Multi-wavelength Detectability of Mass Ejection in Failed Supernovae from Blue Supergiants and Wolf-Rayet Stars

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Jets and Shock Breakouts in Cosmic Transients, May 15, 2018

1. Motivation

2. Shock and Ejecta Evolution

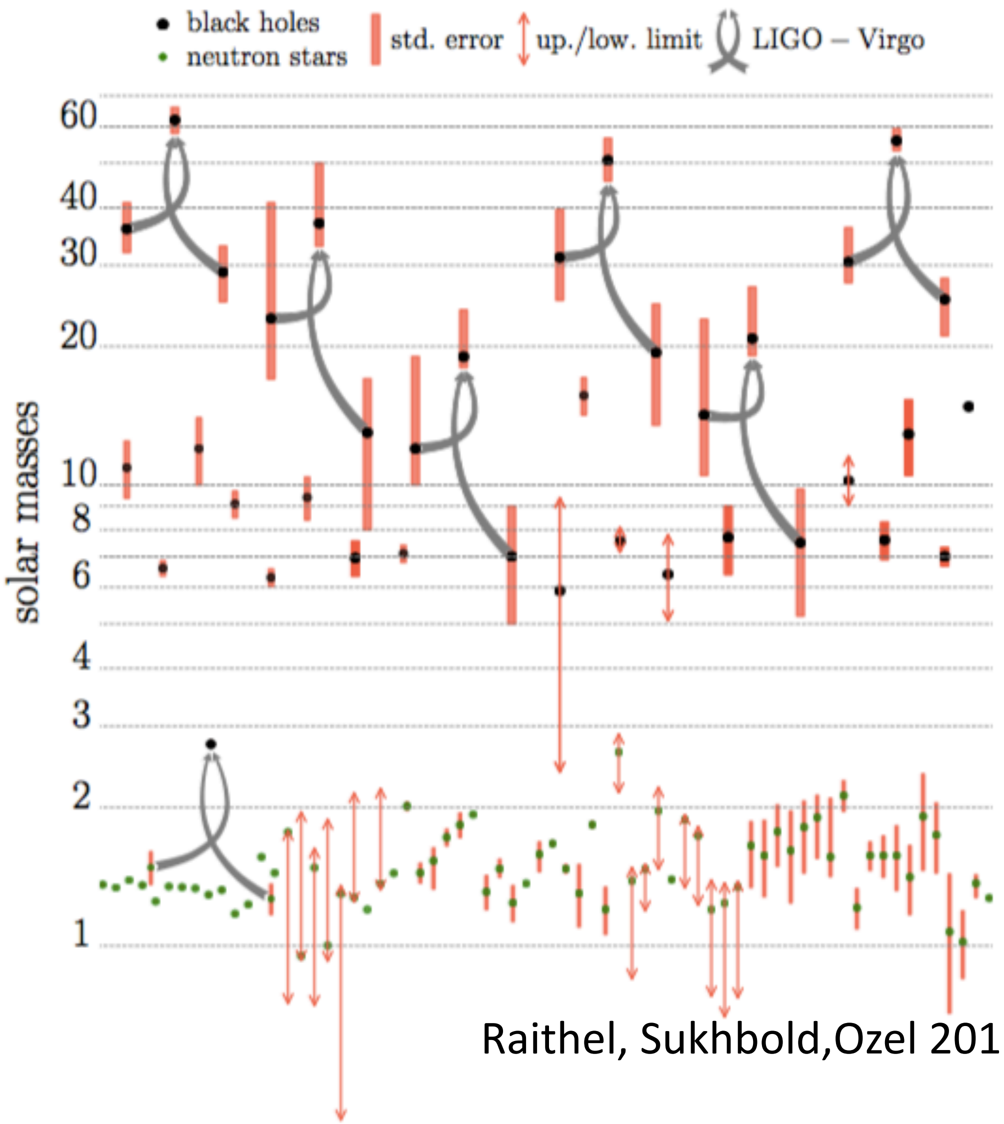
3. Emission and Detectability

Black Holes in Nearby Universe

- Previous X-ray observations find ~20 candidates of BH binaries
- Recent detections of stellar-mass BH mergers by LIGO-Virgo
- Questions:

➢What are their properties?

➢How did they form?



Raithel, Sukhbold,Ozel 2017

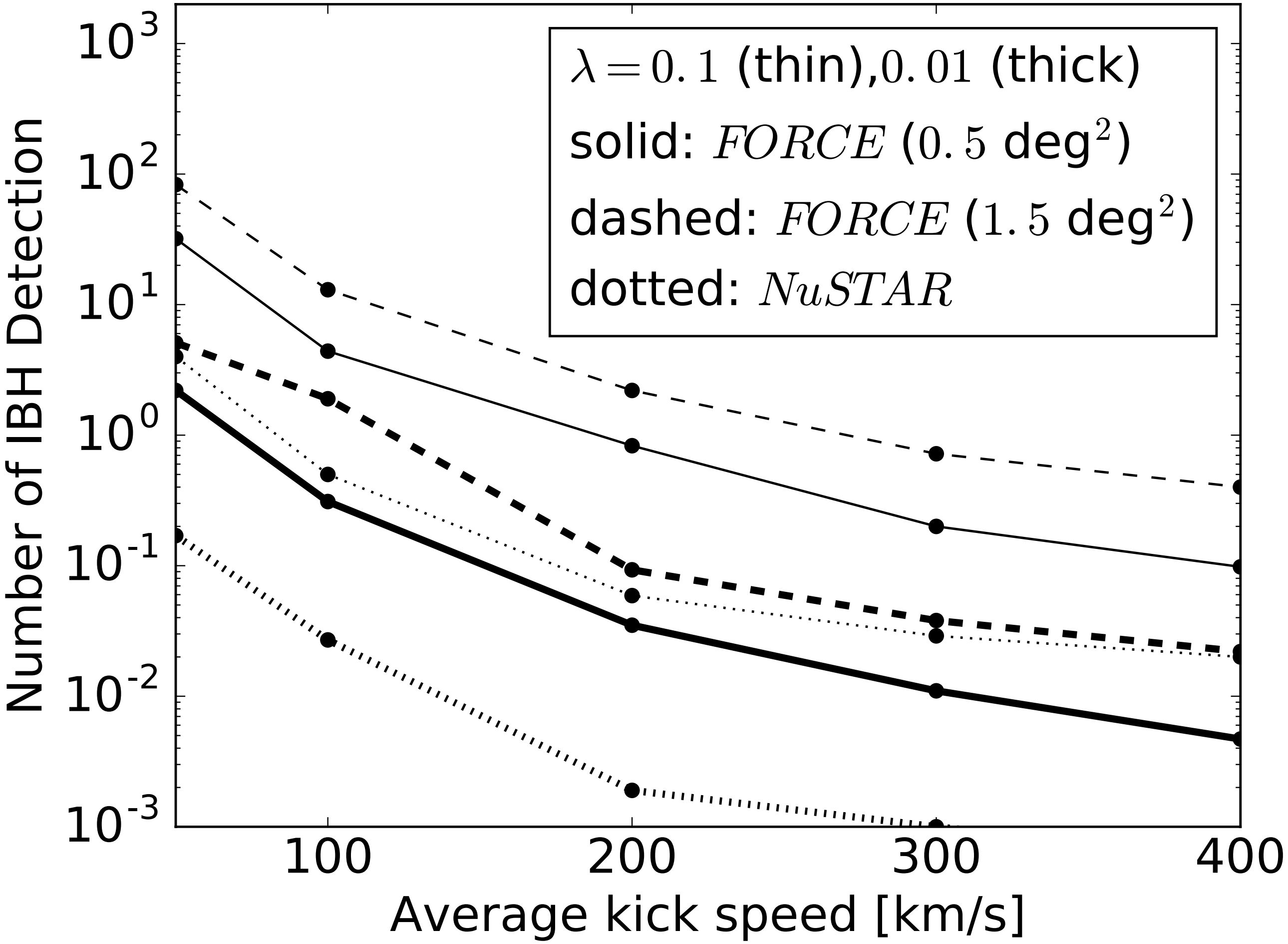
What are their properties?

