A Variety of Tidal Disruption Events of a WD by a BH

Kojiro Kawana (U. Tokyo)

Collaborators

Ataru Tanikawa, Naoki Yoshida (U. Tokyo)

MNRAS accepted, (2018)

Tidal Disruption Events (TDEs)

When a star passes close to a BH, if

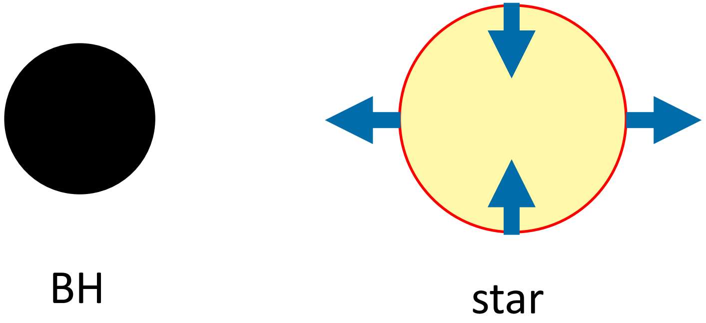
tidal force $$\frac{GM_{\rm BH}R_\star}{r^3} \gtrsim \frac{GM_\star}{R_\star^2}$$ star's self gravity,

the star will be disrupted.

Basic quantities of TDE

- Schwarzschild radius R_S
- Tidal radius $R_t = R_* \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3}$
- Penetration factor $\beta := R_t/R_p$

(R_p: the pericenter radius)



Tidal Disruption Events (TDEs)

When a star passes close to a BH, if

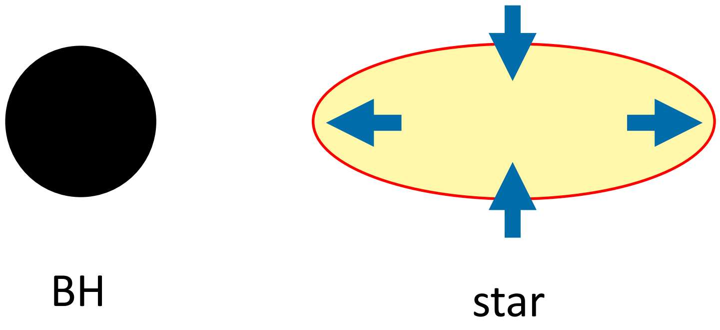
tidal force $\dfrac{GM_{\mathrm{BH}}R_\star}{r^3} \gtrsim \dfrac{GM_\star}{R_\star^2}$ star's self gravity,

the star will be disrupted.

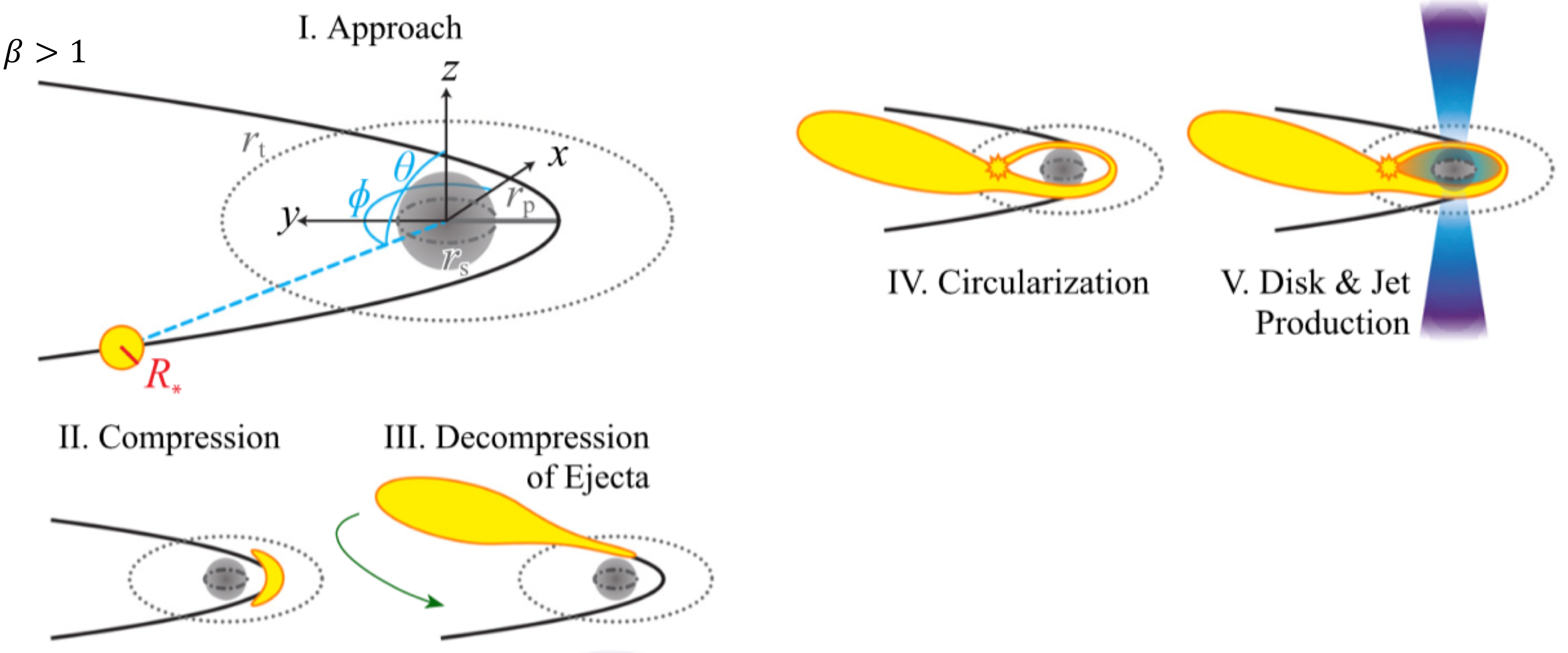
Basic quantities of TDE

- Schwarzschild radius R_S
- Tidal radius $R_t = R_* \left(\dfrac{M_{\mathrm{BH}}}{M_*}\right)^{1/3}$
- Penetration factor $\beta := R_t / R_p$

(R_p: the pericenter radius)



