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Binary neutron star mergers

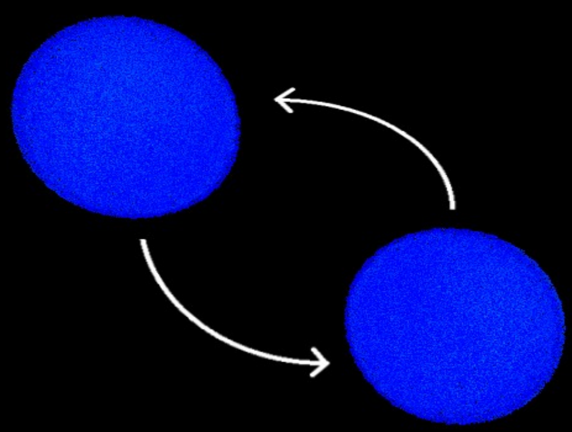
3rd HEL.A.S Summer School and DAAD School

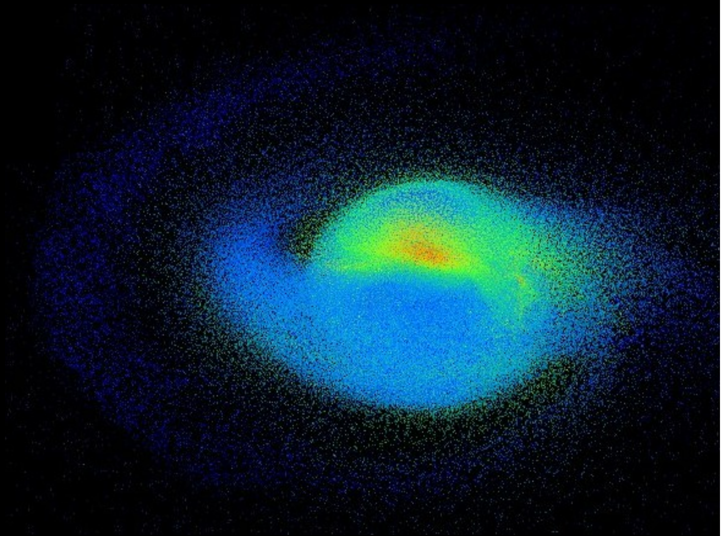
Neutron stars and gravitational waves

Frappe city, 8-12/10/2018

Andreas Bauswein

(GSI Darmstadt)





Outline: Part 1

- Formation, merger rates, overview
- Observations

  - short gamma-ray bursts

  - GW170817 and its follow-up observations

  - tentative evidence
- Rapid neutron-capture process nucleosynthesis

  - general overview

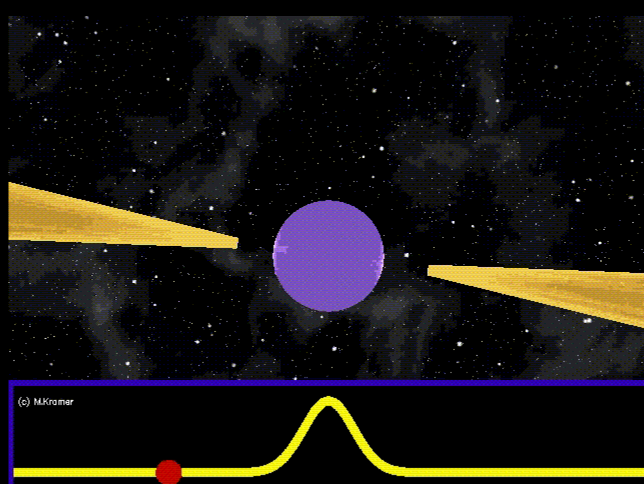
  - stellar observations

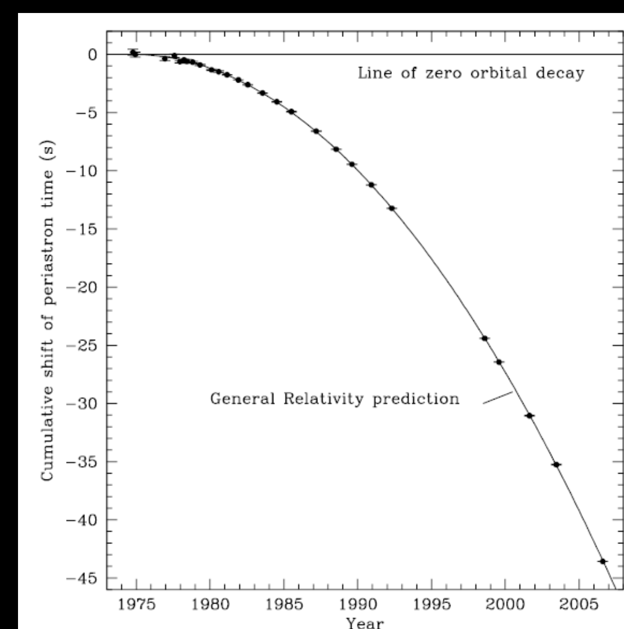
  - r-process and mergers
- Electromagnetic counterparts: kilonovae
- Merger simulations and ejecta properties vs. observations

- Tomorrow: all the EoS stuff

Background: NS and NS binaries

- NSs are end products of massive star evolution
- Compact stars of typically 1.4 Msun, 10-15 km radius → supra-nuclear densities
- A few 1000 NSs observed mostly as radio pulsars (~100 million expected in our Galaxy)
- Many in binary systems with sufficiently "small" orbits (~ 10 known)
- Decaying orbit measured !! (Nobel prize for Hulse and Taylor)
- Merger driven by GW emission: point-particle inspiral → dynamical merger phase





Background: NS and NS binaries

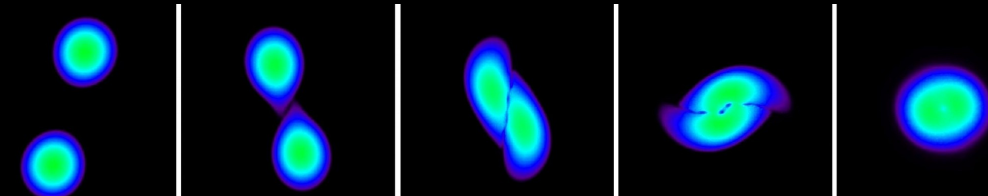
- Merger driven by GW emission: trajectory = spiral → “inspiral”

  point-particle inspiral continuously speeds up → dynamical merger phase

$$E_{orb} = -\frac{1}{2}\frac{M_1 M_2}{a} \qquad \frac{dE_{orb}}{dt} = -L_{GW} \qquad f_{orb} = \sqrt{\frac{G(M_1+M_2)}{4\pi^2 a^3}} = \frac{1}{2} f_{GW}$$

Frequencies

~1/10 h → 10 Hz → 0.5 kHz → ~2kHz

Steady point-particle “inspiral” speeds up	LIGO/Virgo window	

~100 Myrs → 10 sec → ms → ~10 ms

Time scales

See talks by Apostolatos, Chatziioannou

Neutron stars in binaries

System	M_T ($M_\odot$)	M_{PSR} ($M_\odot$)	M_c ($M_\odot$)
	Systems with well-measured component masses		
J0453+1559	2.734(4)	1.559(5)	1.174(4)
J0737−3039	2.58708(16)	1.3381(7)	1.2489(7) y
B1534+12	2.678463(8)	1.3330(4)	1.3455(4)
J1756−2251	2.56999(6)	1.341(7)	1.230(7)
J1906+0746	2.6134(3)	1.291(11) y	1.322(11) ?
B1913+16	2.828378(7)	1.4398(2)	1.3886(2)
B2127+11C g	2.71279(13)	1.358(10)	1.354(10)
	Systems with total binary mass measurement only		
J1518+4904	2.7183(7)	<1.768	>0.950
J1811−1736	2.57(10)	<1.64	>0.93
J1829+2456	2.59(2)	< 1.34	>1.26
J1930−1852	2.59(4)	< 1.32	>1.30
	Non-recycled pulsars with massive WD companions		
J1141−6545	2.2892(3)	1.27(1) y	1.01(1)
B2303+46	2.64(5)	1.24-1.44 y	1.4-1.2

Oezel & Freire 2015

- About 10 NS-NS systems known (at least one star being a pulsar)
- Some masses very accurately measured
- Most systems are fairly symmetric, masses cluster around 1.3 - 1.4 Msun
- But low number statistics – nobody can exclude bias
- Also other types of binaries including one NS are known, e.g. with white dwarf companion
- But no NS-black hole binary known yet

NS binaries

Compilation by Camenzind book 2007, Springer

Pulsar	P [ms]	P_b [hr]	e	Mass [$M_\odot$]	τ_P [Myr]	τ_{merge} [Myr]	Detection
J0737–3039A	22.70	2.45	0.088	2.58	210	87	2003
J0737–3039B	2773	2.45	0.088	2.58	50	87	2004
B1534+12	37.90	10.10	0.274	2.75	248	2690	1990
J1756–2251	28.46	7.67	9.181	2.57	444	1690	2004
B1913+16	59.03	7.75	0.617	2.83	108	310	1975
B2127+11C	30.53	8.04	0.681	2.71	969	220	1990
J1141–6545	393.90	4.74	0.172	2.30	1.4	590	2000
J1518+4904	40.9	8.63d	0.249	2.62		9600	
J1811–1736	104.2	18.78d	0.828	2.60		1700	
J1829+2456	41.0	1.17d	0.14	2.53		60	

- Only thus with sufficiently small orbital separation (with orbital periods of hours) can merger within Hubble time

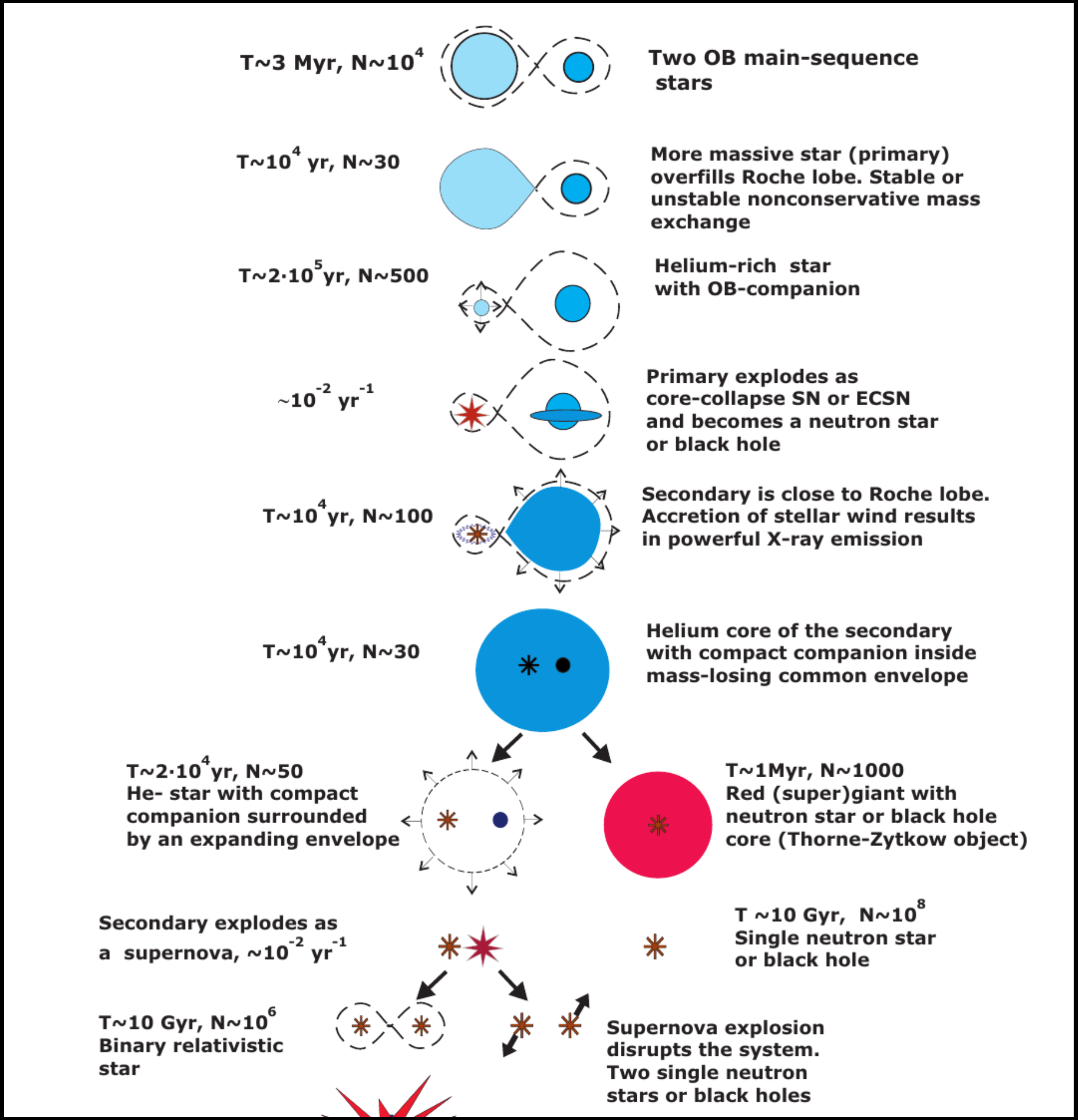
→ roughly solar radius separation

Formation of NS binaries

Standard evolutionary channel: (variations possible, many things still unclear)

- Binary of massive stars (both > 8 M_{sun}), recall many stars in binaries
- More massive component explodes as SN after a few millions (recall more massive stars evolve faster), see Gabler's talk
- Secondary evolves and fills Roche lobe → mass overflow
- NS moves in common envelope (dynamical friction) → reduction of orbital separation (crucial for sufficiently small orbital separations and thus merging !!!), energy deposition in envelope
- Secondary explodes as supernova

Complications: star formation, binary formation, kicks by explosions, common-envelope phase hard to model, outcome of explosion (NS vs. BH), ..., possibly other formation channels: CE before first explosion, dynamical captures in star clusters, ...



Postnov & Yungelson 2014

Merger rates

Expectation that NS binaries merge based on / rate estimates:

- Observed parameters of NS binaries + model
- Short gamma-ray burst rate (assuming that NS mergers are progenitors)
- Population synthesis studies (theoretical modeling of binary population)
- Observed amount of heavy r-process elements (assuming most are produced by mergers)
- GWs + detector sensitivity (low number statistics, local universe)

→ something of the order of 10 … 100 events per Myr per Galaxy like the Milky Way

(still significant uncertainties)

Scientific aspects of NS mergers

- NS mergers likely progenitors of short gamma-ray bursts (observed since the 70ies)
- NS mergers as sources of heavy elements forged by the rapid neutron-capture process
- Electromagnetic transient powered by nuclear decays during/after r-process ("kilonova", "macronova", ...)

  → UV, optical, IR → targets for triggered or blind searches (time-domain astronomy)
- Various other types of em counterparts
- Strong emitters of GWs

  → population properties: rates, masses, ... → stellar astrophysics

  → EoS of nuclear matter / stellar properties of NSs → lecture tomorrow

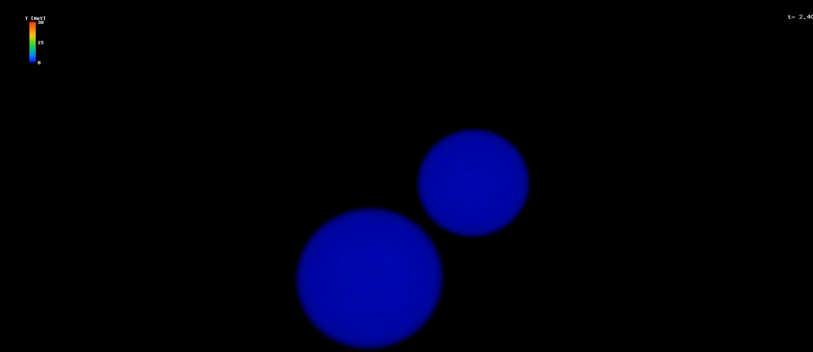
  (NS mergers probe cold and hot matter – pre- and post-merger)
- ...

Dynamics

Inspiral of NS binary

~100 Myrs

Neutron star merger



dependent on EoS, M_{tot}

ms

Prompt formation of a BH + torus

ms

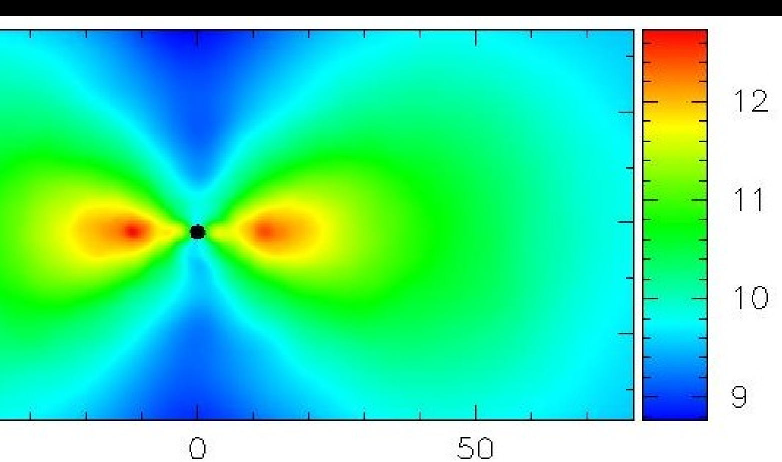
Formation of a differentially rotating massive NS

dependent on EoS, M_{tot}

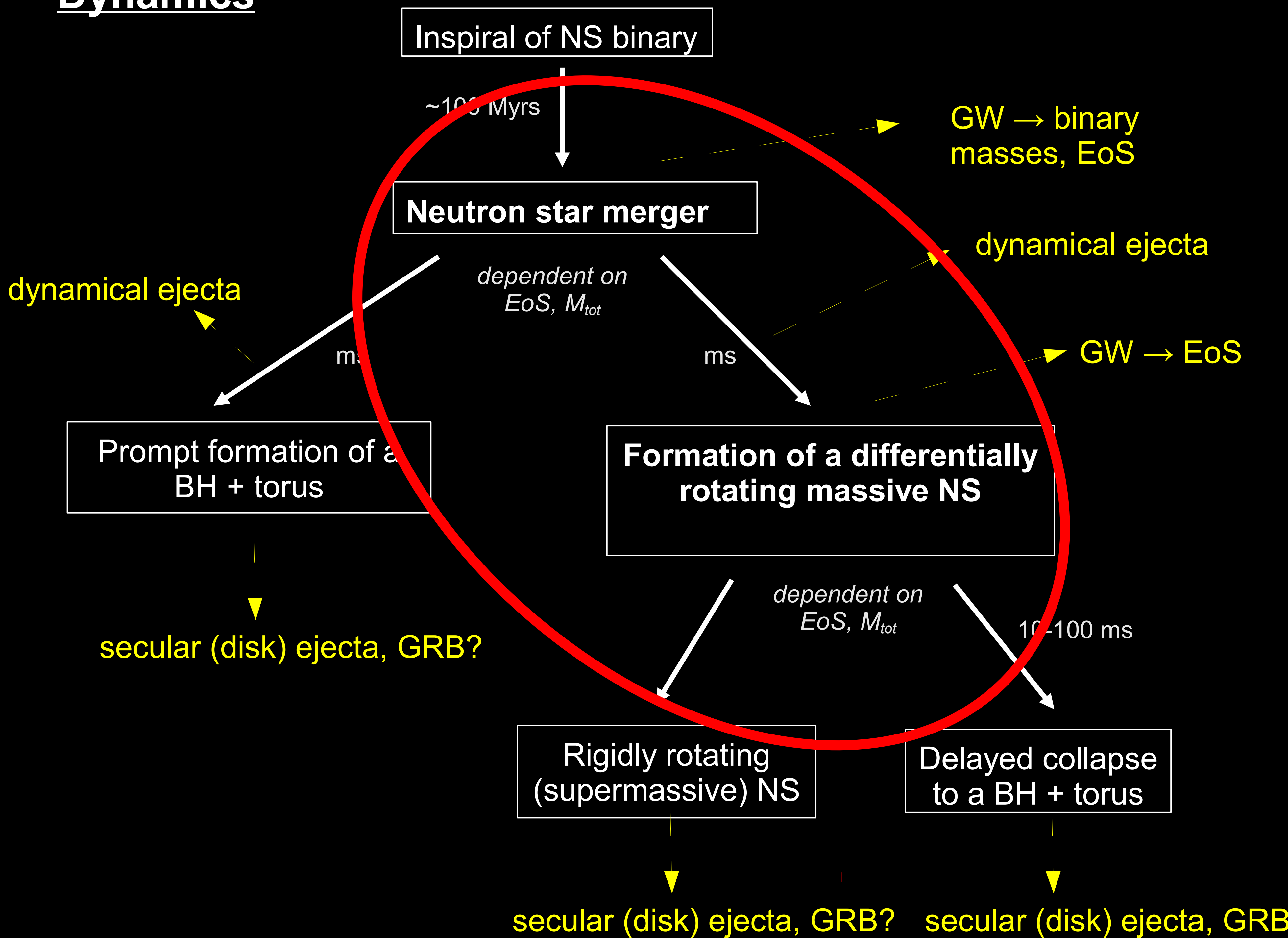
Rigidly rotating (supermassive) NS

10-100 ms

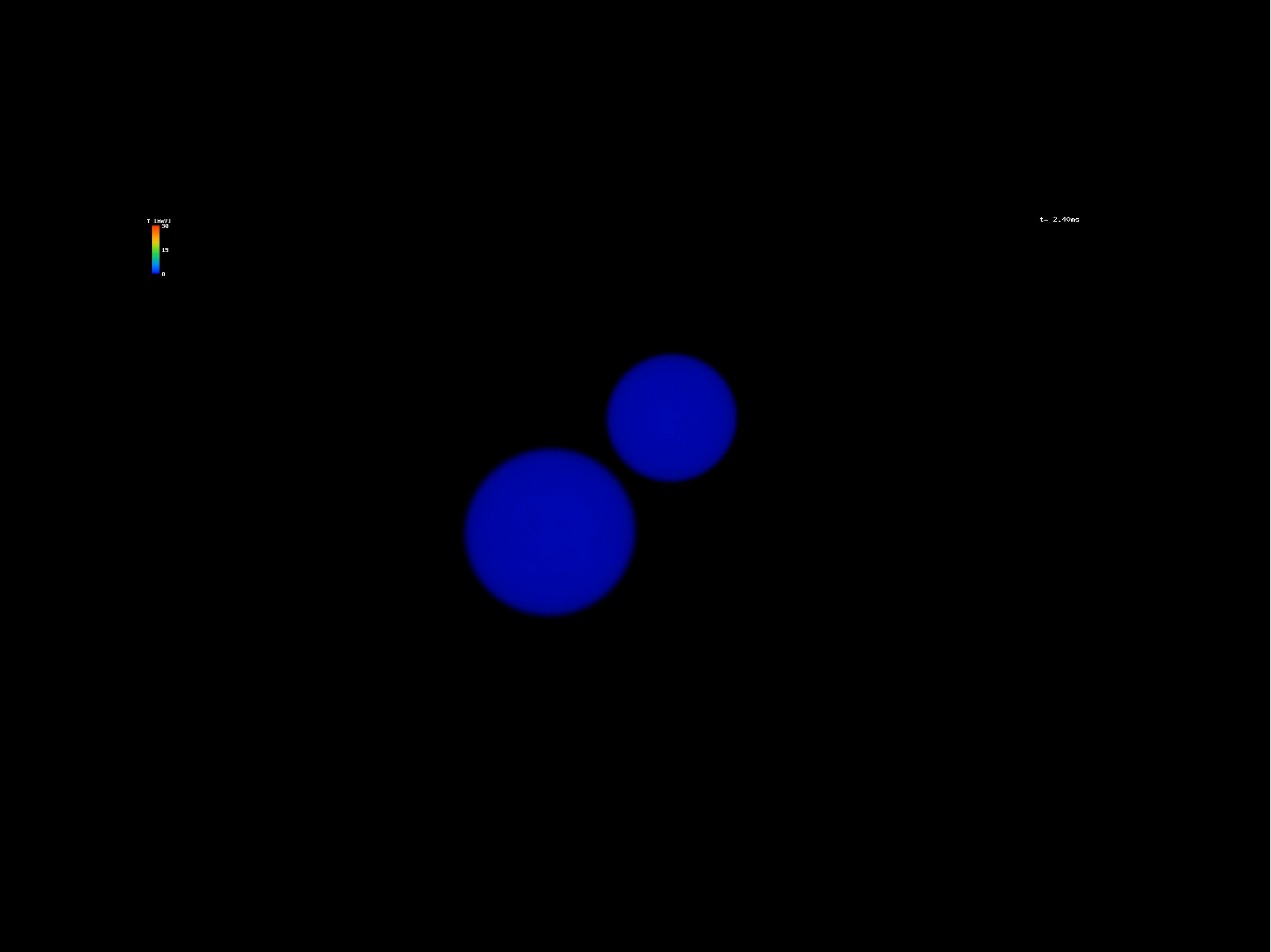
Delayed collapse to a BH + torus



Dynamics



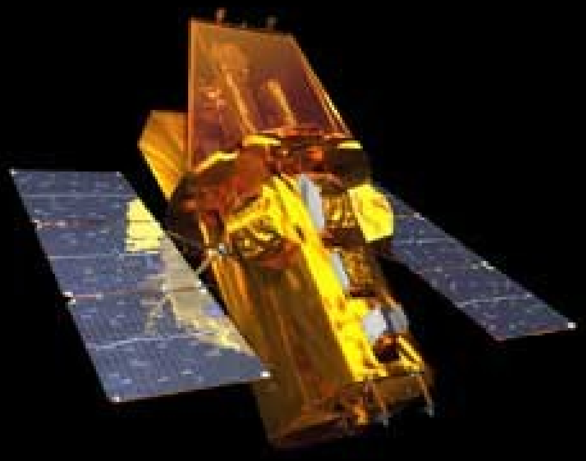
Inspiral of NS binary
GW → binary masses, EoS
Neutron star merger
dependent on EoS, M_{tot}
dynamical ejecta
ms
dynamical ejecta
GW → EoS
Prompt formation of a BH + torus
Formation of a differentially rotating massive NS
secular (disk) ejecta, GRB?
dependent on EoS, M_{tot}
10-100 ms
Rigidly rotating (supermassive) NS
Delayed collapse to a BH + torus
secular (disk) ejecta, GRB?
secular (disk) ejecta, GRB


