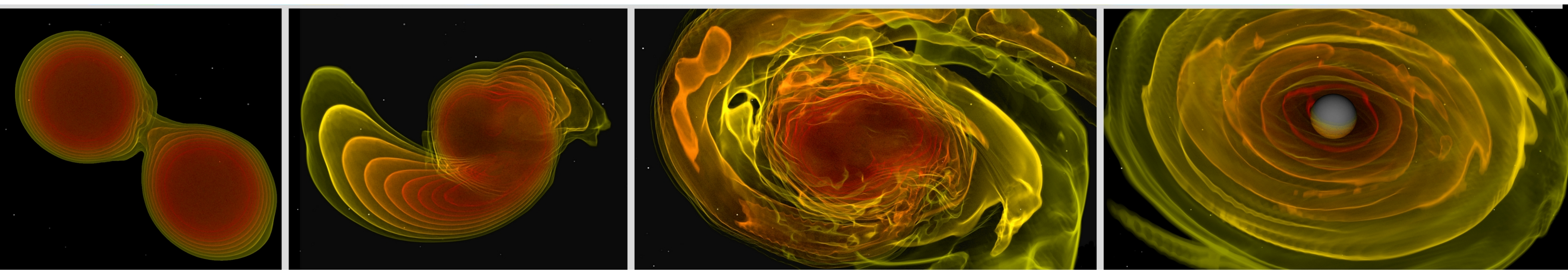
Analyzing Multi-Messenger Astronomy Data to reveal fundamental Properties of the Cosmos

Tim Dietrich

University of Potsdam

Max Planck Institute for Gravitational Physics



17th of December 2021

What are the physics questions that we want to address?

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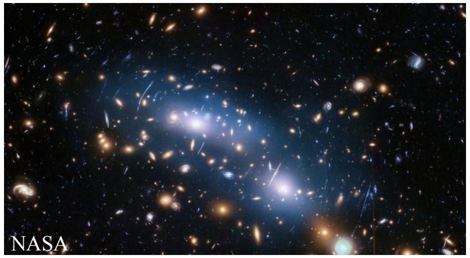
What is the history of our Universe and how fast is it expending?



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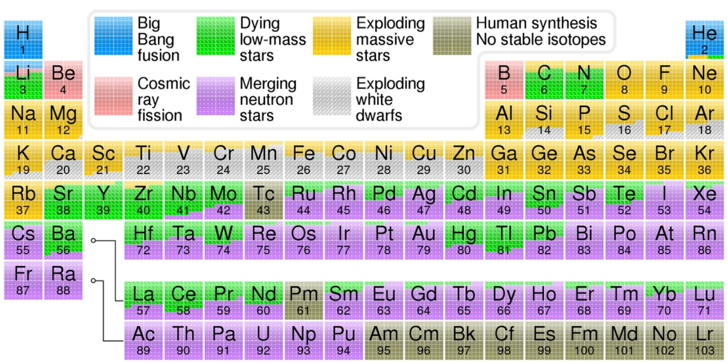

wikipedia

How do we form the elements that are present in our Universe?

What are the physics questions that we want to address?

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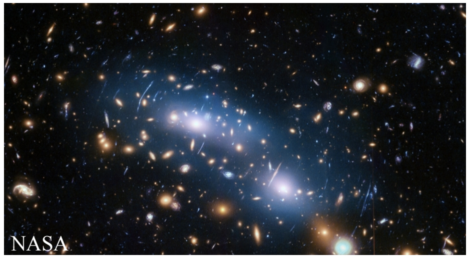

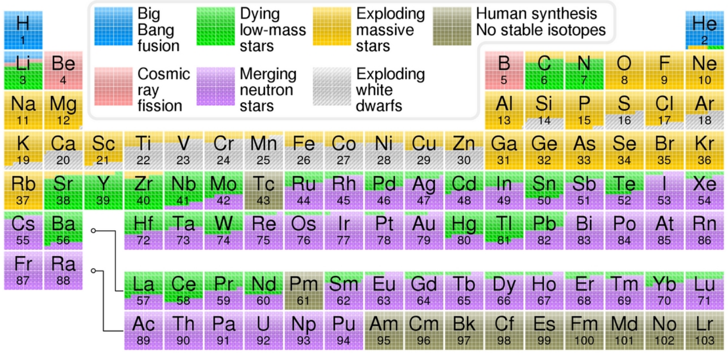

wikipedia

How do we form the elements that are present in our Universe?

What it the state of matter at extreme conditions?

What are the physics questions that we want to address?

Cosmic Scales

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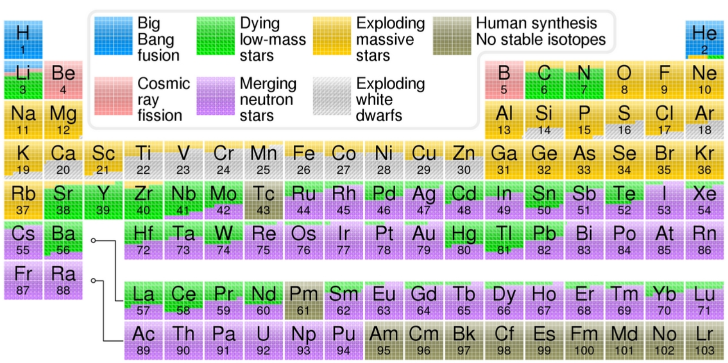
What is the history of our Universe and how fast is it expending?



wikipedia

How do we form the elements that are present in our Universe?

What it the state of matter at extreme conditions?

Subatomic Scales

What are the physics questions that we want to address?

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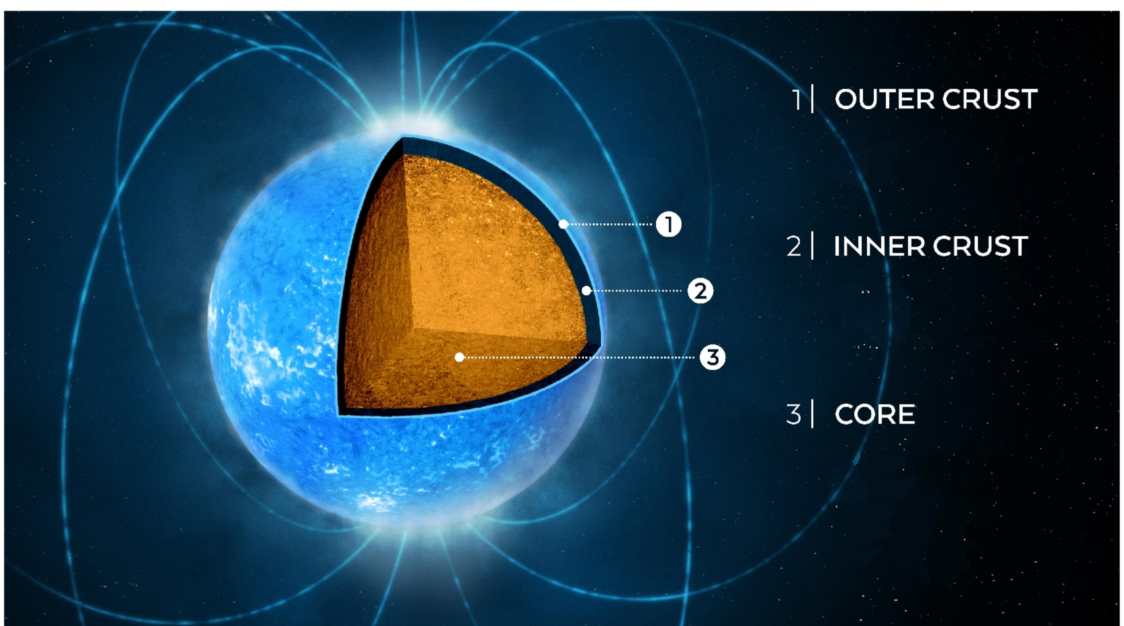
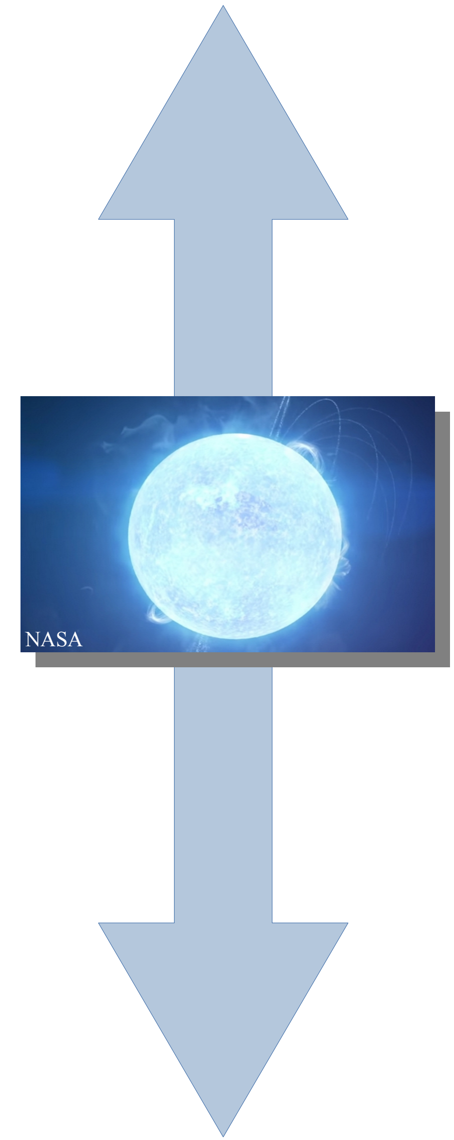
- collapsed core of massive star
- smallest and densest known class of stellar compact objects
- typical size of 12 kilometer and masses between one and two solar masses



Watts et al., Rev.Mod.Phys. 88 (2016) no.2, 021001

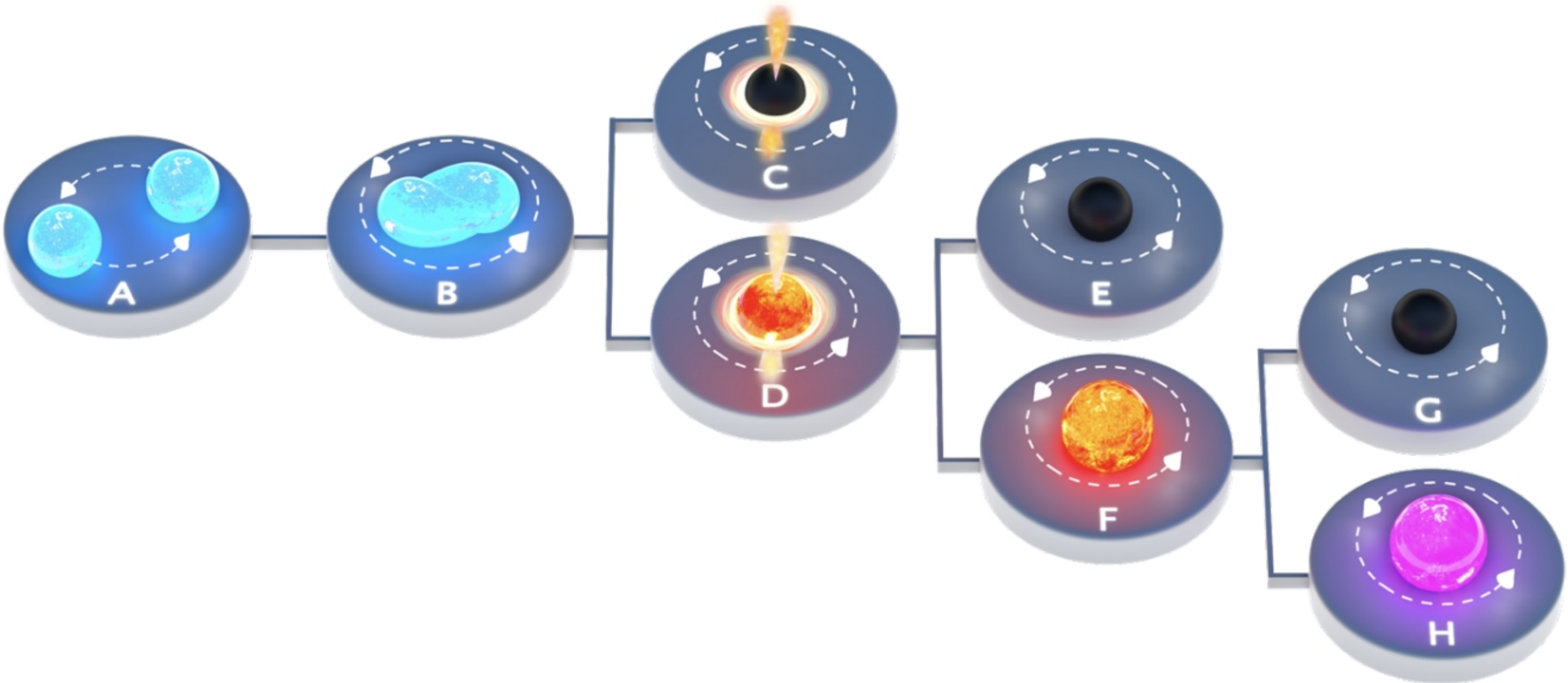
Cosmic Scales



Subatomic Scales

Neutron Stars

As several astrophysical objects,
neutron stars can exist in binaries:



Sarin&Lasky, Gen.Rel.Grav. 53 (2021) 6, 59

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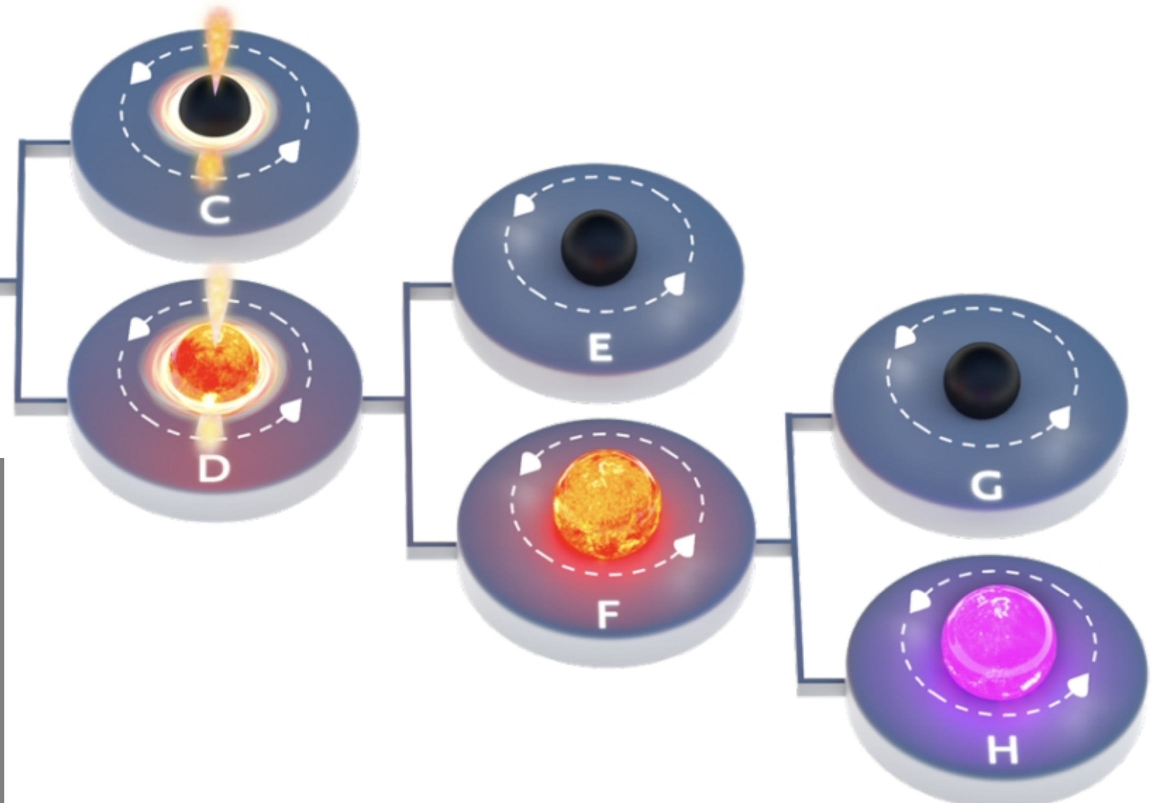
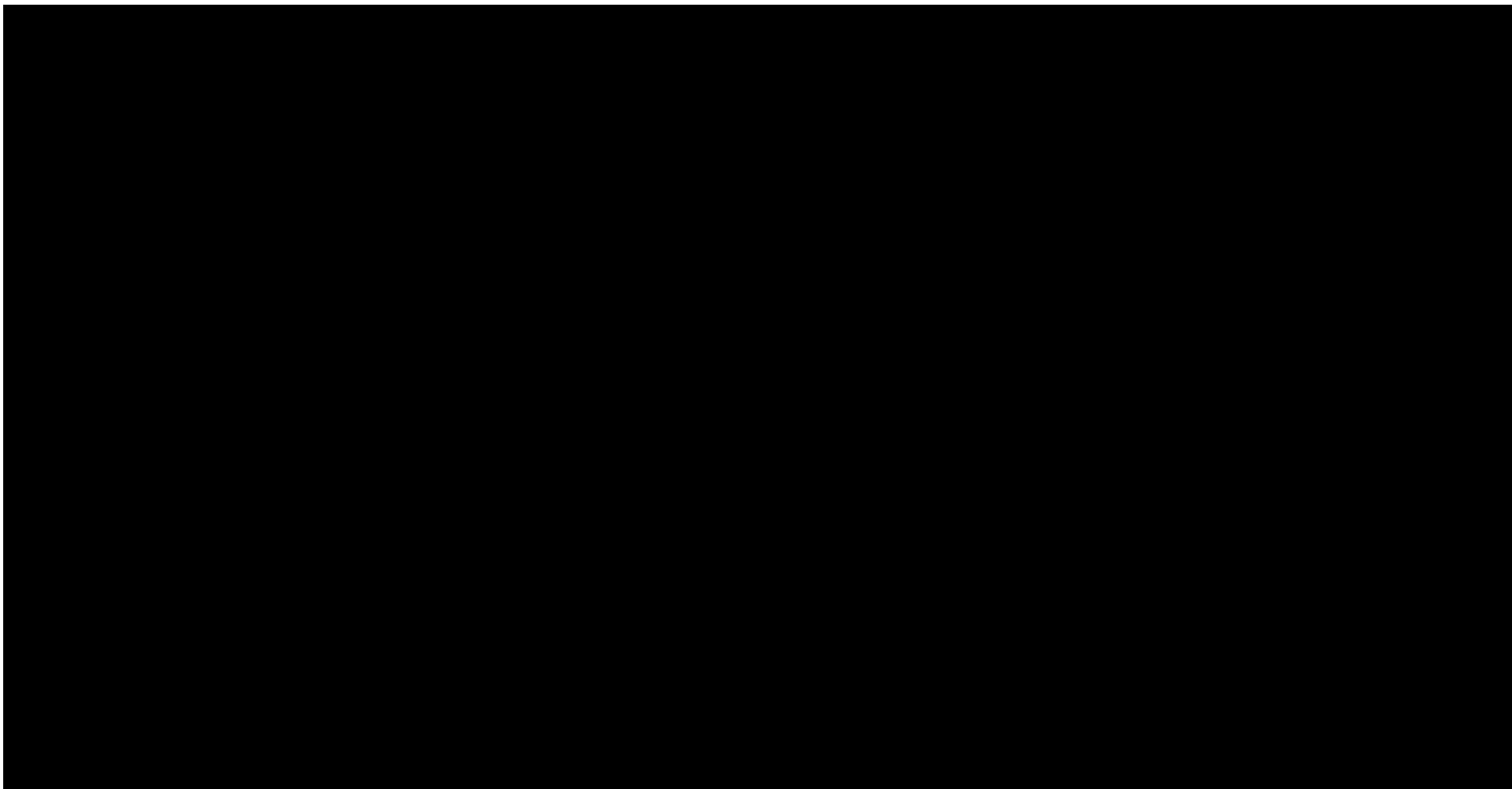


The first binary neutron star merger has been observed on the 17th of August 2017

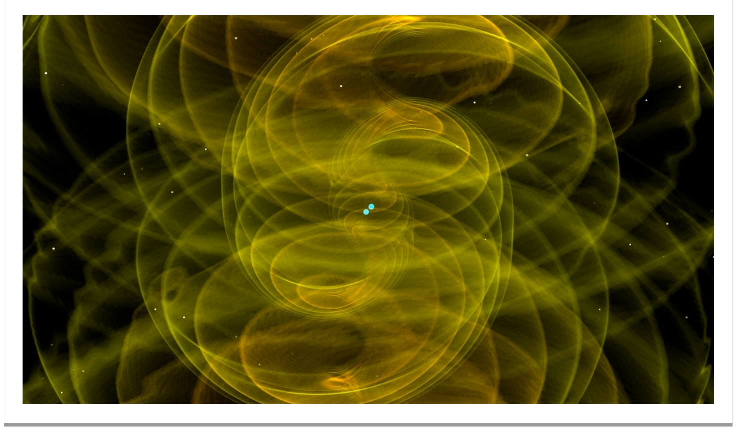
Sarin&Lasky, Gen.Rel.Grav. 53 (2021) 6, 59

Binary Neutron Star Mergers

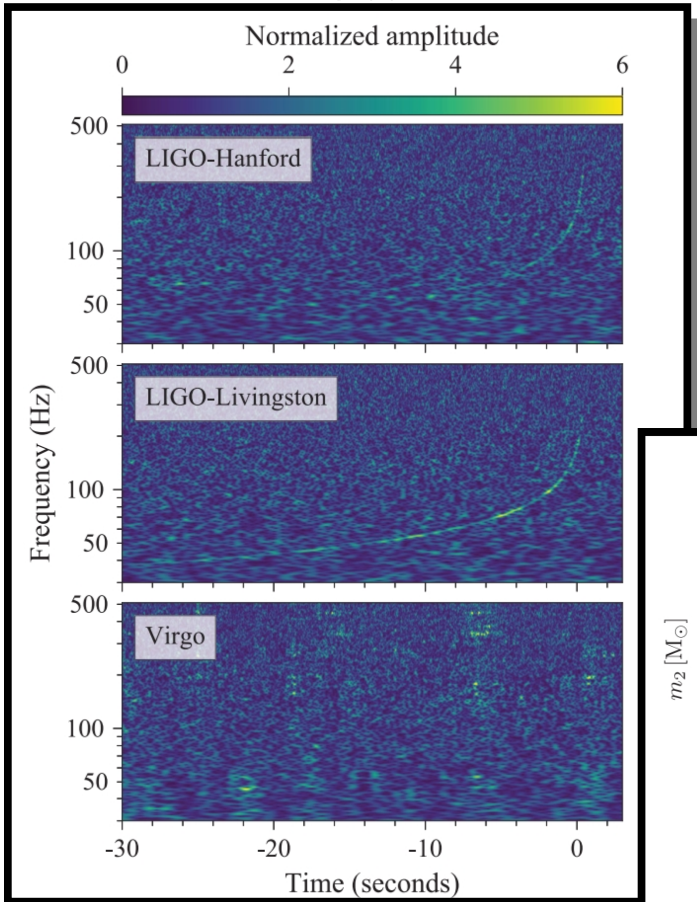


https://www.youtube.com/watch?v=V6cm-0bwJ98

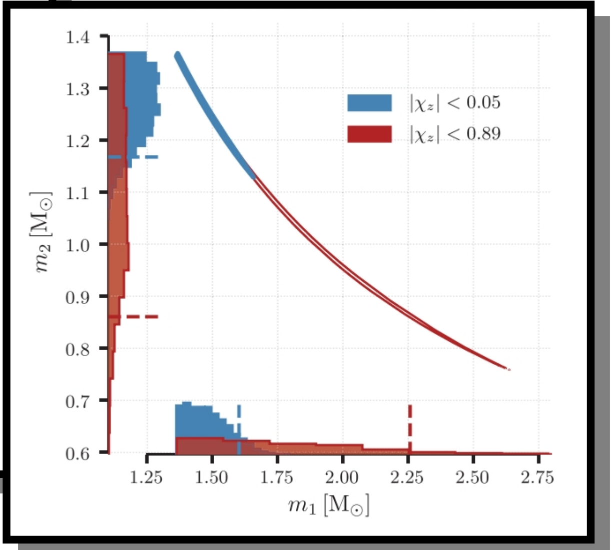
Gravitational Waves



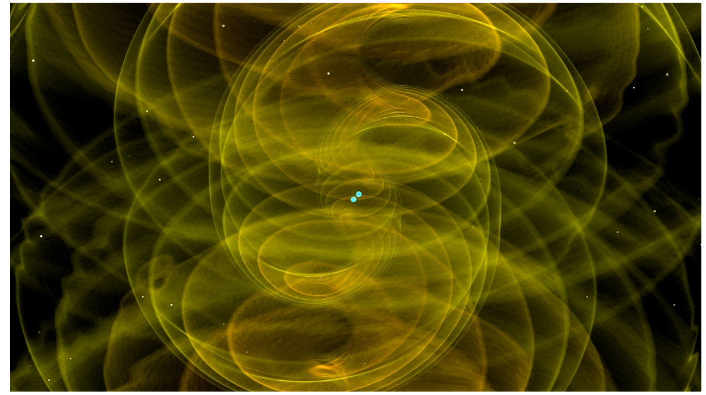
GW170817



PRL 119, 161101 (2017)



