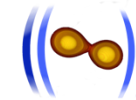




**DFG** Daimler und Benz Stiftung

Alexander von Humboldt Stiftung/Foundation

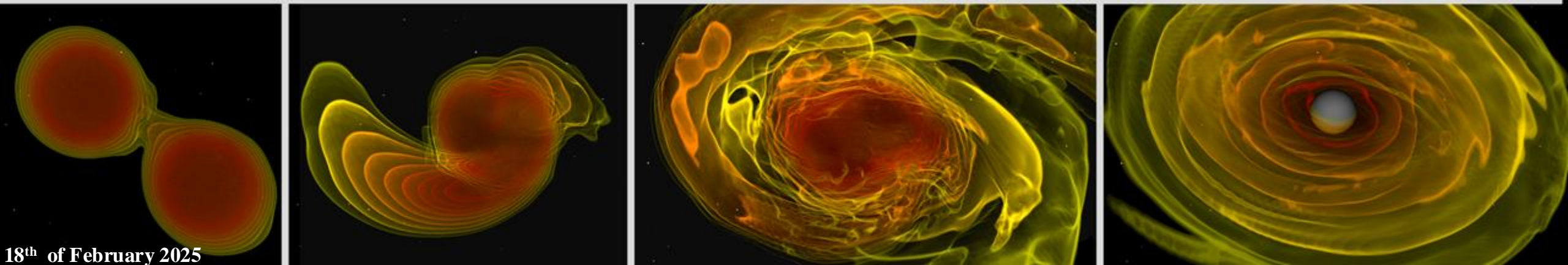


# *Simulating and Interpreting the Multimessenger Picture of Neutron Star Mergers*



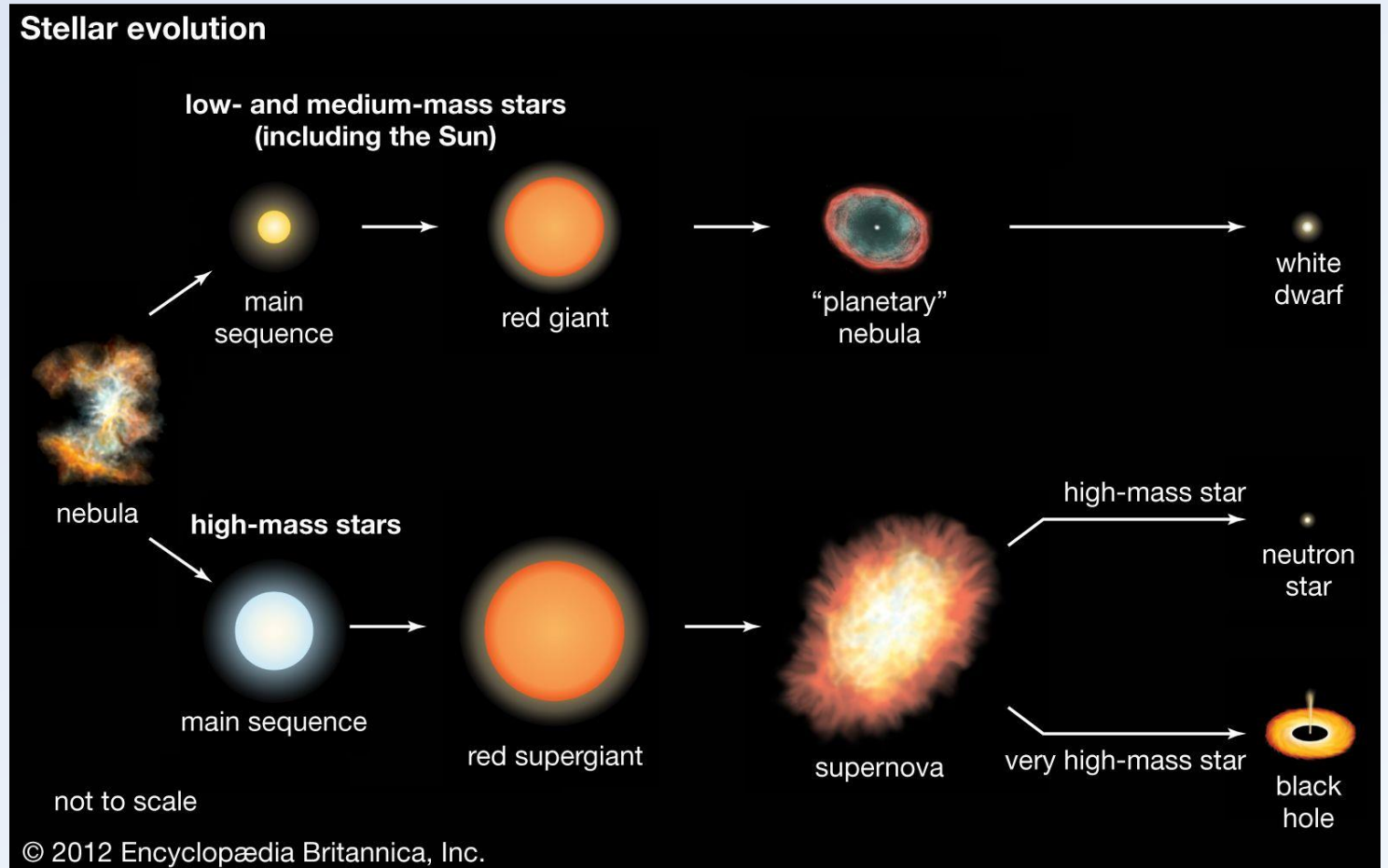
**Tim Dietrich**

University of Potsdam  
Max Planck Institute for Gravitational Physics



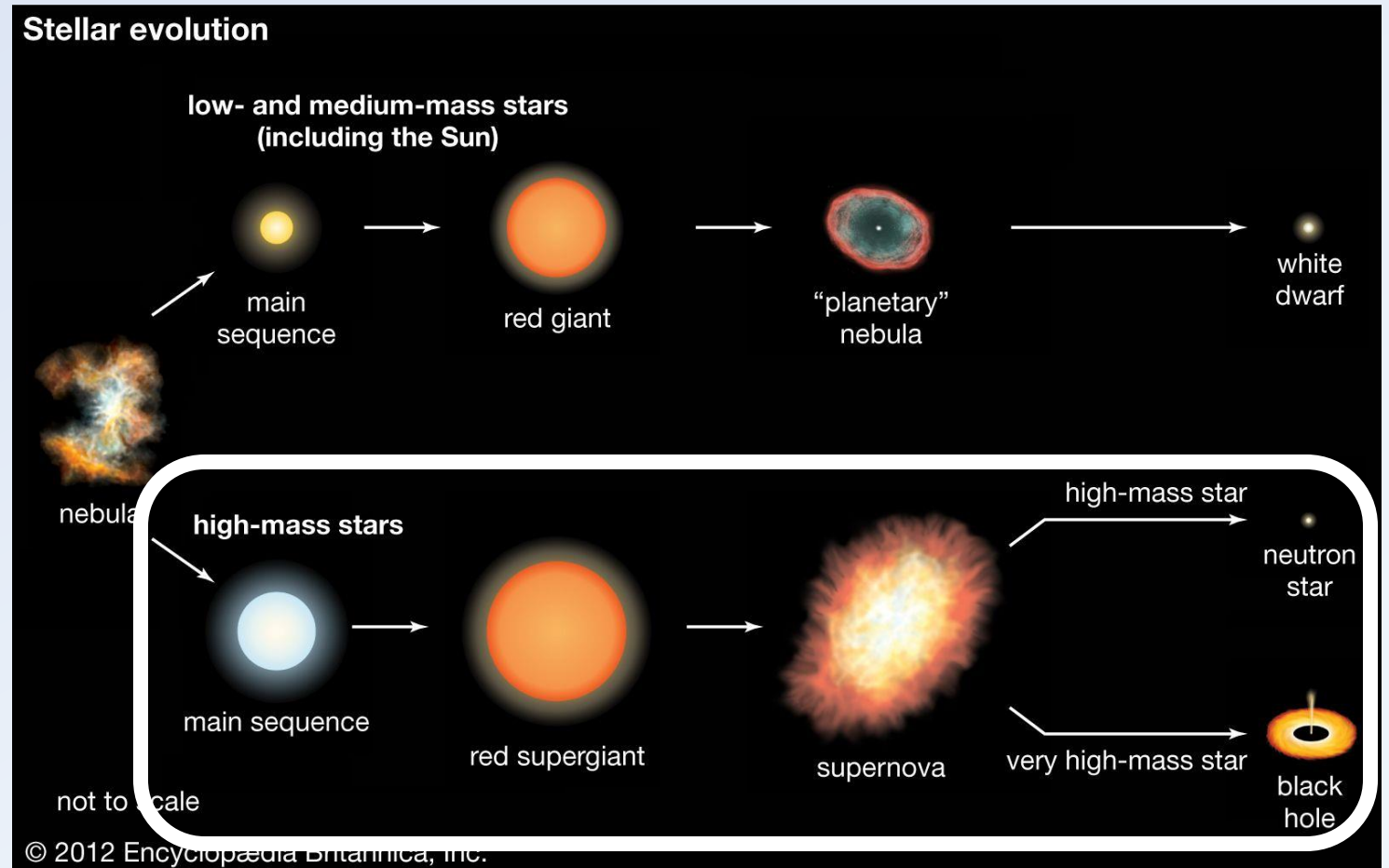
# Neutron stars...

- collapsed core of a massive star
- smallest and densest known class of stellar compact objects



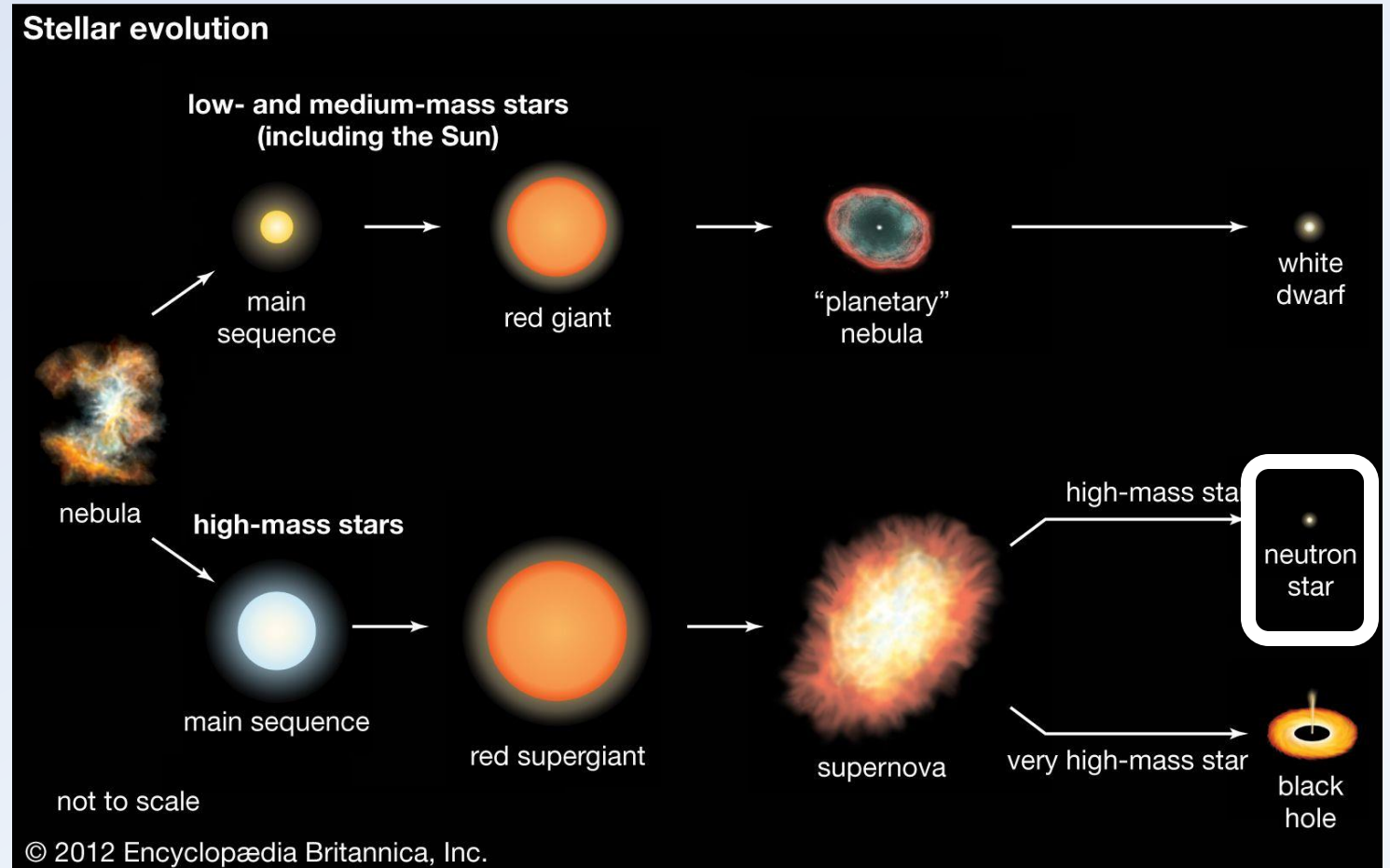
# Neutron stars...

- collapsed core of a massive star
- smallest and densest known class of stellar compact objects



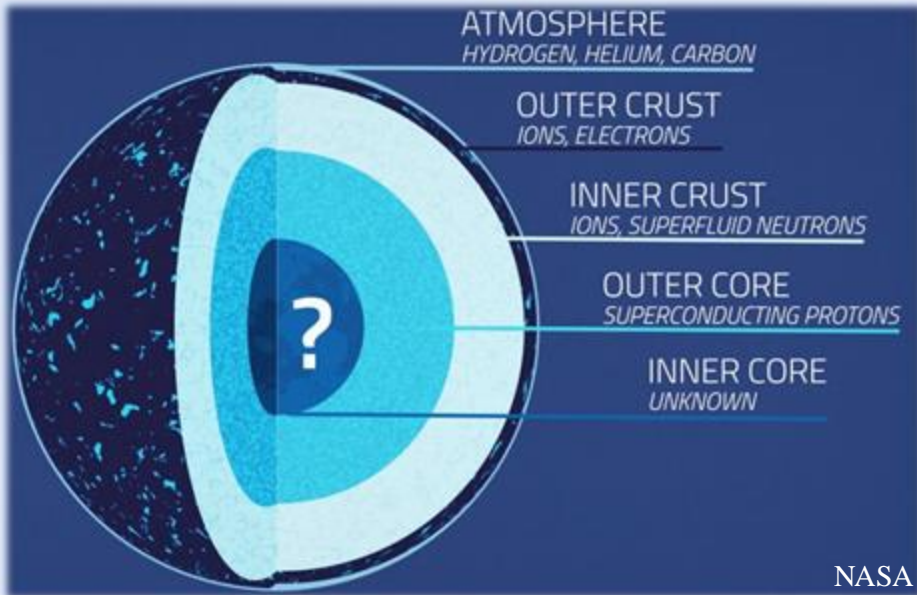
# Neutron stars...

- collapsed core of a massive star
- smallest and densest known class of stellar compact objects



# *Neutron stars...*

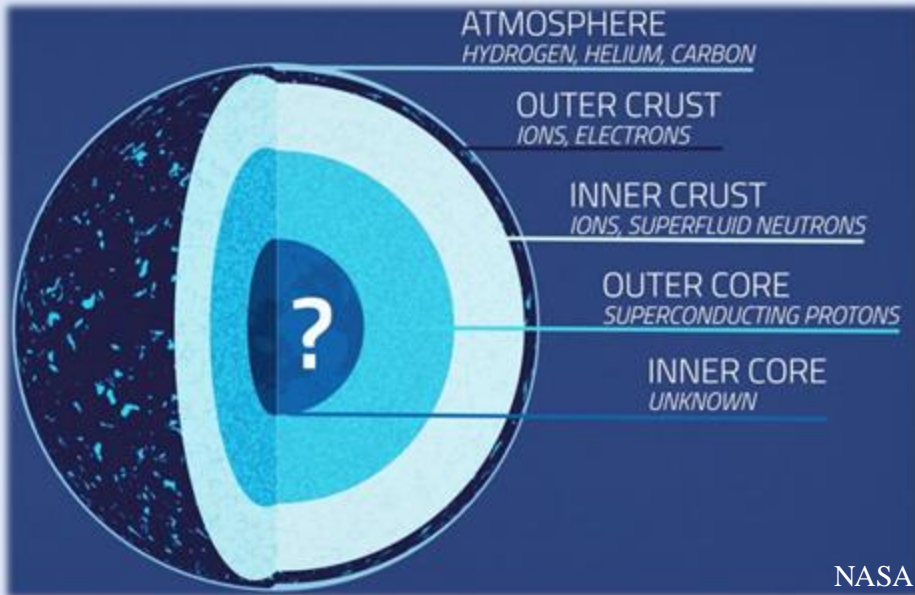
- collapsed core of a massive star
- smallest and densest known class of stellar compact objects
- typical size of 12 kilometer and masses between one and two solar masses





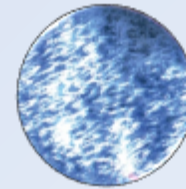
# *Neutron stars...*

- collapsed core of a massive star
- smallest and densest known class of stellar compact objects
- typical size of 12 kilometer and masses between one and two solar masses



# *... how to study them?*

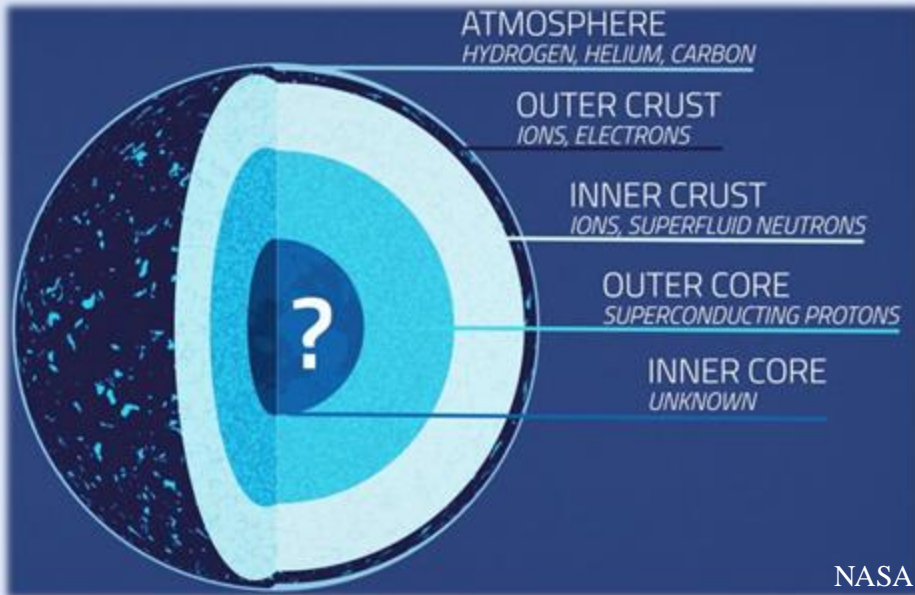
## *Single Neutron Stars*



- radio pulsars
- through X-ray emission

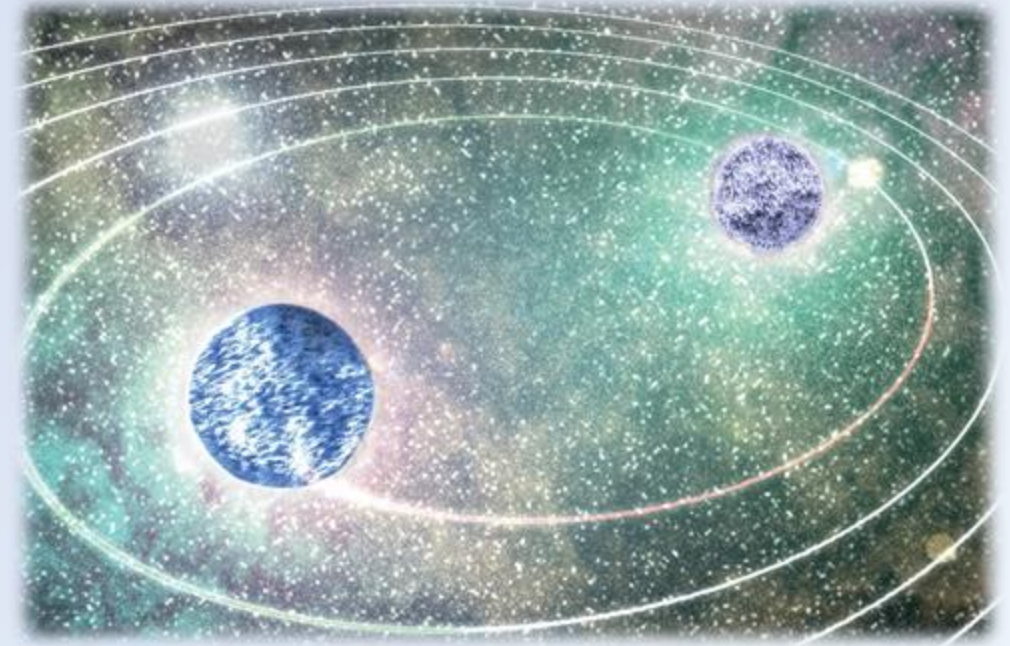
# Neutron stars...

- collapsed core of a massive star
- smallest and densest known class of stellar compact objects
- typical size of 12 kilometer and masses between one and two solar masses



# ... how to study them?

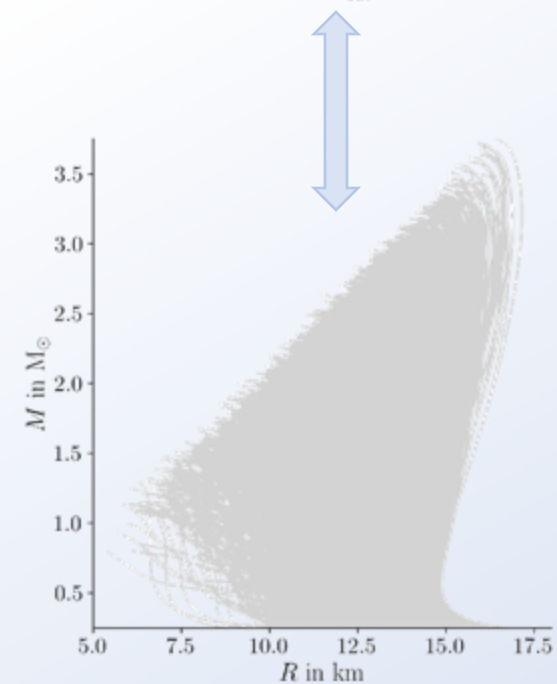
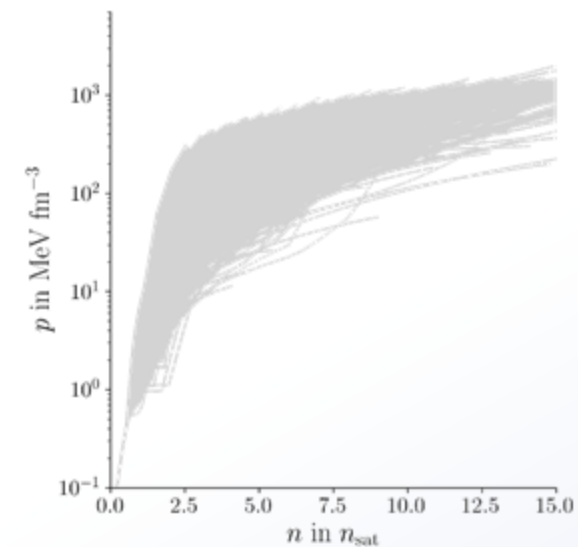
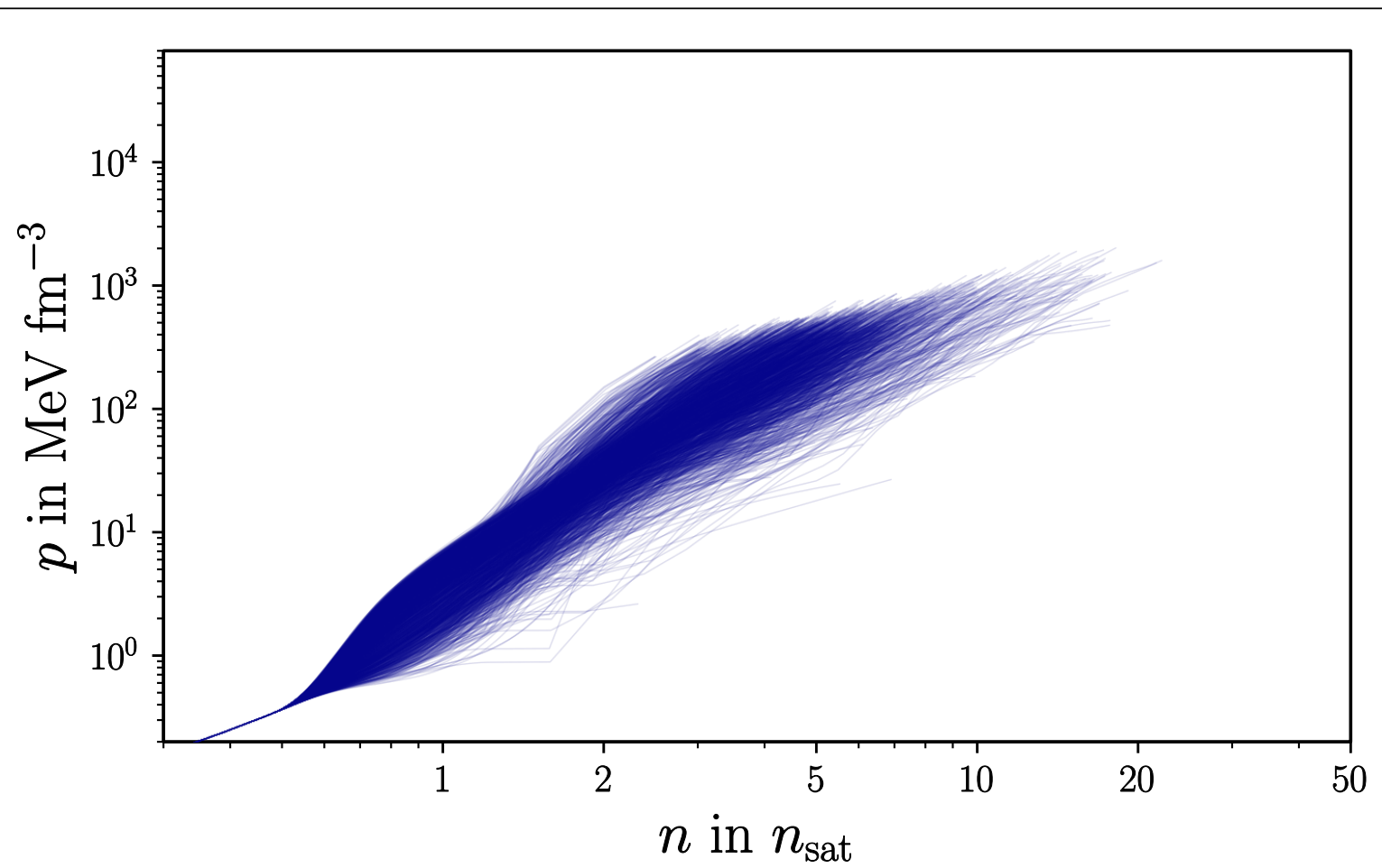
## Binary Neutron Stars



- gravitational-wave sources
- electromagnetic transients
- neutrino sources

# Input from a variety of sources:

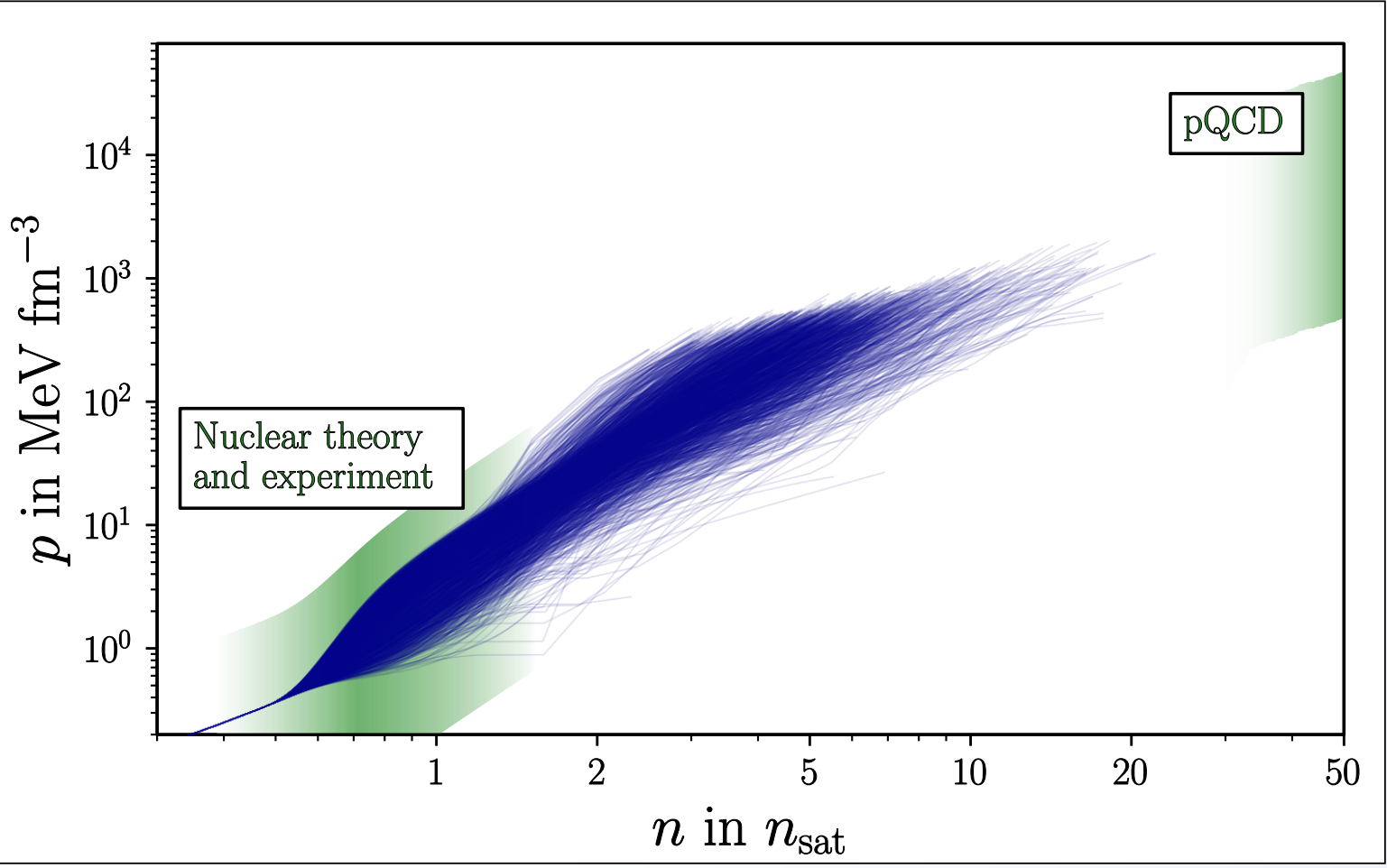
Koehn et al. 2024, 2402.04172 (accepted in PRX) and PRD 110 (2024) 10, 103015





