Supernovae & Gamma-Ray Bursts 2013 in YITP

Blue Supergiant Model for Ultra-Long Gamma-Ray Burst with Superluminous-SN-like Bump

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Introduction

Ultra-Long GRB: A New Population?

	111209A	101225A	121027A	130925A
$E_{\rm iso}^{\rm obs}$ (10^{53} erg)	5.8[1]	$\gtrsim$0.12[2]	2.0[3]	?
$\delta t_{\gamma}^{\rm obs}$(s)	15000[1]	$\gtrsim$2000[1]	10000[3]	10000 [4]
z	0.677[1]	0.847[2]	1.773[2]	0.35 [4]

(1) Gendre et al. 2013; (2) Levan et al. 2013; (3) Peng et al. 2013. (4) Zhang et al. 2013

✓ Above GRBs show extremely long central engine activity.

✓ Duration is as long as ~ 10000 s, > 100 × typical LGRB.

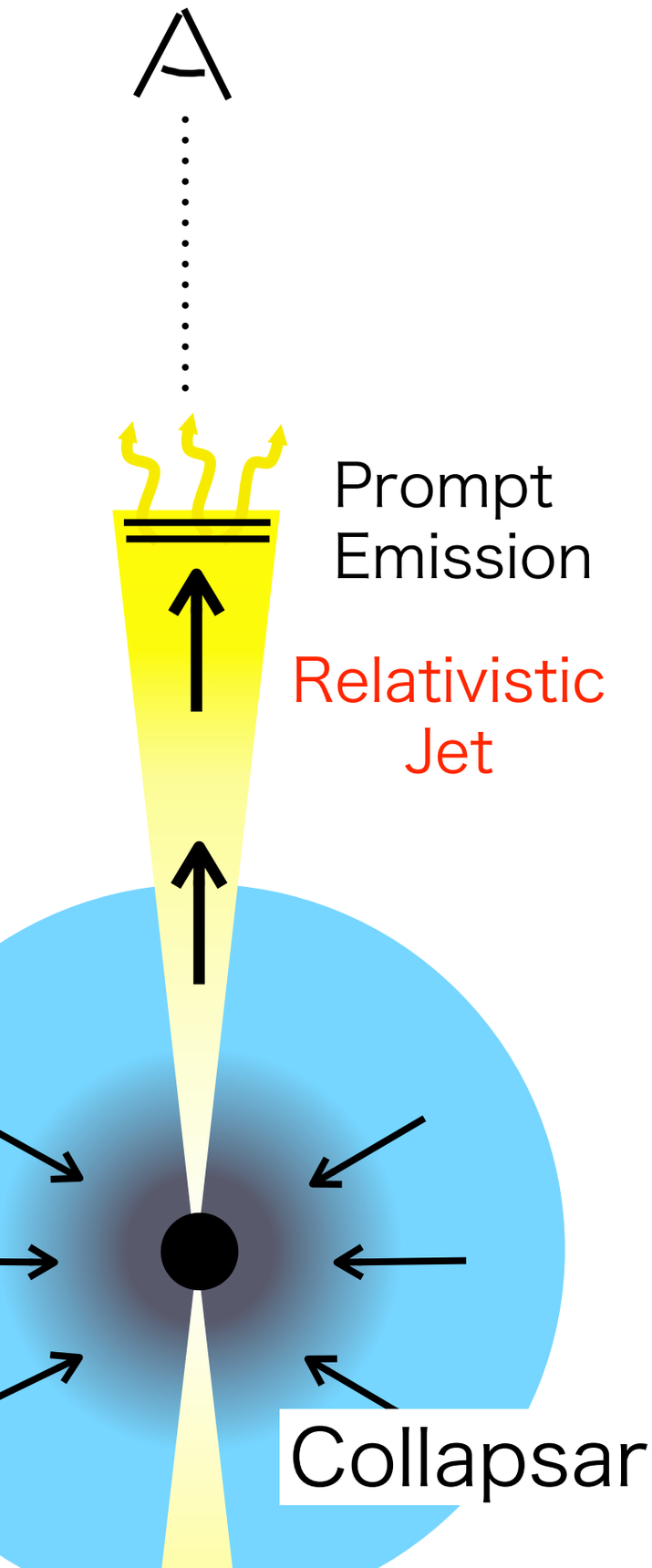
✓ They may form a new population of GRBs, ULGRB.

✓ They bring about difficulty for the progenitor model.

