Title: Multi-Messenger Astrophysics with Neutron Star Mergers

Speakers: David Radice

Series: Strong Gravity

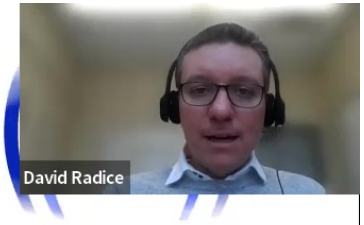
Date: April 21, 2022 - 1:30 PM

URL: https://pirsa.org/22040123

Abstract: What is the nature of neutron stars? Where are r-process elements formed in the Universe? Multi-messenger observations of neutron star mergers might provide us with the key to address these and other important open questions in astrophysics. However, multi-messenger astronomy also poses new challenges to theorists and observers attempting to turn complex data into answers. In this talk, I will review our current theoretical understanding of neutron star mergers, I will discuss how their dynamic is imprinted in their multi-messenger emissions, and I will present recent simulation results and their implications. Finally, I will discuss future challenges and prospective for this field.

Zoom Link: https://pitp.zoom.us/j/93367275850?pwd=YngycnN4ZXFDQUhQb2lVaHY3V2k0UT09

PennState
Eberly College of Science




CoRe collaboration

# Multi-Messenger Astrophysics with Neutron Star Mergers

David Radice – Apr. 21, 2022

NP3M

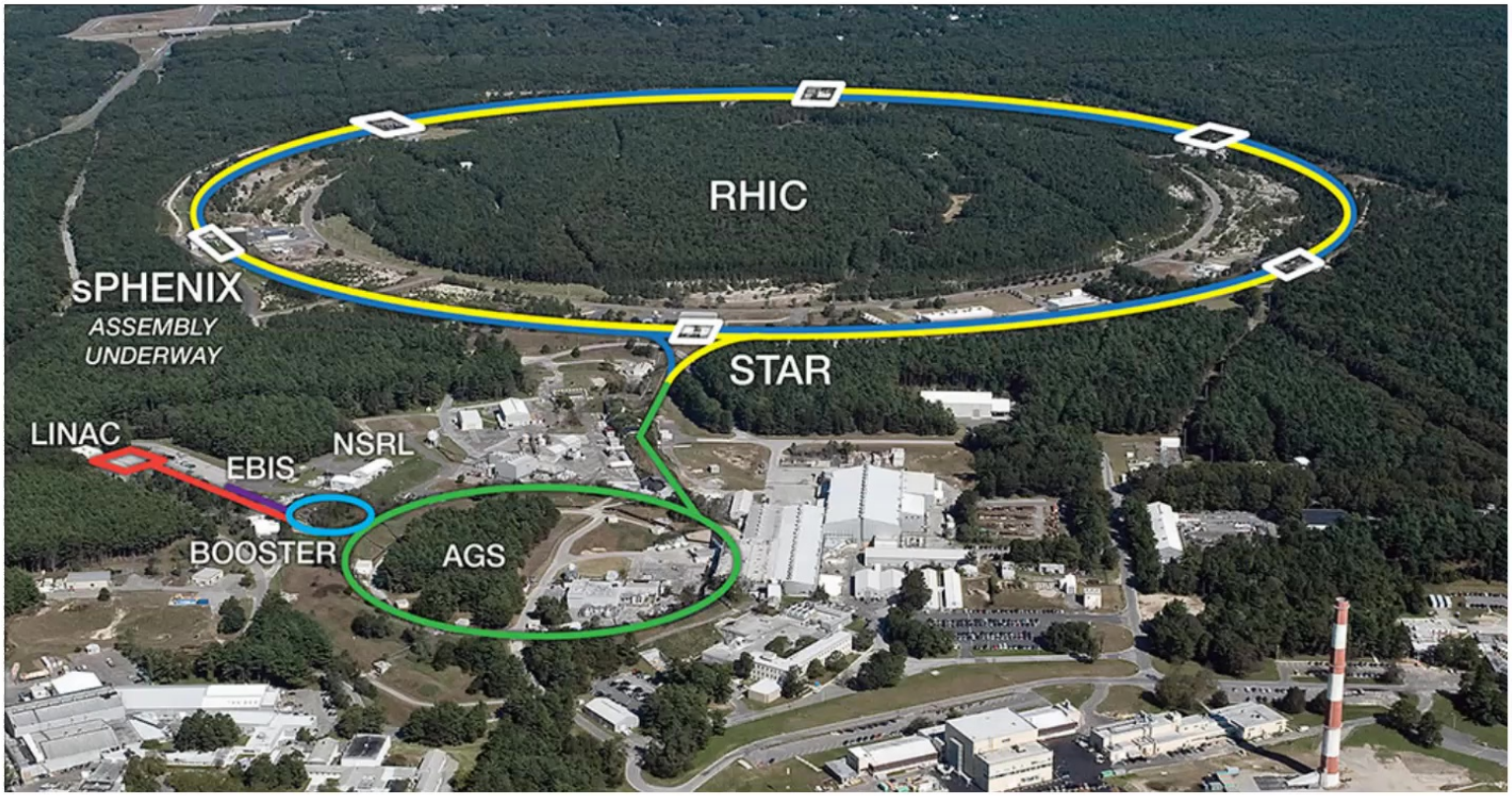
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

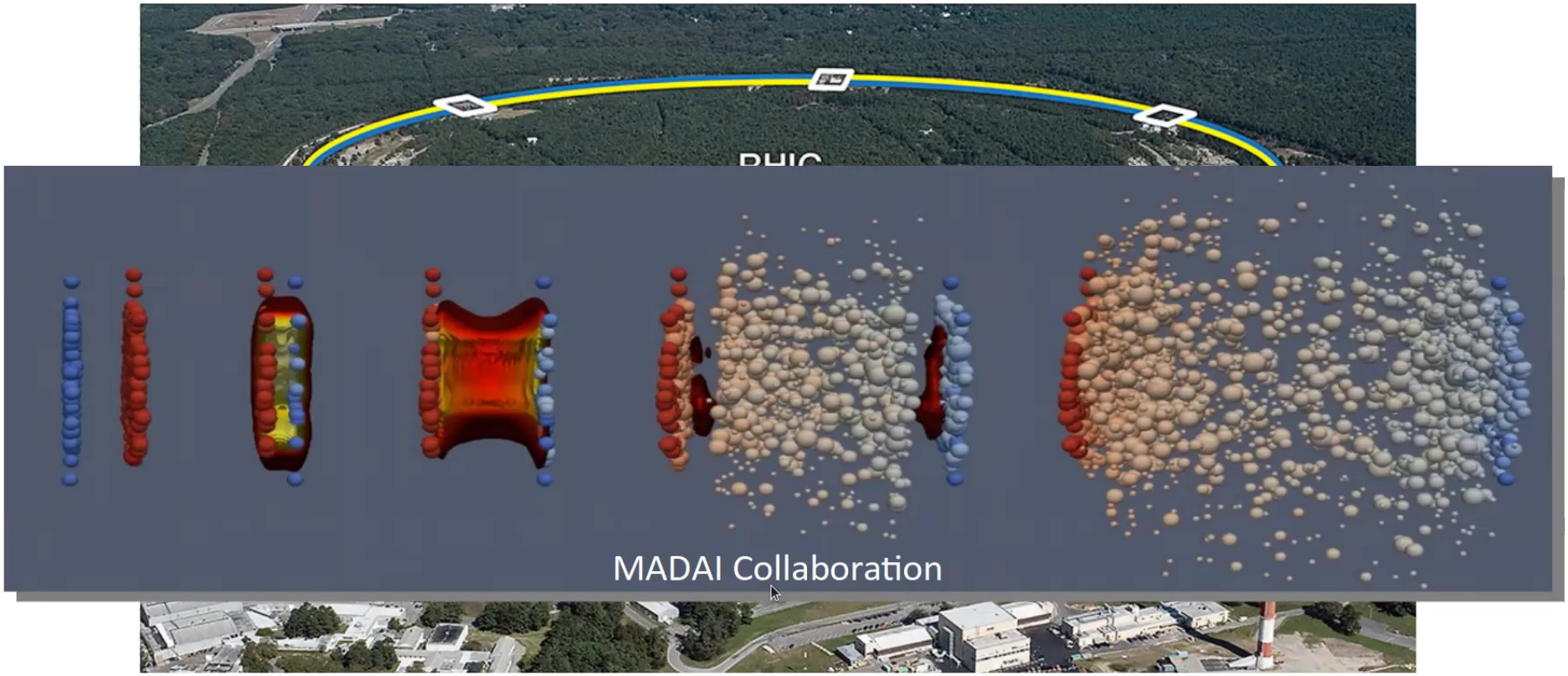
What is the nature of matter at extreme densities?

Where are elements heavier than iron produced?

# Relativistic heavy-ion collision

# Relativistic heavy-ion collision

# Phase diagram of extreme matt

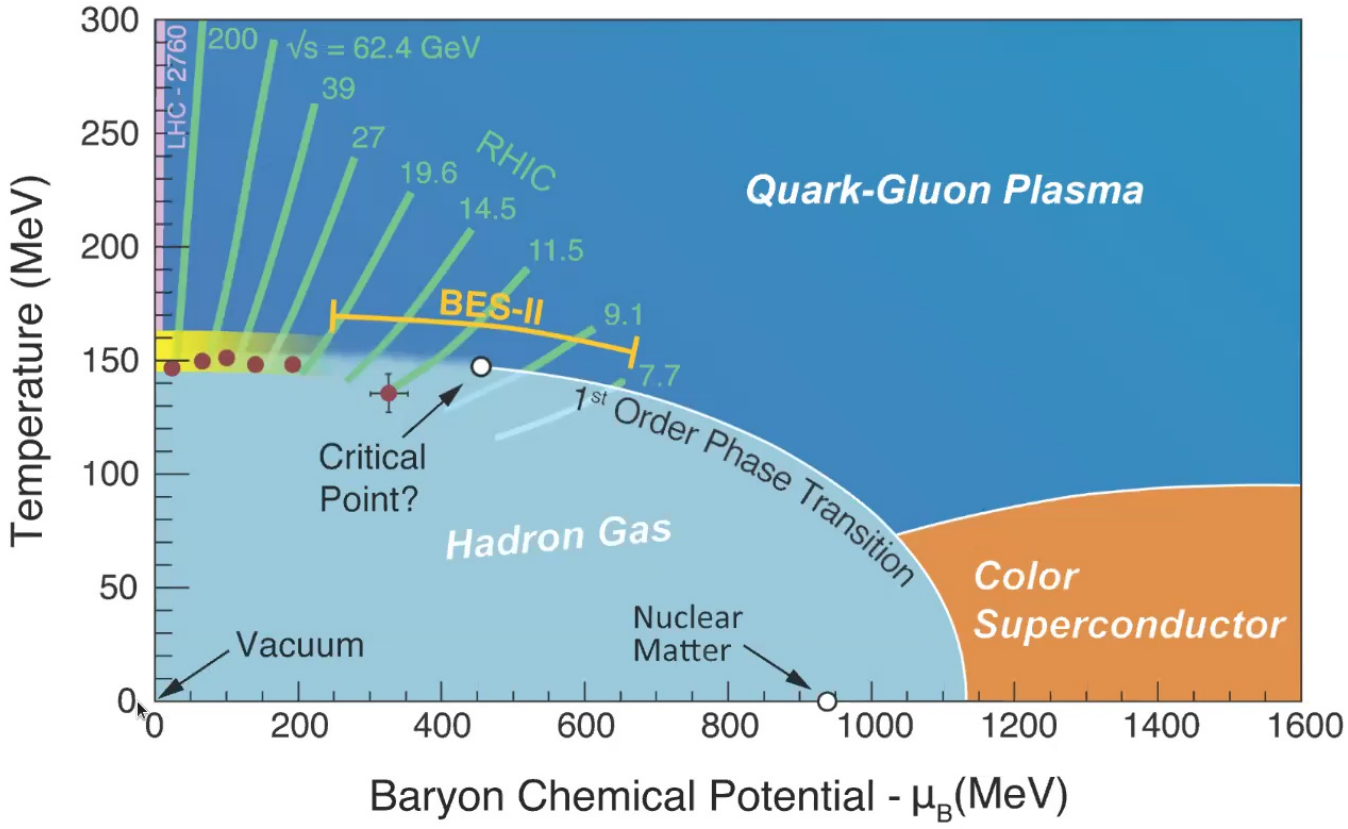
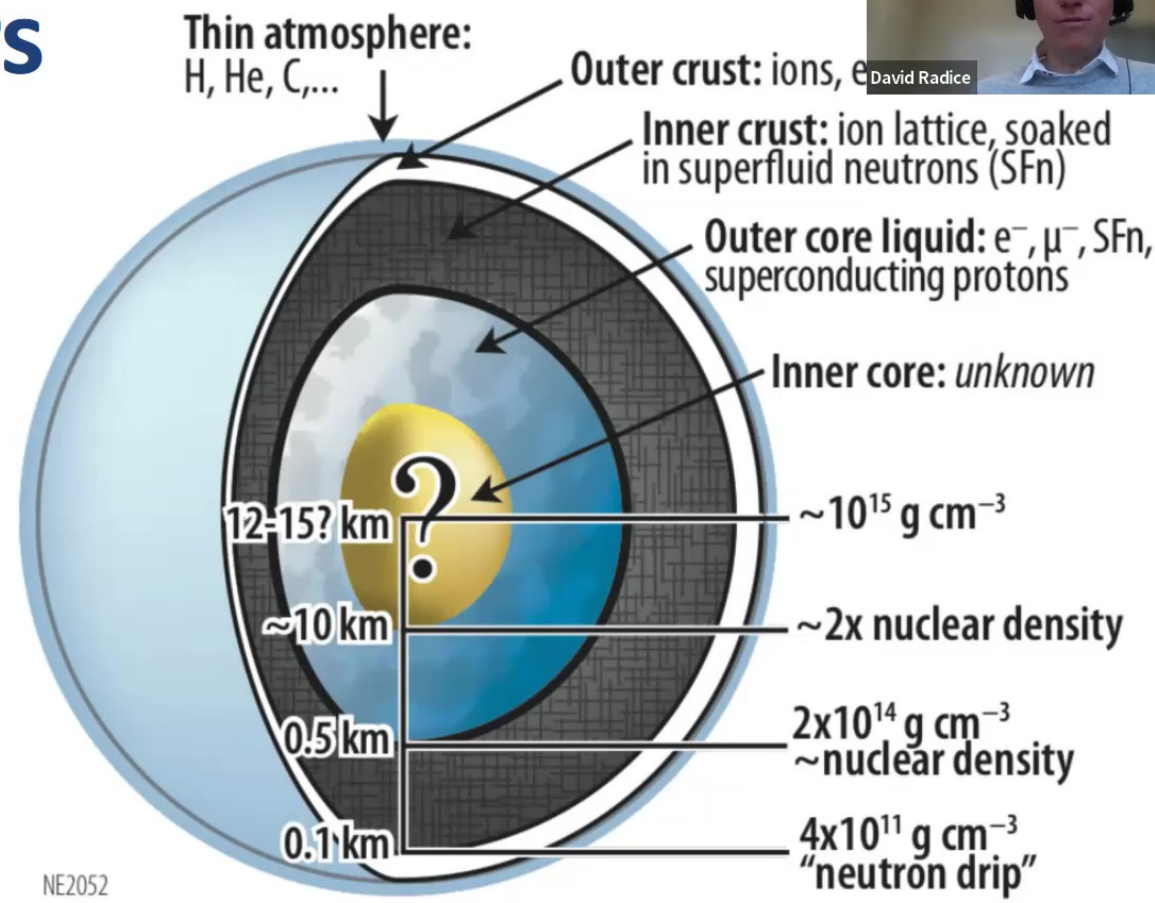




Illustration: Swagato Mukherjee, BNL

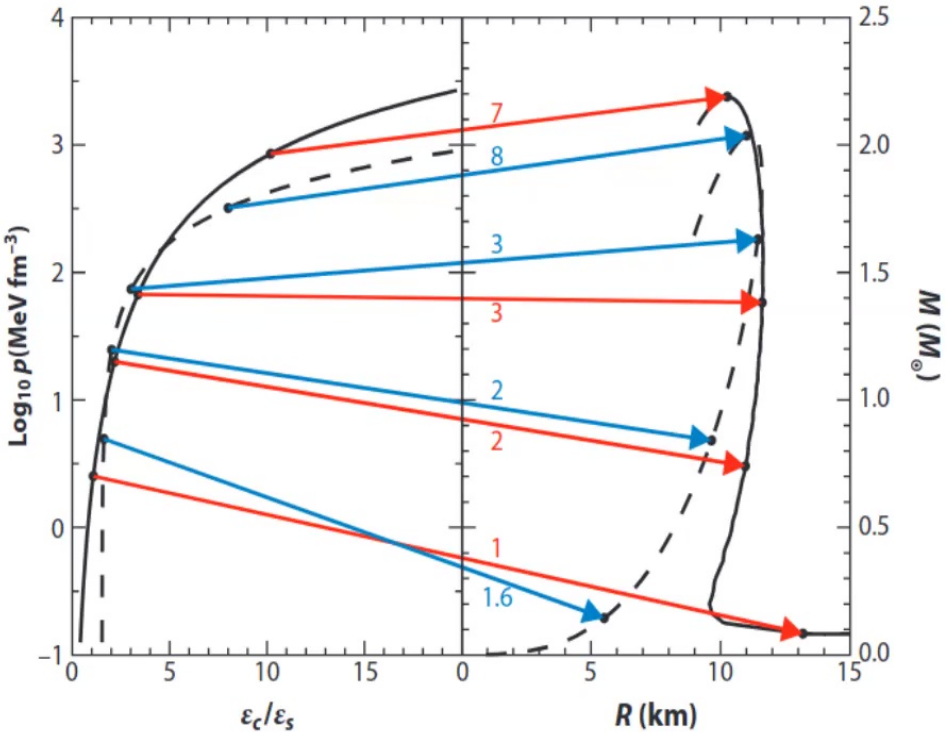
# Neutron stars

- End stage of evolution of massive stars $(M \gtrsim 10\ M_\odot)$
- $1 \lesssim M/M_\odot \lesssim 2{-}3$
- Observed as pulsars




