Life and Death of SuperMassive Stars

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references:

Haemmerlé, Meynet, Mayer, Klessen, Woods, Heger 2019 A&A 632 L2

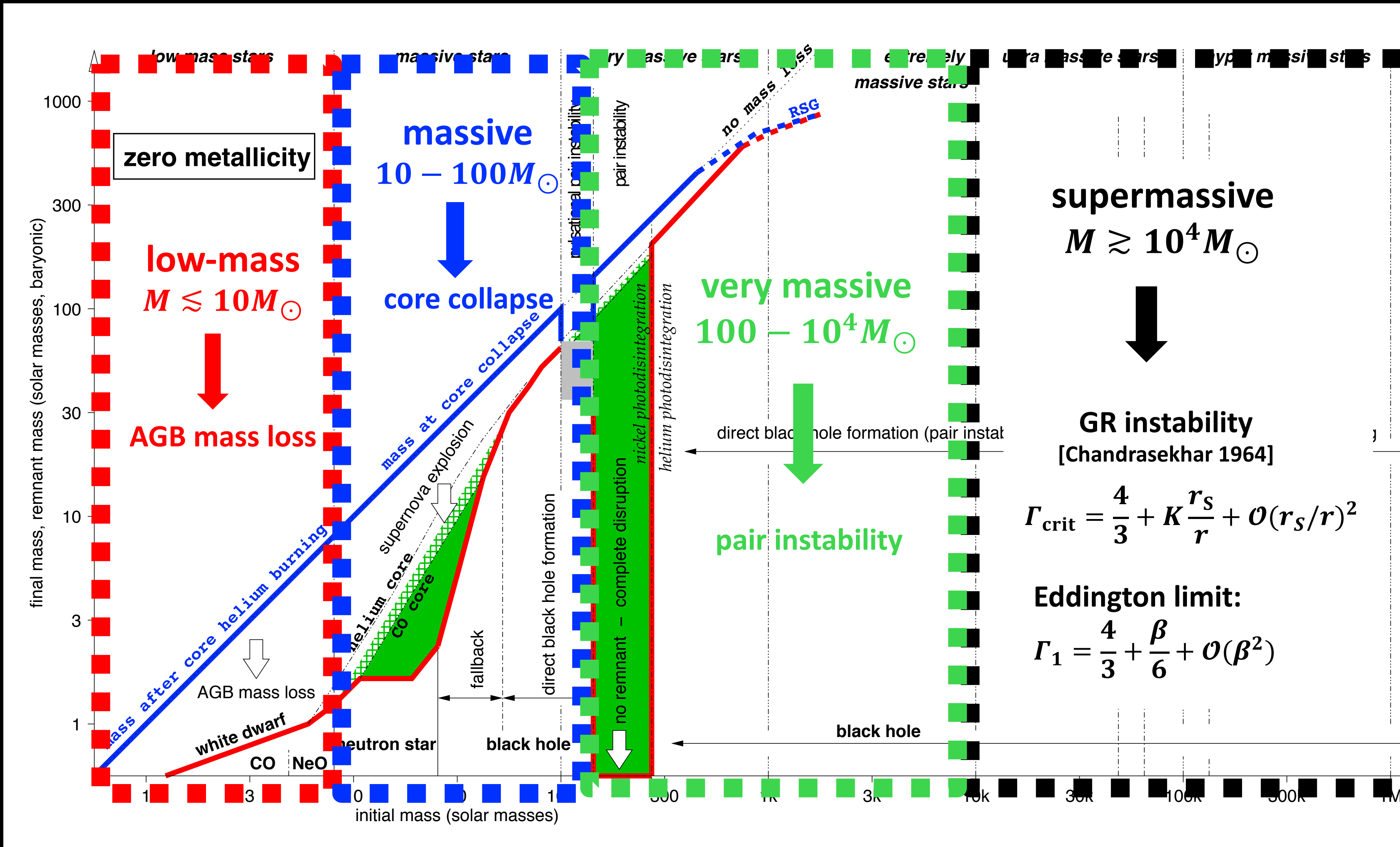
Haemmerlé & Meynet 2019 A&A 623 L7

Haemmerlé, Woods, Klessen, Heger, Whalen 2018 ApJL 853 L3

Haemmerlé, Woods, Klessen, Heger, Whalen 2018 MNRAS 474 2757

Woods, Heger, Whalen, **Haemmerlé**, Klessen 2017 ApJL 842 L6

What are SuperMassive Stars?



Woods, Heger & Haemmerlé, submitted in ApJ

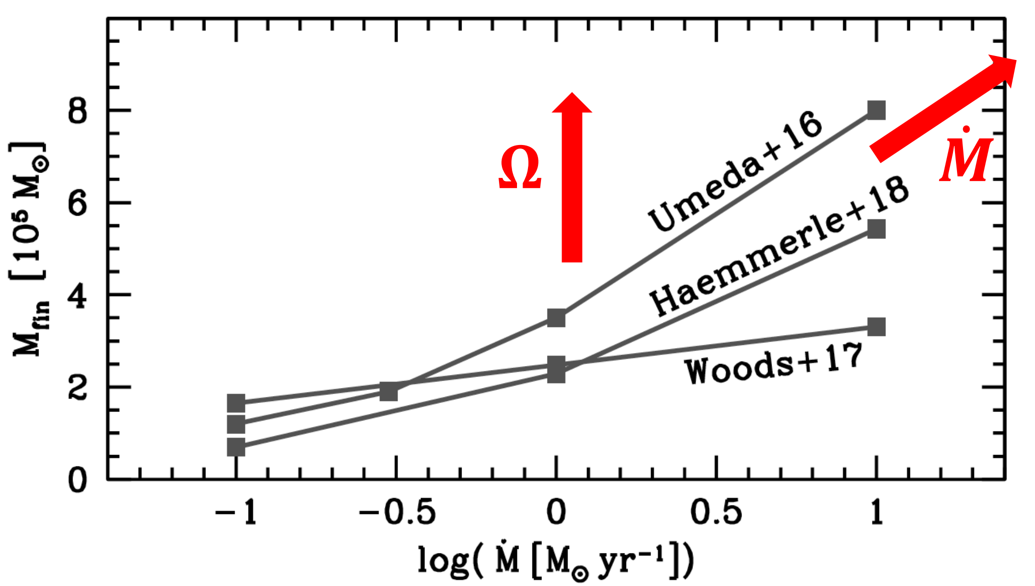
Monolithic vs. Accretion

Monolithic models: [Hoyle & Fowler 1963; Chandrasekhar 1964; Fowler 1964,1966; Bisnovatyi-Kogan, Zel'dovich & Novikov 1967; Appenzeller & Kippenhahn 1971; Baumgarte & Shapiro 1999; …]

- No accretion
- Nearly Eddington ($P \sim P_{\mathrm{rad}}$; $L \propto M$)
- **Fully convective** (thermally relaxed)
- Compact and blue
- Stable H-burning: $M \lesssim 10^5\ M_\odot$

Models with accretion ($\sim 1\ M_\odot\ \mathrm{yr}^{-1}$): [Hosokawa et al. 2013; Sakurai et al. 2015,2016; Umeda et al. 2016; Woods et al. 2017; Haemmerlé et al. 2018; Haemmerlé & Meynet 2019]

- Accretion at the surface
- Nearly Eddington ($P \sim P_{\mathrm{rad}}$; $L \propto M$)
- **90% M radiative** (not relaxed)
- « Redgiant protostar » (Hosokawa+13)
- Final mass: $M \lesssim \mathrm{few} \times 10^5\ M_\odot$



…the most massive stars ever?

Rotation: Why do we care?

