Insights from neutron-star merger simulations

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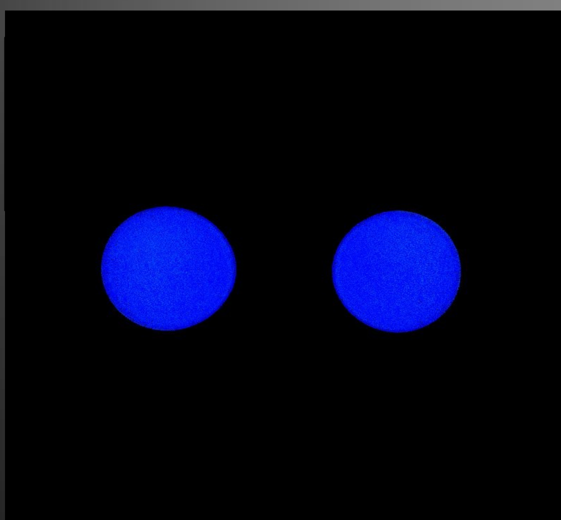
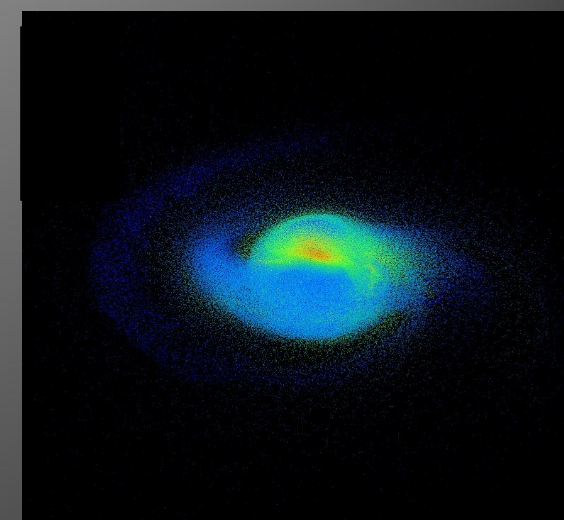
(AUTH Thessaloniki)



NAVI Physics Days

Darmstadt, 26/02/2015



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Neutron-star merger simulations to understand

- Postmerger dynamics
- GW emission (especially postmerger)
- EoS dependence (in turn EoS constraints from observations)
- Collapse behavior (direct, delayed or no BH formation)
- Torus formation (GRB, nucleosynthesis)
- Initial conditions for secular evolution
- Nucleosynthesis conditions (composition, expansion, temperature)
- Ejecta properties (e.g. masses)
- Electromagnetic counterparts
- Binary parameter dependence

Observationally relevant for

- GW detectors: Ad. LIGO (soon operational), Ad. Virgo, Kagra, ET → constraints on NS properties and high-density matter
- at design sensitivity ~4...400 detections / yr
- Numerous astronomical observations of r-process elements and r-process abundance pattern
- Electromagnetic transients (also as follow up of GW detections): Zwicky Transient Facility, BlackGEM, Large Synoptic Survey Telescope, Ultrasat
- Possibly radio telescopes (radio transients)
- Gamma-ray, X-ray satellites: short gamma-ray bursts (plausible to originate from NS mergers)
- Related also to GSI/FAIR through high-density matter properties and nucleosynthesis

