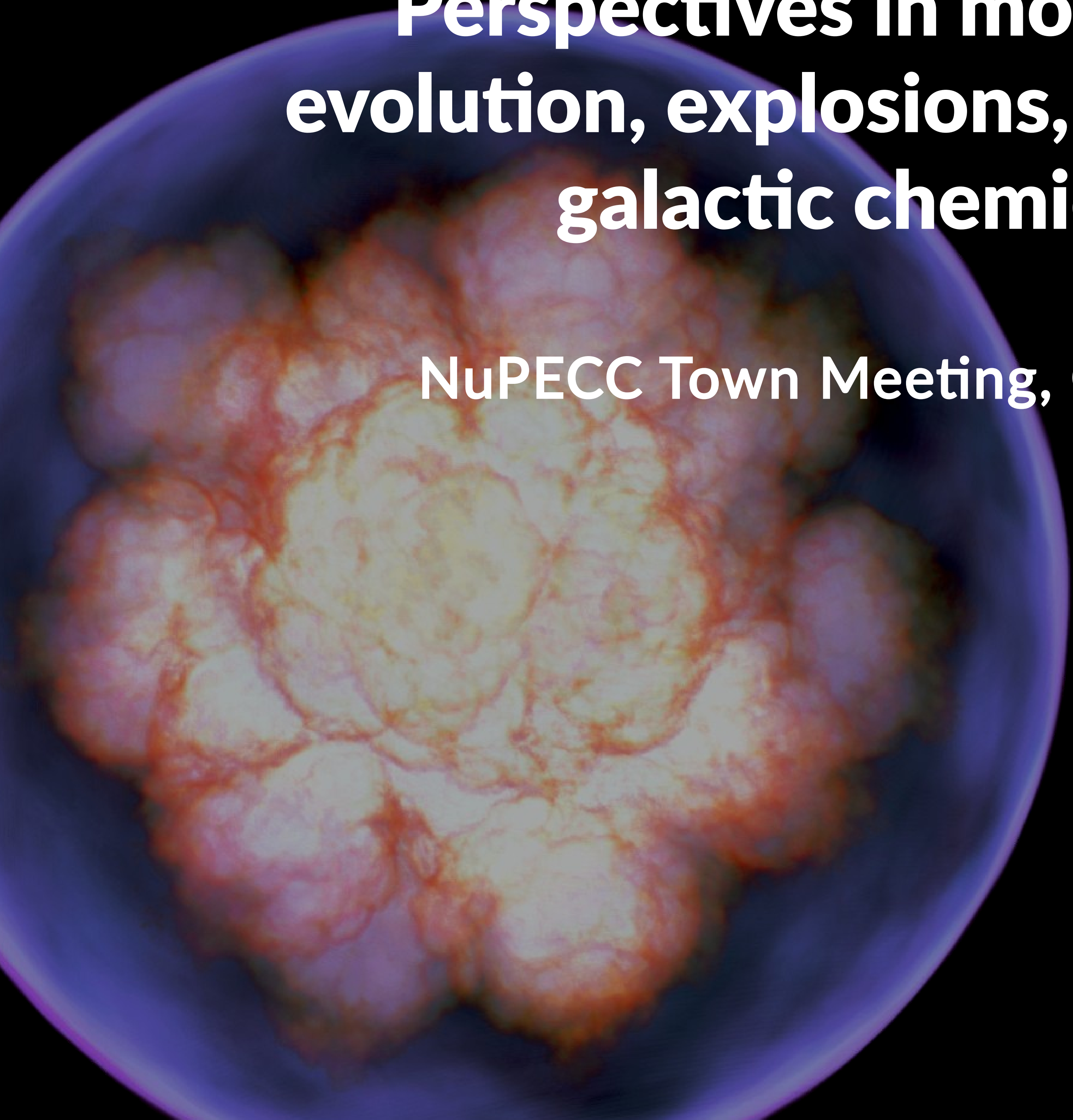
Perspectives in modeling stellar evolution, explosions, mergers and galactic chemical evolution