T [MeV]
30
15
0
t= 2.40ms

Observations

Short gamma-ray bursts

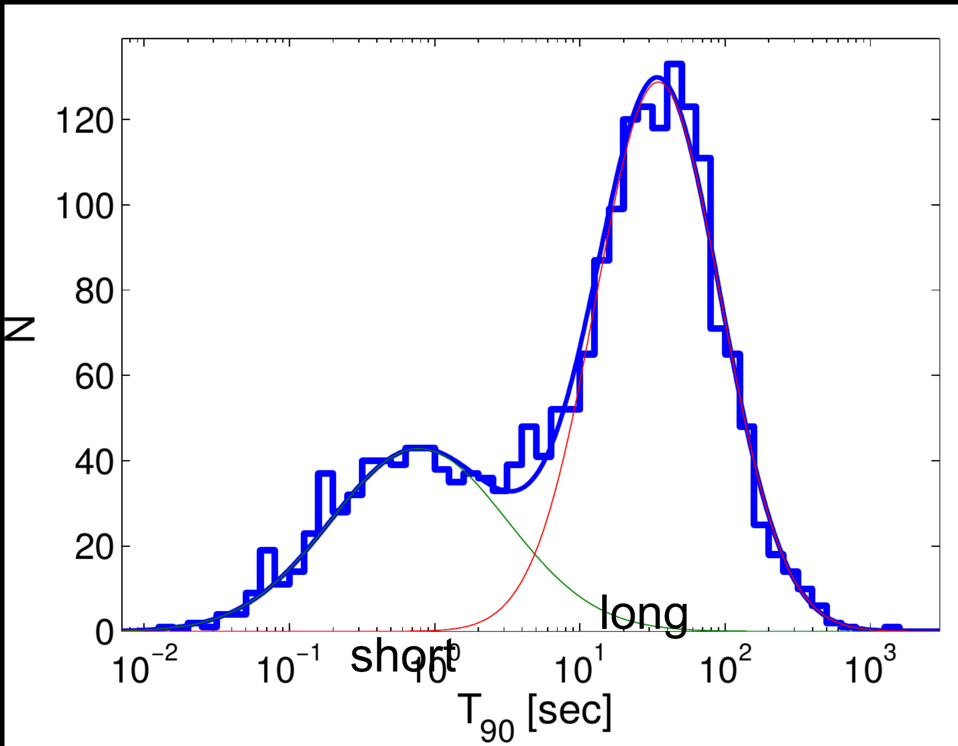
Swift

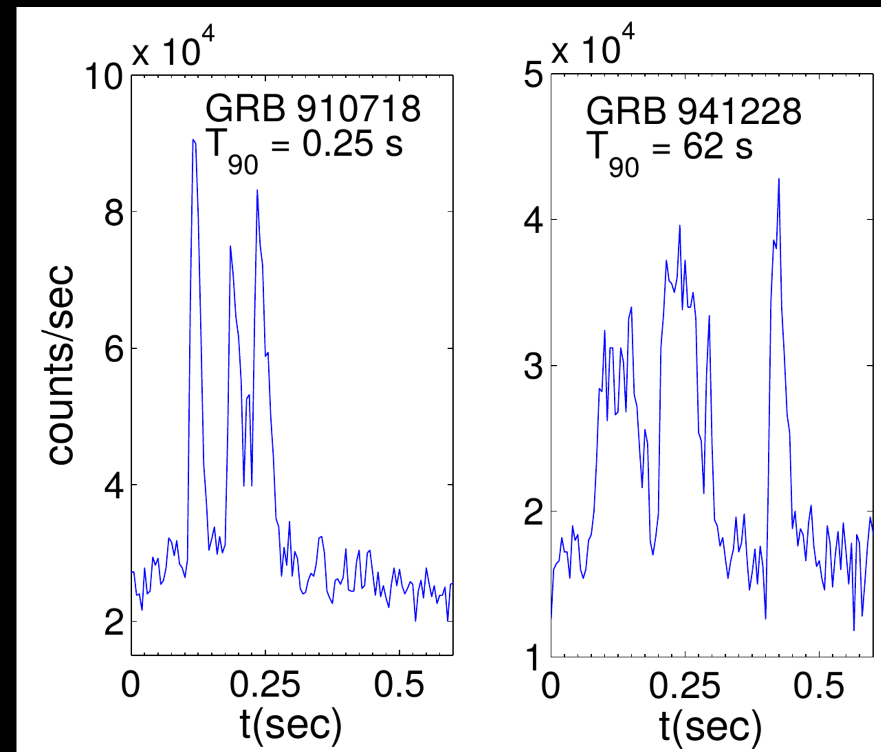


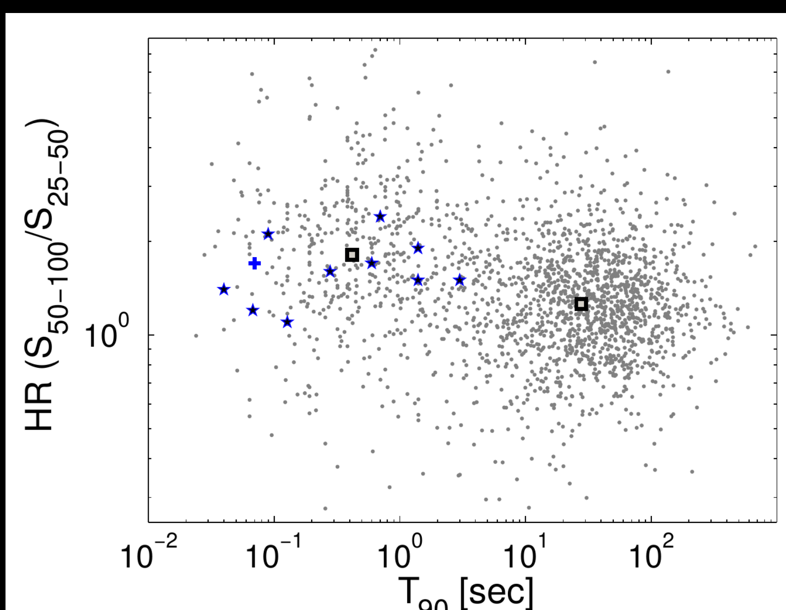
Swift

- Observed since the 70ies
- Intense flashes of gamma rays with duration <~2 secs with 10^{50} … 10^{52} erg/s
- random, non-repeating, isotropic at cosmological distances
- (long GRBs with duration >~2 secs produced by collapse of massive star – confirmed by supernova association = lightcurve observed; tend to be somewhat softer than short bursts)
- produced by jets (baryon-poor relativistic beamed outflow) forming from a BH-torus system after NS merger or NS-BH merger → beamed emission
- Afterglow (=interaction of jet with ambient medium) routinely observed as follow up with X-ray, optical, radio telescopes
- Some GRBs show X-ray plateau emission ~100 … 1000 seconds

Short gamma-ray bursts







Observations with gamma-ray satellites

BATSE catalog

Nakar 2007

Short gamma-ray bursts

- Arguments for mergers as progenitors:

  - energetics and time scales

  - no supernova association (excluded with very good limits)

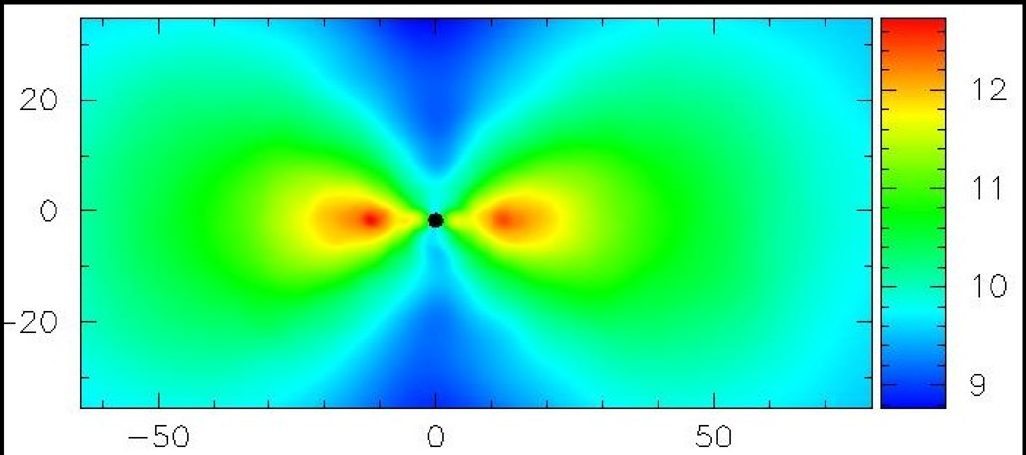
  - occurrence in star-forming and elliptical galaxies

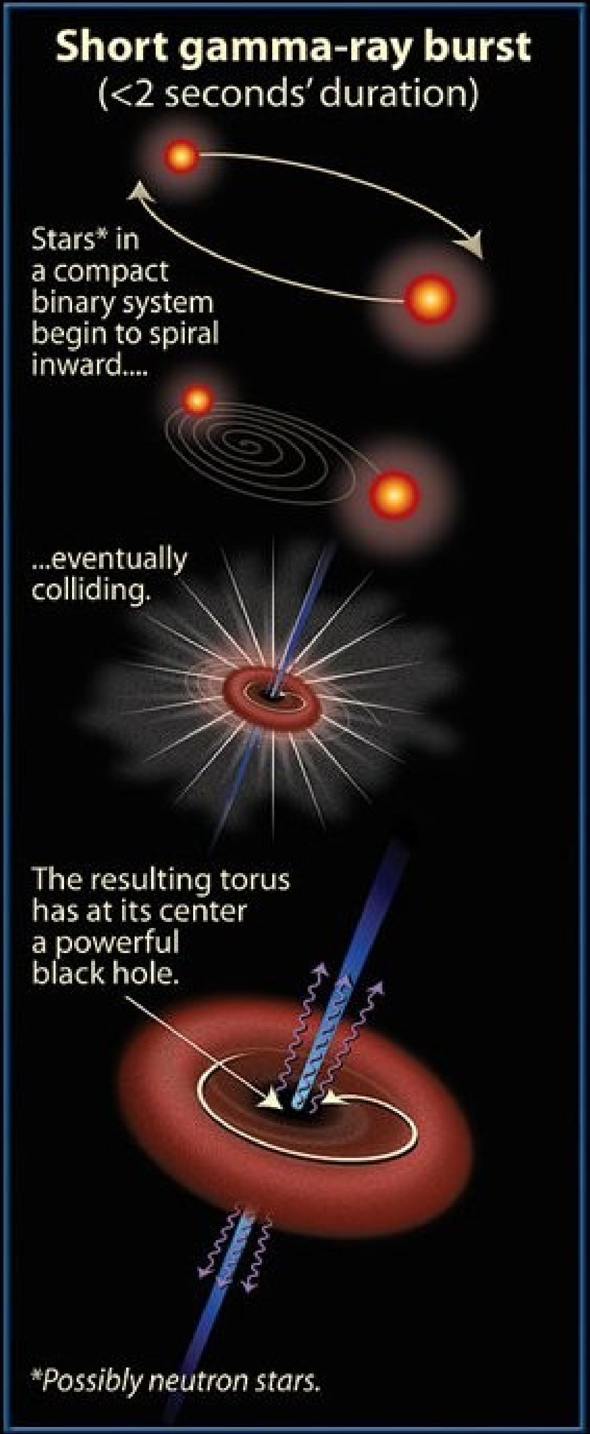
  - off-center from host galaxies

  - rates (as far as we can estimate rates)

- Smoking gun: coincident detection of sGRB and GWs

  → estimate probability to see both simultaneously (assume opening angle ~10 deg.)





Covino 2007

A break-through in astrophysics

- GW170817 first unambiguously detected NS merger (masses only compatible w NSs)
- Mutli-messenger observations: gravitational waves, gamma, X-rays, UV, optical, IR, radio

Detection August 17, 2017 by LIGO-Virgo network

→ GW data analysis

→ follow-up observations - probably largest coordinated observing campaign in astronomy (observations/time)

Announcement October 2017

GW170817 – brief overview

- GWs

  → binary masses (only compatible with NS merger)

  → tidal deformability (see Katerina's talk, tomorrow)

  → distance ~ 40 Mpc (→ rate presumably high)

- Gamma-rays 1.7 sec after GWs (Fermi) → 10^{47} erg/s order of magnitude too subluminous compared to standard short GRB (→ interpretation still discussed)
- About 12 h later: follow-up observations identify electromagnetic counterpart (in UV, optical, IR) and host galaxy – also called SSS17a, AT2017gfo

  → light curve evolution → ejecta masses, outflow velocities, ...

  → compatible with ejecta heated by r-process

  → compatible with theoretical expectations about mass ejection and nucleosynthesis

  → redshift of host galaxy + luminosity distance → independent Hubble constant measurement

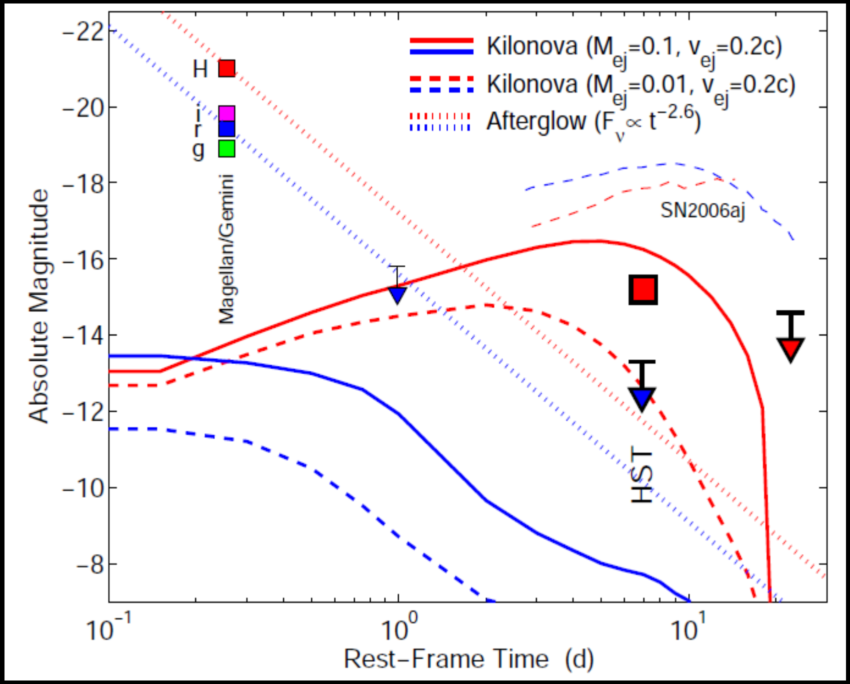
- Several days after merger: X-rays and radio emission (ongoing observations/debate about interpretation)

Tentative/indirect earlier observations

- Possible kilonova emission in the afterglow light curves of short GRBs, e.g. GRB130603b
- Observations of stellar spectra (→ later)

  - metal-poor stars of the Milky Way

  - r-process enrichment in only one out of ~10 ultra-faint dwarf galaxies (Ji et al 2016) → rare but efficient event
- Pu abundance in deep sea floor very low (2-3 orders of magnitude) → rare event, no steady enrichment (Wallner et al 2015)



Gemini and Hubble Space Telescope observations Tanvir et al. 2013, Berger et al. 2013

R-process nucleosynthesis

Archaeological Museum of Thessaloniki

Motivation: nucleosynthesis, r-process

- Explain formation of elements / nuclei

  → more than half of all nuclei heavier than iron are formed by the rapid-neutron capture process (Eu, Au, Pt, U, ...)

- Explain observed abundance pattern

  - solar system

  - meteorites

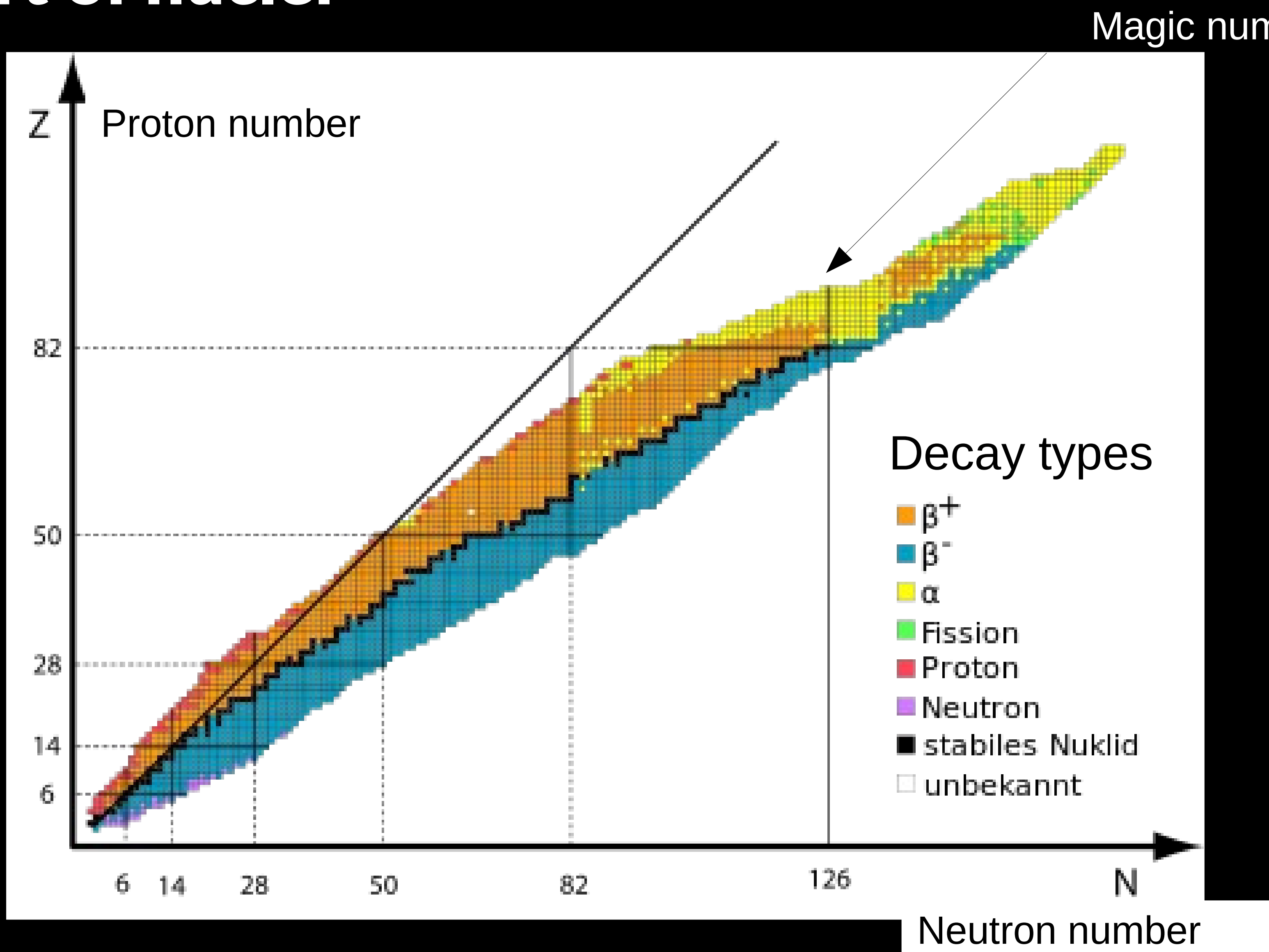
  - stellar atmospheres (extrasolar)

  - in particular in metal-poor stars (i.e. old stars)

- Beyond: explain cosmic, Galactic chemical evolution
- More subtle: understand nuclei and nuclear reactions (experimental data and nuclear theory → theoretically predicted abundances should match observations) → many experimental and theoretical efforts e.g. at GSI/FAIR in Darmstadt
- What are the astrophysical productions sites of the different elements?

  → long story short: for most elements relatively well understood – the site(s) for the r-process elements have been and still are discussed

Chart of nuclei



Dashed lines: magic nuclei, particularly stable

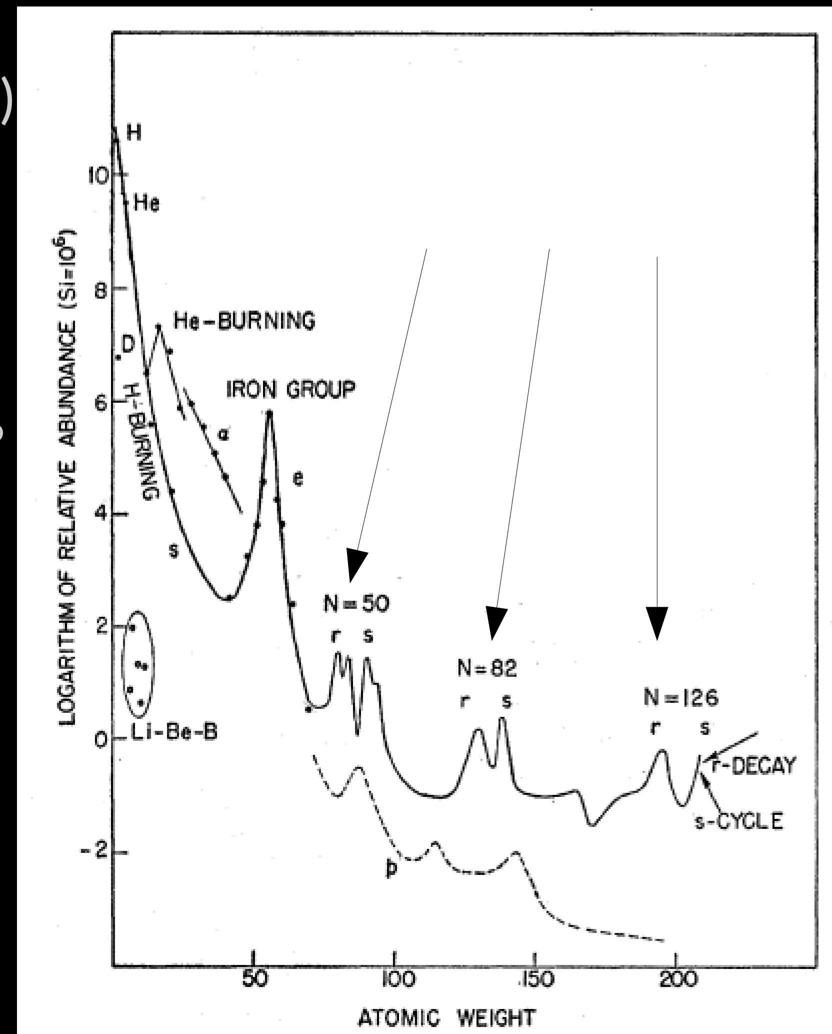
Black nuclei: stable, “valley of stability”

Source: wikipedia

Origin of elements

- Seminal paper: Burbidge, Burbidge, Fowler, Hoyle: Synthesis of the Elements in Stars (1957) - “B2FH”
- Abundance pattern reflects nuclear physics
- Abundance given on log scale; often (as here) normalized such that the abundance of Si = 10^6
- Observed abundance: superposition of primordial element formation + enrichment by certain processes / events
- Lighter elements: primordial, stars, supernovae (iron group), recall that around iron nuclear binding is strongest and fusion stops and Coulomb barrier becomes very high
- Focus here: heavier elements (most of them)

→ neutron capture reactions



Mass number A

connection to mergers only in 70ies by Lattimer, Schramm, .. Eichler,...

