Dynamical mass ejection from black hole-neutron star binaries

Koutarou Kyutoku RIKEN, iTHES

KK, K. Ioka, M. Shibata, PRD 88 (2013) 041502(R)

K. Kawaguchi, KK, et al., PRD 92 (2015) 024014

KK, K. Ioka, H. Okawa, M. Shibata, K. Taniguchi, PRD 92 (2015) 044028

K. Kawaguchi, KK, M. Shibata, M. Tanaka, ApJ 825 (2016) 52

KK, K. Kiuchi, Y. Sekiguchi, M. Shibata, K. Taniguchi, in preparation

Plan of the talk

1. Introduction
2. Study in hydrodynamics
3. Study in neutrino-radiation hydrodynamics
4. Future direction and summary

Prefetch: Summary

- Black hole-neutron star binary mergers can eject $\sim 0.01 - 0.1 M_\odot$ with $\sim 0.2 - 0.3c$ dynamically in a highly anisotropic manner for various cases.
- The electron fraction of dynamical ejecta is low because they do not experience shock heating.
- Neutrinos are not important for dynamical mass ejection and do not drive a strong disk wind.
- Other disk winds could dominate mass ejection and require more investigation.

1. Introduction

Why do we investigate BH-NS?

- Gravitational-wave astronomy

accessible to a larger distance than with NS-NS

- Short-hard gamma-ray burst

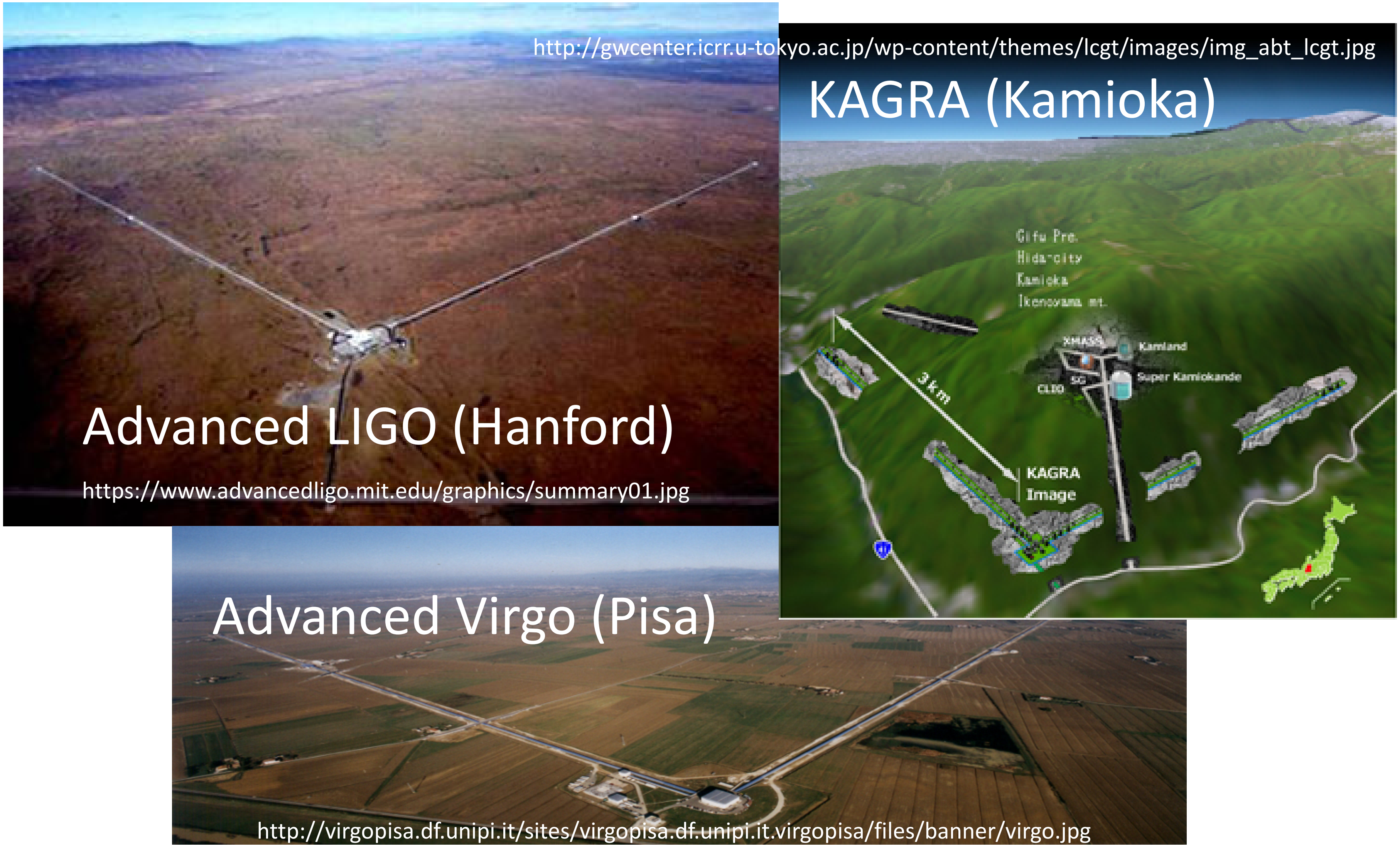
many possibilities from the BH mass/spin diversity?

- Mass ejection and electromagnetic counterpart

r-process nucleosynthesis

macronova/kilonova, synchrotron radio flare, …

Gravitational-wave detector



http://gwcenter.icrr.u-tokyo.ac.jp/wp-content/themes/lcgt/images/img_abt_lcgt.jpg

KAGRA (Kamioka)

Advanced LIGO (Hanford)

https://www.advancedligo.mit.edu/graphics/summary01.jpg

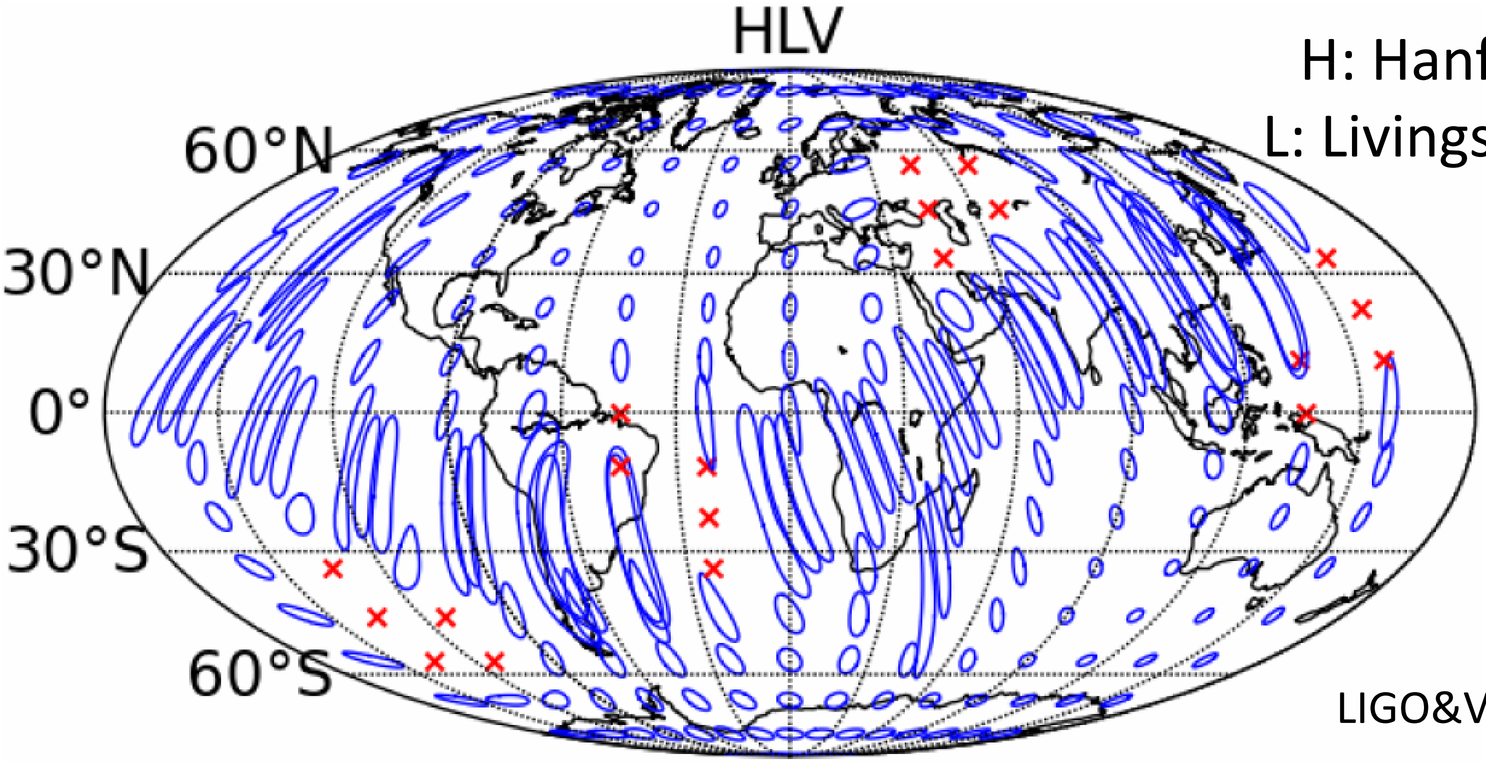
Advanced Virgo (Pisa)

http://virgopisa.df.unipi.it/sites/virgopisa.df.unipi.it.virgopisa/files/banner/virgo.jpg

Poor gravitational-wave localization

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

-> need EM counterparts for accurate localization



H: Hanford LIGO
L: Livingston LIGO
V: Virgo

LIGO&Virgo (2013)

Are BH-NS promising targets?

- No observed black hole-neutron star binaries

 - a Be/X-ray binary MWC 656 may be a progenitor

- If many massive black holes exist, gravitational waves are more frequent for BH-NS than NS-NS

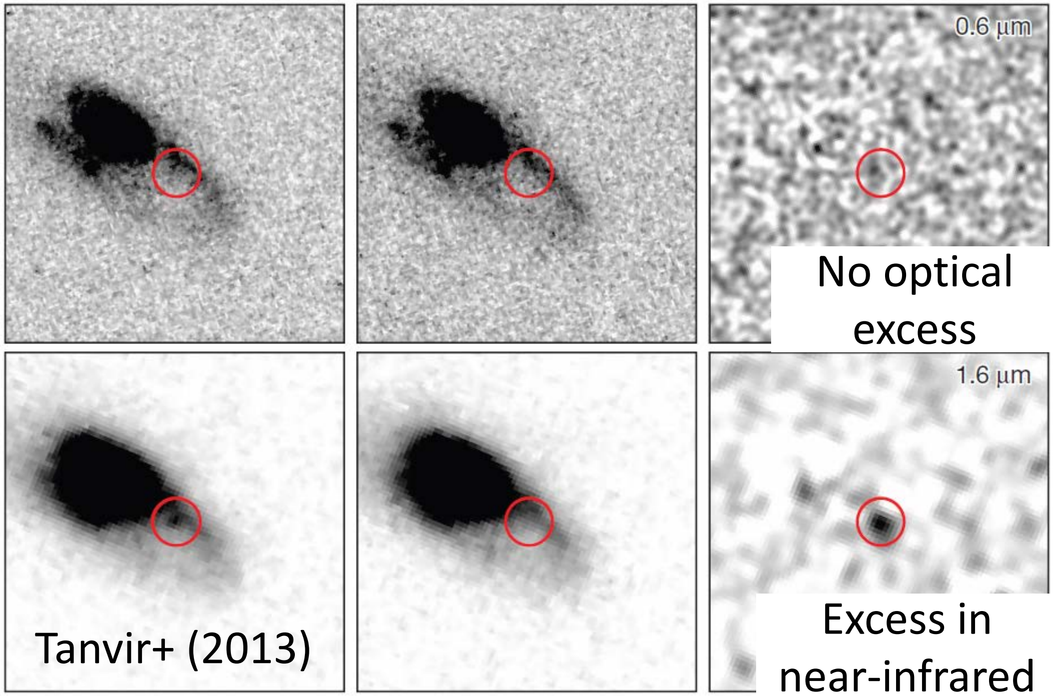
 - LIGO O2 will tell us the answer

 - but if the black hole is massive, the neutron star is not likely to be disrupted for most parameters, and such binaries may not be interesting as a target of electromagnetic counterpart searches

Near-infrared excess of GRB 130603B

$M_{\mathrm{ej}} = 0.02 \sim 0.1 M_{\odot}$ may be required … BH-NS?

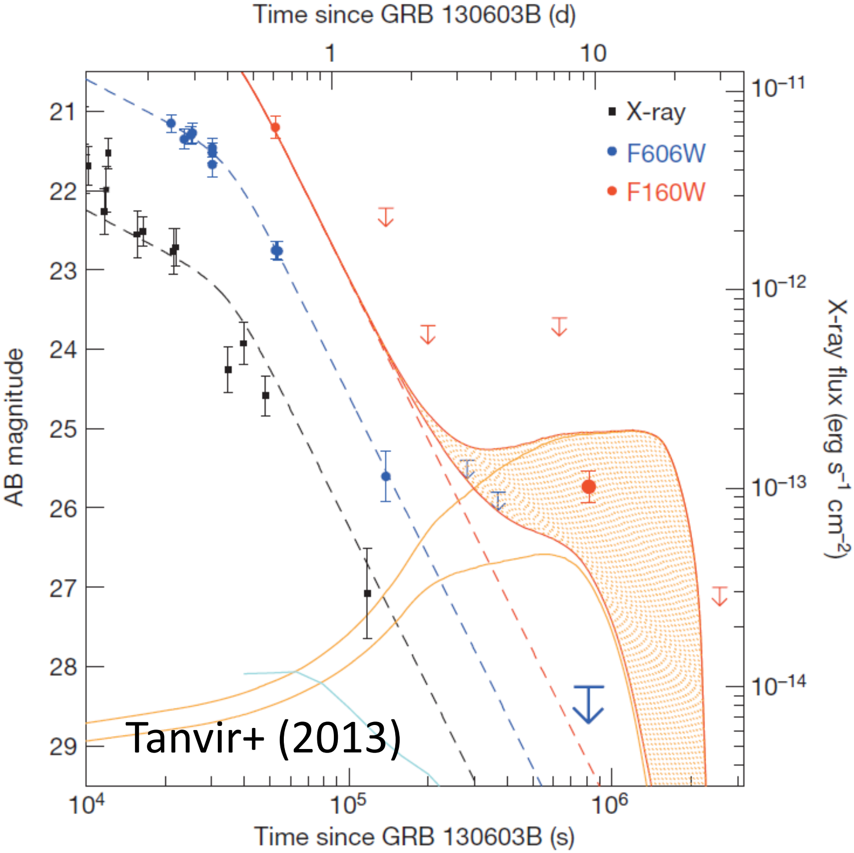
9day (event?) – 30day (background) = Excess brightening



No optical excess

Excess in near-infrared

Tanvir+ (2013)



Tanvir+ (2013)

Channel of mass ejection

Dynamical mass ejection

gravity+pure hydrodynamics may be sufficient

(we explicitly confirm this expectation later)

sometimes obviously dominates disk activity

Disk activity = disk wind

- nuclear heating, viscous heating
- magnetically driven wind (cf Kiuchi+KK+ 2015)
- neutrino driven wind (Kyutoku+ in prep.)

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?

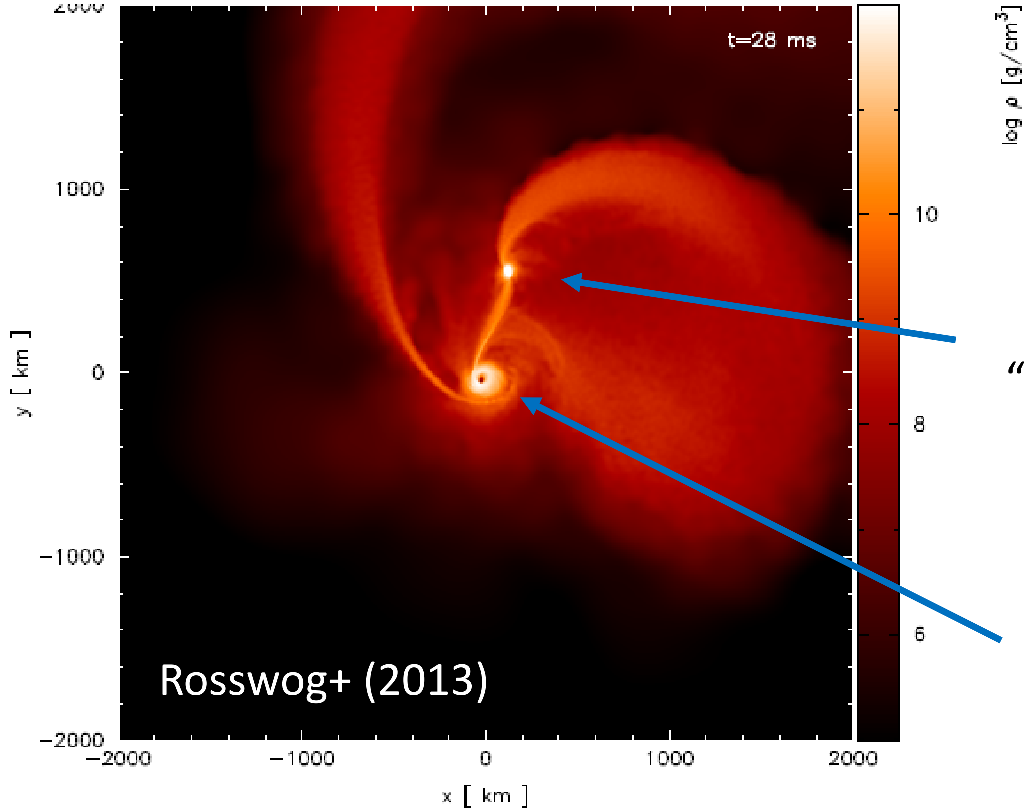
- What are features of associated electromagnetic counterparts? (not to discuss in detail today)

Numerical-relativity simulations will give answers

Newtonian BH-NS simulation

Episodic (repeated stable) mass transfer

qualitatively different from full GR results



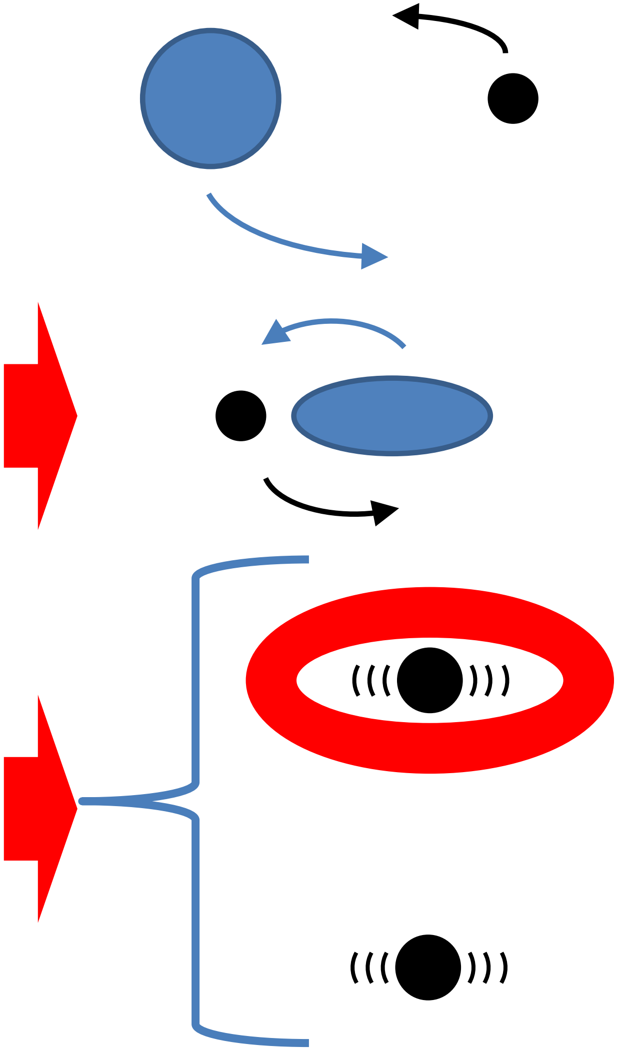
Rosswog+ (2013)

“mini neutron star”

BH-disk

2. Study in hydrodynamics

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

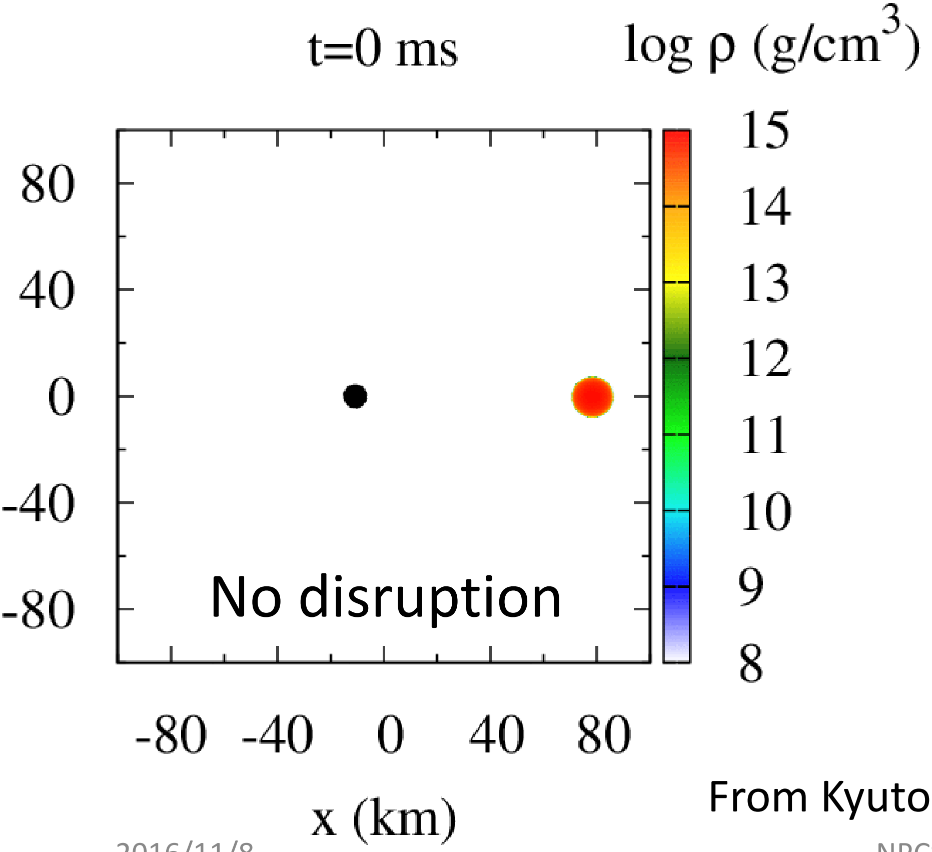
mass ejection, disk formation…

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

Movies for two cases (6.75Mo BH)

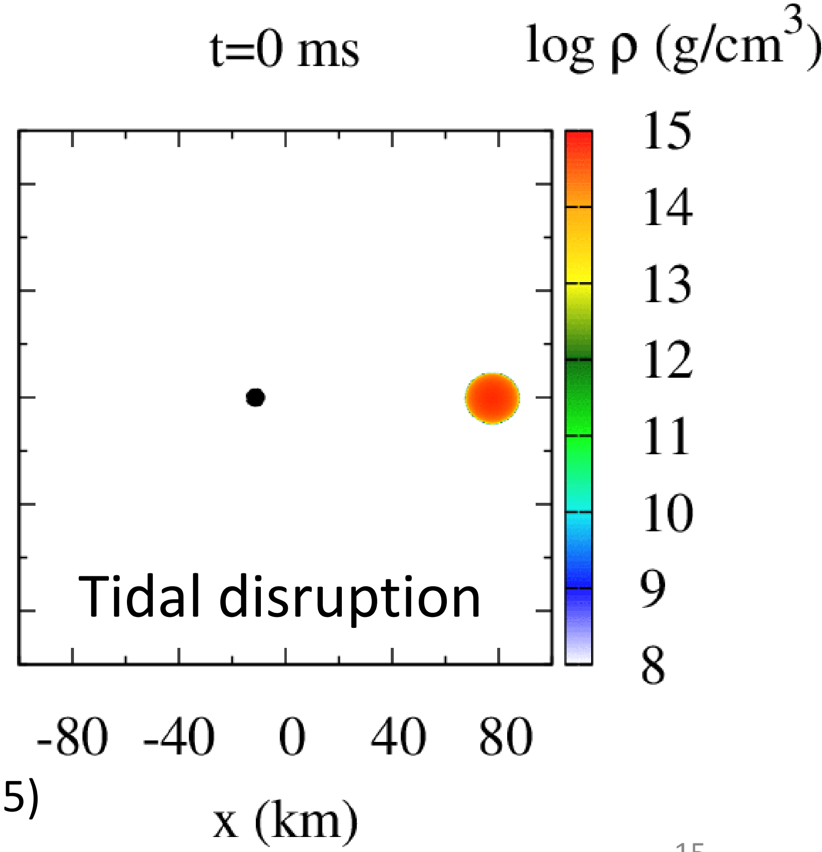
NS radius 11.1km

BH spin 0.5



NS radius 13.6km

BH spin 0.75



From Kyutoku+ (2015)

