Pulsational instability of rapidly accreting protostars during evolution toward supermassive black holes

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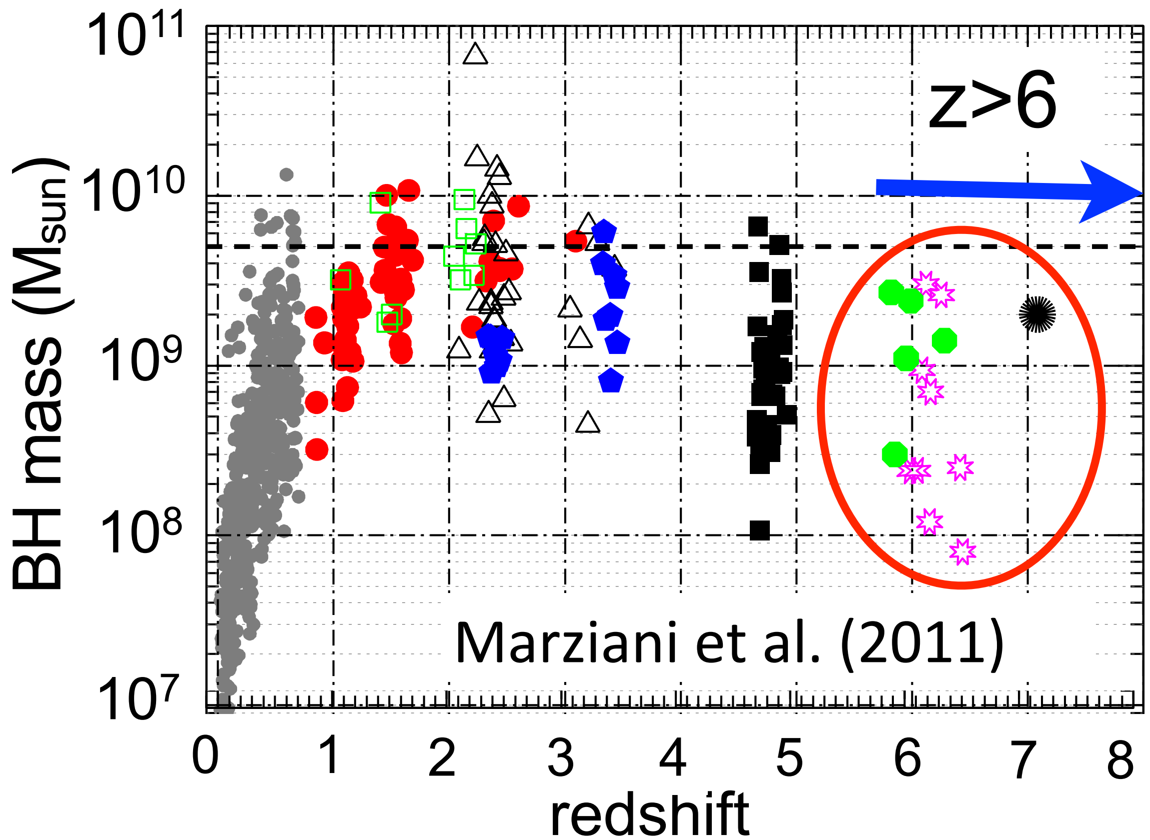
Introduction

Supermassive BH in the early universe

- Supermassive black holes (SMBH)
  - high-z universe (z>6～7)
  - very massive: $M_{BH} \sim 10^{8\text{-}9}\, M_{sun}$



- SMBH formation / growth time
  - gas accretion < Eddington rate

$$t_{\rm gr} = 0.05 \ln \left(\frac{10^9 {\rm M}_\odot}{{\rm M}_{\rm ini}} \right) {\rm Gyr}$$

$$\sim 0.8 \text{ Gyr} \gtrsim \ t_{\rm H}(z=7)$$

(PopIII BH; $100M_{sun}$→SMBH)

We need shorten the formation time !

