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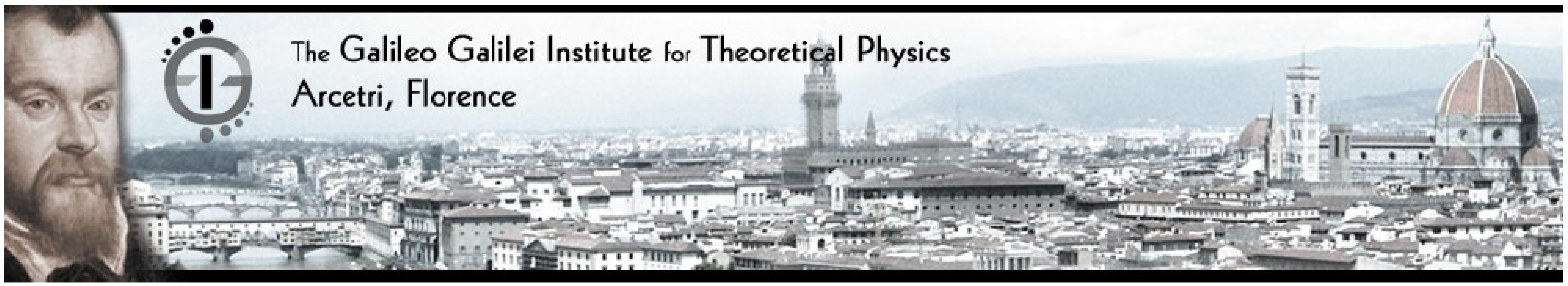


The Structure and Signals of Neutron Stars, from Birth to Death

Firenze, Italia, March 24–28, 2014

Numerical Modeling of Neutron Star Mergers and Their Remnants

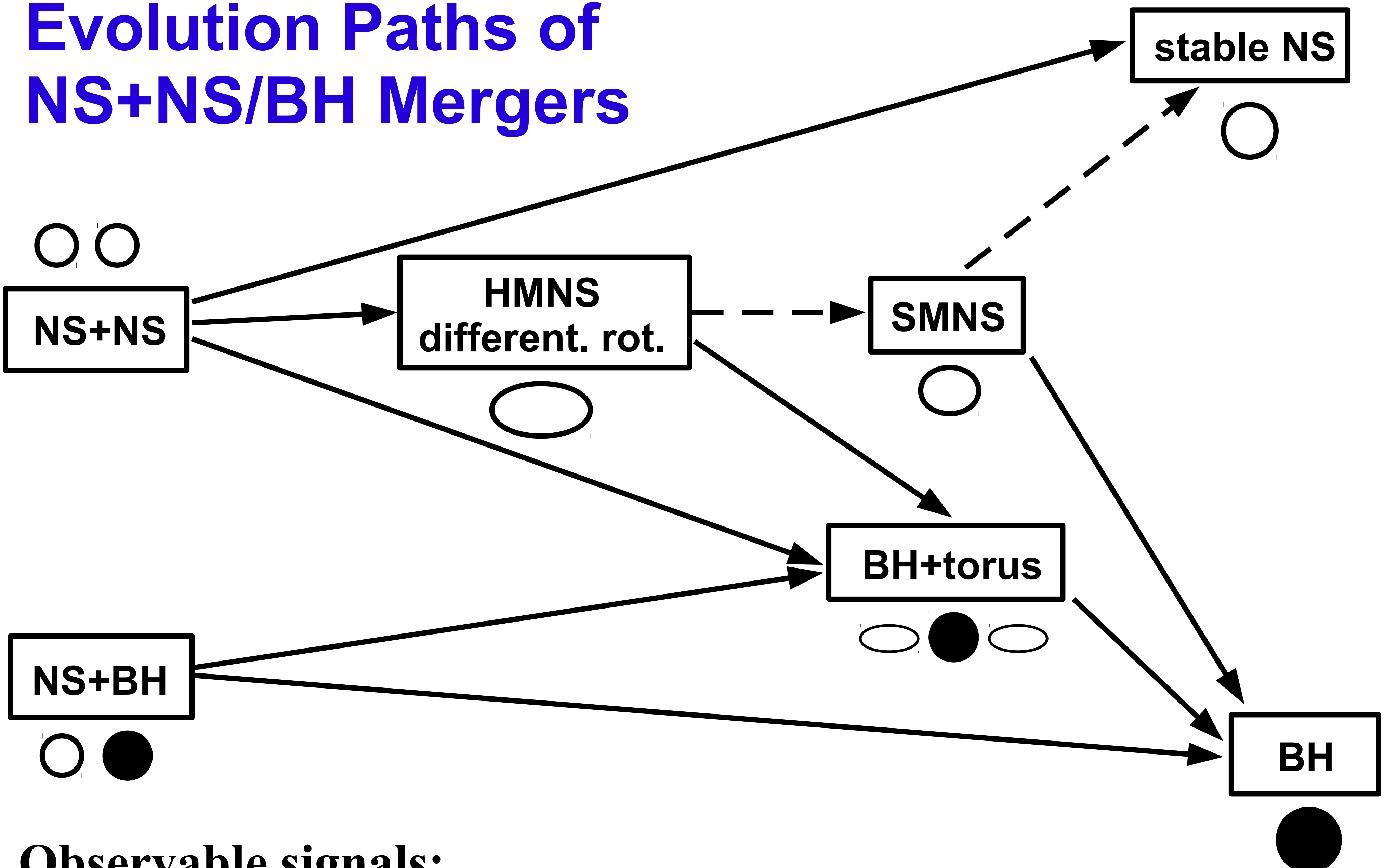
Hans-Thomas Janka

Max Planck Institute for Astrophysics, Garching

Outline

- Compact object mergers and astrophysics consequences
- Neutrinos and gravitational waves
- Ultrarelativistic outflows and gamma-ray bursts
- NS+NS mergers as probes of nuclear EOS physics
- NS merger ejecta and r-process nucleosynthesis
- Electromagnetic transients by radioactively heated ejecta
- Merger Remnants

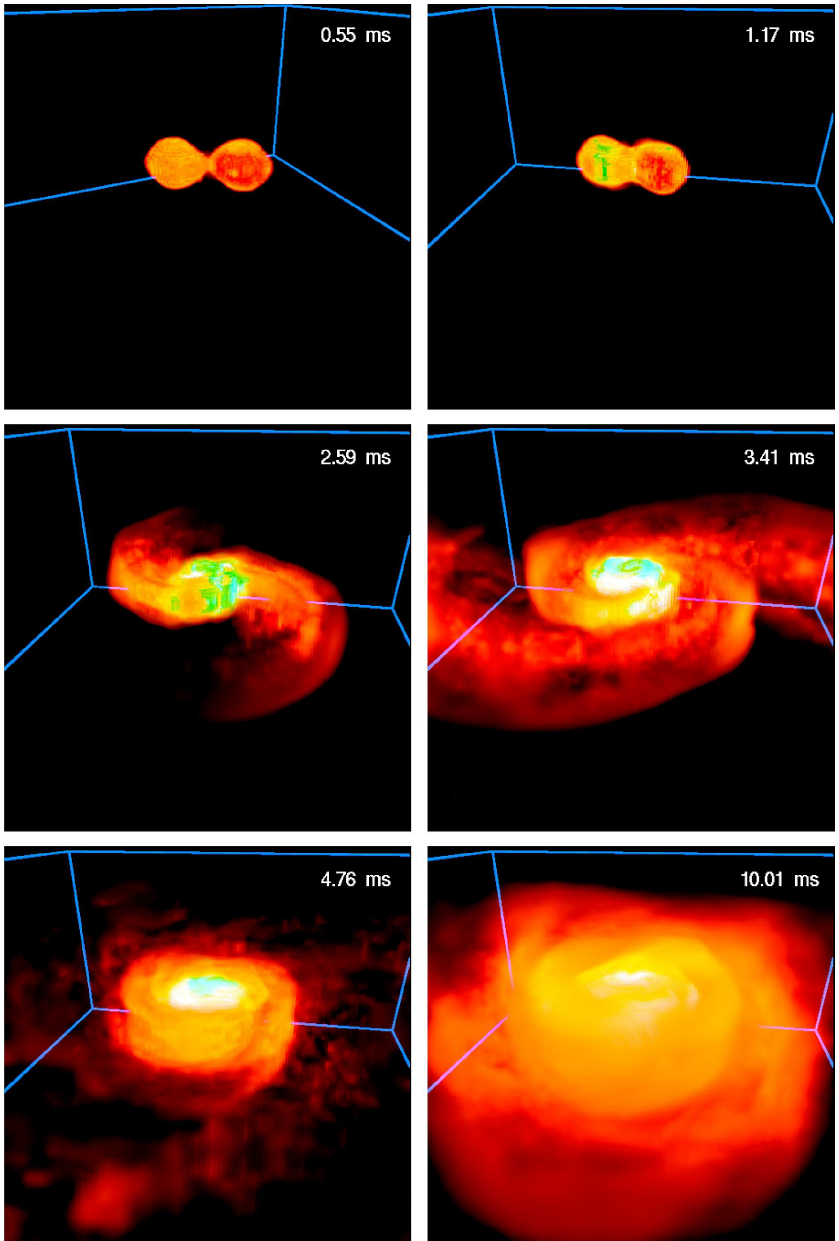
Evolution Paths of NS+NS/BH Mergers

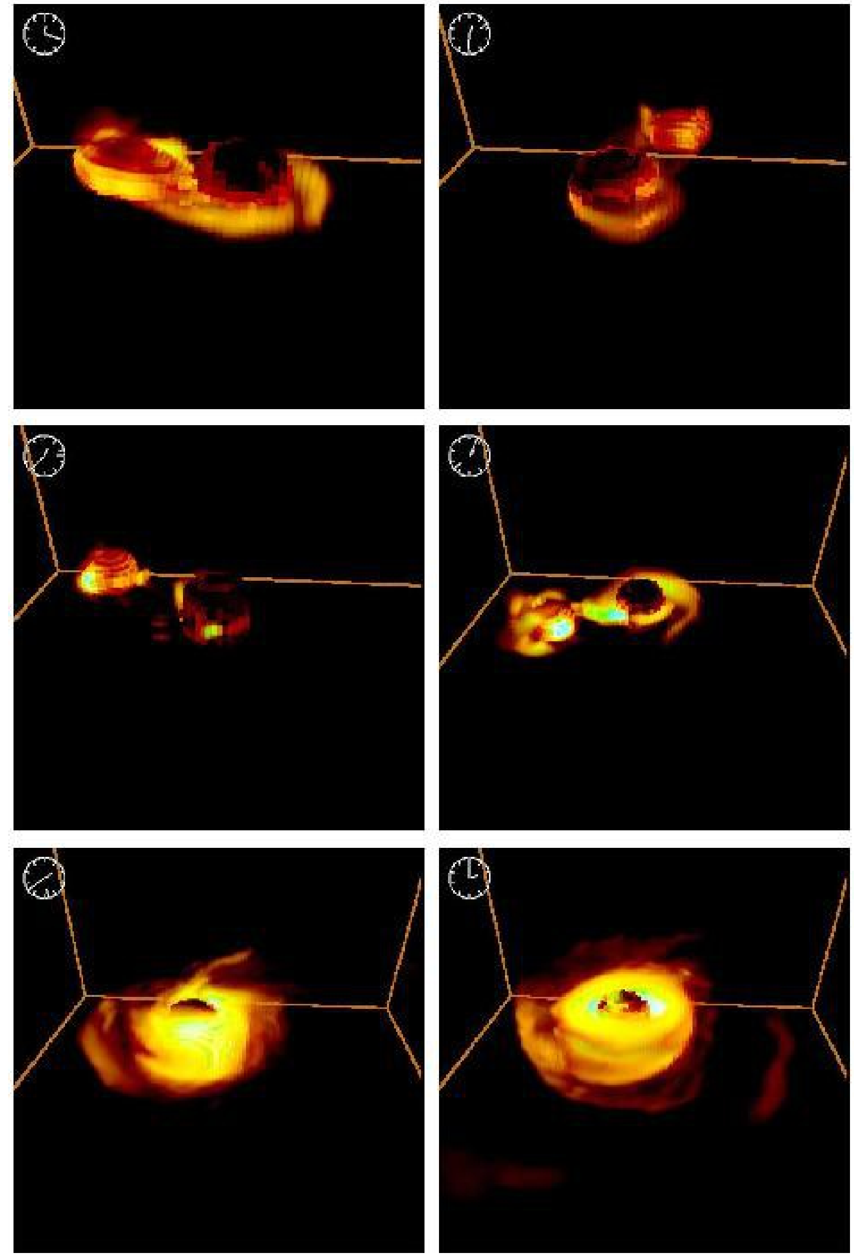


Observable signals:

Gravitational waves, neutrinos, gamma-ray bursts,
mass ejection, r-process elements, electromag. transients

NS+NS/BH Mergers

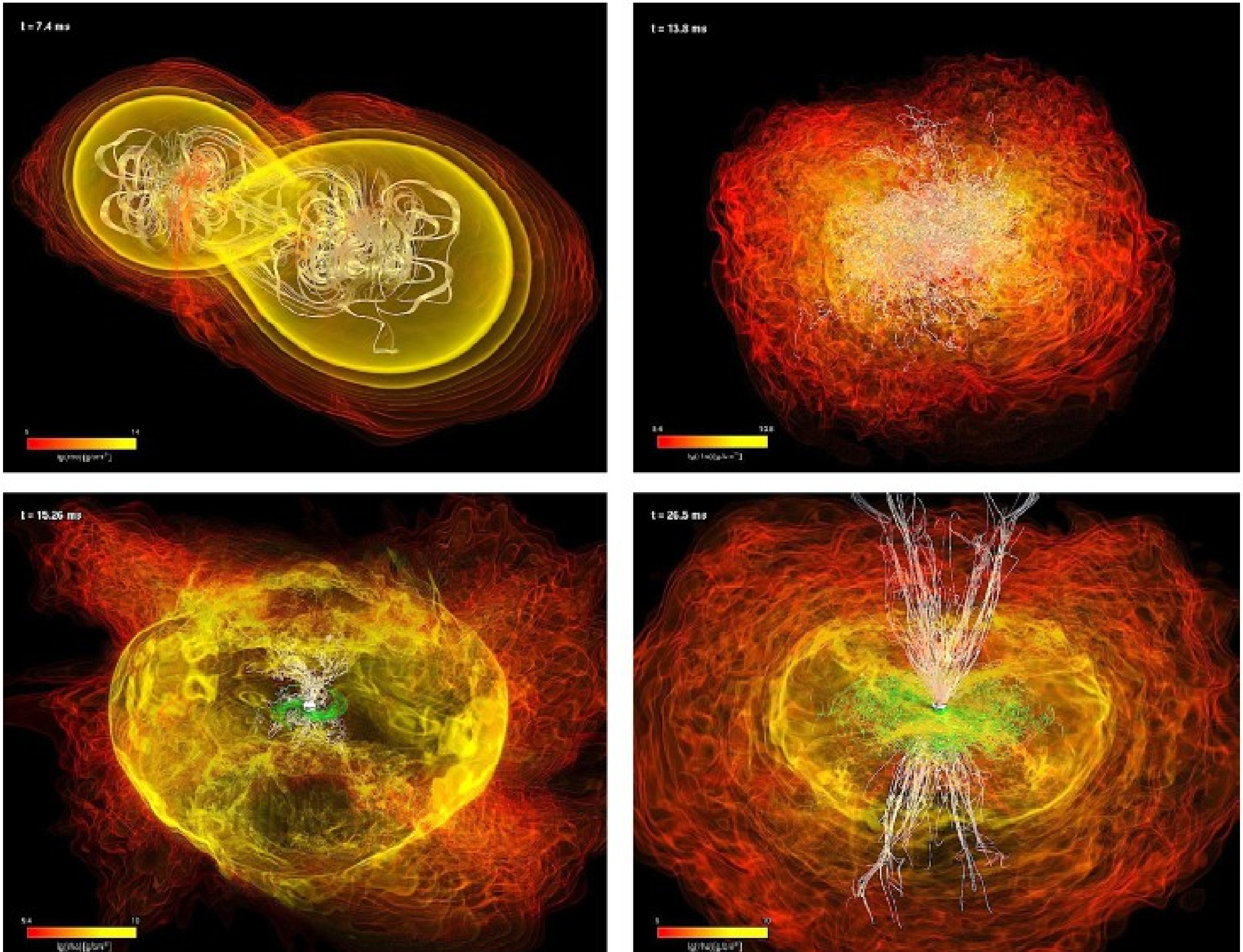




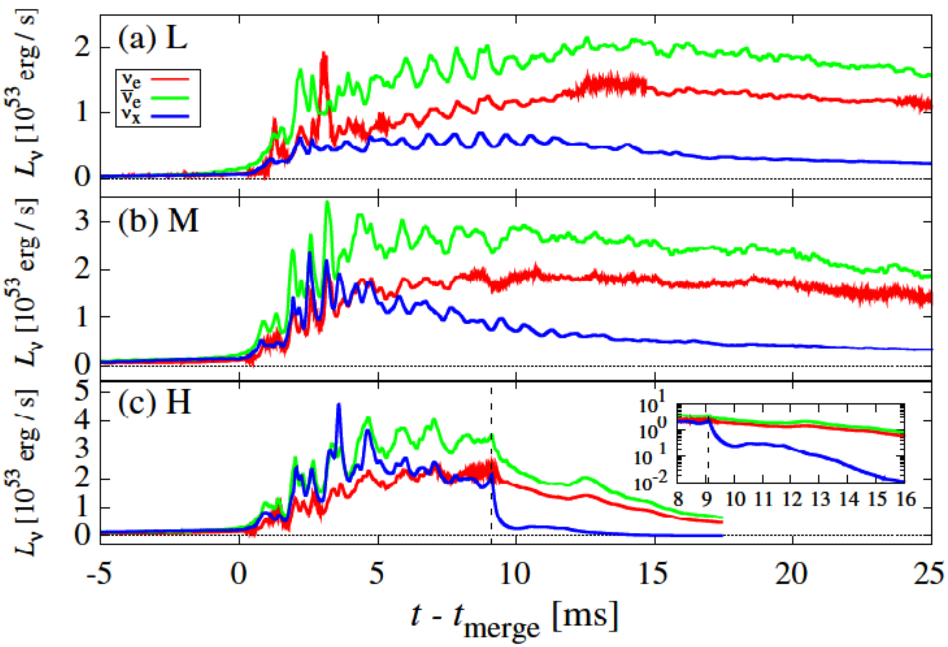
Ruffert et al.
Rosswog et al.
Oechslin et al.
Shibata et al.
Rezzolla et al.
Rasio et al.
Lehner et al.
etc.

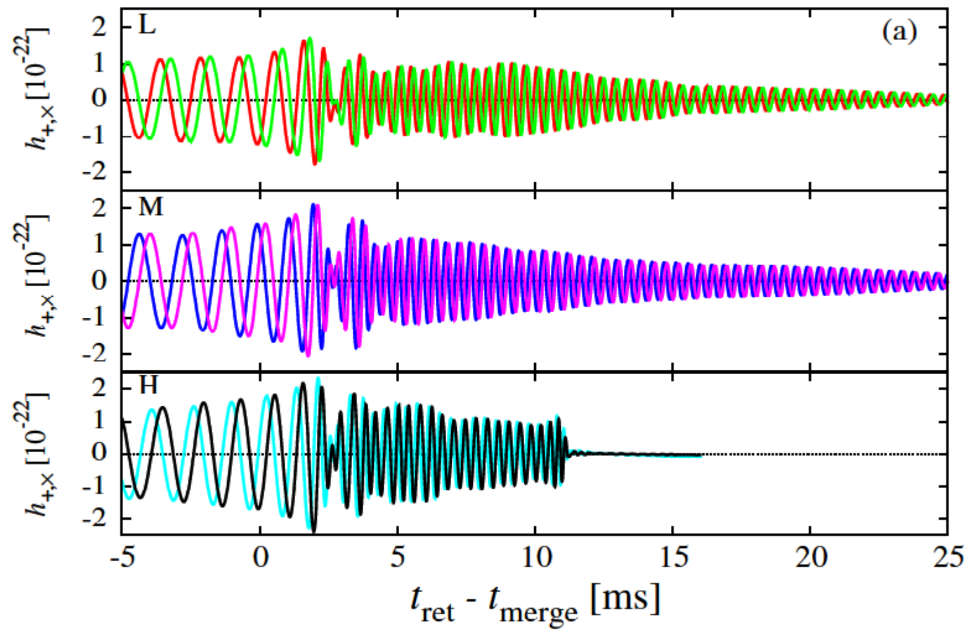
Extreme Magnetic Field Amplification

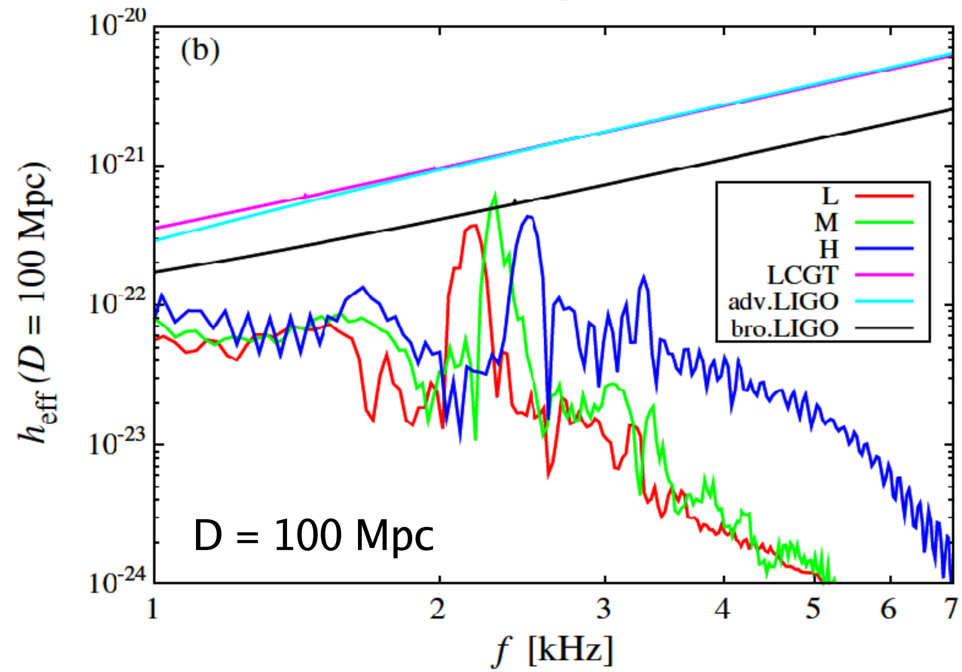
Rezzolla, Giacomazzo, Baiotti, et al., ApJL (2011)



Neutrinos and Gravitational Waves







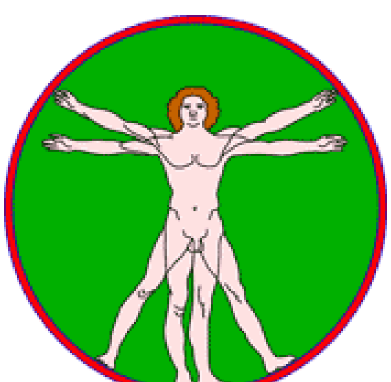
Sekiguchi et al., PRL 107, 051102 (2011)

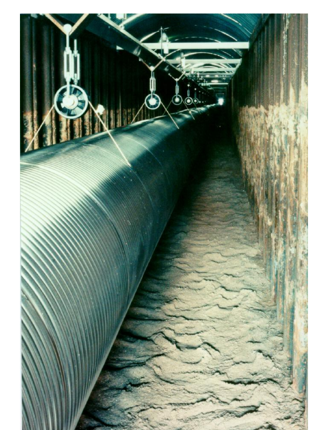
Gravitational Wave Antennas

NS+NS/BH mergers produce GW signals that will be measurable to distances of >100 Mpc.