Credit: NASA

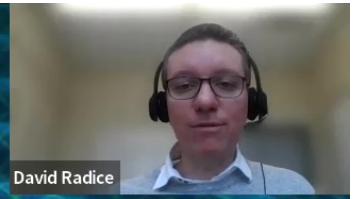
# Statement of the problem


From Lattimer 2012

- Nuclear theory: $p = p(\rho)$
- General relativity: $M = M(R)$
- Astronomical observations of NS masses and radii constrain and inform theory

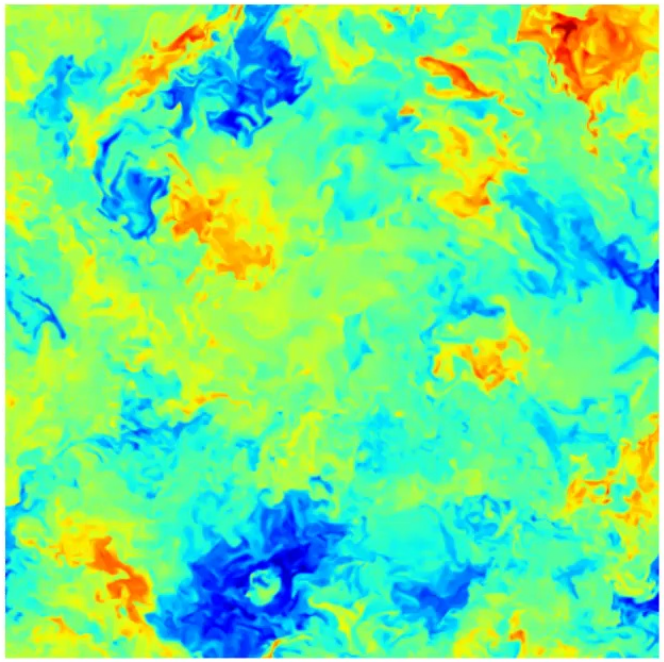
# Binary neutron stars




- Orbital energy radiated in gravitational waves
- Orbit decays
- Gravitational waves increases
- …
- ?!?


# WhiskyTHC

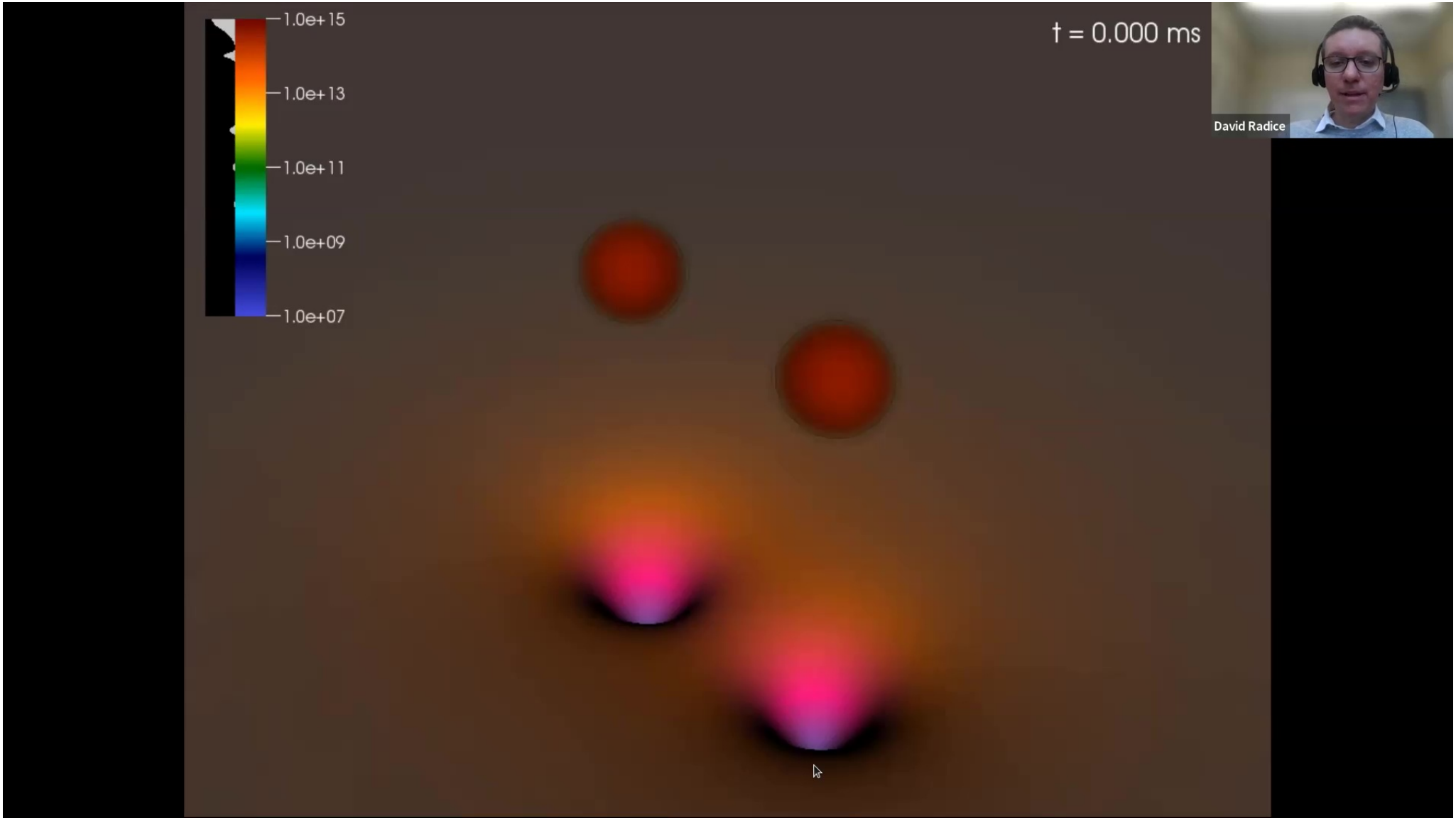
http://personal.psu.edu/~dur566/whiskythc.html

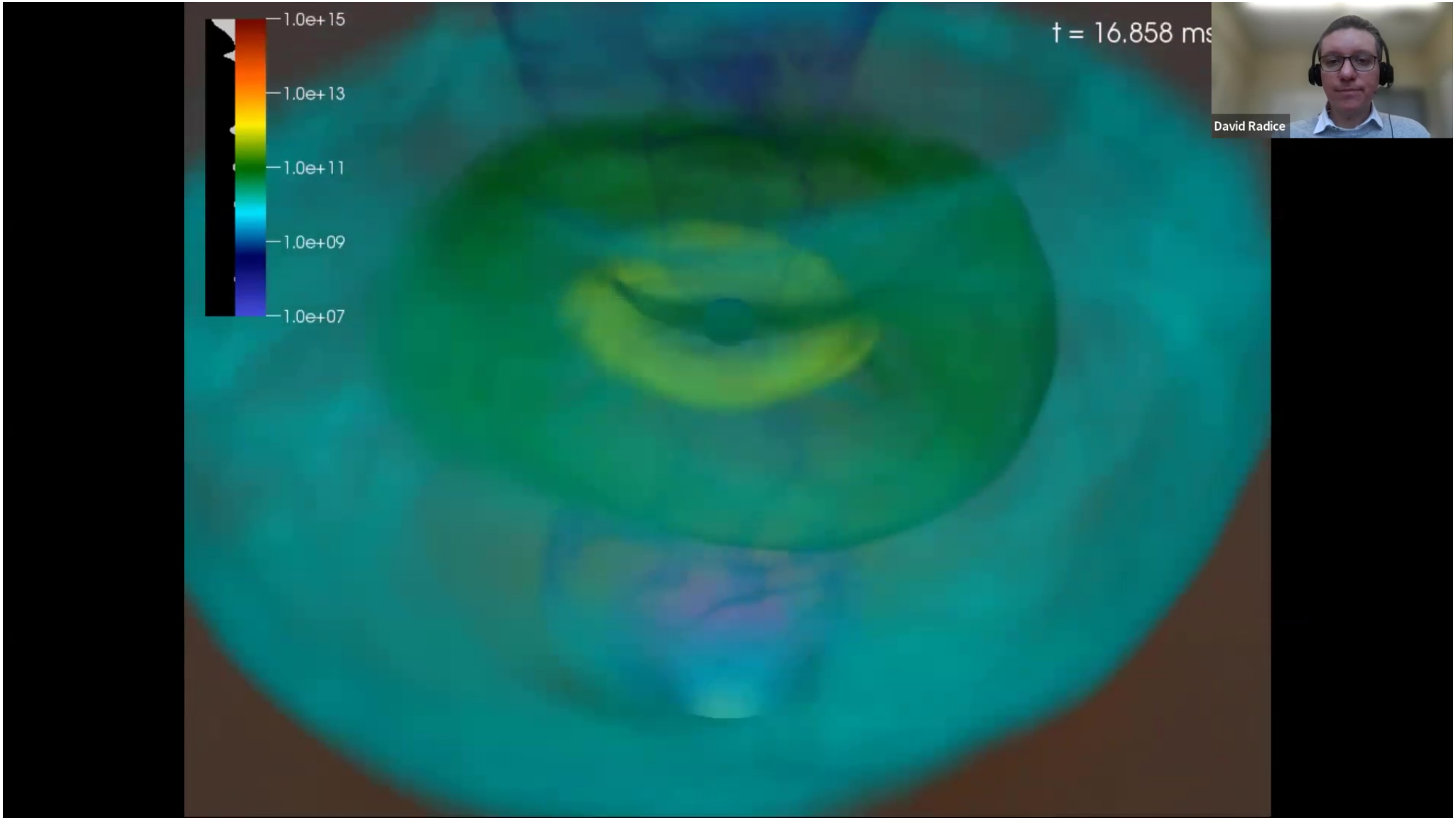


- Full-GR dynamical spacetime
- Nuclear EOS
- M0 & M1 neutrino transport
- Subgrid turbulence modeling
- Builds on top of the Einstein Toolkit and open source