Solution : supermassive stars ($>10^5 M_{sun}$) → seeds of SMBHs

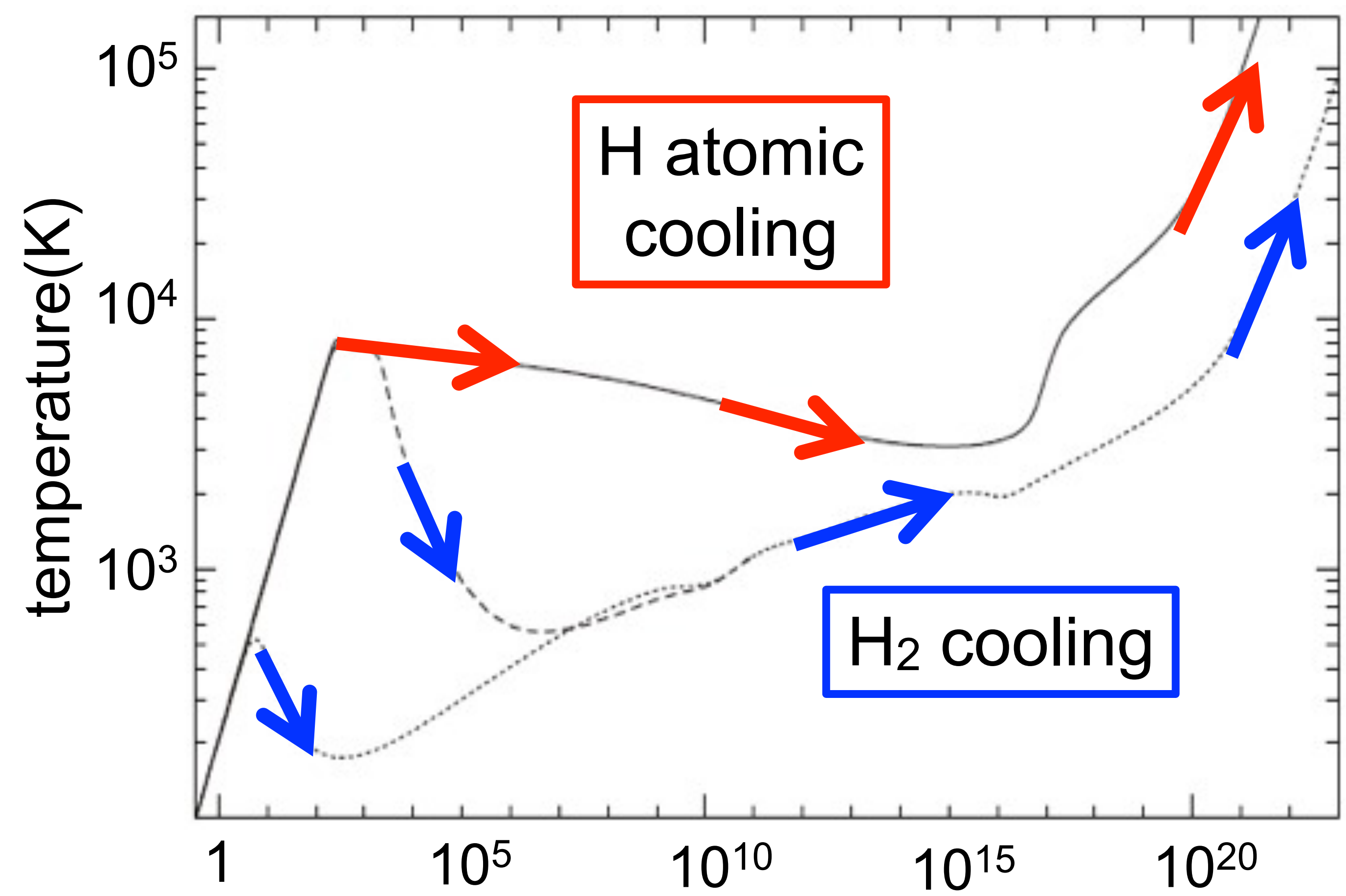
Direct collapse scenario

Supermassive star formation

- primordial gas (w/o H_2 mol)
- H_2 dissociation processes

$$H_2 + \gamma \rightarrow 2H$$

$$H_2 + H \rightarrow 3H$$



(Omukai 2001)

- isothermal collapse (～8000K) by H cooling
- No efficient fragmentation (Bromm & Loeb 2003; Shang et al. 2010)

Supermassive stars ($>10^5 M_{sun}$) form and directly collapse to massive seeds of SMBHs

