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Can Direct Collapse Black Holes Launch Gamma-Ray Bursts?

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Ref. T.Matsumoto et al. arXiv1506.05802 in press

Outline

- ✓Introduction
- ✓Jet propagation in supermassive stars
- ✓Observability of gamma-ray bursts from supermassive stars
- ✓Summary

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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

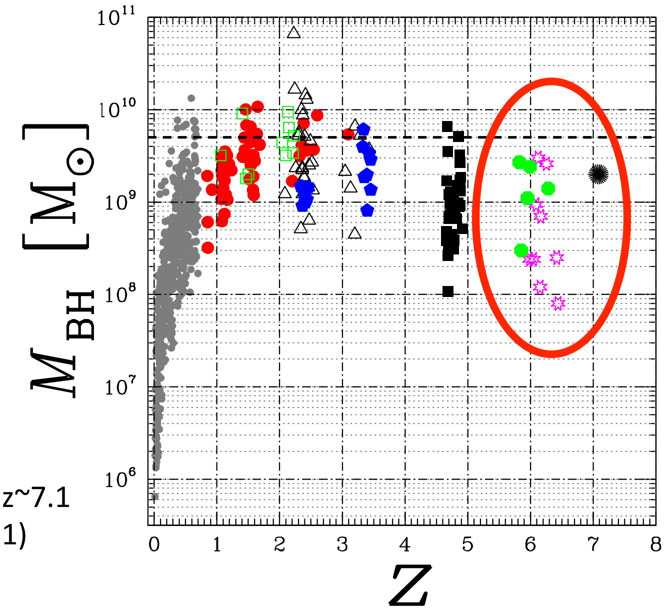
The Origin??

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

⇒ $$\boxed{M_{\rm seed} \gtrsim 300 M_\odot}$$

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

Marziani & Sulentic 2012



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

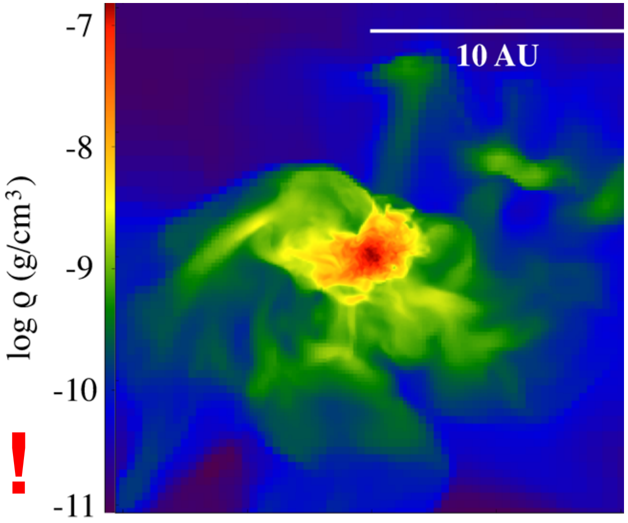
Supermassive Stars

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

⇒ direct collapse BHs

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

✓ plausible formation theory is developing



Inayoshi et al. 2014

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

✓ How to detect such a high-z object??

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

Suwa & Ioka 2011, Nakauchi et al. 2012

We study whether SMSs launch GRBs

and their observability.

