Dynamical mass ejection from black hole-neutron star binaries

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KK, Ioka, Shibata PRD 88 (2013) 041502(R)

KK, Ioka, Okawa, Shibata, Taniguchi PRD 92 (2015) 044028

Why do we investigate BH-NS?

- Gravitational-wave astronomy

accessible to a larger distance than with NS-NS

- Short gamma-ray burst

formation of a BH-hot, massive accretion disk system

many possibilities due to the BH mass/spin diversity

- Mass ejection

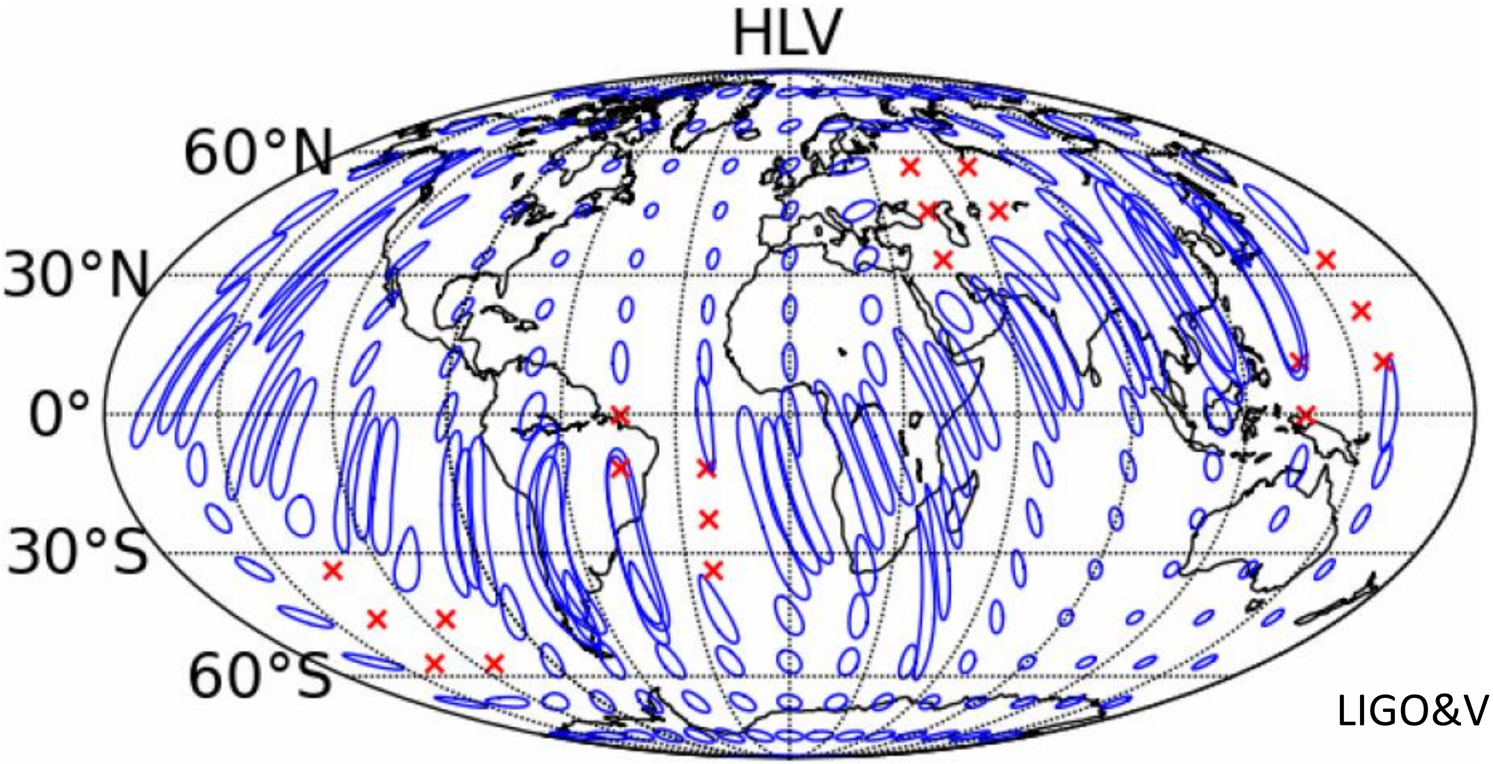
r-process nucleosynthesis

agent of electromagnetic emission = EM counterpart

Poor gravitational-wave localization

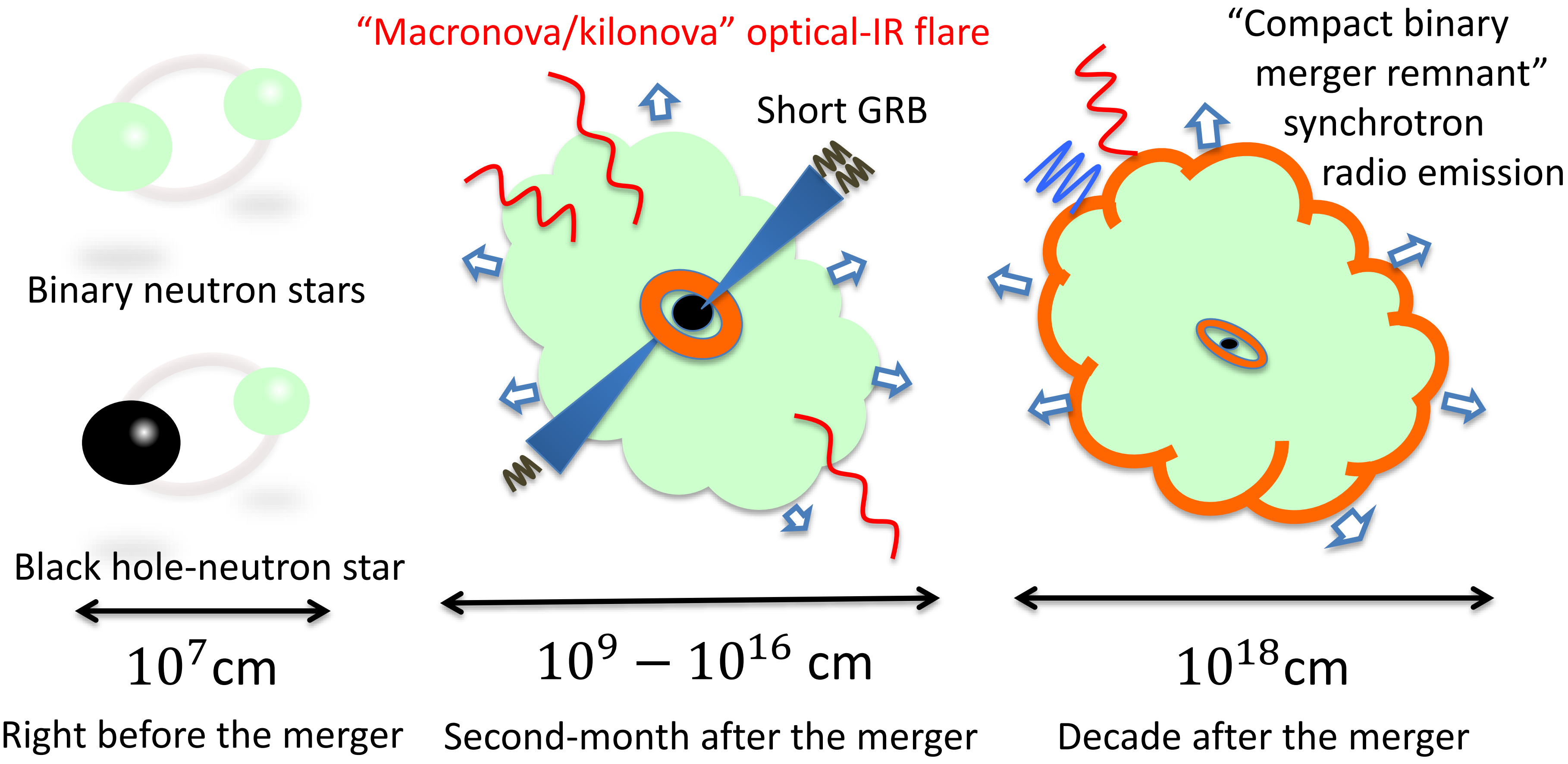
Typically ~20-30 deg^2 by multiple GW detectors

-> need EM counterparts for accurate localization



LIGO&Virgo (2013)

Electromagnetic counterpart



"Macronova/kilonova" optical-IR flare

Short GRB

"Compact binary merger remnant" synchrotron radio emission

Binary neutron stars

Black hole-neutron star

10^{7}cm

Right before the merger

$10^{9} - 10^{16}$ cm

Second-month after the merger

10^{18}cm

Decade after the merger

Drawn originally by Kenta Hotokezaka

Problem to be answered

- How the mass is ejected in the merger process of black hole-neutron star binaries?

- What are characteristic quantities of ejecta? (mass, velocity, morphology, electron fraction…)

- How do they depend on binary parameters?

- What are features of associated electromagnetic counterparts?

Numerical-relativity simulations will give answers

Numerical method

Initial data: LORENE (spectral method)
quasiequilibrium states of BH-NS binaries

Dynamical simulation: SACRA (Yamamoto+ 2008)

- BSSN formalism of the Einstein equation
  4th order finite difference in time and space
- ideal hydrodynamics
  3rd order PPM reconstruction + central scheme
- adaptive mesh refinement

Important parameters

Three dimensionless parameters

1. NS compactness: $C \equiv M_{\mathrm{NS}}/R_{\mathrm{NS}}$
2. Mass ratio of the BH to NS: $Q \equiv M_{\mathrm{BH}}/M_{\mathrm{NS}}$
3. Dimensionless BH spin: $\chi \equiv a_{\mathrm{BH}}/M_{\mathrm{BH}}$

For a fixed value of the NS mass, tidal disruption if

1. The NS radius is large, i.e., C is small
2. The BH mass is small, i.e., Q is small
3. The BH spin is large, i.e., χ is large

Model parameters

NS mass fixed to be $M_{\mathrm{NS}} = 1.35 M_{\odot}$

NS radius = equation of state

$$R_{\mathrm{NS}} = 11.1, 12.4, 13.6, 14.4\mathrm{km}$$

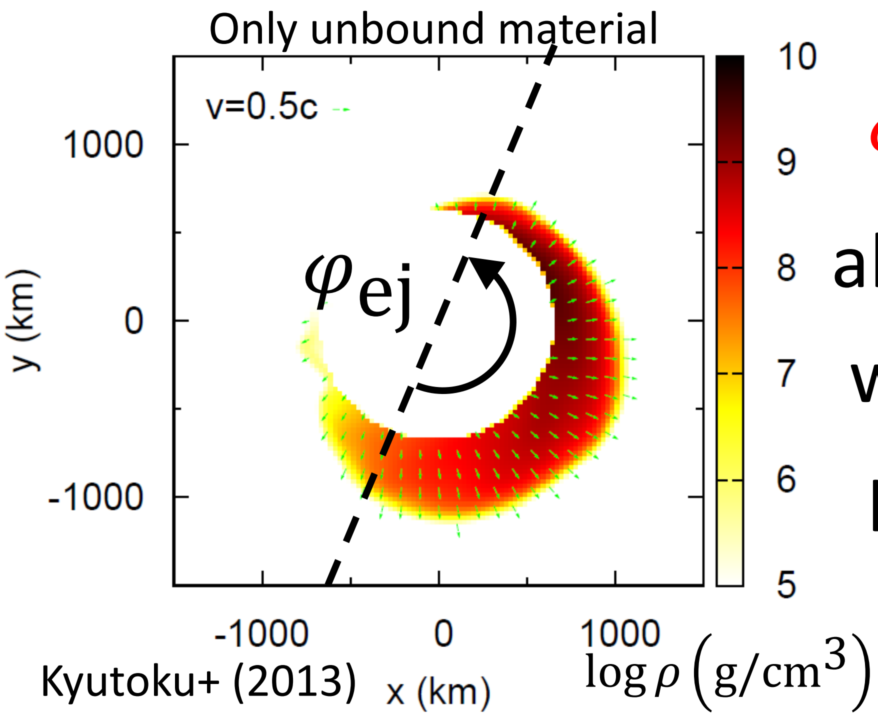
piecewise polytrope (+ ideal-gas-like thermal part)

Mass ratio $Q = 3, 5, 7$

$$M_{\mathrm{BH}} = 4.05, 6.75, 9.45 M_{\odot}$$

BH spin parameter $\chi = 0, 0.5, 0.75$ and prograde

Crescent-like ejecta anisotropy



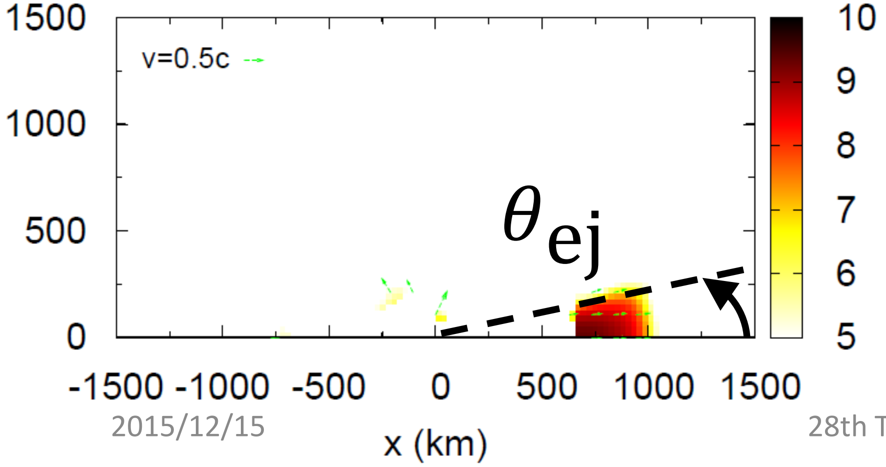
Kyutoku+ (2013)

$\varphi_{\mathrm{ej}} \approx 180°$

also can become ∼ 360°

when tidal disruption is weak

probably periastron advance



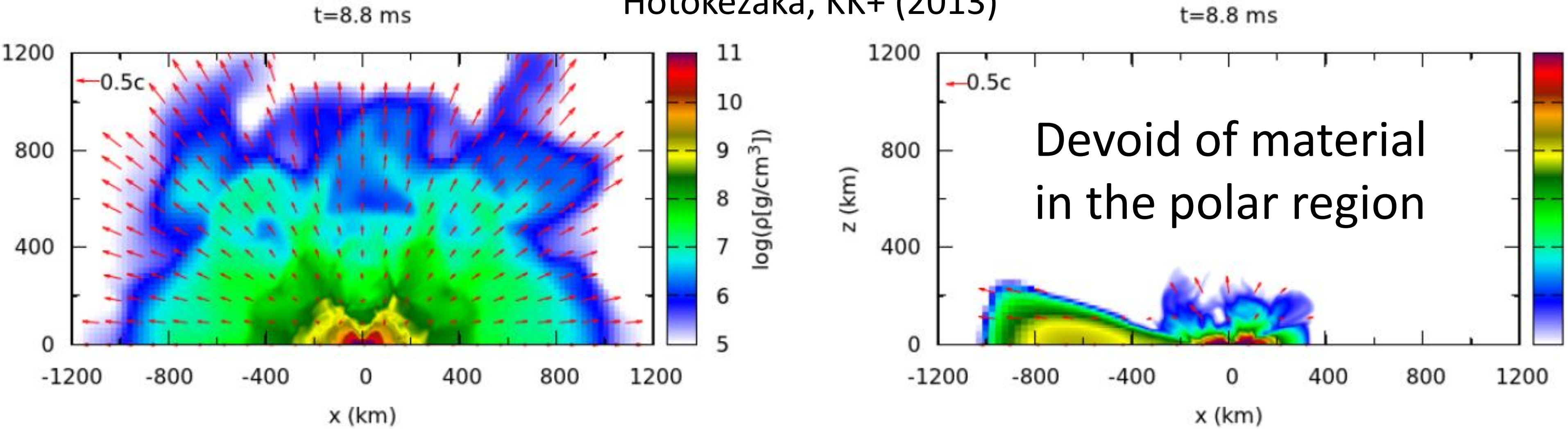
$\theta_{\mathrm{ej}} \approx 10° - 20°$

relatively universal

Comparison with NS-NS

Density profile in the meridional plane

Hotokezaka, KK+ (2013)



