第一回MeVガンマ線天文学研究会 @京都大学　2017.2.27-28

超大質量星の起こすガンマ線バースト

京都大学 天体核研究室

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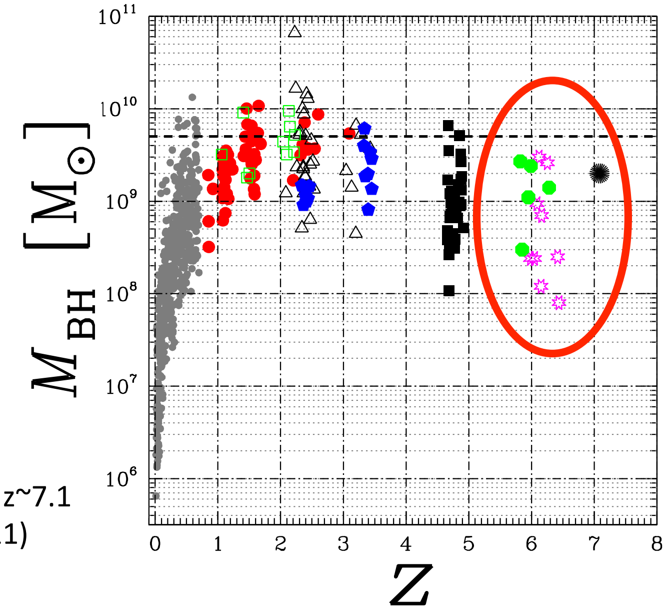
Ref. T.Matsumoto et al. ApJ, 810, 64 (2015)
T.Matsumoto et al. ApJ, 823, 83 (2016)

Supermassive black holes



e.g. Our galaxy : SgA* $M_{\rm BH} \sim 10^6 M_\odot$

z ~ 6-7 : $\sim 10^9 M_\odot$ Fan 2006, Mortlock et al. 2011 Wu et al. 2015

The Origin??

$$M_{\rm BH} = M_{\rm seed} \exp\left(\frac{1-\epsilon}{\epsilon}\frac{t(z)}{t_{\rm Edd}}\right)$$

⇨ $M_{\rm seed} \gtrsim 300 M_\odot$ For M_{BH}~2×10^9 M_{sun} @z~7.1 (Mortlock et al. 2011)

1. Population III stars

⇒ $M_{\rm seed} \sim 10^{2-3} M_\odot$ Hirano et al. 2014, Susa et al. 2014

but, feedbacks make difficult Eddington accretion…

Alvarez et al. 2009

2. Supermassive stars

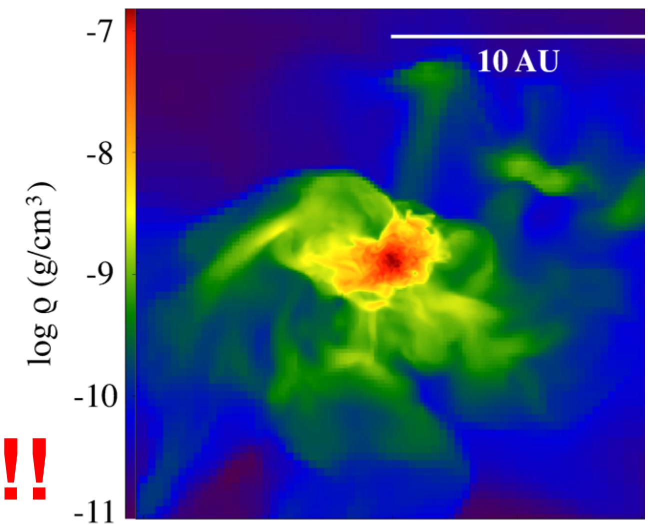
Supermassive Stars

Bromm & Loeb 2003, Shang et al. 2010
Latif et al. 2013, Hosokawa et al. 2013
Inayoshi et al. 2014

⇒ direct collapse BHs

with $M_{\rm seed} \sim 10^5 M_{\odot}$

✓formation theory is developing



Inayoshi et al. 2014

But, there is **No observation!!**

✓How to detect such high-z objects??