# Input from a variety of sources:

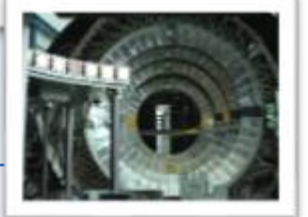
Koehn et al. 2024, 2402.04172 (accepted in PRX) and PRD 110 (2024) 10, 103015



## Nuclear Physics

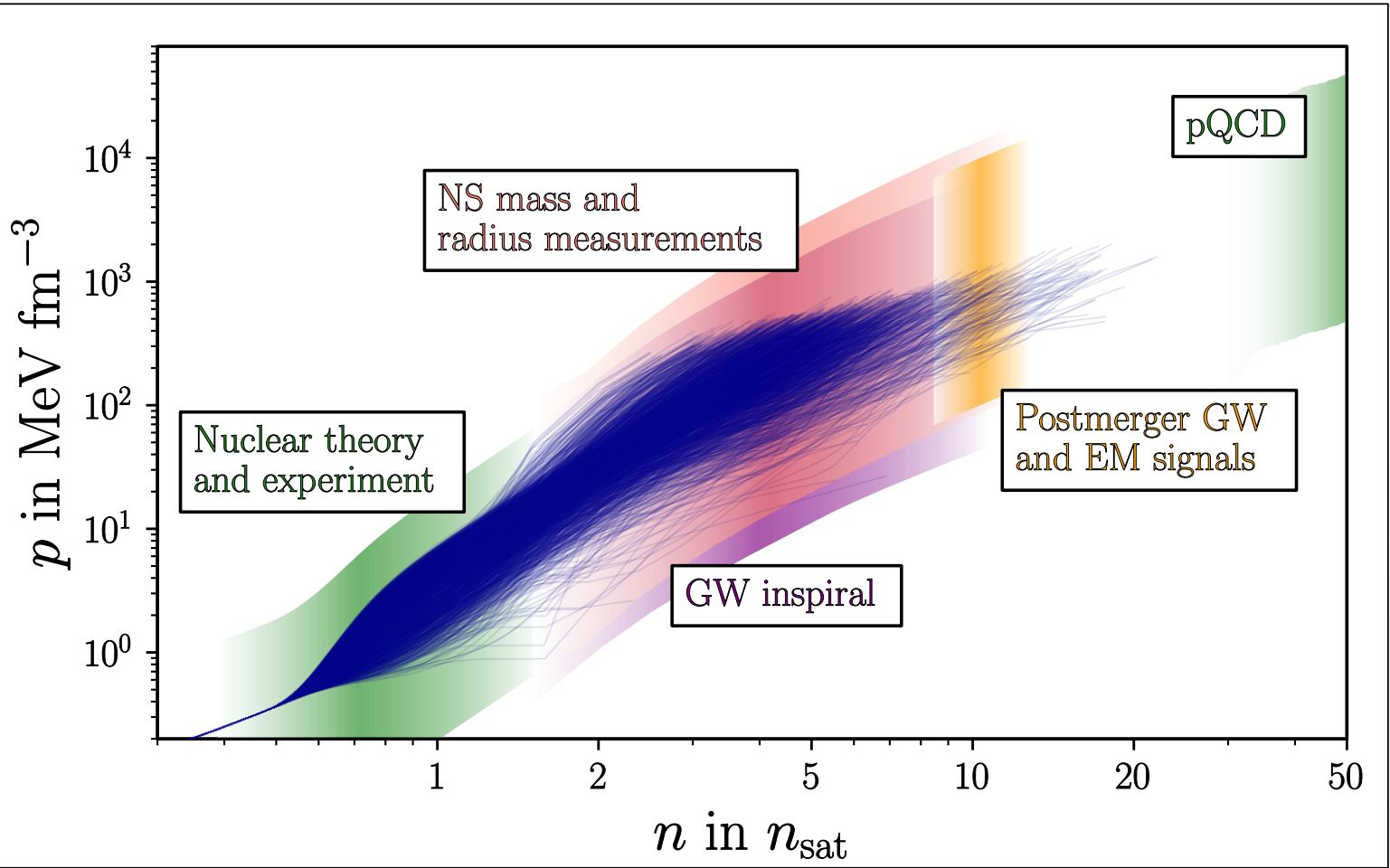
- Chiral EFT
- pQCD
- PREX-II/ CREX
- Pb dipole measurements
- Heavy Ion Collisions
- ...

		NN	3N	4N
LO	$\mathcal{O}(\frac{q^2}{\Lambda^2})$	X H	-	-
(2 LECs)				
NLO	$\mathcal{O}(\frac{q^4}{\Lambda^4})$	X H K	-	-
(7 LECs)				
N <sup>3</sup> LO	$\mathcal{O}(\frac{q^6}{\Lambda^6})$	H K	H H	-
(2 LECs: 3N)			X X X	
N <sup>4</sup> LO	$\mathcal{O}(\frac{q^8}{\Lambda^8})$	X H K	H K	H H
(15 LECs)			H Y	H H



# Input from a variety of sources:

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



## Nuclear Physics

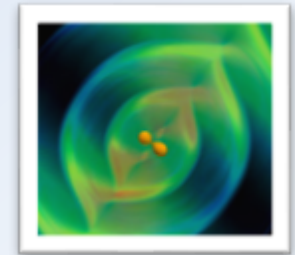
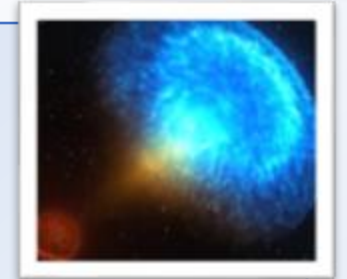
- Chiral EFT
- pQCD
- PREX-II/ CREX
- Pb dipole measurements
- Heavy Ion Collisions
- ...

		NN	3N	4N
LO $O(\frac{p}{\Lambda})^0$	(2 LECs)	X H	-	-
NLO $O(\frac{p}{\Lambda})^2$	(7 LECs)	X H K	-	-
N <sup>3</sup> LO $O(\frac{p}{\Lambda})^4$	(2 LECs: 3N)	H K	H H X X	-
N <sup>4</sup> LO $O(\frac{p}{\Lambda})^6$	(15 LECs)	X H M	H K H	H H



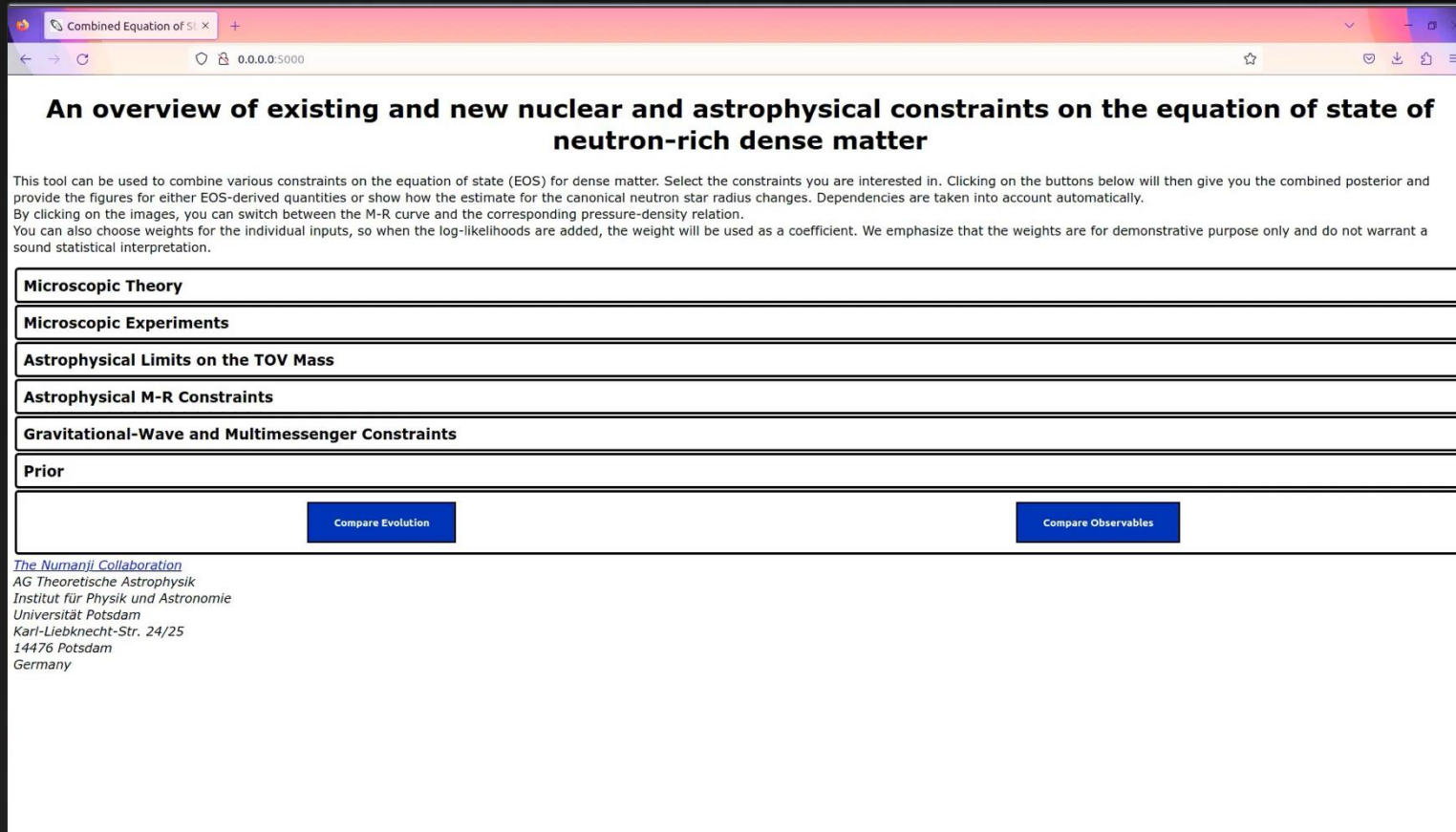
## Astrophysics

- 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



The screenshot shows a web browser window with the following content:

**Combined Equation of State**

0.0.0.5000

## An overview of existing and new nuclear and astrophysical constraints on the equation of state of neutron-rich dense matter

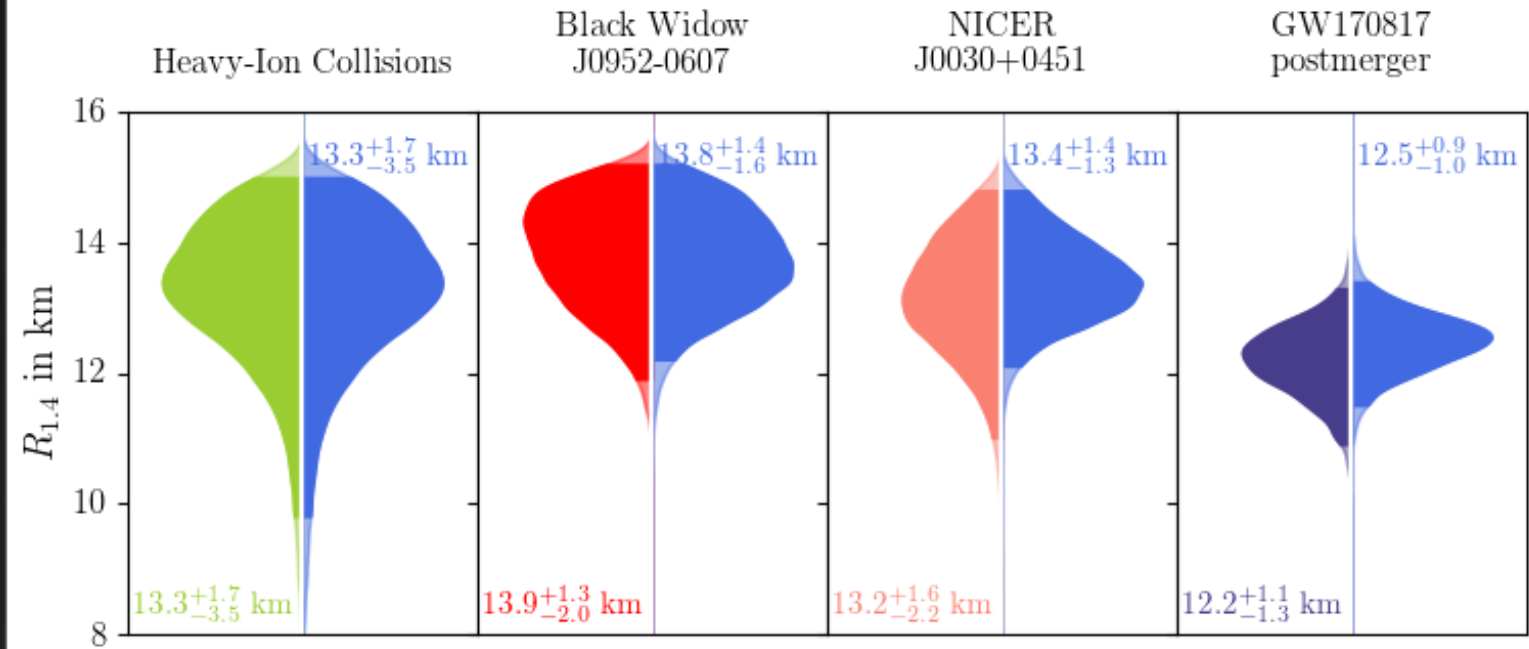
This tool can be used to combine various constraints on the equation of state (EOS) for dense matter. Select the constraints you are interested in. Clicking on the buttons below will then give you the combined posterior and provide the figures for either EOS-derived quantities or show how the estimate for the canonical neutron star radius changes. Dependencies are taken into account automatically. By clicking on the images, you can switch between the M-R curve and the corresponding pressure-density relation. You can also choose weights for the individual inputs, so when the log-likelihoods are added, the weight will be used as a coefficient. We emphasize that the weights are for demonstrative purpose only and do not warrant a sound statistical interpretation.

<b>Microscopic Theory</b>
<b>Microscopic Experiments</b>
<b>Astrophysical Limits on the TOV Mass</b>
<b>Astrophysical M-R Constraints</b>
<b>Gravitational-Wave and Multimessenger Constraints</b>
<b>Prior</b>

*The Numanji Collaboration*  
AG Theoretische Astrophysik  
Institut für Physik und Astronomie  
Universität Potsdam  
Karl-Liebknecht-Str. 24/25  
14476 Potsdam  
Germany



# Combining different constraints on the EOS from different research fields

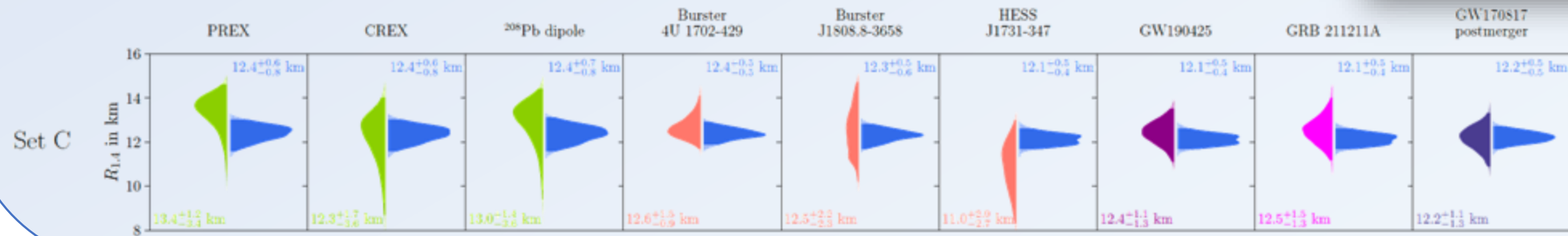
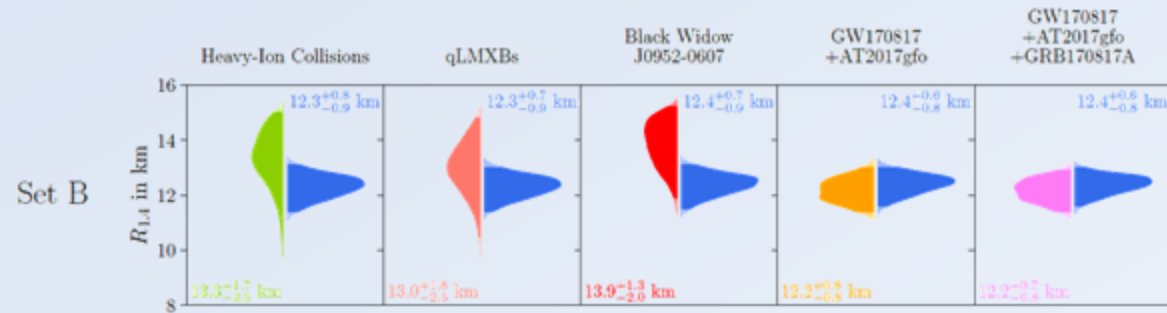
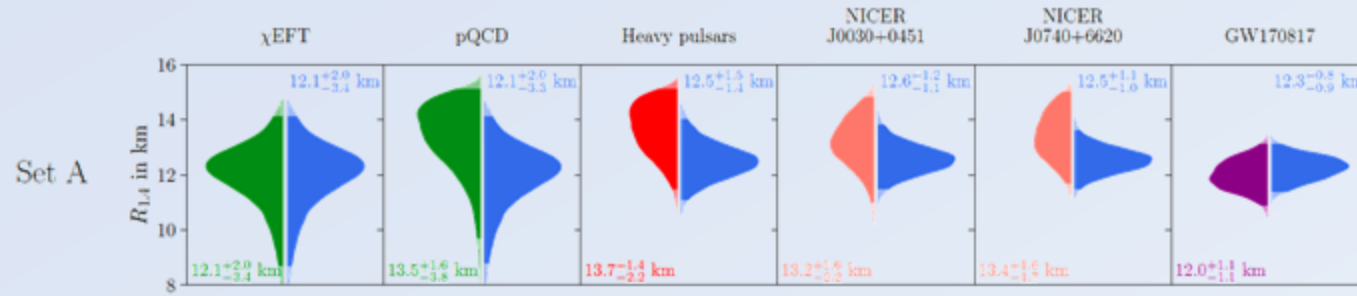


Science case:  
Koehn et al. 2024  
arXiv:2402.04172v1





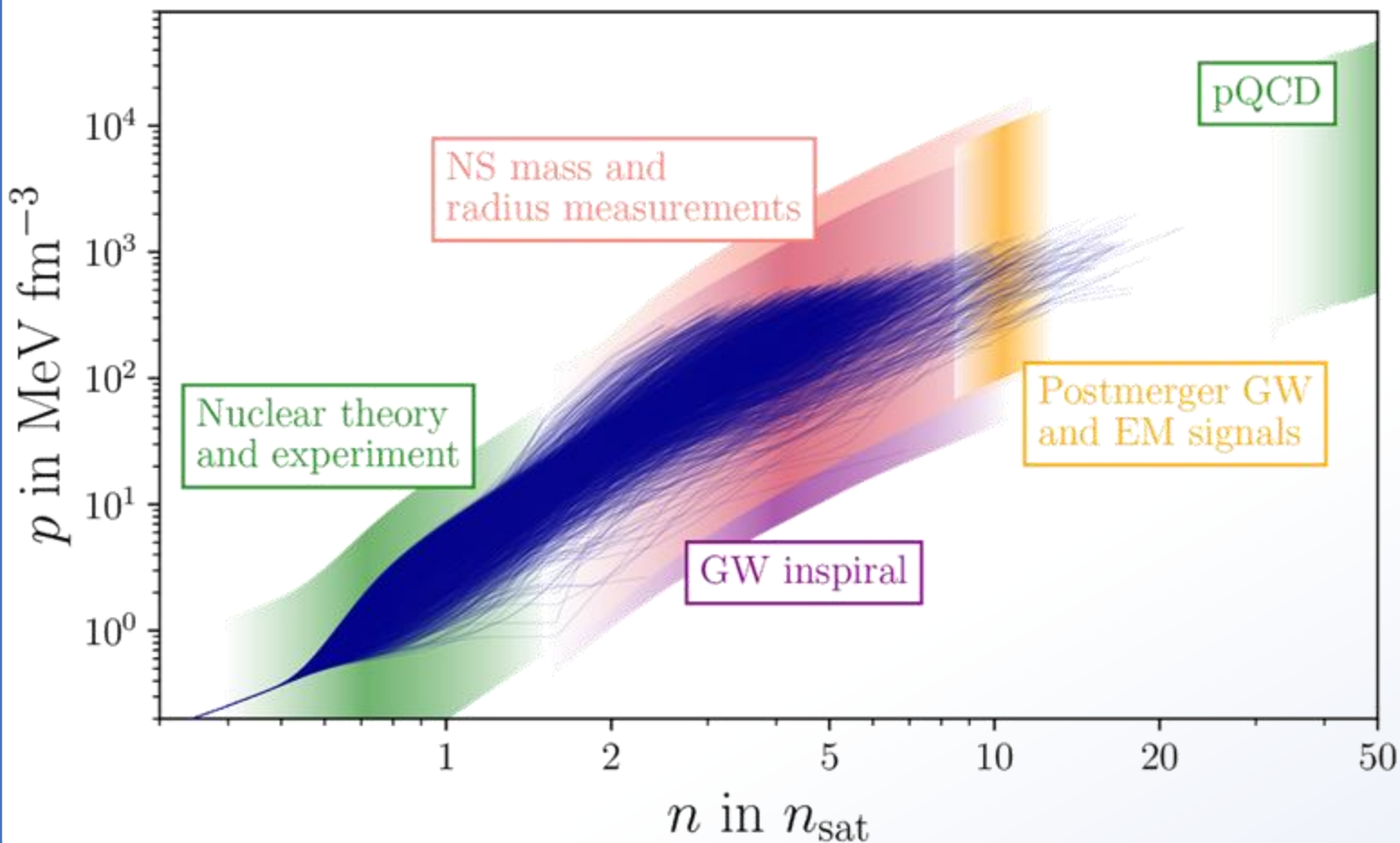
# Combining different constraints on the EOS from different research fields



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

# Input from a variety of sources:

Koehn et al. 2024, 2402.04172



## Nuclear Physics

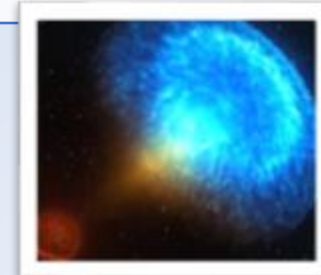
- Chiral EFT
- pQCD
- PREX-II/ CREX
- Pb dipole measurements
- Heavy Ion Collisions
- ...

		NN	3N	4N
LO $O(\frac{q^2}{\Lambda^2})$ (2 LECs)	X H	-	-	
NLO $O(\frac{q^4}{\Lambda^4})$ (7 LECs)	X H K	-	-	
N <sup>3</sup> LO $O(\frac{q^6}{\Lambda^6})$ (2 LECs: 3N)	H K	H H	-	
N <sup>4</sup> LO $O(\frac{q^8}{\Lambda^8})$ (15 LECs)	X H K	H K	H H	

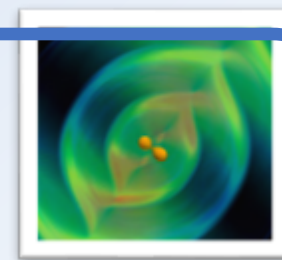


## Astrophysics

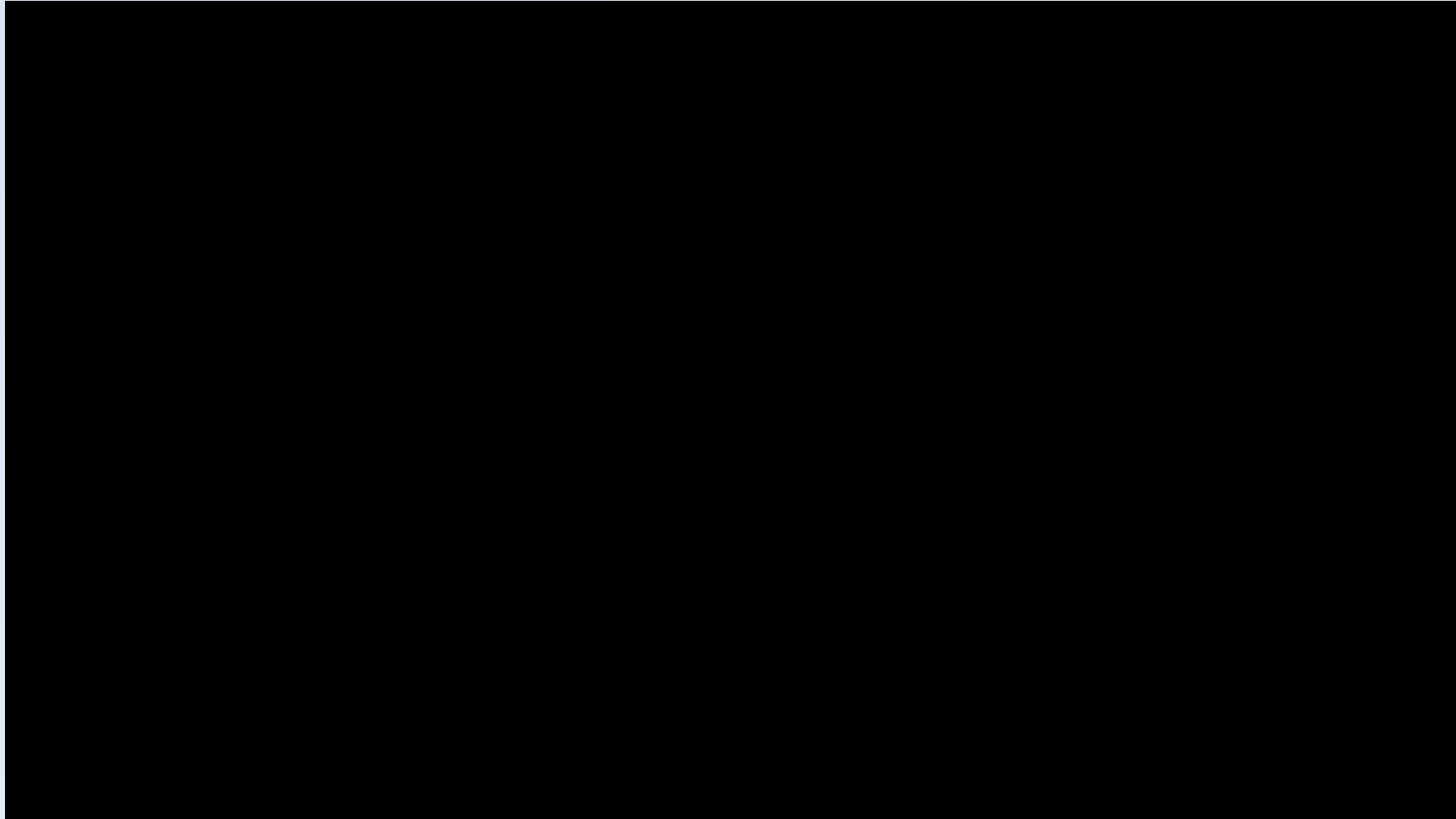
- Heavy pulsars
- NICER
- HESS object
- qLMXBs
- Thermo-nuclear accretion bursts



