Supported by ERC through Starting Grant no. 759253

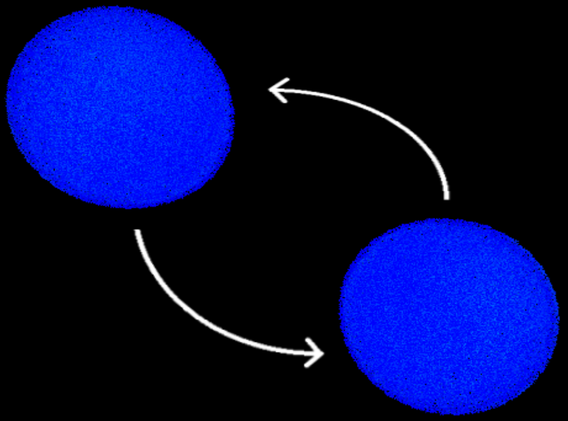
European Research Council
Established by the European Commission

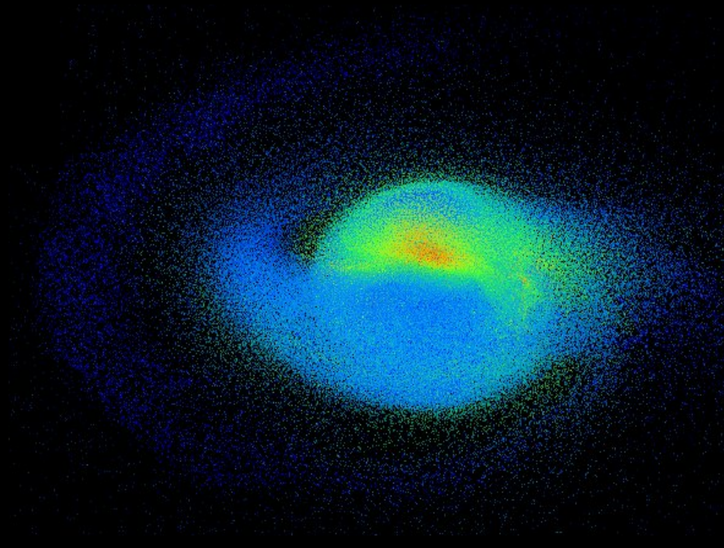
From quarks to black holes: micro- and macrophysics of neutron star mergers

Kolloquium, GSI, 31/01/2023

Andreas Bauswein

(GSI Darmstadt, HFHF)





What are neutron stars?

- Remnants of stellar evolution: NSs are collapsed cores of massive stars formed in core-collapse supernovae
- Typical mass 1.2 … 2.0 M_{sun}, typical radius 10 … 15 km → mean density exceeds nuclear density ($3*10^{14}$ g/cm^3) !!!

  → extreme astrophysical objects → NS are made of high-density matter !!
- A few 1000 NSs are observed: gamma, x-rays, UV, optical, … radio

  most as radio pulsars, i.e. with extremely periodic beamed radio emission (very stable rotator → clock) – light house effect
- Many, many more are expected to exist (invisible)
- More than 10 double NS systems known (containing at least one pulsar)
- Other binaries systems with white dwarfs
- Orbital modulation of radio emission allows very precise mass measurements in binary systems
- Accretion processes, high magnetic fields, NS cooling, …
- NSs as precursor of stellar black holes

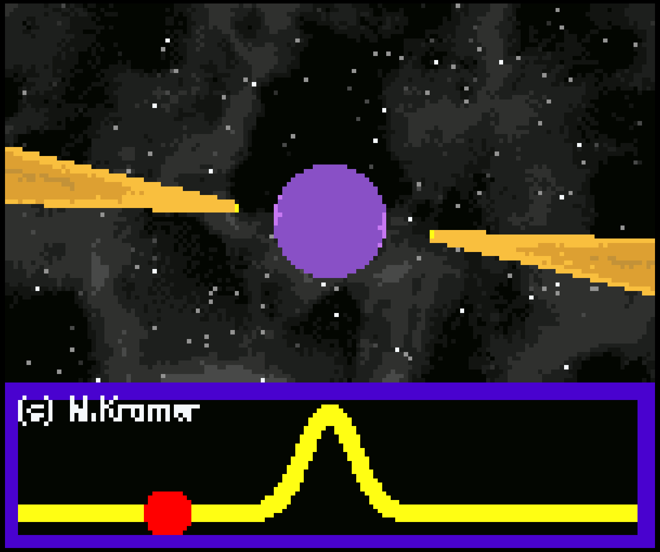
ESO/VLT

What are neutron stars?

- Remnants of stellar evolution: NSs are collapsed cores of massive stars formed in core-collapse supernovae
- Typical mass 1.2 … 2.0 M_{sun}, typical radius 10 … 15 km → mean density exceeds nuclear density ($3*10^{14}$ g/cm^3) !!!

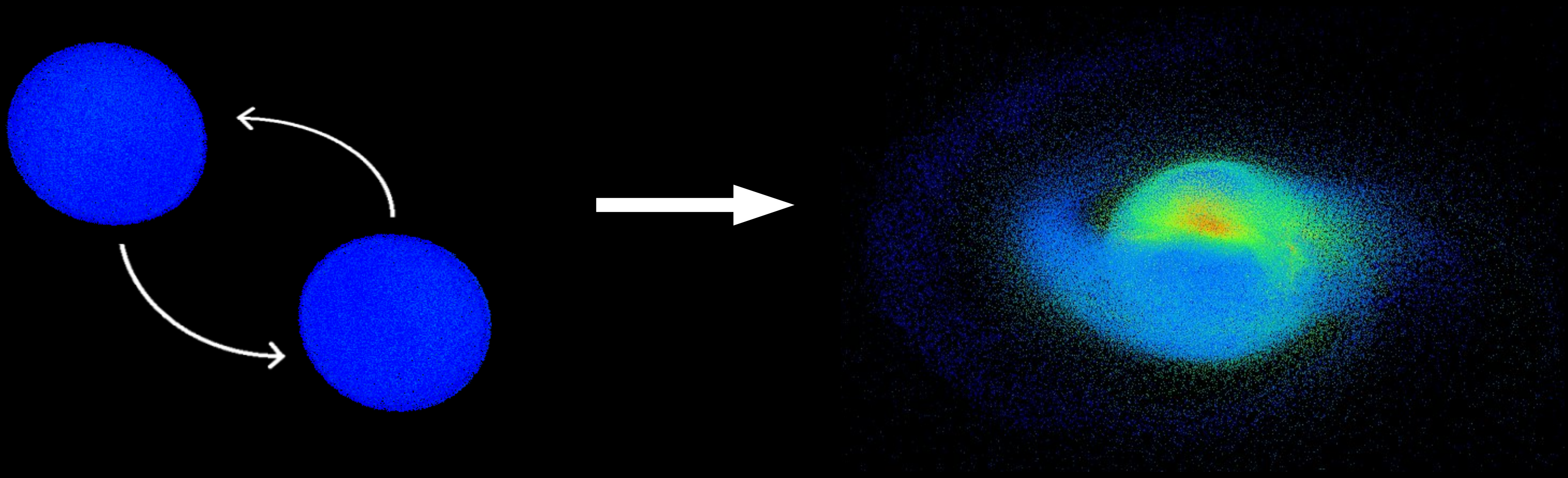
  → extreme astrophysical objects → NS are made of high-density matter !!
- A few 1000 NSs are observed: gamma, x-rays, UV, optical, … radio

  most as radio pulsars, i.e. with extremely periodic beamed radio emission (very stable rotator → clock) – light house effect
- Many, many more are expected to exist (invisible)
- More than 10 double NS systems known (containing at least one pulsar)
- Other binaries systems with white dwarfs
- Orbital modulation of radio emission allows very precise mass measurements in binary systems
- Accretion processes, high magnetic fields, NS cooling, …
- NSs as precursor of stellar black holes



M. Kramer

Neutron star mergers - overview



A break-through in astrophysics

= gravitational wave event on August 17, 2017

- GW170817 first unambiguously detected NS merger
- Multi-messenger observations: gravitational waves (GWs), gamma, X-rays, UV, optical, IR, radio

Detection August 17, 2017 by LIGO-Virgo network

→ GW data analysis providing approximate sky location

→ follow-up observations - probably largest coordinated observing campaign in astronomy (observations/time); starting immediately after – still ongoing in X-rays and radio


Advanced LIGO

→ settled many open/tentative/speculative ideas in the context of NS mergers !!!

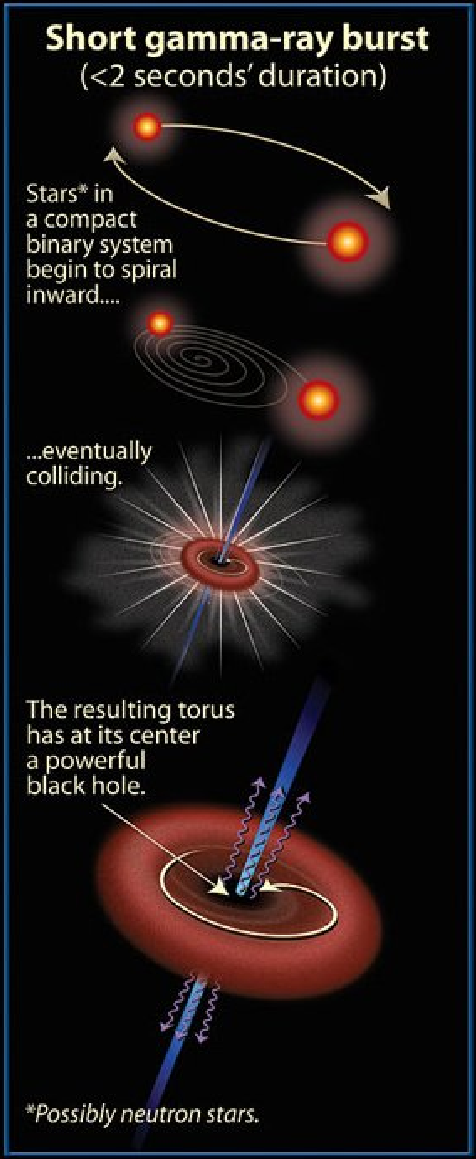
NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

Star-forming region, ESA/Spire

NS mergers as probes for fundamental physics

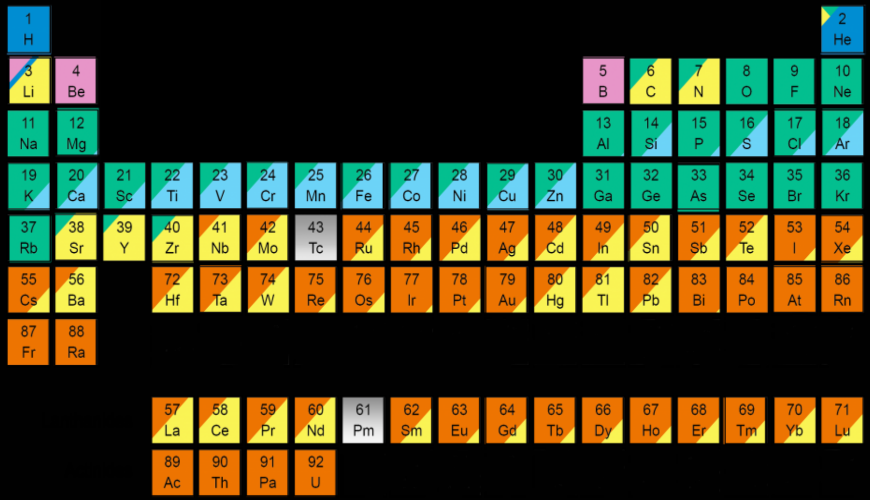
- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!



Covino 2007

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

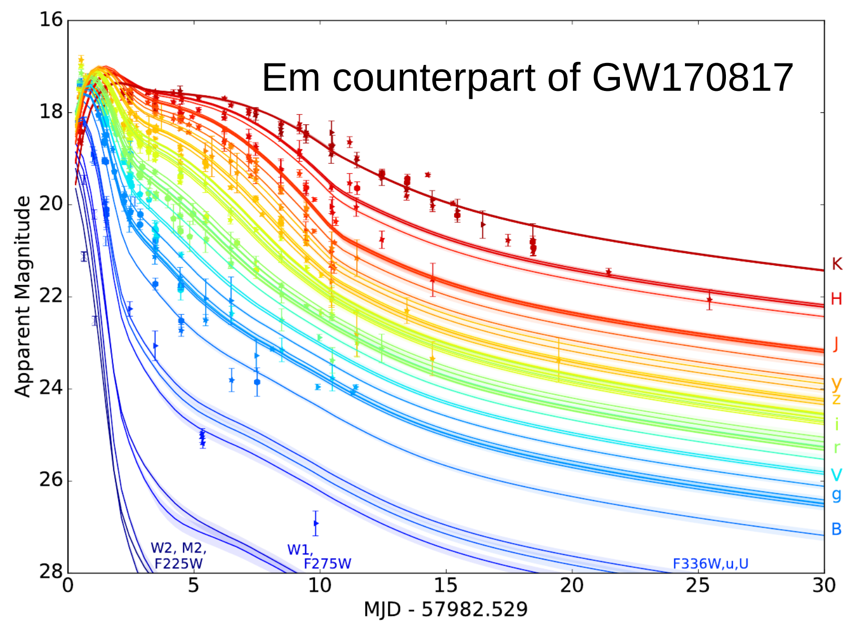


Graphic created by Jennifer Johnson

Astronomical Image Credits:
ESA/NASA/AASNova

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

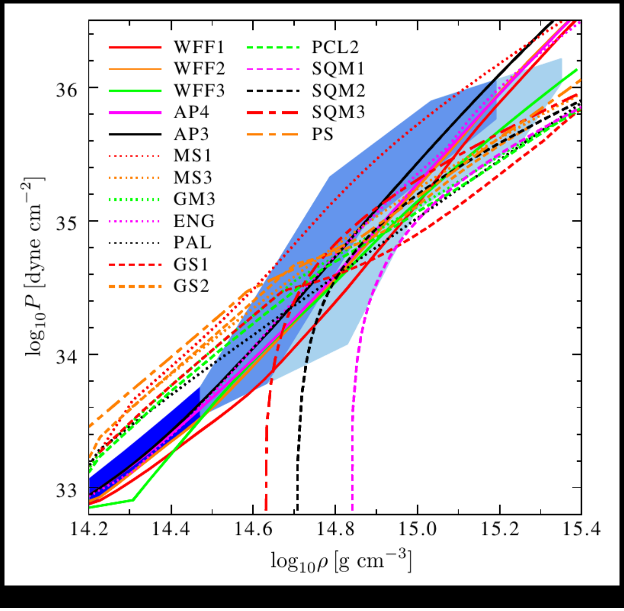


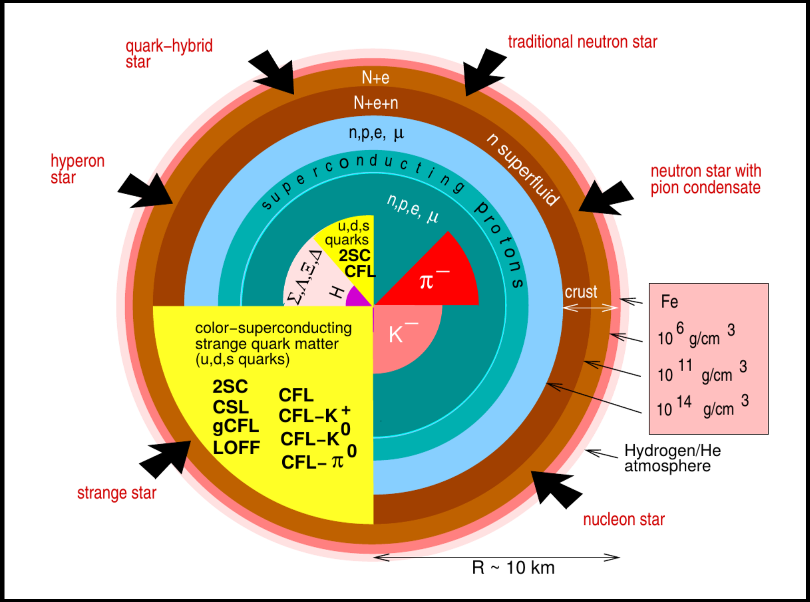
Villar et al. 2017

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

Hebeler & Schwenk 2014

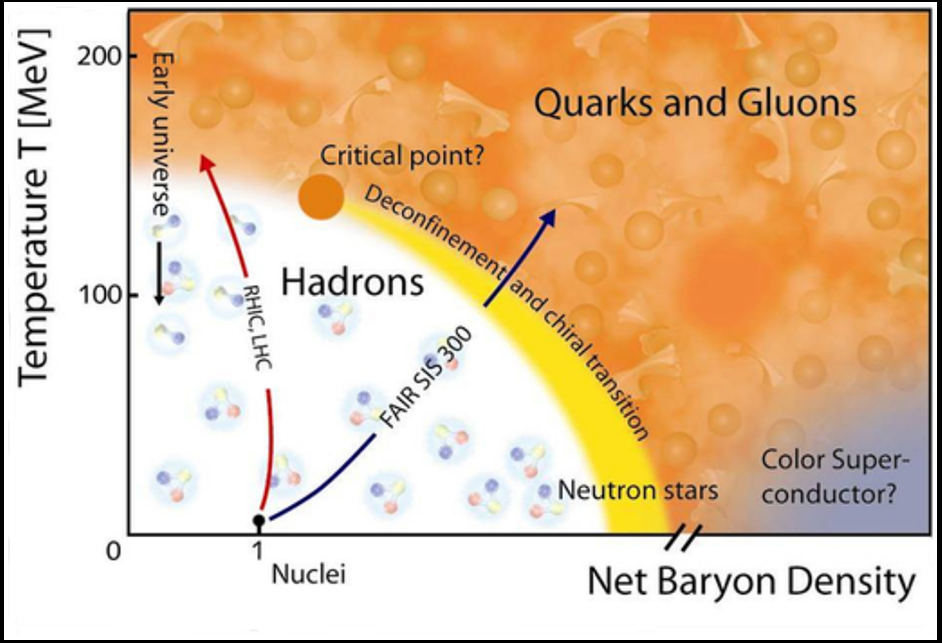




Weber 2004

NS mergers as probes for fundamental physics

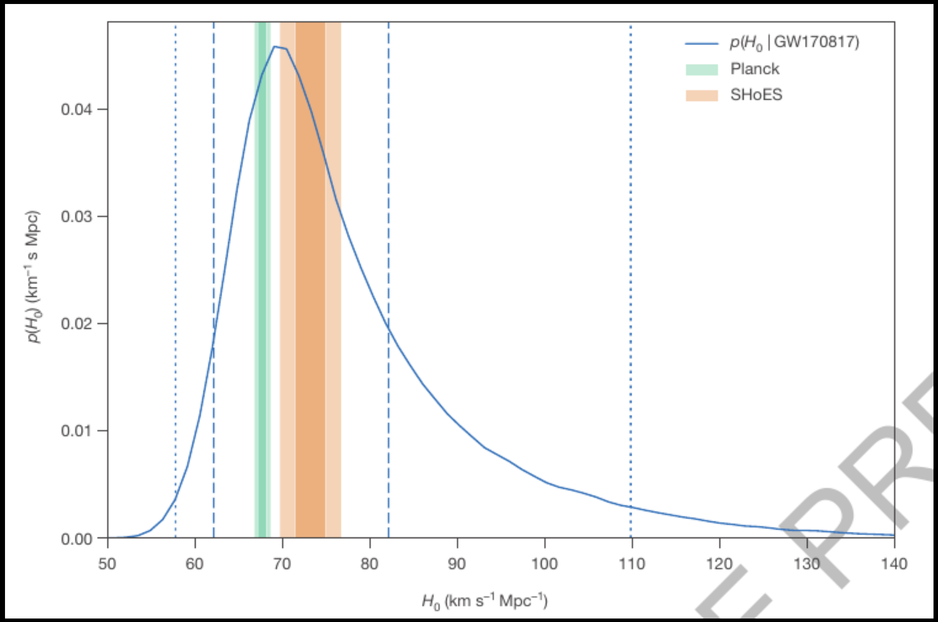
- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!



GSI

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!



