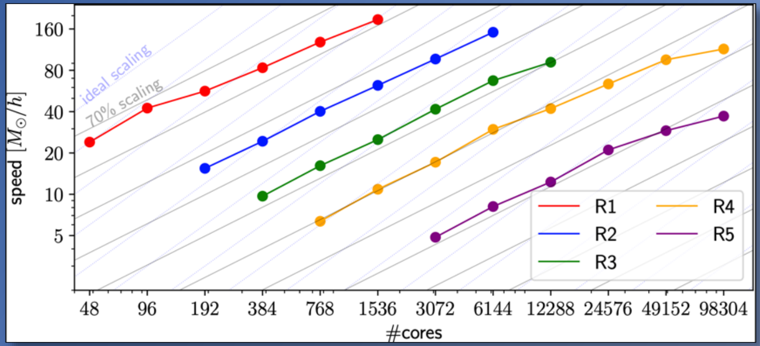
&\quad + \beta^i\partial_i\Theta
\end{aligned}
$$

Computational Methods:

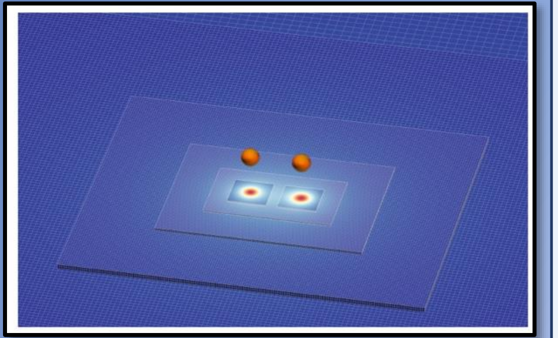
- HPC facilities
- parallelizable code
- numerical techniques



parallelized code



resolving multiple length scales



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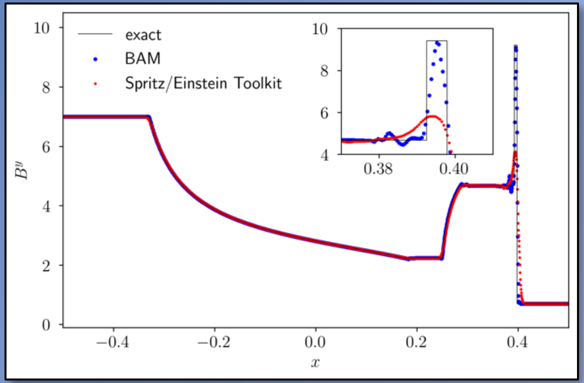
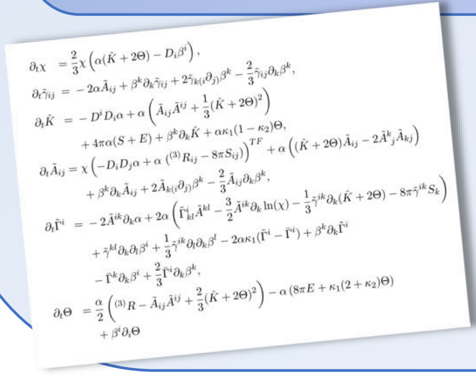
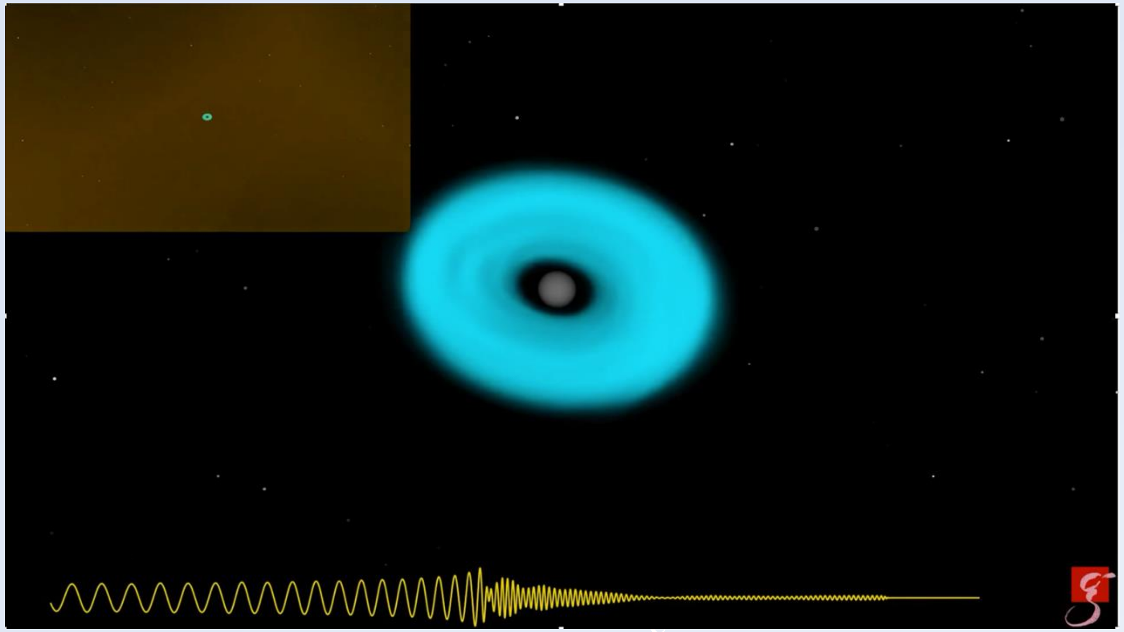


handling discontinuities



deep-learning techniques to speed up matter evolution



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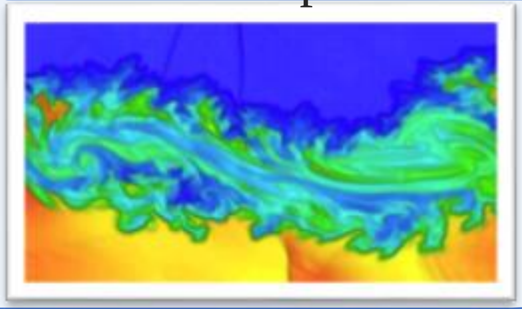
&\quad + \beta^k\partial_k\tilde{A}_{ij} + 2\tilde{A}_{k(i}\partial_{j)}\beta^k - \frac{2}{3}\tilde{A}_{ij}\partial_k\beta^k,\\
\partial_t \tilde{\Gamma}^i &= -2\tilde{A}^{ik}\partial_k\alpha + 2\alpha\left(\tilde{\Gamma}^i_{kl}\tilde{A}^{kl} - \frac{3}{2}\tilde{A}^{ik}\partial_k\ln(\chi) - \frac{1}{3}\tilde{\gamma}^{ik}\partial_k(\hat{K}+2\Theta) - 8\pi\tilde{\gamma}^{ik}S_k\right)\\
&\quad + \tilde{\gamma}^{kl}\partial_k\partial_l\beta^i + \frac{1}{3}\tilde{\gamma}^{ik}\partial_l\partial_k\beta^l - 2\alpha\kappa_1(\tilde{\Gamma}^i - \bar{\Gamma}^i) + \beta^k\partial_k\tilde{\Gamma}^i\\
&\quad - \bar{\Gamma}^k\partial_k\beta^i + \frac{2}{3}\bar{\Gamma}^i\partial_k\beta^k,\\
\partial_t \Theta &= \frac{\alpha}{2}\left({}^{(3)}R - \tilde{A}_{ij}\tilde{A}^{ij} + \frac{2}{3}(\hat{K}+2\Theta)^2\right) - \alpha\left(8\pi E + \kappa_1(2+\kappa_2)\Theta\right)\\
&\quad + \beta^i\partial_i\Theta
\end{aligned}
$$

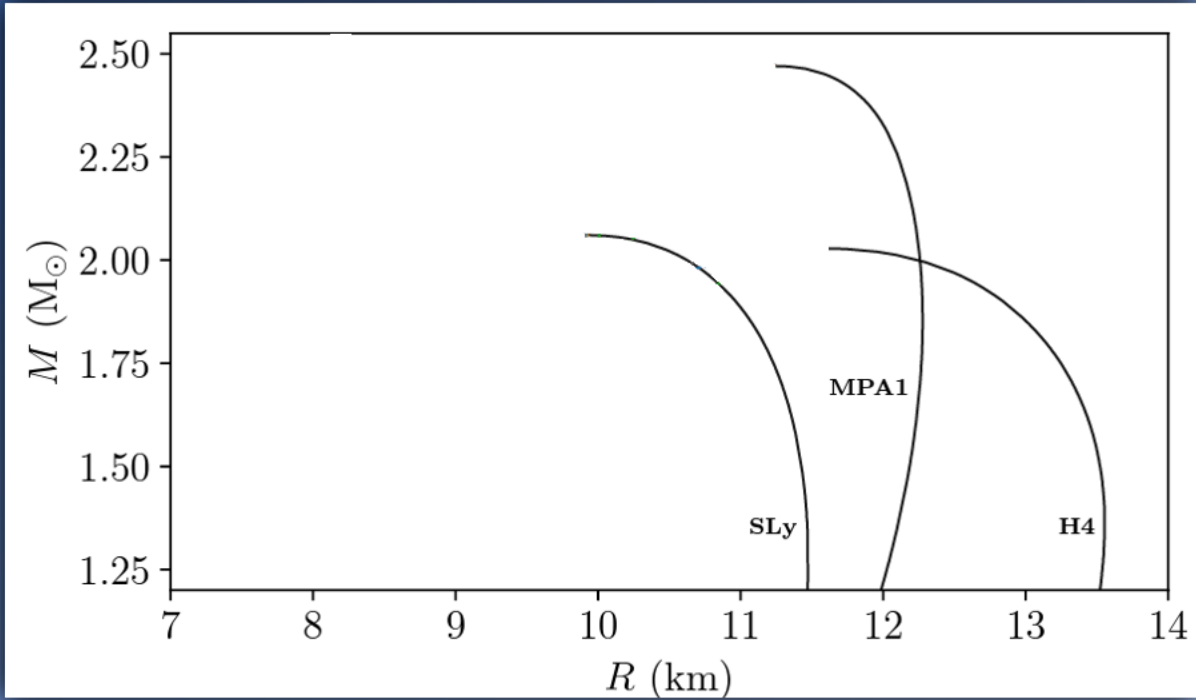
Computational Methods:

- HPC facilities
- parallelizable code
- numerical techniques

Input Physics:

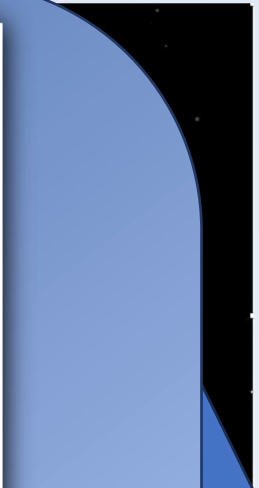
- Microphyics (EOS, Neutrinos)
- Magnetic fields
- Turbulences
- Parameter space

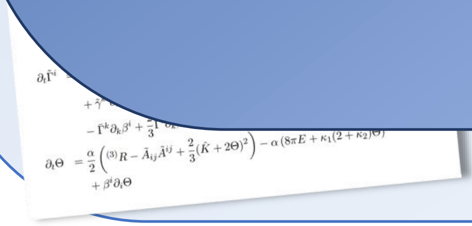




- **Can we test matter above the TOV limit?**

Ujevic et al., Astrophys.J.Lett. 962 (2024) 1, L3





Input Physics:

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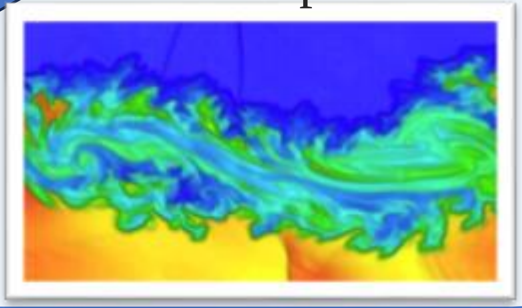

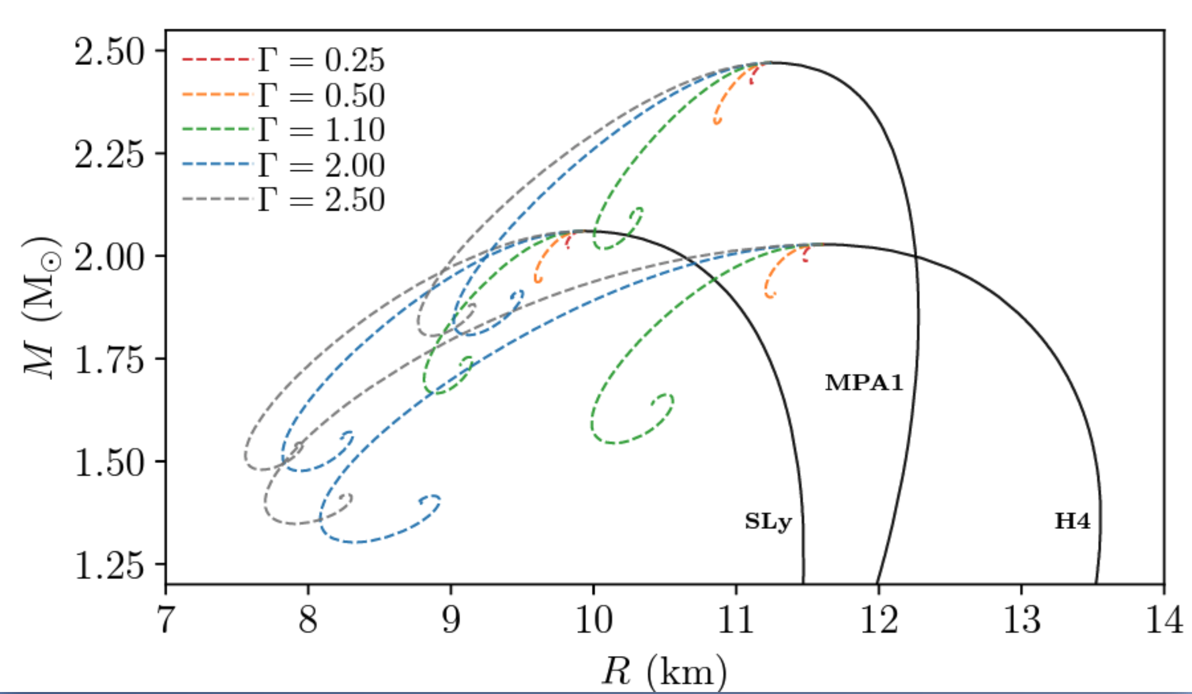

- **Can we test matter above the TOV limit?**

Ujevic et al., Astrophys.J.Lett. 962 (2024) 1, L3

Input Physics:

- Microphysics (EOS, Neutrinos)
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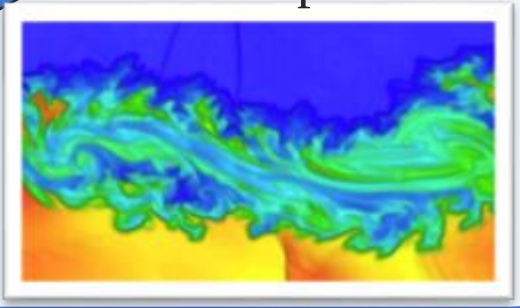
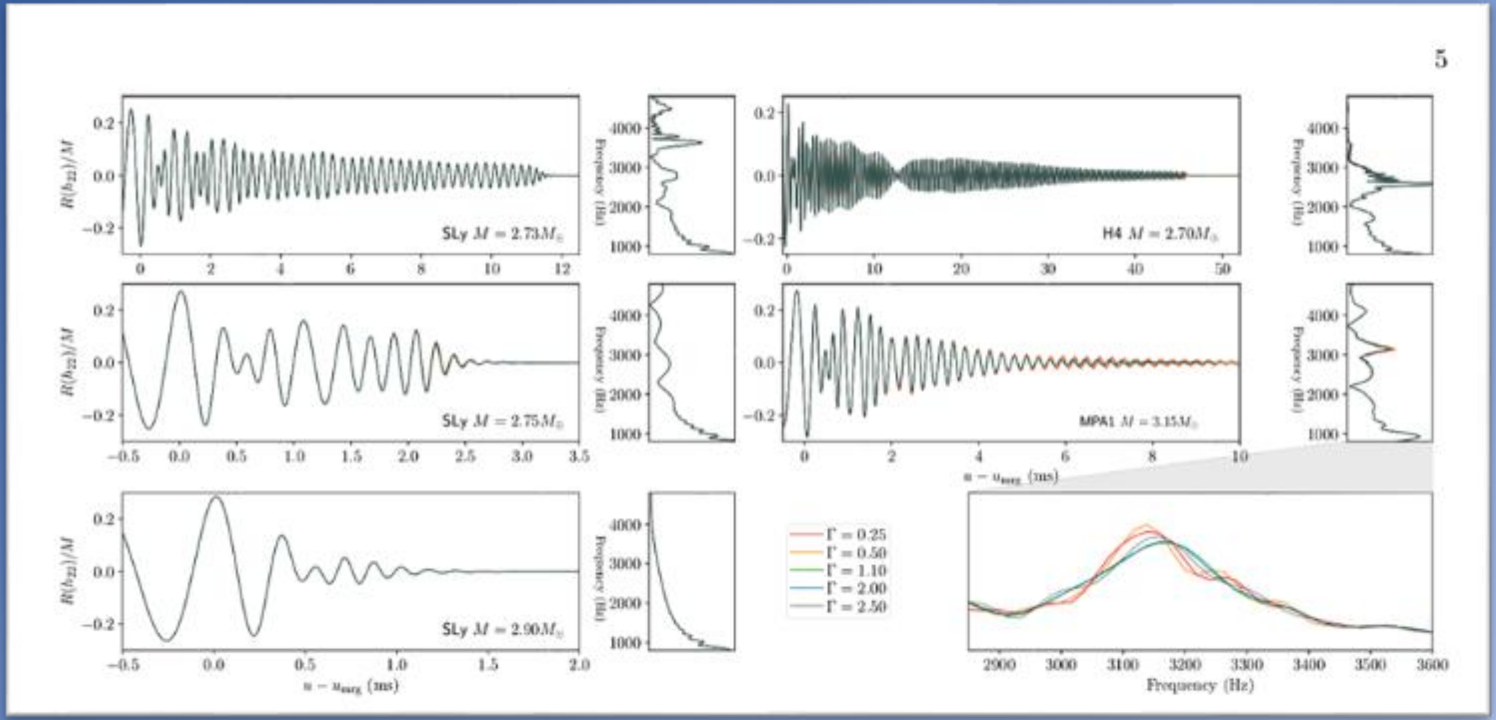




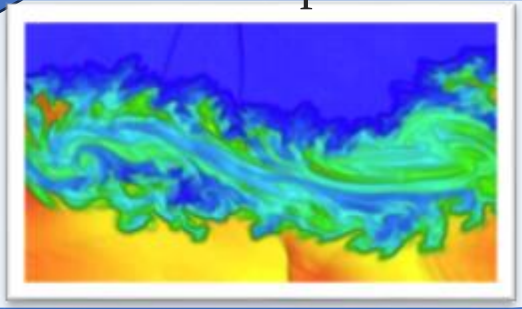
- **Can we test matter above the TOV limit?**

No!

