A technical ecosystem to enable multi-messenger astrophysics

Michael W. Coughlin

August 5, 2022

Alternative Title:
Ask not what nuclear physics can do for you – ask what I can (possibly) do for nuclear physics

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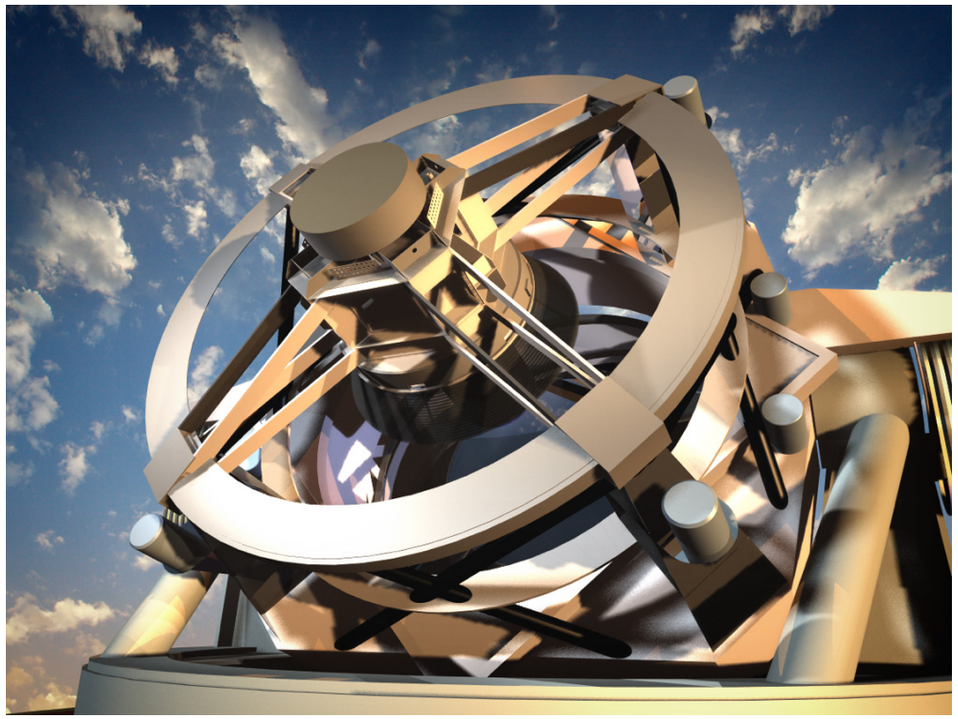
Why observe neutron stars if I care about Nuclear Physics?

Heavy-ion collisions on Earth probe dense matter at densities up to 1-2x nuclear saturation density (FRIB or FAIR will explore densities of 3-4x)

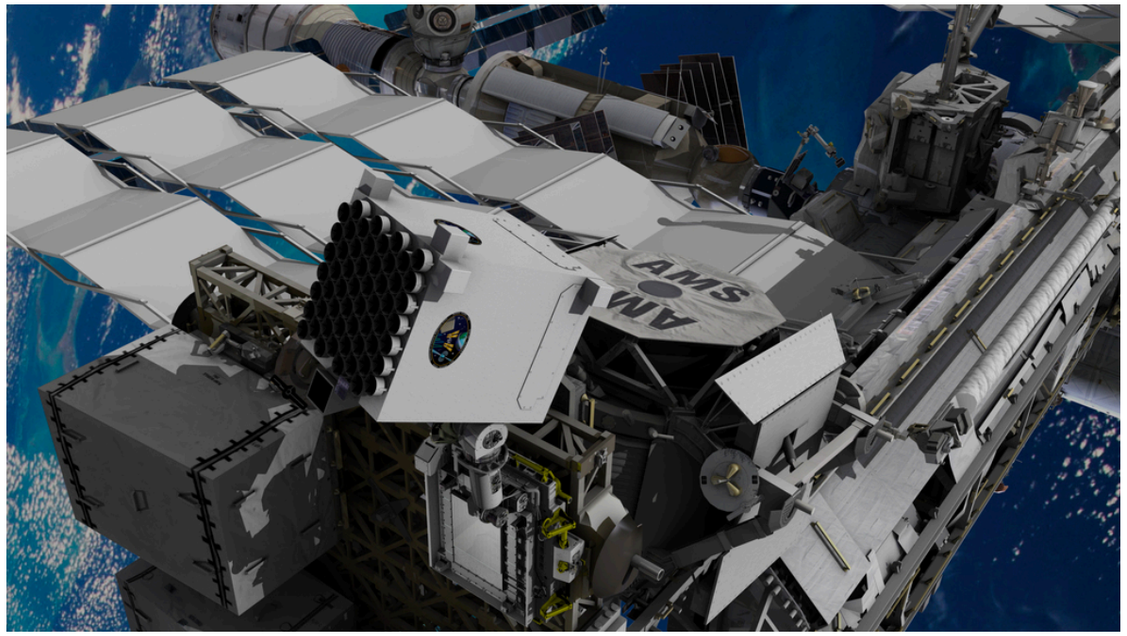
Neutron stars that do not have a companion star probe dense matter at densities up to 5 x, while mergers can reach 8x.

A Golden Era for (Nuclear) Astrophysics

Optical Time Domain: kilonovae



NICER: X-ray measurements of pulsars

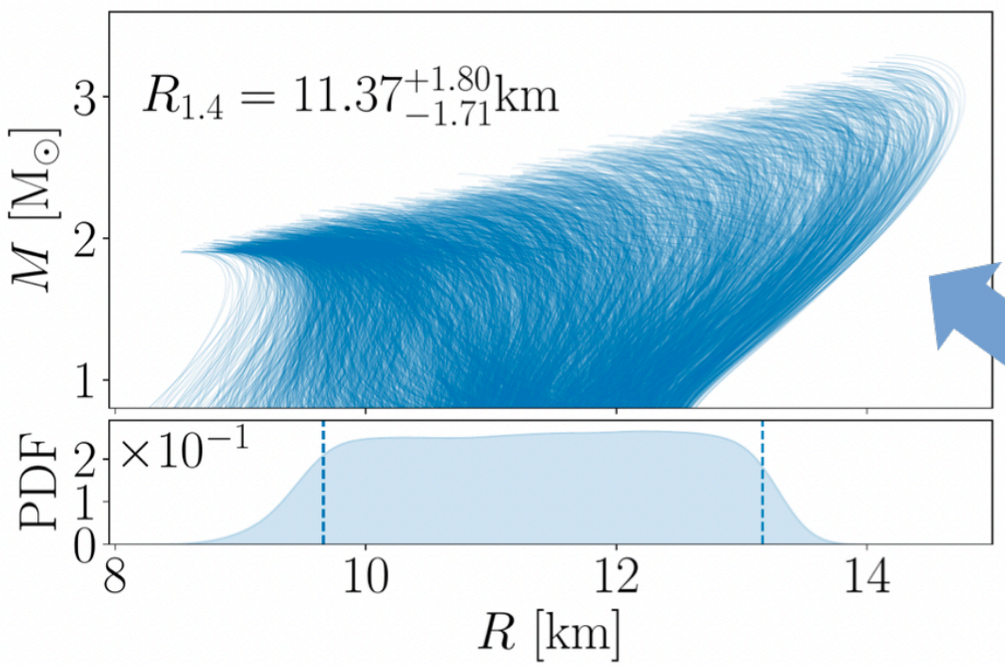


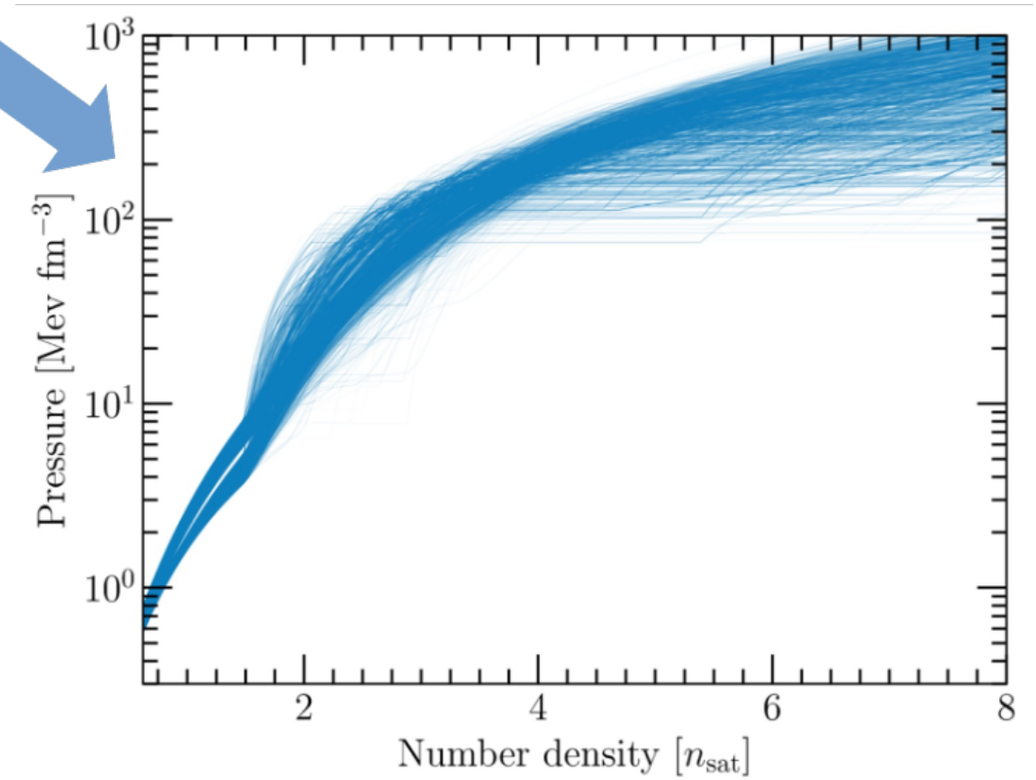
LIGO/Virgo: gravitational-wave measurements of NS mergers

IceCube: neutrinos from a galactic supernova?

The "Nuclear Physics Theory" … Messenger? Chiral EFT

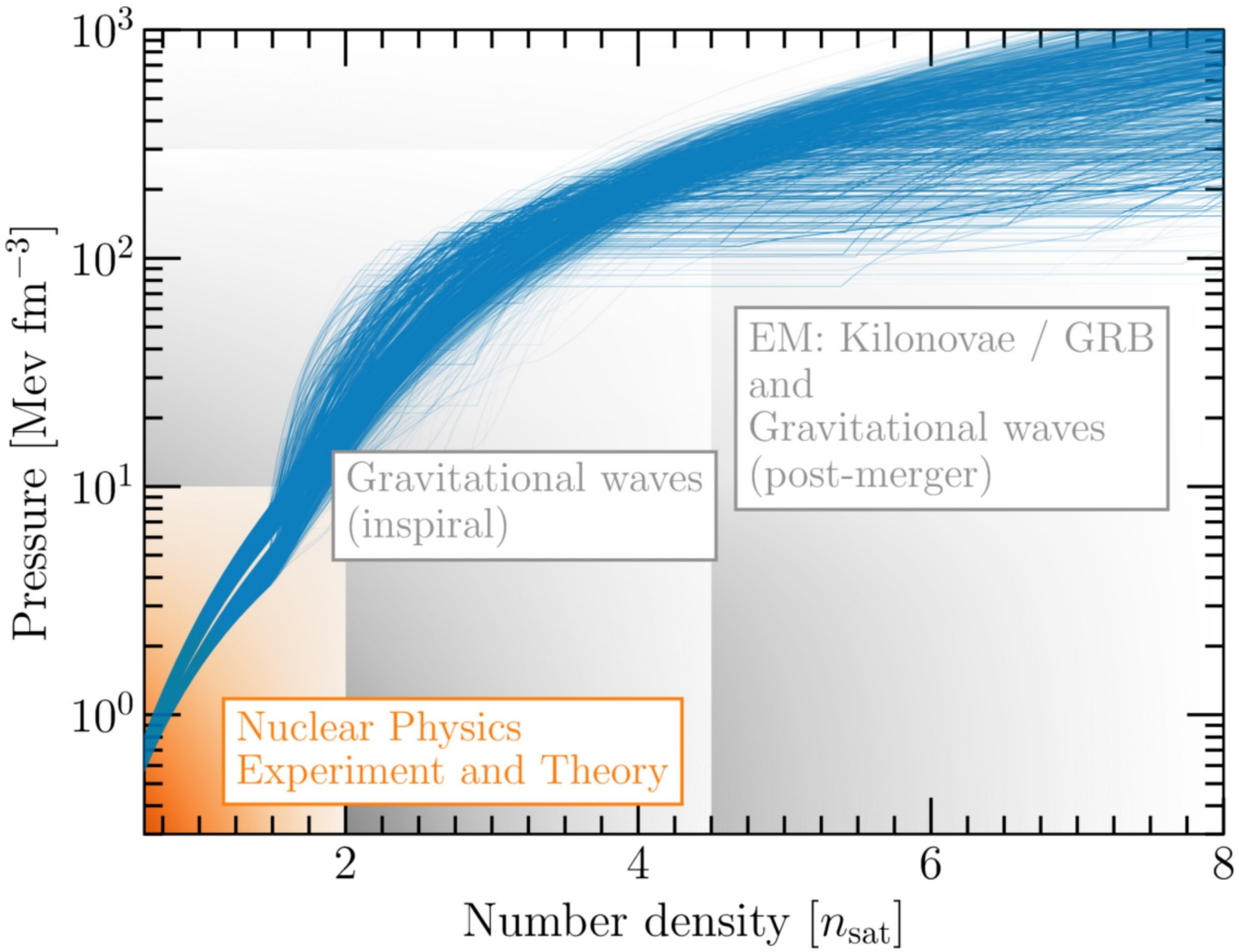
(A) Chiral effective field theory:
EOS derived with the chiral EFT framework

