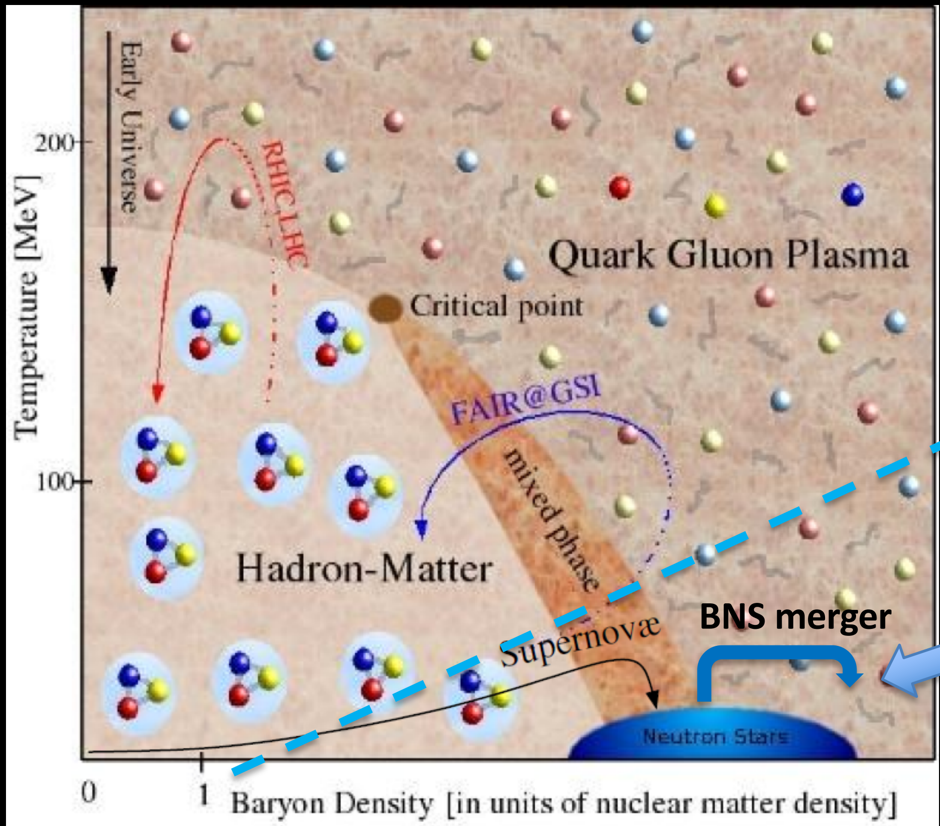
Assemblée générale du GdR Ondes Gravitationnelles

Understanding extreme matter with gravitational waves

Jérôme Margueron (IPN Lyon)

Groupe de travail: Etoiles à neutrons, supernovae et synthèse des éléments lourds (A. Fantina & J. Novak)

QCD phase diagram (Fundamental physics)



