Lecture I: Coalescence of neutron-star binaries

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Outline of lecture I

1. Motivation & background for studying neutron−star (NS) mergers
2. Inspiral toward merger
3. The standard scenario of NS-NS mergers
4. Scenarios of black hole-NS mergers
5. Gravitational waves from neutron-star mergers

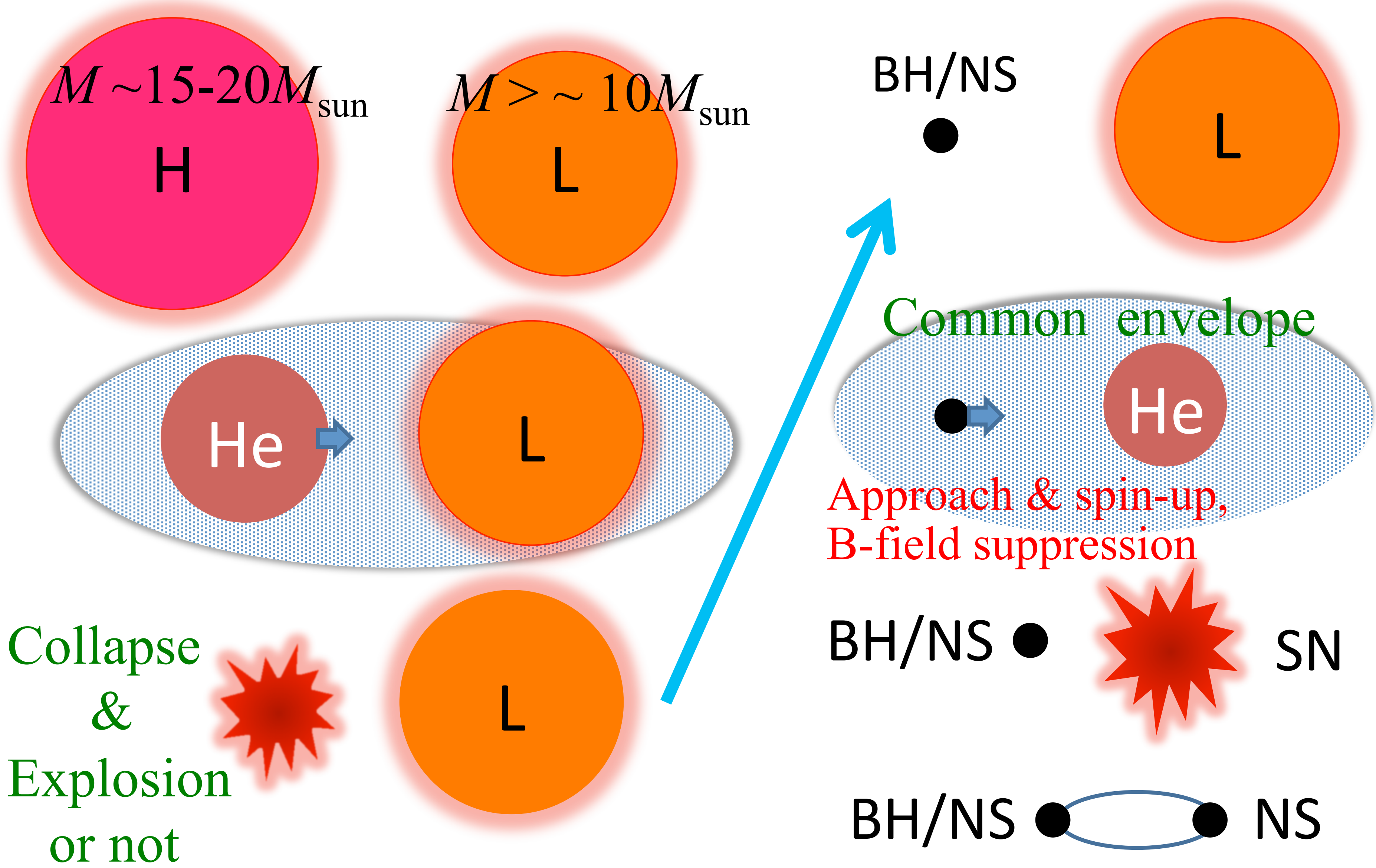
Lecture II:
Mass ejection and electromagnetic counterparts

1 Introduction: Motivation

Why we study NS mergers ?

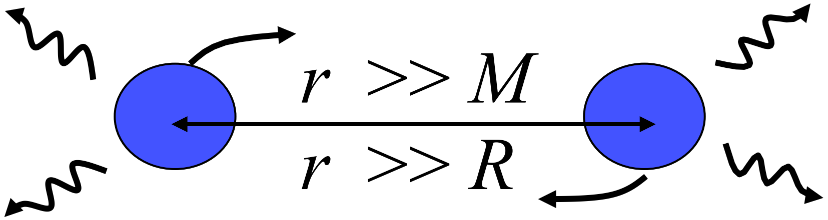
Why it is interesting ?

Compact neutron-star binary formation
--Typical formation scenario (Mapelli's talk) --



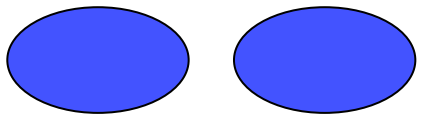
Once formed: Evolution of compact binaries is governed entirely by gravitational radiation

Evolve by GW emission



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

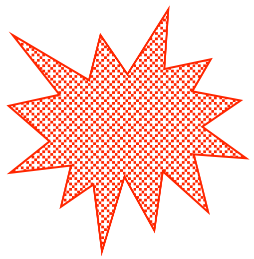
Tidal deformation at $r \sim$ 40-50 km



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

Dynamical evolution

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



"Merger"

Compact NS-NS system in our galaxy

	PSR	Orbital period P(day)	Eccentricity e	$m(M_{sun})$	Each mass M_1	M_2	lifetime T_{GW} $\times 10^8$ yrs
1.	B1913+16	0.323	0.617	2.828	1.441	1.387	3.0
2.	B1534+12	0.421	0.274	2.678	1.333	1.345	27
3.	B2127+11C	0.335	0.681	2.71	1.35	1.36	2.2
4.	J0737-3039	0.102	0.088	2.58	1.34	1.25	0.86
5.	J1756-2251	0.32	0.181	2.57	1.34	1.23	17
6.	J1906+746	0.166	0.085	2.61	1.29	1.32	3.1
7.	J1913+1102	0.206	0.090	2.875	1.65	1.24	5.0
8.	J1757-1854	0.184	0.606	2.74	1.35	1.39	0.77
9.	J1946+2052	0.078	0.064	~2.50	~1.2	~1.3	0.46

- **Total Mass of NS in compact NS-NS** is in a narrow range, $m \approx 2.7 \pm 0.2\ M_{sun}$ and for many, $m < 2.8\ M_{sun}$

Properties of compact binary neutron stars in our galaxy

- First-born NS has relatively low magnetic field strength (~10^9—10^{10} G) and fairly short period ~15—100 ms reflecting the accretion history from companion, but current dimensionless spin is <~0.05; not very large
- Second-born NS has typical magnetic field strength (~10^{12}G) and typical period ~ 0.1—a few second (slow)
- Estimated merger rate in our galaxy is 42^{+30}_{-14} Myr^{-1} → $0.18^{+0.13}_{-0.06}$ $(D/100\mathrm{Mpc})^3$ yr^{-1} (Pol et al. 2018)

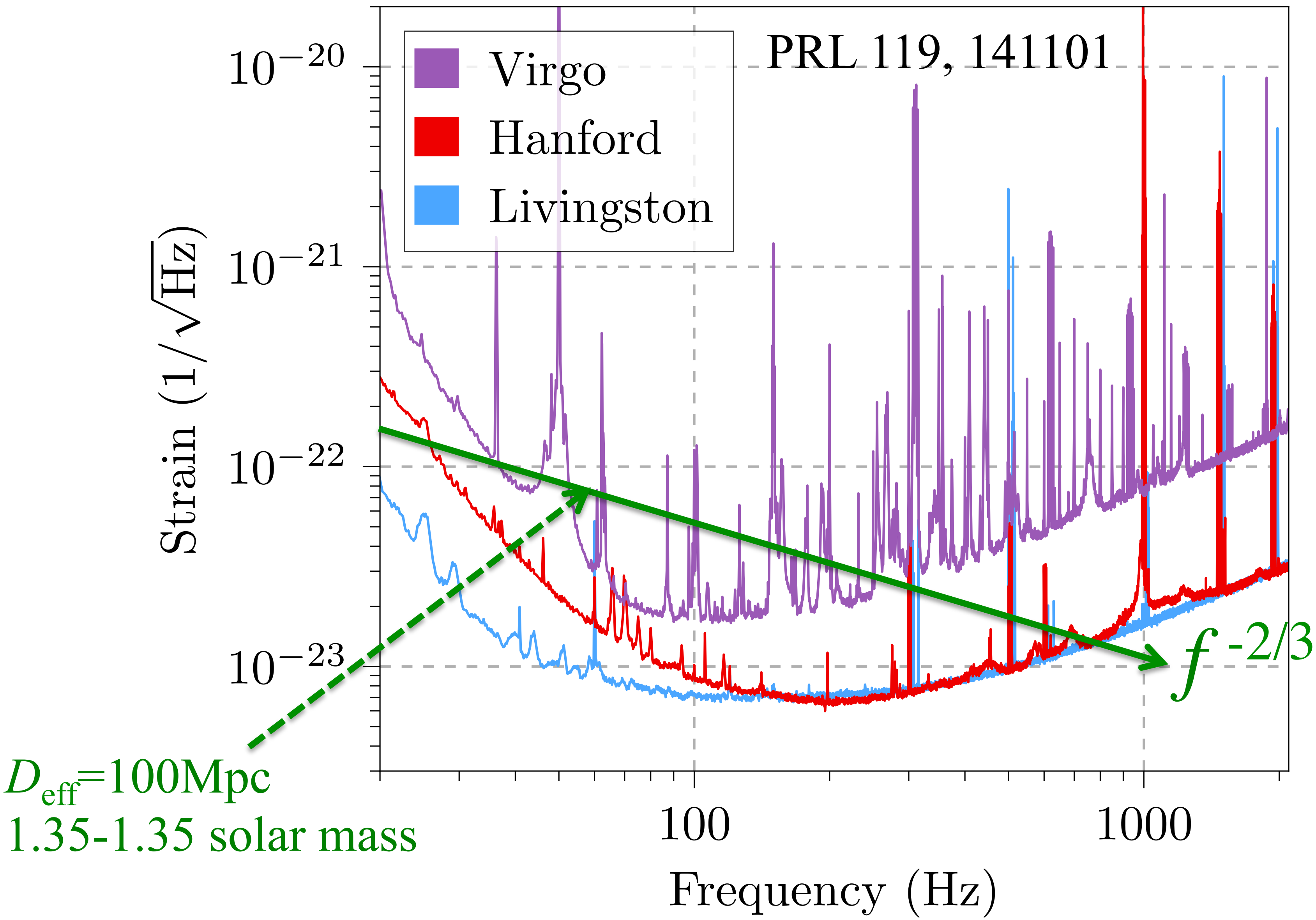
✓ cf, estimated merger rate according to O2 results is $1.54^{+3.20}_{-1.22}$ $(D/100\mathrm{Mpc})^3$ yr^{-1} (Abbott et al. 2017)

- In any case, we may expect >1/yr merger for *D*=200 Mpc

Why we study NS merger ?

A. **Most promising sources of gravitational waves for advanced LIGO/VIRGO/KAGRA**

Sensitivity of LIGO & VIRGO O2

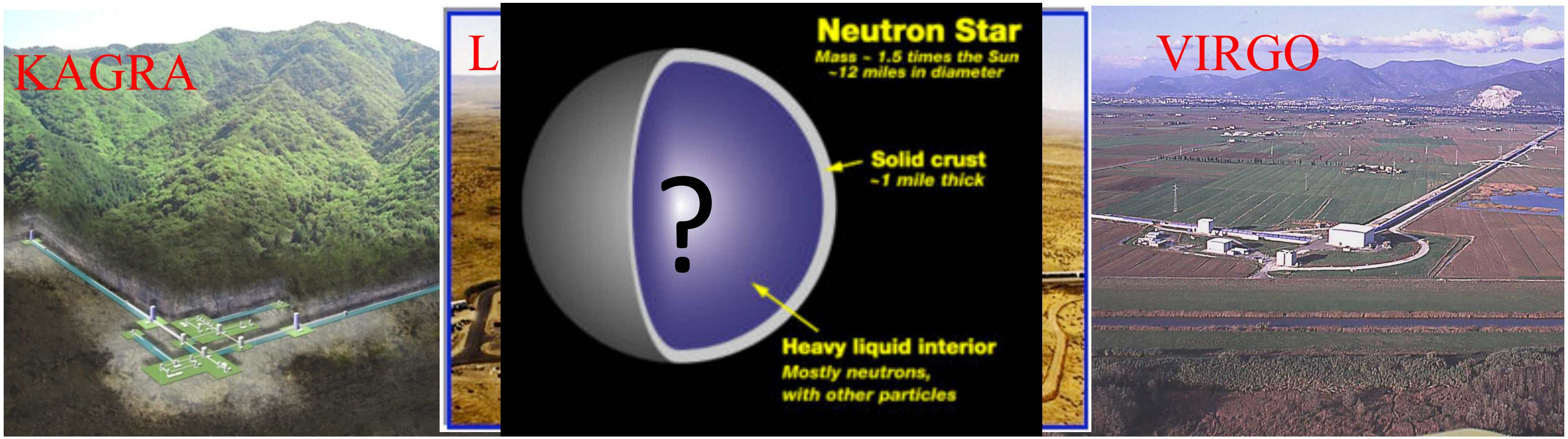


Need accurate theoretical templates for detection and measurement

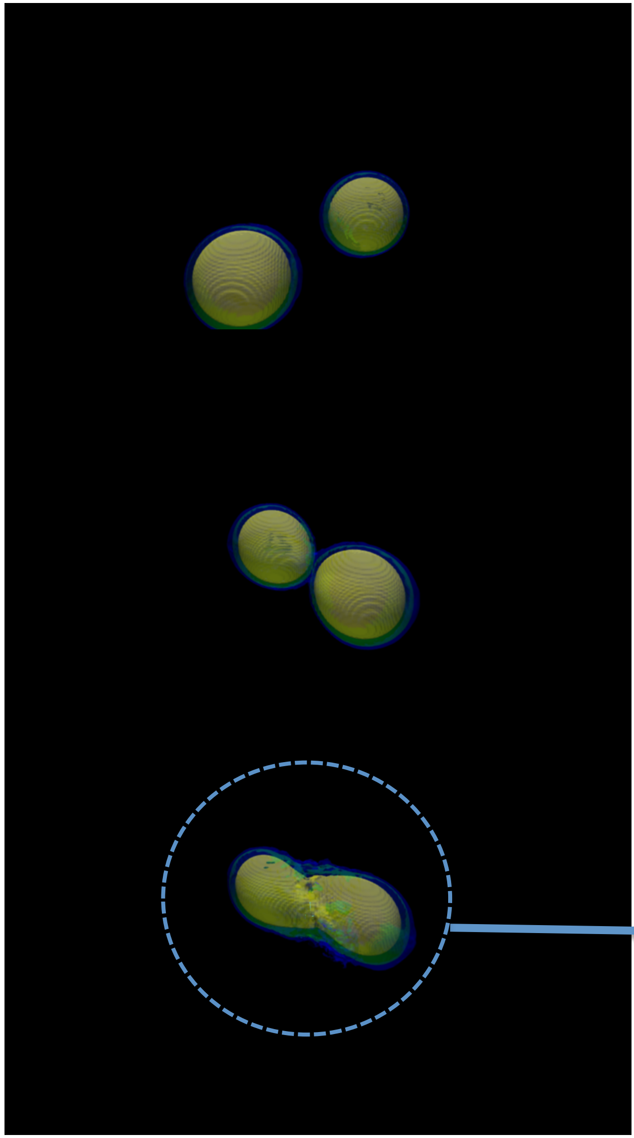
Why we study NS merger ?

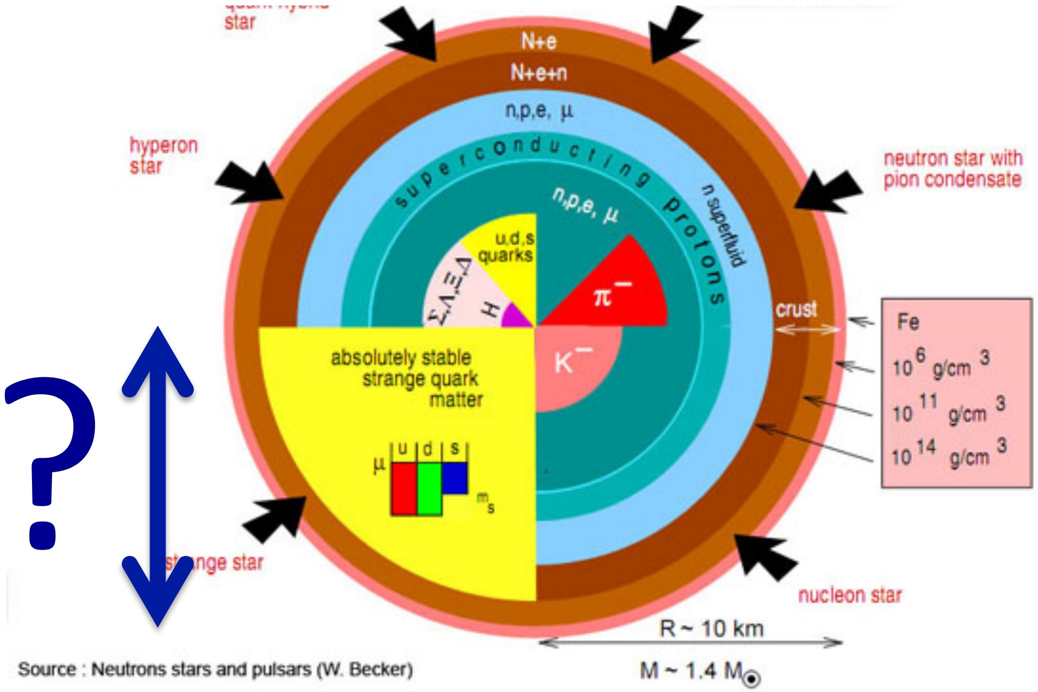
A. Most promising sources of gravitational waves for advanced LIGO/VIRGO/KAGRA

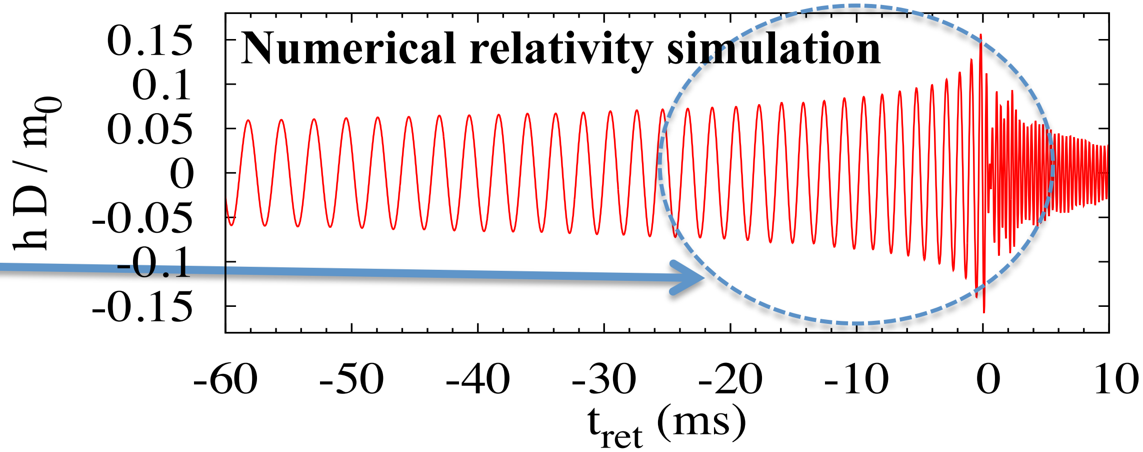
B. Laboratory for high-density nuclear matter



Gravitational waves from NS mergers are likely to tell us NS radius

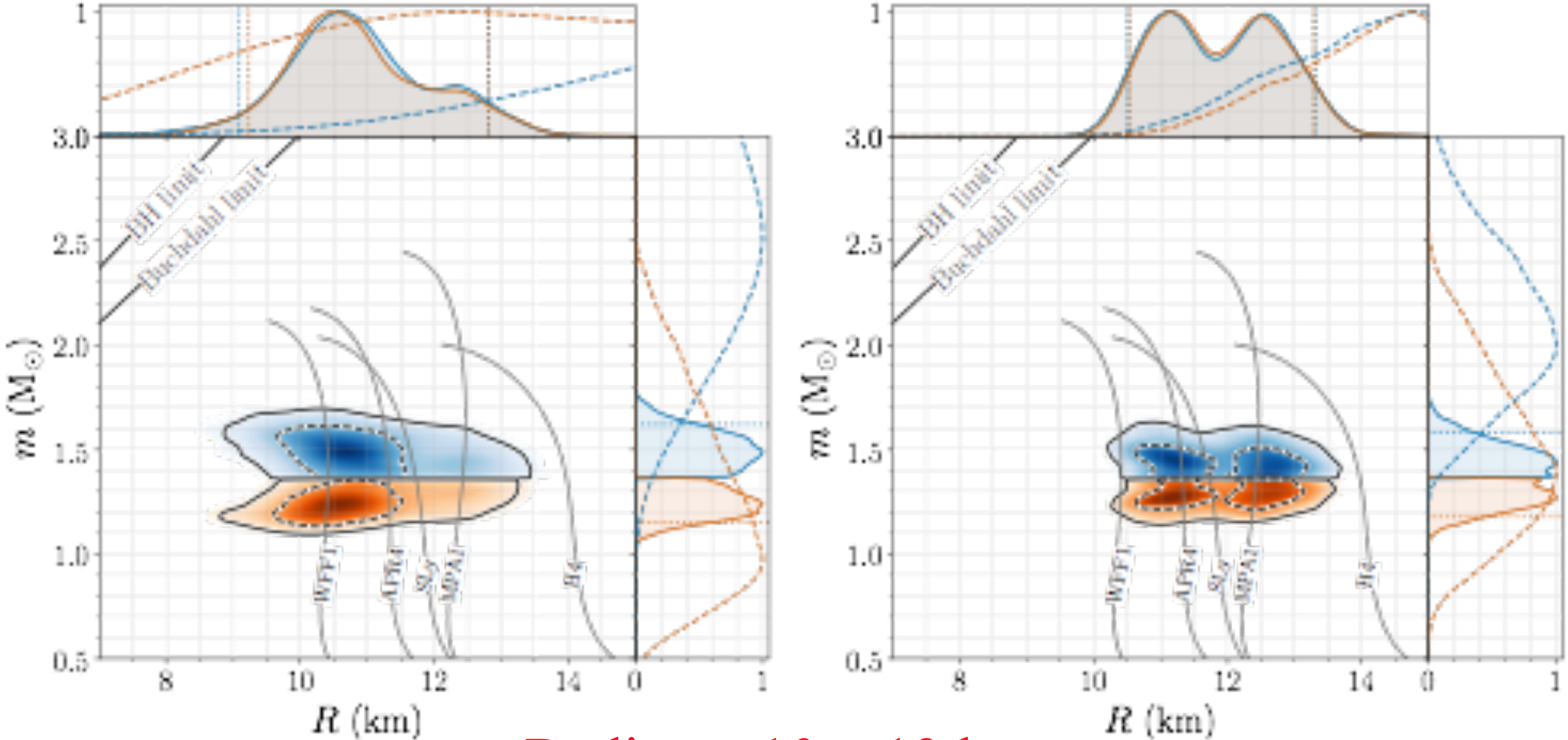






NS Radius measurement from GW170817 event

arXiv: 1805.11581



Radius = 10 ~ 13 km

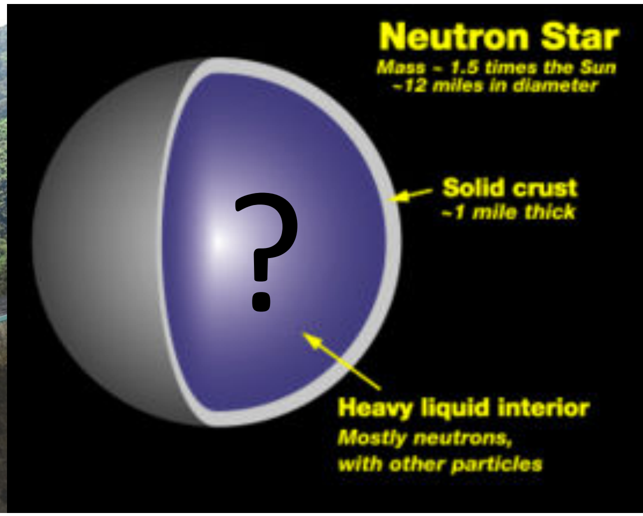
- Detector noise is still too large for accurate measurement but show it a promising method for near future
- Future needs accurate templates of gravitational waves

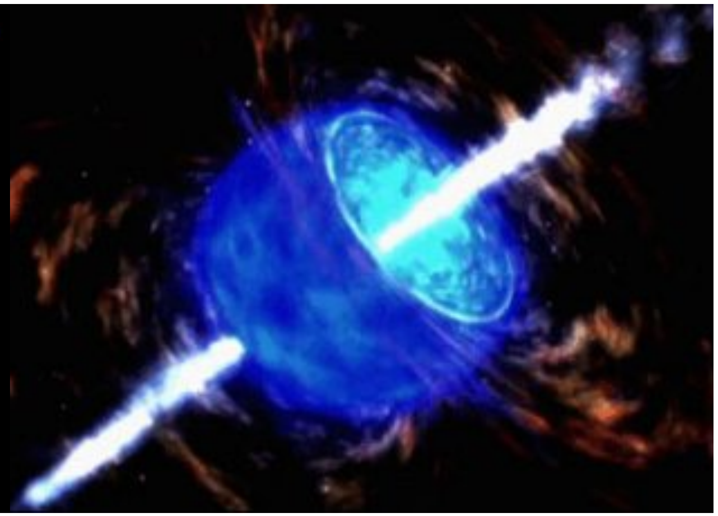
Why we study NS merger ?

A. Most promising sources of gravitational waves for advanced LIGO/VIRGO/KAGRA

B. Laboratory for high-density nuclear matter

C. Promising origins of short-hard GRBs

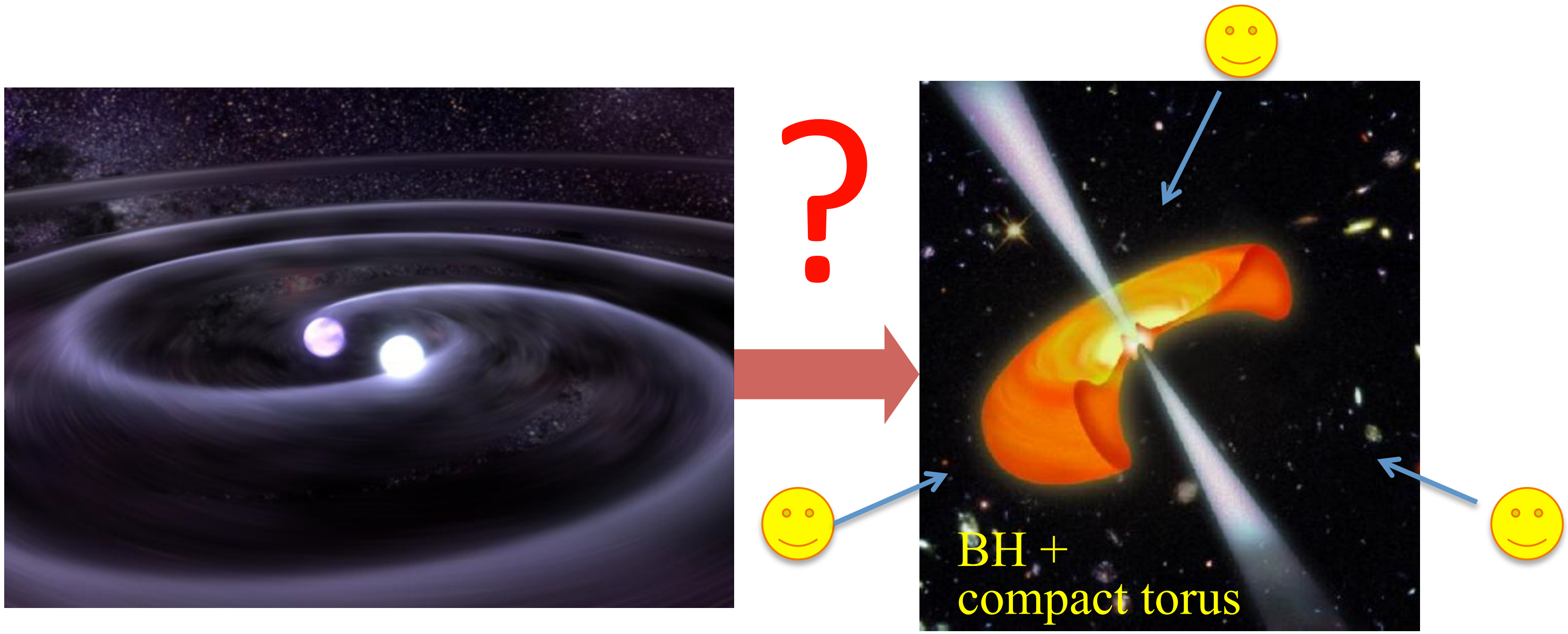




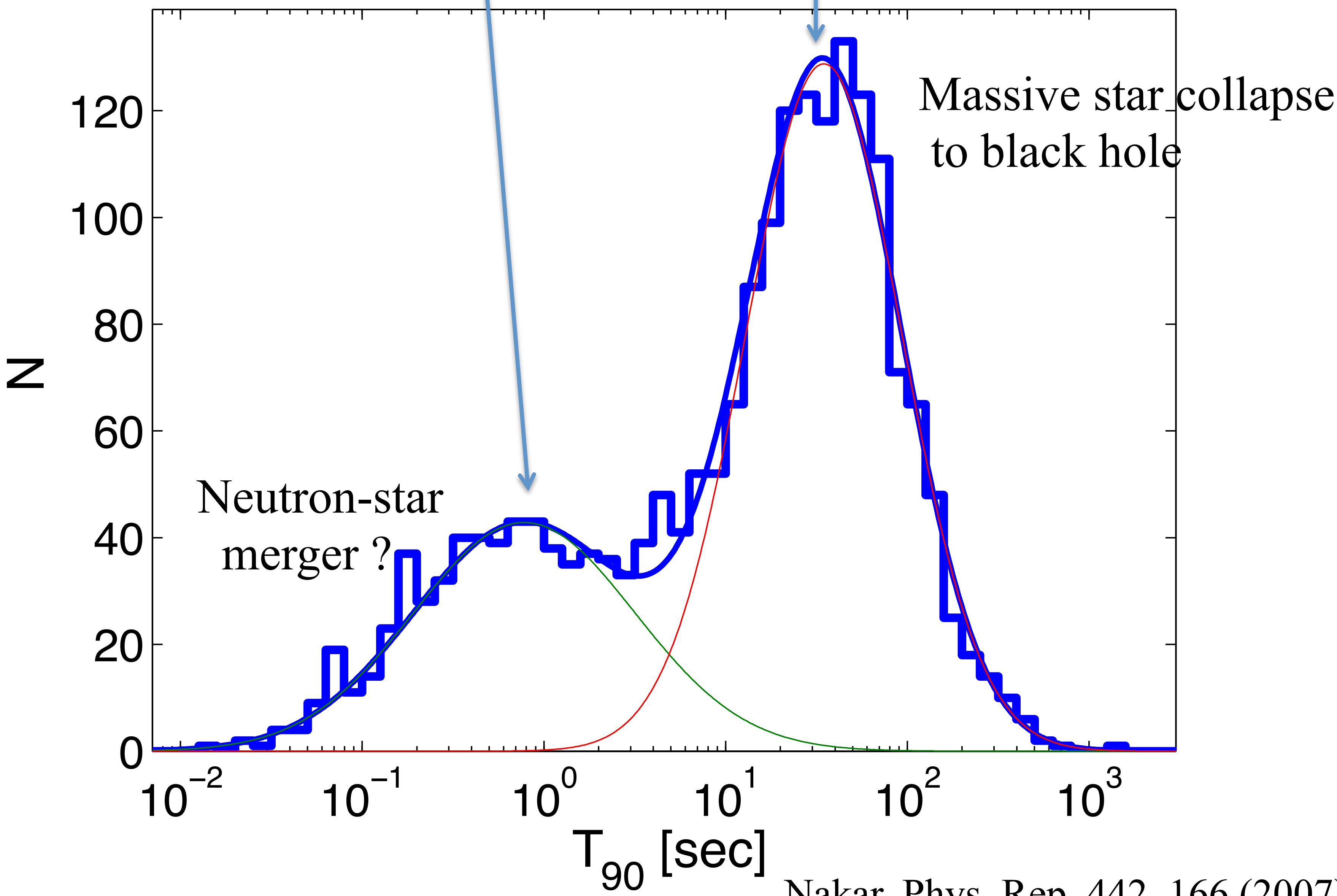
Short γ-ray bursts (SGRBs)

- High luminosity ~ 10^{49}—10^{50} ergs/s
- Short: Δt < ~2 sec (see next page)→ NS merger ?

❖ **Coincident detection of gravitational waves & SGRB will solve this issue, but jet is collimated so it would not be easily achieved → Theoretical prediction for observations of circumstantial evidence plays a role**



Short & Long



Nakar, Phys. Rep. 442, 166 (2007)

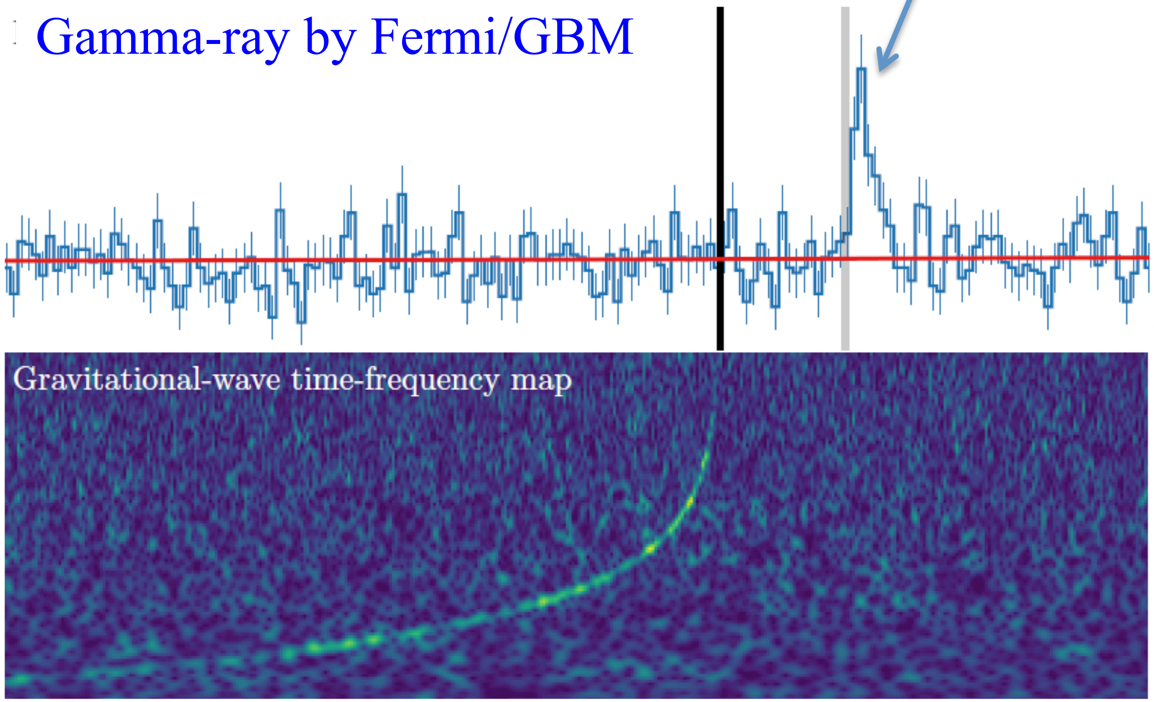
GW170817 and a gamma-ray burst ?

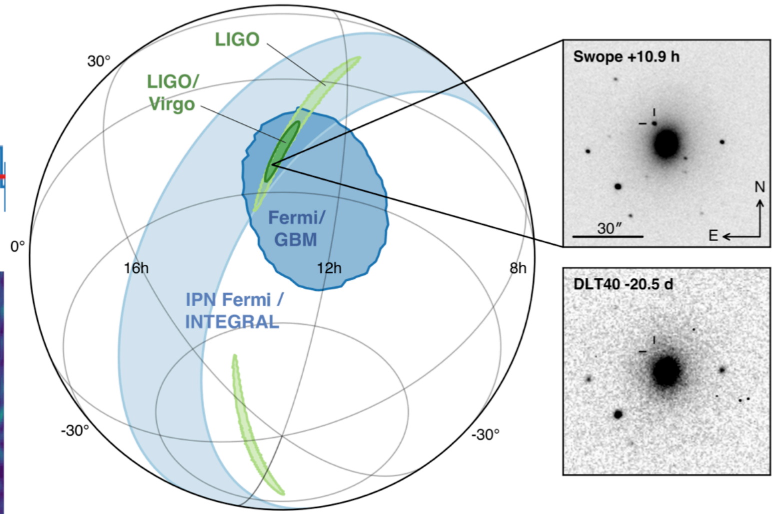
Energy is too small to regard it as GRB
~10^{46} ergs/s

From www.ligo.org

LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

Gamma-ray by Fermi/GBM

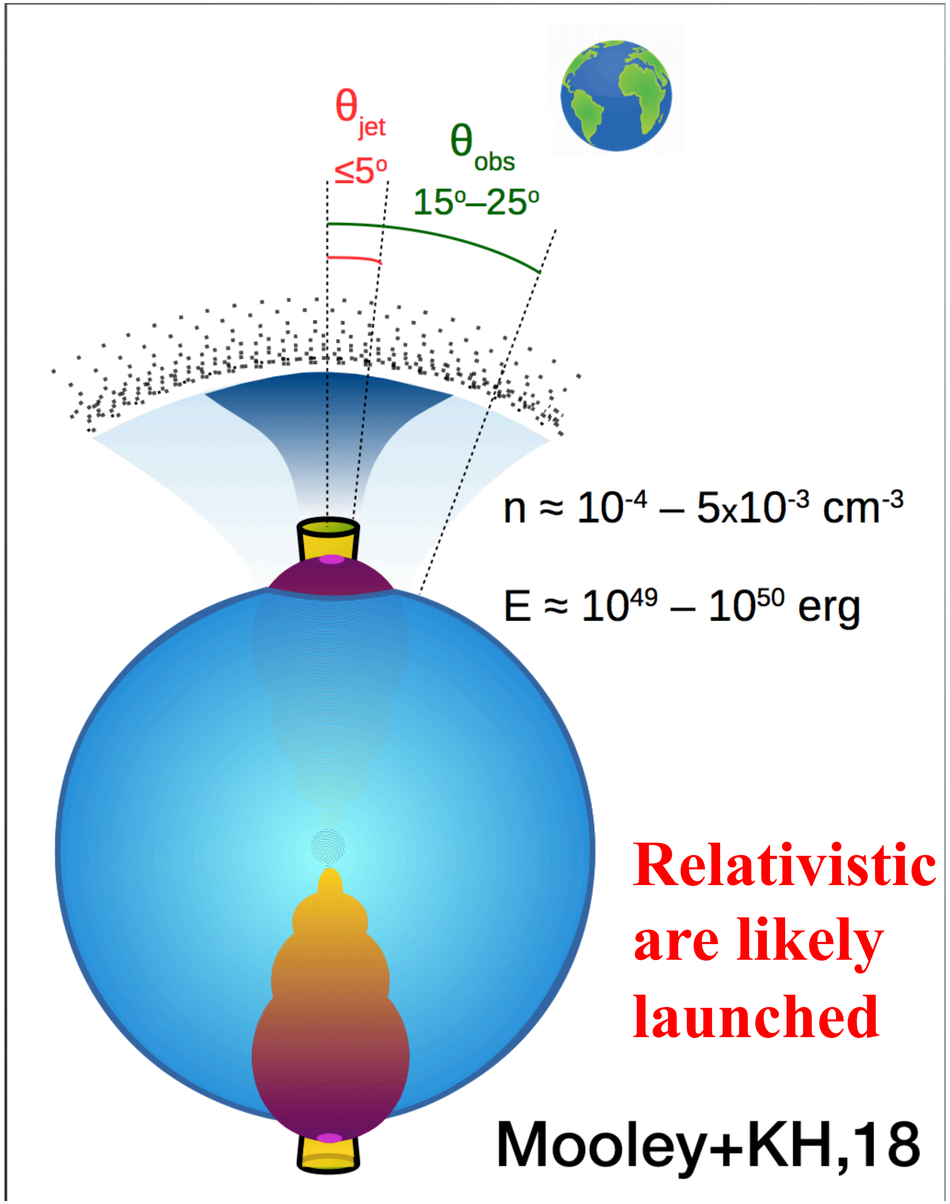




Gravitational waves by LIGO/Livingstone

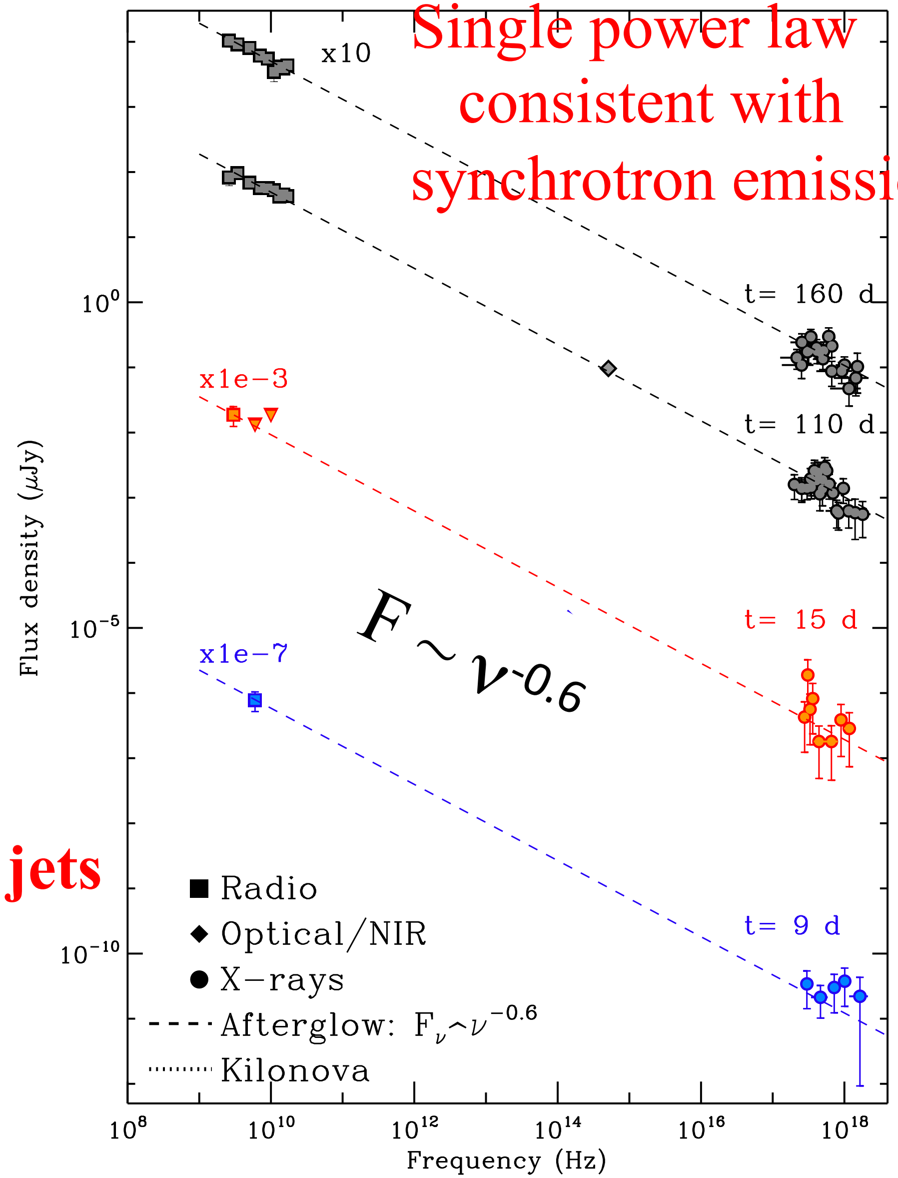
Detection of GWs from *inspiraling* neutron stars

Synchrotron emission from relativistic outflow



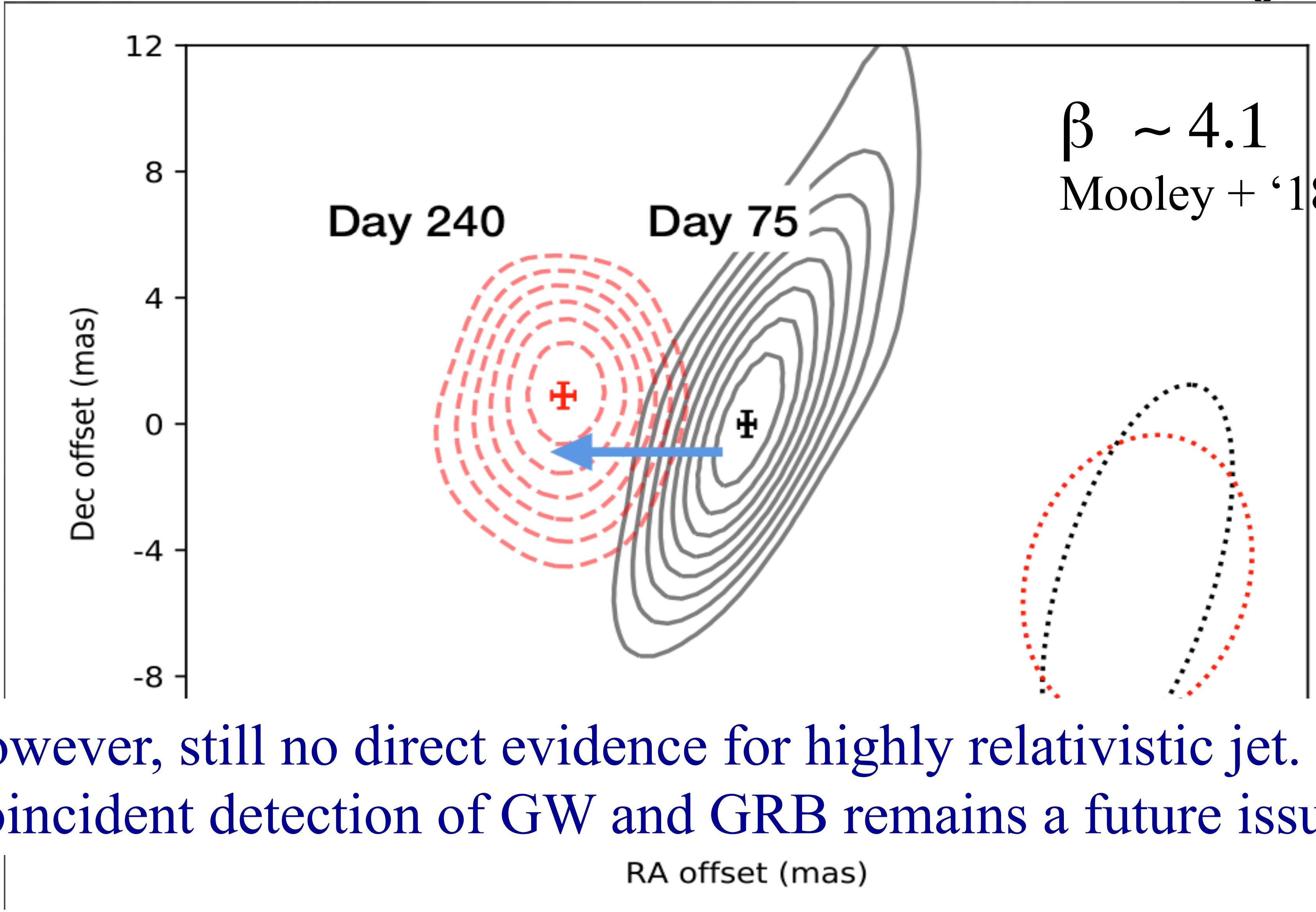
Relativistic jets are likely launched

Single power law consistent with synchrotron emission



Margutti et al 2018

Superluminal motion of radio counterpart of GW170817: an evidence for relativistic jet



$\beta \sim 4.1$

Mooley + '18

However, still no direct evidence for highly relativistic jet.
Coincident detection of GW and GRB remains a future issue.

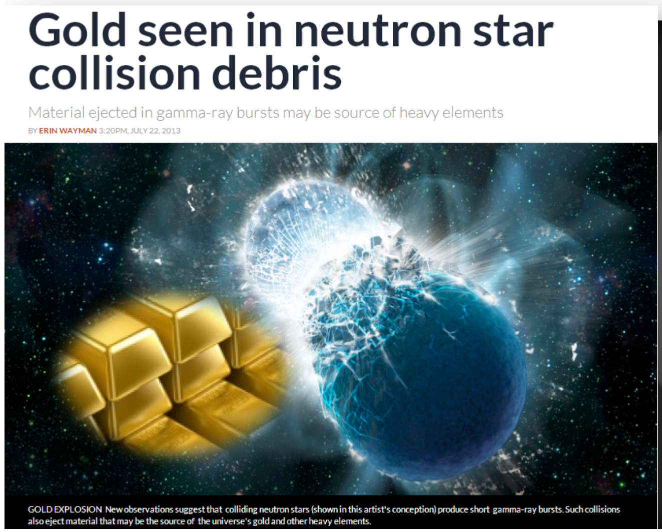
Why we study NS merger ?