- Estimates predict 10^8 BHs in MW, but we know only ~20

- Detecting Isolated BHs in the MW can give hints on
  - ➢ How many are they?
  - ➢ BH Distribution?
  - ➢ BH Mass Function?

- Several tens may be found by future observations

λ = (accretion rate) / (Bondi rate)



DT, Kawanaka, Totani 18 (1801.04667)
(See also Matsumoto, Teraki, Ioka 17)

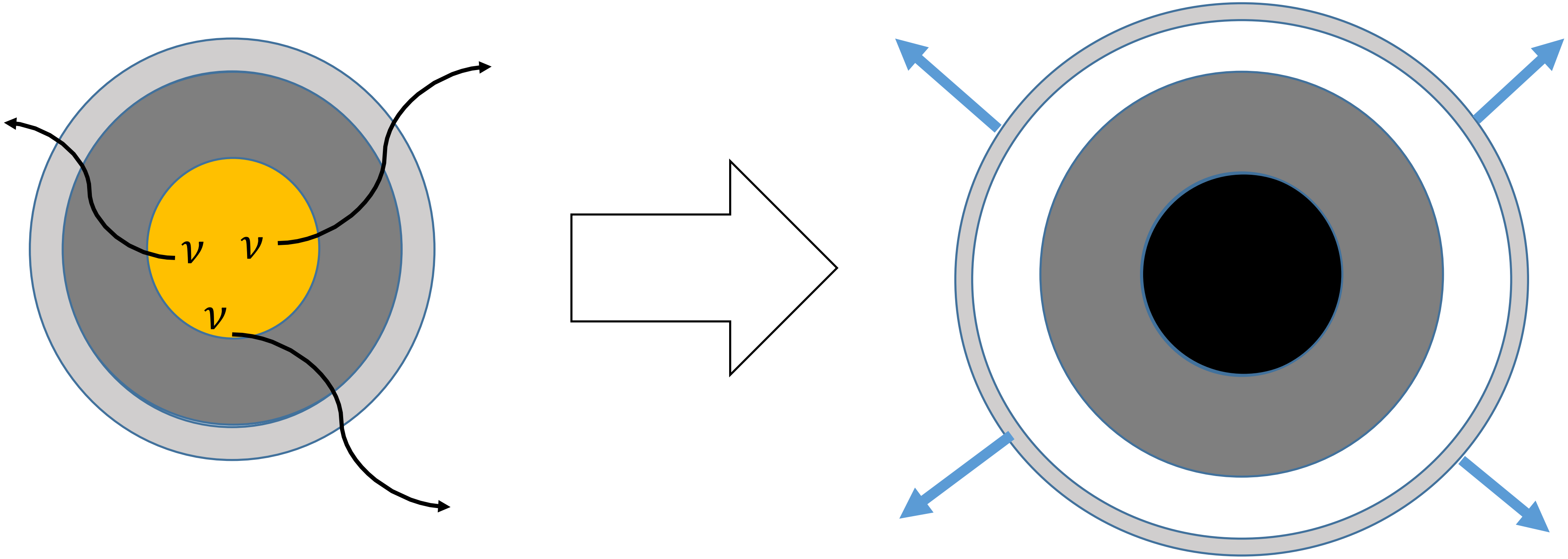
How did they form?

- Simplest scenario: Some stars cannot explode and collapse as <u>failed supernovae</u>
- Core compactness may be the key
  (e.g. O’ Connor & Ott 2011)

$$\xi_M = \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}\bigg|_{t_\mathrm{bounce}}$$

- But the link between massive star evolution and subsequent BH formation is yet highly uncertain

Failed SNe may leave us some clues



Neutrino emission during protoneutron star phase can make a fraction of the outer envelope gravitationally unbound (Nadyozhin 1980)

Red Supergiants

- Ejected envelope will <u>radiate</u>

➢ ~ few day transient upon shock breakout (Piro 2013)

➢ ~ year-long plateau (Lovegrove & Woosley 2017)

- It may have been observed

(Gerke+ 2016, Adams+ 2017)