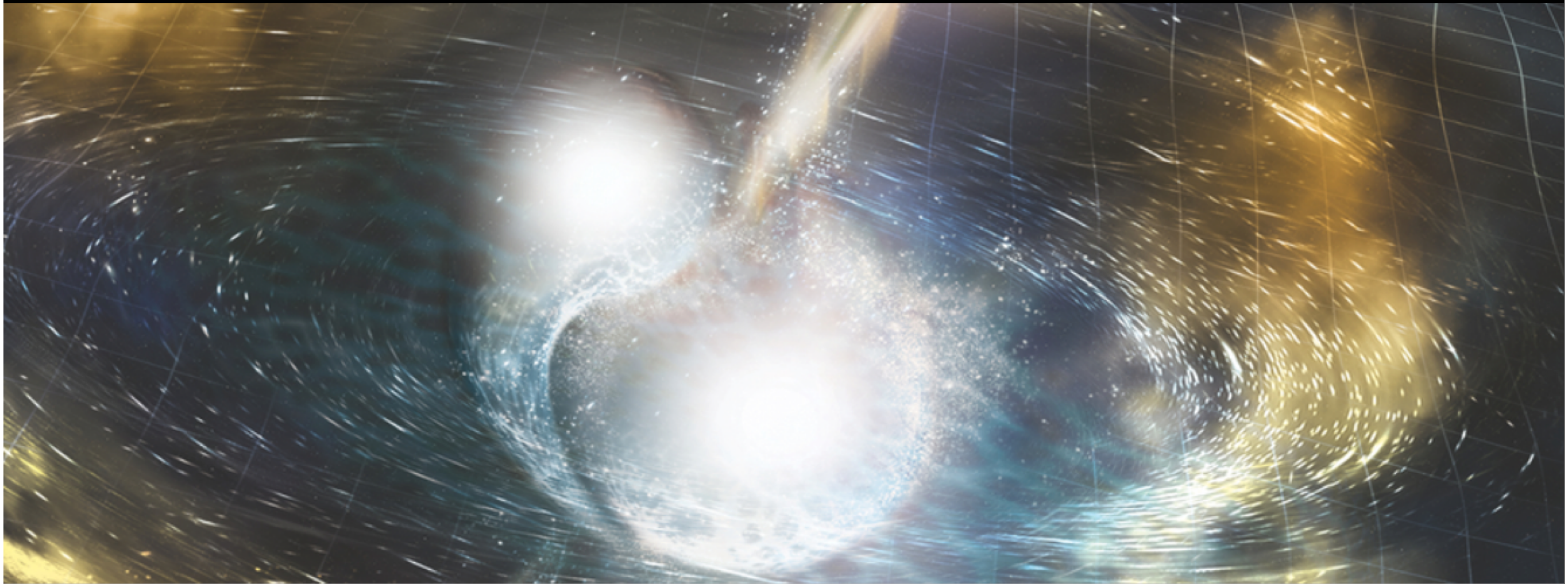
Particle and nuclear accelerators

Astrophysical observations

New limits for extreme matter

August, 17th 2017 (GW170817)

First detection of GW from the merger of two neutron stars (BNS)



Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

From https://www.ligo.caltech.edu/page/press-release-gw170817

See Abbott et al., the LVC, PRL 2017

The birth of multi-messenger astronomy

The multi-messenger astronomy

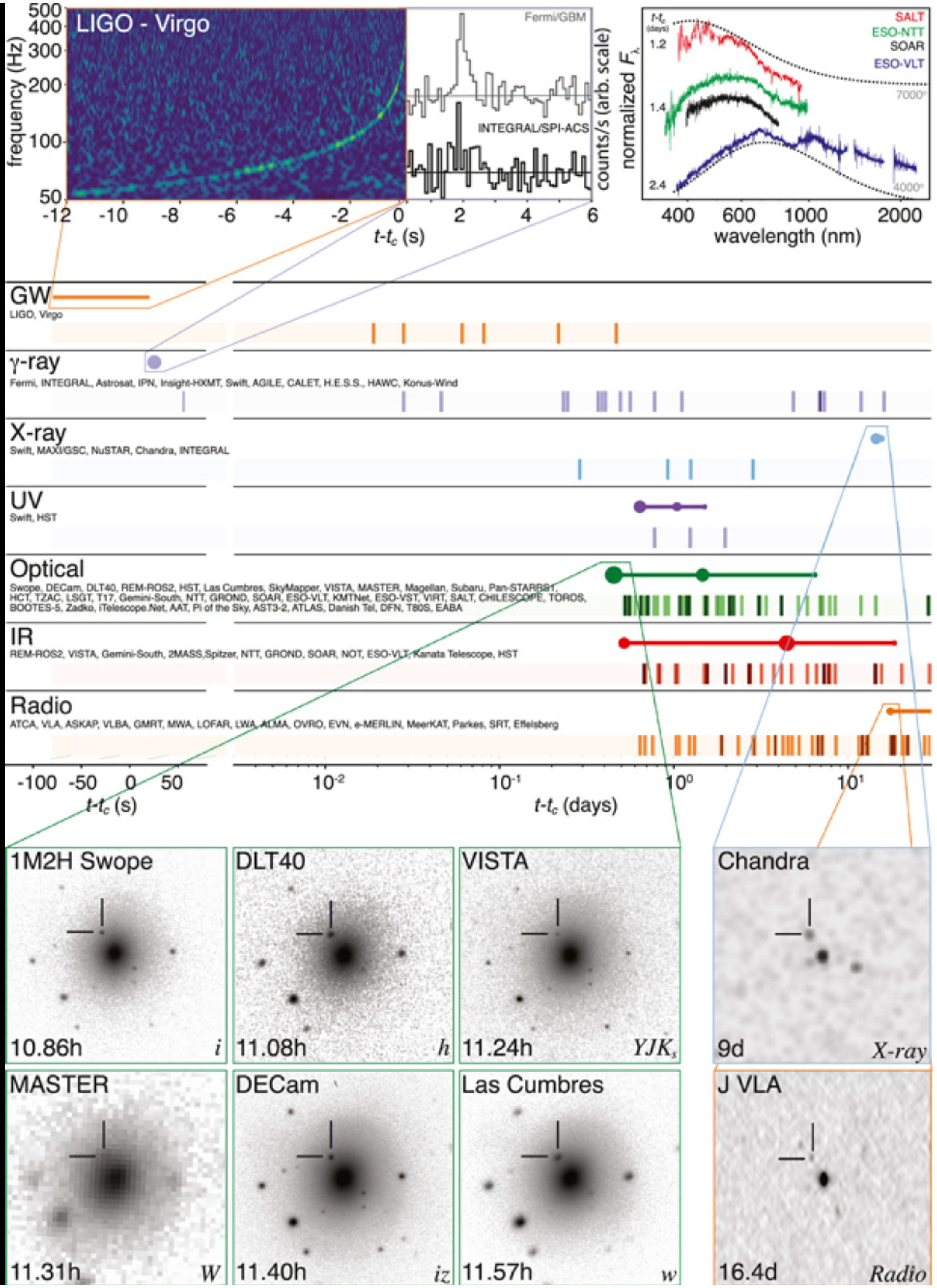
See talk of Susanna Vergani

- GW (interferometers)
- GRB, X (satellites)
- UV, Optical, IR (telescopes)
- Radio (radio-telescopes)

+ 70 instruments
Several weeks

Abbott et al., ApJL 848 (2017) L12

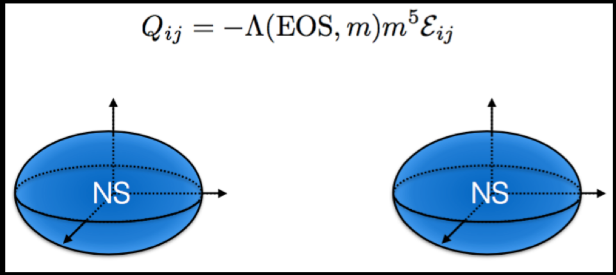
- 59-page “letter” (!)
- More than 2000 authors,
- ~70 collaborations



Extreme matter and inspiral signal

Tidal deformability

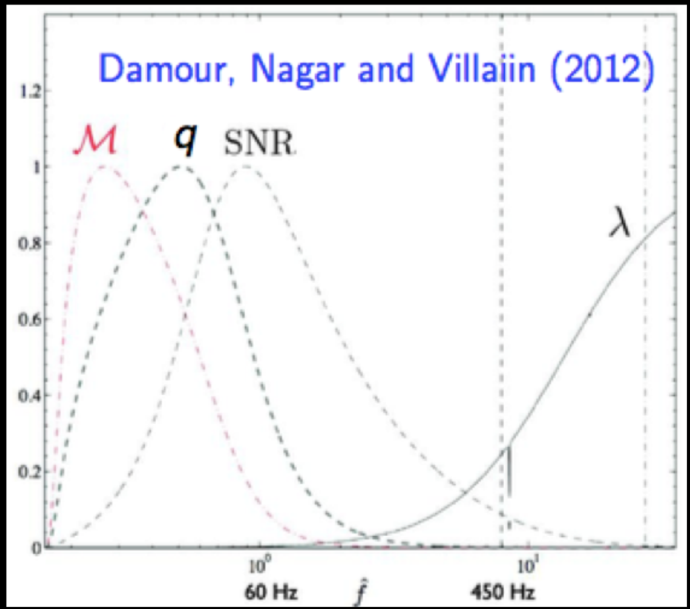
- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability Λ.



Post-Newtonian expansion of the waveform:
Tidal effect enters at 5th order

Hinderer+ 2008, Blanchet, Damour

GW170817 → 70 ≤ Λ ≤ 720 (90% CL)