VIRGO near Pisa in Italy with 3 km arm length

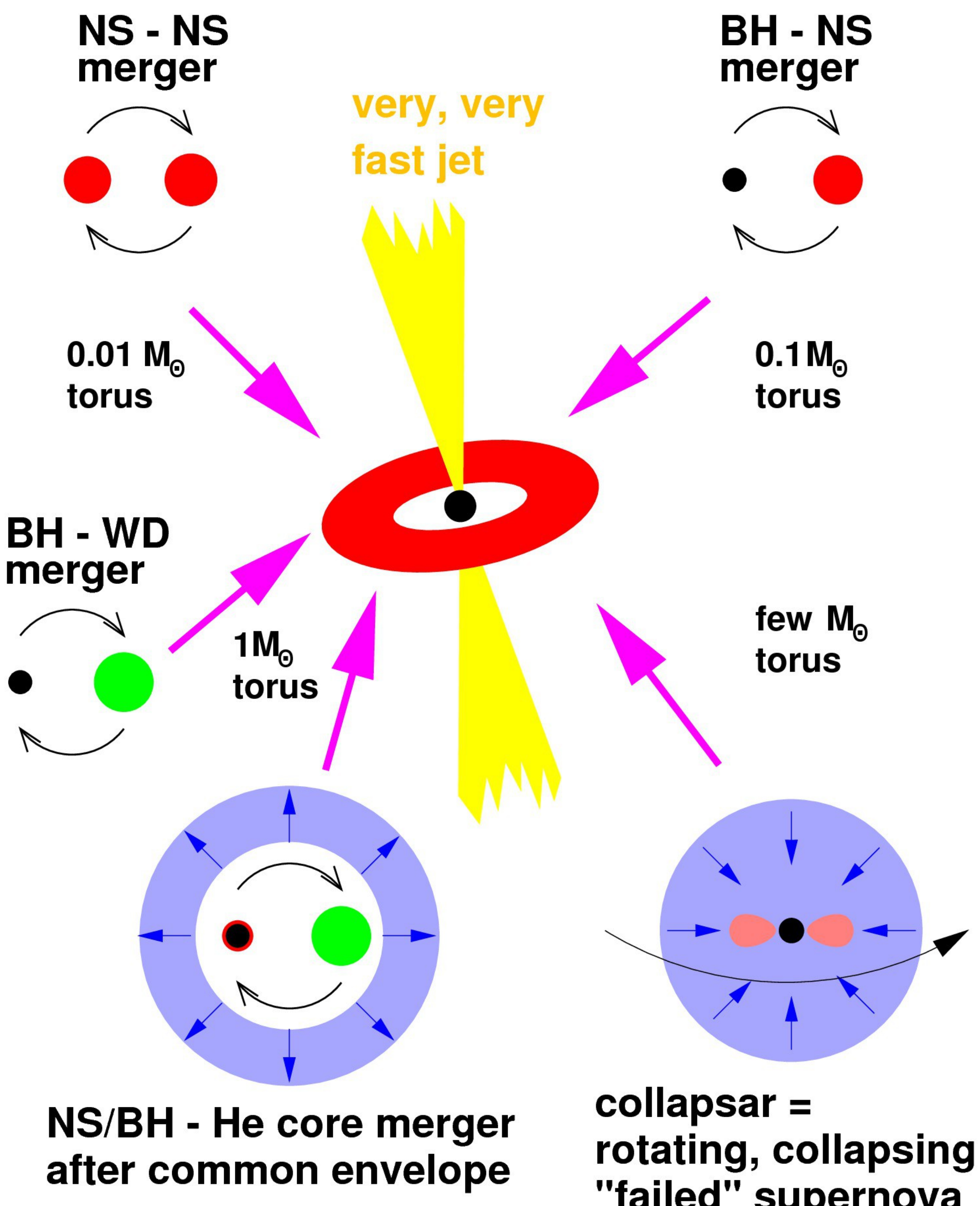
LIGO: Two interferometers in the US with 4 km, one with 2 km arm length



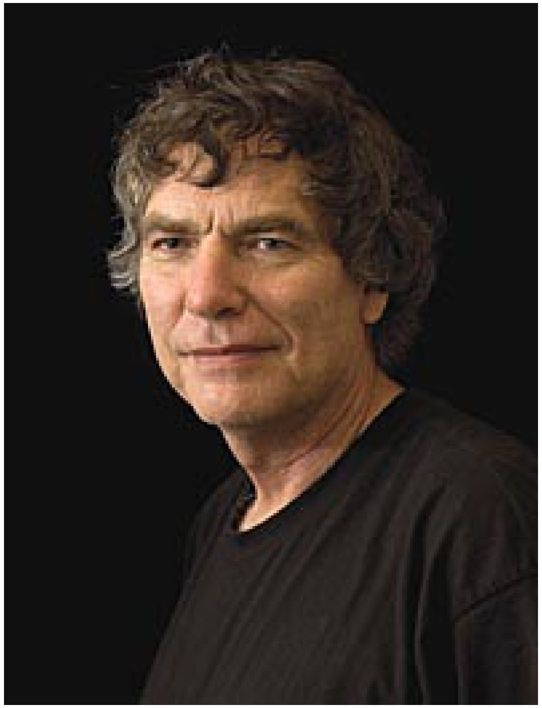


GEO600 near Hannover with 0.6 km arm length

Hyperaccreting Black Holes



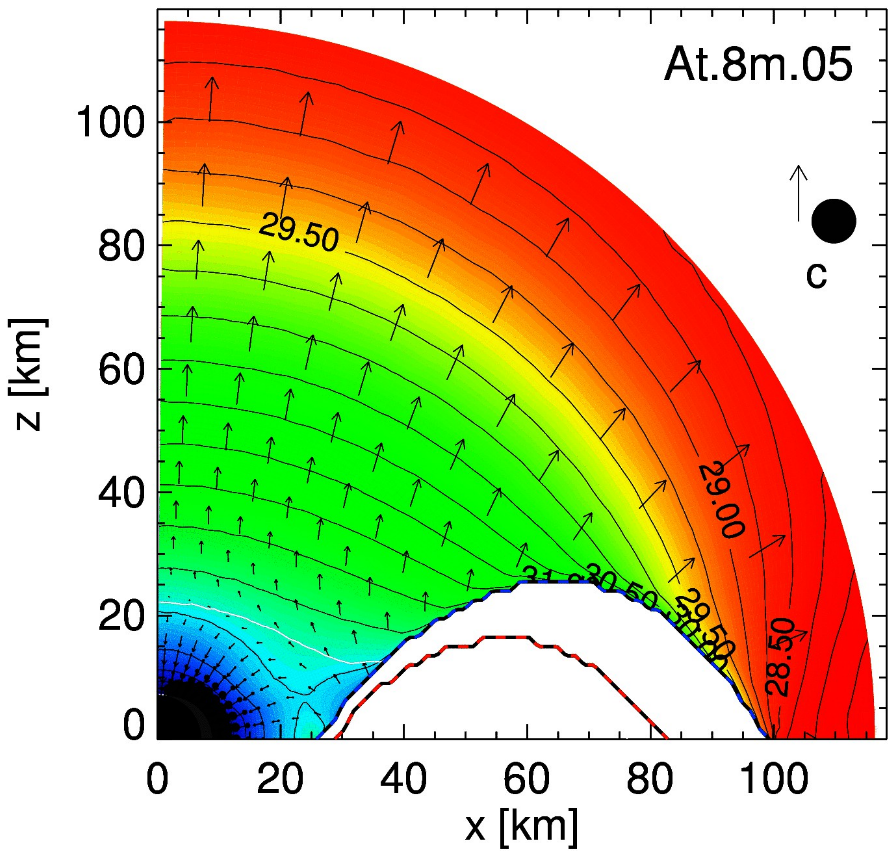
S. Woosley, Ringberg, 1997



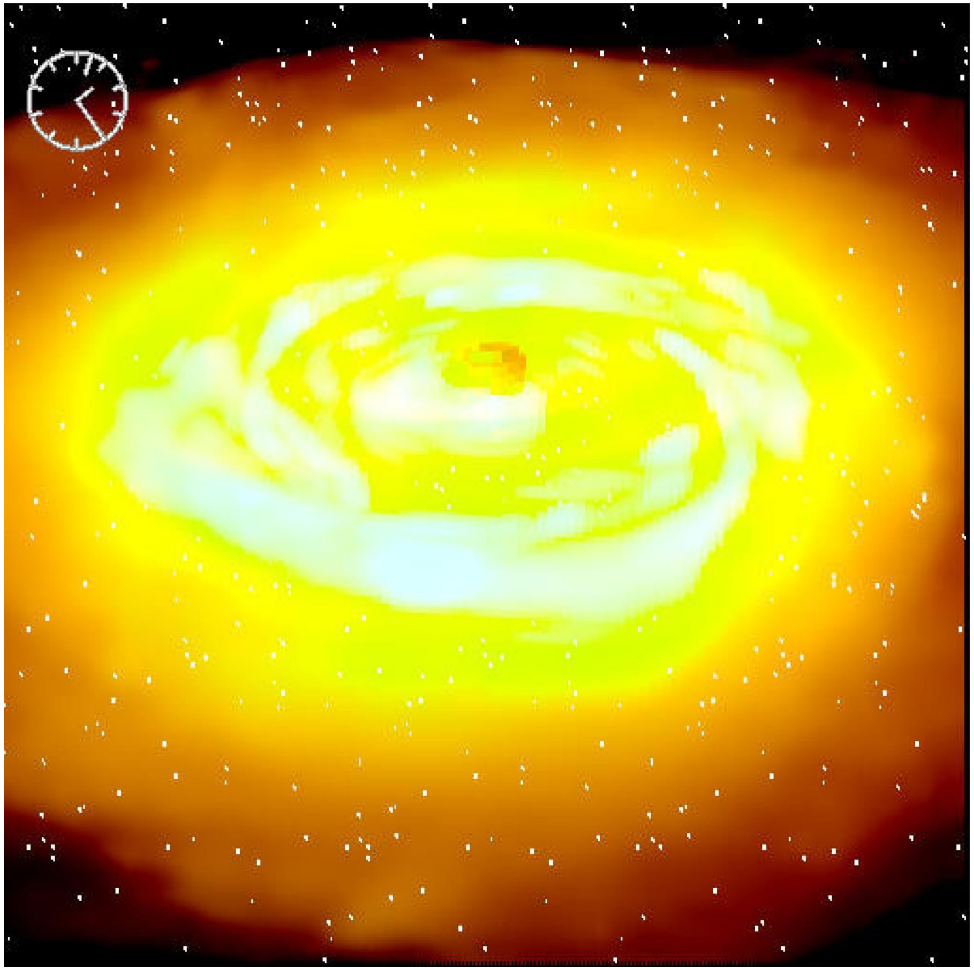
Stan Woosley

BH-Torus Evolution in 3D

- relic BH can accrete from massive, hot, neutrino-radiating torus
- accretion efficiency: 5–20%
- annihilation efficiency: up to a few %
- ~30% of annihilation energy deposited in low-density polar funnels (up to ~10^{50} erg)



Birkl, Aloy, HTJ & Müller, A&A (2007)

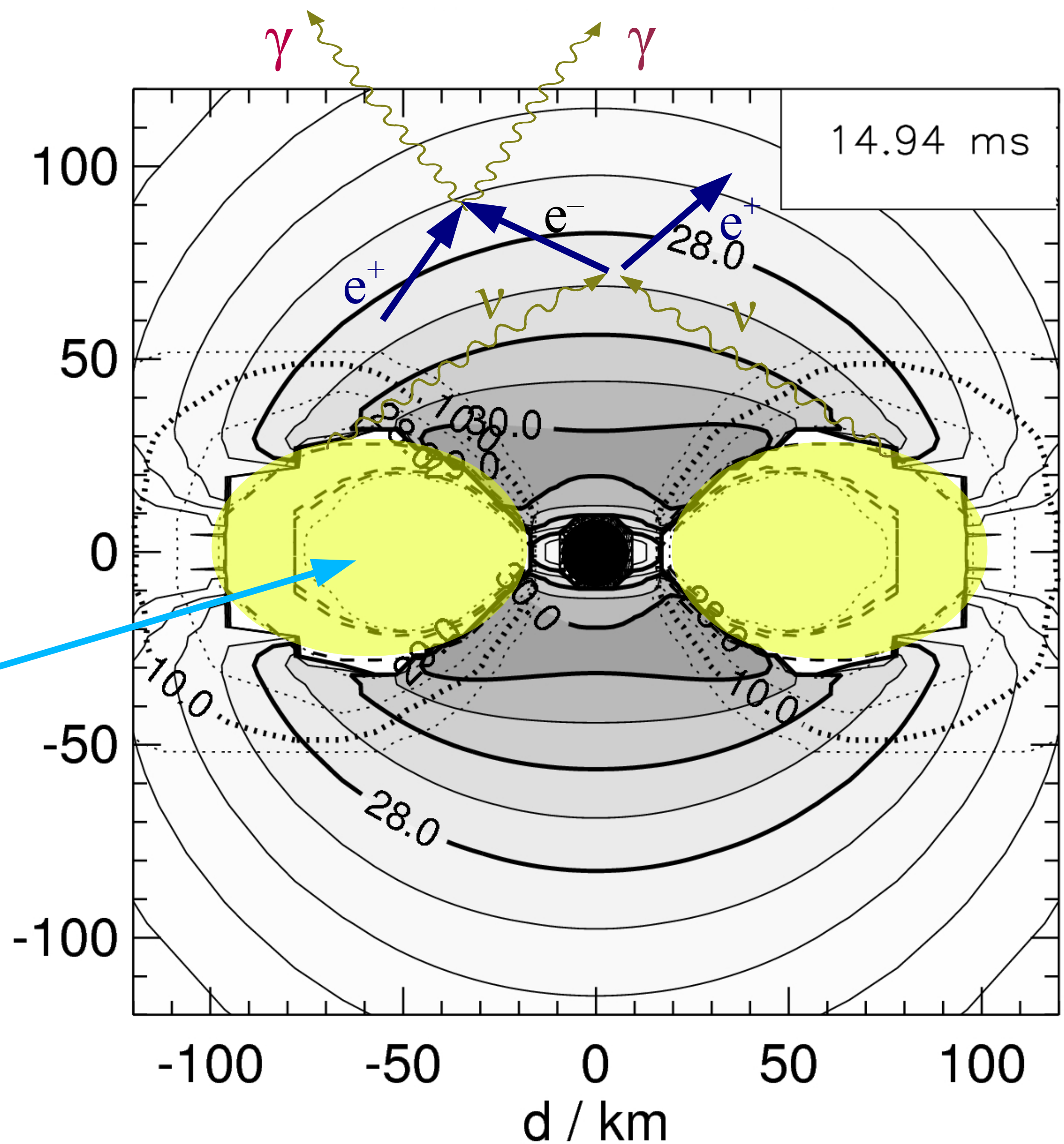


Setiawan, Ruffert, HTJ, MNRAS (2004)

Neutrinos as energy souce of ultra-relativistic, collimated outflow

$\nu + \nu \longrightarrow e^+ + e^- \longleftrightarrow \gamma + \gamma$

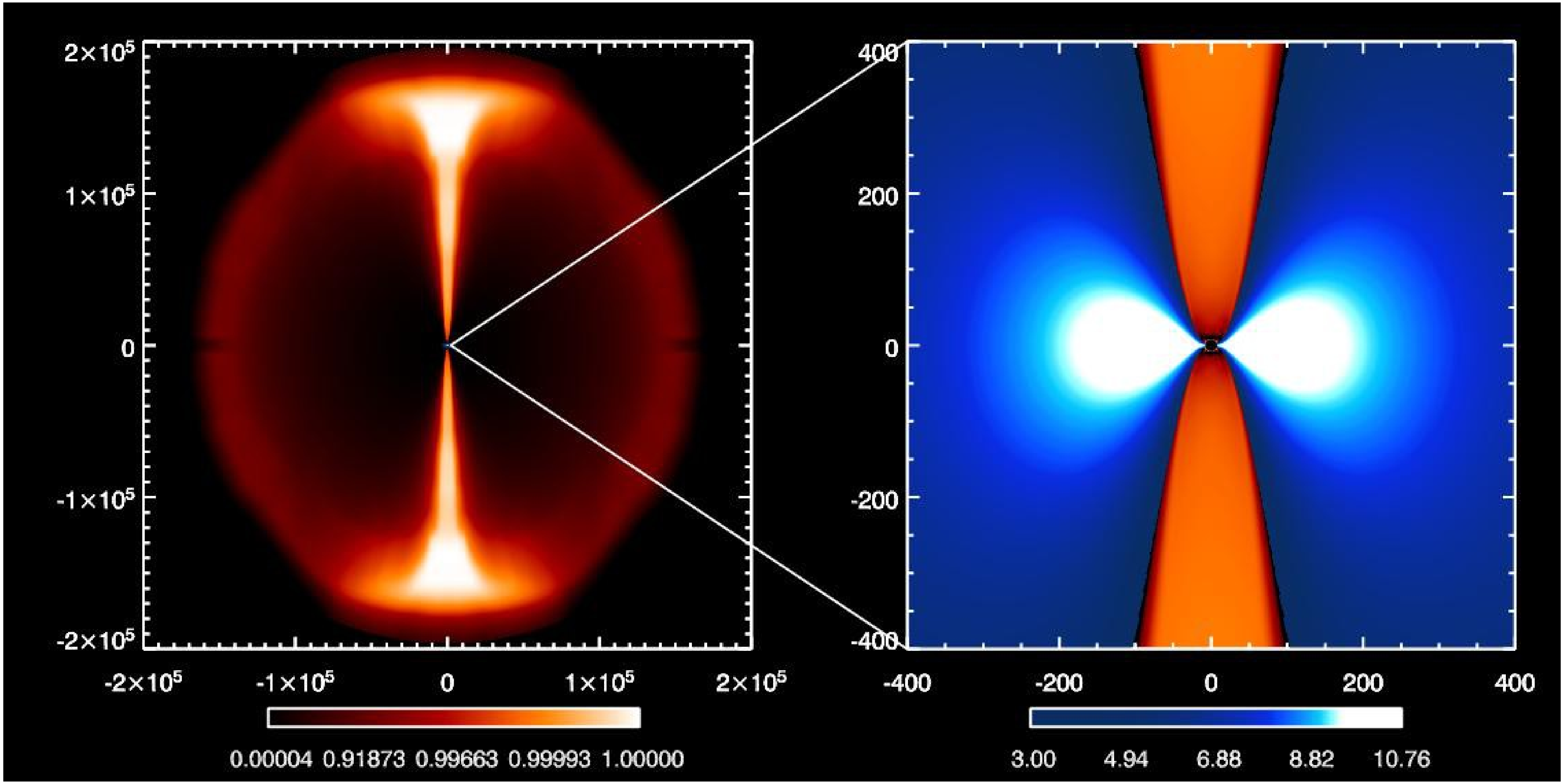
Paar-Plasma Feuerball



Extremely hot torus radiates high neutrino luminosities into polar low-density funnels.