Mass shedding condition

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

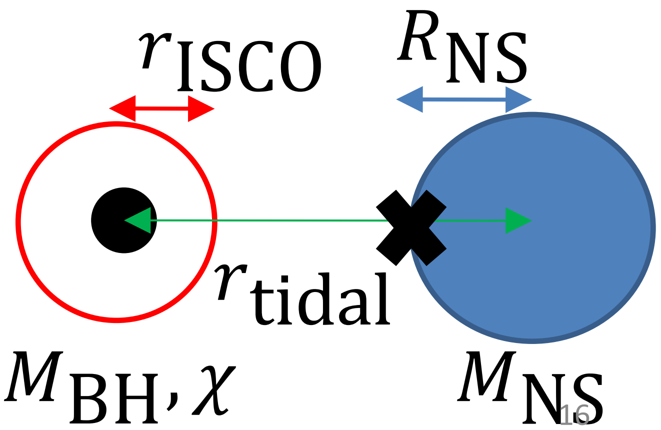
$$\frac{M_{\mathrm{BH}}R_{\mathrm{NS}}}{r_{\mathrm{tidal}}{}^{3}} \sim \frac{M_{\mathrm{NS}}}{R_{\mathrm{NS}}{}^{2}} \Rightarrow r_{\mathrm{tidal}} \sim M_{\mathrm{BH}}\left(\frac{M_{\mathrm{NS}}}{M_{\mathrm{BH}}}\right)^{2/3}\left(\frac{R_{\mathrm{NS}}}{M_{\mathrm{NS}}}\right)$$

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

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



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 $M_{\mathrm{NS}} = 1.35M_{\odot}$

NS radius $R_{\mathrm{NS}} = 11.1, 12.4, 13.6, 14.4\mathrm{km}$
piecewise polytrope (+ ideal-gas-like thermal part)

Mass ratio $Q = 3, 5, 7$ ($M_{\mathrm{BH}} = 4.05, 6.75, 9.45M_{\odot}$)
BH spin parameter $\chi = 0, 0.5, 0.75$ (prograde)

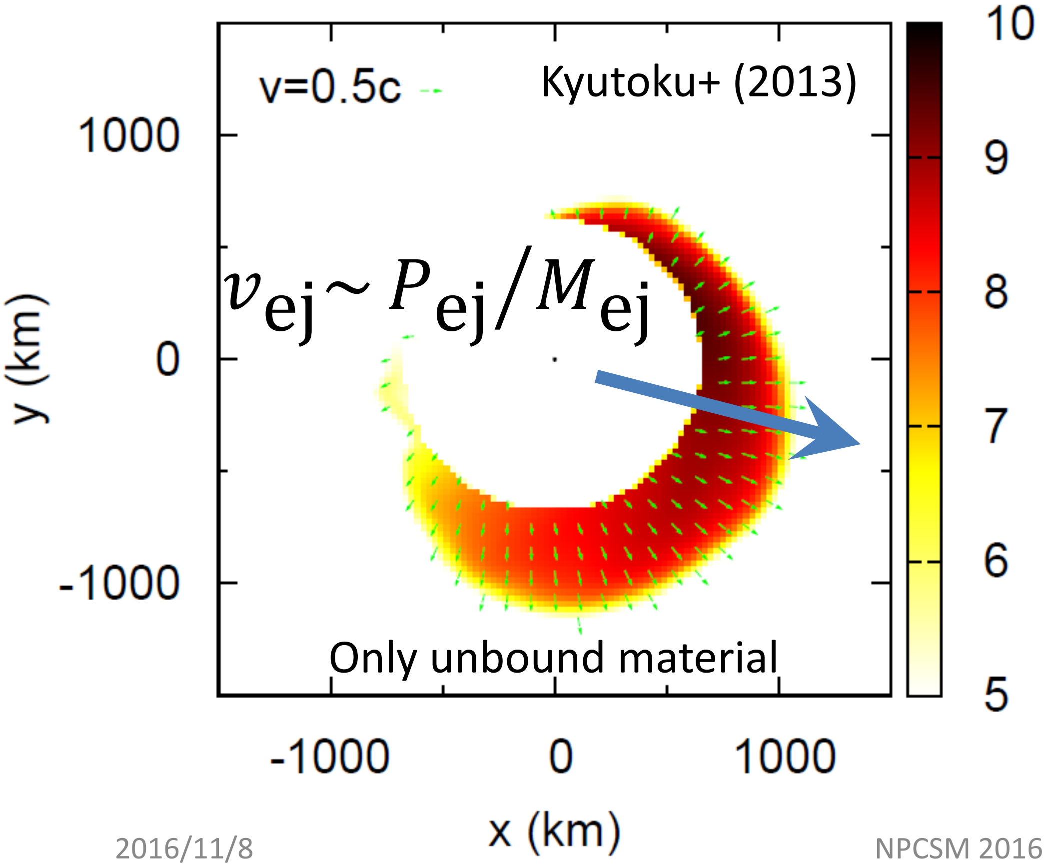
+ spin inclination $i = 30°, 60°, 90°$ available for $Q = 5, \chi = 0.75$ (Kawaguchi, KK+ 2015)

Movie

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

$(0\sim)0.08M_\odot$

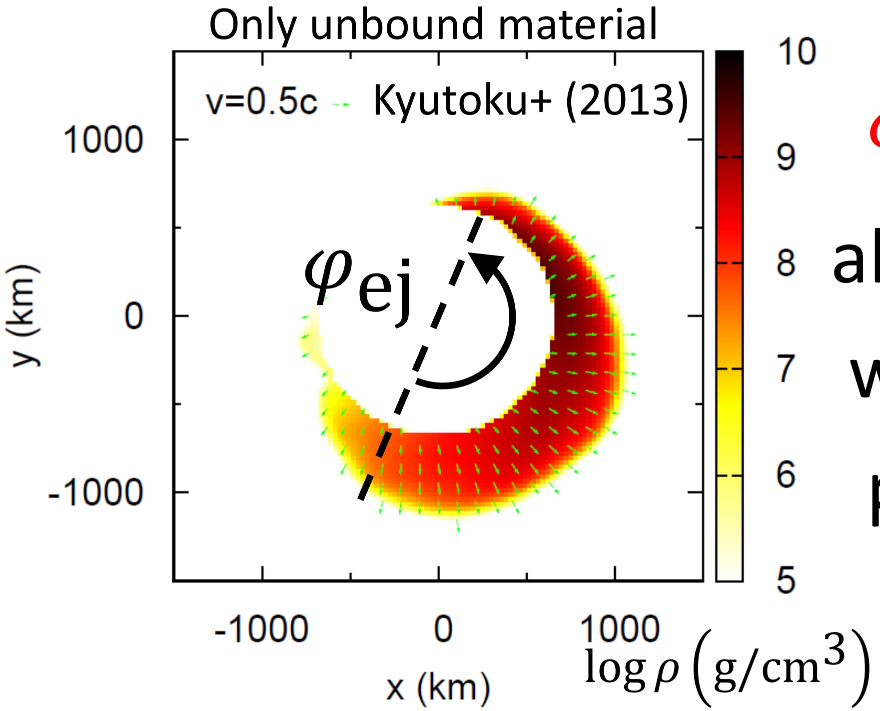
kinetic energy

$(0\sim)5\times10^{51}{\rm erg}$

“bulk” velocity

$v_{\rm ej}\sim0.1-0.2c$

Crescent-like ejecta anisotropy

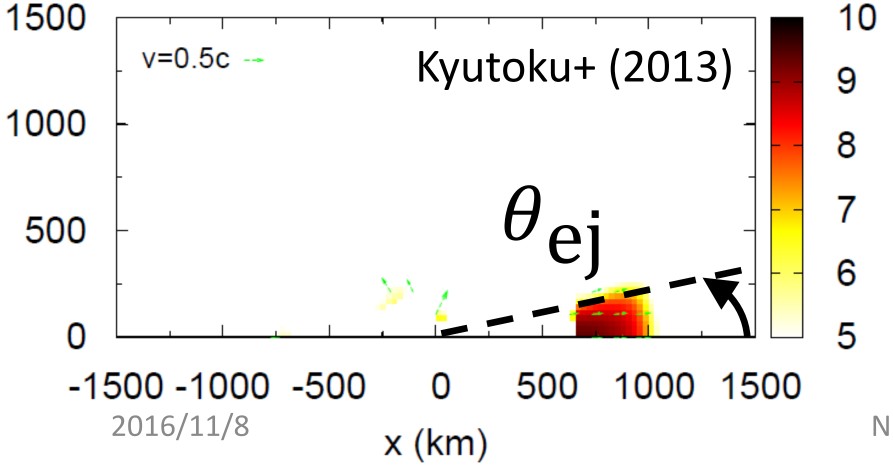

Only unbound material

$\varphi_{\mathrm{ej}} \approx 180°$

also can become $\sim 360°$

when tidal disruption is weak

probably periastron advance



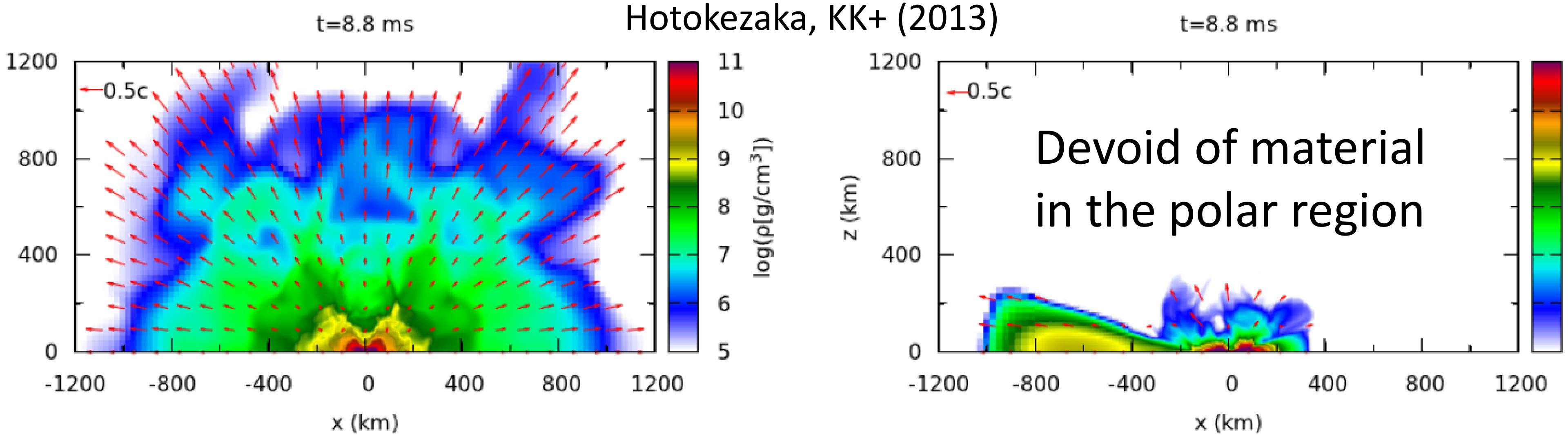
$\theta_{\mathrm{ej}} \approx 10° - 20°$

relatively universal

Comparison with NS-NS

Density profile in the meridional plane

Hotokezaka, KK+ (2013)



Devoid of material in the polar region

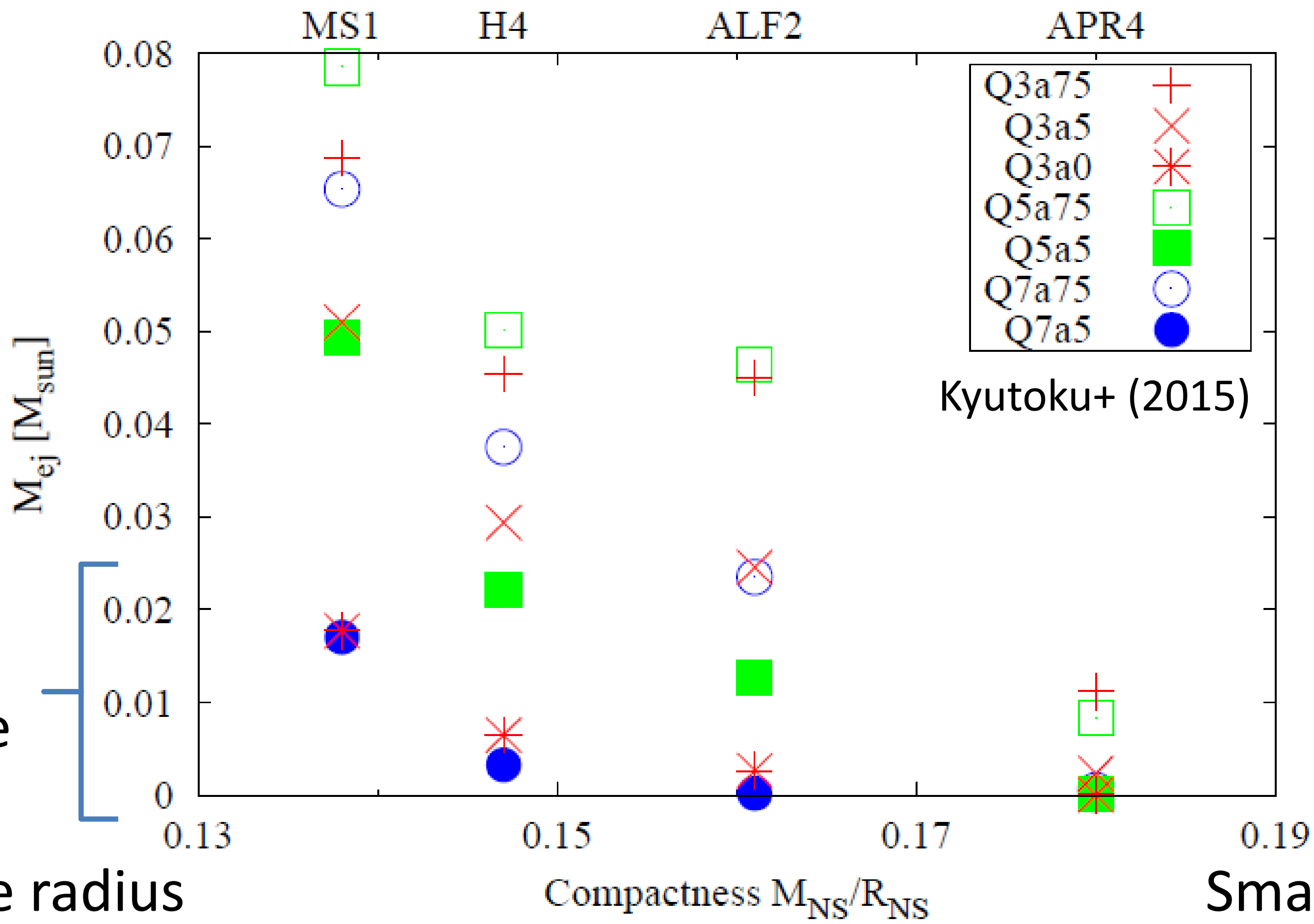
NS-NS: hypermassive NS

BH-NS: BH-disk

(but the reality depends on the disk wind)

Ejecta mass

The ejecta mass is large when the NS radius is large



Kyutoku+ (2015)

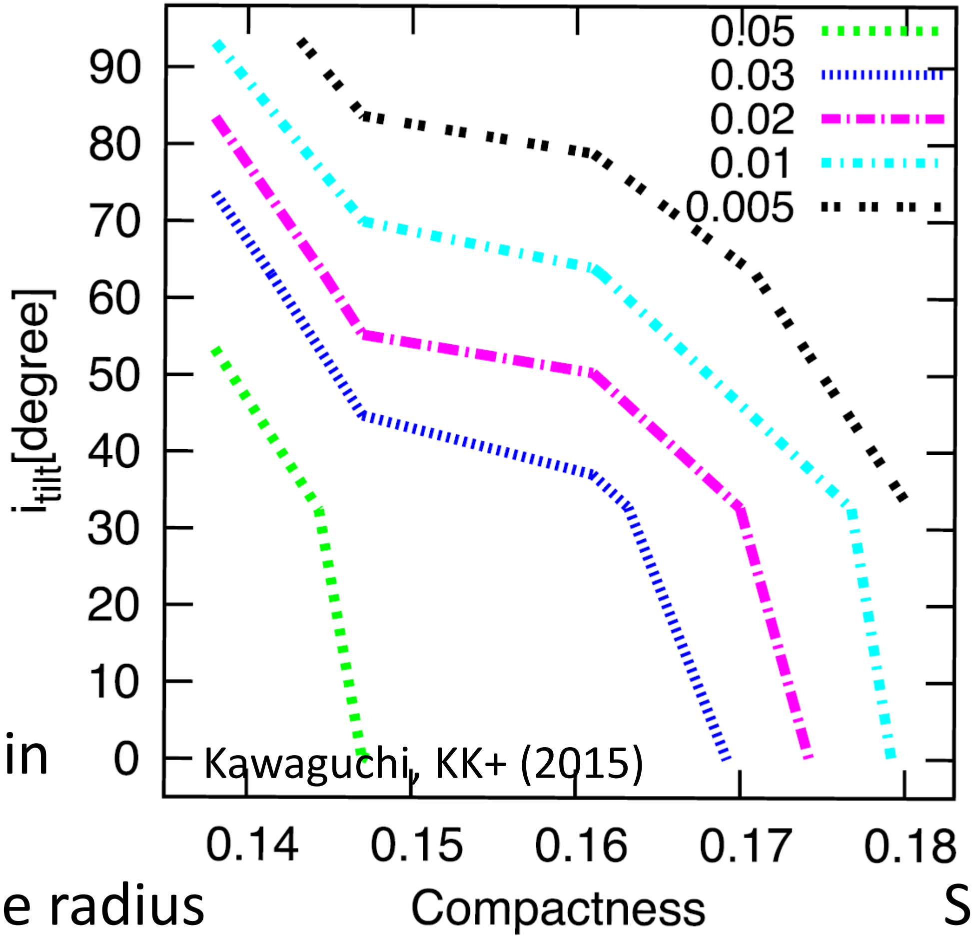
NS-NS range

Large radius

Small radius

Misaligned BH spin

Spin inclination decreases the ejecta mass



Kawaguchi, KK+ (2015)

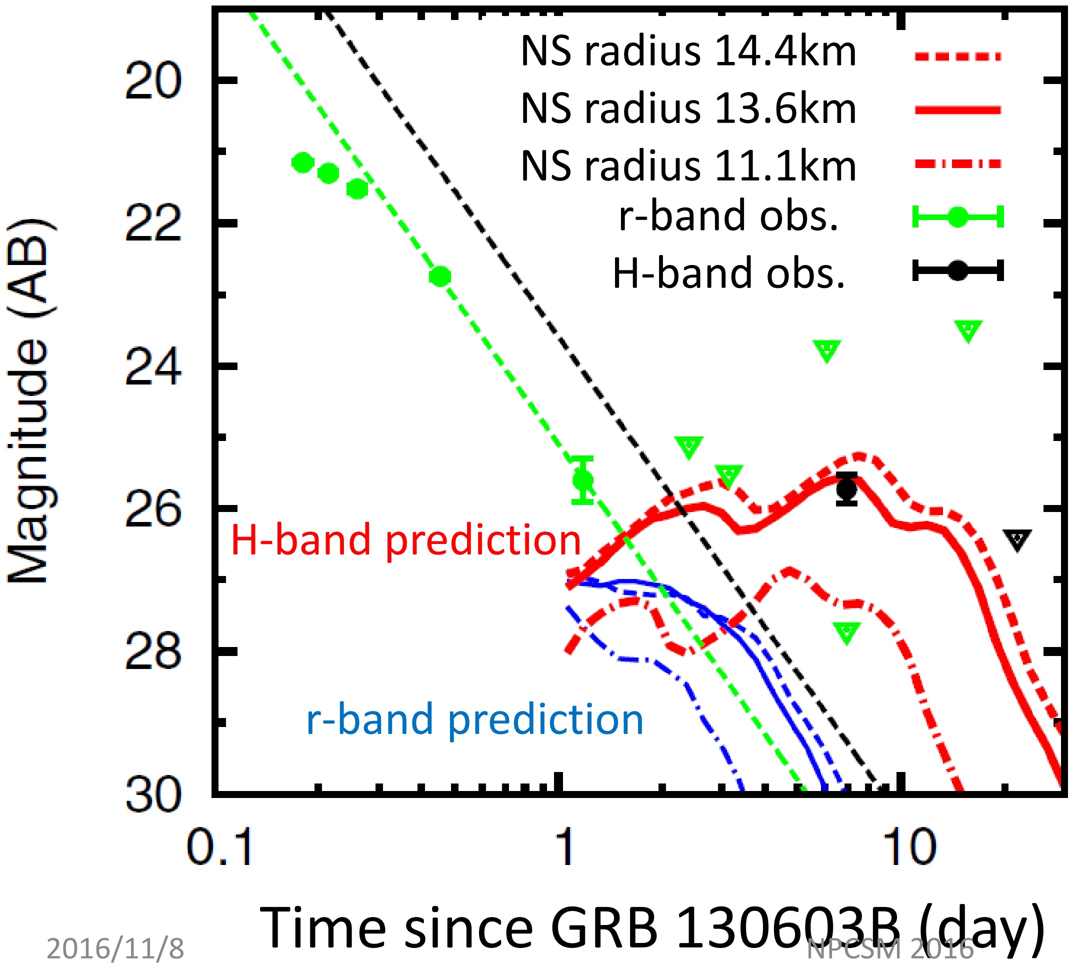
Aligned spin

Large radius

Small radius

Radiation transfer simulation

IR excess of GRB 130603B can be explained



promising as
EM counterparts
to observed GWs

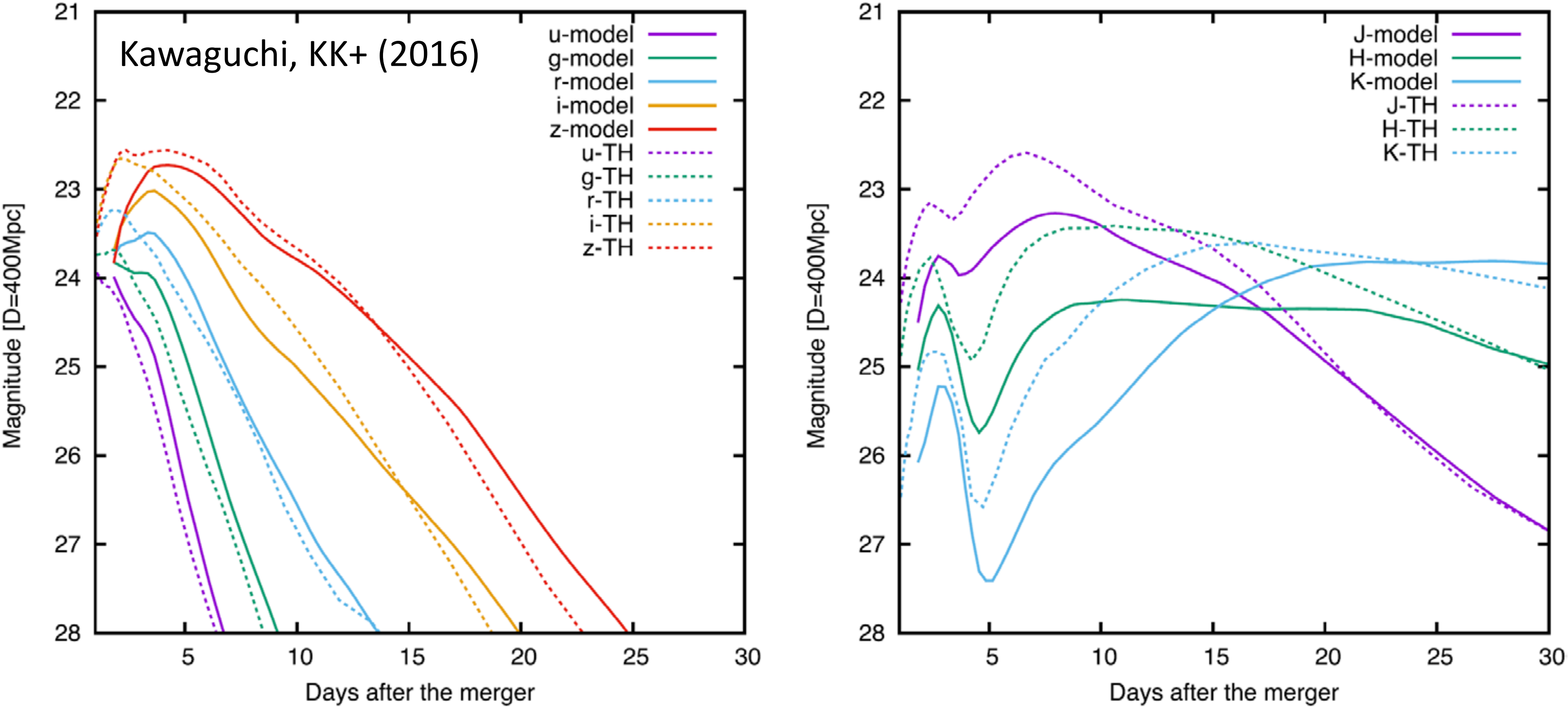
could indicate
r-process events?