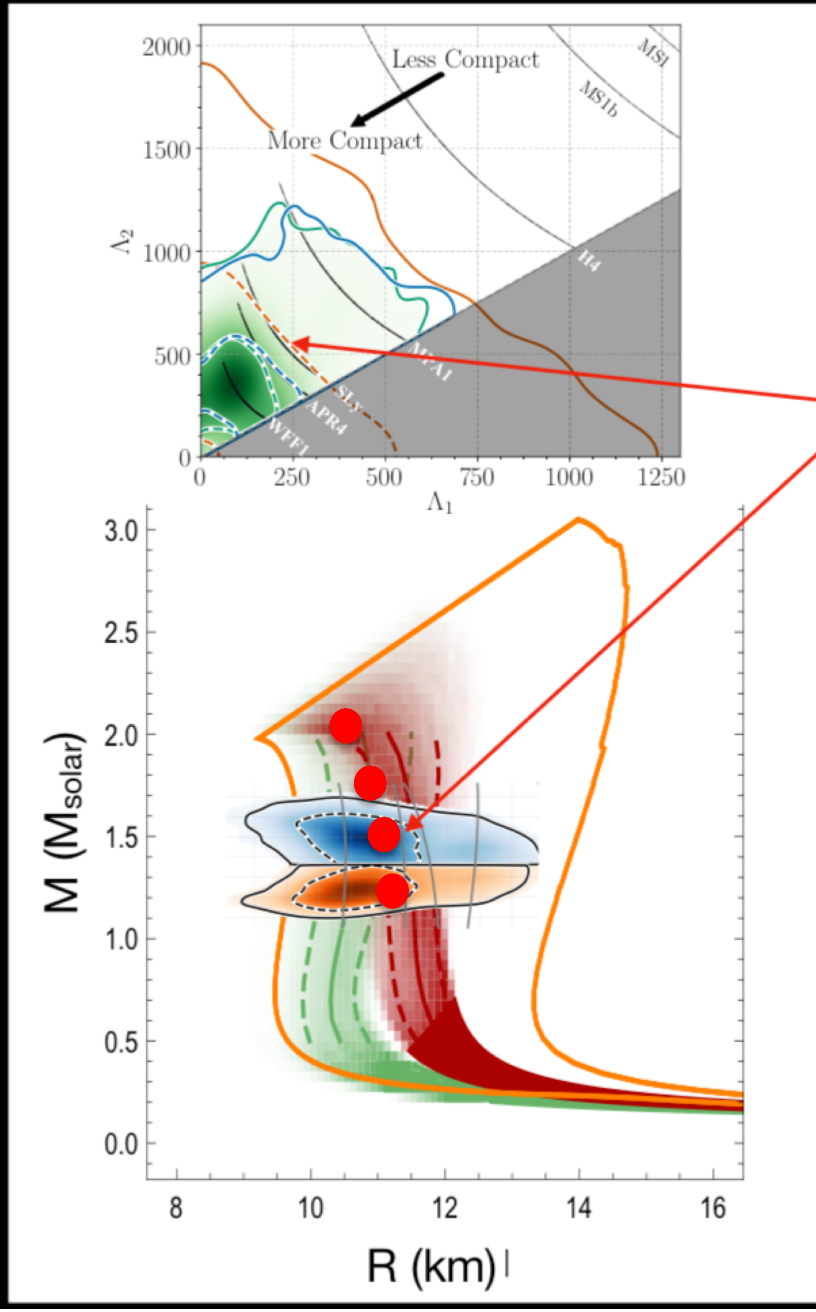


Inspiral NS mass and radius

GW170817 demonstrated that it is possible to constrain the NS mass-radius relation using GW data. **This is a watershed moment in NS science!**

However, **these constraints are not stringent enough** to provide new insights. Realistic nuclear EOSs predict a smaller range of radii (and tidal deformability) compatible with GW170817 constraints.

To address interesting questions related to **QCD matter**: the tidal deformability needs to be **measured to better than 10%** and we will need **several measurements** across the accessible mass range.



