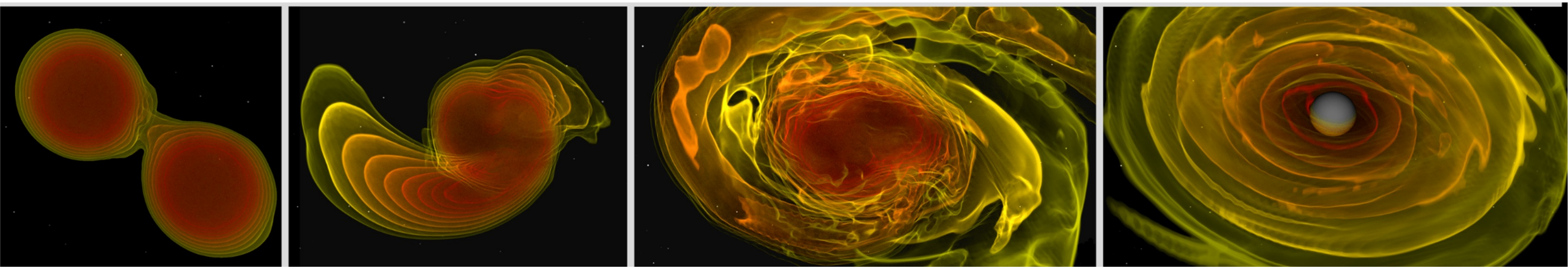
Interpreting the multi-messenger picture drawn by merging neutron stars

Tim Dietrich
University of Potsdam
Max Planck Institute for Gravitational Physics

LIGO Scientific Collaboration

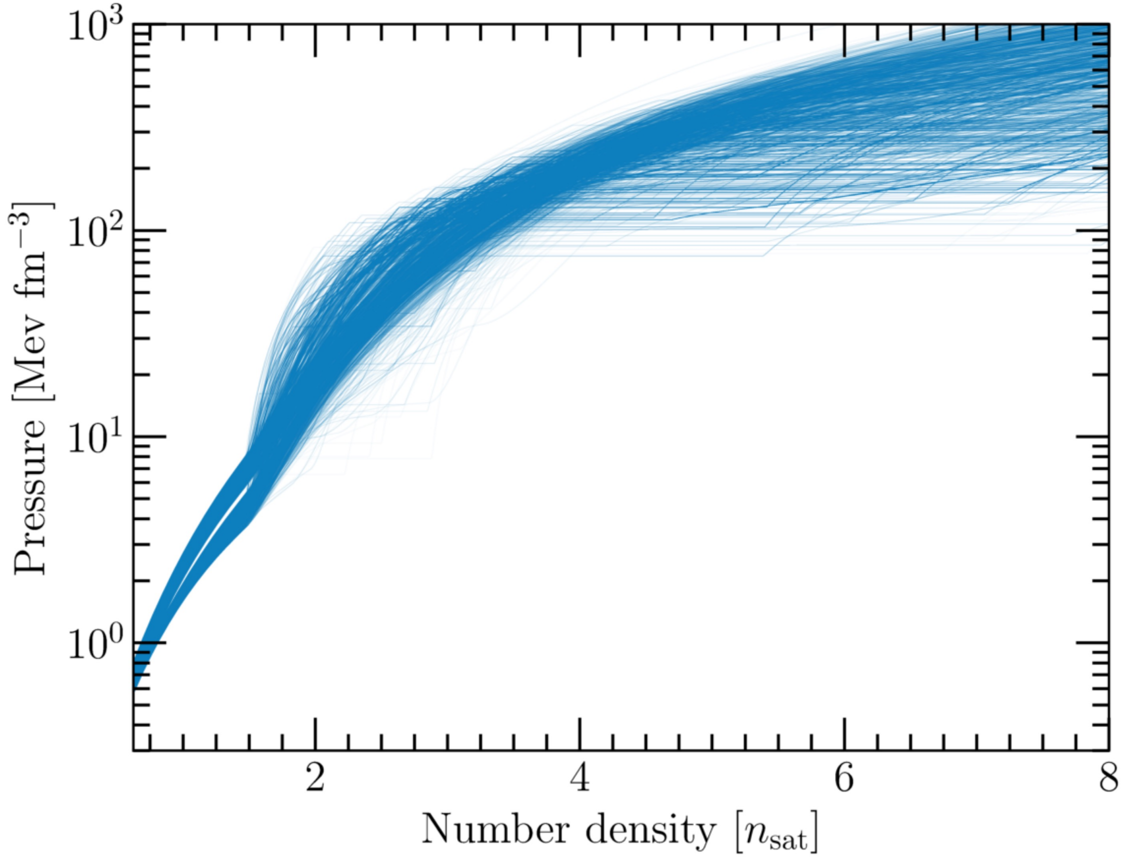
GRANDMA



22th of June 2022

Where do we get our information from?

Neutron stars as multi-messenger laboratories for dense matter

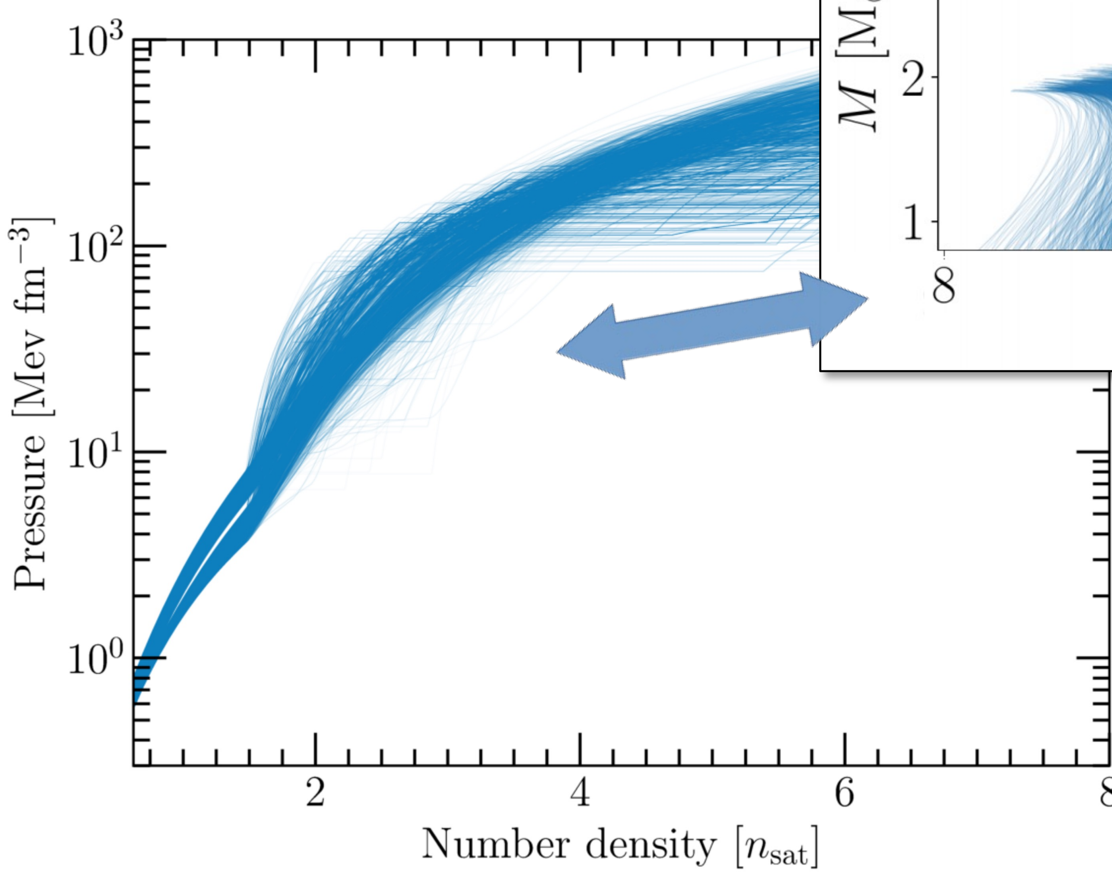


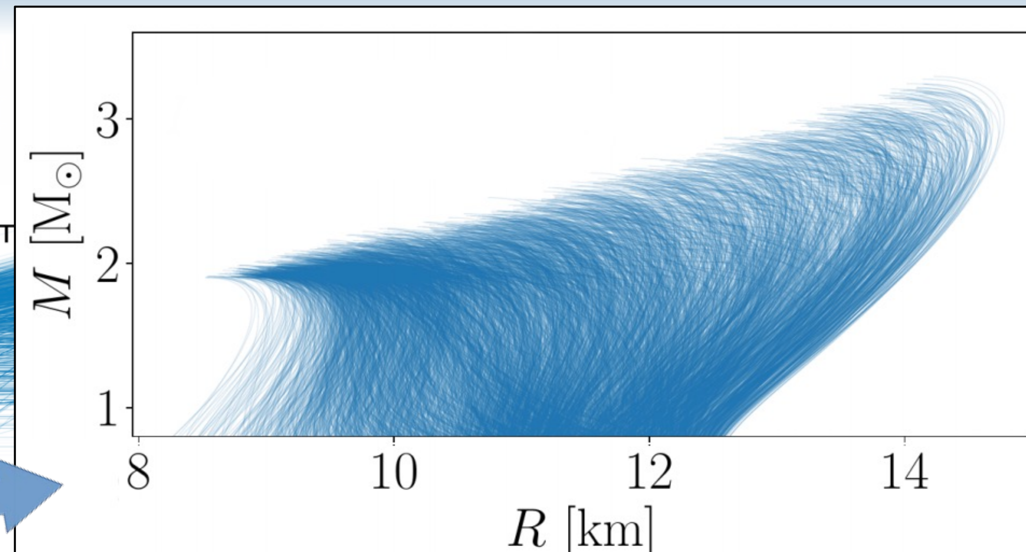
Pang et al., APJ 922 (2021) 1, 14

FONDAZIONE BRUNO KESSLER

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Neutron stars as multi-messenger laboratories for dense matter





Pang et al., APJ 922 (2021) 1, 14

Tolman-Oppenheimer-Volkhoff Equations

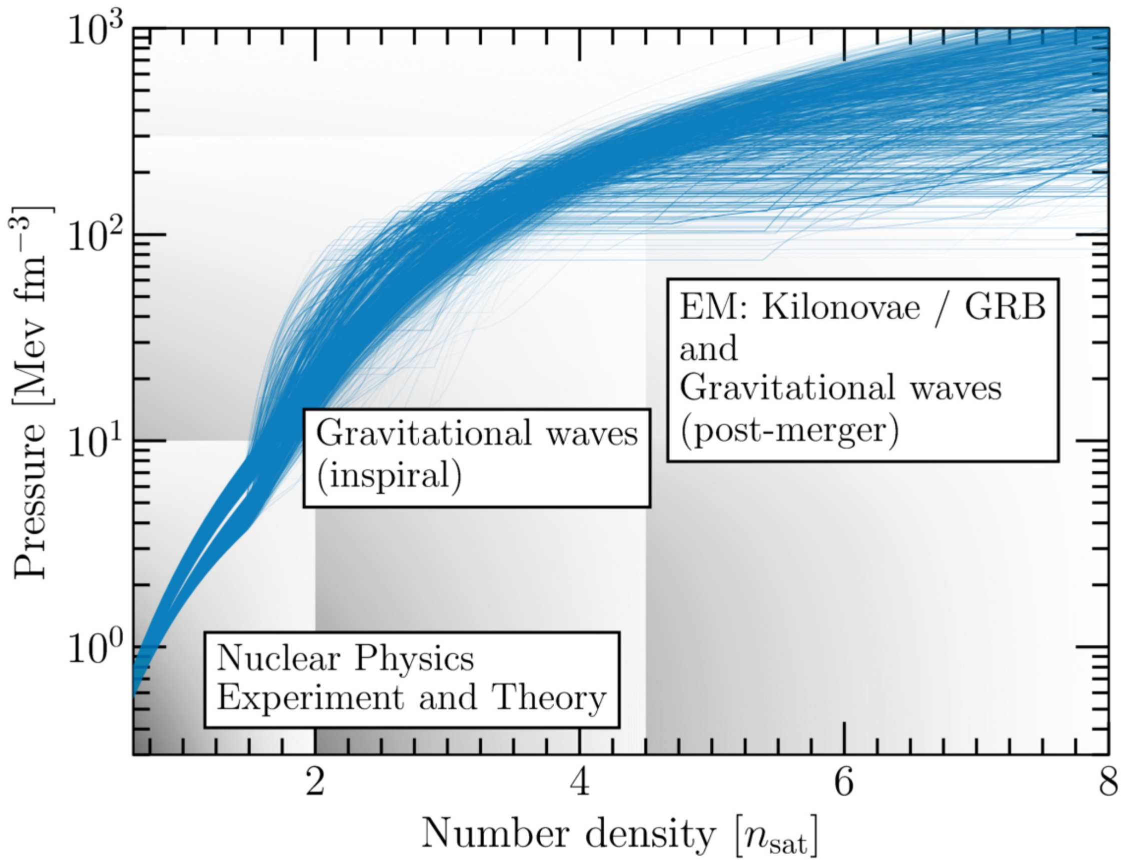
$$\mathrm{d}s^2 = -e^{2\phi}\mathrm{d}t^2 + \left(1 - \frac{2m}{R}\right)^{-1}\mathrm{d}R^2 + R^2\mathrm{d}\Omega^2$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}R} = (\rho(1+\epsilon)+p)\,\frac{m+4\pi r^3 p}{R(R-2m)}\cdot\frac{1}{\frac{\mathrm{d}p}{\mathrm{d}\rho}}$$

$$\frac{\mathrm{d}m}{\mathrm{d}R} = 4\pi R^2\rho(1+\epsilon)$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}R} = \frac{m+4\pi R^3 p}{R(R-2m)}$$

Neutron stars as multi-messenger laboratories for dense matter



Pang et al., APJ 922 (2021) 1, 14

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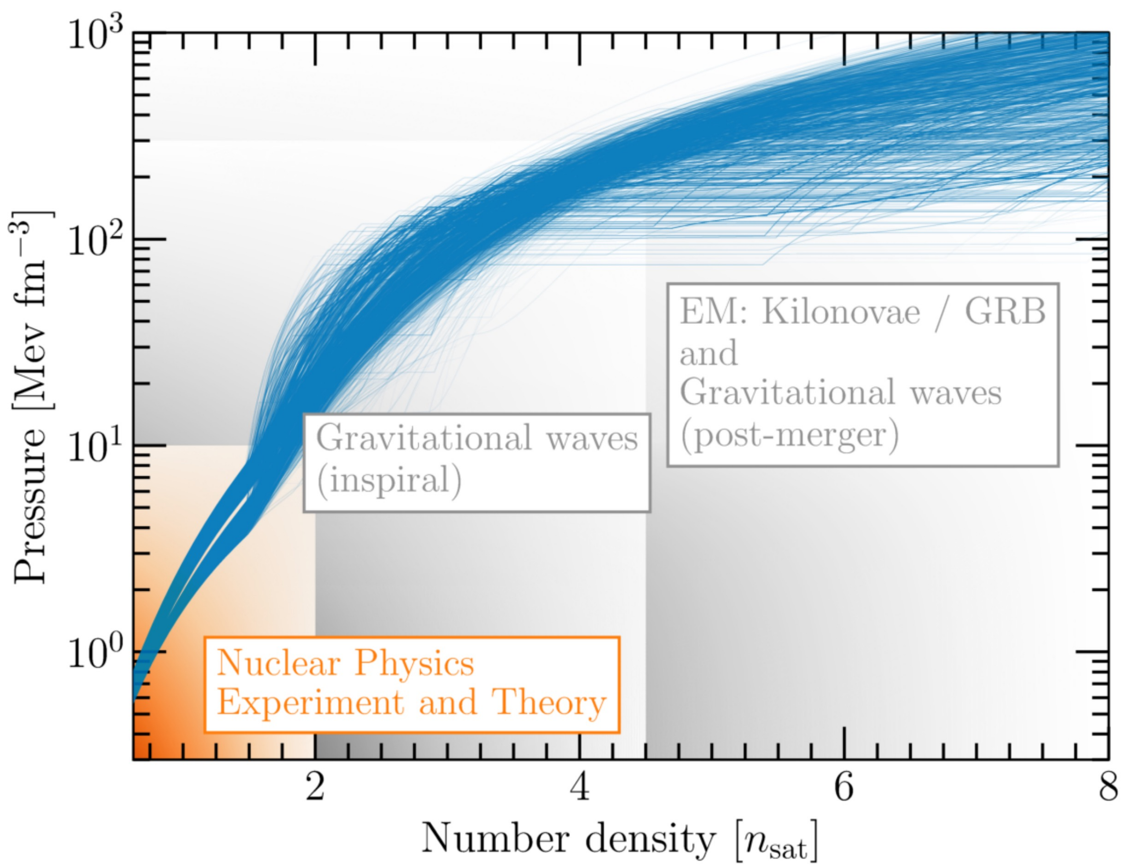
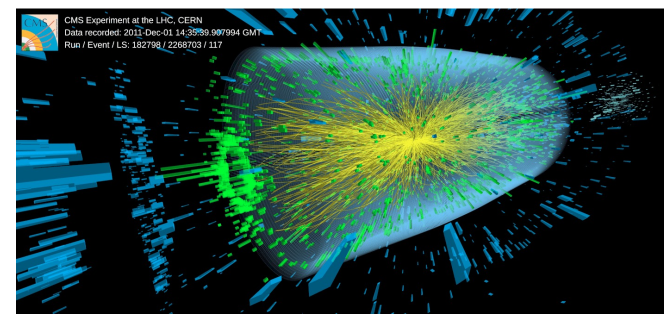
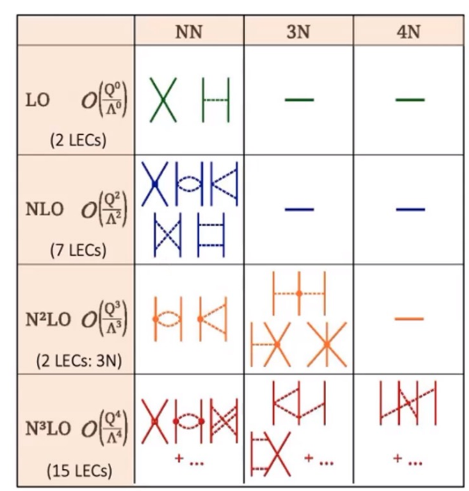


