Coalescence and explosion of compact neutron star binaries

- numerical relativity study -

Masaru Shibata

Yukawa Institute for Theoretical Physics,
Kyoto University

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

In collaboration with Hotokezaka, Kiuchi, Kyutoku, Sekiguchi

Contents

Galactic compact NS-NS observed

	PSR	P(day)	e	$M(M_{sun})$	M_1	M_2	T_{GW}
1.	B1913+16	0.323	0.617	2.828	1.387	1.441	2.45
2.	B1534+12	0.421	0.274	2.678	1.333	1.345	22.5
3.	B2127+11C	0.335	0.681	2.71	1.35	1.36	2.2
4.	J0737-3039	0.102	0.088	2.58	1.35	1.24	0.85
5.	J1756-2251	0.32	0.18	2.58	1.31	1.26	1.69

4+1(GC) NS-NS, which will merge in Hubble time (13.7 Gyr), have been found.

*10^8 yrs **Merger time**

→ **Galactic merger rate ~ $1/10^4 – 1/10^6$ yrs**

→ **Merger in the Universe ~ $10^5 – 10^7$ / yrs**

→ **Event-rate for aLIGO/VIRGO/KAGRA ~ 1 – 100 /yrs**

(e.g. Kalogera+, 2007, Belczyski+, …)

Why NS-NS/BH-NS are important ?

1. The **most promising sources of gravitational waves**
2. Invaluable **laboratory for studying high-density nuclear matter**
3. Possible origins of **short-hard GRBs**
4. Sources of strong **EM emission**

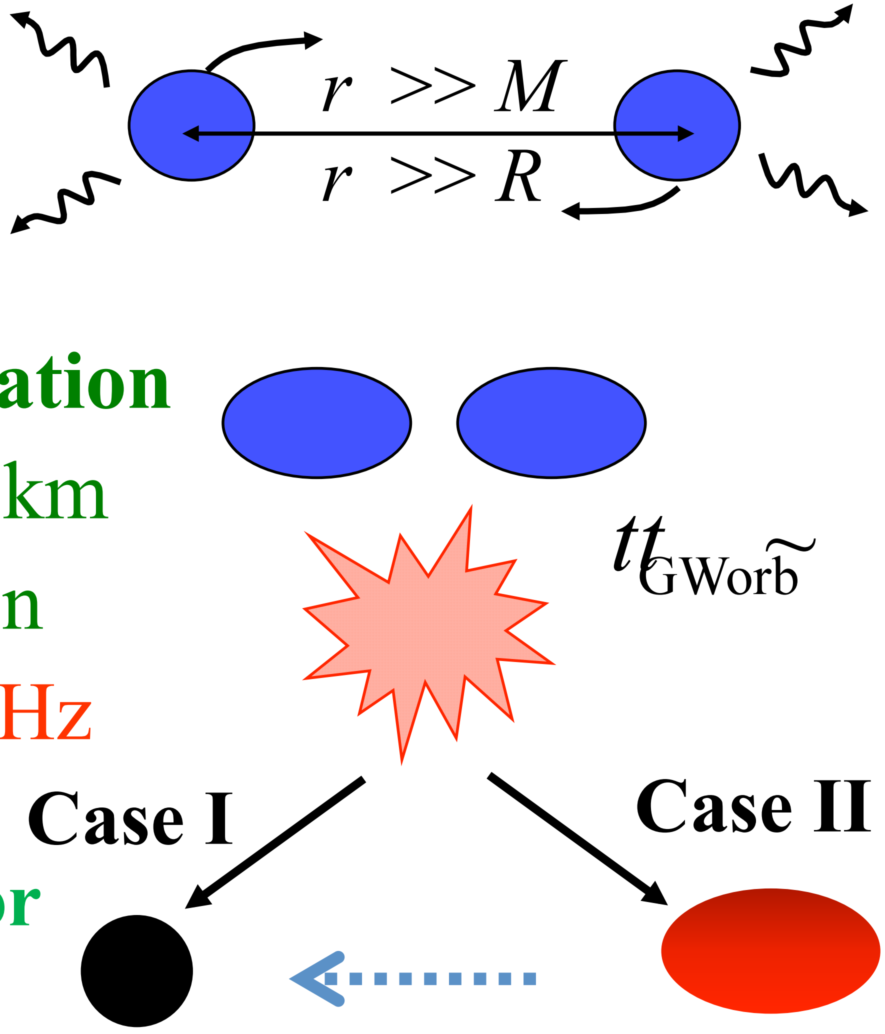
Numerical relativity plays a crucial role for all four issues.

I Gravitational waves & EOS

Status & Issues in numerical relativity

Evolution of NS-NS

Evolve by GW emission



"Inspiral"
Adiabatic evolution
$t_{GW} \gg t_{orb}$

Tidal deformation at $r \sim$ 40-50 km

Merger sets in at $f_{GW} \sim 1$ kHz

Dynamical evolution
"Merger"

High mass or Soft EOS

Black hole is formed

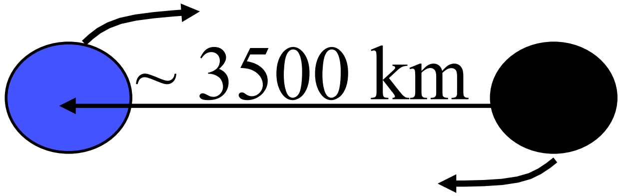
Stiff EOS

"Massive NS"

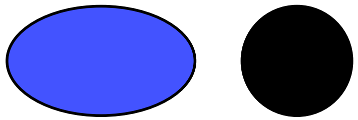
Strong dependence on EOS & mass

Evolution of BH-NS (e.g., $4.05M_{sun}$-$1.35M_{sun}$)

Evolve by
GW emission
Last 1 hour ; $f_{GW} \sim 1$ Hz

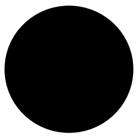


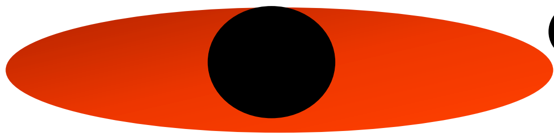
~1 hour



Merger sets in
at $r \sim 40$ km; $f_{GW} \sim 1$ kHz

Case I





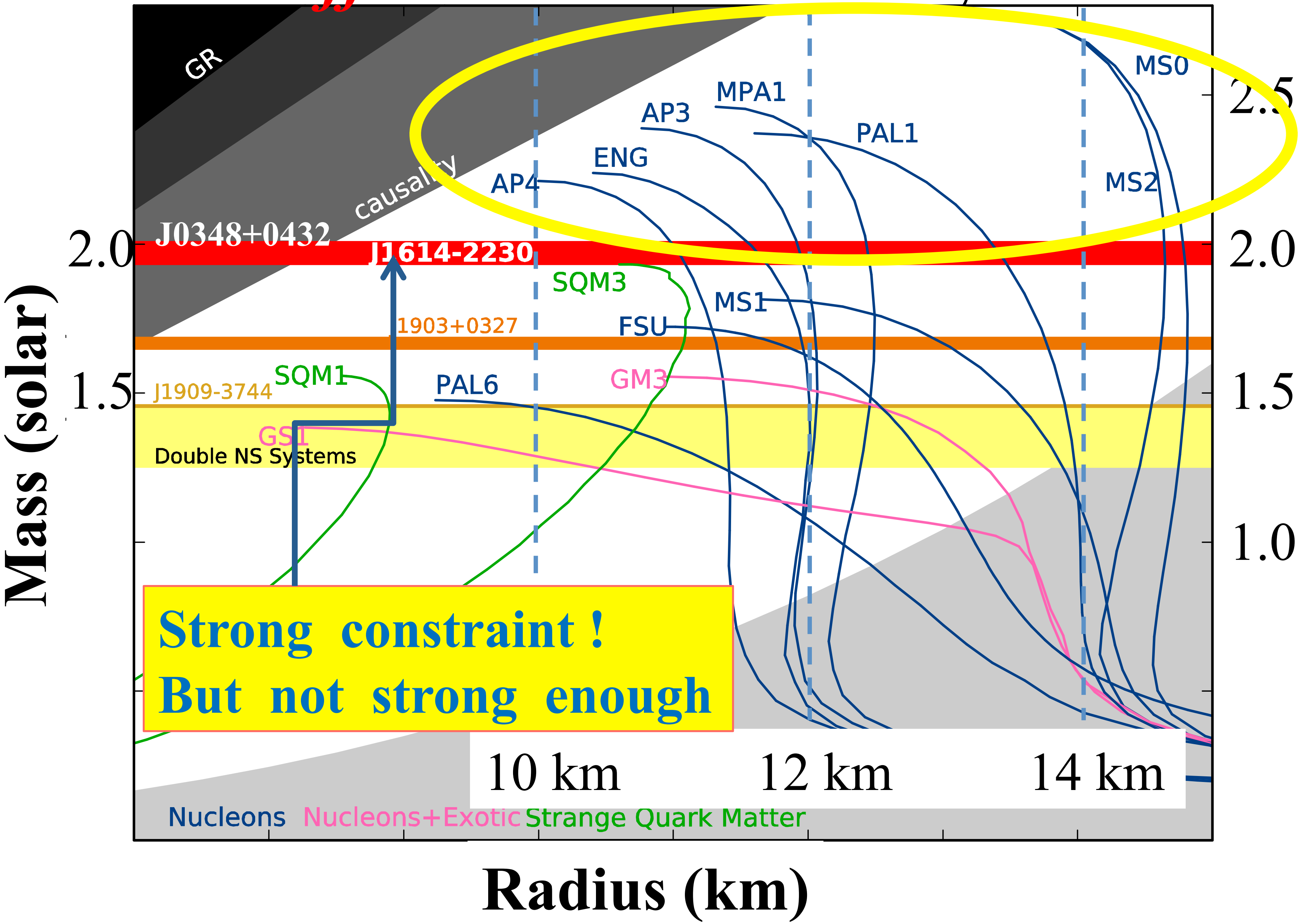
Case II

NS is swallowed by BH
for small R_{NS}* or *$M_{BH} >> M_{NS}$
or small spin (talk later)

NS is disrupted

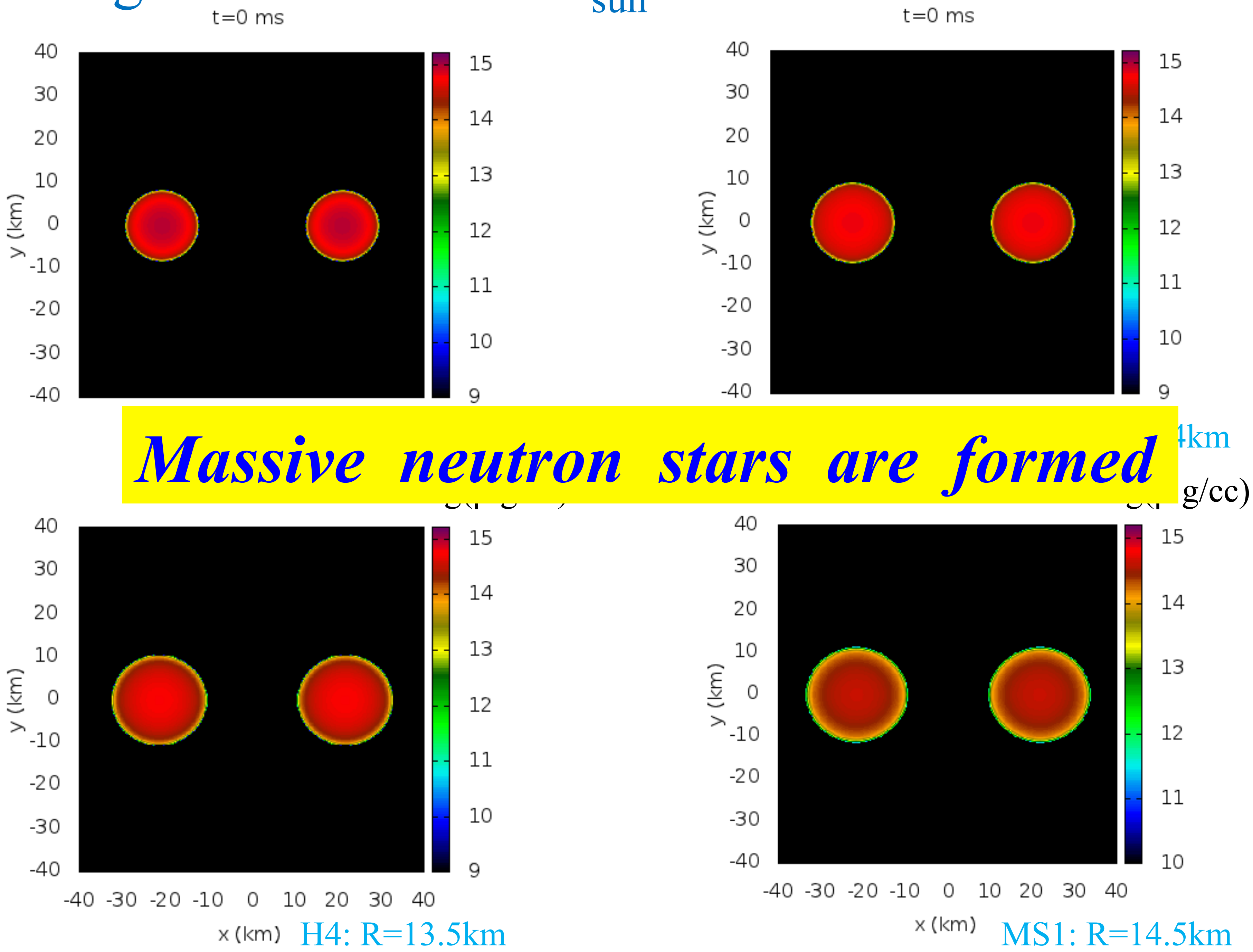
Strong dependence on EOS & spin

EOS is *stiff* : but still too many candidates



Merger of 1.35-1.35M_{sun} NS with four EOSs

By hotokezaka + 2013



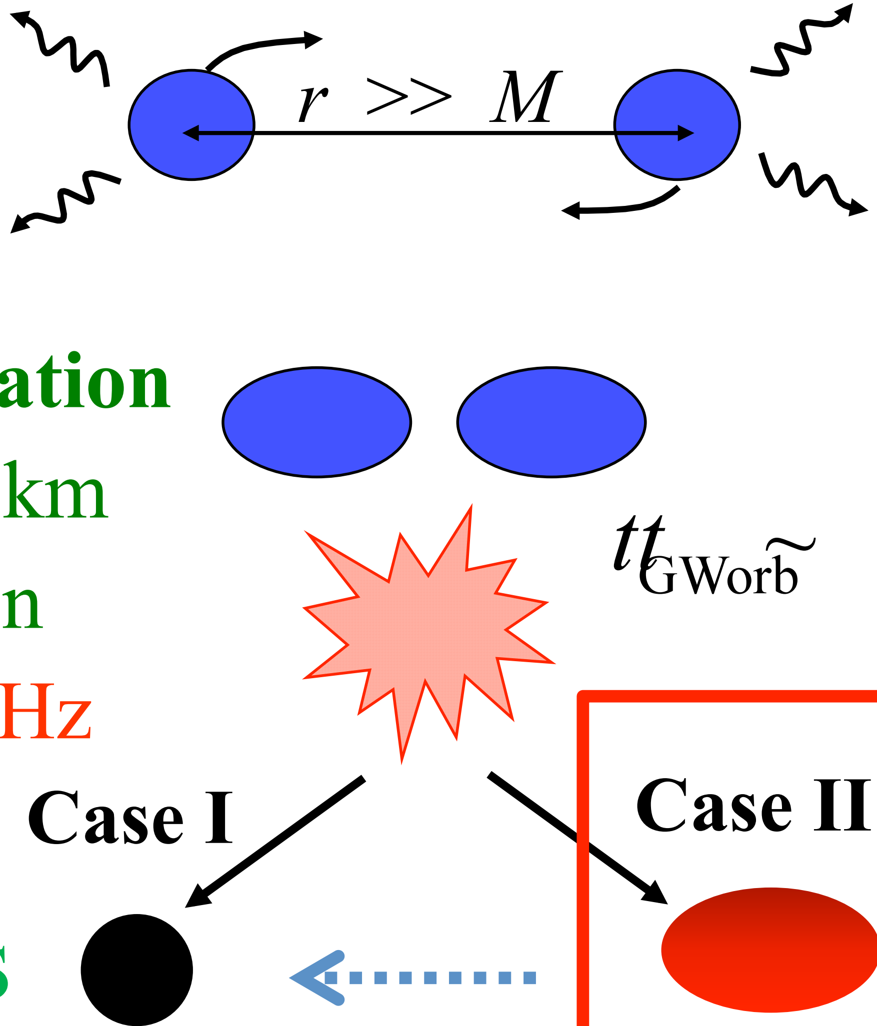
H4: R=13.5km

MS1: R=14.5km

Massive neutron stars are formed

Evolution of NS-NS with *canonical mass*

Evolve by
GW emission



Adiabatic
evolution

$t_{GW} \gg t_{orb}$

Tidal deformation
at $r \sim$ 40-50 km

Dynamical
evolution

$t_{GW} \sim t_{orb}$

Merger sets in
at $f_{GW} \sim 1$ kHz

Soft EOS

Black hole is formed

Stiff EOS

"Massive NS"

Two interesting phases

1. Late Inspiral (Lai+, Hinderer+, Damour+, Baiotti+, Bernuzzi+) **:**

Effects of *tidal deformation*

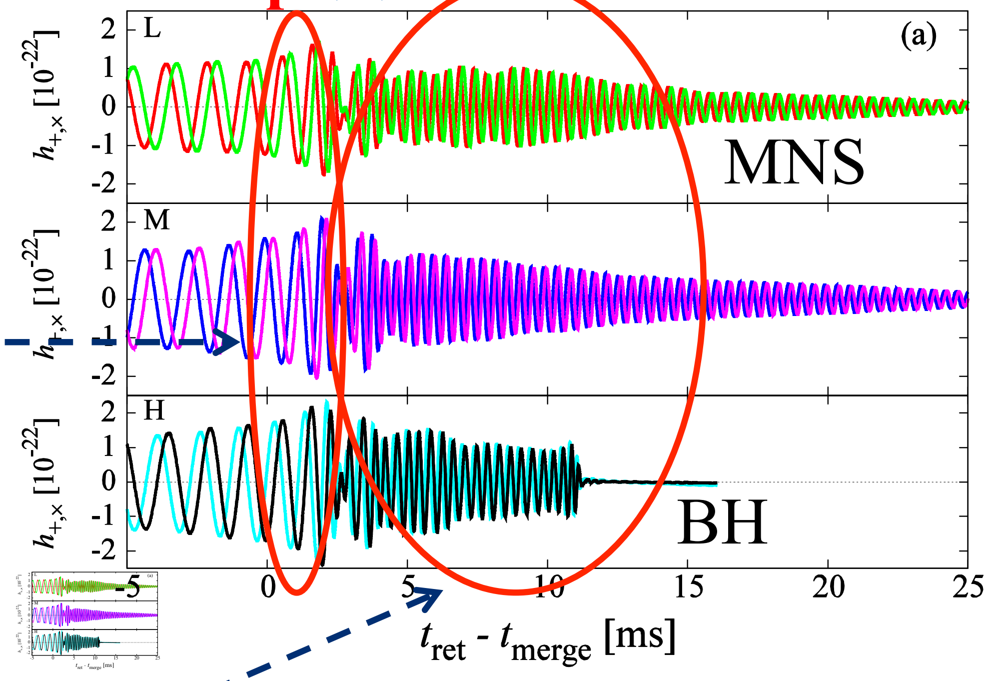
***f* ~ 500 – 1k Hz**

2. Merger → MNS

(Janka+, Hotokezaka+)

Quasi-periodic GW from *MNS* : *f* ~ 2k – 4k Hz

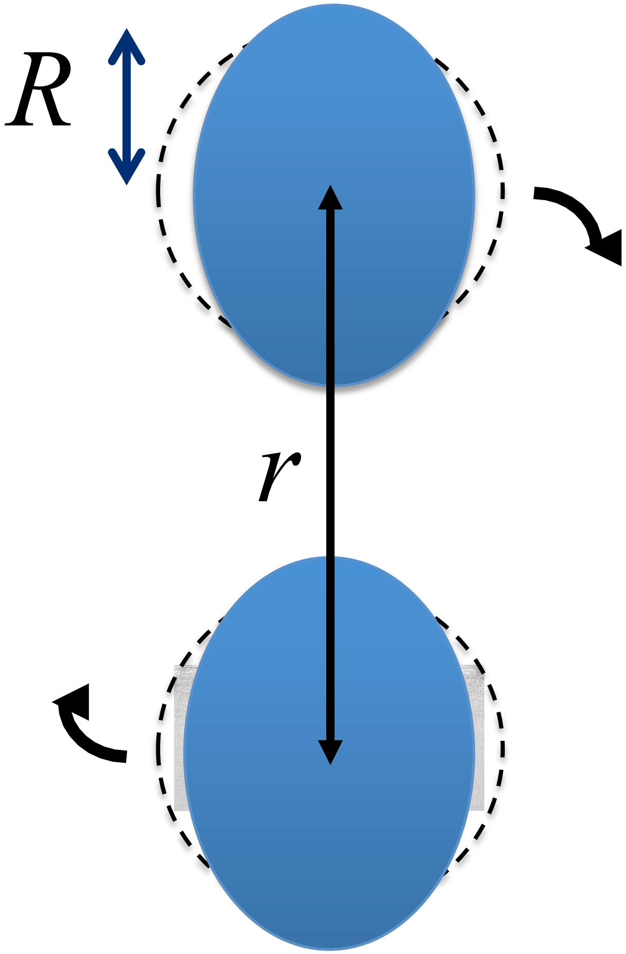
Chirp ↔ GWs from MNS



Both waveforms could be used for constraining EOS of neutron stars

Tidal effects in a binary inspiral

(originally pointed out by Lai+ 1992)



