On the progenitors of (Long) GRBs

回転単独星モデルと連星モデル

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Introduction

- (L-)GRB progenitor – associated with Hypernovae

  ➔ Massive Stars

- Central engine (popular models):
  - BH+DISK (Collapsar) --- progenitor M ≥ ~ 25 $M_\odot$
  - Magnetar --- progenitor M~ 15-20 $M_\odot$?

(Magnetar models may have advantages in explaining long activities of GRB: X-ray shallow decay and flare emissions, e.g., Metzger 2010, Thompson – this conference)

Magnetar Model for GRB ?

22 min

- E.g., Bucciantini et al. (2009), MNRAS:
  - 2D simulation, Collimated relativistic jet, 35$M_\odot$ model assumed
- Several suggestions (e.g., bumps in afterglow LC) that GRBs are associated with hypernovae (likely massive SNe leaving Black holes behind) ,
- but progenitor masses have been estimated for only few cases

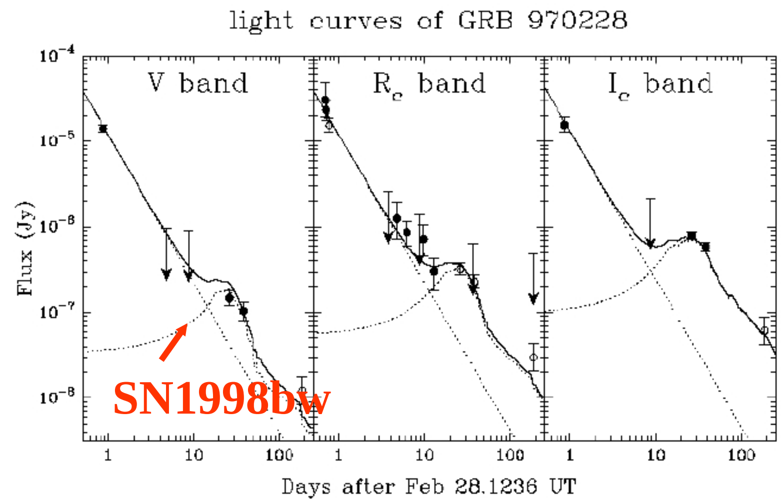
(or possibly only one,

SN2003dh-GRB030329 (typical GRB)

Others:

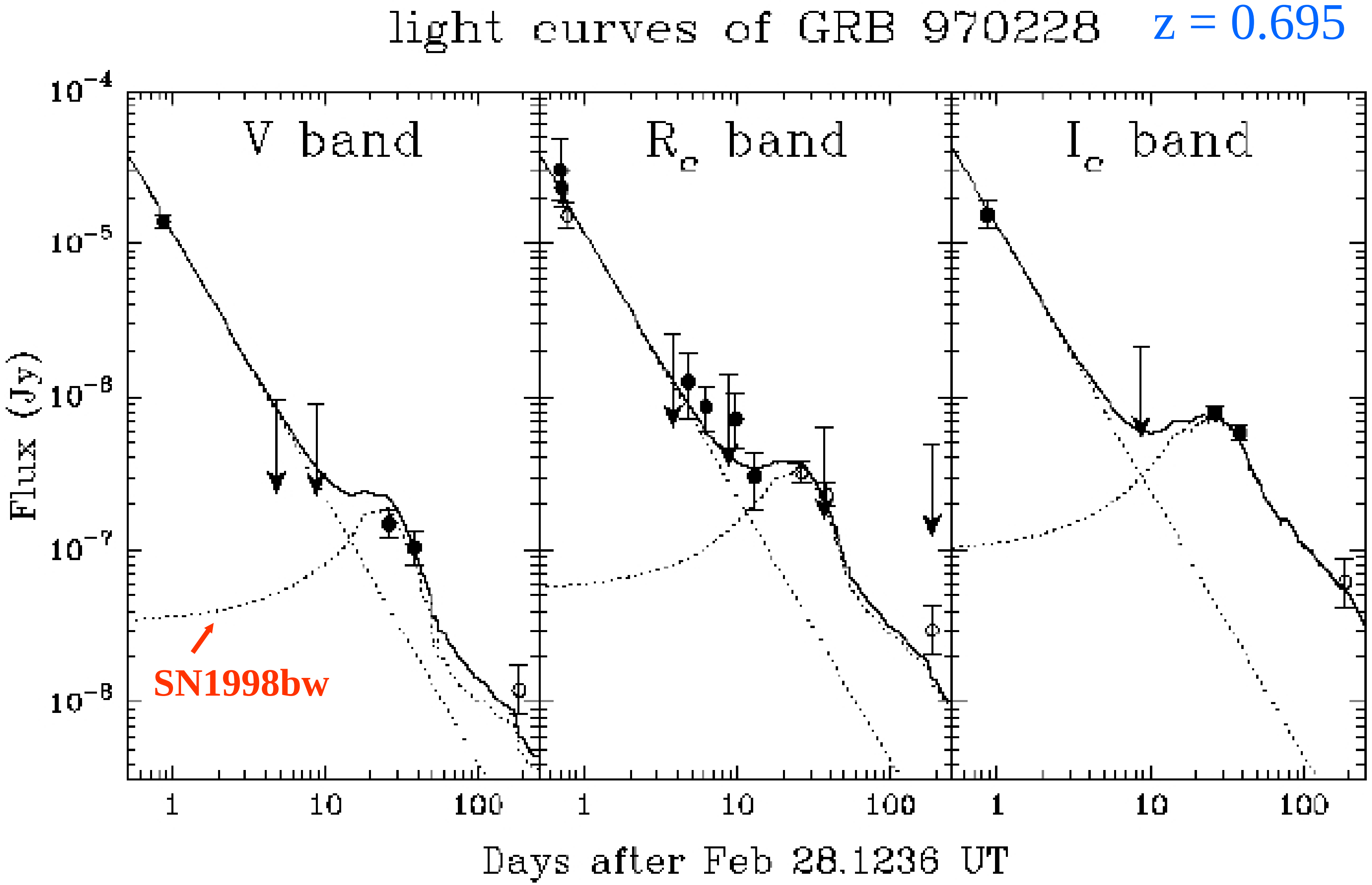
SN1998bw-GRB980425 (weak GRB)

SN2003lw-GRB031203 (XRF)



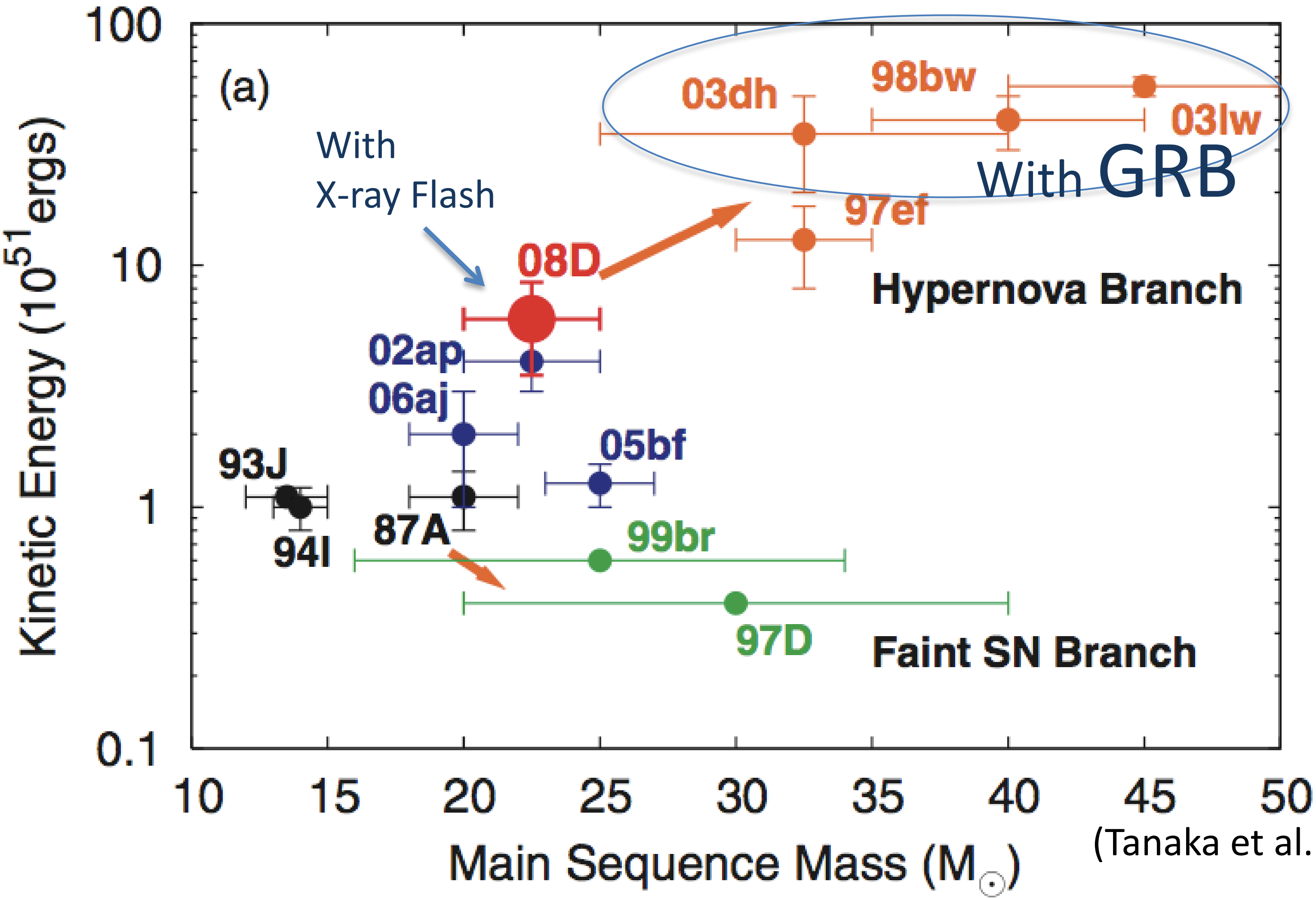
GRB011121 (z = 0.36)