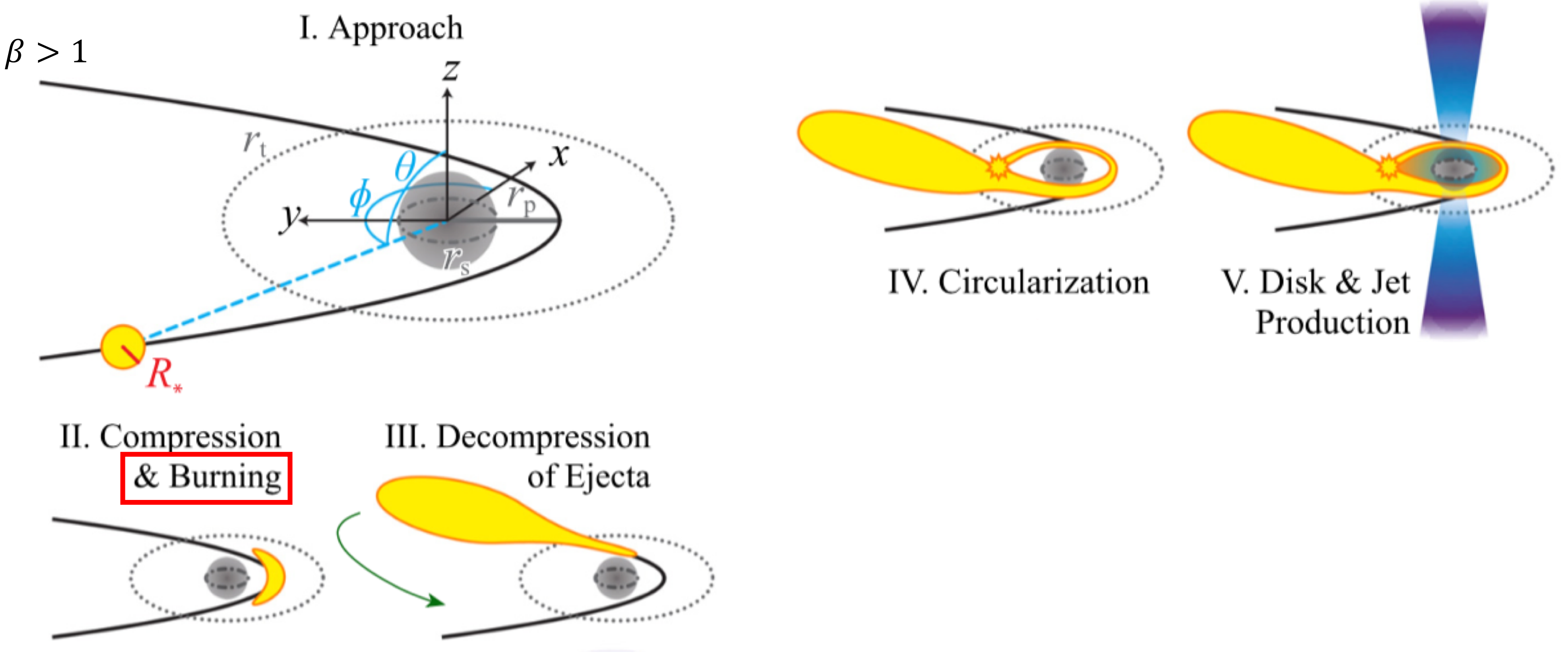
Sequence of TDE



$\beta > 1$

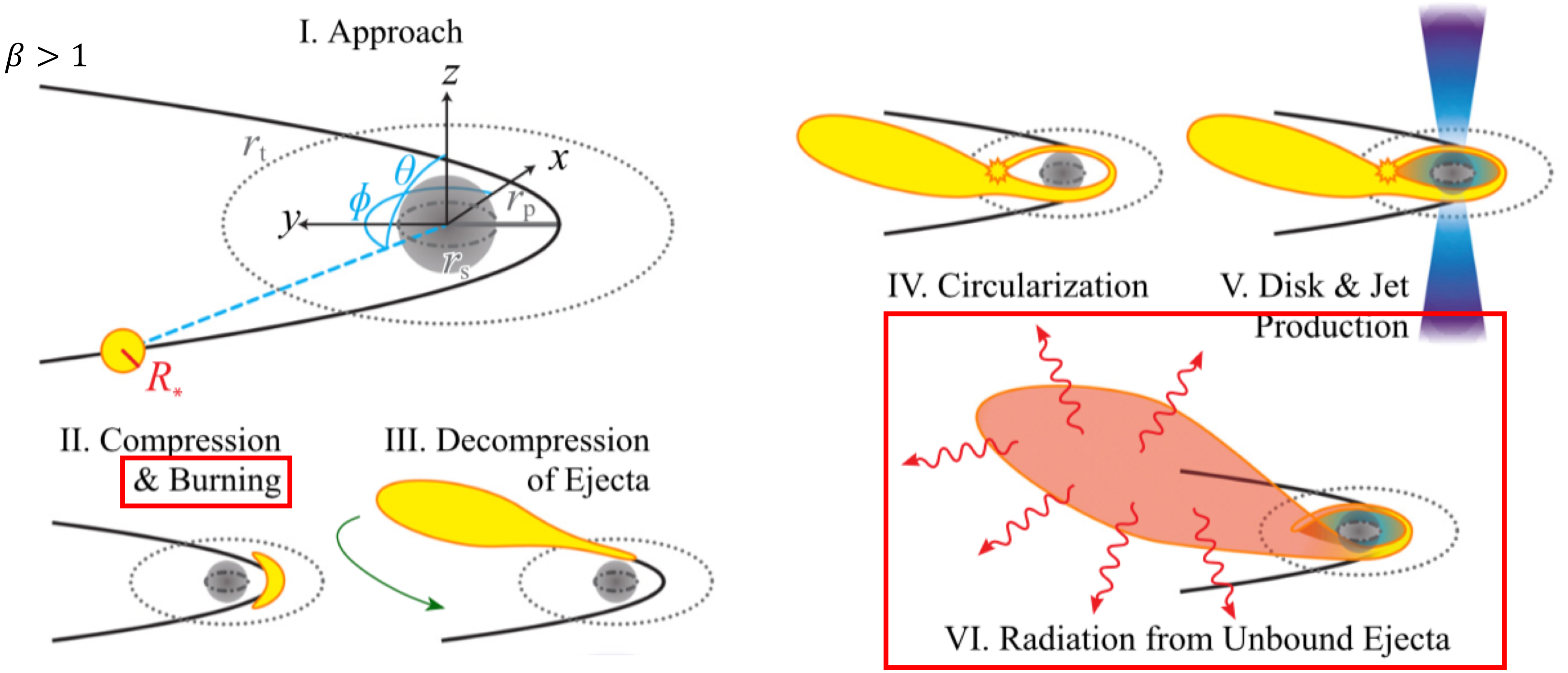
MacLeod + (2016)

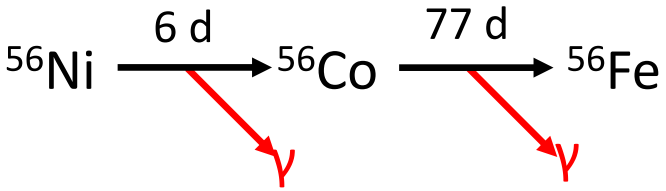
Sequence of WD – BH TDE



MacLeod + (2016)

Sequence of WD – BH TDE





$$ {}^{56}\mathrm{Ni} \xrightarrow[\searrow \gamma]{6\ \mathrm{d}} {}^{56}\mathrm{Co} \xrightarrow[\searrow \gamma]{77\ \mathrm{d}} {}^{56}\mathrm{Fe} $$

MacLeod + (2016)

Interests of WD – BH TDEs

- Strong compression at the pericenter

→ Shock heating, ρ & T increase

→ Thermonuclear reactions

→ SN Ia-like transients?

- Range of $M_{\rm BH}$ is restricted
  1. tidal disruption condition

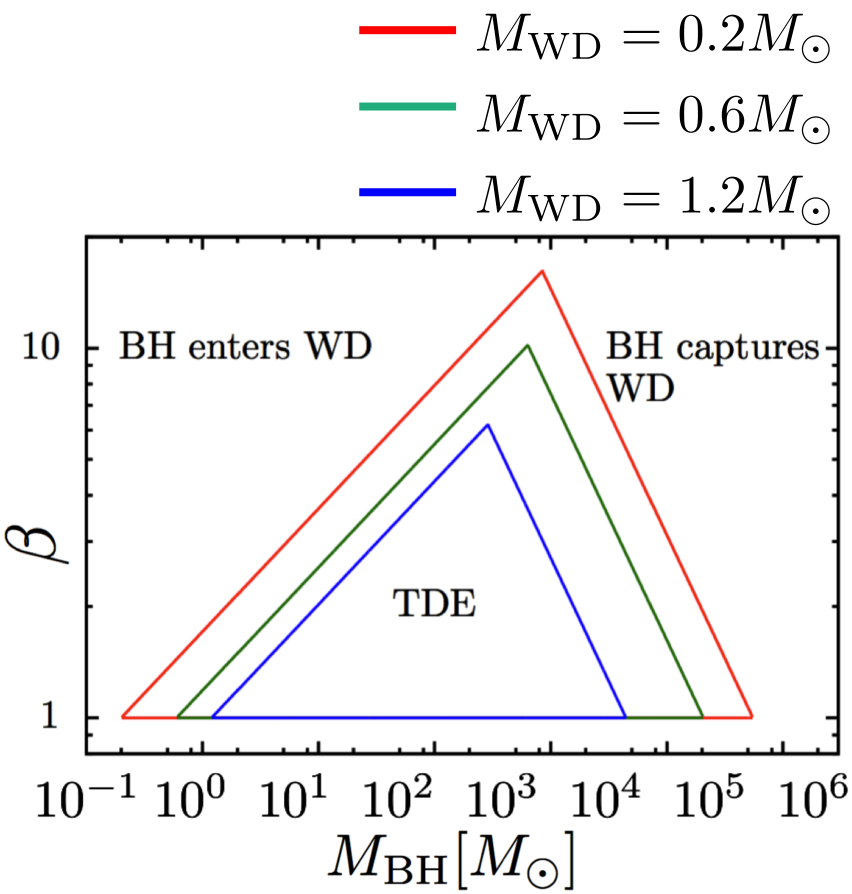
$$R_t > R_p$$

  2. WD is not swallowed by BH

$$R_p > R_S,\ R_{\rm WD}$$

SMBHs w/ $M_{\rm BH} \gtrsim 10^6 M_\odot$ cannot disrupt WDs

→ good probe to study IMBHs



Observations of WD – BH TDEs

So far, few possible (but still uncertain) candidates

Optical counterparts from nuclear burning have not been found yet.

GRB	Swift J1644+57 / GRB 110328A (Krolik & Piran 2011) GRB060218 + SN2006aj (Shcherbakov et al. 2013) GRB111209A (Ioka et al. 2016)
X-ray transient	XRT 000519 (Jonker et al. 2013) CDF-S XT1 (Bauer et al. 2017)

Future surveys may detect ~10 events / yr (MacLeod+ 2016)

Templates of observational signatures are important.

