Population III Gamma-Ray Burst

Kunihito Ioka (KEK)

Suwa & KI arXiv:1009.6001
Nagakura+ arXiv:1104.5691
de Souza, Yoshida & KI arXiv:1105.2395
KI & Meszaros astro-ph/0408487
KI astro-ph/0309200

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

The Graduate University for Advanced Studies
Sokendai

Population III Gamma-Ray Burst

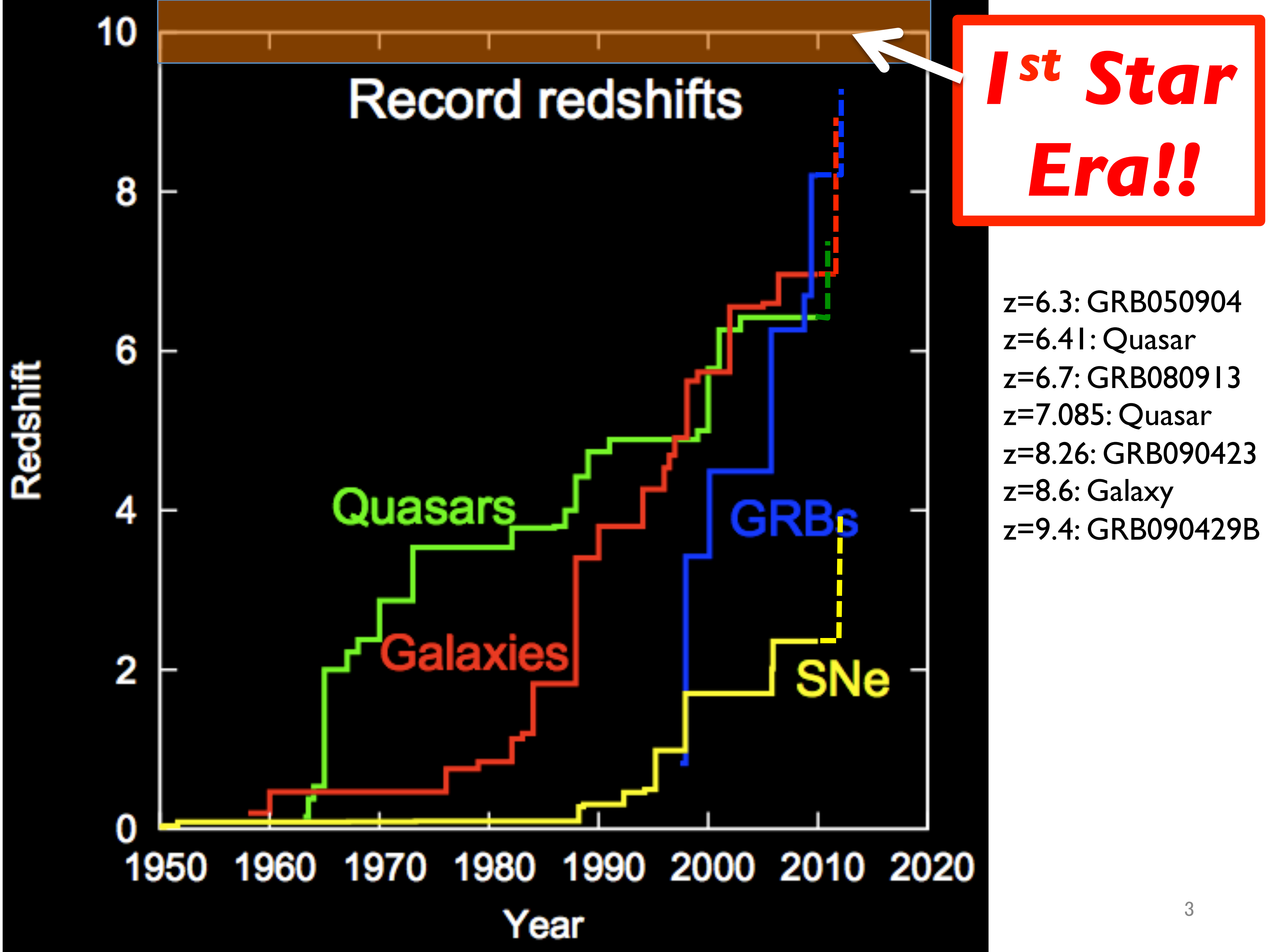
Kunihito Ioka (KEK)

You can find these guys →

Suwa & KI arXiv:1009.6001
Nagakura+ arXiv:1104.5691
de Souza, Yoshida & KI arXiv:1105.2395
KI & Meszaros astro-ph/0408487
KI astro-ph/0309200

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

The Graduate University for Advanced Studies
Sokendai



z=6.3: GRB050904
z=6.41: Quasar
z=6.7: GRB080913
z=7.085: Quasar
z=8.26: GRB090423
z=8.6: Galaxy
z=9.4: GRB090429B

Super-Massive Pop III Star?

Present Day
Massive Star
$\sim 20 M_{\odot}$

Omukai & Nishi 98;
Abel+ 02; Bromm+ 02;
Omukai+ 03; Yoshida+ 08;
Omukai's talk; Whalen's talk

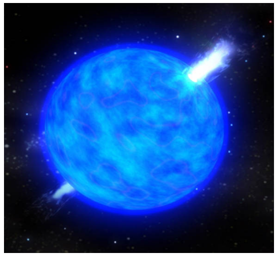
Pop III
(Zero Metal)
$\sim 1000 M_{\odot}$(!?)

Mini halo (first object): $\sim 1000 M_{\odot}$
If all the mass is accreted to a proto-star,

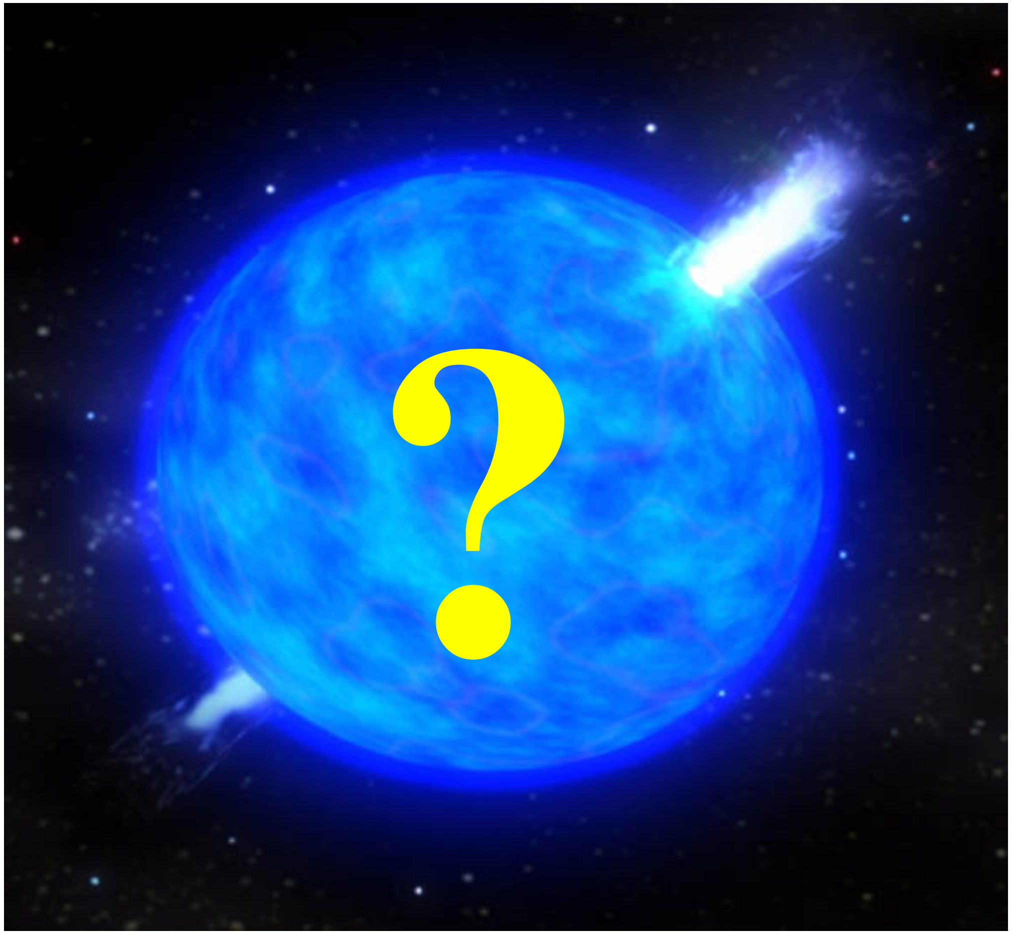
First stars are very MASSIVE?

Pop III GRB?

Present Day GRB

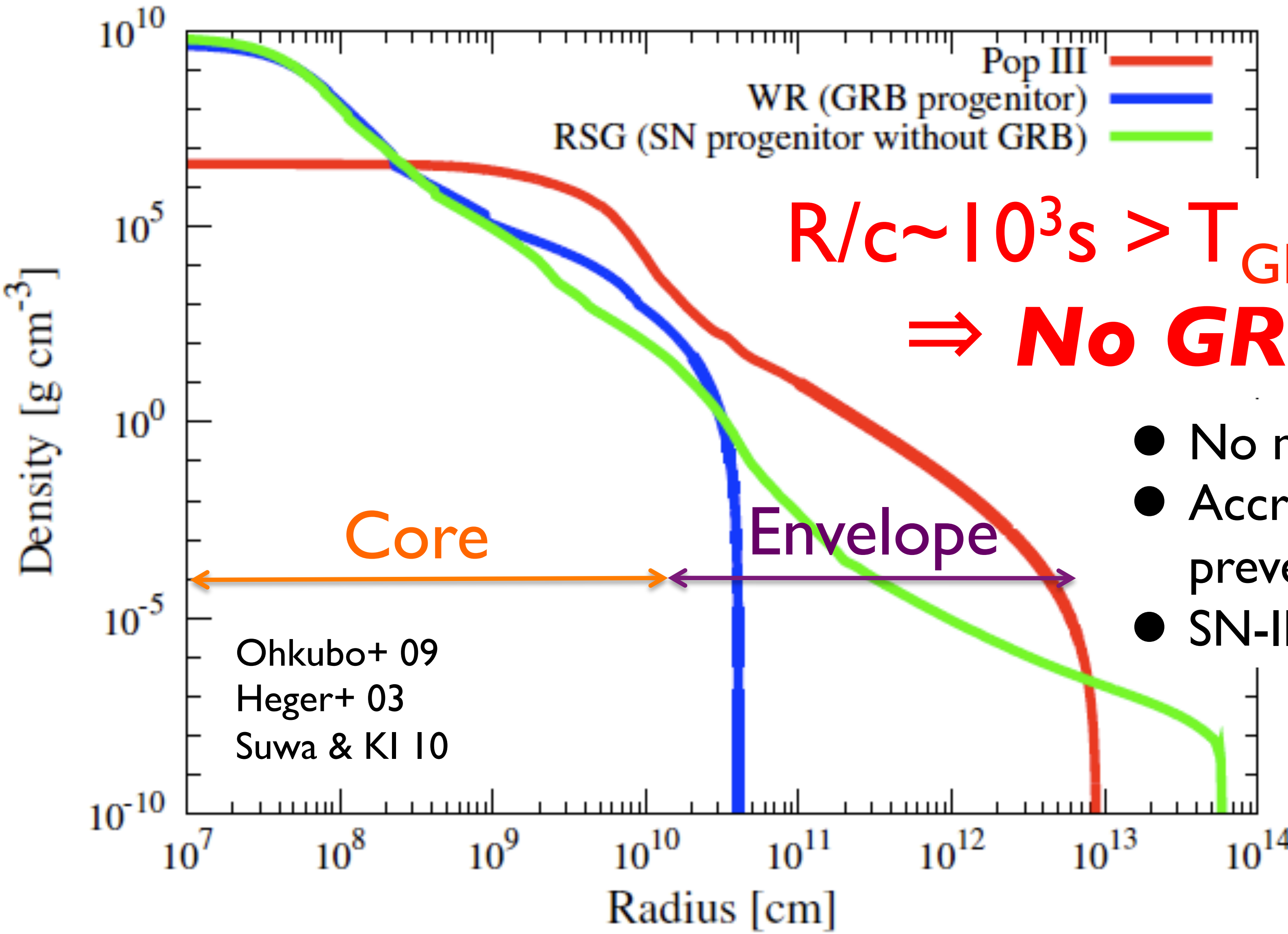


Komissarov & Barkov 10
Meszaros & Rees 10
Suwa & KI 11
Nagakura+ 11



Gigantic (x100) GRB @ z~10-30???

