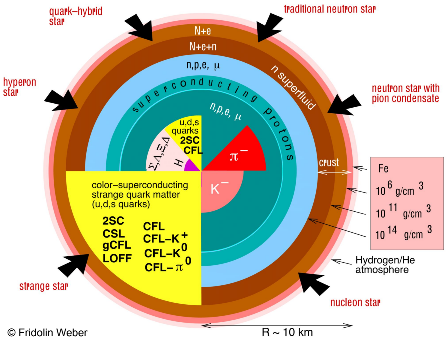

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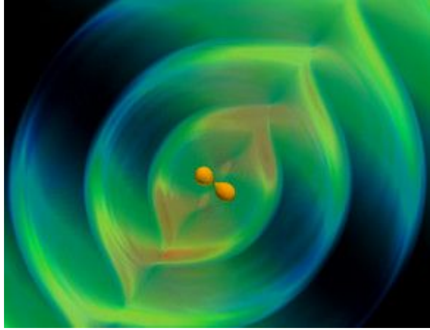
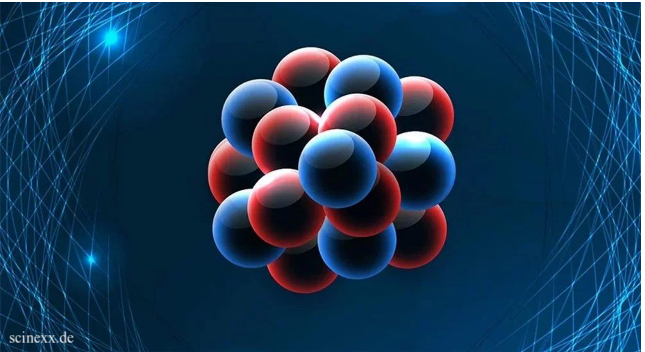
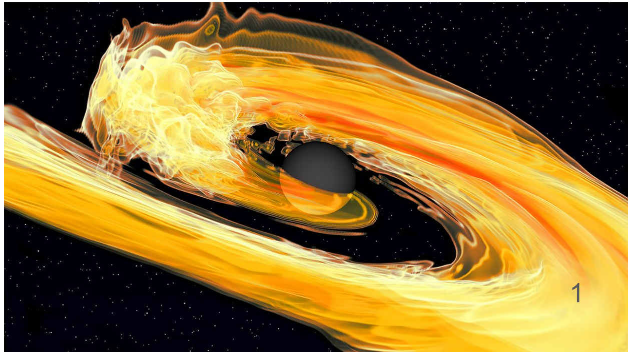