THC: Templated Hydrodynamics Code

Skip Ad


1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 0.000 ms
David Radice


1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
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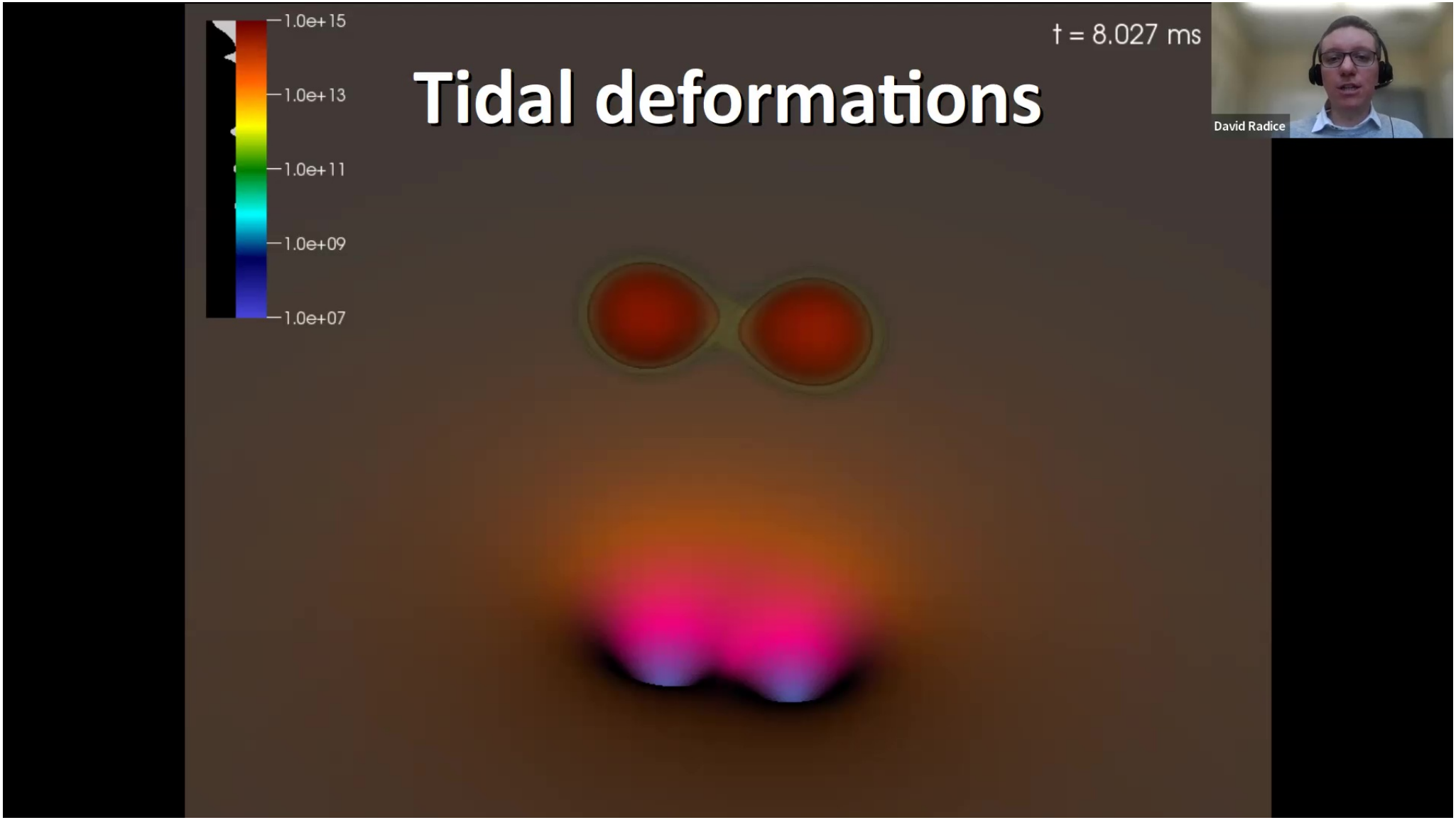
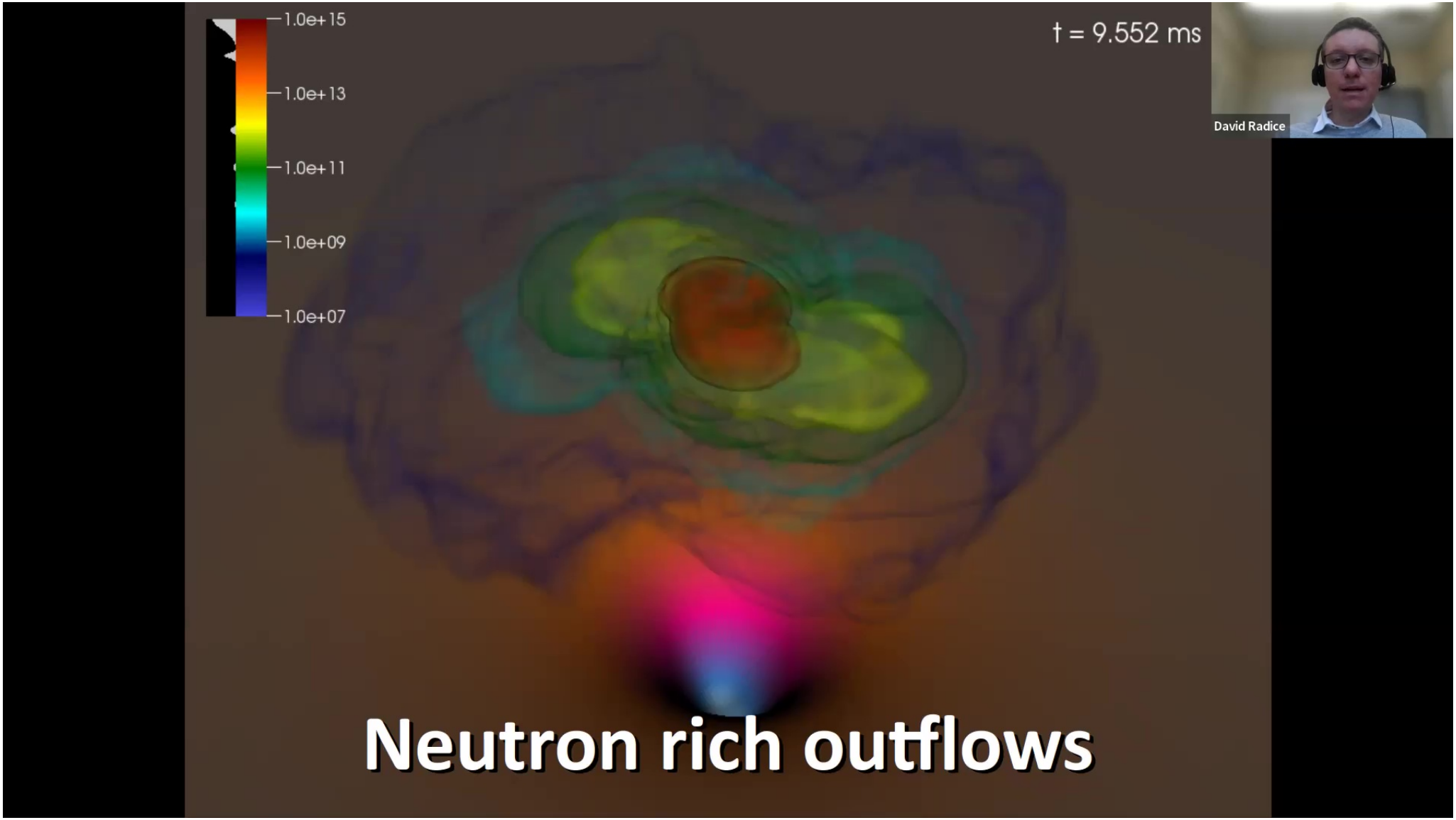
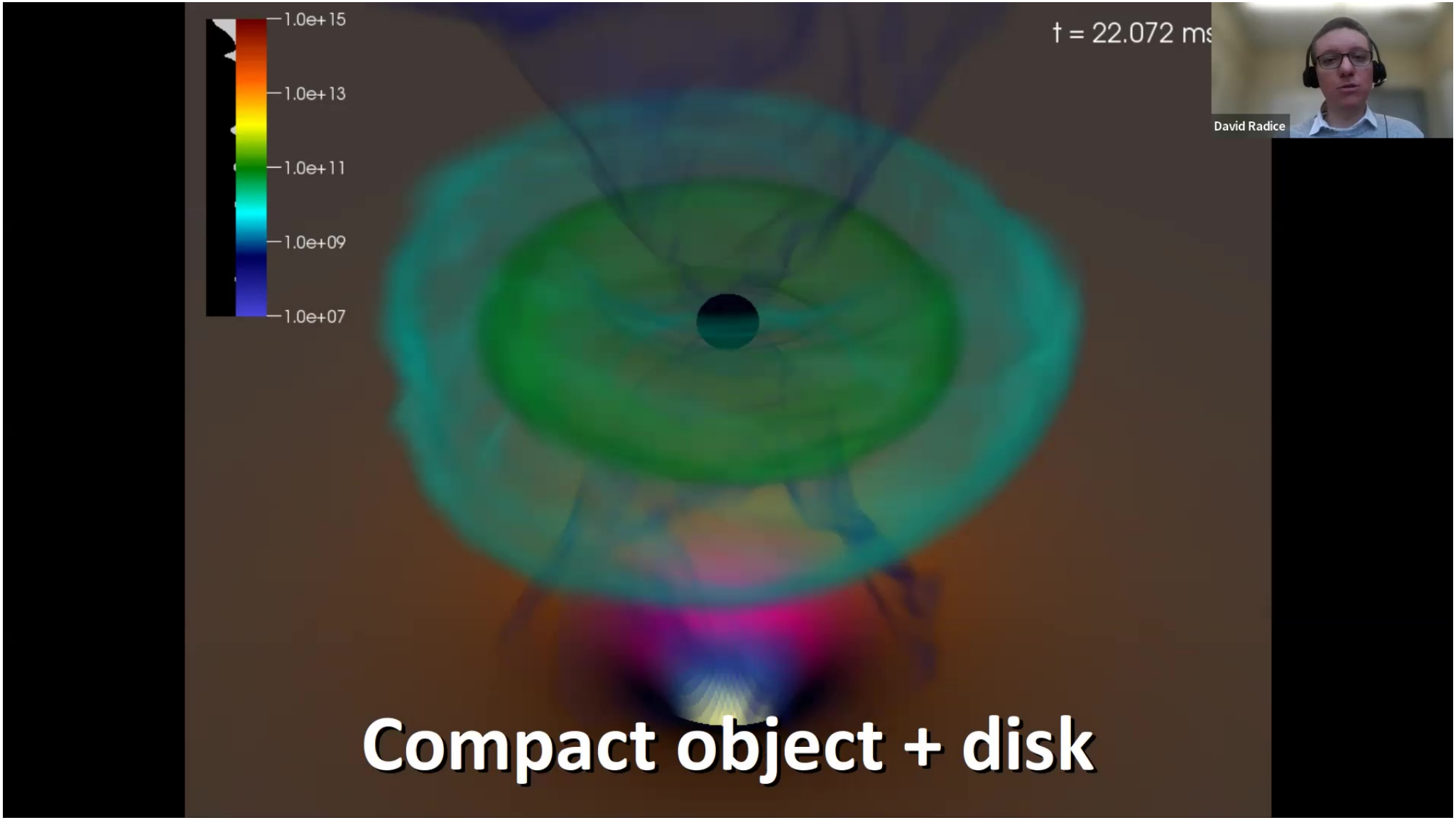
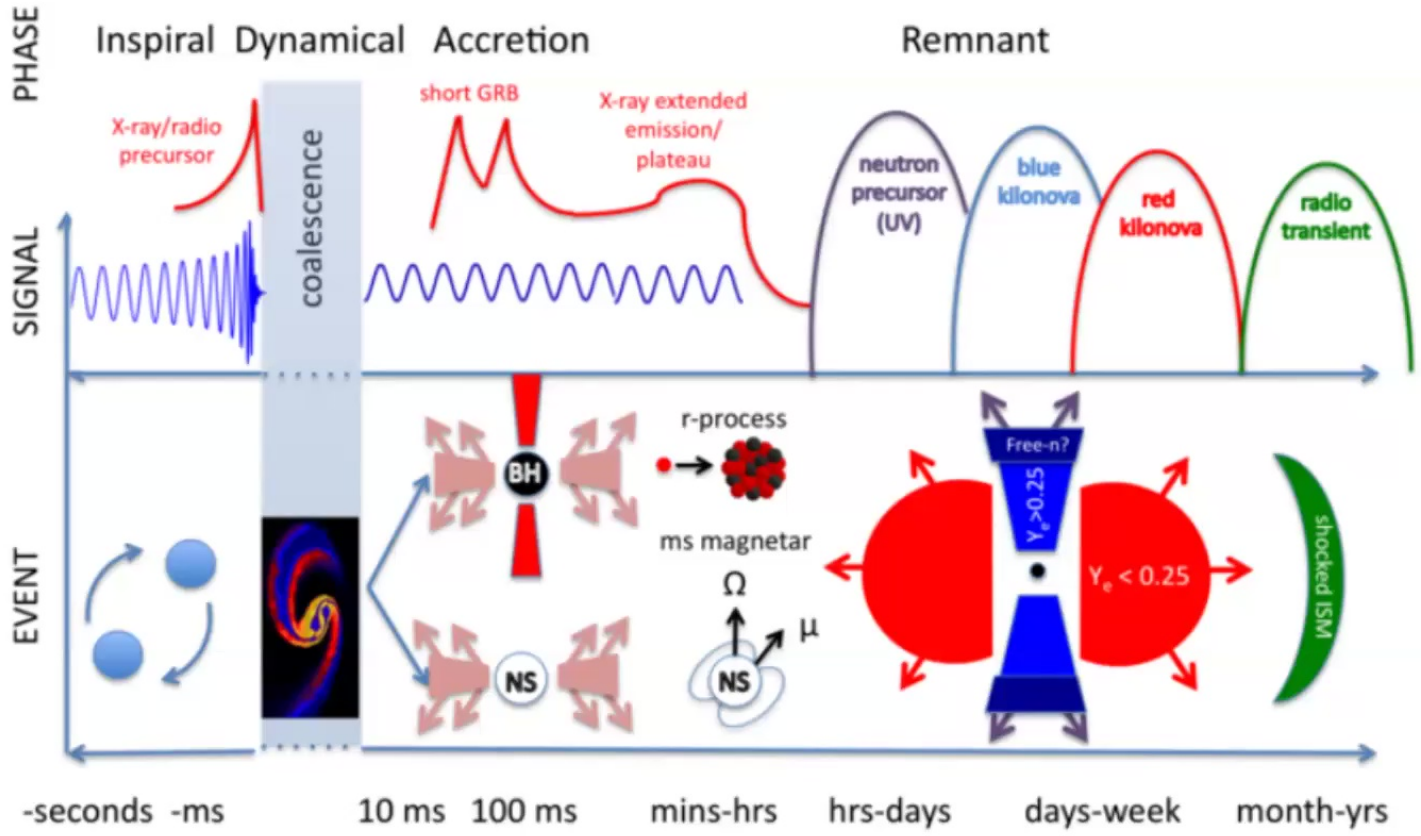
David Radice


1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 8.027 ms
Tidal deformations
David Radice


1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 9.552 ms
David Radice
Neutron rich outflows

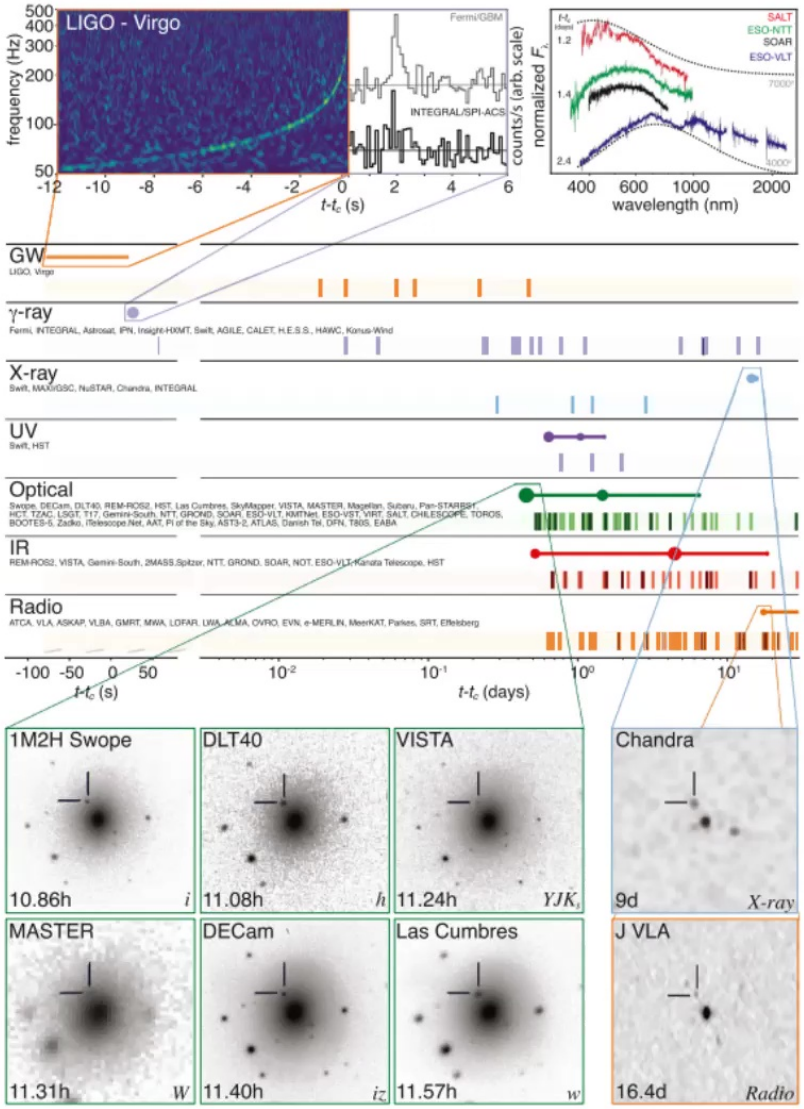

1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 22.072 ms
David Radice
Compact object + disk

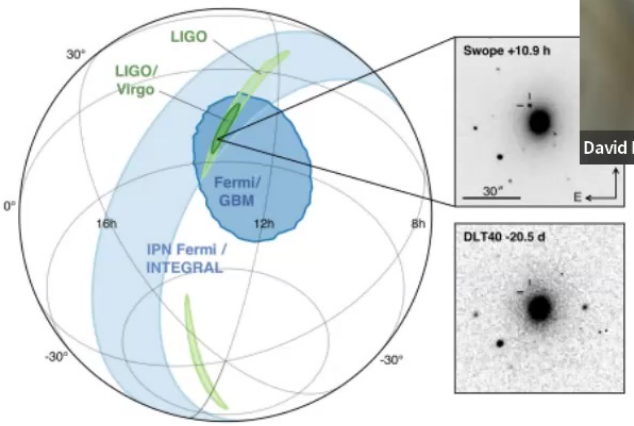
# Theorists' dreams




From Fernandez & Metzger 2016

# GW170817

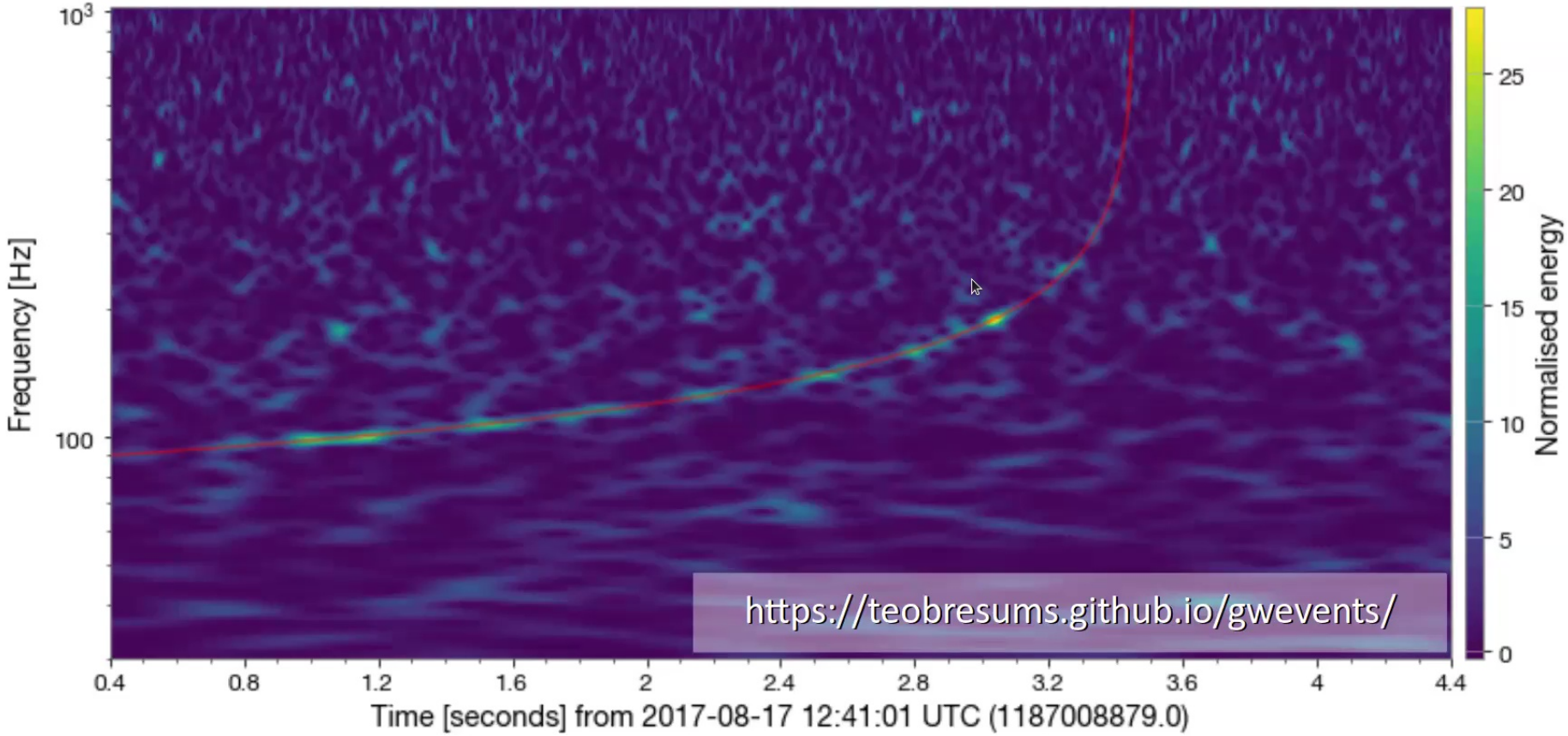




From LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech- NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT ApJL 848:L12 (2017)

# Gravitational waves (I)

# Gravitational waves (II)


Inclination, sky position, etc

$$\tilde{h}(f) = \frac{Q}{D}\mathcal{M}^{5/6} f^{-7/6} \exp\left[i\Psi(f)\right]$$