Massive Envelope



$R/c \sim 10^3 s > T_{GRB} \sim 10s$

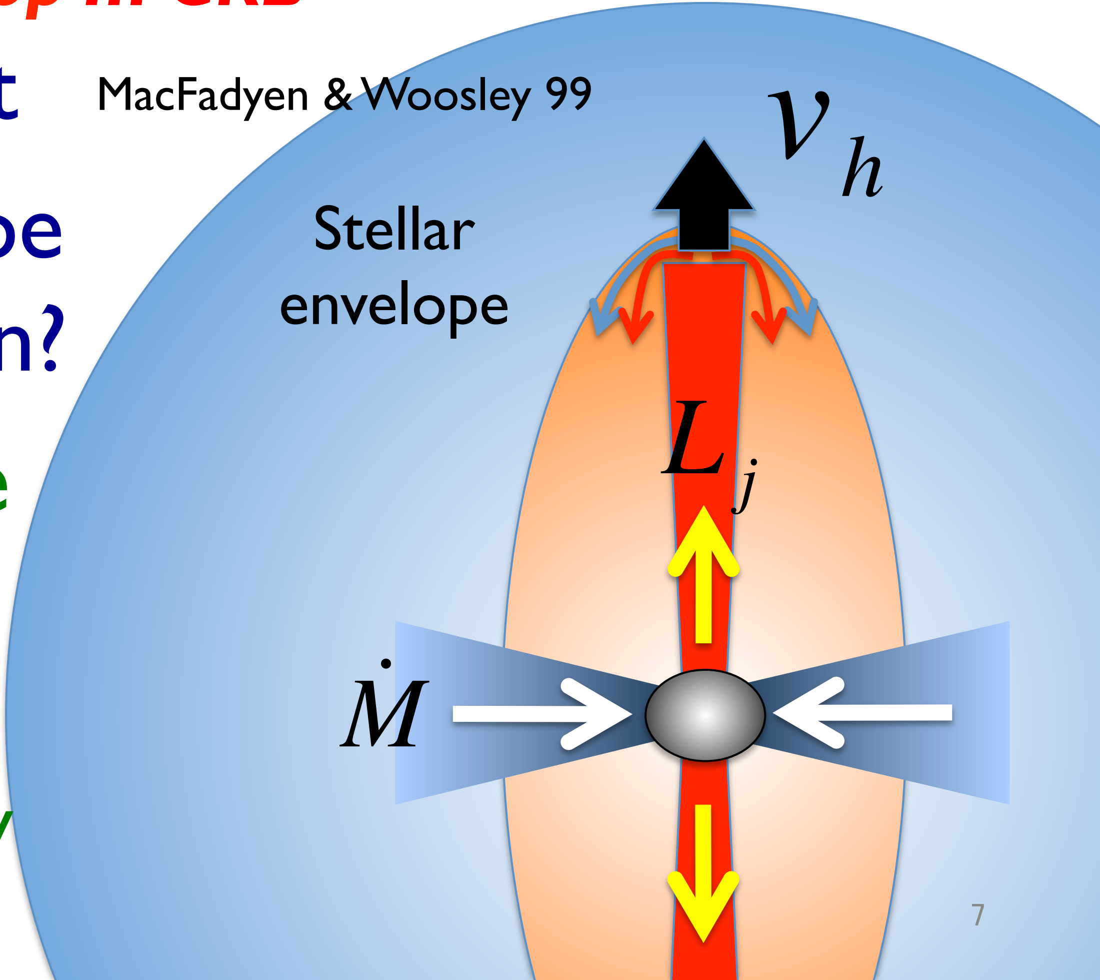
⇒ ***No GRB?***

- No mass loss
- Accretion may prevent CHE
- SN-II w/o GRB

Duration ~10 s ?

- ***Loophole: $T_{Pop\ III\ GRB}$~10 sec?***
- Accretion ⇒ Jet
- Massive envelope
  ⇒ Long duration?
- Stellar envelope determines
  1. Jet luminosity
  2. Jet head velocity

MacFadyen & Woosley 99



Penetration Problem

1. Give the envelope profile
2. Calculate accretion

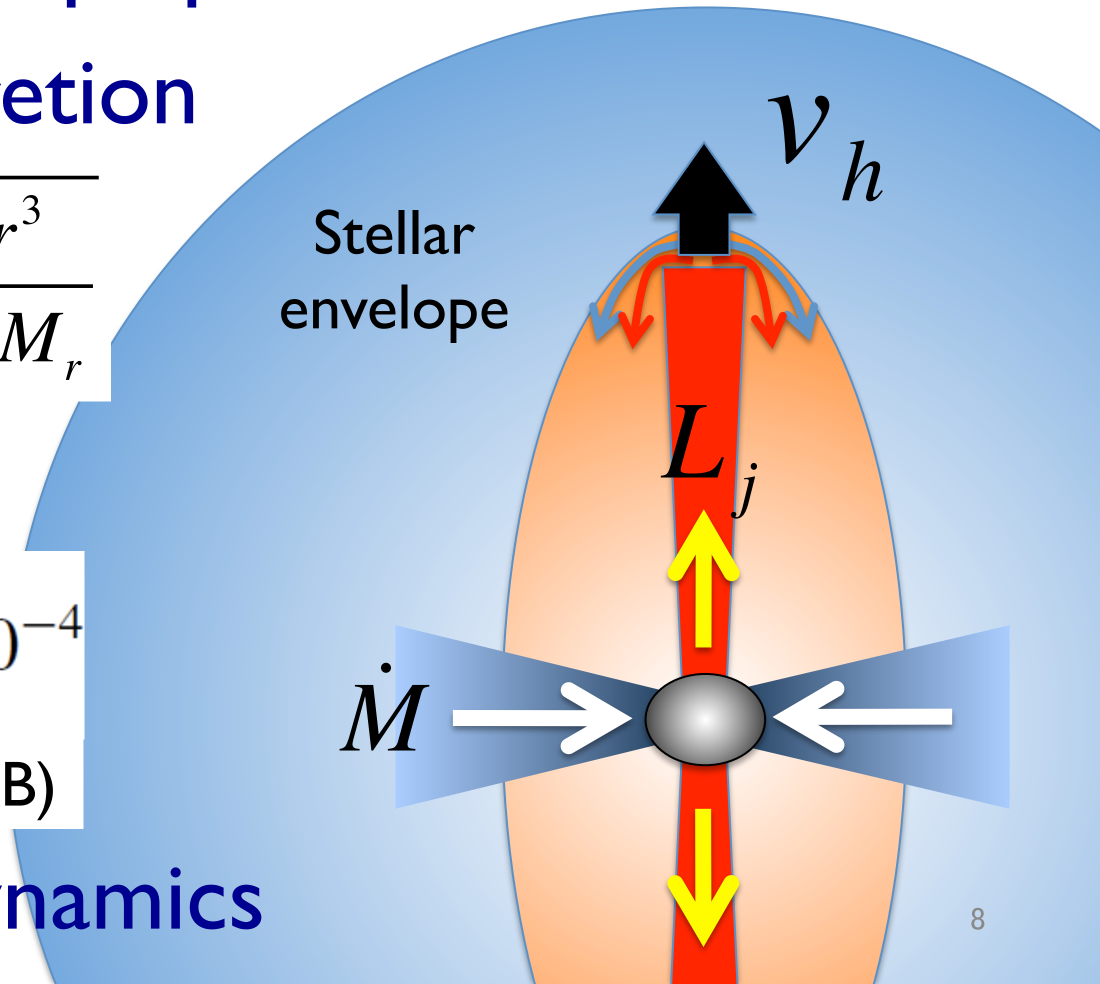
$$\dot{M}(t) = \frac{dM}{dt_{ff}},\ t_{ff} \approx \sqrt{\frac{r^3}{GM_r}}$$

3. $\Rightarrow L_j(t)$

$$\eta = \frac{L_j}{\dot{M}c^2} \approx 6.2 \times 10^{-4}$$

(calibrated by low-z GRB)