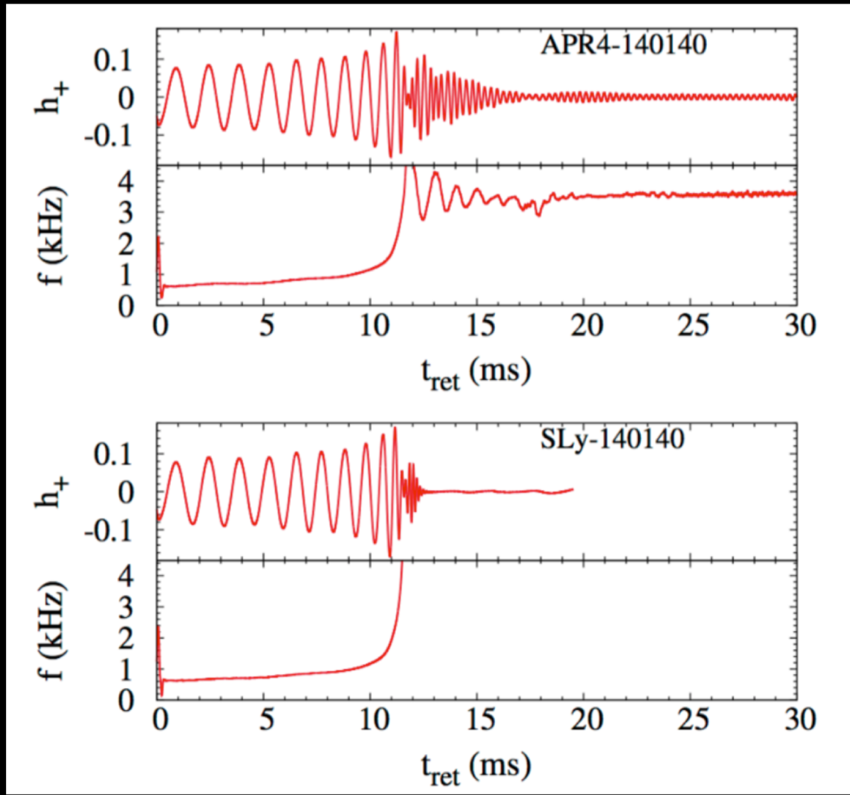
LIGO-Virgo Collab. arXiv:1805.11581.
See also De et al. PRL (2018)

Tews, Margueron, Reddy (2018)

Extreme matter and post-merger signal

EOS determines:

- Remnant fate and lifetime
- Ejecta and composition (together with ν)
- Post-merger oscillations