e.g. Population III stars : Gamma-ray bursts

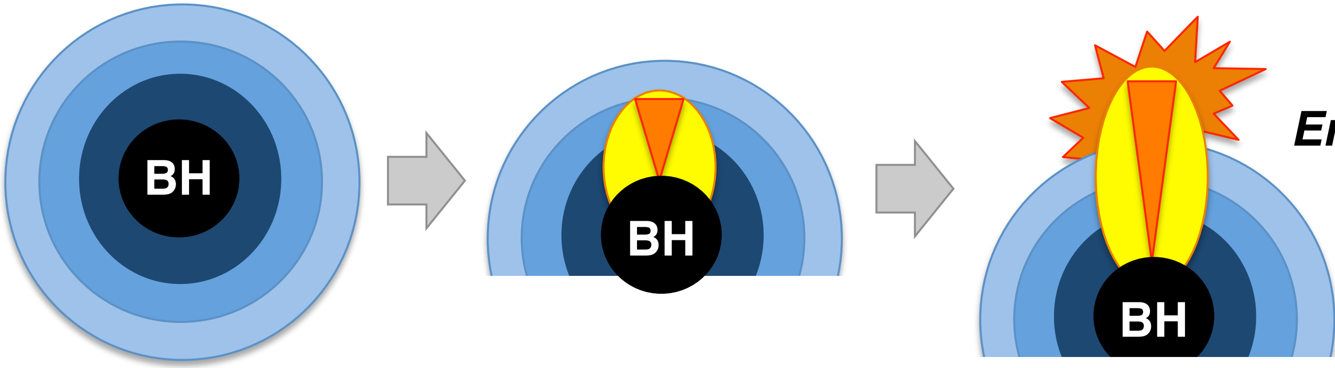
Suwa & Ioka 2011, Nakauchi et al. 2012

We study whether SMSs launch GRBs

and their observability.

Gamma-Ray Bursts

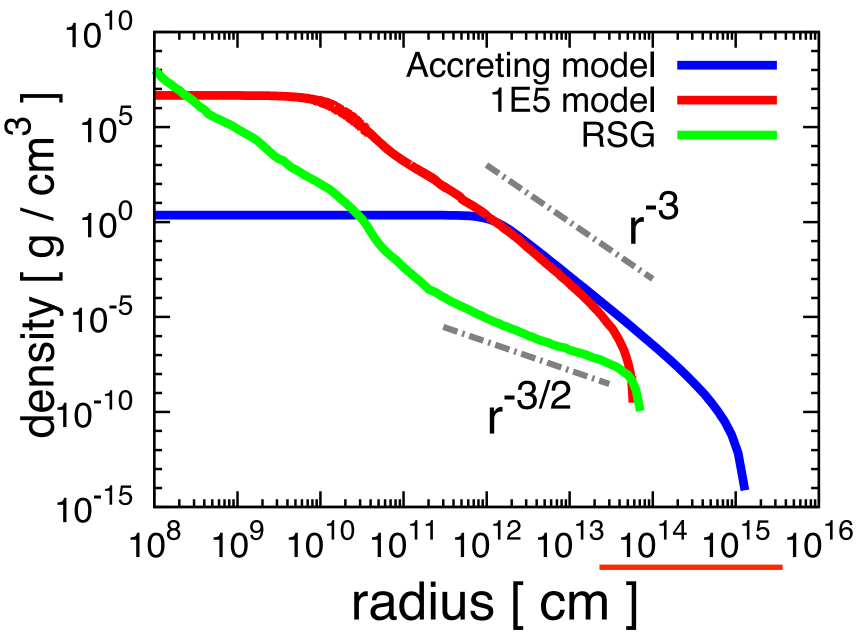
Woosley 1993
MacFadyen & Woosley 1999



Energetic Explosion!!

$L_\gamma \sim 10^{51}\,\mathrm{erg\,s^{-1}}$
$E_\gamma \sim 10^{53}\,\mathrm{erg}$

Gravitational collapse & BH formation — Jet propagation — Successful breakout



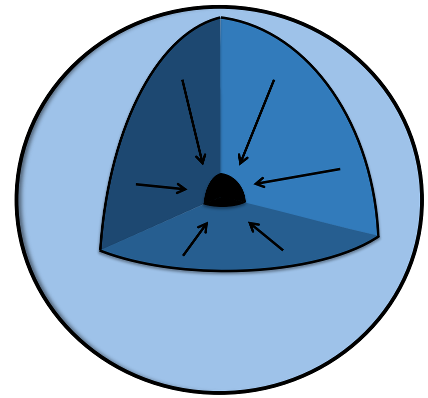
SMS model

1E5 : precollapse progenitor Fryer & Heger 2011
Accreting : proto-star under mass accretion
⇒collapse owing to GR instability
Hosokawa et al. 2013

✓SMSs have very large radii.
Can jets break out successfully??

e.g. Red supergiants (RSGs)
don't produce GRBs Matzner 2003

Jet Propagation in progenitors



Method

1.Gravitaional collapse

mass accretion rate onto BH:

$$\dot{M}(t) = \frac{dM(r)}{dt_{\rm ff}} \qquad t_{\rm ff} \simeq \sqrt{\frac{r^3}{GM(r)}} \qquad M(r) = \int_0^r 4\pi r'^2 \rho dr'$$

2.Jet formation

jet luminosity: powered by mass accretion with MHD process

Blandford & Znajek 1977

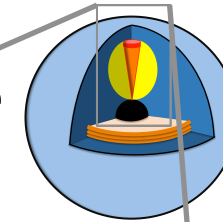
$$L_{\rm j}(t) = \eta_{\rm j} \dot{M}(t) c^2$$

Komissarov & Barkov 2010

$$\eta_{\rm j} = 6.2 \times 10^{-4}$$

Suwa & Ioka 2011

Jet Propagation in progenitors



3.Jet propagation Matzner 2003, Suwa & Ioka 2011
Bromberg et al. 2011, Nakauchi et al. 2012

jet velocity : momentum balance @ shock front

$$\beta_{\rm h} := \frac{v_{\rm h}}{c} \simeq \frac{1}{1+\tilde{L}^{-1/2}}$$

$$\tilde{L} = \frac{L_{\rm j}/c\Sigma_{\rm h}}{\rho c^2}$$

Cross section of jet head ($\Sigma_{\rm h}$)