✓ If we follow collapsar scenario, a peculiar progenitor is more favorable than Wolf-Rayet star.

BSG Model of ULGRB

Kashiyama et al. 2013
Gendre et al. 2013



✓ GRB duration
~ mass accretion time onto central engine.

✓ Wolf-Rayet (no H, He envelope).

$$\delta t_\gamma \sim 77 \left(\frac{R_*}{2\times10^{10}\ \mathrm{cm}}\right)^{3/2} \left(\frac{M_*}{10\ M_\odot}\right)^{-1/2} (1+z)\ \mathrm{s}$$

→ too short for ULGRB.

✓ Blue Supergiant (BSG, w. H envelope).

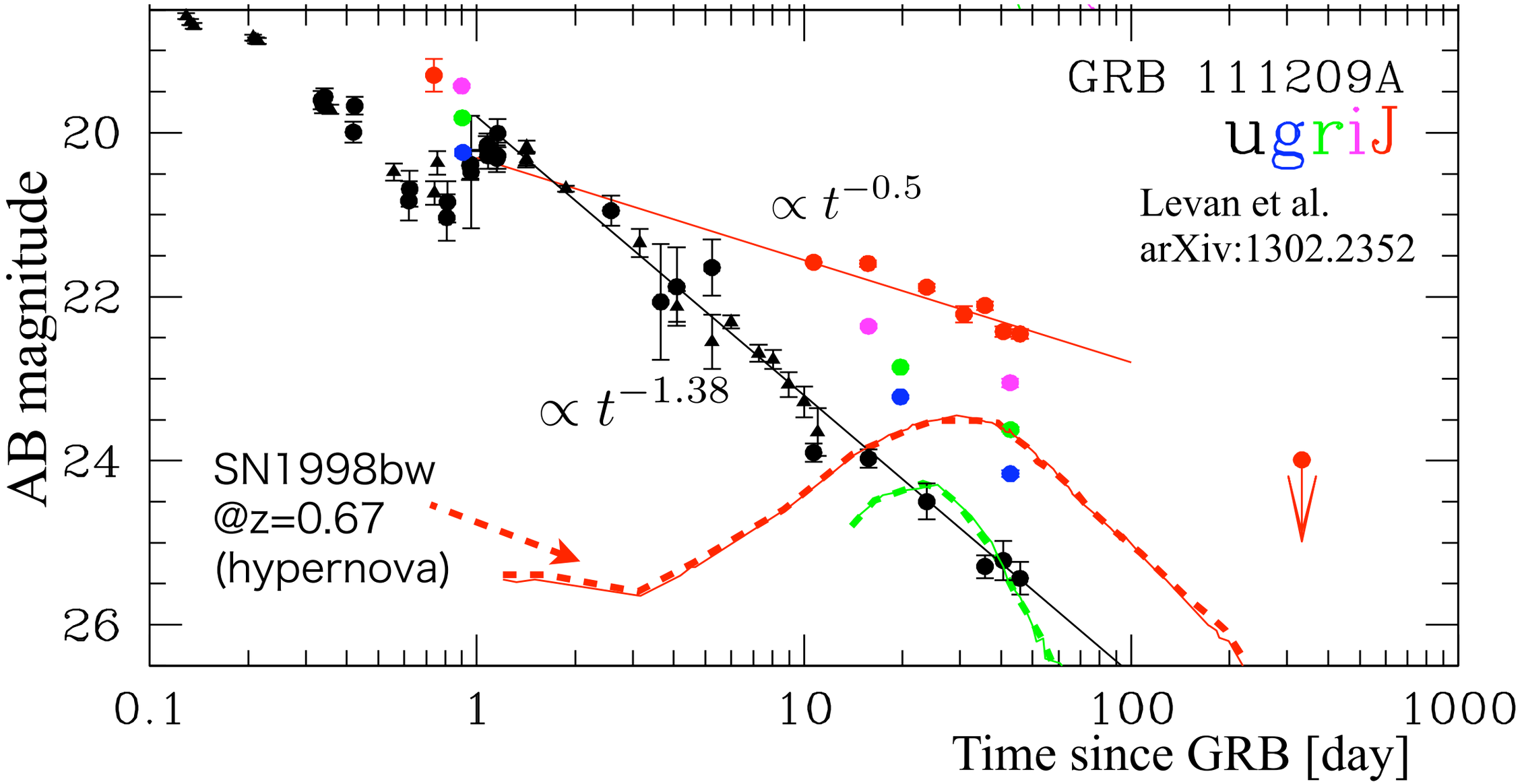
ex) Massive metal-poor stars. Woosley et al. 2002

$$\delta t_\gamma \sim 1.2\times10^{4} \left(\frac{R_*}{10^{12}\ \mathrm{cm}}\right)^{3/2} \left(\frac{M_*}{50\ M_\odot}\right)^{-1/2} (1+z)\ \mathrm{s}.$$

→ consistent with ULGRB. "BSG model"

Examine BSG model with afterglow.