z = 0.695



Galama et al. 2000

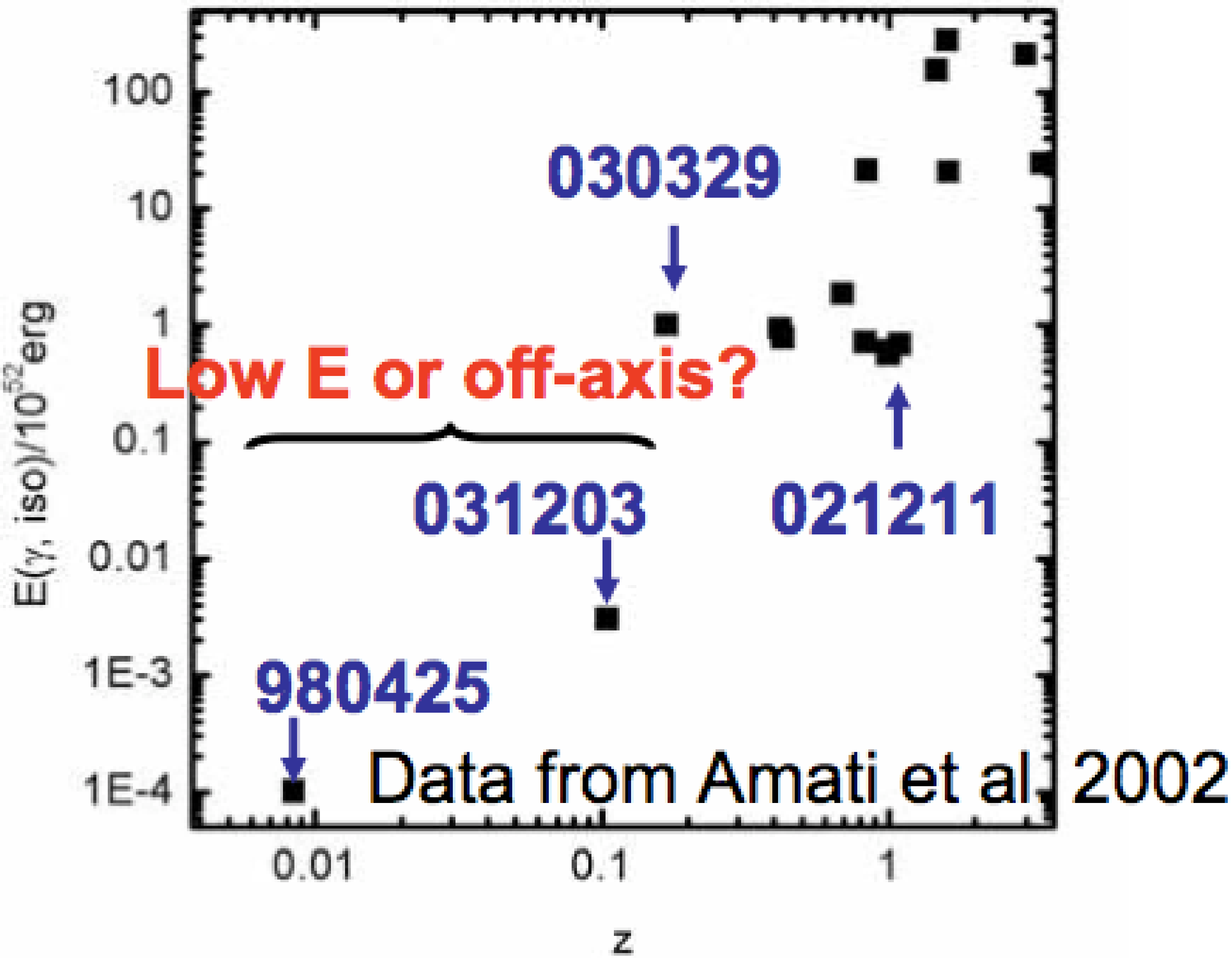
Bloom et al. 2001



(Tanaka et al. 2009)

SN 2003dh, 2003lw are probably too massive to have NS remnants(?).

Any correlation between long activities of GRB and progenitor mass?
~ need more samples

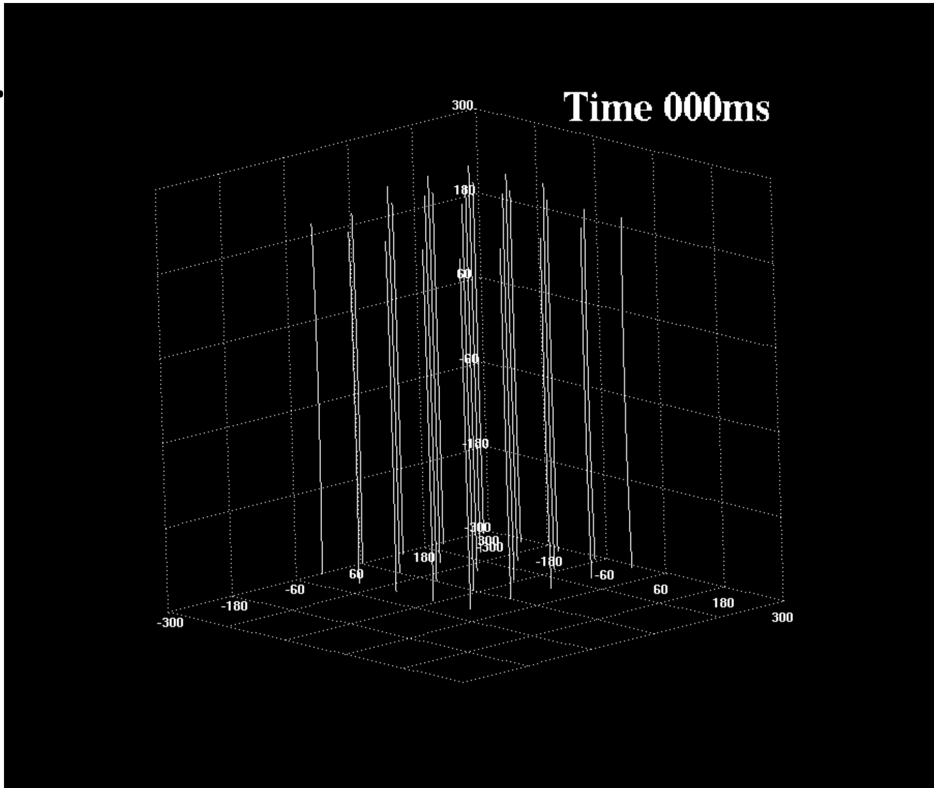


030329
Low E or off-axis?
031203
021211
980425
Data from Amati et al. 2002
E(γ, iso)/10^52 erg
z
100
10
1
0.1
0.01
1E-3
1E-4
0.01
0.1
1

Magnetar Model

- Even if progenitor is $M>25M_{\odot}$, if BH formation is delayed proto-neutron stars (NSs) may become a central engine of a GRB (?.
- BH formation epoch depends on EOS and rotation, (and magnetic filed) of proto-NSs ⇐ quite uncertain
- Simulations (still long way to go..

example of a MHD simulation
(our current, preliminary work,
3D MHD simulation for core-collapse
Kuroda & Umeda (2010) →



Or typical SNe-GRB are not so massive ?

- If a "Hypernova" light curve (LC) with a GRB is powered by a magnetar (Maeda et al. 2007, Woosley 2009, Kasen & Bildsten 2009), the progenitor mass may not be determined from early LC.
  - Later (few years) LC may distinguish Pulsar and Radioactive heating
  - But such observations are difficult for distant supernovae

- Still unclear if progenitors of typical GRBs are too massive to leave Neutron Stars behind.

- Observations of associated SNe are quite important to determine the GRB progenitor mass (and central engine model).

Black hole + Disk (Collapsar) model for GRB

18min

- progenitor M ≥ ~ 25 $M_\odot$ to form a BH
- Pre-collapse Fe core must have sufficiently large angular momentum to form an accretion disk
- Associated SNe so far are all Type Ic SNe
  - Progenitors should have lost Hydrogen and most He envelope (by mass-loss)
  - However, this mass-loss usually causes large angular momentum loss ➔difficult to produce GRBs (Heger & Woosley 2003,2004
- Proposed solution: Chemically homogeneous evolution
  - Yoon&Langer 2005, Woosley & Heger 2006, Yoon et al. 2006

(by Dr. Yoon in this conference)

Black hole + Disk model for GRB

- Chemically homogeneous evolution scenario
  - Metal poor progenitors ($Z \leq Z_{\odot}/5$) for weak mass-loss
  - Fast initial rotation for very efficient chemical mixing
  - These stars remain quasi-chemically homogeneous
    - Evolves bluewards: less mass-loss, keeping fast rotation
    - Surface Hydrogen can be depleted without mass-loss
- This scenario may be the only way to provide the progenitors for collapsars from single stars, however, several uncertainties in the "1D"-rotating star models:
  - Convection, Mixing, Magnetic field, Angular momentum transport
  - Turbulence, Meridian circulation,
  - and Mass-loss (especially for Hydrogen-depleted Wolf-Rayet stars)
- All these uncertainties are complexly related
- "1D"-rotating star models need confront with several observations

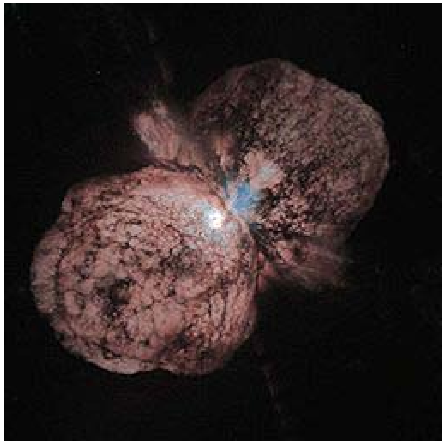
Rotating single star or Binary interaction ?