Hotokezaka+ 2013

Extreme matter and post-merger signal

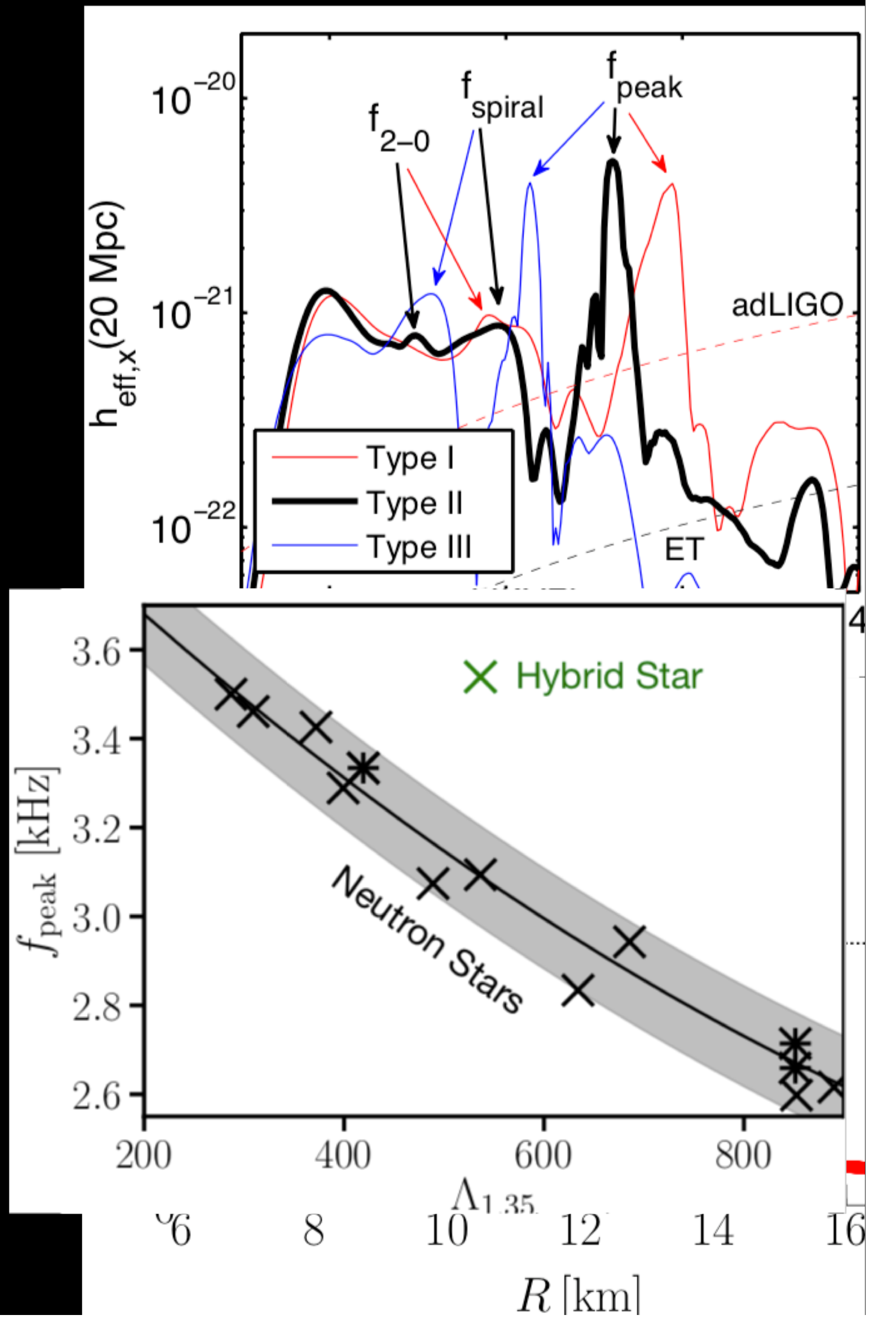
Hypermassive neutron star Seismology

Merger excites high frequency quasi-normal modes. The spectrum is sensitive to the compactness of hypermassive neutron star.

$$
\begin{aligned}
f_{\text{peak}}[\text{kHz}] &= 199(M/R)^2 - 28.1(M/R) + 2.33 \\
f_{\text{spiral}}[\text{kHz}] &= 358(M/R)^2 - 82.1(M/R) + 6.16 \\
f_{2-0}[\text{kHz}] &= 392(M/R)^2 - 88.3(M/R) + 5.95
\end{aligned}
$$