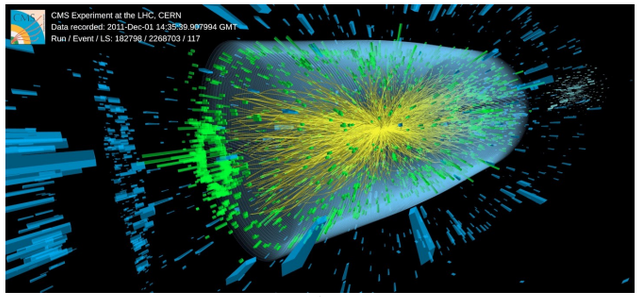


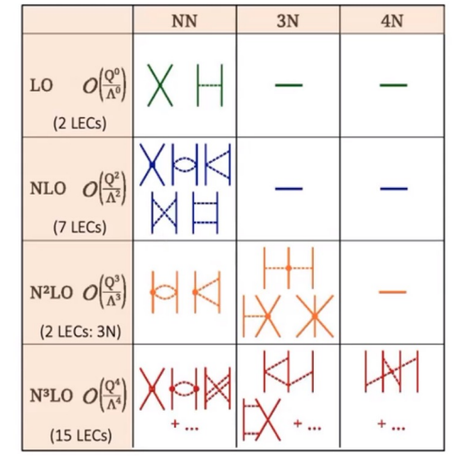


Pang et al., APJ 922 (2021) 1, 14

The Experimental Messengers - HIC



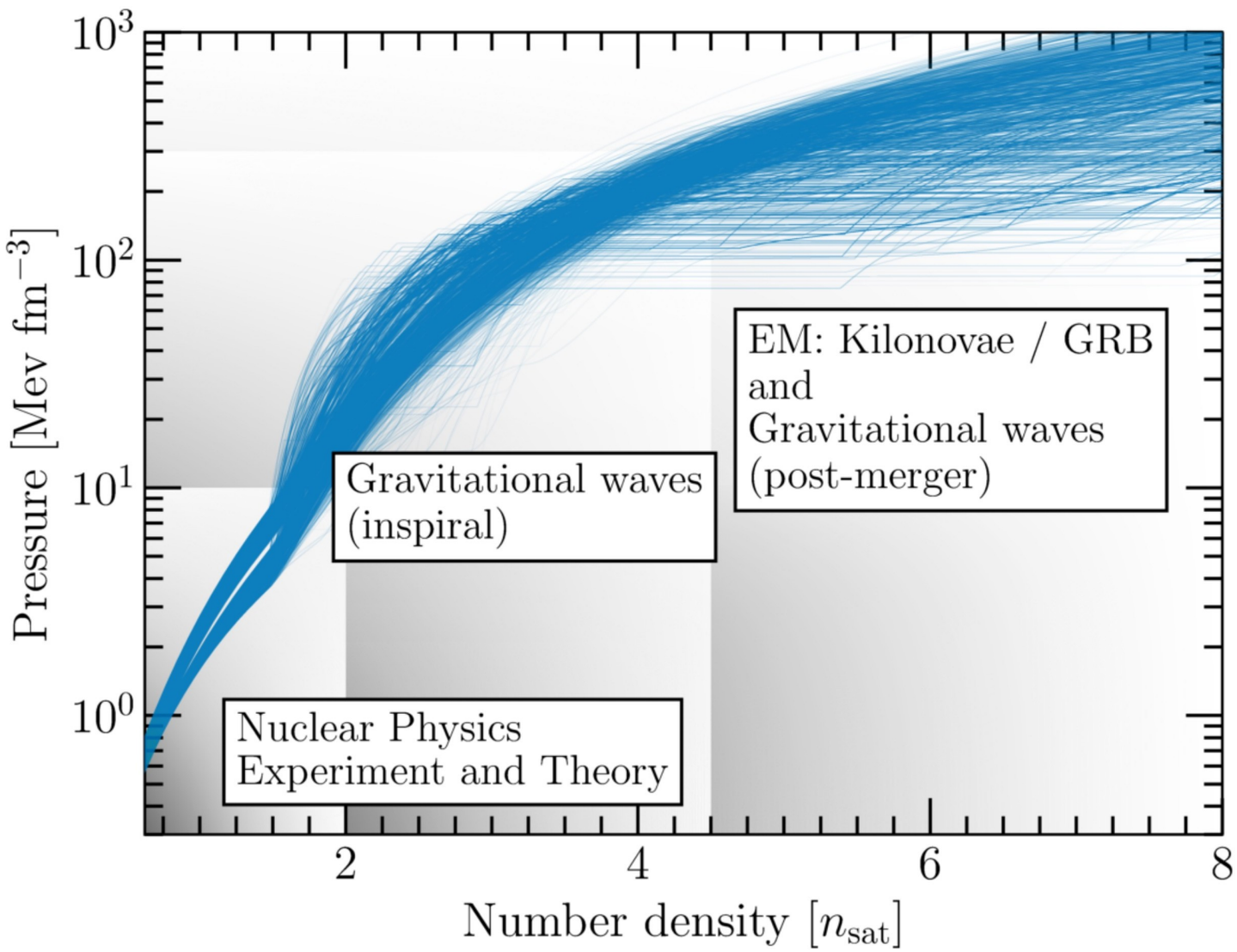




Huth et al., Nature 606 (2022) 276-280

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

The Experimental Messengers - Astronomical



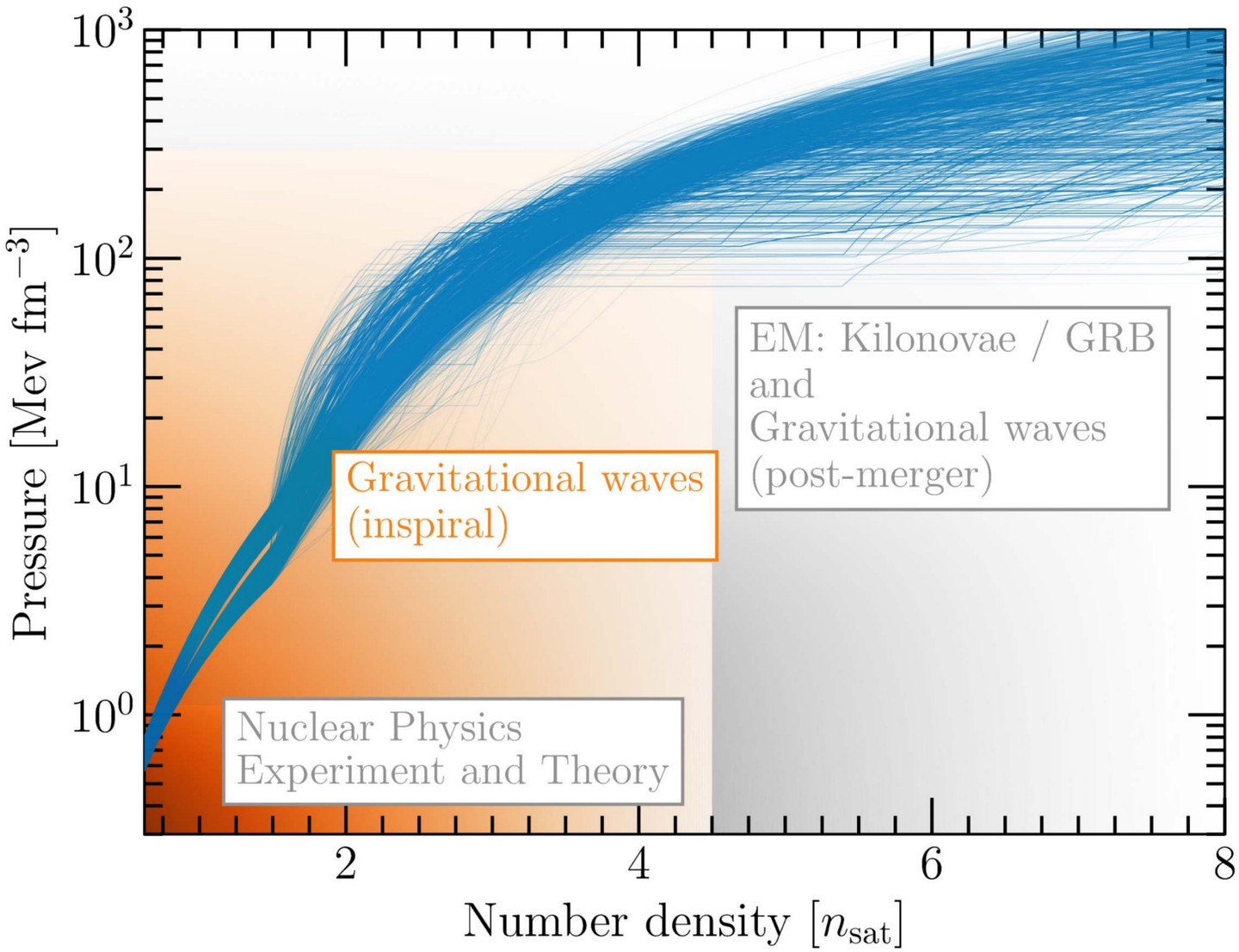
Pulsars (NICER): measures the X-ray pulse-profile of fast rotating NSs and models the emission to extract structure information on the observed NSs.

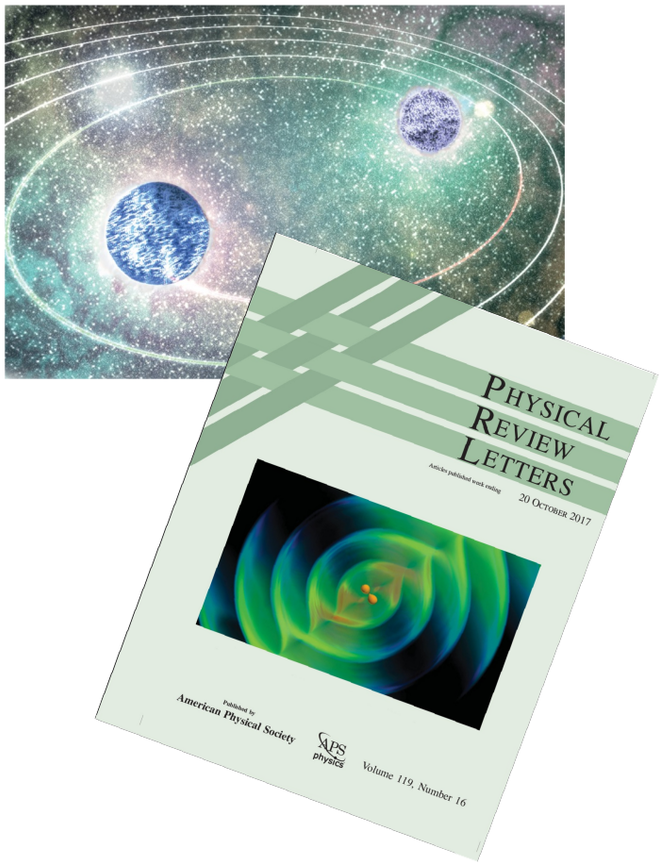
GWs (IGWN): measures changes in phase due to tidal deformation

Kilonovae (UV-O-IR Telescopes): R-process nucleosynthesis induced ultraviolet-near infrared transient (stiffer EOS -> brighter transient)

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

The Experimental Messengers - GWs

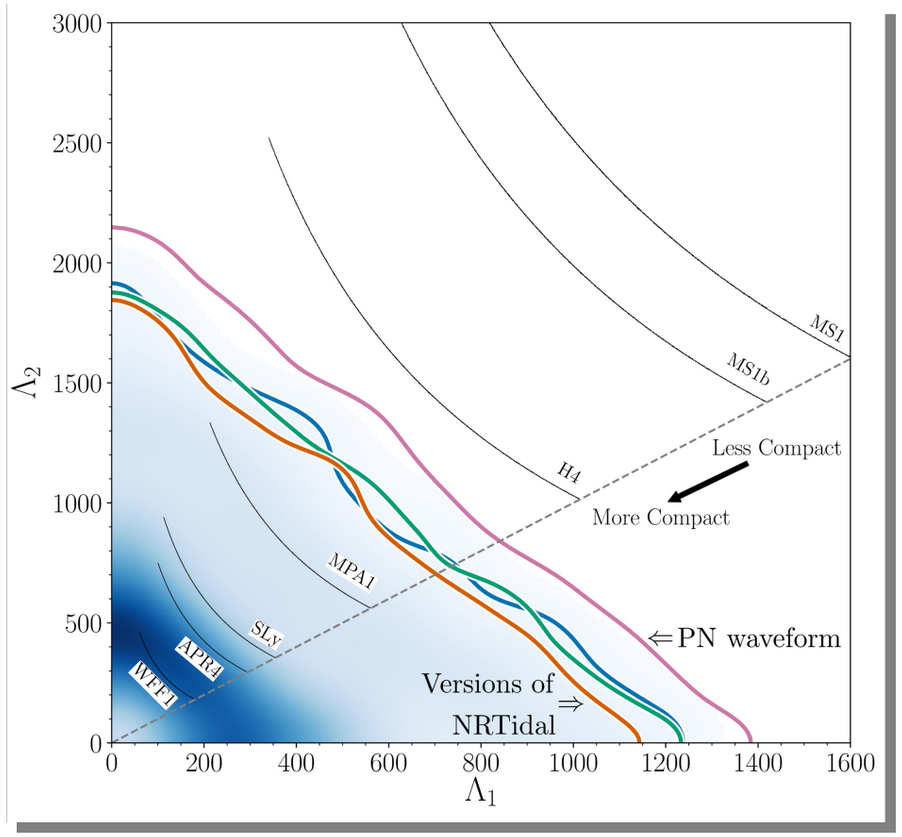




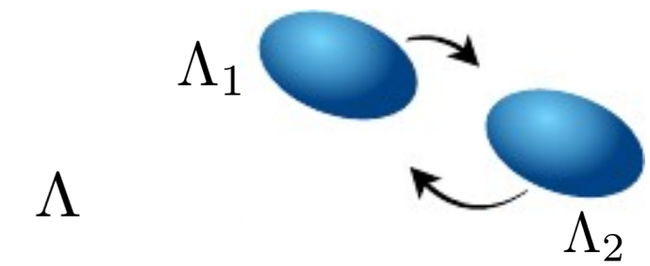
Pang et al., APJ 922 (2021) 1, 14

GW170817 - Tidal Effects

Determine the Equation of State: GW observations favor NSs with smaller radii



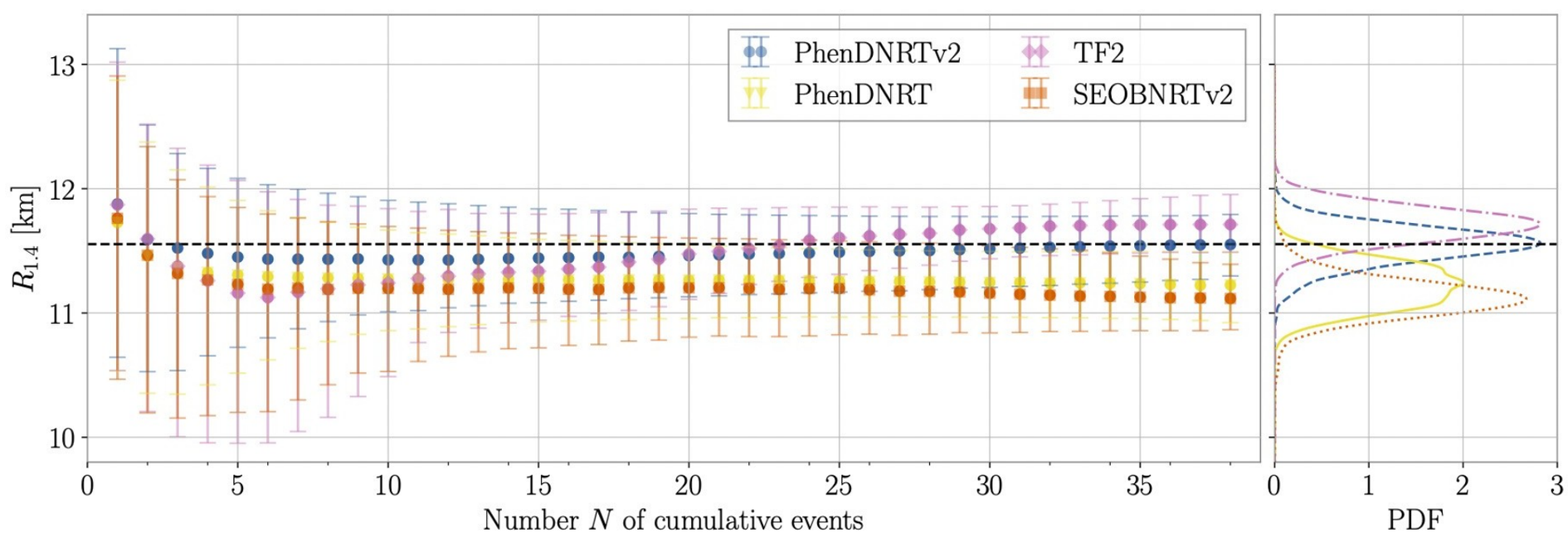
→ no assumption about the type of the compact object



