Electromagnetic Radiations From Binary Black Holes

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ref) SSK, S. Z. Takahashi, & K. Toma, 2017, MNRAS, 465, 4406
SSK, K. Murase, P. Meszaros in prep.

Collaborators
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Kohta Murase, Peter Meszaros (PSU)

Outline

- Introduction
- sub-Energetic Supernovae from Newborn BBHs
- Evolution of Accretion Disks in BBHs
- Summary

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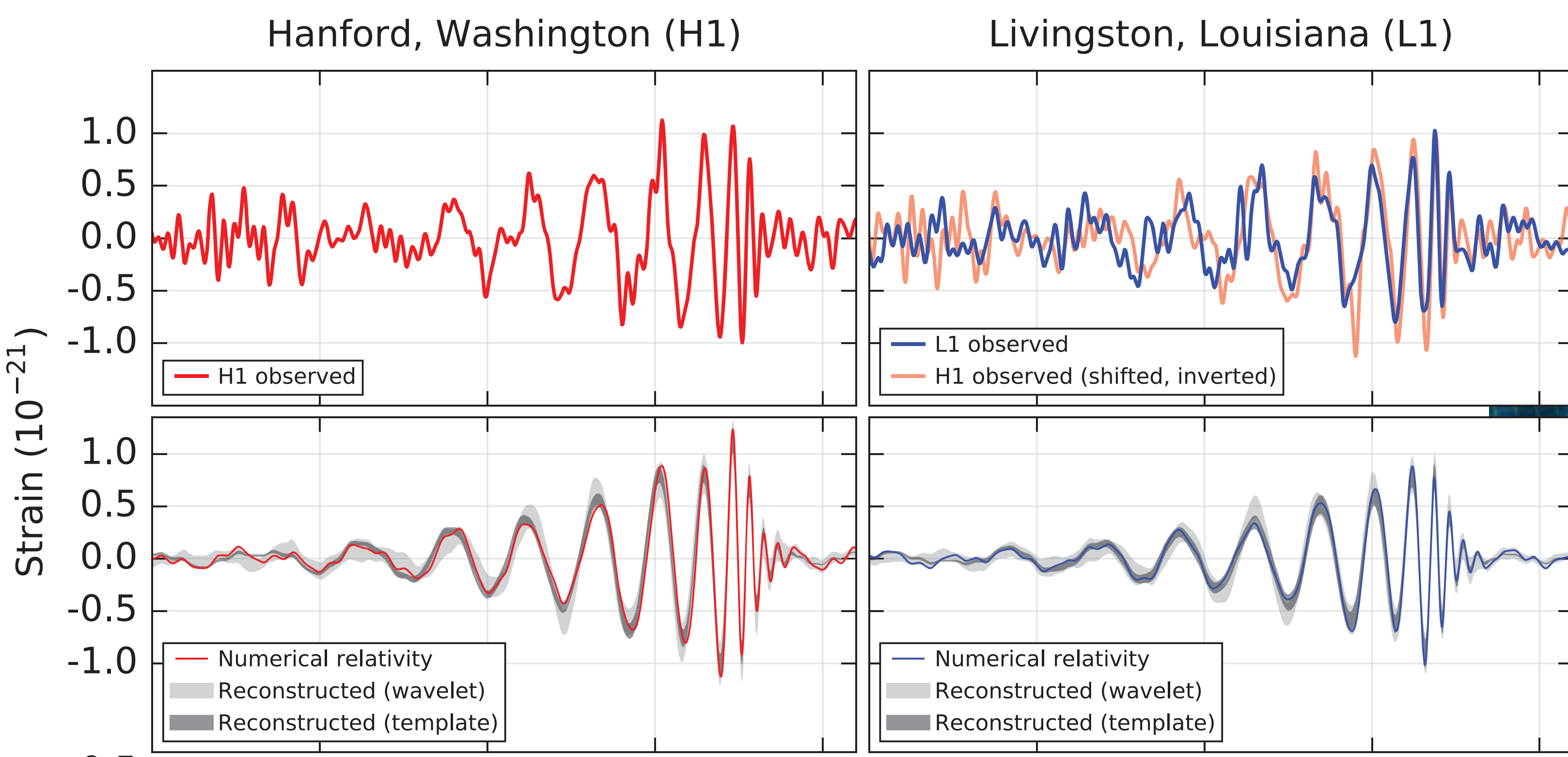
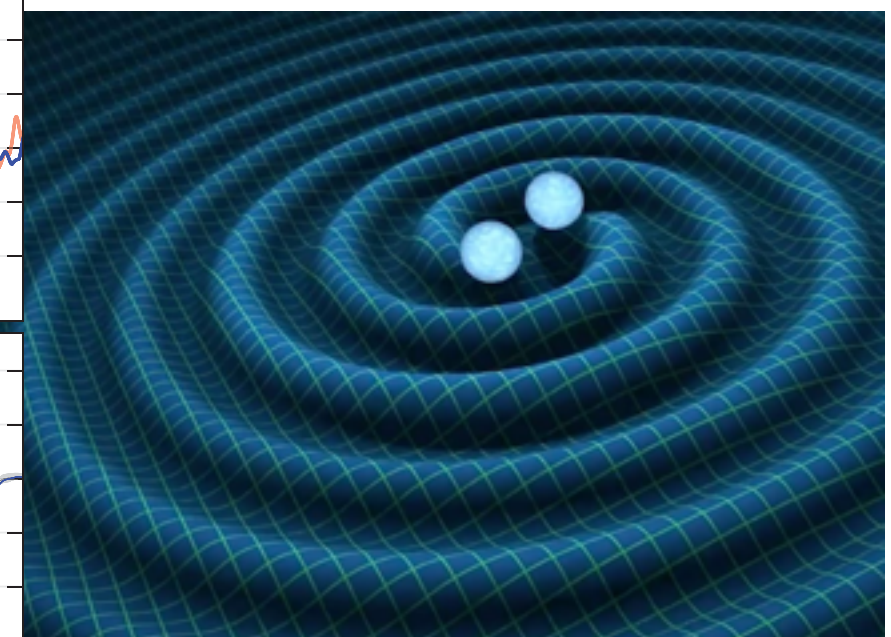
Detection of GWs

LIGO collaboration 16





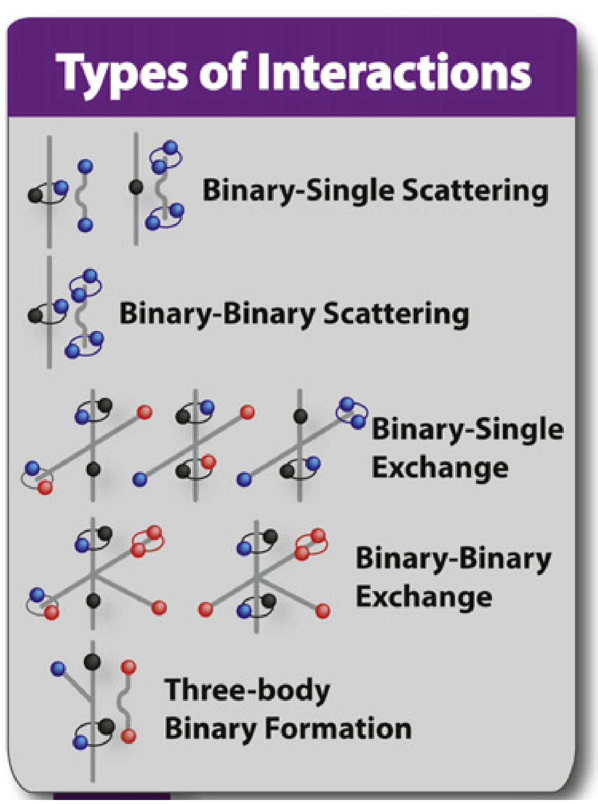
- LIGO collaboration detected the gravitational waves from merging black holes (BHs)
- Revealing existence of BH-BH binaries of $M_{BH} \sim 30\ M_{sun}$

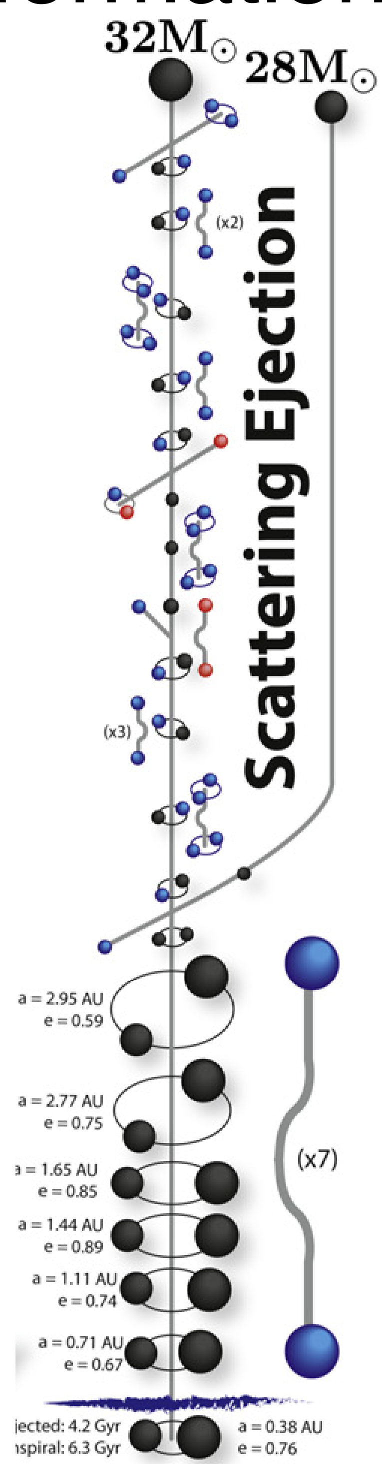
Formation scenarios

- Dynamical formation

Rodriguez+ 16

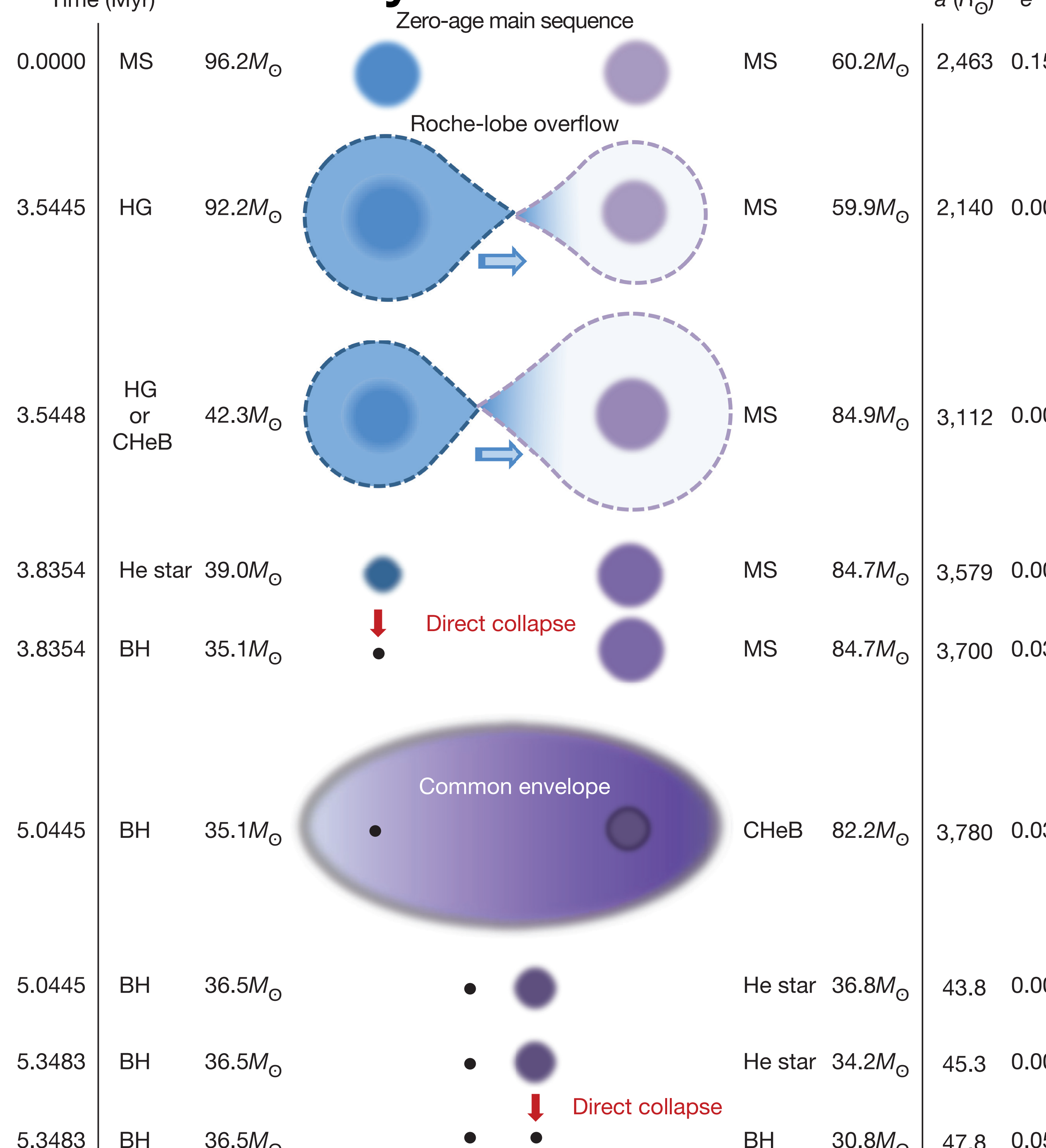
Formation in star cluster through 3-body interactions





