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Neutron star as laboratories for nuclear physics

Bad Honnef, 9/12/2022

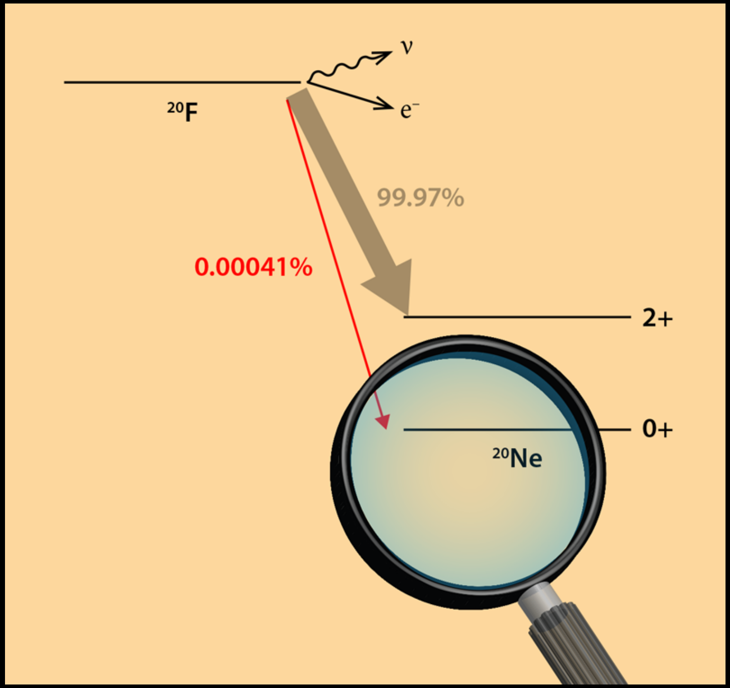
Andreas Bauswein

(GSI Darmstadt)

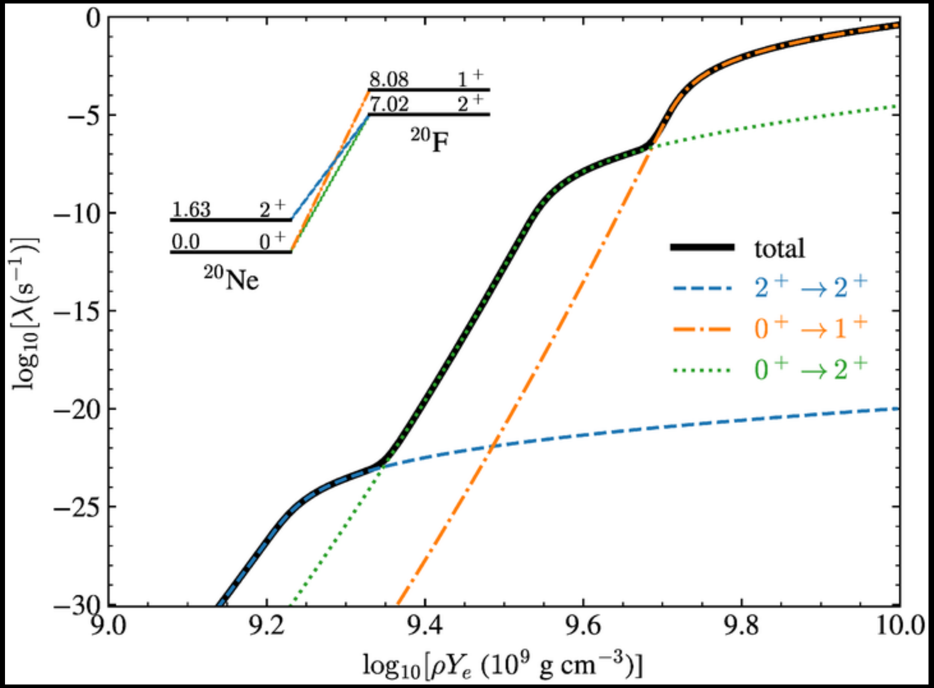
Fate of intermediate-mass stars

- Evolution of O Ne cores affected by e- captures on 20-Ne
- Inclusion of second forbidden transition enhances rate significantly (based on measurement and calculation of rate)
- Changes evolution → earlier heating and O ignition at lower density

  → thermonuclear explosion instead of gravitational collapse (for ignition at higher rho)
- These stars form white dwarfs rather than neutron stars !



https://physics.aps.org/articles/v12/151

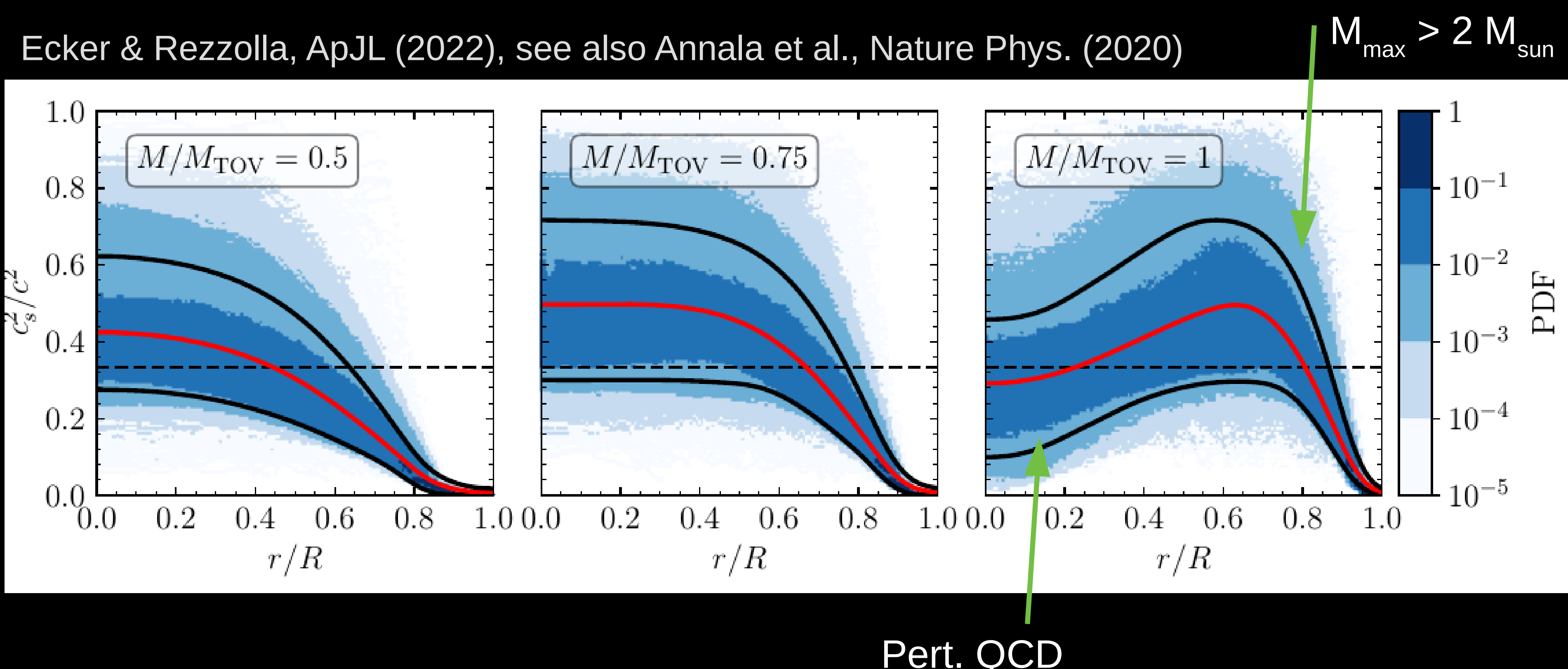


Kirsebom+, PRL 103, 2019

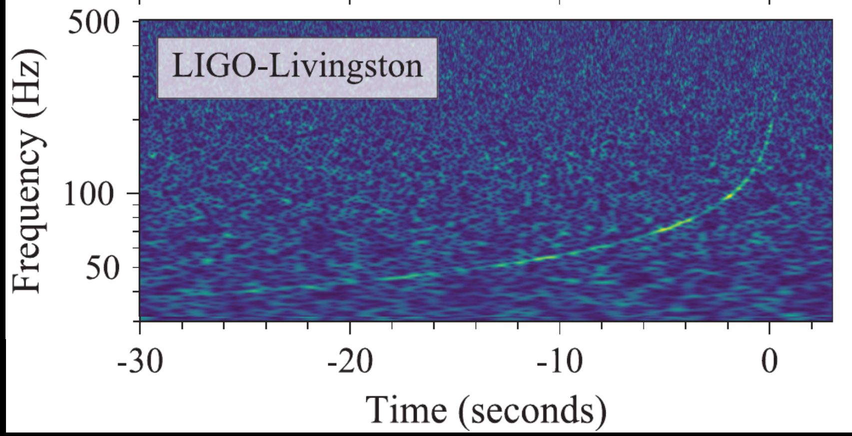
Sound speed in neutron stars

- Model-agnostic parametrizations of neutron star EOS ~ one million of models
- Imposing constraints by chiralEFT (at small rho) and perturbative QCD (at very large rho – much beyond NS densities) + maximum mass from pulsar measurements + NICER and LIGO for lower and upper bounds on radii and tidal deformability
- Heavy NS have small speed of sound in the center → soft in the core

