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GSI

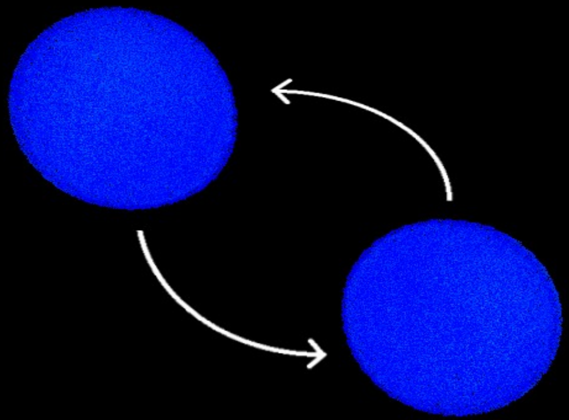
Neutron star mergers and kilonovae: r-process and gravitational waves

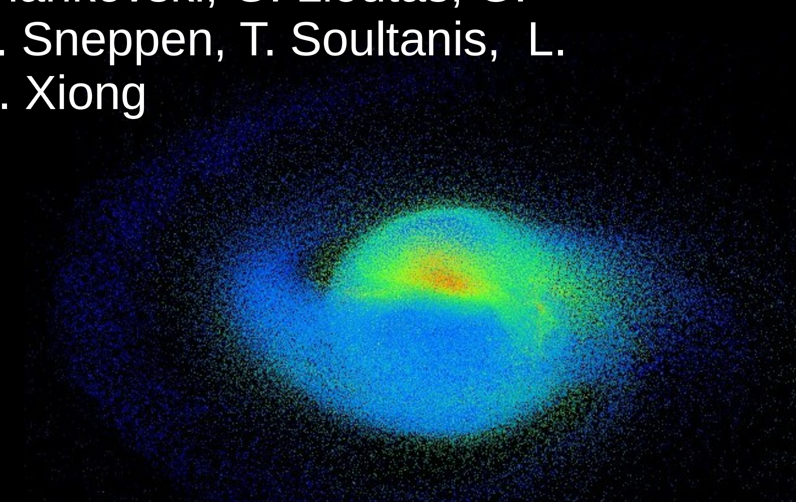
Nuclei in the Cosmos, Girona 18/06/2026

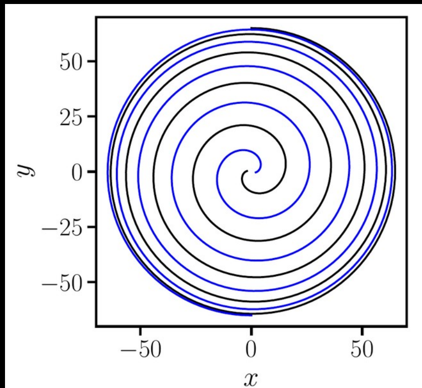
Andreas Bauswein

(GSI Darmstadt)

with S. Balcker, C. Collins, R. Damgaard, H. Kochankovski, G. Lioutas, G. Martinez-Pinedo, A. Ramos, L. Shingles, S. Sim, A. Sneppen, T. Soultanis, L. Tolos, V. Vijayan, D. Watson, Z. Xiong







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

Inspiral of NS binary

~100 Myrs

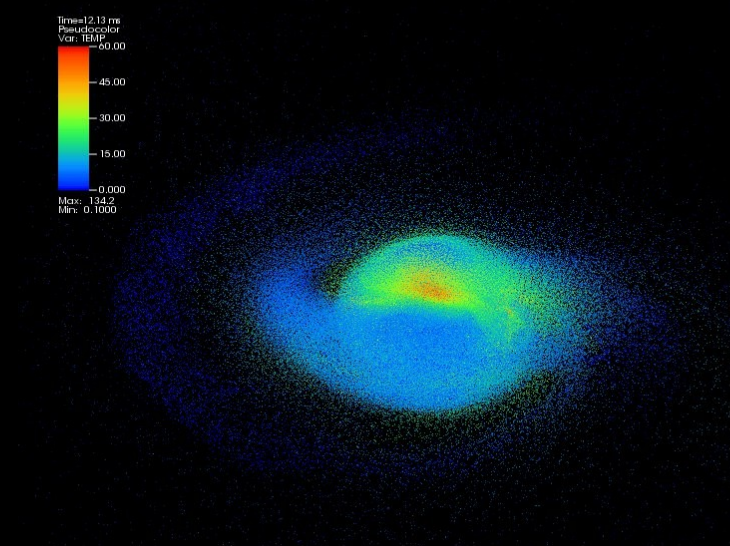
$P_{orb} \sim 1\,ms$

Neutron star merger

dependent on EoS, M_{tot}

ms

ms

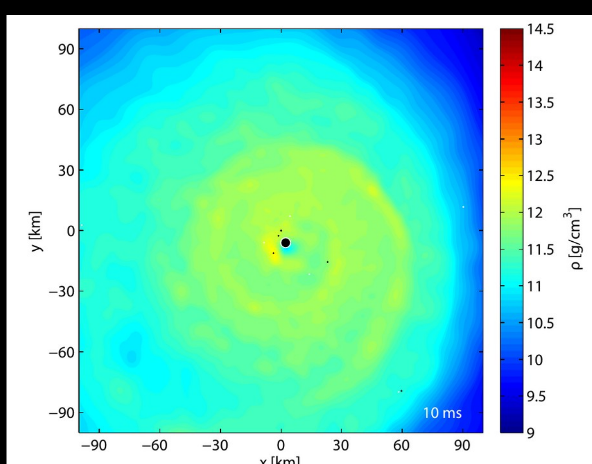


Prompt formation of a BH + torus

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

Major questions to mergers

- What are the properties of neutron stars and high density matter ?

  - stellar parameters of NSs: radii, tidal deformabilty, maximum mass

  - underlying EoS: constituents and their interactions (hyperons? Quark matter?)

- How and where do heavy elements form through the rapid neutron-capture process ?

  - total amount of ejecta

  - elemental abundances

  - velocity distribution and geometry of ejecta/elements

- (Rate of mergers and their binary mass distribution (as function of z))
- Partly entangled
- Interconnected with many other measurements/ experiments/ theory

Kilonova and r-process

Relevant physics

- Two approaches:

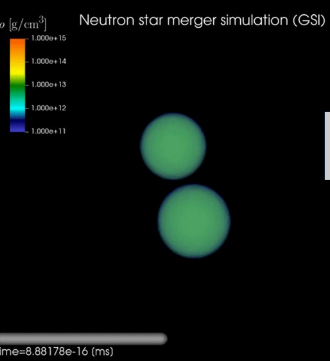
  - forward modeling starting with a NS merger simulation

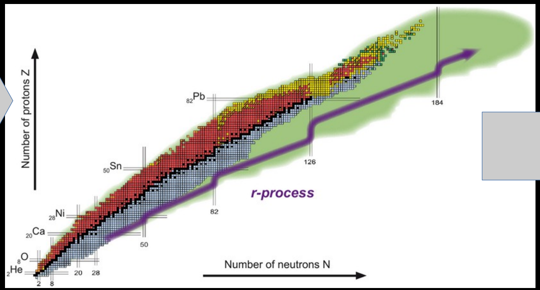
  - backward modeling starting with observational data

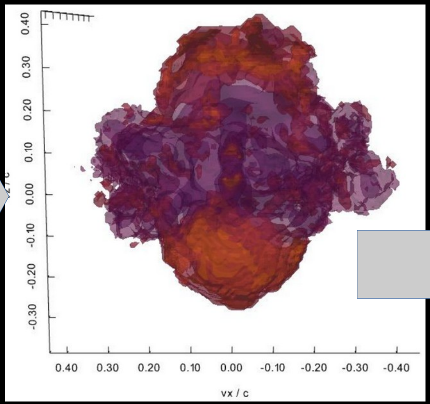
↓ atomic data

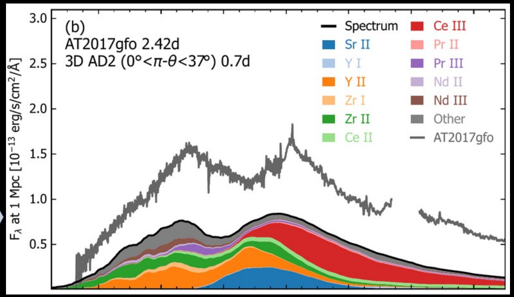
↓ EoS

↓ nuclear reaction rates









r-process nucleosynthesis (potentially with backreaction)

Spectra and light curves

NS mergers

Radiative transfer in photospheric and nebular phase

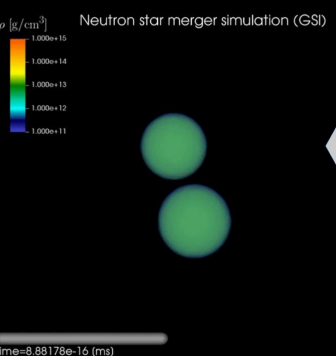
Relevant physics

- Two approaches:

  - forward modeling starting with a NS merger simulation

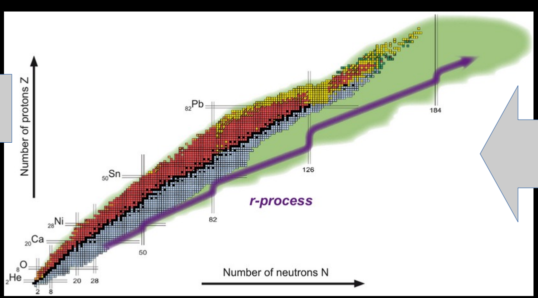
  - backward modeling starting with observational data

↓ EoS



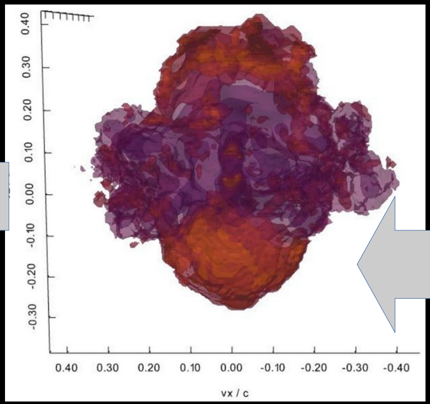
NS mergers

↓ nuclear reaction rates

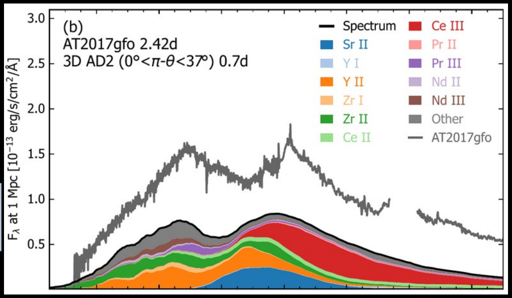


r-process nucleosynthesis (potentially with backreaction)