Devoid of material in the polar region

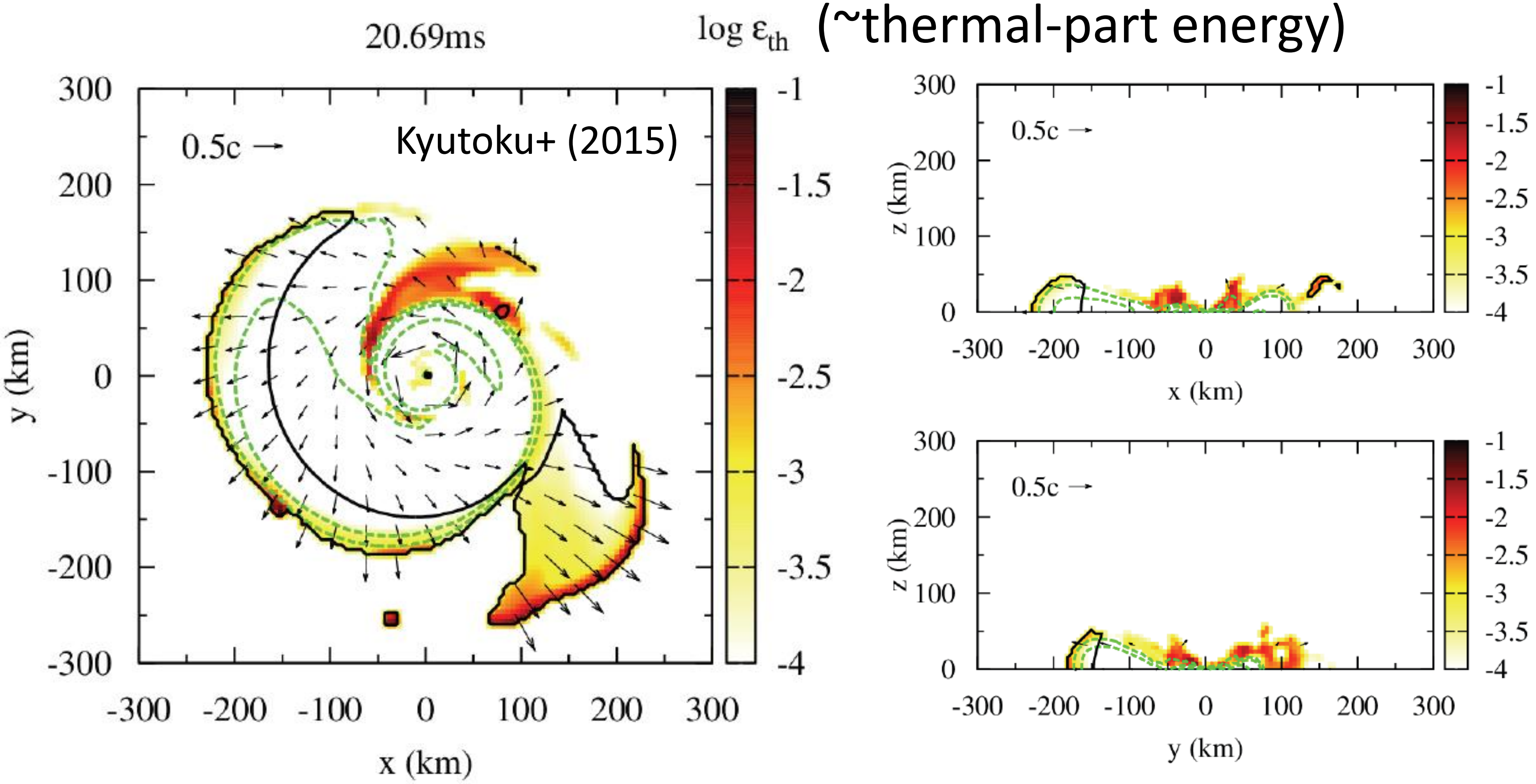
NS-NS: hypermassive NS

BH-NS: BH-disk

(but the reality depends on HMNS/disk winds)

BH-NS Ejecta is very cold

2nd and 3rd peaks of r-process would be formed

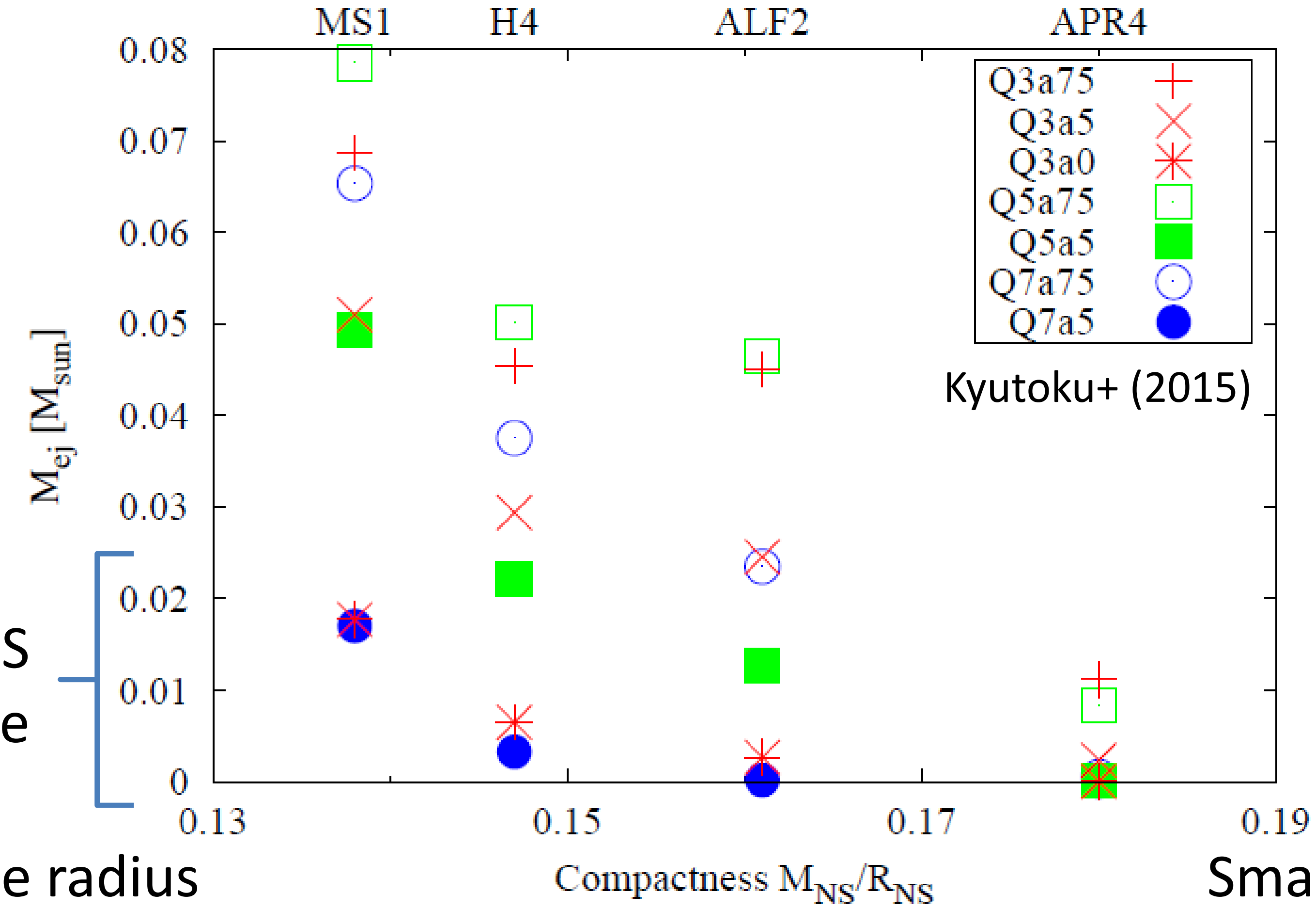


(~thermal-part energy)

Kyutoku+ (2015)

Ejecta mass

The ejecta mass is large when the NS radius is large



Kyutoku+ (2015)

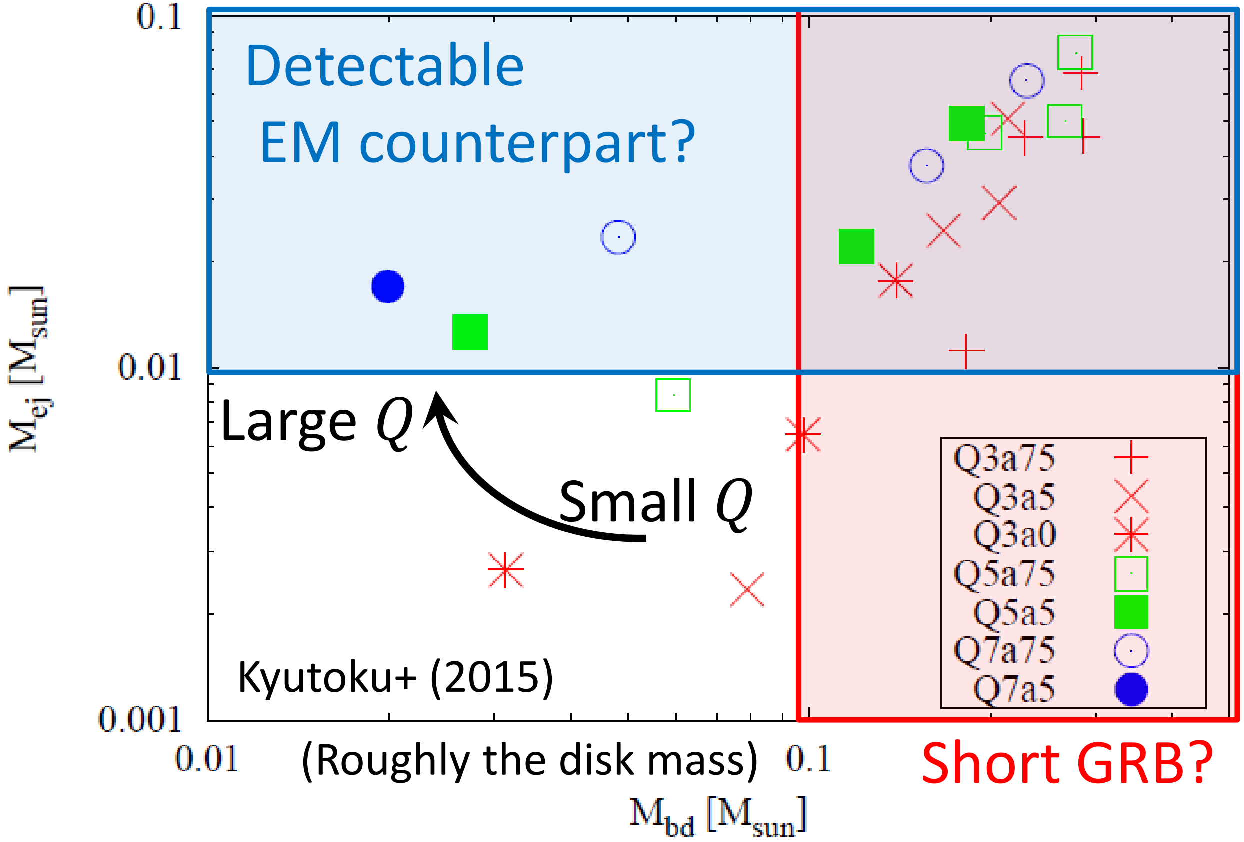
NS-NS range

Large radius

Small radius

Mass ratio dependence

The ejecta mass to disk mass ratio increases as the mass ratio increases (maybe realistic cases)



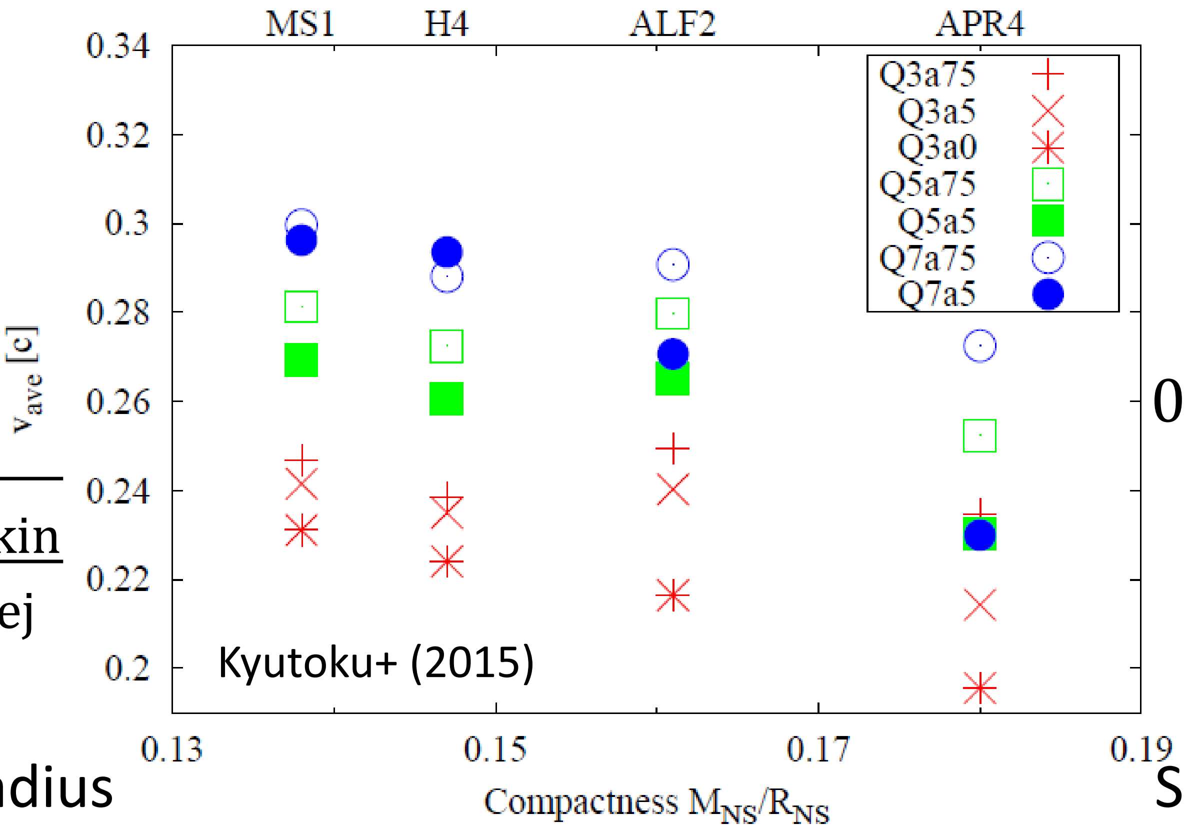
Kyutoku+ (2015)

Average velocity of the ejecta

Also tends to increases as the mass ratio increases

-> the ejecta from a large Q binary is energetic

$$v_{\mathrm{ave}} \equiv \sqrt{\frac{2E_{\mathrm{kin}}}{M_{\mathrm{ej}}}}$$



Kyutoku+ (2015)

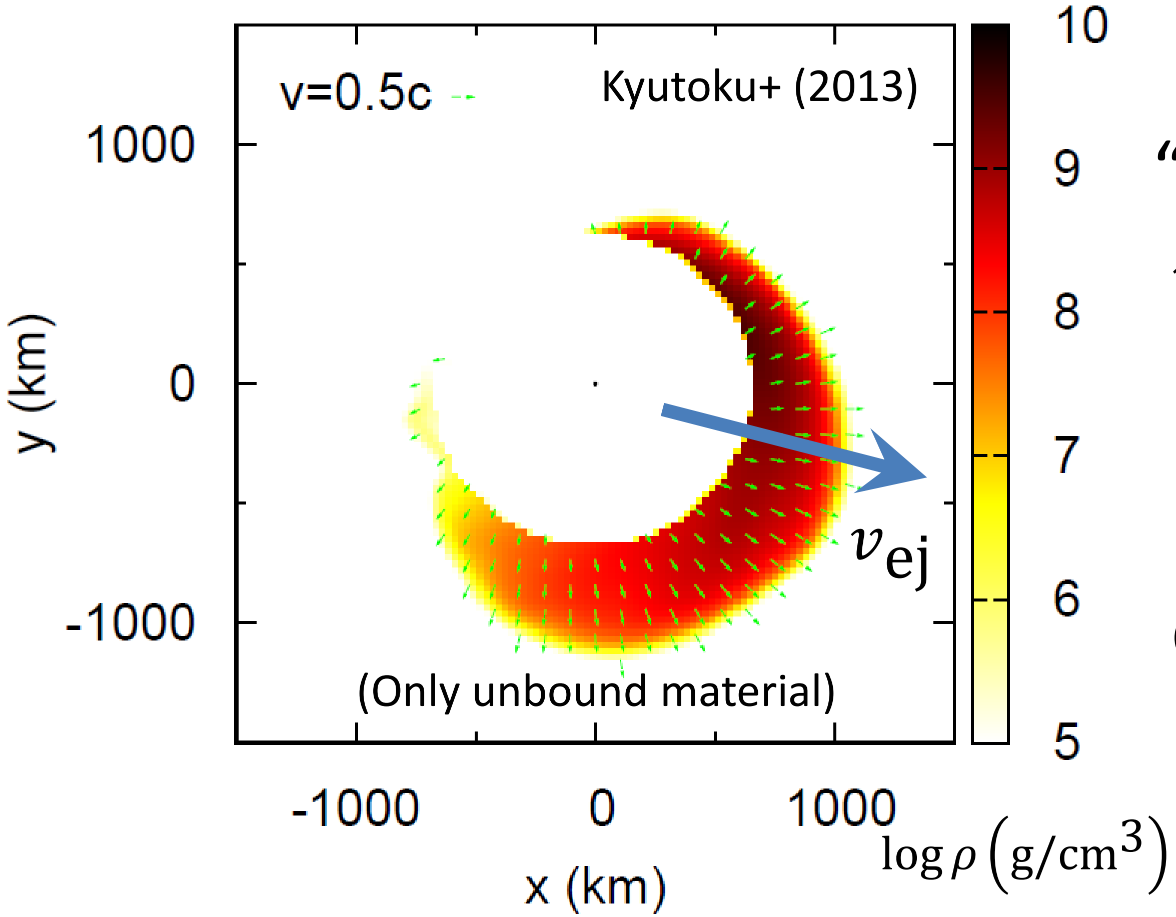
$0.2 - 0.3c$ may be typical

Large radius

Small radius

Bulk velocity of the ejecta

The ejecta has a bulk linear momentum and velocity



“bulk velocity”