Close Binary System

→ Tidal deformation

→ Quadrupole is induced

$$A \sim 2\frac{GM}{r} 2 \frac{C}{r^6}$$

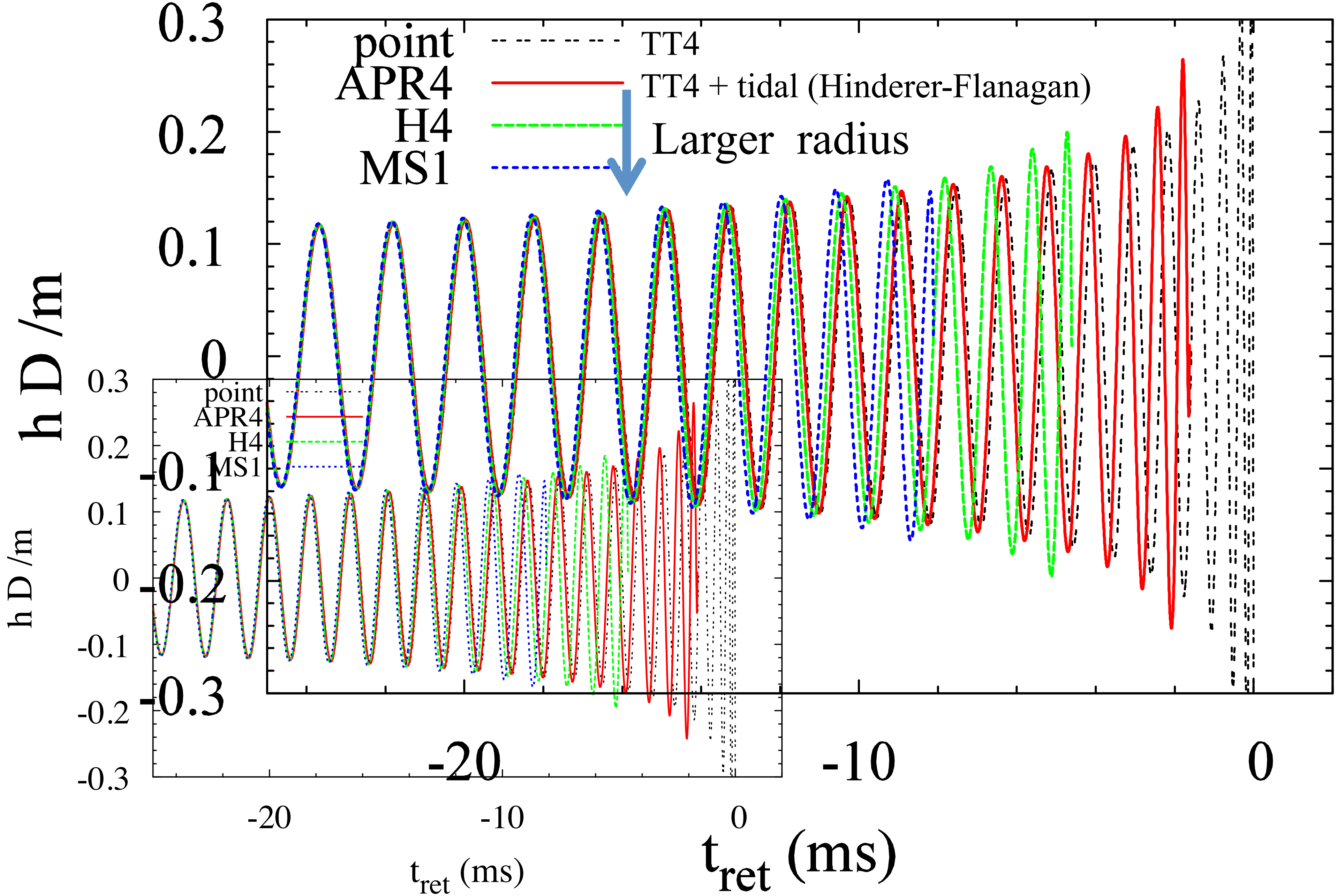
5PN correction (very high):

But $C \sim MR^5$, $R \sim 5$—$8\,M$

For $r \sim 2R$, it could play a role.

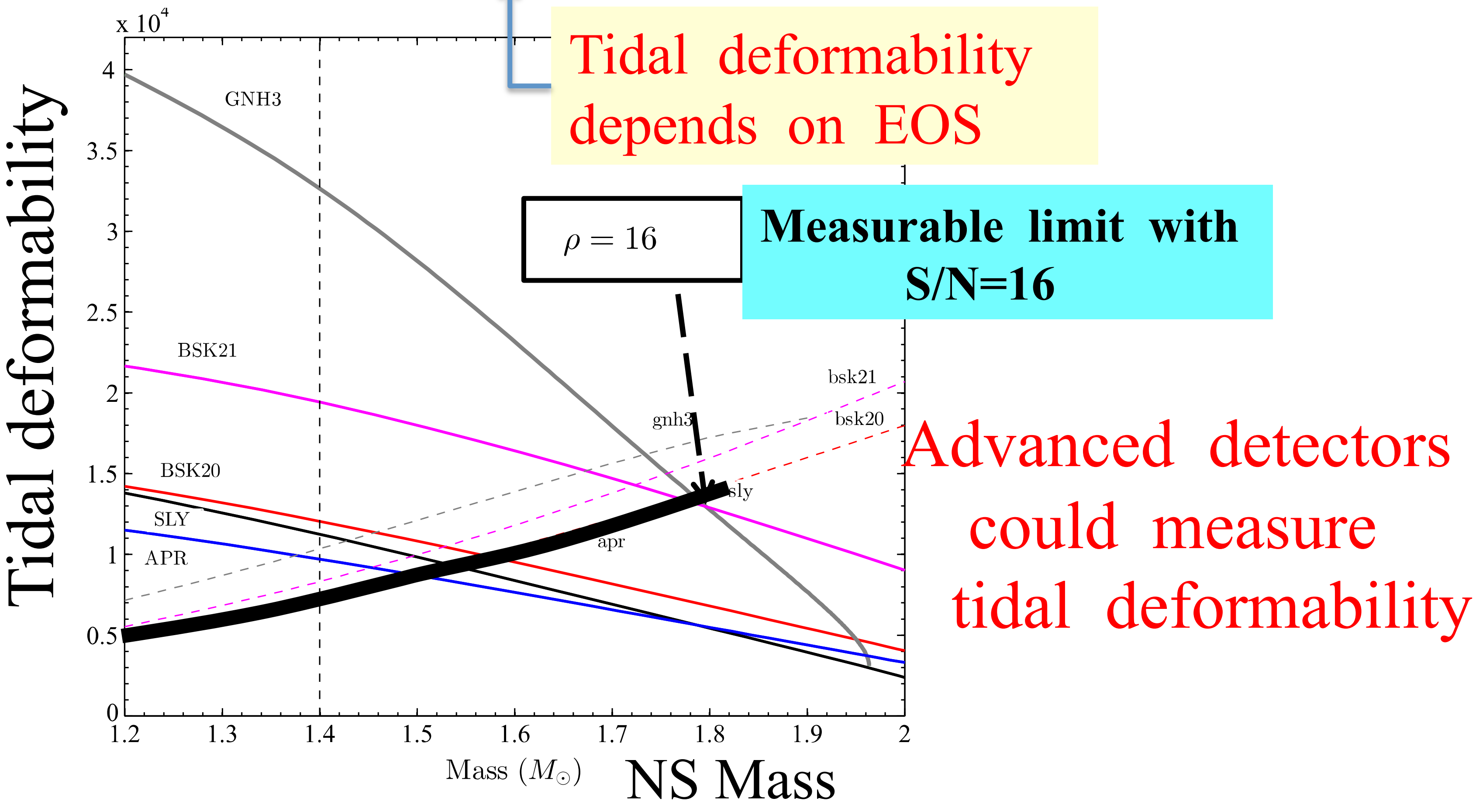
$$h = h(M_1, M_2, C_1, C_2)$$

Late-phase chirp signal



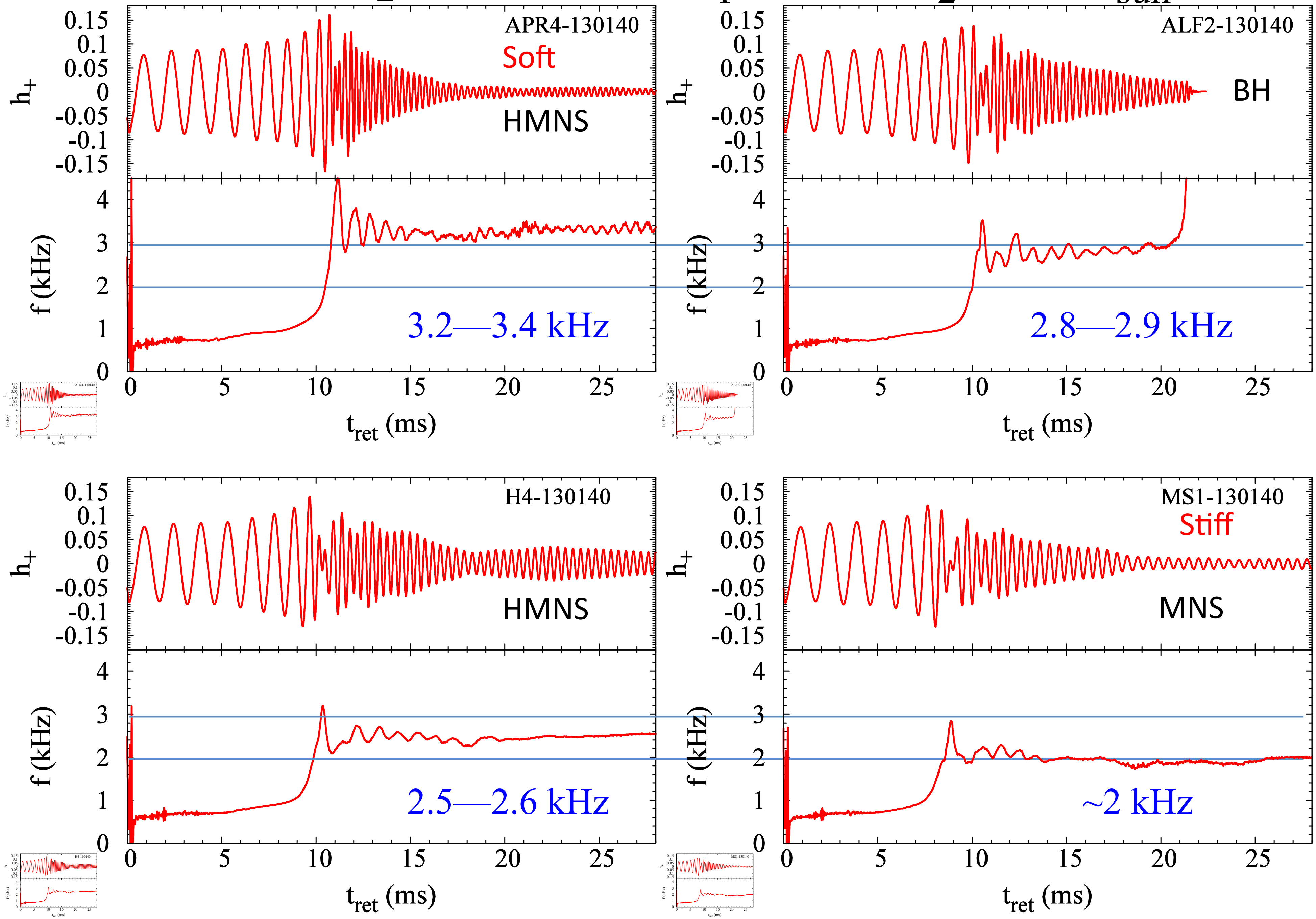
Latest EOB study (Damour, Nagar + 2012)

A static tidal approximation:
Quadrupole moment = **−λ** (tidal field); linear approx.

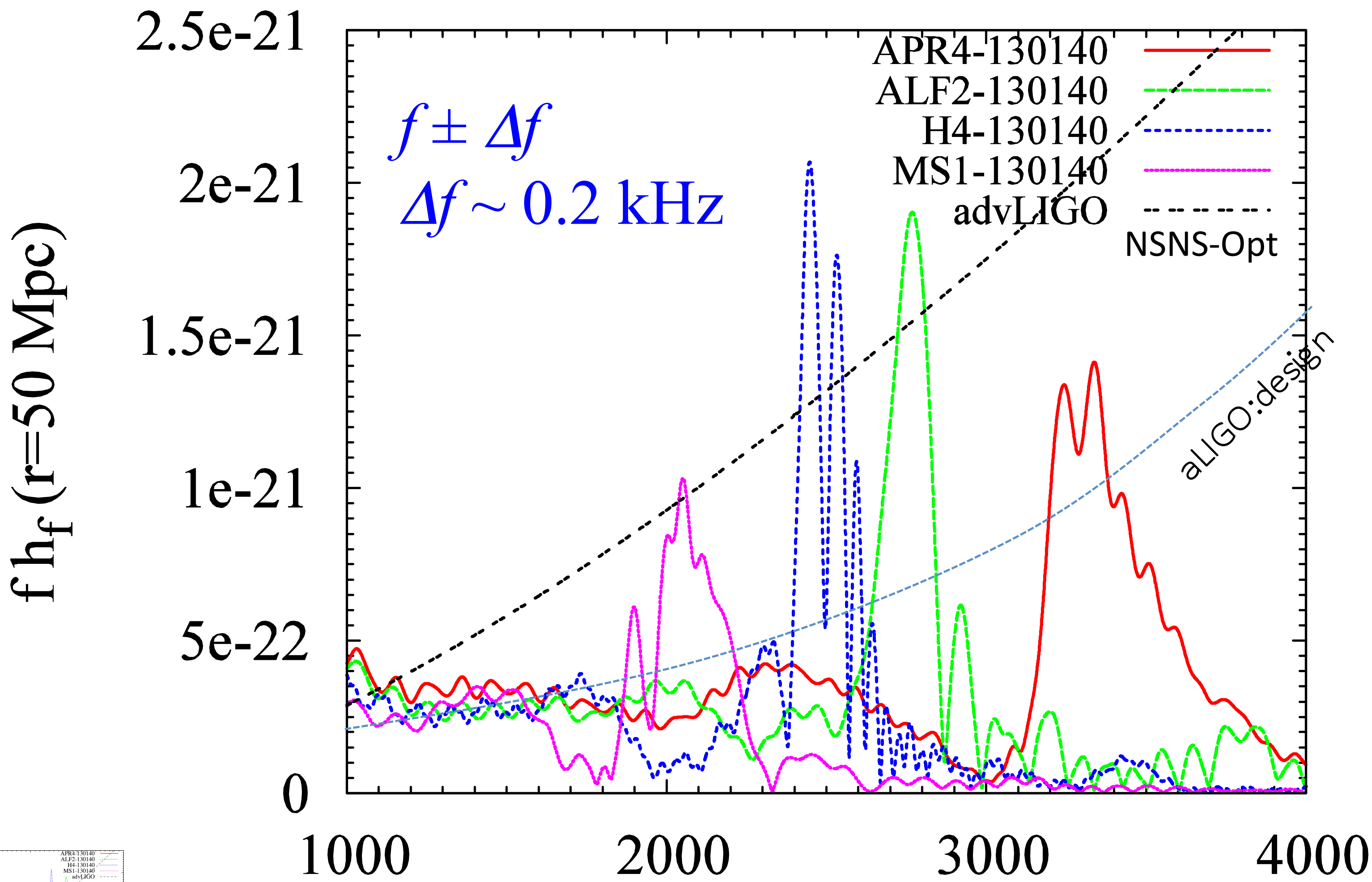


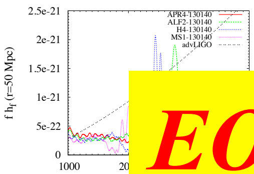
Numerical relativity calibrates this result
(Bernuzzi+, Hotokezaka+)

EOS dependence: M_1=1.3, M_2=1.4M_{sun}



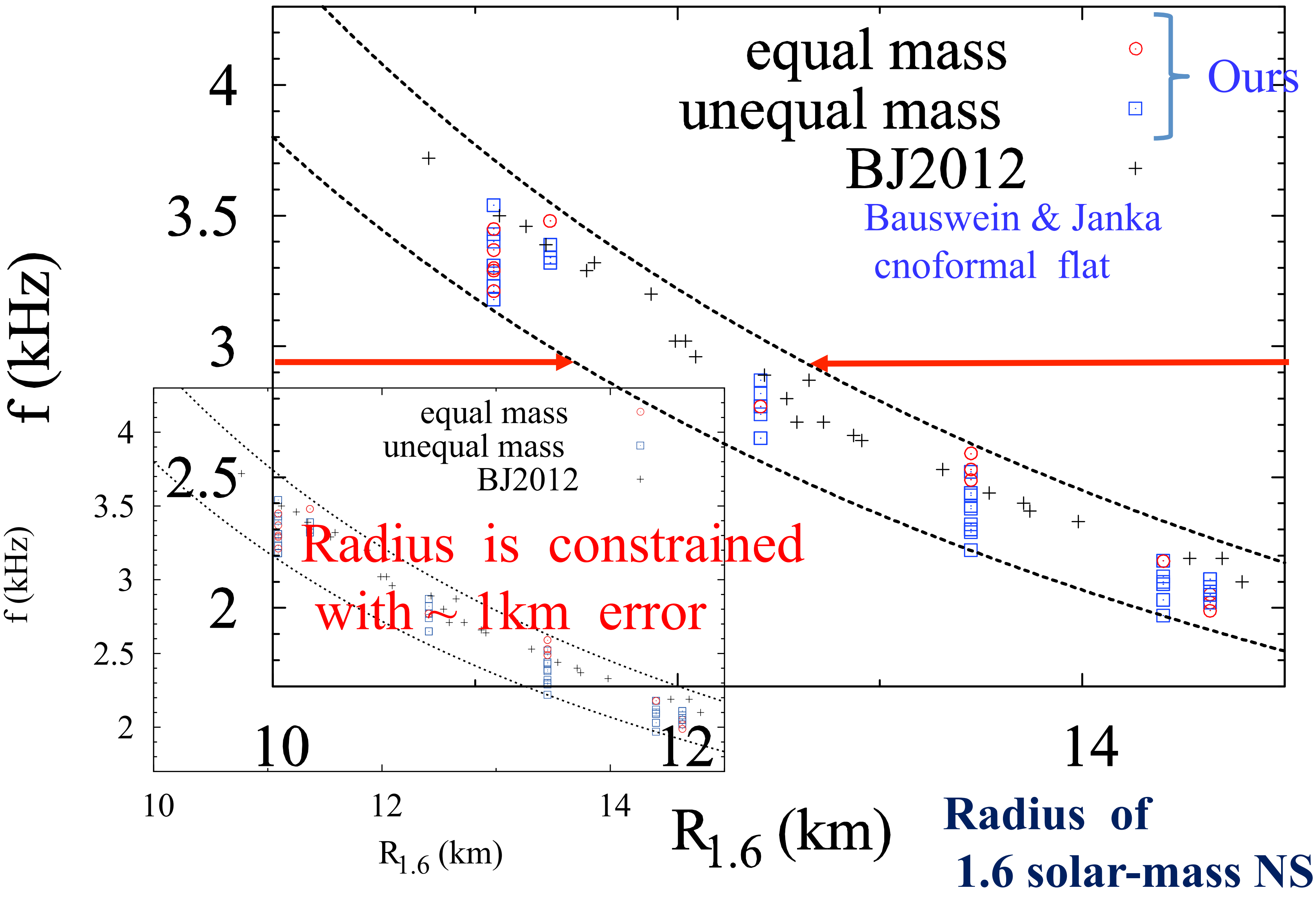
Fourier spectrum





EOS is reflected in the typical frequency

Relation between peak and radius



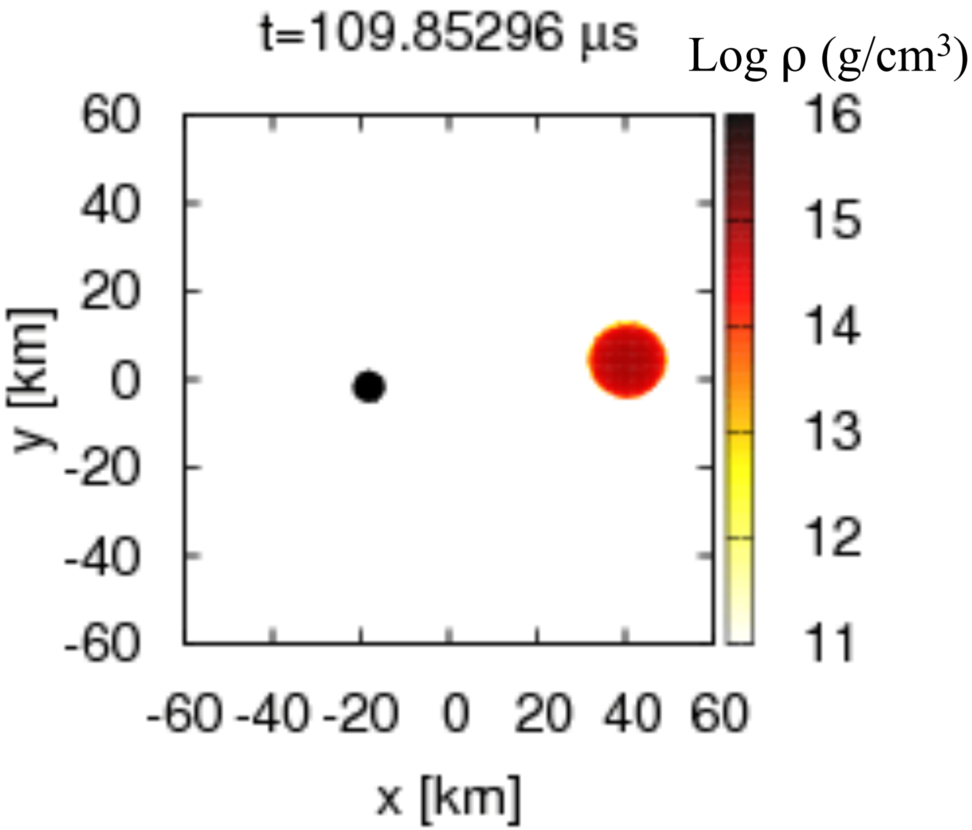
GWs from NSNS: summary

- If $D < 100$ Mpc, **late inspiral waveforms** could be used to constrain EOS (aLIGO/VIRGO/KAGRA)
- If $D < \sim 30$ Mpc, **merger waveforms** could be used to constrain EOS (aLIGO/VIRGO/KAGRA)
- ET will be the robust detector for exploring EOS of NS