Negative reason:

$\ominus$ **The angular momentum problem:** one of the strongest bottleneck in SMBH formation

Positive reasons:

$\oplus$ **Stability:** up to $\sim \mathbf{10^8 - 10^9}\ \boldsymbol{M_\odot}$ ...according to **monolithic models** [Fowler 1966; Bisnovatyi-Kogan et al. 1967]

$\oplus$ **Multi-messenger signatures of direct collapse** (final collapse of the SMS):

- **Gravitational Waves:** breaks spherical symmetry
- **Ultra-Long Gamma-Ray Bursts:** relativistic collimated jets

Monolithic vs. Accretion

Monolithic models: [Hoyle & Fowler 1963; Chandrasekhar 1964; Fowler 1964,1966; Bisnovatyi-Kogan, Zel'dovich & Novikov 1967; Appenzeller & Kippenhahn 1971; Baumgarte & Shapiro 1999; …]

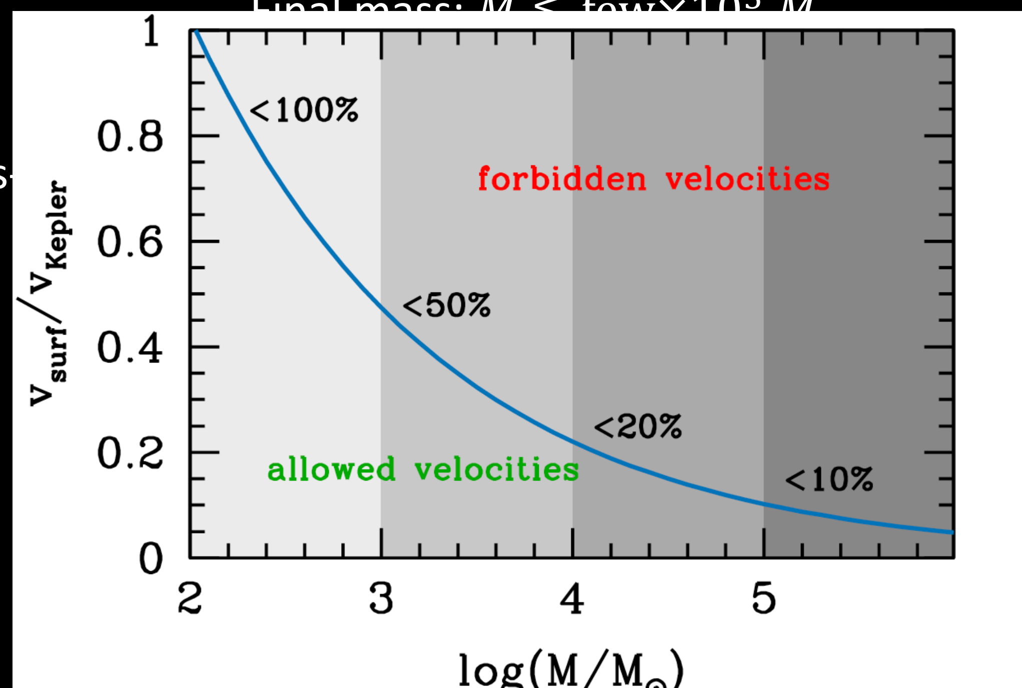
- Analytical approach
- Monolithic formation (no accretion)
- Nearly Eddington ($P{\sim}P_{\mathrm{rad}}$; $L \propto M$)
- **Fully convective** (thermally relaxed)
- Compact and blue
- Stable H-burning: $M \lesssim 10^5\ M_\odot$

Rotation:

- Maximally rotating (Kepler, « mass-
shedding » limit)
- Solid-body rotation (convection)

Models with accretion ($\sim 1\ M_\odot\ \mathrm{yr}^{-1}$): [Hosokawa et al. 2013; Sakurai et al. 2015,2016; Umeda et al. 2016; Woods et al. 2017; Haemmerlé et al. 2018; Haemmerlé & Meynet 2019]