$$v_{\mathrm{ej}} \sim P_{\mathrm{ej}}/M_{\mathrm{ej}}$$
$$\sim 0.1 - 0.2c$$

different from

NS-NS ejecta

Kick velocity of the remnant BH

Two kinds of “kick velocity” of the remnant BH

- ejecta kick: large for strong disruption

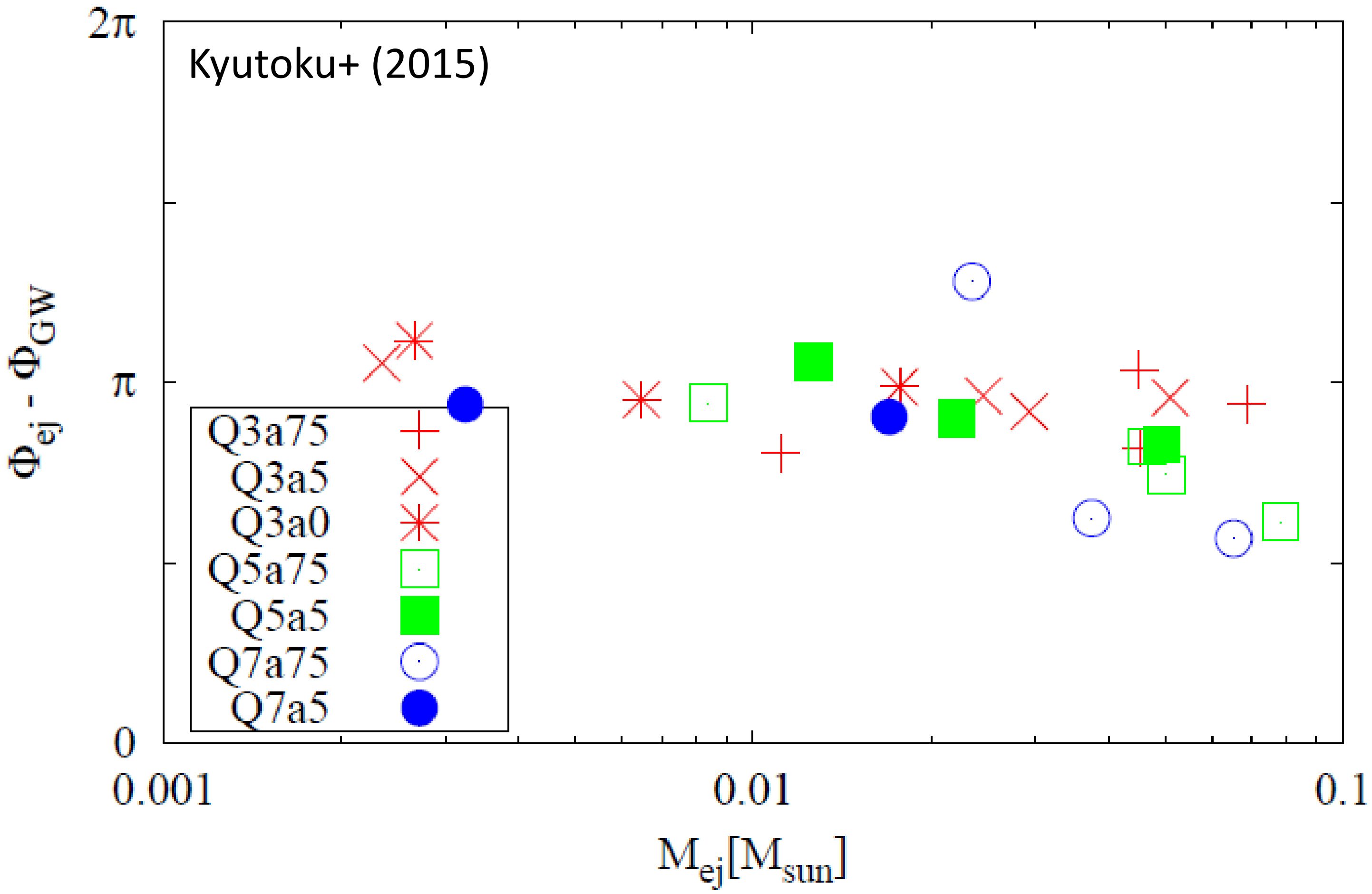
$$V_{\mathrm{ej}} \approx \frac{P_{\mathrm{ej}}}{M_{\mathrm{remnant}}}$$

- gravitational-wave kick: large for weak disruption

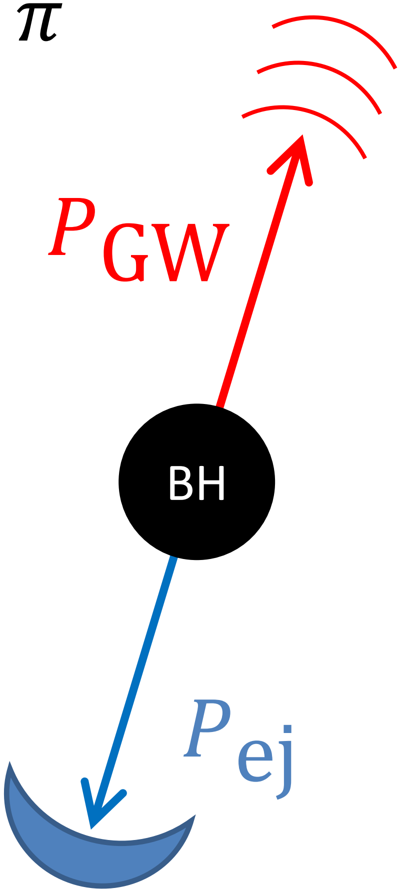
$$V_{\mathrm{GW}} \approx \frac{P_{\mathrm{GW}}}{M_{\mathrm{remnant}}}$$

Anti-correlation of the kick direction

(direction of ejecta) – (direction of GW) $\approx \pi$



Kyutoku+ (2015)

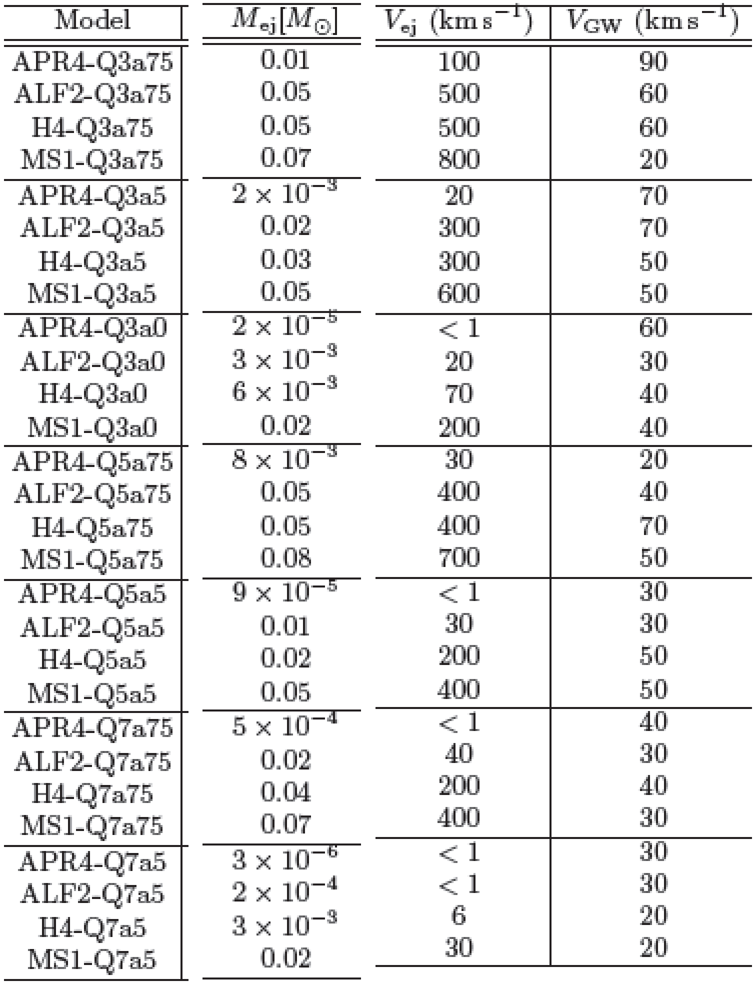


Which of two kick velocities wins?

Threshold at $M_{\mathrm{ej}} \approx 0.01 M_{\odot}$

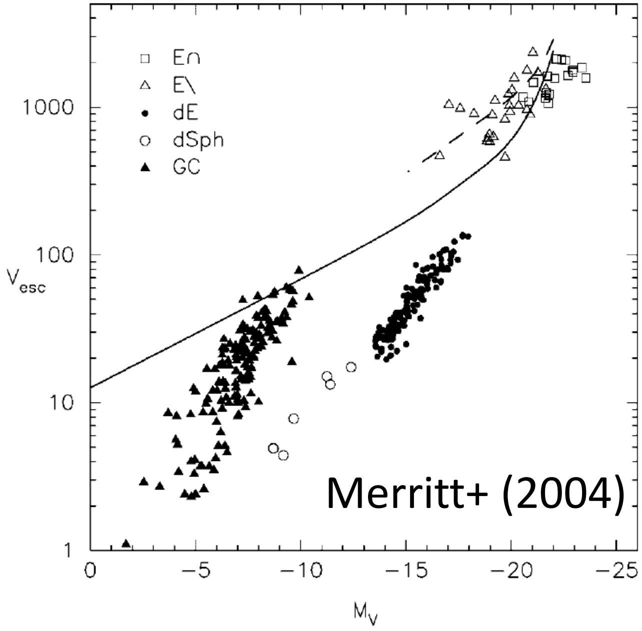
The ejecta kick velocity could be as large as ~1000km/s

Kyutoku+ (2015)



Model	$M_{\mathrm{ej}}[M_{\odot}]$	V_{ej} (km s^{-1})	V_{GW} (km s^{-1})
APR4-Q3a75	0.01	100	90
ALF2-Q3a75	0.05	500	60
H4-Q3a75	0.05	500	60
MS1-Q3a75	0.07	800	20
APR4-Q3a5	2×10^{-3}	20	70
ALF2-Q3a5	0.02	300	70
H4-Q3a5	0.03	300	50
MS1-Q3a5	0.05	600	50
APR4-Q3a0	2×10^{-5}	< 1	60
ALF2-Q3a0	3×10^{-3}	20	30
H4-Q3a0	6×10^{-3}	70	40
MS1-Q3a0	0.02	200	40
APR4-Q5a75	8×10^{-3}	30	20
ALF2-Q5a75	0.05	400	40
H4-Q5a75	0.05	400	70
MS1-Q5a75	0.08	700	50
APR4-Q5a5	9×10^{-5}	< 1	30
ALF2-Q5a5	0.01	30	30
H4-Q5a5	0.02	200	50
MS1-Q5a5	0.05	400	50
APR4-Q7a75	5×10^{-4}	< 1	40
ALF2-Q7a75	0.02	40	30
H4-Q7a75	0.04	200	40
MS1-Q7a75	0.07	400	30
APR4-Q7a5	3×10^{-6}	< 1	30
ALF2-Q7a5	2×10^{-4}	< 1	30
H4-Q7a5	3×10^{-3}	6	20
MS1-Q7a5	0.02	30	20

Escape velocity of galaxies and globular clusters



Merritt+ (2004)

Bright macronova/kilonova

For spherical ejecta (Li-Paczynski 1998)

The peak luminosity: $L_{\mathrm{peak}} \propto f\kappa^{-1/2}M^{1/2}v^{1/2}$

The peak time : $t_{\mathrm{peak}} \propto \kappa^{1/2}M^{1/2}v^{-1/2}$

Heating efficiency f and opacity κ – microphysics

important quantities, but are not discussed here

Ejecta mass M and ejecta velocity v – NR simulation

large ejecta mass -> bright and long emission

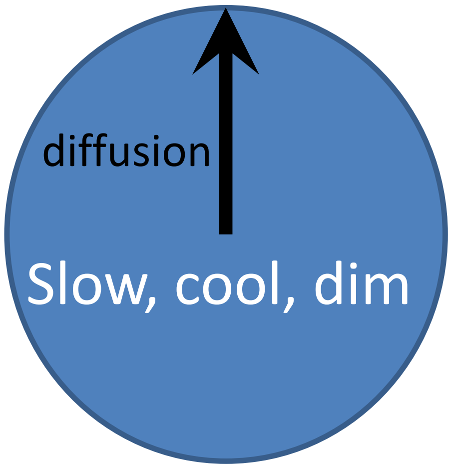
Effect of anisotropy

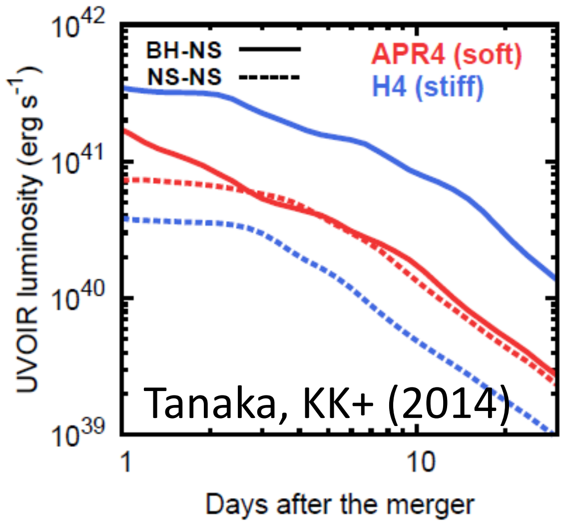
Geometry determines the photon-diffusion direction

sphecial ejecta

BH-NS crescent-like ejecta

aspect ratio: $v_{\parallel}/v_{\perp} \sim 1/\theta_{\mathrm{ej}} \sim 5$





Tanaka, KK+ (2014)

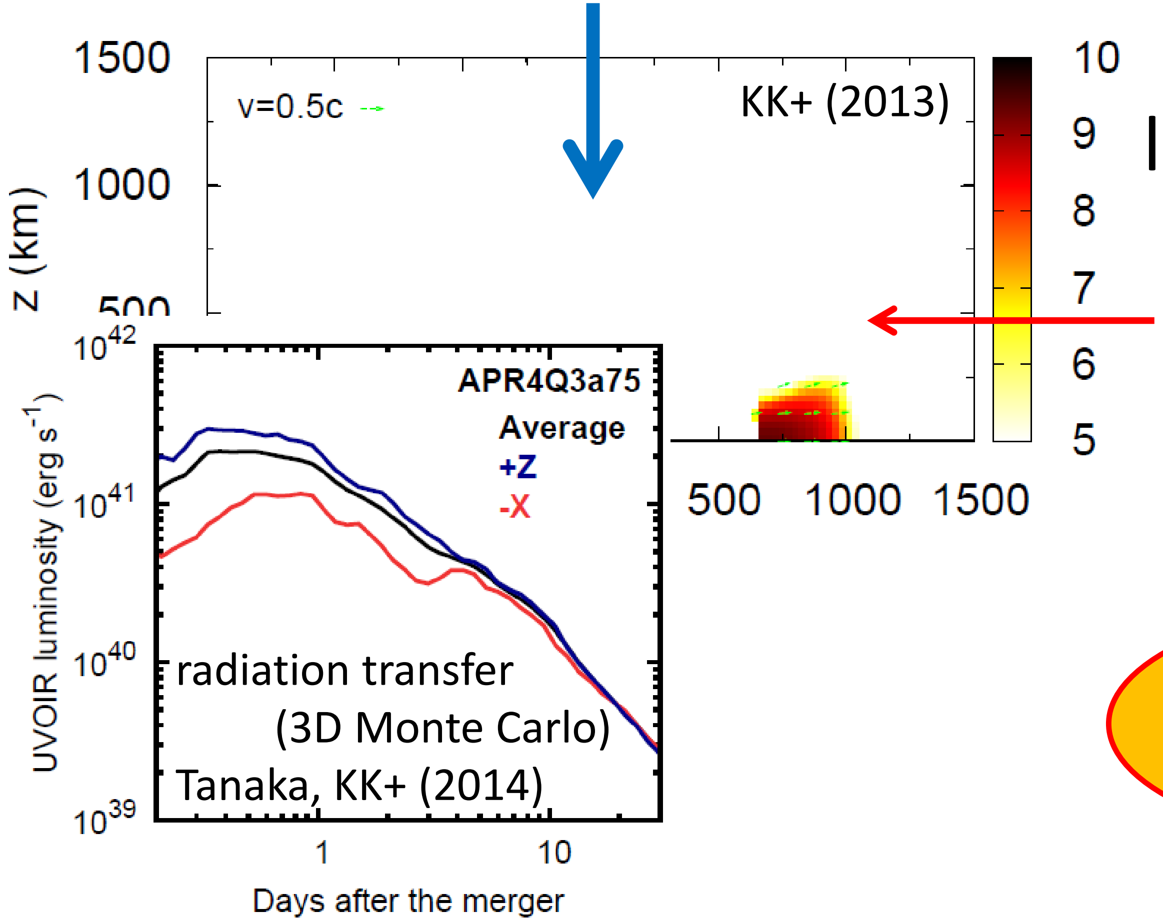
radiation transfer
(3D Monte Carlo)

NS-NS: $t_{\mathrm{peak,s}} \sim \left(3\kappa \mathrm{M}_{\mathrm{ej}}/4\pi c v\right)^{1/2} \sim 8\mathrm{day}$

BH-NS: $t_{\mathrm{peak}} \sim \left(\kappa M_{\mathrm{ej}}\theta_{\mathrm{ej}}/c\varphi_{\mathrm{ej}} v\right)^{1/2} \sim 4\mathrm{day}$

Viewing-angle dependence

High luminosity $L_{\rm peak} \sim f M_{\rm ej}/t_{\rm peak} \sim 10^{41}$ erg/s



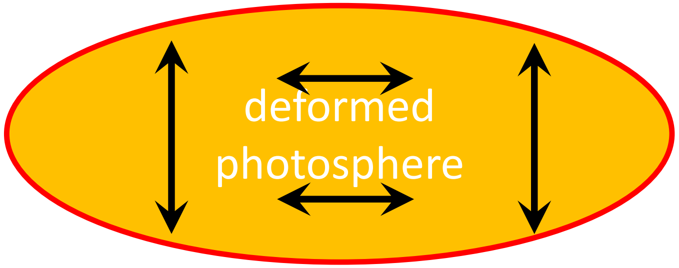
KK+ (2013)

radiation transfer
(3D Monte Carlo)
Tanaka, KK+ (2014)

low luminosity

$\sim \theta_{\rm ej} L_{\rm peak}$

polarization?