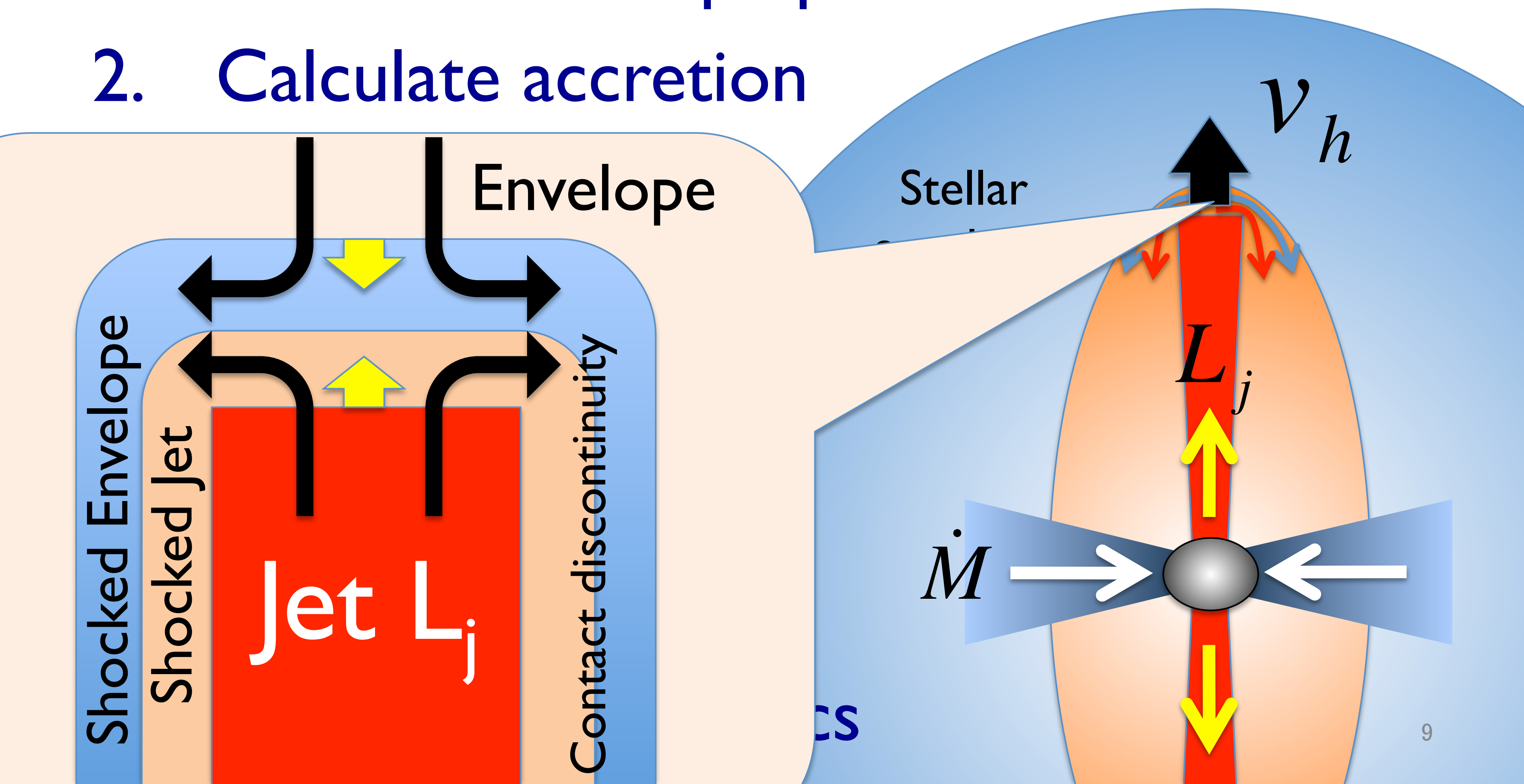
4. $\Rightarrow$ Jet head dynamics



Penetration Problem

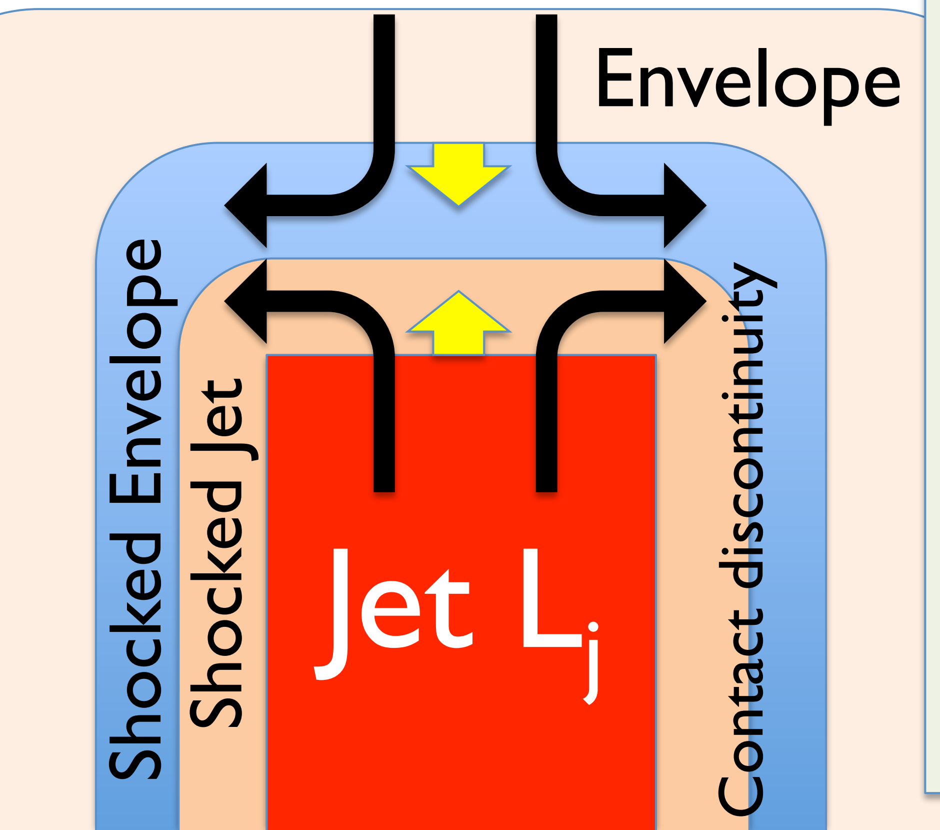
Bromberg's talk

1. Give the envelope profile
2. Calculate accretion



Penetration Problem

1. Give the envelop
2. Calculate accreti



Ram pressure

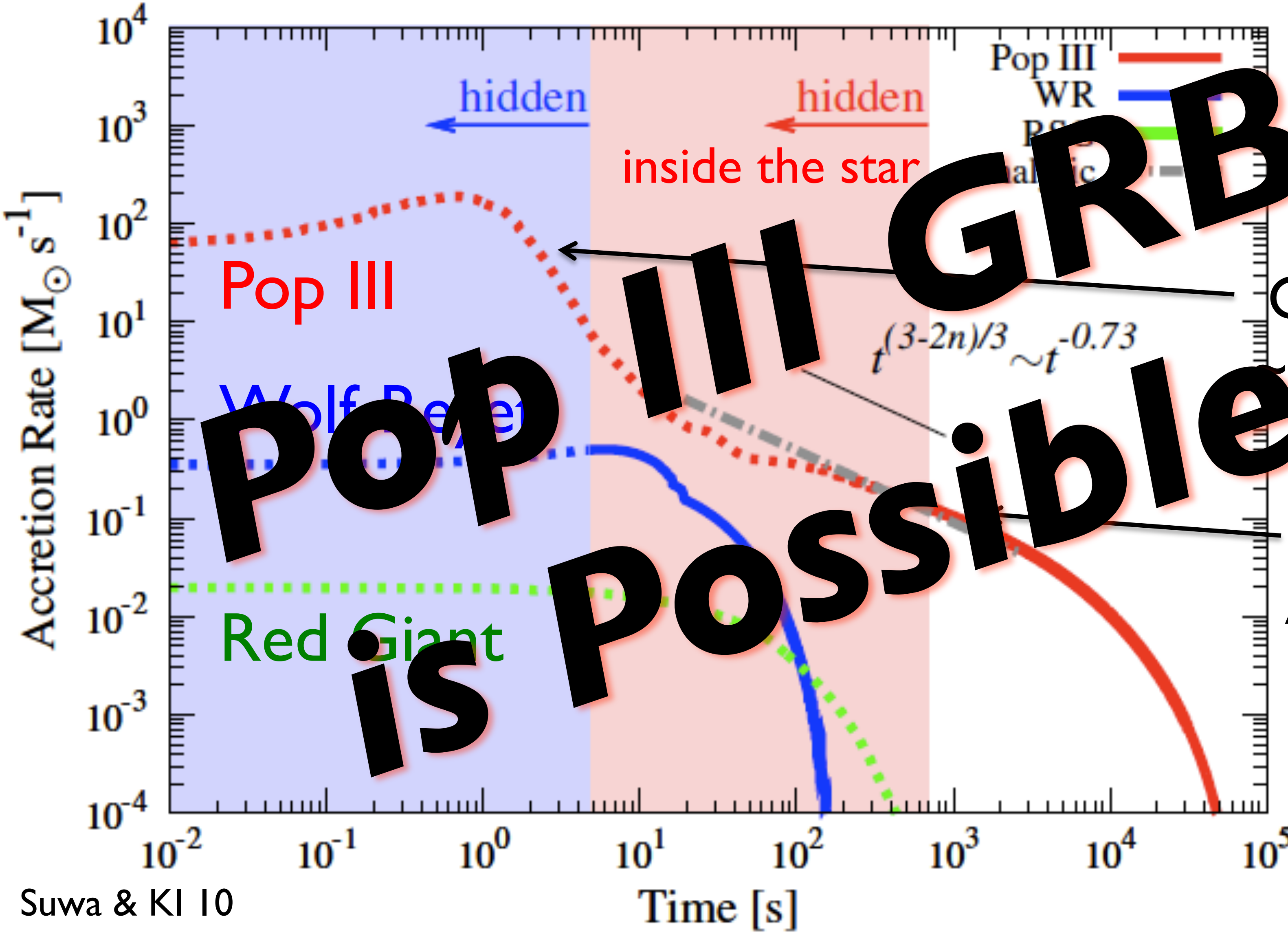
$$\frac{L_j}{\pi\theta^2 r^2 c} \sim \rho_* c^2 \beta_h^2$$

⇒ Jet head velocity

$$c\beta_h \sim \frac{c}{\theta}\left(\frac{L_j}{\pi c^3 \rho_* r^2}\right)^{1/2}$$

$$\beta_h \Gamma_h^2 \sim 0.1 \left(\frac{L_{iso}}{10^{52}\,\mathrm{erg/s}}\right)^{1/2} \times \left(\frac{r}{10^{12}\,\mathrm{cm}}\right)^{-1} \left(\frac{\rho_*}{10^{-3}\,\mathrm{g/cm^3}}\right)^{-1/2}$$