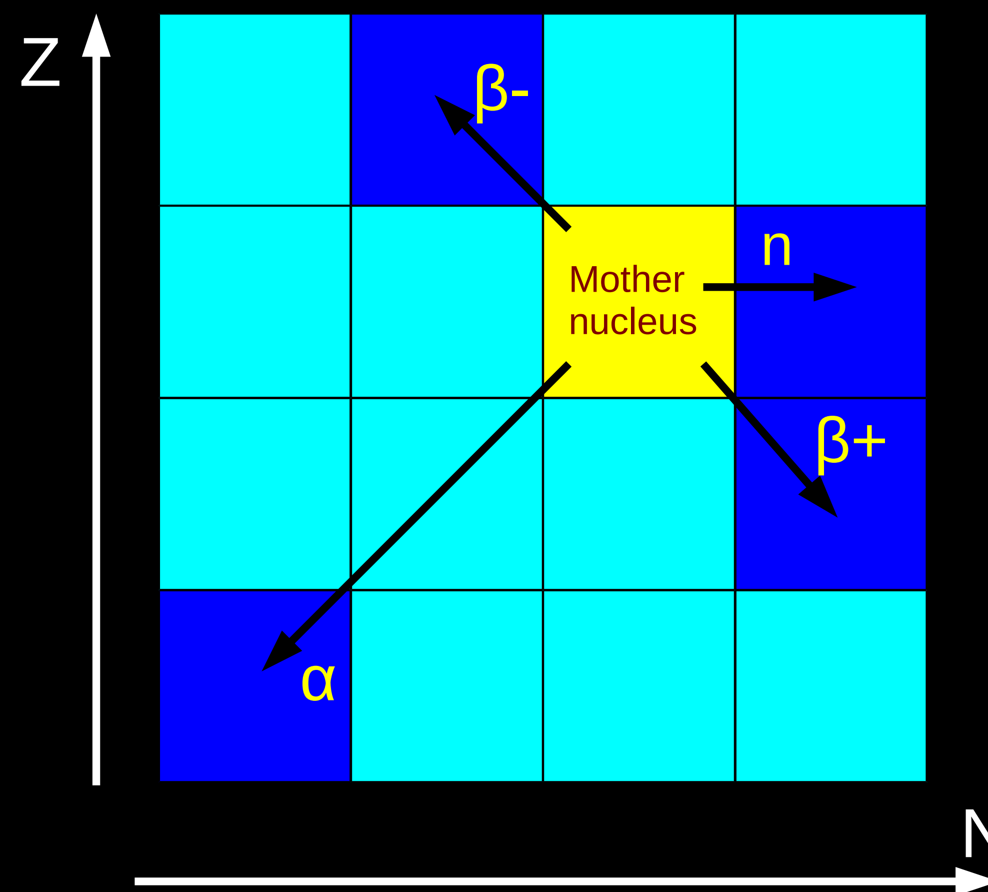
Some relevant reactions

- Nuclei characterized by A (mass number (A=Z+N)), Z (proton number)
- With nuclear reactions we move within the chart of nuclei
- Neutron capture: $(Z,A) + n \rightarrow (Z,A+1)$
- ß⁺ decay: $(Z,A) \rightarrow (Z-1,A) + e^+ + \nu_e$
- ß⁻ decay: $(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e$
- α decay: $(Z,A) \rightarrow (Z-2,A-4) + He$
- Also reverse reactions
- ..... many more reactions like fission

Loosely spoken: all these reactions (with their given rates) tell us how a (seed) nucleus moved through the chart of nuclei

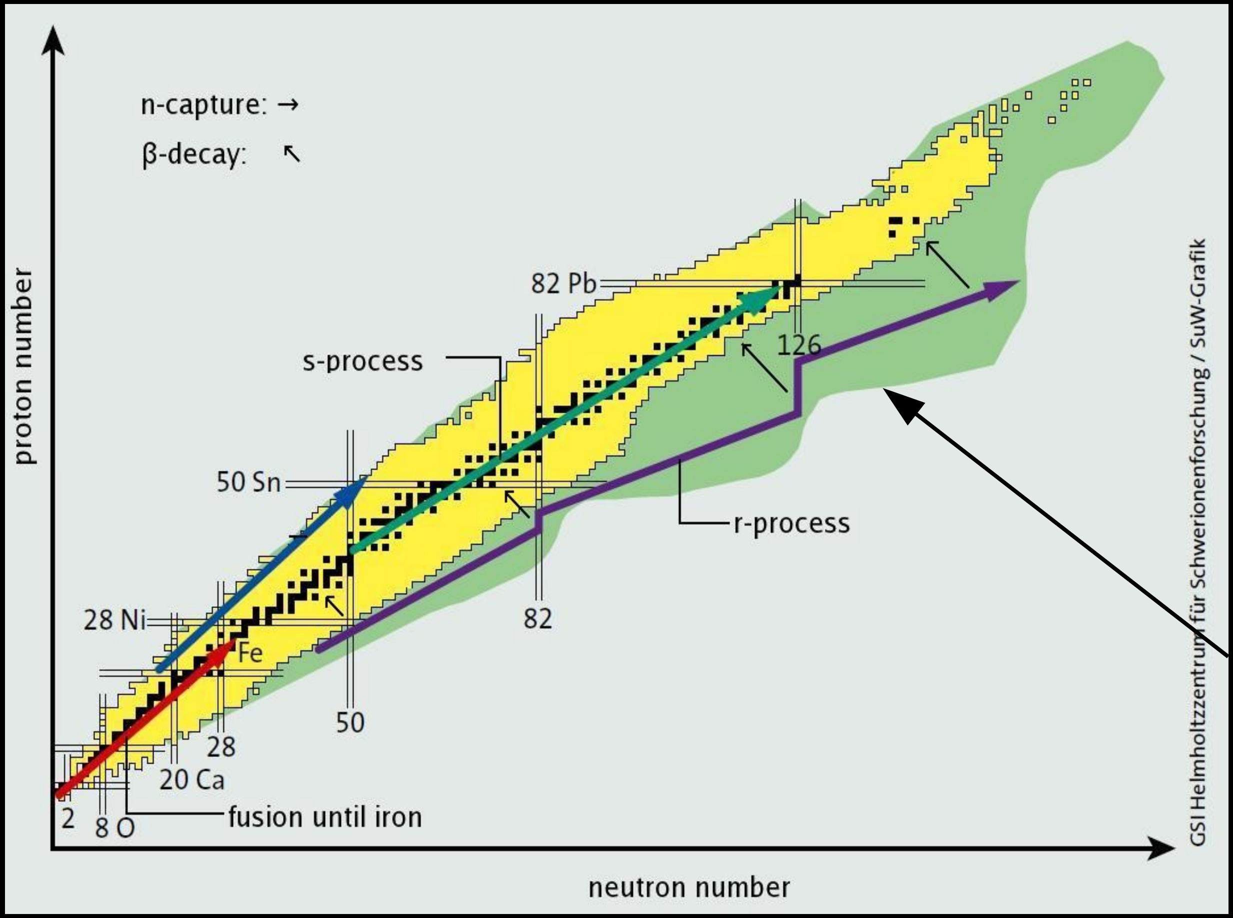
And formation of heavy elements can be understood by considering how seed nuclei (e.g. from iron group) move through the chart of nuclei

Snapshot of chart of nuclei:



Neutron capture processes

Understand r-process by considering sample of seed nuclei



Neutron drip line – no nuclei

To explain formation most of the heavy elements

Neutron capture processes

n-capture versus β-decay

rapid neutron-caputre process

(r-process)

slow neutron-capture process

(s-process)

n-capture timescale << beta-decay timescale

→ high neutron densities required
→ explosive event

N-capture tau >> beta-decay tau

→ moderate neutron densities
→ He burning in Red Giants
→ terminates at Pb, Bi

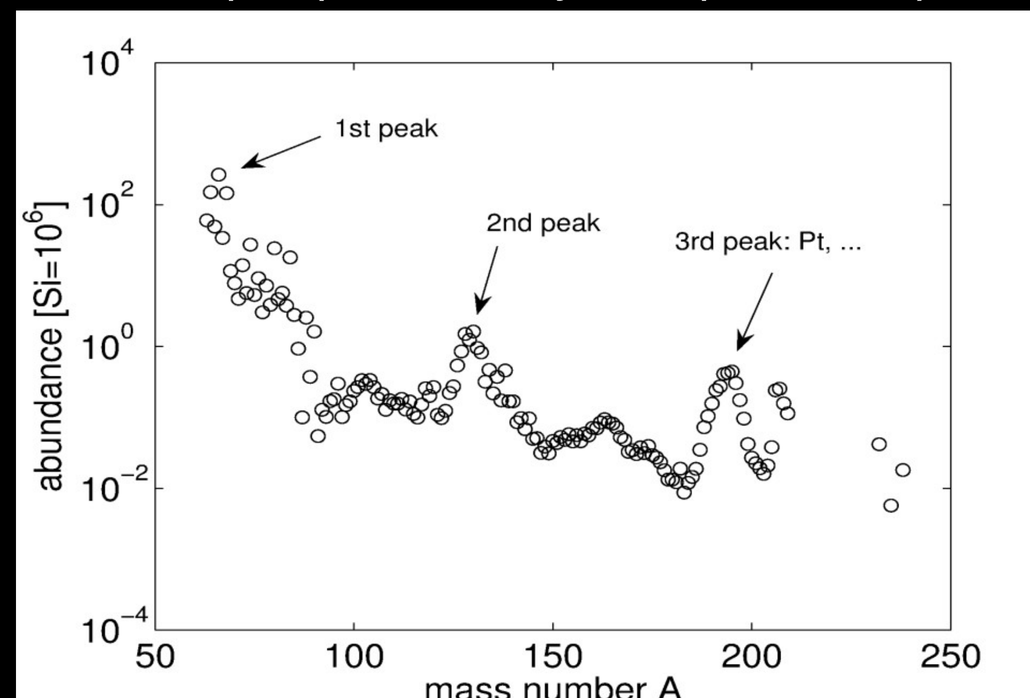
Rapid neutron-capture process

- Neutron capture processes naturally explain abundance peaks (closed neutron shells → bottle necks)
- High neutron densities required
- Particular conditions needed

  → site(s) not precisely known
- Depending on precise conditions

  exact details of r-process differ
- Fission important

Observed (s-process subtracted, some isotopes produced by both processes):



Key parameters for successful r-process

Determine the details / success of the r-process (not only in NS mergers) – parameters set by the astrophysical environment

- Electron fraction (Ye) (= proton fraction) – measure for the neutron-richness
- Entropy - determines neutron/seed ratio
- Fast expansion time scale (to maintain neutron richness)

on top: nuclear physics

- Partially not very well known since very exotic nuclei involved – nuclear physics far away from valley of stability (not accessible by experiments – we rely on theoretical models for the reaction rates, ...)
- Gross properties (abundance peaks) of r-process overall relatively insensitive to nuclear physics, but details depend a lot on nuclear physics

Discussed sites of the r-process

- Neutron-star mergers (and their remnants)
- Neutron star-black hole mergers (and their remnants)
- Dynamical ejecta of prompt exploding O-Ne-Mg core-collapse supernovae
- Neutrino-driven winds from proto-neutron stars
- He- shell exposed to intense neutrino flux (during core collapse)
- Quark-novae
- Magneto-hydrodnamic jets of rare core-collapse supernovae
- Collapsar tori
- ...

All have ideas/models some advantages and some disadvantages !

With GW170817 it is now clear: NS merger play a prominent role for r-process nucleosynthesis!

Note: possibly different sites (operating simultaneously or at different times (metalicities)), different mass ranges may be produced by different sites

Observations

Metal-poor stars represent chemical composition at the time of their formation !

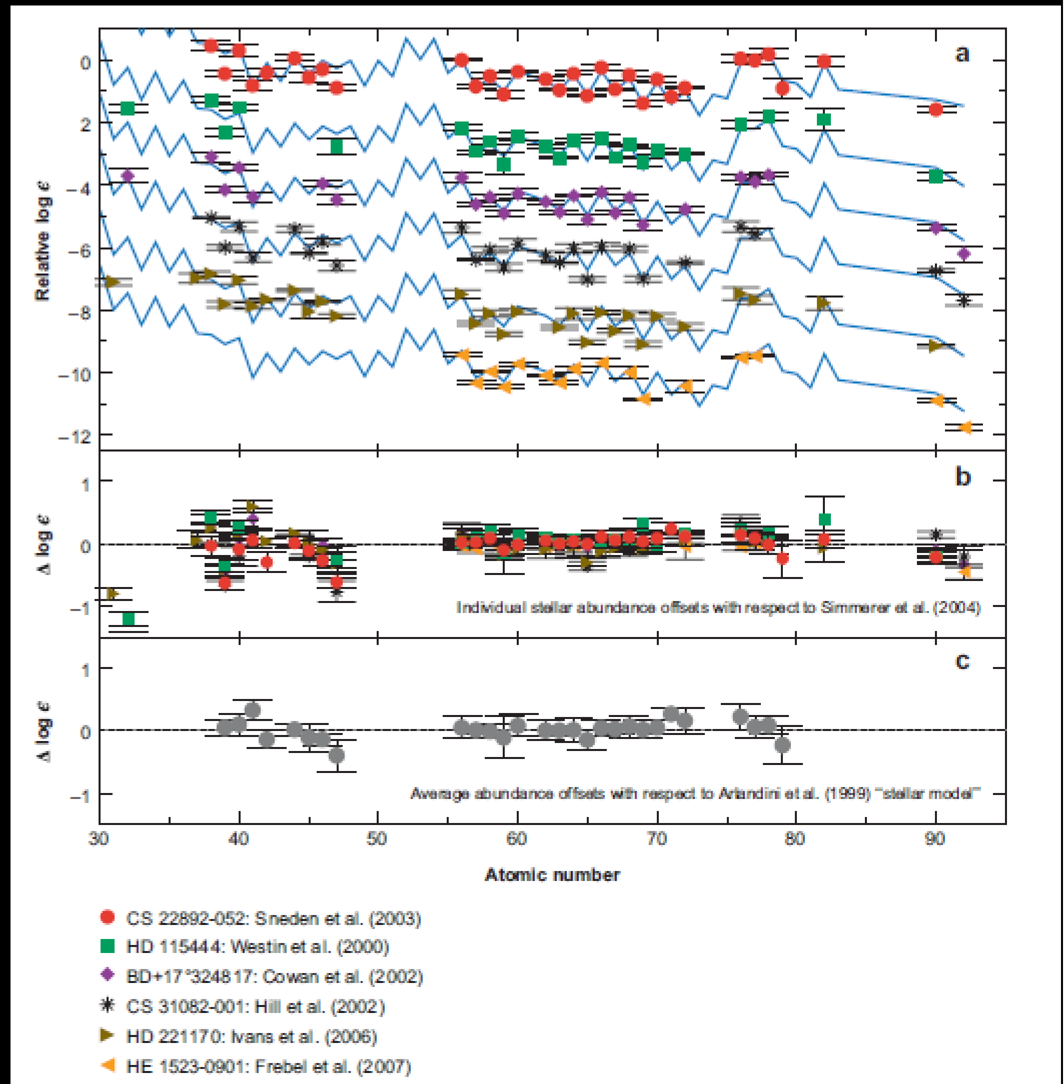
$$\log \varepsilon(A) \equiv \log_{10} (N_A/N_H) + 12.0$$

- Metalicity ~ age

  Elemental r-process abundances in ultra metal-poor stars compared to solar distribution

- Robust at different metalicities
- (solid line = scaled solar)
- Uniform pattern for 56 < Z < 83
- Larger scatter for Z < 50

Sneden et al 2008

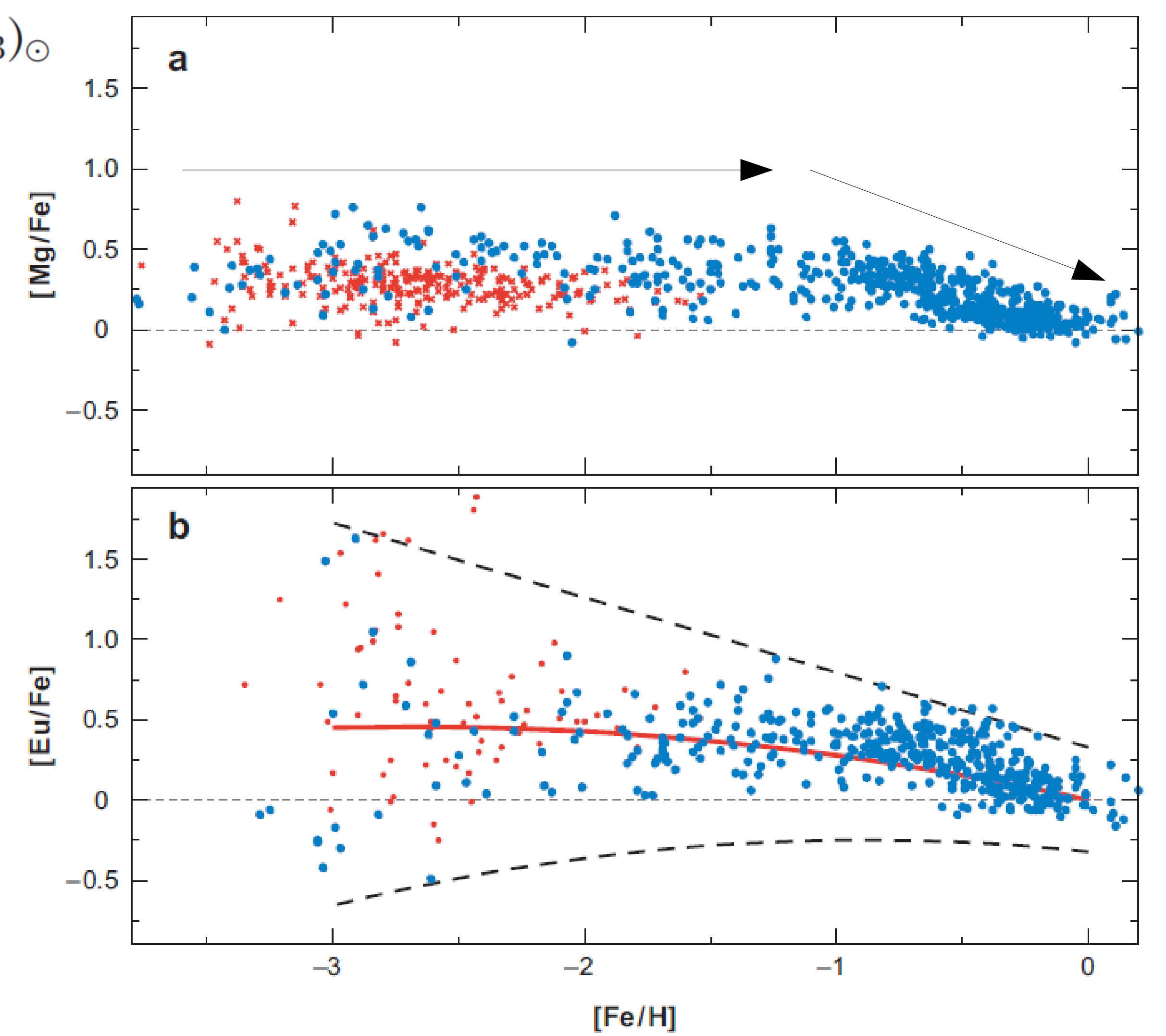


Observations in halo and disk stars

$$[A/B] \equiv \log_{10}(N_A/N_B)_* - \log_{10}(N_A/N_B)_\odot$$

- [A/B] abundance ratio relative to solar
- Dashed line: 0 = solar
- Mg and Fe produced in the same site (core-collapse SN), then Type Ia SN (thermonuclear)
- Eu (nearly) pure r-process element
- Significant scatter of [Eu/Fe] at lower metalicities [Fe/H] (argues for mergers)

  → r-process source is rare in the early Galxy (not so homogenously distrbuted initially)
- Mg and Fe production are not tightly coupled to r-process production

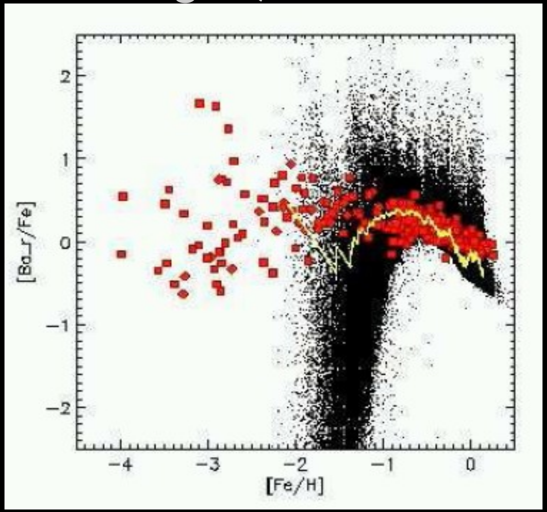


Sneden et al 2008

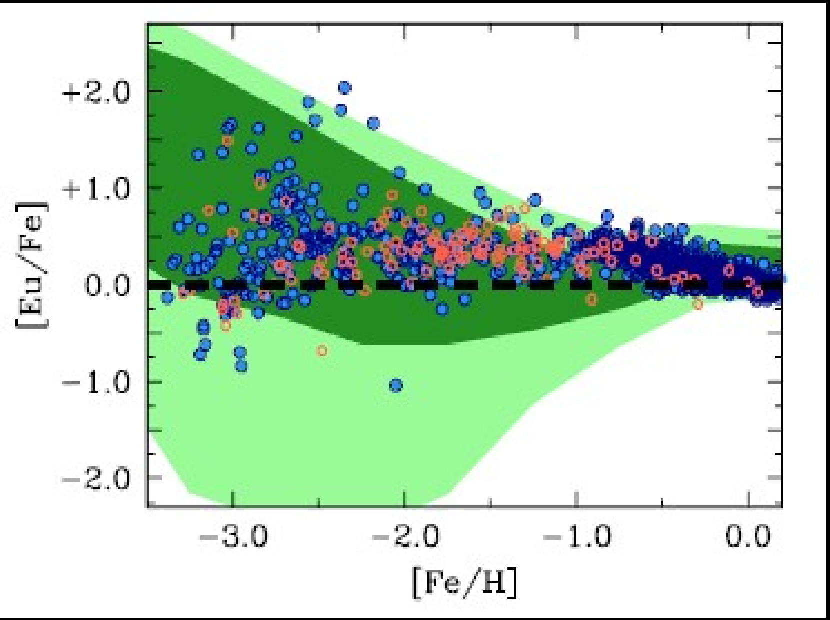
Metallicities ~ roughly time

Observations

- Ejecta masses and merger rates are roughly consistent with NS mergers being the dominant source of heavy r-process elements (details later, see e.g. Bauswein et al. 2014 for a detailed analysis)
- R-process elements are observed in metal-poor (=old) stars with robust abundance pattern (see e.g. Sneden et al. 2008); with large star-to-star scatter → pro mergers
- Formation of NS binary followed by inspiral time of 100…1000 Myrs => merger is delayed
- → Do mergers occur sufficiently "early" to explain the Galactic enrichment → chemogalactical models *Qian 2000, Argast et al. 2004, Ishimaru & Wanajo 1999, Cescutti et al 2006, Mennekens & Vanbeveren 2014, Matteucci et al. 2014, Shen et al 2014, van de Voort et al 2014.* … (different models available currently no consensus whether the early enrichment could be due to mergers)



Argast et al. 2004
(one-zone model)



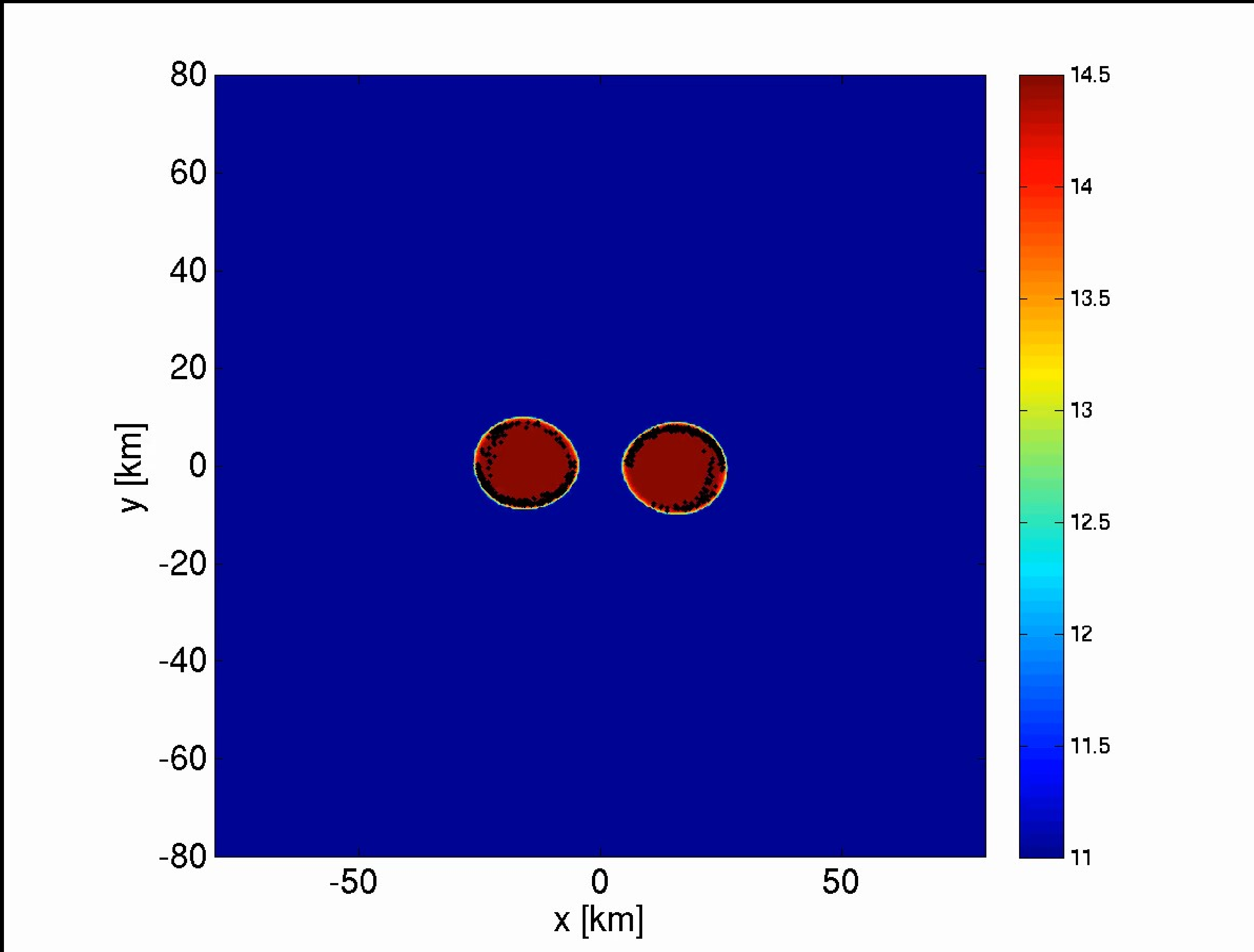
Based on galaxy simulation, *Shen et al. 2014*