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

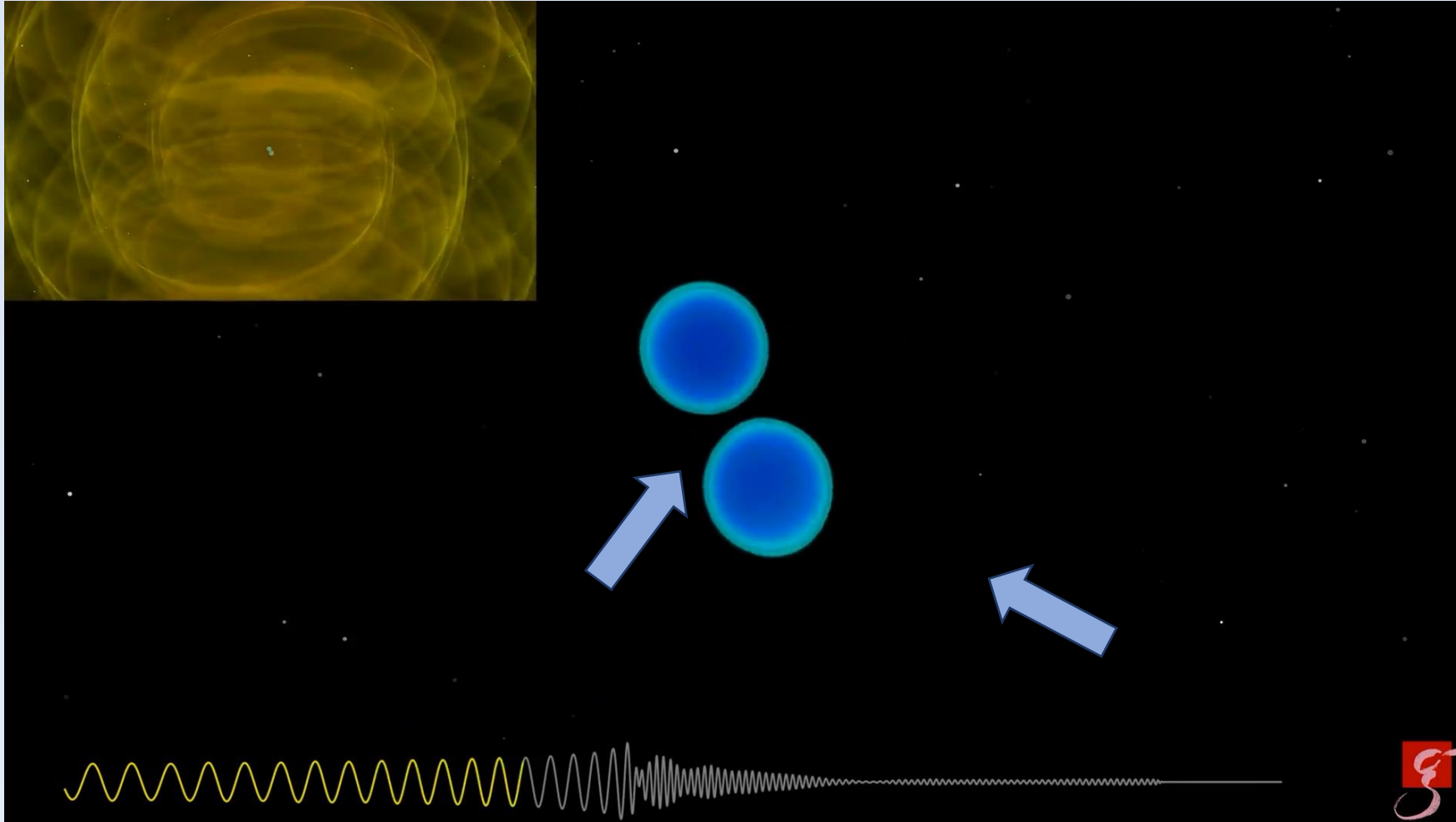


# The Binary Neutron Star Merger Simulation



**gravitational wave  
emission**

# The Binary Neutron Star Merger Simulation

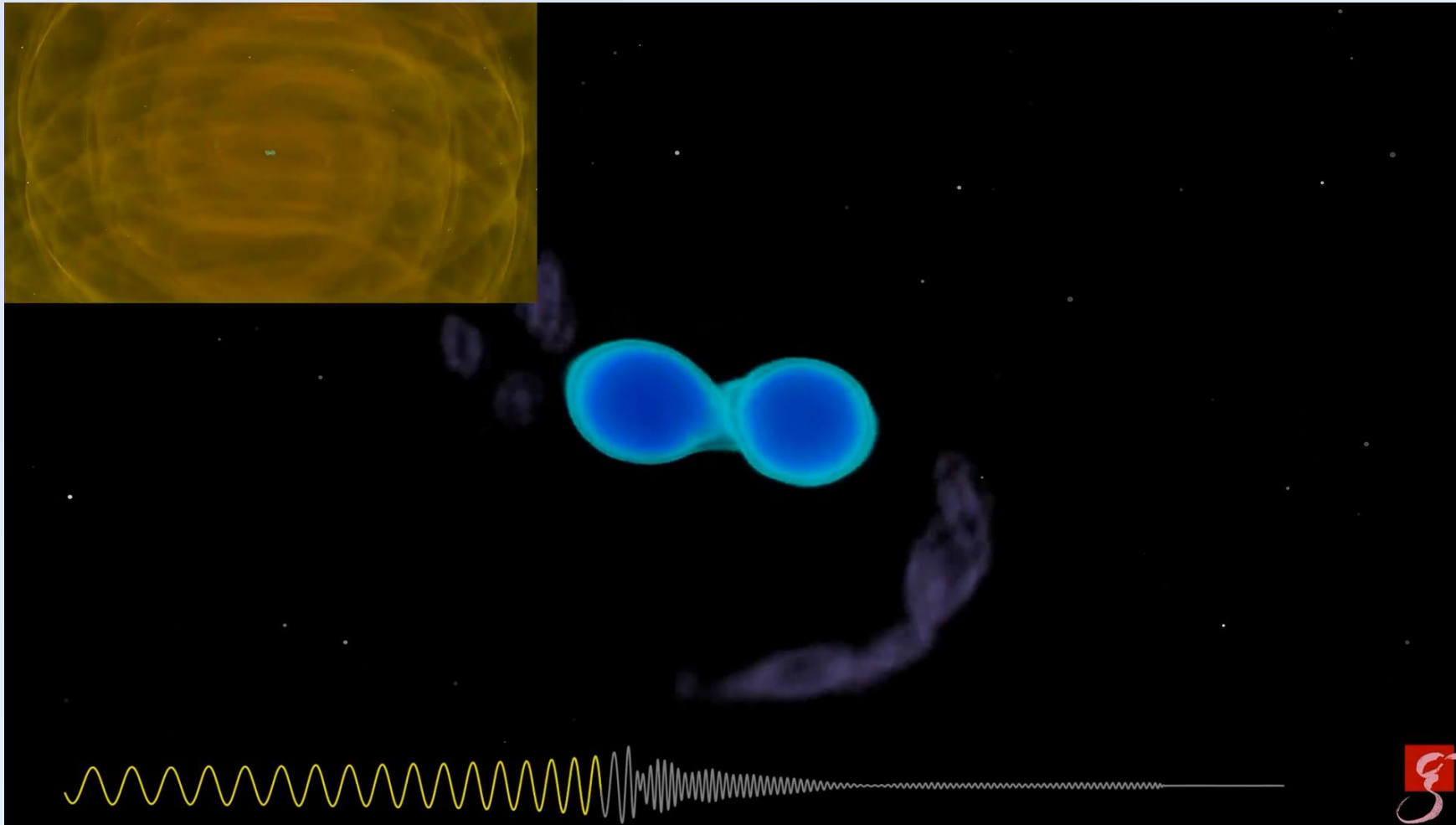


**gravitational wave  
emission**

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



# The Binary Neutron Star Merger Simulation

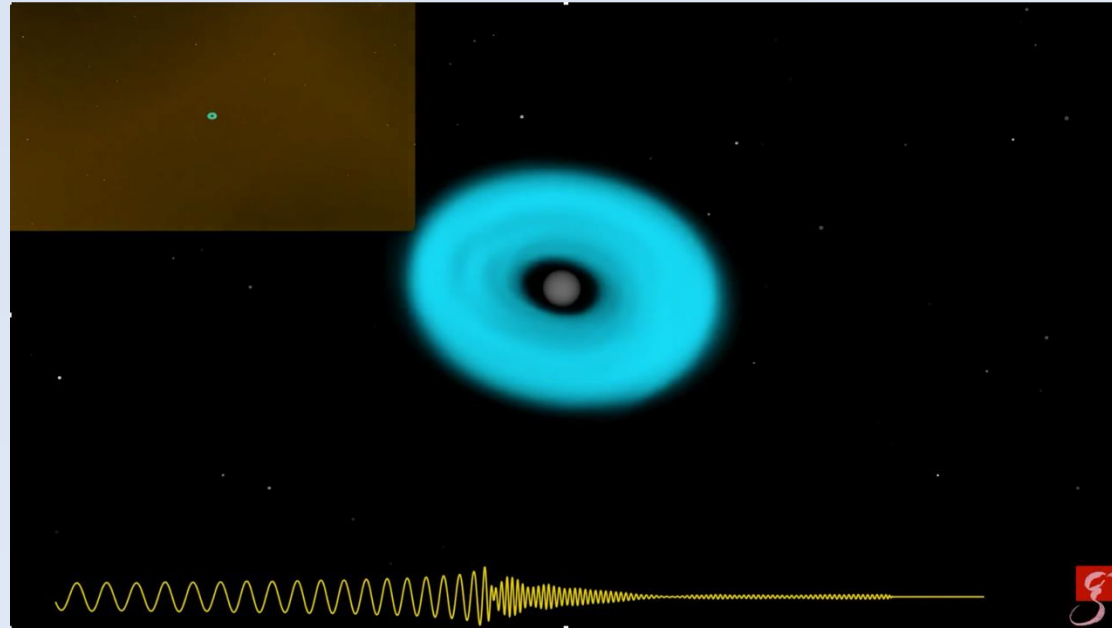


gravitational wave  
emission

deformation before  
merger, ejection of  
material, heavy  
element production

black hole formation

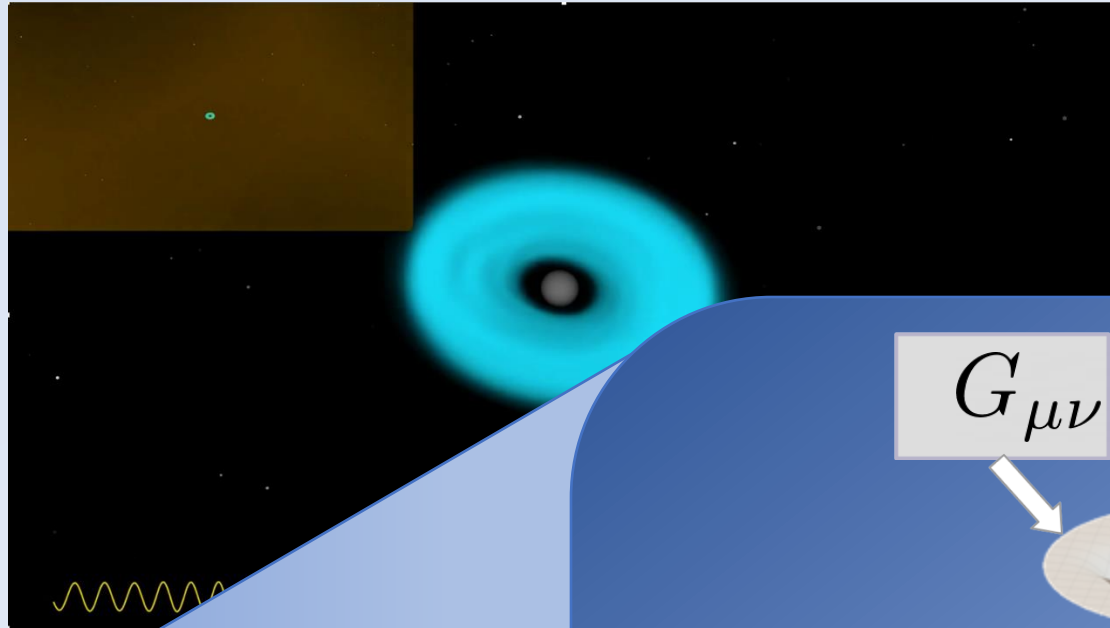
70 milliseconds



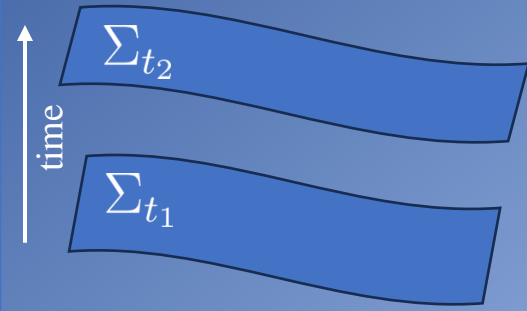
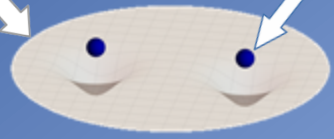
## Theoretical Framework:

- well-posedness of PDEs
- advantageous properties

$$\begin{aligned}
 \partial_t \chi &= \frac{2}{3} \chi (\alpha(\dot{K} + 2\Theta) - D_i \beta^i), \\
 \partial_t \gamma_{ij} &= -2\alpha \dot{A}_{ij} + \beta^k \partial_k \gamma_{ij} + 2\gamma_{ki} \partial_j \beta^k - \frac{2}{3} \gamma_{ij} \partial_k \beta^k, \\
 \partial_t \dot{K} &= -D^i D_i \alpha + \alpha \left( \dot{A}_{ij} \dot{A}^{ij} + \frac{1}{3} (\dot{K} + 2\Theta)^2 \right) \\
 &\quad + 4\pi\alpha(S + E) + \beta^k \partial_k \dot{K} + \alpha \kappa_1 (1 - \kappa_2) \Theta, \\
 \partial_t \dot{A}_{ij} &= \chi \left( -D_i D_j \alpha + \alpha \left( {}^{(3)}R_{ij} - 8\pi S_{ij} \right) \right)^{TF} + \alpha \left( (\dot{K} + 2\Theta) \dot{A}_{ij} - 2\dot{A}^k_j \dot{A}_{ki} \right) \\
 &\quad + \beta^k \partial_k \dot{A}_{ij} + 2\dot{A}_{ki} \partial_j \beta^k - \frac{2}{3} \dot{A}_{ij} \partial_k \beta^k, \\
 \partial_t \dot{\Gamma}^i &= -2\dot{A}^{ik} \partial_k \alpha + 2\alpha \left( \dot{\Gamma}^i_{kl} \dot{\Gamma}^{kl} - \frac{3}{2} \dot{A}^{ik} \partial_k \ln(\chi) - \frac{1}{3} \gamma^{ik} \partial_k (\dot{K} + 2\Theta) - 8\pi \gamma^{ik} S_k \right) \\
 &\quad + \gamma^{kl} \partial_k \partial_l \beta^i + \frac{1}{3} \gamma^{ik} \partial_l \partial_l \beta^i - 2\alpha \kappa_1 (\dot{\Gamma}^i - \dot{\Gamma}^i) + \beta^k \partial_k \dot{\Gamma}^i \\
 &\quad - \dot{\Gamma}^k \partial_k \beta^i + \frac{2}{3} \dot{\Gamma}^i \partial_k \beta^k, \\
 \partial_t \Theta &= \frac{\alpha}{2} \left( {}^{(3)}R - \dot{A}_{ij} \dot{A}^{ij} + \frac{2}{3} (\dot{K} + 2\Theta)^2 \right) - \alpha (8\pi E + \kappa_1 (2 + \kappa_2) \Theta) \\
 &\quad + \beta^i \partial_i \Theta
 \end{aligned}$$



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



3+1-decomposition

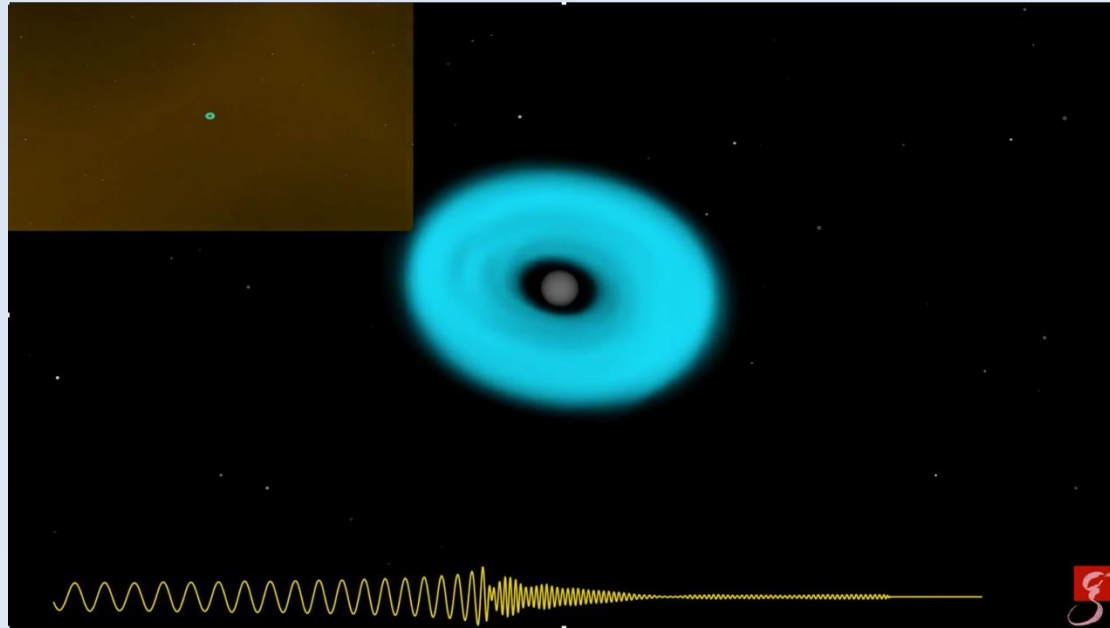
$$\partial_t \mathbf{u} = \mathbf{A}(\mathbf{u})\mathbf{u} + \mathbf{v}$$

Reformulating as initial value boundary problem

**Theoretical Framework:**

- well-posedness of PDEs
- advantageous properties

$$\begin{aligned} \partial_t \chi &= \frac{2}{3} \chi (\alpha(\dot{K} + 2\Theta) - D_i \beta^i), \\ \partial_t \gamma_{ij} &= -2\alpha \dot{\Lambda}_{ij} + \beta^k \partial_k \gamma_{ij} + 2\gamma_{ik} \partial_j \beta^k - \frac{2}{3} \gamma_{ij} \partial_k \beta^k, \\ \partial_t \dot{K} &= -D^i D_i \alpha + \alpha \left( \dot{\Lambda}_{ij} \dot{\Lambda}^{ij} + \frac{1}{3} (\dot{K} + 2\Theta)^2 \right) \\ &\quad + 4\pi\alpha(S + E) + \beta^k \partial_k \dot{K} + \alpha \kappa_1 (1 - \kappa_2) \Theta, \\ \partial_t \dot{\Lambda}_{ij} &= \chi \left( -D_i D_j \alpha + \alpha \left( {}^{(3)}R_{ij} - 8\pi S_{ij} \right)^{TF} + \alpha \left( (\dot{K} + 2\Theta) \dot{\Lambda}_{ij} - 2\dot{\Lambda}^k{}_i \dot{\Lambda}_{kj} \right) \right) \\ &\quad + \beta^k \partial_k \dot{\Lambda}_{ij} + 2\dot{\Lambda}_{ik} \partial_j \beta^k - \frac{2}{3} \dot{\Lambda}_{ij} \partial_k \beta^k, \\ \partial_t \dot{\Gamma}^i{}_k &= -2\dot{\Lambda}^i{}_k \partial_t \alpha + 2\alpha \left( \dot{\Gamma}^i{}_k \dot{\Lambda}^m{}_m - \frac{3}{2} \dot{\Lambda}^i{}_k \partial_t \ln(\chi) - \frac{1}{3} \gamma^{ik} \partial_k (\dot{K} + 2\Theta) - 8\pi \gamma^{ik} S_k \right) \\ &\quad + \gamma^{kl} \partial_k \partial_l \beta^i + \frac{1}{3} \gamma^{ik} \partial_l \partial_l \beta^i - 2\alpha \kappa_1 (\dot{\Gamma}^i{}_i - \dot{\Gamma}^k{}_k) + \beta^k \partial_k \dot{\Gamma}^i{}_i \\ &\quad - \dot{\Gamma}^k{}_k \partial_k \beta^i + \frac{2}{3} \dot{\Gamma}^i{}_k \partial_k \beta^i, \\ \partial_t \Theta &= \frac{\alpha}{2} \left( {}^{(3)}R - \dot{\Lambda}_{ij} \dot{\Lambda}^{ij} + \frac{2}{3} (\dot{K} + 2\Theta)^2 \right) - \alpha (8\pi E + \kappa_1 (2 + \kappa_2) \Theta) \\ &\quad + \beta^i \partial_i \Theta \end{aligned}$$



## Theoretical Framework:

- well-posedness of PDEs
- advantageous properties

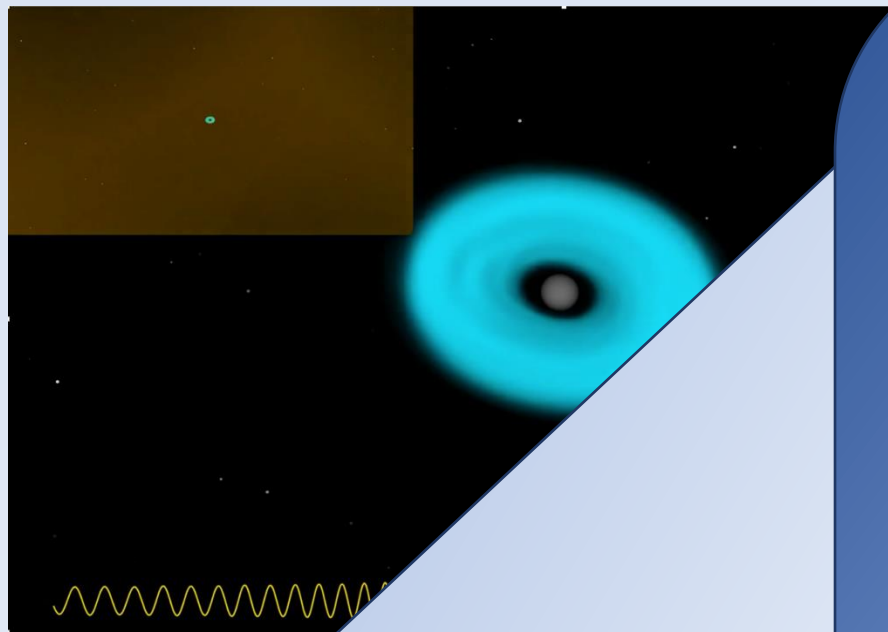
## Computational Methods:

- HPC facilities
- parallelizable code
- numerical techniques



$$\begin{aligned}
 \partial_t \chi &= \frac{2}{3} \chi (\alpha(\bar{K} + 2\Theta) - D_t \beta^k), \\
 \partial_t \bar{\gamma}_{ij} &= -2\alpha \bar{A}_{ij} + \beta^k \partial_k \bar{\gamma}_{ij} + 2\gamma_{ik} \partial_j \beta^k - \frac{2}{3} \bar{\gamma}_{ij} \partial_k \beta^k, \\
 \partial_t \bar{K} &= -D^i D_i \alpha + \alpha \left( \bar{A}_{ij} \bar{A}^{ij} + \frac{1}{3} (\bar{K} + 2\Theta)^2 \right) \\
 &\quad + 4\pi\alpha(S + E) + \beta^k \partial_k \bar{K} + \alpha \kappa_1 (1 - \kappa_2) \Theta, \\
 \partial_t \bar{A}_{ij} &= \chi \left( -D_i D_j \alpha + \alpha \left( {}^{(3)}R_{ij} - 8\pi S_{ij} \right) \right)^{TF} + \alpha \left( (\bar{K} + 2\Theta) \bar{A}_{ij} - 2\bar{A}^k_j \bar{A}_{ki} \right) \\
 &\quad + \beta^k \partial_k \bar{A}_{ij} + 2\bar{A}_{ki} \partial_j \beta^k - \frac{2}{3} \bar{A}_{ij} \partial_k \beta^k, \\
 \partial_t \bar{\Gamma}^i &= -2\bar{A}^{ik} \partial_k \alpha + 2\alpha \left( \bar{\Gamma}^i_{kl} \bar{A}^{kl} - \frac{3}{2} \bar{A}^{ik} \partial_k \ln(\chi) - \frac{1}{3} \bar{\gamma}^{ik} \partial_k (\bar{K} + 2\Theta) - 8\pi \gamma^{ik} S_k \right) \\
 &\quad + \gamma^{ij} \partial_k \partial_j \beta^k + \frac{1}{3} \gamma^{ij} \partial_k \partial_j \beta^k - 2\alpha \kappa_1 (\bar{\Gamma}^i - \bar{\Gamma}^i) + \beta^k \partial_k \bar{\Gamma}^i \\
 &\quad - \bar{\Gamma}^i \partial_k \beta^k + \frac{2}{3} \bar{\Gamma}^i \partial_k \beta^k, \\
 \partial_t \Theta &= \frac{\alpha}{2} \left( {}^{(3)}R - \bar{A}_{ij} \bar{A}^{ij} + \frac{2}{3} (\bar{K} + 2\Theta)^2 \right) - \alpha (8\pi E + \kappa_1 (2 + \kappa_2) \Theta) \\
 &\quad + \beta^k \partial_k \Theta
 \end{aligned}$$





## Theoretical Framework:

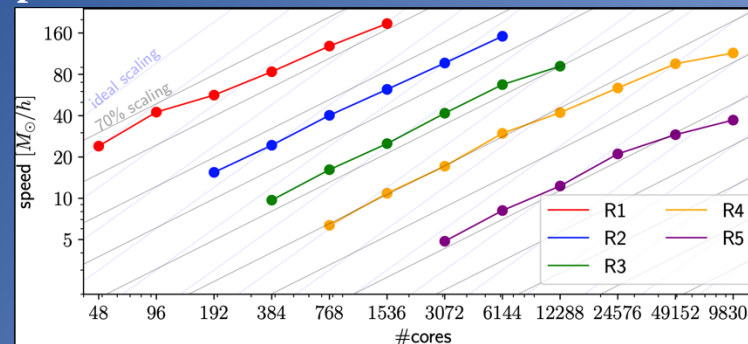
- well-posedness of PDEs
- advantageous properties

## Computational Methods:

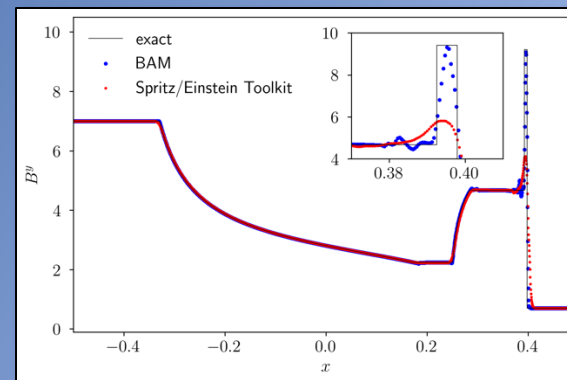
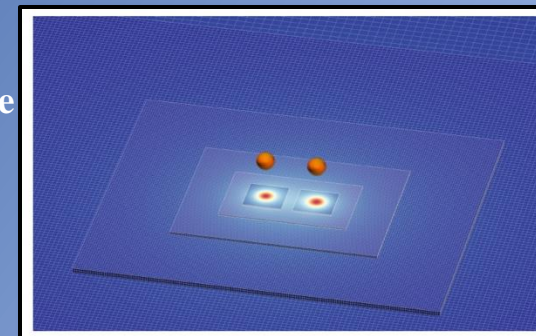
- HPC facilities
- parallelizable code
- numerical techniques



## parallelized code



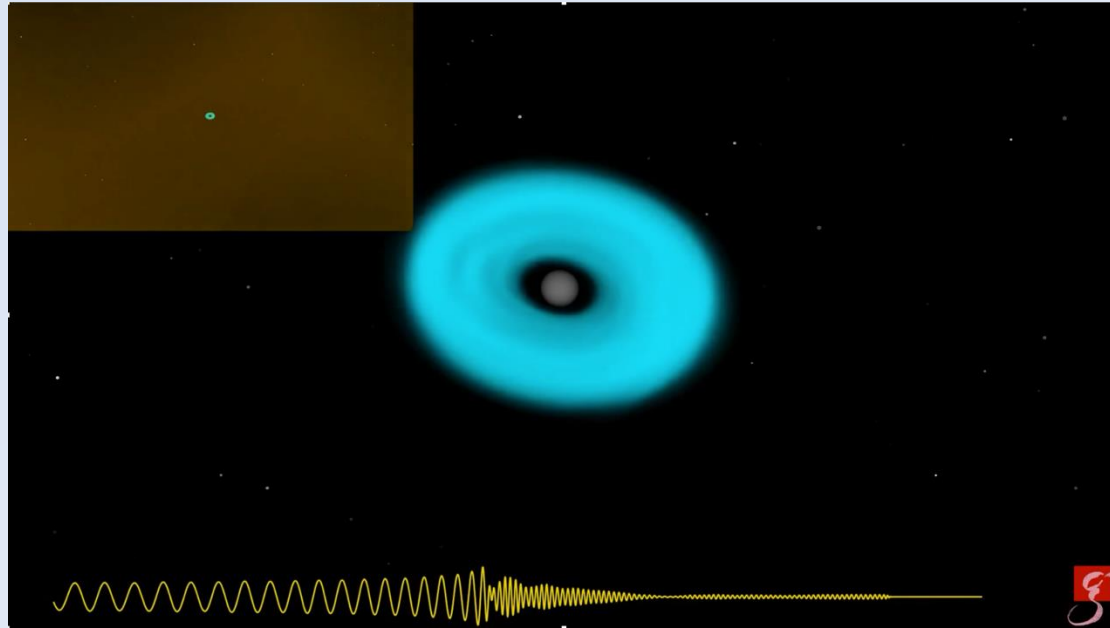
## resolving multiple length scales



handling discontinuities

deep-learning techniques to speed up matter evolution

$$\begin{aligned}
 \partial_t \chi &= \frac{2}{3} \chi (\alpha (\dot{K} + 2\Theta) - D_i \beta^i), \\
 \partial_t \gamma_{ij} &= -2\alpha \dot{A}_{ij} + \beta^k \partial_k \gamma_{ij} + 2\gamma_{ik} \partial_j \beta^k - \frac{2}{3} \gamma_{ij} \partial_k \beta^k, \\
 \partial_t \dot{K} &= -D^i D_i \alpha + \alpha \left( \dot{A}_{ij} \dot{A}^{ij} + \frac{1}{3} (\dot{K} + 2\Theta)^2 \right) \\
 &\quad + 4\pi\alpha(S + E) + \beta^k \partial_k \dot{K} + \alpha \kappa_1 (1 - \kappa_2) \Theta, \\
 \partial_t \dot{A}_{ij} &= \chi \left( -D_i D_j \alpha + \alpha \left( {}^{(3)}R_{ij} - 8\pi S_{ij} \right) \right) + \alpha \left( (\dot{K} + 2\Theta) \dot{A}_{ij} - 2\dot{A}^k_j \dot{A}_{ki} \right) \\
 &\quad + \beta^k \partial_k \dot{A}_{ij} + 2\dot{A}_{ik} \partial_j \beta^k - \frac{2}{3} \dot{A}_{ij} \partial_k \beta^k, \\
 \partial_t \tilde{\Gamma}^i &= -2\dot{A}^{ik} \partial_k \alpha + 2\alpha \left( \tilde{\Gamma}^i_{jk} \dot{A}^{jk} - \frac{3}{2} \dot{A}^{ik} \partial_k \ln(\chi) - \frac{1}{3} \gamma^{ik} \partial_k (\dot{K} + 2\Theta) - 8\pi \gamma^{ik} S_k \right) \\
 &\quad + \gamma^{ij} \partial_k \partial_j \beta^k + \frac{1}{3} \gamma^{ik} \partial_k \partial_j \beta^j - 2\alpha \kappa_1 (\tilde{\Gamma}^i - \tilde{\Gamma}^i) + \beta^k \partial_k \tilde{\Gamma}^i \\
 &\quad - \tilde{\Gamma}^{ik} \partial_k \beta^j + \frac{2}{3} \tilde{\Gamma}^{ik} \partial_k \beta^j, \\
 \partial_t \Theta &= \frac{\alpha}{2} \left( {}^{(3)}R - \dot{A}_{ij} \dot{A}^{ij} + \frac{2}{3} (\dot{K} + 2\Theta)^2 \right) - \alpha (8\pi E + \kappa_1 (2 + \kappa_2) \Theta) \\
 &\quad + \beta^i \partial_i \Theta
 \end{aligned}$$