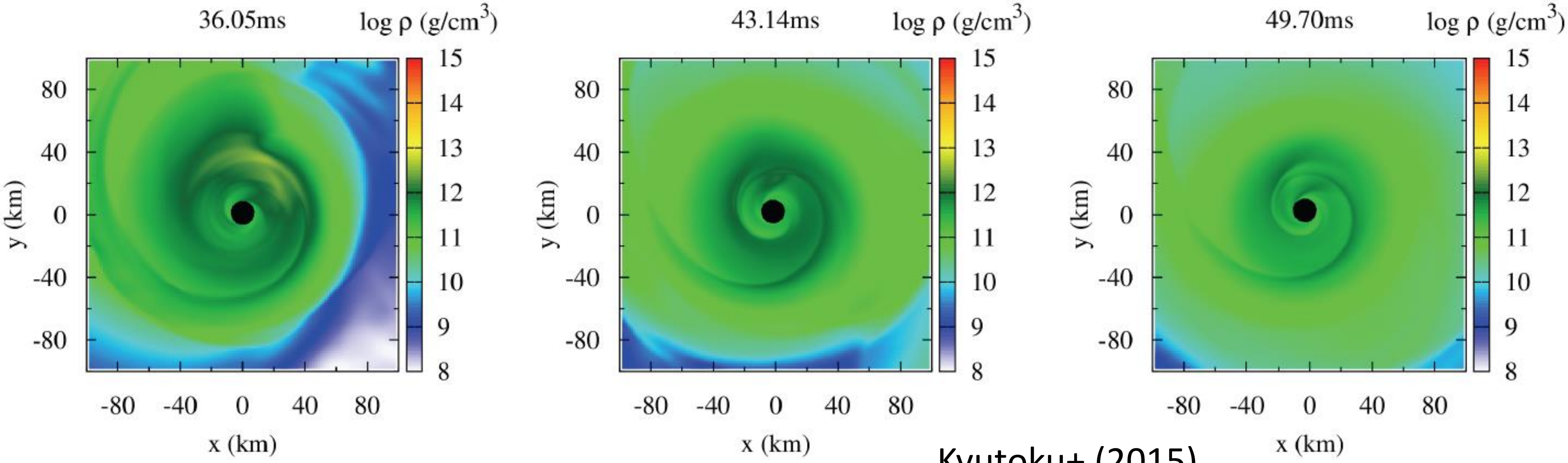


deformed photosphere

Standing spiral shock in the disk

Formed as a result of the self-collision of tidal tail

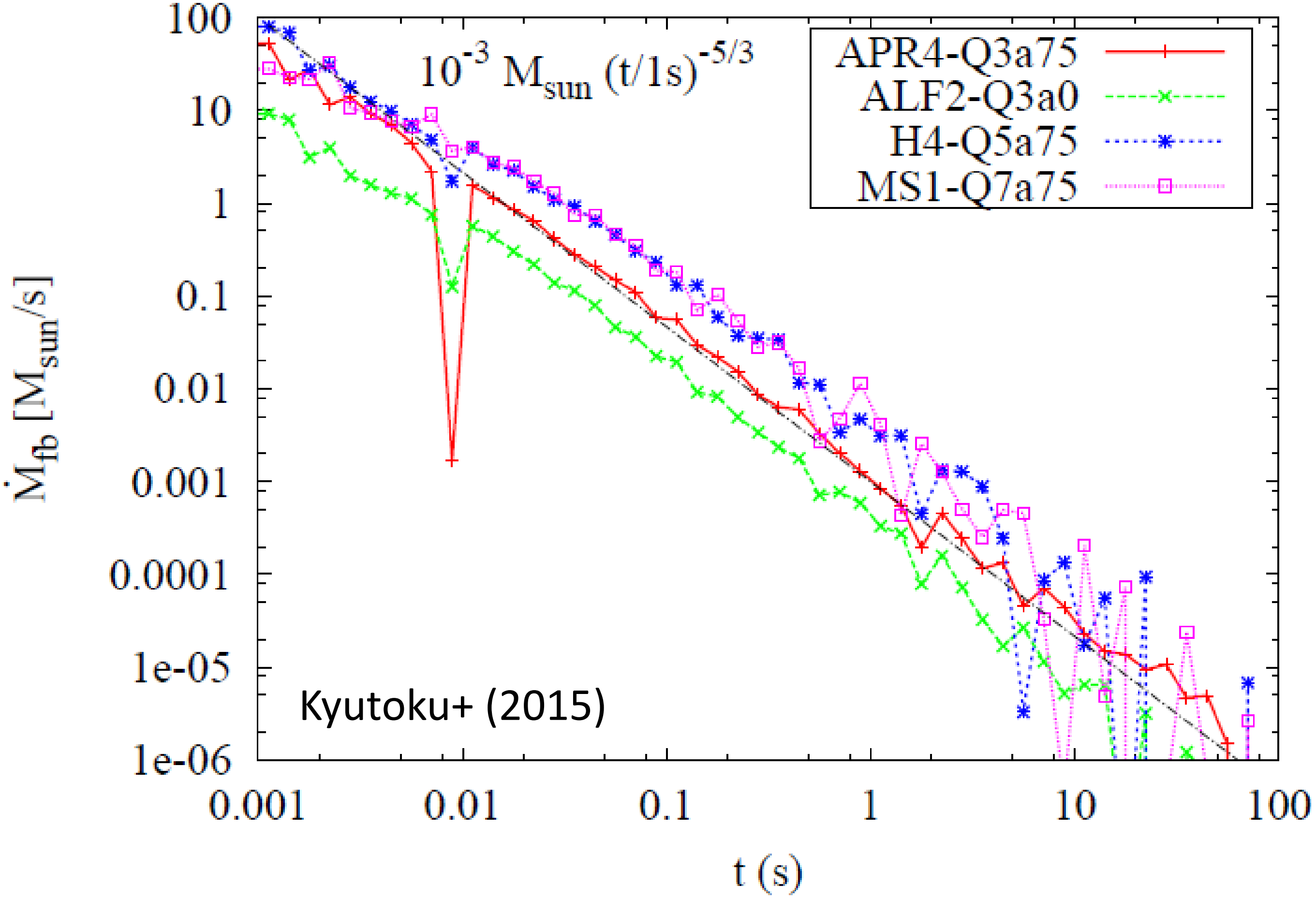
Drive mass accretion even for the perfect fluid



Kyutoku+ (2015)

Fallback material

"canonical" power law with the index -5/3



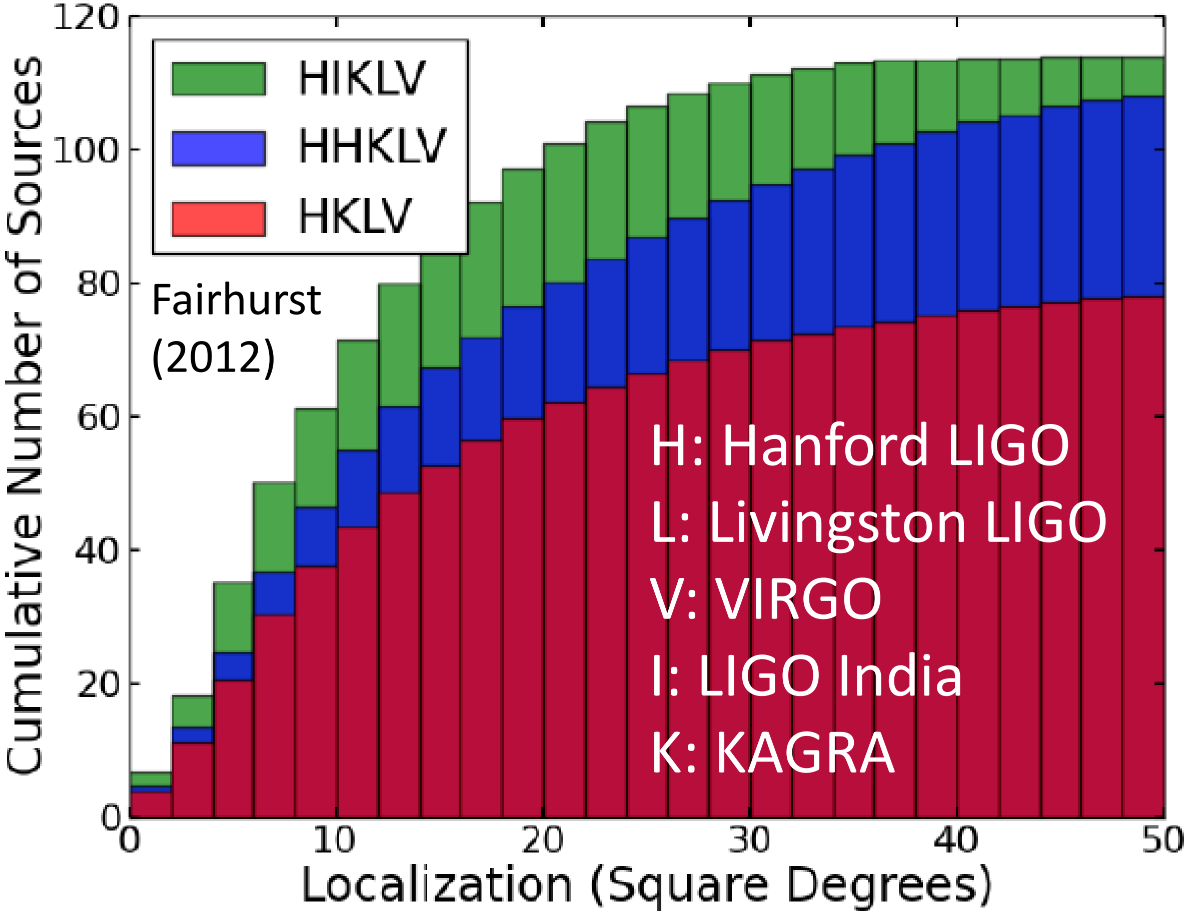
Kyutoku+ (2015)

Summary

- Black hole-neutron star binary mergers can eject $\sim 0.01 - 0.1 M_{\odot}$ with $0.2 - 0.3c$ dynamically in various cases particularly when the NS radius is large (the equation of state is stiff).
- BH-NS ejecta are anisotropic, are concentrated within a small angle around the orbital plane, and carry nonzero linear momenta.
- Anisotropy of the ejecta could bring diversity to electromagnetic counterparts.

Why do we need EM counterparts?

One GW detector cannot localize the GW source

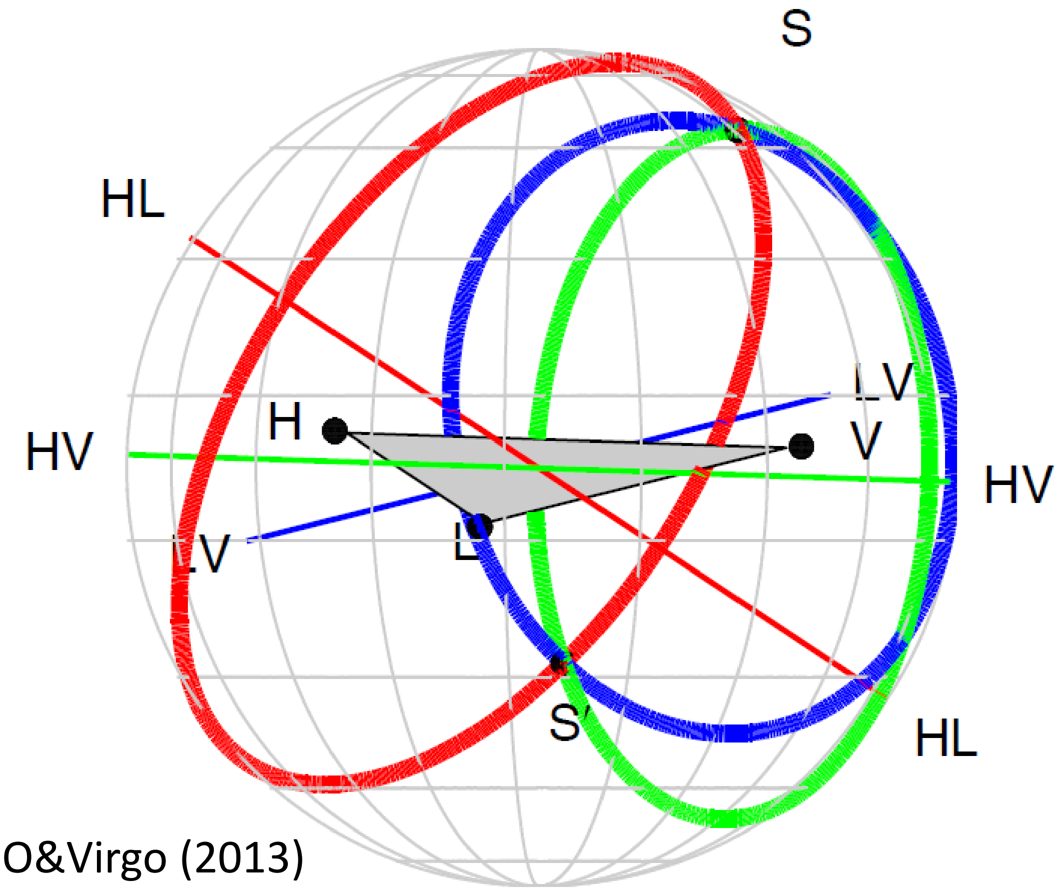


Fairhurst (2012)

H: Hanford LIGO
L: Livingston LIGO
V: VIRGO
I: LIGO India
K: KAGRA

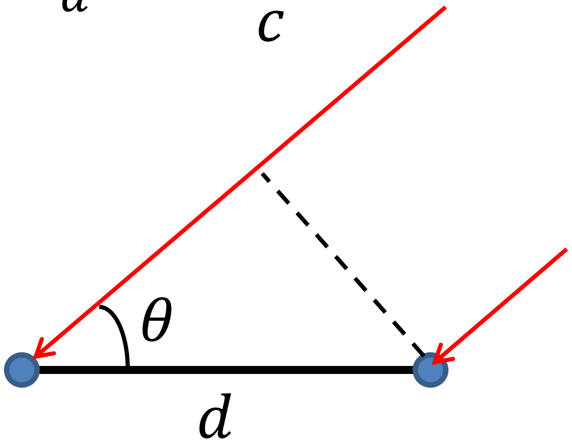
Triangulation by a detector network

Determine the sky position from timing difference



LIGO&Virgo (2013)

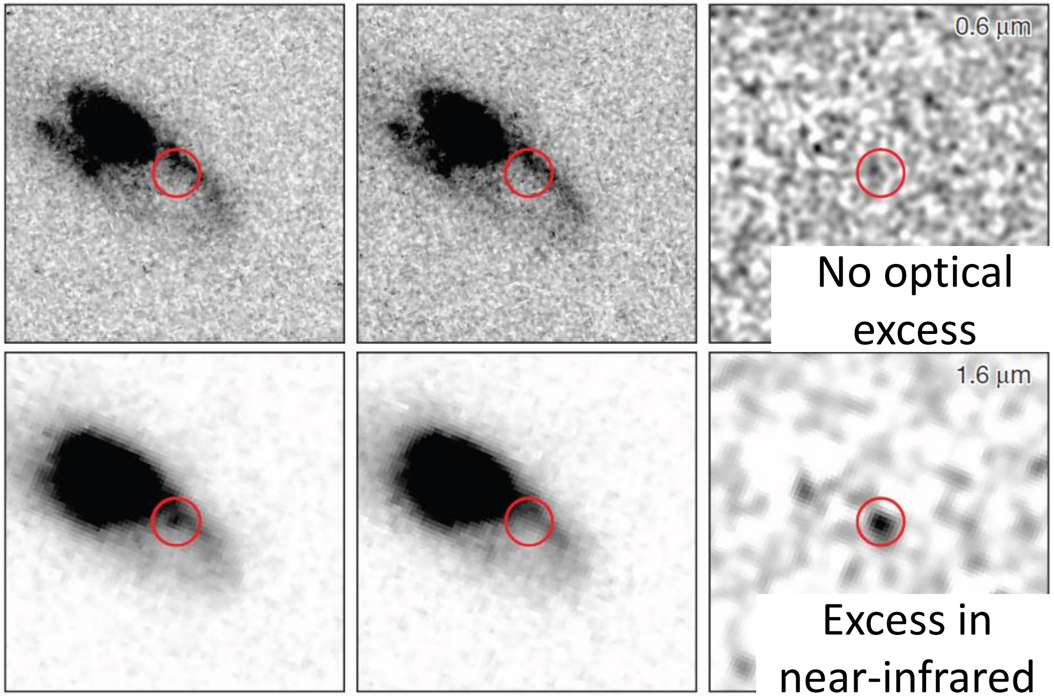
$$t_d = \frac{d\cos\theta}{c}$$



Near-infrared excess of GRB 130603B

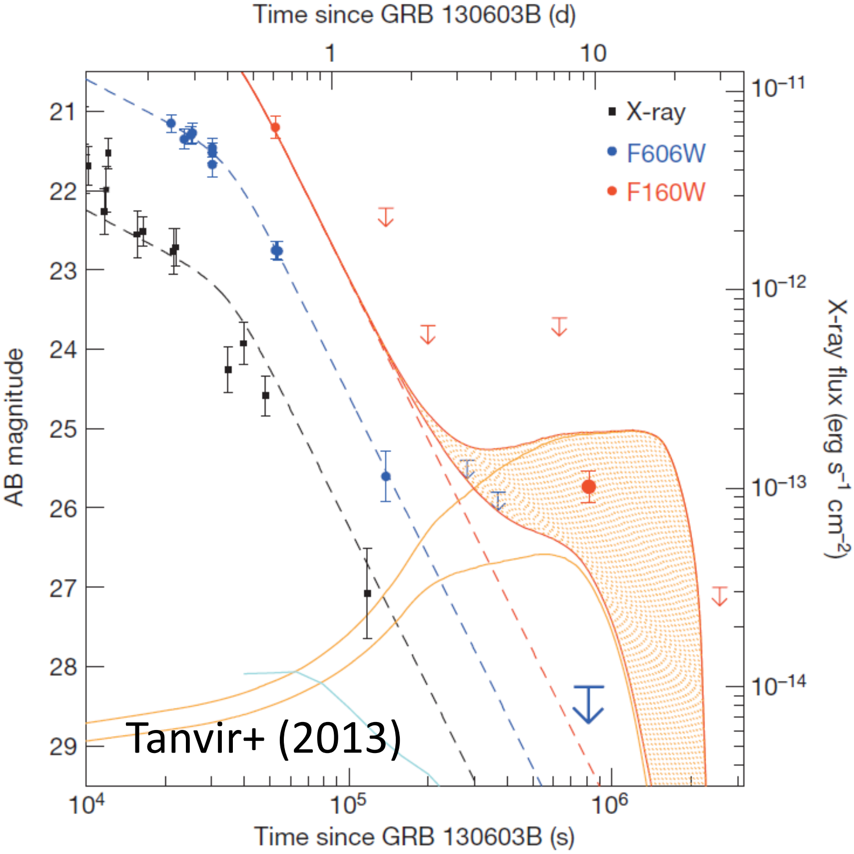
Ejecta mass $M_{\mathrm{ej}} = 0.02{\sim}0.1 M_{\odot}$ may be required