Nuclear Physics

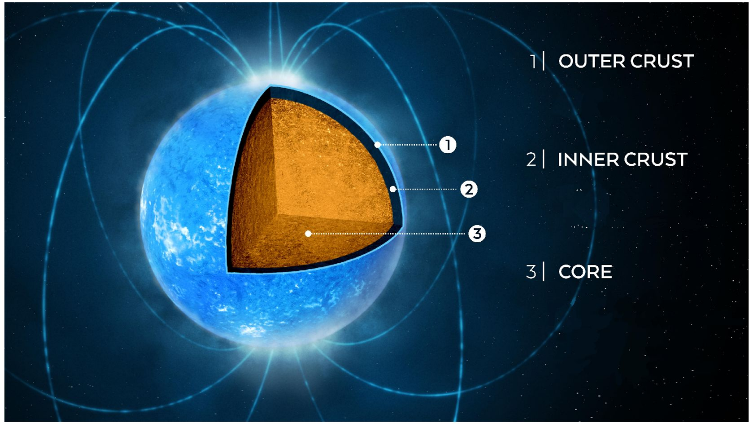
-- Division 6 --

division chairs: Tim Dietrich, Tanja Hinderer, Micaela Oertel

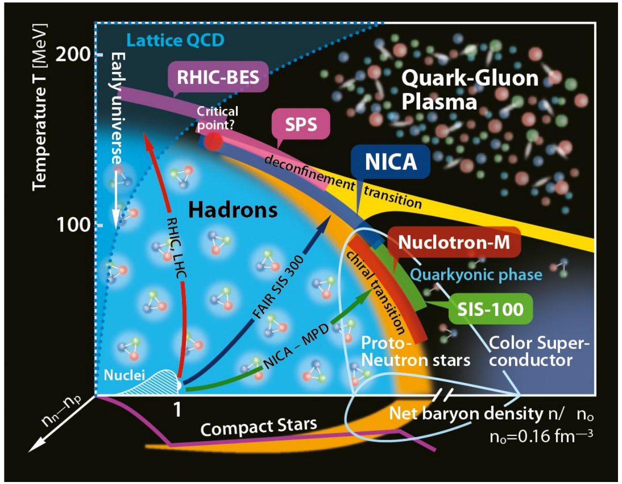




The Einstein Telescope: A new fundamental physics laboratory



Watts et al., Rev.Mod.Phys. 88 (2016) no.2, 021001



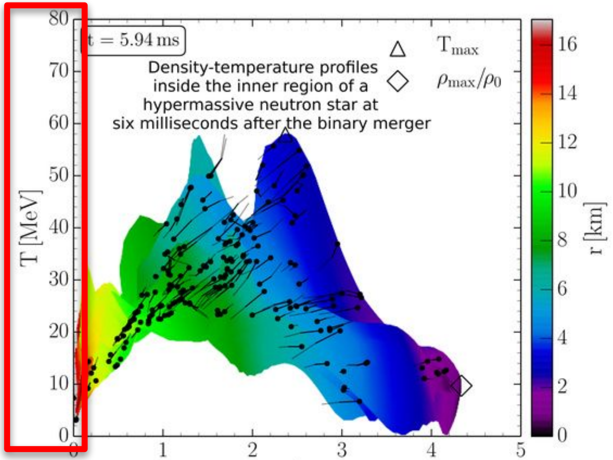
[NICA White Book]

- neutron stars probe extreme densities beyond nuclear saturation density
- the Einstein Telescope will allow us to probe aspects of the equation of state not accessible with other experiments (density+asymmetry+temperature), are there phase transitions, condensates? degenerate quark matter? multi-body interactions? effects of isospin asymmetry?

The Einstein Telescope: A new fundamental physics laboratory

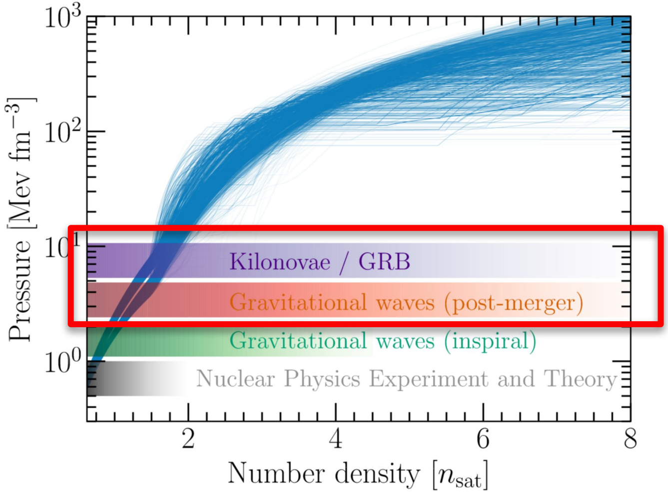
Detecting the postmerger will allow us to study entirely unexplored regimes