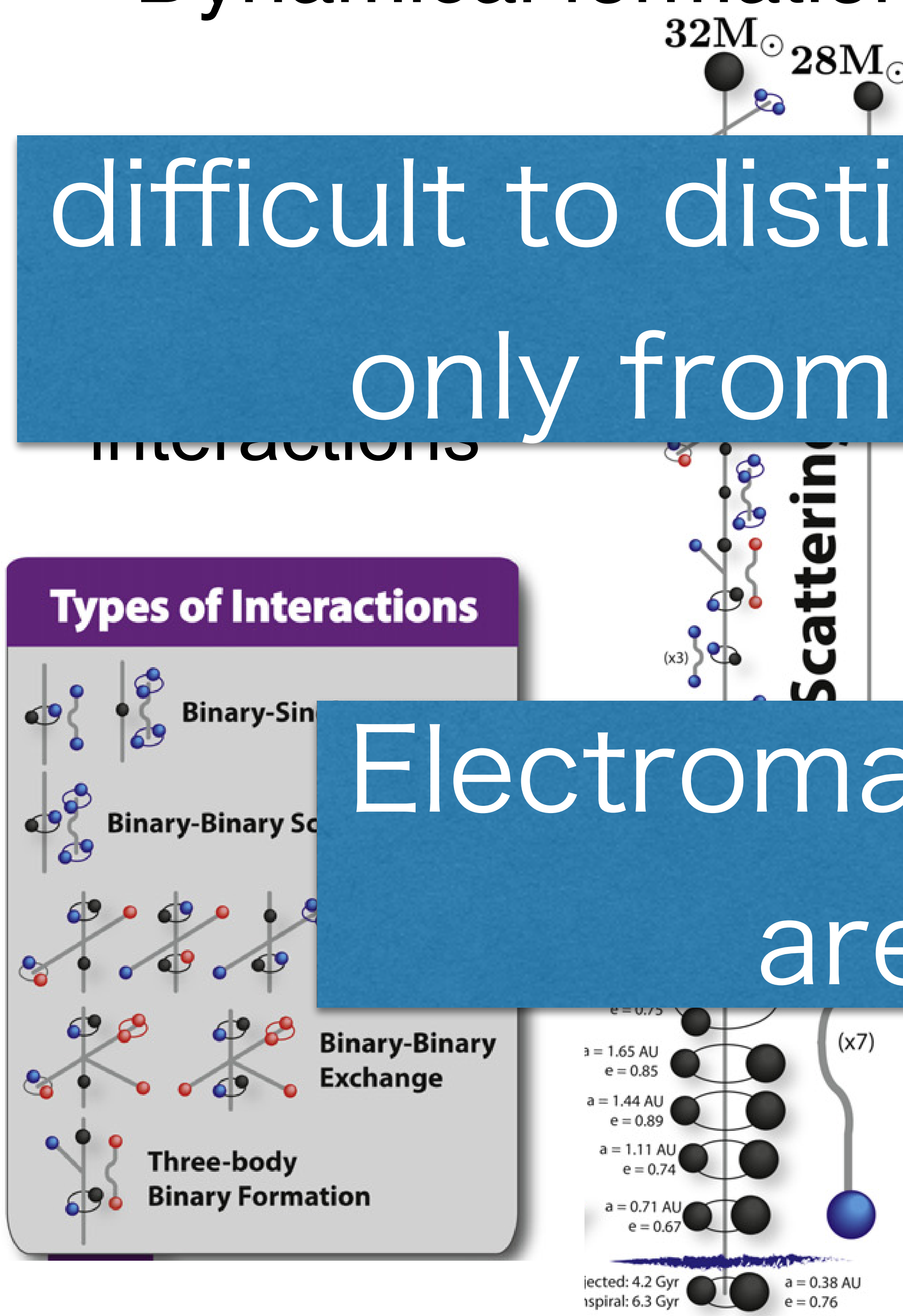
- Binary evolution

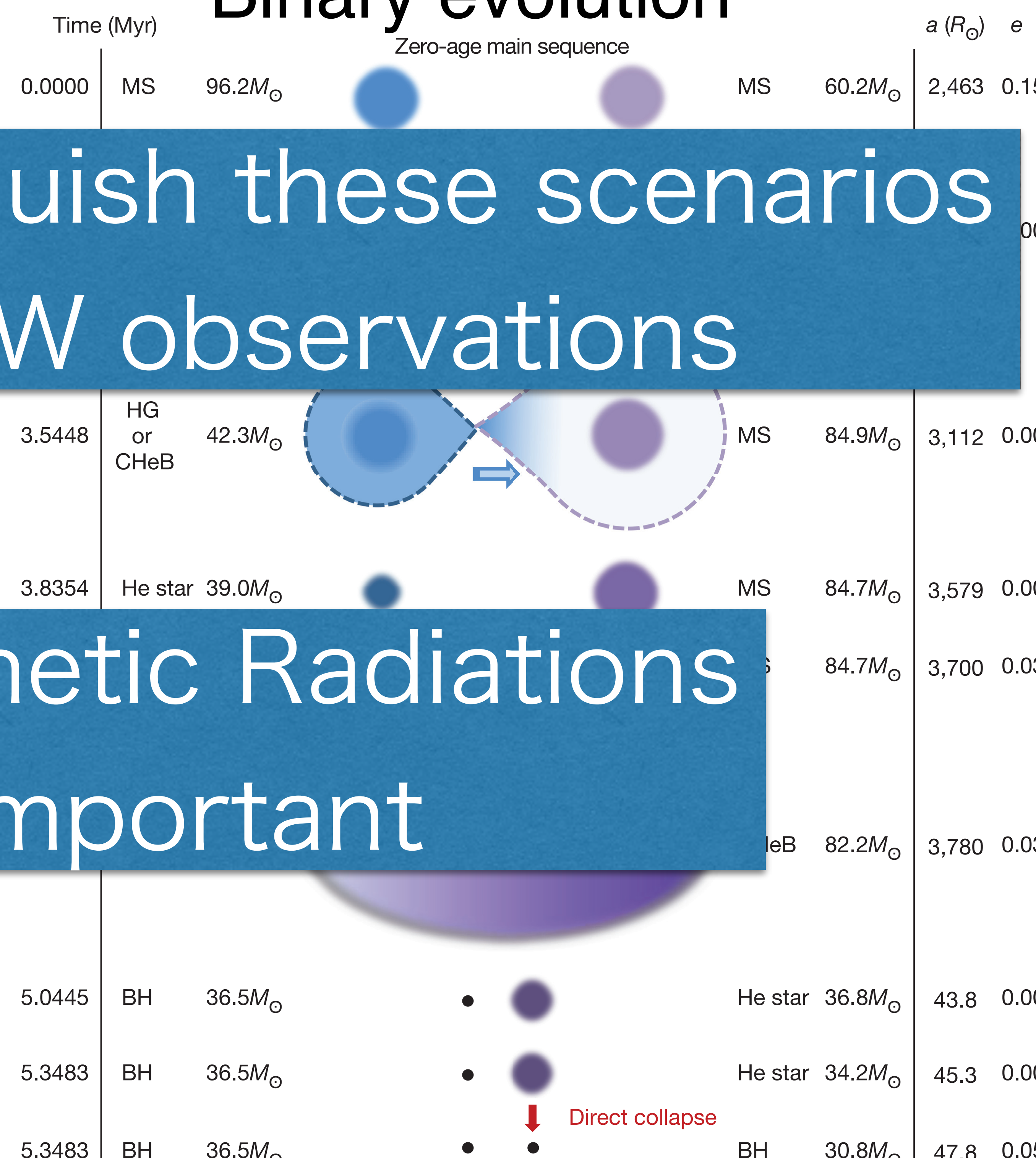
Belczynski+ 16



Formation scenarios

- Dynamical formation
- Binary evolution

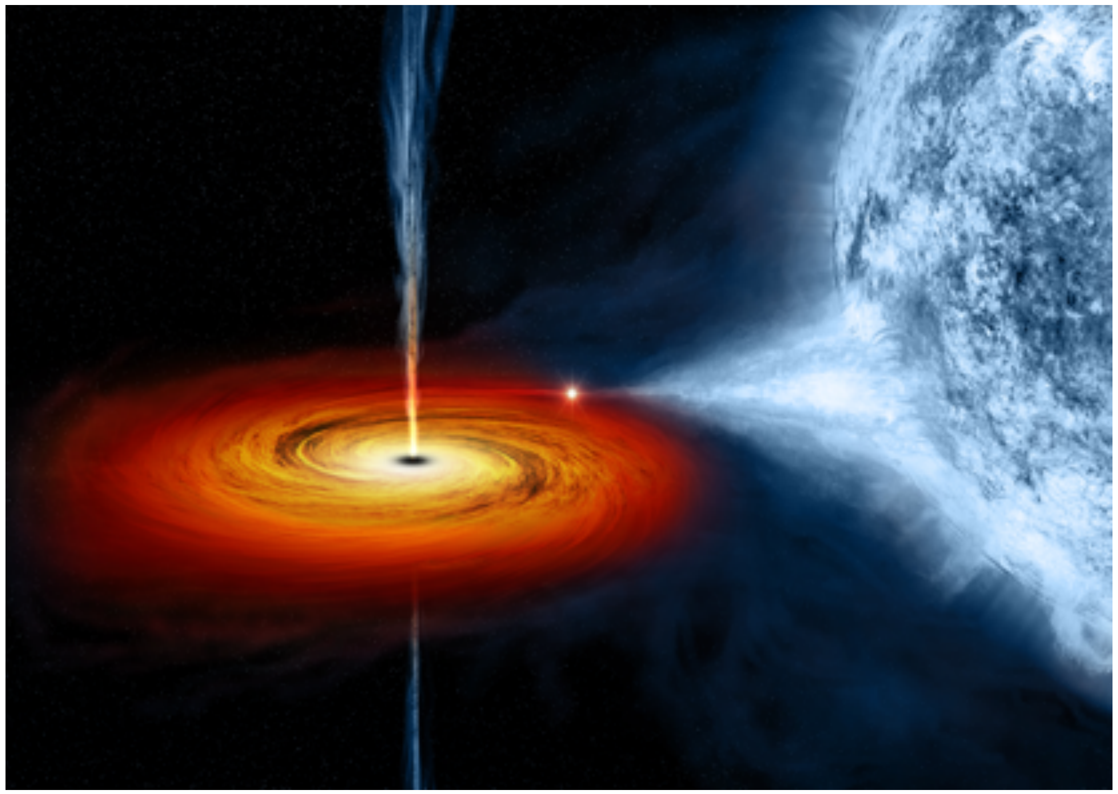


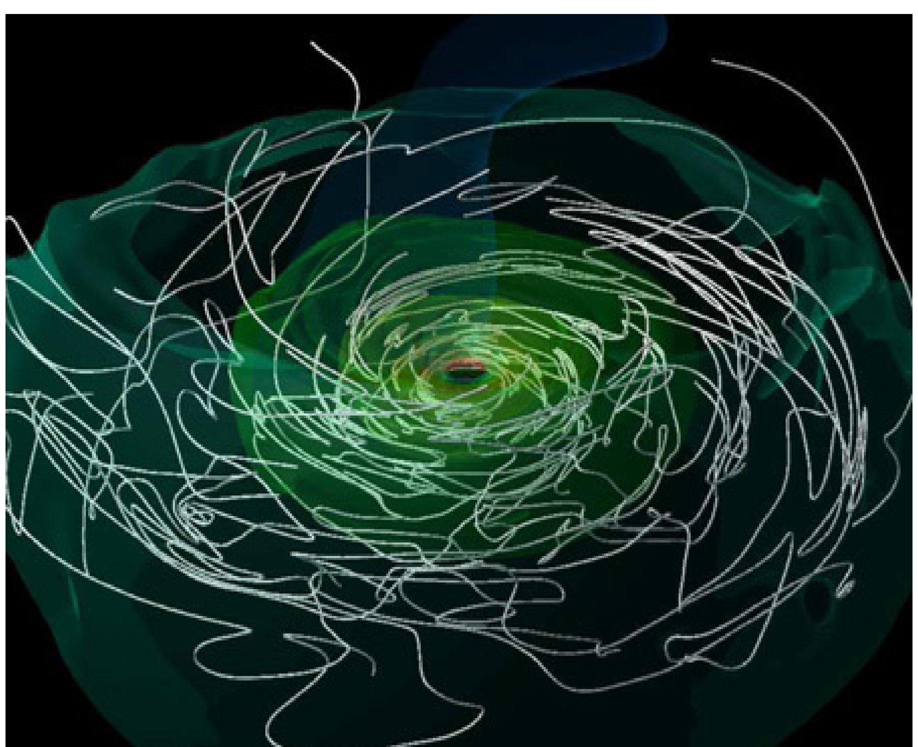


difficult to distinguish these scenarios only from GW observations

Electromagnetic Radiations are important

Accretion onto BHs





Suzuki & Inutsuka 14

- Gravitational energy
  —> Radiation energy
- Angular momentum
  —> Accretion disk
- Angular momentum transport is necessary for continuous accretion
  —> MHD turbulence made by magnetorotational instability (MRI) Balbus & Hawley 91
- Accretion may take place when BBHs are born and/or merging

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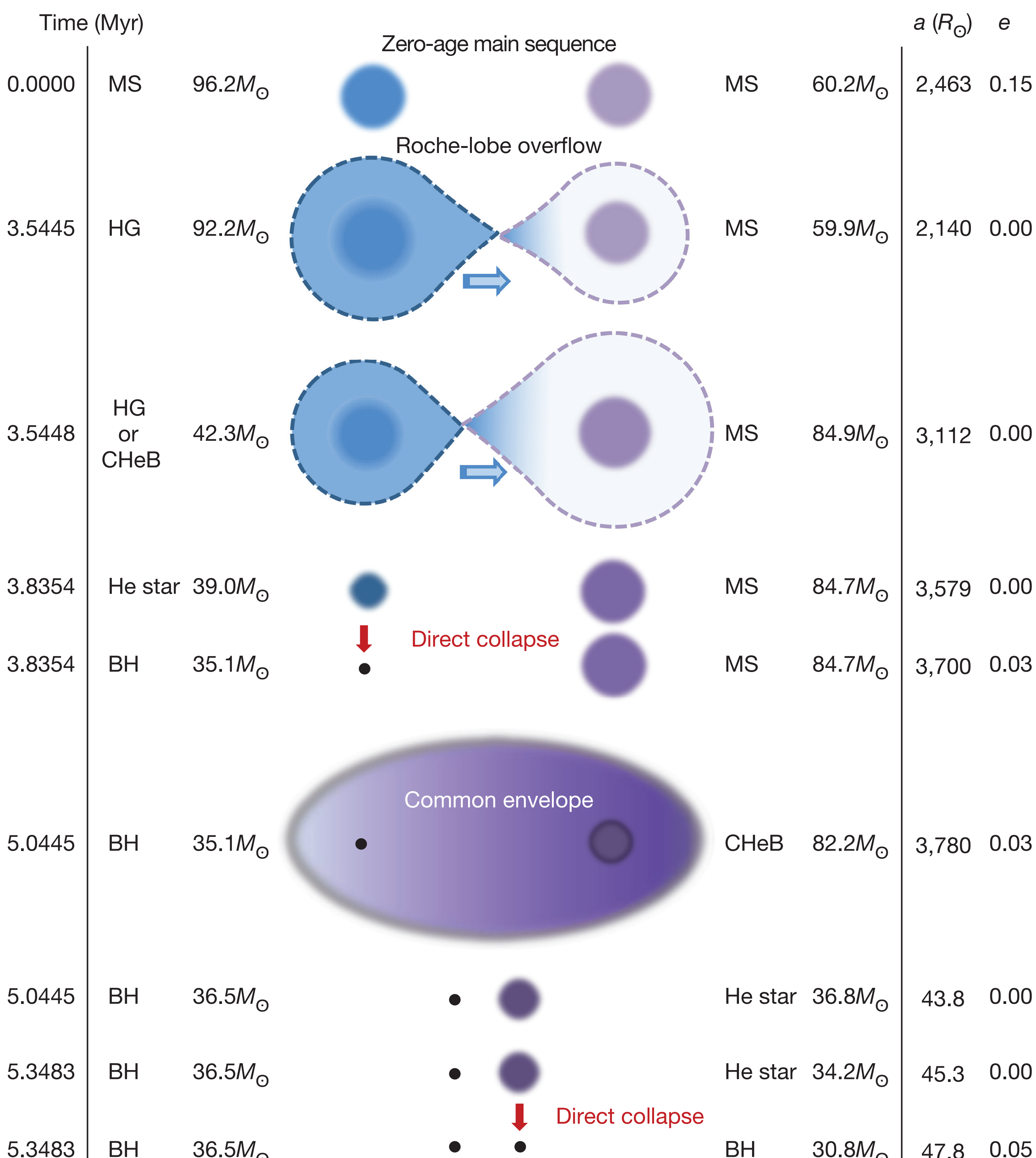
Binary Evolution scenario

