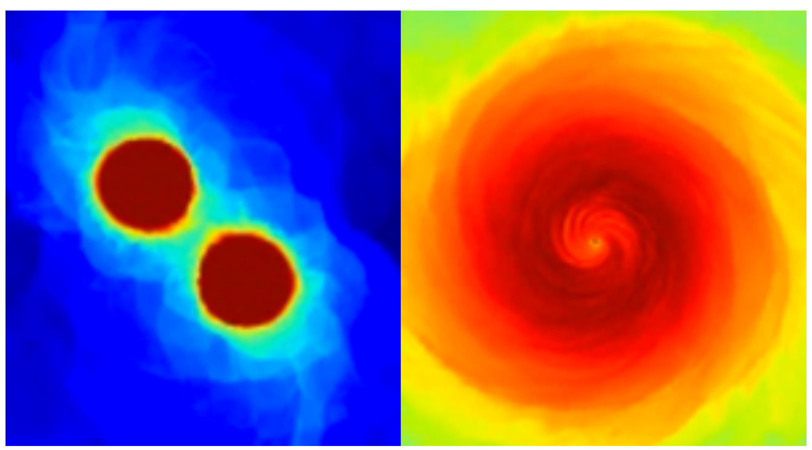
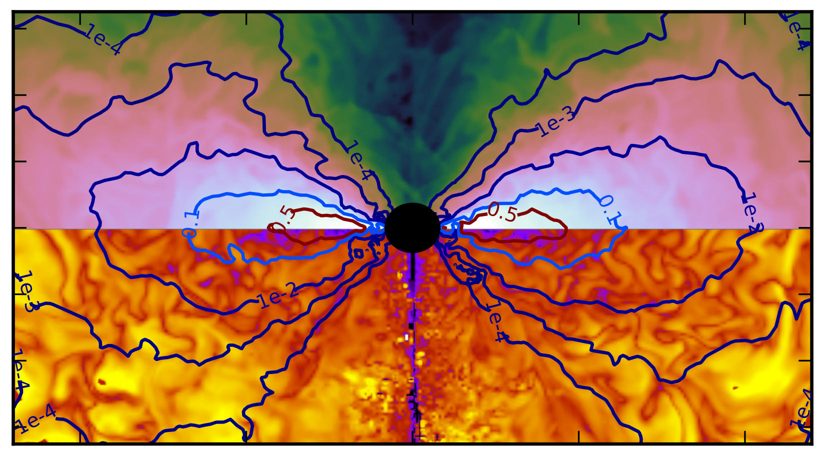
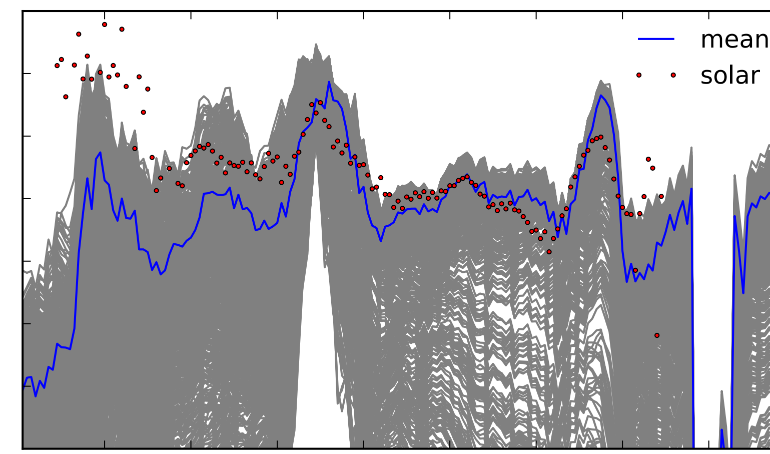
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Neutron star mergers and multi-messenger astronomy







Daniel M. Siegel

NASA Einstein Fellow

Center for Theoretical Physics, Columbia Astrophysics Laboratory, Columbia University

TeVPA 2017, Columbus, Ohio, 7-11 August, 2017

LIGO: NS mergers


LSC LIGO Scientific Collaboration

Detections | News | About | LIGO science | Educational resources | Multimedi

Latest news | News archive | Press releases | Press information | Blog | Awards & Recogni

NEWS

UPGRADED VIRGO JOINS LIGO DURING THE 2ND OBSERVING RUN (O2)

1 August 2017 -- On August 1, 2017 the Virgo detector began taking science-quality data in concert with LIGO. While LIGO and Virgo have operated together in the past, this marks the first time they are jointly taking data after significant upgrades to both detectors. This 2nd observing run (O2) began at the end of November 2016 and will continue until August 25, 2017.

Virgo, located near Pisa, Italy, began taking engineering-mode data alongside the two LIGO detectors in mid-June. Since that time the Virgo team has been working to hunt down sources of instrument noise and improve the stable operation of the interferometer. Besides providing further confirmation of any detected events, the addition of Virgo is expected to improve their sky localization by an average factor of 2 or better. At the end of O2 both detectors will return to improving their sensitivities in preparation for the next joint observation run (O3, currently scheduled to begin in Fall 2018).

For more information see the Virgo press release.

Virgo joined LIGO during O2!

LIGO: NS mergers

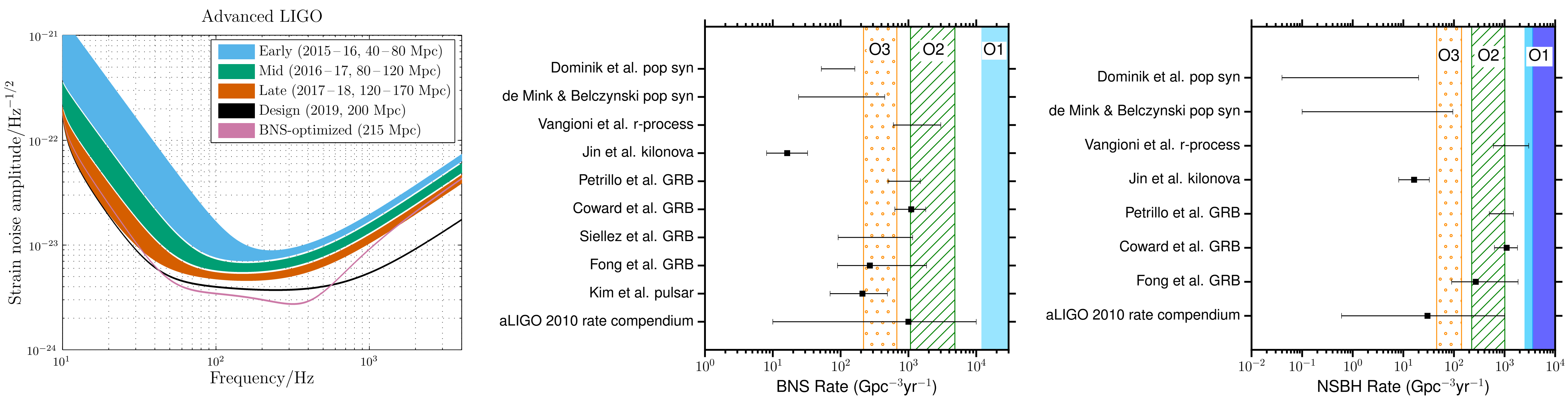
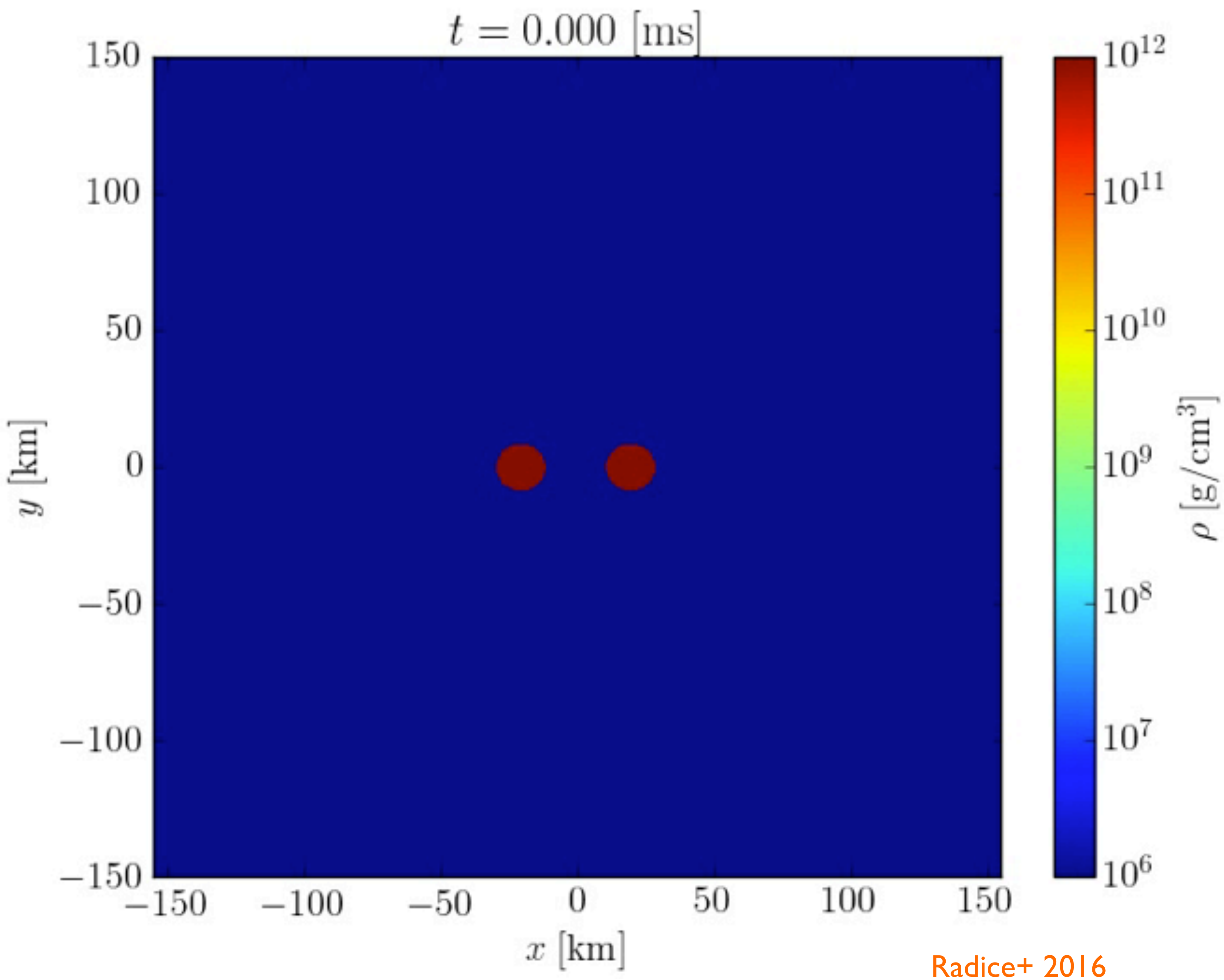


Fig.: Sensitivity of LIGO to BNS mergers (left) and sensitivity vs. predicted NS merger rates (right) Abbott+ 2016c

LIGO will probe deeply into the predicted NS merger rate distributions by 2018 (O3)

⟶ exciting discoveries expected soon

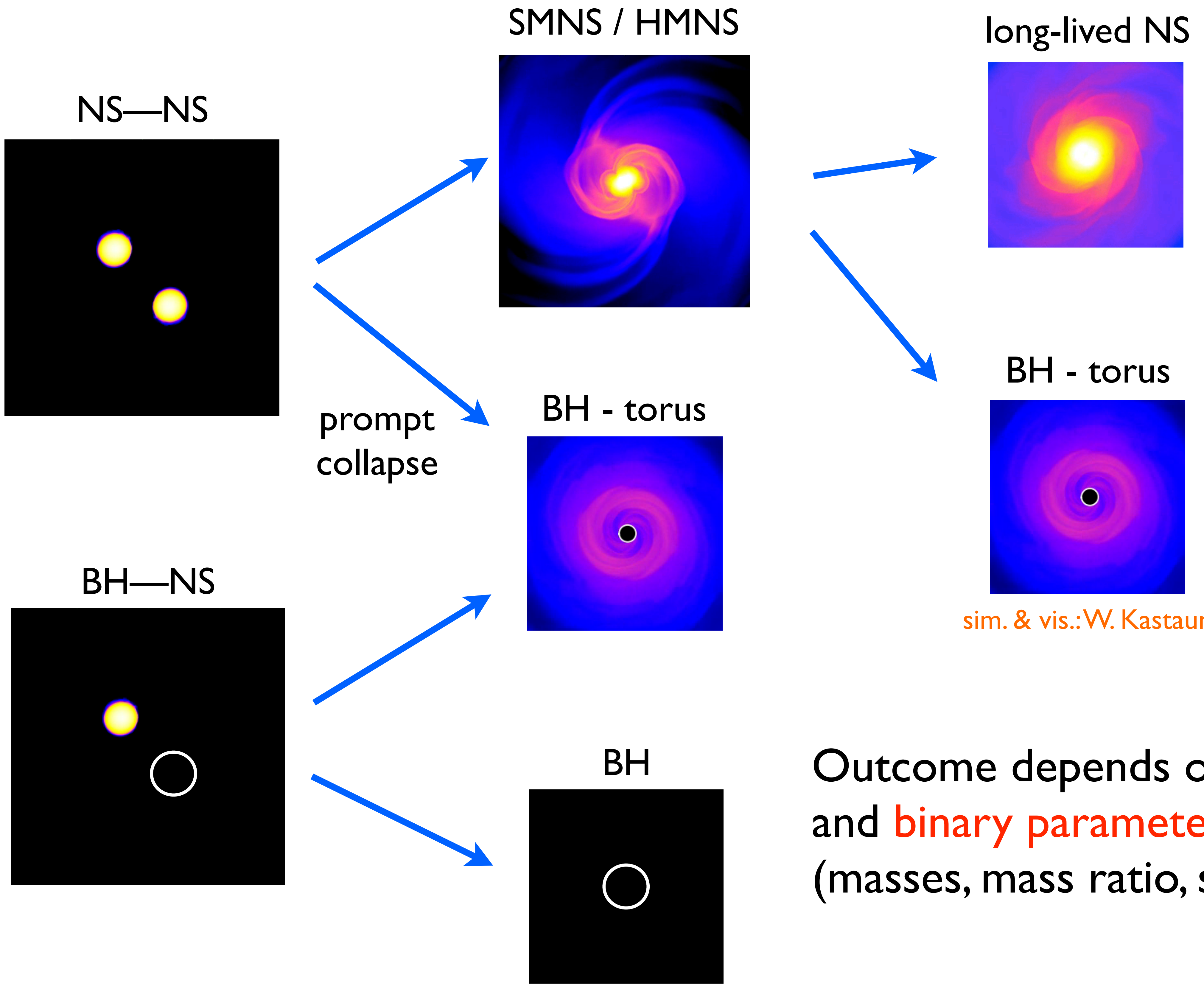
BNS merger: numerical simulation



Radice+ 2016

Movie: BNS merger with prompt black-hole formation, showing dynamical ejecta and disk formation

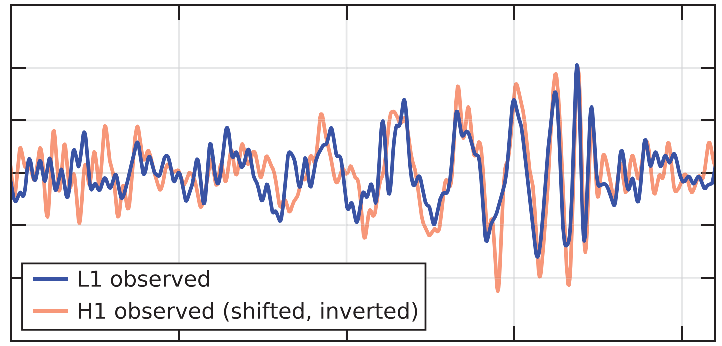
NS merger phenomenology



Outcome depends on EOS and binary parameters (masses, mass ratio, spin, ...)