Ecker & Rezzolla, ApJL (2022), see also Annala et al., Nature Phys. (2020)

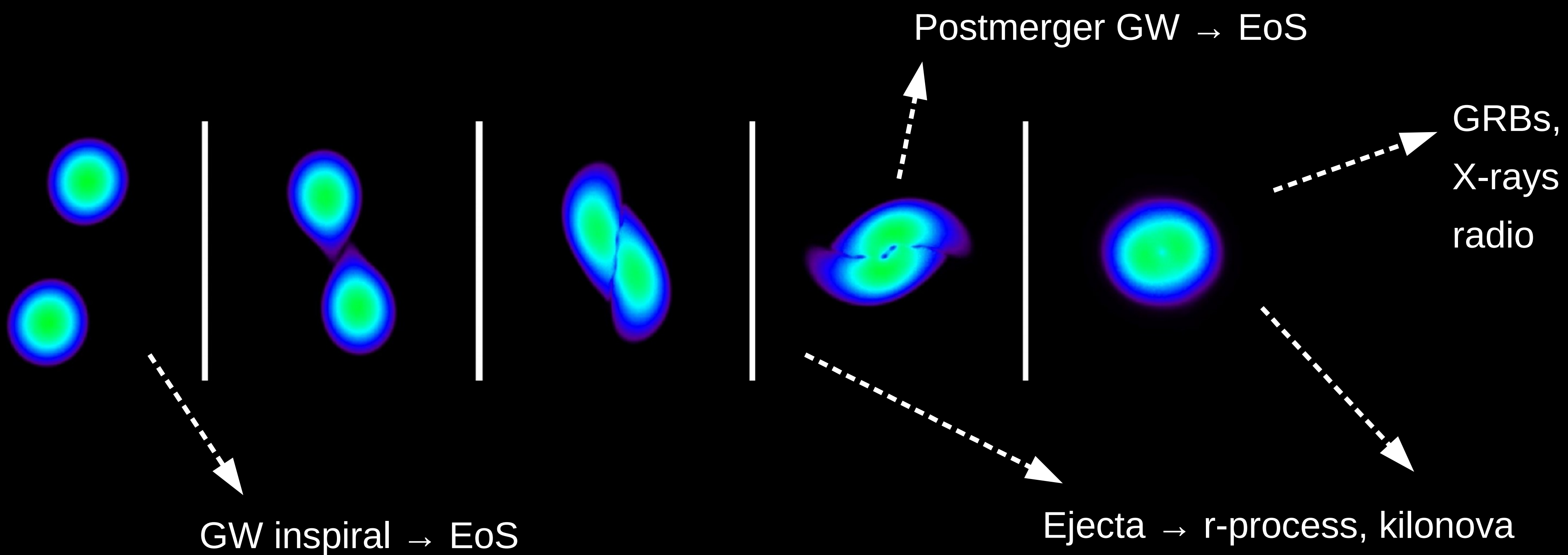


Neutron star mergers



GW170817 - first observed NS merger

- Impact of multi-messenger event GW170817
  - sources of gravitational waves → high-density EoS
  - sources of heavy elements (r-process) → first and only confirmed site for r-process
  - sources of electromagnetic radiation, e.g. gamma-ray bursts, kilonovae
  - ..., standard sirens for cosmology, ...



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
  - strong signal – weaker EoS effect → NS smaller than about 13.5 km

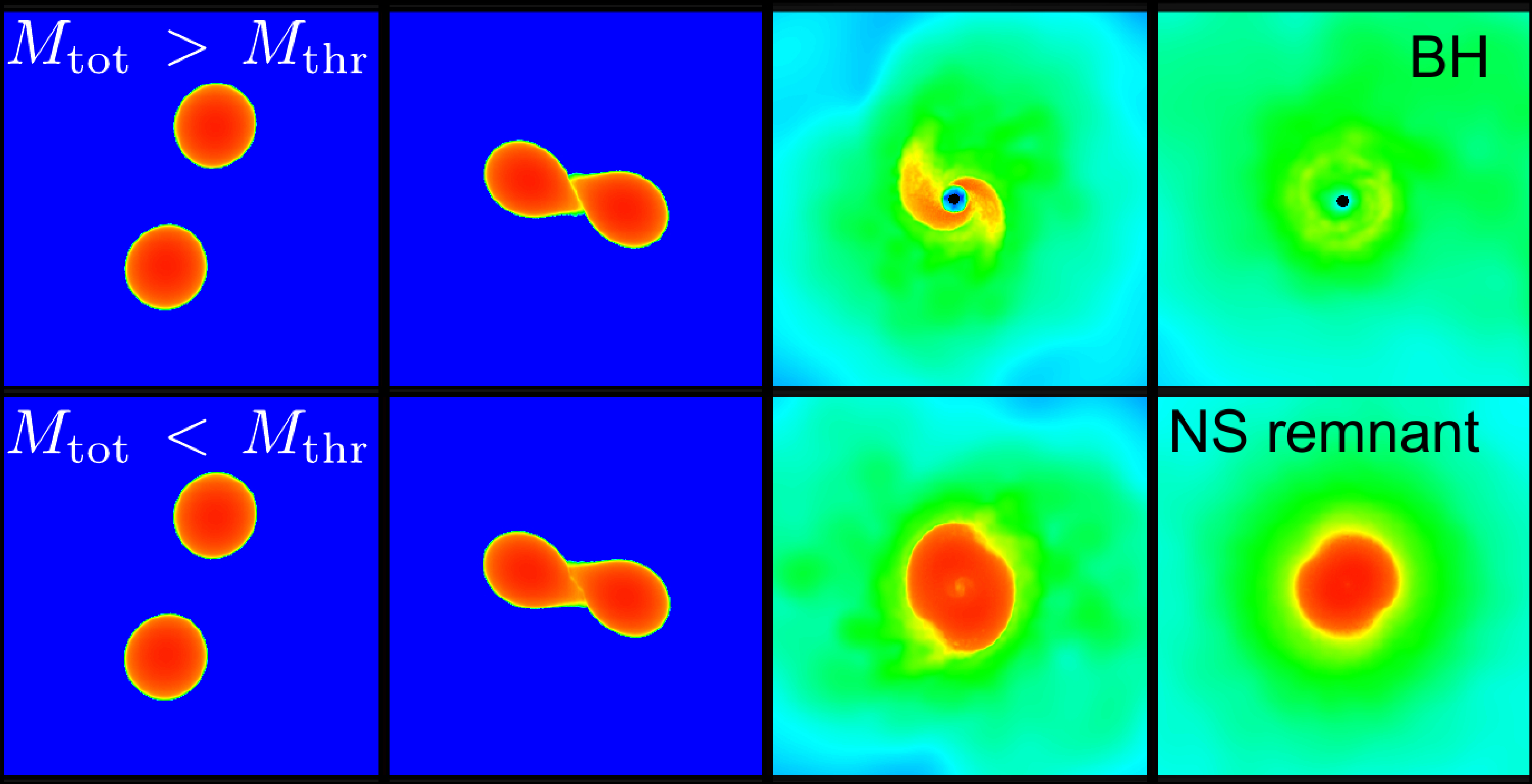
- Multi-messenger interpretation (many different ideas, can be quite model-dependent)