Dynamical ejecta of NS mergers and the r-process

Comments:

- only unbound material is relevant for nucleosynthesis

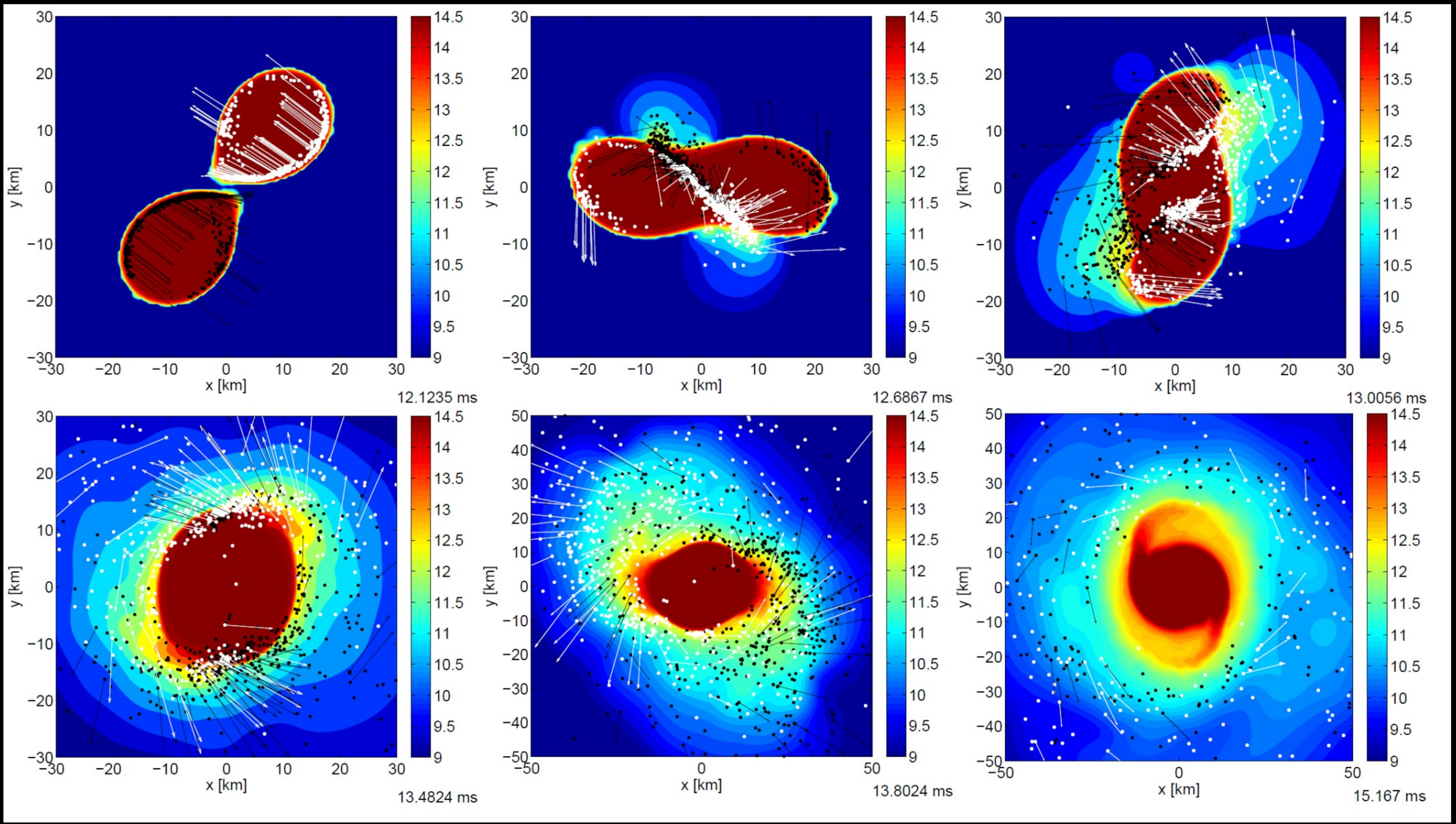
- recall that we need to distinguish different types of ejecta



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

Simulations

Dots trace ejecta (DD2 EoS 1.35-1.35 M_{sun})



Bauswein et al. 2013

Modeling approaches – key incredients

- Relativistic hydrodynamics (grid-based or smooth particle hydrodynamics – Eulerian vs. Lagrangian treatment, many different methods)
- Gravity: solve Einstein field equations
- Microphysical EoS P(rho,T,Ye) – nuclear physics input (tomorrow) – not completely understood/solved, i.e. model dependent
- Neutrino treatment / weak interactions (approximate radiation transport)
- Magnetohydrodynamics
- Vacuum treatment (not necessary for SPH)
- Tracer particle (naturally implemented in SPH)

- Different codes implement these aspects with different degree of sophistication
- In particular all ejecta aspects still resolution dependent → still we'll see that simulations find relatively robust production of r-process elements

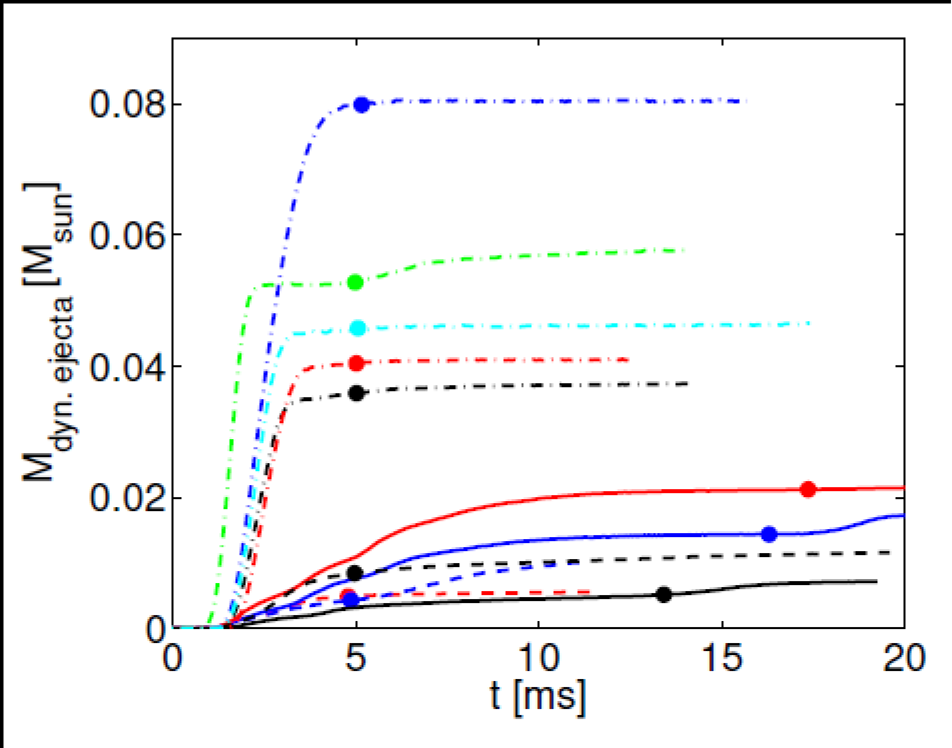
Faber & Rasio 2012, Duez & Zlochower 2018

Comments on ejecta mass/properties /modeling

- Don't take numbers literally

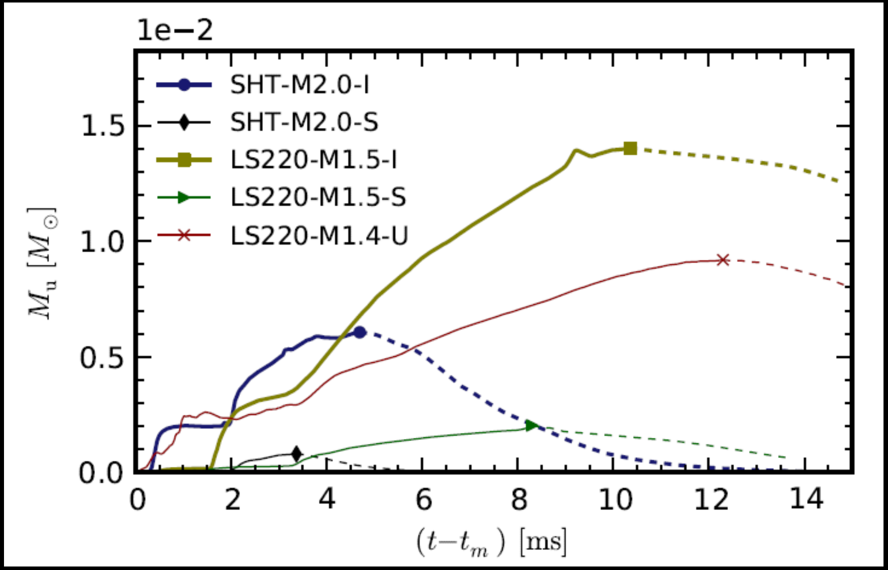
  (small masses are hard to resolve)
- Evaluated at different times
- Different criteria are employed for determining ejecta (purely ballistic vs. inclusion of hydrodynamical effects)

Different binary systems:



Just et al. 2014

+ no self-consistent inclusion of long-term ejecta, which is hard to simulate on its own



Kastaun & Galeazzi 2015

Ejecta properties – nuclear network calculations

- Robust features: fast expansion, neutron rich (neutrinos/weak interactions increase Y_e, see Wanajo et al. 2014, Groriely et al 2015, …)
- Originating from inner neutron crust 10^{14} g/cm3 (initial Y_e very low)
- Matter heated to NSE and frozen out at ~ neutron drip $4*10^{11}$ g/cm^3
- Ejecta expansion typically followed for a few 10 ms by simulations, then extrapolation (outcome insensitive), homologous expansion well justified
- Post-processing hydrodynamical trajectories with nuclear network

  - Properties of ~5000 nuclei (mostly theoretical models)

  - Theoretical and experimental reaction rates: beta-decays, neutron captures, photodissosication, multiple-particle reactions (n,2n)

  - Neutron-induced fission, spontaneous fission, beta-delayed fission, photofission, beta-delayed neutron emission

  - Heating due to beta-decays, fission, alpha decays
- Note that nuclear physics are uncertain far away from valley of stability: mass model, reaction rates, fission yields

Network codes

- Evolve for every trajectory (or at least representative sample)

$$\frac{dY_i}{dt} = f_i(\rho, T, Y_1, ..., Y_N)$$

N number of all involved nuclei – coupled system of ODEs

(starting from initial composition)

- Sum up results weighted by mass that given trajectory represents

$\rightarrow$ abundance pattern

- Scale appropriately to compare with observations

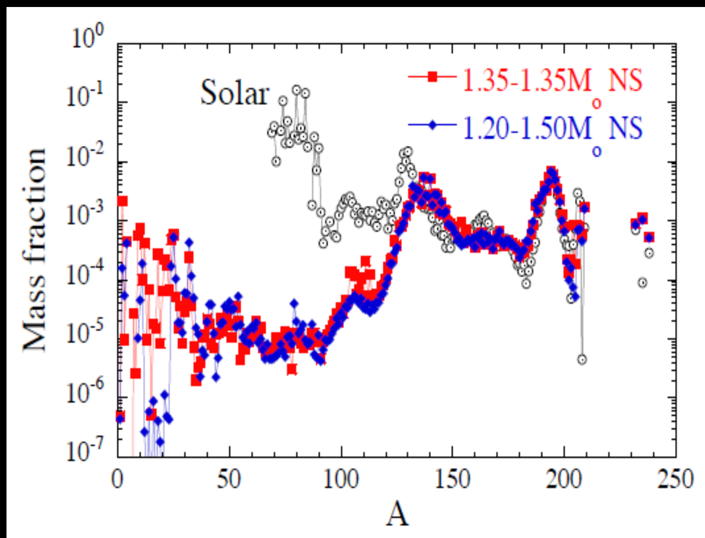
Dependent on thermodynamics condition, nuclear physics

Important comment: Nuclear physics, i.e. rates, of these exotic nuclei far from being understood → significant uncertainties due to chosen nuclear physics model (lecture on it own)

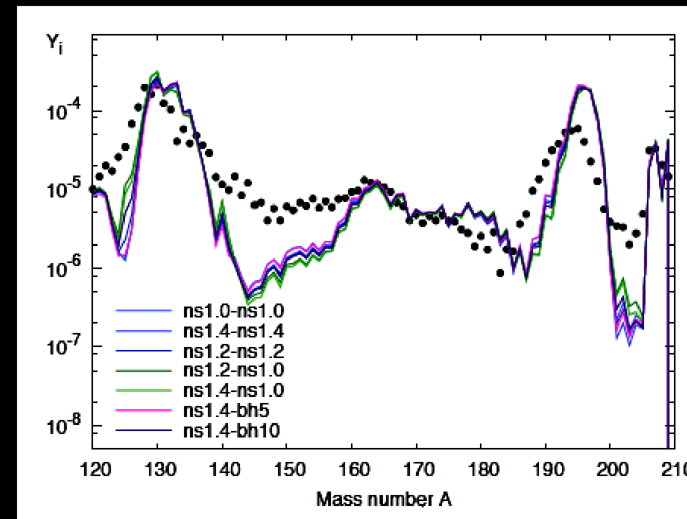
Nucleosynthesis results

Some results: different hydrodynamical models, different nuclear network codes, different NS EoS, different binary systems → robust pattern (fission)

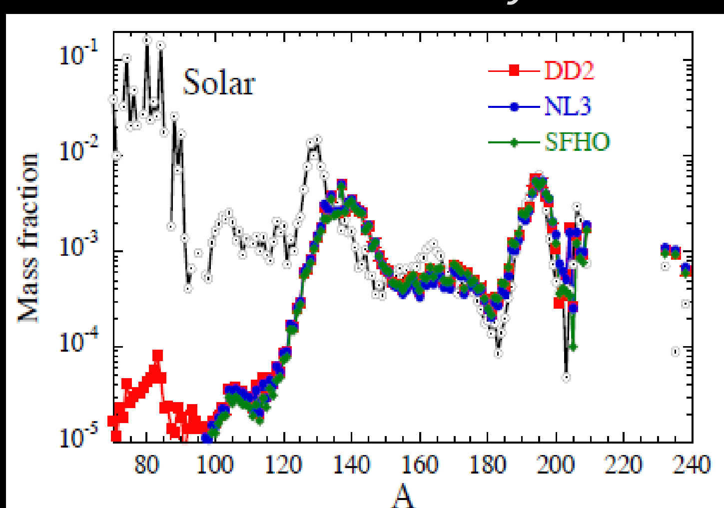
Black dots: observed abundances (results scaled)



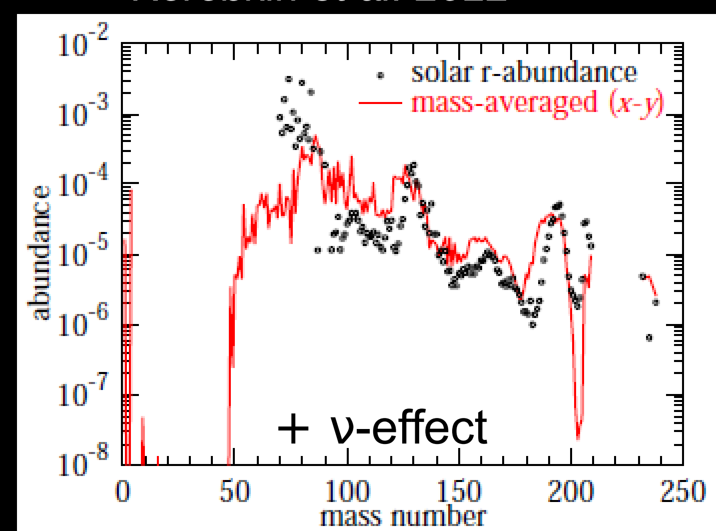
Goriely et al 2011



Korobkin et al. 2012



Bauswein et al 2013



Wanajo et al. 2014

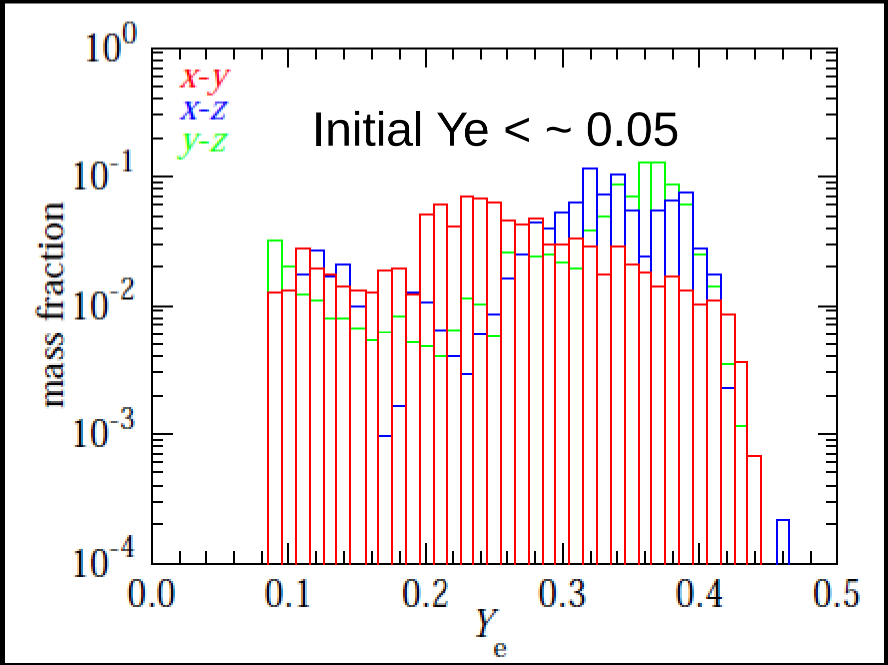
See also Freiburghaus et al 1999, Metzger et al. 2010, Roberts et al. 2011,...

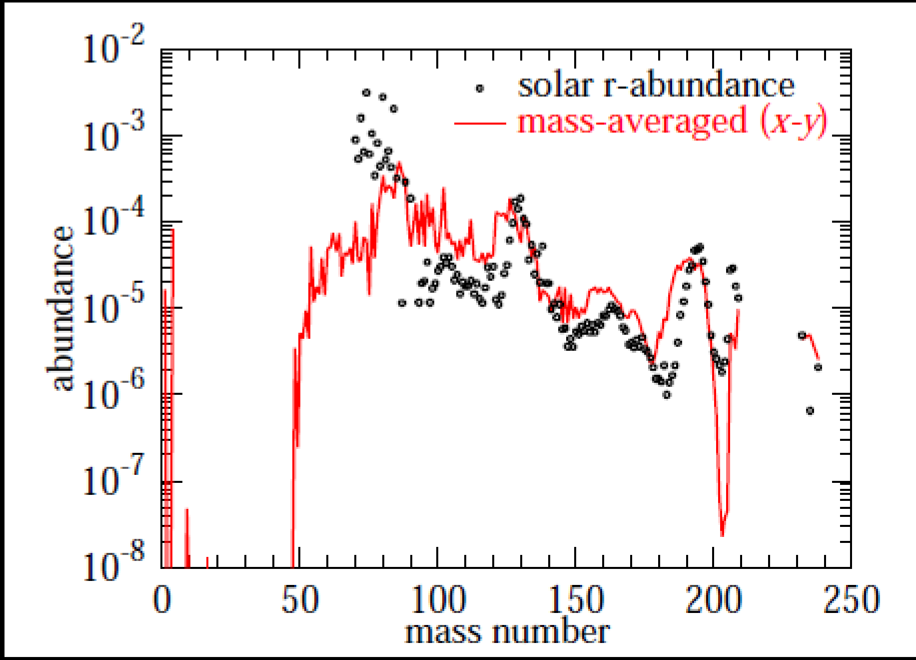
Impact of neutrinos/weak interactions

- At high temperatures (shock-heated matter): a lot of positrons are present which are captured on neutrons → increasing Ye
- In addition: matter is irradiated by neutrinos (emitted from central object) modifying Ye
- Production of lighter r-process elements in addition
- And iron group elements
- depend on details (still under investigation)
- Overall: robust production of r-process elements in NS mergers, in particular compared to other alternative sites

$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

Wanajo et al 2014





Long-term ejecta of NS mergers and the r-process

Secular ejecta

NS mergers leave a remnant

- Long-lived NS remnant
- BH-torus system (also from NSBH binary)

→ neutrino-driven, magnetically driven, nuclear recombination produces ejecta on longer timescales

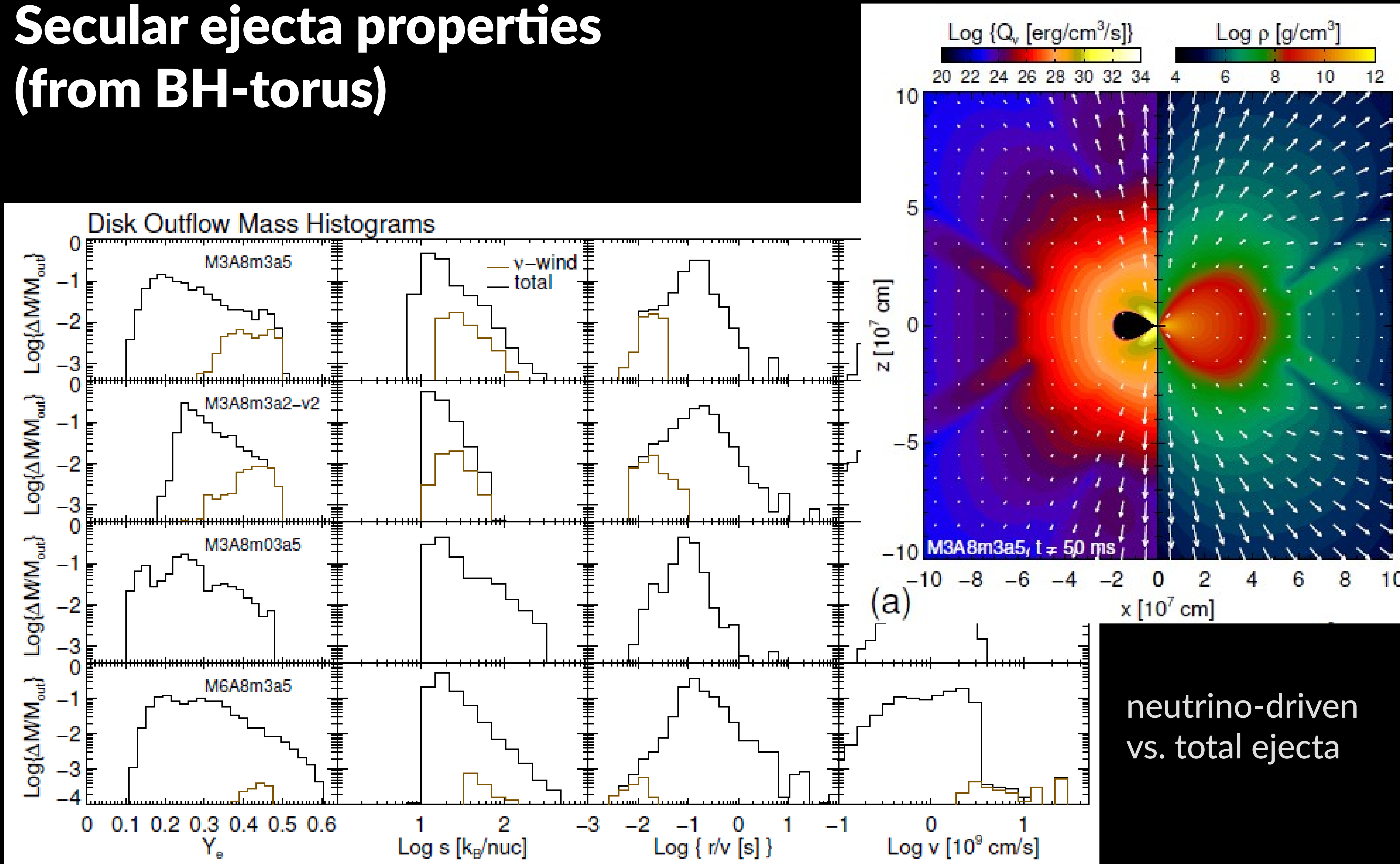
→ neutron-rich outflow for r-process (light r-process elements)

→ because of timescales neutrino effects are important

→ can be comparable to dynamical ejecta in mass

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, Martin et al 2015, ...