↓ atomic data



Radiative transfer in photospheric and nebular phase

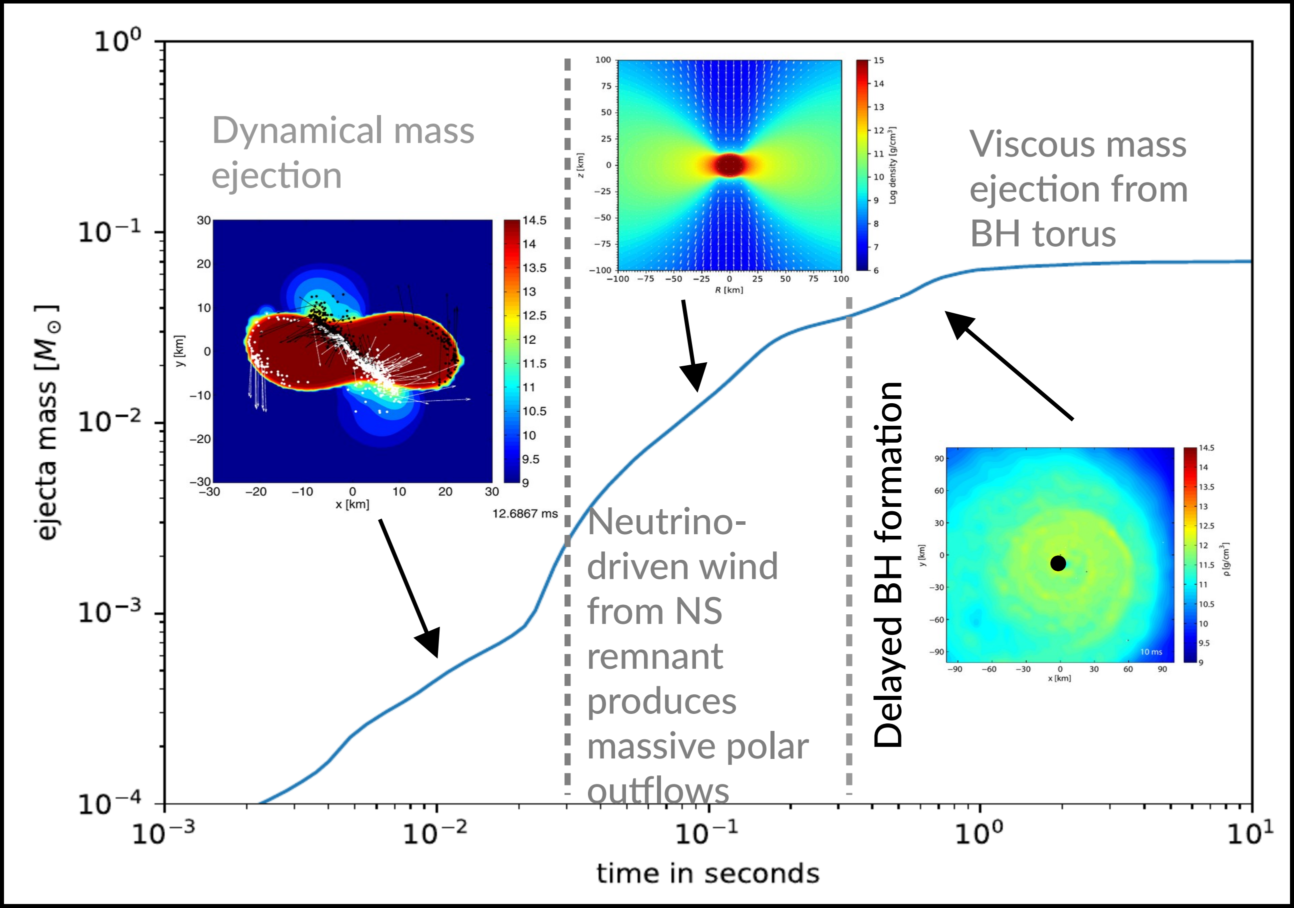


Spectra and light curves

Forward modeling

Towards consistent models of all ejecta components

- Different ejecta components of comparable mass ejected by different mechanisms on different time scales – Just, Vijayan, Xiong et al. 2023 (see also Kiuchi et al 2022, Fujibayashi et al. 2022 for short or very long-lived models)
- Intermediate remnant lifetime (BH formation → EoS and binary mass dependence)
- Modeling generally challenging



Towards consistent models of all ejecta components

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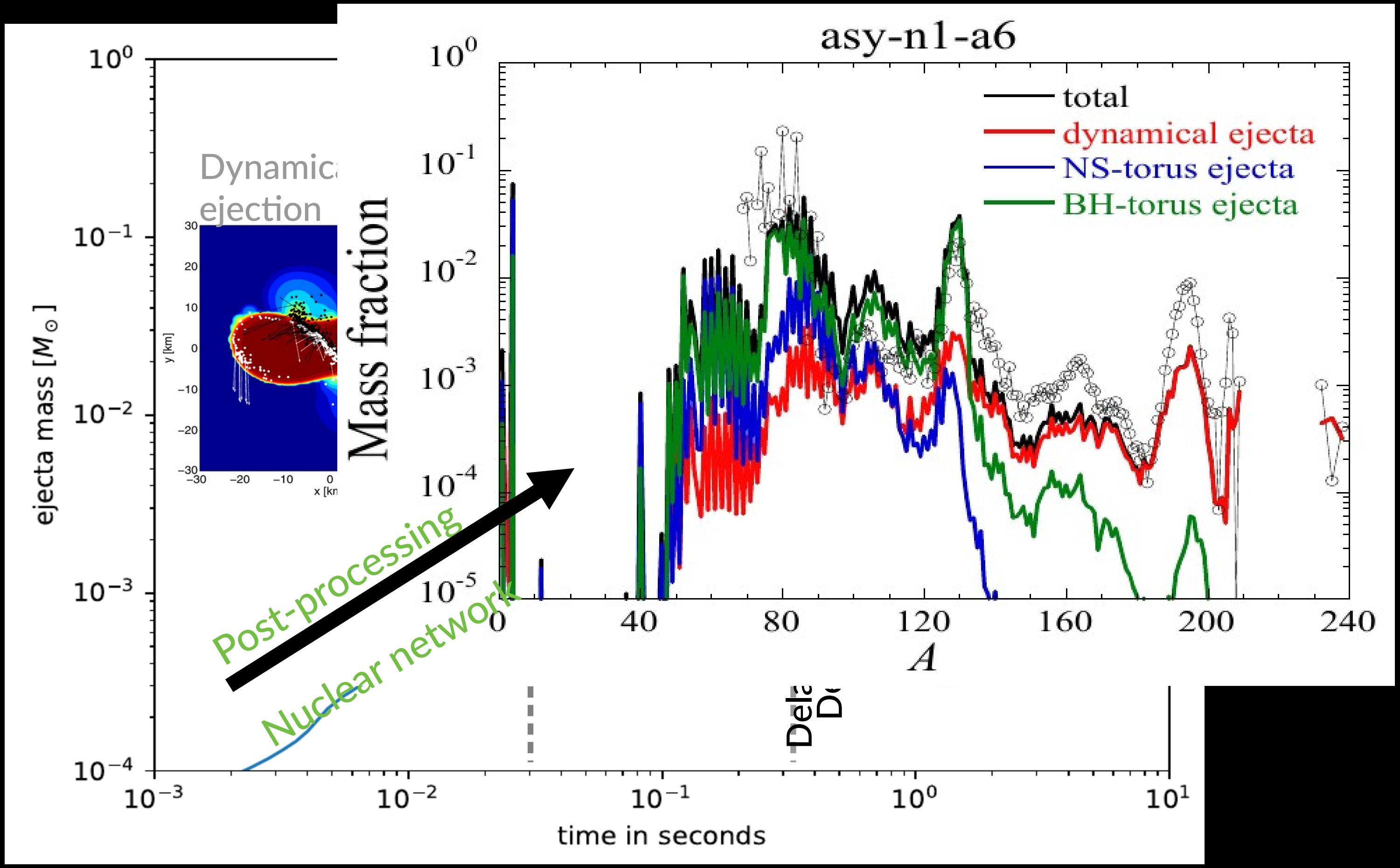
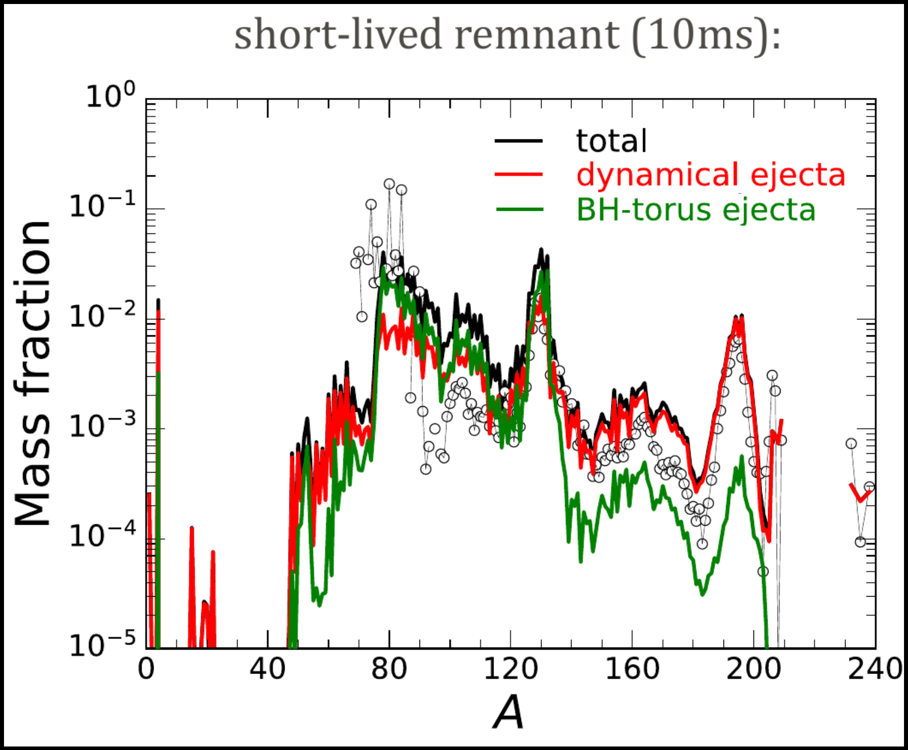
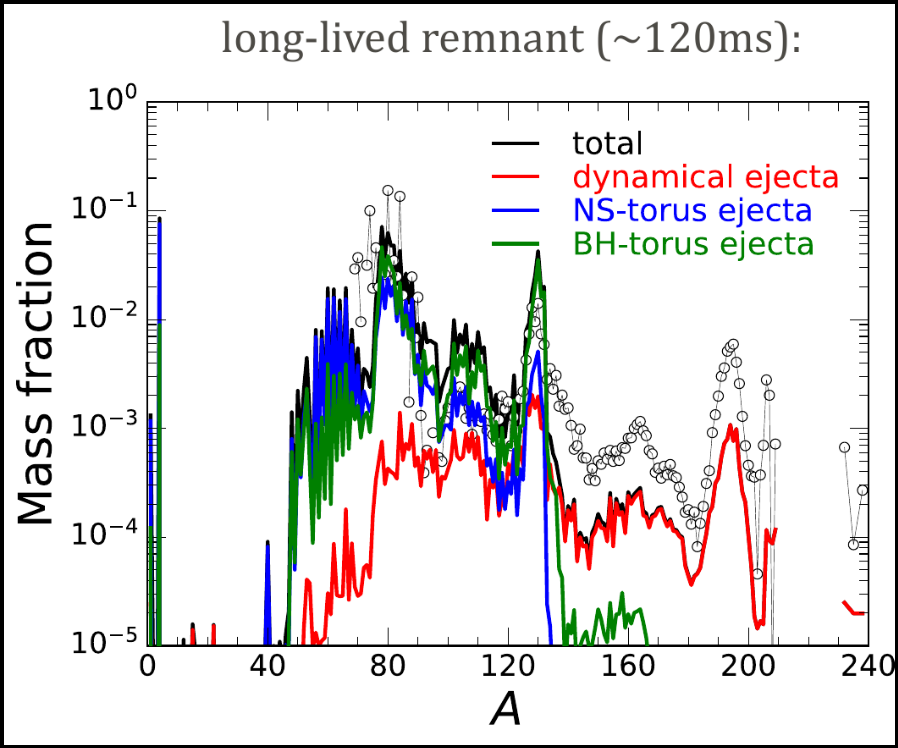
- Intermediate remnant lifetime (BH formation → EoS and binary mass dependence)
- Abundance does not match solar too well → not main systems ? (see also Fujibayashi+ 2023)



- All mass ejection channels – GW170817 like binary masses
- Longer remnant life time leads to subsolar abundance pattern
- Most merger events short-lived ?