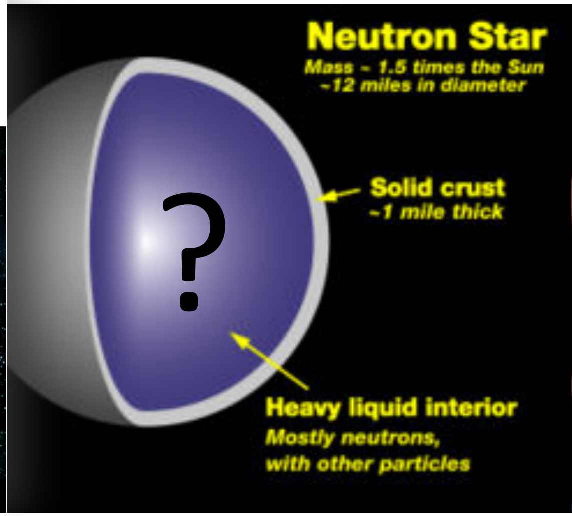
A. Most promising sources of gravitational waves for advanced LIGO/VIRGO/KAGRA

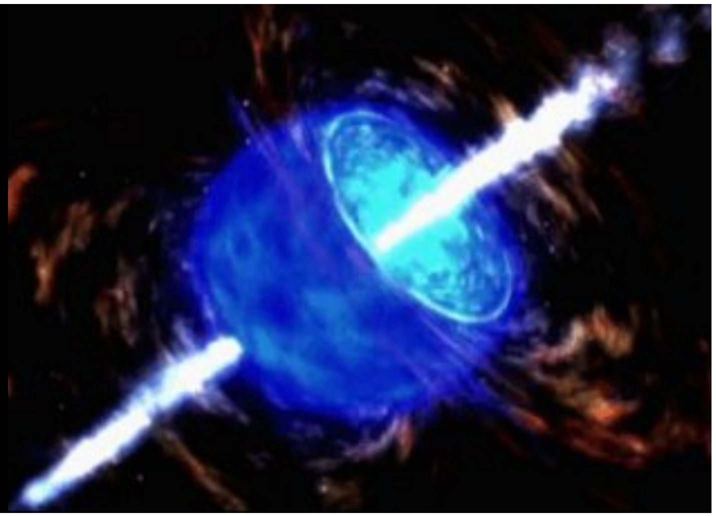
B. Laboratory for high-density nuclear matter

C. Promising origins of short-hard GRBs

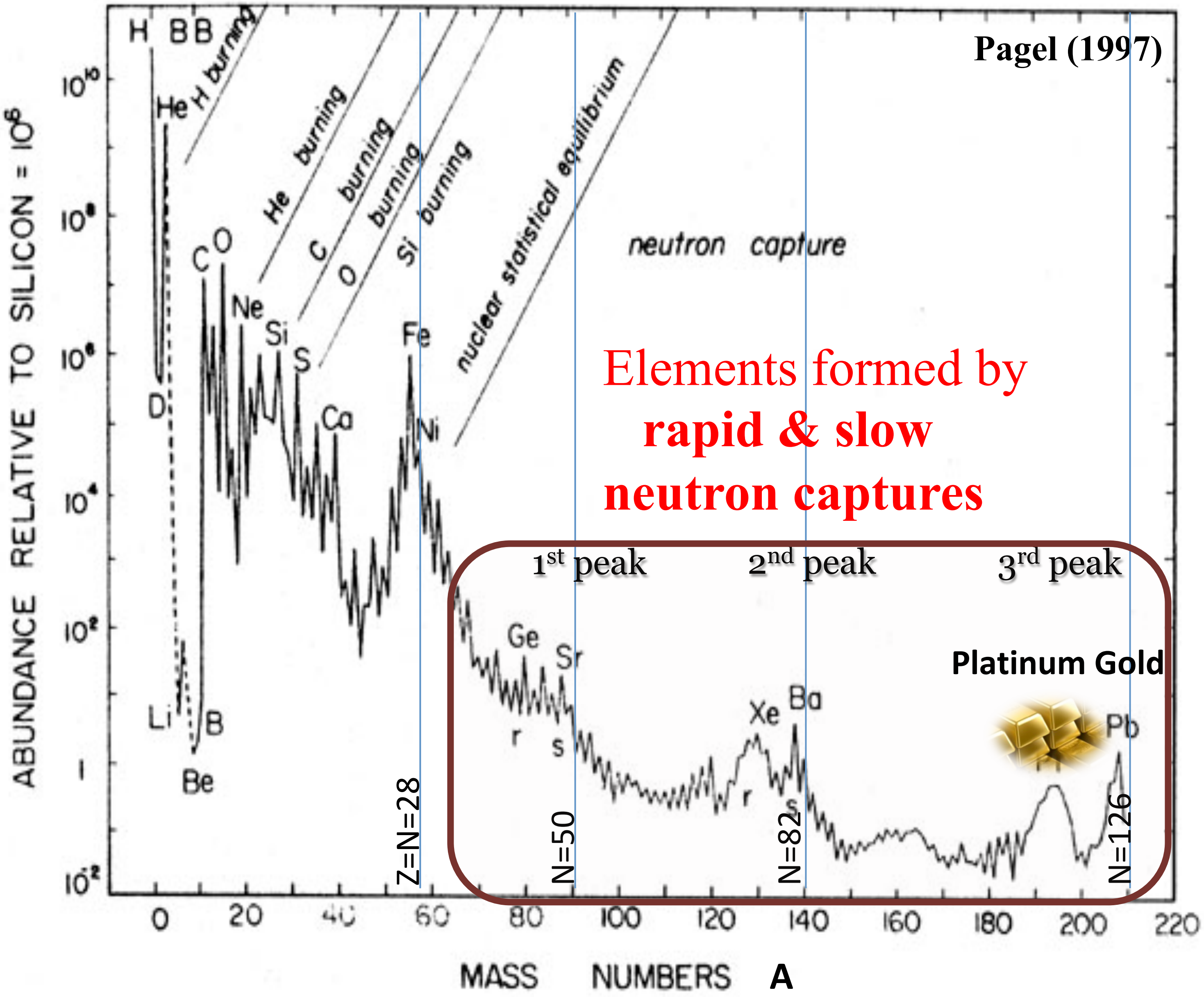
D. Promising site for heavy elements produced by rapid neutron-capture process (r-process)







Origin of heavy elements?



Origin of heavy elements for A >~ 80

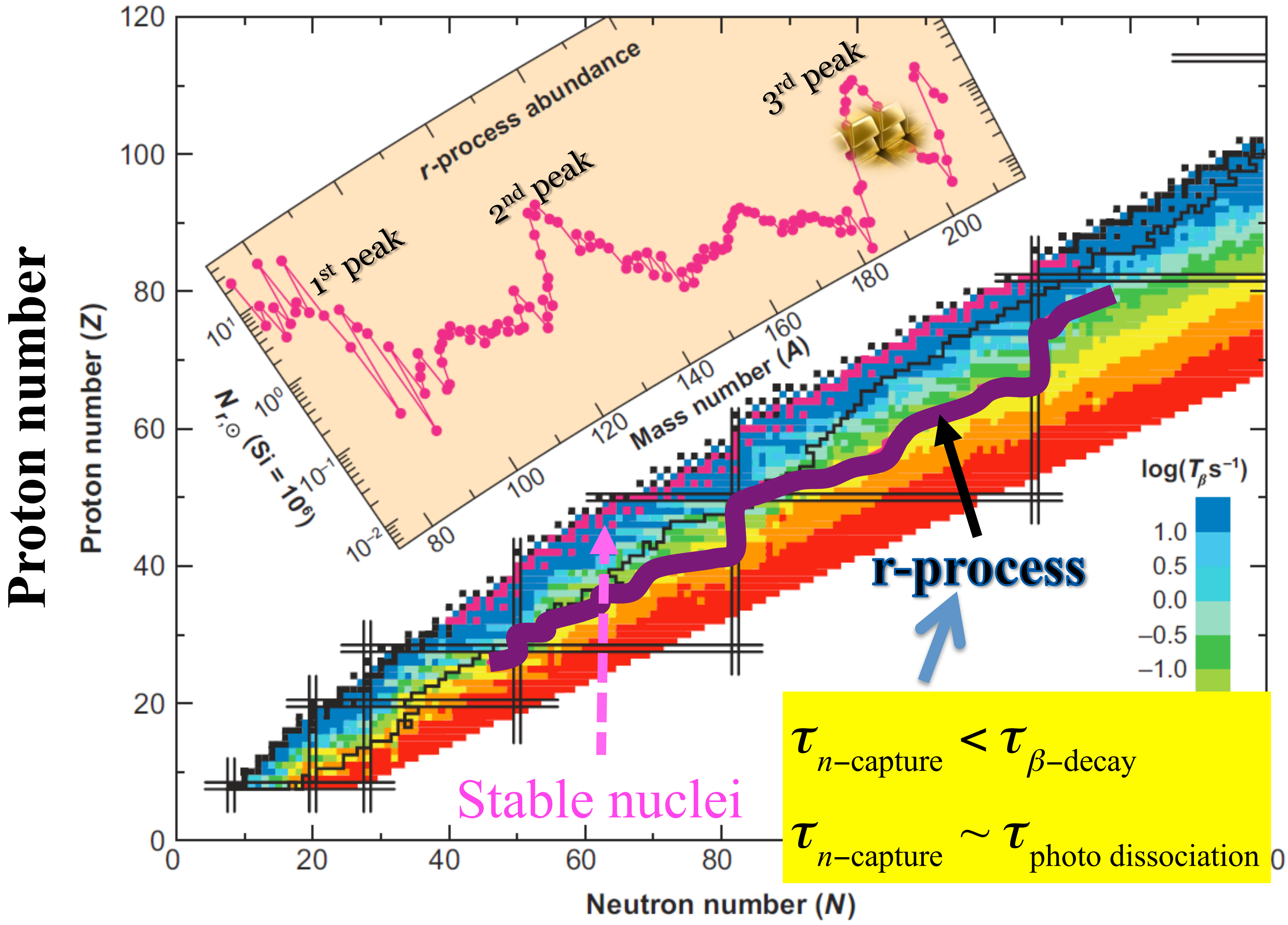
- **Mass is likely to be increased by neutron capture**
- **Slow process: $\tau_\beta < \tau_{n\ capture}$**

✓ This is believed to occur in an evolved star

- **Rapid process: $\tau_\beta > \tau_{n\ capture}$**

✓ The origin for this is still unsolved

✓ Neutron-star mergers are among the promising candidates

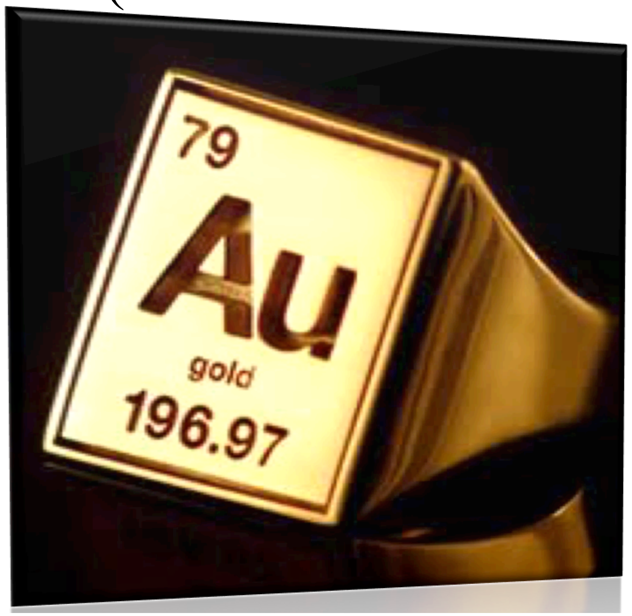


Neutron number

Snedin et al. ARAA 2008

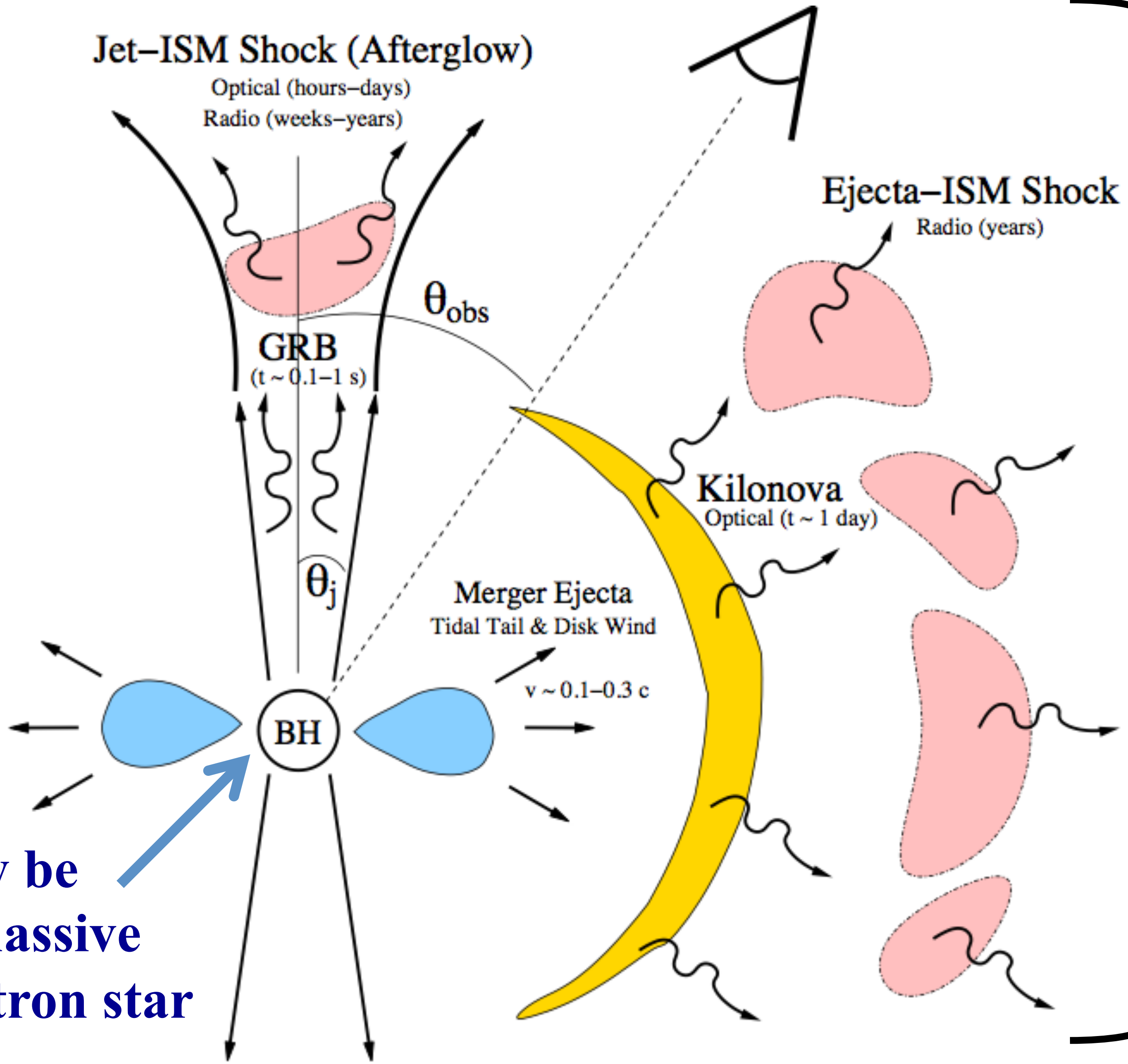
Origin of r-process elements
(gold, silver, platinum) ?

- People long believed that core-collapse supernovae (CCS) would be the synthesis site for r-process elements (textbooks say usually so)
- Latest CCS simulations indicate ***heavy r-elements are unlikely to be synthesized*** (Wanajo, Janka, Roberts …)
- **NS merger is another potential candidate** (Lattimer & Schramm 1974, Eichler et al. 1989)



Schematic picture of NS mergers

Metzger & Berger, 2012



May be a massive neutron star

Mass ejection
↓
r-process, β-decay
↓
Shine !
↓
Could be detected

Summary of Introduction

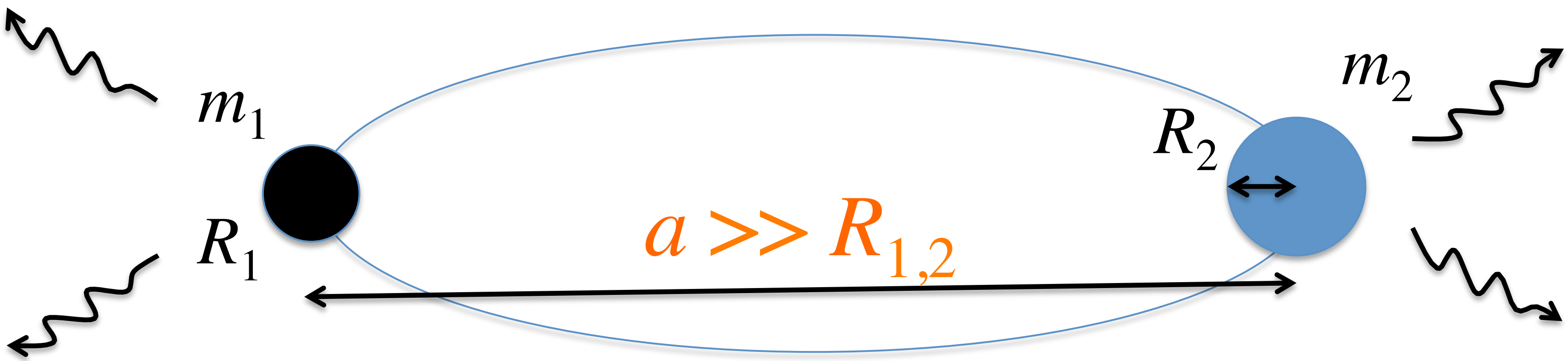
Many unsolved issues are being solved by observing gravitational waves & electromagnetic signals from neutron-star mergers

&

Numerical relativity plays a key role in this business

2 Inspiral toward merger

- Consider a binary in a large orbital separation, which evolves by gravitational-radiation reaction



For distant orbits, compact stars can be treated as point particles (we do not care BH or NS)

Evolution of two point masses in circular orbits by gravitational radiation

◆ Newtonian motion + Quadrupole formula

Quadrupole formula gives (E.g., Shapiro & Teukolsky)

$$\left[\frac{dE}{dt}\right]_{\mathrm{GW}} = -\frac{32}{5}\frac{G^4}{c^5}\left(\frac{\mu}{M}\right)^2\left(\frac{M}{a}\right)^5$$

Energy balance gives evolution eq. of a

$$E = -\frac{GM\mu}{2a} \quad \Rightarrow \quad \frac{dE}{dt} = \frac{GM\mu}{2a^2}\frac{da}{dt} = \left[\frac{dE}{dt}\right]_{\mathrm{GW}}$$

$$\Rightarrow \boxed{\frac{da}{dt} = -\frac{64}{5}\frac{G^3M^2\mu}{c^5a^3}}$$

$M = m_1 + m_2$: Total mass, $\mu = m_1m_2/M$: Reduced mass

$\eta = \dfrac{\mu}{M} = \dfrac{m_1m_2}{M^2}$: Symmetric mass ratio

Continued

$$\frac{da}{dt} = -\frac{64}{5}\frac{G^3M^2\mu}{c^5a^3} \Rightarrow a^4 = a_0^4 - \frac{256}{5}\frac{G^3M^2\mu}{c^5}t$$

$$\Rightarrow \text{Coalescence time} \quad t_{\text{gw}} = \frac{5}{256}\frac{c^5a_0^4}{G^3M^2\mu} = \frac{5}{256\pi^{8/3}}\frac{c^5f_0^{-8/3}}{G^{5/3}\mathcal{M}^{5/3}}$$

$$\text{where } f_0 = \frac{1}{\pi}\sqrt{\frac{GM}{a_0^3}} \quad \& \quad \mathcal{M} = M^{2/5}\mu^{3/5} : \text{ chirp mass}$$

$$t_{\text{gw}} = 94\left(\frac{a_0}{400\ \text{km}}\right)^4\left(\frac{M}{2.8M_\odot}\right)^{-3}\left(\frac{\eta}{1/4}\right)^{-1} \text{sec} :$$

$$f_0 = 24.3\ \text{Hz}\left(\frac{a_0}{400\ \text{km}}\right)^{-3/2}\left(\frac{M}{2.8M_\odot}\right)^{1/2}$$

Approximate lifetime of the binary

t_{gw} & f_0 are observable

Ratio of radiation reaction time to orbital period

$$\frac{t_{\rm GW}}{P_0} = \frac{5}{512\pi}\left(\frac{c^2 a}{GM}\right)^{5/2}\left(\frac{M}{\mu}\right) \approx 1.1\left(\frac{c^2 a}{6GM}\right)^{5/2}\left(\frac{M}{4\mu}\right) > 1$$

$$\text{for} \quad a > \frac{6GM}{c^2} = 24.8\text{km}\left(\frac{M}{2.8M_\odot}\right) \qquad \text{Note:} \ \frac{\mu}{M} \le \frac{1}{4}$$

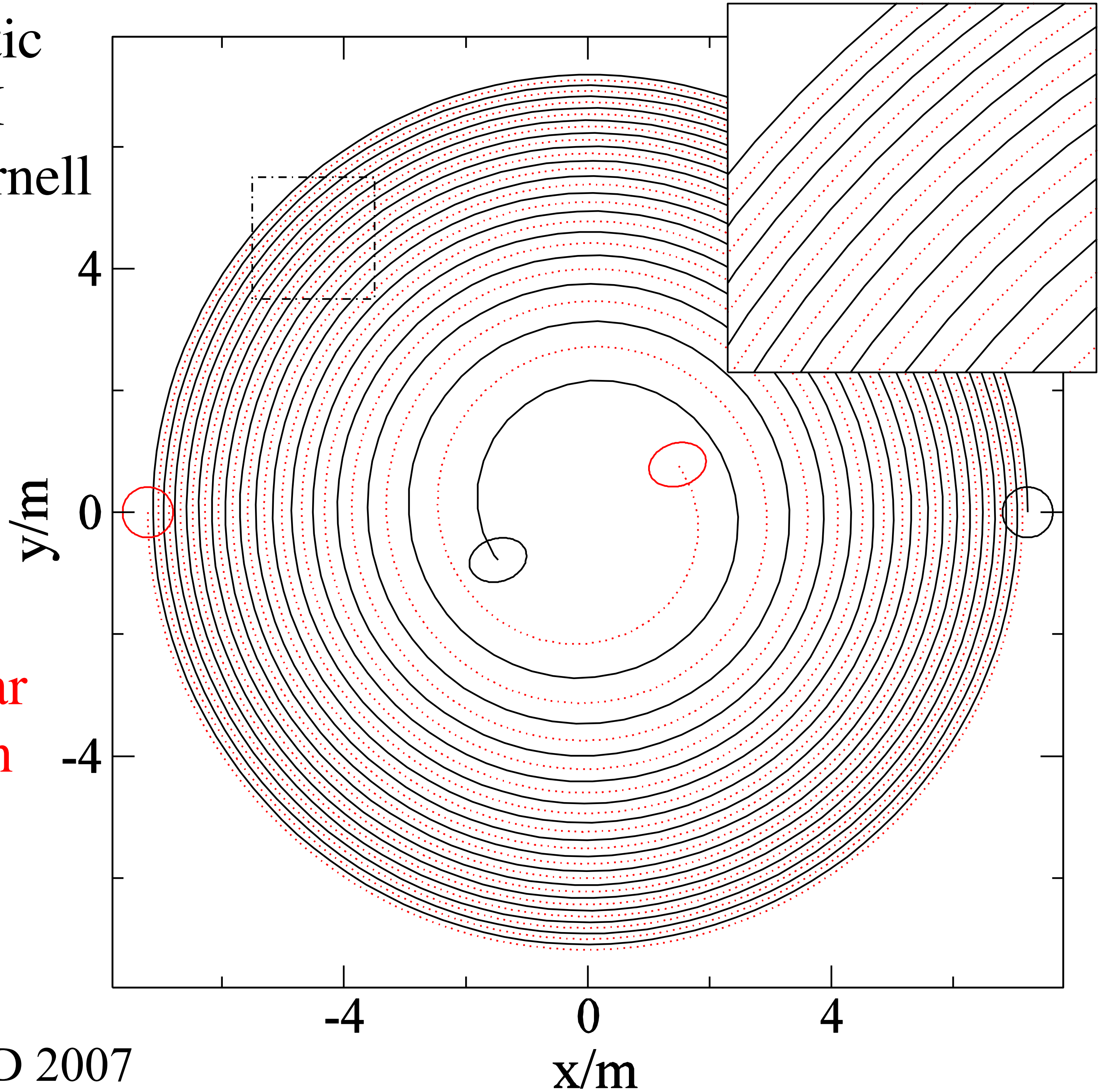
- **Binary orbits are mostly adiabatic (not dynamical)**

➢ For NS-NS, the **radiation reaction timescale is always longer than the orbital period**

→ **The orbits are always adiabatic (quasi-circular)**

➢ For **spinning** BH-NS, **for which *a* can be smaller than 6*GM*/*c*², the radiation reaction timescale may be shorter than the orbital period before ISCO**

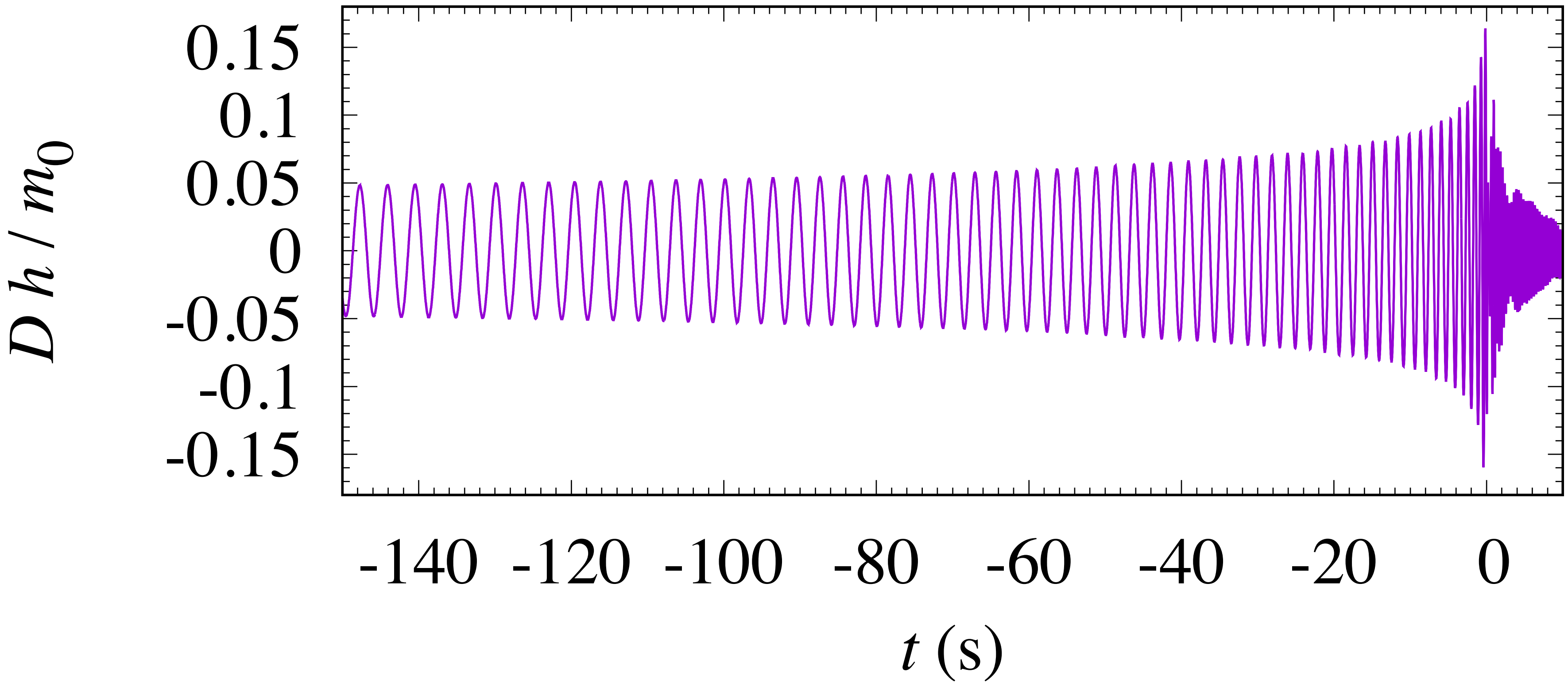
The first realistic run for BH-BH by Caltech-Cornell



“Quasi-circular orbits” is seen

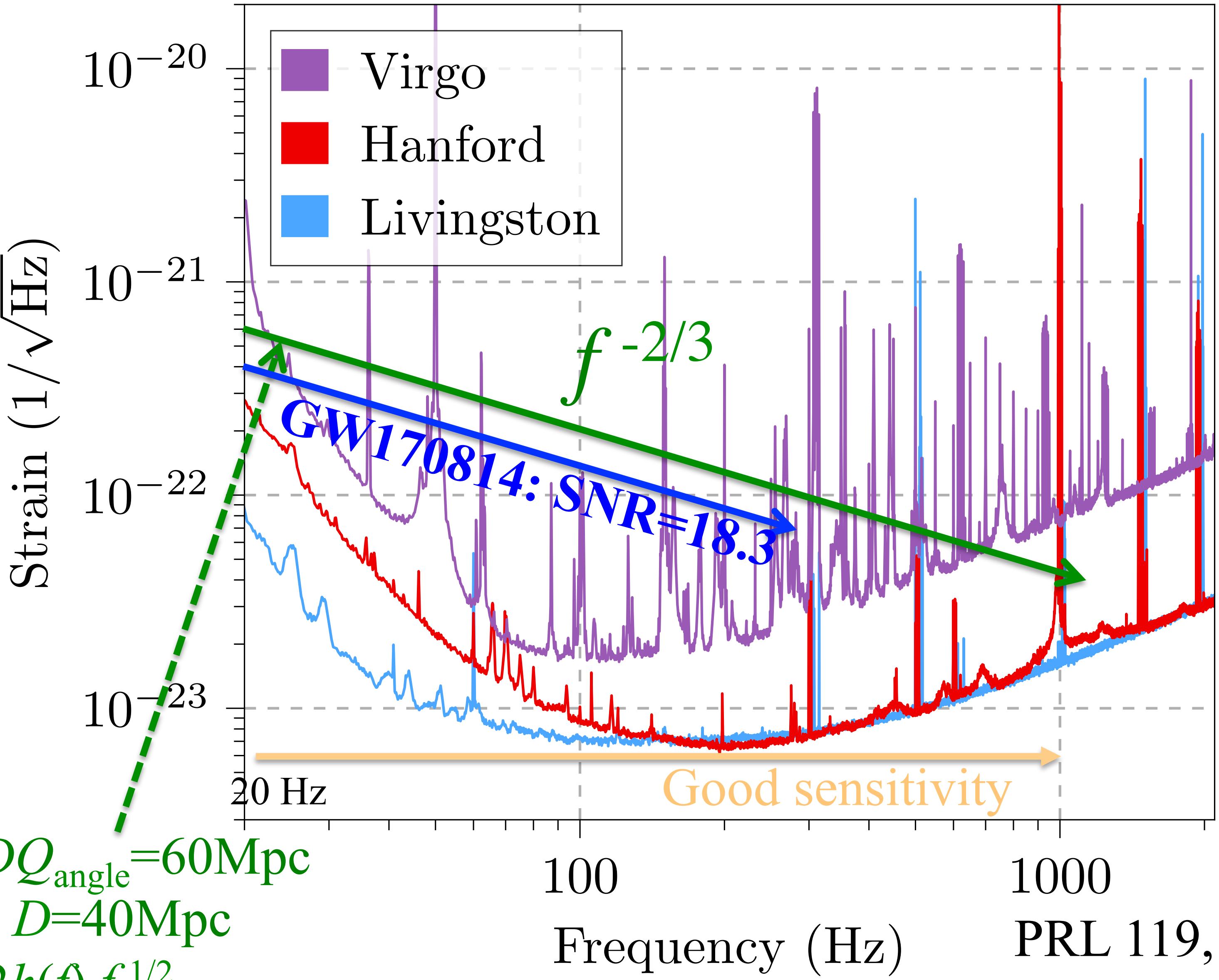
Boyle et al. PRD 2007

Gravitational waves in the late inspiral phase of binary neutron stars



Chirp signal: Quasi-periodic but amplitude and frequency of gravitational waves increase with time

LIGO & VIRGO O2 @ GW170814, GW170817



SNR=26.4 for L

SNR=18.8 for H

SNR =32.4 in total

$D_{\mathrm{eff}}=DQ_{\mathrm{angle}}$=60Mpc
where D=40Mpc
Plot: $2h(f)\,f^{1/2}$

PRL 119, 141101 (for GW170814)

Post-Newtonian corrections cannot be neglected

$$t_{\rm gw} = \frac{5}{256\pi^{8/3}} \frac{c^5 f_0^{-8/3}}{G^{5/3}M^{5/3}} \left[1 + \left(\frac{743}{252} + \frac{11\eta}{3} \right) x - \frac{32\pi}{5} x^{3/2} + O\left(x^2\right) \right]$$

$$x = \left(\pi G M c^{-3} f_0\right)^{2/3} = 0.01191 \left(\frac{M}{2.8 M_\odot} \right)^{2/3} \left(\frac{f_0}{30\mathrm{Hz}} \right)^{2/3}$$

Post-Newtonian parameter

PN correction = A few % correction

Assume no spin

GW170817: initial announcement

$E.g.,\ \text{if}\ t_{\rm gw} = 74\ \text{sec}\ \ \&\ f_0 = 27\mathrm{Hz},\ \text{then}\ M \approx 1.19 M_\odot$

$\eta \approx 0.245 - 0.25$ for typical binary neutron stars

An important property of chirp mass

$$\mathcal{M} := M^{2/5}\mu^{3/5} = \frac{\left(m_1 m_2\right)^{3/5}}{M^{1/5}} = M\eta^{3/5} : \eta = \frac{\mu}{M} \le \frac{1}{4}$$

$$\Rightarrow M = \mathcal{M}\eta^{-3/5} \ge 4^{3/5}\mathcal{M}\left(\frac{\eta}{1/4}\right)^{-3/5} = 2.2974\mathcal{M}\left(\frac{\eta}{1/4}\right)^{-3/5}$$

$$\therefore \quad \mathcal{M} = 1.19M_\odot \Rightarrow M \ge 2.73M_\odot\left(\frac{\eta}{1/4}\right)^{-3/5}\left(\frac{\mathcal{M}}{1.19M_\odot}\right)$$

Chirp mass gives *the lower bound of the total mass*

Post-Newtonian corrections up to 1.5PN order

$$t_{\rm gw} = \frac{5}{256\pi^{8/3}} \frac{c^5 f_0^{-8/3}}{G^{5/3} M^{5/3}} \left[1 + \left(\frac{743}{252} + \underline{\underline{\frac{11\eta}{3}}} \right) x - \frac{32\pi}{5} x^{3/2} + \underline{\underline{ASx^{3/2}}} \right]$$

$$x = \left(\pi G M c^{-3} f_0\right)^{2/3} = 0.01191 \left(\frac{M}{2.8 M_\odot}\right)^{2/3} \left(\frac{f_0}{30\mathrm{Hz}}\right)^{2/3}$$

$$\chi = \frac{cS_1}{GM_1^2} + \frac{cS_2}{GM_2^2}: \text{ spin parameter,} \qquad A: \text{constant of O(1)}$$

Degeneracy between χ and η occurs

→ Constraint to mass ratio is not very strong

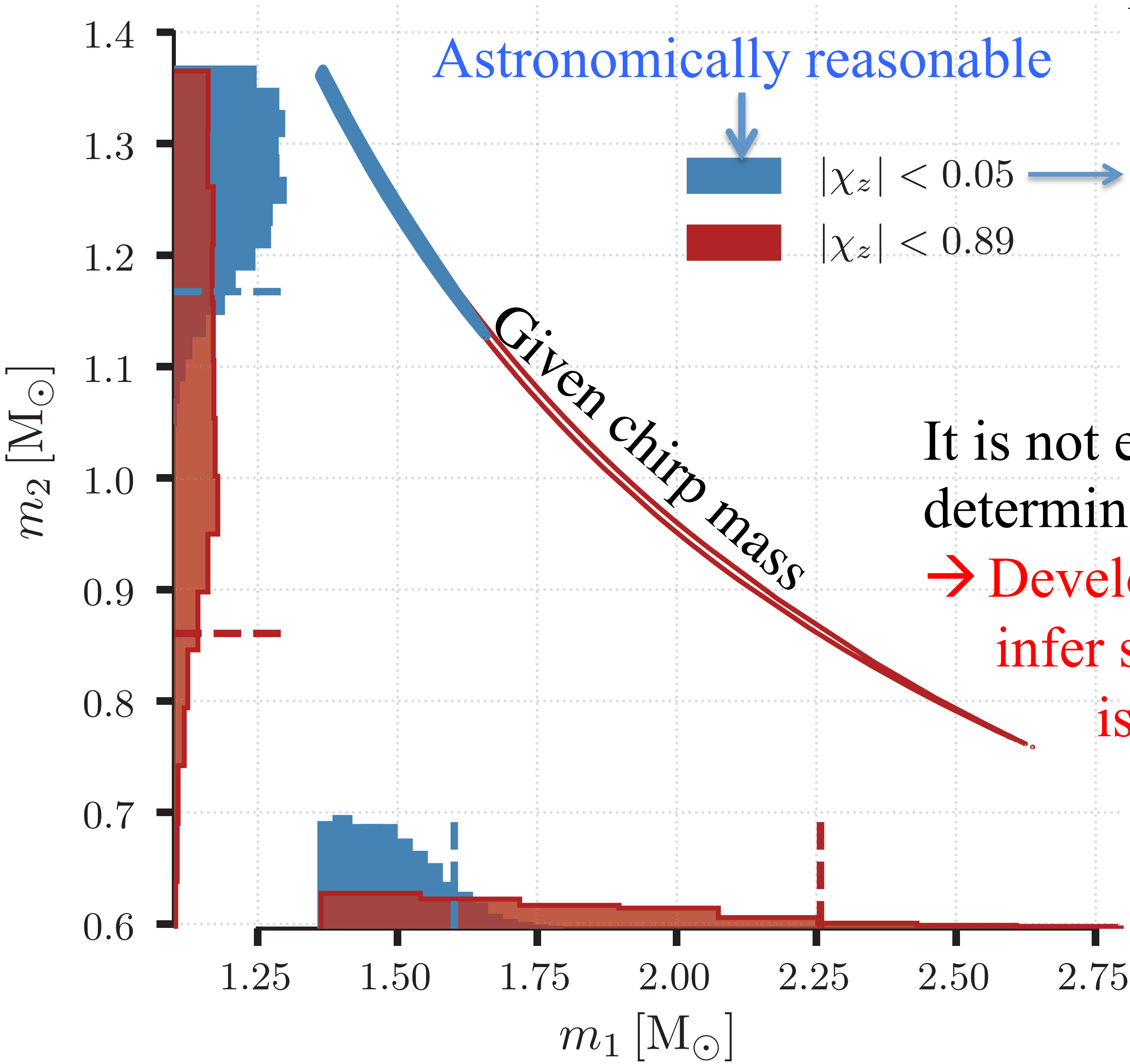
(Cutler & Flanagan 1994)

GW170817: Assuming $|\chi| < 0.05$: reasonable assumption

$$0.7 \le \frac{M_2}{M_1} \le 1 \quad \text{or} \quad 0.242 \le \eta \le 0.250 \quad (2\sigma \text{ level})$$

Constraint for each mass of GW170817

PRL 119 161101



M_{tot}=2.73—2.78 solar mass

It is not easy to accurately determine each mass

→ Developing methods to infer spin/mass ratio is important

3 Standard scenario for NS-NS merger in NR

- **Constraints from radio-telescope observations**:

1. Approximately 2 solar-mass neutron stars exist
   → equation of state (EOS) for NS has to be stiff
2. Typical total mass of binary neutron stars
   → ~ 2.5—2.8 solar mass (but higher mass exists)

- **Merger typically results in high-mass neutron stars (not BH)** (Shibata et al. 2005, 2006, Hotokezaka et al. 2011,.. many work)
- Difference in EOS is reflected in gravitational waves emitted from the late inspiral to merger phases
  (Shibata et al. 2005, Hotokezaka et al. 2011, Bauswein 2013, Bernuzzi et al. 2015.. many similar work of similar conclusion)
- During the merger, neutron-rich matter is dynamically ejected with mass of 0.001—0.01 solar mass
  (Hotokezaka et al. 2013, Bauswein et al. 2013, Sekiguchi et al. 2015,…….)

Current understanding of NS-NS

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

APR4: R=11.1km

ALF2: R=12.4km

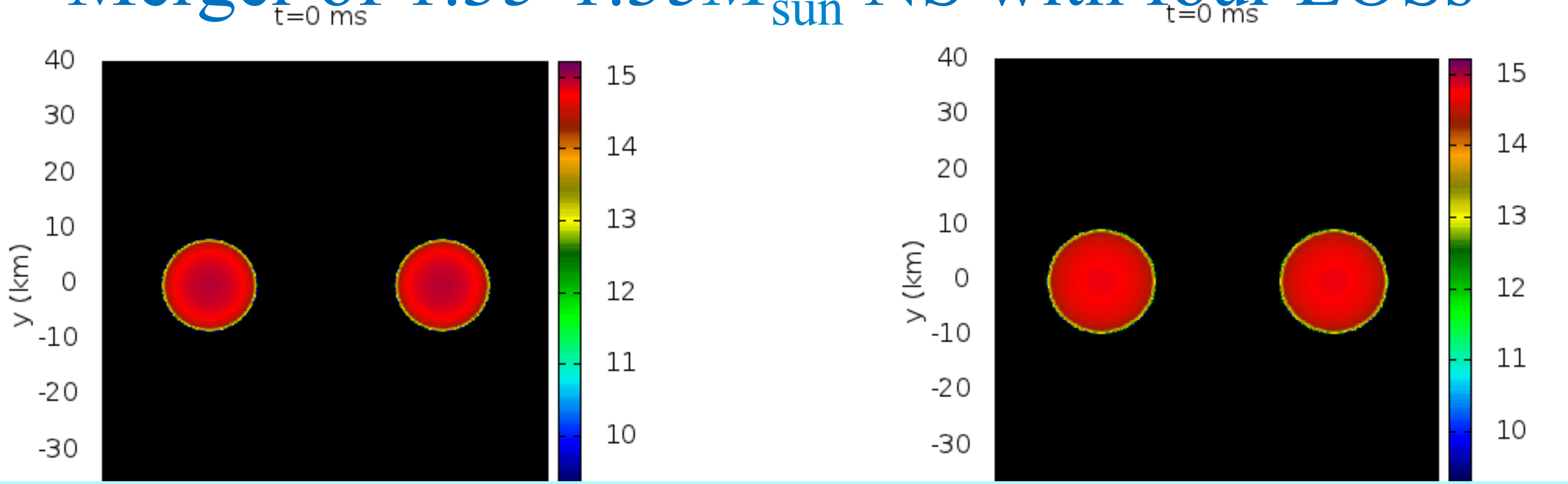
All EOSs satisfy $M_{max} > 2M_{sun}$

H4: R=13.6km

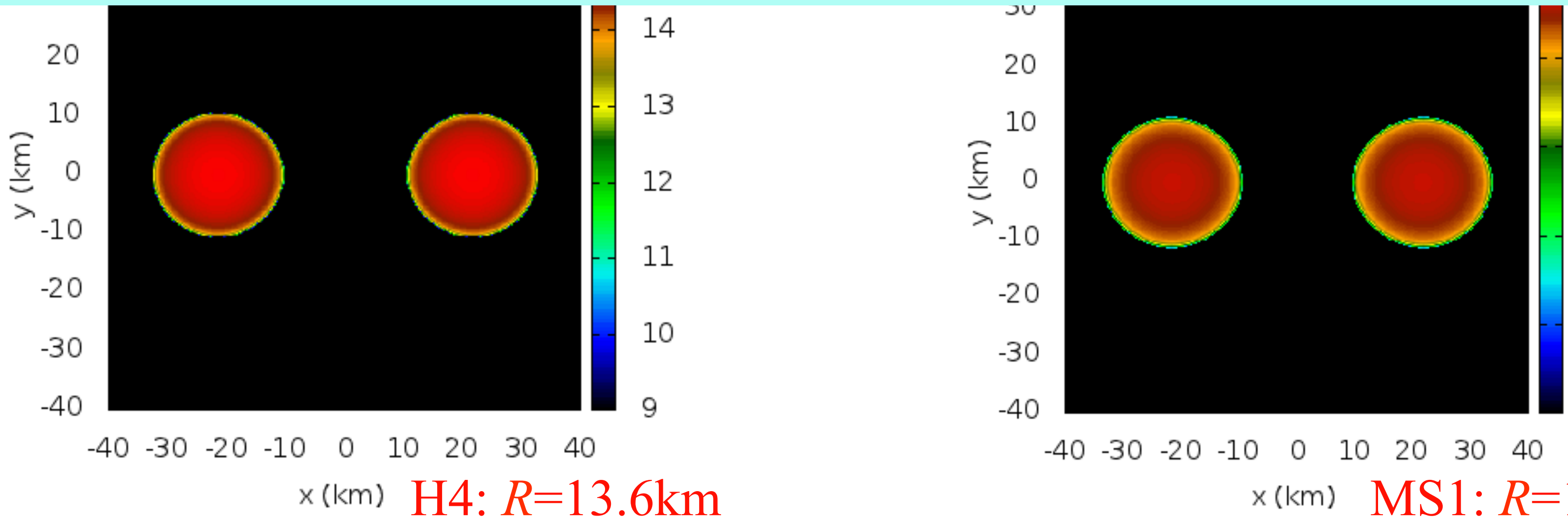
MS1: R=14.5km

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

By Hotokezaka + 2013



Massive neutron stars are remnants
Irrespective of EOS for canonical mass

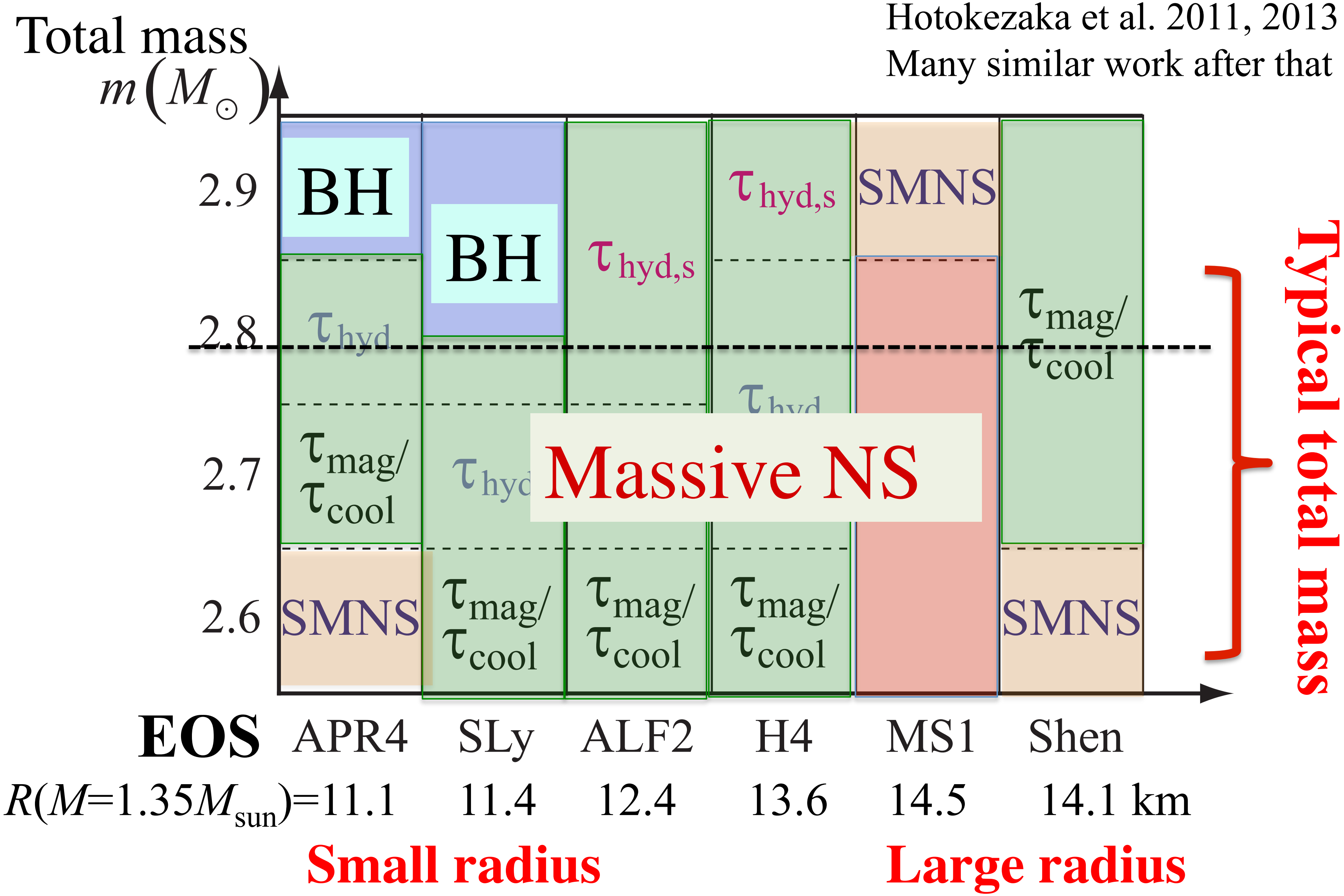


H4: R=13.6km

MS1: R=14.5km

Dependence on EOS and total mass

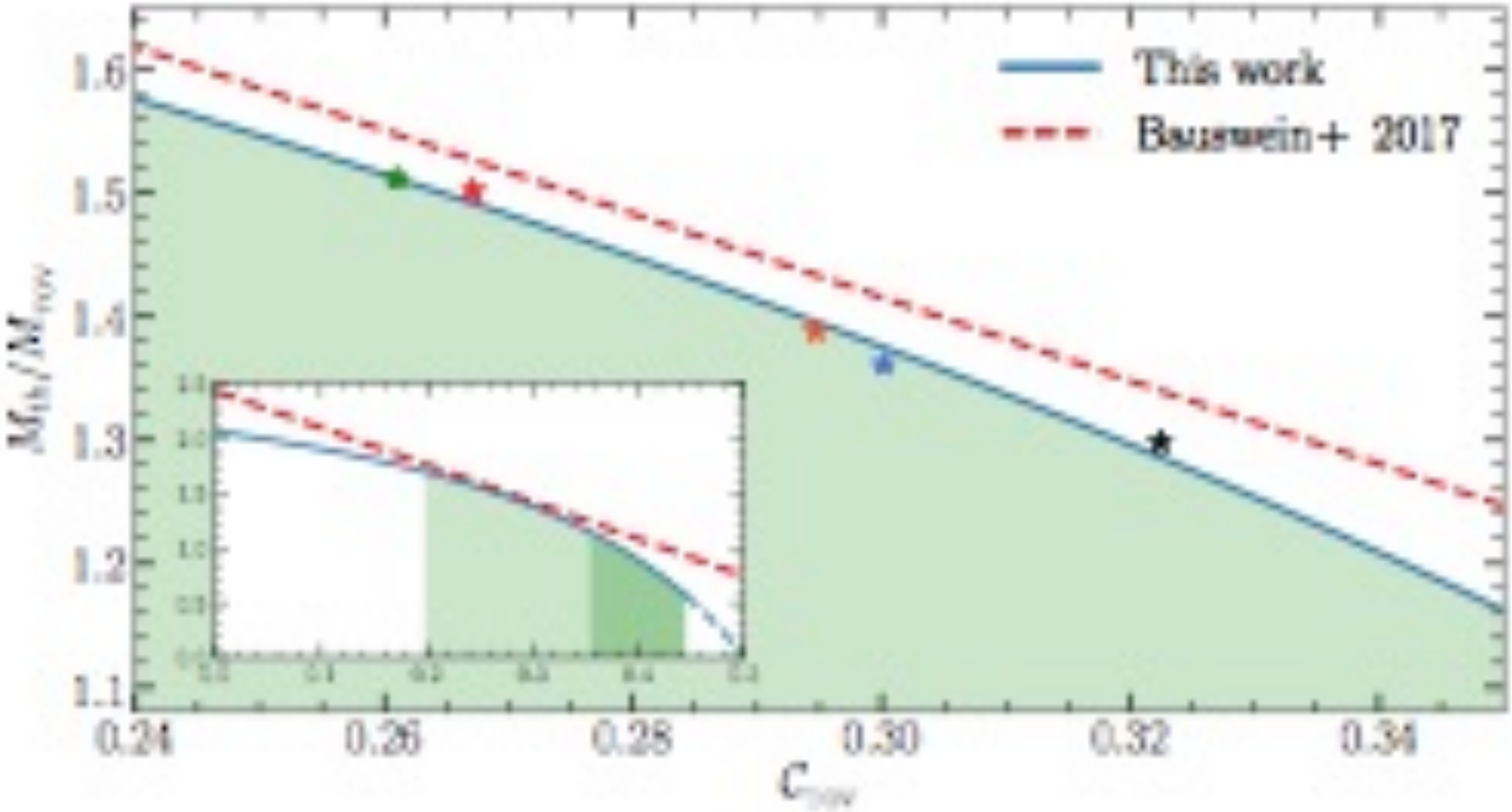
Hotokezaka et al. 2011, 2013
Many similar work after that