temperature effects *and* the higher densitites



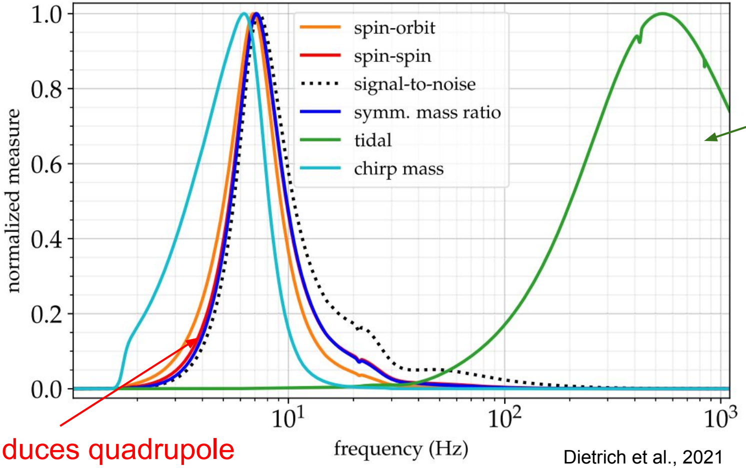
Density-temperature profiles inside the inner region of a hypermassive neutron star at six milliseconds after the binary merger

Hanauske et al., Particles 2019, 2(1), 44-56



Pang et al., arXiv: 2105.08688

BNS & NSBH mergers: dominant effects in inspiral phase



spin-induces quadrupole

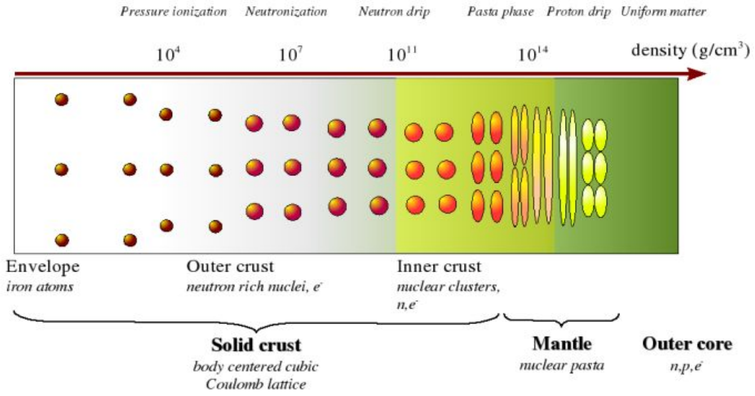
Dietrich et al., 2021

tidal deformability

- Core EoS from (semi-)agnostic approaches informed from nuclear data (experiment+theory) and other observations
- Explicit modeling for questions of composition at high densities and crust EoS

*accurate inspiral measurements are **crucial** for interpreting new postmerger physics*

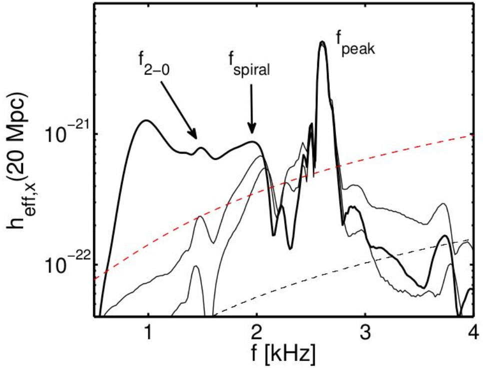
Cold NS in beta-equilibrium with crust+core



Chamel&Haensel, 2008

BNS & NSBH mergers: post-merger phase

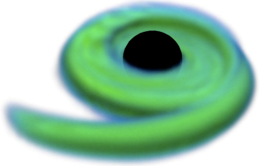
- presence of postmerger signals depends on binary properties
- rich frequency spectrum, very sensitive to matter properties and EoS
- Hot matter not necessarily in beta equilibrium; no more crust



Bauswein+2016

- Peak frequency strongly correlated with NS radius and tidal deformability
- Strong prospect to detect phase transition

- tidal disruption depends on binary properties
- characteristic shut-off frequency sensitive to EoS
- no shock formation → cold matter