9day (event?) − 30day (background) = Excess brightening



No optical excess

Excess in near-infrared



Tanvir+ (2013)

Mass ejection channel

Dynamical mass ejection: this study

we can study with gravity+pure hydrodynamics

sometimes obviously dominates disk winds

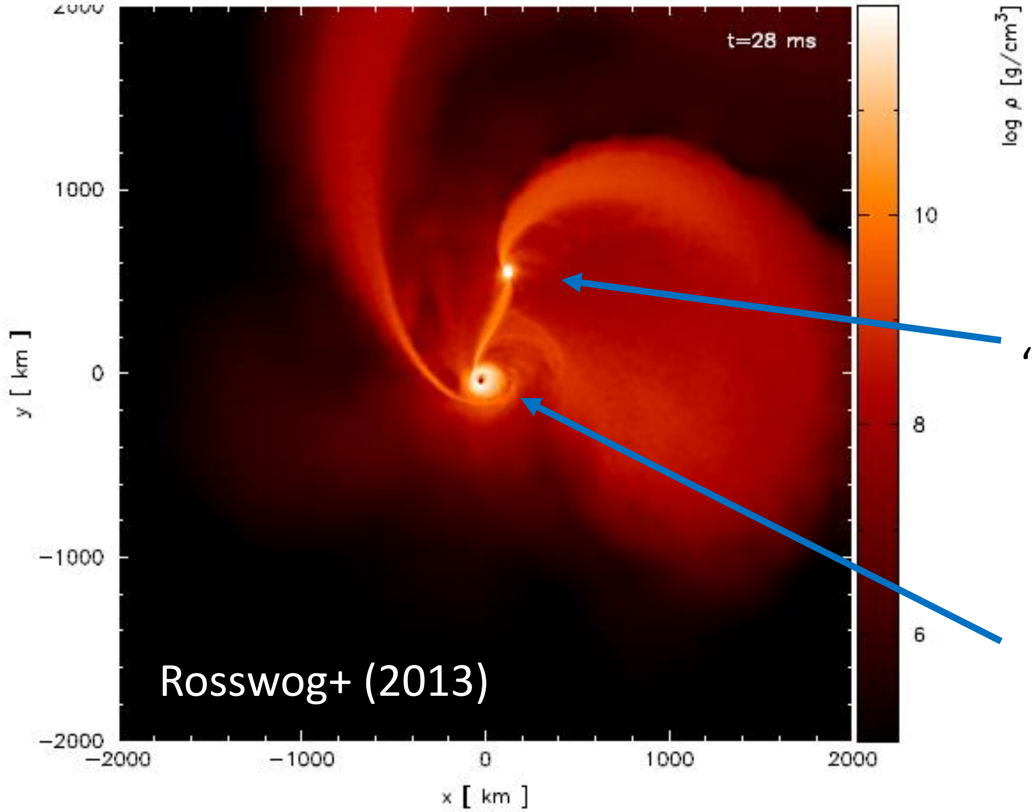
Disk activity (winds): ongoing study

- nuclear heating
- viscous heating (Shibata-san)
- magnetically driven wind (Kiuchi-san)
- neutrino driven wind (Sekiguchi-san)

Newtonian BH-NS simulation

Episodic (repeated stable) mass transfer

qualitatively different from full GR results



"mini neutron star"

BH-disk

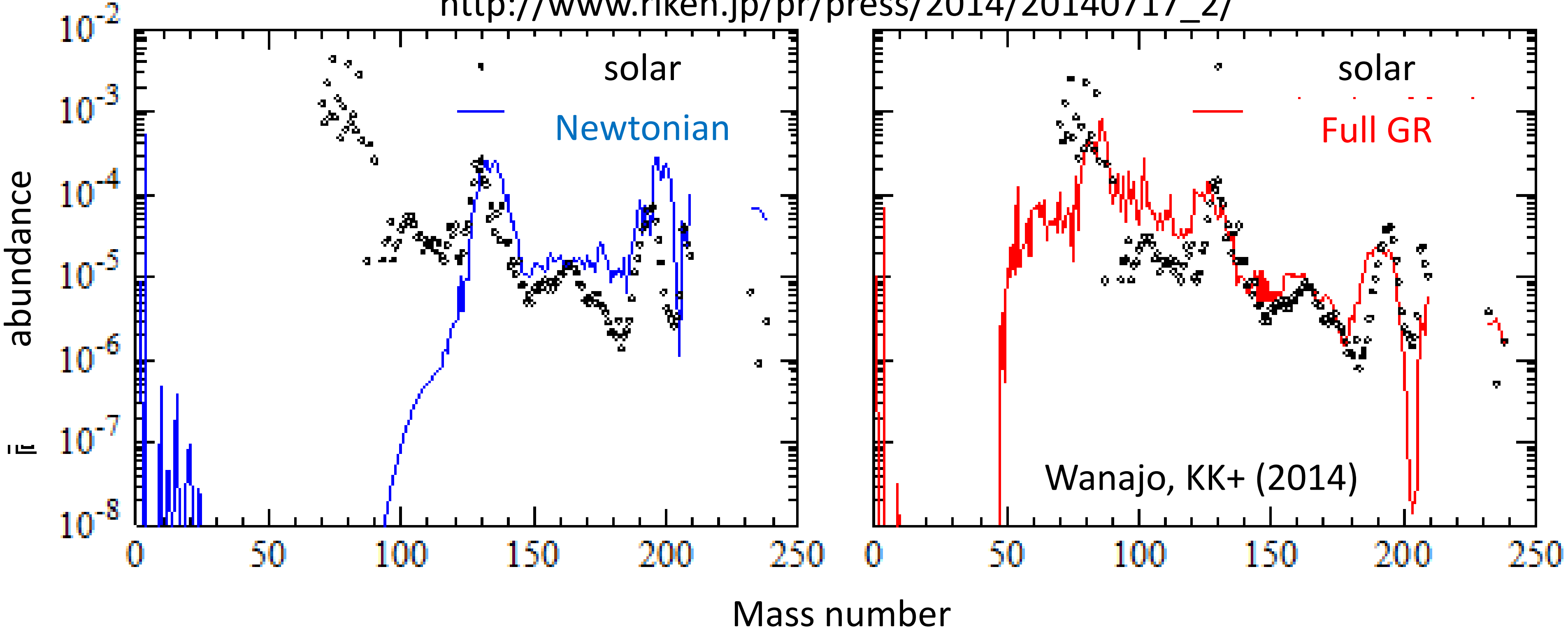
Rosswog+ (2013)

R-process nucleosynthesis

GR sometimes changes the situation qualitatively

e.g., nucleasynthesis in NS-NS dynamical ejecta

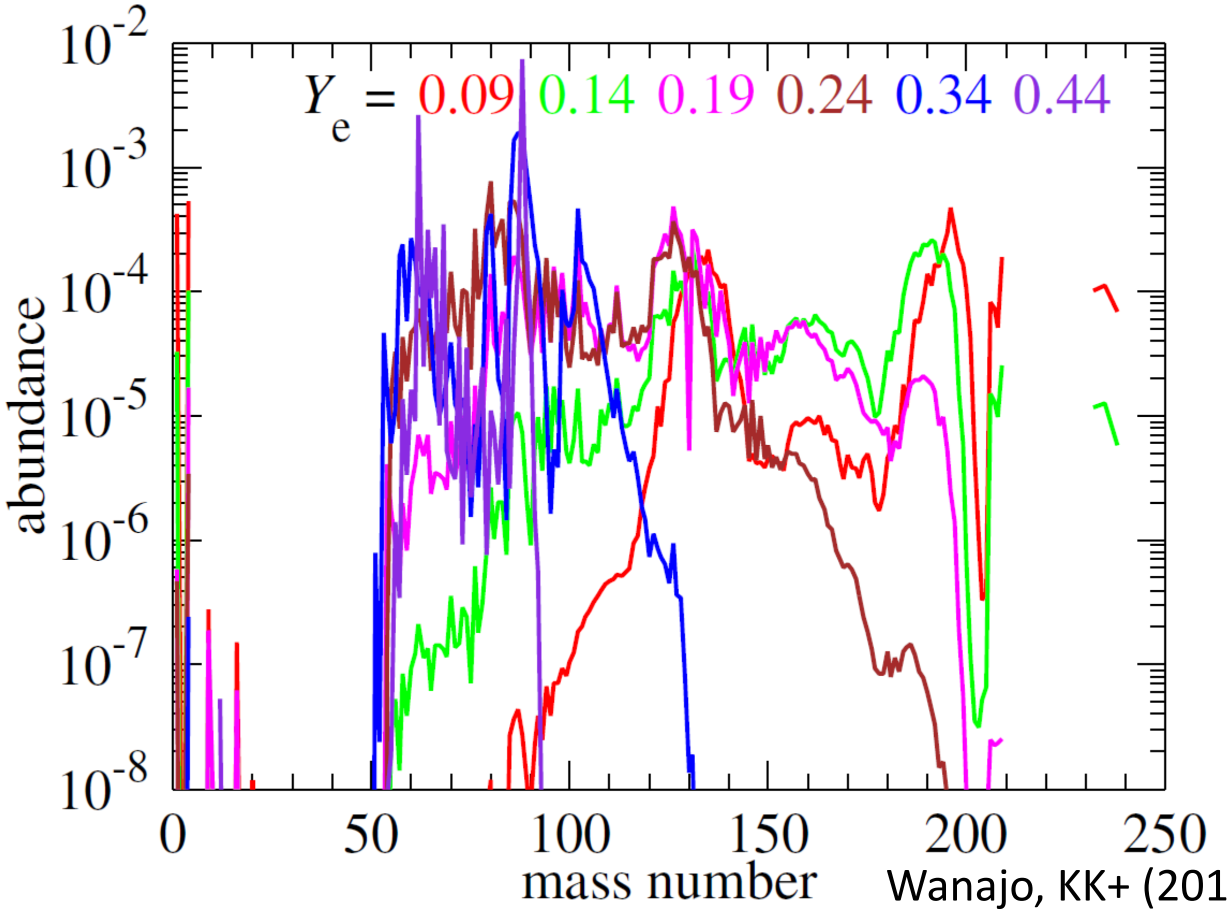
http://www.riken.jp/pr/press/2014/20140717_2/



Wanajo, KK+ (2014)

Why successful r-process?

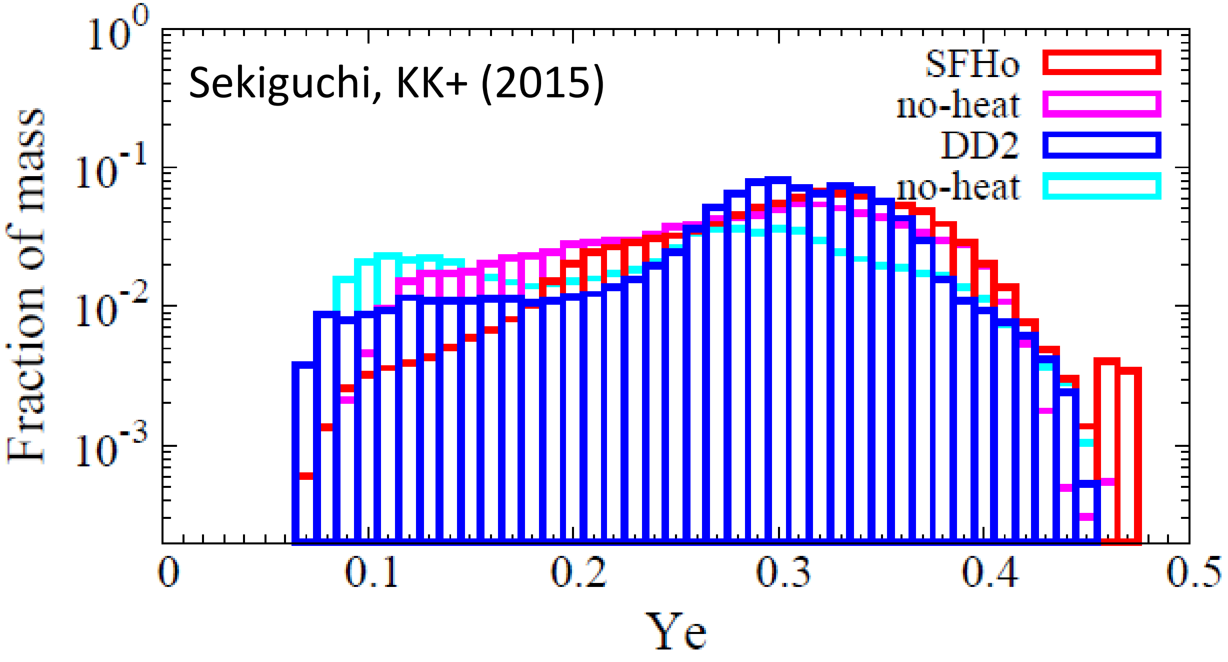
Broad distribution of electron fraction in full GR

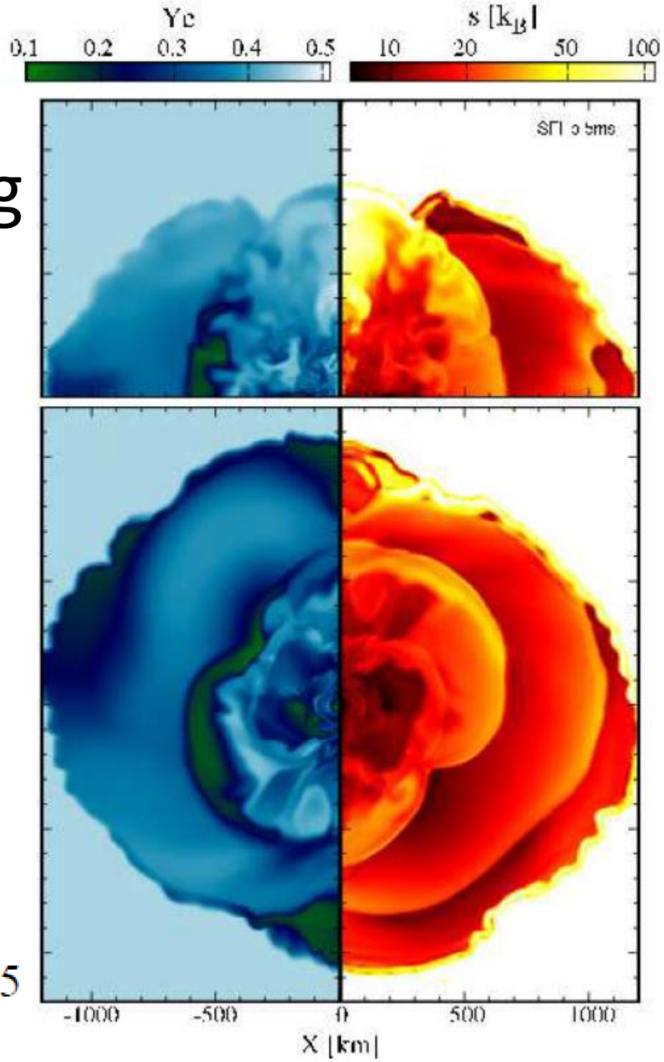


Wanajo, KK+ (2014)

GR NS-NS ejecta

The electron fraction can be increased by strong shock heating (and also neutrino irradiation)

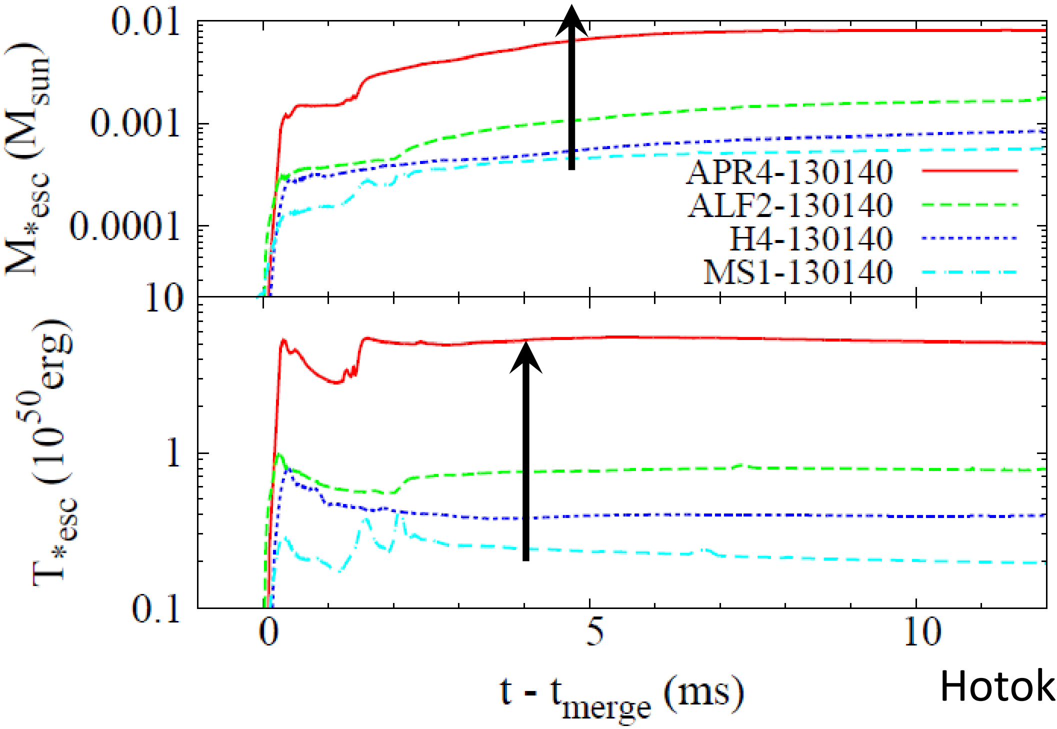




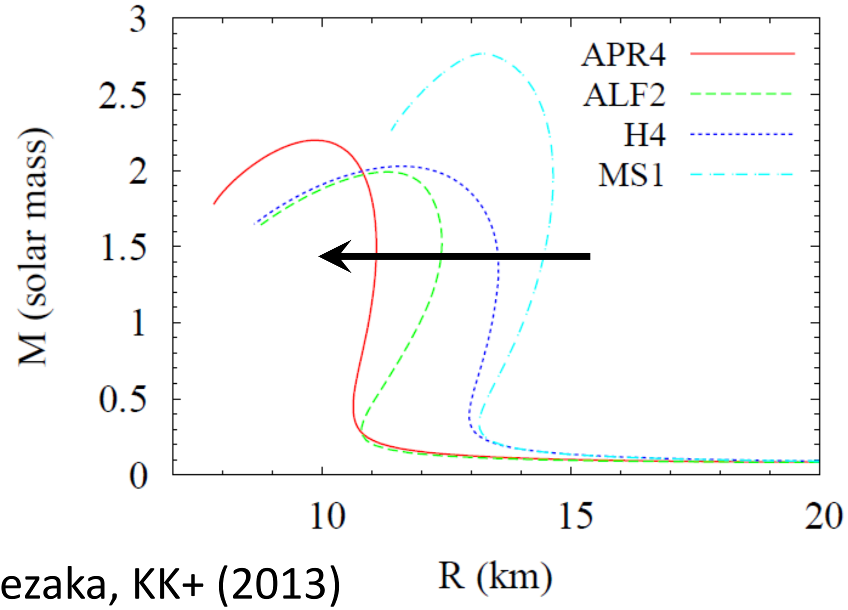
Sekiguchi, KK+ (2015)