Secular ejecta properties (from BH-torus)

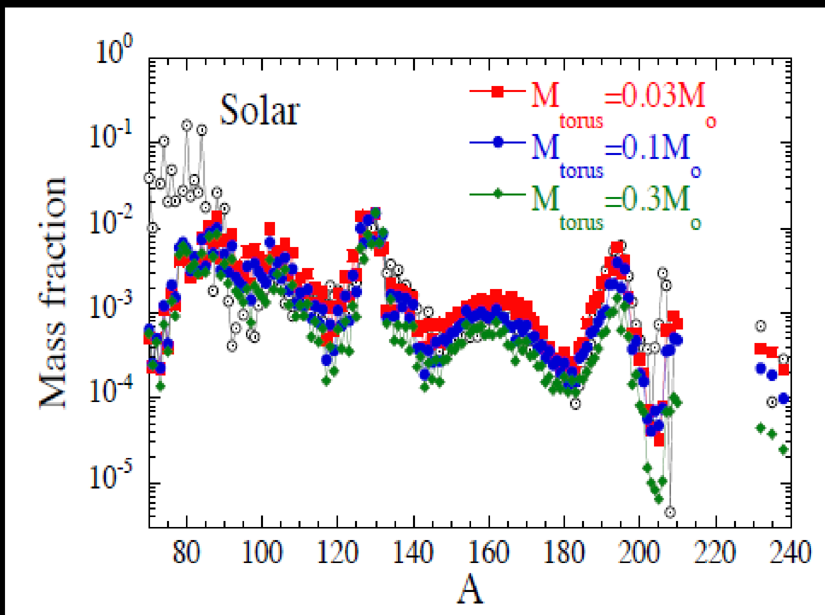


neutrino-driven vs. total ejecta

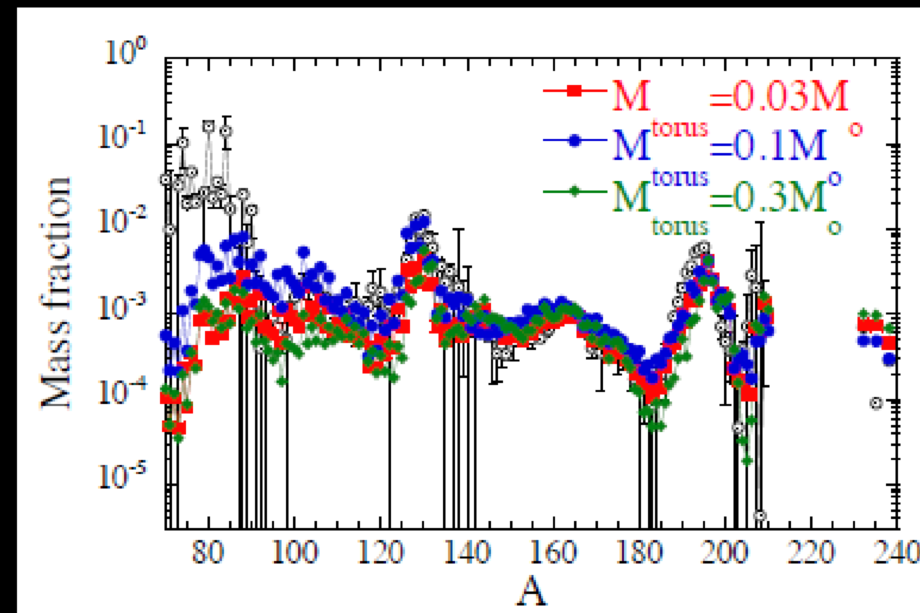
Just et al. 2014.

Long-term torus evolution including detailed neutrino transport (connected with merger simulations)

Nucleosynthesis of secular ejecta



Only secular ejecta



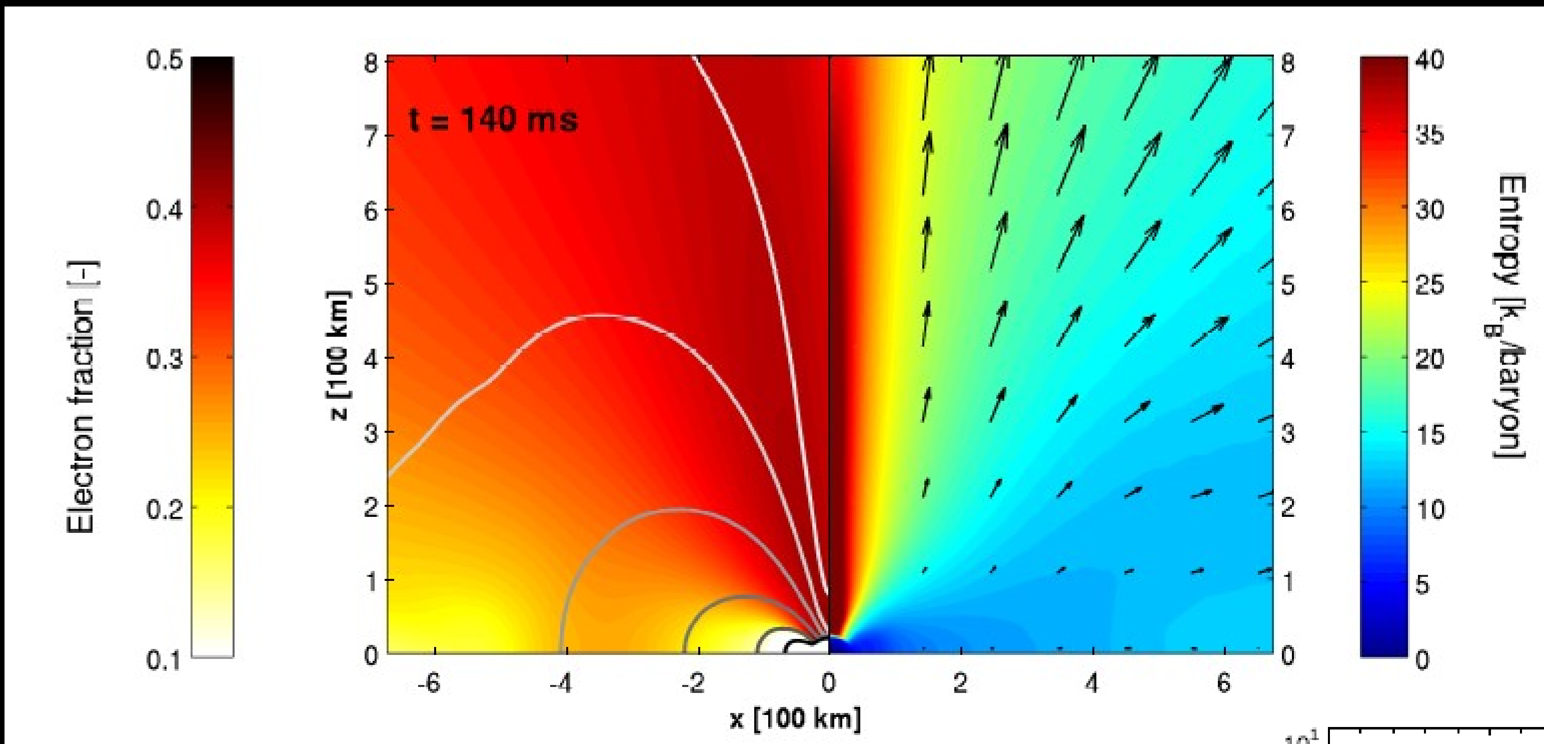
Secular and dynamical ejecta

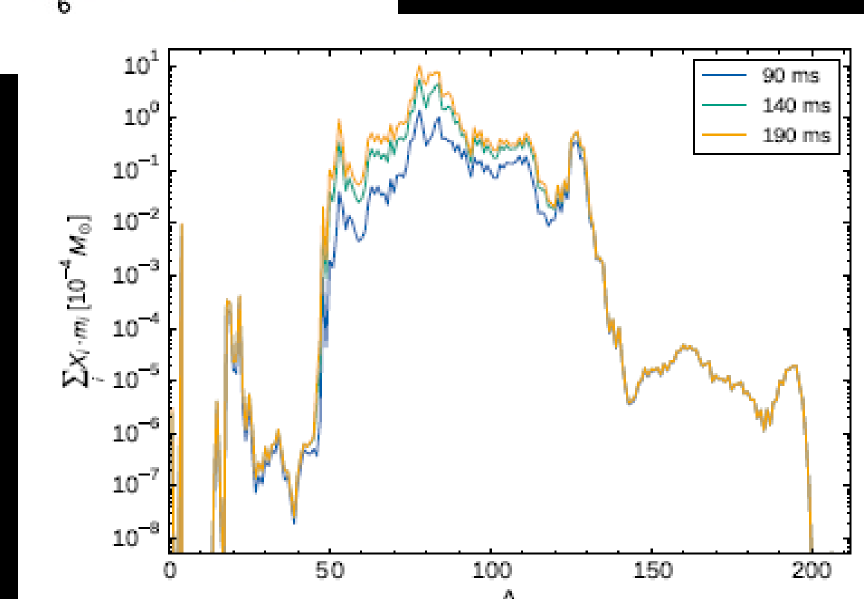
Just et al. 2014.

Mergers produce also the low A r-process elements

(similar for secular ejecta from long-lived NS remnant)

Secular ejecta from NS remnant



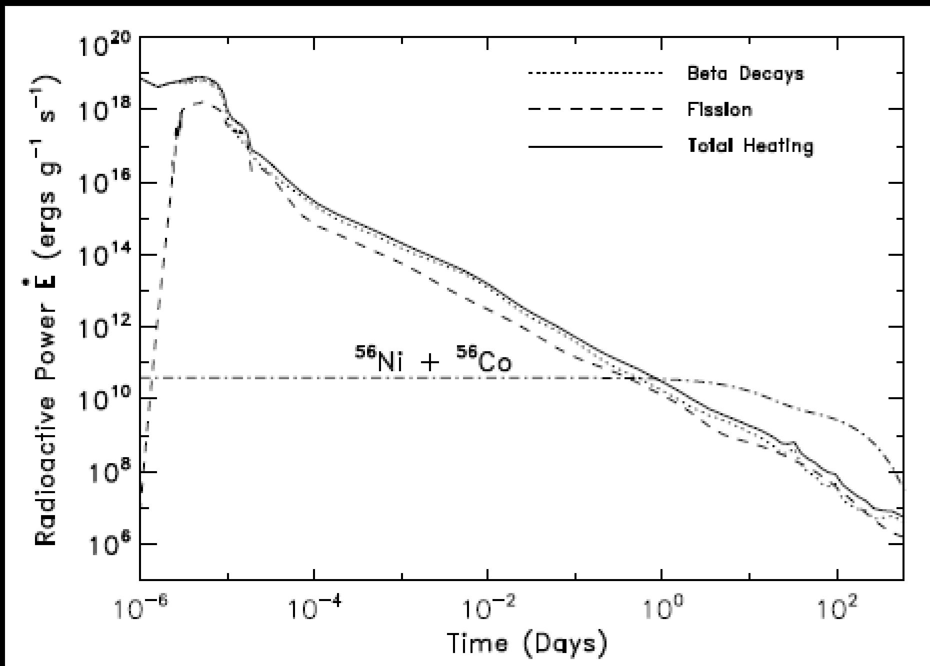


- Neutrino driven wind
- Total amount of wind ejecta crucially depends on life time of remnant (for long lived: ~10^{-2} Msun)
- Directional dependence
- Production of elements with A<130

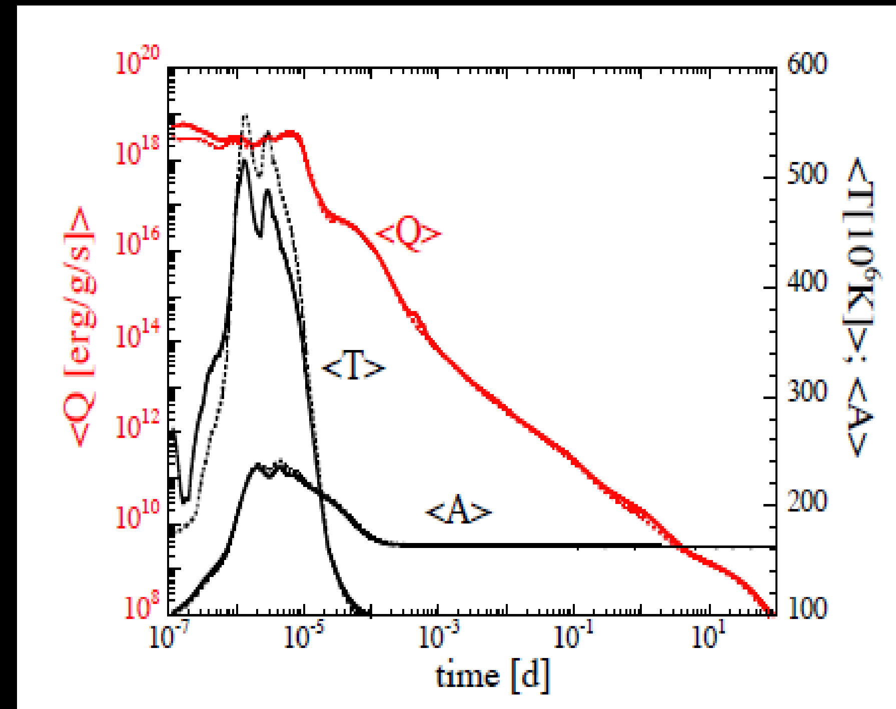
Martin et al. 2015

Electromagnetic counterparts of NS mergers powered by heating during the r-process
= Kilonova, macronova

Radioactive heating by r-process



Metzger et al. 2010



Goriely et al. 2011

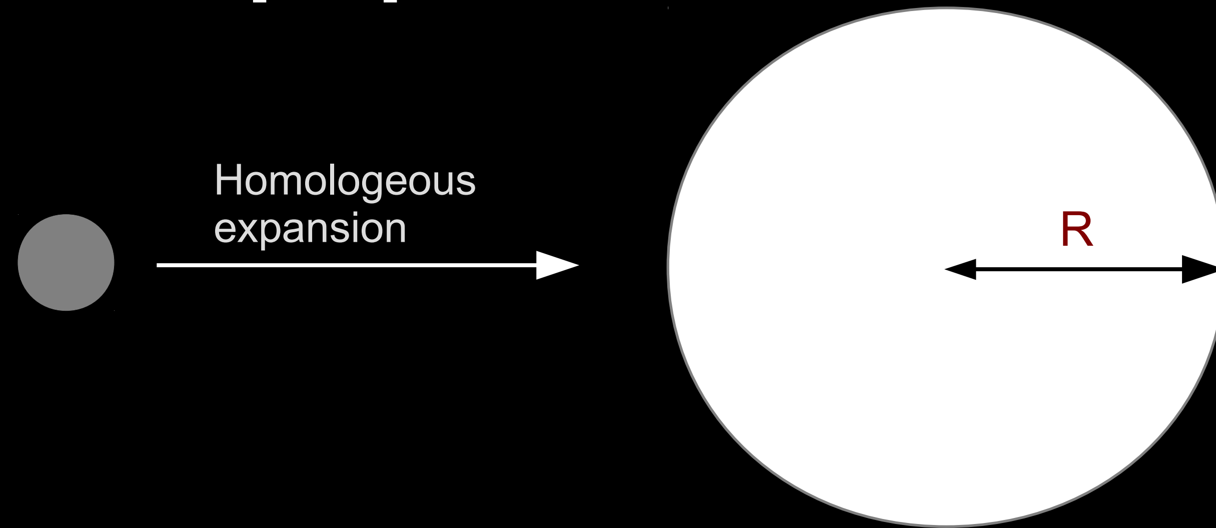
- Heating by beta-decays, fission and alpha-decays: about 3 – 4 MeV per nucleon (thermalized)
- Most energy released within seconds; power law because many nuclei with different half life times are involved
- Problem: matter opaque (not transparent) => initially not very bright (radiates only from surface), energy goes in expansion

Electromagnetic counterparts

- “kilonova” and “macronova” are synonym for em transient/counterpart powered by radioactive decays
- 3-4 MeV per nucleon by alpha and beta decays and fission → thermalize
- Potentially already observed in the aftermath of short GRBs (e.g. GRB130603B - triggered follow-up observation) → problem superseded by afterglow emission of GRB (interaction of jet with ambient medium)
- Thermal emission of initially opaque expanding ejecta bubble (a few 0.1 c)
- On time scale of ~hours - day ejecta becomes transparent → peak luminosity
- Problem in modeling/interpreting: opacities of heavy elements not well known (~100 times higher than Fe) → strongly dependent on composition of ejecta
- Relativistic hydrodynamical models of ejecta still challenging
- Depending on opacities, ejecta mass, velocities peaks in UV, optical or IR
- Targets of blind and triggered searches

Estimate emission properties

Metzger et al. 2010, Arnett 1982



$R = v \cdot t_{ex}$ Homologeous expansion (justified by numerical simulation)

t_{ex} measures size of expanding bubble

$$t_{diff} = \frac{0.07 \kappa M_{ej}}{c R}$$

Photon diffusion time (0.07 numerical factor for this geometry; kappa = opacity)

→ decreasing since R grows (all other quantities constant)

Initially only a few photons from the surface can escape

At $t_{ex} = t_{diff}$ photons from the center have enough time to diffuse out

→ peak of luminosity since we start seeing the whole bubble

Equating diffusion time and expansion time $\Rightarrow R_{peak} = v \cdot t_{peak} = \sqrt{\frac{0.07 \kappa v M_{ej}}{c}}$

$$\Rightarrow t_{peak} = \sqrt{\frac{0.07 \kappa M_{ej}}{v\,c}} = 1.6\,d \left(\frac{\kappa}{1\,cm^2/g}\right)^{1/2} \left(\frac{v}{0.1\,c}\right)^{-1/2} \left(\frac{M_{ej}}{10^{-2}\,M_\odot}\right)^{1/2}$$

Time of peak luminosity

Peak luminosity $L_{peak} = Q_{peak}/t_{peak}$

$$Q_{peak} \approx \dot{Q}_{peak}(t_{peak})/t_{peak} \approx f\,M_{ej}c^2$$

Available heat is some fraction of rest mass f<<1 (can be taken from calculations)

Combining yields:

$$L_{peak} = 1.6 \times 10^{41}\,erg/s \left(\frac{f}{10^{-6}}\right)^{1/2} \left(\frac{\kappa}{1\,cm^2/g}\right)^{-1/2} \left(\frac{v}{0.1\,c}\right)^{1/2} \left(\frac{M_{ej}}{10^{-2}\,M_\odot}\right)^{1/2}$$

→ temperature from Stefan-Boltzmann law

Key parameters: ejecta mass and velocity, heating efficiency, opacity (strongly dependent on composition: between ~0.1 … 100 cm^2/g – still uncertain) → strong variations possible, still uncertainties

More sophisticated radiative transfer models confirm that ballpark (e.g. Kasen et al. 2013,...)

Comments

- More advanced models available, but always based on one or the other assumption

  - Multi-component semi-analytic

  - Radiative transfer

- Challenge: interpretation/prediction requires calculation of opacities which are not fully available for r-process elements (complex atoms)

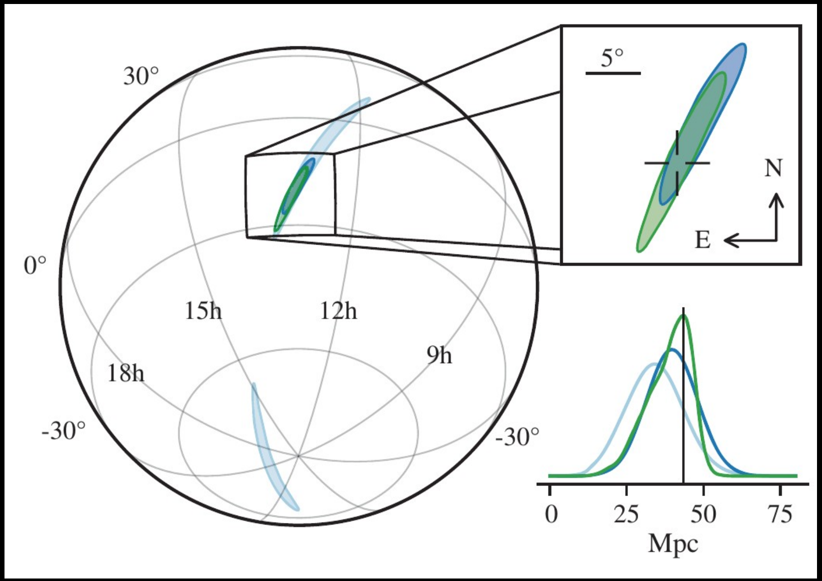
  - small admixture of lanthanides increases opacities drastically !!!