16 min

- Several puzzles that can not be explained by the "standard" (1D spherical, non-rotating) stellar evolution models.
- (e.g., surface abundance anomaly, ratio of blue stars to red stars) have been attempted to be explained by the rotation effects (e.g., Geneva group.
- However, it is not clear if all (or most of) the puzzles should be explained by the rotation effects,
- because binary interaction sometimes may lead similar results.
  - E.g., anisotropic mass-loss by eta carinae
  - Relative numbers of O stars, Red stars, Wolf-Rayet etc.

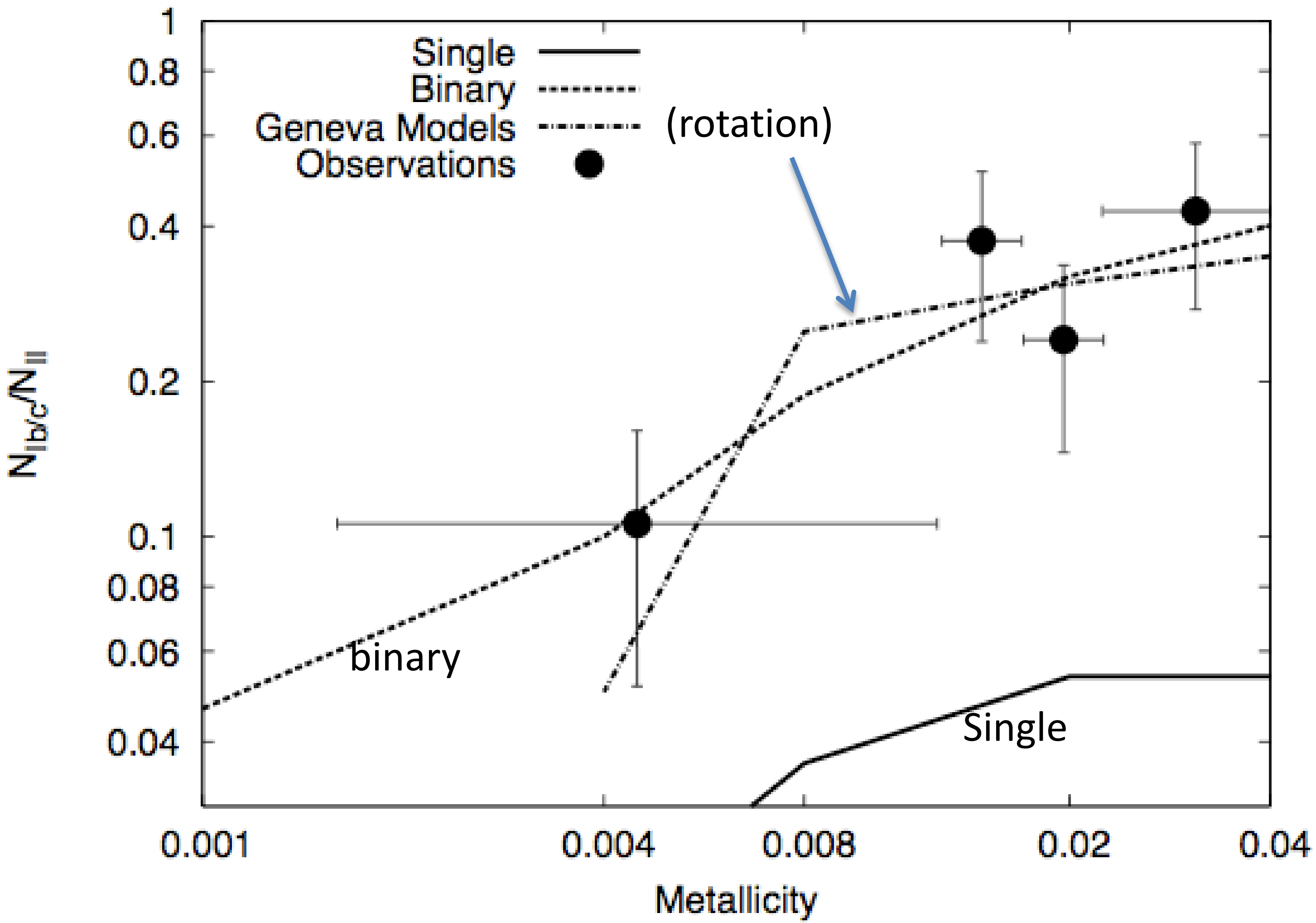
Binary interaction > hydrogen envelope removed

➢ Fewer RSGs, More WR, More SNe Ib/c as observed (next page)



Rotating single star or Binary interaction ?

Eldridge et al. 2009

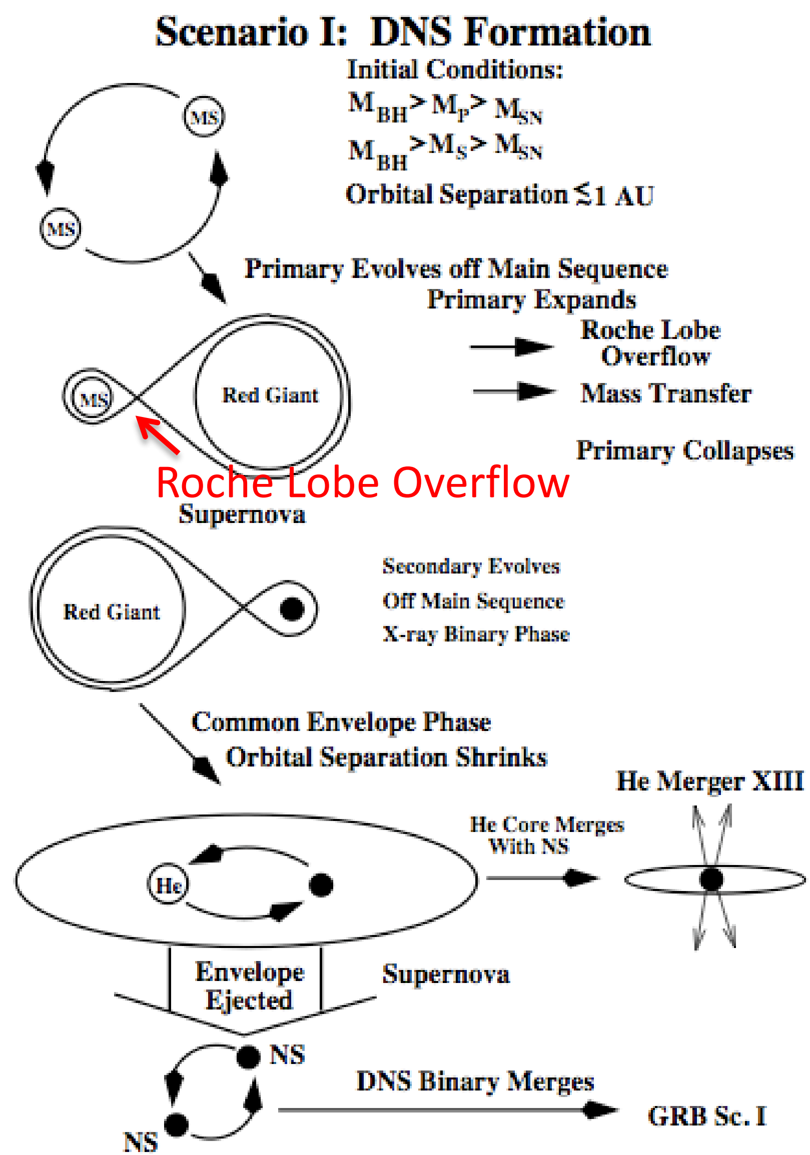


Binary interactions and progenitors for collapsars

- Binary evolution is very complicated and various possibilities.
- But, binaries certainly exist and are very important.

- Roche Lobe Overflow/
  Common envelope mass ejection

1. Stripping H (& He)envelopes efficiently ➔ Making SNe Ic progenitor easier than single star models.
2. Time scales for envelope stripping is shorter than single star cases.
   ➔ Less angular momentum loss



Fryer, Woosley & Hartmann 1999

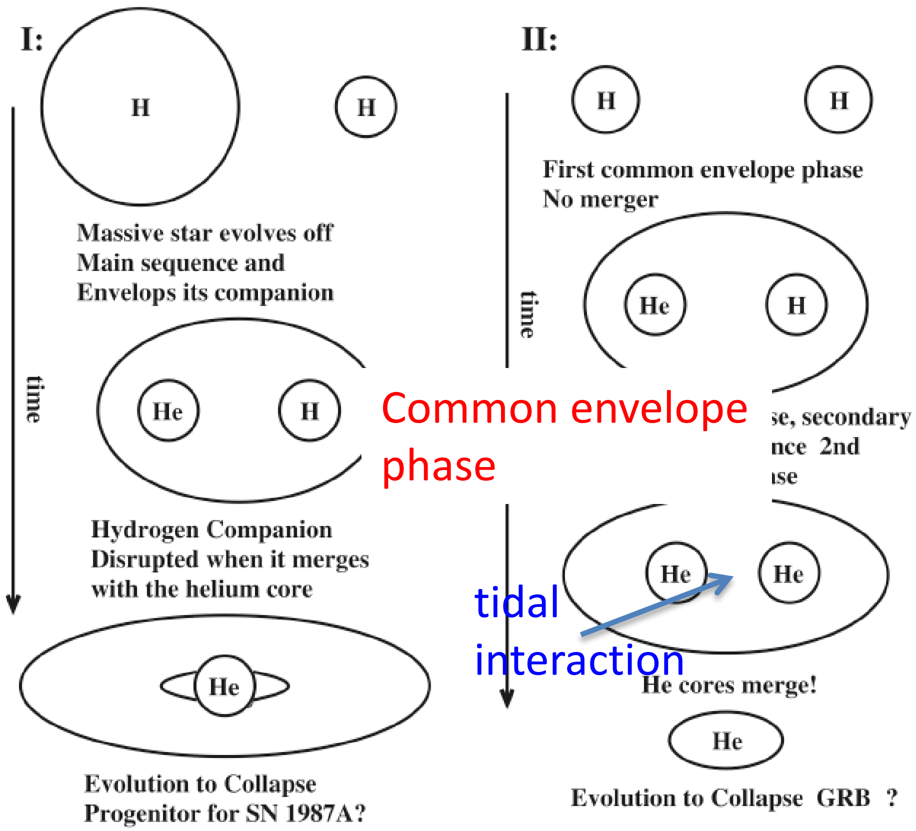
Binary interactions and progenitors for collapsars