### Theoretical Framework:

- well-posedness of PDEs
- advantageous properties

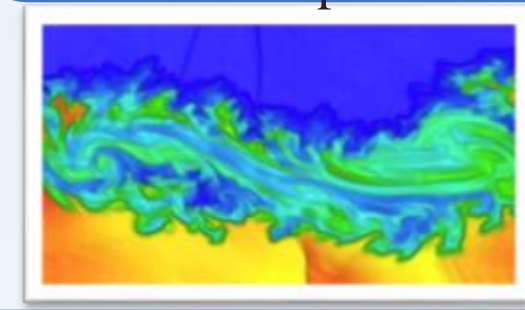
### Computational Methods:

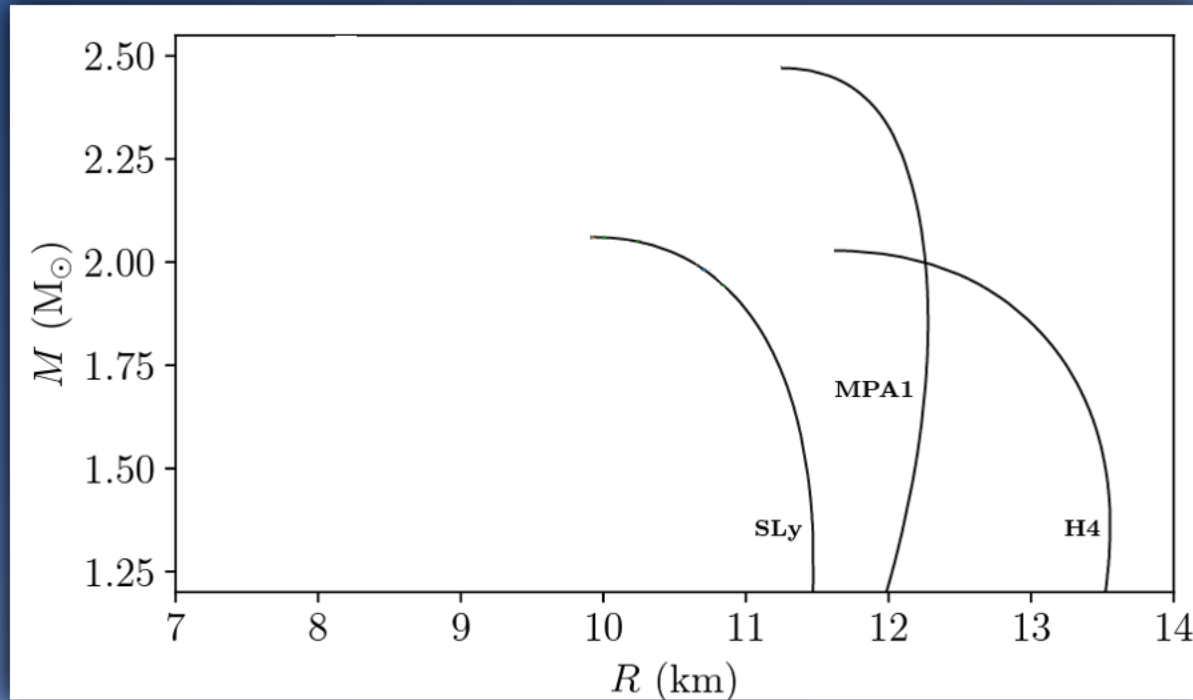
- HPC facilities
- parallelizable code
- numerical techniques

### Input Physics:

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

$$\begin{aligned}
 \partial_t \chi &= \frac{2}{3} \chi (\alpha(\dot{K} + 2\Theta) - D_i \beta^i), \\
 \partial_t \gamma_{ij} &= -2\alpha \dot{A}_{ij} + \beta^k \partial_k \gamma_{ij} + 2\gamma_{ki} \partial_j \beta^k - \frac{2}{3} \gamma_{ij} \partial_k \beta^k, \\
 \partial_t \dot{K} &= -D^i D_i \alpha + \alpha \left( \dot{A}_{ij} \dot{A}^{ij} + \frac{1}{3} (\dot{K} + 2\Theta)^2 \right) \\
 &\quad + 4\pi\alpha(S + E) + \beta^k \partial_k \dot{K} + \alpha \kappa_1 (1 - \kappa_2) \Theta, \\
 \partial_t \dot{A}_{ij} &= \chi \left( -D_i D_j \alpha + \alpha \left( {}^{(3)}R_{ij} - 8\pi S_{ij} \right) \right)^{TF} + \alpha \left( (\dot{K} + 2\Theta) \dot{A}_{ij} - 2\dot{A}^k_j \dot{A}_{ki} \right) \\
 &\quad + \beta^k \partial_k \dot{A}_{ij} + 2\dot{A}_{ki} \partial_j \beta^k - \frac{2}{3} \dot{A}_{ij} \partial_k \beta^k, \\
 \partial_t \tilde{\Gamma}^i &= -2\dot{A}^{jk} \partial_k \alpha + 2\alpha \left( \tilde{\Gamma}^i_{jk} \tilde{A}^{jk} - \frac{3}{2} \dot{A}^{jk} \partial_k \ln(\chi) - \frac{1}{3} \gamma^{jk} \partial_k (\dot{K} + 2\Theta) - 8\pi \gamma^{ik} S_i \right) \\
 &\quad + \gamma^{ij} \partial_k \partial_j \beta^k + \frac{1}{3} \gamma^{ij} \partial_k \partial_k \beta^i - 2\alpha \kappa_1 (\tilde{\Gamma}^i - \tilde{\Gamma}^i) + \beta^k \partial_k \tilde{\Gamma}^i \\
 &\quad - \tilde{\Gamma}^k \partial_k \beta^i + \frac{2}{3} \tilde{\Gamma}^{ij} \partial_k \beta^k, \\
 \partial_t \Theta &= \frac{\alpha}{2} \left( {}^{(3)}R - \dot{A}_{ij} \dot{A}^{ij} + \frac{2}{3} (\dot{K} + 2\Theta)^2 \right) - \alpha (8\pi E + \kappa_1 (2 + \kappa_2) \Theta) \\
 &\quad + \beta^i \partial_i \Theta
 \end{aligned}$$

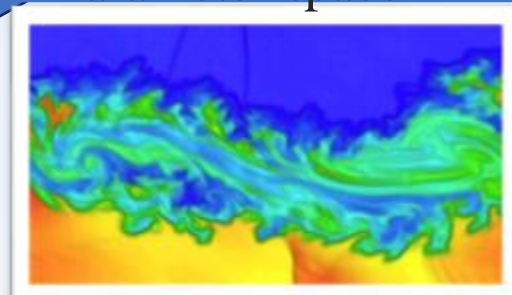




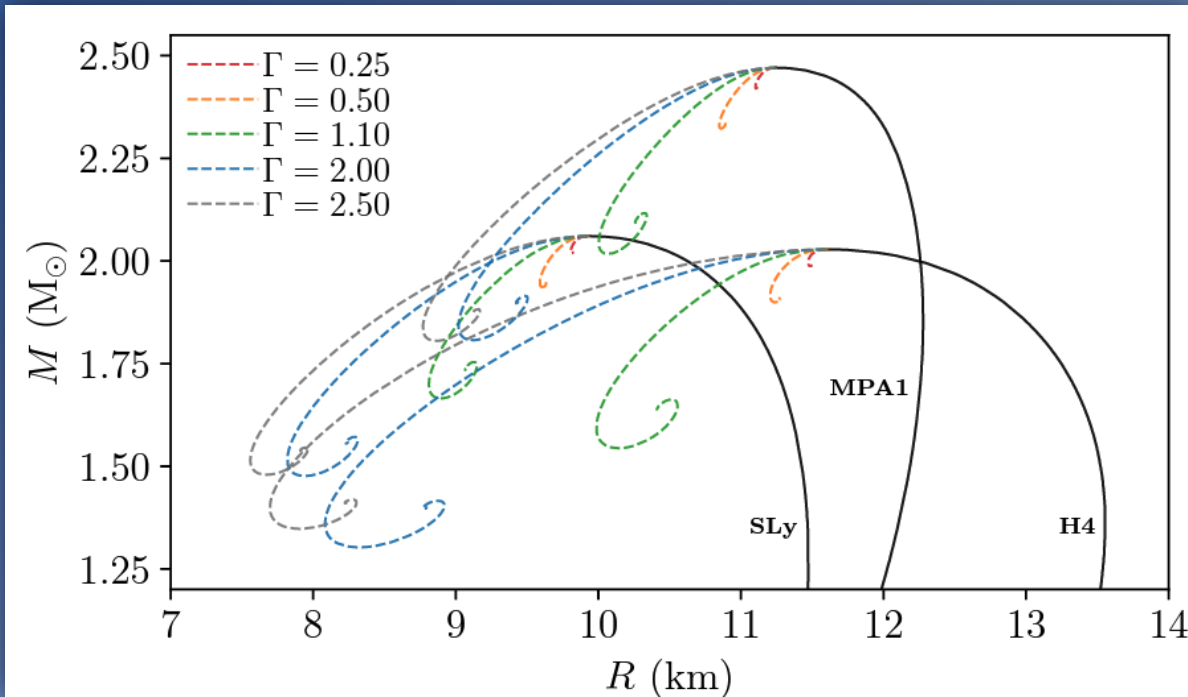
- Can we test matter above the TOV limit?

### Input Physics:

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



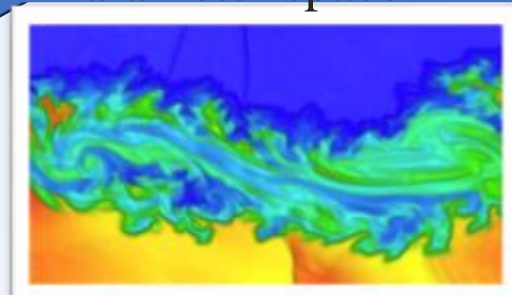
$$\partial_t \bar{\Gamma}^{\alpha} + \bar{\Gamma}^{\alpha} \partial_t \beta^{\alpha} + \frac{2}{3} \bar{\Gamma}^{\alpha} \partial_t \bar{\Gamma}^{\alpha} - \alpha \left( 8\pi E + \kappa_1 (2 + \kappa_2) \Theta \right) - \alpha \left( \bar{\omega} R - \bar{\Lambda}_{ij} \bar{A}^{ij} + \frac{2}{3} (\bar{K} + 2\Theta)^2 \right) + \beta^{\alpha} \partial_{\alpha} \Theta$$



• Can we test matter above the TOV limit?

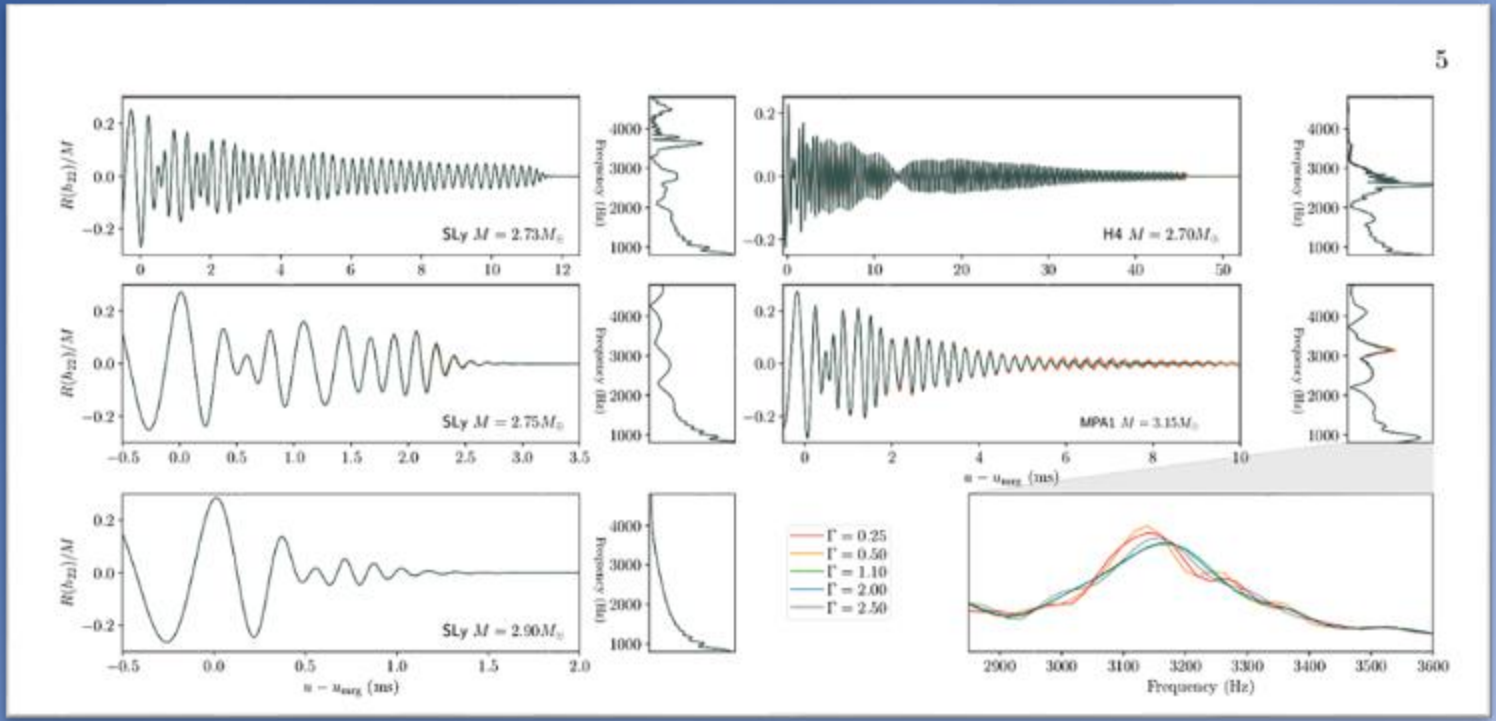
### Input Physics:

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



$$\partial_t \Gamma^4 = \frac{\alpha}{2} \left( \omega R - \bar{A}_{ij} \bar{A}^{ij} + \frac{2}{3} (\bar{K} + 2\Theta)^2 \right) - \alpha (8\pi E + \kappa_1 (2 + \kappa_2 \Theta)) + \beta^i \partial_i \Theta$$



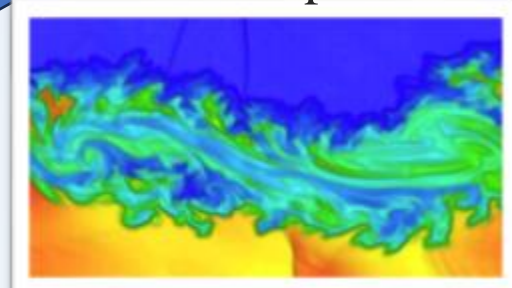


- Can we test matter above the TOV limit?

No!

### Input Physics:

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

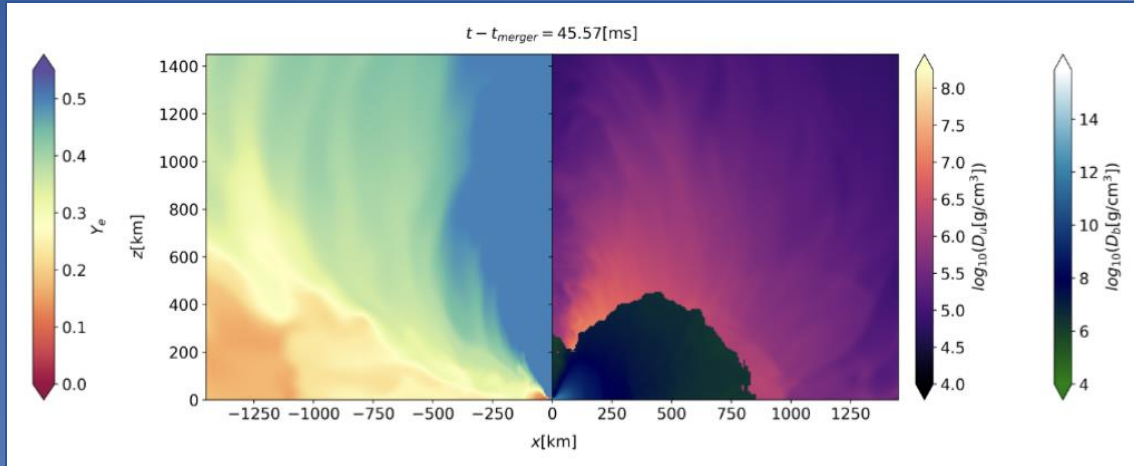


$$\partial_t \Gamma^4 = \dots$$

$$\partial_t \Theta = \frac{\alpha}{2} \left( \omega R - \dot{\Lambda}_{ij} \dot{\Lambda}^{ij} + \frac{2}{3} (\dot{K} + 2\Theta)^2 \right) - \alpha (\delta\pi E + \kappa_1 (2 + \kappa_2) \Theta) + \beta \partial_t \Theta$$



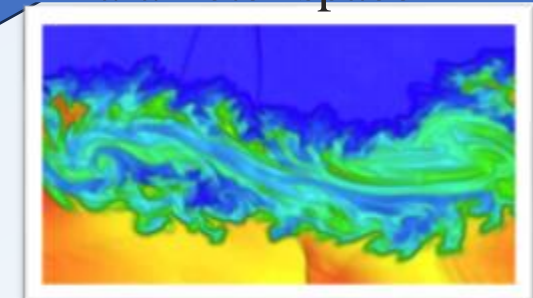
## neutrino radiation



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

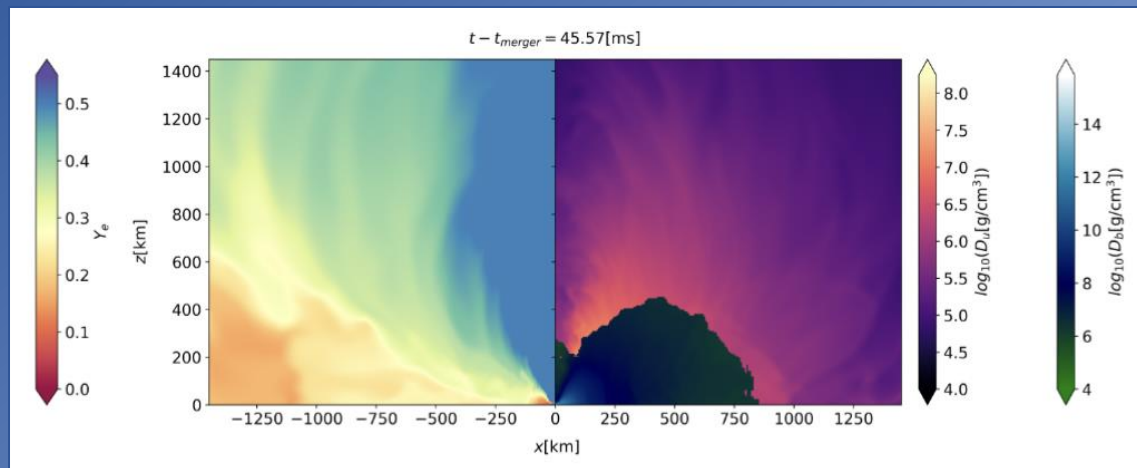
## Input Physics:

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



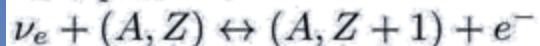
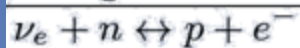
$$\partial_t \bar{\rho} = -\nabla \cdot (\bar{\rho} \mathbf{v}) + \bar{\rho} \beta$$
$$\partial_t \bar{\rho} = \frac{\alpha}{2} \left( \bar{\omega} R - \bar{A}_{ij} \bar{A}^{ij} + \frac{2}{3} (\bar{K} + 2\Theta)^2 \right) - \alpha (\delta \pi E + \kappa_1 (2 + \kappa_2) \Theta) + \beta \partial_t \Theta$$

## neutrino radiation

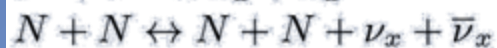
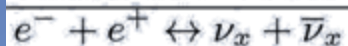


Schianchi et al., arXiv: 2307.04572  
Gieg et al., Universe 8 (2022) 7, 370

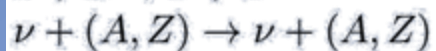
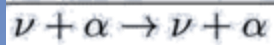
### Charged Current Processes



### Thermal Processes



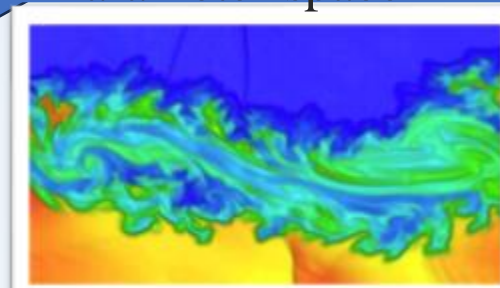
### Elastic Scattering



- 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
- Turbulences
- Parameter space

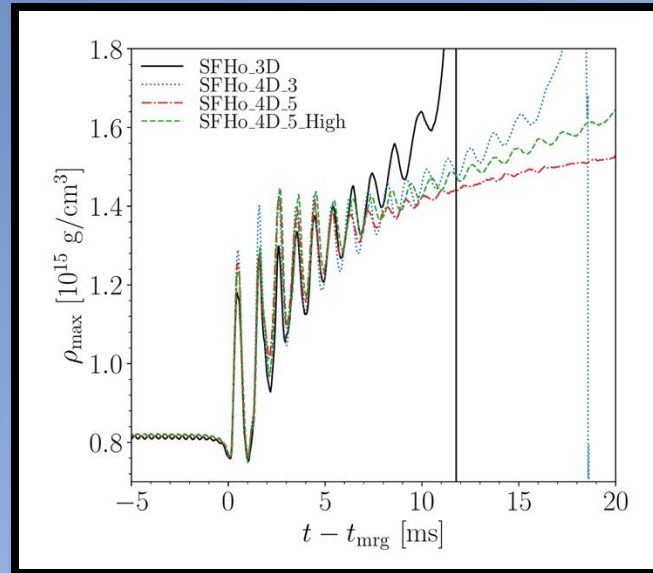
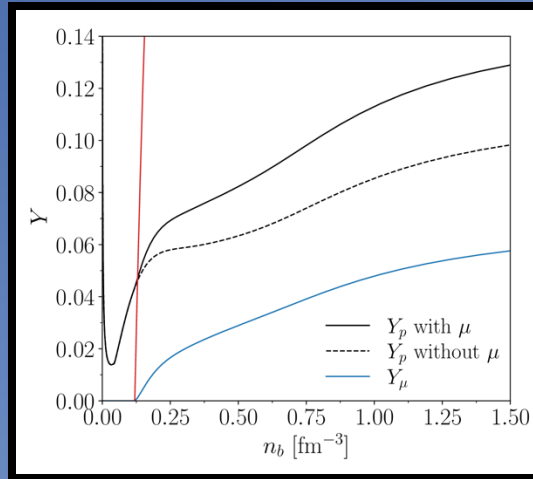


$$\partial_t \Gamma^{\alpha} = \dots$$

$$\partial_t \Theta = \frac{\alpha}{2} \left( \omega R - \bar{\lambda}_{ij} \bar{A}^{ij} + \frac{2}{3} (\bar{K} + 2\Theta)^2 \right) - \alpha (\delta \pi E + \kappa_1 (2 + \kappa_2) \Theta) + \beta^i \partial_i \Theta$$

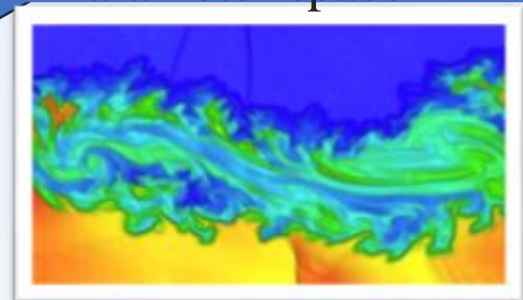
# Inclusion of muonic neutrinos – Gieg et al., 2024, arXiv: 2409.04420

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



## Input Physics:

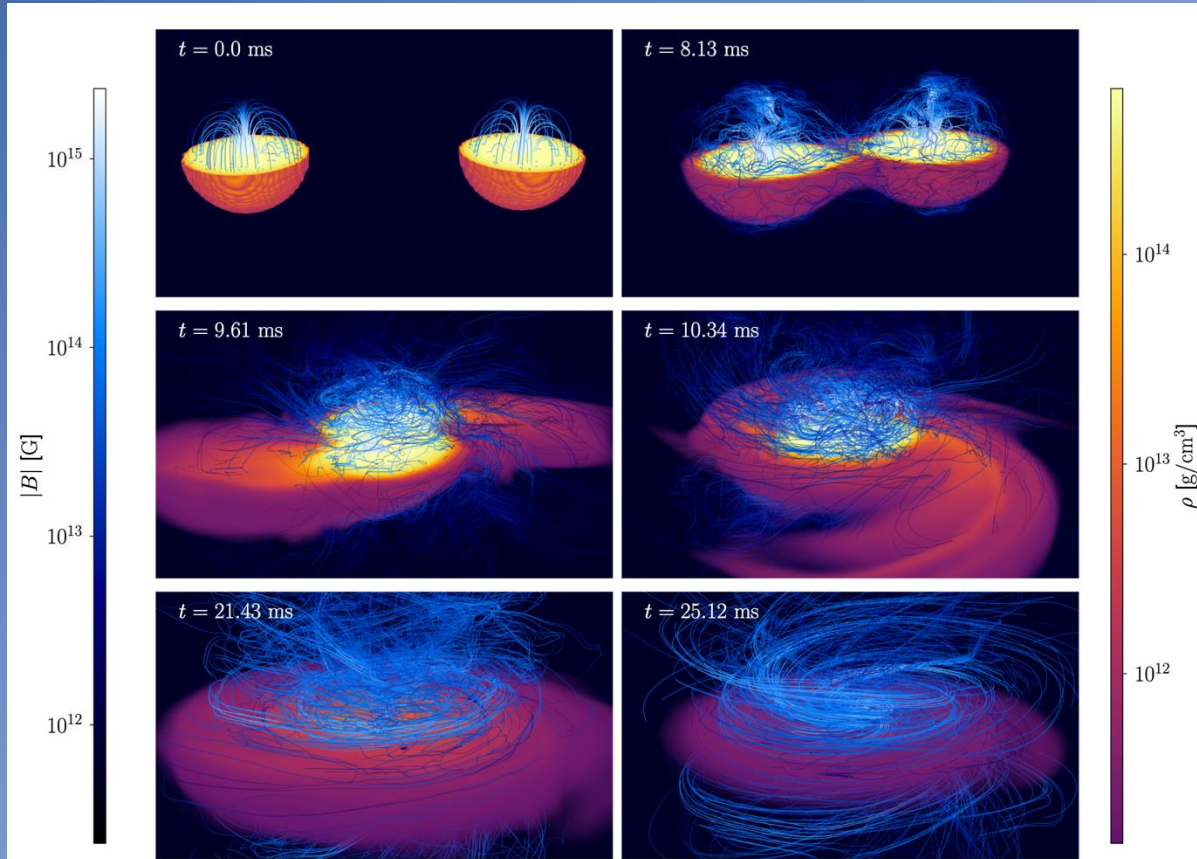
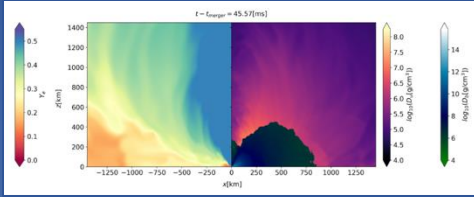
- Microphysics (EOS, Neutrinos)
- Magnetic fields
- Turbulences
- Parameter space



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

$$\partial_t \theta = \frac{\alpha}{2} \left( \omega R - \bar{A}_{ij} \bar{A}^{ij} + \frac{2}{3} (\bar{K} + 2\Theta)^2 \right) - \alpha (8\pi E + \kappa_1 (2 + \kappa_2) \Theta) + \beta^i \partial_i \Theta$$