SLSN-like Bump in Opt/IR Afterglow



✓ X/UV: power-law decay.

(Spectrum not taken.)

✓ Opt/IR: Superluminous-SN-like bump ~ HN×10.

➡ We examine whether they are explained with BSG model.

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SLSN-like Bump from Cocoon Fireball Photospheric Emission (CFPE)

Overview of Our Model

✓ As an energy source, we focus on the energy stored in the cocoon.

✓ We calculate the jet evolution in the star.

✓ Progenitor: BSG with $75\ M_\odot, 10^{-4}\ Z_\odot$. Woosley et al. 2002

✓ Jet: Cold relativistic jet.

$\theta_{\rm j}$ =const.

$$L_{\rm j}(t) = \eta_{\rm j} \dot{M}(t) c^2. \quad \dot{M} = dM_r/dt_{\rm ff,r}$$

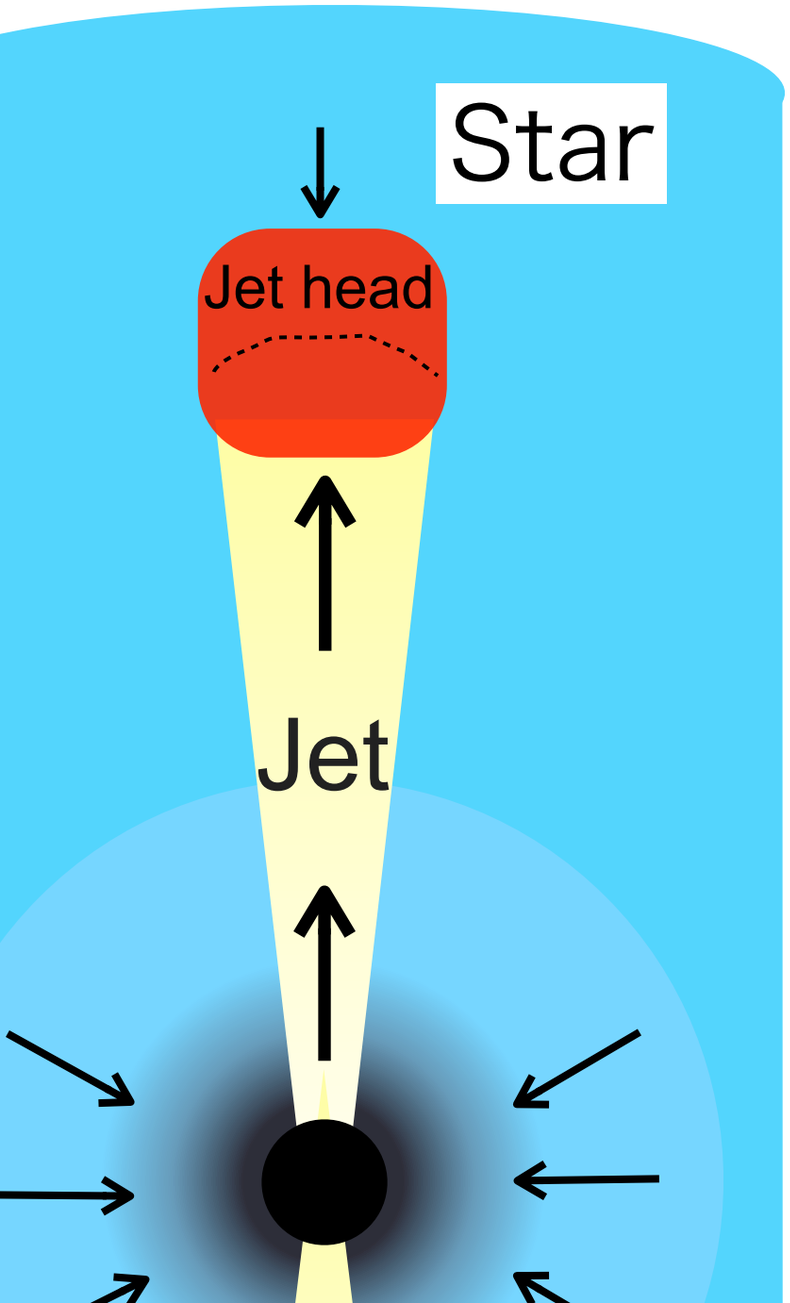
We choose the parameters so that our model becomes consistent with observations of prompt emission & afterglow.