Pang et al., APJ 922 (2021) 1, 14

see talk by S. Huth





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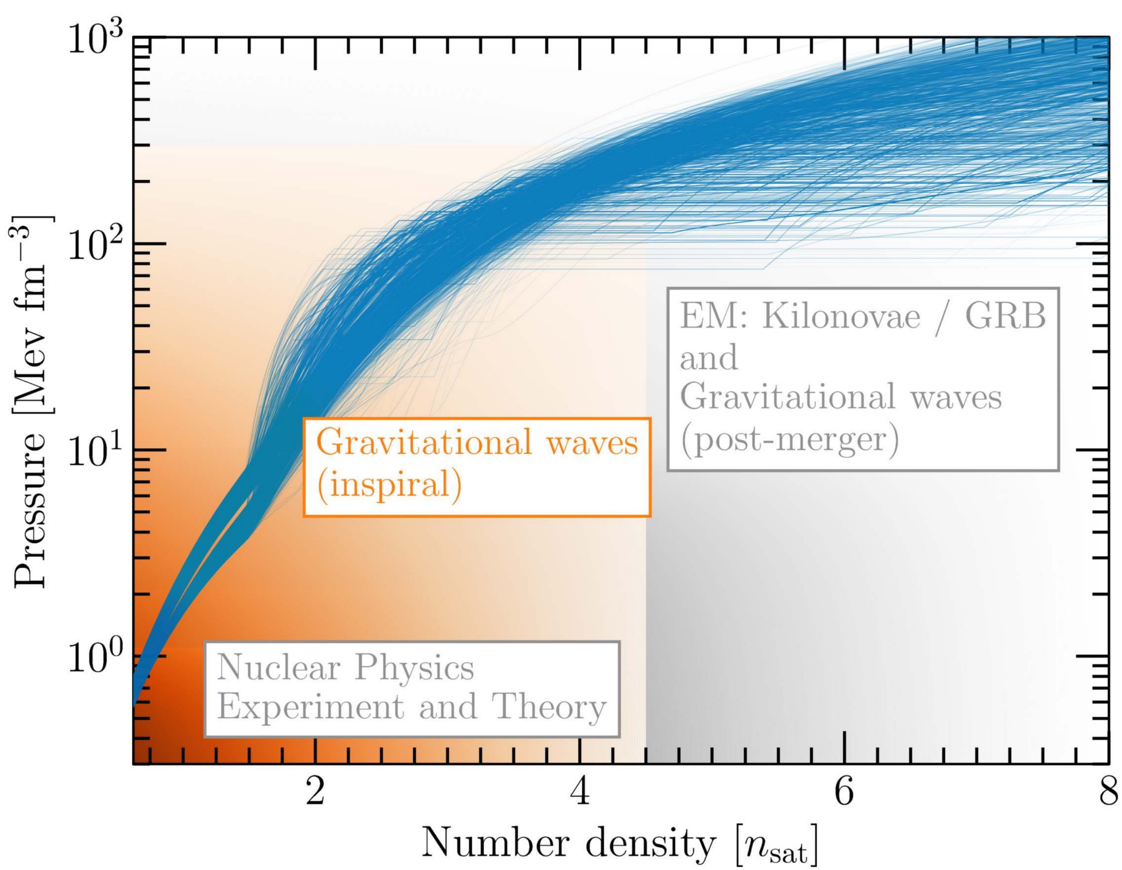
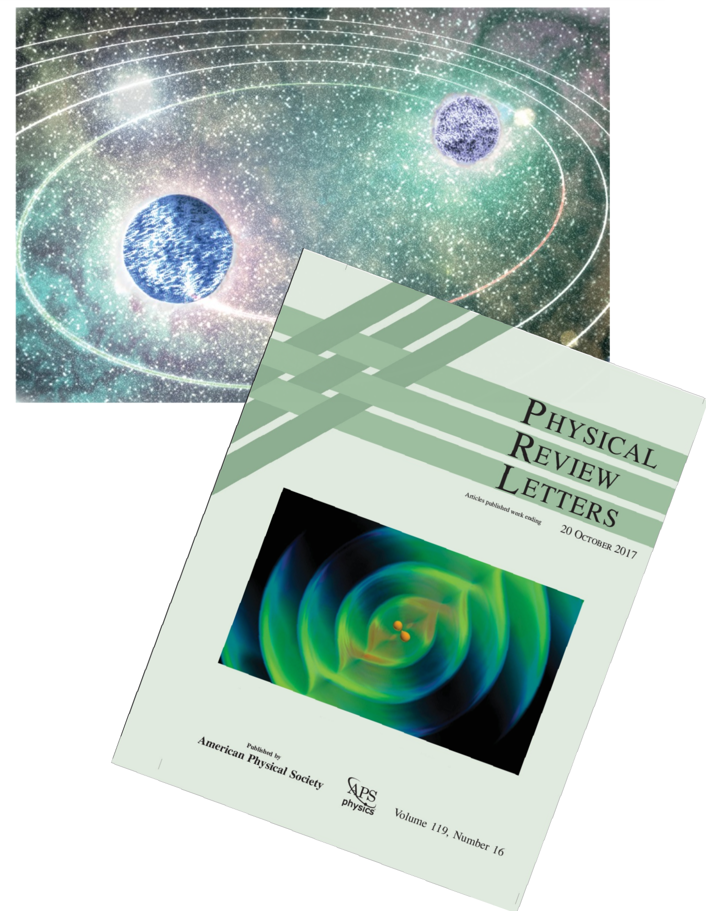


Pang et al., APJ 922 (2021) 1, 14



FONDAZIONE BRUNO KESSLER

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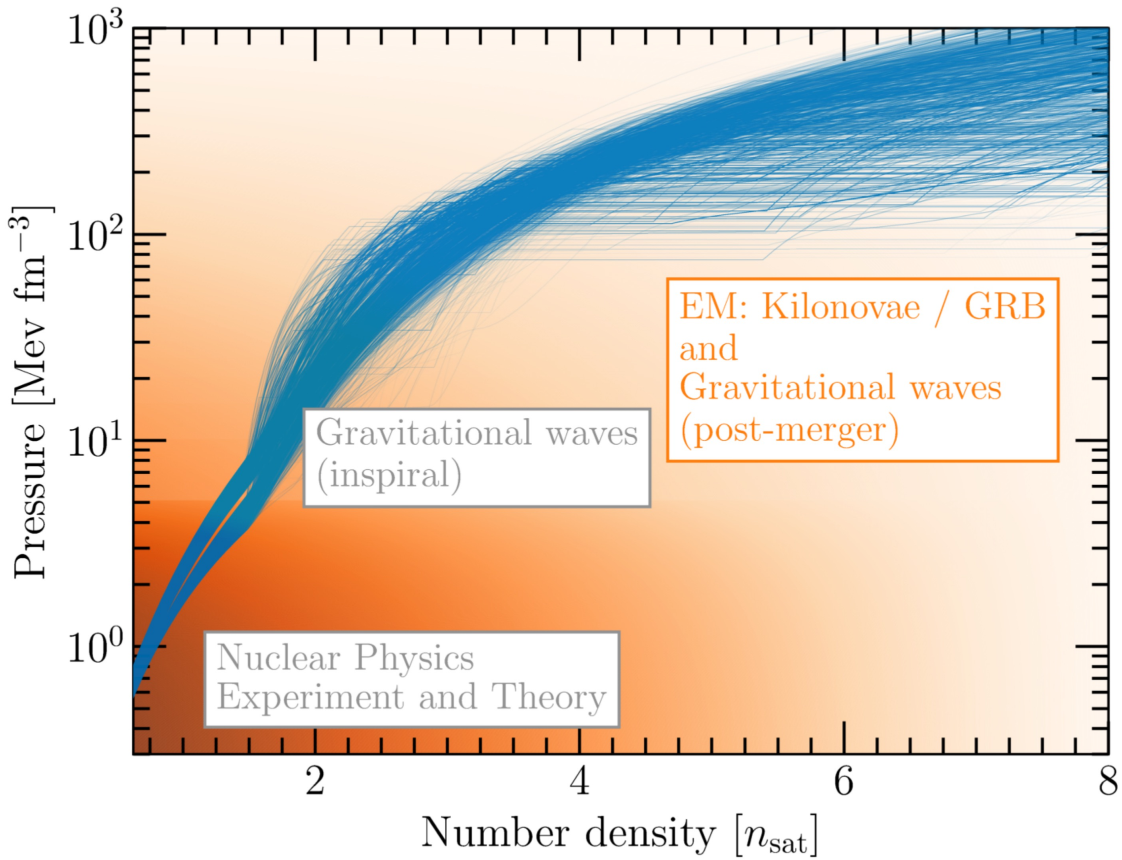
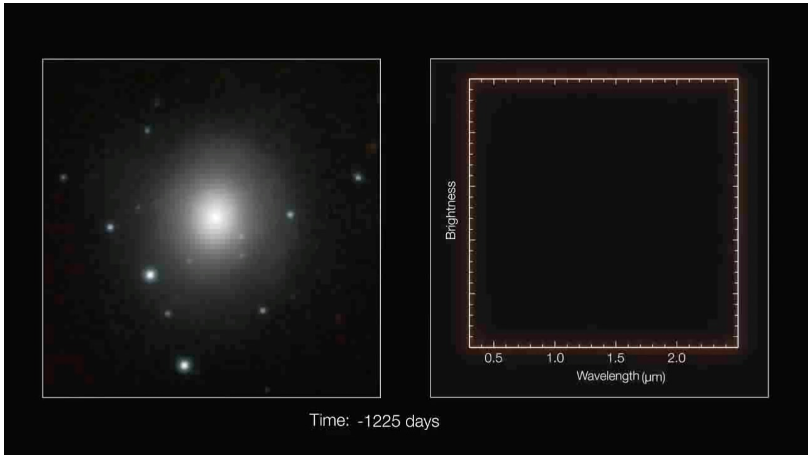
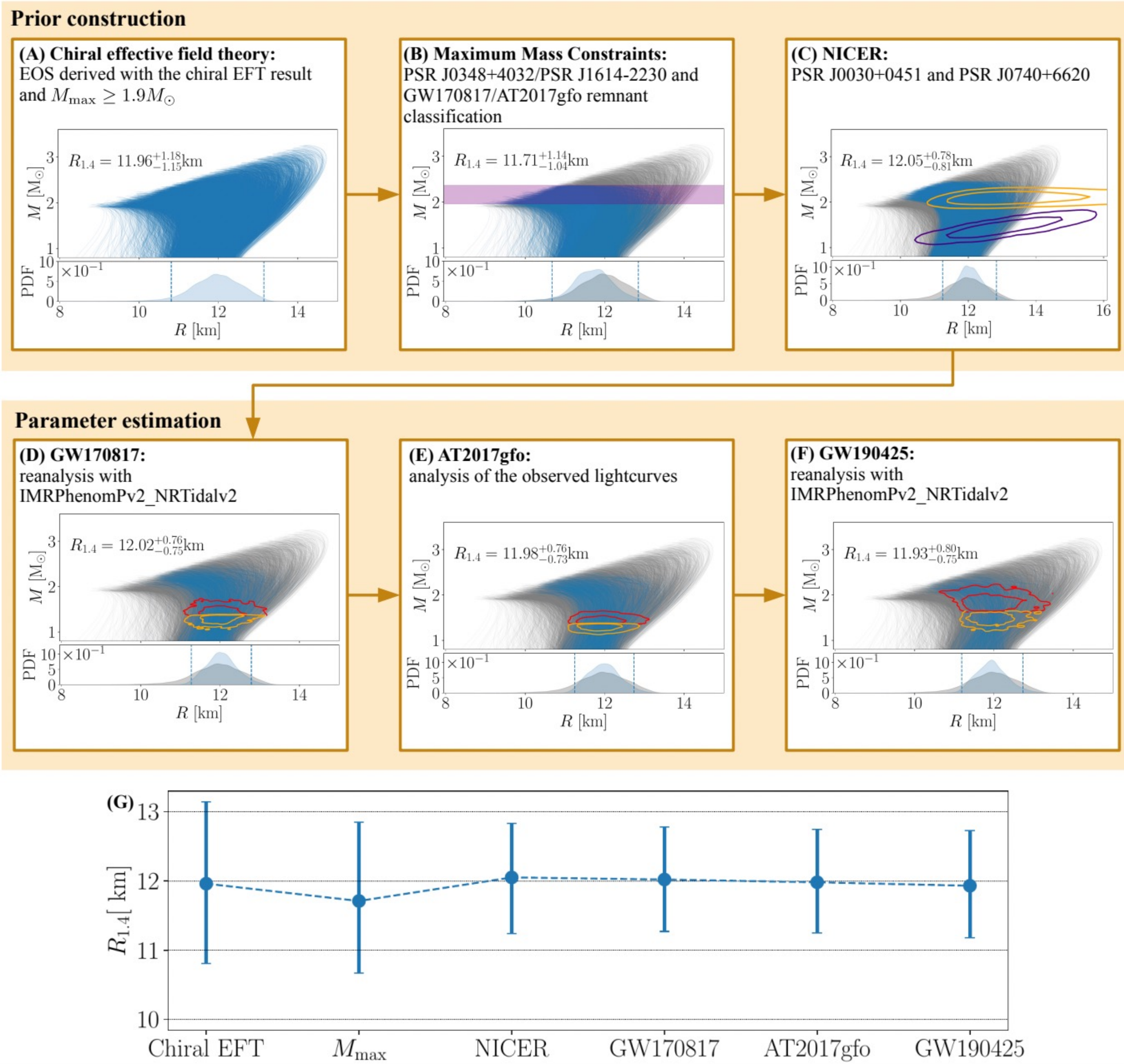
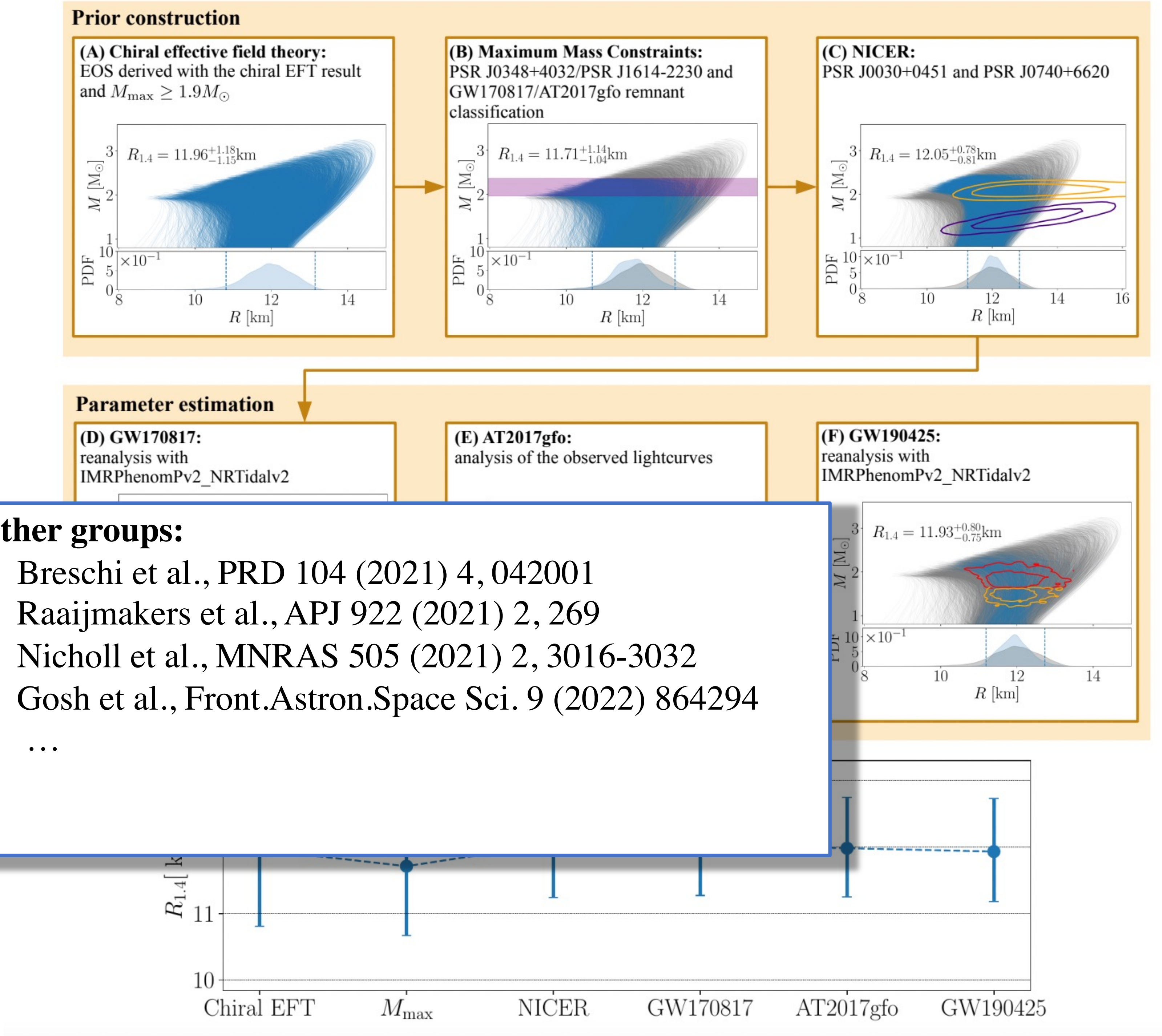


Pang et al., APJ 922 (2021) 1, 14





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



Other groups:

- Breschi et al., PRD 104 (2021) 4, 042001
- Raaijmakers et al., APJ 922 (2021) 2, 269
- Nicholl et al., MNRAS 505 (2021) 2, 3016-3032
- Gosh et al., Front.Astron.Space Sci. 9 (2022) 864294

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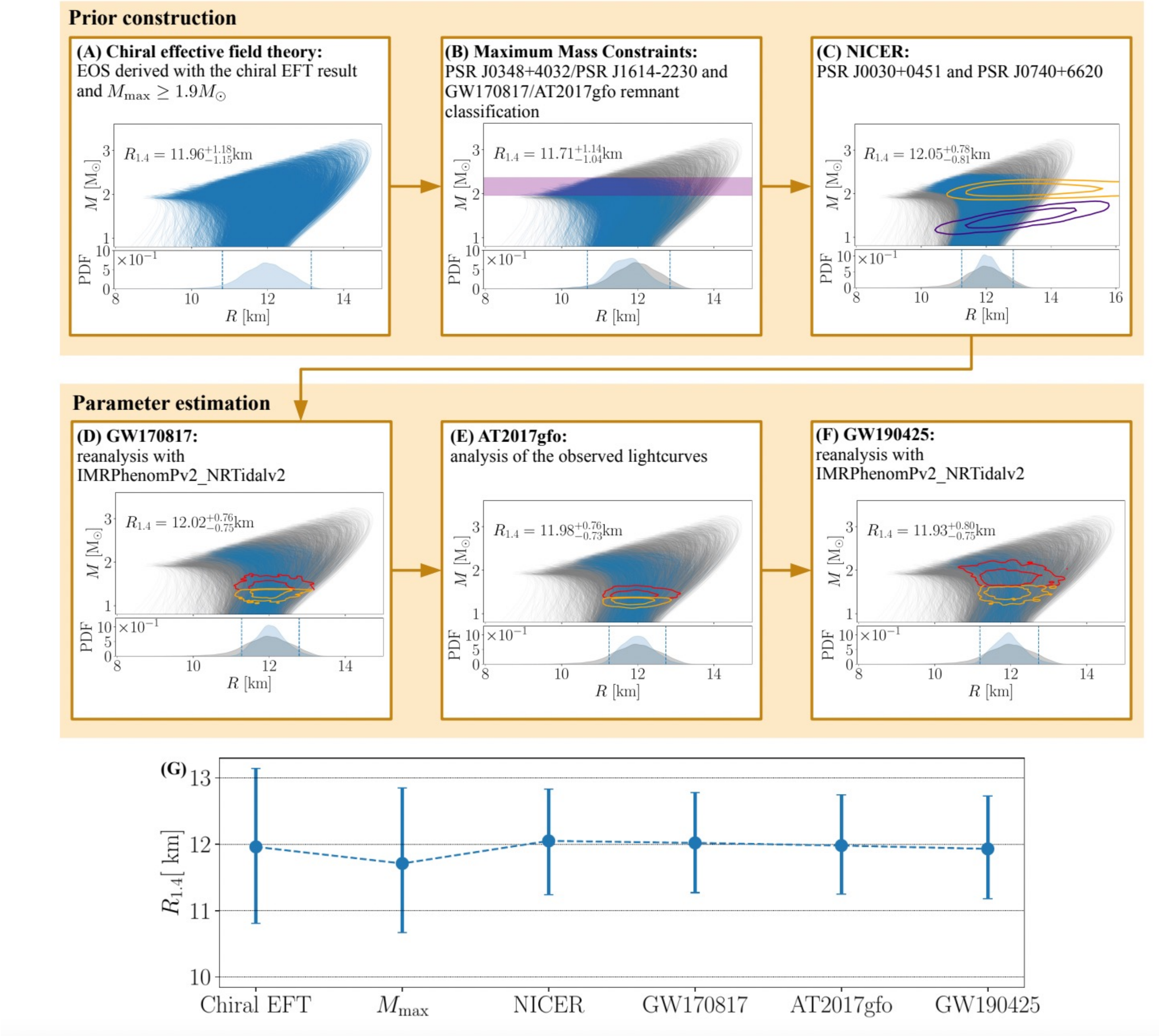
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., Nature 606 (2022) 276-280