NuPECC Town Meeting, GSI, 02/17/2016



Friedrich Röpke

Samuel Jones

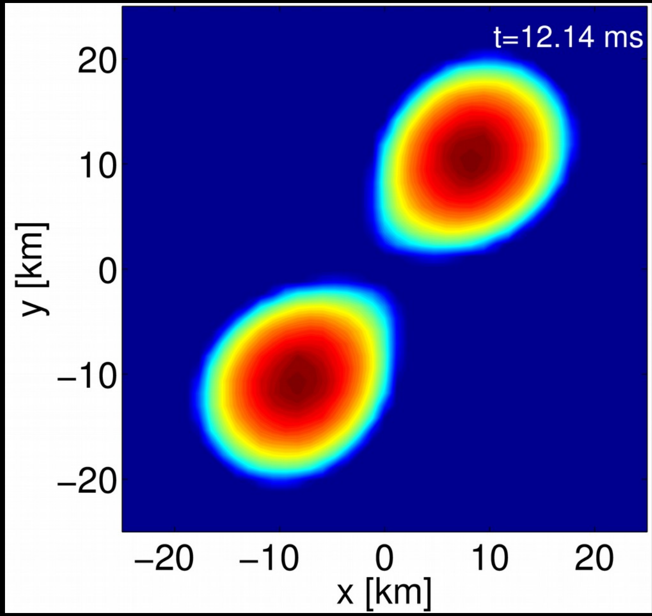
Andreas Bauswein

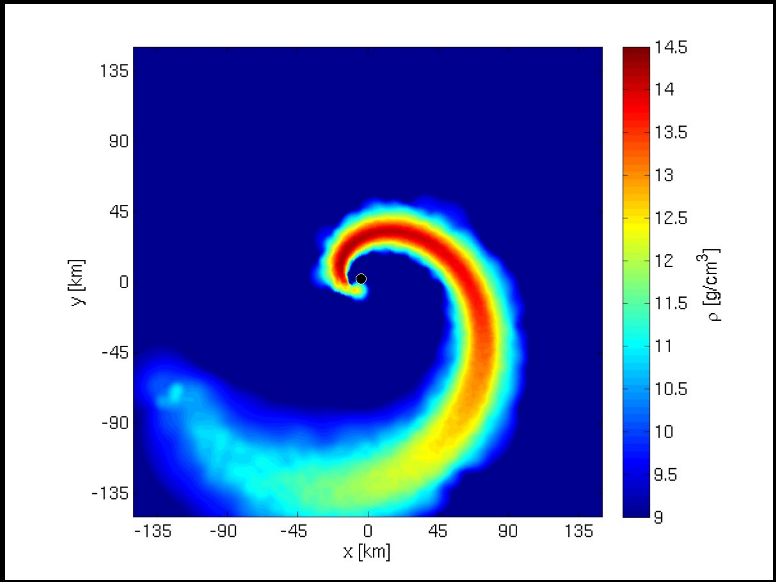
Raphael Hirschi

et al.

Compact object mergers: Long-term goals
- challenges, required input, current activities -

- Constrain properties of high-density matter by detection of gravitational waves
- Are compact object mergers the dominant source of r-process nuclei?
- Explain observations of electromagnetic counterparts (kilonovae – heated by nuclear decays, short gamma-ray bursts, ...), connect to physical parameters, multi-messenger astronomy



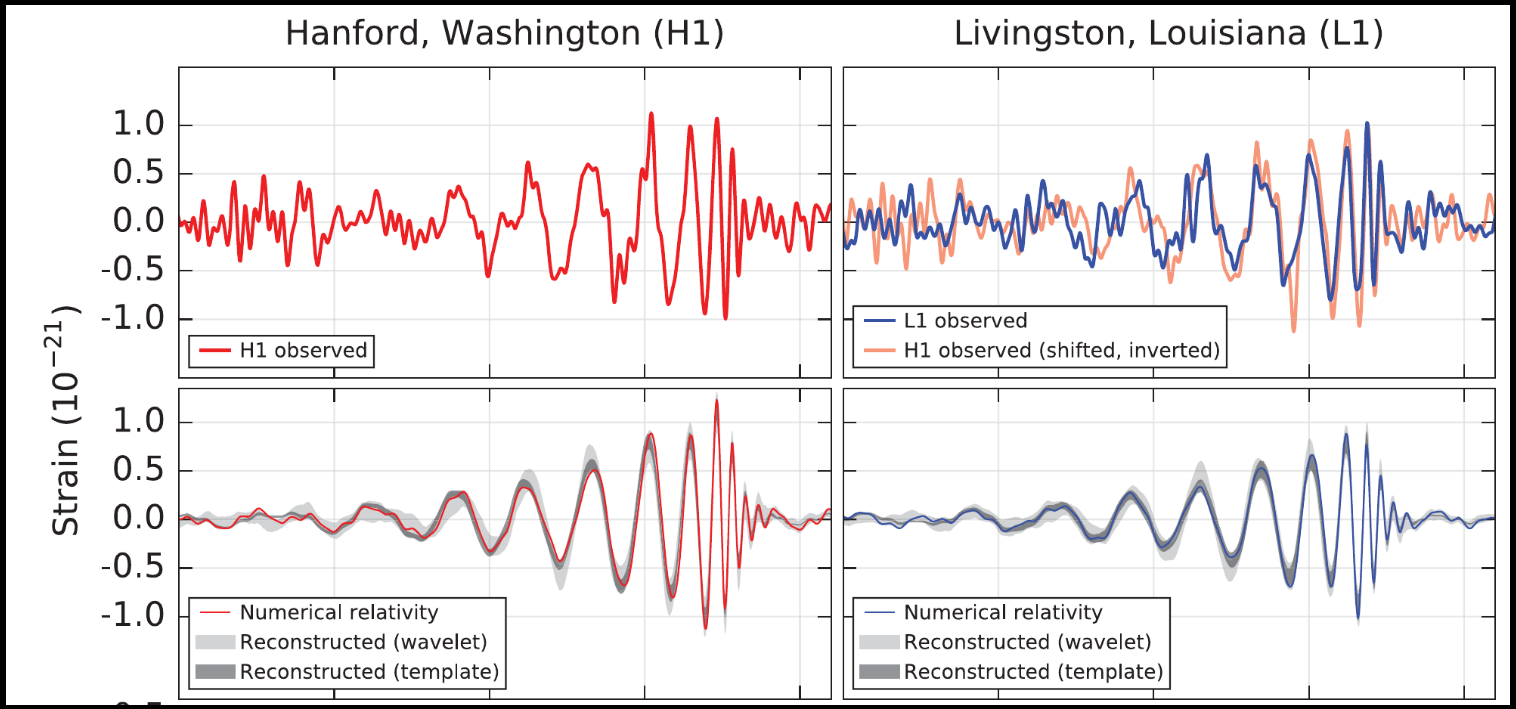


→ biased by provided input and personal view, focus on European activities

Implications by GW150914

- GW detection of merger of two massive BHs by Advanced LIGO (September 2015)
- Implications for NS-NS merger rate speculative, but
- Gravitational waves exist
- Instruments work
- No deviations from General Relativity found

Abbott et al. 2016



Constraining the nuclear EoS from GWs - requirements

- Detections (instruments are running, more will join, approach design sensitivity during next years)
- Data analysis strategies (the more sensitive ones rely on predicted models)
- Understanding of EoS dependence of GW signal for the interpretation of future measurements
- In general: EoS affects dynamics of inspiral and merger and thus the GW signal
- Two complementary approaches:

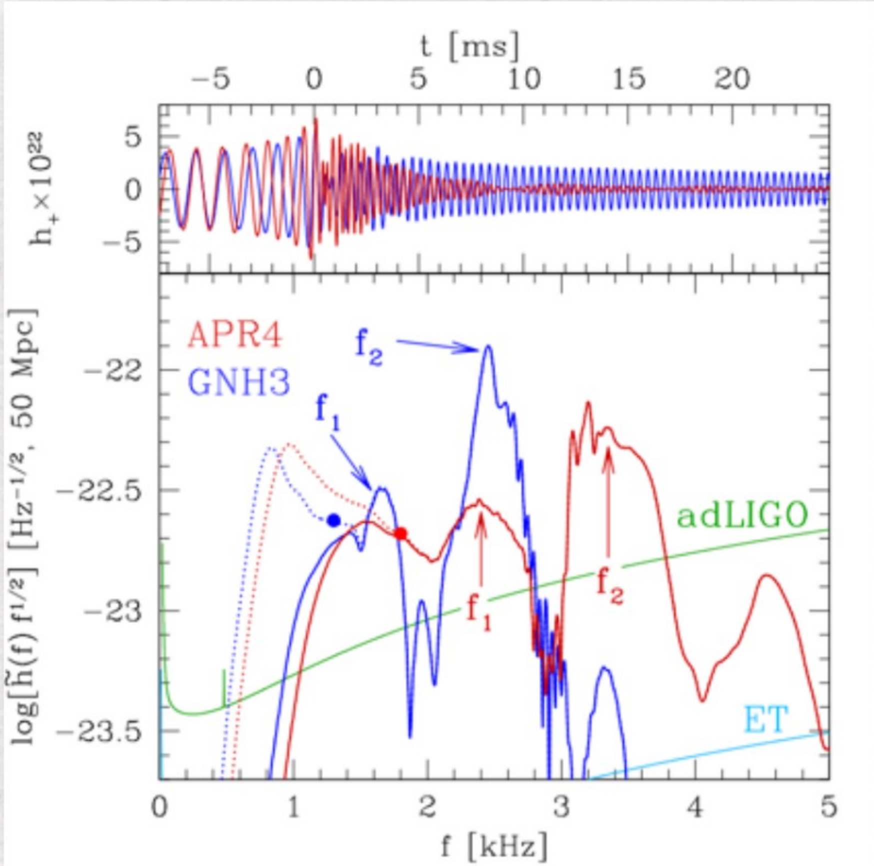
  - Finite-size effects alter GW signal of late inspiral (premerger) phase

  - EoS affects structure of merger remnant and thus its frequencies

Constraining the nuclear EoS from GWs - requirements

- Candidate EoS (for postmerger in particular more temperature dependent EoSs are needed, constraints from nuclear physics) → Working group 1
- General relativistic hydrodynamical simulations of mergers (possibly including subdominant effect of magnetic fields and neutrinos on GW signal)
- systematic studies are possible, but huge parameter space, computationally expensive
- Simulation results are funneled into effective-one-body models for inspiral, analytic models for postmerger
- template bank purely based on simulations prohibitive (must contain true EoS)

Activities in Frankfurt



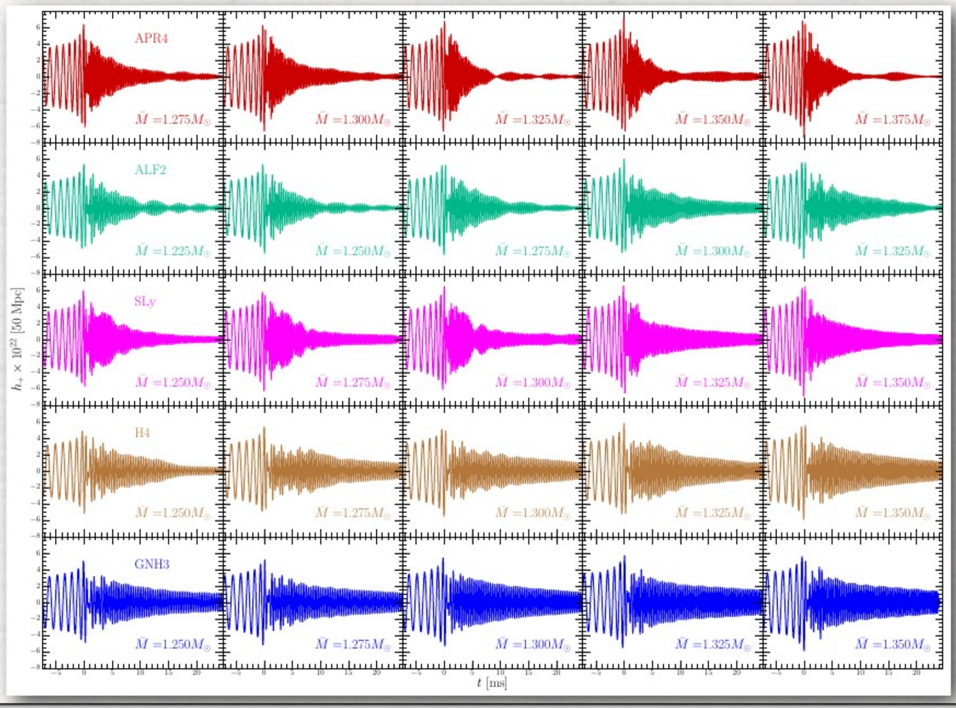
✶ Gravitational waves from inspiral and merger provide key insights into general-relativistic dynamics.

✶ This information is essential on the verge of first direct detection.