Outline

General overview

Gravitational waves and EoS constraints

Collapse behavior

Ejecta properties, r-process

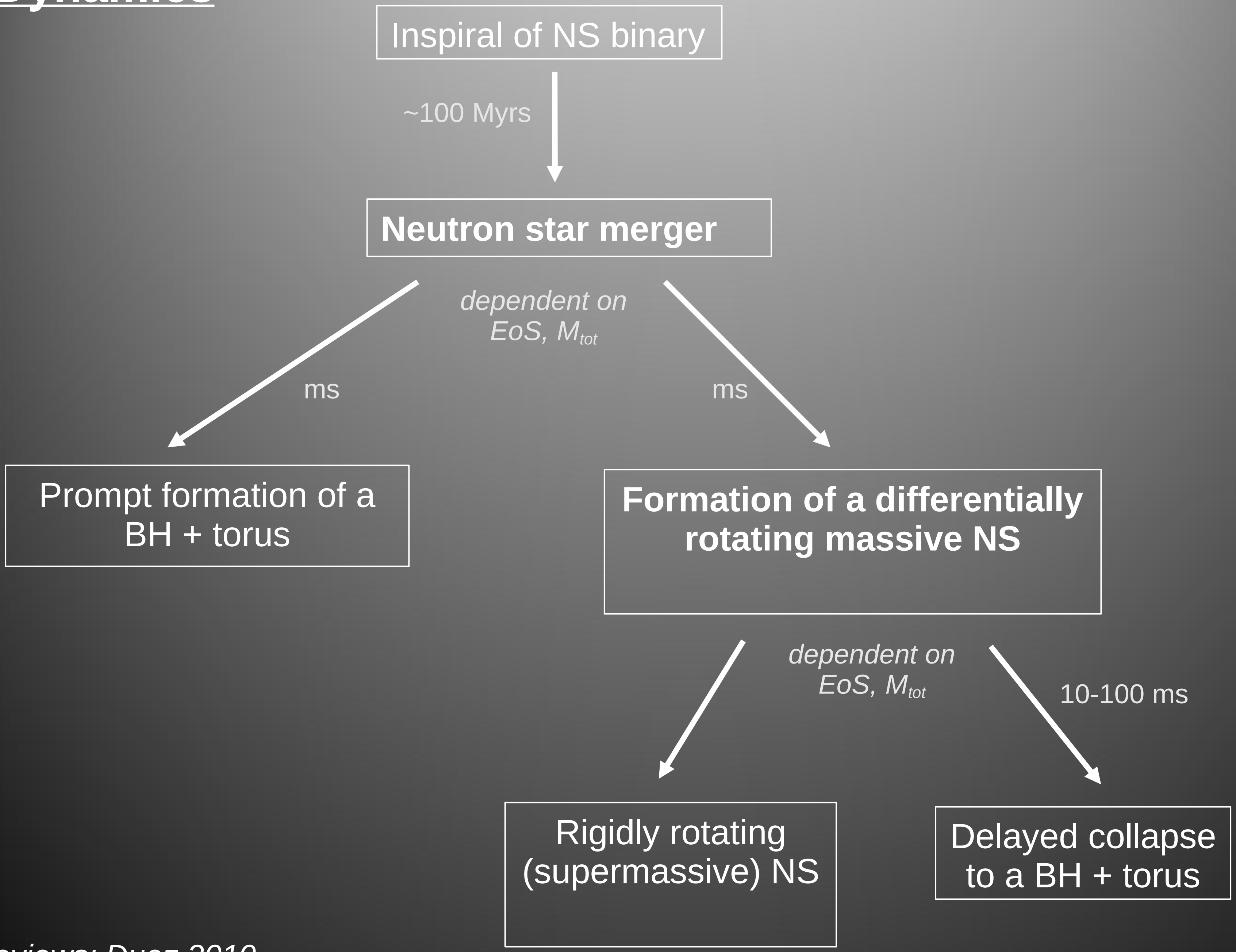
Electromagnetic counterparts

Neutron-decay powered precursors

Merger rate estimates and nucleosynthesis

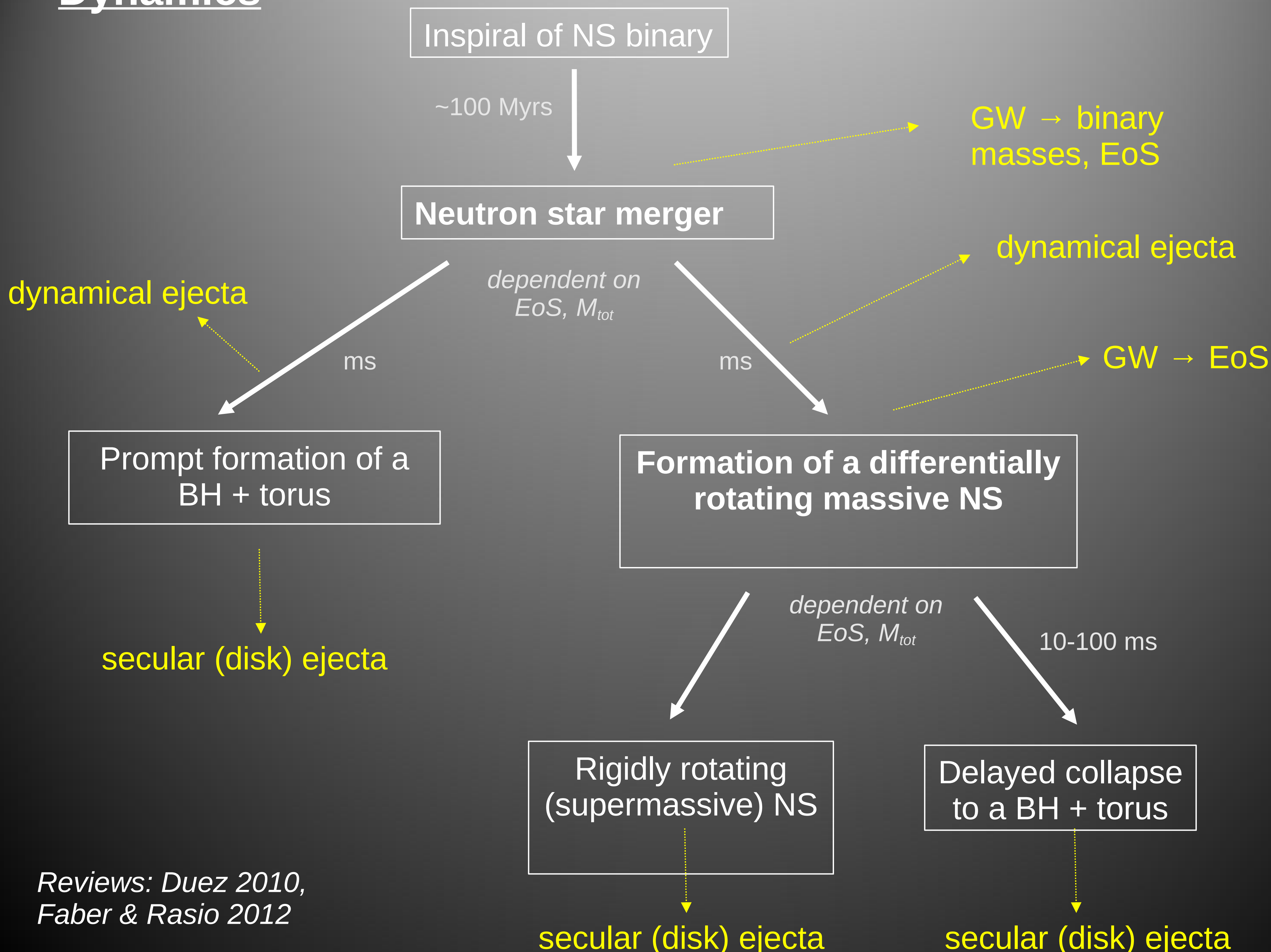
Summary

Dynamics



Reviews: Duez 2010,
Faber & Rasio 2012

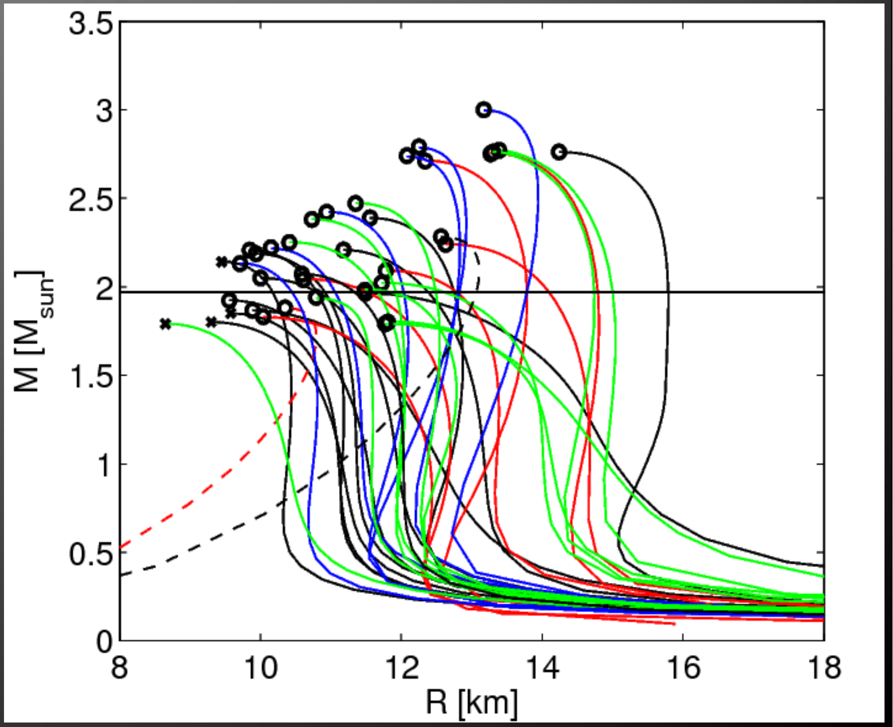
Dynamics



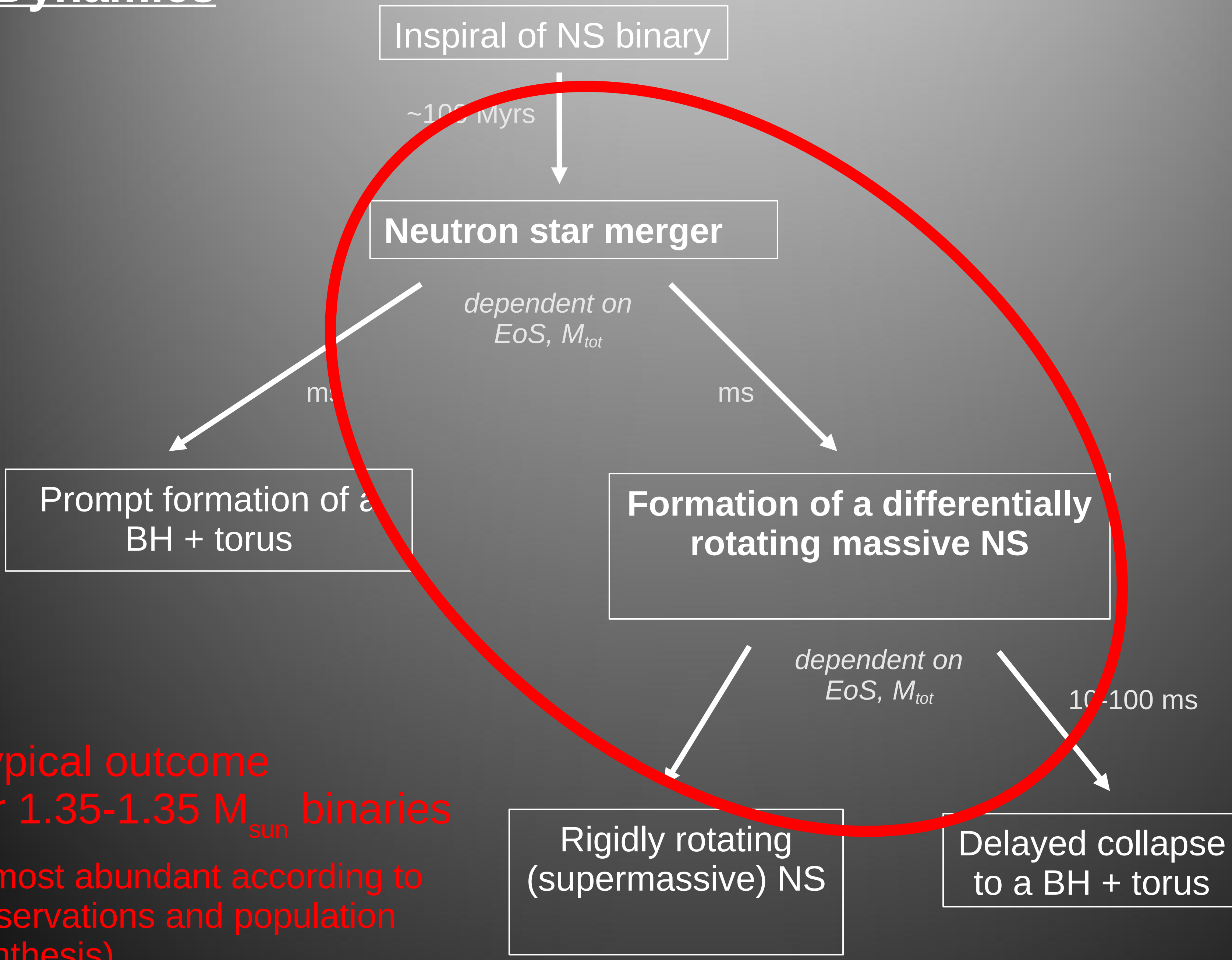
Reviews: Duez 2010, Faber & Rasio 2012

Simulation details

- 3D relativistic smooth particle hydrodynamics (SPH) code: Lagrangian hydro formulation (comoving with the fluid elements) (Oechslin et al. 2002, Oechslin et al. 2007, Bauswein et al. 2010, ...)
- Conformal flatness condition for spatial part of the metric (simplifies Einstein eqs.; GW backreaction scheme; higher performance compared to grid-based codes, but quantitatively accuarte)
- 13 microphysical, temperature-dependent EoSs, 50 microphysical, cold EoSs with approximate treatment of thermal effects
- Initial conditions: quasi-equilibrium orbits a few orbits before merging; cold, neutrinoless beta-equilibrium; usually intrinsically non-rotating NSs (because tidal locking unlikely and rotation slow compared to orbital motion)



Dynamics



Typical outcome
for 1.35-1.35 M_{sun} binaries

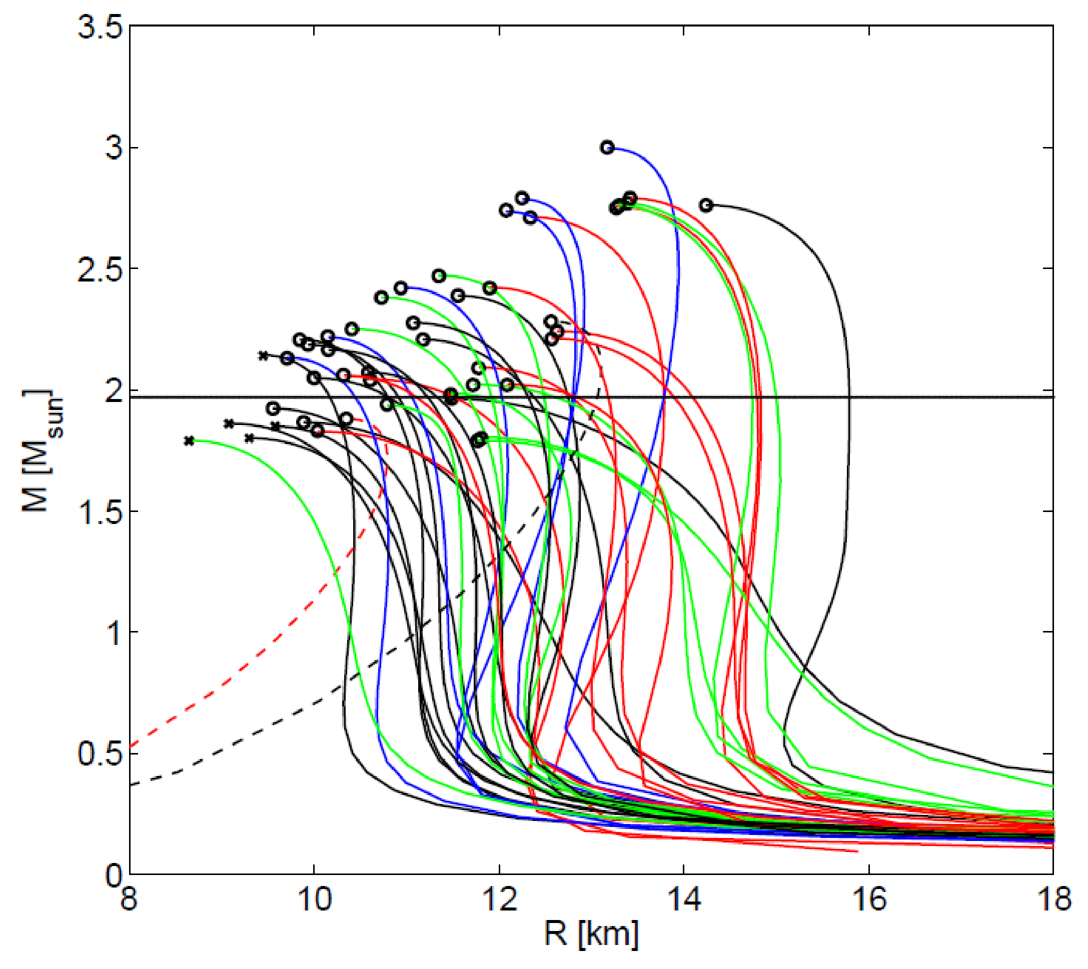
(~most abundant according to observations and population synthesis)

General outcome

for 1.35-1.35 M_{sun} binaries

Demorest et al. 2010

Antoniadis et al. 2013



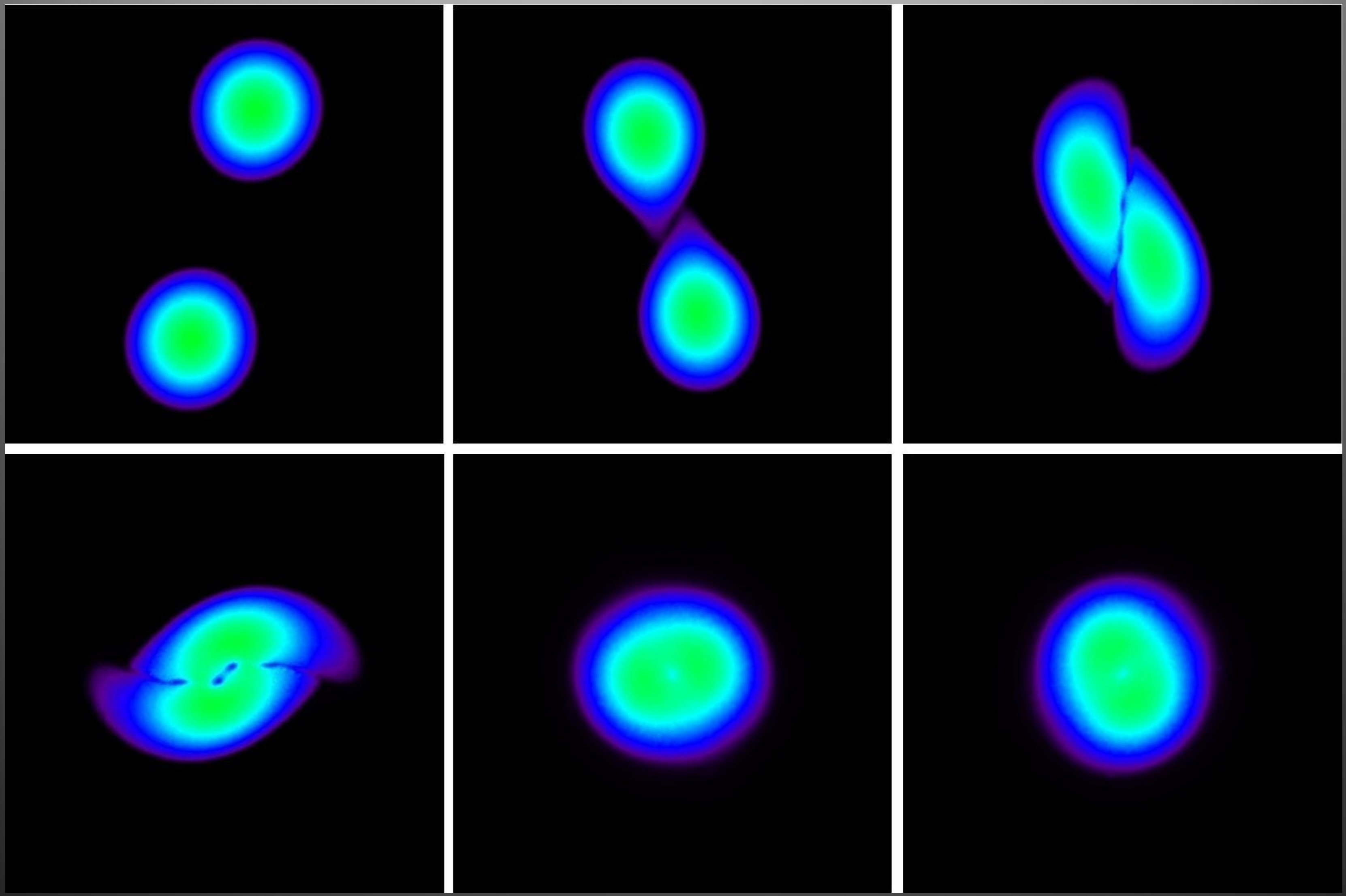
M_{max} with circle: rotating NS merger remnant