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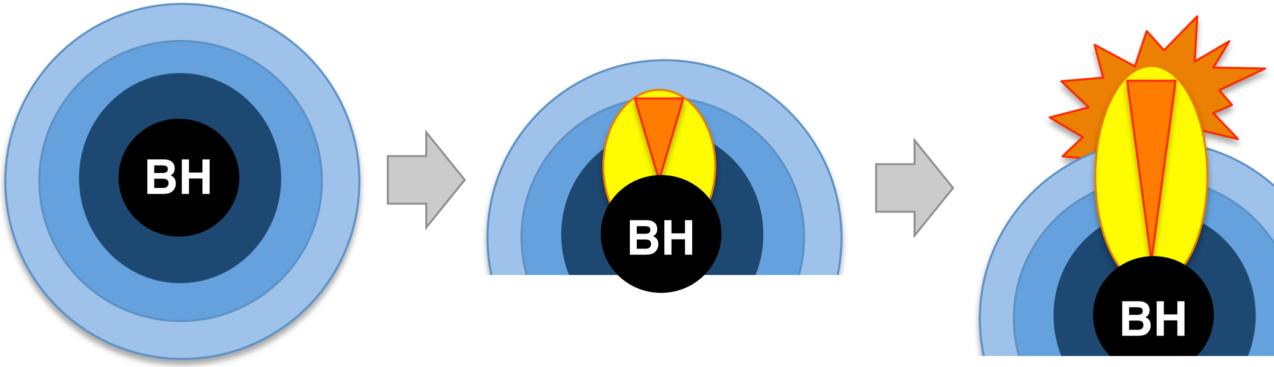
Gamma-Ray Bursts

Woosley 1993
MacFadyen & Woosley 1999



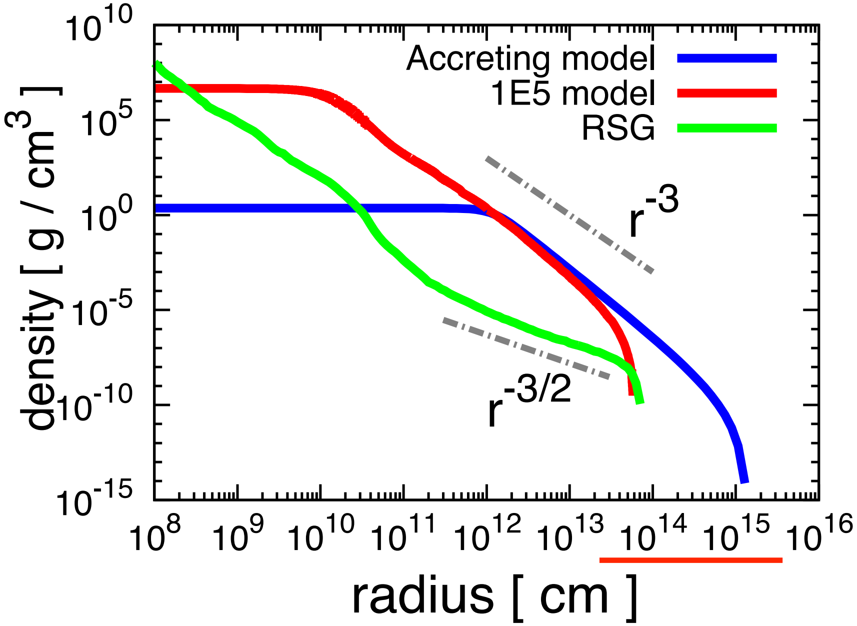
Energetic Explosion!!

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

Gravitational collapse
& BH formation

Jet propagation

Successful breakout



SMS model

1E5 : precollapse progenitor Fryer & Heger 2011

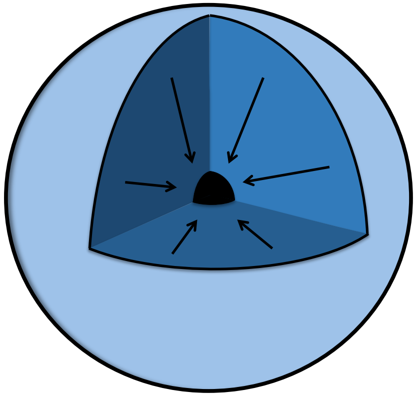
Accreting : proto-star under mass accretion
⇒collapse owing to GR instability
Hosokawa et al. 2013

✓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:

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

2.Jet formation

jet luminosity: powered by mass accretion with MHD process

Blandford & Znajek 1977

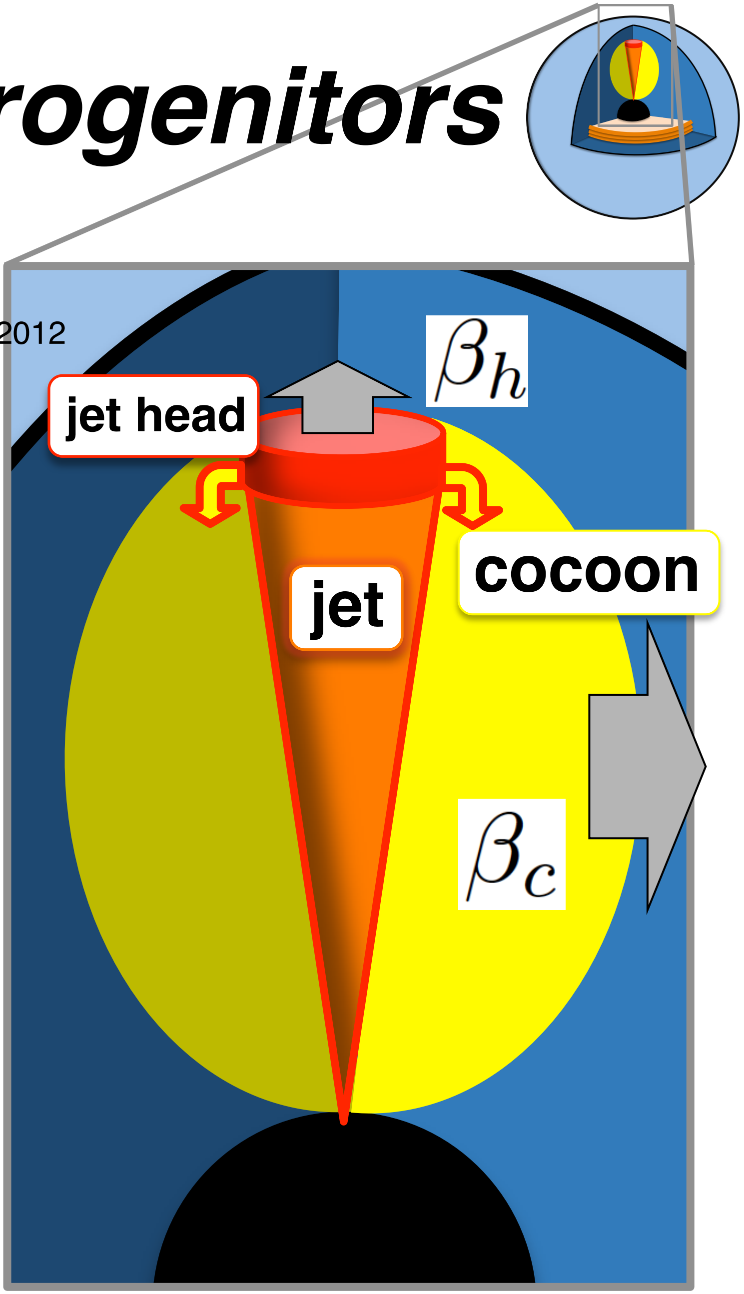
$$L_{\text{j}}(t) = \eta_{\text{j}} \dot{M}(t) c^2$$

Komissarov & Barkov 2010

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

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

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

$$\tilde{L} = \frac{L_{\rm j}/c\overbrace{\Sigma_{\rm h}}^{\text{Cross section of jet head}}}{\rho c^2}$$

← Energy density @ jet

← Mass energy density of progenitor

cocoon velocity :