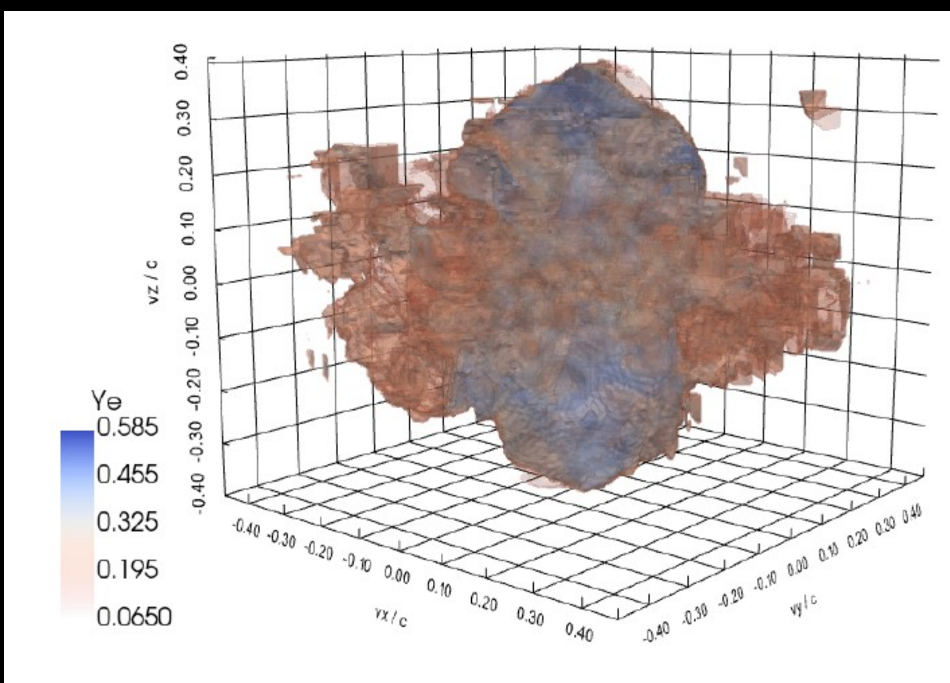
Just et al. 2023, see also Fujibayashi et al. 2020, 2023 with similar trends

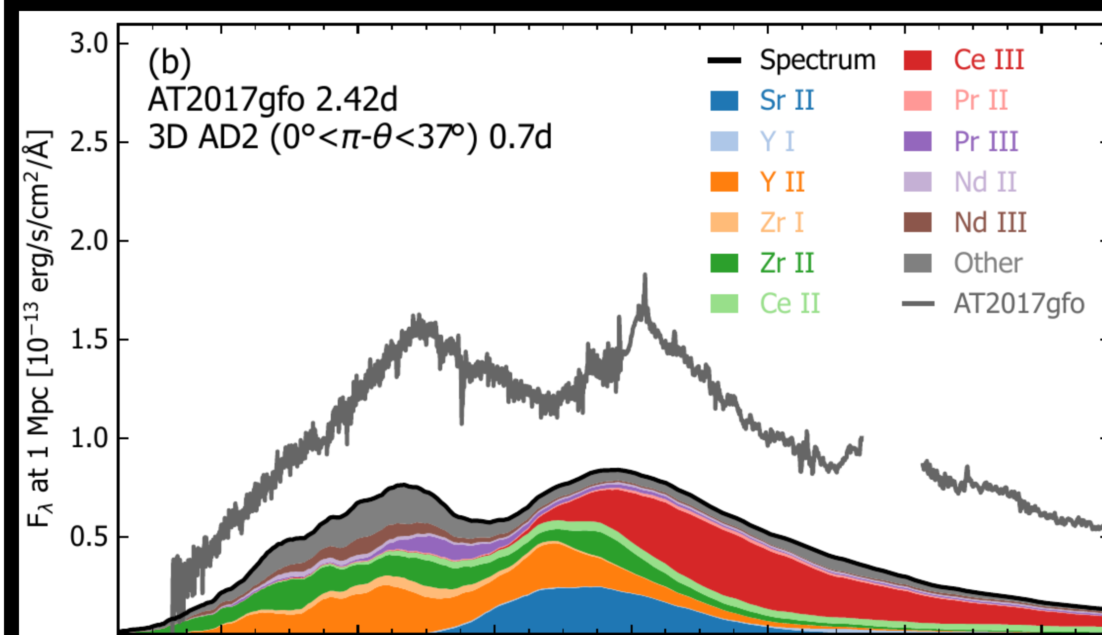
3d Radiative transfer modeling

- 3d radiative transfer (with Monte-Carlo code ARTIS) on actual merger data
- Time-dependent, local abundance and energy deposition form simulations
- Line-by-line treatment of atomic transition – to connect to specific elements

→ essential ingredients for reliable forward modeling (i.e. extraction of underlying physics)

Here only dynamical ejecta considered
→ match of spectra at different times

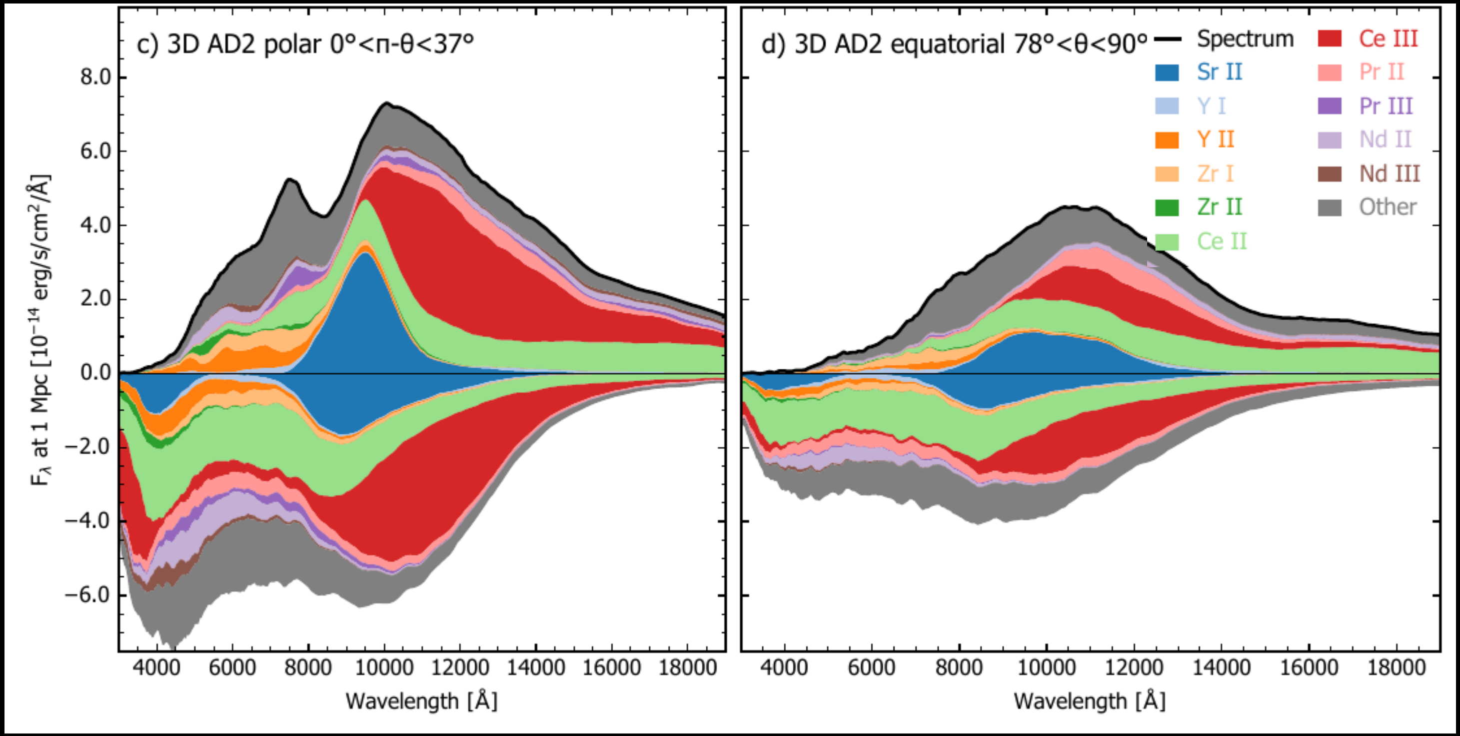




Collins et al. 2023; Shingles et al. 2023, Collins et al. 2024

3d Radiative transfer modeling - Findings

- Spectra surprisingly similar to AT2017gfo (without any attempt to match/tune)
- Spectra show strong observer angle dependence → 3d is very important
- Important elements for spectrum shape: Sr, Y, Ce (quality of atomic data important)
- Photosphere of asymmetric ejecta distribution appears more spherical (Collins+ 2024)

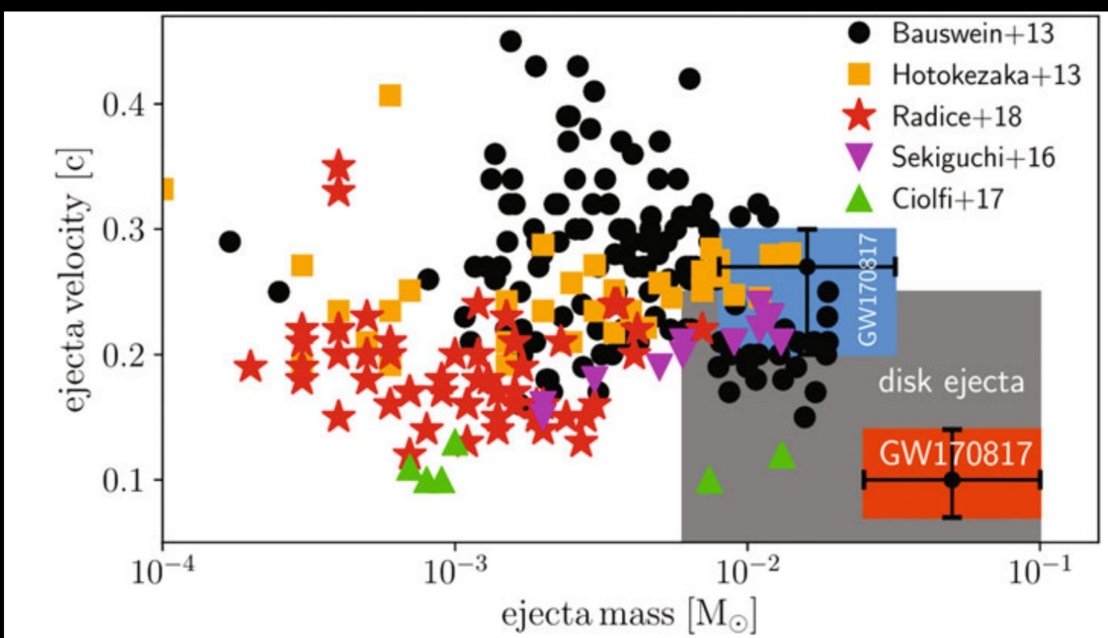


Collins et al. 2023; Shingles et al. 2023, Collins et al. 2024; see also e.g. Tanaka & Hotokezaka 2013, Kasen et al 2015, Kawaguchi 2018, Wollaeger et al. 2021 for 2D parameter study, Pognan et al. 2023 for NLTE in 1D, i.e. late time emission, Neuweiler et al 2023, Kawaguchi et al. 2024 for NS-BH, Vieira et al. 2024, Brethauer et al. 2024 for assessment of uncertainties in inference, ….

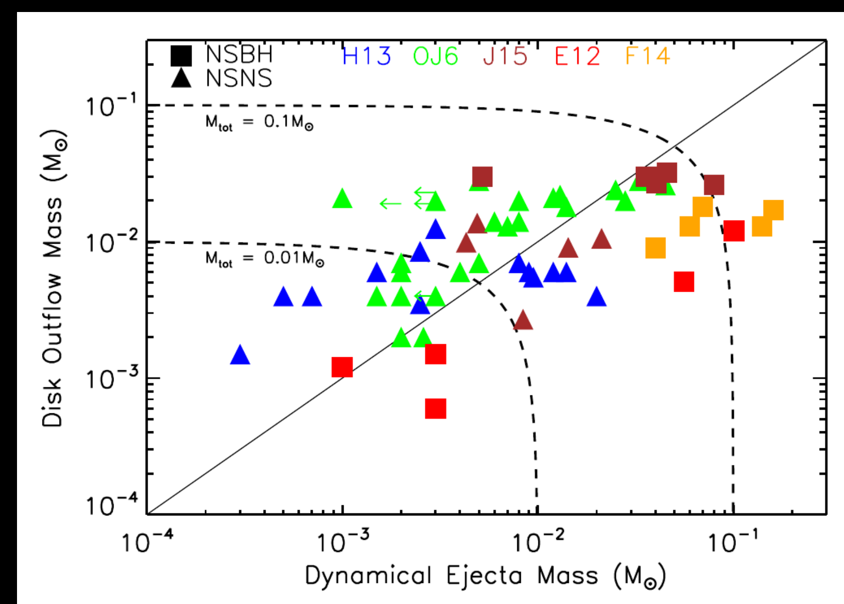
Backward modeling

- Kilonova roughly follows black body and decay compatible with r-process heated ejecta and high opacity
- Ejecta mass and velocity estimates e.g. through bolometric luminosity (color evolution, opacity estimate, etc) – various different models including typical r-process heating rate and considering for instance different “components”

  → broadly compatible with ejecta masses from simulations



Siegel 2019



Wu et al. 2016

Spectroscopic identification of r-process

- Features imprinted, but hard to interpret:

  - blue-shift (v ~ 0.3c)