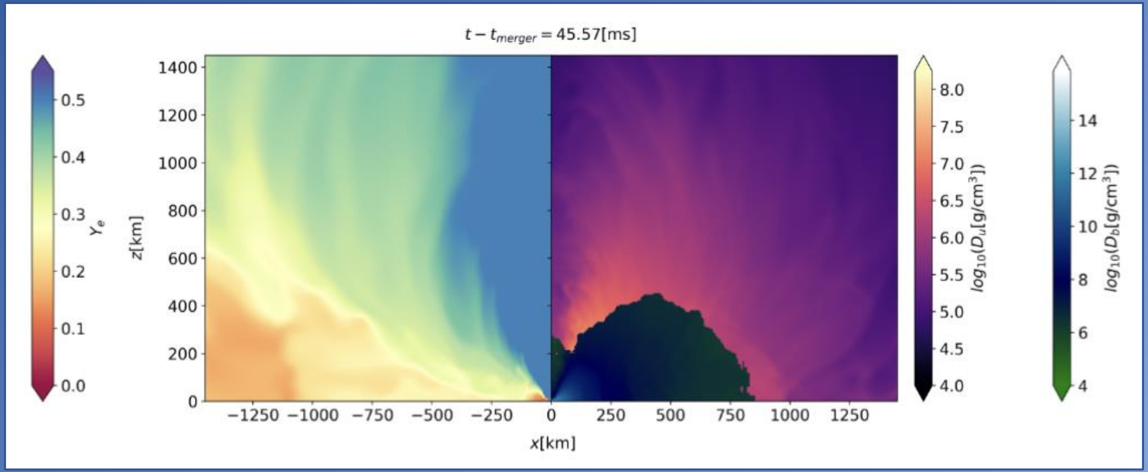
Ujevic et al., Astrophys.J.Lett. 962 (2024) 1, L3

Input Physics:

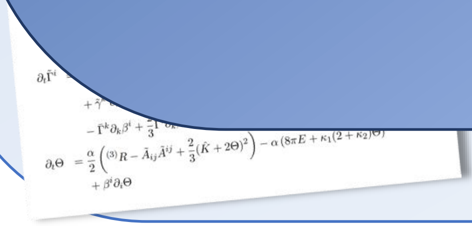
- Microphysics (EOS, Neutrinos)
- Magnetic fields
- Turbulences
- Parameter space



neutrino radiation



Schianchi et al., arXiv: 2307.04572
Gieg et al., Universe 8 (2022) 7, 370



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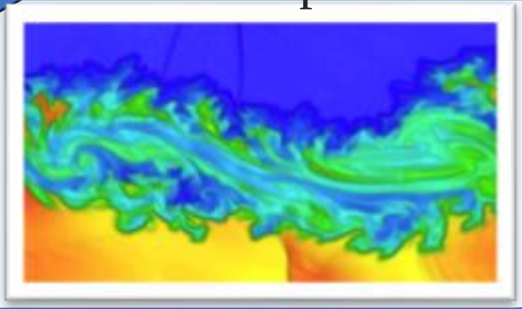
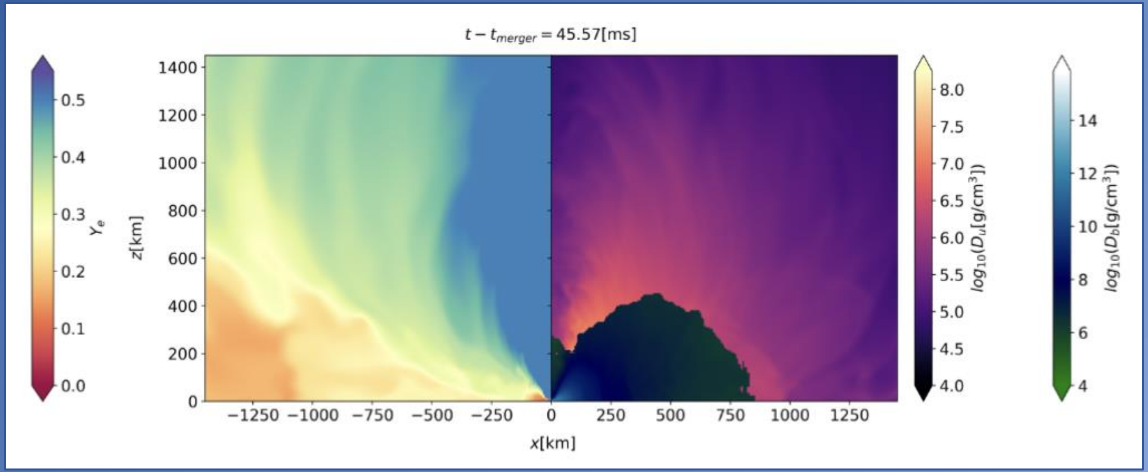
- Magnetic fields
- Turbulences
- Parameter space



neutrino radiation



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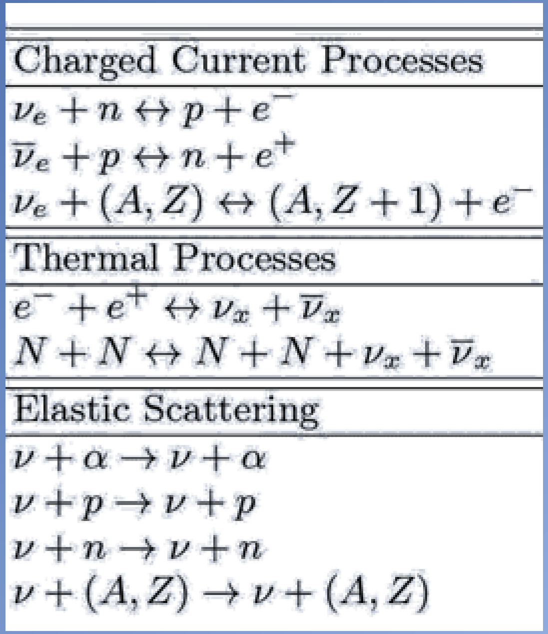
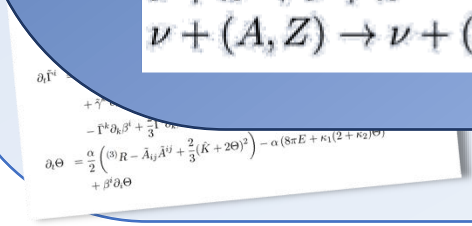
Gieg et al., Universe 8 (2022) 7, 370



Charged Current Processes
$\nu_e + n \leftrightarrow p + e^-$
$\bar{\nu}_e + p \leftrightarrow n + e^+$
$\nu_e + (A,Z) \leftrightarrow (A,Z+1) + e^-$
Thermal Processes
$e^- + e^+ \leftrightarrow \nu_x + \bar{\nu}_x$
$N + N \leftrightarrow N + N + \nu_x + \bar{\nu}_x$
Elastic Scattering
$\nu + \alpha \rightarrow \nu + \alpha$
$\nu + p \rightarrow \nu + p$
$\nu + n \rightarrow \nu + n$
$\nu + (A,Z) \rightarrow \nu + (A,Z)$

- **Inclusion of neutrinos changes matter outflow and remnant's lifetime**
- **Amount of produced elements and their abundance depend on merger properties and neutrino scheme**



Input Physics:

- Microphysics (EOS, Neutrinos)
- Magnetic fields
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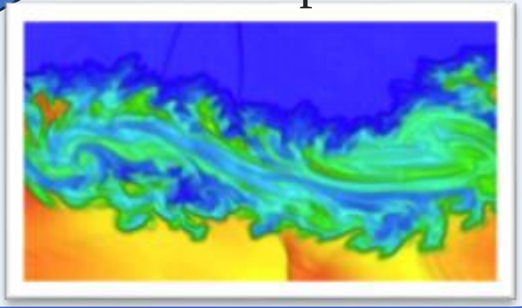
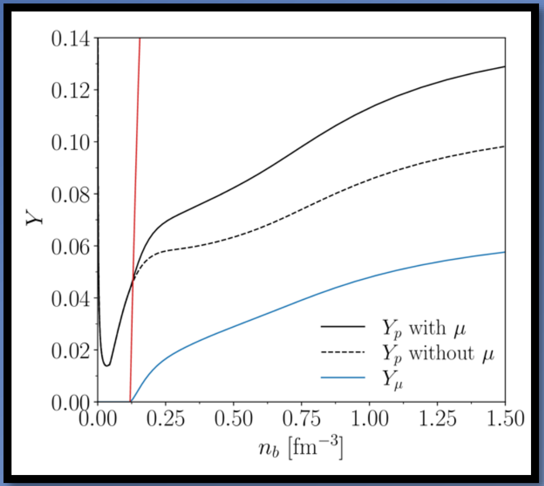
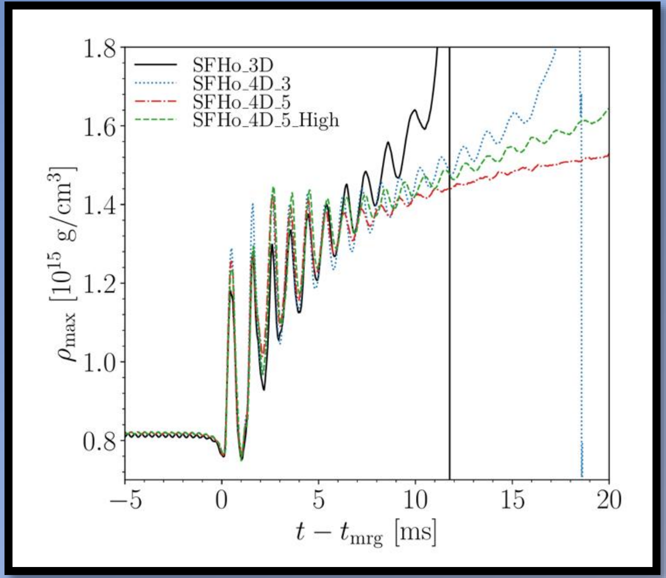
- Parameter space



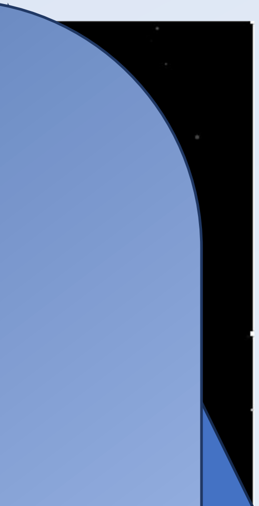
Inclusion of muonic neutrinos – Gieg et al., 2024, arXiv: 2409.04420

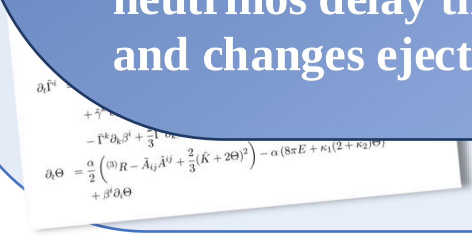
Charged-Current Processes
$\nu_\mu + n \leftrightarrow p + \mu^-$
$\bar{\nu}_\mu + p \leftrightarrow n + \mu^+$
Pair Processes
$e^- + e^+ \rightarrow \nu + \bar{\nu}$
$\gamma \rightarrow \nu + \bar{\nu}$
Elastic Scattering
$\nu + p \rightarrow \nu + p$
$\nu + n \rightarrow \nu + n$
$\nu + A \rightarrow \nu + A$





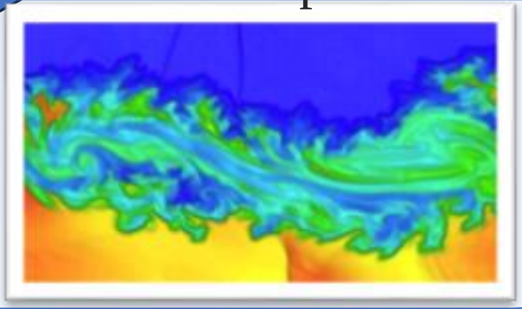
The inclusion of muonic neutrinos delay the collapse and changes ejecta properties

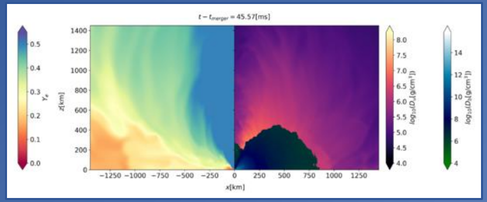


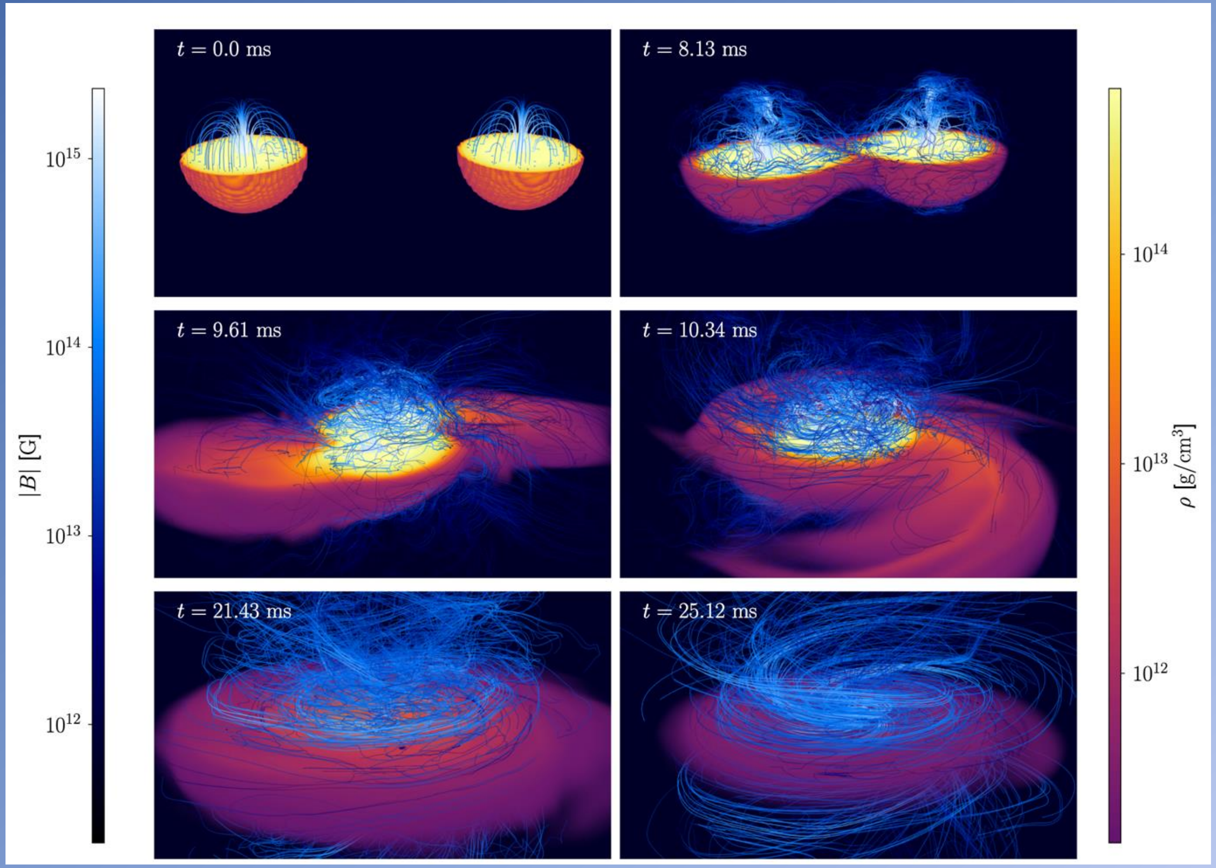


Input Physics:

- Microphyics (EOS, Neutrinos)
- Magnetic fields
- Turbulences
- Parameter space





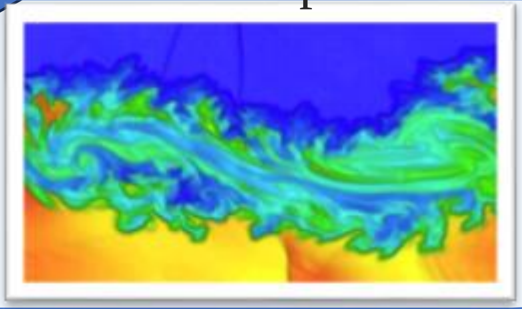


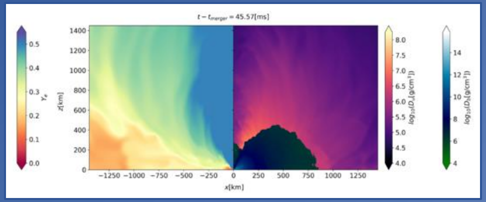
magnetic fields and turbulences

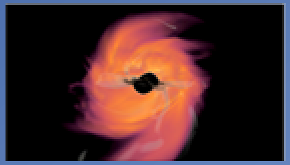
Neuweiler et al., PRD 110 (2024) 8, 084046

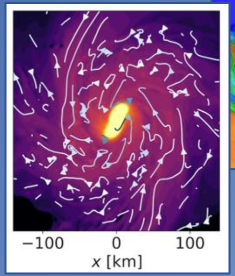
Input Physics:

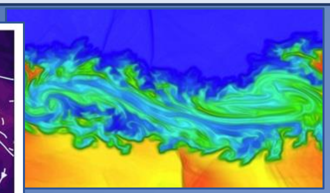
- Microphyics (EOS, Neutrinos)
- Magnetic fields
- Turbulences
- Parameter space



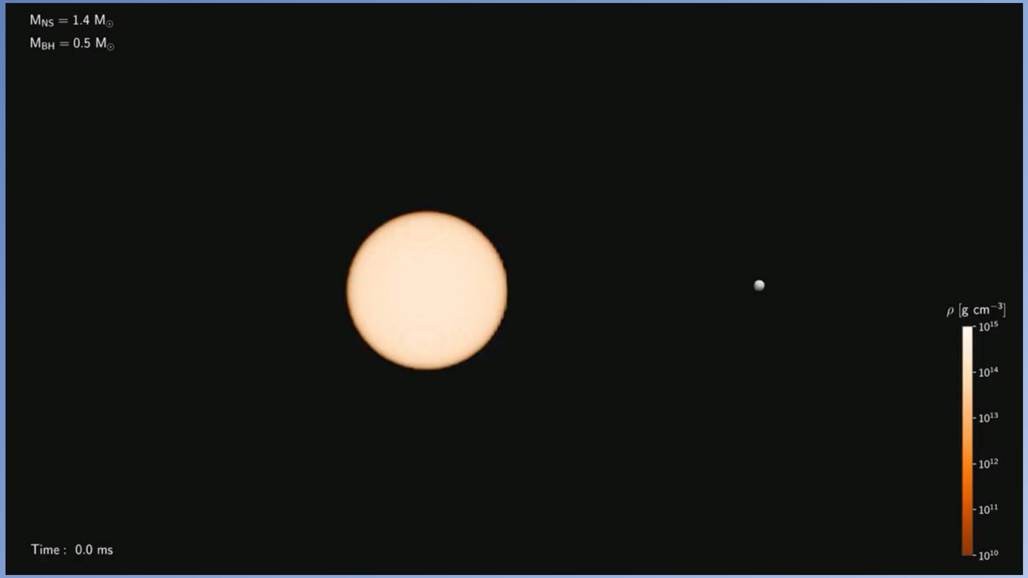




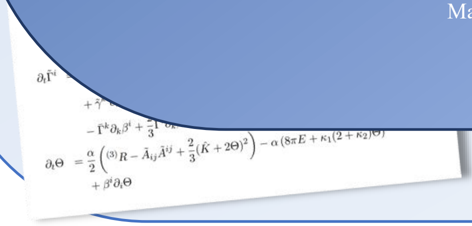




parameter space coverage



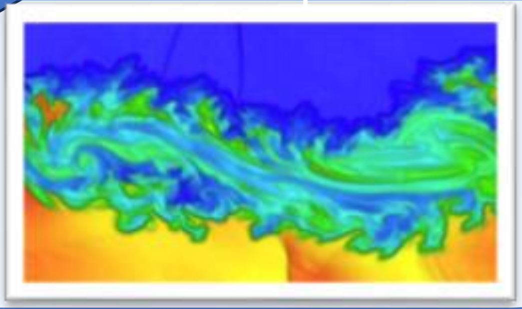
Markin et al., PRD 108 (2023) 2, 023016

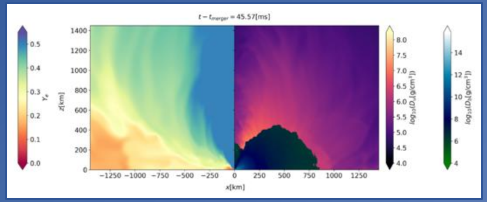


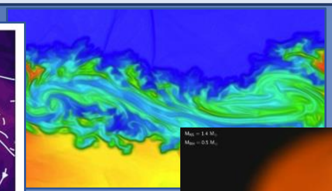
- First simulation of a subsolar mass BH – neutron star merger
- large amount of ejecta
- existing waveform models perform badly when describing such systems

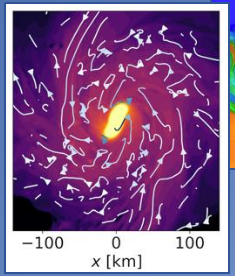
Input Physics:

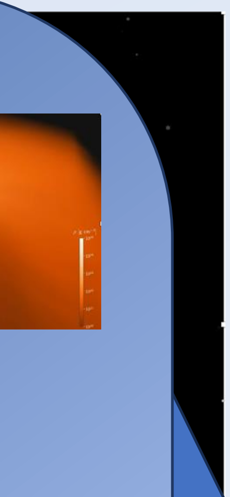
- Microphyics (EOS, Neutrinos)
- Magnetic fields
- Turbulences
- Parameter space

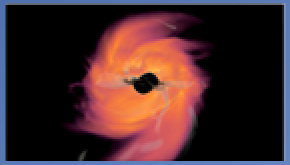




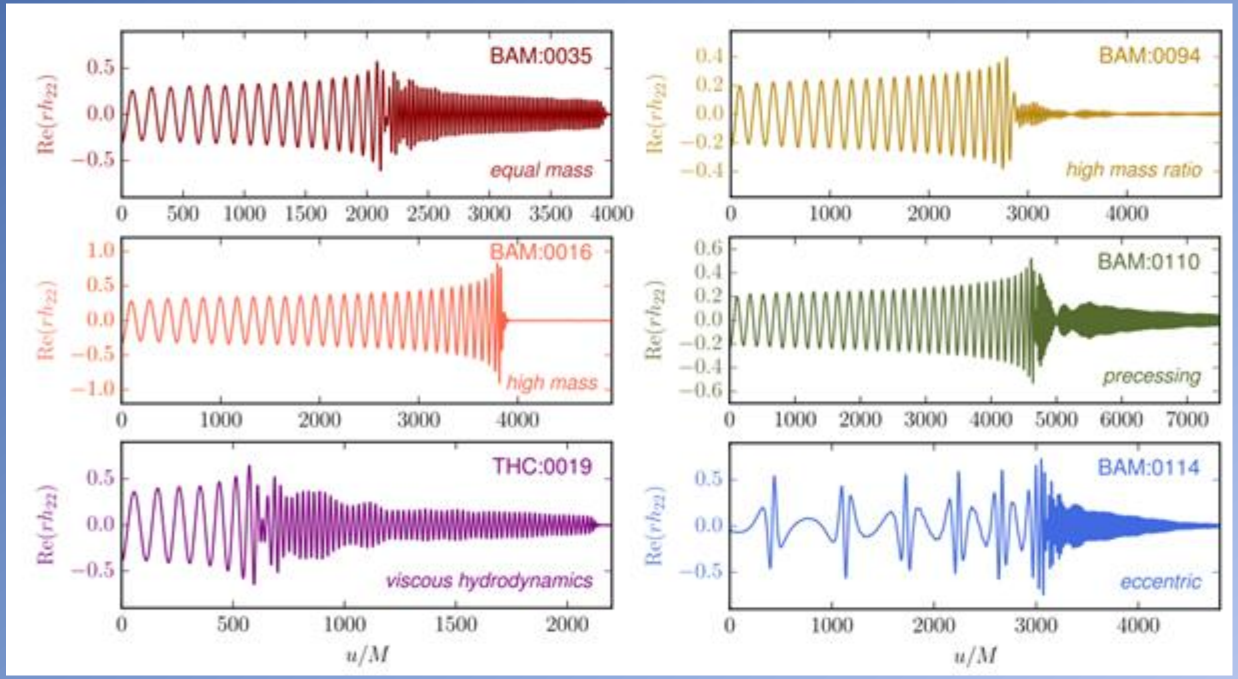






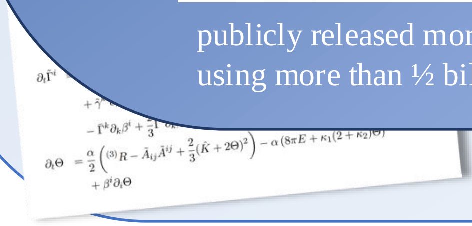


parameter space coverage



publicly released more than 590 individual simulations using more than ½ billion CPUhs

Dietrich et al., CCG 35 (2018) 24, 24LT01
Gonzales et al., QCG 40 2023) 8, 085011



Input Physics:

- Microphyics (EOS, Neutrinos)
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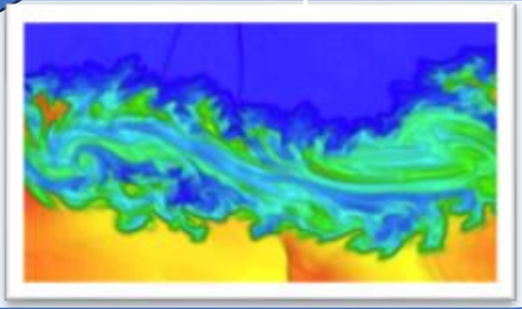
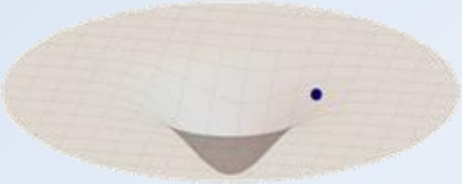


Inspiral waveforms

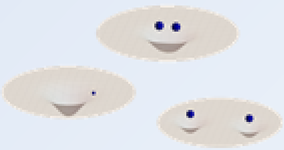
Various models

Numerical Relativity Simulations

Post-Newtonian Theory

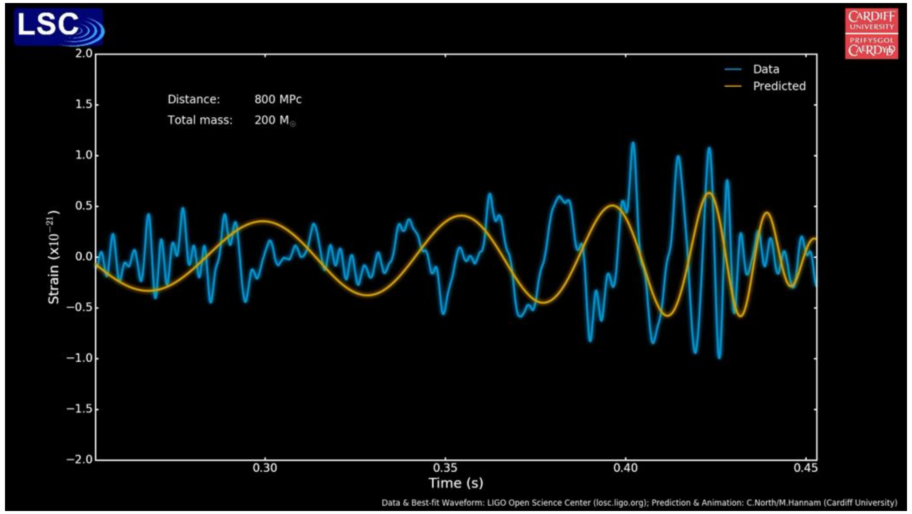


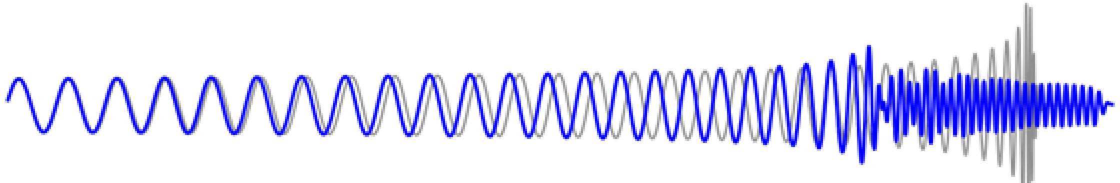
Effective-one-body Formalism



Phenomenological Models

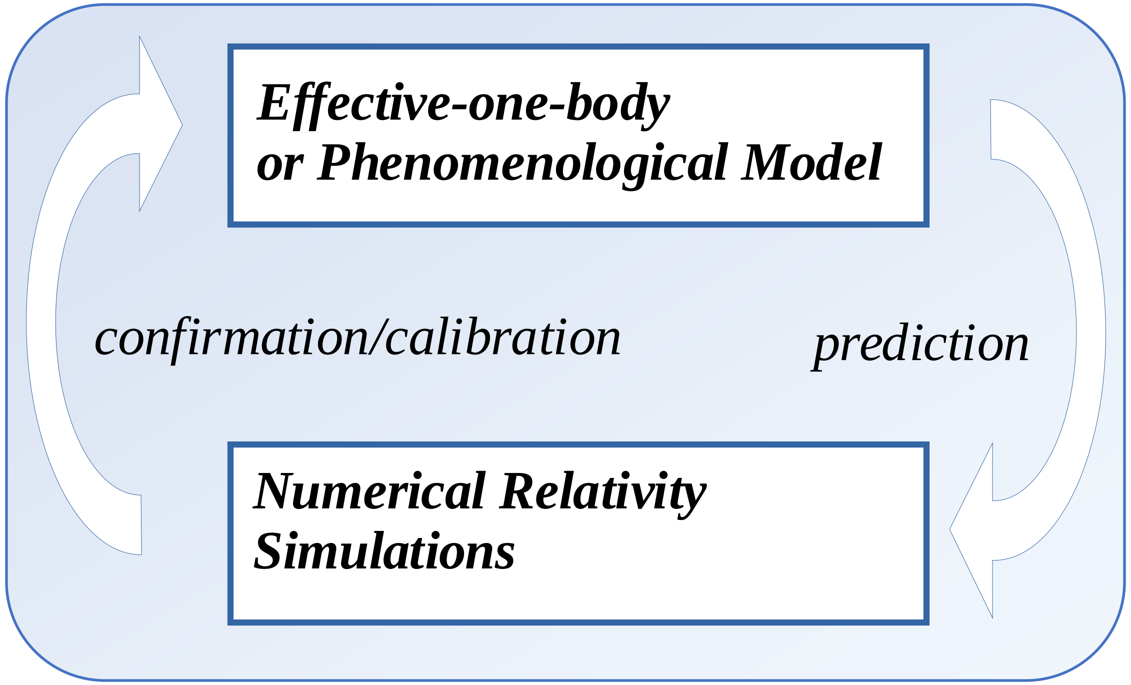
hundreds of millions of templates need to interpret the data