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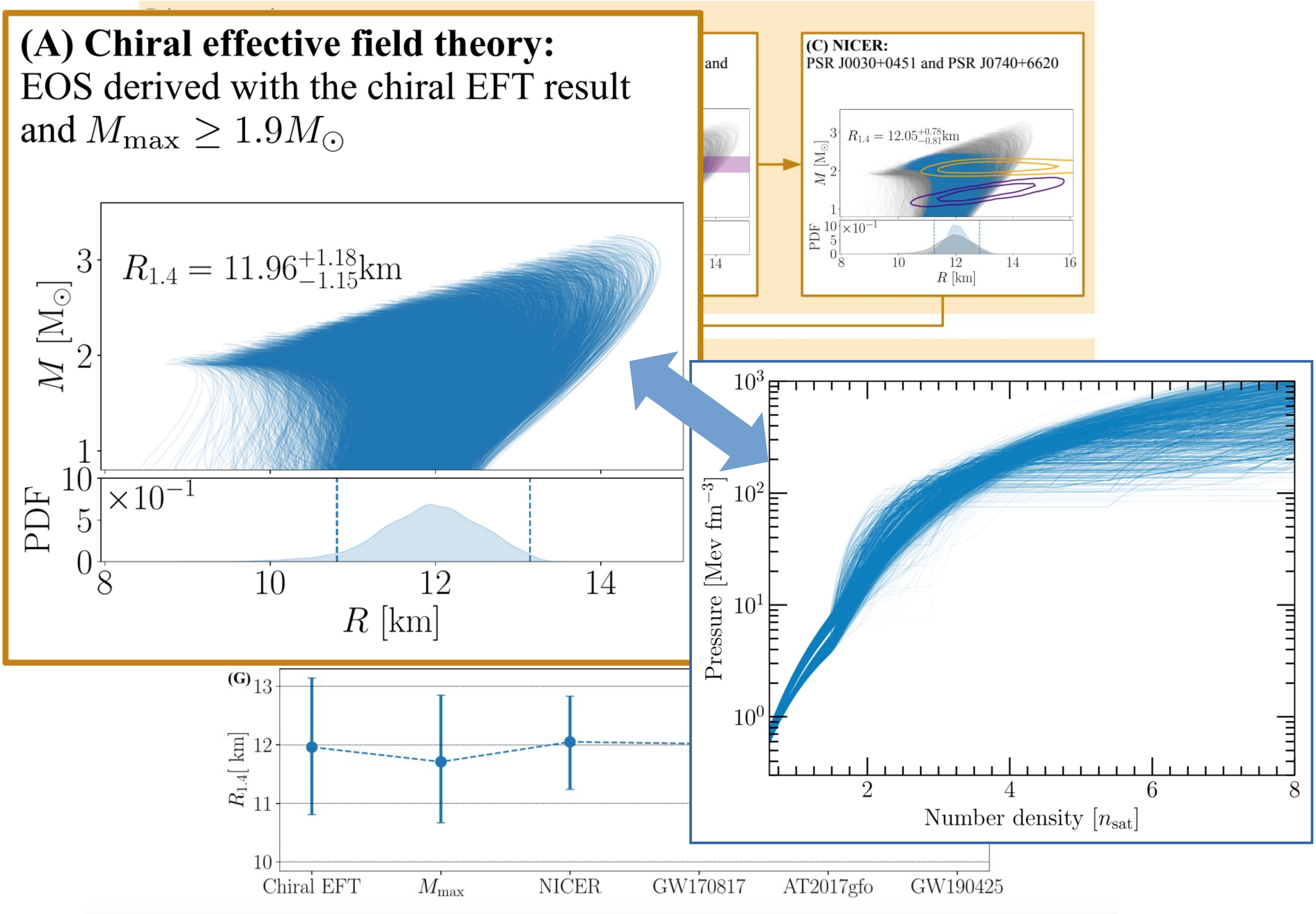
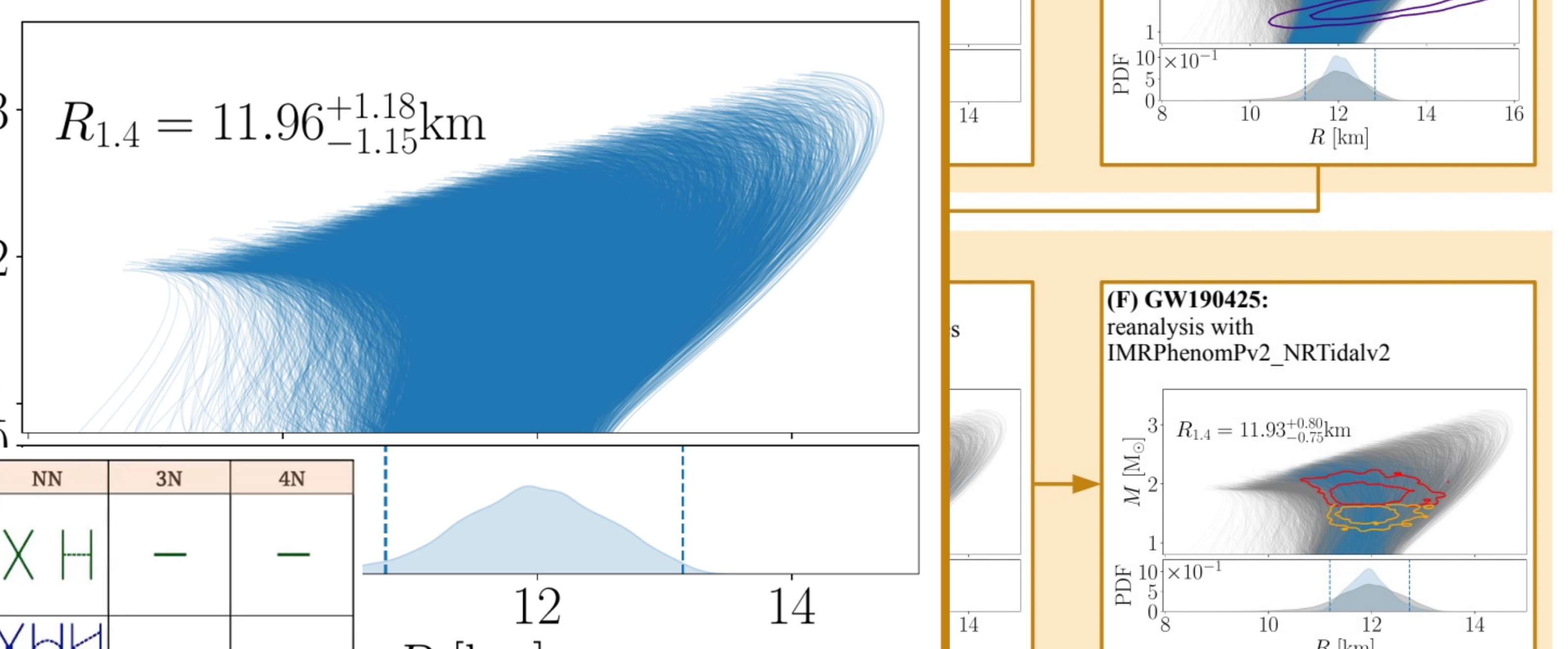
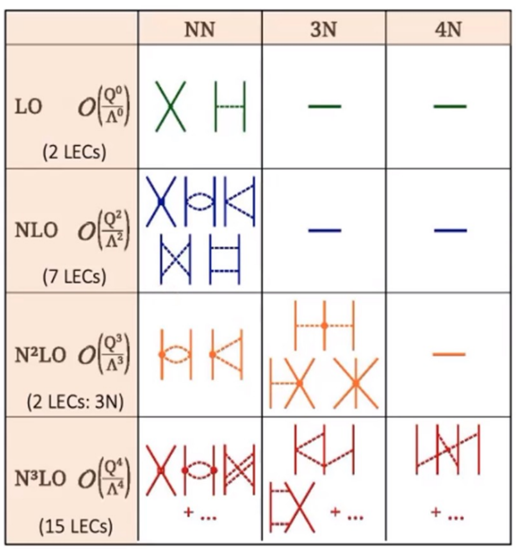
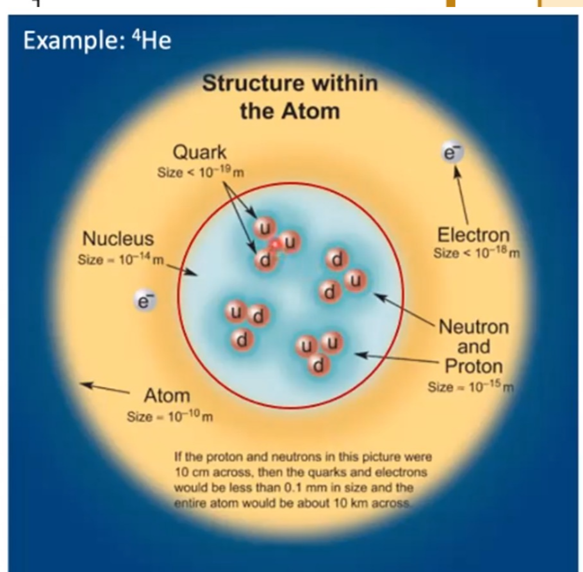

(A) Chiral effective field theory:
EOS derived with the chiral EFT result and $M_{\max} \geq 1.9 M_\odot$
$R_{1.4} = 11.96^{+1.18}_{-1.15}$km
M [M$_\odot$]
PDF
$\times 10^{-1}$
R [km]
(C) NICER:
PSR J0030+0451 and PSR J0740+6620
$R_{1.4} = 12.05^{+0.78}_{-0.81}$km
Pressure [Mev fm^{-3}]
Number density [$n_{\rm sat}$]
(G)
$R_{1.4}$[km]
Chiral EFT
$M_{\max}$
NICER
GW170817
AT2017gfo
GW190425

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

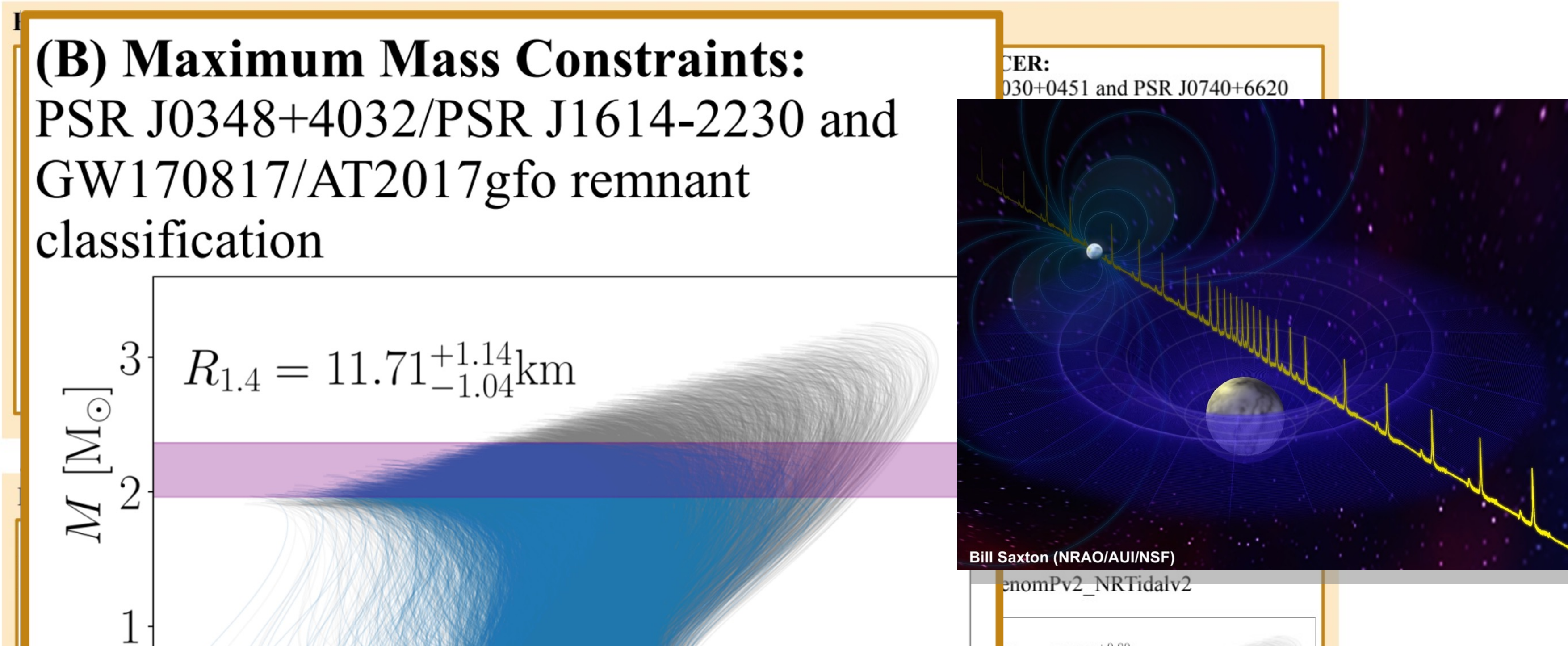






$$\mathcal{H}|\Psi\rangle = E|\Psi\rangle$$

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

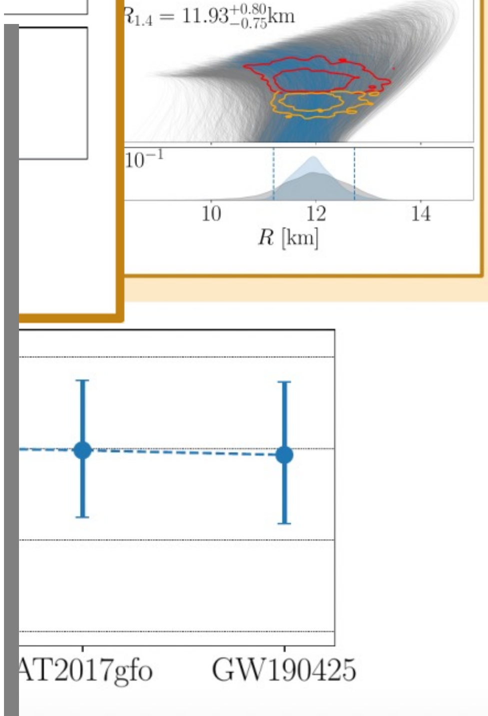


Lower bound on the maximum mass through measurement of heavy pulsars (Shapiro Delay)

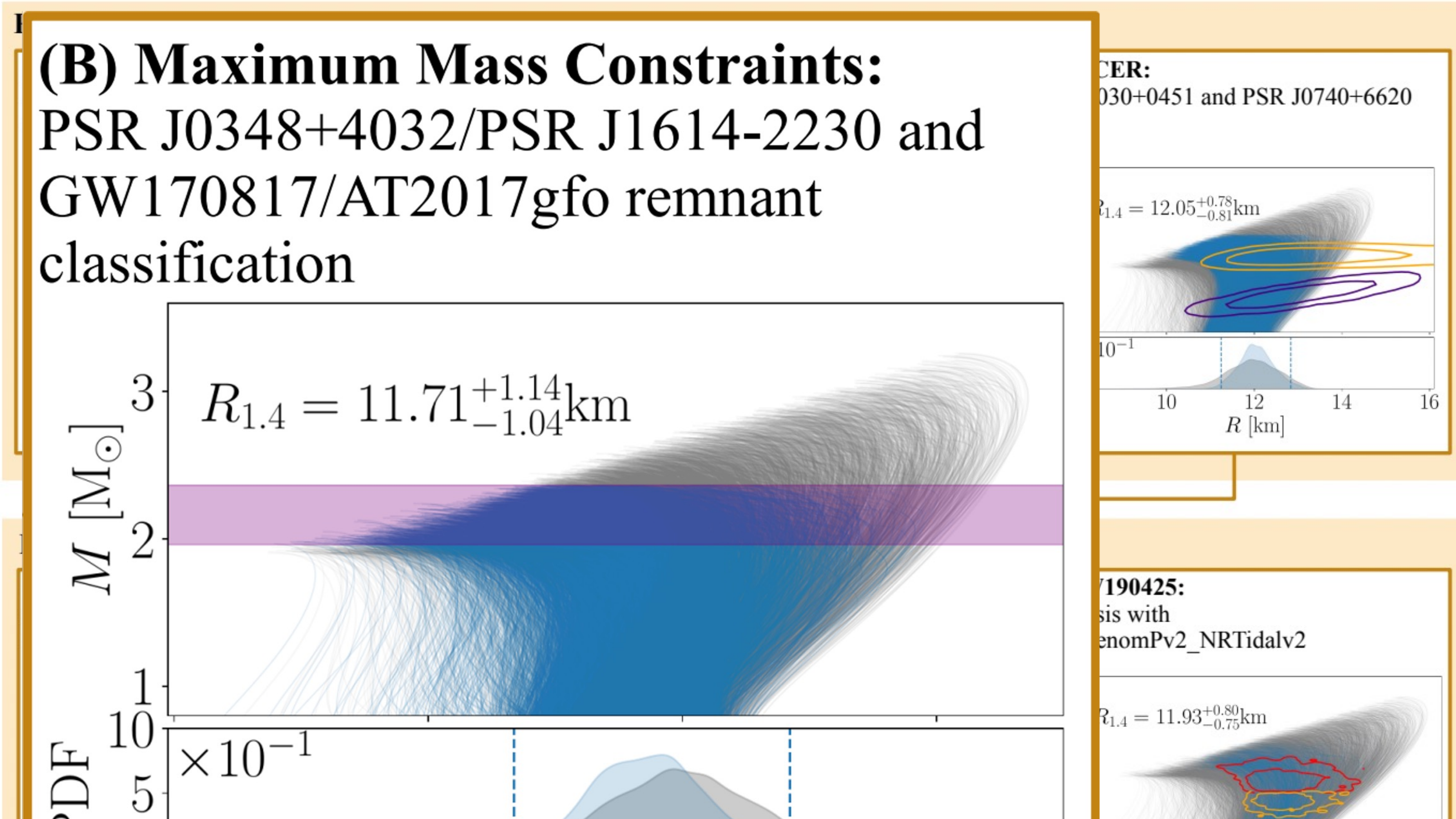
PSR J0740+6620
H. T. Cromartie, et al., Nature Astron. 4, 72 (2019).
updatd in: Fonseca, E., et al. 2021, arXiv:2104.00880

PSR J0348+4032
J. Antoniadis, et al., Science 340, 6131 (2013).