  - line lists of heavy elements limited

  Strong absorption feature (P Cygni): Strontium

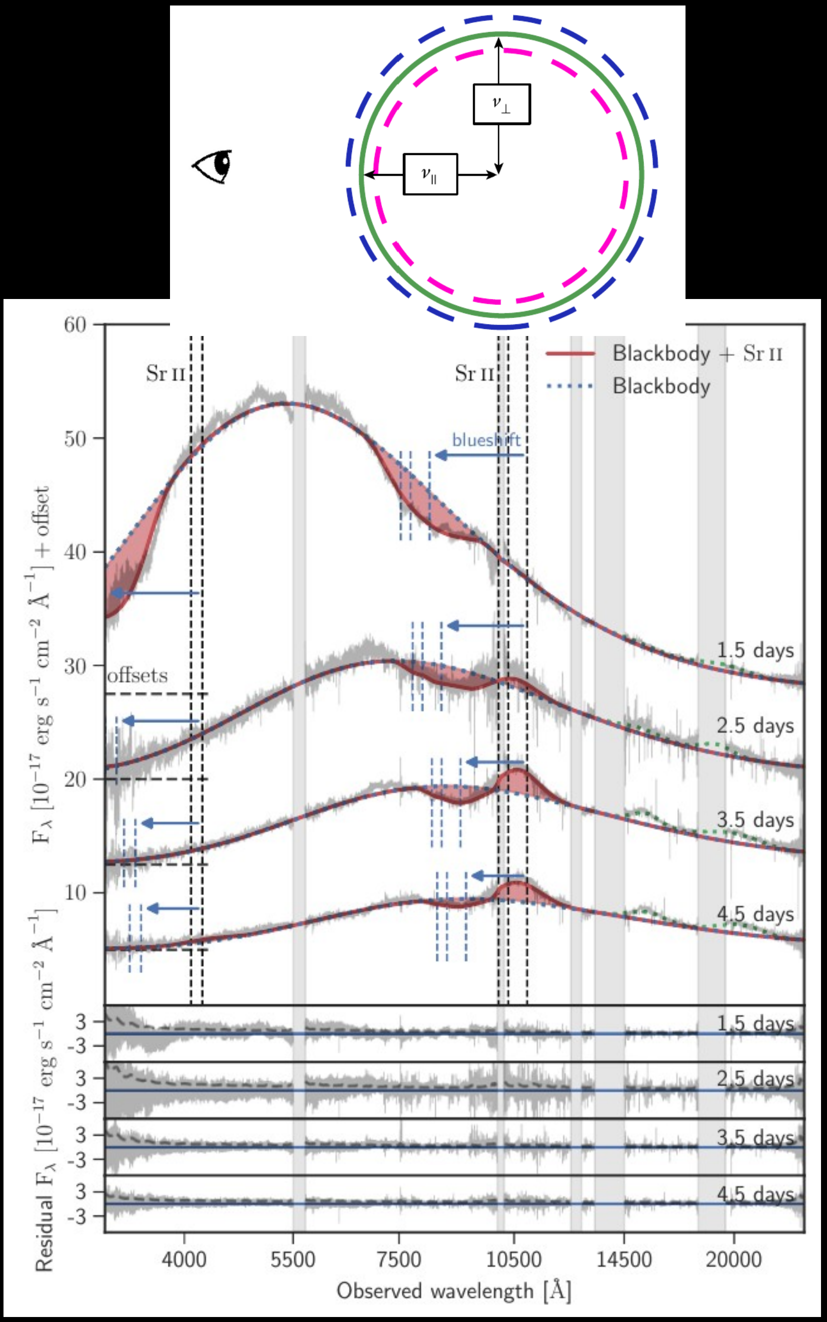
  → further evidence for r-process in NS mergers !!!

- (tentative) evidence for other elements Y, Te, Zr, La, Ce, He, W, … [Gillanders et al 2022, Domoto et al 2022, Perego et al. 2022, Vieira et al 2023, Sneppen & Watson 2023, Tarumi et al 2023, Hotokezaka et al 2023, Tanaka et al 2023, McCann et al 2025, …] also from AT2023vfi

  → more information on geometry, stratification etc. from spectroscopy

  as well as distance and Hubble constant from line profiles and expanding photosphere (Sneppen+ 2023)

  but exact amounts hard to estimate



Watson et al. 2019

EoS / NS constraints and multi-messenger interpretation

EoS constraints from GW170817 / mergers

- Constraints on the tidal deformability from GW inspiral → R < 13.5 km
- General arguments about the collapse of the remnant (via em radiation)

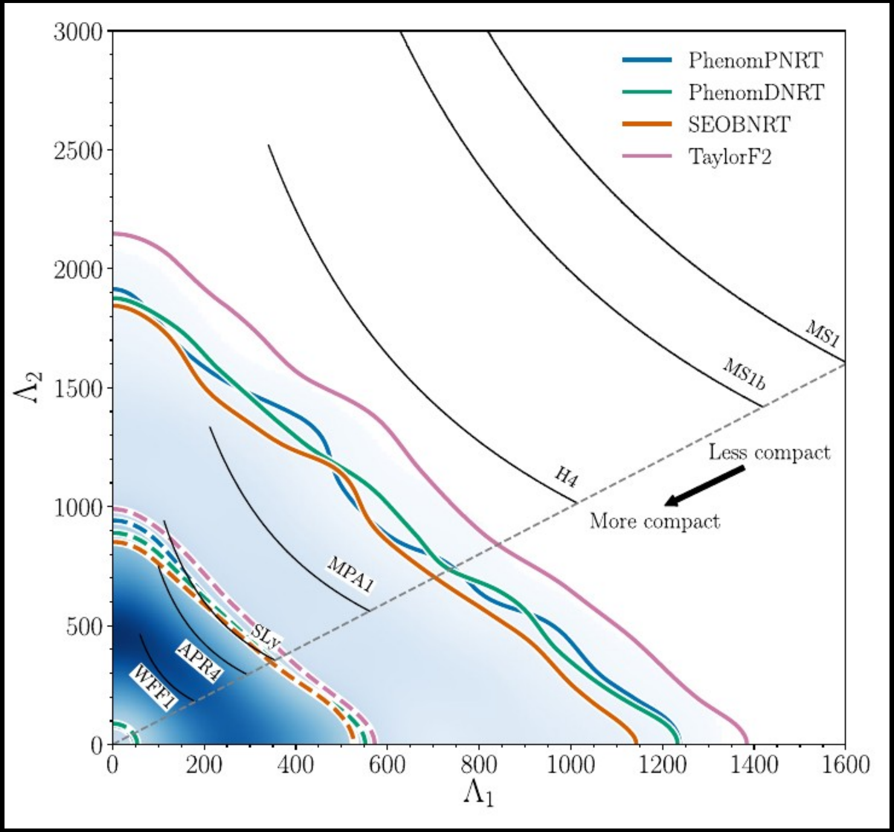
  - no prompt collapse → minimum stiffness / radius required → R > 10.5 km

  - collapse to BH (because of GRB) → tentative M_{max} limit ~2.3 M_{sun}
- Modeling of kilonova light curve → M_{ej} → EoS via fit formulae (suffers from various uncertainties)

- Note: coarse classification with vast amount of literature* (partly overlapping, partly in combination with other constraints)

  → different arguments, different model assumptions/uncertainties/robustness

  And many other NS observations and constraints (e.g.NICER)



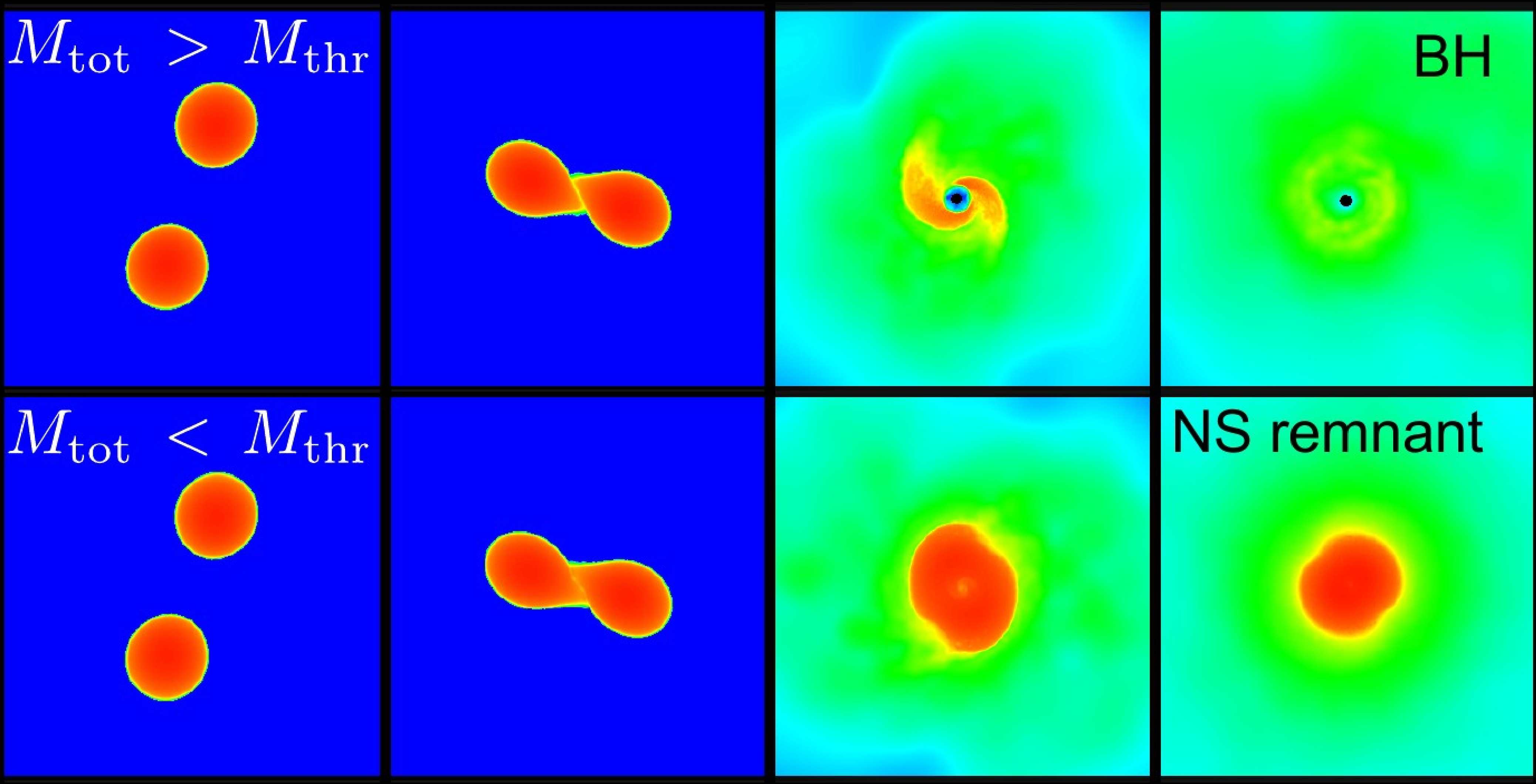
Abbott et al. 2019

* Some references multi-messenger constraints: Margalit & Metzger 2017, Bauswein+ 2017, Shibata+2017, Radice+ 2018, Rezzolla+ 2018, Ruiz+ 2018, Most+ 2018, Coughlin+ 2018, Koeppel+ 2019, Kiuchi+ 2019, Capano+ 2020, Dietrich+ 2020, Breschi+ 2021, Raaijmakers+ 2021, Bauswein+ 2021, Huth+ 2022, Lund+2024, Sneppen+ 2024, …

Multimessenger EoS constraints

(2 examples)

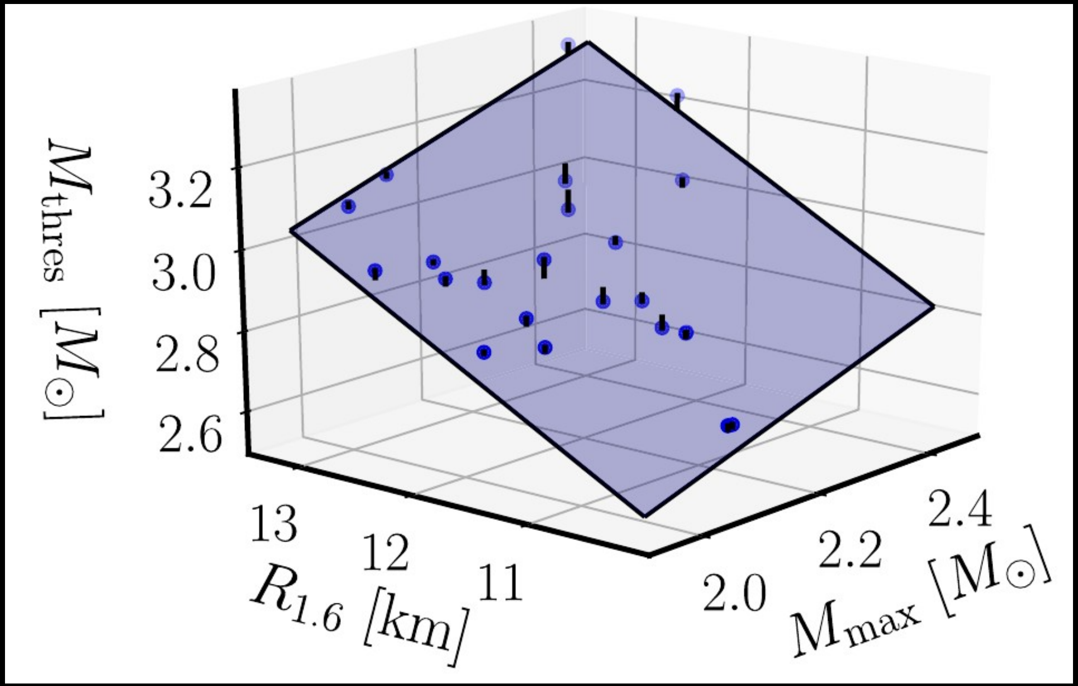
Collapse behavior – M_{thres} measurable – masses from GWs



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, Koeppel et al 2019, Agathos et al. 2020, Bauswein et al. 2020, Bauswein 2021, Kashyap et al 2022, Perego et al 2022, Koelsch et al 2022, ...]