Distance

Chirp mass

Phase

$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

# Gravitational waves (III)


$$\Psi(f) = 2\pi f t_0 + \phi_0 + \frac{3}{4}(8\pi\mathcal{M}f)^{-\frac{5}{3}}\left[1 + \sum_{j=0}^{\infty}\Psi_j f^{\frac{2j}{3}}\right]$$

Chirp mass

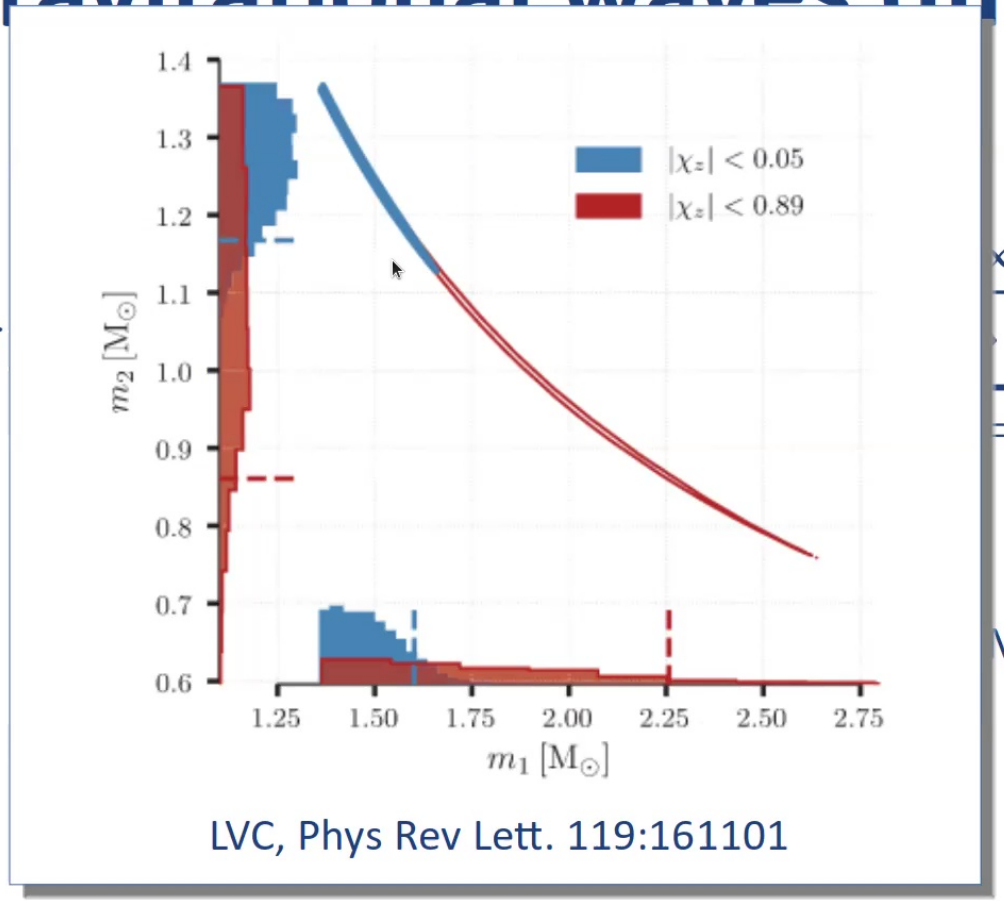
Mass ratio, spin, tides

$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

# Gravitational waves (III)




$$\Psi(f) = 2\pi$$



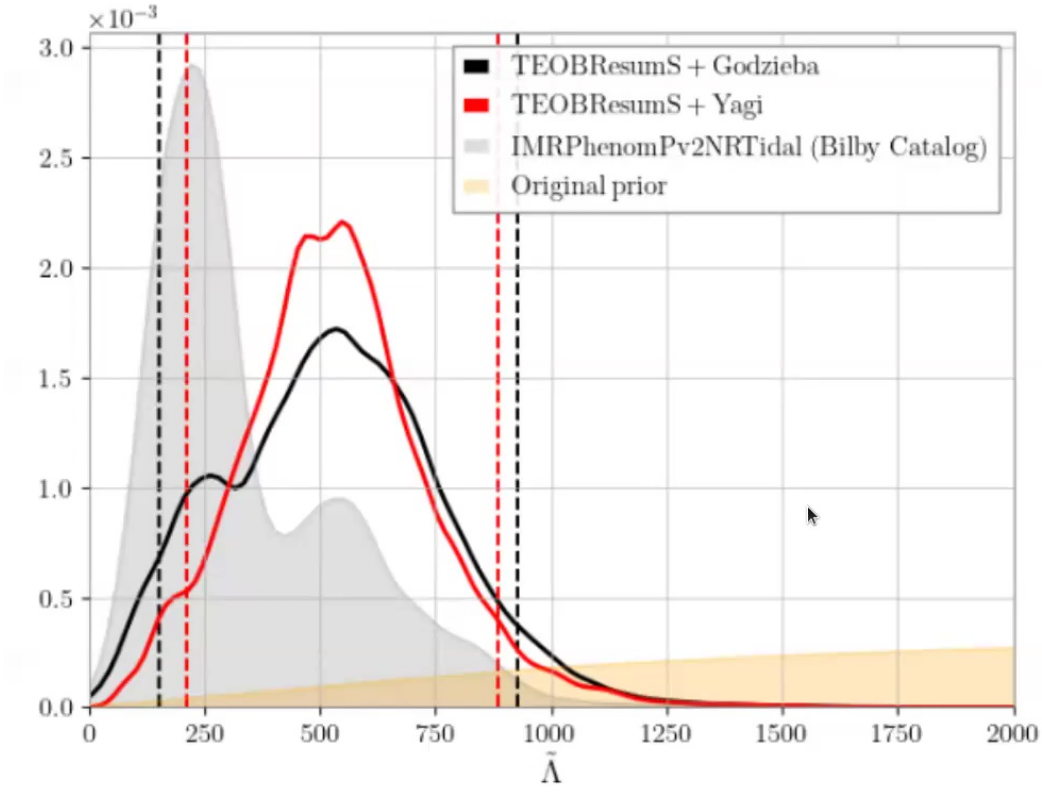

LVC, Phys Rev Lett. 119:161101

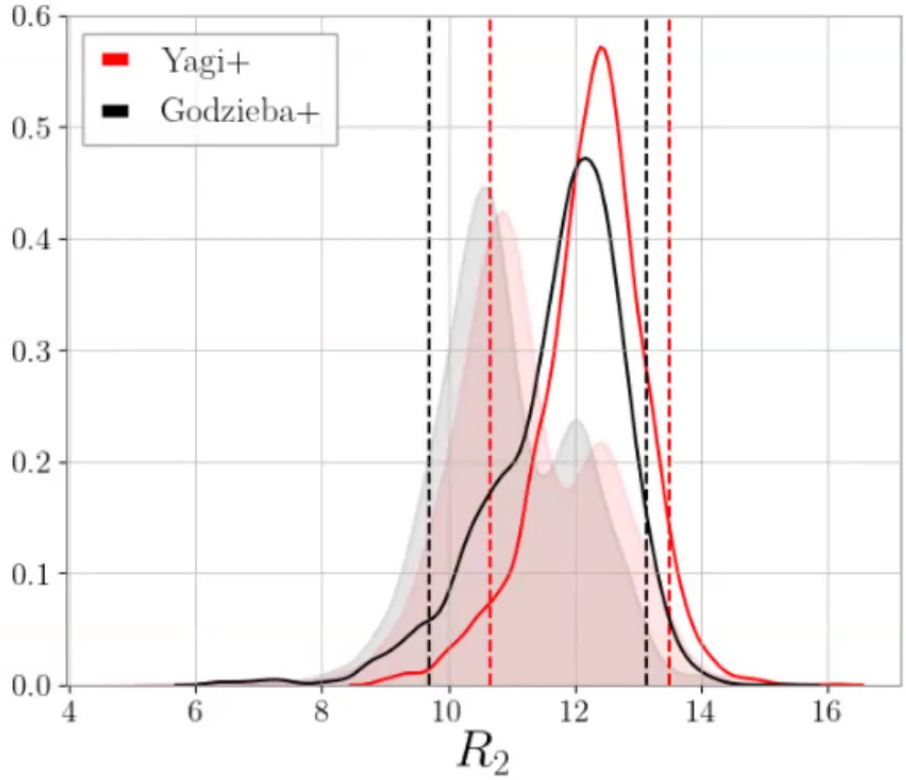
$$=0$$

$$\sum \Psi_j f^{\frac{2j}{3}} \Big]$$

Mass ratio, spin, tides

# GW170817

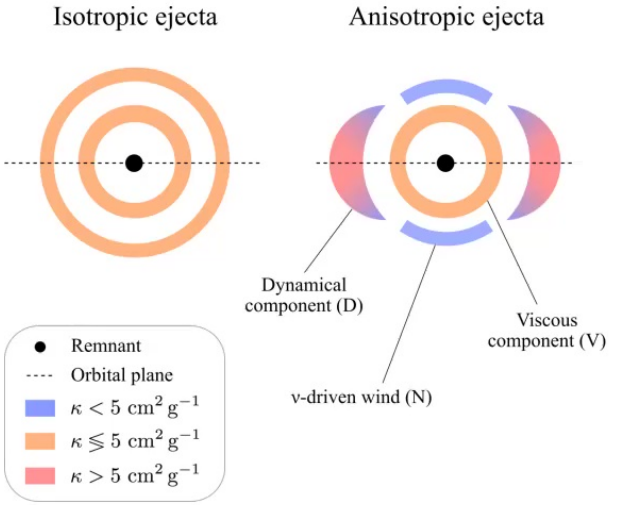

See also LVC 2017, 2018, De+ 2018, Choughlin+ 2018, Radice+ 2018, Capanno 2019, Raaijmakers+ 2021, ...

From Godzieba+ 2021

# Multi-messenger constraints

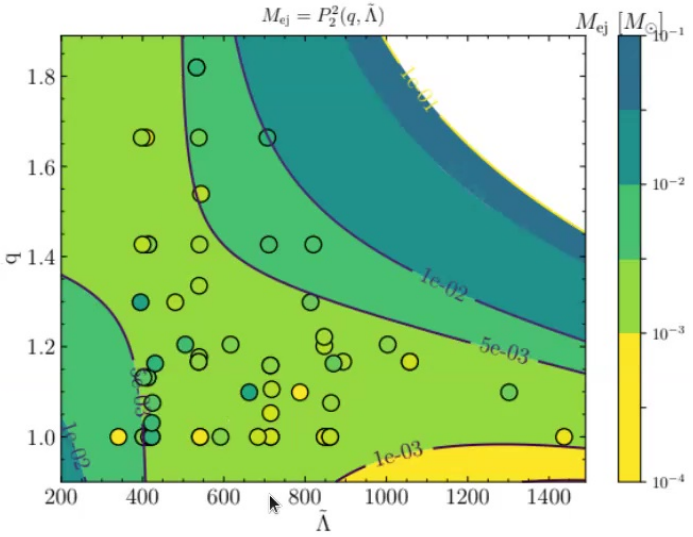

$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\rm GW}|\theta]P[d_{\rm EM}|\theta]$$

GW modeling and data analysis




kilonova modeling

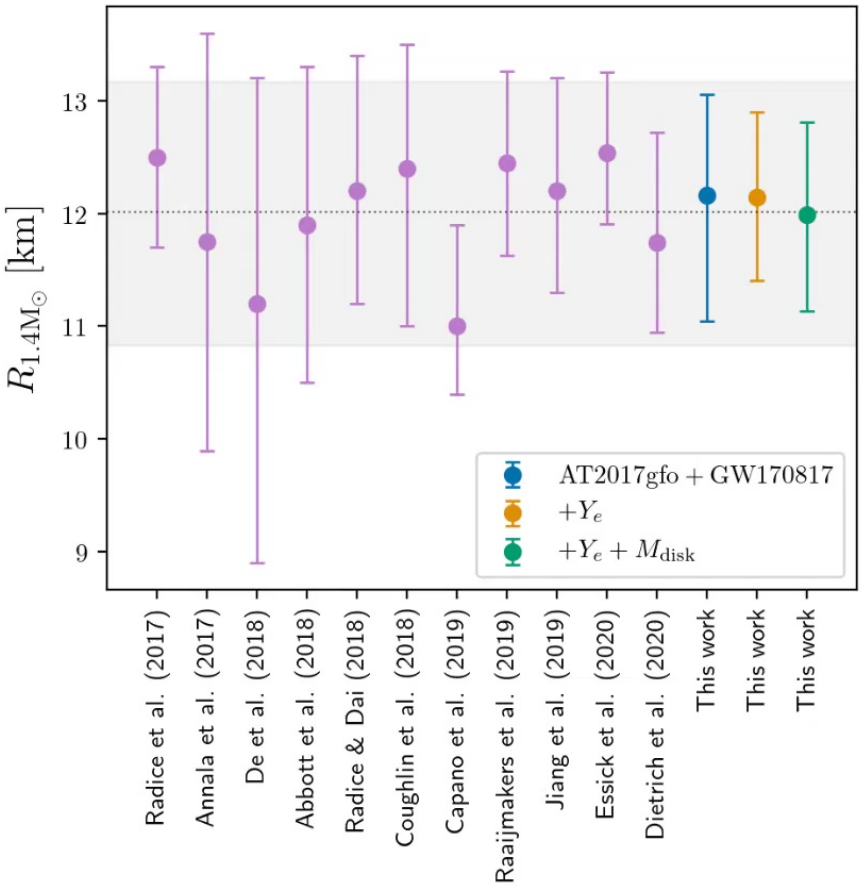
NR simulations




Perego+, ApJL 850:L37 (2017)

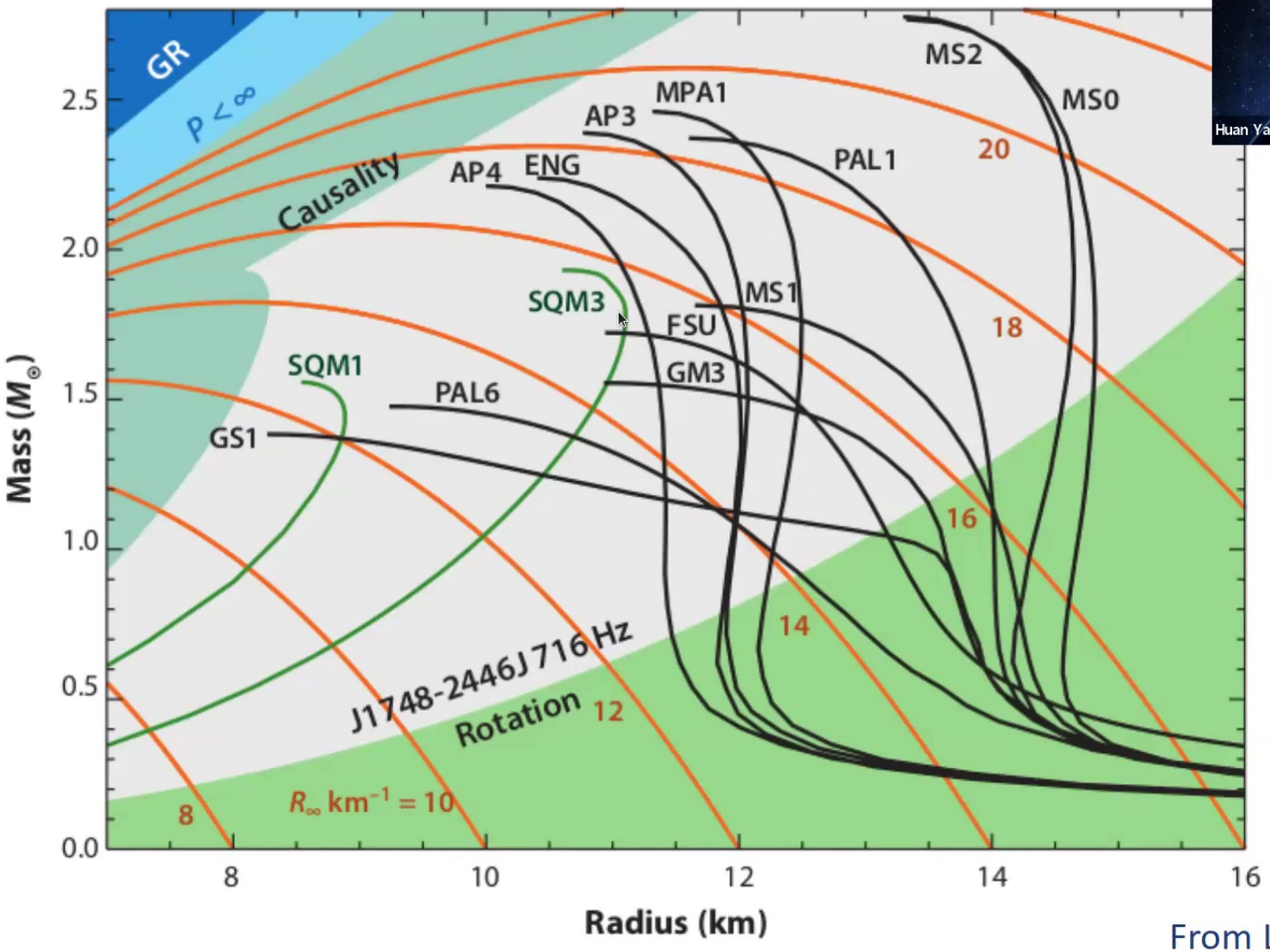
Nedora+, CQG 39:015008 (2022)