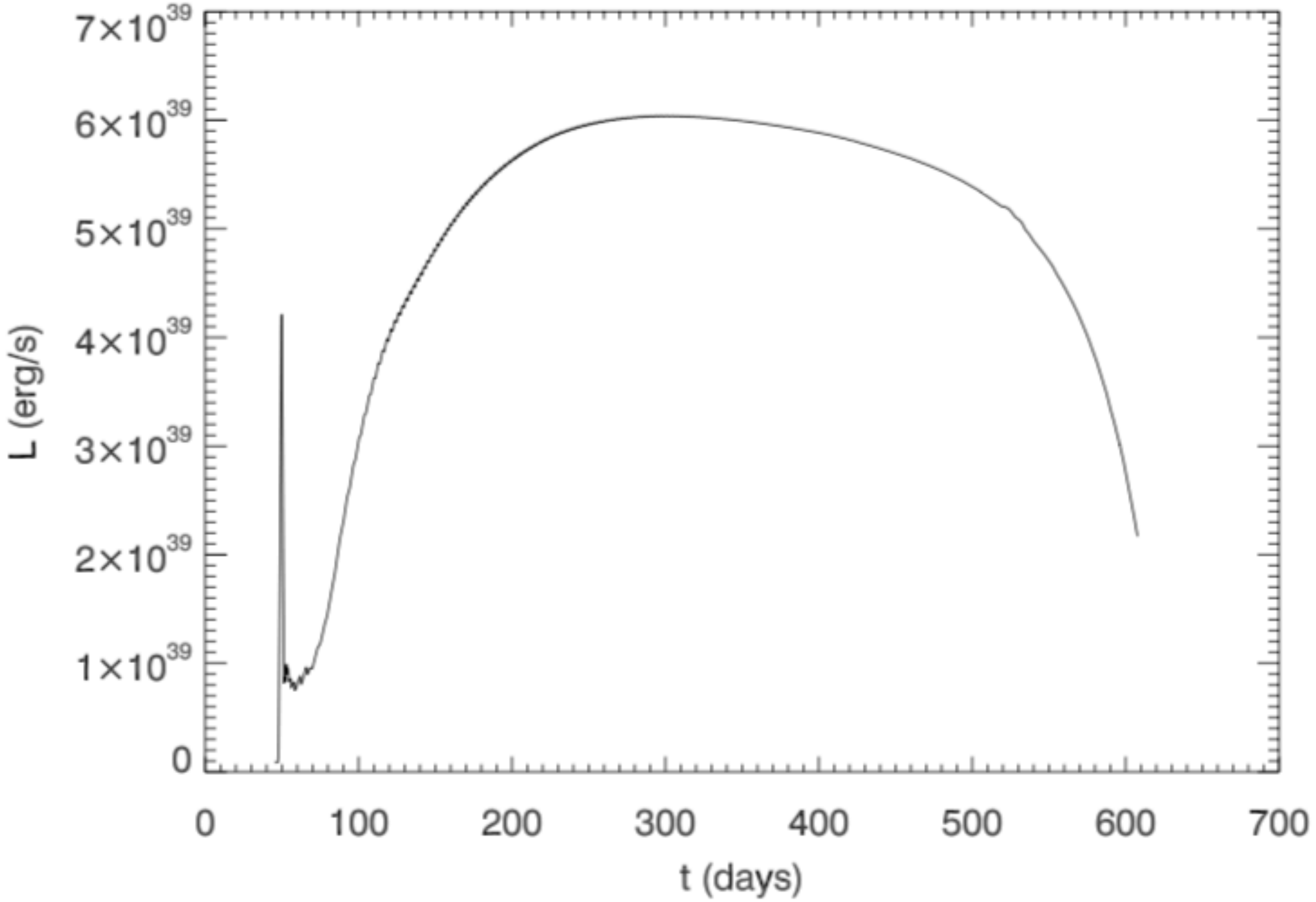
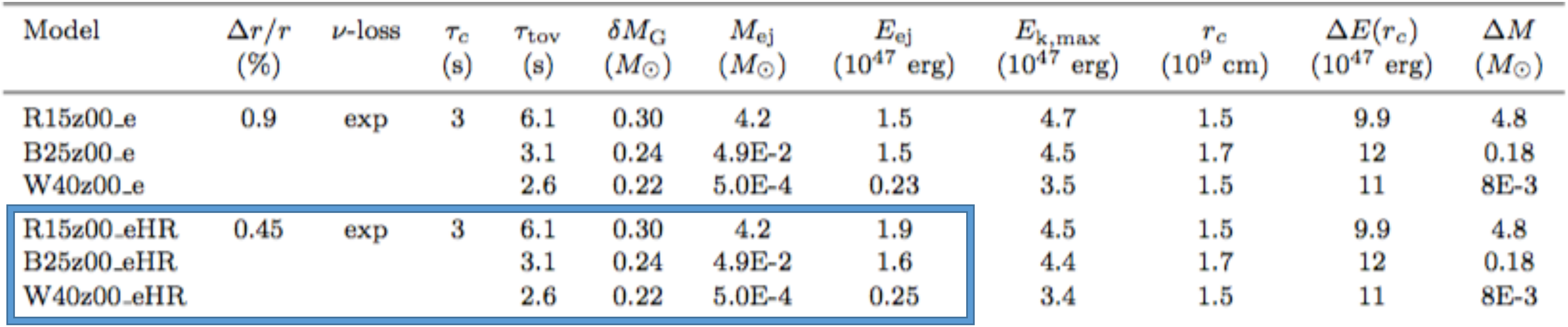


Figure 12. KEPLER light curve for a transient from RSG15, TOV = 2.5. The transient is low luminosity but lasts for around a year.

Lovegrove & Woosley 2013
Piro 2013

Blue Supergiants and Wolf-Rayet Stars



Model	$\Delta r/r$ (%)	ν-loss	τ_c (s)	$\tau_{\rm tov}$ (s)	$\delta M_{\rm G}$ ($M_\odot$)	$M_{\rm ej}$ ($M_\odot$)	$E_{\rm ej}$ (10^{47} erg)	$E_{\rm k,max}$ (10^{47} erg)	r_c (10^9 cm)	$\Delta E(r_c)$ (10^{47} erg)	ΔM ($M_\odot$)
R15z00_e	0.9	exp	3	6.1	0.30	4.2	1.5	4.7	1.5	9.9	4.8
B25z00_e				3.1	0.24	4.9E-2	1.5	4.5	1.7	12	0.18
W40z00_e				2.6	0.22	5.0E-4	0.23	3.5	1.5	11	8E-3
R15z00_eHR	0.45	exp	3	6.1	0.30	4.2	1.9	4.5	1.5	9.9	4.8
B25z00_eHR				3.1	0.24	4.9E-2	1.6	4.4	1.7	12	0.18
W40z00_eHR				2.6	0.22	5.0E-4	0.25	3.4	1.5	11	8E-3

Fernandez, Quataert, Kashiyama, Coughlin (2018)

- BSGs and WRs have strongly bounded envelopes
- Similar ejecta energy w/ RSGs but lighter, thus larger ejecta velocity

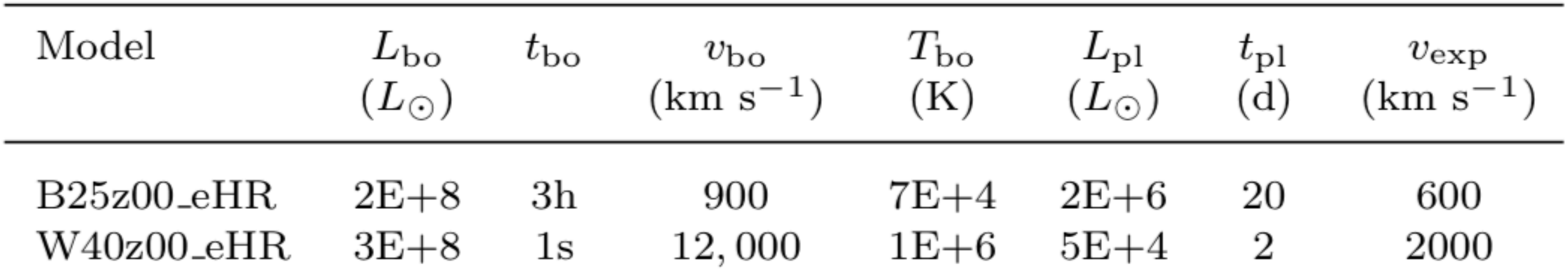
Observation strategies?