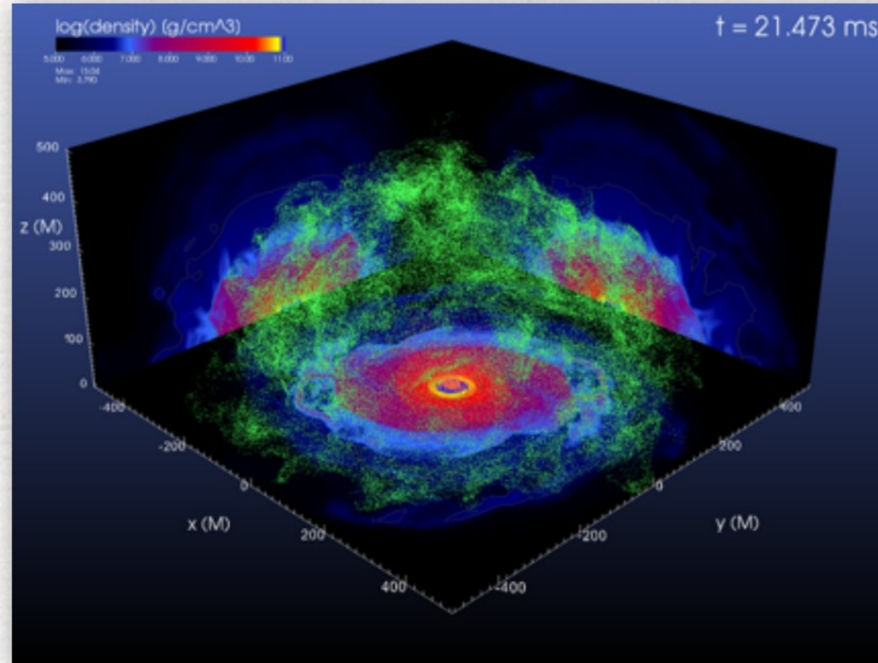
✶ Codes developed over last decade allow systematic investigation.

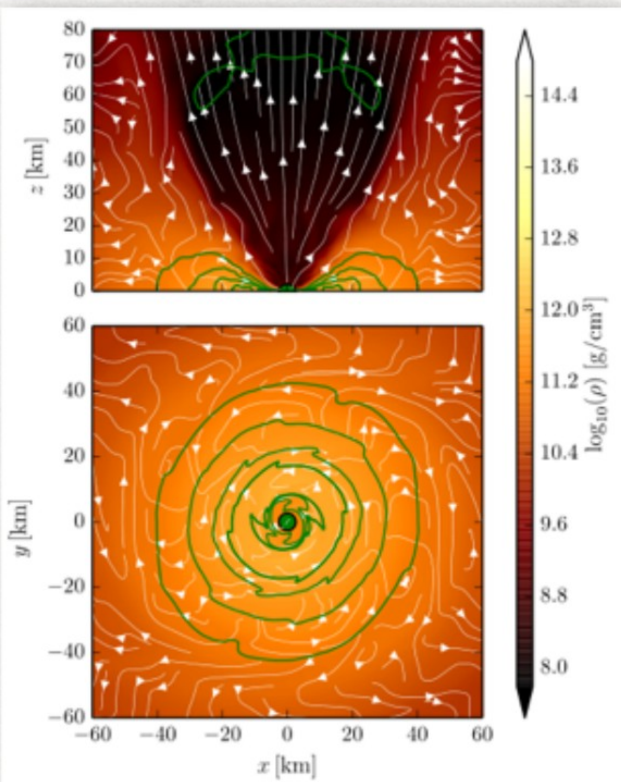
✶ Spectra of emitted GWs have "lines" can be associated to EOS.

✶ GWs could act as Rosetta stone to decipher the interior of NSs.



* Binary mergers of neutron stars also contribute to chemical abundance.
* Emission from radioactive decay of ejected matter (kilonova) could be missing link between SGRBs and NS binaries.



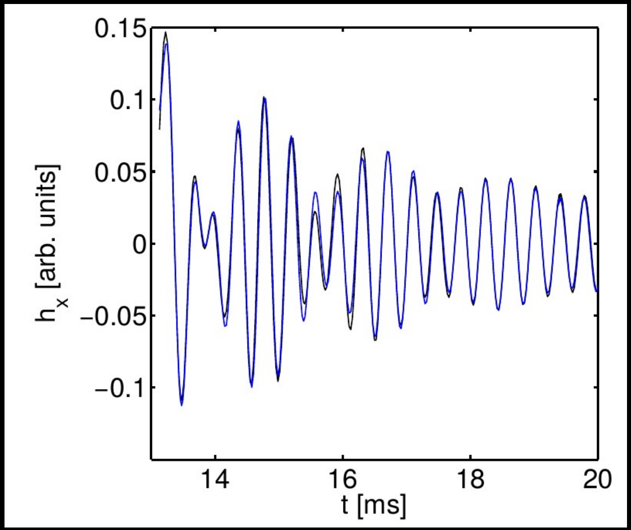


* Maturity of codes, realism of description (e.g., full GR, resistive MHD, microphysics, neutrino transport) make simulations invaluable tools to explore nuclear and relativistic astrophysics, e.g., short gamma-ray bursts.

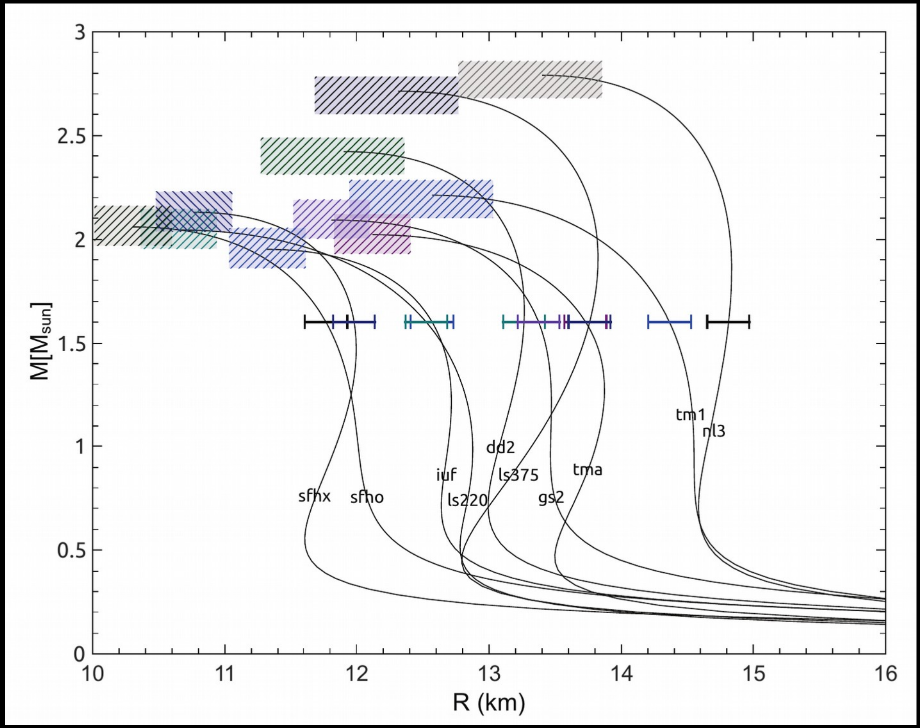
Further activities in Frankfurt (input by L. Rezzolla)