Abbott et al 2017

Outline

- Understanding properties of hot and dense matter from mergers

  - Finite-size effects affect orbital motion

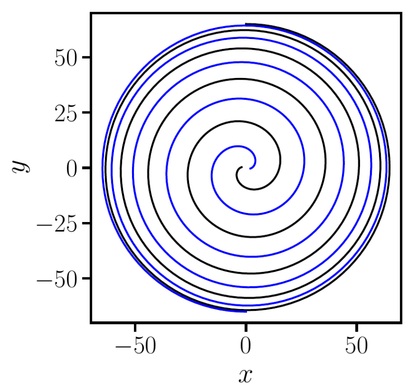
  - Black hole formation in neutron star mergers

  - Postmerger GW oscillations
- Quark matter in neutron star mergers
- Nucleosynthesis of heavy elements in ejecta of NS mergers

  → ongoing work on r-process and kilonovae

- Many interesting and important aspects of NSMs cannot be covered:

  - Gamma-ray bursts, X-ray emission, binary population, Hubble constant, ...



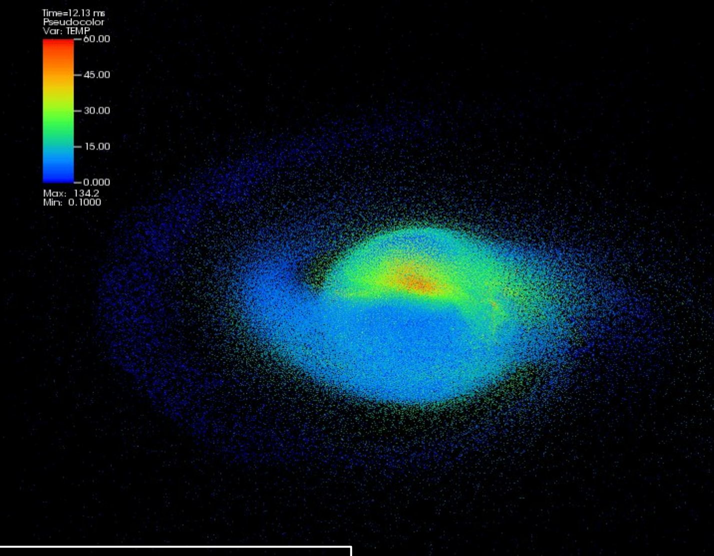
$P_{orb} \sim 10\,h$

Inspiral of NS binary

~100 Myrs

$P_{orb} \sim 1\,ms$

Neutron star merger



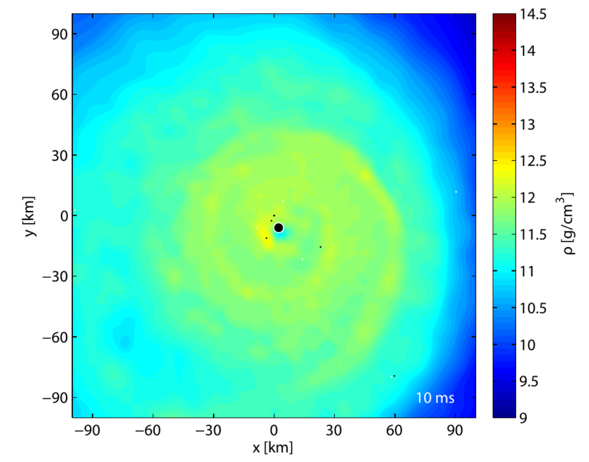
dependent on EoS, M_{tot}

ms

ms

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS



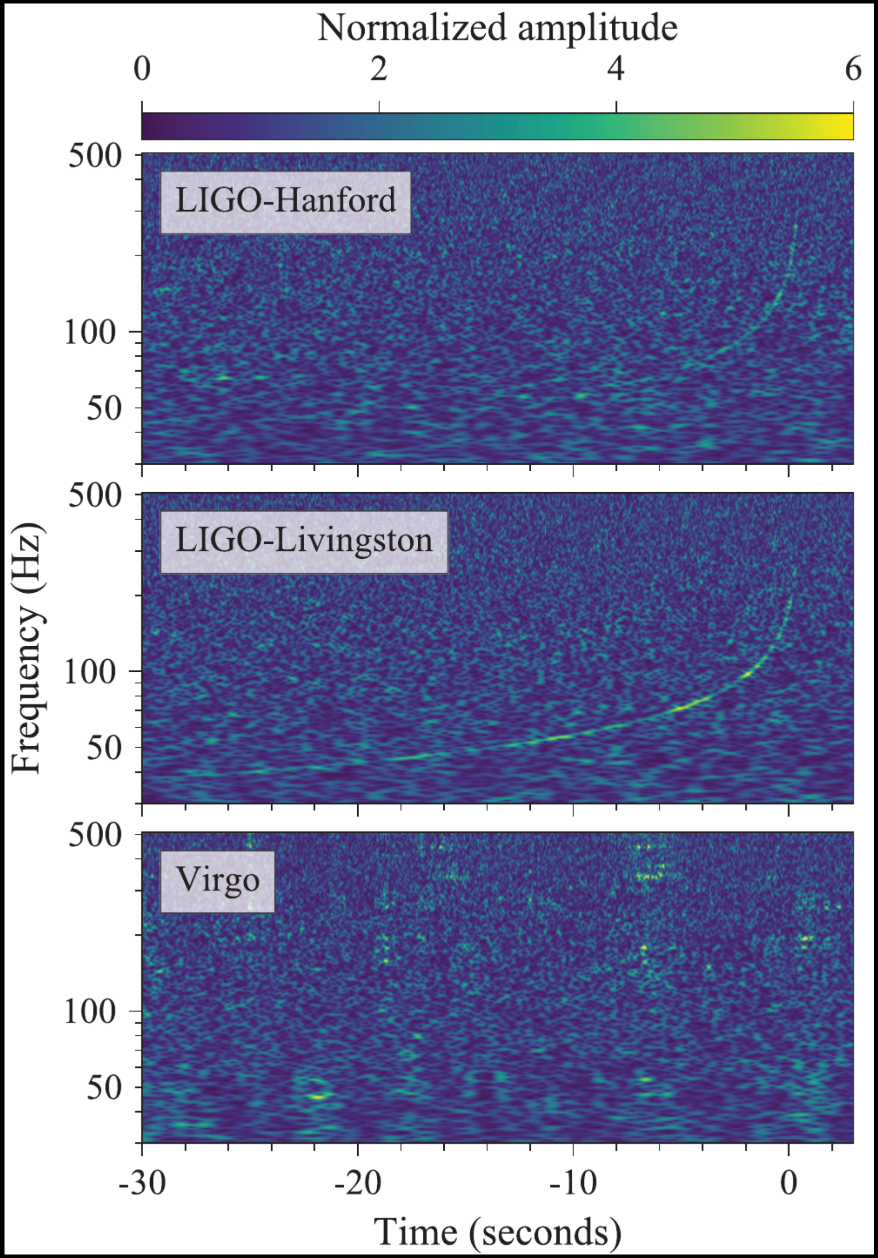
dependent on EoS, M_{tot}

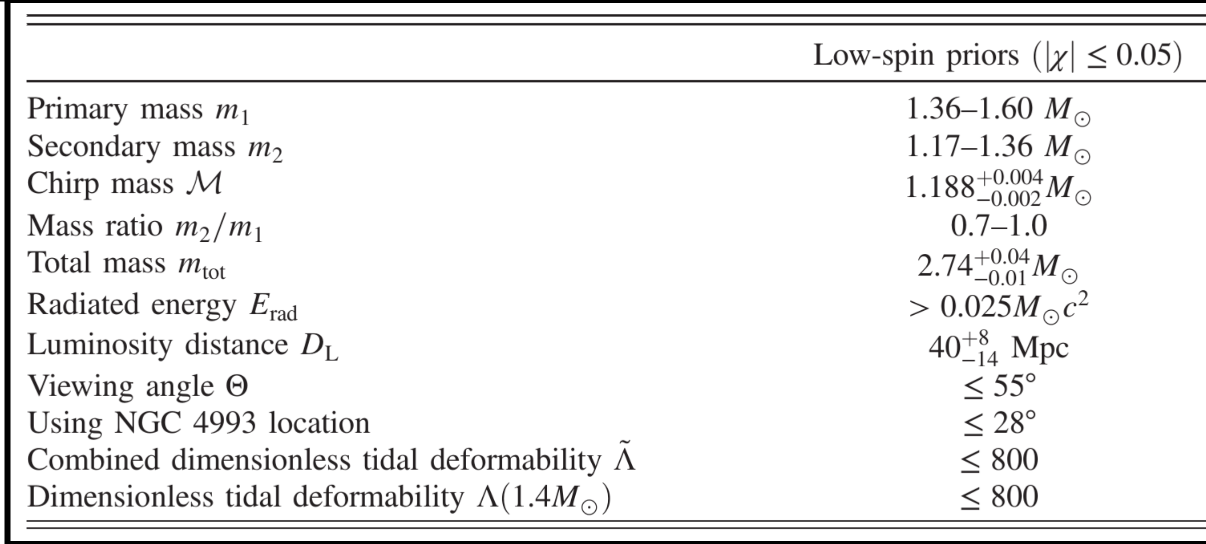
10-100 ms

Rigidly rotating (supermassive) NS (stable or long-lived)

Delayed collapse to a BH + torus

GW170817





	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

Binary masses measured by GWs !!!

Generally:

- chirp mass and total mass measured accurately
- mass ratio and component masses less

(but instrument sensitivity increases !)

Distance: 40 Mpc ~ 140 Mega light years

Abbott et al 2017

More (puzzling) events

- No em counterparts (recall distance)
- Pretty high mass compared to known NSs !
- What’s the nature of the 2.6 Msun object?

  - BH → no mass gap ?

  - slowly rot. NS → high Mmax

  - rapidly rot. NS → why rotation?

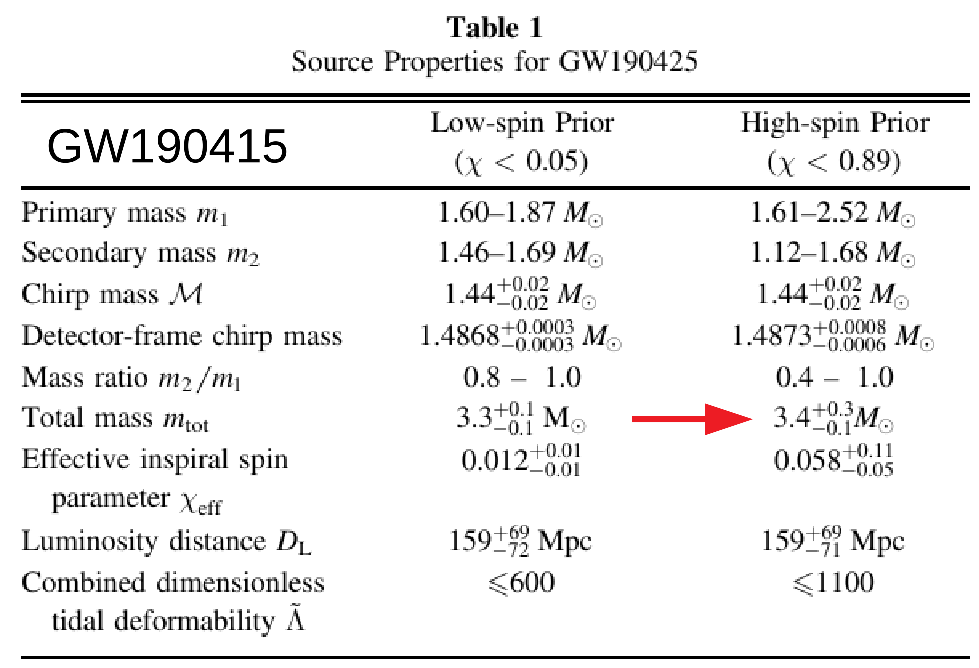
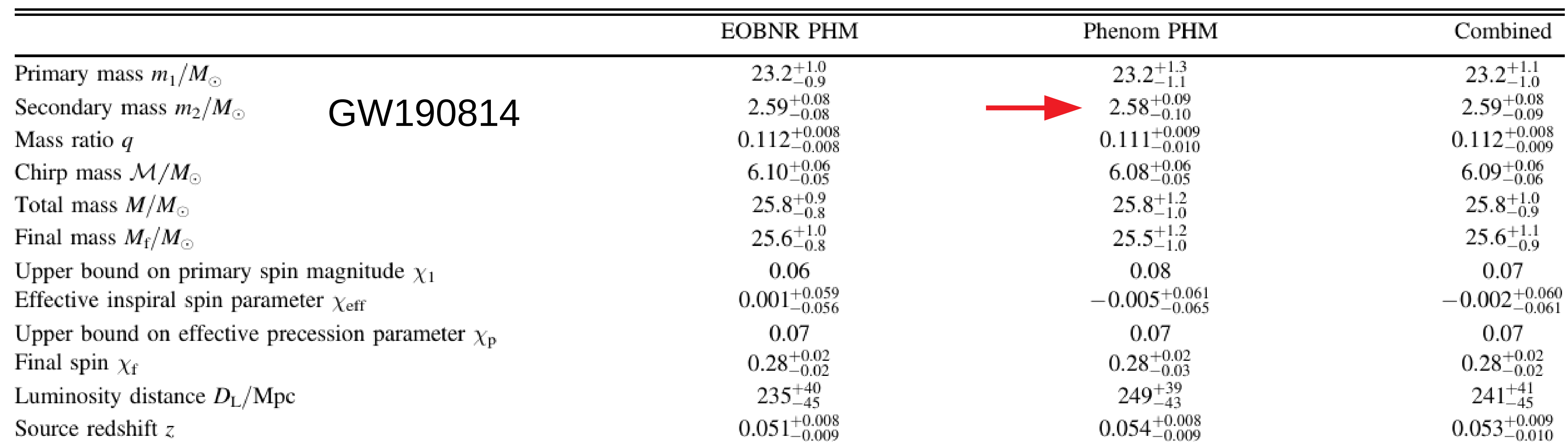


Table 1
Source Properties for GW190425

GW190415	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_\odot$	1.61–2.52 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$	1.12–1.68 $M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}$ $M_\odot$	$1.44^{+0.02}_{-0.02}$ $M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}$ $M_\odot$	$1.4873^{+0.0008}_{-0.0006}$ $M_\odot$
Mass ratio m_2/m_1	0.8 – 1.0	0.4 – 1.0
Total mass $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}$ $\mathrm{M}_\odot$	$3.4^{+0.3}_{-0.1} M_\odot$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.012^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance $D_{\rm L}$	159^{+69}_{-72} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\leqslant 600$	$\leqslant 1100$



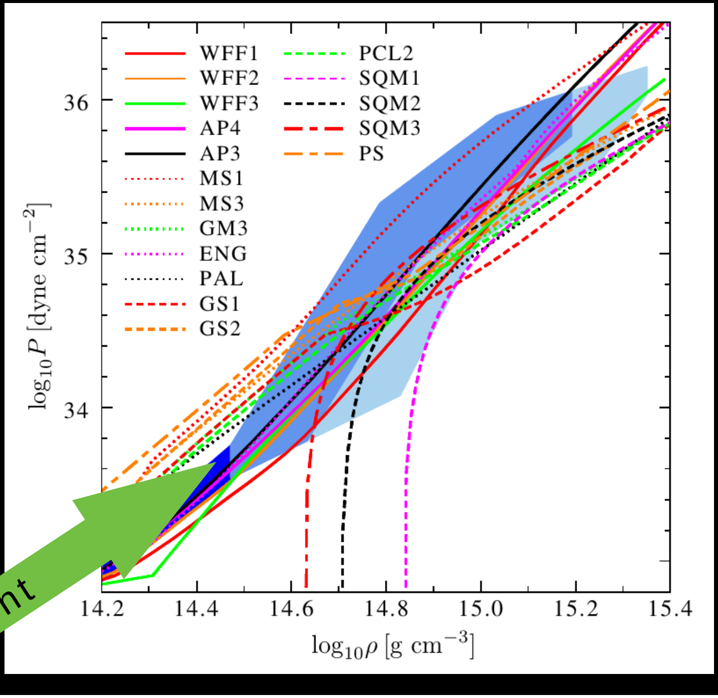
GW190814

	EOBNR PHM	Phenom PHM	Combined
Primary mass $m_1/M_\odot$	$23.2^{+1.0}_{-0.9}$	$23.2^{+1.3}_{-1.1}$	$23.2^{+1.1}_{-1.0}$
Secondary mass $m_2/M_\odot$	$2.59^{+0.08}_{-0.08}$	$2.58^{+0.09}_{-0.10}$	$2.59^{+0.08}_{-0.09}$
Mass ratio q	$0.112^{+0.008}_{-0.008}$	$0.111^{+0.009}_{-0.010}$	$0.112^{+0.008}_{-0.009}$
Chirp mass $\mathcal{M}/M_\odot$	$6.10^{+0.06}_{-0.05}$	$6.08^{+0.06}_{-0.05}$	$6.09^{+0.06}_{-0.06}$
Total mass $M/M_\odot$	$25.8^{+0.9}_{-0.8}$	$25.8^{+1.2}_{-1.0}$	$25.8^{+1.0}_{-0.9}$
Final mass $M_{\rm f}/M_\odot$	$25.6^{+1.0}_{-0.8}$	$25.5^{+1.2}_{-1.0}$	$25.6^{+1.1}_{-0.9}$
Upper bound on primary spin magnitude χ_1	0.06	0.08	0.07
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.001^{+0.059}_{-0.056}$	$-0.005^{+0.061}_{-0.065}$	$-0.002^{+0.060}_{-0.061}$
Upper bound on effective precession parameter $\chi_{\rm p}$	0.07	0.07	0.07
Final spin $\chi_{\rm f}$	$0.28^{+0.02}_{-0.02}$	$0.28^{+0.02}_{-0.03}$	$0.28^{+0.02}_{-0.02}$
Luminosity distance $D_{\rm L}/\mathrm{Mpc}$	235^{+40}_{-45}	249^{+39}_{-43}	241^{+41}_{-45}
Source redshift z	$0.051^{+0.008}_{-0.009}$	$0.054^{+0.008}_{-0.009}$	$0.053^{+0.009}_{-0.010}$

The holy grail of NS physics:

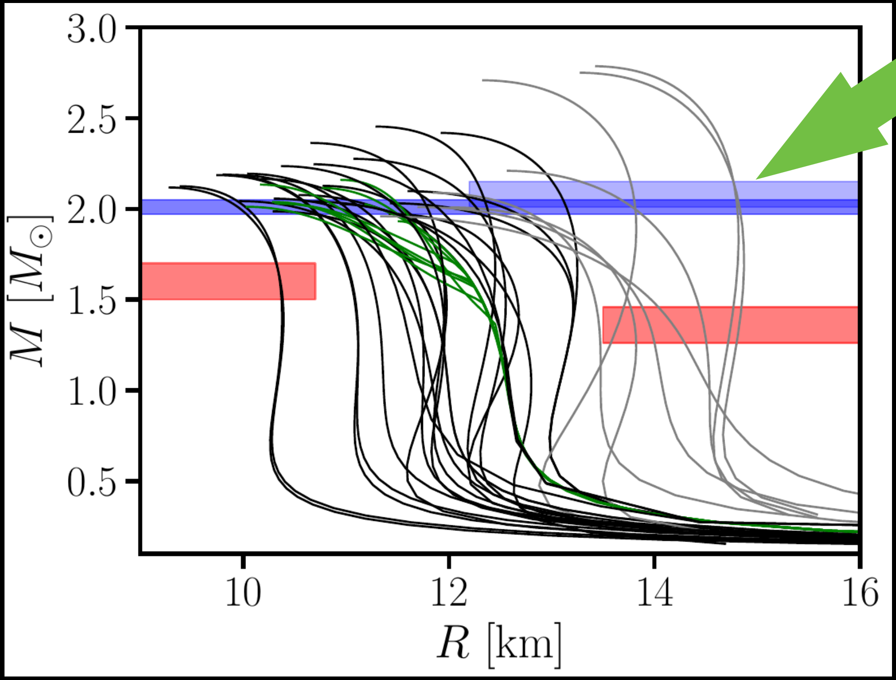
Everything depends on the EoS !!!