BSGs

- ➢High-cadence optical Surveys (Tomo-e Gozen, LSST) can be helpful

WRs

- ➢Too fast and too faint
- ➢Radio surveys may be better strategies



Model	$L_{\rm bo}$ $(L_\odot)$	$t_{\rm bo}$	$v_{\rm bo}$ (km s^{-1})	$T_{\rm bo}$ (K)	$L_{\rm pl}$ $(L_\odot)$	$t_{\rm pl}$ (d)	$v_{\rm exp}$ (km s^{-1})
B25z00_eHR	2E+8	3h	900	7E+4	2E+6	20	600
W40z00_eHR	3E+8	1s	12,000	1E+6	5E+4	2	2000

Fernandez, Quataert, Kashiyama, Coughlin (2018)

This work

- Calculate emission from mass ejection of failed SNe
- Are Failed BSGs detectable by high-cadence surveys?
- Are Failed WRs detectable by blind radio surveys?

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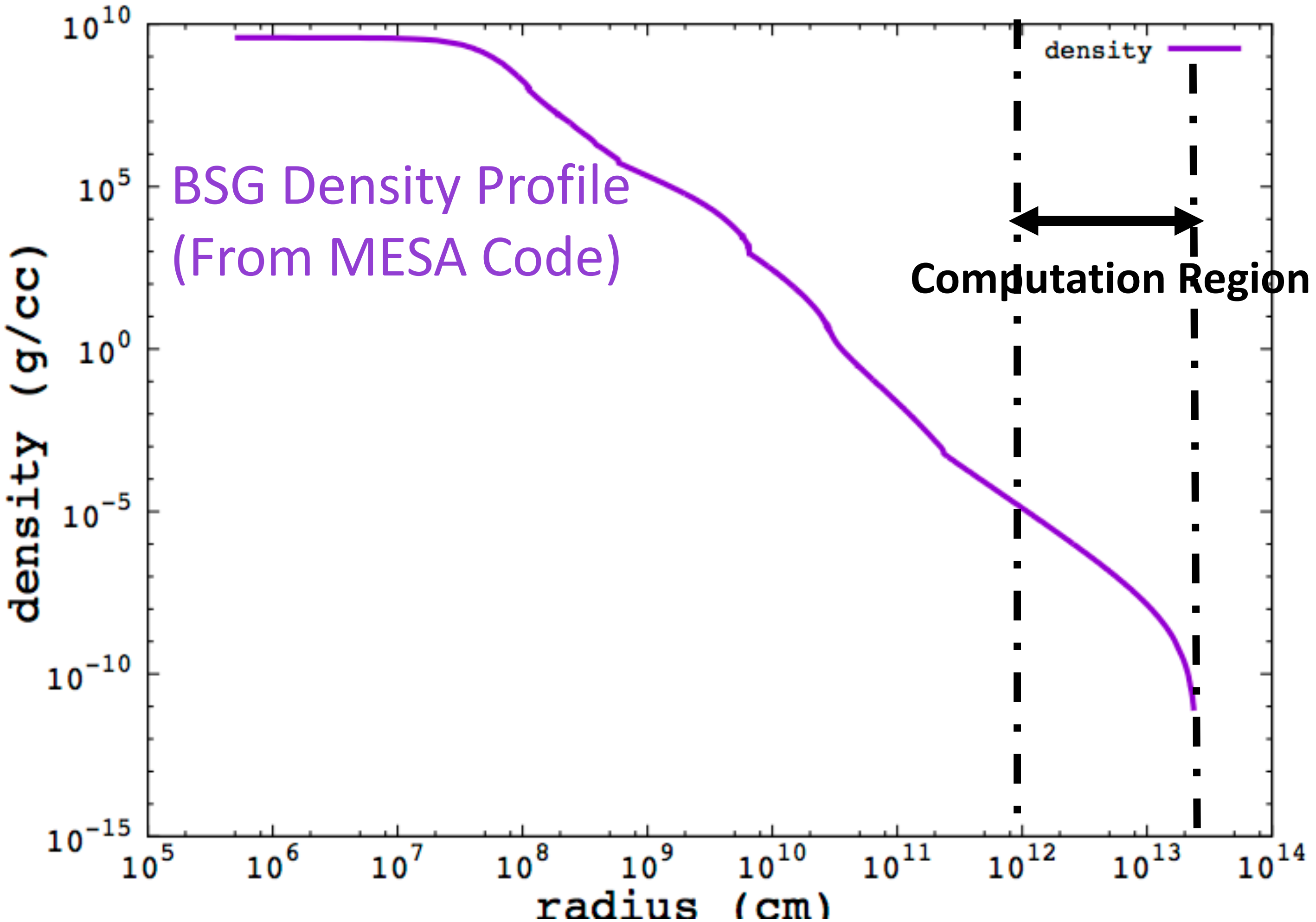
Initial Conditions

- Pre-collapse structure: assume polytropic envelope w/ n=3
- Simulation inner boundary set where the above approx. holds
- Inject energy at inner boundary

(injection energy calibrated using results by Fernandez+ 18)

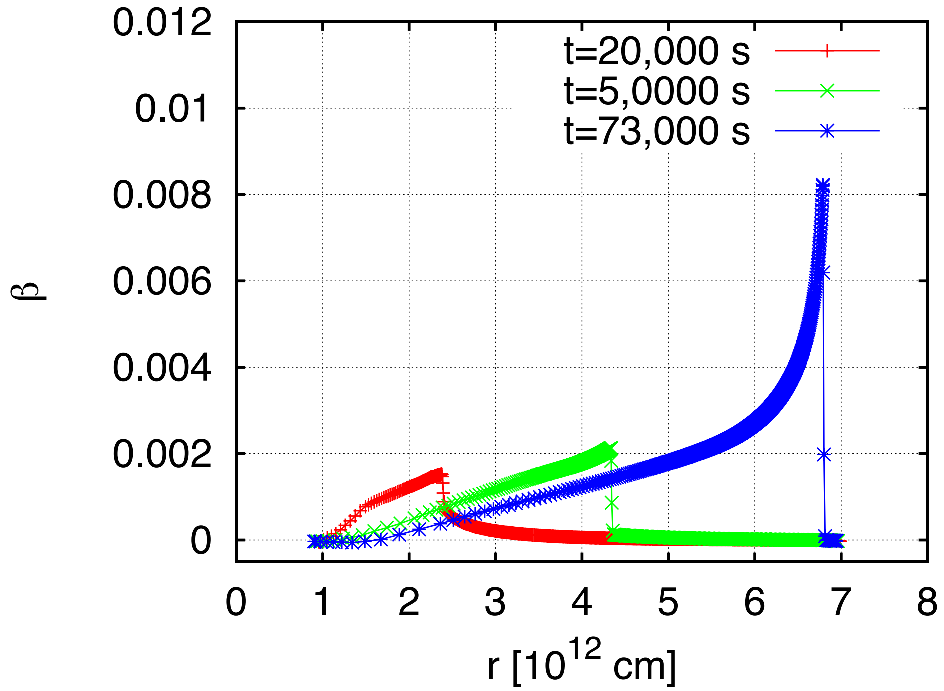


	ZAMS Mass ($M_\odot$)	Final Mass ($M_\odot$)	Final Radius (cm)	Simulation Inner Boundary (cm)
BSG model	25	11.7	7×10^{12}	1×10^{12}
WR model	40	10.3	3×10^{10}	3×10^{9}