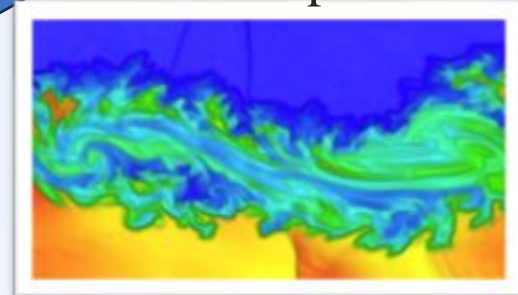
## magnetic fields and turbulences

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

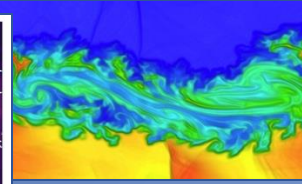
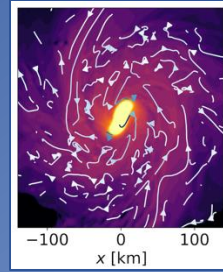
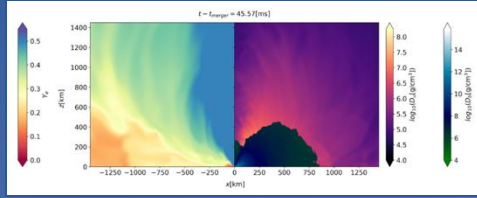
$$\partial_t \theta = \frac{\alpha}{2} \left( \omega R - \tilde{A}_{ij} \tilde{A}^{ij} + \frac{2}{3} (\tilde{K} + 2\Theta)^2 \right) - \alpha (\delta \pi E + \kappa_1 (2 + \kappa_2) \Theta) + \beta^i \partial_i \Theta$$

## Input Physics:

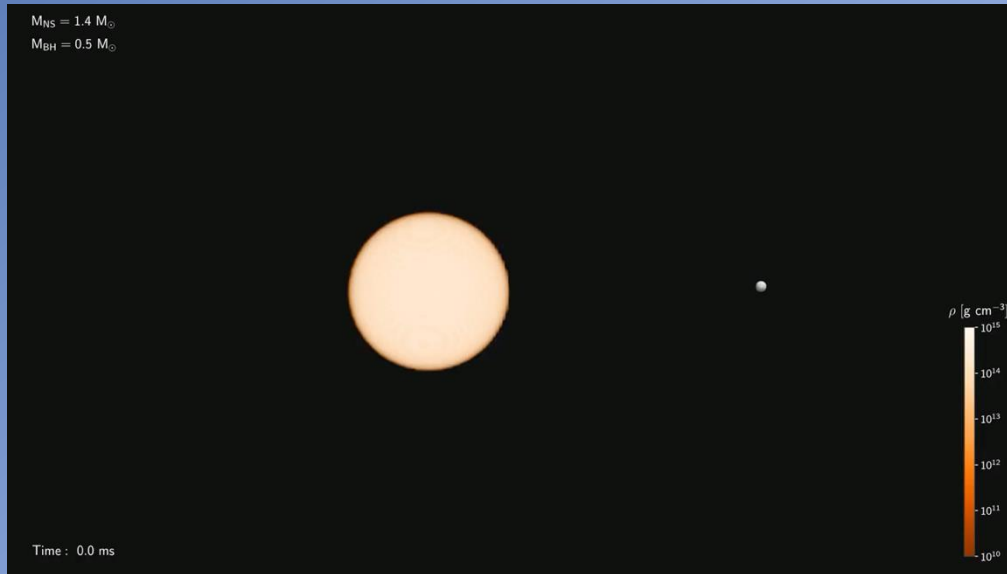
- Microphysics (EOS, Neutrinos)
- Magnetic fields
- Turbulences
- Parameter space







parameter  
space coverage

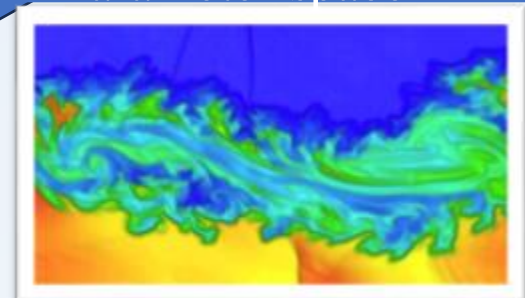


Markin et al., PRD 108 (2023) 2, 023016

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

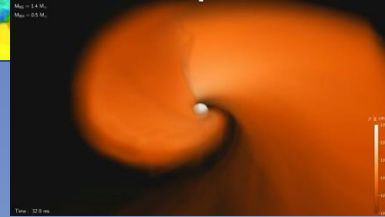
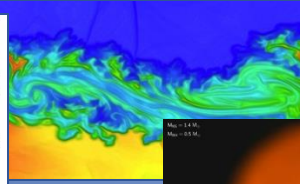
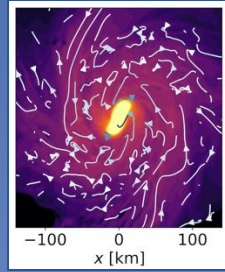
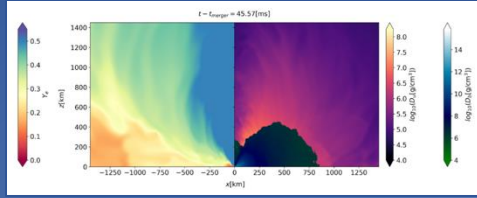
### Input Physics:

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

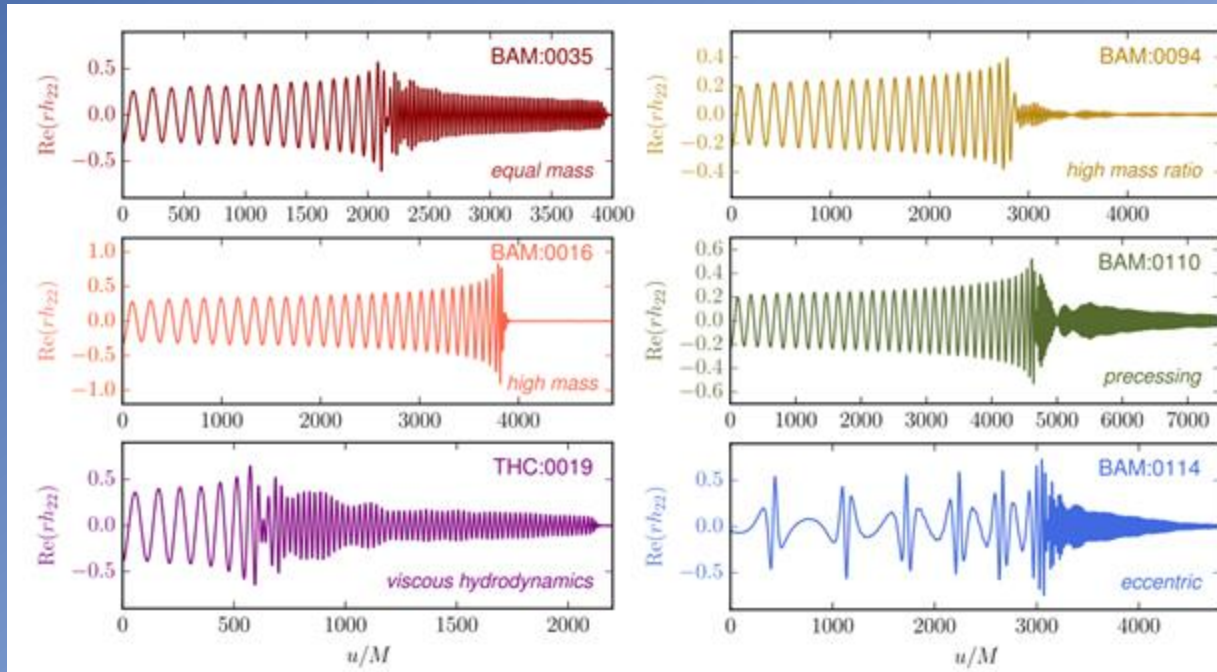


$$\partial_t \bar{\rho} = \frac{\alpha}{2} \left( \bar{\omega} R - \bar{\Lambda}_{ij} \bar{A}^{ij} + \frac{2}{3} (\bar{K} + 2\Theta)^2 \right) - \alpha (8\pi E + \kappa_1 (2 + \kappa_2) \Theta) + \beta^i \partial_i \Theta$$



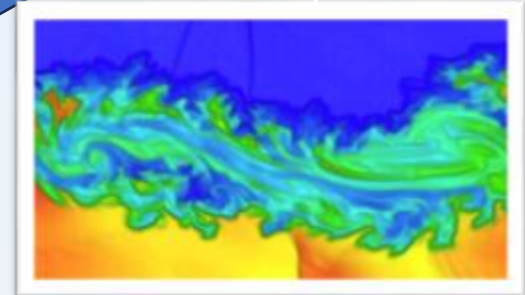


parameter space coverage



### Input Physics:

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



publicly released more than 590 individual simulations using more than 1/2 billion CPUHs

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

$$\partial_t \theta = \frac{\alpha}{2} \left( \omega R - \tilde{A}_{ij} \tilde{A}^{ij} + \frac{2}{3} (\tilde{K} + 2\theta)^2 \right) - \alpha (\delta \pi E + \kappa_1 (2 + \kappa_2) \theta) + \beta^i \partial_i \theta$$



# Inspiral waveforms

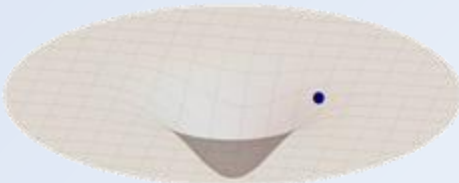
## Various models



*Numerical Relativity Simulations*



*Post-Newtonian Theory*

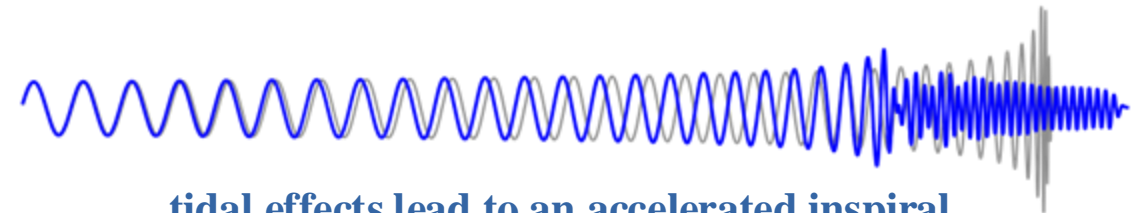
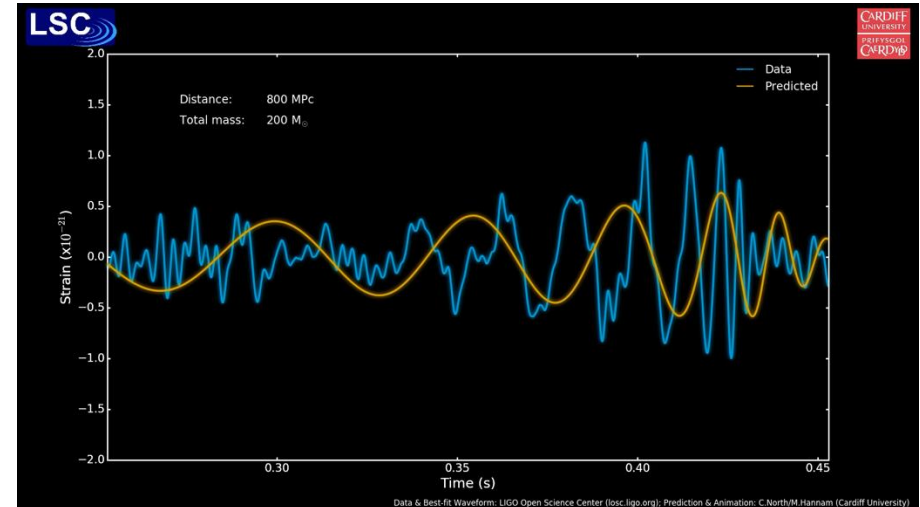


*Effective-one-body Formalism*



*Phenomenological Models*

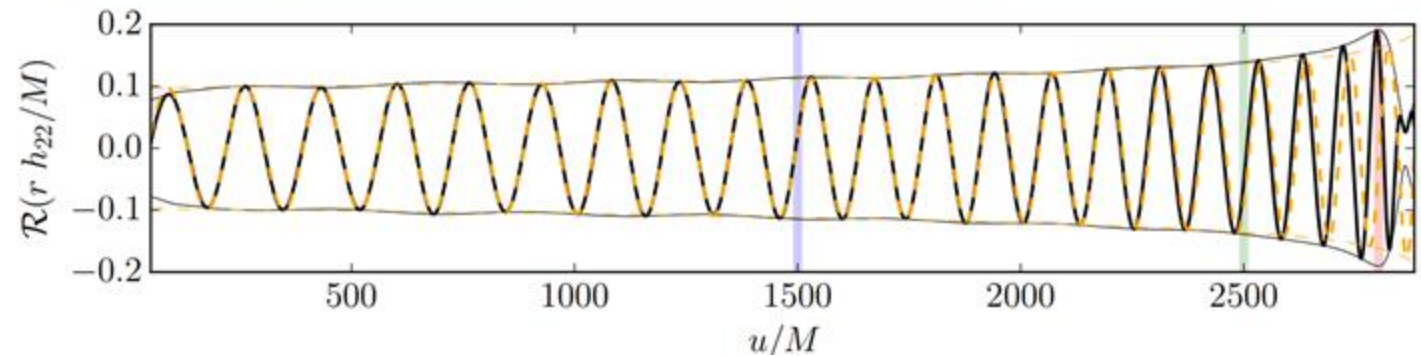
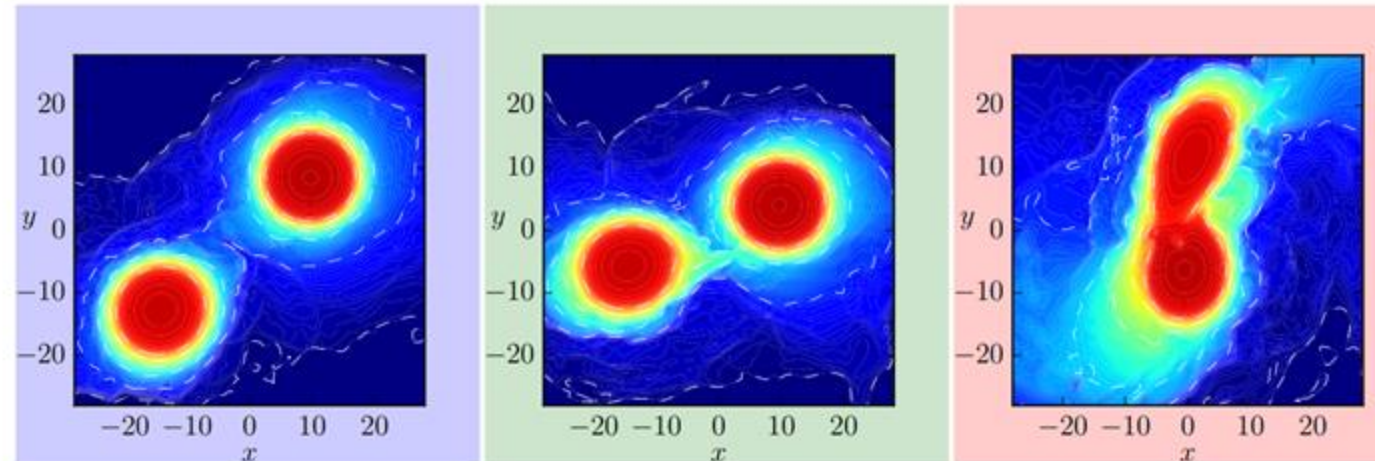
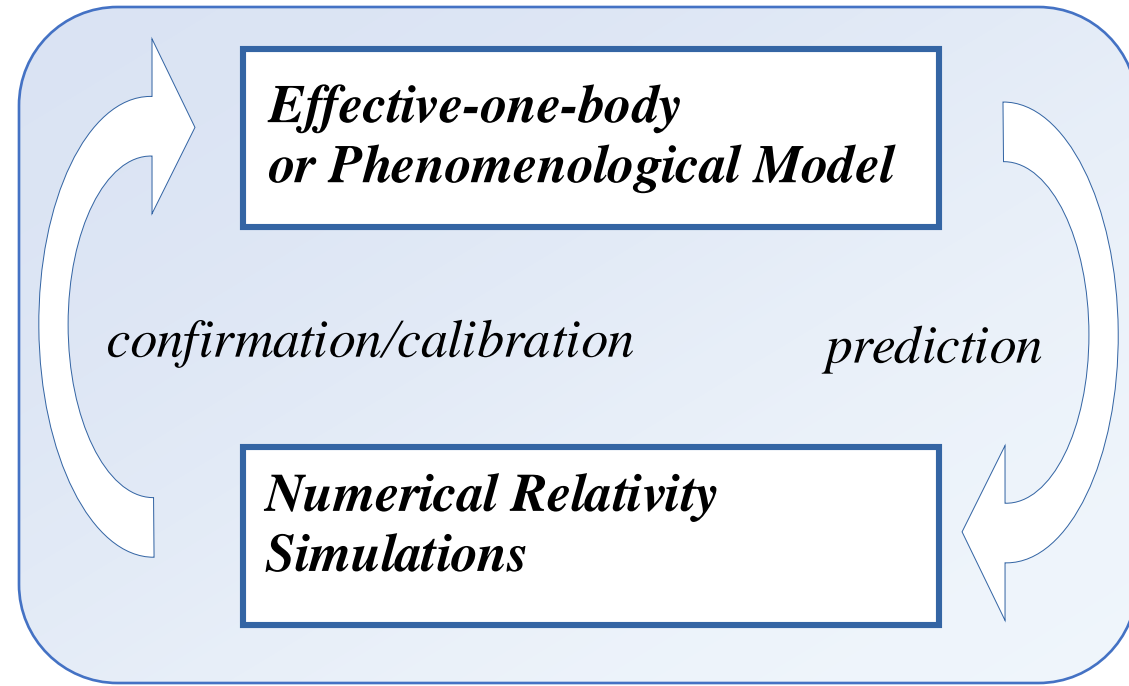
hundreds of millions of templates  
need to interpret the data



tidal effects lead to an accelerated inspiral

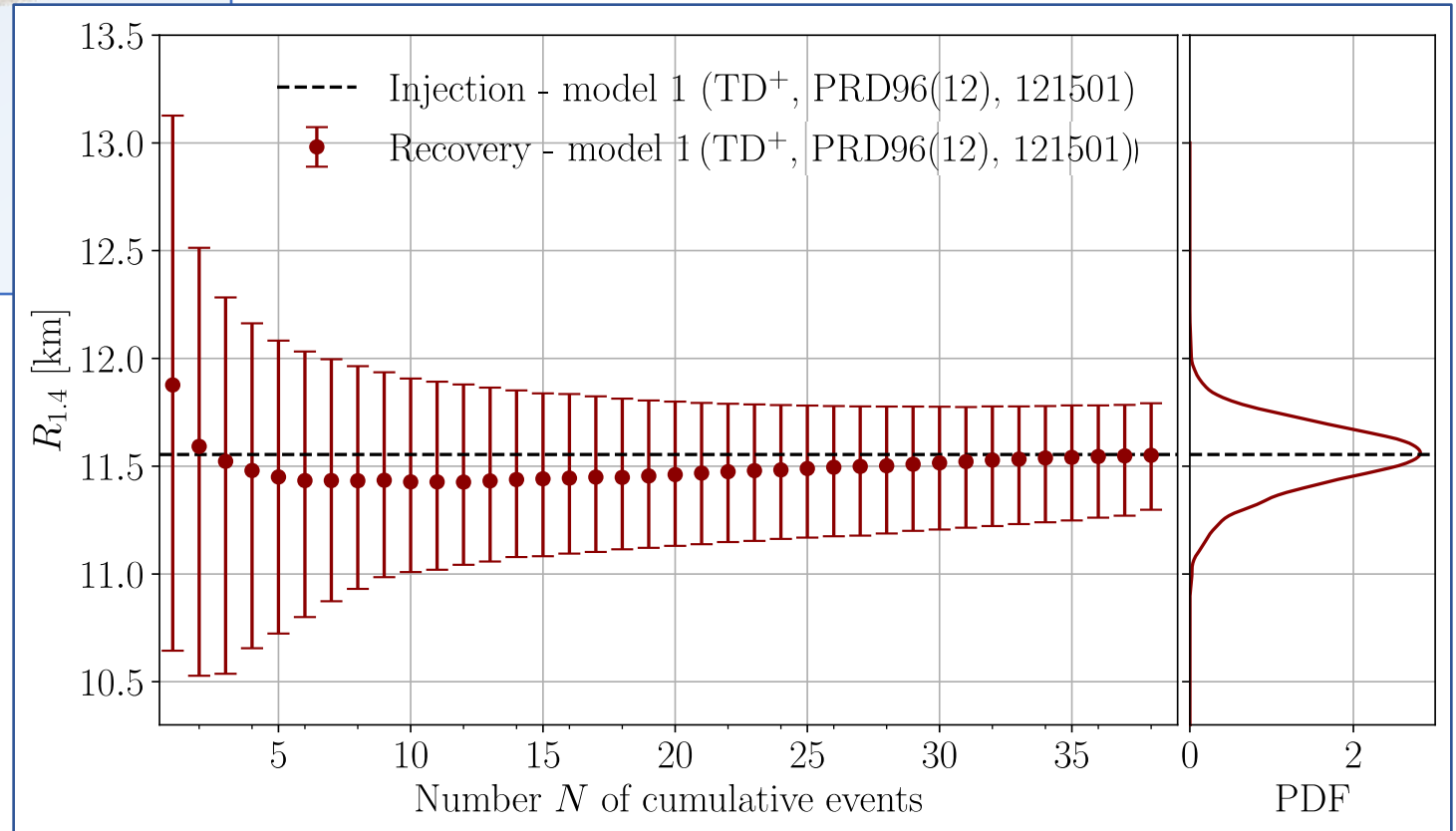
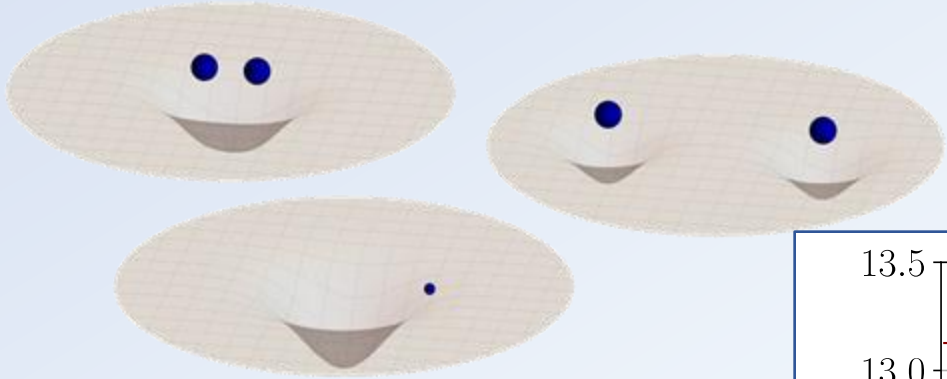


# Waveform Model Development through NR simulations



# Inspiral waveforms

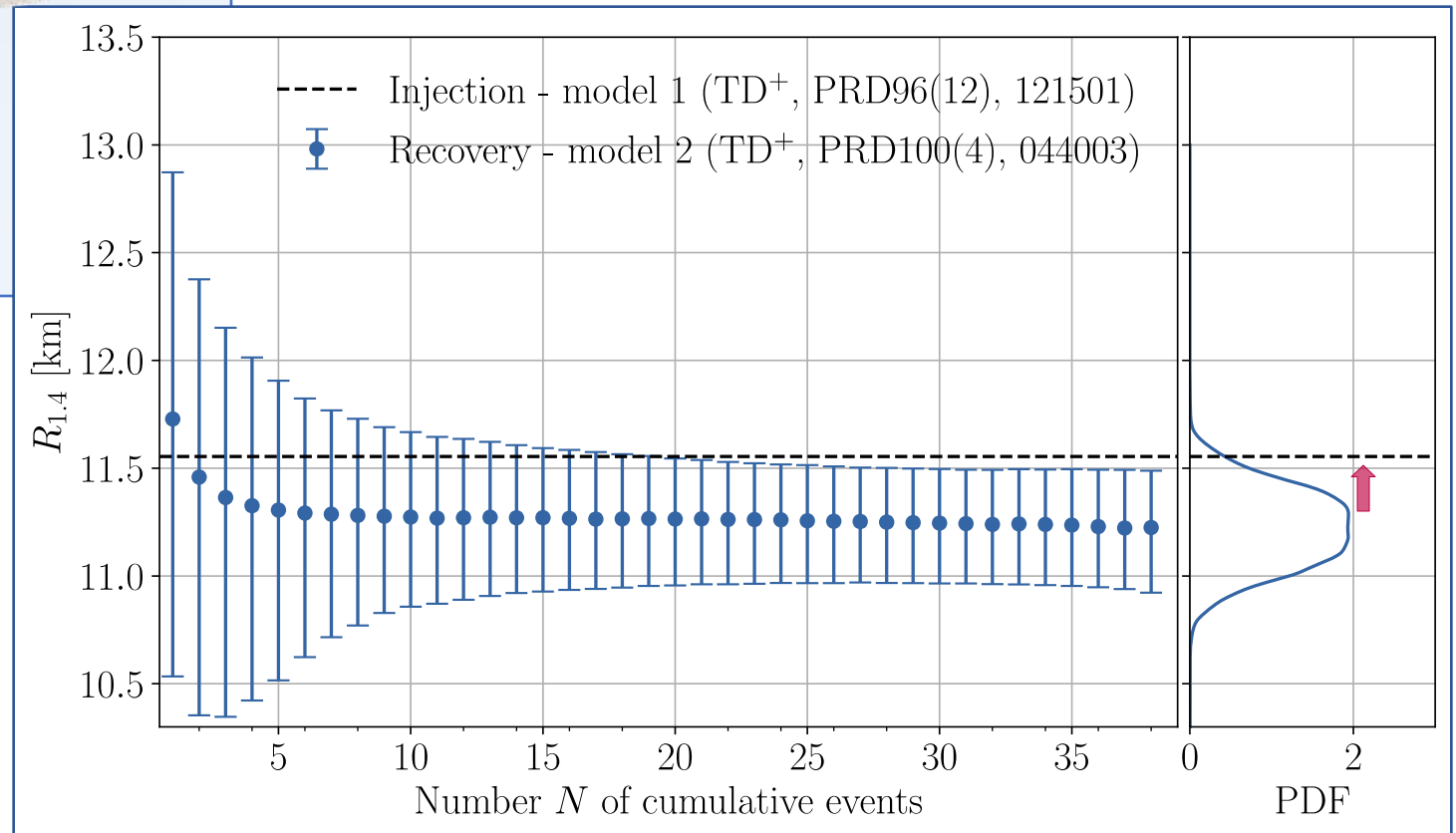
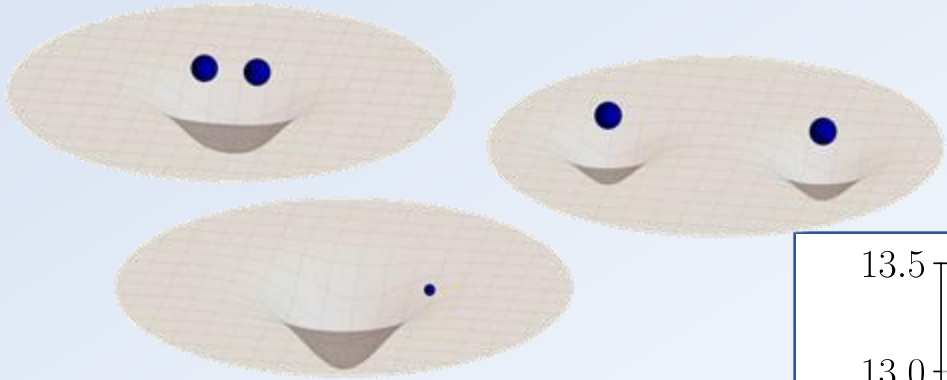
## Various models





# Inspiral waveforms

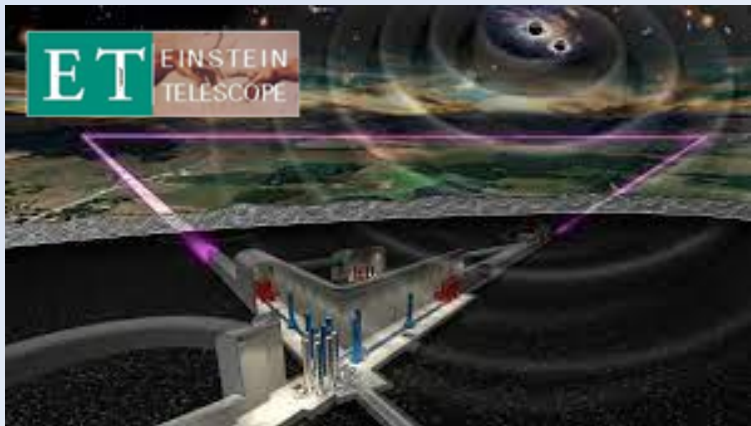
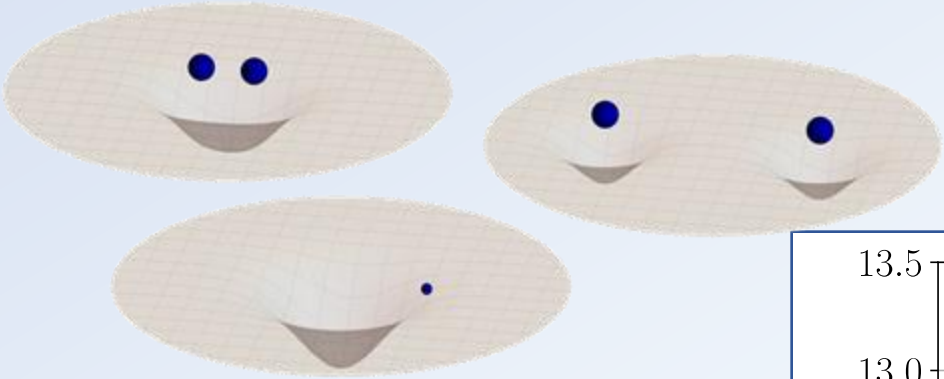
## Various models