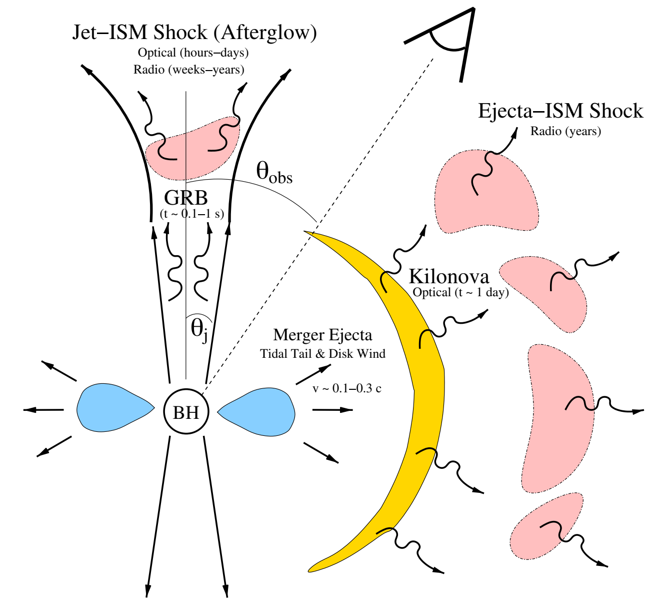
NS mergers: multi-messengers

gravity

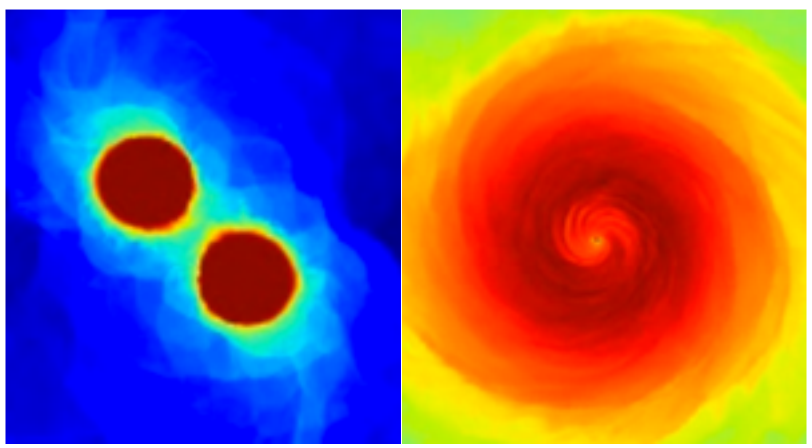


Gravitational Waves

electromagnetic

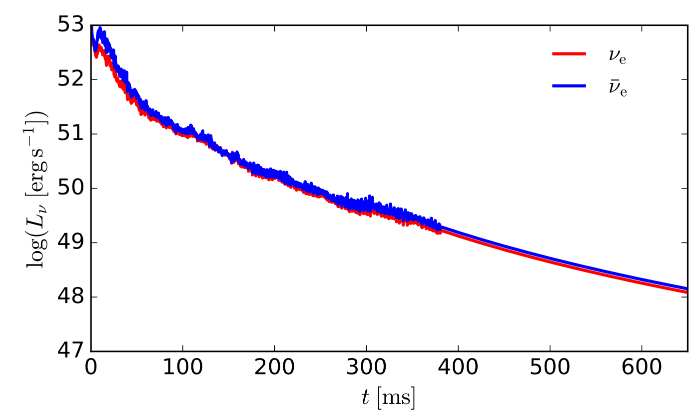


EM transients



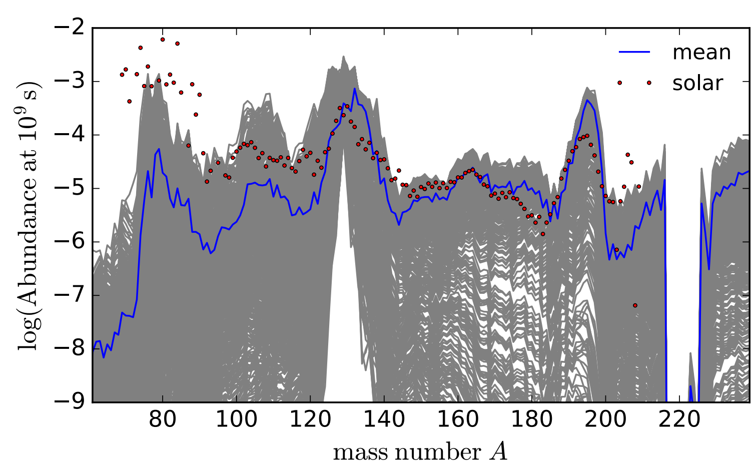
NS mergers

particles



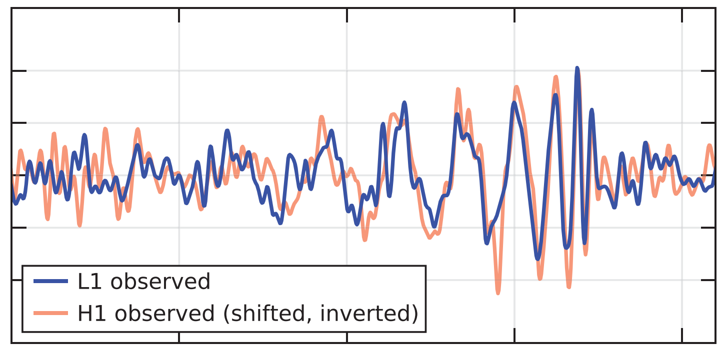
neutrinos

heavy elements



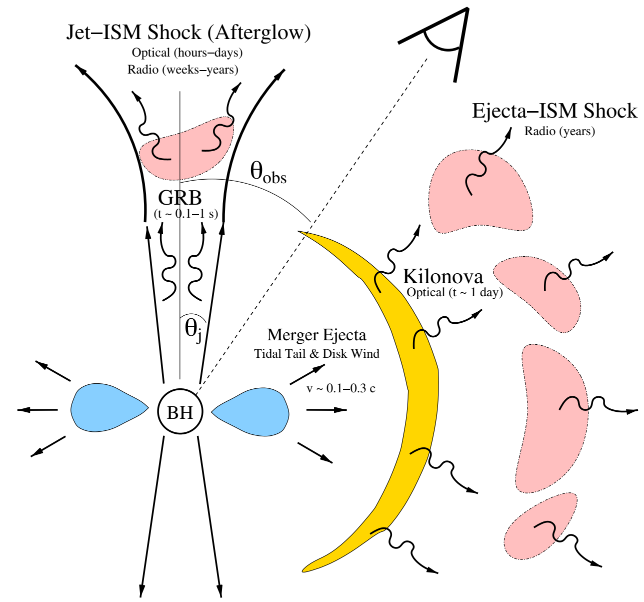
r-process nucleosynthesis of heavy elements