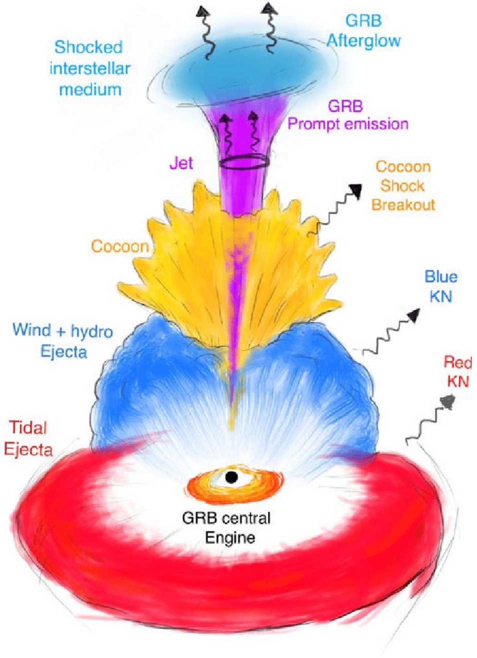
credit: F. Foucart

- Ejecta different from BNS mergers (very neutron rich,...)

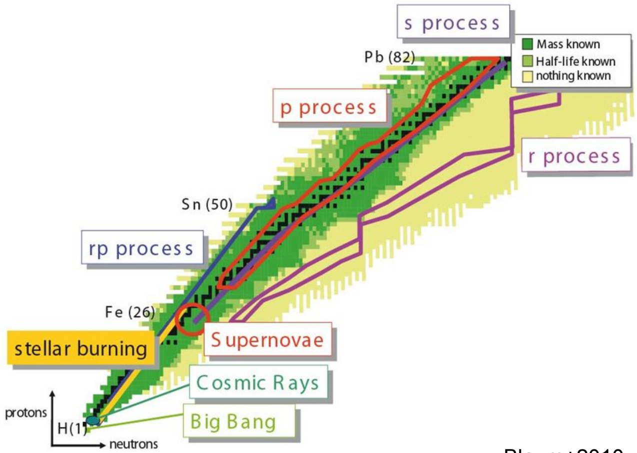
- Post-merger modeling needs input from EoS and neutrino interactions

BNS & NSBH mergers: sites for r-process nucleosynthesis

- matter outflows
- rapid neutron capture in neutron rich environments
- final abundances depend on neutron density



Ascenzi et al., 2020

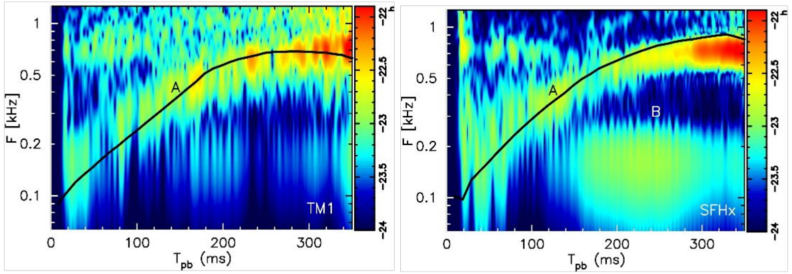


Blaum+2010

- r-process path far away from stability → large nuclear uncertainties on relevant reaction rates and nuclear masses
- n/p ratio in ejecta depends on dynamics and neutrino interactions

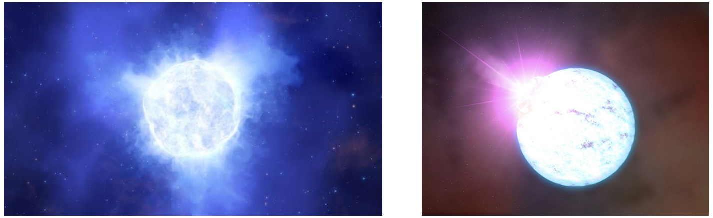
Core-collapse supernovae, proto-NSs, single NSs GWs

- detection possible for galactic events
- possible GWs from PNS oscillations and hydrodynamic instabilities in the region behind the shock



Kuroda+2016

GW signal sensitive to the detailed dynamics and among others to the EoS of hot and dense matter