Optical : ZTF, LSST

X-ray : LOFT, Einstein Probe

radio : SKA

GW : LISA, DECIGO, BBO, (Advanced LIGO, KAGRA)

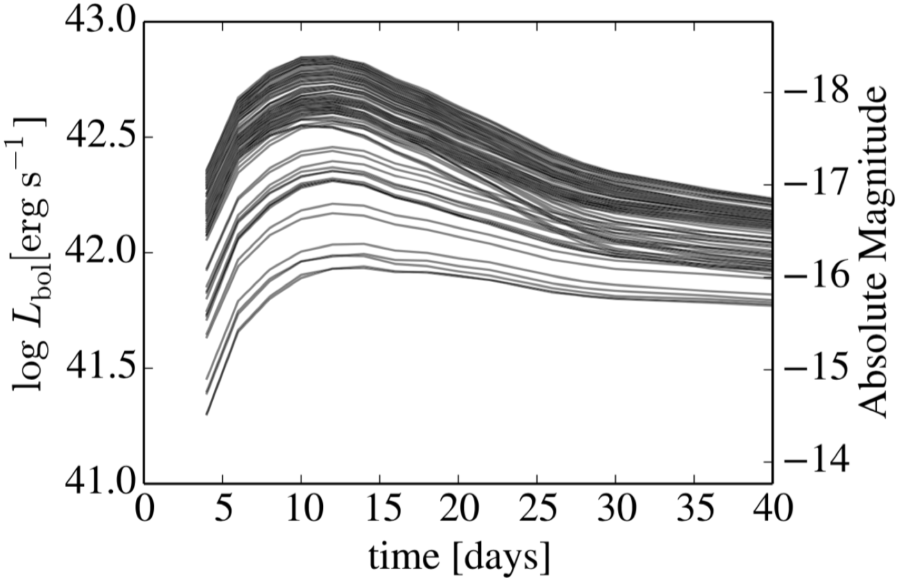
Observational signatures

MacLeod+ (2016)

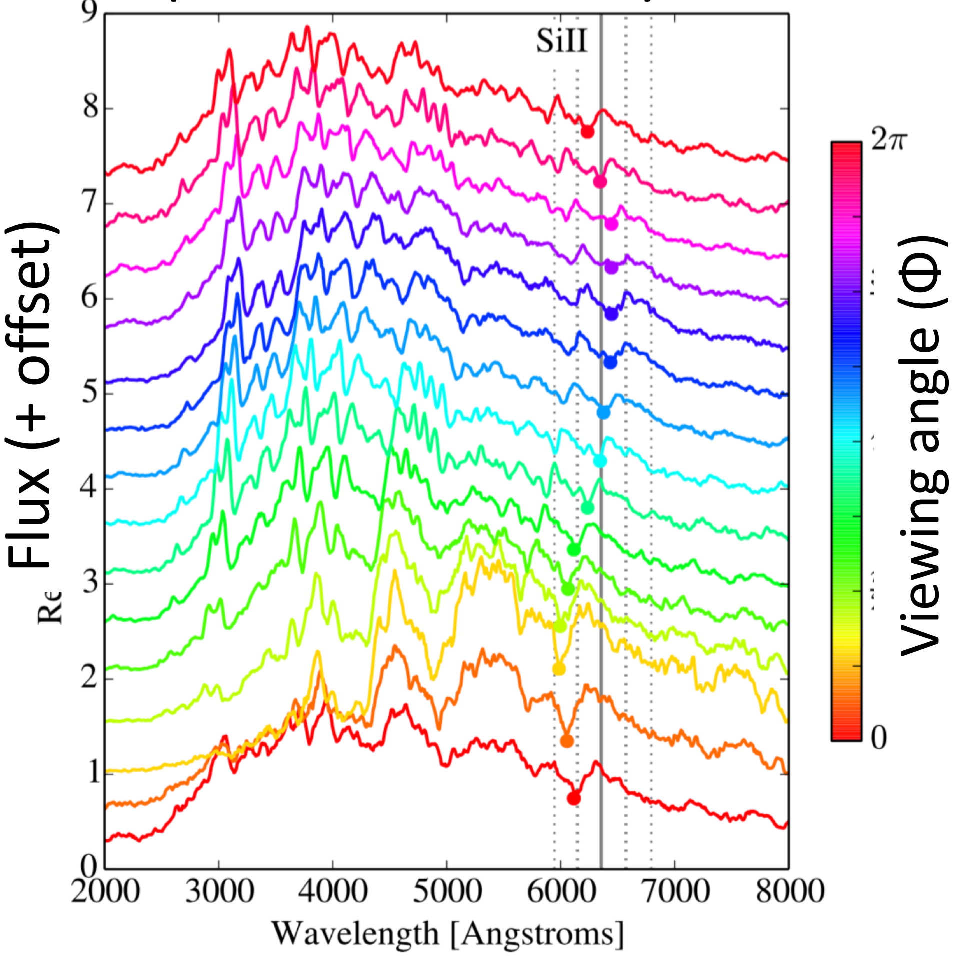
CO WD, $M_{\rm WD} = 0.6M_{\odot}$, $M_{\rm BH} = 500M_{\odot}$, $\beta = 5.0$ (Rosswog + 2009)

- Similar to SNe Ia
- Strong viewing angle dependence
- Key feature:
  Doppler shift ~ 10^4 km s^{-1}

Light curve



Spectra at t = 20 days



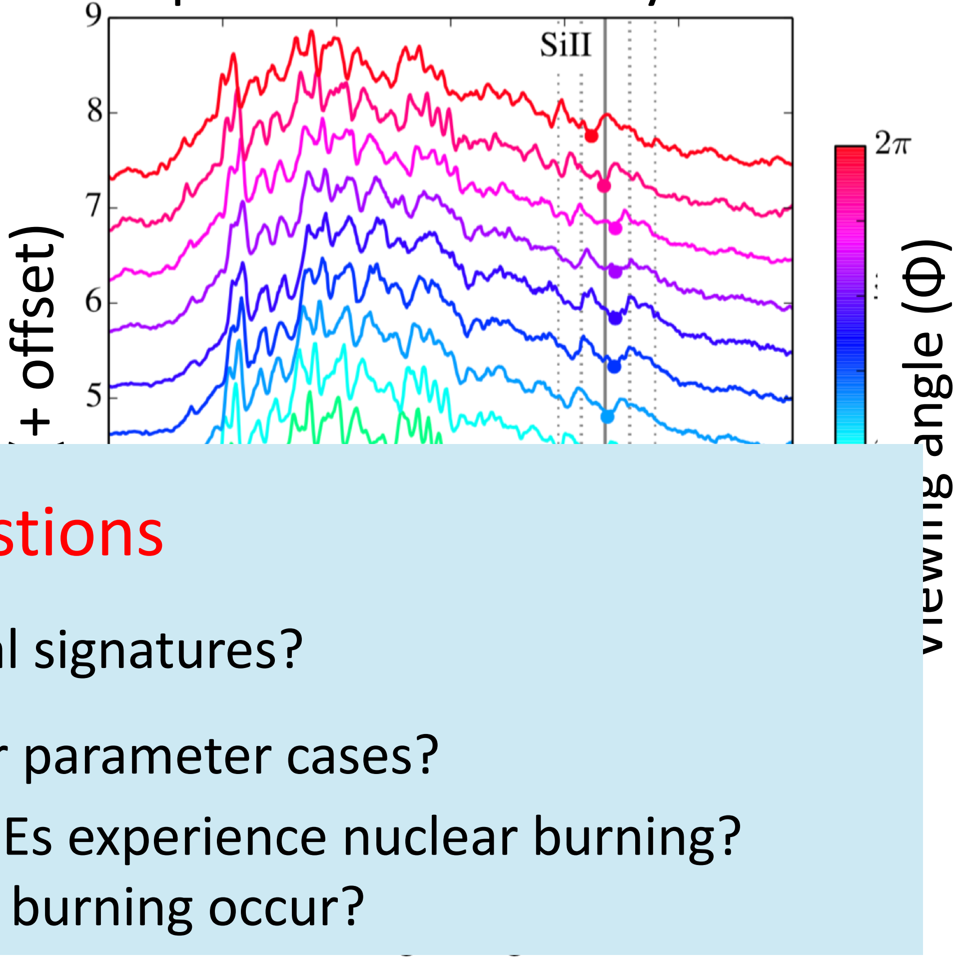
Observational signatures

MacLeod+ (2016)