- Gravitational-wave postmerger emission (not yet measured but promising for future)
  - strong EoS impact – weaker signal (at higher frequencies)

Also combinations of these approaches employed

Collapse behavior – BH formation

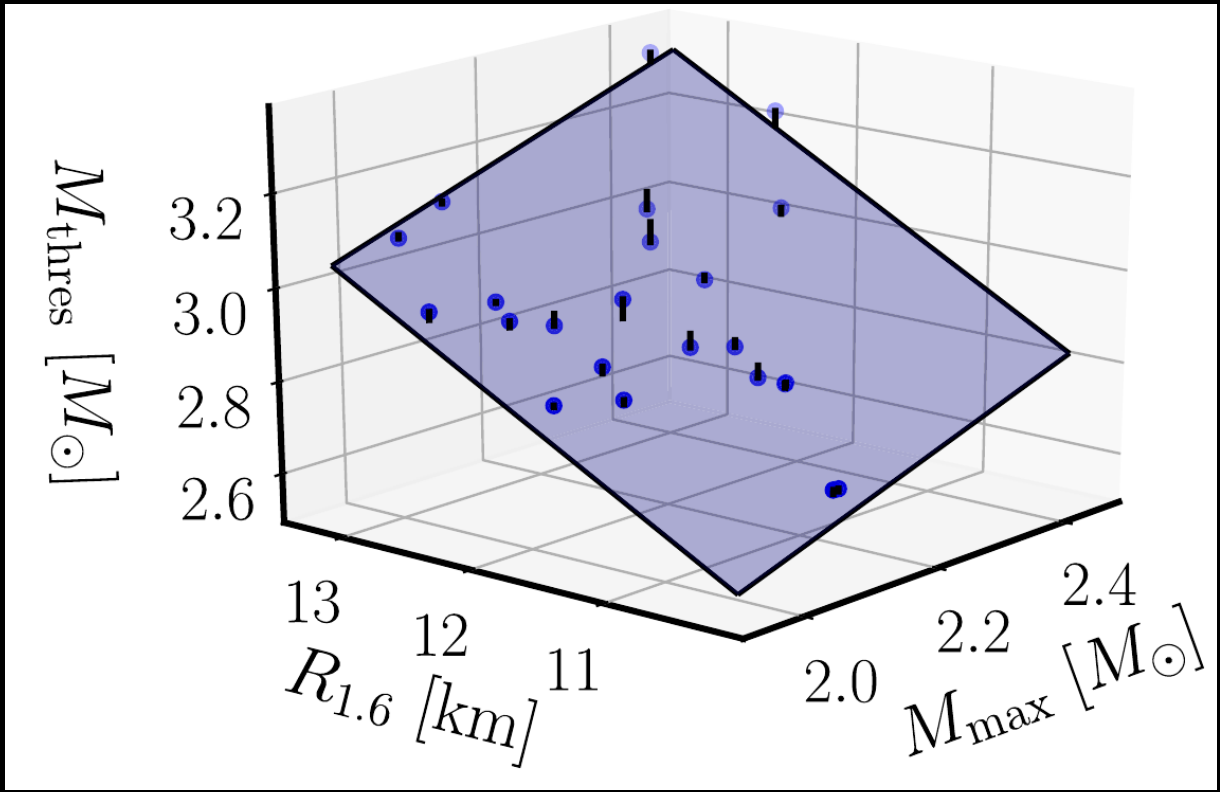
- BH formation directly after merger – M_{thres} most basic feature of NS coalescence



Collapse behavior – BH formation

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

(based on ~ 400 HPC relativistic hydrodynamics merger simulations with 40 EoS models – most comprehensive study to date)



Dots: model EoSs

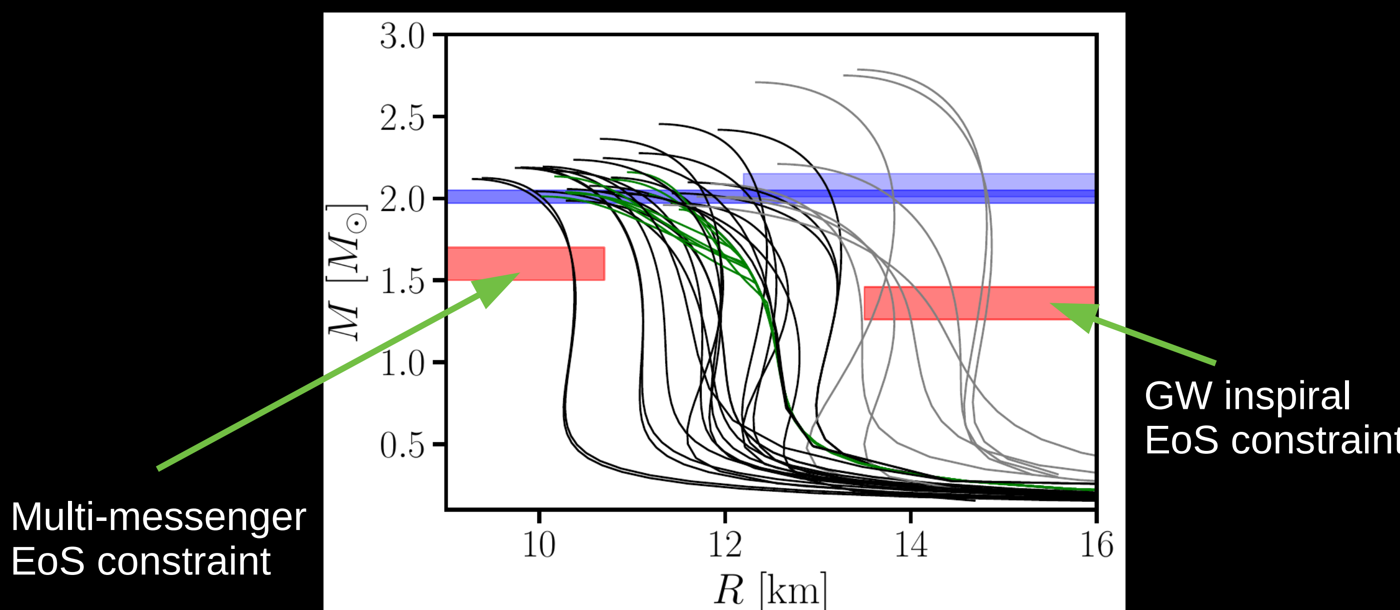
Bauswein et al., PRL (2020); Bauswein et al., PRD (2021)

EoS constraints from multi-messenger interpretation

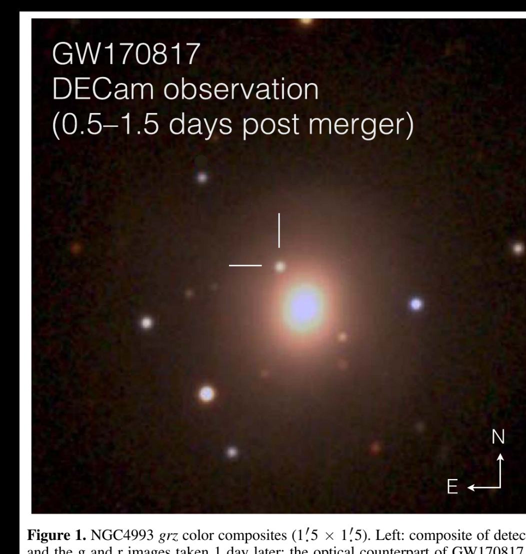
- Multi-messenger interpretation of NS mergers (here GW170817)

  $M_{thres} > M_{tot} = 2.74\ M_{sun}$ → lower limit on NS radius excluding very soft EoSs !