Current activities at HITS/MPA/AUTH

- Prospects for NS radius measurements
- Constraining NS maximum mass from collapse behavior
- Understanding of postmerger emission mechanisms
- Analytic postmerger models
- Data analysis (burst searches, PCA)
  → near-by mergers will reveal EoS information



Prospects for EoS constraints from postmerger phase:



Bauswein et al. 2014

Are compact object mergers the dominant source of (heavy) r-process nuclei?

- Robustness of r-process in merger ejecta

  - impact of neutrinos on neutron richness (→ include more sophisticated neutrino transport schemes and hydro models)

  - reaction rates, mass models, fission treatment, ...

- Amounts of ejecta (reliable resolution of ejecta masses and properties)

  - resolution of different scales (→ improve hydrodynamical model, also crucial for weak interactions)

  - strong impact of nuclear EoS

  - secular ejecta (from massive NS or BH-tori) require detailed models (hydrodynamics, neutrino transport, magnetic fields)

  - possibly insights from observations of em counterparts

- Merger rates (for overall production)

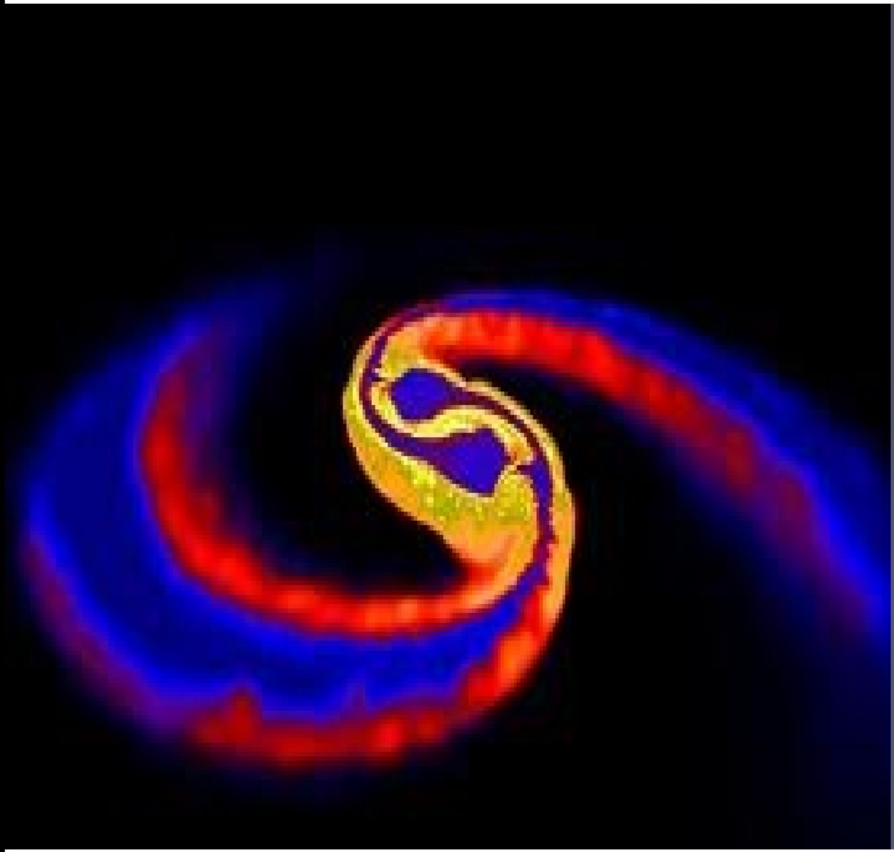
  - from detected NS mergers (GW events)