Evolution of supergiant protostars

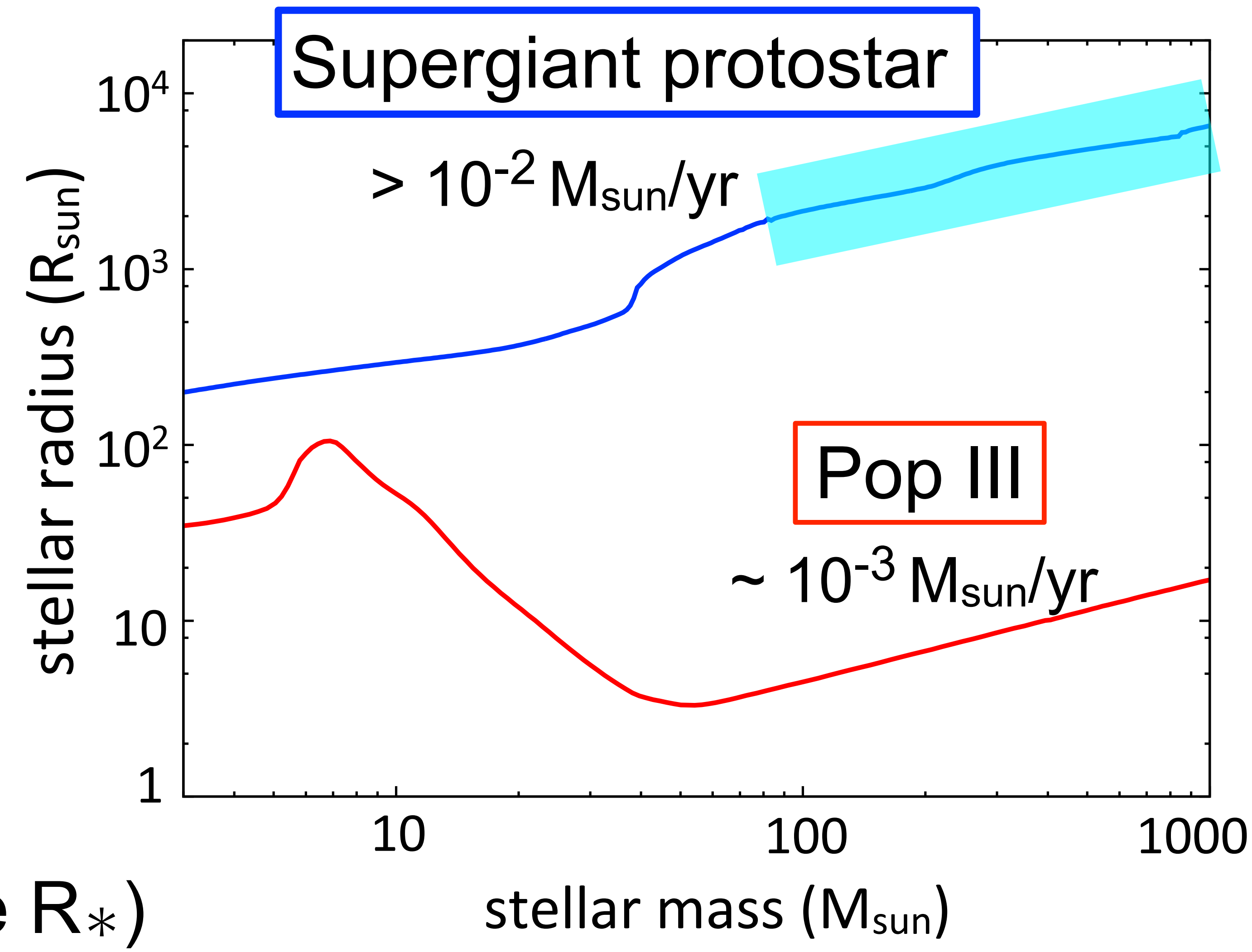
- Protostar evolution after the isothermal collapse

— high accretion rate

$$\dot{M} \sim \frac{c_s^3}{G} \sim 0.1\ M_\odot/\mathrm{yr} \left(\frac{T}{8000\mathrm{K}}\right)^{3/2}$$

— *"supergiant protostars"*

{ contracting core
expanding envelope (large R_*)
low $T_{\rm eff}$ (~5000K) → No UV feedback



(data from Hosokawa et al. 2012)