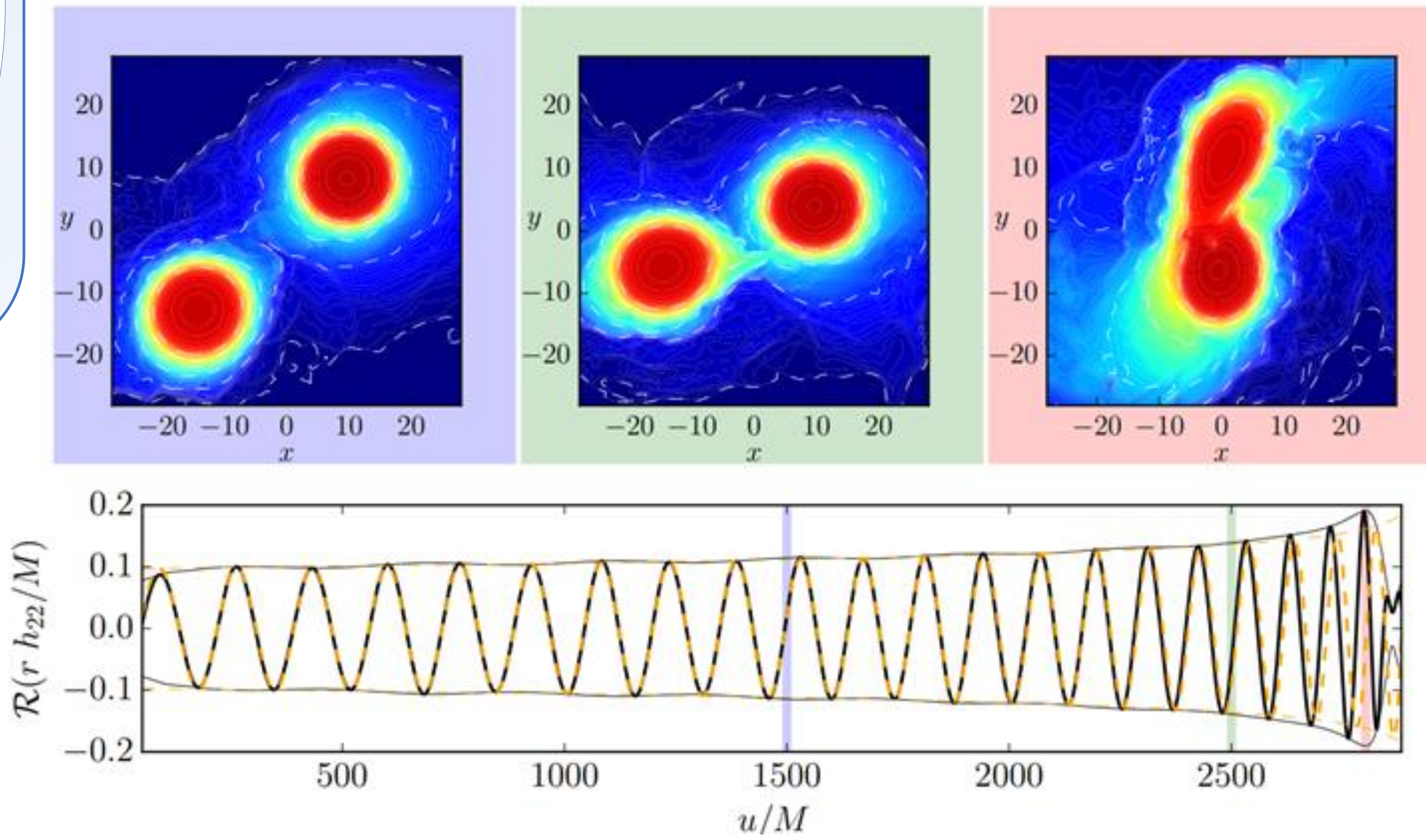




tidal effects lead to an accelerated inspiral

Waveform Model Development through NR simulations

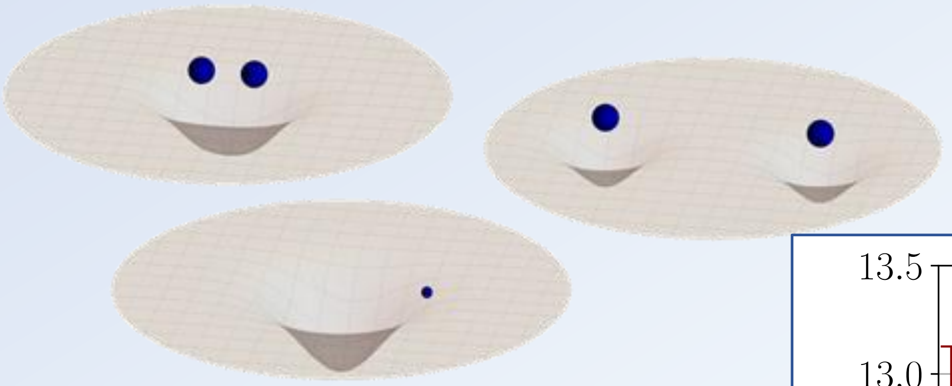


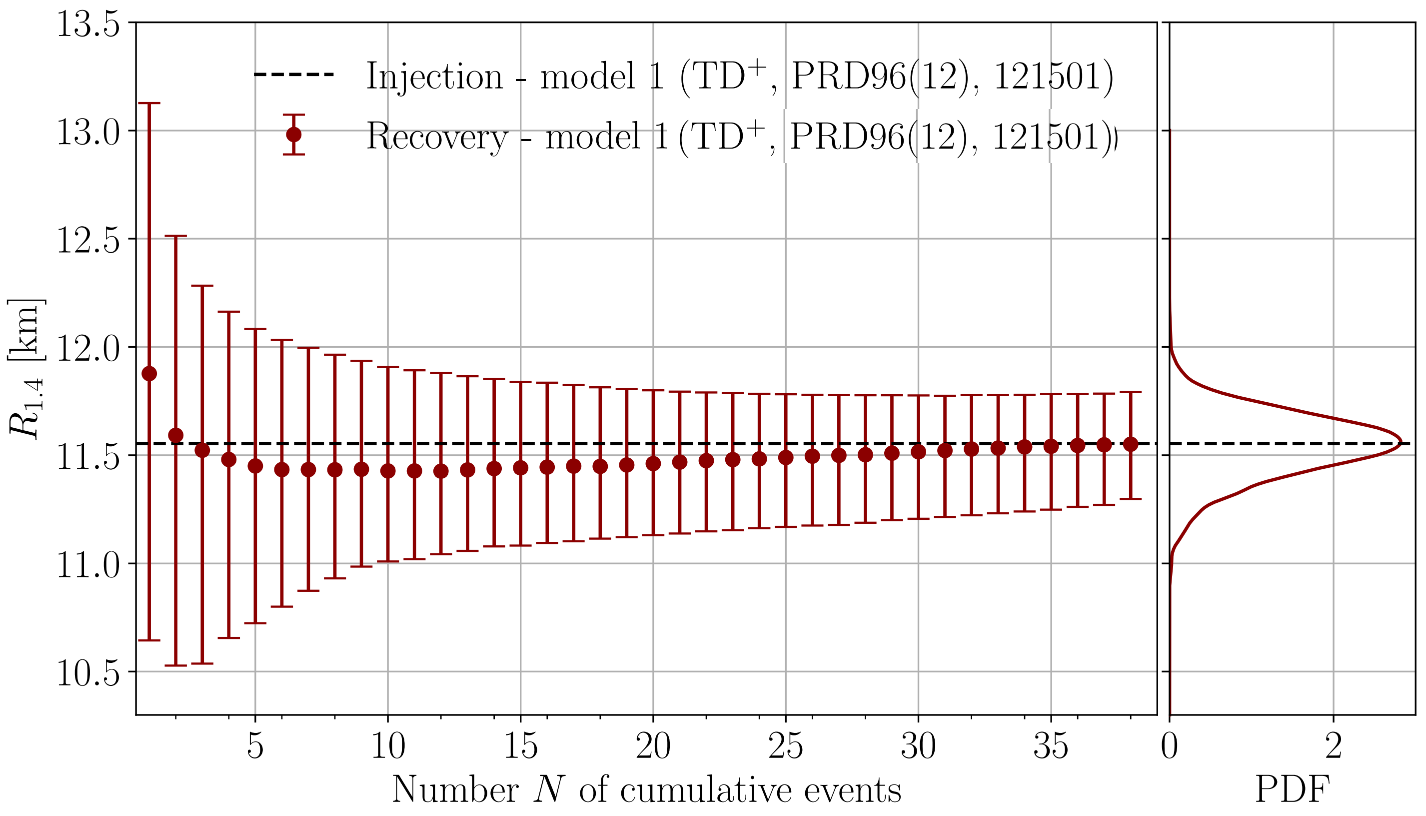


TD & Hinderer, Phys.Rev.D 95 12, 124006

Inspiral waveforms

Various models

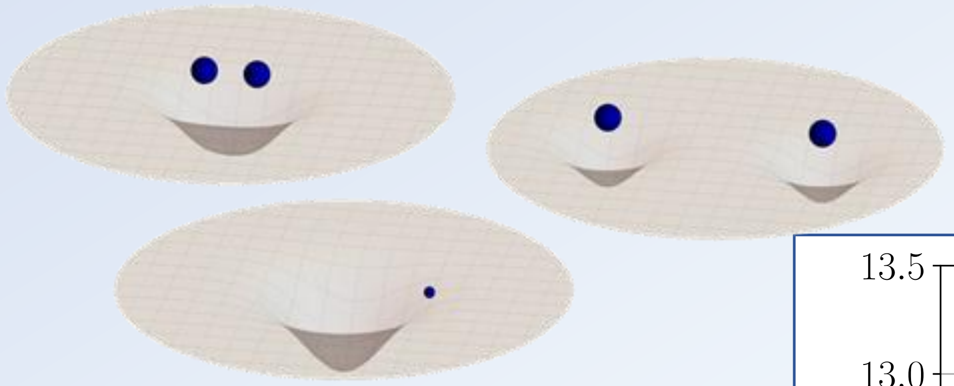


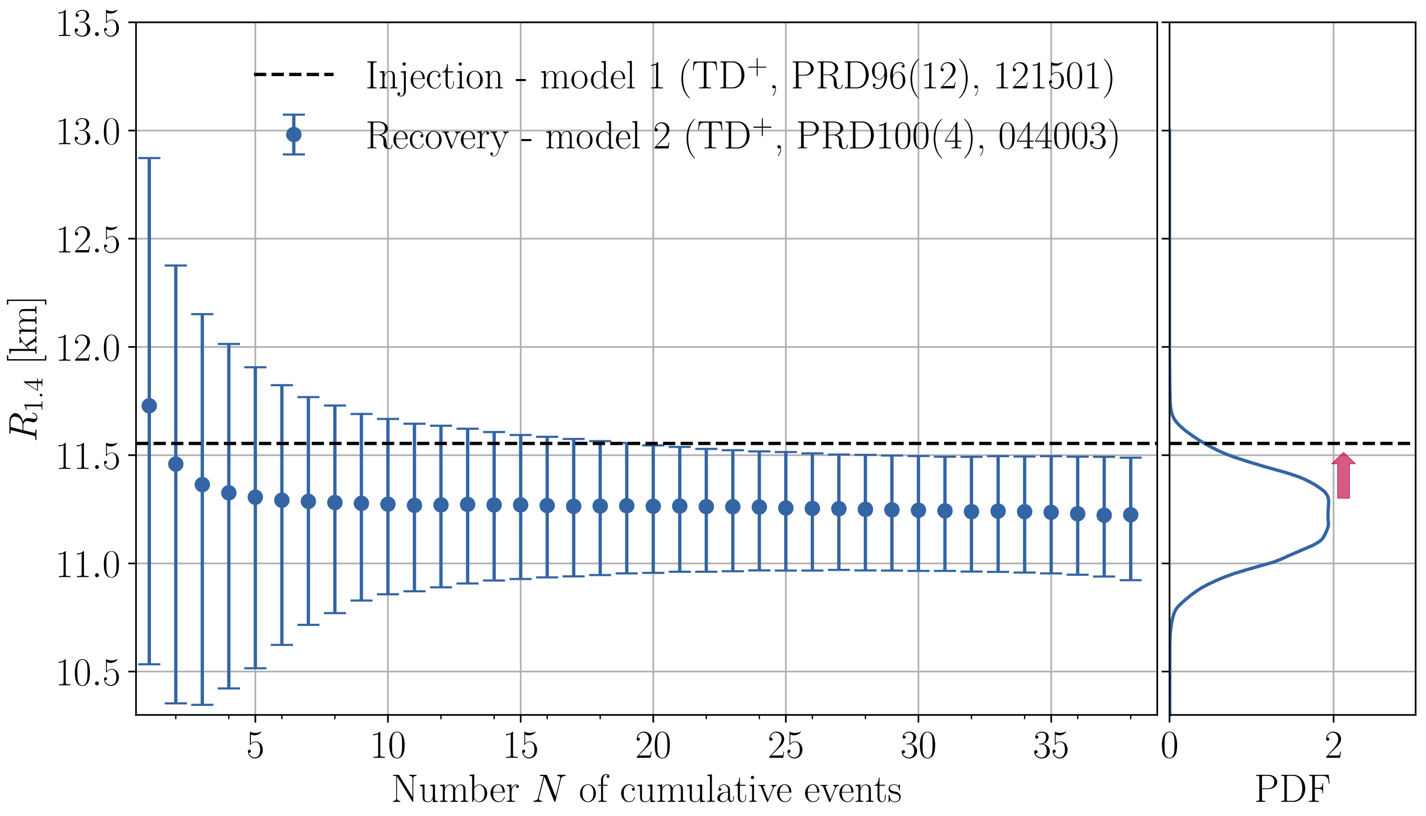


N.Kunert et al., PRD105 (2022) 6, L061301

Inspiral waveforms

Various models

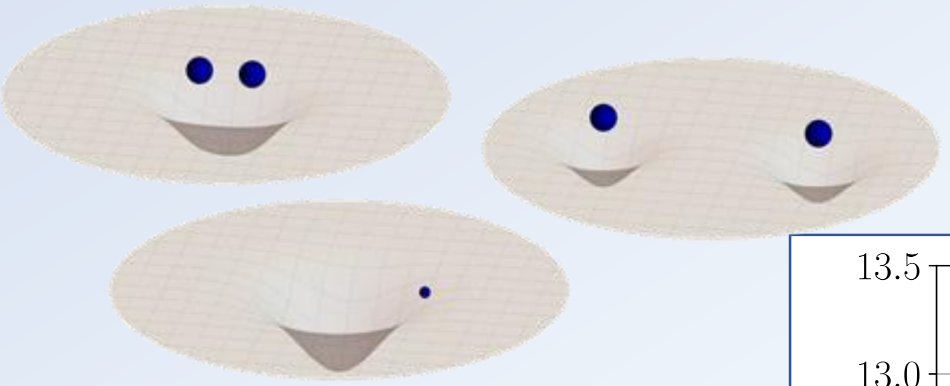




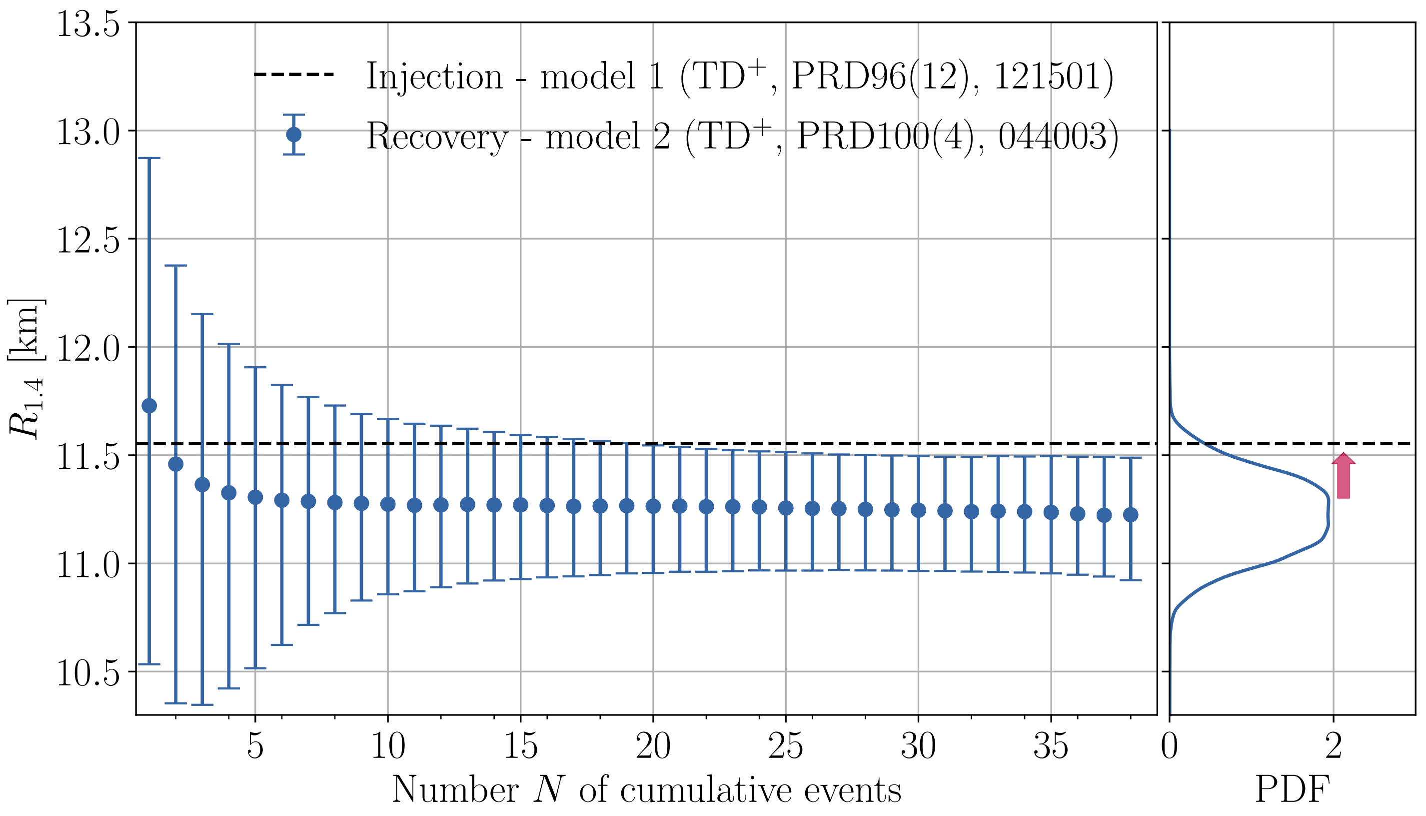
N.Kunert et al., PRD105 (2022) 6, L061301

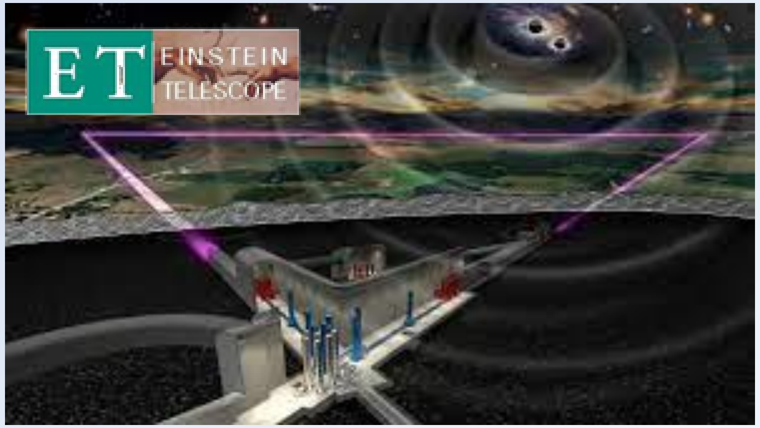
Inspiral waveforms

Various models



Note: Kunert et al., PRD 110 (2024) 4, 4 shows that Hubble constant measurements show less waveform modelling bias.





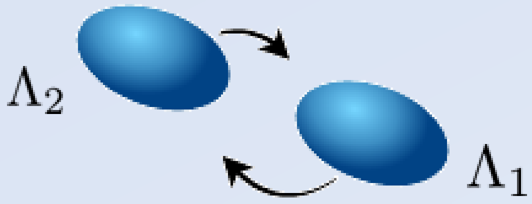
Einstein Telescope

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

Gravitational Wave Analysis

GW170817

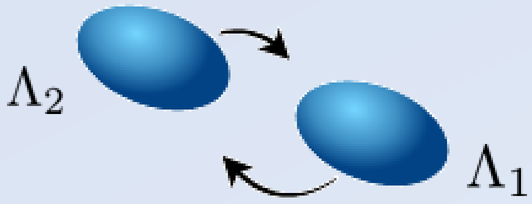
Λ determines tidal deformability

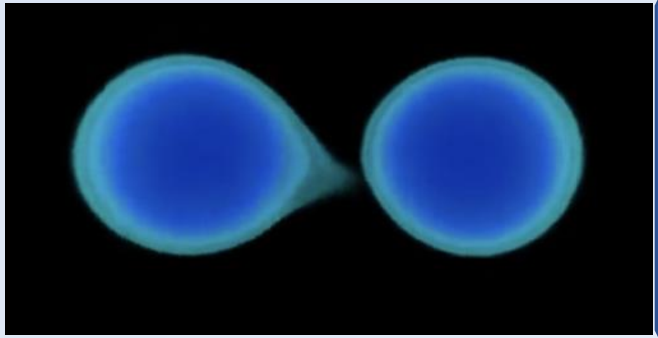


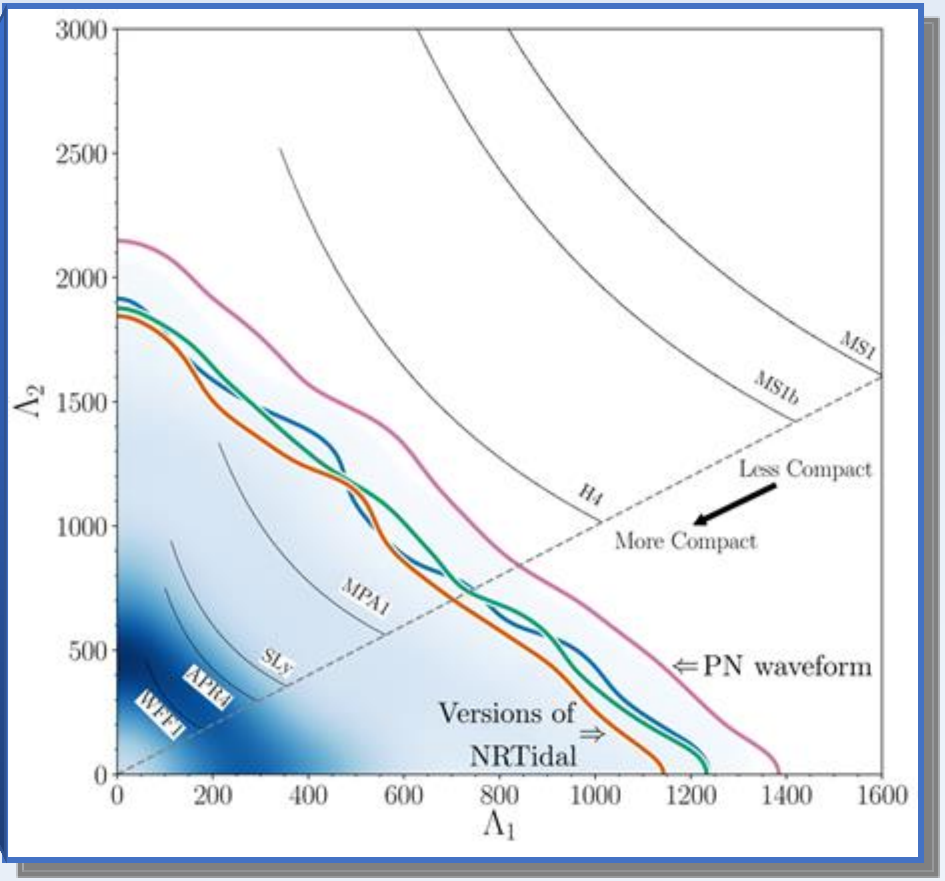
Gravitational Wave Analysis

GW170817

Λ determines tidal deformability







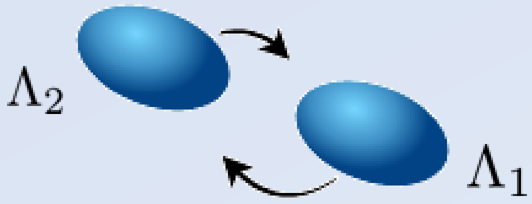
Phys.Rev. X9 (2019) 011001

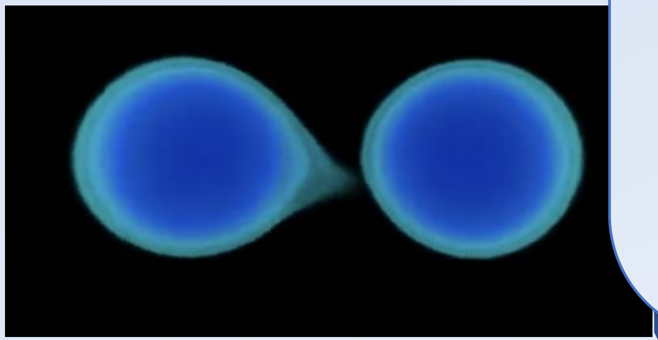
→ no assumption about the type of the compact object

Gravitational Wave Analysis

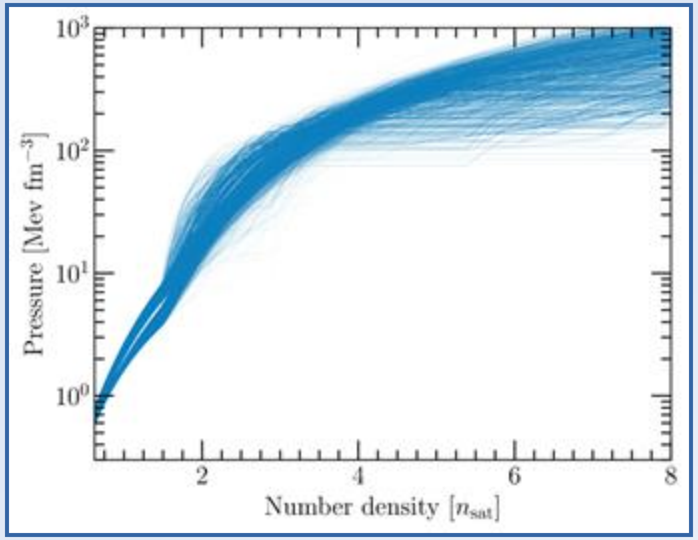
GW170817

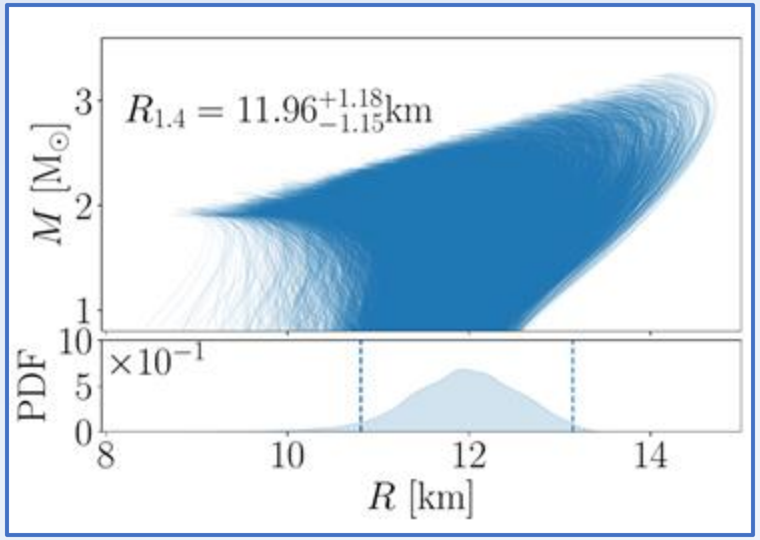
Λ determines tidal deformability



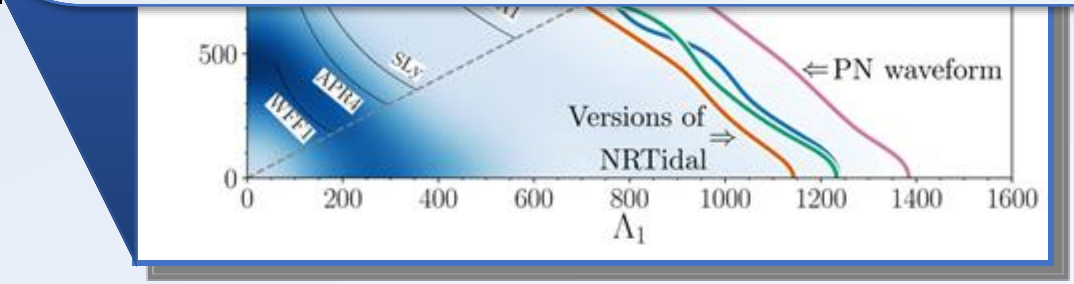


Assumption: The merging objects were neutron stars





nuclear-physics computations



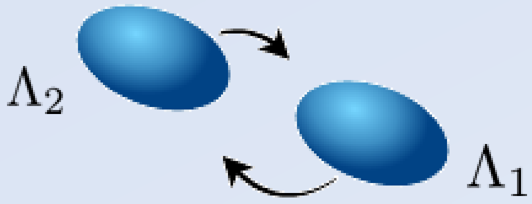
→ no assumption about the type of the compact object