  - complementary to inspiral constraint !
- Particularly robust constraint – future potential, e.g. M_{max}



Soares-Santos et al. 2017



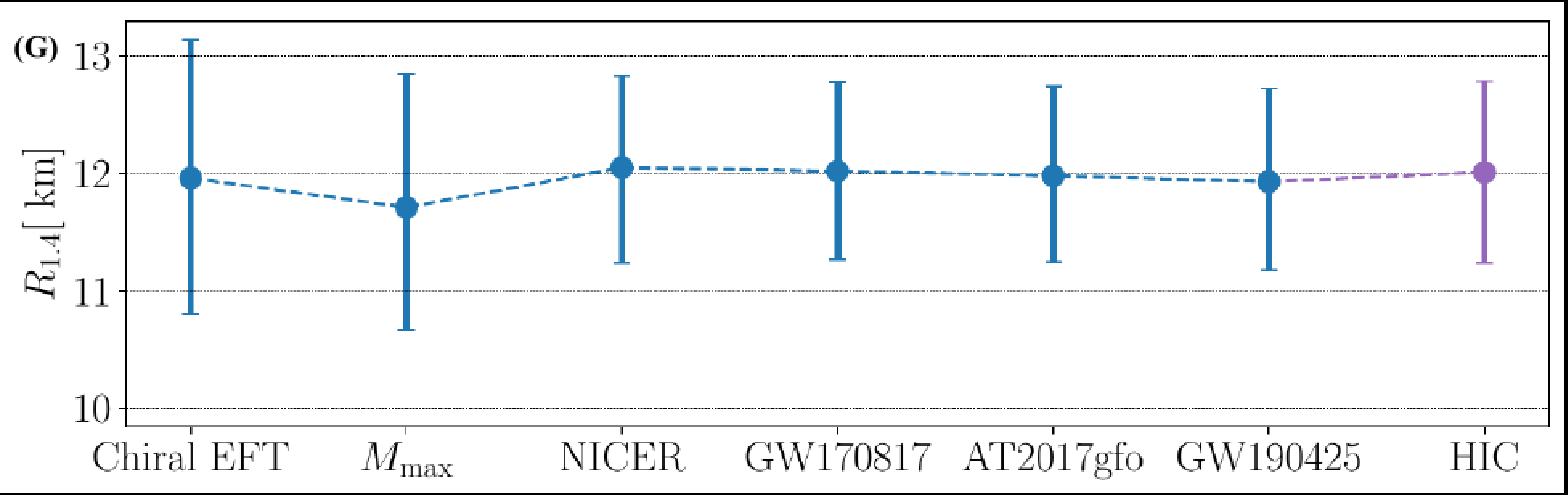
Brightness of kilonova implies no prompt BH formation

Bauswein et al., PRD (2021); Bauswein et al., ApJL (2017)

Combining existing constraints on NS EoS

- Bayesian inference including results from chiral EFT, maximum mass of NS (pulsras + interpretation of GW170817), X-ray pulse profile modeling of pulsars, GW inspiral signals from GW170817 and GW190425, kilonova modeling, heavy-ion collisions

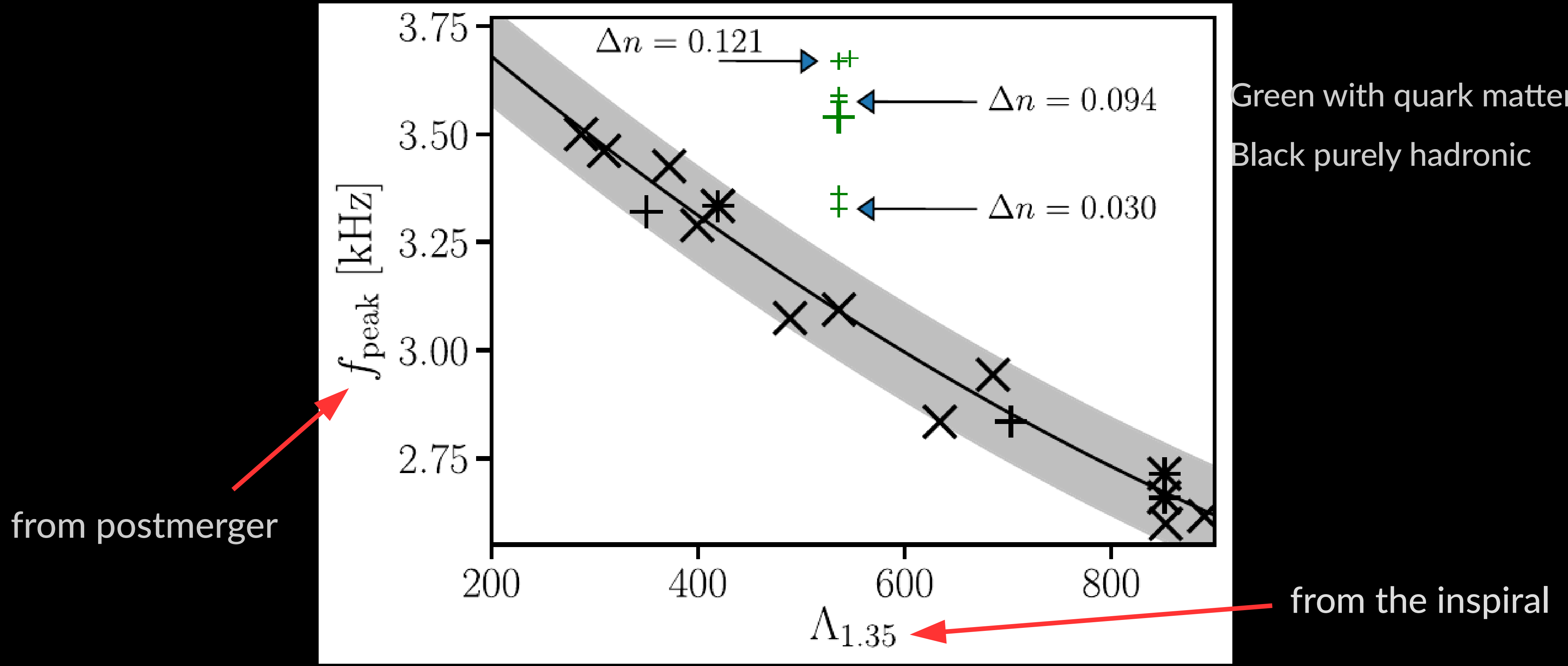
→ $R_{1.4} = (12.0 \pm 0.8)\ km$



Huth et al., Nature (2022)

Future: GWs tell presence of quark matter

- GWs from inspiral and postmerger measurable with sufficient precision in future



Bauswein et al., PRL (2019), Blacker et al., PRD (2020)

- Characteristic increase of postmerger GW frequency compared to tidal deformability

  → frequency shift (by sudden "compactification" of remnant / softening of EoS) - evidence of presence of quark matter core

- Also impact on BH formation → reduction of Mthres (Bauswein et al., PRL 2020, PRD 2021)

R-process and kilonovae

- Properties of light curve in excellent agreement with r-process heated ejecta of a few 0.01 Msun

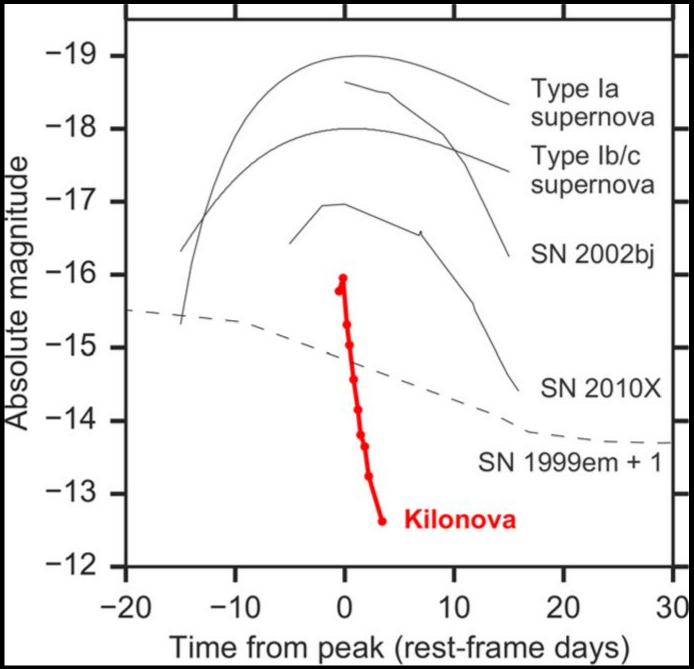
  → first and only confirmed site of r-process