Hotokezaka, KK+ (2013)

Phenomenological model

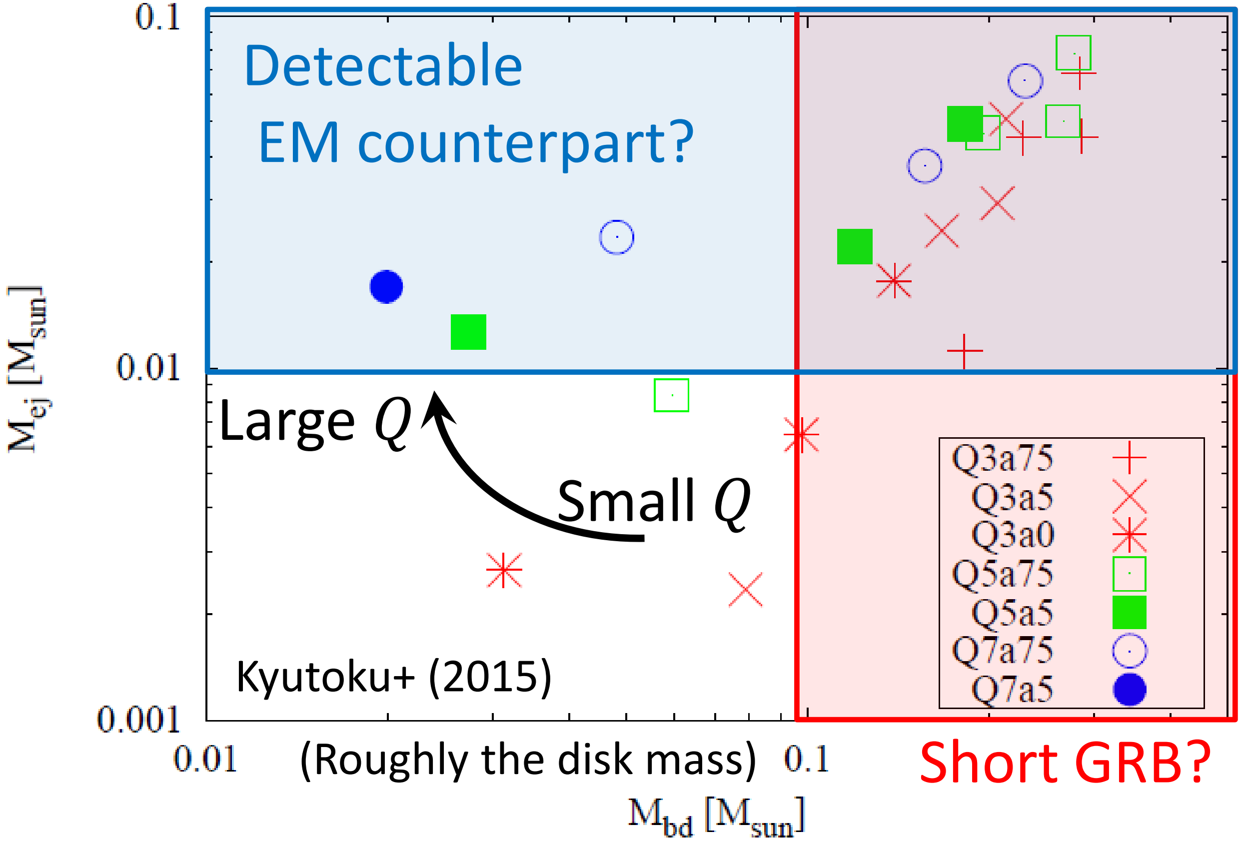
Ejecta mass/velocity, multiband light curve

http://www2.yukawa.kyoto-u.ac.jp/~kyohei.kawaguchi/kn_calc/main.html



Mass ratio dependence

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



Detectable EM counterpart?

Large Q

Small Q

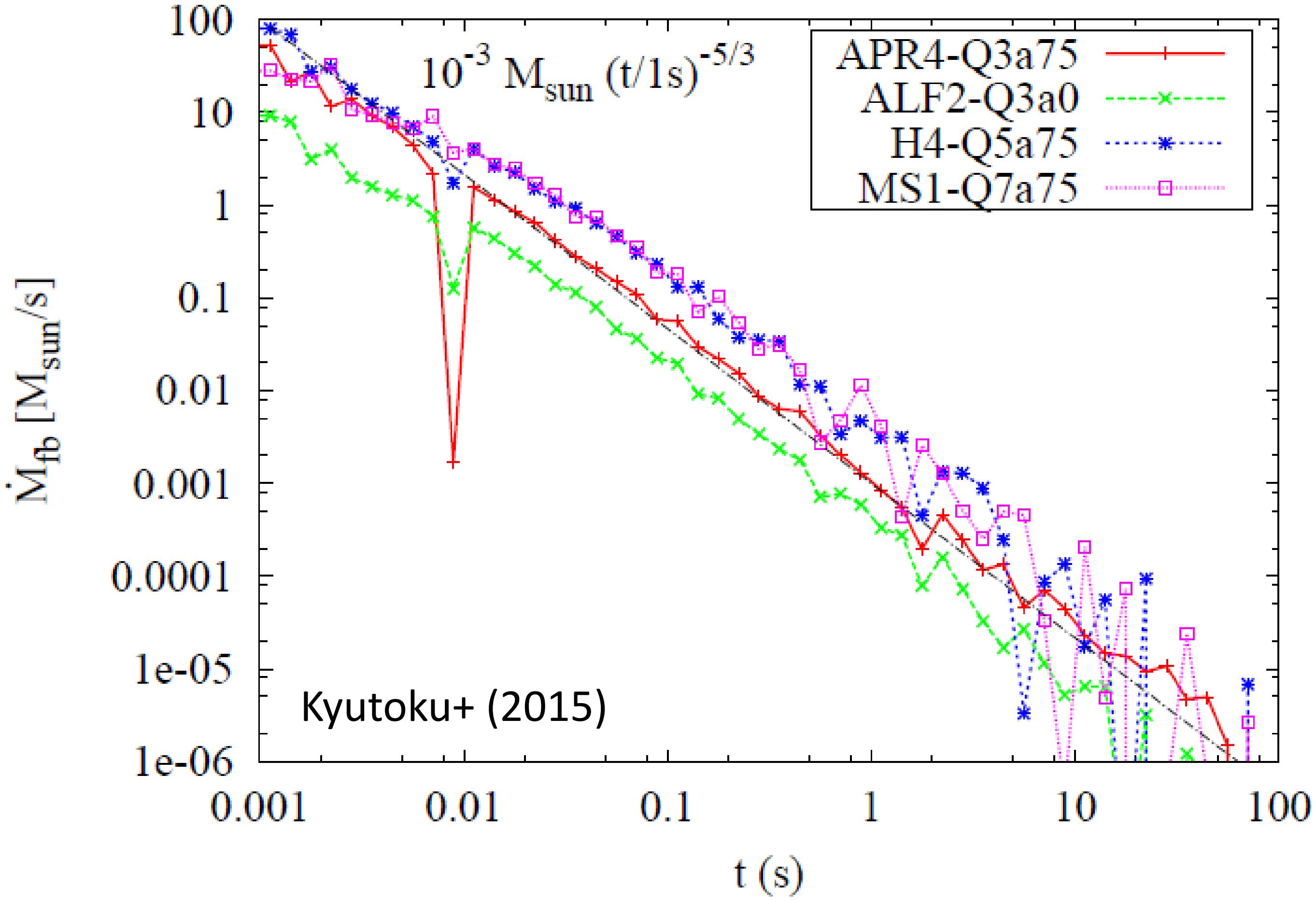
Kyutoku+ (2015)

(Roughly the disk mass)

Short GRB?

Fallback material

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

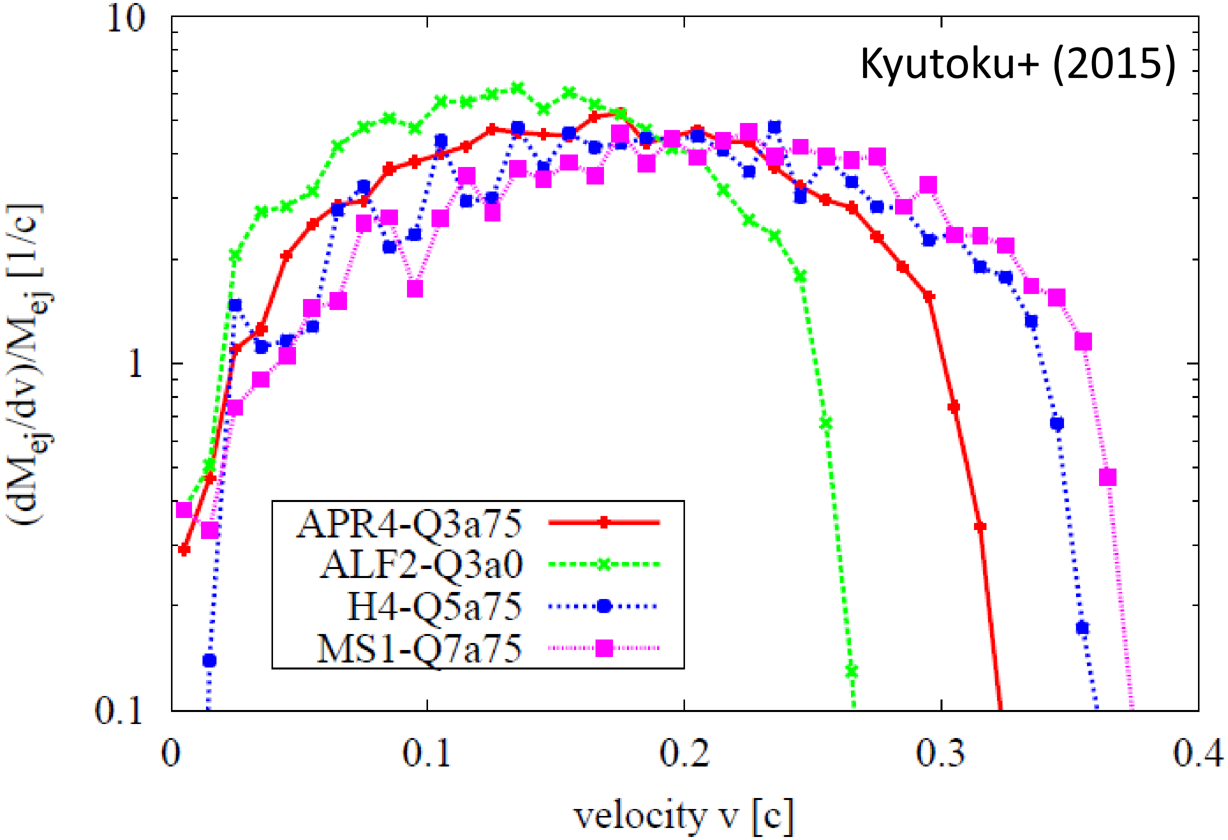


Kyutoku+ (2015)

Velocity distribution

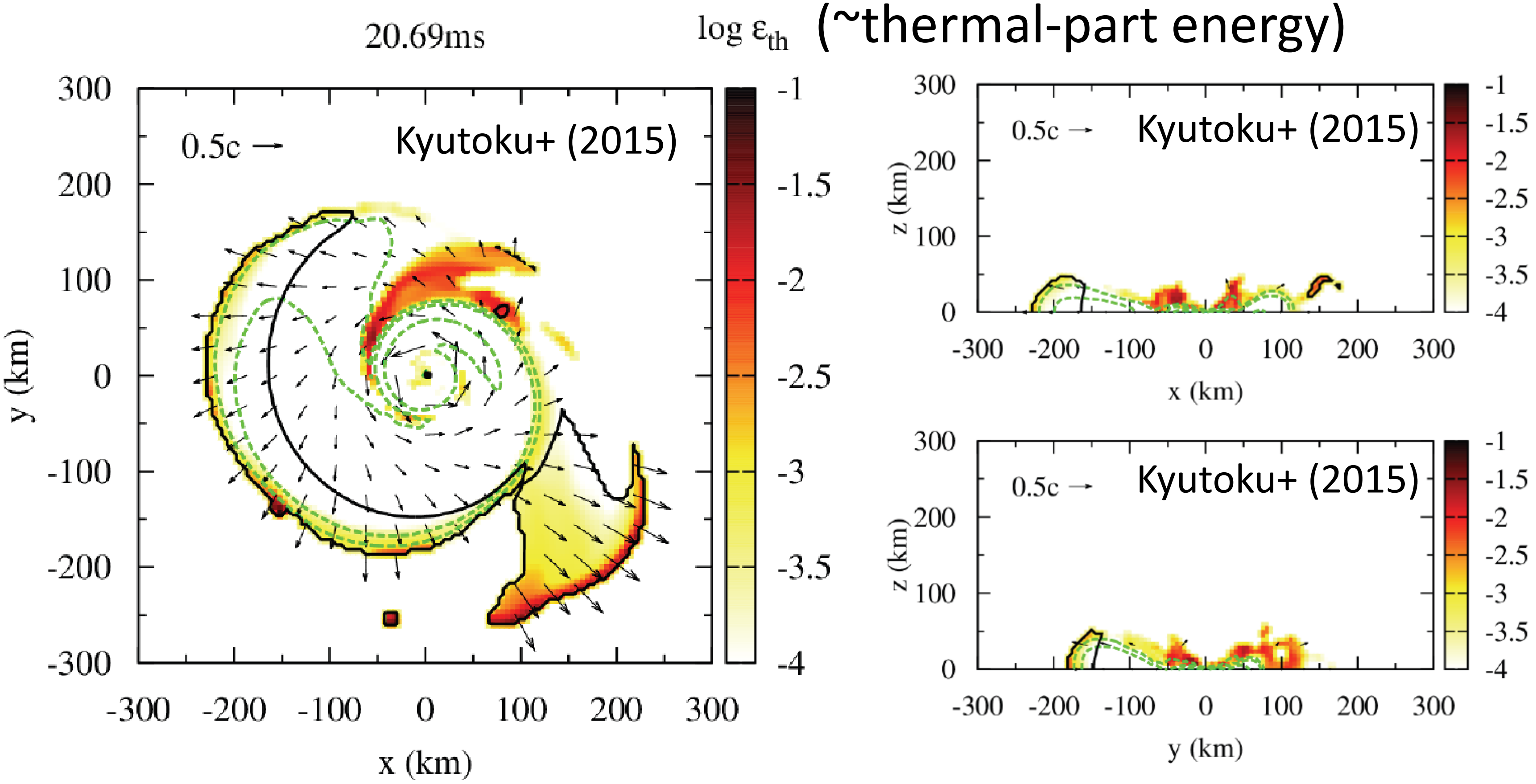
Relatively flat w/ cutoffs rather than a power law

seems to be flatter than that for NS-NS ejecta



BH-NS Ejecta is very cold

Because the ejecta experience no shock heating



(~thermal-part energy)

Kyutoku+ (2015)

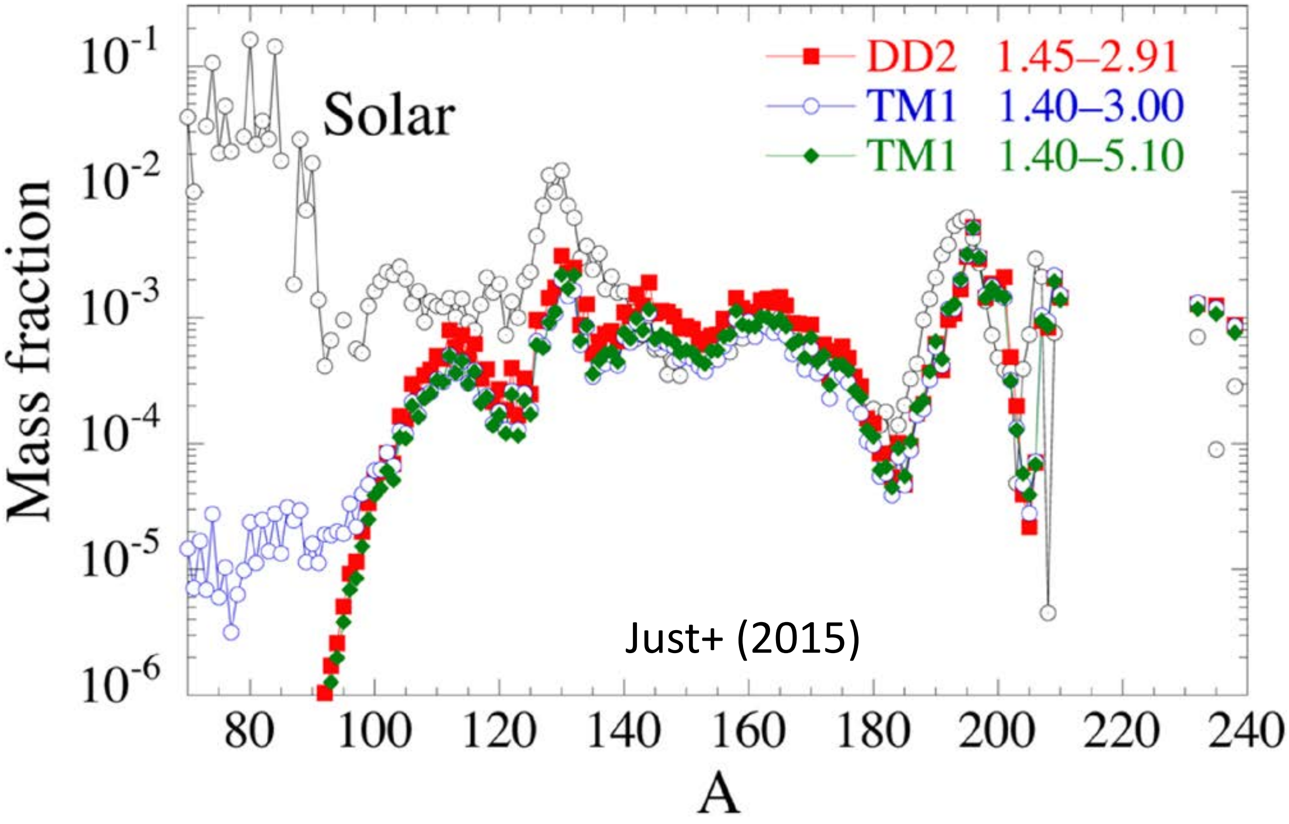
Kyutoku+ (2015)

Kyutoku+ (2015)

Expected nucleosynthetic yield

Significant fission cycling -> 2nd/3rd peak formation

- our own nuclear network calculations are ongoing

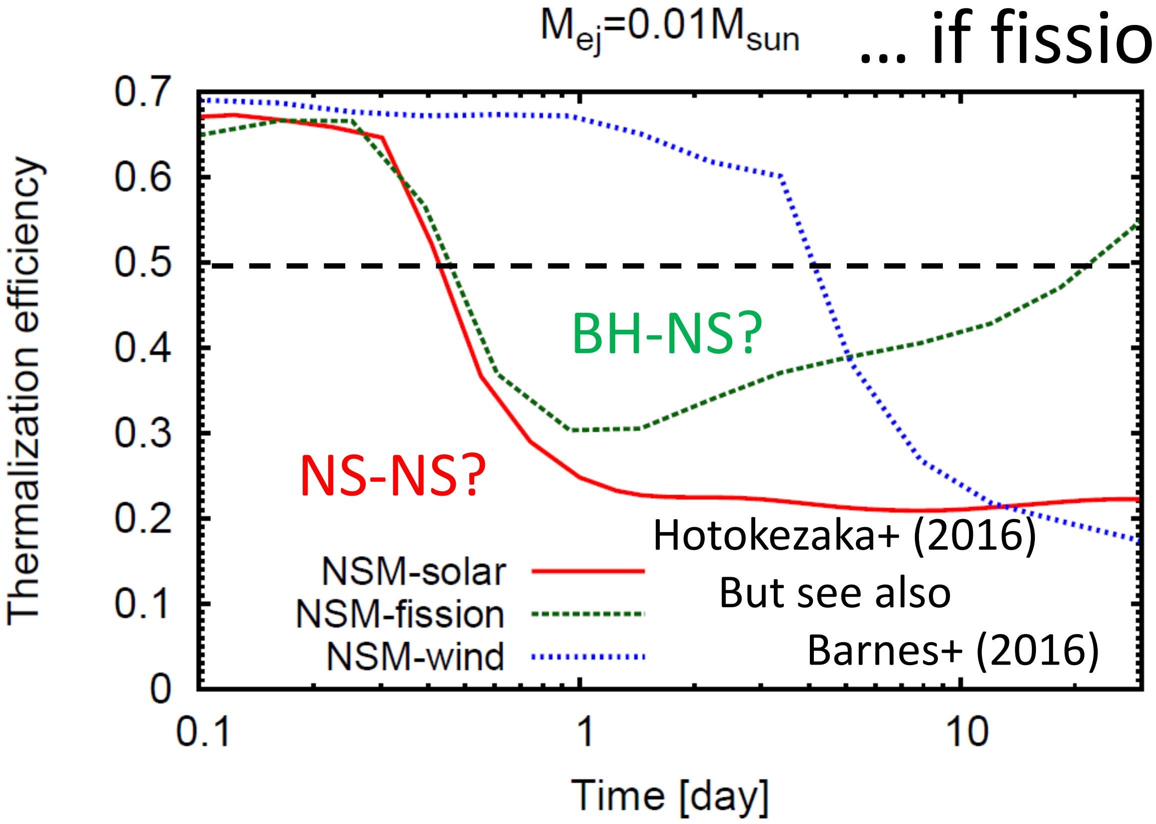


Just+ (2015)

Bright macronova/kilonova?

Heavy r-process elements may result in efficient, fission-dominated heating on a week time scale

... if fission occurs



BH-NS?

NS-NS?

Commonly adopted value

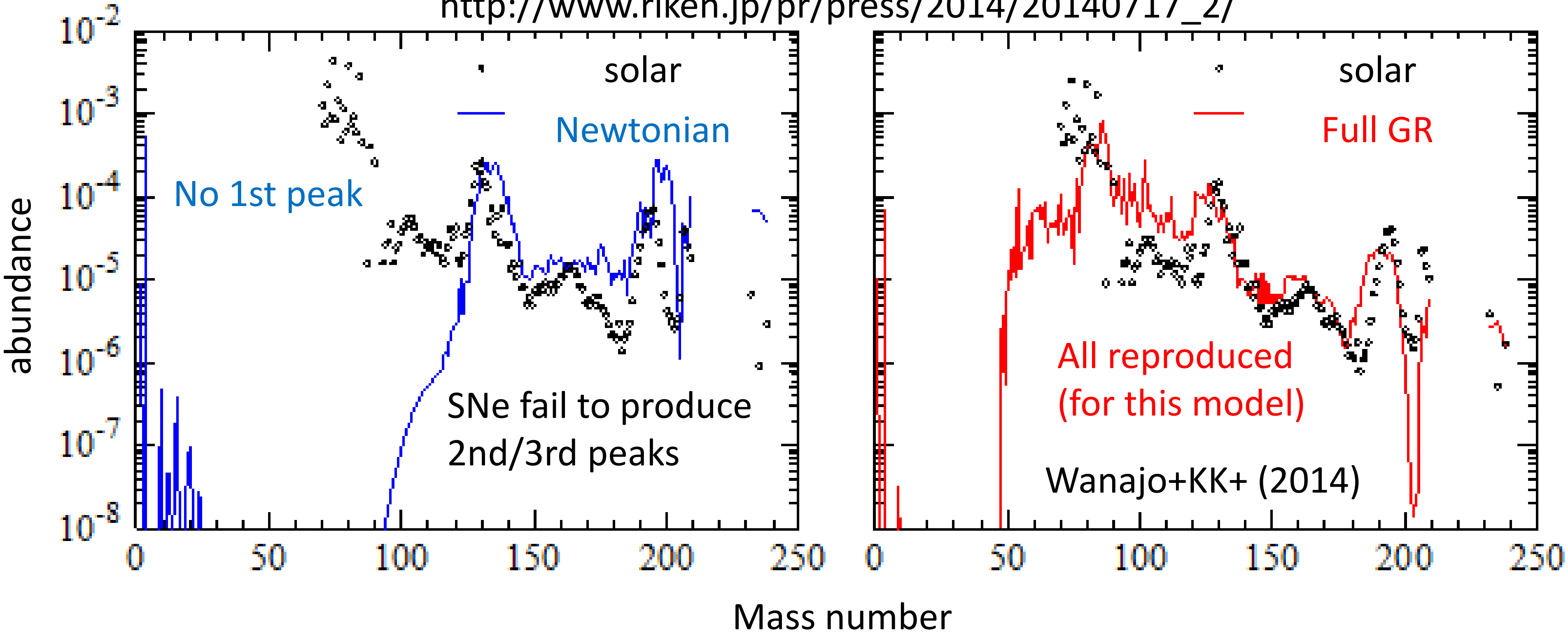
Hotokezaka+ (2016)

But see also Barnes+ (2016)

Lesson from binary neutron stars

Numerical relativity with neutrino transport could be crucial for reproducing r-process abundances

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



No 1st peak

SNe fail to produce 2nd/3rd peaks

All reproduced (for this model)

Wanajo+KK+ (2014)

3. Study in neutrino-radiation hydrodynamics

Necessity of neutrino transport

How do neutrinos affect the merger dynamics and mass ejection in black hole-neutron star mergers?