M_{max} with cross: direct BH formation

42 out of 47 models lead to the formation of a differentially rotating NS

(for this binary setup only one accepted EoS leads to prompt collapse)

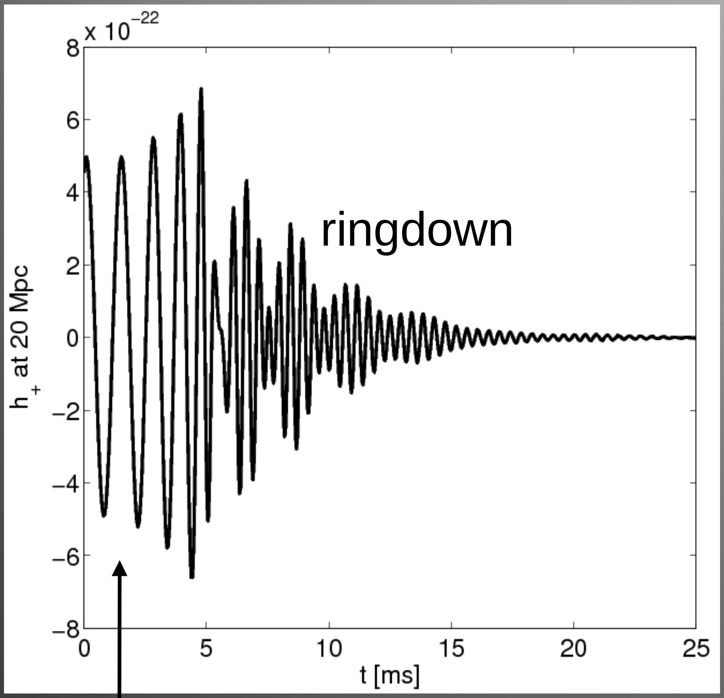
Simulation: snapshots



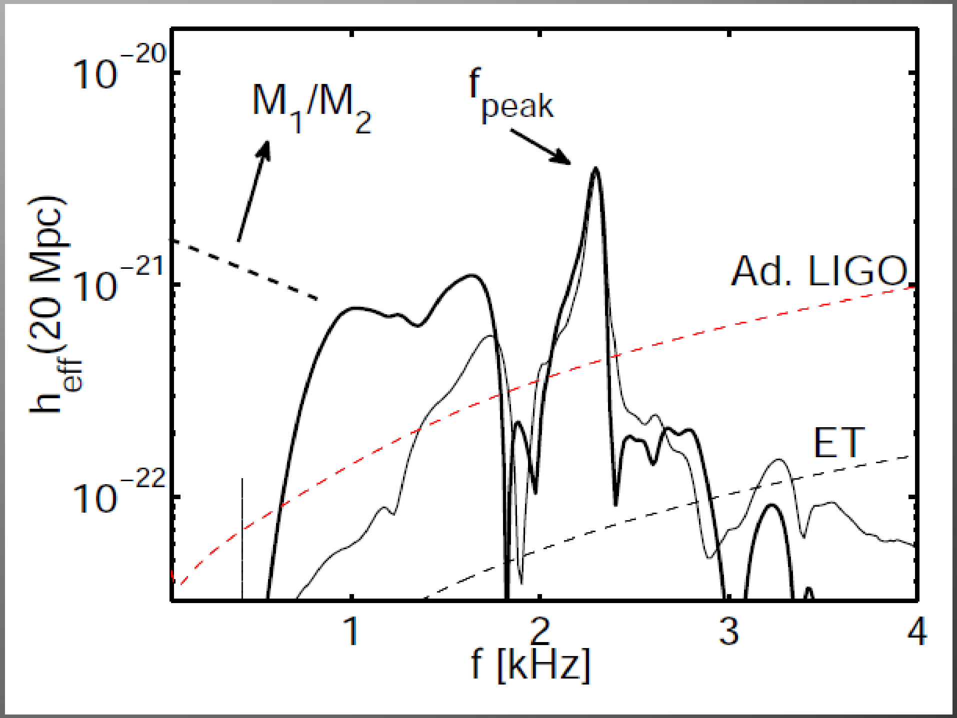
Rest-mass density evolution in equatorial plane: 1.35-1.35 M_{sun} Shen EoS

Gravitational-wave spectrum

1.35-1.35 M_{sun} TM1 equation of state (EoS), 20 Mpc

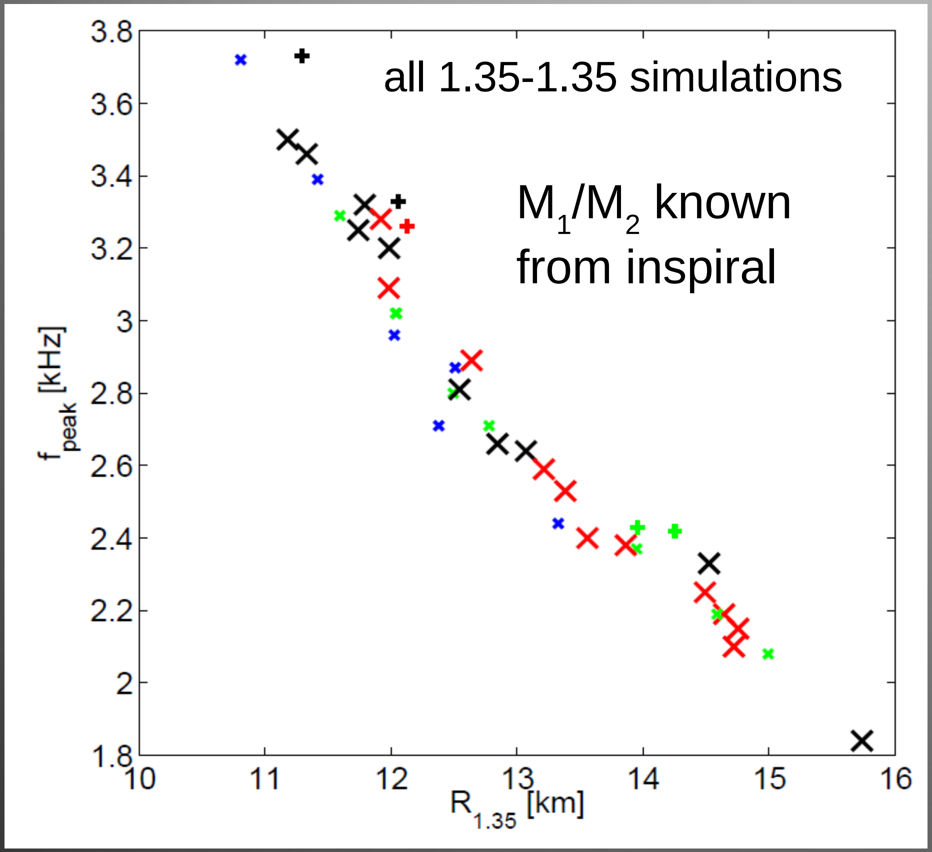


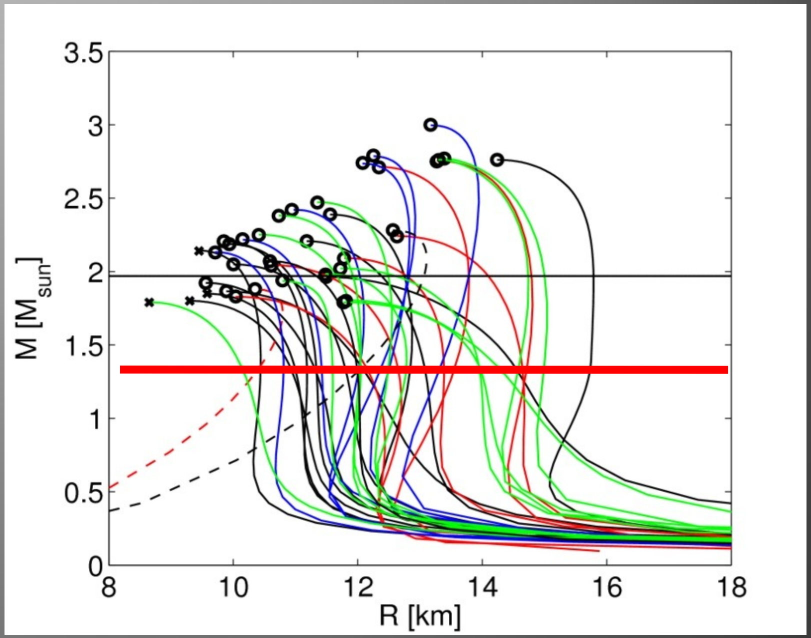
inspiral



- Pronounced peak in the kHz range as a robust feature of all models forming a differentially rotating NS
- Characteristic GW feature: f_{peak}
- Binary masses M_1/M_2 are measurable from GW inspiral signal (most of the inspiral not covered by simulation)