GW170817

Observations

- 1.7 sec after gamma-rays (→ short GRB ???)
- Follow up observation (UV, optical, IR) starting ~12 h after merger

  → ejecta masses, velocities, opacities
- Several days later X-rays, radio (ongoing)



Abbott et al. 2017

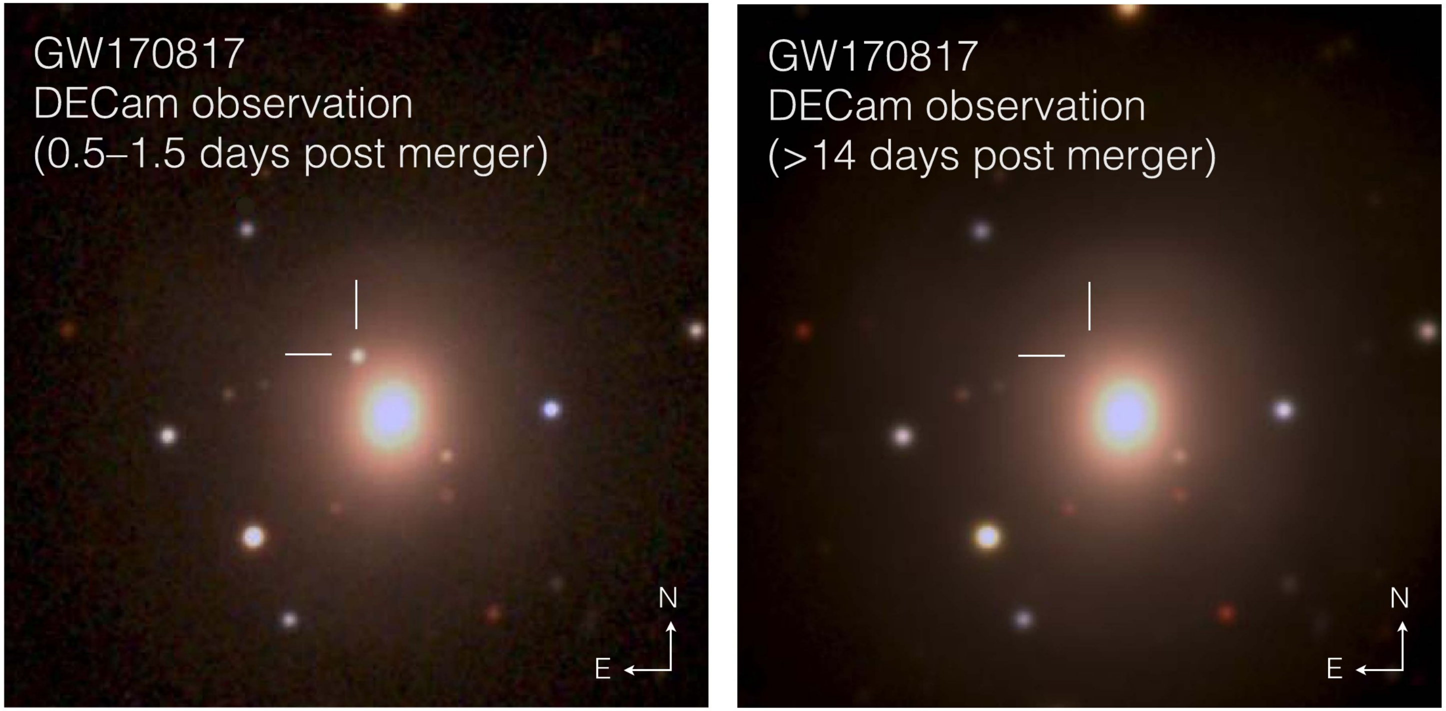
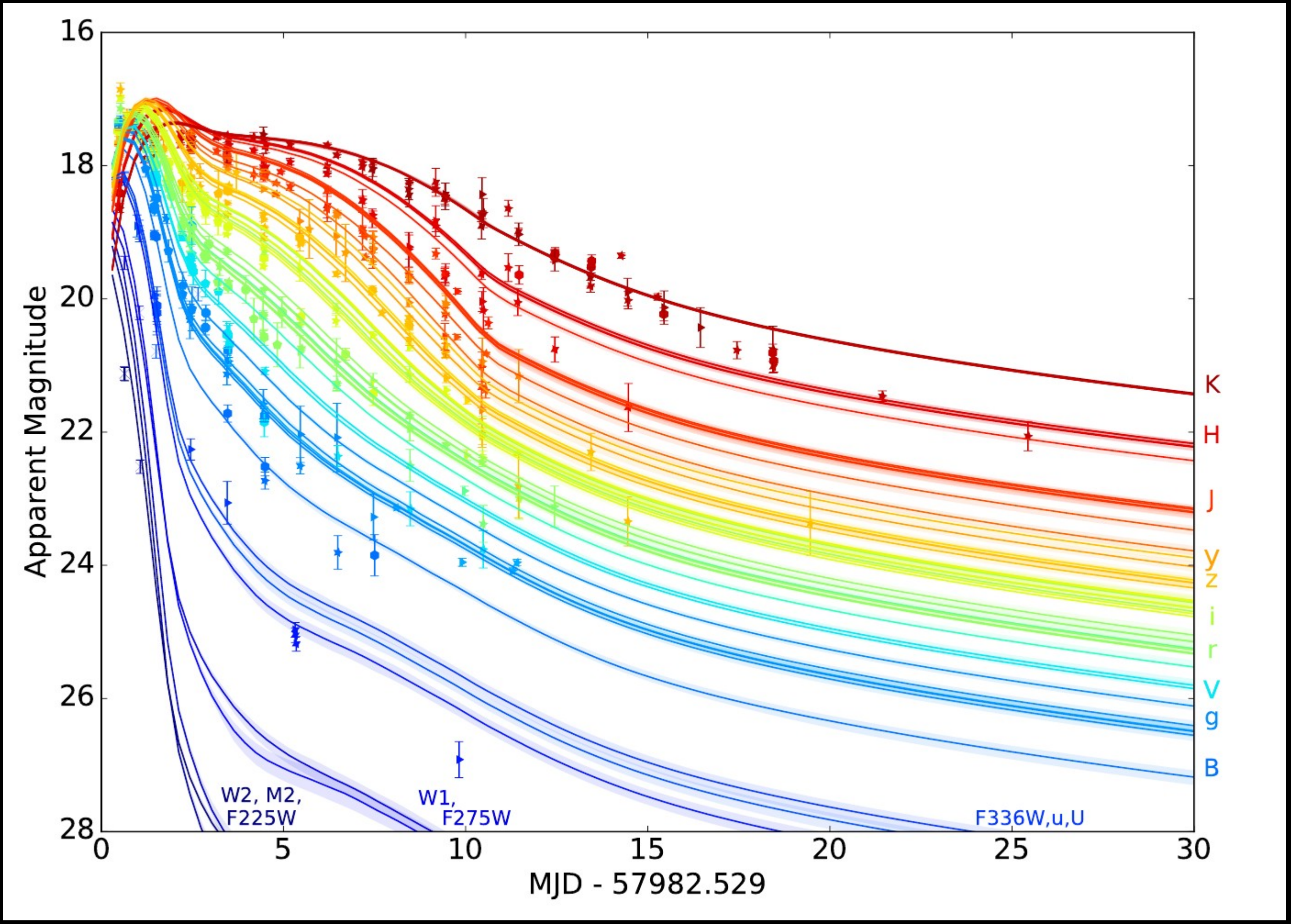


Figure 1. NGC4993 *grz* color composites ($1'.5 \times 1'.5$). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area two weeks later.

Soares-Santos et al 2017

Observations UVOIR – combined from different groups/observations



Villar et al. 2018

- From early blue to red
- Reasonable agreement with theoretical expectations

Basic picture

- High Ye (> 0.25) ↔ low opacities (lanthanide-free) ↔ bluish emission
- Low Ye (< 0.25) ↔ high opacities (lanthanides present) ↔ reddish emission

  → fission possibly important

- Simple scaling law (spherically symmetric expansion), see Metzger et al. 2010:

$$L_{peak} = 1.6 \times 10^{41}\, erg/s \left(\frac{f}{10^{-6}}\right)^{1/2} \left(\frac{\kappa}{1\, cm^2/g}\right)^{-1/2} \left(\frac{v}{0.1\, c}\right)^{1/2} \left(\frac{M_{ej}}{10^{-2}\, M_\odot}\right)^{1/2}$$

- More sophisticated models based on radiative transfer calculations, e.g. Kasen, Tanaka, ... (all models make some sort of assumptions)

Light curve interpretation

- Different modeling → overall good agreement with theoretical expectations
- blue + (purple) + red component, i.e. low-opacity material + high opacity material

  → component without / with lanthanides (heavy r-process elements)

  → component with high Ye (>~0.25) / low Ye
- No detailed abundance measurements (possibly Cs and Te, Smartt et al. 2017)

Villar et al. 2018

Model	M_{ej}^{blue}	v_{ej}^{blue}	κ_{ej}^{blue}	T^{blue}	M_{ej}^{purple}	v_{ej}^{purple}	κ_{ej}^{purple}	T^{purple}	M_{ej}^{red}	v_{ej}^{red}	κ_{ej}^{red}	T^{red}	σ	θ	WAIC
2-Comp	$0.023^{0.005}_{0.001}$	$0.256^{0.005}_{0.002}$	(0.5)	3983^{66}_{70}	-	-	-	-	$0.050^{0.001}_{0.001}$	$0.149^{0.001}_{0.002}$	$3.65^{0.09}_{0.28}$	1151^{45}_{72}	$0.256^{0.006}_{0.004}$		-1030
3-Comp	$0.020^{0.001}_{0.001}$	$0.266^{0.008}_{0.008}$	(0.5)	674^{486}_{417}	$0.047^{0.001}_{0.002}$	$0.152^{0.005}_{0.005}$	(3)	1308^{42}_{34}	$0.011^{0.002}_{0.001}$	$0.137^{0.025}_{0.021}$	(10)	3745^{75}_{75}	$0.242^{0.008}_{0.008}$		-1064
Asym. 3-Comp	$0.009^{0.001}_{0.001}$	$0.256^{0.009}_{0.004}$	(0.5)	3259^{302}_{306}	$0.007^{0.001}_{0.001}$	$0.103^{0.007}_{0.004}$	(3)	3728^{94}_{178}	$0.026^{0.004}_{0.002}$	$0.175^{0.011}_{0.008}$	(10)	1091^{29}_{45}	$0.226^{0.006}_{0.006}$	66^{1}_{3}	-1116

See also Chronock et al. 2017, Levan & Tanvir 2017, Kasliwal et al. 2017, Coulter et al. 2017, Allam et al. 2017, Yang et al. 2017, Arcavi et al. 2017, Kilpatrick et al. 2017, McCully et al. 2017, Pian et al. 2017, Arcavi et al. 2017, Evans et al. 2017, Drout et al. 2017 Lipunov et al. 2017, Cowperthwaite et al. 2017, Smarrt et al. 2017, Shappee et al. 2017, Nicholl et al. 2017, Kasen et al. 2017, Tanaka et al. 2017, …..

Warning: many quantitative uncertainties – inferring EoS properties just from em counterpart is basically hopeless !!!

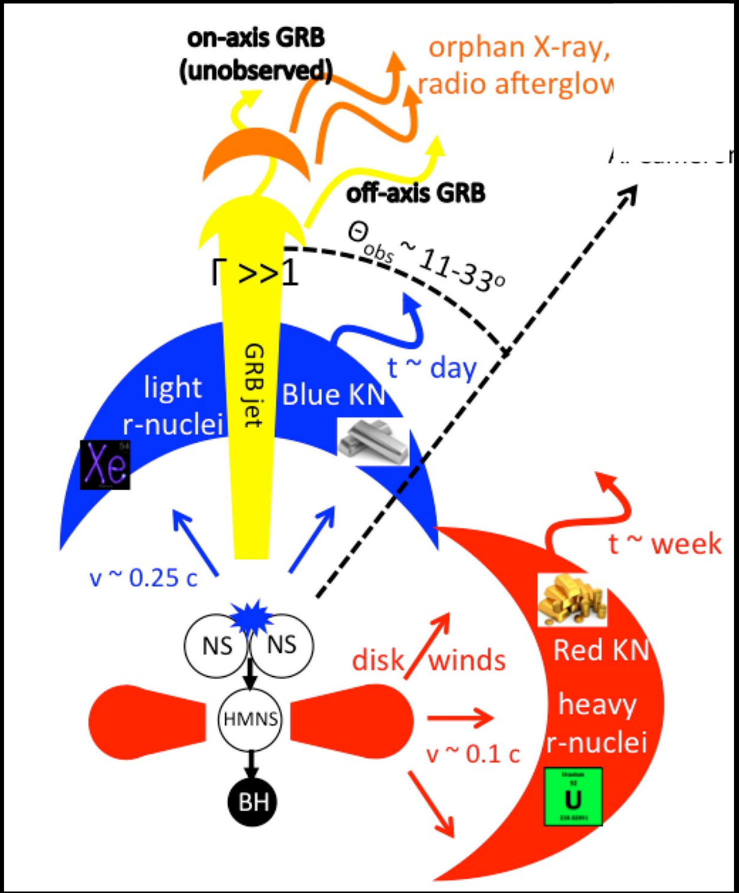
Observations

- Many IR/opt/UV observations by many groups
- Different interpretations / modeling
- Red and blue component
- Spectral features?
- Derived total ejecta masses all in the range 0.03 … 0.05 Msun

Chronock et al. 2017, Levan & Tanvir 2017, Kasliwal et al. 2017, Coulter et al. 2017, Allam et al. 2017, Yang et al. 2017, Arcavi et al. 2017, Kilpatrick et al. 2017, McCully et al. 2017, Pian et al. 2017, Arcavi et al. 2017, Evans et al. 2017, Drout et al. 2017 Lipunov et al. 2017, Cowperthwaite et al. 2017, Smarrt et al. 2017, Shappee et al. 2017, Nicholl et al. 2017, Kasen et al. 2017, Tanaka et al. 2017, …..

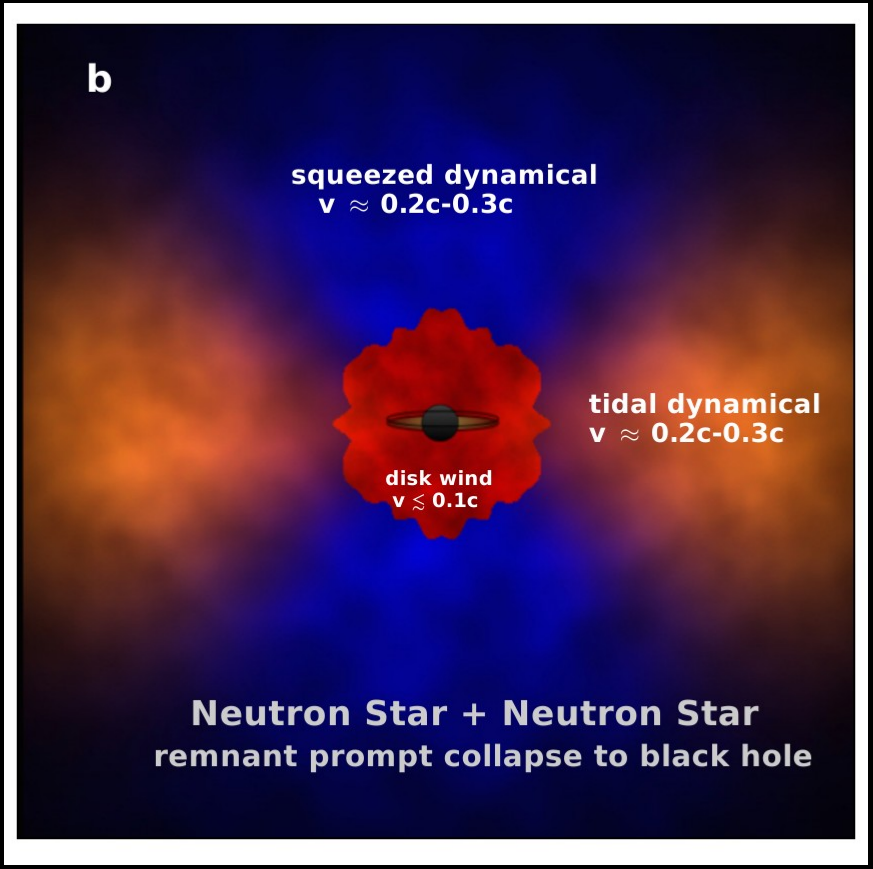
Reference	$m_{\rm dyn}$ $[M_\odot]$	$m_{\rm w}$ $[M_\odot]$
Abbott et al. (2017a)	$0.001 - 0.01$	–
Arcavi et al. (2017)	–	$0.02 - 0.025$
Cowperthwaite et al. (2017)	0.04	0.01
Chornock et al. (2017)	0.035	0.02
Evans et al. (2017)	$0.002 - 0.03$	$0.03 - 0.1$
Kasen et al. (2017)	0.04	0.025
Kasliwal et al. (2017b)	> 0.02	> 0.03
Nicholl et al. (2017)	0.03	–
Perego et al. (2017)	$0.005 - 0.01$	$10^{-5} - 0.024$
Rosswog et al. (2017)	0.01	0.03
Smartt et al. (2017)	$0.03 - 0.05$	0.018
Tanaka et al. (2017a)	0.01	0.03
Tanvir et al. (2017)	$0.002 - 0.01$	0.015
Troja et al. (2017)	$0.001 - 0.01$	$0.015 - 0.03$

Compilation by Cote et al 2018



Metzger 2017

Possible interpretation



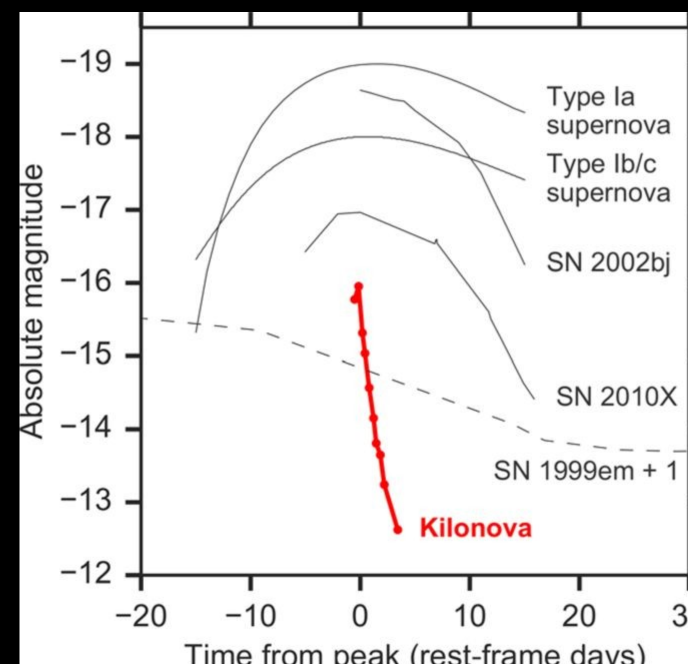
Kasen et al. 2017

Interpretation - implications

- heating and derived opacities are compatible with r-processing ejecta !!!

  (not surprising for a theorist, see earlier work on r-process and em counterparts)
- Ejecta velocities and masses in ballpark of simulation results (→ later)
- Precise composition basically unknown (claims for spectral features), red component suggest some admixture of heavy r-process elements with high opacities
- Derived ejecta masses are compatible with mergers being the main source of heavy r-process elements in the Universe

  → overall strong evidence that NS mergers play a prominent role for heavy element formation

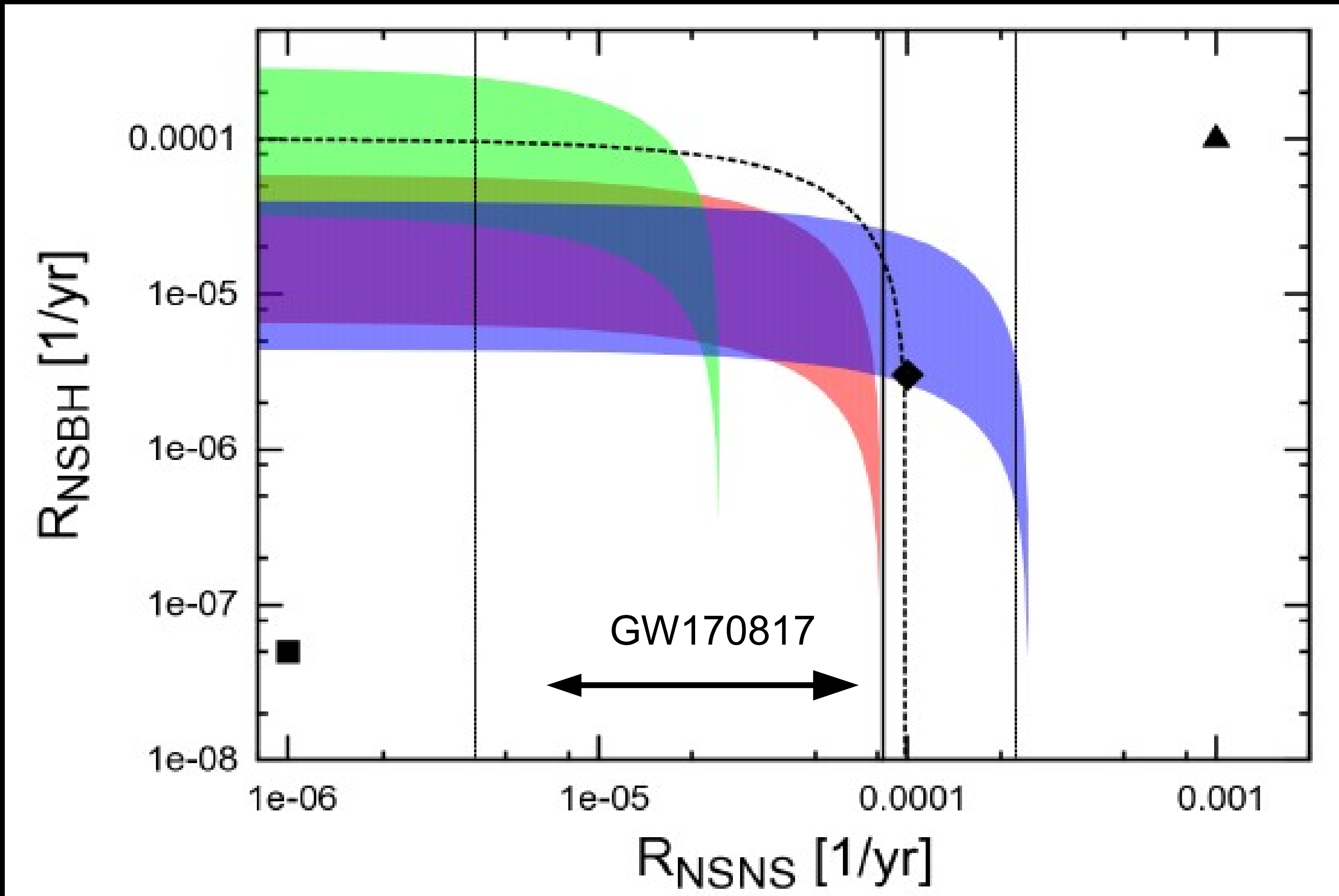


Arcavi et al. 2017

$$M_{A>140,Galaxy} = \left(\bar{M}_{NSNS} R_{NSNS} + \bar{M}_{NSBH} R_{NSBH}\right) \tau_{Galaxy}$$

Considering only heavy elements with A > 140

=> not clear how much of this material in GW170817 !!!



M_{ej}(NSNS):

Blue: 10^{-3} M_{sun}

Red: $3*10^{-3}$ M_{sun}

Green: 10^{-2} M_{sun}

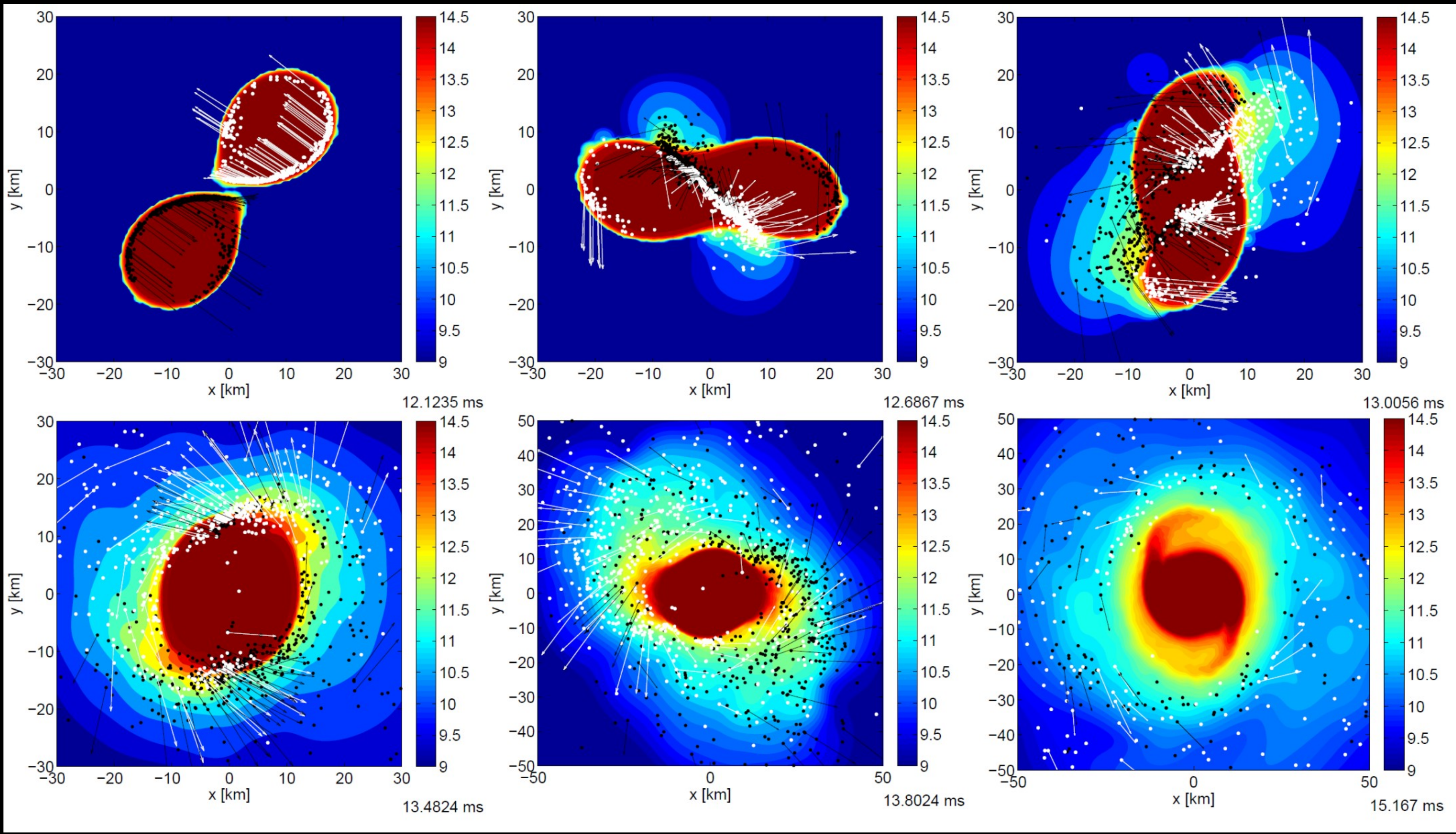
- Colored bands: rates for different EoSs
- Symbols: population synthesis predictions (Abadie et al. 2010)
- Vertical lines: pulsar observations (Kalogera et al. 2004)
- Dashed curve: short GRBs (Berger 2013)
- Arrow: volumetric rate (Abbott et al. 20017) converted to Galactic rate