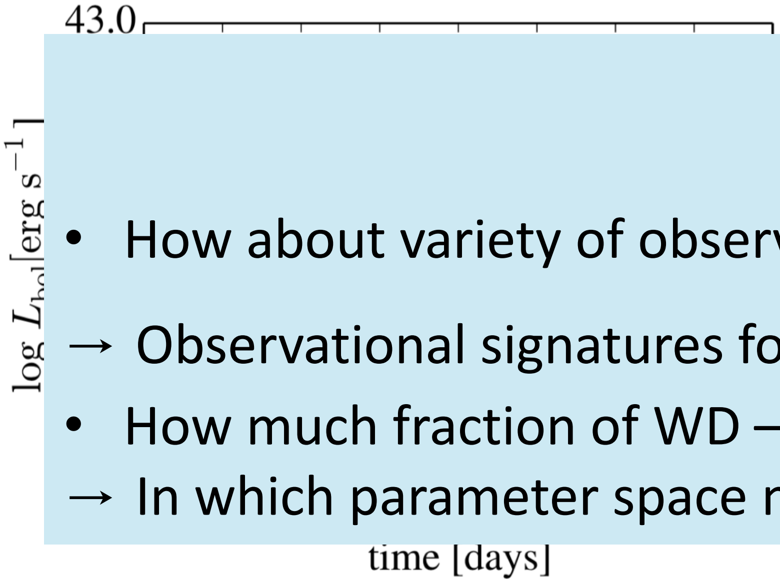
CO WD, $M_{\rm WD} = 0.6 M_\odot$, $M_{\rm BH} = 500 M_\odot$, $\beta = 5.0$ (Rosswog + 2009)

- Similar to SNe Ia
- Strong viewing angle dependence
- Key feature:
  Doppler shift ~ 10^4 km s^{-1}

Spectra at t = 20 days



Light curve



Questions

- How about variety of observational signatures?

→ Observational signatures for other parameter cases?

- How much fraction of WD – BH TDEs experience nuclear burning?

→ In which parameter space nuclear burning occur?

Methods

- **Systematic and comprehensive parameter study varying** $\boldsymbol{M_{\mathrm{BH}}, M_{\mathrm{WD}}, \beta}$

→ focus on the nucleosynthesis in the WD – BH TDEs

- 3D SPH simulations coupled with nuclear reactions.

- BH ：fixed gravity source (Schwarzschild BH)

- WD：represented with 0.8 M SPH particles
  self-gravity fluid
  still inadequate to correctly follow the shock heating
  (→ discuss later)

3 types of WDs $M_{\mathrm{WD}} = \begin{cases} 0.2\ M_\odot & (^{4}\mathrm{He}\ 100\%) \\ 0.6\ M_\odot & (^{12}\mathrm{C}\ 50\%\ ^{16}\mathrm{O}\ 50\%) \\ 1.2\ M_\odot & (^{16}\mathrm{O}\ 60\%\ ^{20}\mathrm{Ne}\ 35\%\ ^{24}\mathrm{Mg}\ 5\%) \end{cases}$

Simulation methods

Basic equations

Equation of motion

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \left(\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t}\right)_{\mathrm{diss}} + \boldsymbol{g}_{\mathrm{BH}} + \boldsymbol{g}_{\mathrm{WD}}$$

Energy equation

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\cdot\boldsymbol{v} - \left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_{\mathrm{diss}} + \dot{\epsilon}_{\mathrm{nuc}}$$

Nuclear reactions

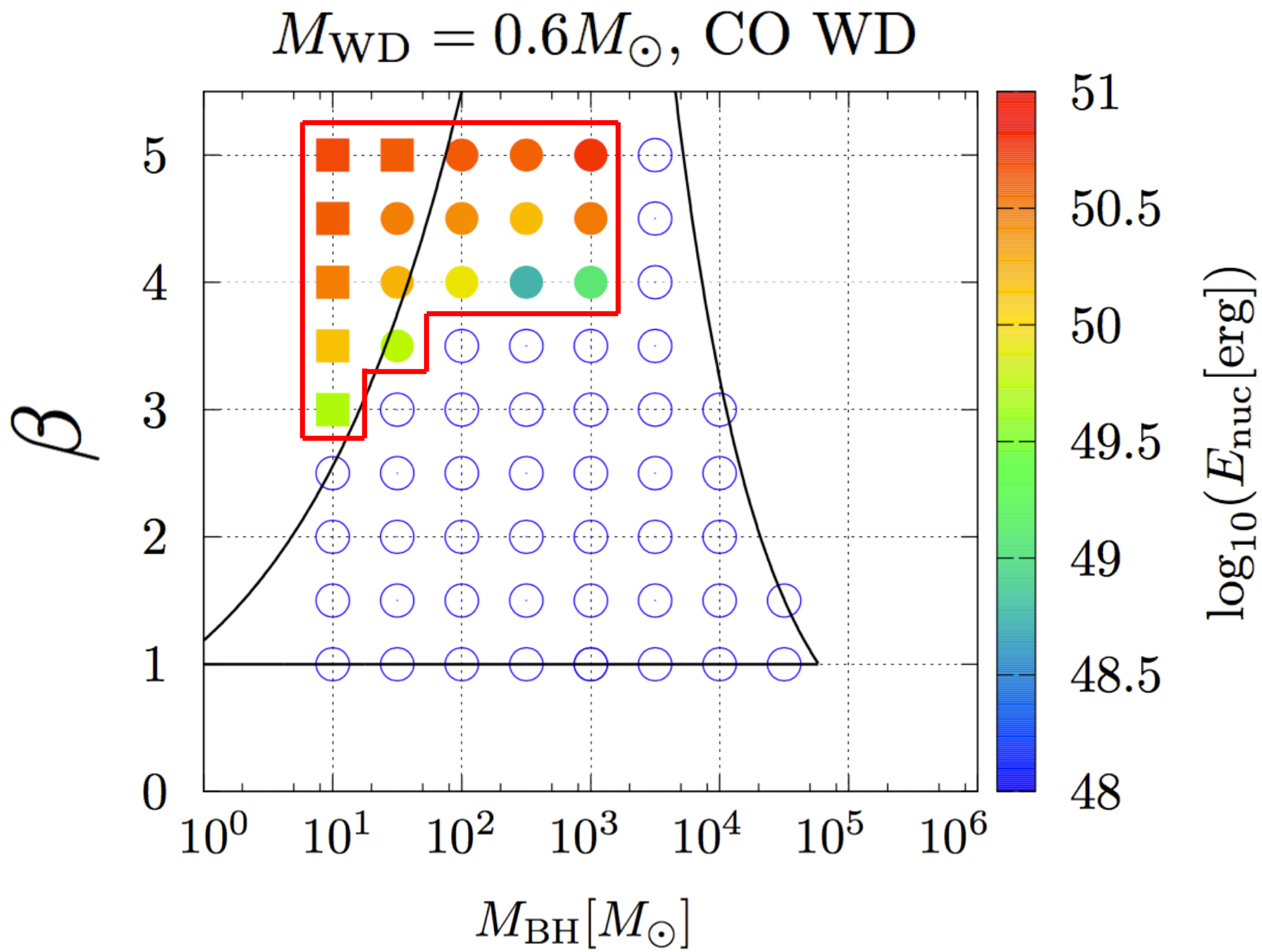
$$\frac{\mathrm{d}X_a}{\mathrm{d}t} = \dot{X}_a(\rho, u, \boldsymbol{X})$$

- BH gravity: approximation of Schwarzschild BH gravity

  Tejeda & Rosswog (2013)
- EOS: HELMHOLTZ EOS
- Nuclear reactions: α-Chain Network from ^{4}He to ^{56}Ni (13 species)
- Initial condition: parabolic orbits in Schwarzschild metric

Results

WD – BH TDEs with explosive nuclear reactions



Interests of WD – BH TDEs

- Strong compression at the pericenter

→ Shock heating, ρ & T increase

→ Thermonuclear reactions

→ SN Ia-like transients?