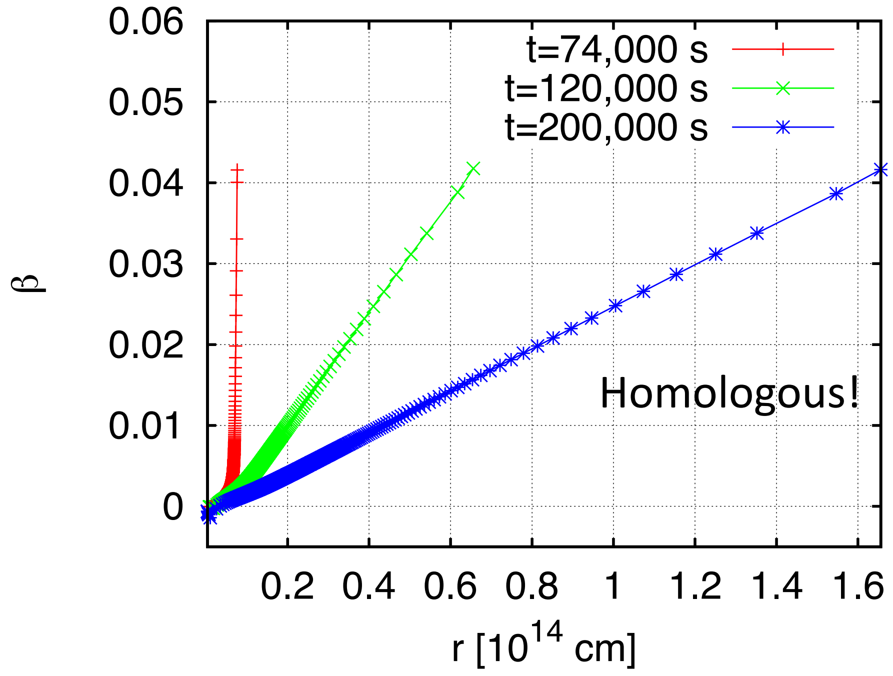
Shock Evolution

- 1D Lagrangian code by Ishii+ (arXiv: 1805.04909) around shock breakout
- After kinetic energy is stable, expand ejecta homologously

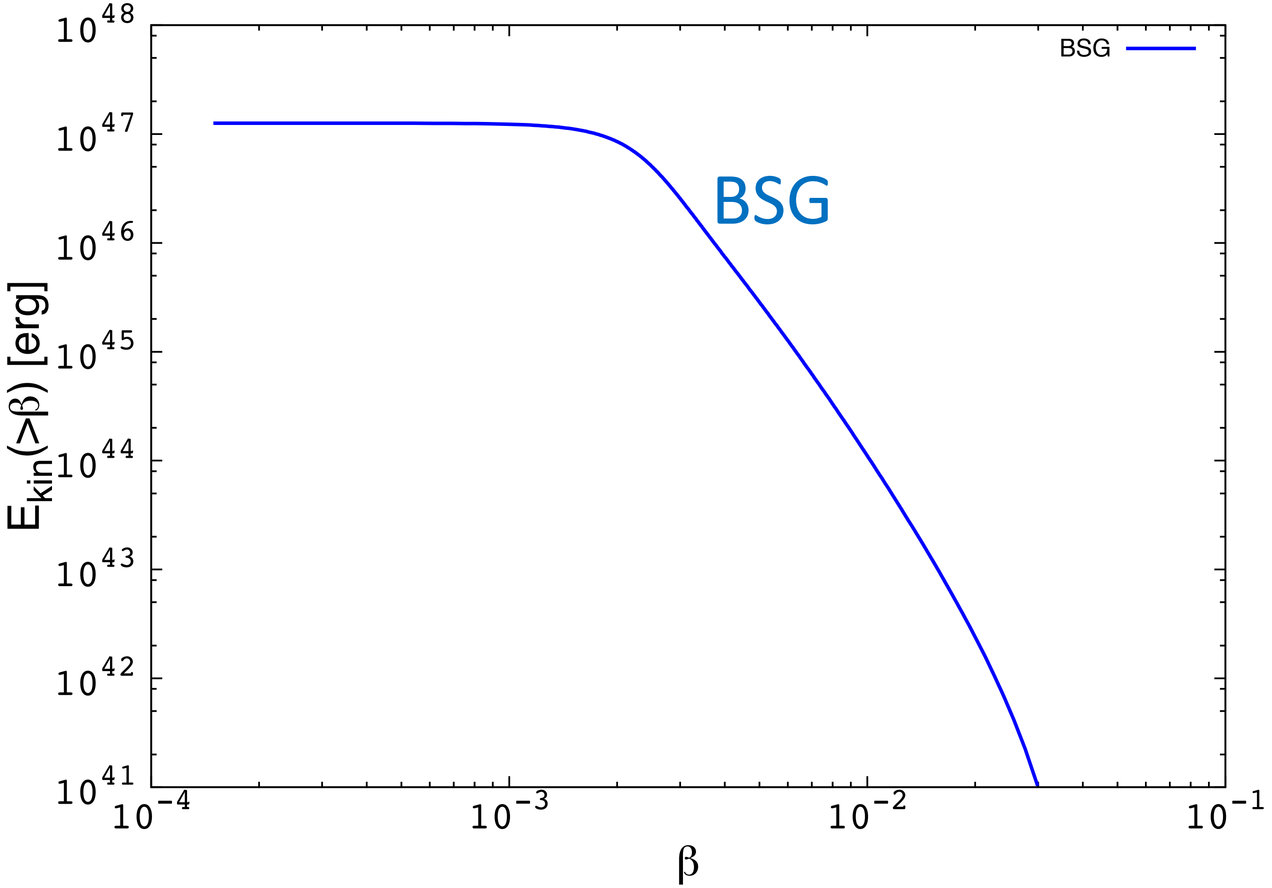
Before Shock Breakout (BSG model)