Jet - Cocoon Structure

Matzner 2003,
Suwa & Ioka 2011
Nagakura et al. 2012
Nakauchi et al. 2012

Shock region in jet head.　Non-relativistic $\beta_{\rm h} \sim 0.1$.

⇒ Jet head expands sideways to form cocoon.



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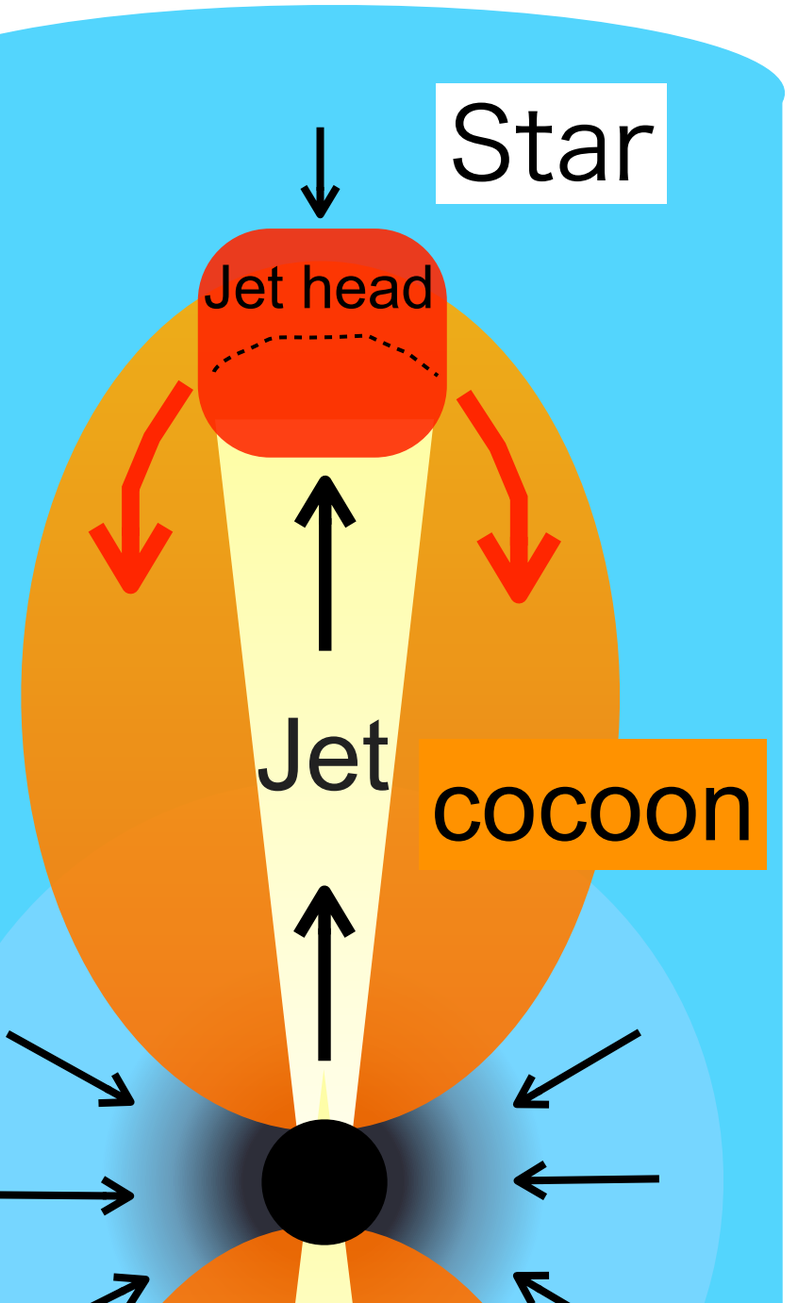

Cocoon ~ shocked stellar + jet materials.

✓ All the jet energy flows into cocoon before breakout.

✓ Cocoon loads stellar mass along with its expansion.