EOS dependence of NS-NS ejecta

Ejecta are massive when the NS radius is small due to violent activity of a compact remnant NS



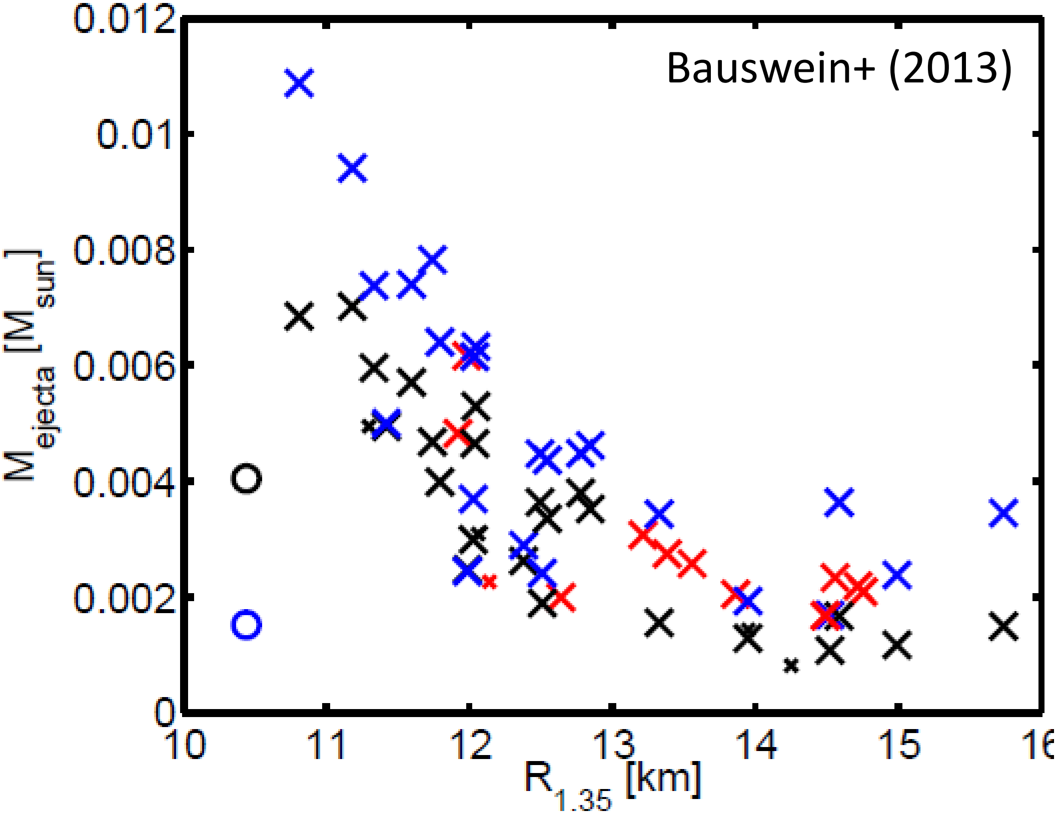
Hotokezaka, KK+ (2013)

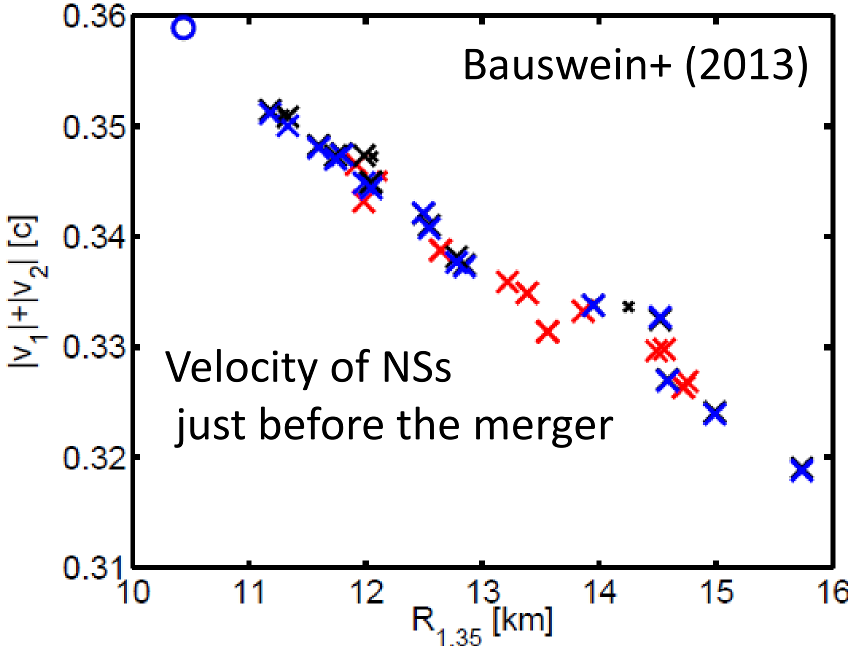


GRSPH simulation

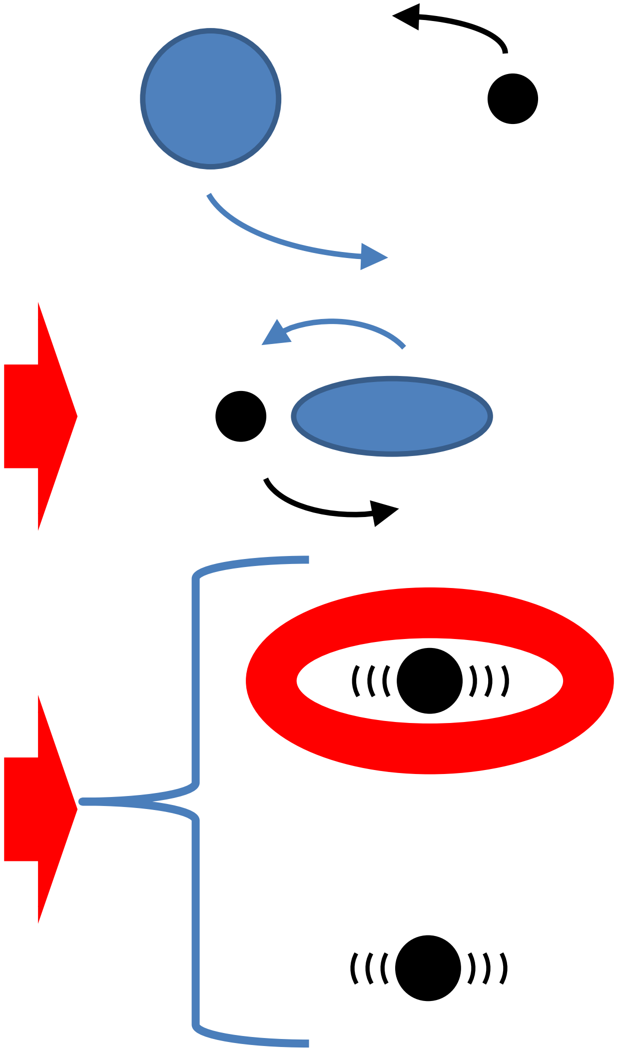
Independent confirmation with approx. GR

shock ejection is important (suppress tidal ejection)




Velocity of NSs just before the merger

Merger dynamics



inspiral due to GW backreaction

NS deformation due to tidal force

further drive the inspiral motion

$r_{\mathrm{tidal}} > r_{\mathrm{ISCO}}$: tidal disruption

mass ejection, disk formation…

$r_{\mathrm{tidal}} < r_{\mathrm{ISCO}}$: like BH-BH

Mass shedding condition

1. BH tidal force=NS self gravity at the NS surface

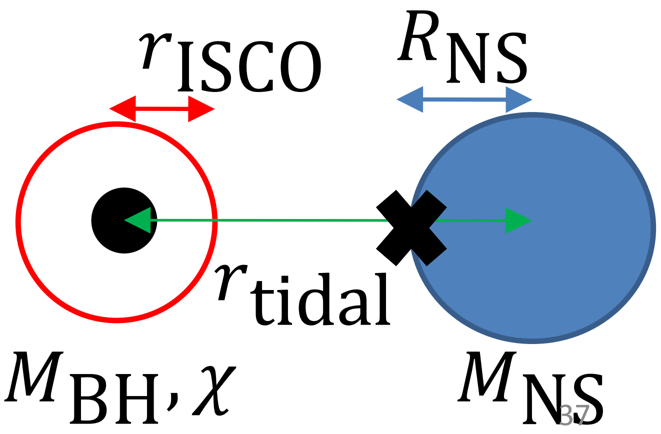
$$\frac{M_{\mathrm{BH}}R_{\mathrm{NS}}}{r_{\mathrm{tidal}}{}^{3}} \sim \frac{M_{\mathrm{NS}}}{R_{\mathrm{NS}}{}^{2}} \Rightarrow r_{\mathrm{tidal}} \sim M_{\mathrm{BH}}\left(\frac{M_{\mathrm{NS}}}{M_{\mathrm{BH}}}\right)^{2/3}\left(\frac{R_{\mathrm{NS}}}{M_{\mathrm{NS}}}\right)$$

2. BH innermost stable circular orbit w/ spin χ

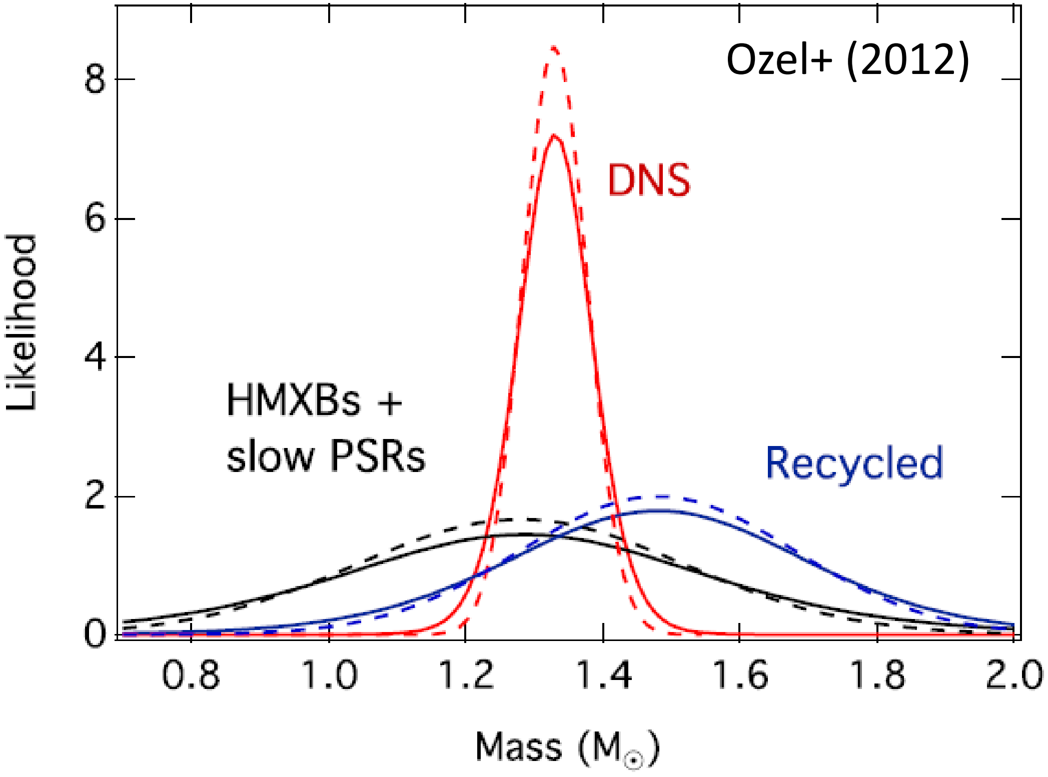
$r_{\mathrm{ISCO}} = \hat{r}(\chi)M_{\mathrm{BH}}$ ($\hat{r}$ is a decreasing function of χ)

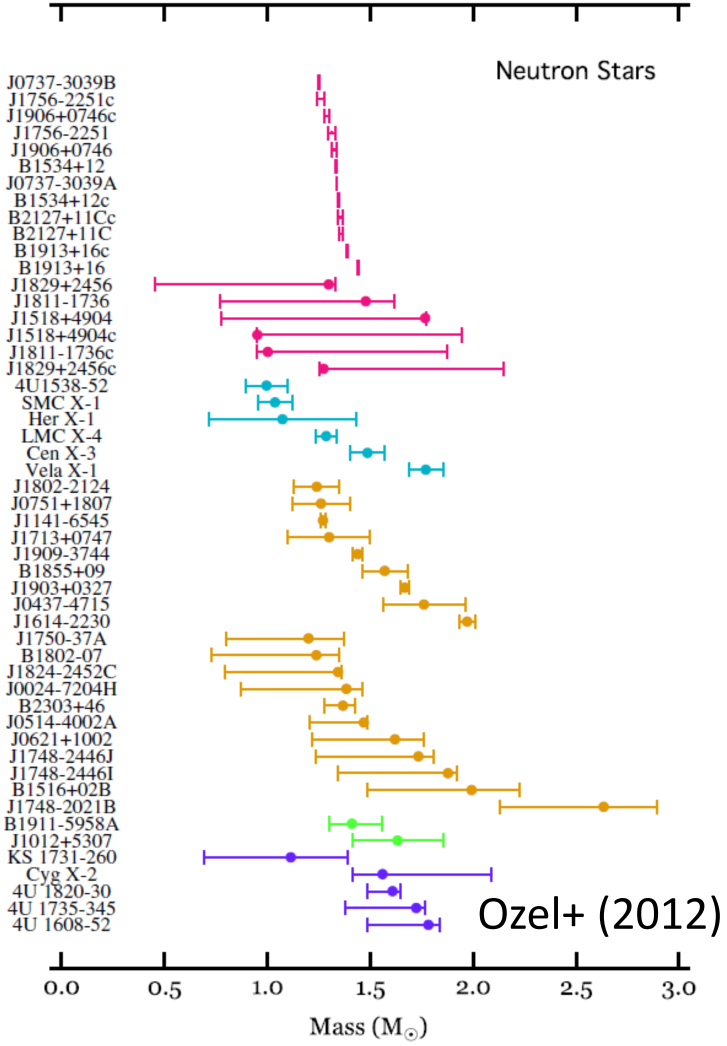
3. Disruption if this value is large

$$\frac{r_{\mathrm{tidal}}}{r_{\mathrm{ISCO}}} \sim \frac{1}{\hat{r}(\chi)}\left(\frac{M_{\mathrm{NS}}}{M_{\mathrm{BH}}}\right)^{2/3}\left(\frac{R_{\mathrm{NS}}}{M_{\mathrm{NS}}}\right)$$