What is the electron fraction of the ejecta?

$Y_e \equiv n_e/n_B$: #electron per #baryon (p+n)

small Ye = neutron rich, <~0.1 for neutron stars

How bright is the neutrino emission? Flavors?

Is the neutrino-driven wind launched from the disk?

Numerical method

Einstein equation: BSSN formalism+puncture gauge

Radiation transfer (neutrino transport):

fully general-relativistic leakage scheme + heating

fluid+trapped ν: $\nabla_\beta T^{\alpha\beta} = -Q^\alpha_{\mathrm{cool}} + Q^\alpha_{\mathrm{heat}}$

Equation of state: tabulated finite-temperature EOS

streaming ν: $\nabla_\beta T^{\alpha\beta}_{\mathrm{S}} = Q^\alpha_{\mathrm{cool}} - Q^\alpha_{\mathrm{heat}}$

An M1 closure is applied to the streaming neutrino

Model parameters

We fix some parameters as $M_{\mathrm{NS}} = 1.35M_{\odot}$, $M_{\mathrm{BH}} = 5.4M_{\odot}$, $\chi = 0.75$ due to limitations

- systematic study is planned in the near future

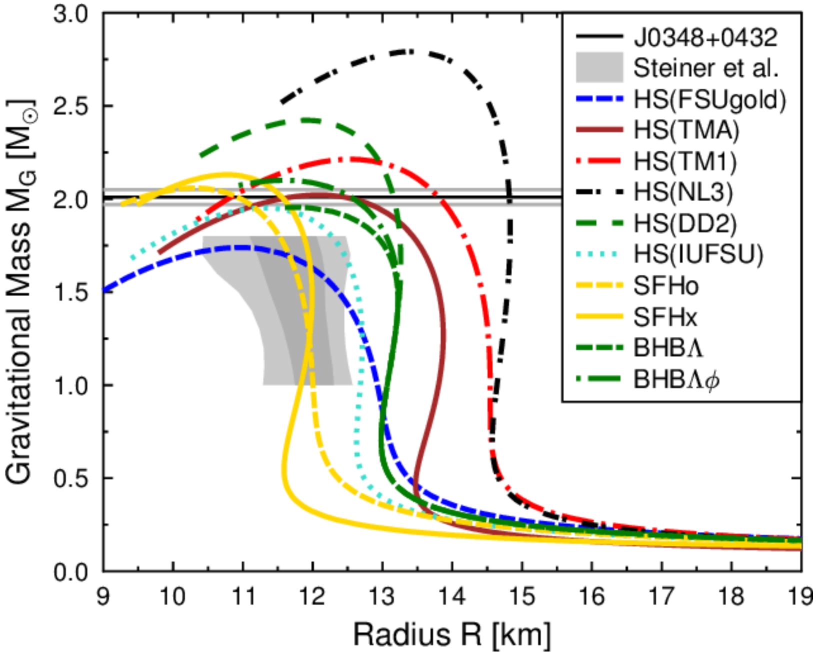
Equations of state are

chosen from 3 models

SFHo: 11.9km (soft)

DD2: 13.2km (middle)

TM1: 14.5km (stiff)

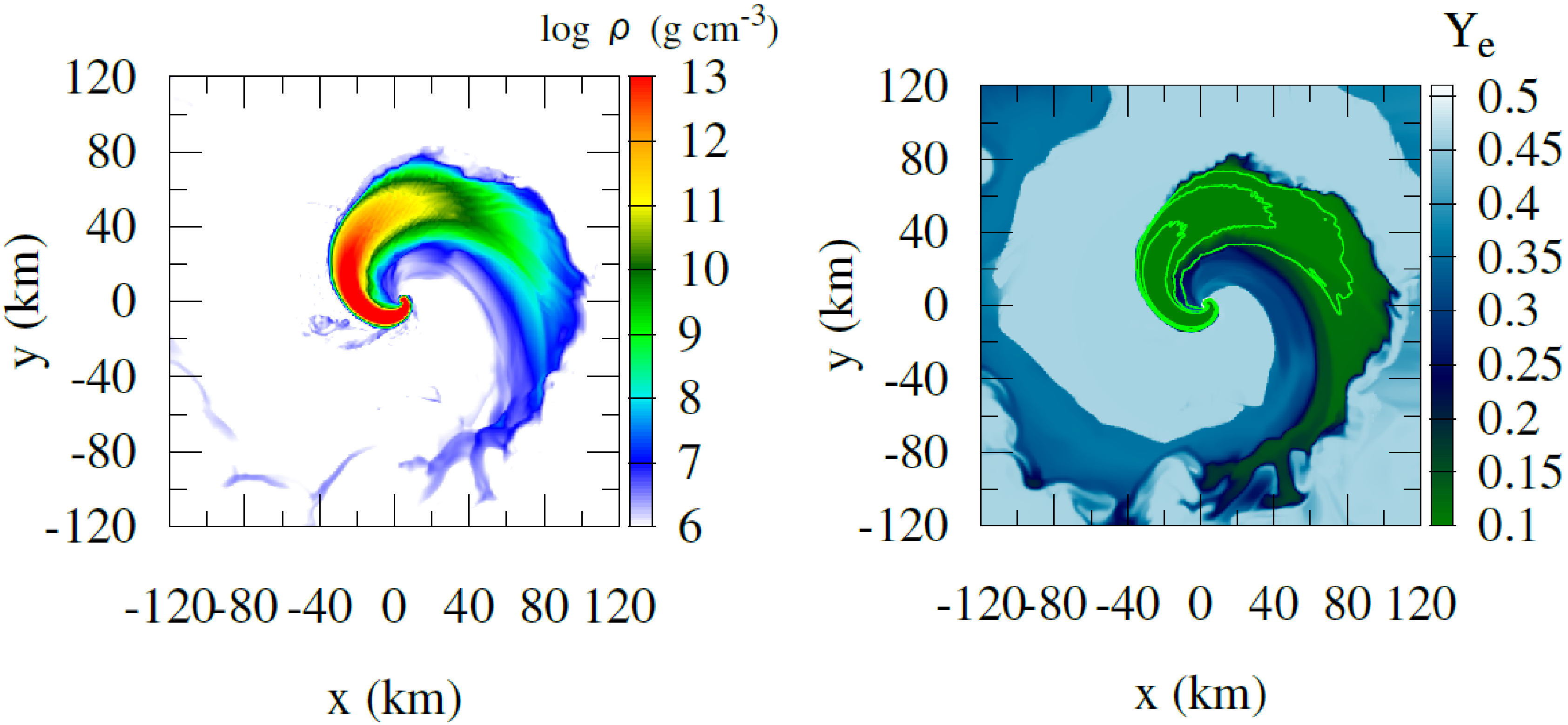


http://www.hou.usra.edu/meetings/gammaray2016/pdf/program.pdf

Overview of the merger dynamics

Similar to the results of hydrodynamics study

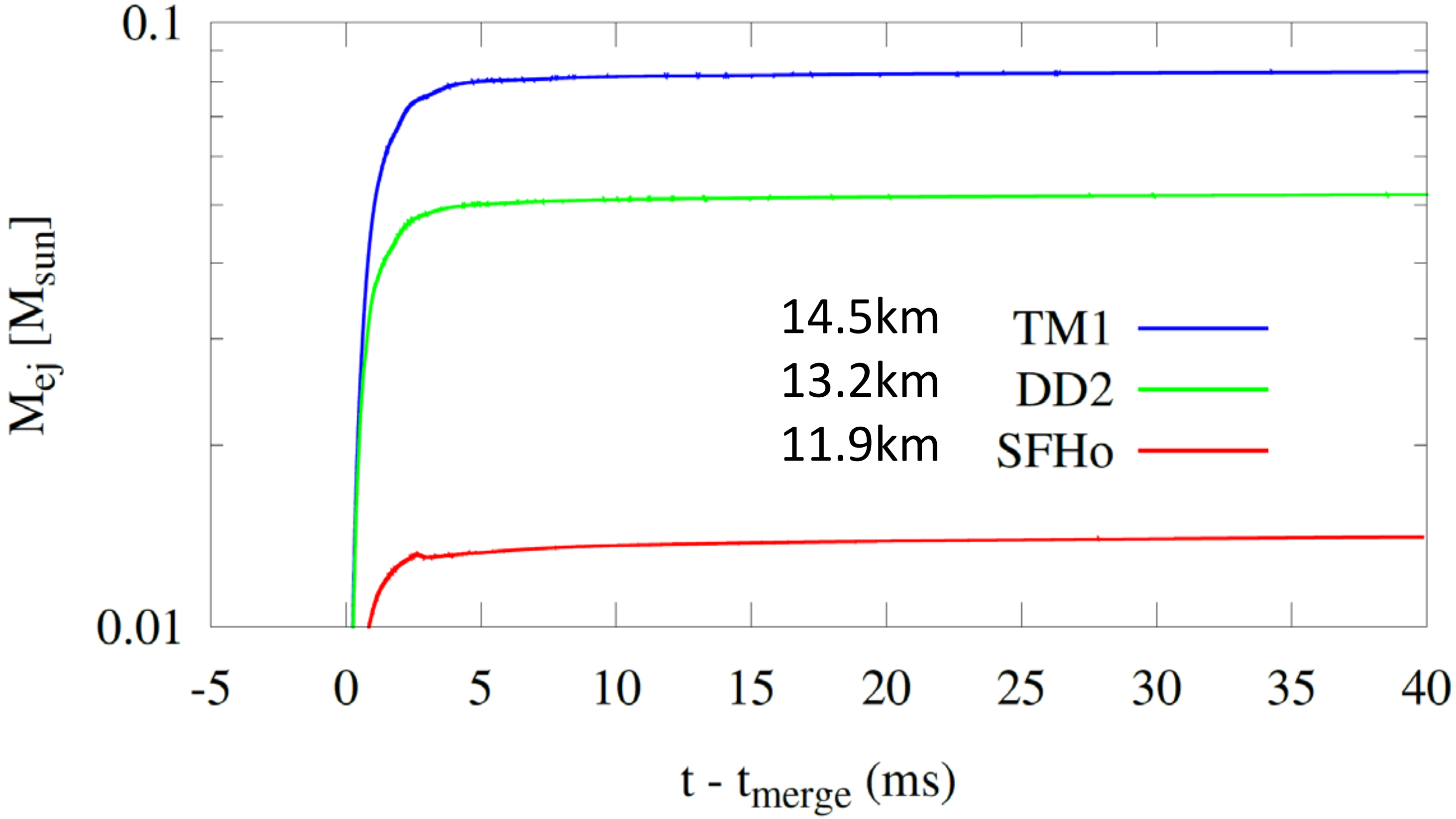
- outer parts become unbound ejecta with low Y_e



Ejecta mass

Larger ejecta mass for larger neutron-star radii

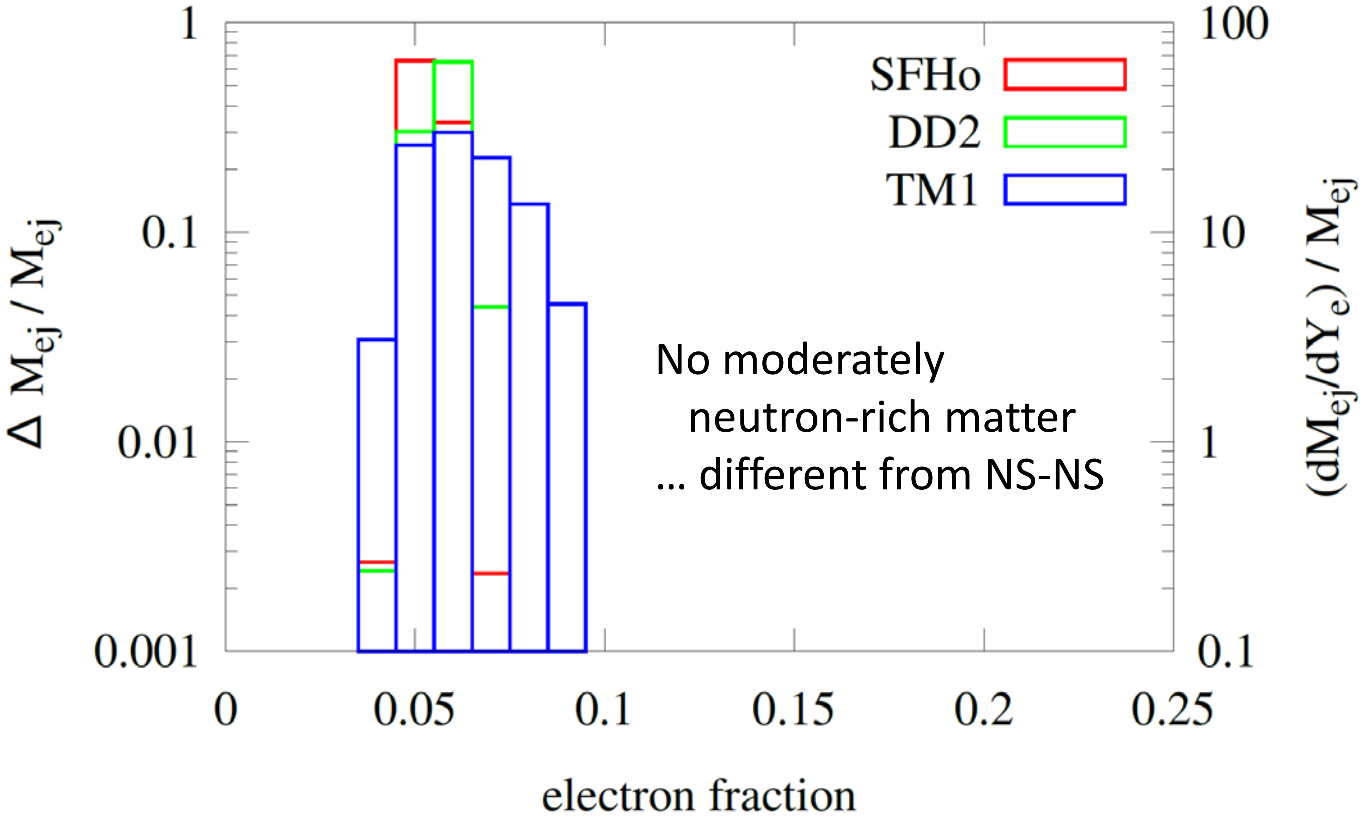
Agree w/ previous hydro. dynamical mass ejection



Electron fraction distribution

Strongly peaked below $Y_e = 0.1$ for all the models

i.e., original composition of neutron stars is kept

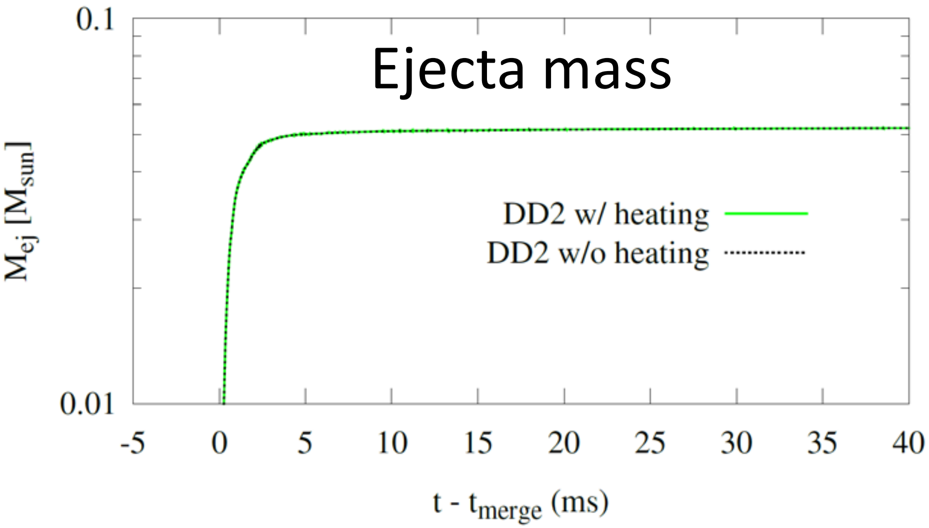


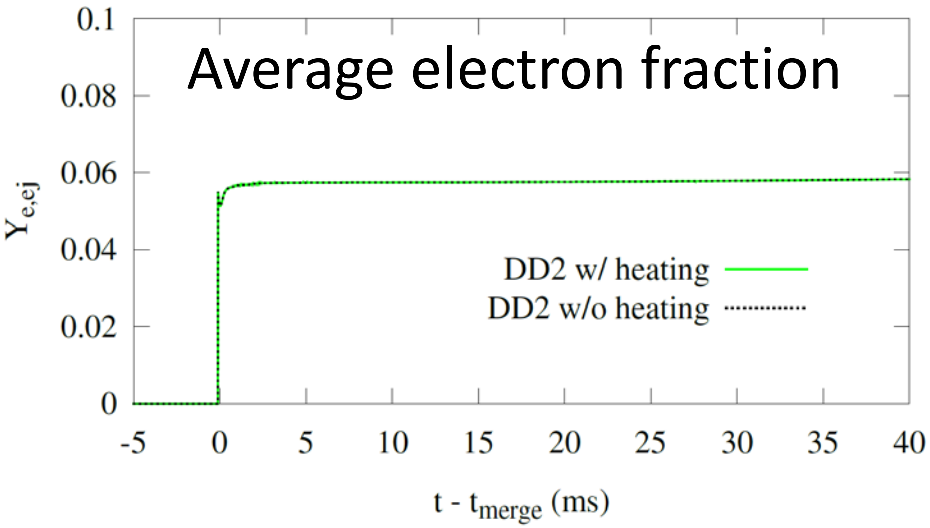
No moderately neutron-rich matter … different from NS-NS

Negligible neutrino-driven wind

The ejecta properties do not depend on ν-heating

- consistent with previous Newtonian simulations


Ejecta mass

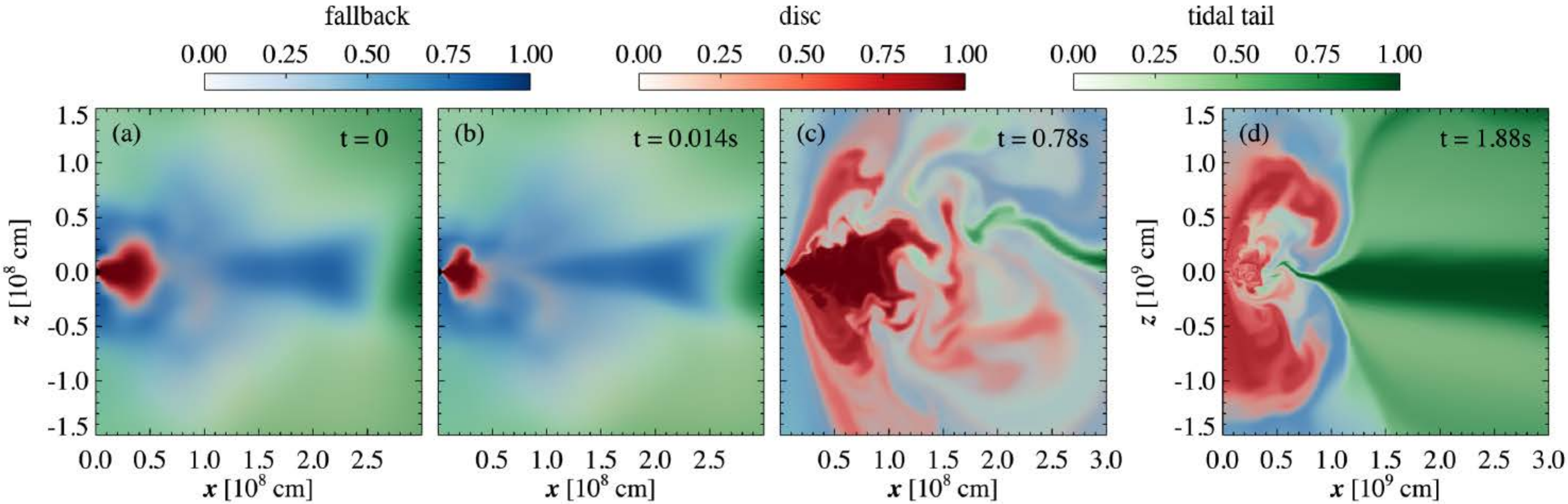

Average electron fraction

Are the disk winds negligible in the mass ejection?