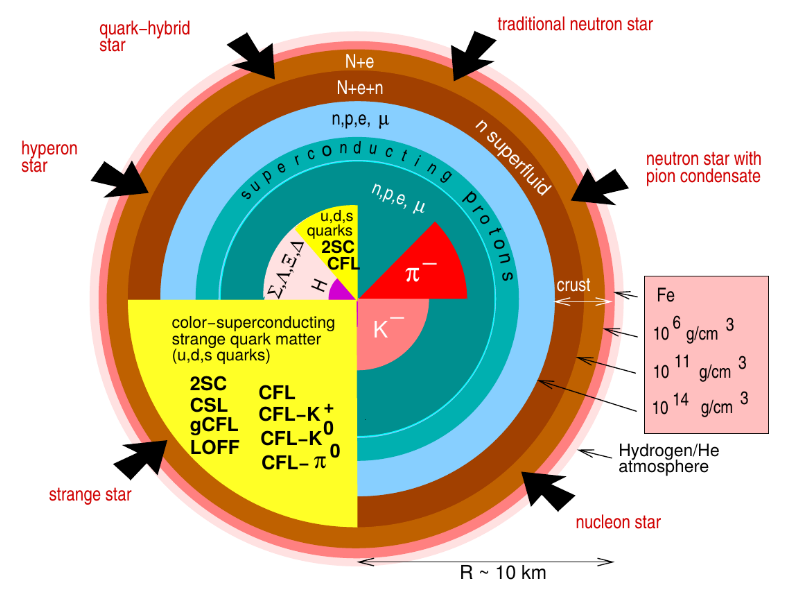
Different approaches to high density matter



Hebeler & Schwenk 2014

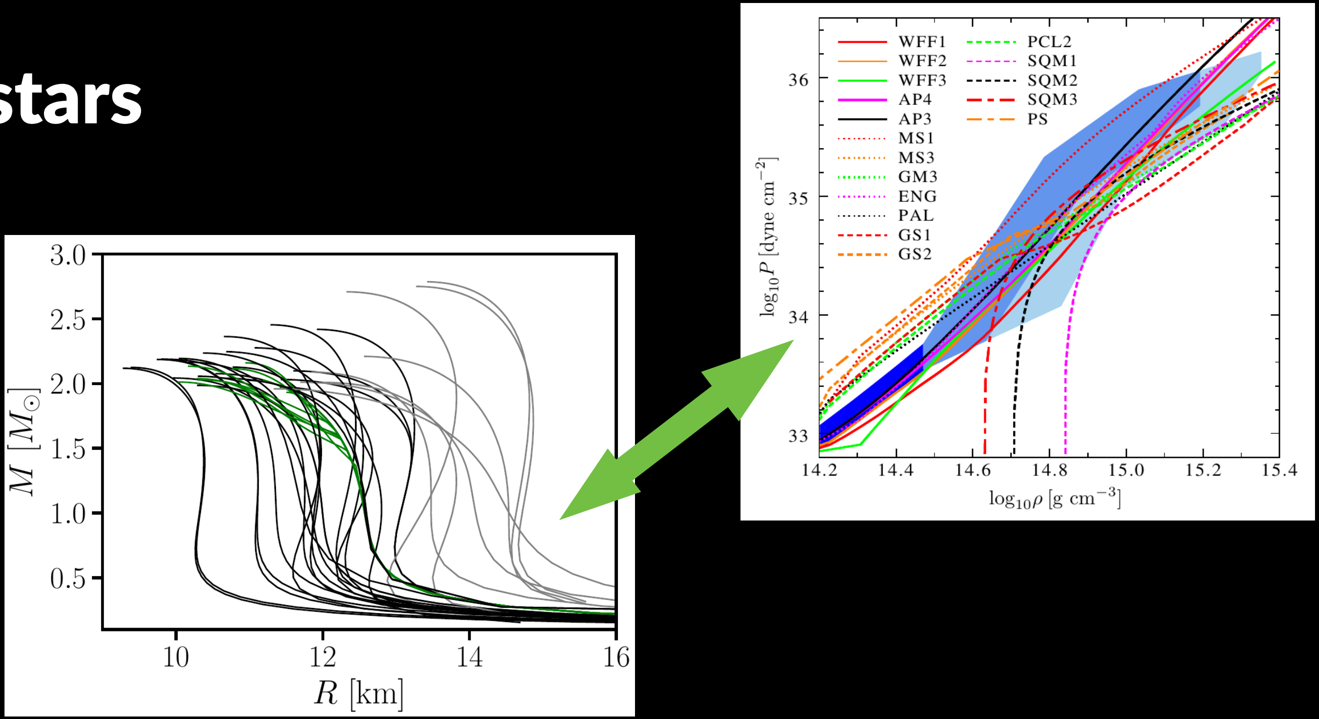
equivalent





Weber 2004

Neutron stars



Hebeler & Schwenk 2014

- Important here: EoS and stellar structure (mass-radius relation) uniquely linked !

  All neutron stars follow the same M-R relation / EoS !

  → measure / constrain stellar properties → EoS

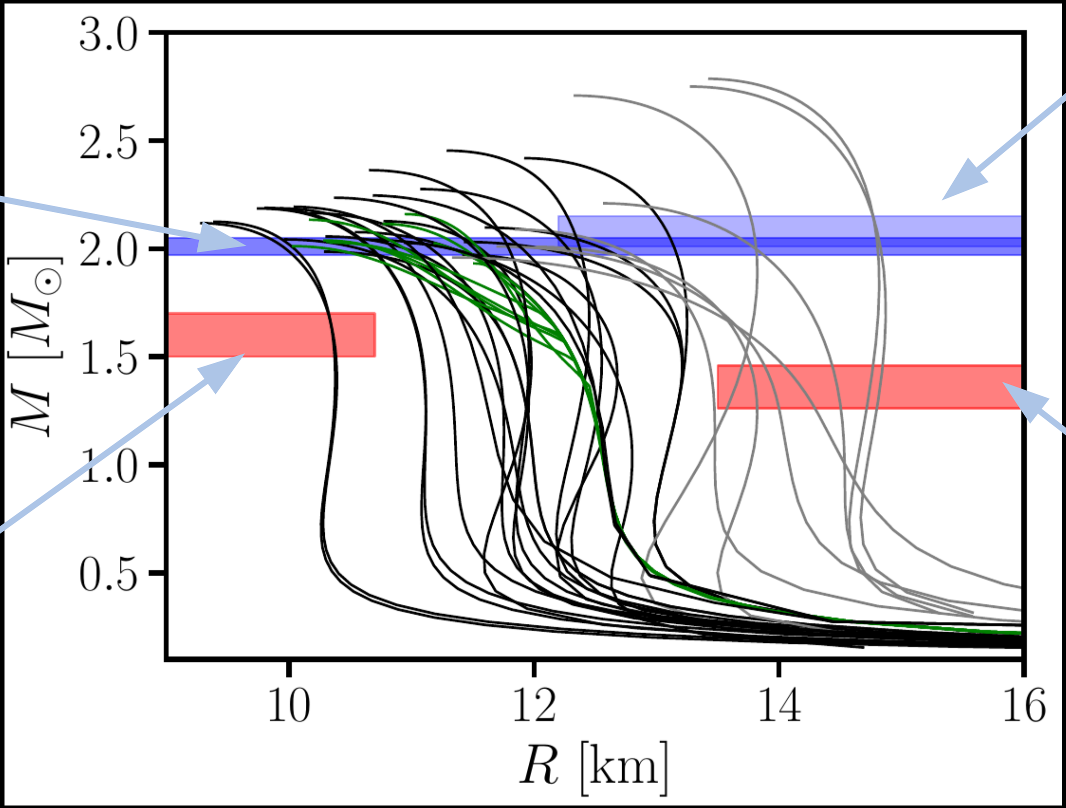
$$\frac{dM}{dr} = 4\pi r^2 \rho \qquad (1)$$

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}\left(1+\frac{P}{c^2\rho}\right)\left(1+\frac{4\pi r^3 P}{Mc^2}\right)\left(1-\frac{2GM}{c^2 r}\right)^{-1} \qquad (2)$$

Tolman, Oppenheimer, Volkoff eqs. (1939) → slang: TOV properties = stellar parameters

Stellar properties of NS are key

- Narrow down stellar properties of NSs: only one true mass-radius curve
  - → key parameter e.g. radius at given mass or maximum mass



X-ray timing NICER

Pulsar mass measurements

Multi-messenger interpretation of GW170817

Finite-size effects in GW inspiral (GW170817)

Reddish bands = excluded

- Many more ideas and measurements
- Include different uncertainties / usually hard to assess all uncertainties

Mergers and EoS/NS constraints

Basic idea: EoS affects structure and dynamics and thus observables

Three complementary strategies:

- Finite-size effects during the inspiral → accelerate inspiral compared to BH-BH
- Multi-messenger interpretation (many different ideas, can be quite model-dependent)
- Oscillations of the postmerger remnant (not yet measured but promising for future)

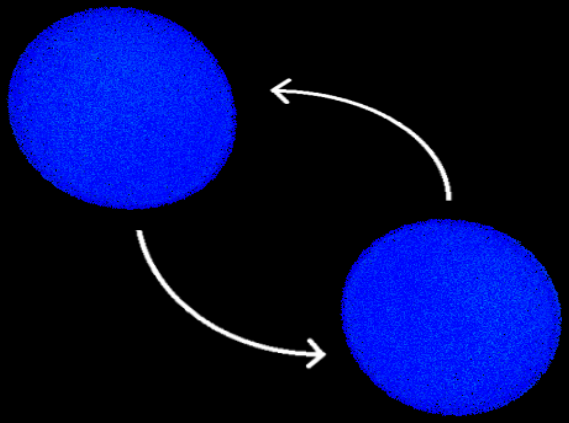
+ many efforts to combine these constraints with other measurements, e.g. Coughlin et al. 2018, Dietrich et al 2020, Raaijmakers et al 2021, Huth et al. 2022

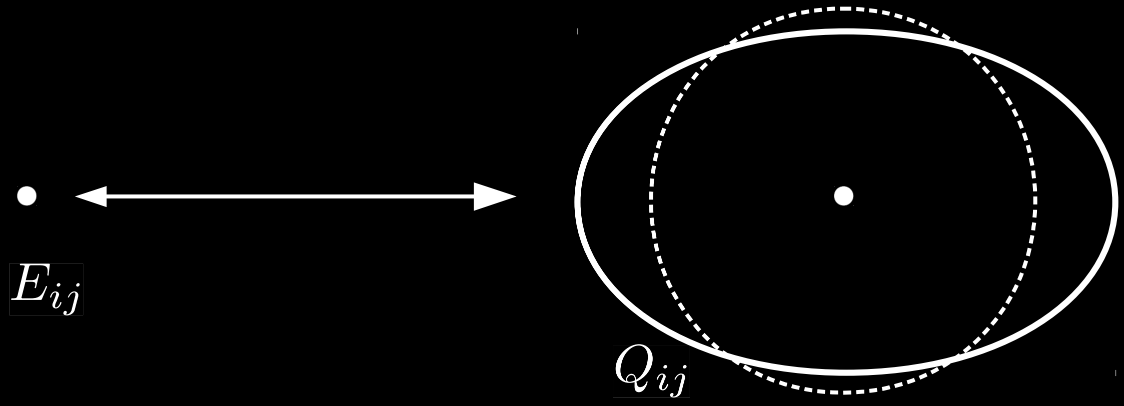
Finite-size effects during late GW inspiral

- For close orbits → finite size effects:

  GW differs for point particles and extended bodies

  → larger stars lead to “faster” inspiral

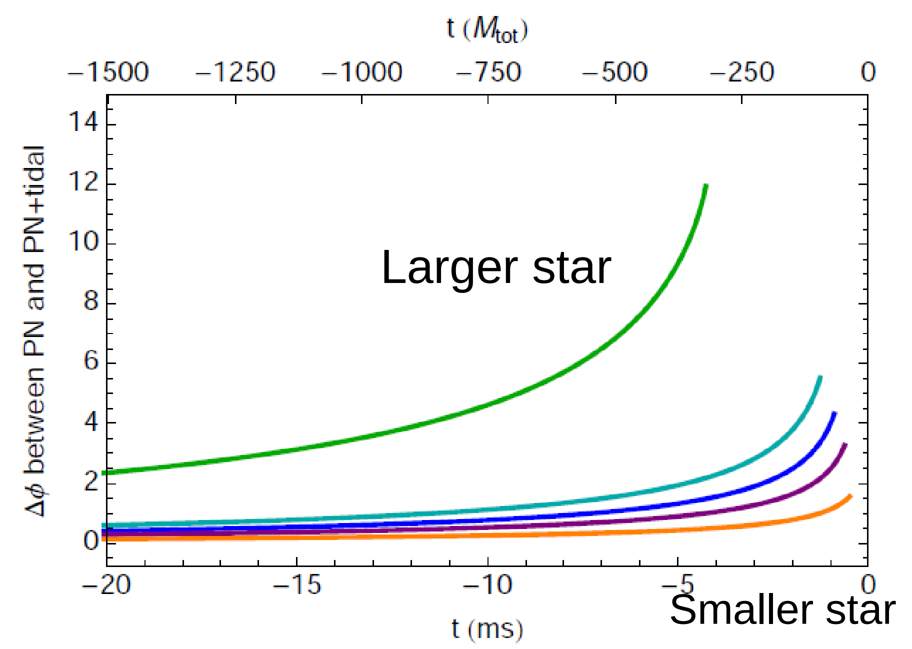


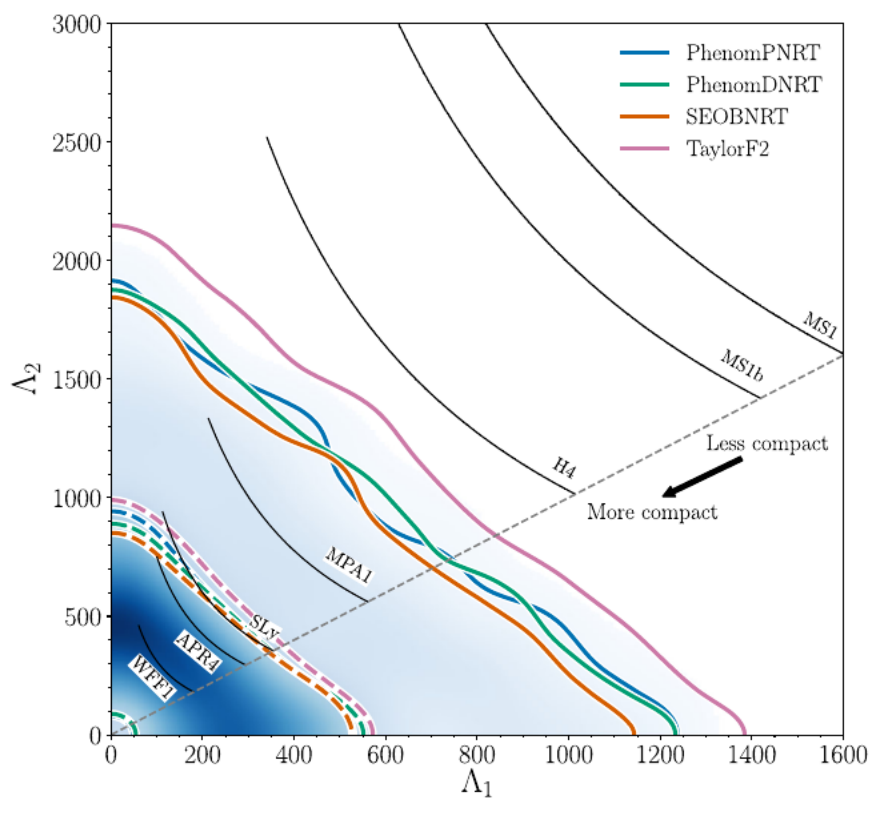


Finite-size effects during late GW inspiral

- Encoded by "tidal deformability"
- Accelerates inspiral
- GW170817 excludes R > 13.5 km

$$\Lambda(M) = \frac{2}{3} k_2(M) \left(\frac{c^2 R}{G\,M} \right)^5$$





Abbott et al. 2017, 2019
see also later publications by Ligo/Virgo collaboration, De et al. 2018

→ better constraints in future

e.g. Read et al. 2013

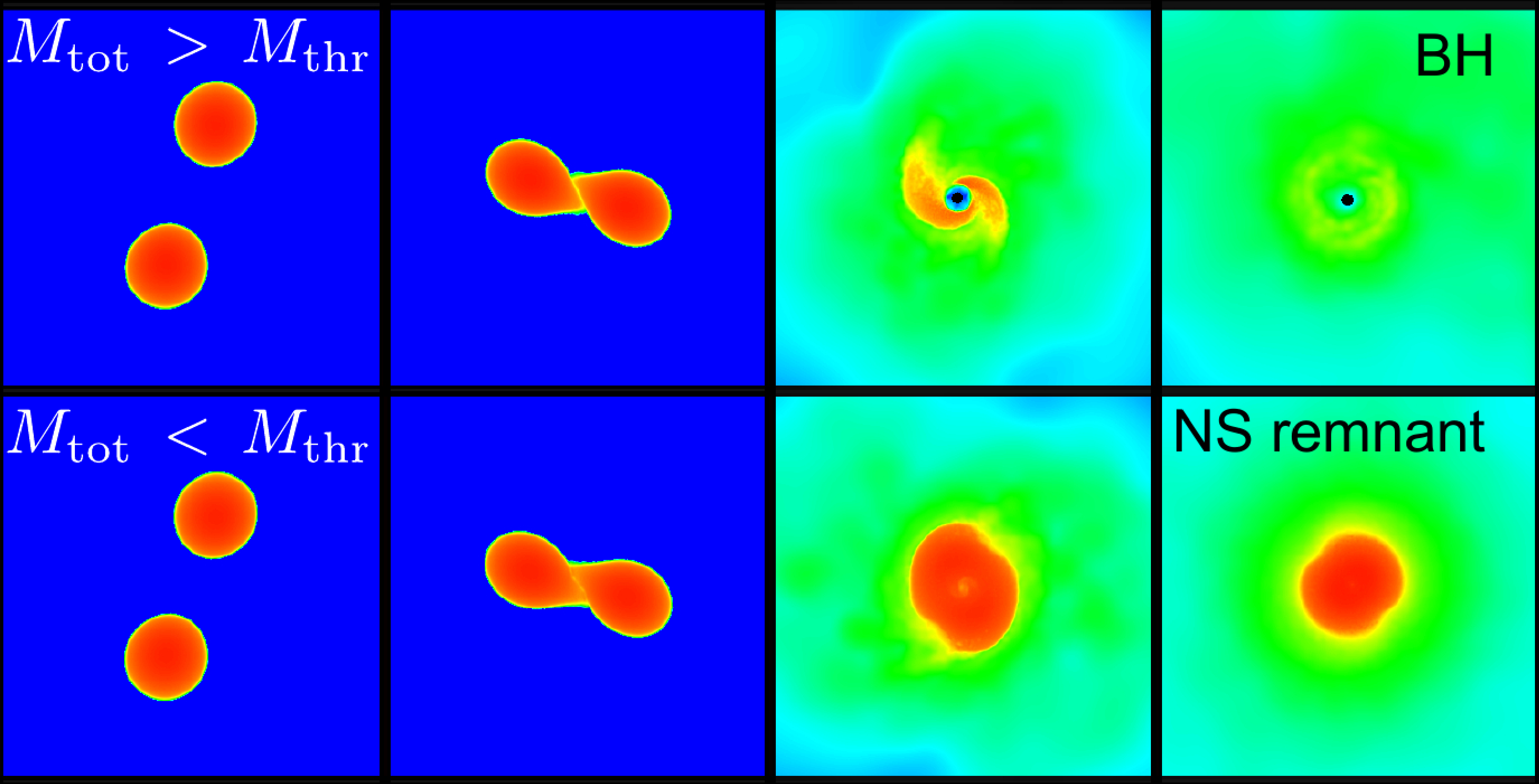
↑ Merger time of point particle

Multi-messenger constraints:

BH formation in NS mergers

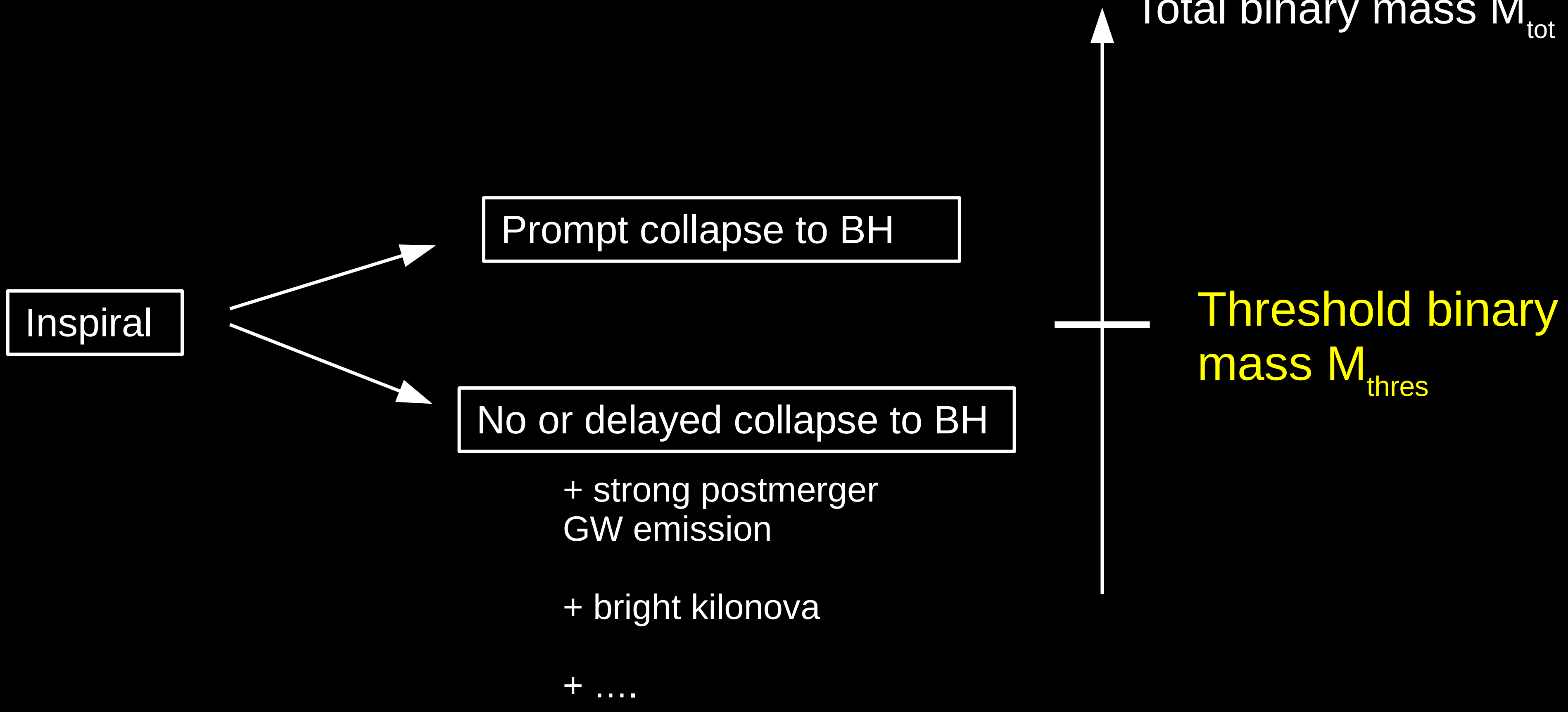
Threshold binary mass

Collapse behavior



Understanding of BH formation in mergers [e.g. Shibata 2005, Baiotti et al. 2008, Hotokezaka et al. 2011, Bauswein et al. 2013, Bauswein et al 2017, Agathos et al. 2020, Bauswein et al. 2020]

Collapse behavior



Inspiral

Prompt collapse to BH

No or delayed collapse to BH

+ strong postmerger
GW emission

+ bright kilonova

+ ….

Total binary mass M_{tot}

Threshold binary mass M_{thres}

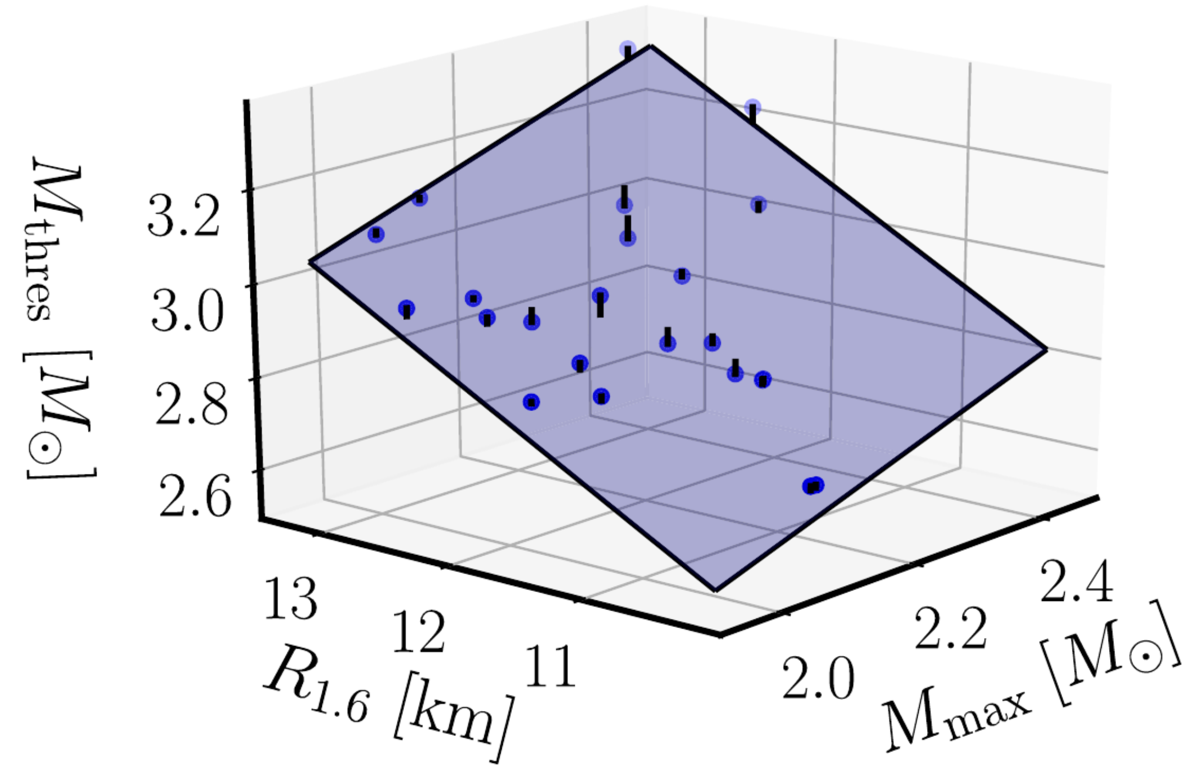
M_{thres} - EoS dependent !!!

Collapse behavior – BH formation

- Critical for interpretation of GW emission, gamma-ray bursts, kilonova, …
- Strong EoS dependence expressed through stellar paramters

$$M_{\rm thres} = M_{\rm thres}(M_{\rm max}, R_{1.6}) = aM_{\rm max} + bR_{1.6} + c$$

(based on ~ 400 HPC relativistic hydrodynamics merger simulations)



Dots: model EoSs

Bauswein et al., PRL (2020); Bauswein et al., PRD (2021)

Example: NS radius constraint from GW170817

- If GW170817 did not directly form BH as indicated by relatively bright kilonova
- NSs cannot be too small/ EoS too soft because this resulted in a prompt collapse
- Relatively simple and robust: Quantitatively based on threshold binary mass for prompt collapse

Soares-Santos et al 2017

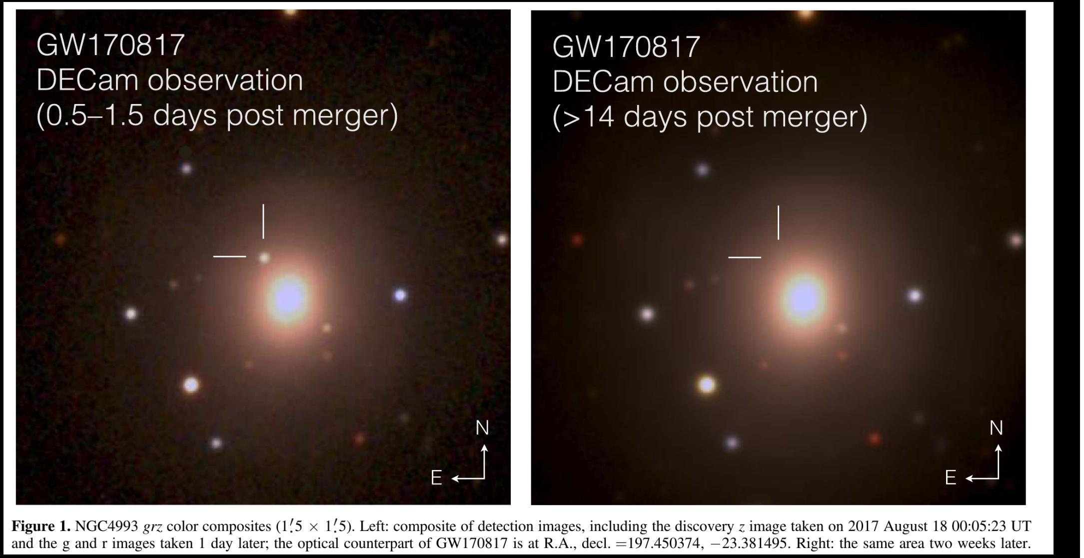
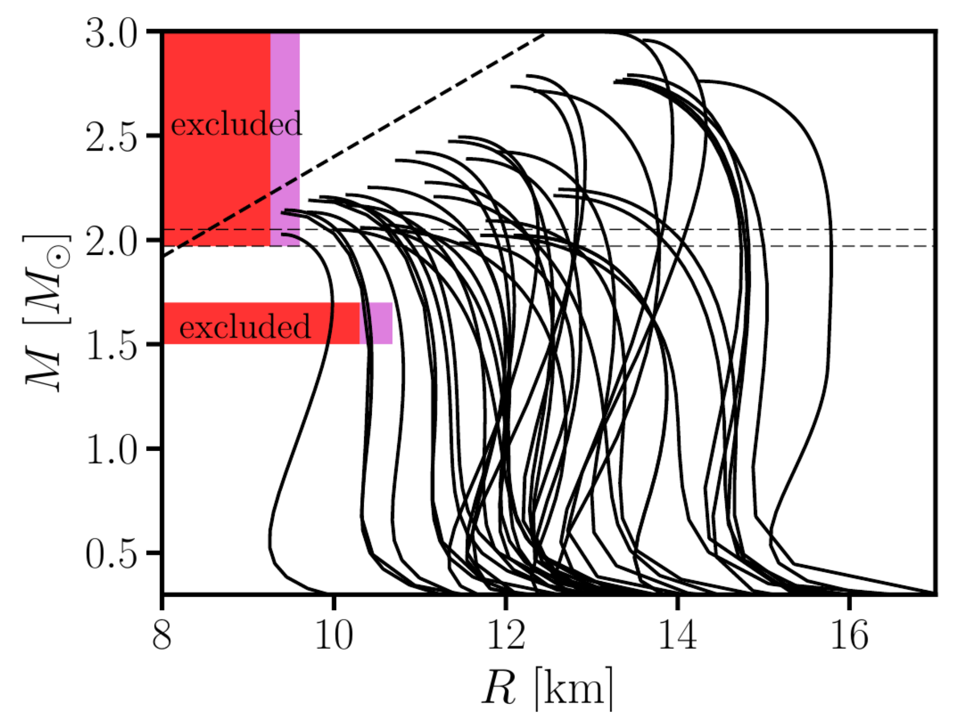


Figure 1. NGC4993 *grz* color composites ($1'.5 \times 1'.5$). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area two weeks later.

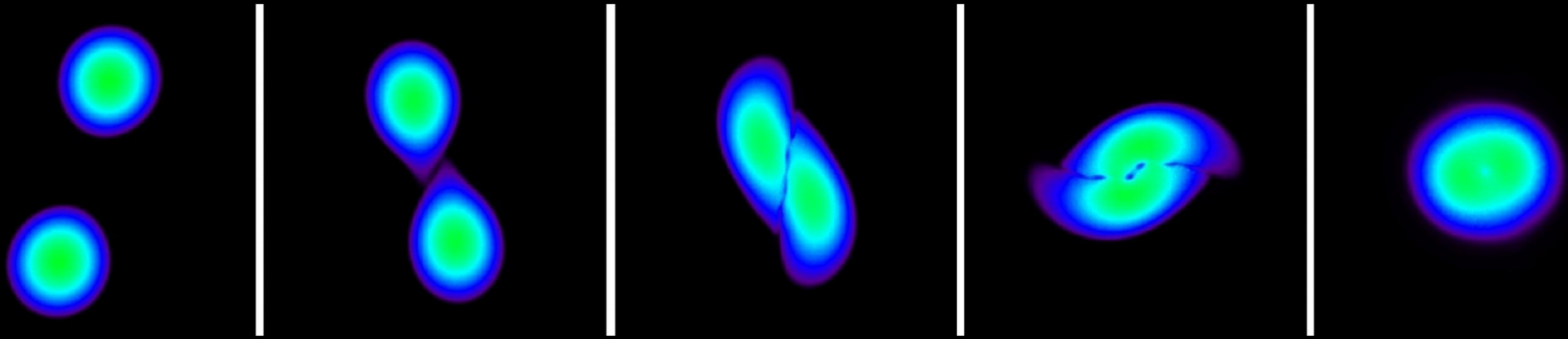
$$L_{\mathrm{bol}} \propto \sqrt{M_{\mathrm{ejecta}}}$$

→ Inferred ejecta mass 0.02-0.05 Msun

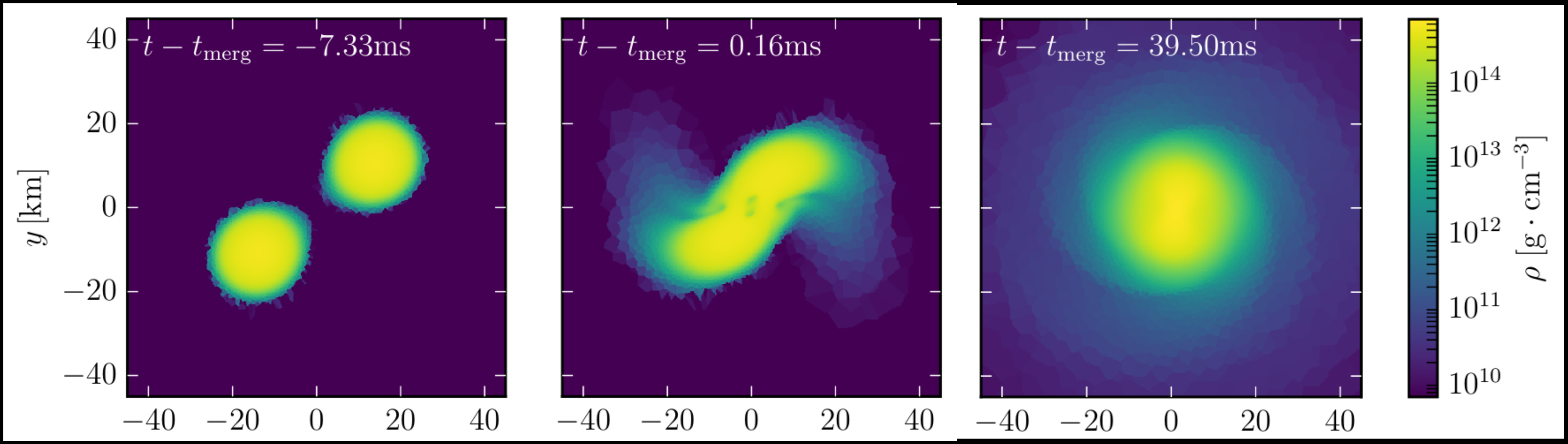


Bauswein et al. 2017, 2021

Future prospects: postmerger GW emission



- Simulations by a relativistic moving mesh hydrodynamics code (Lioutas et al. 2022, based on Arepo by V. Springel)



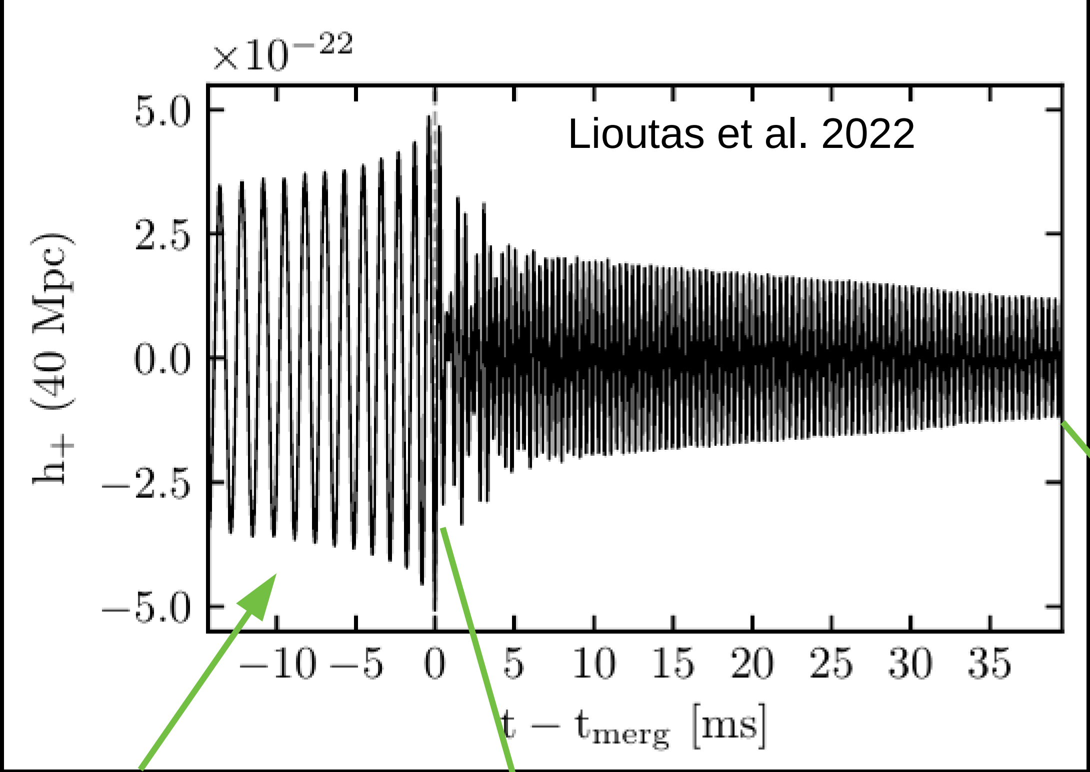
1.35-1.35 Msun, DD2 EoS

Lioutas et al. 2022

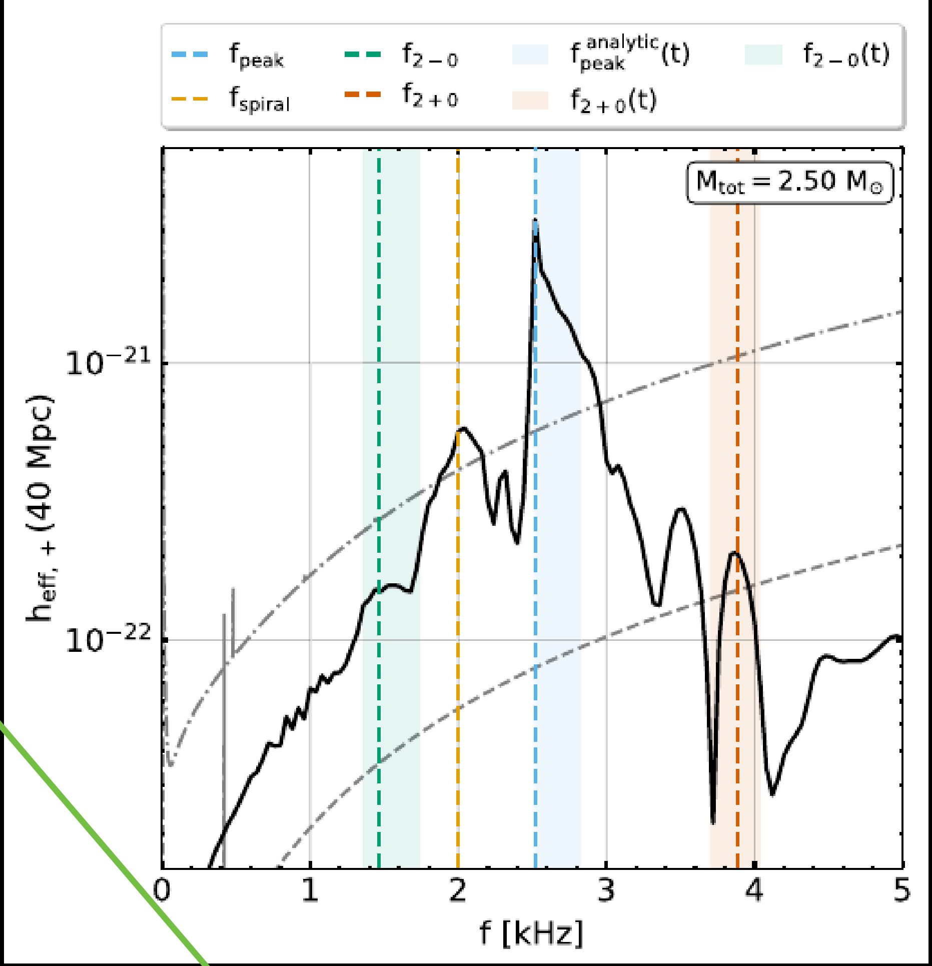
Postmerger GW signal

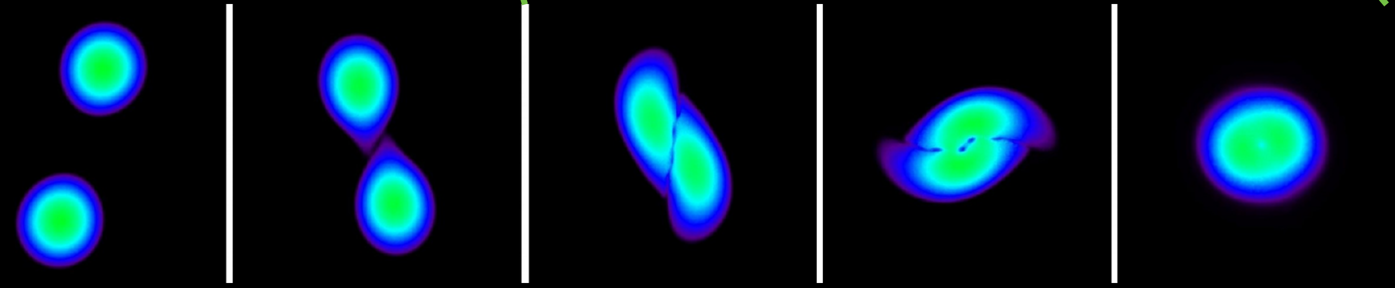
- Dominated by a single frequency
- But several subdominant modes excited