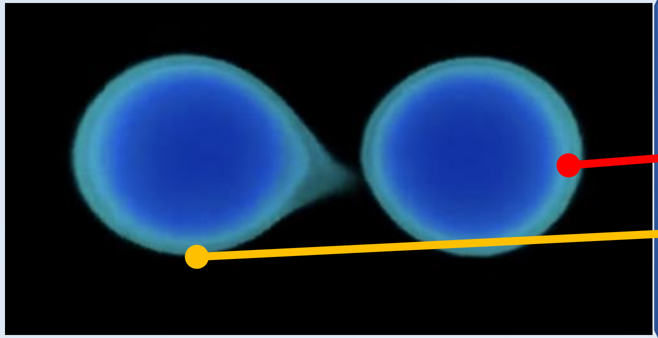
Phys.Rev. X9 (2019) 011001

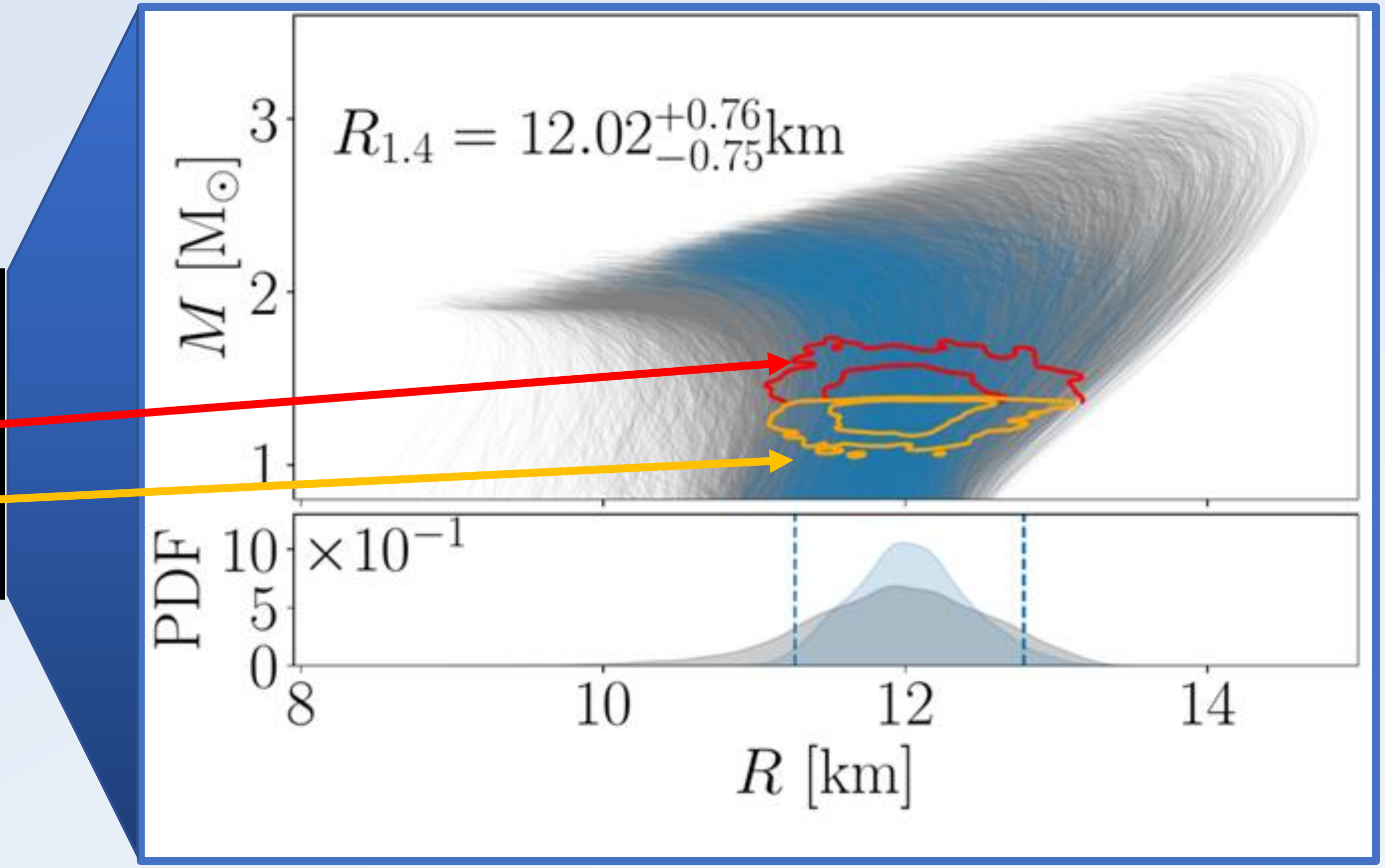
Gravitational Wave Analysis

GW170817

Λ determines tidal deformability







Assumption: The merging objects were neutron stars

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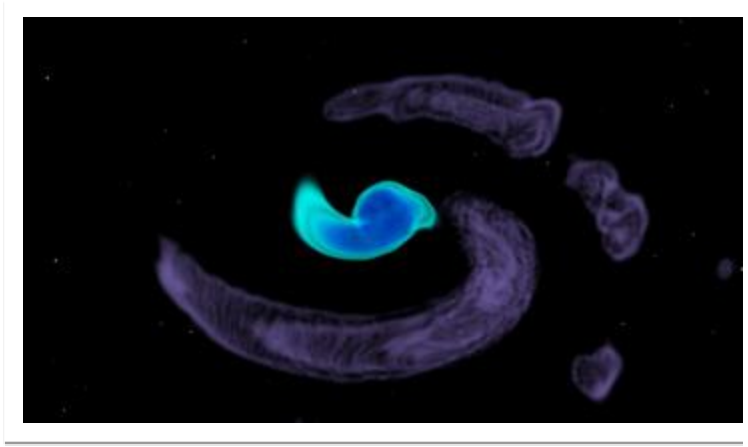
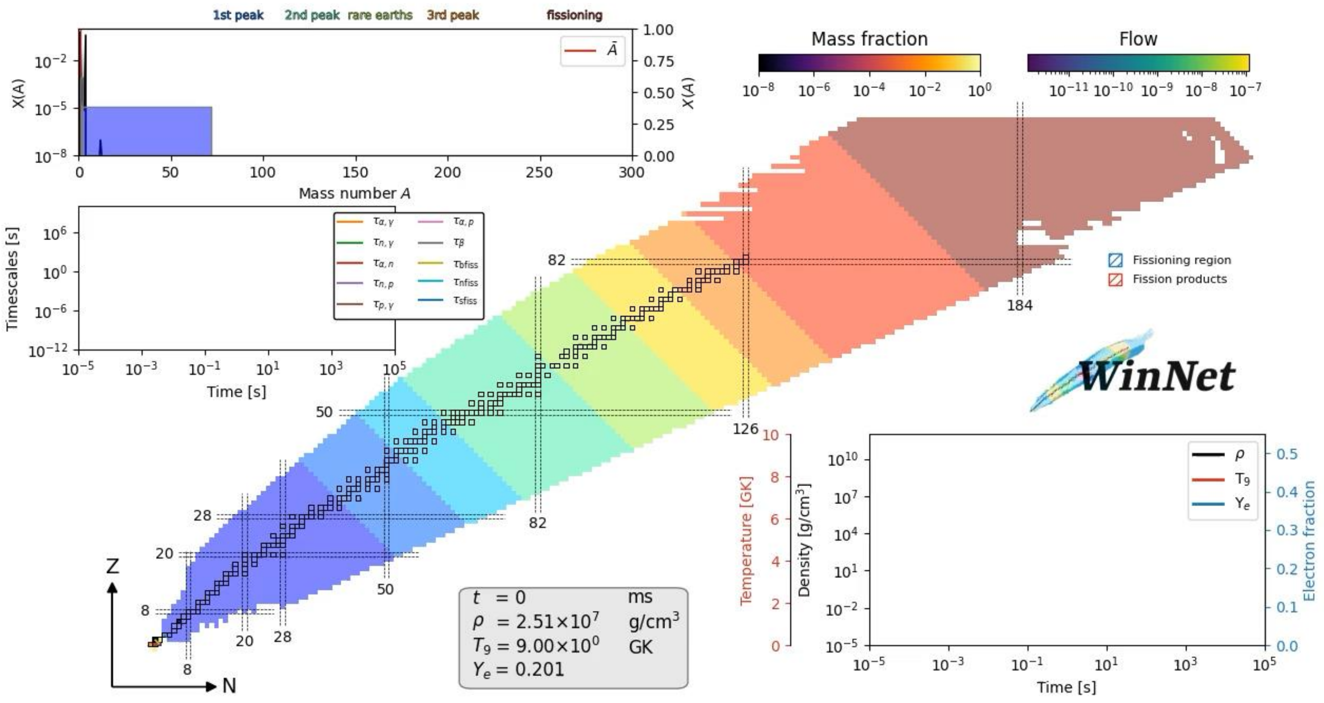
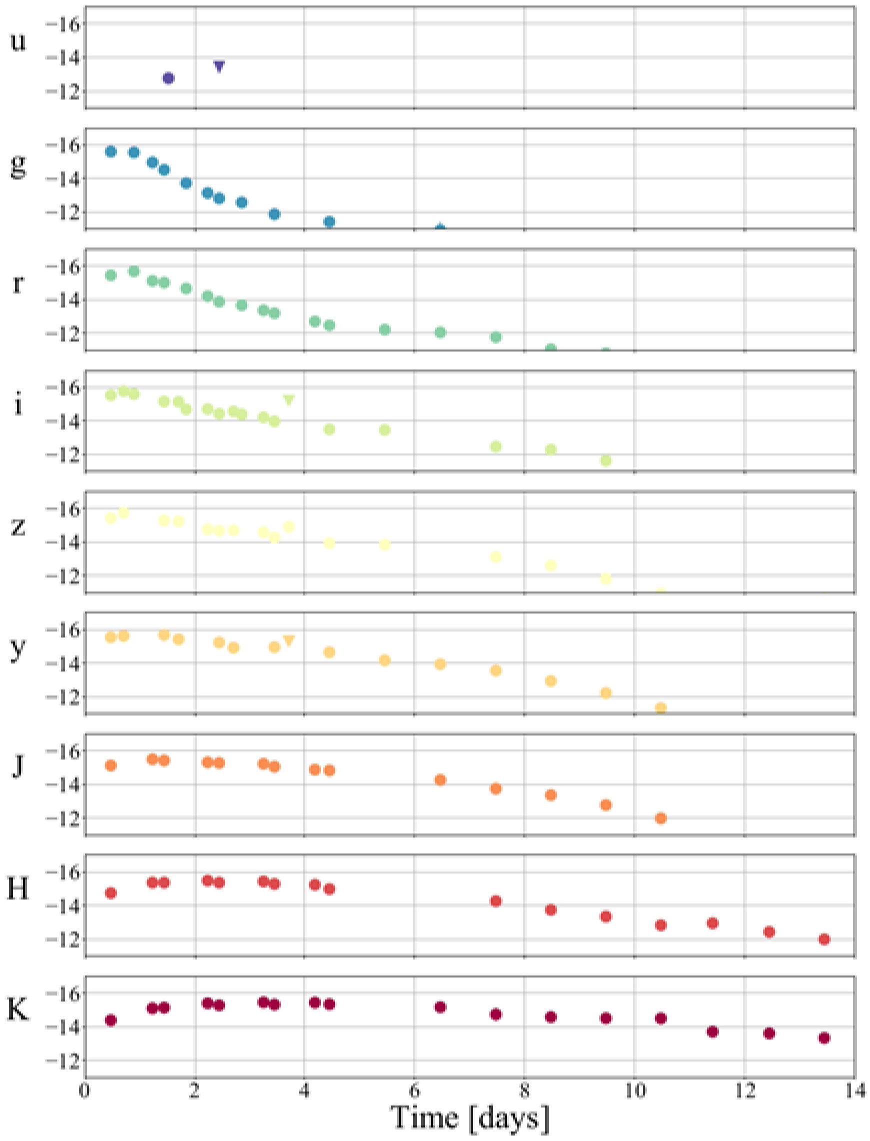
EM Signals – Kilonova