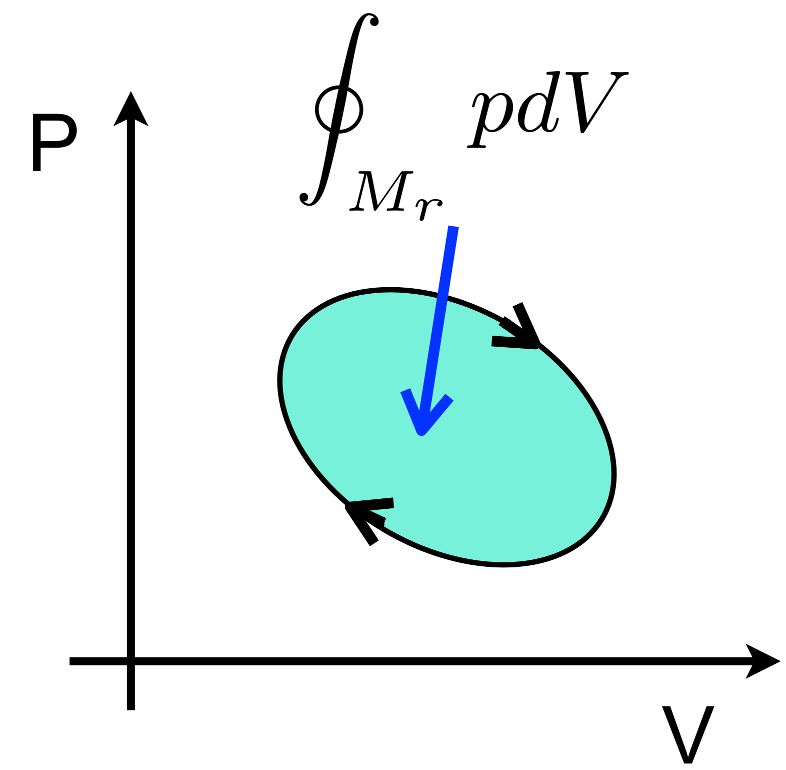
- Can supergiant protostars continue to grow stably ?
- If protostars are pulsationally unstable ⇨ mass loss !!

Stability analysis

Pulsational instability

mechanisms driving instability

- epsilon mechanism
  - — nuclear burning (CNO cycle)
  - — strong T dependence of nuclear-energy generation rate
- kappa mechanism
  - — energy-flux blocking by the opacity bumps
  - — ionization layer (H, He, He^+) in the bloated envelope



⇨ Supergiant protostars could be unstable by both the driving mechanisms

Analysis method

- Basic Eq. (mechanical × 3 + thermal × 2)

perturbation : $Q' = Q'(r)\exp(i\sigma t)$ ($\sigma=\sigma_R+i\sigma_I$), displacement : $\xi_r(r)$

$$\frac{1}{r^2}\frac{d}{dr}(r^2\xi_r) - \frac{g}{c_s^2}\xi_r + \frac{p'}{\rho c_s^2} = v_T\frac{\delta S}{c_P}$$

$$\frac{1}{\rho}\frac{dp'}{dr} + \frac{g}{\rho c_s^2}p' + (N^2-\sigma^2)\xi_r + \frac{d\Phi'}{dr} = g v_T\frac{\delta S}{c_P}$$

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\Phi'}{dr}\right) - 4\pi G\rho\left(\frac{p'}{\rho c_s^2} + \frac{N^2}{g}\xi_r\right) = -4\pi G\rho v_T\frac{\delta S}{c_P}$$

$$i\sigma T\delta S = \delta\epsilon - \frac{d\delta L_{\rm rad}}{dM_r}\ , \qquad \frac{\delta L_{\rm rad}}{L_{\rm rad}} = -\frac{\delta\kappa}{\kappa} + 4\frac{\delta T}{T} + 4\frac{\xi_r}{r} + \frac{d(\frac{\delta T}{T})/d\ln r}{d\ln T/d\ln r}$$

→ eigenfrequency(σ) and functions(Q', δQ) under proper BCs

→ $\sigma_I<0$; unstable ($\sigma_I>0$; stable)