- Mass transfer from the companion / tideal interaction

3. Spin-up by gaining mass (Petrovic et al. 2005), or by tidal interaction (Detmers et al. 2010) are not significant for most cases.
4. Main product of close WR binaries with compact companions is a He star – compact object merger (Detmers et al. 2010).

- He star – He star (or compact object) merger

5. Progenitors can have large angular momentum relatively easily
6. He-He merger can be GRB (Fryer & Heger 2005)
7. He – compact merger: likely GRB but haven't been studied much yet.



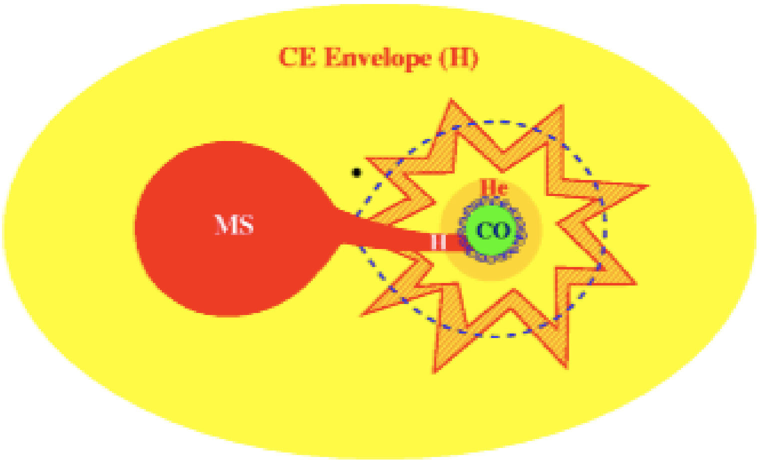
Fryer & Heger 2005

Binary interactions and progenitors for collapsars

- Common envelope (CE) evolution is complicated and the results are often controversial

8. A new mechanism for the ejection of a CE (Explosive CE ejection, Podsiadlowski et al. 2010)

   to explain short-period blackhole – low-mass binaries.



Podsiadolowski et al. 2010

Orbital energy release during spiral-in is too small
Explosive hydrogen burning may be strong enough to remove H & He envelope ➔ progenitor of SN Ic

CE ejection occurs late ➔ angular momentum loss is small ➔ GRB

Low mass BH binaries are progenitors of LGRB (see also, Brown et al. 2007)
Rate ~ 10^{-6} yr $^{-1}$ (significant fraction of all LGRBs

Rotating single star or Binary interaction ?

- How can we distinguish these scenarios?
- Metallicity distribution
  - Binary model can occur even in super-solar metal (but more common at low metallicity, Podsiadlowski et al. 2010)

    (already found?, e.g., Levesque et al. 2010)
- Properties of associated SNe
  - Especially the amount of He (any associated SN Ib?

    (single star models tend to predict larger amount of He in the ejecta)
  - Ejecta mass and Ni56 mass (to constrain magnetar models)
- Finding any evidence of chemically homogeneous WR stars without mass-loss
- Theory
  - CE Ejection
  - Origin of Magnetars
  - Convection, magnetic filed, anugular momentum transfer, and mixing in the progenitors

Early Black Hole Formation by Accretion of Gas and Dark Matter (annihilation)

H. Umeda (Univ. of Tokyo),
N.Yoshida, K. Nomoto (IPMU),
S. Tsuruta, M. Sasaki, T. Ohkubo

Introduction

- It is not known how super massive blackholes (SMBH) $\sim 10^9 M_\odot$ were formed as early as $z \sim 6$ as observed.
- A popular scenario: (e.g., Li et al. 2007; Tanaka & Haiman 2008
  - Bondi accretion onto a Pop III ($z \sim 30$) seed BH $\sim 100 M_\odot$
  - Eddington accretion rates is enough?
  - Or Super Eddington accretion？

- Pop III seed BH $\gtrsim 100 M_\odot$ is required but the mass function of the first stars are not well known.

Bondi 降着

$$\dot{m}(r,v) = \frac{4\pi G^2 \rho_b(r)}{(c_s^2 + v^2)^{3/2}} m^2 \qquad (1)$$

$$m_{\rm Edd} = \frac{1-\epsilon}{\epsilon} \frac{c_s^3}{4\pi G^2 \rho_b \, \tau_{\rm Edd}} \approx 3500 \left(\frac{c_s}{4\ {\rm km\ s^{-1}}}\right)^3 \left(\frac{\rho_b}{M_\odot {\rm pc}^{-3}}\right)^{-1} M_\odot$$

- Bondi 降着率（1）は中心天体の質量Mの2乗で増える
  ⇒ seed BH mass が重いほど有利 （速く成長
- BH 質量が $M_{edd} \sim 10^{3\text{-}4} M_\odot$に達した後はEddington rate で成長

The virial temperature is given by

$$T_{\rm vir} \approx 380(1+z) \left(\frac{M}{10^7 M_\odot}\right)^{2/3} \left(\frac{\Omega_0 h^2}{0.14}\right)^{1/3} {\rm K},$$

the isothermal sound speed is

$$c_s \approx 1.8\ (1+z)^{1/2} \left(\frac{M}{10^7 M_\odot}\right)^{1/3} \left(\frac{\Omega_0 h^2}{0.14}\right)^{1/6}\ {\rm km\ s^{-1}}$$

Evolution of First Stars

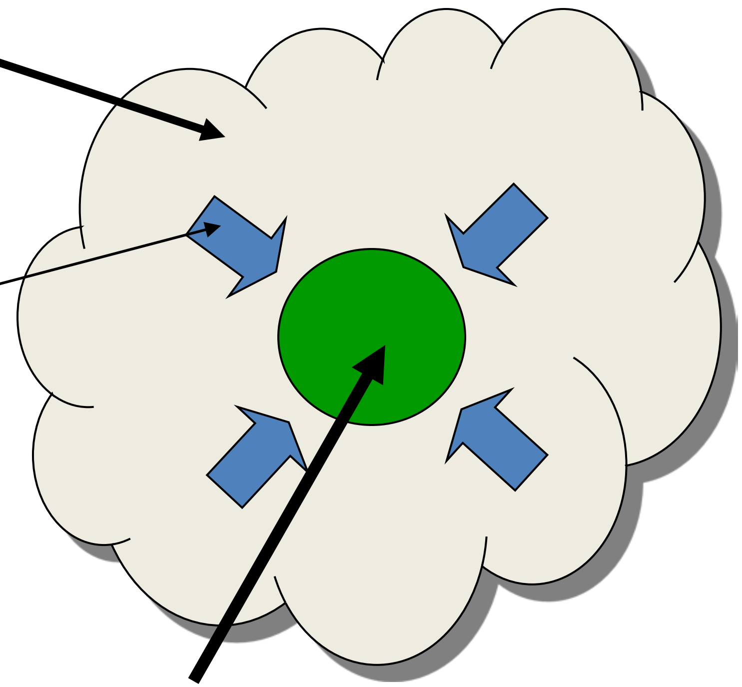
(~1000$M_\odot$ molecular cloud in a ~$10^6 M_\odot$ dark halo)

No Metal
$\Rightarrow$ radiation pressure to prevent mass accretion is lower.