Threshold mass for prompt collapse

- Empirical relations: M_{thres} (M_{max},$R_{1.6}$) from simulations for large set of EoSs
  → M_{thres} limit simultaneously constrains R and M_{max}
- $R_{1.6}$ can be replaced by R_{14}, Lambda_14, R_{max}

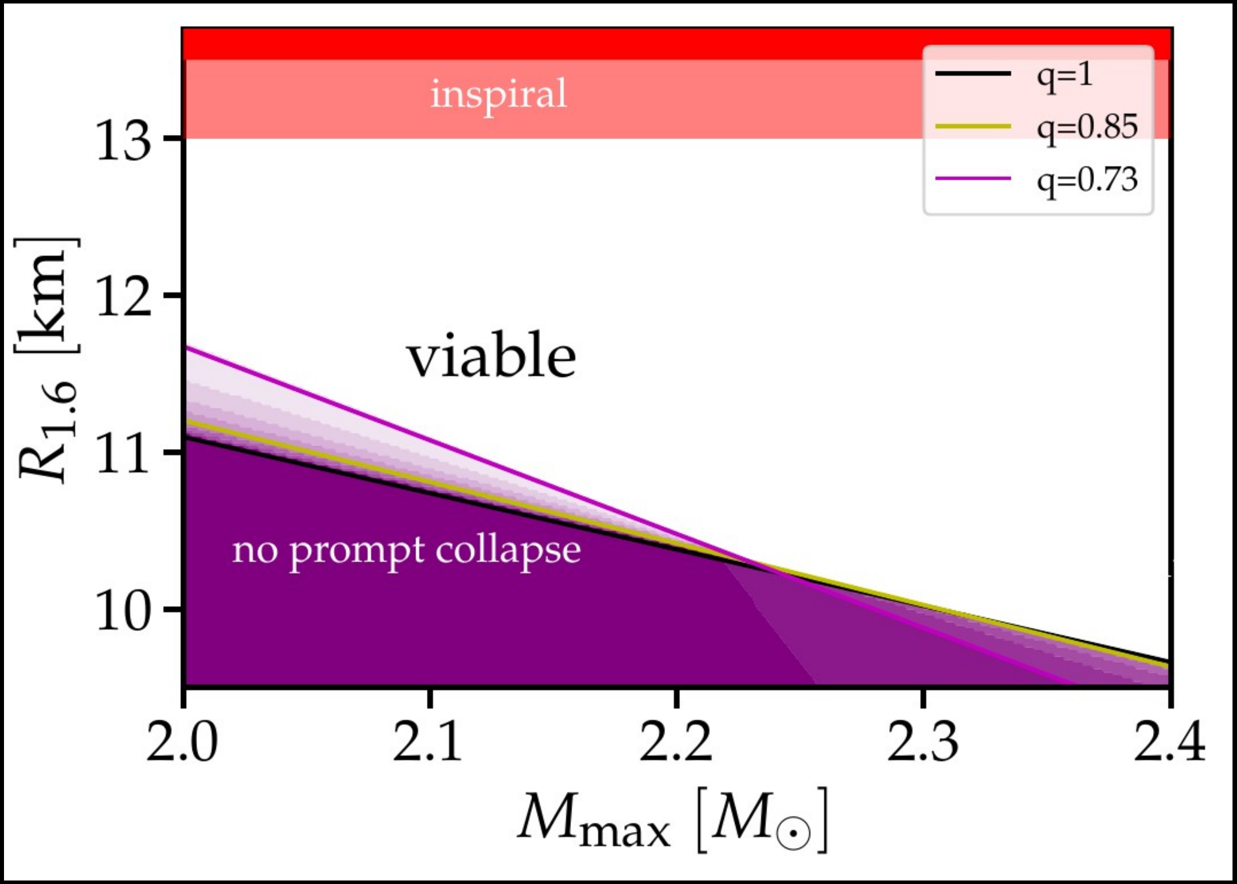


Here only equal-mass shown, but extension to asymmetric binaries possible; Bauswein et al. 2021

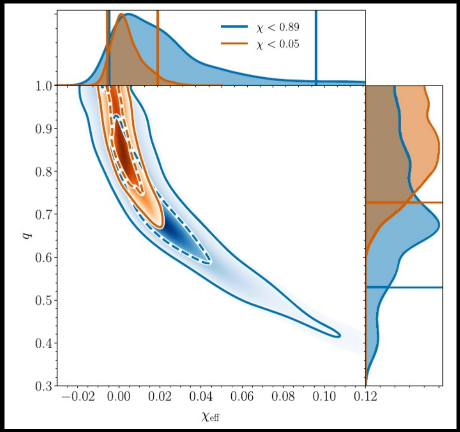
$$M_{\rm thres}(q, M_{\rm max}, R_{1.6}) = c_1 M_{\rm max} + c_2 R_{1.6} + c_3 + c_4 \delta q^3 M_{\rm max} + c_5 \delta q^3 R_{1.6} + c_6 \delta q^3. \qquad (10)$$

Constraints on EoS/NS parameters

- Bright kilonova points to no direct BH formation
- No prompt collapse: $M_{tot} < M_{thres}(R1.6, M_{max})$ => $R < -a^*M_{max} + b$
- Mass ratio not exactly known → use posterior



Bauswein et a 2017, updated in Sneppen et al. 2024, arXiv:2411.03427



Abbott et al 2019

Helium for remnant lifetime and EoS constraints

New EoS constraint from GW170817/AT2017gfo

- Exploting so far unused information in 3 major steps

  - Limits on He abundance in ejecta from kilonova spectrum

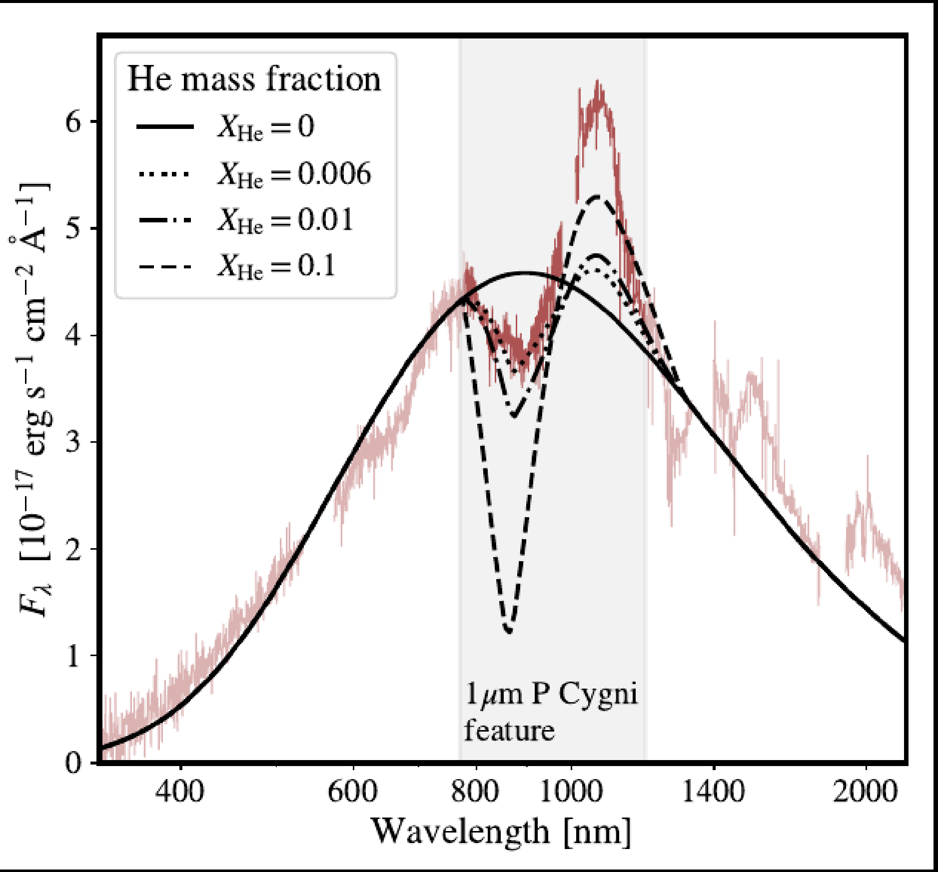
  - theoretically expected He enrichment from simulations limits lifetime

  - Lifetime limit constrains M_{thres} → EoS/NS constraints

He spectral features in spectrum

- Already tiny amounts of He would produce strong absorption feature

  → mass fraction X(He) < 0.006 … 0.05



Sneppen et al. 2024

See also Perego et al 2022 and Tarumi et al. 2022 for discussion of helium in AT207gfo

Helium production

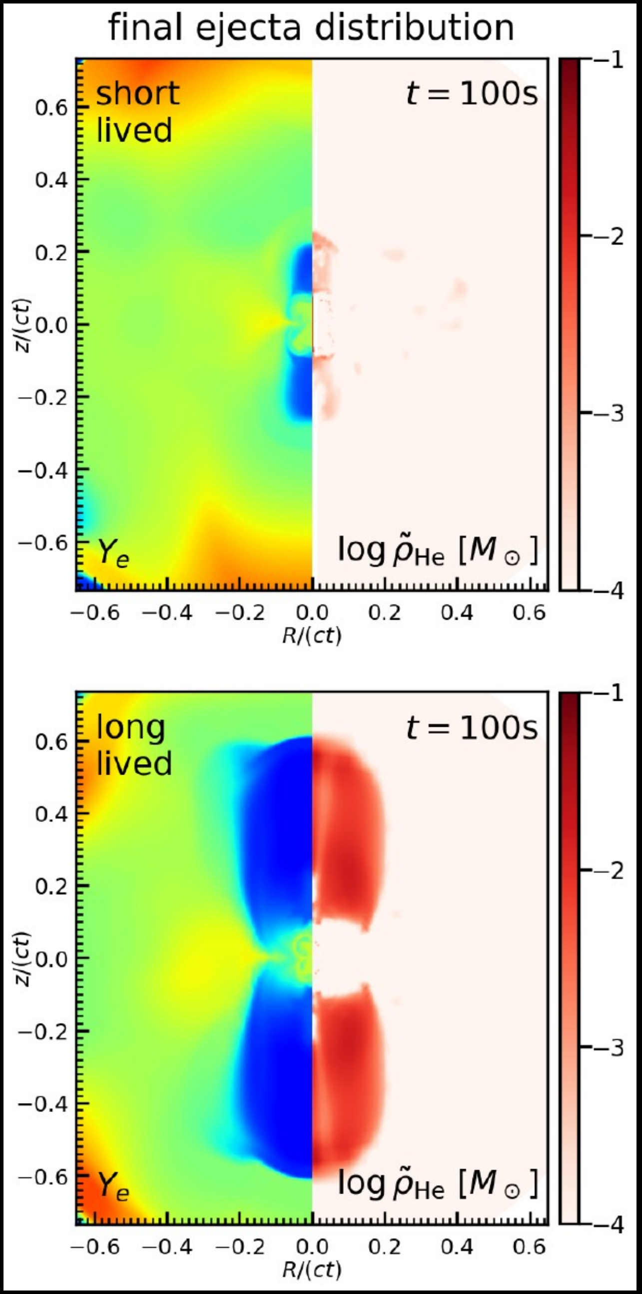
- Helium is produced for high Ye and high entropy

  → predominantly during the neutrino driven wind

  → acts as tracer of remnant life time

Model	M_1	M_2	$t_{\rm pm}$	$t_{\rm BH}$	$M_{\rm ej}$	$M_{\rm ej}^r$	$M_{\rm ej}^p$	$M_{\rm ej}^{\rm He}$	$M_{\rm ej}^{\rm Ni}$
	$[M_\odot]$		[ms]		$[10^{-3} M_\odot]$				
BLh_q1.49	1.64	1.15	103	114	10.85	4.01	3.72	3.03	0.84
DD2_q1.77	1.81	1.08	111	-	25.31	19.30	1.59	1.56	0.43
DD2_q1.0	1.35	1.35	79	-	5.80	1.18	1.53	1.23	0.41
SFHo_q1.0	1.35	1.35	35	5.7	6.25	3.51	0.00	0.09	0.01