NS mergers: multi-messengers



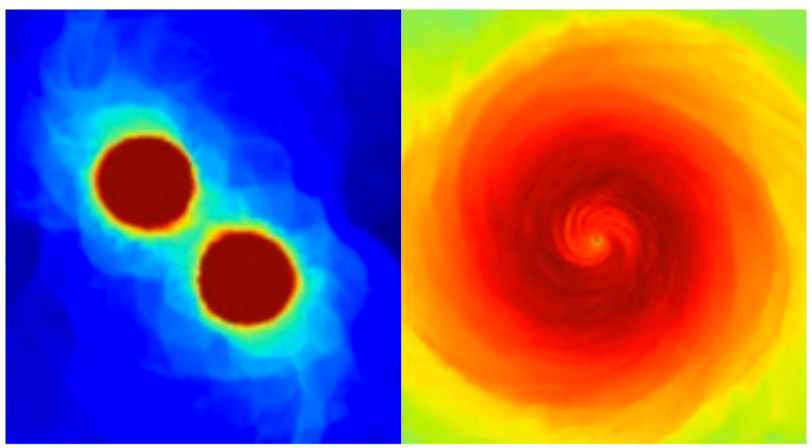
Gravitational Waves

gravity



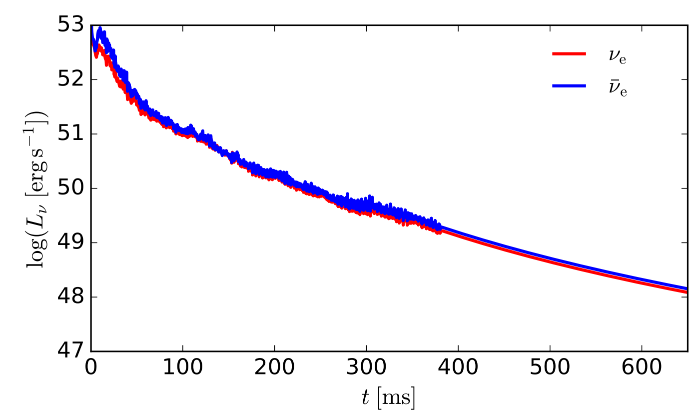
EM transients

electromagnetic



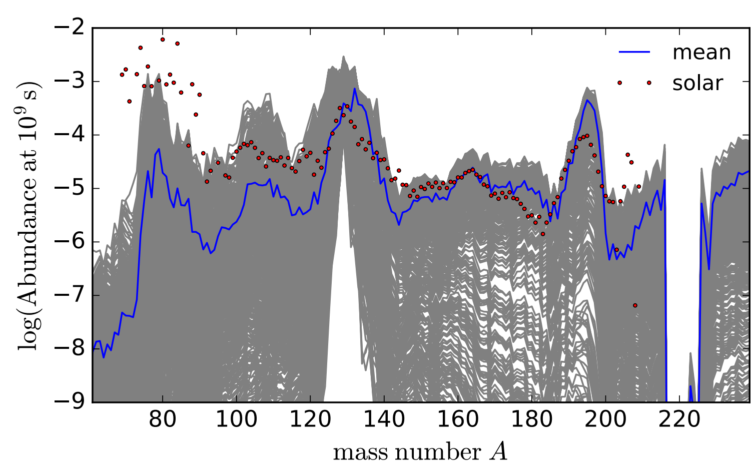
NS mergers

particles



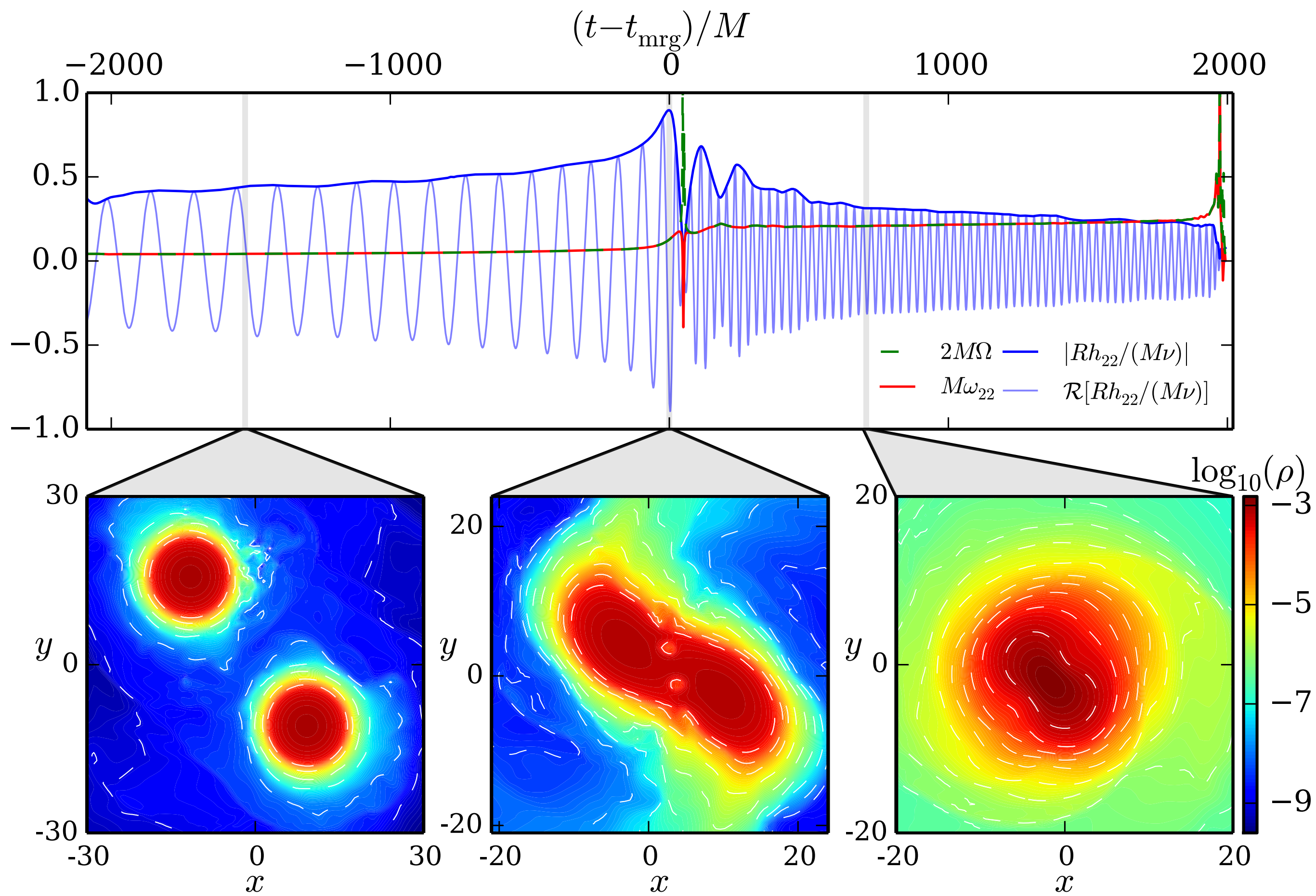
neutrinos

heavy elements

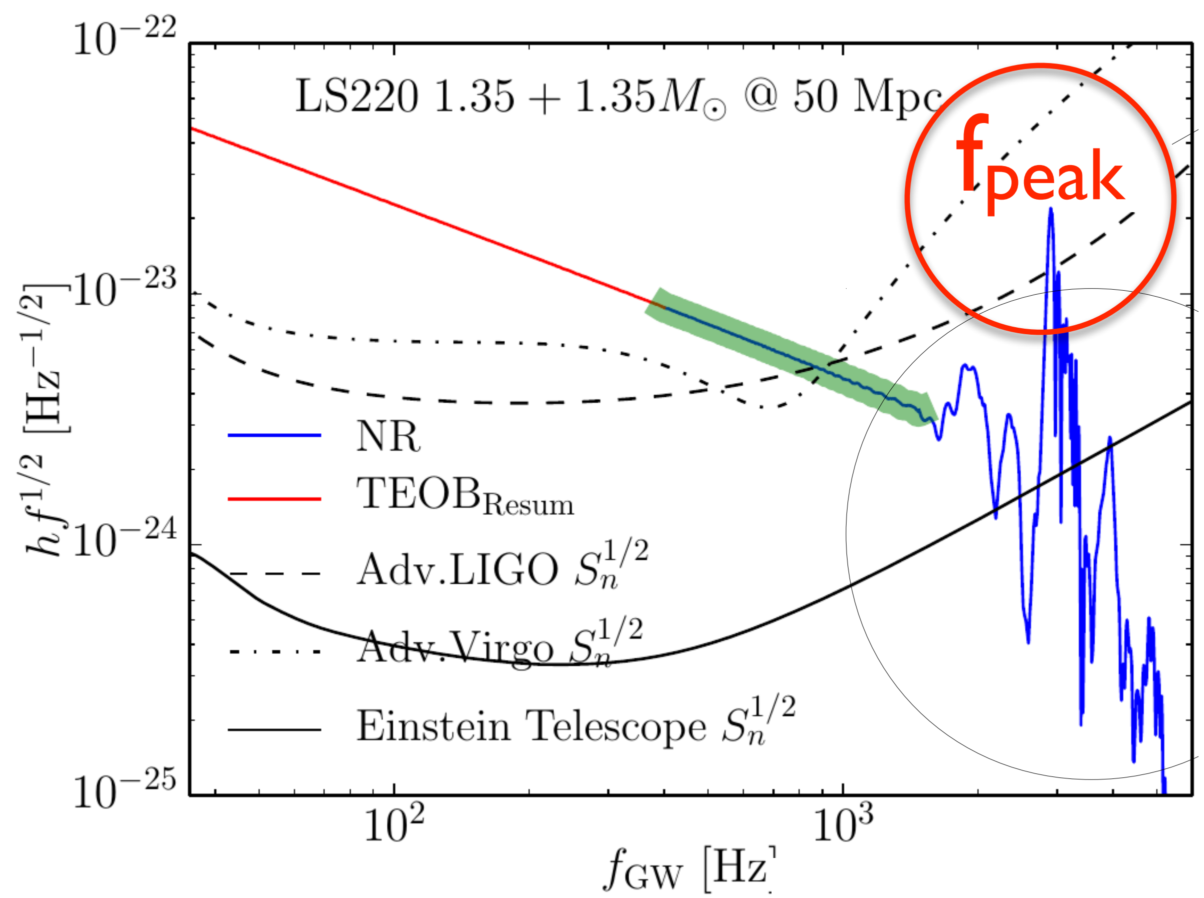


r-process nucleosynthesis of heavy elements

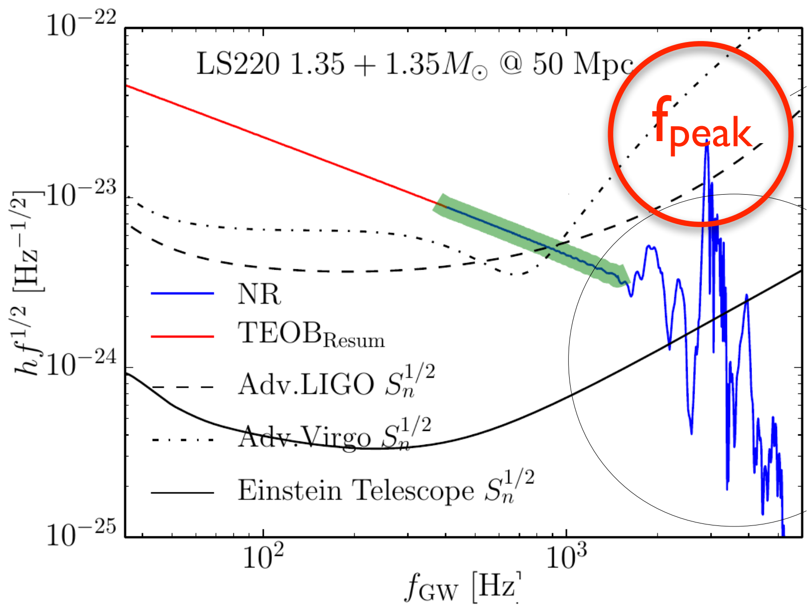
Gravitational waves from BNS mergers

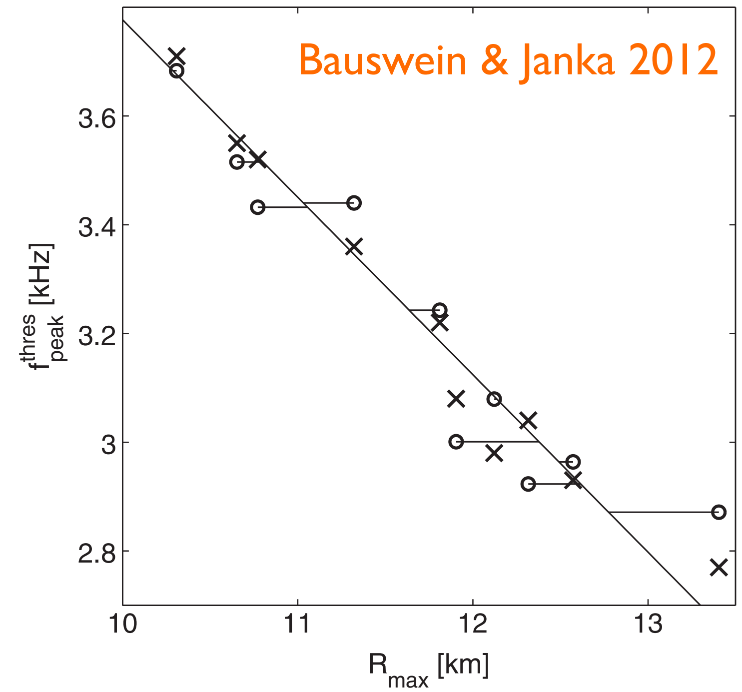


Bernuzzi+ 2015

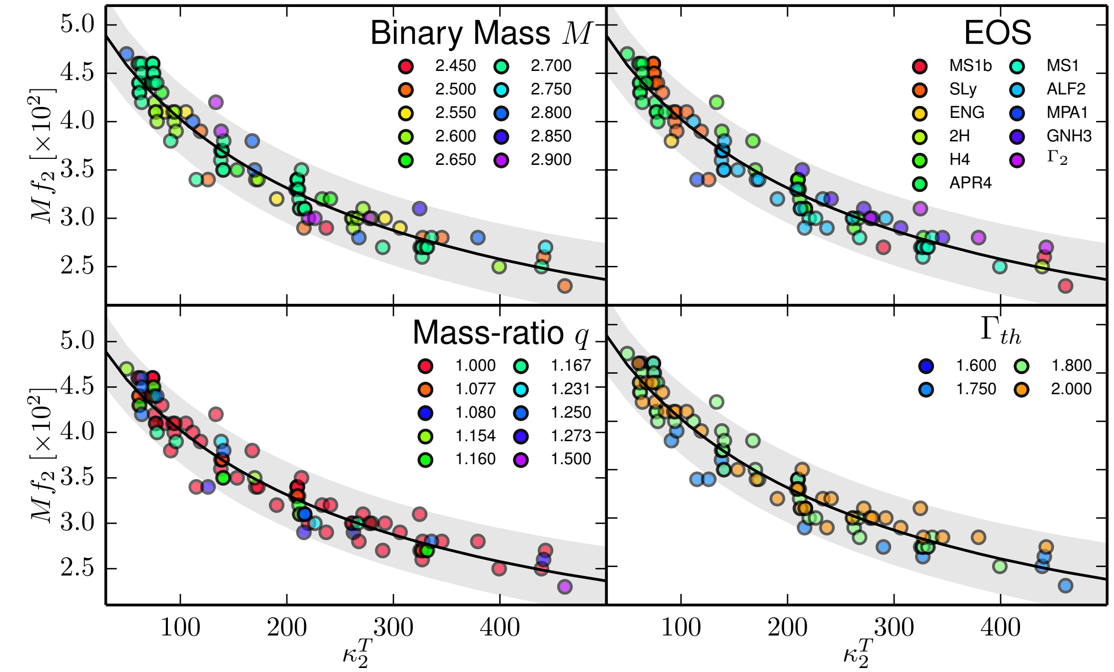


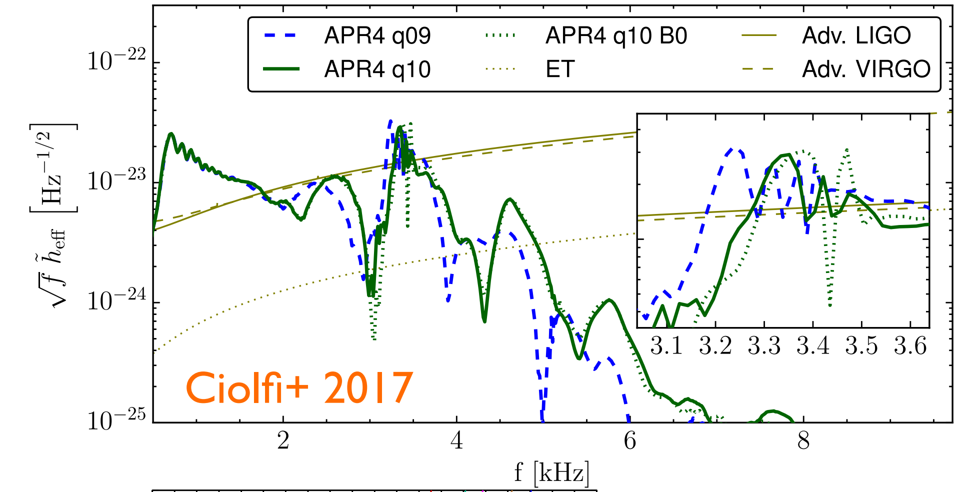
Inferring the EOS from gravitational waves

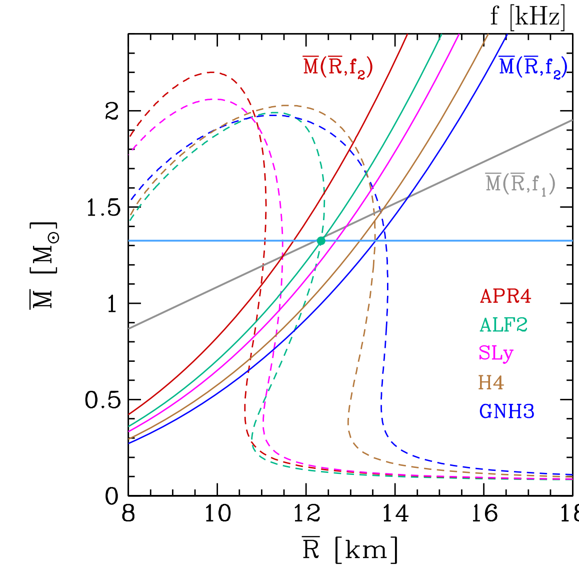




Bernuzzi+ 2015





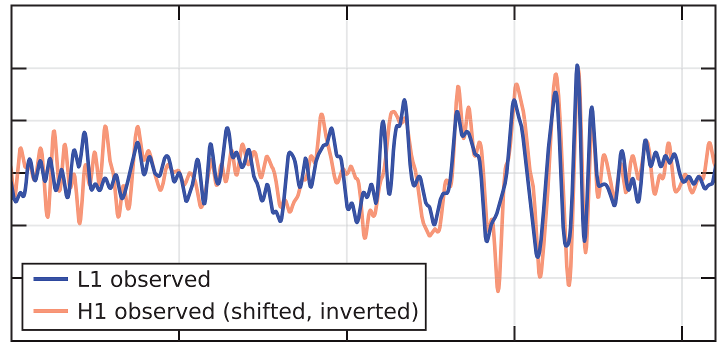


Takami+ 2014

- post-merger NS frequency peak f_2 (f_{peak}) correlates with EOS
  Bauswein & Janka 2012 Hotokezaka+ 2013, Takami+ 2014
- tidal deformability (imprinted in the inspiral GW signal) correlates with f_2 (f_{peak}) Bernuzzi+ 2015
  - independent of EOS, binary parameters, thermal effects Bernuzzi+ 2015
  - independent of magnetic fields Ciolfi+ 2017