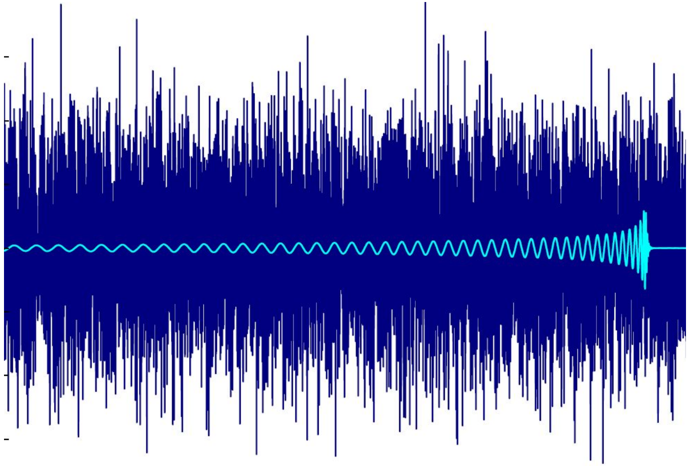


credit: APS

- Continuous wave from deformed spinning neutron stars (deformation caused by magnetic fields, accretion,r-mode instability, "mountains", ...)
- Magnetar bursts and glitches
- NS asteroseismology
- probes for crust physics

How to extract source properties from GWs

Matched filtering



Gabbard et al., PRL 120, 141103

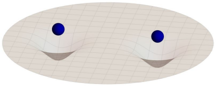
accurate theoretical templates required to detect GW signals in noise and measure the properties of the binary source

Available techniques

template based

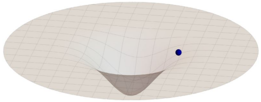
Post-Newtonian Theory

Tidal information known up to 7.5PN



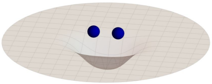
Effective-one-body

- tidal effects change the potential



Numerical Relativity

- no assessment of full inspiral
- accuracies of ~1 rad error during last 20 GW cycles



Phenomenological models

-combination of PN/EOB/NR information to allow a fast evaluation

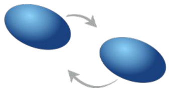
alternative:

burst searches

State-of-the art: Waveform modelling (analytical)

connection between microphysics and GWs computed via a tapestry of approximation schemes

key quantities: spacetime multipole moments -- importance of point-mass baseline



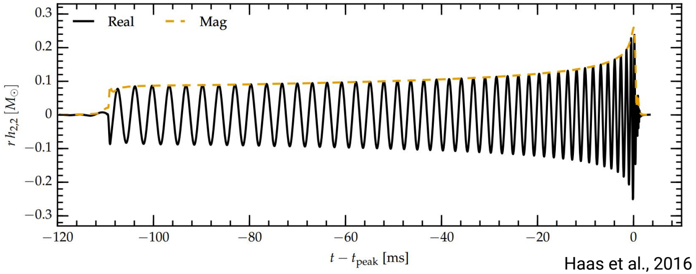
Matter effects in current waveform models available for data analysis:

- **inspirals:**
  - spin-induced multipoles
  - dominant tidal effects (circular orbits)
  - analytical (PN, EOB) and NR-calibrated tidal models, different approaches to including matter effects

- **mergers:**
  - full frequency-domain NS-BH models for aligned BH spin, dominant mode, calibrated in part of parameter space

- **remaining challenges**:
  - higher modes of GW signals
  - resonant tidal excitation of various quasi-normal modes (direct probes of phase transitions, gravitomagnetic modes)
  - spin-tidal effects
  - relativistic effects (missing effects + higher-order corrections)
  - eccentricity
  - NS-BH: higher modes, spin precession. parameter space coverage, independent approach
  - understand effects from beyond GR, standard model physics, exotica
  - ...