Gravitational Waves



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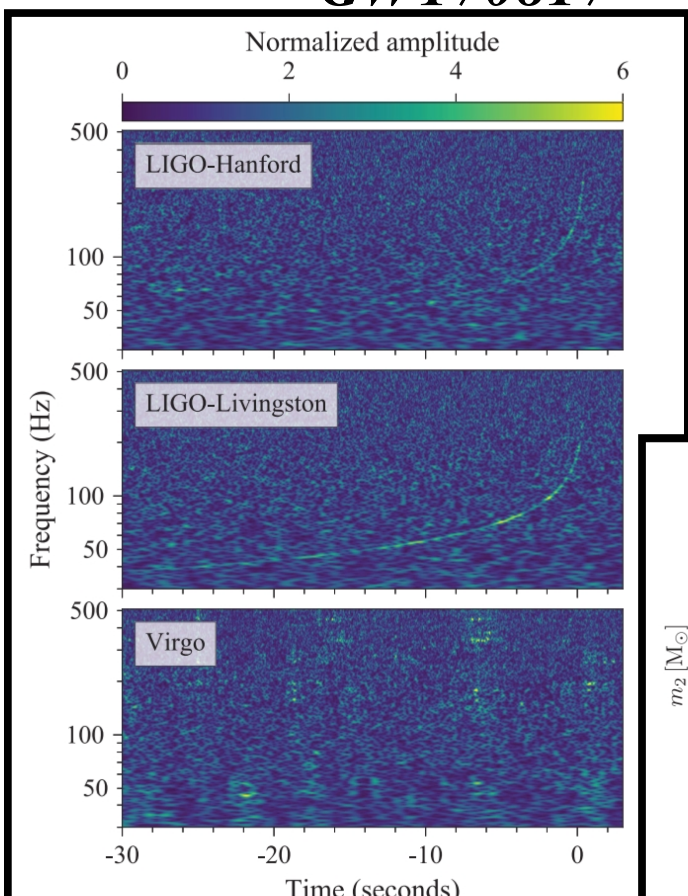

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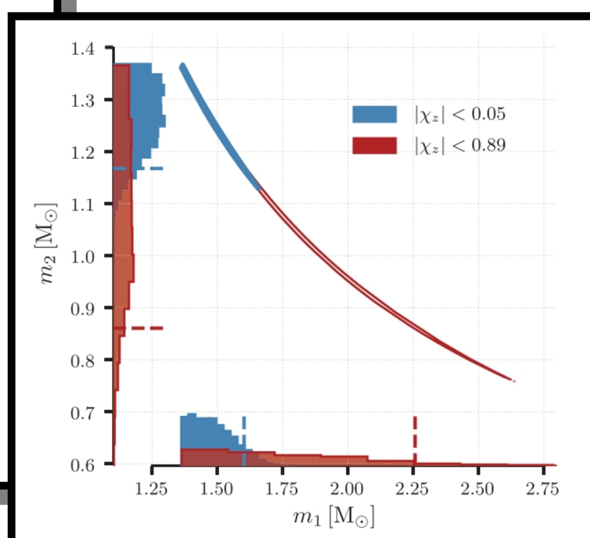
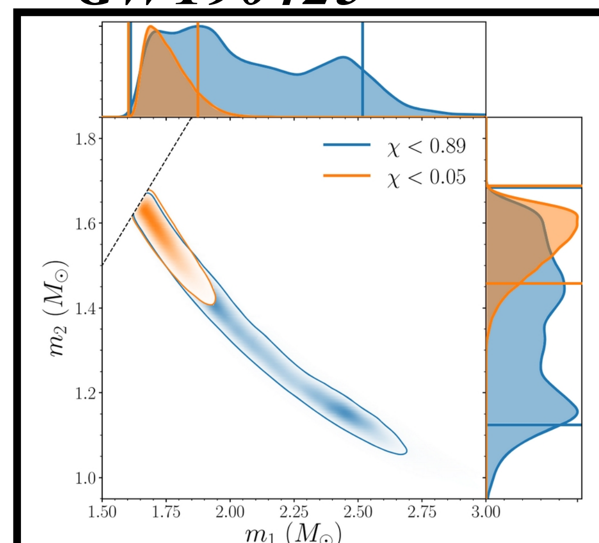
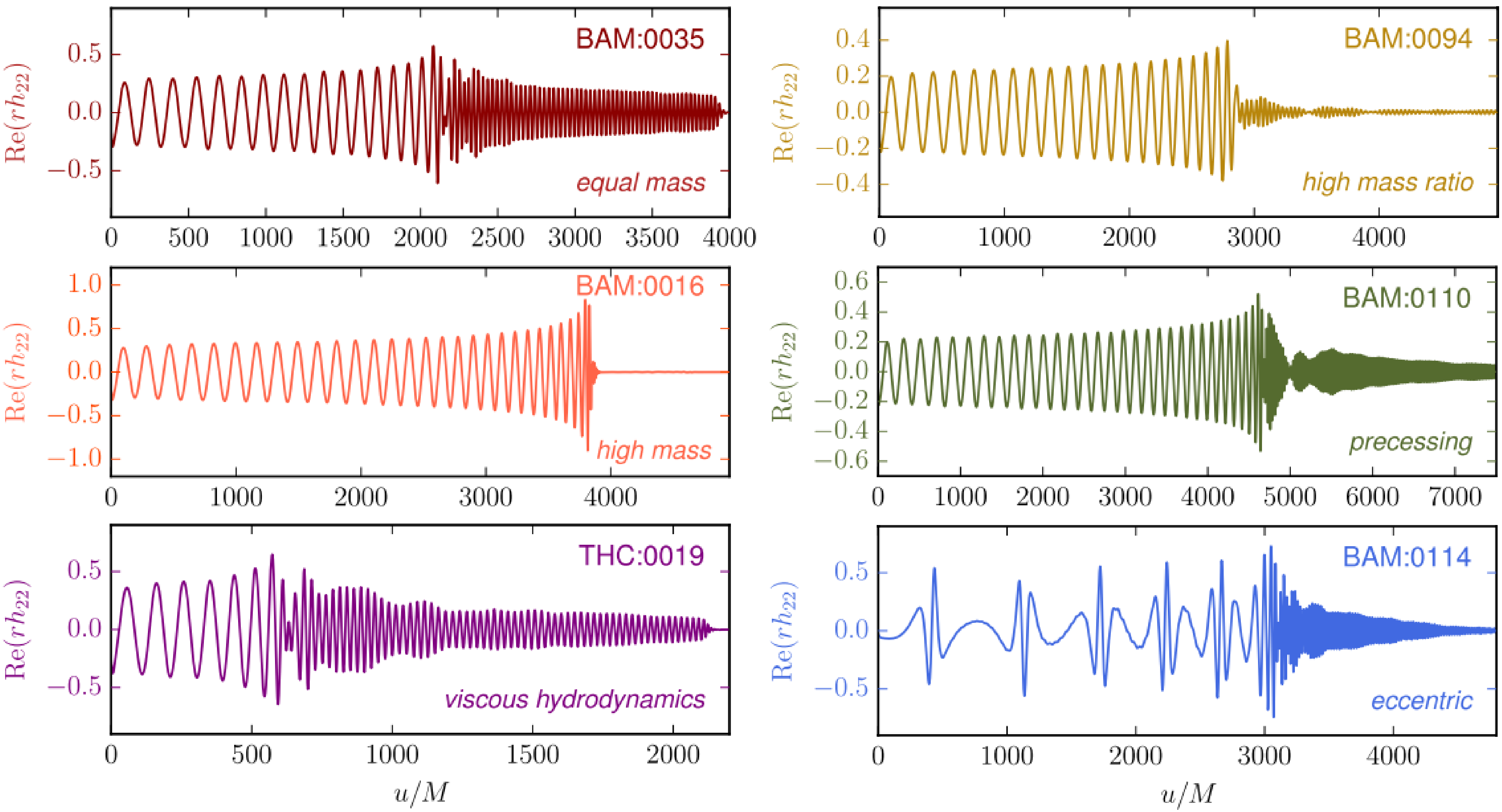


GW190425



APJL 892 (2020)

Simulation variety:

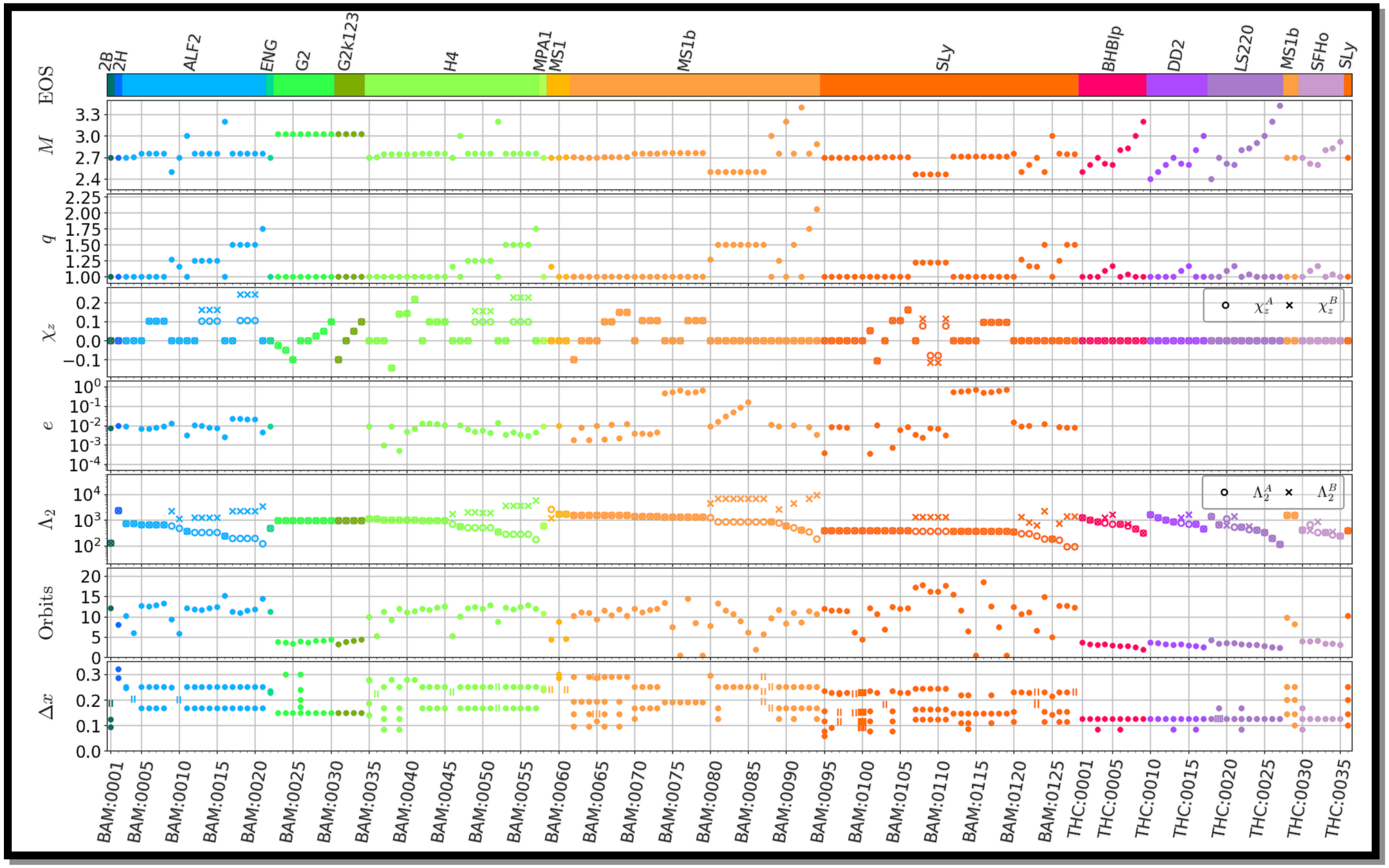


TD et al, CQG 35 (2018) 24LT01

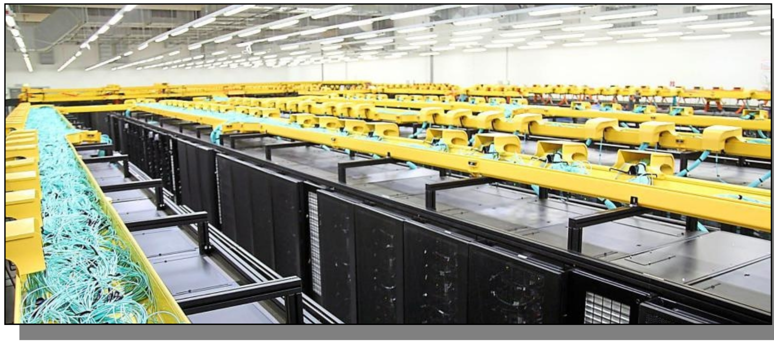
BNS database

http://www.computational-relativity.org/

TD et al, CQG 35 (2018) 24LT01



- first publicly available database for BNSs
- several hundred individual simulations
- more than 500 million CPUhs



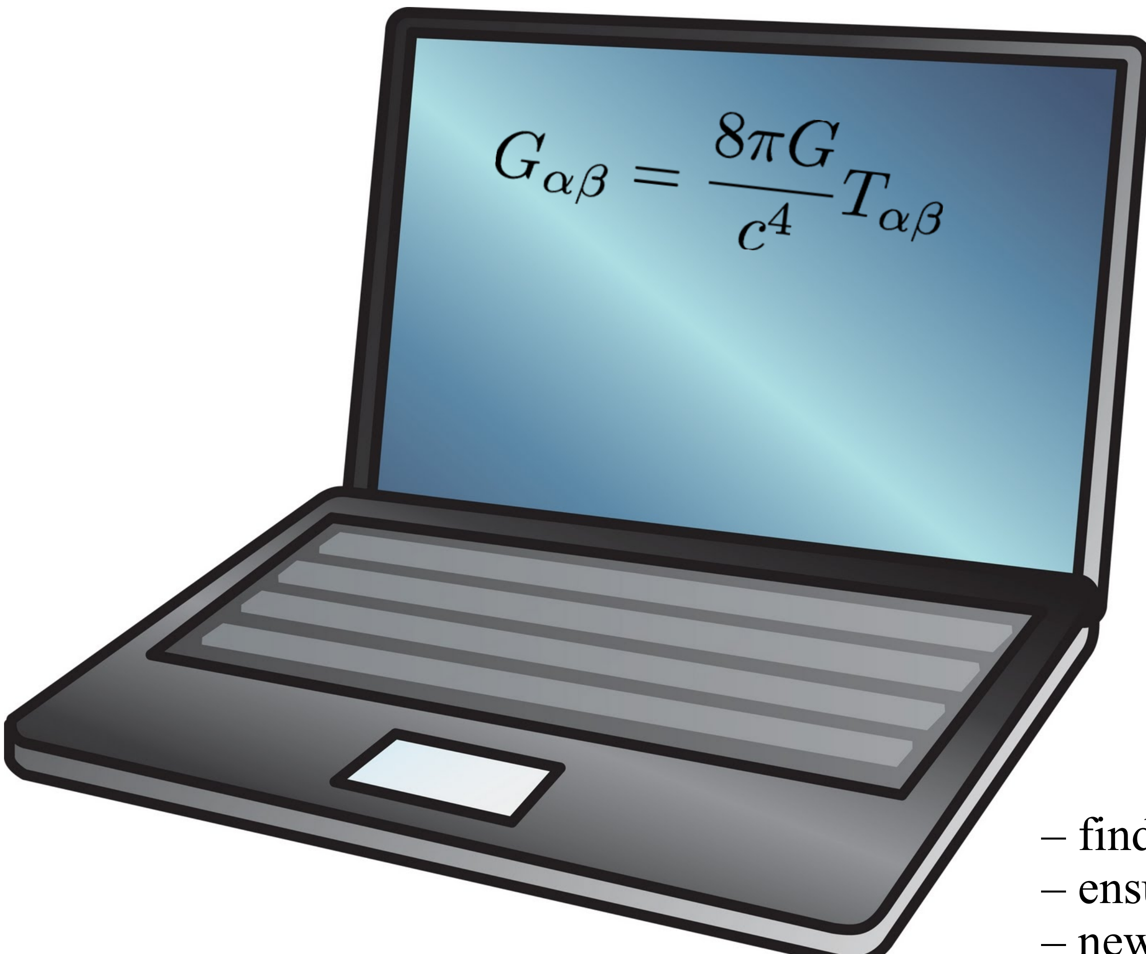
(c) Lino Mirgeler (dpa)

high velocities

and

strong field region

numerical simulations



high velocities
and
strong field region

numerical simulations

– find formulation suited for numerical simulations
– ensure good performance and parallelism
– new high-performance codes
– incorporate the physics you want to simulate

Numerical Relativity

– basics–

$$g_{\alpha\beta}$$

4d metric

$$\mathrm{d}s^2 = g_{\alpha\beta}\mathrm{d}x^\alpha \mathrm{d}x^\beta$$

Numerical Relativity

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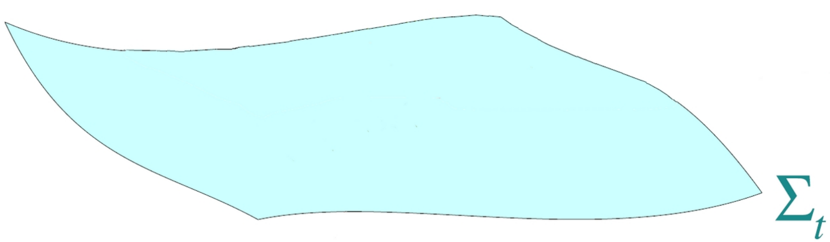

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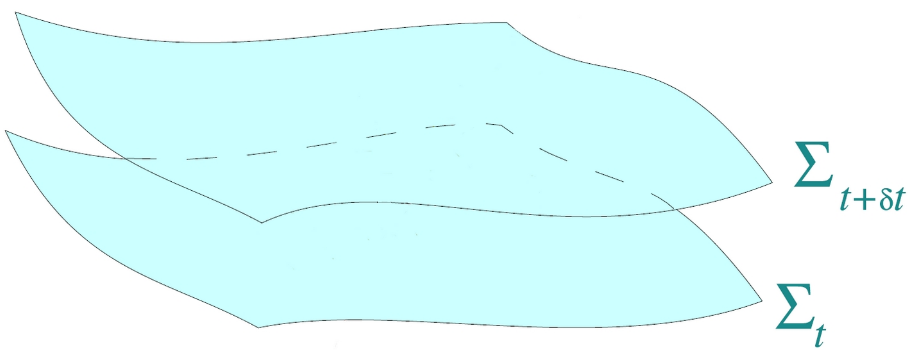
$$\mathrm{d}s^2 = g_{\alpha\beta}\mathrm{d}x^\alpha \mathrm{d}x^\beta$$



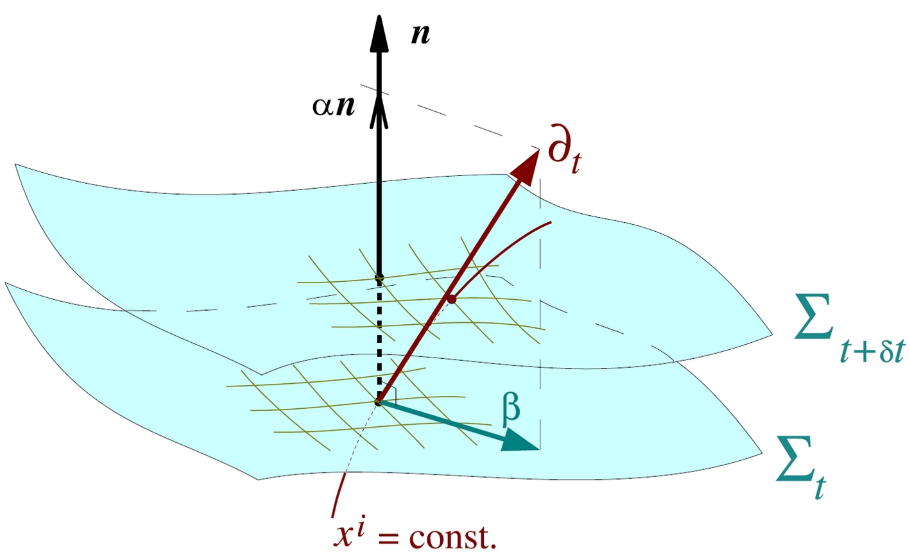
Numerical Relativity

– basics–

$$g_{\alpha\beta} \quad \Leftrightarrow \quad (\gamma_{ij}, K_{ij})$$

4d metric — 3d metric, extrinsic curvature

$$\mathrm{d}s^2 = g_{\alpha\beta}\mathrm{d}x^\alpha \mathrm{d}x^\beta \quad = \quad (-\alpha^2 + \beta_i\beta^i)\mathrm{d}t^2 + 2\beta_i \mathrm{d}t\mathrm{d}x^i + \gamma_{ij}\mathrm{d}x^i\mathrm{d}x^j$$



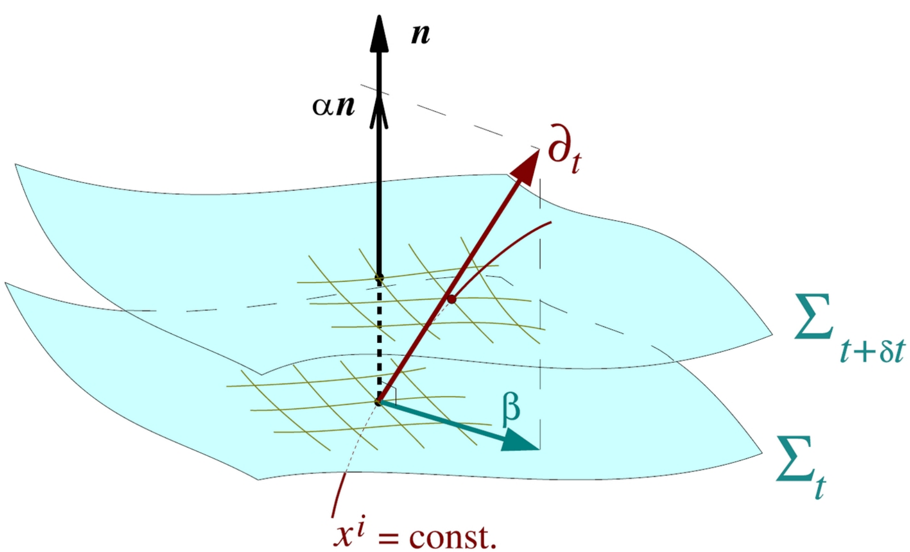
Numerical Relativity

– basics–

$$g_{\alpha\beta} \qquad \Leftrightarrow \qquad (\gamma_{ij}, K_{ij})$$

4d metric — 3d metric, extrinsic curvature

$$ds^2 = g_{\alpha\beta}dx^\alpha dx^\beta \quad = \quad (-\alpha^2 + \beta_i\beta^i)dt^2 + 2\beta_i dt dx^i + \gamma_{ij}dx^i dx^j$$

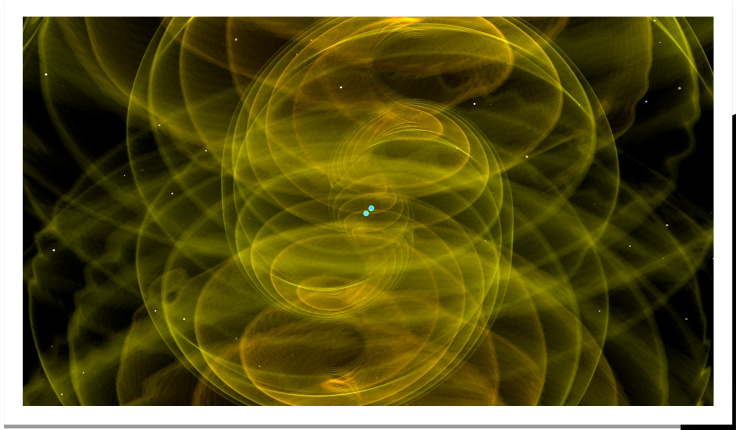


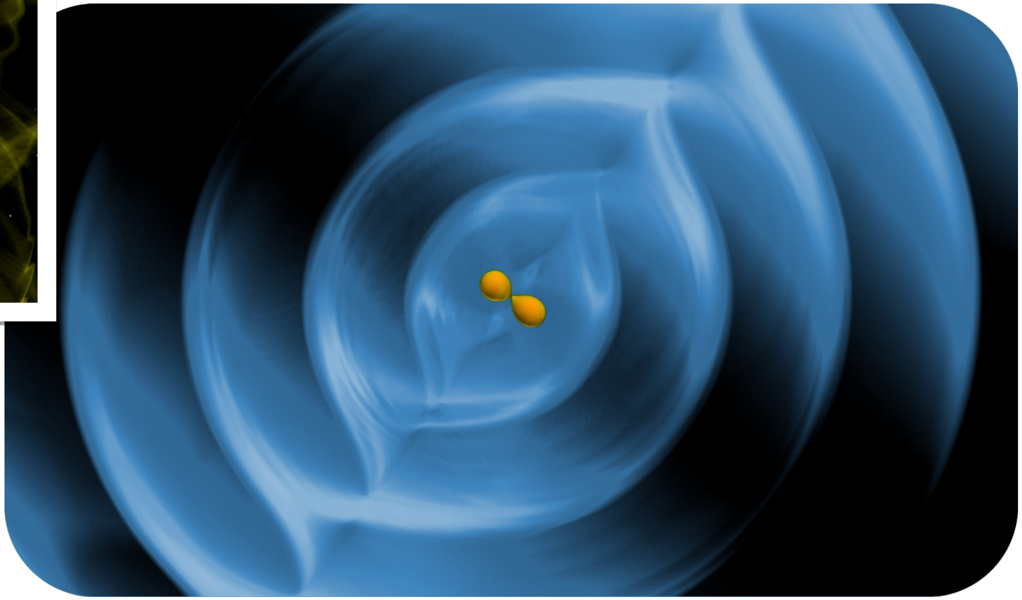
Constraint Equations for each hypersurface