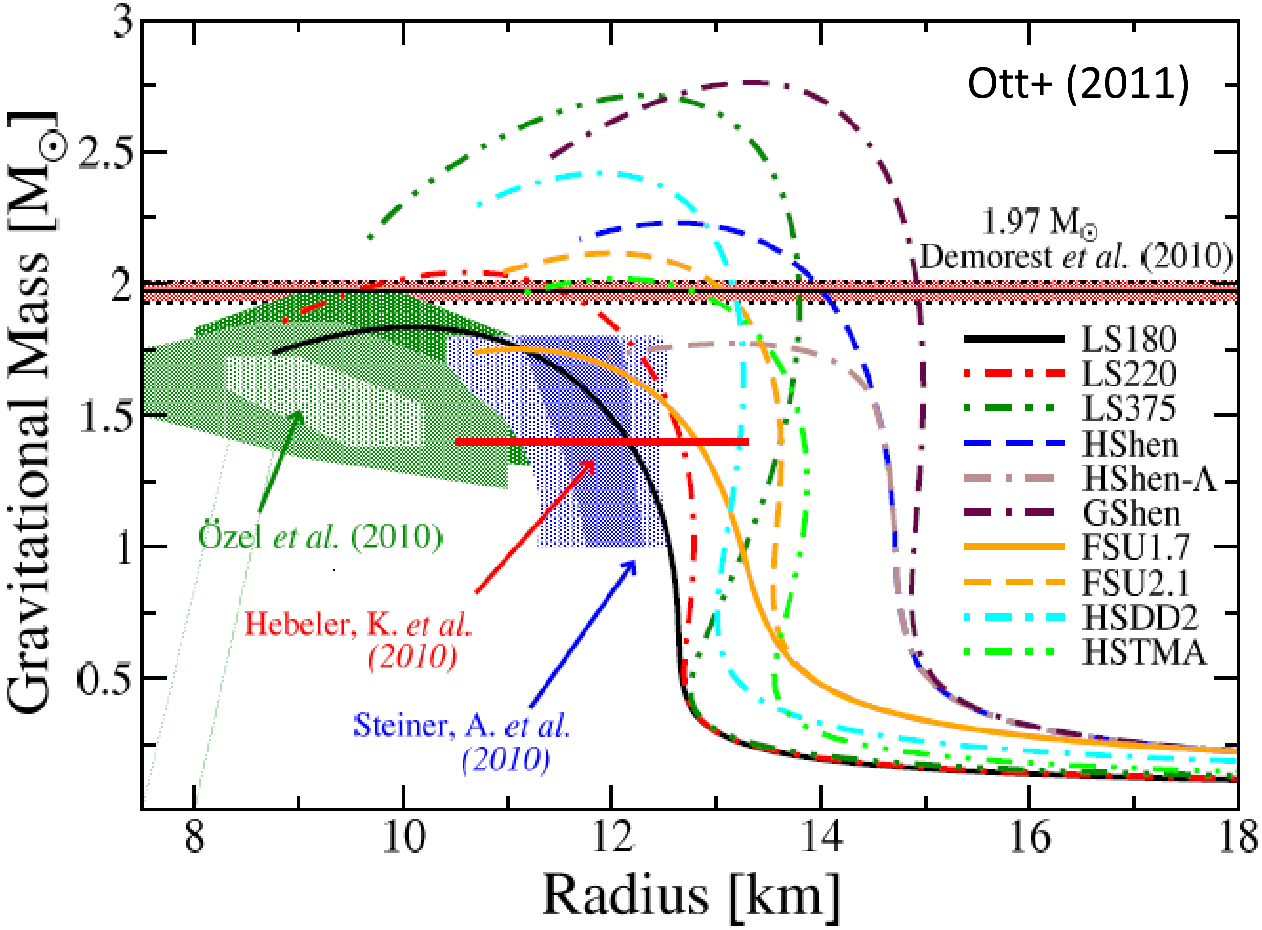
Neutron star mass





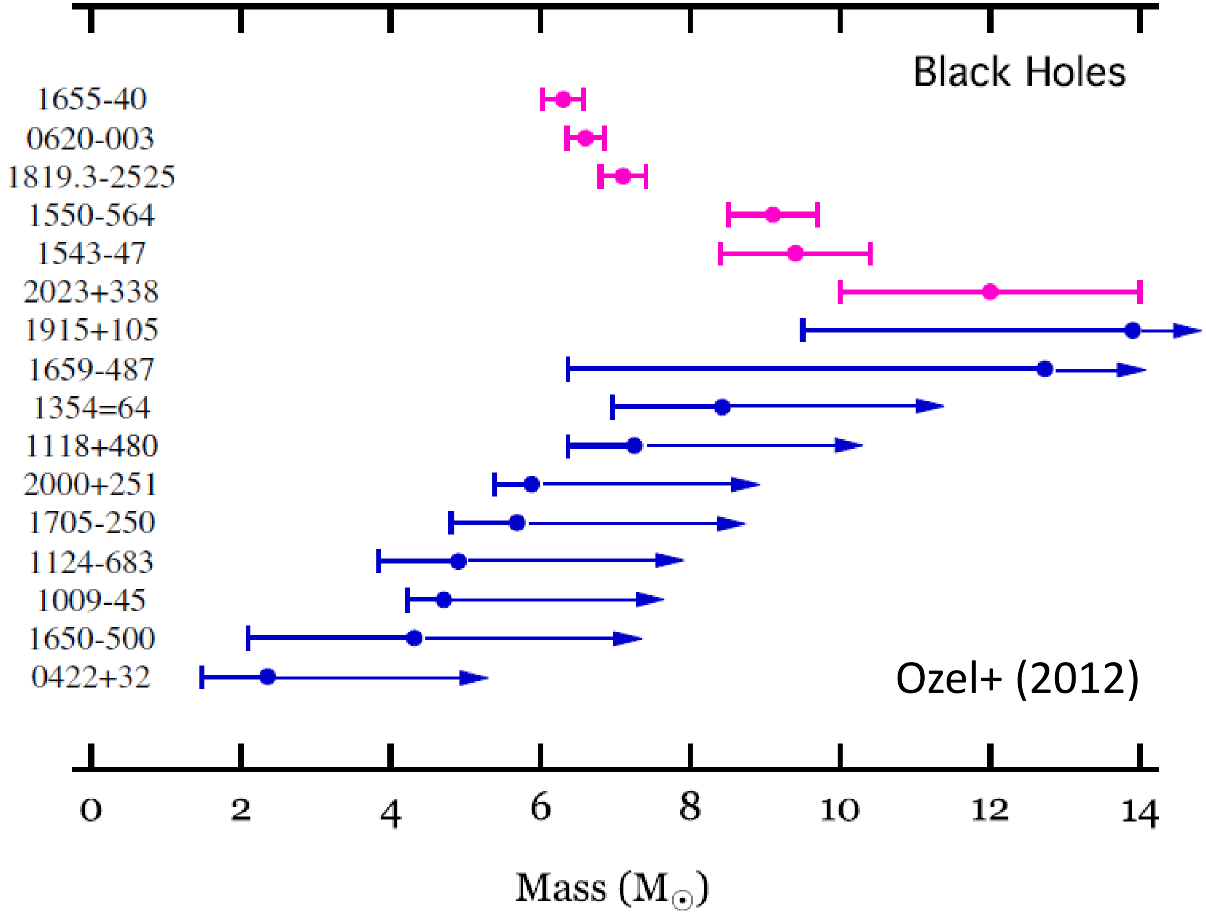
Neutron star radius

No firm conclusion, but may not be very large



Black hole mass

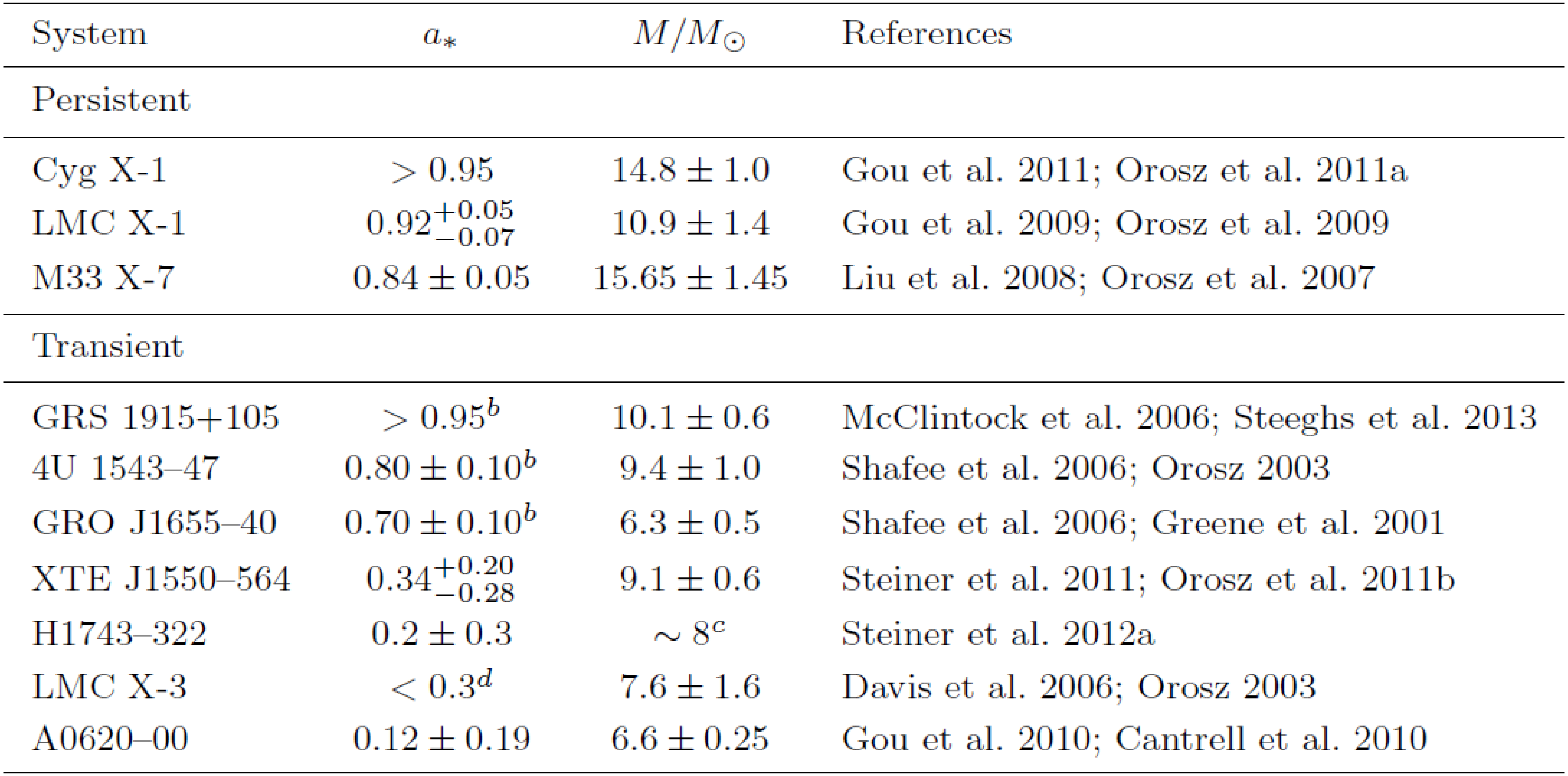
Mass gap around $3-5M_{\odot}$ is frequently debated



Black hole spin

Uncertain but no typical value exists

McClintock+ (2014)

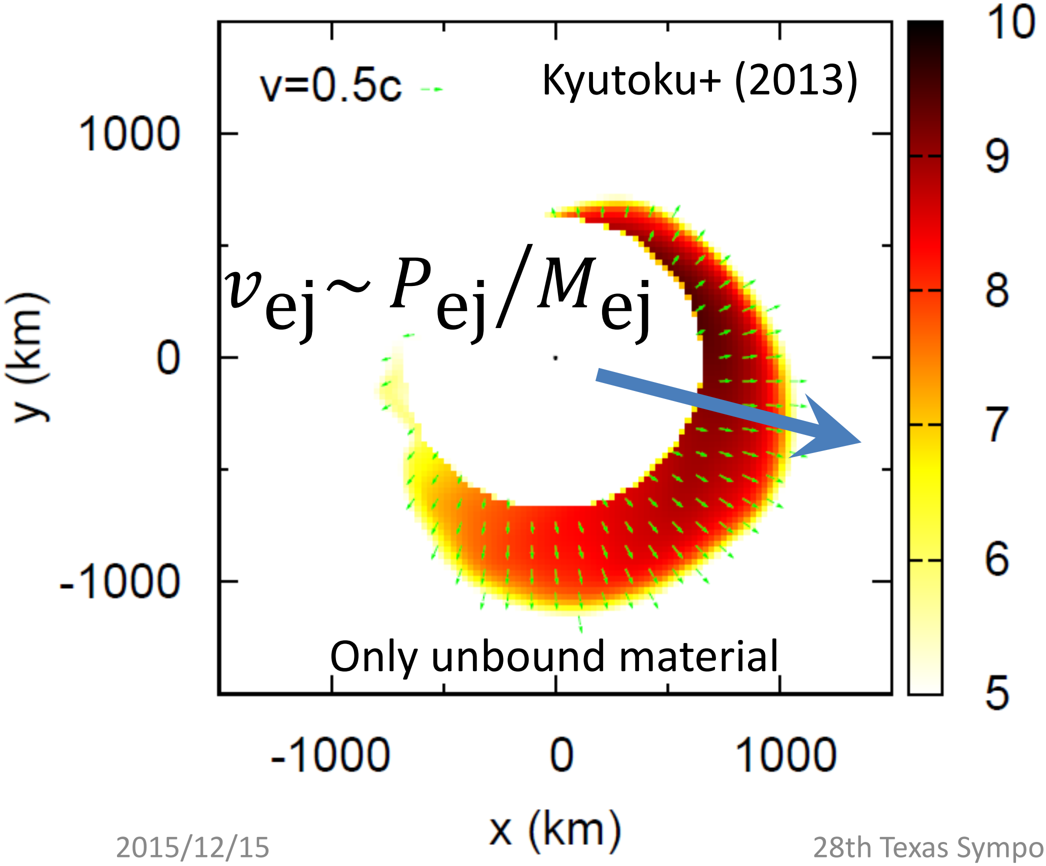


System	a_*	$M/M_\odot$	References
Persistent			
Cyg X-1	> 0.95	14.8 ± 1.0	Gou et al. 2011; Orosz et al. 2011a
LMC X-1	$0.92^{+0.05}_{-0.07}$	10.9 ± 1.4	Gou et al. 2009; Orosz et al. 2009
M33 X-7	0.84 ± 0.05	15.65 ± 1.45	Liu et al. 2008; Orosz et al. 2007
Transient			
GRS 1915+105	$> 0.95^b$	10.1 ± 0.6	McClintock et al. 2006; Steeghs et al. 2013
4U 1543–47	0.80 ± 0.10^b	9.4 ± 1.0	Shafee et al. 2006; Orosz 2003
GRO J1655–40	0.70 ± 0.10^b	6.3 ± 0.5	Shafee et al. 2006; Greene et al. 2001
XTE J1550–564	$0.34^{+0.20}_{-0.28}$	9.1 ± 0.6	Steiner et al. 2011; Orosz et al. 2011b
H1743–322	0.2 ± 0.3	$\sim 8^c$	Steiner et al. 2012a
LMC X-3	$< 0.3^d$	7.6 ± 1.6	Davis et al. 2006; Orosz 2003
A0620–00	0.12 ± 0.19	6.6 ± 0.25	Gou et al. 2010; Cantrell et al. 2010

Characteristic quantities

Ejection is efficient when the NS radius is large

opposite to NS-NS mass ejection (Hotokezaka, KK+ 2013)



$v_{\rm ej} \sim P_{\rm ej}/M_{\rm ej}$

ejecta mass

$(0\sim)0.08 M_\odot$

kinetic energy

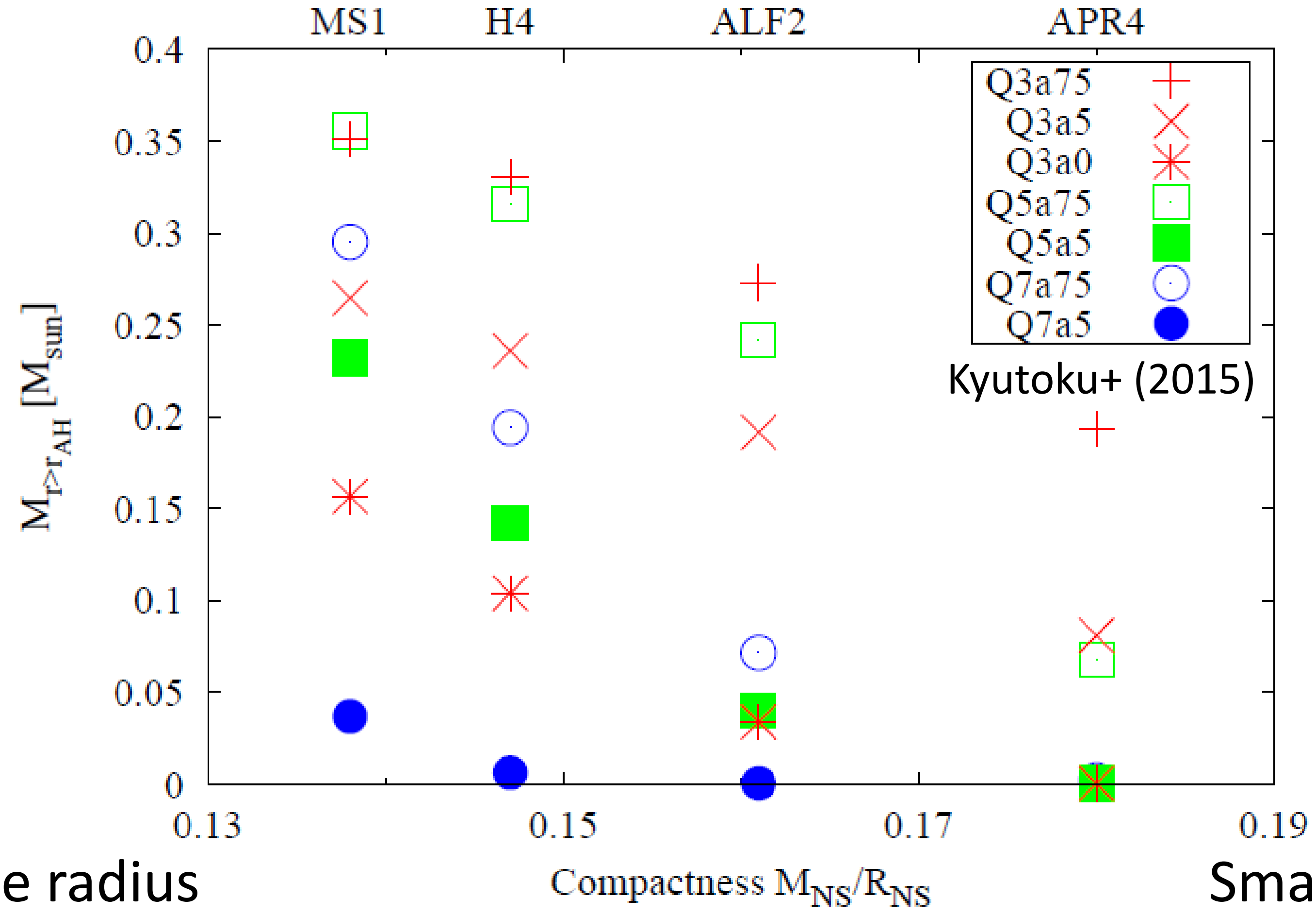
$(0\sim)5 \times 10^{51}\,\mathrm{erg}$

“bulk” velocity

$v_{\rm ej} \sim 0.2c$

Mass left outside the black hole

Nicely correlated with the NS compactness (radius)



Kyutoku+ (2015)