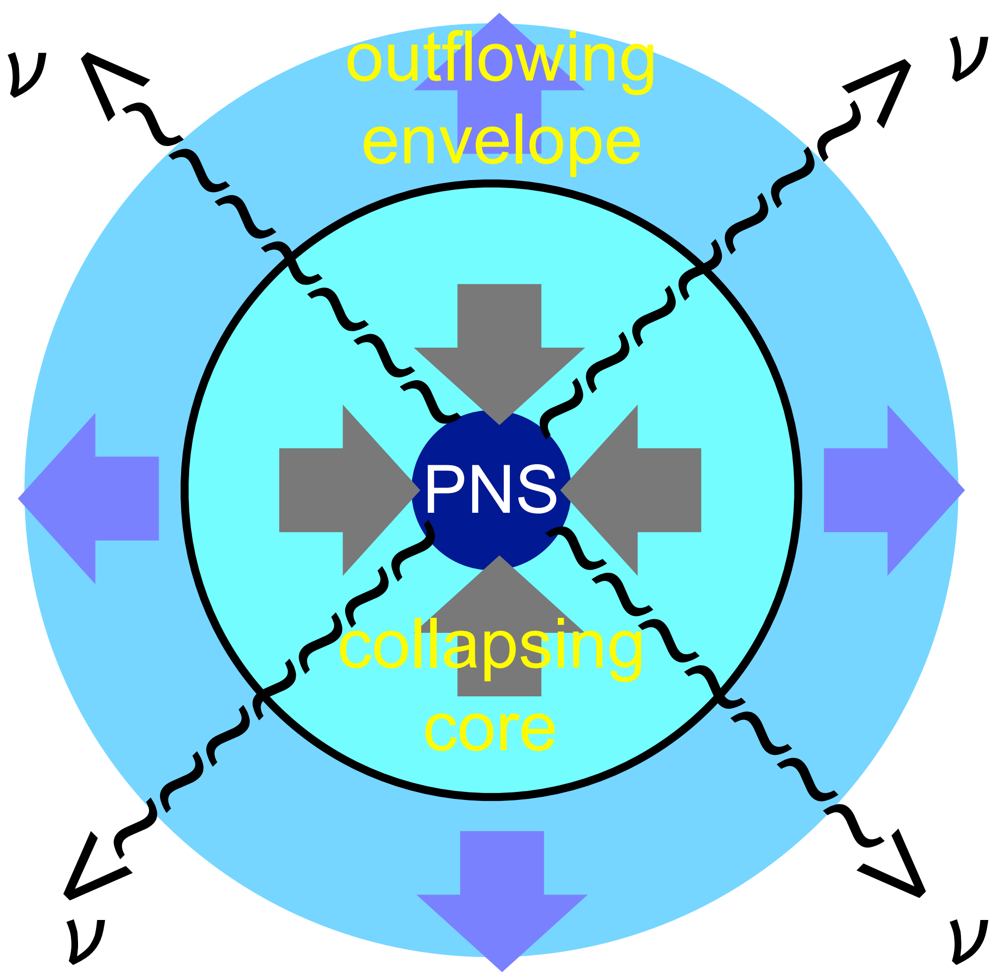


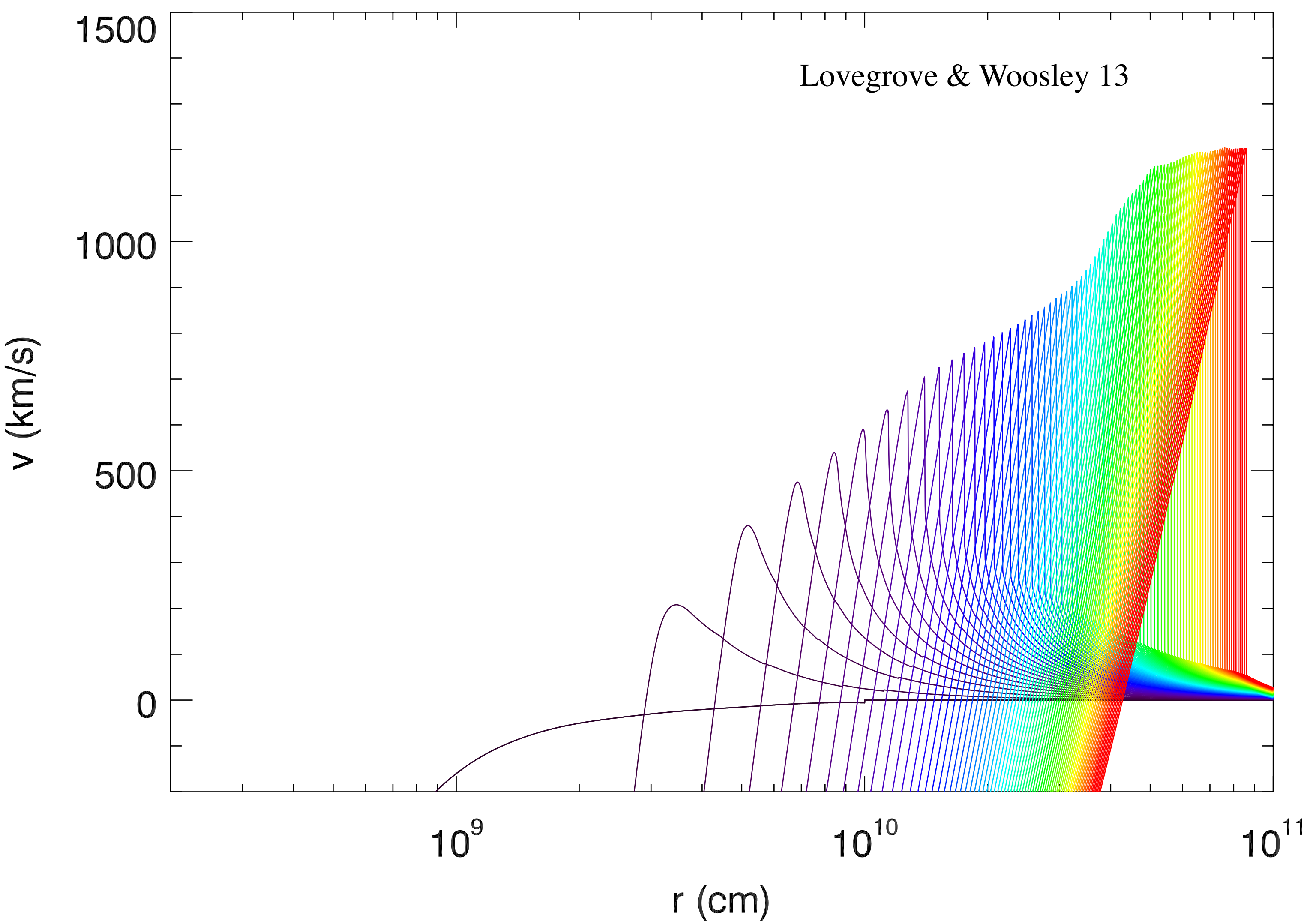
Kinugawa+14, Belczynski+ 16

- massive star binary
  —> Binary Black Hole
- First, Primary —> BH
- Secondary becomes giant
  —>Common envelope
- Ejection of CE
  —> close BH-WR binary
- WR collapses to BH
  —> BBH formation
- Direct Collapse
  = Failed Supernovae

Failed Supernovae

Nadyozhin 80



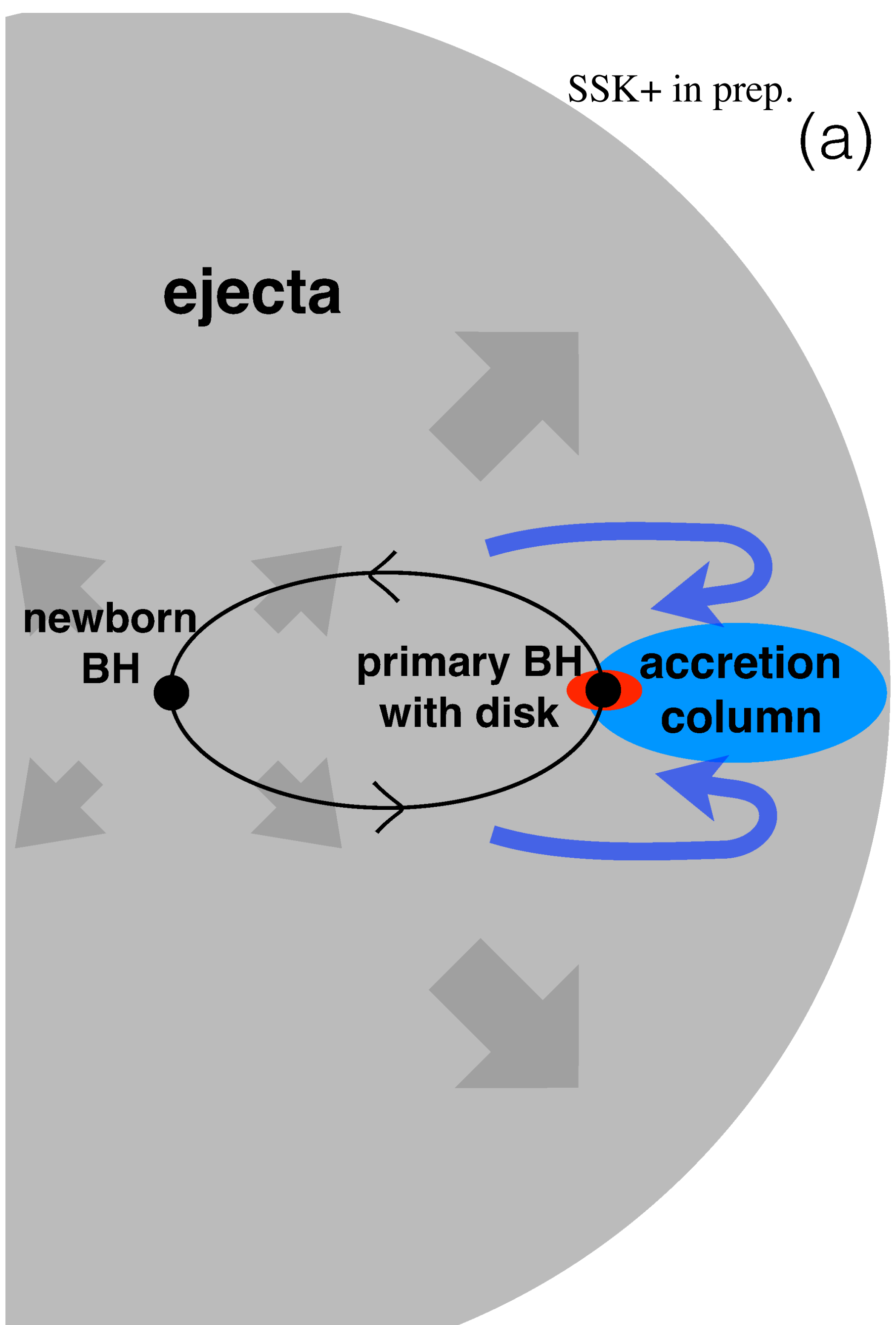


- ProtoNeutron Star forms when massive star collapses
- Neutrino loss —> Binding energy decrease —> shock propagation —> envelope ejection ~ $0.01M_{sun}$

Bondi-Hoyle Accretion

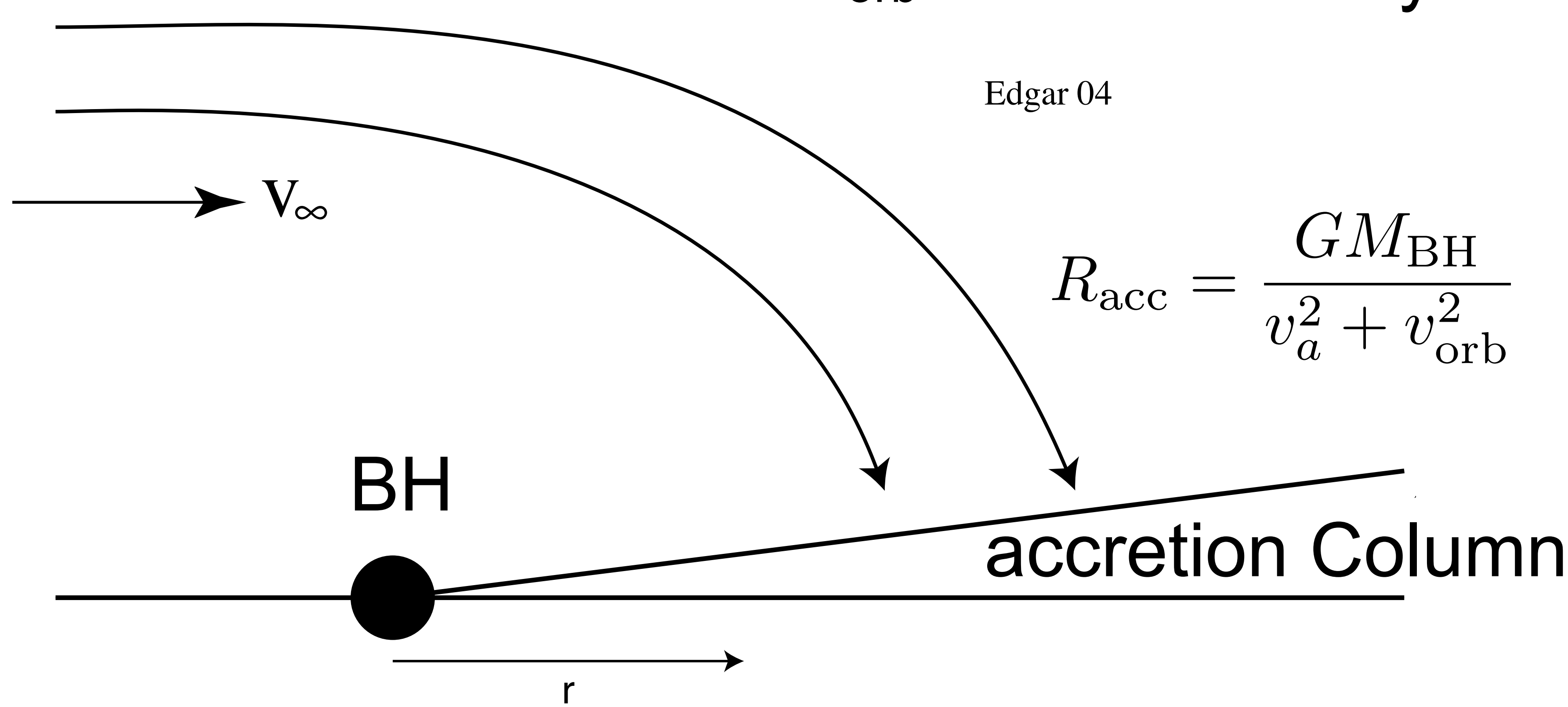
- The primary BH accretes the failed SN ejecta by Bondi-Hoyle accretion rate