Threshold mass for the prompt collapse to a BH

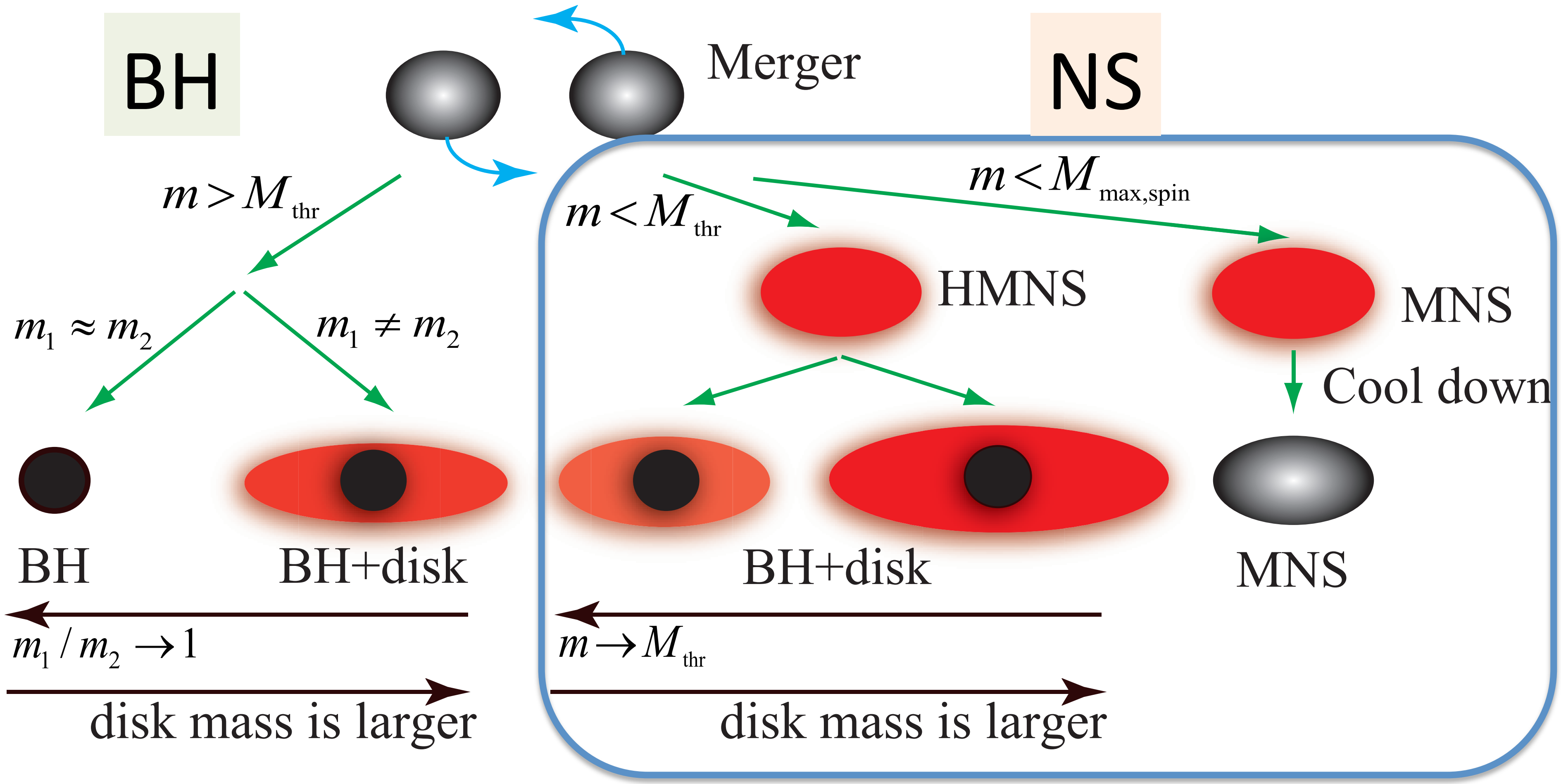
$M_{\mathrm{TOV}} \sim$ 2.1-2.4 solar mass

Koeppel et al. 2019



Compactness of non-rotating Maximum mass star

Possible fates of NS-NS mergers



$M > \sim 2.8 M_{\text{sun}}$

Likely for $M < \sim 2.8 M_{\text{sun}}$

I.e., irrespective of EOS, threshold mass $> \sim 2.8 M_{\text{sun}}$

Note: for J1913+1102, total mass~2.88 solar mass

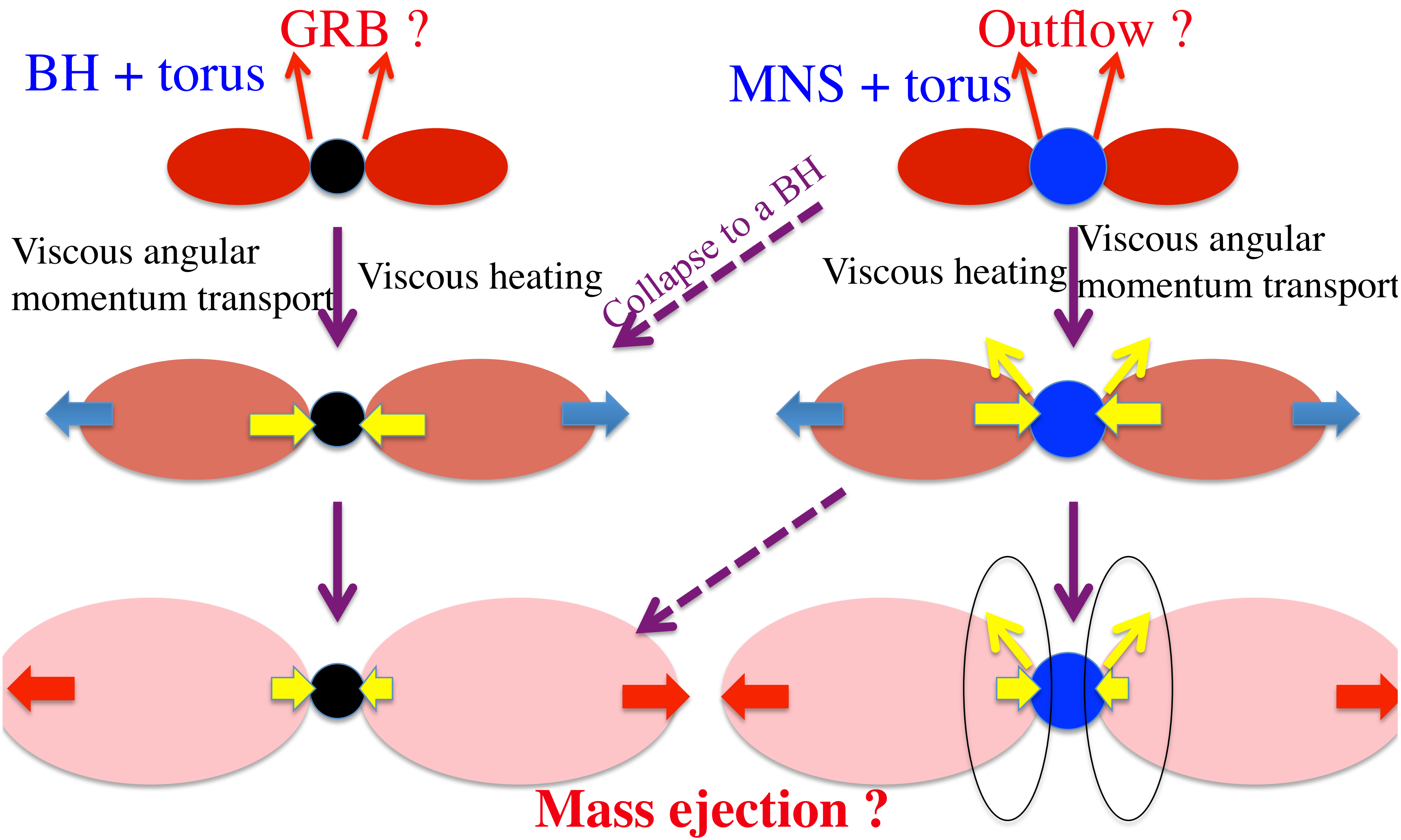
Merger remnants and their evolution

✓ Remnant is either a massive neutron star (MNS) or a black hole (BH), but **MNS is more likely**

✓ In either case, in general, a **massive torus** is likely to surround the central object

- Remnant MNS and torus are expected to be **differentially rotating and strongly magnetized**
  → Subject to magneto-hydrodynamics effects such as magnetorotational instability and magnetic winding
- **MHD and resulting viscous effects** are likely to be the driving force for the evolution of merger remnants
  → Need MHD/viscous simulations in NR (later)

Evolution processes in the post-merger phase

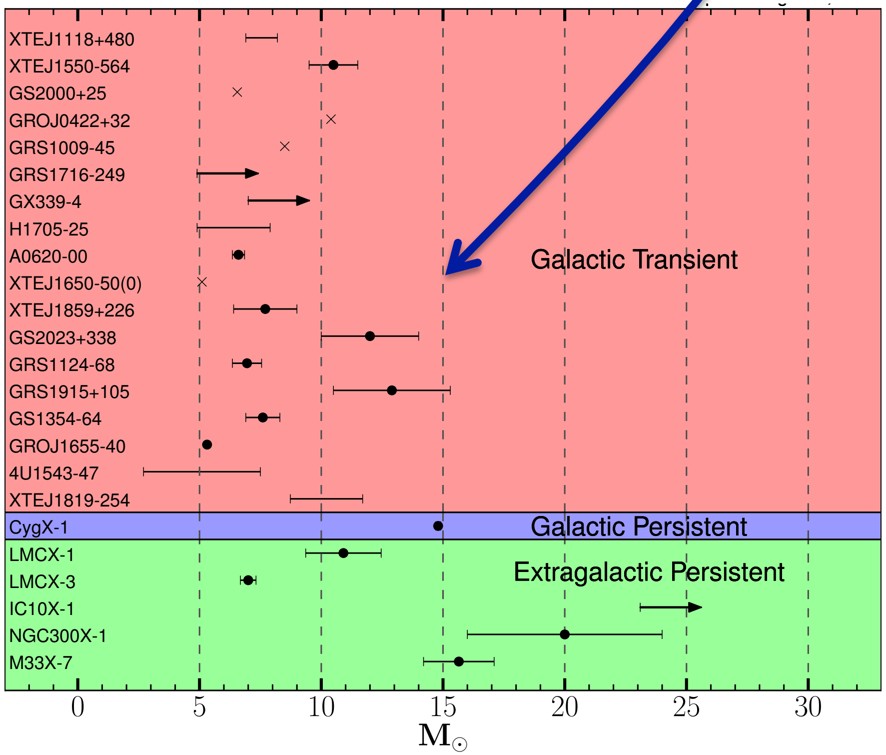


Numerical relativity plays an important role for exploration

4 Scenarios for BH-NS merger

- **Almost no observational constraints but for black hole mass which is likely >~ 5M_{sun}**
  → Wide parameter space has to be explored
- **Fate = two possibilities:**

1. **Tidal disruption of NS**
2. **Plunge of NS into BH**



https://www.stellarcollapse.org/bhmasses

Two possibilities: Tidal disruption or not

For tidal disruption, $\left(\text{Self gravity of NS}\right) < \left(\text{BH tidal force}\right)$

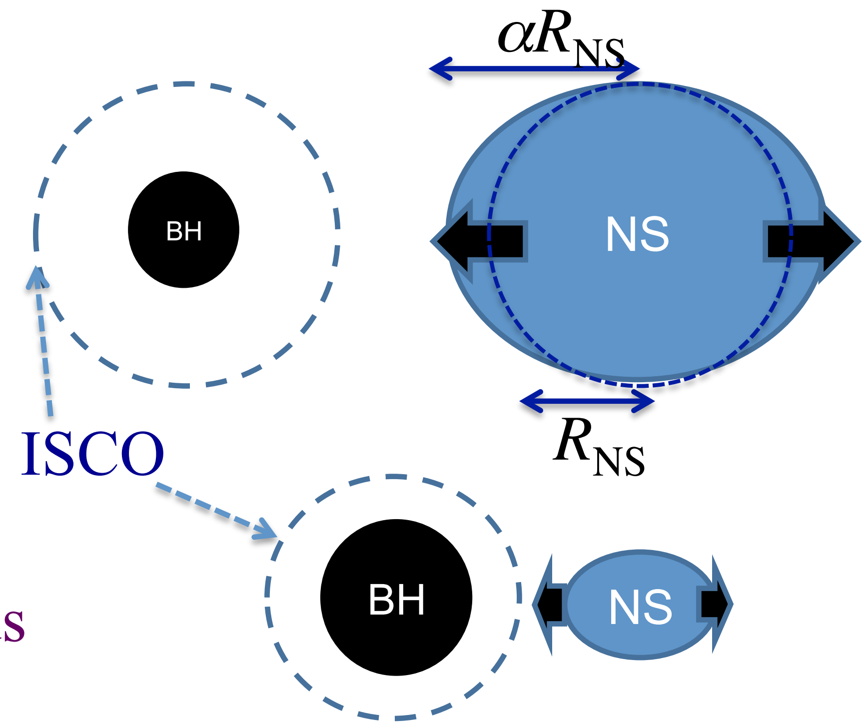
$$\Downarrow$$

$$\frac{M_{\rm NS}}{\left(\alpha R_{\rm NS}\right)^2} < \frac{M_{\rm BH}\left(\alpha R_{\rm NS}\right)}{r^3} \quad \left(\alpha > 1\right) \Rightarrow \boxed{1 \leq \left(\frac{M_{\rm BH}}{r_{\rm ISCO}}\right)^3 \left(\frac{M_{\rm NS}}{M_{\rm BH}}\right)^2 \left(\frac{\alpha R_{\rm NS}}{M_{\rm NS}}\right)^3}$$

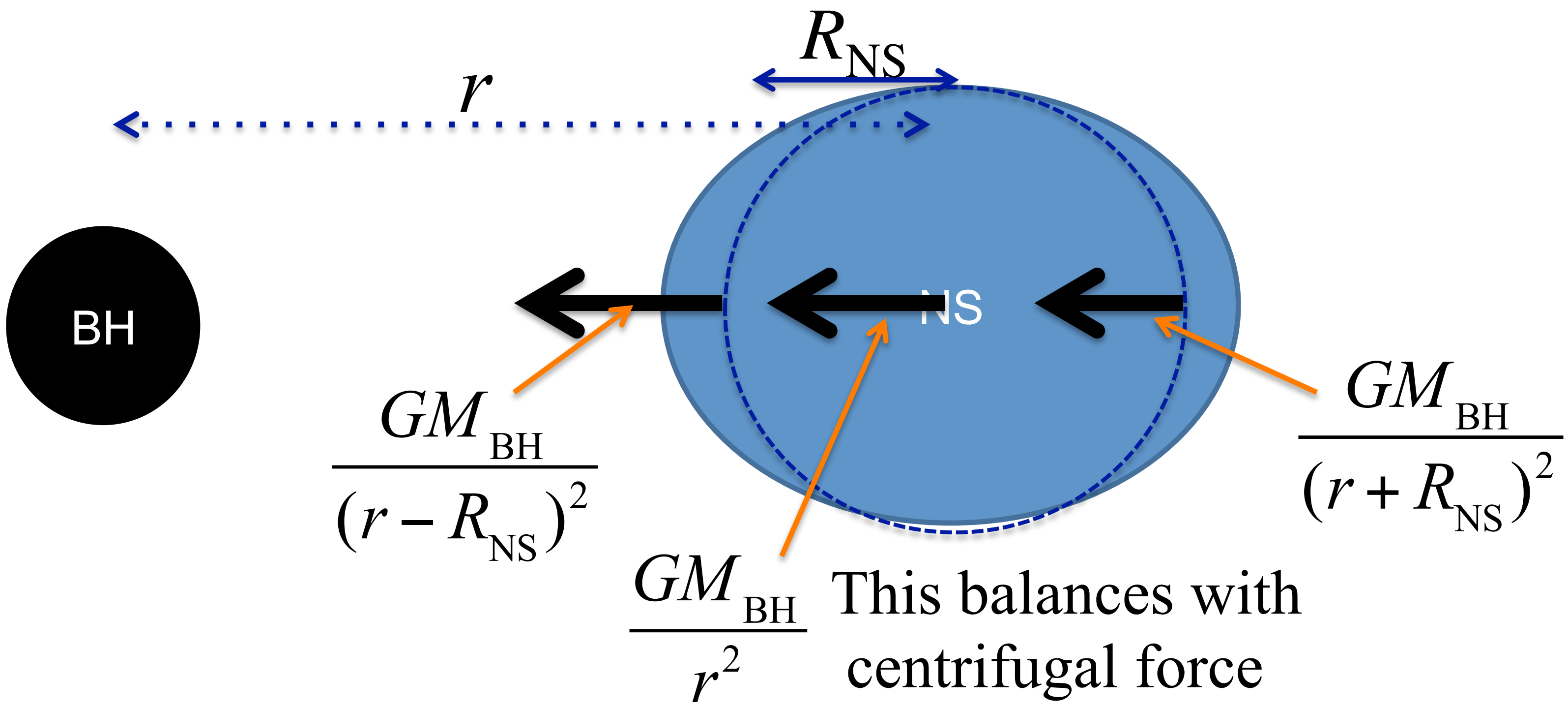
- **For tidal disruption**
  - **Large NS Radius** or
  - **Small BH mass** or
  - **High corotation spin**

  is necessary

GW170817 indicates that NS radius would not be very large

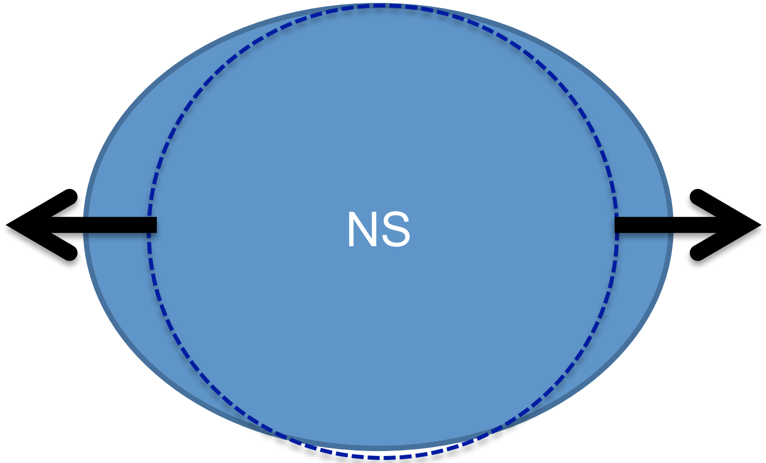


Mode detail about tidal force



$$\text{Residual}=\frac{GM_{\mathrm{BH}}}{(r-R_{\mathrm{NS}})^2}-\frac{GM_{\mathrm{BH}}}{r^2}$$

$$\sim\frac{2GM_{\mathrm{BH}}R_{\mathrm{NS}}}{r^3}:\textit{tidal force}$$



View from center of NS

BH-NS with aligned BH spin

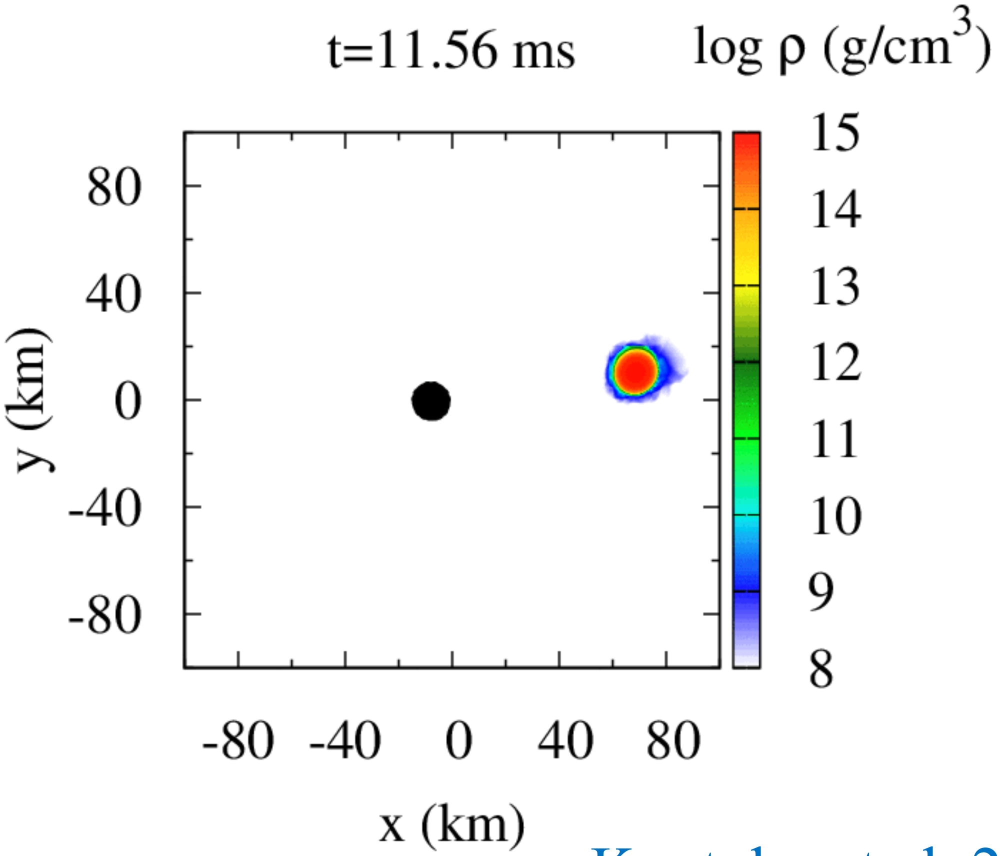
M_{BH}=6.75M_{sun}
a=0.75
M_{NS}=1.35M_{sun}
R=11.1 km

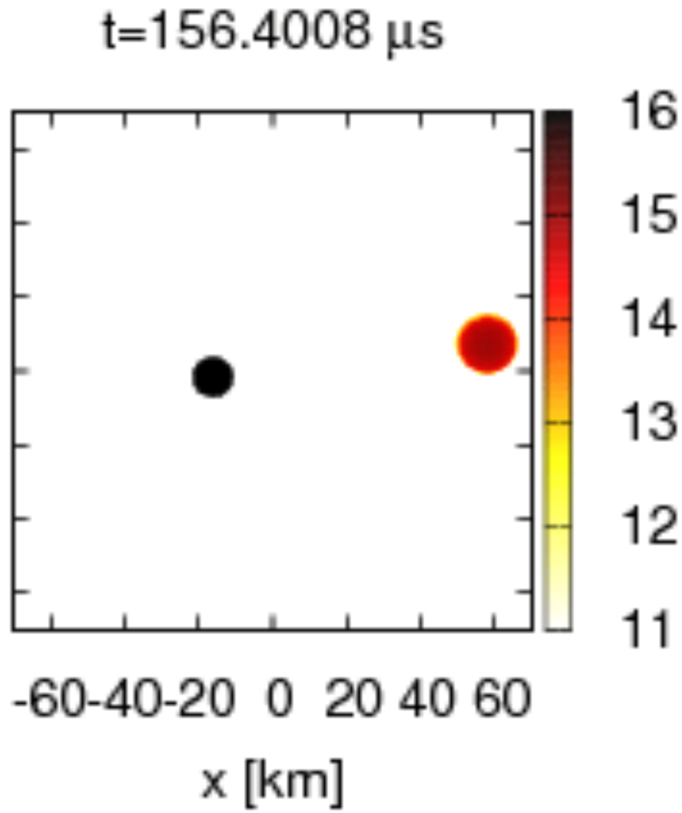
M_{BH}=4.05M_{sun}
a=0
M_{NS}=1.35M_{sun}
R=11.0 km

BH-NS with aligned BH spin

$M_{BH}=6.75M_{sun}$
$a=0.75$
$M_{NS}=1.35M_{sun}$
$R=11.1$ km

$M_{BH}=4.05M_{sun}$
$a=0$
$M_{NS}=1.35M_{sun}$
$R=11.0$ km





Kyutoku et al. 2011, 2015

For tidal disruption of plausible BH-NS with M_{NS}=1.35M_{sun}, R_{NS} ~ 12 km, & M_{BH} > 6 M_{sun}

High BH spin is necessary > ~ 0.5

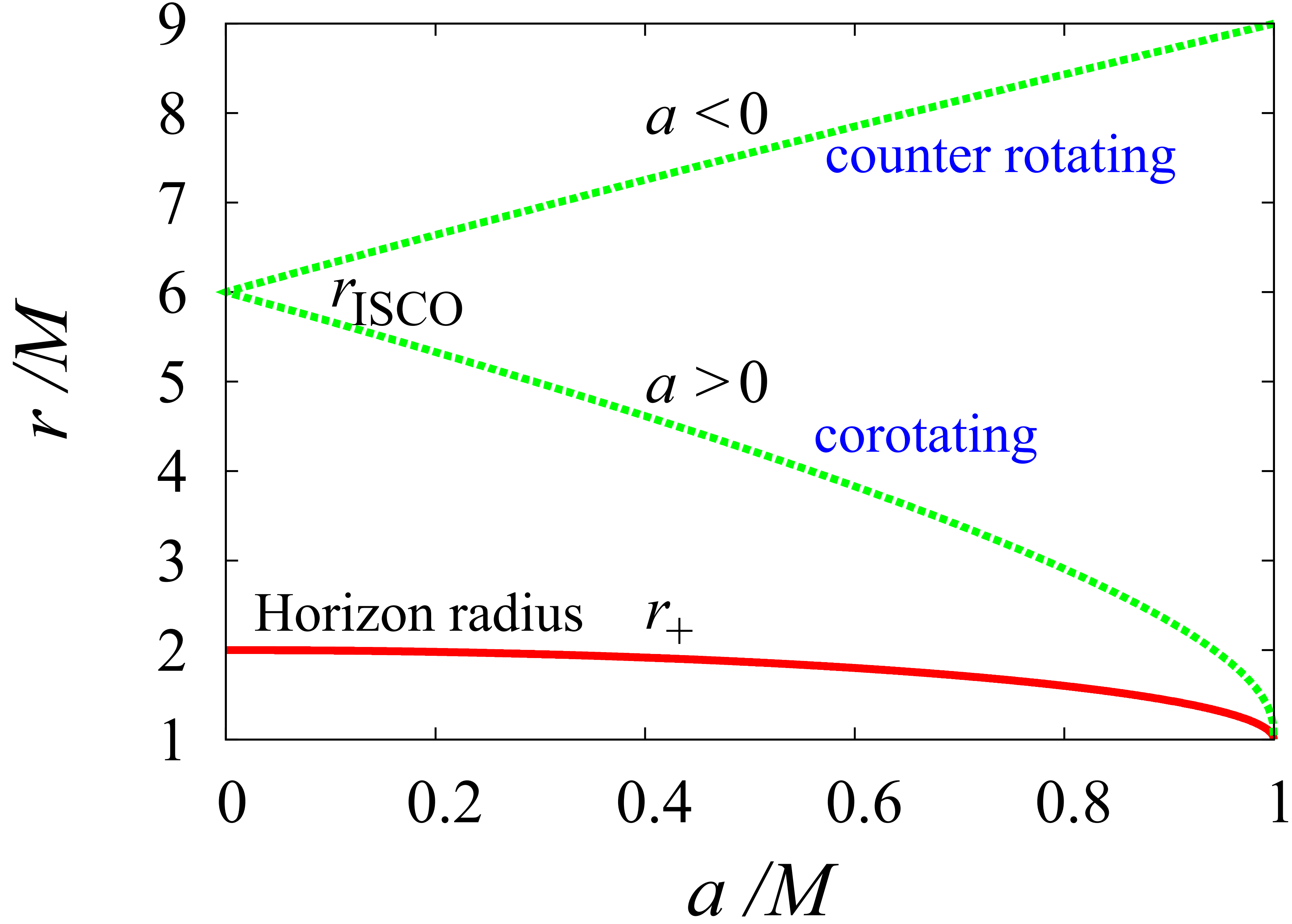
Foucart et al. ('13,14,…); Kyutoku et al. ('15)

$$1 \leq 0.1 \left(\frac{6M_{BH}}{r_{ISCO}}\right)^3 \left(\frac{7M_{NS}}{M_{BH}}\right)^2 \left(\frac{R_{NS}}{6M_{NS}}\right)^3 \left(\frac{\alpha}{1.7}\right)^3$$

$$(M_{BH} \leq r_{ISCO} \leq 9M_{BH})$$

- Natural conclusion: BH-disk systems formed as a remnant should have a high BH spin

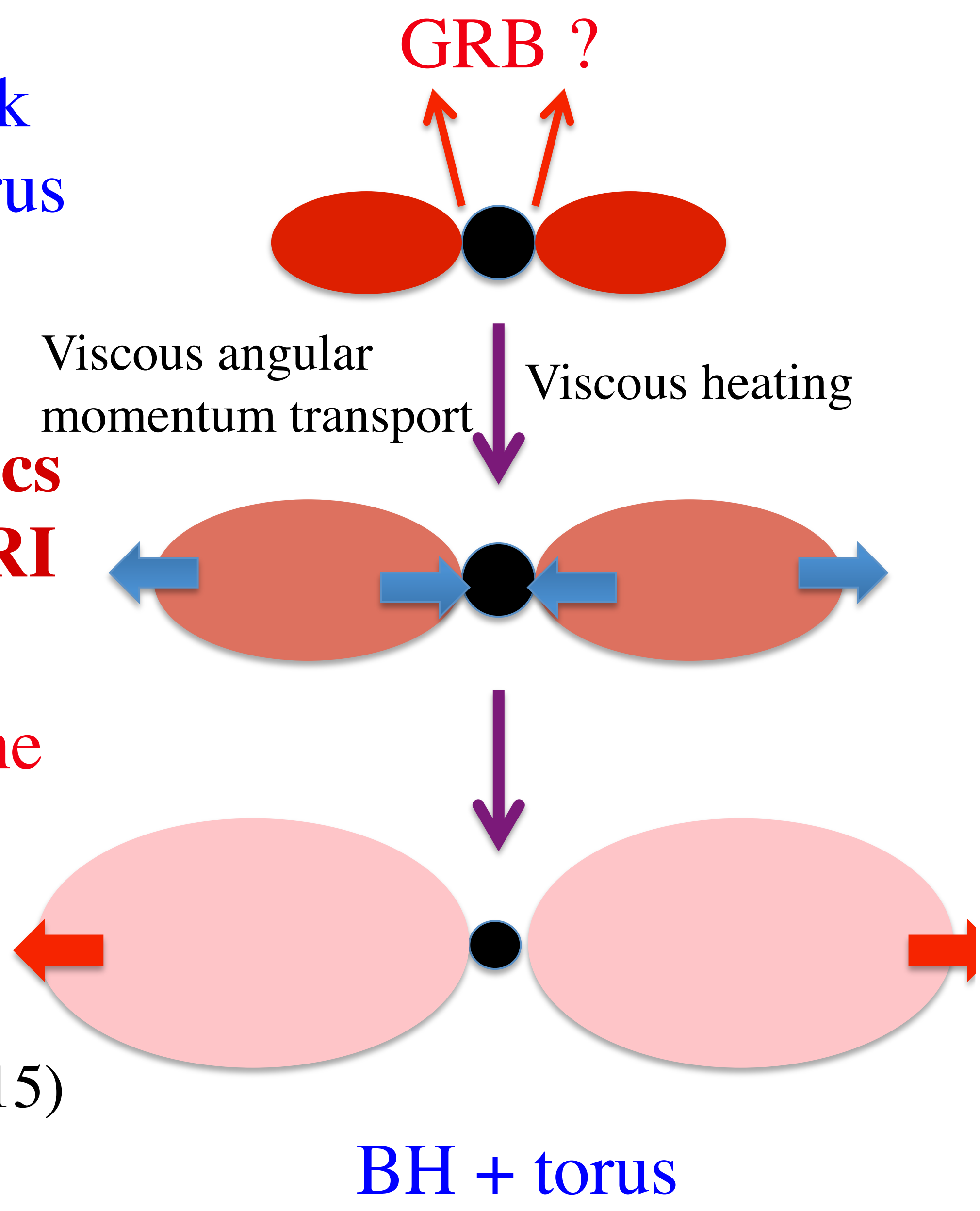
ISCO radius as a function of *a/M*



Merger remnants

✓ Remnant is either a black hole surrounded by a torus (or simply BH)

- **Torus is subject to magneto-hydrodynamics instabilities such as MRI**
- The resulting viscous effects are likely to be the driving force for the evolution of the merger remnants (Fernandez& Metzger '13-15, Just et al. '15)



5 Gravitational waves from neutron-star mergers: Promising experimental site for exploring neutron-star equation of state

5a NS-NS case

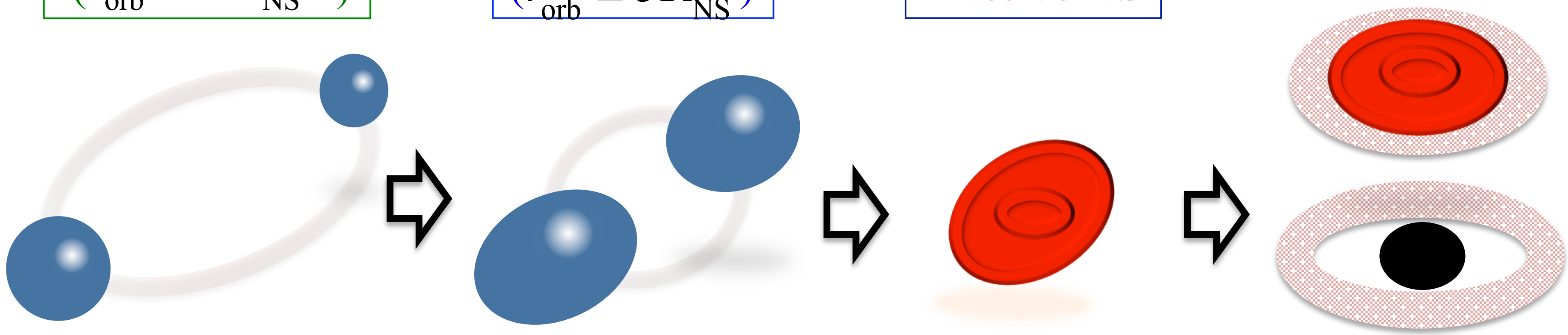
$M \sim 2.5 - 2.8 M_{sun}$

Early Inspiral
($r_{orb} >> R_{NS}$)

Late inspiral
($r_{orb} \leq 5 R_{NS}$)

Merger =>
Massive NS

Black hole/MNS
+ torus → GRB?



Point mass +
adiabatic phase

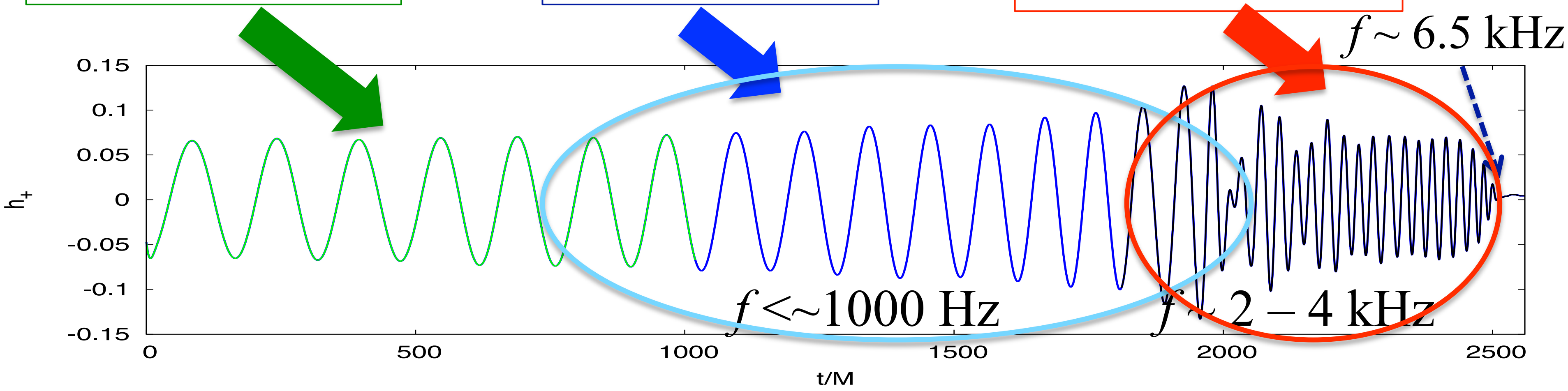
Tidally deformed phase

Dynamical & GR phase

Post-Newtonian

Late inspiral

Post merger
Massive NS/BH

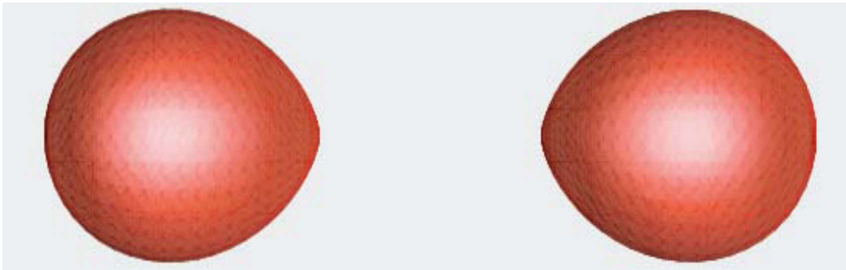


Imprint of EOS on late inspiral waveform

In a binary system, the tides raised on each NS depend on the **deformability** of that NS:

Stiff EOS = lager radius = large deformability

Soft EOS = small radius = small deformability



Courtesy J. Friedman

$$\phi \sim -\frac{GM}{r} - \boxed{\frac{3GI_{ij}^{TF} n^i n^j}{2r^3}} : I_{ij}^{TF} = O\left(r^{-3}\right)$$

Lai et al. (1994)

Tidal deformability

Newtonian potential

$$\phi \sim -\frac{GM}{r} - \frac{3GI_{ij}^{TF} n^i n^j}{2r^3} \quad \& \quad I_{ij}^{TF} \sim M\lambda \frac{n^i n^j}{r^3}, \; \lambda \propto R^5$$

$$\Rightarrow \phi \sim -\frac{GM}{r} - \frac{GM\lambda}{r^6} \quad \text{or} \quad \phi \sim -\frac{GM}{r} - \frac{GM\Lambda}{r^6}\left(\frac{Gm}{c^2}\right)^5$$

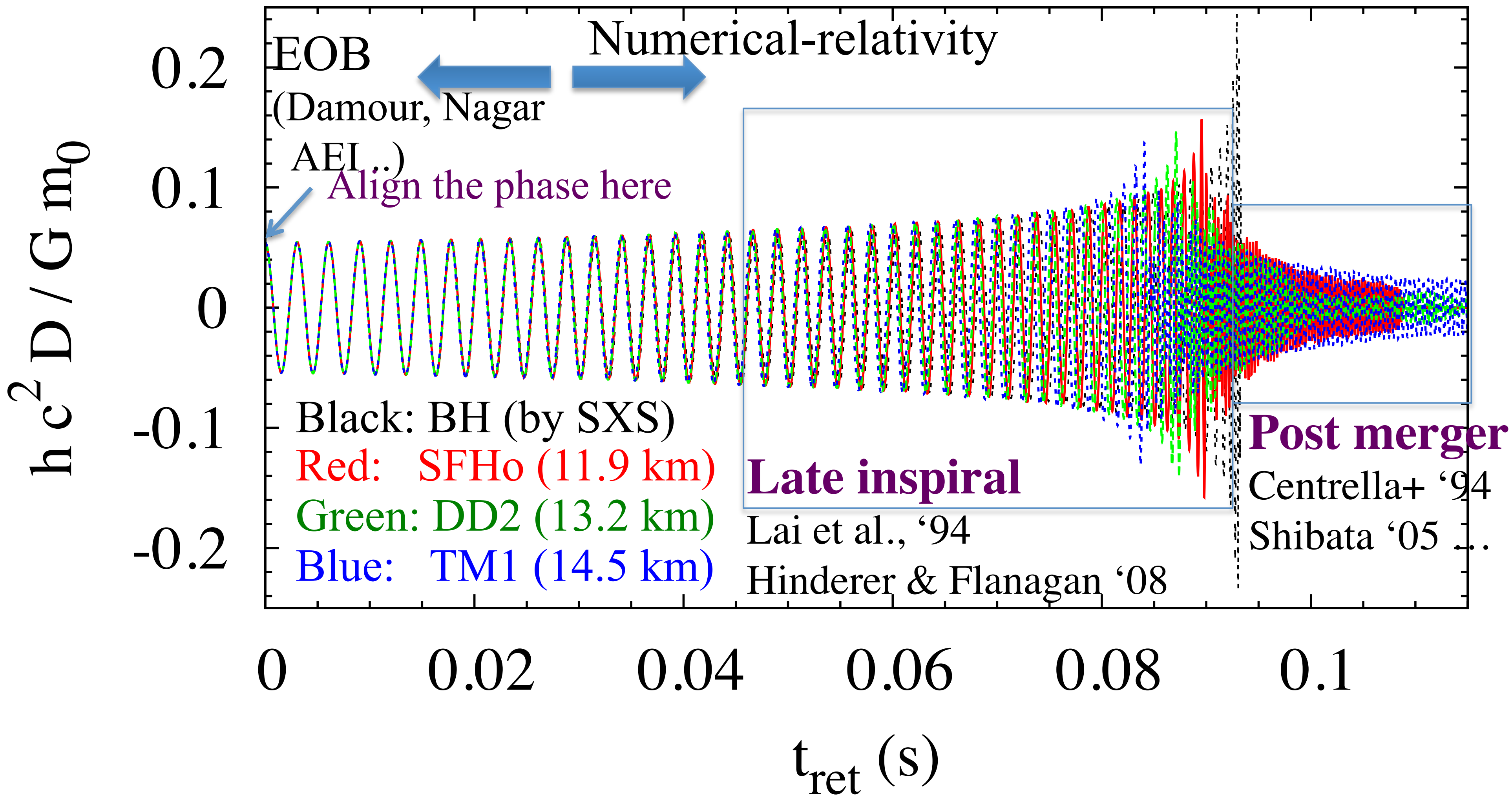
Λ : dimensionless tidal deformability of O(100)-O(1000)

for neutron stars of mass ~1.4 solar mass

Tanja Hinderer will talk more details:

Note: I here do not care numerical factor

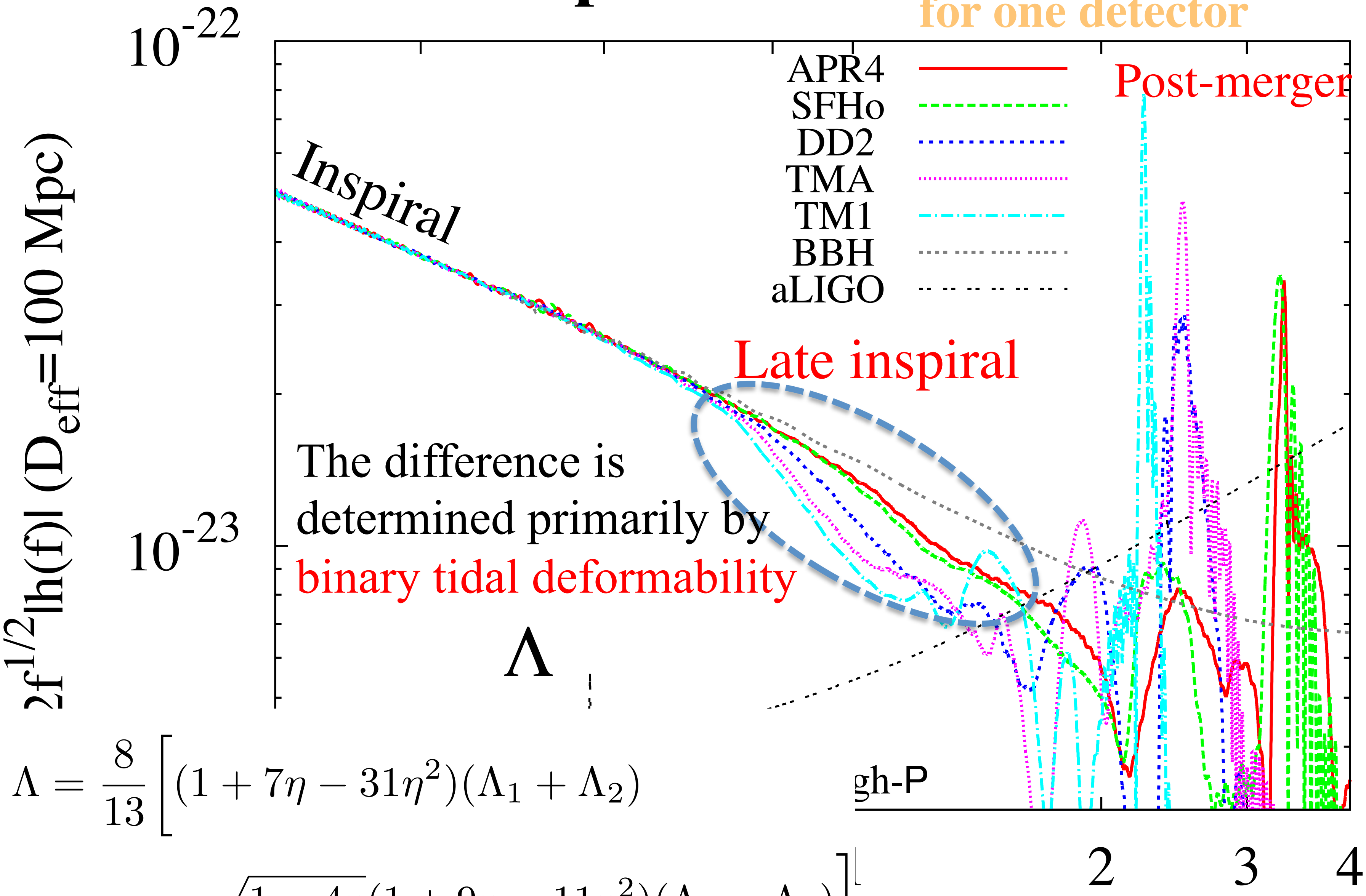
Gravitational waveform from NS-NS:
hybrid waveforms (1.35-1.35 solar mass)



Hotokezaka et al. 2016 (see also many efforts by Bernuzzi,…2011–)