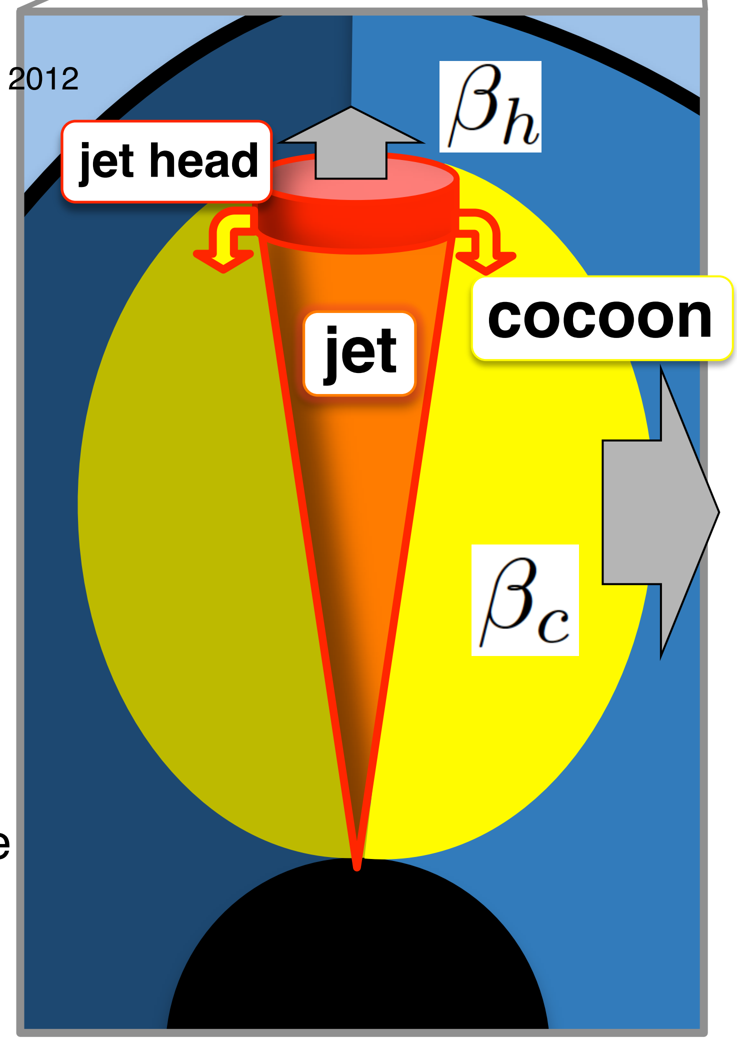
Energy density @ jet ($L_{\rm j}/c\Sigma_{\rm h}$)

Mass energy density of progenitor (ρc^2)

cocoon velocity :

$$\beta_{\rm c} := \frac{v_{\rm c}}{c} = \sqrt{\frac{P_{\rm c}}{\rho c^2}}$$

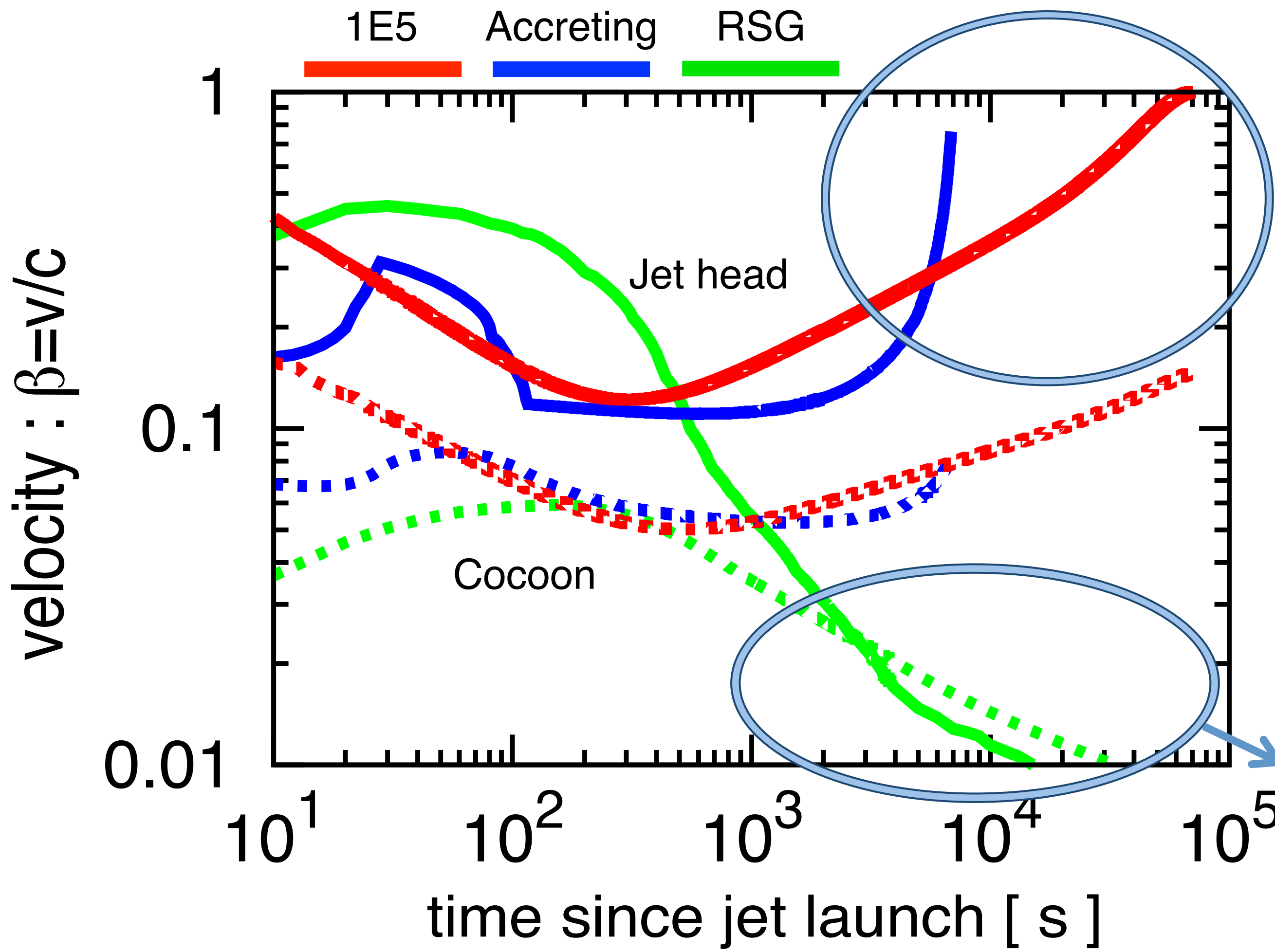
Cocoon pressure ($P_{\rm c}$)