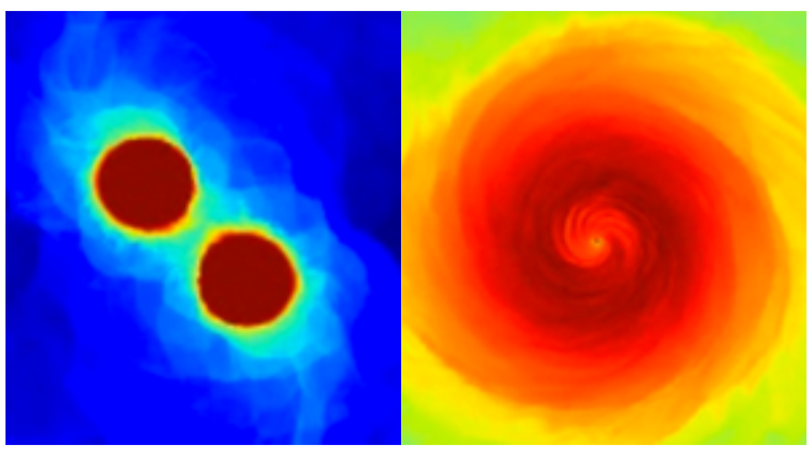
⟶ combine correlations to infer EOS

NS mergers: multi-messengers



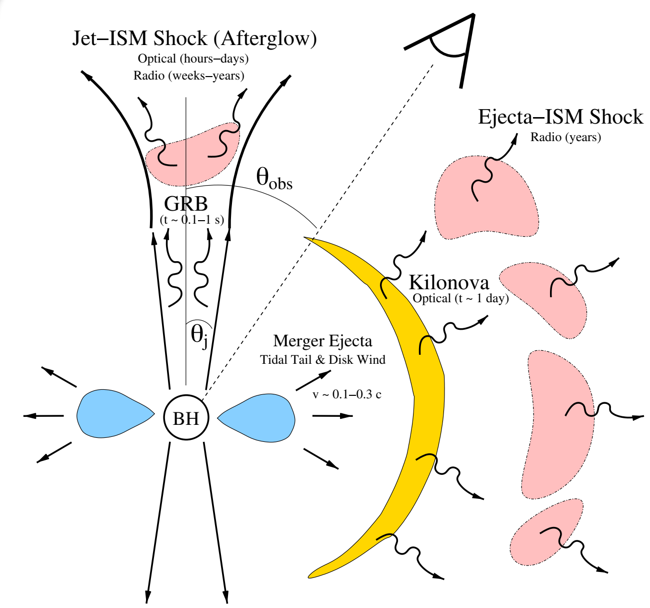
gravity

Gravitational Waves



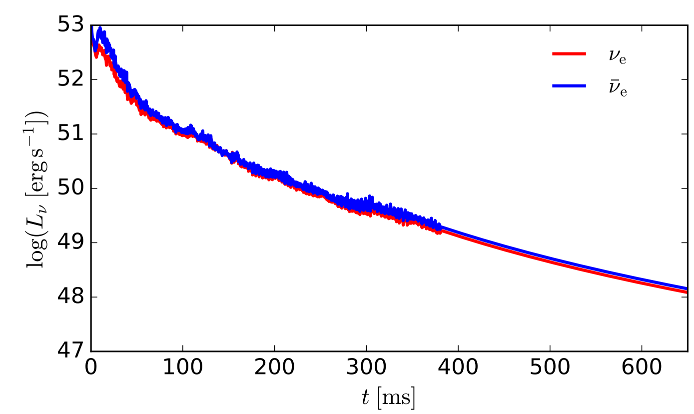
NS mergers

electromagnetic



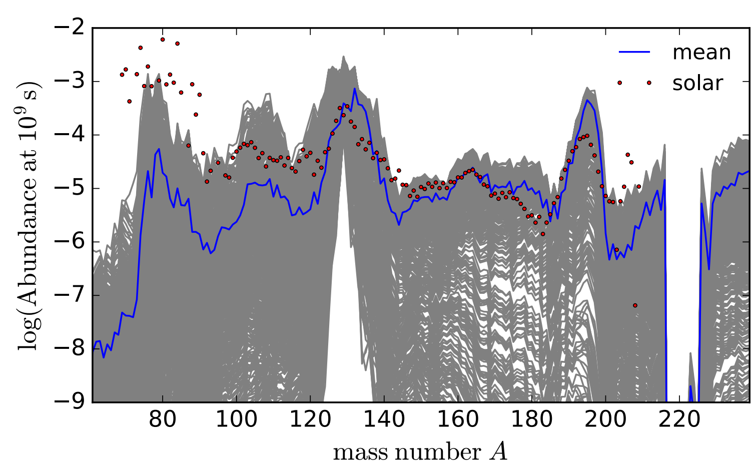
EM transients

particles



neutrinos

heavy elements

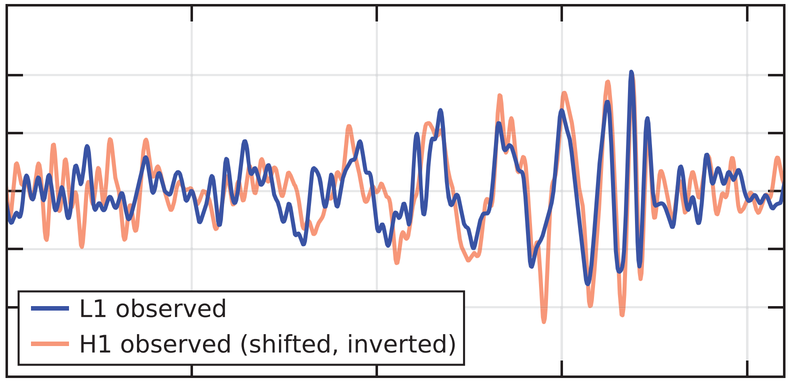


r-process nucleosynthesis of heavy elements

EM follow-up across the EM spectrum

LIGO Hanford

LIGO Livingston



GW event

gamma rays

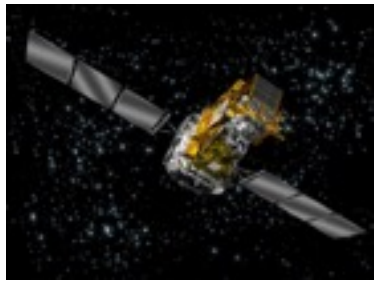
X-rays

optical

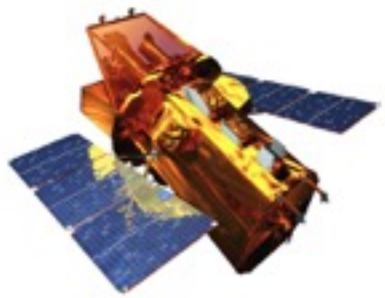
NIR

radio

Fermi



INTEGRAL



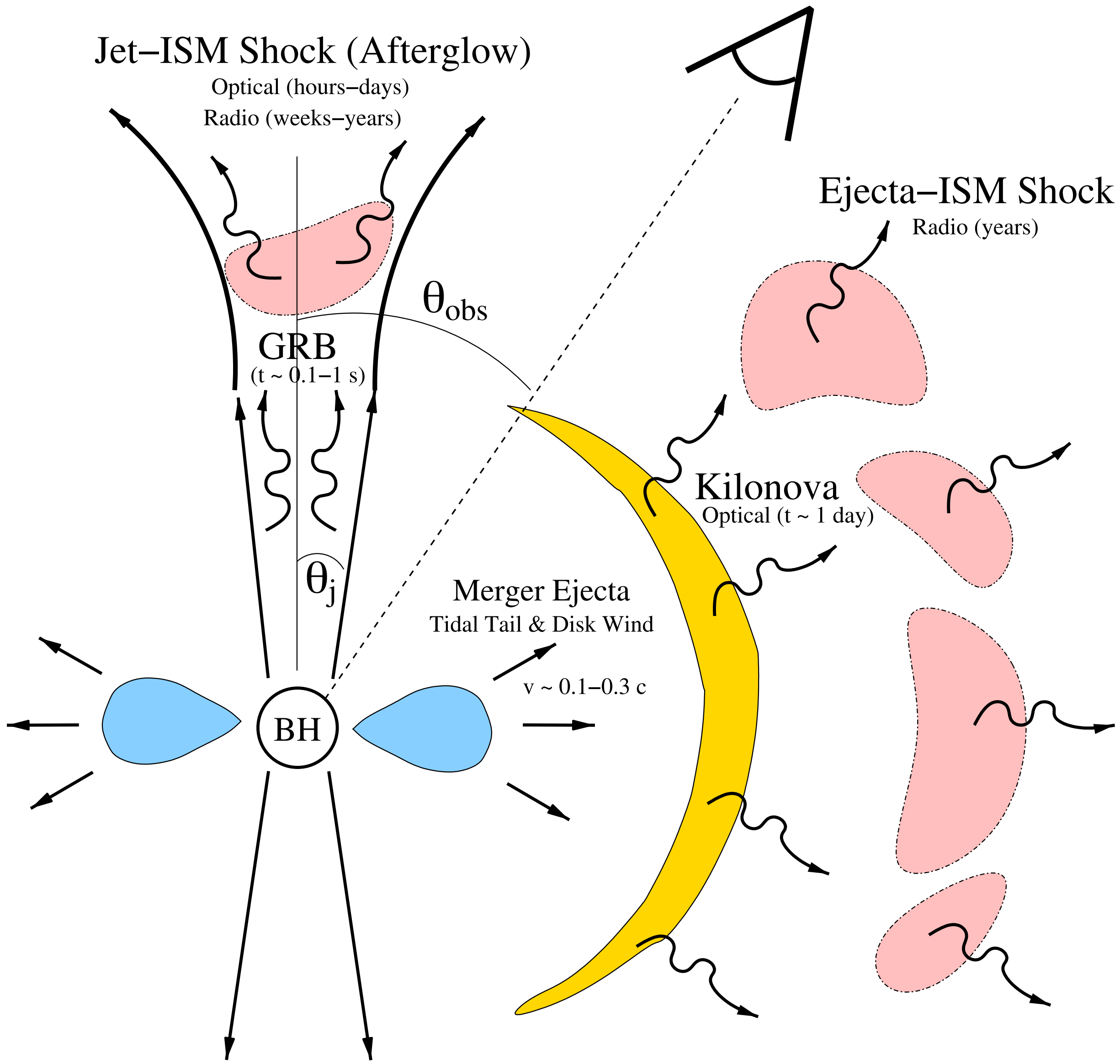
Swift

Pan-STARRS

VISTA

LOFAR

EM counterparts to NS-NS and BH-NS mergers



Metzger & Berger 2012

- Short gamma-ray bursts (SGRBs)
  "Standard" afterglows:
  - X-ray
  - UV/optical
  - radio

  Berger 2014
  Kumar & Zhang 2015

  "Non-standard" X-ray afterglows:
  - Extended Emission
  - X-ray plateaus
  - X-ray flares

  Rowlinson+ 2013
  Gompertz+ 2013,2014
  Lue+ 2015

- "Thermal" transients
  - kilonovae/macronovae (radioactively powered)
    Li & Paczynski 1998, Rosswog 2005, Metzger+ 2010, Barnes & Kasen 2013, Piran+ 2013, Tanaka & Hotokezaka 2013
  - magnetar-powered transients
    Siegel & Ciolfi 2016a,b, Metzger+2014, Yu+2013

- Interaction of dynamical ejecta with ISM (radio)
  Hotokezaka & Piran 2015

Short GRBs: Jet or no jet?

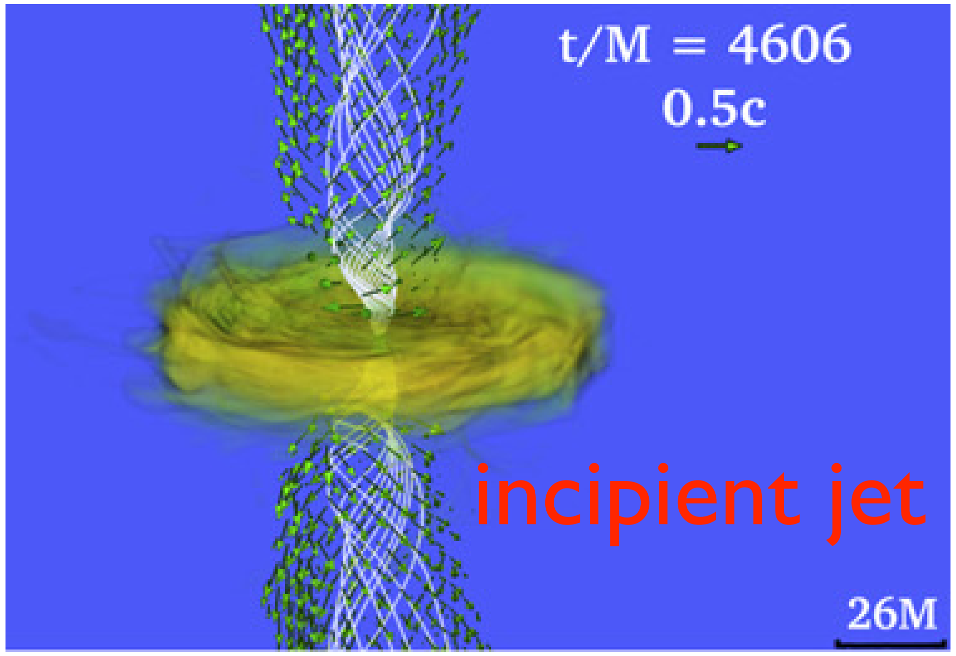


Fig.: Magnetic funnel ("incipient jet") emerging from a BH-torus system (BNS merger)

Ruiz+ 2016

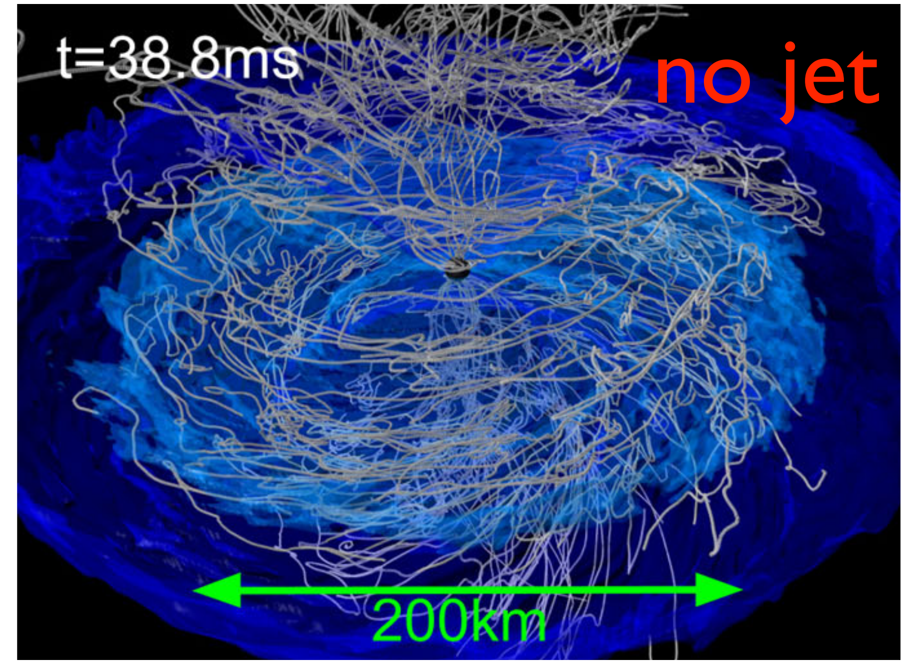


Fig.: Magnetic configuration from the highest resolution BNS simulations: no jet

Kiuchi+ 2017

→ jet formation in NS mergers not understood yet

no jet

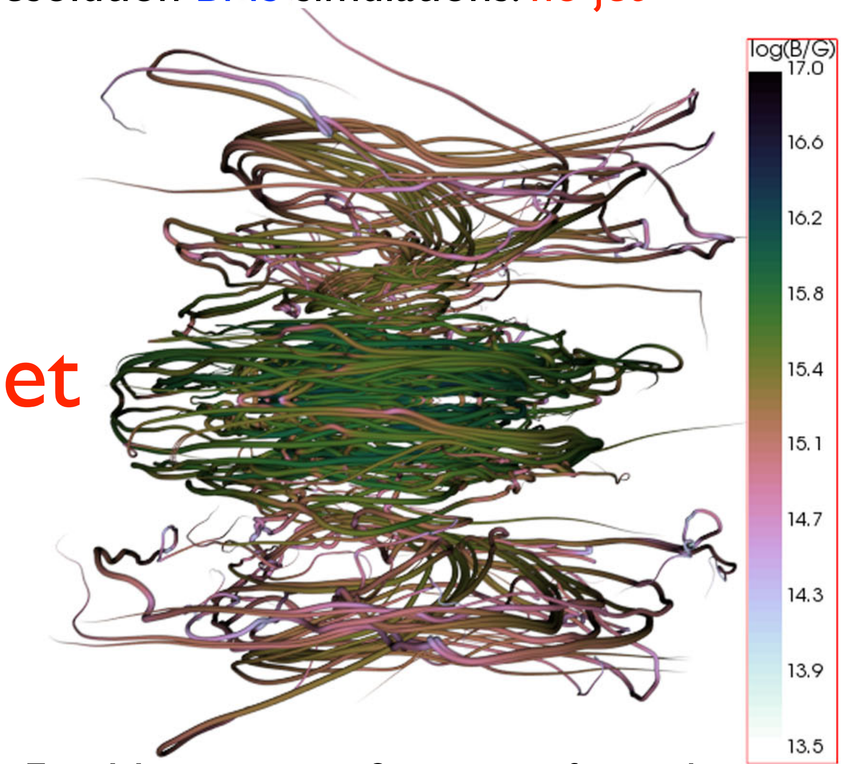
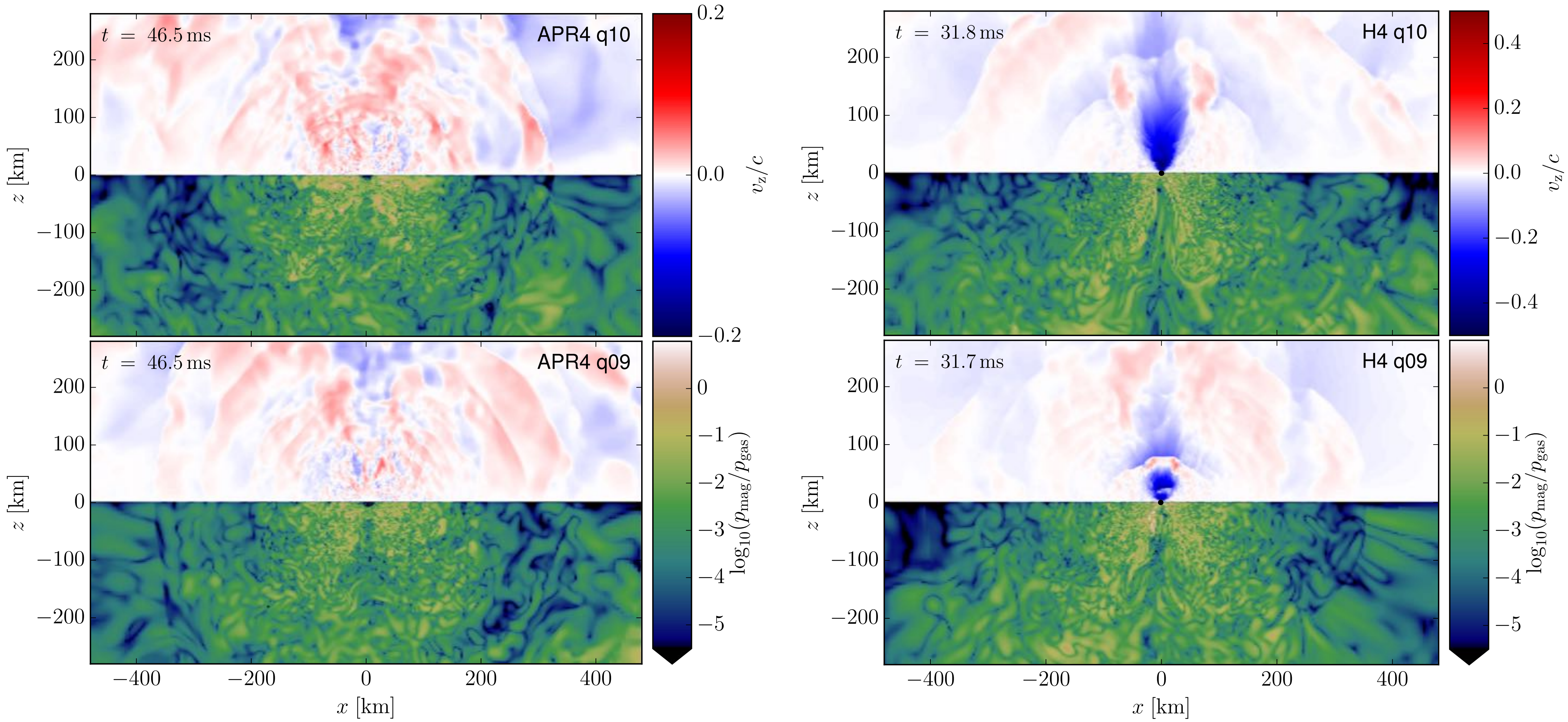


Fig.: Magnetic configuration from the latest BNS simulations: no jet

Ciolfi+ 2017

Short GRBs: baryon pollution in BNS mergers



Ciolfi+ 2017

BNS ⟶ NS
isotropic baryon pollution

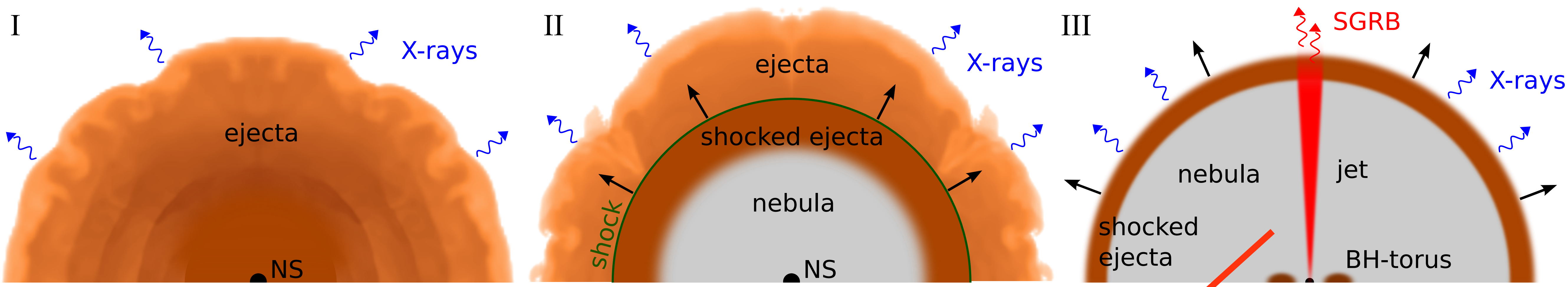
relativistic outflows likely choked
or prevented to form

BNS ⟶ BH
low-density polar funnel

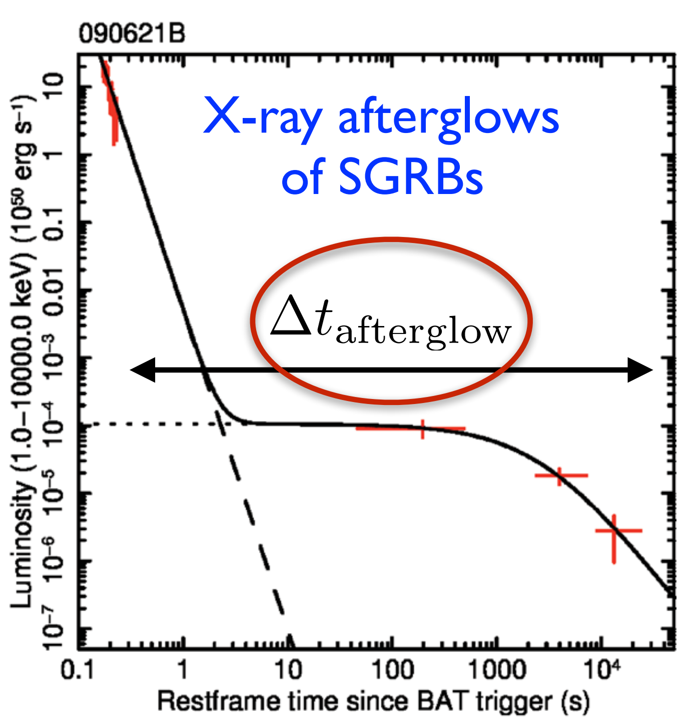
Murguia-Berthier+ 2015,2016
Nagakura+ 2014

⟶ how should GRB jets be produced at all in BNS⟶NS events?