Spectrum

Figure for total SNR=34
for one detector

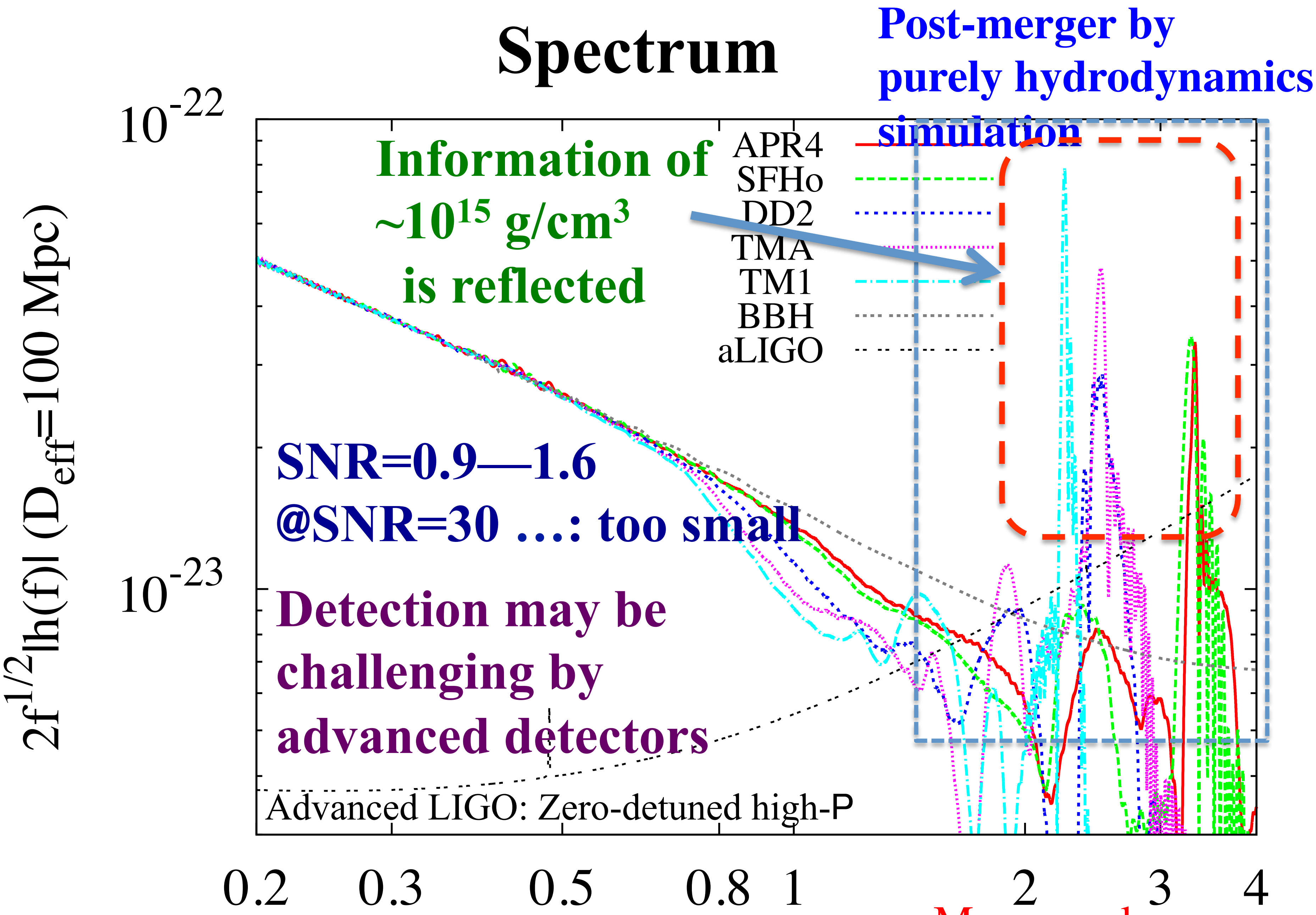


$$\Lambda = \frac{8}{13}\left[(1+7\eta-31\eta^2)(\Lambda_1+\Lambda_2) - \sqrt{1-4\eta}(1+9\eta-11\eta^2)(\Lambda_1-\Lambda_2)\right]$$

GW170817

- 100 < Λ < 800 at 2σ level (for χ < 0.05)
  → ~11 km < R < ~ 13 km
- Error is still not small: To get stronger constraints for Λ, we may need an event of high SNR >> 30 ?
  In particular, improvement of the sensitivity in the f > 400 Hz band is required
- **Better template for numerical relativity** is also necessary in future [current systematic error is O(10) and smaller than by the detector's noise]
- **Independent data analysis by many groups** would be necessary and quite important (when analyzing noisy data)

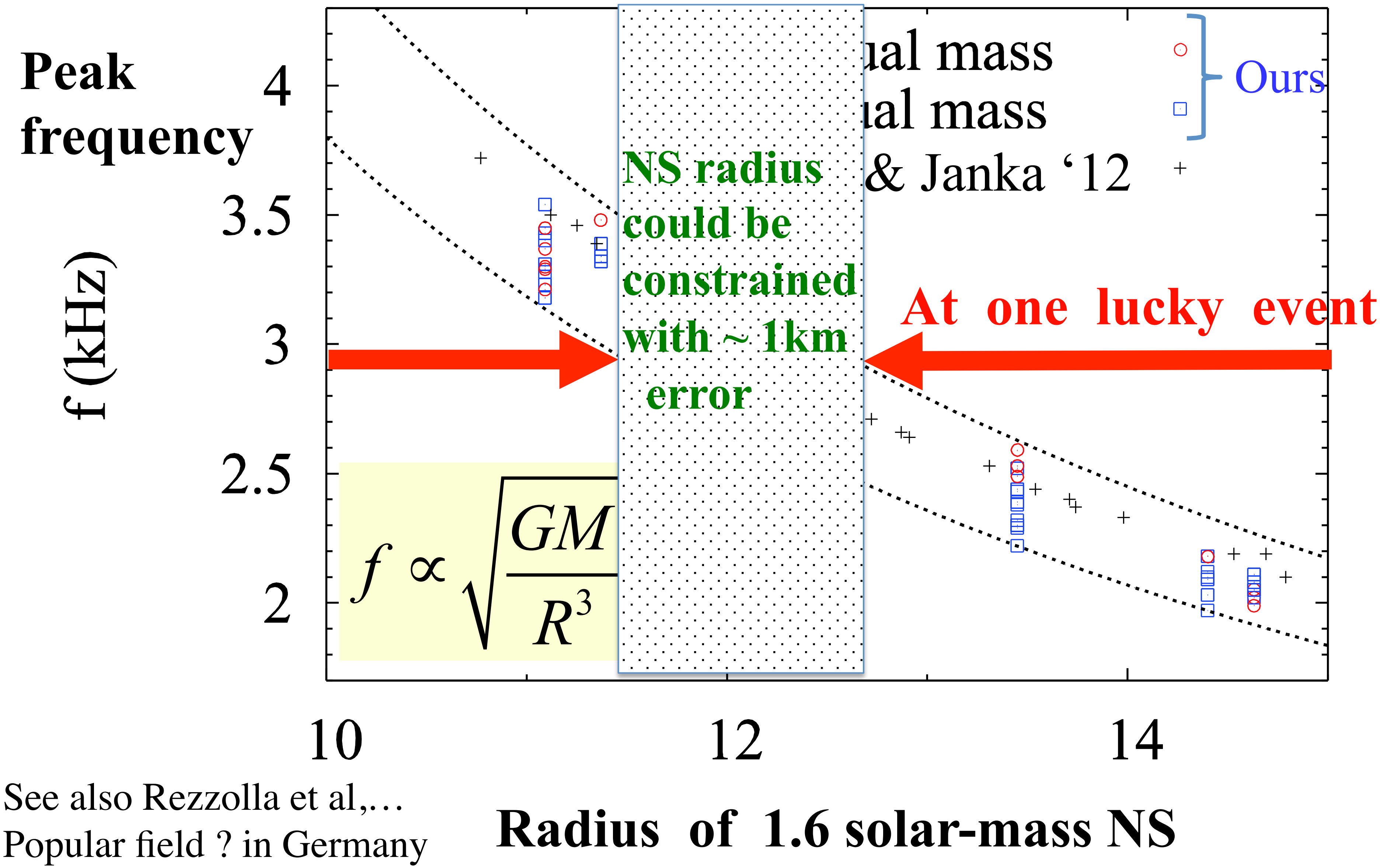
Spectrum



Many works: Popular in Europe

Hotokezaka et al. PRD 93 2016

Clear correlation between peak and radius



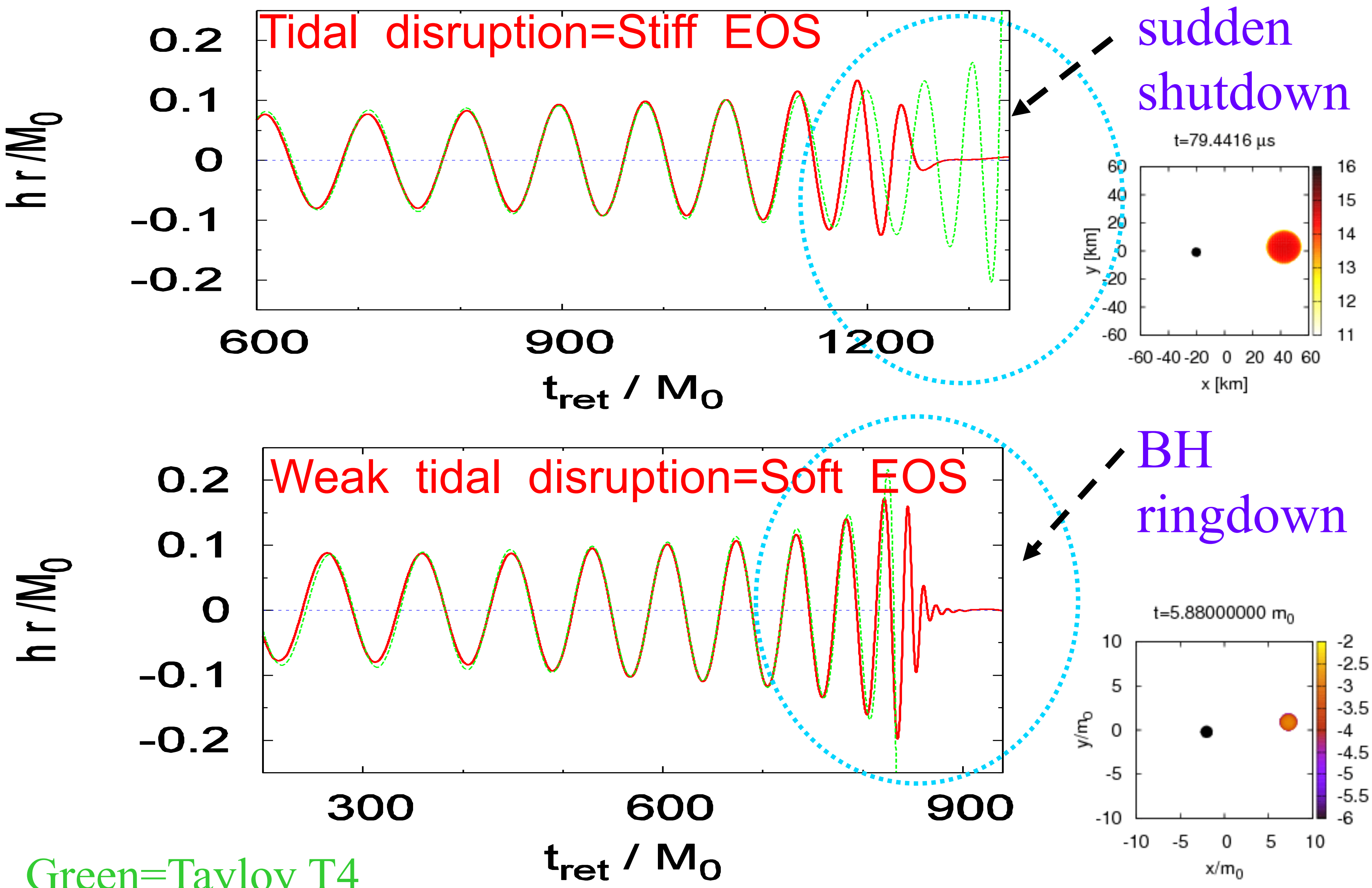
See also Rezzolla et al,…
Popular field ? in Germany

Current issues for NS-NS (theoretical side)

- For late inspiral phase (*clean system*):
  Need to construct ***accurate measurement templates***
  → **high-resolution** numerical relativity simulations
  for a wide range of $(m_1, m_2, \Lambda_1, \Lambda_2, s_1, s_2)$ +
  sophisticated **modeling** (e.g., TEOB) are necessary
  (effort is ongoing by several groups)

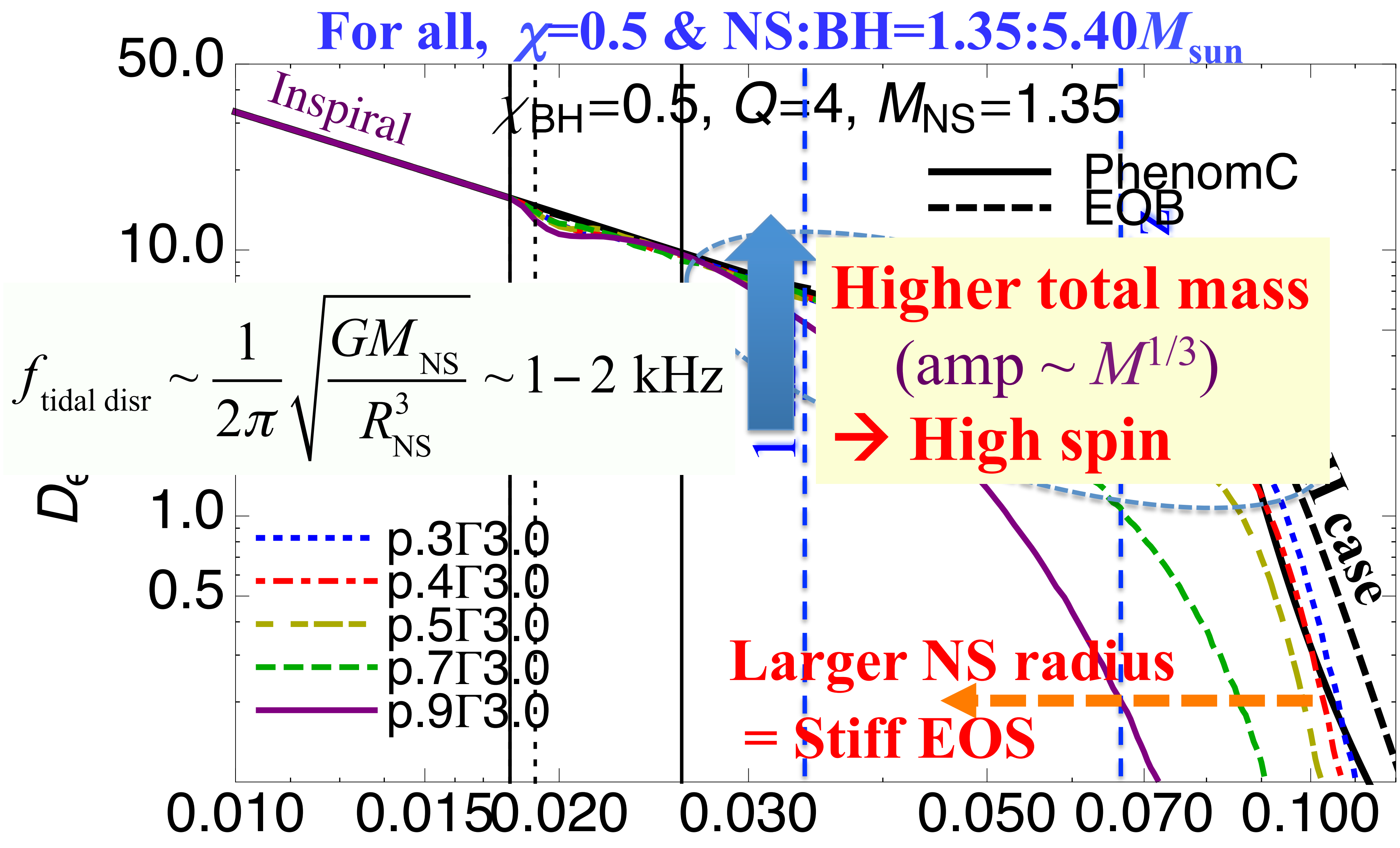
- For the post-merger phase (***many physics play roles***):
  Careful *physical* modeling is necessary:
  Most of previous studies have neglected **systematics**
  which could be significant (→ section 5c)

5b BH-NS: Signal of tidal disruption



Green=Tayloy T4

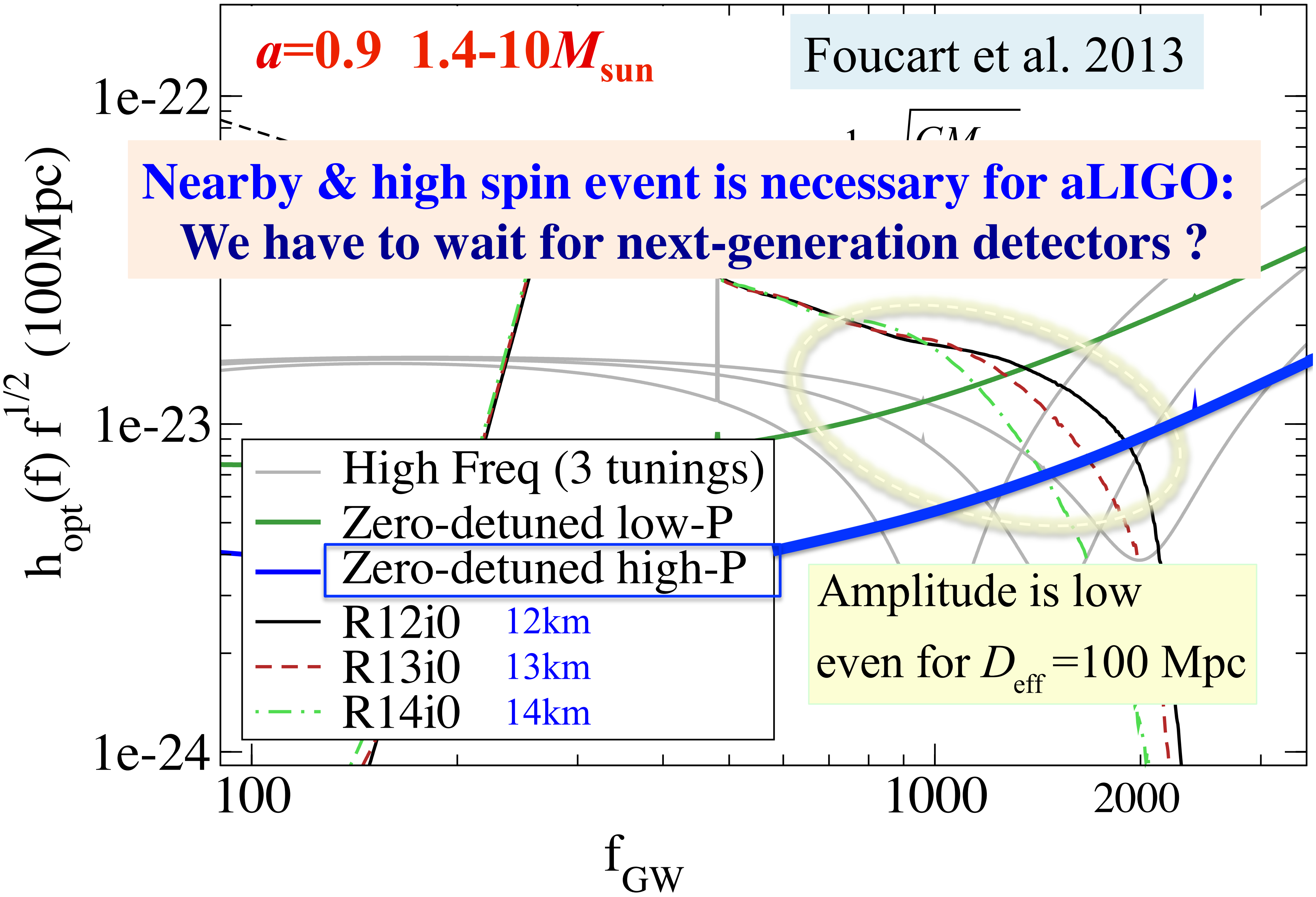
BH-NS Fourier spectrum



Lackey et al. 14; Pannarale et al. 14

Mf **Frequency**

Cutoff frequency is high, & SNR is still small



Nearby & high spin event is necessary for aLIGO:
We have to wait for next-generation detectors ?

Current issues for BH-NS (theoretical side)

- Numerical relativity is obviously necessary
- A wide parameter space: mass*2, black hole spin, equation of state, spin misalignment
- There are only two groups currently working in this
- More simulations are urgently required

5c Viscous hydrodynamics for post-merger of NS-NS

❖ **Physical state for the merger remnants ?**

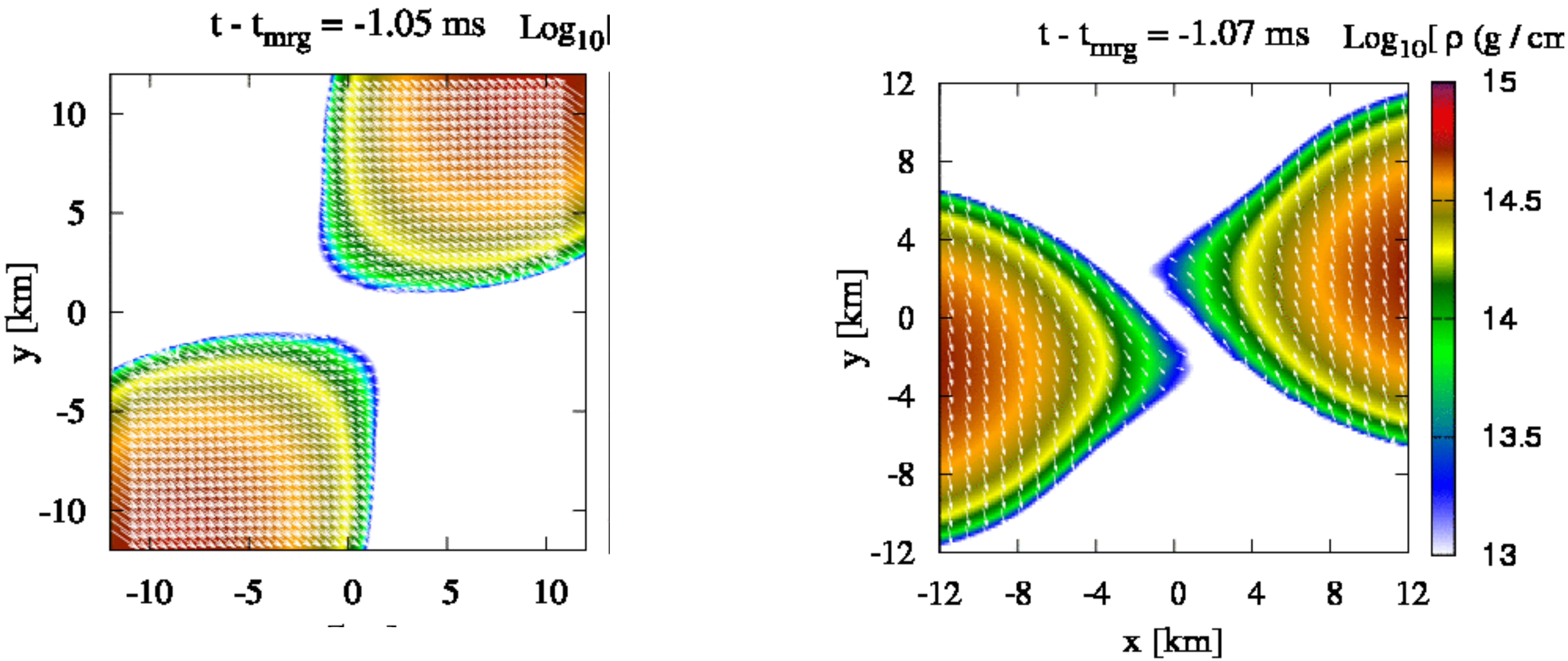
- Massive neutron stars (MNS) are typical remnants
- MNS are ***magnetized & differentially rotating***

  → **subject to MHD instabilities**
- MHD simulations suggest that **magnetic fields would be significantly amplified by Kelvin-Helmholtz instability and subsequent quick winding**
  (e.g., Price & Rosswog, '06, Kiuchi et al. '14, '15, '17)

  → **turbulence could be induced**

High-resolution GRMHD for NS-NS

Kiuchi et al. 2015



Δx=17.5m Δx=70m

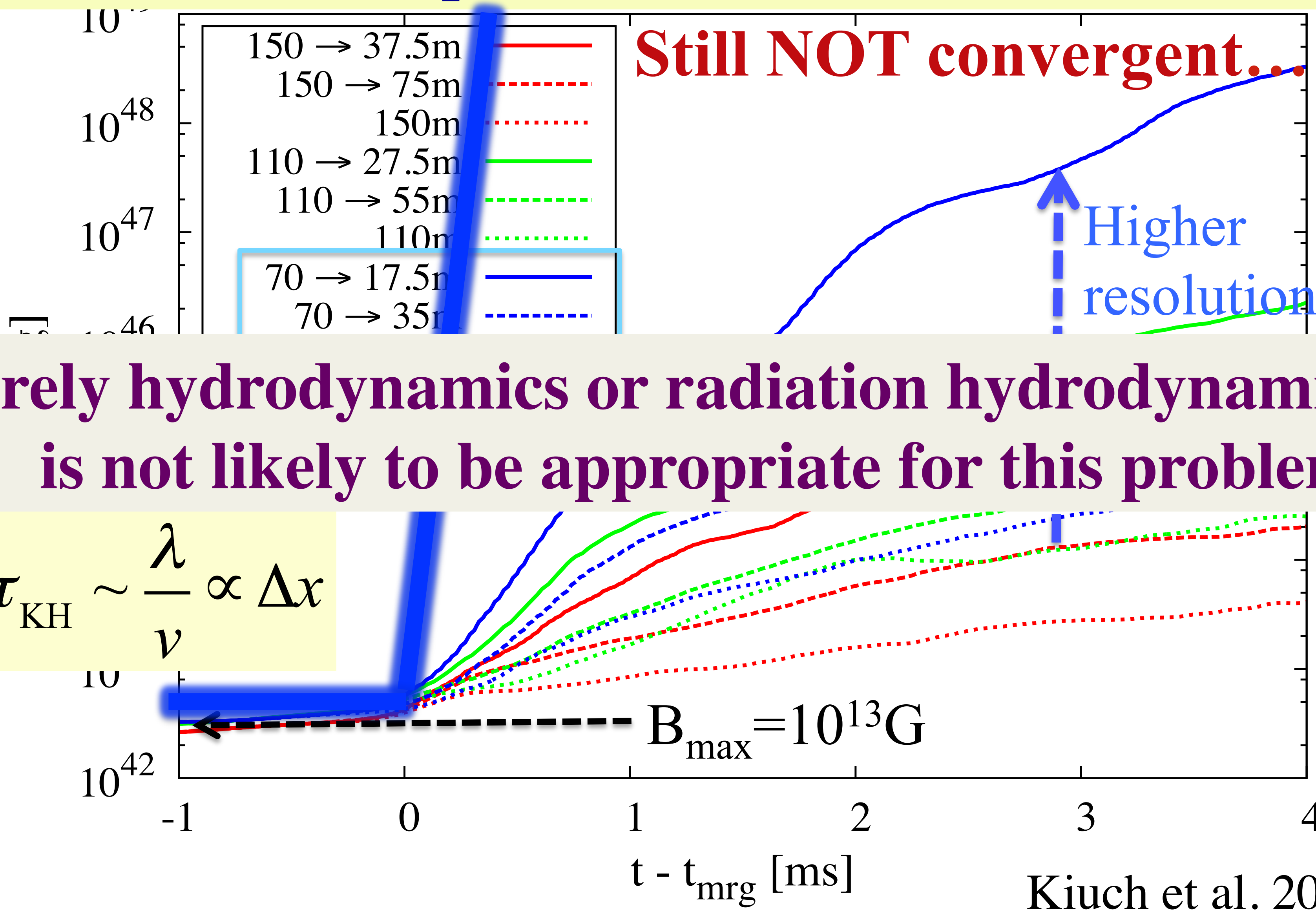
Kelvin-Helmholtz instability:

→ Magnetic field should be amplified by winding

→ Quick angular momentum transport ? (not yet seen)

Magnetic energy: Resolution dependence

B field would be amplified in $\Delta t \ll 1$ ms → turbulence ?



Purely hydrodynamics or radiation hydrodynamics is not likely to be appropriate for this problem

$$\tau_{\rm KH} \sim \frac{\lambda}{v} \propto \Delta x$$

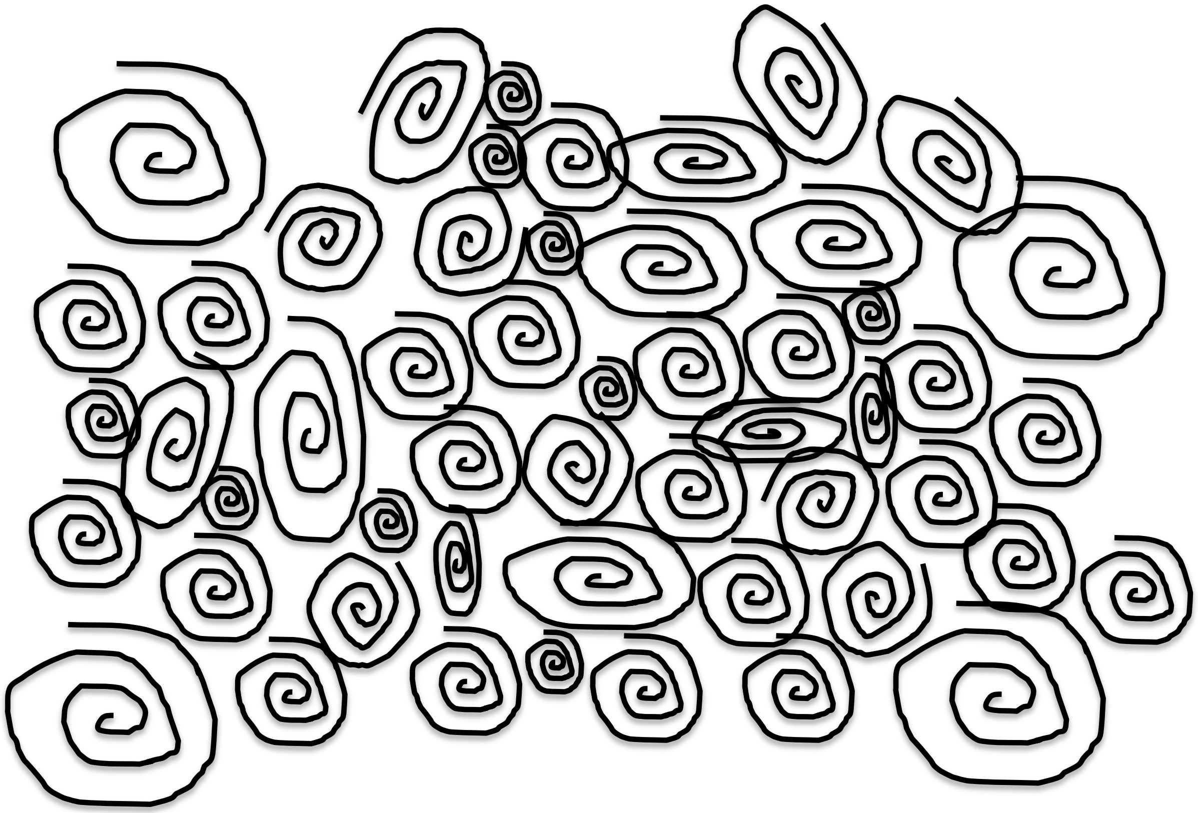
Kiuch et al. 2015

Shear motion at the merger →

huge number of vortexes are formed and magnetic field is quickly amplified

→ further shear motion → turbulence

→ turbulent (effectively global) viscosity



Current status in this issue

- High-resolution MHD simulation indicates that **obviously better resolved simulation is needed**
  → But it is not feasible due to the restriction of the computational resources (in future we have to do)

- **One alternative for exploring the possibilities is GR viscous hydrodynamics** (Shibata et al. '17)

✓ Note that we do not know whether viscous hydrodynamics can appropriately describe the state resulting from turbulence fluid: But, viscous hydrodynamics would be able to explore one possible limiting case.

3D viscous hydrodynamics simulation for remnant of binary neutron star merger

(Shibata & Kiuchi PRD 2017)

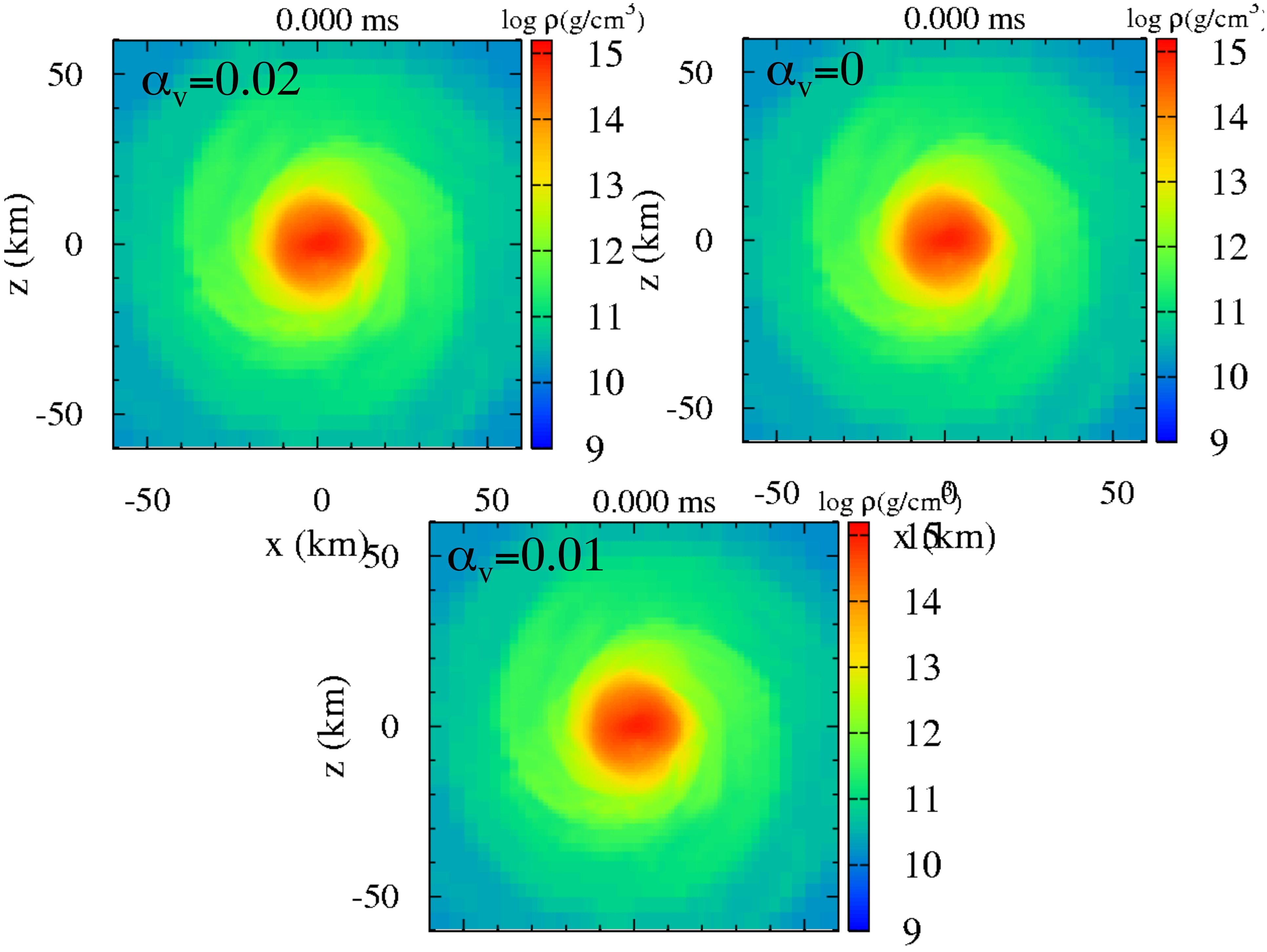
- Merger remnant is used as initial condition

✓ H4 EOS (stiff EOS: R=13.5km)

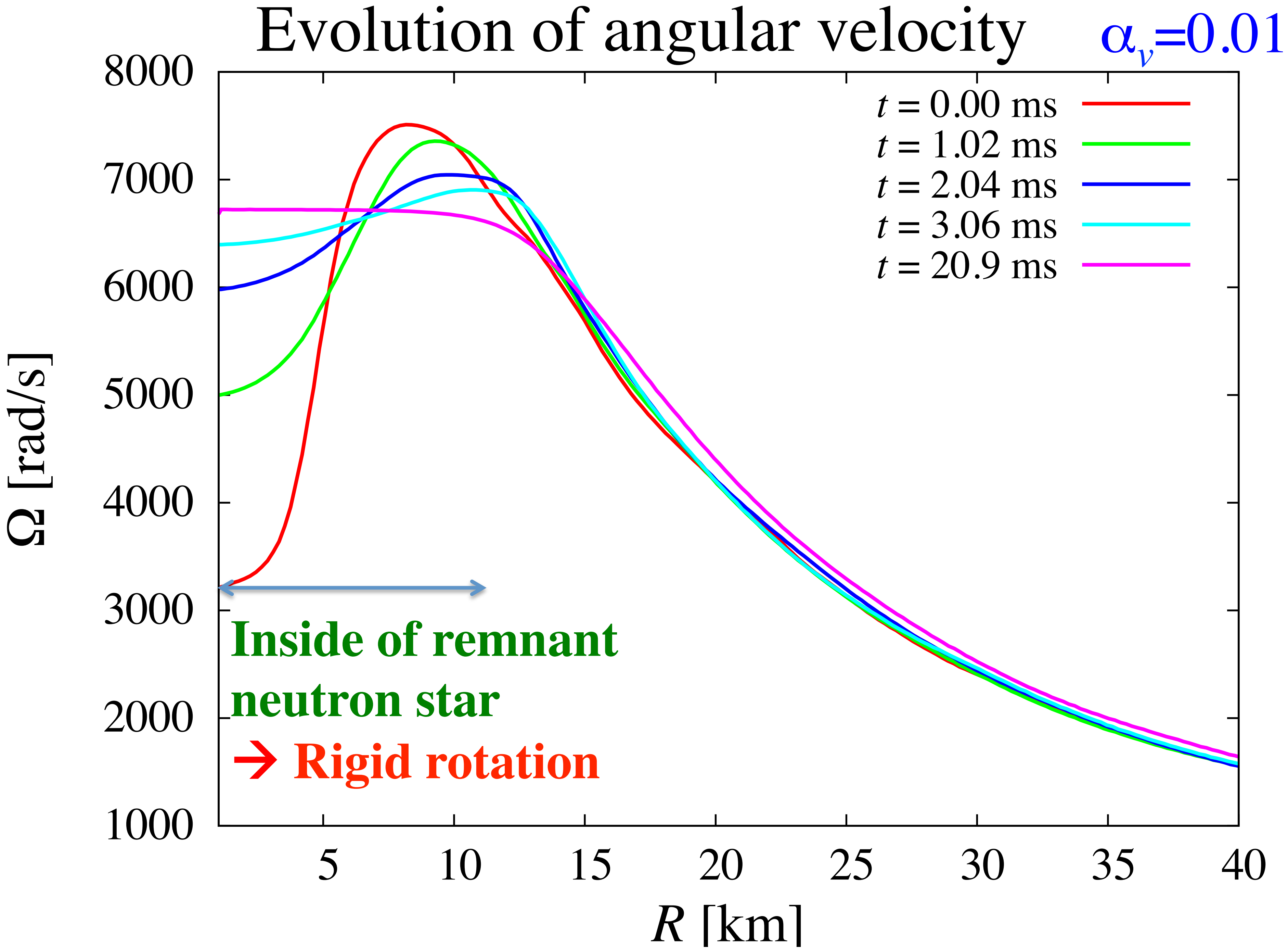
✓ Mass = 1.35-1.35 solar mass

- Simulation is started at ~ 5ms after the onset of merger
- ν is set to be $\alpha_\nu c_s H$ (H ~ 10 km): α model
- α_ν parameter = 0.01—0.02 taking into account the latest MHD simulation results for accretion disks (e.g., by Jim Stone and his colleagues)

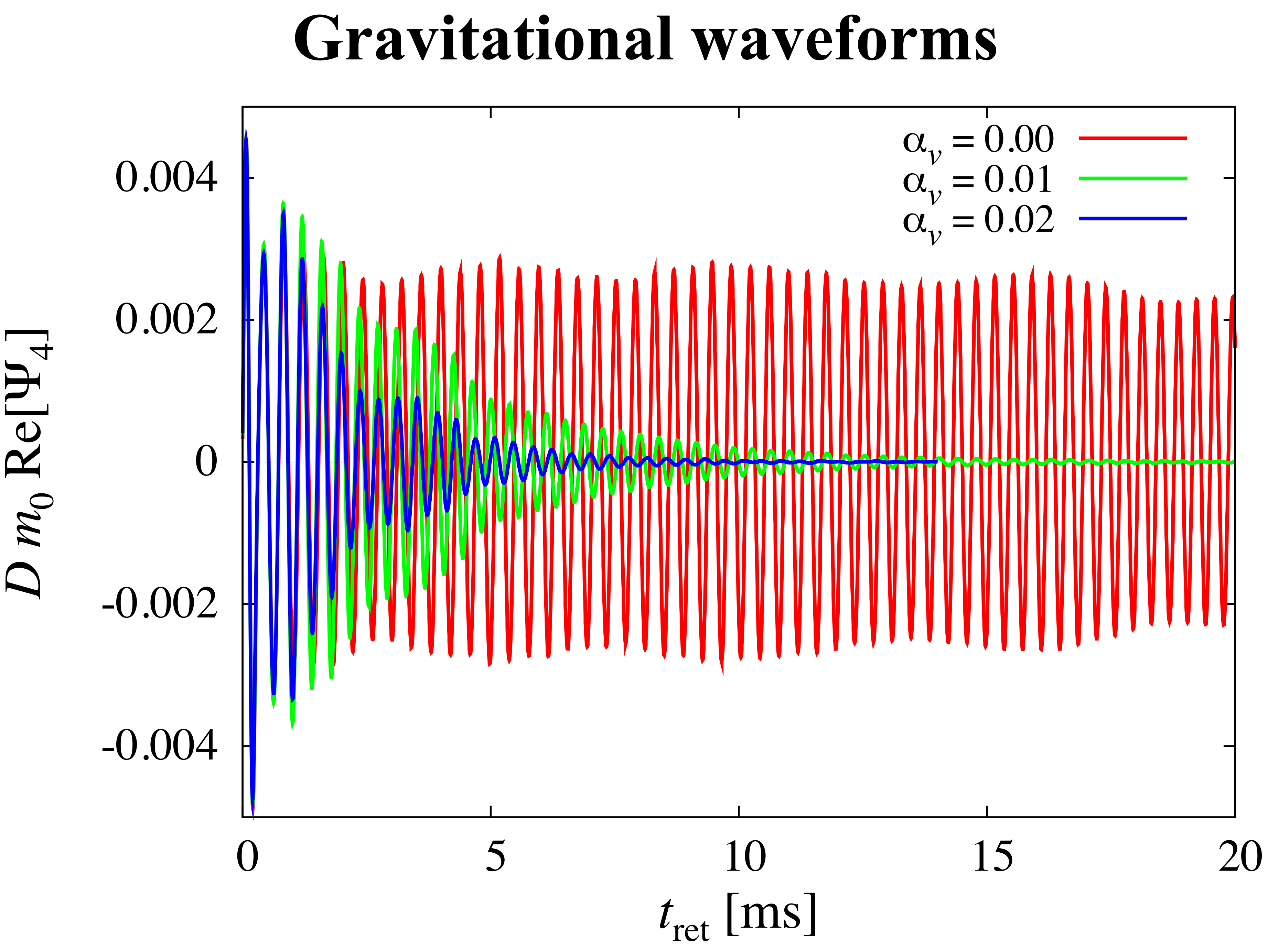
See also recent work by Radice (2017)



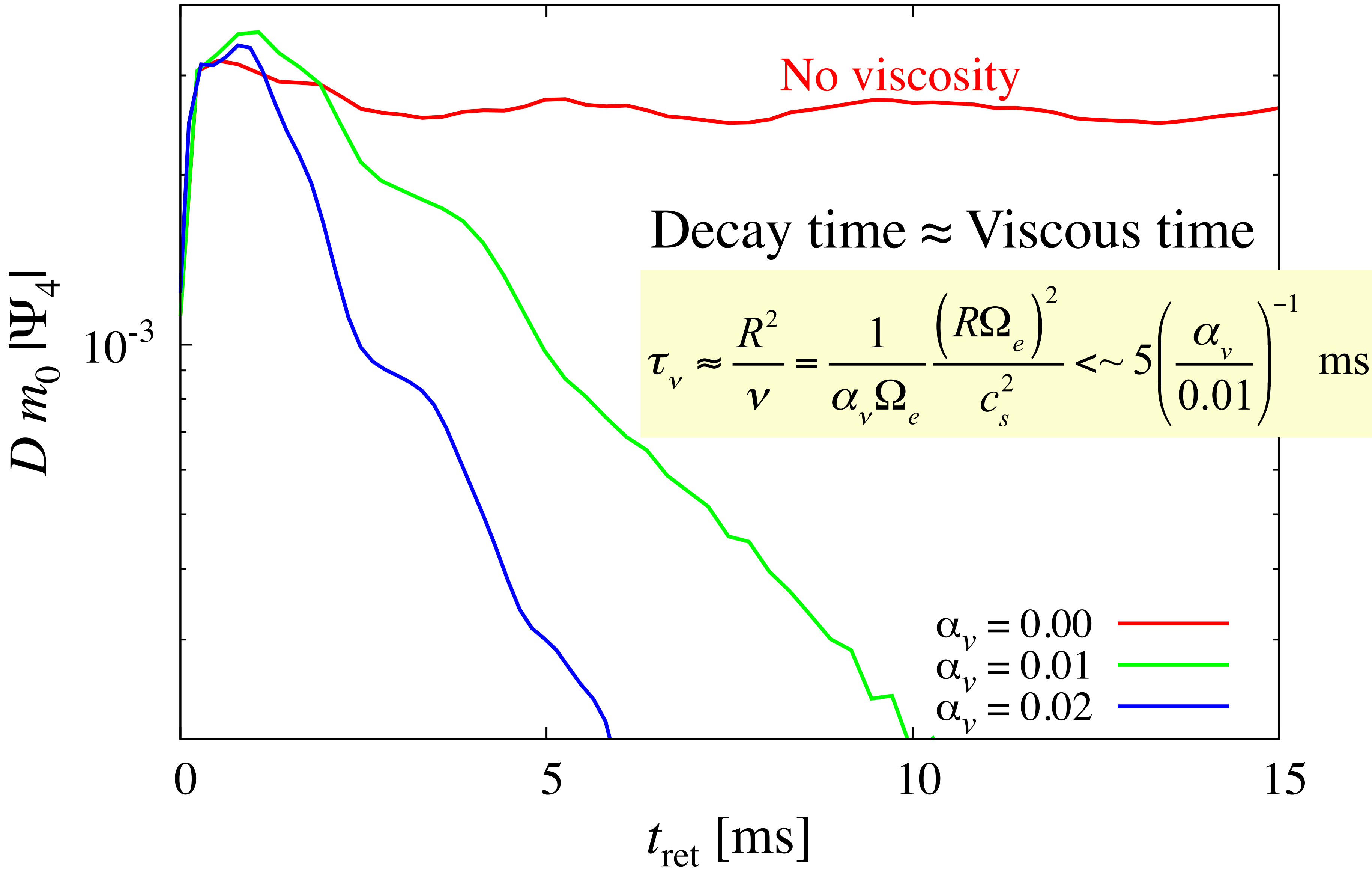
0.000 ms
log ρ(g/cm³)
αv=0.02
αv=0
αv=0.01
z (km)
x (km)
50
0
-50
15
14
13
12
11
10
9



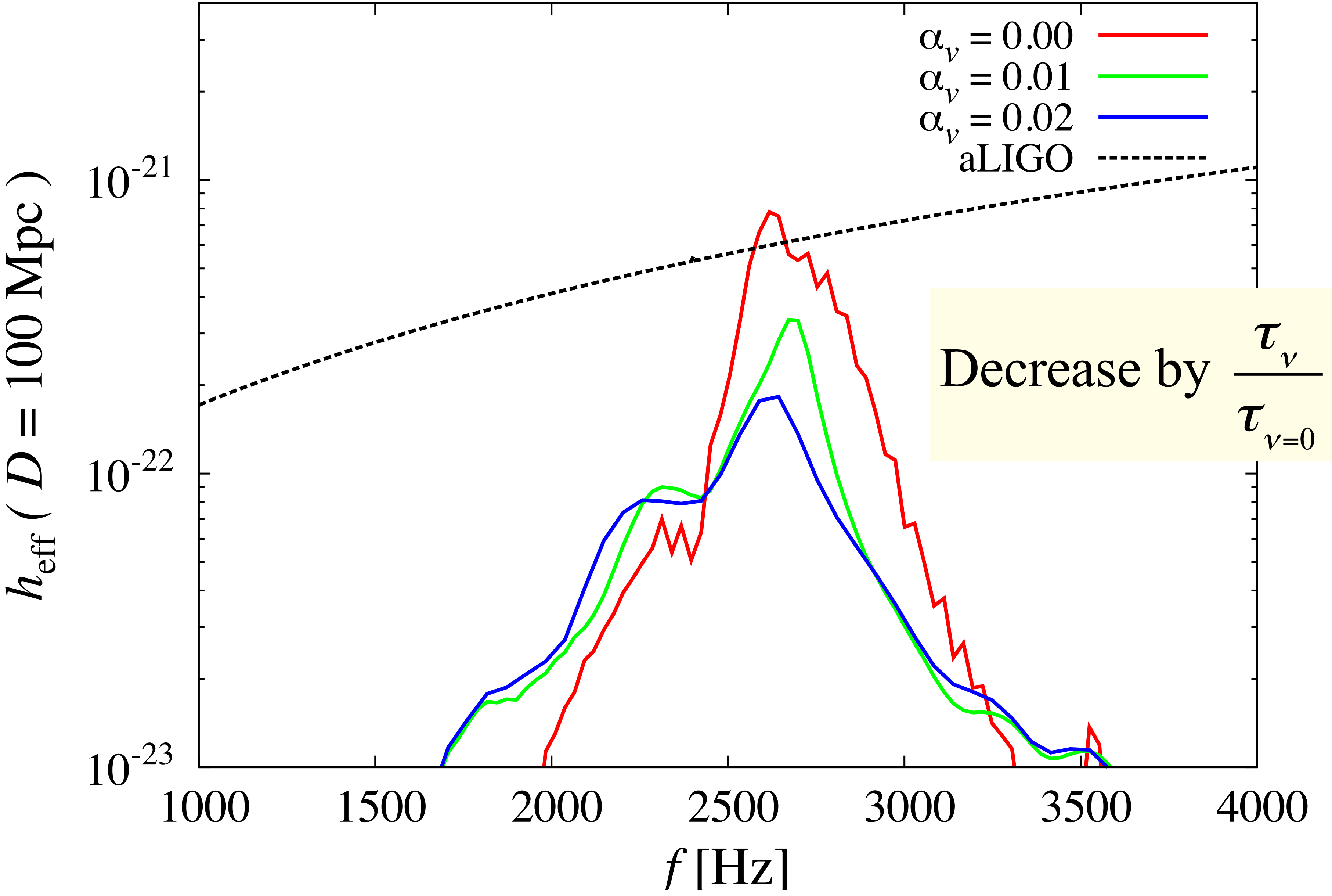
Evolution of angular velocity
α_v=0.01
t = 0.00 ms
t = 1.02 ms
t = 2.04 ms
t = 3.06 ms
t = 20.9 ms
Ω [rad/s]
1000
2000
3000
4000
5000
6000
7000
8000
5
10
15
20
25
30
35
40
R [km]
Inside of remnant
neutron star
→ Rigid rotation


Gravitational waveforms
$\alpha_v = 0.00$
$\alpha_v = 0.01$
$\alpha_v = 0.02$
0.004
0.002
0
-0.002
-0.004
$D\, m_0\, \mathrm{Re}[\Psi_4]$
0
5
10
15
20
t_{ret} [ms]

Amplitude of gravitational waves



Spectrum



$\alpha_\nu = 0.00$
$\alpha_\nu = 0.01$
$\alpha_\nu = 0.02$
aLIGO
Decrease by $\frac{\tau_\nu}{\tau_{\nu=0}}$
10^{-21}
10^{-22}
10^{-23}
1000
1500
2000
2500
3000
3500
4000
$h_{\rm eff}$ (D = 100 Mpc)
f [Hz]

Short summary on GW and EOS

- **Late inspiral phase of neutron-star binaries is a promising experimental field for NS EOS**
- Post-merger GWs of NS-NS leading to MNS are also invaluable but need better sensitivity of detectors for detection (target for 3rd generation detectors ?)
- However, note many uncertainties in the post-merger GWs → need **serious** effort for better modeling to reduce systematics in theoretical waveforms
- If MHD turbulence ≈ viscous hydrodynamics with $\alpha_\nu \geq 0.01$, evolution of merger remnant of NS-NS would be **highly different from that by ideal fluid dynamics**: **post-merger gravitational waves could be quite weak**
- How large is α_ν ?
  → **High-resolution MHD is necessary in the future**

Lecture II: Mass ejection and electromagnetic counterparts of neutron-star mergers

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YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

CGP
Center for Gravitational Physics
Yukawa Institute

Outline

I. Introduction: Why mass ejection is important ?

II. Short summary of typical scenarios for merger and mass ejection of NS-NS merger

III. Dynamical mass ejection

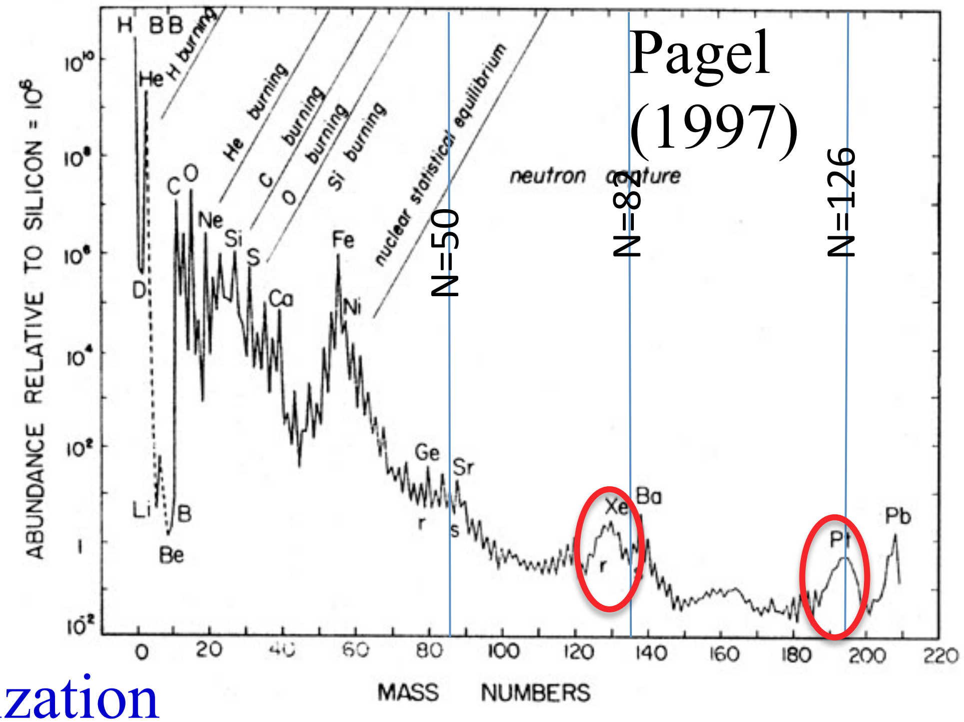
IV. Post-merger mass ejection

V. Next events ?

VI. Unsolved issues

I Introduction: Why mass ejection from neutron–star binaries is important ?