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

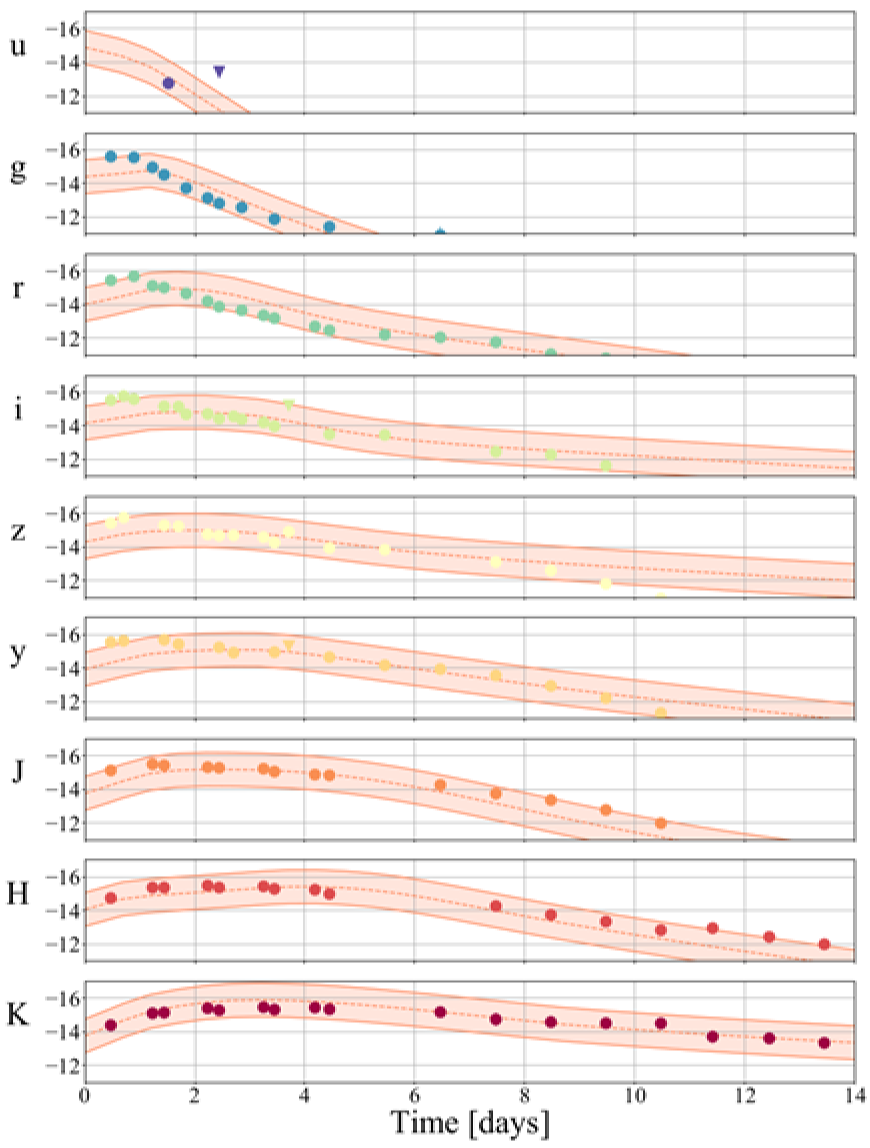




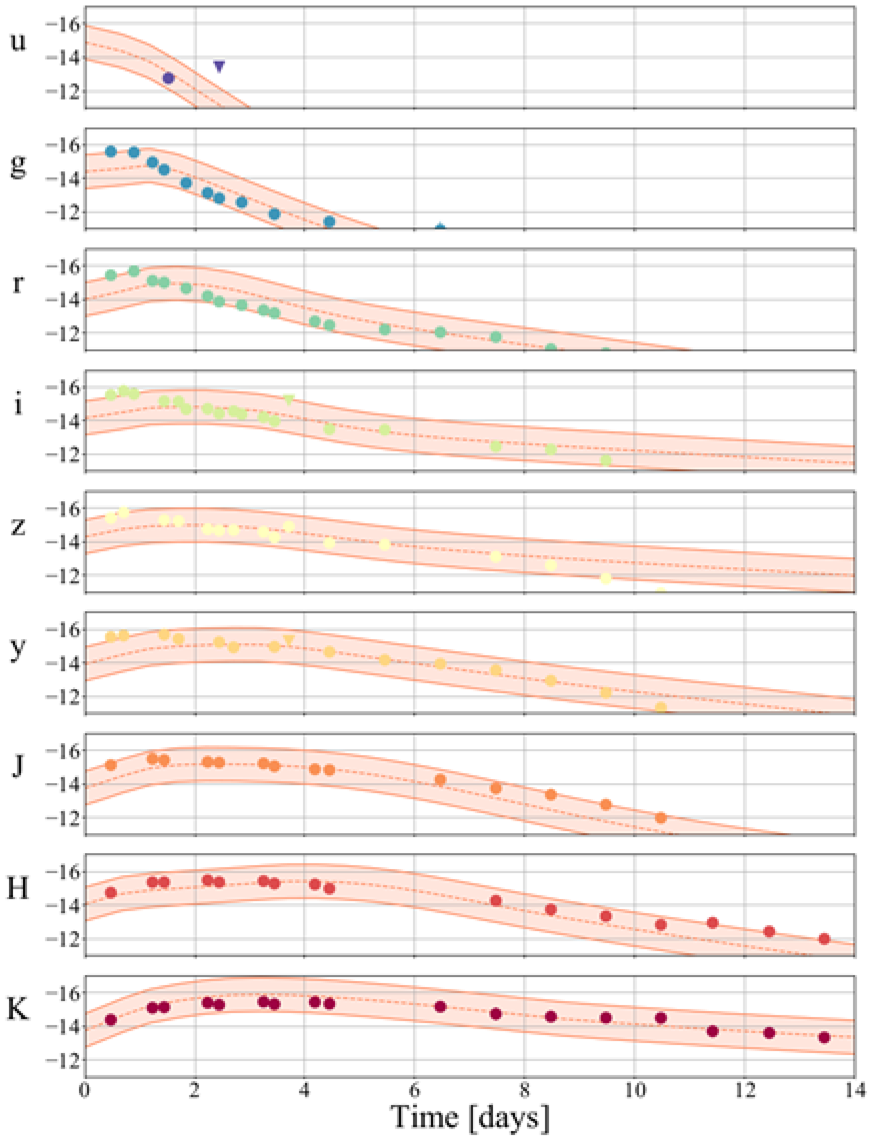
Photometric lightcurves



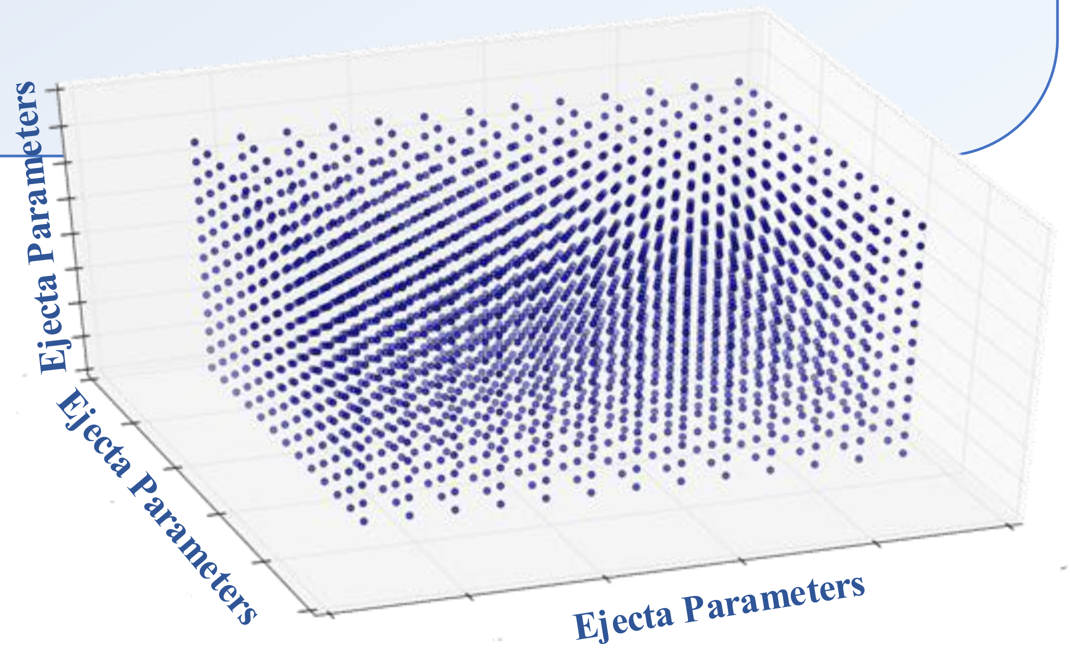
Photometric lightcurves



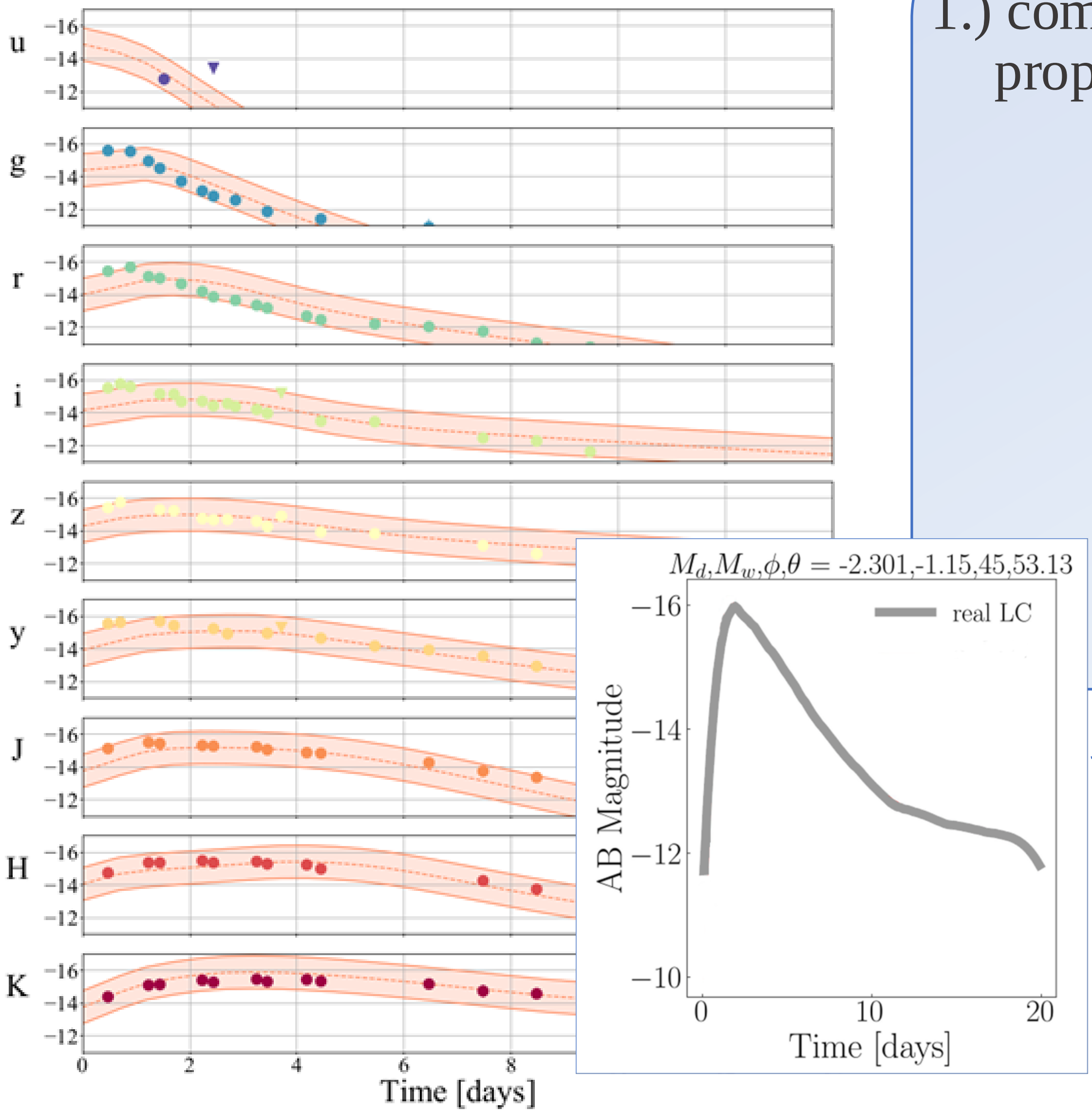
Photometric lightcurves



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



Photometric lightcurves



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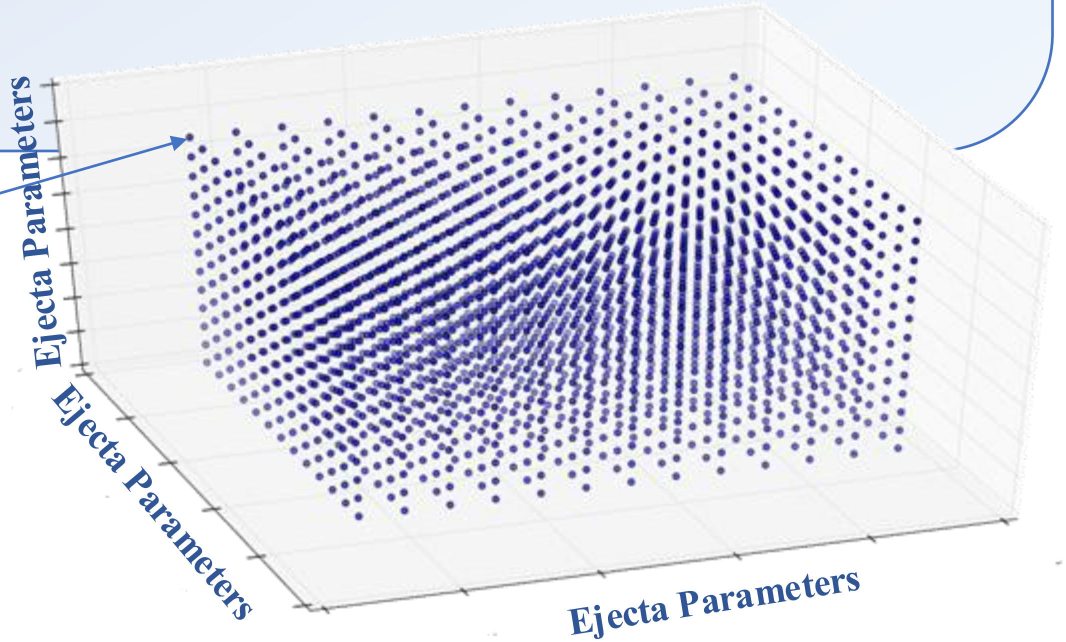
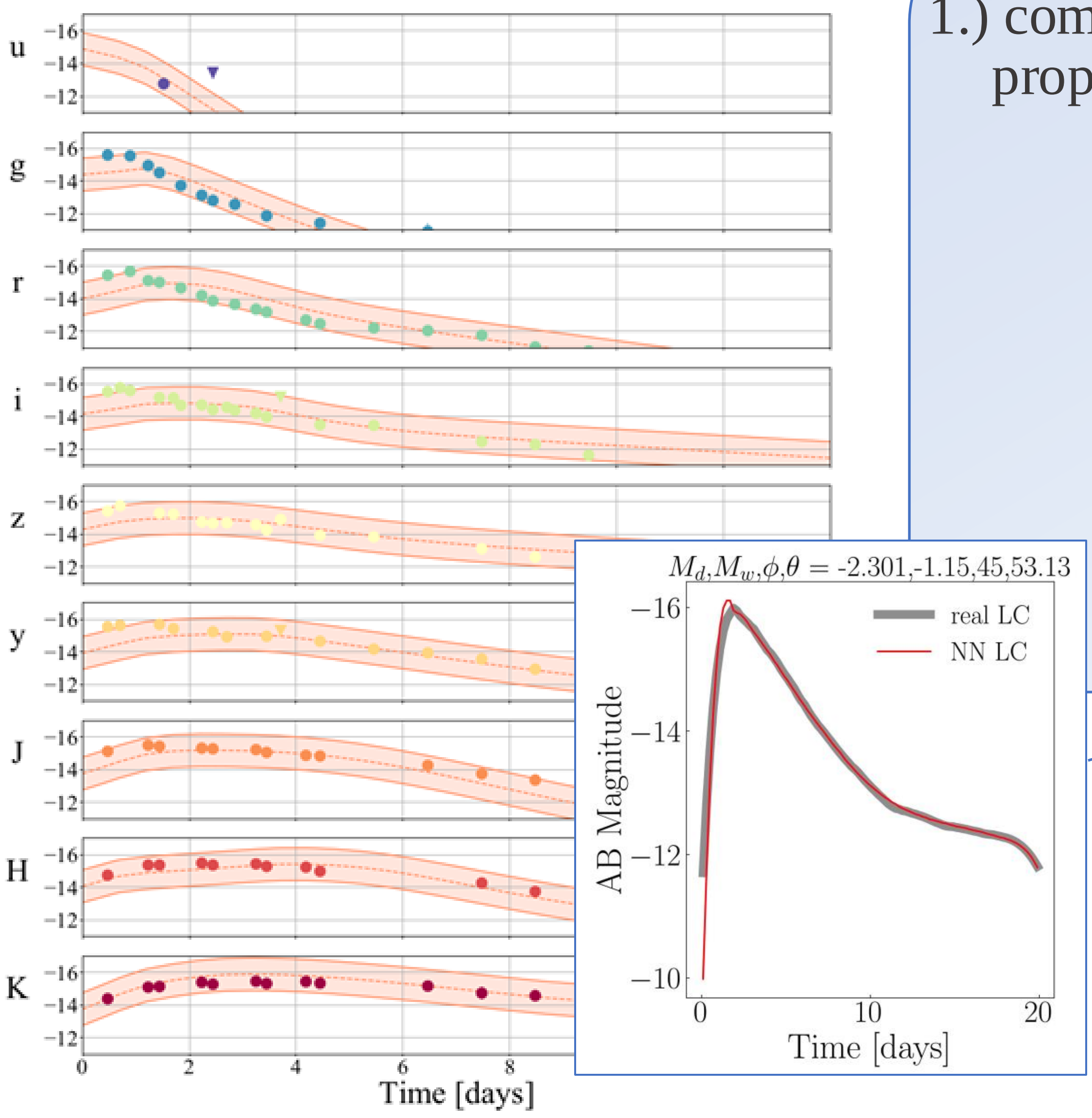


Photometric lightcurves



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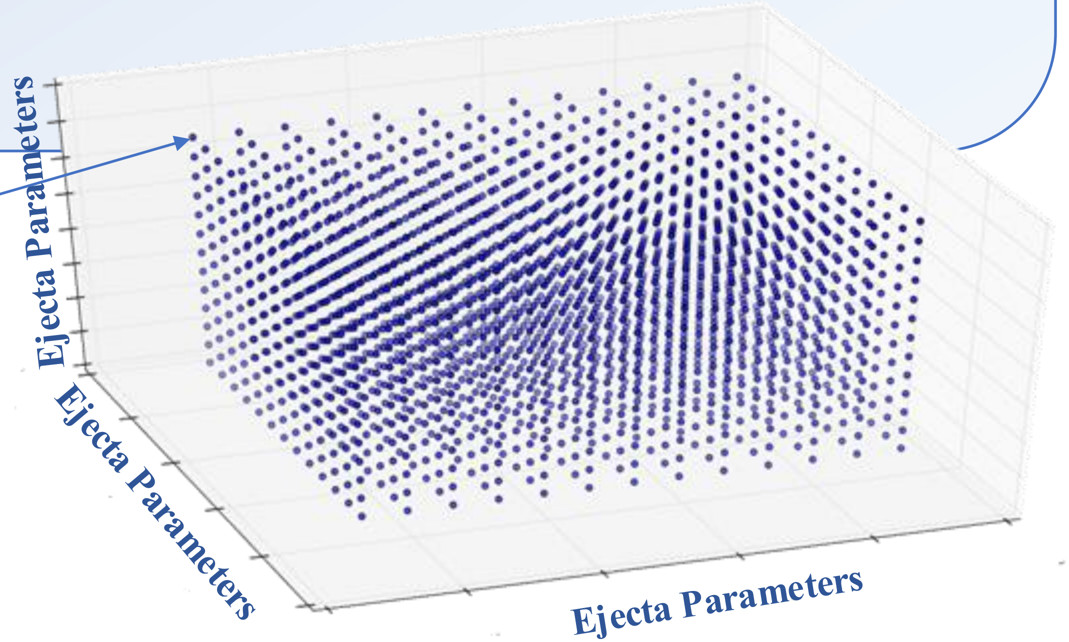
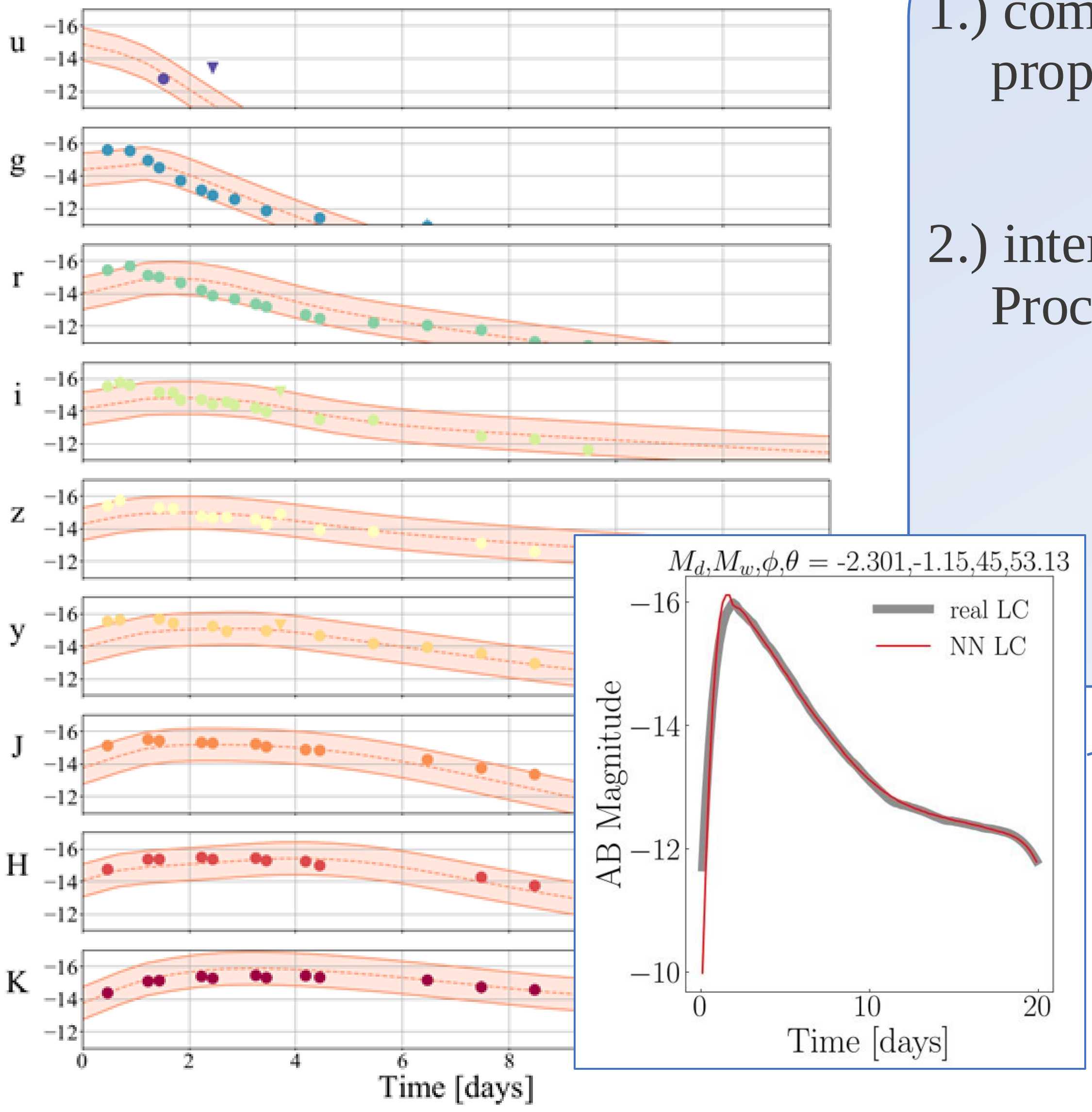
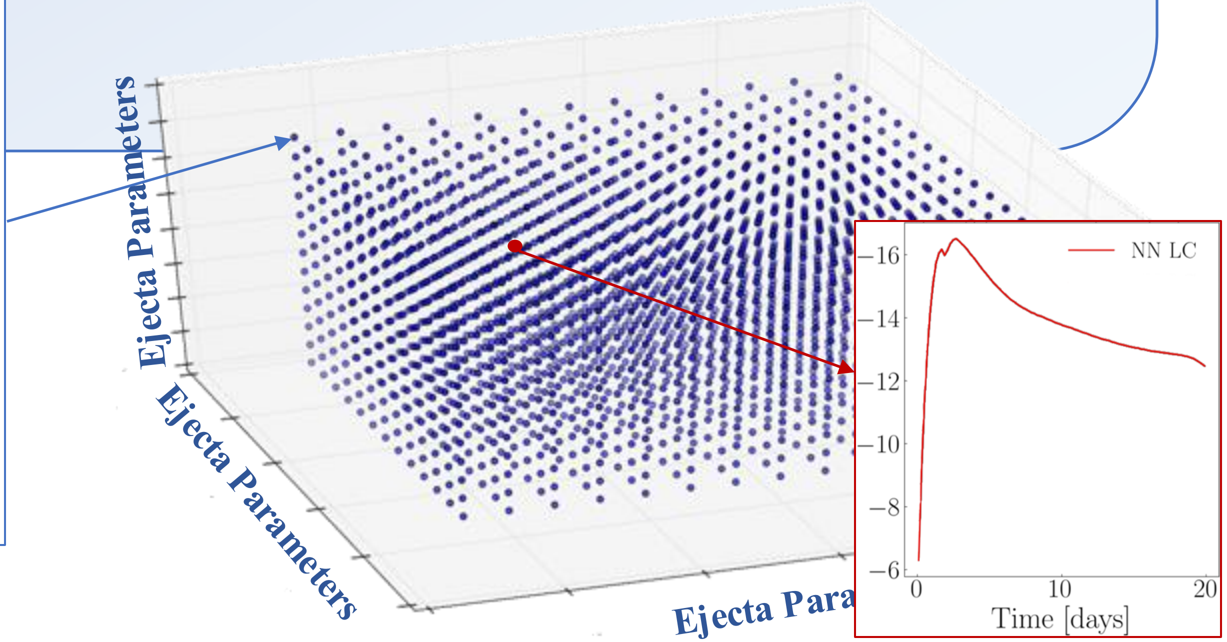


Photometric lightcurves



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

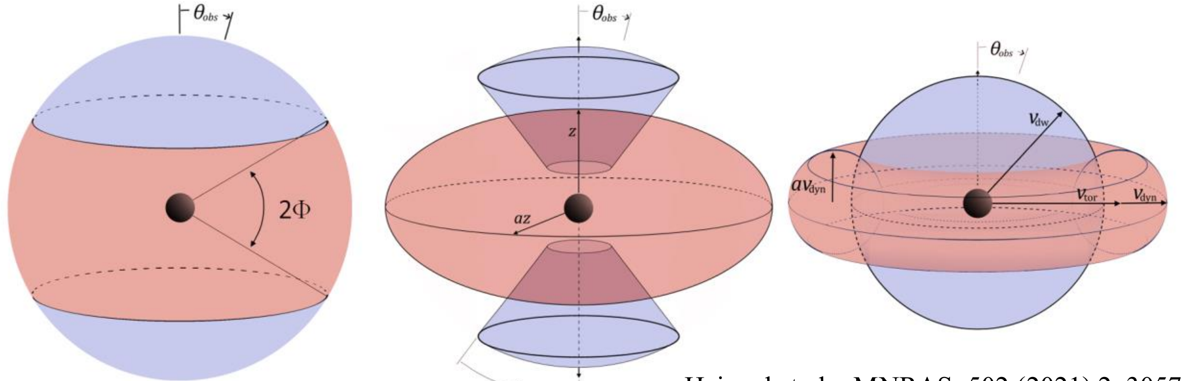


Uncertainties

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

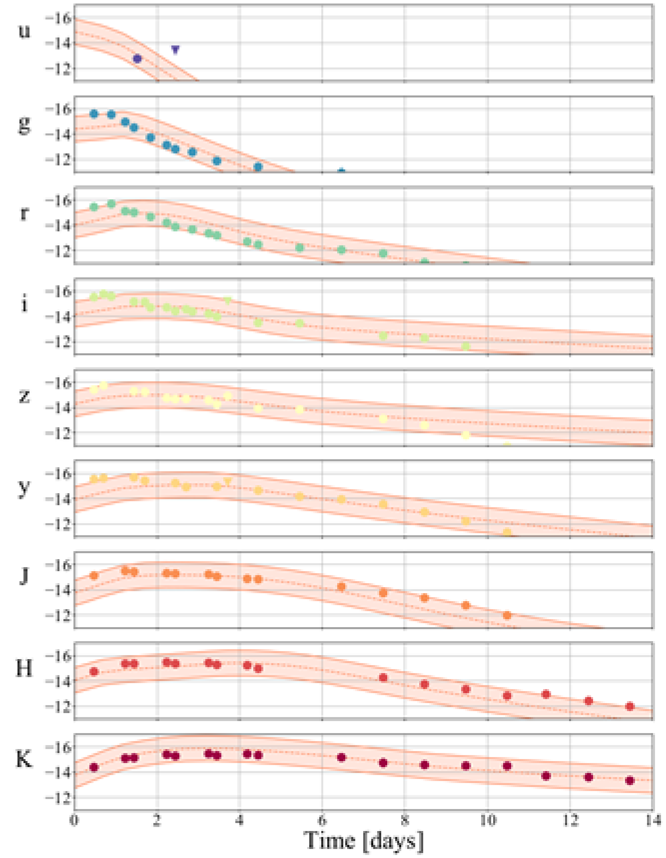
2.) Heating rates depend on the formed elements and ejecta properties