→ GW asteroseismology

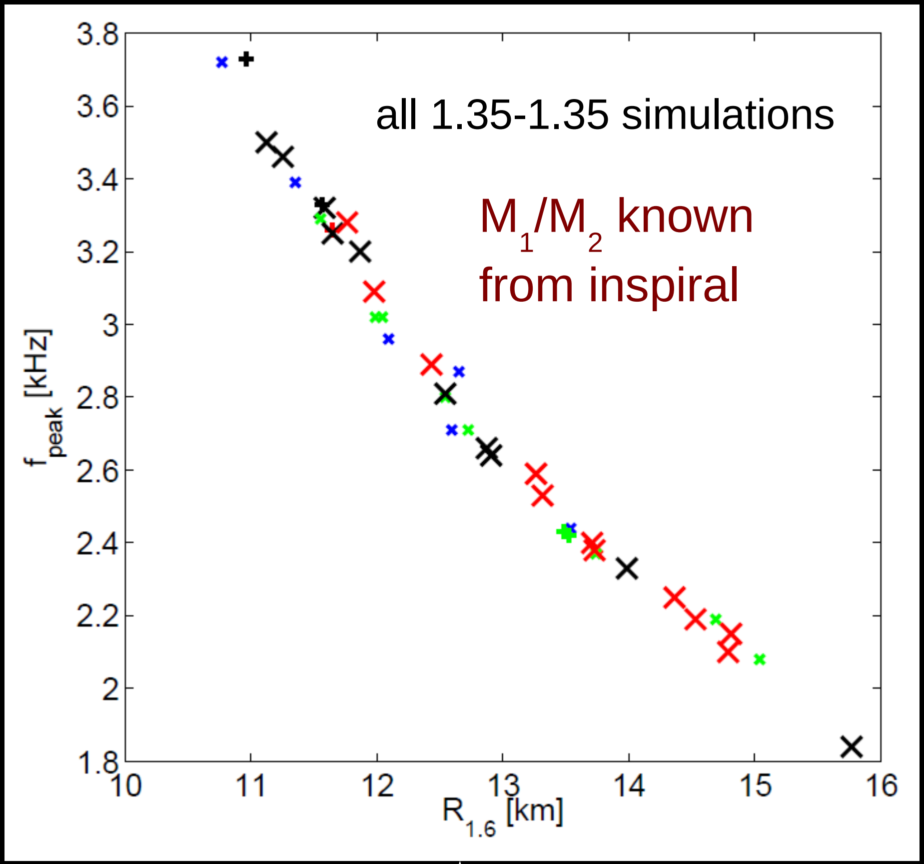

Lioutas et al. 2022

Soultanis et al. 2022

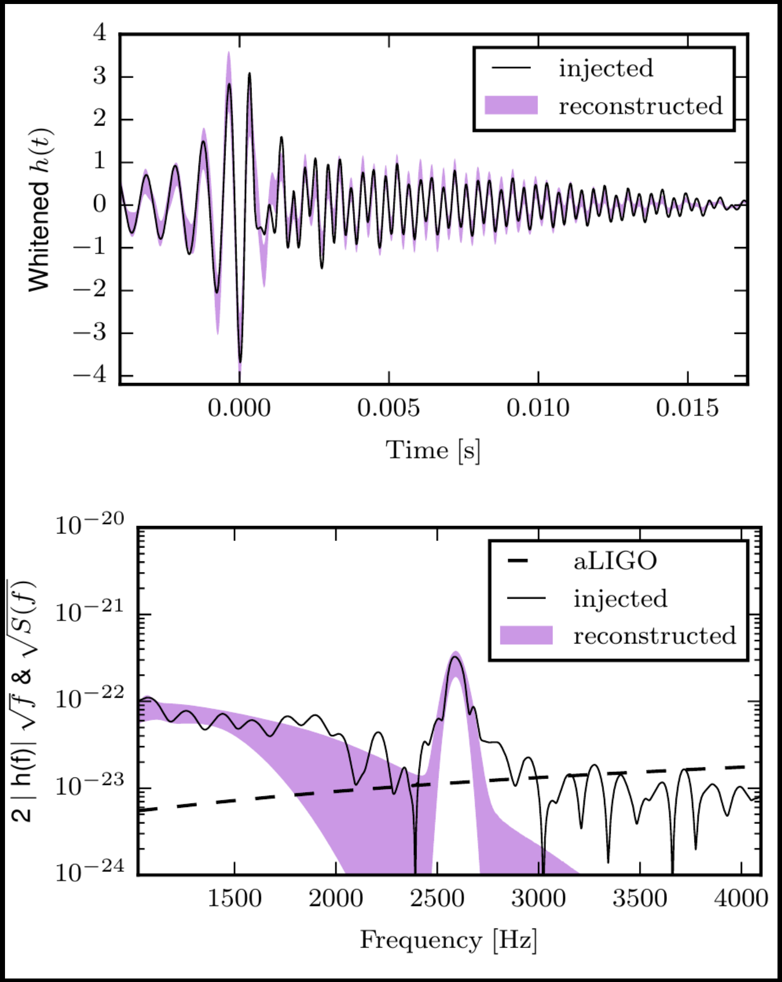




A.B., et al. (2012)



Chatziioannou et al. (2017)



Pure TOV/EoS property => Radius measurement via f_{peak}

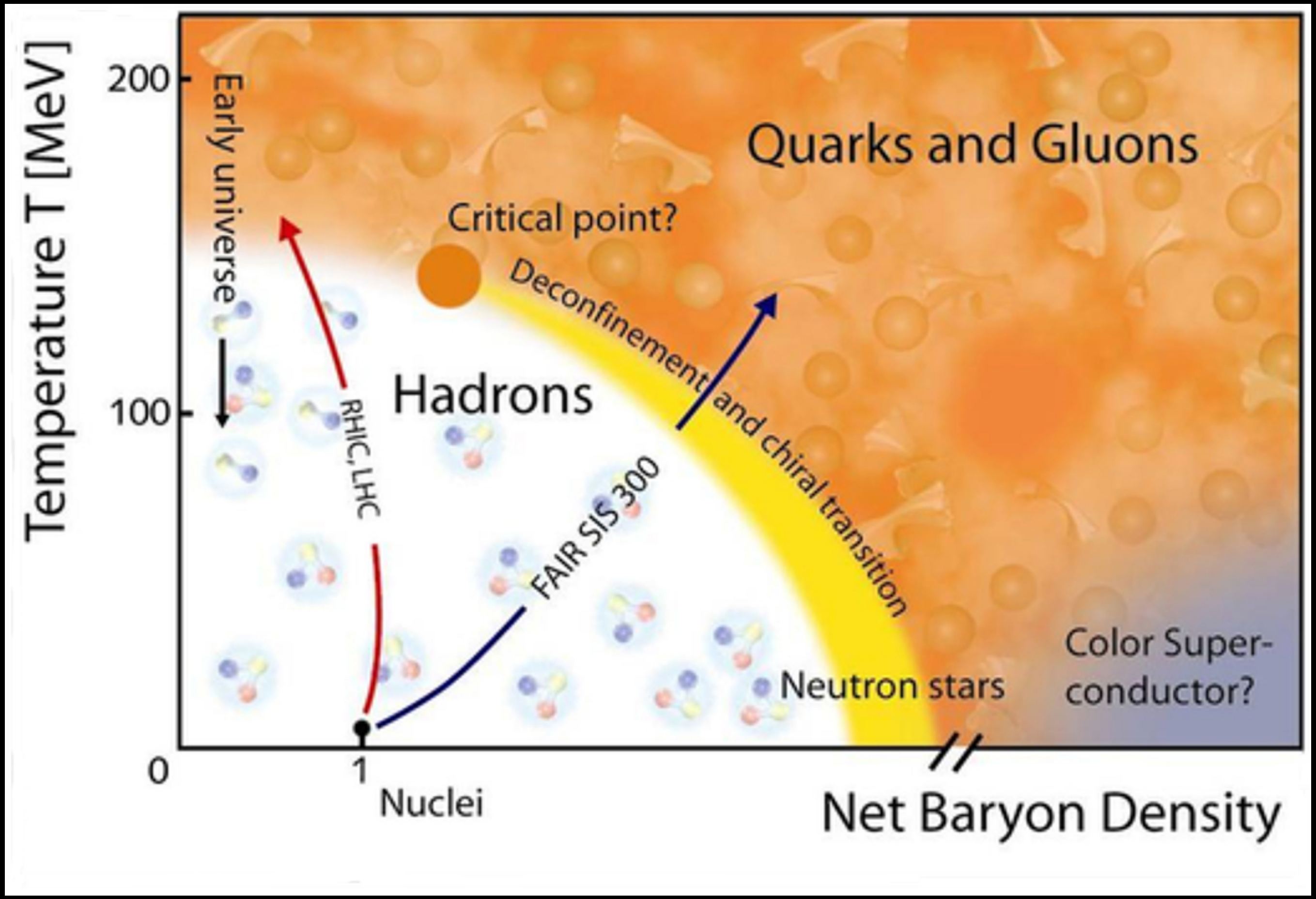
GW data analysis critical → simulated injections → detectable at a few 10 Mpc @ design sensitivity (see Clark et al 2016, Chatzioannou et al. 2017, Torres-Riva et al 2019)

See also Takami et al. 2015, Bernuzzi et al. 2015, ...

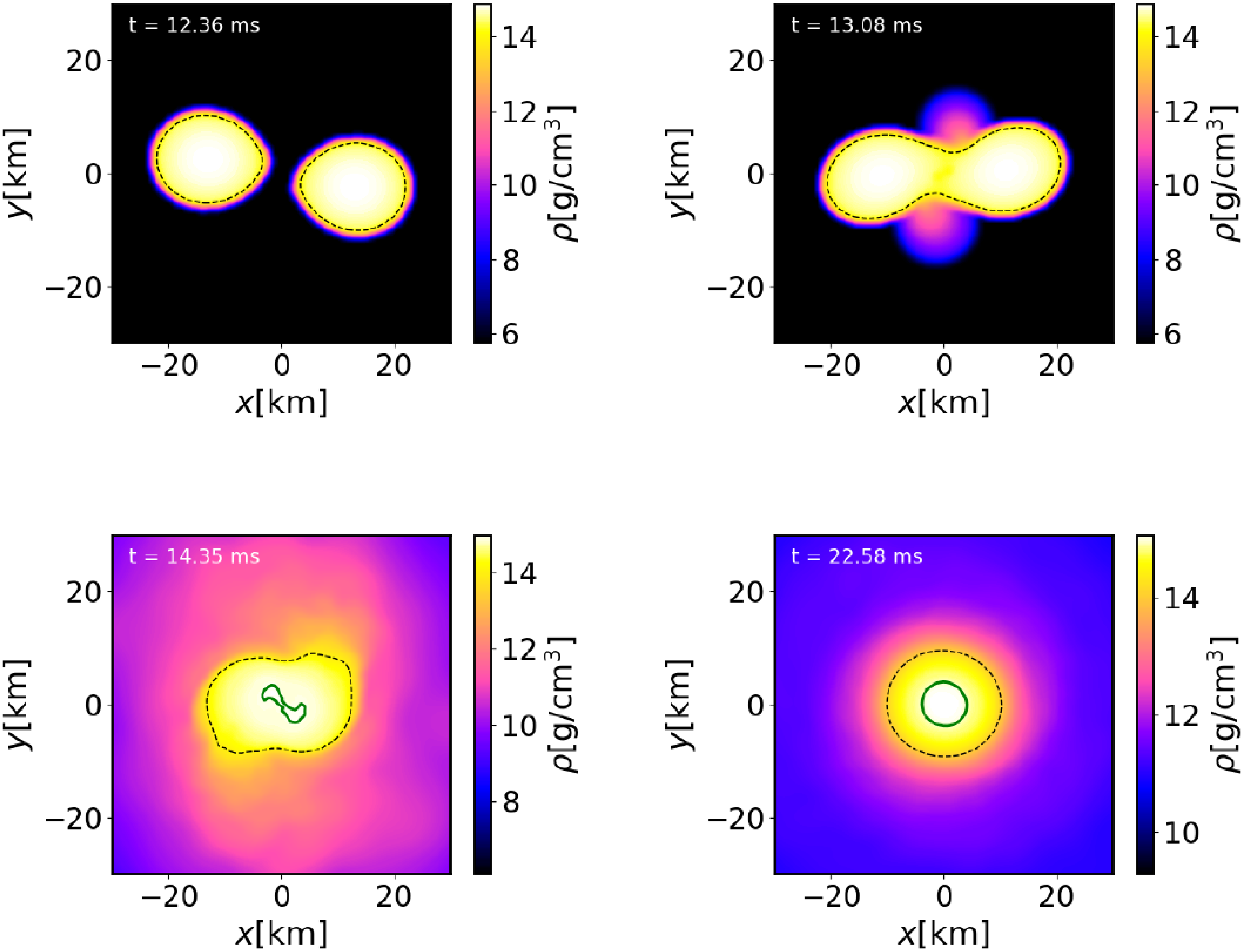
Quark matter in NS mergers ?

Phase diagram of matter of strongly interacting matter

GSI/FAIR



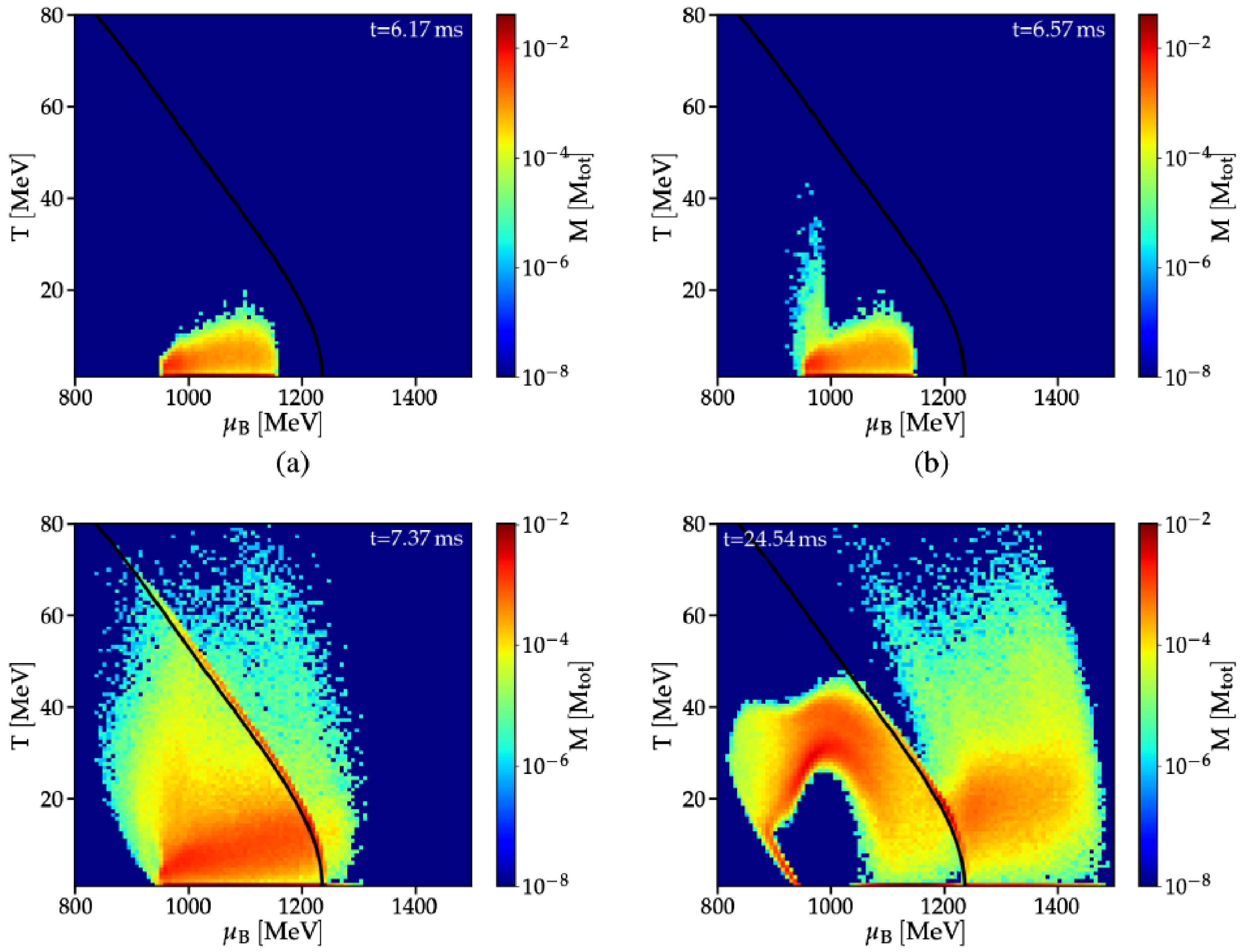
Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities?