determines tidal deformability

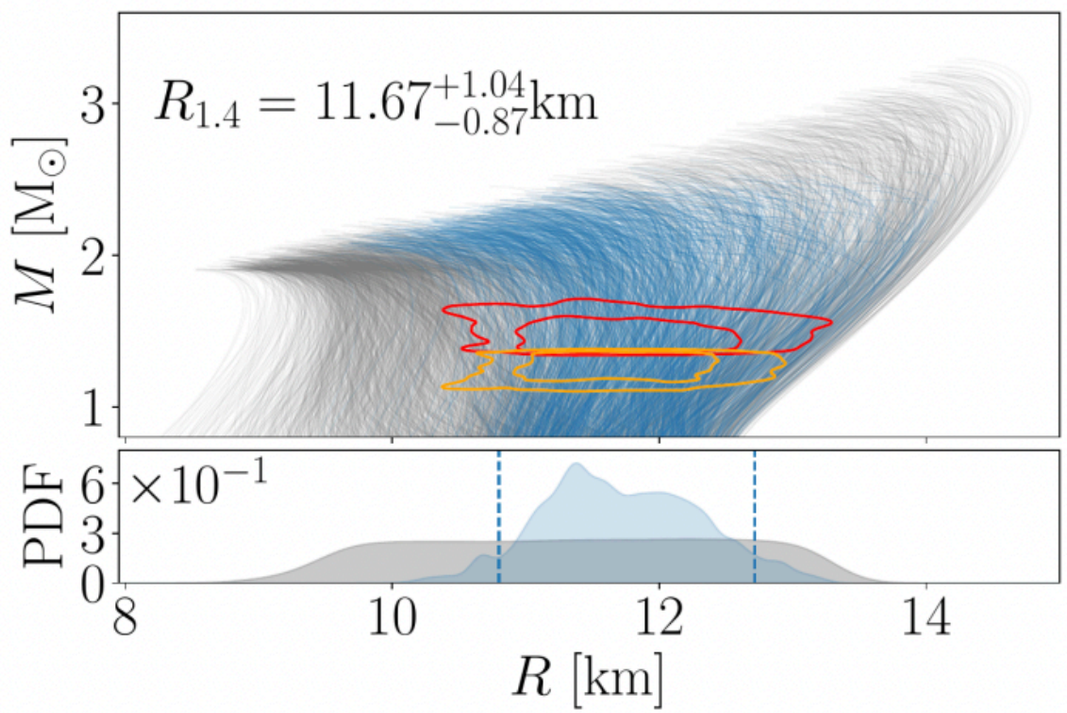
Phys.Rev. X9 (2019) 011001

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

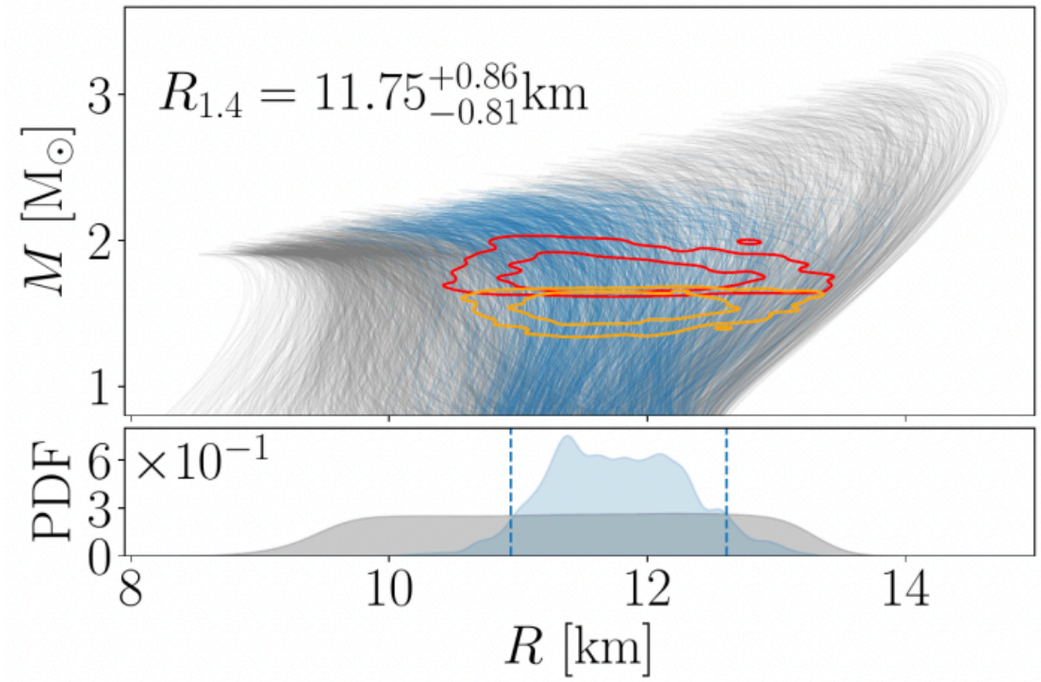


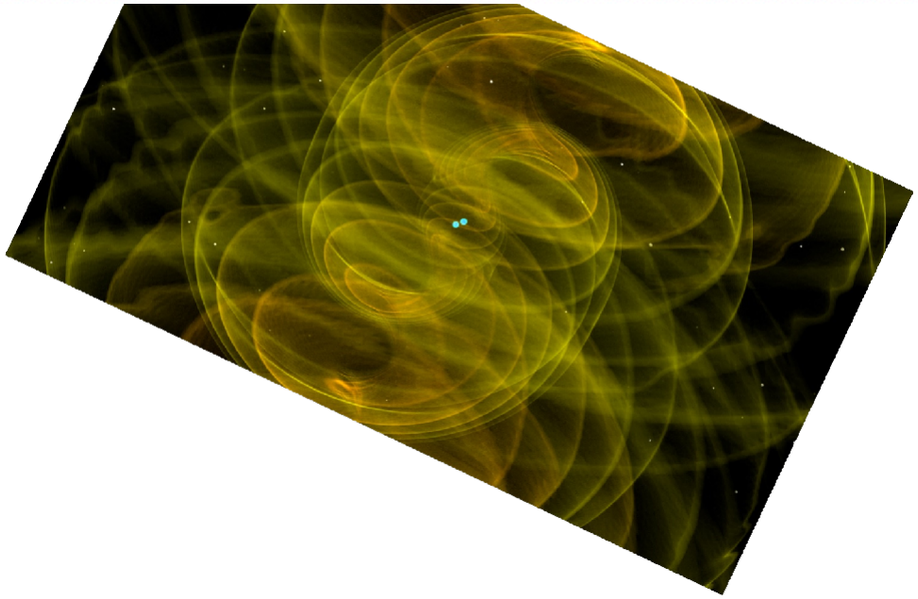
Gravitational-wave constraints

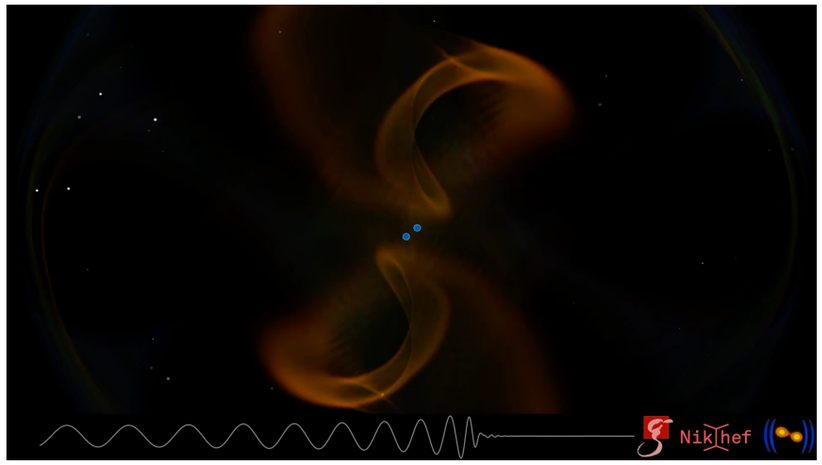
(D) GW170817:
reanalysis with
IMRPhenomPv2_NRTidalv2