1. Electromagnetic counterparts of NS merger:
   Key for confirming gravitational-wave detection & important for getting information of GW source
2. Promising site of **heavy r-process nucleosynthesis** (in particular after detecting GW170817)



Not good localization

kilonova Scenario

(Li-Paczyski 1998, Metzger et al. 2010)

- Neutron-rich ejecta $\tau_{n-\mathrm{capture}} < \tau_{\beta-\mathrm{decay}}$

→ **Rapid-neutron-capture nucleosynthesis**

(Lattimer-Schramm '74, Symbalisty-Schramm '82)

→ **Production of unstable heavy nuclei (A ≥ 90)**

R-process nucleosynthesis: white circles=stable nuclei

Animation by S. Wanajo

Kilonova Scenario

(Li-Paczyski 1998, Metzger et al. 2010)

- Neutron-rich ejecta $\tau_{n-\text{capture}} < \tau_{\beta-\text{decay}}$

→ **rapid-neutron-capture nucleosynthesis**

(Lattimer-Schramm '74, Symbalisty-Schramm '82)

→ **Production of unstable heavy nuclei (A ≥ 90)**

→ β-decay/fission → Heating ejecta

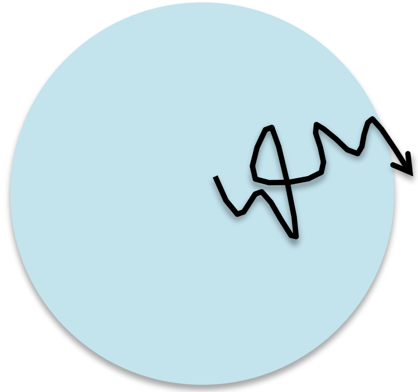
→ After adiabatic expansion $\tau_{\text{photon diffusion}} \leq \tau_{\text{ejecta expansion}}$

→ Optical ~ IR emission

Kilonova luminosity & peak time

$$\rho = \frac{3M}{4\pi r^3}, \quad v = \frac{r}{t}, \quad \kappa : \text{opacity}$$

Assume uniformly expanding spherical ejecta



diffusion time: $t_{diff} = \frac{1}{\kappa\rho c} \times (\kappa\rho r)^2 = \kappa\rho r^2 c^{-1}$

If $t > t_{\text{diff}}$ photons diffuse out and ejecta shine, otherwise low luminosity. Peak comes at $t = t_{diff}$:

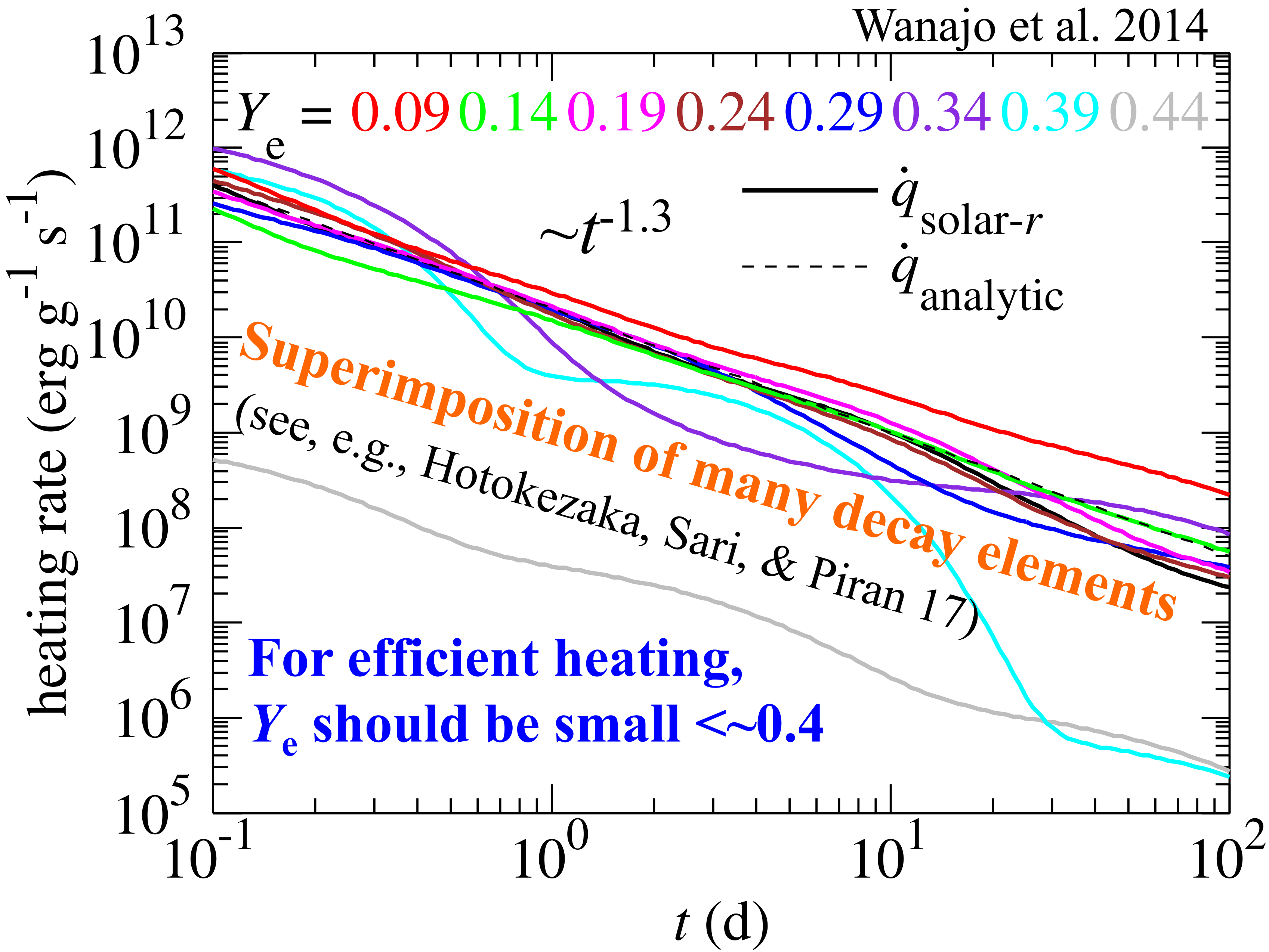
$$\Rightarrow \kappa\rho r^2 c^{-1} = \frac{r}{v} \;\Rightarrow\; \frac{3M\kappa}{4\pi c r} = \frac{r}{v} \;\Rightarrow\; r = \sqrt{\frac{3\kappa M v}{4\pi c}} \;\Rightarrow\; t_{\text{peak}} = \sqrt{\frac{3\kappa M}{4\pi c v}}$$

$$L_{\text{peak}} = f\frac{Mc^2}{t_{\text{peak}}} = fc^2\sqrt{\frac{4\pi c v M}{3\kappa}}$$

e.g., Metzger et al. MNRAS 2010

f = radioactive heating mass fraction ~ 10^{-6}@1 day and in proportional approximately to $t^{-1.3}$

Heating rate by radioactive decay



Peak luminosity & time of kilonova

(Li-Paczyski 1998, Metzger et al. 2010)

$t_{\text{diffusion}} \sim t_{\text{expansion}}$

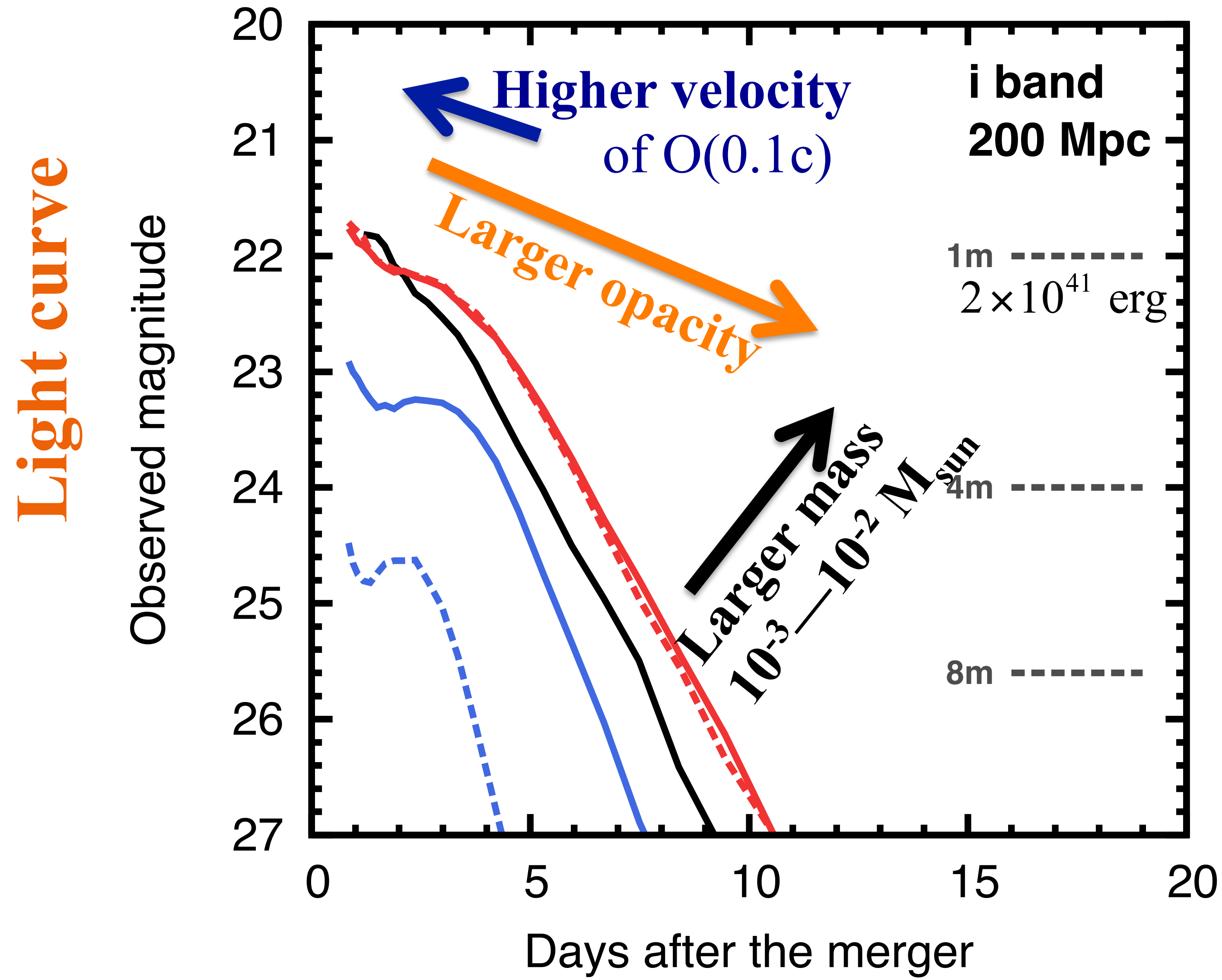
10^{-6} at ~ 1 day:
Depends on time

$$L_{\text{peak}} \sim 2 \times 10^{41}\ \text{ergs/s} \left(\frac{M}{0.01 M_\odot} \right)^{1/2} \left(\frac{v}{0.2c} \right)^{1/2} \left(\frac{\kappa}{1\ \text{cm}^2/\text{g}} \right)^{-1/2} \left(\frac{f}{1 \times 10^{-6}} \right)$$

$$\text{at} \quad t \sim 1\ \text{days} \left(\frac{M}{0.01 M_\odot} \right)^{1/2} \left(\frac{v}{0.2c} \right)^{-1/2} \left(\frac{\kappa}{1\ \text{cm}^2/\text{g}} \right)^{1/2}$$

Depend on mass, velocity, & opacity of ejecta

3 Key quantities and light curve



Tanaka & Hotokezaka 2013

Among three, opacity has strongest impact

- $M \sim$ **O(0.001)—O(0.01) solar mass**
- $v \sim$ **O(0.1)c**
- $\kappa \sim$ **0.1—10 cm²/g: change by two orders of mag**

$$L_{\mathrm{peak}} \sim 7\times10^{40}\ \mathrm{ergs/s}\left(\frac{M}{0.01M_{\odot}}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{1/2}\left(\frac{\kappa}{10\ \mathrm{cm}^2/\mathrm{g}}\right)^{-1/2}\left(\frac{f}{1\times10^{-6}}\right)$$

$$\text{at}\quad t\sim 3.5\ \mathrm{days}\left(\frac{M}{0.01M_{\odot}}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{-1/2}\left(\frac{\kappa}{10\ \mathrm{cm}^2/\mathrm{g}}\right)^{1/2}$$

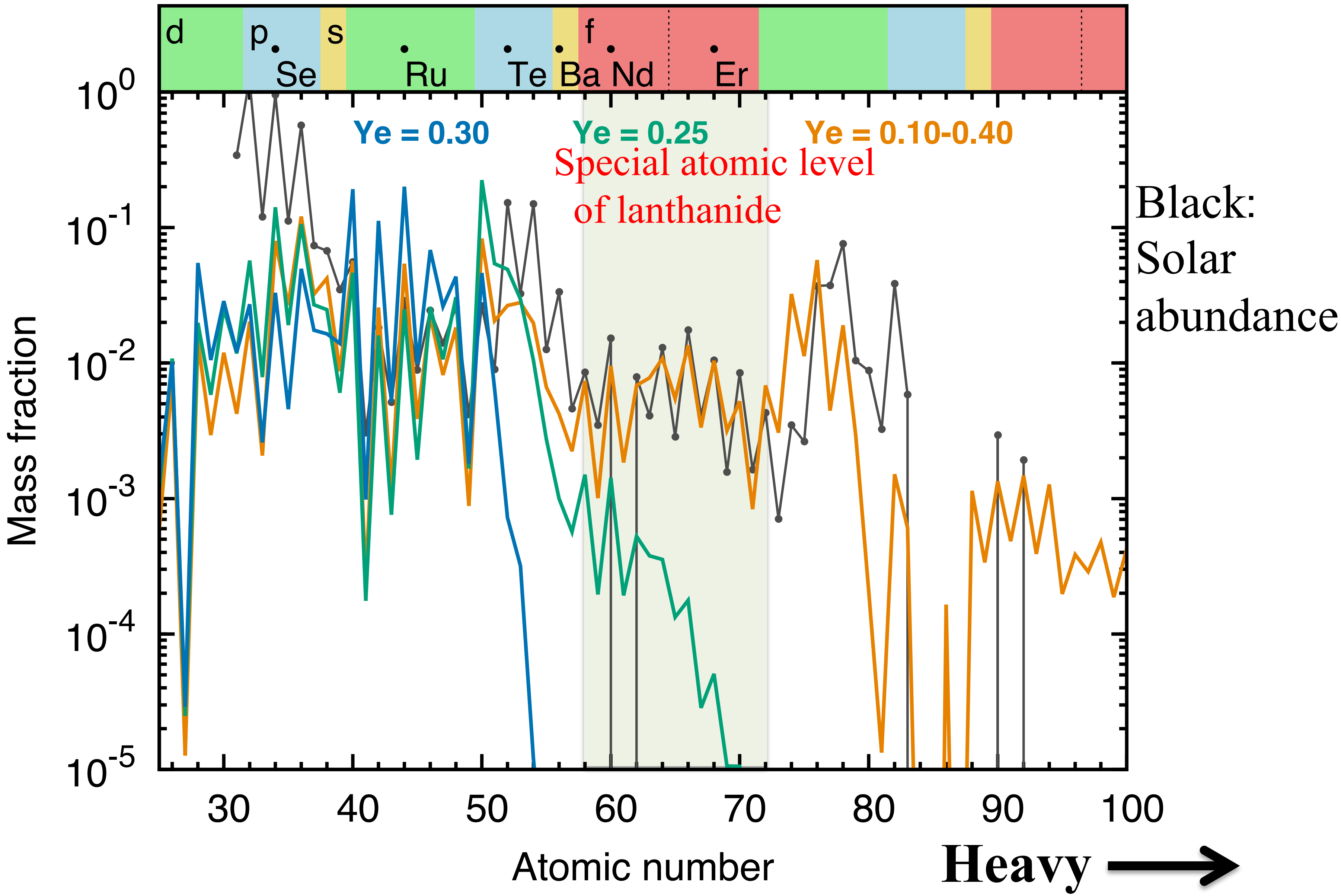
$$L_{\mathrm{peak}} \sim 7\times10^{41}\ \mathrm{ergs/s}\left(\frac{M}{0.01M_{\odot}}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{1/2}\left(\frac{\kappa}{0.1\ \mathrm{cm}^2/\mathrm{g}}\right)^{-1/2}\left(\frac{f}{1\times10^{-6}}\right)$$

$$\text{at}\quad t\sim 0.35\ \mathrm{days}\left(\frac{M}{0.01M_{\odot}}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{-1/2}\left(\frac{\kappa}{0.1\ \mathrm{cm}^2/\mathrm{g}}\right)^{1/2}$$

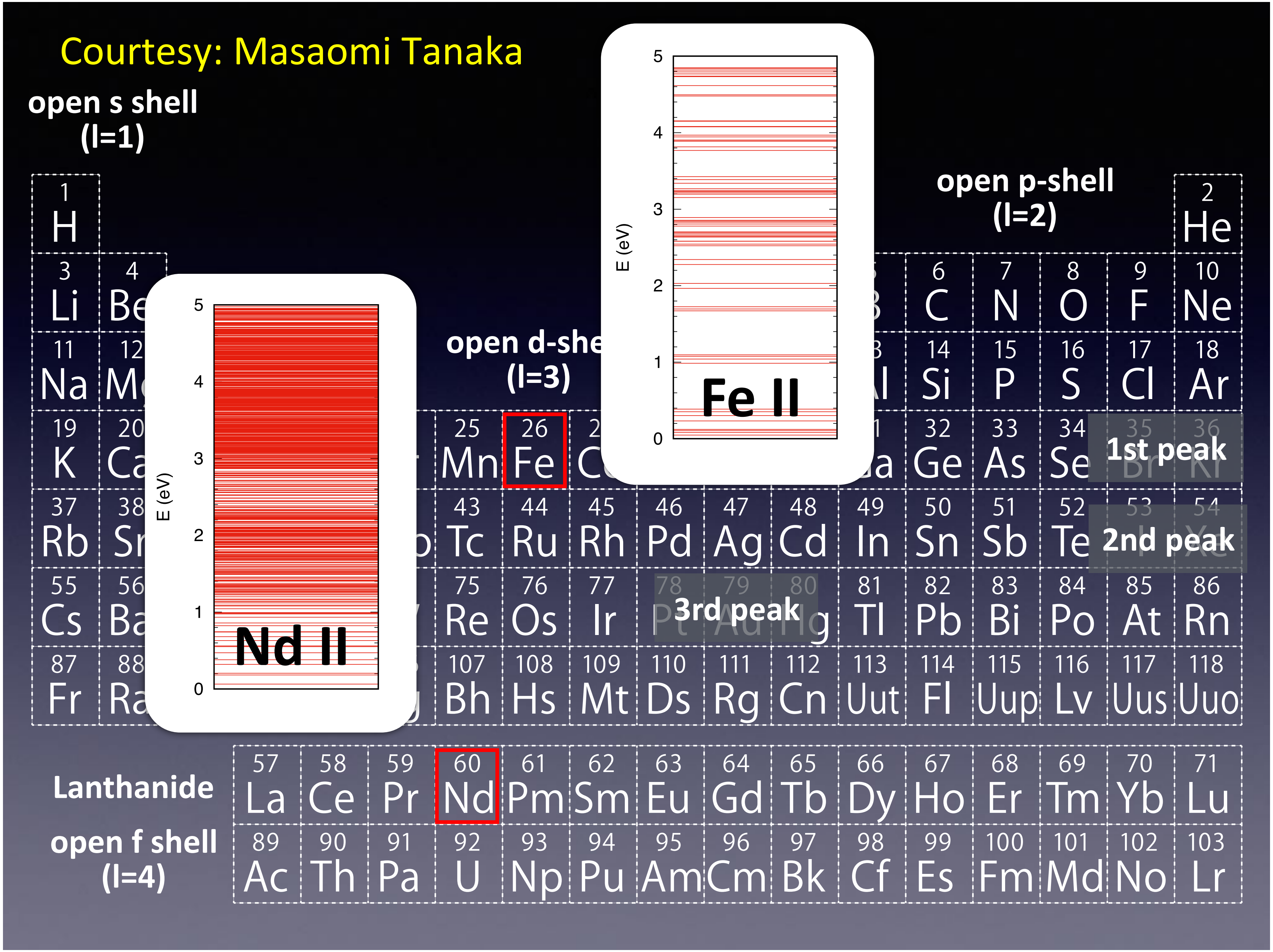
Appreciable difference

Nucleosynthesis depends on Y_e=[p]/([p]+[n])

(M. Tanaka et al., 1708.09101)

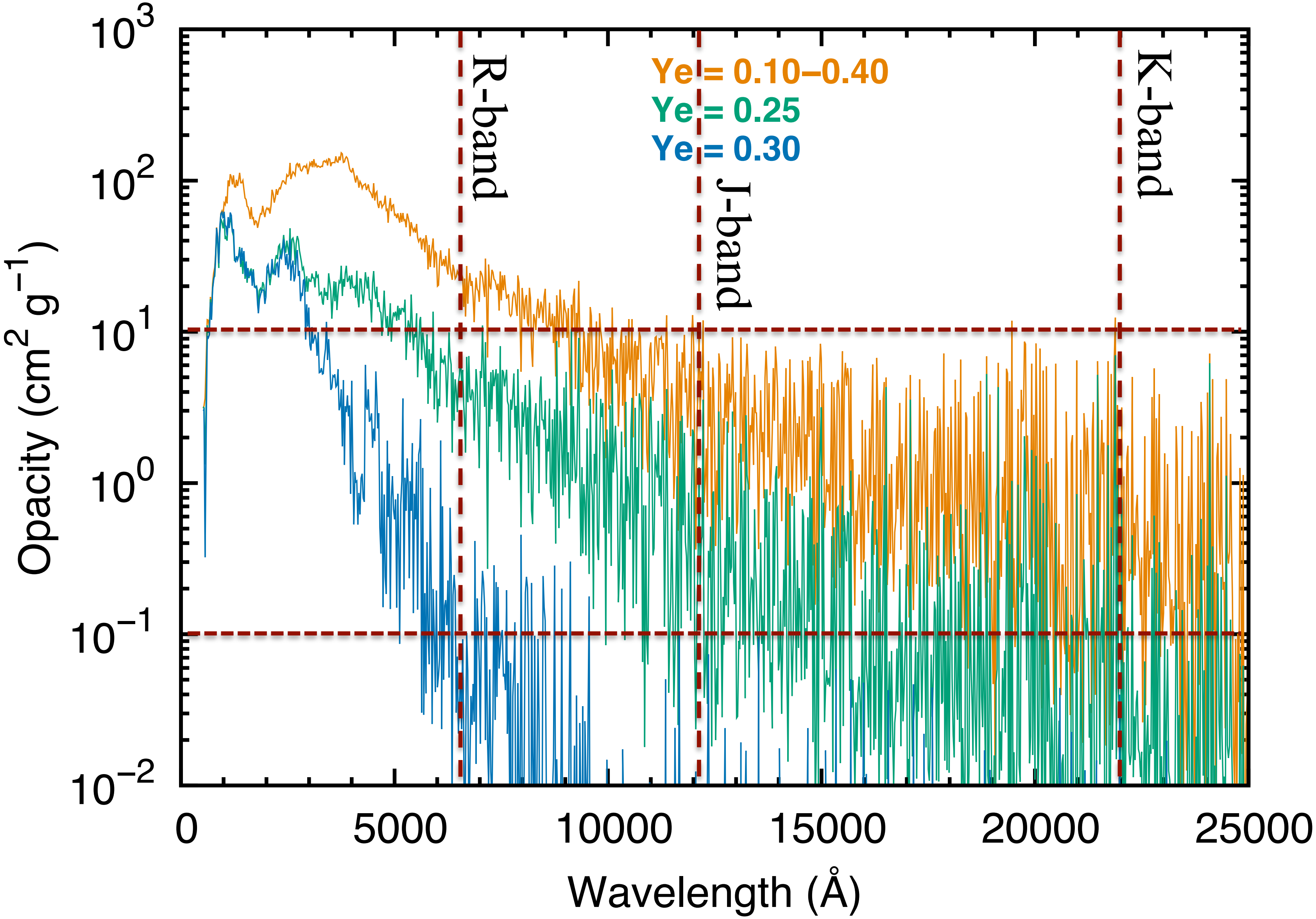


Heavy →

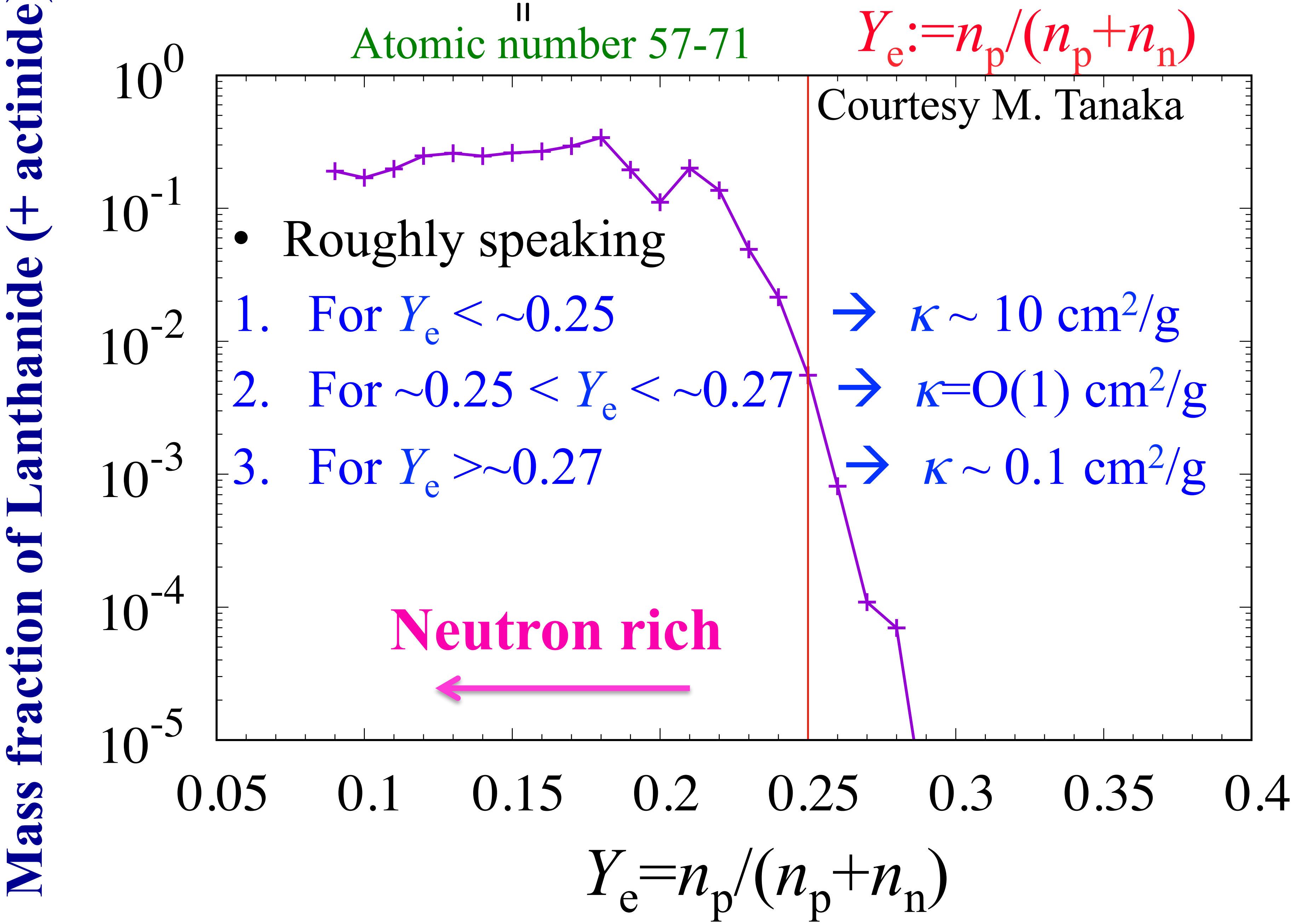

Courtesy: Masaomi Tanaka
open s shell
(l=1)
open p-shell
(l=2)
open d-she
(l=3)
Lanthanide
open f shell
(l=4)
1st peak
2nd peak
3rd peak
Nd II
Fe II
E (eV)
0 1 2 3 4 5
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No 103 Lr

Opacity depends strongly on Y_e

(M. Tanaka et al., 1708.09101)

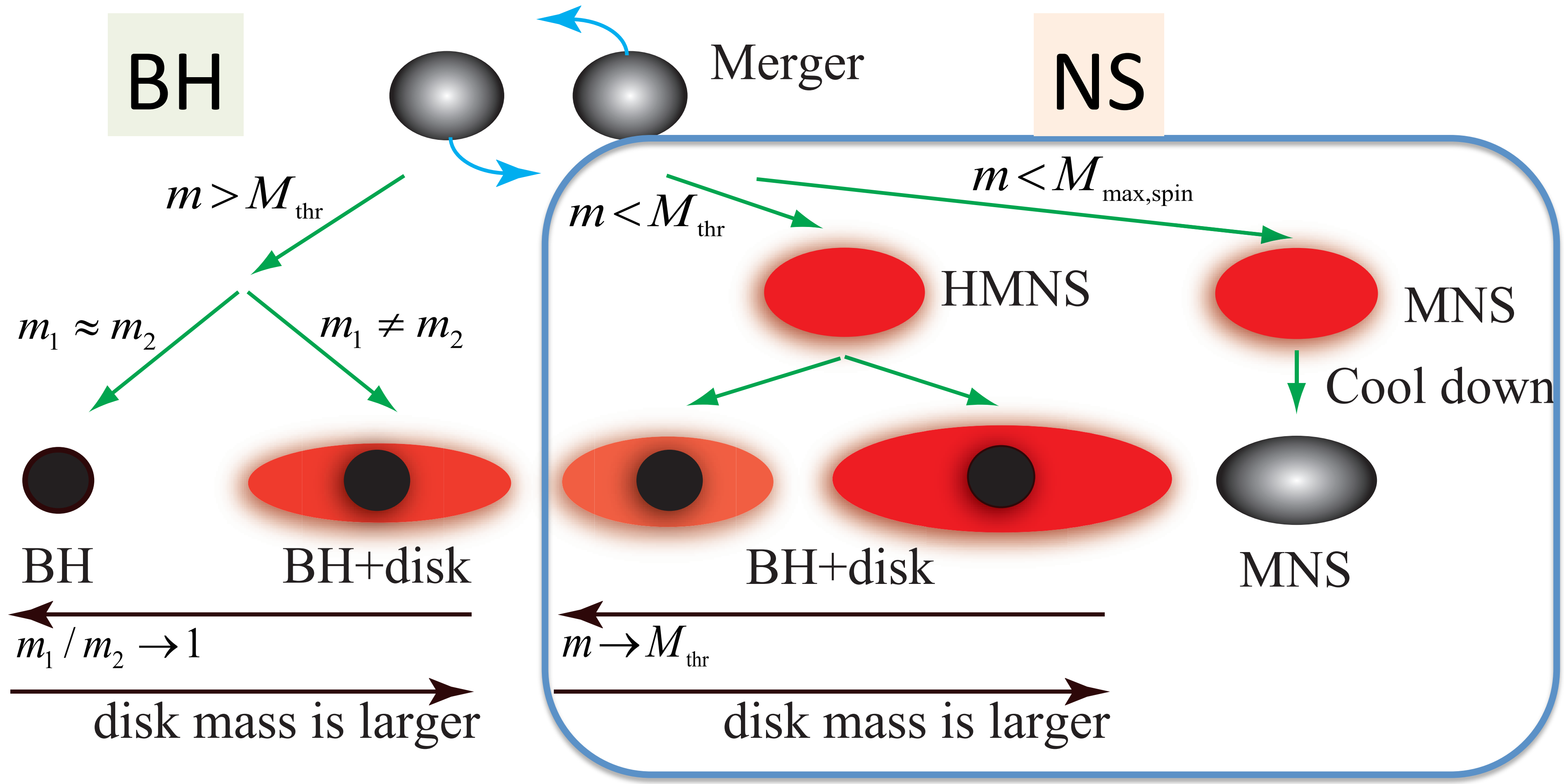


Fraction of lanthanides vs electron fraction



II Short summary for typical scenarios of merger and mass ejection of neutron-star merger

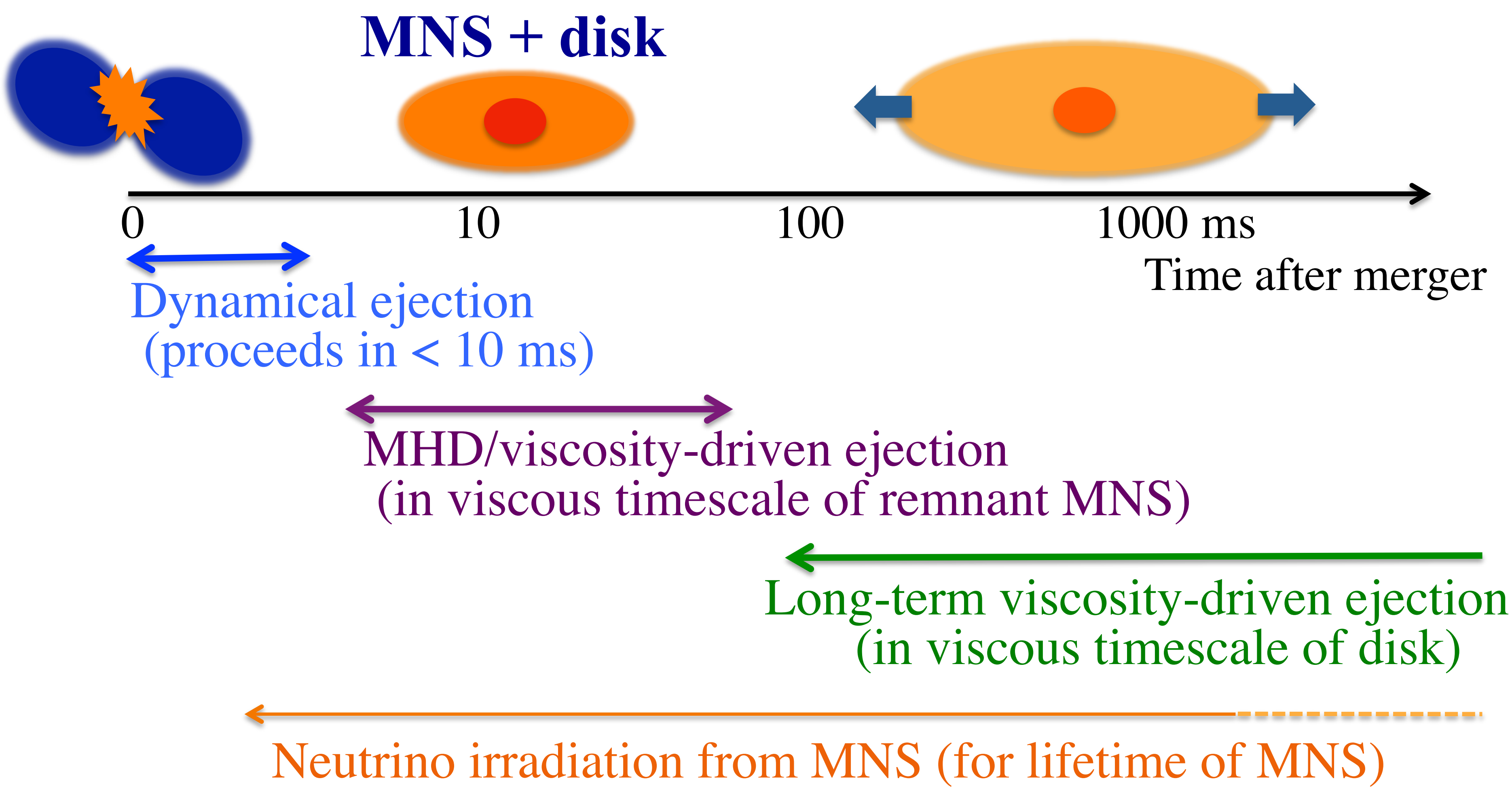
Possible outcomes of NS-NS mergers



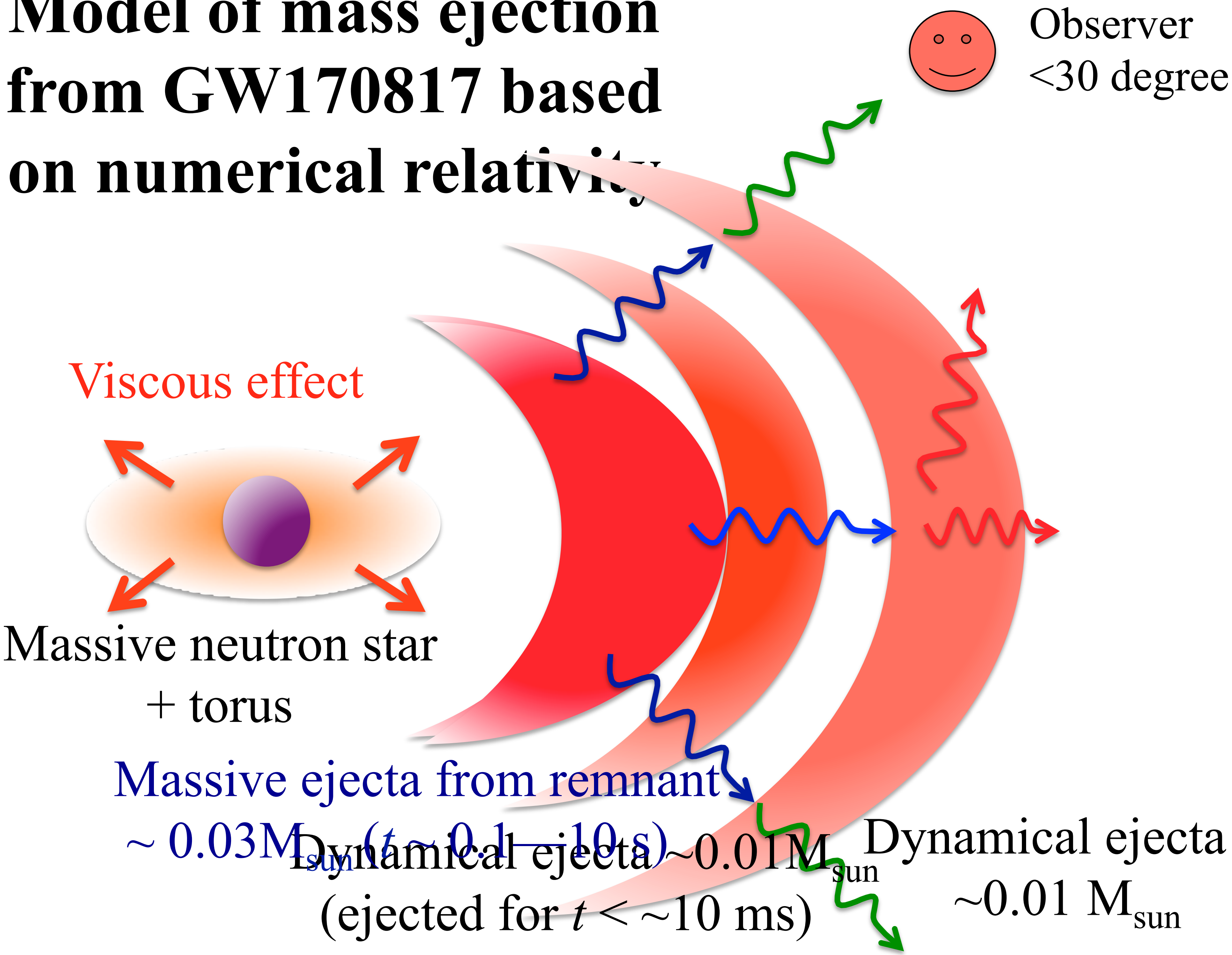
Likely for $M_{tot} < \sim 2.8 M_{sun}$

Note: total mass of GW170817 is 2.73—2.78 M_{sun}

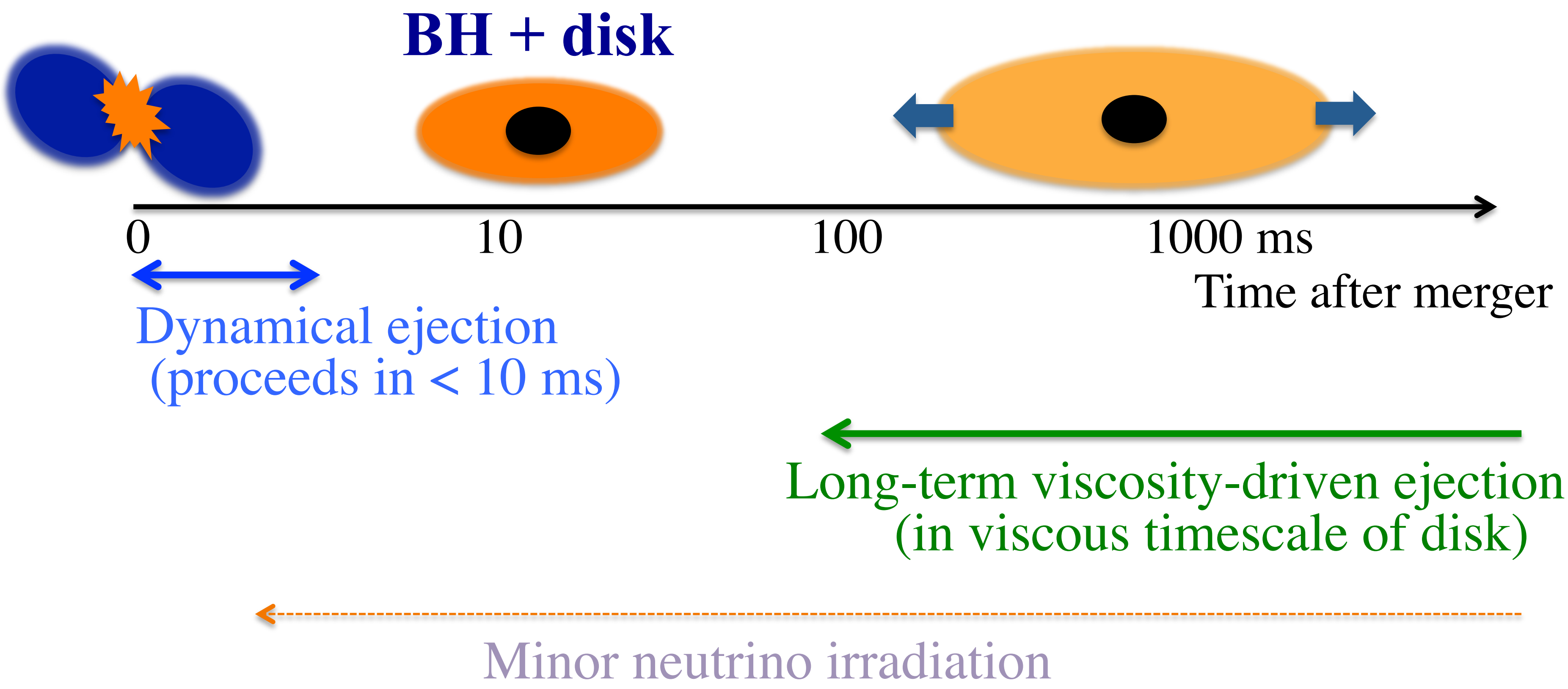
Mass ejection scenario (NS-NS typical case)



Model of mass ejection from GW170817 based on numerical relativity



High-spin / small-mass BH-NS
or
High total mass & asymmetric NS-NS



III Dynamical mass ejection

- For exploring this, we need merger simulations in **numerical relativity**:
  General relativity, hydrodynamics, neutrino radiation, & possibly magneto-hydrodynamics play key roles
- In the following example, we solve Einstein's and neutrino radiation hydrodynamics equations
- Radiation transport: leakage + M1, no momentum-space dependence is taken into account

What one solves is

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

Einstein's equation with
3+1 (BSSN) formalism

$$\left.\begin{aligned} \nabla_\mu T^\mu_\nu &= 0 \\ \nabla_\mu \left(\rho u^\mu\right) &= 0 \end{aligned}\right\}$$