Relativistic Jets from BH-Tori

- General relativistic simulations of jet formation at the BH.
- Thermal energy deposition dE/dt a few 10^{50} erg/s for about 0.1 s.
- Energy deposition in axial cone with varied opening angle, decline as z^{-5}.



Aloy, HTJ, & Müller, A&A 436 (2005) 273

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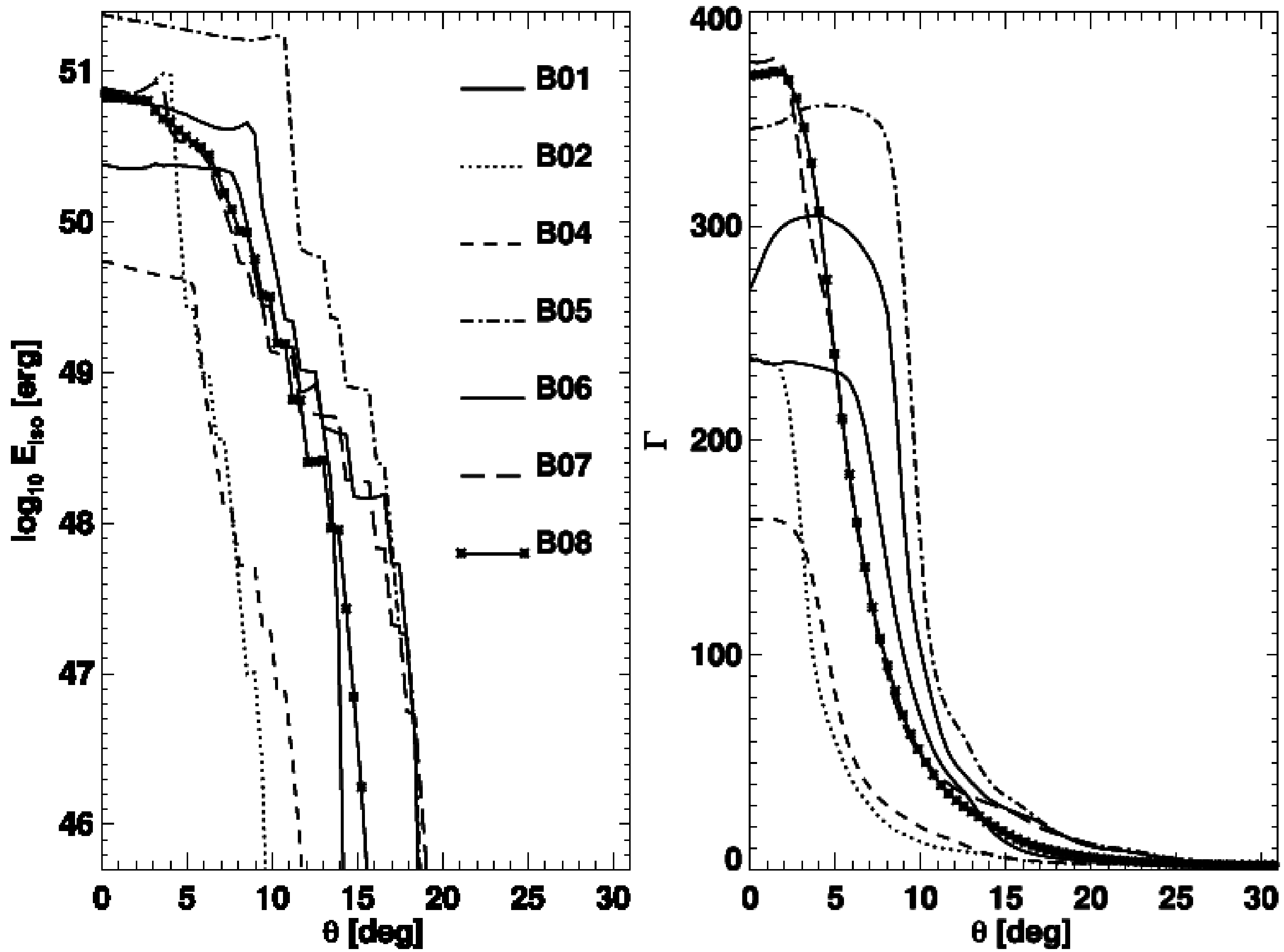
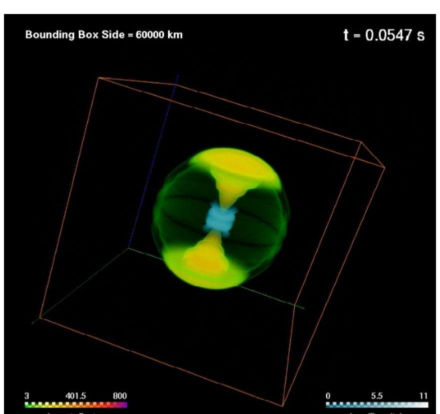
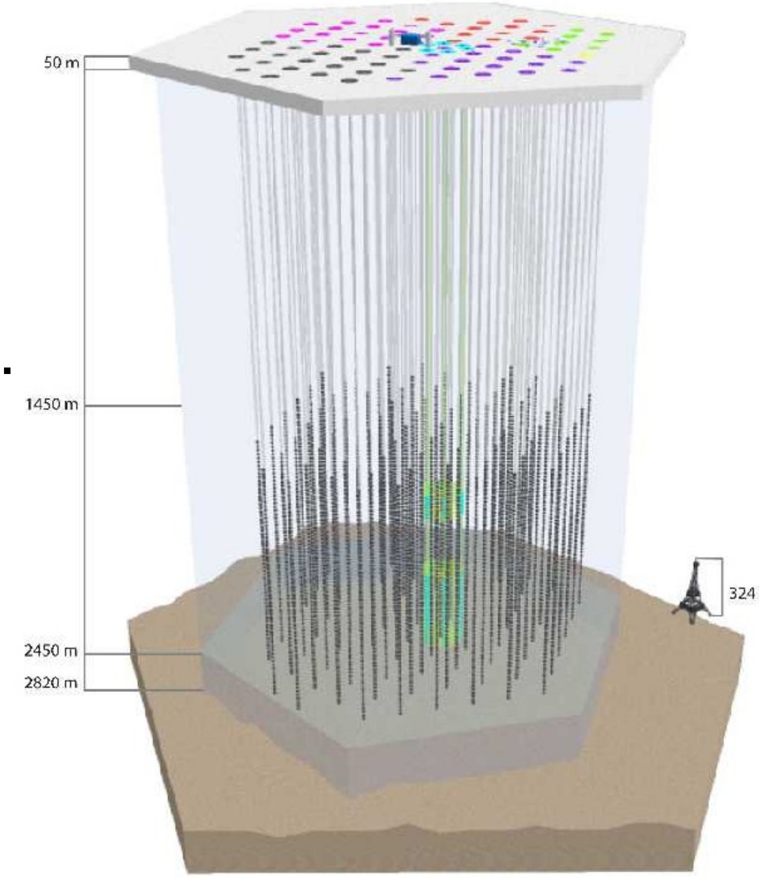




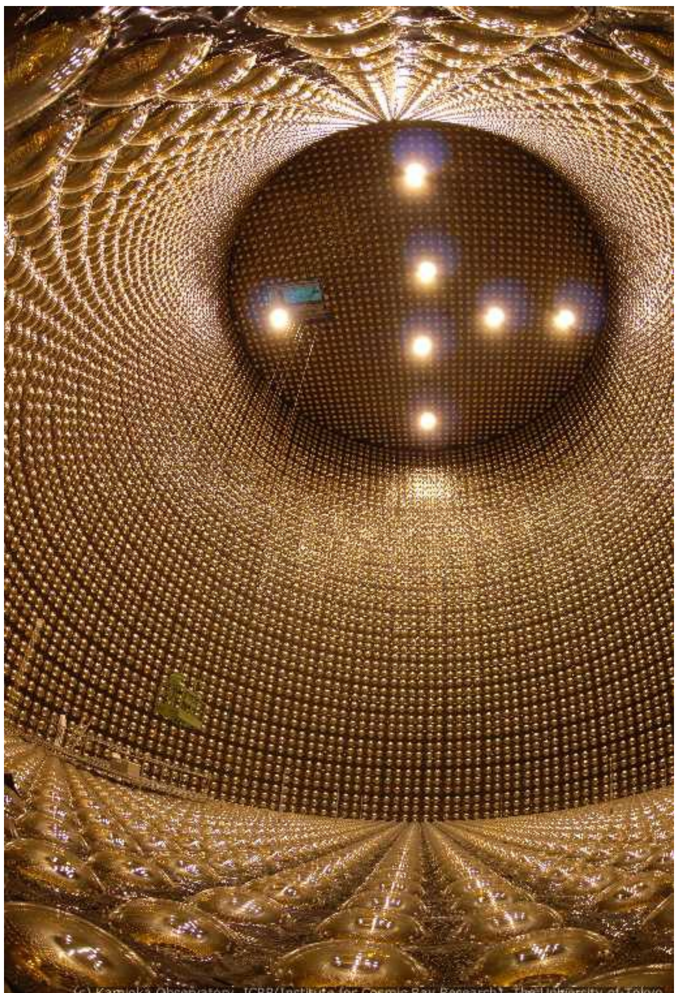
Aloy, HTJ, & Müller, A&A 436 (2005) 273; THJ et al., ApJ 654 (2006) 1305

Detecting Neutrinos from Compact Binary Mergers

No evidence for UHE neutrinos so far.
MeV neutrinos require source distance of <300 kpc.

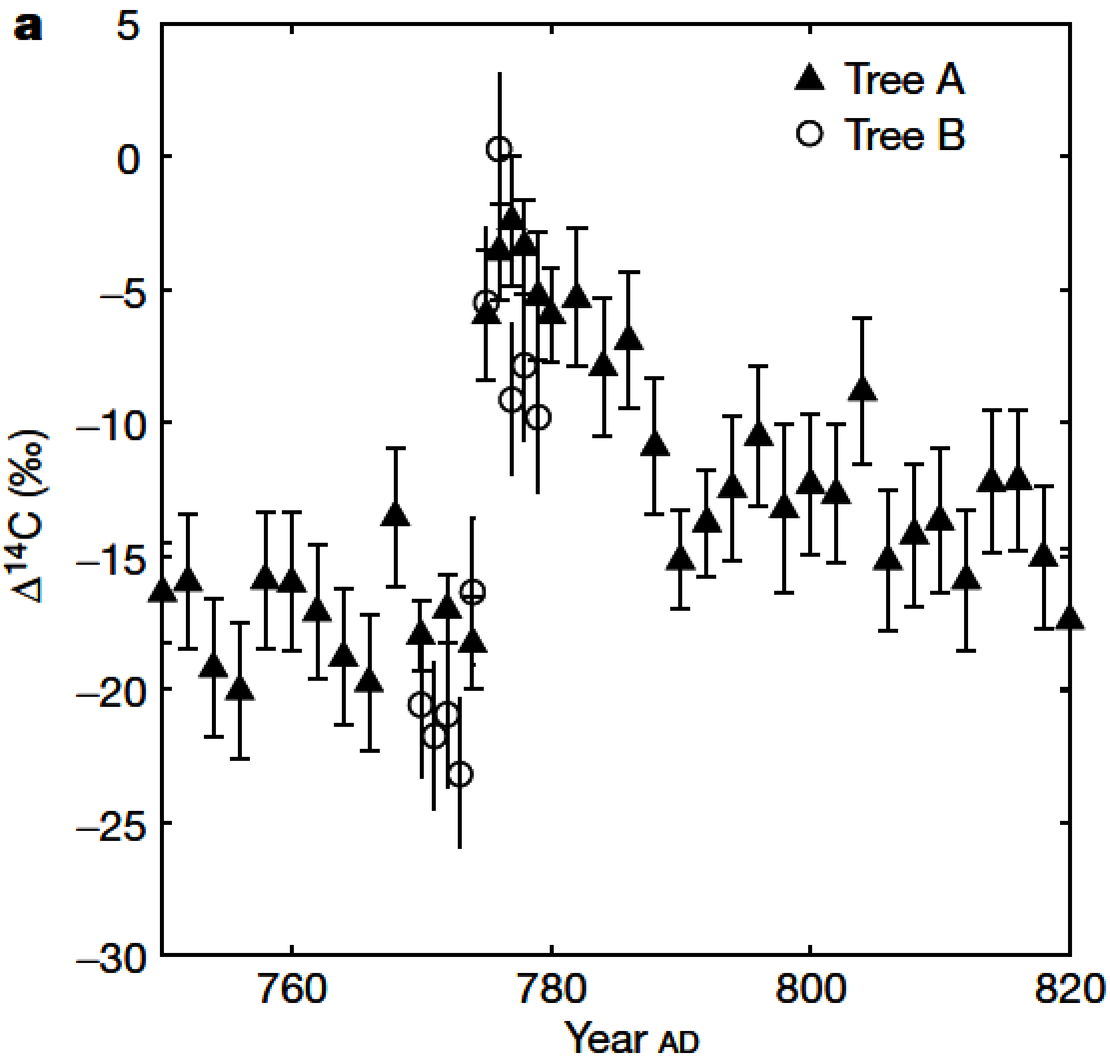


Superkamiokande



IceCube

Nearby Short Gamma-Ray Burst in AD 774/5?



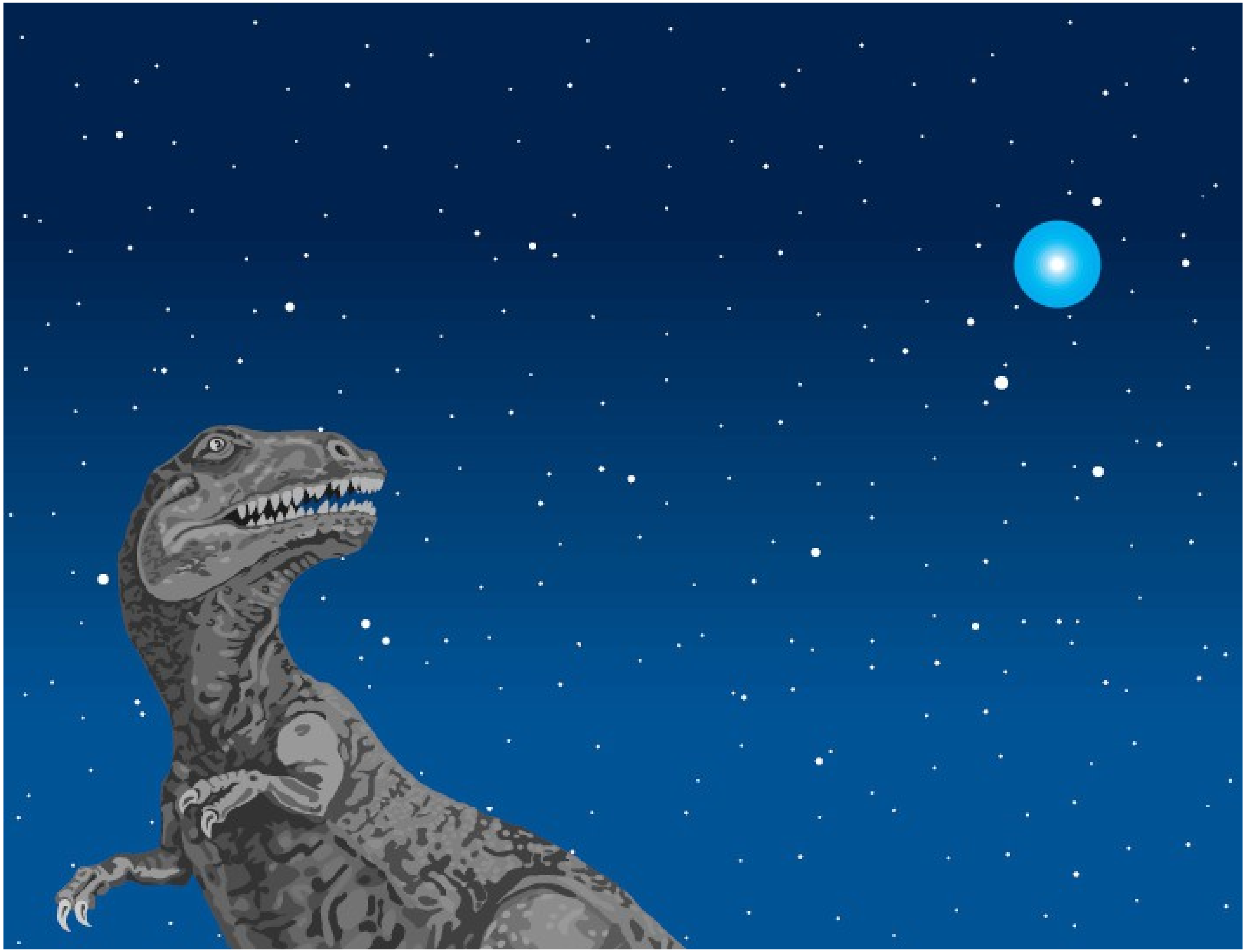
- Significant, rapid increase of ^{14}C by about 1.2% in annual rings of Japanese cedar trees from AD 774 to 775.
- 20 times larger than normal solar modulation.
- **No observation of a supernova!**

Miyake et al., Nature 486 (2012) 240

- **Possible Reason:** Gamma radiation from a short GRB at a distance of 3000–12000 light years.

Hambaryan & Neuhäuser, MNRAS 430 (3013) 32

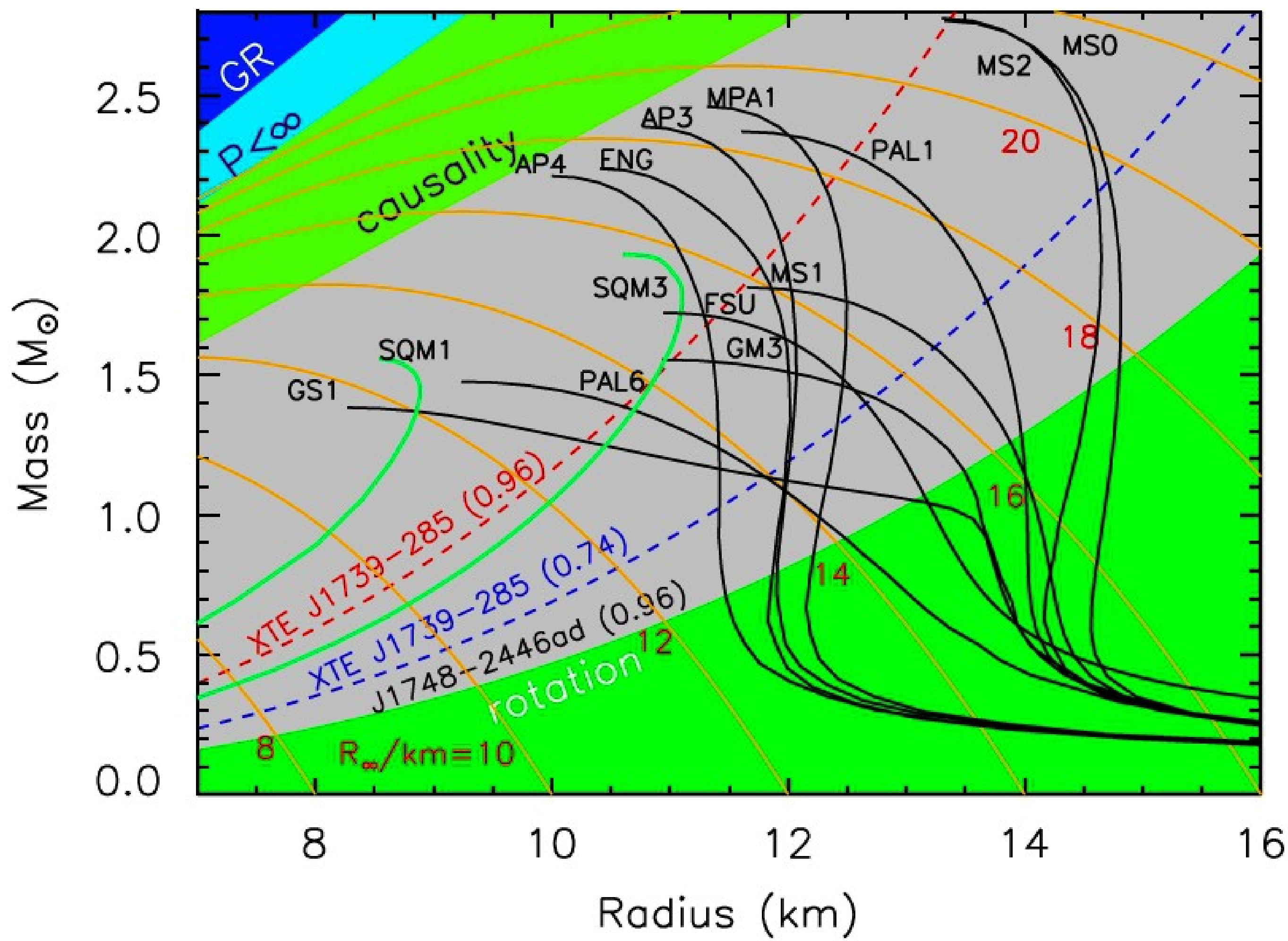
Mass Extinctions by Cosmic Gamma-Ray Bursts?