(F) GW190425:
reanalysis with
IMRPhenomPv2_NRTidalv2

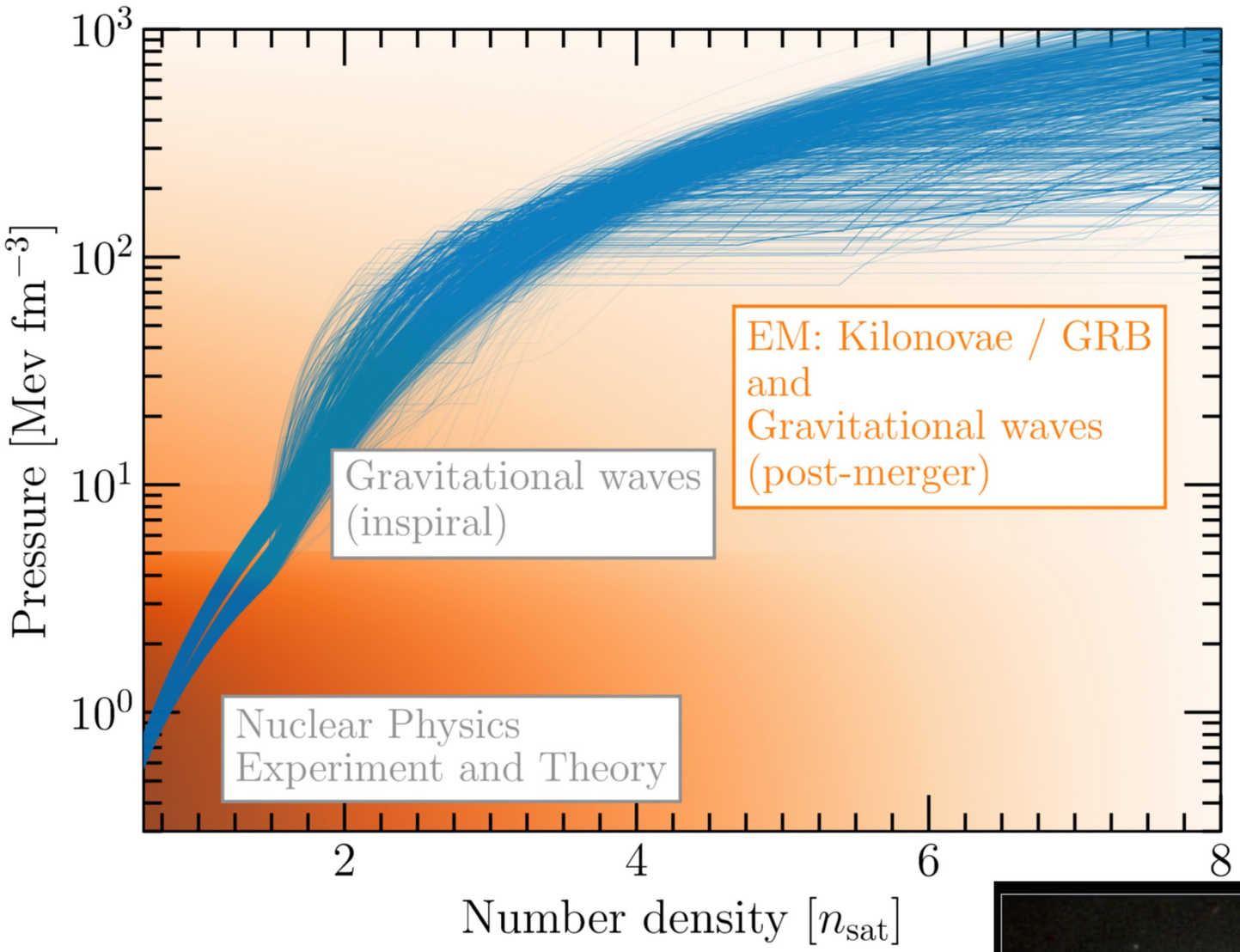


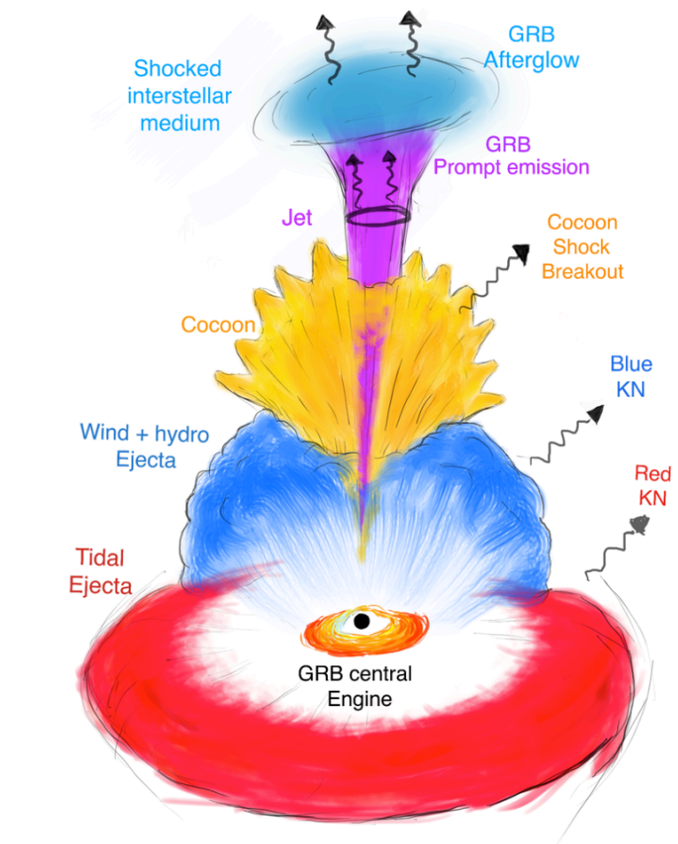


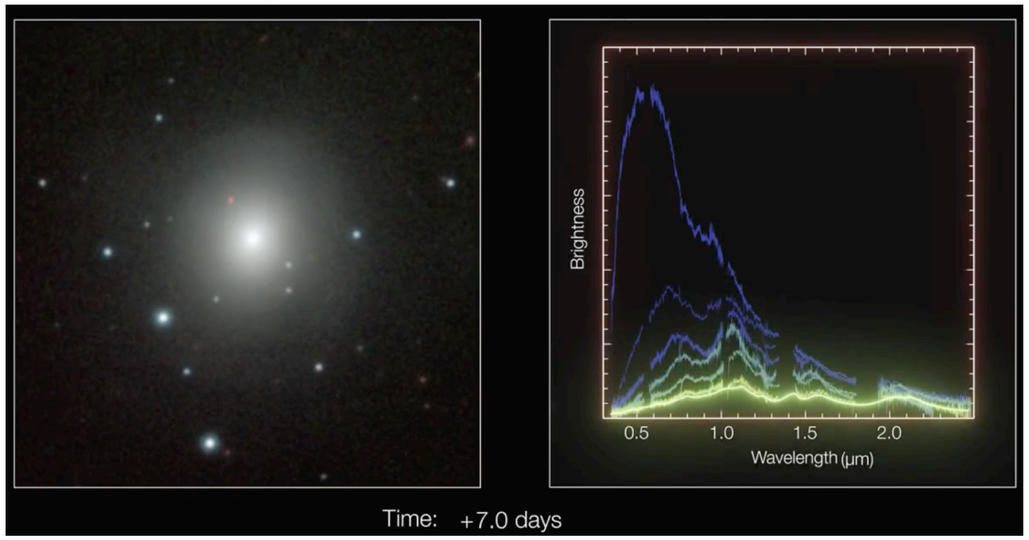


TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

The Experimental Messengers - EM

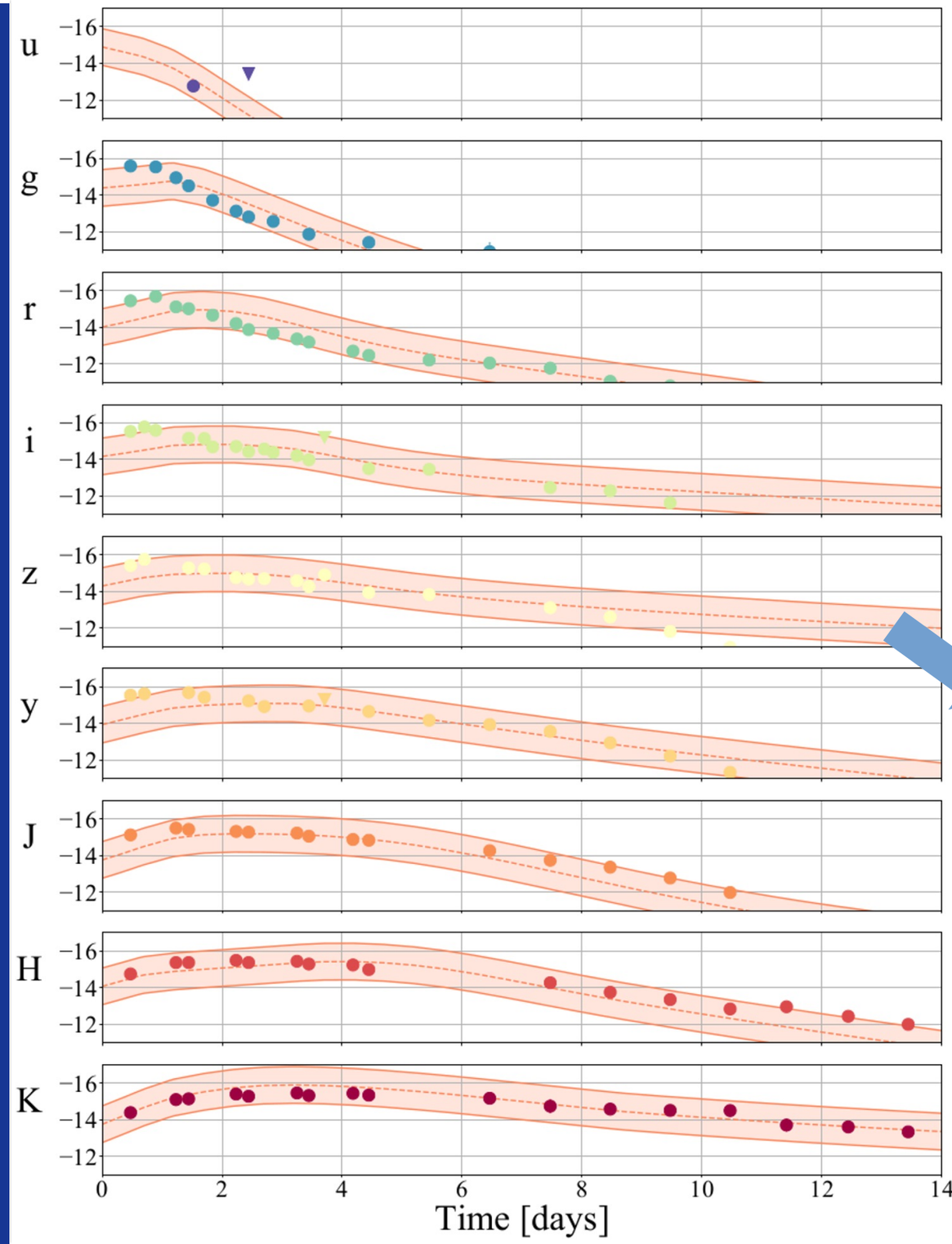






Pang et al., APJ 922 (2021) 1, 14

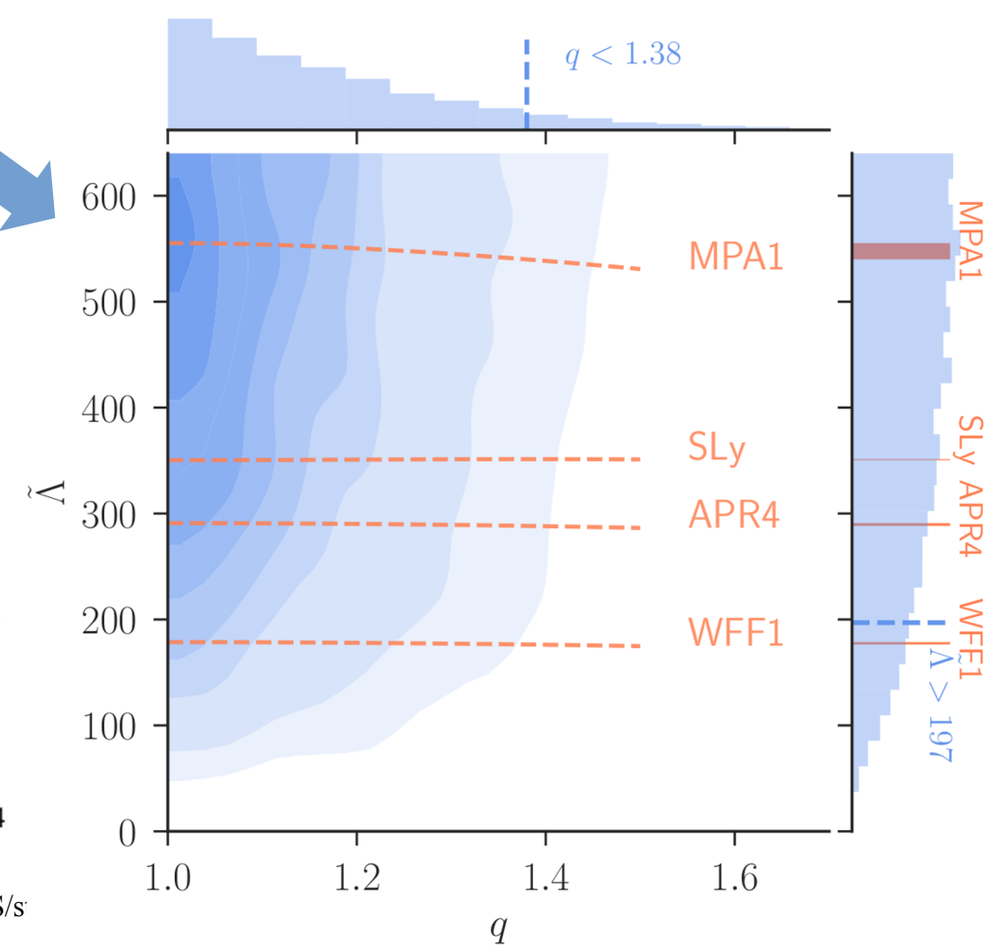
Electromagnetic Signals - Kilonova



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

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

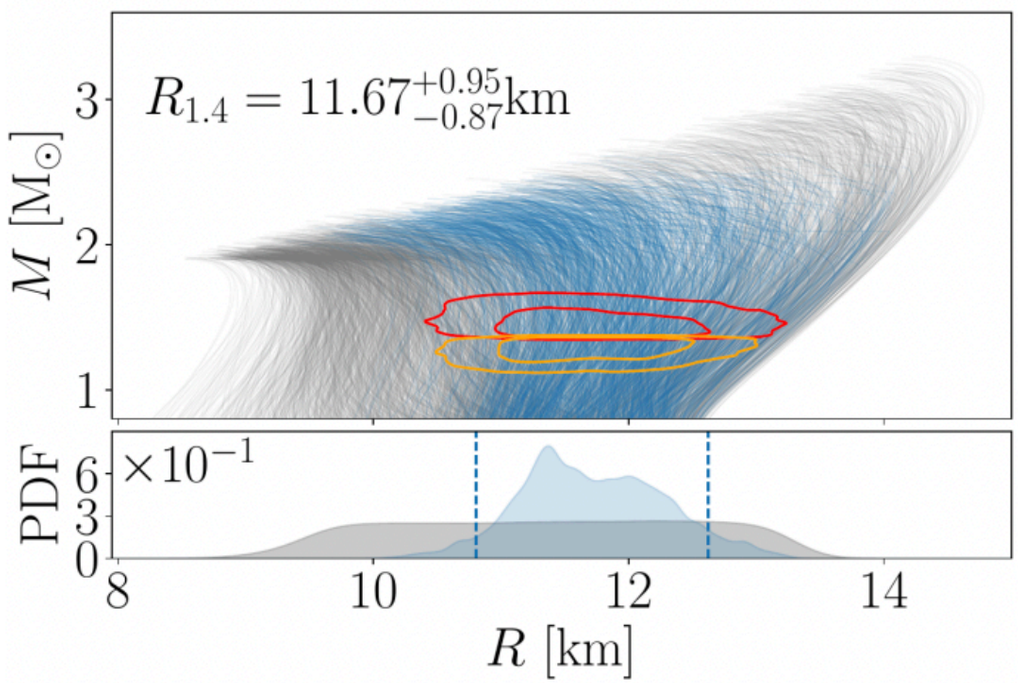
3.) link ejecta properties through numerical-relativity predictions to the binary properties



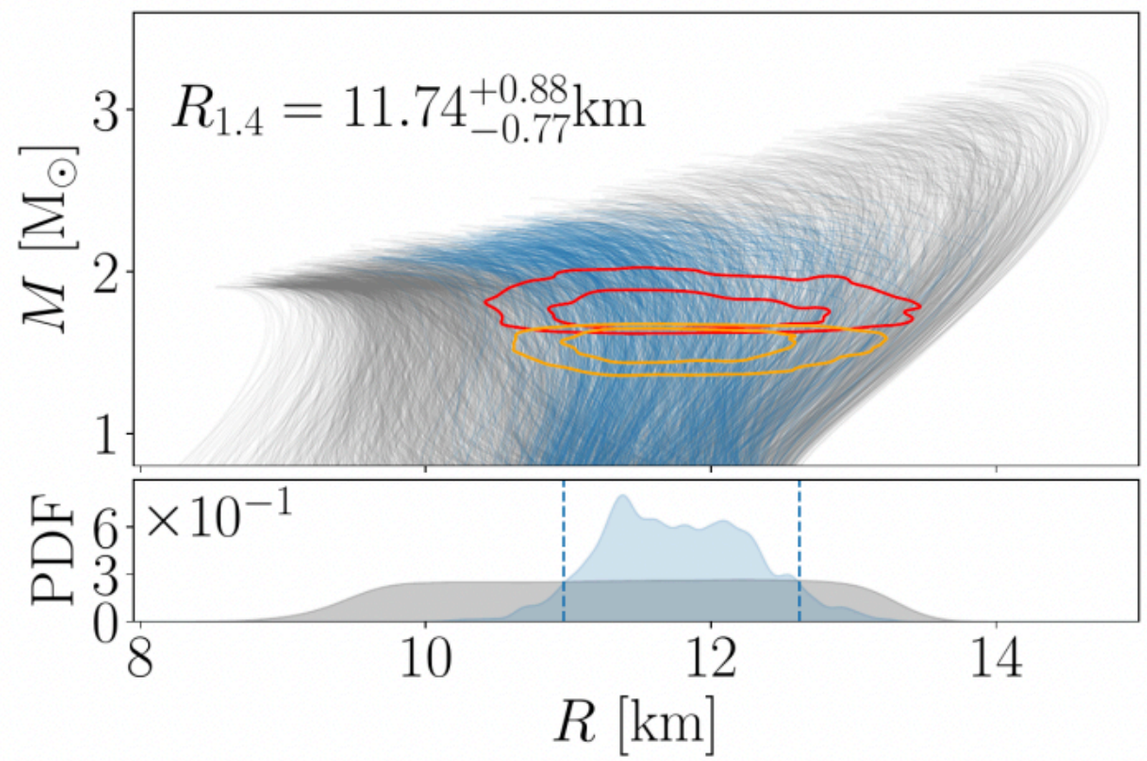
Coughlin, TD, et al., MNRAS/s

Electromagnetic Signals - Kilonova

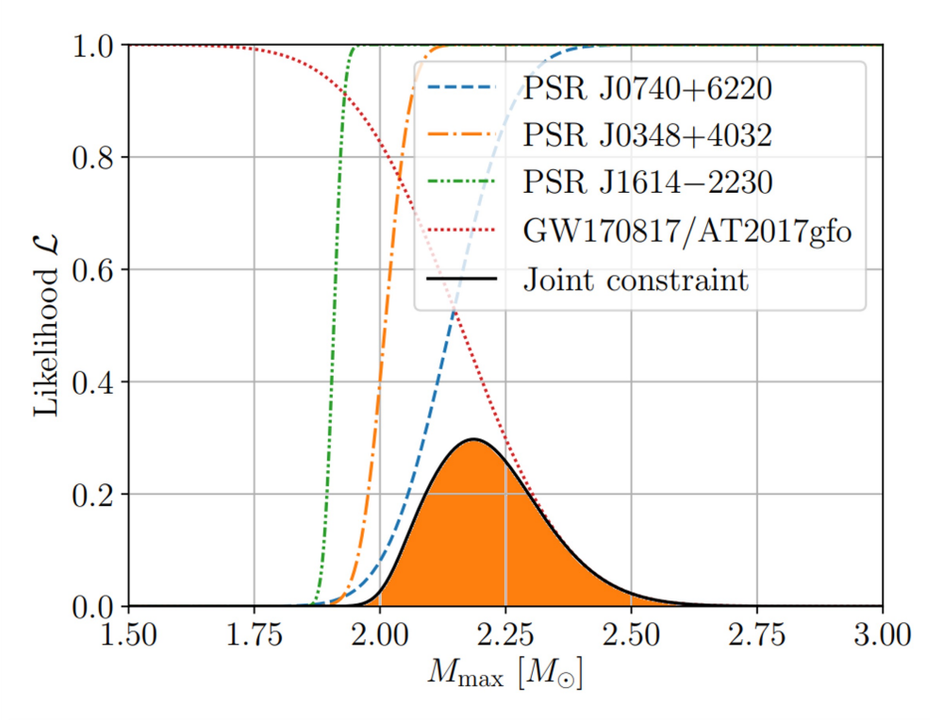
(E) AT2017gfo:
analysis of the observated lightcurves



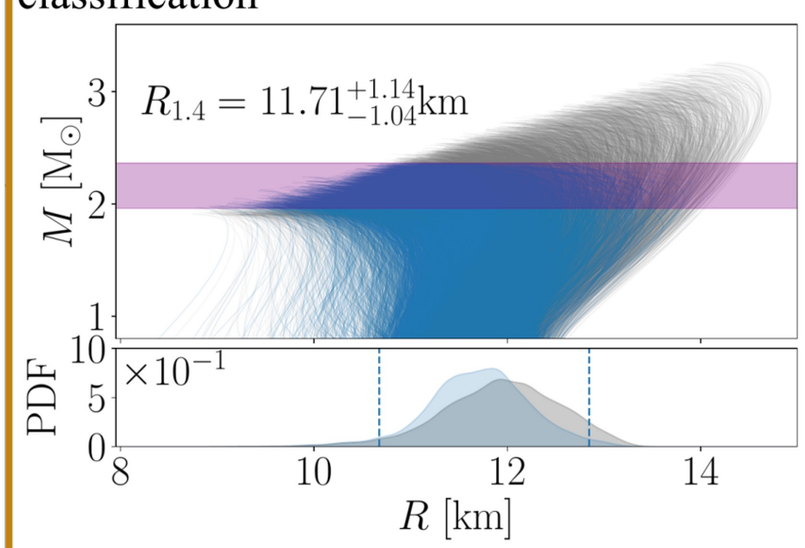
(G) No EM detection for GW190425:



Electromagnetic Signals - Mass Measurements



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



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

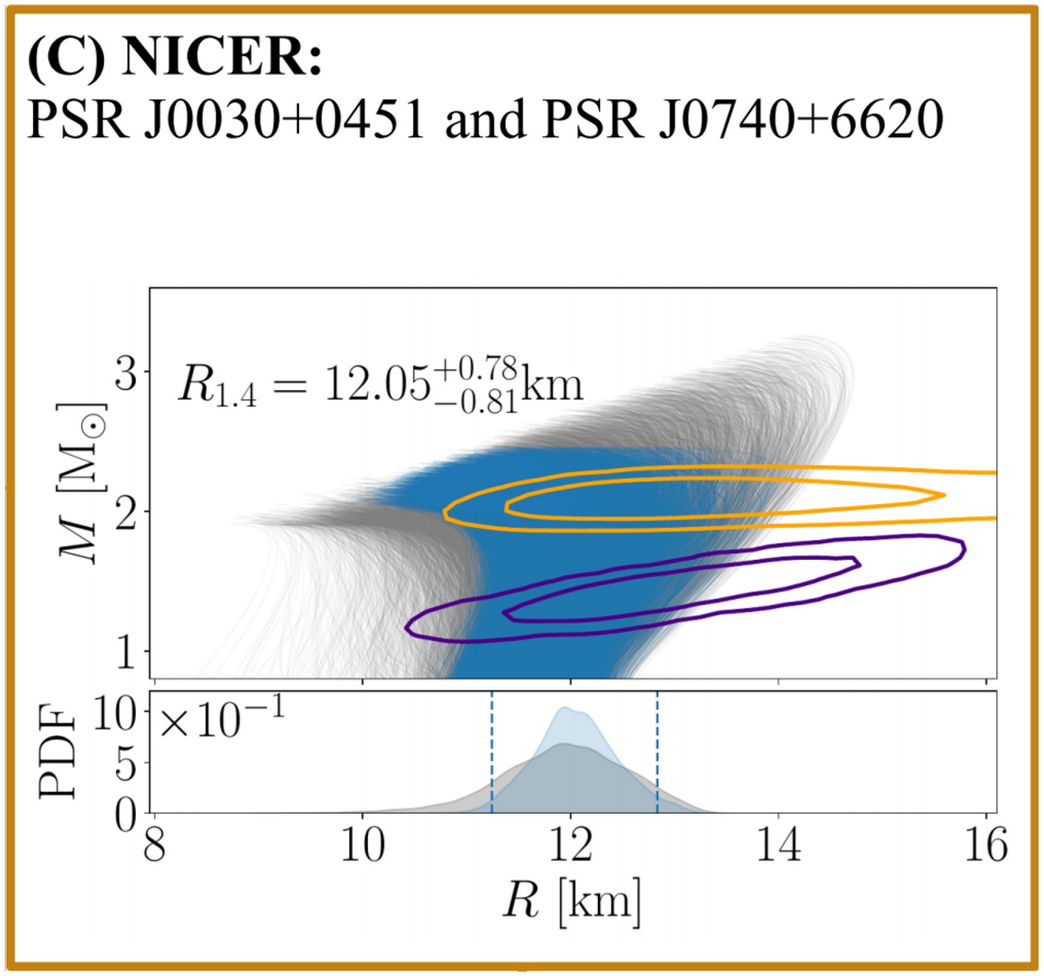
PSR J0348+4032
J. Antoniadis, et al., Science 340, 6131 (2013).

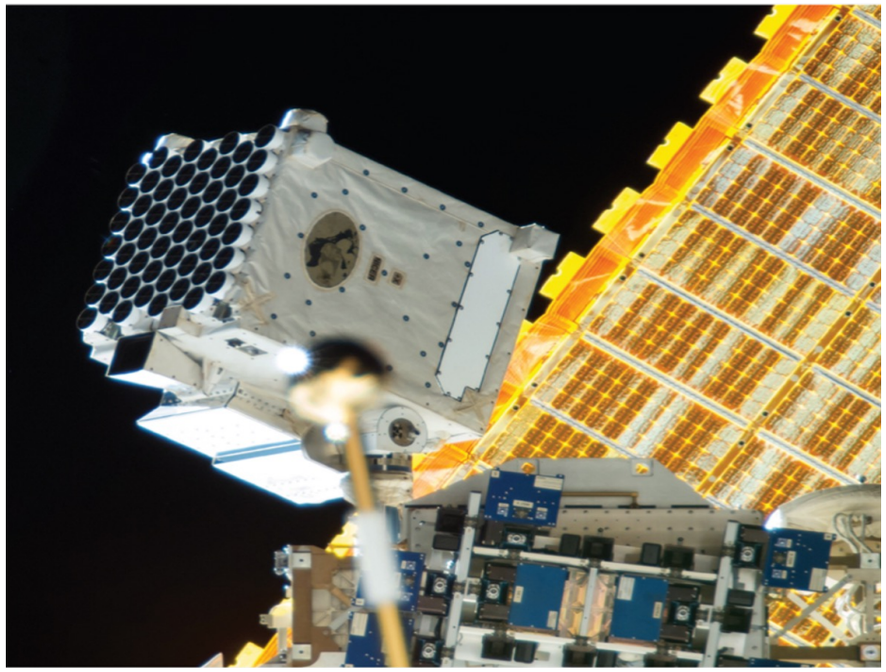
PSR J1614-2230
Z. Arzoumanian, et al., Astrophys. J. Suppl. 235, 37 (2018)

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

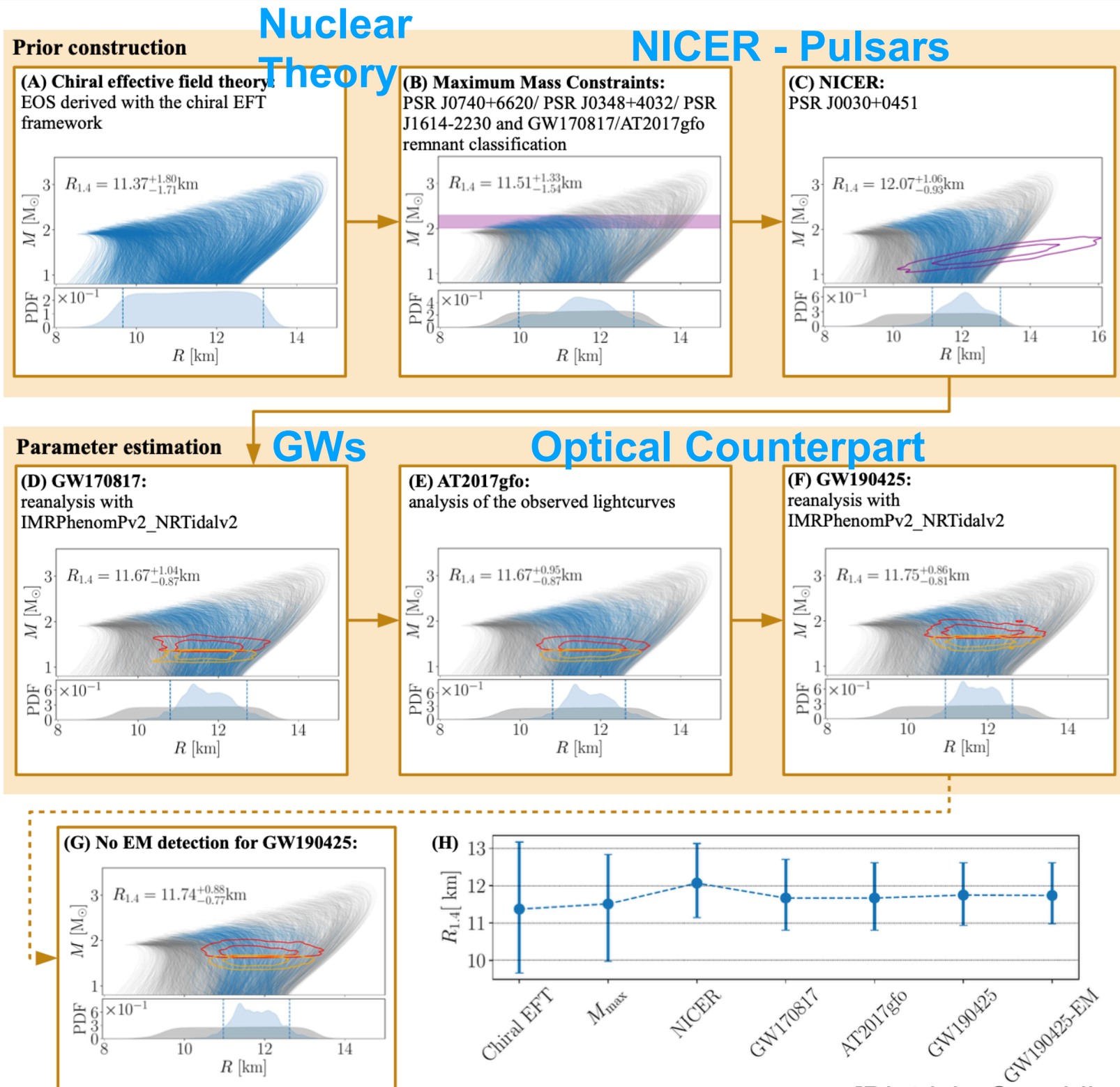
e.g.
Margalit & Metzger, APJL 850 (2017) 2, L19,
Ruiz et al., PRD 97 (2018) 2, 021501
Rezzolla et al., APJL 852 (2018) 2, L25
Shibata et al., PRD 100 (2019) 2, 023015