State-of-the art: Waveform modelling (numerical)

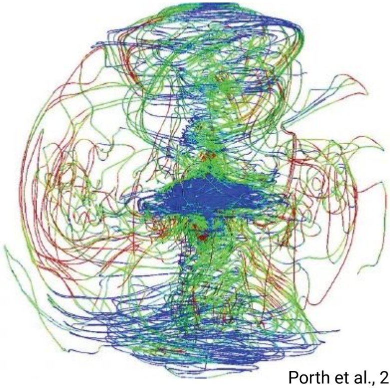


Haas et al., 2016

Compact binary coalescence
inspiral:
- about 20 orbits before merger
- phase accuracies of the ~1rad regime

postmerger:
- incorporation of microphysics (composition effects, neutrino emission, magnetic fields, viscosity ...)
  → none of these is handled with sufficient accuracy

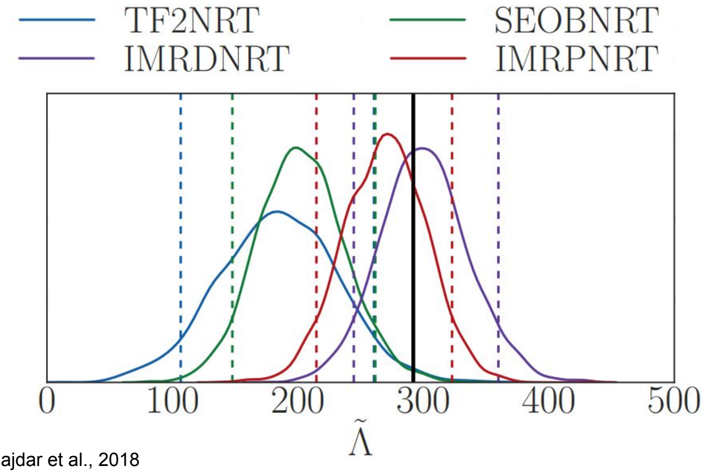
Supernovae
- similar situation wrt. the postmerger situation; basic principles are understood and broad features of the GW signal are revealed, but uncertainties about the requirements to launch a SN are not clear



Porth et al., 2013

What can we expect? ... systematic uncertainties

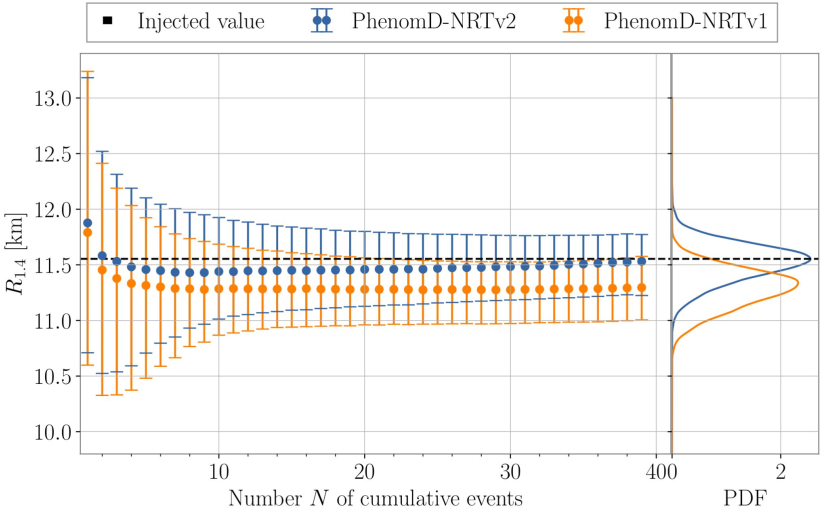
Systematic uncertainties -- singel loud events



Samajdar et al., 2018

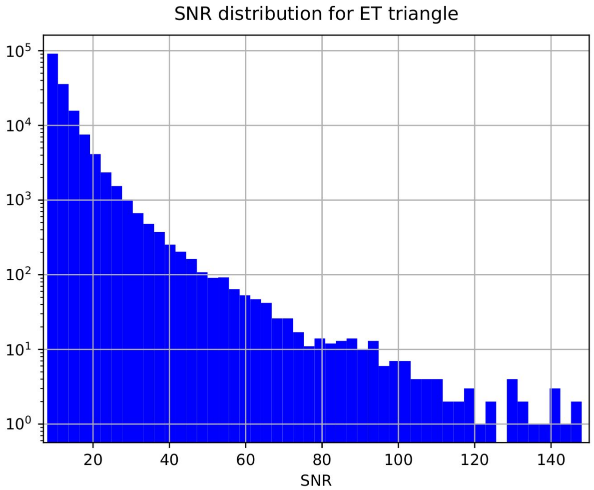
- GW170817-like source
- Advanced LIGO/Virgo design sensitivity