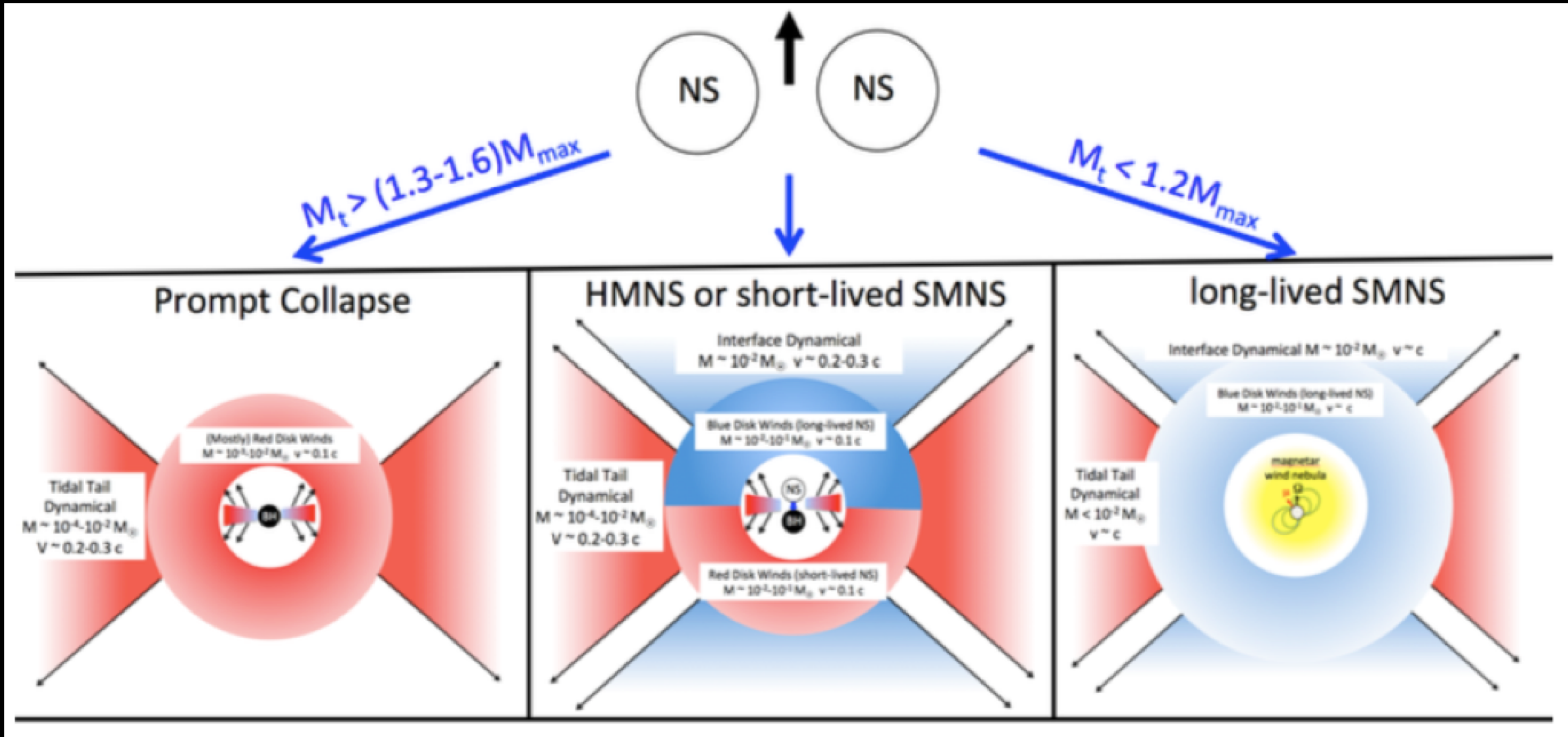
Bauswein and Stergioulas 2015

Phase transitions in the hypermassive NS can alter the correlation between compactness measured from the tidal deformability and post-merger oscillations.



Extreme matter and EM signal

Margalit & Meitzger ApJ 2017



Kilonova (macronova) AT2017gfo → Mmax = 2.1-2.3 Mo

Rezzolla+ 2018

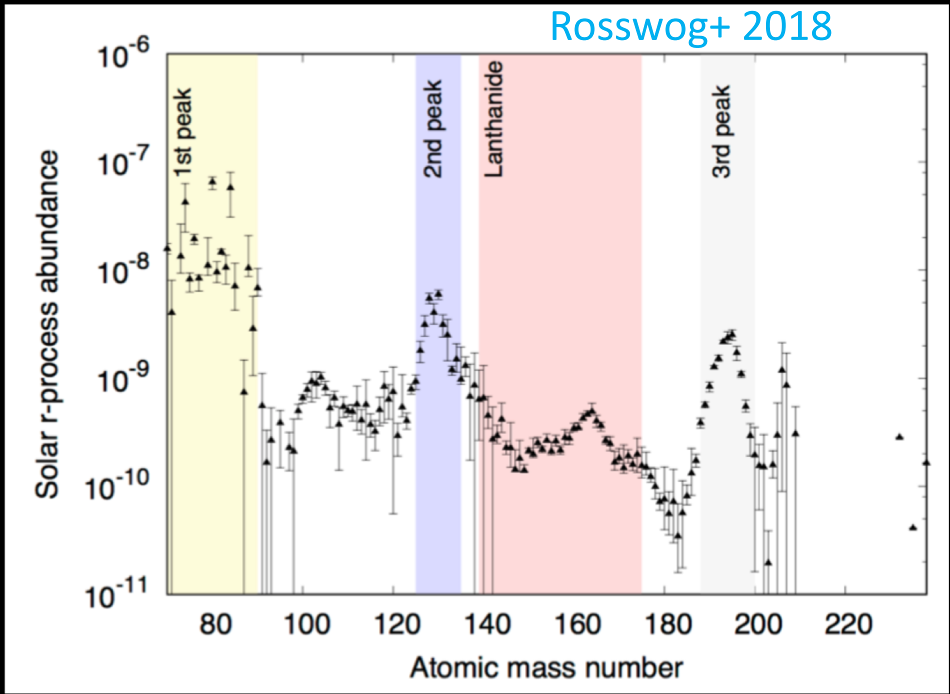
Extreme matter and EM signal

Nucleosynthesis and Ye of ejecta

Synthesis of heavy nuclei (above 2nd peak):
What are the conditions for the r-process?