Evolution Equations

$$\begin{aligned}
\partial_t\chi &= \frac{2}{3}\chi[\alpha(\hat{K}+2\Theta) - D_i\beta^i] \\
\partial_t\tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij} + \beta^k\tilde{\gamma}_{ij,k} + \tilde{\gamma}_{ik}\beta^k_{,j} - \frac{2}{3}\tilde{\gamma}_{ij}\beta^k_{,k} \\
\partial_t\hat{K} &= -D^iD_i\alpha + \alpha[\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}(\hat{K}+2\Theta)^2] \\
&+ 4\pi\alpha[S+\rho_{\mathrm{ADM}}] + \beta^iK_{,i} + \alpha\kappa_1(1-\kappa_2)\Theta \\
\partial_t\tilde{A}_{ij} &= -\chi[-D_iD_j\alpha + \alpha(R_{ij} - 8\pi S_{ij})]^{\mathrm{tf}} \\
&+ \alpha[(\hat{K}+2\Theta) - 2\tilde{A}^k{}_i\tilde{A}_{kj}] \\
&+ \beta^k\tilde{A}_{ij,k} + \tilde{A}_{ik}\beta^k{}_{,j} - \frac{2}{3}\tilde{A}_{ij}\beta^k{}_{,k} \\
\partial_t\tilde{\Gamma}^i &= -2\tilde{A}^{ij}\alpha_{,j} + 2\alpha[\tilde{\Gamma}^i_{jk}\tilde{A}^{jk} - 2\tilde{A}^{ij}\ln(\chi)_{,j} \\
&\quad -\frac{2}{3}\tilde{\gamma}^{ij}(\hat{K}+2\Theta)_{,j} - 8\pi\tilde{\gamma}^{ij}S_j] + \tilde{\gamma}^{jk}\beta^i_{,jk} \\
&\quad +\frac{1}{3}\tilde{\gamma}^{ij}\beta^k_{,kj} + \beta^j\tilde{\Gamma}^i_{,j} - \tilde{\Gamma}_{\mathrm{d}}{}^j\beta^i_{,j} + \frac{2}{3}\tilde{\Gamma}_{\mathrm{d}}{}^i\beta^j_{,j} \\
\partial_t\Theta &= \alpha[\frac{1}{2}H + \partial_kZ^k - (2+\kappa_2)\kappa_1\Theta] + \beta^i\Theta_{,i}
\end{aligned}$$

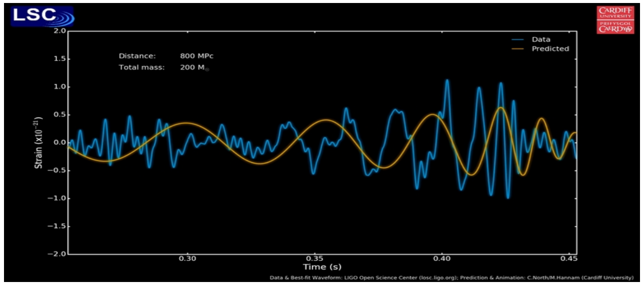
Real Life: Gravitational-Wave Astronomy





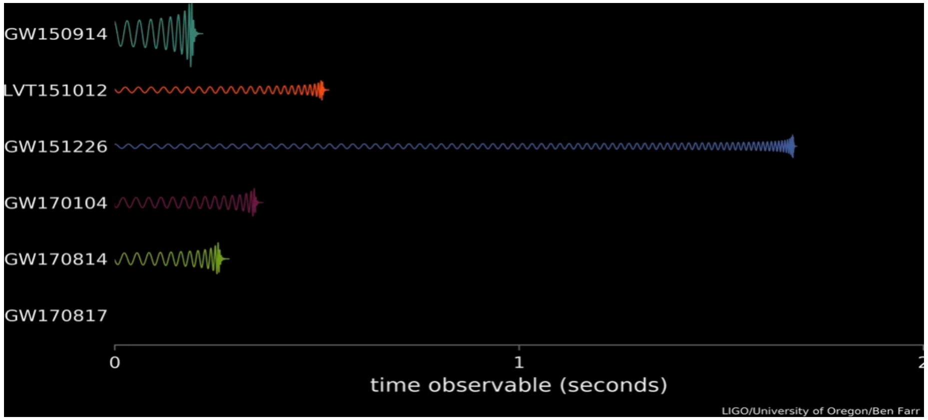
Gravitational Waves

hundreds of millions of templates need to interpret the data



(c) M.Hannam, C. North

BNS signals significantly longer than BBH ones

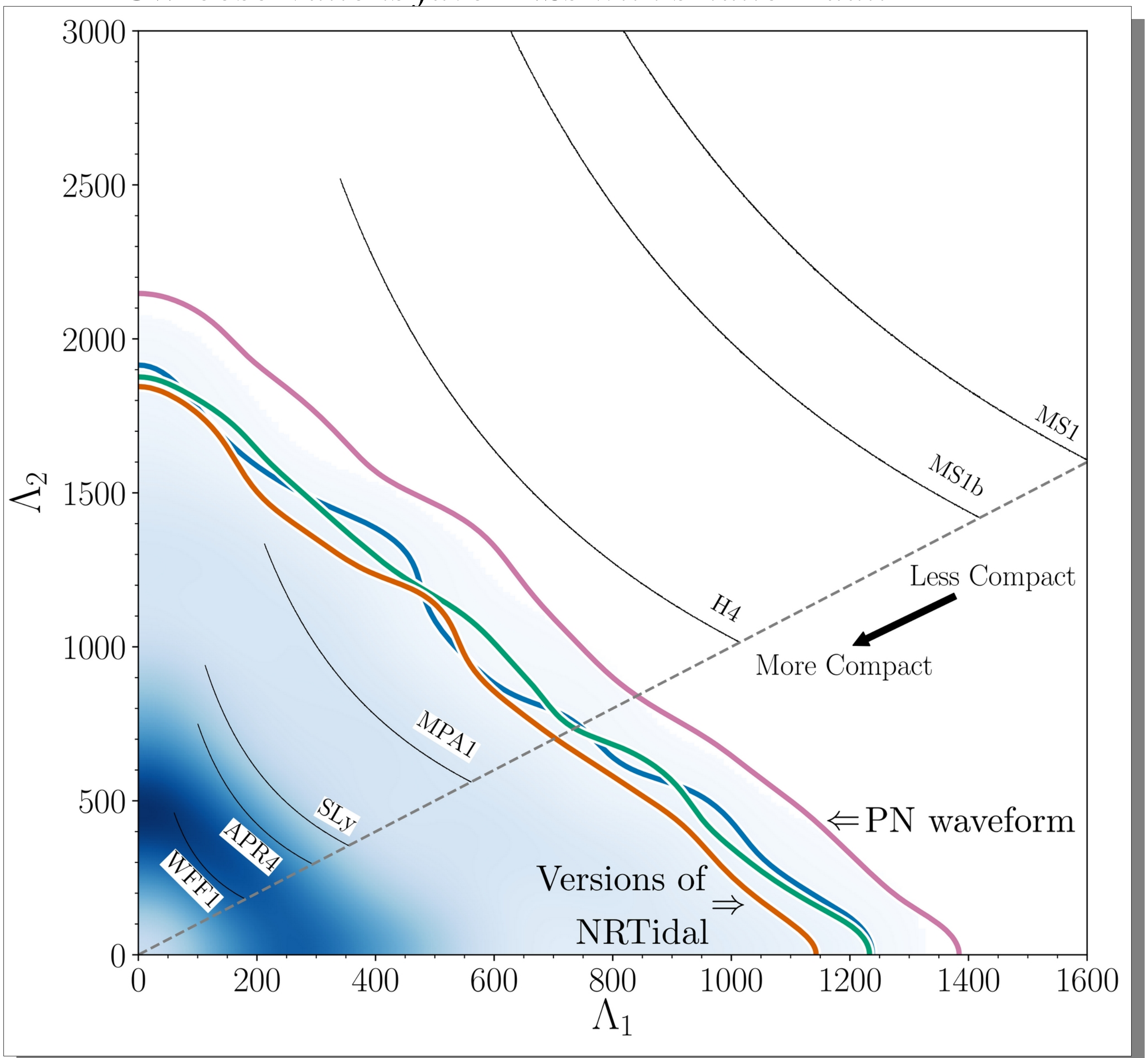


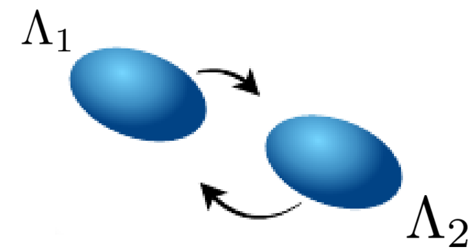
https://www.youtube.com/watch?v=vTeAFAGpfso

Application: GW170817 – Tidal Effects

Determine the Equation of State

GW observations favor NSs with smaller radii



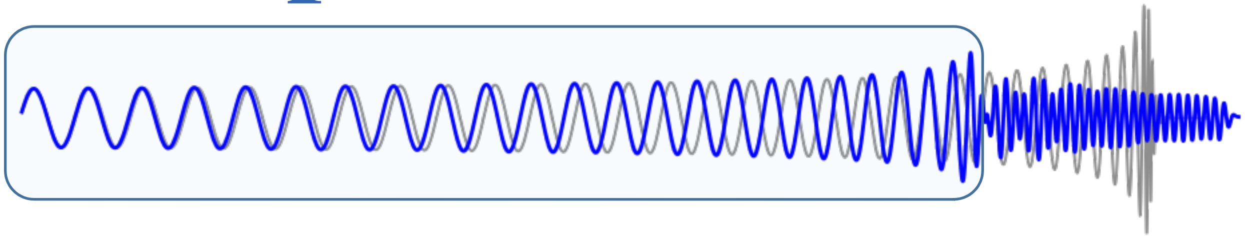


Λ determines tidal deformability

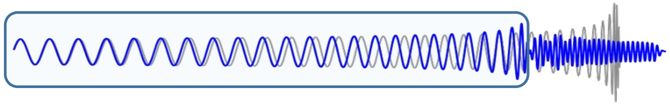
→ no assumption about the type of the compact object

Phys.Rev. X9 (2019) 011001

Inspiral waveforms

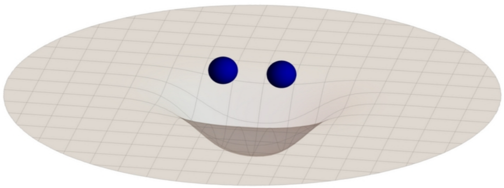


Inspiral waveforms



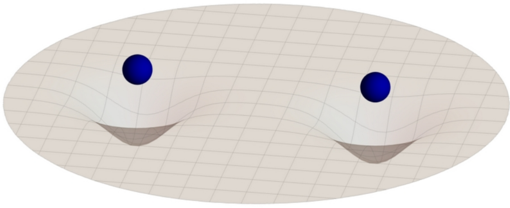
Numerical Relativity Simulations

+ solve Einstein equations
+ predictions of postmerger
– very slow



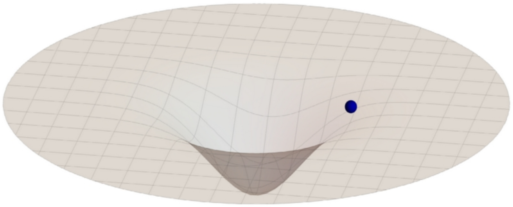
Post-Newtonian Theory

+ fast to compute
– inaccurate near merger



Effective-one-body Formalism

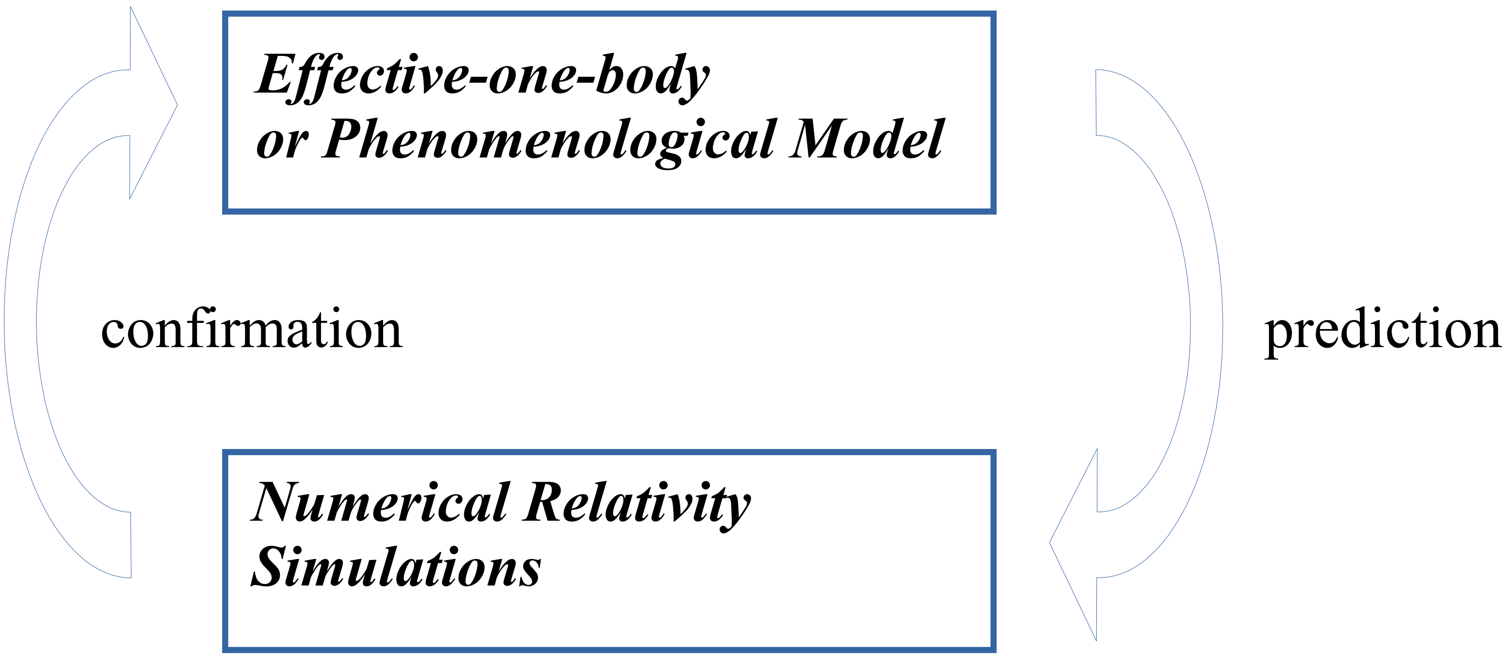
+ agree well with most NR data
– slow to compute



Phenomenological Models

+ combination of PN/EOB/NR
+ accurate until merger
– just a fit

Waveform Model Development



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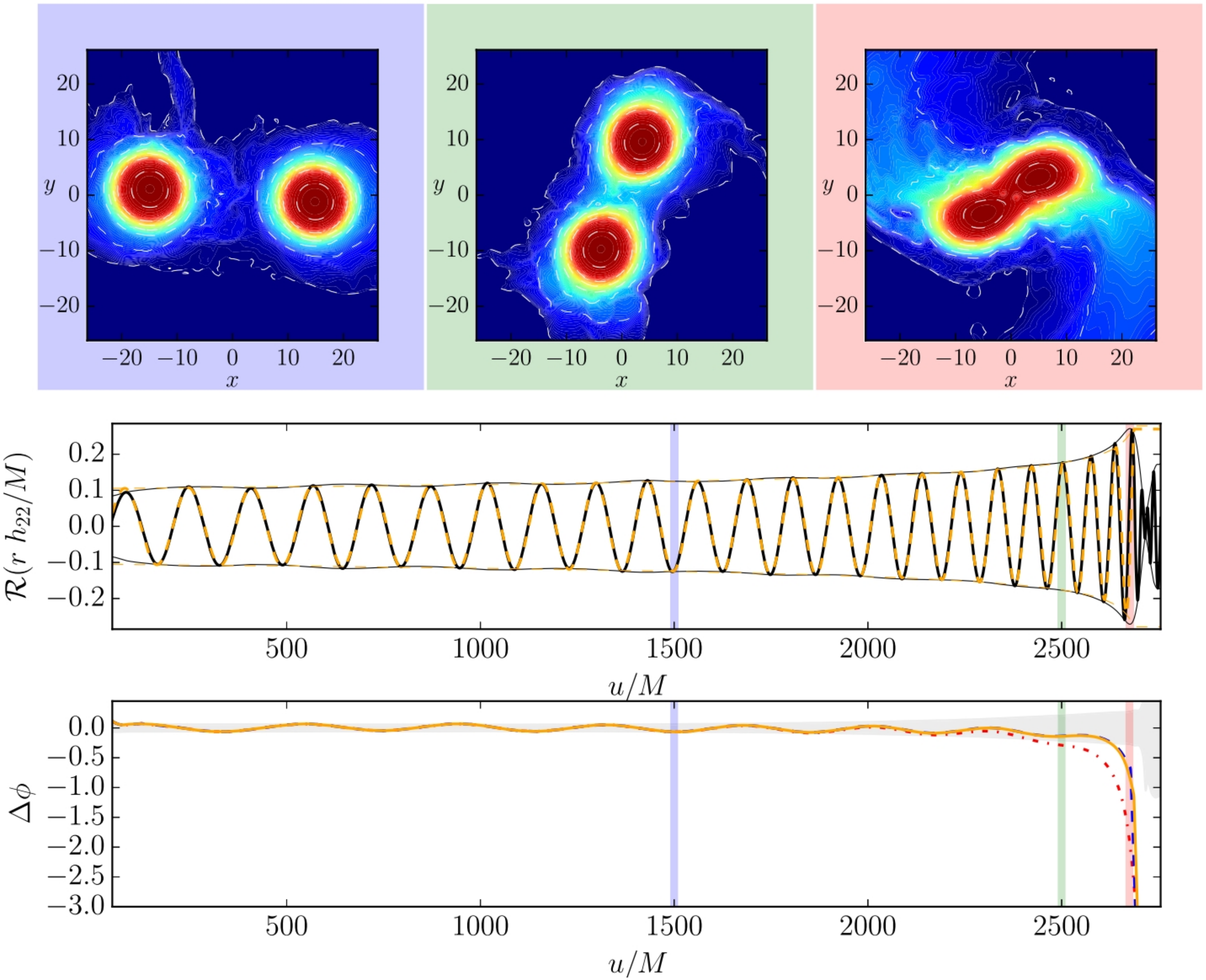


Numerical simulation

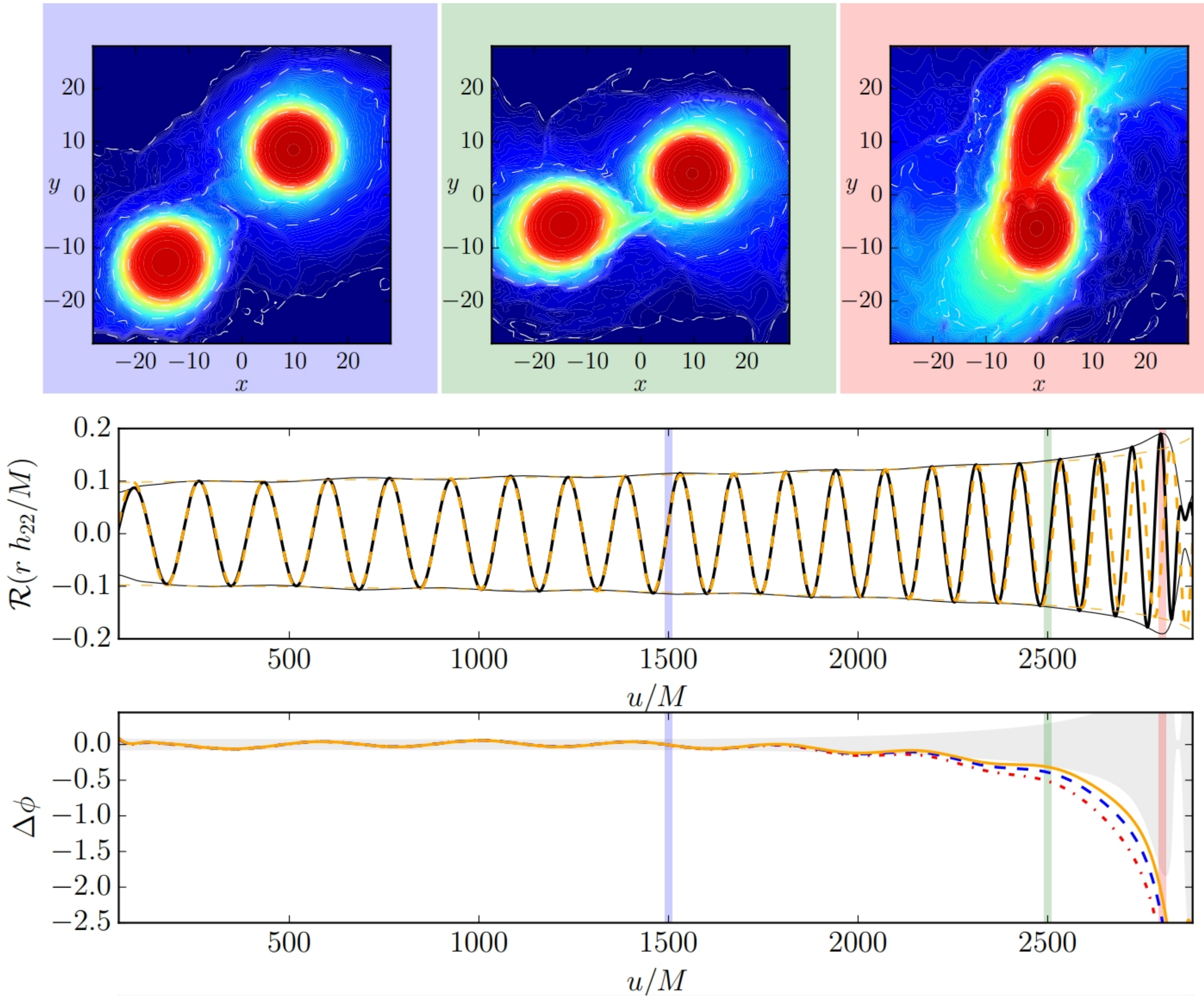
Numerical simulation

Model

Phase difference

TD & Hinderer, PRD 95 (2017) 12, 124006

Waveform Model Development



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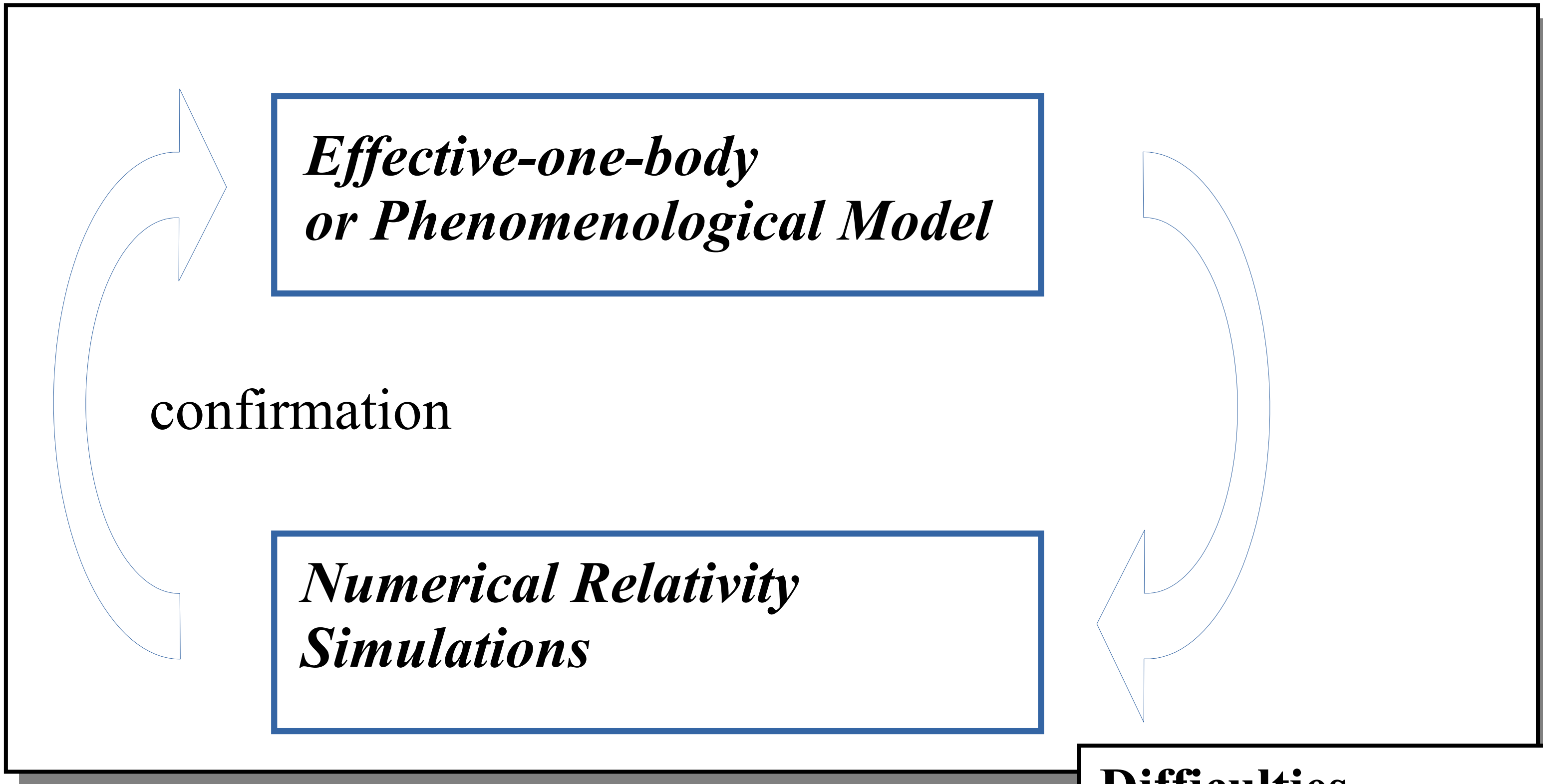