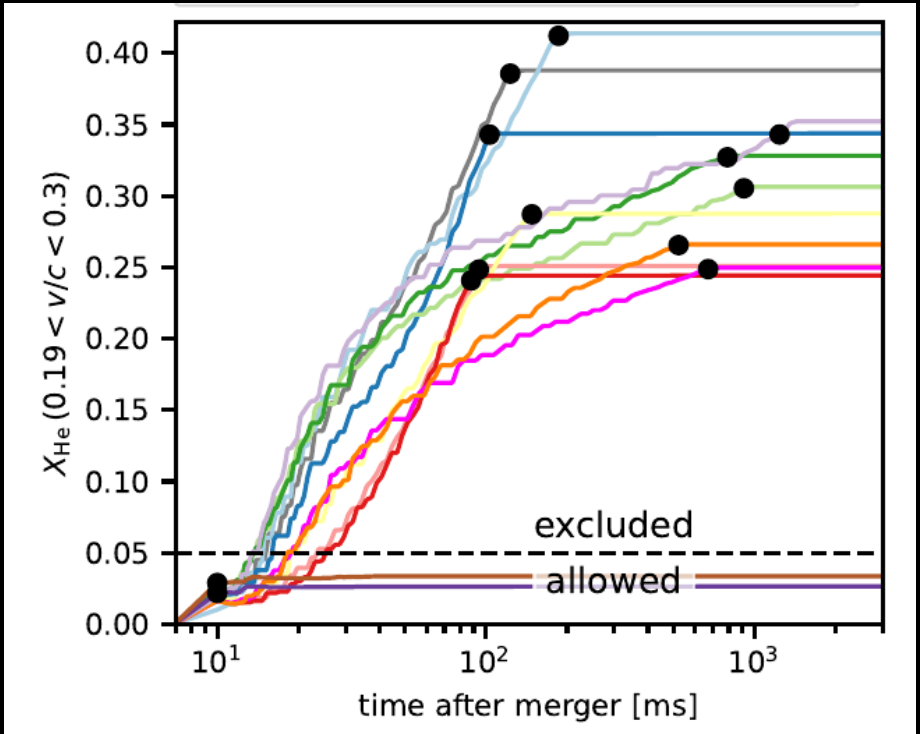
cf. He and Ni production in Jacobi et al 2025



Sneppen et al 2024

He production in merger simuations

- Efficient He production only by long-lived merger remnants (producing neutrino driven wind with less neutron-rich outflows – after BH formation He production shuts off)
- Low He abundance → remnant in GW170817 collapse latest after 20-30 ms (short-lived)



Sneppen et al. 2024

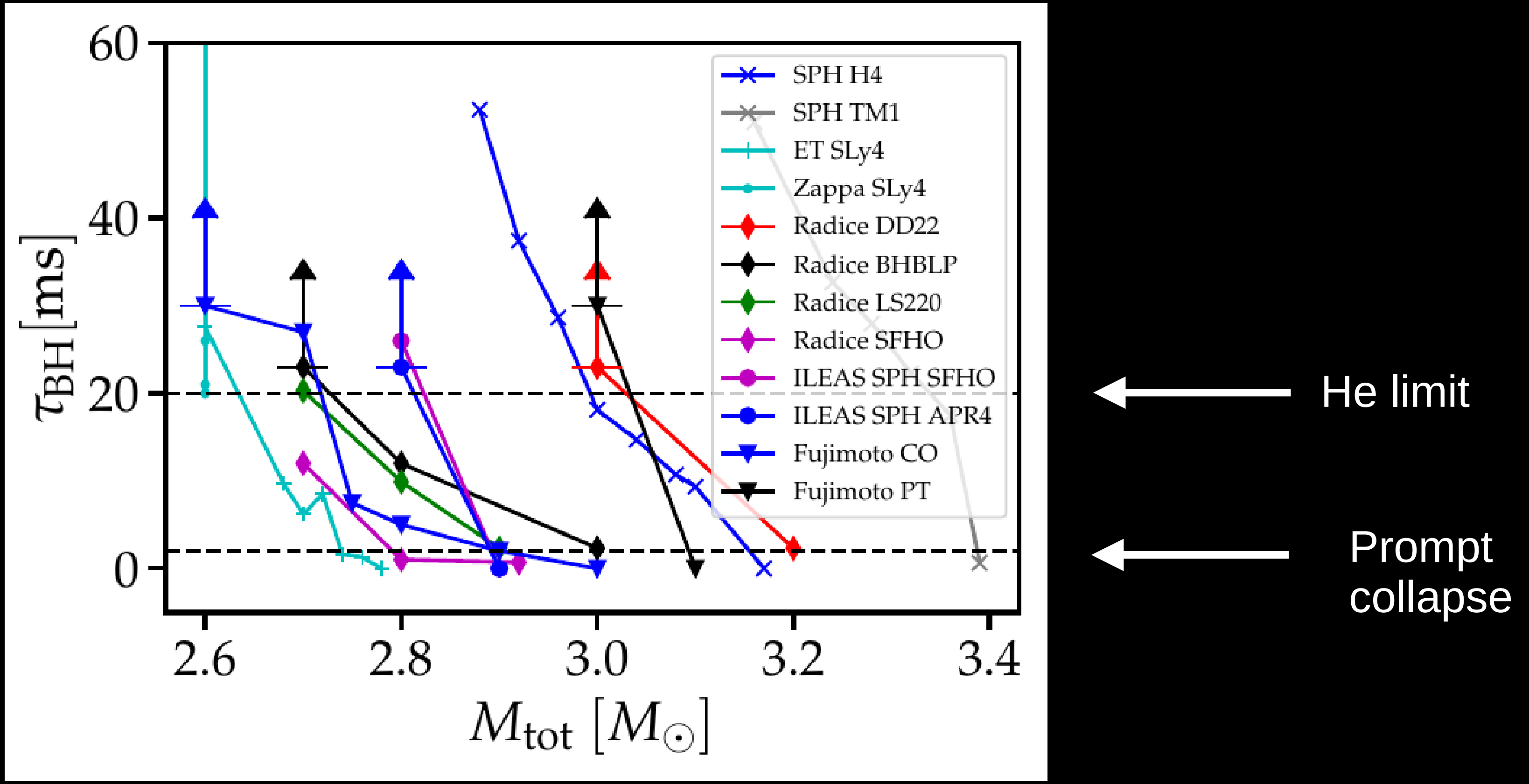
Basic argument: If remnant lived too long, produced amount of helium is incompatible with observations.

Several studies advocate long-lived remnant base on other arguments, e.g. Vieira et al 2025 via light curve and abundance from spectra

Short-lived remnant constraints M_{thres}

- Lifetime steeply declines with total binary mass reaching ~0 at M_{thres}
- Lifetime of ~20 ms implies that GW170817 was "close" to prompt collapse

→ M_{tot}=2.73 M_{sun} => M_{thres} < 2.93 M_{sun}



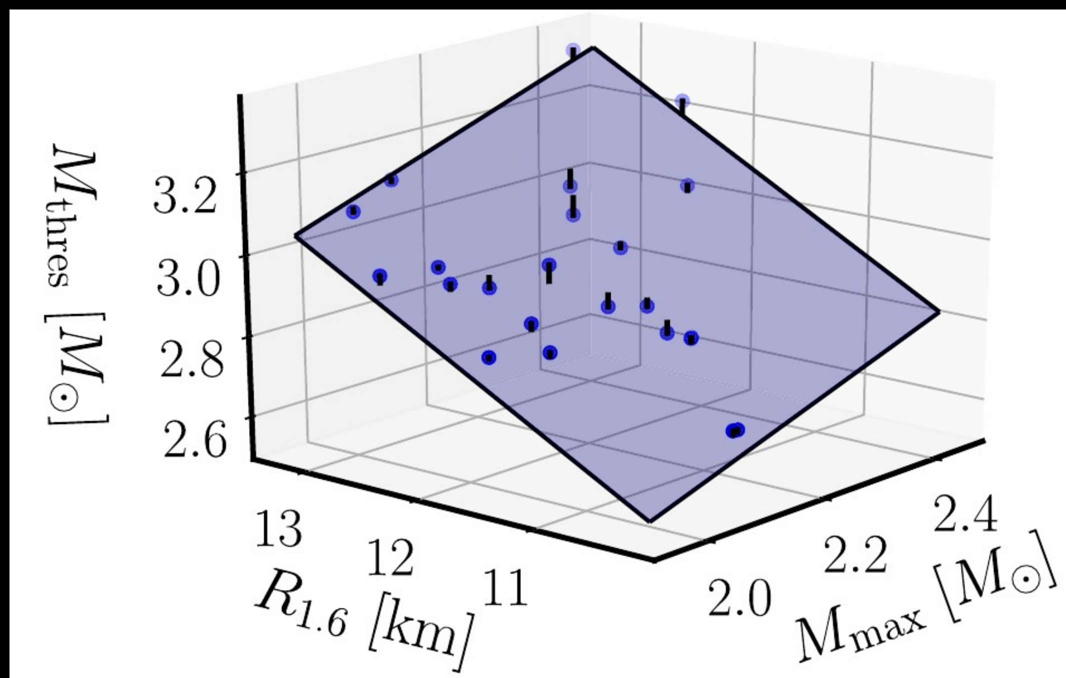
Most studies avoid concrete limits for tau or favor long-lived model – recall GRB after 1700 ms

Sneppen et al 2024, arXiv:2411.03427

Threshold mass for prompt collapse

- Empirical relations: M_{thres} (M_{max},$R_{1.6}$) from simulations for large set of EoSs

  → Mthres limit simultaneously constrains R and M_{max}
- R_{16} can be replaced by R_{14}, Lambda_14, R_{max}



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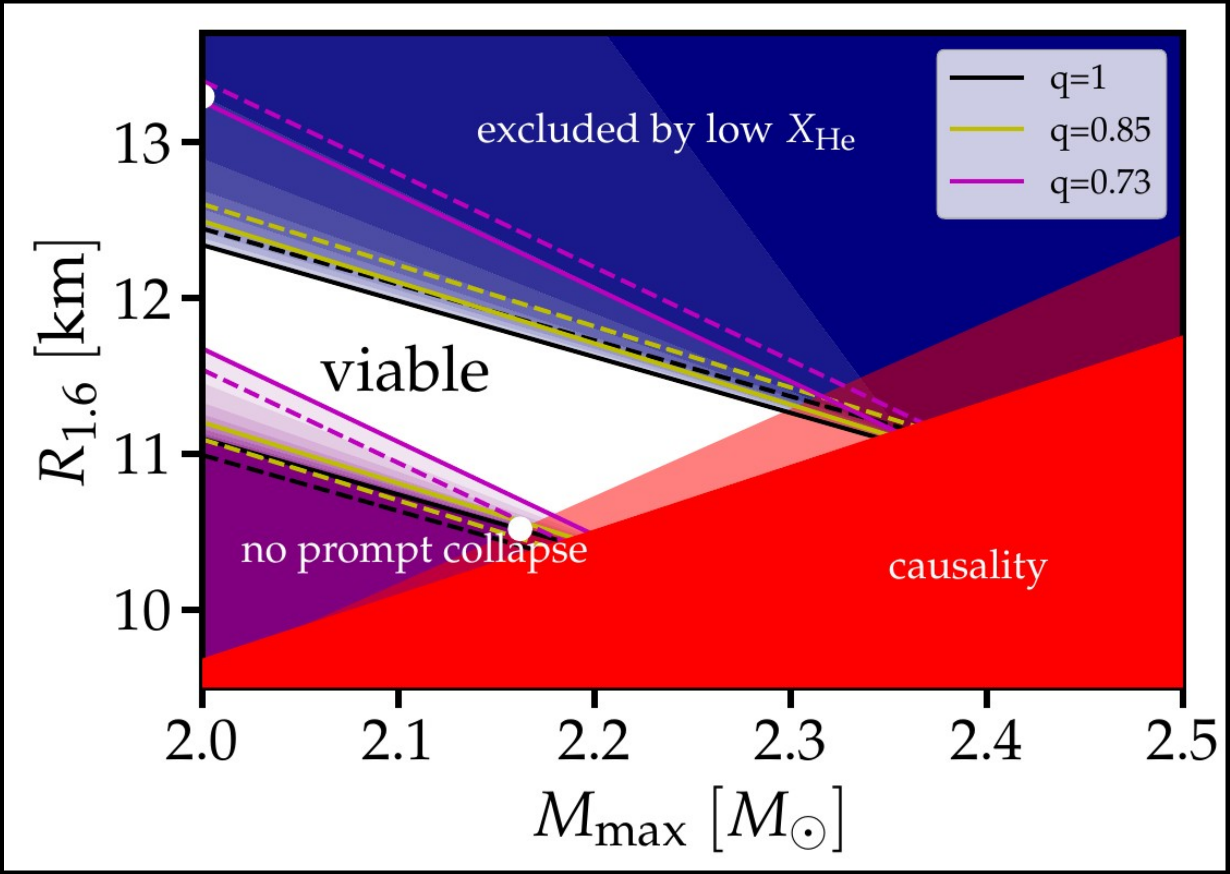
Constraints on EoS/NS parameters