Electromagnetic Signals - NICER Mass-Radius





MMA Equation of State Constraints



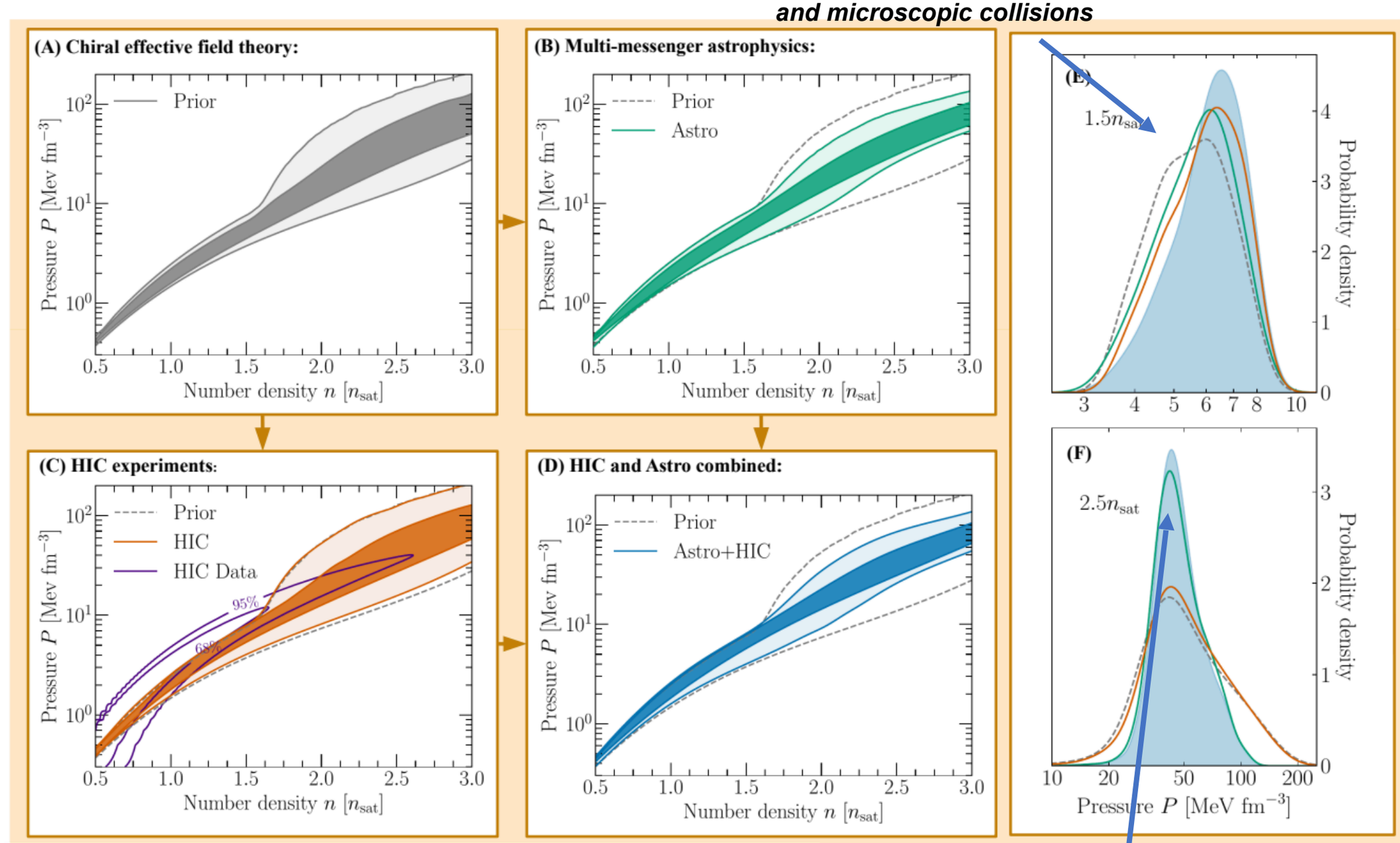
Also many others!

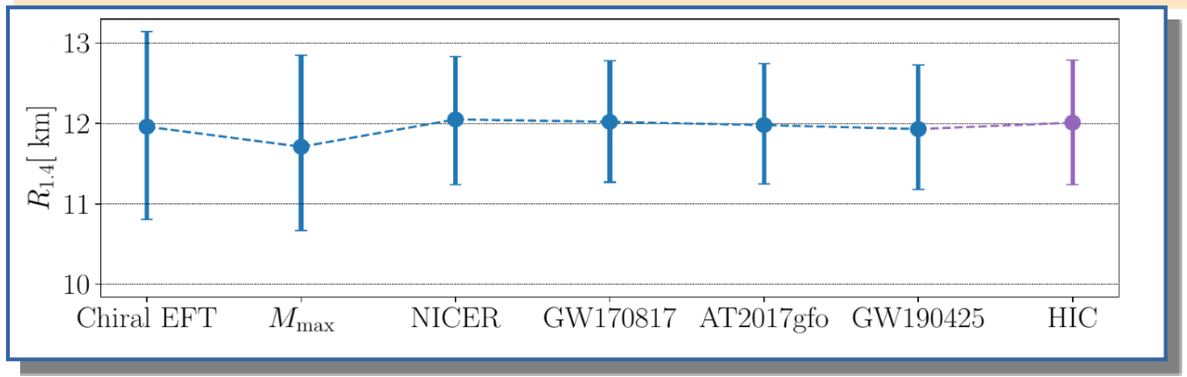
- Breschi et al., PRD 104 (2021) 4, 042001
- Raaijmakers et al., APJ 922 (2021) 2, 269
- Nicholl et al., MNRAS 505 (2021) 2, 3016-3032
- Gosh et al., Front.Astron.Space Sci. 9 (2022) 864294

[Dietrich, Coughlin, Pang+2020, Science]

Equation of State - Inclusion of HIC

Good agreement between macroscopic and microscopic collisions





high-density information from astrophysical studies

[Huth+2022, Nature]

A nuclear physics and multi-messenger framework (NMMA)

github.com/nuclear-multimessenger-astronomy

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Nuclear Multimessenger Astronomy

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0 0 0 0 Updated on 2 Feb

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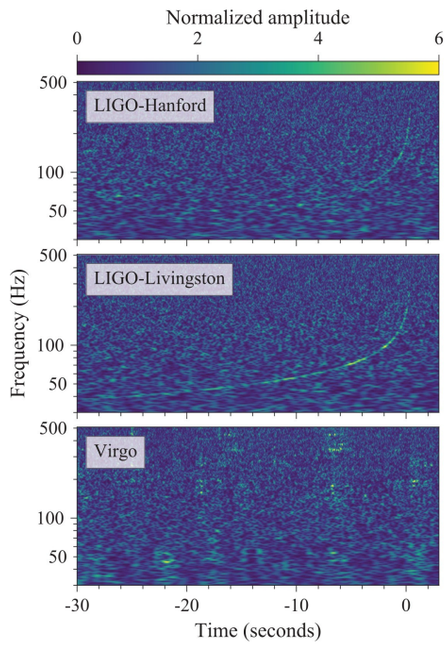
Top languages

Python

NMMA - Consider using it!



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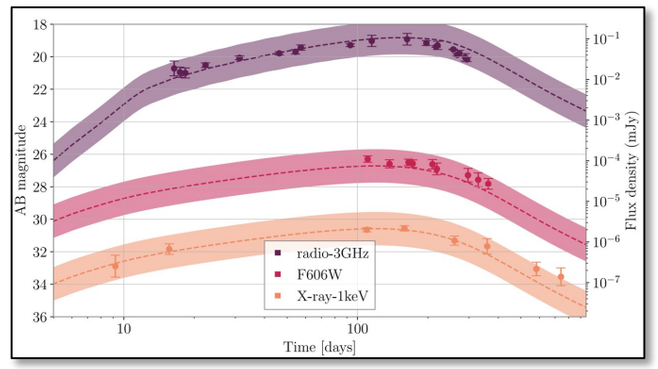

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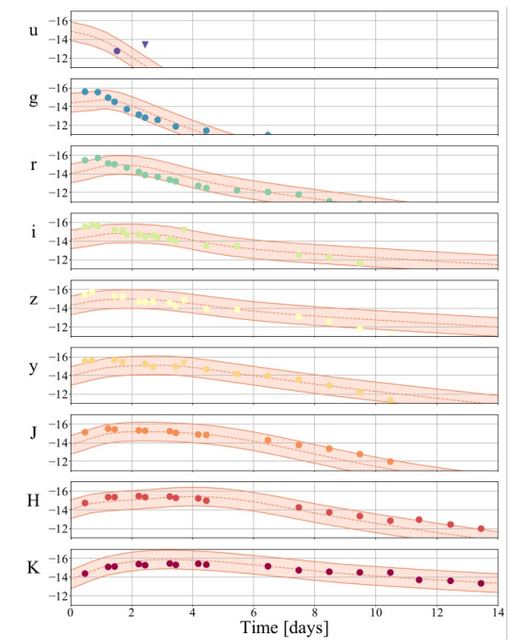
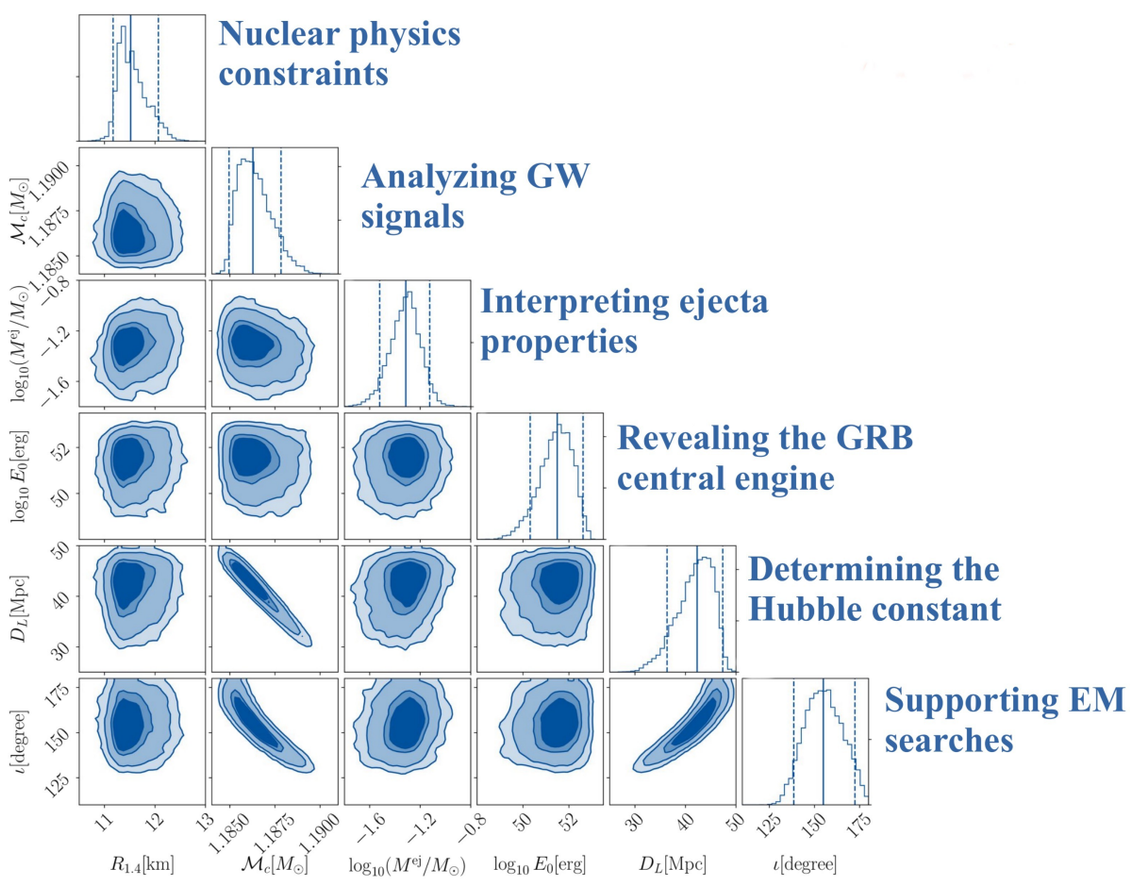
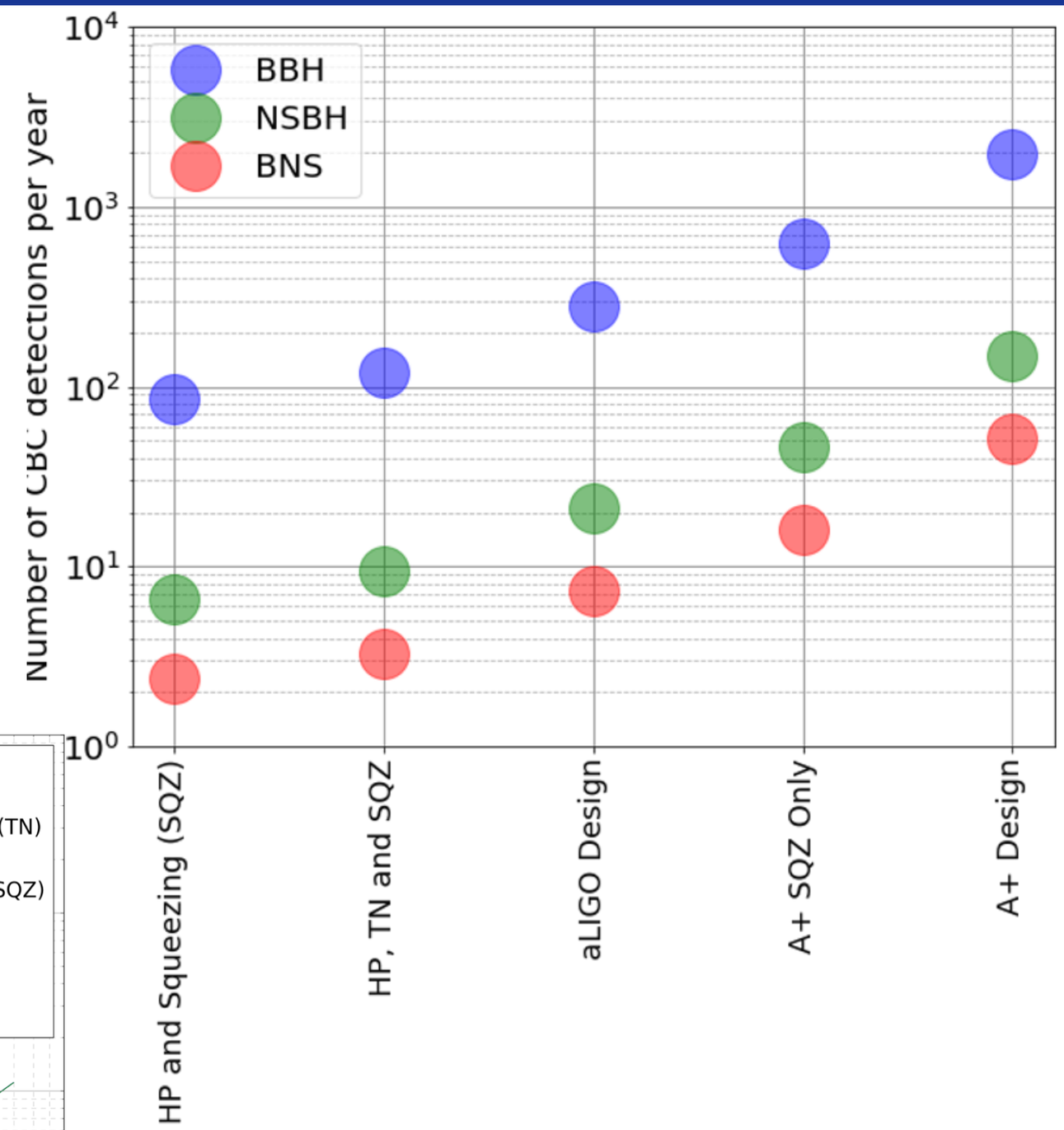