First stars may become very massive (over 100 or even 300$M_\odot$) ?

e.g., Omukai & Palla 2003,
Tan & McKee 2004

Mass accretion



proto star core

Pop III BH $\gtrsim$100M$_\odot$ really existed？

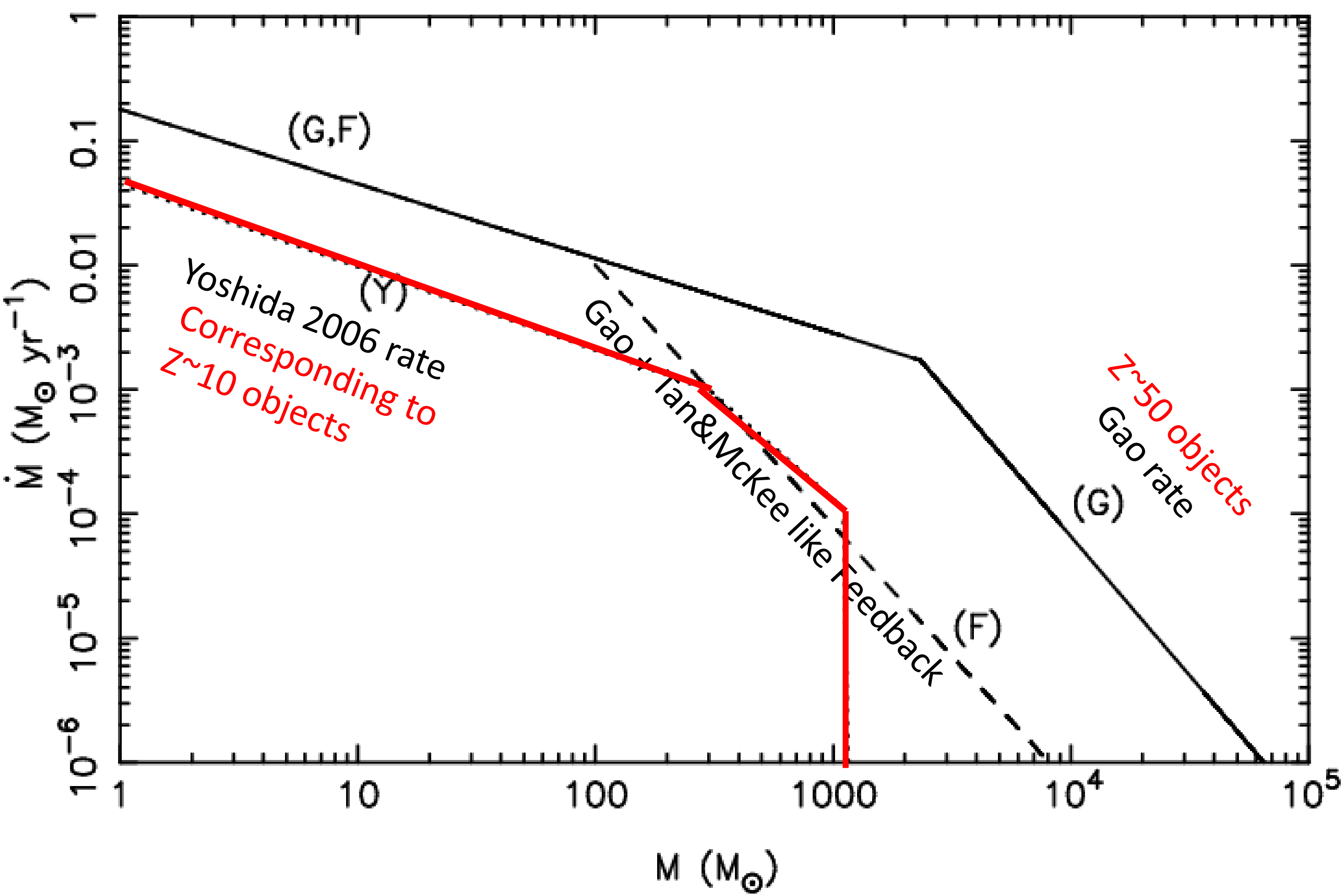
- Stellar mass and fate （without Mass-loss）
  - ～8－140M$_\odot$: Fe Core collapse (SNe)
  - ～140－280M$_\odot$: e^+-e^- Pair Instability (PISNe)
  - >～280M$_\odot$: Fe core collapse
- It was once considered that most PopIII stars became PISNe
  - PISNe do not leave BHs
  - No evidence of PISNe in the abundance patters of metal-poor stars (e.g., Umeda & Nomoto 2002)

Purpose of This Work

- BH $\gtrsim 100 M_{\odot}$ really existed？
  - Mass of First stars and their fate
- Stellar Evolutionary calculations with mass accretion
  - Realistic accretion rates from cosmological simulations
  - Mass of seed BHs
- Effects of dark matter annihilation on Pop III star evolution

- Related papers：
  - H. Umeda et al. : Journal of Cosmology and Astroparticle Physics, 08, 024 (2009)
  - T. Ohkubo et al.: ApJ accepted (2009), arXiv0902.4573

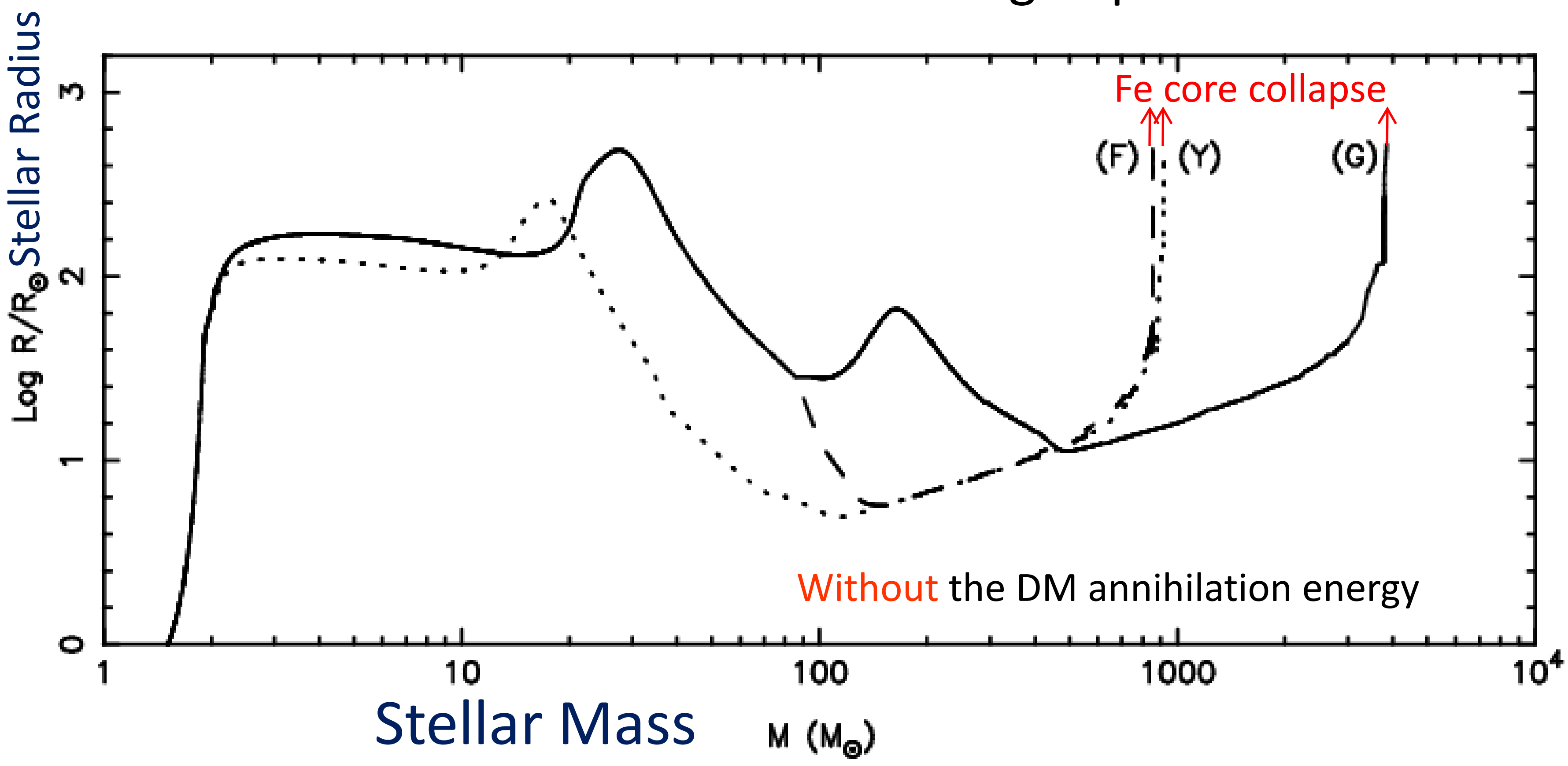
Mass Accretion Rates from Cosmological simulations



Yoshida et al & Gao et al. rates

- Yoshida et al. 2006 rates:
  - Without Feed back --- $M_{final} \sim 1000 M_{\odot}$ BH (Pop III.1)
    - Maybe $M_{final} \lesssim 200 M_{\odot}$ with Tan&McKee like feedback
  - Typical formation epoch z~10
    - Too late and too many to explain Z~6 SMBHs
- Gao et al. 2007 (model R5wt) : corresponding to firstest stars in the universe (z~50)
  - Compared with Z~10 objects
    - Located in a denser halo
      $\Rightarrow$ temperature of the gas cloud is higher
      $\Rightarrow$ larger mass accretion rates $\Rightarrow$ heavier stars
    - Rarer objects
      - May avoid over production of high-z SMBH

Results: Evolution of Accreting Pop III stars



- All models evolve to Fe-core collapse
- Final Mass： 916 M $_\odot$(Y), 3901 M $_\odot$(G), 856 M $_\odot$(F)
- Life time: few million years

(Gao+Feedback)

Effects of DM annihilation onto a PopIII star evolution

- If (self-annihilating) WIMP (weakly interacting massive particles) exist, the annihilation energy may overcome the nuclear energy in Pop III stars:
  - E.g., Spolyar et al. (2008), Freese et al. (2008), Iocco et al. (2008), Taoso et al. (2008), Yoon et al. (2008)

⇒ The star is sustained by the DM annihilation energy

⇒ called "Dark stars"

- If DM density is sufficiently high (or $\rho_x \sigma \; m_x^{-1}$ is large), stellar evolution is "stalled" until the DM is exhausted.