# Multi-messenger EOS constrain




- Potential to also constrain the mass ratio
- Error dominated by modeling uncertainty, but well understood
- Constraints set by the merger and early post-merger dynamics
- Parameter exploration and inclusion of long-term disk winds from remnant needed

From Breschi+ MNRAS 505:1661 (2021)



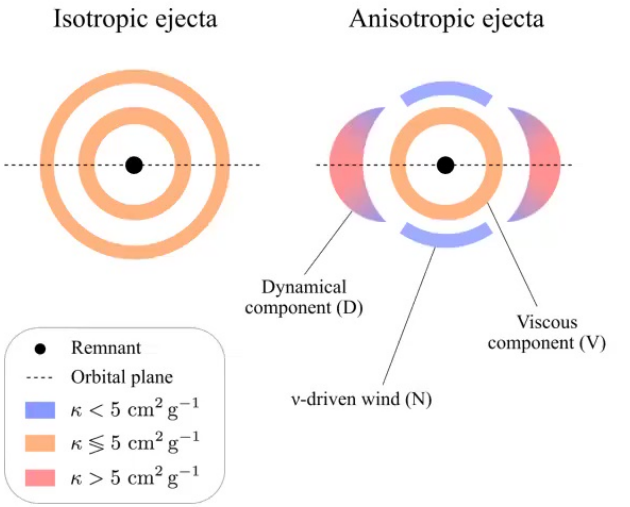


From Lattimer 2012

# Multi-messenger constraints

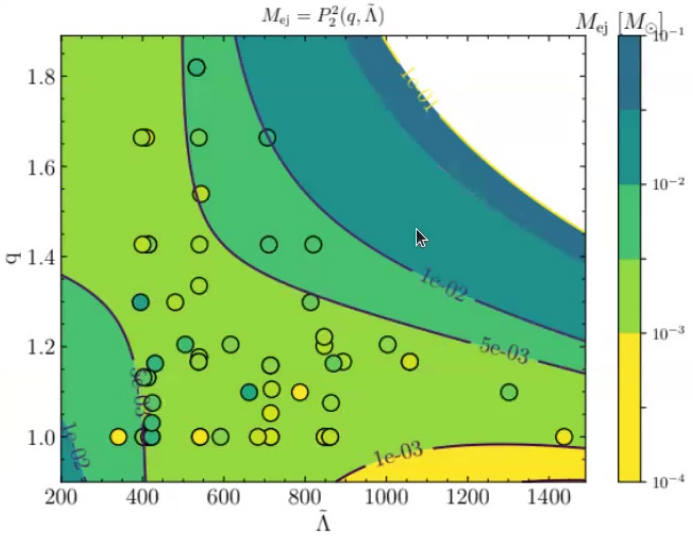

$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\rm GW}|\theta]P[d_{\rm EM}|\theta]$$

GW modeling and data analysis



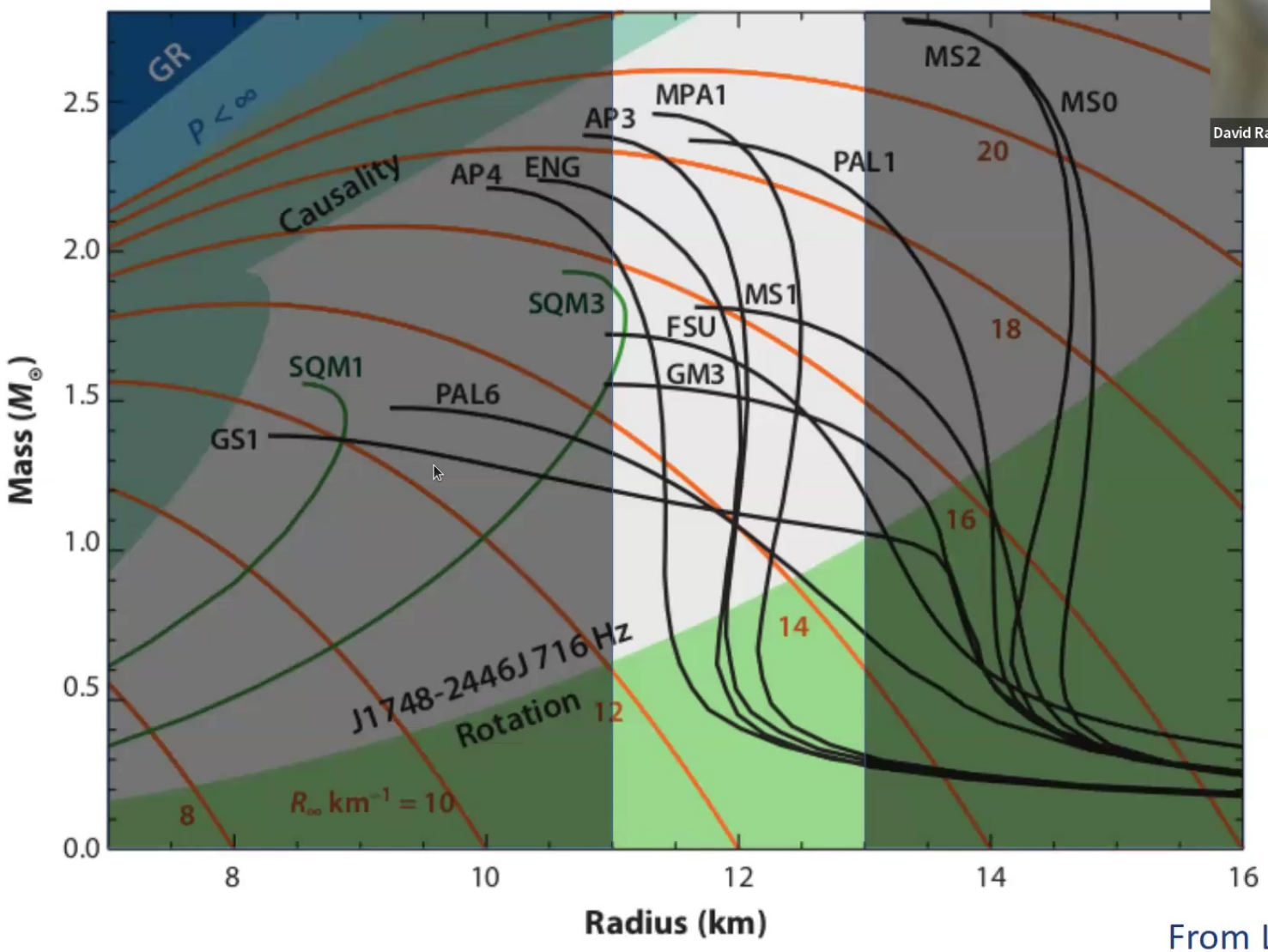

kilonova modeling

NR simulations



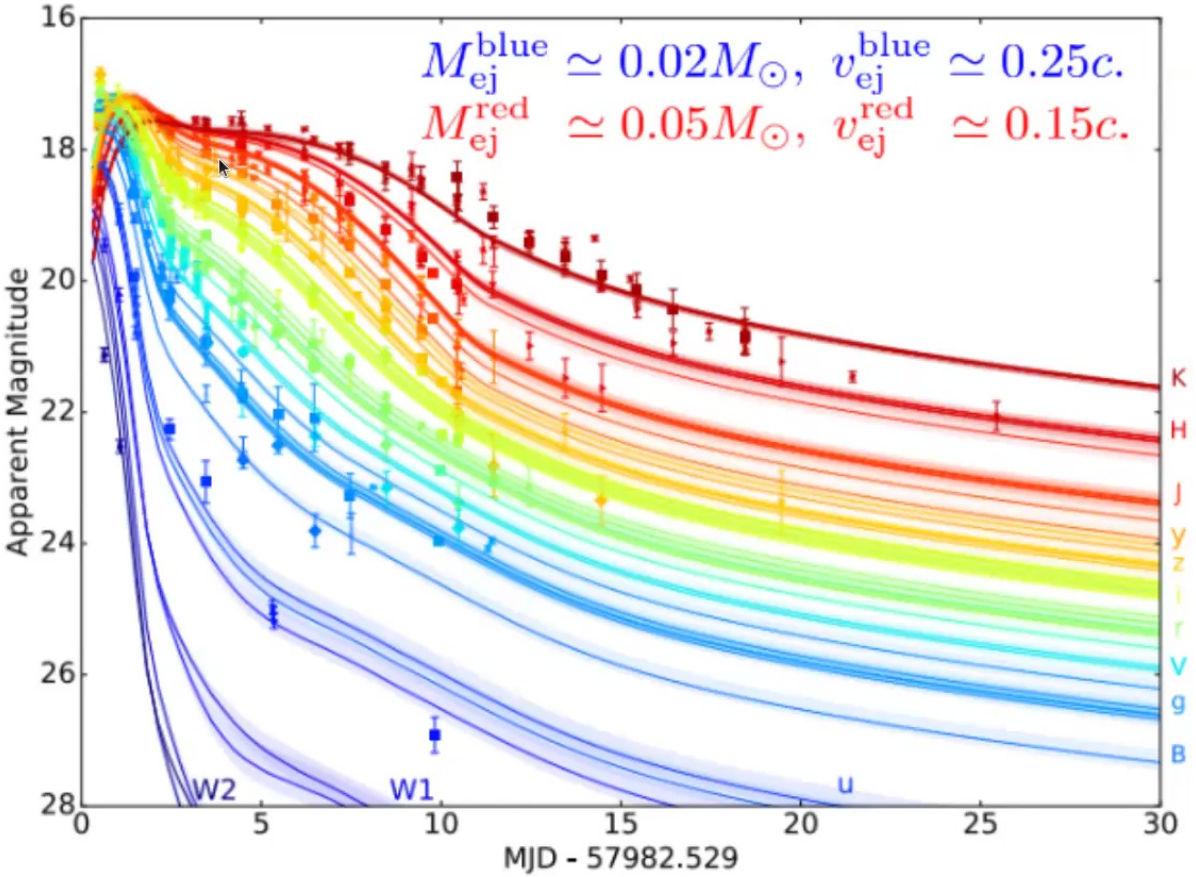

Perego+, ApJL 850:L37 (2017)

Nedora+, CQG 39:015008 (2022)