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

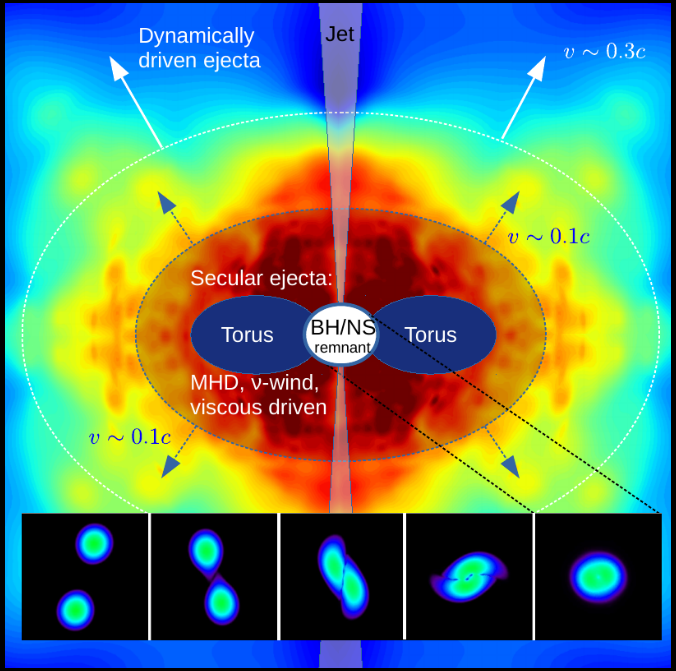
  → estimated rate * ejecta mass = compatible with mergers being main/only source of heavy r-process elements

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

- Detailed composition ? How much r-process material ? Are there other r-process sources ?
- main argument for r-process from heating



Arcavi et al., ApJL 2017



Spectral properties of KN and element identification

- Spectra can be well fitted by black-body radiation of a cooling photosphere
- But clearly additional features, e.g. pronounced absorption
- modelling with 1D radiation transfer:

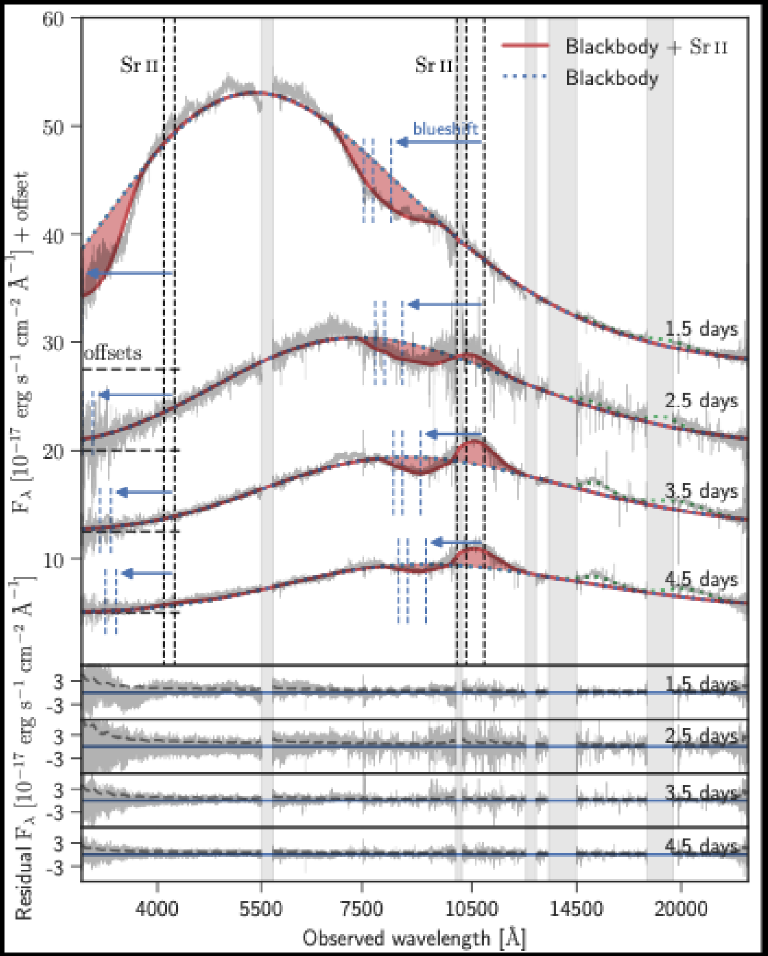
  - BB temperature → photosphere

  - expanding atmosphere on top where absorbtion and emission takes place

  → explains prominent features by Sr lines for v=0.25 c (“P Cygni feature”)

- Sr is light r-process element (but also produced s-process)
- Ongoing analysis to identify more features/elements (e.g. Gillanders+2022, Vieira+ 2022, Domoto+ 2022 → possibly features of La, Ce)

  - one issue: atomic data for heavy elements



Watson et al., Nature 2019

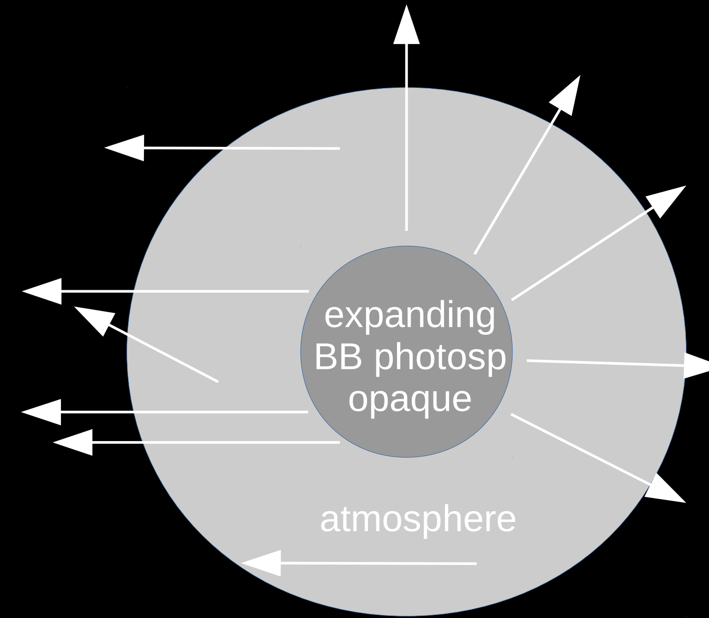
Ejecta velocities

- Profile of P Cygni features → expansion velocity
- Cross-check via BB
- Stefan-Boltzmann law: $L = \sigma A T^4$

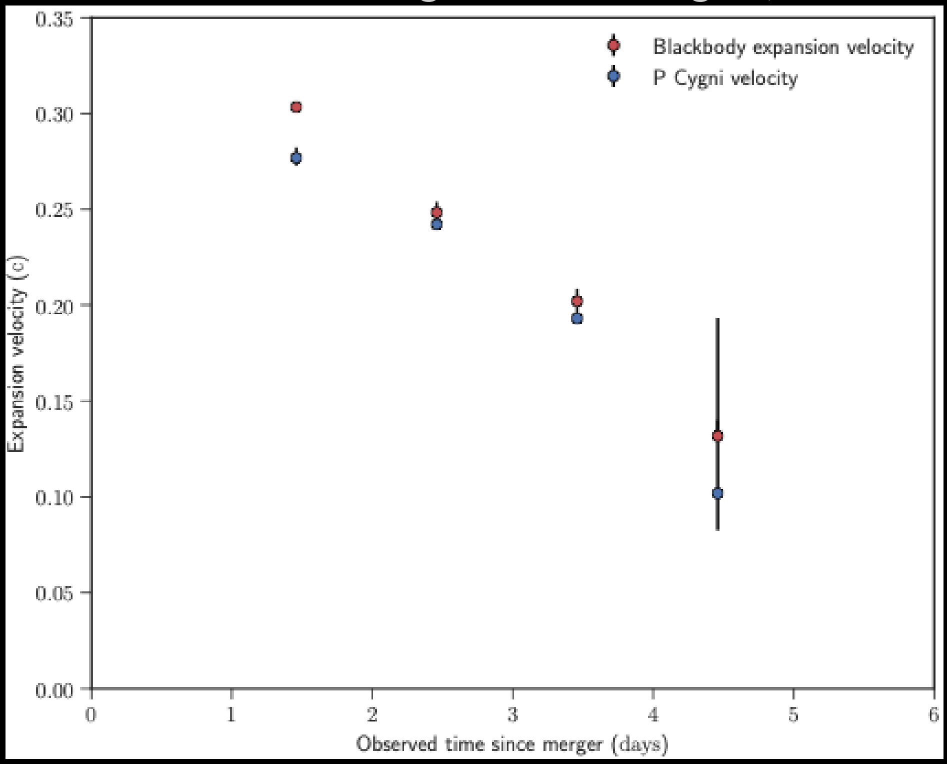
  - we know T and L from spectrum

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

- Btw, these are typical numbers seen in numerical simulations



P Cygni feature: absorption along line of sight (blue-shifted)
+ scattering into line of sight (rest wavel)