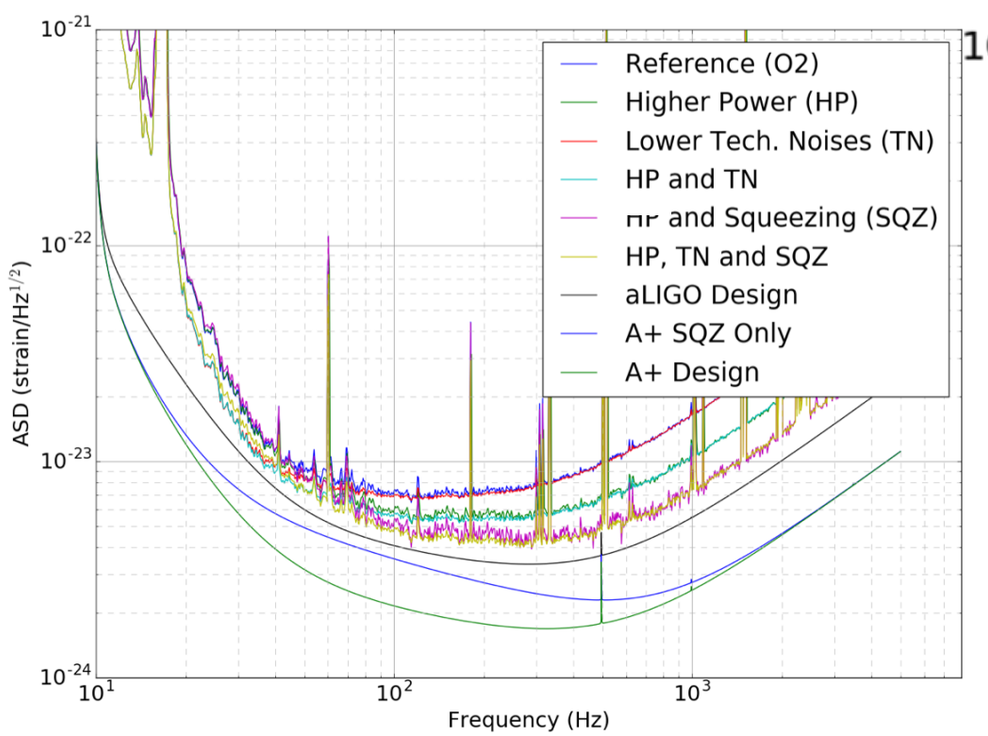


- incorporation of nuclear-physics information
- <u>simultaneous</u> analysis of GW, kilonova, and GRB afterglow
- (some) unit testing and (growing) documentation!
- Used in online kilonova searches
- HPC facilities needed

A New Era

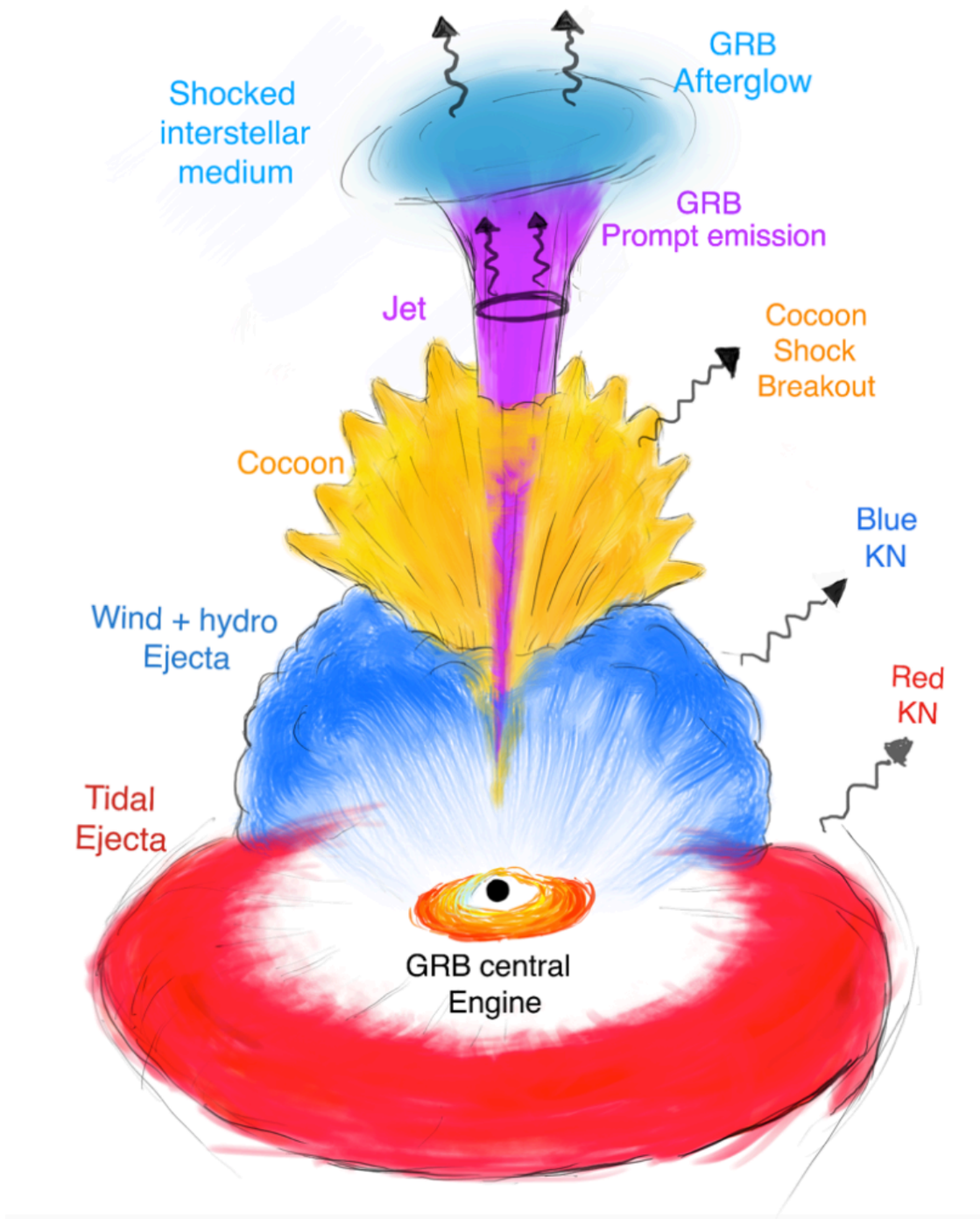
Many detections are coming





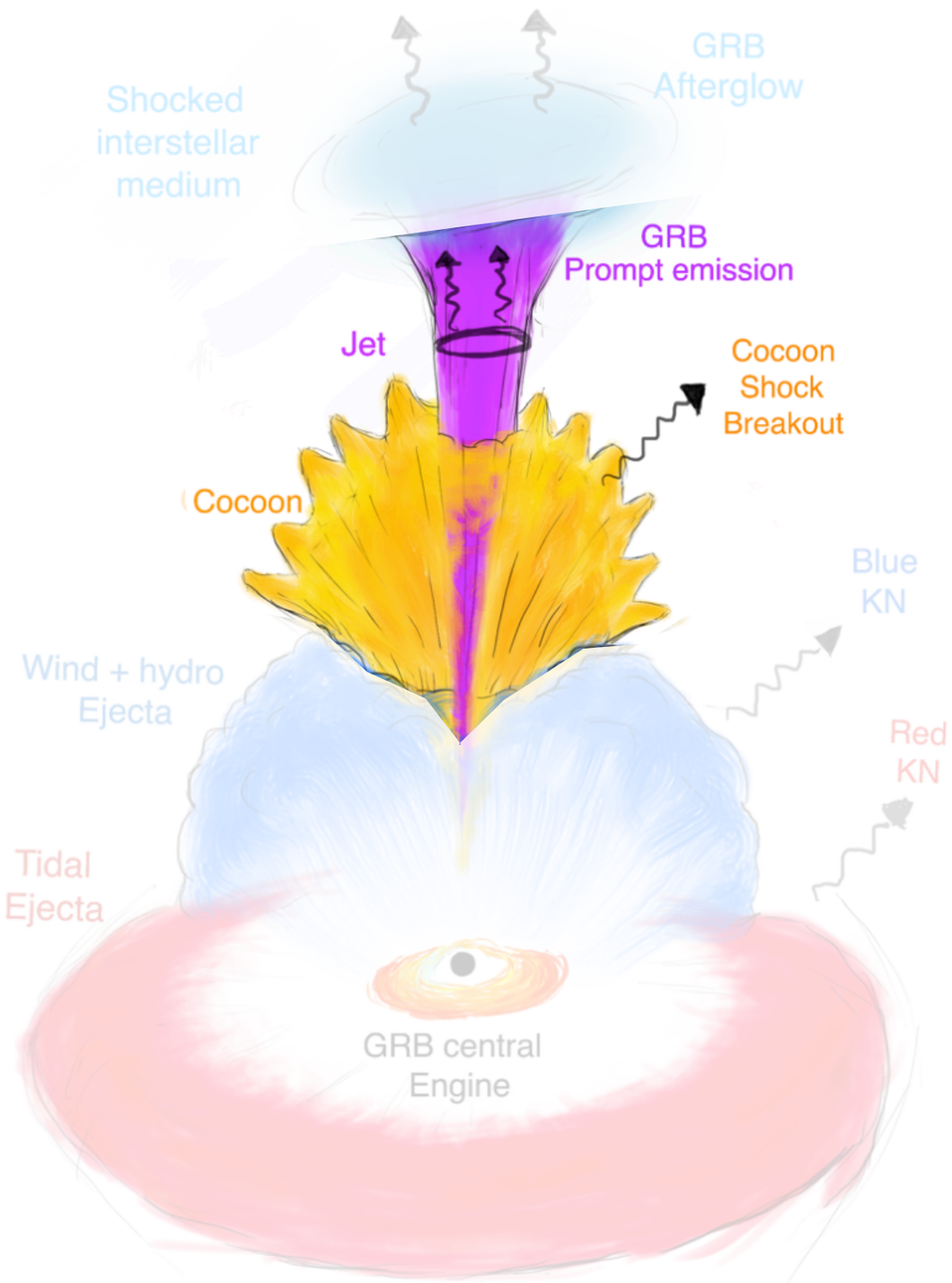
Thank you!

Compact Binary Coalescences



[Ascenzi+, arXiv:2011.04001]

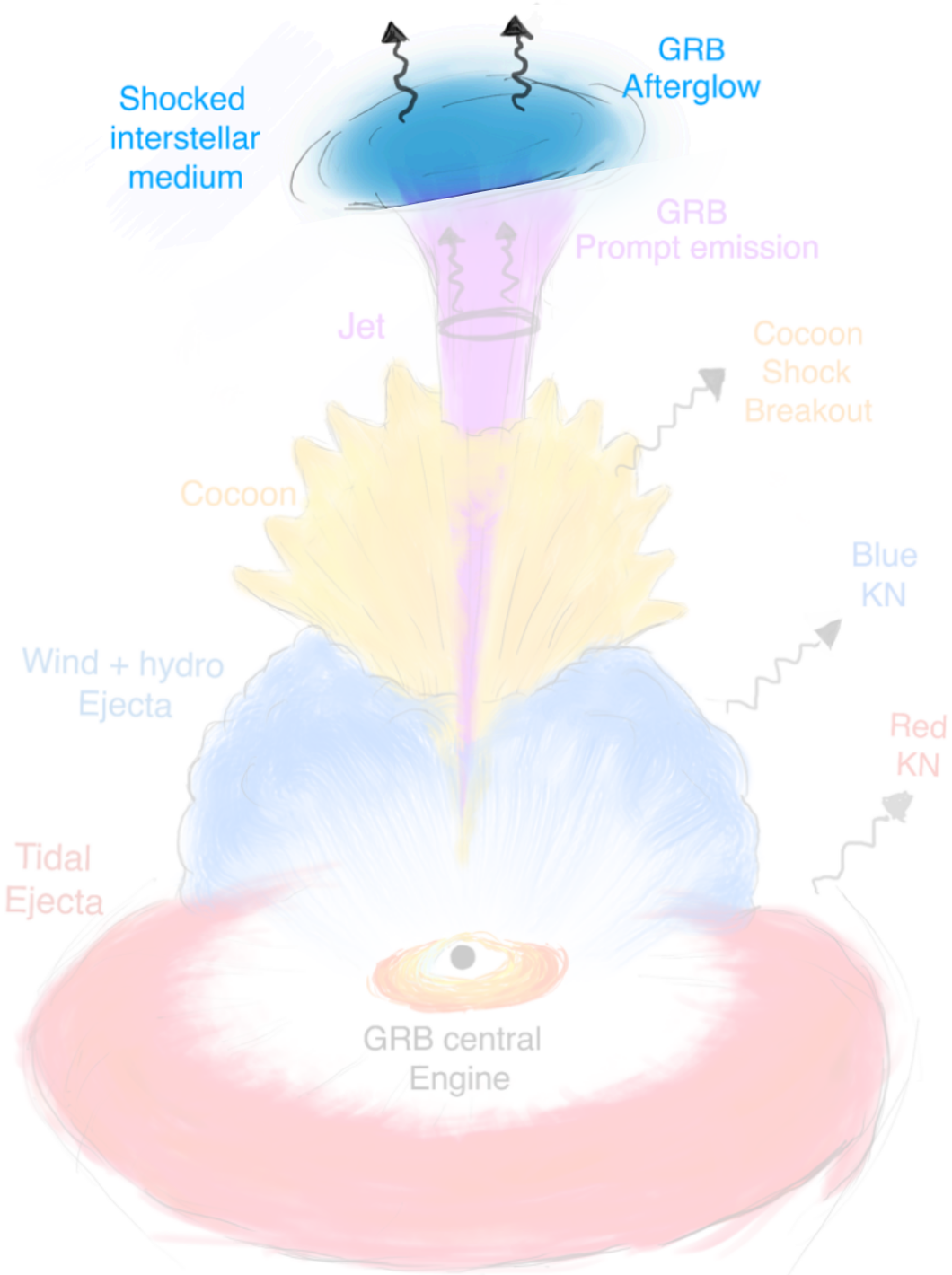
Compact Binary Coalescences



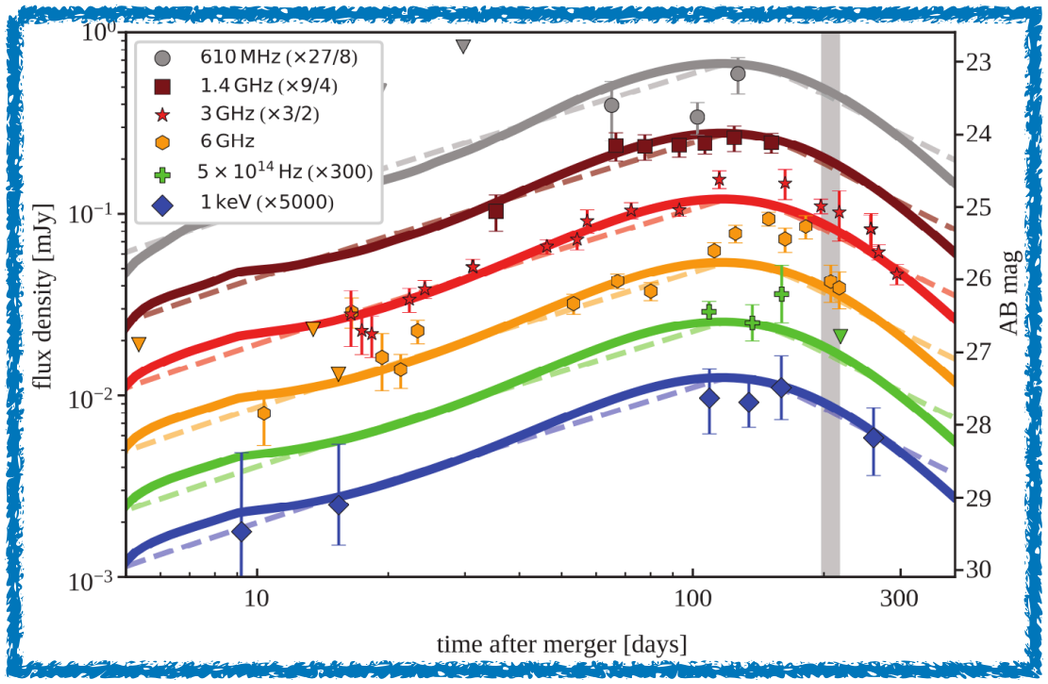
Gamma Ray Burst (GRB)

[Ascenzi+, arXiv:2011.04001]