SSK+ in prep.



v_a: ejecta velocity
v_{orb}: orbital velocity

Edgar 04

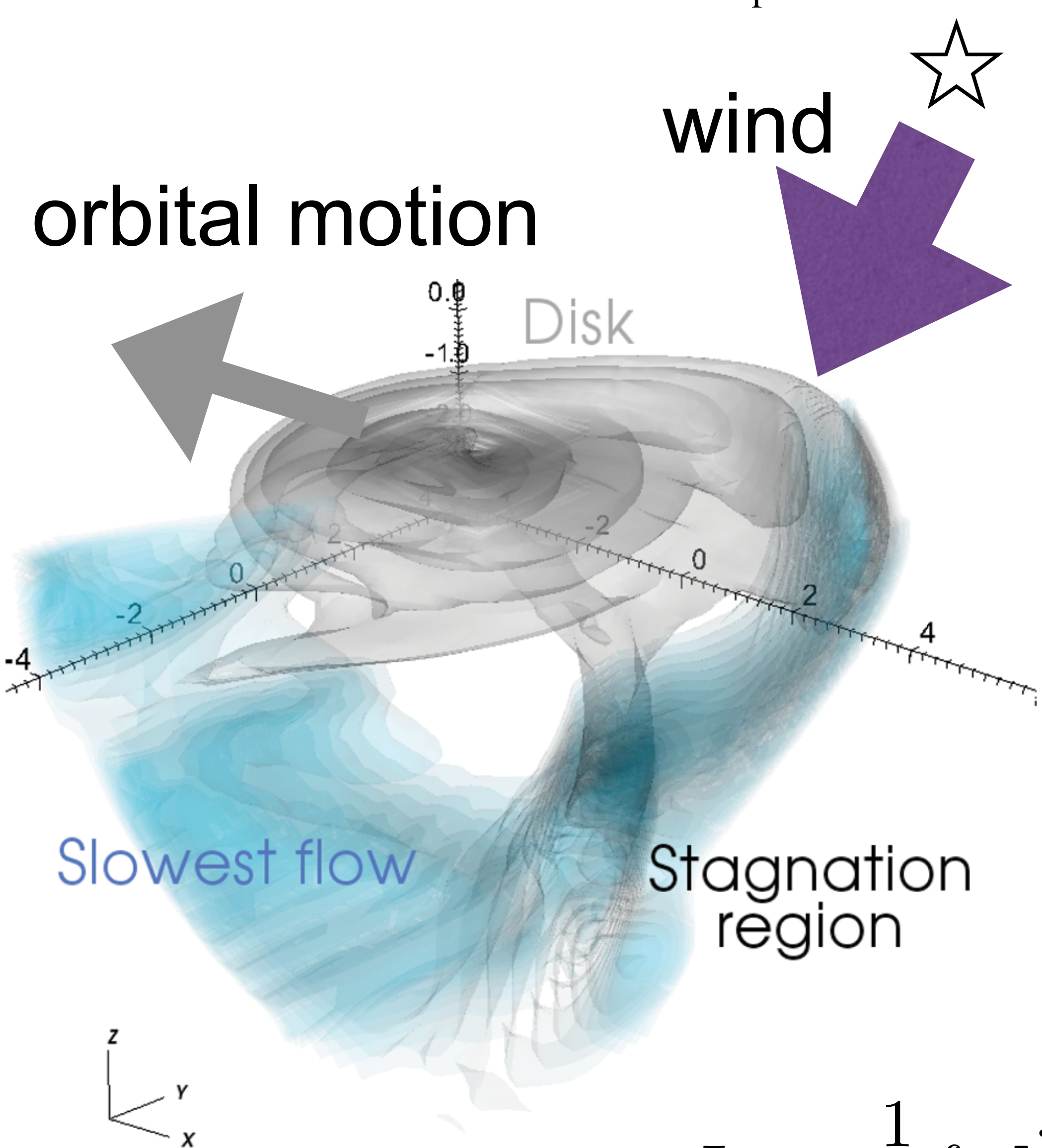


$$R_{\rm acc} = \frac{GM_{\rm BH}}{v_a^2 + v_{\rm orb}^2}$$

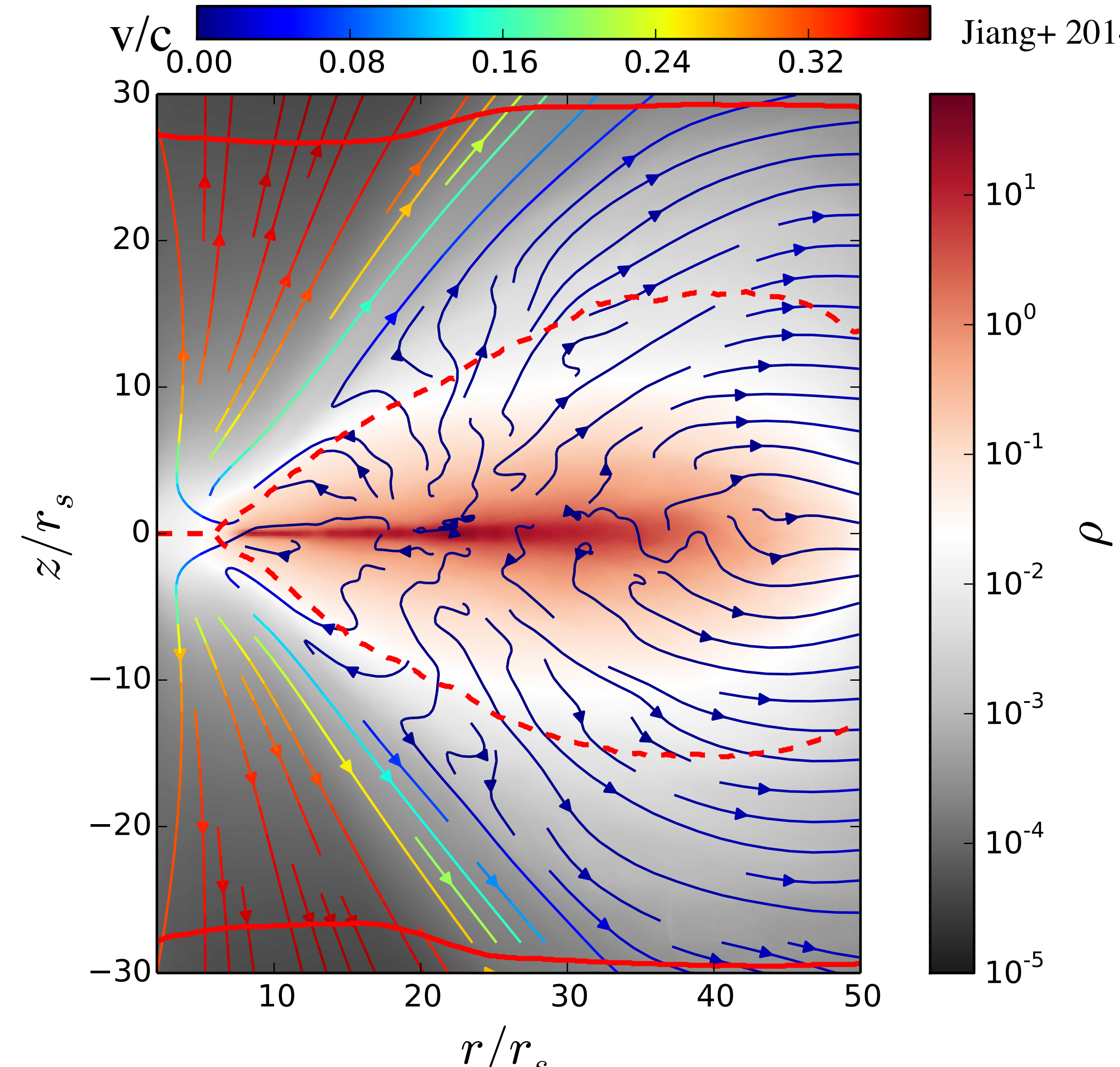
$$\dot{M}_{\rm B\text{-}H} \approx 4\pi R_{\rm acc}^2 \rho_{\rm ej,m} \sqrt{v_a^2 + v_{\rm orb}^2} \sim 4.2\times10^{25}\ {\rm g/s} \gg \dot{M}_{\rm Edd}$$

Radiation-driven Outflow

- Accreted material forms a disk

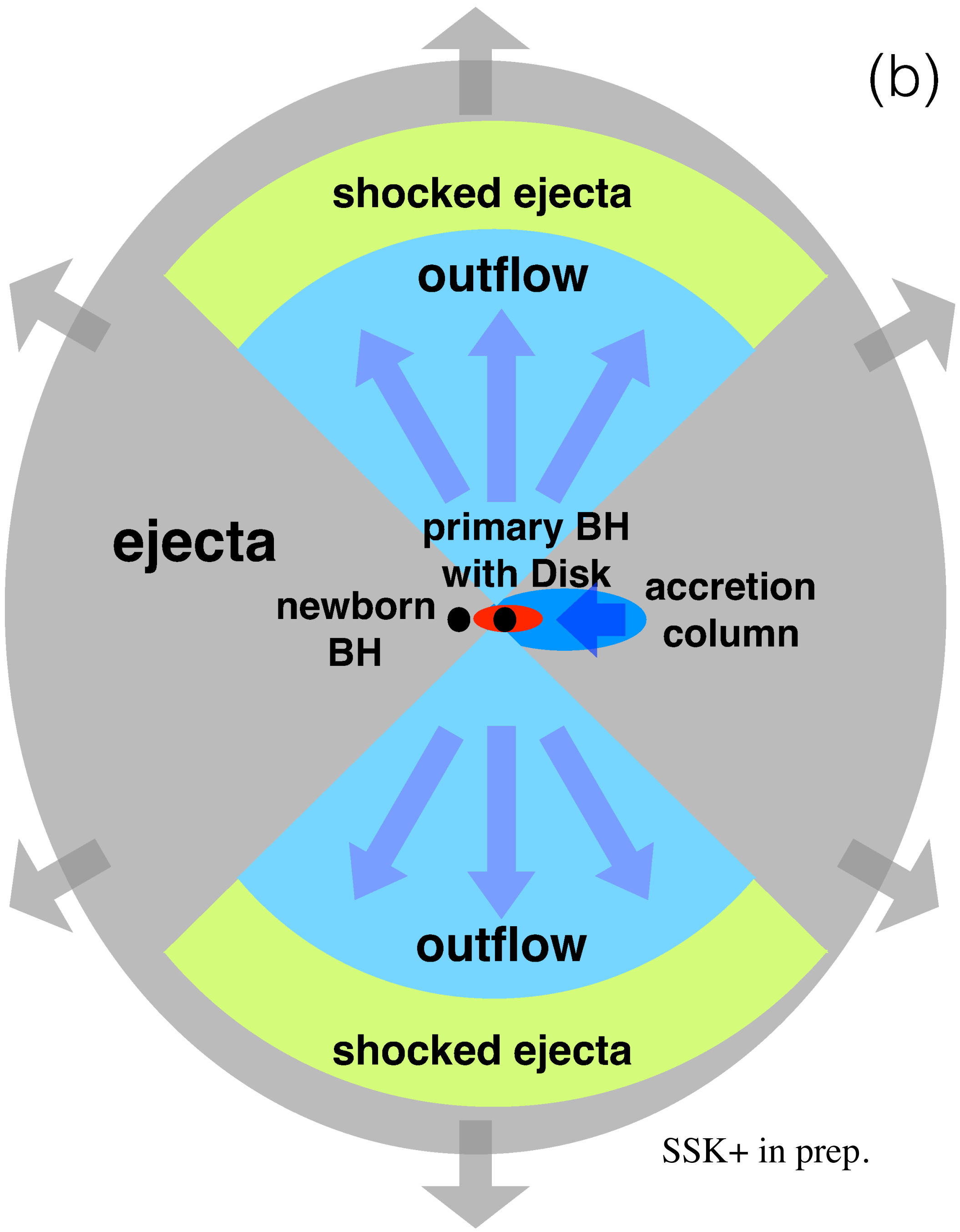


- super-Eddington accretion rate —> A radiation-driven outflow



$L_w \approx \frac{1}{2} f_w \dot{M}_{\text{B-H}} v_w^2$ ~ 6.3x10^{44} erg/s

Outflow-driven SNe



SSK+ in prep.

Assumption: Spherical Symmetric
Homologas expansion

$$\rho_{\rm ej,m} \approx \frac{3m_{\rm ej}}{4\pi a^3}\left(\frac{t}{t_{\rm arr}}\right)^{-3} \qquad v_a = a/t.$$

EoM

$$\frac{dE_{\rm kin}}{dt} = \frac{E_{\rm int}}{t_{\rm dyn}}, \qquad \frac{dR_{\rm ej}}{dt} = v_{\rm ej}.$$

Energy eq.