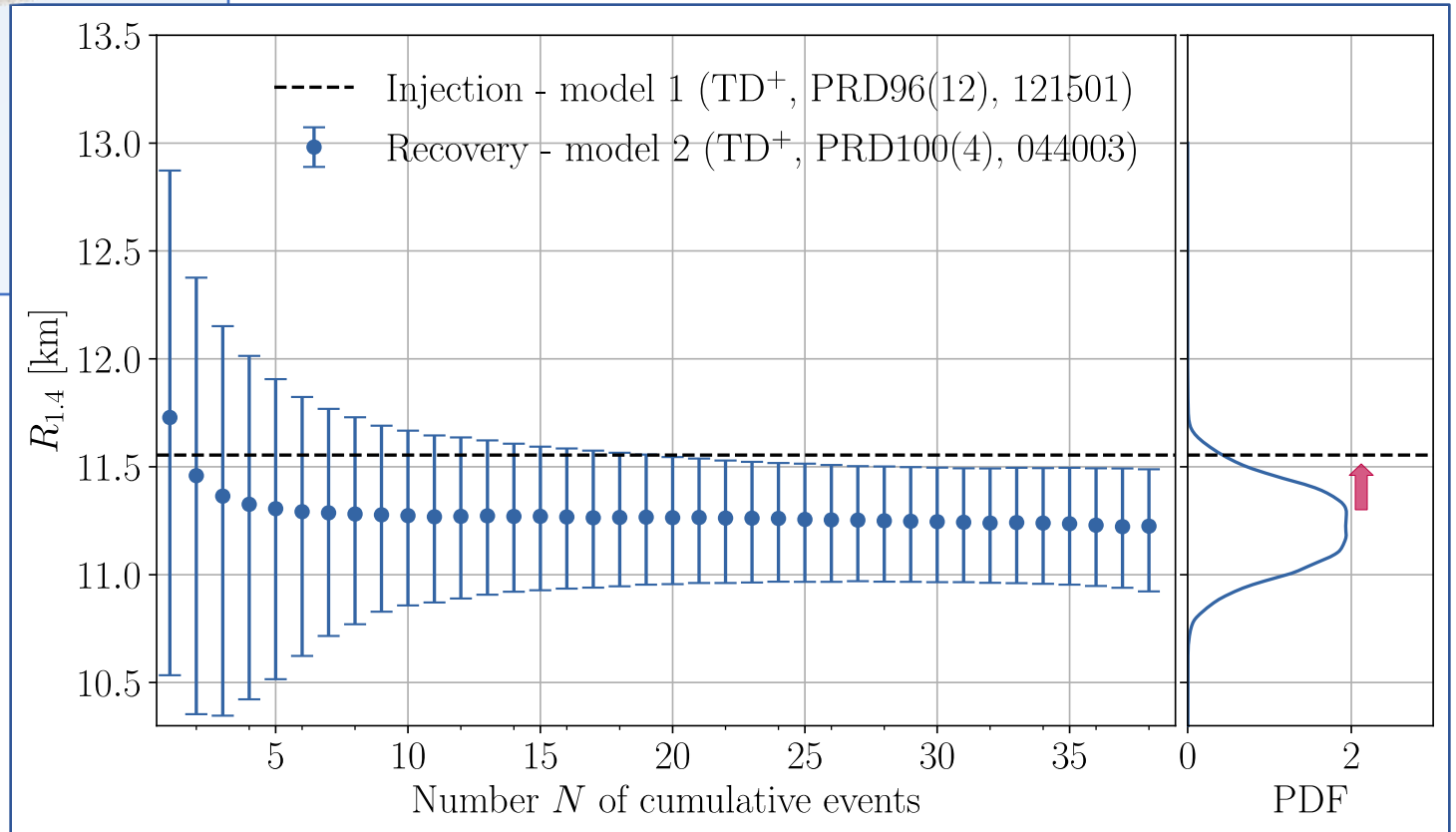
# Inspiral waveforms

## Various models

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



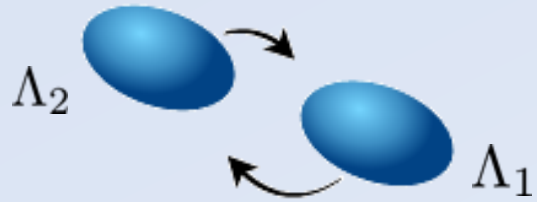
Einstein Telescope



# Gravitational Wave Analysis

*GW170817*

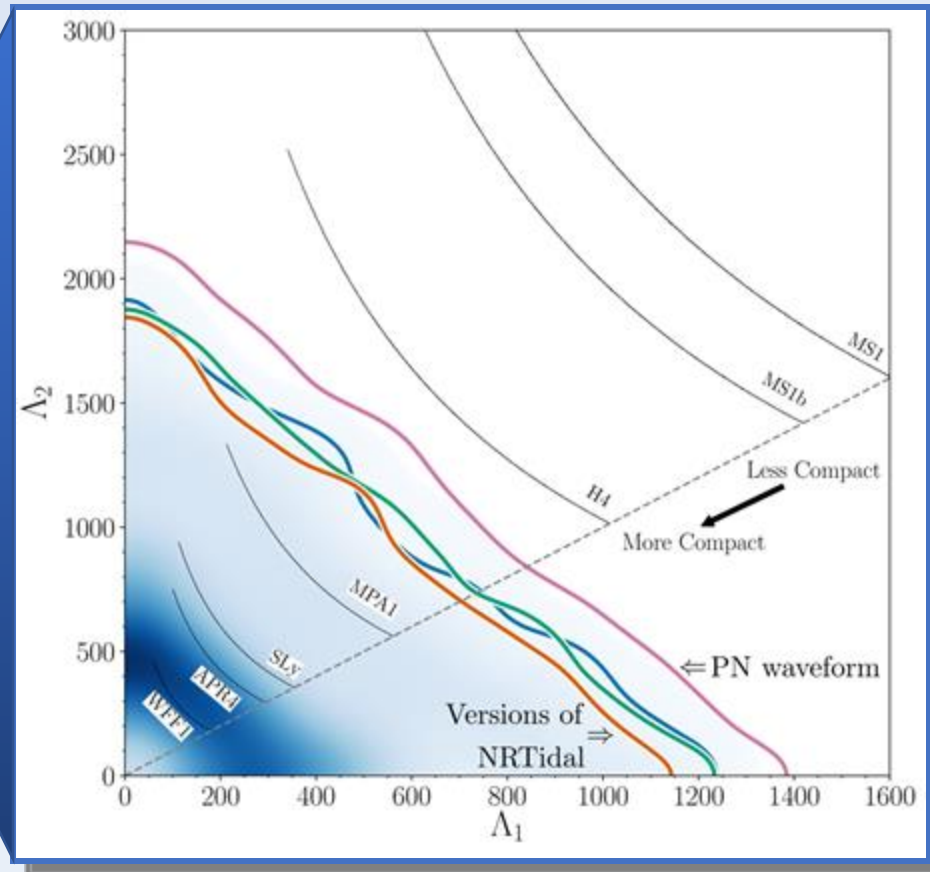
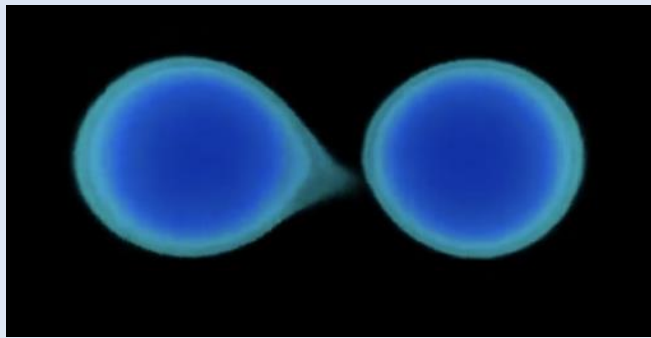
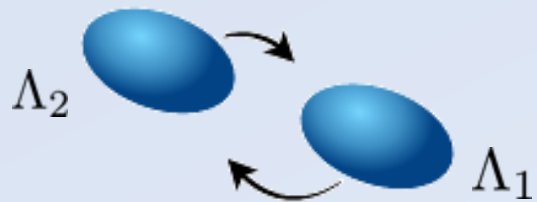
$\Lambda$  determines tidal deformability



# Gravitational Wave Analysis

*GW170817*

$\Lambda$  determines tidal deformability

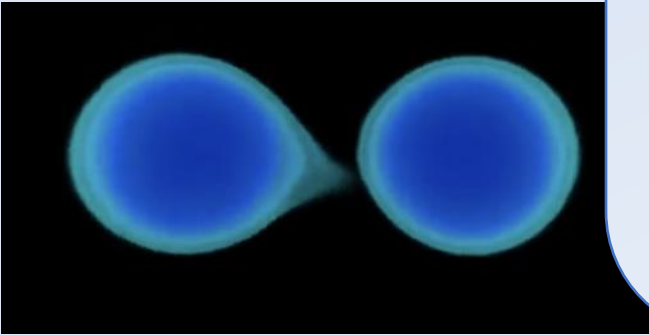
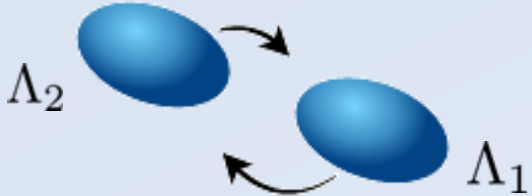


→ no assumption about the type of the compact object

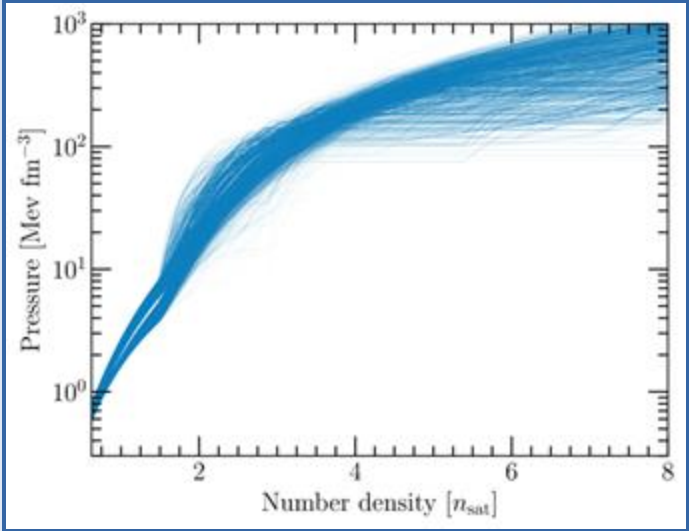
# Gravitational Wave Analysis

*GW170817*

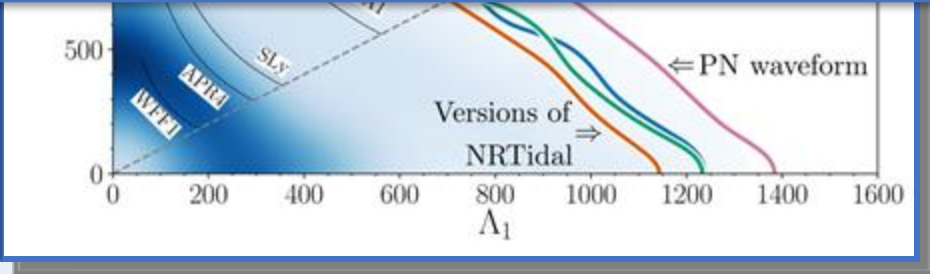
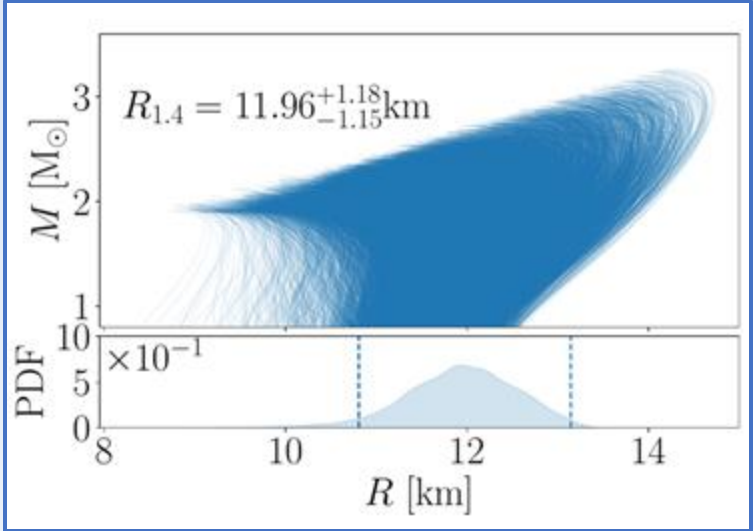
$\Lambda$  determines tidal deformability



**Assumption: The merging objects were neutron stars**



**nuclear-physics computations**



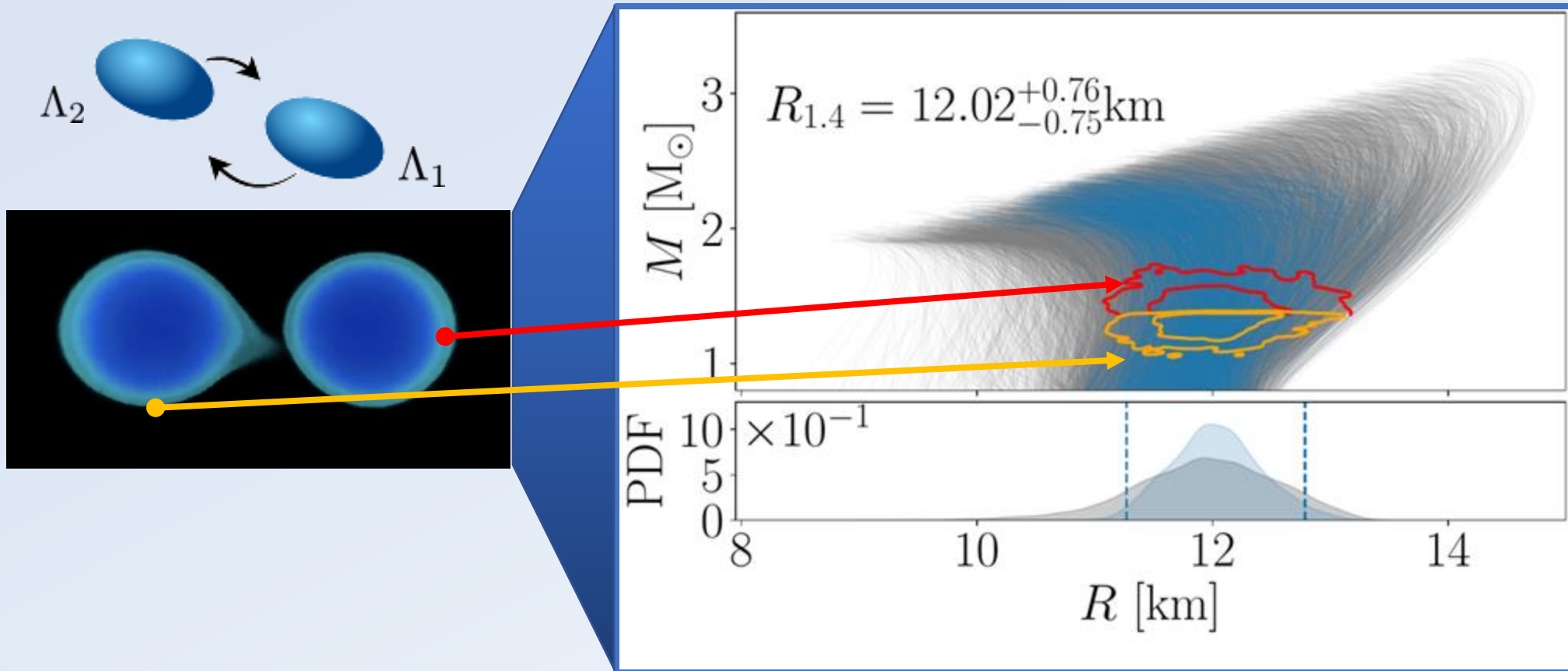
→ no assumption about the type of the compact object



# Gravitational Wave Analysis

*GW170817*

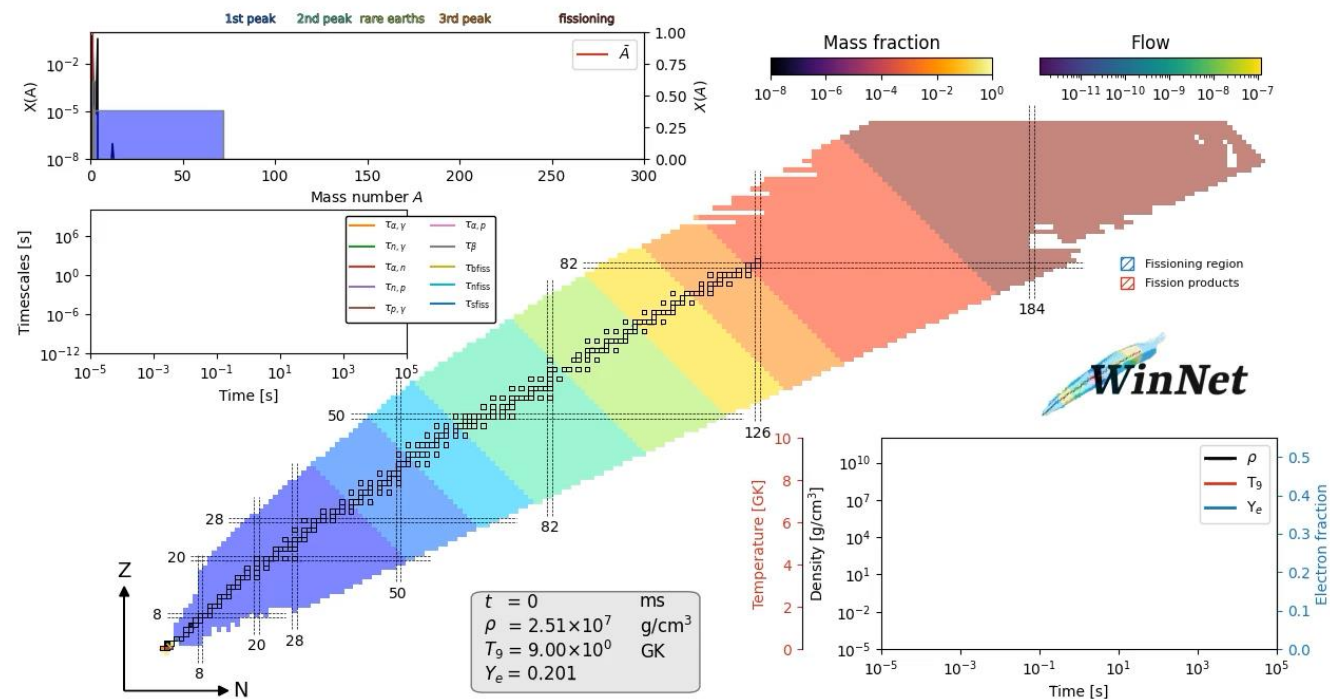
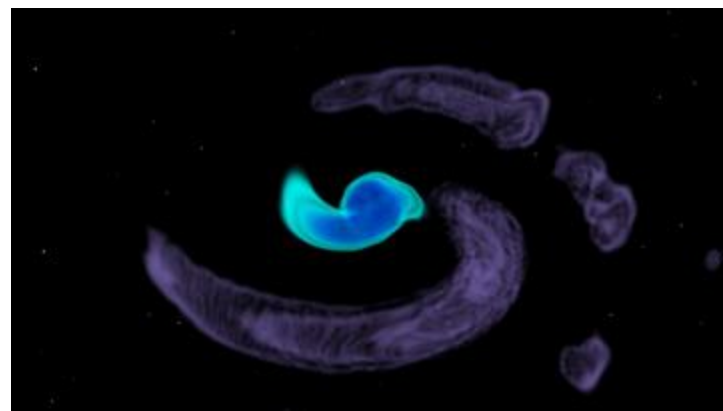
$\Lambda$  determines tidal deformability



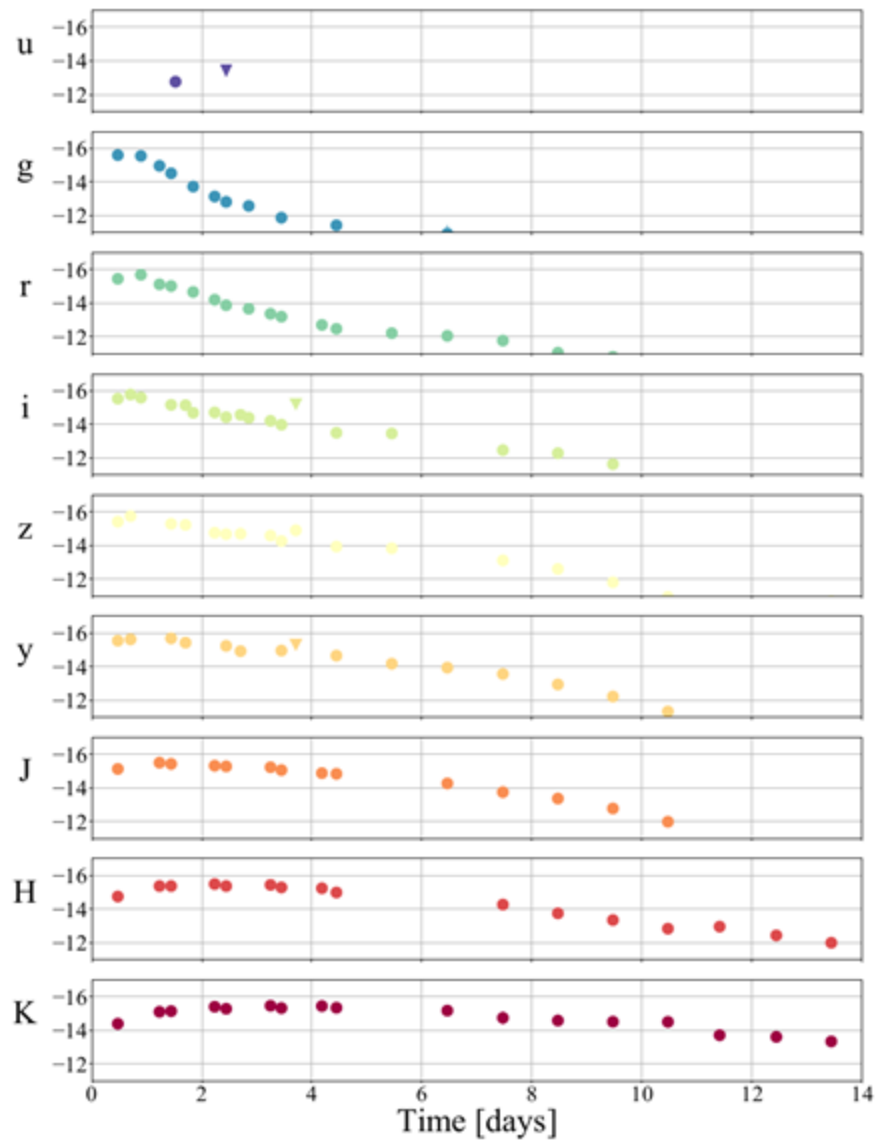
Assumption: The merging objects were neutron stars

# EM Signals – Kilonova

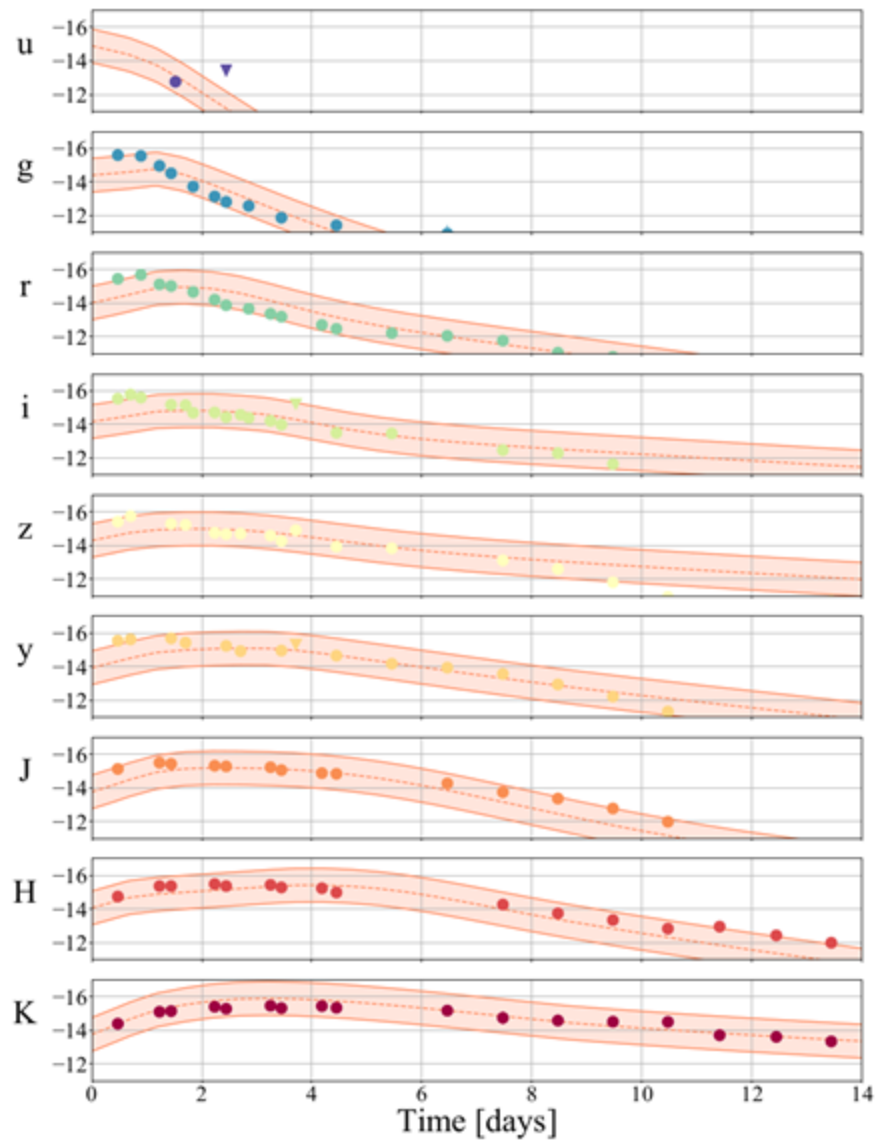
- neutron rich ejecta produce heavy r-process elements
- pseudo-black body radiation from r-process elements
- mergers are major sites for the formation of heavy elements