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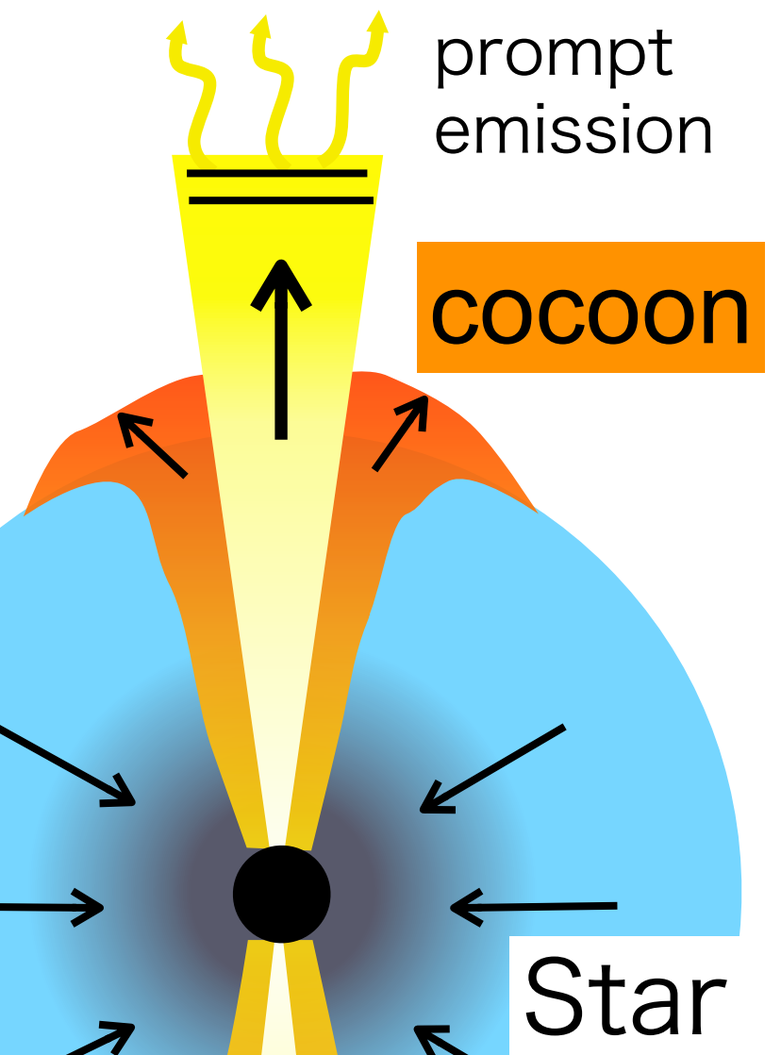