Cosmic GRB at a distance of less than 1000–2000 light years would damage the ozon layer of Earth severely. One event per several 100 million years on average?

The Quest for the NS EOS

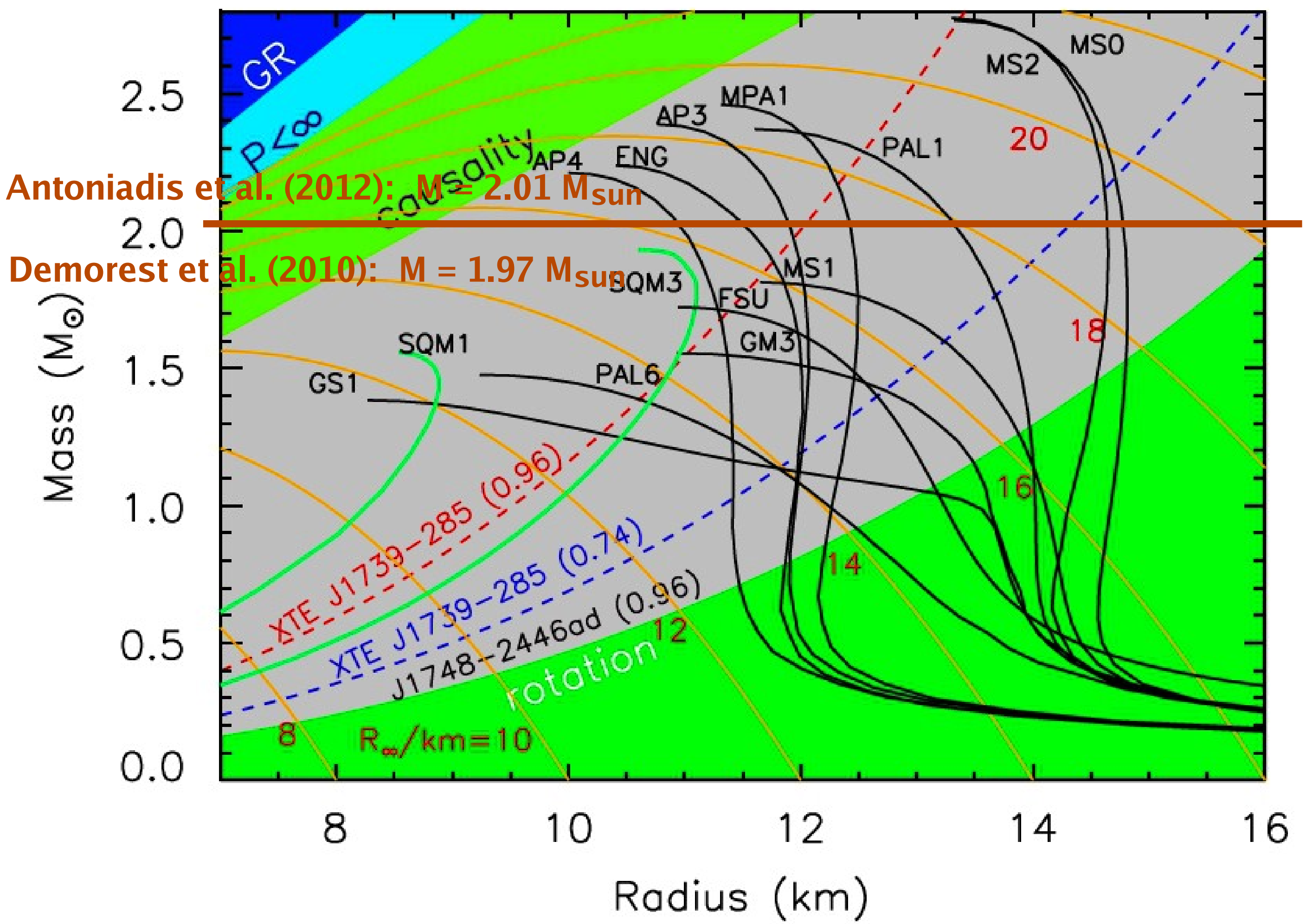
Neutron Star Equations of State



- NS+NS mergers are sensitive to the nuclear EOS of neutron stars.
- Gravitational waves from NS+NS mergers offer powerful tool to probe NS matter properties around and above nuclear saturation density ρ_0

Lattimer & Prakash, Phys. Rep. 442 (2007)

Neutron Star Equations of State



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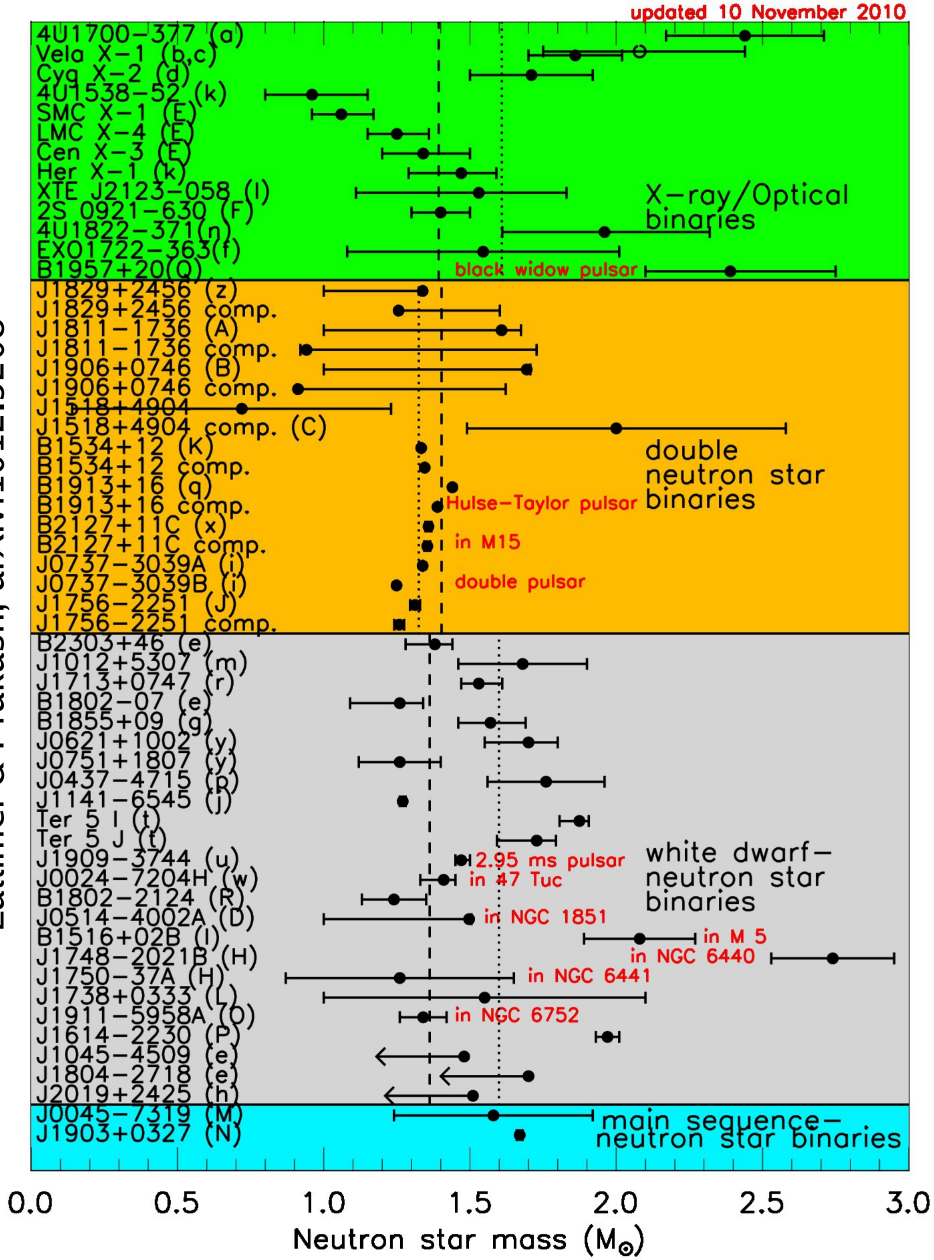
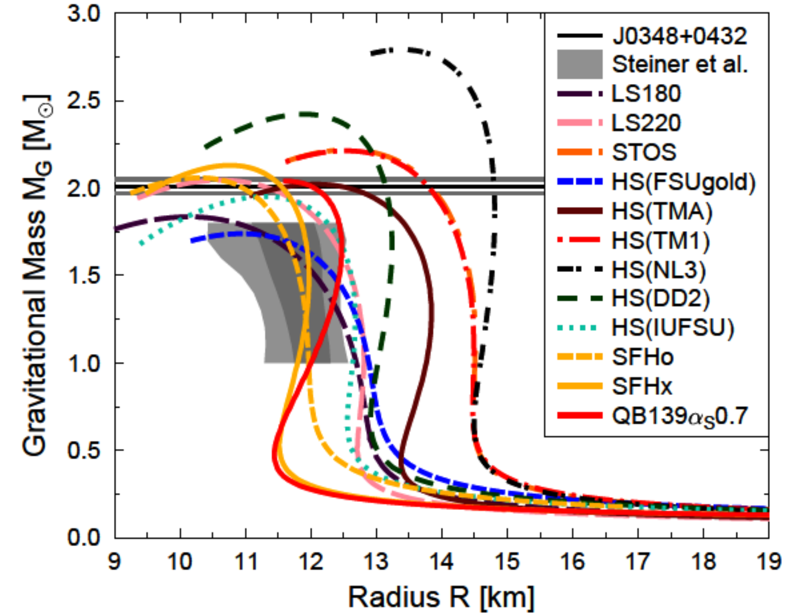
Lattimer & Prakash, Phys. Rep. 442 (2007)

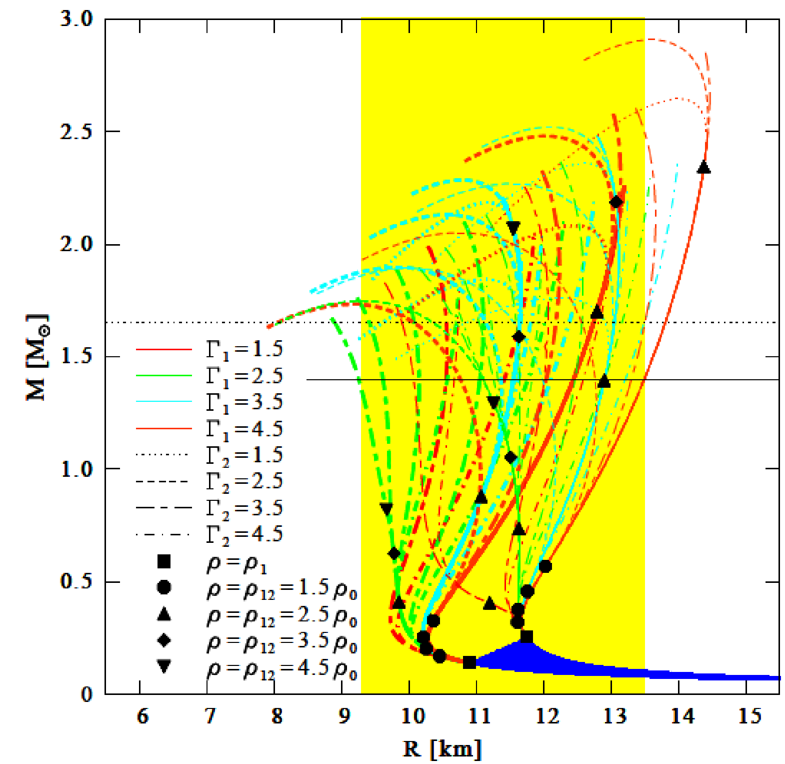
NS Masses and Radii

Lattimer & Prakash, arXiv:1012.3208





Steiner et al. (2012)

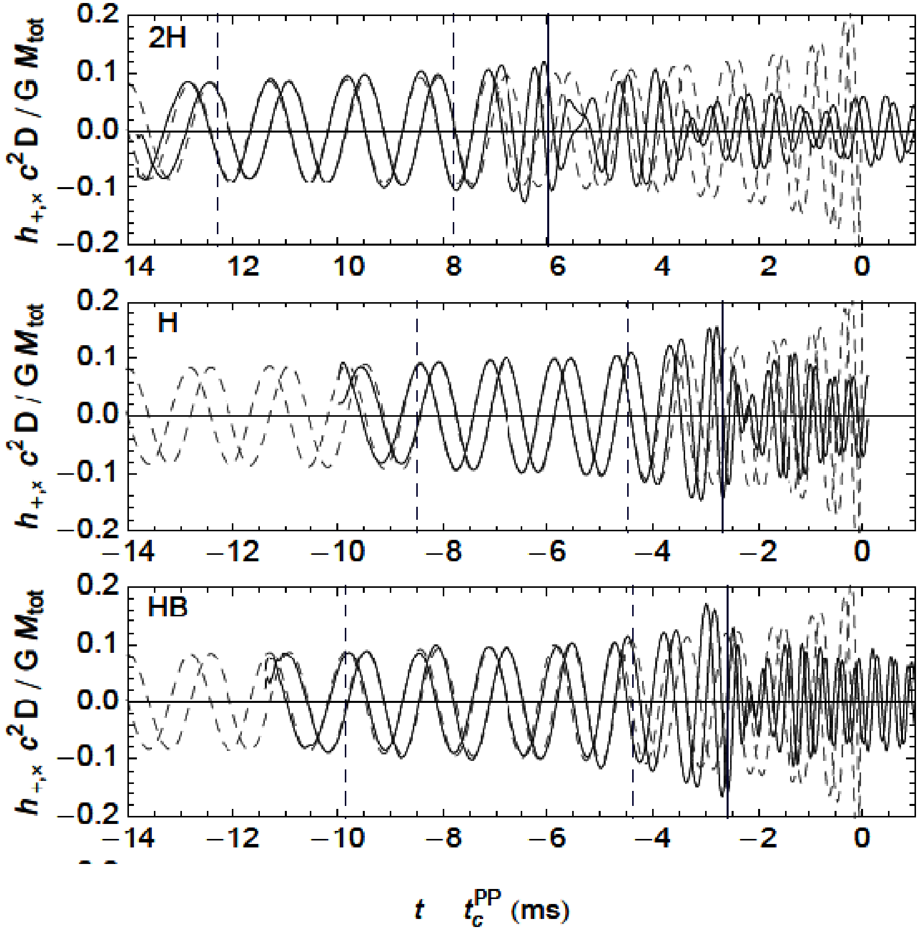


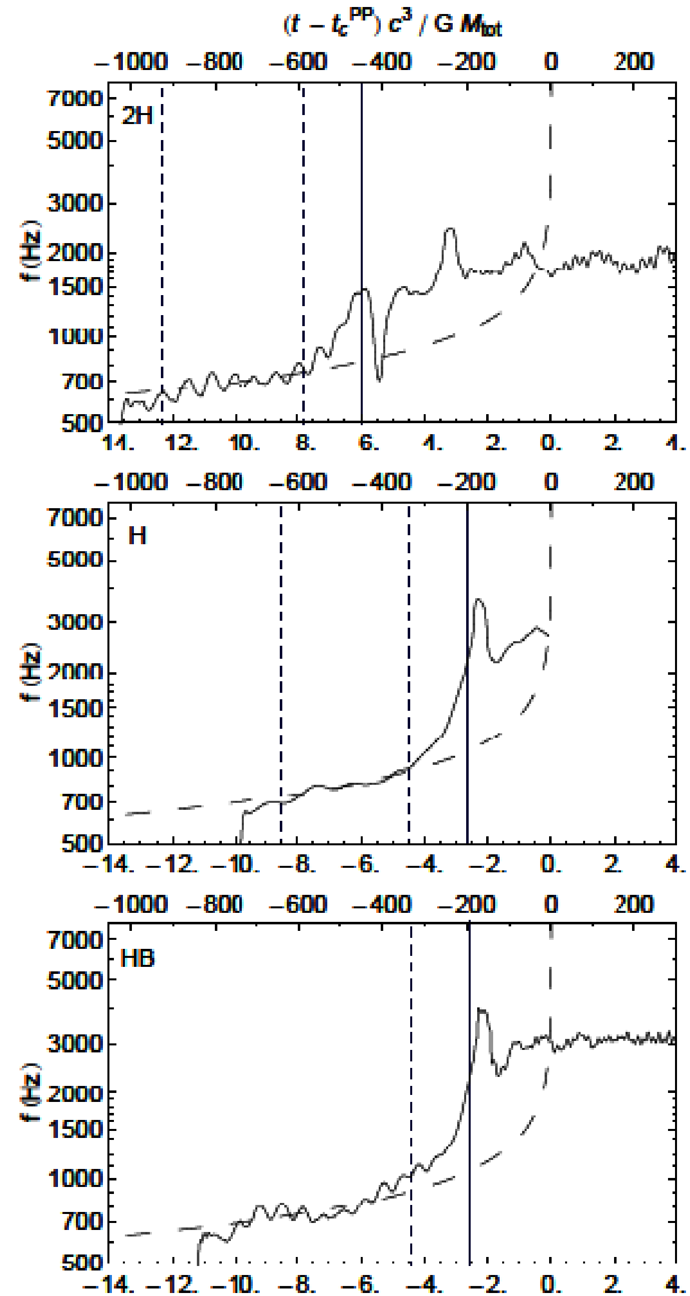
Hebeler et al., arXiv:1007.1746

NS Constraints from GW Signals

Use deviation from point-mass post-Newt. behavior during final stages of inspiral

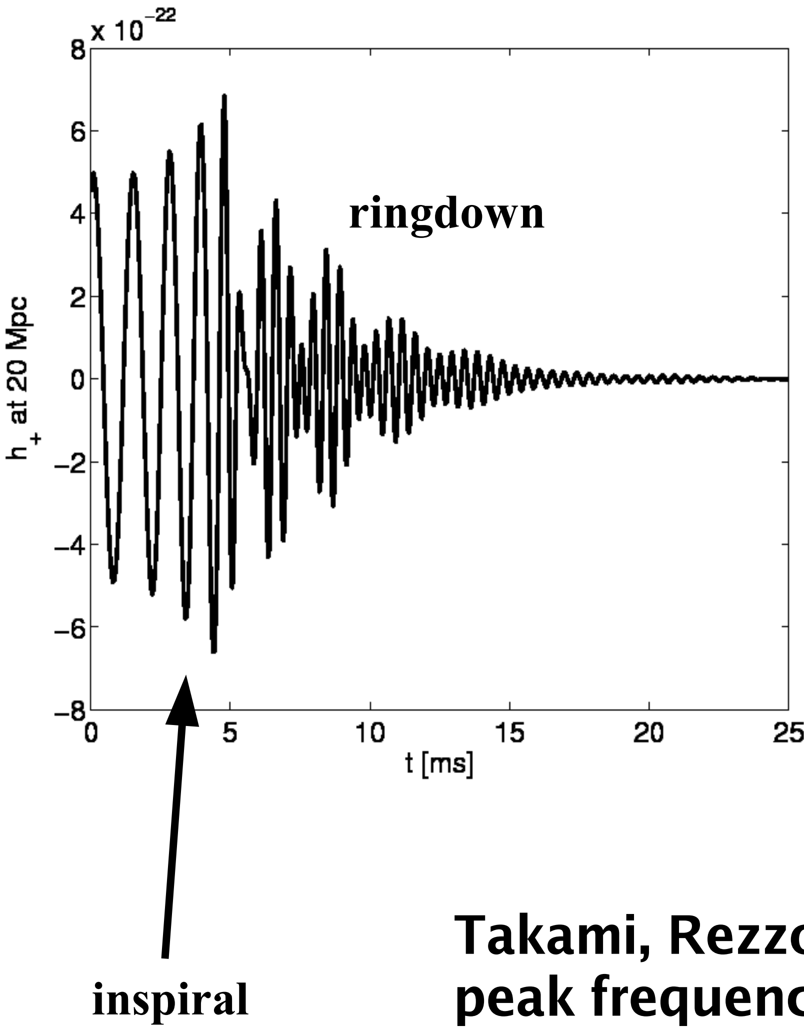
Read, Markakis et al., arXiv:0901.3258

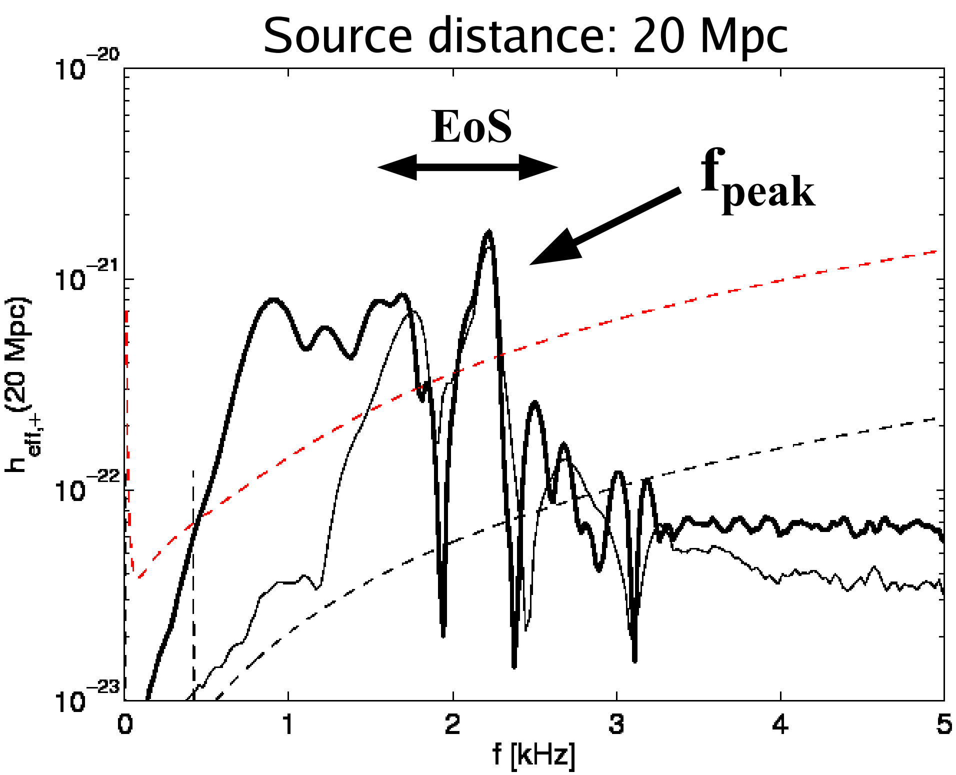




Gravitational Waves from Ringdown phase: Amplitude & Spectrum

1.35-1.35 M_{sun} Shen equation of state (EoS)