Gravitational waves – EoS survey



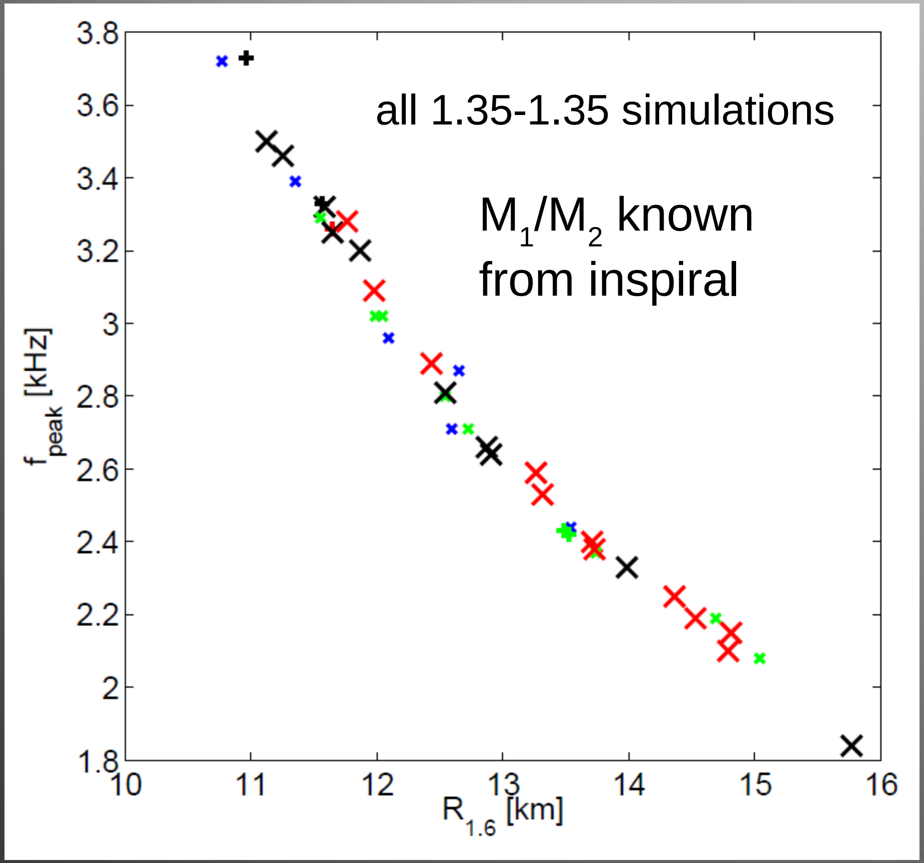


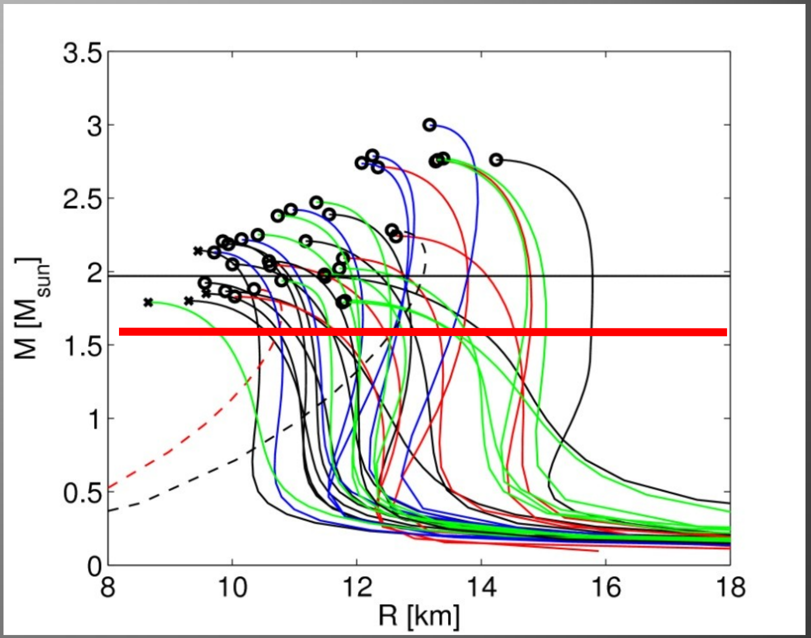
characterize EoS by radius of nonrotating NS with 1.35 M_{sun}

Triangles: strange quark matter; red: temperature dependent EoS; others: ideal-gas for thermal effects

Bauswein et al. 2012

Gravitational waves – EoS survey





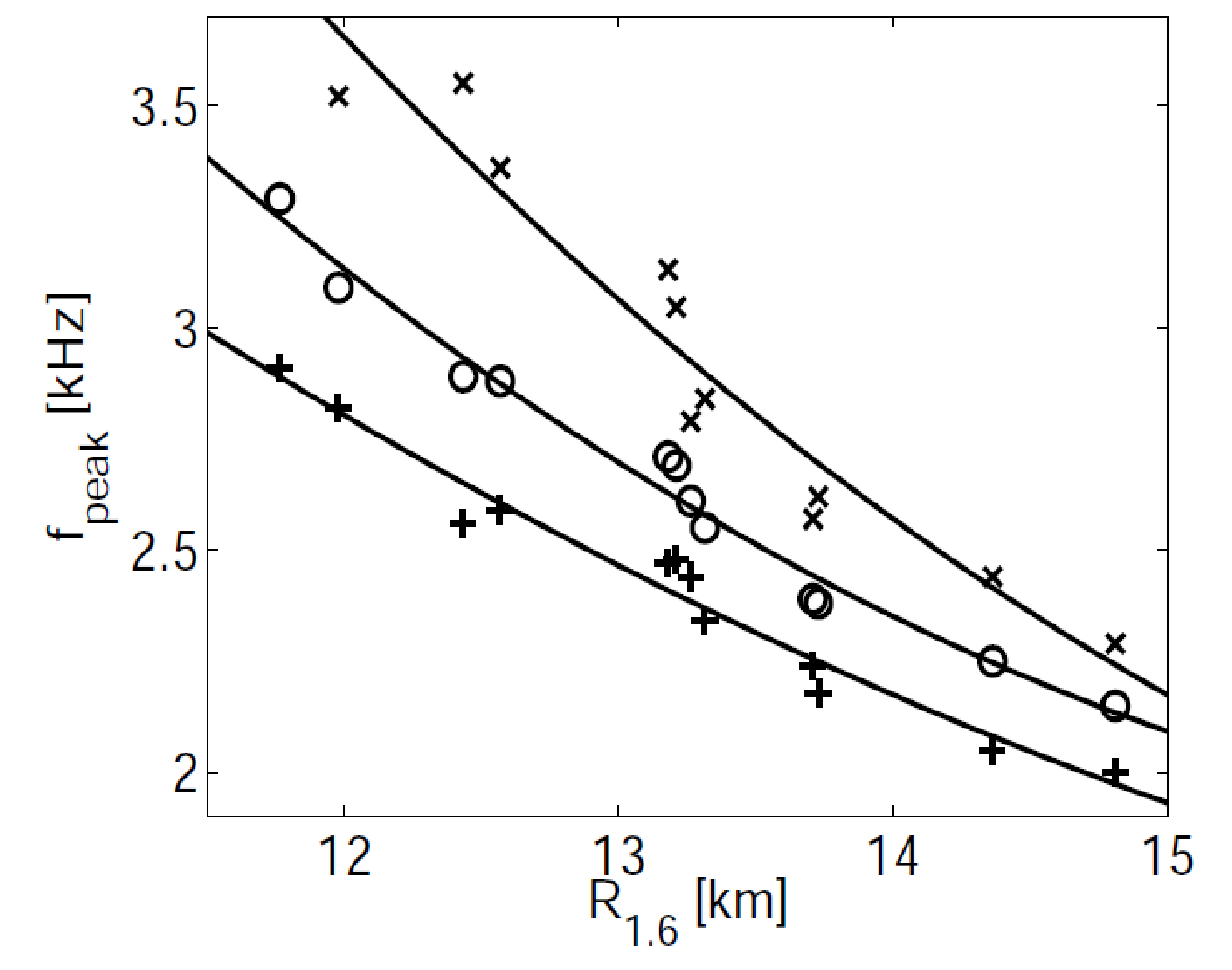
characterize EoS by radius of nonrotating NS with 1.6 M_{sun}

Triangles: strange quark matter; red: temperature dependent EoS; others: ideal-gas for thermal effects

Bauswein et al. 2012

Note: R of 1.6 M_{sun} NS scales with f_{peak} from 1.35-1.35 M_{sun} mergers (density regimes comparable)

Strategy: Different binary masses



\+ 1.2-1.2 M_{sun}

o 1.35-1.35 M_{sun}

x 1.5-1.5 M_{sun}

Maximum deviation determines error:

2.4 M_{sun}: 300 m
2.7 M_{sun}: 200 m
3.0 M_{sun}: 300 m

(can be further minimized)
(very similar relations for unequal masses)

Strategy: → Measure binary masses from inspiral GW signal
→ Choose relation depending on binary mass
→ Invert relation to obtain NS radius

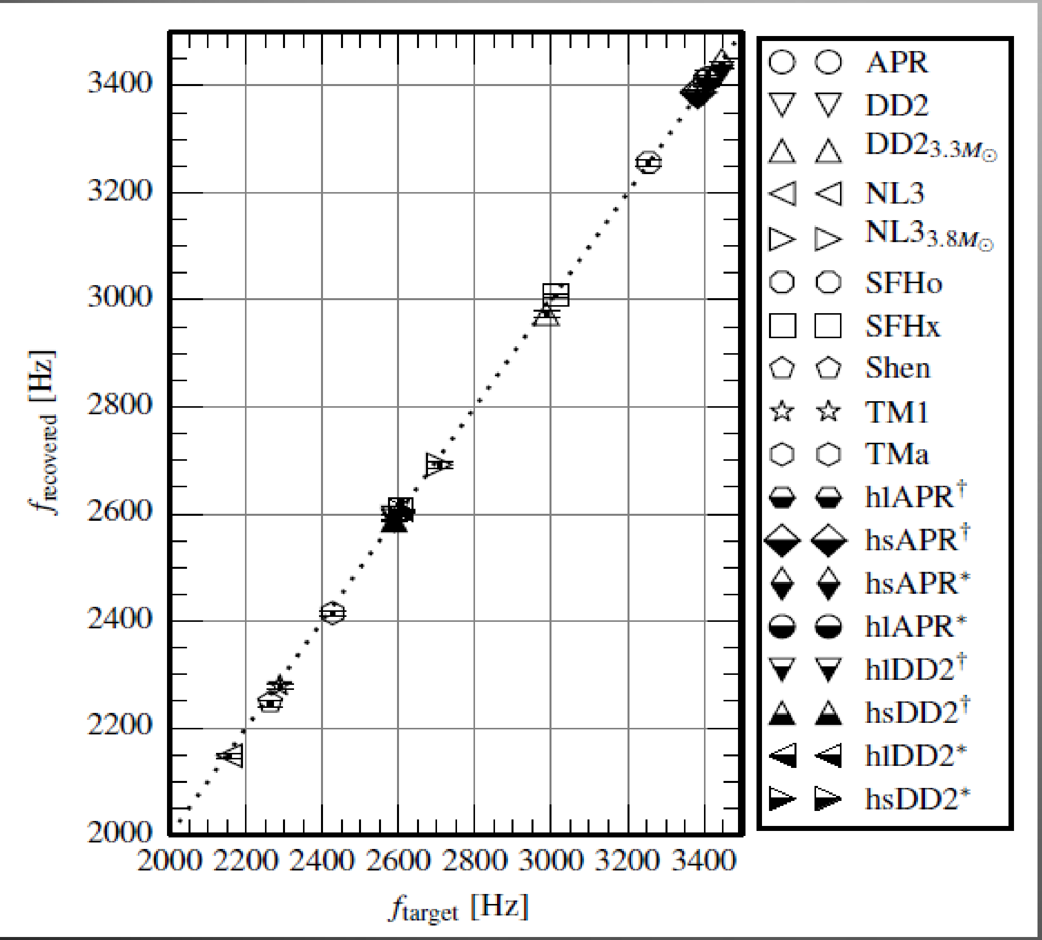
Remarks

- Relations exist also for asymmetric systems and other binary masses
- Very good quantitative agreement with Kyoto group and Frankfurt group (grid-based hydro solver; full GR), e.g. Hotokezaka et al. 2013, Takami et al. 2014, Kastaun & Galeazzi 2014
- Maximum mass can be inferred from several detections by an extrapolation procedure (see Bauswein et al. 2014)
- Inspiral signal measures tidal deformability / radius (complementary)
- Collapse behavior (prompt BH formation vs NS remnant) depends in particular way on EoS:

threshold binary mass $M_{thres} = k * M_{max}$ with $k = k(C_{max})$ (Bauswein et al. 2013)

→ may be used to infer M_{max}

Measuring the dominant GW frequency



Clark et al. 2014

Model waveforms hidden in rescaled LIGO noise

Peak frequency recovered with burst search analysis

Error ~ 10 Hz

For signals within ~10-25 Mpc

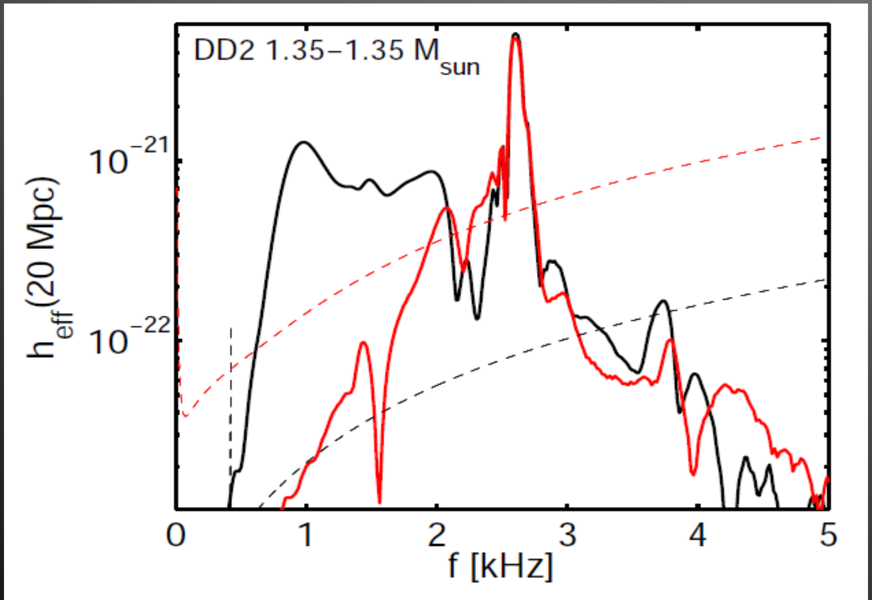
=> for near-by event radius measurable with high precision (~0.01-1/yr)