Compact Binary Coalescences

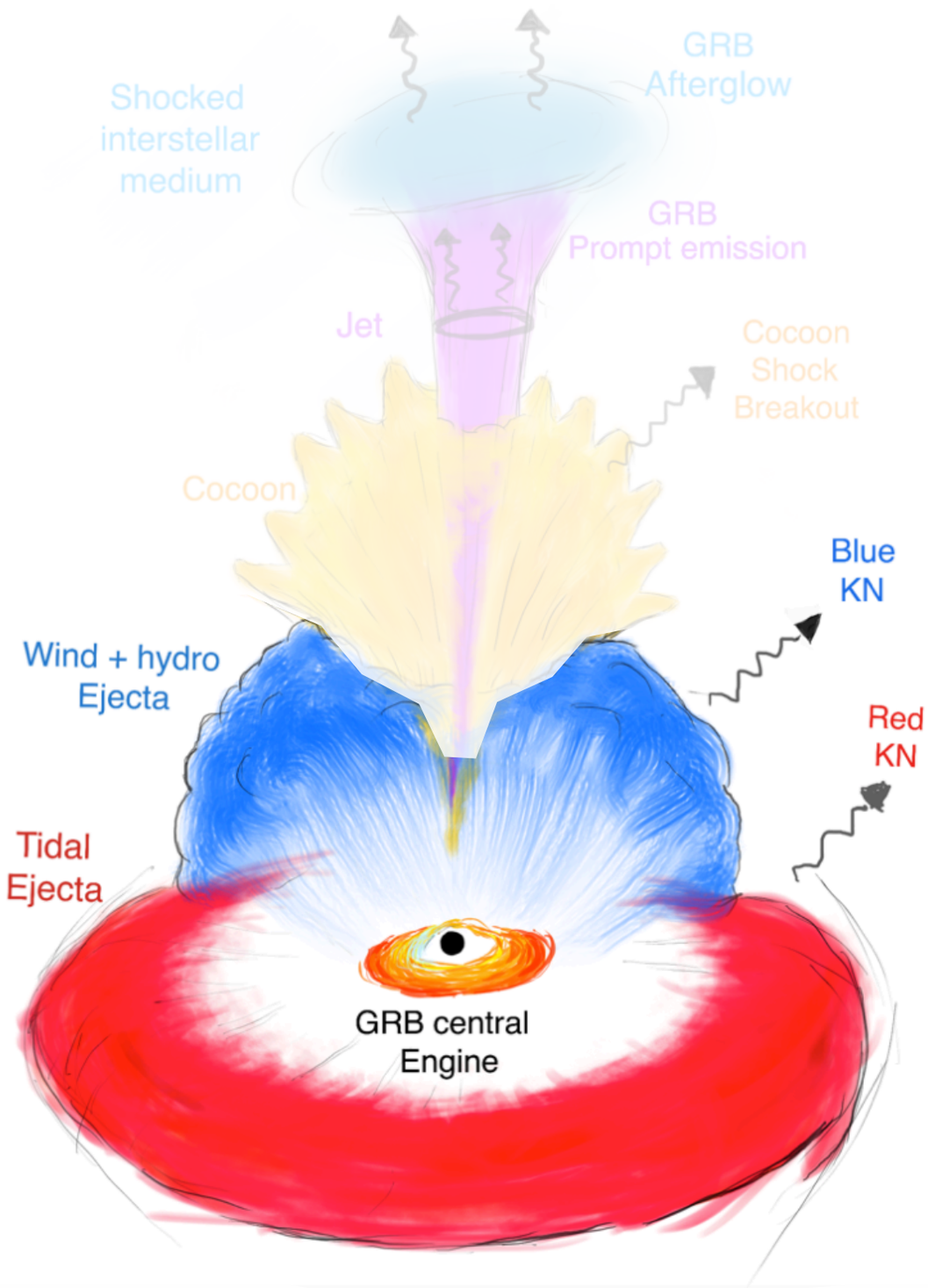


GRB Afterglow



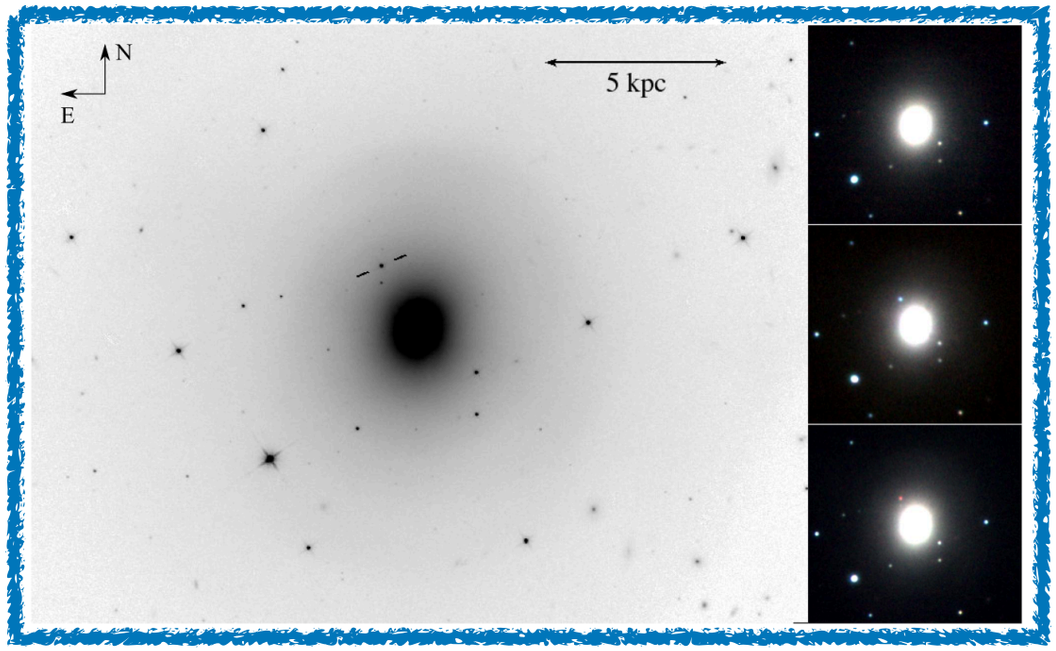
[Ascenzi+, arXiv:2011.04001]

Compact Binary Coalescences



[Ascenzi+, arXiv:2011.04001]

Kilonova



[Tanvir+2017, ApJ]

Kilonovae

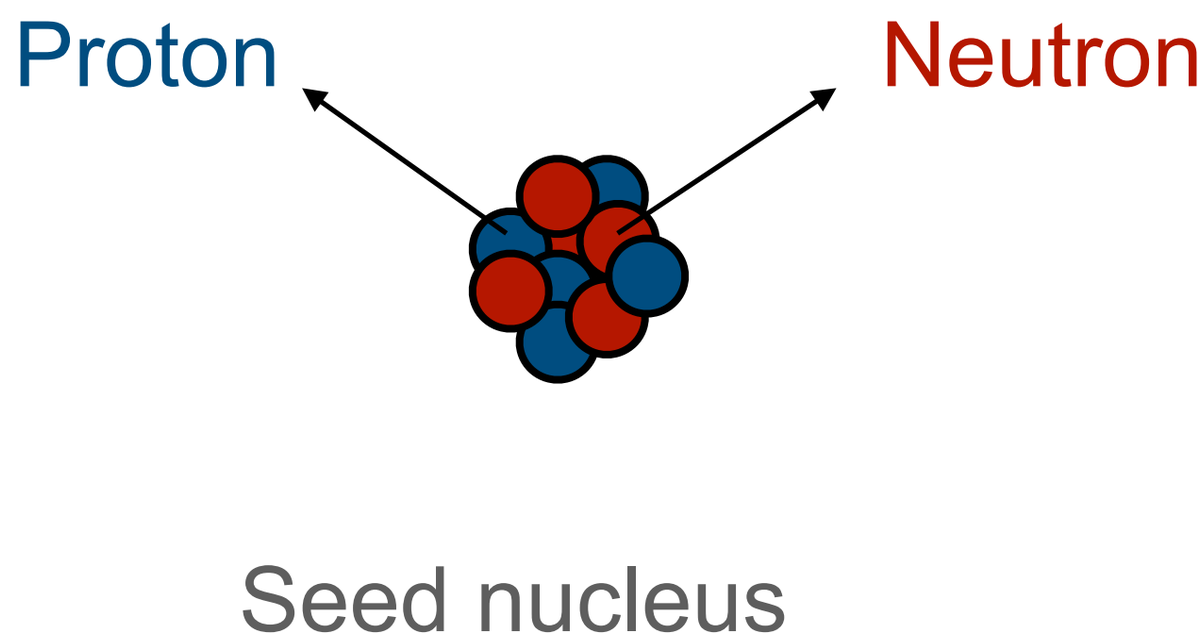
"Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei"

[Metzger+2010, MNRAS]

Kilonovae

"Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei"

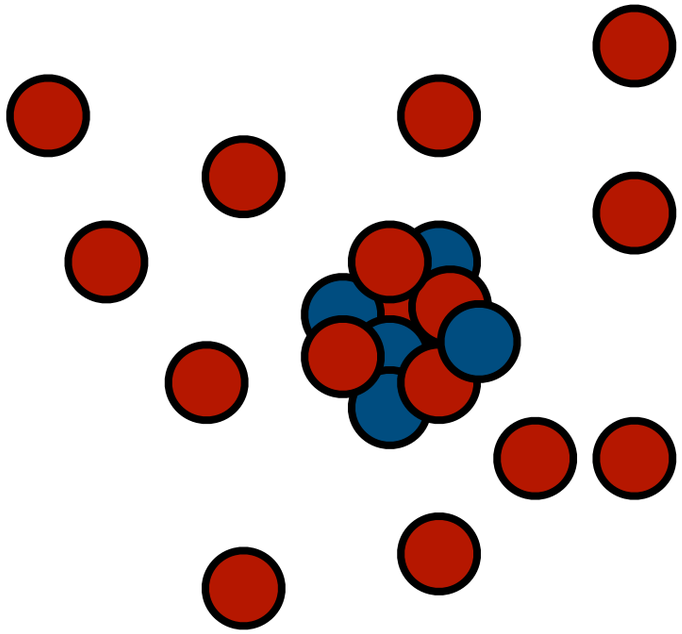
[Metzger+2010, MNRAS]



Kilonovae

"Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei"

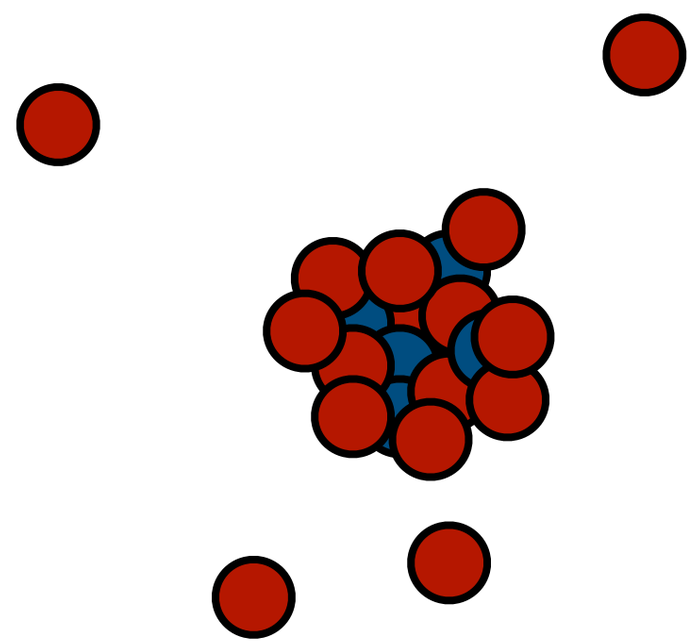
[Metzger+2010, MNRAS]



Kilonovae

"Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei"

[Metzger+2010, MNRAS]

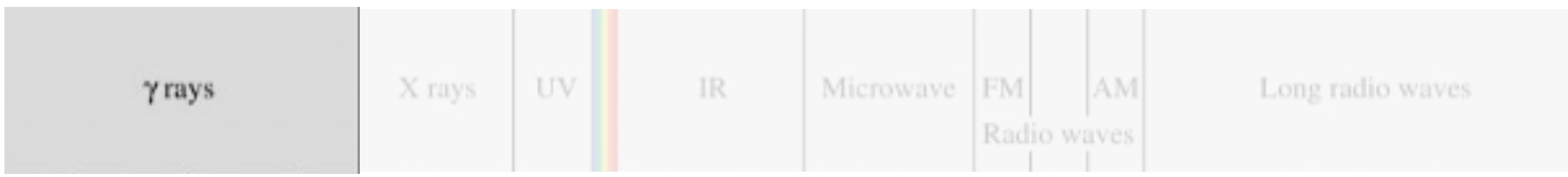


Neutron capture via r-process

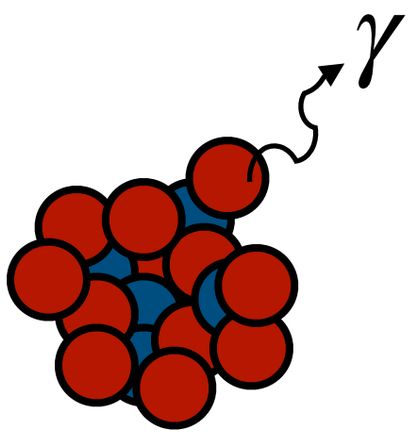
Kilonovae

"Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei"

[Metzger+2010, MNRAS]



—> Increasing wavelength

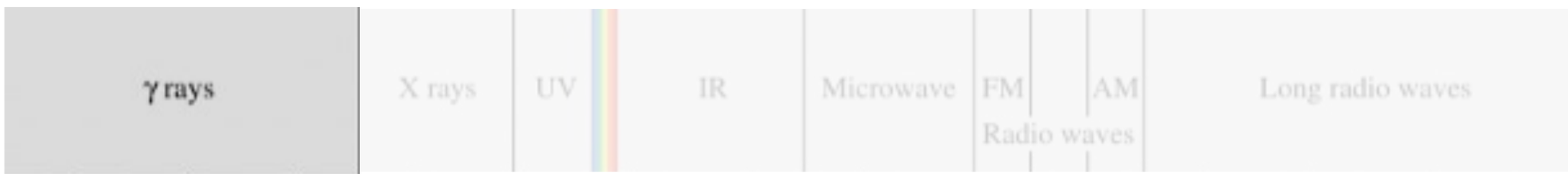


Unstable nuclei -> radioactive decay -> γ photons

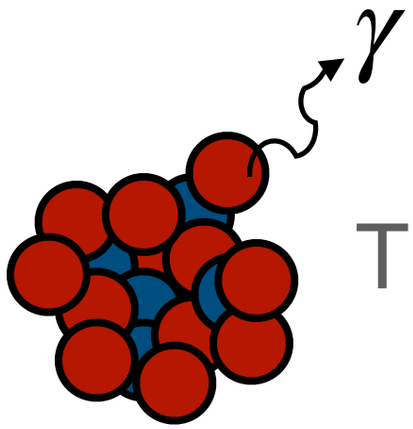
Kilonovae

"Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei"

[Metzger+2010, MNRAS]