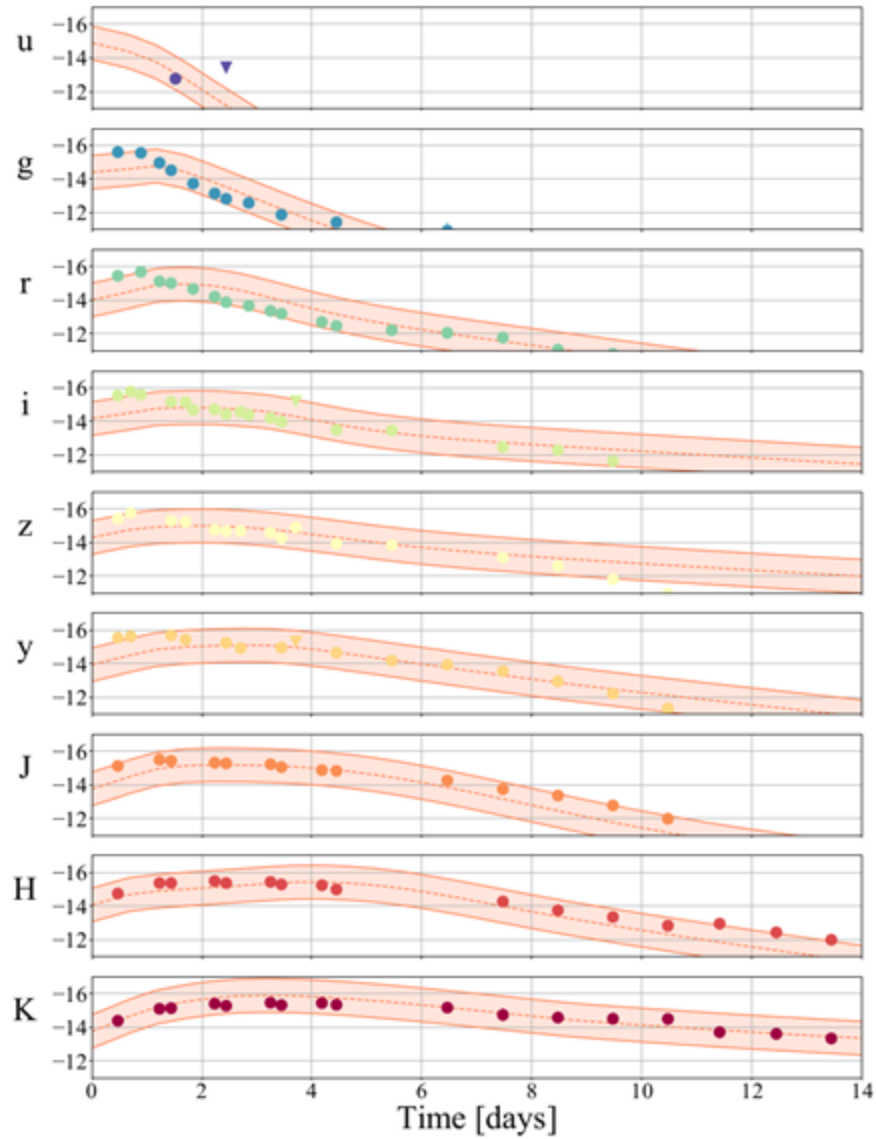
# Photometric lightcurves



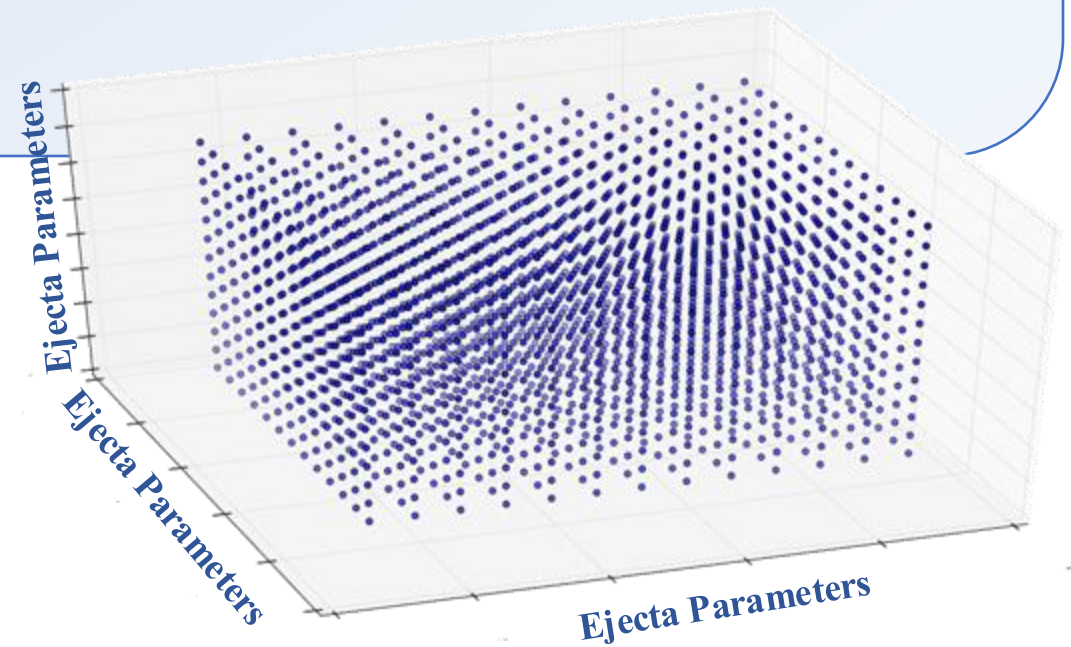
# Photometric lightcurves



## Photometric lightcurves



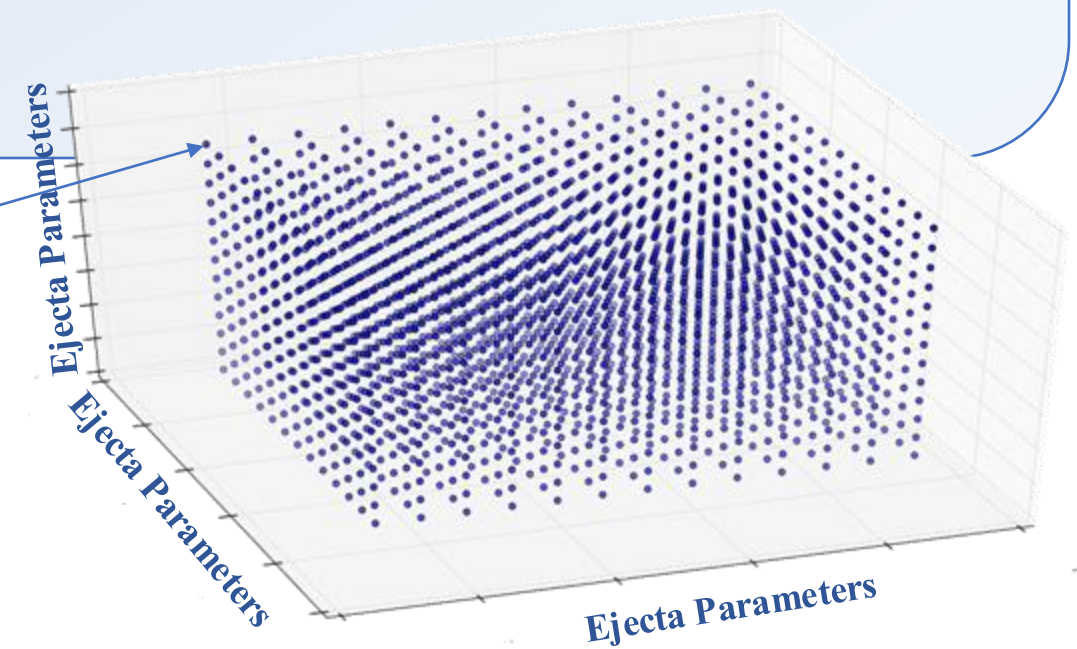
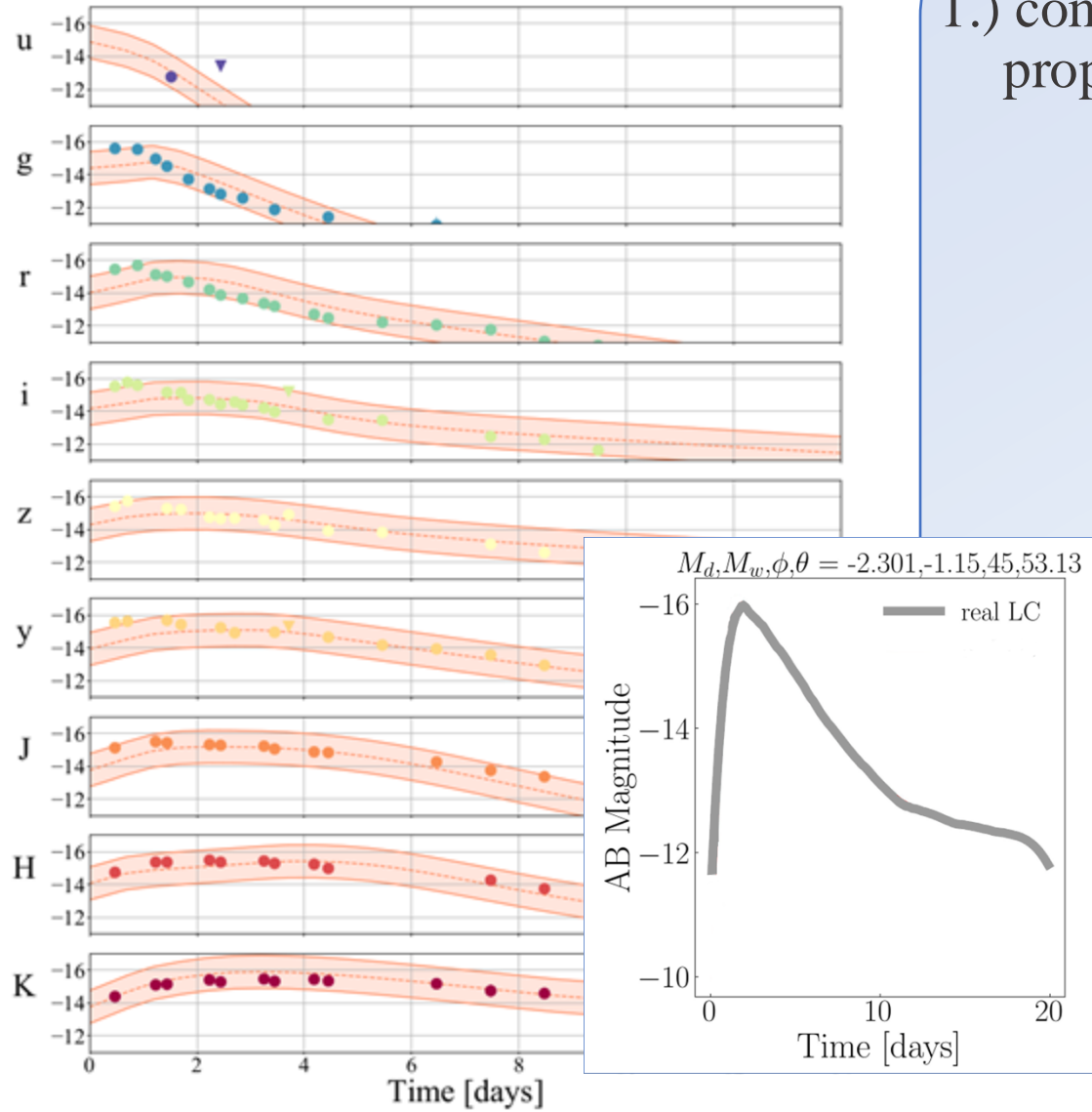
1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code





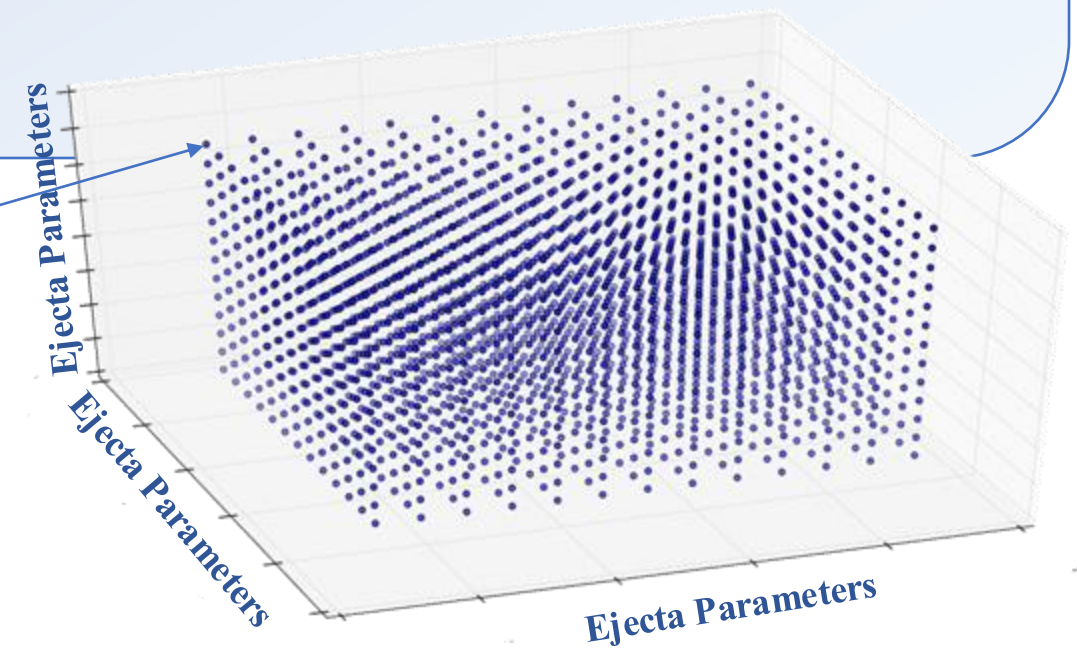
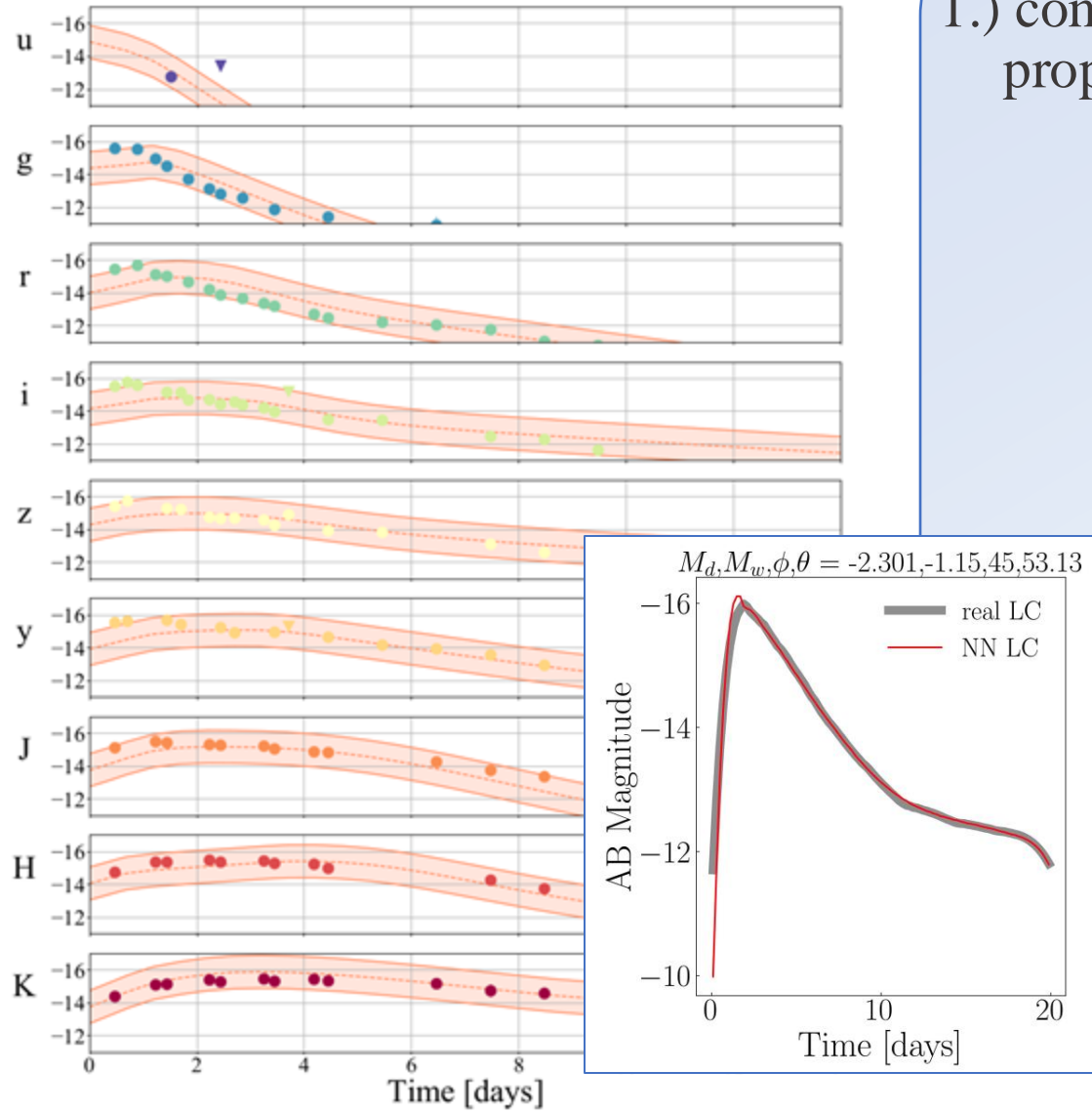
# Photometric lightcurves

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



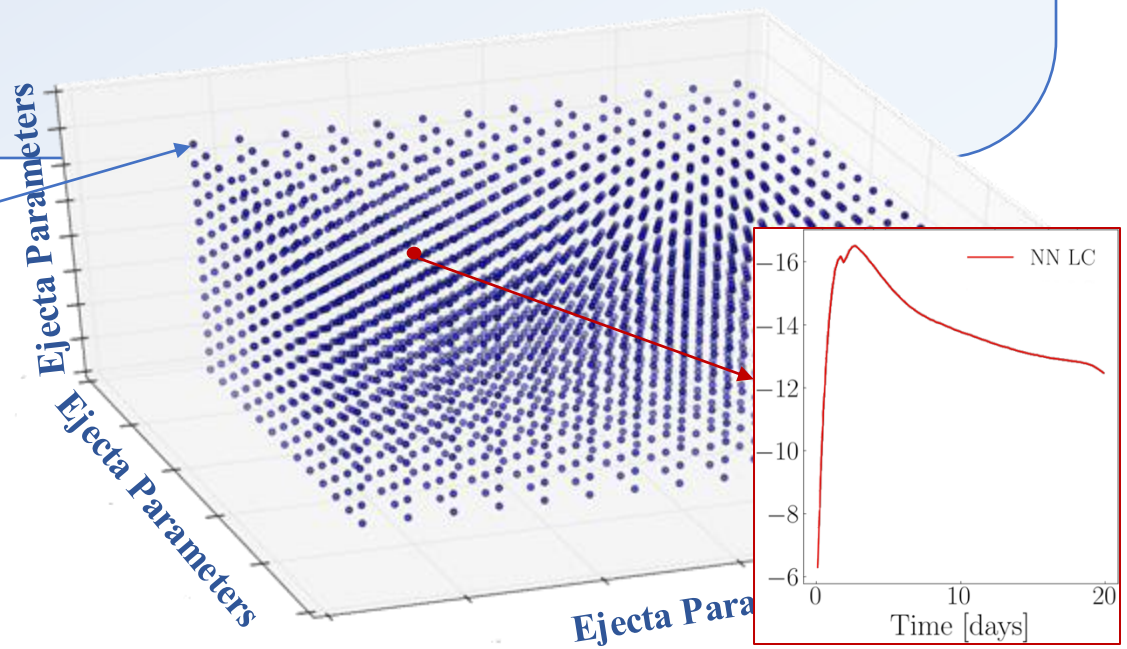
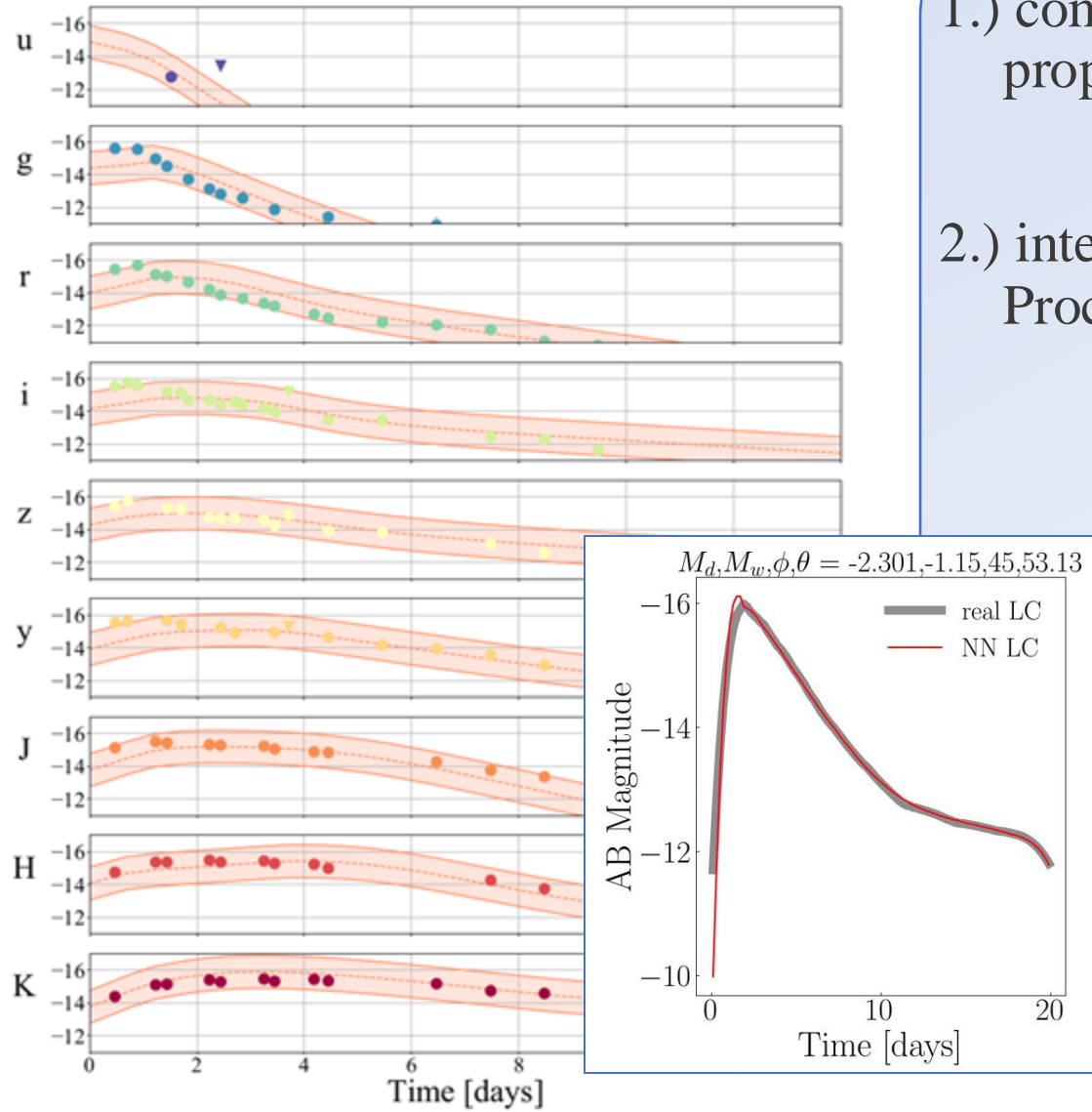
# Photometric lightcurves

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



# Photometric lightcurves

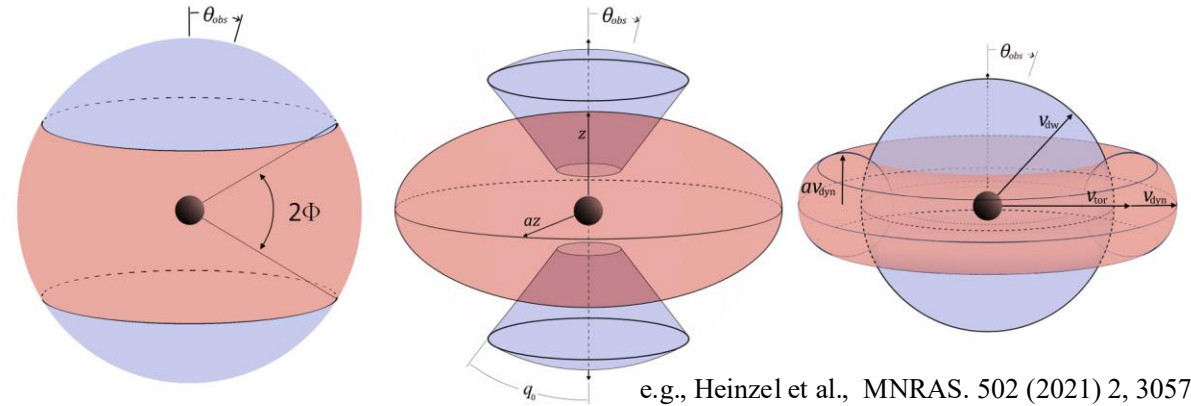
- 1.) compute lightcurves for a set (grid) of ejecta properties with a radiative transfer code
- 2.) interpolate within this grid through Gaussian Process Regression or a Neural Network



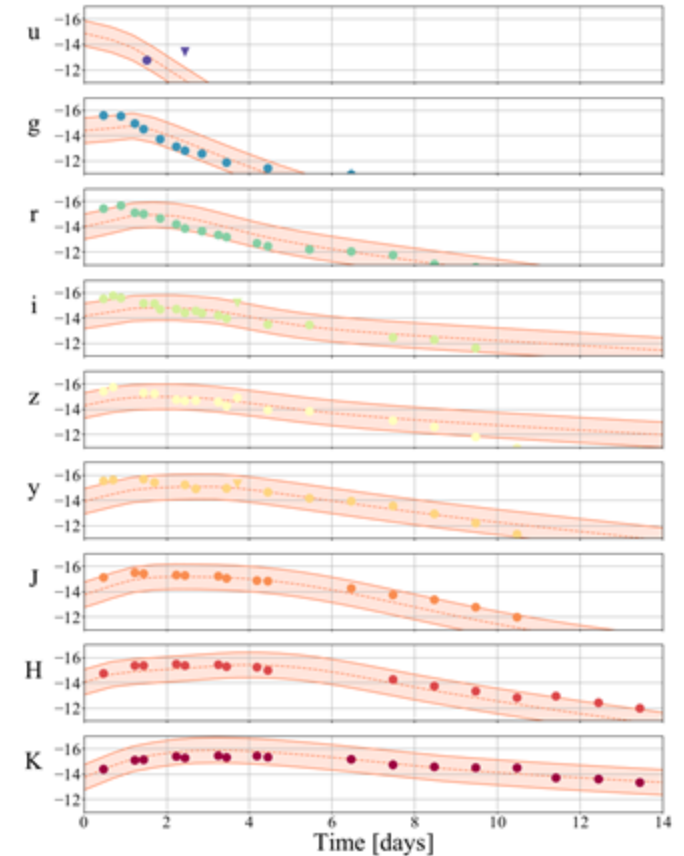


# Uncertainties

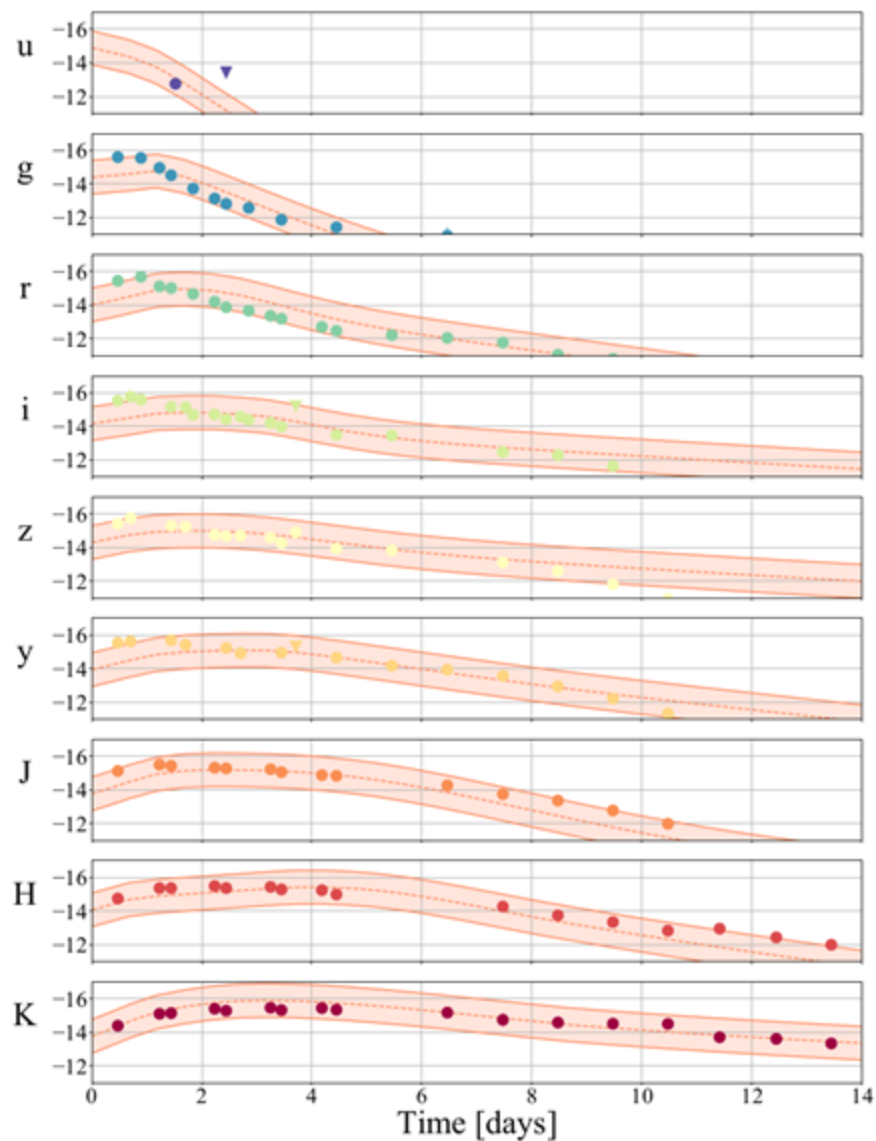
- 1.) Knowledge about the outflowing material (mass, velocity, geometry, composition)
- 2.) Heating rates depend on the formed elements and ejecta properties
- 3.) Incomplete knowledge about opacities for complicated elements



*Cross-code comparisons for numerous geometries and assumptions  $\rightarrow$  estimate on the modelling uncertainty*



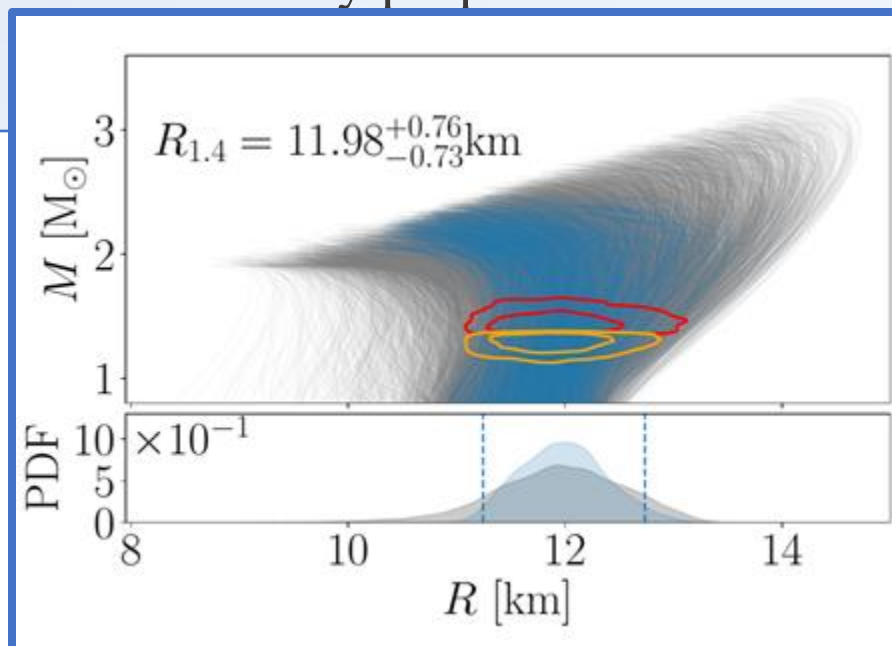
## Photometric lightcurves



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

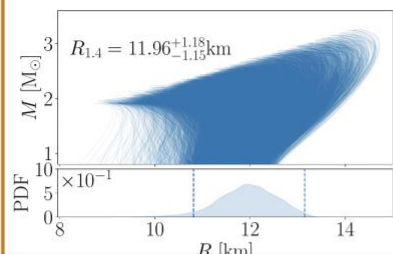
3.) link ejecta properties through numerical-relativity predictions to the binary properties