Bauswein et al. 2019

NS merger in the phase diagram

Blacker et al. 2020



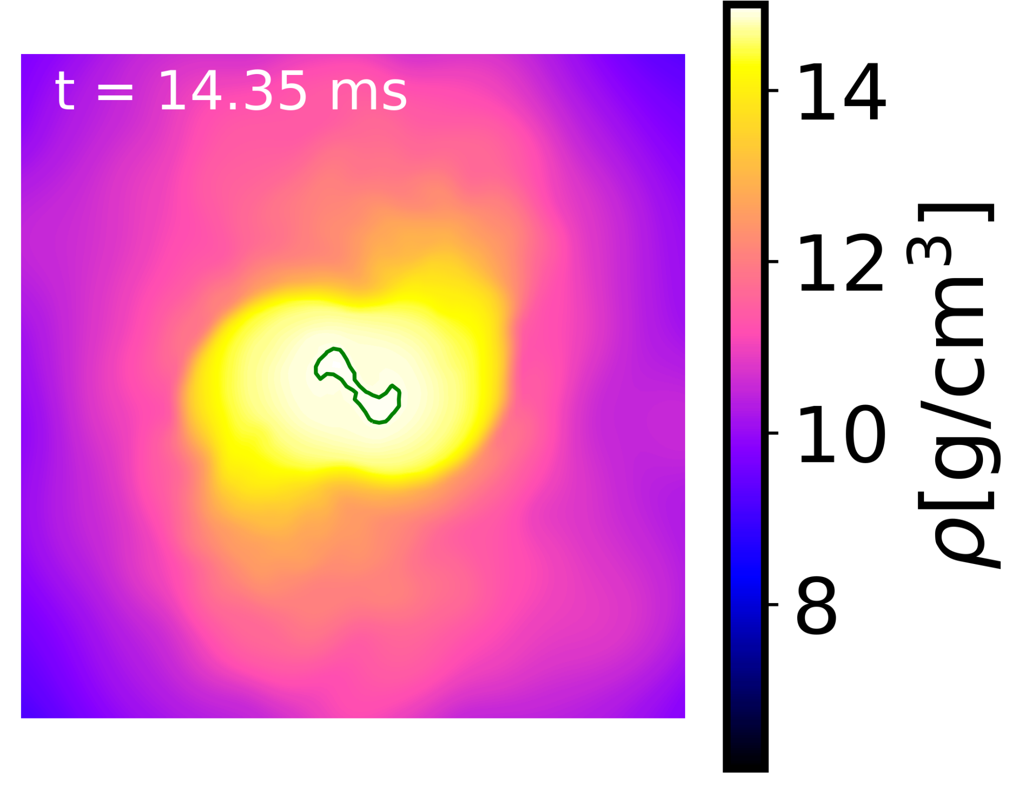
(a)

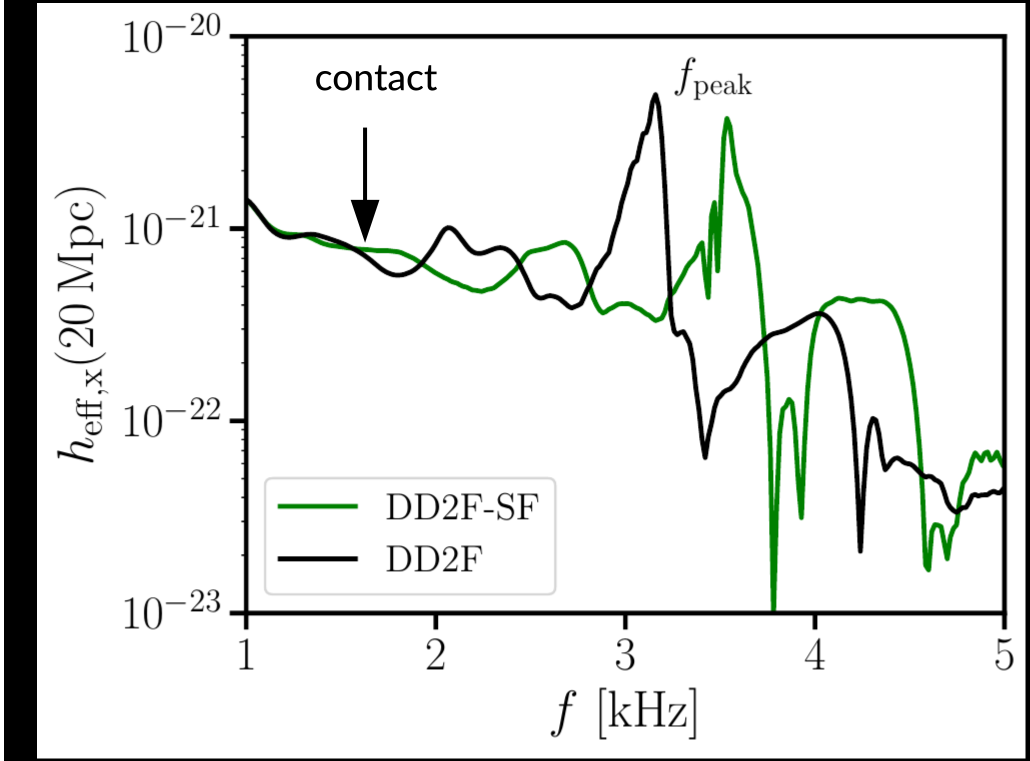
(b)

- Simulation: 1.35-1.35 Msun merger, EoS model with 1st order phase transition (EoS from Wroclaw group); see also, e.g., Most el al. 2019, Hanauske et al. 2021, …

Merger simulations with quark matter core

- GW spectrum 1.35-1.35 Msun



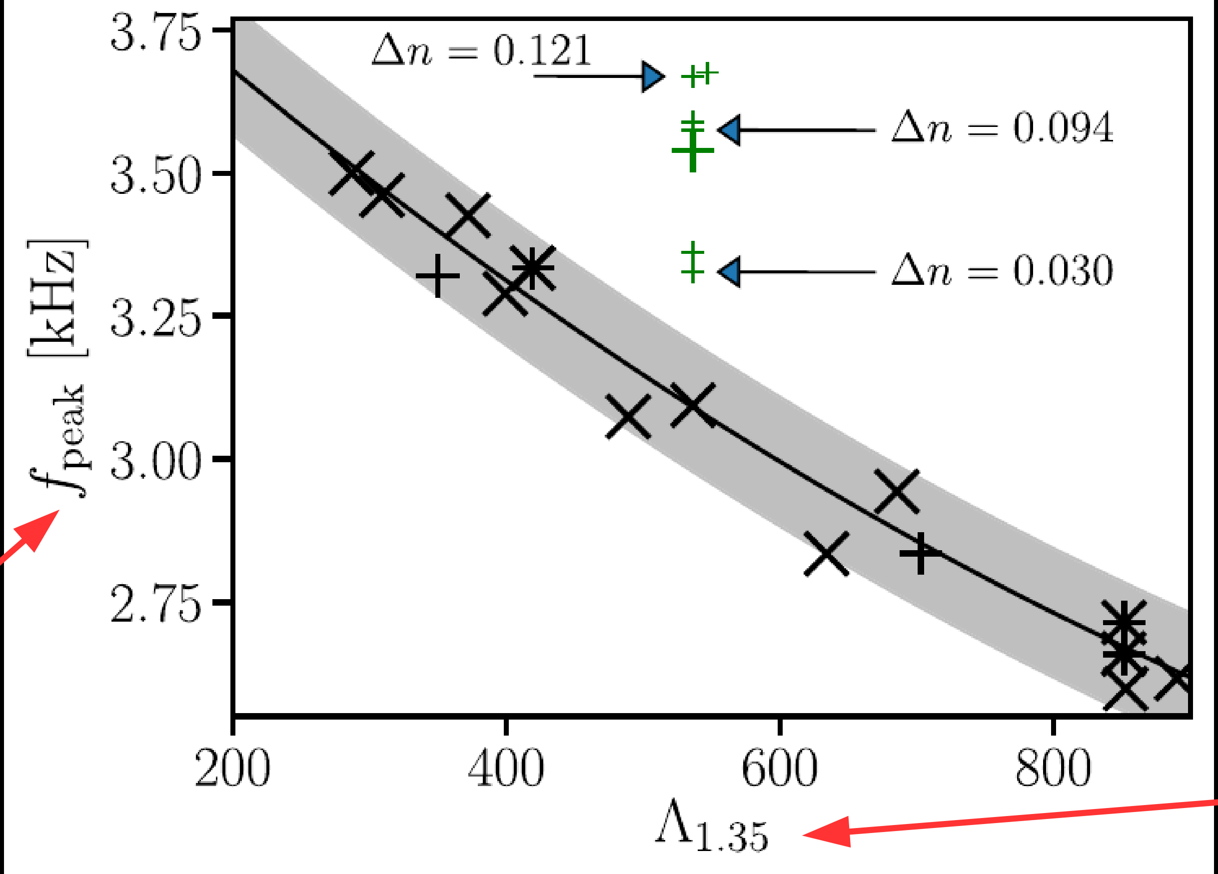


A.B. et al. 2019

But: a high frequency on its own may not yet be characteristic for a phase transition

→ unambiguous signature

Signature of 1st order phase transition



from postmerger

from the inspiral

A.B. et al 2019

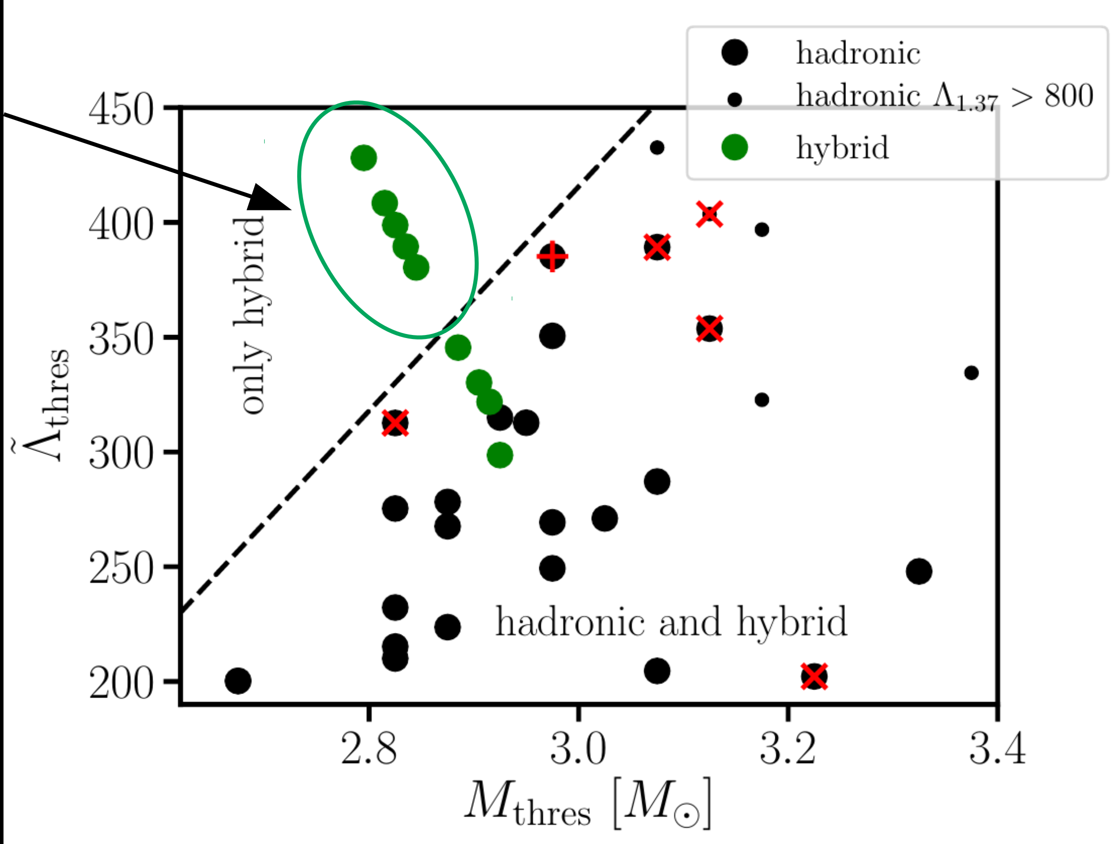
- Characteristic increase of postmerger frequency compared to tidal deformability

  → evidence of presence of quark matter core

  → in any case constraint on onset density of hadron-quark phase transition

QCD phase transition from collapse behavior

- Quark matter may lead to characteristic reduction of M_{thres}
- Already single events may indicate presence of quark matter



Evidence for quark matter

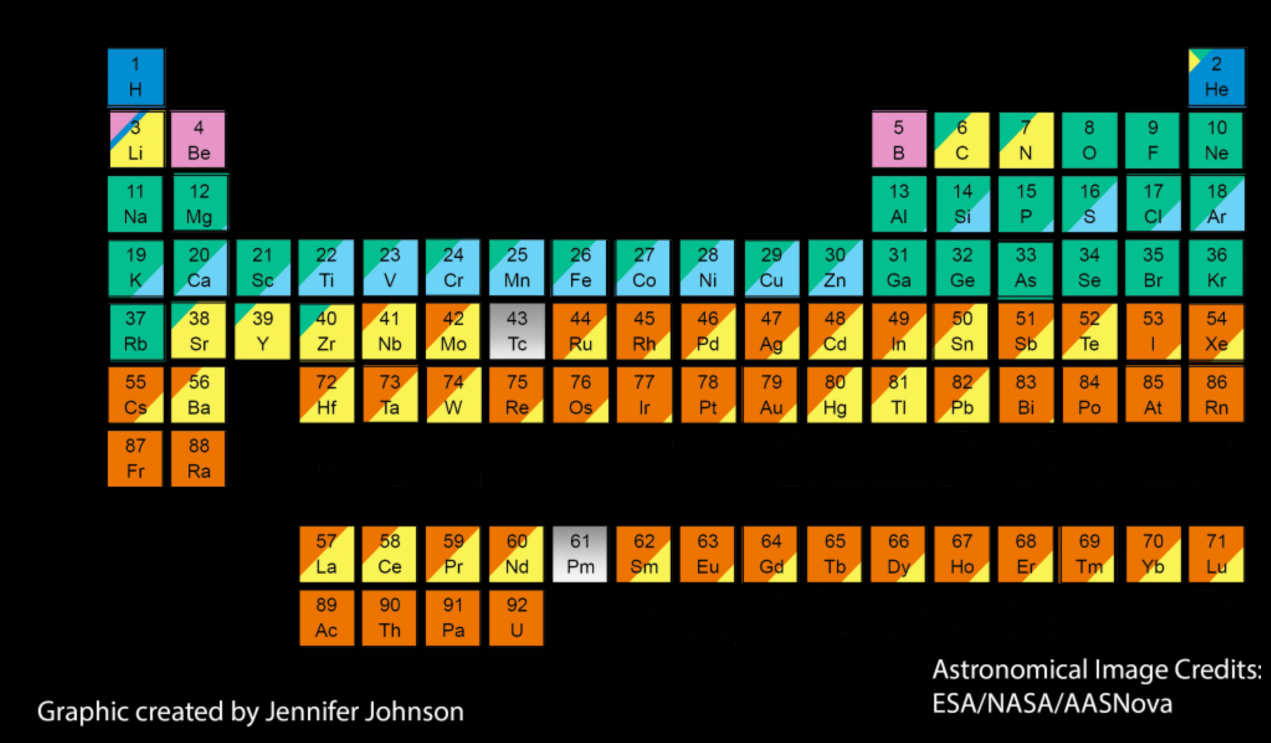
Measurable from GW inspiral

A.B. et al 2020

Measurable from inspiral + information on merger product

R-process nucleosynthesis and kilonovae

Where and how do heavy elements form?



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

Graphic created by Jennifer Johnson

Astronomical Image Credits:
ESA/NASA/AASNova

Early works on NS mergers: Lattimer+ 1974, Freiburghaus+ 1999, Li&Paczynski 1998, Metzger+ 2010, Goriely+ 2011, Korobkin+ 2012, Bauswein+2013, Fernandez+2013, Perego+ 2014, Wanajo et al 2014, Just+2015, Mendoz-Temis+2015, … and many many more

Optical/IR emission from GW170817 detected

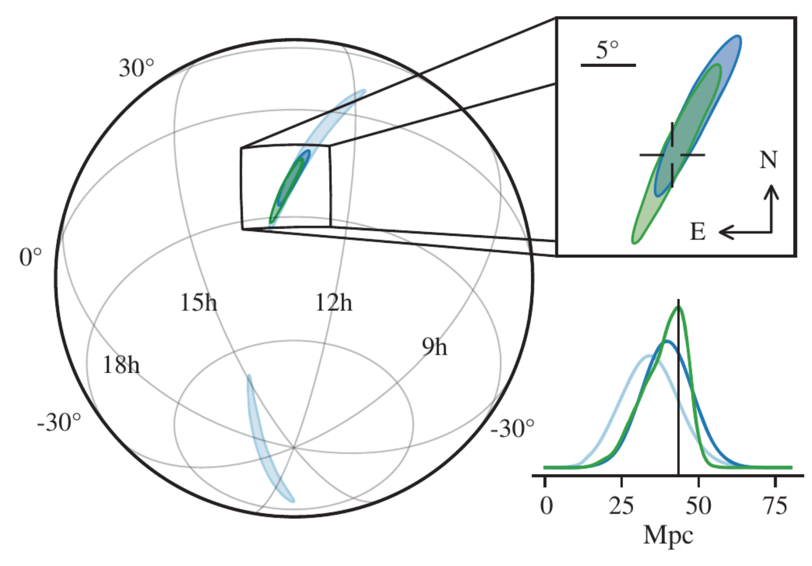
- GW signal → approximate sky location
- Follow up observation (UV, optical, IR) starting ~12 h after merger

  - light curve evolves on time scale of days

  generated by unbound matter: ejecta

  → ejecta masses, velocities, opacities

  (Metzger et al. 2010, ...)



Abbott et al. 2017

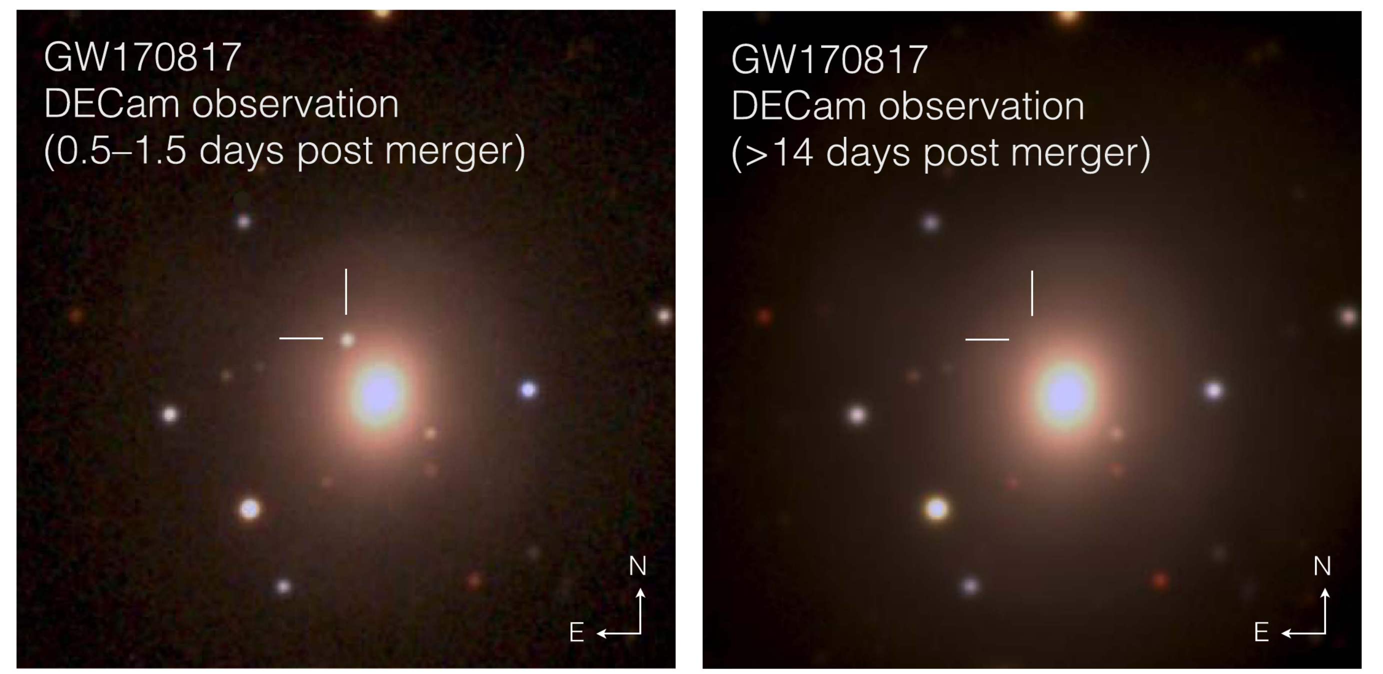


Figure 1. NGC4993 *grz* color composites (1.′5 × 1.′5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area two weeks later.