Dark stars

- 典型的WIMP mass ～100GeV, 対消滅断面積<σ v>=3x10^{-26} cm^3/s を採ると、DM密度が充分濃い（ρ_x~10 ^{11}GeV/cm^{3}など)場合には DM annihilation energy が核燃焼によるエネルギー生成を卓越する (e.g., Spolyar et al. 2008)

  ⇒ 星がDM対消滅によって支えられる

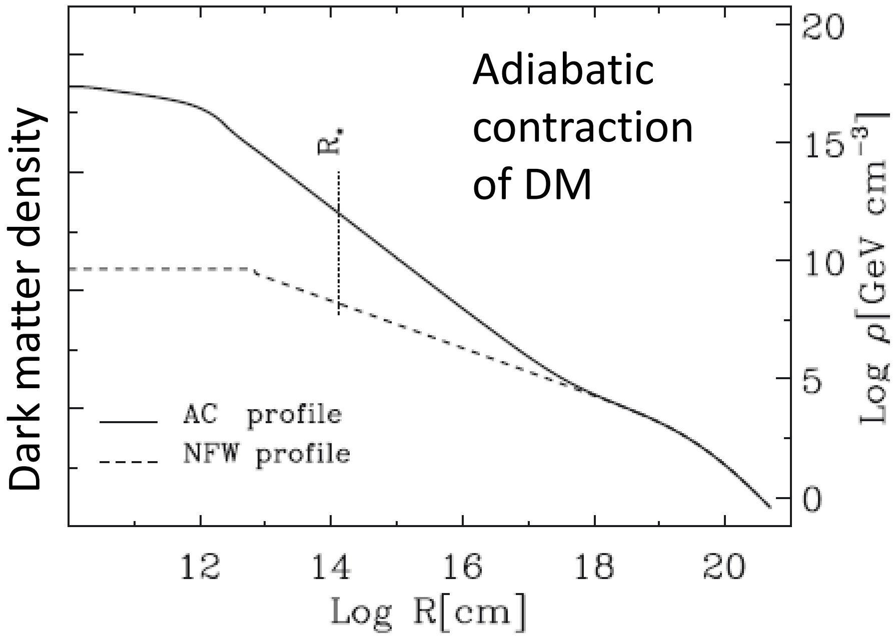
  ⇒ このような星を Dark stars と呼ぶ（人がいる

  （ちなみに見た目は暗くない– 宇宙で最も明るいかも

- これまでの研究の多くは一定の星質量の場合：

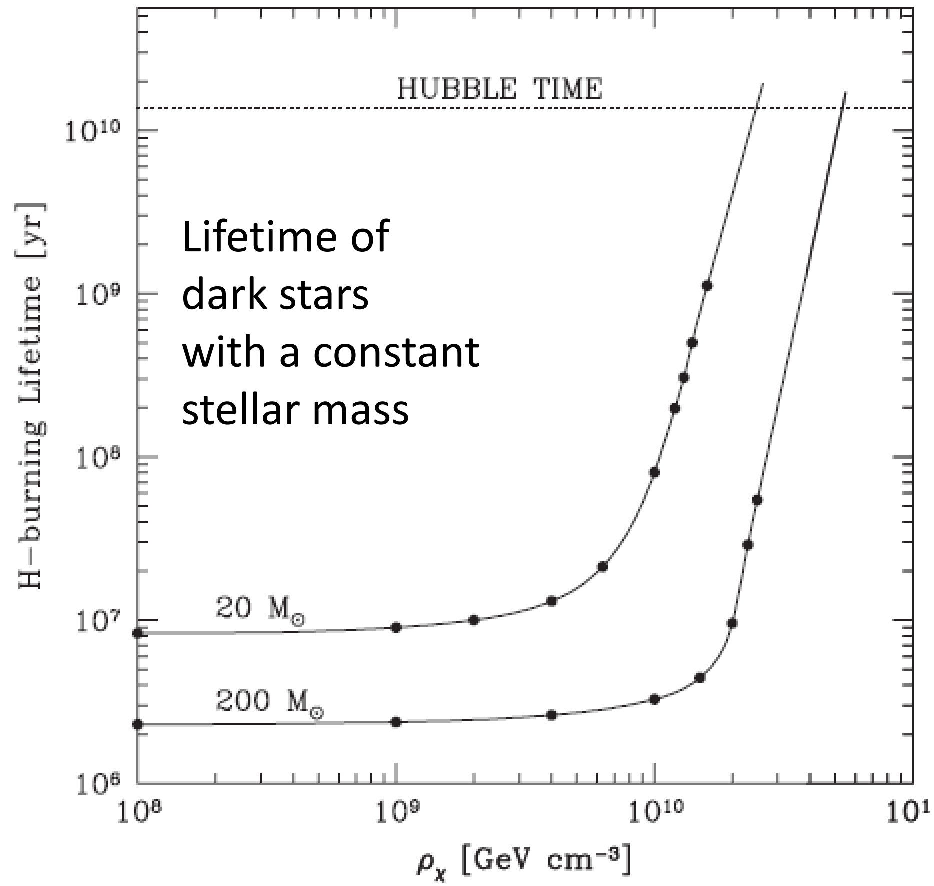
DMが濃い場合(ρ_x σ m_x^{-1}が大きい）星の進化はDMが消費され尽くすまで事実上停止する。

Previous work:
dark matter density and dark star evolution



. Initial NFW DM density profile of adopted $M = 10^6\,M_\odot$ line) and adiabatically contracted DM profile at the time of otostellar phase for the fiducial $100\,M_\odot$ star. The vertical da ks the radius of the star at the beginning of the computation.

Taoso et al. 2008



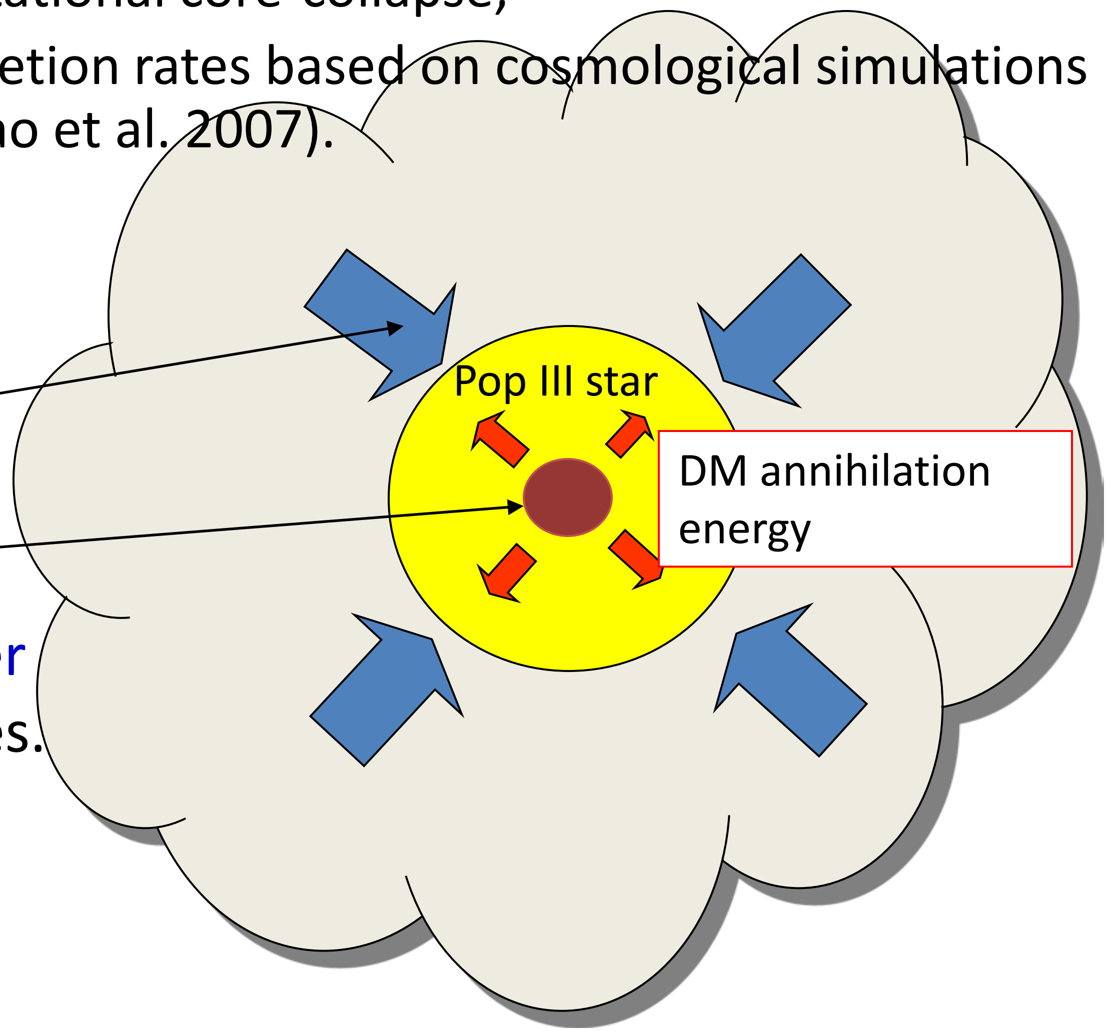
Dark matter density

e.g., Spolyar et al. 2008, Iocco et al. 2008, Freese et al. 2009

This work (Umeda et al. 2009,JCAP)

- We have investigated the evolution of mass accreting dark star models up to the onset of gravitational core-collapse,
- using realistic mass accretion rates based on cosmological simulations (Yoshida et al 2006 & Gao et al. 2007).

Gas accretion＋
DM capture



Captured DM concentrates at the center of the star, and annihilates.