4. Future direction and summary

Viscously-driven wind

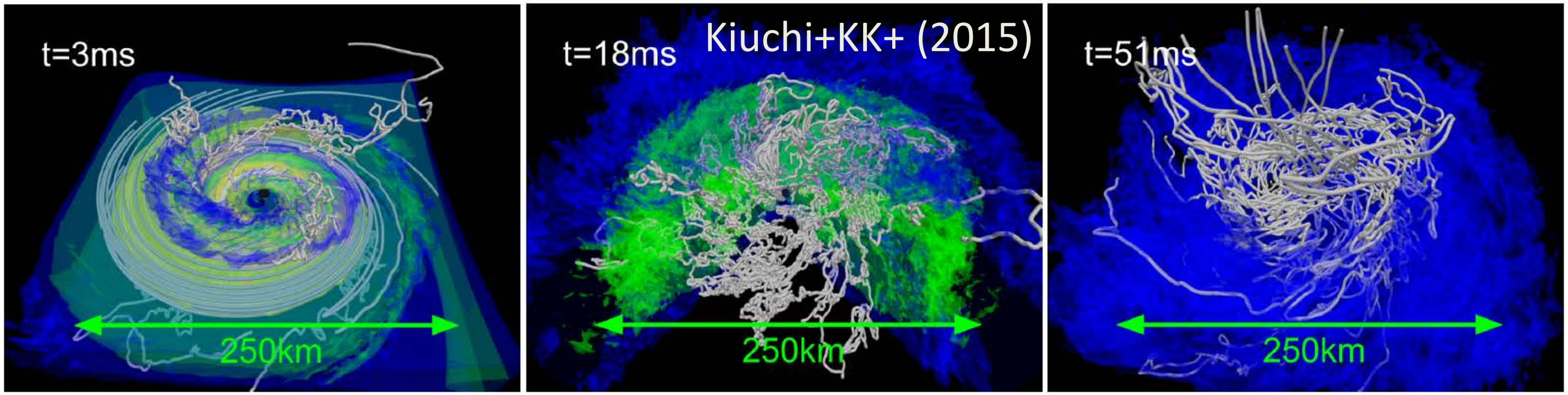
Should be more important than ν-driven winds, where the viscosity comes from magnetic effects



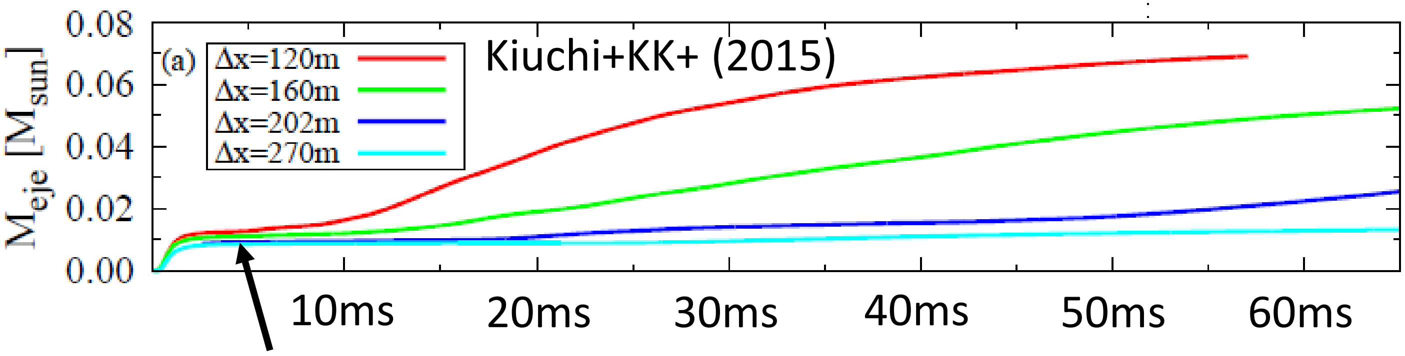
Fernandez+ (2015)

Thermally-driven wind in MHD

High-resolution MHD simulations launch winds via turbulence-like states and efficient thermalization



Kiuchi+KK+ (2015)



Kiuchi+KK+ (2015)

Resolution Dependent Wind (typical MHD)

Dynamical ejecta

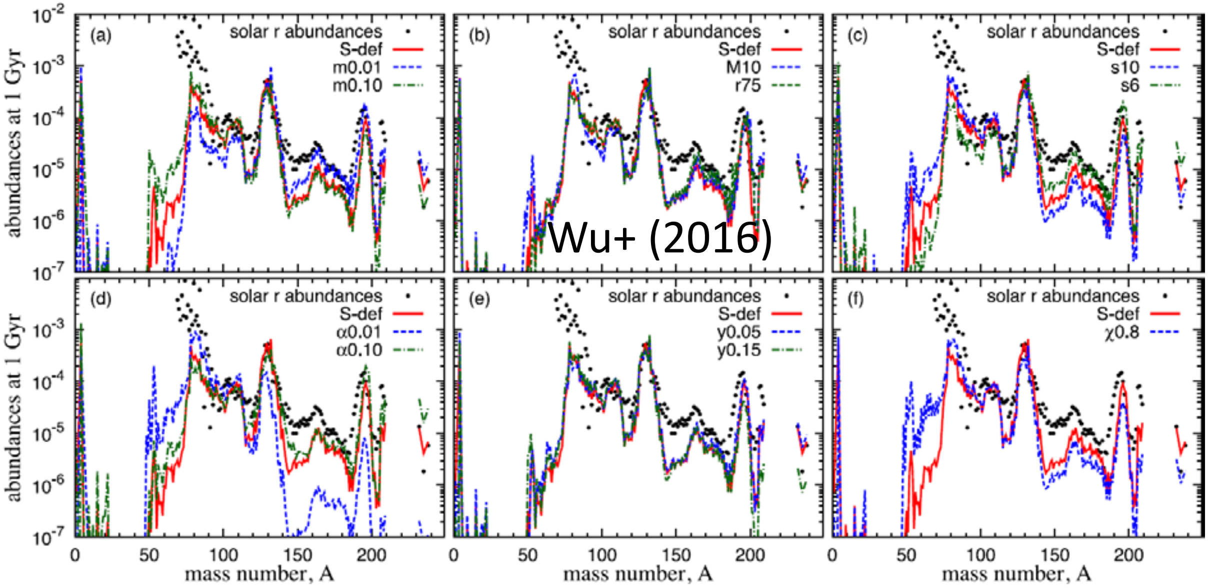
Diversity of the nucleosynthesis

When Ye is high (say >0.25),

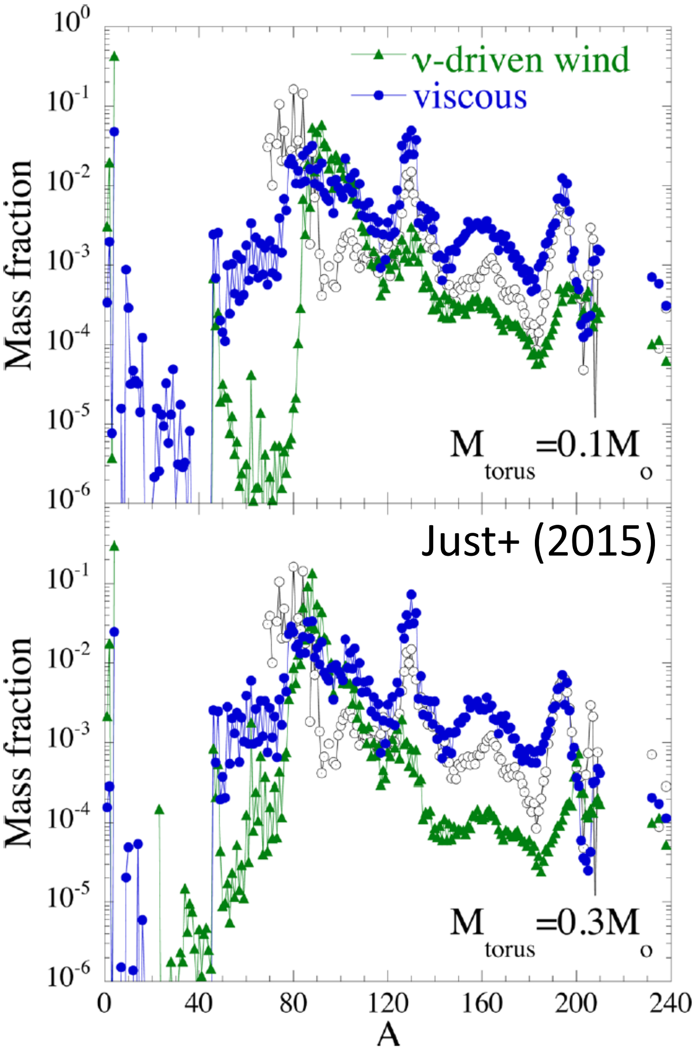
lanthanoids may not be formed

Low velocity traps gamma-rays

-> bright macronova/kilonova?



Wu+ (2016)



Just+ (2015)

Summary

- Black hole-neutron star binary mergers can eject $\sim 0.01 - 0.1 M_{\odot}$ with $\sim 0.2 - 0.3c$ dynamically in a highly anisotropic manner for various cases.
- The electron fraction of dynamical ejecta is low because they do not experience shock heating.
- Neutrinos are not important for dynamical mass ejection and do not drive a strong disk wind.
- Other disk winds could dominate mass ejection and require more investigation.

Appendix

Event rate estimation (to change)

Uncertainties are orders of magnitude

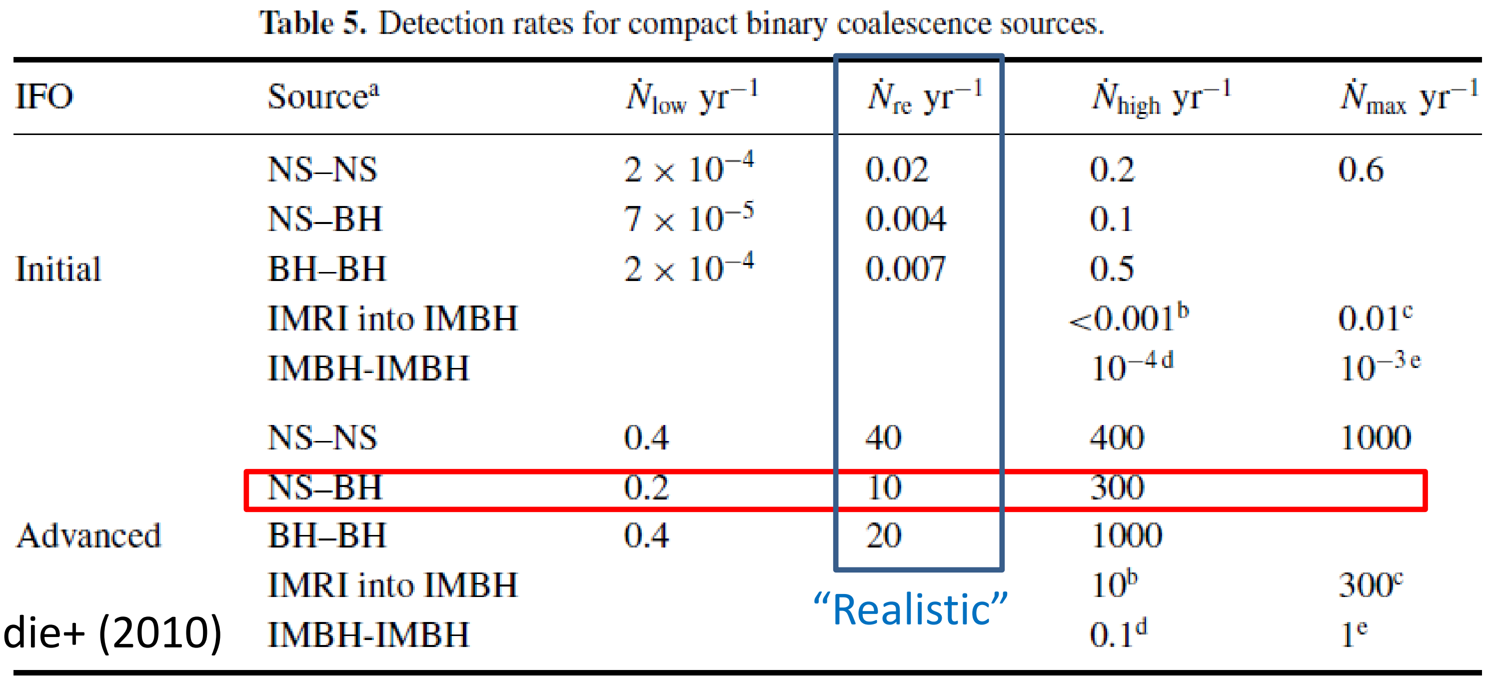


Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
Initial	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

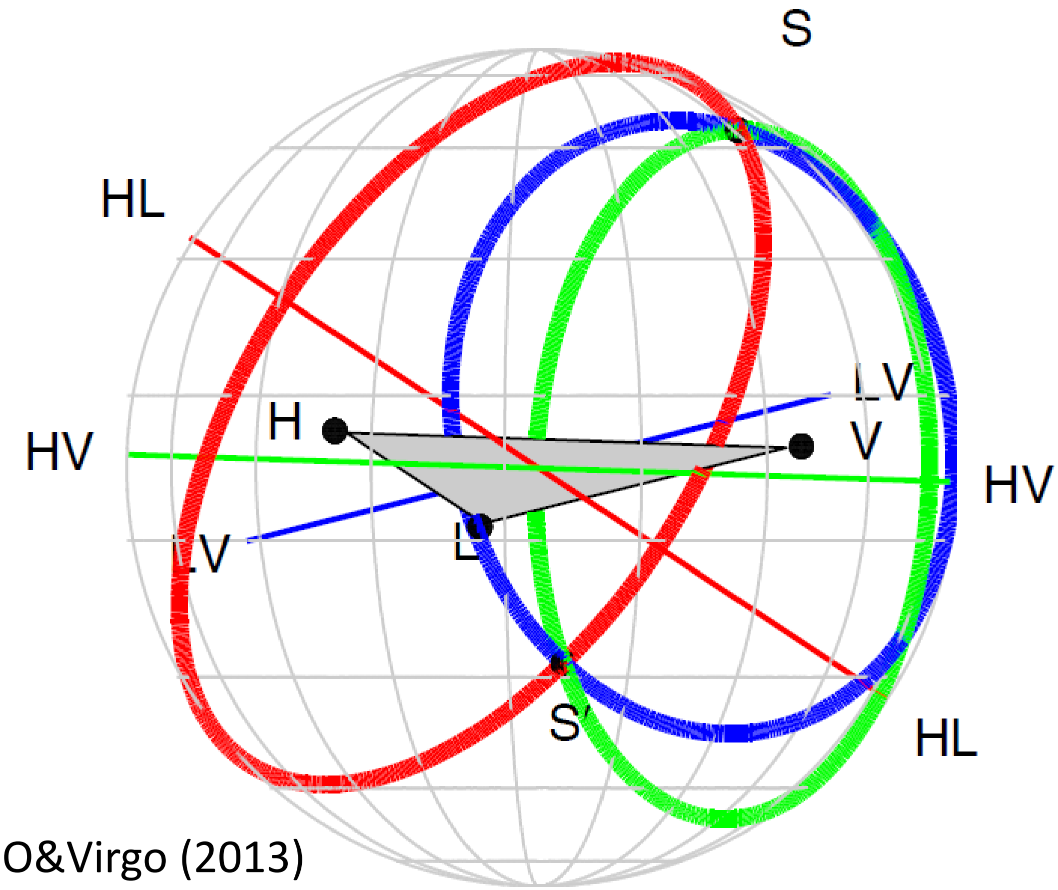
"Realistic"

Abadie+ (2010)

Anyway - yearly detection may be expected

Triangulation by a detector network

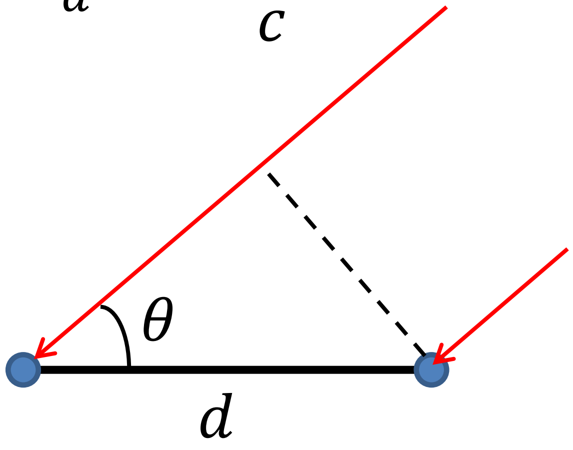
Determine the sky position from timing difference



LIGO&Virgo (2013)

d~O(1000km)

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



Dependence of peak luminosity/time

For spherical ejecta (Li-Paczynski 1998, also Arnett 1982)

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 not discussed today

Ejecta mass M and ejecta velocity v – macrophysics

hydrodynamic calculations can give answers

Li-Paczynski model: macroscopic

Spherical ejecta with mass M and surface velocity v

Homologous expansion w/ constant-density

$$R = vt, \qquad \rho = \frac{3M}{4\pi R^3} = \frac{3M}{4\pi v^3 t^3}$$

Thermodynamic evolution for per-mass quantities

$$TdS = dE + PdV \to Tds = d\left(\frac{e}{\rho}\right) + Pd\left(\frac{1}{\rho}\right)$$

Nuclear heating and radiative cooling per mass

$$Tds/dt = \dot{\varepsilon} - L/M$$

Li-Paczynski model: microscopic

The ejecta should be radiation-dominated $P = e/3$

Nuclear heating may obey a power-law

$$\dot{\varepsilon} = \frac{fc^2}{t}$$

Radiative cooling is given by the diffusion approx.

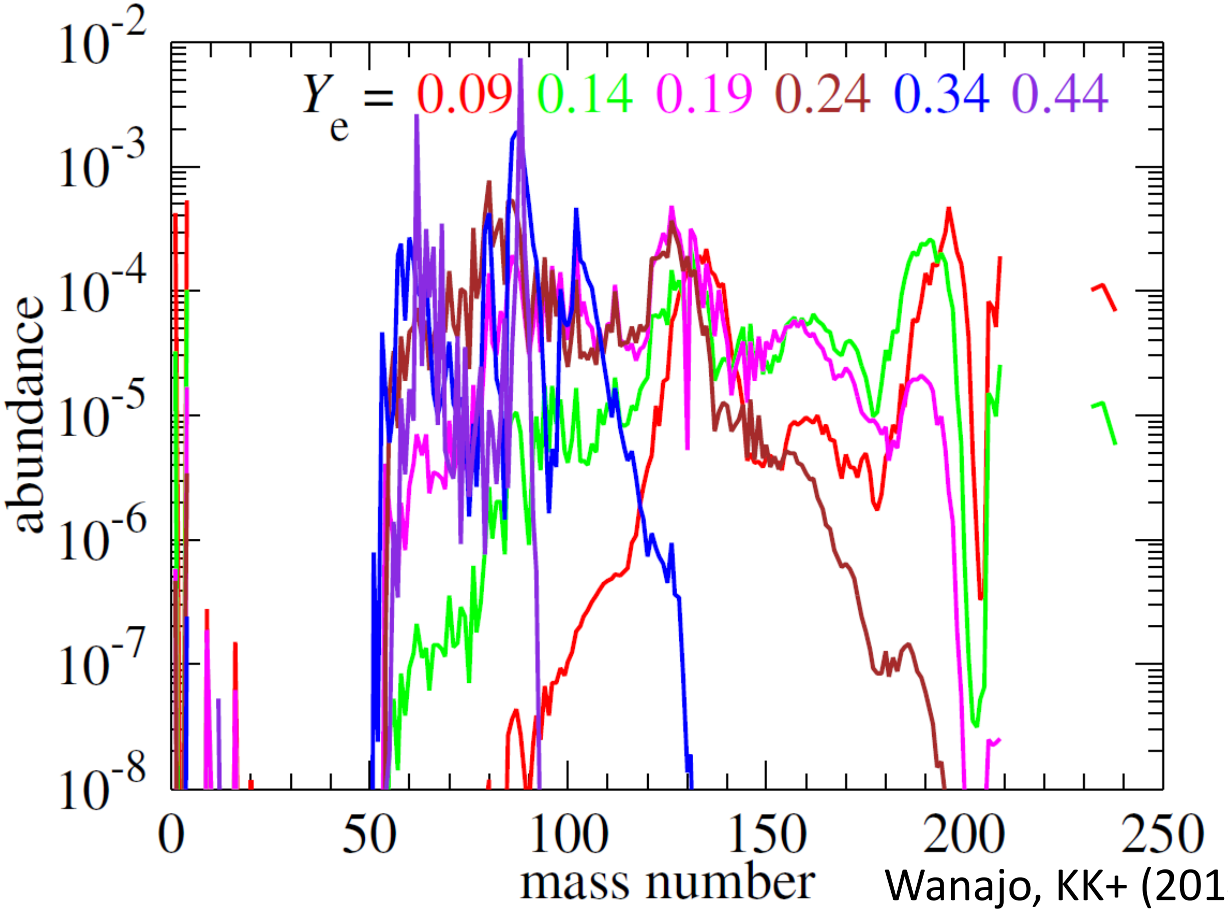
$$L = 4\pi R^2 F, \qquad F = \frac{c}{3\kappa\rho}\left(-\frac{dE}{dr}\right) \approx \frac{ceR^2}{\kappa\rho}$$

-> time evolution of e can be solved analytically

the bolometric light curve is also derived

Why successful r-process?

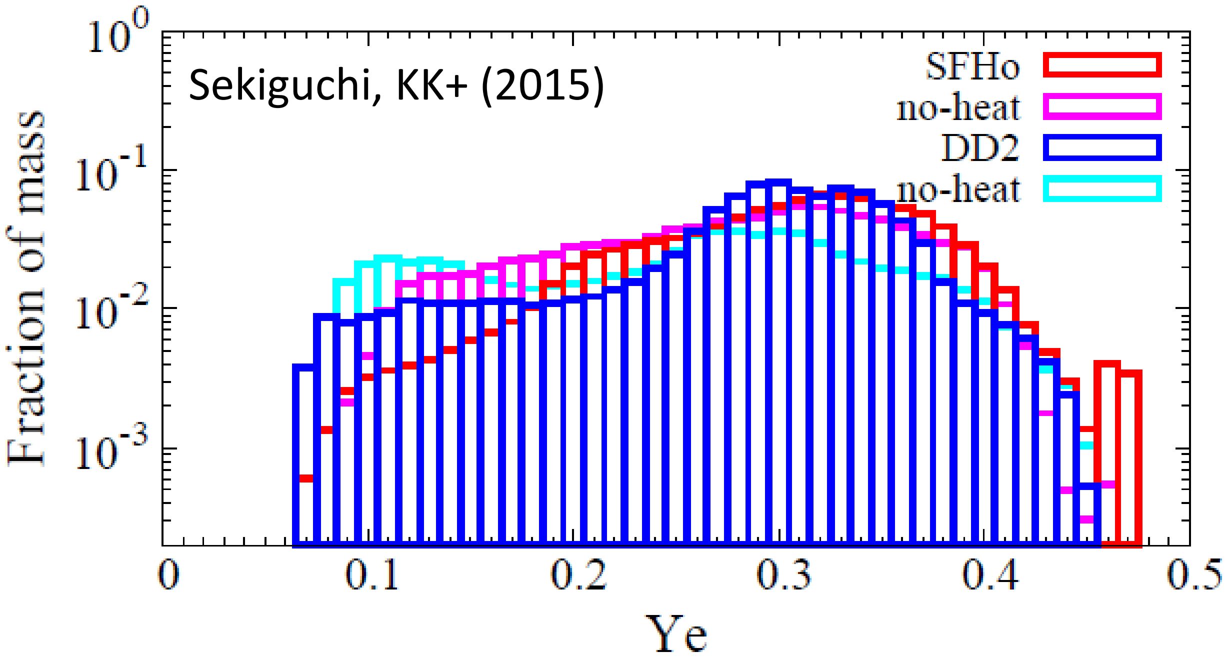
Broad distribution of electron fraction in full GR

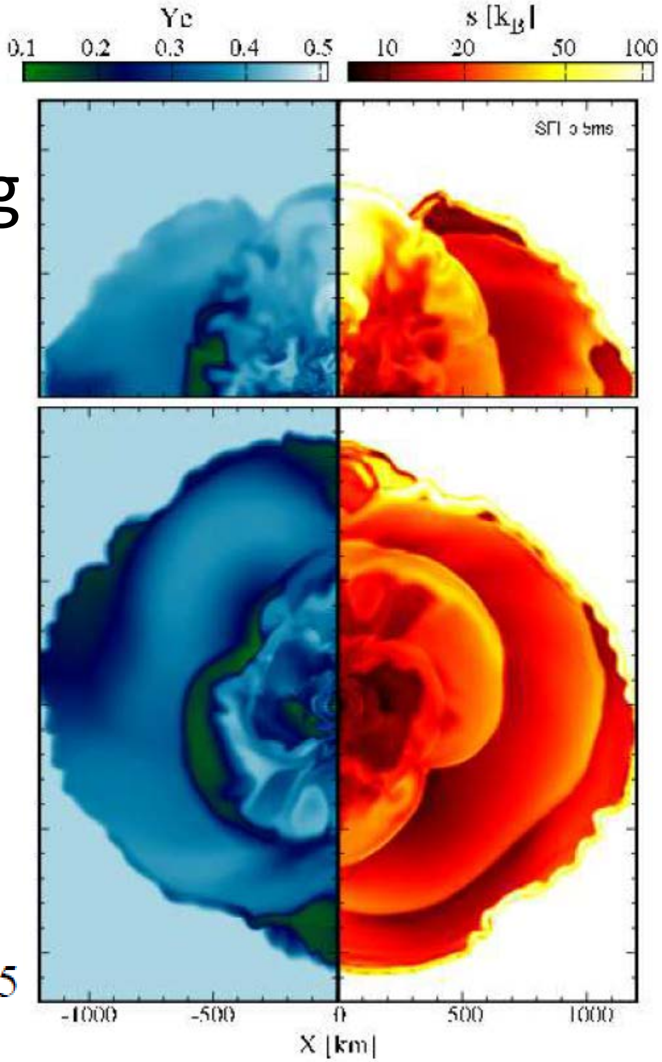


Wanajo, KK+ (2014)