⇒ ***We calculate time evolution of jet head & cocoon***

Result

Accelerating & Successful Breakout !!



$$\beta_{\rm h} \sim \tilde{L}^{1/2}$$

$$\rho \propto r^{-n}$$

$$L_{\rm j} \propto \dot{M}(t) \sim t^{\frac{3-2n}{3}}$$

$$r_{\rm h} \sim \beta_{\rm h} t$$

$$\beta_{\rm h} \propto t^{\frac{n-3}{9-2n}}$$

n ~ 3 for SMSs (rad pressure dom.)

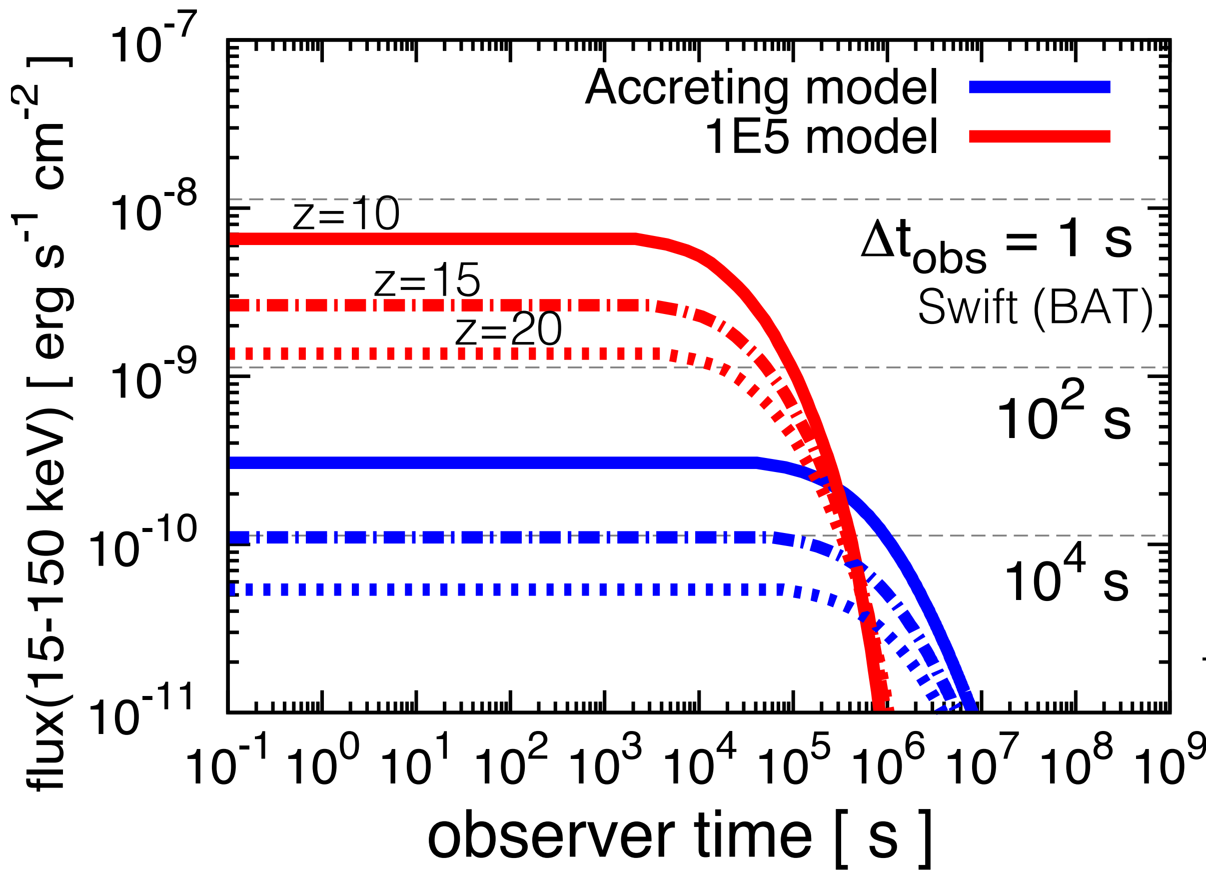
Decelerating & Not collimated GRB…

n ~ 3/2 for RSGs (gas pressure dom.)

SMSs can produce GRBs!!

Observability

✓ Prompt emission



When E_p-L_p relation holds

$$\frac{L_p}{10^{52}\,\mathrm{erg\,s^{-1}}} \simeq 2\times10^{-5}\left(\frac{E_p}{1\,\mathrm{keV}}\right)^{2.0}$$

Yonetoku et al. 2004

$$f_{\rm sig}(t_{\gamma,\rm obs}) = F_{\rm bol}(t_\gamma)\frac{\int_{E_{\rm min}}^{E_{\rm max}} EN(E)dE}{\int_0^\infty EN(E)dE}$$

$$F_{\rm bol}(t_{\gamma,\rm obs}) = \frac{L_{\gamma,\rm iso}(t_\gamma)}{4\pi d_L(z)^2}$$