- Range of $M_{\rm BH}$ is restricted

1. tidal disruption condition

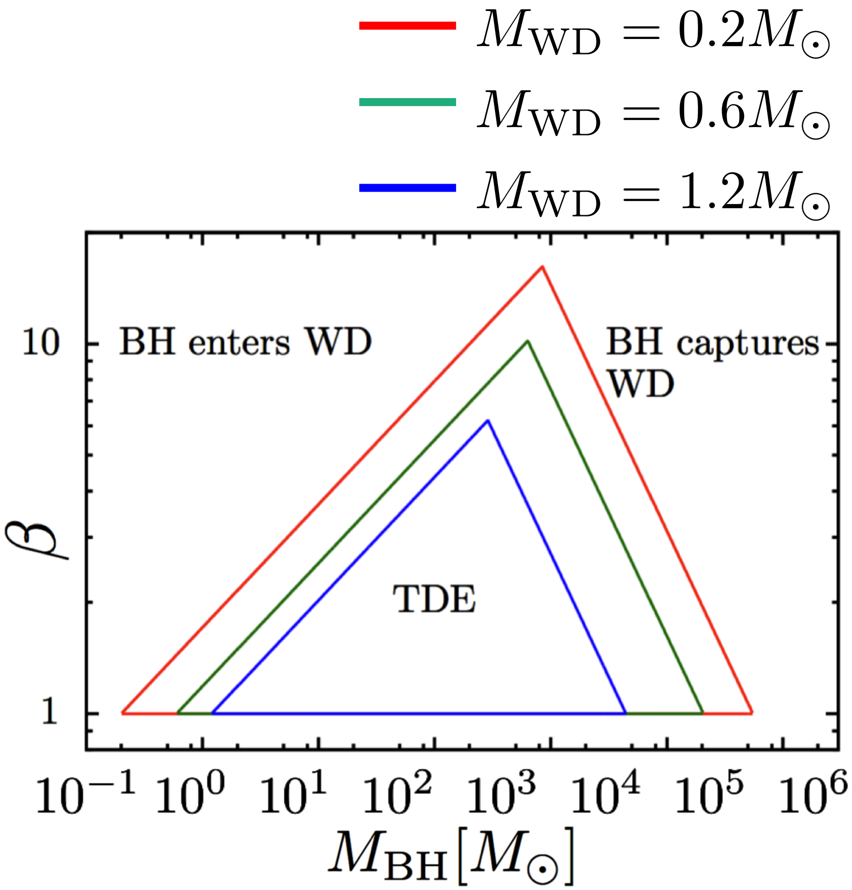
$$R_t > R_p$$

2. WD is not swallowed by BH

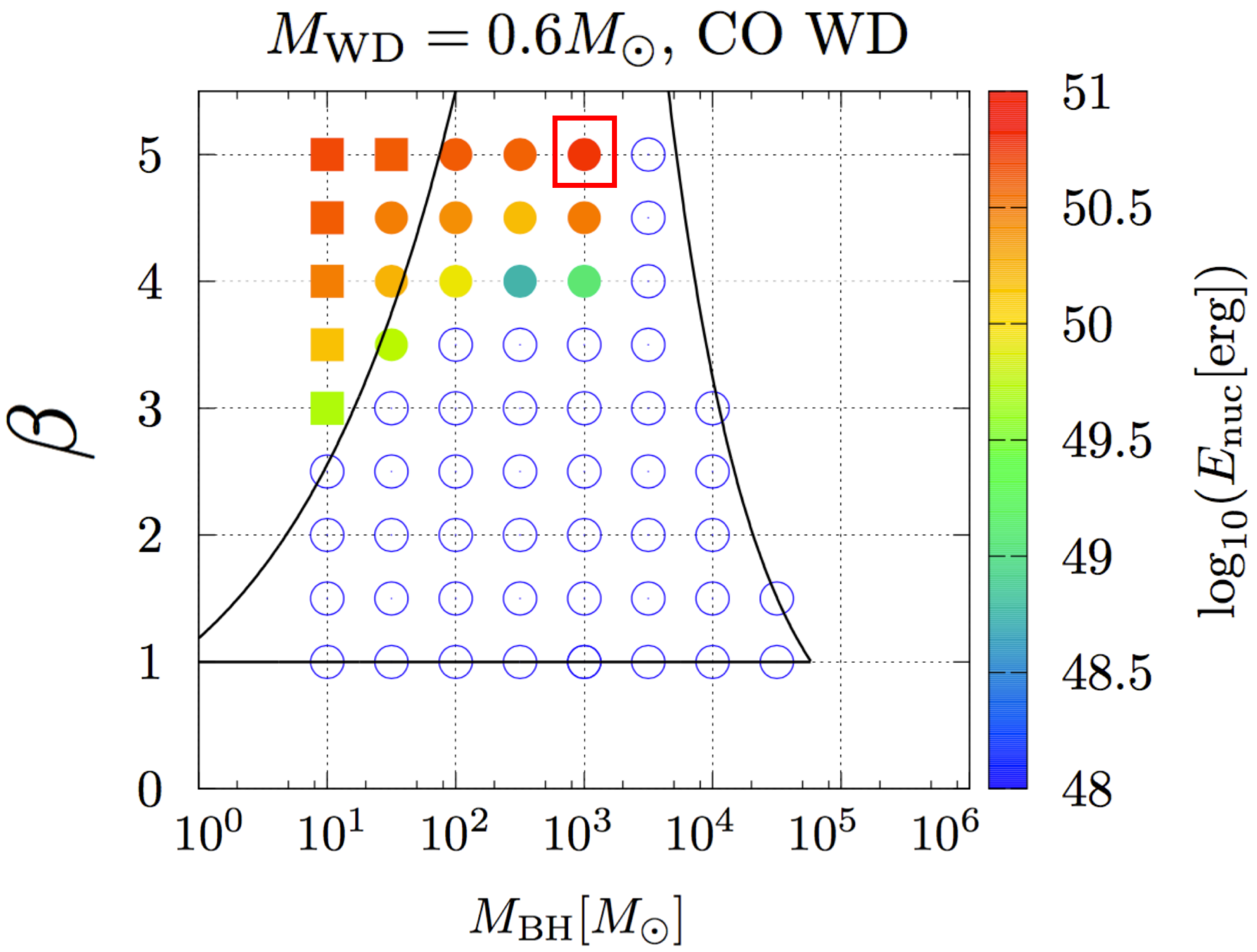
$$R_p > R_S,\ R_{\rm WD}$$

SMBHs w/ $M_{\rm BH} \gtrsim 10^6 M_\odot$ cannot disrupt WDs

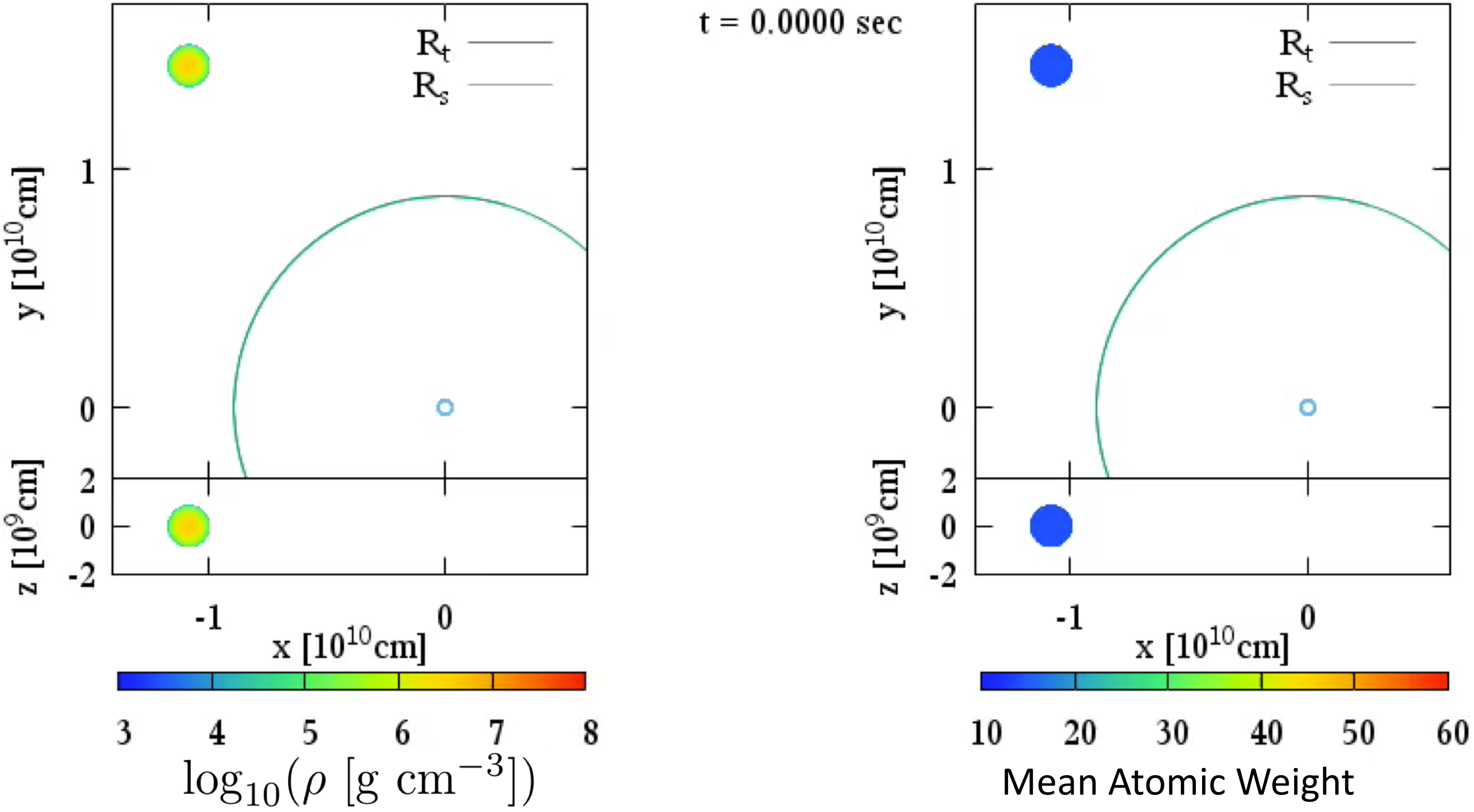
→ good probe to study IMBHs



WD – BH TDEs with explosive nuclear reactions

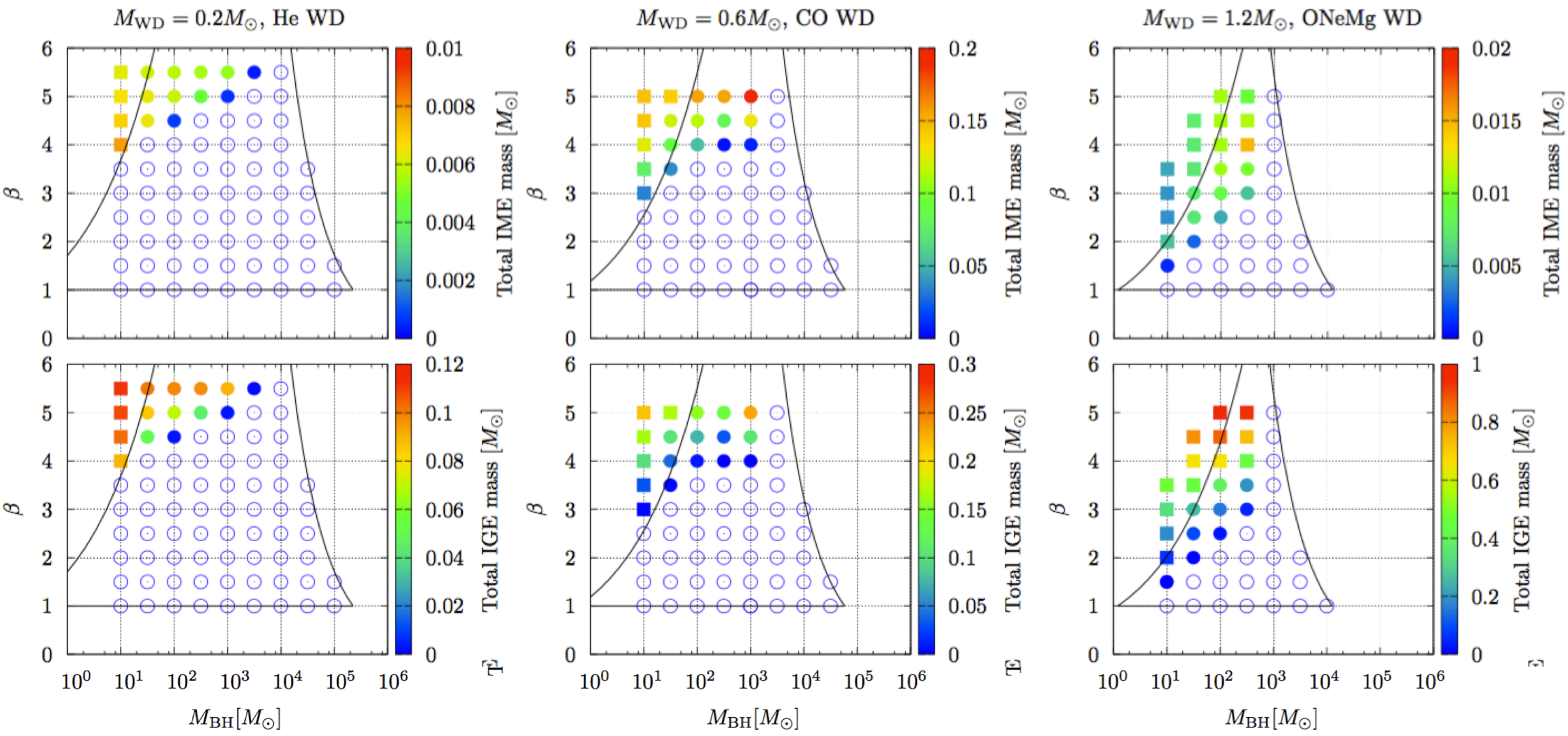


TDEs w/ explosive nuclear reactions



Nuclear burning yields

- We derive the abundances of nuclear burning yields for a lot of cases. → useful as templates



Interesting cases: Helium WD – BH TDEs