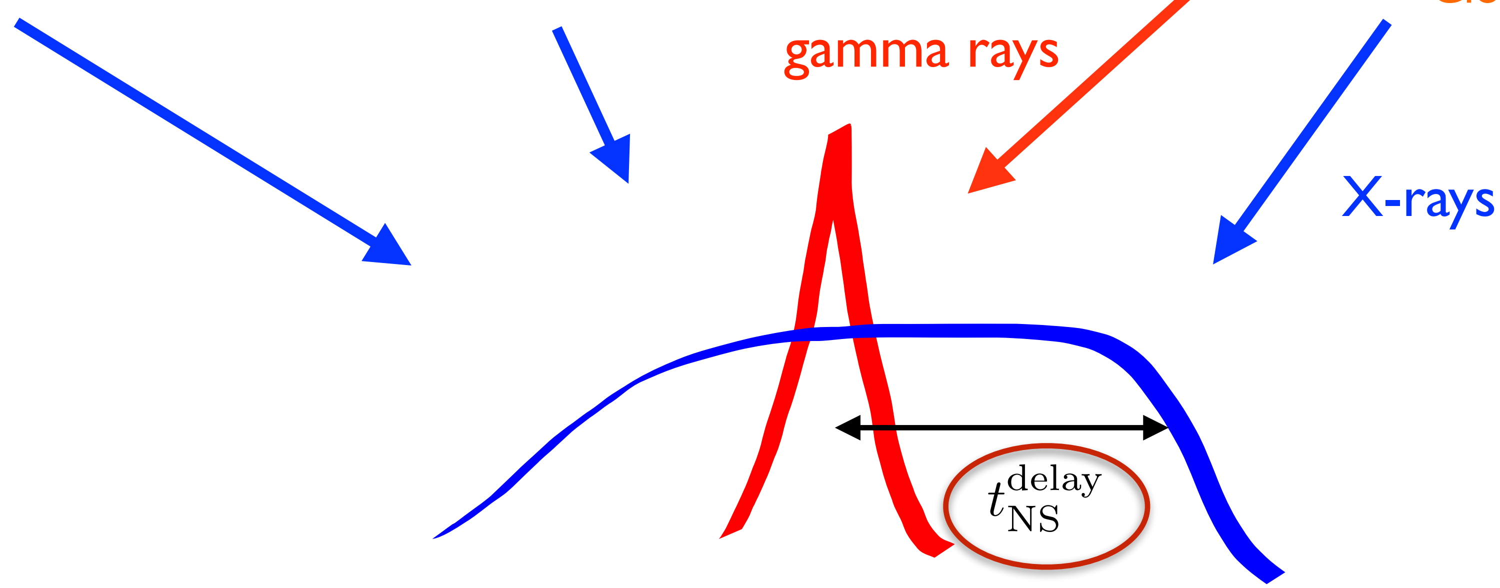
Time-reversal scenario Ciolfi & Siegel 2015a,b



Ciolfi & Siegel 2015a,b

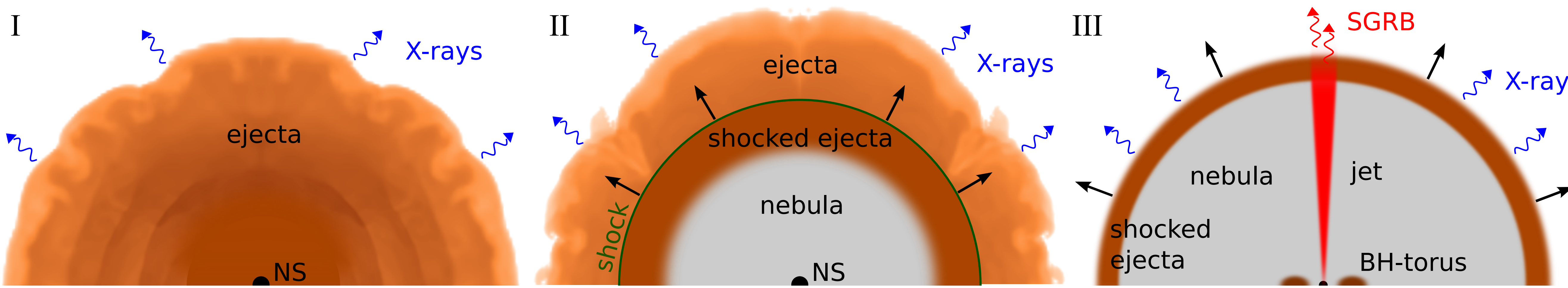


Rowlinson+2013

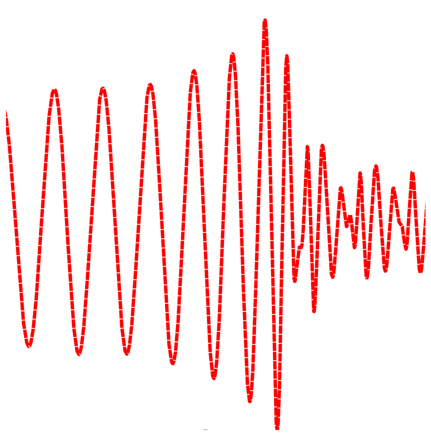


→ SGRB at time of NS collapse
X-ray precursor and afterglow

Time-reversal scenario Ciolfi & Siegel 2015a,b



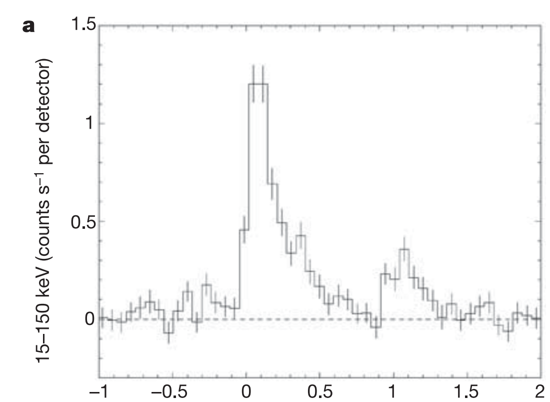
Ciolfi & DMS 2015a,b



peak amplitude GW signal

$t_{\rm coll} \sim t_{\rm sd} \sim 10^3\,{\rm s}$

lifetime of the NS



EM SGRB signal

→ GW-EM multimessenger observations ideal to reveal the origin of SGRBs!

Kilonovae

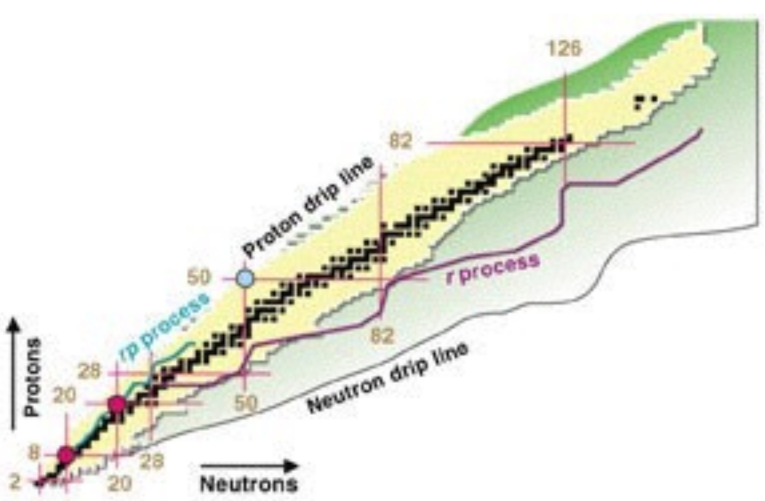
neutron rich ejecta from
NS-NS or NS-BH mergers
(Y_e~0.1-0.4)

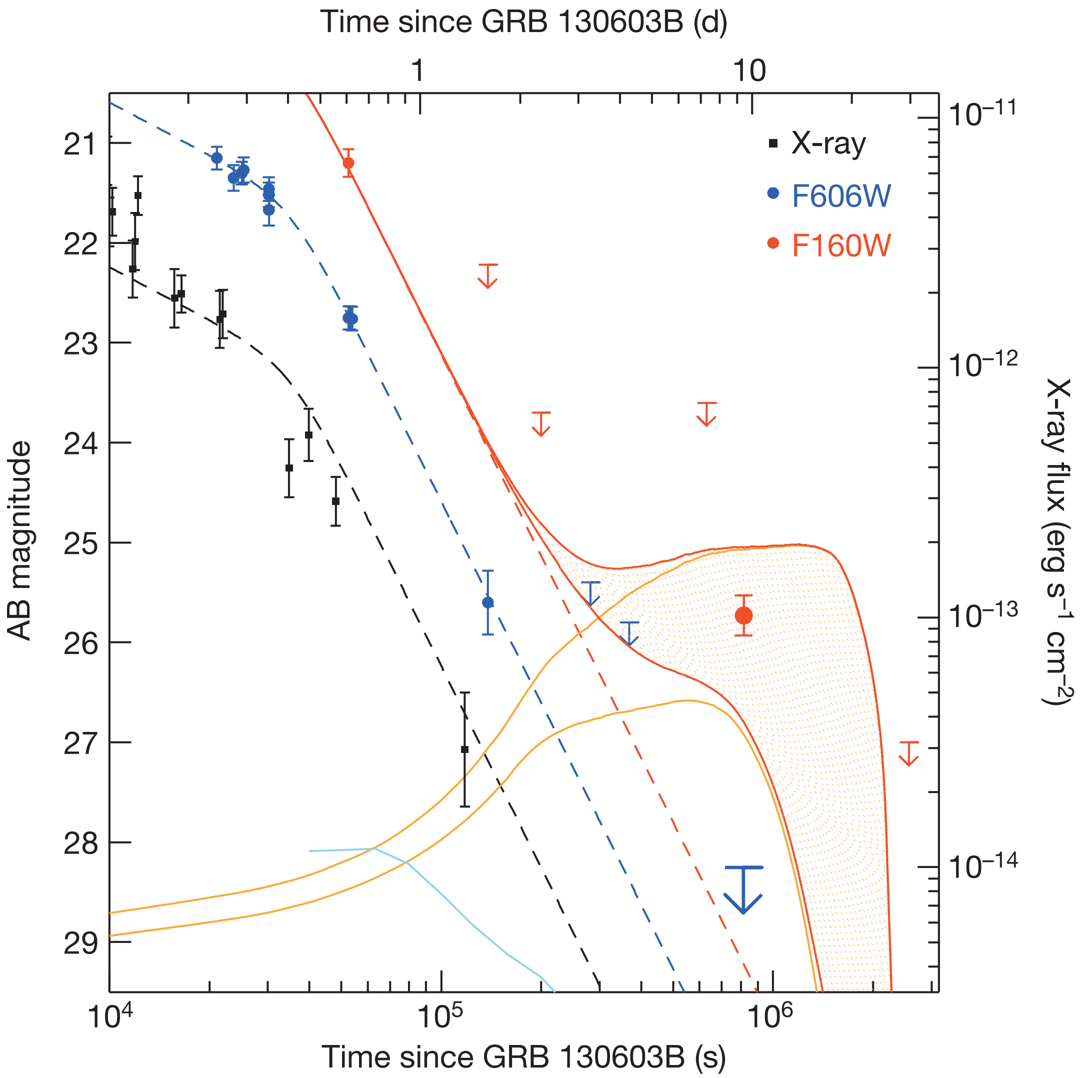
~1s — decompression, rapid neutron capture (r-process)

heavy radioactive elements

~ days — alpha, beta decay, nuclear fission, further expansion

thermal emission (kilonova)
(quasi isotropic, long lasting, high fraction of events)





Tanvir+ 2013

- So far 3 candidate events identified (GRB 130603B, GRB 060614, GRB 050709)

Tanvir+ 2013, Berger+ 2013, Yang+ 2015, Jin+ 2016

Kilonovae

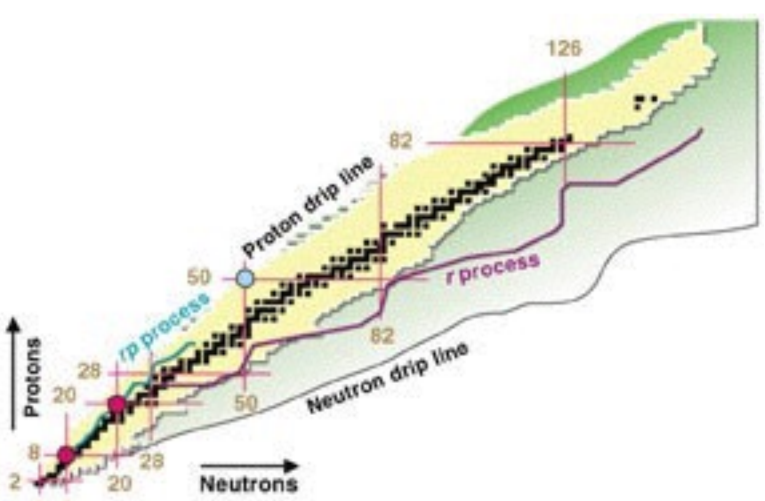
neutron rich ejecta from
NS-NS or NS-BH mergers
(Y_e~0.1-0.4)

~1s — decompression, rapid neutron capture (r-process)

heavy radioactive elements

~ days — alpha, beta decay, nuclear fission, further expansion

thermal emission (kilonova)
(quasi isotropic, long lasting, high fraction of events)