Accreting “Dark Star”

Parameters & Assumptions

- WIMP mass ＝100GeV,

  annihilation cross section $\langle \sigma v \rangle = 3\mathrm{x}10^{-26}$ cm^3/s、

  DM density ρ_x＝10^{11} GeV/cm^3
- Only consider captured DM
  - DM by adiabatic contraction (c.f. Spolyar et al 2009) is neglected
- DM Capture rate : according to Iocco et al. 2008

- Gas (baryon) mass accretion rates

  $dM/dt = 10^{-2, -3, -4} M_\odot$ /yr (constant) &

  Time dependent (from cosmological simulations)

DM capture & annihilation energy generation rate

$$C = 4\pi \int_0^{R_*} dR\, R^2 \frac{dC(R)}{dV},$$ (capture rate)

where

$$\begin{aligned}
\frac{dC(R)}{dV} &= \left(\frac{6}{\pi}\right)^{1/2} \sigma_0 A_n^4 \frac{\rho_*}{M_n} \frac{\rho}{m_\chi} \frac{v^2(R)}{\bar{v}^2} \frac{\bar{v}}{2\eta A^2} \\
&\times \left\{ \left(A_+ A_- - \frac{1}{2}\right) [\chi(-\eta, \eta) - \chi(A_-, A_+)] \right. \\
&+ \left. \frac{1}{2} A_+ e^{-A_-^2} - \frac{1}{2} A_- e^{-A_+^2} - \eta e^{-\eta^2} \right\}, \\
A^2 &= \frac{3 v^2(R) \mu}{2 \bar{v}^2 \mu_-^2}, \quad A_\pm = A \pm \eta, \quad \eta = \sqrt{\frac{3 v_*^2}{2 \bar{v}^2}}, \\
\chi(a, b) &= \int_a^b dy\, e^{-y^2} = \frac{\sqrt{\pi}}{2} [\mathrm{erf}(b) - \mathrm{erf}(a)],
\end{aligned}$$

$$n_\chi(R) = n_\chi^c \exp(-R^2/R_\chi^2), \quad n_\chi^c = \frac{C\tau_\chi}{\pi^{3/2} R_\chi^3};$$

Maxwell-Boltzman distribution
（in thermal equilibrium）

$$\epsilon_\chi(r) = \frac{2}{3} < \sigma v > n_\chi^2(r) m_\chi \quad [\mathrm{erg\ cm^{-3}\ s^{-1}}]$$

Energy generation rate

Stellar Luminosity（approximately）

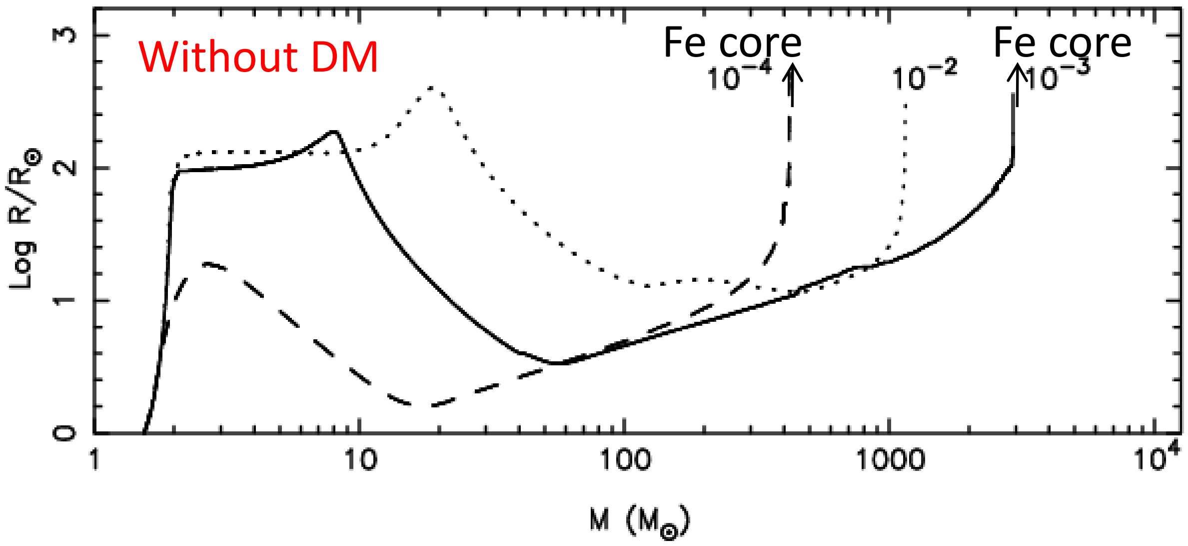
$$L_{\rm DM} = 1.4 \times 10^{47} \frac{\rm erg}{\rm s} \frac{M_*^2}{R_*} \frac{\rho_{11} \sigma_{38}}{m_{100}}.$$

$$\propto \rho_x\, \sigma\ \ m_x^{-1}$$

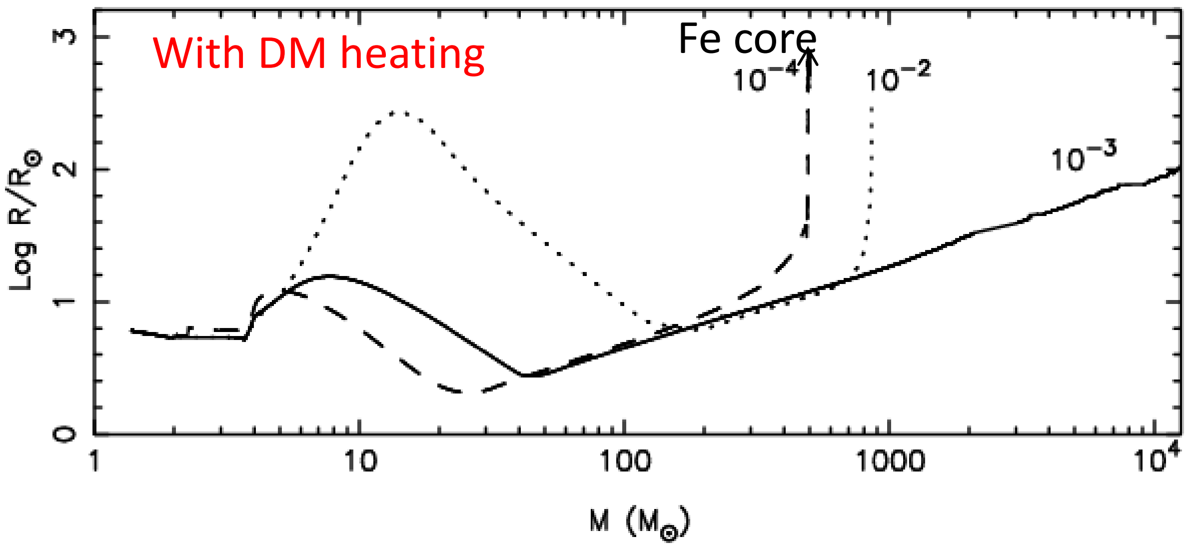
σ : DM-baryon elastic scattering
Cross-section
M_x : DM mass

Gould 1987; Iocco et al. 2008; Yoon et al.2008

Results（constant dM/dt）



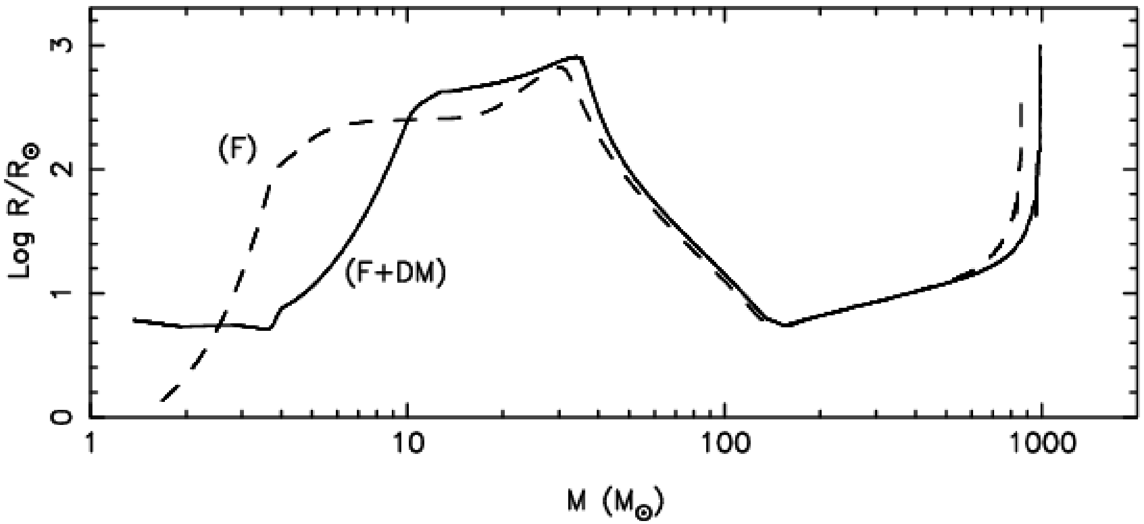
dM/dt=10^{-2} M⊙ /yr
> critical rate
⇒stellar envelope expand during H-burning
⇒may disturb mass accretion