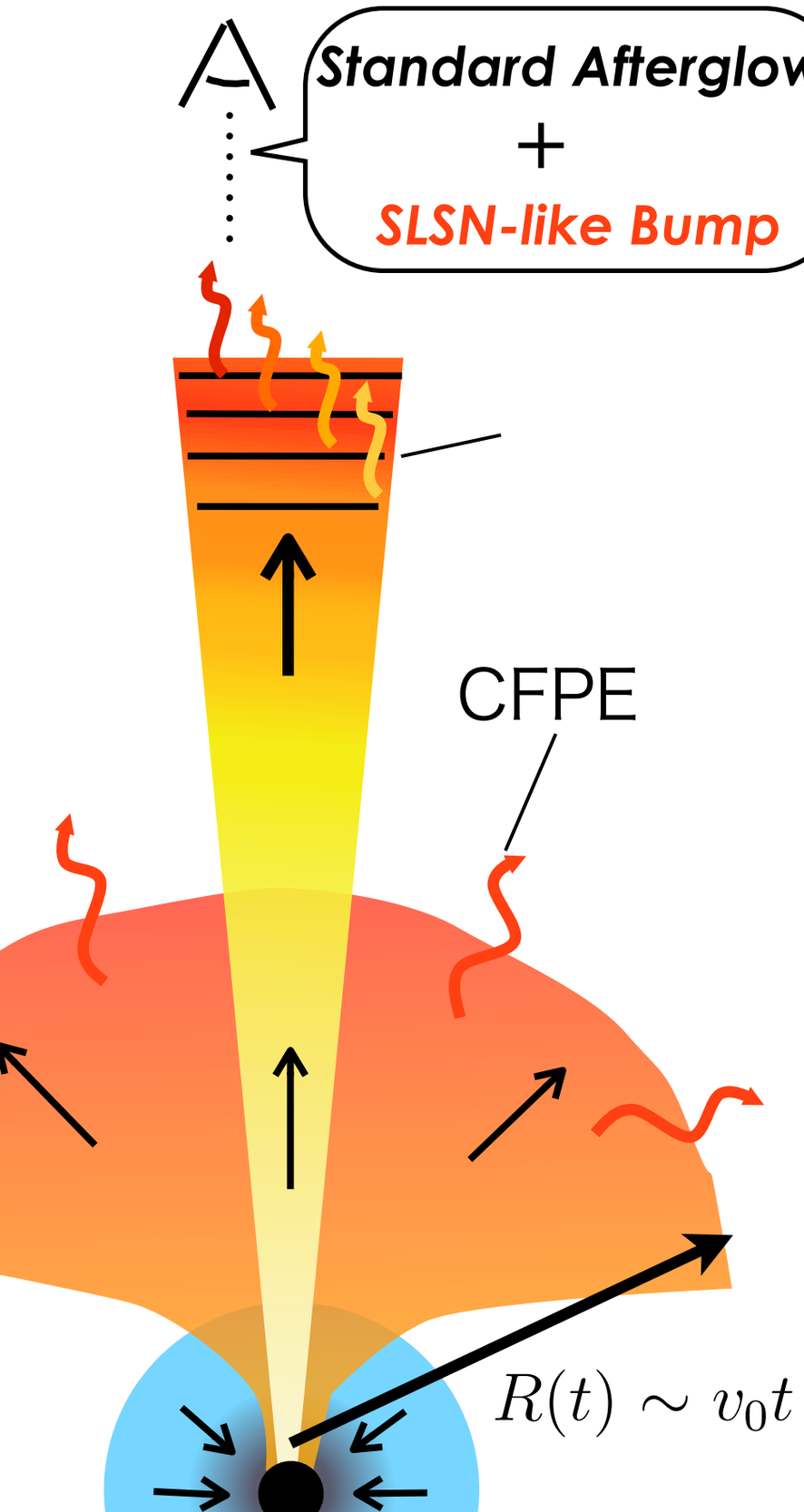
✓ Cocoon loads stellar mass along with its expansion.

✓ We want the cocoon energy & mass.

✓ We calculate jet evolution until breakout.

✓ Along with jet, cocoon breakouts star and releases its energy.

Cocoon Fireball Photospheric Emission



✓ Outside the star, cocoon expands to an almost spherical shape.

✓ After the optical depth becomes low enough, photons can escape.

✓ Photospheric emission from expanding cocoon fireball (CFPE). ~ application of SN model.

Arnett 1980
Popov 1993

✓ CFPEs from BSGs will look like Type IIP SNe, because of H envelope.