Band fnc.

GRBs show Ultralong duration!!

Event rate

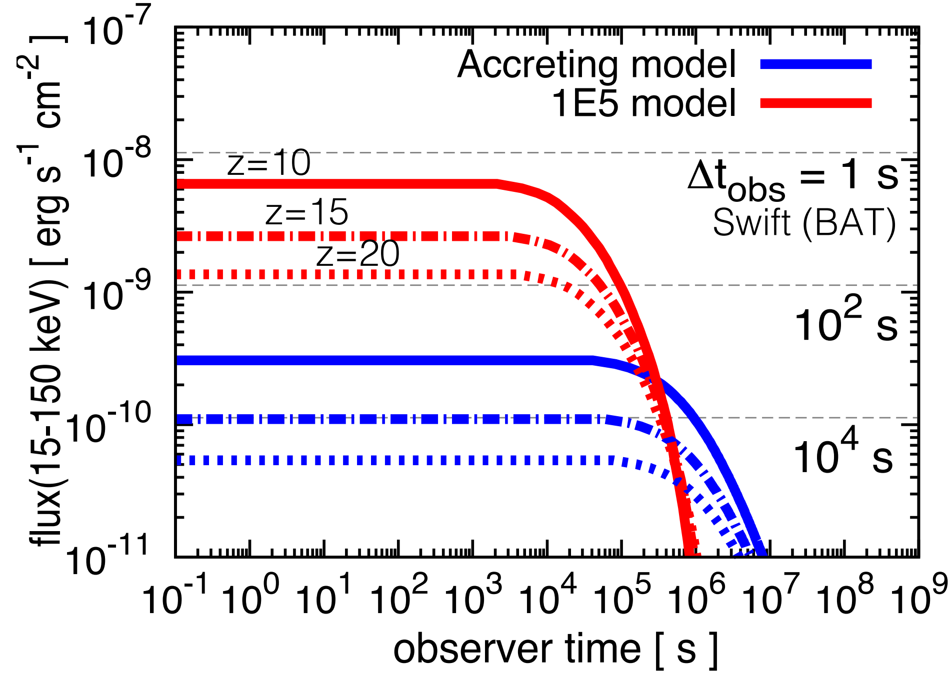
* dN/dt < 600 /yr/sky

Yue et al. 2014

* beaming ~ θ^2

⇒ < a few events /yr/sky

MeV Gamma-rays



光度の評価

Nakauchi et al.2012

E_p-L_p relation

$$\frac{L_p}{10^{52}\,\mathrm{erg\,s^{-1}}} \simeq 2\times10^{-5}\left(\frac{E_p}{1\,\mathrm{keV}}\right)^{2.0}$$

Yonetoku et al. 2004

E_p-$E_{\gamma,iso}$ relation

$$\frac{E_p}{1\,\mathrm{keV}} \simeq 80\left(\frac{E_{\gamma,\mathrm{iso}}}{10^{52}\,\mathrm{erg}}\right)^{0.57}$$

Amati et al. 2002

親星モデル	Accreting	1E5
$E_{\gamma,\mathrm{iso}}$ [erg]	1.8×10^{57}	2.5×10^{56}
E_p^{obs} [MeV]	4.9	1.6
L_p [erg/s]	6.1×10^{51}	6.2×10^{52}
E_p^{obs} [keV]	11	35

$$f_{\mathrm{MeV}} \sim 10^{-10} - 10^{-9}\,\mathrm{erg/s/cm^2}$$

$$f_{\mathrm{sig}}(t_{\gamma,\mathrm{obs}}) = F_{\mathrm{bol}}(t_\gamma)\frac{\int_{E_{\min}}^{E_{\max}} EN(E)dE}{\int_0^\infty EN(E)dE}$$