Envelope Accretion



$L \propto \dot{M}$

⇒ $v_{\text{Jet head}}$

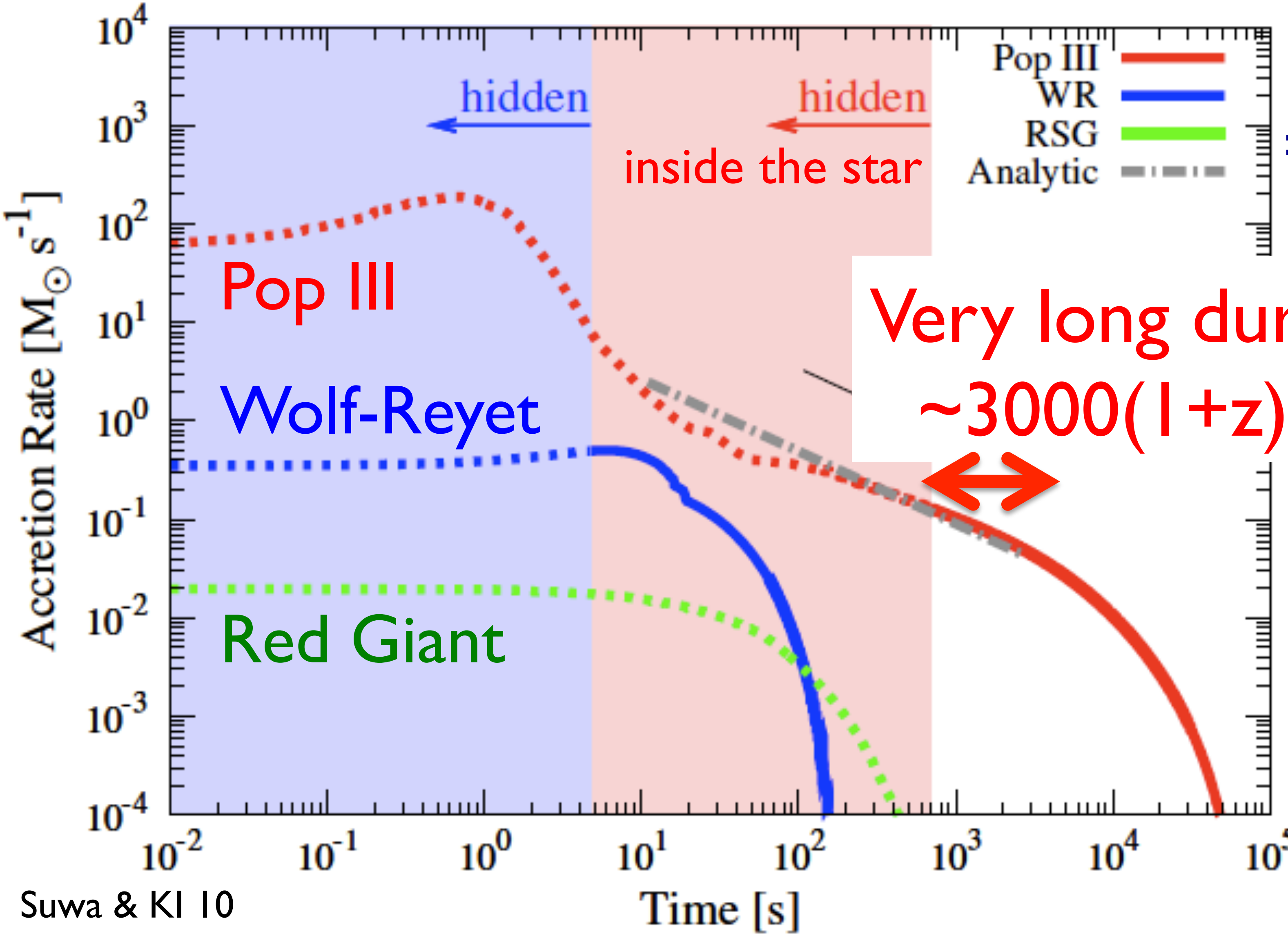
Core Acc.
~ a few sec

Envelope
Accretion

Pop III GRB is Possible

Suwa & KI 10

Long Duration

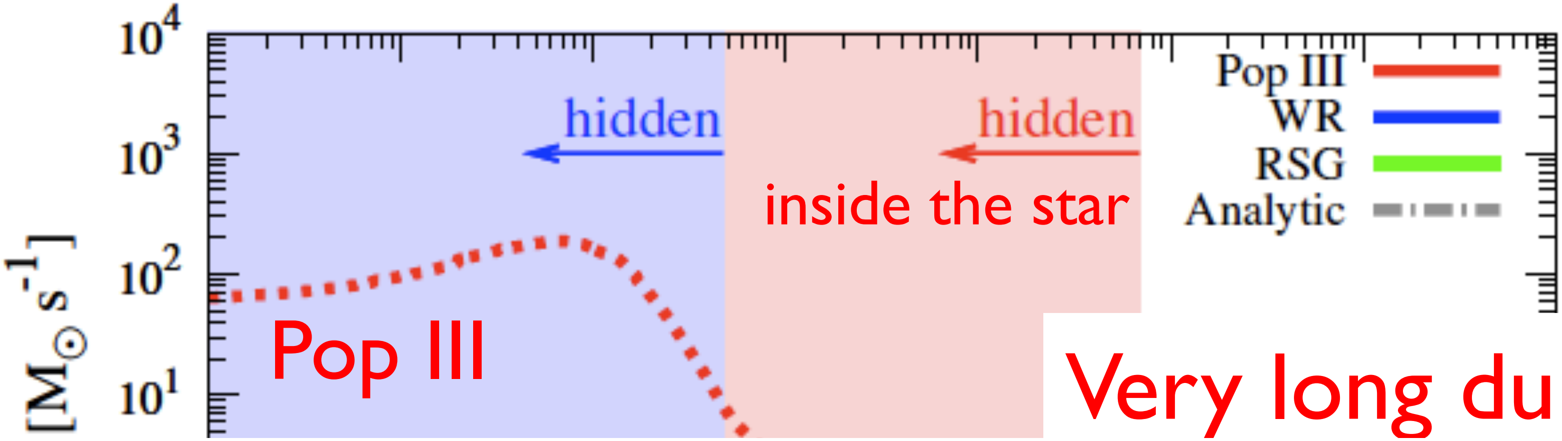


$L \propto \dot{M}$

$\Rightarrow v_{\text{Jet head}}$

Suwa & KI 10

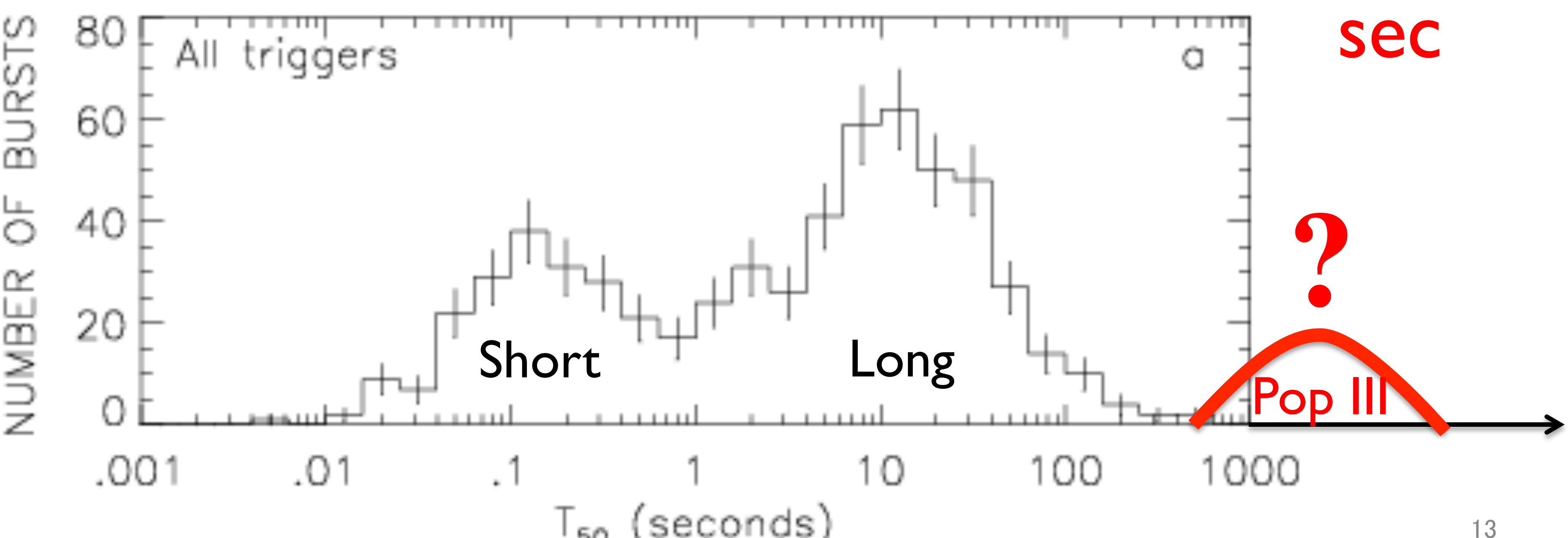
Long Duration



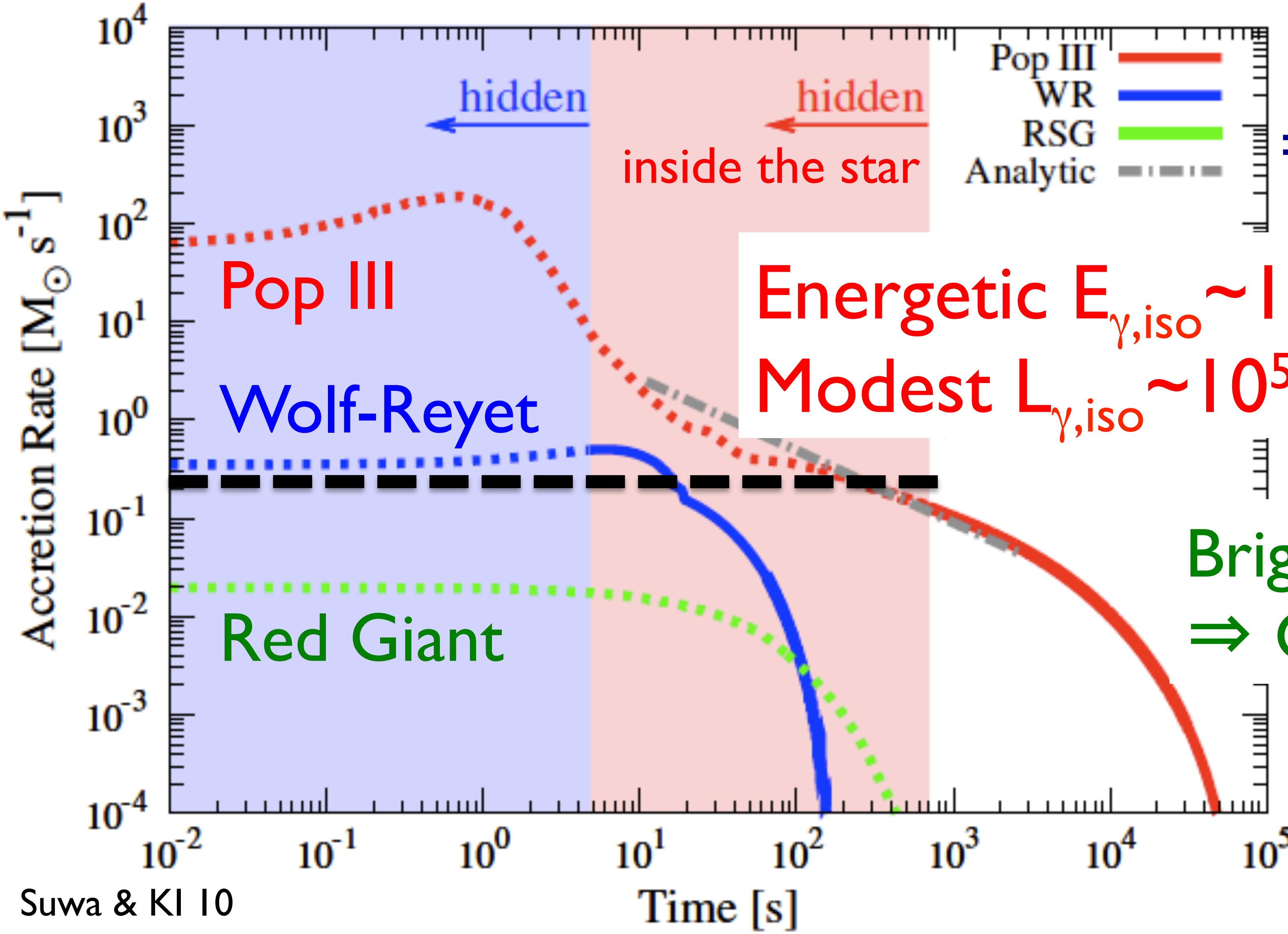
$L \propto \dot{M}$

$\Rightarrow v_{\text{Jet head}}$

Very long duration sec



Not so Bright



$L \propto \dot{M}$

$\Rightarrow v_{\mathrm{Jet\ head}}$

Bright phase
$\Rightarrow$ Cocoon

Suwa & KI 10

Detectability

- Pop III GRB at z~20

$$F = \frac{\varepsilon_\gamma L_{\rm iso}}{4\pi r_L^2} \sim 10^{-9}\ {\rm erg\ cm^{-2}\ s^{-1}}$$

- Swift BAT sensitivity ~10^{-8} erg cm^{-2} s^{-1}
- Future (LOFT, HiZ-GUNDAM, …) ~10^{-9} erg cm^{-2} s^{-1}

Analytic Expressions

$$R_* \sim 10^{13}\ \mathrm{cm} \left(\frac{R_c}{10^{10}\ \mathrm{cm}}\right) \left(\frac{M_c}{400 M_\odot}\right)^{-2.5} \left(\frac{M_{\rm env}}{500\ M_\odot}\right)^{2.5} \quad (9)$$

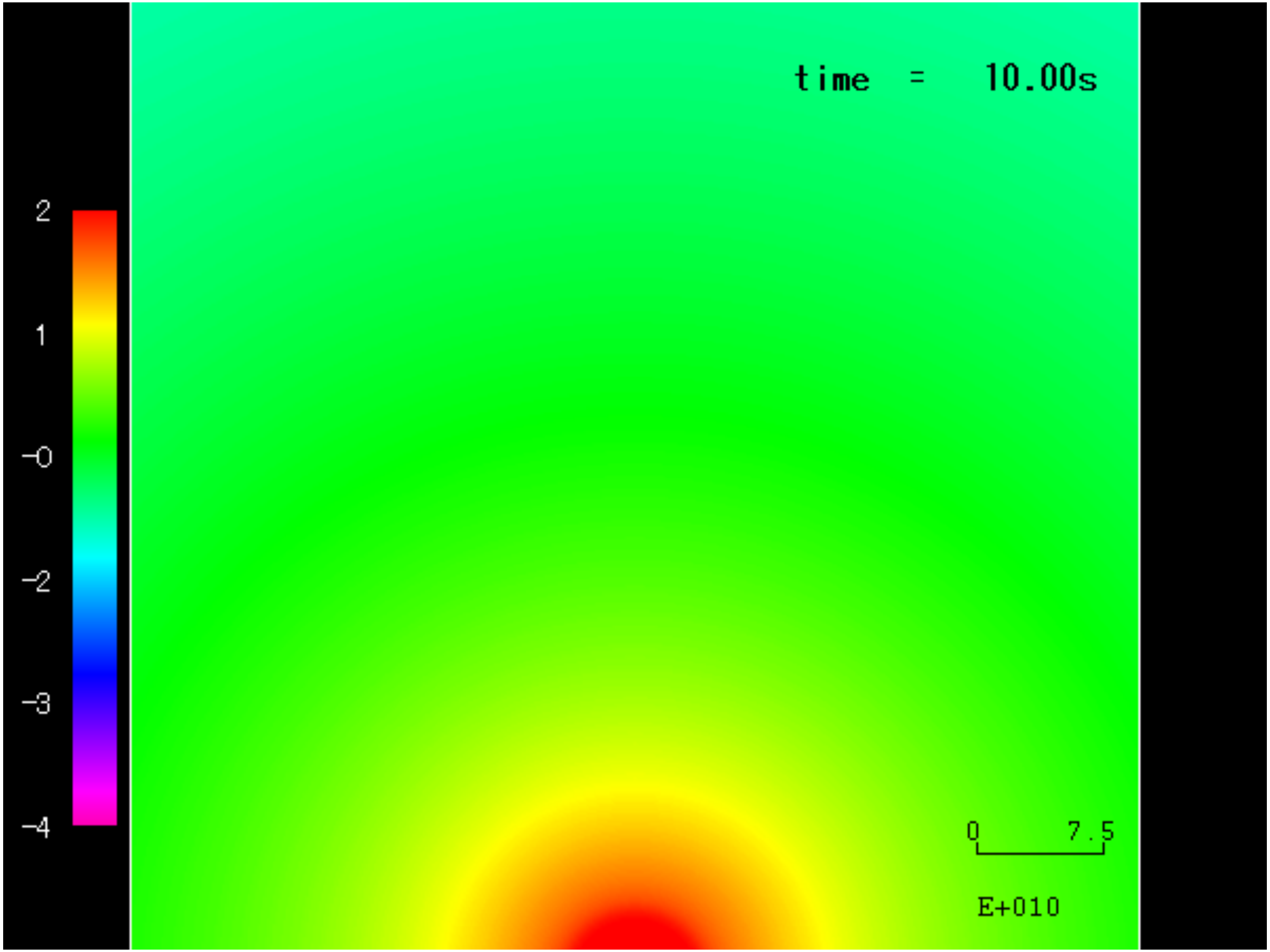
$$t_b \sim 700\ \mathrm{s} \left(\frac{\eta}{10^{-3}}\right)^{-0.79} \left(\frac{\theta_j}{5^\circ}\right)^{1.6} \left(\frac{R_c}{10^{10}\ \mathrm{cm}}\right)^{1.1} \times \left(\frac{M_c}{400 M_\odot}\right)^{-2.9} \left(\frac{M_{\rm env}}{500 M_\odot}\right)^{2.8}, \quad (11)$$