Calcium-rich gap transients: tidal detonations of white dwarfs?

P. H. Sell ✉, T. J. Maccarone, R. Kotak, C. Knigge, D. J. Sand

Monthly Notices of the Royal Astronomical Society, Volume 450, Issue 4, 11 July 2015, Pages 4198–4206,

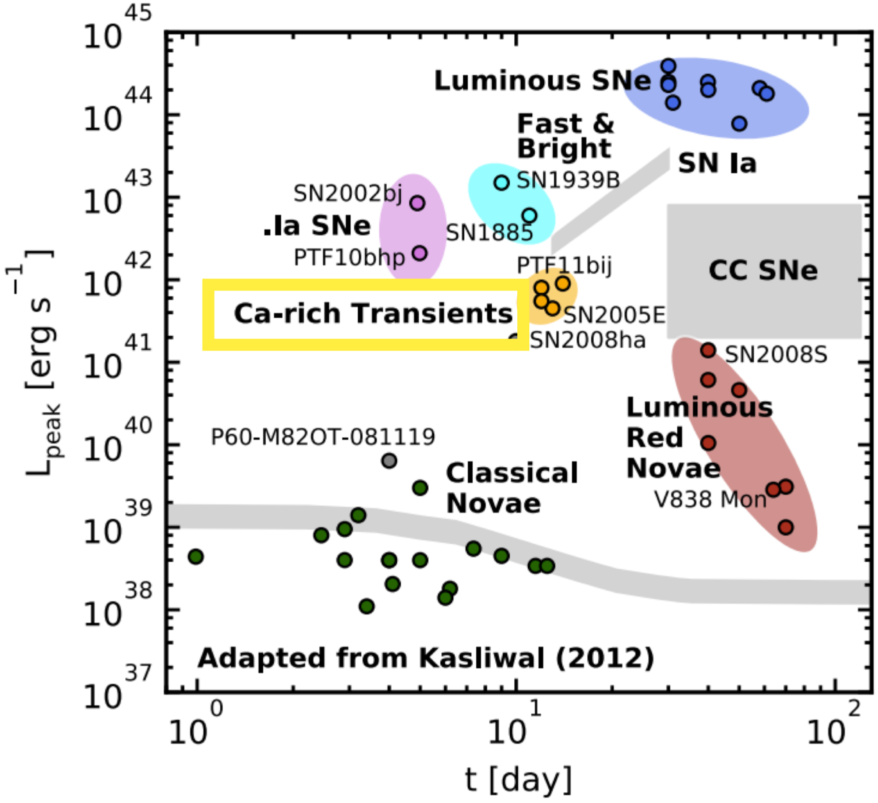
Ca-rich gap transients

- Similar to SNe Ia
- Fainter, faster than SNe Ia
- Large calcium abundance
- High velocity

(6000 - 11000 km/s)

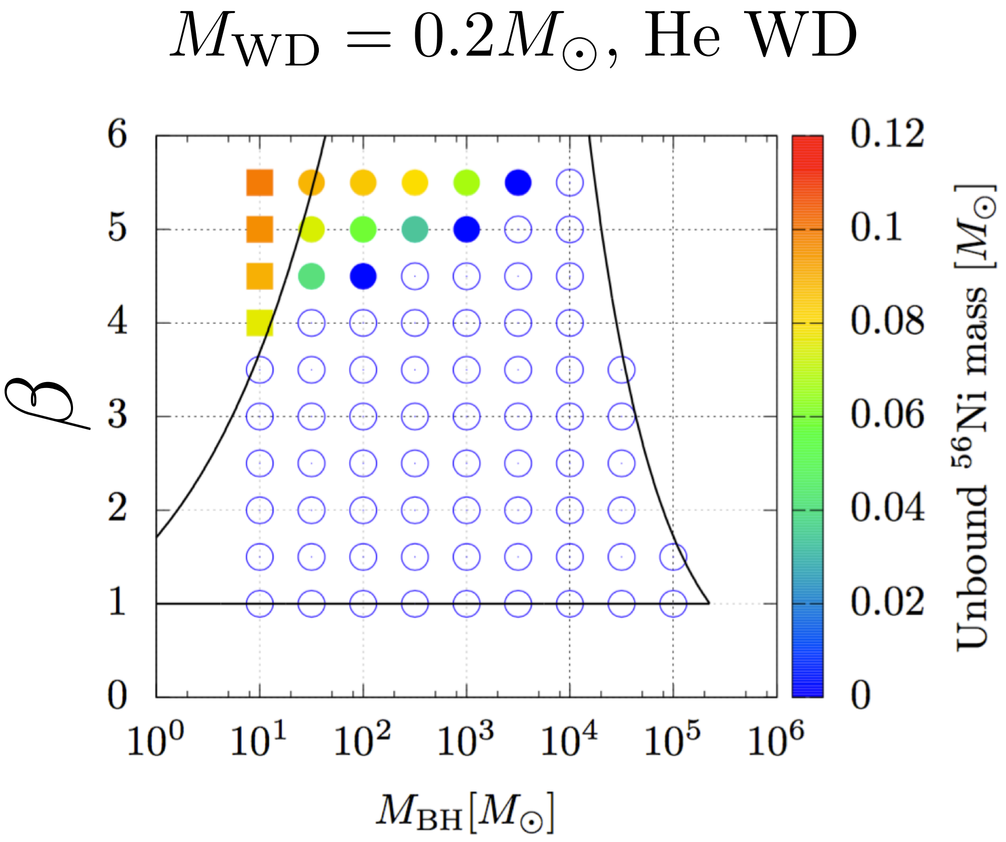
- In the outskirts of galaxies
- Small nickel abundance

$M_{\mathrm{Ni}} \lesssim 0.015\, M_\odot$



Garcia-Berro (2017)

Can Helium WD - BH TDEs cause Ca-rich gap transients? → No!