Ye < 0.25:
- Strong r-process A>130
- Insensitive to details of trajectory

Ye>0.25
- A<130
- Sensitive to details of trajectory

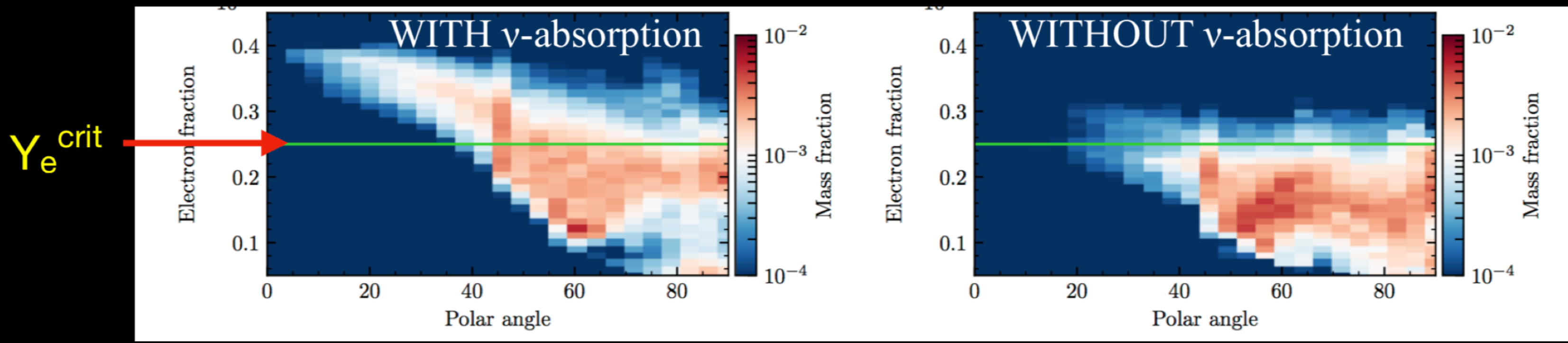


Production of lanthanides (large opacities) → redding of the EM signal

Extreme matter and EM signal

Neutrinos and EM signal

neutrino heating: ejecta from 1.35+1.35Mo



SFHO-EOS Perego+ 2017
Shibata+ 2017

Ye>0.25
Blue transient

Ye<0.25
Red transient

→ neutrino-matter interaction determines the color of the kilonova.

Accurate treatment of neutrino transport needed to predict EM-transient.

The beginning of a new astronomy

Various sources

1- Merging BNSs and NS-BHs

Inspiral: masses and tidal deformability
Post-merger dynamics: oscillations, ejecta, connection to EM.

2- Spinning Neutron Stars (Continuous GWs)

Elastic and magnetic deformations: properties of dense matter.
Instabilities (eg. r-modes): transport and dissipation in dense matter

3- Bursting, Flaring or Glitching Neutron Stars

Evolution of internal magnetic fields
Superfluid and solid phases and their dynamics

Addressing **fundamental** questions at the forefront

From the GWIC 3G science-case meeting (oct. 2018, Postdam)
Sanjay Reddy, Neutron Star WG

1. Does matter in NS and NS mergers contain **novel QCD phases** not realized inside nuclei and heavy-ion collisions?
2. Can NS observations guide and validate **theories of nuclei and nuclear matter**?
3. Is there a diversity in the NS population and what are its implications (families)?
4. How do **nuclear** and **neutrino reactions** shape NS mergers dynamics and **nucleosynthesis**?
5. How do the properties of **nuclei far from stabil**ity impact on the electromagnetic emission from NS merger ejecta?
6. Can NSs sustain long-lived large quadrupolar deformations?
7. Do large scale (magneto)hydrodynamic instabilities influence spinning and merging NSs?
8. Can we combine GW and EM signatures to validate multi-physics simulations of BNS and BHNS mergers to predict ejecta, nucleosynthesis, and the gamma-ray burst mechanisms?
9. Can we model and observe post-merger oscillations to reliably constrain dense matter and merger dynamics.
10. Does **dark matter** and **physics beyond the standard model** play a role in NSs and NS mergers?

Conclusions and outlooks

Near future with Ad. LV:

- To constrain the **equation of state** of dense matter the **tidal deformability** of a **tens of neutron stars** needs to be measured with **few percent** accuracy.
- Correlations between the inspiral tidal deformability and **post-merger** neutron star dynamics (seismology and the lifetime) can reveal **phase transitions** in massive neutron stars – need to observe the high frequency (1-5 kHz) GW signal.
- Validating **multi-physics** simulations needed to connect **merger dynamics** to **EM** and **nucleosynthetic signatures** will rely on our ability to detect and interpret the post-merger GW signal. Accurate treatment of neutrino transport is necessary.

Next generation (3-G) GW detectors (ET):

- Increase **accuracy** of the **tidal deformability** measurement down to **few percent**.
- Searches for **continuous GWs** (from neutron star ellipticity).
- GWs from **bursting**, **flaring** or **glitching** neutron stars (clues about internal dynamics).