Estimation of mass-loss rate

- mass loss driven by pulsation (Appenzeller 1970)
  - surface velocity grows sound speed $\xi_{r,\mathrm{surf}} = c_\mathrm{s}/\sigma_\mathrm{R}$
  - maximum mass-loss rate

$$\frac{\dot{M}_\mathrm{loss}}{2} v_\mathrm{esc}^2 = \frac{\sigma_\mathrm{R}}{2\pi} W(M_*)$$

v_esc : escape velocity

$W(M_*)$: gain energy during one period

acceleration of outflow ⇐ pulsation energy

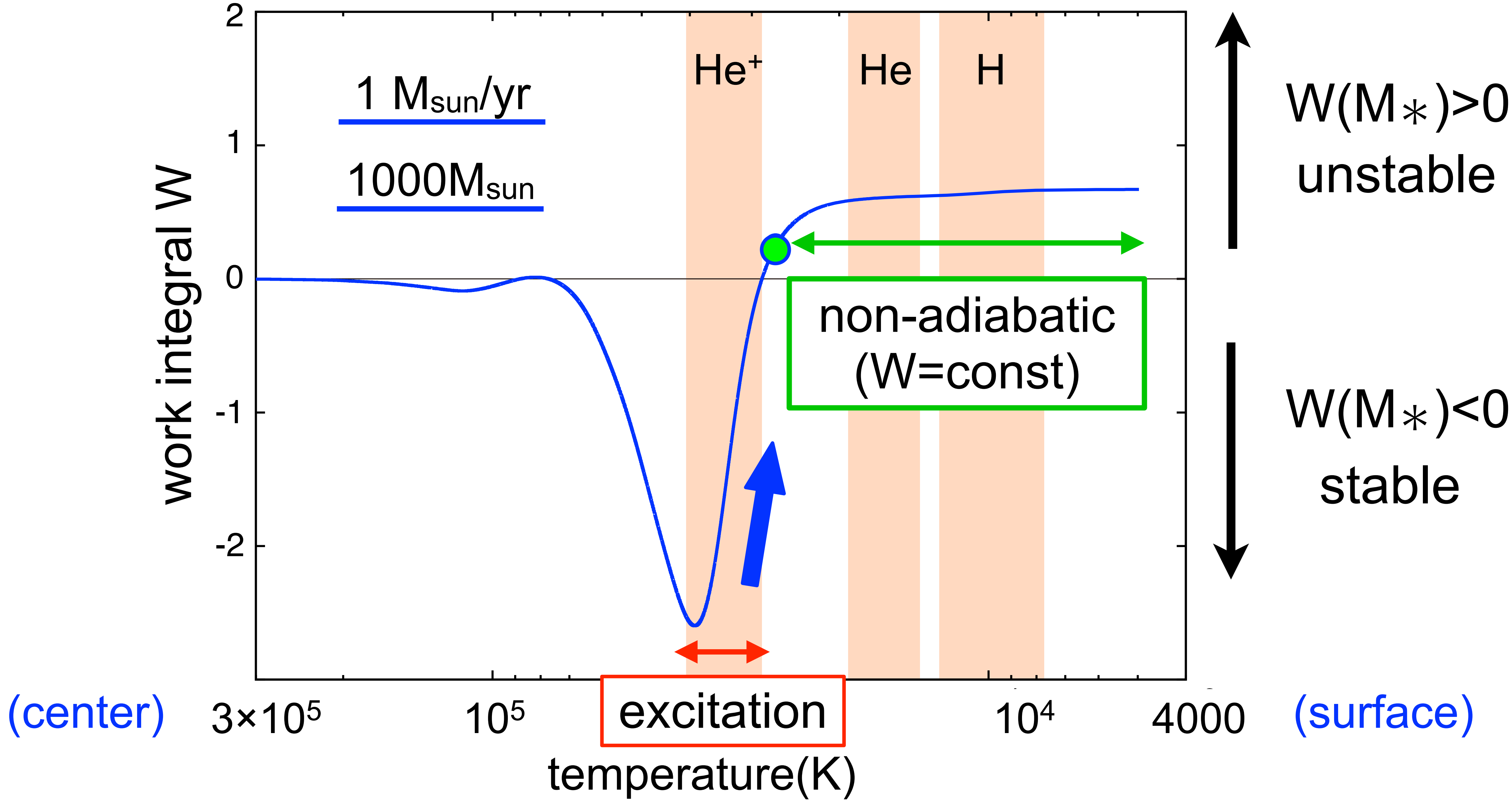
- Work integral (in erg)

$$W(M_r) = \int_0^{M_r} \oint_{M_r} p dV dM_r$$

$$= \frac{\pi}{\sigma_\mathrm{R}} \int_0^{M_r} \Re \left[\frac{\delta T^*}{T} \left(\delta\epsilon - \frac{d}{dM_r} \delta L_\mathrm{rad} \right) \right] dM_r$$