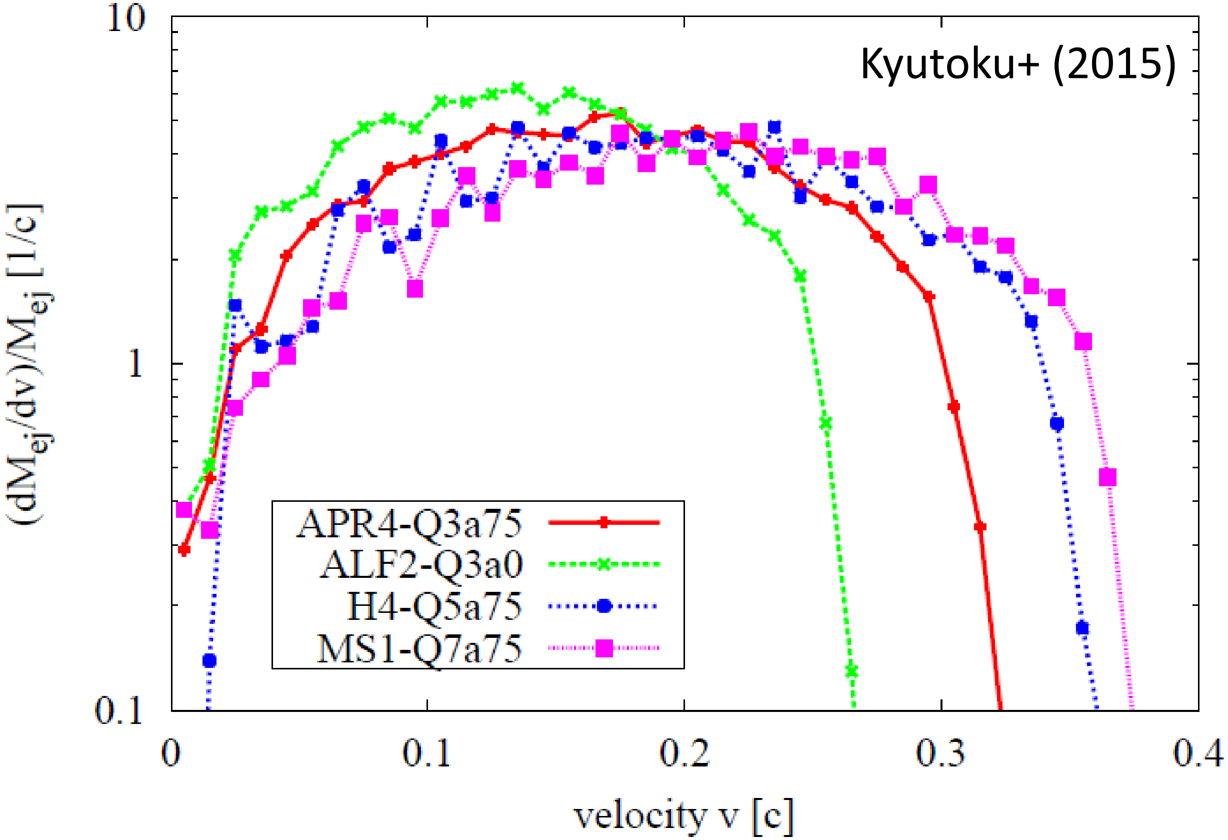
Large radius

Small radius

Velocity distribution

Relatively flat w/ cutoffs rather than a power law

seems to be distinct from NS-NS ejecta



Reason of the power-law index 5/3

Orbital period – semimajor axis – binding energy

$$P \propto a^{3/2} \propto |E|^{-3/2}$$

The fallback rate ~ the period distribution

$$\dot{M} = \frac{dM}{dP} = \frac{dM}{dE}\frac{dE}{dP} \propto \frac{dM}{dE} P^{-5/3} = \frac{dM}{dE} t^{-5/3}$$

Why dM/dE is constant? Not fully understand yet

[e.g., Lodato+ (2009) for SMBH-MS disruption]

Leading candidate of EM counterpart

- (Short-hard gamma-ray burst)

- Macronova/kilonova

IR-optical flare on a week time scale

driven by decay of unstable r-process elements

- Synchrotron radio flare

radio(-opt, X) emission on a decade time scale

emitted by nonthermal electrons in magnetic fields

Synchrotron radio emission

Ejecta decelerate when accumulate M_{ej} from ISM

For a spherical ejecta (with $n_{\mathrm{H}} = 1\mathrm{cm}^3$)

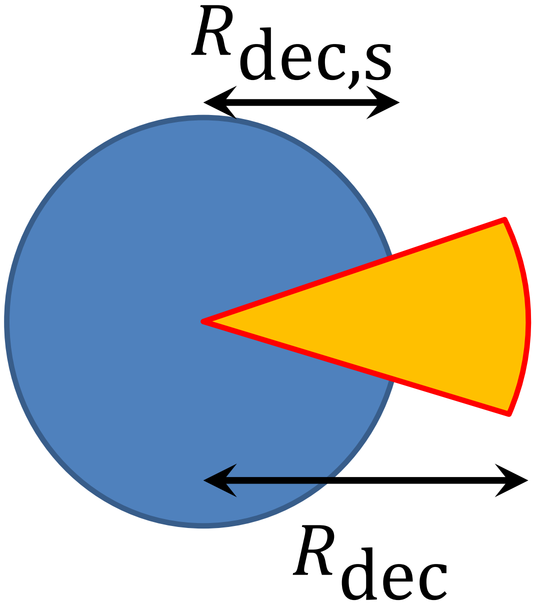
$R_{\mathrm{dec,s}} \sim \left(3M_{\mathrm{ej}}/4\pi m_{\mathrm{p}} n_{\mathrm{H}}\right)^{1/3} \sim 0.7\mathrm{pc}$

$t_{\mathrm{dec,s}} \sim R_{\mathrm{dec,s}}/v \sim 7\mathrm{yr}$

For crescent-like BH-NS ejecta

$R_{\mathrm{dec}} \sim 1.7\mathrm{pc}\, \theta_{\mathrm{ej},1/5}{}^{-1/3} \varphi_{\mathrm{ej},\pi}{}^{-1/3}$

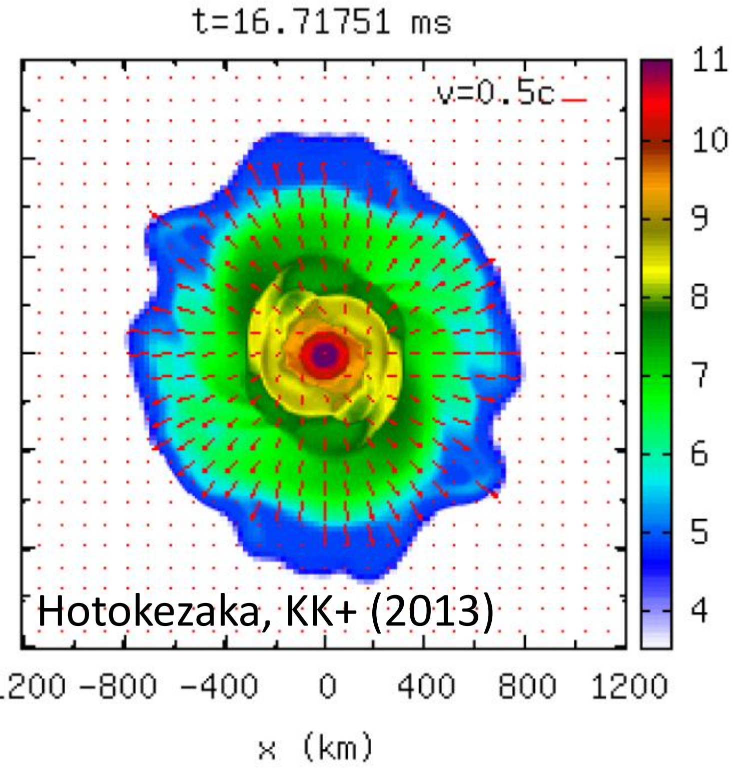
$t_{\mathrm{dec}} \sim 18\mathrm{yr}\, \theta_{\mathrm{ej},1/5}{}^{-1/3} \varphi_{\mathrm{ej},\pi}{}^{-1/3}$



Proper motion of radio images

Typical proper motion in terms of the angle

$$v_{\mathrm{ej}} t_{\mathrm{dec}} / D \sim 1\mathrm{pc}/100\mathrm{Mpc} \sim 1\mathrm{mas}$$



Hotokezaka, KK+ (2013)

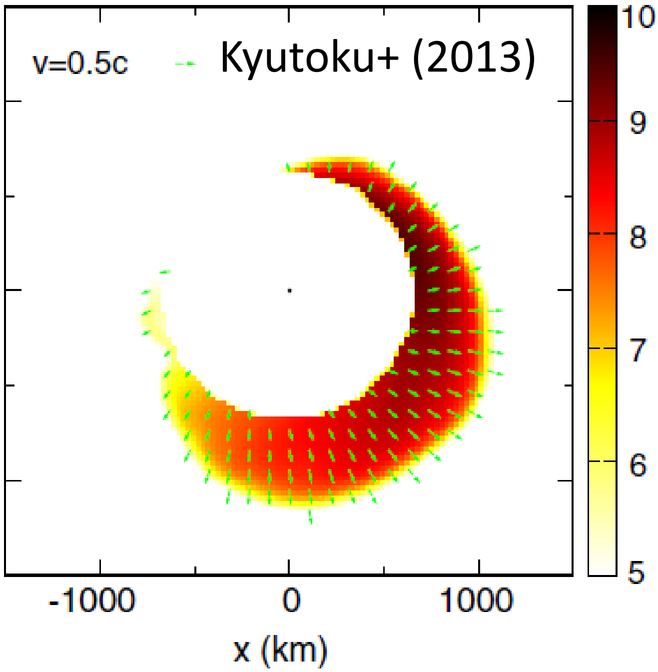
resolvable by radio instruments?

both images

expand in time

but only BH-NS

moves in time

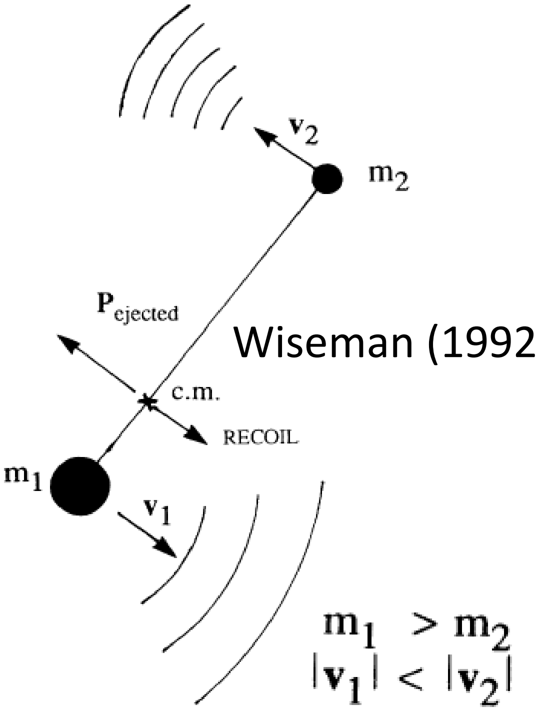


Kyutoku+ (2013)

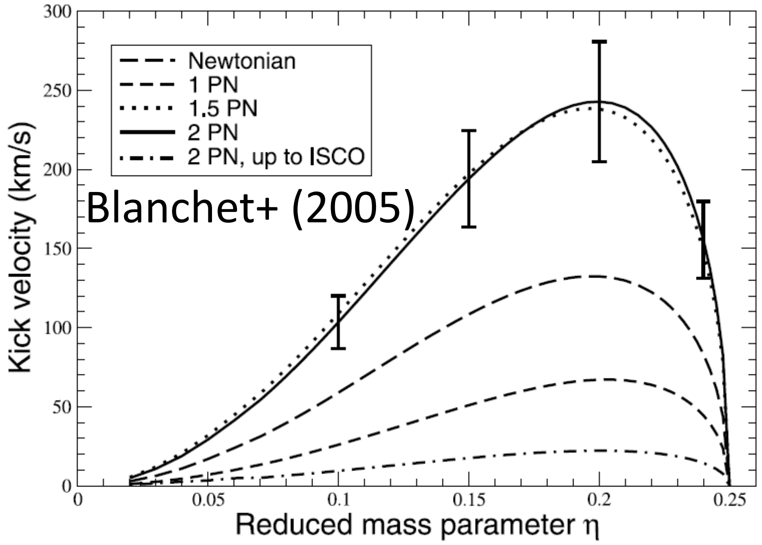
Possible explanation

Opposite motion of the ejecta <-> plunge material

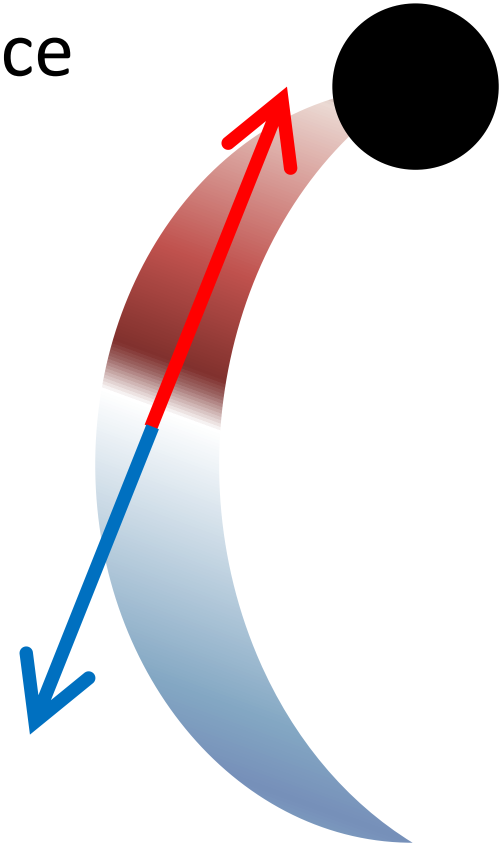
Plunge motion: fastest in the coalescence dominant to the recoil



Wiseman (1992)

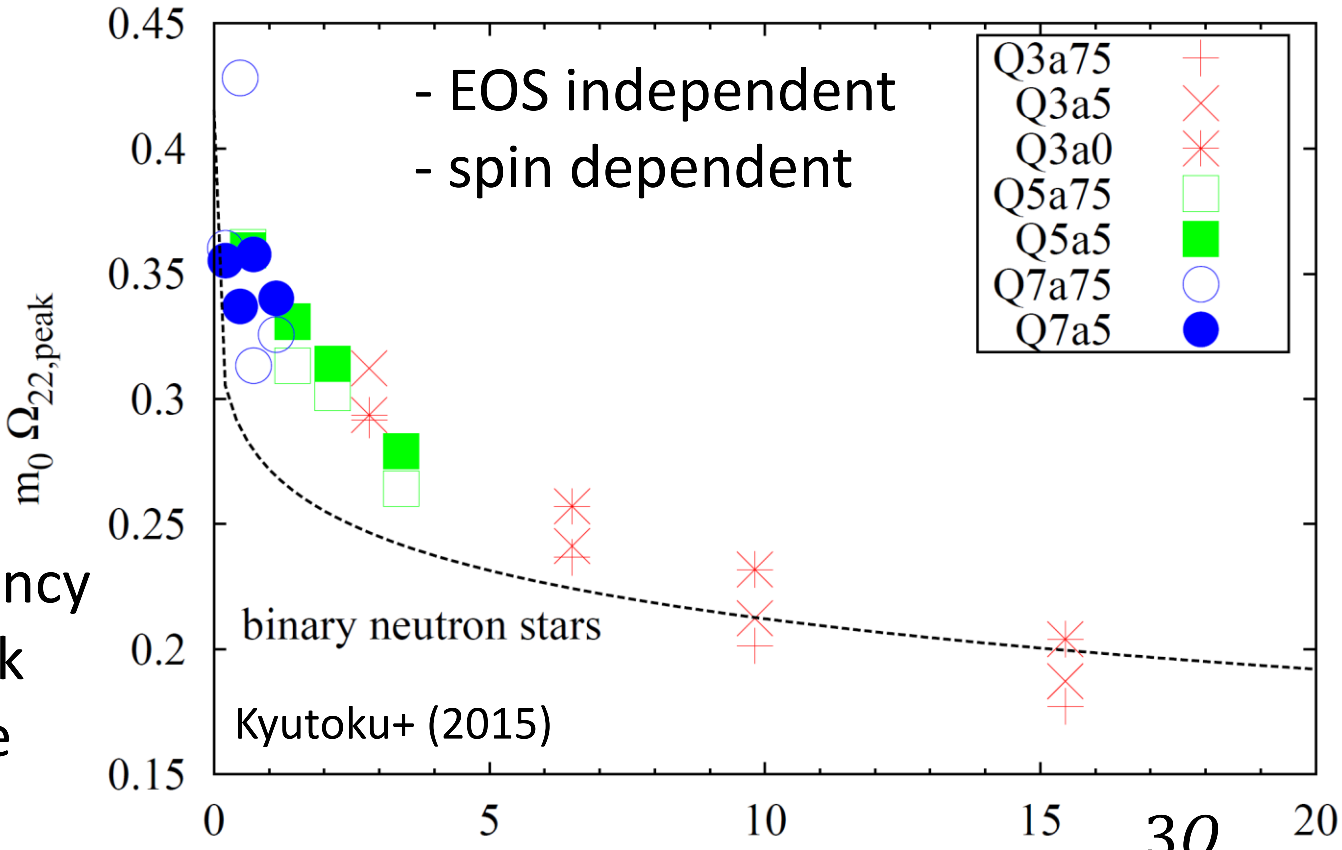


Blanchet+ (2005)



Quasiuniversal relation

Might differ from NS-NS relations (Read, KK+ 2013)



- EOS independent
- spin dependent

Kyutoku+ (2015)

GW frequency at the peak amplitude

tidal coupling constant $\kappa \equiv \frac{3Q}{(1+Q)^5}\Lambda$

GW memory

In addition to nonlinear and GRB jet memory

“ejecta memory” by $M_{\rm ej}\sim 0.01-0.1M_\odot, v_{\rm ej}\sim 0.2c$

$$\delta h\sim\frac{2M_{\rm ej}{v_{\rm ej}}^2}{D}\sim 10^{-24}\left(\frac{M_{\rm ej}}{0.03M_\odot}\right)\left(\frac{v_{\rm ej}}{0.2c}\right)^2\left(\frac{D}{100{\rm Mpc}}\right)^{-1}$$

Detectable by ET for massive ejecta with $\geq 0.1M_\odot$

Former two are weak along the rotational axis

Ejecta memory is strongest along this axis