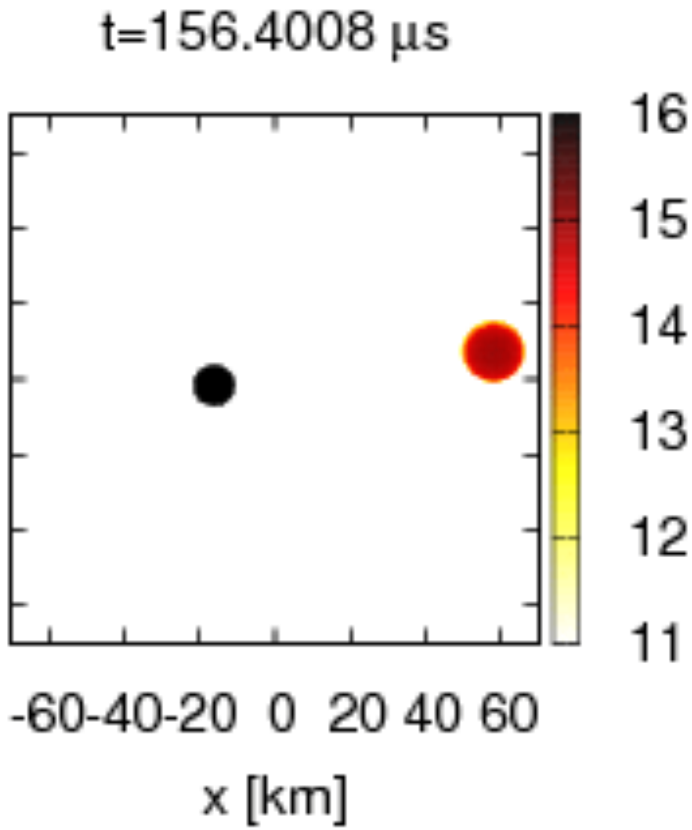
BH-NS binary (zero BH spin)

Piece-wise polytropic EOS

$M_{BH}=2.7M_{sun}$
$M_{NS}=1.35M_{sun}$
***R*=11.6 km, *Q*=2**



$M_{BH}=4.05M_{sun}$
$M_{NS}=1.35M_{sun}$
***R*=11.0 km, *Q*=3**

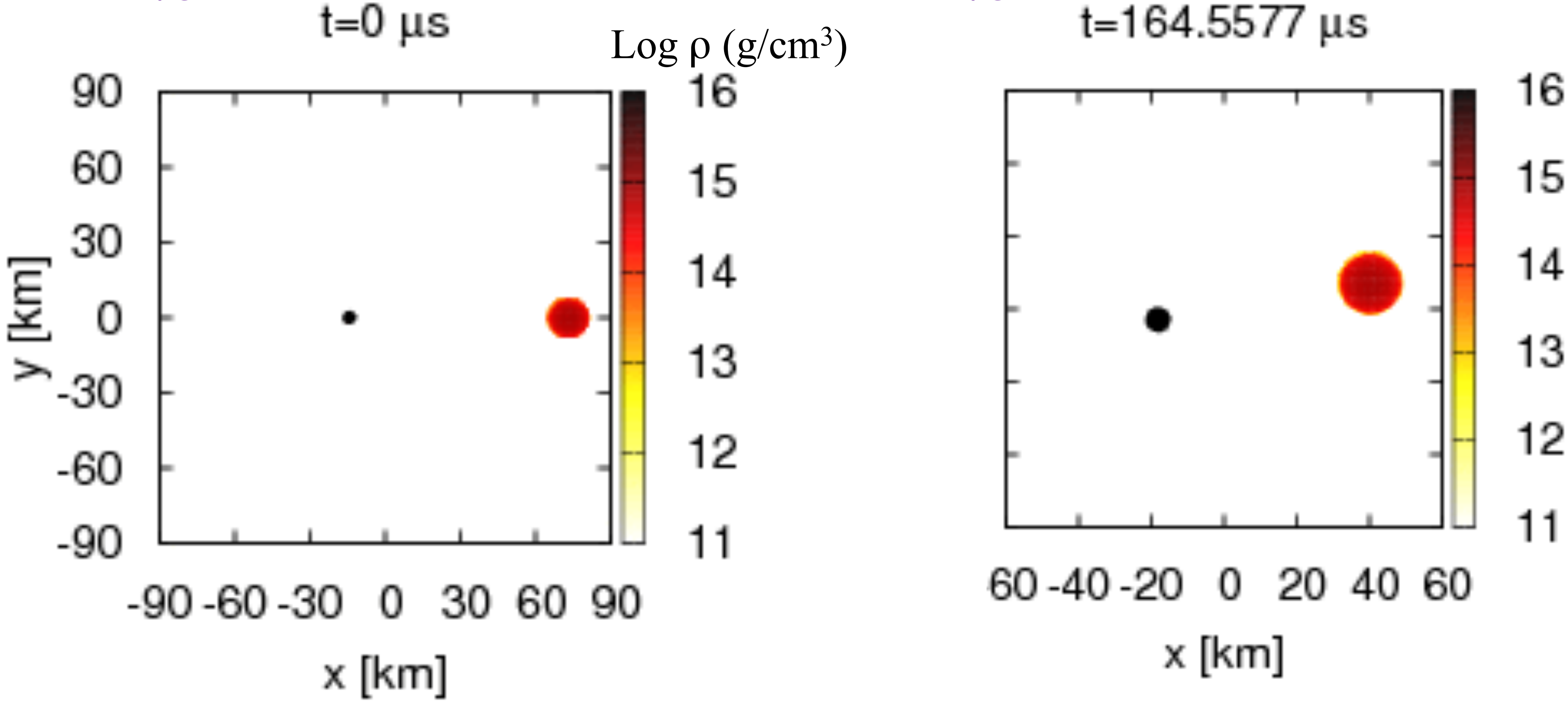


Kyutoku + PRD 2011: See also Etienne +, Duez, Foucart +

Spinning BH-NS; more promising

M_{BH}=5.4M_{sun}
***a*=0.75, *Q*=4**
M_{NS}=1.35M_{sun}
R=11.6 km

M_{BH}=2.7M_{sun}
***a*=−0.5, *Q*=2: Counter rot**
M_{NS}=1.35M_{sun}
R=11.6 km



Kyutoku + PRD 2011: Piece-wise polytropic EOS

Condition for tidal disruption

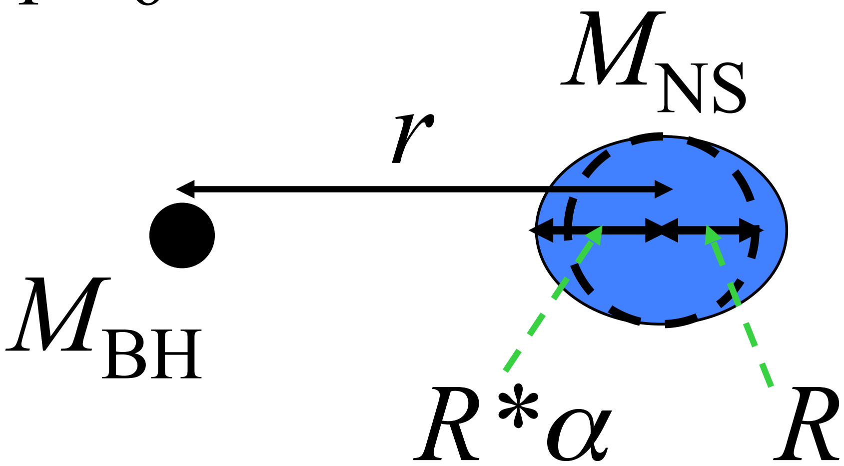
BH tidal force > NS self-gravity

$$Q := \frac{M_{BH}}{M_{NS}} \lesssim \left(\frac{\alpha R c^2}{6 G M_{NS}}\right)^{3/2} \approx \left(\frac{\;\;\;\;^{2}}{61.5}\right) \left(\frac{\alpha}{\;\;}\right)^{3/2}$$

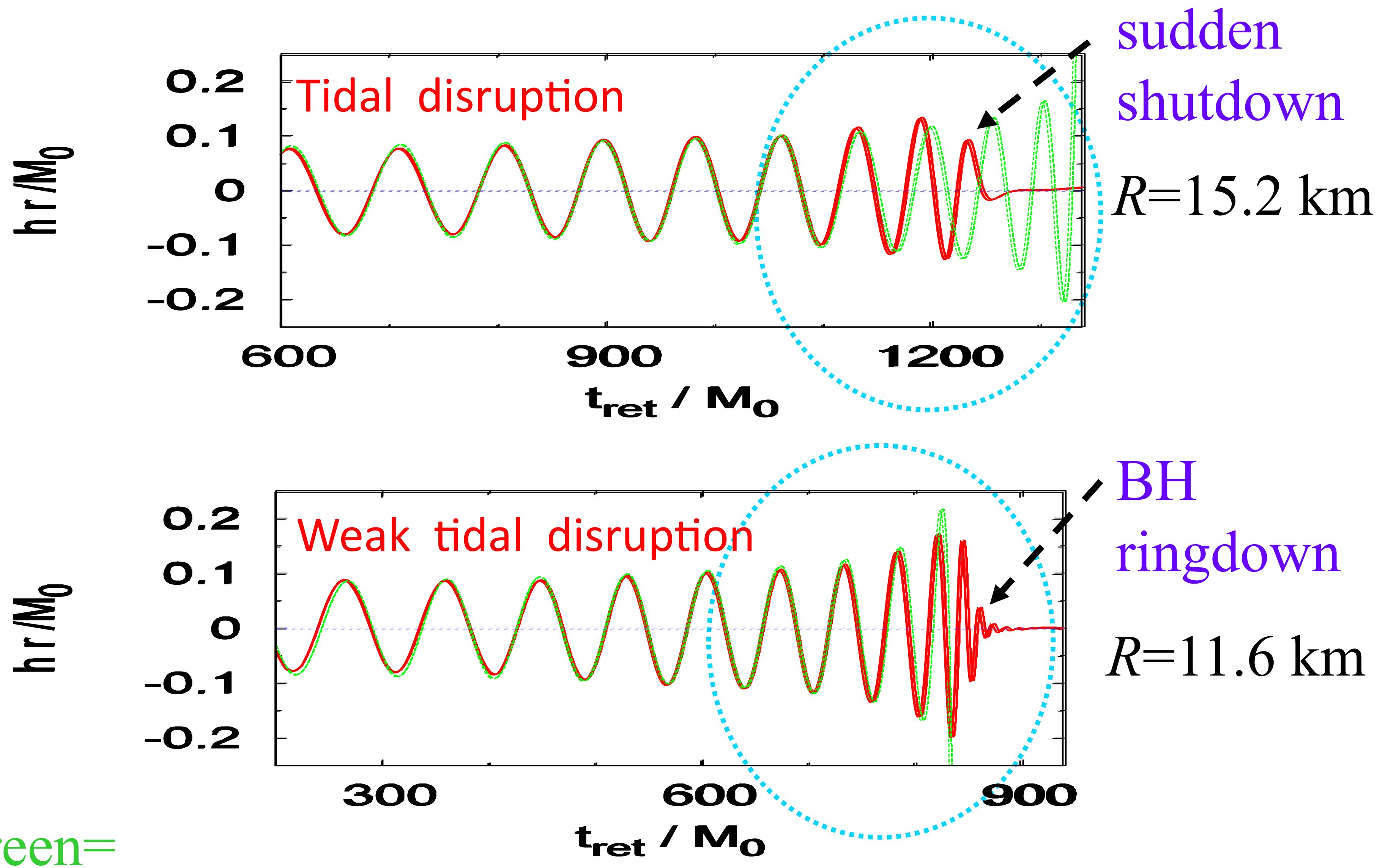
$1 \sim 6$

- ✓ **Low-mass BH** or
- ✓ **Large NS radius** or
- ✓ **Large BH spin**

is necessary



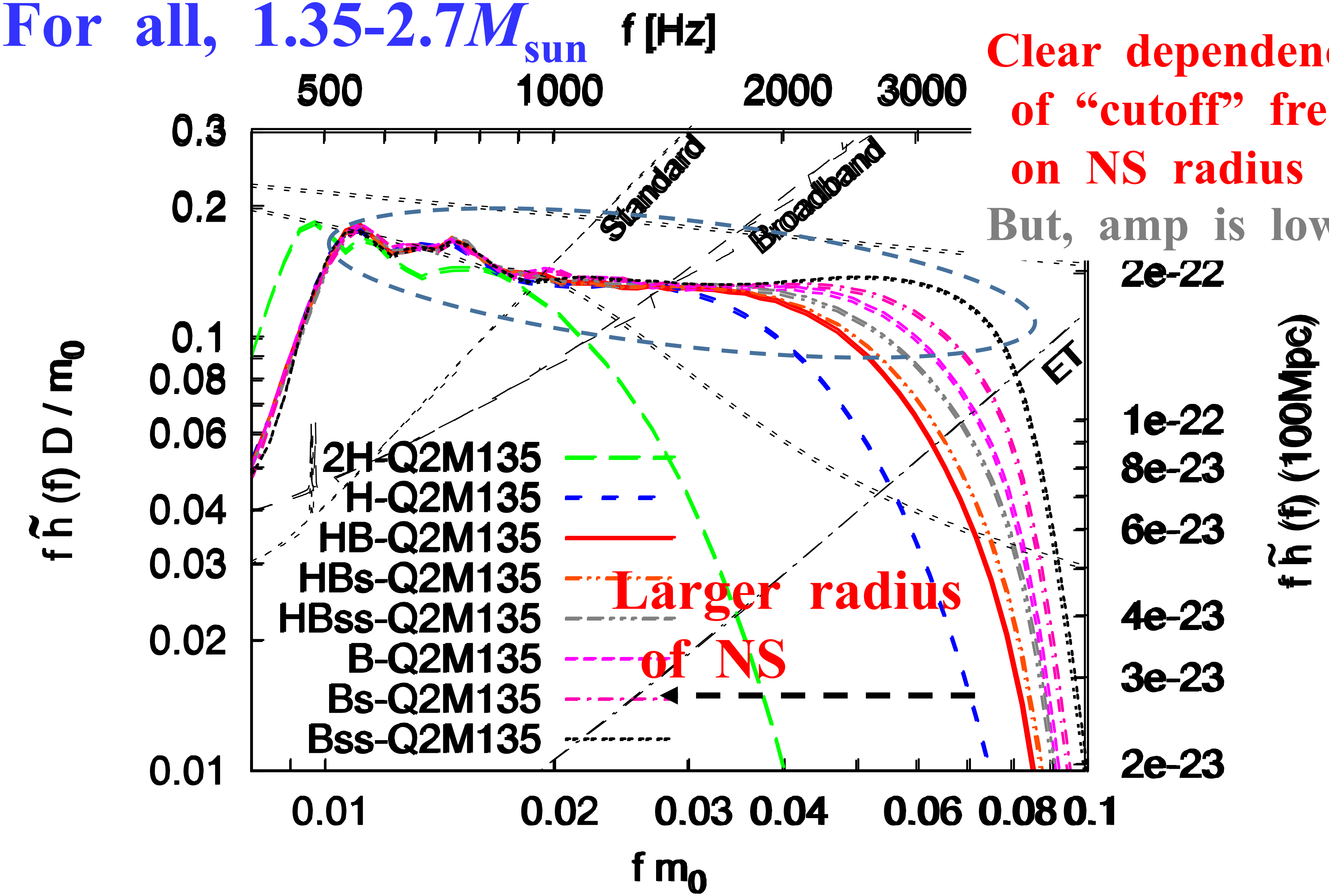
$M_{\rm BH}$=2.7$M_{\rm sun}$, a=0, $M_{\rm NS}$=1.35$M_{\rm sun}$



Green=
Tayloy T4 (point particle + PN)

BH-NS with piecewise polytrope (a=0)