$$L_{\rm iso}(t = t_b) \sim 5 \times 10^{52} \left(\frac{\eta}{10^{-3}}\right)^{1.6} \left(\frac{\theta_j}{5^\circ}\right)^{-3.2} \times \left(\frac{R_c}{10^{10}\ \mathrm{cm}}\right)^{-1.2} \left(\frac{M_c}{400 M_\odot}\right)^{3.2} \left(\frac{M_{\rm env}}{500 M_\odot}\right)^{-2.0} \mathrm{erg\ s^{-1}} \quad (13)$$

$$t_{\rm ff}(r = 0.1 R_*) \sim 3000 \left(\frac{R_c}{10^{10}\ \mathrm{cm}}\right)^{1.5} \left(\frac{M_c}{400 M_\odot}\right)^{-3.8} \times \left(\frac{M_{\rm env}}{500 M_\odot}\right)^{3.8} \left(\frac{M_c + 0.4 M_{\rm env}}{600 M_\odot}\right)^{-0.5} \mathrm{s} \quad (14)$$

$$L_{\rm iso}[t = t_{\rm ff}(r = 0.1 R_*)] \sim 2 \times 10^{52} \left(\frac{\eta}{10^{-3}}\right) \left(\frac{\theta_j}{5^\circ}\right)^{-2} \times \left(\frac{R_c}{10^{10}\ \mathrm{cm}}\right)^{-1.5} \left(\frac{M_c}{400 M_\odot}\right)^{3.9} \left(\frac{M_{\rm env}}{500 M_\odot}\right)^{-2.8} \times \left(\frac{M_c + 0.4 M_{\rm env}}{600 M_\odot}\right)^{0.37} \mathrm{erg\ s^{-1}} \quad (15)$$

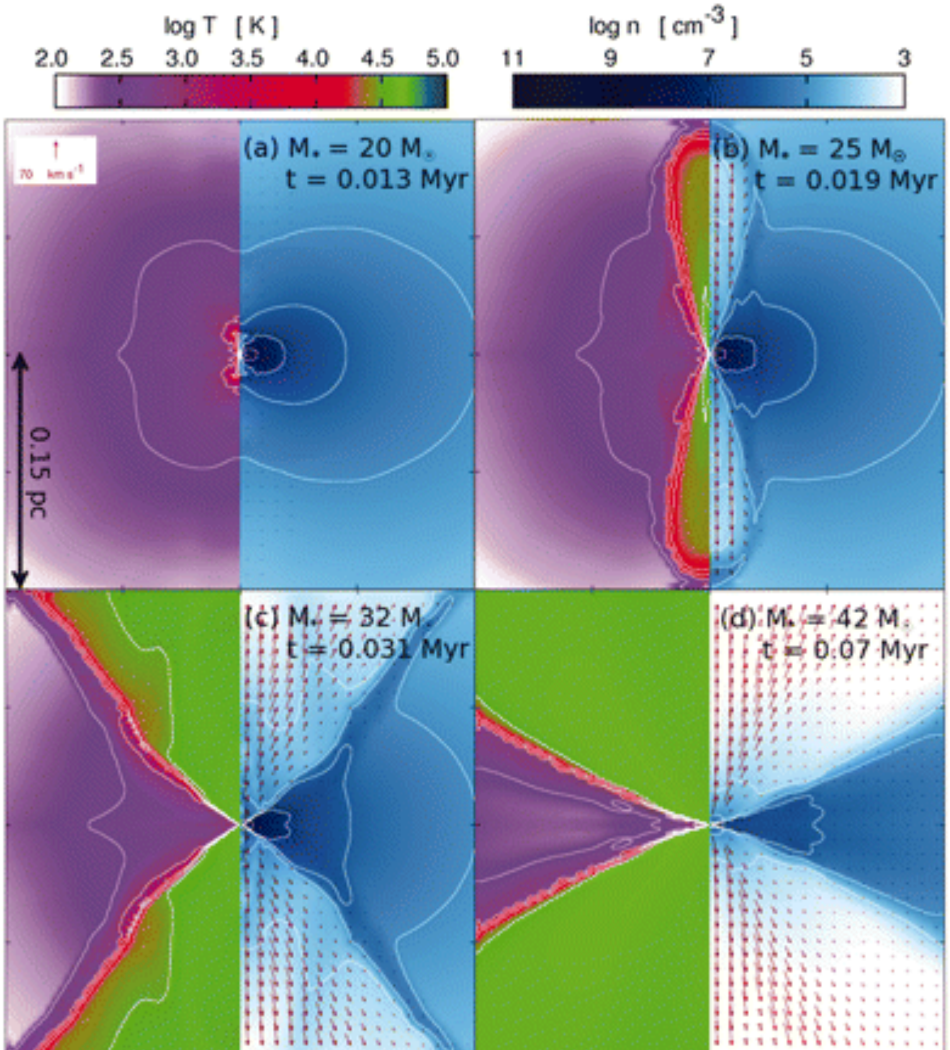
Suwa & KI 10

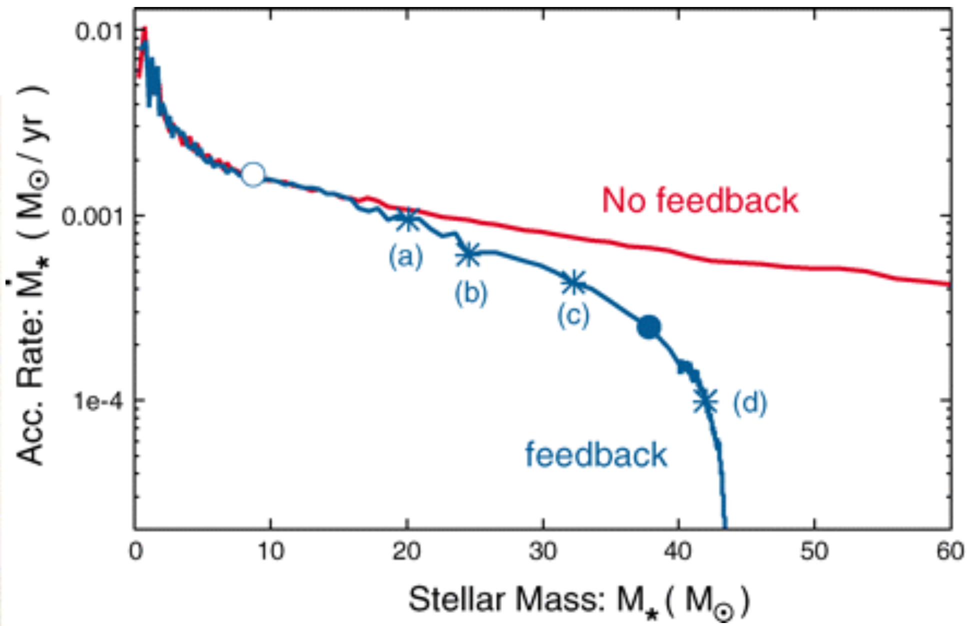


Nagakura+ 11 2D, rela-hydro, Mass accretion from inner boundary ⇒ Jet


GRB jet can breakout
the first star!

Stop Accretion?