Systematic uncertainties -- combining multiple events

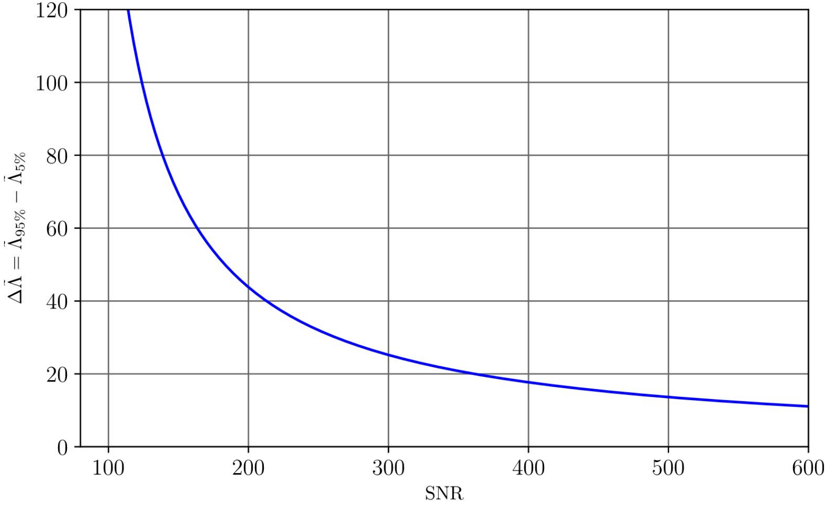


injection campaign using 40 sources with Advanced LIGO/Virgo design sensitivity

The Challenges ahead!



Estimates of SNR distribution for ET during 1 year observation (image credit: J. Janquart)



Estimated uncertainty in tidal deformability for a single detection with 3G detectors; based on Gamba et al. 2020

Challenges: Nuclear Physics Modelling

Different physical conditions for the different systems

BNS-NSBH inspiral and NS :

Cold matter (in beta equilibrium)

- Needs precision crust models, coherent with core
- Composition at high densities (phase transition?)
- Influence of superfluidity/superconductivity on potentially excited oscillation modes

BNS merger remnant/CCSN:

Hot matter with different electron fractions

- Thermal effects in the EoS
- Neutrino-matter interactions
- Parametric studies including potential phase transitions

- Transport properties
- r-process nuclear physics

Need the nuclear physics data available for modeling to relate input to GW signal

Planned work packages [subject to changes]

1. Constraints on microphysics from BNS and NS-BH inspirals & mergers: data analysis and modeling challenges

- cold EoS inference from inspiral/tidal disruption: effect of EoS modeling accuracy (e.g. crust-core matching, sound speed)? universal relations? ...
- BNS merger: new physical conditions, density, temperature - dependence on microphysics?
- phase transitions in NS and/or BNS mergers: analysis strategies, parameter space where discernible, interpretation of GW results for the fundamental physics, ...
- influence of superfluidity / color superconductivity (e.g. oscillation modes)?
- access to transport?

2. Waveform models

- accuracy, wide parameter space, more realistic physics
- efficiency
- BNS post-merger models based on deeper understanding

Planned work packages cont. [subject to changes]

3. Uncertainties in simulations

- microphysics assumptions (neutrinos, magnetic field, …) and connection with EM, nucleosynthesis
- missing reliable microphysics inputs (hot EoS, weak interaction rates, transport, ...), accuracy needed?
- uncertainties in radiative transfer simulations (many unknowns), code comparisons

4. Degeneracies with modified gravity, BSM physics, microphysics uncertainties

- most degenerate parameters? analysis strategies to lift degeneracies?
- better understanding of possible effects

5. EoS from core-collapse supernovae, proto-neutron stars, and magnetars

6. EoS from continuous GWs

This list is preliminary, more ideas are welcome.
If you are interested in contributing, please contact the chairs.