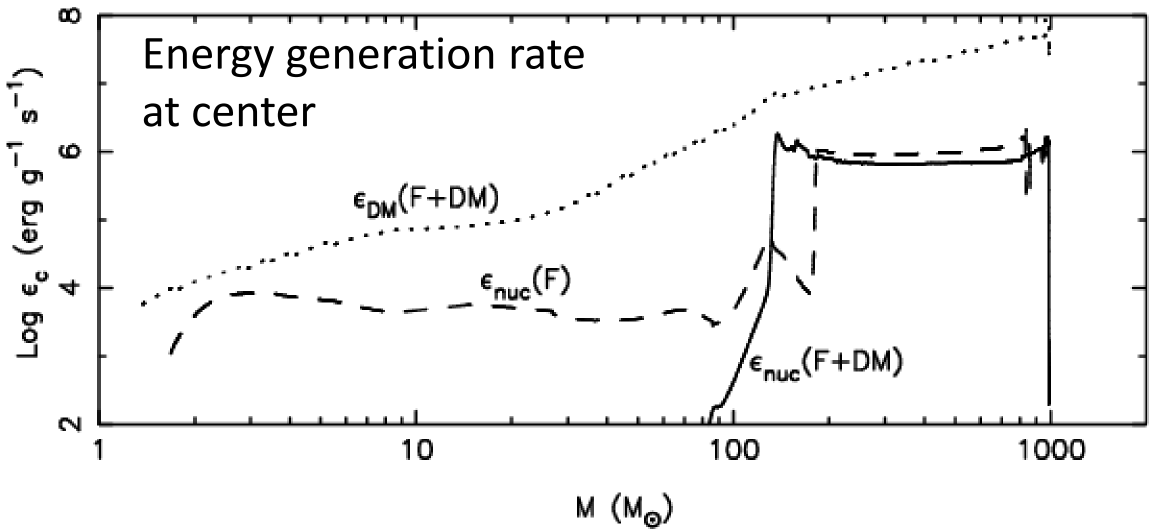


dM/dt=10^{-4} M⊙ /yr:
Fe core formation

dM/dt=10^{-3} M⊙ /yr:
DM annihilation effect is very large

Time dependent dM/dT（model Fd）



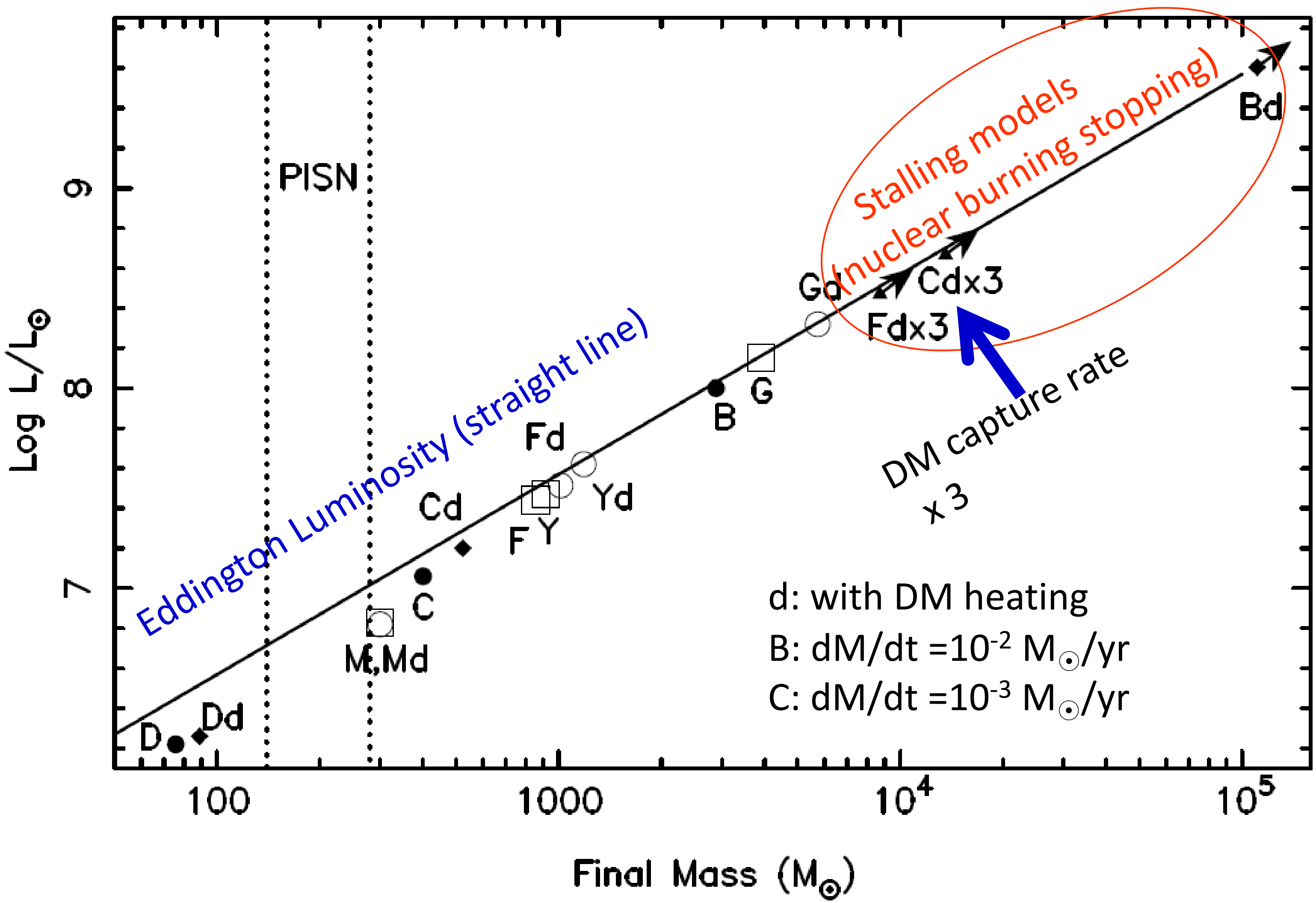


This star is sustained mostly by the DM annihilation energy ~dark star~

However, its appearance is not much different from an ordinal star for M>50.

Final Mass and Stellar Luminosity

$L \approx L_{edd}$ for all models with $M \gtrsim 1000 M_\odot$



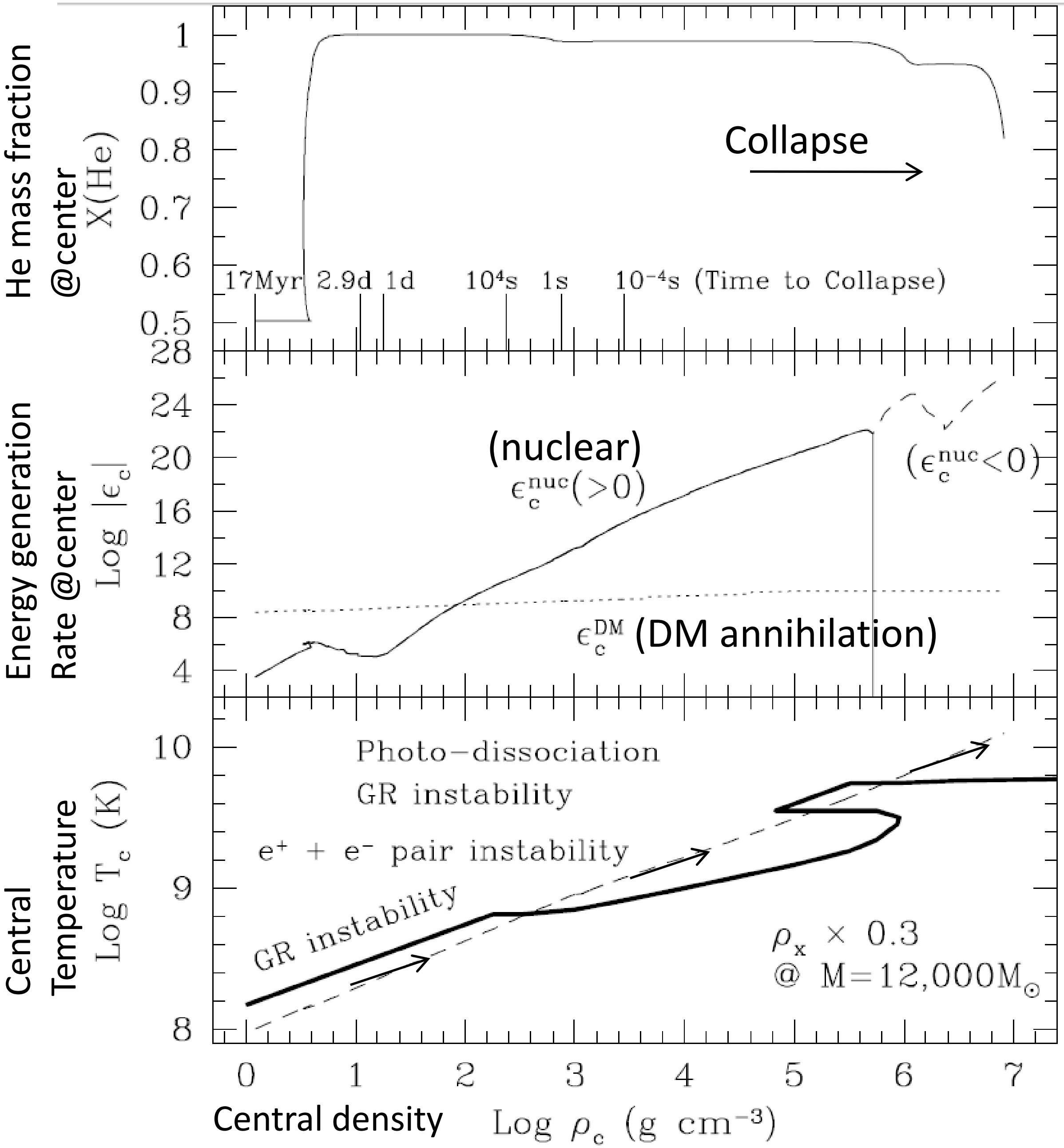
Results

model	dM/dt $=10^{-2}$	dM/dt $=10^{-3}$	dM/dt $=10^{-4}$	Gao+ Feedback (model F)
Final mass (without DM)	>1150 $M_\odot$ X(H)=0.72	2920 $M_\odot$	418 $M_\odot$	860 $M_\odot$
Final Mass （with DM）	>850 $M_\odot$ X(H)=0.72	>10^5 $M_\odot$	515 $M_\odot$	988 $M_\odot$

（the masses of the 10^{-2} models are still increasing ）

X(H) initial =0.753

Gravitational collapse of the Model (Bd)



Model Bd (dM/dt=1e-2) with DM heating: stalls during H-burning

（Left Figure）
DM density is reduced by a factor of 3 @M=12,000$M_\odot$

⇒H-burning resumed

⇒Gravitational Collapse during He-burning stage