- Low He fraction provides upper limits on R – dependent on M_{max}
- Significant dependence on binary mass ratio (0.7<q<1 for GW170817)
- Causality limits stiffness and no prompt collapse argument provides lower limit on R



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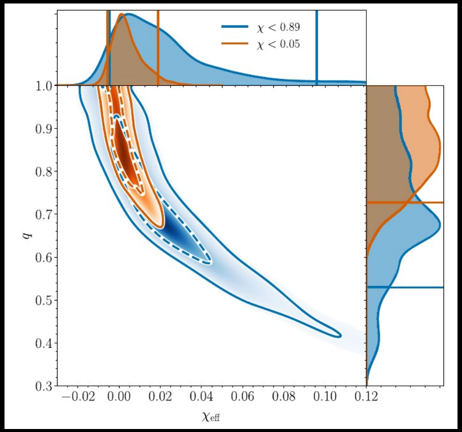
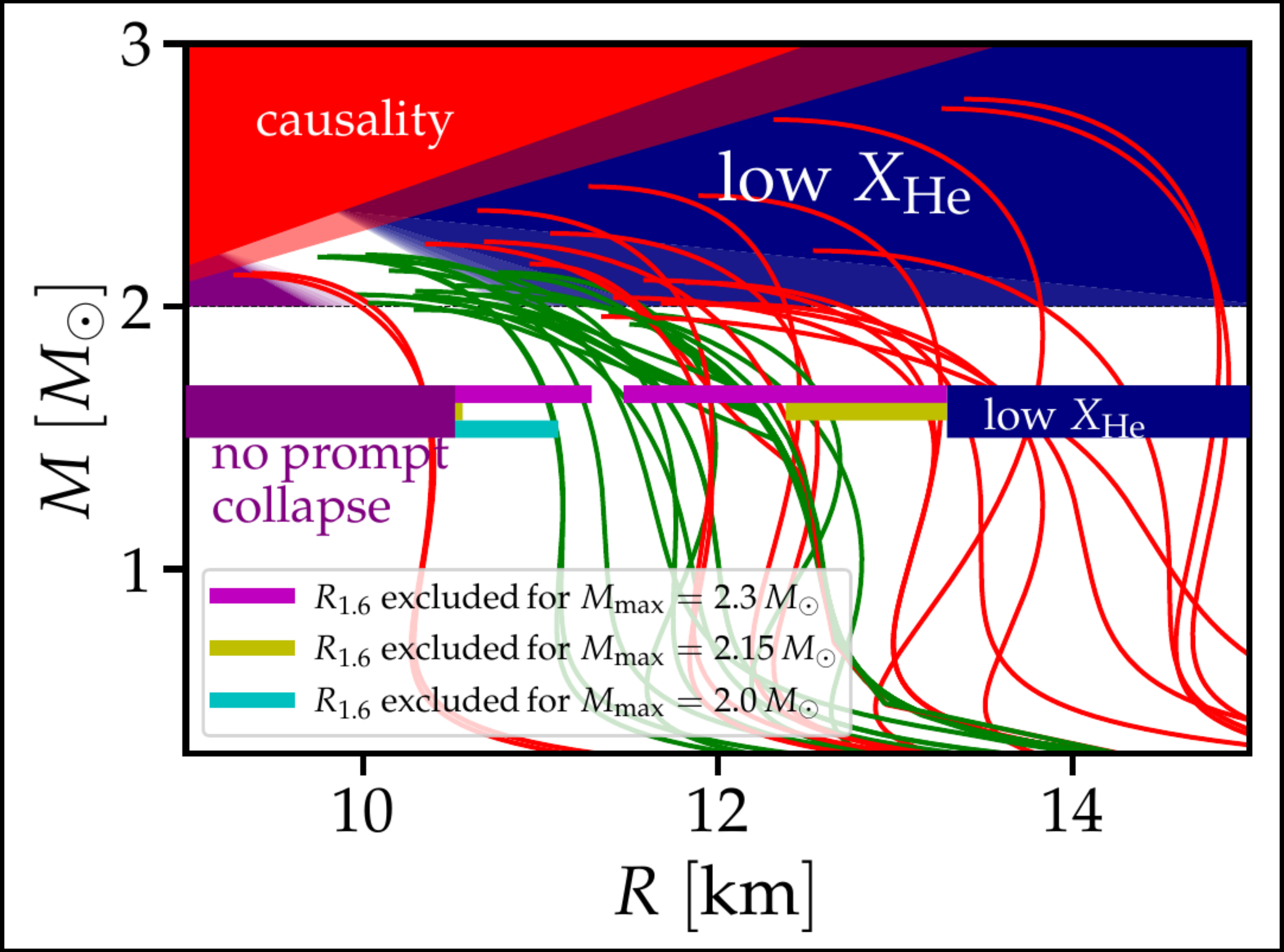


Abbott et al 2019

Constraints on EoS/NS parameters

- $M_{max} < 2.3\ M_{sun}$
- Radii limited to narrow range (sliding window)
- Rules out a number of current EoS models



Sneppen et al. 2024, arXiv:2411.03427

Implications

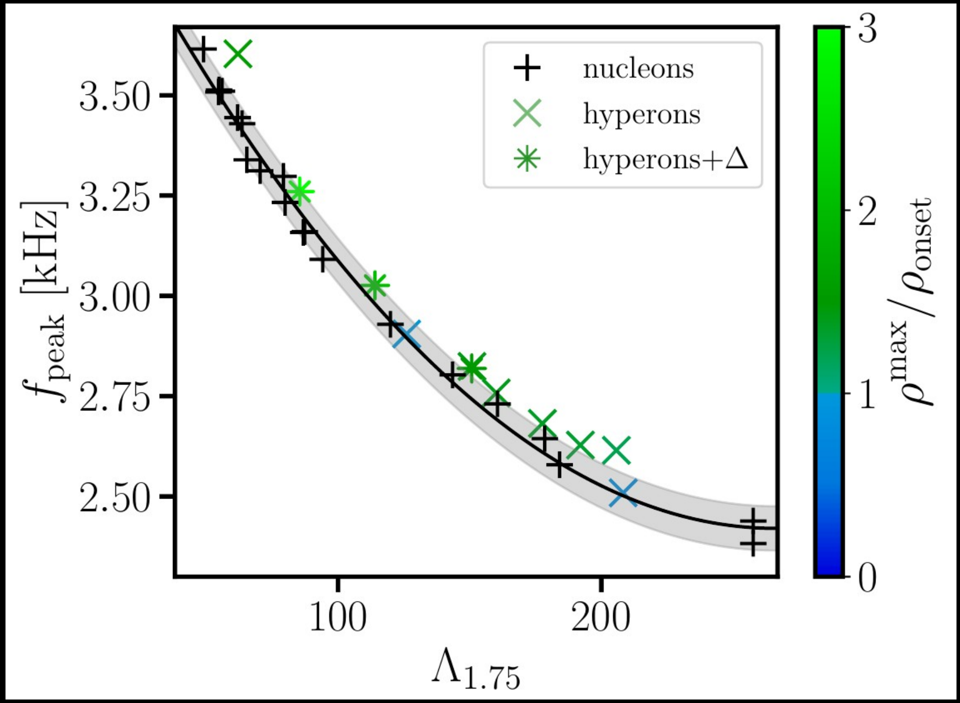
- Clear and testable predictions for which binary should show He features or undergo prompt collapse (dim kilonova)
- GRB in GW170817 was powered by black hole (not a magnetized NS)
- Very potential method exploiting so far unused information

  → future events can further tighten constraints
- However, still connected with uncertainties (ongoing work)

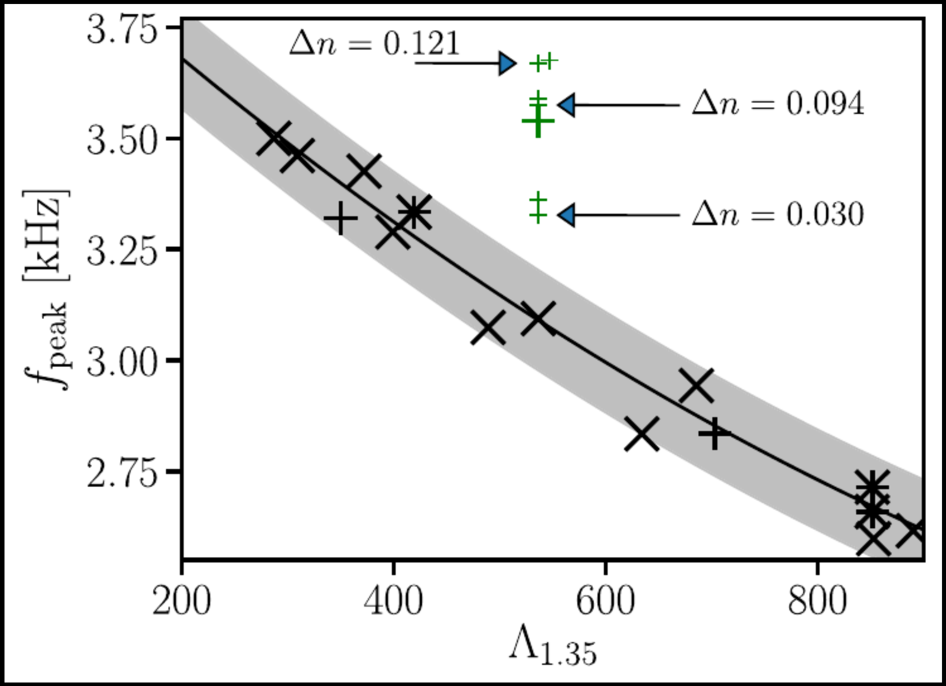
Future: postmerger GW emission

- GW oscillation frequency of postmerger remnant probes highest densities and finite temperature

  - impact by e.g. by hyperons (moderate frequency shift) or quark matter (possibly strong frequency shift) -- ambiguities and masquerade problem



Kochankovski et al 2025



Bauswein et al. 2019; see Blacker et al 2024 for large parameter scan (~250 EoS models)

Summary

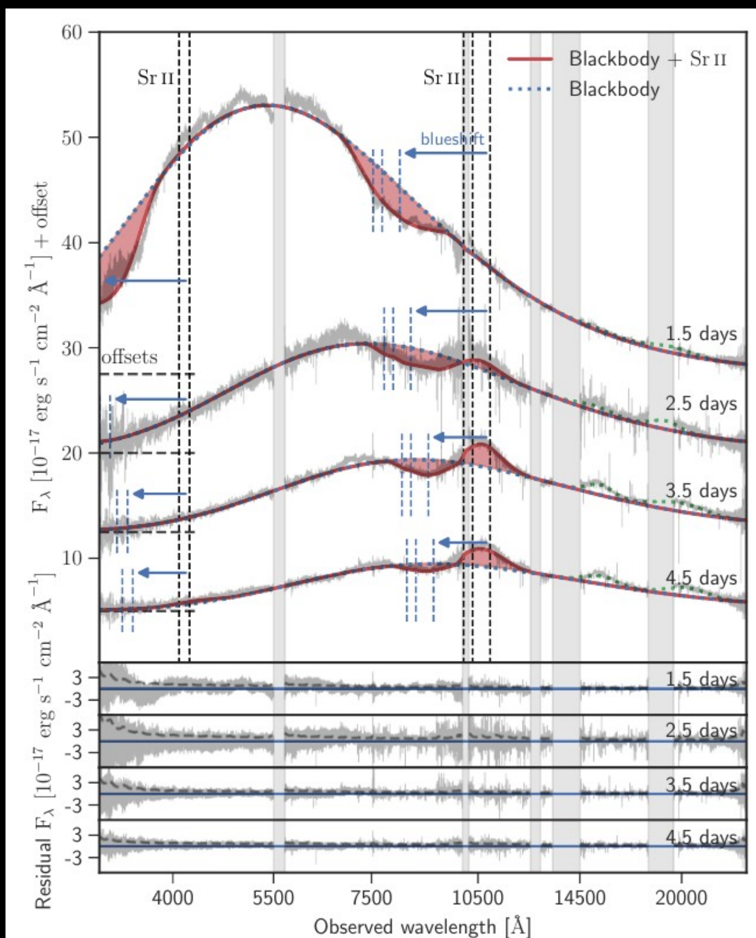
- Complex modeling of NS merger ejecta and r-process (backward / forward approach)
- Short-lived remnants favored (long-lived yield subsolar abundance)
- 3d radiative transfer with line by line treatment show strong sensitivity to observer angle
- Kilonovae reveal elemental abundance and ejecta geometry
- Various EoS constraints from GW170817