GR NS-NS ejecta

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

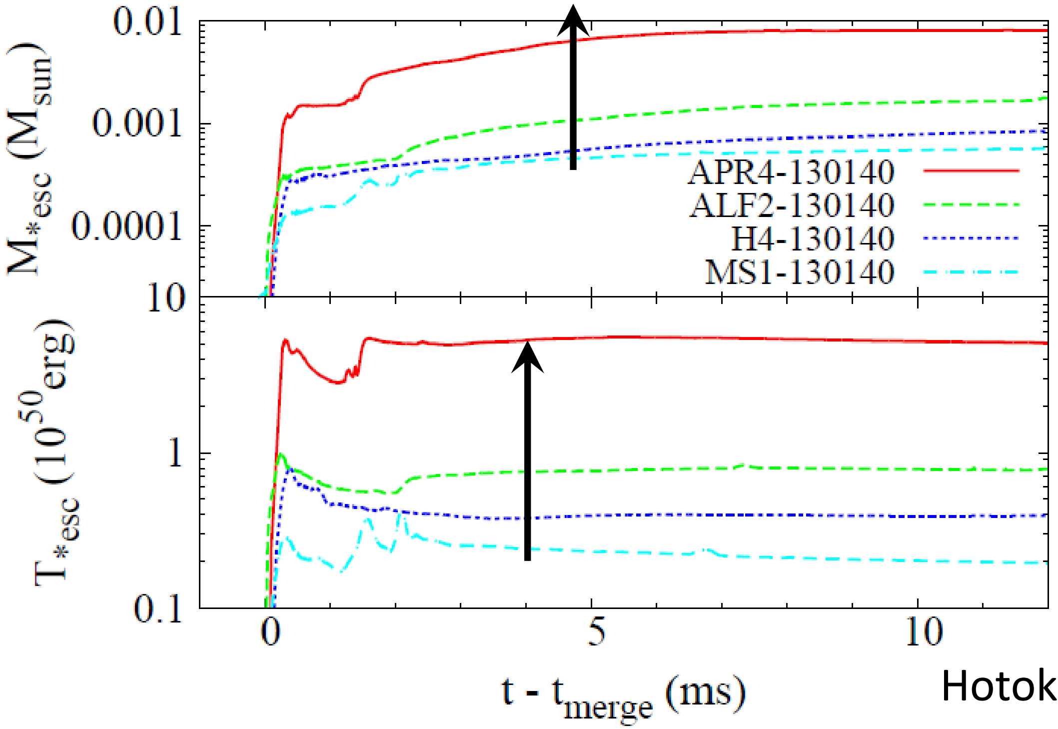




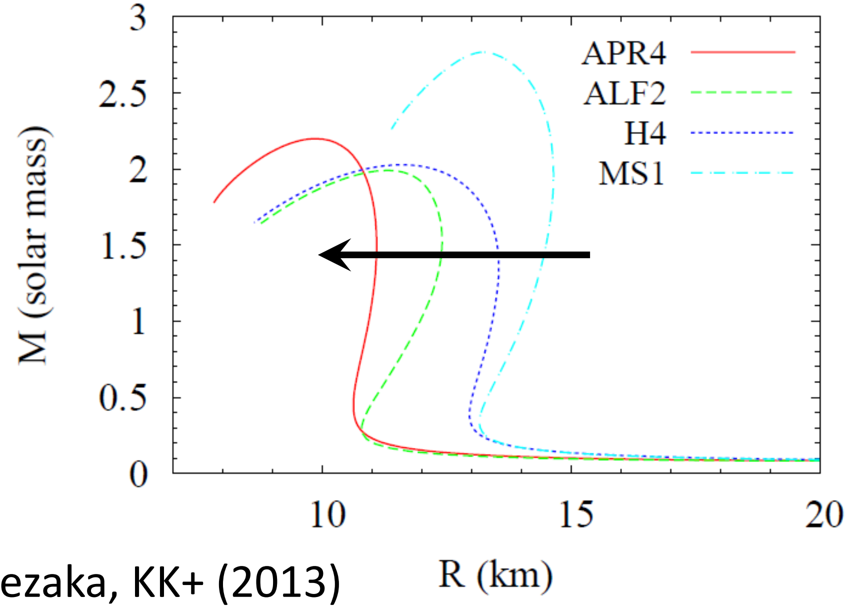
Sekiguchi, KK+ (2015)

EOS dependence of NS-NS ejecta

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

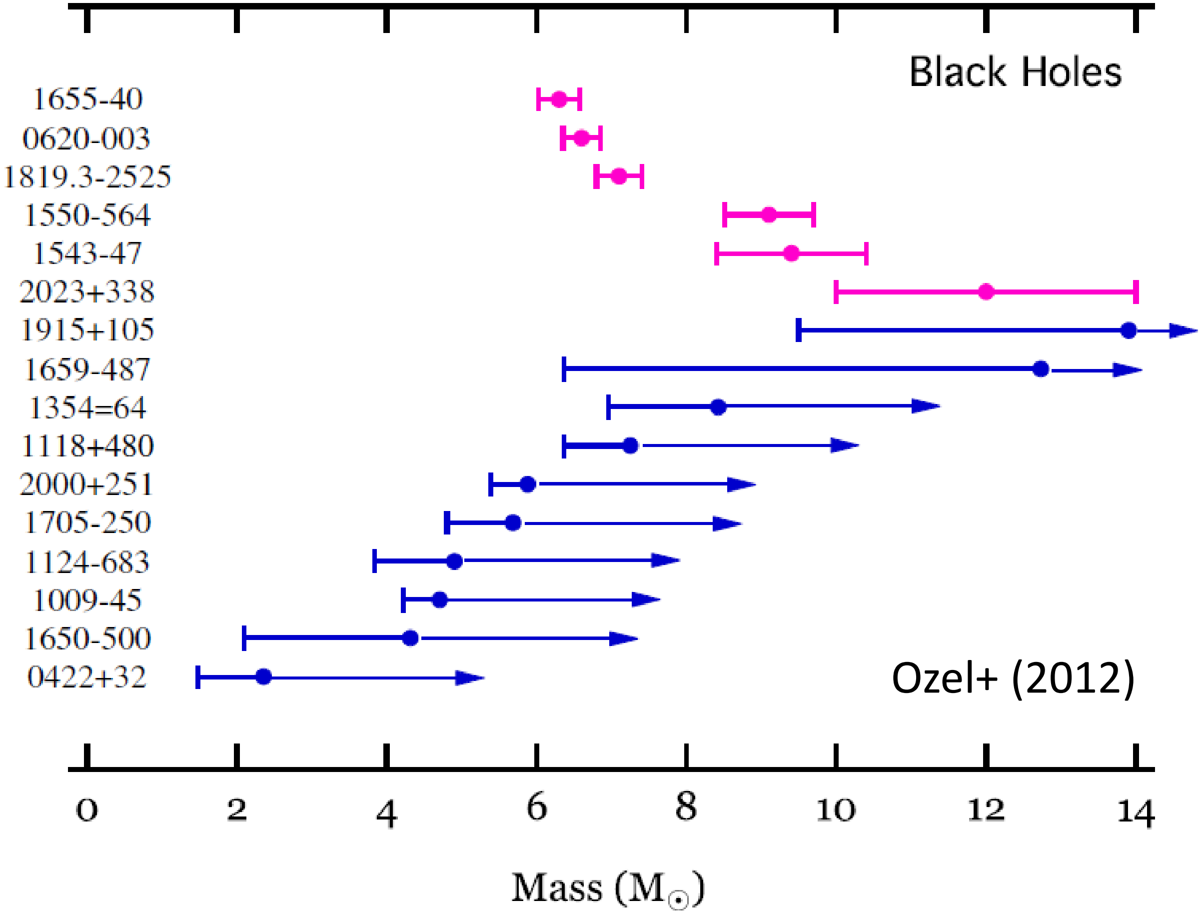


Hotokezaka, KK+ (2013)



Black hole mass

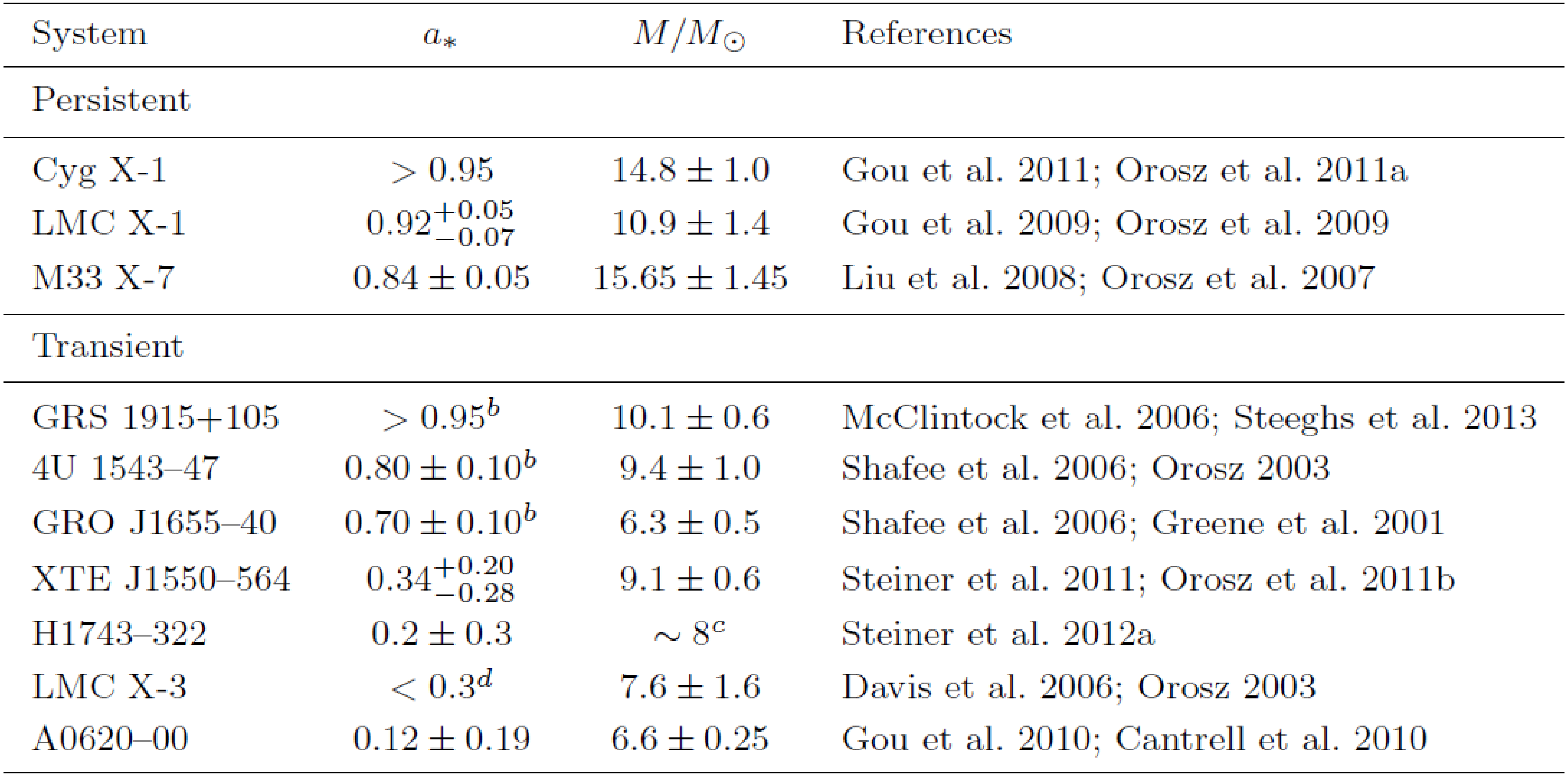
Mass gap around $3 - 5M_{\odot}$ is frequently debated



Black hole spin

Uncertain but no typical value exists?

McClintock+ (2014)



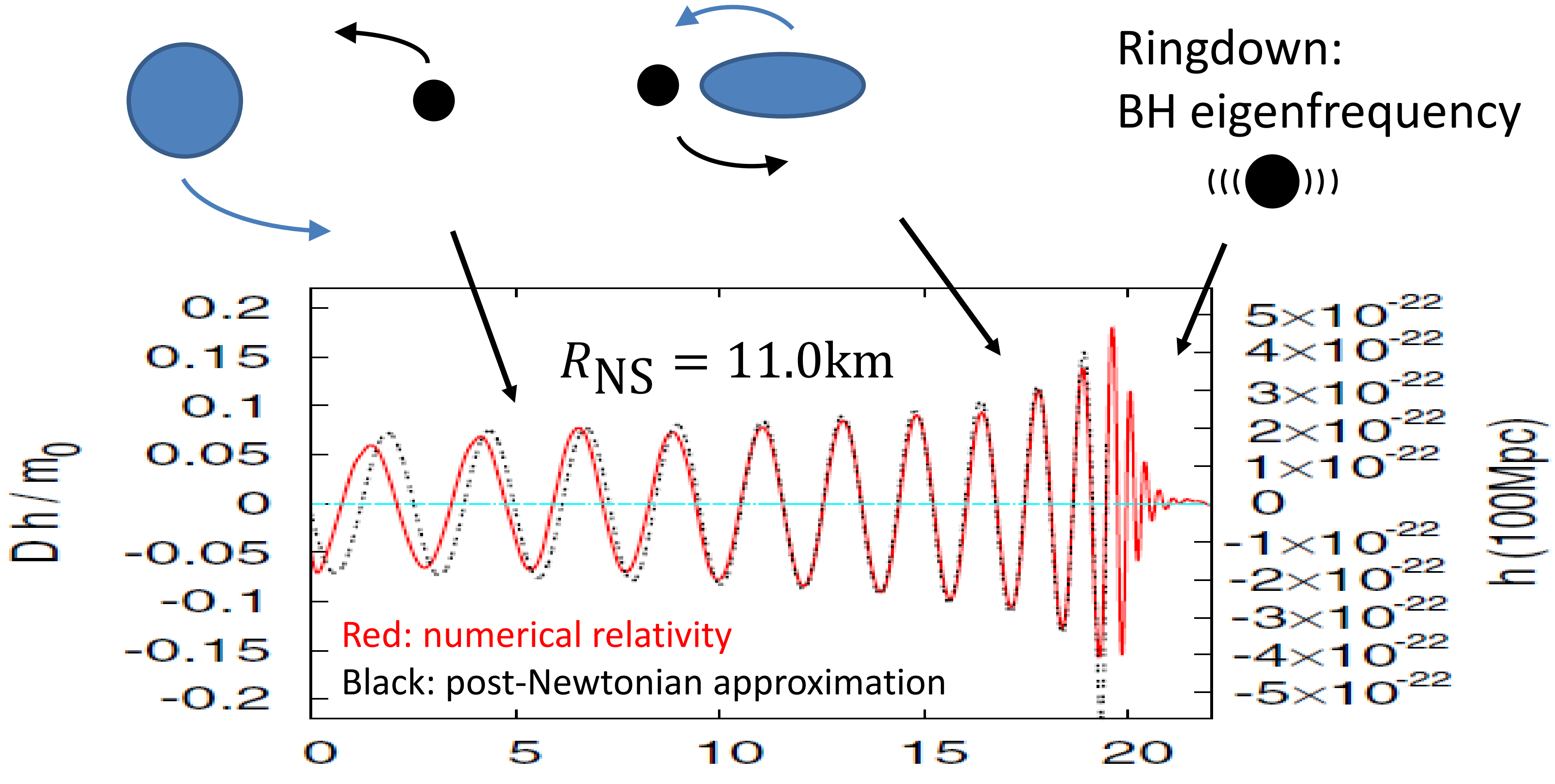
System	a_*	$M/M_\odot$	References
Persistent			
Cyg X-1	> 0.95	14.8 ± 1.0	Gou et al. 2011; Orosz et al. 2011a
LMC X-1	$0.92^{+0.05}_{-0.07}$	10.9 ± 1.4	Gou et al. 2009; Orosz et al. 2009
M33 X-7	0.84 ± 0.05	15.65 ± 1.45	Liu et al. 2008; Orosz et al. 2007
Transient			
GRS 1915+105	$> 0.95^b$	10.1 ± 0.6	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

Gravitational waves without disruption

Early inspiral: mass, spin

Late inspiral: tidal deformability
(only weak effect in this case)

Ringdown:
BH eigenfrequency



$R_{\mathrm{NS}} = 11.0\mathrm{km}$

Red: numerical relativity

Black: post-Newtonian approximation

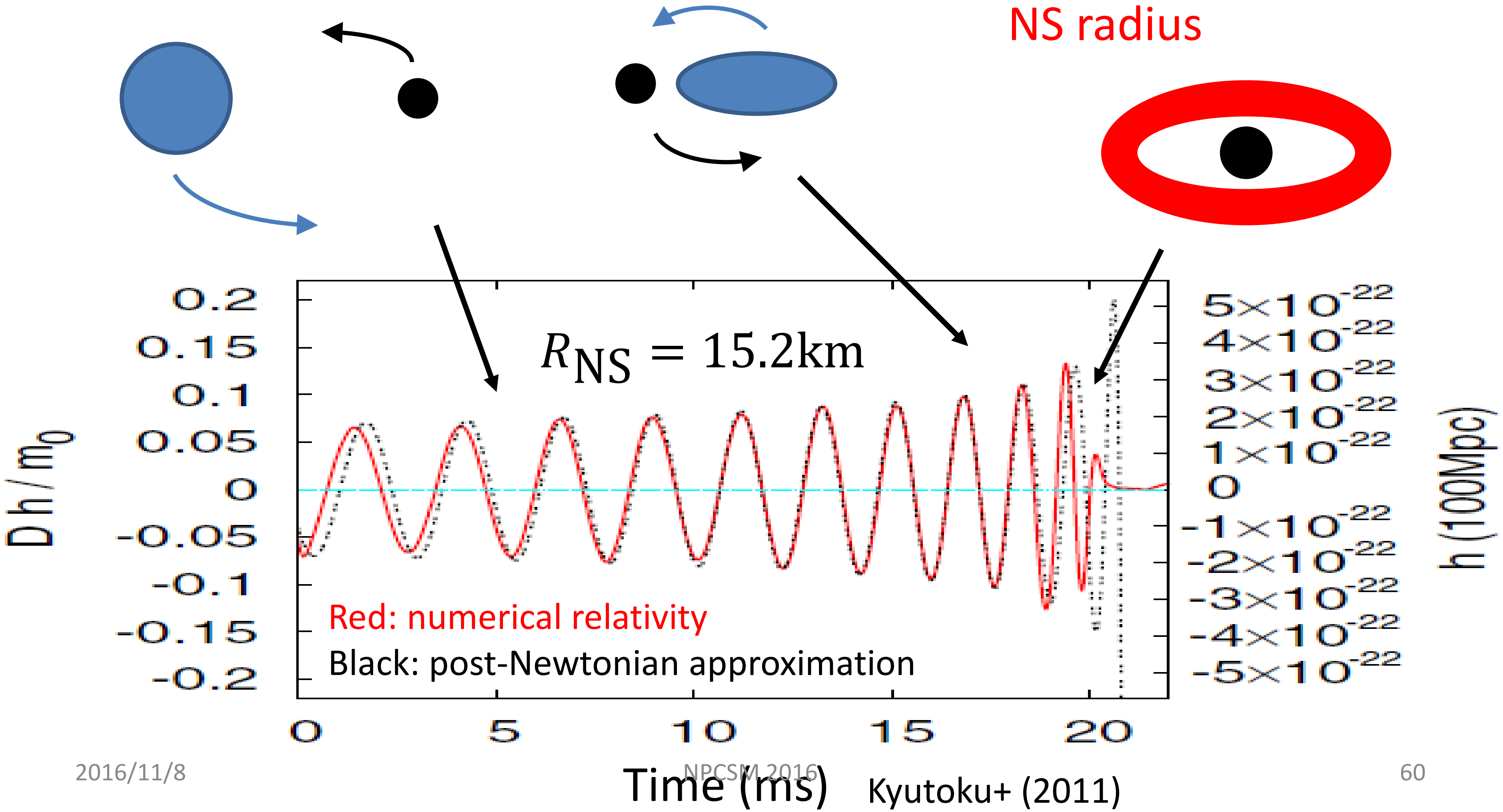
Kyutoku+ (2011)

Gravitational waves with disruption

Late inspiral: tidal deformability

Early inspiral: mass, spin

Tidal disruption cutoff: NS radius



Red: numerical relativity

Black: post-Newtonian approximation

Kyutoku+ (2011)

Numerical relativity

The Einstein equation

$$G_{ab} = 8\pi T_{ab}, \qquad (G = c = 1)$$

Local energy-momentum conservation equation

$$\nabla_b T^{ab} = 0,$$

Rest-mass (or particle number) continuity equation

$$\nabla_a(\rho u^a) = 0$$

+ equation of state e.g., $P = P(\rho), P(\rho, T, Y_e)$ …

also solve Magneto/Radiation-HD Eqs. if you want

Numerical method

Initial data: LORENE (spectral method)

quasiequilibrium states of BH-NS binaries

Dynamical simulation: SACRA (Yamamoto+ 2008)

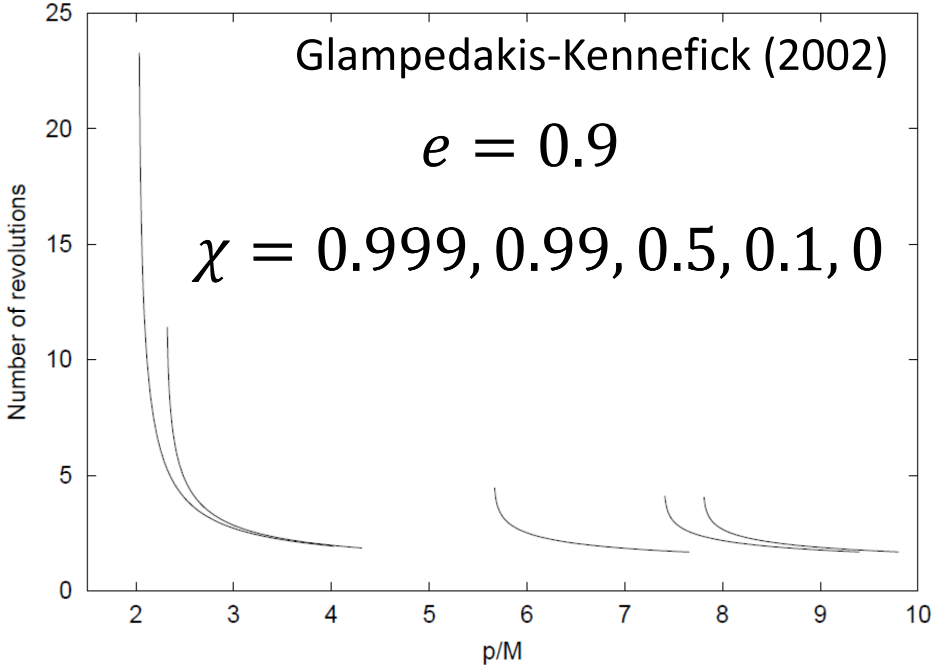
- BSSN formalism of the Einstein equation

  4th order finite difference in time and space
- ideal hydrodynamics

  3rd order PPM reconstruction + central scheme
- adaptive mesh refinement

Periastron advance: zoom-whirl

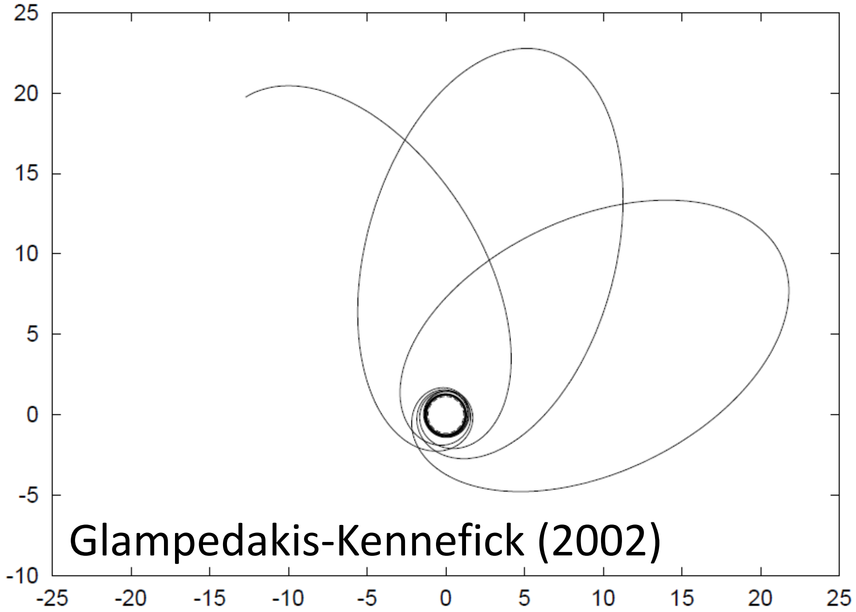
Eccentric orbits can experience many cycles near the last bound orbit


Glampedakis-Kennefick (2002)