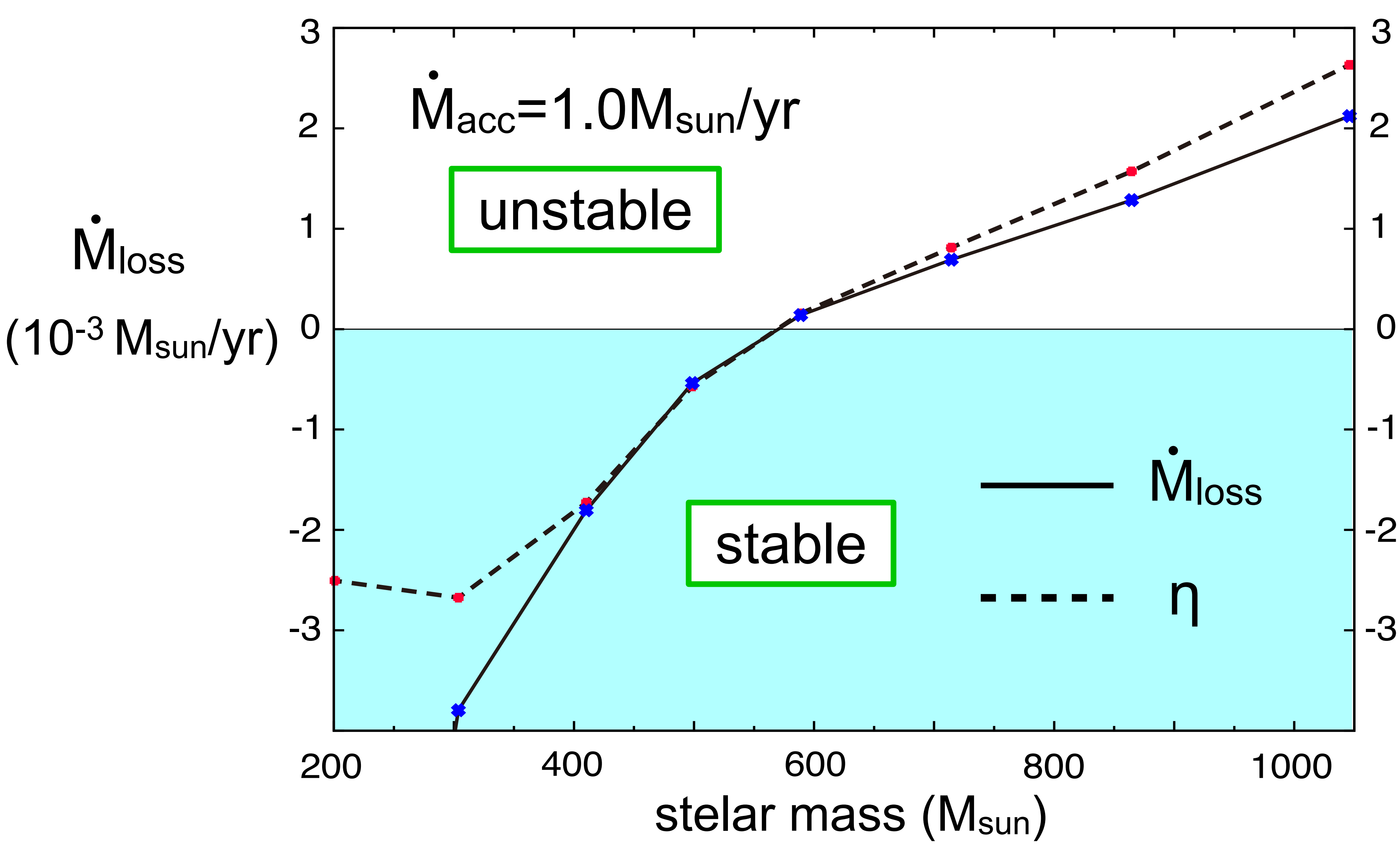
Results

Result (1) : excitation mechanism



- The instability is driven in the He^{+} ionization layer
- Non-adiabatic effect ⇨ W=const (>0) ⇨ unstable