Soares-Santos et al 2017

Importance of optical/IR emission from GW170817

- GW signal → undoubtful a NS merger
- Properties of light curve in excellent agreement with r-process heated ejecta

  → first and only confirmed site of r-process – after decades of research and observations pointing to very different astrophysical sites

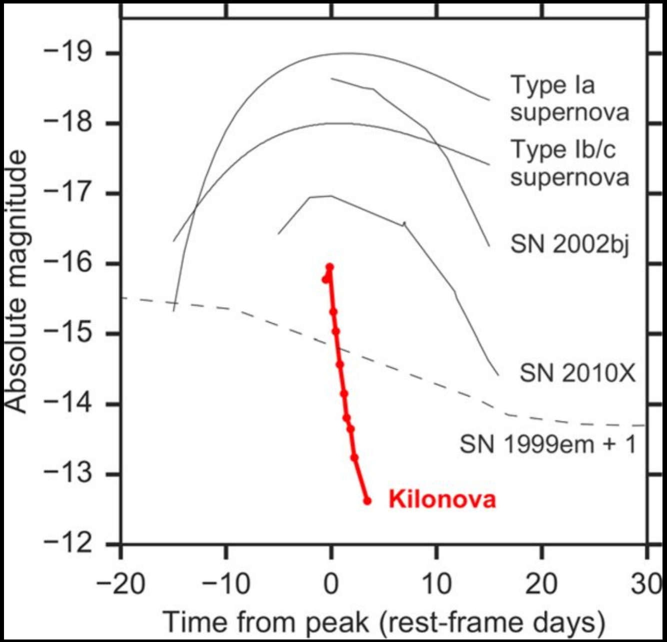
  → ejecta mass (a few 0.01 Msun) and other properties consistent with results from simulations - remarkable agreement considering the challenges to model ejecta

  → estimated rate * ejecta mass = compatible with mergers being main/only source of heavy r-process elements

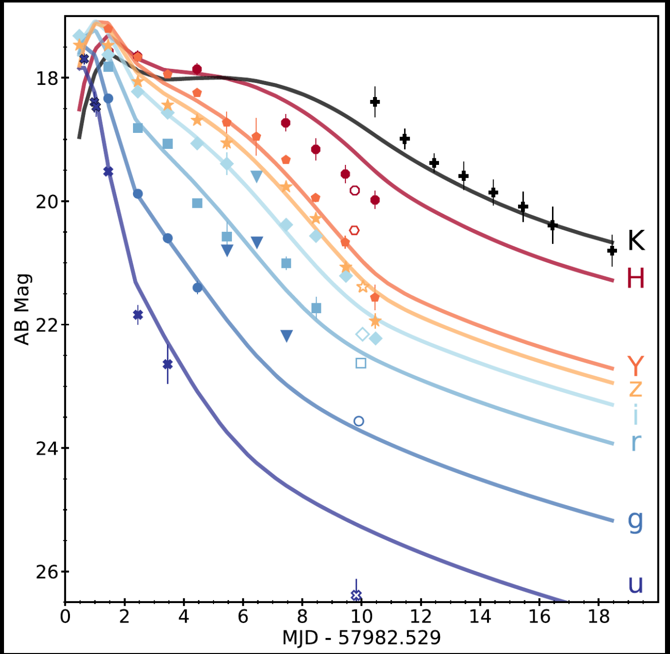
$$M_{r-process\,Galaxy} = \bar{M}_{NSNS}\,R_{NSNS}\,\tau_{Galaxy}$$

- However: only coarse models, order-of-magnitude estimates, uncertain ejecta paramters, unknown composition, ...

  → many details still unclear



Arcavi et al. 2017



Cowperthwaite et al. 2017 (DECam, Gemini-South, HST observations)

Spectroscopic identification of r-process

- Kilonova roughly follows black body
- Features imprinted, but hard to interpret:

  - blue-shift (v ~ 0.3c)

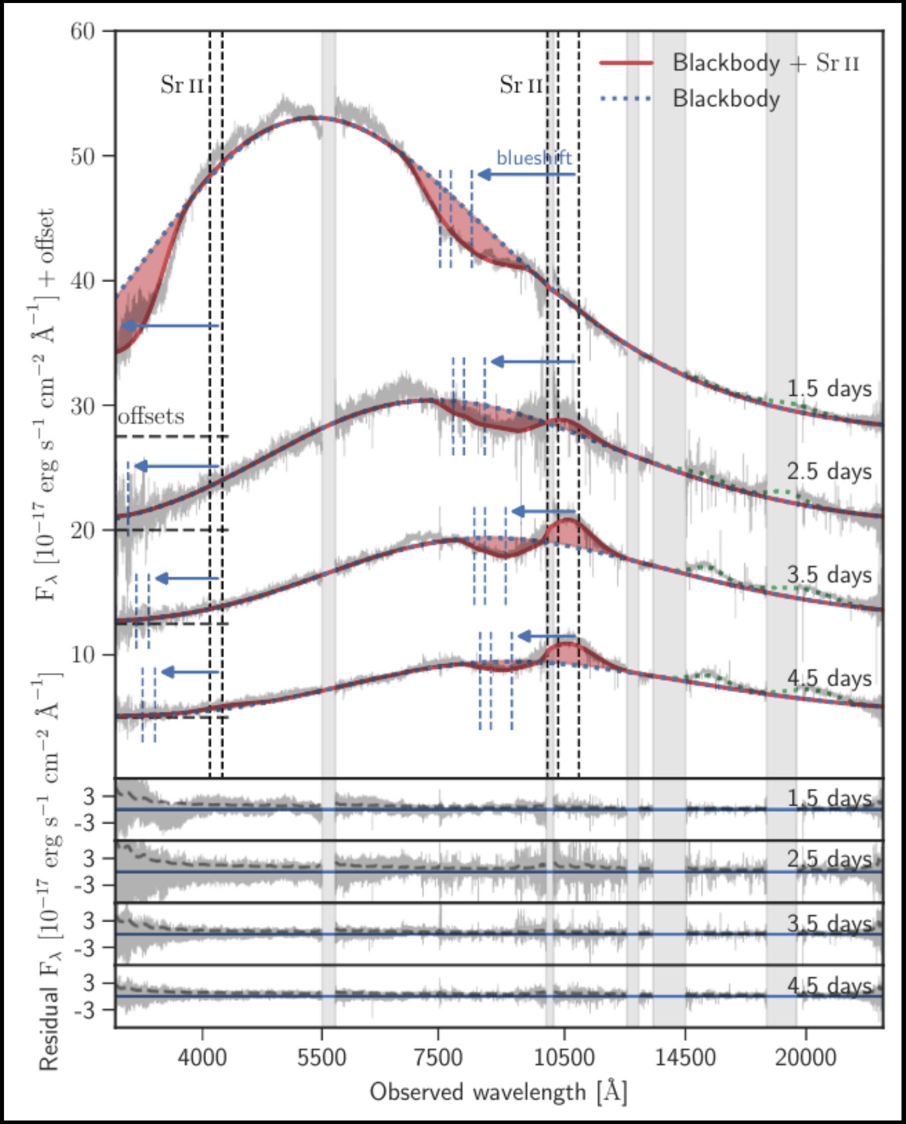
  - line lists of heavy elements limited

- Strong absorption feature: Strontium

  (which is a r-process element)

→ next piece of evidence of r-process in NS mergers !!!

→ more information on geometry, stratification etc. from spectroscopy



Watson et al. 2019

Challenges and open questions

Captured Spectra

Astronomical Observations

Spectrum formation

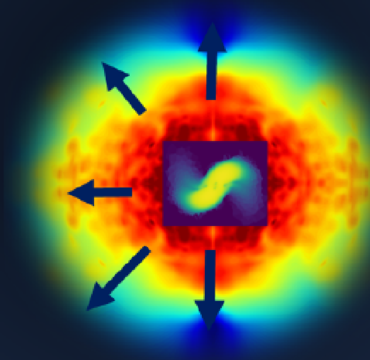
photons

Radiative Transfer Calculations

Sr
Zr
Ba
Au
Nd
Pt
Eu

Atomic Physics

Merger physics



Hydrodynamic Simulations

Nuclear reactions

Challenges and open questions

- What was the composition of the outflow ? Was it solar ?
- Are there other sites contributing to the observed solar abundance ?
- What are the detailed (plasma/nuclear/atomic) physics in the outflow ?

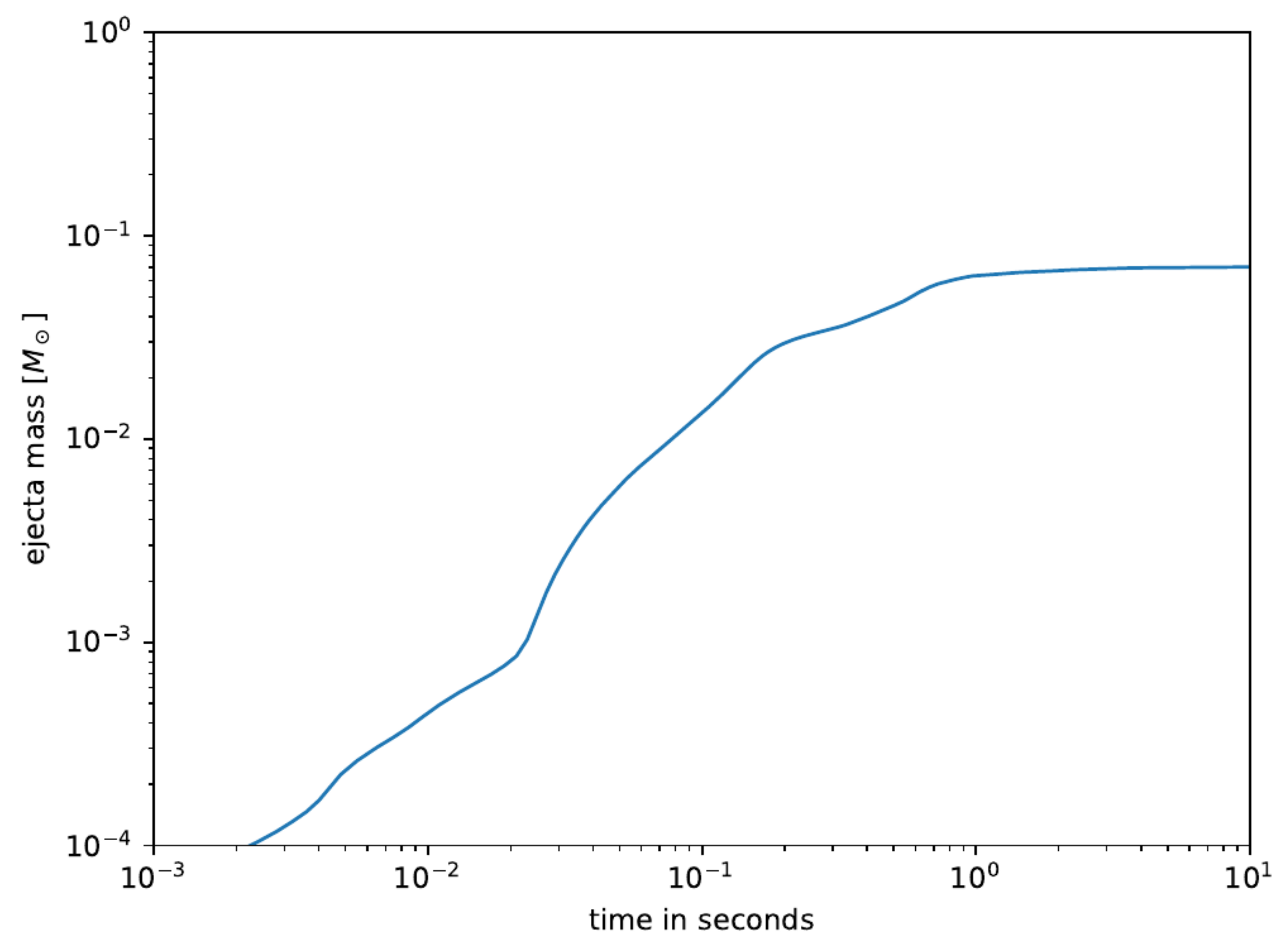
- Interpretation of current and future observations (James Webb, ELT)
- Modeling of different ejecta components / mass ejection channels
- Nuclear physics of the r-process
- Radiation transfer in the expanding ejecta flow
- Atomic processes in the outflow / opacities / atomic data

→ HeavyMetal consortium: GSI – Copenhagen – Dublin – Belfast

Open PhD and PD positions (ERC funded)

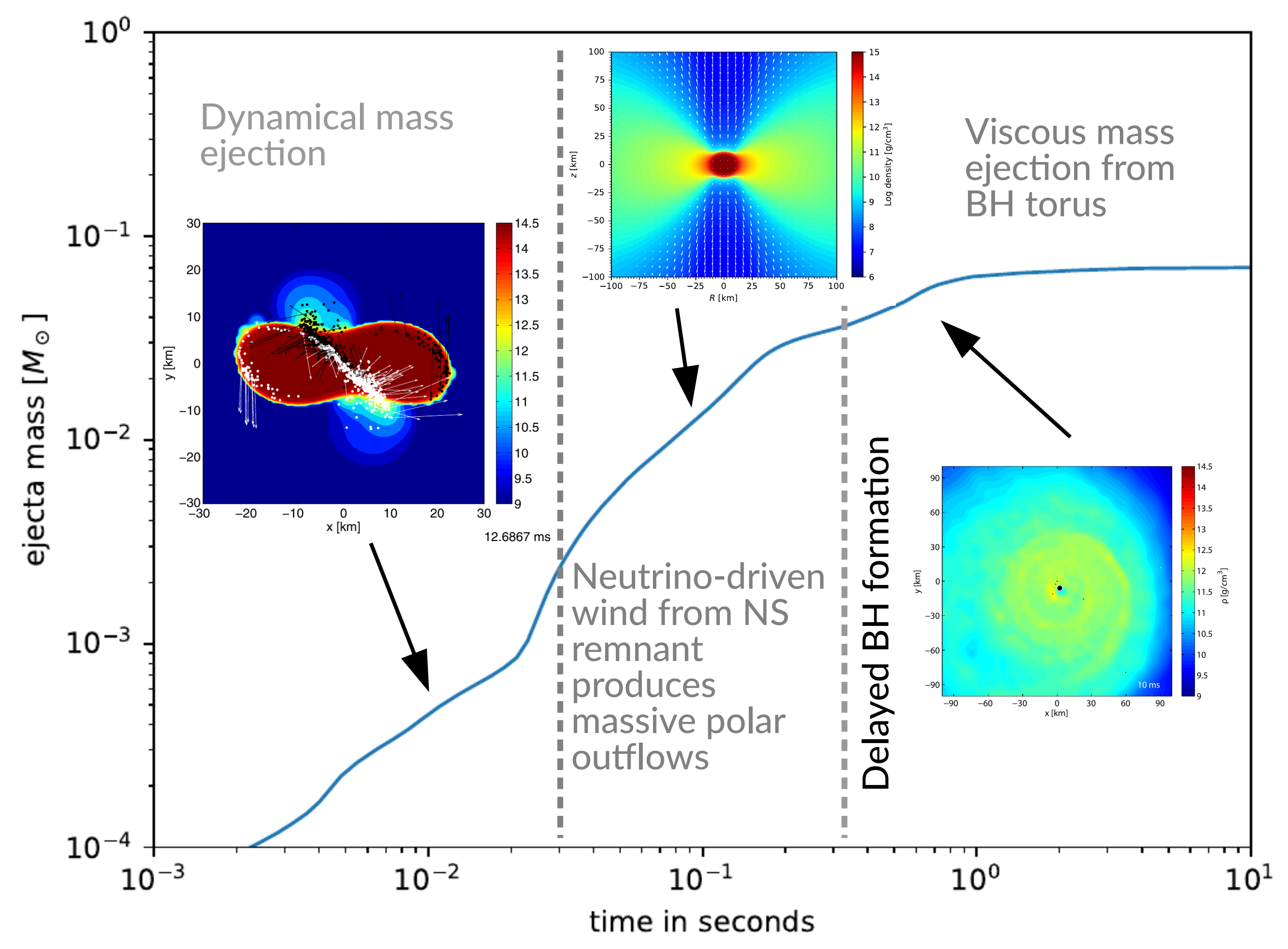
Consistent models of all ejecta components

- Different ejecta components of comparable mass ejected by different mechanisms on different time scales → challenging to model: multi-scale multi-physics problem - first models on the way – Just, Vijayan, Xiong et al. 2023 (see also Kiuchi et al 2022, Fujibayashi et al. 2022 for short or very long-lived models; and numerous earlier studies focusing on individual components)



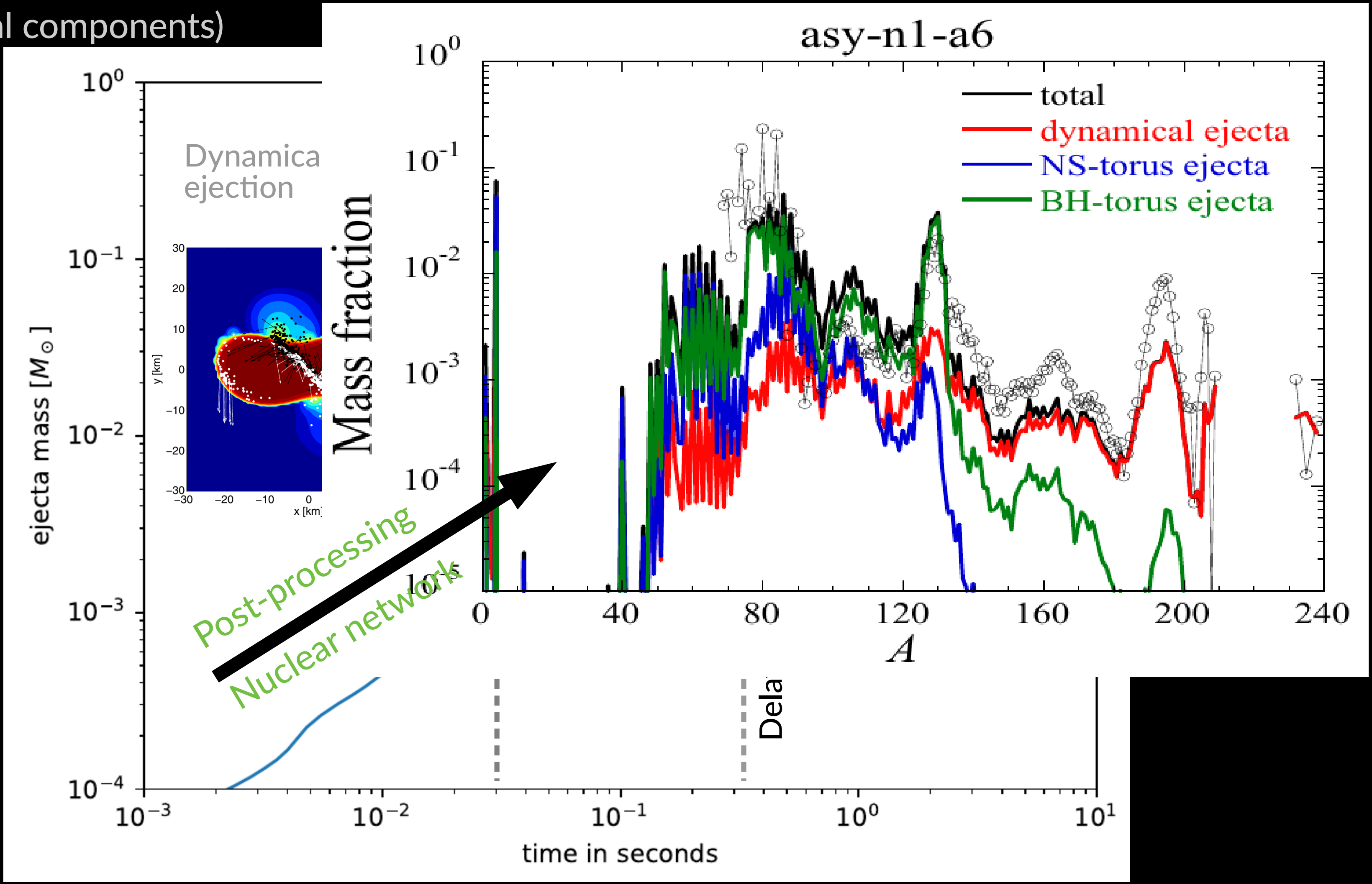
Consistent models of all ejecta components

- Different ejecta components of comparable mass ejected by different mechanisms on different time scales → challenging to model: multi-scale multi-physics problem - first models on the way – Just, Vijayan, Xiong et al. 2023 (see also Kiuchi et al 2022, Fujibayashi et al. 2022 for short or very long-lived models; and numerous earlier studies focusing on individual components)