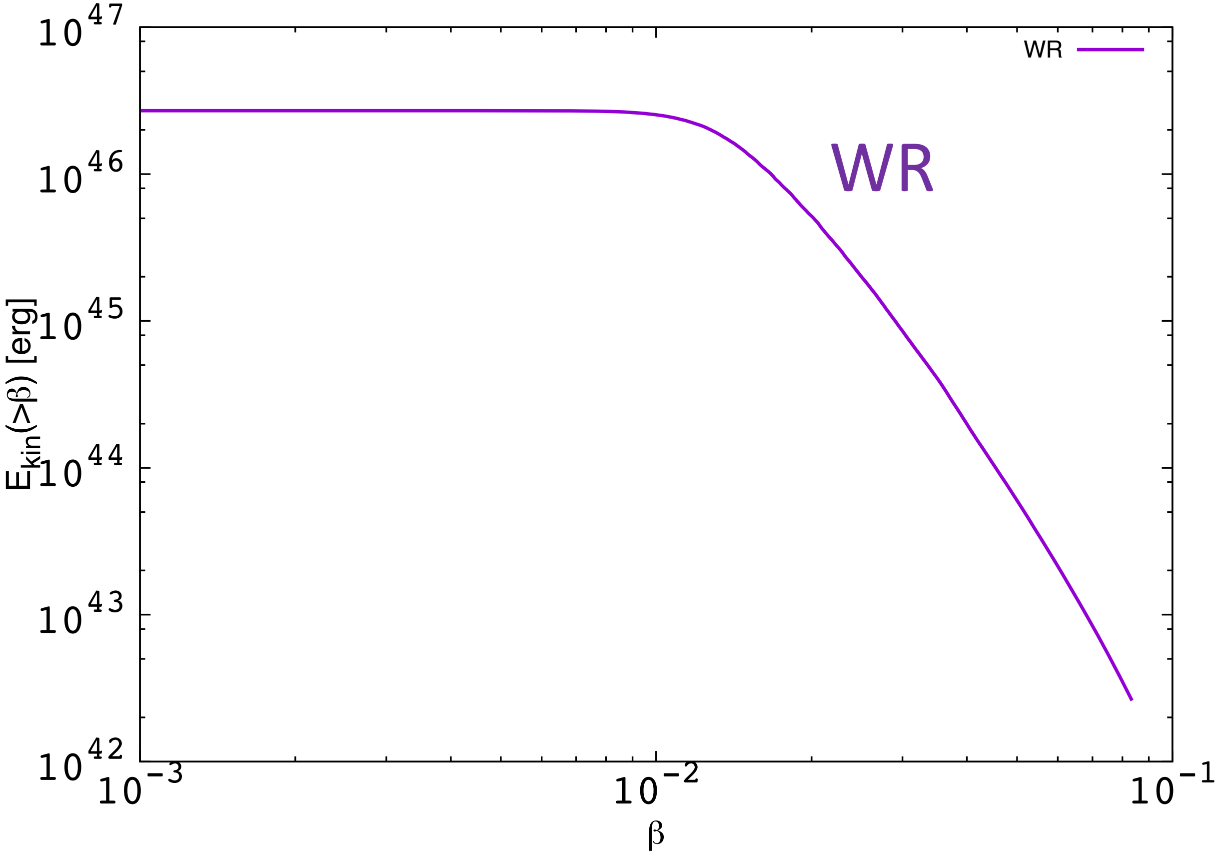


After Shock Breakout (BSG model)



Final ejecta property





Roughly $E_{kin}(> v) \propto v^{-5}$

Consistent with analytical expectations (Matzner & McKee 99, Tan et al. 01)

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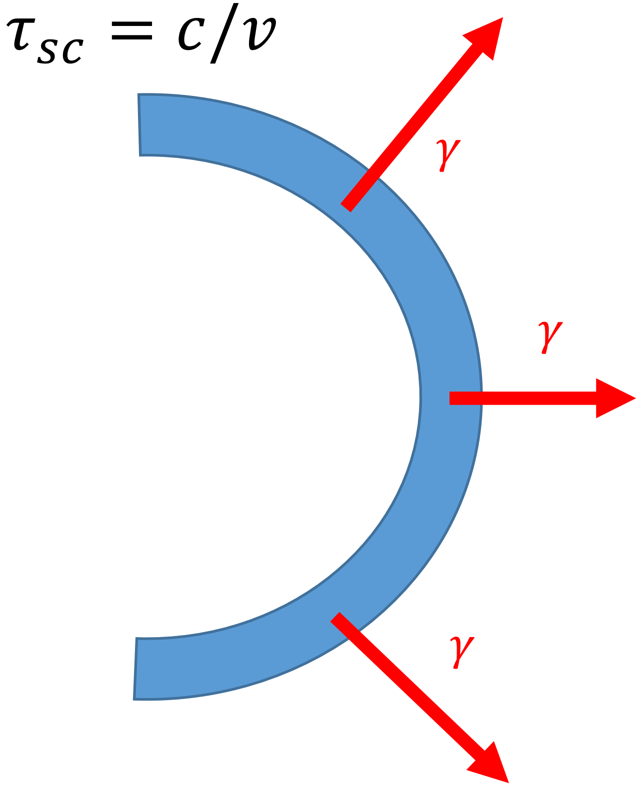
Luminosity

- Photons can diffuse out from the radius where scattering optical depth $\tau_{sc} = \int \kappa\rho \, dr$ = c/v
  - $\kappa = 0.34\ \mathrm{cm}^2/\mathrm{g}$ (Thomson opacity)
  - ρ : electron density
  - v : velocity of the fluid

- At this radius, $L = 4\pi r^2 \sigma T^4 / \tau_{sc}$

- This is observed with a delay of $\sim\tau_{sc}(r_{ph} - r_{diff})/c$



Temperature

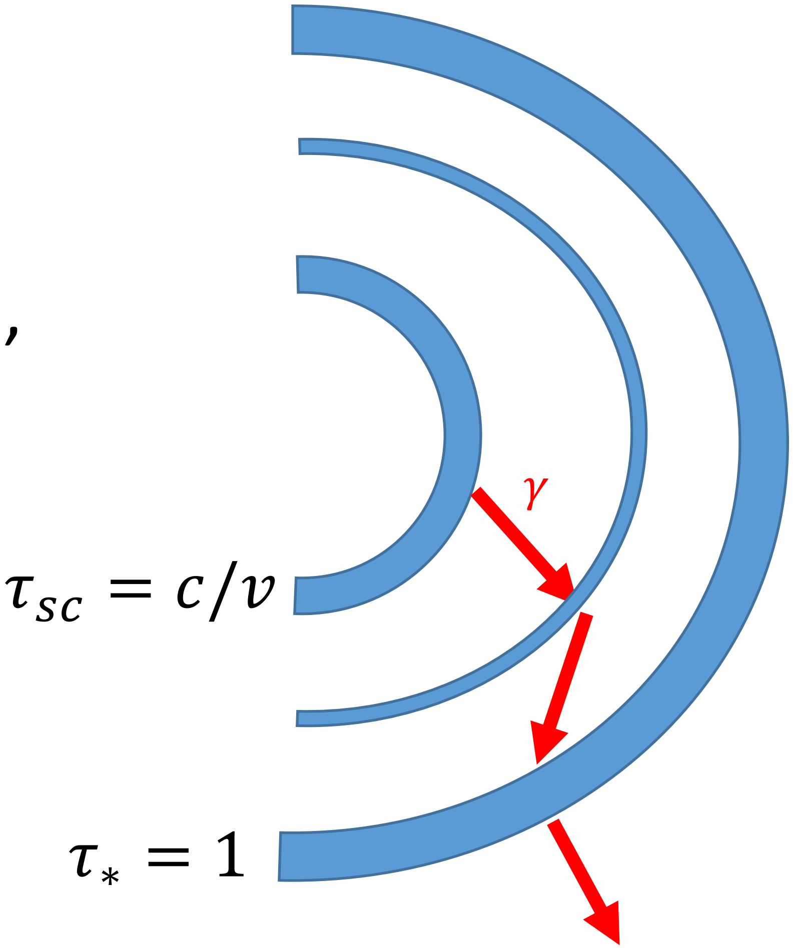
- Diffused photons experience scattering/absorption, and escape where thermalization optical depth $\tau_* = \int \sqrt{\alpha_{ff}(\alpha_{ff} + \alpha_{sc})}\, dr \approx 1$