Watson et al., Nature (2019)

Sneppen et al., accepted by Nature 2022

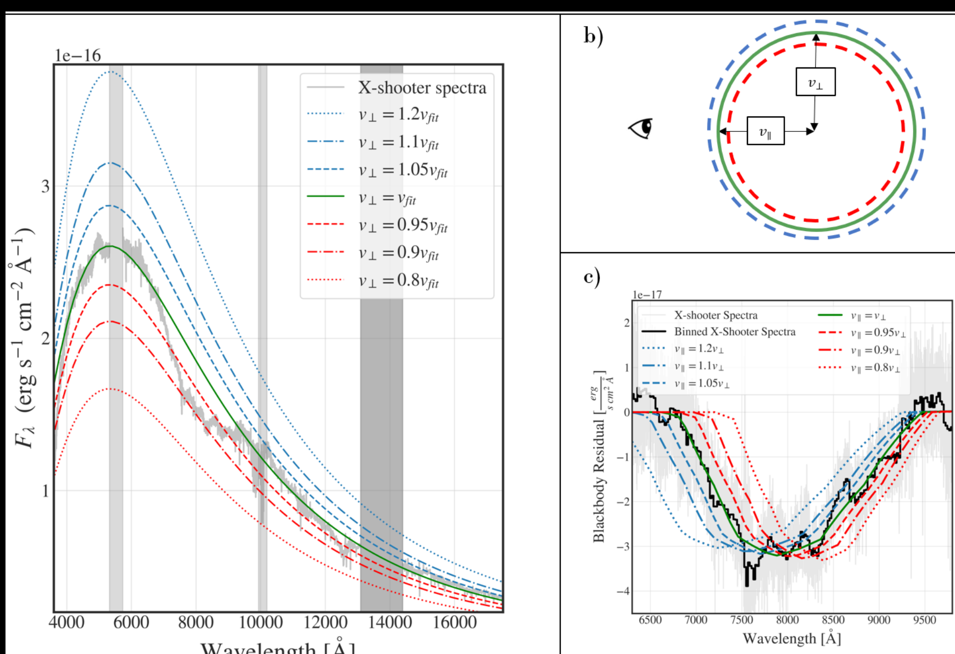
Geometry of kilonova GW170817/AT2017gfo

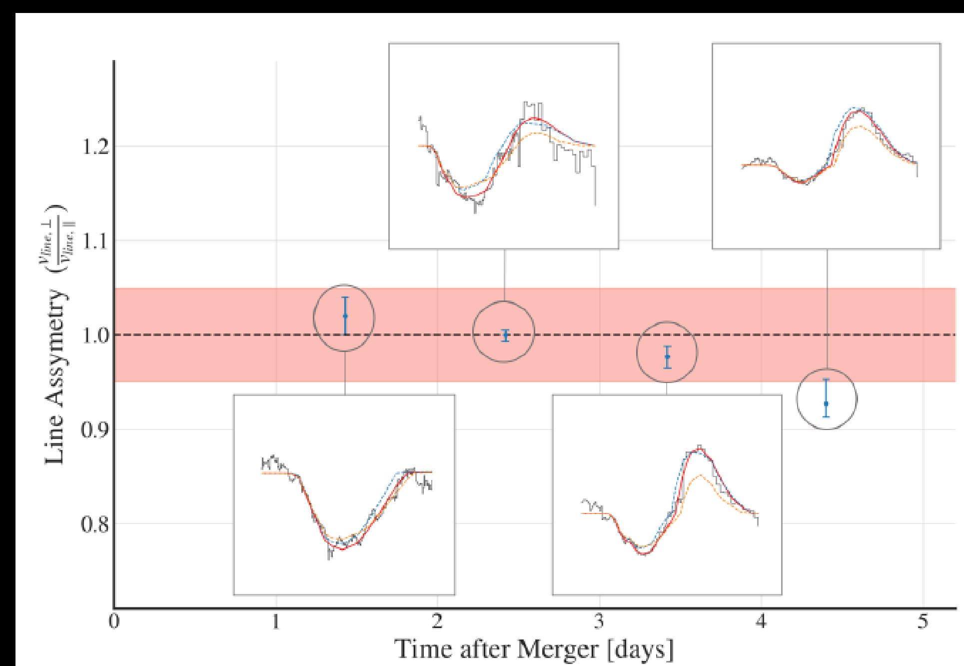
- Compare radial and tangential size of ejecta
- Radial: from velocity along line of sight
- Tangential: Stefan-Boltzmann law, i.e. via emitting area

Distance enters here

→ Kilonova of GW170817 was *highly spherical*

→ Theory: not impossible, but requires coincidence, no obvious and robust mechanism that makes ejecta spherical by some kind of tuned energy injection





Sneppen et al., accepted by Nature 2022

Geometry AT2017gfo

- In addition, shape of line reveals sphericity, i.e. $v_{||} / v_{\perp}$, independently
  $\rightarrow$ independent distance measure !!! very useful for cosmology

d

BB + Sr absorption + host z + CMB H_0 => $v_{||} / v_{\perp}$

SN Ia H_0

d'

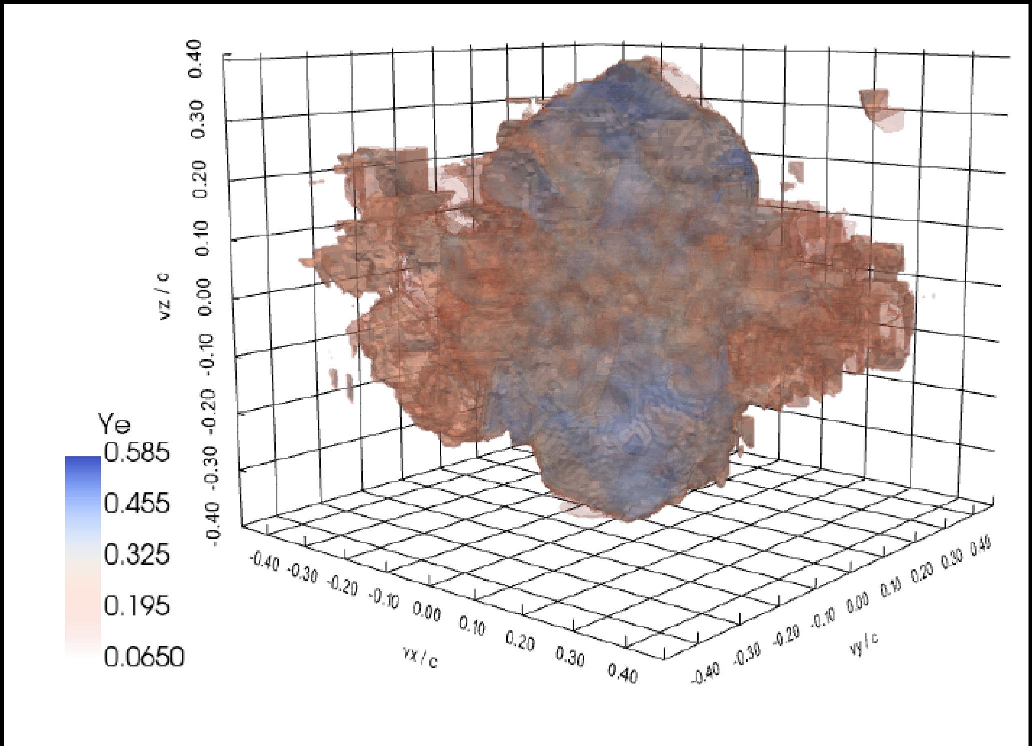
BB + Sr absorption + host z + line shape $v_{||} / v_{\perp}$ => d $\rightarrow$ H_0