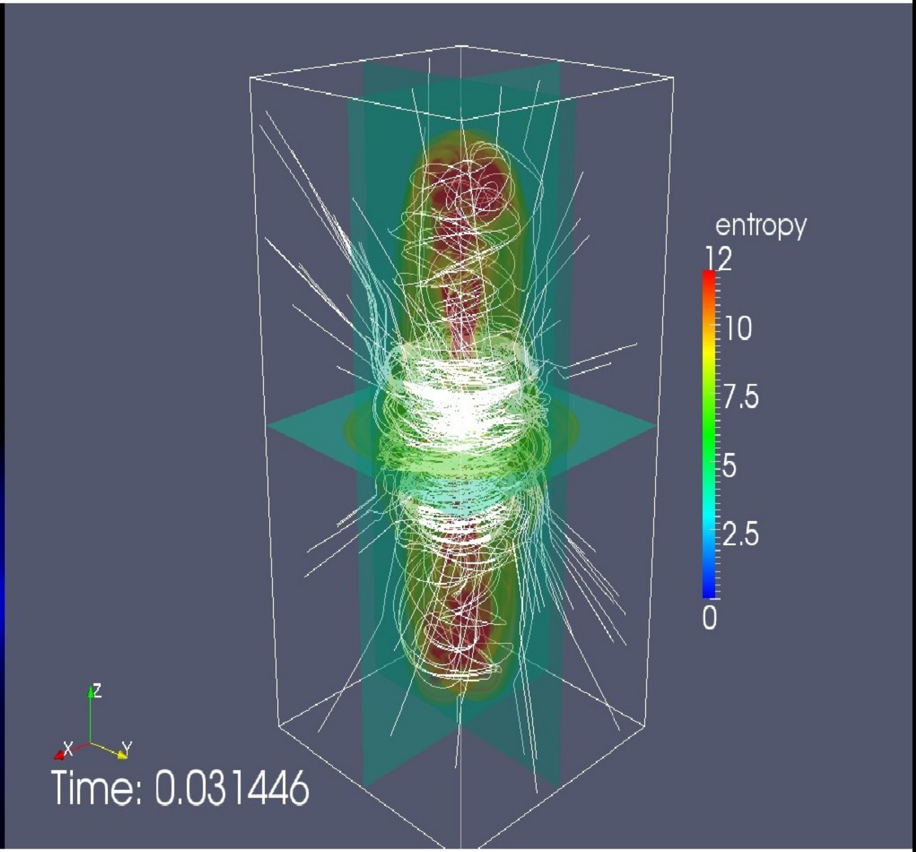
  - from theoretical models of population over Galactic/Cosmic history

- Chemical evolution - Early enrichment compatible with mergers? – explore alternative sites

Activities in Basel (input from F. Thielemann)

Which events contribute to the strong r-Process??





Neutron star mergers in binary stellar systems vs. supernovae of massive stars with fast rotation and high magnetic fields

Activities in Basel (input from F. Thielemann)

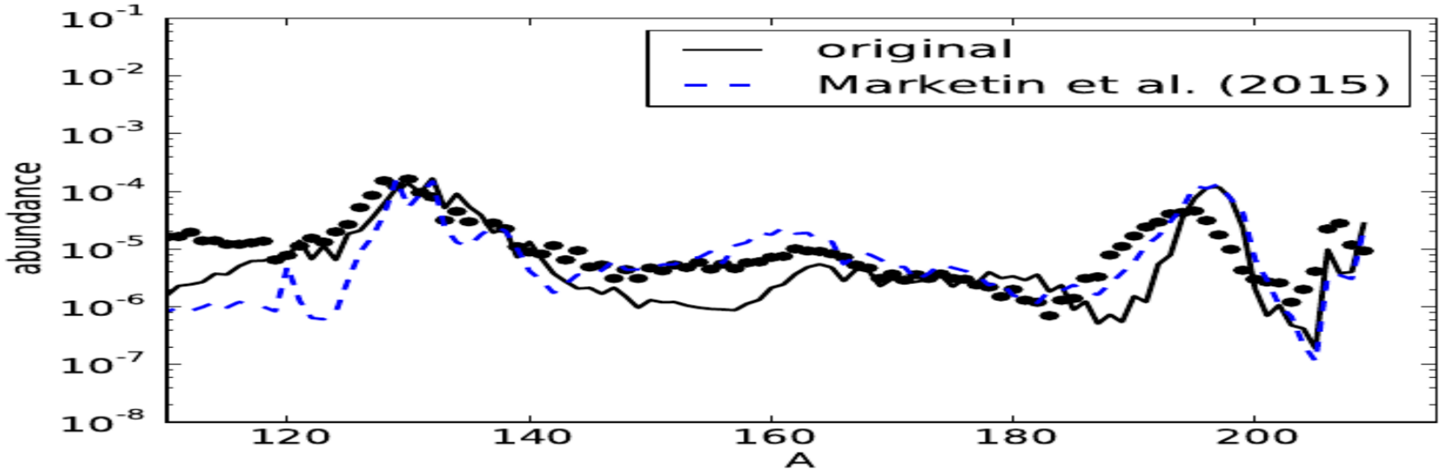
Nucleosynthesis Results of Neutron Star Mergers (Eichler et al. 2015)

Non-relativistic merger calulations eject matter with very low Ye (0.03). These very neutron-rich conditions lead initially to a perfect r-process path with the correct abundance peaks. However, in the final freeze-out from n,γ-γ,n equilibrium, there is still a large amount of matter in ***fissioning nuclei, releasing neutrons which are captured preferentially by the r-process peak elements and the peaks are shifted to higher masses (problem!)***.

Possible solutions: (a) modern fission fragment distributions (ABLA)

and (b) exploring variations in beta-decay rates

Shorter half-lives of heavies release neutrons (from fission/fragments) earlier ***(still in n,γ-γ,n equilibrium), avoiding the late shift???***



(c) fully relativistic calculations (Wanajo et al. 2014) which seem to lead to higher Ye's (like in MHD jets) and avoid the problem

Activities in Basel (input from F. Thielemann)