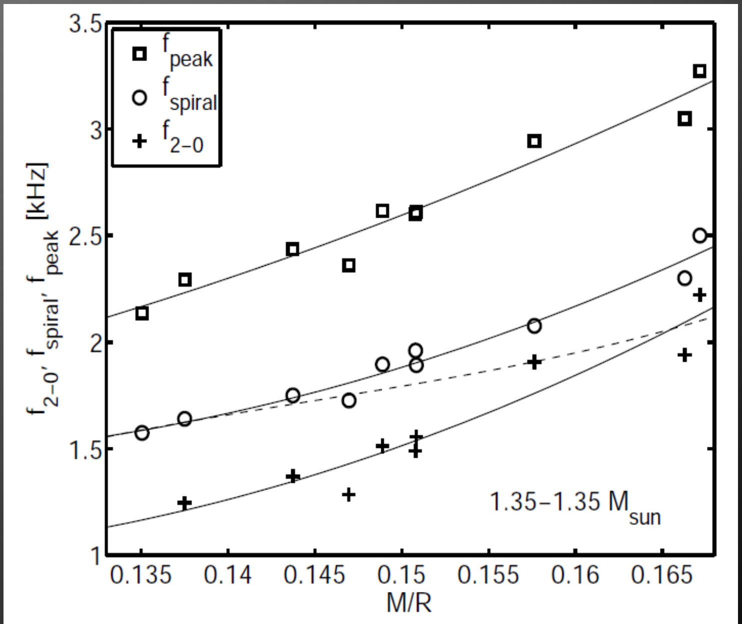
Proof-of-principle study
→ improvements likely

(Binary mass measurable with sufficient accuracy for such distances, e.g. Arun et al. 2005, Hannam et al. 2013, Rodriguez et al. 2014)

Secondary peaks in the GW spectrum

- Two distinct mechanism produce secondary peaks: oscillation mode coupling and orbital motion of tidal bulges
- Presence / strength depends on the exact binary system
- → classification scheme of the postmerger dynamics and GW emission (see Bauswein & Stergioulas 2015 – arXiv:1502.03176)
- For fixed binary mass relations of secondary frequencies with radii of inspiralling stars (Bauswein & Stergioulas 2015)
- But for representative range of binary masses no universal mass-independent relation (as in Takami et al. 2014)



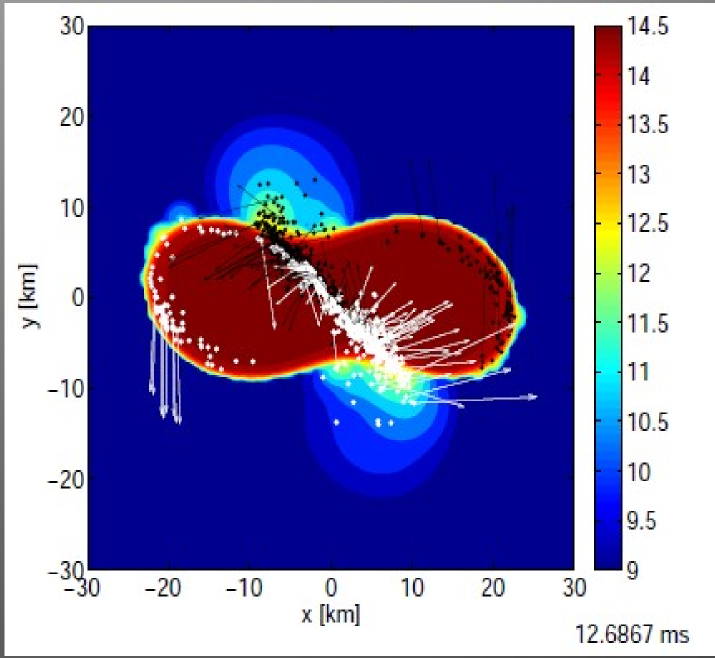


Ejecta properties

for r-process nucleosynthesis and electromagnetic counterparts

Unbound matter in NS mergers

Dynamical mass ejection found in hydrodynamical models: *e.g. Ruffert & Janka 1999, Rosswog et al. 1999, Freiburghaus et al. 1999, Oechslin et al. 2007, Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011, Korobkin et al. 2012, Hotokezaka et al. 2013, Bauswein et al. 2013, Rosswog et al. 2013, Piran et al. 2013, Wanajo et al. 2014, …* (with and without nucleosynthesis calculations; different degrees of sophistication regarding EoS, gravity, neutrinos)



Bauswein et al. 2013

Ejecta from contact interface and from tips of spiral arms

Tendencies:

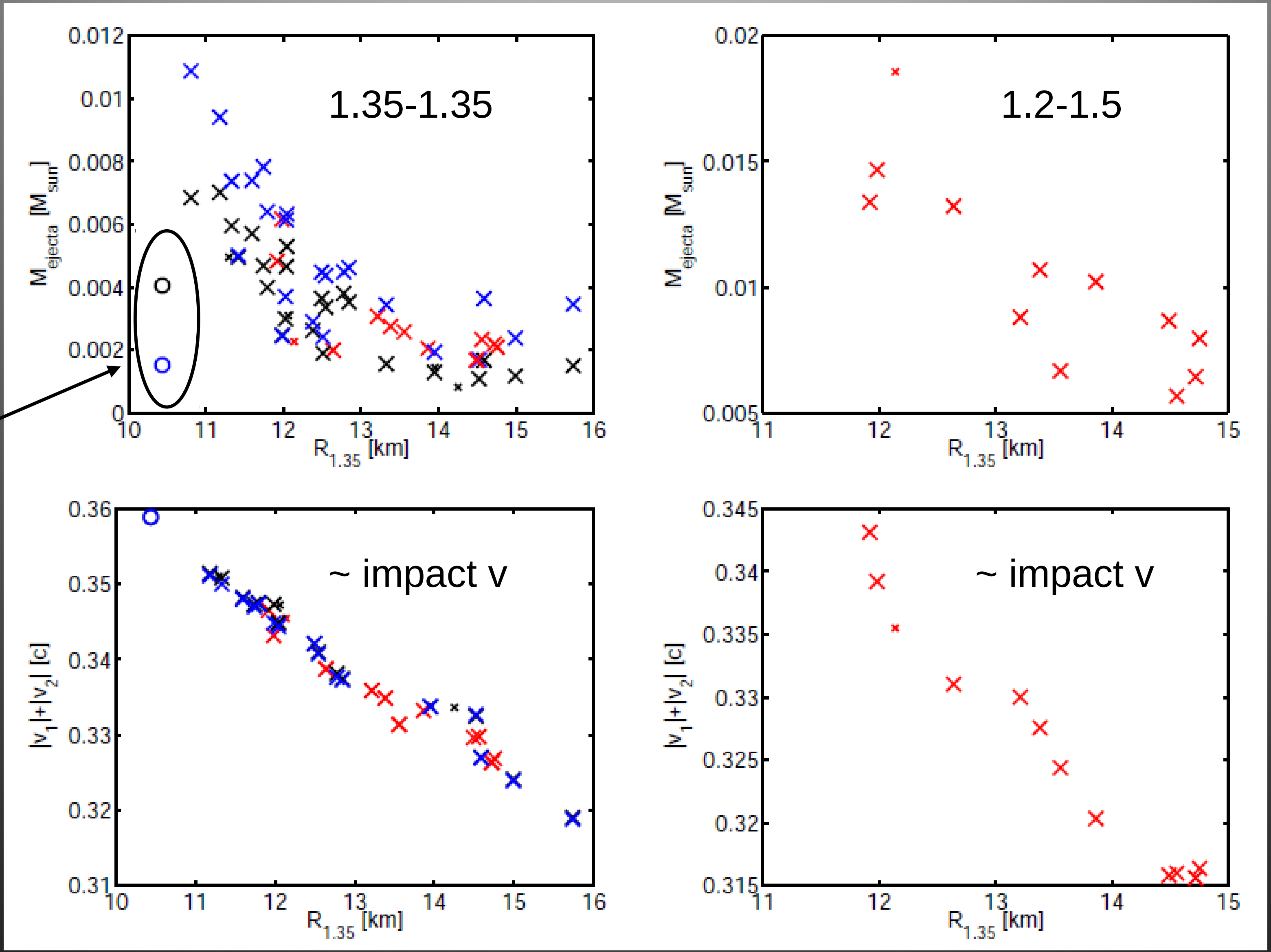
- typical masses 10^{-3} … 10^{-2} M_{sun}
- asymmetric mergers eject more (tidal)

(also a number of NSBH simulations and eccentric mergers available: typically higher ejecta masses, but rates?)

DD2 1.35-1.35 M_{sun}, representative ejecta particles (white unbound)

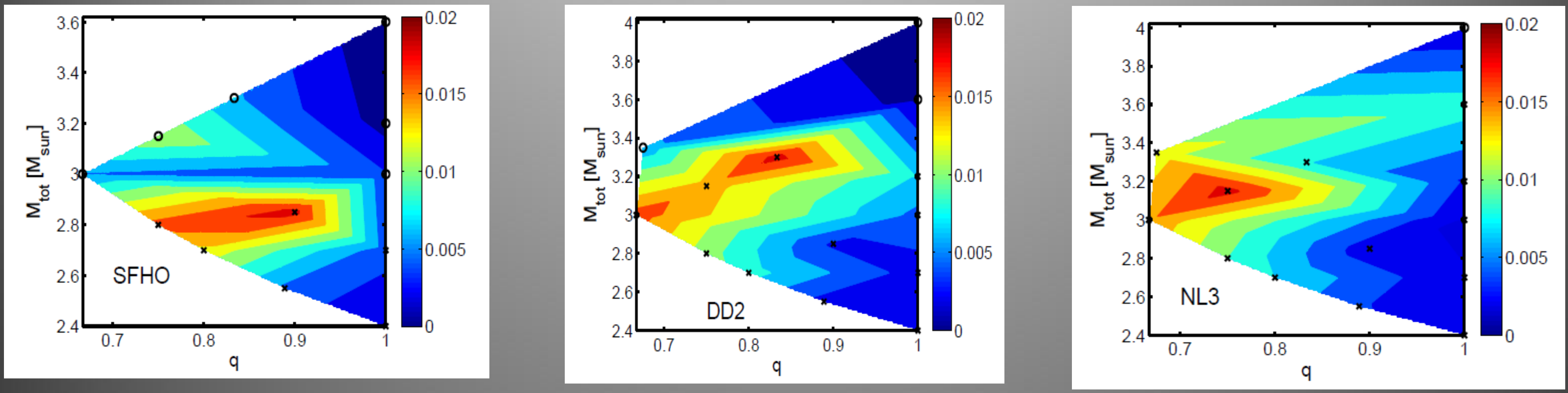
Ejecta mass dependence

Prompt collapse



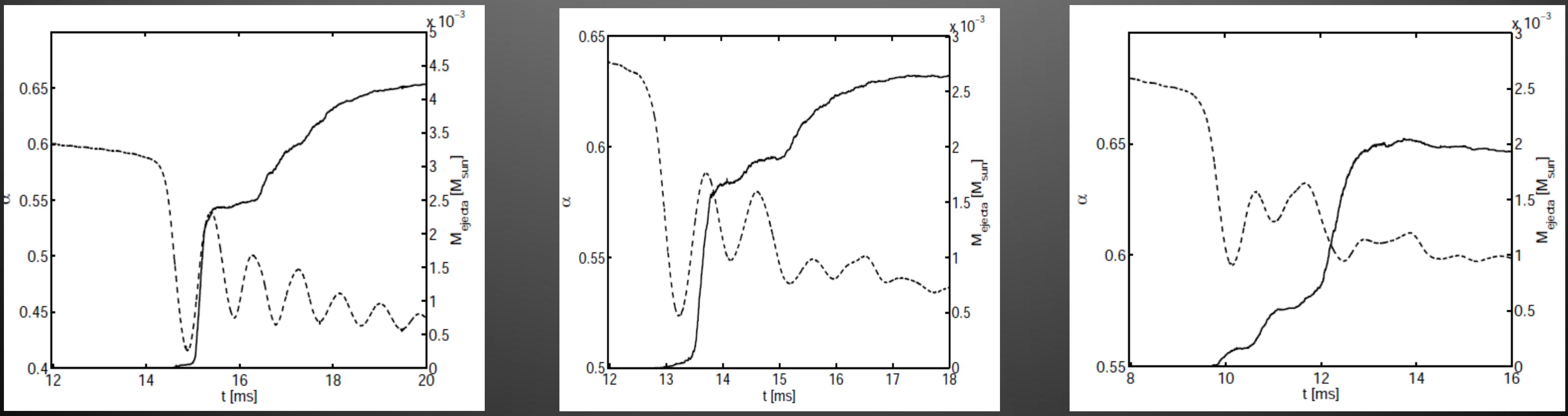
Different EoSs characterized by radii of 1.35 M_{sun} NSs (note importannce of thermal effects)

Ejecta mass dependencies: binary para.