PSR J1614-2230
Z. Arzoumanian, et al., Astrophys. J. Suppl. 235, 37 (2018)

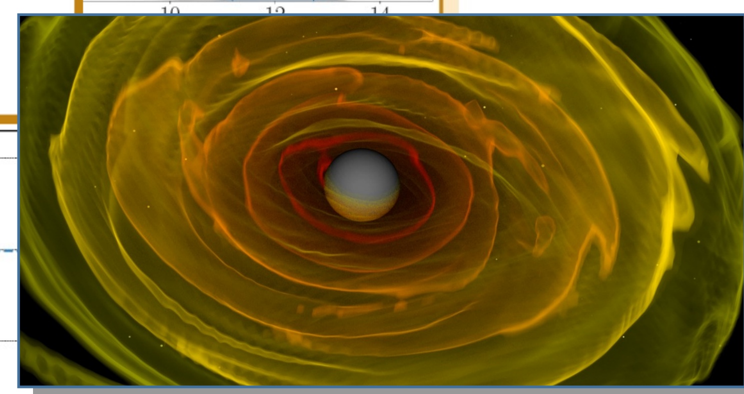


see talks by T. Cromatie



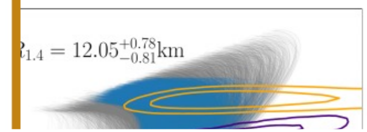
Possible upper bound comes from the assumption that GW170817 formed a black hole

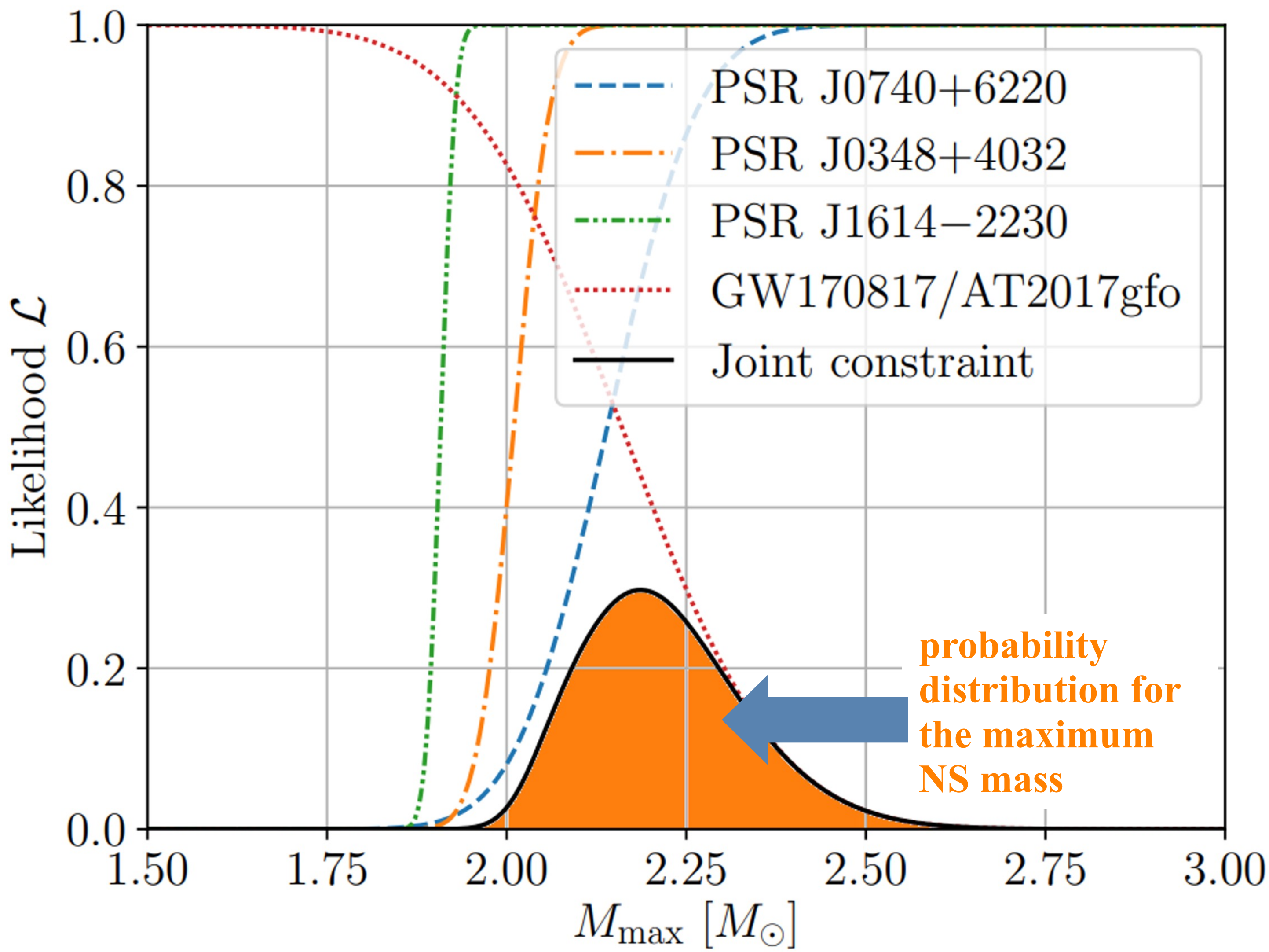
e.g.
Margalit & Metzger, APJL 850 (2017) 2, L19,
Ruiz et al., PRD 97 (2018) 2, 021501
Rezzolla et al., APJL 852 (2018) 2, L25
Shibata et al., PRD 100 (2019) 2, 023015



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

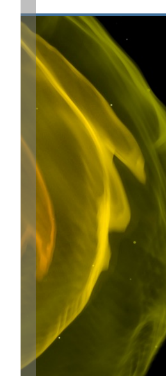
030+0451 and PSR J0740+6620

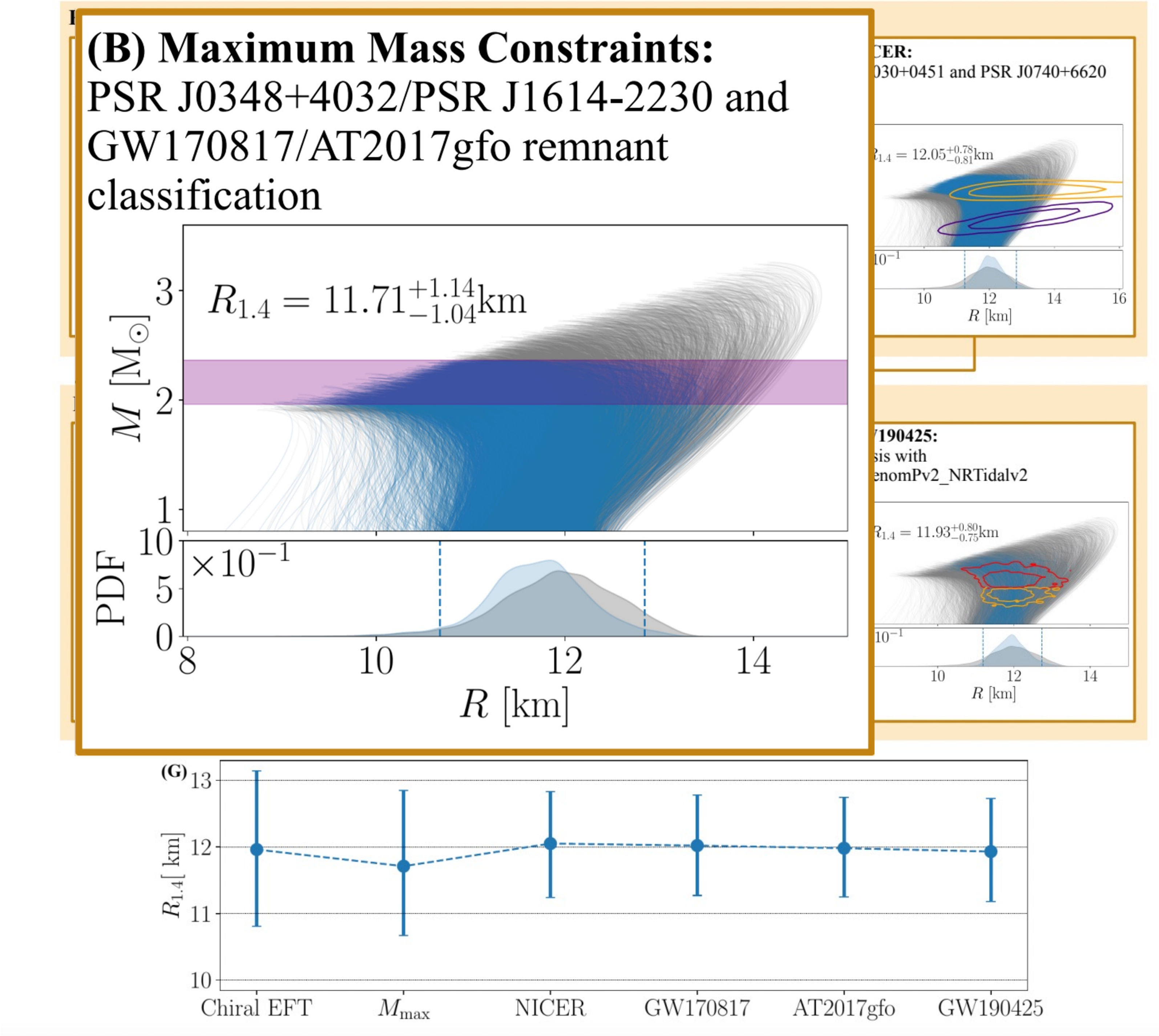




Possible uppe
that GW1708

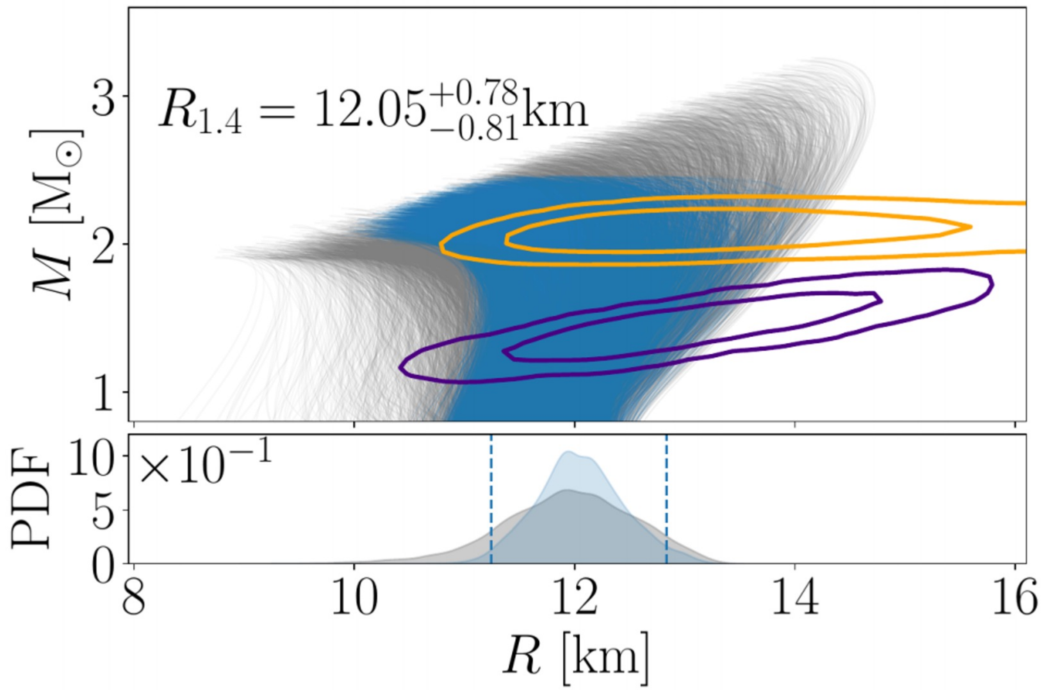
e.g.
Margalit & Metzg
Ruiz et al., PRD 9
Rezzolla et al., A
Shibata et al., PR

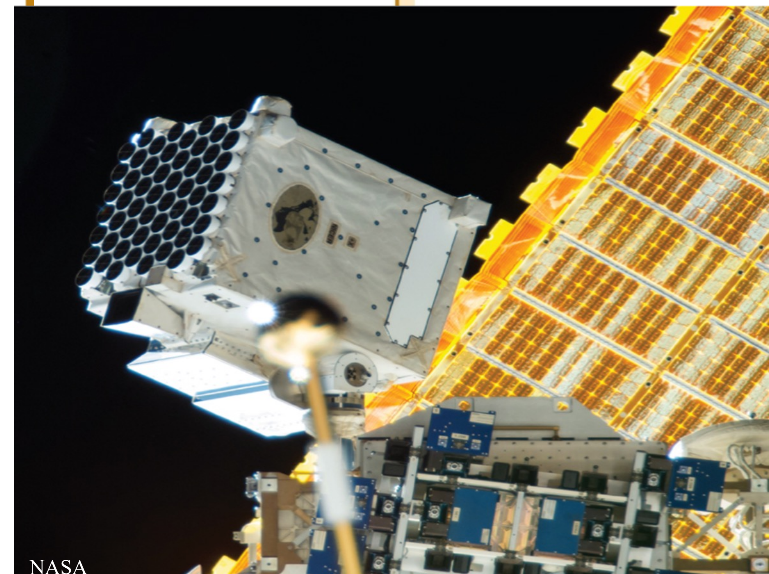


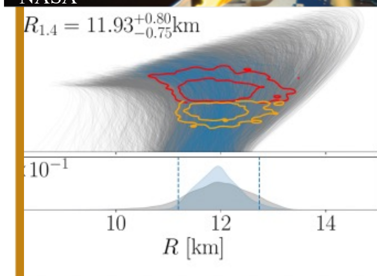


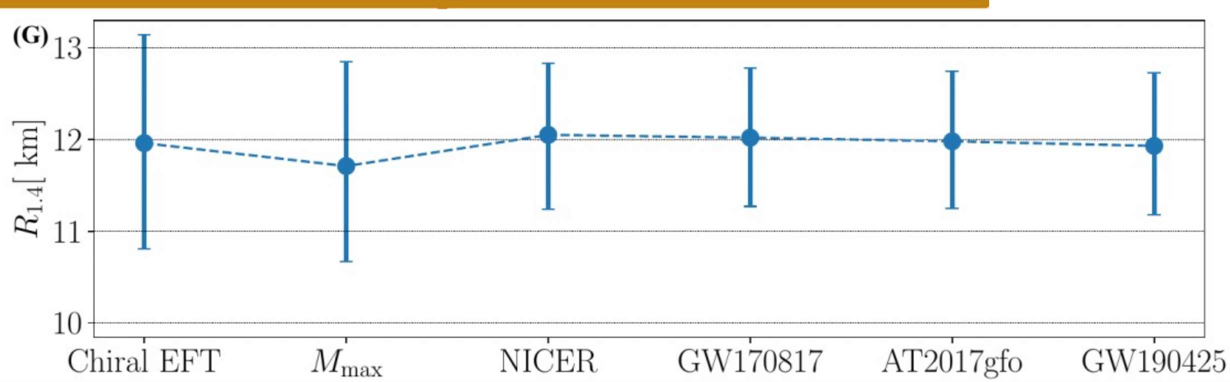
(B) Maximum Mass Constraints:
PSR J0348+4032/PSR J1614-2230 and GW170817/AT2017gfo remnant classification
$R_{1.4} = 11.71^{+1.14}_{-1.04}$km
M [M$_\odot$]
PDF
×10^{-1}
R [km]
CER:
030+0451 and PSR J0740+6620
$R_{1.4} = 12.05^{+0.78}_{-0.81}$km
190425:
sis with
enomPv2_NRTidalv2
$R_{1.4} = 11.93^{+0.80}_{-0.75}$km
(G)
$R_{1.4}$[km]
Chiral EFT
$M_{\rm max}$
NICER
GW170817
AT2017gfo
GW190425

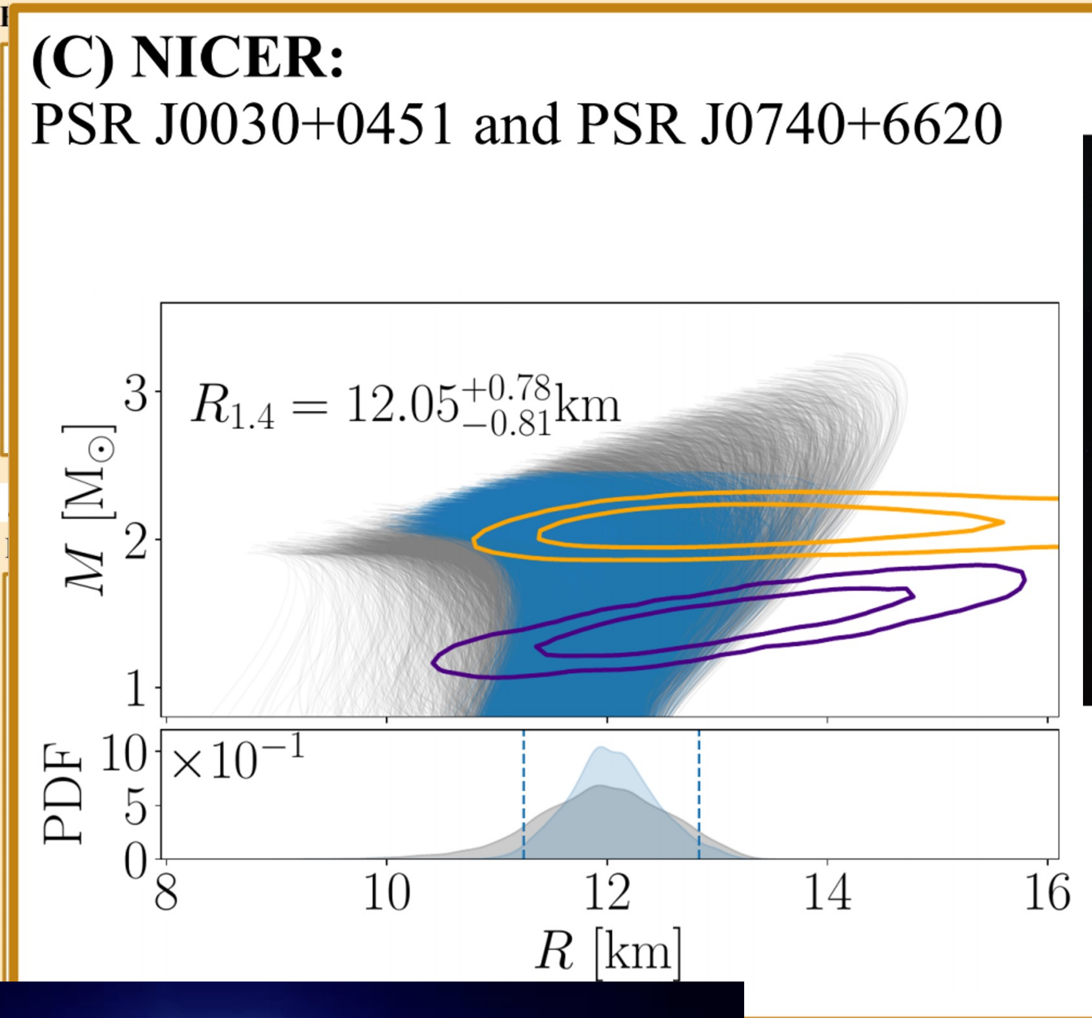
(C) NICER:
PSR J0030+0451 and PSR J0740+6620