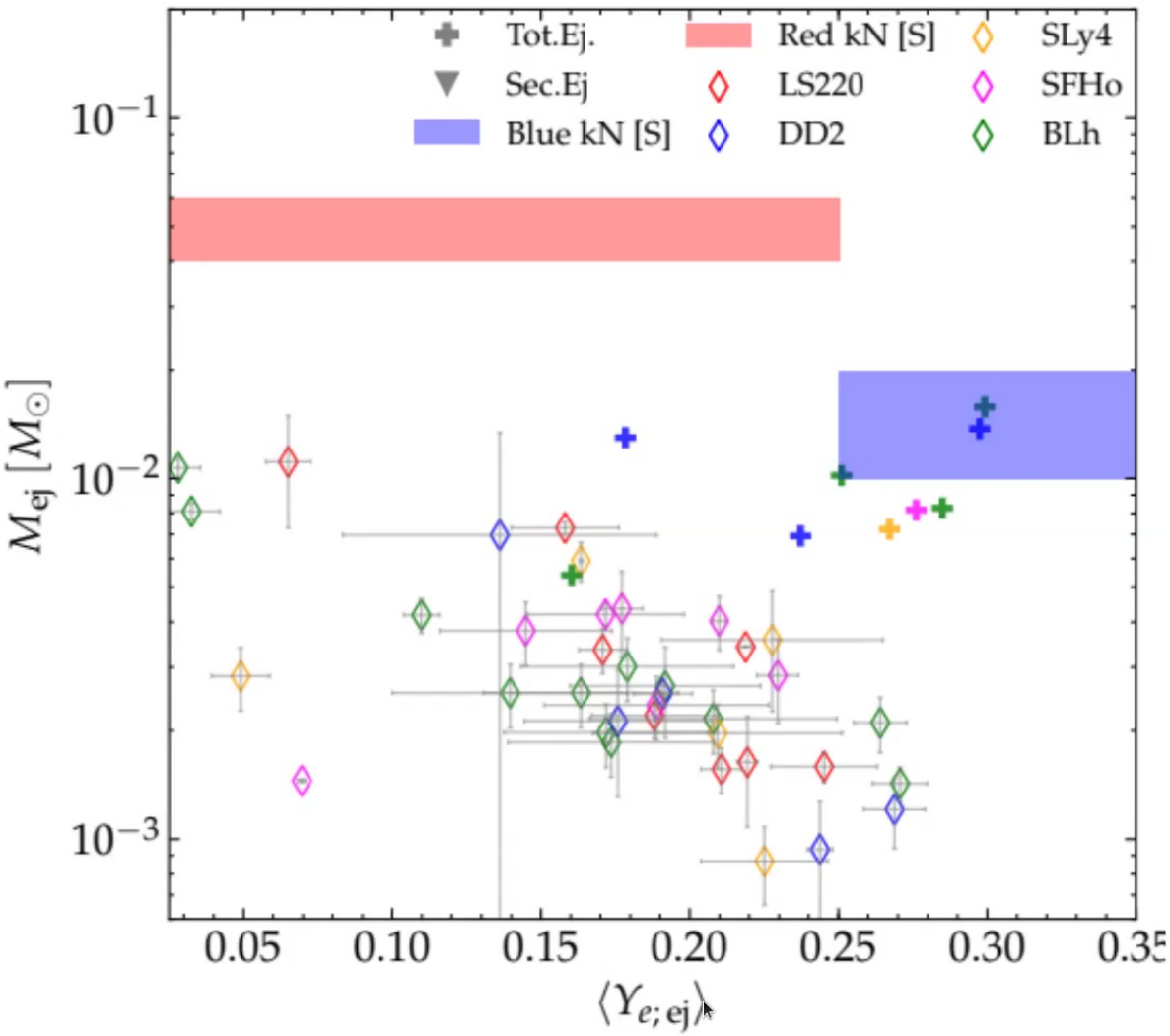



From Lattimer 2012


# What about the gold?

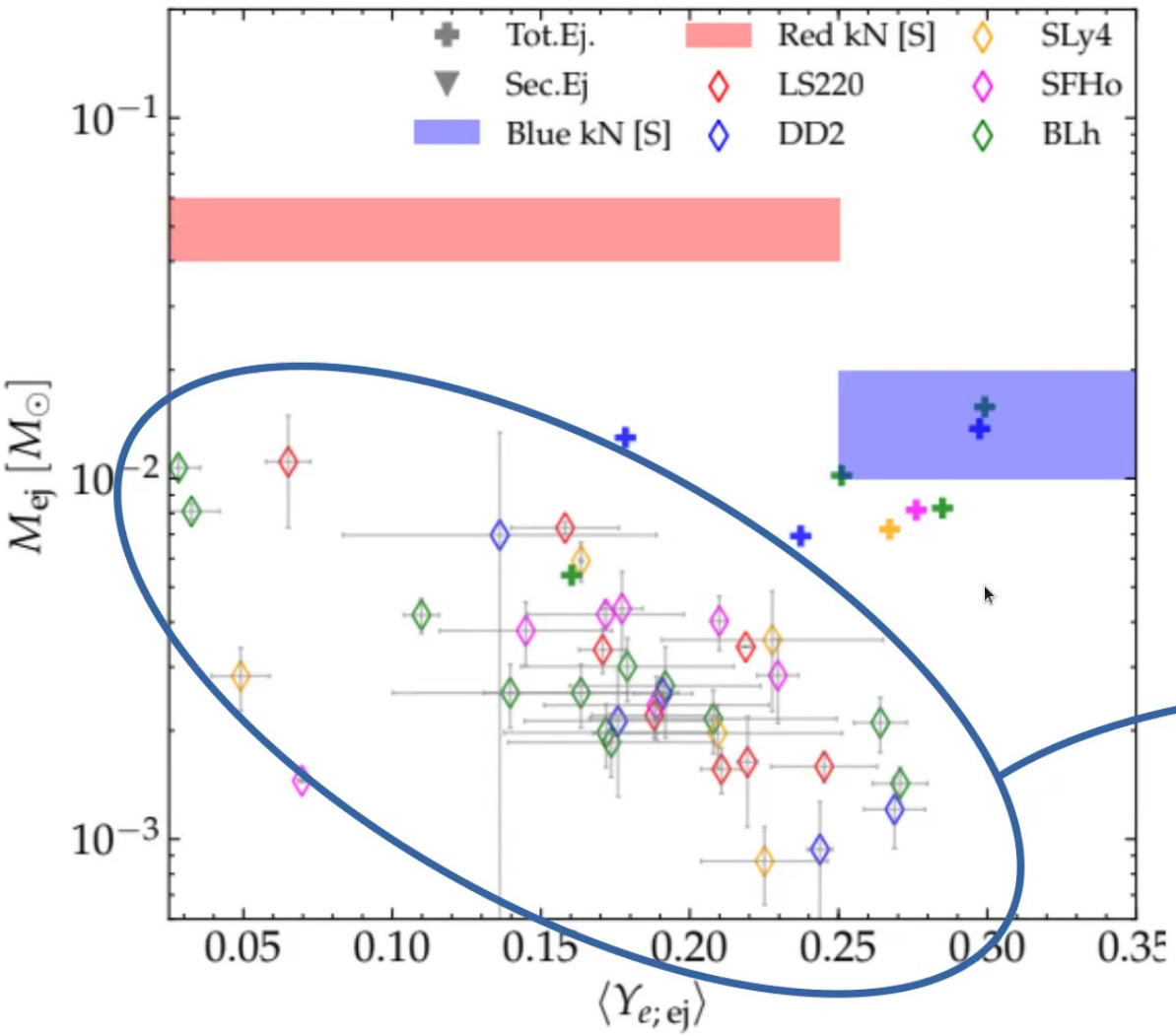



From Villar+ 2017



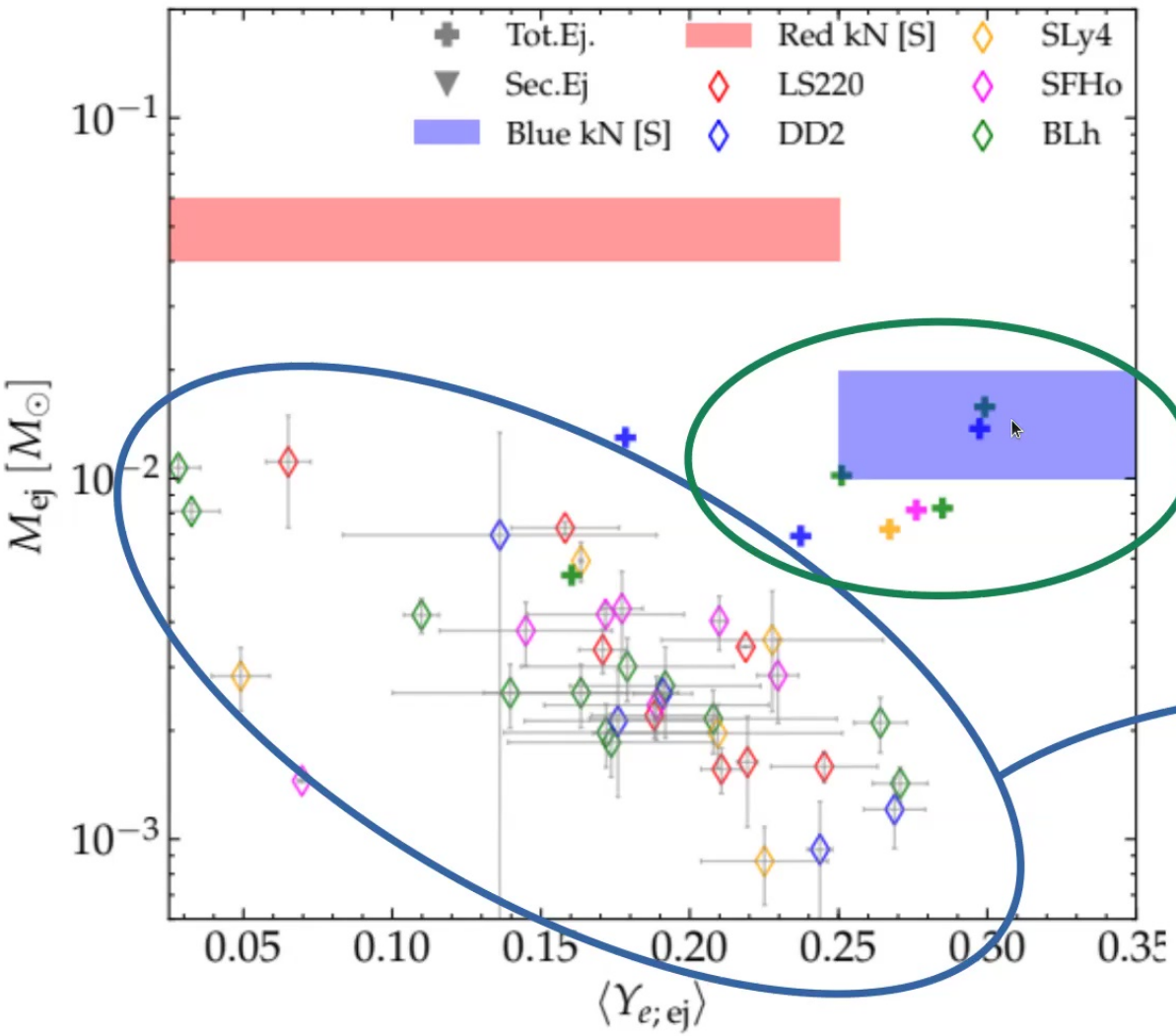


From Nedora+, ApJ 906:98 (2021)




Dynamical ejecta

From Nedora+, ApJ 906:98 (2021)

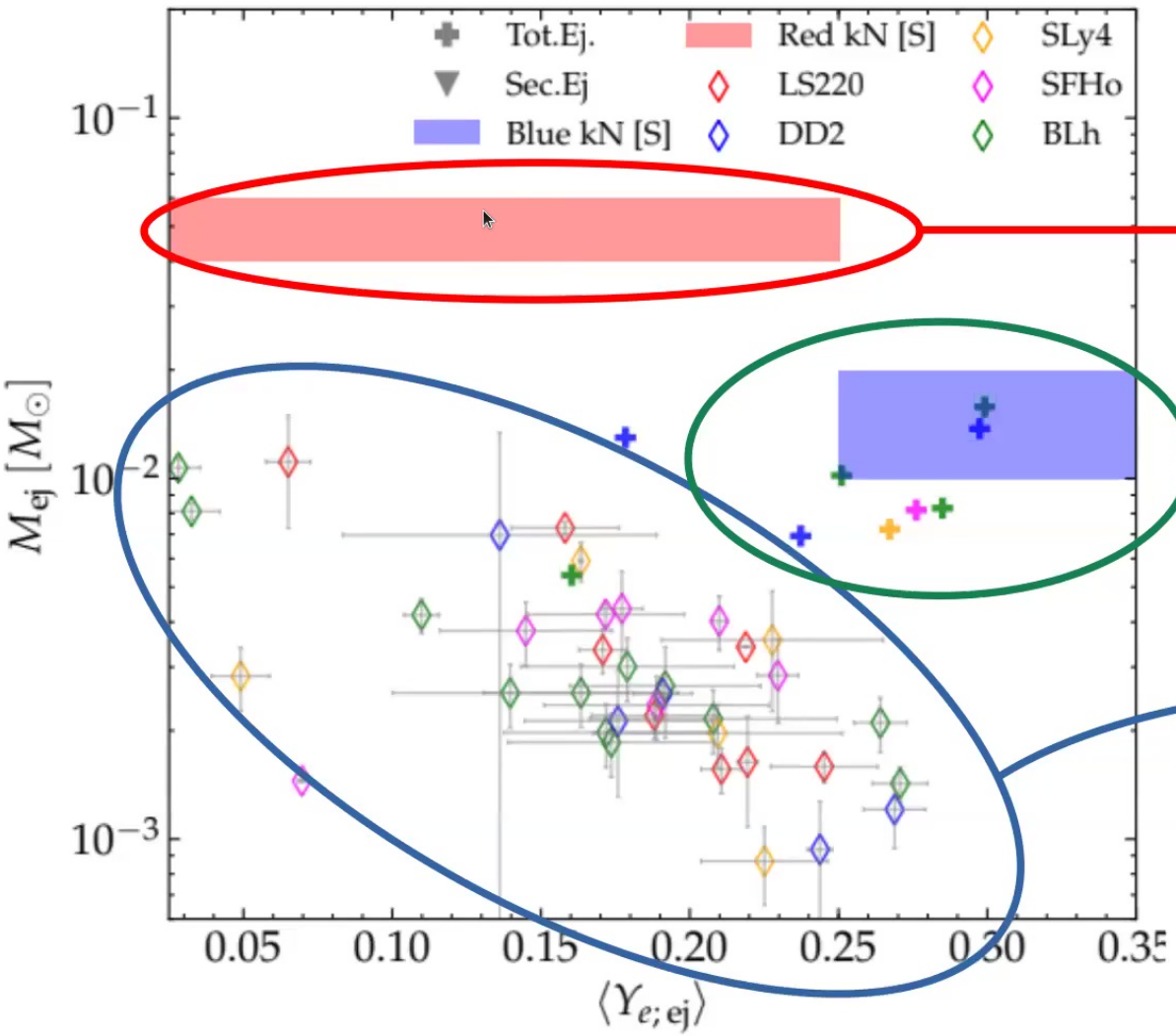




Spiral-wave wind?

Dynamical ejecta

From Nedora+, ApJ 906:98 (2021)



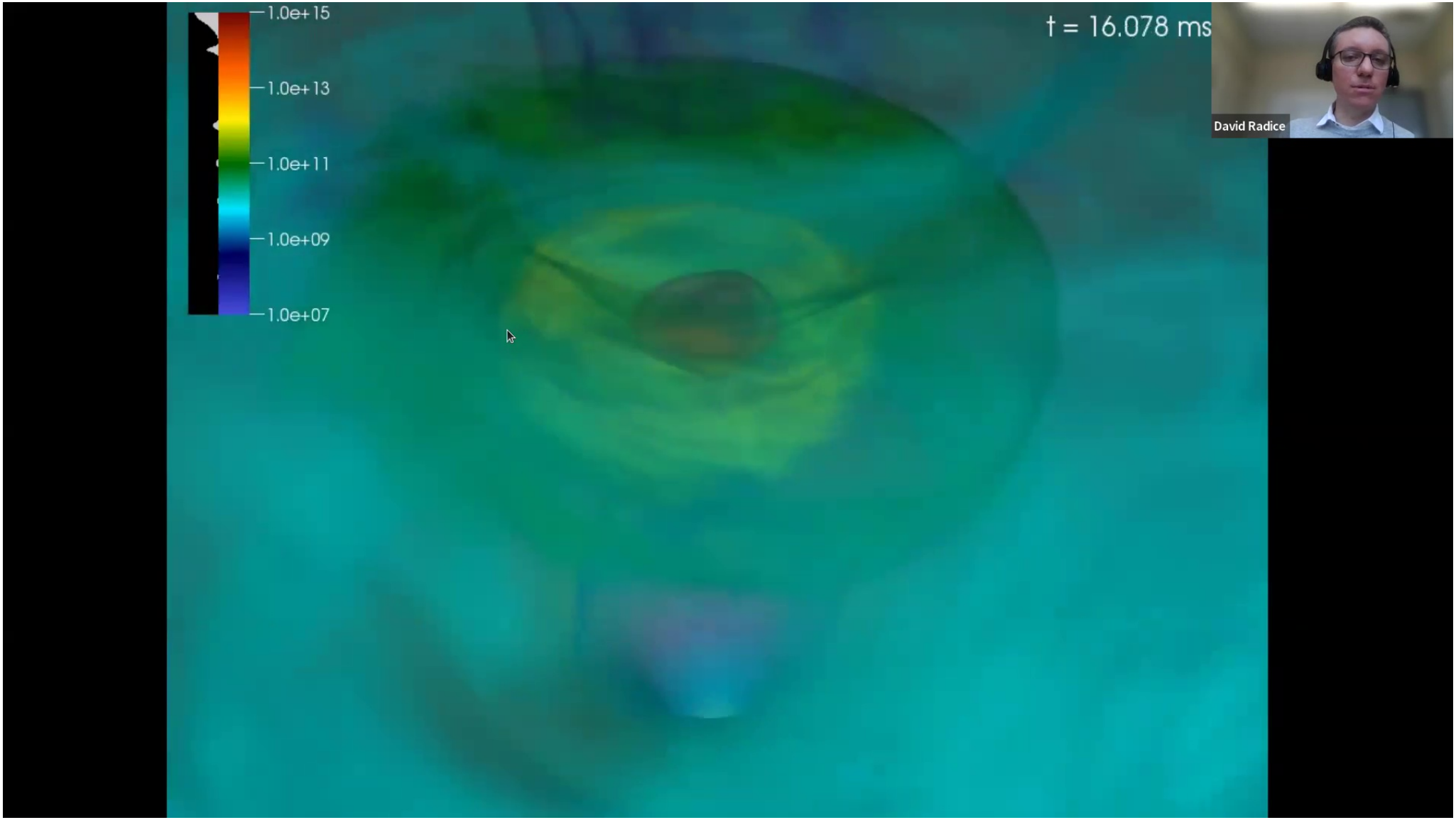


Disk recombination wind?!?

Spiral-wave wind?

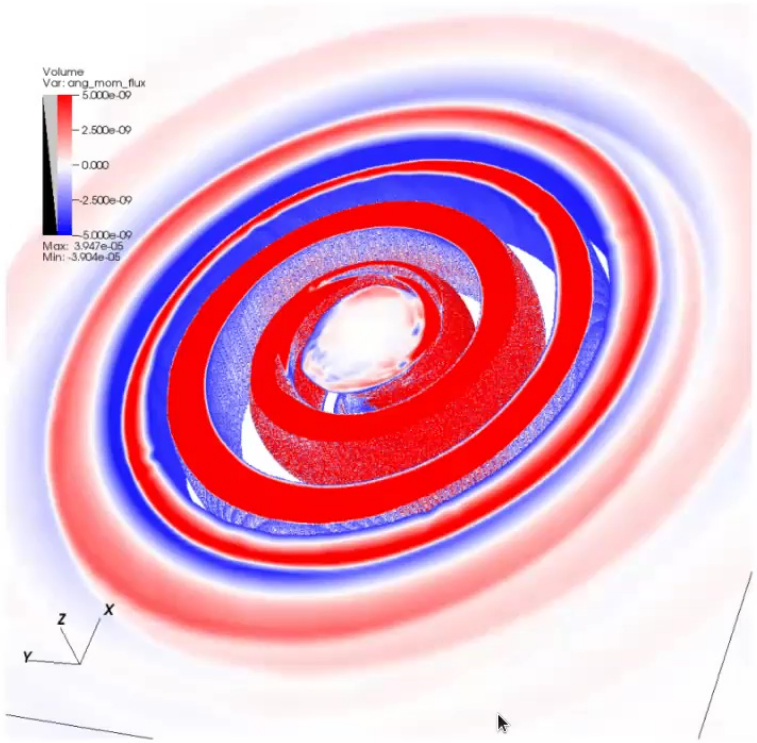
Dynamical ejecta

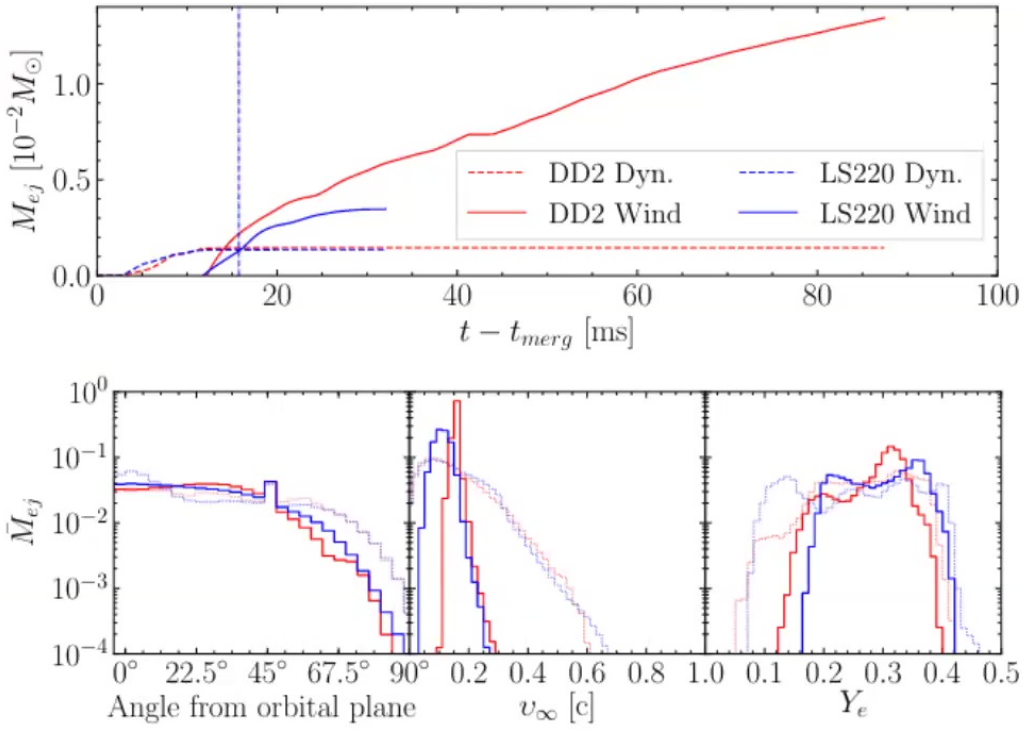
From Nedora+, ApJ 906:98 (2021)