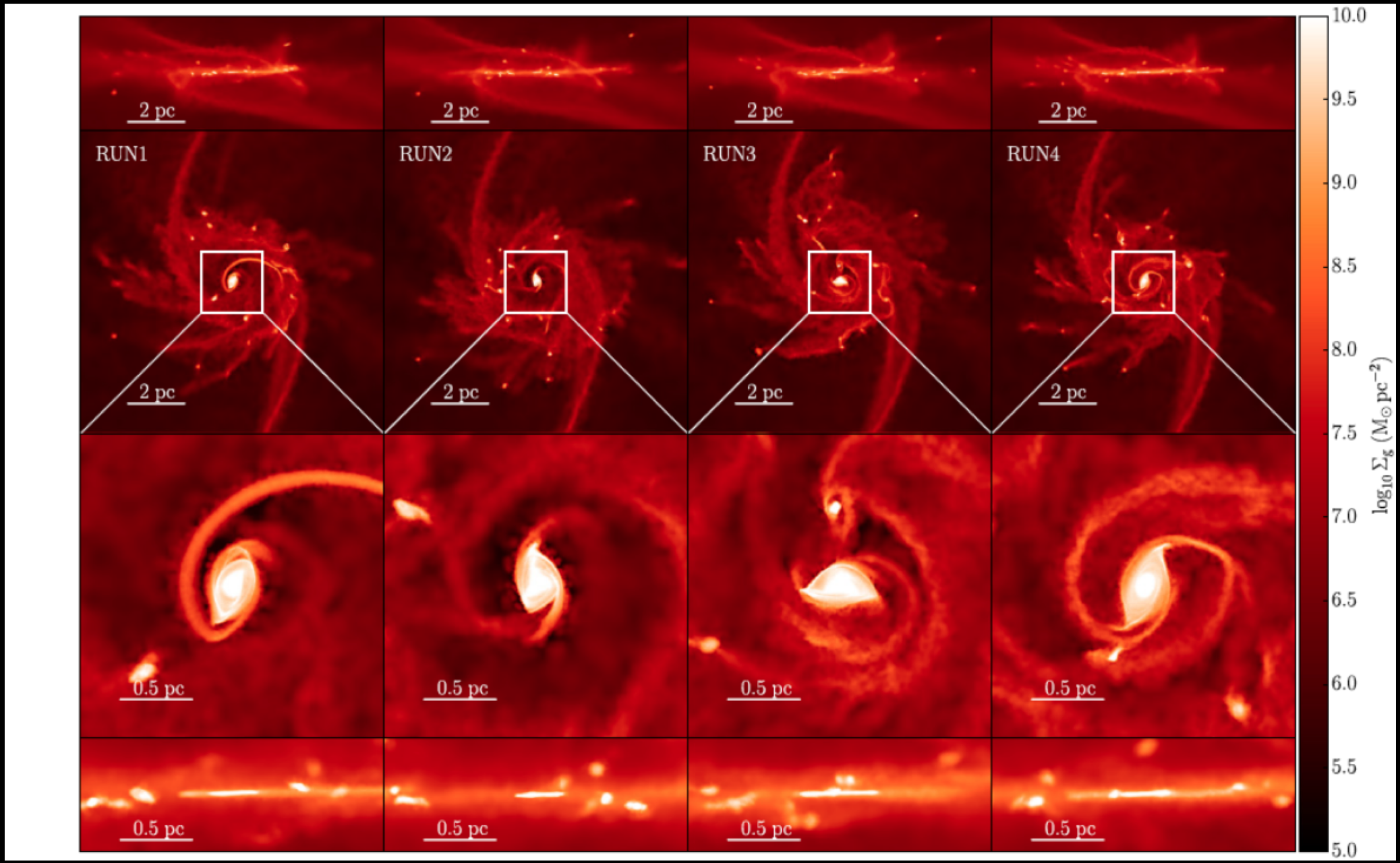
- Numerical approach
- Accretion at the surface
- Nearly Eddington ($P{\sim}P_{\mathrm{rad}}$; $L \propto M$)
- **90% M radiative** (not relaxed)
- « Redgiant protostar »
- Final mass: $M \lesssim$ few$\times 10^5\ M$