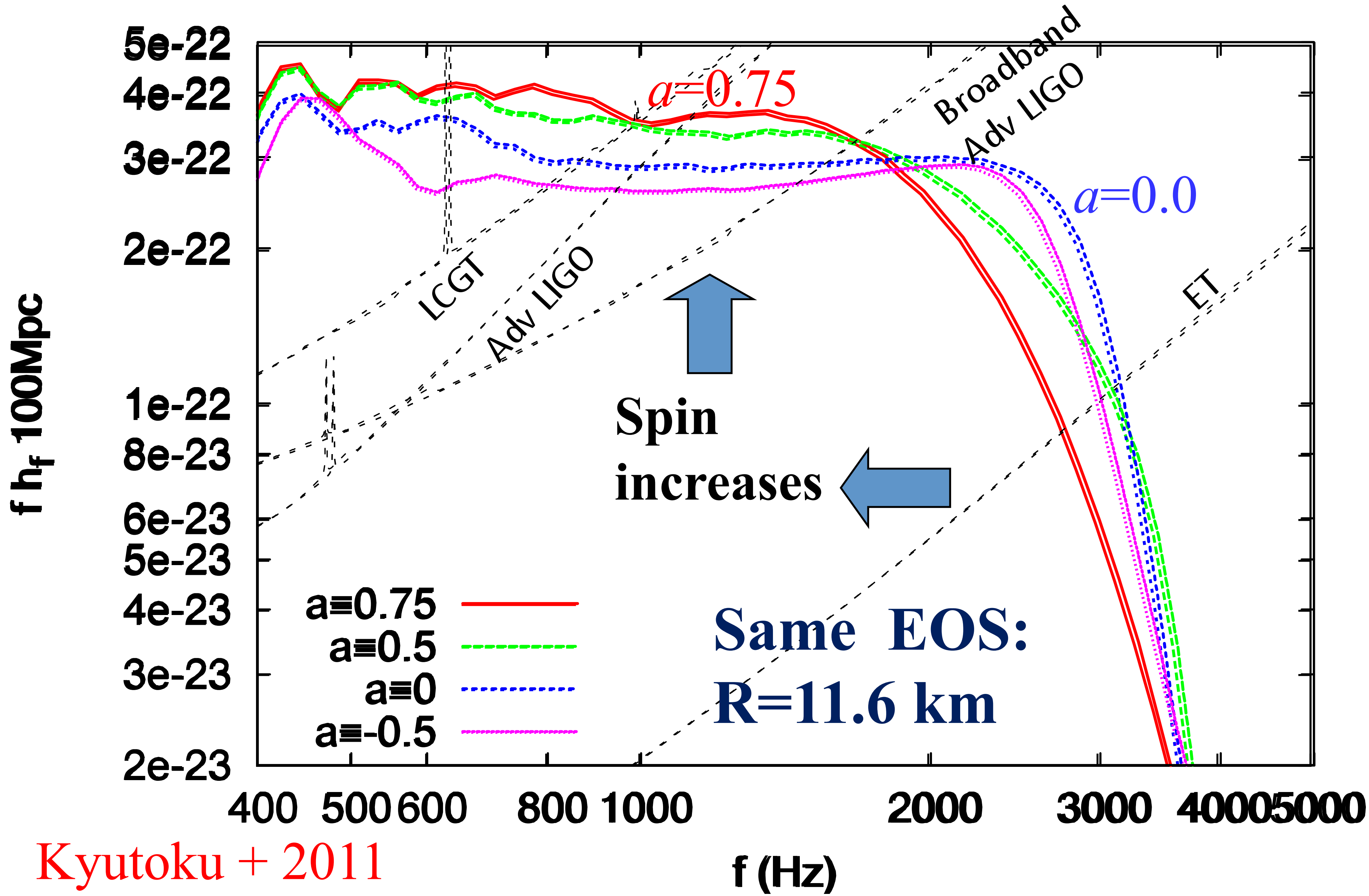
For all, 1.35-2.7M_{sun}



Clear dependence of "cutoff" freq. on NS radius

But, amp is low…

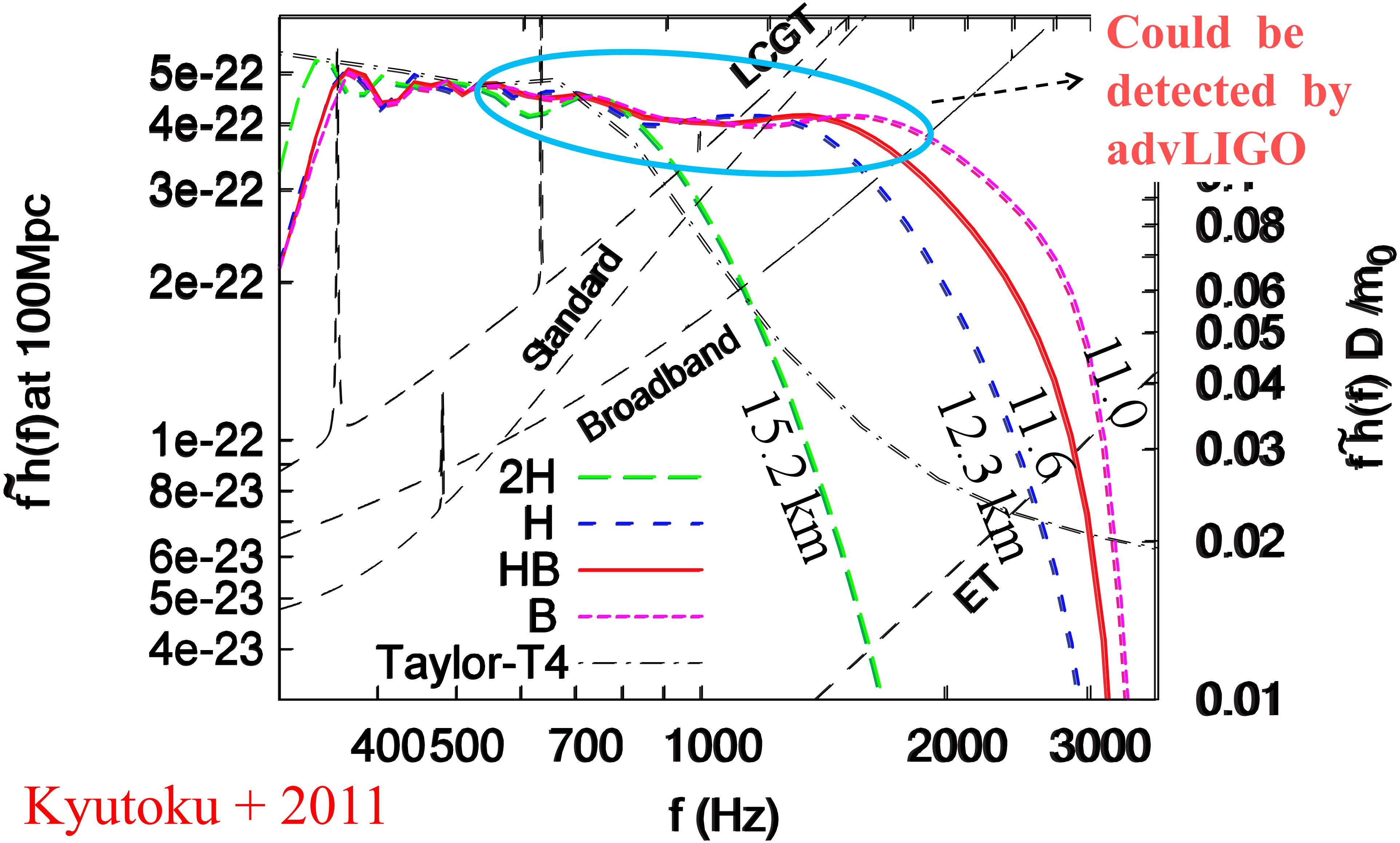
GW spectrum for Q=3, M_{NS}=1.35M_{sun}



Kyutoku + 2011

With BH spin & high-mass BH

For all, a=0.75 1.35 – 5.4M_{sun}

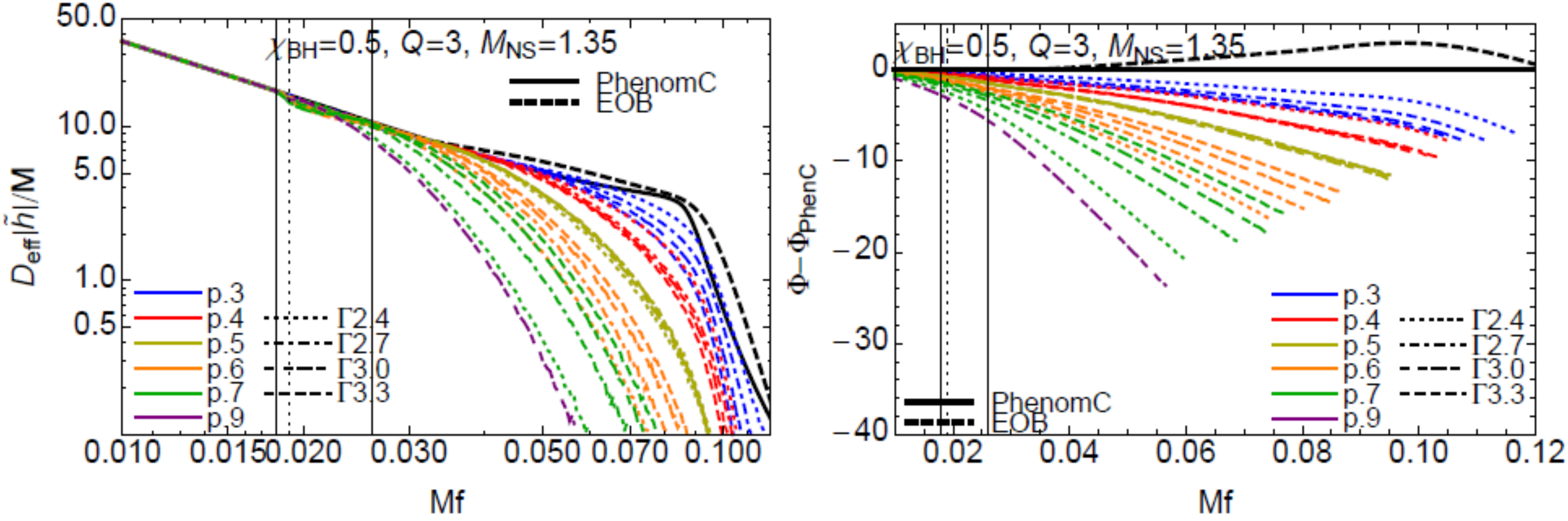


Kyutoku + 2011

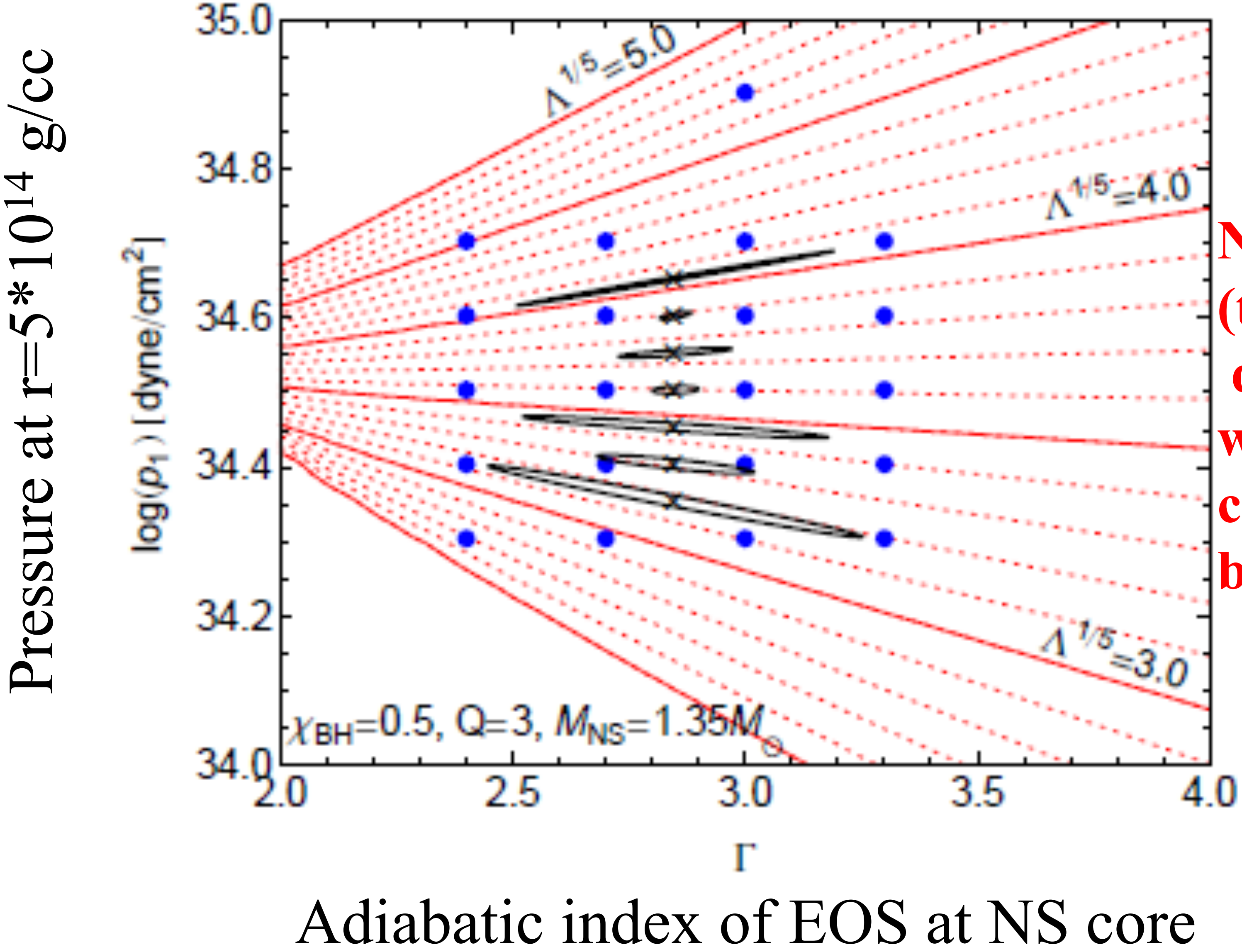
Latest systematic study (Lackey, Kyutoku+ '13)

> 100 simulations

For all, a=0.50 1.35 – 4.05M_{sun}



Fisher analysis with hybrid waveforms
(Lackey, Kyutoku + '13)



NS radius (tidal deformability) will be constrained by ET

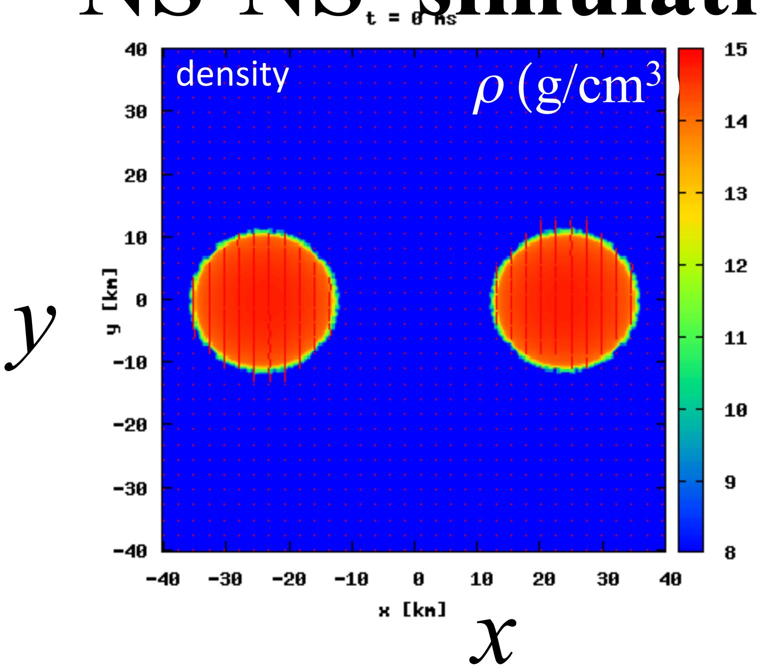
GWs from BH-NS binaries

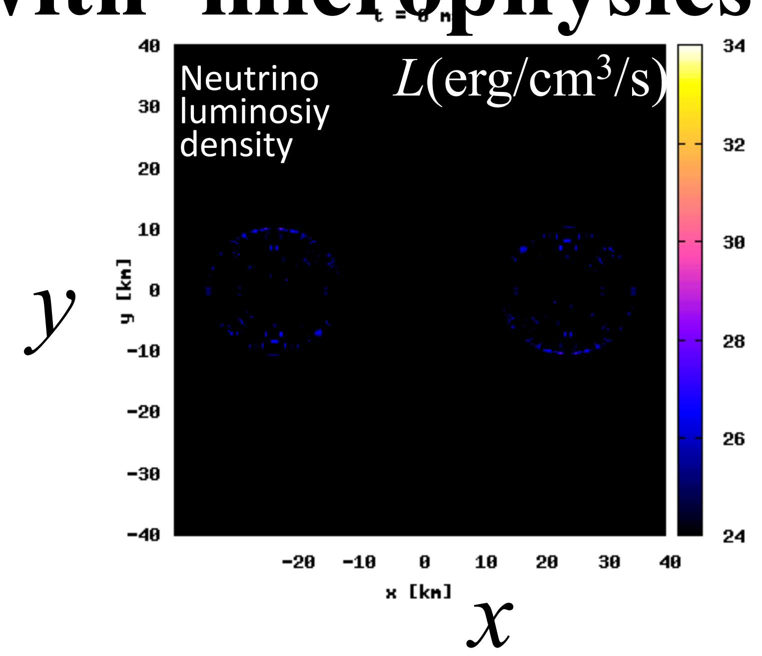
- For the case that tidal disruption occurs, GWs have a characteristic feature
- Tidal disruption occurs only for low-mass BH for *zero BH spin*.
  But, tidal disruption occurs for a realistic mass of BH is BH spin > ~0.5
- GWs from tidal disruption events could be used for constraining EOS
- In particular, ET will be powerful

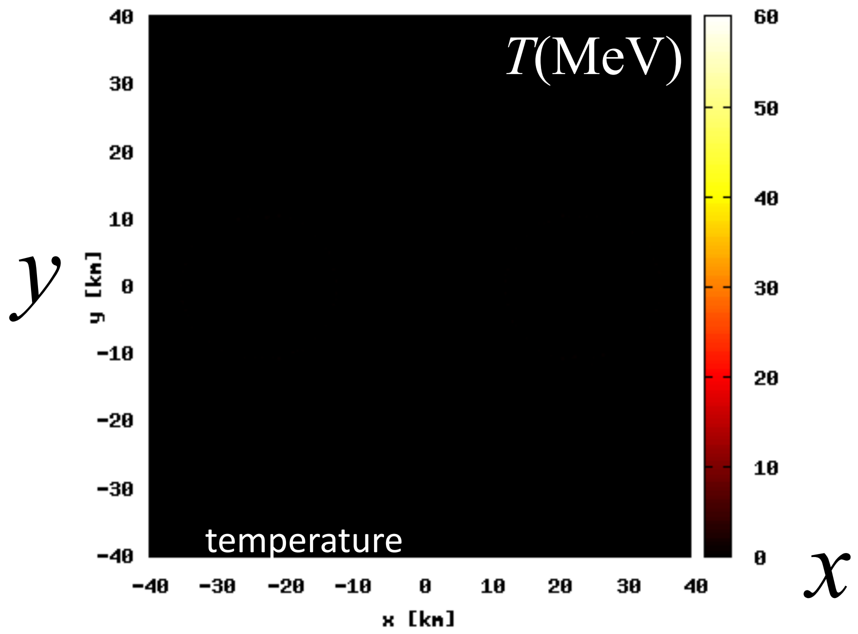
II Merger as high-energy phenomena:

Theoretical study for short-hard GRB models

NS-NS simulation with microphysics



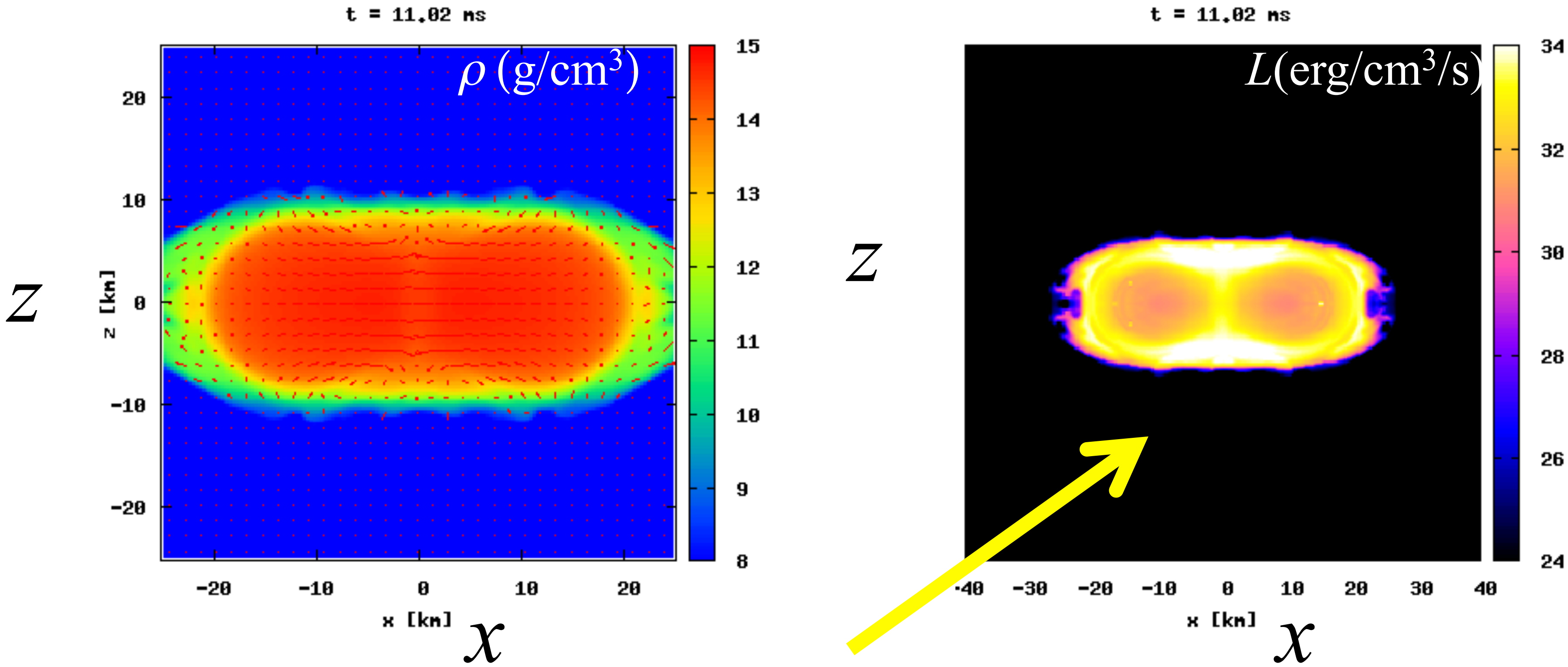




Sekiguchi, Kiuchi,
Kyutoku, Shibata
PRL107, 2011

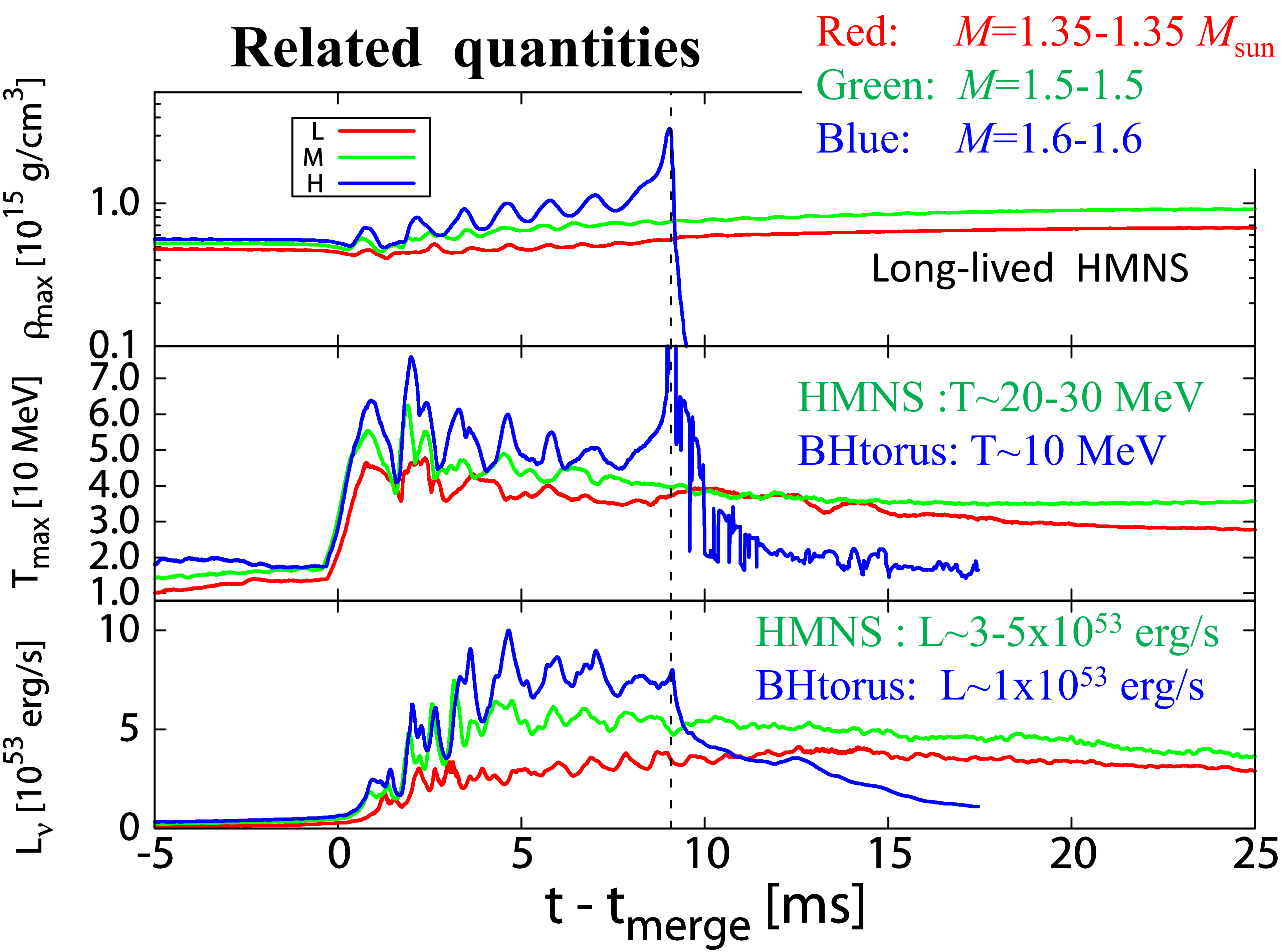
NS-NS simulation with microphysics

Contour in *x-z* plane; only after the merger



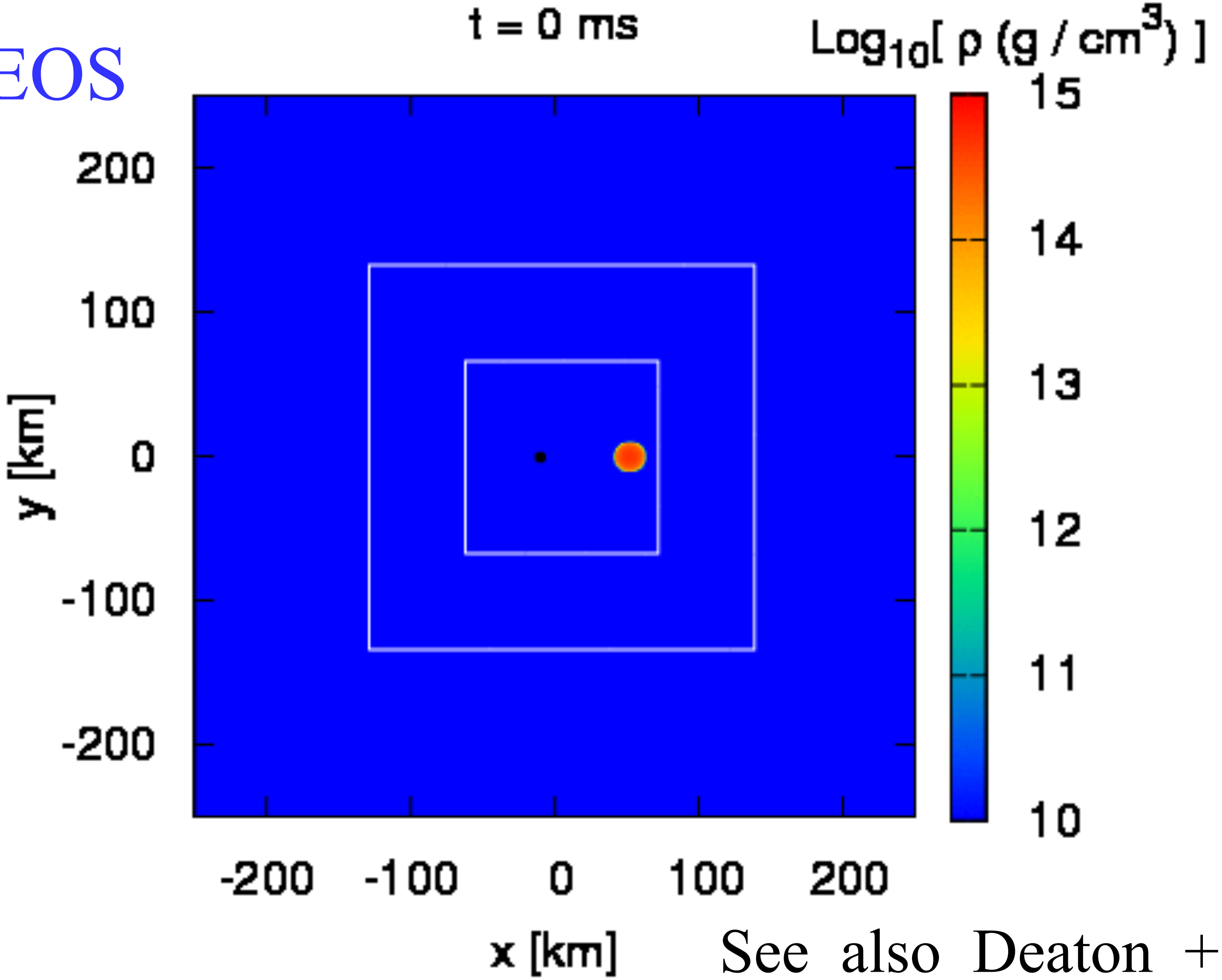
- **High-neutrino luminosity near pole** (white region)
- Now, no neutrino heating, pair annihilation

Related quantities



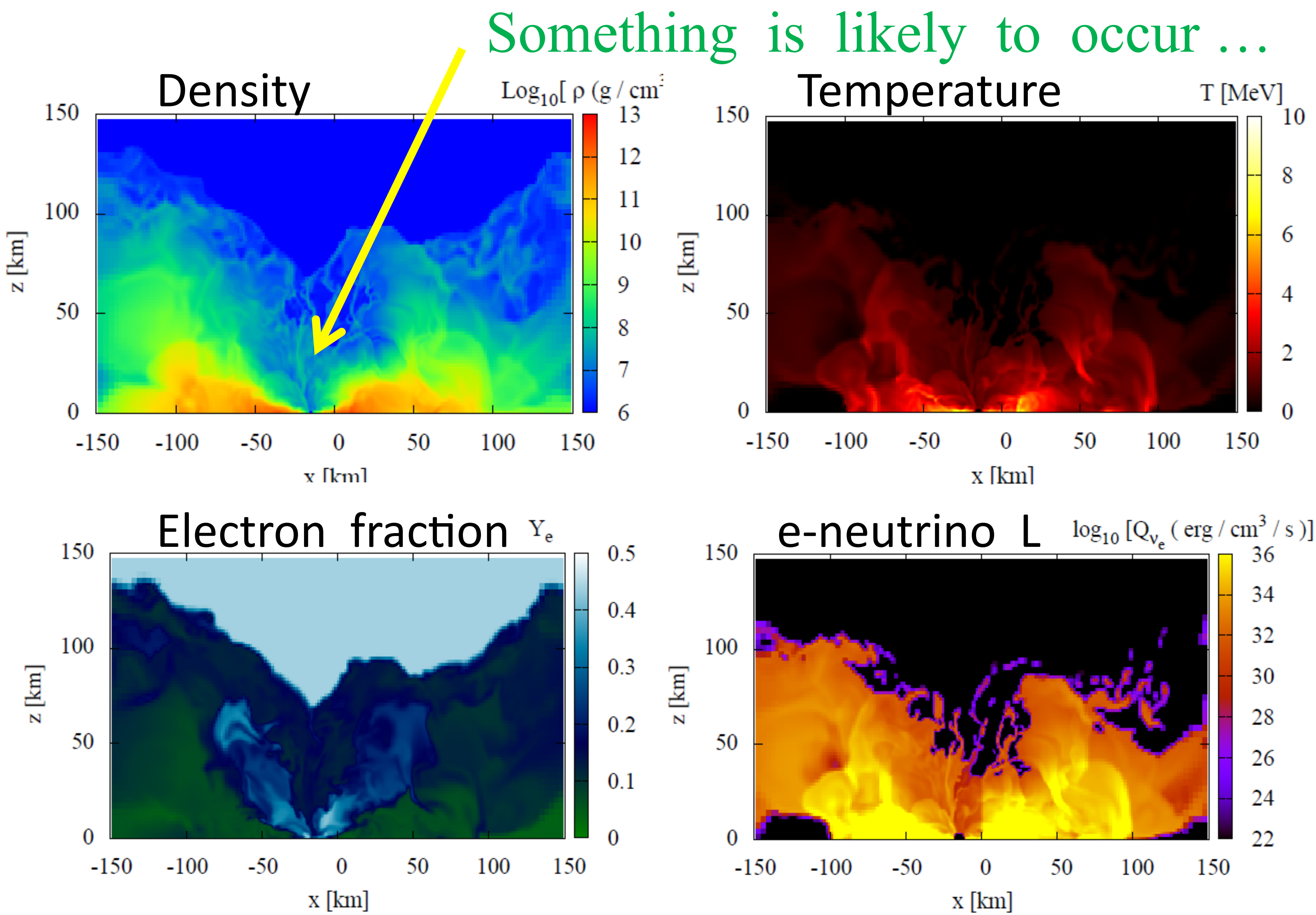
BH(a=0, M=4.05M_{sun}) — NS(1.35M_{sun}): New

Shen's EOS



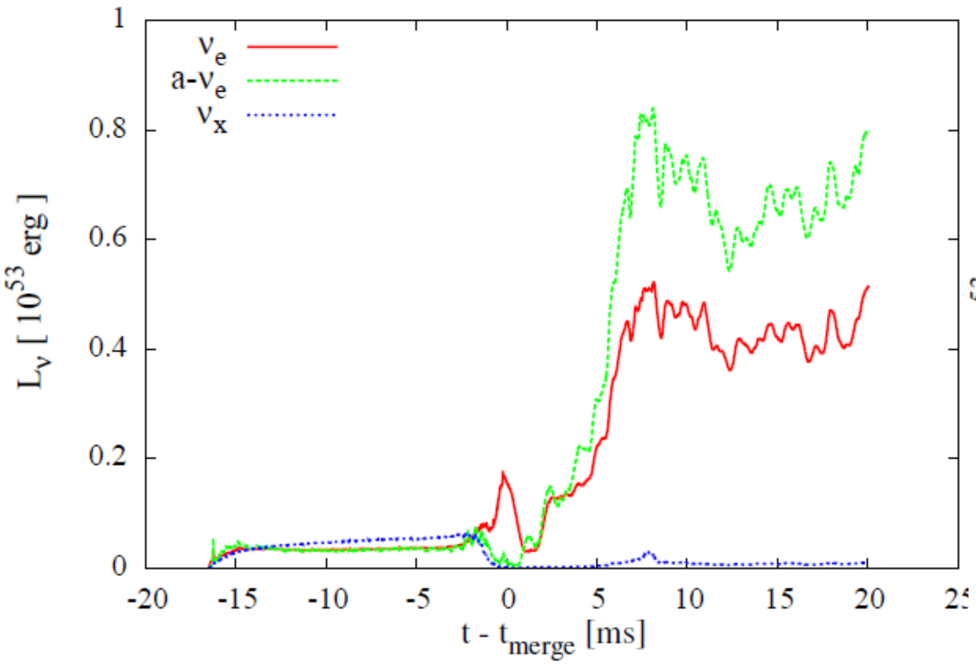
See also Deaton + (2013) for other work

Kiuchi et al. (2013?)

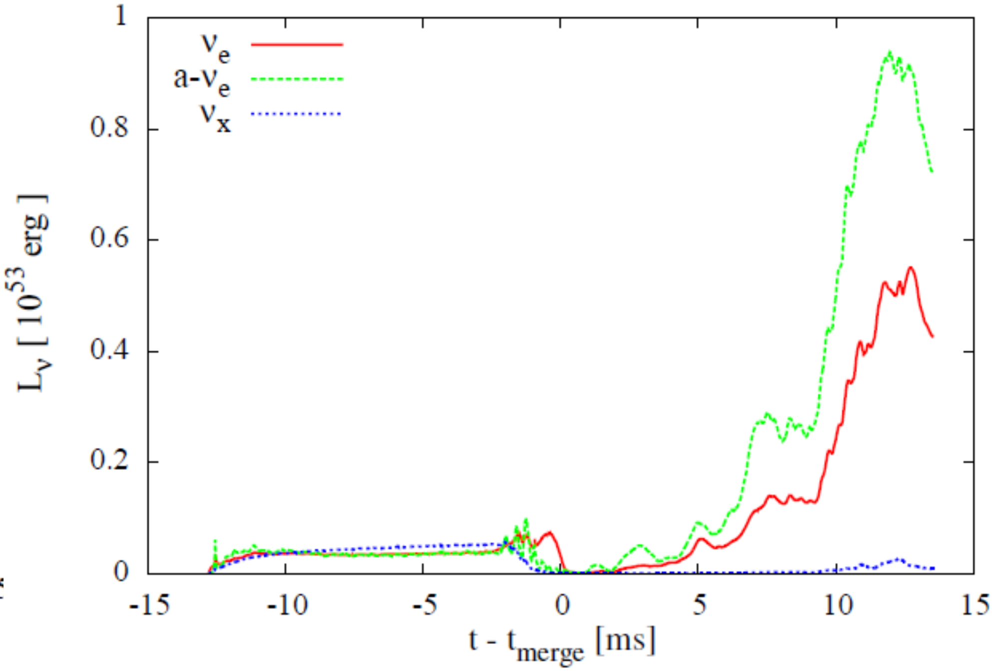

Something is likely to occur …
Density
Log10[ρ (g / cm3
Temperature
T [MeV]
Electron fraction
Ye
e-neutrino L
log10 [Qνe (erg / cm3 / s)]
z [km]
x [km]
-150 -100 -50 0 50 100 150
0 50 100 150

Neutrino luminosity

a=0.5



a=0



- Neutrino luminosity is also high ~ 10^{53} erg/s:
- In the presence of viscosity/B-field, the luminosity could be enhanced.

Annihilation rate (Beloborodov '08)

$$\frac{dE_{\nu\bar{\nu}\to e^{+}e^{-}}}{dt\,dr} \sim \frac{\sigma_0 \cos^2}{c\,m_e^2 c^4\, 2 N_{\rm opening}^2}\,(E_\nu + E_{\bar{\nu}})\,\dot{E}_\nu \dot{E}_{\bar{\nu}} \left(\frac{1}{r}\right)^2 f_{\rm collision}$$

$$\sim 10^{51}\,{\rm ergs/s} \left(\frac{10^7\,{\rm cm}}{r}\right)\left(\frac{0.1\,{\rm rad}}{N_{\rm opening}}\right)^2 \left(\frac{E_\nu + E_{\bar{\nu}}}{10\,{\rm MeV}}\right)$$

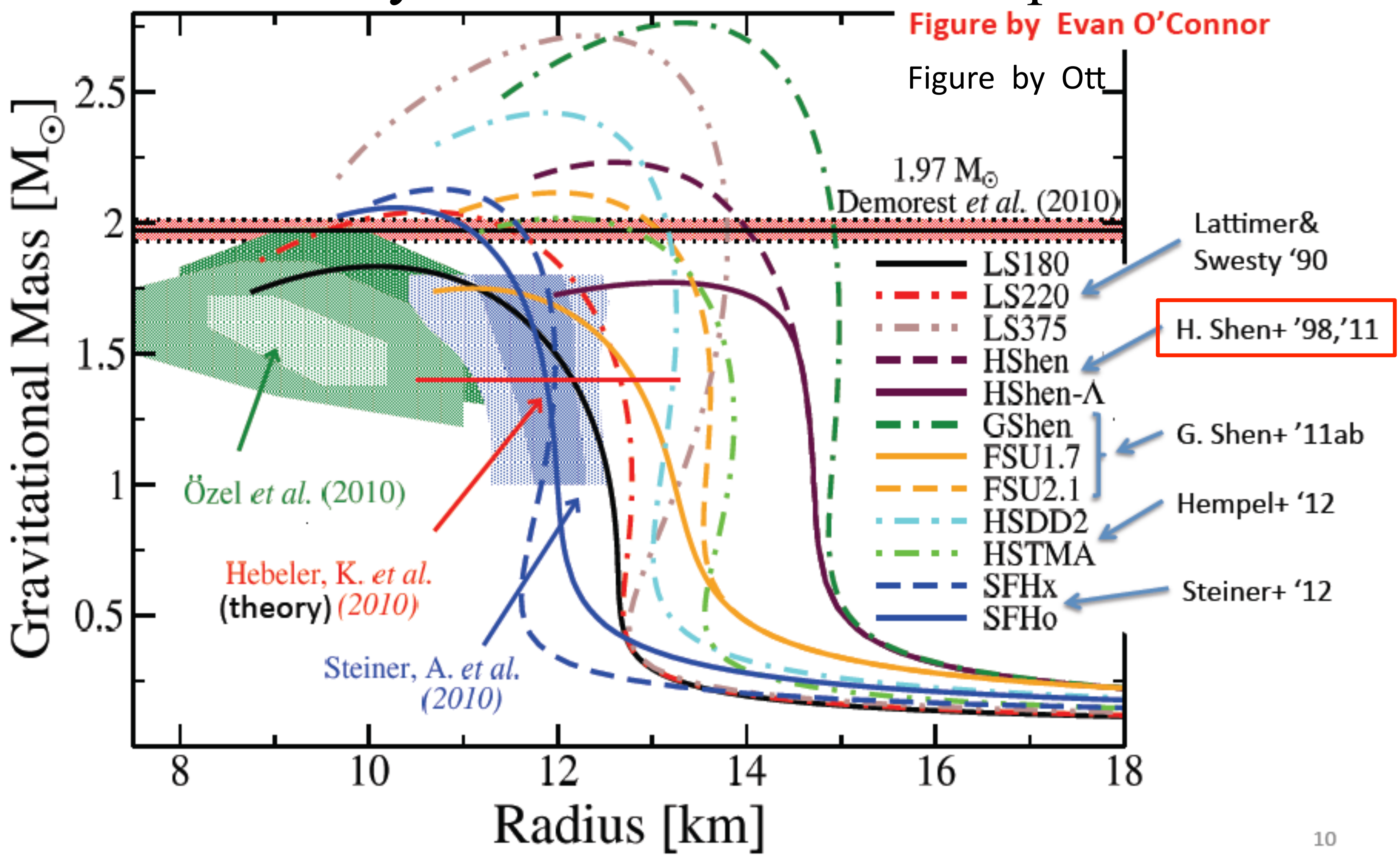
$$\times \left(\frac{\dot{E}_\nu}{10^{53}\,{\rm ergs/s}}\right)\left(\frac{\dot{E}_{\bar{\nu}}}{10^{53}\,{\rm ergs/s}}\right)\left(\frac{\cos^2 f_{\rm collision}}{0.1}\right)$$

Could supply SGRB power

- Neutrino heating and pair creation are important
- We should take into account them in the future

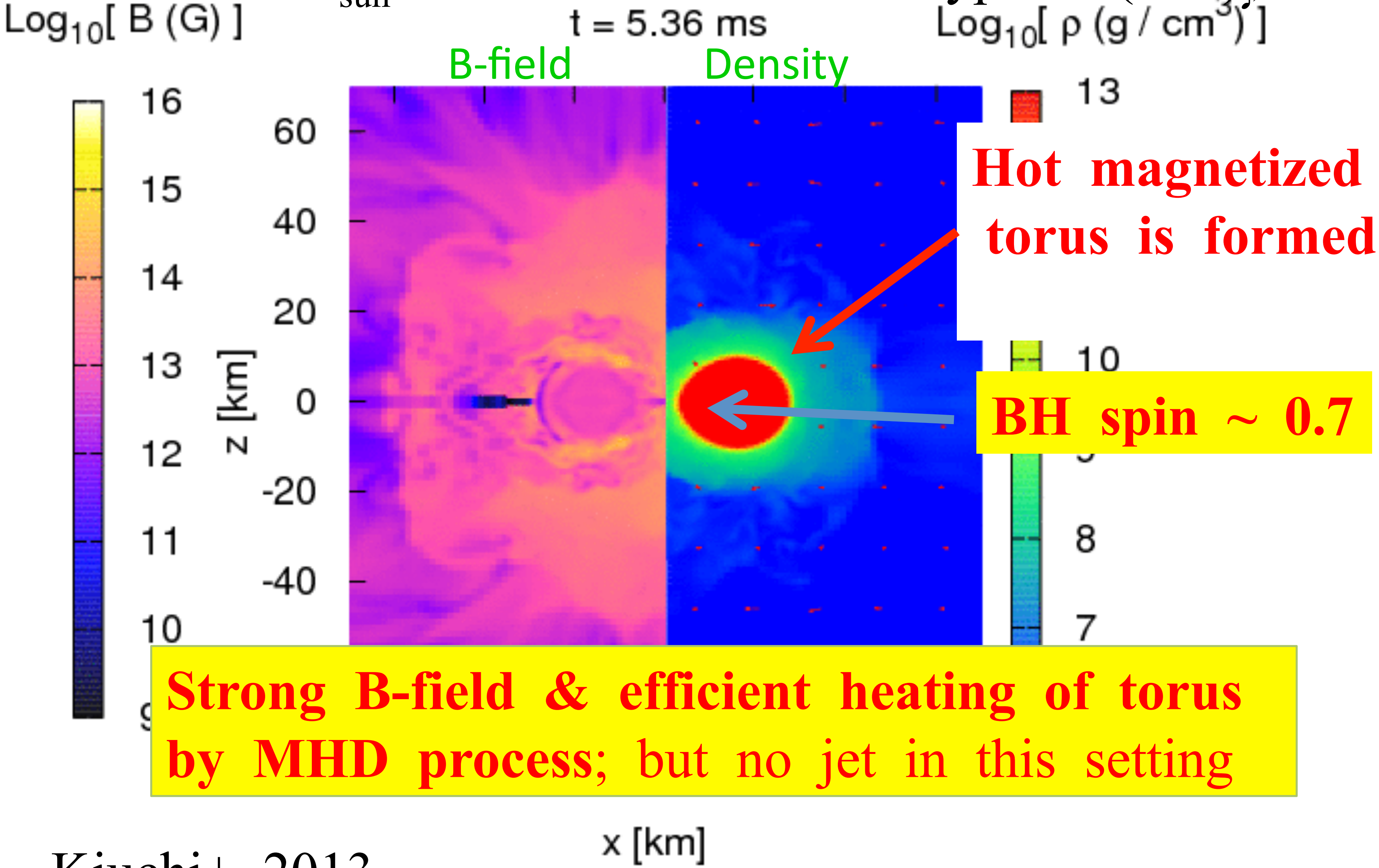
Simulation with many EOSs:

Many EOS has been developed



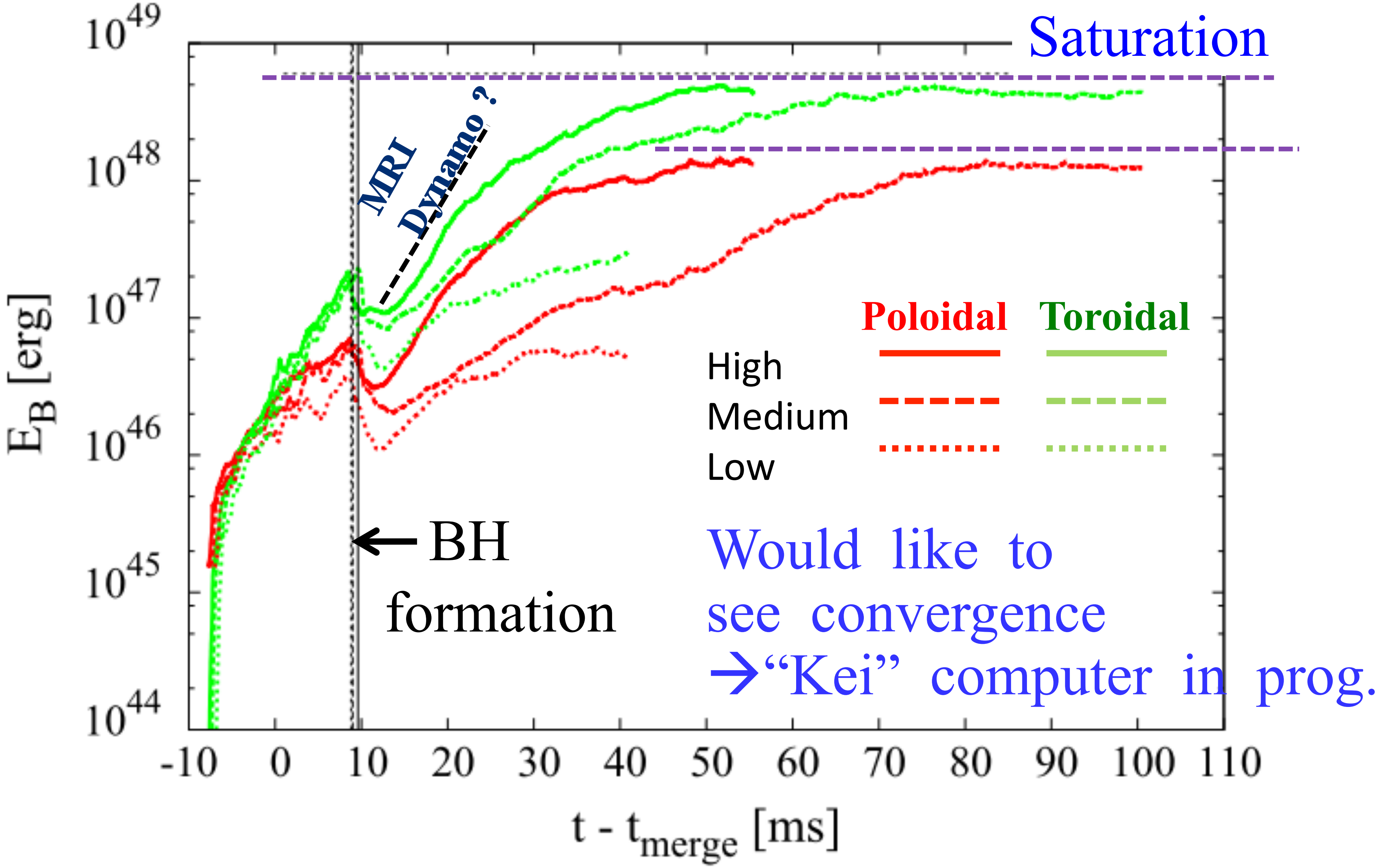
GRMHD simulation

1.4-1.4M_{sun} : EOS: H4=Nucleon + hyperon (stiff)



Kiuchi+ 2013

Evolution of magnetic energy



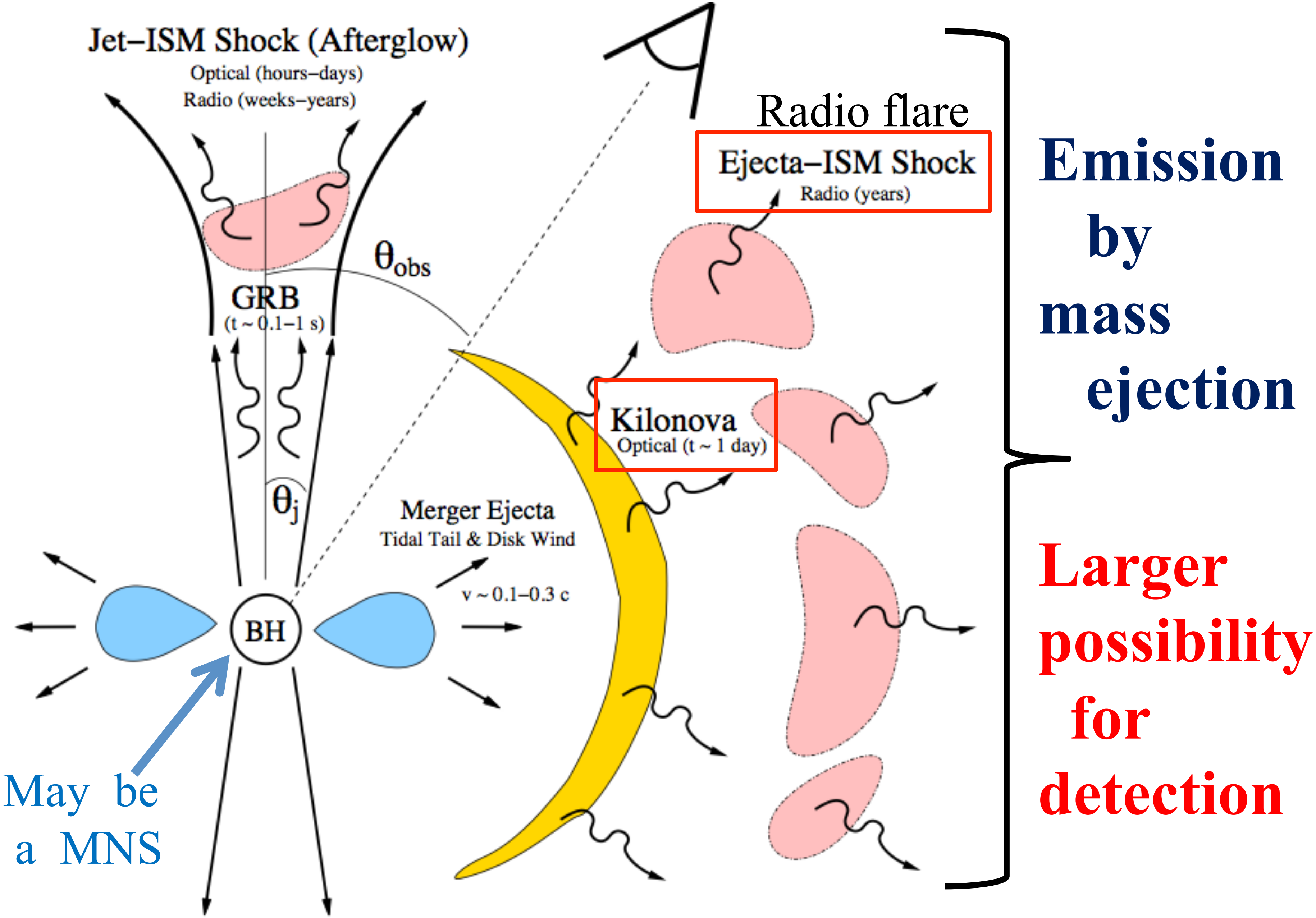
- **Saturation level ≈ 6-7 10^{48} erg (2-3 % of kinetic energy)**

Status

- Simulations with neutrino-heating and finite-temperature EOS is ongoing (Kyoto, Caltech/Cornell/CITA/Was)
- High-resolution simulation with B-field is ongoing (AEI, Kyoto, Illinois…)
- Simulation with microphysics & high-res B-field is next step

III Electromagnetic counter parts

Summary by Metzger & Berger, 2012



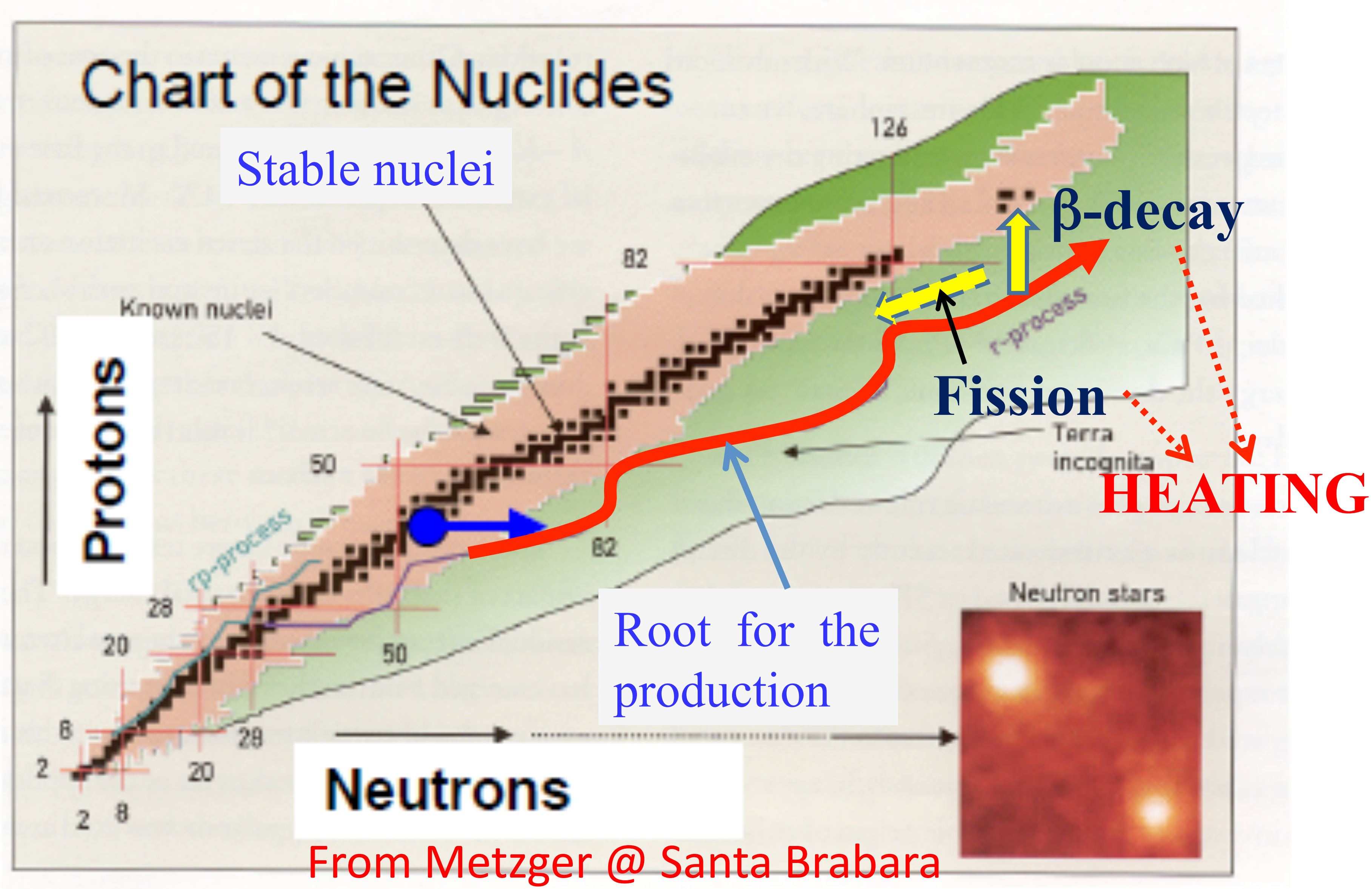
Mass ejection and EM counter parts

- ***Neutron-rich & high-velocity ejecta could generate observable EM signals*** *via*

➢ **Kilo-nova/Macro-nova**: Production and Decay of r-process-heavy nuclei
(Li & Paczynski 1998, Kulkarni 05, Metzger+ '10, …. Barnes+ '13, Tanaka-Hotokezaka '13)
Required mass >~0.01 M_{sun}

➢ **Long-term radio flare** (Nakar-Piran 2011)
Required kinetic energy >~10^{49} erg with a large $v/c >\sim 0.1$; need high-density of ISM

r-process → β-decay or fission → heating material → UV ~ IR



Li-Paczynski's estimate (i)

- Ejected material is heated by r-process elements, but initially the ejecta is optically thick

$$t_{diff} \sim \left(\frac{r}{l}\right)^2 \frac{l}{c}, \quad l = \frac{1}{\rho\kappa}, \quad r = v t_{exp}$$

ρ: Typical density $\rho \sim \frac{3M}{4\pi r^3}$ l: Mean free path

κ: Typical optical depth

r: Ejecta size v: Ejecta velocity

$\Rightarrow t_{exp} < t_{diff}$ Diffusion

$\Rightarrow t_{exp} > t_{diff}$ Free stream of photon

Li-Paczynski's estimate

At $t_{exp} = t_{diff}$ Luminosity becomes maximum

$$t \sim \left(\frac{3\kappa M}{4\pi c v}\right)^{1/2} \sim 3\ \text{days} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.3c}\right)^{-1/2} \left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{1/2}$$

$$L_{max} \sim \frac{f M c^2}{t} \sim 3 \times 10^{41}\ \text{ergs/s} \left(\frac{f_{\text{r-proc}}}{3\times10^{-6}}\right) \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.3c}\right)^{1/2} \left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{-1/2}$$

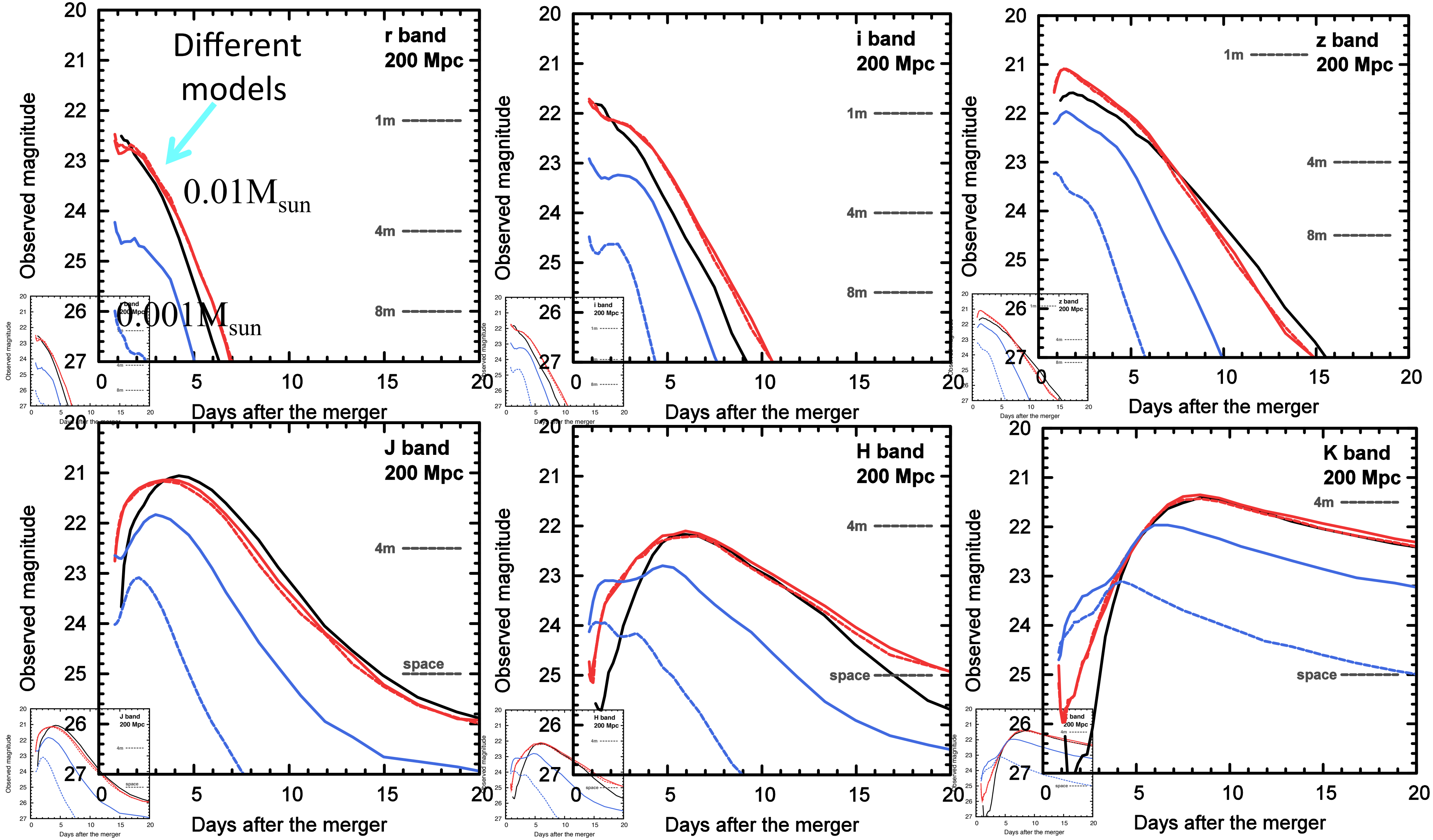
3×10^{41} ergs/s → M = −15.0 mag

→ m = 20.0 mag @ 100Mpc

m = 21.5 mag @ 200Mpc

These depend on mass, velocity, & opacity

Model luminosity curve of NS-NS@200Mpc
(M. Takana & Hotokezaka, ‘13)



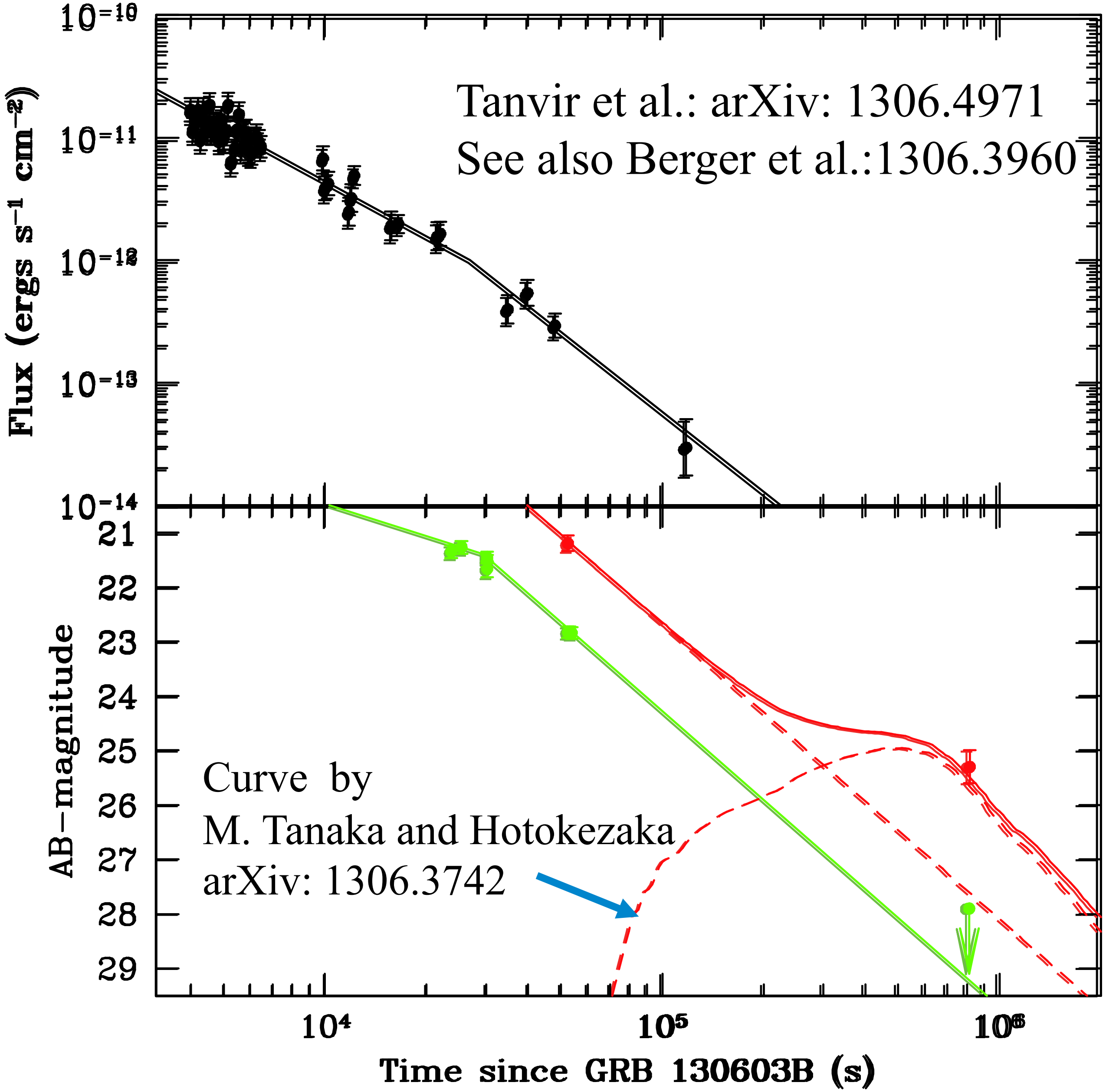
GRB130603b: Kilonova ?