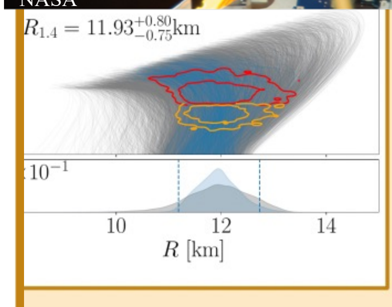


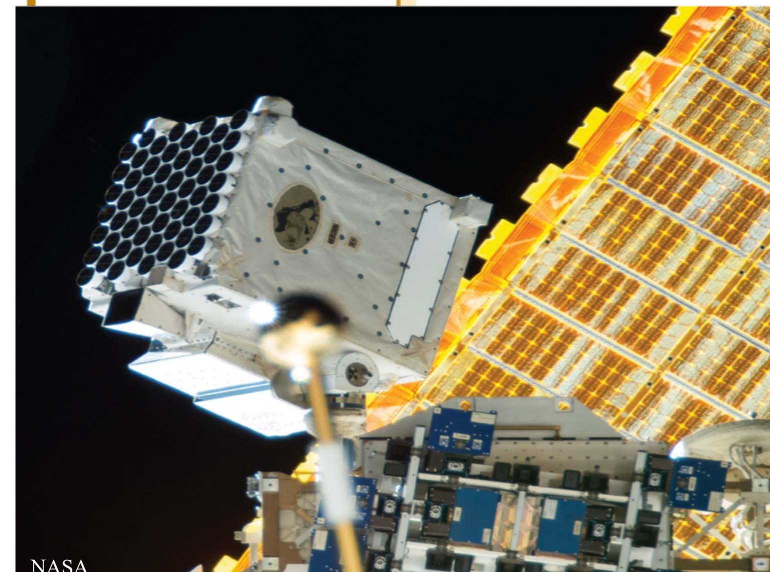


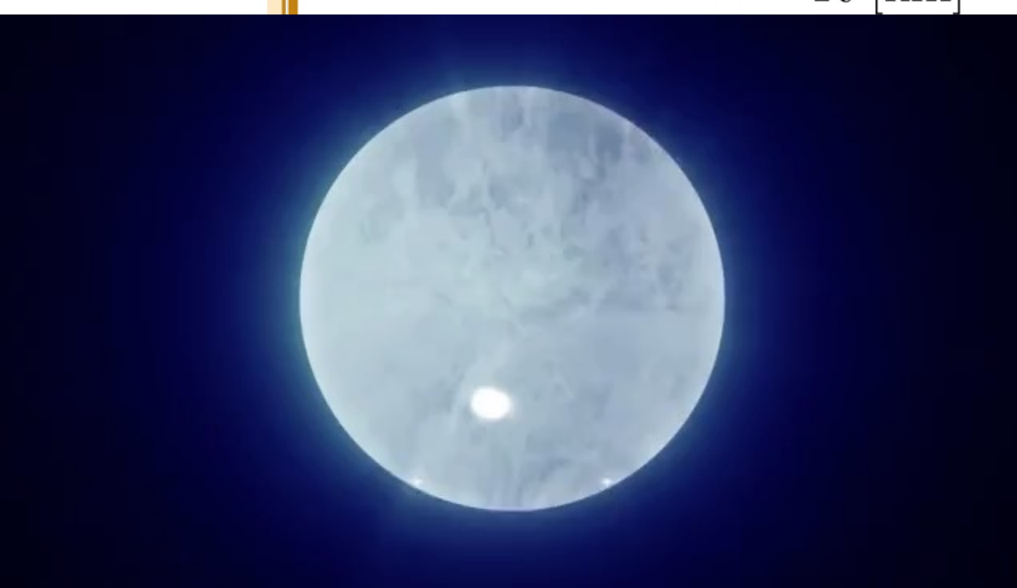


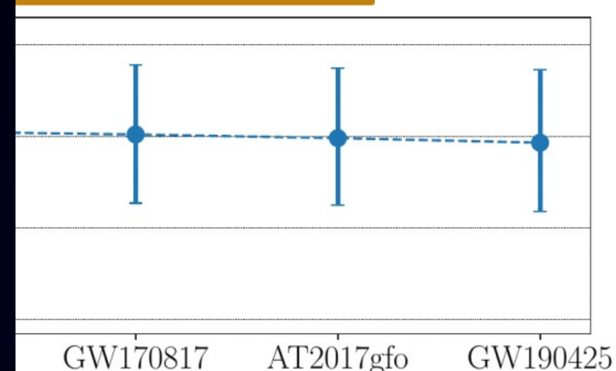






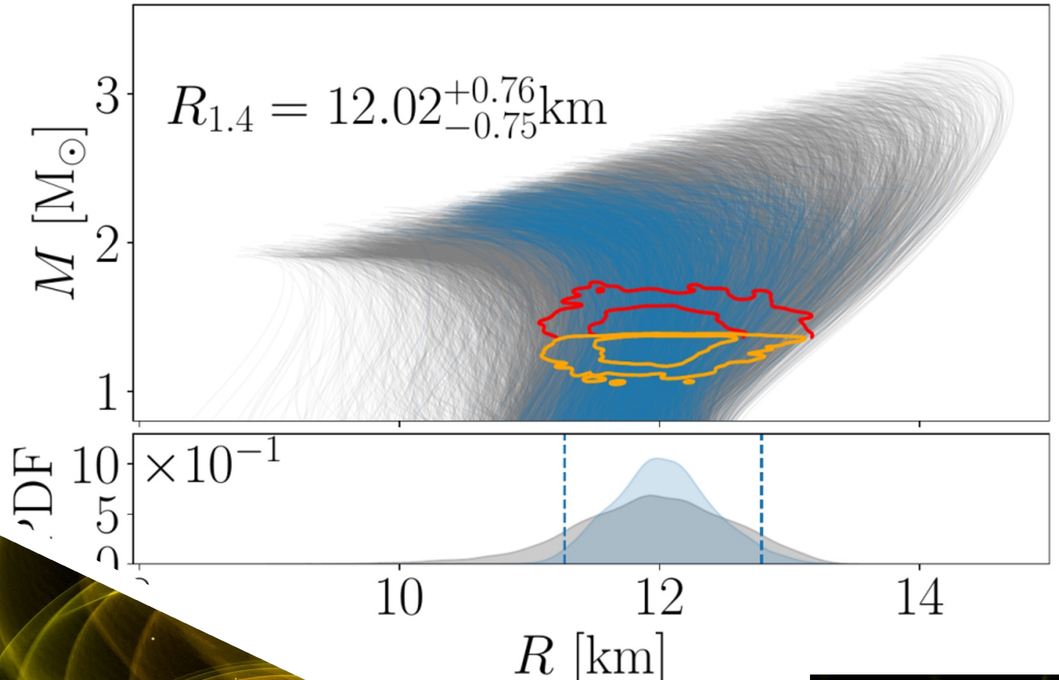


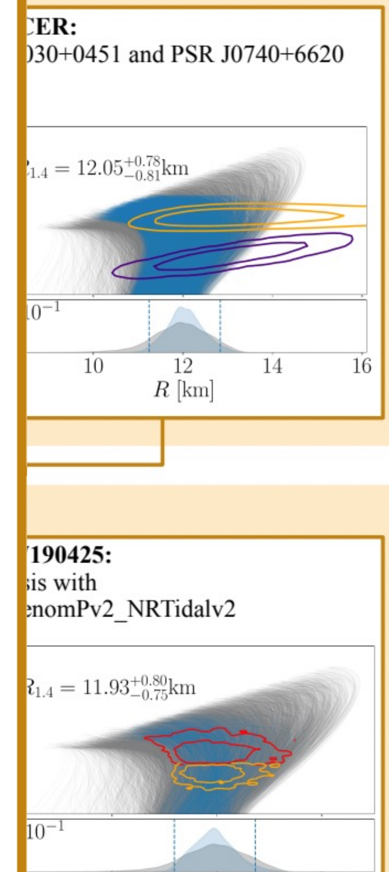


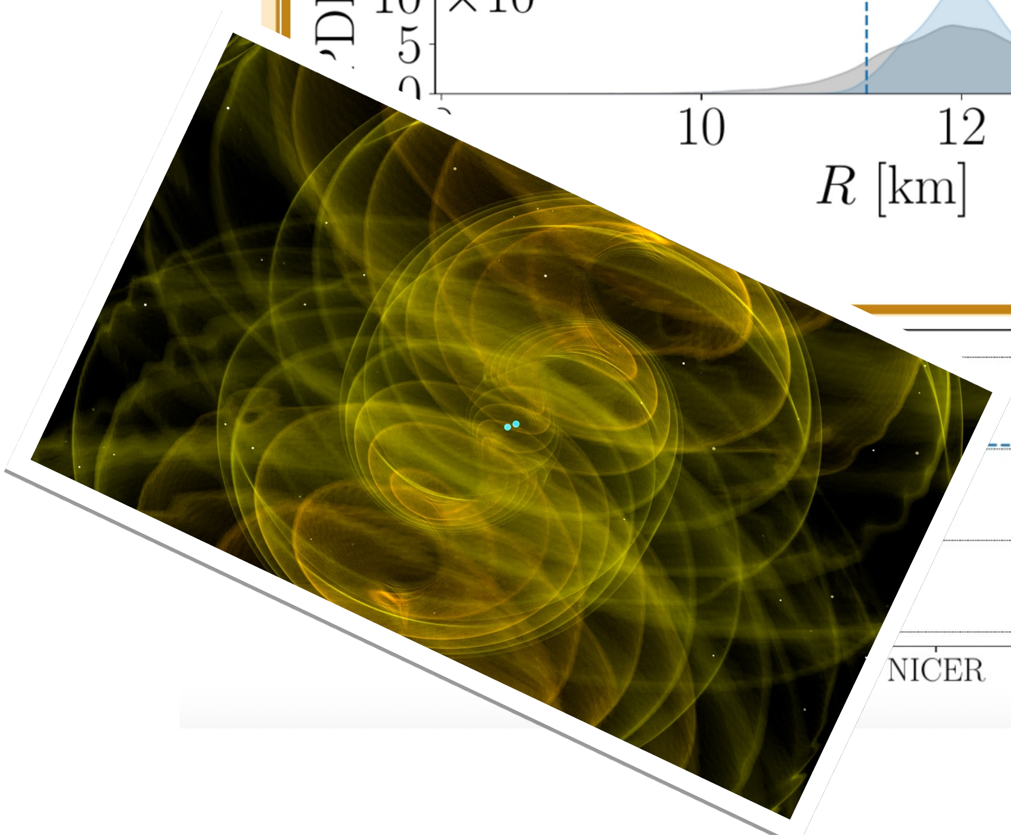


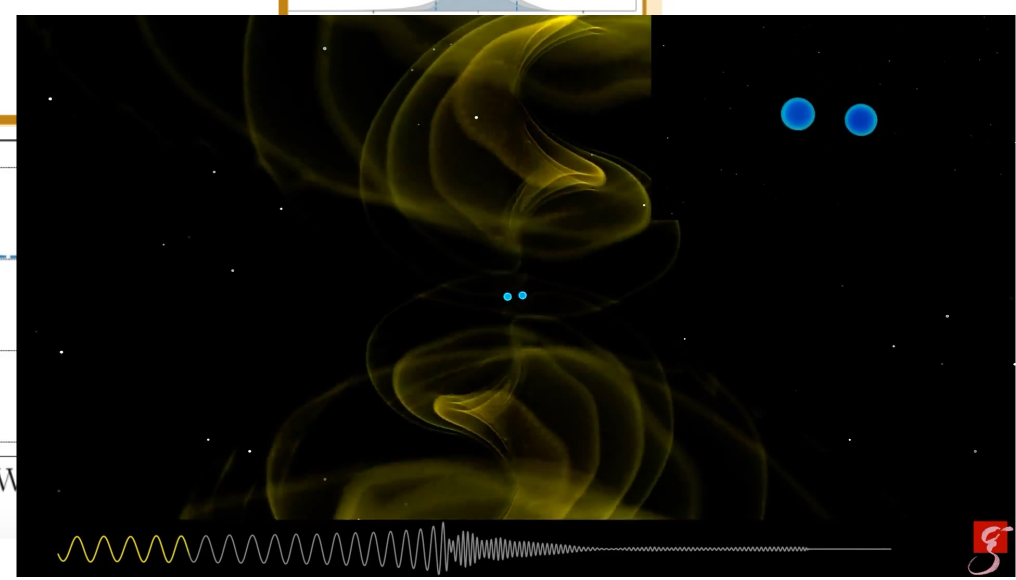
see talks by
S. Vinciguerra, C. Miller,
G. Raaijmakers &
C. Capano

(D) GW170817:
reanalysis with
IMRPhenomPv2_NRTidalv2





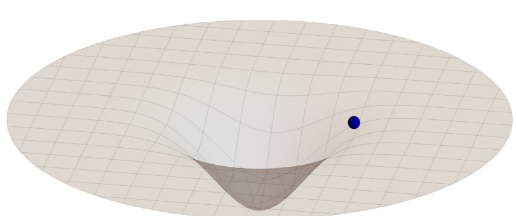




Inspiral waveforms

Effective-one-body Formalism

+ agree well with most NR data
– slow to compute

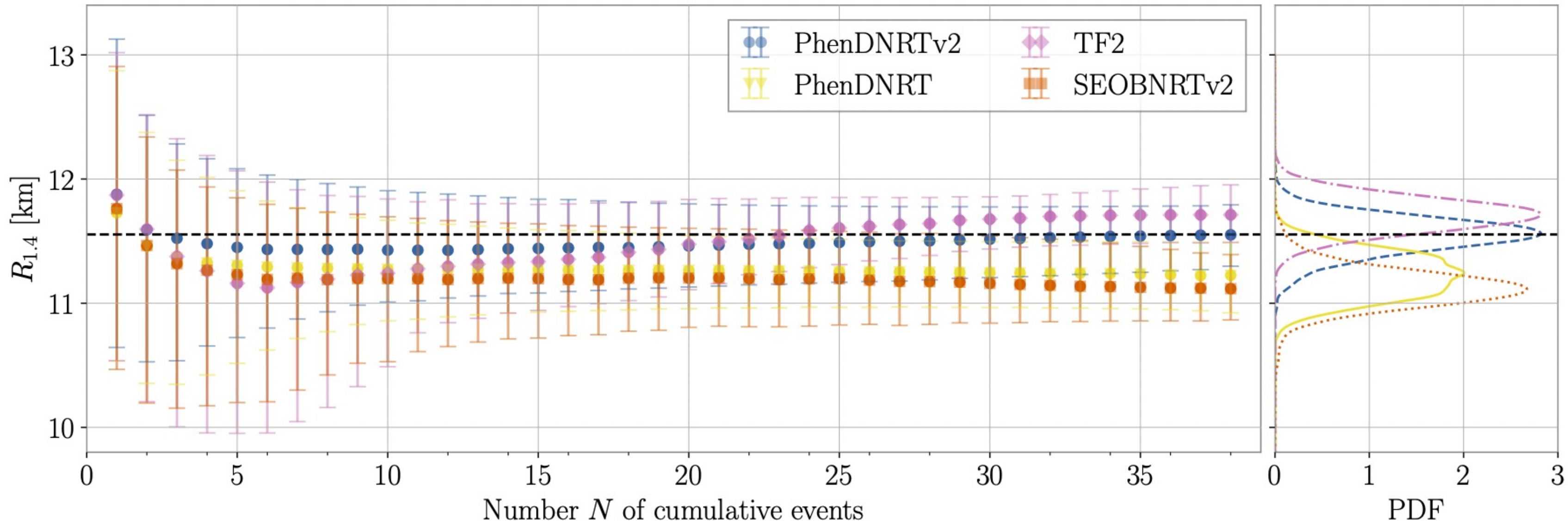


see talk by
S. Bernuzzi

Phenomenological Models

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

Inspiral waveforms



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

Effective-one-body Formalism

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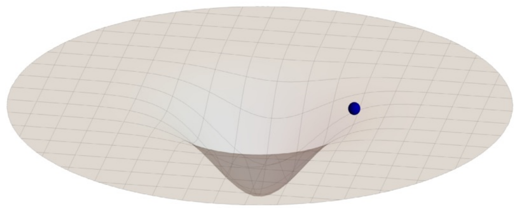


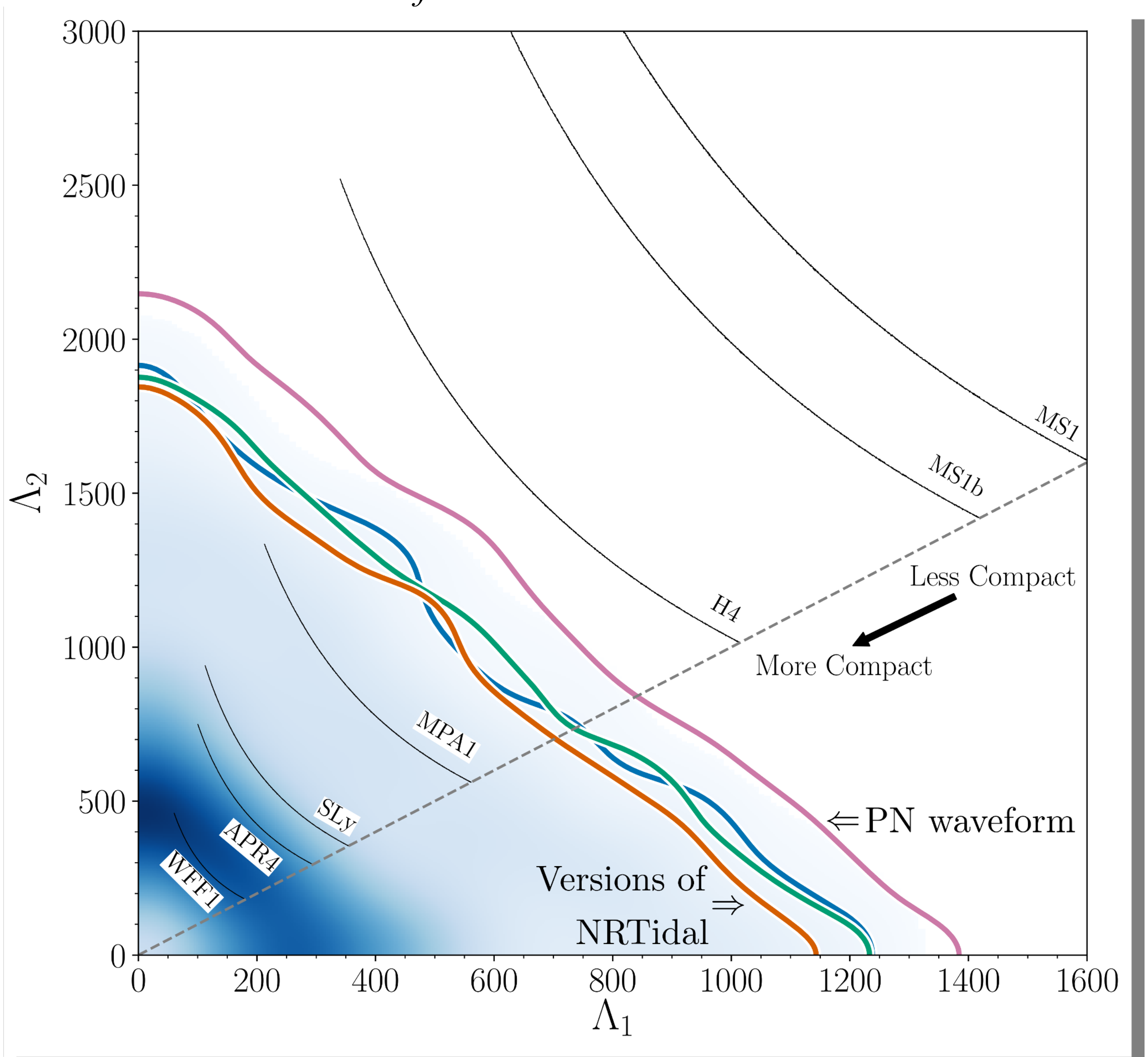
Phenomenological Models

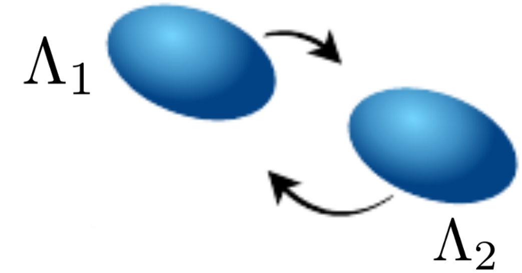
+ combination of PN/EOB/NR
+ accurate until merger
– just a fit