Consistent models of all ejecta components

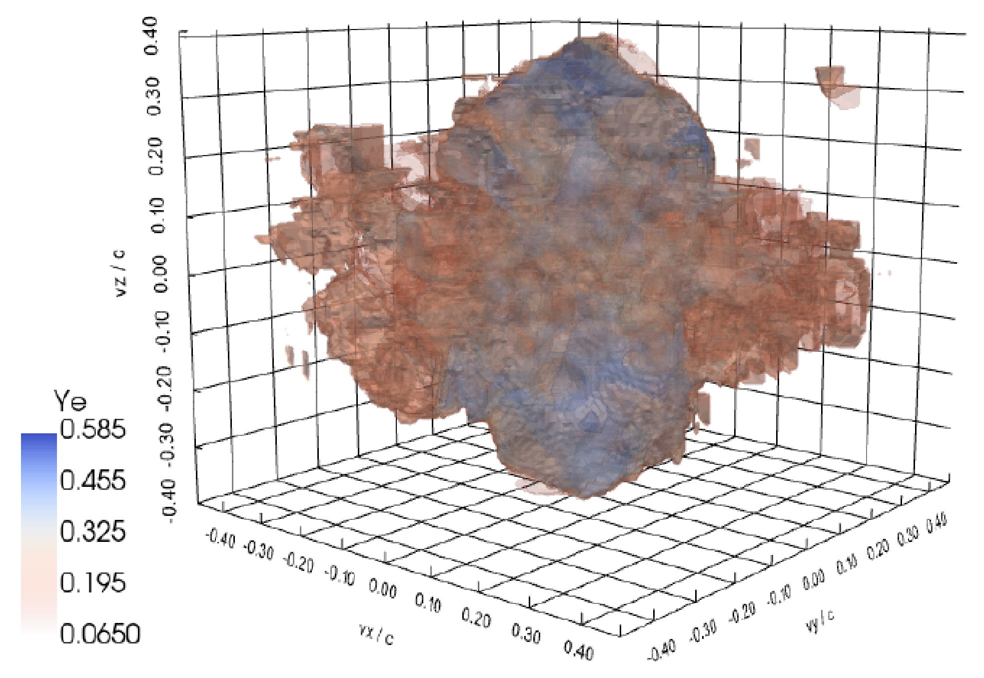
- Different ejecta components of comparable mass ejected by different mechanisms on different time scales → challenging to model: multi-scale multi-physics problem - first models on the way – Just, Vijayan, Xiong et al. 2023 (see also Kiuchi et al 2022, Fujibayashi et al. 2022 for short or very long-lived models; and numerous earlier studies focusing on individual components)

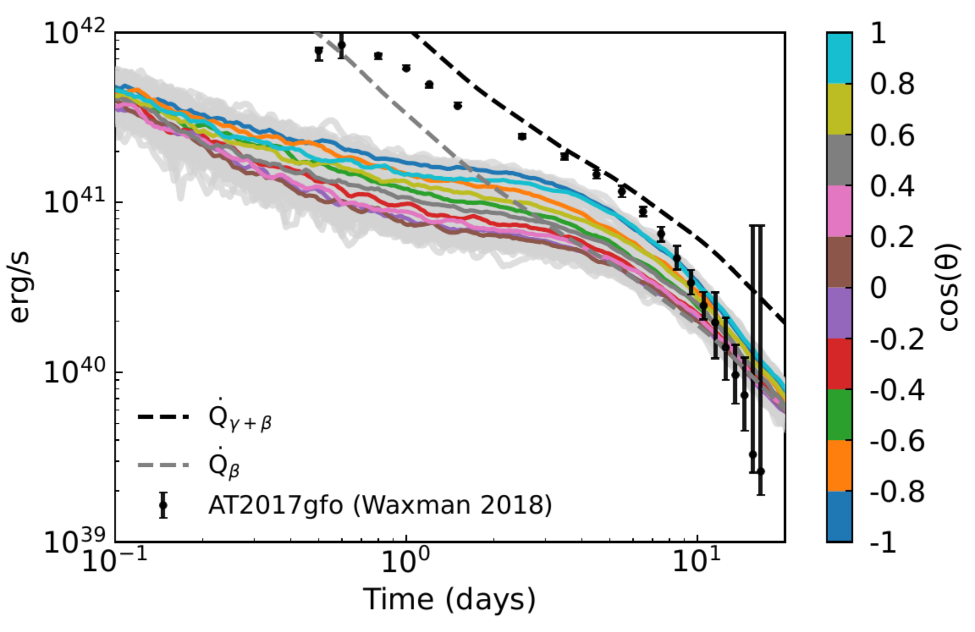


3d Radiative transfer modeling

- Towards full modeling pipeline of kilonovae (Collins et al, subm. to MNRAS 2022, ...)

  NS merger simulations → nuclear network calculation → 3d radiative transfer
- i.e. consistently connect theoretical models with observations to infer underlying processes: details of r-process: final abundance pattern, masses, velocity structure, path of r-process and involved reactions/nuclei

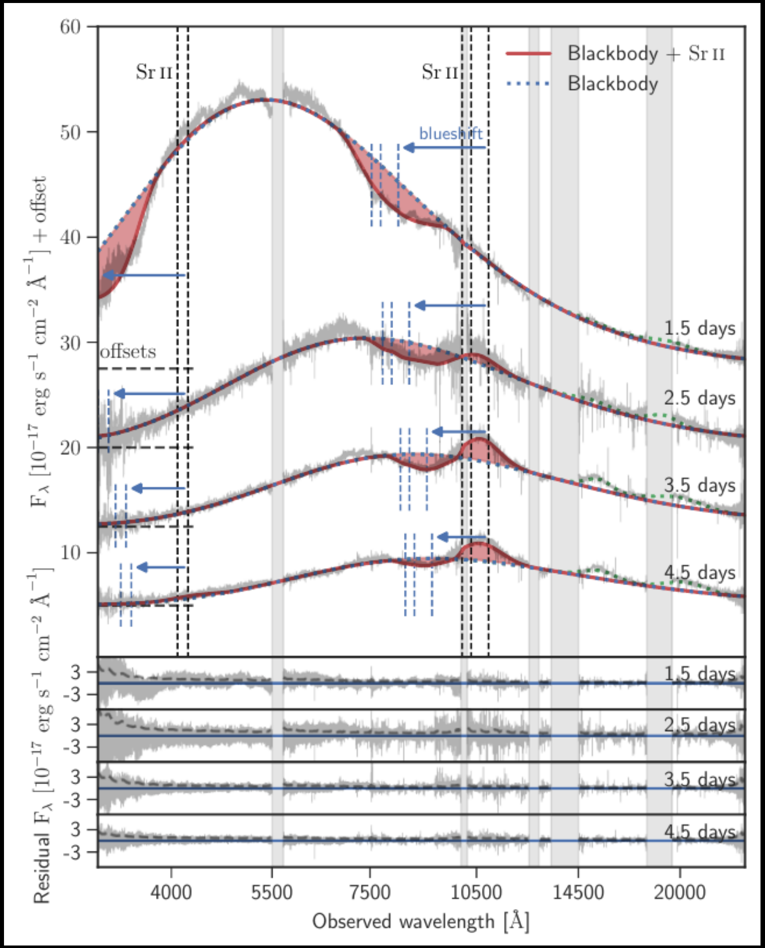




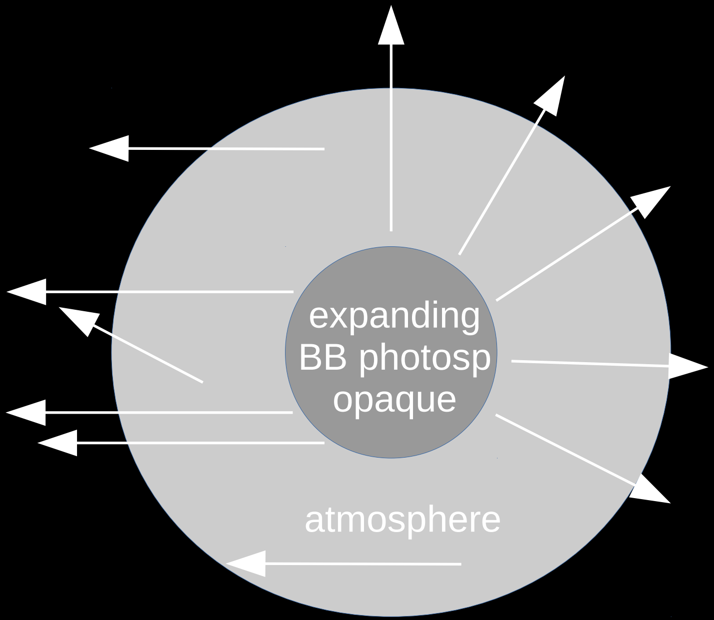
Collins et al., subm. to MNRAS 2022

Geometry of the kilonova

- Spectral features (like Sr) combination of absorption along the line of sight and emission scattered into he line of sight (= P Cygni feature)
- Allows to determine outflow velocity along light of sight (Doppler blue-shifted)



Watson et al. 2019



P Cygni feature: absorption along line of sight (blue-shifted)

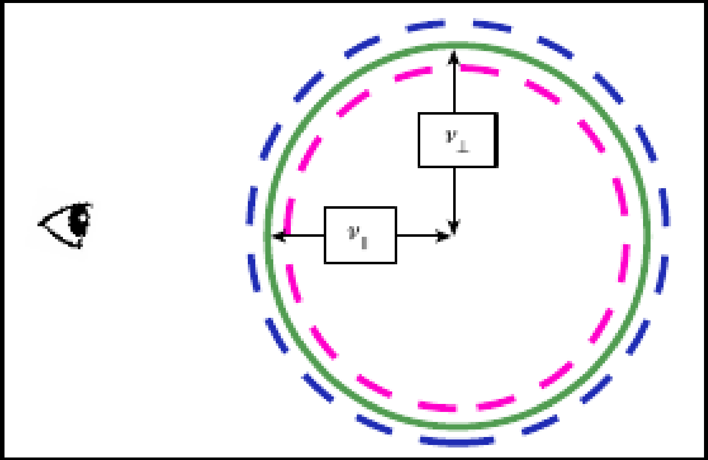
+ scattering into line of sight (rest wavelength)

Geometry of the kilonova

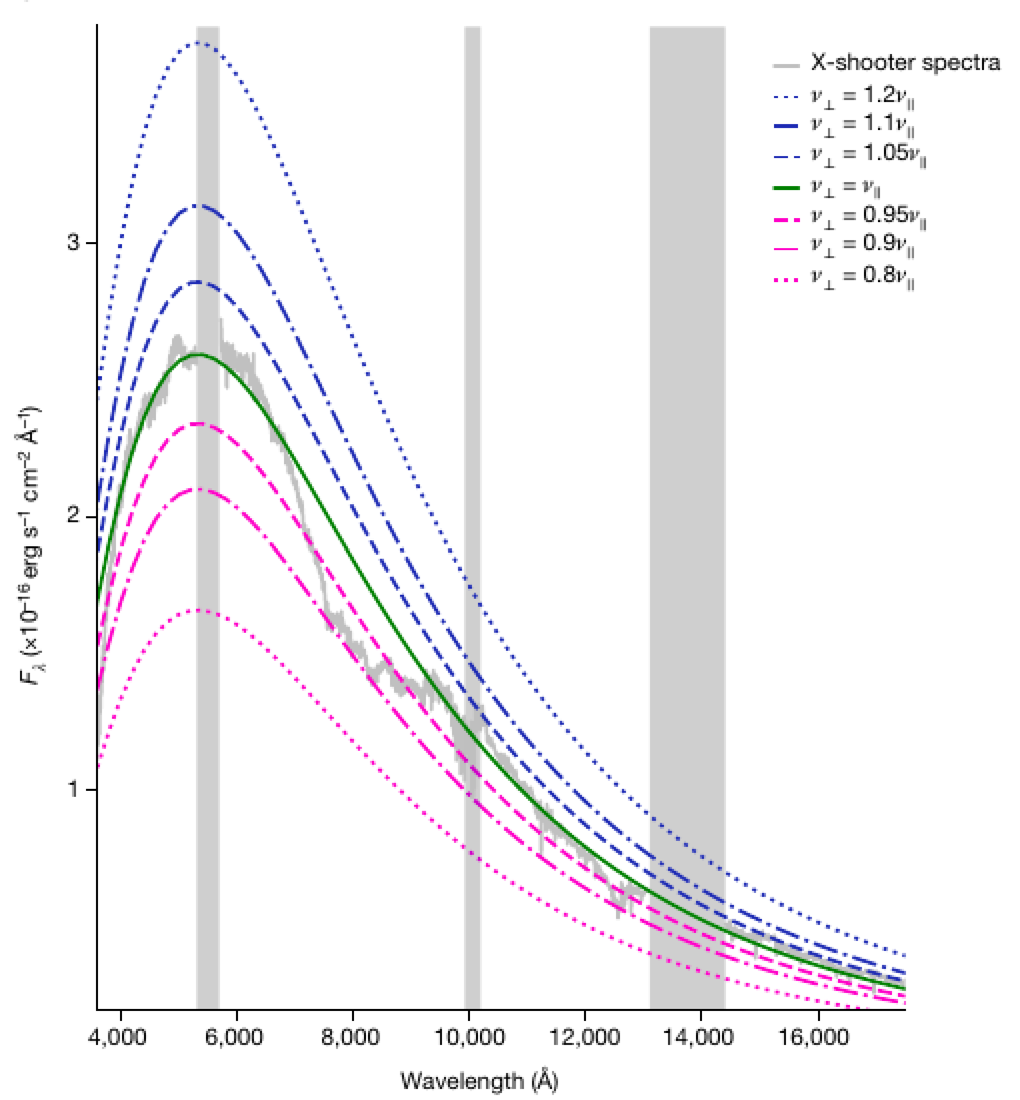
- Black body emission
- Stefan-Boltzmann law: $L = \sigma A T^4$

  - we know T and L from spectrum

  - and explosion time
- $R = v \cdot t \quad A = \pi R^2 \quad \Rightarrow v$



→ Kilonova was highly spherical



Sneppen et al., to appear in Nature (2023)

Geometry of kilonova

- Kilonova of GW170817 was highly spherical

  - not impossible but quite surprising

  → just a coincidence or physics that make it spherical (no obvious mechanism)

  → potential to constrain ejecta models

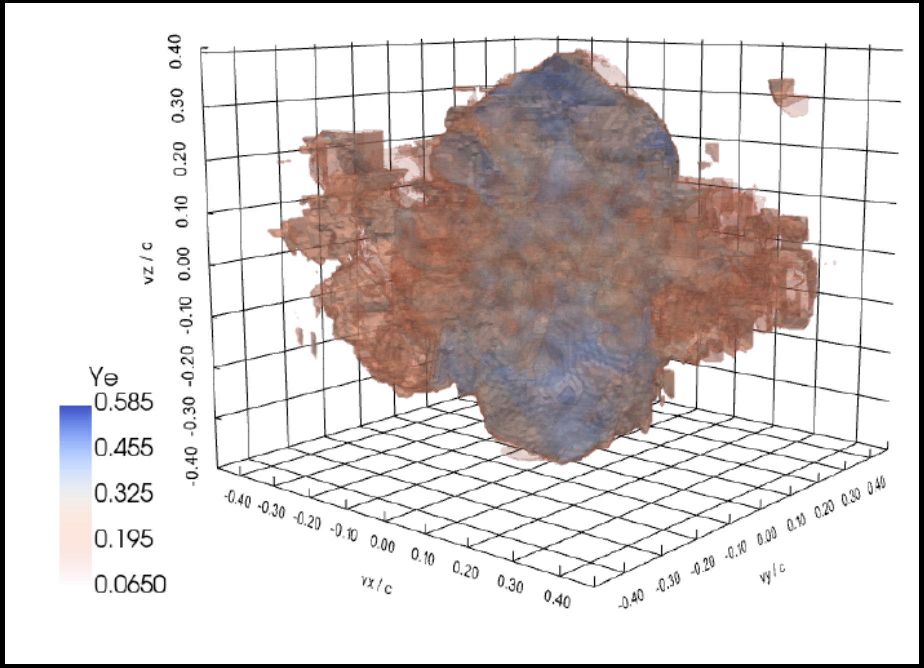
  BB luminosity depends on distance !

  (modeling of line shape provides $v_{||} \,/\, v_{\perp}$ independently)

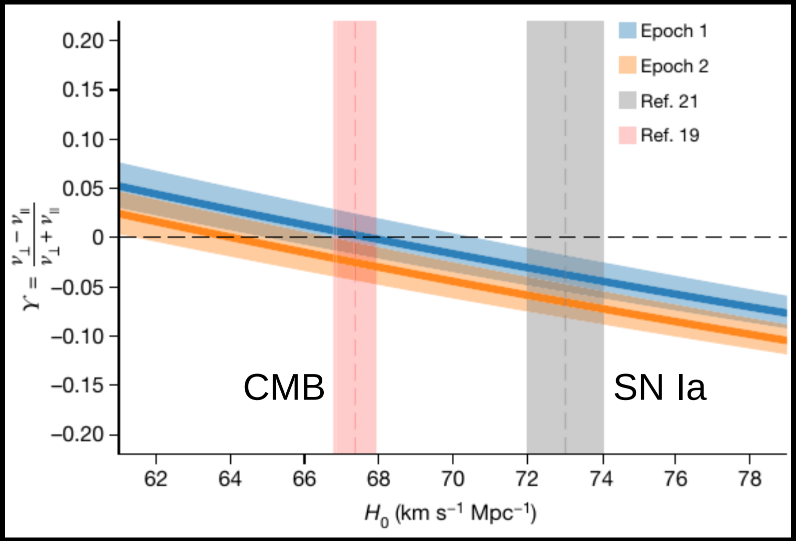
  → best measured distance of GW170817 so far

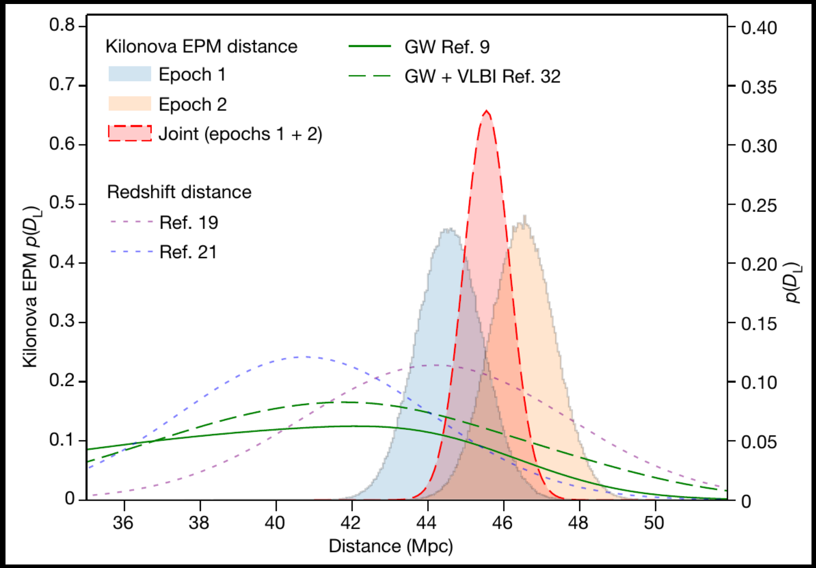
  → future constraints of Hubble constant

Rad. transfer: C. Collins; merger simulation: V. Vijayan



$$Y = \frac{v_{\perp} - v_{||}}{v_{\perp} + v_{||}}$$





Sneppen et al., to appear in Nature (2023)

Summary

- NS mergers connect to several different fundamental questions: origin of elements, time-domain astronomy, gamma-ray bursts, cosmology, properties of high-density matter, ...
- Many new or upgraded instruments become operational: upgraded Advanced Ligo, James Webb Space Telescope, Extremely Large Telescope
- NS merger forge heavy elements through r-process (likely the dominant channel)

  → kilonovae are key to understand nucleosynthesis

  → can provide independent information on distance and Hubble constant
- Stellar parameters inform about EoS – already a number of constraints exist from different observations / calculations
- Finite-size effects during insprial: EoS cannot be too stiff
- Prompt BH formation in NS mergers as most basic characteristic

  - M_{thres} encodes valuable information about high-density EoS

  - Multi-messeneger interpretation of GW170817: EoS cannot be too soft
- Postmerger GW oscillations → future EoS constraints

  - Quark matters leaves characteristic imprint on GWs
- ....