Stiffness

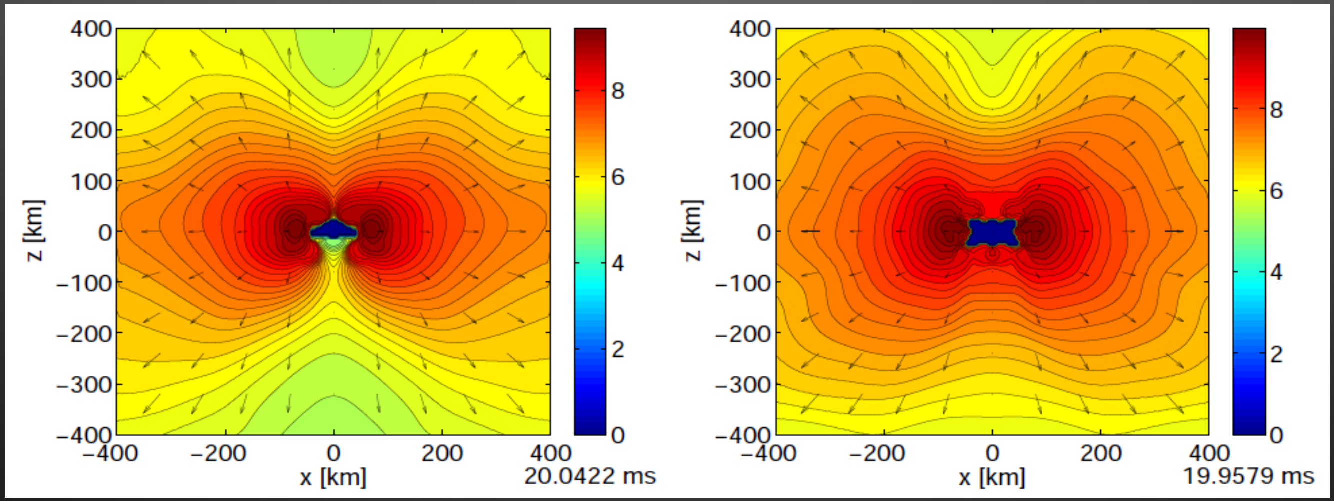
understandable by different dynamics / impact velocity / postmerger oscillations



Central lapse α traces remnant compactness / oscillations / dynamics (dashed lines)

Ejecta properties

- Robust features: fast expansion, neutron rich (neutrinos effects may lead to a broader distribution of Y_e, see Wanajo et al. 2014) (ejecta originates from inner neutron crust (initial Y_e very low)
- Matter heated to NSE and frozen out at ~ neutron drip $4*10^{11}$ g/cm^3 and reheated (see e.g. discussion in Mendoza-Temis et al.)
- Rather isotropic ejection
- Ejecta expansion typically followed for several 10 ms by simulations, then extrapolation (outcome insensitive)
- Post-processing hydrodynamical trajectories with nuclear network → r-process nucleosynthesis



Bauswein et al. 2013

r-process

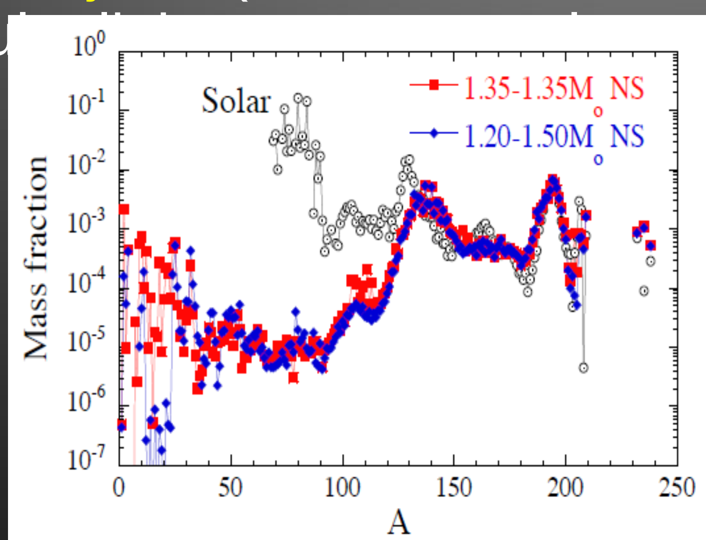
Overall robust r-process in dynamical ejecta producing heavy elements

Good agreement between different models (EoS, binary parameter, prompt vs. delayed collapse) and groups (Freiburghaus et al. 1999, Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011, Korbokin et al. 2012, Bauswein et al. 2013, Rossog et al. 2014, Wanajo et al. 2014, Just et al., Eichler et al. 2014, Mendoza-Temis et al. 2014, ...)

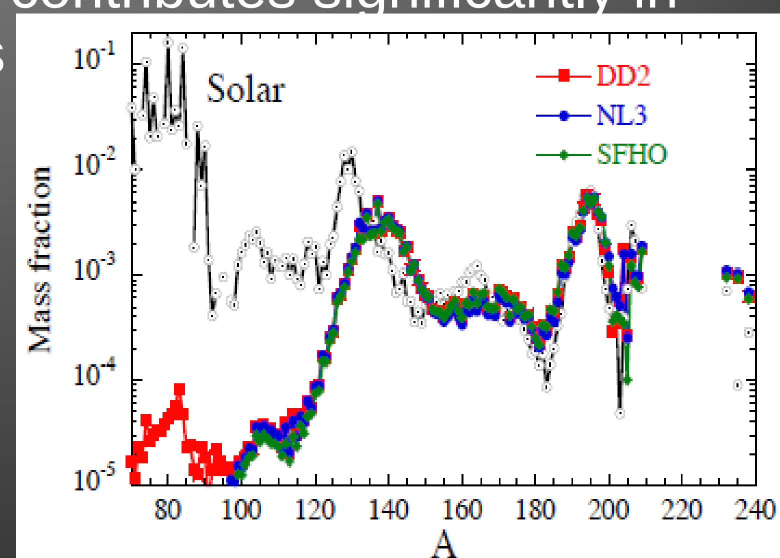
Nuclear models impact (e.g. Eichler et al. 2014, Mendoza-Temis et al. 2014, …, Friedel's and Dirk's talk)

Secular ejecta (not discussed here) contributes significantly in particu … nts

Black dots: observed solar r-process abundance



Goriely et al. 2011



Bauswein et al. 2013

Secular ejecta

NS mergers leave a remnant

•Long-lived NS remnant (Albino's talk)

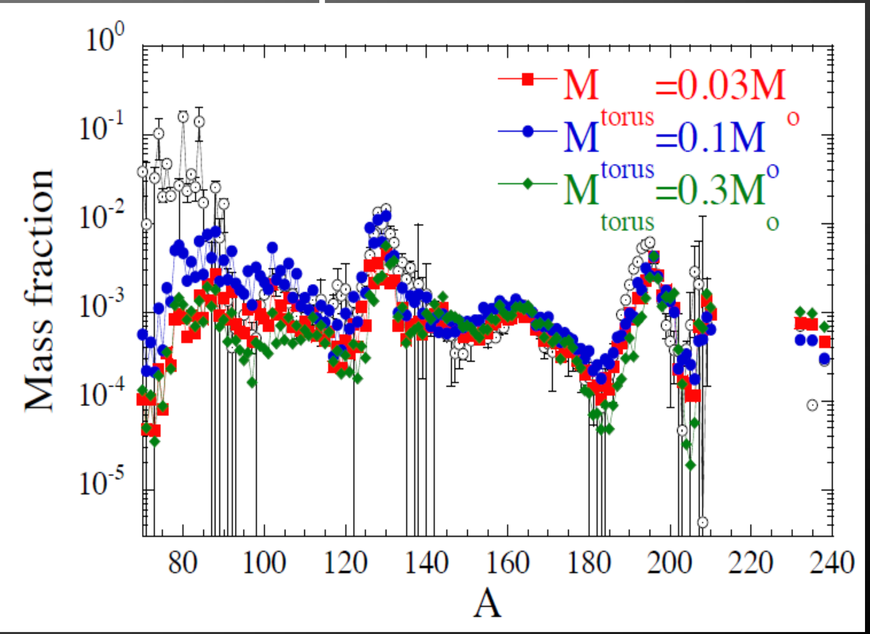
•BH-torus system (also from NSBH binary)

→ neutrino-driven, magnetically driven, viscosity-driven ejecta on longer timescales

→ neutron-rich outflow for r-process (light r-process elements)

→ because of timescales neutrino effects are important

e.g. Surman et al. 2008, Metzger et al. 2008, Lee et al. 2009, Metzger et al. 2009, Dessart et al. 2009, Lee et al. 2009, Wanajo & Janka 2012, Surman et al 2013, Fernandez & Metzger 2013, Rosswog et al. 2014, Grossmann et al. 2014, Metzger & Fernandez 2014, Siegel et al. 2014, Perego et al. 2014, Just et al 2014, Kasen et al. 2014



Dynamical and secular ejecta
(merger + remnant) Just et al. 2014

Electromagnetic counterparts powered by radioactive decays

(Note: also other types of possible counterparts proposed, e.g. radio transients, magnetic field effects, crust breaking, …, short GRBs)

Electromagnetic counterparts: „kilonova”

Li & Paczynski 1998, Kulkarni 2005, Metzger et al. 2010

Radioactive decays during r-process (beta, alpha, fission) heat ejecta
→ electromagnetic thermal emission, adiabatic expansion

optically thick at early times – estimate peak properties via photon diffusion timescale

Peak luminosity:
$$L_{\rm peak} \approx 5 \times 10^{40} {\rm erg/s} \left(\frac{f}{10^{-6}}\right) \left(\frac{v}{0.1c}\right)^{1/2} \left(\frac{M_{\rm ej}}{10^{-2} M_\odot}\right)^{1/2} \quad (1)$$

Peak timescale:
$$t_{\rm peak} \approx 5 \ {\rm d} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{M_{\rm ej}}{10^{-2} M_\odot}\right)^{1/2}, \quad (2)$$