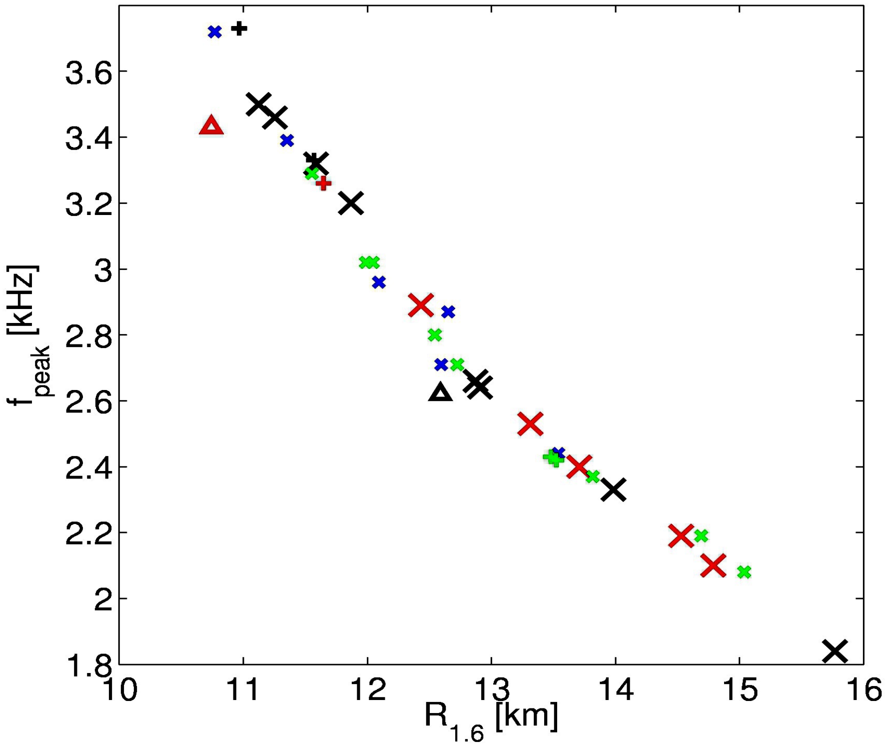


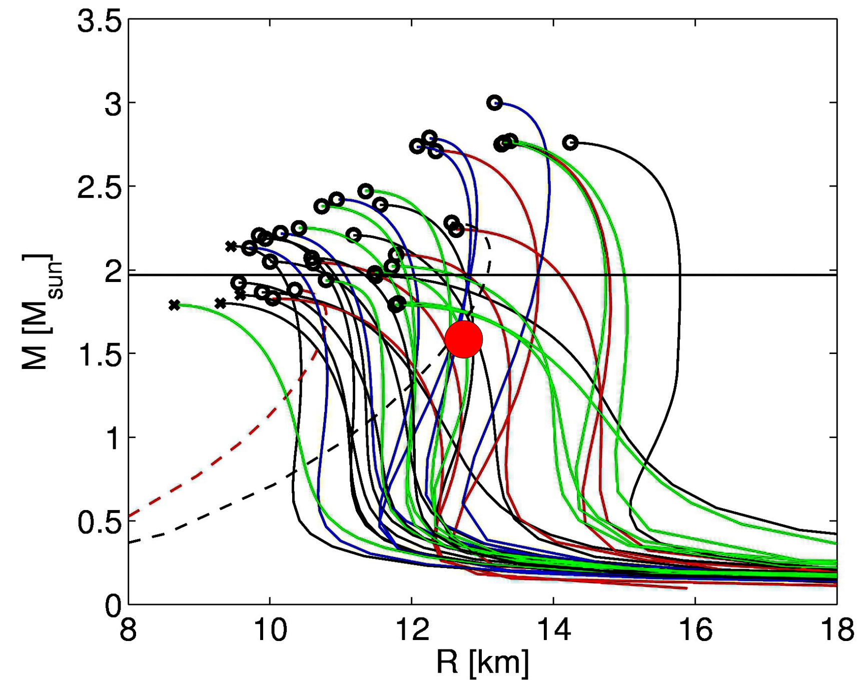


Bauswein & THJ, PRL (2012)

Takami, Rezzolla & Baiotti (arXiv:1403.5672) confirm peak frequencies and claim detectability up to 50 Mpc!

Gravitational waves – EoS survey



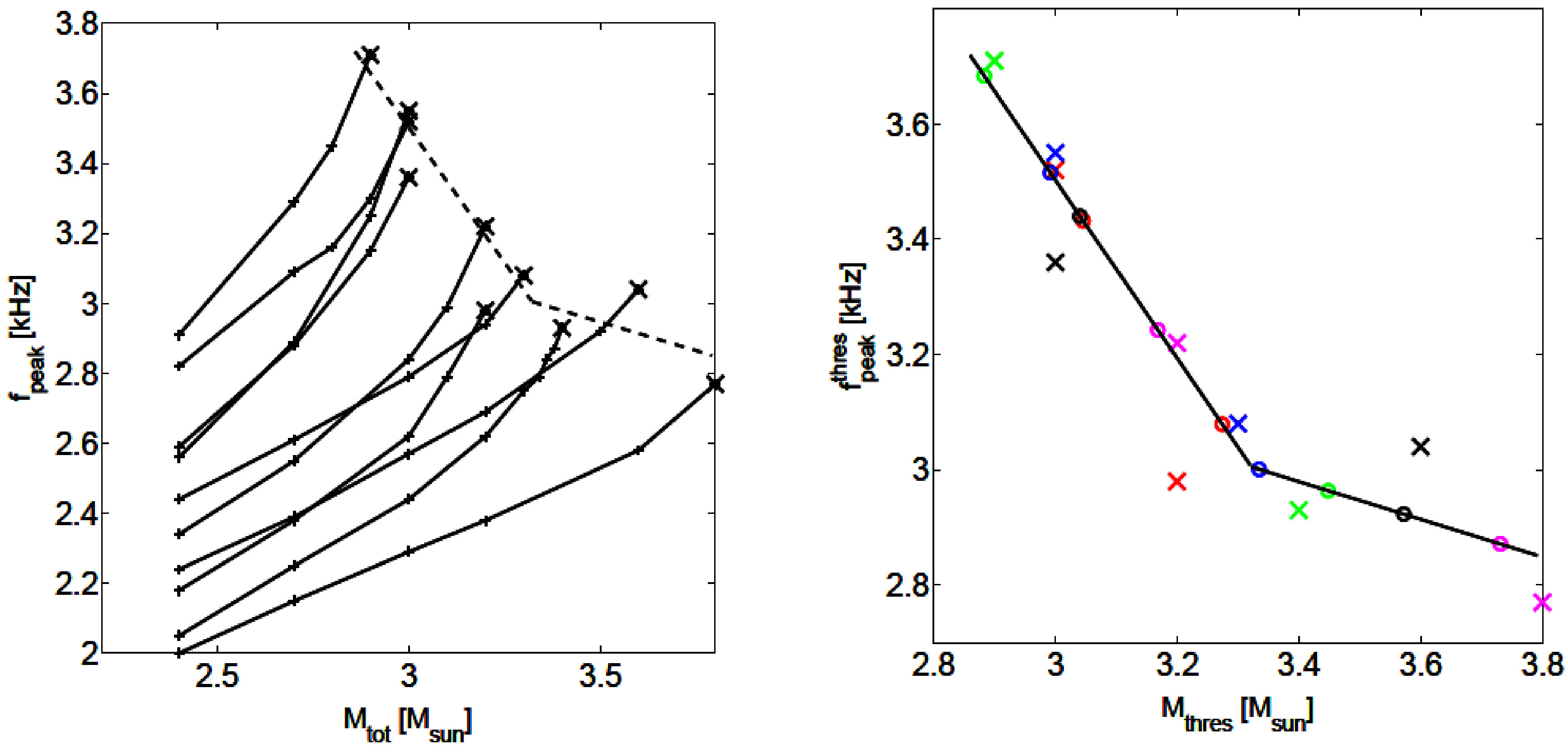


characterize EoS by radius of nonrotating NS with 1.6 M_{sun}

Bauswein, THJ, Hebeler, Schwenk, PRD (2012)

- f_{peak} dominant gravitational-wave frequency of the post-merger phase
- Detection determines neutron-star mass and radius (within ~200 meters)
- Event rate for Advanced LIGO: 0.01–1 per year (conservative)
- Strong constraint on high-density equation of state and other NS properties

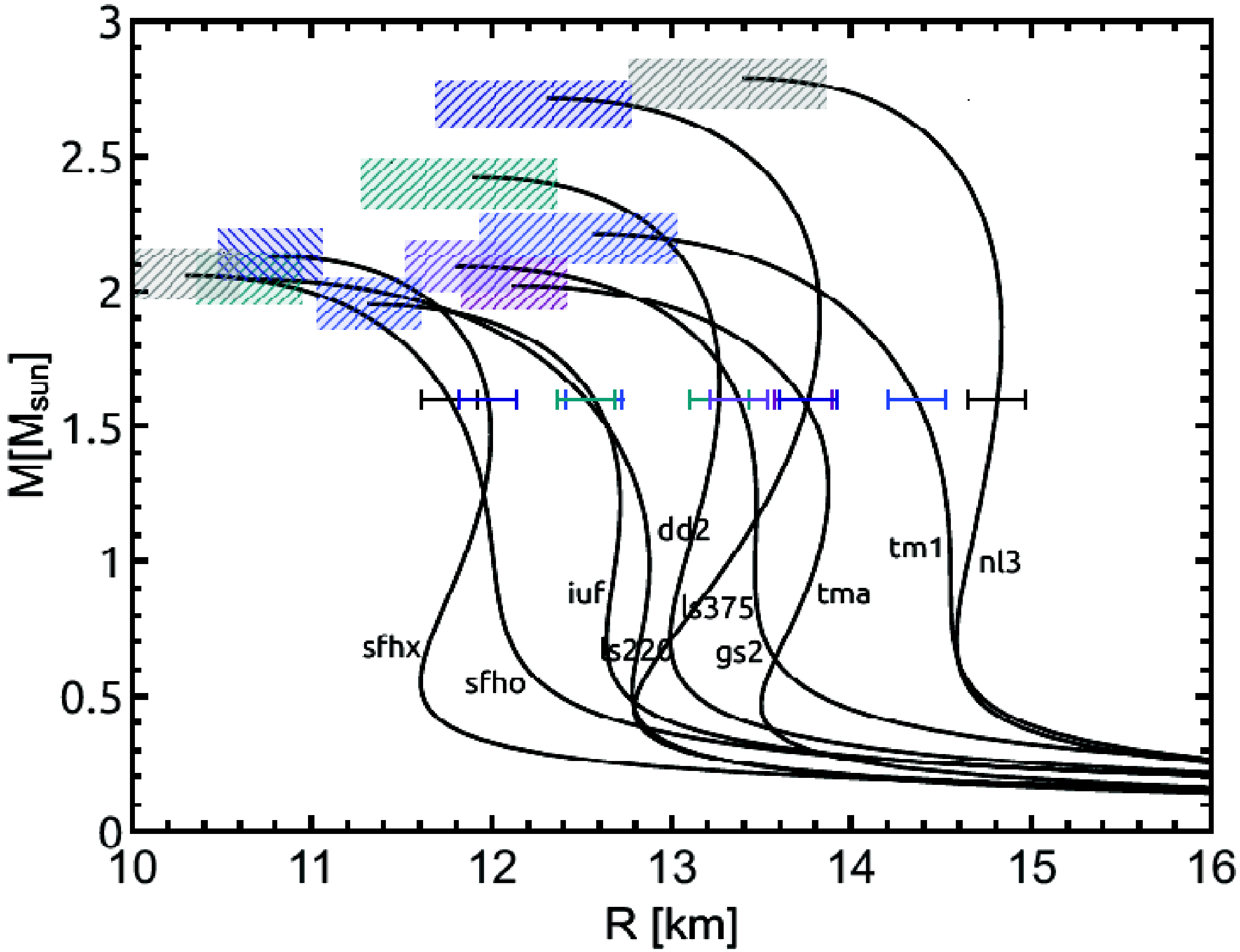
Gravitational-wave Ringdown Peak Frequencies and NS Mass Limit



Bauswein, Stergioulas & THJ, arXiv:1403.5301

Extrapolation of peak frequencies measured for typical NS binaries allows to estimate threshold mass for BH formation and thus maximum mass of cold, nonrotating NSs.

Gravitational-wave Ringdown Peak Frequencies and NS Mass Limit



Bauswein, Stergioulas & THJ, arXiv:1403.5301

Radius estimate of 1.6 Msun NS and estimated properties of maximum-mass configuration yield tight constraints for NS EOS.

More details in Andi Bauswein's talk in the afternoon!

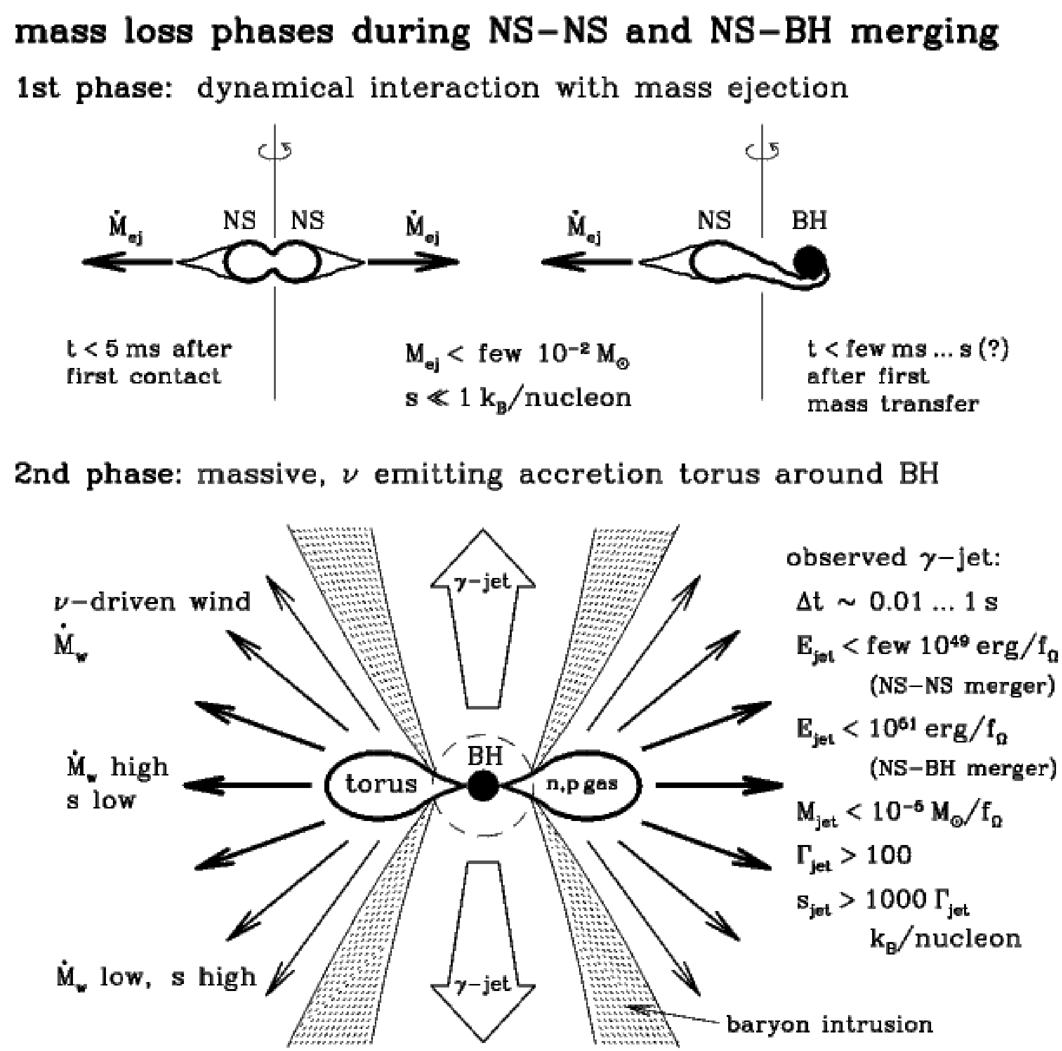
Compact Binary Mergers as Origin of r-Process Elements

Neutron Star Mergers as Production Sites of Ejecta & Heavy Elements

Compact binary mergers

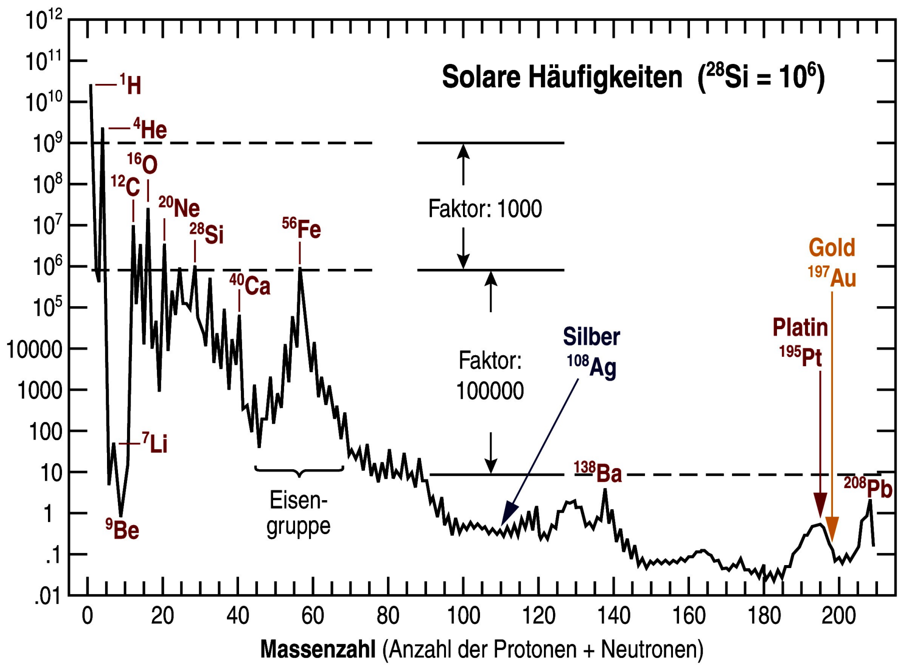
- are likely sources of short gamma-ray bursts
  (Paczynski, Jaroszynski, etc.)
- are among strongest sources of gravitational waves
- are potential production sites of r-process nuclei
  (Lattimer & Schramm & Arnett 1974, 1976; Lattimer et al. 1977; Meyer 1989)
- May be observable transient sources of optical radiation
  (Li & Paczynski 1998, Kulkarni 2005, Metzger et al. 2010, Roberts et al. 2011)

  and radio flares (Piran & Nakar 2011)



(Ruffert & Janka 1999)

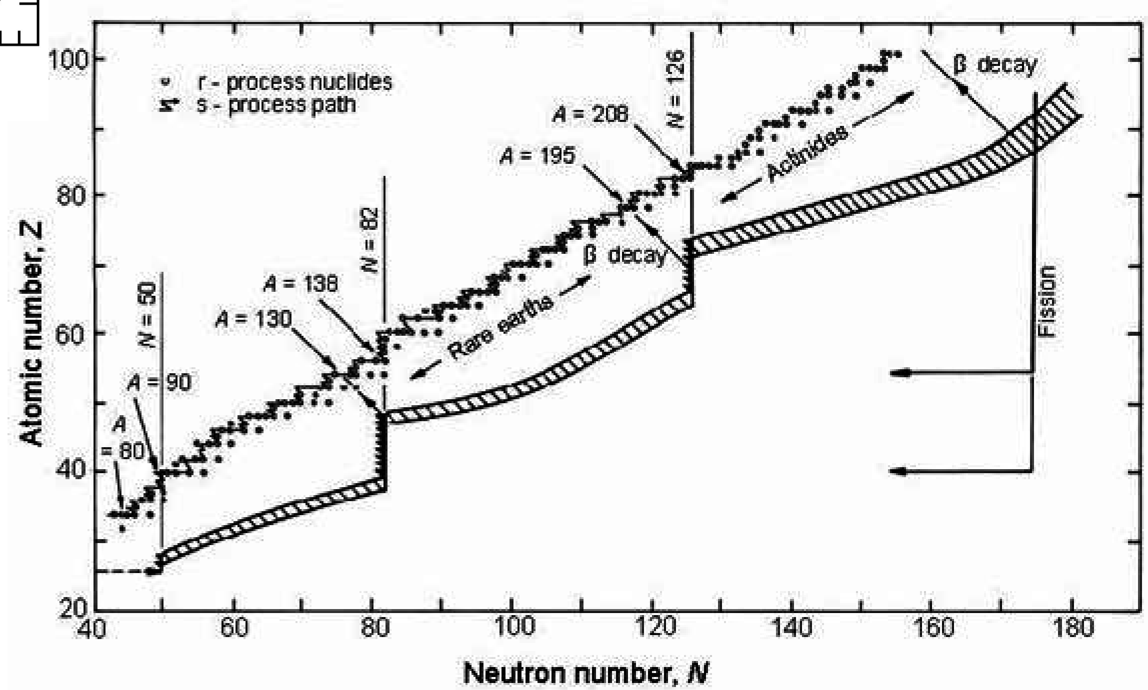
R-Process Nucleosynthesis in SN Ejecta?