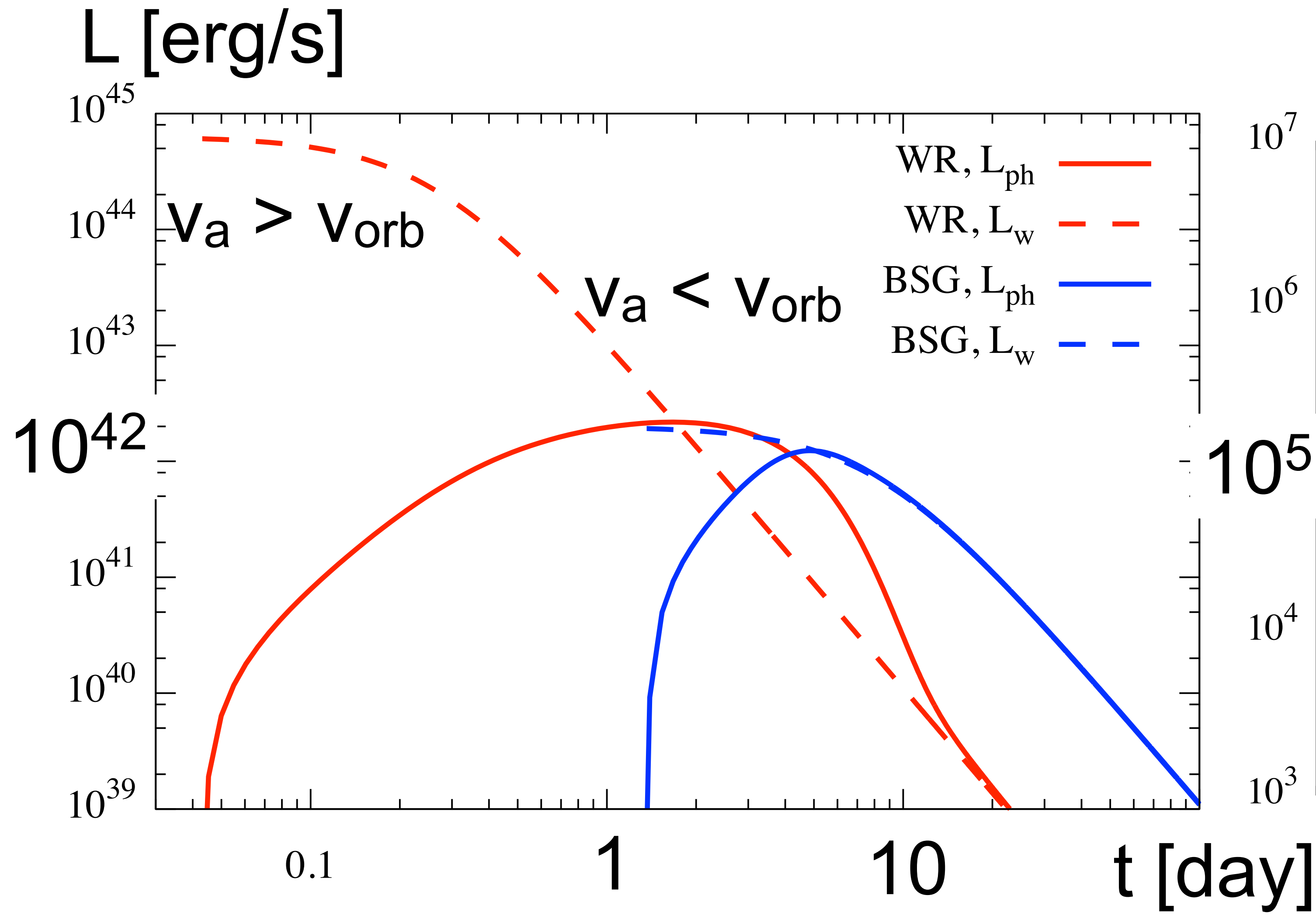
$$\frac{dE_{\rm int}}{dt} = f_i L_w - \frac{E_{\rm int}}{t_{\rm dyn}} - L_{\rm ph},$$

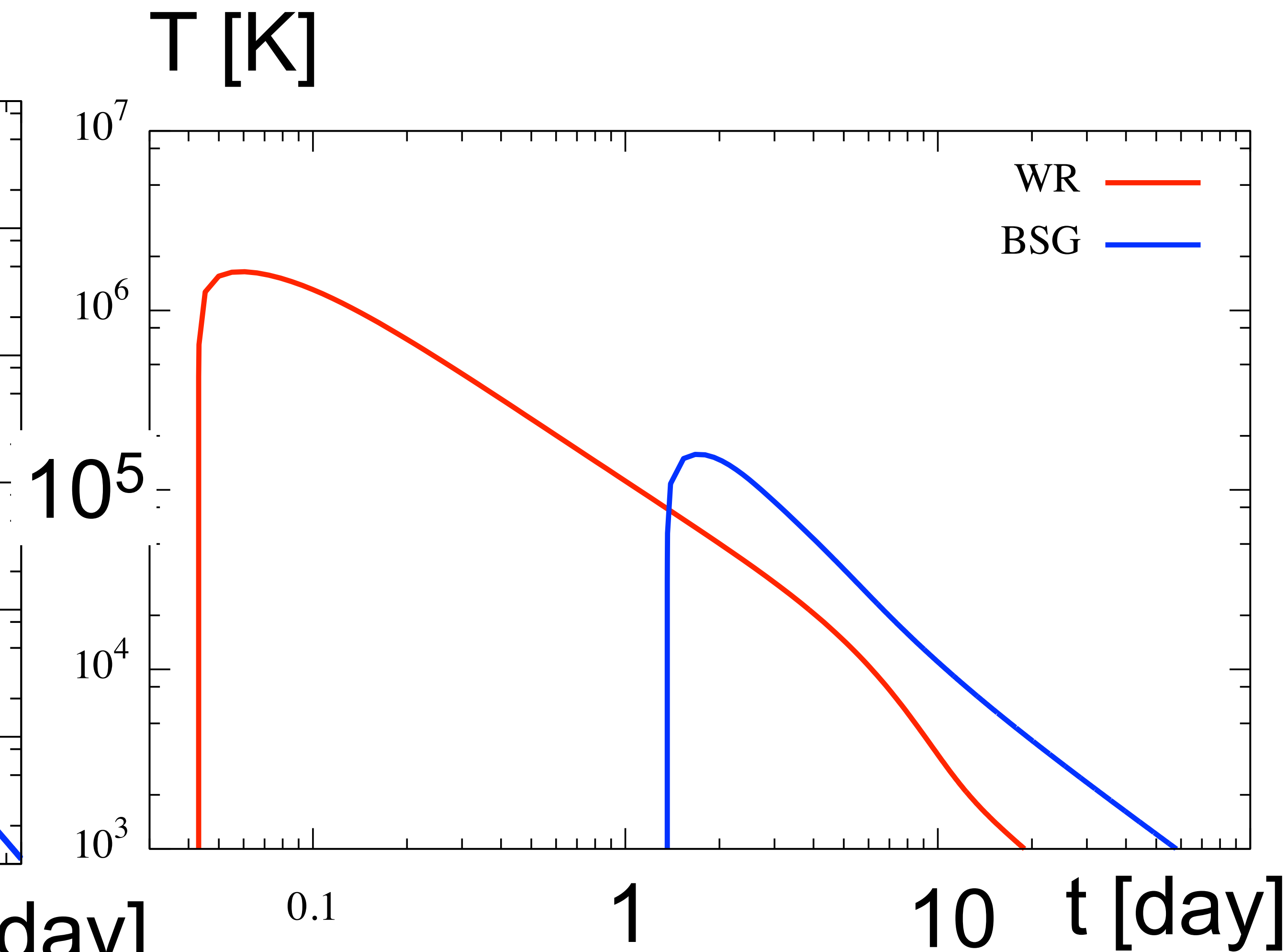
$$L_{\rm ph} = \frac{\epsilon_{\rm rad} E_{\rm int}}{t_{\rm ph}} = \frac{E_{\rm int}}{(1+\tau_{\rm ej})R_{\rm ej}/c}$$

$$\dot{M}_{\rm B\text{-}H} \approx 4\pi R_{\rm acc}^2 \rho_{\rm ej,m} \sqrt{v_a^2 + v_{\rm orb}^2}.$$

- Radiation-driven outflow pushes the ejecta
  —> sub-energetic supernova $\quad E_w \sim 1.4\times10^{49}$ erg

Time Evolution

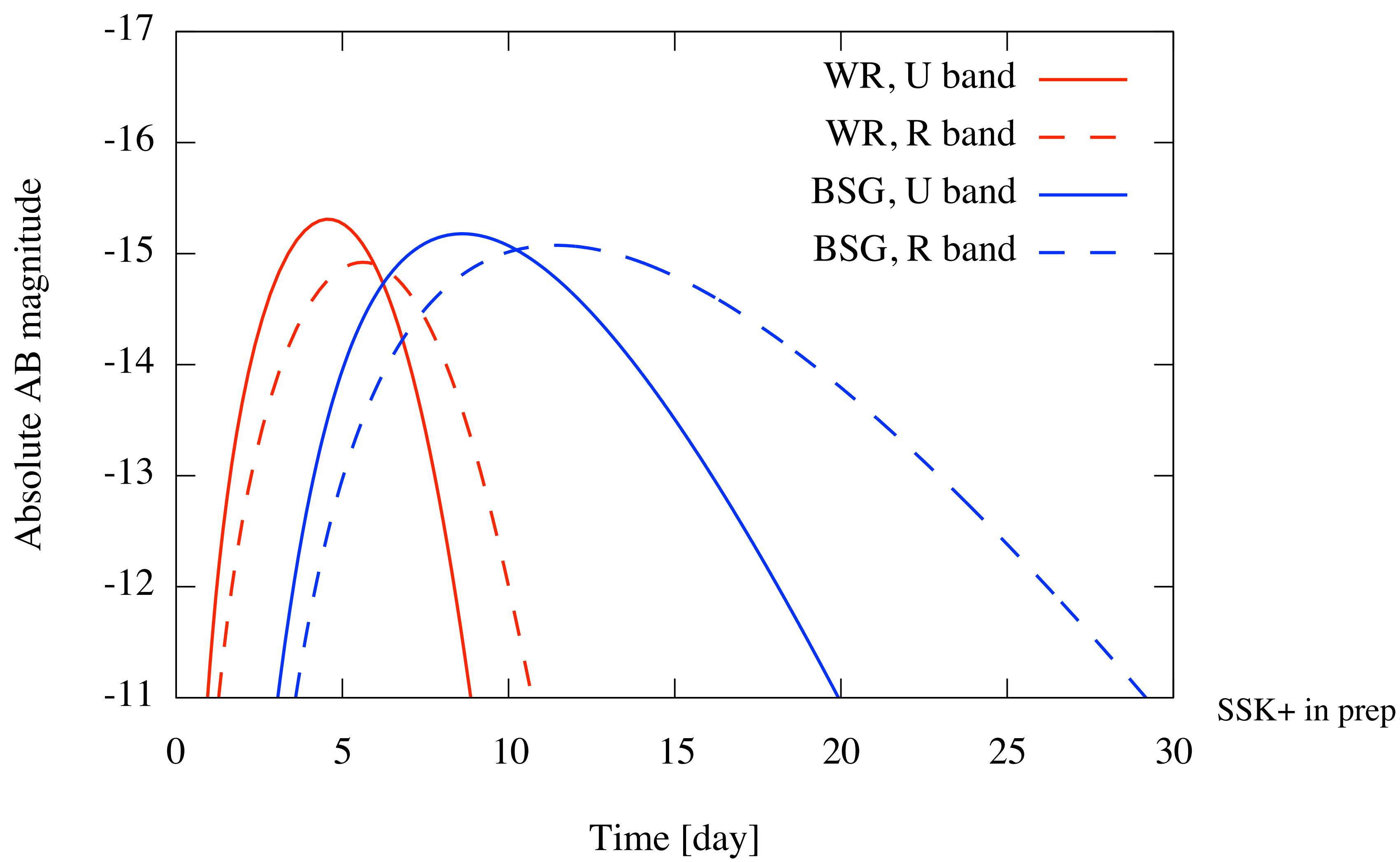




SSK+ in prep.

- Duration: a few days
- Temperature: 10^4 — 10^5 K

Light Curve



- Event rate: similar to LIGO ~ 10–100 Gpc^{-3} yr^{-1}
  —> expected distance ~300 Mpc
  —> ~22 mag. @ 300 Mpc
  —> detectable by Current optical transient survey

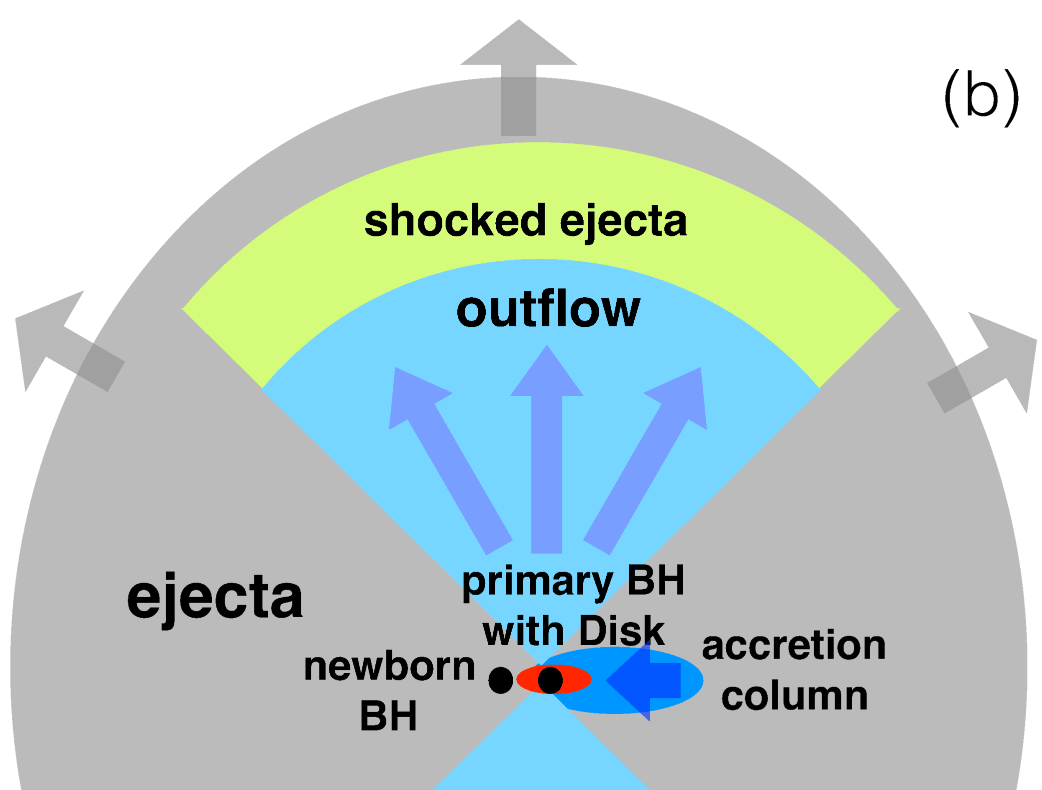
Caveat

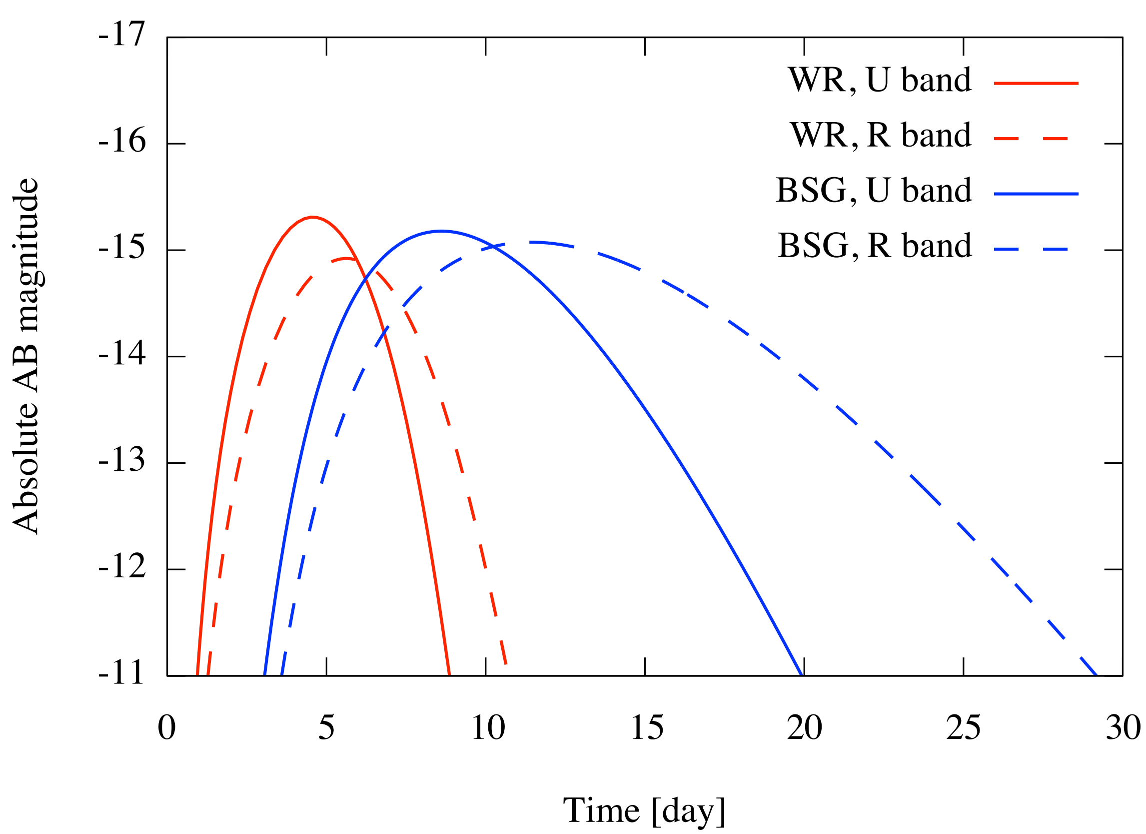
- Spherical symmetric treatment is not accurate
  a) Effect of the outflow on ejecta
  b) Finite binary separation
- To investigate these effect, we need 3D (radiation) hydrodynamic simulation with feedback of outflows from the BH, which might be similar to the galaxy formation simulation with AGN feedback.