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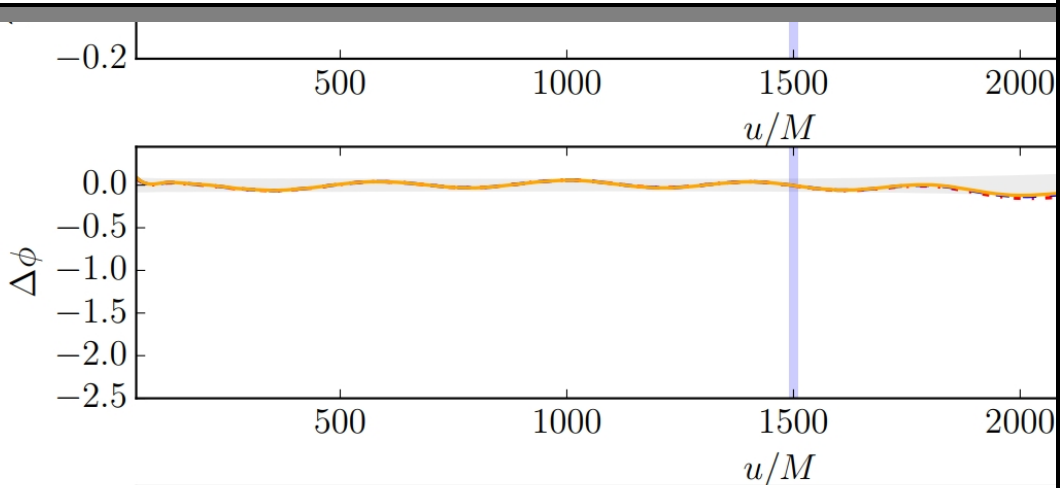


Difficulties

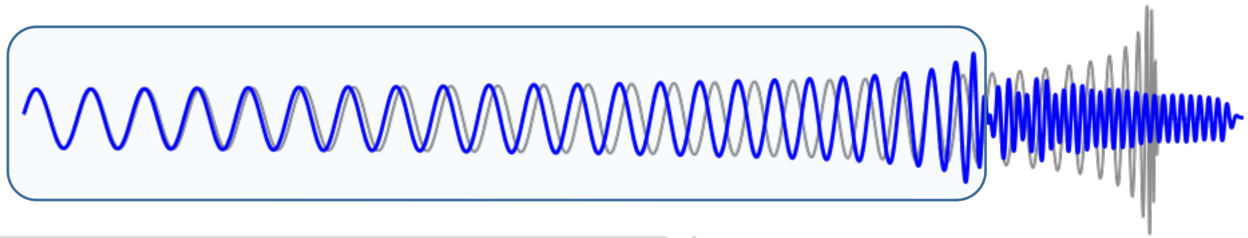
→ require large computational resources

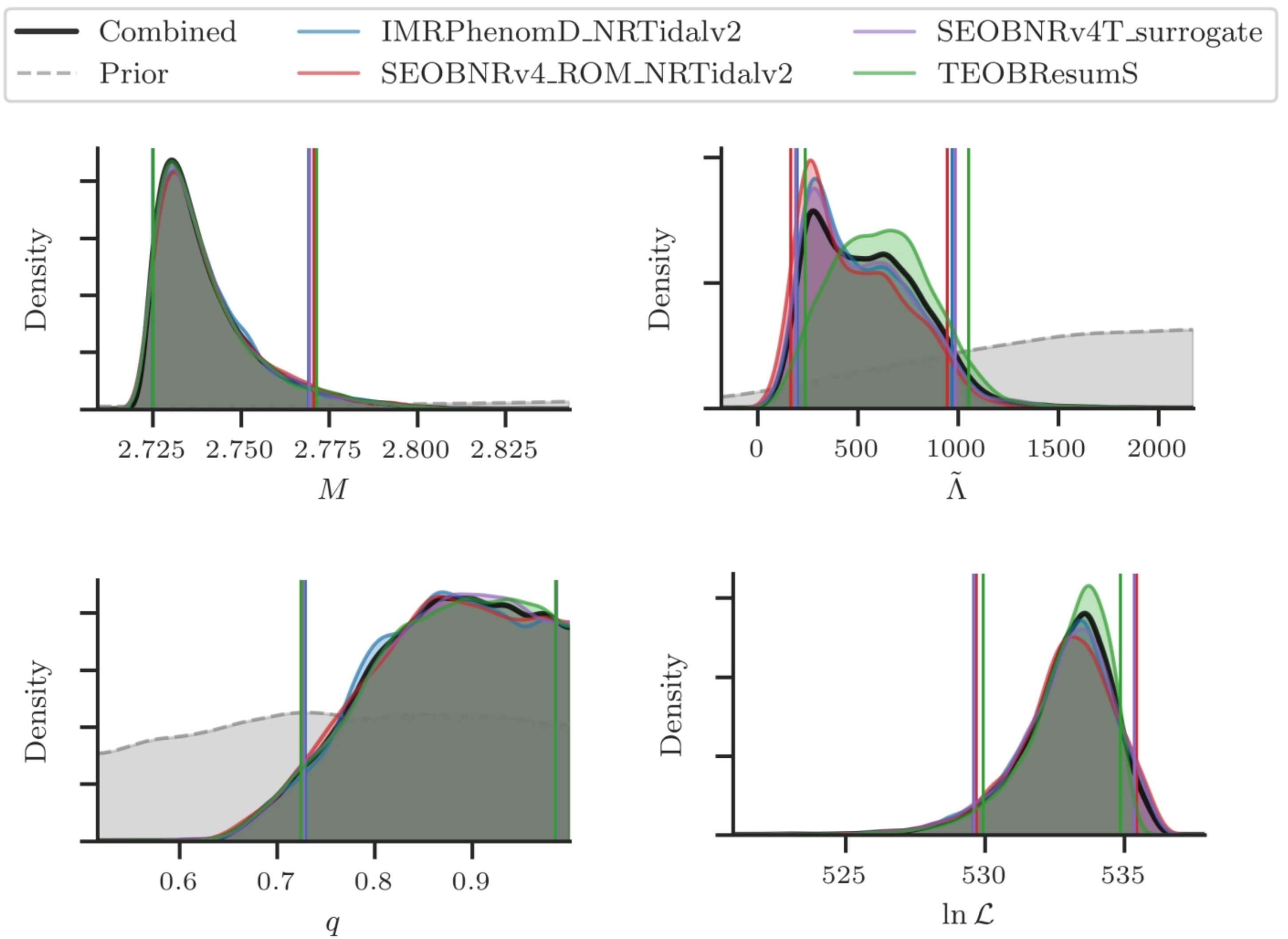
→ numerical simulations also have uncertainties

TD & Hinderer, PRD 95 (2017) 12, 124006

An Alternative Approach

G. Ashton & TD, aXiv: 2111.09214 [gr-qc]





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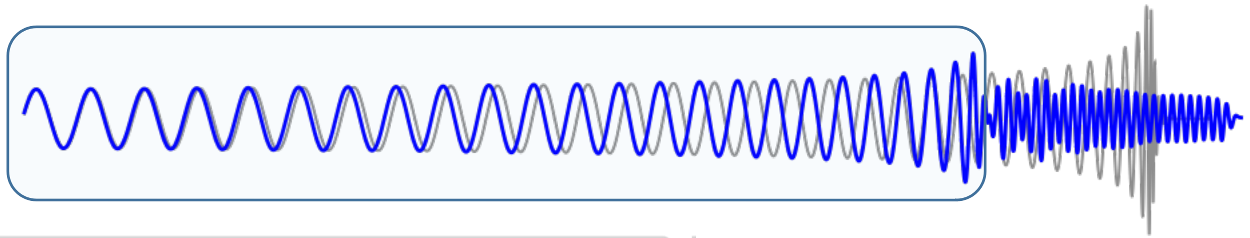

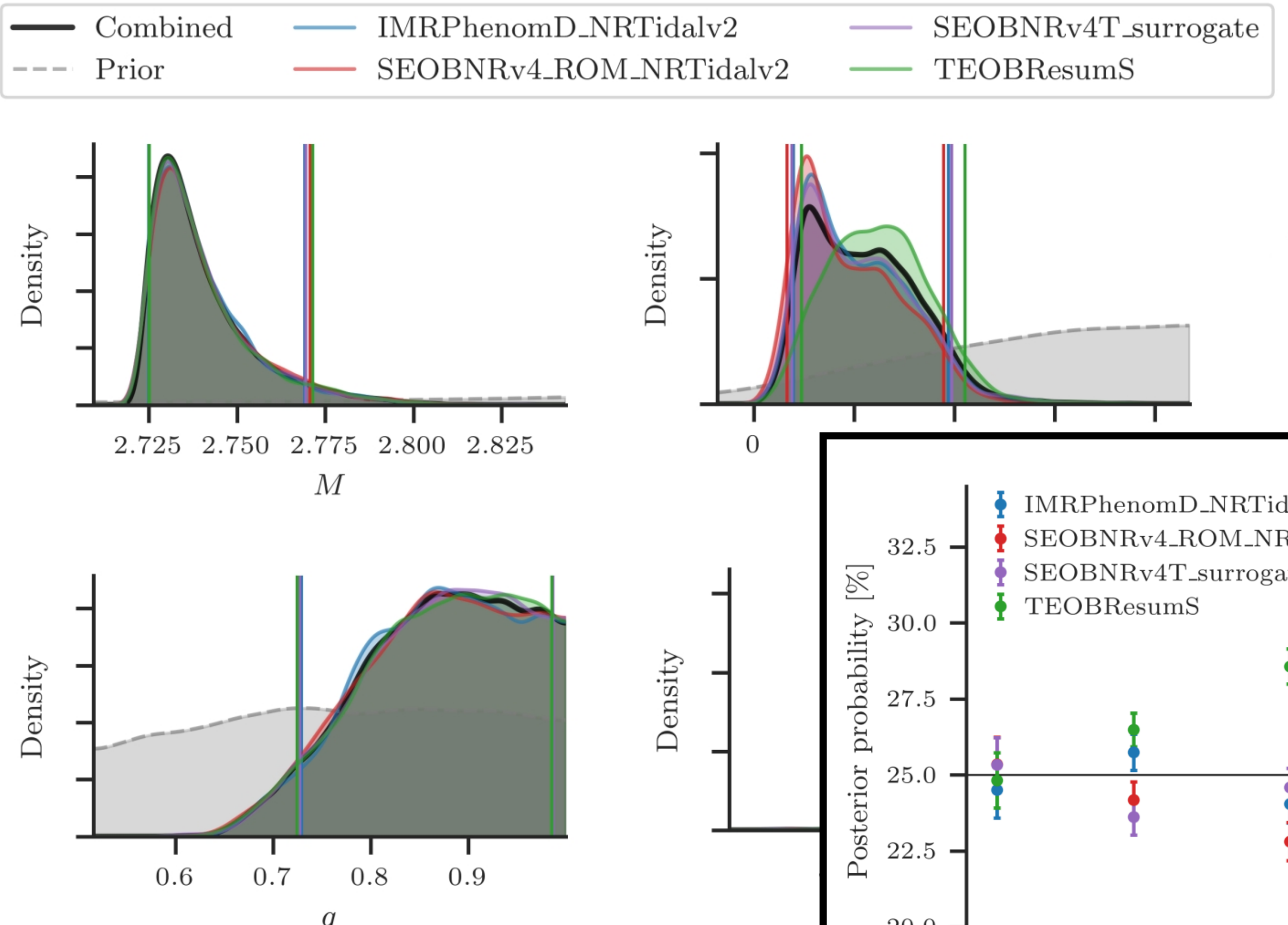

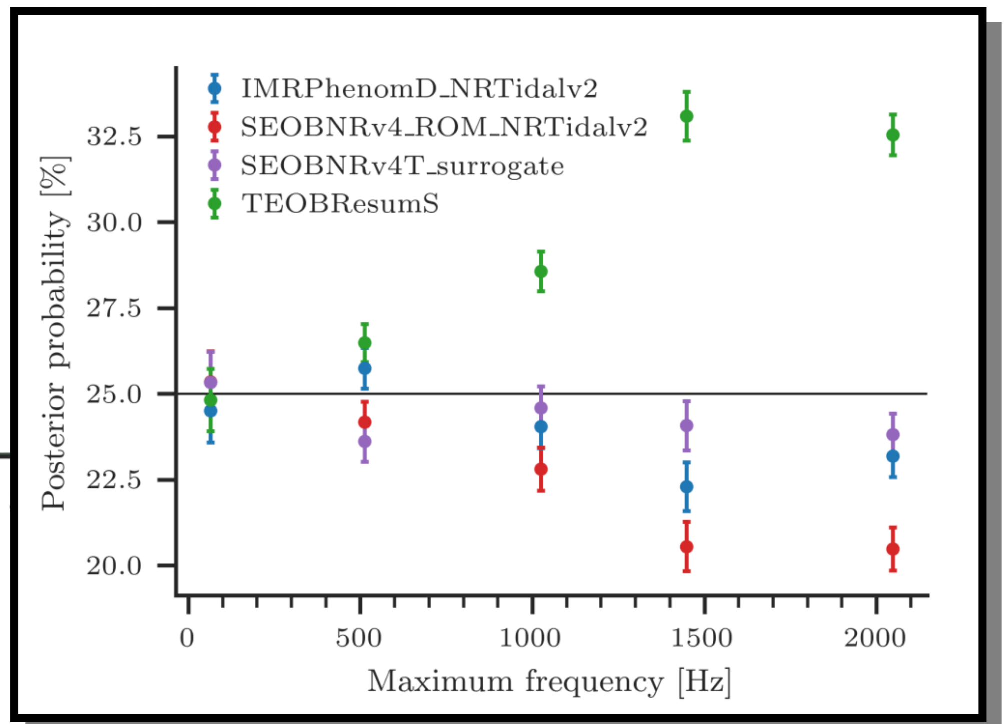

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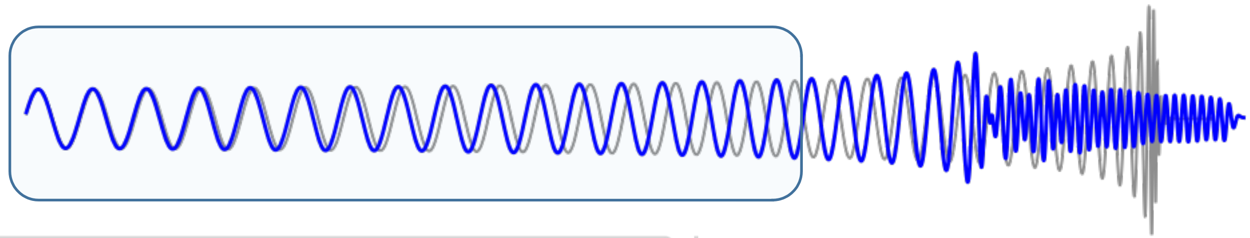