Magneto/viscous hydrodynamics

$$\frac{Df}{Dt} = \dot{f}_{\mathrm{int}}$$

Neutrino radiation transfer
with a very approximate level

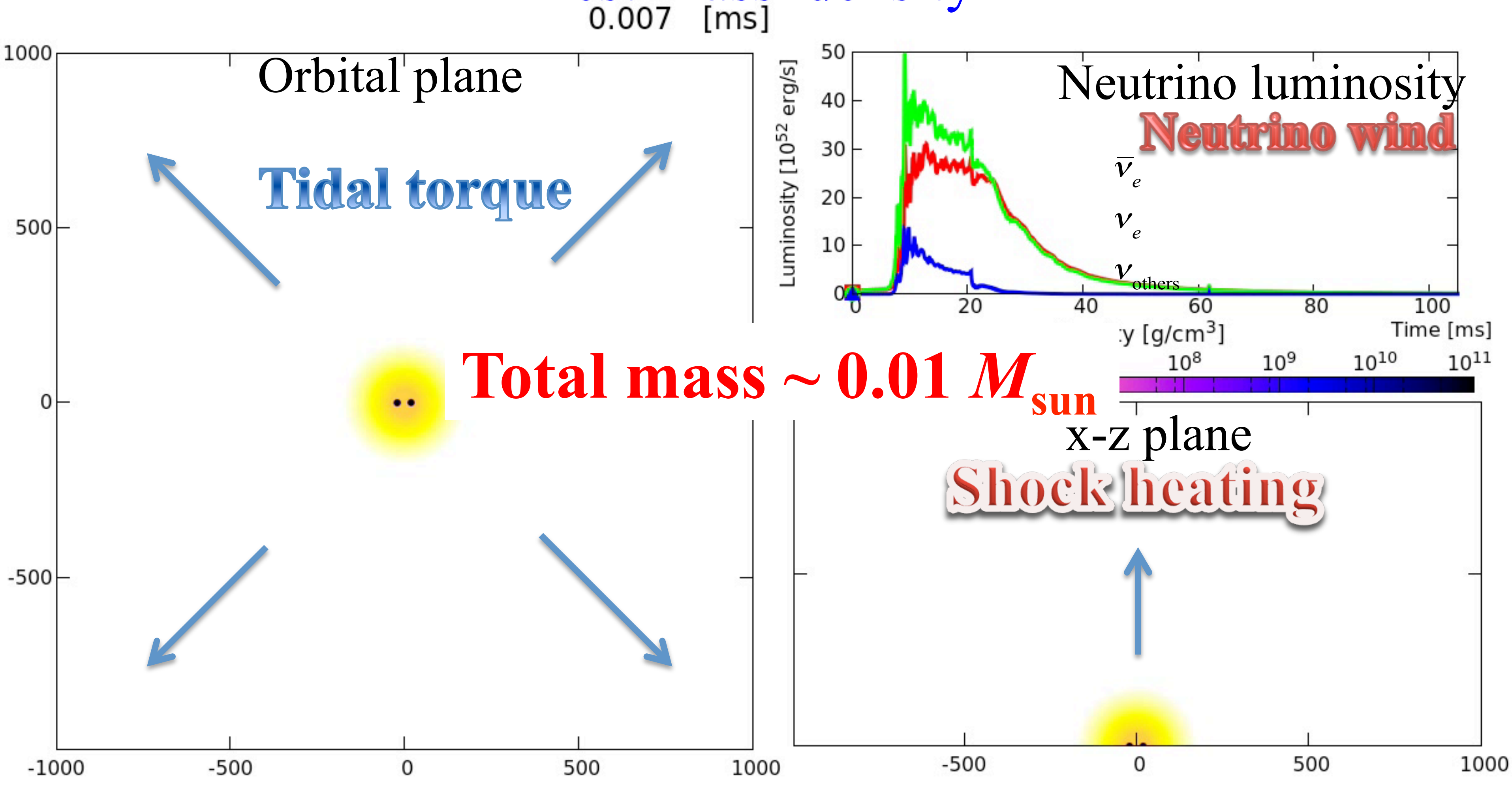
⬆

Should be improved in future

NS-NS: Neutrino-radiation hydro simulation

Soft EOS (SFHo, R~11.9 km): 1.30-1.40 M_{sun}

Rest-mass density

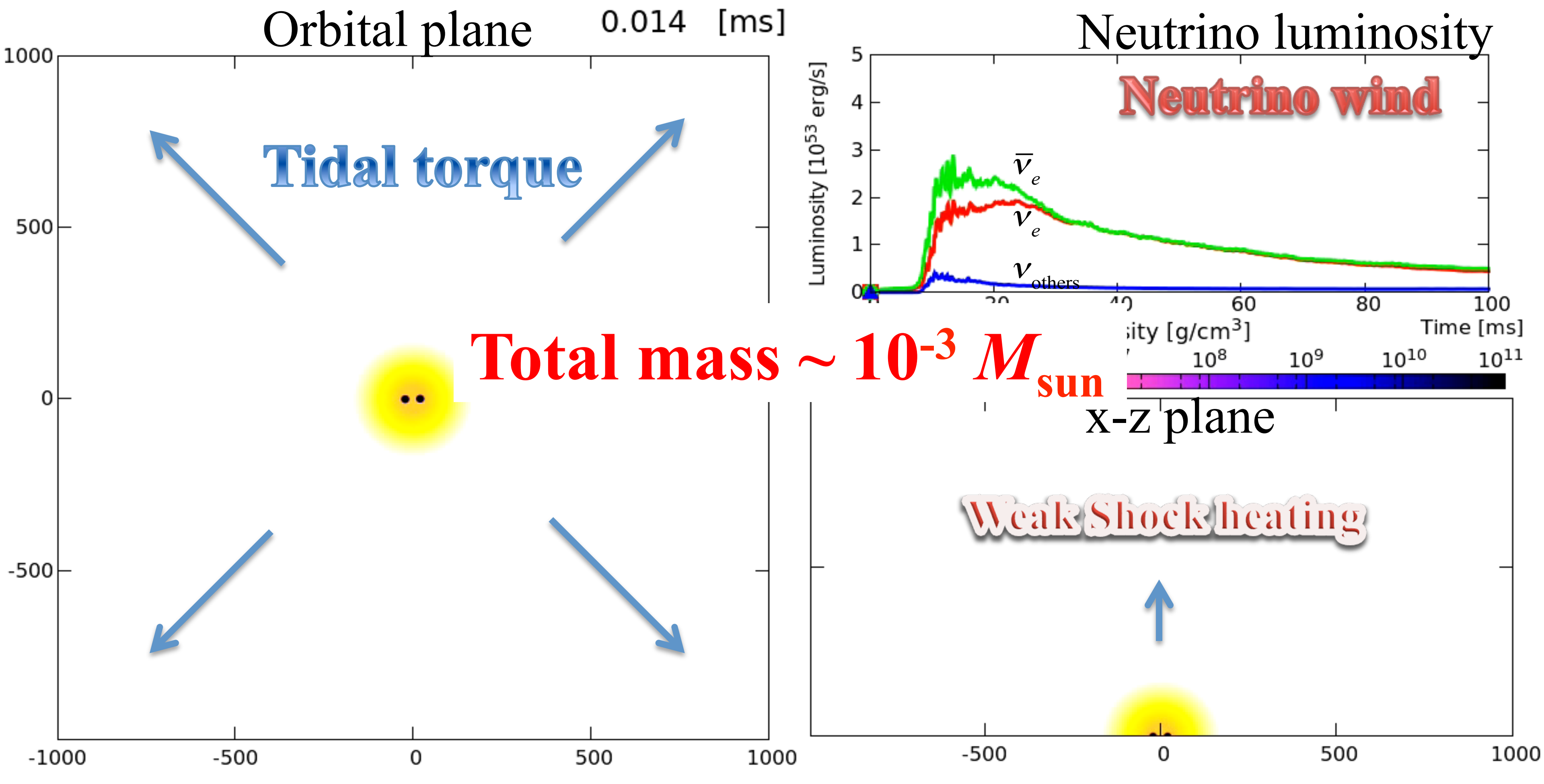


Sekiguchi et al. 2016

NS-NS: Neutrino-radiation hydro simulation

Stiff EOS (DD2, R~13.2 km): 1.30-1.40 M_{sun}

Rest-mass density

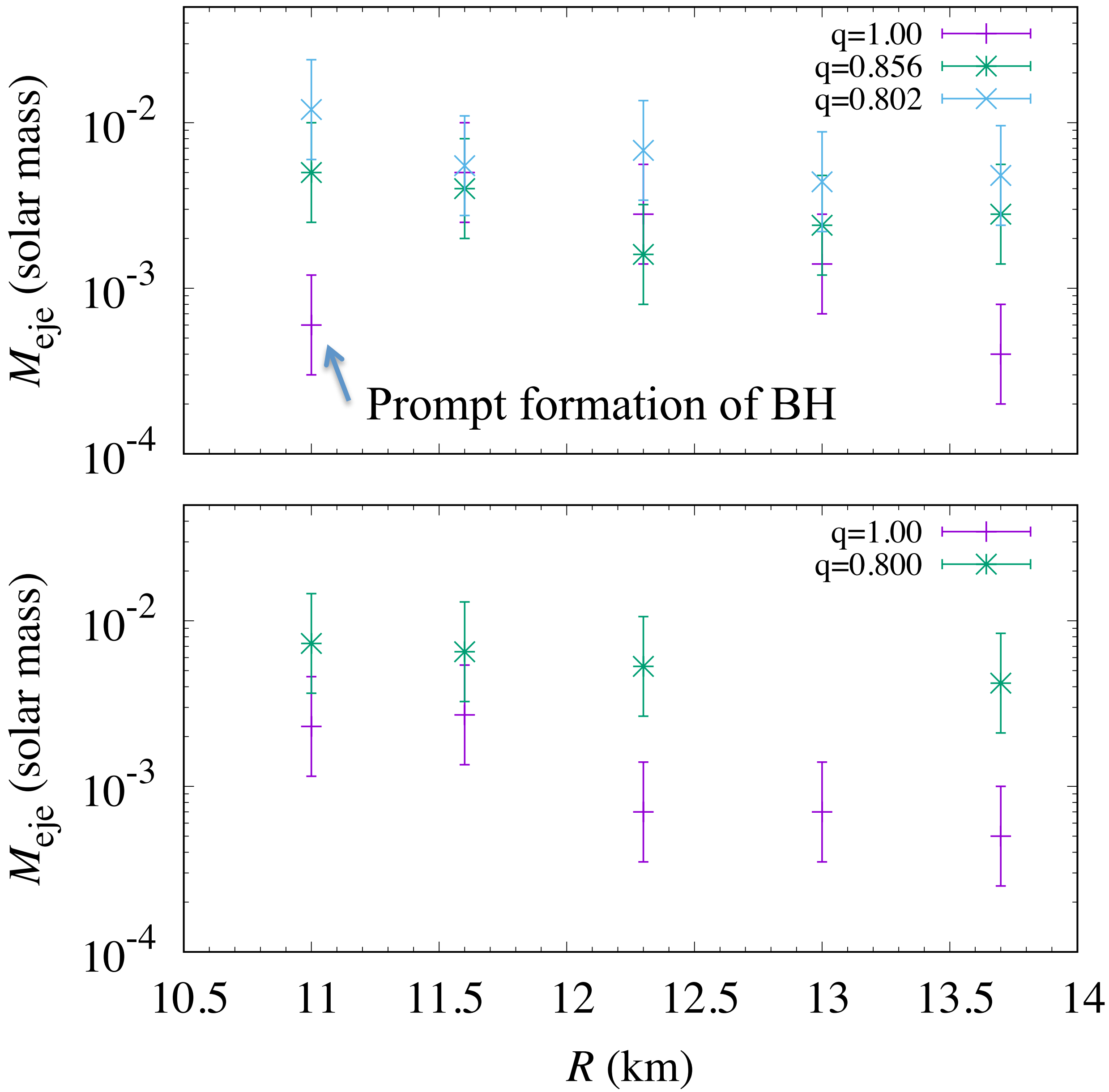


Sekiguchi et al. 2016

Three mechanisms for mass ejection

- **Tidal torque**: Gravitational torque associated with non-axisymmetric structure of self-gravitating objects. This effect is important irrespective of NS-NS/BH-NS and NS mass, EOS, etc.
- **Shock heating**: Thermal pressure resulting from matter heated by shocks (collision of two NSs and NS with surrounding matter): For NS-NS with compact neutron stars, this effect is more appreciable
- **Neutrino heating**: Neutrino radiation pressure; this is minor effect for mass ejection but important as a weak interaction source (change Y_e): A. Perego will talk more details.

Dynamical ejecta mass by high-res simulation



Chirp mass is the same as 1.35-1.35 solar mass case

Chirp mass is the same as 1.25-1.25 solar mass case

Summary for dynamical ejecta mass in NR

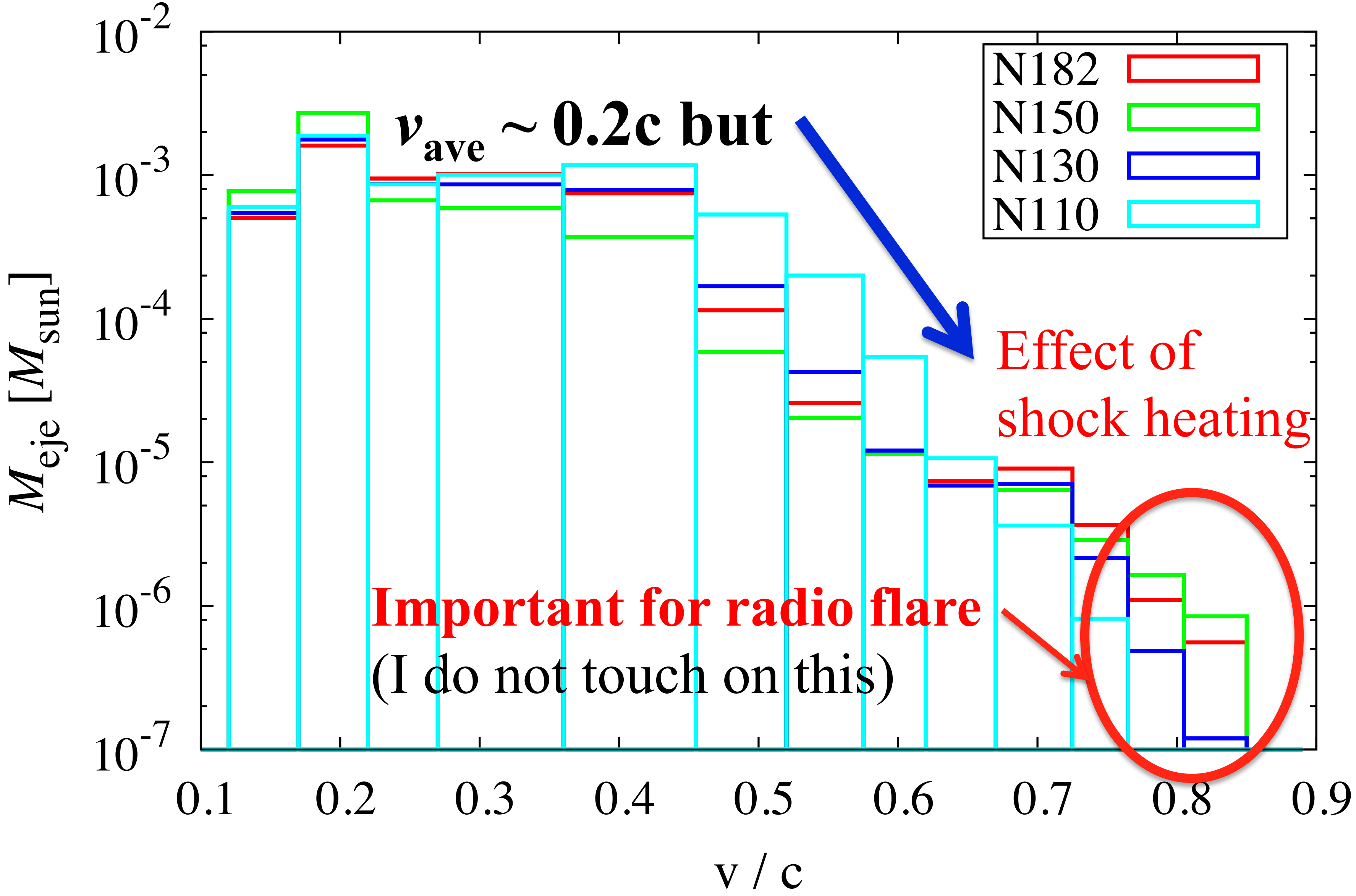
Dynamical ejecta mass depends significantly on masses

Total mass	Remnant	Nearly equal mass	Unequal mass: $m_1/m_2 < \sim 0.8$
Low $<\sim 2.6\ M_{sun}$	**SupramassiveNS** (long-lived NS)	$M_{eje} \sim 10^{-3}\ M_{sun}$	$M_{eje} \sim 10^{-2.5}\ M_{sun}$
Middle $\sim 2.7\ M_{sun}$	**HypermassiveNS** → BH	$M_{eje} \sim 10^{-3}$-$10^{-2}\ M_{sun}$ (EOS dependent)	$M_{eje} \sim 10^{-2.5}$-$10^{-2}\ M_{sun}$
High $>\sim 2.8\ M_{sun}$	**Prompt BH formation**	$M_{eje} < 10^{-3}\ M_{sun}$ (also tiny disk)	$M_{eje} \sim 10^{-3}$-$10^{-2}\ M_{sun}$

e.g, Hotokezaka+ '13, Sekiguchi+ '15, Palenzela+ '15, Radice+ '16, Foucart et al. '16, Dietlich+ '17, many similar recently ….

- Typical average velocity: 0.15—0.25 c
- A fraction of ejecta has high velocity up to ~0.8 c

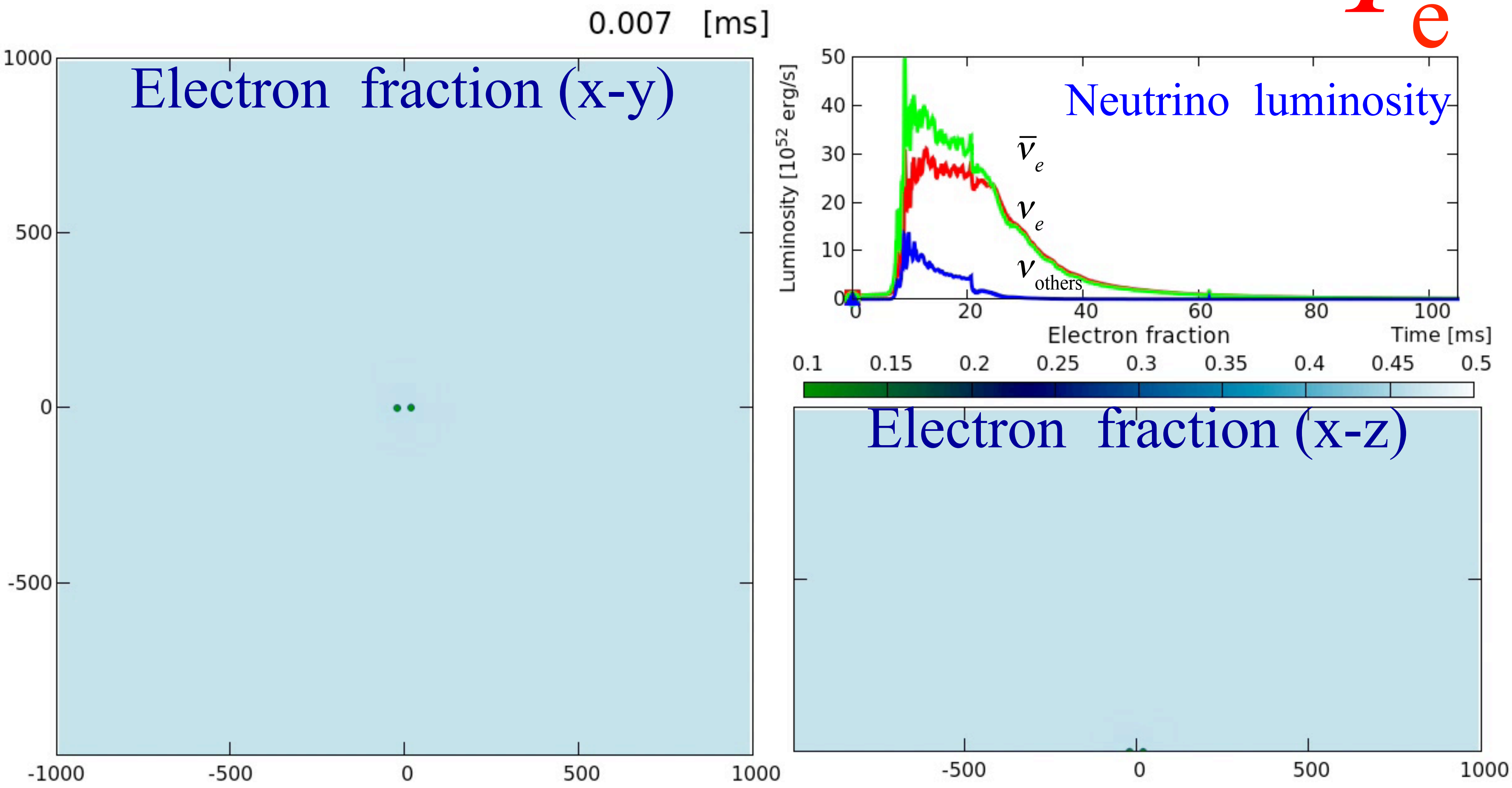
Ejecta velocity distribution: *high v is present*



Neutrino-radiation hydrodynamics simulation

SFHo (R~11.9 km): 1.30-1.40 M_{sun}

Y_e



Green = neutron rich

Sekiguchi et al. (2016)

Importance of weak interaction on neutron richness

High temperature $\Rightarrow \gamma\gamma \rightarrow e^- + e^+$

$\Rightarrow \quad n + e^+ \leftrightarrow p + \bar{\nu}_e \quad \& \quad p + e^- \leftrightarrow n + \nu_e$

Neutrino irradiation

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

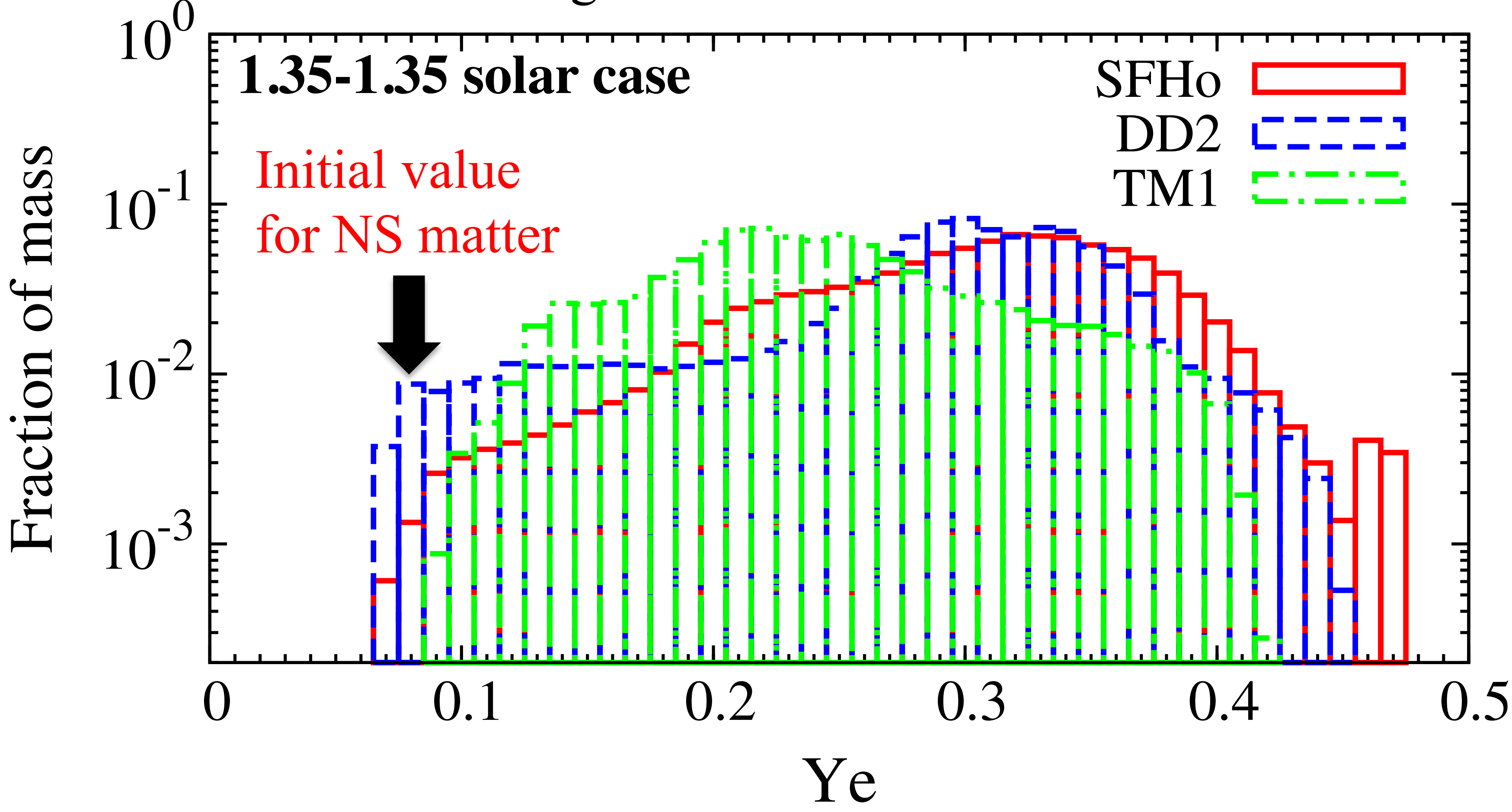
For long-term neutrino irradiation,
n-p ratio approaches a chemical equilibrium

$$\frac{[p]}{[n]+[p]} \approx \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\bar{\varepsilon}_{\bar{\nu}_e} - 2Q}{\bar{\varepsilon}_{\nu_e} + 2Q} \right]^{-1} : Q = \left(m_n - m_p \right) c^2 \approx 1.293 \text{ MeV}$$

Qian & Woosley 1996

Electron fraction profile: Broad

Sekiguchi et al. 2015 PRD



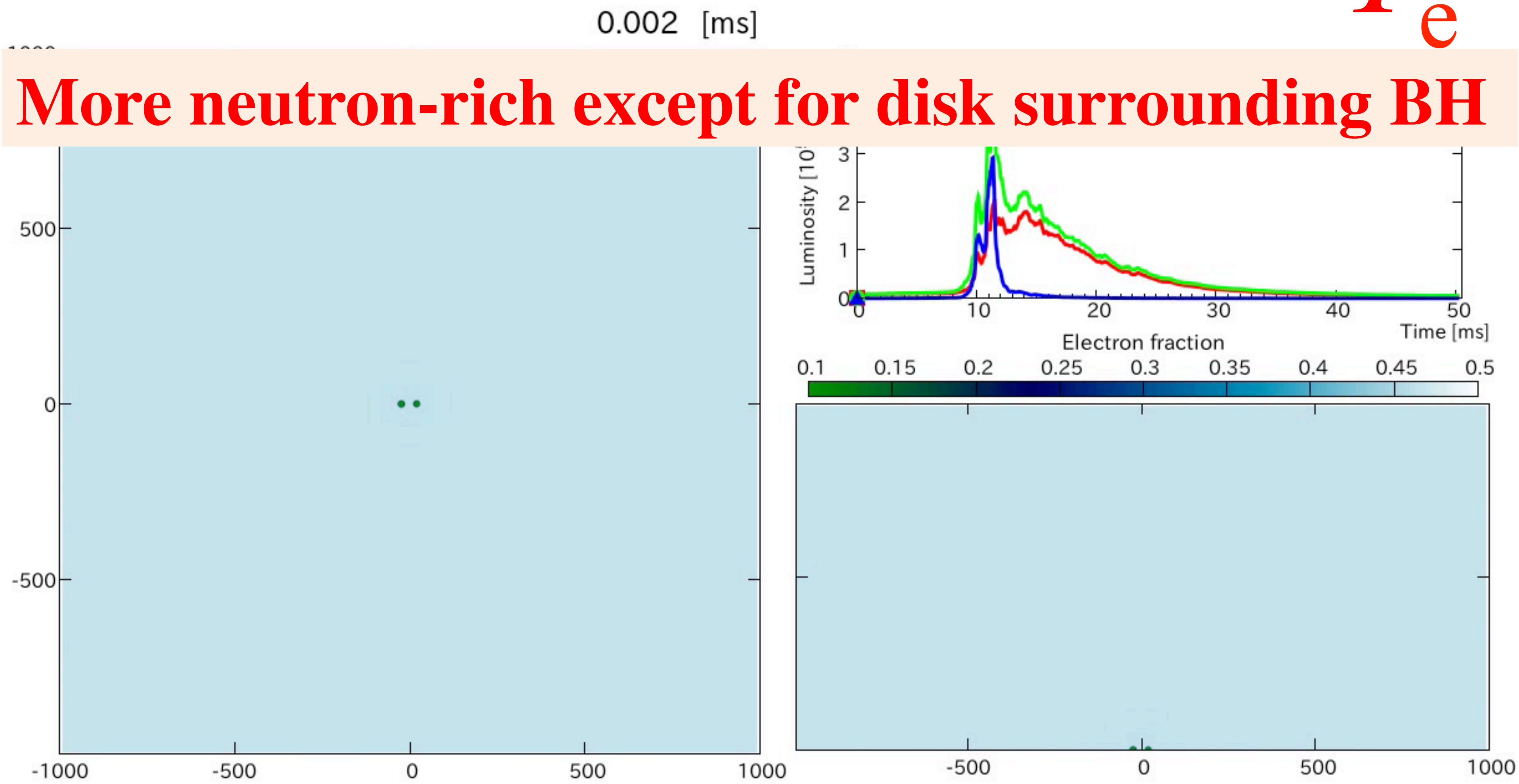
- ➢ Average depends on EOS but typically peak at 0.2—0.3
- ➢ **Broad distribution** irrespective of EOS

Neutrino-radiation hydrodynamics simulation

SFHo (R~11.9 km): 1.25-1.55 M_{sun}

Y_e

More neutron-rich except for disk surrounding BH



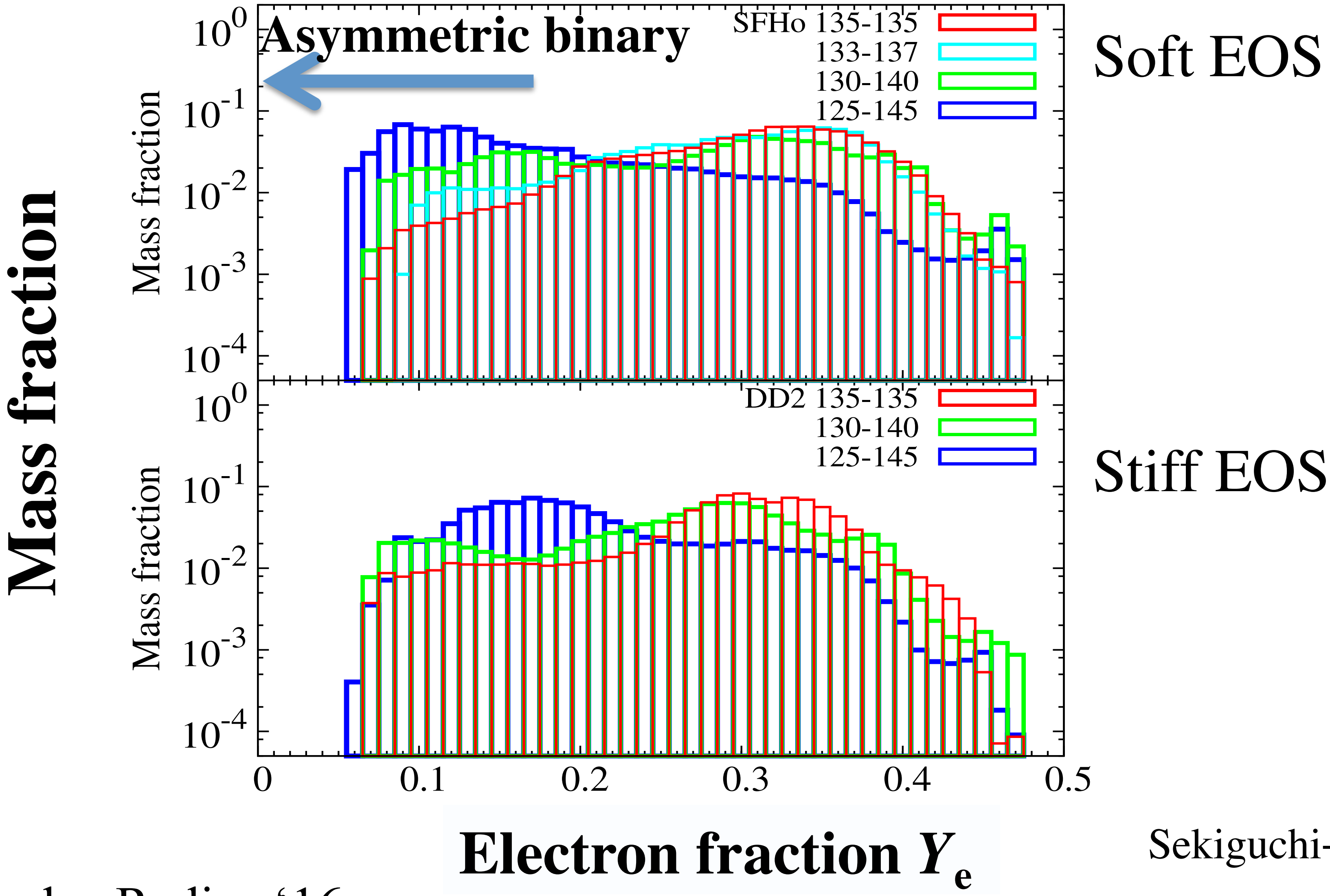
Green = neutron rich

Sekiguchi et al.

Electron fraction distribution:

Broad irrespective of EOS and mass

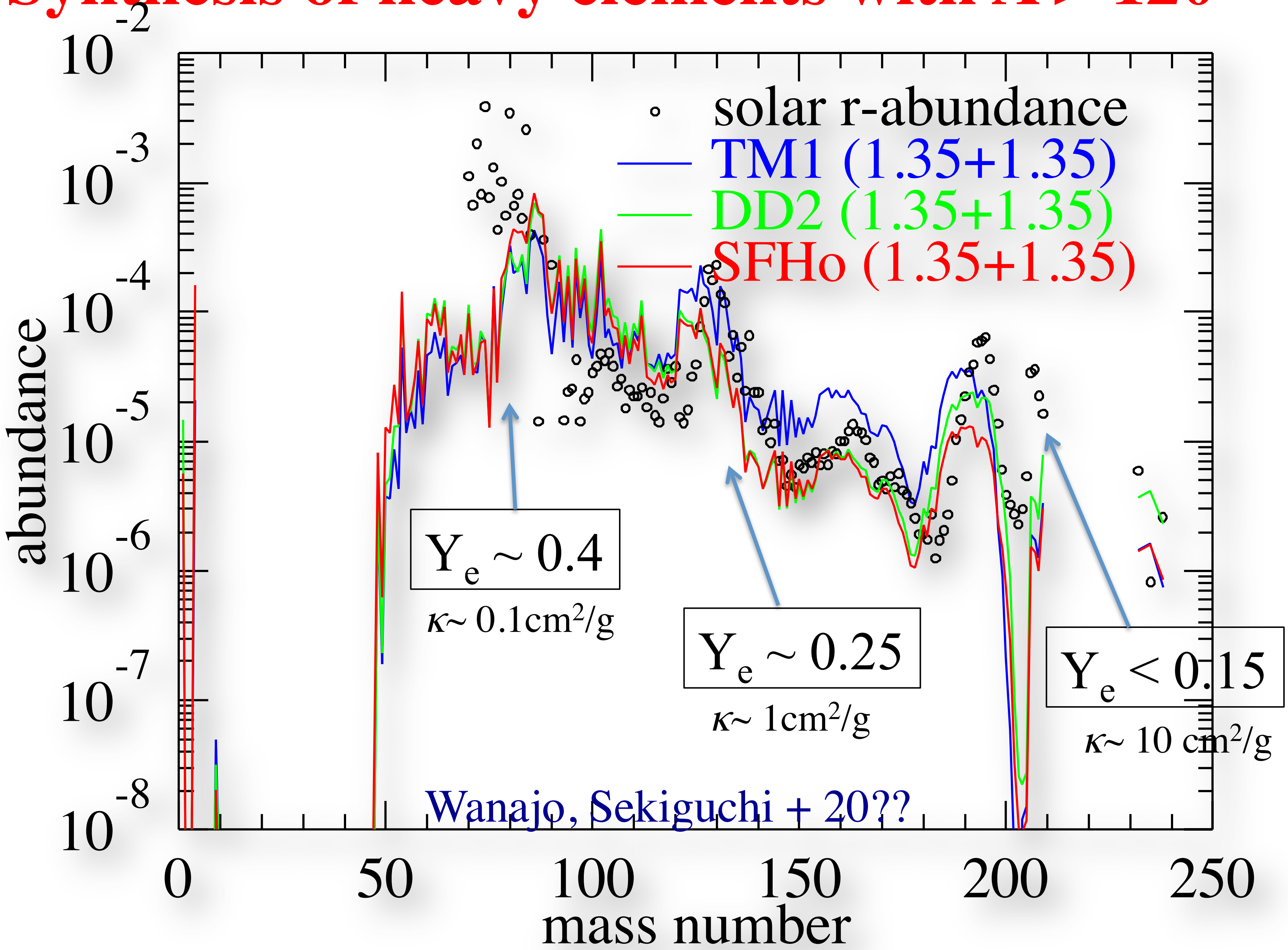
→ Good for producing a variety of r-elements



Sekiguchi+ '16

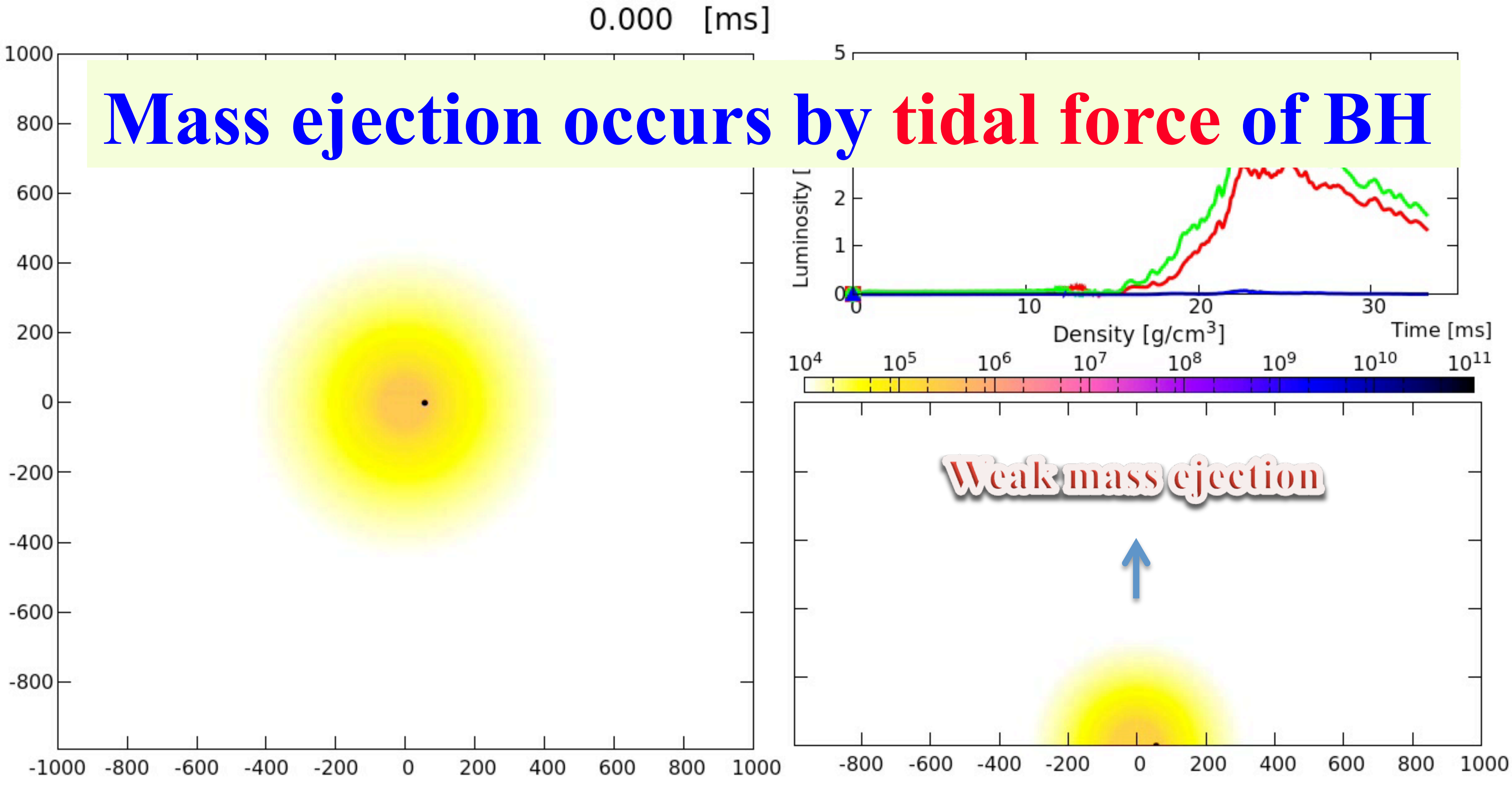
See also Radice '16

Synthesis of heavy elements with A > 120



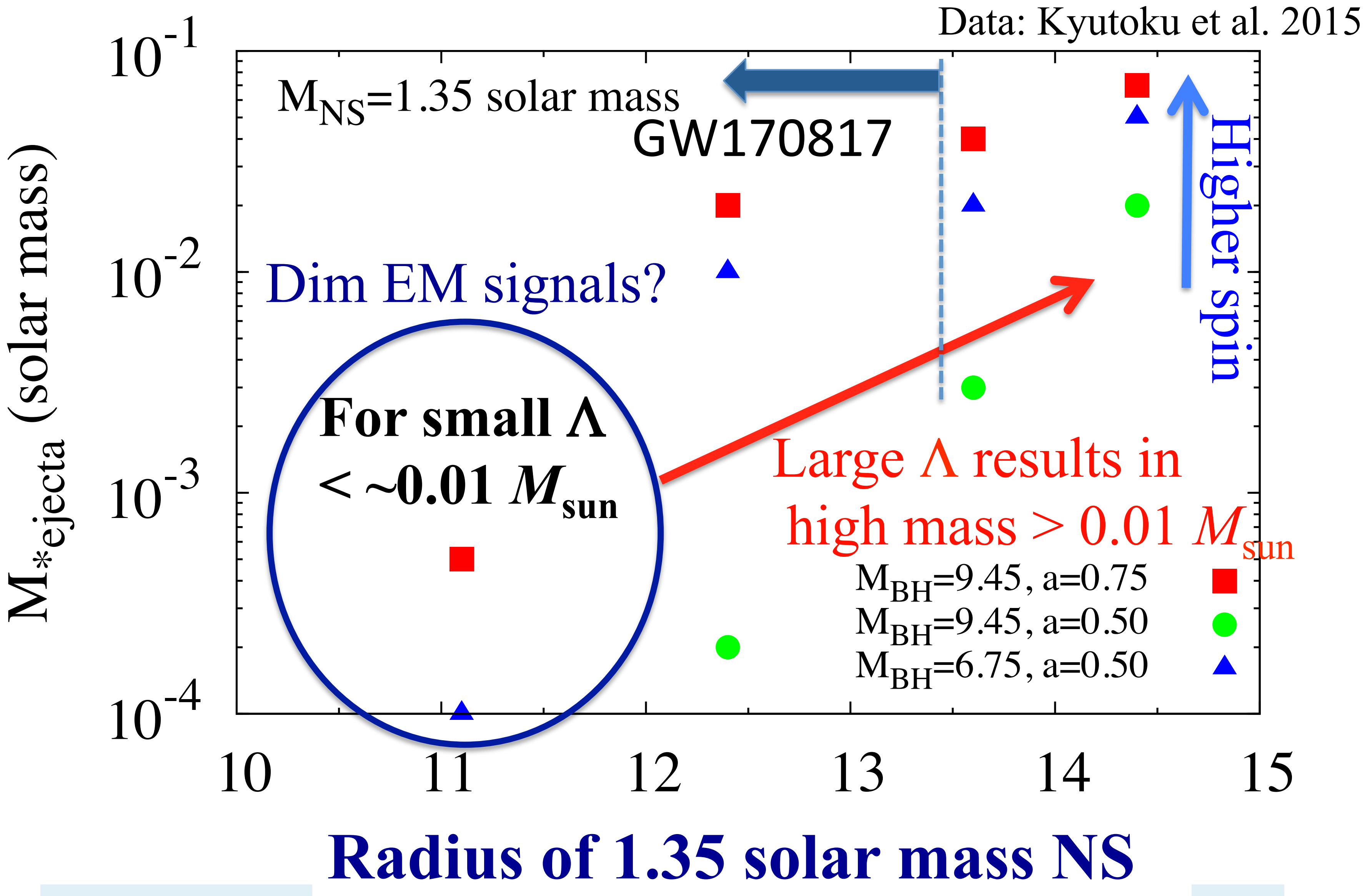
BH-NS merger (SFHo EOS: density)

M_{BH}=5.4M$_{sun}$, M_{NS}=1.35M$_{sun}$, a_{BH}=0.75



Kyutoku et al. 2018; Also many pioneer works by F. Foucart et al.

BH-NS with NS mass $1.35M_{sun}$ (Q=5 & 7)



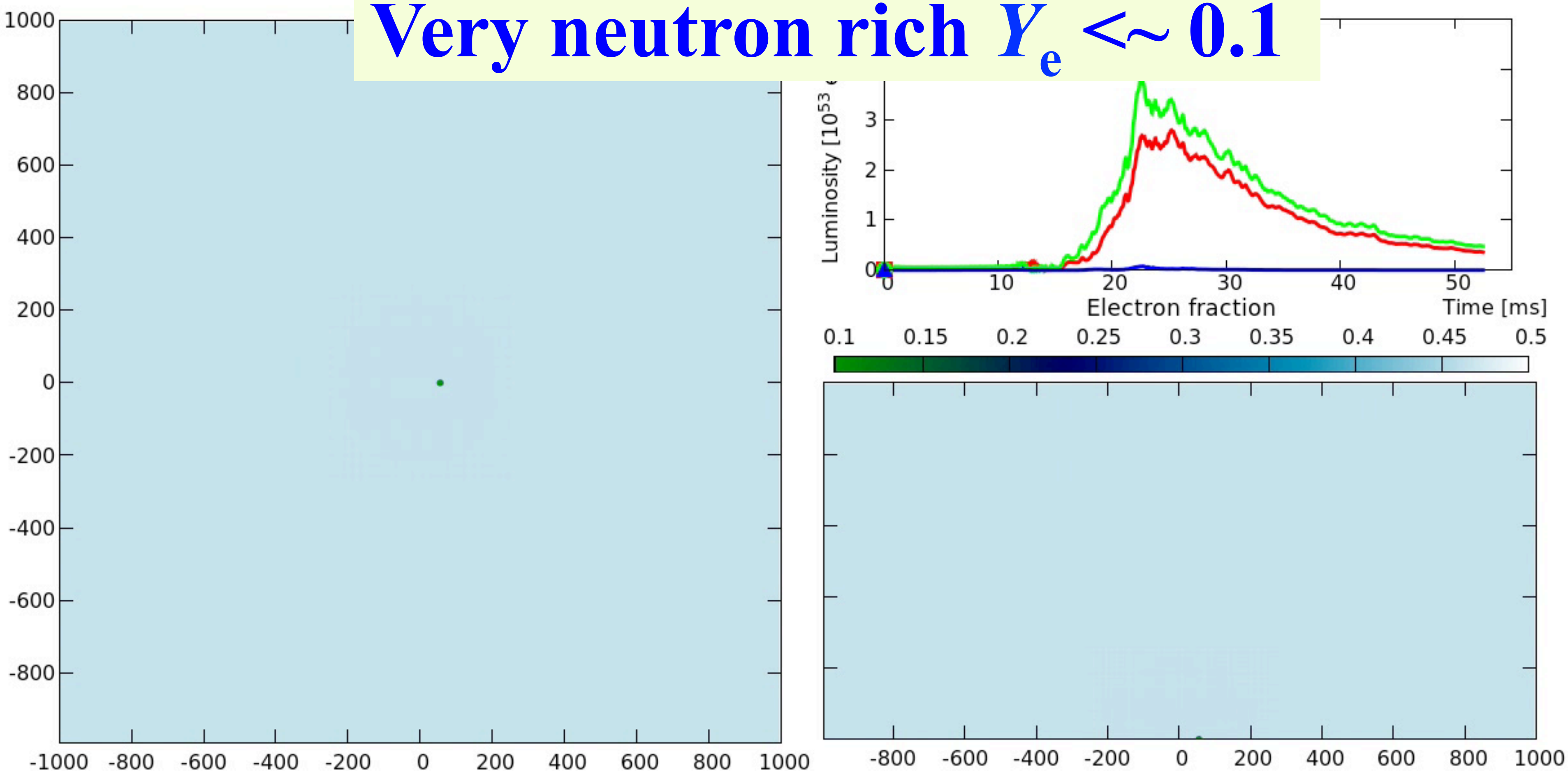
High BH spin is important for mass ejection

BH-NS merger (SFHo EOS: electron fraction)

M_{BH}=5.4M$_{sun}$, M_{NS}=1.35M$_{sun}$, a_{BH}=0.75

Y_e

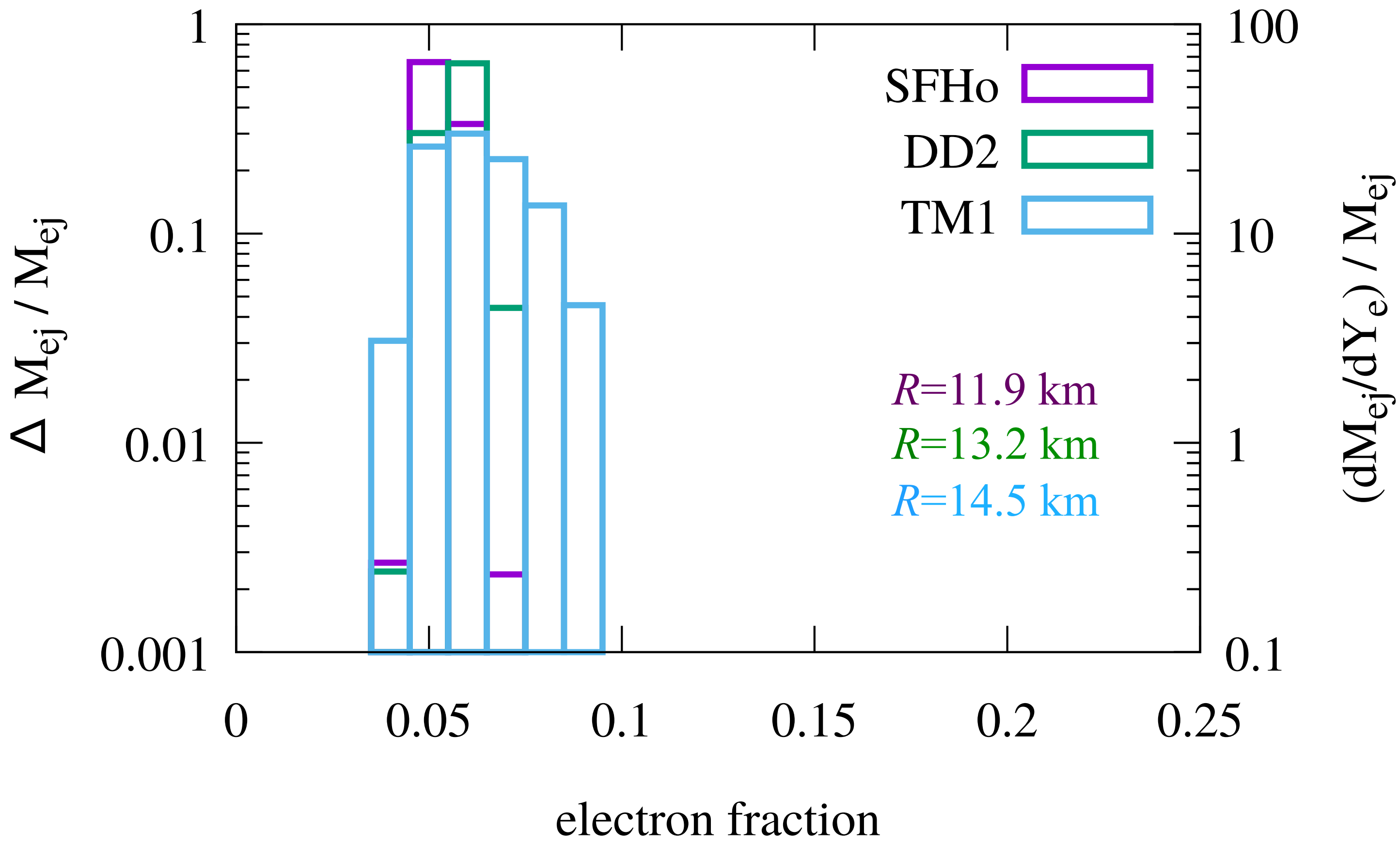
Very neutron rich Y_e <~ 0.1



Green = Neutron rich

Kyutoku et al. 2018; Also many works by F. Foucart et al.