1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 16.078 ms
David Radice


1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 30.240 ms
David Radice

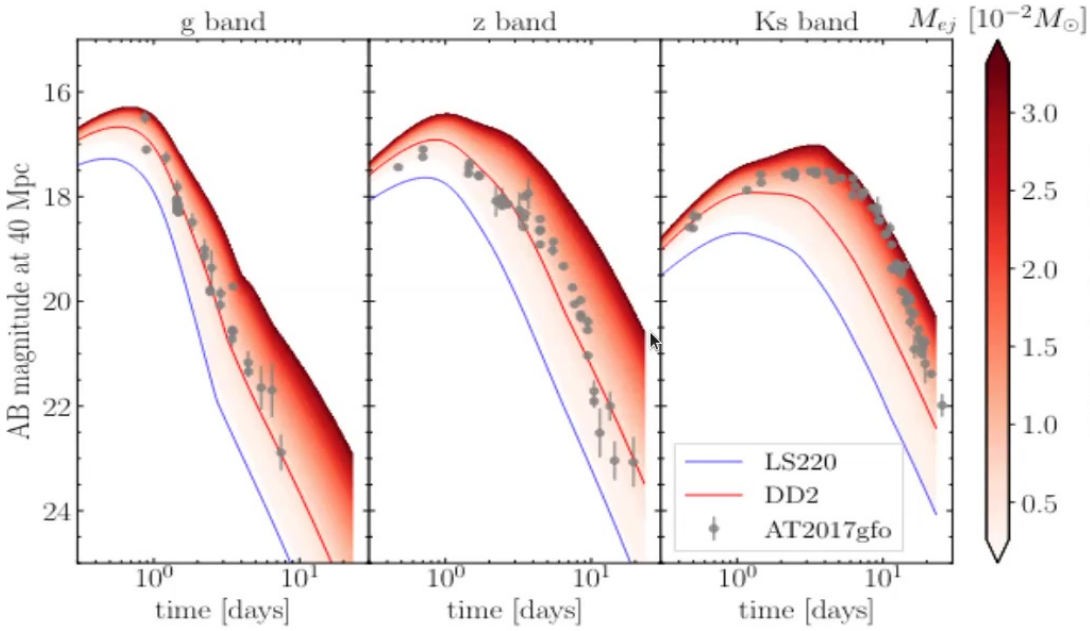
# Spiral-wave driven wind (I)

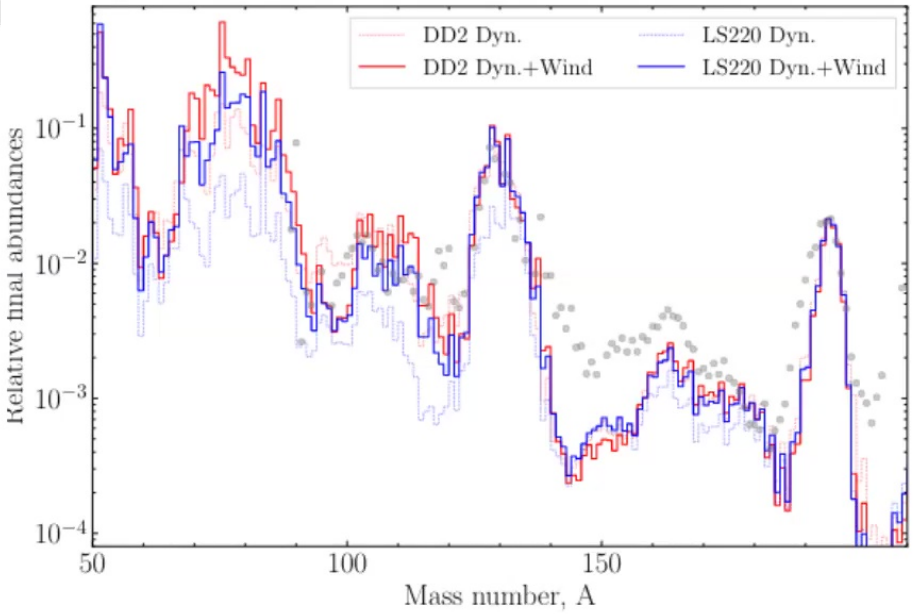



From Nedora+, ApJL 886:L30 (2019)

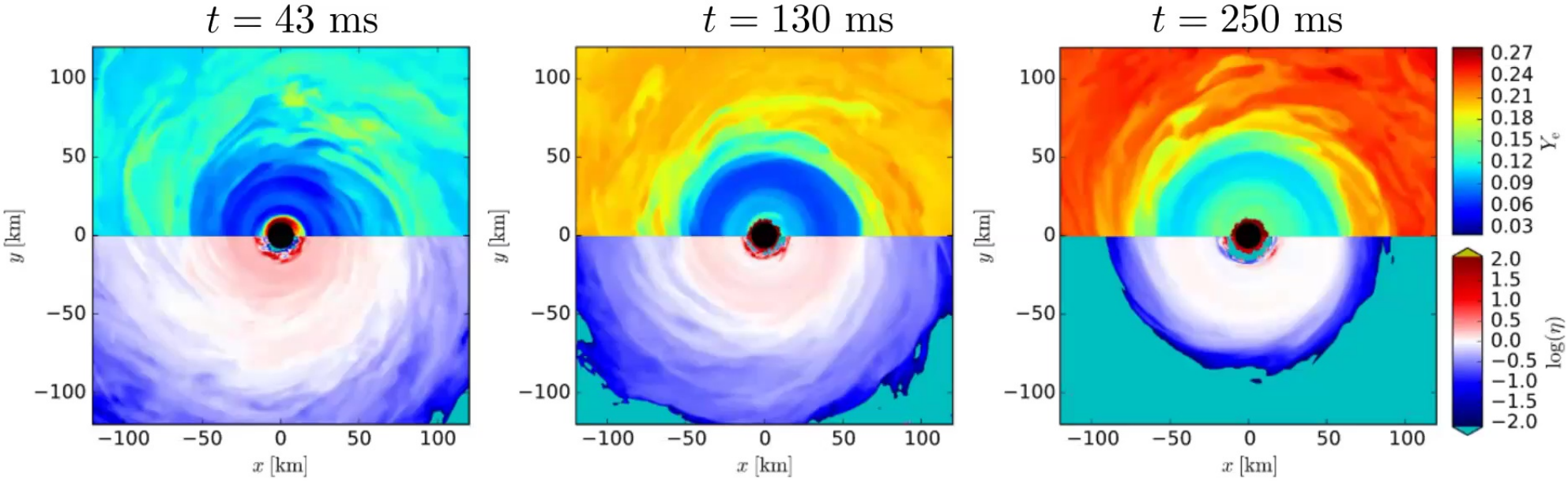
# Spiral-wave driven wind (II)


From Nedora+, ApJL 886:L30 (2019)

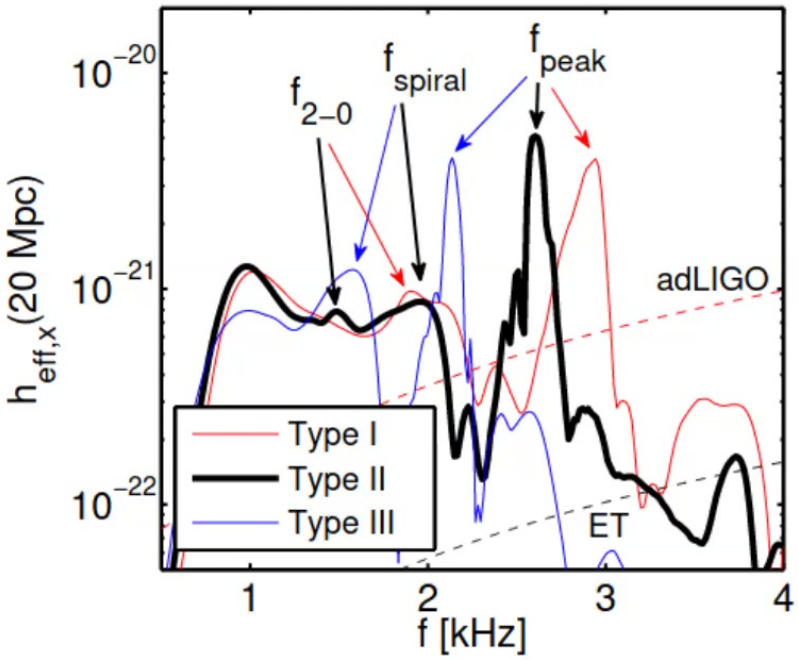
# What about the IR data?




From Siegel & Metzger, ApJ 858:52 (2018)

# Postmerger GW signal

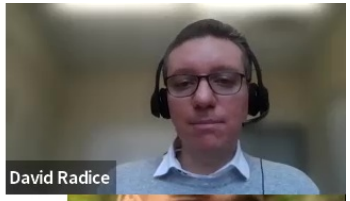

From Bauswein+ 2015

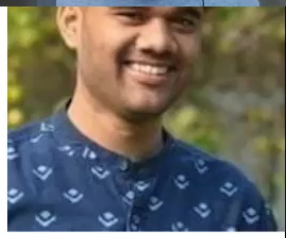


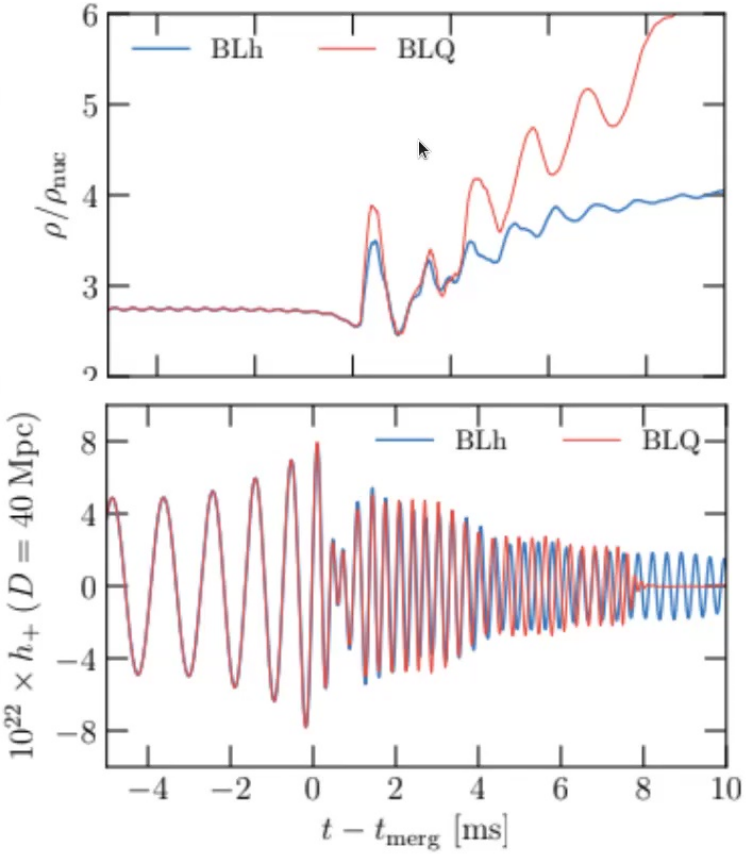

- Postmerger signal characterized by dominant frequency $f_{peak}$
- Need next gen. GW experiments, or very close (rare) events
- What can we learn from $f_{peak}$?
- Many ideas in the literature

See also Takami+ 2014; Bernuzzi 2015, Rezzolla+ 2016; Dietrich+ 2016; Breschi+ 2019; Bauswein+ 2019; …

# High-density physics





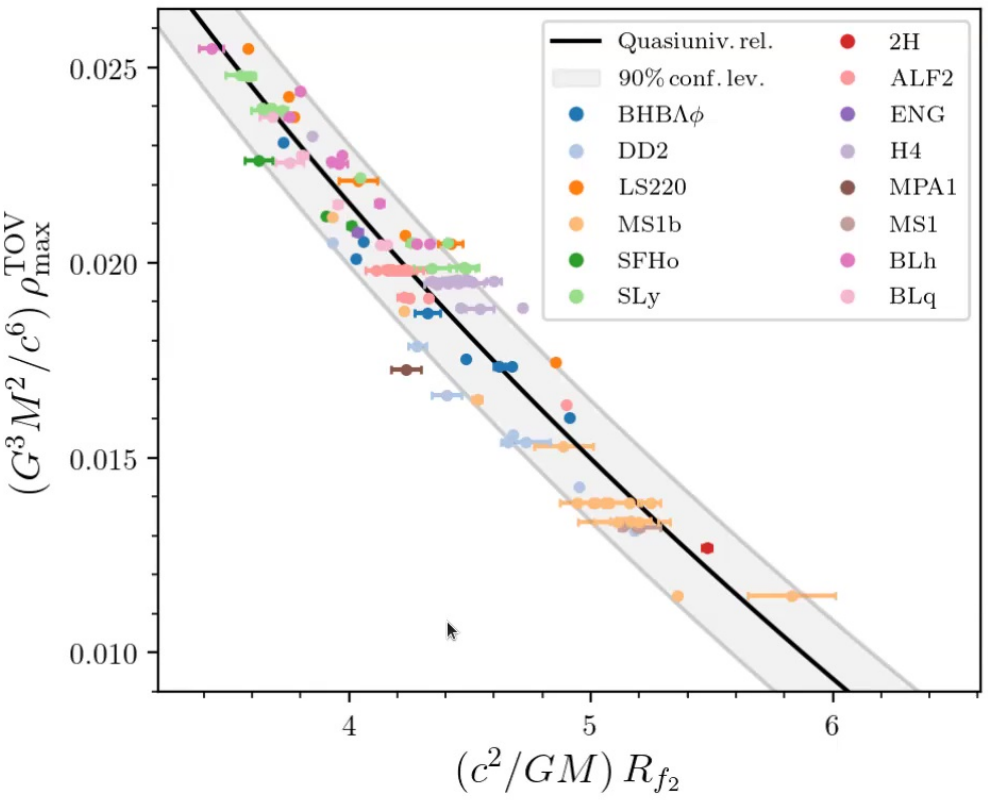

Prakash+, PRD 104:083029 (2021)

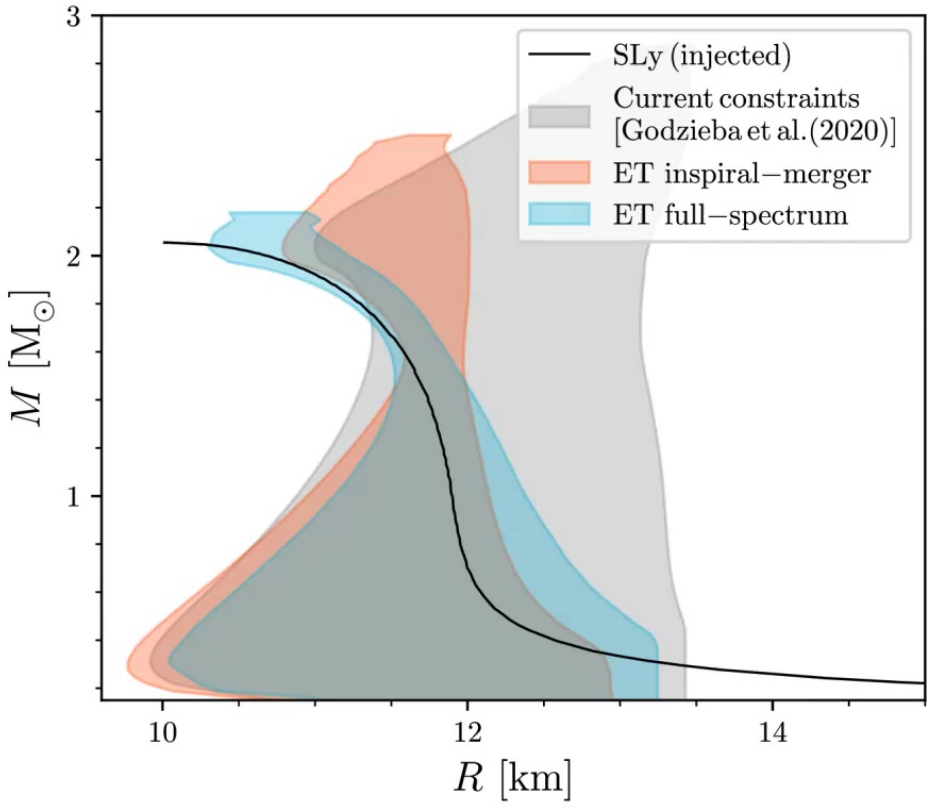
Blh: hadrons only
BLQ: deconfined quarks

- Phase transitions impact the life time of the remnant and the GWs
- Phase transition also cause more violent centrifugal bounce

See also: Bauswein+ 2019, 2020; Most+ 2019, Weigh+ 2019; Blacker+ 2020; Liebling+ 2021; ...