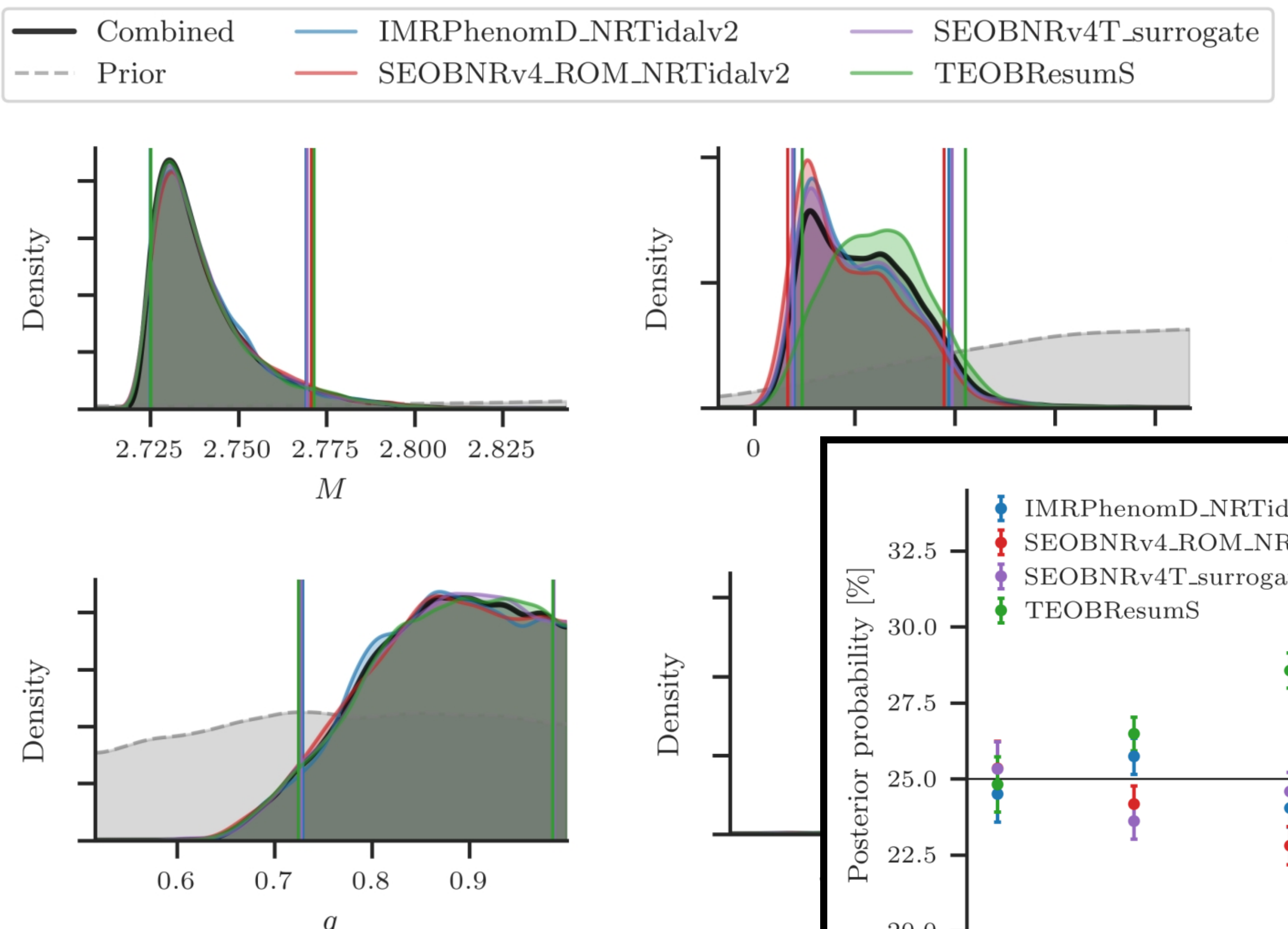

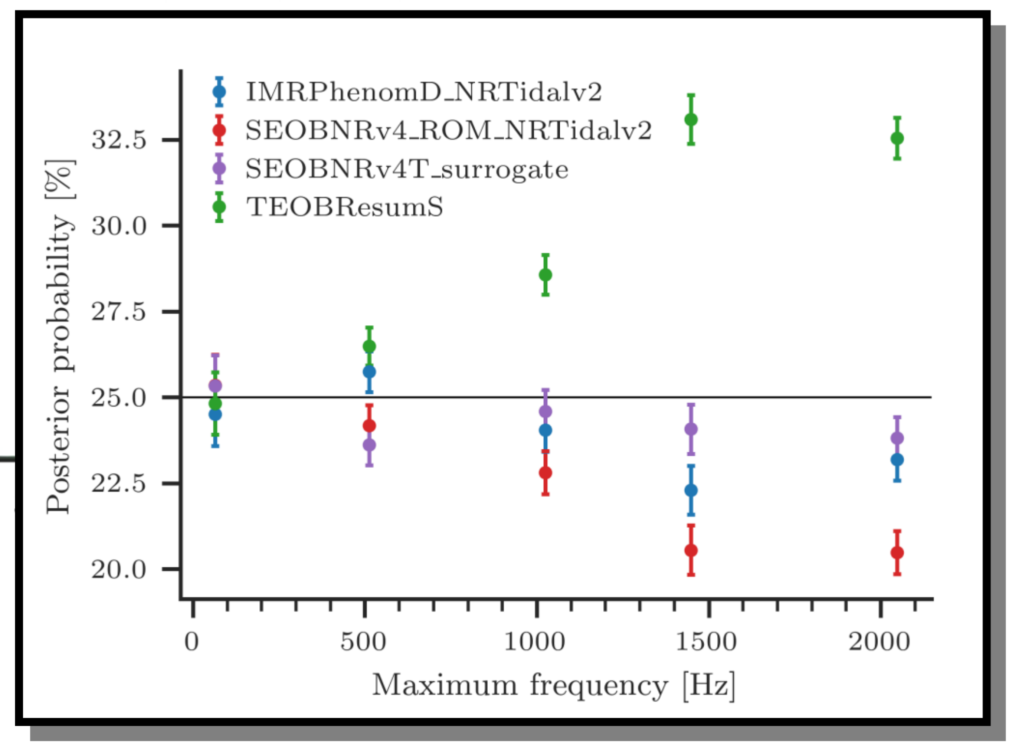

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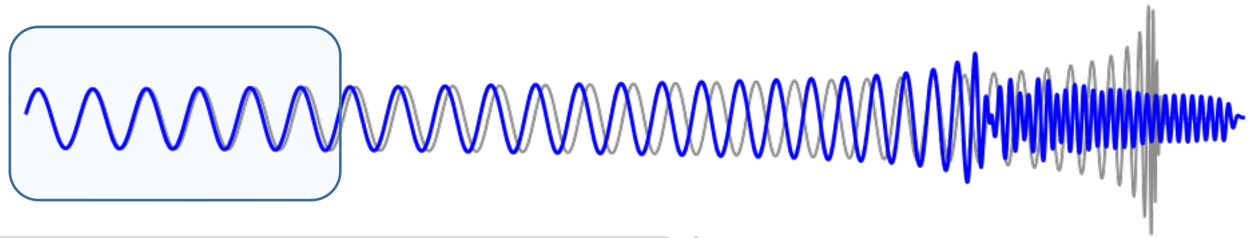
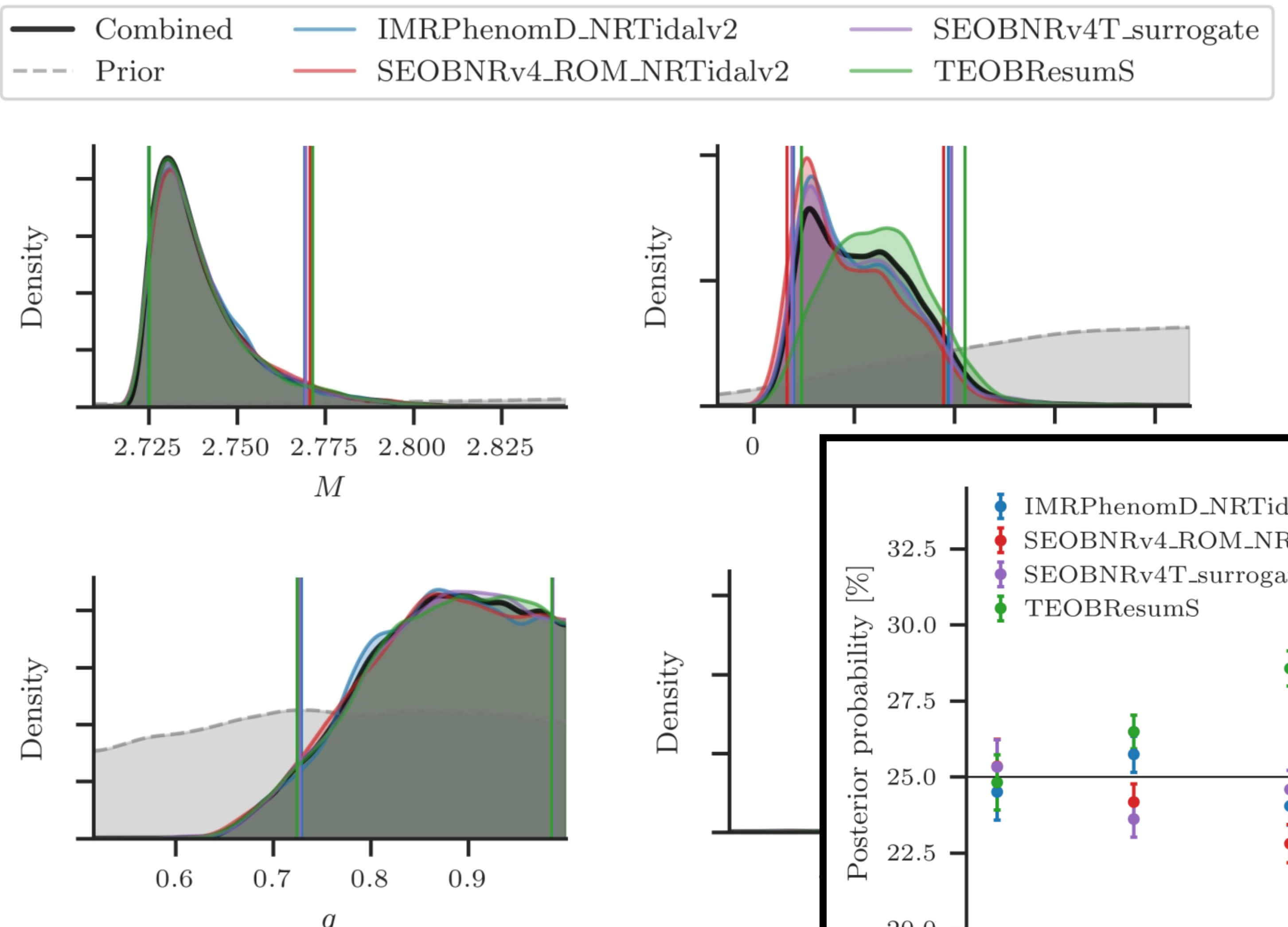
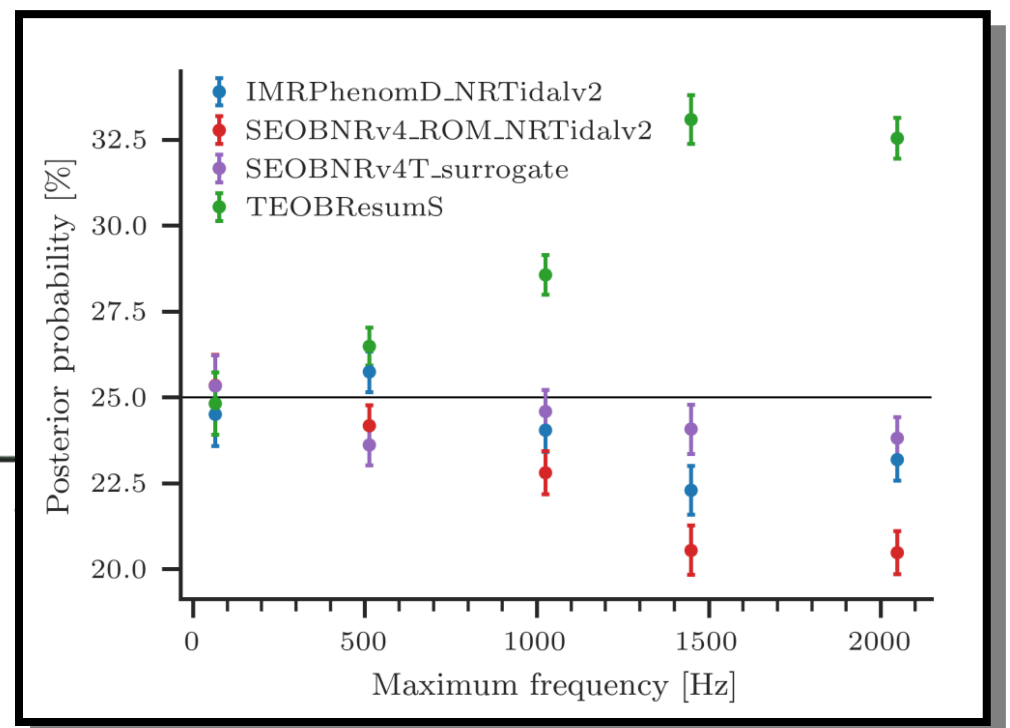
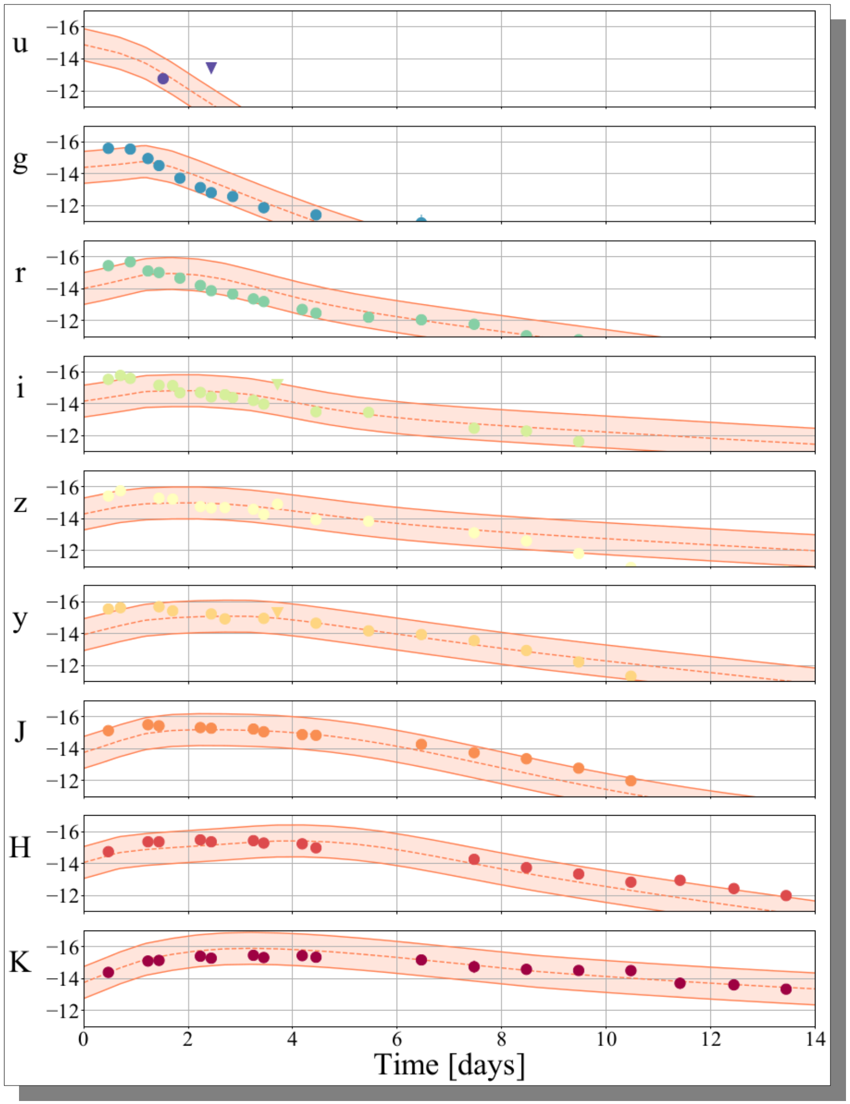
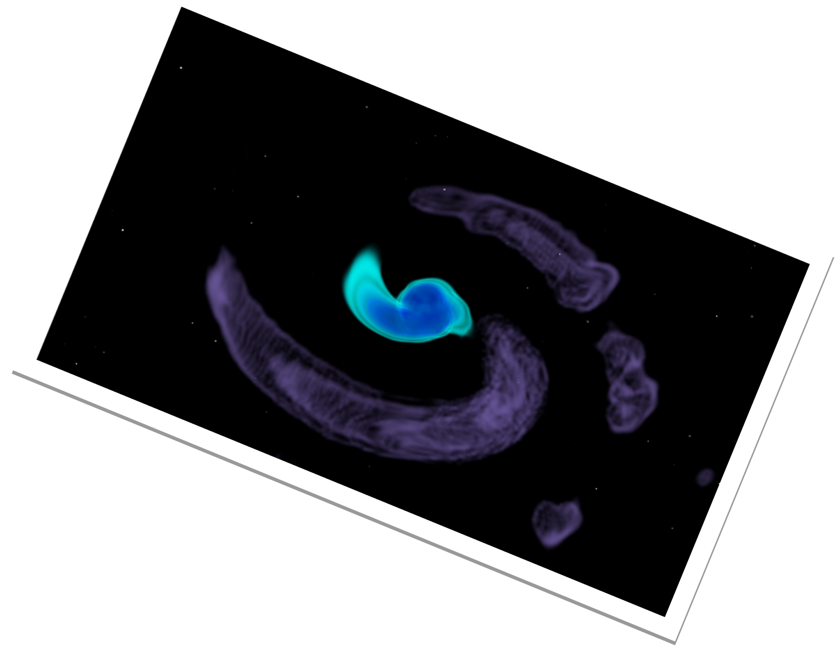






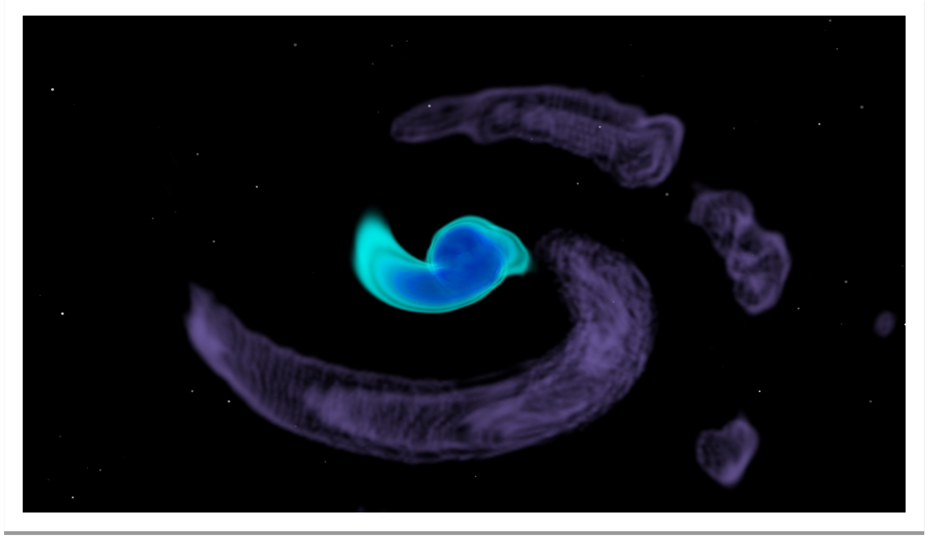
Electromagnetic Signals and Multi-messenger Astronomy

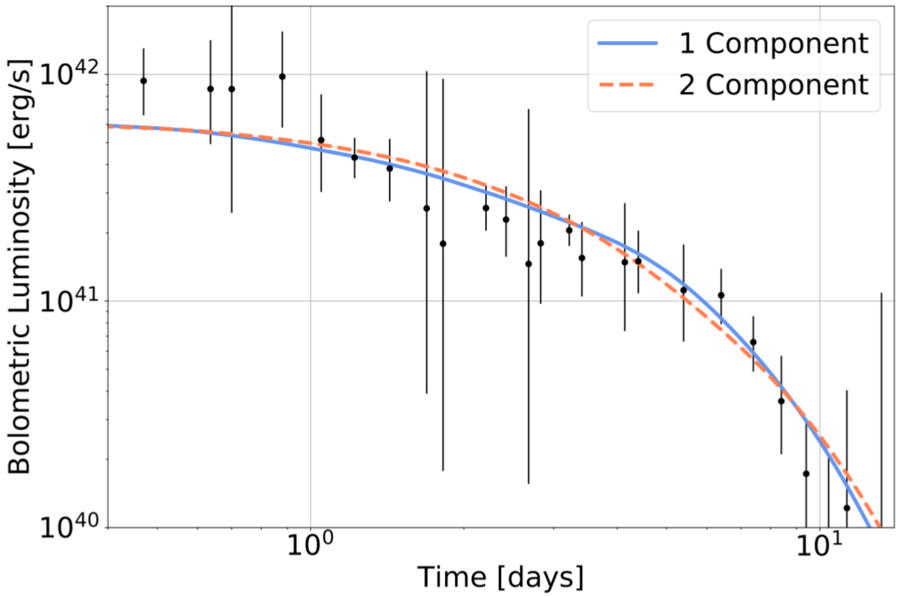




EM Signals – Kilonova

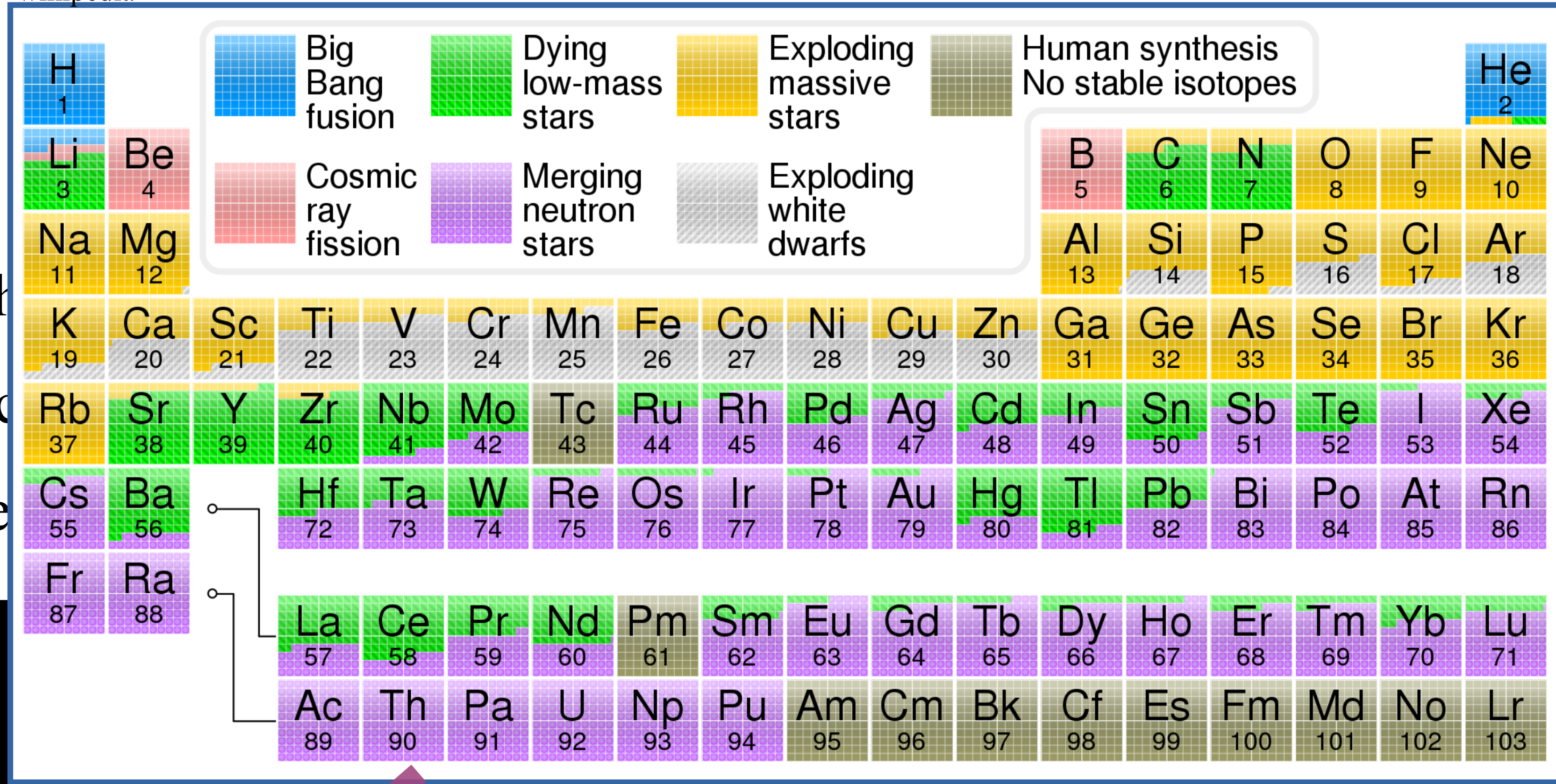
- neutron rich ejecta produce heavy r-process elements
- pseudo-black body radiation from r-process elements
- mergers are major sites for the formation of heavy elements





Coughlin, TD, et al., MNRAS/sty2174

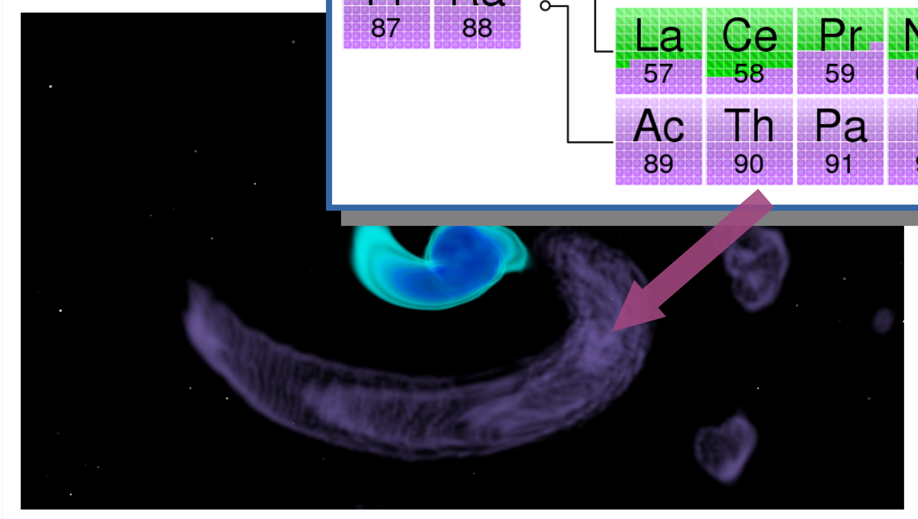
wikipedia

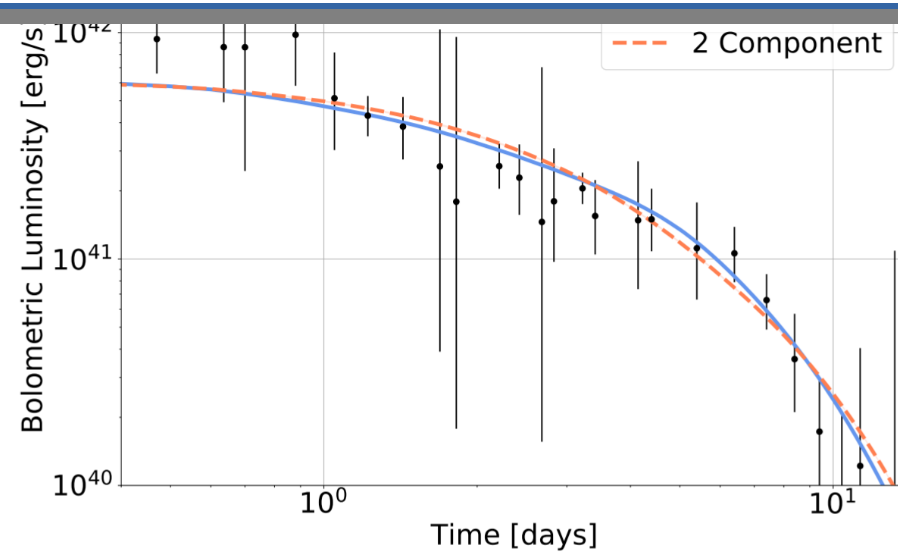


- neutron rich

- pseudo-blac

- mergers are



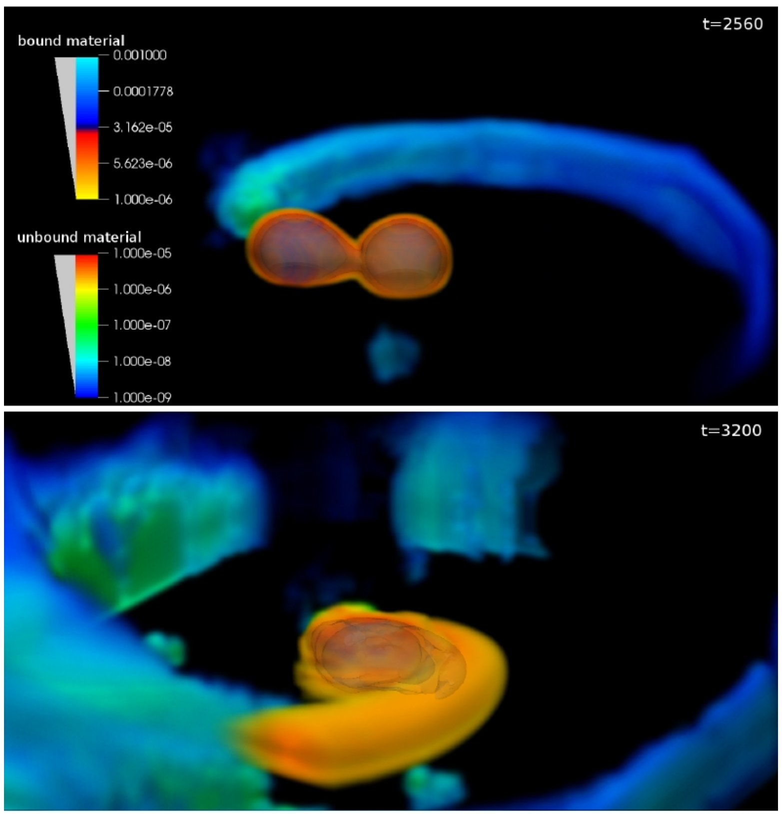


Coughlin, TD, et al., MNRAS/sty2174

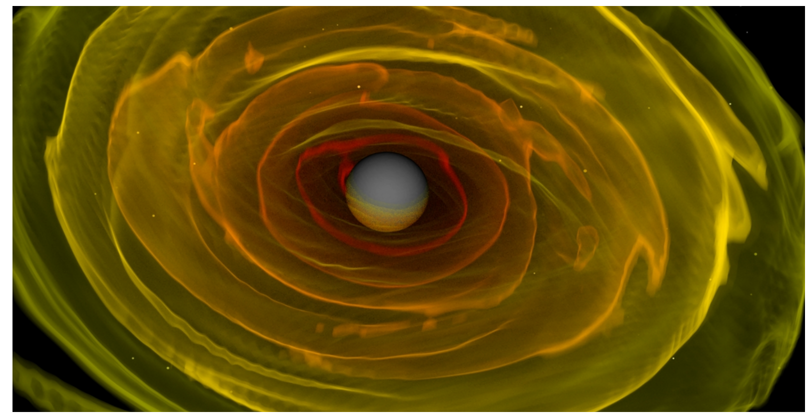
Incorporating NR results

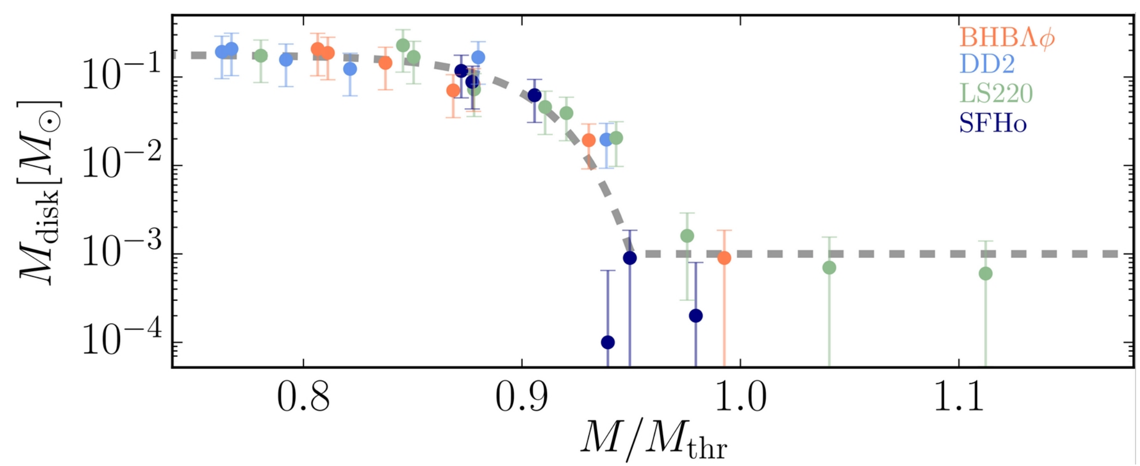
Predictions about ejecta mass and compositions