Electron fraction of ejecta



- **Quite low electron fraction** irrespective of EOS (Foucart, Duez et al., ‘13—18, Kyutoku ‘18)
- **Tiny neutrino irradiation, weak shock heating**
- Likely to primarily synthesize **heavy r-elements**

Summary of dynamical ejecta properties in NR

- **Mass**: M_{eje}

- NS-NS: $\sim 10^{-3}$—10^{-2} M_{sun} depending on total mass, mass ratio, & EOS (Hotokezaka+ 13, Bauswein+ 13, Sekiguchi+ 15,16, Radice+ 16, Lehner+ 15,16…….many others)
- BH-NS: **0—0.05 M_{sun} typically $M_{\text{eje}} \sim 0.2\, M_{\text{disk}}$**
  High BH spin is the key (for NS radius < 13km)
  (Foucart+ 13-15, Kyutoku+ '15, 18)

- **Electron fraction: Y_e**

- NS-NS: Broad distribution with $\langle Y_e \rangle \sim 0.2$—$0.3$:
  For highly asymmetric case, $\langle Y_e \rangle < 0.2$:
  For prompt BH formation case, $Y_e < \sim 0.1$
- BH-NS: Peak at $Y_e < 0.1$ (Foucart+ '13-18, Kyutoku+ '18)

$\kappa \sim 10\ \text{cm}^2/\text{g}$

- **Typical velocity**: 0.15—0.25 c; max could be ~ 0.8 c

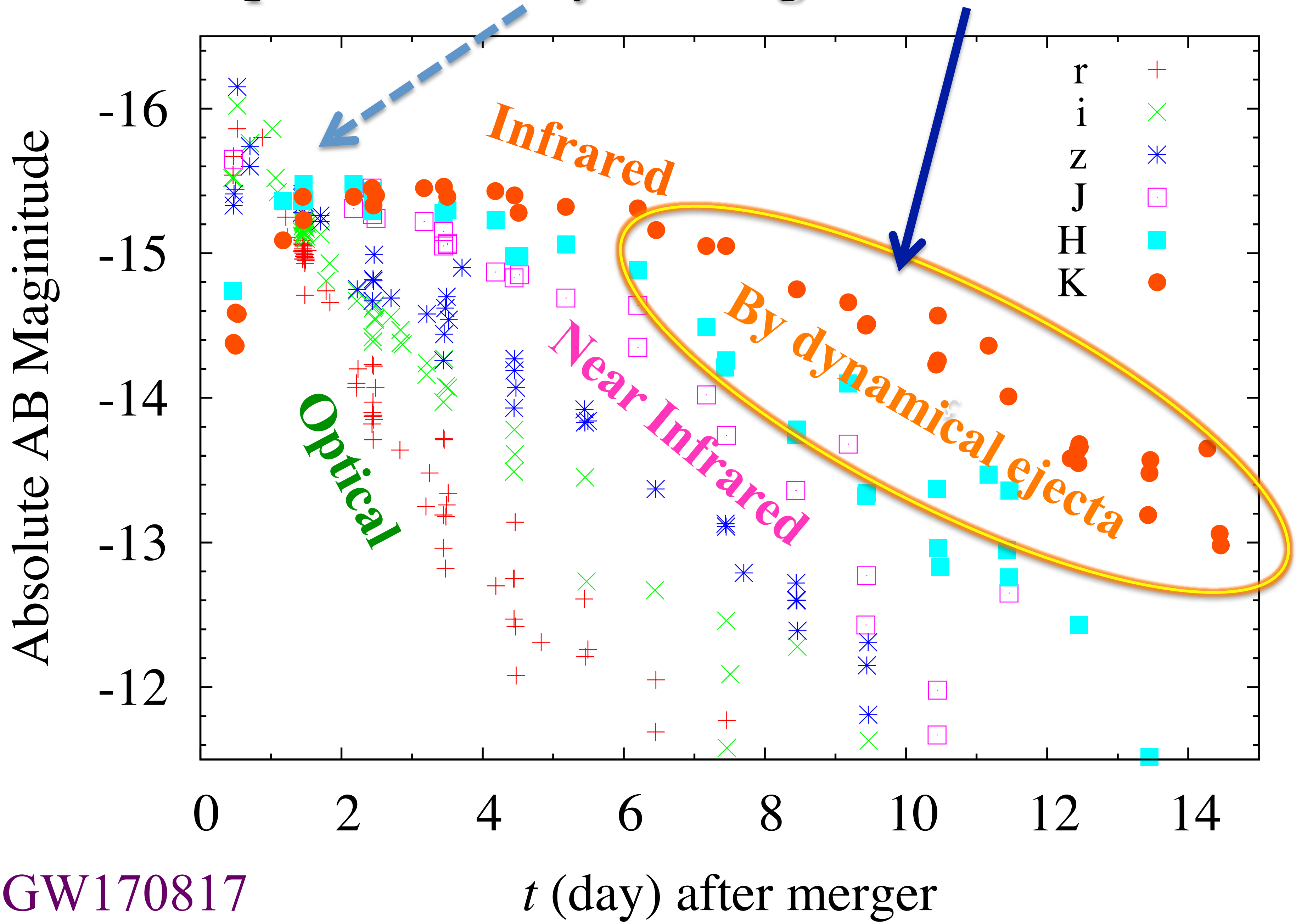
Kilonova by *dynamical* ejecta for NS/BH-NS

- An appreciable component has $Y_e < 0.15$
  → Very good for r-process nucleosynthesis, and
  → $\boxed{\kappa \sim 10\ \mathrm{cm^2/g}}$: large value
- Mass: ~ 0.001—0.01 M_{sun} : at most ~ 0.01M_{sun}
- "Average" velocity: 0.15—0.25c

$$L_{max} \sim \underbrace{7\times 10^{40}\ \mathrm{ergs/s}}_{\textbf{dim}} \left(\frac{M}{0.01M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{10\ \mathrm{cm^2/g}}\right)^{-1/2} \left(\frac{f_{\text{r-proc}}}{10^{-6}}\right)$$

$$\text{at } t \sim \underbrace{3.5\ \mathrm{days}}_{\textbf{late}} \left(\frac{M}{0.01M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{10\ \mathrm{cm^2/g}}\right)^{1/2}$$

Cannot reproduce early shining but late infrared



GW170817

EM counterpart of GW170817

- Peak time for the optical band is ~ 1 day
- Peak luminosity is ~ 7×10^{41} ergs/s

Dynamical ejecta alone cannot describe EM counterpart of GW170817 because of too high opacity and low ejecta mass

→ It was shown that something else was present

But, dynamical ejecta could still describe the late-phase red component

→ Evidence for r-process nucleosynthesis

IV Post−merger mass ejection

- MHD/viscous effects on ***torus*** are likely to play a key role for mass ejection
  (Fernandez-Metzger+ ’13-15, Perego et al. ’14, Just et al. ‘15, Siegel-Metzger ’17, Fujibayashi et al. ‘18)
- **Two cases** are present: **BH + torus** & **MNS + torus**

1. Typical remnants for NS+NS= **MNS + torus**
2. For BH+NS or massive NS-NS, the remnant is **BH + torus**

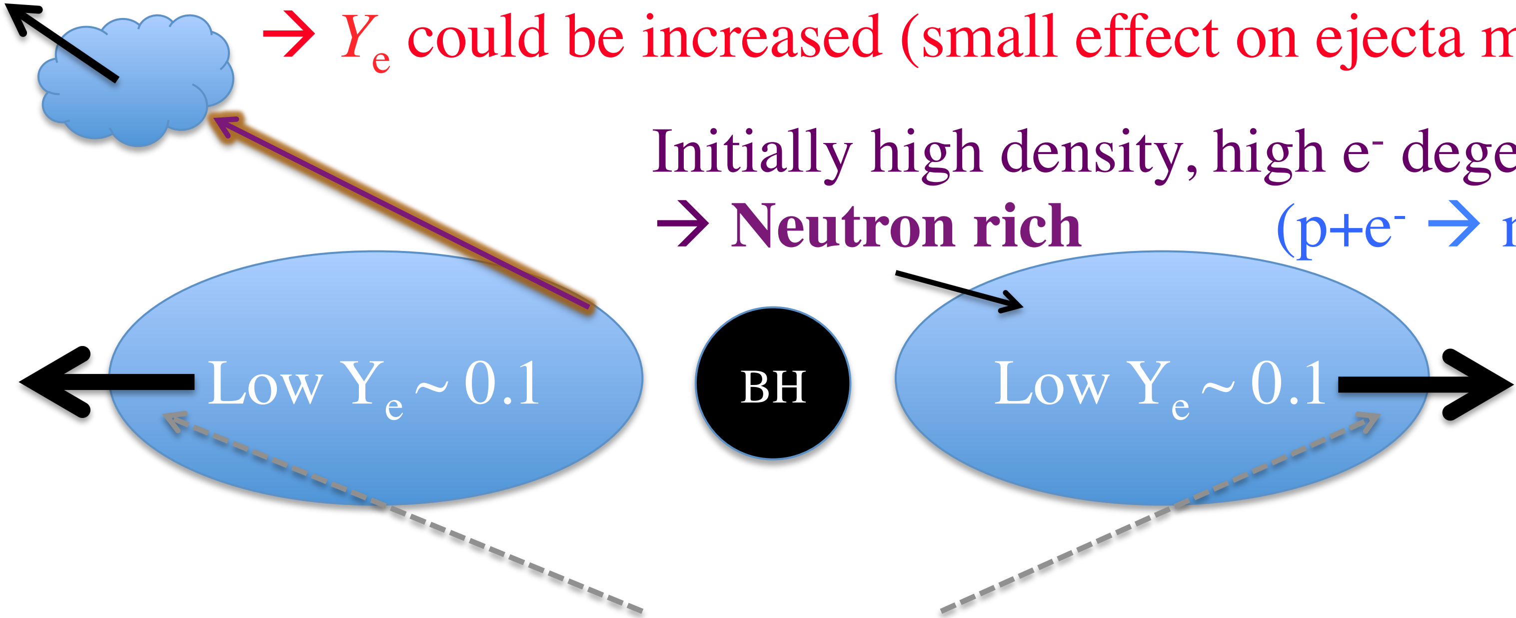
- **The presence of MNS can give significant difference on neutron richness of ejecta**

Basic Picture for BH-torus

(Fernandez-Metzger '13,14, Just '15, ……)

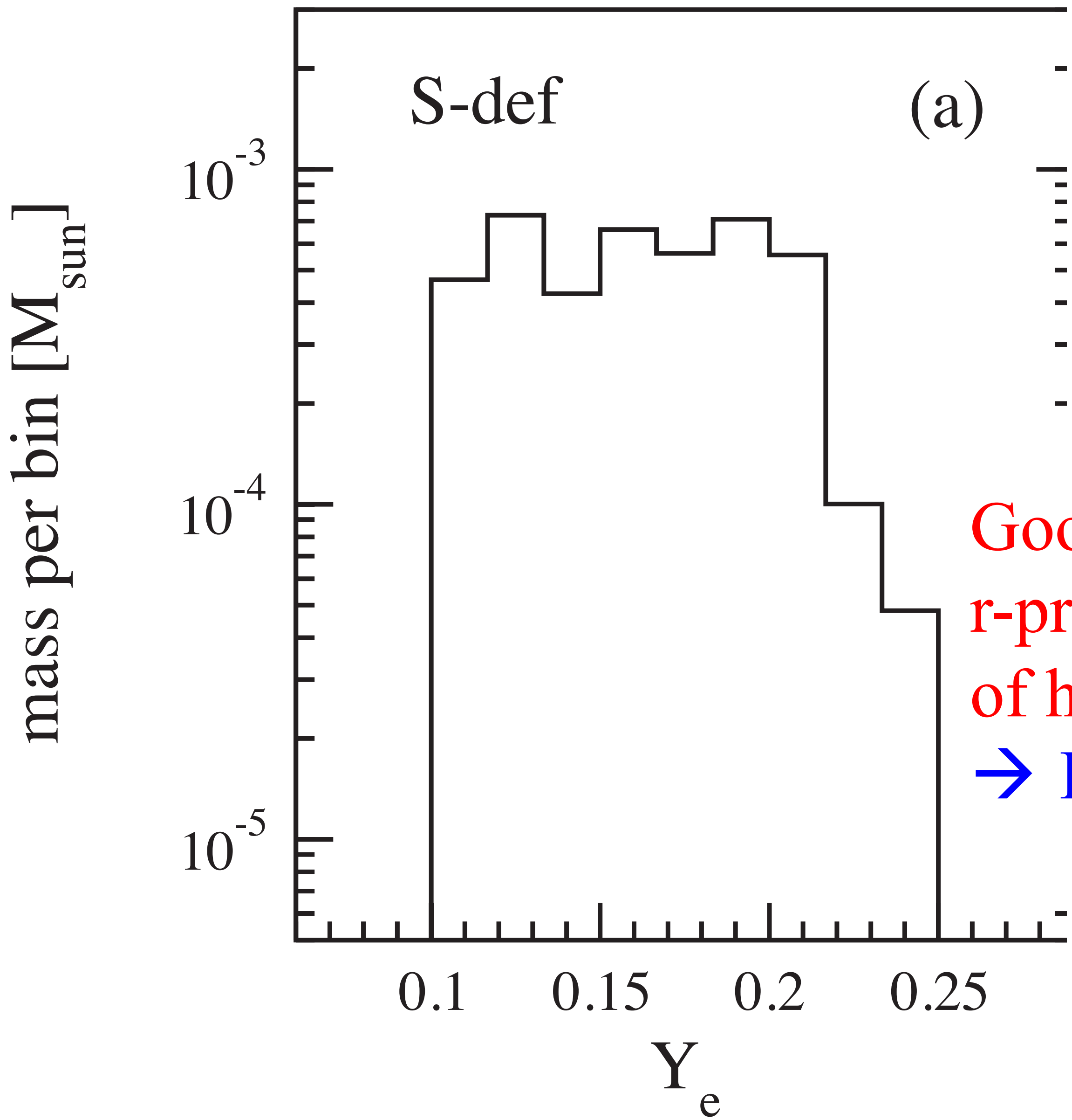
Neutrino irradiated ejection (not-strong effect)
→ Y_e could be increased (small effect on ejecta mass)

Initially high density, high e^- degeneracy
→ **Neutron rich** ($p+e^- \rightarrow n + \nu_e$)



Viscosity is likely to drive evolution:
Viscous ejection of mass 10—30% of torus mass
after temperature decreases below ~ 1 MeV
(neutrino cooling becomes inefficient)
Y_e freeze out → Low Y_e is preserved (good r-process)

Ejecta from BH + disk is likely to have low Y_e



Fernandez & Metzger
MNRAS (2013)

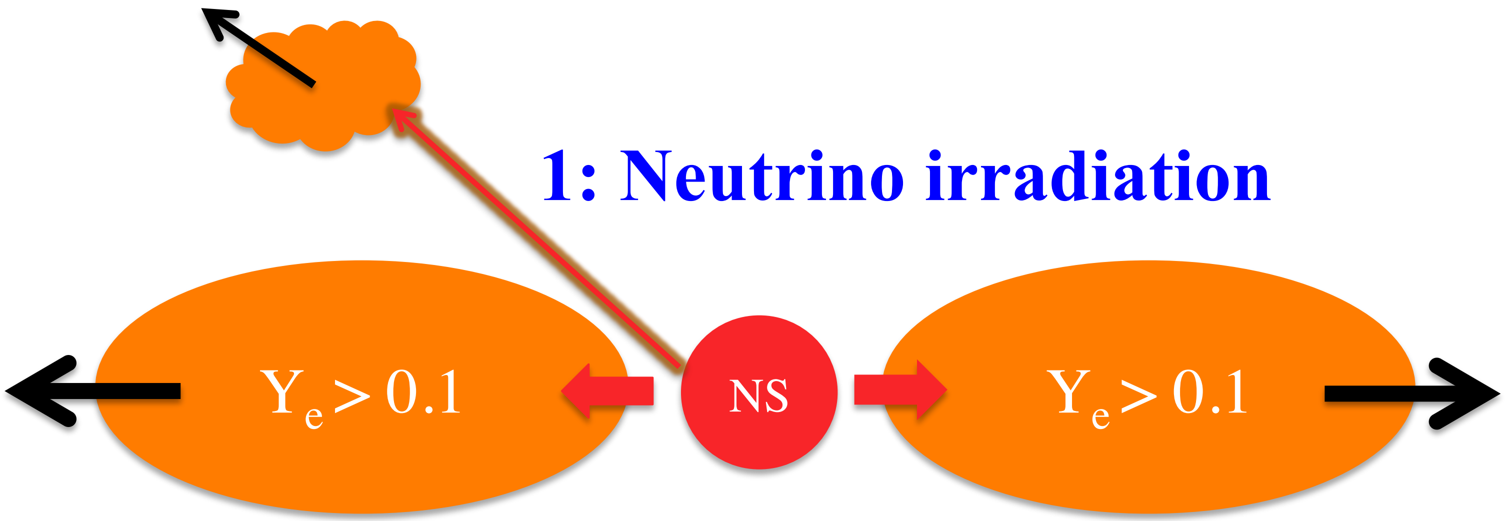
Good for
r-process nucleosynthesis
of heavy elements

→ Large value of opacity
$\kappa \sim 10$ cm^2/g

Long-term viscous ejecta from torus: NS-NS case

- **The presence of a strong neutrino emitter like MNS would change Y_e significantly**

(Metzger-Fernanndez '14, Perego+ '14, Fujibayashi+ '18)

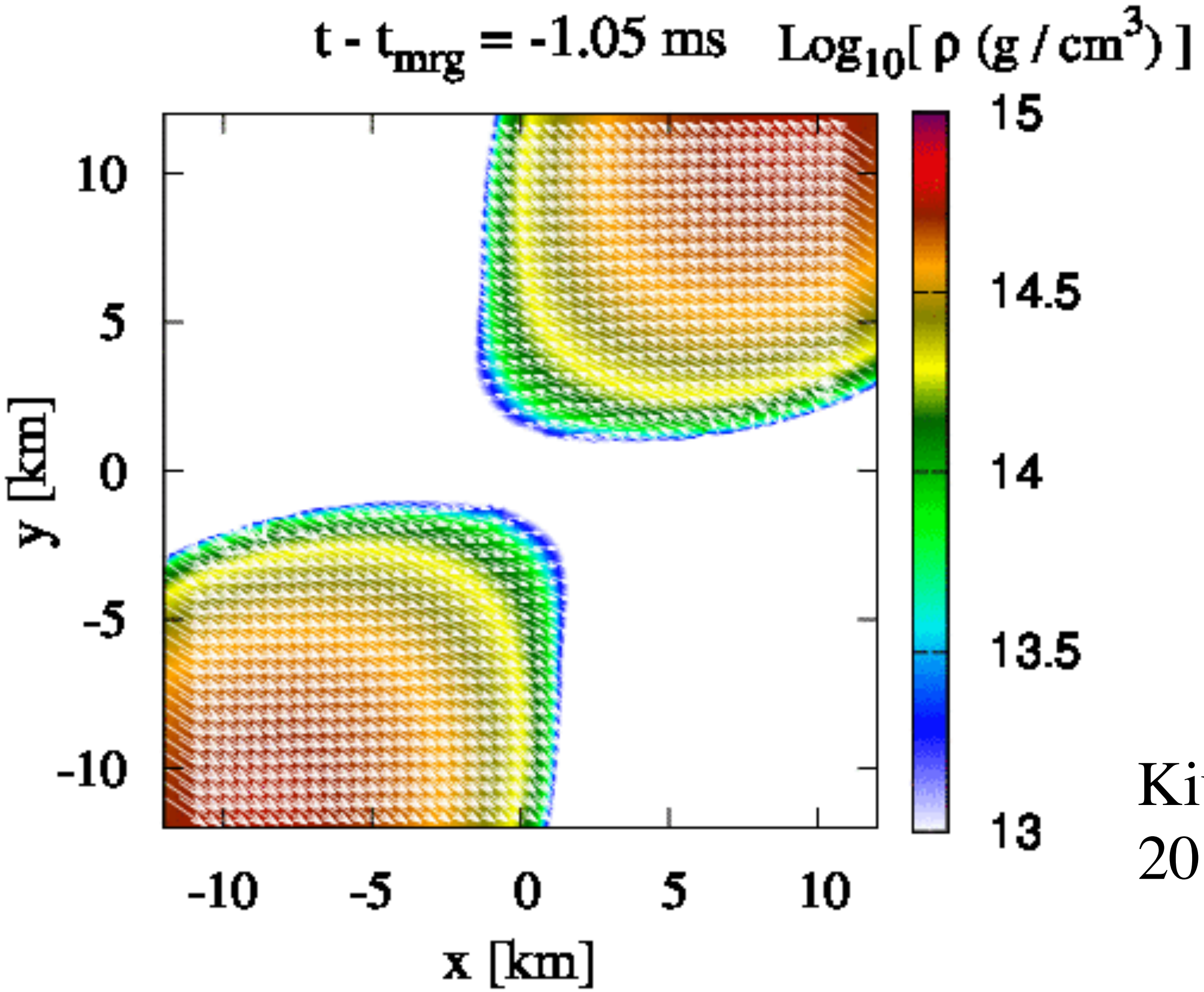


2: NS is not absorber of matter

→ More ejecta

3: MNS in differential rotation can be additional engine

High-resolution GRMHD for NS-NS



Δx=17.5m

Kiuchi et al. 2015

Kelvin-Helmholtz instability:

→ **Magnetic field should be amplified by winding**

→ **Turbulence would be enhanced**

Viscous neutrino radiation hydrodynamics for post-merger MNS

(S. Fujibayashi et al. ApJ 2018)

- Employ covariant & causal GR viscous hydro (following Israel & Steward '79)
- Initial condition: Remnant of NS-NS merger with mass 1.35-1.35$M_{\rm sun}$
- Axial symmetry is assumed (to evolve for seconds)
- Alpha viscosity; $\nu = \alpha_\nu c_s H$ with $\alpha_\nu = 0.04$ and H=10 km
- EOS: DD2 ($R_{\rm NS}$ = 13.2 km)

Viscous time scale of MNS: $\nu = \alpha_\nu c_s H \sim \alpha_\nu c_s R$

$$\tau_\nu \approx \frac{R^2}{\nu} = \frac{1}{\alpha_\nu \Omega}\frac{(R\Omega)}{c_s} \sim 10\left(\frac{\alpha_\nu}{0.02}\right)^{-1}\left(\frac{\Omega}{5000\ \mathrm{rad/s}}\right)^{-1}\frac{(R\Omega)}{c_s}\,\mathrm{ms}$$

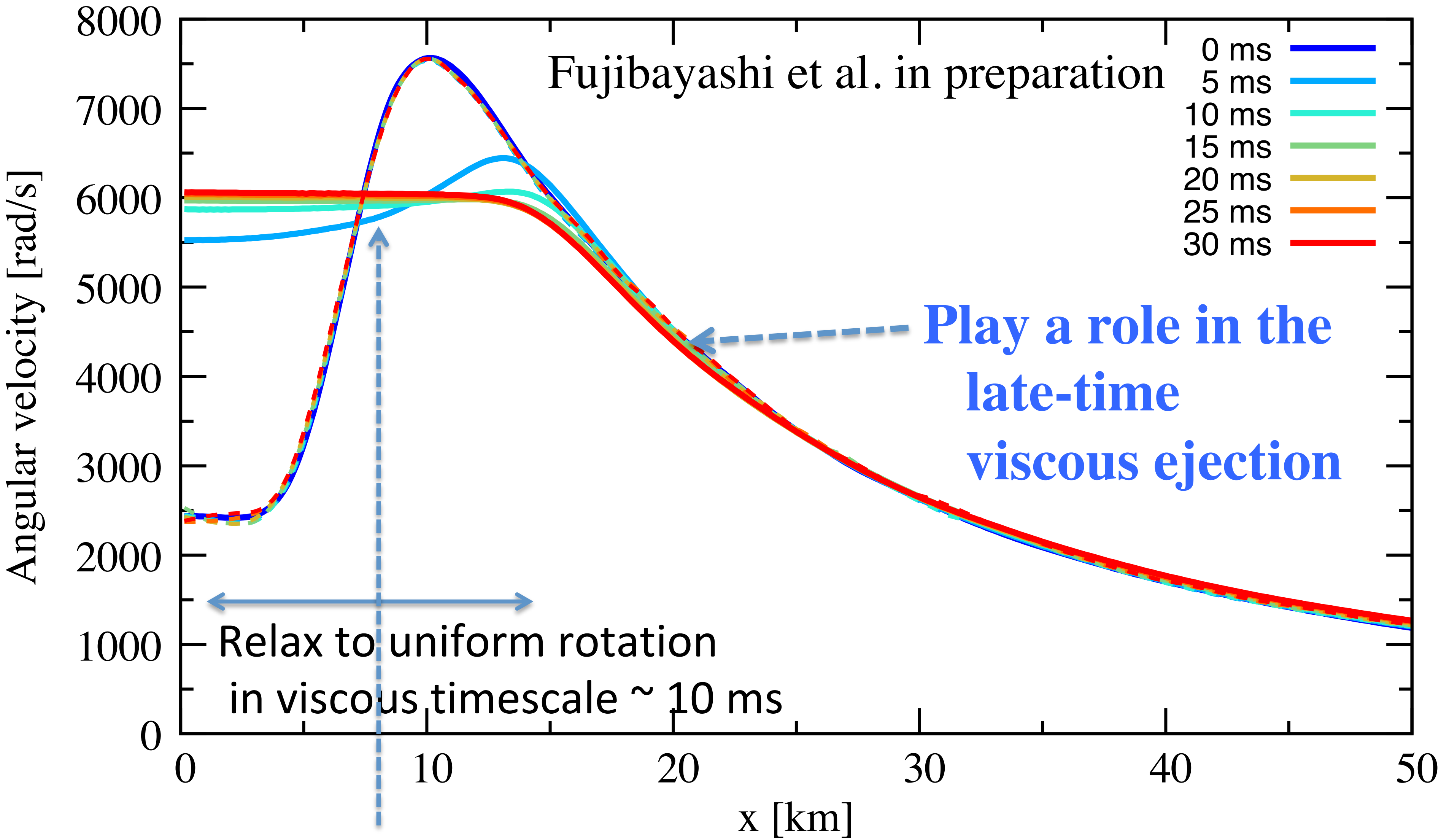
Viscous neutrino radiation hydrodynamics for post-merger MNS

(S. Fujibayashi et al. ApJ 2018)

Wide 1500×1500 km 300×300 km

Density in *x*-*z* plane

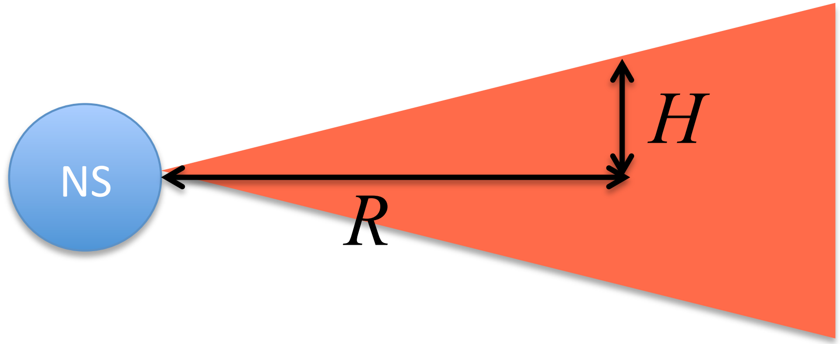
Evolution of angular velocity (α_{vis}=0.01)



Kinetic energy of ~10^{52} erg is released

→ early viscous ejection

Viscous time scale for disks



$$\nu = \alpha_\nu c_s H \sim \alpha_\nu \frac{c_s^2}{\Omega_{disk}}$$

$$\tau_\nu \approx \frac{R_{disk}^2}{\nu} = \frac{1}{\alpha_\nu \Omega_{disk}} \left(\frac{H\Omega_{disk}}{c_s} \right)^2 \left(\frac{R_{disk}}{H} \right)^2$$

$$\sim 0.76 \left(\frac{\alpha_\nu}{0.02} \right)^{-1} \left(\frac{M_{MNS}}{2.6 M_{sun}} \right)^{-1/2} \left(\frac{R_{disk}}{100\ \mathrm{km}} \right)^{3/2} \left(\frac{H\Omega_{disk}}{c_s} \right)^2 \left(\frac{R_{disk}}{3H} \right)^2 \mathrm{sec}$$

~ 1 second evolution

Viscous-rad hydrodynamics for post-merger MNS

(S. Fujibayashi et al. ApJ 2018)

M ~ 0.05 solar mass, *v* ~ 0.05 *c*

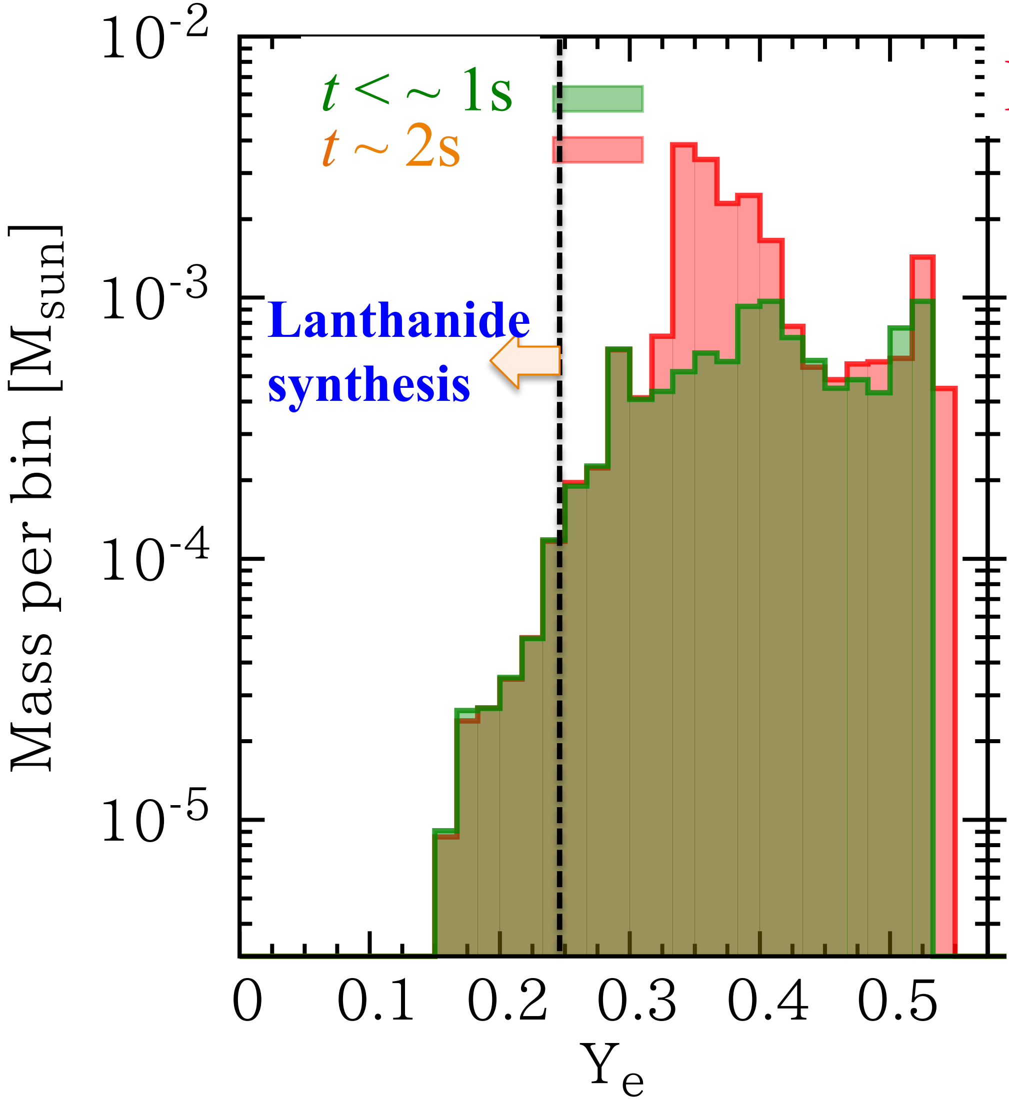
Substantial fraction of disk mass is ejected

Electron fraction is not very low

Electron fraction

Density

Electron fraction distribution by viscosity (total)



Neutrino irradiation is key

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

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

$$\Downarrow$$

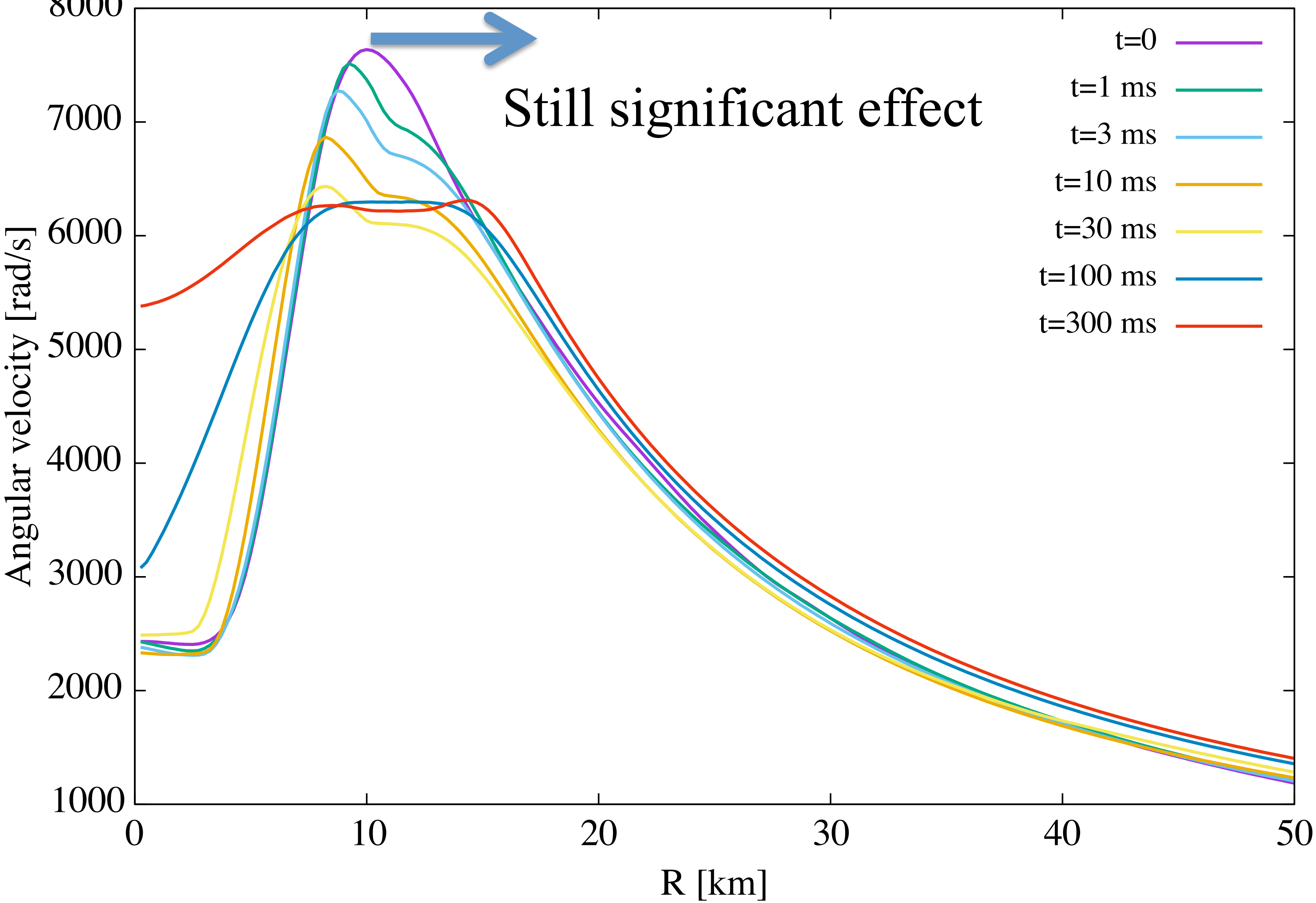
Longterm irradiation

$$\Downarrow$$

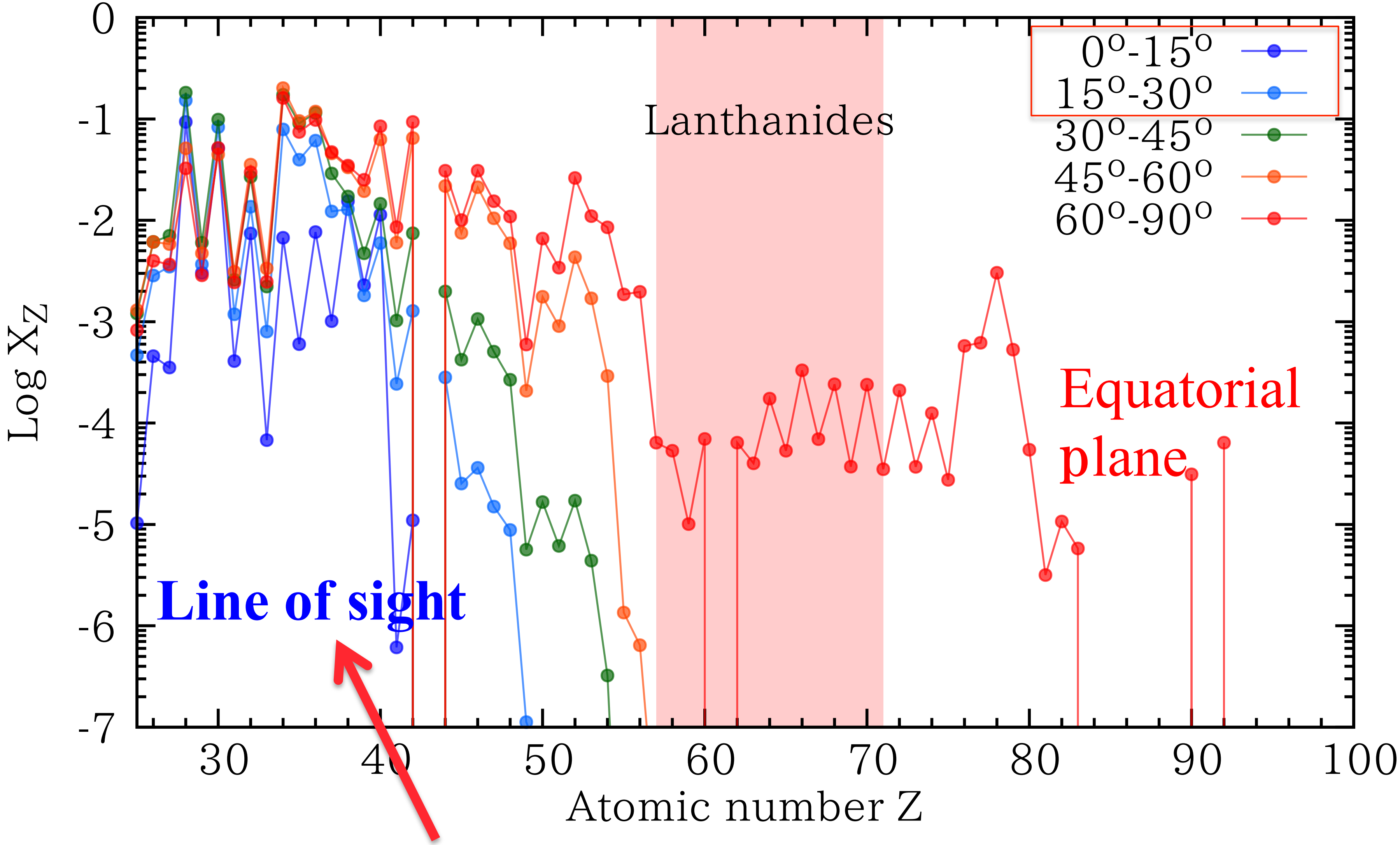
Y_e approaches 1/2

Only ***small lanthanide synthesis*** → $\kappa \sim 0.1\ \mathrm{cm^2/g}$

Viscosity on only for $d\Omega/dR < 0$ (mimicking MRI)



No lanthanide along the line of sight from merger remnant ejecta



Neutrino irradiation from remnant neutron star

Post-merger ejecta properties

◆ **Mass**: M_{eje}

- <u>BH formation case</u>: **~10^{-3}–10^{-2} M_{sun}** (Fernandez & Metzger '13—15, Just+ '15, Siegel-Metzger '17, 18, Fernandez '18)
- <u>MNS formation case</u>: **> 10^{-2} M_{sun}** (Metzger & Fernandez '14, Fujibayashi+ '18)

◆ **Electron fraction: Y_e**

- <u>BH formation case</u>: Y_e **~ 0.1—0.3** → efficient r-process nucleosynthesis & high opacity (κ~10 cm^2/g, red)
- <u>MNS formation case</u>: Y_e **> 0.25** → light r-process, low opacity (κ~0.1 cm^2/g, blue)

◆ **Typical velocity**: < 0.1 c; magnetic wind/MNS viscous effect may enhance up to ~0.2 c

(Siegel & Metzger '17, 18, Fernandez+ '18, Fujibayashi+ '18)

Peak luminosity and peak time for the post-merger ejecta with MNS

$$L_{\max} \sim \underline{\underline{1\times 10^{42}\ \text{ergs/s}}}\left(\frac{M}{0.04M_{\odot}}\right)^{1/2}\left(\frac{v}{0.05c}\right)^{1/2}\left(\frac{\kappa}{0.1\ \text{cm}^2/\text{g}}\right)^{-1/2}\left(\frac{f_{\text{r-proc}}}{10^{-6}}\right)$$

bright

$$\text{at} \quad t \sim \underline{\underline{1\ \text{days}}}\left(\frac{M}{0.04M_{\odot}}\right)^{1/2}\left(\frac{v}{0.05c}\right)^{-1/2}\left(\frac{\kappa}{0.1\ \text{cm}^2/\text{g}}\right)^{1/2}$$

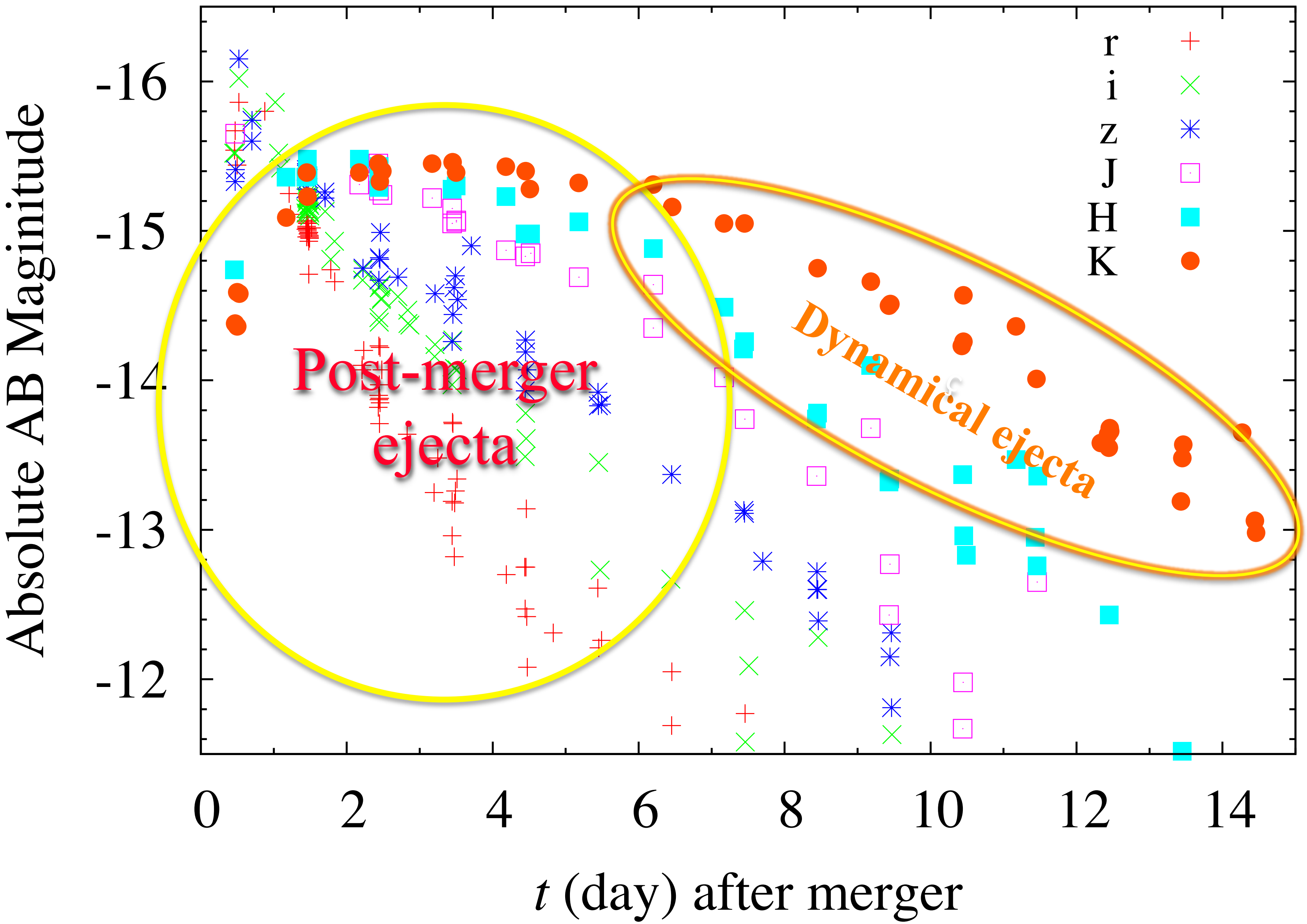
fast

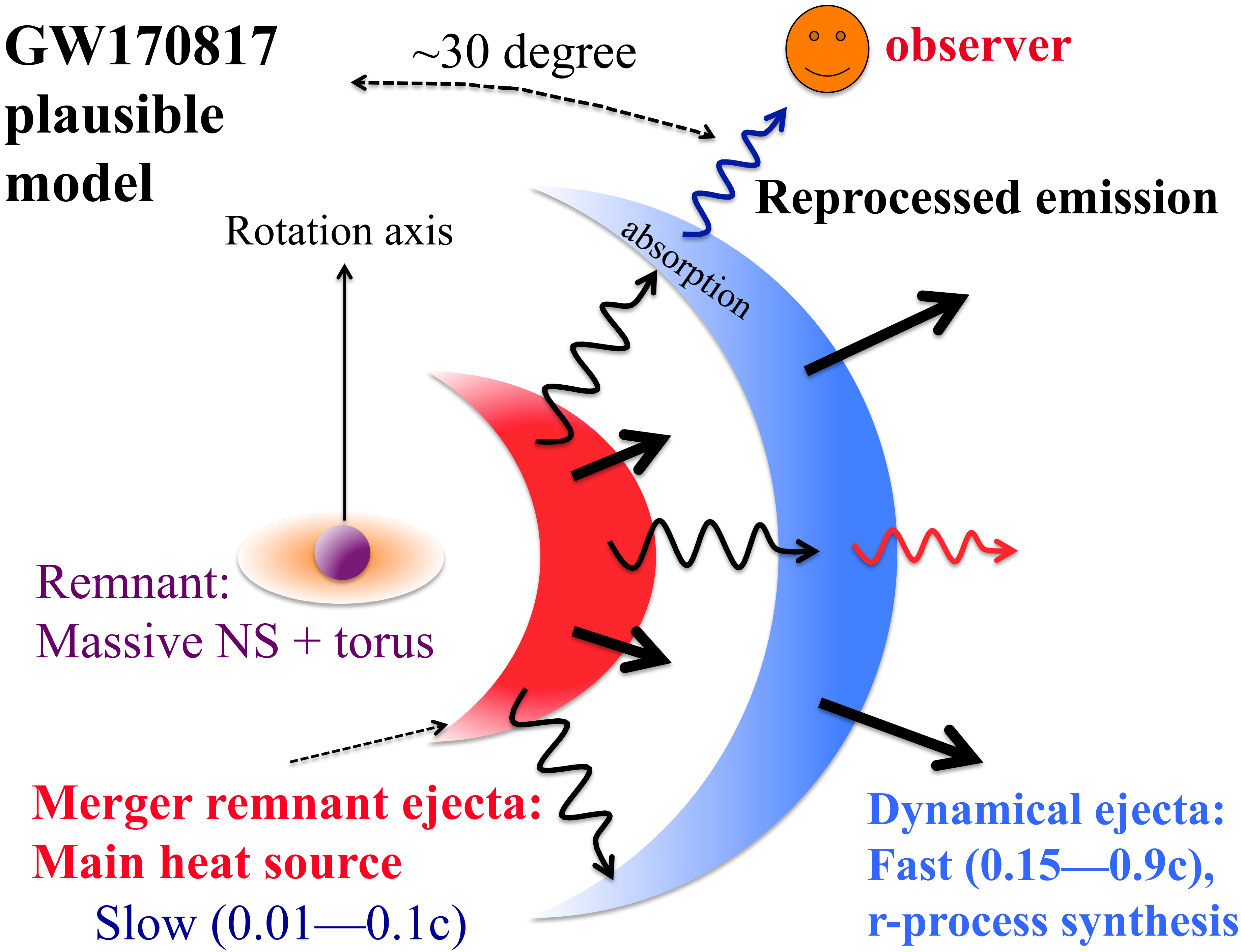
$$\Downarrow$$

$$L_{\max} \sim 10^{42}\ \text{ergs/s} \quad \& \quad t \sim 1\ \text{days} \ \text{ for } \ M \sim 4\times 10^{-2} M_{\odot}$$