X-ray

z=0.356

NIR

UV



Long-term radio flare (Nakar & Piran 2011)

- Ejecta sweeps interstellar matter
  → Shock → synchrotron emission

$$M_{ejecta} = \frac{4\pi}{3}\rho_{IS}(vt)^3 \quad t \approx 4\,\mathrm{yrs}\left(\frac{M_{ejecta}}{0.003M_\odot}\right)^{1/3}\left(\frac{v}{0.2c}\right)^{-1}\left(\frac{n_{IS}}{1\,\mathrm{cm}^{-3}}\right)^{-1/3}$$

$$F_\nu \approx 20\,\mu\mathrm{Jy}\left(\frac{E_{ejecta,kin}}{10^{50}\,\mathrm{erg}}\right)\left(\frac{v}{0.2c}\right)^{2.8}\left(\frac{D}{200\,\mathrm{Mpc}}\right)^{-2}\left(\frac{n_{IS}}{1\,\mathrm{cm}^{-3}}\right)^{0.9}\left(\frac{\nu}{1.4\,\mathrm{GHz}}\right)^{-0.75}$$

Radio Facility	Obs Freq. (GHz)	Field of view (deg^2)	1 hr rms μJy **(highlighted)**	ns^2 1 hr horizon† $n = 1cm^{-3}$	ns^2 10 hr horizon†† $n = 0.1cm^{-3}$	nsbh 1 hr horizon† $n = 1cm^{-3}$	nsbh 10 hr horizon†† $n = 0.1cm^{-3}$
EVLA[a]	1.4	0.25	7	360 Mpc	200Mpc	1.8 Gpc	1.4 Gpc
ASKAP[b]	1.4	30	30	170 Mpc	100 Mpc	850Mpc	700 Mpc
MeerKAT[c]	1.4	1.5	35	160 Mpc	90 Mpc	800 Mpc	650 Mpc
Apertif[d]	1.4	8	50	135 Mpc	75 Mpc	670 Mpc	550 Mpc
LOFAR[e]	0.15	20	1000	70 Mpc	40 Mpc	300Mpc	250 Mpc

Uncertainties: Mass and velocity as well as configuration

Many uncertainties

- Opacity → Significant difference between iron-type and heavier r-process elements
  (Kasen et al. ’13, Tanaka & Hotokezaka ‘13);
  → **Opacity is quite high in the UV band**
- Ejecta mass → Need numerical relativity
- Ejecta speed → Need numerical relativity
- Ejecta configuration → Need numerical relativity
- R-process → More realistic simulations including electron fraction, neutrino heating/cooling

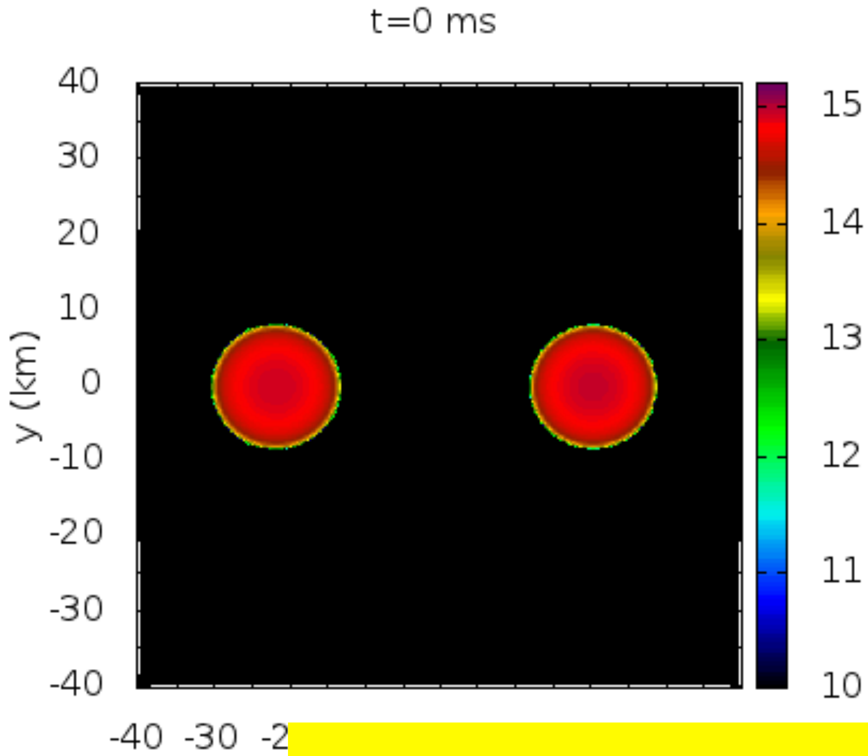
Many issues in numerical relativity and associated numerical works

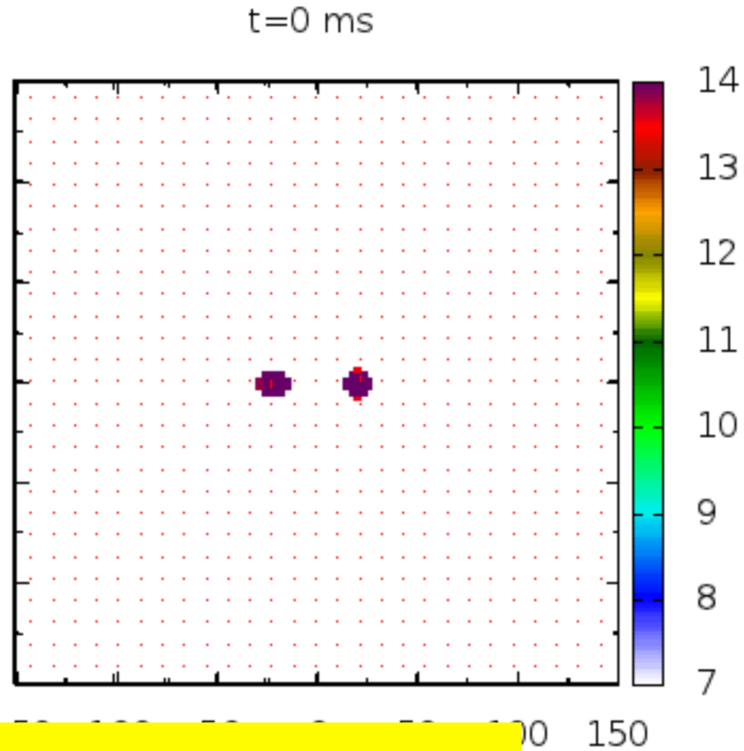
First step: Merger of 1.3-1.4 M_{sun} NS:

EOS=APR4; stiff but relatively soft:

NS radius ~ 11 km

Log ρ (g/cm^3)





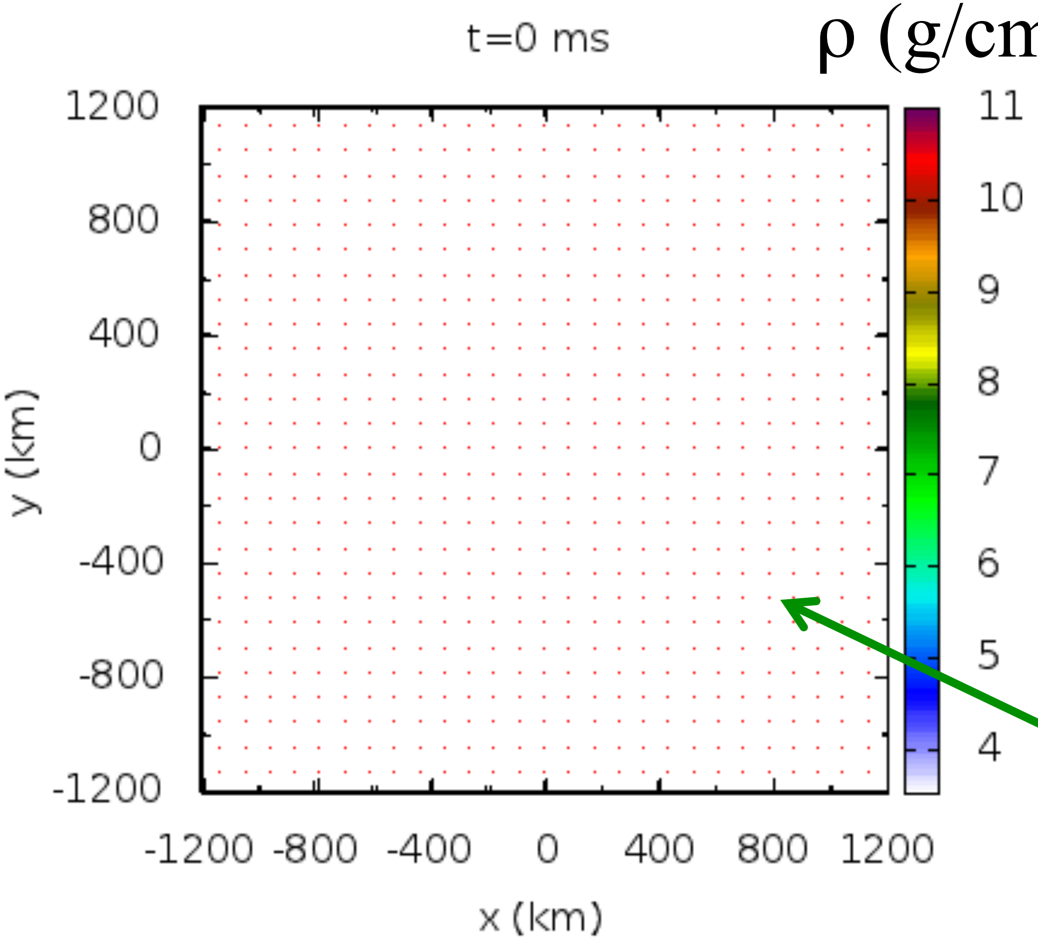
Mass ejection by
Shock + torque exerted by HMNS

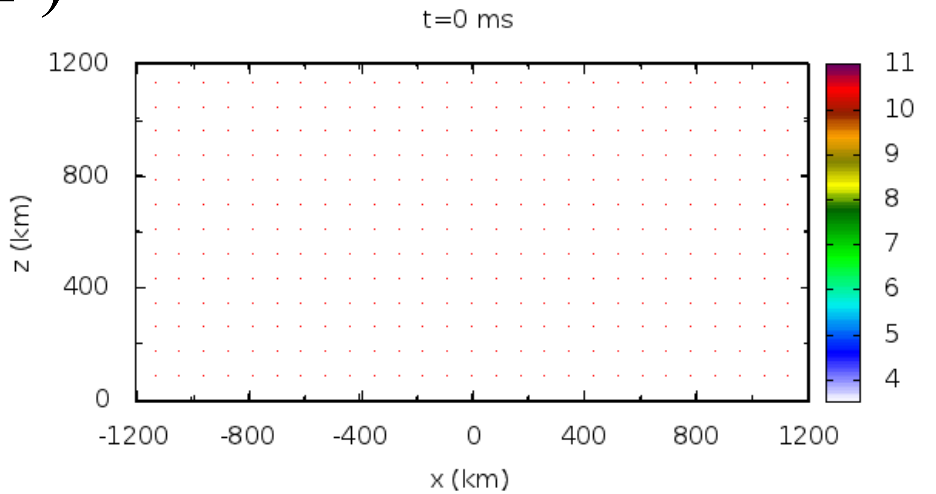
W

Hotokezaka + '13

Much wider view: L ~ 1200 km

Merger sets in at t ~ 11 ms





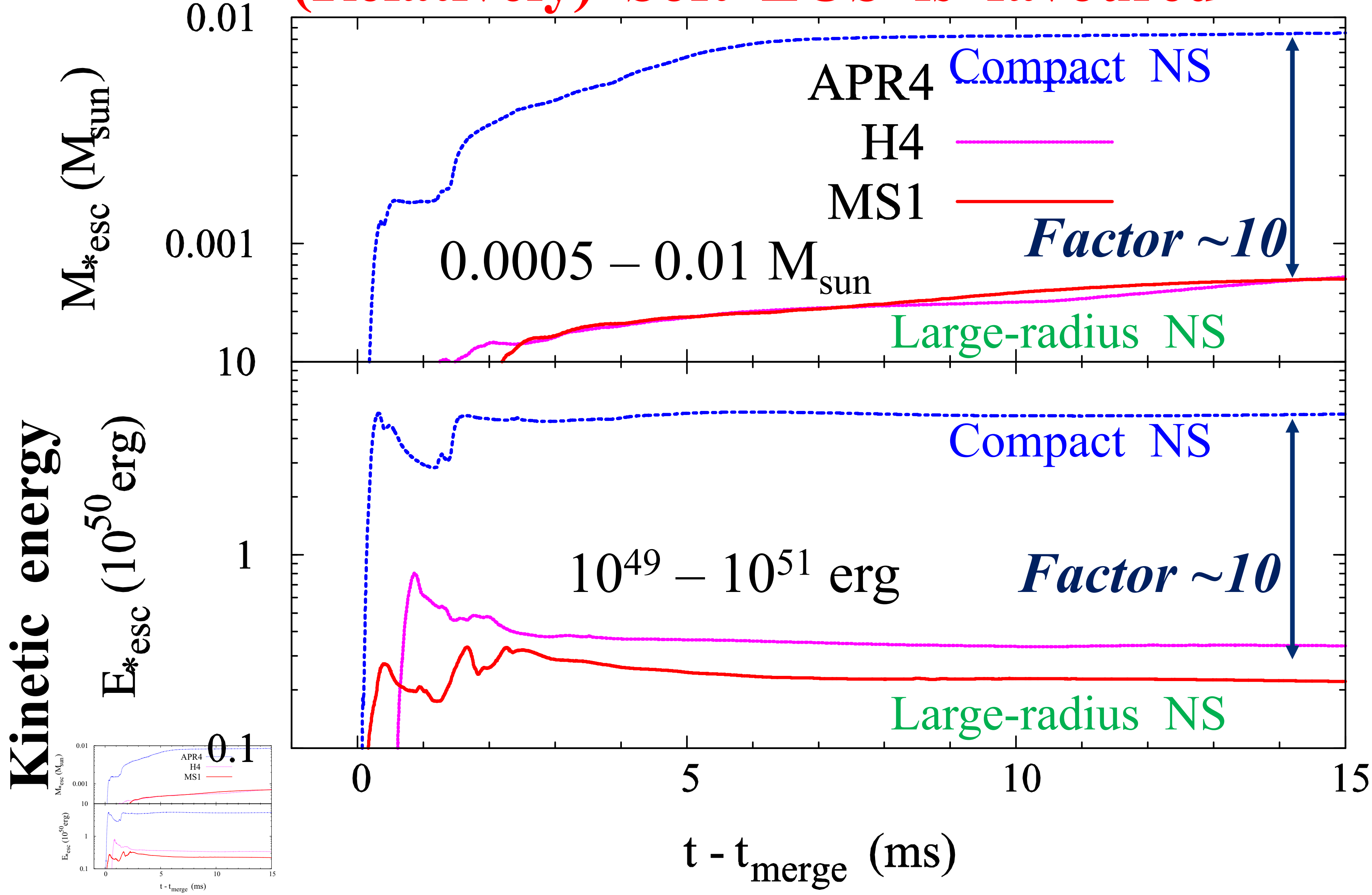
Initial blue: atmosphere

Average velocity
~ 0.2—0.3 c
Max ~ 0.7—0.8 c

Orbital plane **_X-Z_ plane**

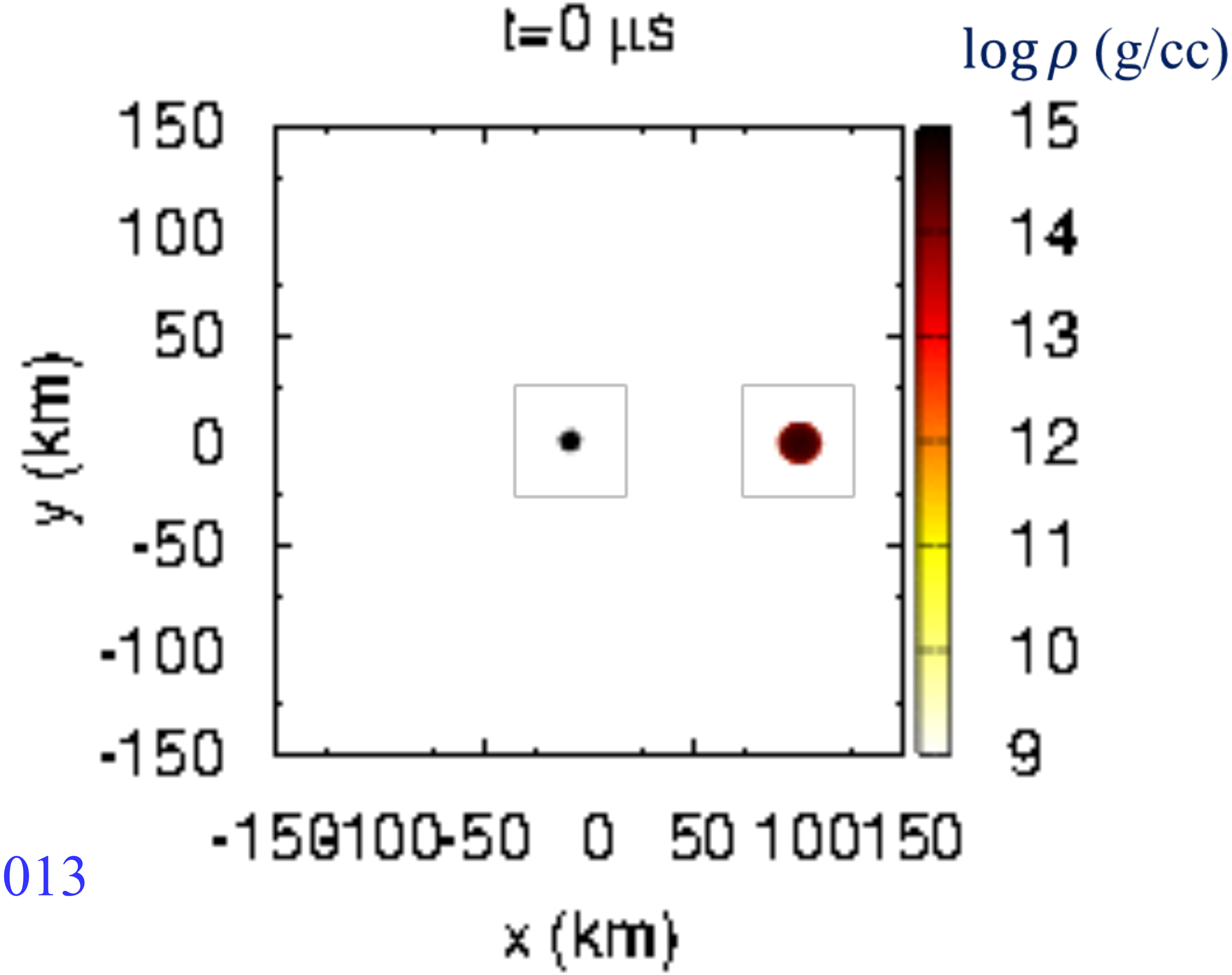
Amount of ejection depends strongly on EOS

(Relatively) Soft EOS is favoured



Long-run with plausible mass: NEW

BH(a=0.75, M=9.45M_{sun}) — NS(1.35M_{sun})