Application: GW170817 – Tidal Effects

Determine the Equation of State

GW observations favor NSs with smaller radii





Λ determines tidal deformability

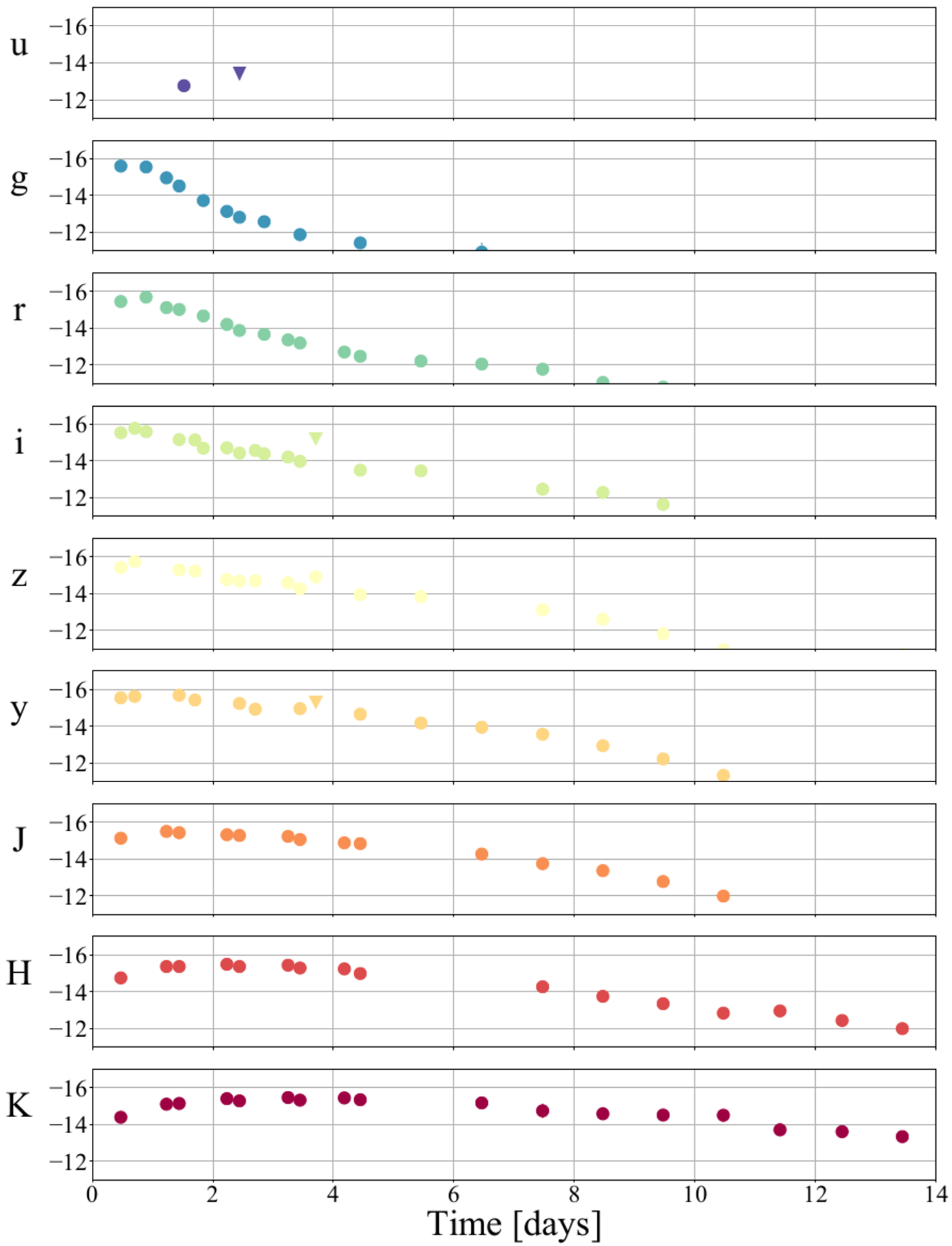
→ no assumption about the type of the compact object

see talk by J. Read

Phys.Rev. X9 (2019) 011001

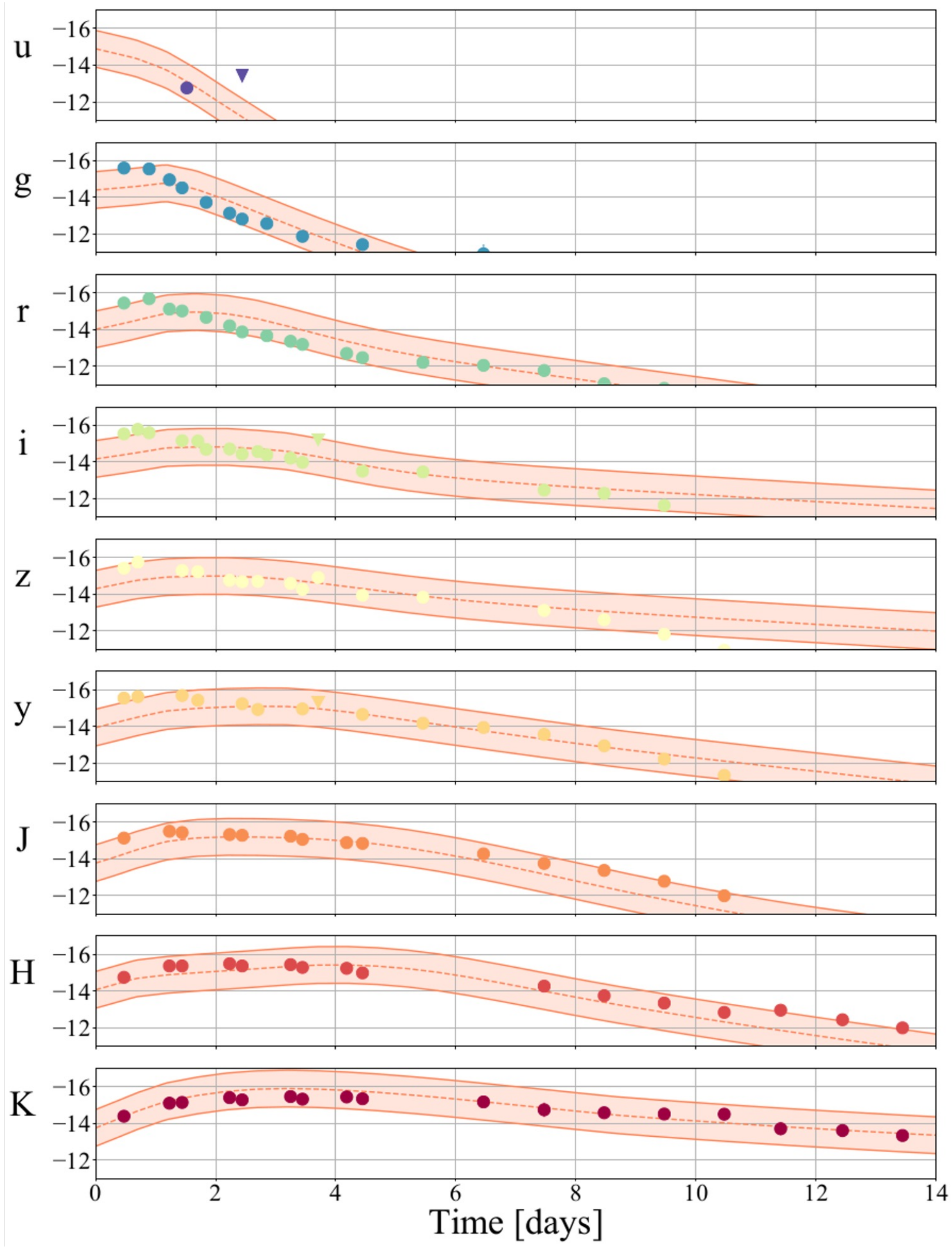
Electromagnetic Signals: Kilonova

Photometric lightcurves



Electromagnetic Signals: Kilonova

Photometric lightcurves



1.) compute lightcurves for a set (grid) of ejecta properties

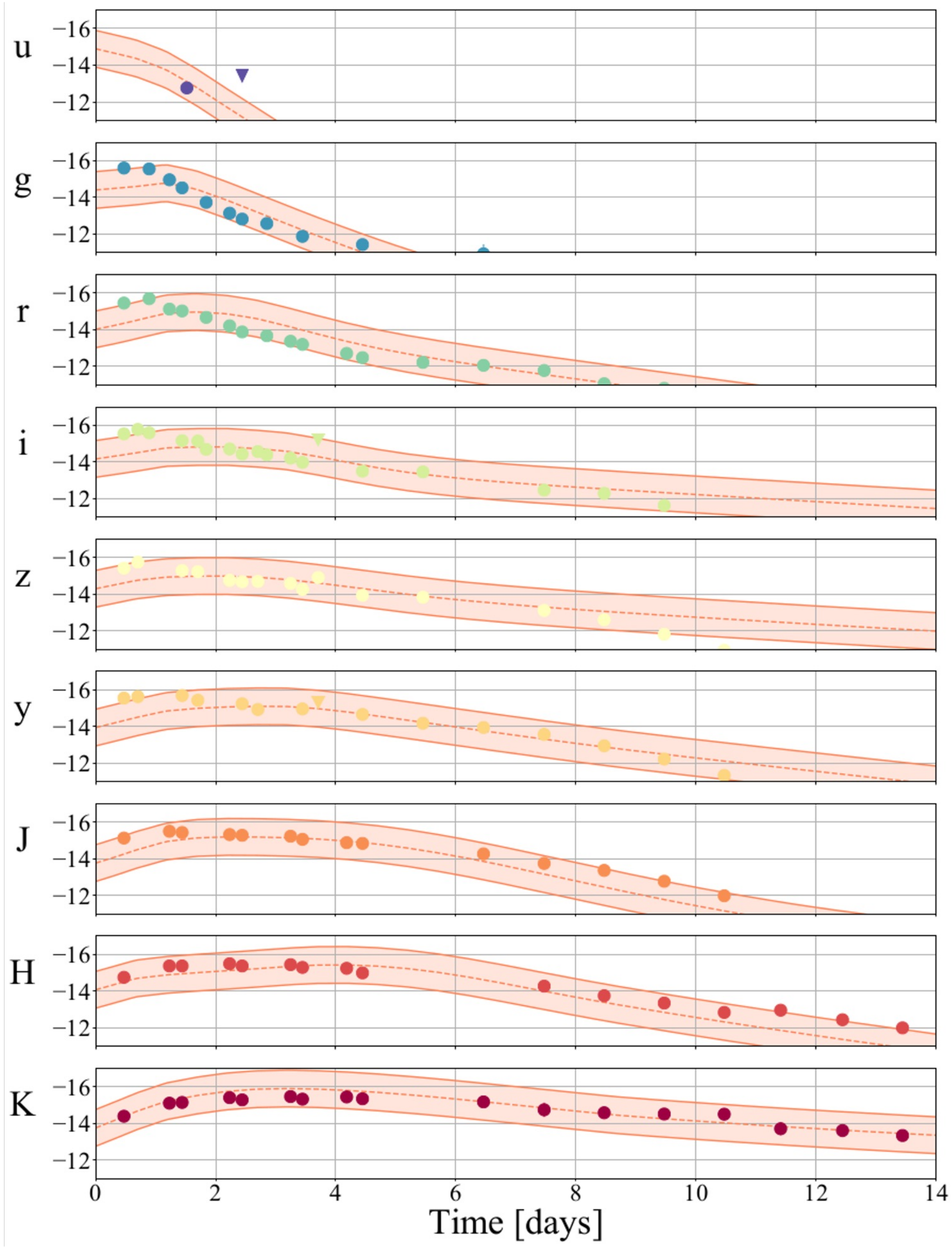
2.) interpolate within this grid through Gaussian Process Regression or a Neural Network

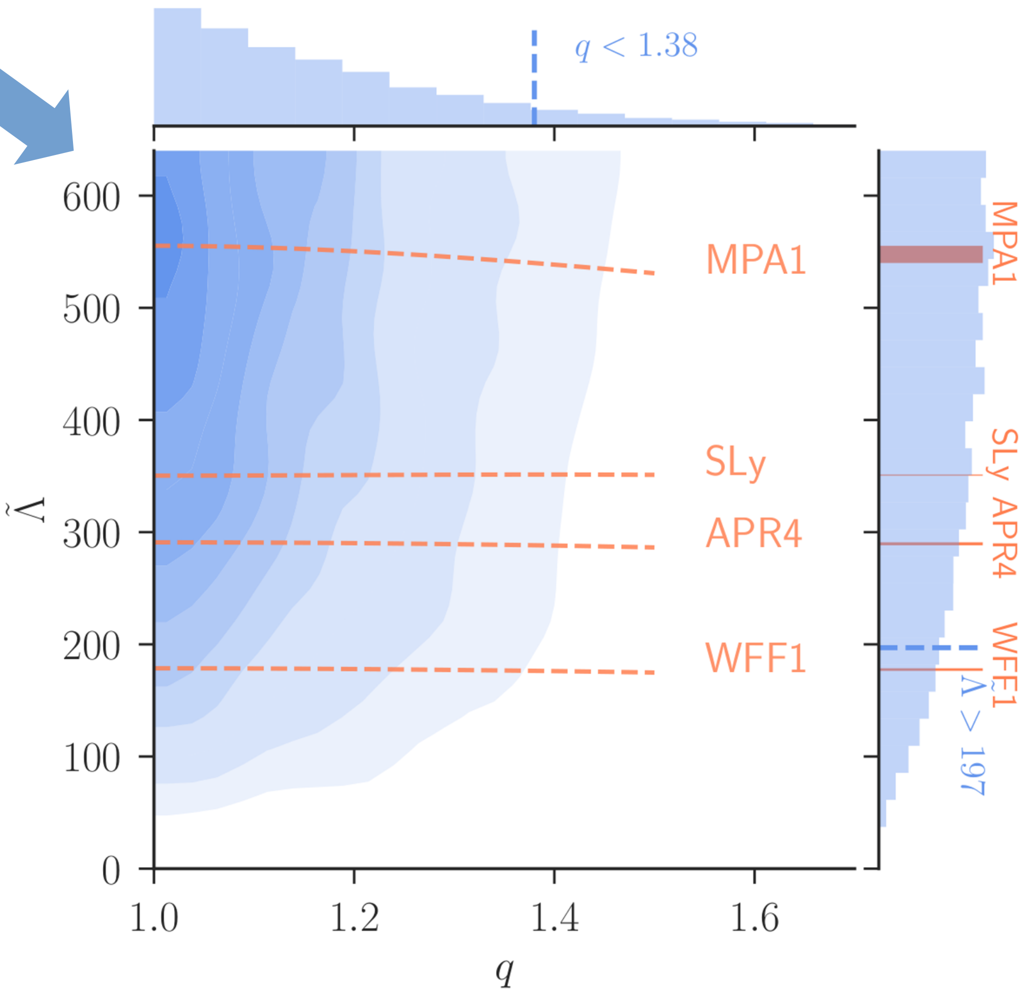
3.) link ejecta properties through numerical-relativity predictions to the binary properties

Coughlin, TD, et al., MNRAS/sty2174

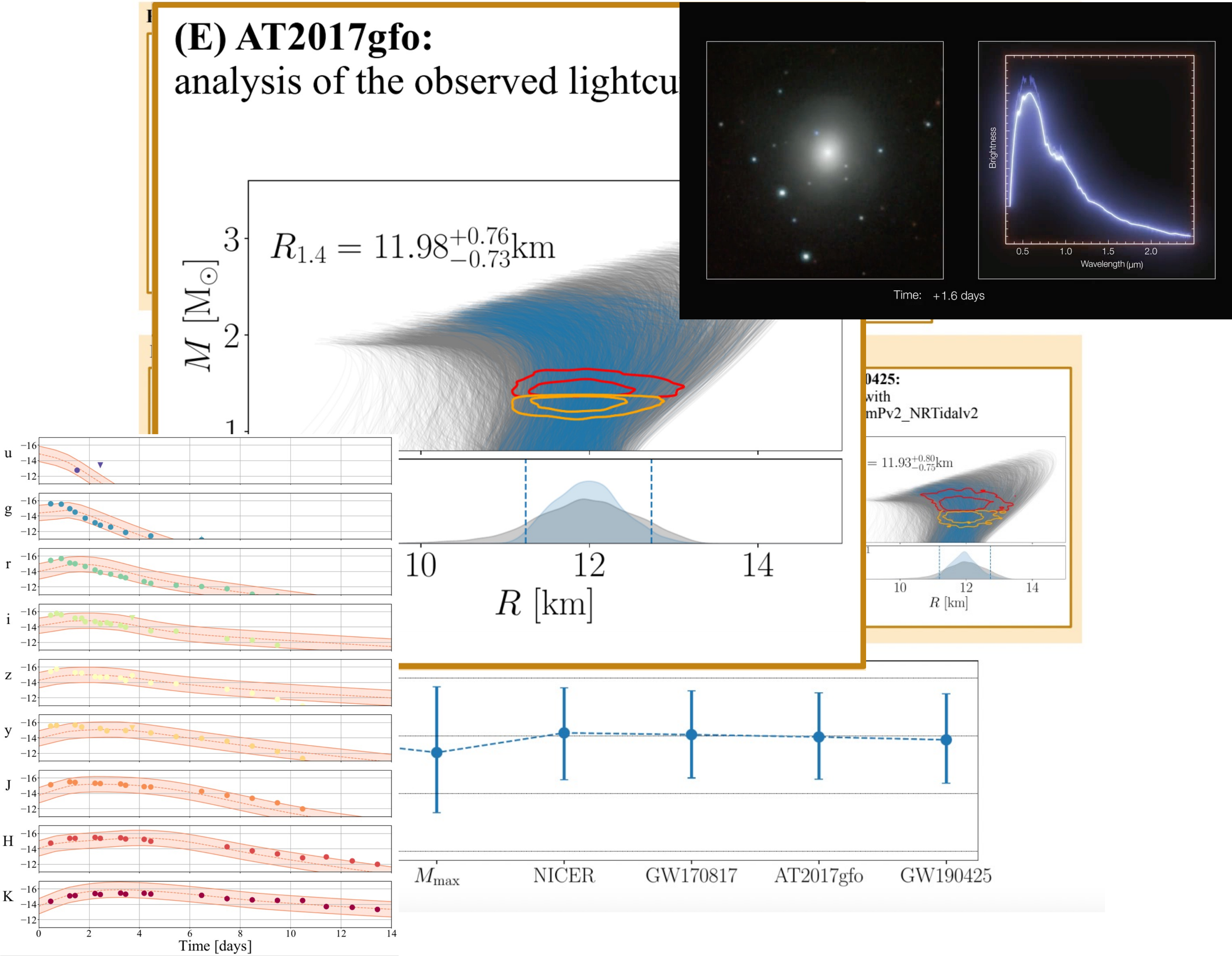
Electromagnetic Signals: Kilonova

Photometric lightcurves

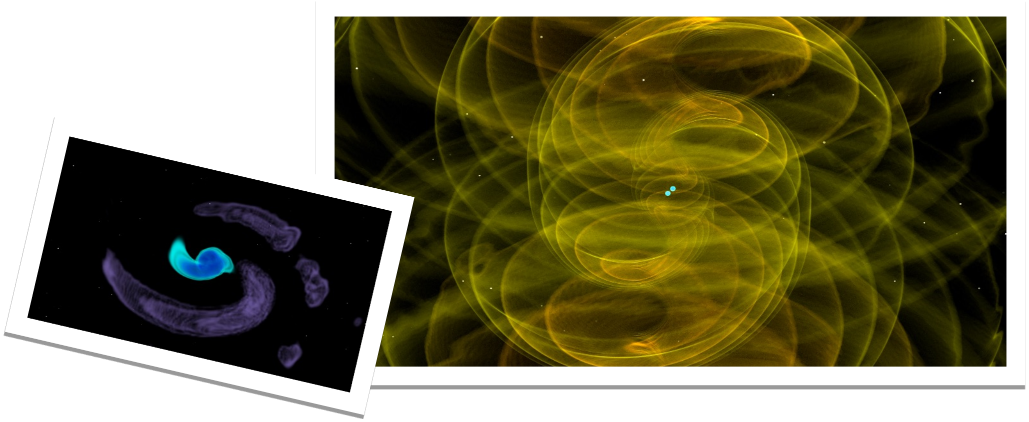




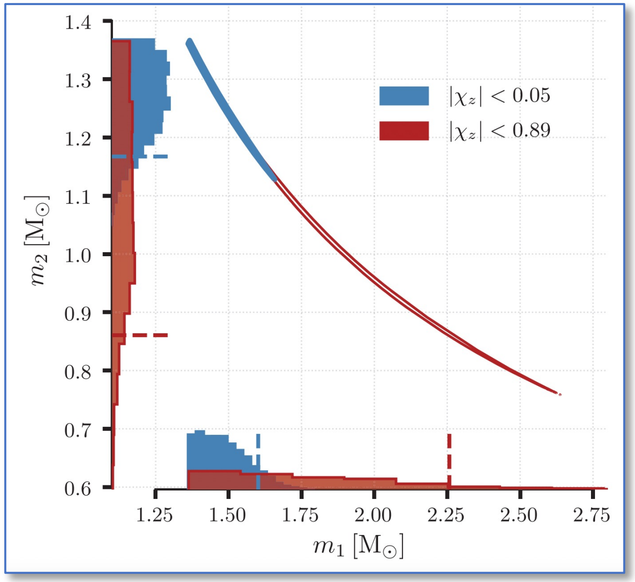
Coughlin, TD, et al., MNRAS/sty2174


(E) AT2017gfo:
analysis of the observed lightcu
$R_{1.4} = 11.98^{+0.76}_{-0.73}$km
M [$M_\odot$]
R [km]
Brightness
Wavelength (µm)
Time: +1.6 days
0425:
with
mPv2_NRTidalv2
= $11.93^{+0.80}_{-0.75}$km
Time [days]
u
g
r
i
z
y
J
H
K
$M_{\rm max}$
NICER
GW170817
AT2017gfo
GW190425