Short Summary I

- Accretion of ejecta onto primary BH produces a energetic outflows, which leads to sub-energetic SNe
- Duration of the SNe is a few days, absolute magnitude is ~ -15
- Color is bluer than the usual supernovae

SSK+ in prep.





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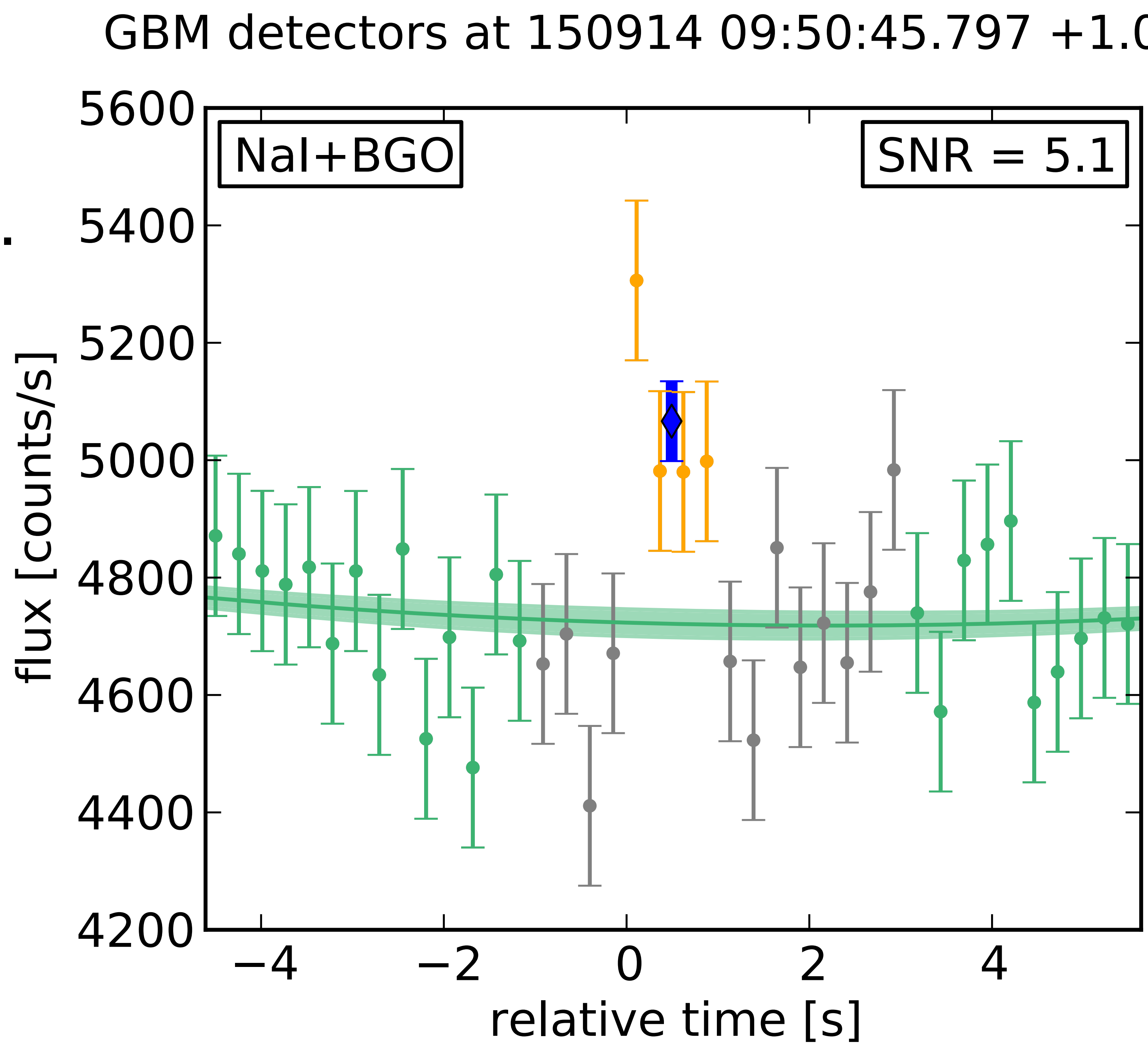
EM Counterparts of GWs

- Fermi GBM reported possible EM counterparts.
Connaughton + 16
- However, some consider this signal is a false alert.
Zhang+16, Greiner+16, Xiong 16
- Theoretical studies show possible models.
Perna+16, Loab 16, Januik+17
- However, these models seem unlikely.
Lyutikov+16, SSK+17, Dai+16



Timescale

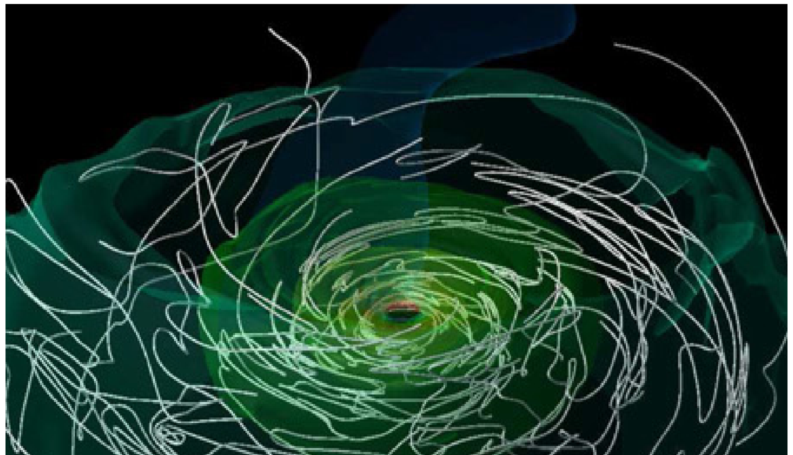
- The material accretes to BH in the viscous time

$$t_{\rm vis} = \frac{1}{\alpha \Omega_{\rm K}} \left(\frac{r_{\rm out}}{H}\right)^2$$

- The BBH merges in a merger time

$$t_{\rm mer} = \frac{5}{512} \frac{c^5}{G^3} \frac{R_{\rm ini}^4}{M_{\rm BH}^3}$$

- t_{vis} ~ 3×10^4 s << t_{mer} ~ 4×10^{15} s @ R_{ini}~10^{12} cm, M~30 Msun
  —> The material completely accretes to BH if angular momentum is efficiently transported by MHD turbulence

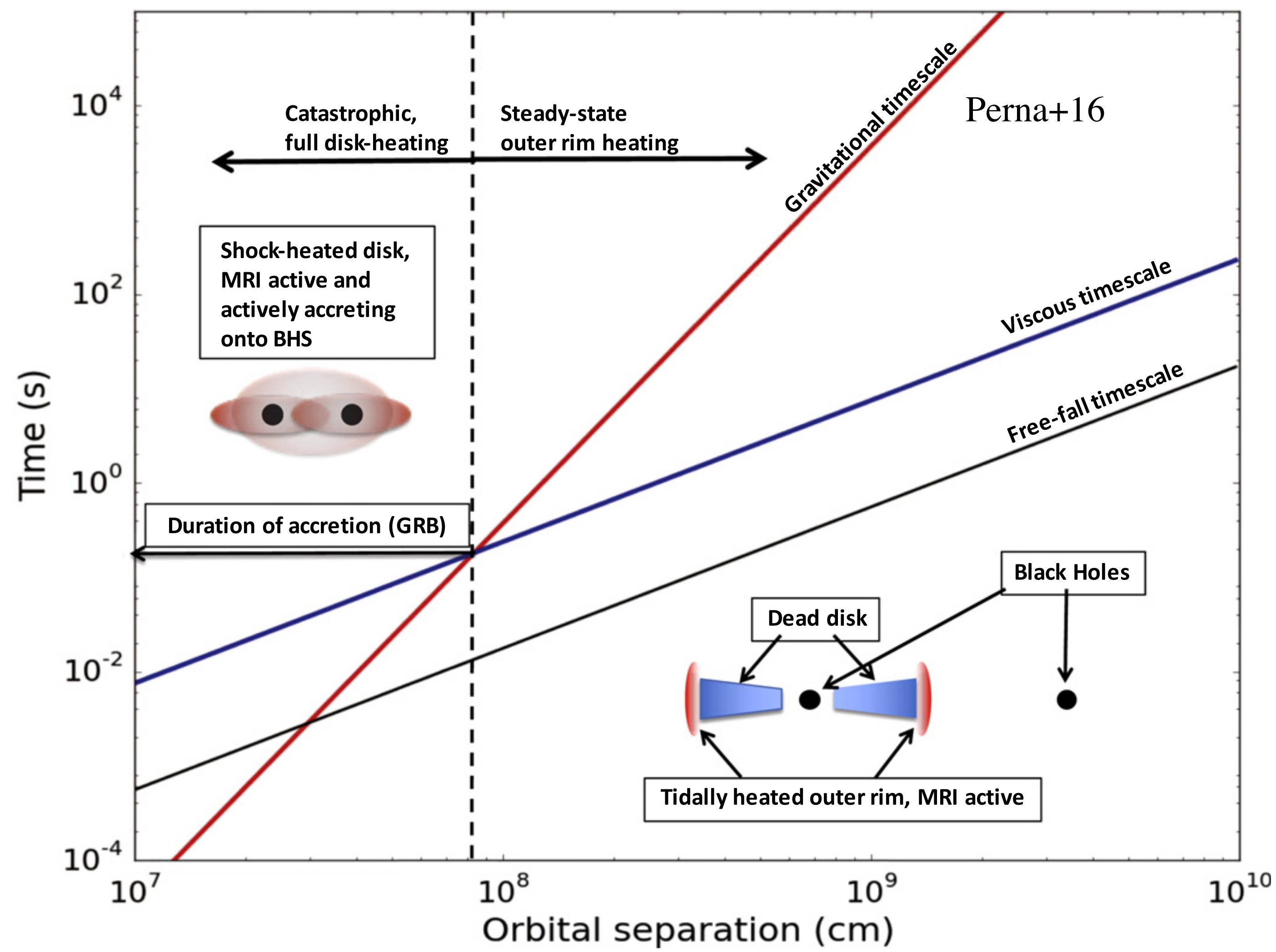


Dead disk model

- Perna+2016 propose the dead disk model for Fermi GBM event

If the disk cools down and becomes neutral, the MHD turbulence becomes weak, and make a “dead disk” where angular momentum transform is inefficient.

a) dead disk survives until $t_{mer} < t_{vis}$ (~1 s before the merger event).
b) rapid accretion can produce GRB.



Motivation

Perna's model seems to misestimate or ignore

i) tidal torque from the companion

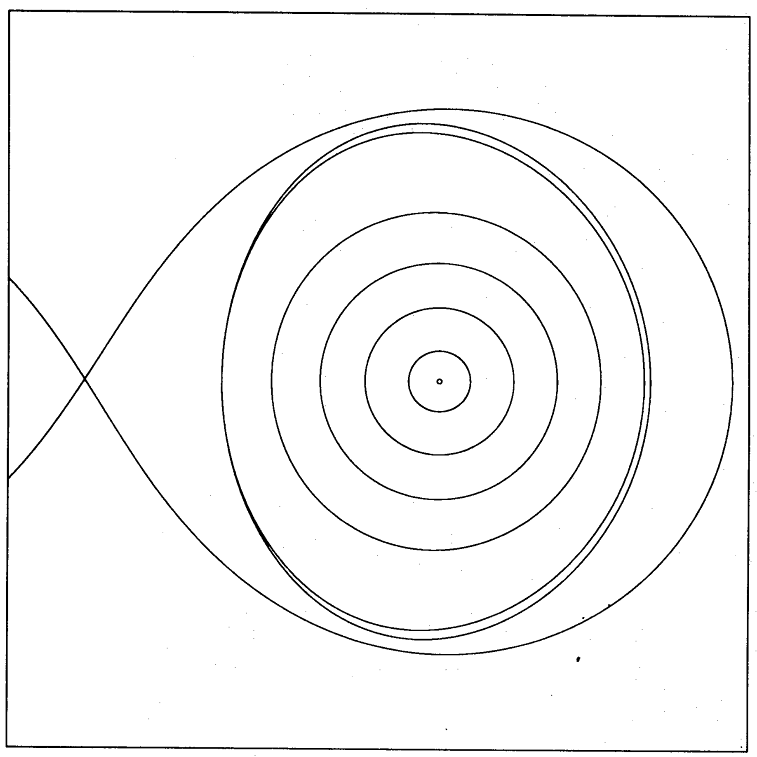
ii) condition for MRI activation/inactivation

iii) mass inflow due to separation decrease

We examine the dead disc model, taking account of the above processes more carefully.