Band fnc.

$$F_{\mathrm{bol}}(t_{\gamma,\mathrm{obs}}) = \frac{L_{\gamma,\mathrm{iso}}(t_\gamma)}{4\pi d_L(z)^2}$$

※Ultra Long GRB111209の観測では E_p-$E_{\gamma,iso}$ relationが2σで成立

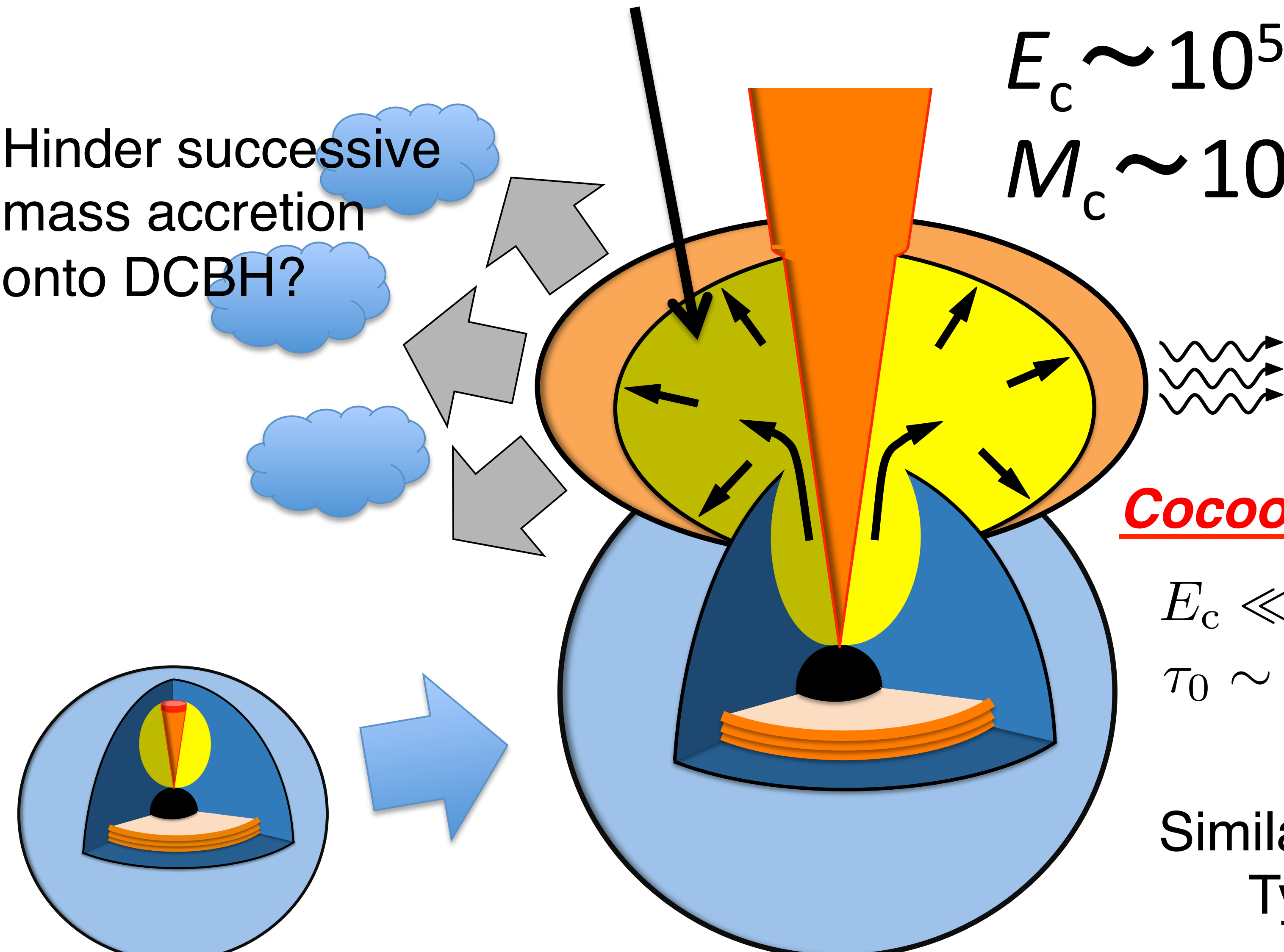
Gendre et al. 2013

Energetic Cocoon Fireball

Kashiyama et al. 2013
Nakauchi et al. 2013

$E_c \sim 10^{55\text{-}56}$ erg
$M_c \sim 10^{2\text{-}3}$Msun

Hinder successive mass accretion onto DCBH?