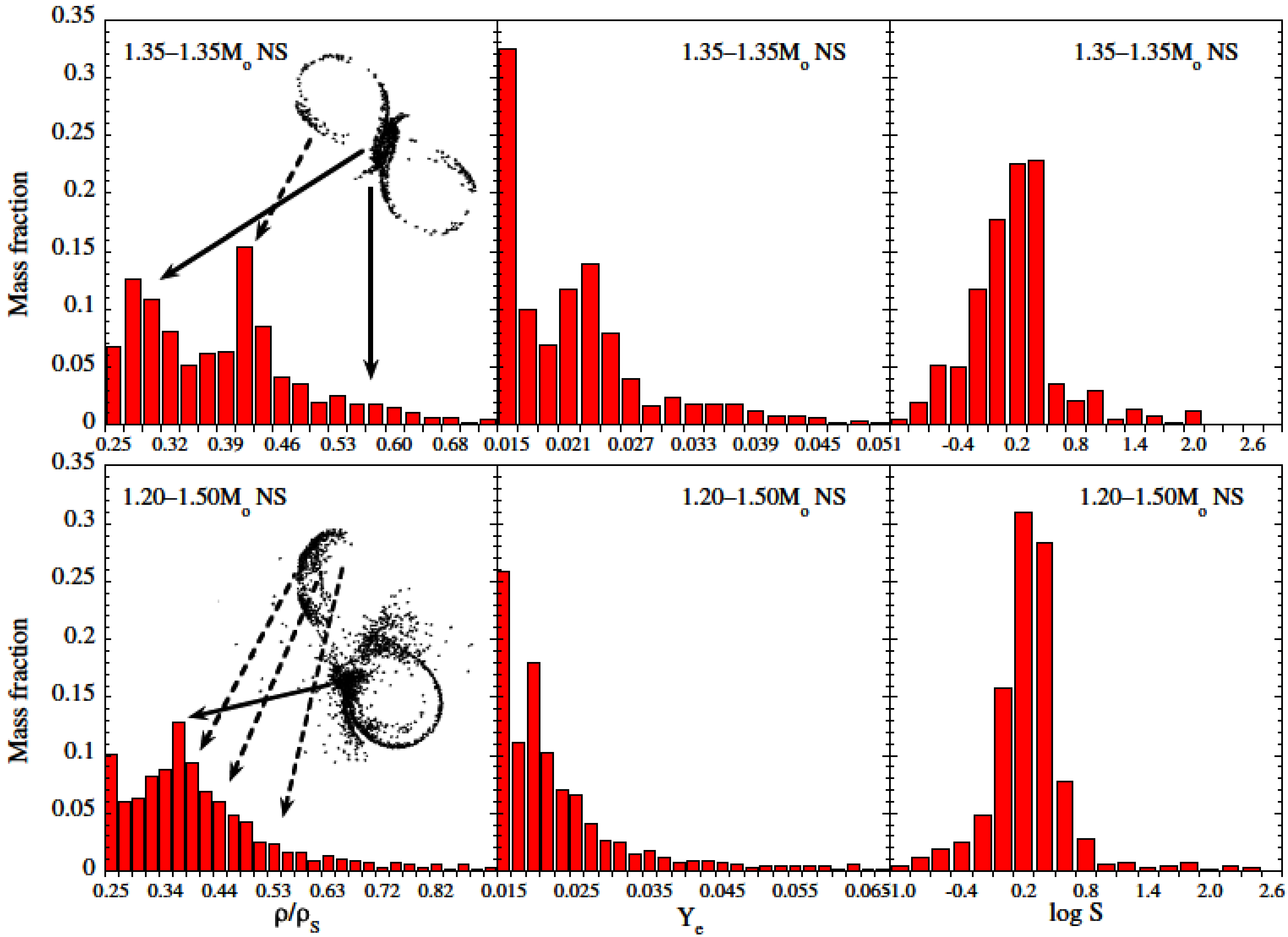
Rapid neutron-capture process (r-process) is responsible for production of ~50% of n-rich nuclei heavier than iron.

Astrophysical site of r-process is still unknown;

One of greatest mysteries of nuclear astrophysics.



Properties of Dynamical Merger Ejecta



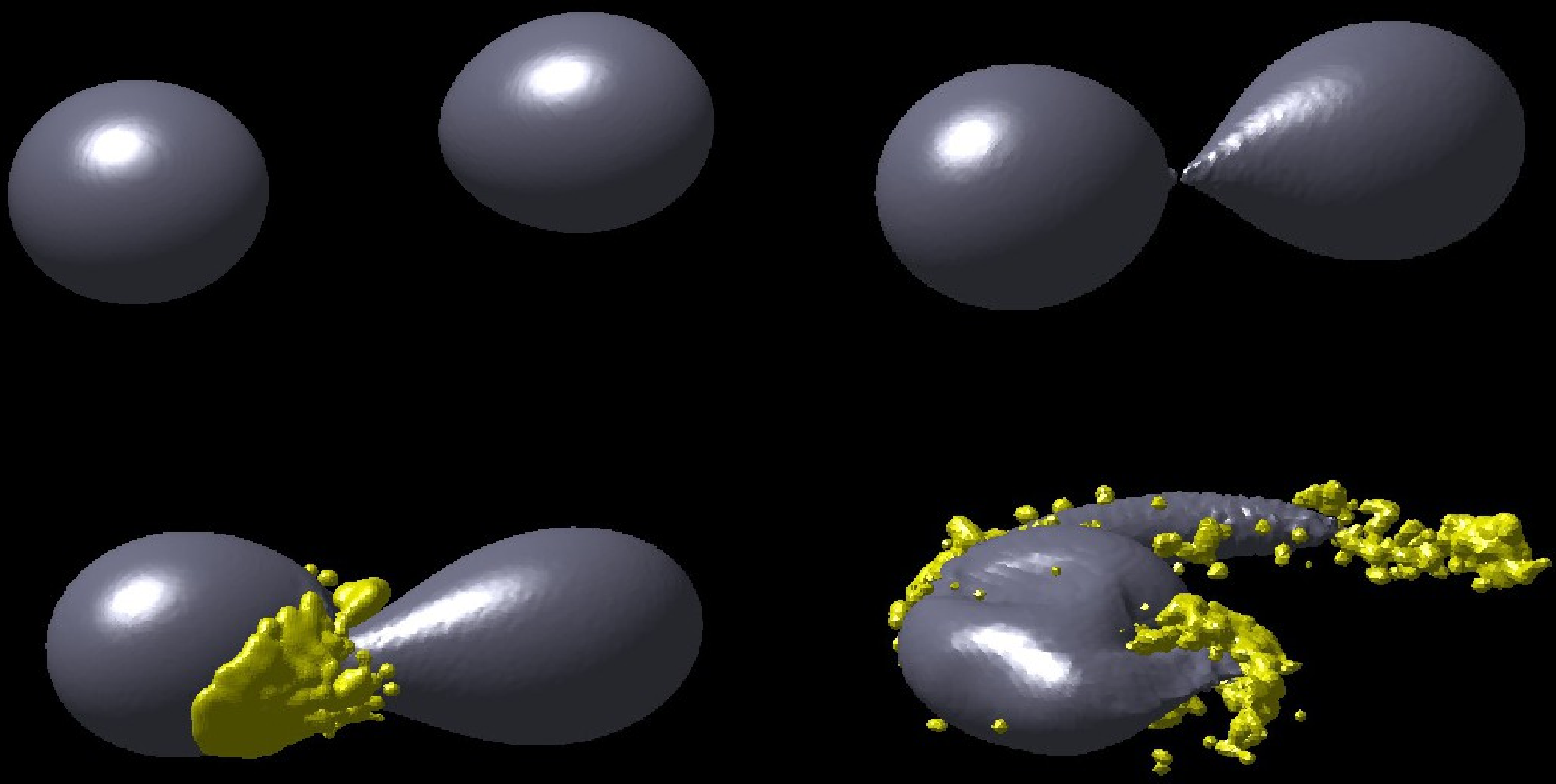
Symmetric NS-NS merger

Asymmetric NS-NS merger

(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

Mass distributions of initial density and Y_e and final entropy S per nucleon (at beginning of free expansion) of ejecta from NS-NS merger with Shen et al. (1998) EoS.

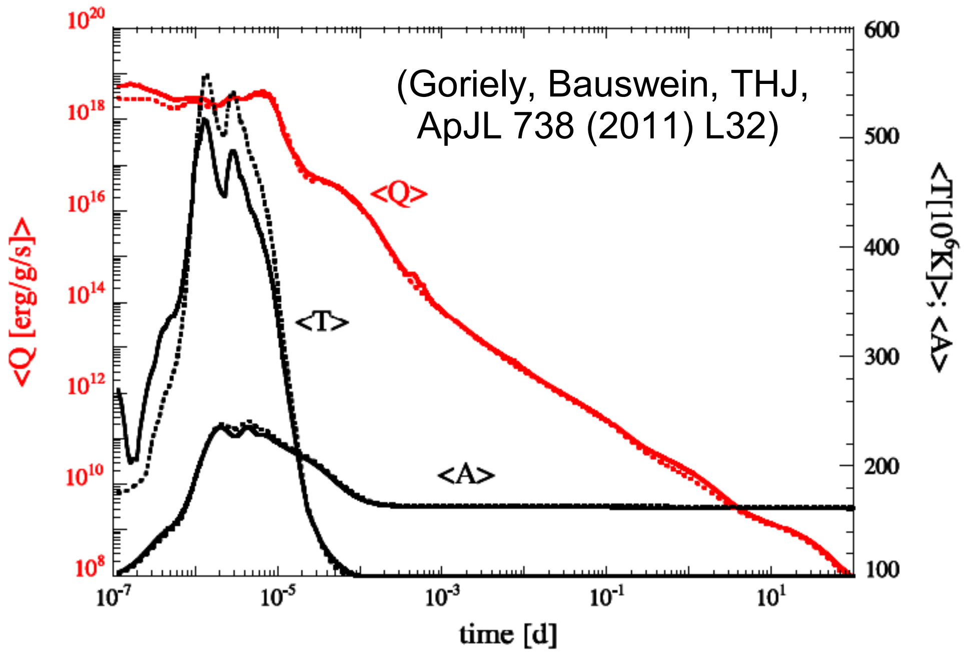
Properties of Dynamical Merger Ejecta



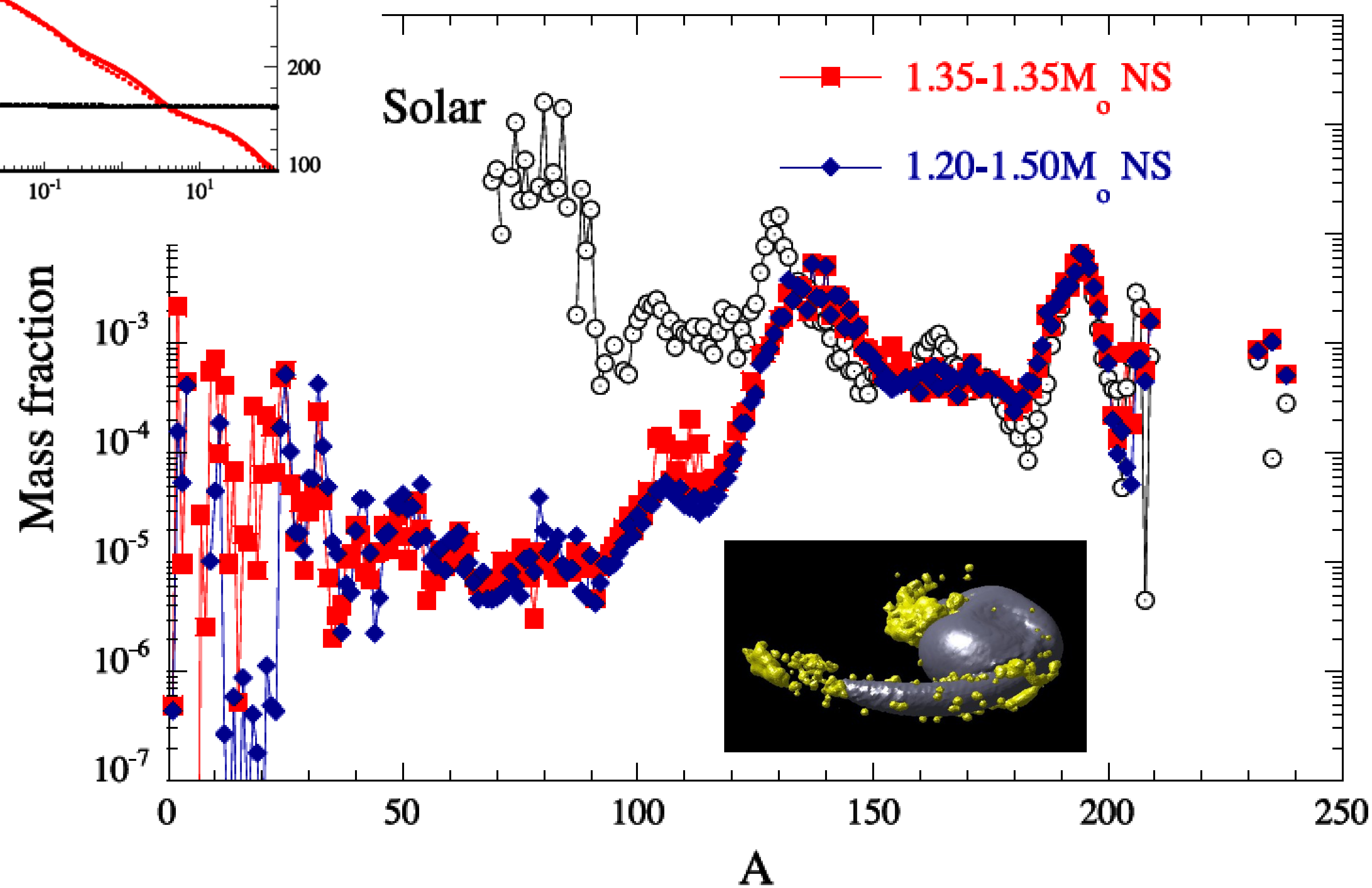
Asymmetric NS-NS merger

(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

Nucleosynthesis in Dynamical Merger Ejecta



During r-processing fission recycling takes place and produces roughly solar abundances for A > 130.

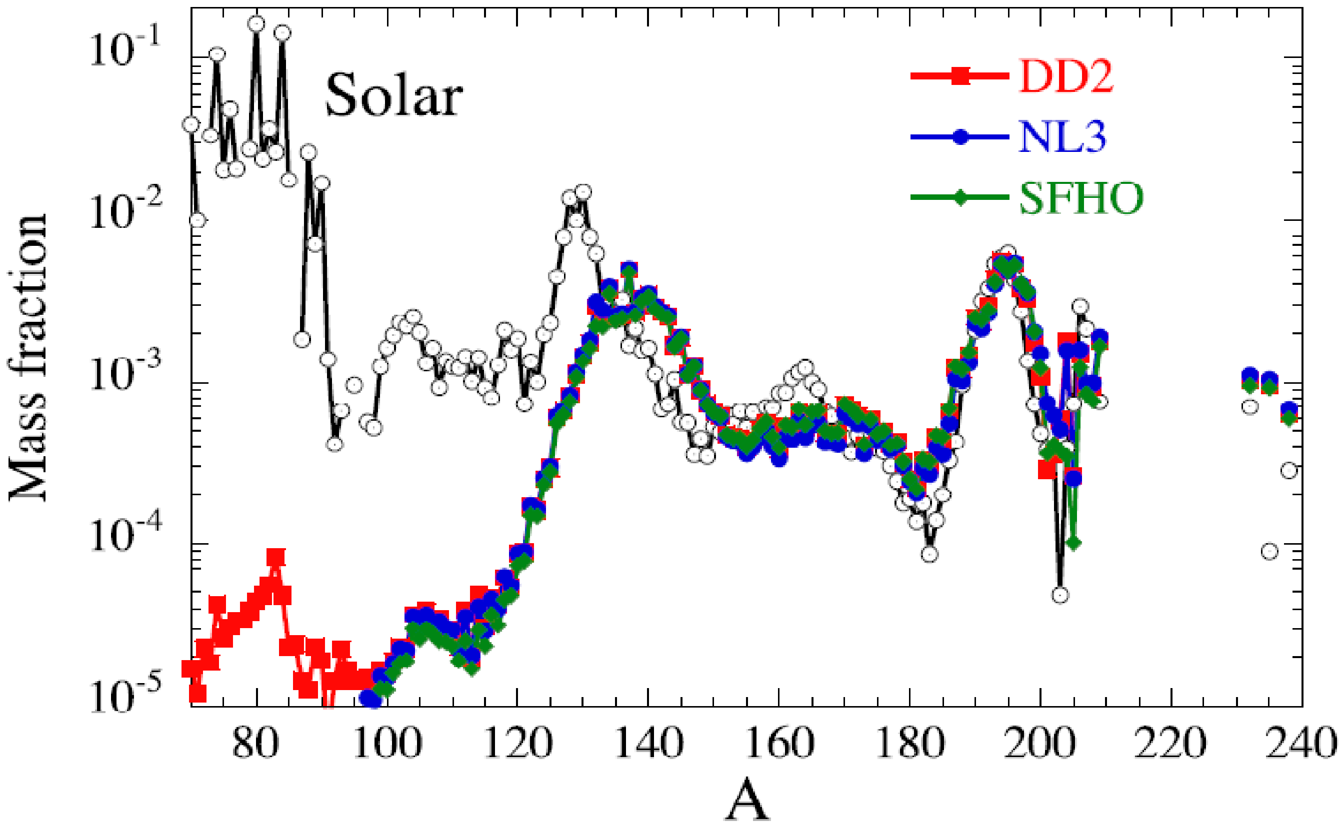


Per merger event 10^{-3}–10^{-2} M_{sun} are ejected.

With rate of 10^{-5} events per year and galaxy, NS mergers could be the main source of heavy r-process material.