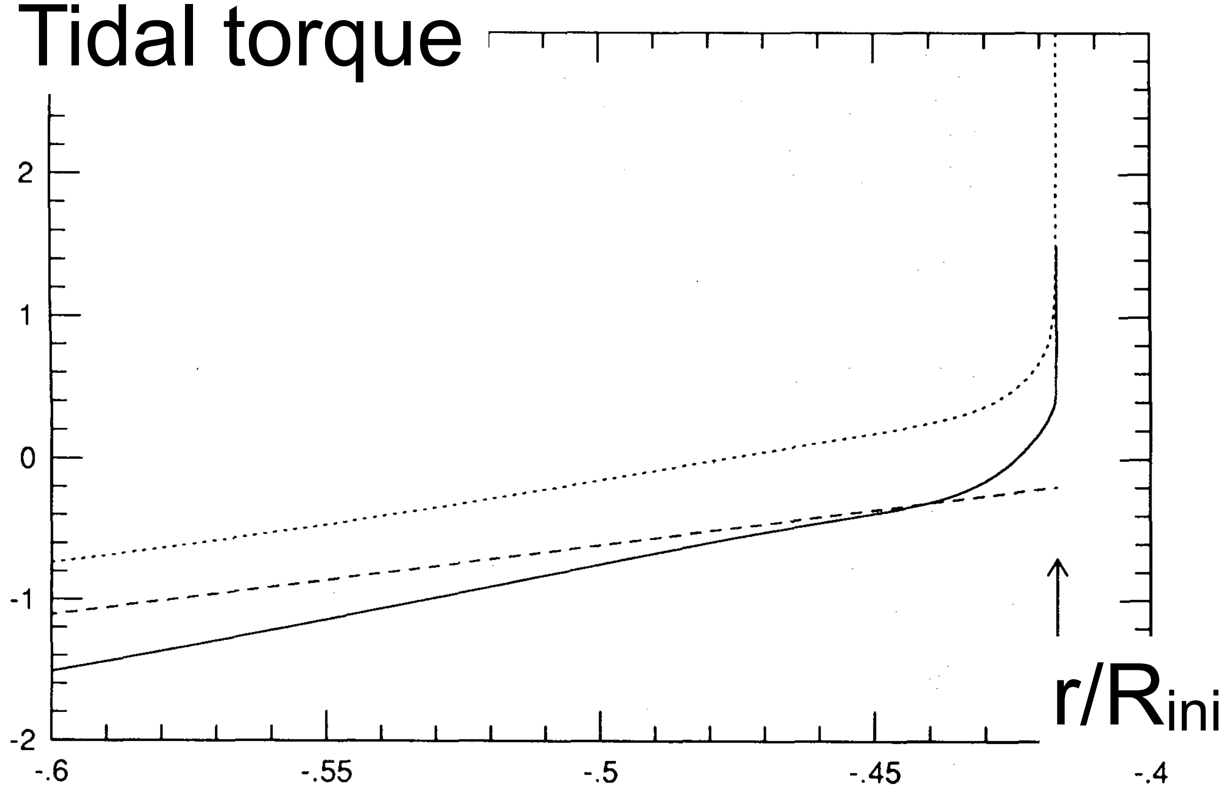
Tidal torque

Non-Axisymmetric gravity induces torque



Orbits of test particles

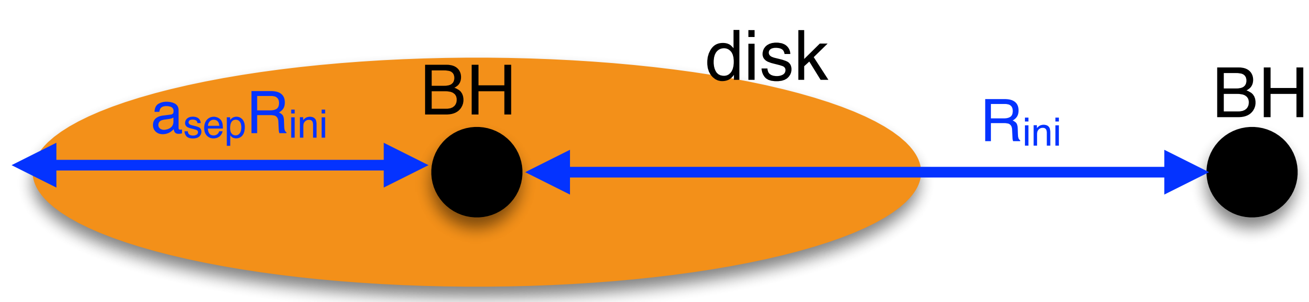
Ishikawa & Osaki 94



Radial profile of tidal torque

Tidal torque diverges at tidal truncation radius

→ The disk cannot expand outward beyond there



Disk Evolution in BBH

$t_{vis} \sim 3\text{x}10^4$ s << $t_{mer} \sim 4\text{x}10^{15}$ s
@ $R_{ini} \sim 10^{12}$ cm
—> separation does not change during initial evolution

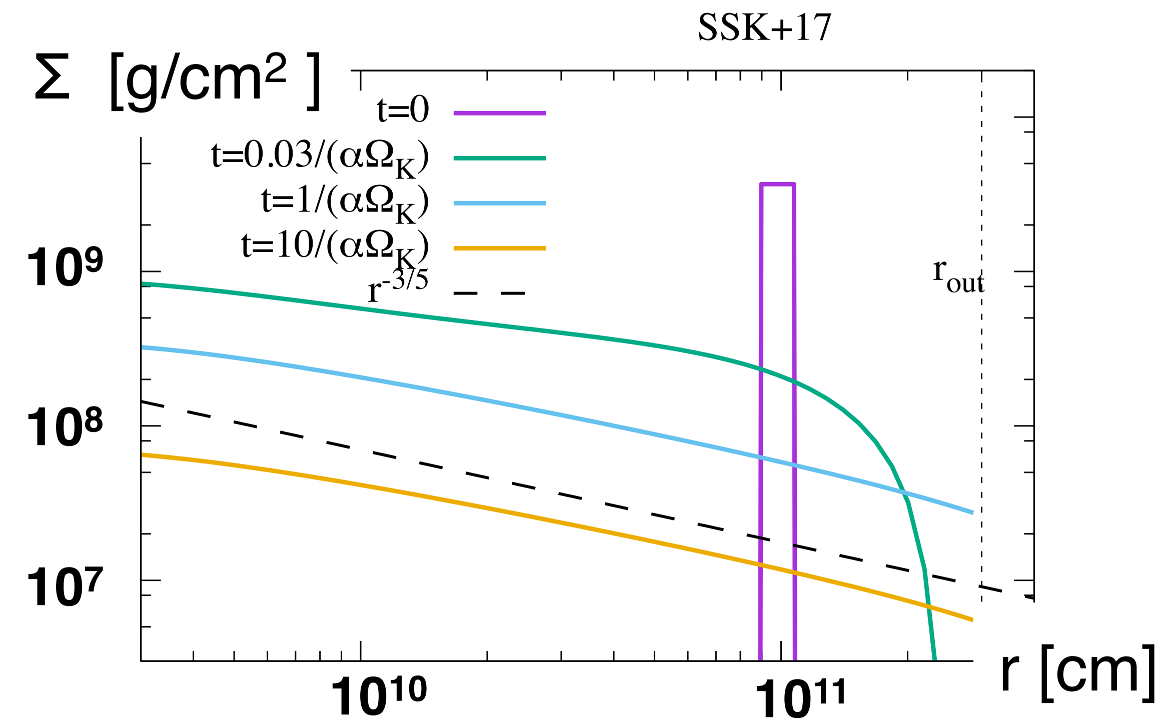
$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[\frac{1}{dj/dr}\frac{\partial}{\partial r}\left(\nu\Sigma r^3\frac{d\Omega}{dr}\right)\right]$$

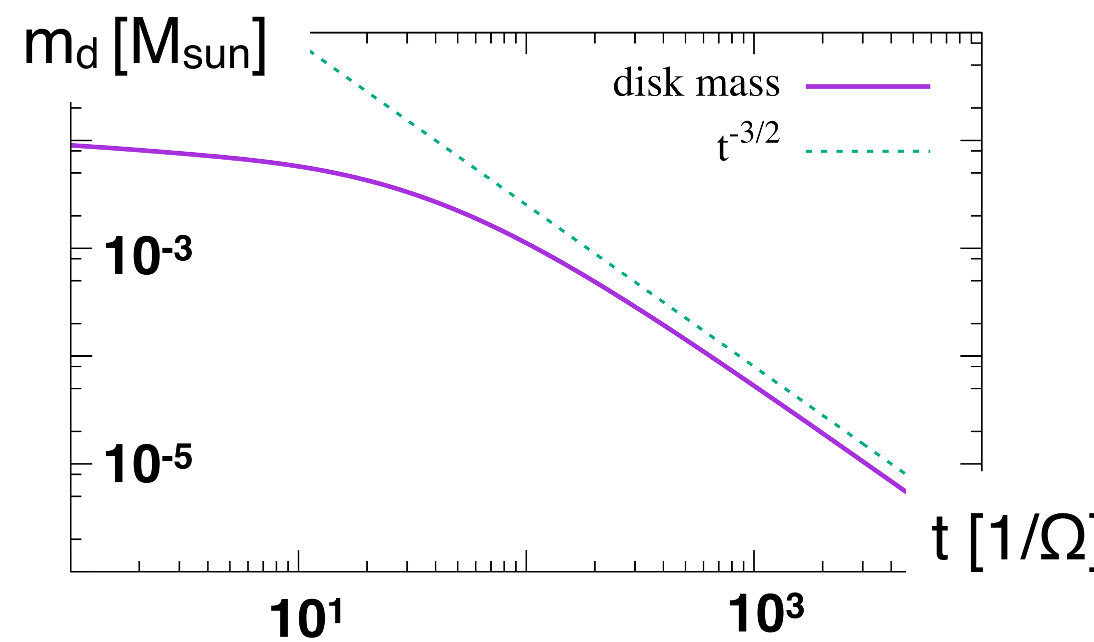
$Q_{\rm vis} = Q_{\rm rad}$, $\dot{M}=0$ at $r=r_{out}$

$$m_{\rm d} = m_0\,(t/t_{\rm ini})^{-3/2}$$

$$\Sigma = \Sigma_0\,(t/t_{\rm ini})^{-3/2}\,(r/r_{\rm out})^{-3/5}$$

$$T = T_0\,(t/t_{\rm ini})^{-1}\,(r/r_{\rm out})^{-9/10}$$





Formation of Dead disk

Condition for MRI activation: $\Lambda = \frac{v_A^2}{\eta\Omega_K} > 1,$

Saha's equation

$$\frac{\chi_e^2}{1-\chi_e} = \frac{1}{n}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} \exp\left(-\frac{E_i}{k_B T}\right)$$

Ohmic resistivity

$$\eta = 234(T/1\mathrm{K})^{1/2}\chi_e^{-1}\mathrm{cm}^2\mathrm{s}^{-1}$$

Blae+94

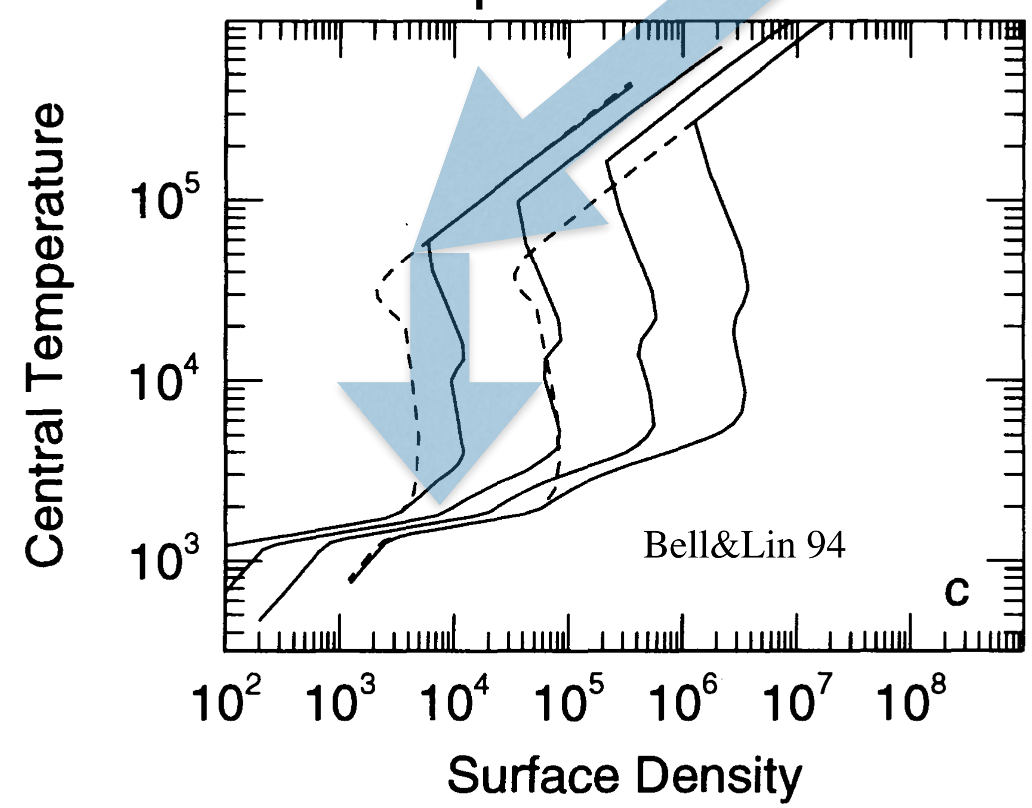
$T > T_{dead}$ ~3000K

Lasota'01

Thermal instability@T~ 40000K

—> rapid temperature drop to $T<T_{dead}$

Thermal equilibrium curves

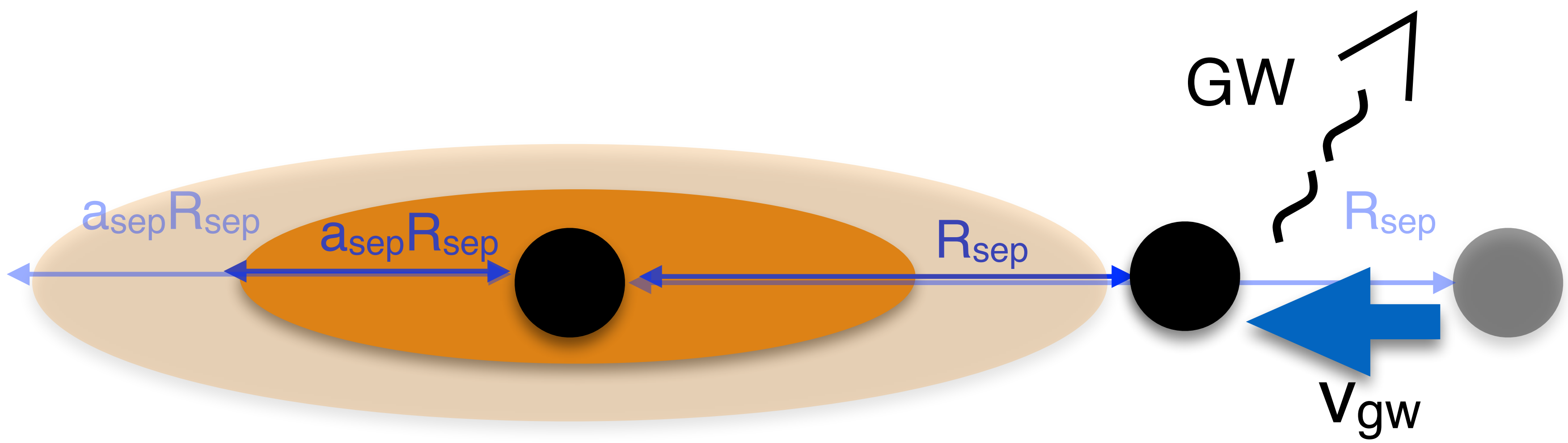


Dead disk formation

$m_{dead} \sim 5\text{x}10^{-7} M_{sun}$

$t_{dead} \sim$ a few years

Disk Revival



- Separation decreases due to GW
  —> The dead disk shrinks due to tidal torque
  —> Disk heats up due to mass inflow
  —> Disk Revival: MRI becomes active ($T > T_{dead}$)
- Disk revival condition: $Q_+ \sim \dot{M}_{sd}\,\Omega^2 > Q_{rad}(T_{dead})$
  —> $R_{rev} \sim 1.4 \times 10^{11}$ cm, $\dot{M}_{rev} \sim 2.6 \times 10^{14}$ g/s $\ll \dot{M}_{Edd}$
- Time until merger: $t_{mer} - t_{rev} \sim 10^{12}$ s