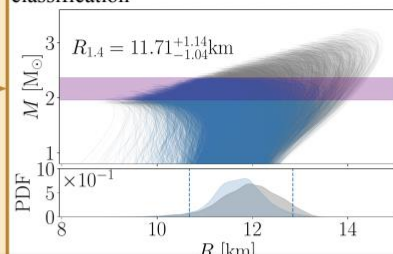


**Prior construction**

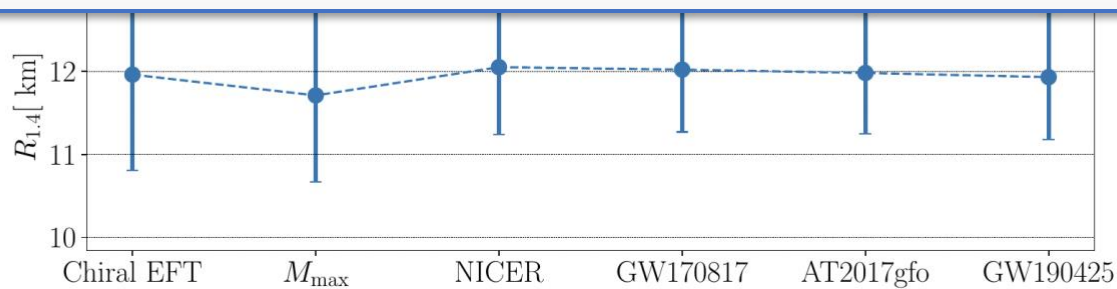
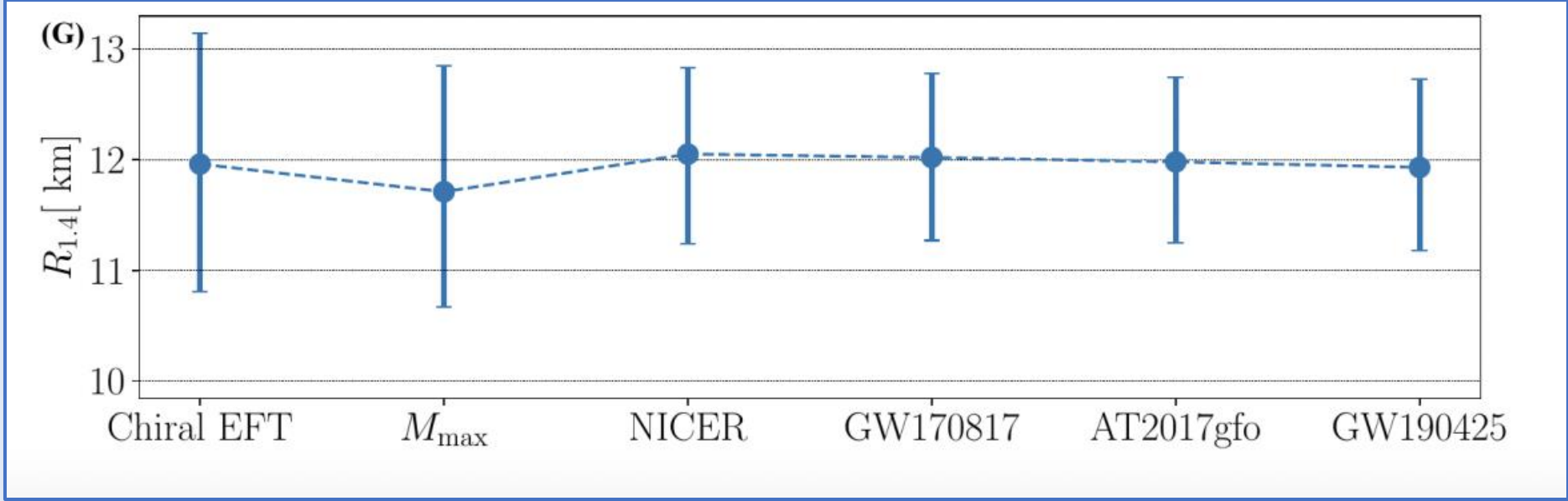
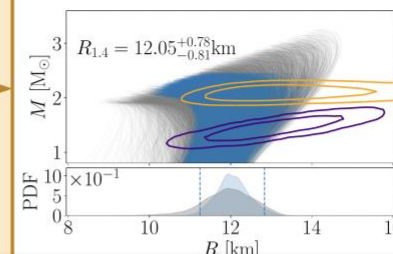
**(A) Chiral effective field theory:**  
EOS derived with the chiral EFT result  
and  $M_{\max} \geq 1.9M_{\odot}$



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



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



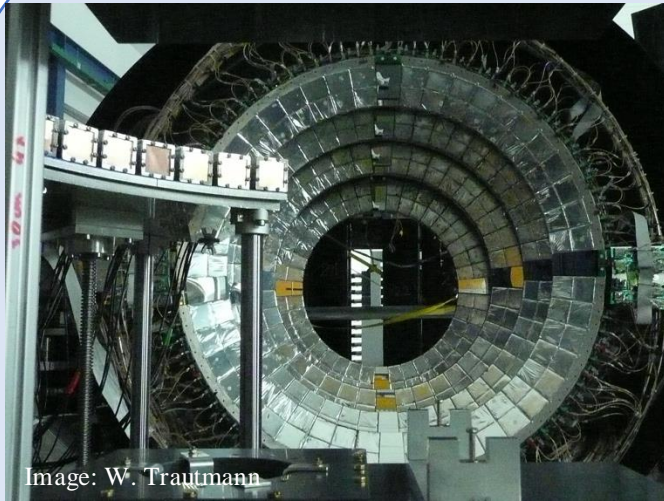
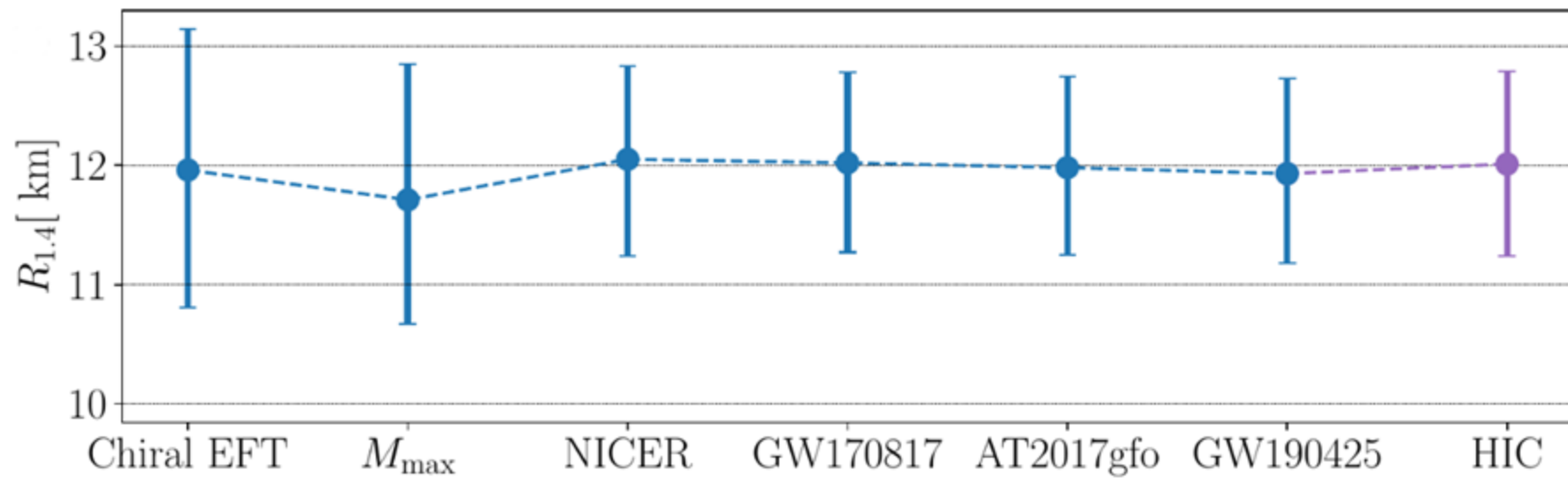


Image: W. Trautmann

## 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](#)

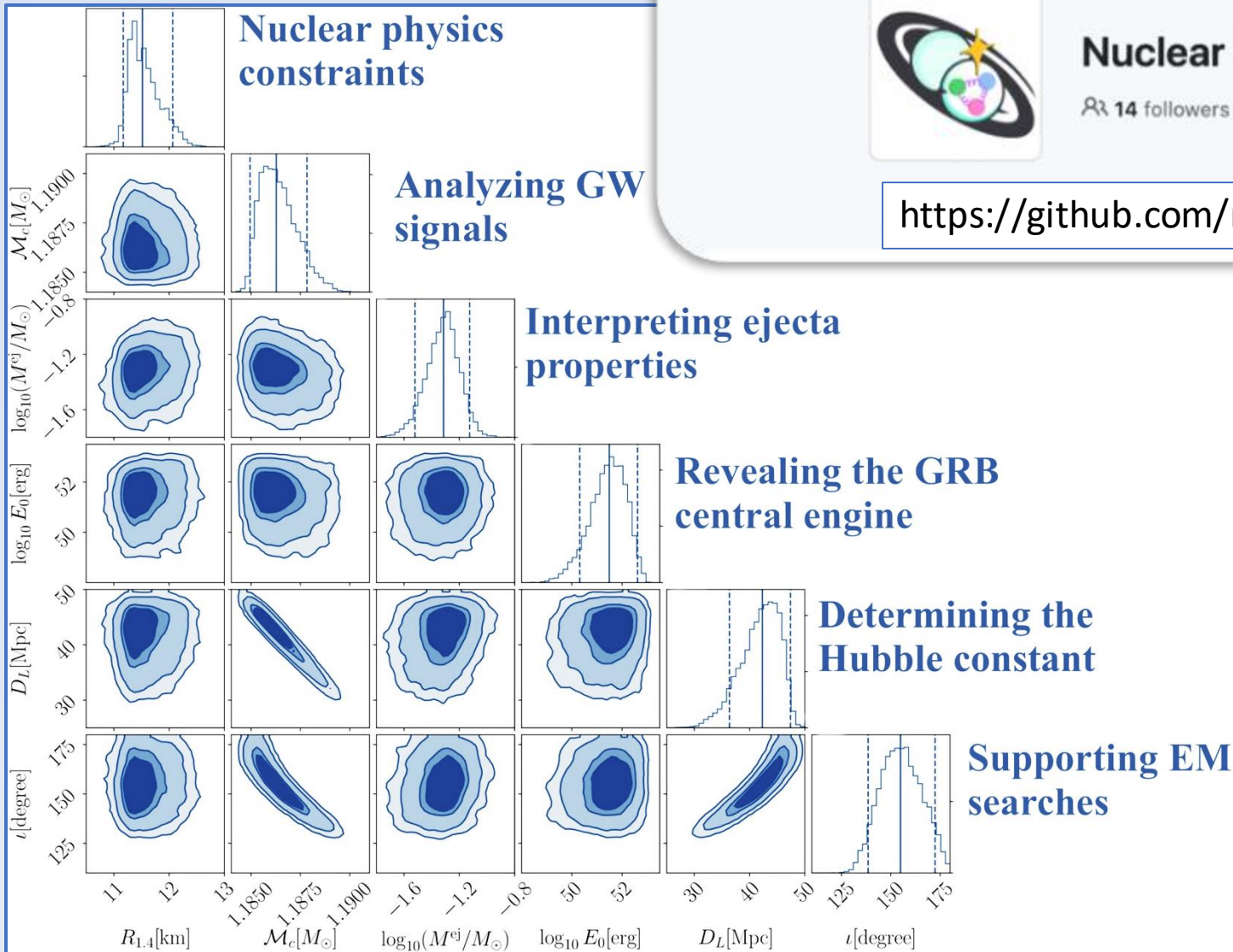




## Nuclear Multimessenger Astronomy

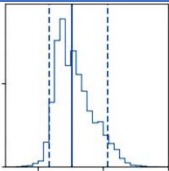
👤 14 followers ✉ nuclear\_multimessenger\_astronom...

<https://github.com/nuclear-multimessenger-astronomy>

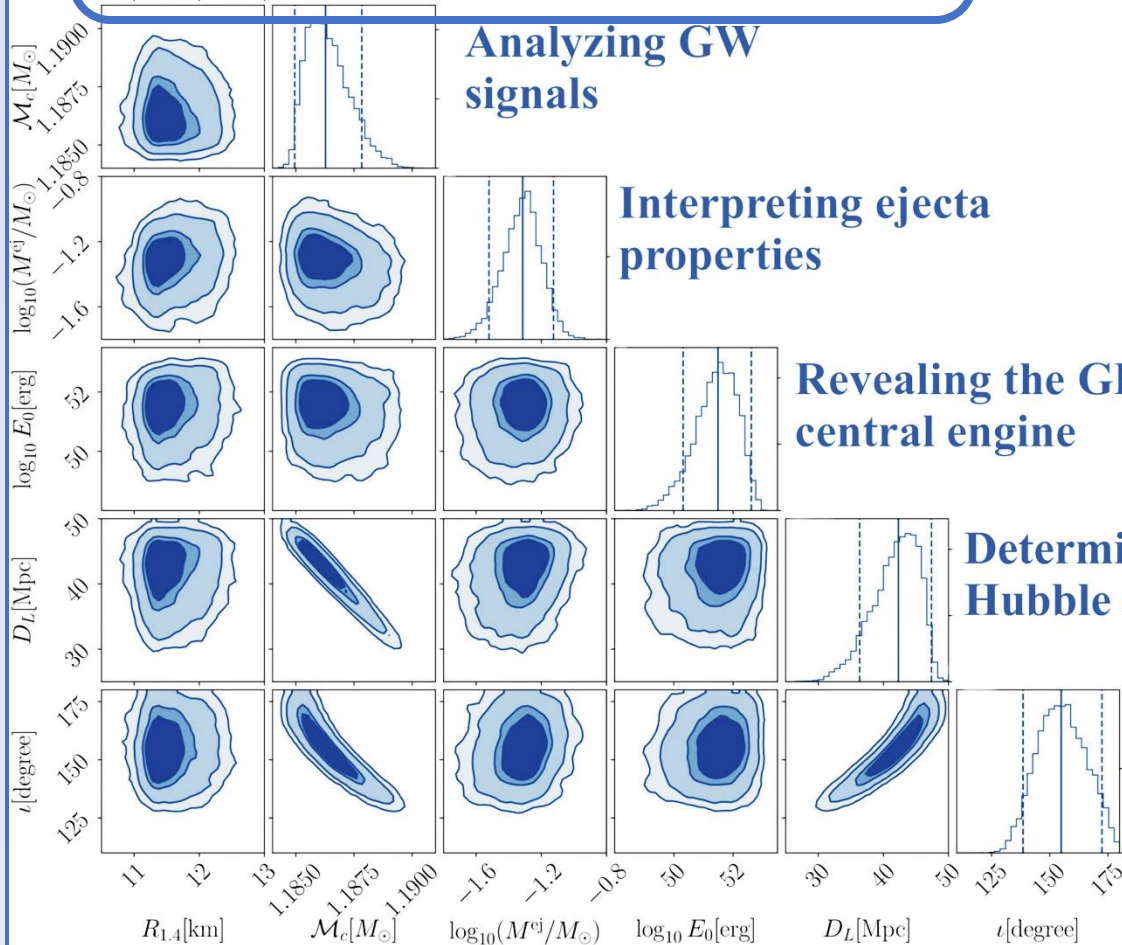


Pang et al., Nat. Comm. 14 (2023) 1, 8352





**Nuclear physics constraints**



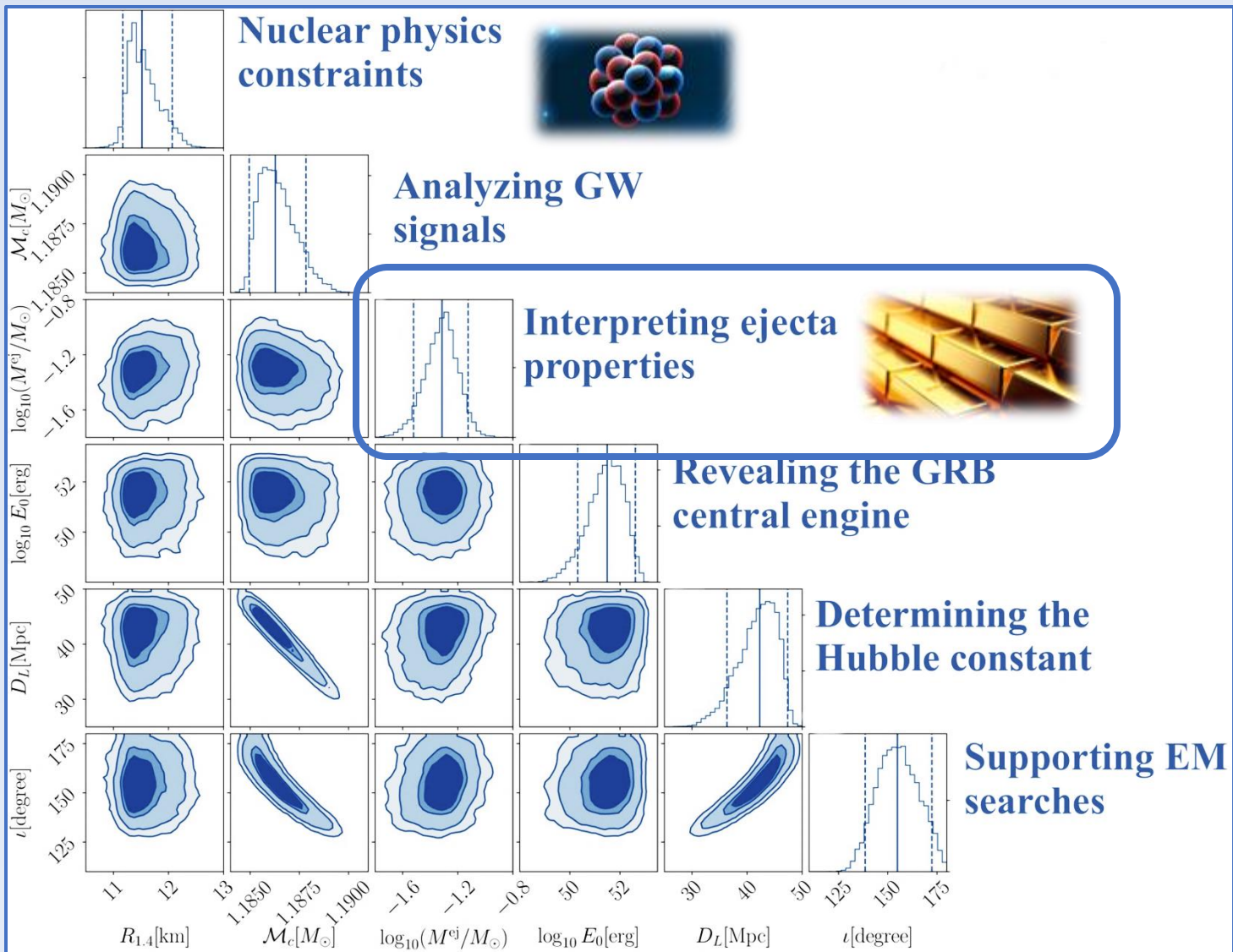
**Analyzing GW signals**

**Interpreting ejecta properties**

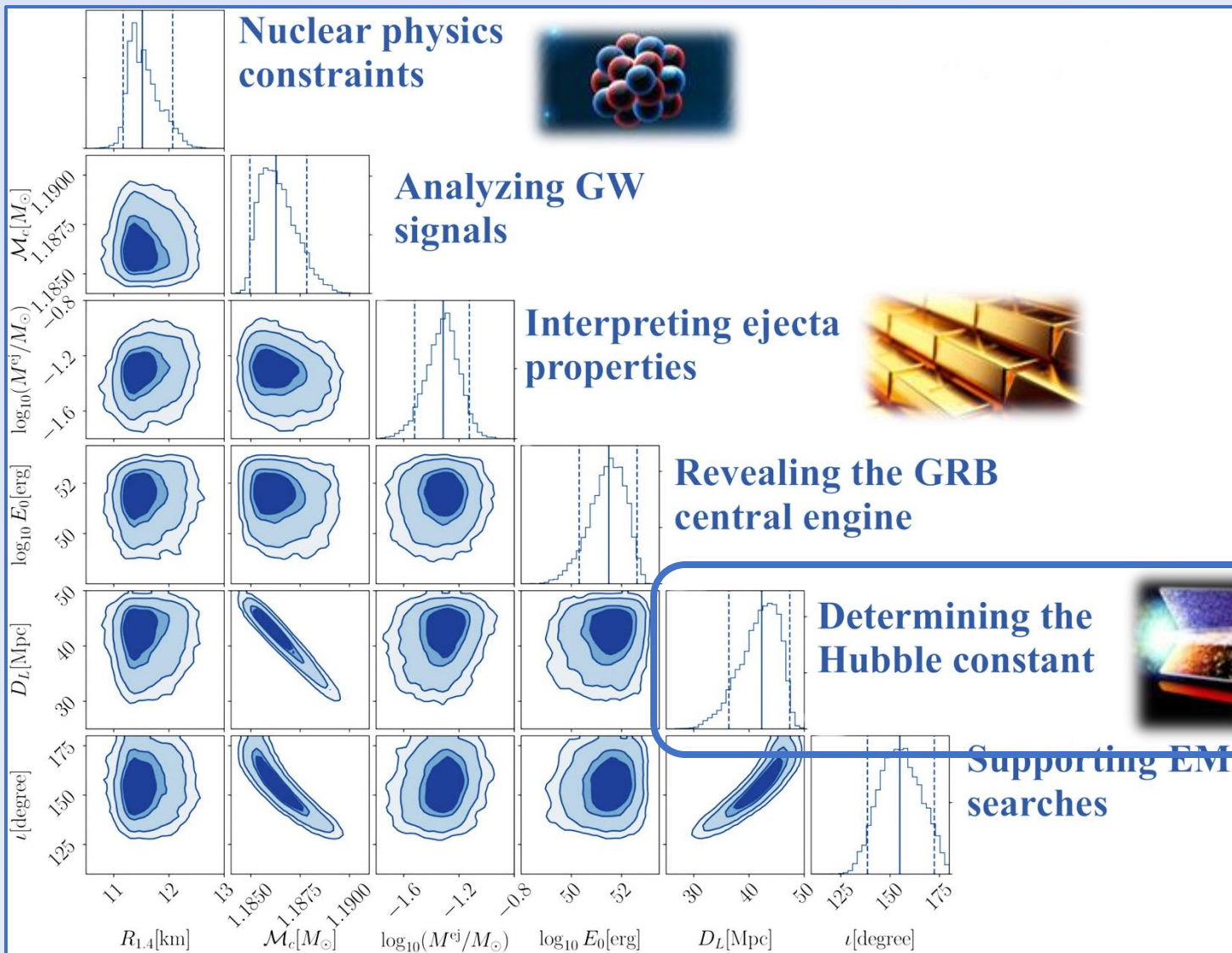
**Revealing the GRB central engine**

**Determining the Hubble constant**

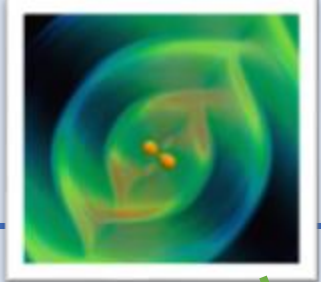
**Supporting EM searches**



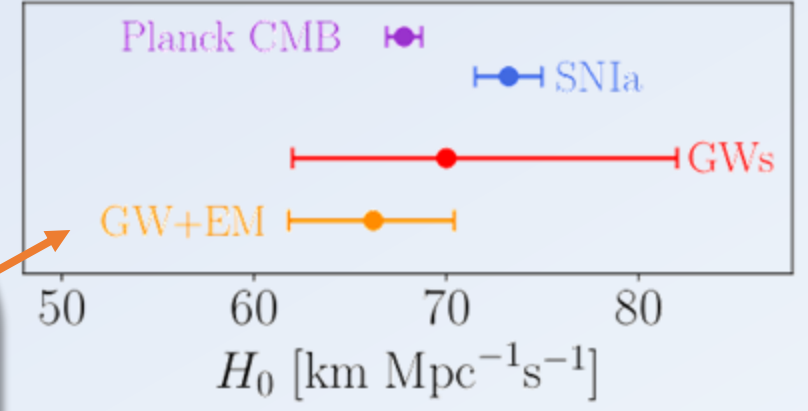
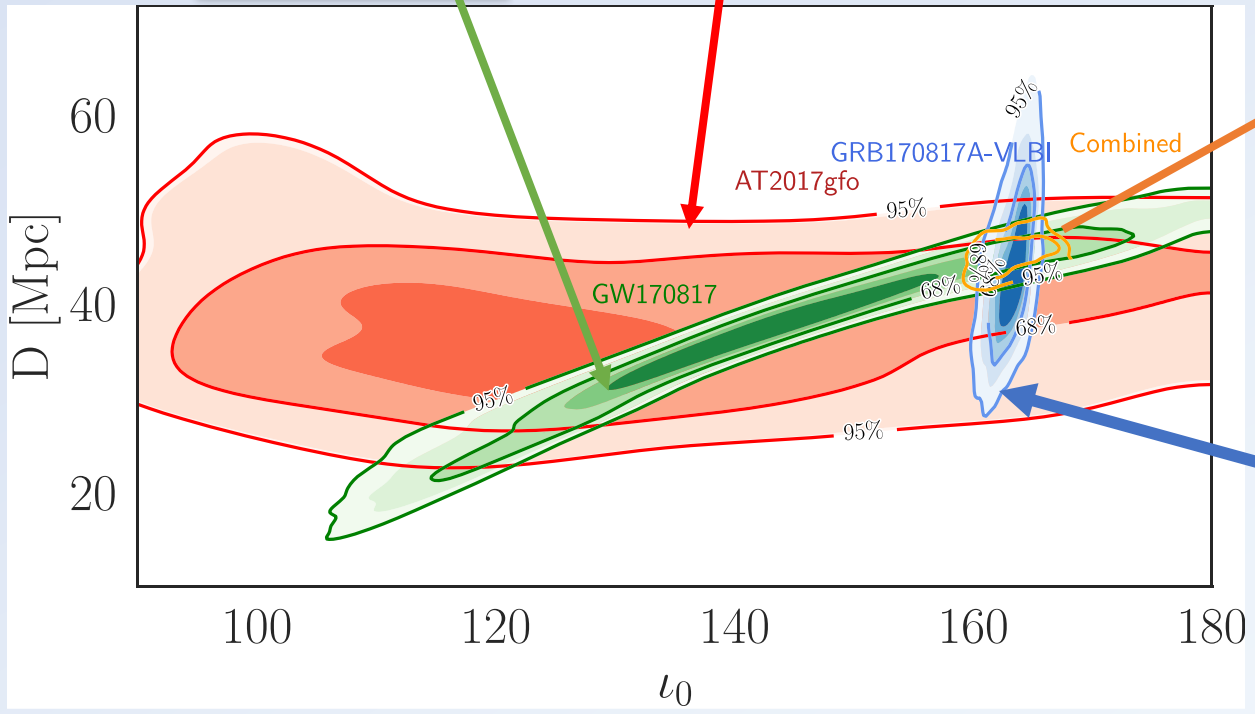
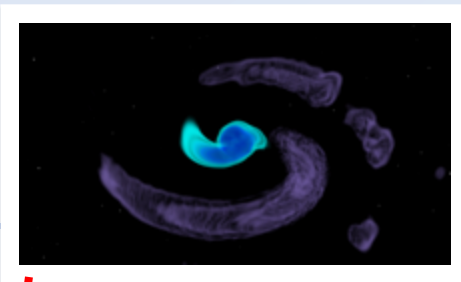




Gravitational Wave

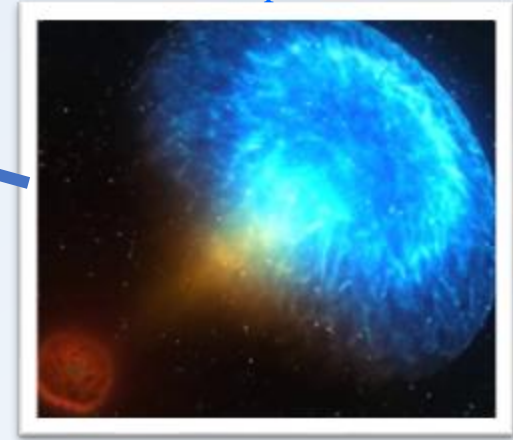


Kilonova



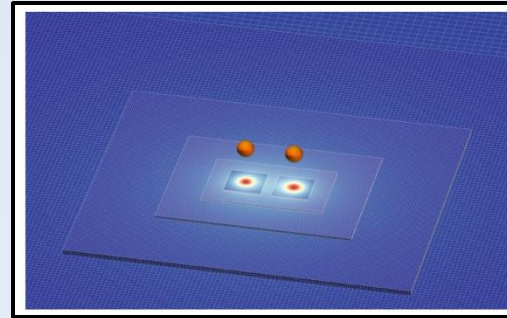
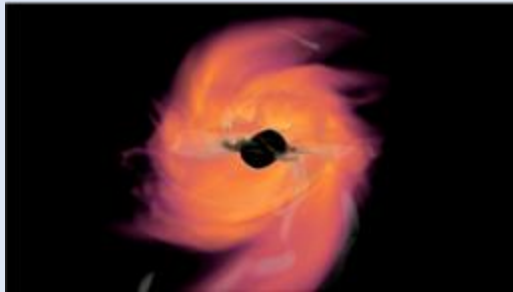
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Radio Counterpart



# Science Summary and Outlook

- numerical-relativity simulations (microphysics and parameter coverage)

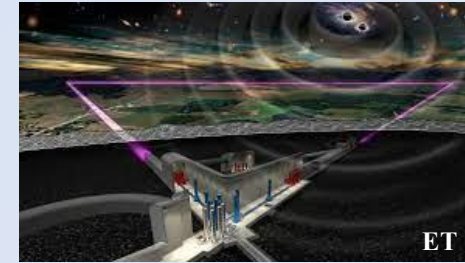


- new nuclear physics and multi-messenger astrophysics framework

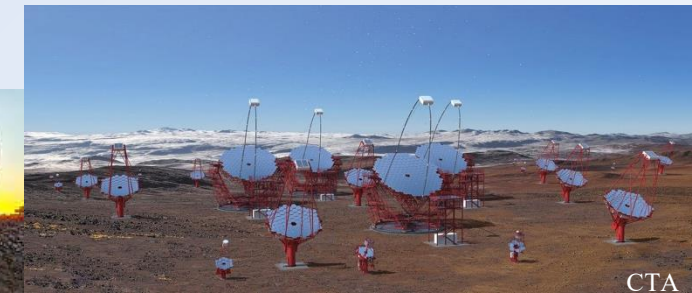


- constraints on the Hubble constant and supranuclear-dense equation of state

## Gravitational Waves



## Electromagnetic Signals



... neutrino detectors, nuclear physics facilities, ...