  - bright kilonova → minimum radius

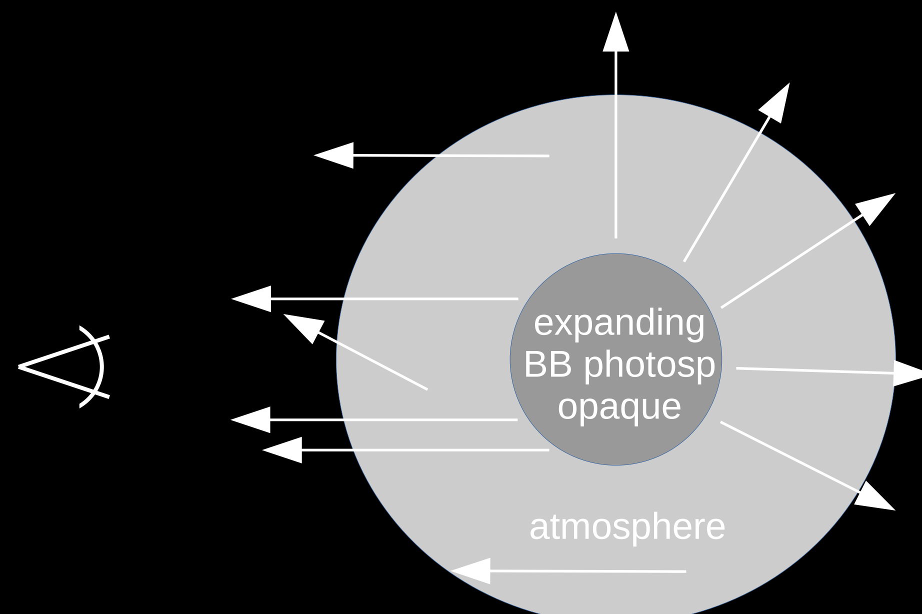
  - absence of He limits NS radii and M_{max} from above
- Postmerger phase particularly interesting (higher densities, higher temperatures)

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)

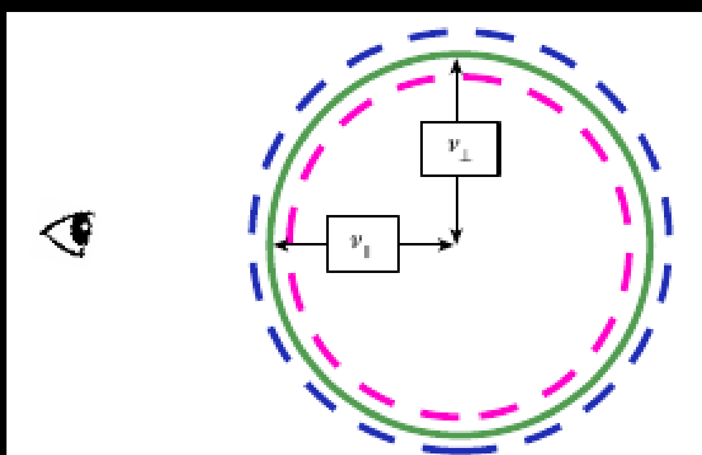
+ scattering into line of sight (rest wavelength)

Geometry of the kilonova

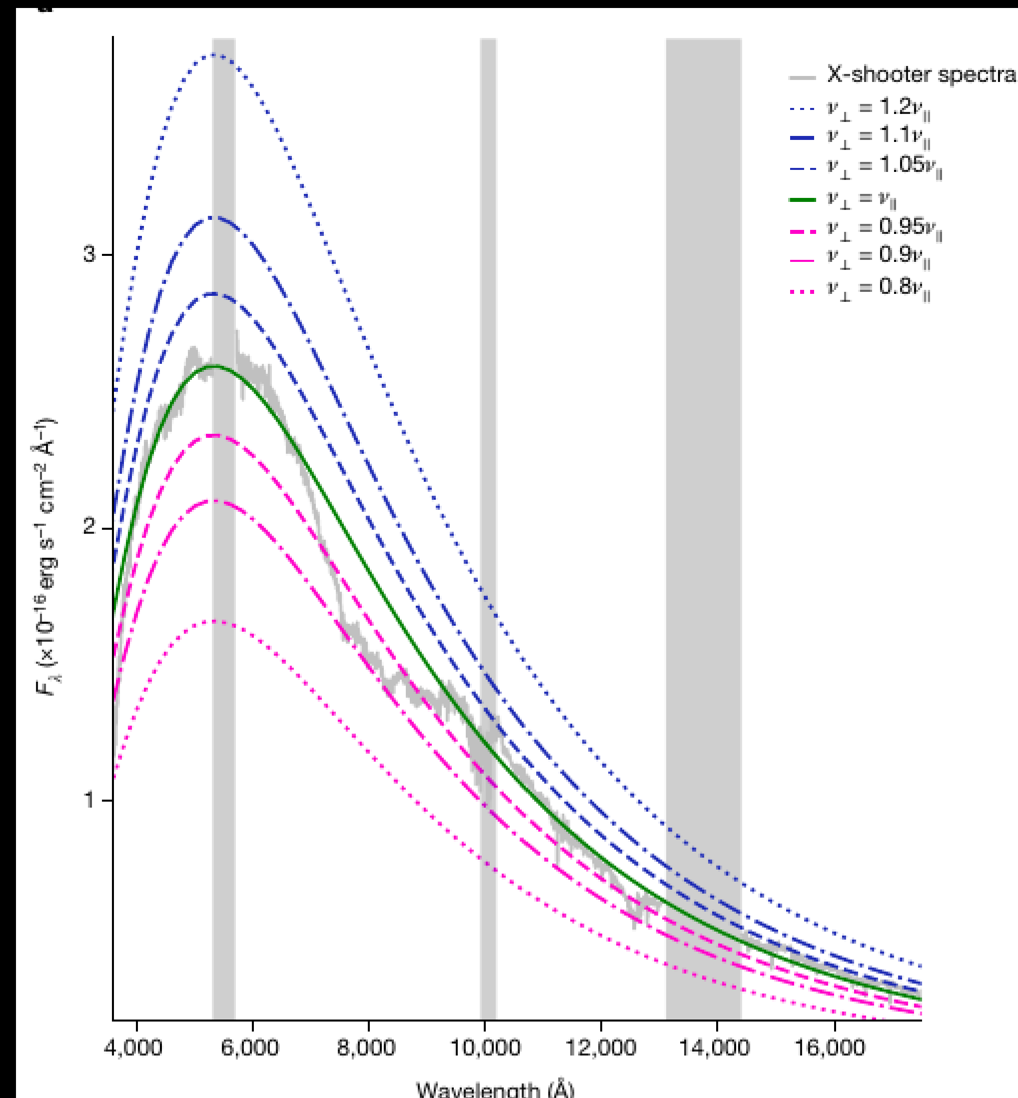
- Black body emission $L = \sigma A T^4$
- Stefan-Boltzmann law:

  - we know T and L from spectrum

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



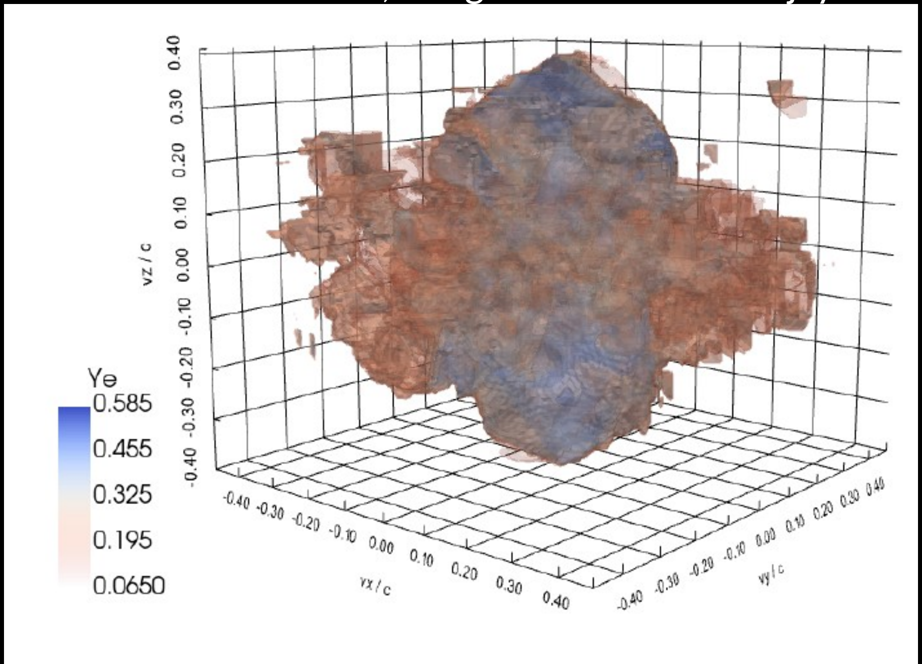
→ Kilonova appears spherical



Sneppen et al. (2023)

Geometry of kilonova

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



- Kilonova of GW170817 was highly spherical

  - not impossible but maybe? surprising

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

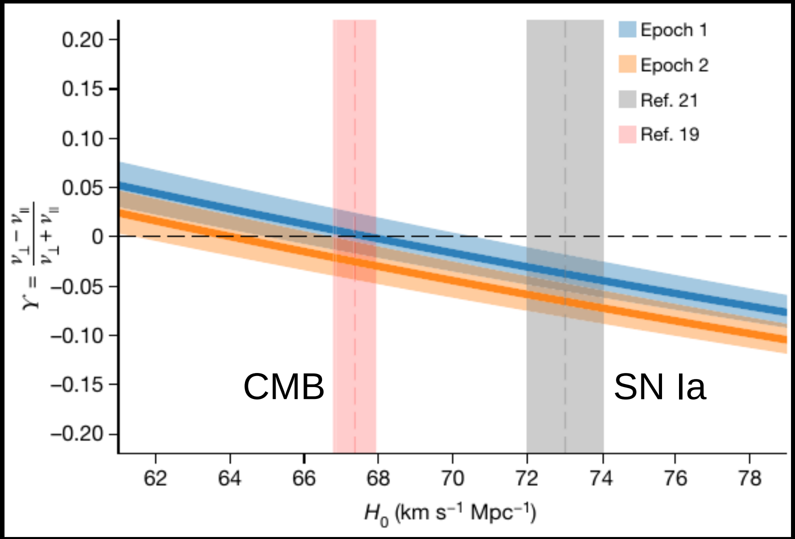
  BB luminosity depends on distance !

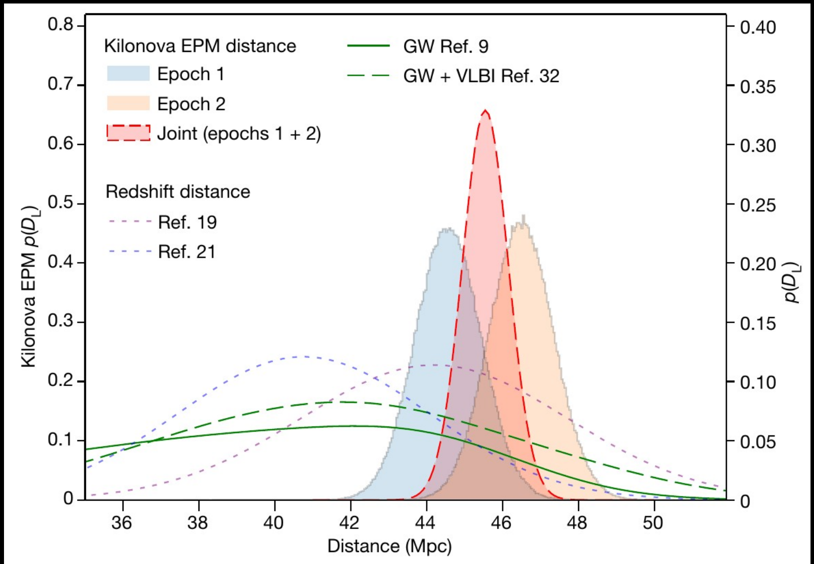
  (modeling of line shape provides $v_{||} / v_{\perp}$ independently)

  → best measured distance of GW170817 so far

  → future constraints of Hubble constant

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





Sneppen et al. (2023)