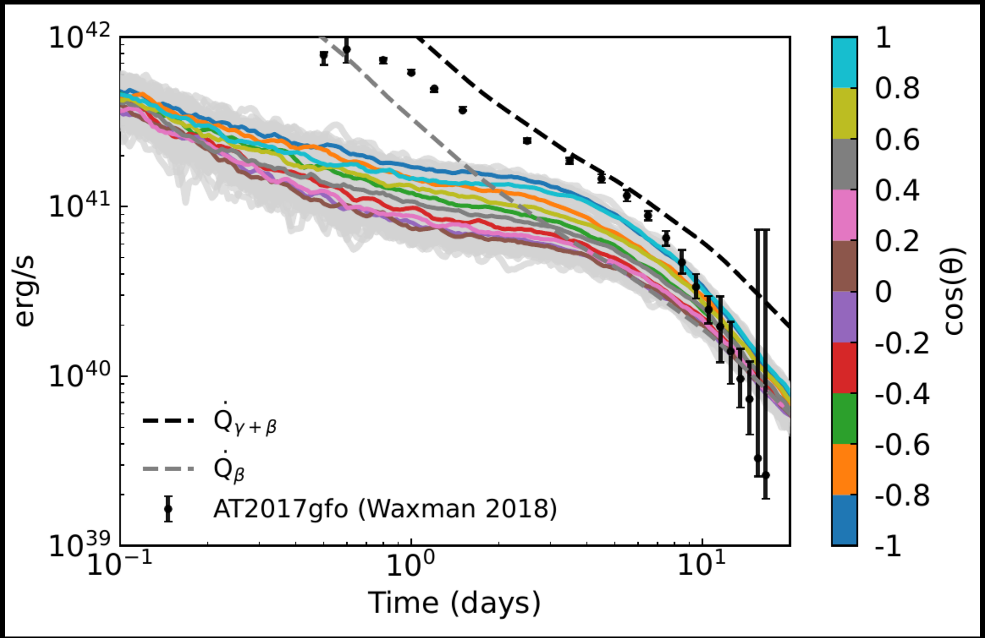
Best measured distance so far

Steps forward: 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

R-process sites in the context of chemical evolution

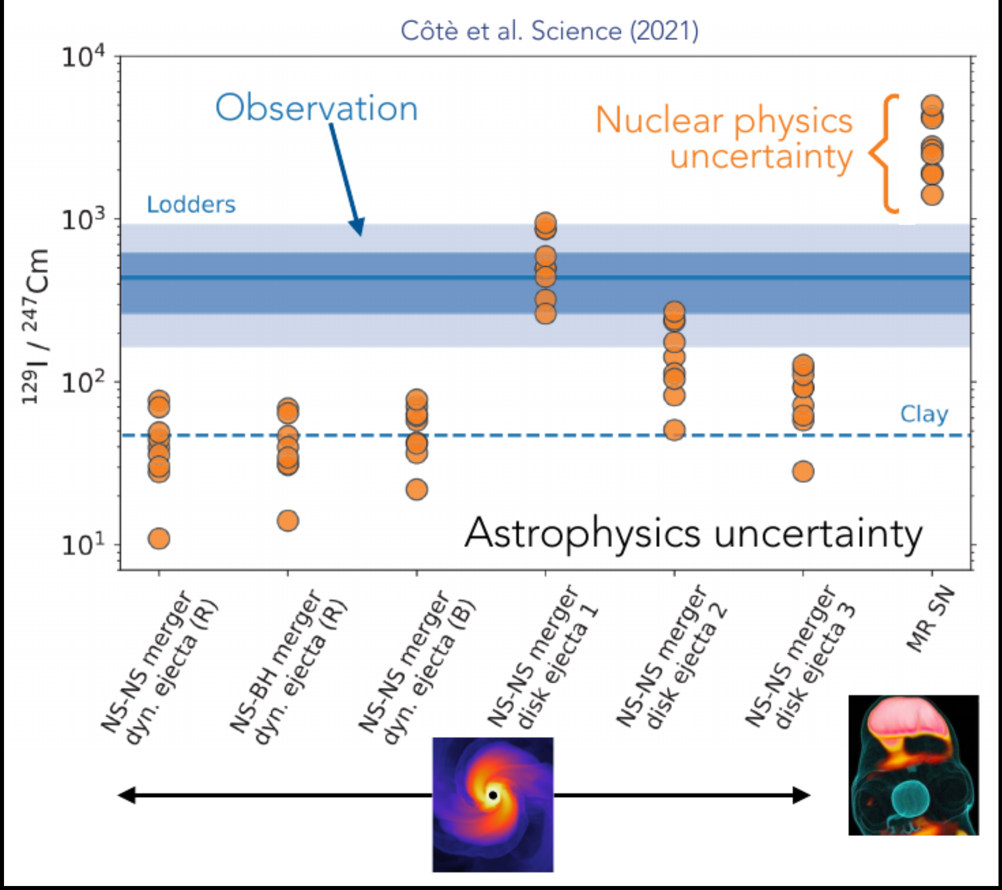
- i.e. understanding the enrichment of Galaxy/Universe by different nucleosynthesis events

  → tracers are metal-poor, i.e. old stars or currently measured abundances in the solar system, e.g. meteorites (freeze r-process content at formation of solar system)

- Abundance ratio ^{129}I to ^{247}Cm

  (unstable, similar and short half-lives)

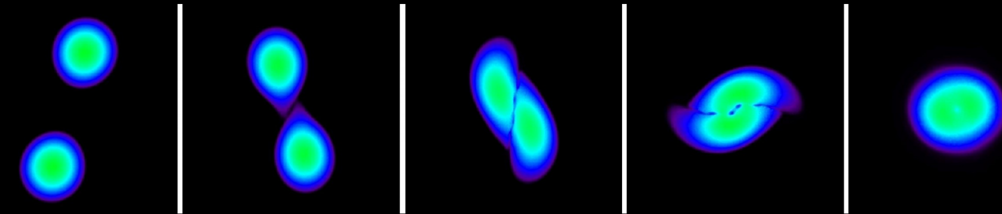
- → point to NS merger as last enrichment event



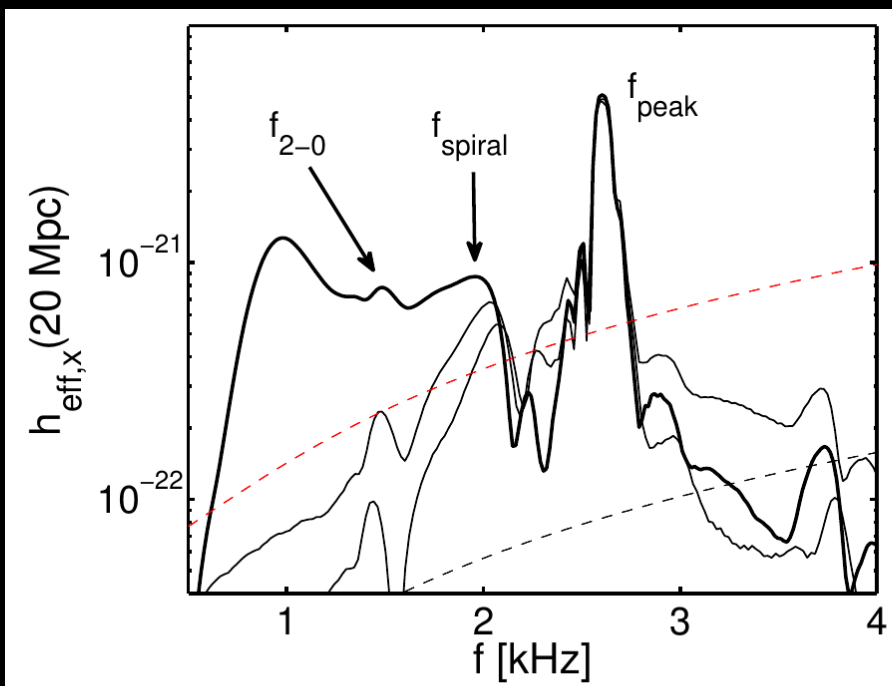
Outlook

- More merger detections with em counterpart
- More / improved instruments: GW detectors with high sensitivity, James Webb for IR regime of kilonova, Extremely Large Telescope for better spectra (or comparable spectra at larger distances), ...
- EoS constraints: inspiral, kilonova interpretation, postmerger frequency
- Kilonova and r-process: as more observations become available theoretical understanding will grow → detailed composition in outflows, r-process path, masses, chemical evolution, ...
- Atomic and nuclear data for r-process elements
- Nearby core-collapse supernova overdue