3.) Incomplete knowledge about opacities for complicated elements

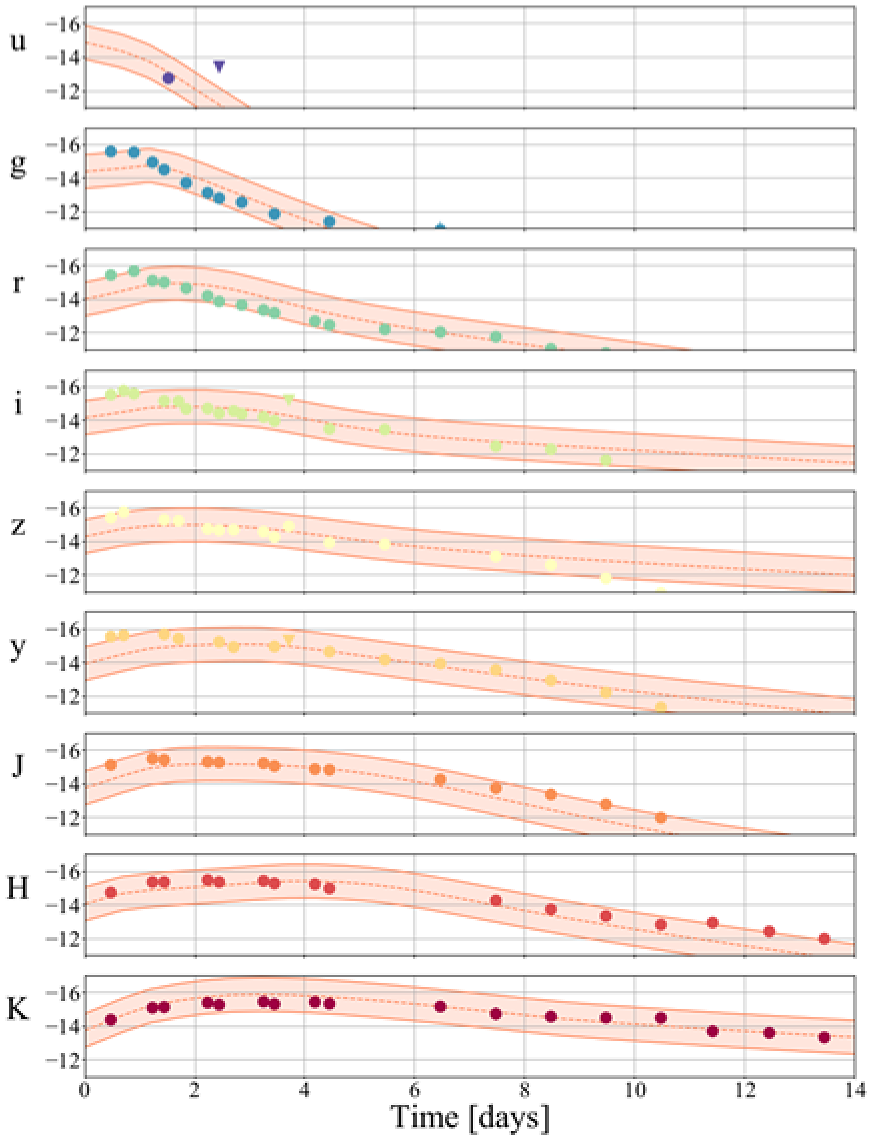


e.g., Heinzel et al., MNRAS. 502 (2021) 2, 3057-3065

Cross-code comparisons for numerous geometries and assumptions → estimate on the modelling uncertainty



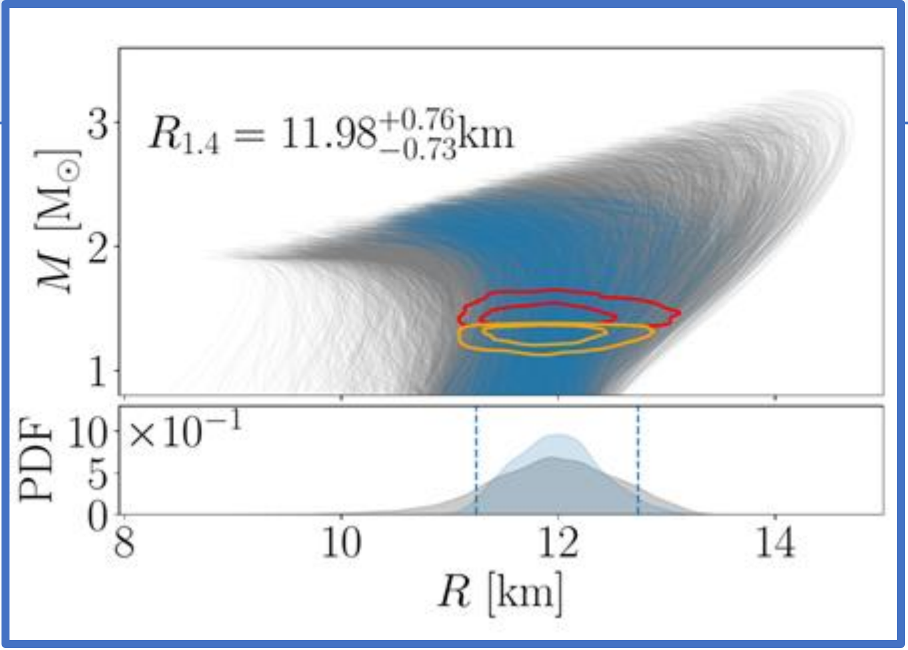
Photometric lightcurves

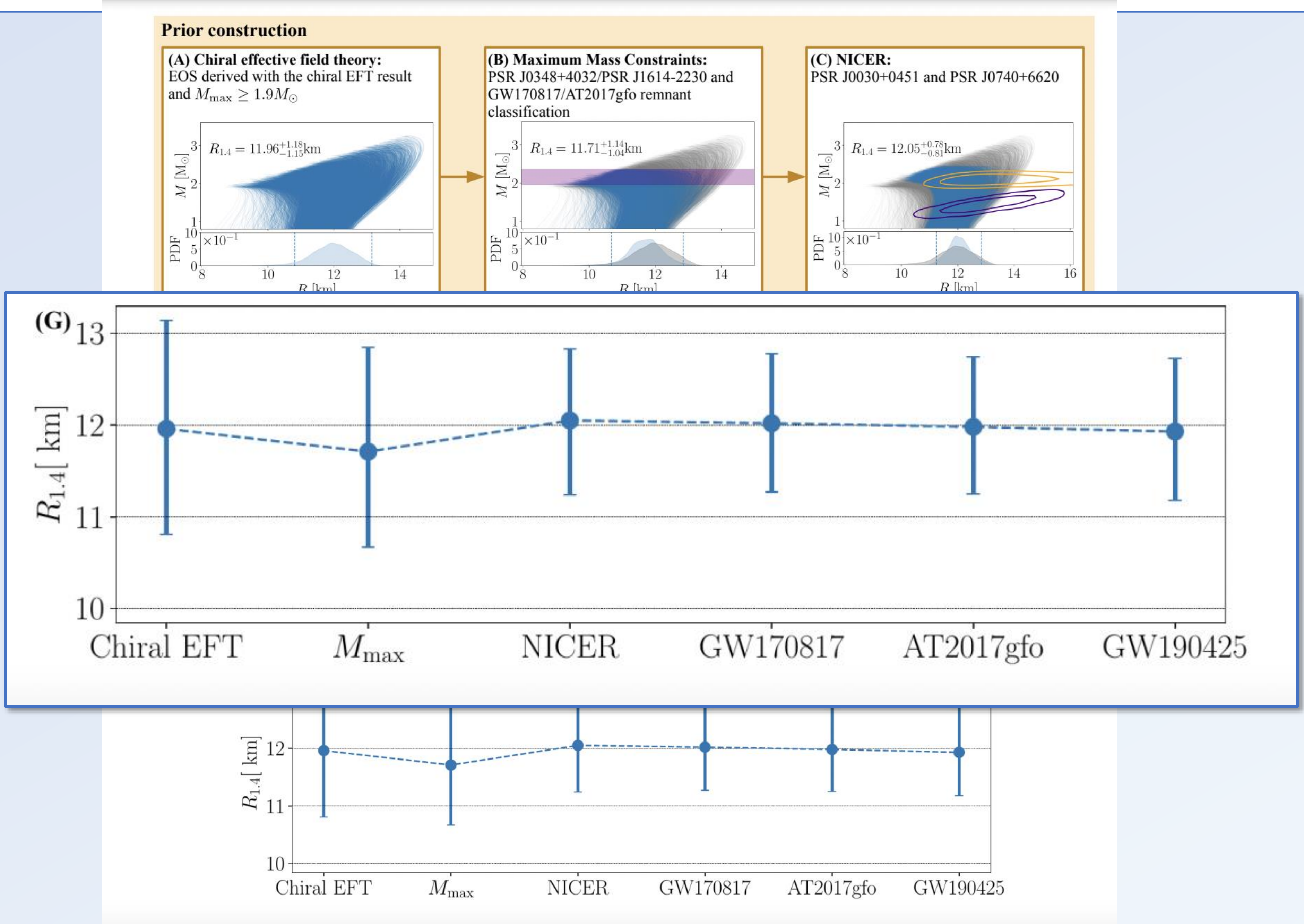


1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code

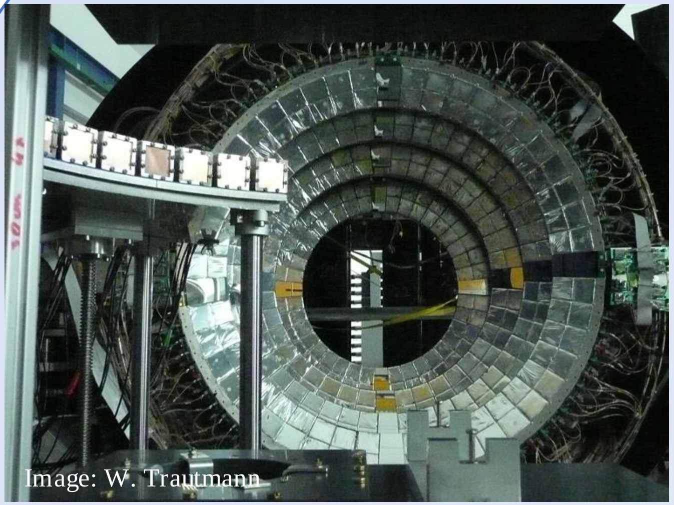
2.) interpolate within this grid through Gaussian Process Regression or a Neural Network

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





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



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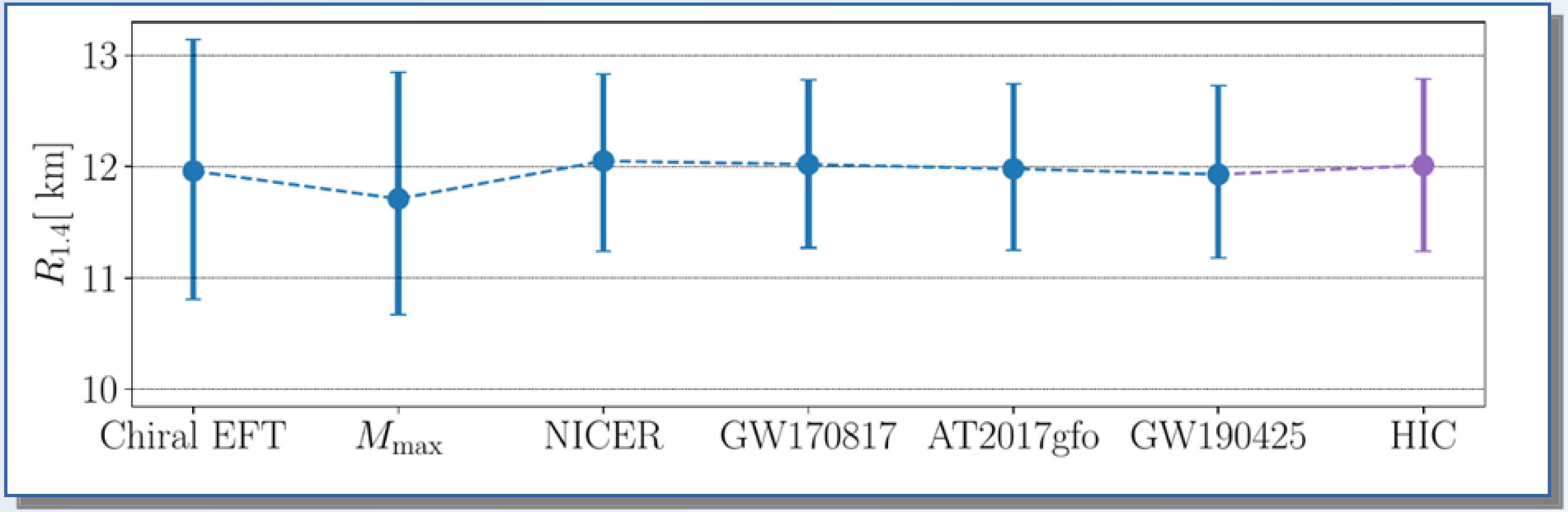
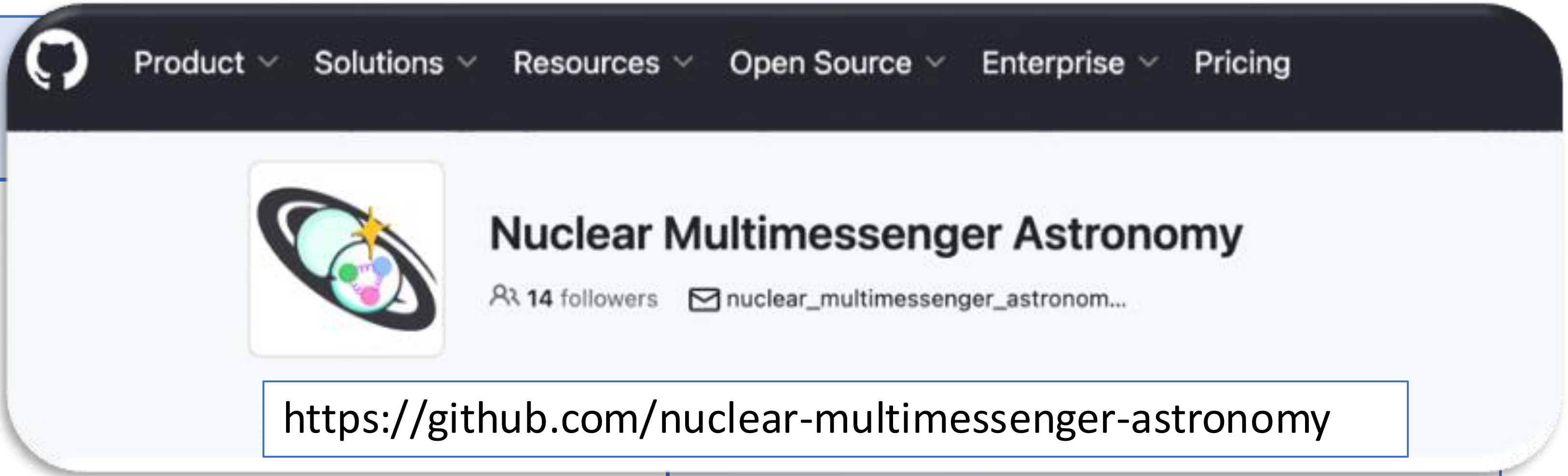
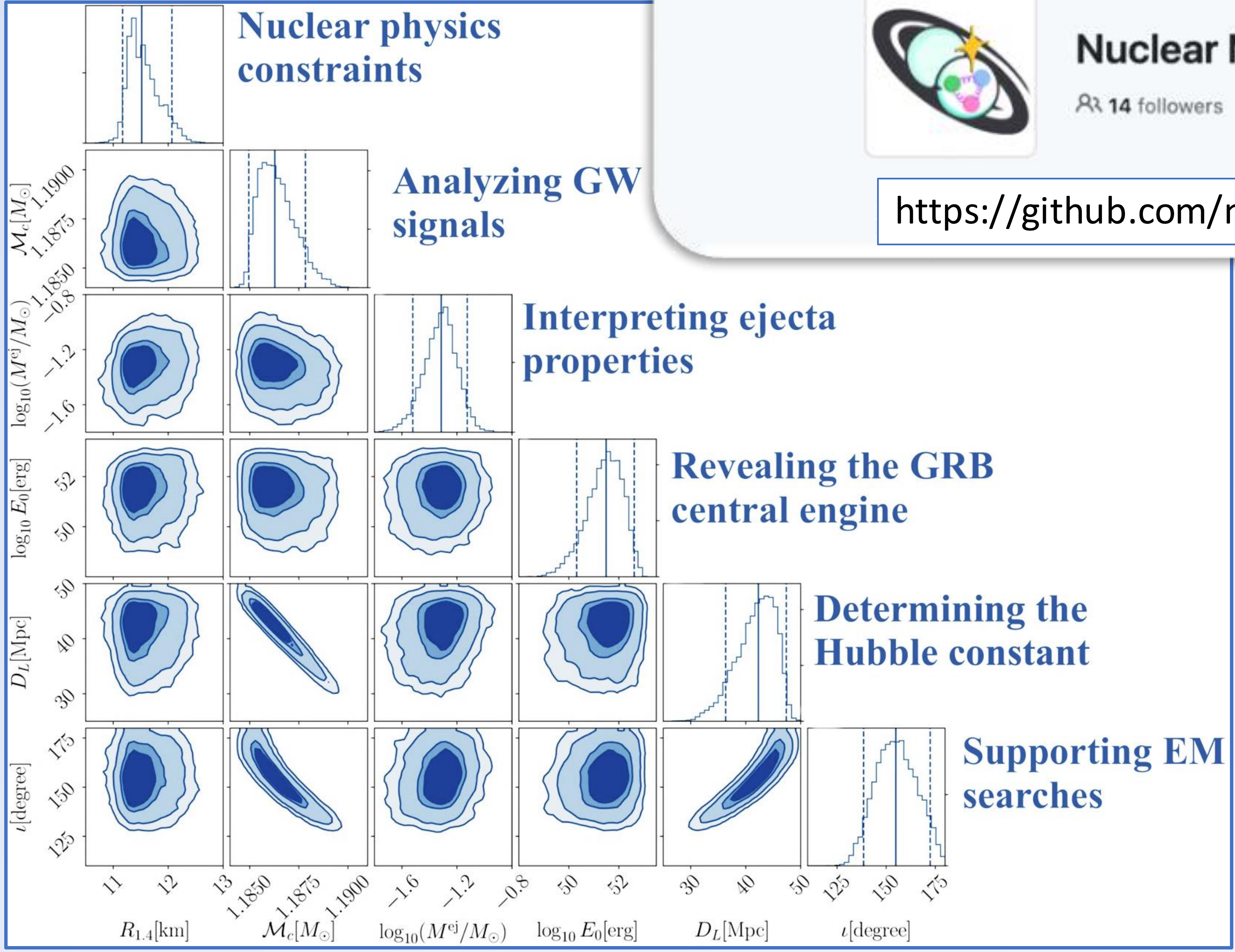
Constraining neutron-star matter with microscopic and macroscopic collisions