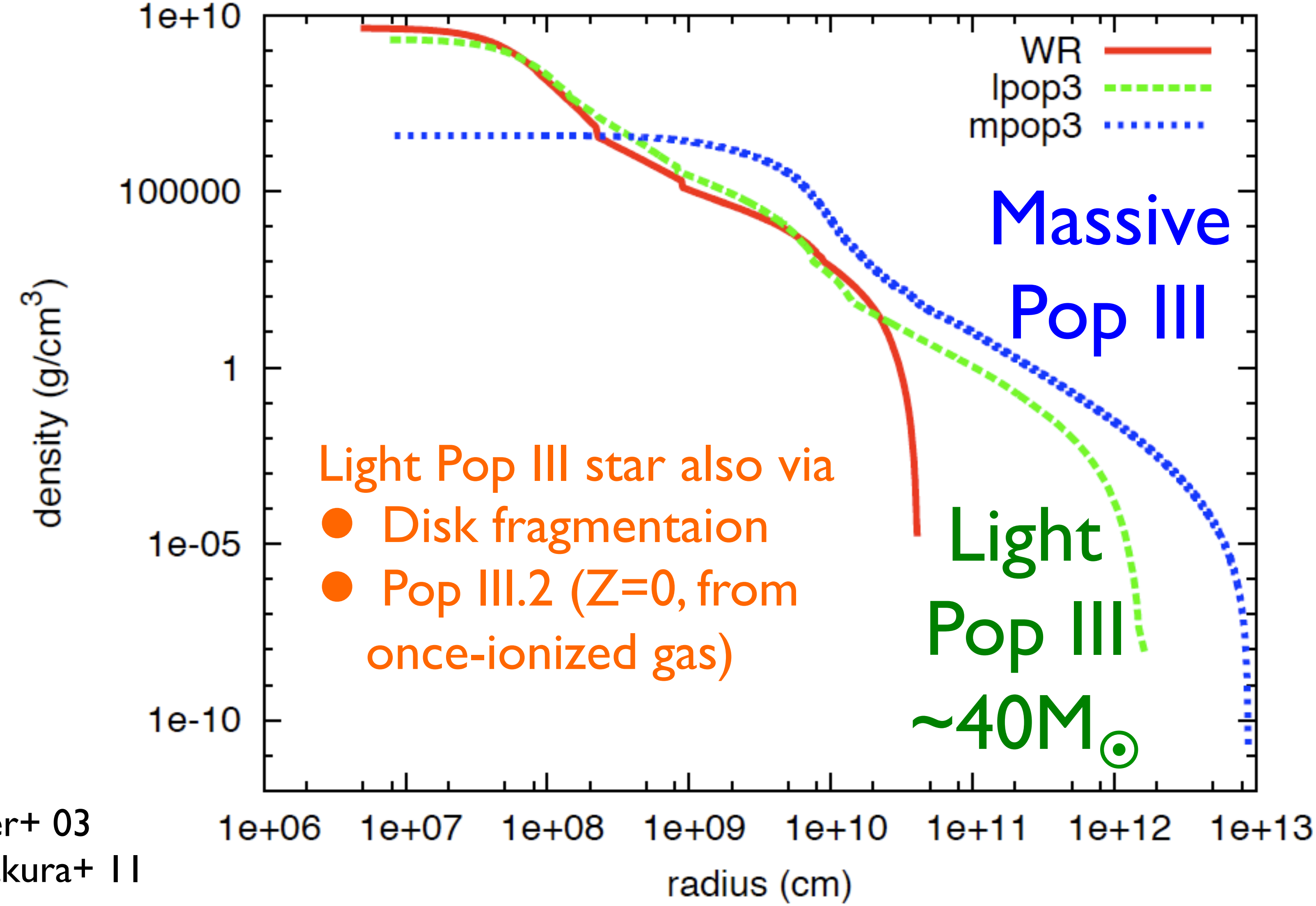


Hosokawa+ 11; McKee & Tan 08; Omukai's talk

HII region breakout & Photoevaporation of the accretion disk

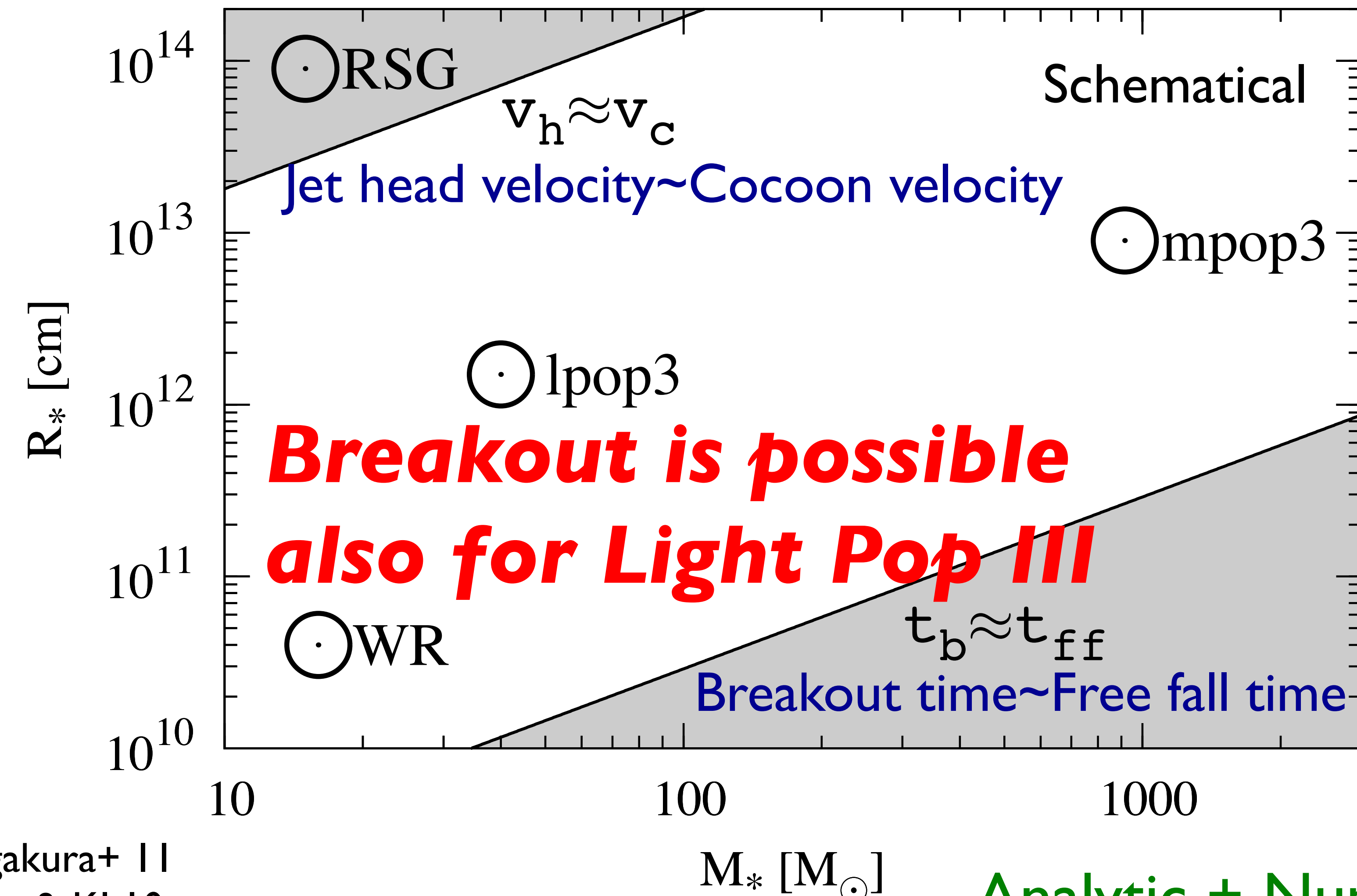
⇒ **~40M⊙**

Light Pop III Star



Heger+ 03
Nagakura+ 11

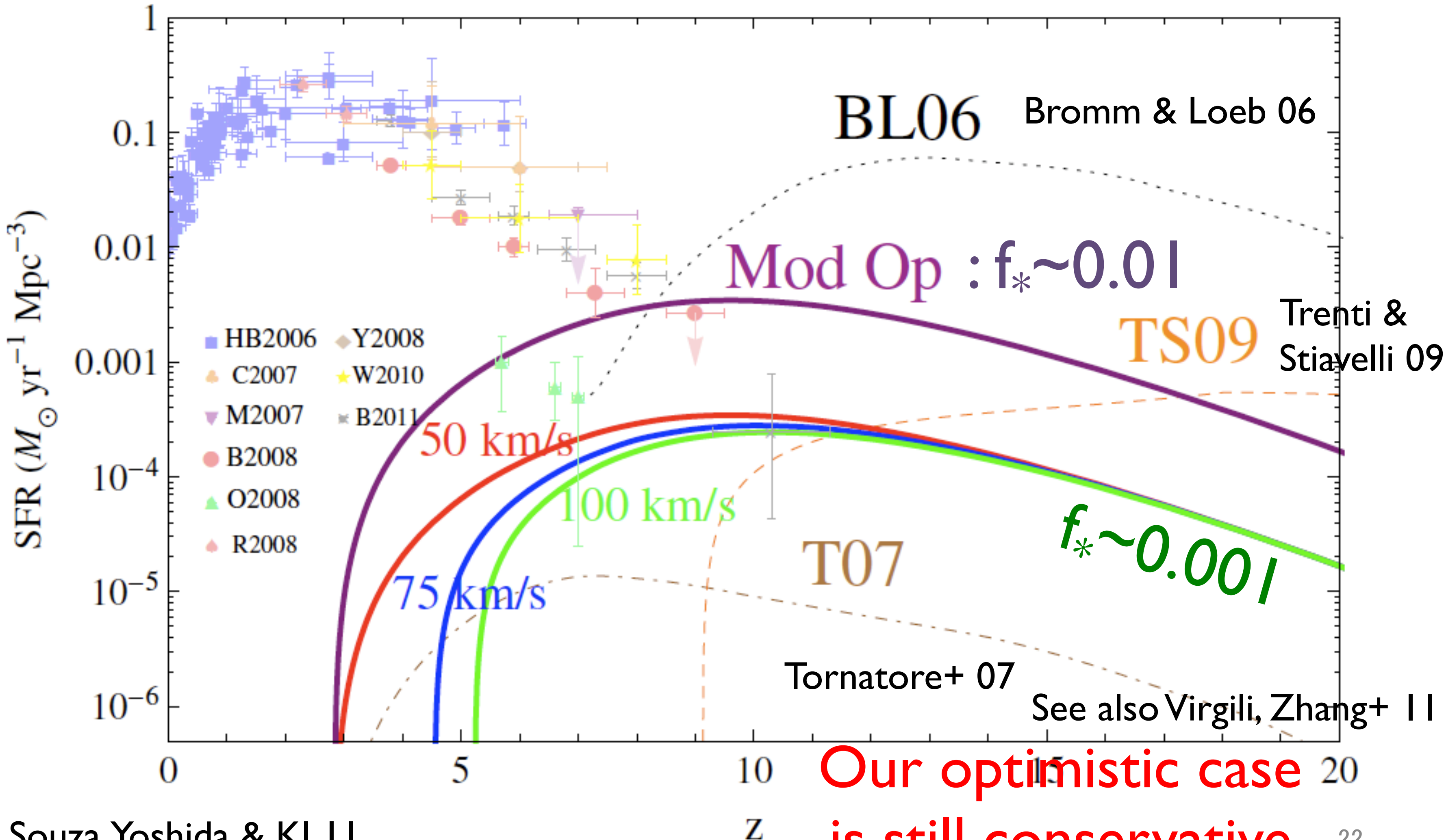
Light Pop III GRB



Nagakura+ 11
Suwa & KI 10

Analytic + Numerial

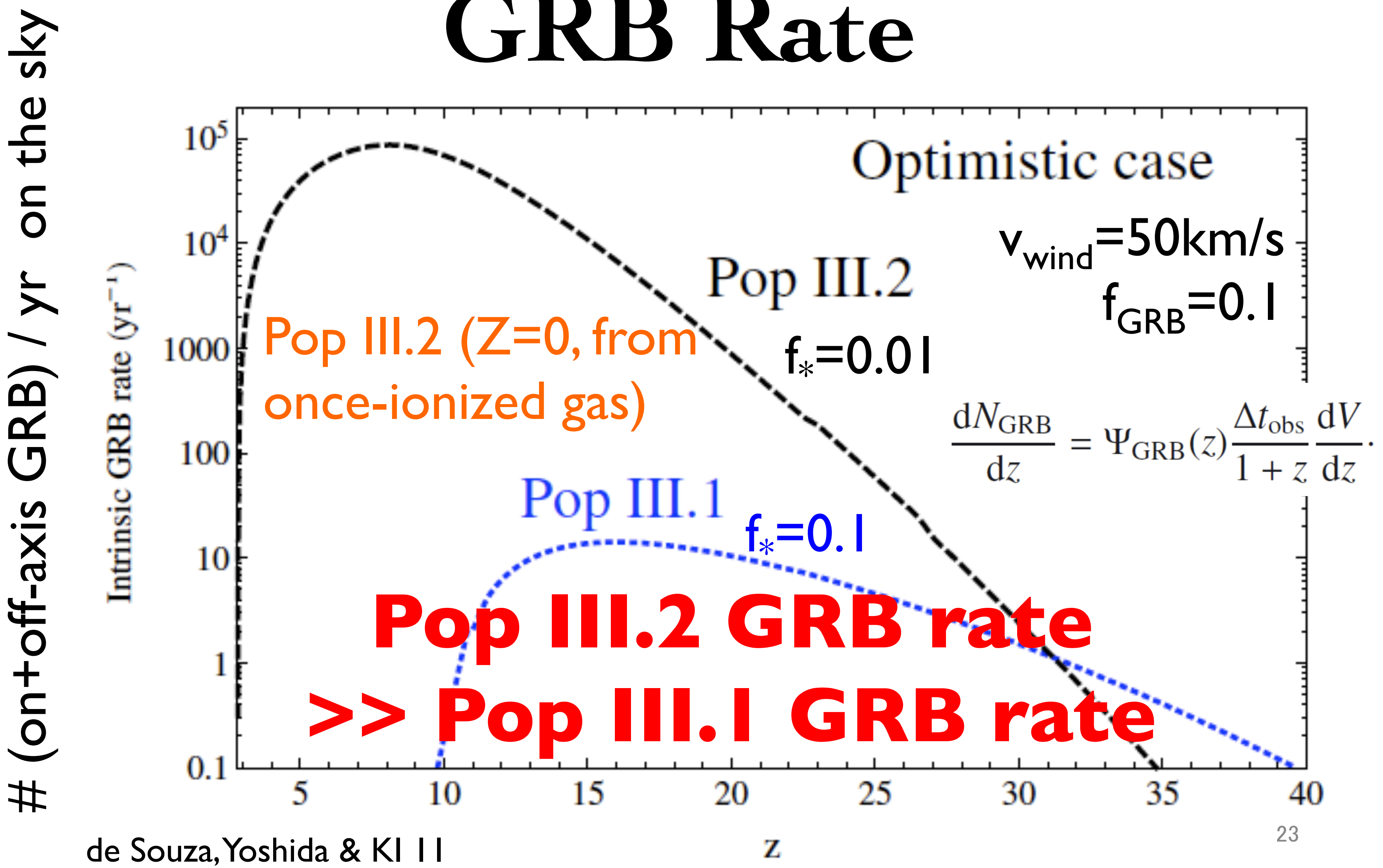
Pop III.1+III.2
Star Formation Rate



Our optimistic case is still conservative

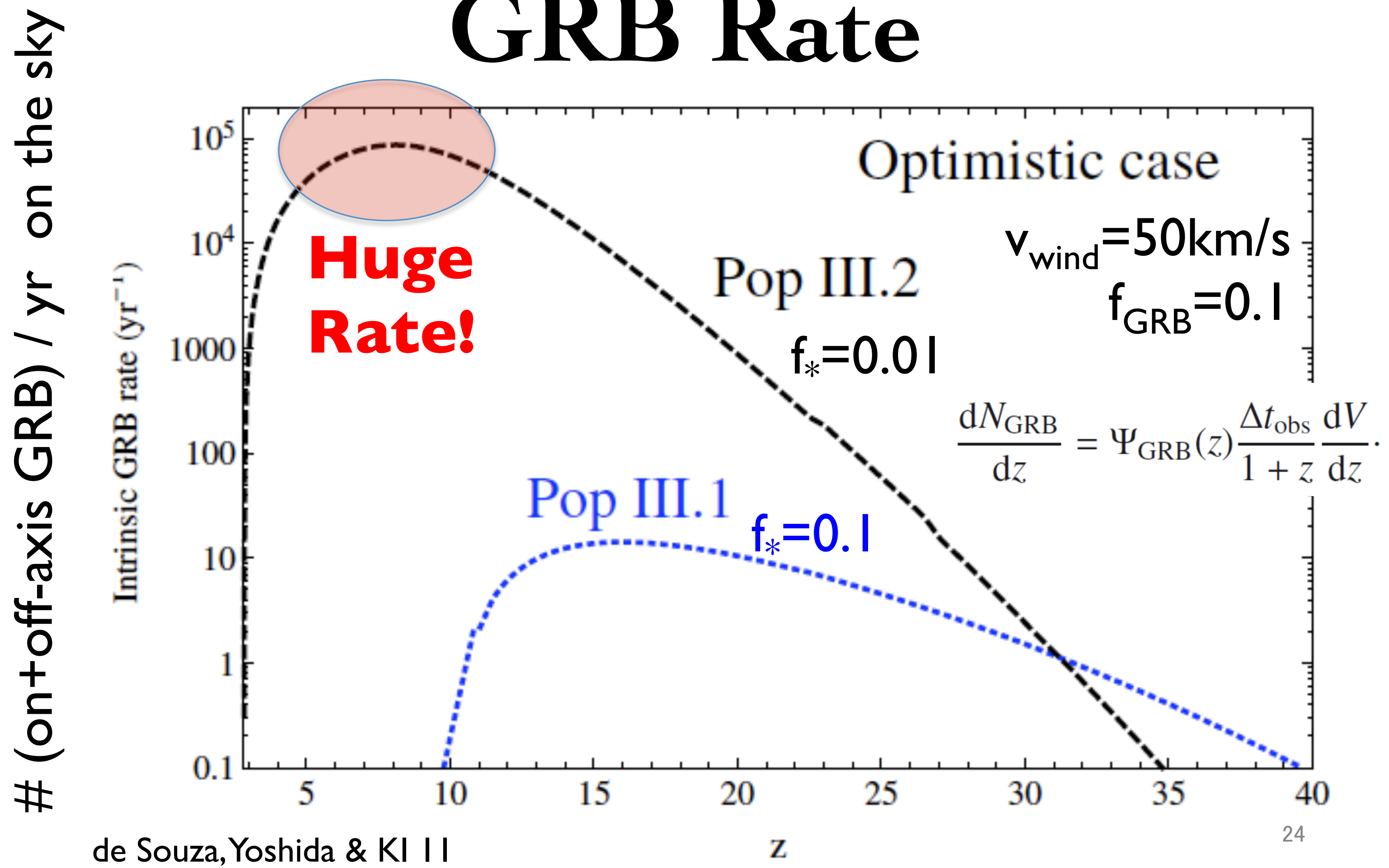
de Souza, Yoshida & KI 11

Pop III.1. & III.2 GRB Rate



de Souza, Yoshida & KI 11