Shine (peak) at one day

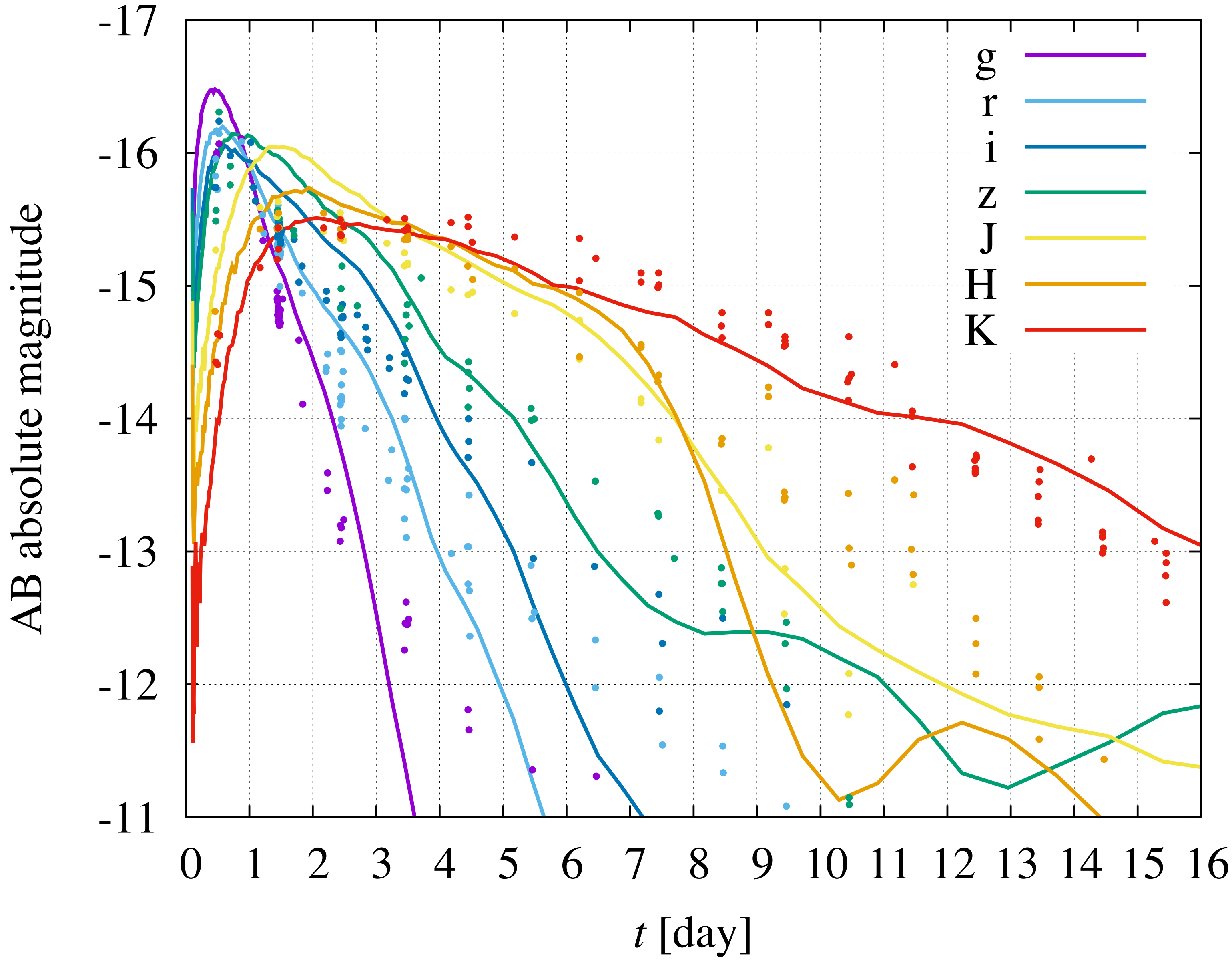
Two components model for GW170817



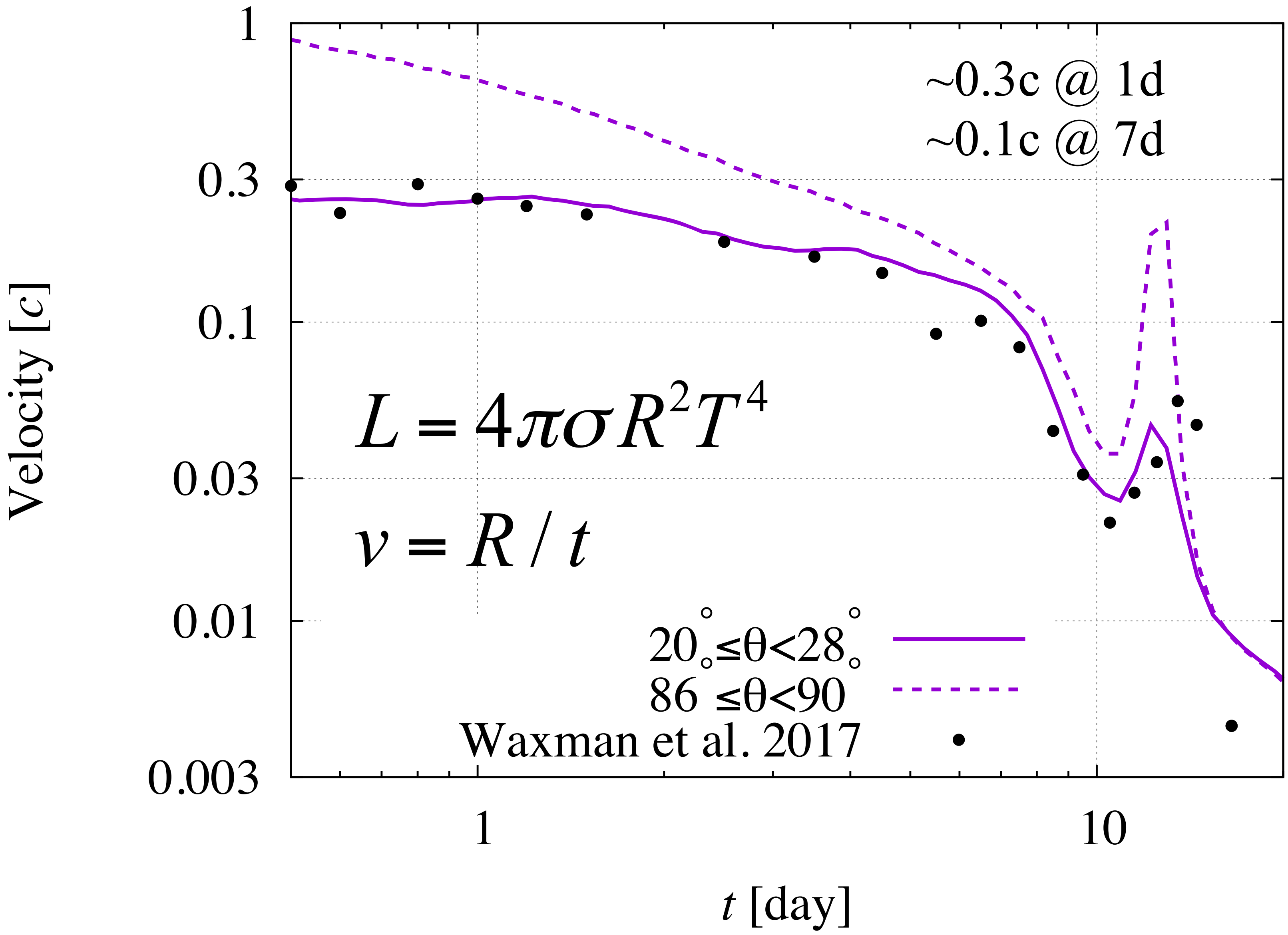

GW170817
plausible
model
~30 degree
observer
Reprocessed emission
Rotation axis
absorption
Remnant:
Massive NS + torus
Merger remnant ejecta:
Main heat source
Slow (0.01—0.1c)
Dynamical ejecta:
Fast (0.15—0.9c),
r-process synthesis

Radiation transfer simulation: good agreement

(K. Kawaguchi, M. Tanaka, MS, ApJL 2018)



Looks fast (apparently)



Peak luminosity and peak time for the post-merger ejecta with BH

$$L_{\max} \sim \underline{\underline{1\times 10^{41}\ \text{ergs/s}}} \left(\frac{M}{0.04 M_\odot}\right)^{1/2} \left(\frac{v}{0.05c}\right)^{1/2} \left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{-1/2} \left(\frac{f_{\text{r-proc}}}{10^{-6}}\right)$$

Not bright

$$\text{at} \qquad t \sim \underline{\underline{10\ \text{days}}} \left(\frac{M}{0.04 M_\odot}\right)^{1/2} \left(\frac{v}{0.05c}\right)^{-1/2} \left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{1/2}$$

late

$$\Downarrow$$

$$L_{\max} \sim 10^{41}\ \text{ergs/s} \quad \& \quad t \sim 10\ \text{days} \ \text{ for } \ M \sim 4\times 10^{-2} M_\odot$$

- **Shine (peak) at 10 day**
- **Red**

What will be the next event ?

Mass & Y_e could be varied both for dynamical and post-merger ejecta

Dynamical ejecta properties in NR

- **Mass:** M_{eje}

- NS-NS: **~10^{-4}—10^{-2} M_{sun}** depending on total mass, mass ratio, & NS radius (Hotokezaka+ 13, Bauswein+ 13, Sekiguchi+ 15,16, Radice+ 16, Lehner+ 15,16…….many others)

- BH-NS: **0—0.1 M_{sun}** depending on mass, spin, NS radius: **High BH spin is the keys** (Foucart+ 13-15, Kyutoku+ '15, 18)

- **Electron fraction:** Y_e

- NS-NS: MNS formation case, **Y_e=0.1—0.5**
  For prompt BH formation case, **Y_e < ~0.1**

$\kappa \sim 10\ \mathrm{cm}^2/\mathrm{g}$

- BH-NS: **Y_e < 0.1** (Foucart+ '13-18, Kyutoku+ '18)

- **Typical velocity**: 0.15—0.25 c; max could be ~ 0.8 c

Post-merger ejecta properties

◆ **Mass**: M_{eje}

- <u>BH formation case</u>: **$\sim 10^{-3}$–10^{-2} M_{sun}** (Fernandez & Metzger '13—15, Just+ '15, Siegel-Metzger '17, 18, Fernandez '18)
- <u>MNS formation case</u>: **$> 10^{-2}$ M_{sun}** (Metzger & Fernandez '14, Fujibayashi+ '18)

◆ **Electron fraction**: Y_e

- <u>BH formation case</u>: **$Y_e \sim 0.1$—0.3** → efficient r-process nucleosynthesis & high opacity ($\kappa \sim 10$ cm^2/g, red)
- <u>MNS formation case</u>: **$Y_e > 0.25$** → light r-process, low opacity ($\kappa \sim 0.1$ cm^2/g, blue)

◆ **Typical velocity**: < 0.1 c; magnetic wind/MNS viscous effect may enhance up to ~0.2 c
(Siegel & Metzger '17, 18, Fernandez+ '18, Fujibayashi+ '18)

V Next events ?

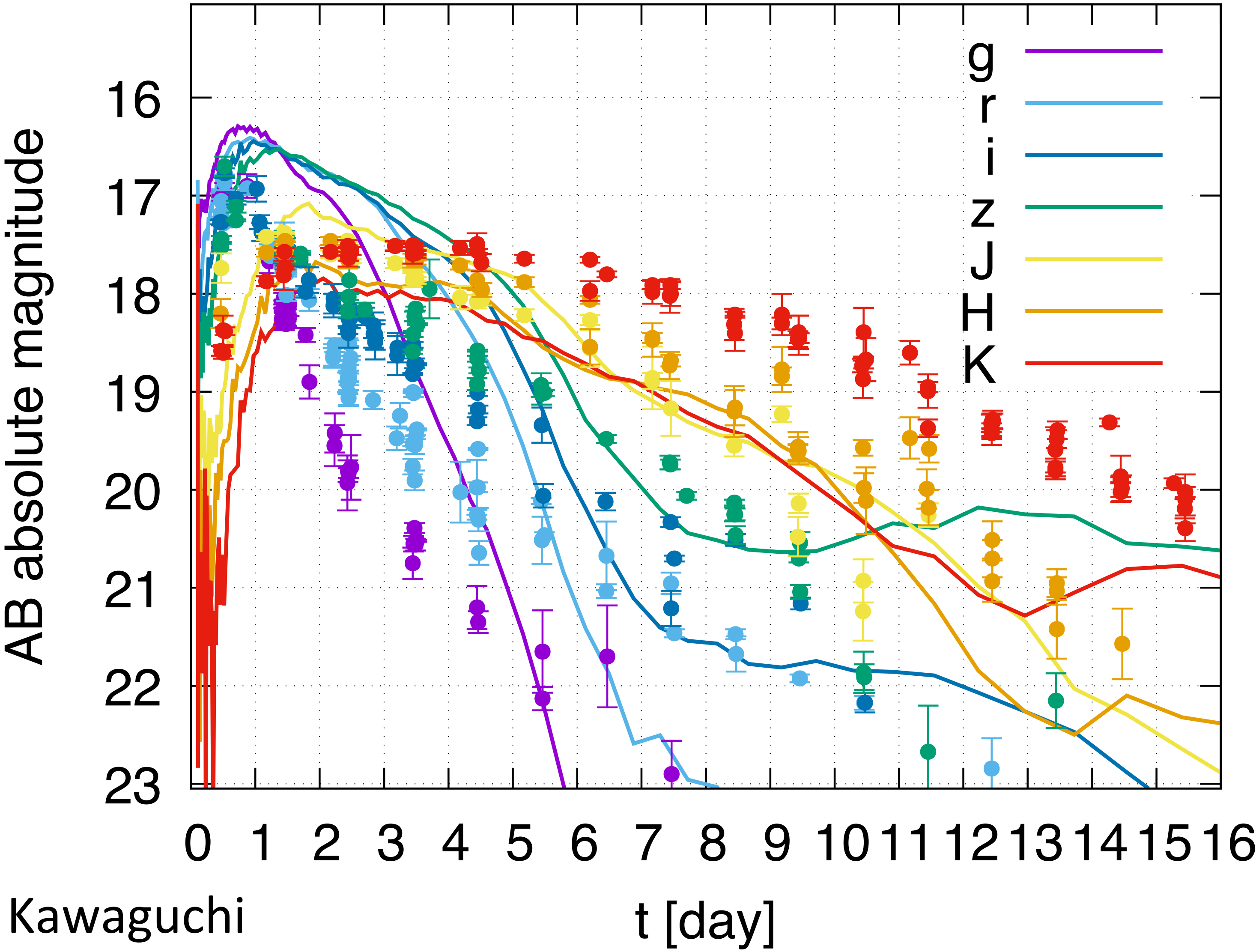
	Dynamical ejection	Post-merger ejection
1. Low-mass NS-NS → long-lived MNS	$M \sim 10^{-3}$–$10^{-2.5}$ M_{sun} $Y_e \sim 0.05$—0.5	$M \sim 10^{-2}$ –10^{-1} M_{sun} $Y_e \sim 0.3$—0.5
2. NS-NS→HMNS (e.g., GW170817)	$M \sim 10^{-3}$ –10^{-2} M_{sun} $Y_e \sim 0.05$—0.5	$M > 10^{-2}$ M_{sun} $Y_e \sim 0.2$—0.5
3. NS-NS → BH (assume not very asymmetric)	$M < \sim 10^{-3}$ M_{sun} $Y_e <\sim 0.1$	$M < 10^{-3}$ M_{sun} $Y_e <\sim 0.1$
4. BH-NS with tidal disruption and/or asymmetric NS-NS	$M \sim 10^{-3}$ –$10^{-1.5}$ M_{sun} $Y_e <\sim 0.1$	$M \sim 10^{-3}$—$10^{-1.5}$ M_{sun} $Y_e \sim 0.1$—0.25

V Prediction for next events

	Dynamical ejection	Post-merger ejection
1. Low-mass NS-NS → long-lived MNS	$M \sim 10^{-3}$–$10^{-2.5}\ M_{sun}$ $Y_e \sim 0.05$—0.5 Red, not luminous	$M \sim 10^{-2}$ –$10^{-1}\ M_{sun}$ $Y_e \sim 0.3$—0.5 Blue, **very luminous**
2. NS-NS→HMNS (e.g., GW170817)	$M \sim 10^{-3}$ –$10^{-2}\ M_{sun}$ $Y_e \sim 0.05$—0.5	$M > 10^{-2}\ M_{sun}$ $Y_e \sim 0.2$—0.5
3. NS-NS → BH (assume not very asymmetric)	$M < \sim 10^{-3}\ M_{sun}$ $Y_e <\sim 0.1$	$M < 10^{-3}\ M_{sun}$ $Y_e <\sim 0.1$
4. BH-NS with tidal disruption and/or asymmetric NS-NS	$M \sim 10^{-3}$ –$10^{-1.5}\ M_{sun}$ $Y_e <\sim 0.1$	$M \sim 10^{-3}$—$10^{-1.5}\ M_{sun}$ $Y_e \sim 0.1$—0.25

$M_{\rm dyn}$= 0.001$M_{\rm sun}$, $M_{\rm post\text{-}merger}$=0.05$M_{\rm sun}$

D=40 Mpc, 0°≤θ<20°

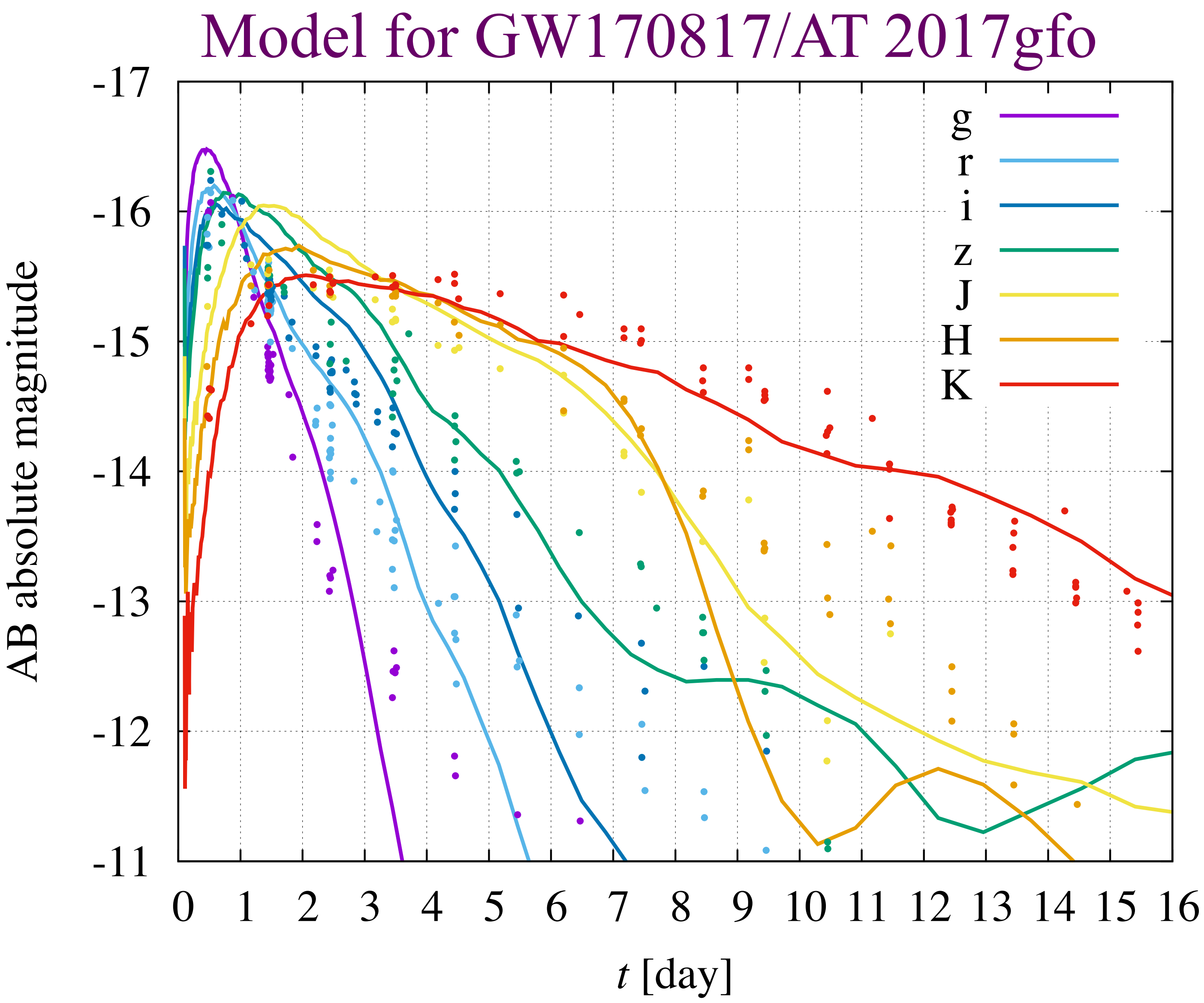


By K. Kawaguchi

V Prediction for next events

	Dynamical ejection	Post-merger ejection
1. Low-mass NS-NS → long-lived MNS	$M \sim 10^{-3}$–$10^{-2.5}$ M_{sun} $Y_e \sim 0.05$—0.5 Red, not luminous	$M \sim 10^{-2}$ –10^{-1} M_{sun} $Y_e \sim 0.3$—0.5 Blue, **very luminous**
2. NS-NS→HMNS (e.g., GW170817)	$M \sim 10^{-3}$ –10^{-2} M_{sun} $Y_e \sim 0.05$—0.5 Late Red, **luminous**	$M > 10^{-2}$ M_{sun} $Y_e \sim 0.2$—0.5 Early Blue, **luminous**
3. NS-NS → BH (assume not very asymmetric)	$M < \sim 10^{-3}$ M_{sun} $Y_e <\sim 0.1$	$M < 10^{-3}$ M_{sun} $Y_e <\sim 0.1$
4. BH-NS with tidal disruption and/or asymmetric NS-NS	$M \sim 10^{-3}$ –$10^{-1.5}$ M_{sun} $Y_e <\sim 0.1$	$M \sim 10^{-3}$—$10^{-1.5}$ M_{sun} $Y_e \sim 0.1$—0.25

$M_{\rm dyn}= 0.01M_{\rm sun}$, $M_{\rm post\text{-}merger}=0.03M_{\rm sun}$

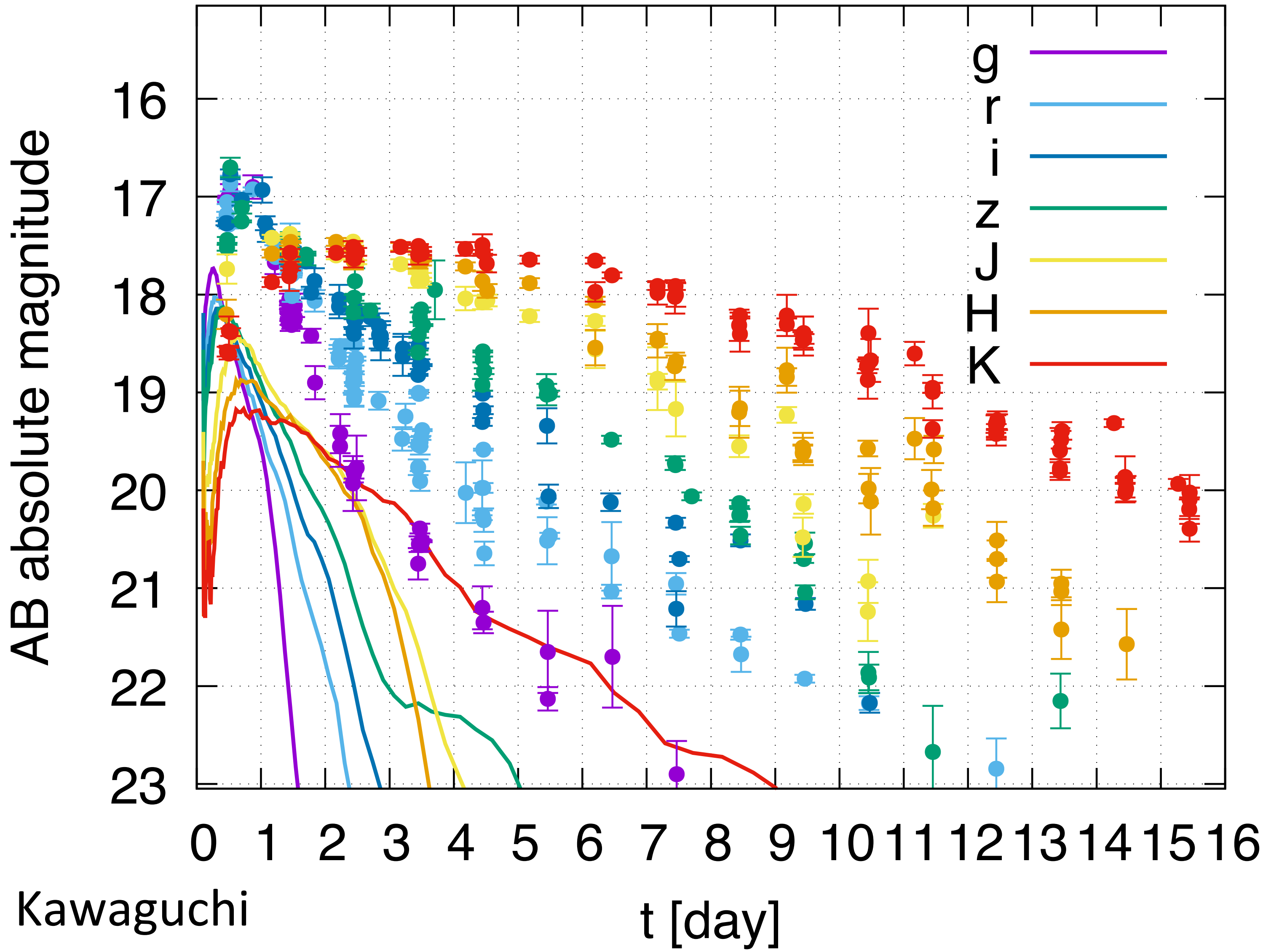


V Prediction for next events

	Dynamical ejection	Post-merger ejection
1. Low-mass NS-NS → long-lived MNS	$M \sim 10^{-3}$–$10^{-2.5}$ M_{sun} $Y_e \sim 0.05$—0.5 Red, not luminous	$M \sim 10^{-2}$ –10^{-1} M_{sun} $Y_e \sim 0.3$—0.5 Blue, **very luminous**
2. NS-NS→HMNS (e.g., GW170817)	$M \sim 10^{-3}$ –10^{-2} M_{sun} $Y_e \sim 0.05$—0.5 Late Red, **luminous**	$M > 10^{-2}$ M_{sun} $Y_e \sim 0.2$—0.5 Early Blue, **luminous**
3. NS-NS → BH (assume not very asymmetric)	$M < \sim 10^{-3}$ M_{sun} $Y_e <\sim 0.1$ Faint	$M < 10^{-3}$ M_{sun} $Y_e <\sim 0.1$ Faint
4. BH-NS with tidal disruption and/or asymmetric NS-NS	$M \sim 10^{-3}$ –$10^{-1.5}$ M_{sun} $Y_e <\sim 0.1$	$M \sim 10^{-3}$—$10^{-1.5}$ M_{sun} $Y_e \sim 0.1$—0.25

$M_{\text{dyn}}= 0.001M_{\text{sun}}, M_{\text{post-merger}}=0.001M_{\text{sun}}$

D=40 Mpc, 0°≤θ<20°



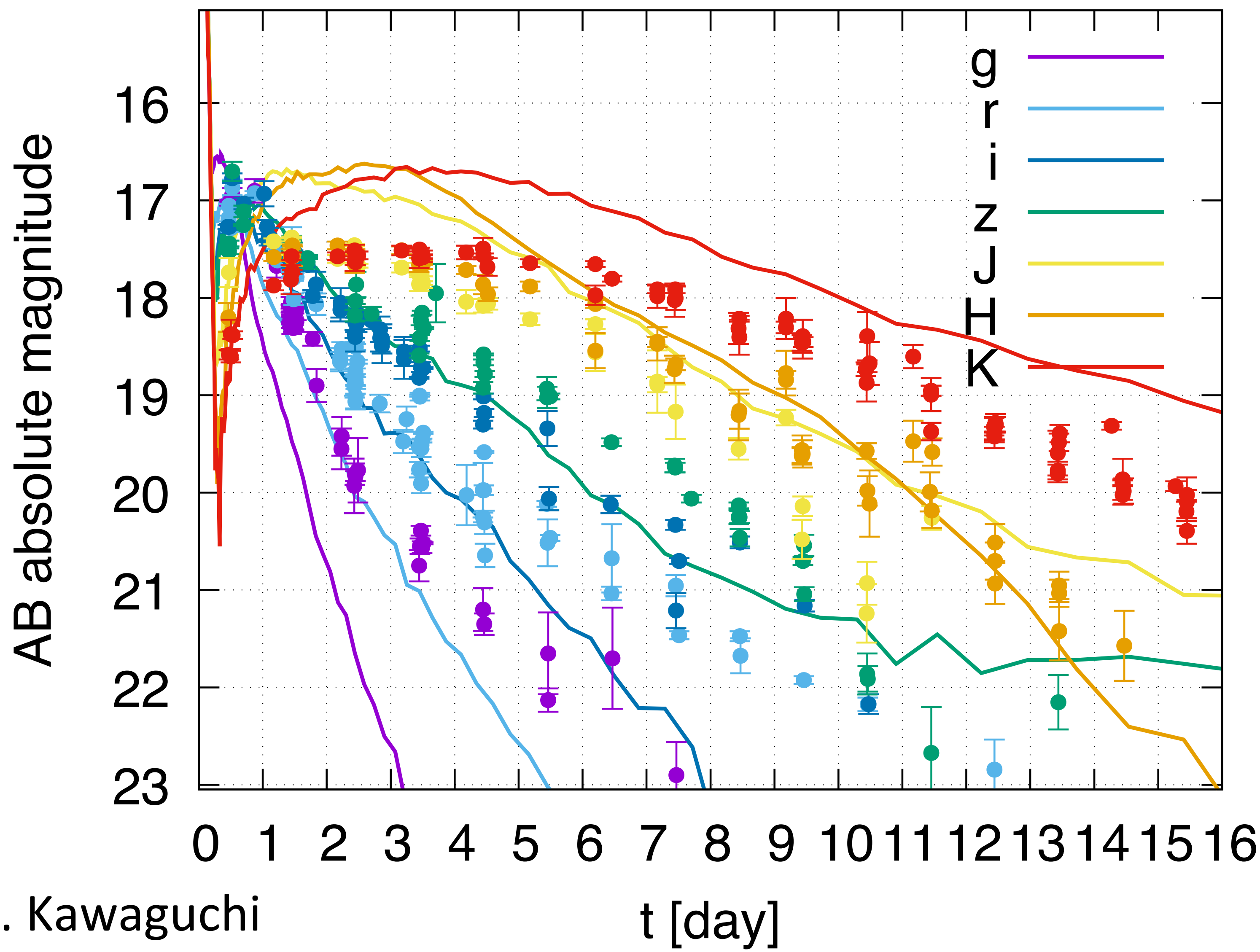
By K. Kawaguchi

V Prediction for next events

	Dynamical ejection	Post-merger ejection
1. Low-mass NS-NS → long-lived MNS	$M \sim 10^{-3}$–$10^{-2.5}\ M_{sun}$ $Y_e \sim 0.05$—0.5 Red, not luminous	$M \sim 10^{-2}$ –$10^{-1}\ M_{sun}$ $Y_e \sim 0.3$—0.5 Blue, **very luminous**
2. NS-NS→HMNS (e.g., GW170817)	$M \sim 10^{-3}$ –$10^{-2}\ M_{sun}$ $Y_e \sim 0.05$—0.5 Late Red, **luminous**	$M > 10^{-2}\ M_{sun}$ $Y_e \sim 0.2$—0.5 Early Blue, **luminous**
3. NS-NS → BH (assume not very asymmetric)	$M < \sim 10^{-3}\ M_{sun}$ $Y_e <\sim 0.1$ Faint Red	$M < 10^{-3}\ M_{sun}$ $Y_e <\sim 0.1$ Faint Red
4. BH-NS with tidal disruption and/or asymmetric NS-NS	$M \sim 10^{-3}$ –$10^{-1.5}\ M_{sun}$ $Y_e <\sim 0.1$ Late Red, Could be luminous	$M \sim 10^{-3}$—$10^{-1.5}\ M_{sun}$ $Y_e \sim 0.1$—0.25 Late Red, Could be luminous

$M_{\rm dyn}= 0.01M_{\rm sun}$, $M_{\rm post\text{-}merger}=0.01M_{\rm sun}$

D=40 Mpc, $0^\circ \le \theta < 20^\circ$



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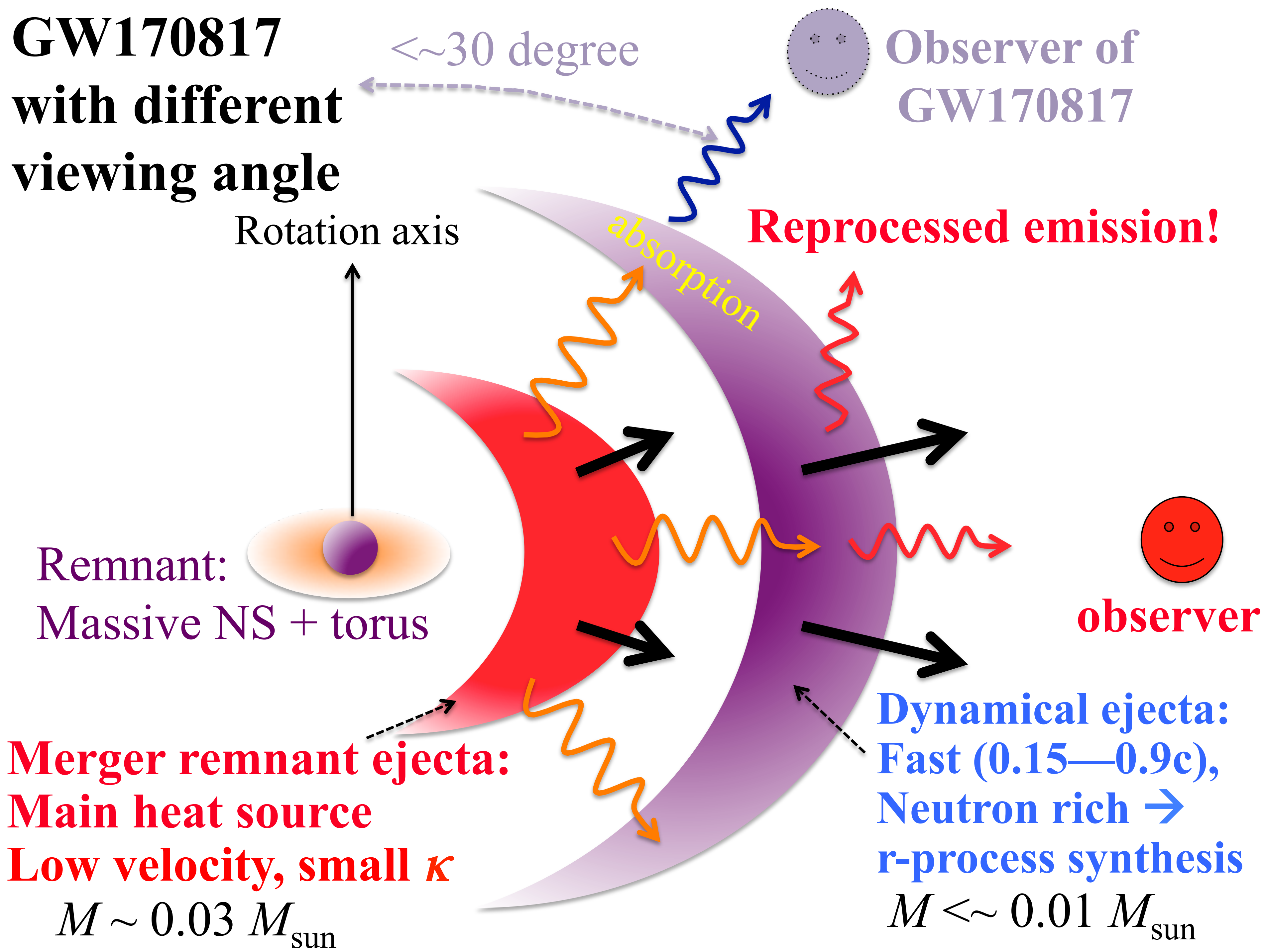
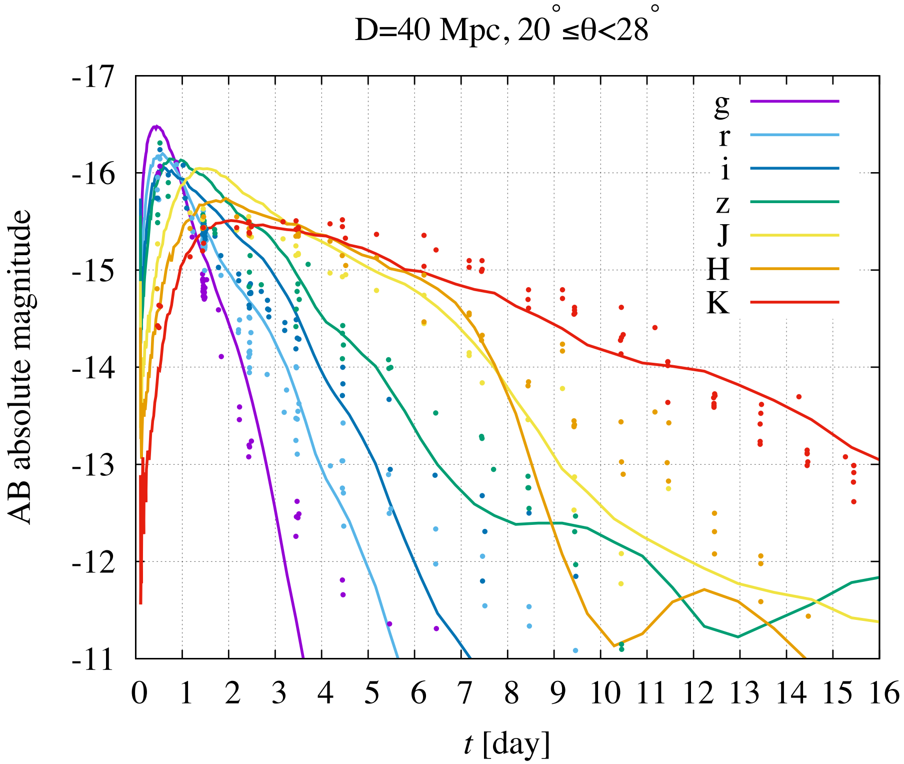
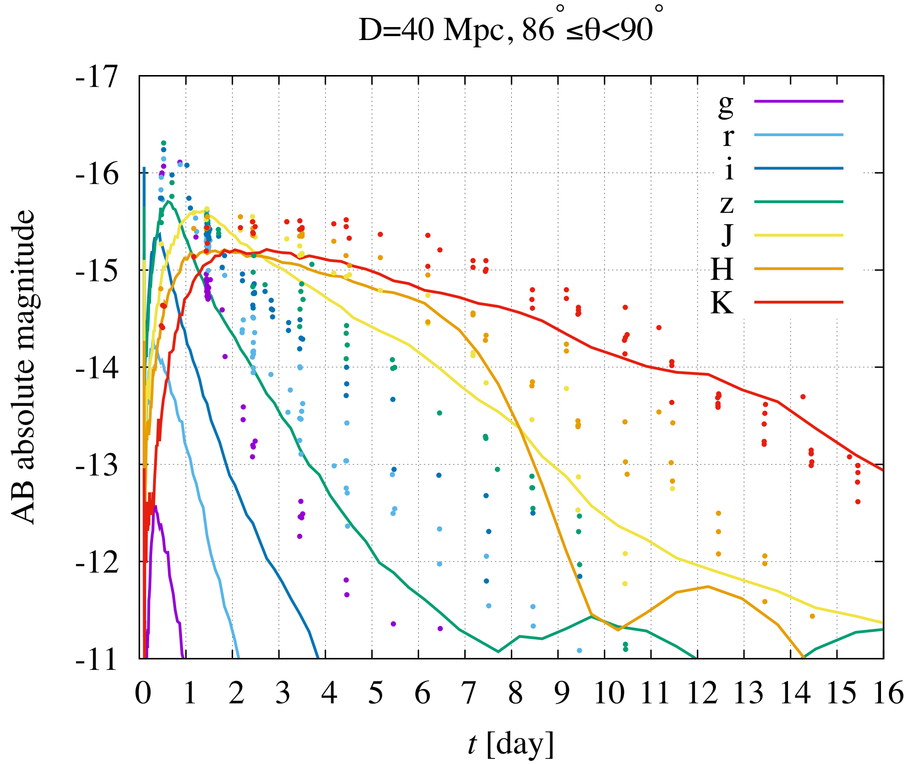

GW170817
with different
viewing angle
<~30 degree
Observer of
GW170817
Rotation axis
absorption
Reprocessed emission!
Remnant:
Massive NS + torus
observer
Merger remnant ejecta:
Main heat source
Low velocity, small κ
$M \sim 0.03\ M_{sun}$
Dynamical ejecta:
Fast (0.15—0.9c),
Neutron rich →
r-process synthesis
M <~ $0.01\ M_{sun}$

Viewing angle dependence



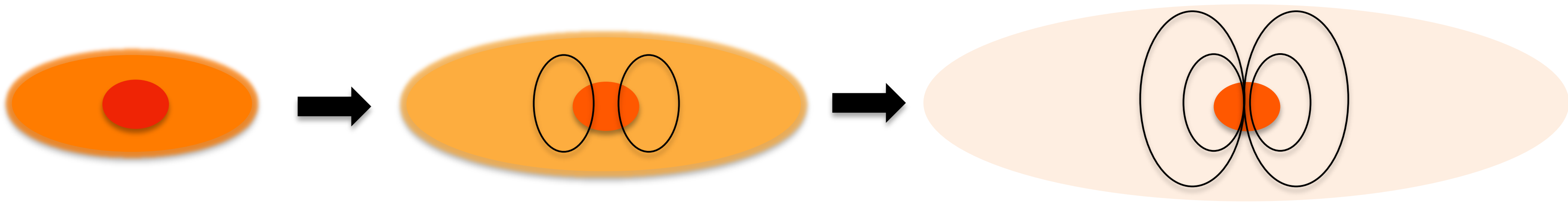


From ~ 25 degree
Blue + Red

From ~ 90 degree
Dimmer blue + Red

Hopefully, next several events will give us information on whether our understanding is correct or not !

Unsolved issue: longterm evolution of massive neutron star (> 10 seconds)



$\rho_{disk} \sim 10^{11}$ g/cm^3 → $\rho_{disk} \sim 10^8$ g/cm^3 → $\rho_{disk} <\sim 10^3$ g/cm^3 ?

Viscous evolution
$\tau < \sim 10$ s ?

Propeller evolution
$\tau \sim 10$—100 s ?
Angular momentum transport
from MNS to disk
by magnetic torque
through winding
→ Disk is ejected ?

Magnetic dipole radiation
$\tau > \sim 100$ s ?
Angular momentum loss
by EM radiation

P_{rot}=1 ms → R_{corot}=300km
Force free for $r < R_{corot}$

Magnetar-engined ejecta

- Rotational kinetic energy and luminosity by dipole radiation

$$T_{\rm rot} \approx 1.1\times10^{53}\ \text{ergs}\left(\frac{M_{\rm MNS}}{2.5M_\odot}\right)\left(\frac{R}{15\ \text{km}}\right)^2\left(\frac{\Omega}{7000\ \text{rad/s}}\right)^2$$

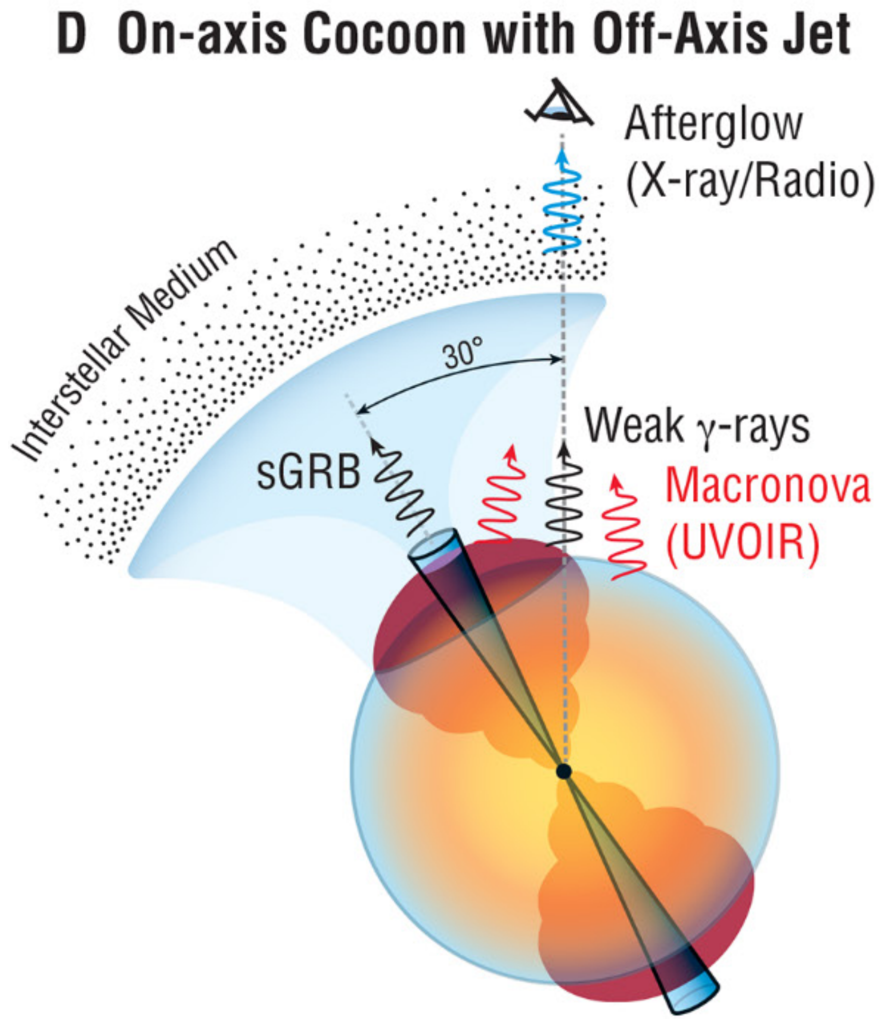
$$L_{\rm mag} \approx 1.7\times10^{50}\ \text{ergs/s}\left(\frac{B_P}{10^{15}\text{G}}\right)^2\left(\frac{R}{15\ \text{km}}\right)^6\left(\frac{\Omega}{7000\ \text{rad/s}}\right)^4$$

$$\Rightarrow \tau \approx \frac{T_{\rm rot}}{L_{\rm mag}} \approx 650\ \text{s}\left(\frac{B_P}{10^{15}\text{G}}\right)^{-2}\left(\frac{M_{\rm MNS}}{2.5M_\odot}\right)\left(\frac{R}{15\ \text{km}}\right)^{-4}\left(\frac{\Omega}{7000\ \text{rad/s}}\right)^{-2}$$

- This luminosity could accelerate the ejecta to be relativistic speed because $T_{\rm rot}$ is comparable to $M_{\rm eje}c^2$; but details are not known

How GRB is launched and what is the effect to kilonova ?

- GRB is likely to be launched after dynamical ejecta
- Cocoon could affect the ejecta motion
- Cocoon could shine in the early time in UV and optical band



Kasliwal et al science 2017