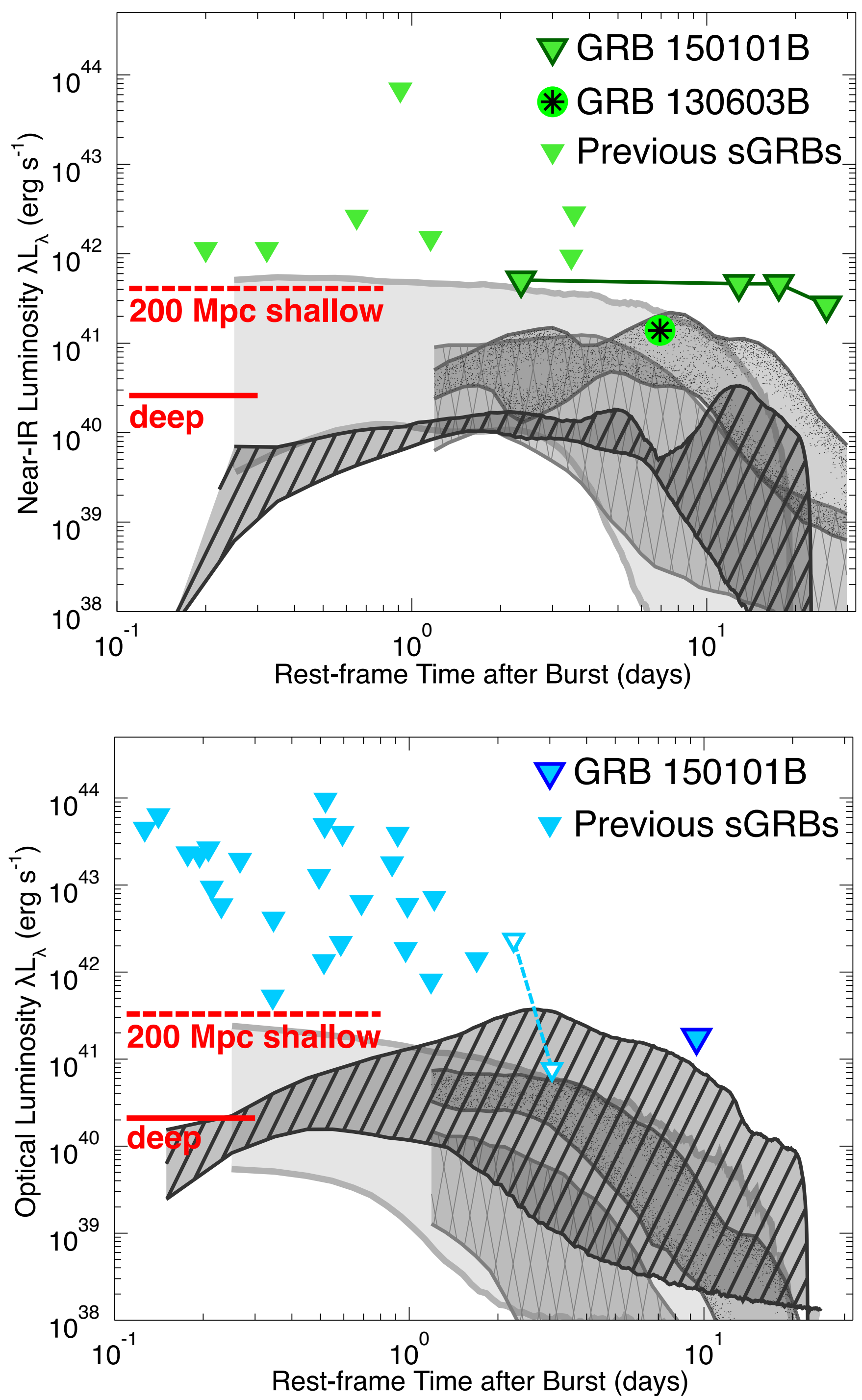
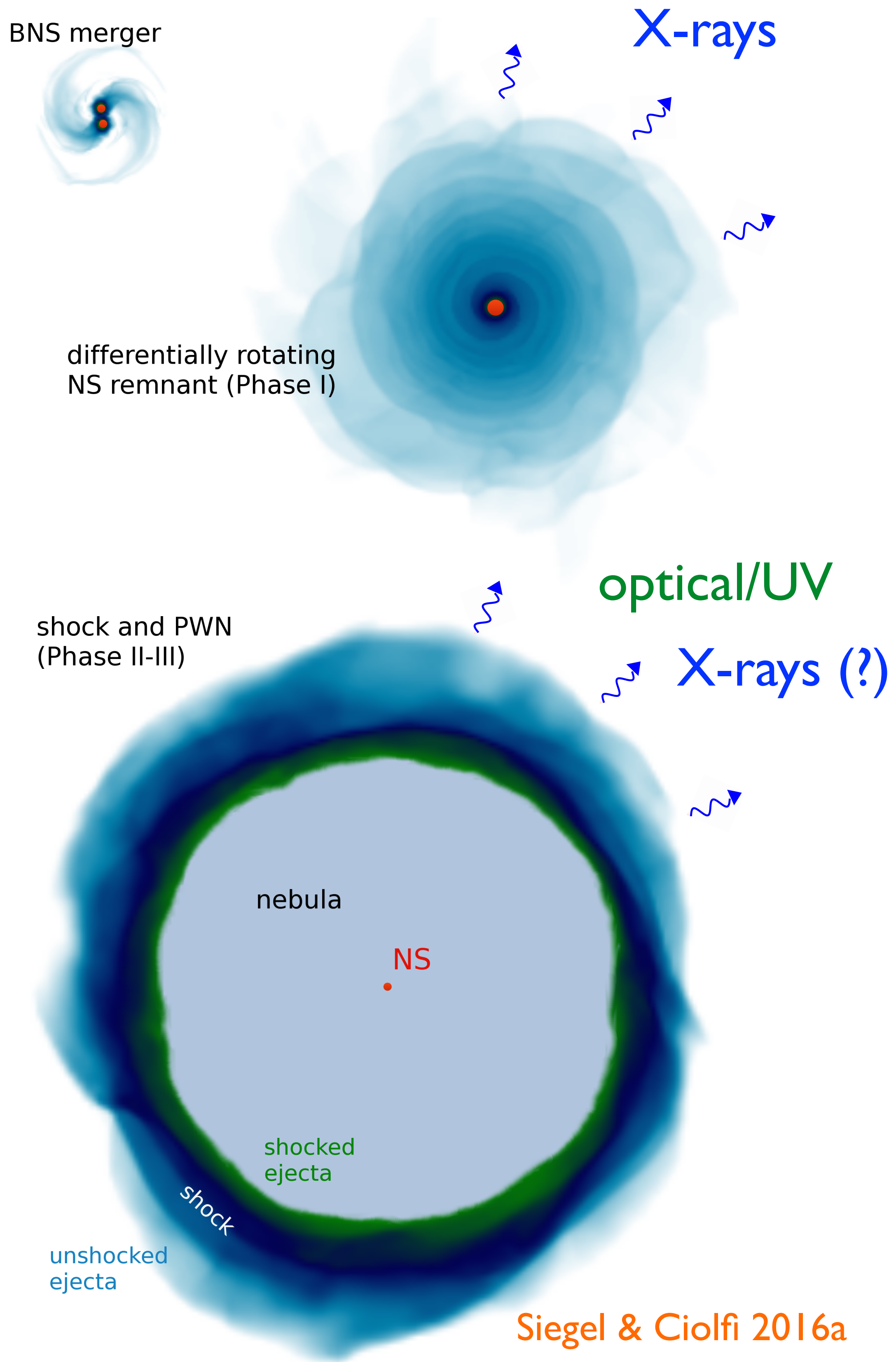


Fig.: compilation from Fong+ 2016: kilonova models and present observational constraints

Magnetar-powered transients

Siegel & Ciolfi 2016a,b
Metzger & Piro 2014



Siegel & Ciolfi 2016a

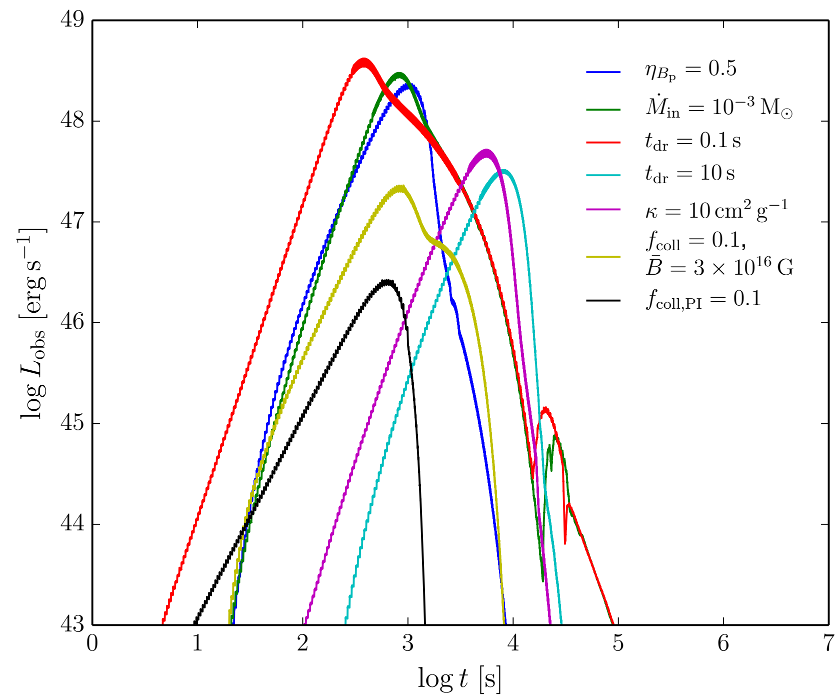
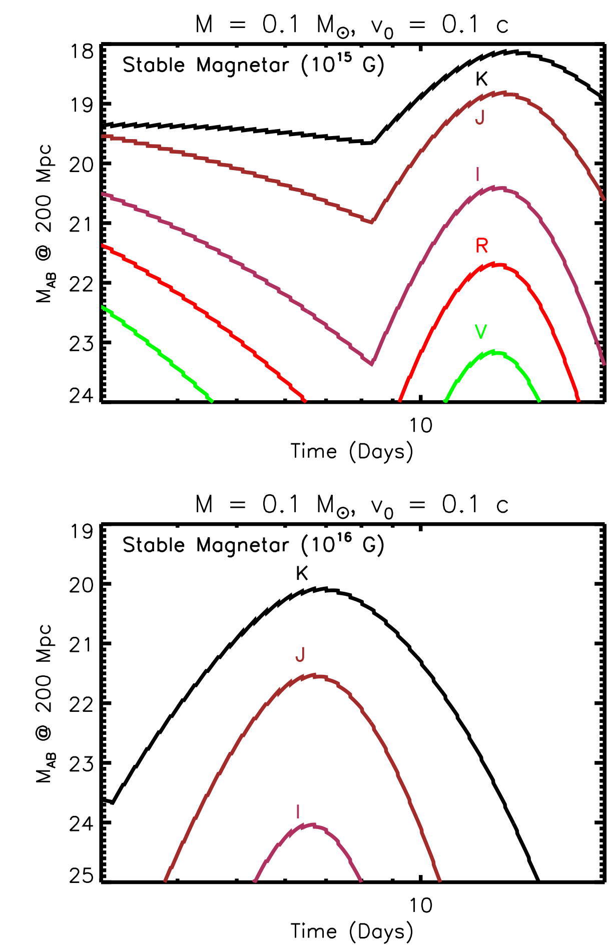


Fig.: Reconstructed X-ray lightcurves
0.3-10 keV

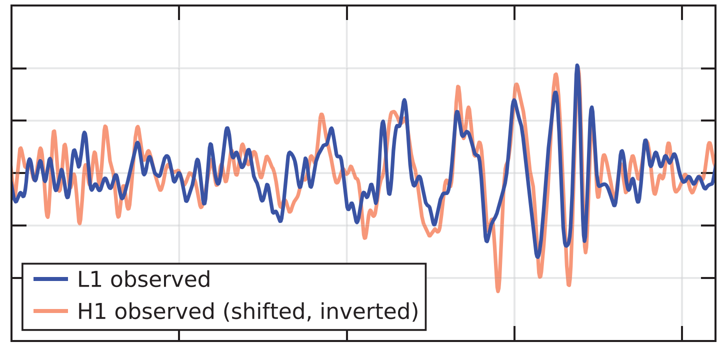
Siegel & Ciolfi 2016b



Metzger 2016

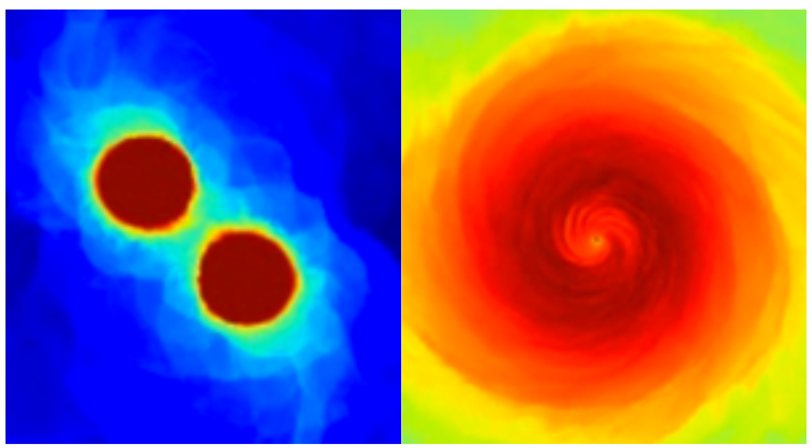
- ejecta shell downgrades hard interior radiation to soft X-ray/UV/optical
- simple models show that presence of magnetar can outshine the standard kilonova Metzger 2016
- reprocessing of radiation involves complicated physics, more detailed models soon

NS mergers: multi-messengers



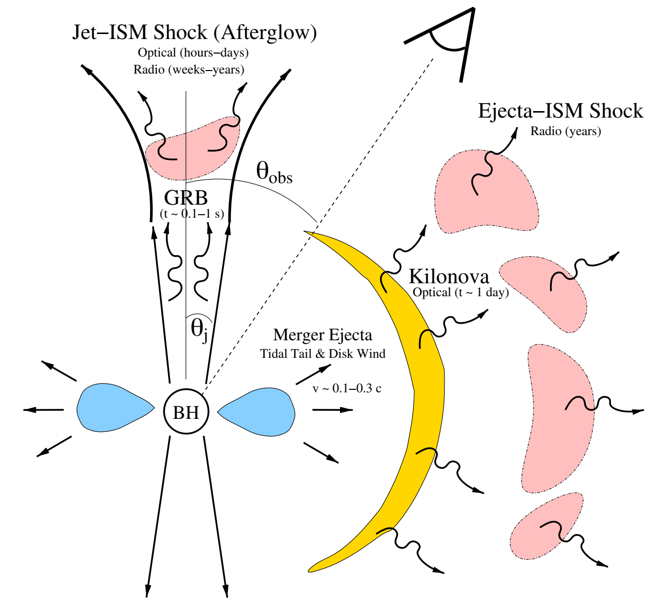
gravity

Gravitational Waves



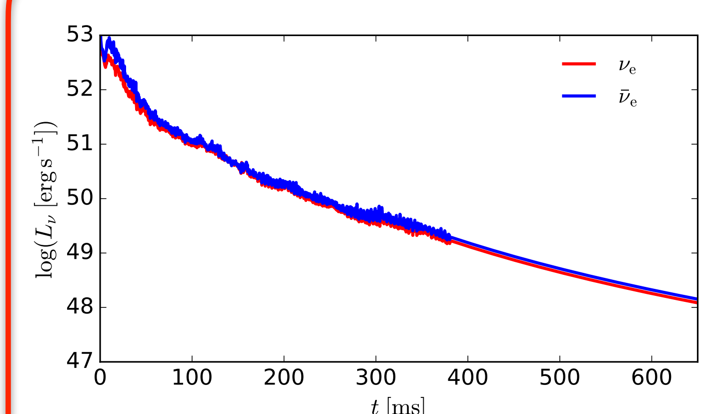
NS mergers

electromagnetic



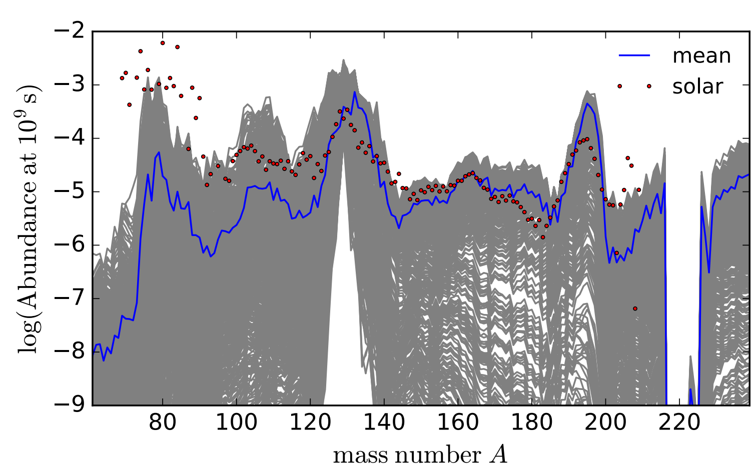
EM transients

particles



neutrinos

heavy elements



r-process nucleosynthesis of heavy elements

Neutrinos from NS mergers

(Meta-)stable remnant NS (t~100ms):

Sekiguchi+ 2016

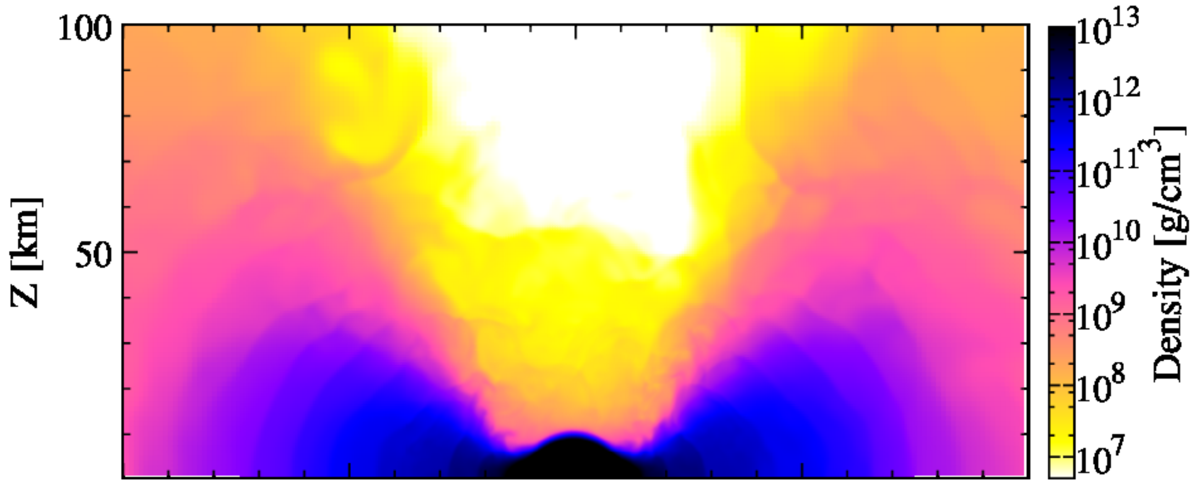


Fig.: hot long-lived remnant NS

Neutrino emission from hot (T~1-10MeV) nuclear matter:

charged-current processes:

$$e^- + p \to n + \nu_e$$

$$e^+ + n \to p + \bar{\nu}_e$$

pair annihilation:

$$e^- + e^+ \to \nu_e + \bar{\nu}_e$$

$$e^- + e^+ \to \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

plasmon decay:

$$\gamma \to \nu_e + \bar{\nu}_e$$

$$\gamma \to \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

Post-merger accretion disks (t~sec):