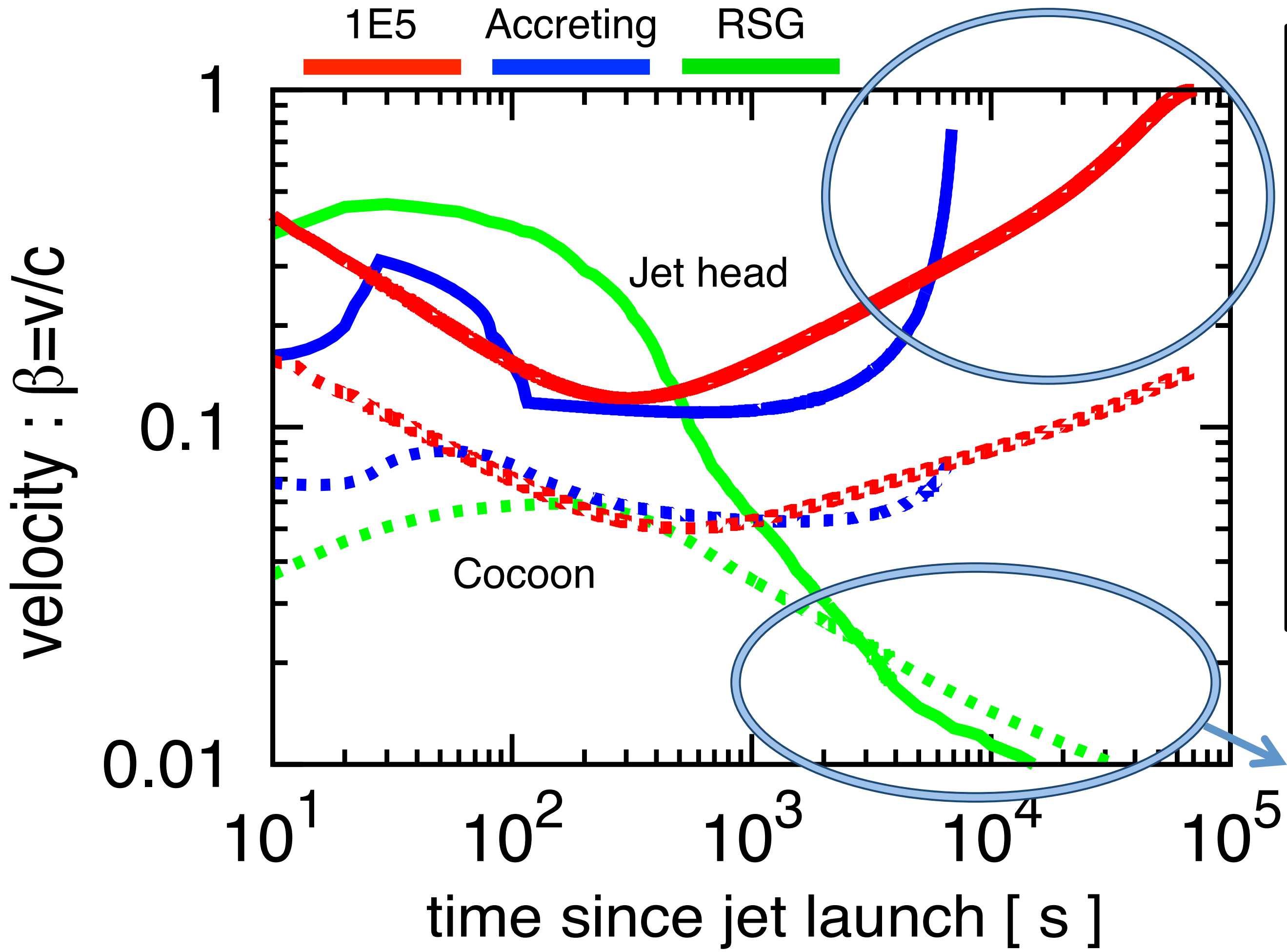
$$\beta_{\rm c} := \frac{v_{\rm c}}{c} = \sqrt{\frac{P_{\rm c}}{\rho c^2}}$$

← Cocoon pressure

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

Result

Accelerating & Successful Breakout !!



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

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

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

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

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

n ~ 3 for SMSs (rad pressure dom.)

Decelerating & Not collimated GRB…

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

SMSs can produce GRBs!!