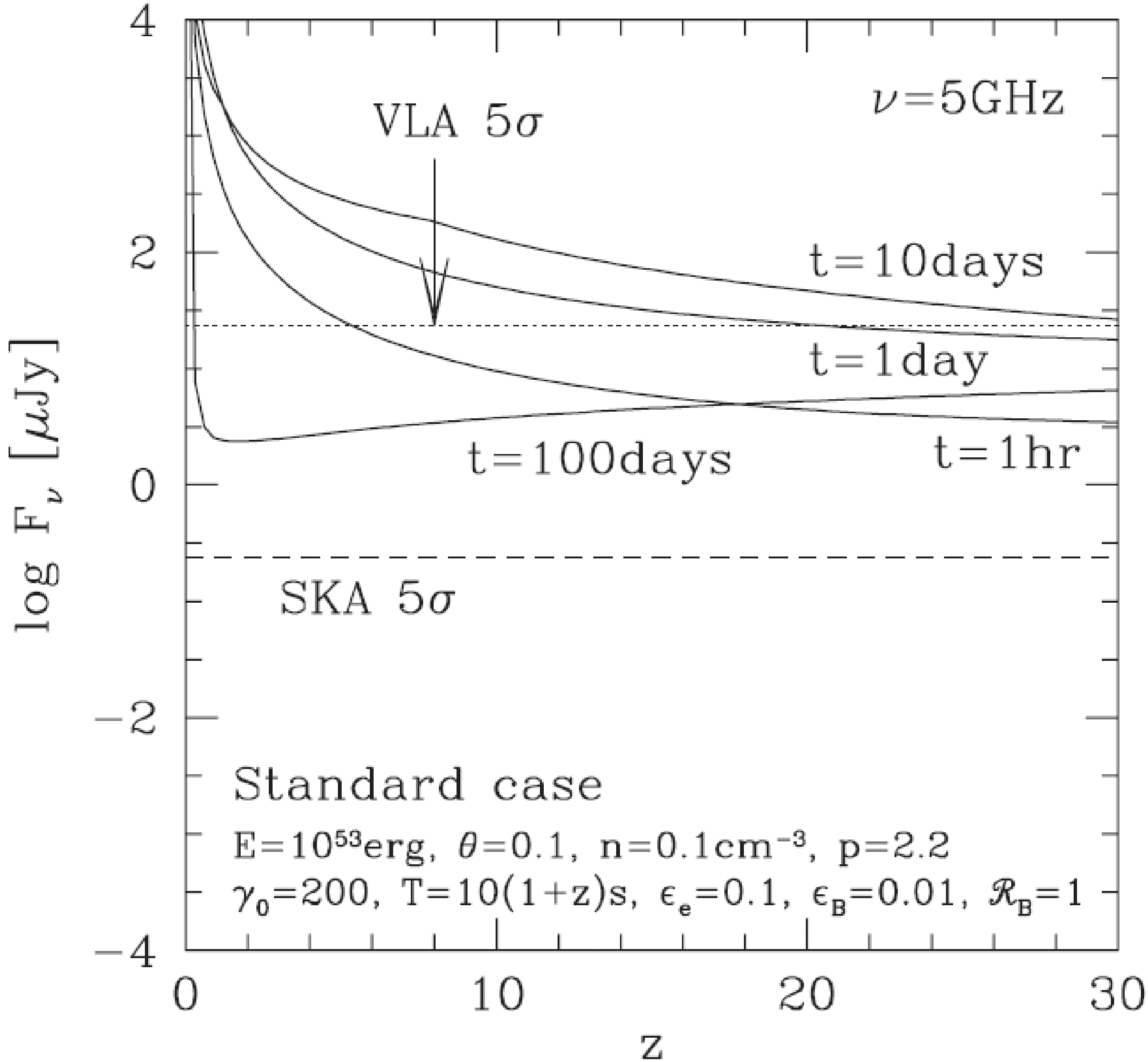
Pop III.1. & III.2 GRB Rate

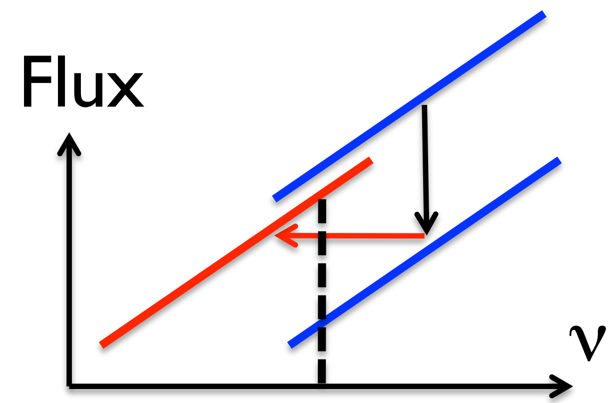


$$\frac{dN_{GRB}}{dz} = \Psi_{GRB}(z)\frac{\Delta t_{obs}}{1+z}\frac{dV}{dz}.$$

de Souza, Yoshida & KI 11

Radio Afterglow





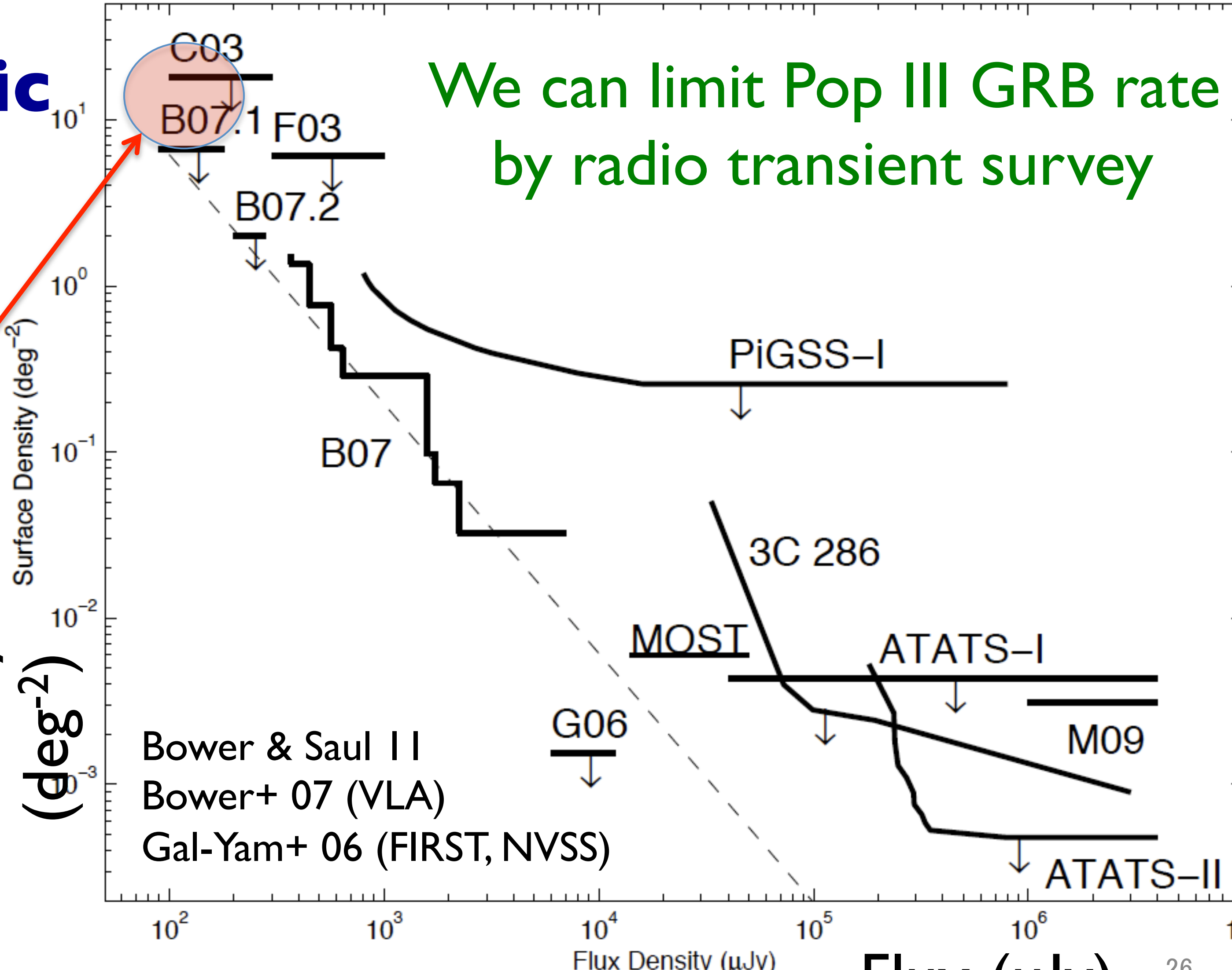
K-correction ⇒ Not dim @high-z

Spherical after jet break

KI & Meszaros 05
Inoue+ 07, Toma+ 10

Radio Transient

Optimistic
~10^5/yr/z
x (z~10)
x 100day
~3×10^5
on the sky



We can limit Pop III GRB rate by radio transient survey

Surface density (deg^{-2})

Flux (μJy)

Δt ~ 1yr

Radio Transient

Optimistic

~10^5/yr/z

x (z~10)