dynamical ejecta



disk winds





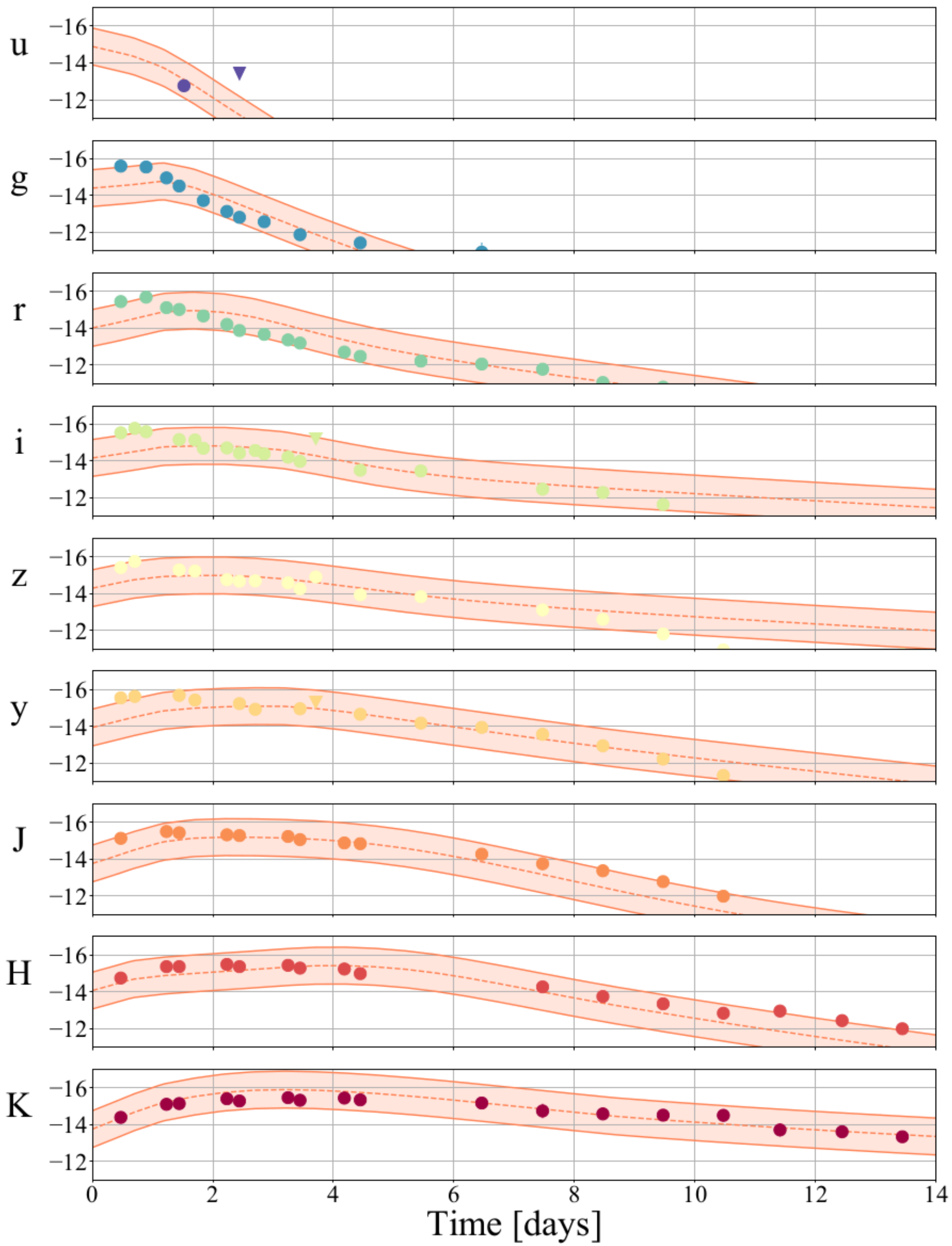
Combine predictions with radiative transfer simulations

Kasen et al., Nature 551

EM Signals Kilonova

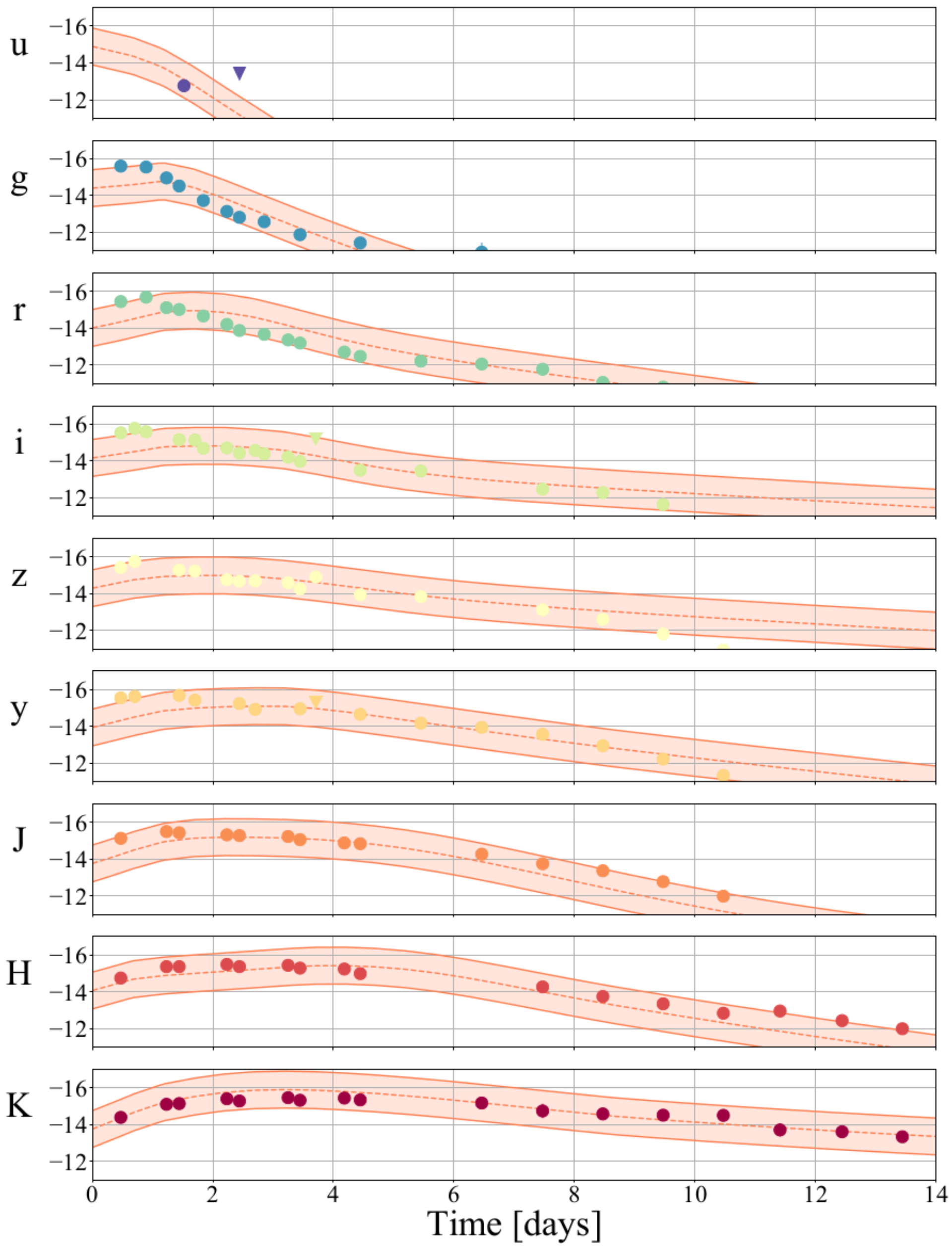
Coughlin, TD, et al., MNRAS/sty2174

Photometric lightcurves



Full radiative transfer simulation linked to Gaussian Process Regression to access full parameter space

Photometric lightcurves



Full radiative transfer simulation linked to Gaussian Process Regression to access full parameter space

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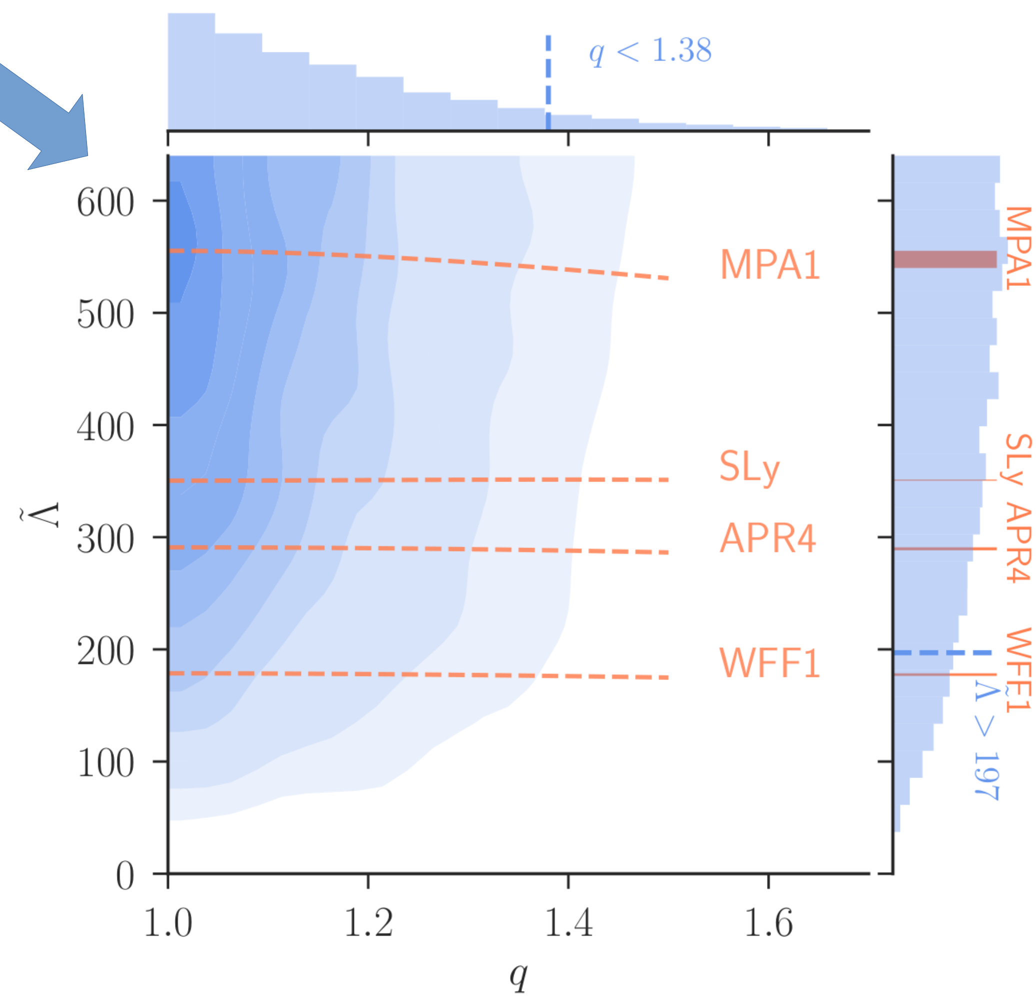
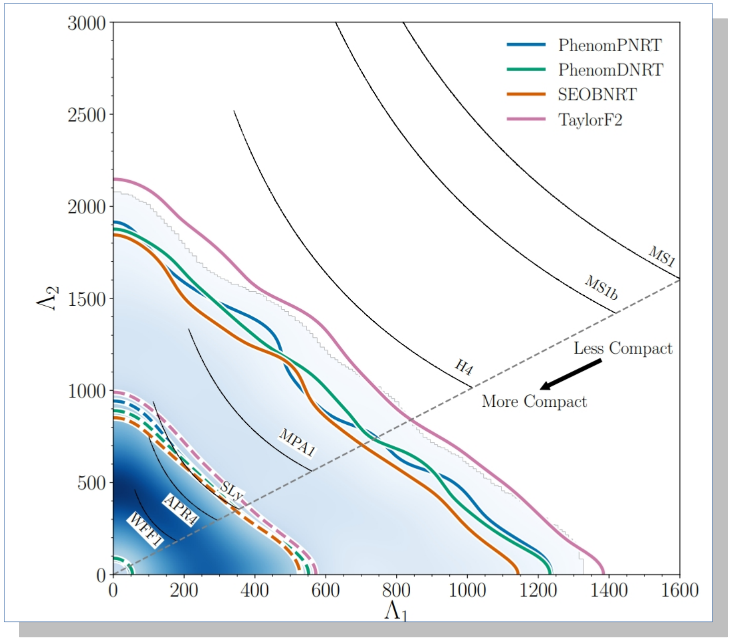
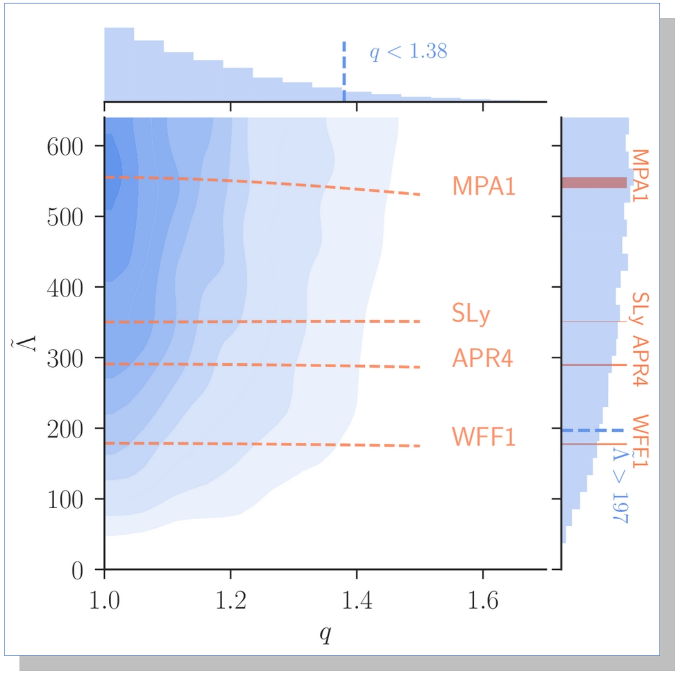
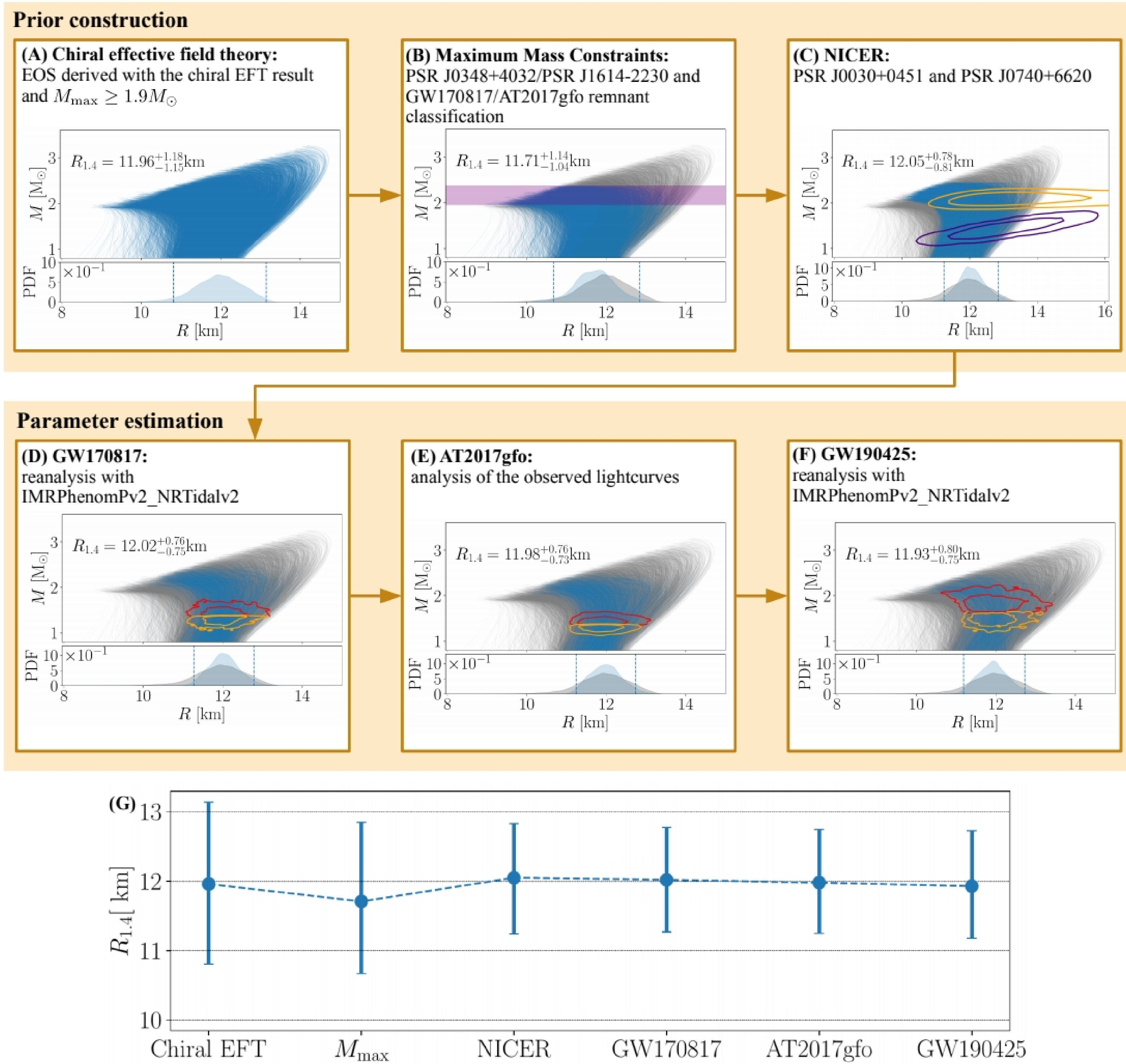
Coughlin, TD, et al., MNRAS/sty2174



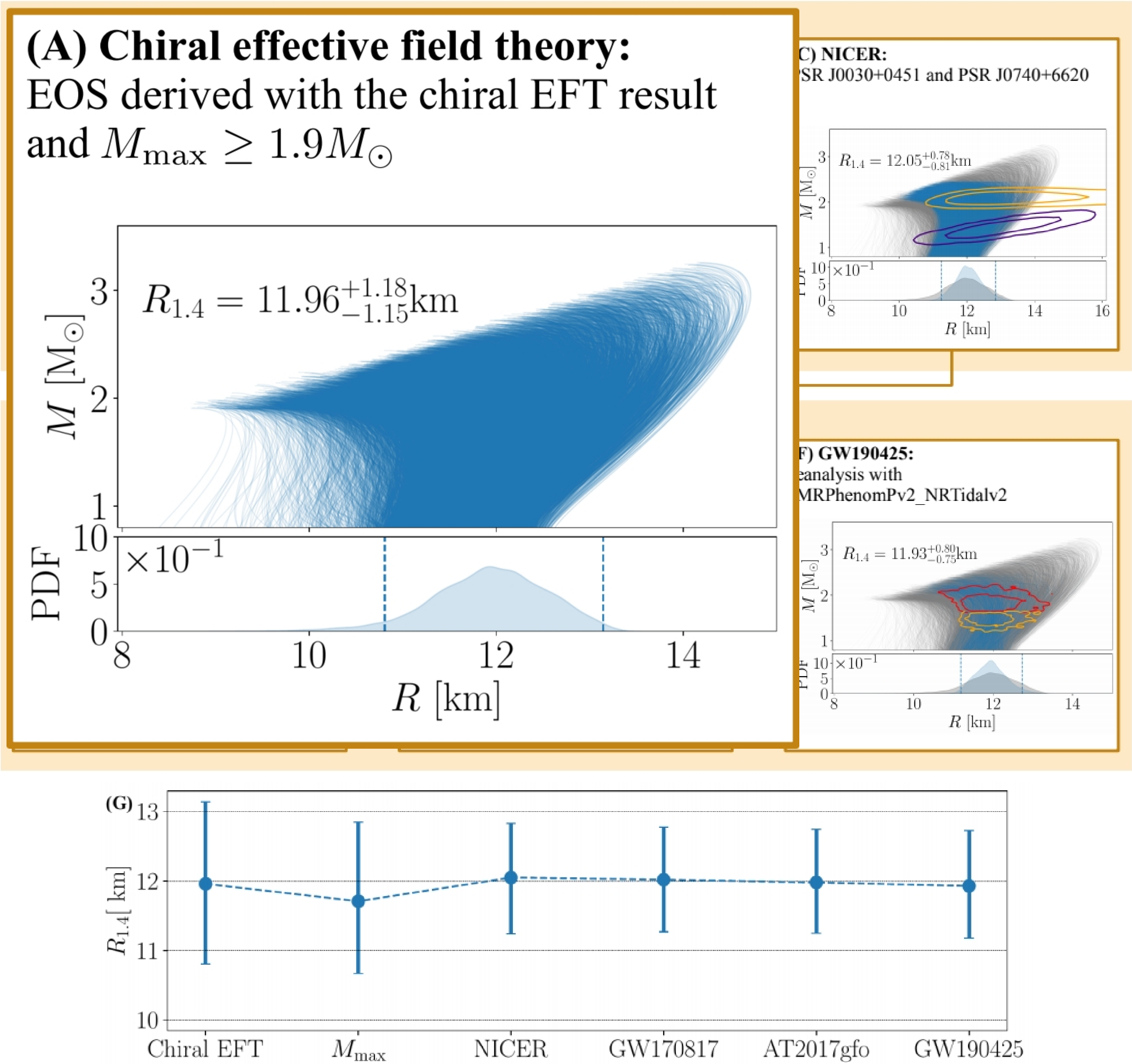
Fundamental physics with Multi-messenger astronomy