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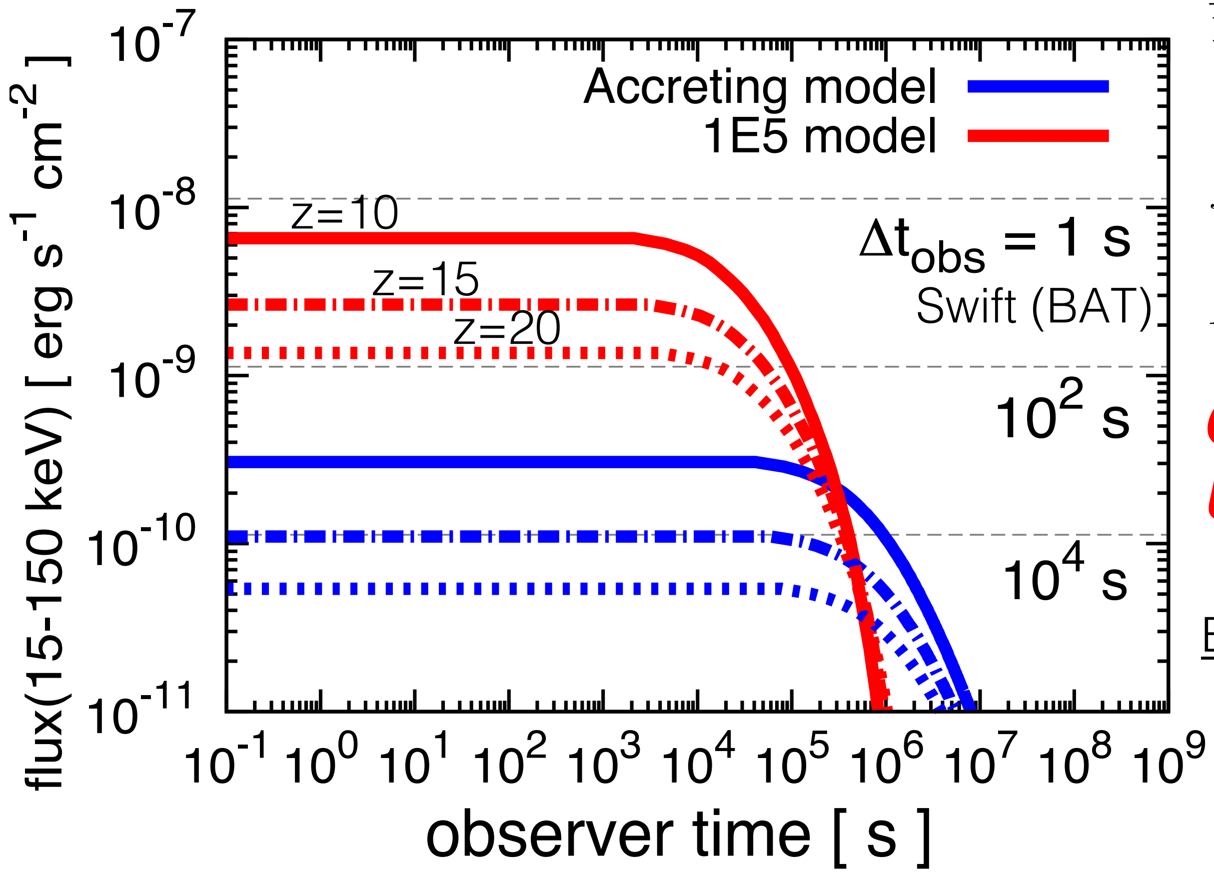
Observability of GRBs from SMSs

✓ Prompt emission



When E_p-L_p relation holds

$$\frac{L_{\rm p}}{10^{52}\,{\rm erg\,s^{-1}}} \simeq 2\times 10^{-5}\left(\frac{E_{\rm p}}{1\,{\rm keV}}\right)^{2.0}$$

Yonetoku et al. 2004

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

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

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

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Summary

✓SMSs : seed candidate of SMBHs.
No observational evidence.

✓SMSs can produce ultralong GRBs
: radiation pressure dominated
duration > 10^4 s
detectable with *Swift*