$e = 0.9$

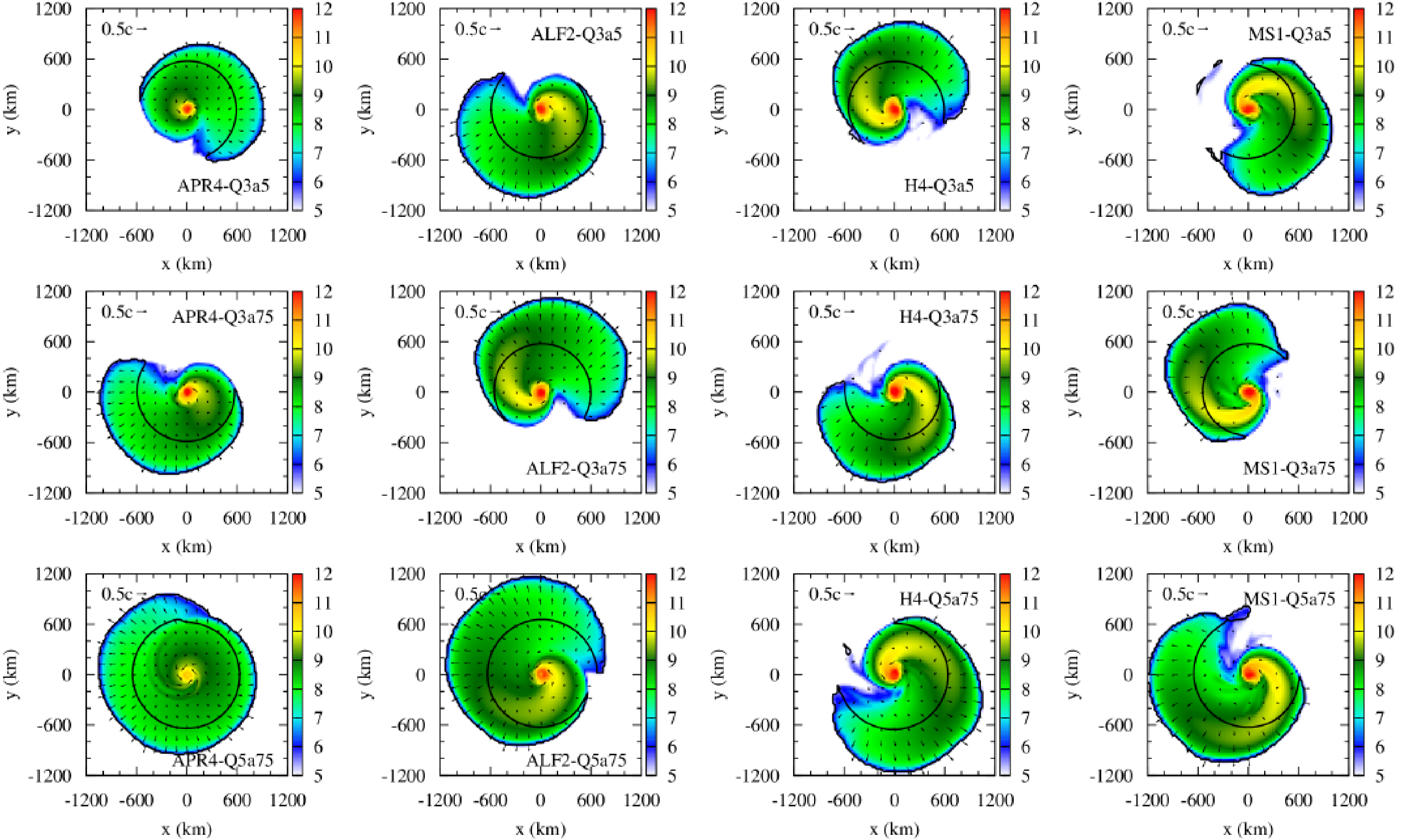
$\chi = 0.999, 0.99, 0.5, 0.1, 0$

Semi-latus rectum


Glampedakis-Kennefick (2002)

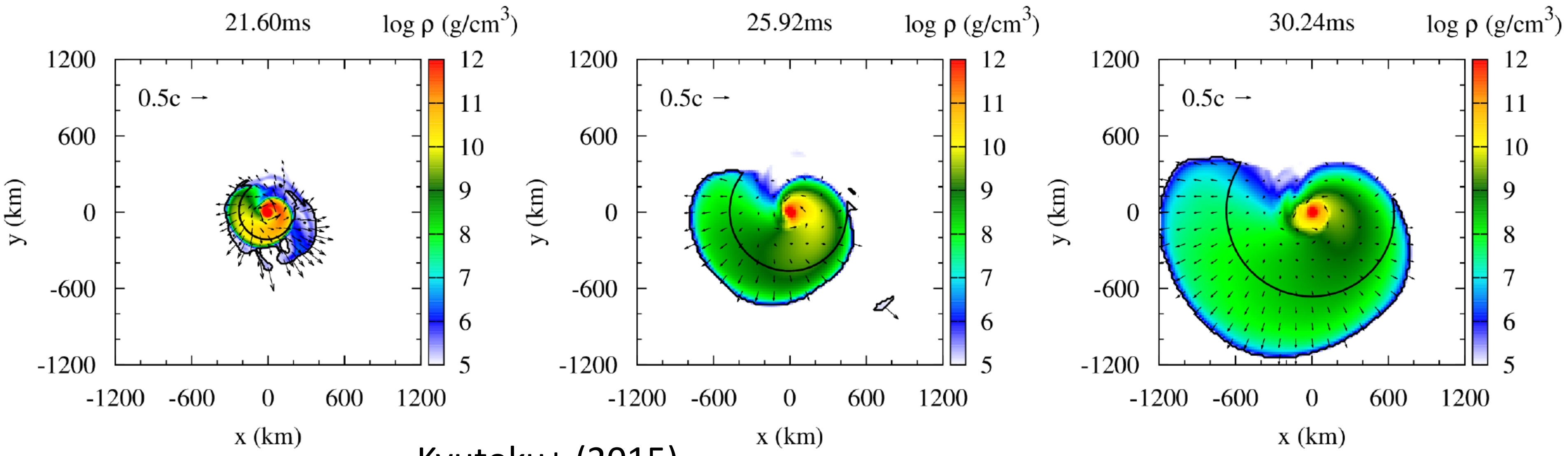
This "zoom-whirl" is an extreme example of periastron advance

Various ejecta opening angle



Kyutoku+ (2015)

Late-time evolution

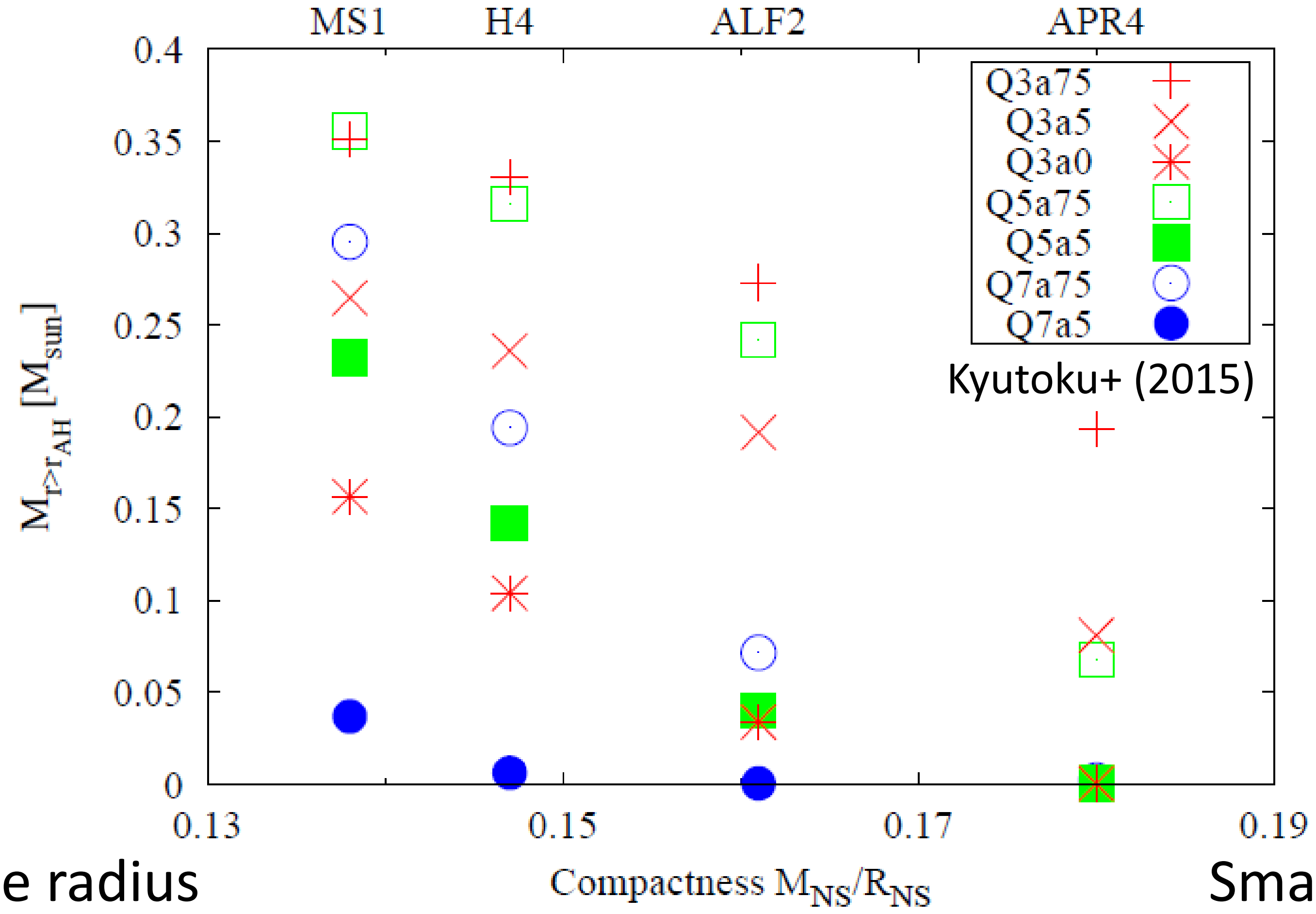


Kyutoku+ (2015)

- homologous evolution (crescent to half-disk)
- radial-motion dominated (angu. mom conserv.)

Mass remaining outside the BH

Nicely correlated with the NS compactness (radius)



Kyutoku+ (2015)

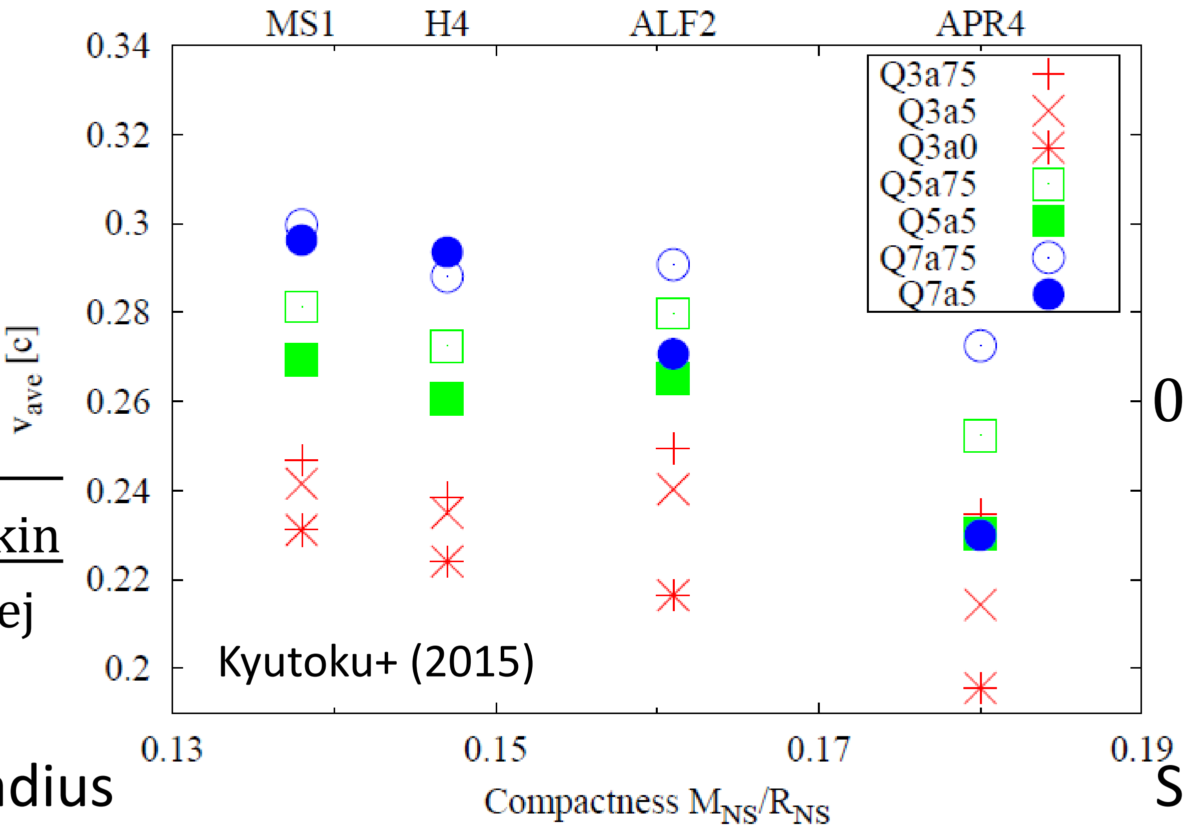
Large radius

Small radius

Average velocity of the ejecta

Also tends to increases as the mass ratio increases

-> the ejecta from a large Q binary is energetic



Kyutoku+ (2015)

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

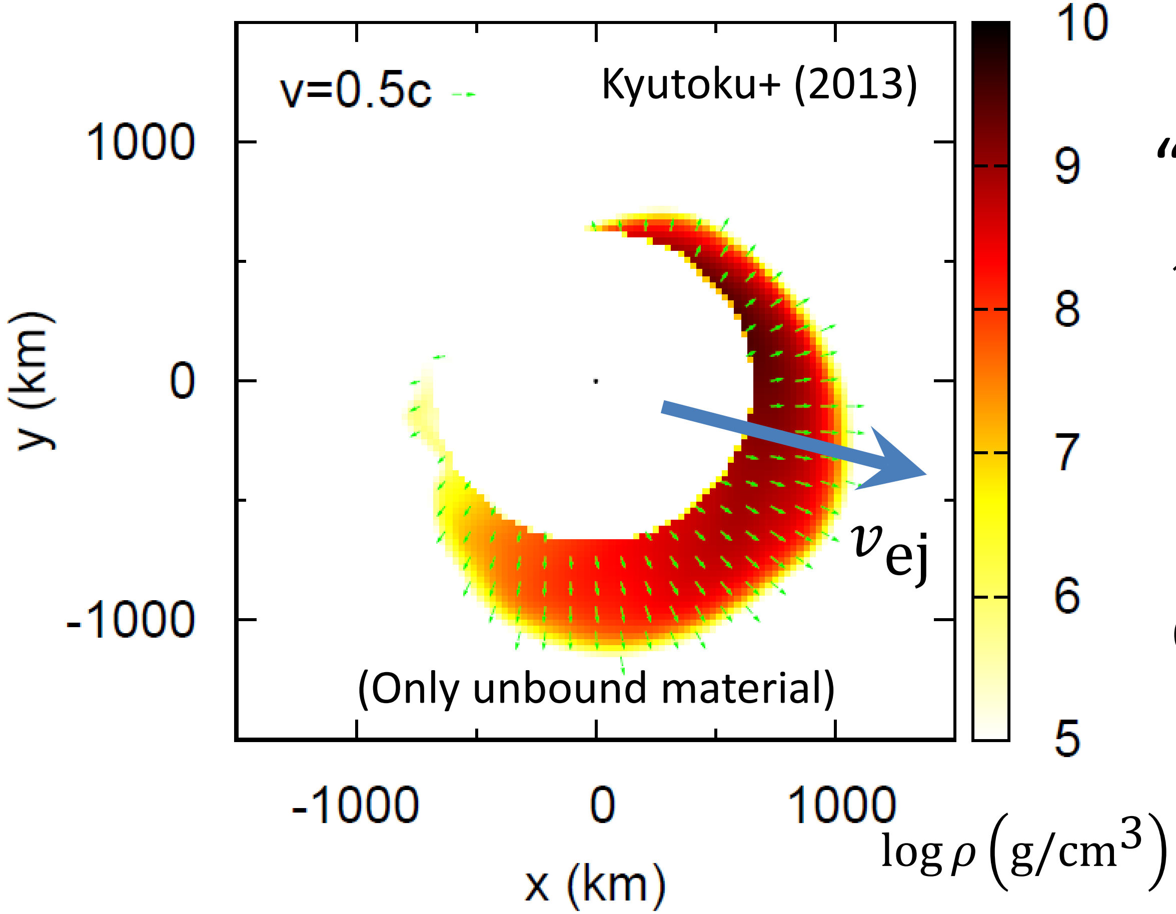
$0.2 - 0.3c$ may be typical

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

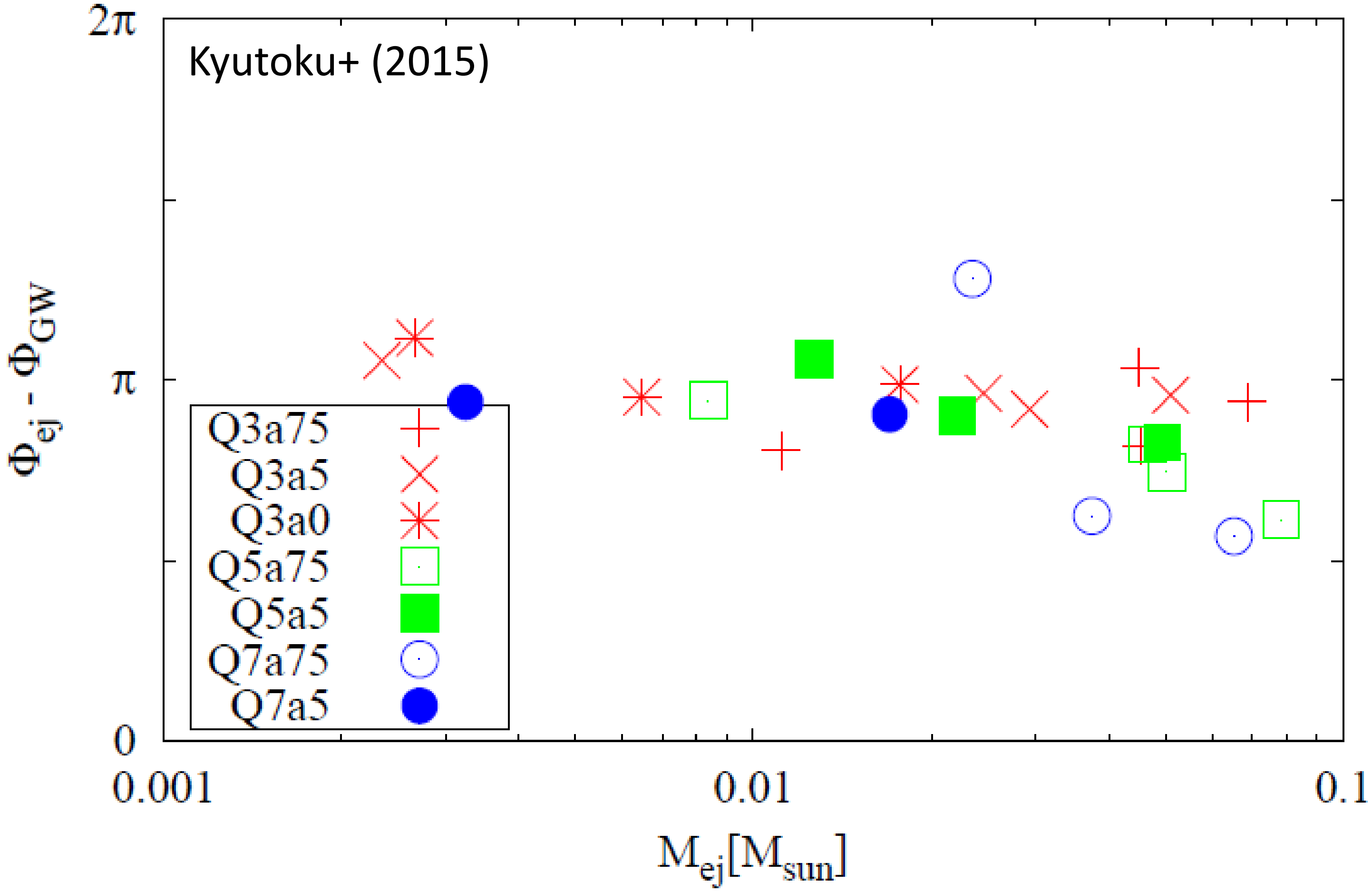
$$V_{\mathrm{ej}} \approx \frac{P_{\mathrm{ej}}}{M_{\mathrm{remnant}}}$$

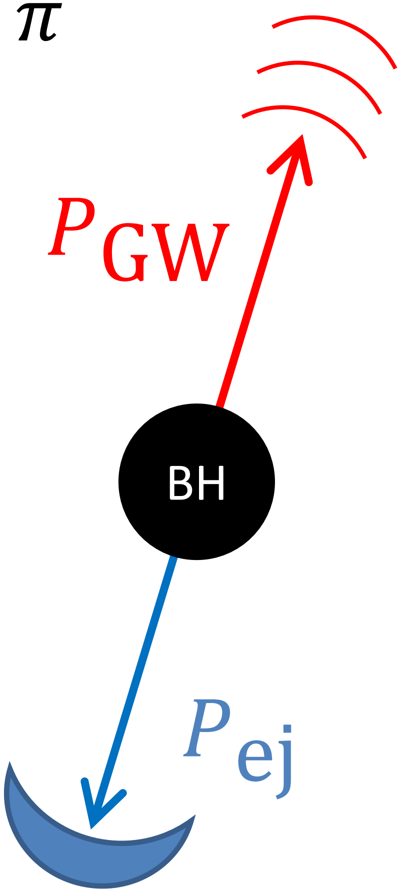
- gravitational-wave kick: large for weak disruption

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

Anti-correlation of the kick direction

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

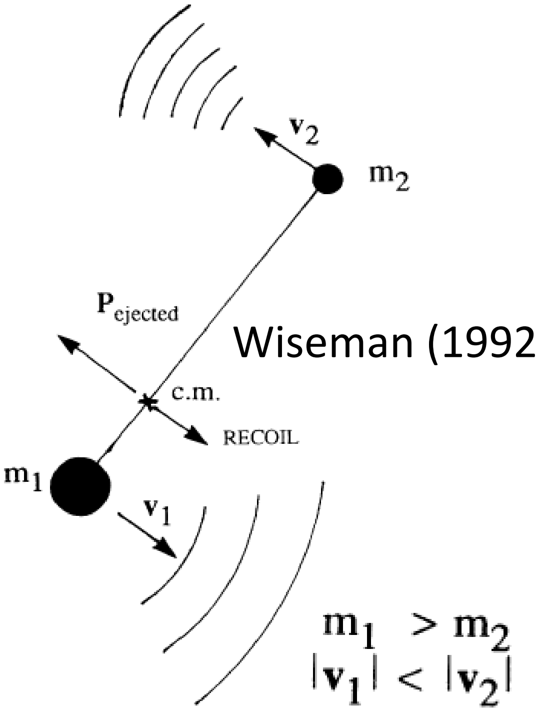




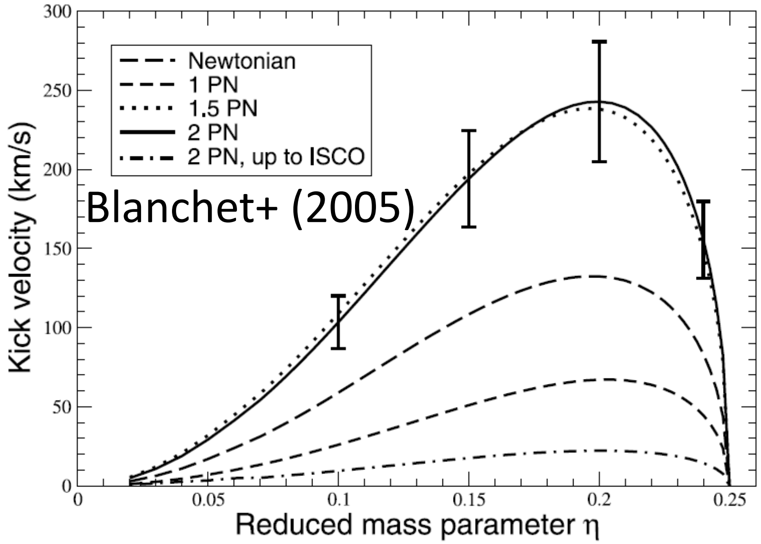
Possible explanation

Opposite motion of the ejecta <-> plunge material

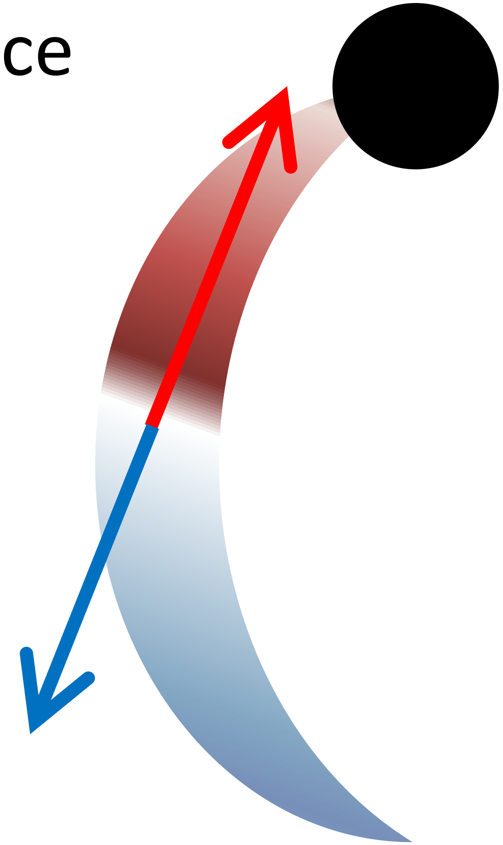
Plunge motion: fastest in the coalescence dominant to the recoil



Wiseman (1992)



Blanchet+ (2005)

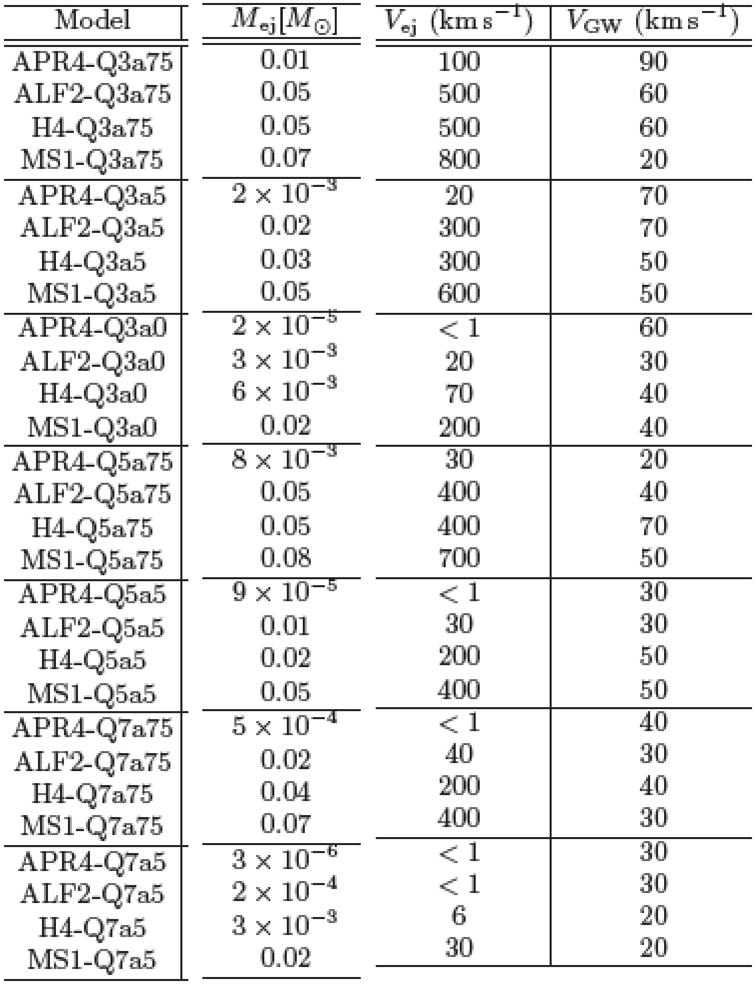


Which of two kick velocities wins?