Helium WD - BH TDEs

$$M_{\rm Ni} \gtrsim 0.03 M_\odot$$

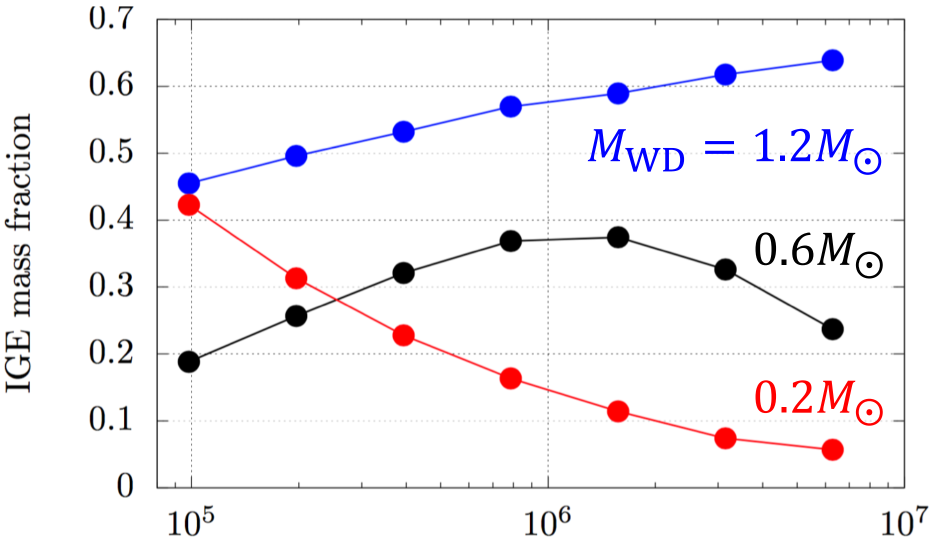
$$M_{\rm Ni}/M_{\rm ej} \gtrsim 30\%$$

Observed Ca-rich gap transients

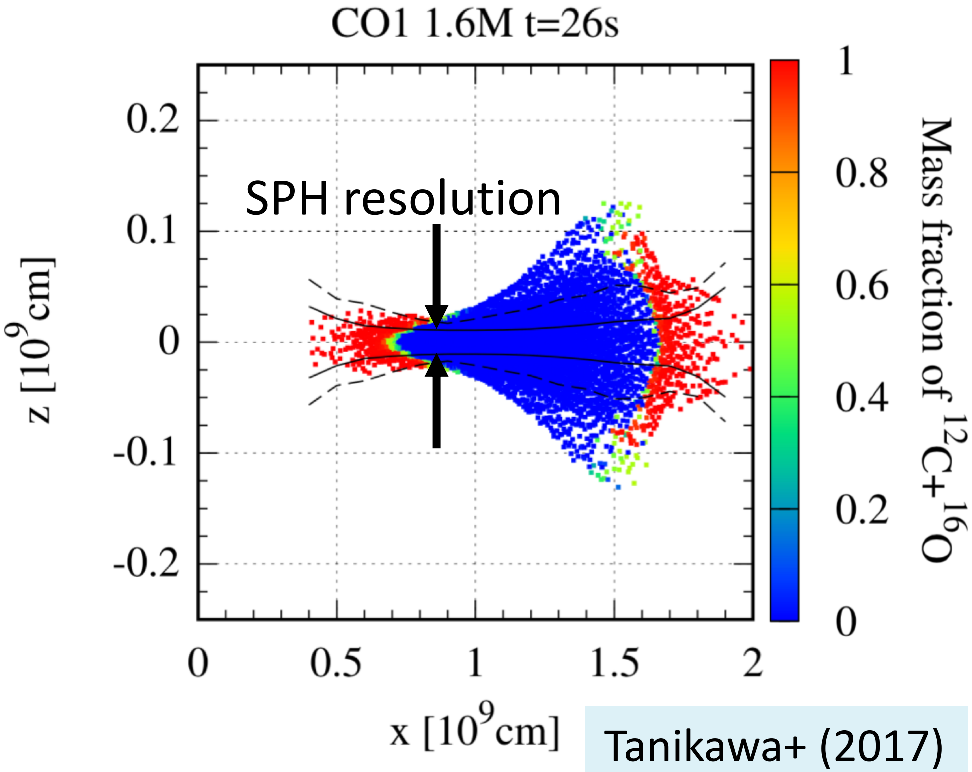
$$M_{\rm Ni} \lesssim 0.015\, M_\odot$$

$$M_{\rm Ni}/M_{\rm ej} \lesssim 5\%$$

Problem: resolution is insufficient to follow shock heating



# of SPH particles

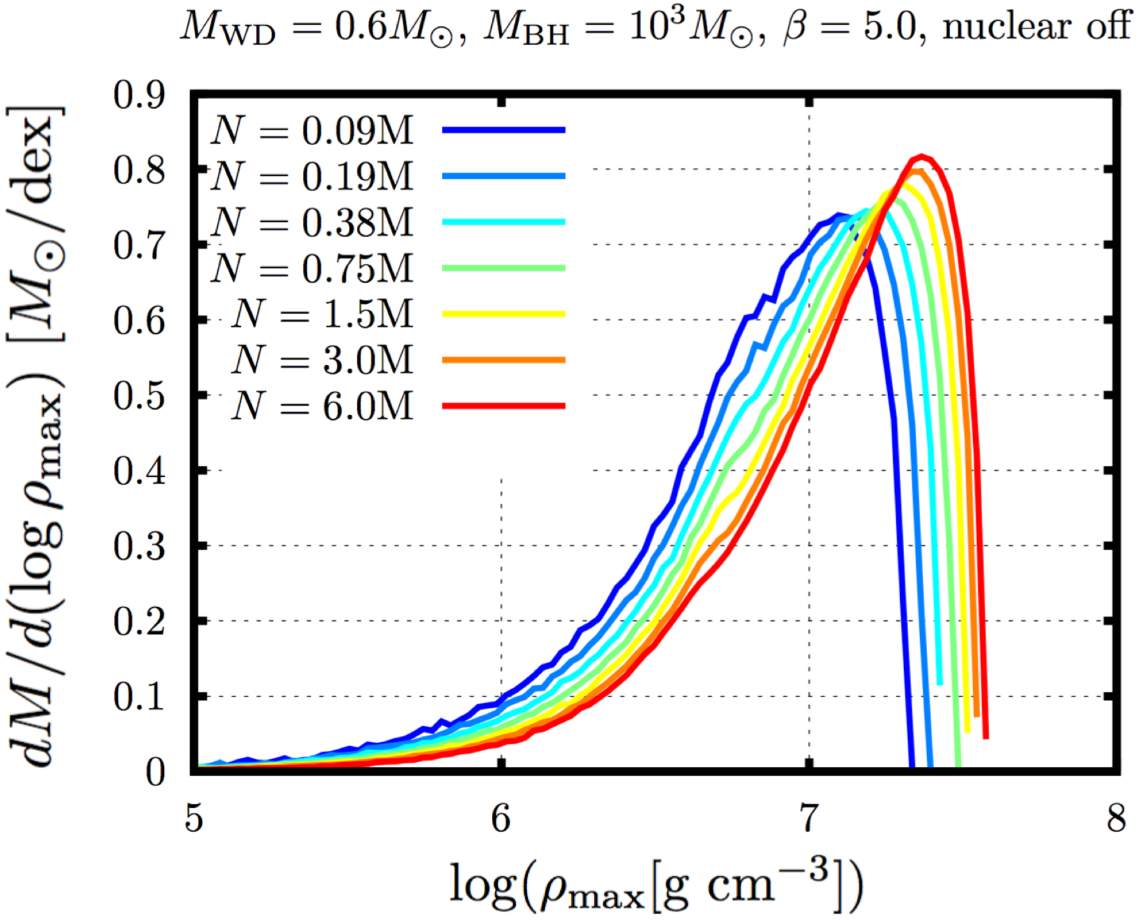


Tanikawa+ (2017)

Our resolution is insufficient to follow the shock structure perpendicular to the orbital plane.