R-process Nucleosynthesis

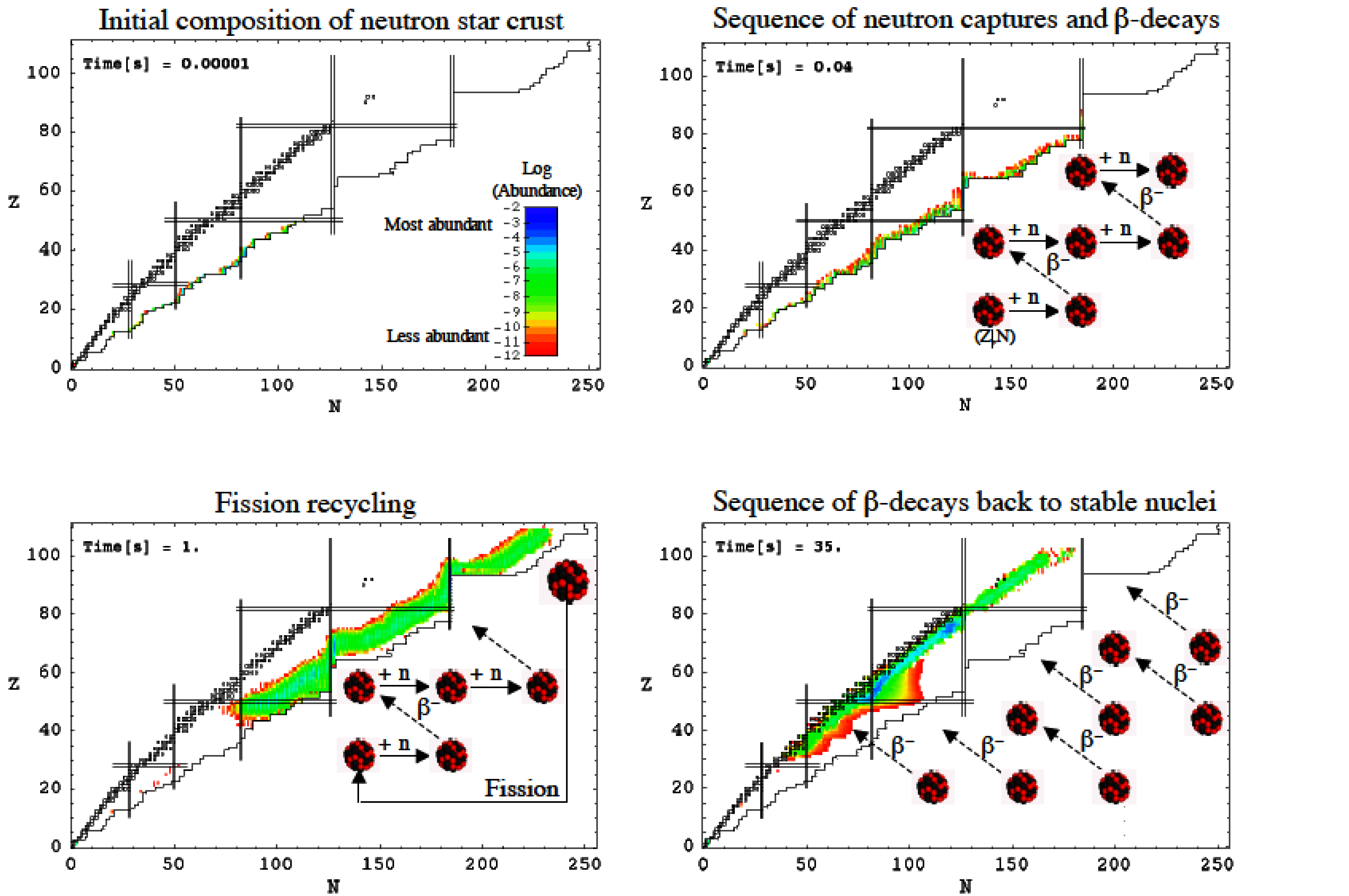
for 1.35-1.35 binaries (most abundant in binary population)



Goriely, Bauswein & THJ, ApJ 773 (2013) 78

- Robust r-process with solar abundance above A ~130
- Insensitive to high-density equation of state? Caveat: neutrinos??
- Radioactive decays power optical transient

Nucleosynthesis in Dynamical Merger Ejecta

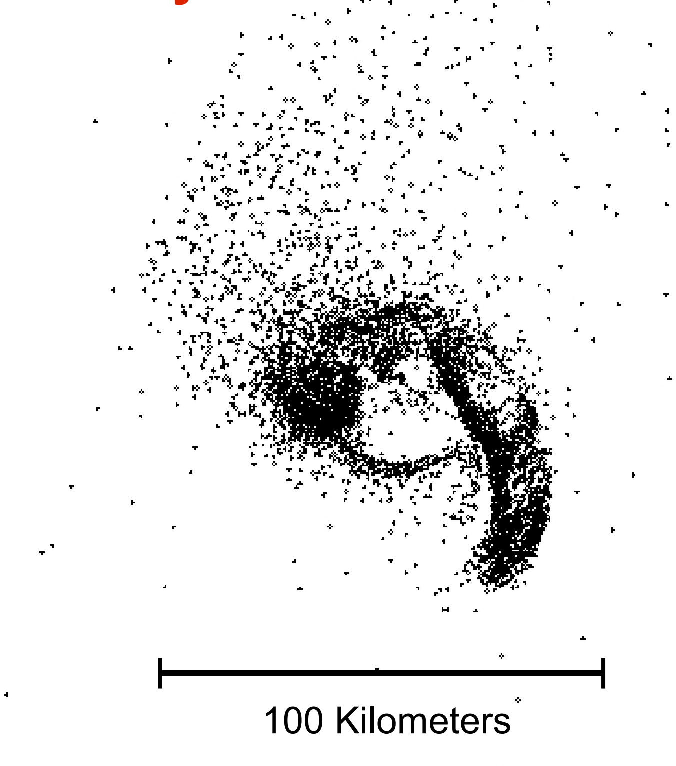


(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

Fission recycling leads to robust abundance distribution.

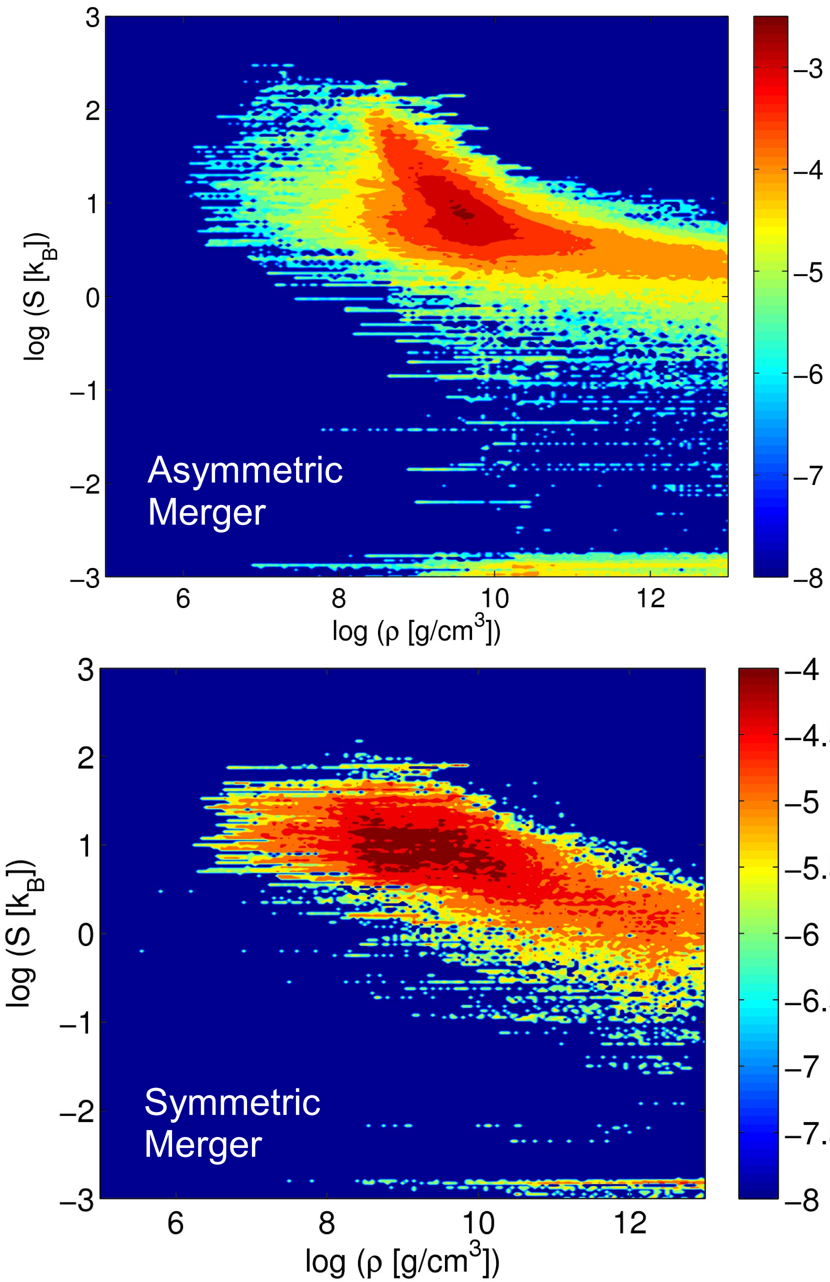
Properties of Dynamical Merger Ejecta

Asymmetric NS-NS merger



(A. Bauswein 2011; simulation code originating from R. Oechslin)

- Detailed conditions of ejecta depend on merger dynamics.
- Cold and hot (shocked) ejecta components.
- Significant differences dependent on binary parameters ! Models needed!



Nucleosynthesis in Neutrino-Heated Ejecta

Crucial parameters for nucleosynthesis in neutrino-driven outflows:

* Electron-to-baryon ratio Y_e (<---> neutron excess)
* Entropy (<----> ratio of (temperature)^3 to density)
* Expansion timescale

Determined by the interaction of stellar gas with neutrinos from radiating merger remnant:

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

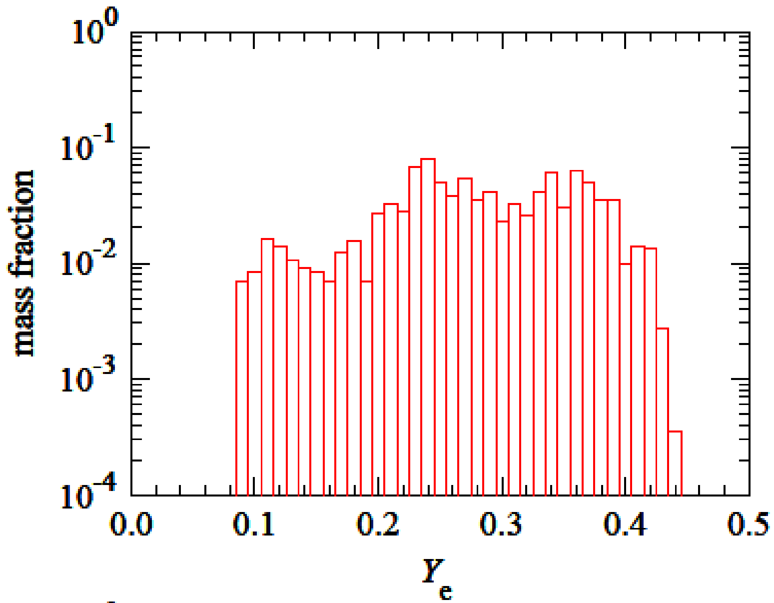
$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta)}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta)}\right]^{-1}$$

with $\epsilon_\nu = \frac{\langle \epsilon_\nu^2 \rangle}{\langle \epsilon_\nu \rangle}$ and $\Delta = (m_n - m_p)c^2 \approx 1.29\,\mathrm{MeV}.$

If $L_{\bar{\nu}_e} \approx L_{\nu_e}$, one needs for $Y_e < 0.5$ (i.e. neutron excess):

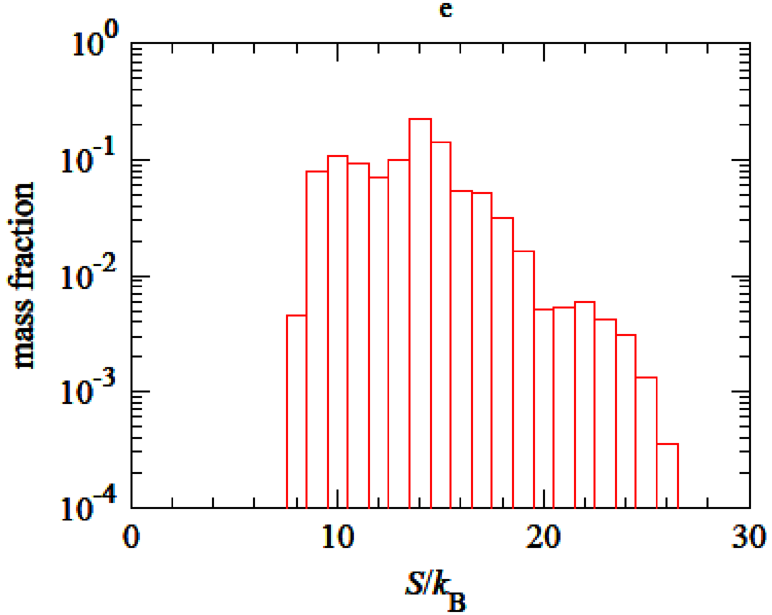
$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} > 4\Delta.$$

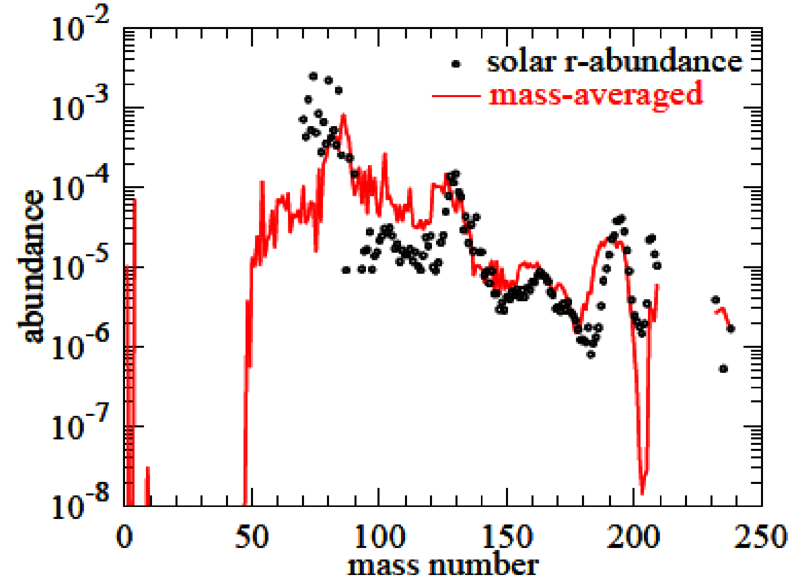
Nucleosynthesis in Neutrino-processed Merger Ejecta



- Compact NSs produce strongly shock-heated ejecta.
- Electron fraction increases considerably in hot ejecta, mostly due to positron capture.
- Heavy r-process is still produced, but also A < 130 nuclei.

(Wanajo et al., arXiv:1402.7317)

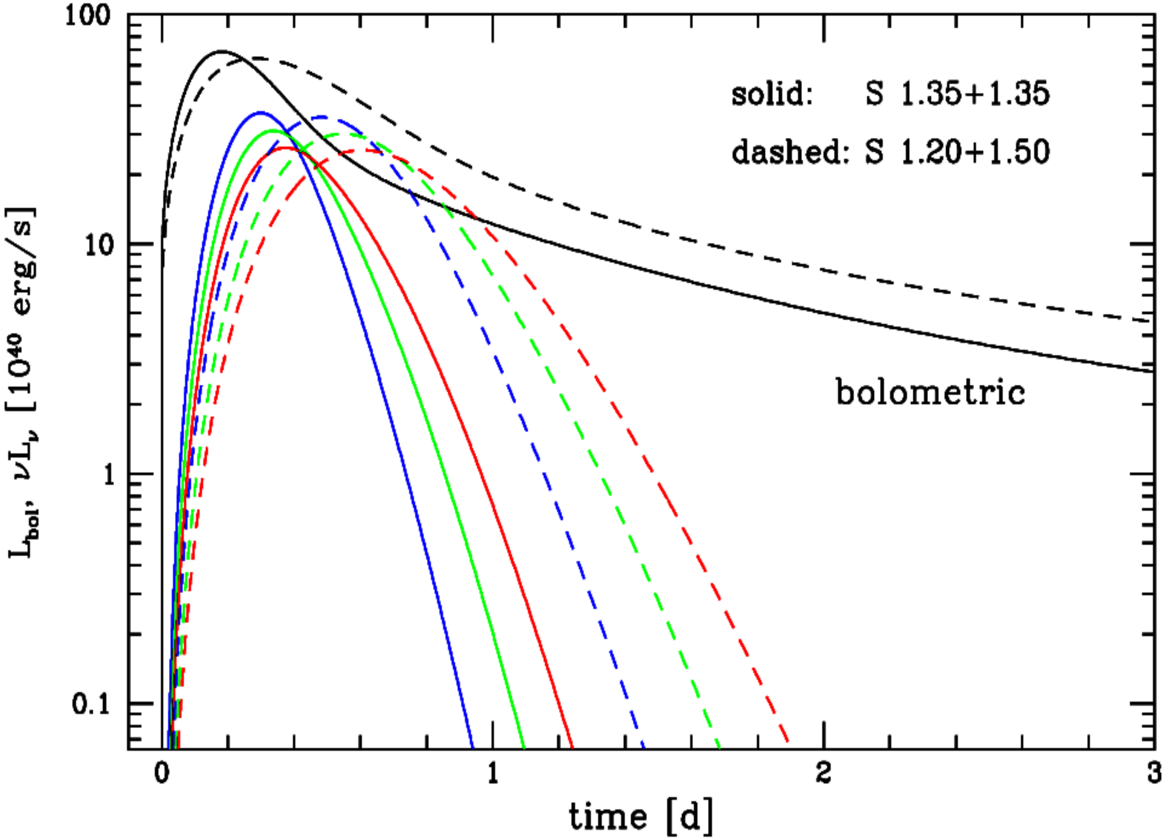




Electromagnetic Transients from Compact Binary Mergers

Electromagnetic Transients: Light Curve

Goriely, Bauswein & THJ, ApJL (2011)



Shen EoS;

Light curves from one-zone ejecta modell

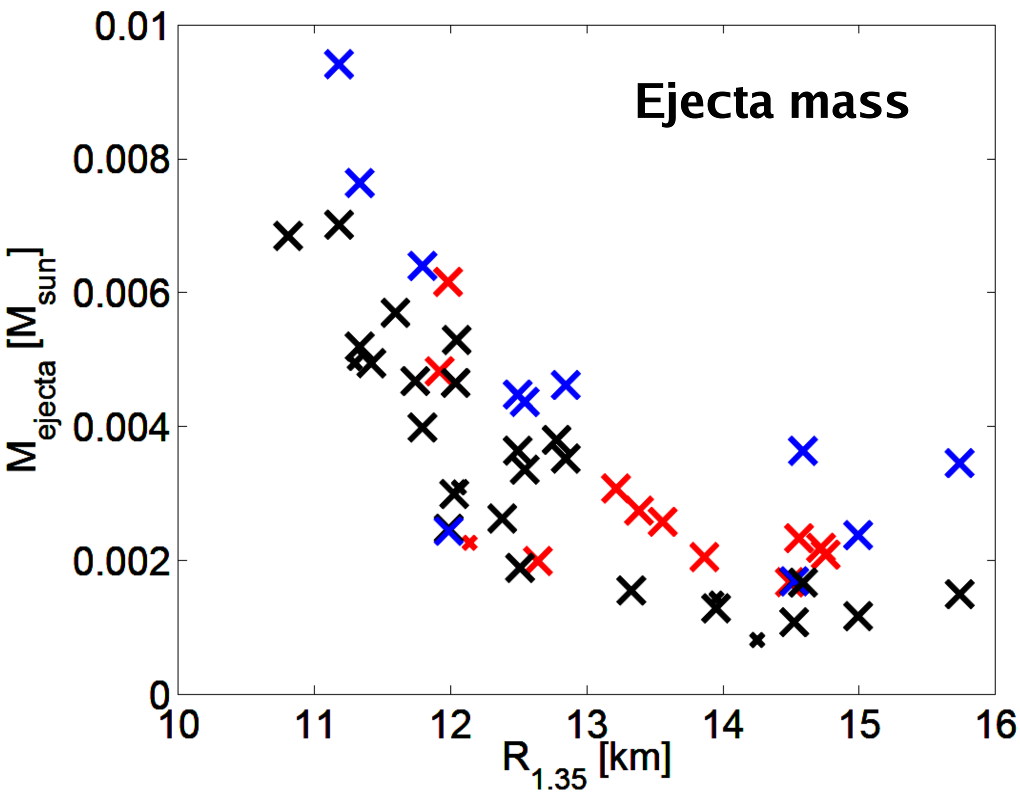
Estimates: $L_{bolo} \sim 7.5*10^{41}$ erg/s $\kappa^{-1/2}$ $(v/0.1c)^{1/2}$ $(M_{ejecta}/10^{-2}M_{sun})^{1/2}$

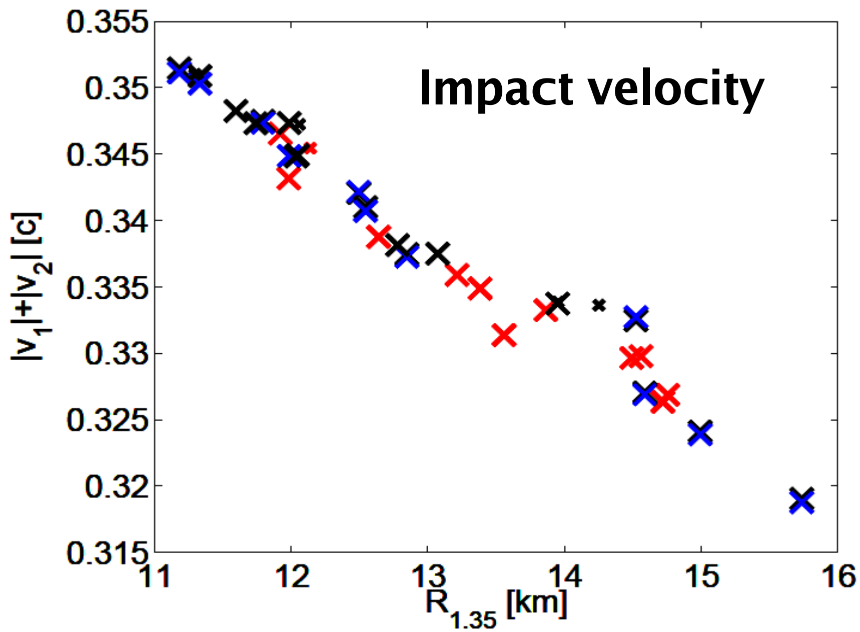
$t_{peak} \sim 0.5$ d $\kappa^{1/2}$ $(v/0.1c)^{-1/2}$ $(M_{ejecta}/10^{-2}M_{sun})^{1/2}$

$T_{eff} \sim 1.4*10^4$ K $\kappa^{-3/8}$ $(v/0.1c)^{-1/8}$ $(M_{ejecta}/10^{-2}M_{sun})^{-1/8}$

Ejecta Masses

for 1.35-1.35 binaries (most abundant in binary population)