Impossible to explain short GRBs

Evolution of Revival Disk

GW determines evolution of R_{sep}

$$R_{\rm sep} = R_{\rm rev}\left(\frac{t_{\rm mer}-t}{t_{\rm mer}-t_{\rm rev}}\right)^{1/4}$$

Tidal torque controls $\dot{M}$ of revival disk

$$\dot{M}_{\rm GW} = -2\pi r_{\rm out}\Sigma_{\rm out} a_{\rm sep} v_{\rm GW} = -\frac{7 m_{\rm d} v_{\rm GW}}{5 R_{\rm sep}}$$

Solve $dm_d/dt = -\dot{M}_{GW}$

$$m_{\rm d} = m_{\rm dead}\left(\frac{t_{\rm mer}-t}{t_{\rm mer}-t_{\rm rev}}\right)^{7/20}$$

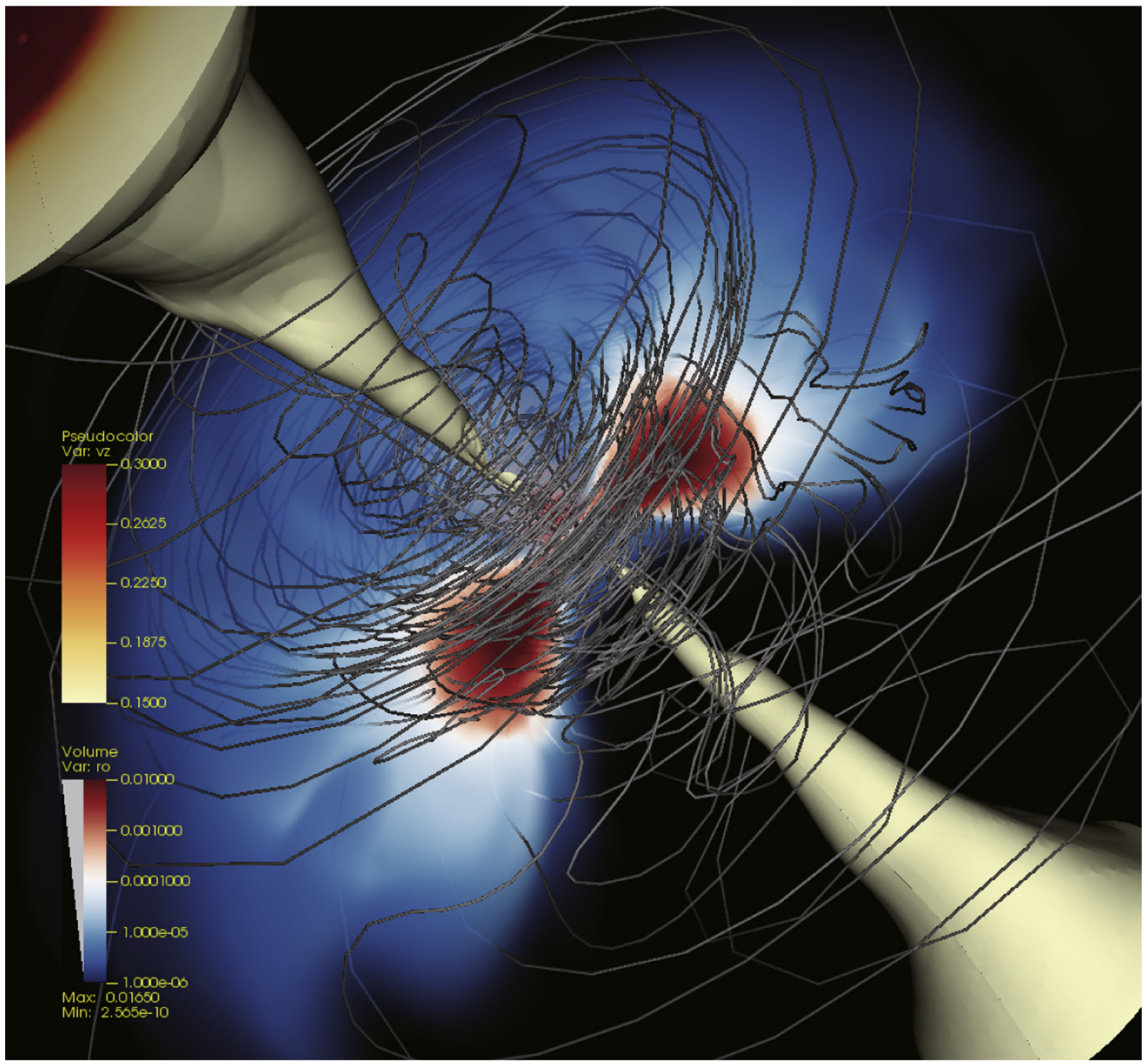
$$\dot{M}_{\rm GW} = \frac{7 m_{\rm dead}}{20(t_{\rm mer}-t_{\rm rev})}\left(\frac{t_{\rm mer}-t}{t_{\rm mer}-t_{\rm rev}}\right)^{-13/20}$$

$\dot{M}_{GW}$ increases with time and

$\dot{M}_{GW}$ can be super Eddington before merger

Jet launching

Takahashi & Ohsuga 16



- High Accretion rate
  —> Geometrically thick
  & strong magnetic field
  —> jet can be launched
- Jet launch condition:
  $\dot{M}_{GW} > \dot{M}_{jet} \sim 10L_{Edd}/c^2$
- Luminosity of Jets:
  $L_{jet} \sim \dot{M}_{GW}c^2$

Emission from Jet

estimate with simplest modeling

- Internal Shock: 10% of L_{jet} goes to X-ray

$$F_{band} \sim 0.1 L_{jet} / (4 \pi d_L^2)$$

- Afterglow: 10% of L_{AG} goes to optical

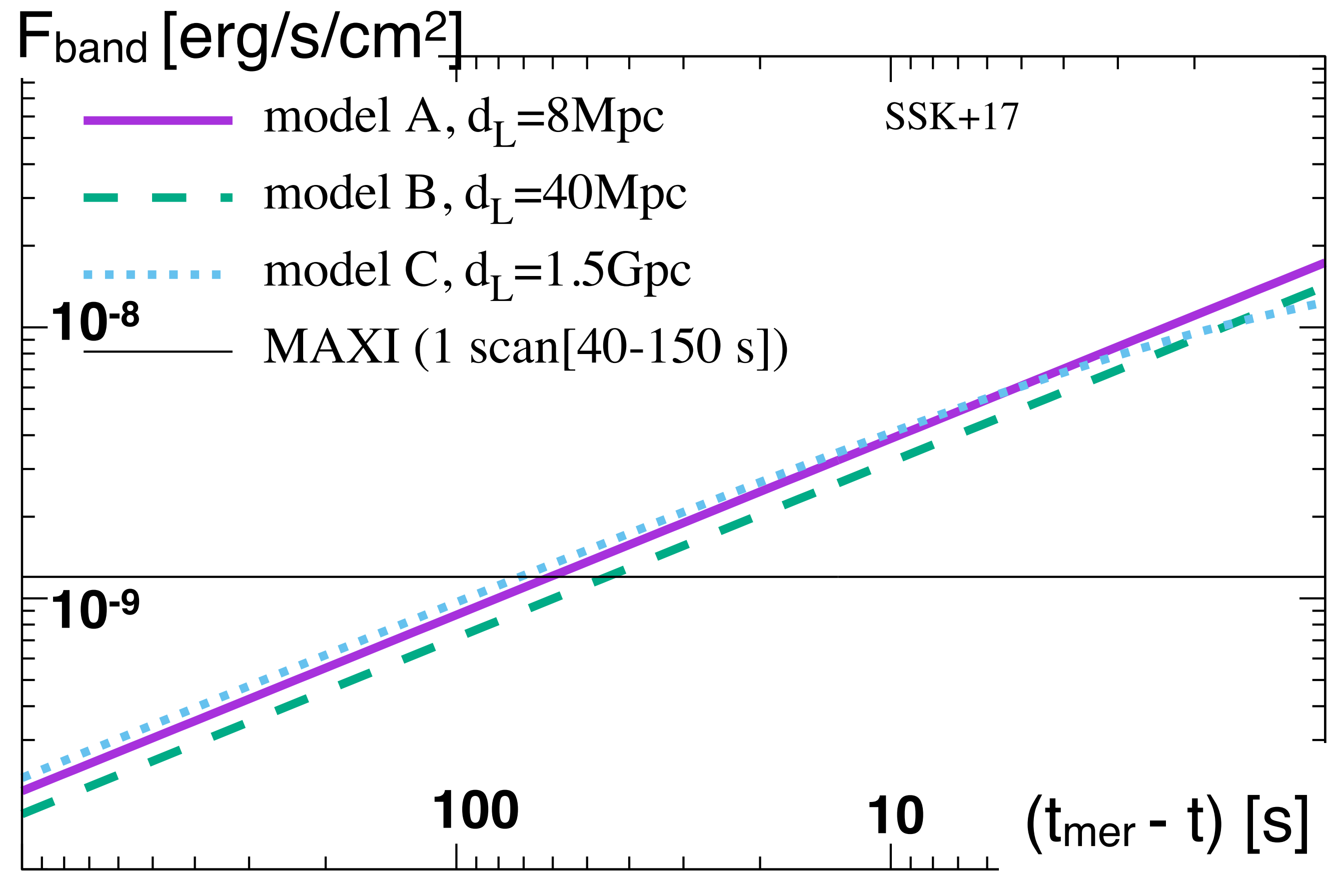
$$L_{AG} \sim \frac{E_{jet}(t)}{t - t_{jet}} = \frac{\int_{t_{jet}}^{t} L_{jet} dt'}{t - t_{jet}} \sim \dot{M}_{GW} c^2 \sim 10 L_{Edd}$$

J-GEM, Pan-STARRS

Detectable by optical followup and/or X-ray monitoring

MAXI, SWIFT

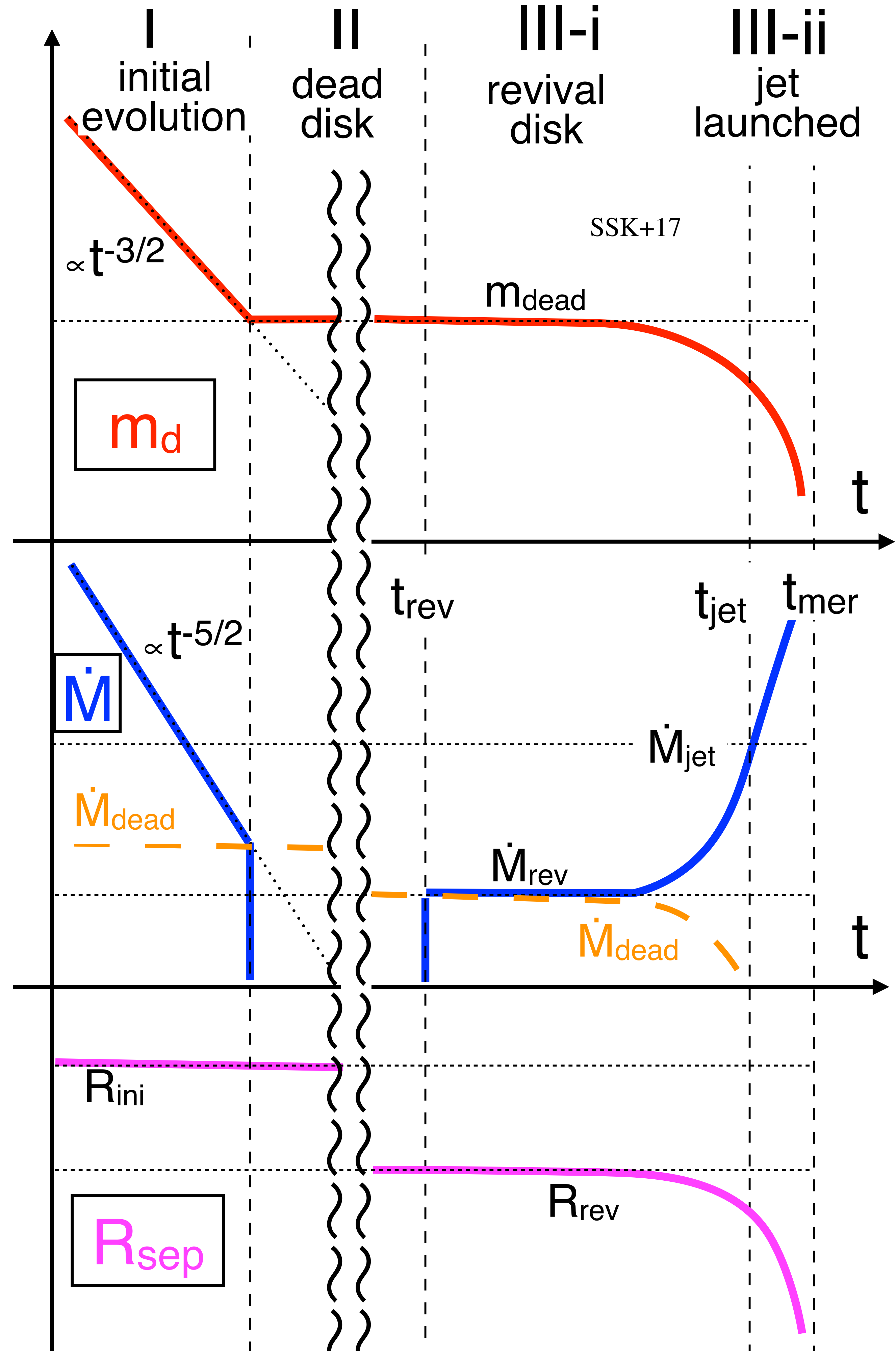
Light curves of internal shock emission



model	$M_{BH}[M_\odot]$	R_{ini} [cm]	$(t_{mer} - t_{jet})$ [s]	L_{AG} [erg s^{-1}]	T_{AG} [s]	$d_{L,limit}$ [Mpc]
A	30	3×10^{12}	3.0×10^5	3.8×10^{40}	1.5×10^3	19
B	10^3	3×10^{13}	4.7×10^6	1.3×10^{42}	1.0×10^4	1.1×10^2
C	10^5	10^{15}	4.36×10^8	1.3×10^{44}	2.1×10^5	1.1×10^3

Short Summary II

- Evolution of accretion disk in BBHs are shown in the left panel.
- Disk becomes dead when the disk sufficiently cools down.
- The dead disk revives due to tidal torque ~10^5 yr before the merger event.
- EM counterparts are detectable before the merger if merger happens around 10 Mpc.



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Summary

- Detection of GW reveals existence of BBHs.
- BBHs can emit EM radiation when they are born or they merge.
- Sub-energetic SNe from newborn BBHs are detectable by current optical transient surveys.
- Dead disk revives ~10^5 years before the merger, and it produces not GRB like burst but weak transient of longer duration.