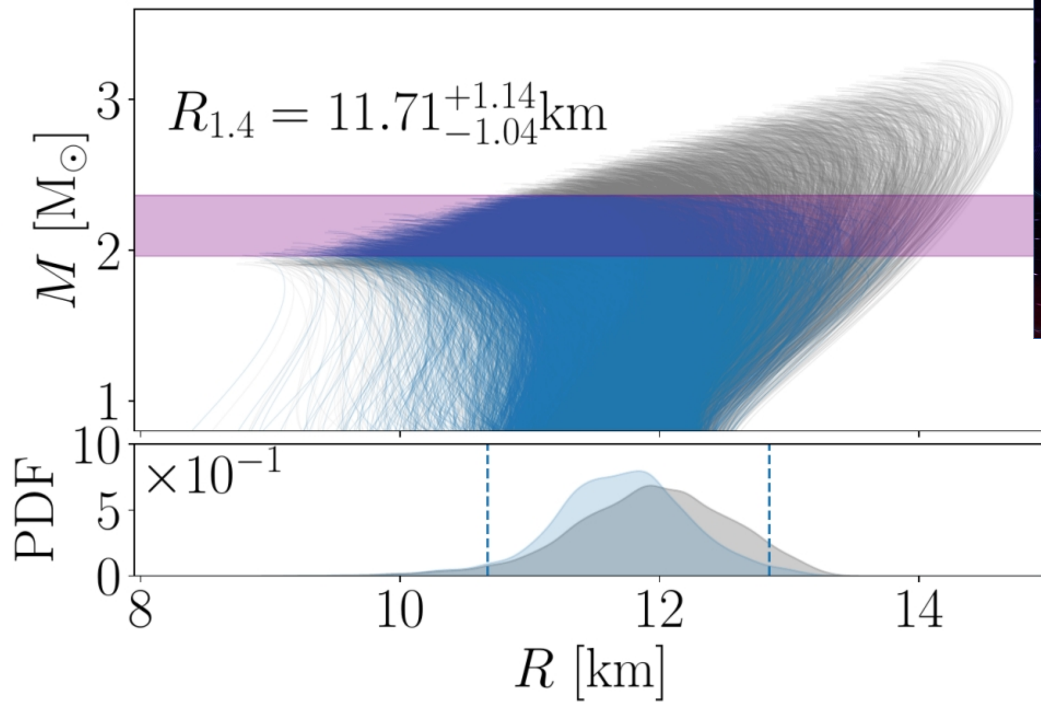


TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., arXiv: 2017.06229

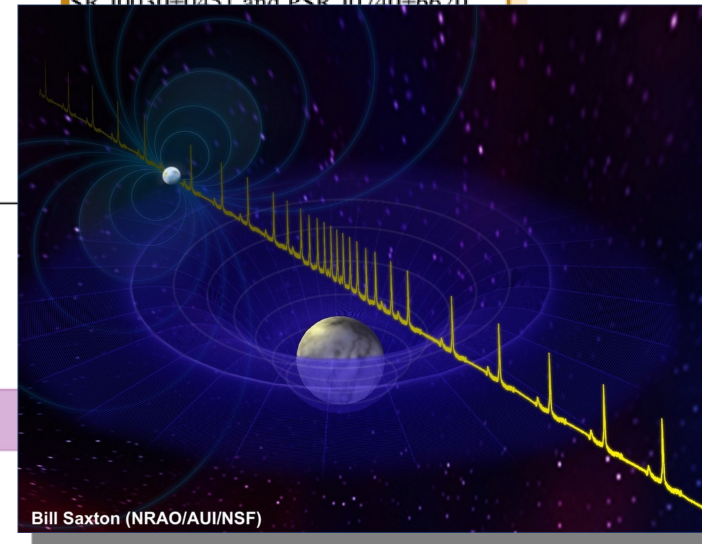


TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., arXiv: 2017.06229

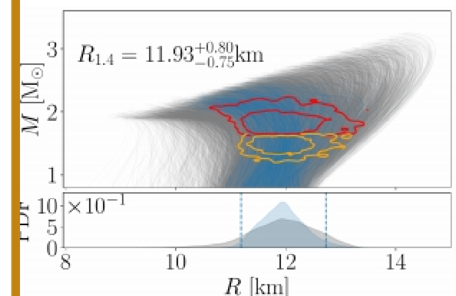
(B) Maximum Mass Constraints:
PSR J0348+4032/PSR J1614-2230 and GW170817/AT2017gfo remnant classification

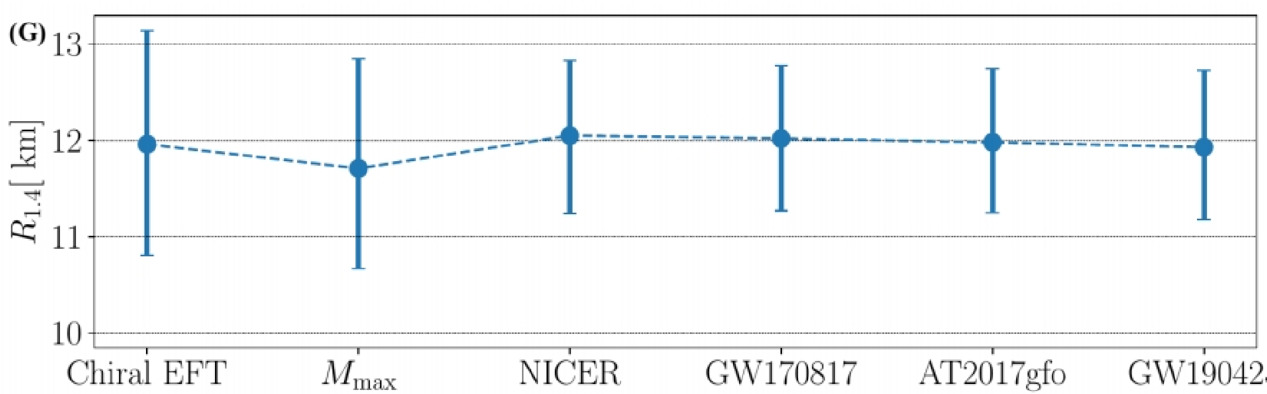


C) NICER:
SR J0030+0451 and PSR J0740+6620



analysis with
MRPhenomPv2_NRTidalv2





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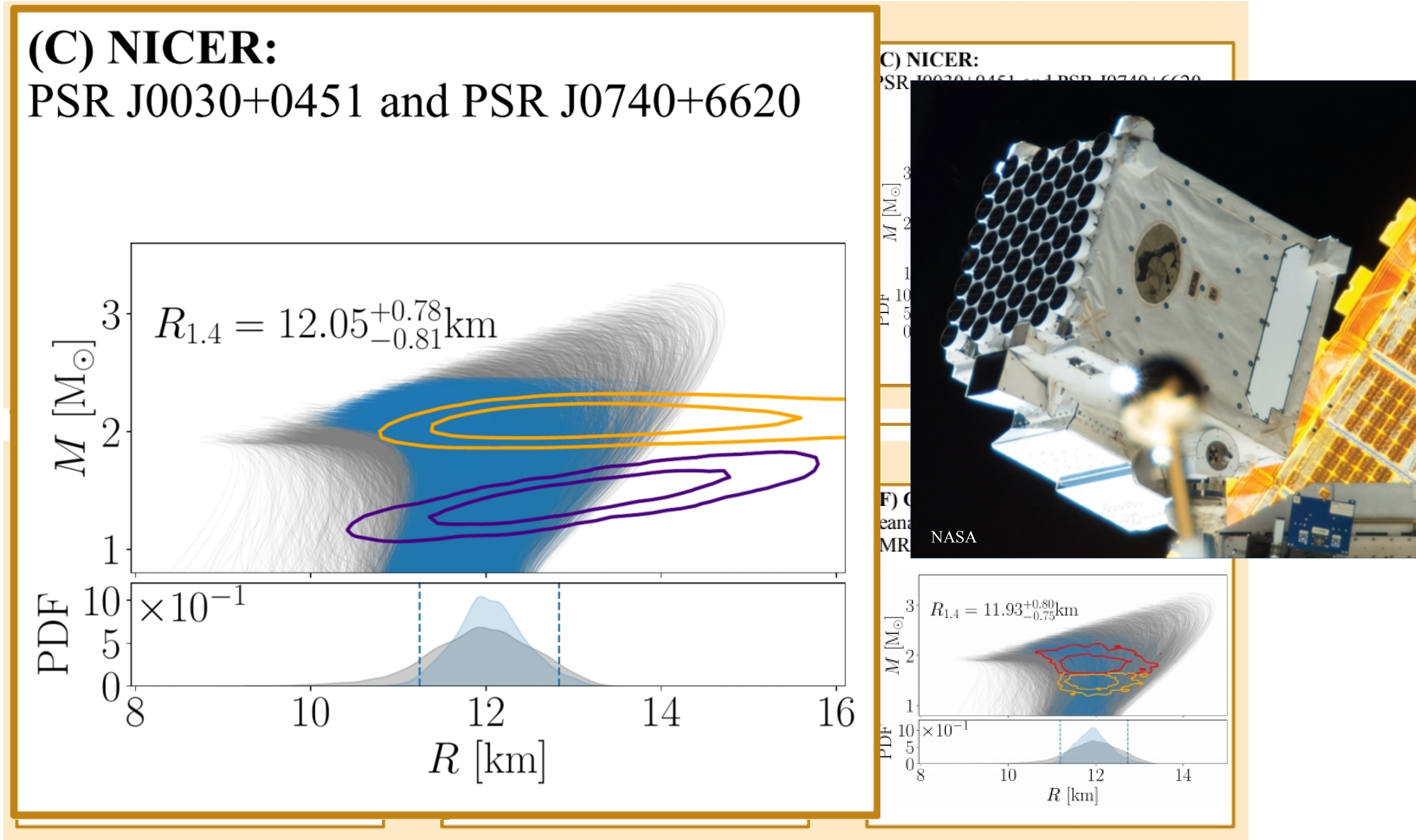

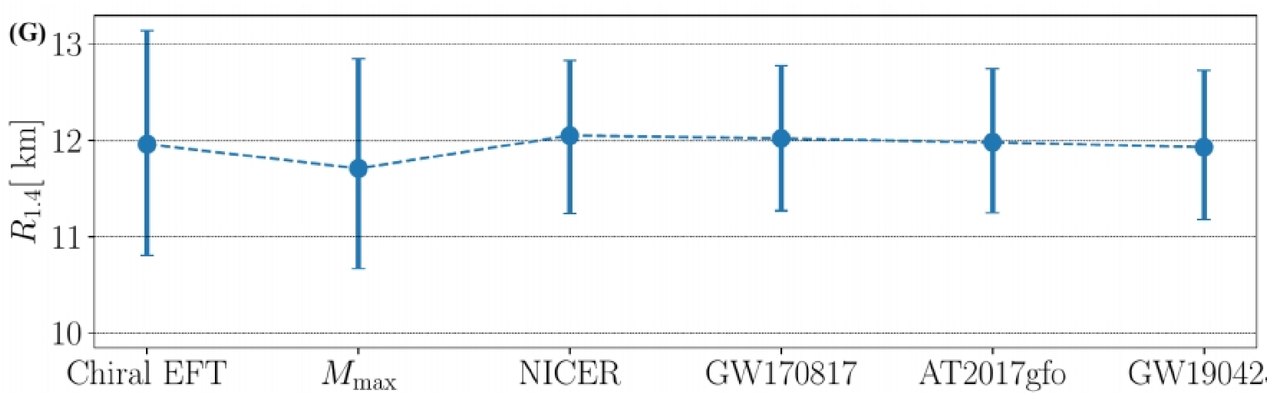

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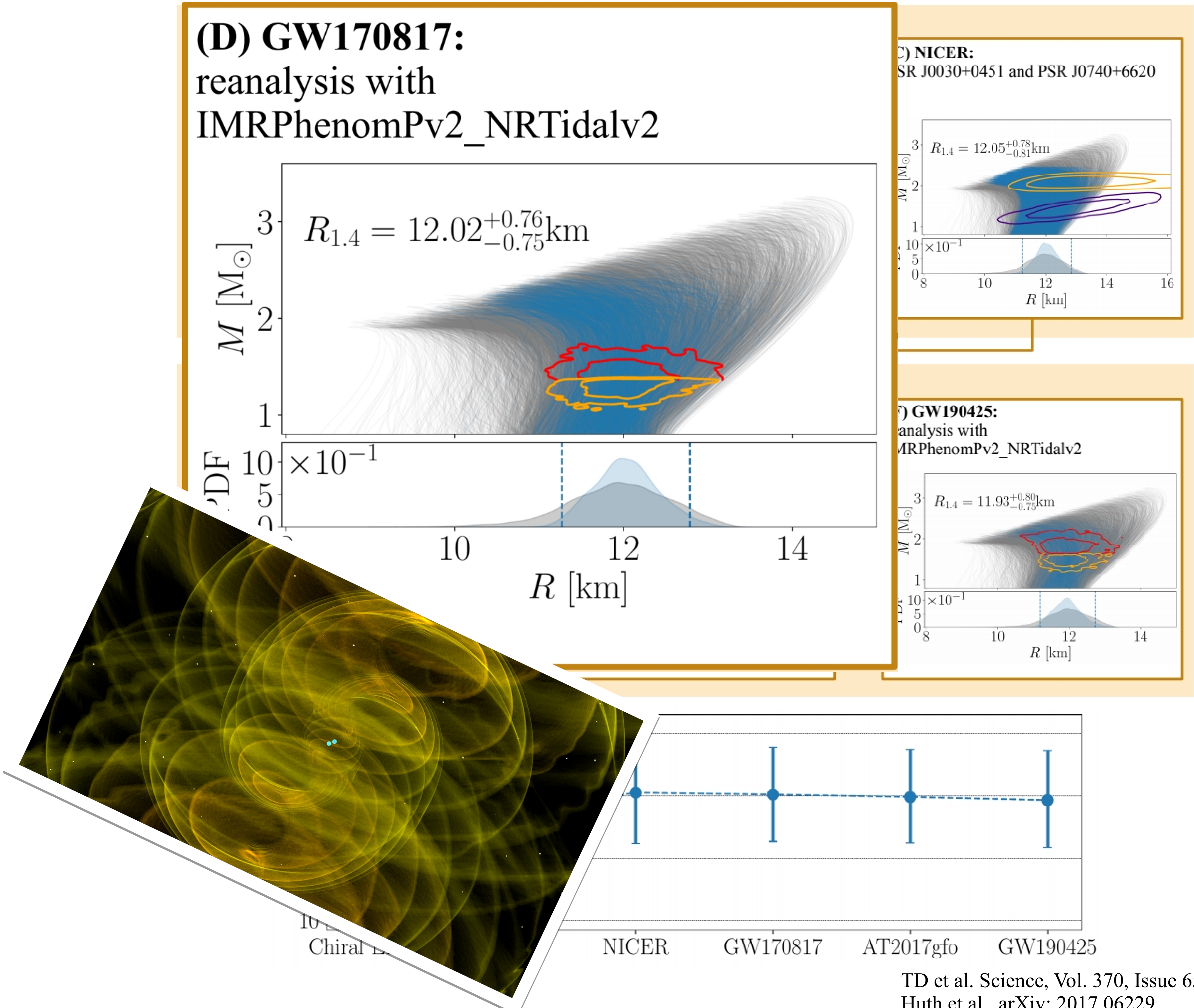
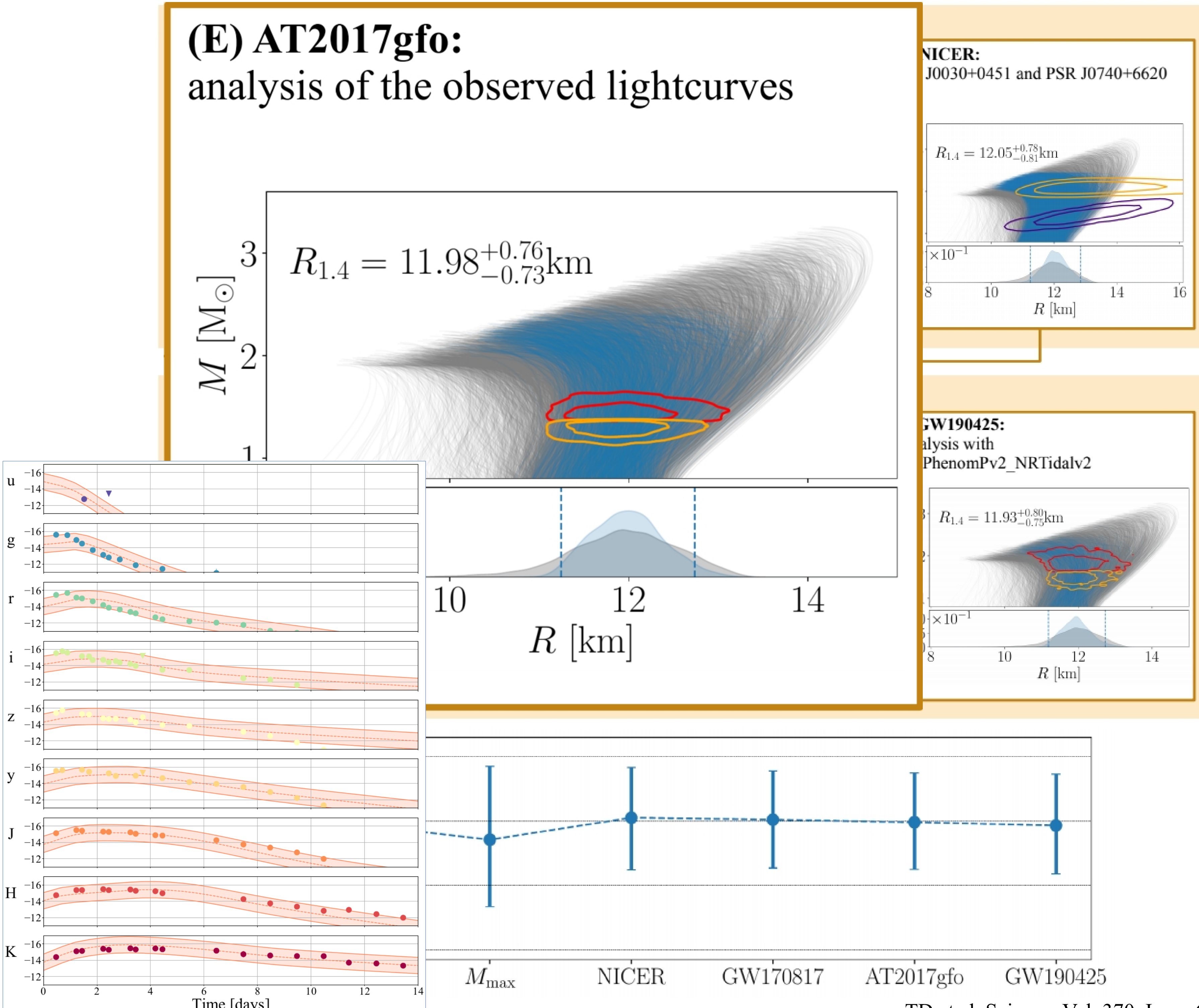
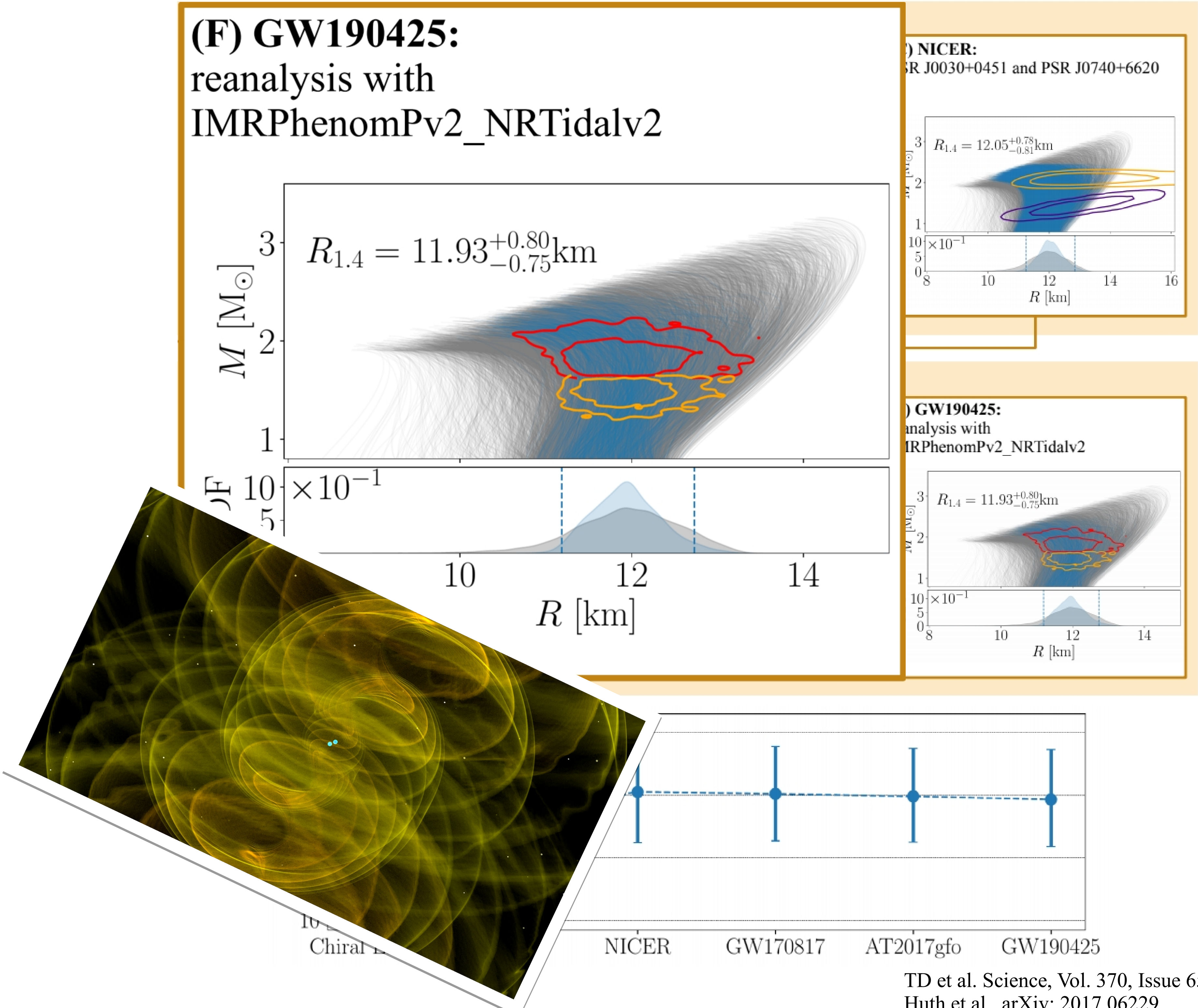


TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., arXiv: 2017.06229

(E) AT2017gfo:
analysis of the observed lightcurves

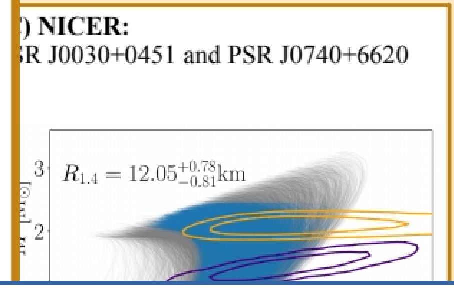


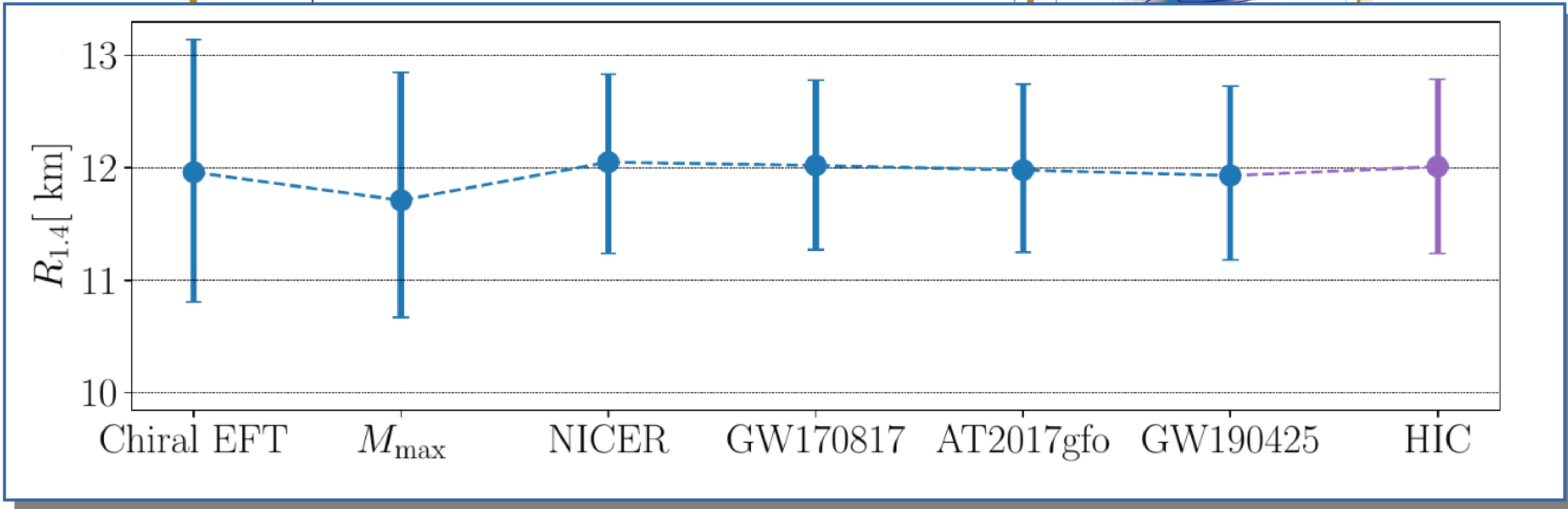
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., arXiv: 2017.06229