Gravitational Waves



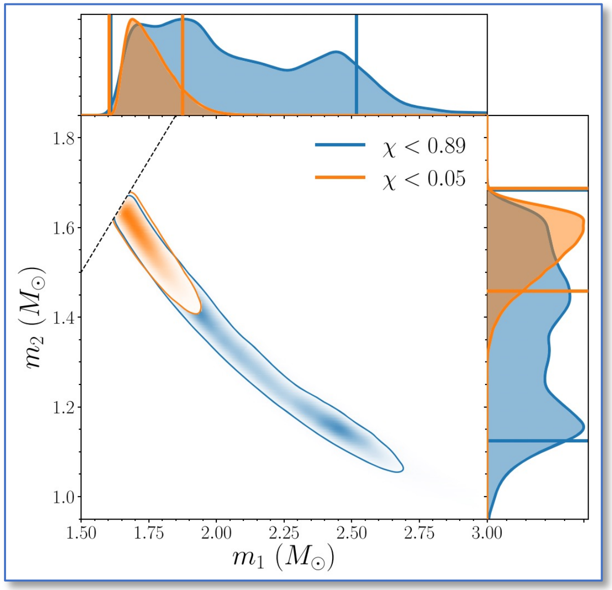
GW170817



PRL 119, 161101 (2017)

Primary mass m_1 1.36–1.60 $M_\odot$
Secondary mass m_2 1.17–1.36 $M_\odot$

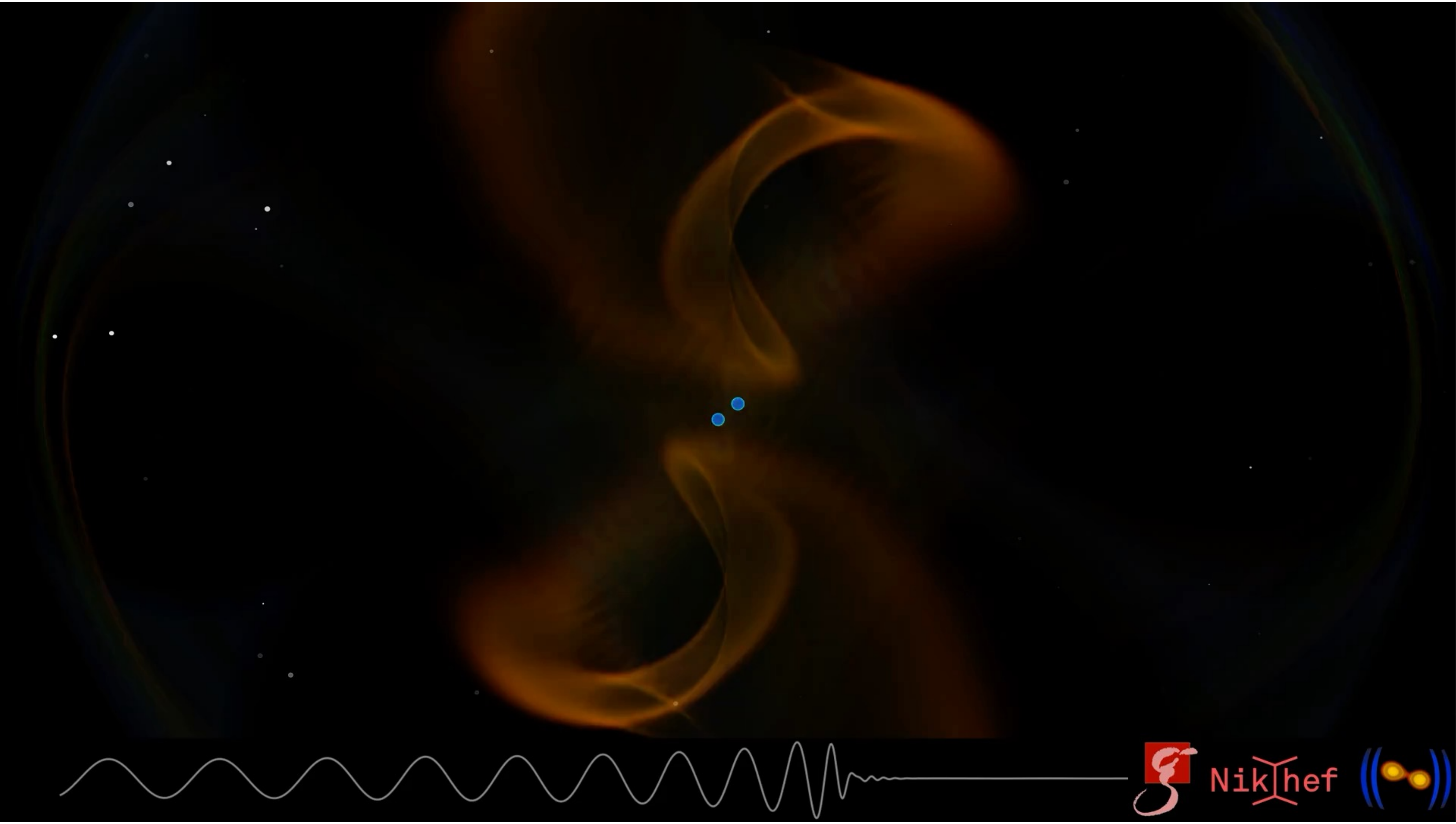
GW190425



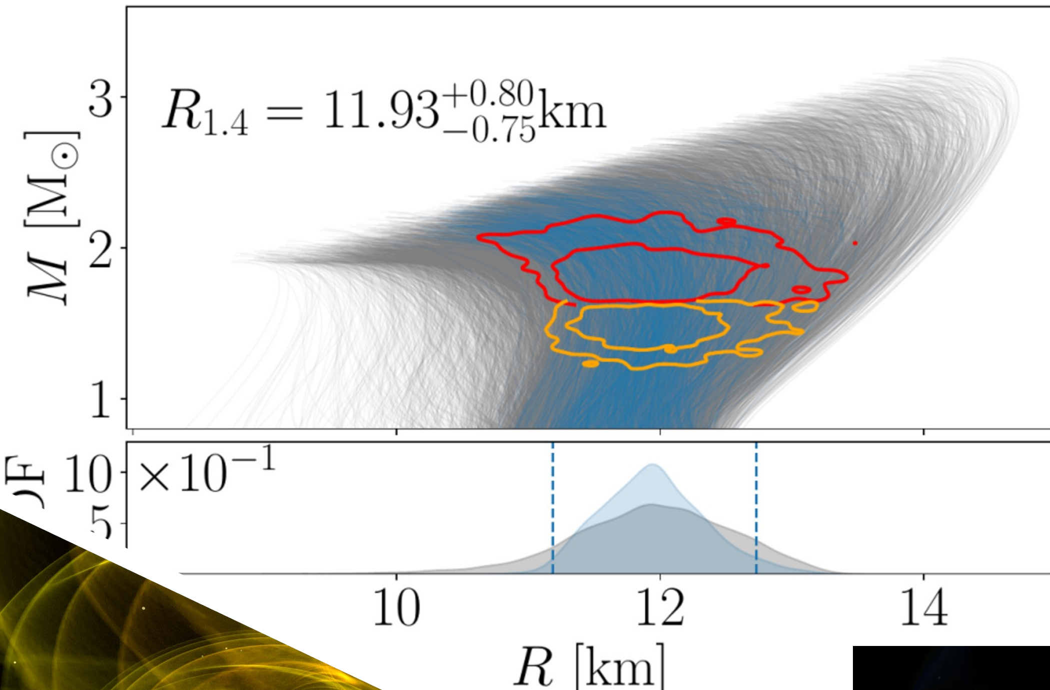
APJL 892 (2020)

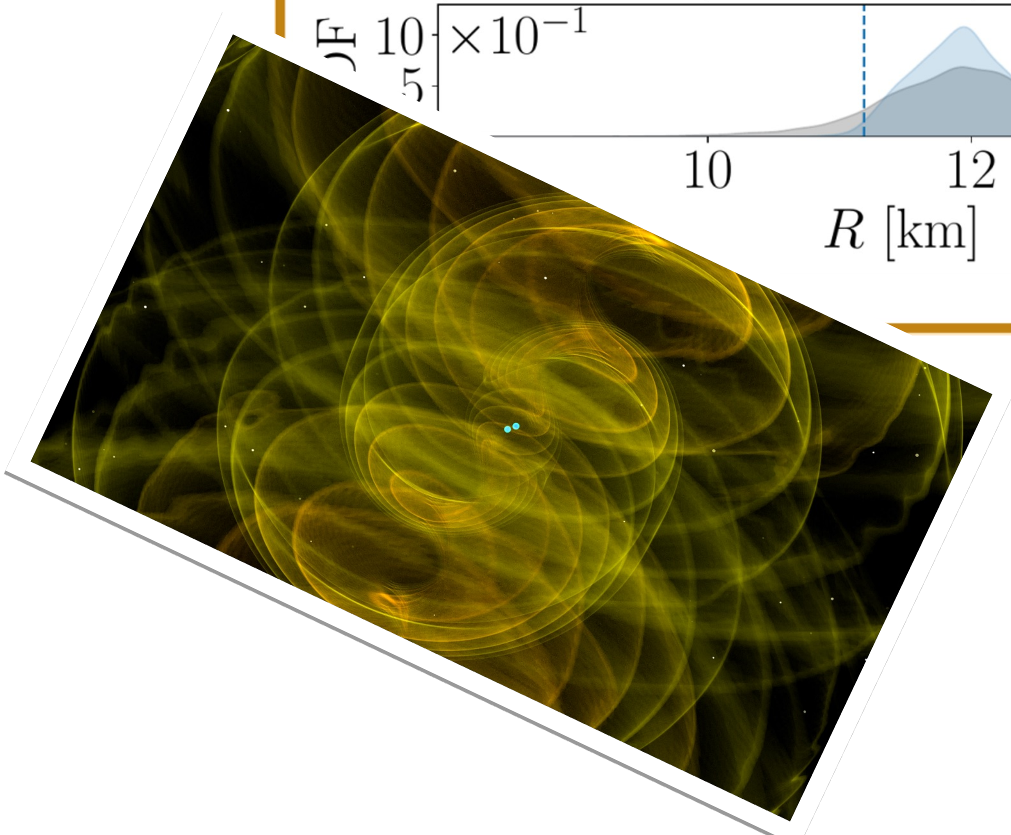
Primary mass m_1 1.60–1.87 $M_\odot$
Secondary mass m_2 1.46–1.69 $M_\odot$

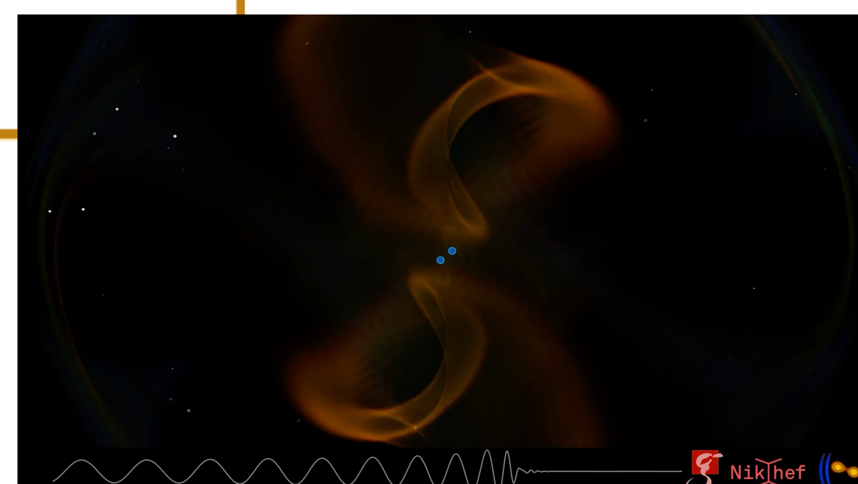
GW190425



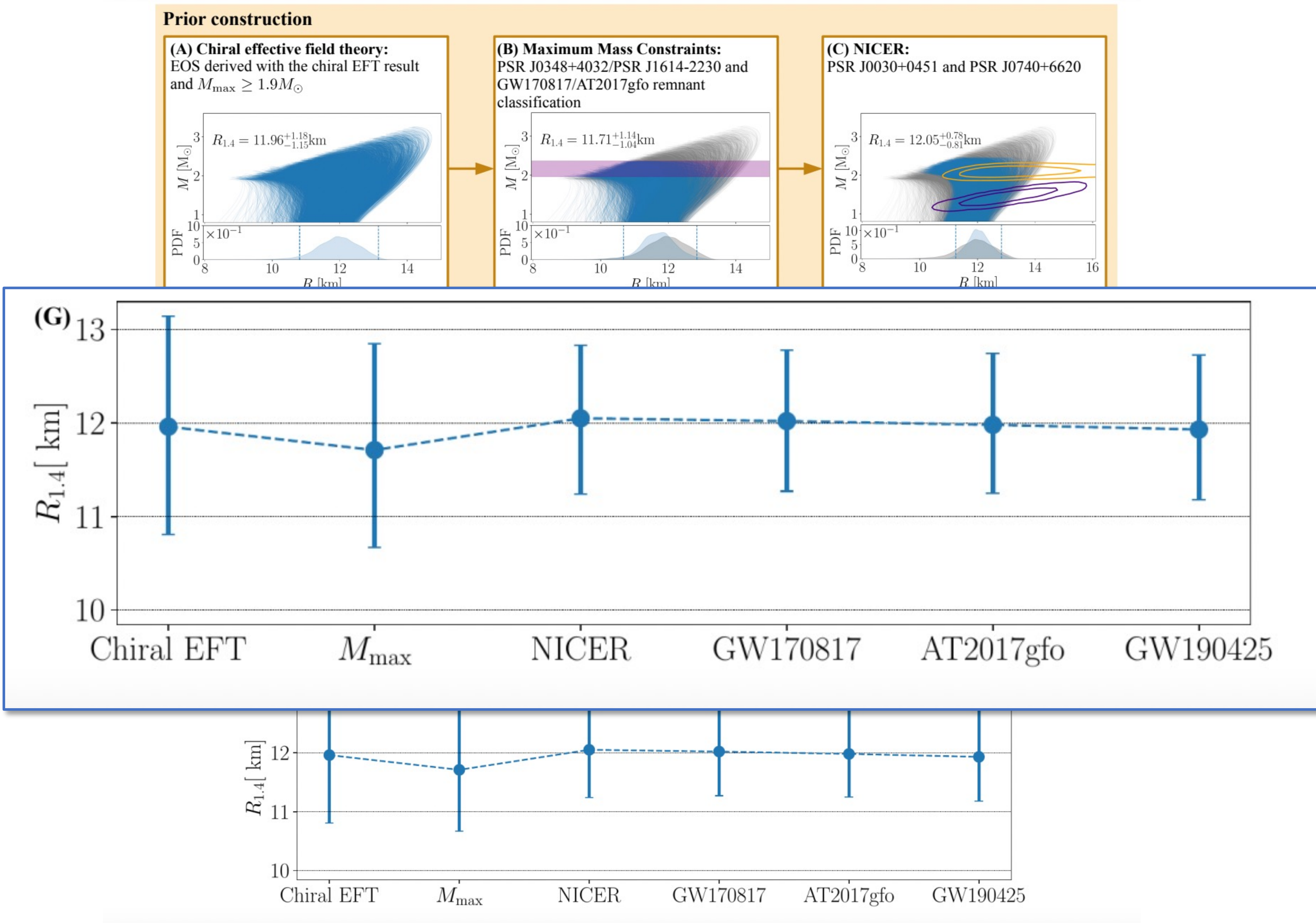
(F) GW190425:
reanalysis with
IMRPhenomPv2_NRTidalv2



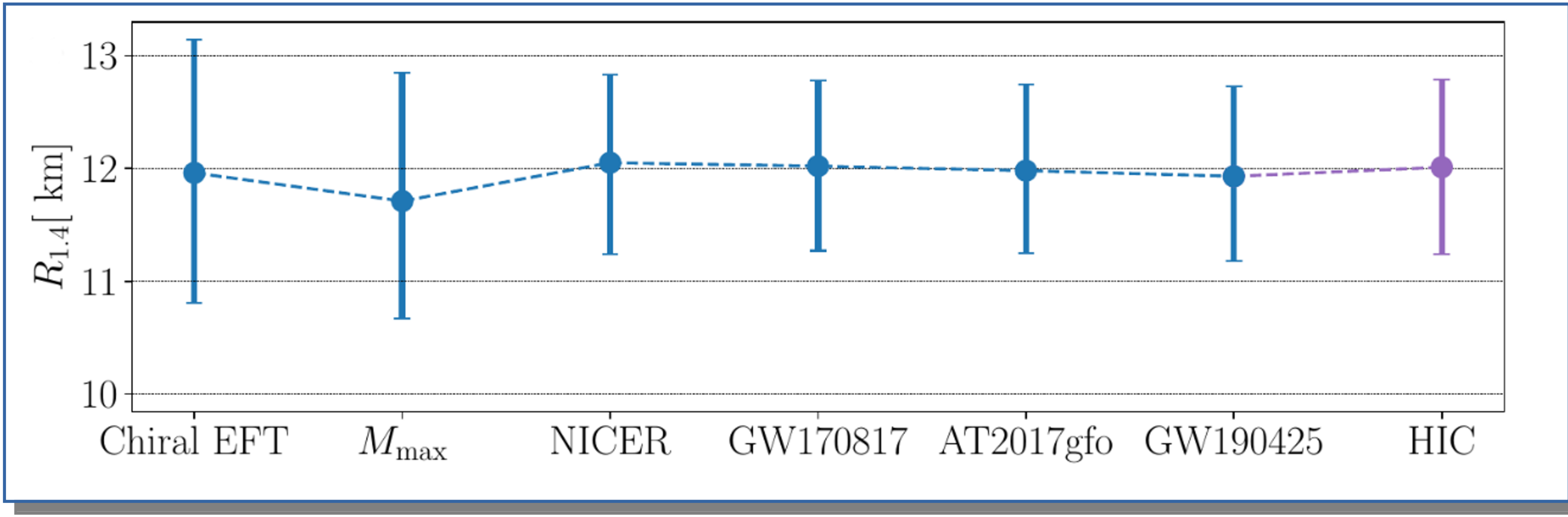




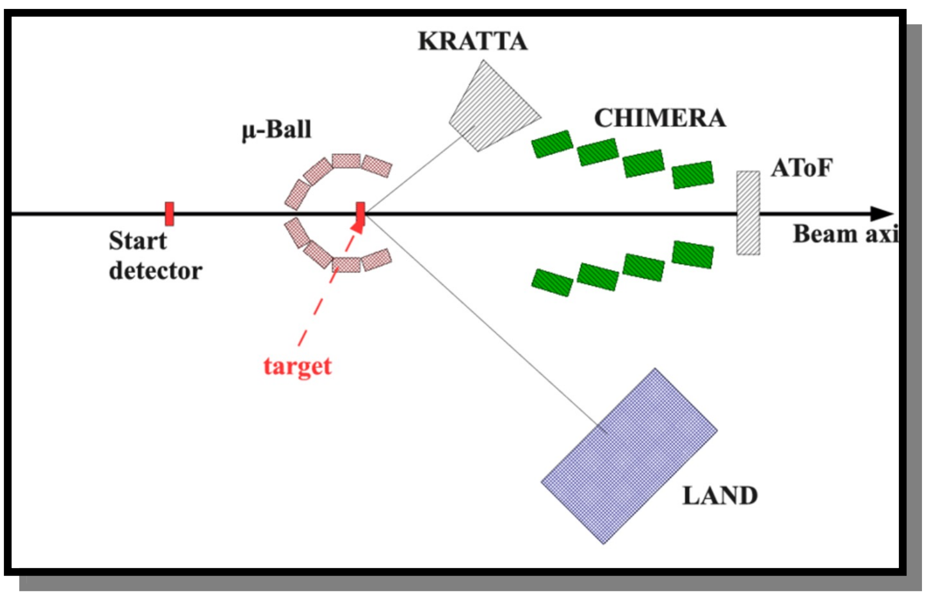
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Huth et al., Nature 606 (2022) 276-280