Simulation results – ejecta

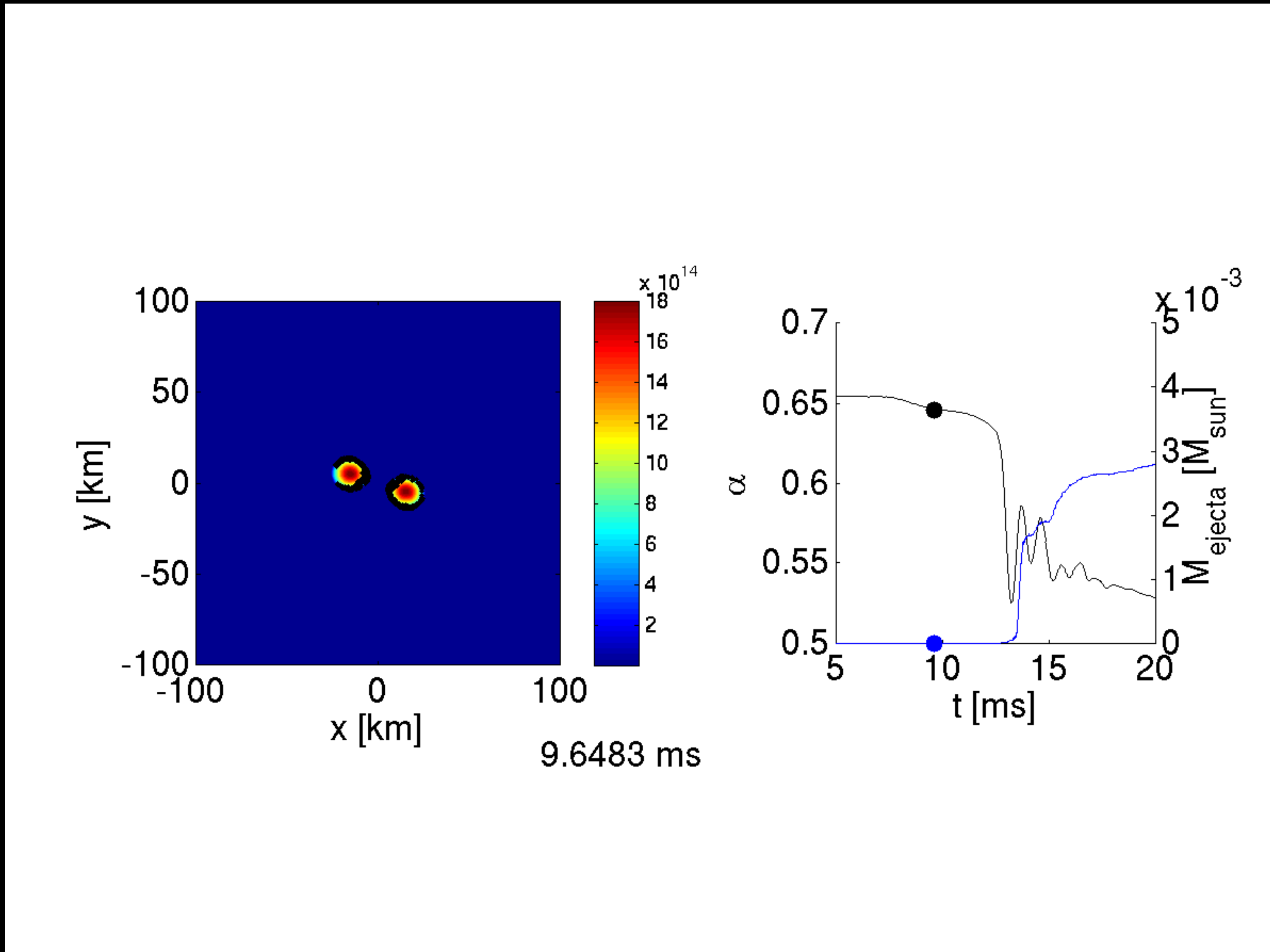
(EoS and binary mass dependence)

Simulations

Dots trace ejecta (DD2 EoS 1.35-1.35 M_{sun})



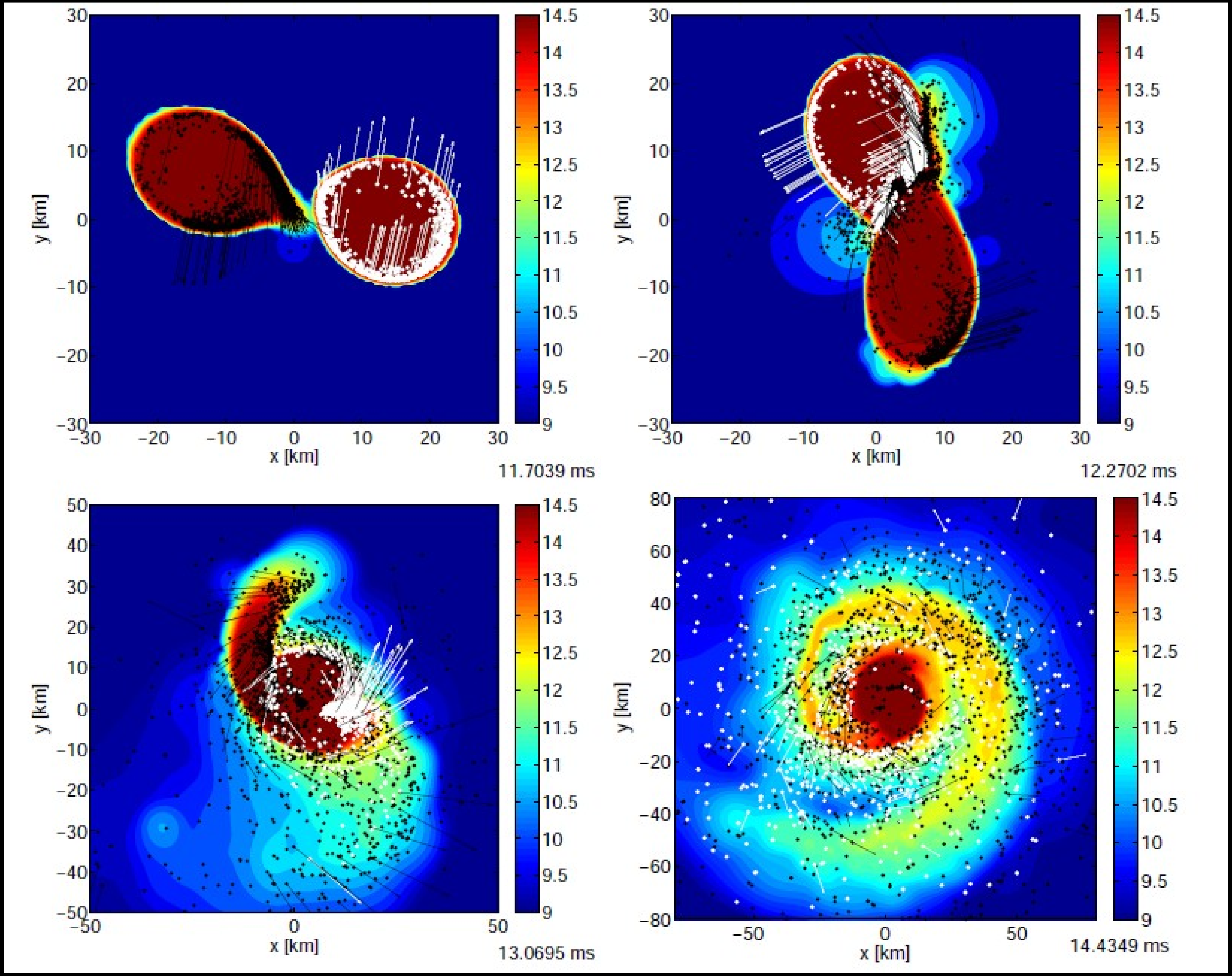
Bauswein et al. 2013



Black: bound; white: unbound (formally)

Central lapse: measure for compactness

Asymmetric mergers

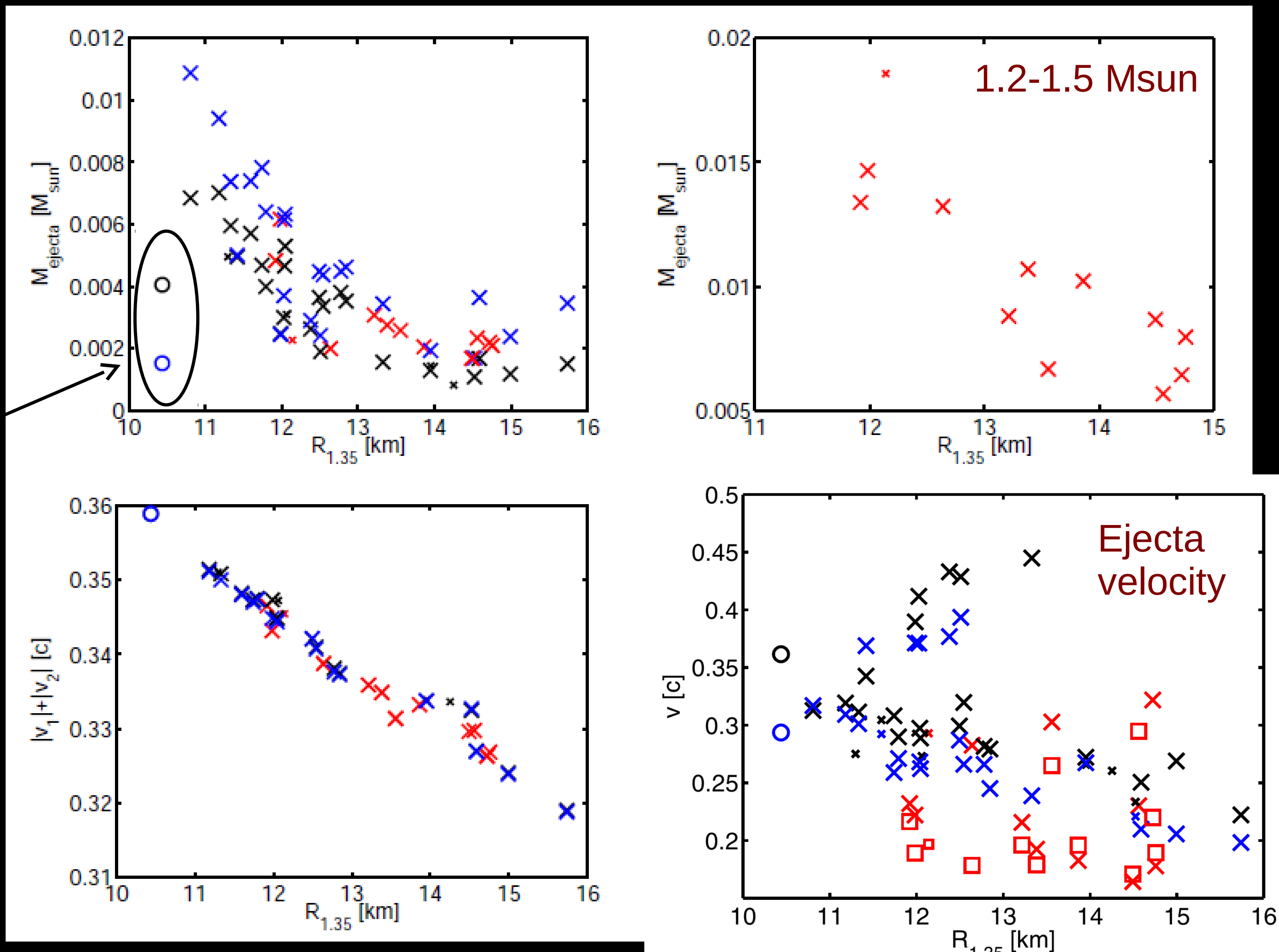


→ larger tidal component, larger total ejecta masses

Bauswein et al. 2013

Ejecta mass dependence

Prompt collapse



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

Coarse picture: EoS dependence of ejecta mass

- Ejecta mass 0.03-0.05 Msun in GW170817
- Excludes tentatively very stiff EoSs
- Excludes tentatively very soft EoSs – prompt collapse !!!

Reference	$m_{\rm dyn}$ $[M_\odot]$	$m_{\rm w}$ $[M_\odot]$
Abbott et al. (2017a)	$0.001-0.01$	–
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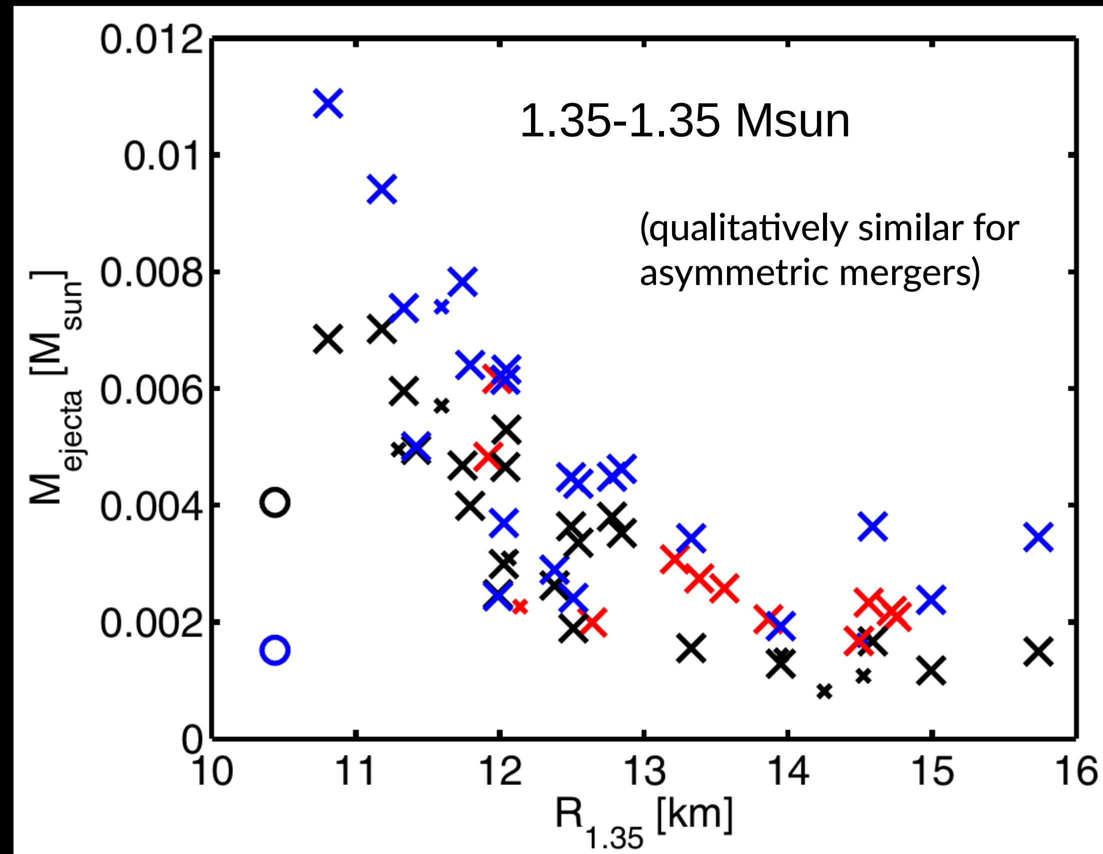
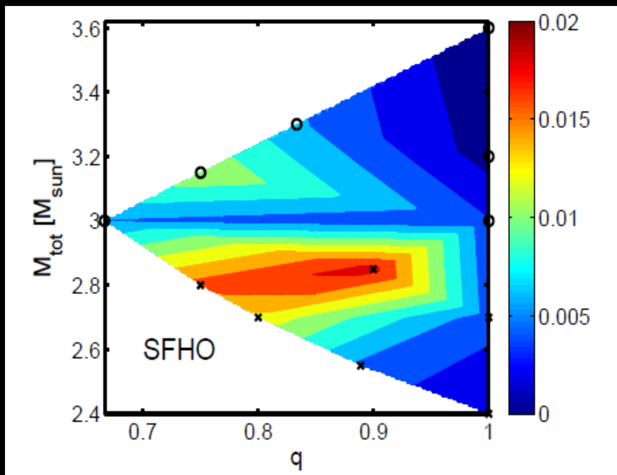


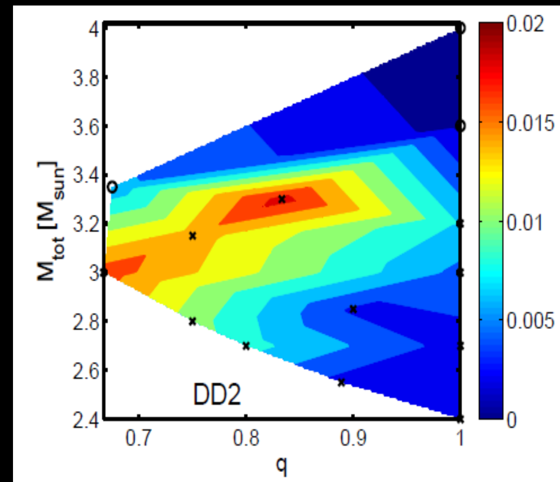
Bauswein et al 2013, see also Hotokezaka et al 2013

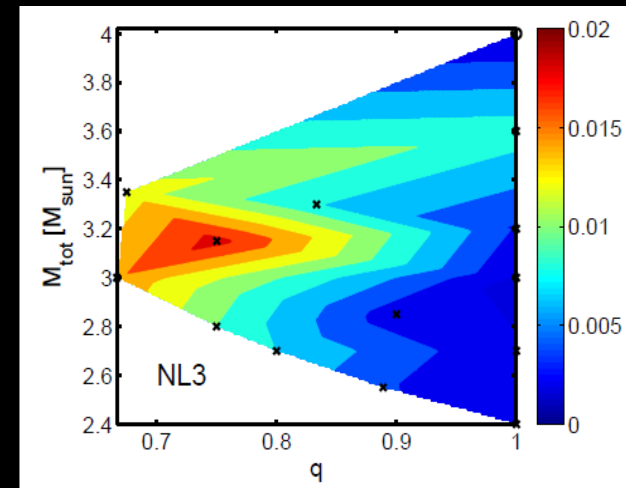
+ secular ejecta (viscous, neutrino)

Compilation in Cote et al 2018

Ejecta mass dependencies: binary para.

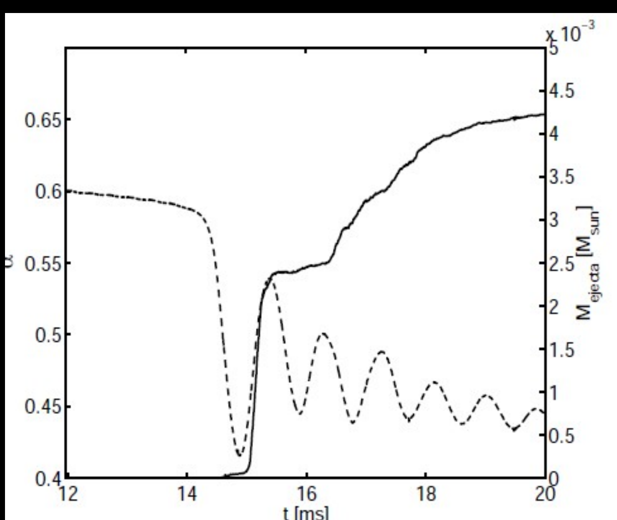


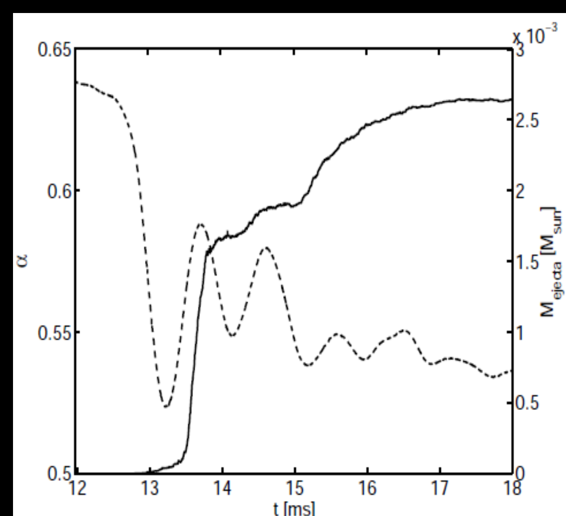


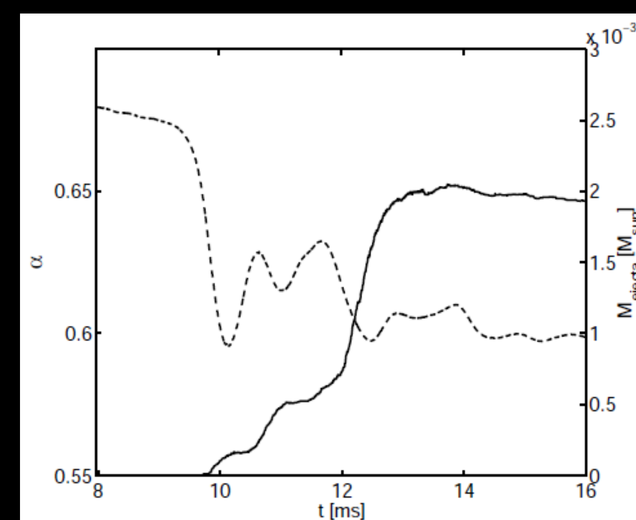


Stiffness

understandable by different dynamics / impact velocity / postmerger oscillations



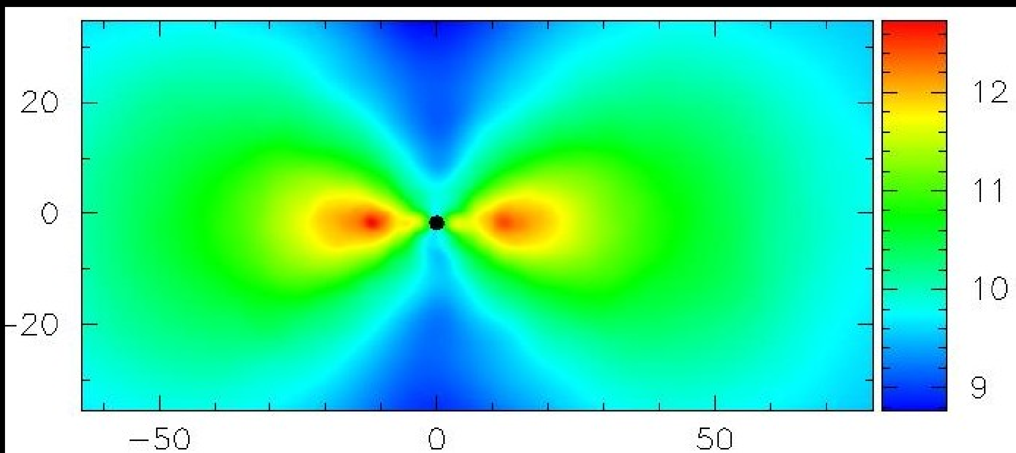


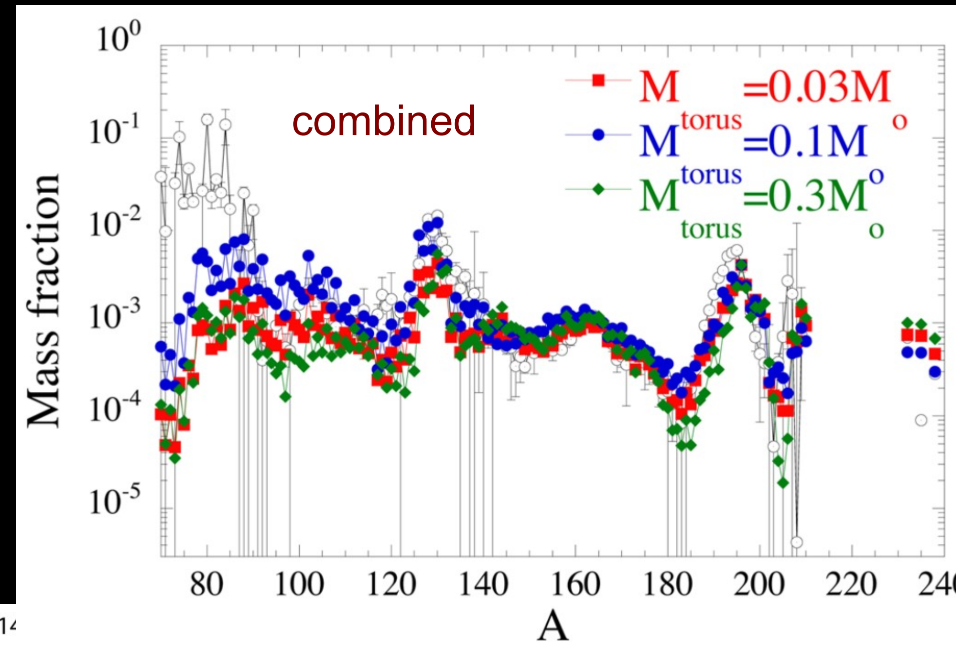


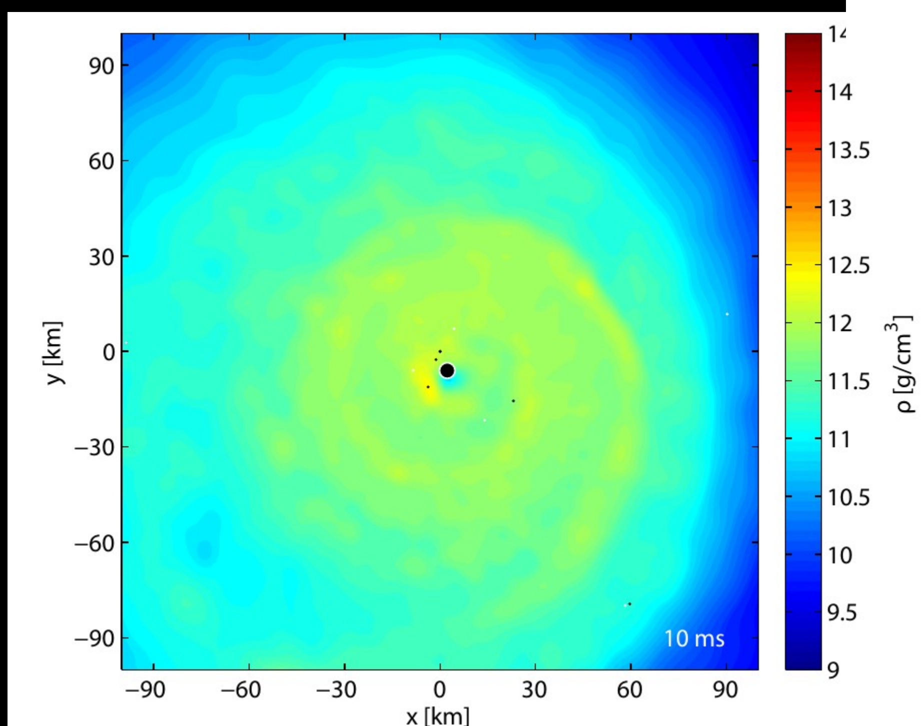
Central lapse α traces remnant compactness / oscillations / dynamics (dashed lines)