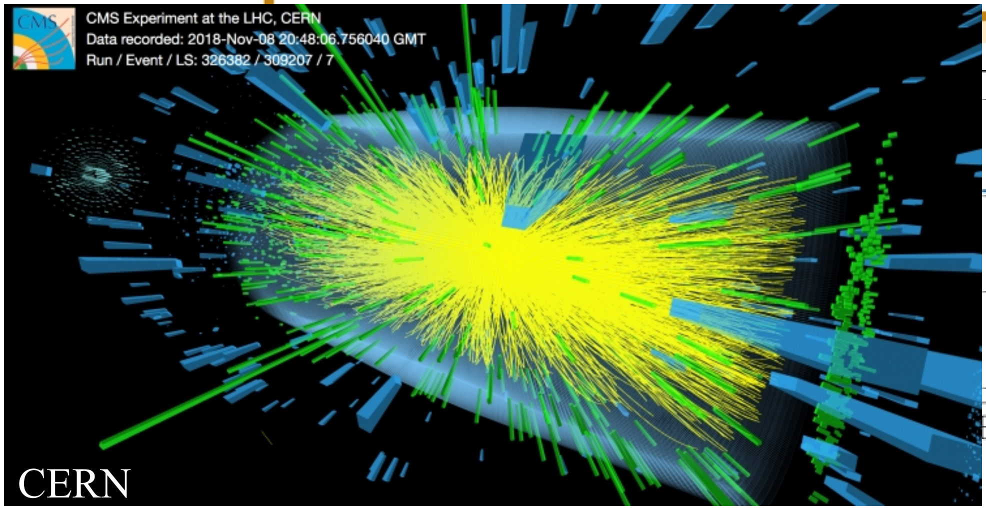


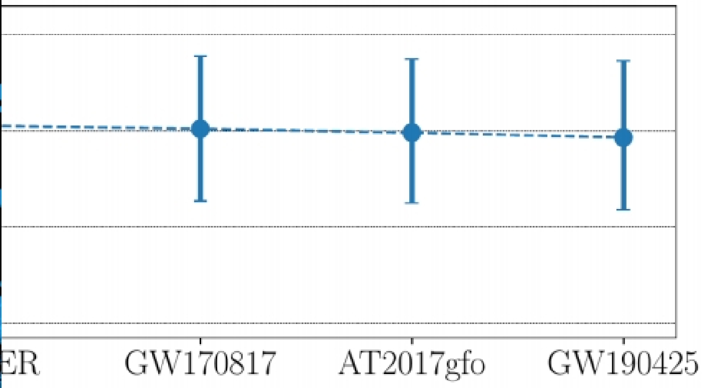
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., arXiv: 2017.06229

(F) GW190425:
reanalysis with
IMRPhenomPv2_NRTidalv2









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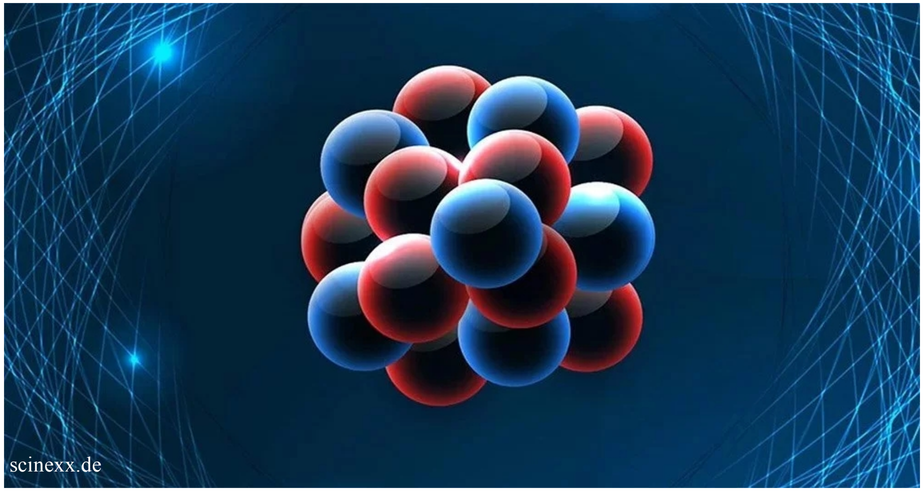
Huth et al., arXiv: 2017.06229 (under review in Nature)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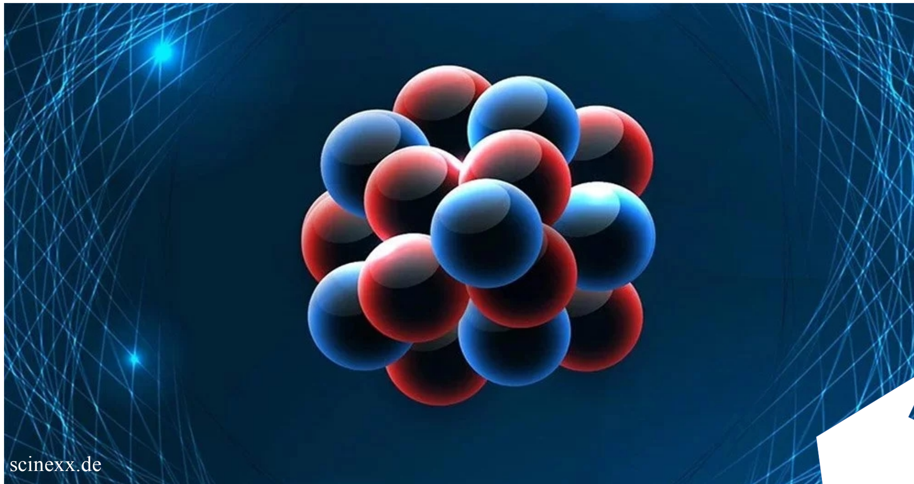
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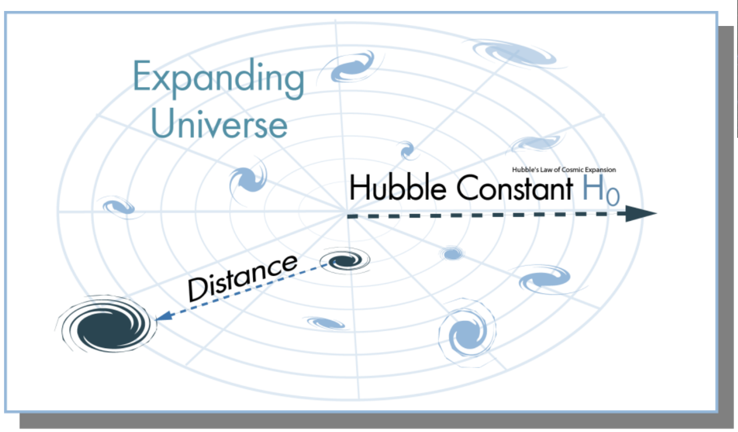
NASA


Expanding
Universe
Hubble's Law of Cosmic Expansion
Hubble Constant H0
Distance

Multi-messenger astronomy: Hubble constant measurement

Hubble constant

$$v(z) = H_0 d$$

Redshift

Distance

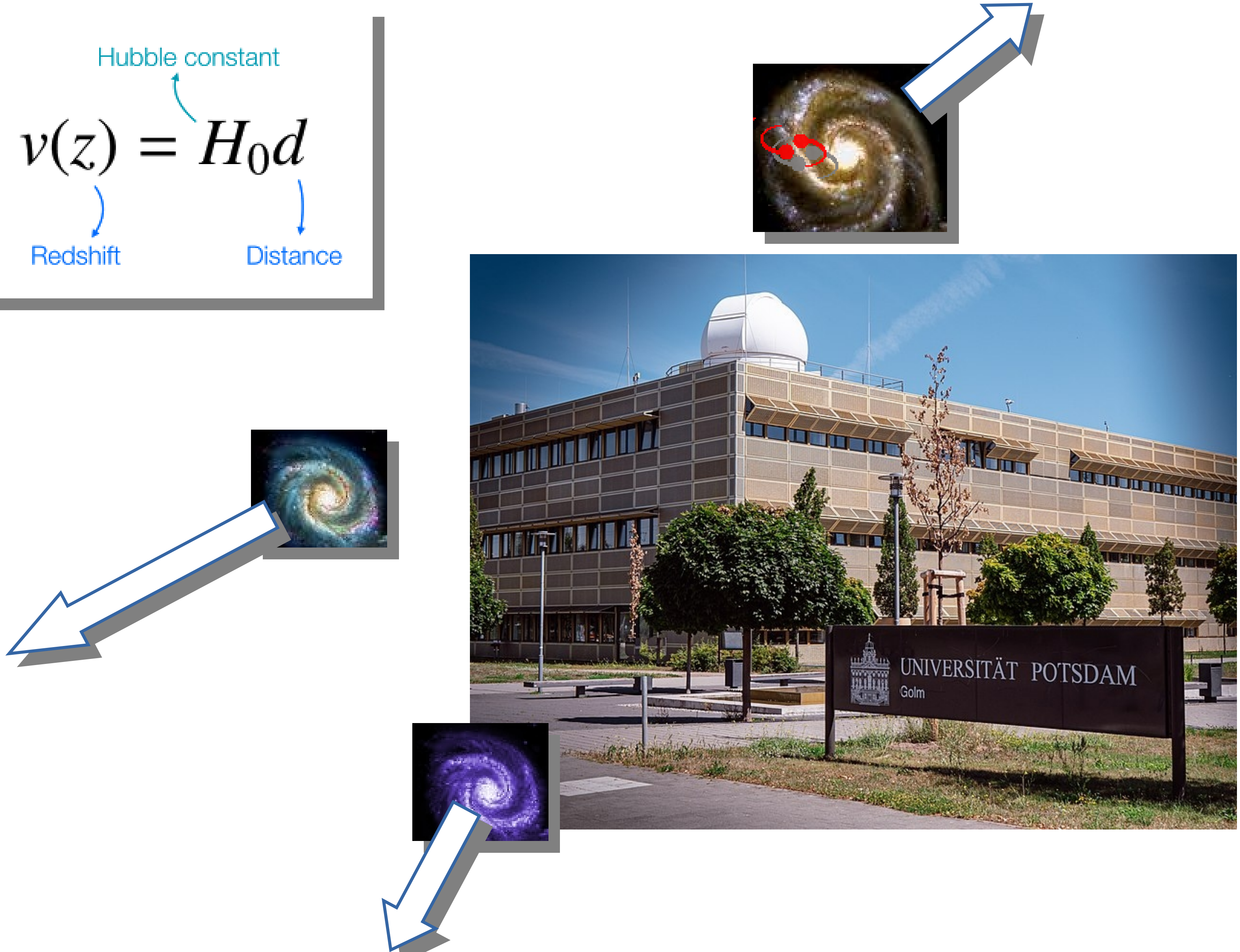
Multi-messenger astronomy: Hubble constant measurement

Hubble constant

$$v(z) = H_0 d$$

Redshift

Distance

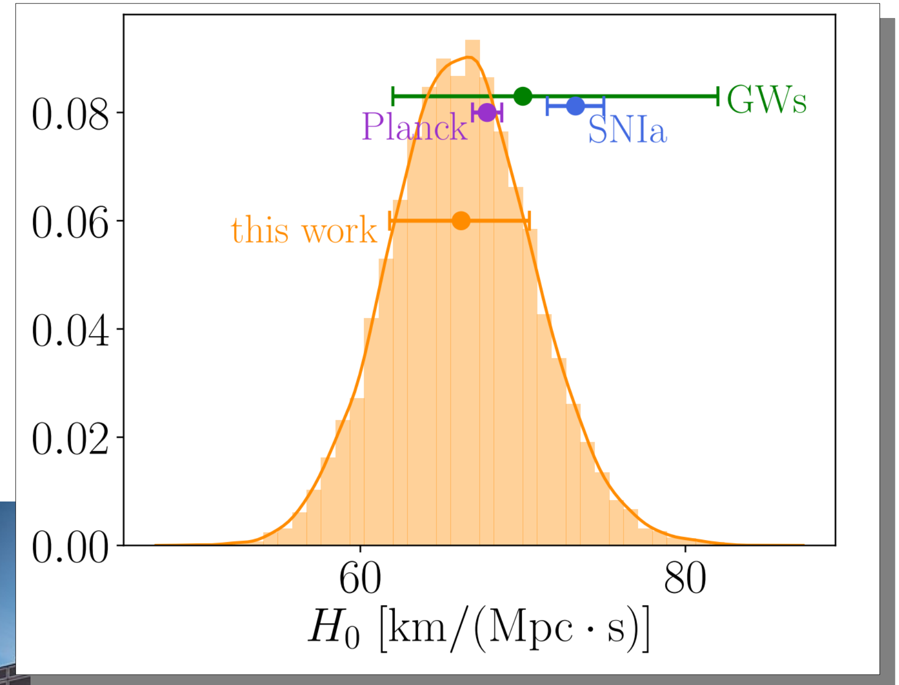


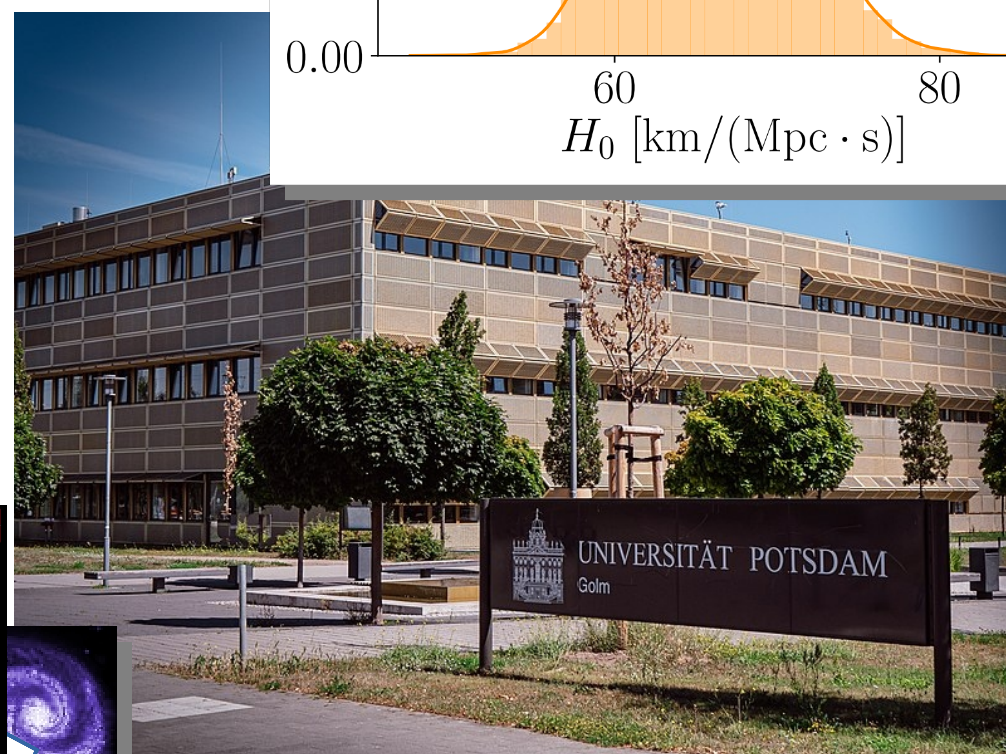
Multi-messenger astronomy: Hubble constant measurement

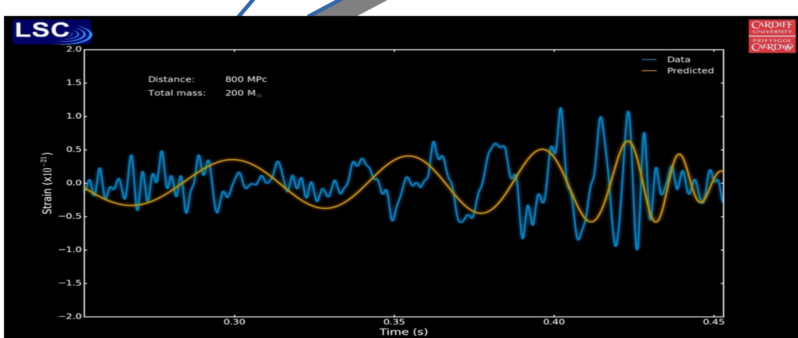
Hubble constant

$$v(z) = H_0 d$$

Redshift Distance







Coughlin et al., Nature Commun. 11 (2020) 1, 4129
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Summary

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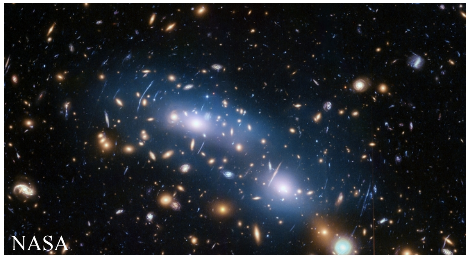
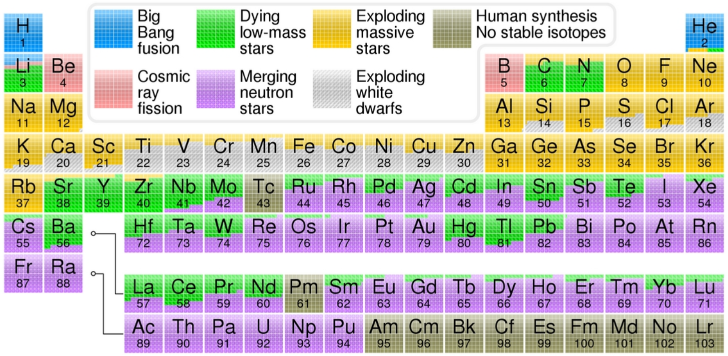
What is the history of our Universe and how fast is it expending?





wikipedia

How do we form the elements that are present in our Universe?

What it the state of matter at extreme conditions?

Summary

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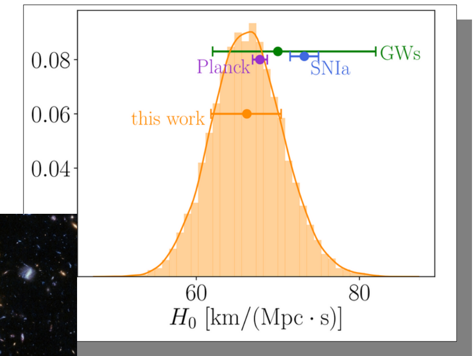

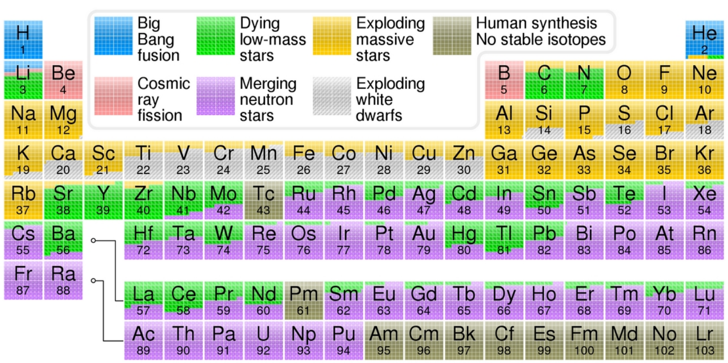

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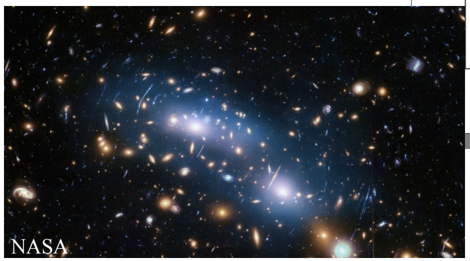

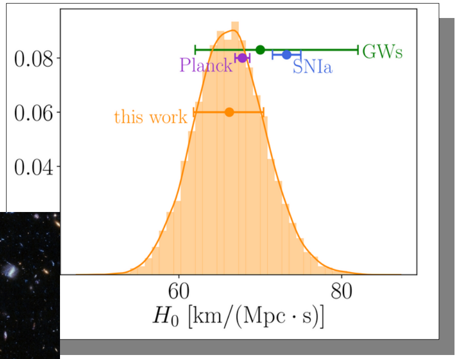

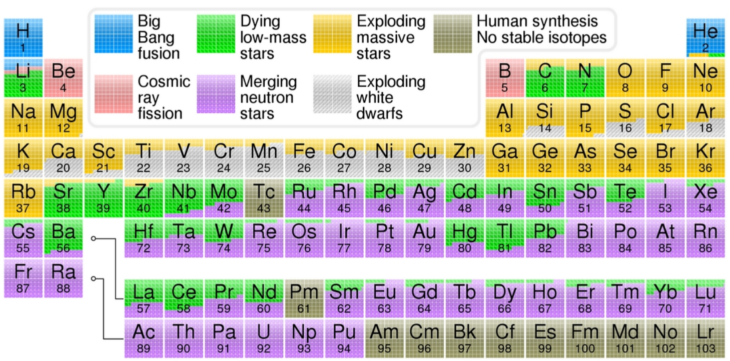

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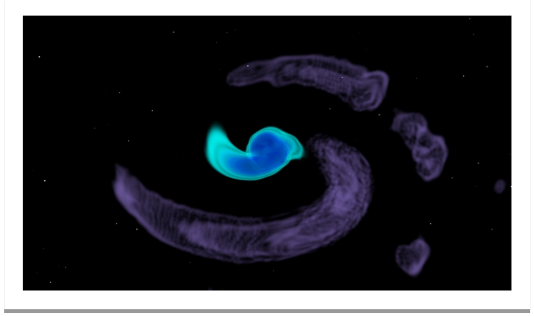

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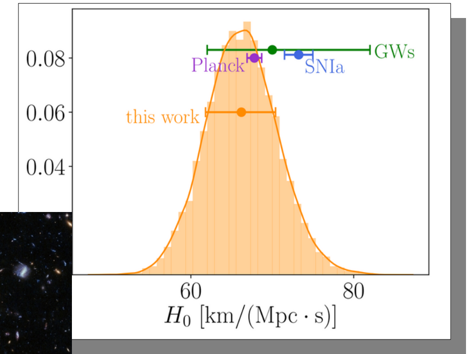

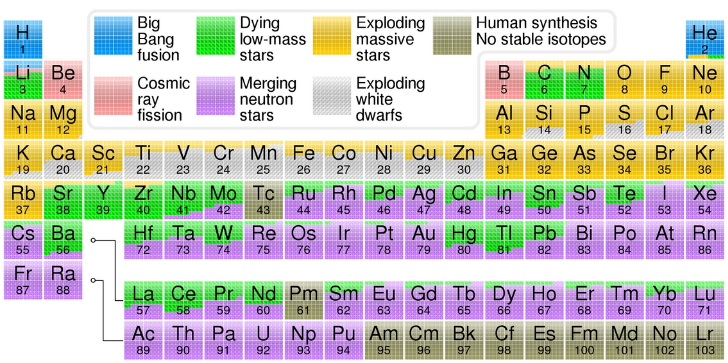

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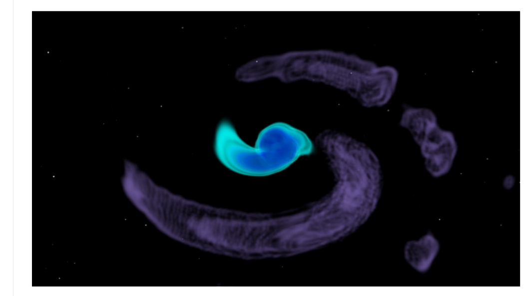

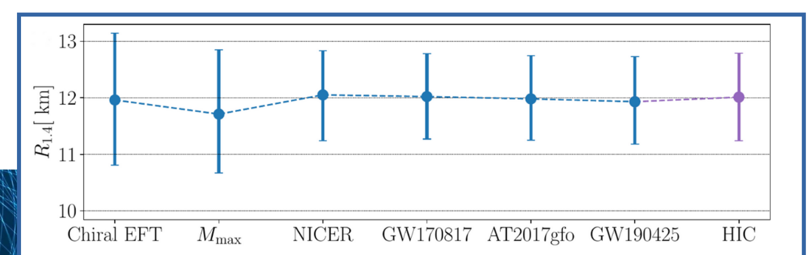

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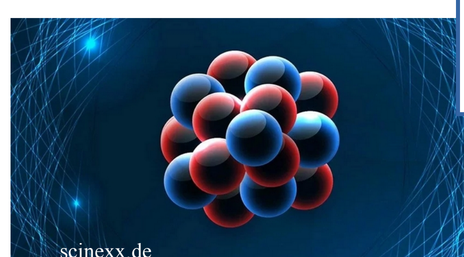

Summary

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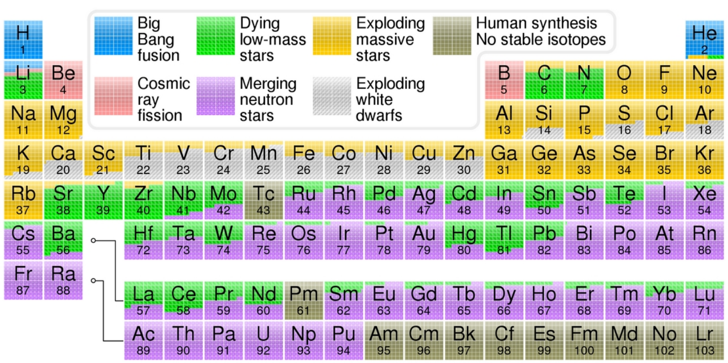

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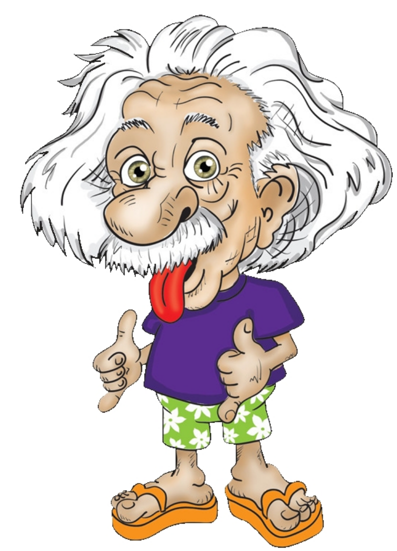

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