Siegel & Metzger 2017a

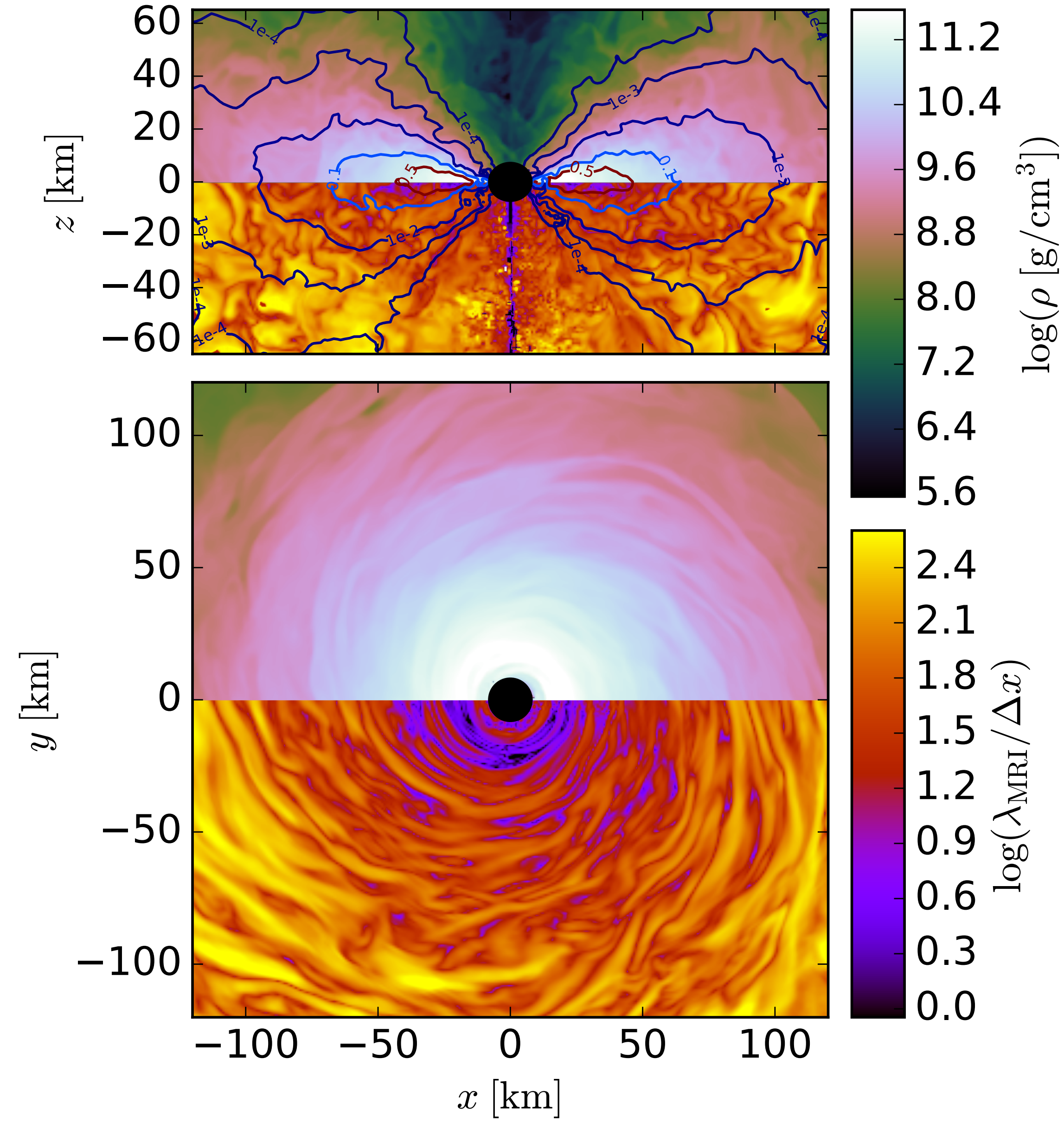


Fig.: post-merger neutrino cooled accretion disk (meridional plane, top; equatorial plane, bottom)

Neutrinos from NS mergers

(Meta-)stable remnant NS (t~100ms):

Sekiguchi+ 2016

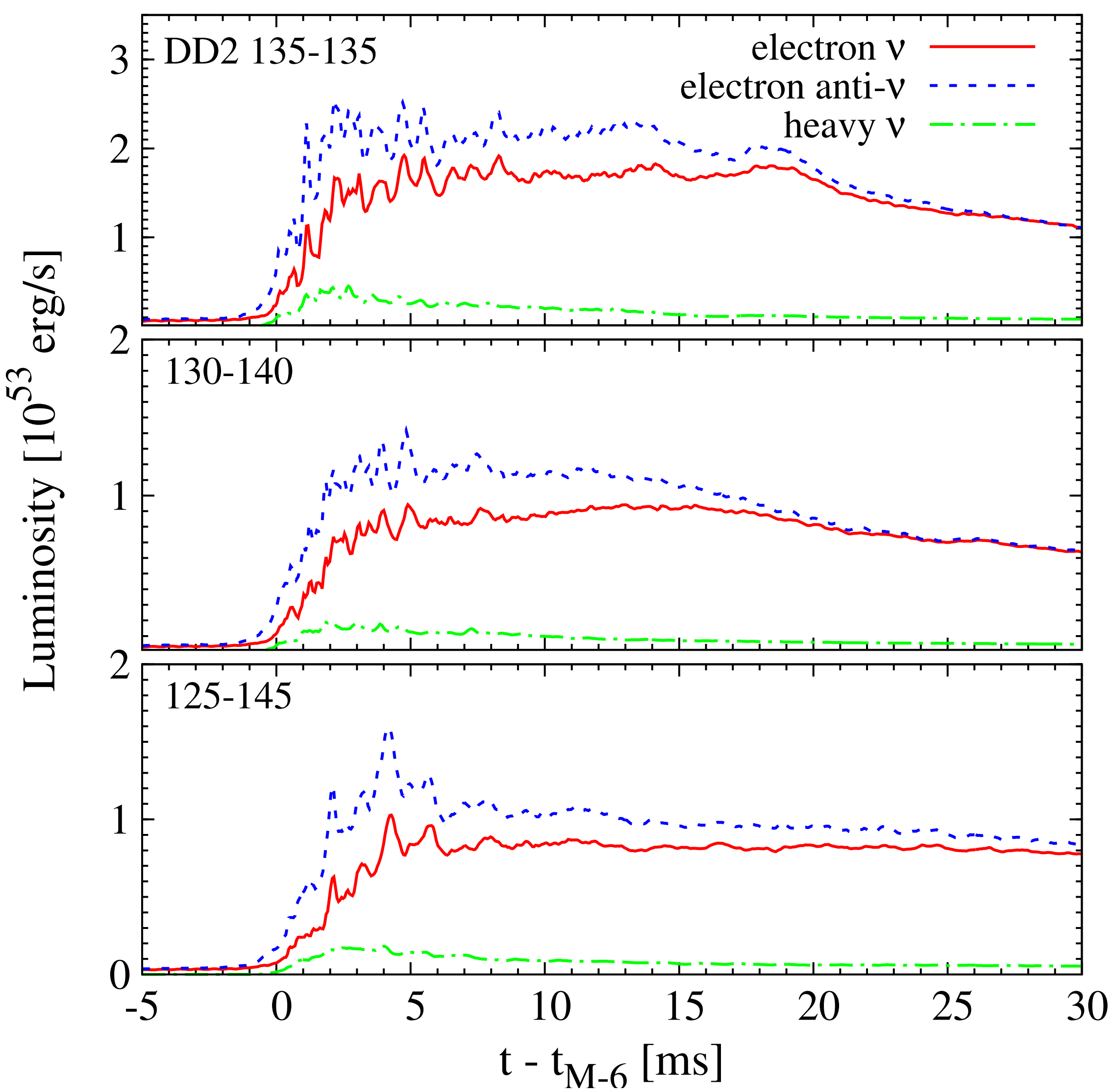
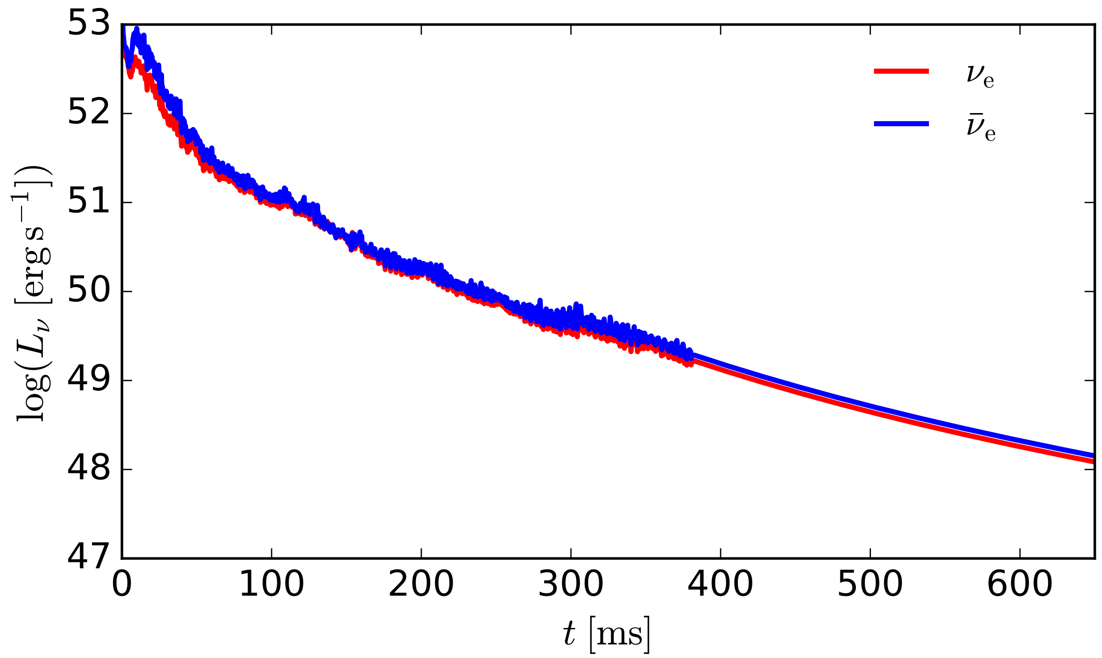


Fig.: neutrino luminosities from long-lived remnant NS

Post-merger accretion disks (t~sec):

Siegel & Metzger 2017a



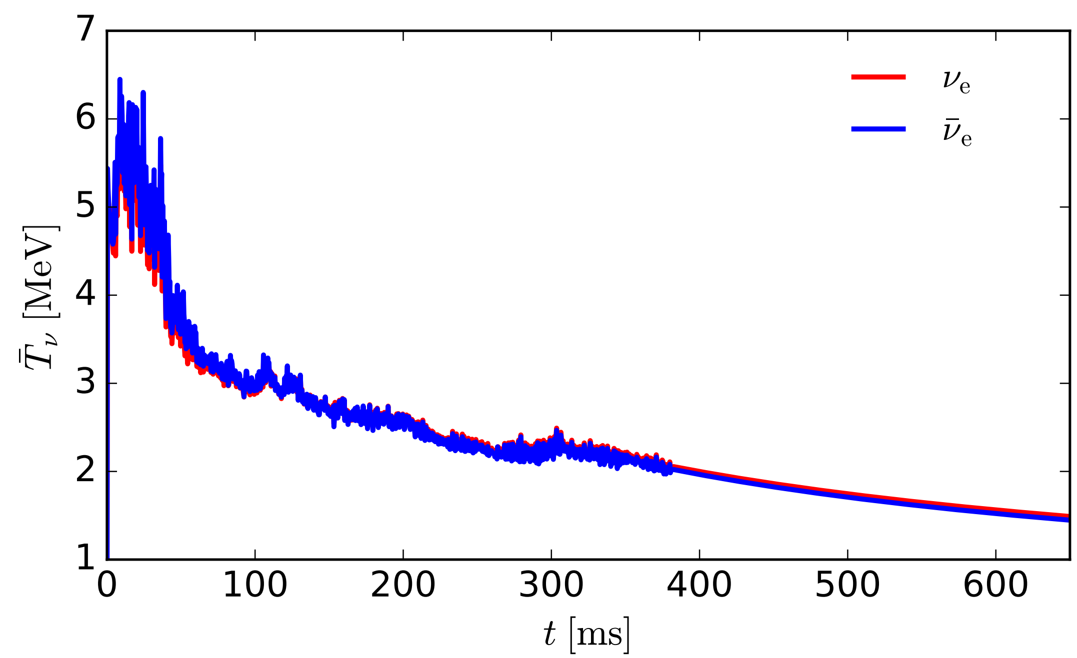
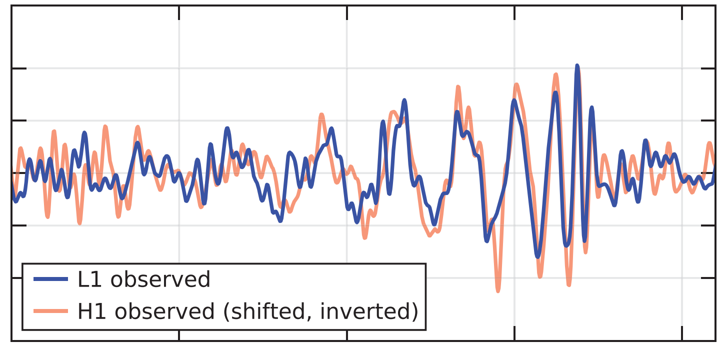


Fig.: neutrino luminosities from post-merger neutrino cooled accretion disk

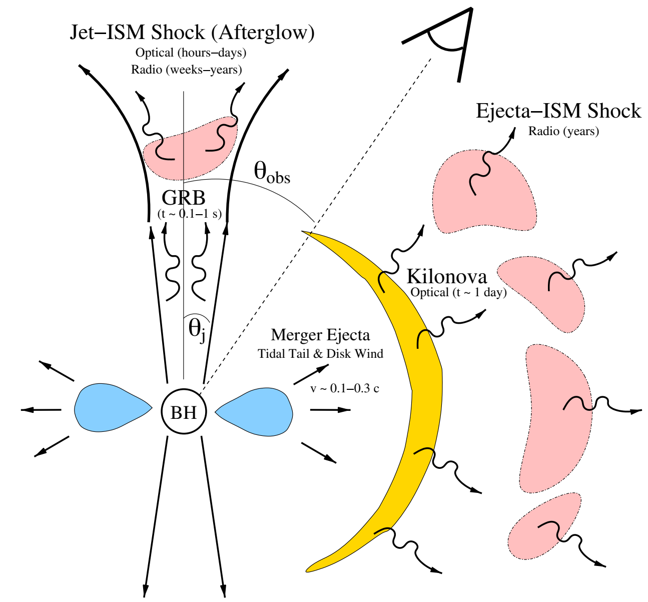
Siegel & Metzger 2017b, in prep.