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

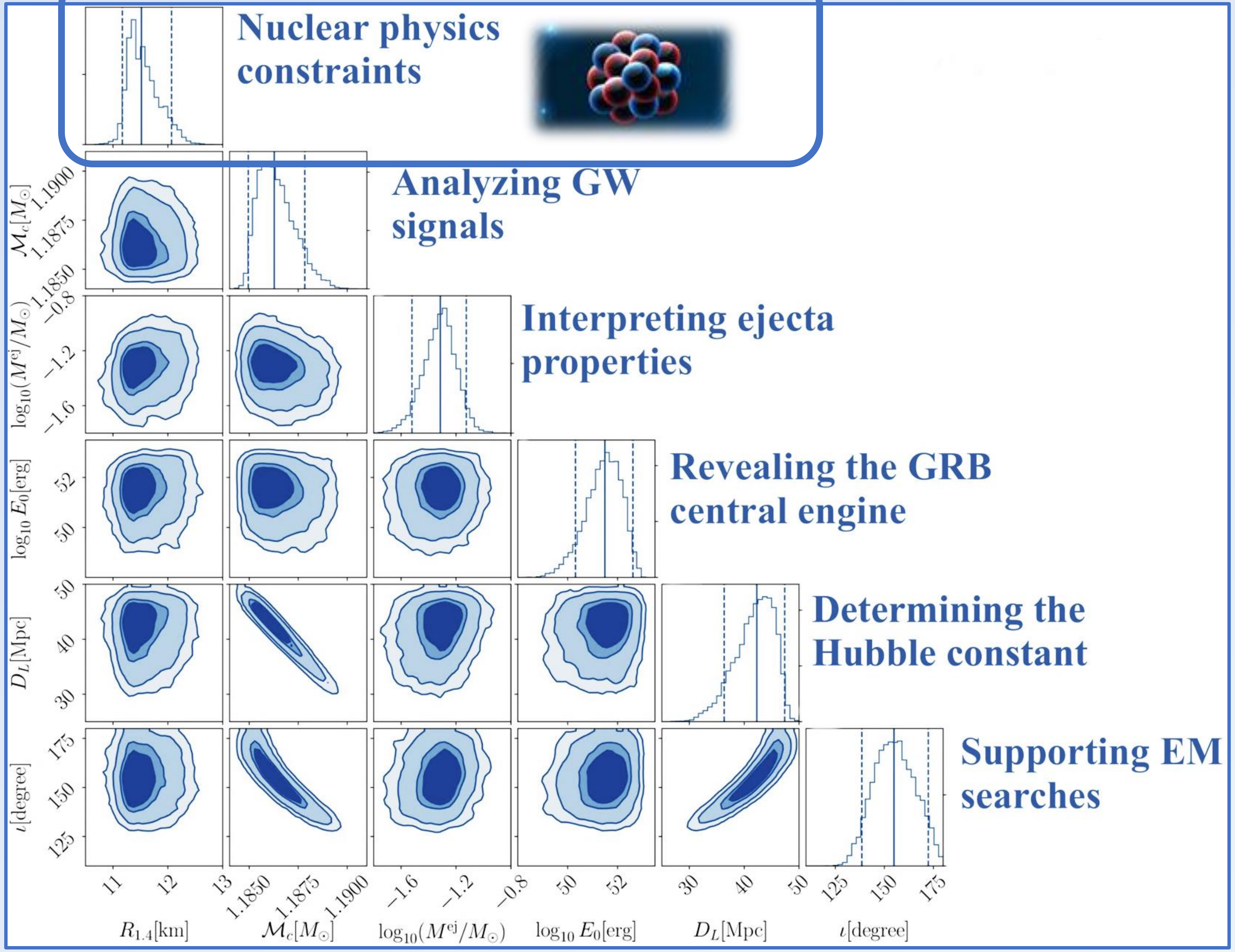


Huth et al., Nature 606 (2022) 276-280

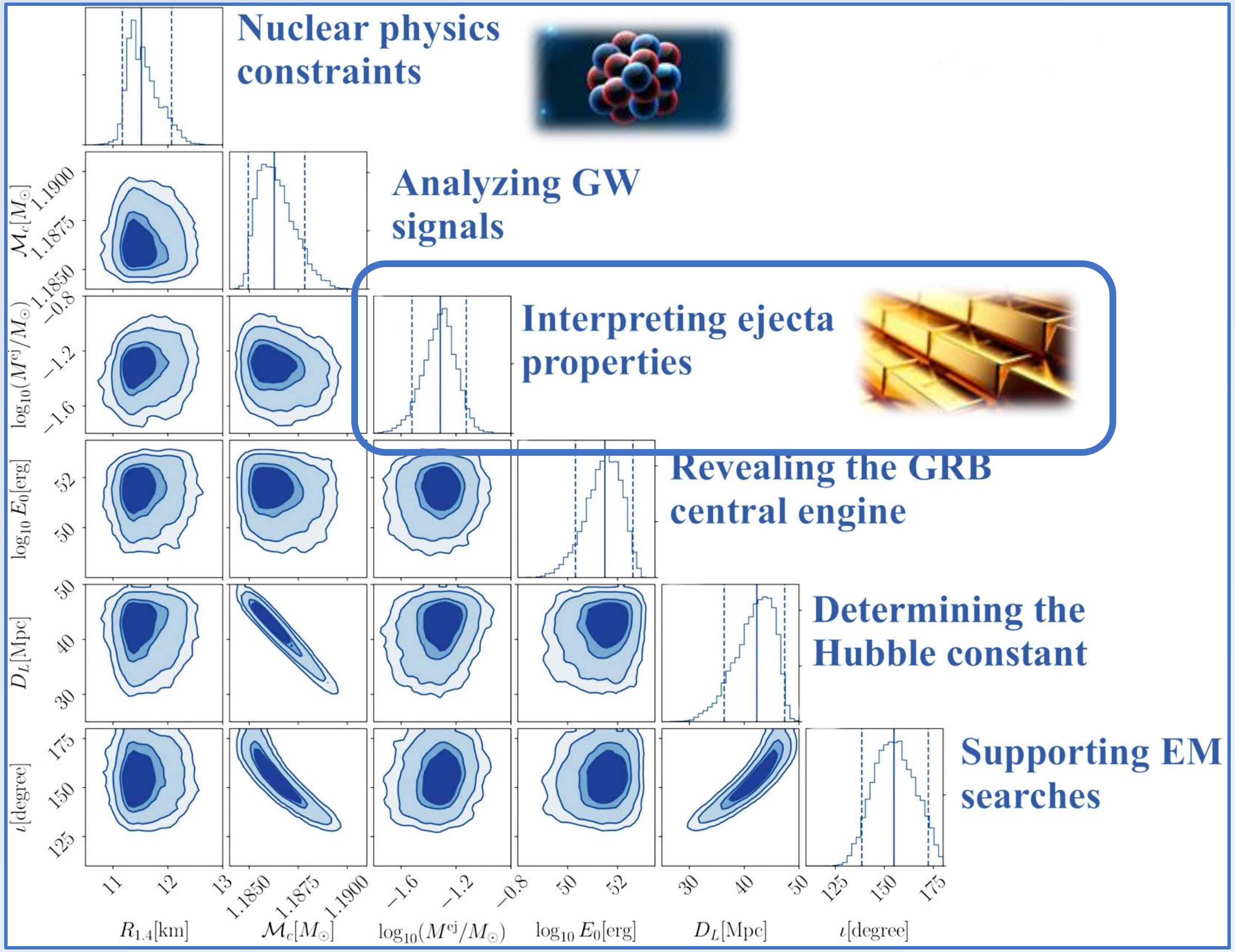


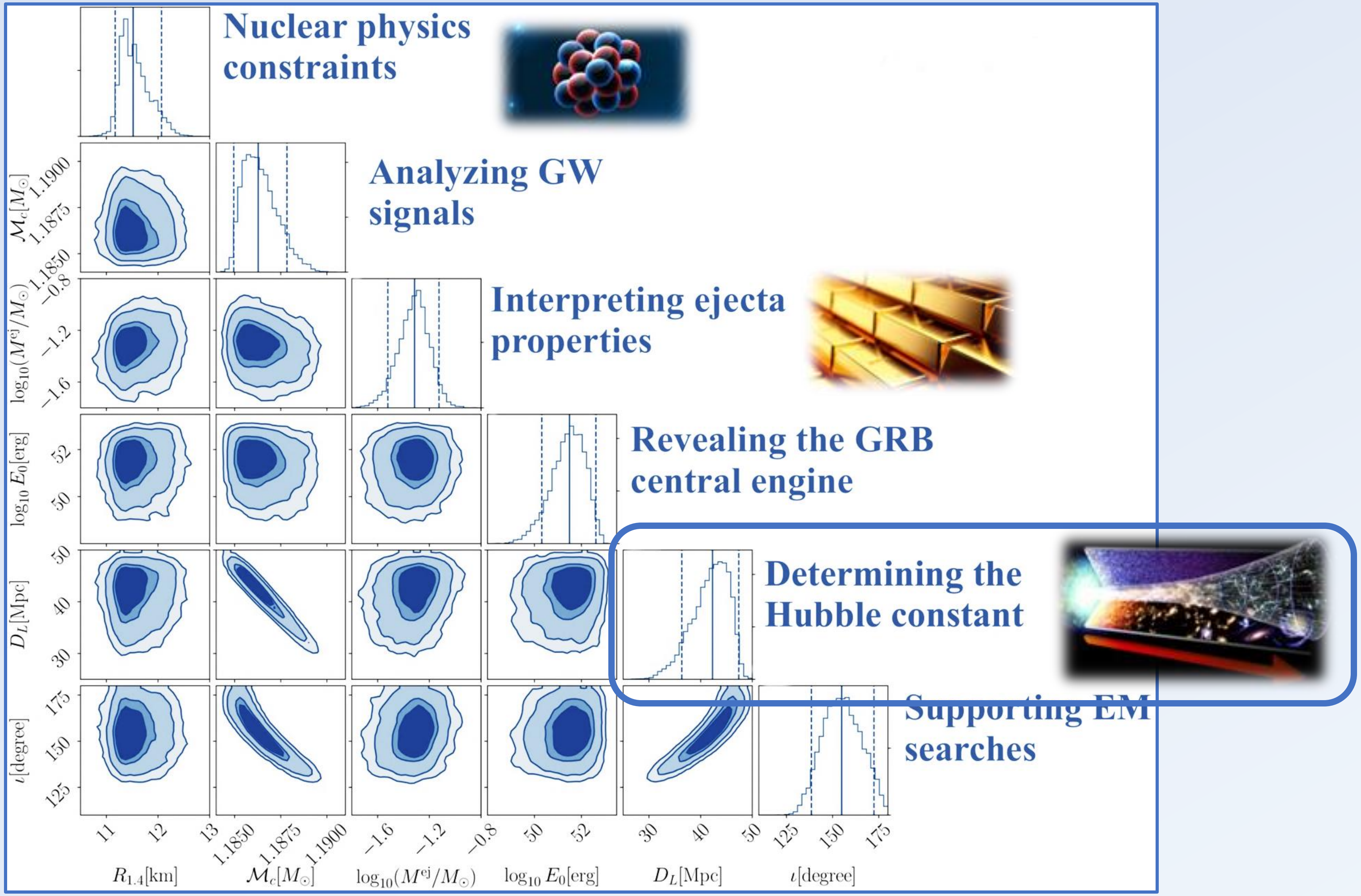


Pang et al., Nat. Comm. 14 (2023) 1, 8352


Nuclear physics constraints
Analyzing GW signals
Interpreting ejecta properties
Revealing the GRB central engine
Determining the Hubble constant
Supporting EM searches
$R_{1.4}$[km]
$\mathcal{M}_c[M_\odot]$
$\log_{10}(M^{ej}/M_\odot)$
$\log_{10} E_0$[erg]
D_L[Mpc]
ι[degree]

Nuclear Physics and Multi-messenger Astrophysics




Nuclear physics constraints
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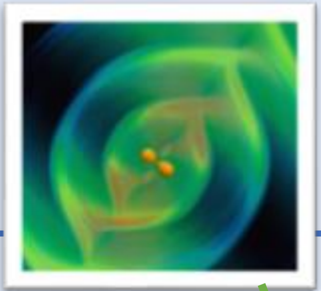
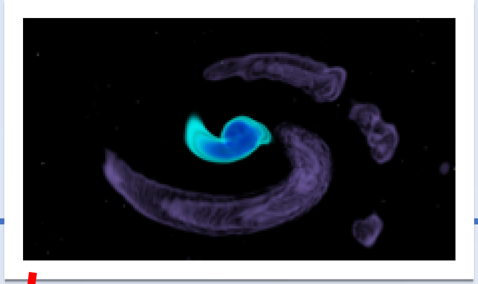
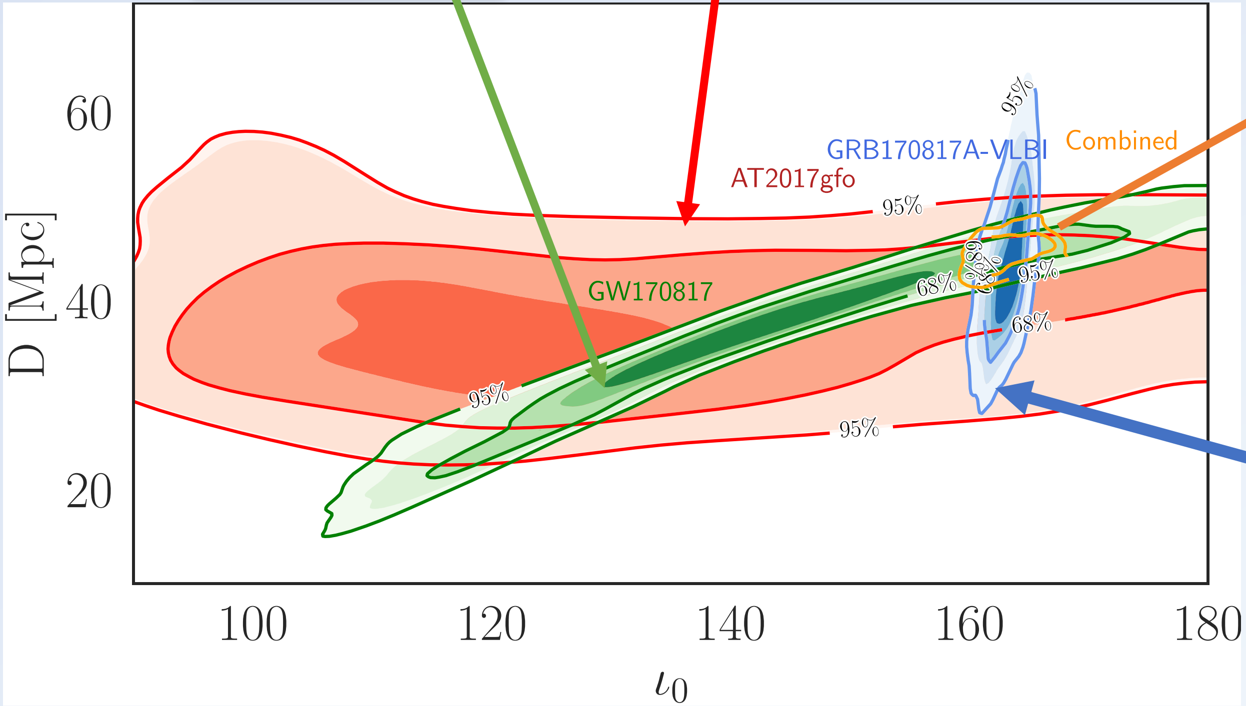
Nuclear Physics and Multi-messenger Astrophysics

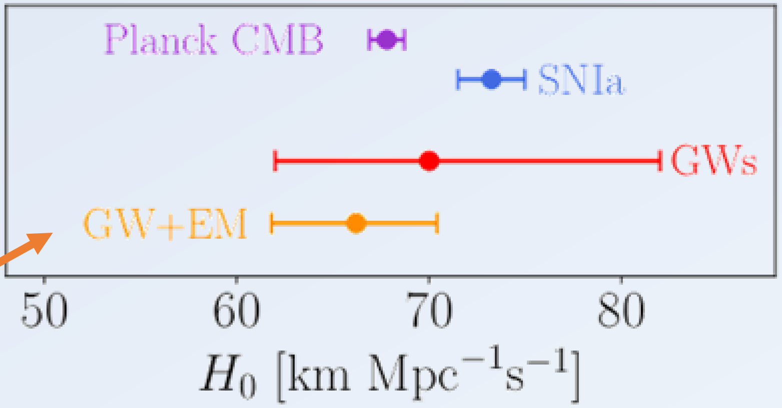
Gravitational Wave



Kilonova







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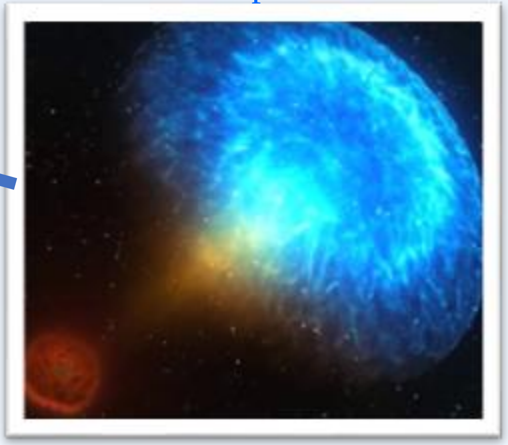
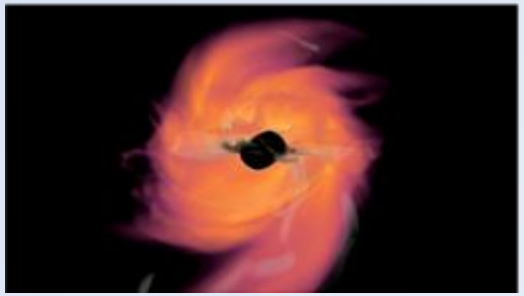
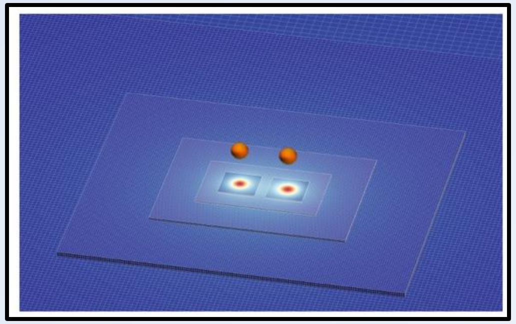
Radio Counterpart



Science Summary and Outlook

- numerical-relativity simulations (microphysics and parameter coverage)

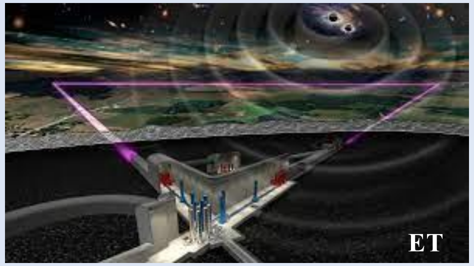




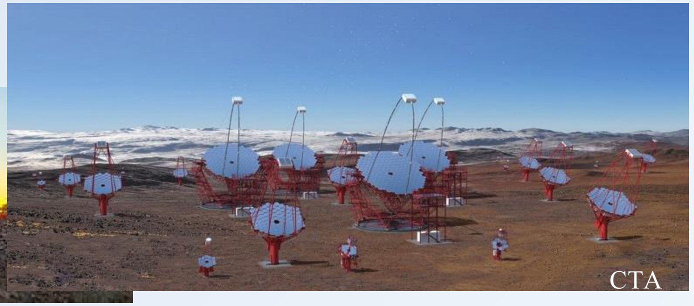
- new nuclear physics and multi-messenger astrophysics framework

- constraints on the Hubble constant and supranuclear-dense equation of state

Gravitational Waves



Electromagnetic Signals



… neutrino detectors, nuclear physics facilities, ….