Secular and dynamical ejecta

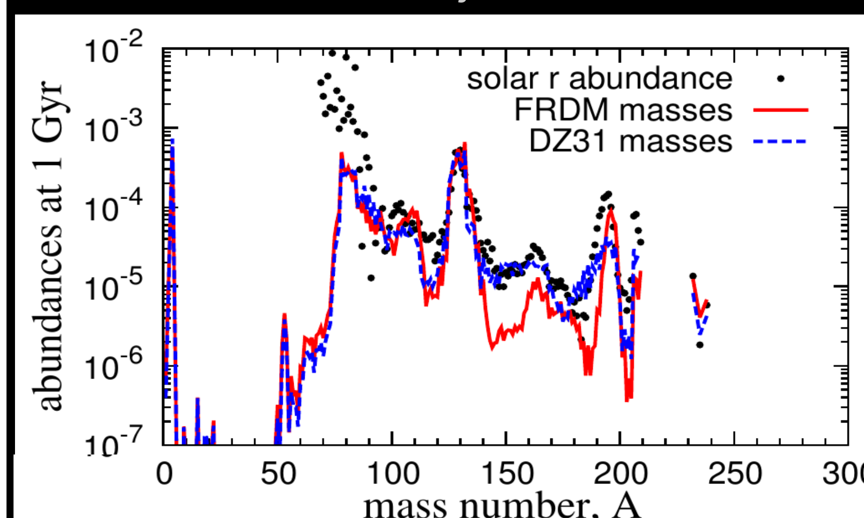
Just et al. 2015



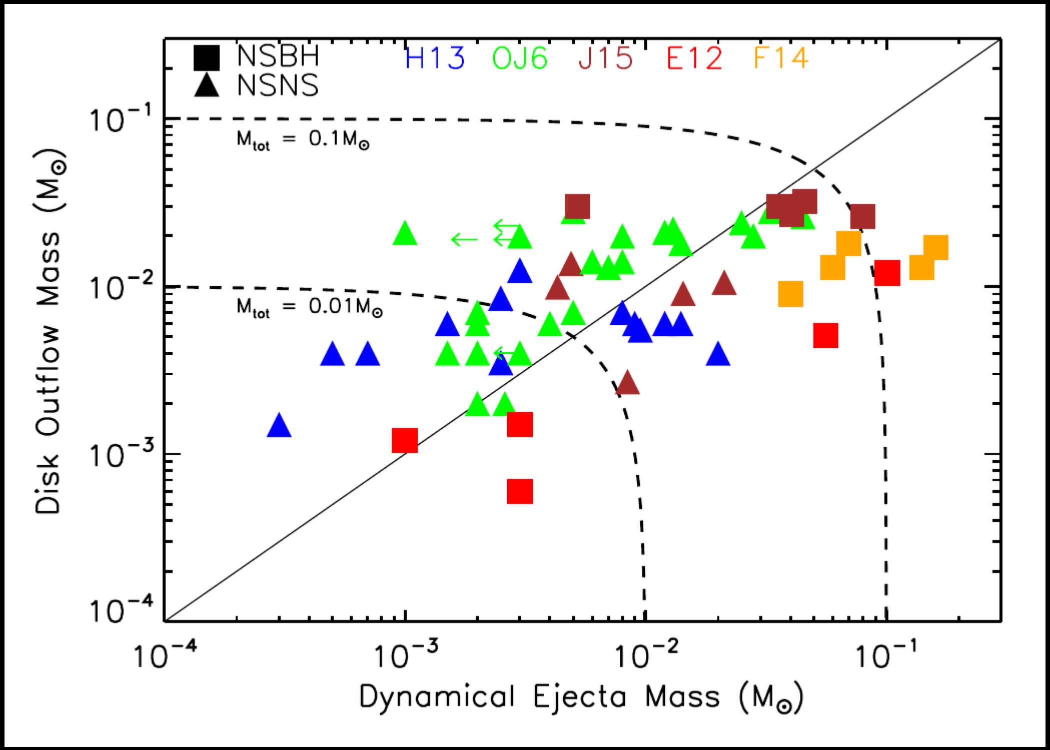




Wu et al. 2016, only secular ejecta



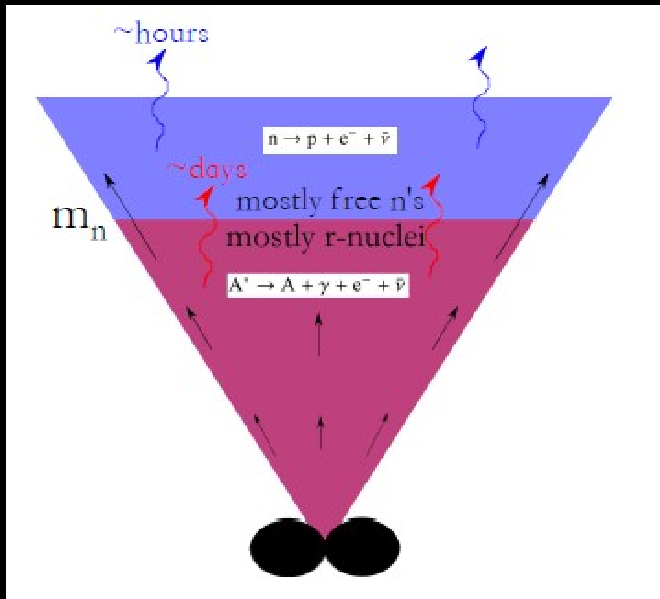
Secular ejecta

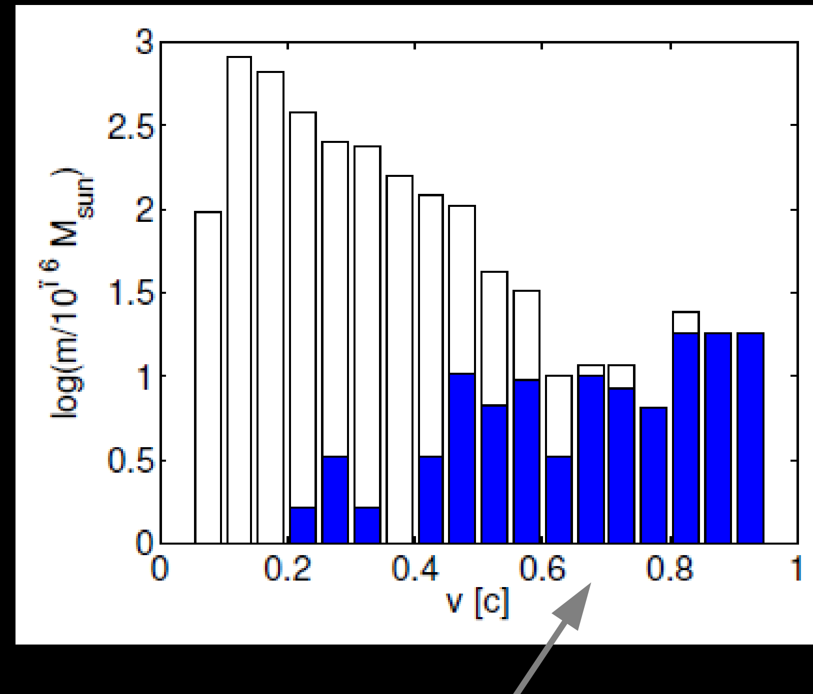


Wu et al. 2016

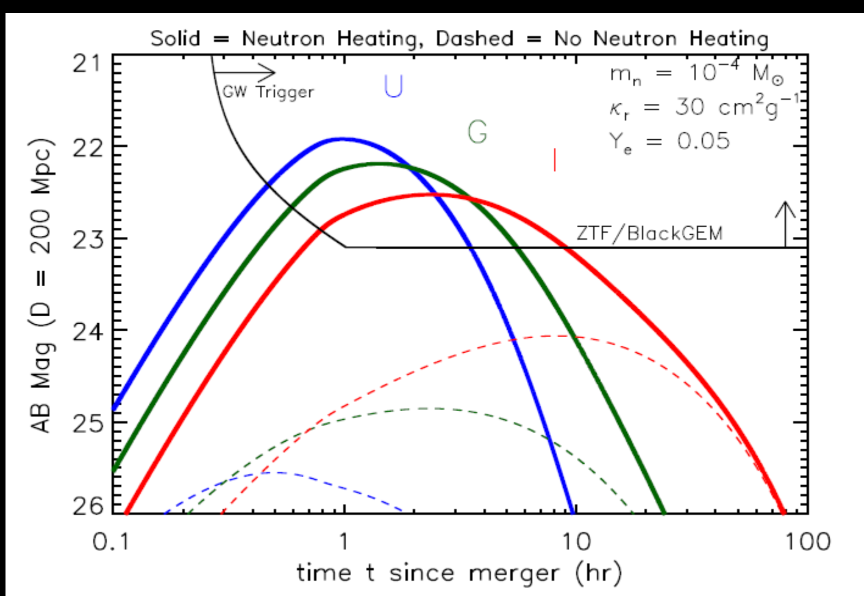
Typically several per cent of disk mass ejected (e.g. Fernandez et al. 2014, Perego et al. 2014, Just et al 2015) → production of light and heavy r-process elements, contributing to em counterpart

Kilonova precursors





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



Metzger et al. 2015

- Neutron decay leads to early, bright, optical emission
- Easier to detect, interesting for GW follow up and as trigger for deeper observations of the later lightcurve
- Very promising but hard to resolve numerically (model uncertainties)

Summary – Part 1

- NS mergers very likely progenitors of short gamma-ray bursts
- Different ejecta components: dynamical vs secular ejecta (comparable in mass)
- NS mergers produce heavy elements through the rapid neutron capture process (theoretically expected then observed)

  - possibly dominant source of heavy elements
- NS mergers produce electromagnetic counterpart (quasi-thermal emission) powered radioactive decays during r-process
- Light curve properties and inferred parameter (like ejecta masses) compatible with theoretical expectations (from simulations)
- Still a lot of work ahead to understand mass ejection, nucleosynthesis and emission properties

EoS / NS constraints

Importance of EoS

- Understand properties of high-density matter (hardly accessible by laboratory experiments – theoretically challenging)

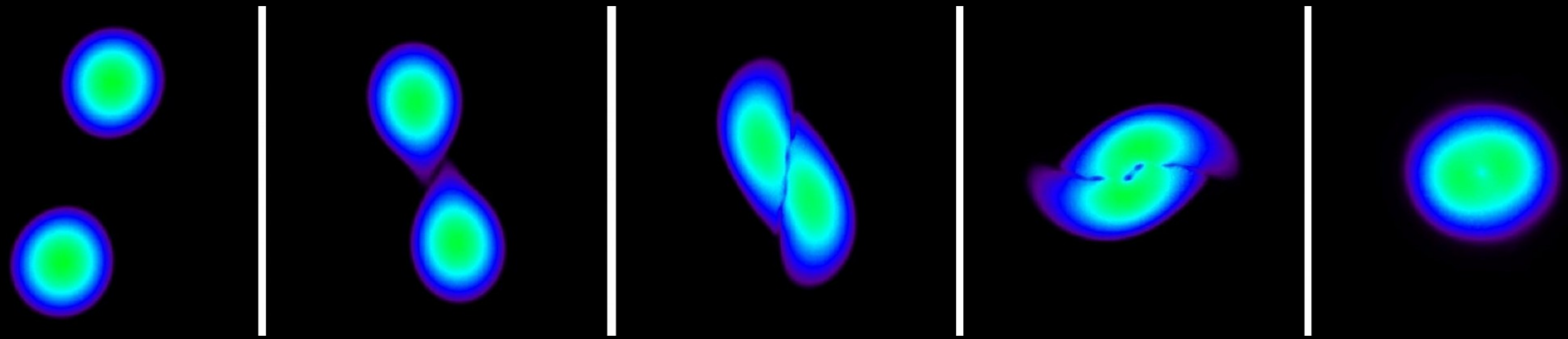
  → e.g. nuclear parameter/models (also important for nucleosynthesis models)

  → phase transition to hyperonic matter? Quark matter?

- Stellar properties of NS (observationally challenging)

  → EoS affects dynamics/phenomenology of mergers (e.g em counterparts, nucleosynthesis, GRBs), supernovae, NS cooling, ...

Finite-size effects during late inspiral



See Lattimer's talk

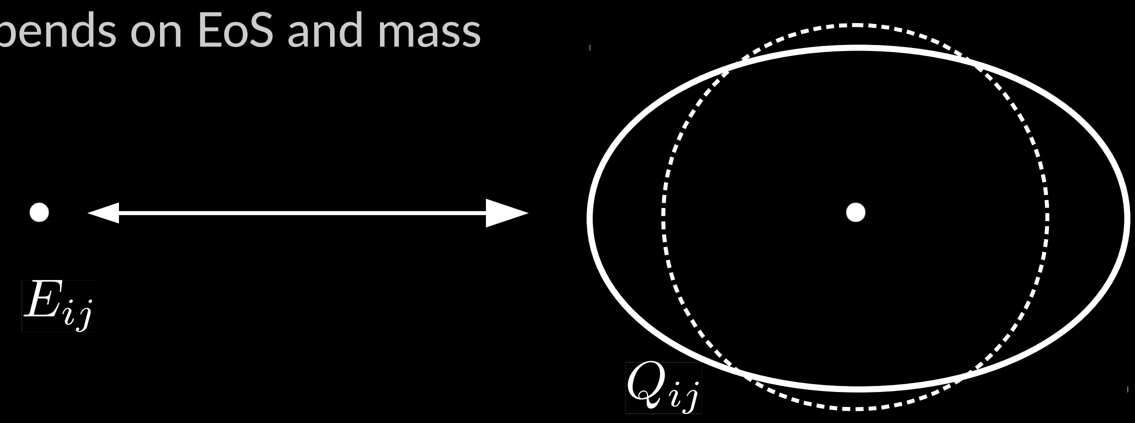
Description of tidal effects during inspiral

- Tidal field E_{ij} of on star induces change of quadrupole moment Q_{ij} of other component
- Changed quadrupole moment affects GW signal, especially phase evolution

  → inspiral faster compared to point-particle inspiral
- Strength of induced quadrupole moment depends on NS structure / EoS:

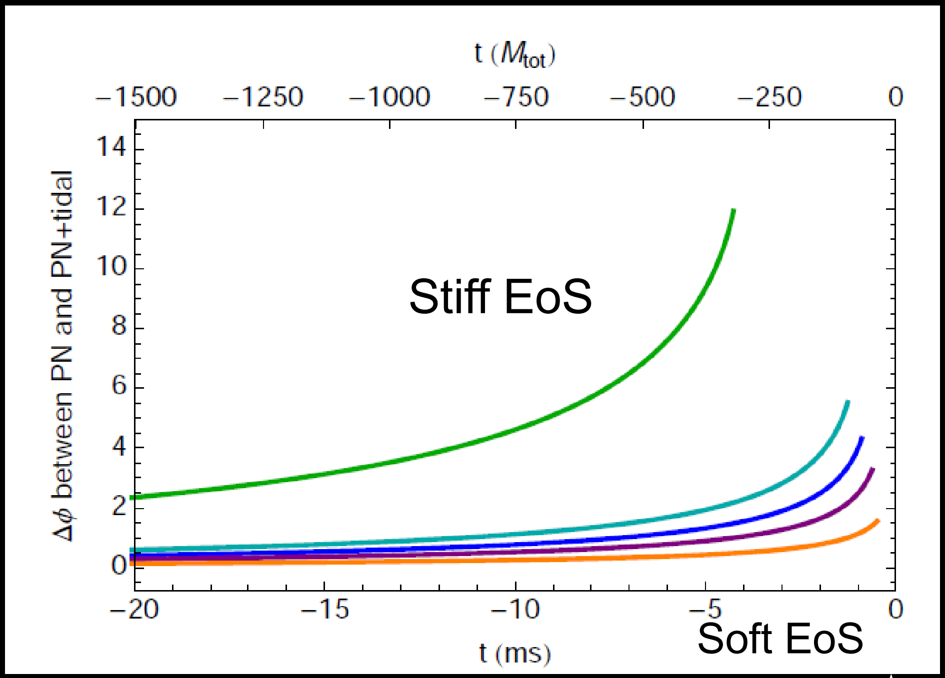
$$Q_{ij} = -\lambda(M)\, E_{ij} \qquad\qquad \lambda(M) = \frac{2}{3} k_2(M) R^5$$

- Tidal deformability depends on radius (clear – smaller stars are harder to deform) and "Love number" k_2 (~"TOV" properties)
- k_2 also depends on EoS and mass



Inspiral

- Orbital phase evolution affected by tidal deformability – only during last orbits before merging
- Inspiral accelerated compared to point-particle inspiral for larger Lambda
- Difference in phase between NS merger and point-particle inspiral:



EoS impact measured by tidal deformability

$$\Lambda(M) = \frac{2}{3} k_2(M) \left(\frac{c^2 R}{G\, M} \right)^5$$

e.g. Read et al. 2013

Merger time of point particle

Challenge: construct faithful templates for data analysis

Measurement

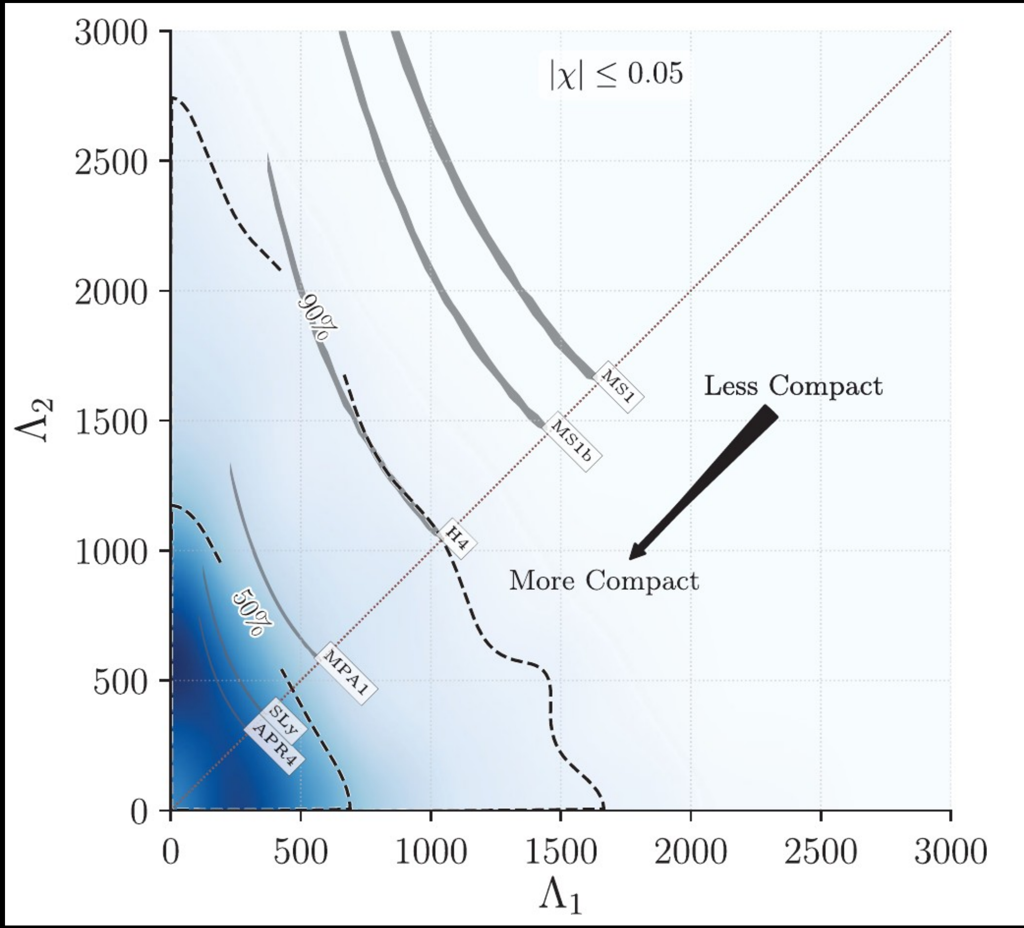
- Lambda < ~800

  → Means that very stiff EoSs are excluded

- Recall uncertainties in mass measurements (only Mchirp accurate)
- systematic errors in waveform model

  → ongoing research

- Better constraints expected in future as sensitivity increases

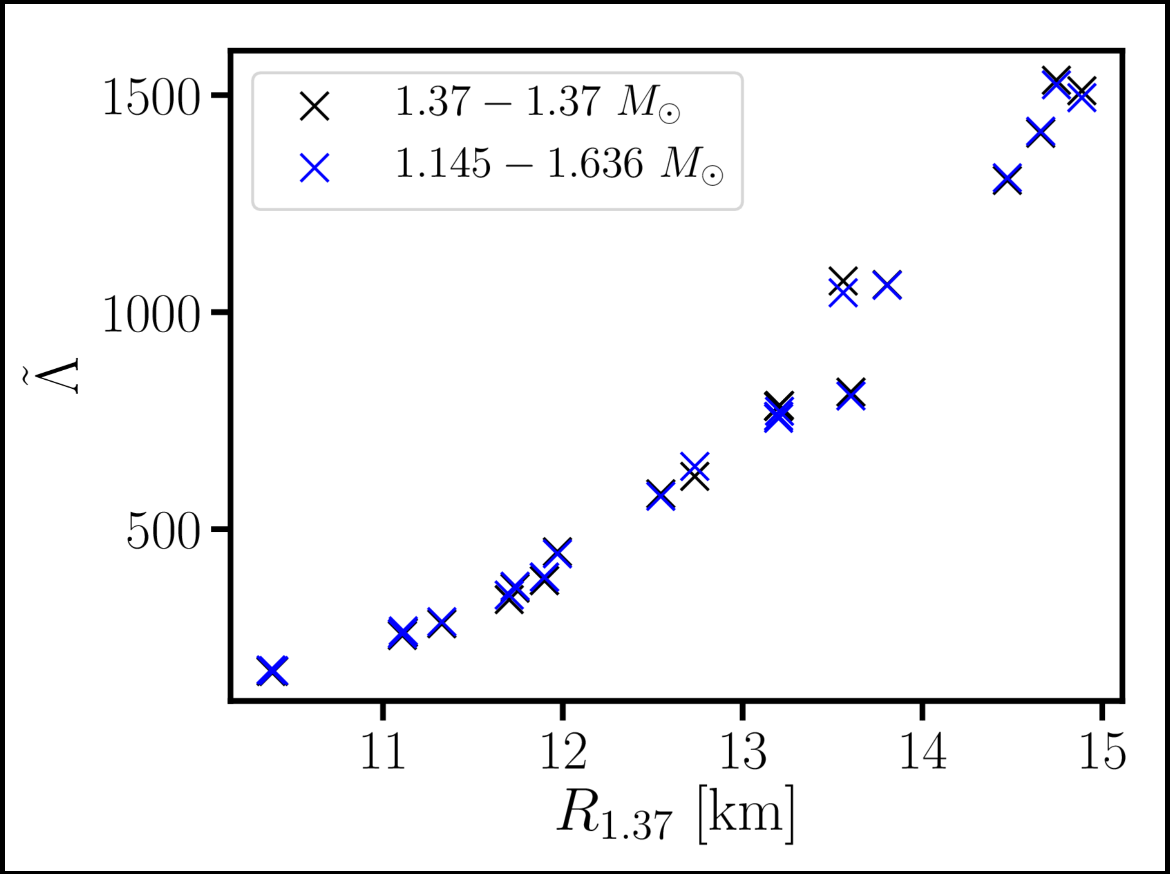


$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

Abbott et al. 2017
See also later publications by Ligo/Virgo collaboration, De et al. 2018

See Lattimer's talk

- Combined tidal deformability vs. radius (for constant chirp mass)



→ GW170817 constrains NS radii from above