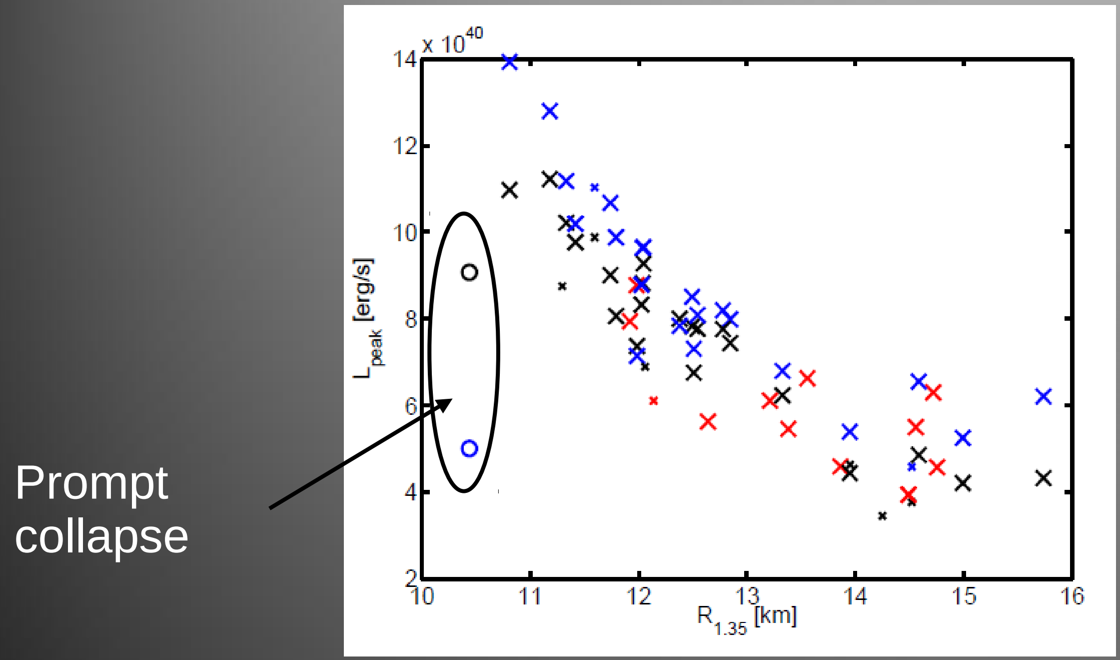
Effective temperature:
$$T_{\rm peak} \approx 0.25 \times 10^{4} {\rm K} \left(\frac{f}{10^{-6}}\right)^{1/4} \left(\frac{v}{0.1c}\right)^{-1/8} \left(\frac{M_{\rm ej}}{10^{-2} M_\odot}\right)^{-1/8} \quad (3)$$

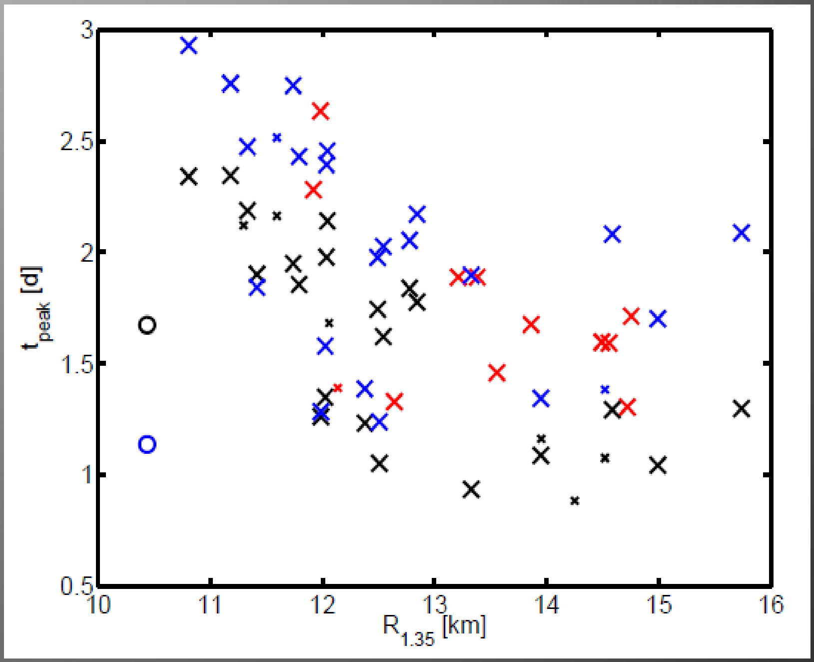
Formulae adopted from Metzger et al. 2010 with high r-process opacities of r-process elements 10 cm^2/g (*see Kasen et al. 2013,Barnes & Kasen 2013, Tanaka & Hotokezaka 2013*)

Key parameters: ejecta mass, ejecta velocity, (heating efficiency)

More advanced models available radiative transfer (Barnes & Kasen 2013, Kasen et al. 2013, Tanaka & Hotokezaka 2013), long-term ejecta evolution (Grossmann et al. 2013, Rosswog et al. 2013)

EoS dependence





Bauswein et al. 2013

→ potential constraint for NS radius from observations

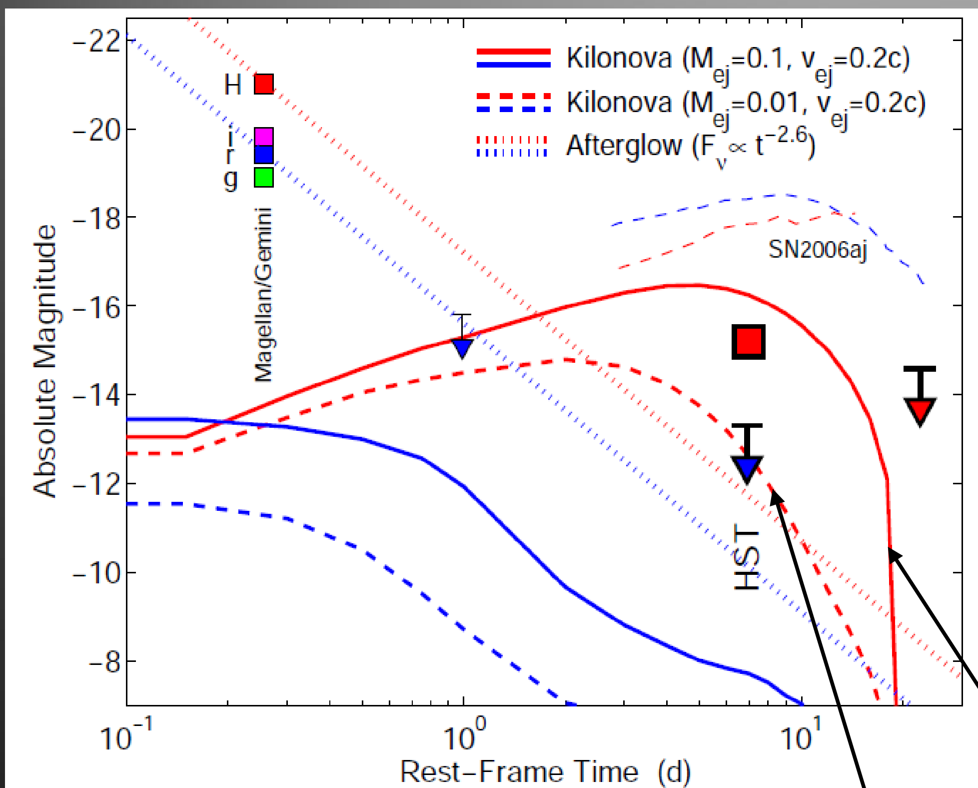
(similar findings for asymmetric binaries; also effective temperature shows characteristic behavior)

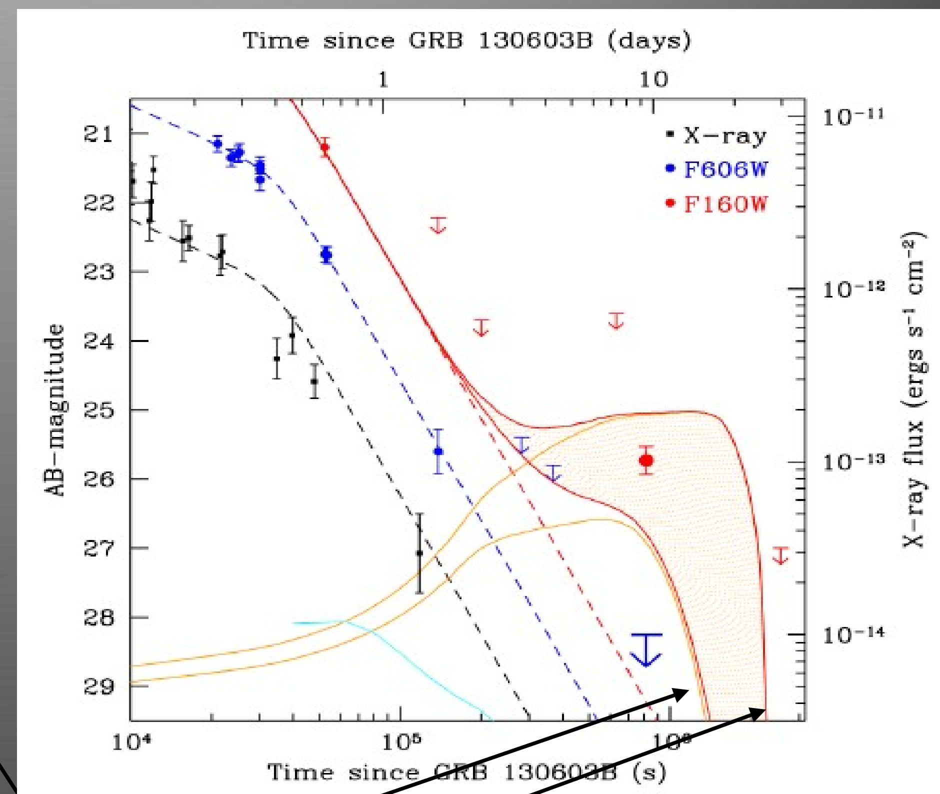
(derived from scaling models with updated opacities)

See also Hotokezaka et al. 2013, also for an interpretation in the context of GRB130603B; see Kyutoku et al. 2013, Tanaka et al. 2014 for NS-BH mergers

A possible em counterpart observation associated with GRB130603B

in near IR on top of the GRB afterglow (z=0.356)





Gemini and HST observations
Berger et al. 2013

HST Tanvir et al. 2013

0.01 and 0.1 M_{sun} ejecta

Prospects for existing and upcoming surveys and wide-field facilities (LSST, BlackGEM, ZTF, ...)

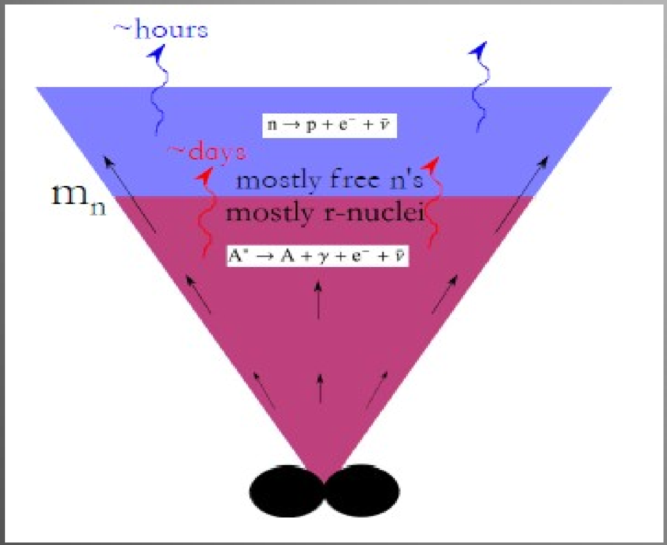
Perspective: Multimessenger astronomy

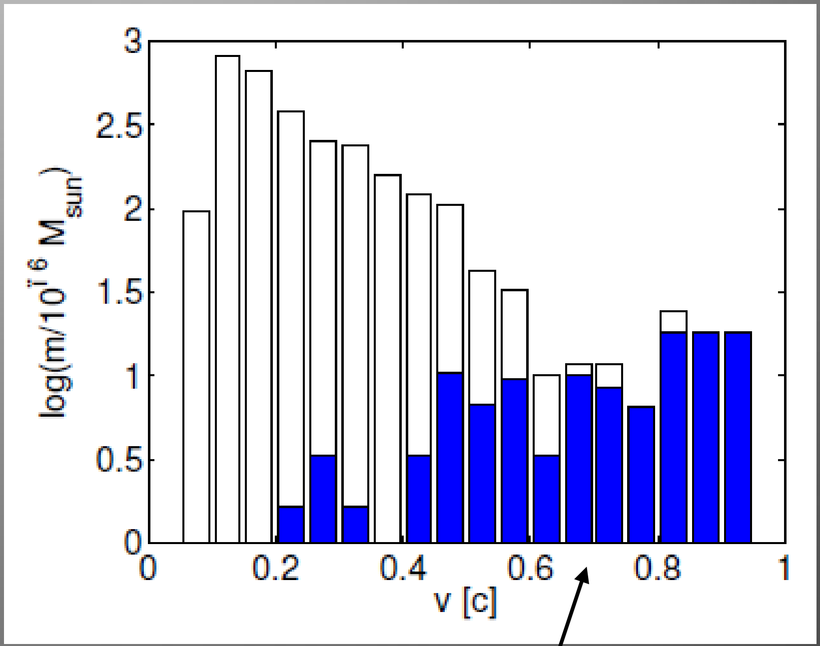
Kilonova for GW follow-up / blind survey → host galaxy, sky localization of GW events, demographics, sensitivity, interpreting kilonova properties (remember that masses can be measured from GW inspiral)