NS mergers: multi-messengers

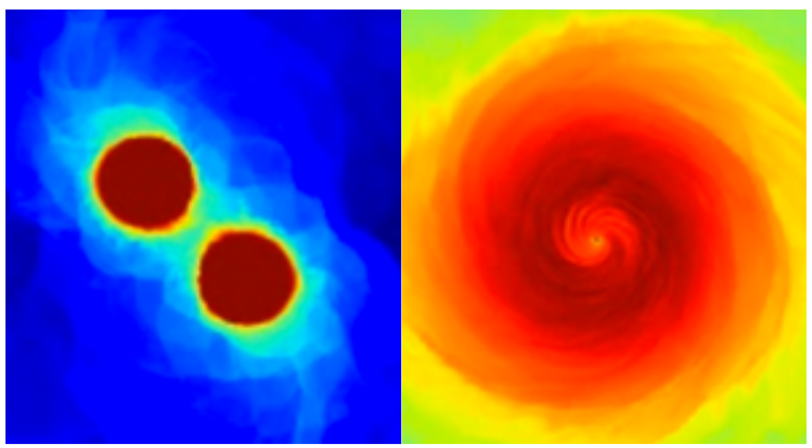


gravity

Gravitational Waves



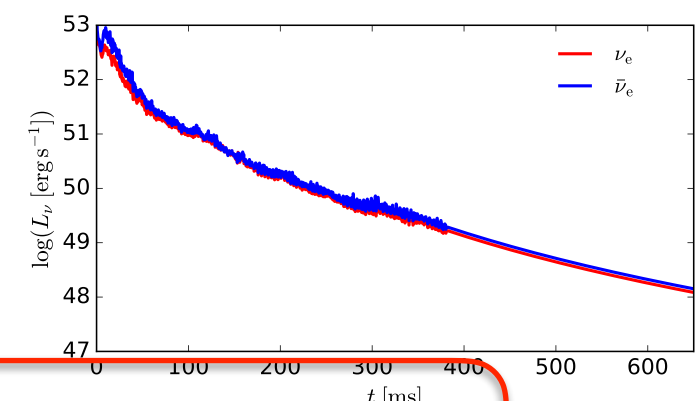
EM transients



electromagnetic

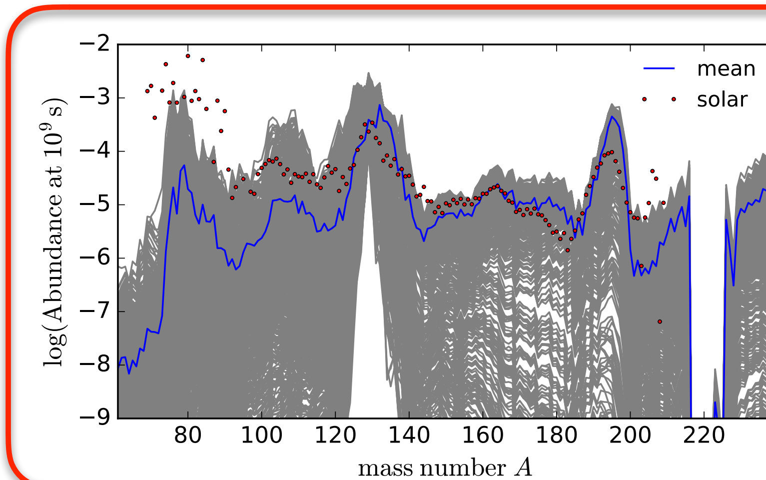
NS mergers

particles



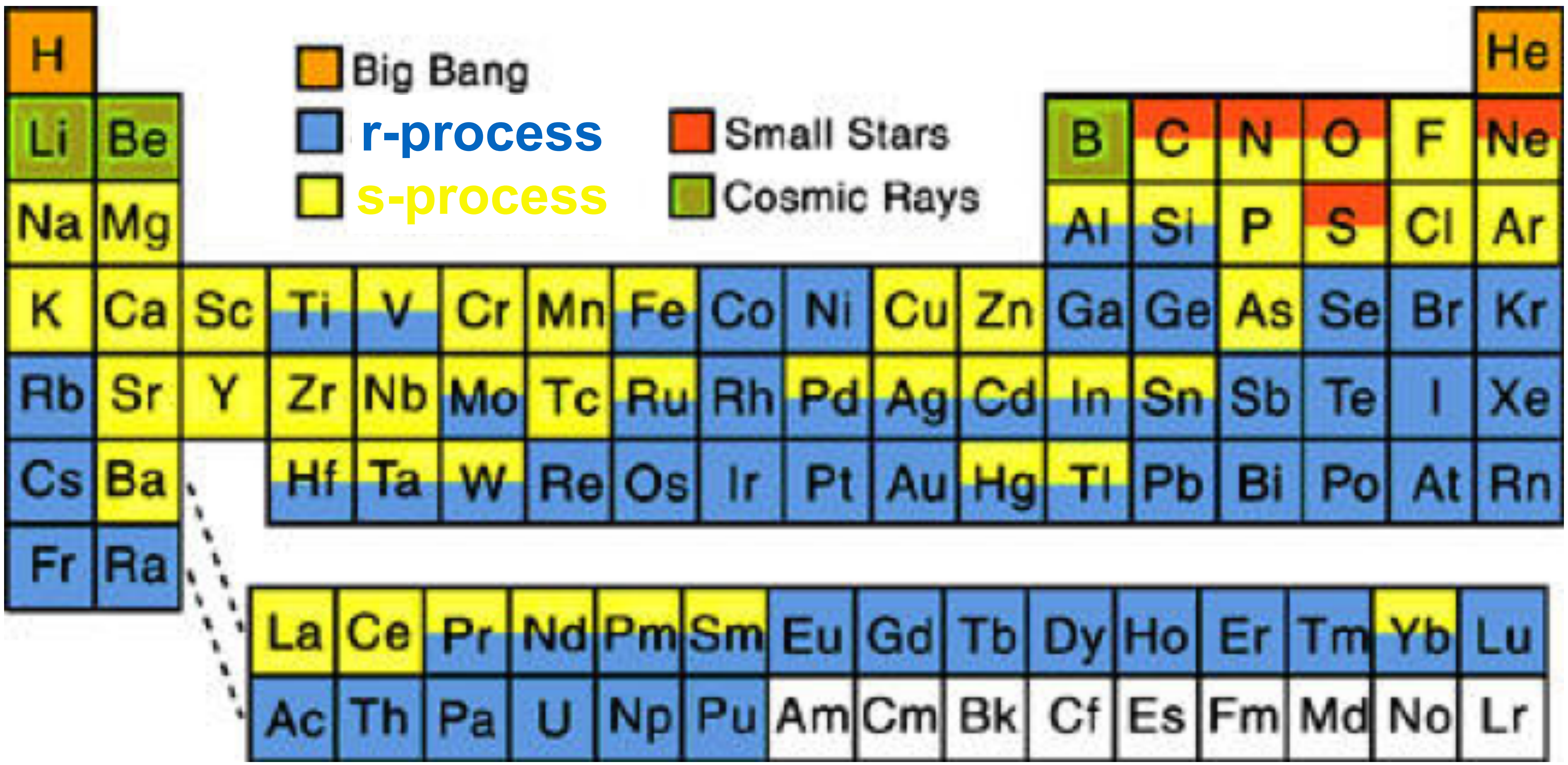
neutrinos

heavy elements



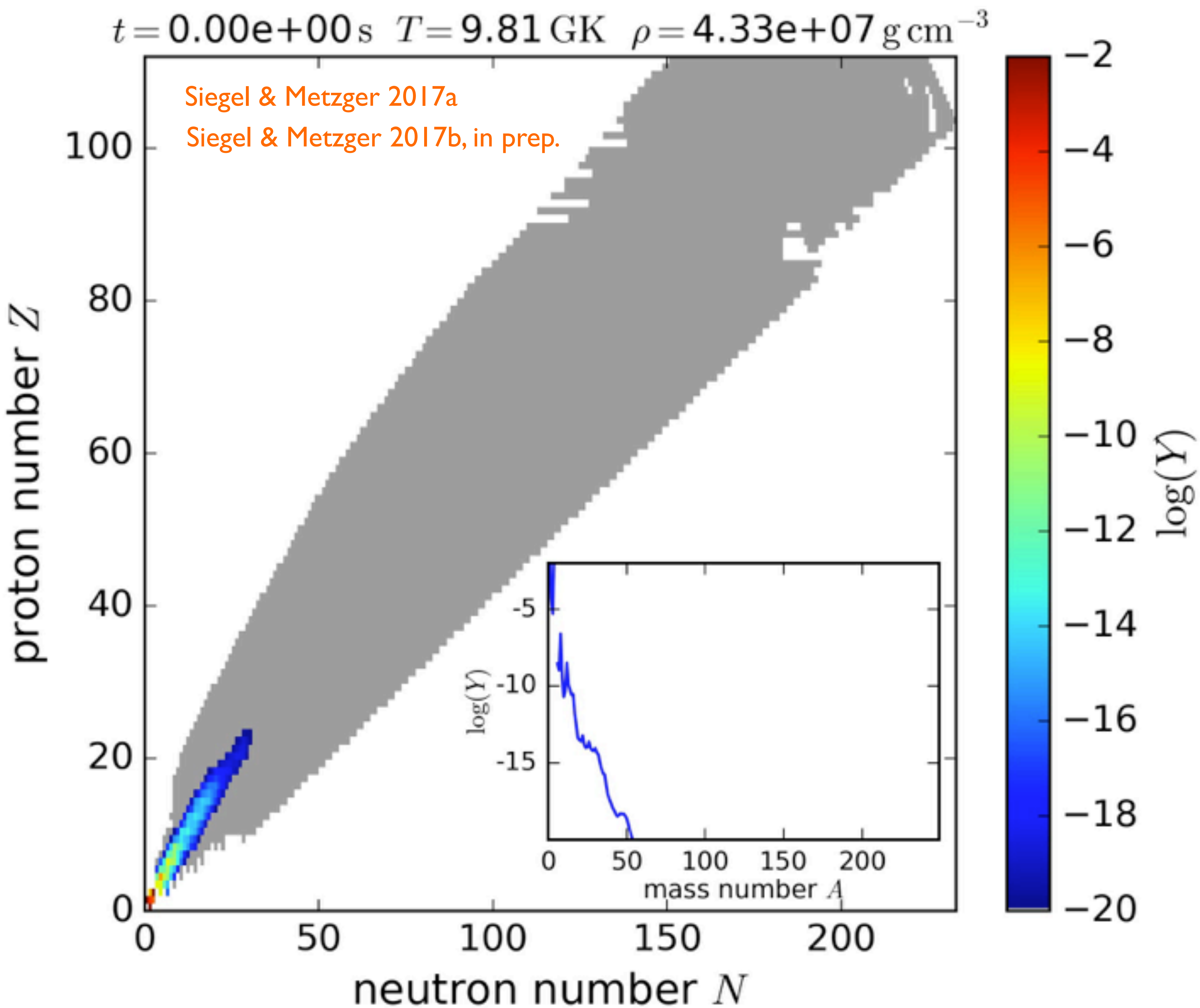
r-process nucleosynthesis of heavy elements

The origin of the elements



How are the heavy elements formed?

The origin of heavy nuclei: r-process nucleosynthesis



Movie: r-process nucleosynthesis from NS merger remnant disks

r-process nucleosynthesis from NS mergers

NS merger (dynamical ejecta):

Radice+ 2016

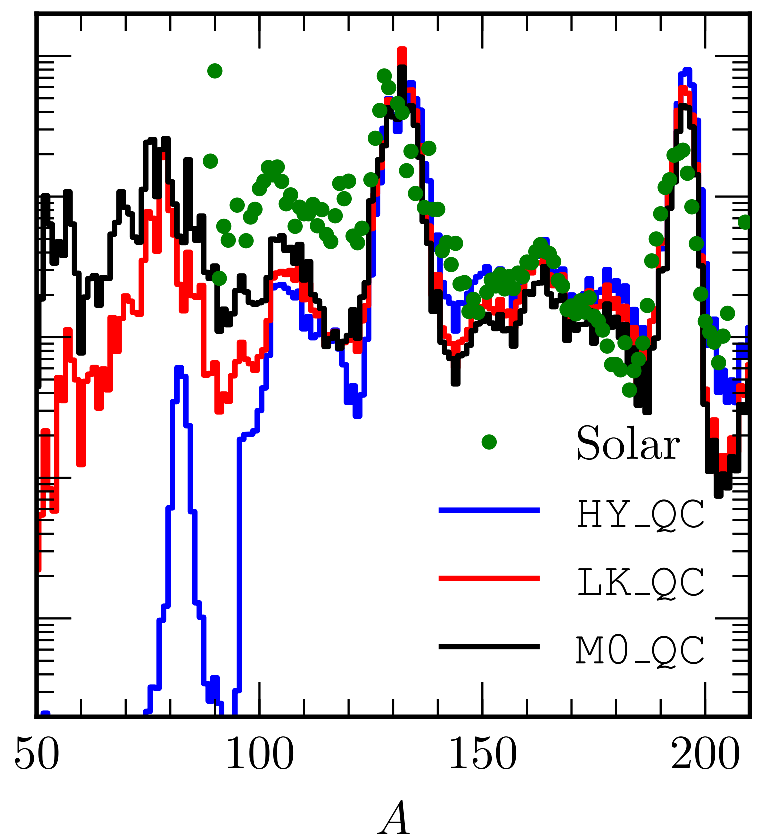


Fig.: production of r-process elements from early ejecta of a BNS merger (dynamical ejecta, neutrino-driven winds)

Post-merger accretion disk outflows:

Siegel & Metzger 2017a
Siegel & Metzger 2017b, in prep.

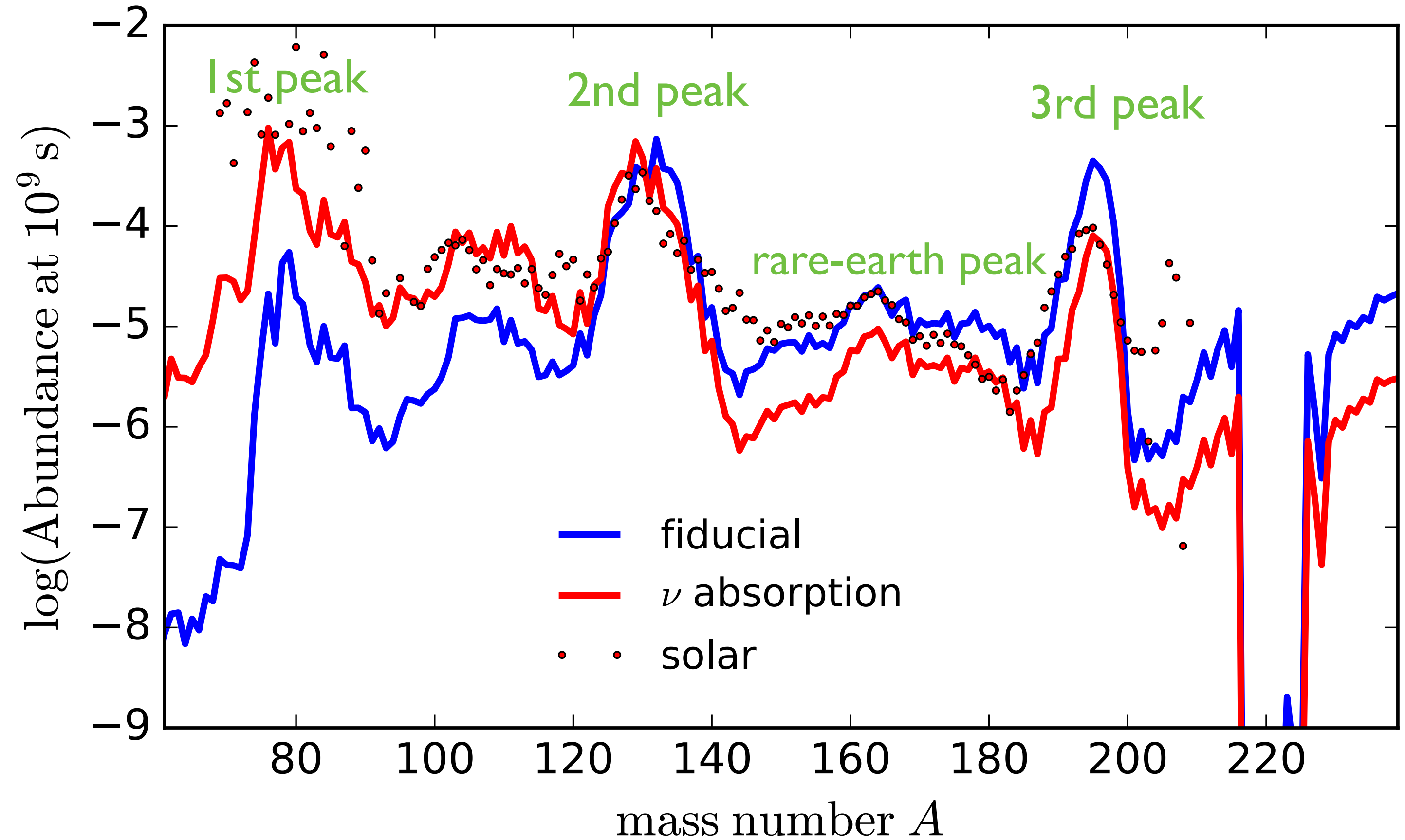


Fig.: production of all r-process elements from outflows of post-merger accretion disk

Overall ejecta mass per event:

$$\lesssim 10^{-3} - 10^{-2}\, M_\odot$$

strongly depends on EOS!

$$\gtrsim 0.4\, M_{\rm disk} \gtrsim 10^{-2}\, M_\odot$$

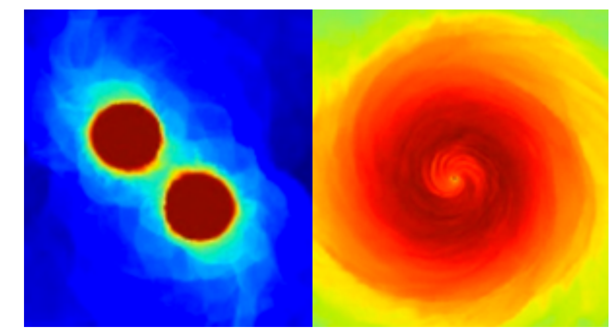
robust lower limit

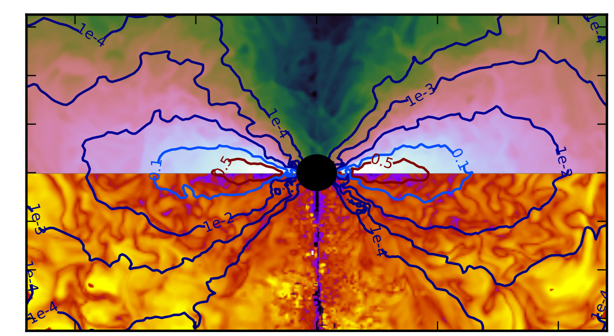
Conclusions

NS mergers are multimessengers:

- GW observations will infer/constrain the EOS of nuclear matter at high densities

- Joint EM and GW observations will:
  - reveal the origin of SGRBs, inform theory of jet formation
  - provide direct observation of the formation of heavy nuclei (kilonovae) and input to nuclear physics
  - reveal the formation of long-lived NS (magnetars), pulsar wind nebulae (?)
    - → measure lifetime of NS, constrain EOS





- NS mergers are source of (thermal) neutrinos
  - similar properties as in supernovae
  - non-thermal high-energy neutrinos from post-merger PWN?

- NS mergers are a robust site of the r-process
  - post-merger outflows can produce all r-process