Result (2) : evolution of instability



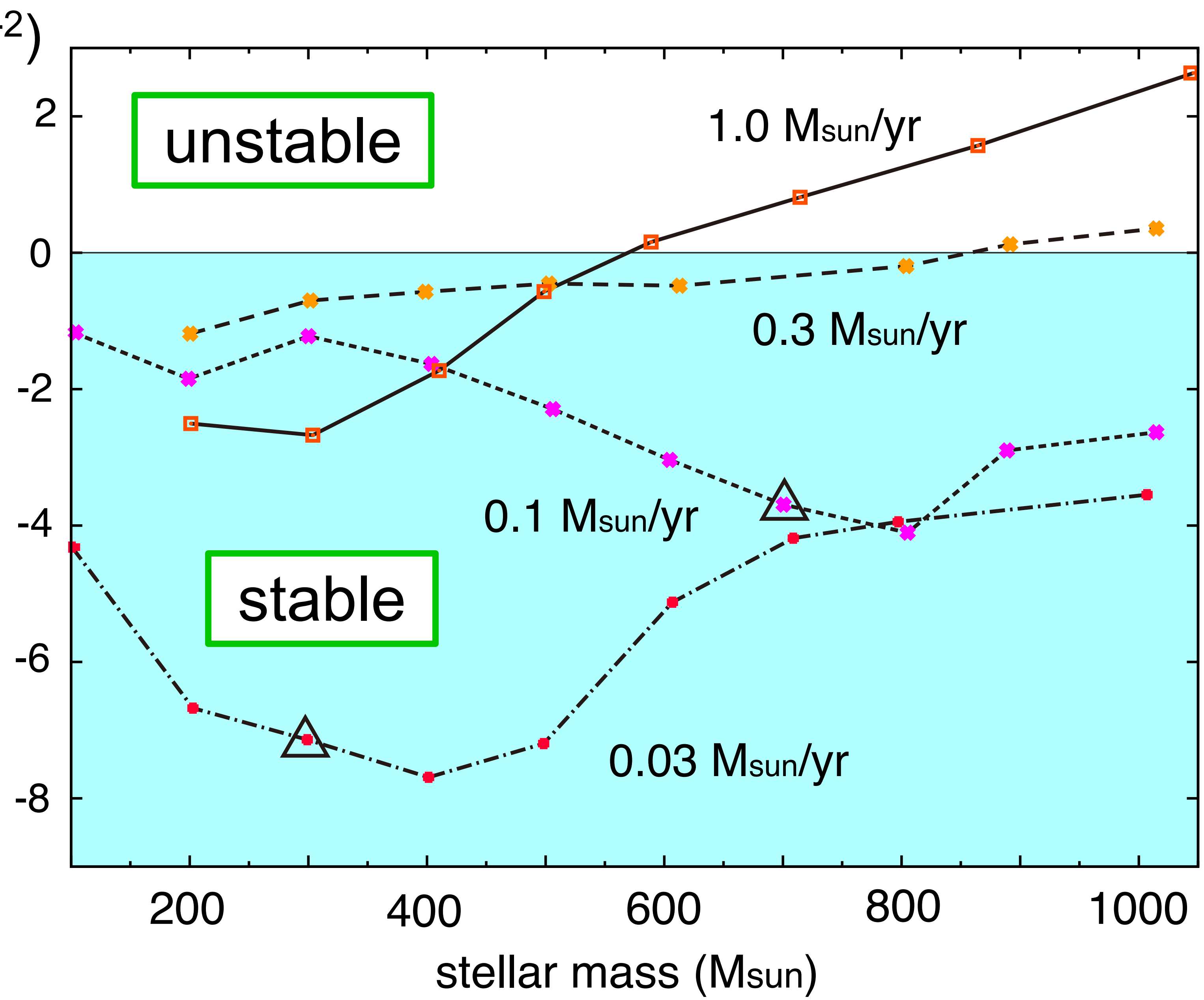
$$\eta = -\frac{\sigma_I}{\sigma_R} \left(= \frac{\text{period}}{\text{growth time}} \right)$$