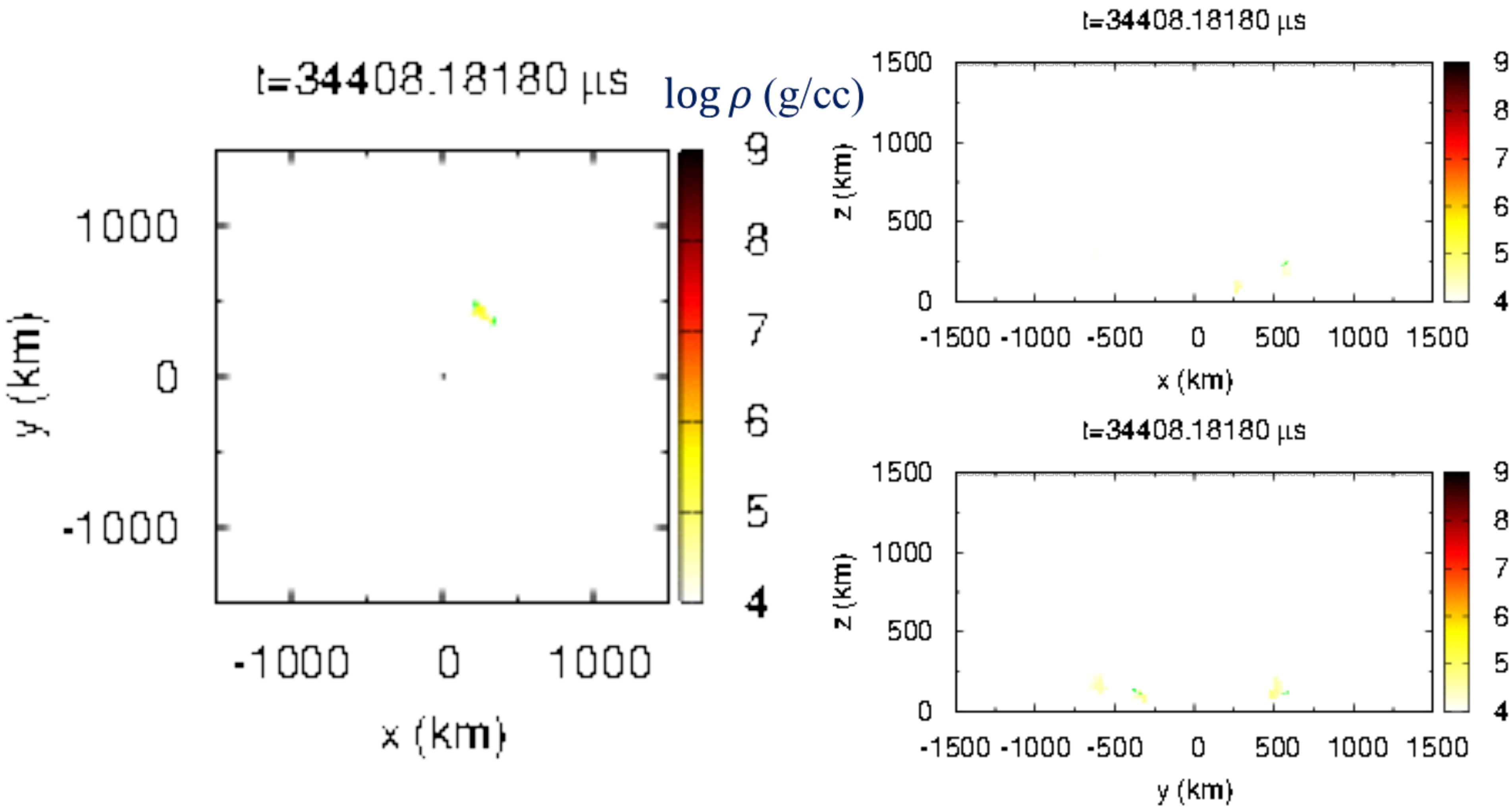


Kyutoku+ 2013

Note: Similar work has been done by Fourcart+

Mass ejection (> $0.01 M_{sun}$)

Mass ejection is anisotropic for BH-NS binaries



Only ejecta with escape velocity is shown

Effect of morphology is important

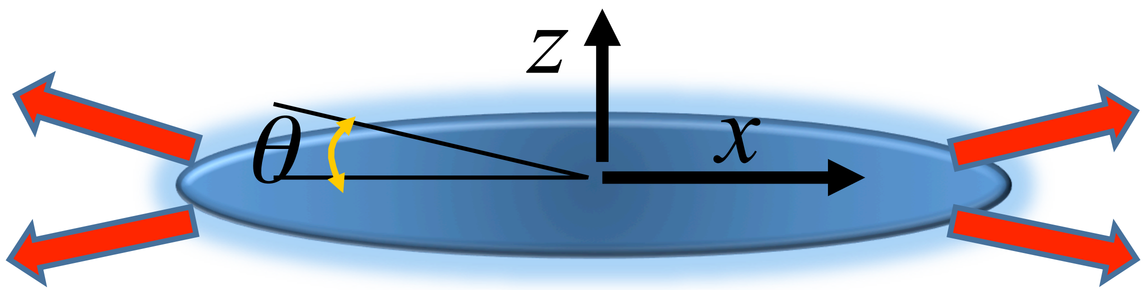
$$t \sim \left(\frac{3\propto M H}{4 M c v}\right)^{1/2} \sin N$$

Observe from z direction

$$\sim 3\ \mathrm{days}\left(\frac{\propto M_v}{0.005 M_\odot}\right)^{1/2}\left(\frac{\propto}{10\ \mathrm{cm^2/g}}\right)^{1/2}\left(\frac{\propto H}{\ {}^2}\right)^{1/2} \sin^{1/2} N$$

$$L_{max} \sim \frac{M c f_{\text{r-proc}}^2}{t M c} \sim 3 \times 10^{41}\ \mathrm{ergs/s}\left(\frac{\propto M_v}{0.005\, 0.3 M_\odot}\right)^{1/2}\left(\frac{\propto}{}\right)^{1/2}$$

$$\notin \left(\frac{\propto H}{10\ \mathrm{cm}^{26}/\mathrm{g}\ 3}\right)^{2\,1/2}\left(\frac{\notin f_{\text{r-proc}}}{\notin 10^2}\right) \sin^{2\,1/2} N$$



Issue for the mass ejection

- Scenario basically OK
- First step: Properties of mass ejection should be clarified: total mass, energy, morphology, dependence on EOS & binary masses
- Are magnetic power and neutrino wind important for mass ejection ?
- Advanced steps: NR simulation data + r-process calculation; details of light-curve & spectrum ? (Many calculations were based on one-zone cal)
- Detailed study of fall back signal is interesting

Many things to do; new topic in NR

Summary

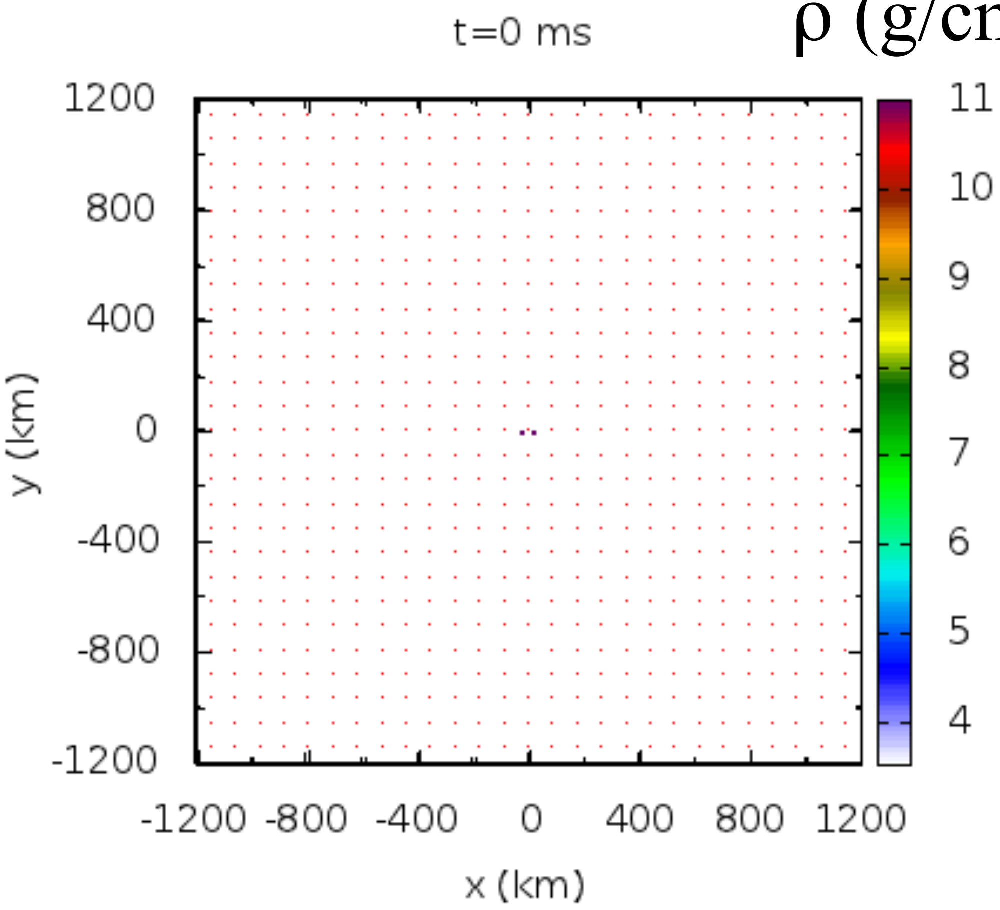
- Many systematic simulations for NS-NS and BH-NS coalescence are ongoing: Many gravitational waveforms are in hand.
- Quantitative modeling of GW is necessary
- Advanced numerical simulations (+neutrinos, magnetic fields, …) are also ongoing: However, more detailed modeling with high grid resolution will be necessary
- Study for electromagnetic counter parts is new field that should be developed soon

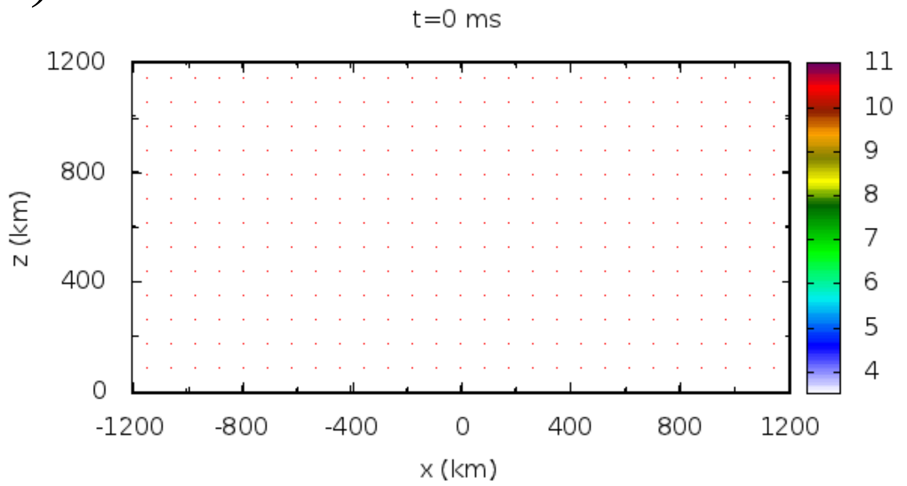
BH formation case: APR4, mass=1.3-1.6M_{sun}

Wider view: L ~ 1200 km

Merger sets in at t ~ 11 ms

ρ (g/cm^3)





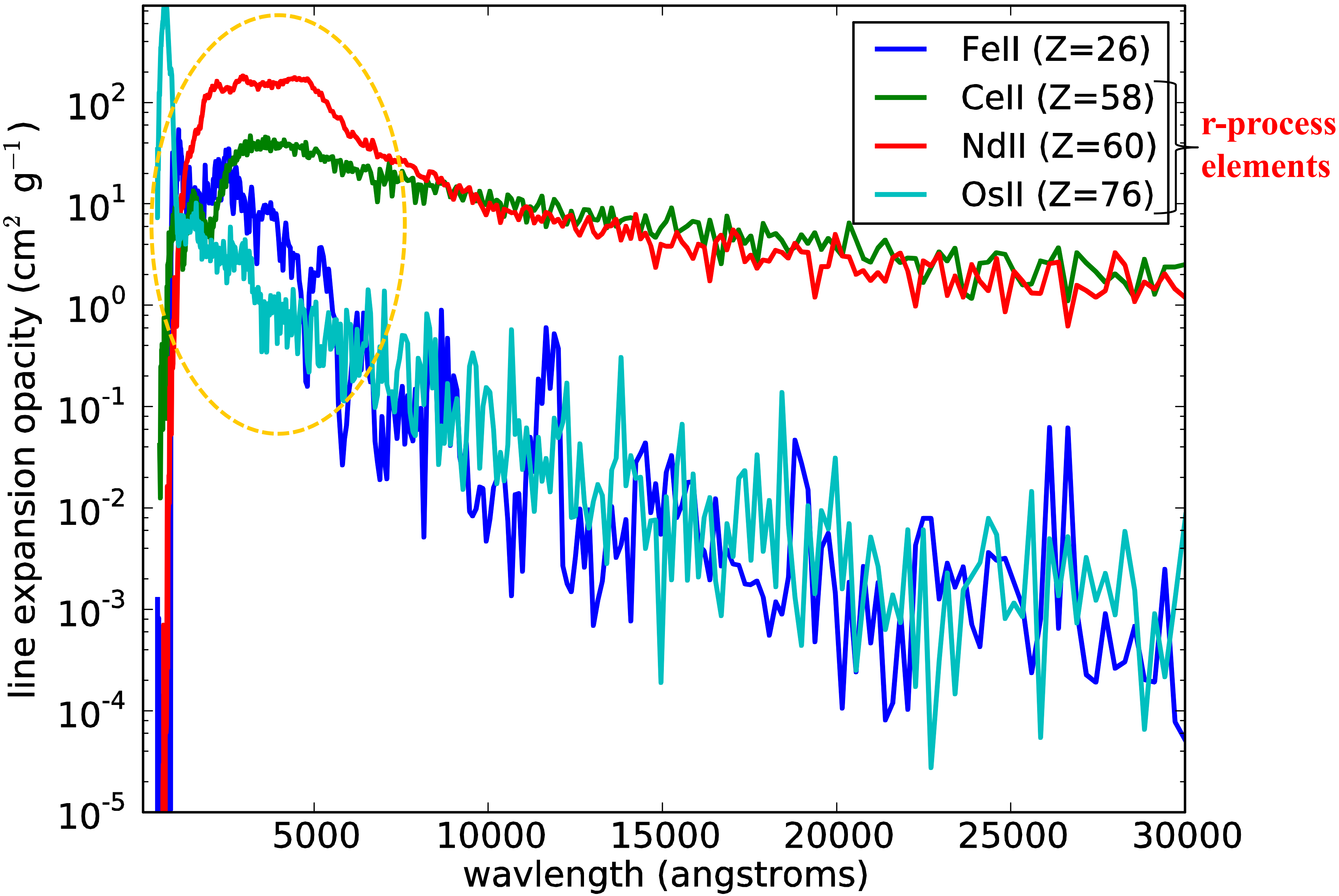
Initial blue: atmosphere

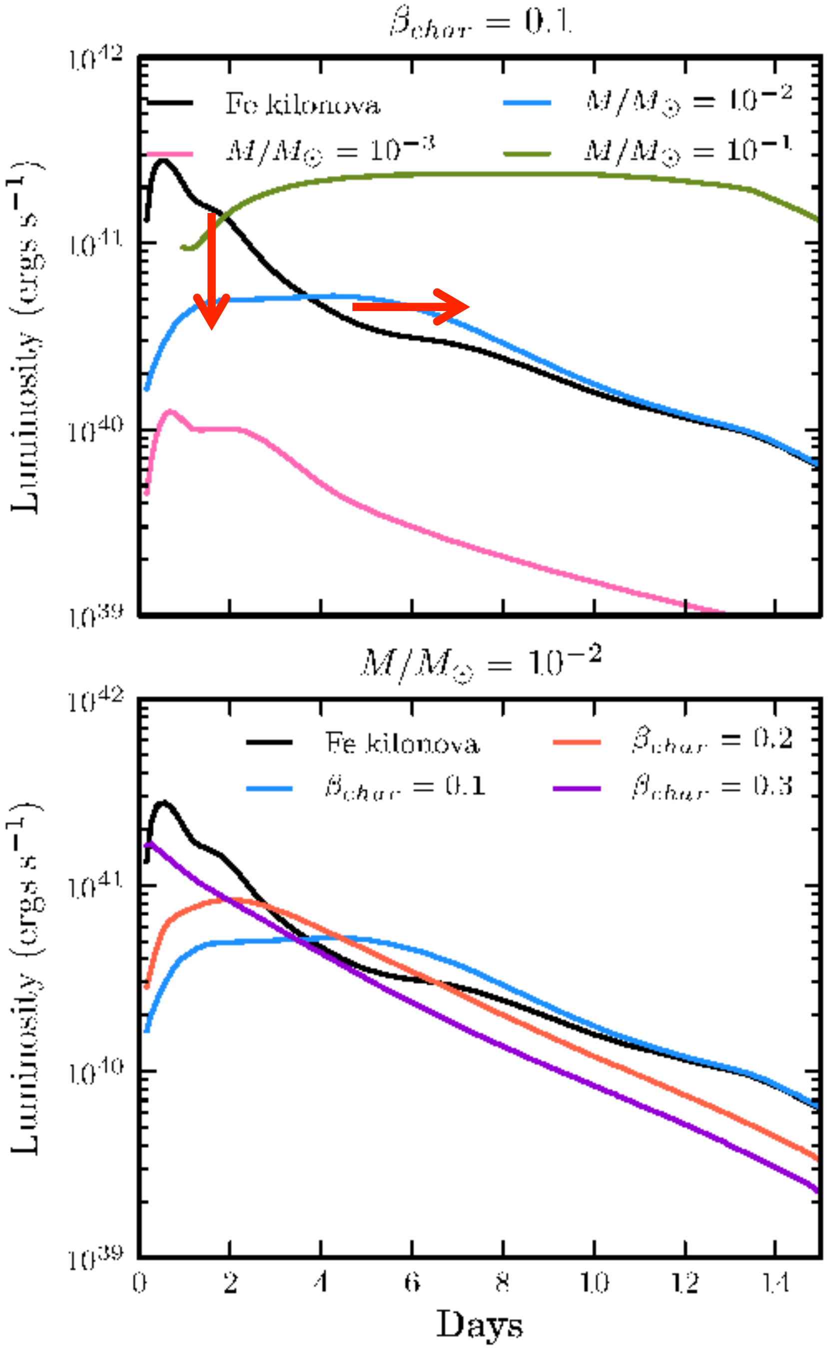
Not very spherical

Orbital plane

***X-Z* plane**

Kasen+ '13 (last week)





Smaller peak luminosity

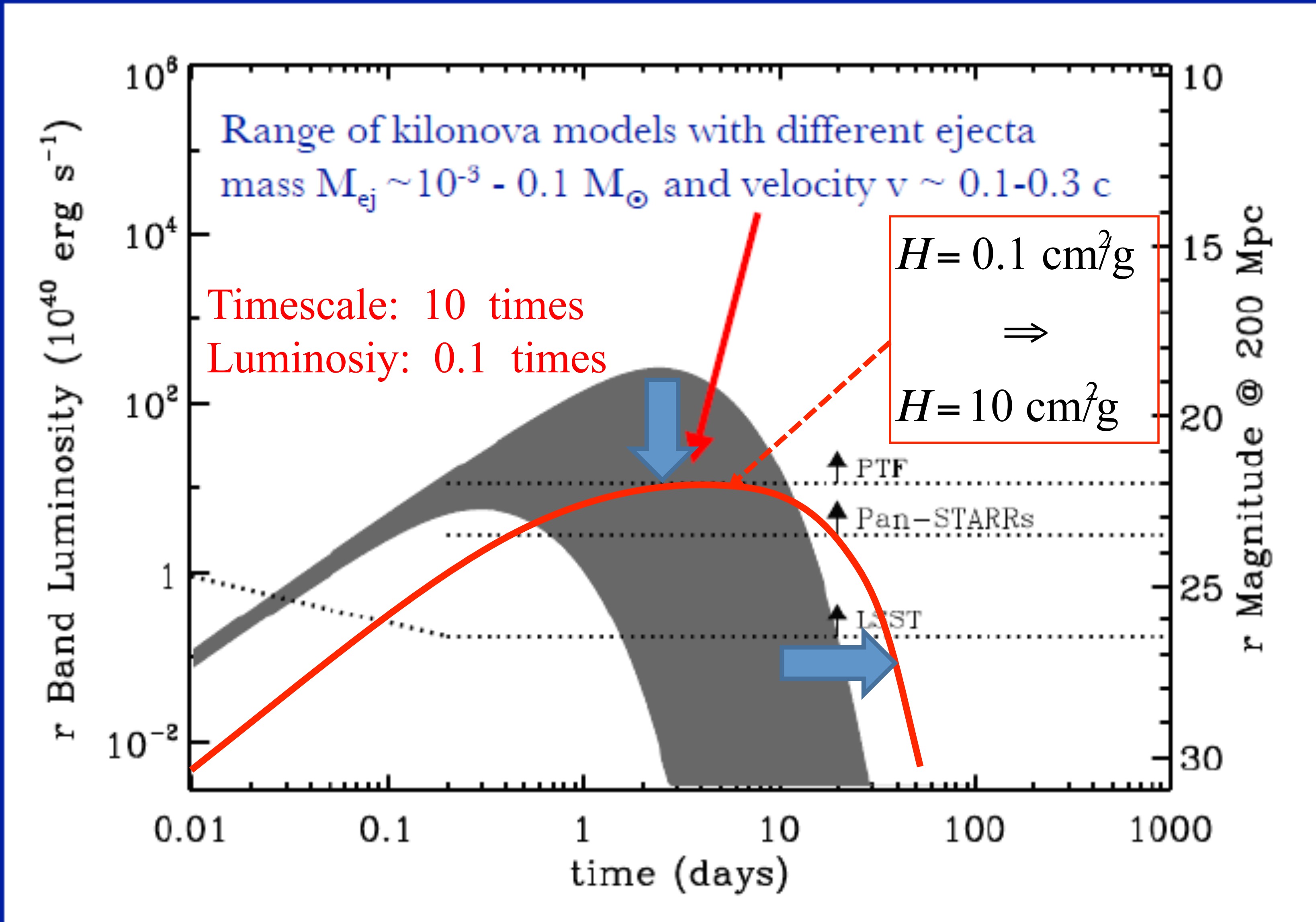
→ Bad

Longer time scale

→ Good

Barnes-Kasen '13

Optical Search Following a GW Trigger



Modify the file by Metzger @Santa-barbara