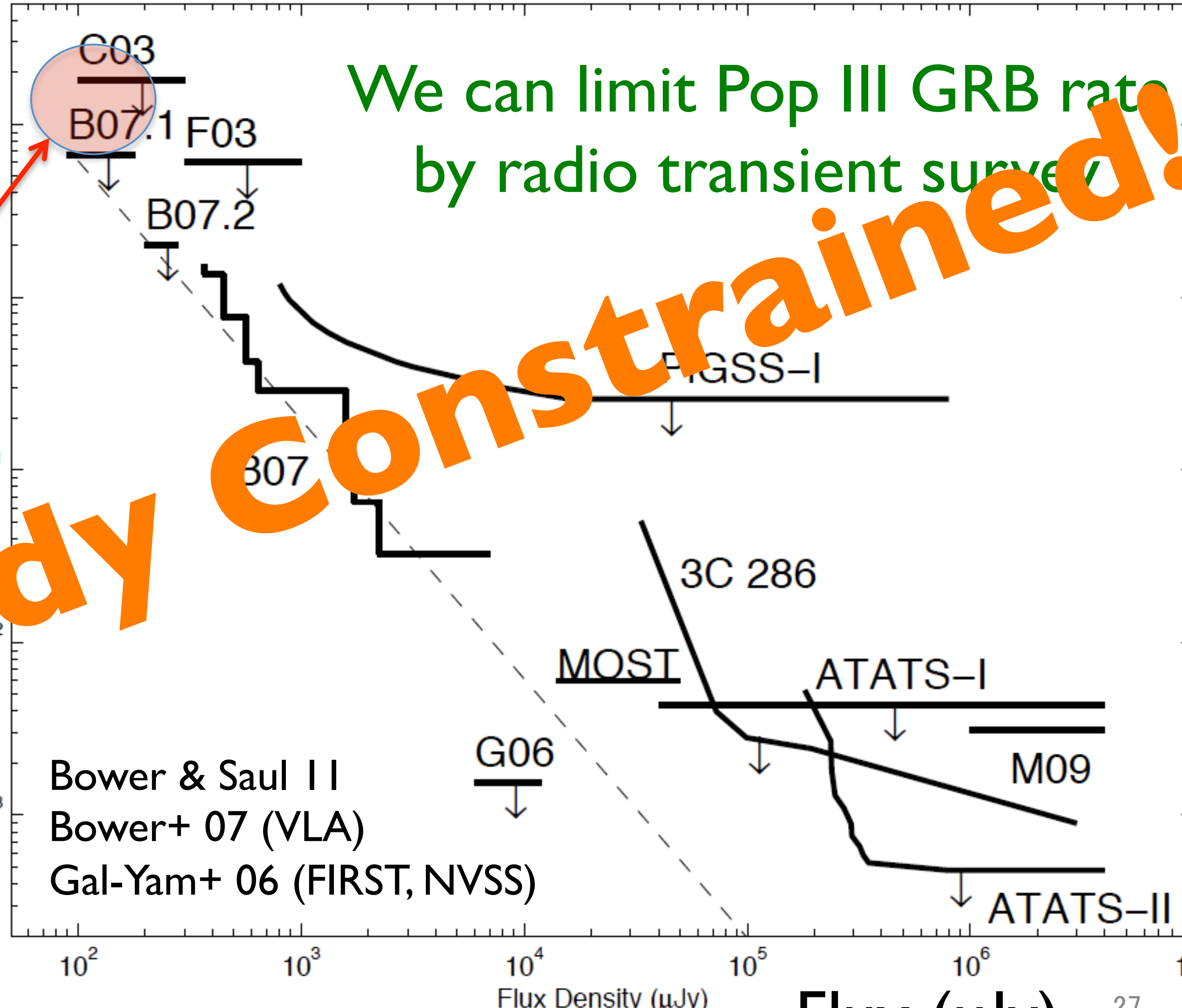
x 100day

~3×10^5

on the sky

We can limit Pop III GRB rate by radio transient survey

Already Constrained!

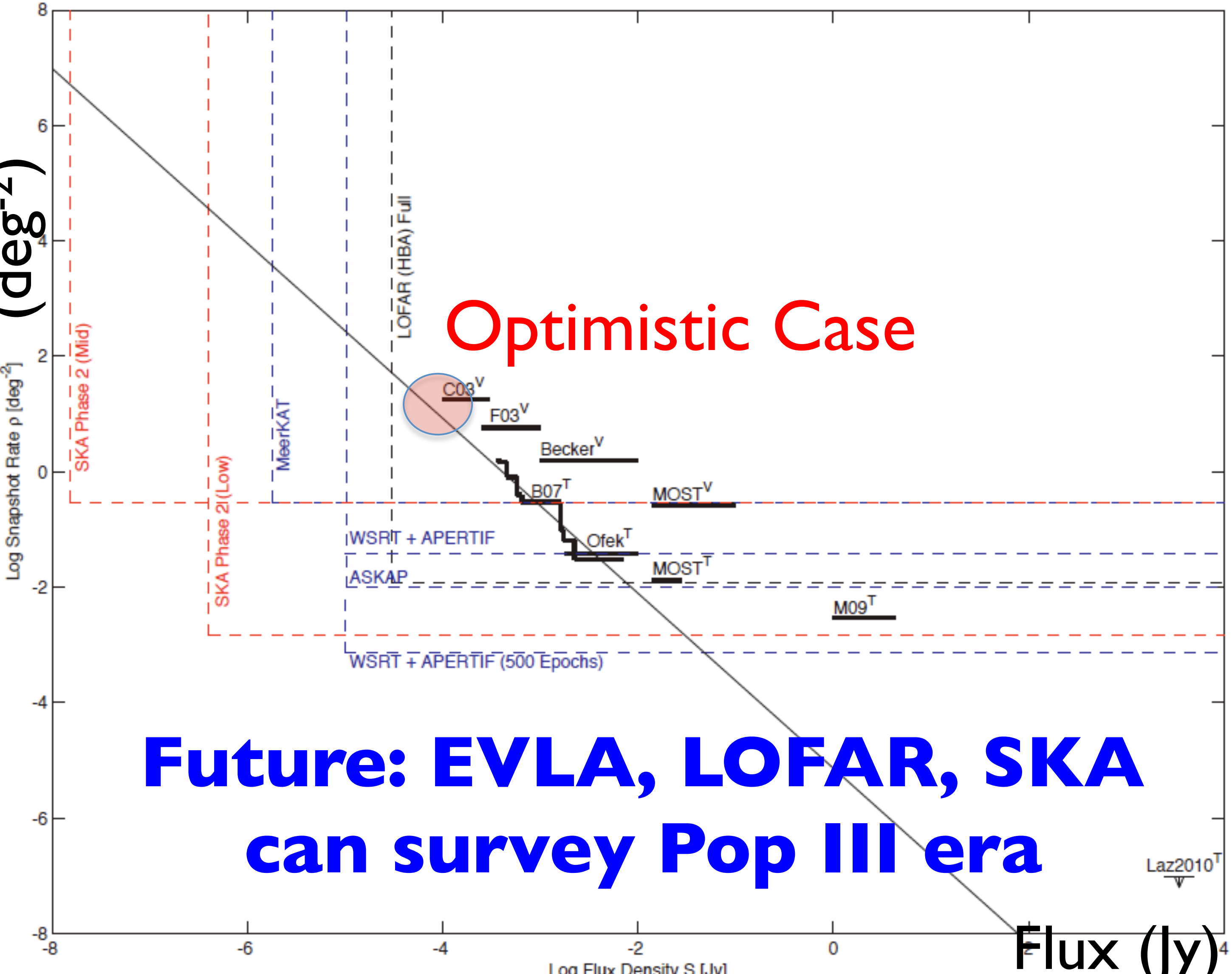


Surface density (deg^{-2})

Flux (μJy)

Δt ~ 1yr

Future Radio Transient



Surface density (deg^{-2})

Flux (Jy)

Future: EVLA, LOFAR, SKA can survey Pop III era

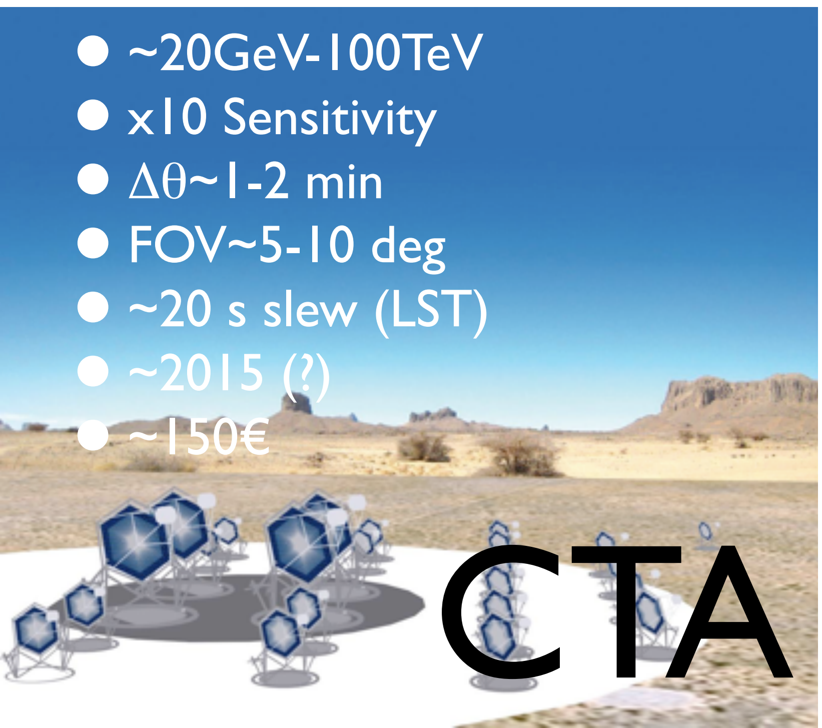
1112.2579

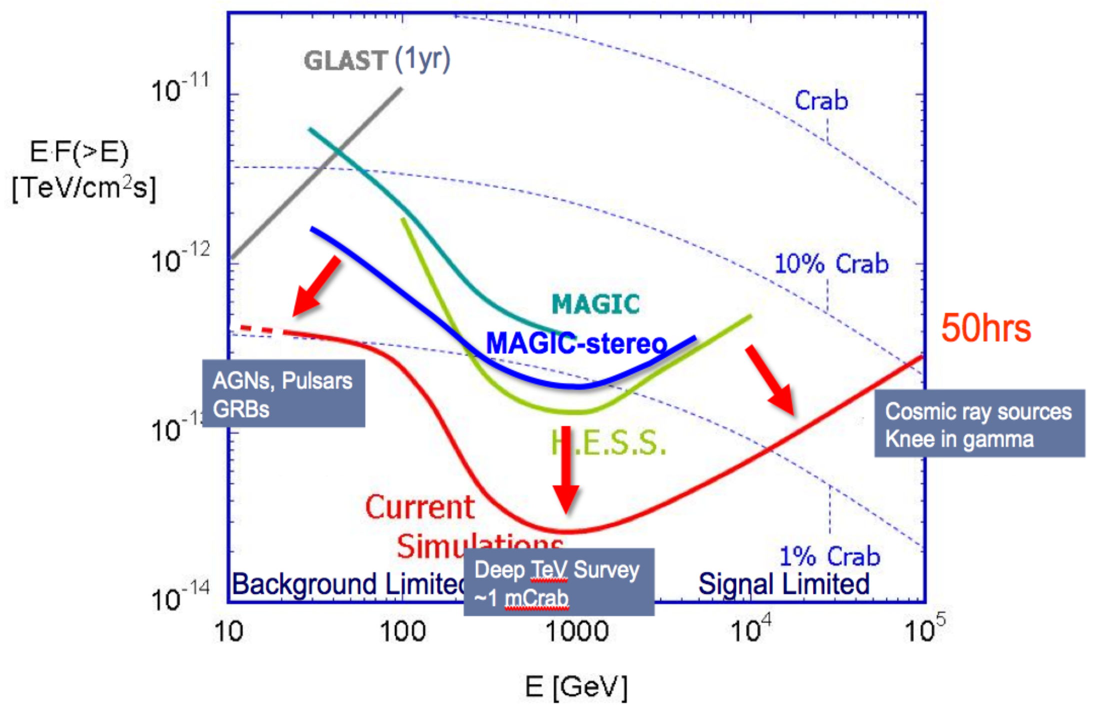
arXiv:1112.5940

Prospects for Detecting Gamma-Ray Bursts at Very High Energies with the Cherenkov Telescope Array

Jun Kakuwa,[1*] Kohta Murase,[2] Kenji Toma,[3] Susumu Inoue,[4] Ryo Yamazaki,[5] and Kunihito Ioka[6]

- ~20GeV-100TeV
- x10 Sensitivity
- Δθ~1-2 min
- FOV~5-10 deg
- ~20 s slew (LST)
- ~2015 (?)
- ~150€





Summary

- Can GRB jets break out the first stars?
  - **Yes!**
  - Massive & Light Pop III stars
  - Envelope accretion: Long, Energetic, Modest L
  - Sensitive to the envelope mass

Suwa & KI 10
Nagakura+ 11

- Pop III GRB Rate
  - Pop III.2 GRB (~$40M_{\odot}$) > III.1 GRB
  - Radio afterglow is observable up to high-z
  - Radio & X-ray transient survey

de Souza+11
KI & Meszaros 05
KI 03