- pulsational instability grows with increasing the stellar mass
- mass loss rate (~10^{-3} M_{sun}/yr) << accretion rate (~1 M_{sun}/yr)
- growth via accretion is not prevented by the mass loss

Result (3) : various $\dot{M}_{acc}$ cases

$$\eta = -\frac{\sigma_I}{\sigma_R}$$

$$\left(= \frac{\text{period}}{\text{growth time}} \right)$$



- only highest accretion-rate case (1 M_{sun}/yr) is unstable
- lower accretion-rate cases are stable

Maximum mass

- The mass-loss rate (from result 2)

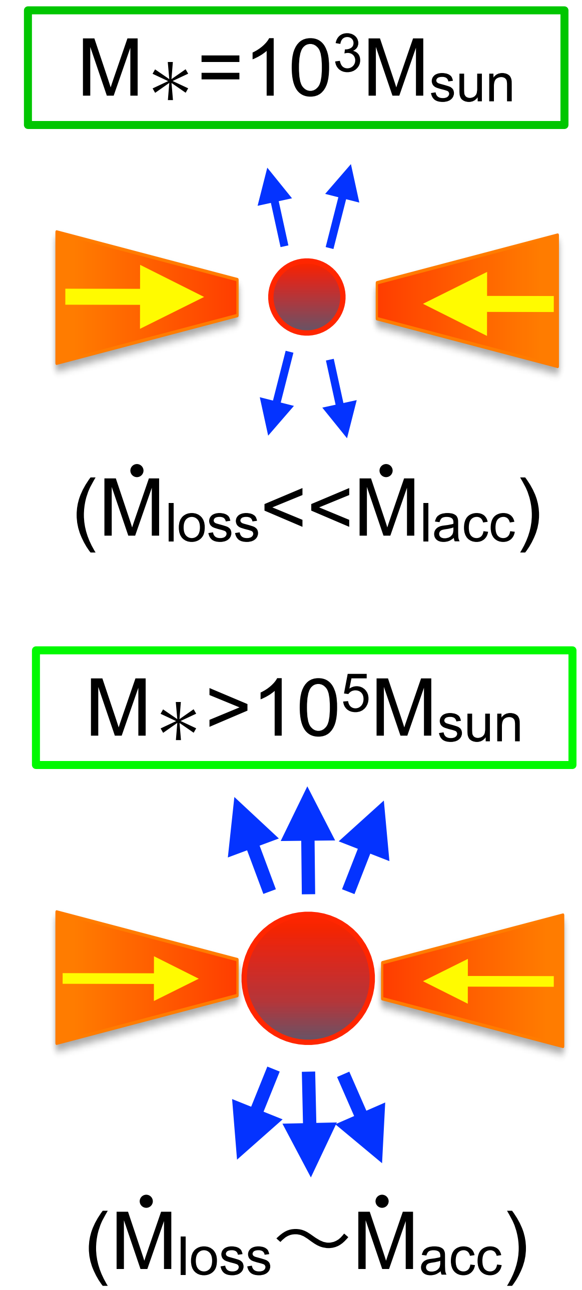
$$\dot{M}_{\rm loss} \sim 5.0 \times 10^{-4} \left(\frac{M_*}{100\ \mathrm{M}_\odot} - 6 \right)\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$$

- Maximum mass of supergiant protostars

$\dot{M}_{loss} << \dot{M}_{acc}$ (growth ○)

$\dot{M}_{loss} << \dot{M}_{acc}$ (growth ×)

⇨ $M_{max} \sim 2\times10^5\ M_{sun}$



Supergiant protostars are expected to stably evolve into supermassive stars with $>10^5\ M_{sun}$ ⇨ **seeds of SMBH**

Summary

- We study the pulsational stability of rapidly accreting protostars
- Such protostars (=supergiant protostars) have the structure with the bloated envelope
- Supergiant protostars ($\dot{M}_{acc}$～1 M_{sun}/yr) are pulsationally unstable by the κ mechanism in the He^{+} ionization layer

　ー mass loss rate (~10^{-3} M_{sun}/yr) << accretion rate (~1 M_{sun}/yr)

　ー protostars become more unstable with increasing the mass

- Supergiant protostars could grow in mass via rapid accretion and evolve to supermassive stars with >10^{5} M_{sun} (→ seeds of SMBH)

Danke schön !