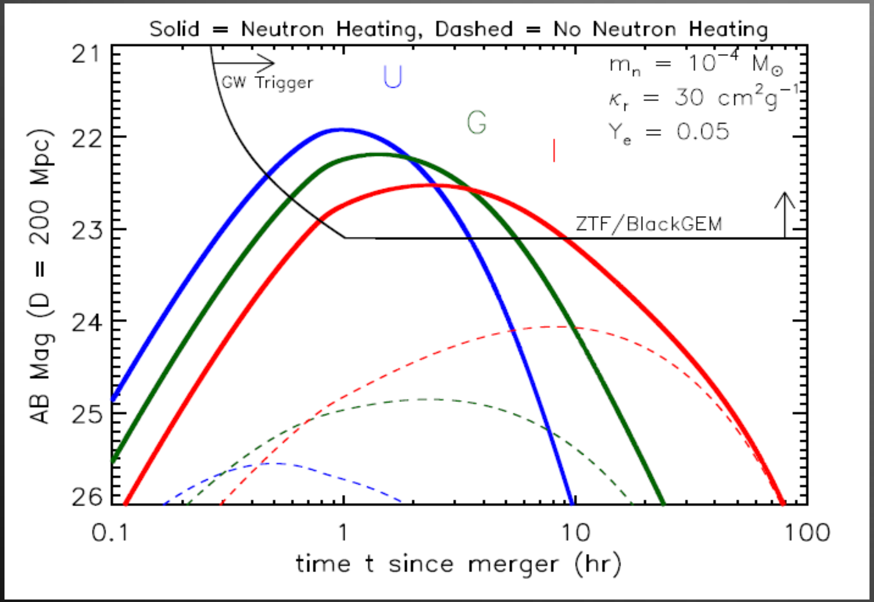
GW – GRB coincidence → GRB progenitor models

e.g. Metzger & Berger 2012, Nissanke et al. 2013, Kasliwal & Nissanke 2014, Singer et al. Clark et al. 2014, ...

Kilonova precursors







Neutrons left about $10^{-4}\ M_{sun}$

Neutron decay leads to early, bright, optical emission

→ easier to detect, in particular interesting for GW follow up

200 Mpc

Metzger et al. 2014

Comments

Very promising for follow up in the optical/UV !

- since bulk emission dimmer and in IR

- since dynamical ejecta cannot obscure emission (problem of "lanthanide/actinide curtains")

Neutron shell after r-process until now only seen in my simulation → numerical robustness needs to be investigated (work in progress) (may be hard by grid code, very small amounts of matter)

Are ejecta masses and current rate estimates compatible with mergers as dominant source of r-process elements?

(similar estimates: Lattimer & Schramm 1974, Freiburghaus et al. 1999, Qian 2000, Metzger et al. 2010, Goriely et al. 2011, Korobkin et al. 2012, Rosswog et al. 2013, Bauswein et al. 2013, Piran et al. 2014)

Consider observed amount of r-process elements → derive merger rates from know ejecta masses (for NS-NS and NS-BH) → uncertainty factor of a few (detailed analysis, Bauswein et al. 2014)

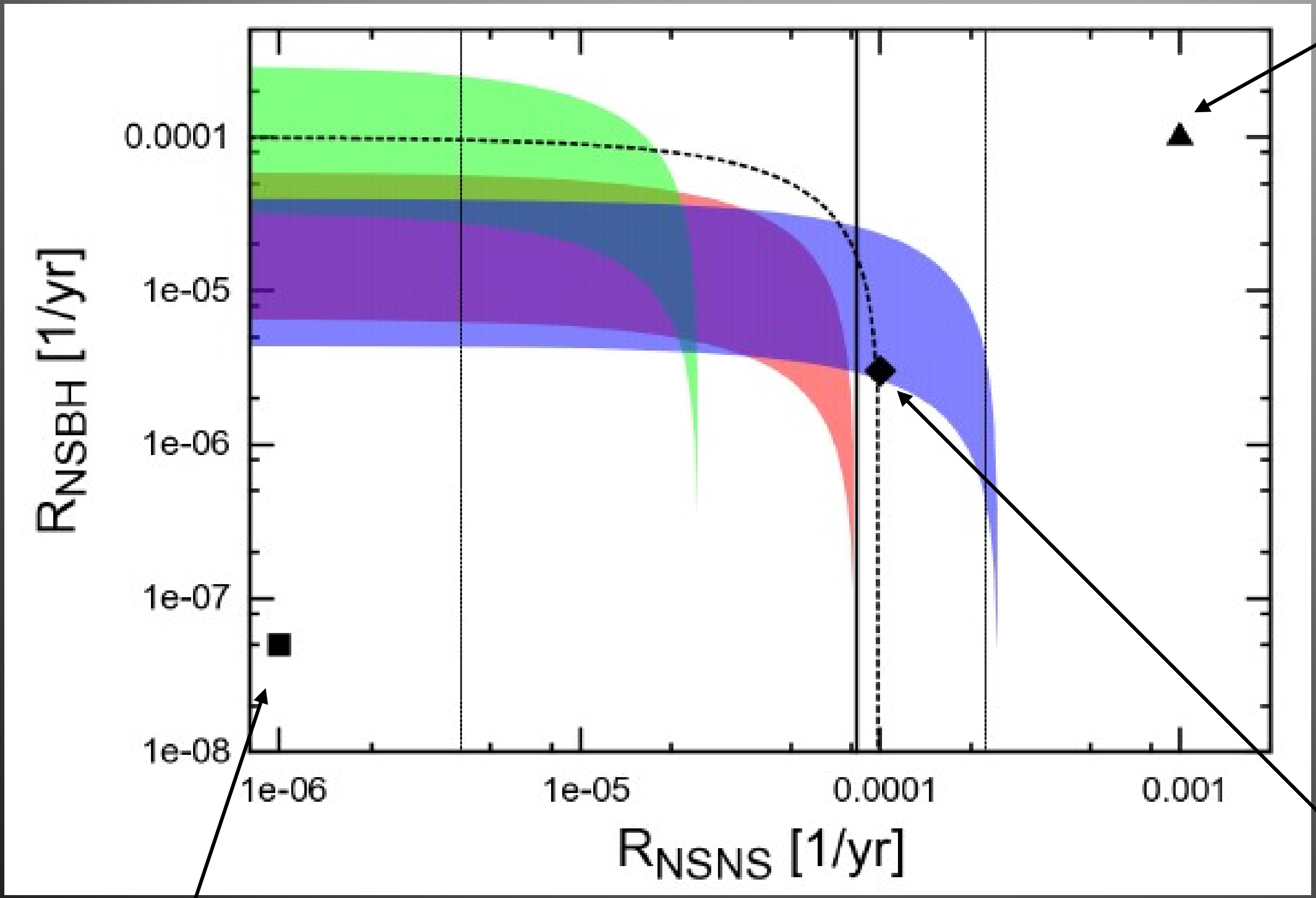
→ mergers are compatible with being the dominant source of r-process elements

→ in turn one can estimate merger rates assuming that most r-process matter was produced by mergers (→ GW and counterpart detection rates)

(keeping in mind that also other sources may contribute, e.g. MHD jets, see Friedel's talk)

Galactic merger rates

40 detections per yr (with Ad. LIGO-Virgo network)



Optimistic detection rate (ruled out by our study, but compatible with constraints from recent science runs)

10 detections per yr

Blue: stiff EoS
Green: soft EoS

“realistic” detection rate

Bauswein et al. 2014

Pessimistic detection rate (only if additional r-process source)

Symbols taken from Abadie et al. (2010) (complied mostly from pop. synthesis studies)

Summary and conclusions

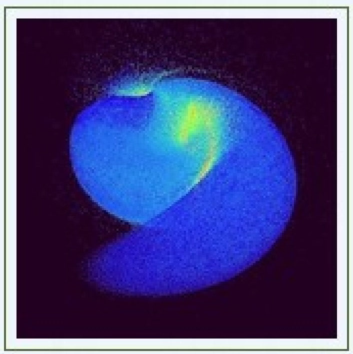
- Dominant postmerger GW frequency measures NS radii
- Collapse threshold depends in particular way on EoS
- Ejecta masses and em counterpart properties correlate with NS radii / EoS
- Early, bright counterpart component powered by neutron decay
- Merger rate estimates via nucleosynthesis – compatible with mergers being the dominant source

Home | Registration | Participants | Program | Venue/Travel | Accommodation | Contact

WORKSHOP ON BINARY NEUTRON STAR MERGERS

MAY 27-29, 2015

THESSALONIKI, GREECE



The summer of 2015 will mark the onset of the first science run of 2nd-generation interferometric gravitational wave detectors and over the next years several such detectors will form a world-wide network. The most promising sources of gravitational waves for these instruments are mergers of compact binaries. In particular, the coalescences of binary neutron star systems are considered to be the most probable events. Through gravitational wave observations, the equation of state of high-density matter is expected to be significantly constrained. But the merger events also include a rich phenomenology, such as r-process nucleosynthesis, magnetohydrodynamic processes and high-energy emission. Ultimately, merger events will be an ideal target for multi-messenger astronomy.

The workshop will bring together experts from various fields that are relevant to the astrophysics of binary neutron star mergers, in order to foster interaction and a better understanding of the phenomenology. The presentation and discussion of the latest research results will allow for setting up new observational strategies and for devising new methods for arriving at observational constraints. We encourage the participation of young researchers and for this reason several talks will give a concise overview of particular aspects of binary neutron star astrophysics.

The workshop will take place in the new building of the "Research Dissemination Center" at the Aristotle University of Thessaloniki. Partial funding to a limited number of participants is provided by the Virgo-Ego Scientific Forum (VESF) and by the ERC COST action "NewCompStar".

www.astro.auth.gr/~bns2015

Information

- Registration
- Participants
- Program
- Venue/Travel
- Accommodation
- Contact

Organizing Committee

Invited Review Speakers

*S. Bose (Washington State) **
J. Friedman (Milwaukee)
T. Janka (MPA Garching)
K. Kokkotas (Tuebingen)
J. Lattimer (Stony Brook)
*B. Metzger (Columbia) **
S. Reddy (Seattle)
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Details: Bauswein & Stergioulas submitted to PRL (2015) arXiv:1502.03176
Just, Bauswein, Ardevol, Goriely Janka, MNRAS 448, 541 (2015)
Mendoza-Temis, Martinez-Pinedo, Langanke, Bauswein, Janka, submitted to PRC (2014)
Metzger, Bauswein, Goriely, Kasen, MNRAS 446, 1115 (2015)
Bauswein, Ardevol, Goriely, Janka, ApJL 795, L9 (2014)
Clark, Bauswein, Cadonati, Janka, Pankow, Stergioulas, PRD 90, 062004 (2014)
Bauswein, Stergioulas, Janka, PRD 90, 023022 (2014)
Bauswein, Baumgarte, Janka, PRL 111, 131101 (2013)
Bauswein, Goriely, Janka, ApJ 773, 78 (2013)
Bauswein, Janka, Hebeler, Schwenk, PRD 86, 063001 (2012)
Bauswein, Janka, PRL 108, 011101 (2012)
Goriely, Bauswein, Janka, ApJL 738, L32 (2011)