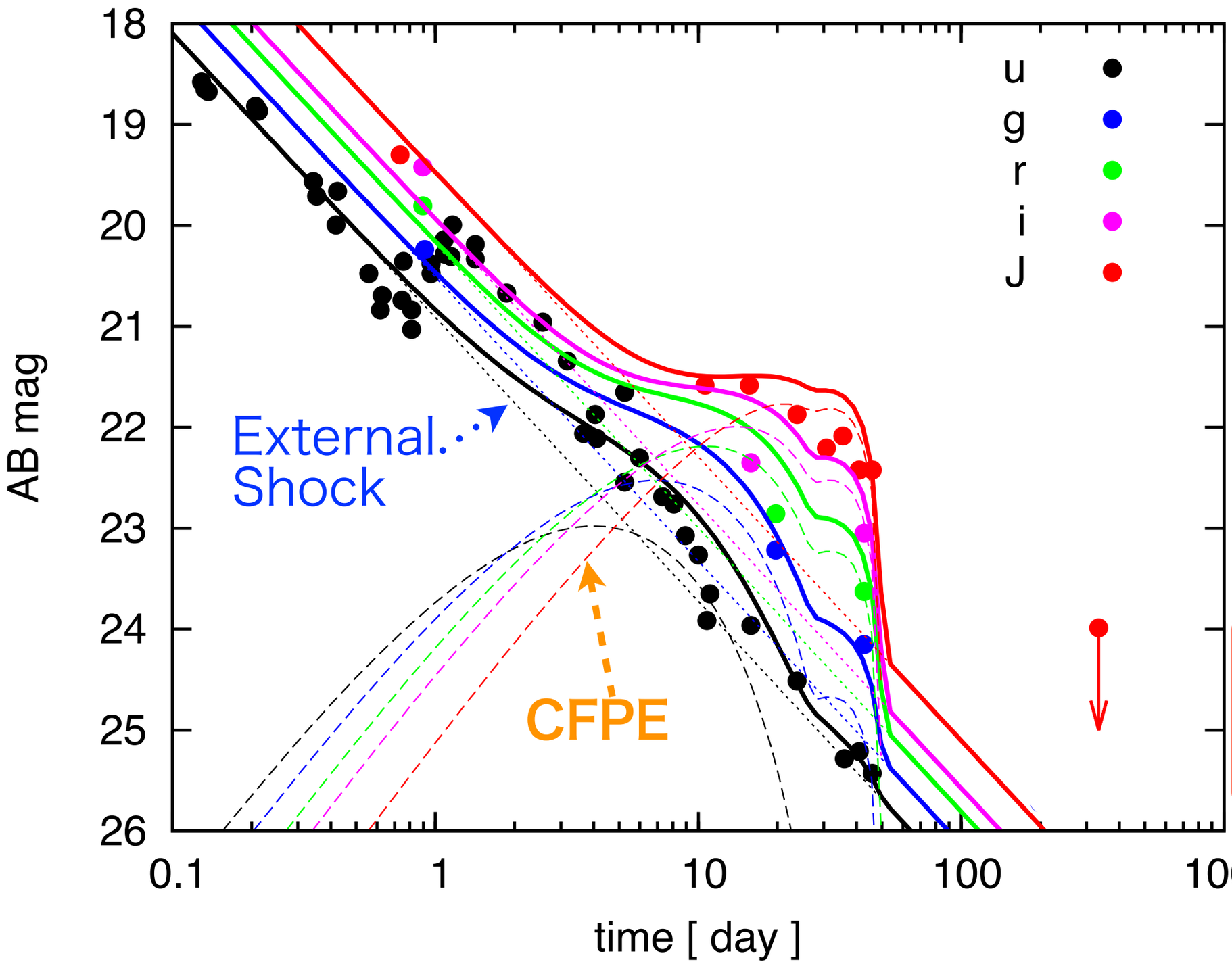
✓ For LC fitting, we add CFPE to standard external shock component.

GRB 111209A

arXiv:1307.5061

CFPE + external shock component.

SLSN-like bump is explained quite well.



Jet parameter.

$\theta_{\rm j} = 12^\circ$

$\eta_{\rm j} = 1.24 \times 10^{-3}$

Constrained by

$\delta t_\gamma^{\rm obs}$ $E_{\rm iso}^{\rm obs}$

X-ray afterglow.

UV-IR afterglow.

Cocoon parameter.

$E_{\rm c} \sim 10^{53}$ erg

$M_{\rm c} \sim 6\ {\rm M}_\odot$

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Discussion & Summary

CFPE as a Clue for Progenitor Model

✓ A bright CFPE can be a smoking gun evidence for BSG model.

✓ For larger progenitor, jet breakout time becomes longer.

✓ Larger energy is stored in the cocoon before breakout.

✓ Cocoon energy for BSG and WR case.

(BSG radius >> WR radius.)