➢ α_{ff} : free-free absorption coefficient

➢ $\alpha_{ff} \approx 1.7\times10^{-25}\ \mathrm{cm}^{-1}\ T^{-3.5} n_e n_i$

- We define here as the photosphere, and assume the temperature here as the color temperature

➢ Obtain AB magnitude

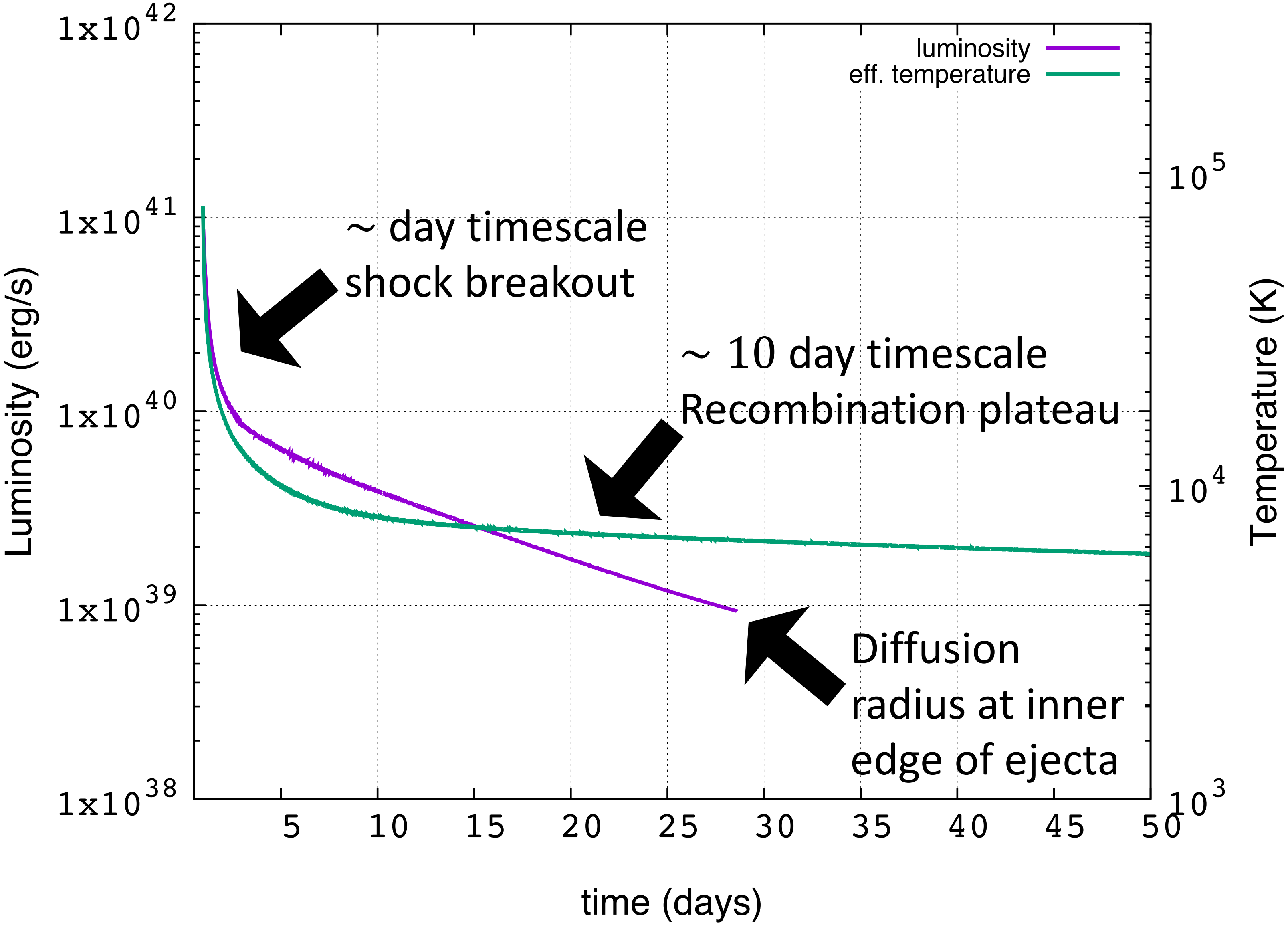


γ

$\tau_{sc} = c/v$

$\tau_* = 1$

BSG light curve



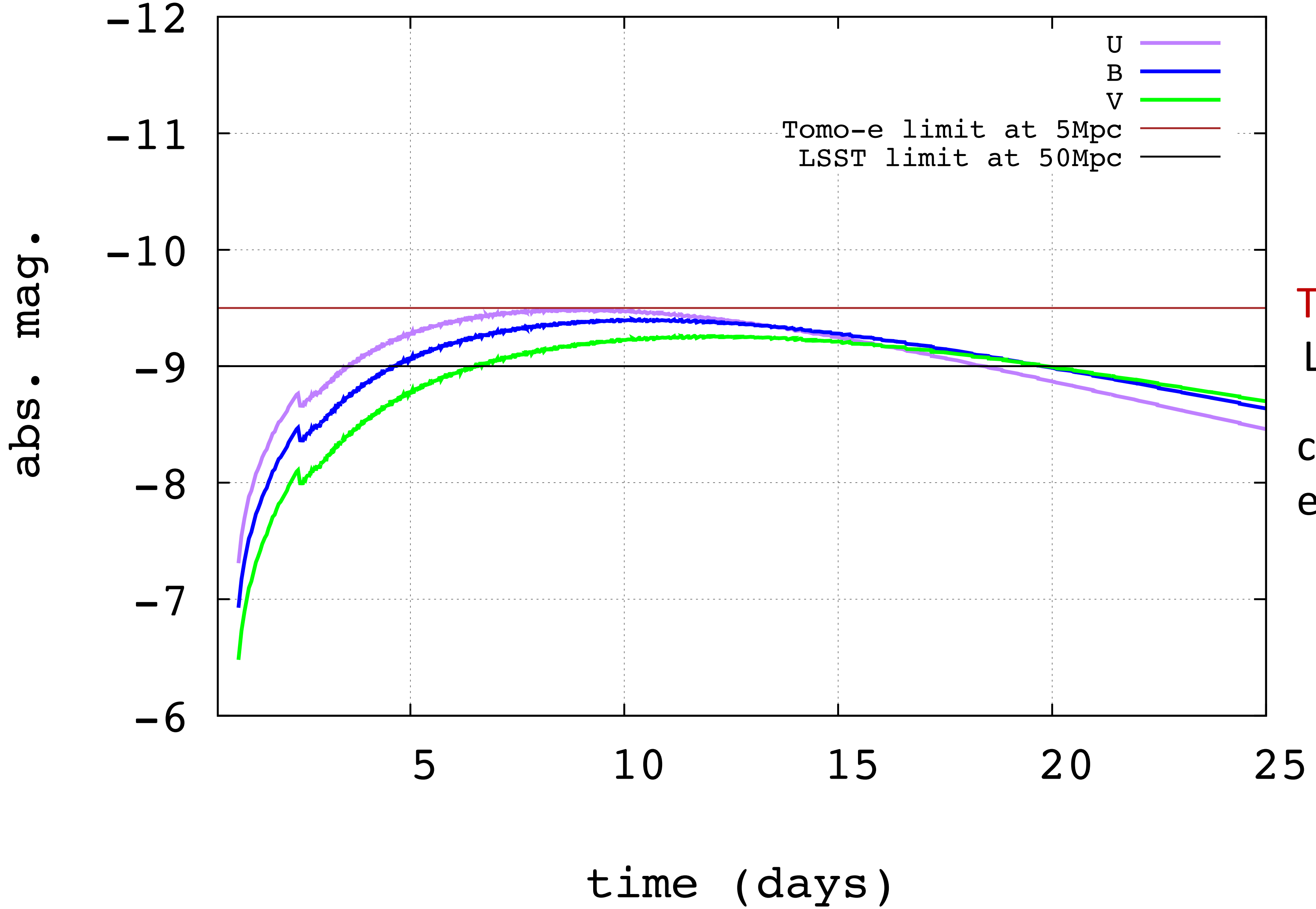
~ day timescale
shock breakout

~ 10 day timescale
Recombination plateau

Diffusion
radius at inner
edge of ejecta

Note: Hydrogen-dominant
envelope assumed

AB magnitude



Tomo-e Gozen, 5Mpc

LSST, 50Mpc

cf.
event rate ~ 1/yr at $\lesssim$ 20Mpc

WR radio emission

- Fast ($\gtrsim 0.1c$) ejecta colliding wind medium

➢ collisionless shock, magnetic amplification

➢ e^- acceleration & synchrotron emission?

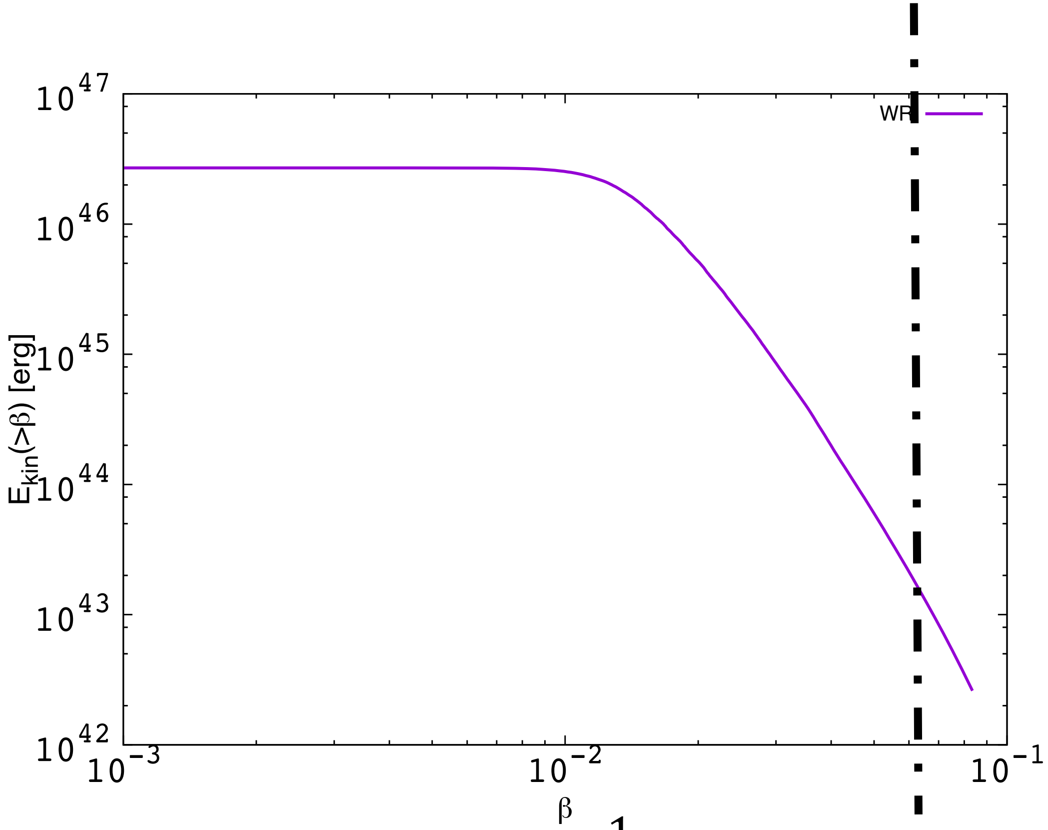
- But the mass of fast ejecta

$$M_{ej} \sim \frac{10^{42-43}\ \mathrm{erg}}{(3\times10^{9}\ \mathrm{cm\,s^{-1}})^{2}} \sim 10^{23-24}\mathrm{g}$$

is very small, and will be stopped at distance

$$v_{ej}t_{stop} \sim \frac{M_{ej}v_w}{\dot{M}_w} \sim 10^{11-12}\mathrm{cm}\left(\frac{\dot{M}/v_w}{10^{12}\mathrm{g\,cm^{-1}}}\right)^{-1}$$

- Energy budget already very small, and with serious free-free absorption at this region radio emission is probably dim.



$$\frac{1}{2}m_p\beta^2c^2\xi_e \sim 2m_ec^2$$

$\xi_e \sim 0.4$: e^- acc. efficiency

(Park et al. 2015)

Summary

- Estimated the detectability of emission of mass ejection of failed BSGs and WRs

- Breakout and plateau emission from BSGs can be interesting targets for present/future surveys

- Radio emission from failed WRs is probably difficult to detect unless favorable conditions (e.g. weak explosion?)