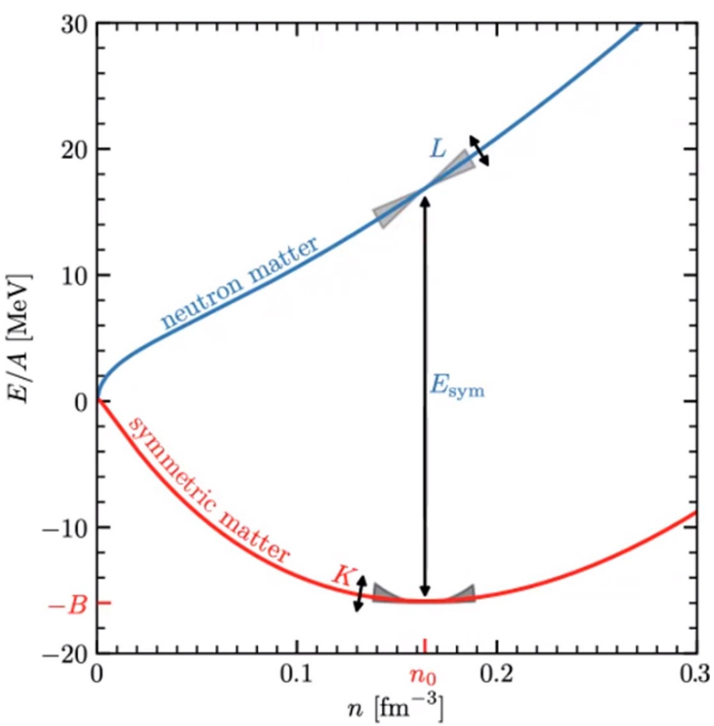
Prior construction
(A) Chiral effective field theory:
EOS derived with the chiral EFT result and $M_{\max} \geq 1.9 M_{\odot}$
$R_{1.4} = 11.96^{+1.18}_{-1.15}$km
(B) Maximum Mass Constraints:
PSR J0348+4032/PSR J1614-2230 and GW170817/AT2017gfo remnant classification
$R_{1.4} = 11.71^{+1.14}_{-1.04}$km
(C) NICER:
PSR J0030+0451 and PSR J0740+6620
$R_{1.4} = 12.05^{+0.78}_{-0.81}$km
M [$M_{\odot}$]
PDF
$\times 10^{-1}$
R [km]
(G)
$R_{1.4}$[km]
Chiral EFT
$M_{\max}$
NICER
GW170817
AT2017gfo
GW190425



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

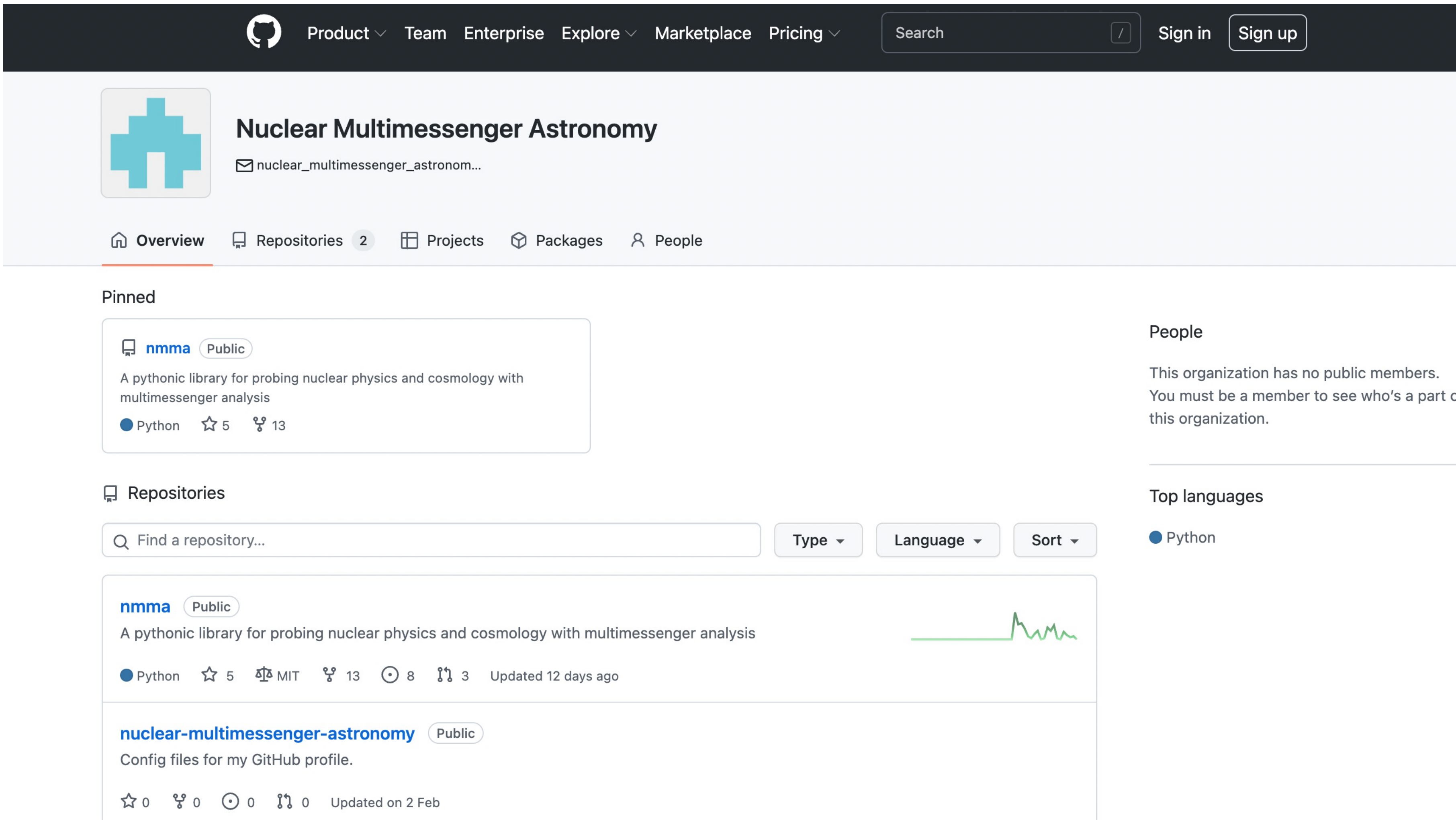


Russotto et al., J.Phys.Conf.Ser. 420 (2013)



First steps towards a nuclear-physics and multi-messenger astrophysics framework

github.com/nuclear-multimessenger-astronomy



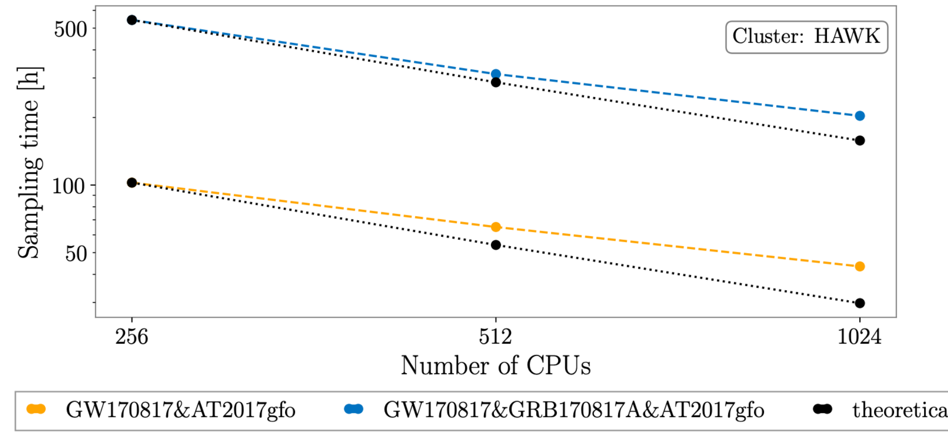
Pang et al., arXiv: 2005.08513

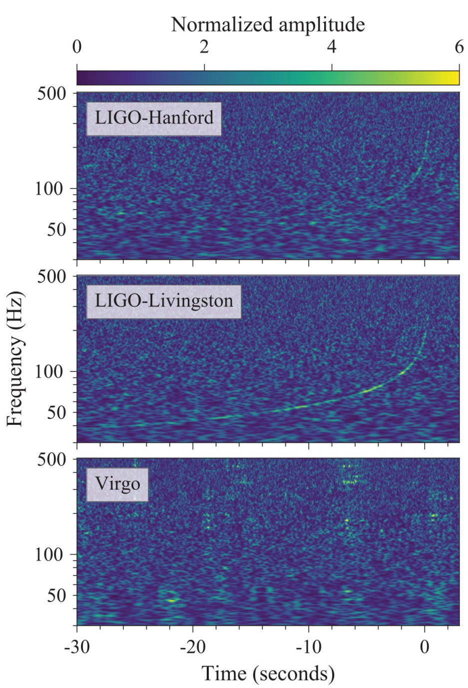
First steps towards a nuclear-physics and multi-messenger astrophysics framework

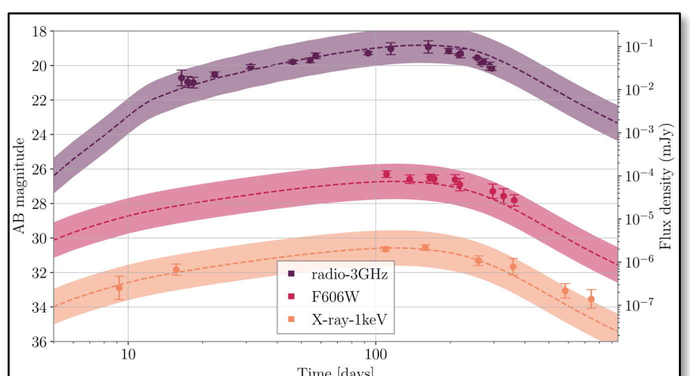
- incorporation of nuclear-physics information

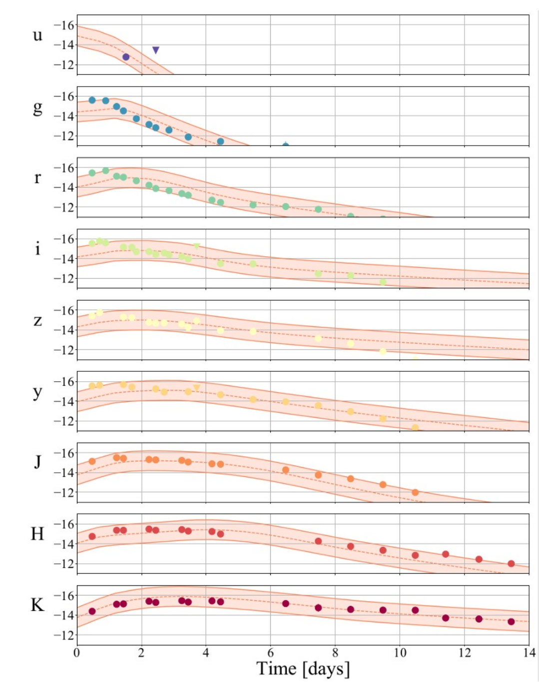
- <u>simultaneous</u> analysis of GW, kilonova, and GRB afterglow

- HPC facilities needed

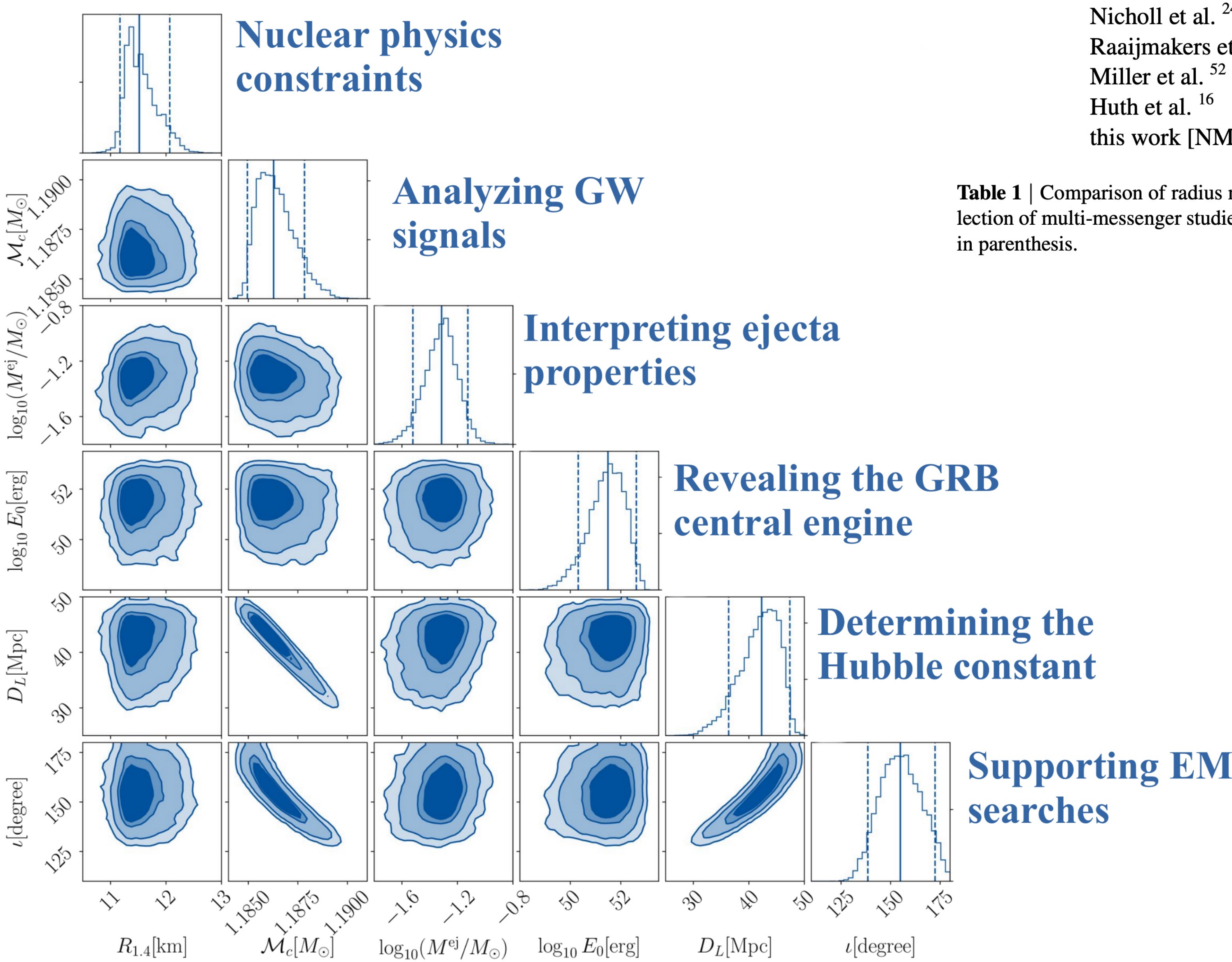








First steps towards a nuclear-physics and multi-messenger astrophysics framework



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

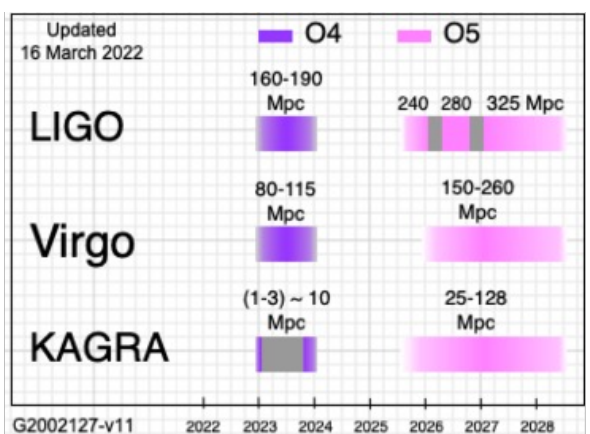
Table 1 | Comparison of radius measurements of a $1.4M_\odot$ neutron star for a selection of multi-messenger studies. We denote the corresponding credible interval in parenthesis.

Pang et al., arXiv: 2005.08513

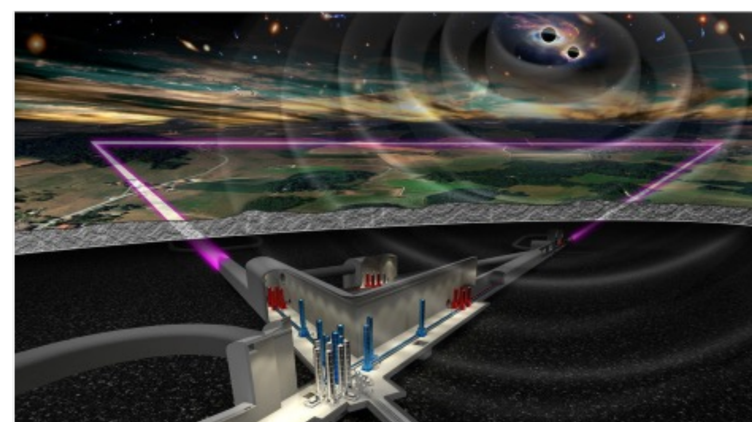
Outlook

	GW		Kilonova + GW O4			GRB Afterglow + GW O4			GRB Prompt + GW O4	
	HLV O3	HLVK O4	J	z	g	Radio	Optical	X-rays	*Swift*/BAT	*Fermi*/GBM
Count. Search										
Limit	12	12	21	22	22	0.1	22	10^{-13}	3.5	4
Rate	$1.8^{+2.7}_{-1.3}$	$7.7^{+11.9}_{-5.7}$	$2.4^{+3.6}_{-1.8}$	$5.1^{+7.8}_{-3.8}$	$5.7^{+8.7}_{-4.2}$	$0.29^{+0.44}_{-0.22}$	$0.06^{+0.09}_{-0.04}$	$0.32^{+0.51}_{-0.23}$	$0.03^{+0.04}_{-0.02}$	$0.17^{+0.26}_{-0.13}$
(% of O4 GW)	(23%)	(100%)	(36%)	(67%)	(74%)	(4%)	(0.8%)	(4%)	(0.4%)	(2%)
Cand. Monitoring										
Limit	/	/	28	28	28	0.01	28	10^{-15}	1	1
Rate	/	/	$6.0^{+9.2}_{-4.4}$	$6.0^{+9.2}_{-4.4}$	$6.0^{+9.2}_{-4.4}$	$0.78^{+1.21}_{-0.58}$	$0.47^{+0.74}_{-0.35}$	$0.57^{+0.89}_{-0.42}$	$0.05^{+0.07}_{-0.04}$	$0.31^{+0.48}_{-0.23}$
(% of O4 GW)	/	/	(78%)	(78%)	(78%)	(10%)	(6%)	(7%)	(0.6%)	(4%)
GW subthreshold										
Limit	6	6	21	22	22	0.1	22	10^{-13}	3.5	4
Rate	$13^{+20}_{-9.6}$	54^{+84}_{-40}	$3.4^{+5.3}_{-2.5}$	$14^{+20}_{-10.4}$	21^{+34}_{-15}	$0.95^{+1.45}_{-0.70}$	$0.24^{+0.38}_{-0.18}$	$1.23^{+1.89}_{-0.91}$	$0.12^{+0.19}_{-0.09}$	$0.75^{+1.16}_{-0.55}$

Colombo et al., arXiv:2204.07592



Next observing run starts in a few months



Development of the next generation of gravitational-wave telescopes


ULTRASAT
Ultraviolet Transient Astronomy Satellite
Exploring the
Dynamic UV Sky