GW asteroseismology

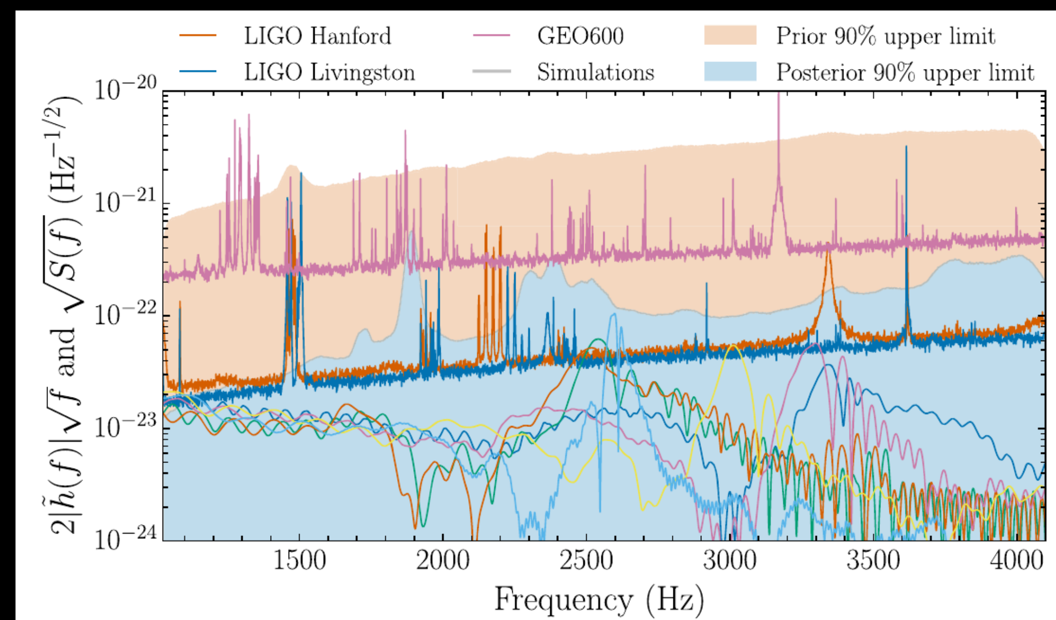


- Two phase of merger inform about different EoS regime
  - inspiral → tidal deformability Λ
  - our focus: postmerger → oscillation modes inform about hot EoS at higher densities
    → harder to measure but on long run more informative (also about dynamics)



Bauswein et al., EPJA 52 (2016)

Merger excites different oscillation modes of remnant NS → GW asteroseismology

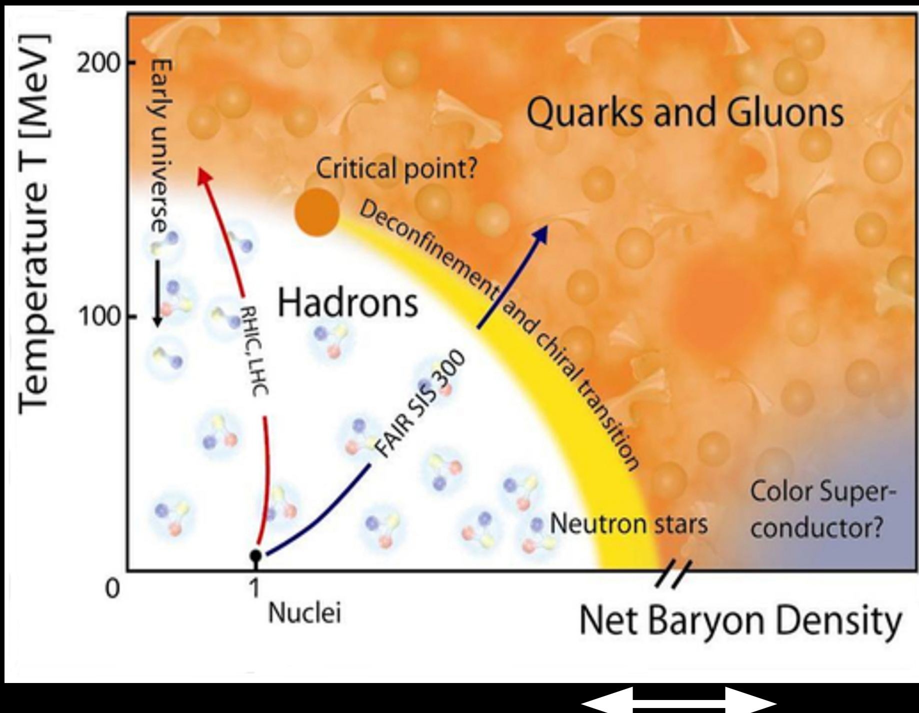


Ligo-Paper *Abbott et al., PRX (2019)*:
Postmerger search for GW170817 → within reach
cf. *Torres-Rivas et al., PRD 99 (2019)*

Hadron-quark phase transition in NS mergers

- Does quark matter occur in NSs / NS mergers ?
- What can we learn about the properties of the hadron-quark phase transition, e.g. onset density?

GSI/FAIR



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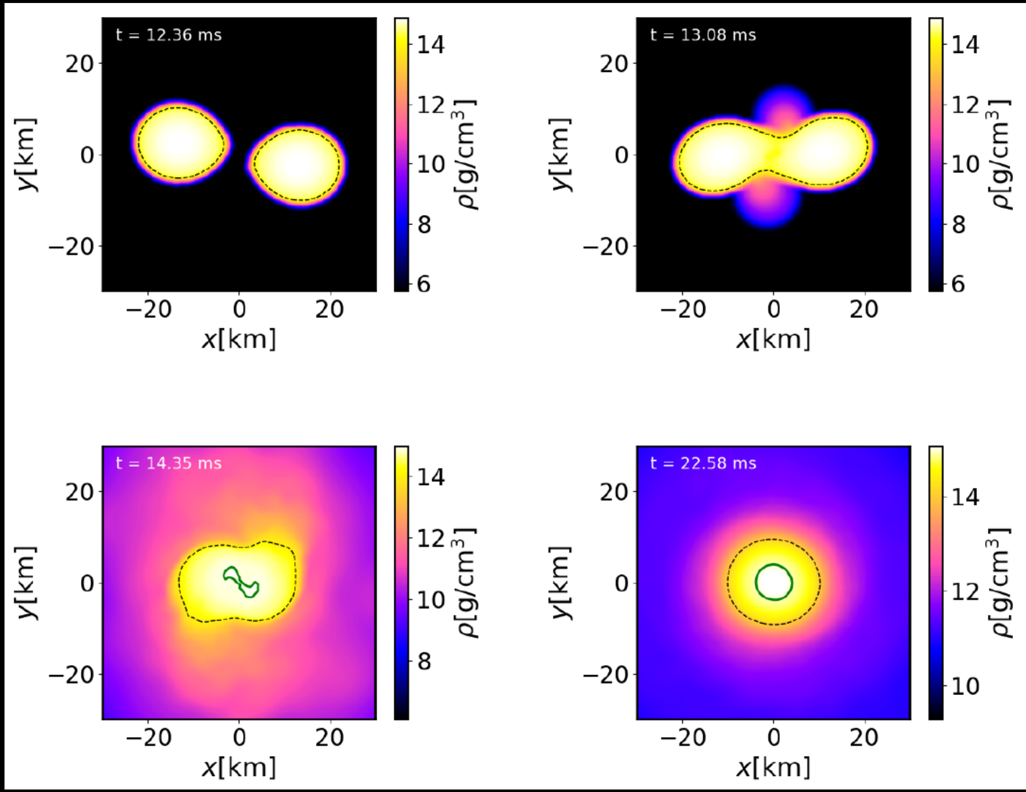

Bauswein et al., AIP proceedings (2019)