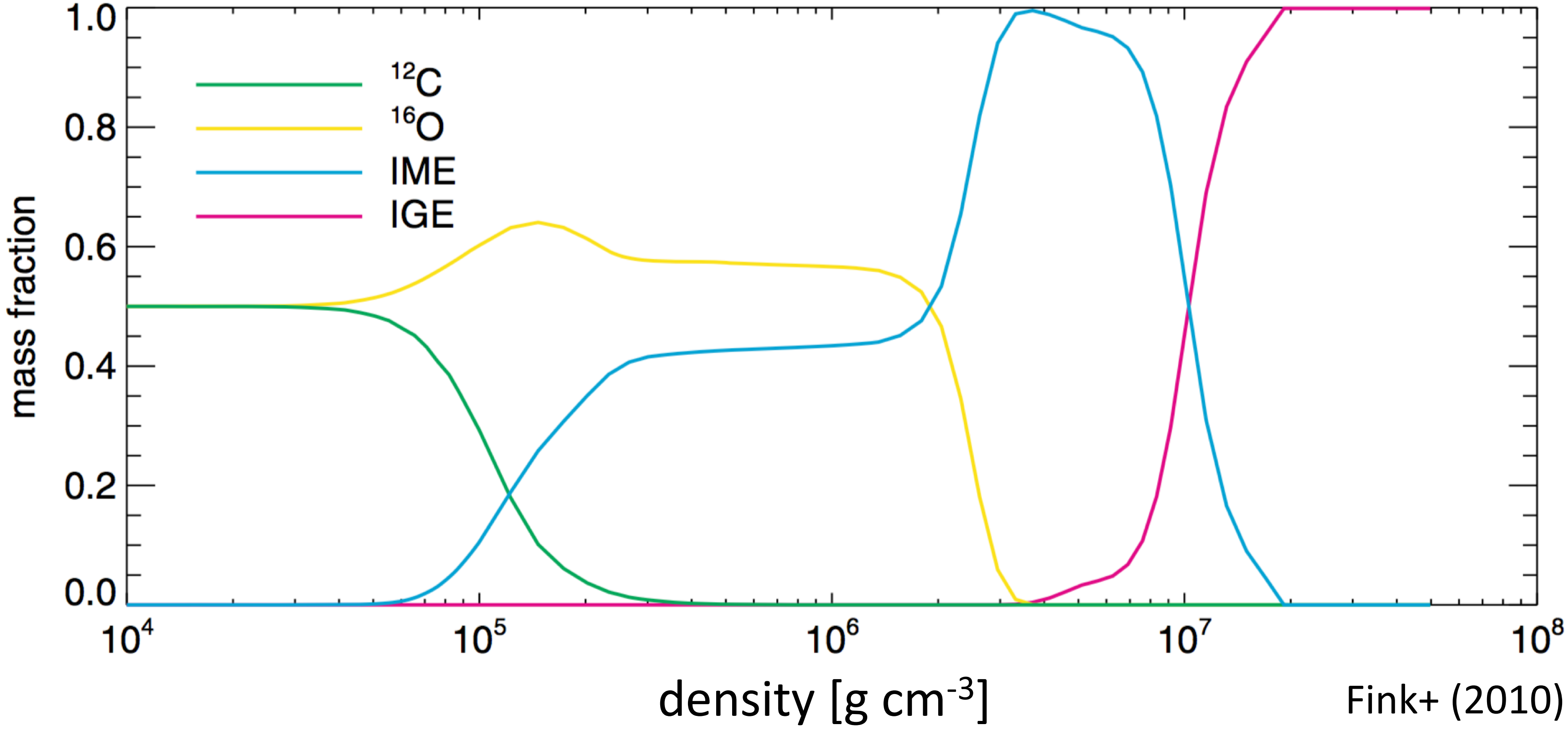
- ➢ Nuclear reaction results do not converge, and may be inaccurate.

Even so, profiles independent on shock heating do converge



$\rho_{\rm max}$: max. density of each SPH particle during simulation
~ density at the detonation point

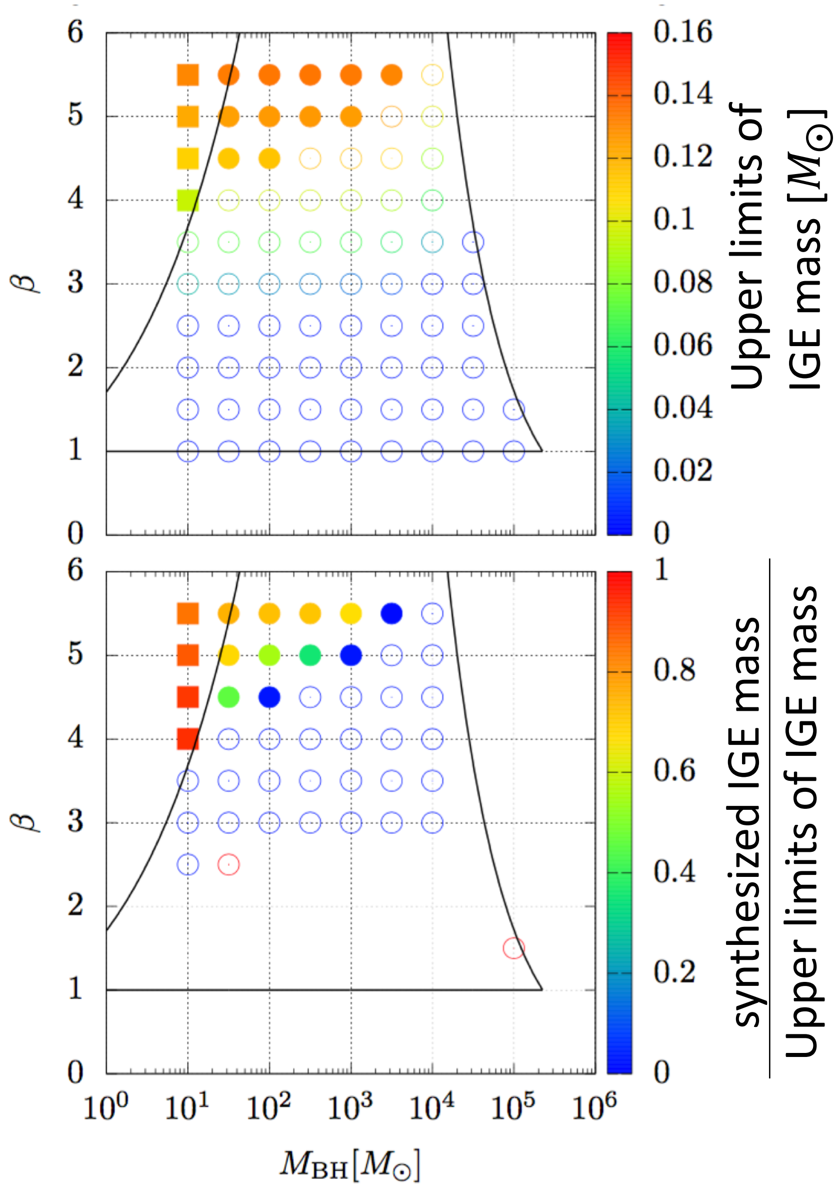
Nucleosynthetic yields as functions of density



Fink+ (2010)

derived for nucleosynthesis in SNe Ia by iterating hydrodynamic simulations and post-processing nuclear reaction calculations

Results independent on numerical resolutions



- We additionally perform hydro-simulations uncoupled with nuclear reactions, and obtain ρ_{max} distribution.
- We assume that the whole WD burns with the ρ_{max} distribution, and derive nucleosynthetic yields with the functions of Fink+ (2010).

➢ Upper limits of nucleosynthetic yields

- This method is not suffered from the resolution issue.
- Both results given the 2 different ways are well consistent.

Summary

- WD-BH TDEs are interesting transients: thermonuclear transients, good probe to study IMBH.
- We perform SPH simulations coupled with nuclear reactions
- We derive templates of nuclear burning yields for a lot of cases.
- Helium WD-BH TDEs are not the origin of Ca-rich gap transients.
- We check our results of nucleosynthesis by comparing the amounts of the synthesized elements with the upper limits of them derived in a way where we can avoid uncertainties due to low resolution.