# Universal relations

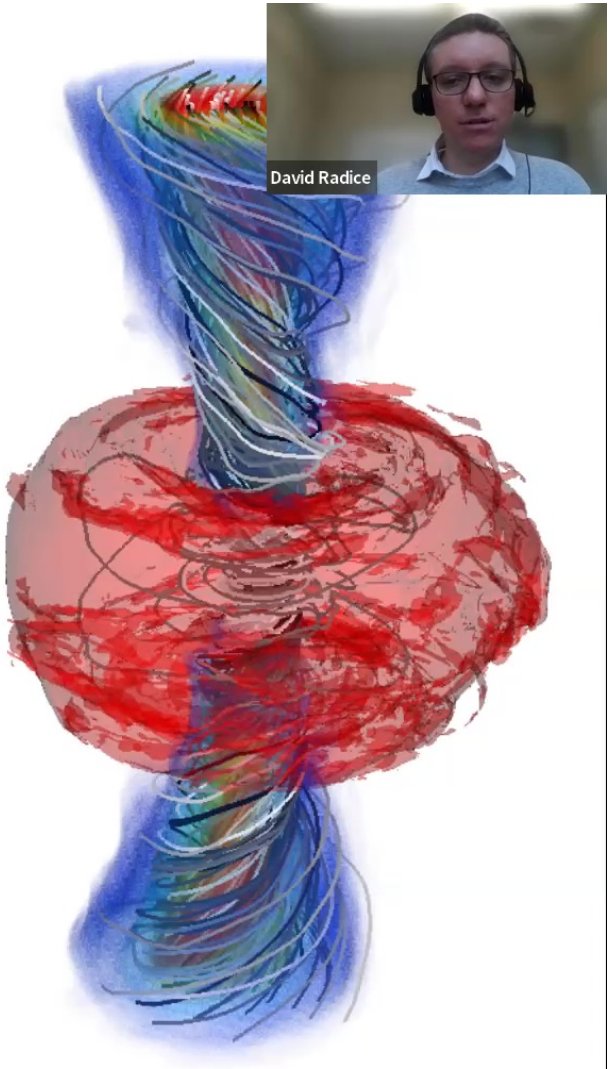




From Breschi+ 2110.06957

# Challenges

- Long-term GRMHD simulations to understand the full extent of the mass ejection from remnants
- Capture MHD turbulence and dynamo processes in the remnant
- Non-LTE neutrino radiation transport
- Neutrino flavor conversion

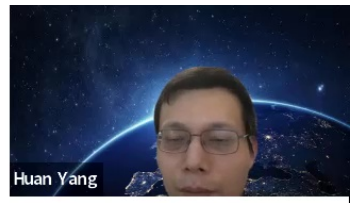


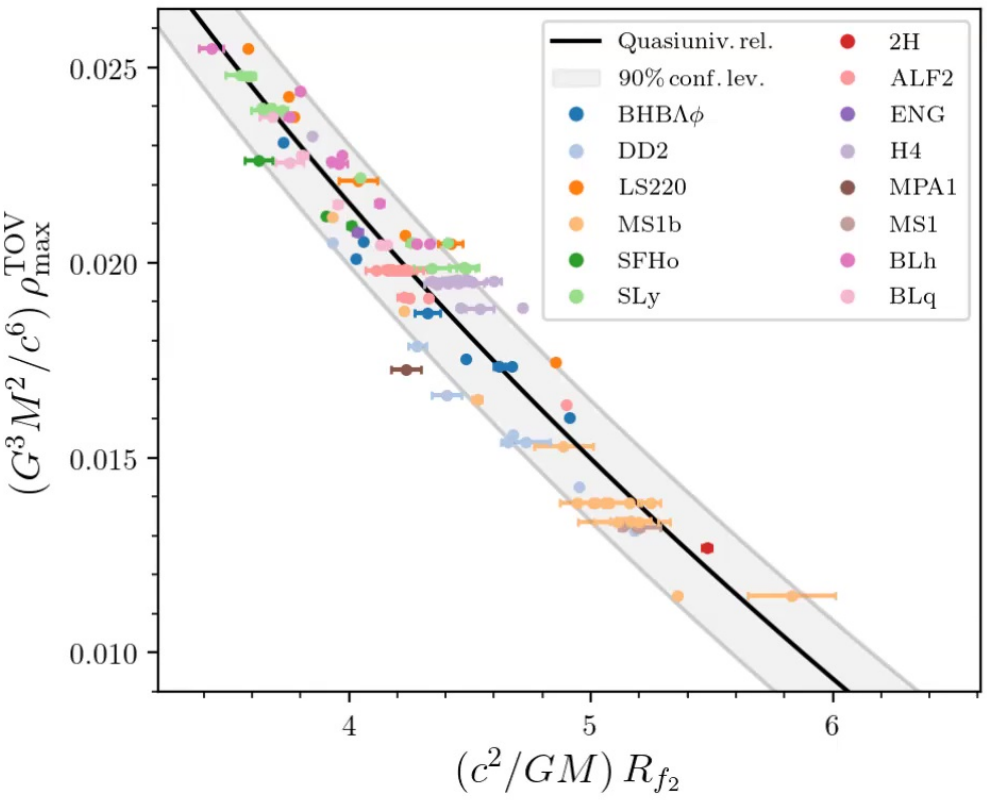

From Moesta+ ApJL, 901:L37 (2020)

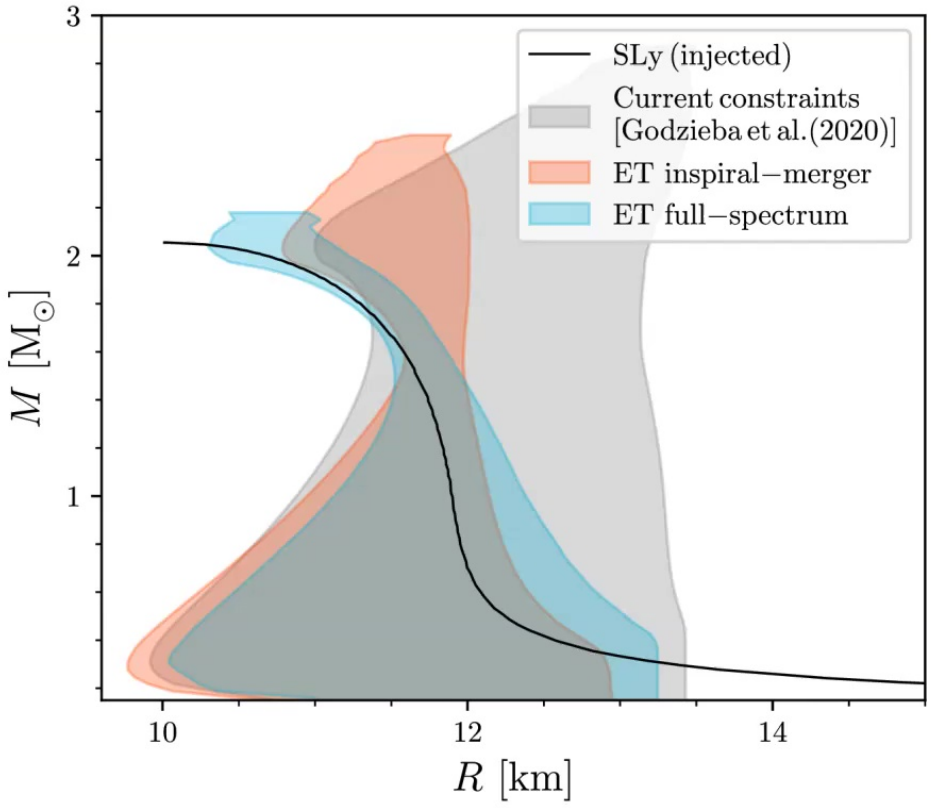
# Conclusions


- Numerical relativity is key for the interpretation of multi-messenger signals from compact binary mergers
- Multi-messenger data is starting to constrain the properties of dense matter and the origin of r-process elements
- Towards an ab-initio model of GW170817 and GW190425
- There is a bright future ahead for the field of multi-messenger astronomy with gravitational waves

# Universal relations

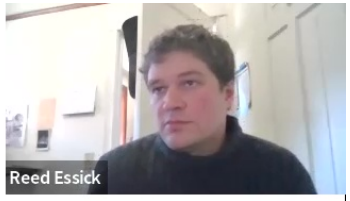


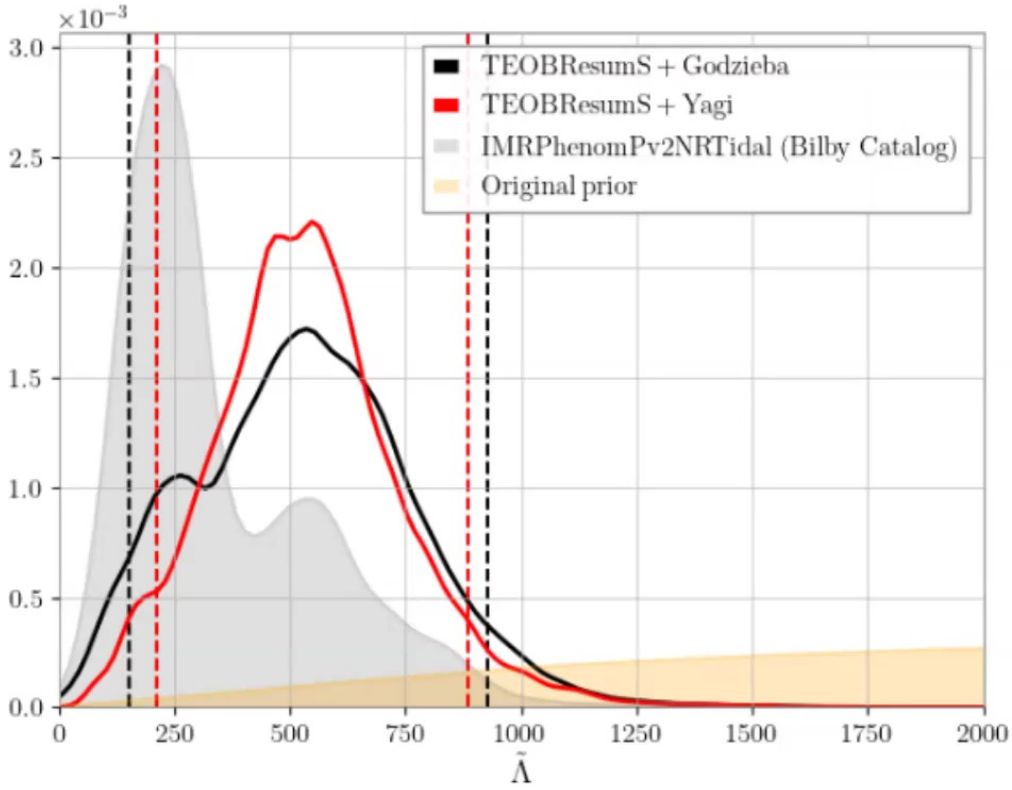



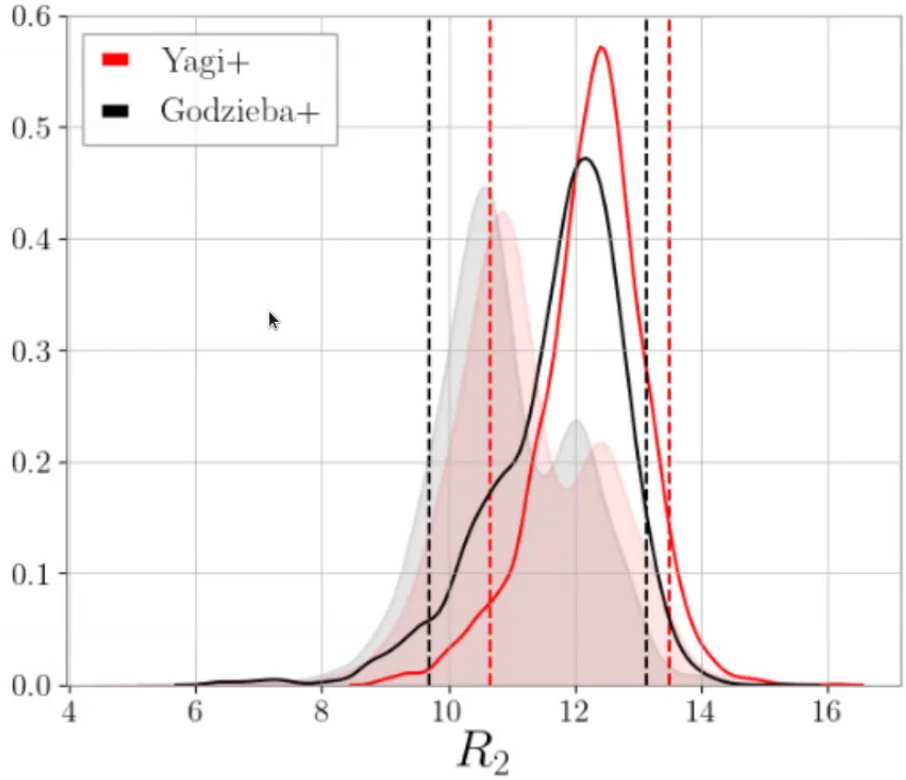




From Breschi+ 2110.06957

# GW170817



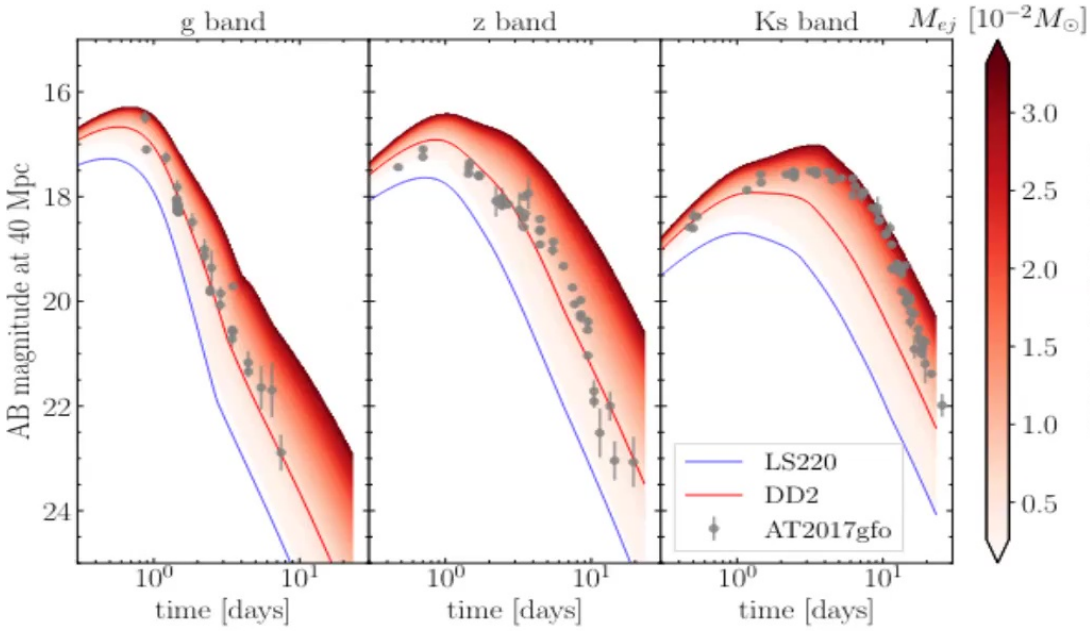



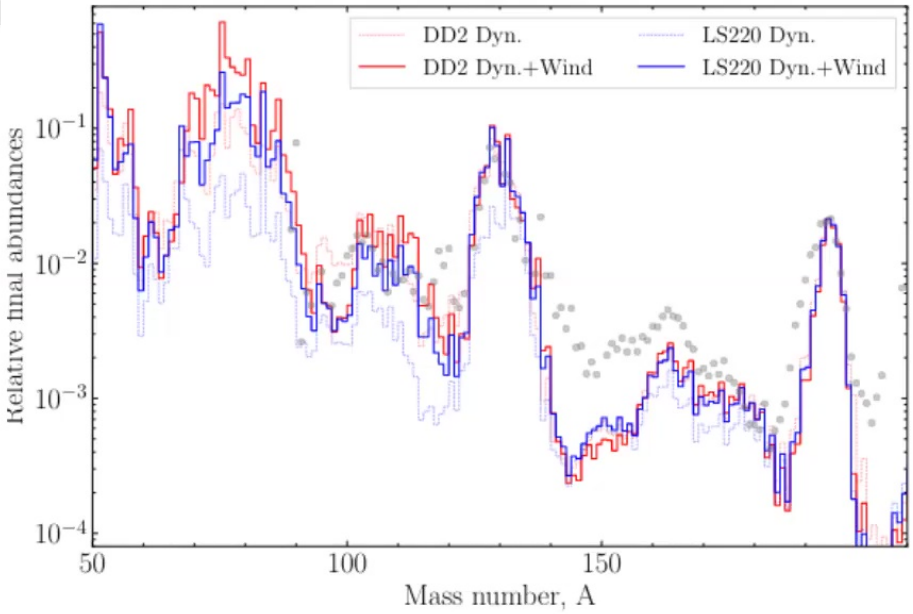




See also LVC 2017, 2018, De+ 2018, Choughlin+ 2018, Radice+ 2018, Capanno 2019, Raaijmakers+ 2021, ...

From Godzieba+ 2021

# Spiral-wave driven wind (II)


From Nedora+, ApJL 886:L30 (2019)