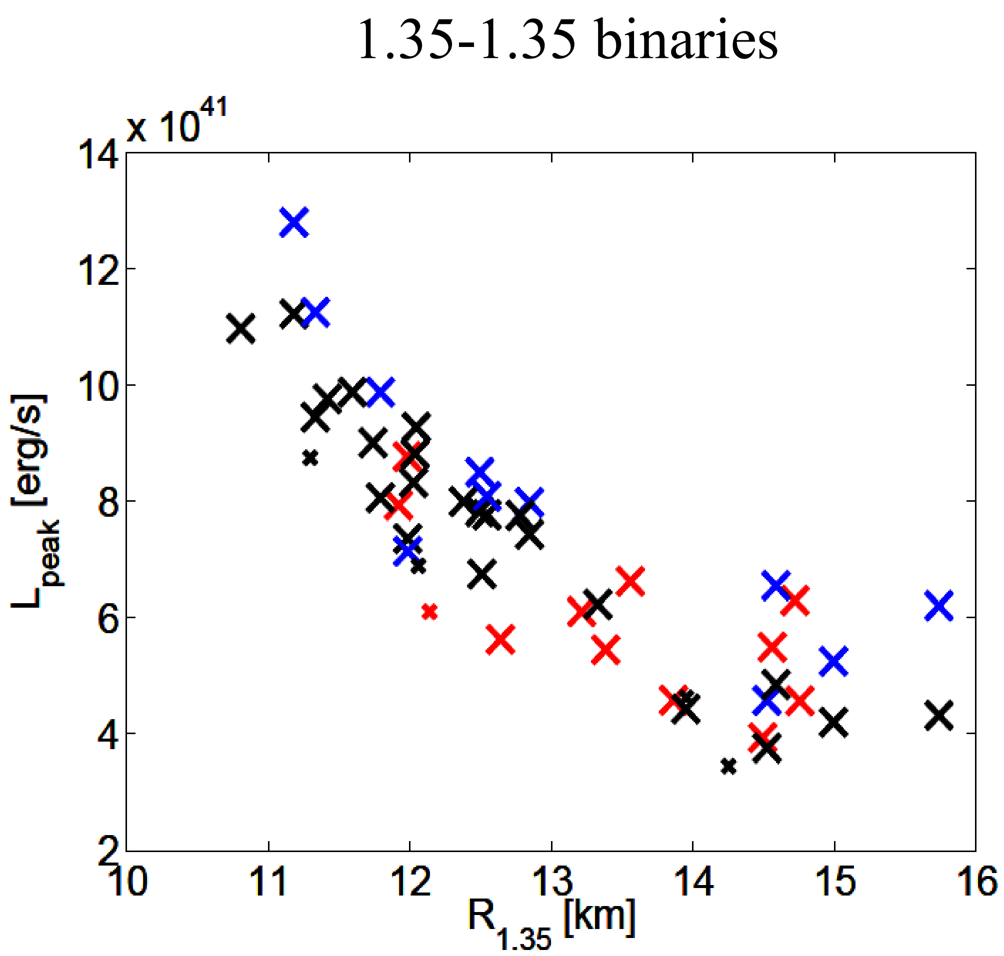




Bauswein, Goriely & THJ, ApJ (2013)

- NS compactness is the crucial parameter affecting ejecta
- i.e. determines amount of nucleosynthesized ejecta
- Similar results for 1.2-1.5 binaries

Electromagnetic Transients: Peak Luminosity



Bauswein, Goriely & THJ, ApJ (2013)

→ also peak time and effective temperature show scaling

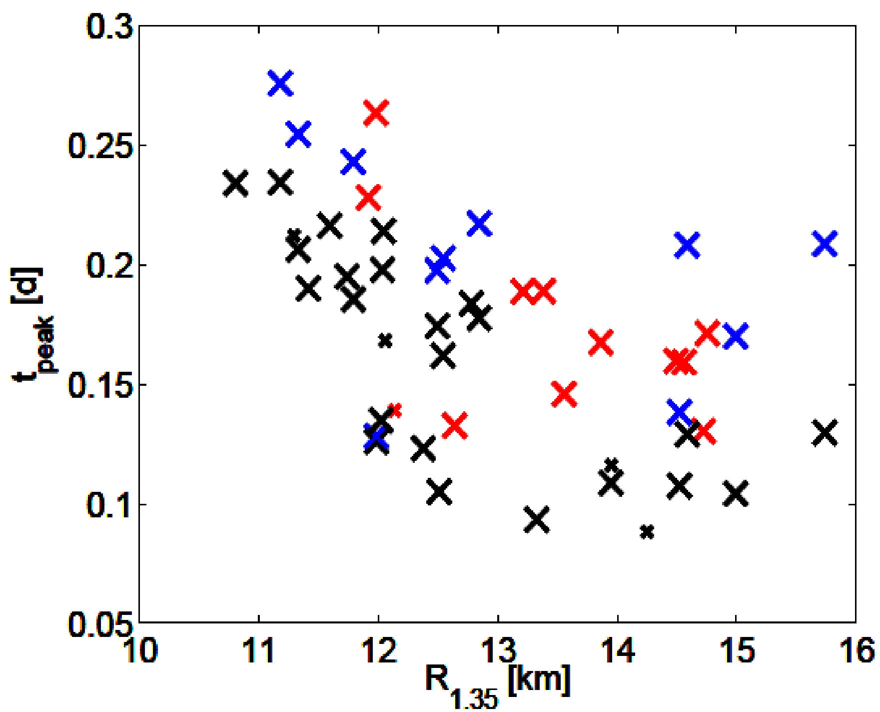
→ potential constraint for NS radius from optical observations

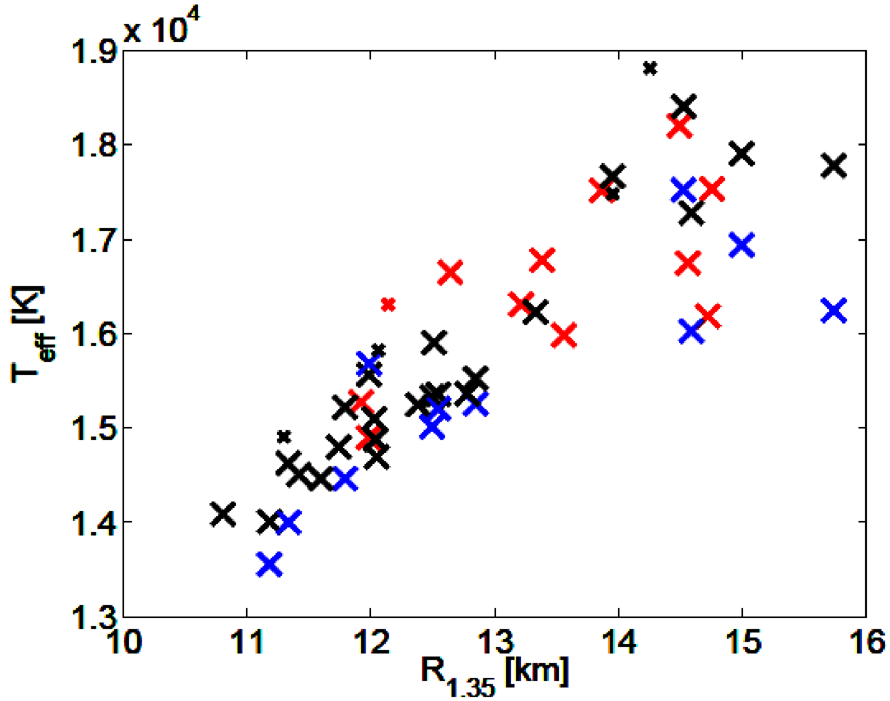
(similar findings for asymmetric binaries)

Peak Time and Effective Temperature

1.35-1.35 binaries

Bauswein, Goriely & THJ, ApJ (2013)

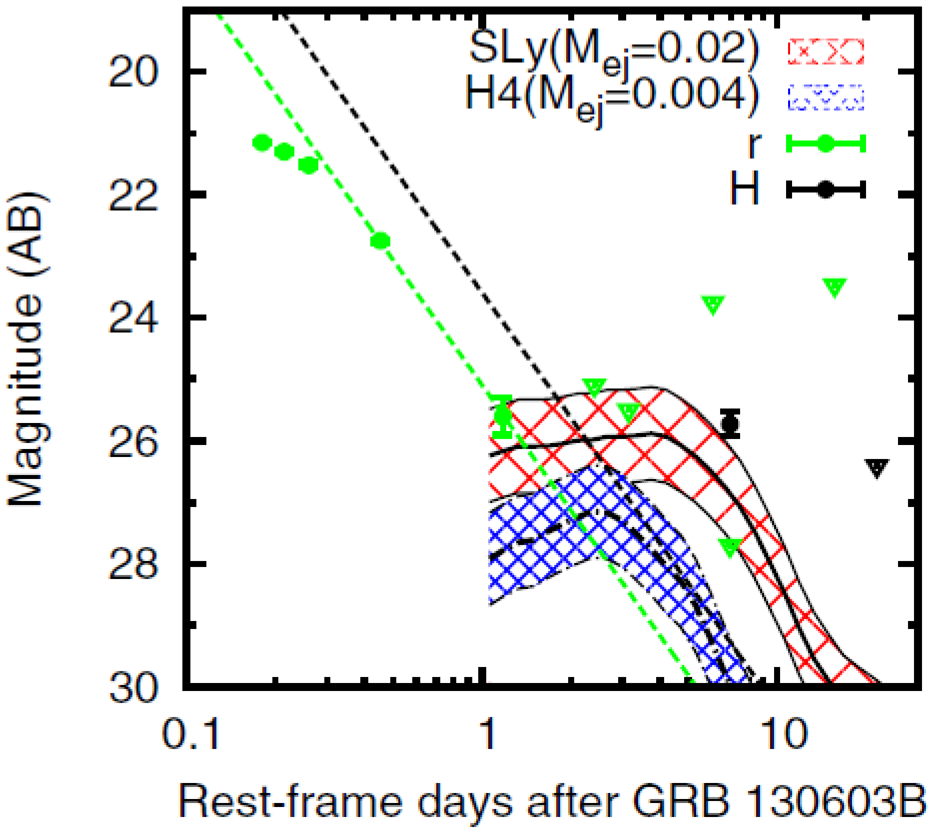




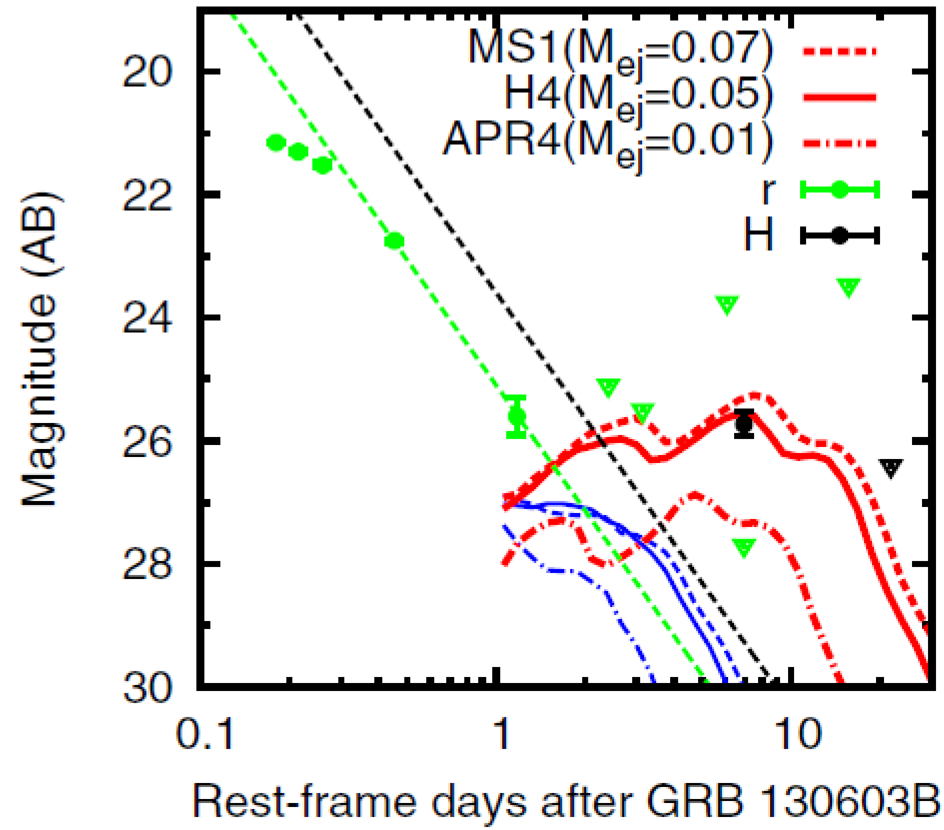
- Timescales substantially reduced compared to Newtonian models
- However: Fe-group opacity can be considerable underestimation!

Kasen, Badnell, & Barnes, ApJ (2013); Hotokezaka et al., ApJ (2013); Tanaka et al. ApJ (2014)

Infrared Transient of GRB 130603B and NS EOS Implications



Soft EOS with small NS radius needed for NS+NS merger



Stiff EOS with large NS radius needed for NS+BH merger

Hotokezaka et al., ApJ (2013)

Outlook:

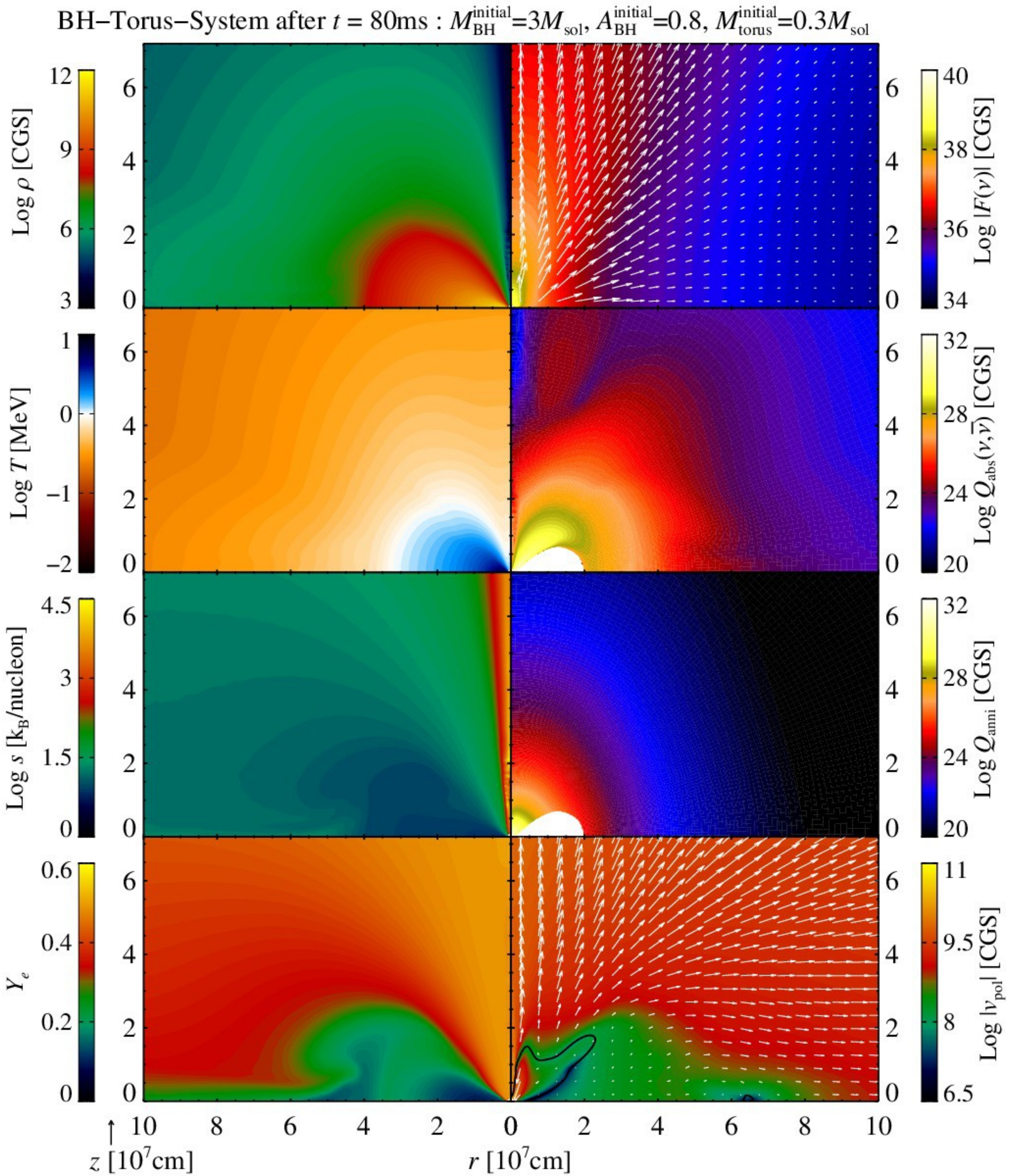
Simulations of Remnant Evolution of Compact Binary Mergers

Compact and Gaseous NS+NS/BH Merger Remnants

- Long-time evolution of remnant HMNS or BH-torus system adds to mass loss and (r-process) nucleosynthesis.
- Viscously and neutrino-driven outflows (Fernandez & Metzger 2013, Metzger & Fernandez 2014, A. Perego, this conference)
- Also nickel can be produced (Surman et al. 2014)
- Nucleosynthesis products with A < 130 decrease opacity compared to rare earths (Lanthanides) and cause electromagnetic transient to be blue instead of red (Metzger & Fernandez 2014)
- First 3D long-time simulations of gaseous remnant support light curve analysis on basis of 1D models (Rosswog et al. 2014, Grossman et al. 2014)

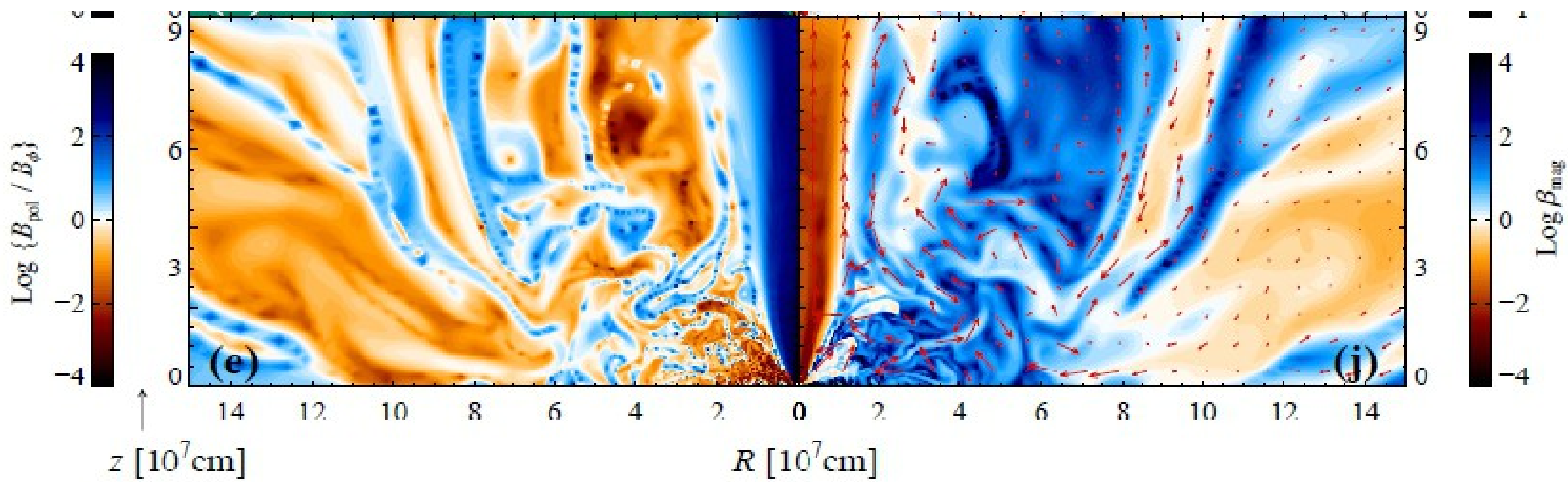
BH-Torus Outflows

- Hydrodynamical 2D models of BH-torus evolution.
  (Just, PhD Thesis 2011;
  Just, Obergaulinger, THJ, in prep.)
- New Newtonian MHD-code with 2D, energy-dependent neutrino transport based on two-moment closure scheme.
  (Obergaulinger, PhD Thesis 2008;
  O. Just, PhD Thesis 2012)
- BH treated by Artemova-Novikov potential.
- Displayed model based on Shakura-Sunyaev α-viscosity
- MHD yields turbulent tori !



(O. Just et al., in preparation)

Outflows from Magnetized BH-Torus



(O. Just et al., in preparation)

Summary and Conclusions

- NS+NS/BH mergers sensitively depend on the nuclear equation of state
- Generic outcome of 1.35-1.35 M_{sun} merger:
  Formation of a differentially rotating NS → Pronounced peak in the GW spectrum due to quadrupole oscillations
- Peak GW frequency scales very well with the radius of a nonrotating NS with 1.6 M_{sun}: Measurement with an accuracy of 100-200 meters possible for sources at 20 Mpc (even 50 Mpc?)
- Correlations / constraints for other EoS properties
- Ejecta mass and features of electromagnetic counterparts are strongly and systematically affected by EoS (cf. GRB130603B)
- Nucleosynthesis insensitive/weakly sensitive to EoS, but depends on neutrino emission (and absorption) —> relevance for opacities!