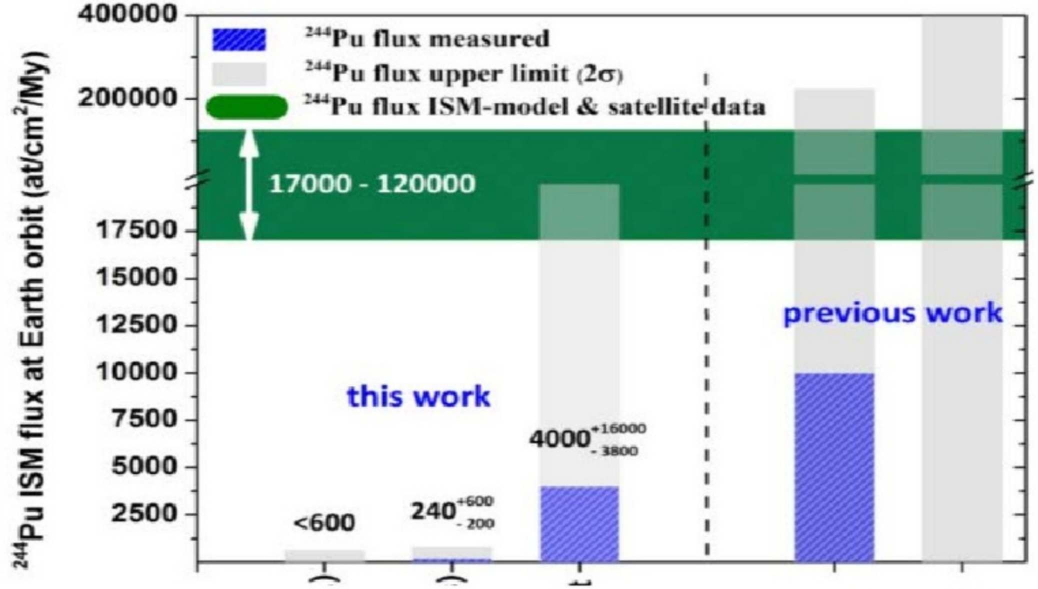
^{244}Pu, half-life 81 My

Status:

^{244}Pu in terrestrial crust:

- ***crust: dust collection over 25 Myr***
- ***^{244}Pu: time window - alive a few 100 Myr***
- ***neutron star mergers?***

100:1 estimated vs measured



New limit of ^{244}Pu on Earth points to rarity of heavy r-process nucleosynthesis

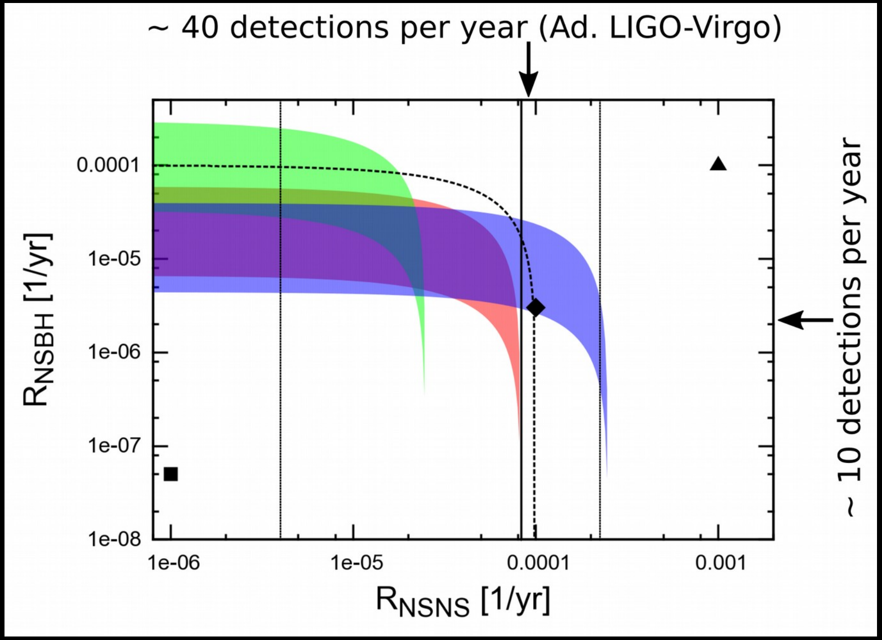
A. Wallner, T. Faestermann, C. Feldstein, K. Knie, G. Korschinek, W. Kutschera, A. Ofan, M. Paul, F. Quinto, G. Rugel & P. Steier 2015, Nature Communications

The continuous production of ^{244}Pu in regular CCSNe (10^{-4}-10^{-5} Msol each, in order to reproduce solar system abundances) would result in green band → no recent (regular) supernova contribution. MHD jets and neutron star mergers cause large variations due to rarity of events, large amounts of ejecta, but due to last event in distant past, Pu has essentially decayed.

Current activities at HITS/MPA/TUD/Brussels

- Ejecta masses of NS-NS and NS-BH mergers – EoS impact (Bauswein et al. 2013)
- Compatibility with merger rate (Bauswein et al. 2014)
- Improving hydro models, neutrino impact (Goriely et al. 2015)
- Secular ejecta of BH-tori as postmerger remnants (Just et al. 2015)
- Impact by different mass models (Mendoza-Temis, Wu, ... (2015))
- Impact of fission (Goriely et al. 2013)

Merger rate estimate based on nucleosynthesis yields:



Bauswein et al. 2014

Similar activities by groups of A. Arcones (Darmstadt), S. Rosswog (Stockholm), F. Thielemann (Basel): e.g. Martin et al. (2015), Perego et al. 2014, Eichler et al. 2015, Rosswog et al. 2014, ...

Electromagnetic counterparts

- Several types considered: e.g. short gamma-ray bursts, radio transients, ...
- Kilonovae powered by radioactive decays of r-process nuclei (possibly also neutron decay)
- Challenges

  - opacities (composition dependent)