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

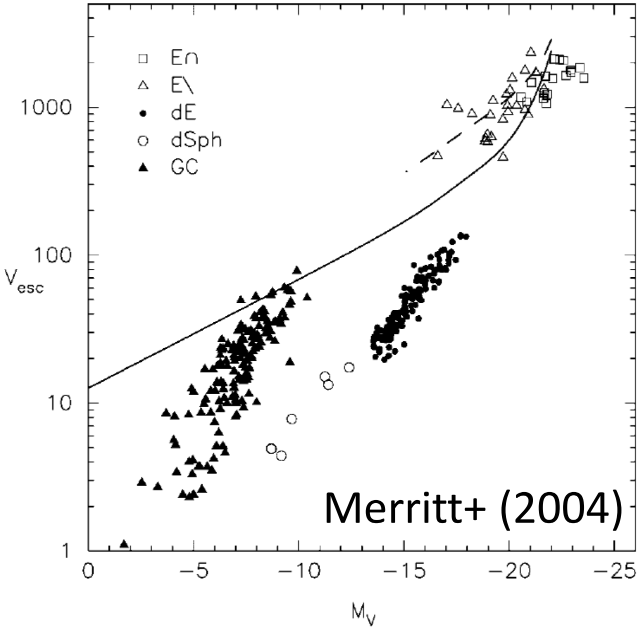
The ejecta kick velocity could be as large as ~1000km/s

Kyutoku+ (2015)



Model	$M_{\mathrm{ej}}[M_{\odot}]$	V_{ej} $(\mathrm{km\,s^{-1}})$	V_{GW} $(\mathrm{km\,s^{-1}})$
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)

Reason of the power-law index 5/3

Rees 1988, Phinney 1989 for SMBH-MS disruption

Orbital period – semimajor axis – binding energy

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

The fallback rate ~ the period distribution

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

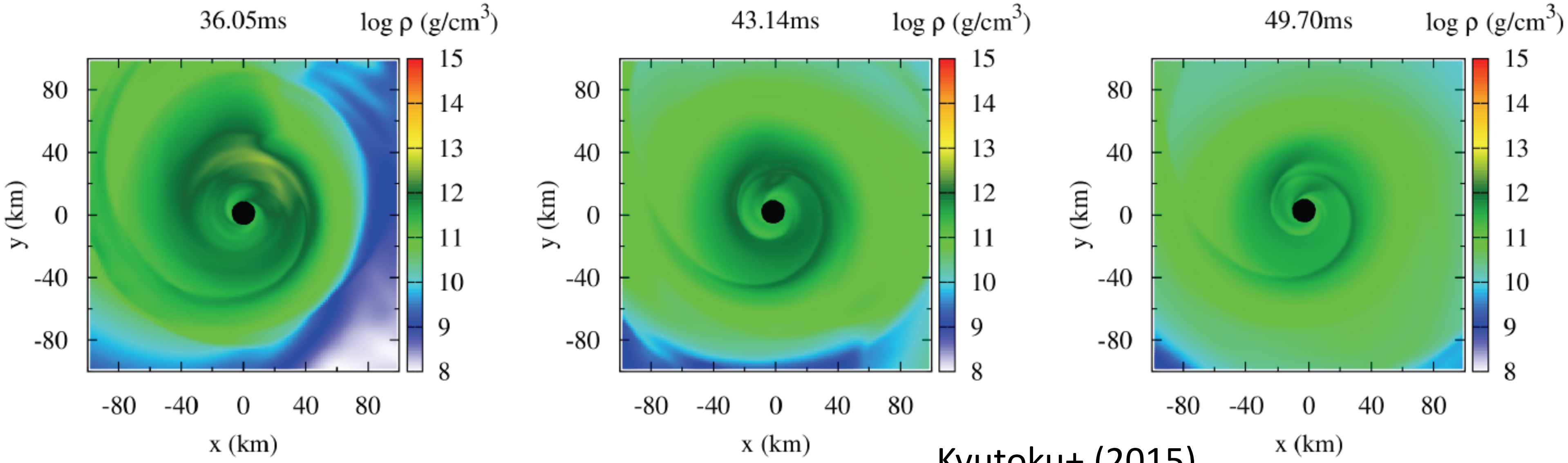
Why dM/dE is constant? Not fully understand yet

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

Standing spiral shock in the disk

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

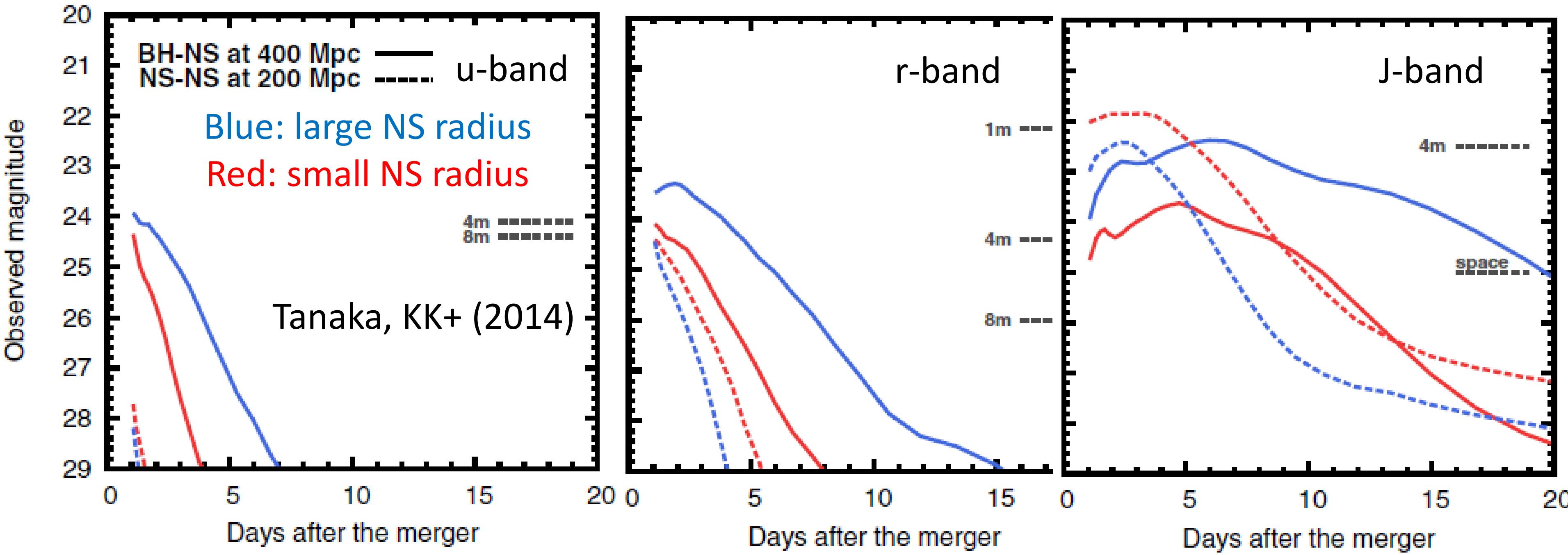
Drive mass accretion even for the perfect fluid



Kyutoku+ (2015)

Macronova/kilonova simulation

Red spectrum with opacity from r-process line lists



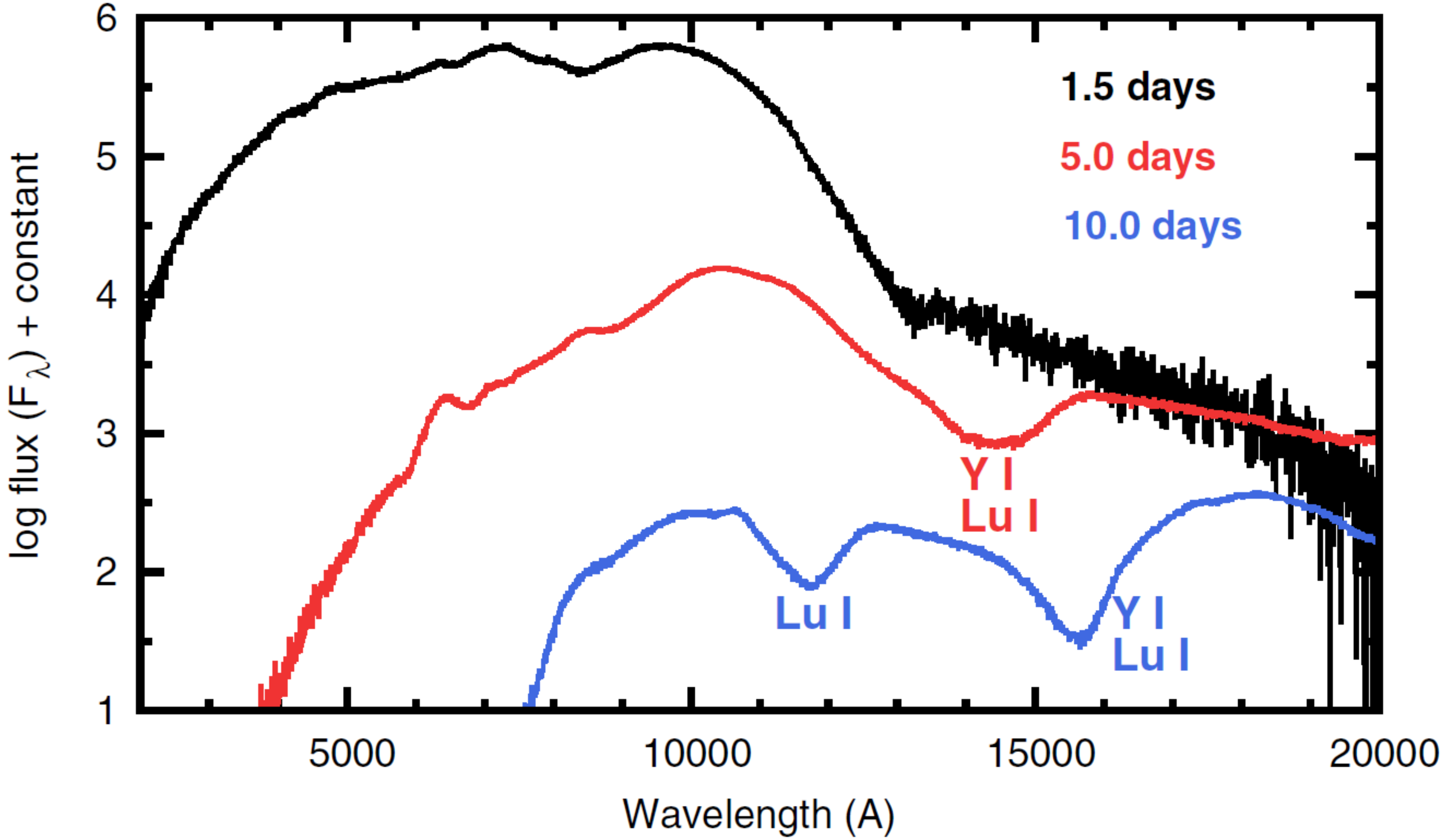
Blue: large NS radius

Red: small NS radius

Tanaka, KK+ (2014)

Absence of r-process lines

No line may be found with all the r-process lines…



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

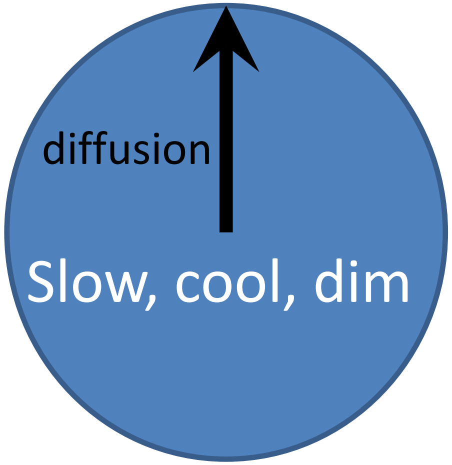
Ejecta mass M and ejecta velocity v – NR simulation

large ejecta mass -> bright and long emission

Effect of anisotropy

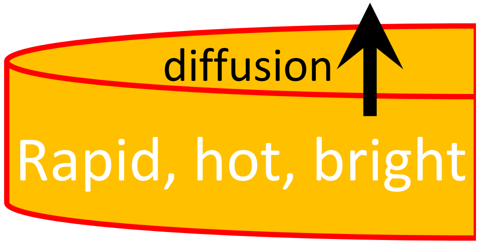
Geometry determines the photon-diffusion direction

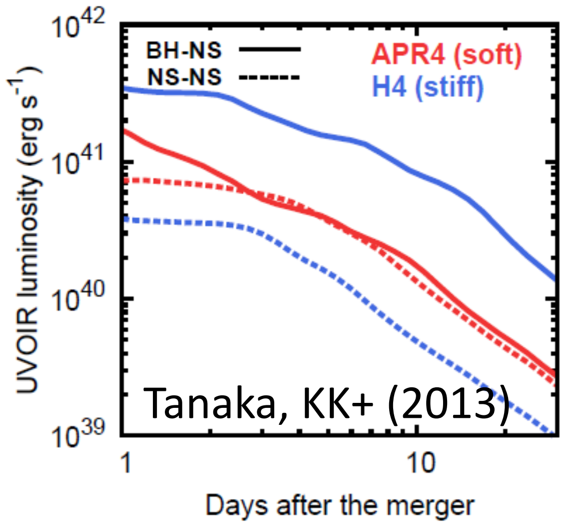
spherical ejecta



BH-NS crescent-like ejecta

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





Tanaka, KK+ (2013)

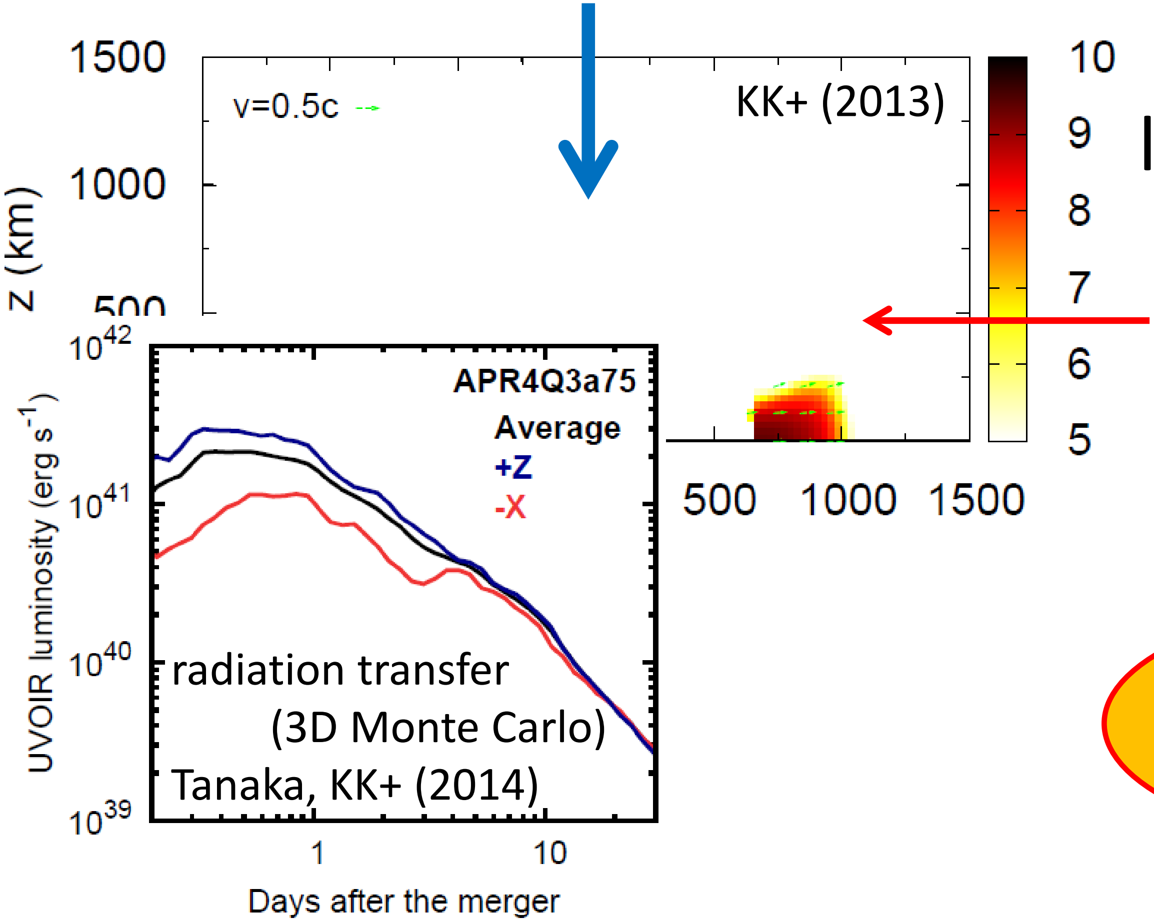
radiation transfer
(3D Monte Carlo)

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



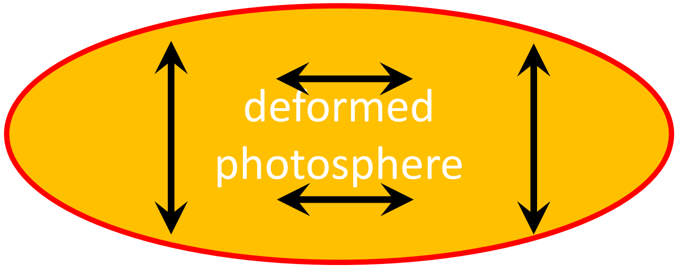
radiation transfer (3D Monte Carlo)

Tanaka, KK+ (2014)

low luminosity

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

polarization?



Synchrotron radio emission

Ejecta decelerate when accumulate M_{ej} from ISM

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

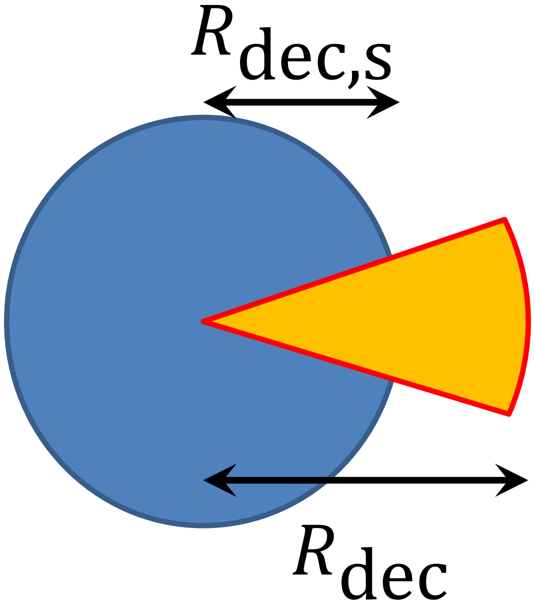
$$R_{\mathrm{dec,s}} \sim \left(3M_{\mathrm{ej}}/4\pi m_{\mathrm{p}} n_{\mathrm{H}}\right)^{1/3} \sim 0.7\mathrm{pc}$$

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

For crescent-like BH-NS ejecta

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

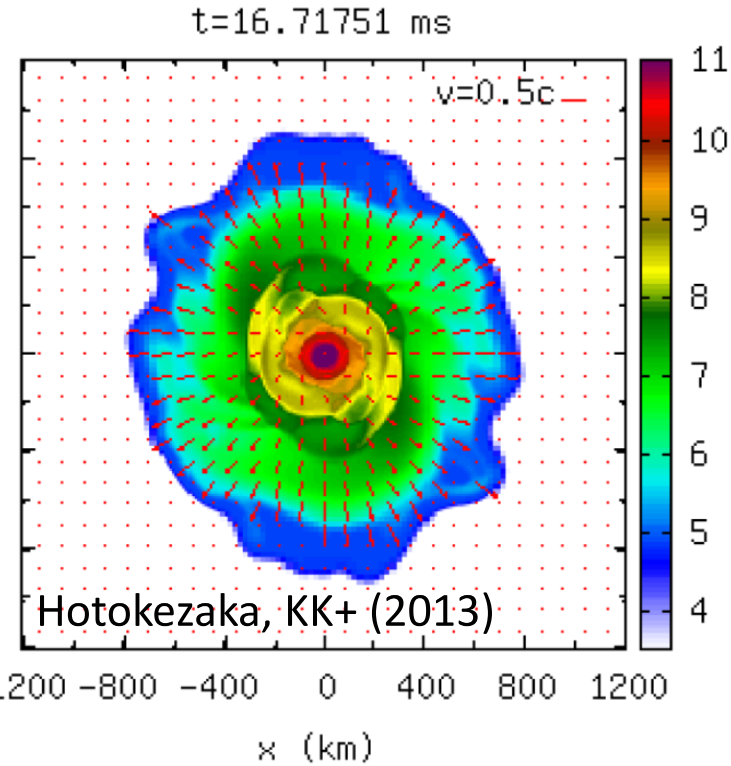
$$t_{\mathrm{dec}} \sim 18\mathrm{yr}\, \theta_{\mathrm{ej},1/5}{}^{-1/3} \varphi_{\mathrm{ej},\pi}{}^{-1/3}$$



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)

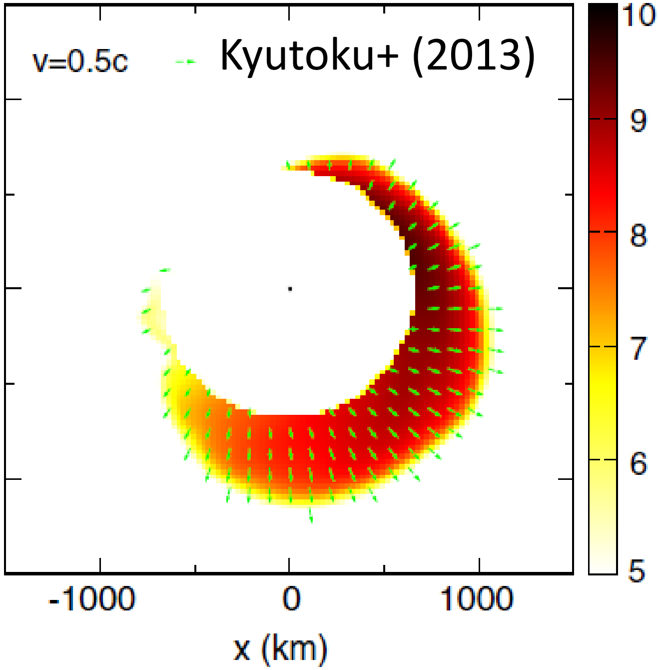
resolvable by radio instruments?

both images

expand in time

but only BH-NS

moves in time



Kyutoku+ (2013)

Heating rate

R-process elements decay back to beta-stability

- beta decay: releases about ~90% of energy

goes to electron -> totally thermalize the ejecta

neutrino -> totally escape

gamma-ray -> escape at the releant epoch

- (spontaneous) fission: releases about ~10%

nearly all the energy thermalize the material

This ratio is determined by detailed microphysics