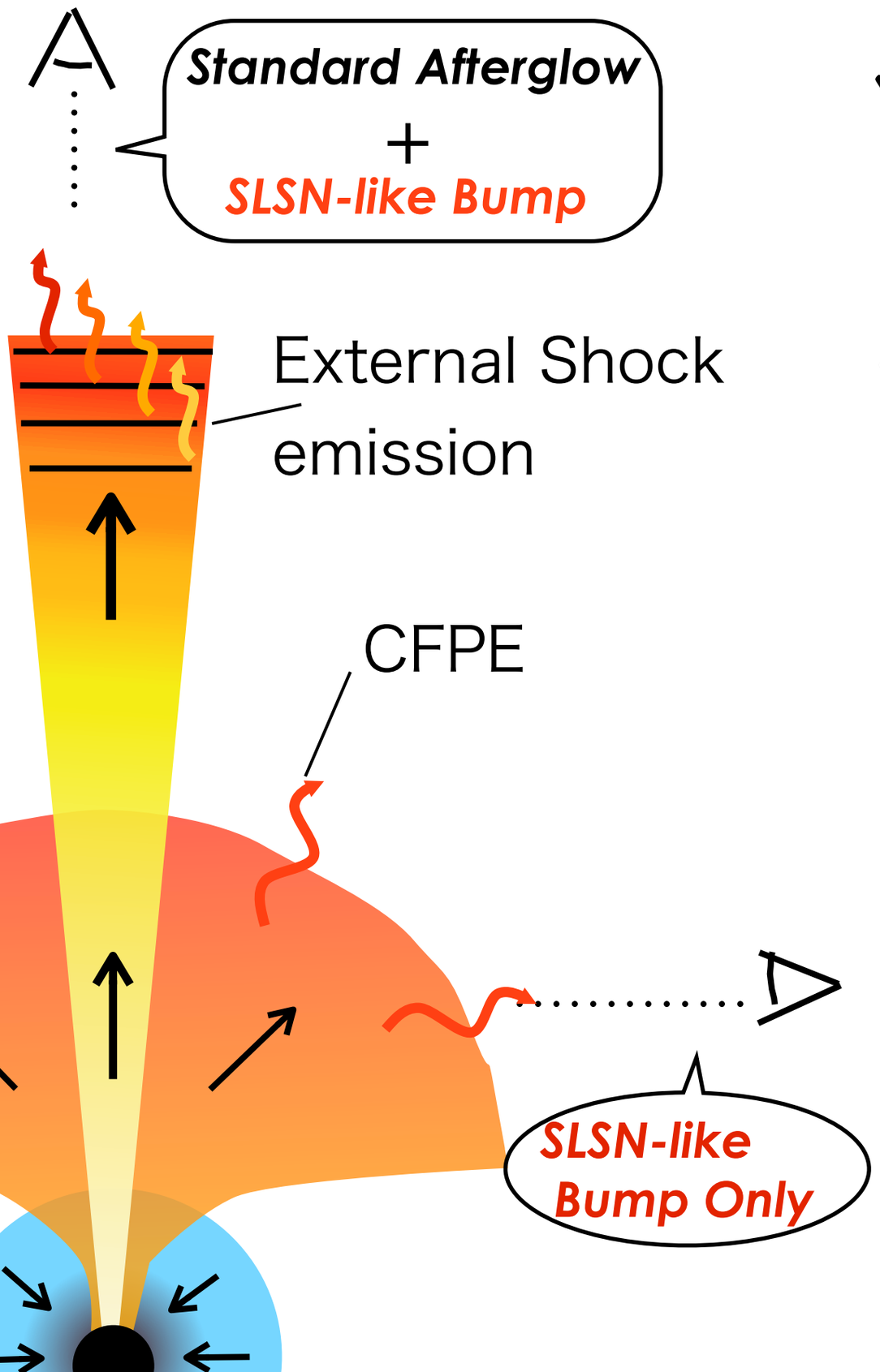
$$E_{\rm c}(t_{\rm bo}) \sim 10^{53}\ {\rm erg} \quad >> \quad E_{\rm c}(t_{\rm bo}) \sim 7.3 \times 10^{51}\ {\rm erg}$$

BSG　　WR

(Same parameter values are adopted.)

✓ Larger progenitor is more favorable for bright CFPE.

Possible Subclass of SLSN



✓ For an off-axis observer of ULGRB, only SLSN-like component from CFPE can be seen.

✓ Event rate.

$$R_{\rm ULGRB} \sim 2 \times 10^{-3} {\rm Gpc}^{-3} {\rm yr}^{-1}$$

$$R_{\rm CFPE} \sim 0.1 \left(\theta_{\rm j}/12^\circ\right)^{-2} {\rm Gpc}^{-3} {\rm yr}^{-1}$$

$$R_{\rm SLSN} \sim 10 {\rm Gpc}^{-3} {\rm yr}^{-1}$$ Gal-Yam. 2012

Type IIP SLSN from CFPE rate
~ 0.1% of SLSN rate.

✓ This conjecture can be tested by simultaneous & follow-up observation of orphan afterglow.

Summary

✓ ULGRB may form a new population of GRBs.

✓ BSG model is favorable for their duration.

✓ GRB111209A shows a SLSN-like bump in Opt/IR afterglow.

✓ We calculate the propagation of jet and cocoon.

✓ We find that SLSN-like bump can be explained by CFPE.

BSG model is consistent both with prompt & SLSN-like bump.

✓ Bright CFPE is characteristic to BSG collapsar.

⇨ It can be a smoking gun evidence of progenitor model.

✓ Our result supports the BSG model for ULGRB.