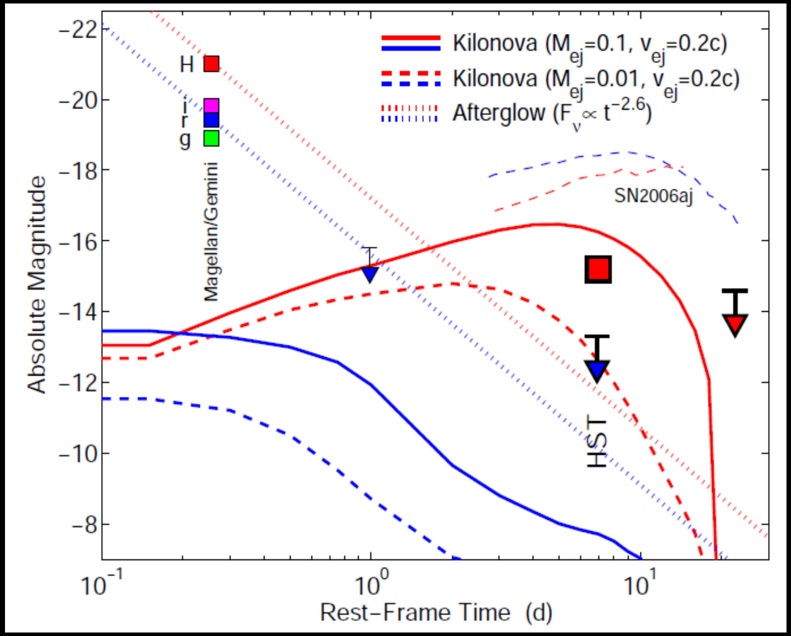
  - exact heating rate

  - ejecta masses and ejecta velocities and richness affect light curve

  - previously mentioned challenges

  - light curves require radiative transport
- Prospects: may reveal those properties existing and upcoming surveys: (Palomar Transient Factory), (ZTF) Zwicky Transient Facility, BlackGem array, LSST (Large Synoptic Survey Telescope))

Kilonova (candidate) in the aftermath of a short gamma-ray burst



Berger et al. 2013

- Modelling activities by groups in Basel, Darmstadt, Frankfurt, Garching, Heidelberg, Stockholm, Trento

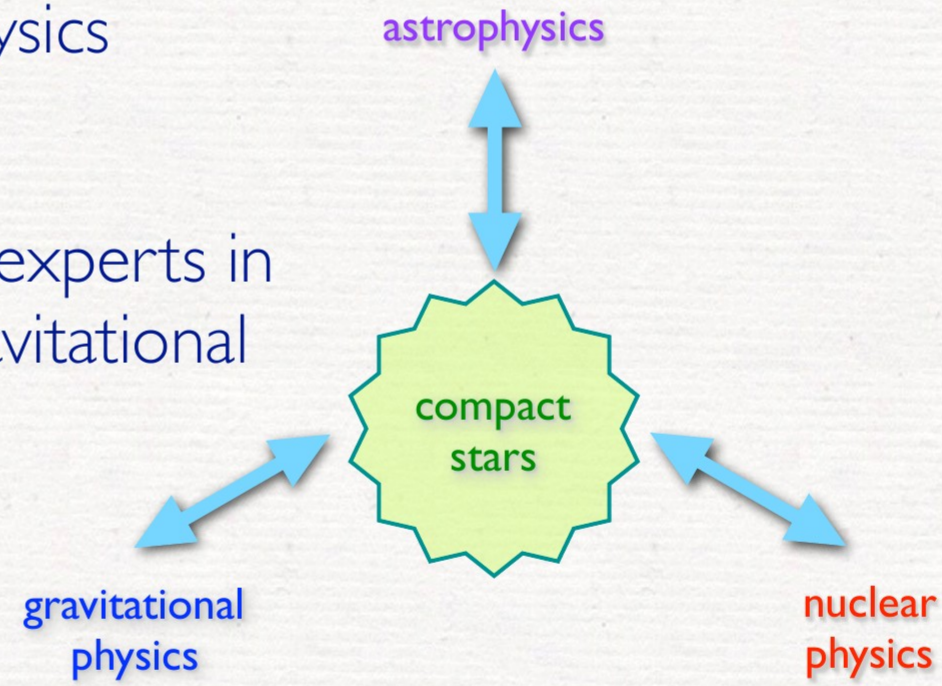
NewCompStar: the physics and astrophysics of compact stars

- The Action is driven to research fundamental physics and astrophysics through the study of compact stars.

- This Action addresses a few fundamental but challenging questions concerning the physics and astrophysics of compact stars.

- Brings together leading European experts in astrophysics, nuclear physics and gravitational physics of compact stars.

- Provides important value to the large-scale European efforts in observational astrophysics and experimental nuclear physics.



Participating countries

NewCompStar essentially collects all scientists in Europe working on **Nuclear Astrophysics** and related fields.

COST Participants
Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Malta*, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom.

COST Participants subject to MoU acceptance
Lithuania (still pending)

COST Near Neighbour Countries Institutions
IOFFE, Sternberg Astronomical Institute, Yerevan State University

*: joined 2014

COST International Partner Countries Institutions
Monash University, University of Melbourne, Kent State University

Scientific coordination and networking

- Chair / Vice Chair: Luciano Rezzolla / Pierre Pizzochero
- Working Group Leader (astrophysics): Nanda Rea
  - Topic Leaders: N. Bucciantini, P. Cerdá-Durán, T. di Salvo, W. Ho
- Working Group Leader (nuclear physics): Jerome Margueron
  - Topic Leaders: G. Barnafoldi ,N. Chamel, L. Tolos, I. Vidana
- Working Group Leader (gravitational physics): Ian Jones
  - Topic Leaders: A. Bauswein, B. Giacomazzo, L. Gualteri, T. Hinderer
- Synergy agents: Valeria Ferrari, Pawel Haensel, Micaela Oertel
- Website manager (WM): Toni Font
- Outreach coordinator (OC): Constanca Providencia
- Gender Coordinator (GC): Fiorella Burgio
- STSM Coordinator: Armen Sedrakian
- Grant Holder Manager: Daniela Radulescu
- Scientific assistant: Barbara Betz
- Financial Rapporteurs: M. Chernyakova, G. Barnafoldi

Activities

Every year **NewCompstar** organises a number of activities, including:

★ Annual meeting (this year in Istanbul, Turkey, April)

★ Training School (this year in Coimbra, Portugal, September)

★ A half-a-dozen Working Group meetings

★ Short Term Scientific Missions (STMSs): from 1 to 6 weeks in different groups (about 25 a year)

NewCompstar is an excellent example of the thriving European community in Nuclear Astrophysics;

It's a model to preserve and further develop.

More on: http://compstar.uni-frankfurt.de