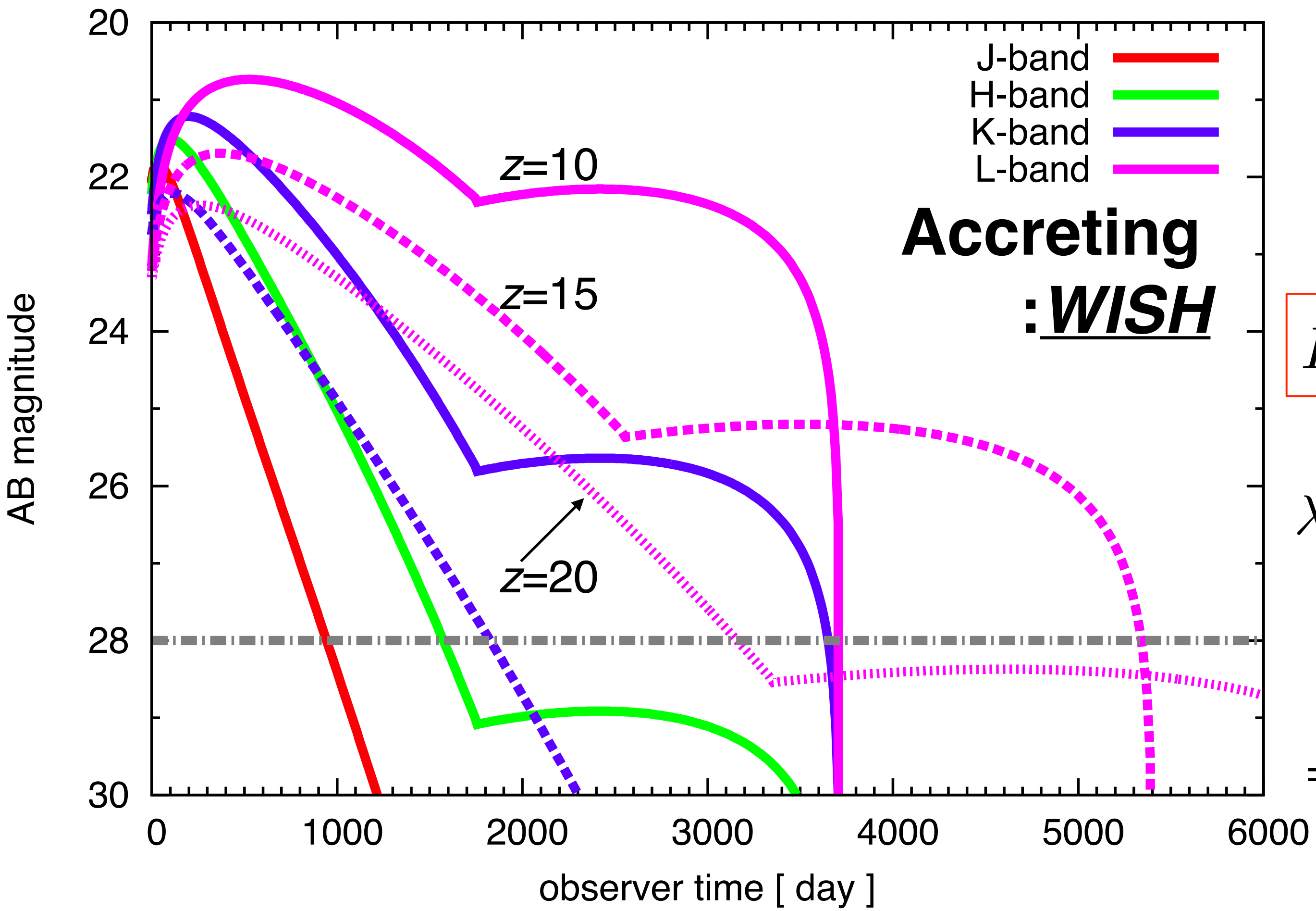
Cocoon Emission

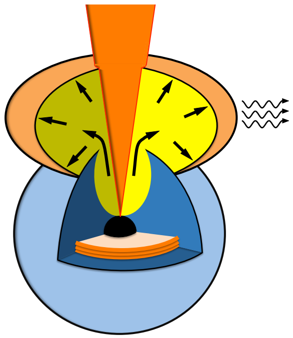
$$E_c \ll M_c c^2$$

$$\tau_0 \sim \kappa M_c / R_c(0)^2 \gg 1$$

Similar to Type IIP SNe

Cocoon Emissions are very bright





$L_{\rm c} \sim 10^{45} {\rm erg\,s^{-1}}$

$R_{\rm c,14} E_{\rm c,56} M_{\rm c,3}^{-1}$

$\lambda_{\rm obs} \gtrsim 1.95 \mu{\rm m}$

$[(1+z)/16]$

Lyman-α absorption

$\Rightarrow$ Near Infrared

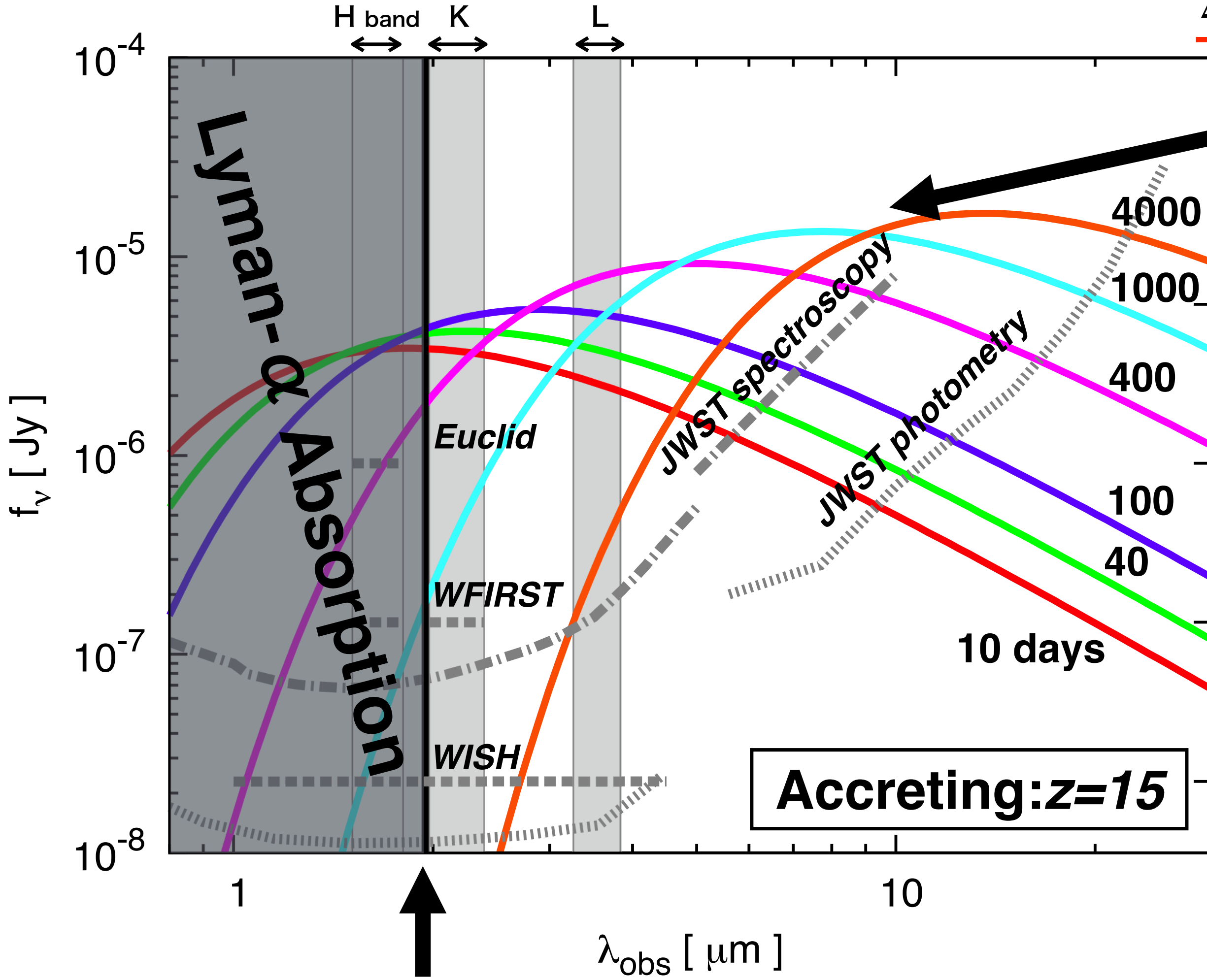
e.g. *Euclid, WFIRST*
WISH,

Arnett 1980 Popov 1993 Dexter & Kasen 2013
Kashiyama et al. 2013 Nakauchi et al. 2013

Evidence for SMSs

$L_c \sim 10^{45} \mathrm{erg\,s^{-1}}\, R_{c,14} E_{c,56} M_{c,3}^{-1}$

$\Delta t_{co} \sim 10^{7} \mathrm{s}\; R_{c,14}^{1/7} E_{c,56}^{-5/28} M_{c,3}^{15/28}$



Line e.g. Hα

$v_{ph} \sim 10^{10} \mathrm{cm\ s^{-1}}\; E_{c,56}^{1/2} M_{c,3}^{-1/2}$

$R_c \simeq 10^{14}\ \mathrm{cm}\ L_{c,45} v_{ph,10}^{-2}$

$E_c \simeq 10^{56}\ \mathrm{erg}\ \Delta t_{co,7}^{14/5} L_{c,45}^{-2/5} v_{ph,10}^{19/5}$

$M_c \simeq 10^{3}\ M_\odot\ \Delta t_{co,7}^{14/5} L_{c,45}^{-2/5} v_{ph,10}^{9/5}$

z **Redshift from GP trough**

Litvinova & Nadezhin 1985
Popov 1993

Outline

- ✓ Introduction
- ✓ Jet propagation in supermassive stars
- ✓ Cocoon Emissions from SMS GRBs
- ✓ **Summary**

Summary

- ✓ SMSs : seed candidate of SMBHs.
  No observational evidence.
- ✓ SMSs can produce ultra-long GRBs
  : radiation pressure dominated
  duration > 10^4 s
  detectable with *Swift*
  MeV detectors are needed to detect GRBs with long durations.
- ✓ Energetic cocoon fireballs may be an evidence for SMSs