Haemmerlé et al. 2018 ApJL (**GENEC** models)

Larger $\dot{M}$: merger-driven direct collapse

Mergers of protogalaxies [Mayer+10,15]: $\Rightarrow \dot{M} \sim 10^3 - 10^5\, M_\odot\, \mathrm{yr}^{-1}$



Mayer et al. (2015)

Accretion at $\dot{M} \sim 10^3\ M_\odot$ yr^{-1}

- **accretion time** $= M/\dot{M}$ $\sim$**1 year** for $M = 10^3\ M_\odot$
  $\sim$**100 years** for $M = 10^5\ M_\odot$

vs.

- **sound-crossing time** $\sim$**1 year** for accreting SMSs

Hydrostatic equilibrium is maintained by **sound-waves.**

$\Rightarrow$ **The evolution of the core is delayed by a SC time** compared to hydrostatic models (GENEC).

$\Rightarrow$ **Hydrodynamical term:**

$$\ddot{r} = -\frac{1}{\rho}\nabla P - g$$

⇒ need for __hydrodynamical__ stellar evolution code

PhD: **Devesh Nandal** => hydrodynamics in GENEC
(starts: 1st of March 2020; supervisor: **Georges Meynet**)

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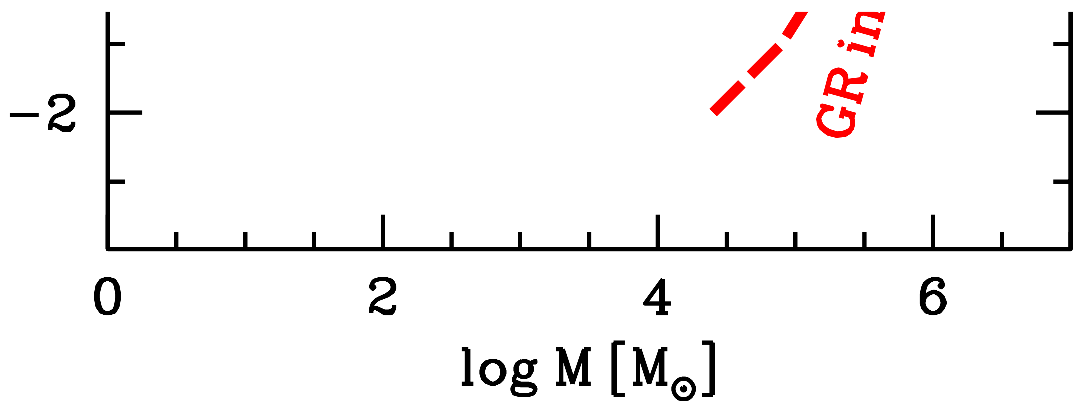

Haemmerlé et al. (2019)

SUMMARY AND CONCLUSIONS:

SuperMassive Stars are candidates for
the progenitors of supermassive black holes.

They can form by accretion only at rates of
atomically cooled haloes ($\mathbf{0.1-10}\ \boldsymbol{M_\odot}$ yr$^{\mathbf{-1}}$).

In this case, they evolve as **red-supergiant protostars**,
are **mostly radiative**, and **slow rotators**.

Non-rotating models indicate an upper mass-limit of $\mathbf{few} \times \mathbf{10^5}\ \boldsymbol{M_\odot}$.
It might be **the most massive stars ever formed in the Universe.**

references:

Haemmerlé, Meynet, Mayer, Klessen, Woods, Heger 2019 A&A 632 L2
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