—> Increasing wavelength



T ~ 10 000 K @ 1 day

γ photons thermalize within the dense ejected material

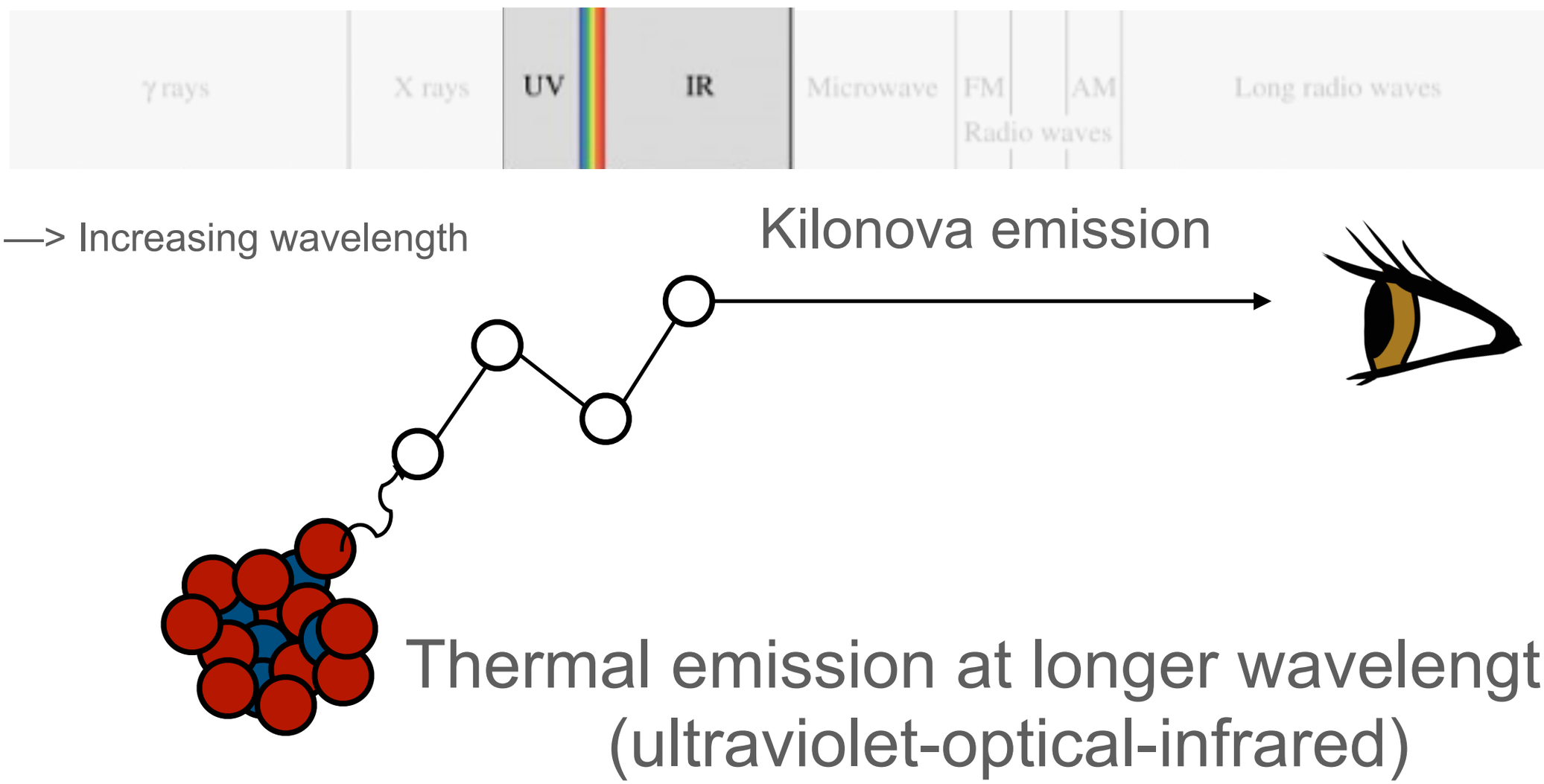
->

setting the temperature

Kilonovae

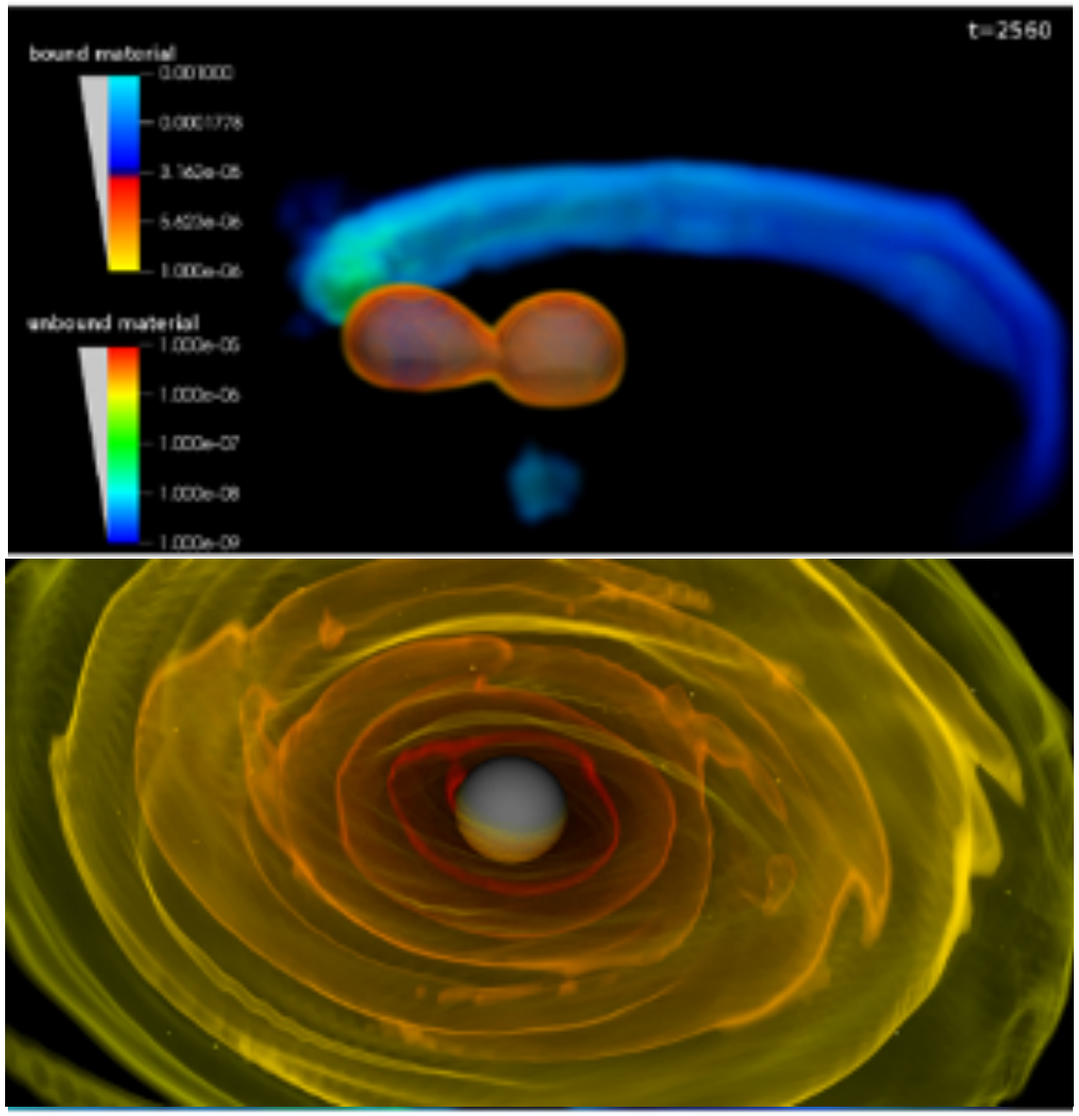
"Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei"

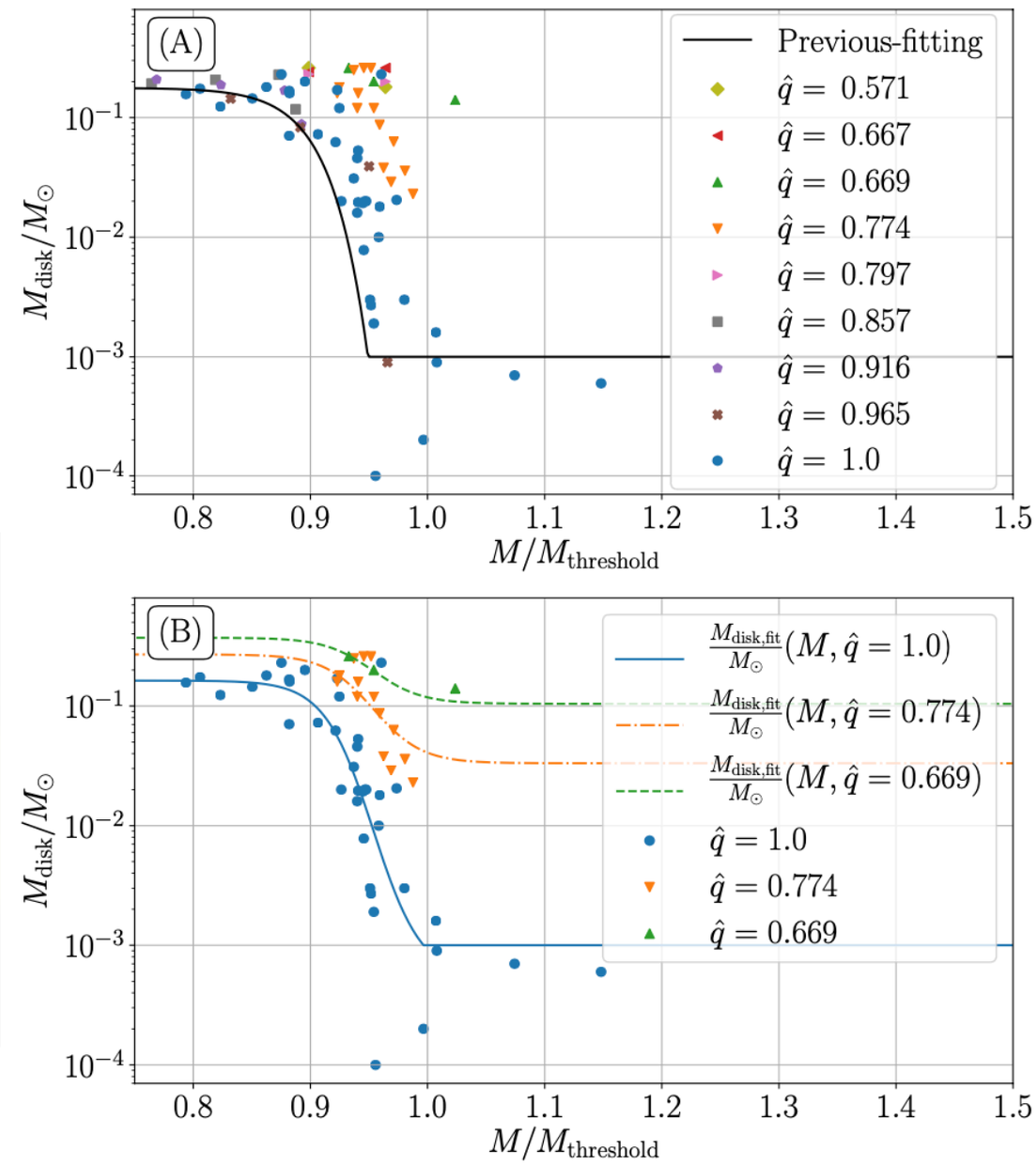
[Metzger+2010, MNRAS]



Matter and GW Simulations

Dynamical Ejecta



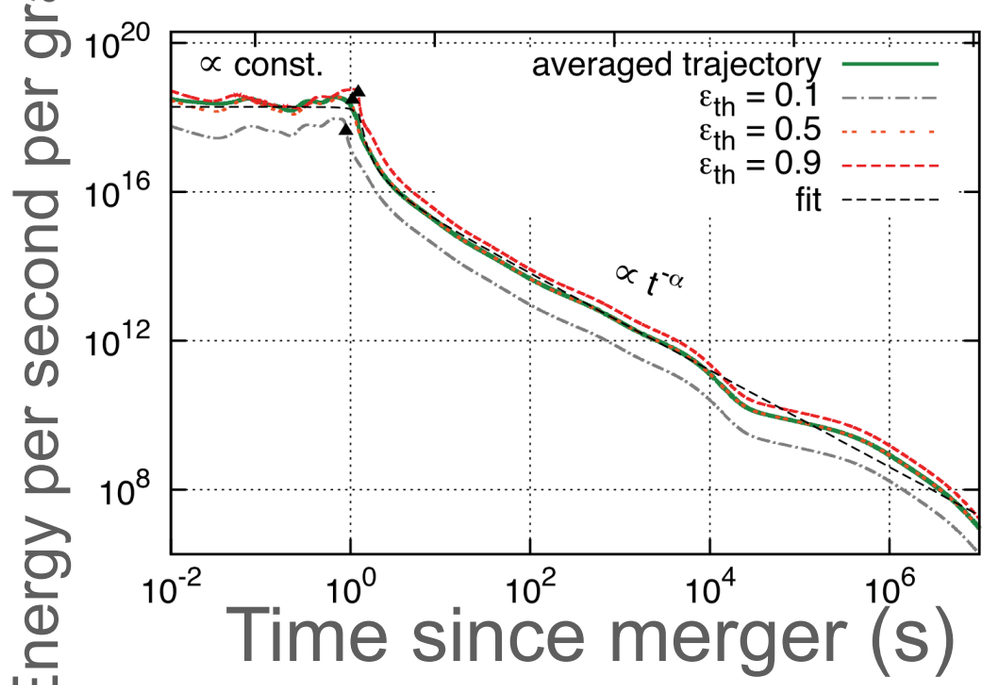


Disk Winds

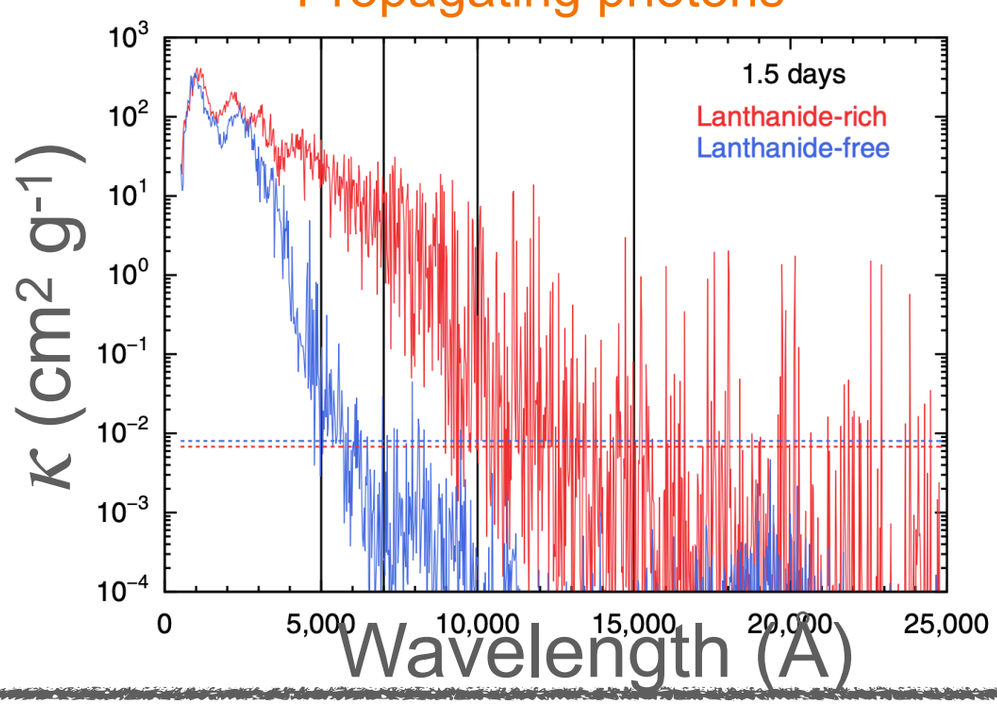
[Dietrich, Coughlin, Pang+2020, Science]

Combine Predictions with Radiative Transfer

Creating photons

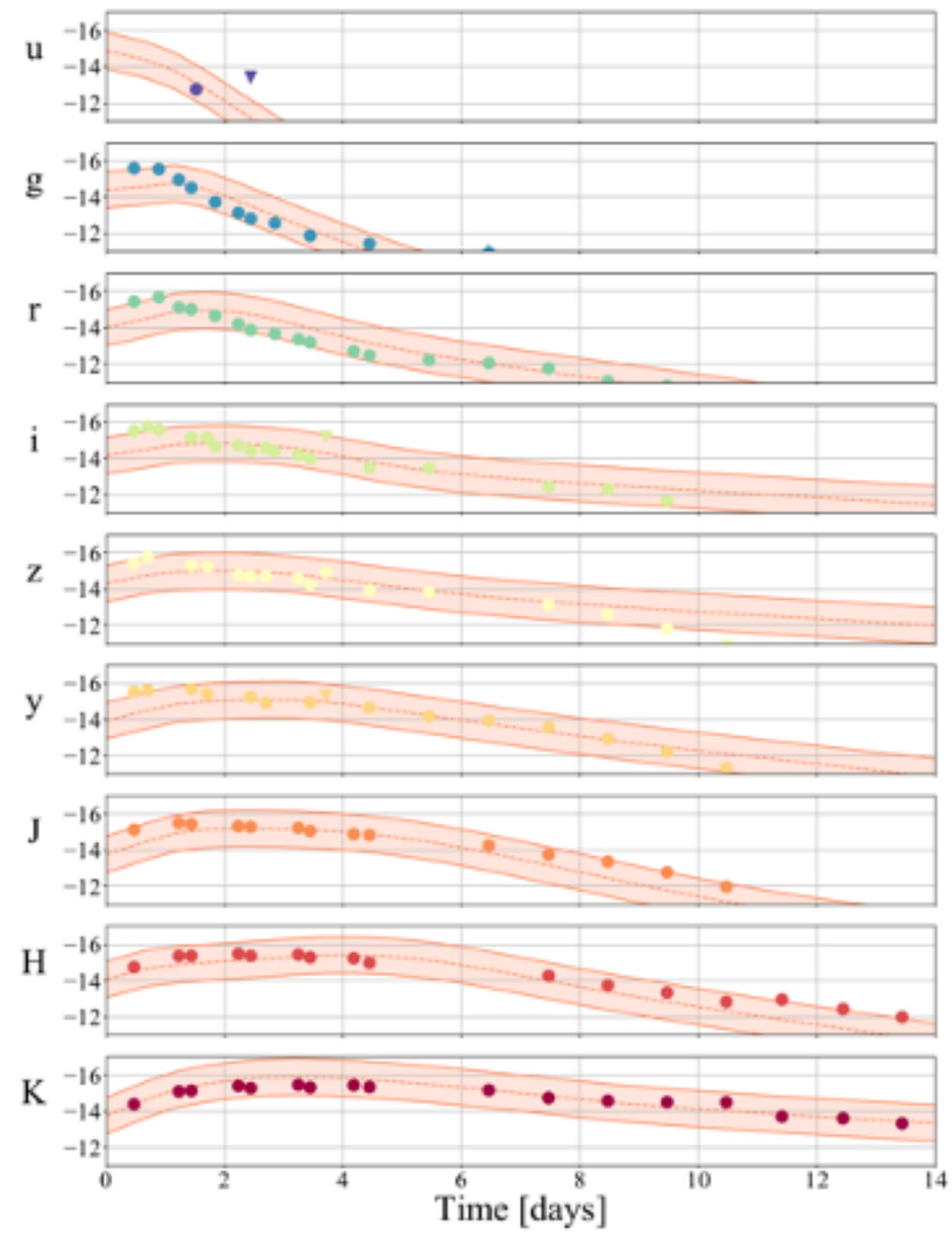


Propagating photons



[Coughlin+2018, MNRAS]

Gaussian Process Regression to cover parameter space



[Possis 2019, MNRAS]