Theoretical Modeling of Massive Star Formation

Kei E. I. Tanaka (Osaka Univ. / NAOJ)

J. C. Tan (Chalmers/Virginia), Y. Zhang (RIKEN), T. Hosokawa (Kyoto),

V. Rosero (NRAO), J. E. Staff (Virgin Islands), J. M. De Buizer (SOFIA), M. Liu (Virginia), K. Tomida (Osaka) *and more*

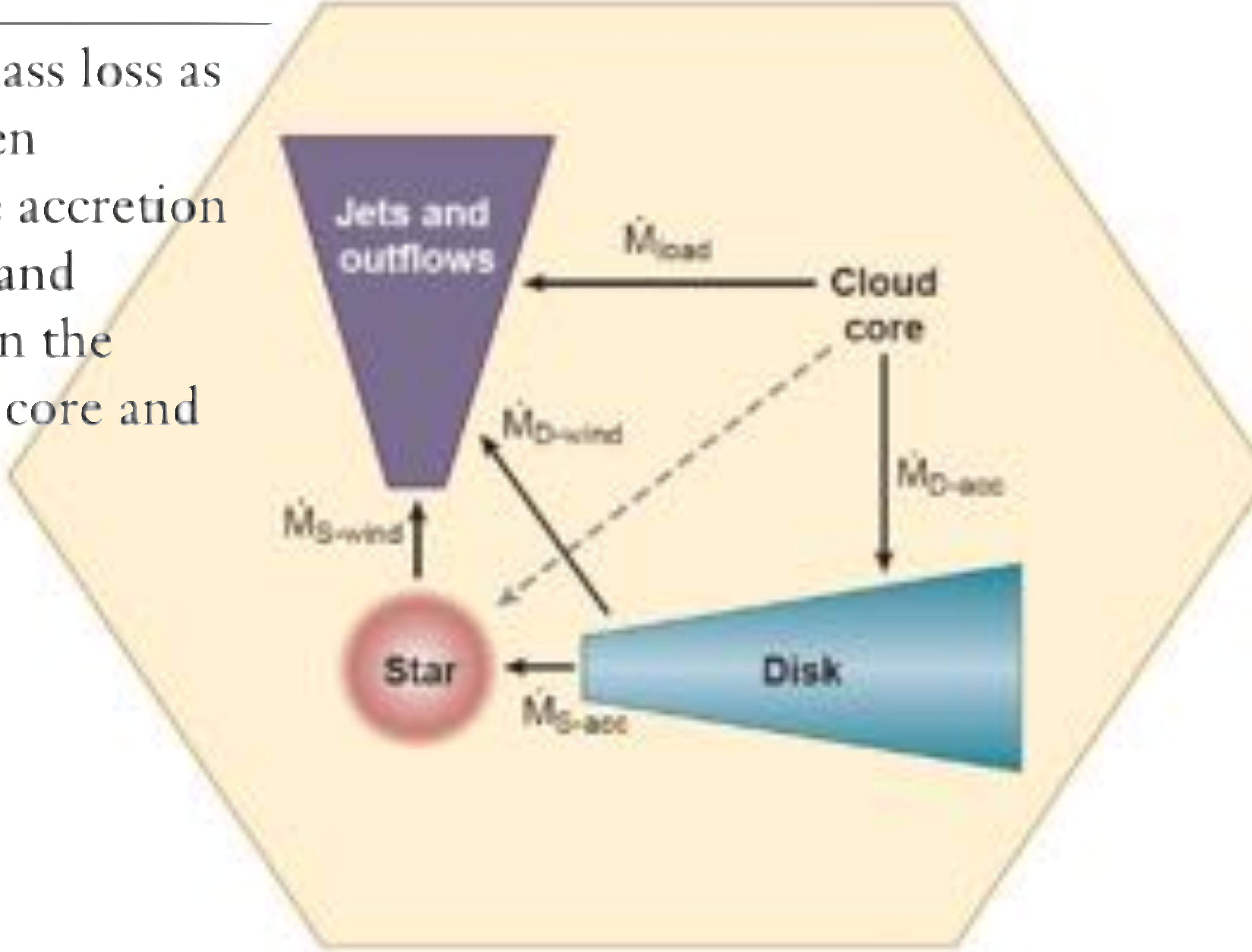
Toward Understanding Massive Star Formation*

Hans Zinnecker[1] and Harold W. Yorke[2]

2007, ARAA, 45, 481

Figure 1

Accretion and mass loss as exchange between components: the accretion disk is reservoir and interface between the molecular cloud core and the forming star.



Theoretical Modeling of Massive Star Formation

Kei E. I. Tanaka (Osaka Univ. / NAOJ)

J. C. Tan (Chalmers/Virginia), Y. Zhang (RIKEN), T. Hosokawa (Kyoto),

V. Rosero (NRAO), J. E. Staff (Virgin Islands), J. M. De Buizer (SOFIA), M. Liu (Virginia), K. Tomida (Osaka) *and more*

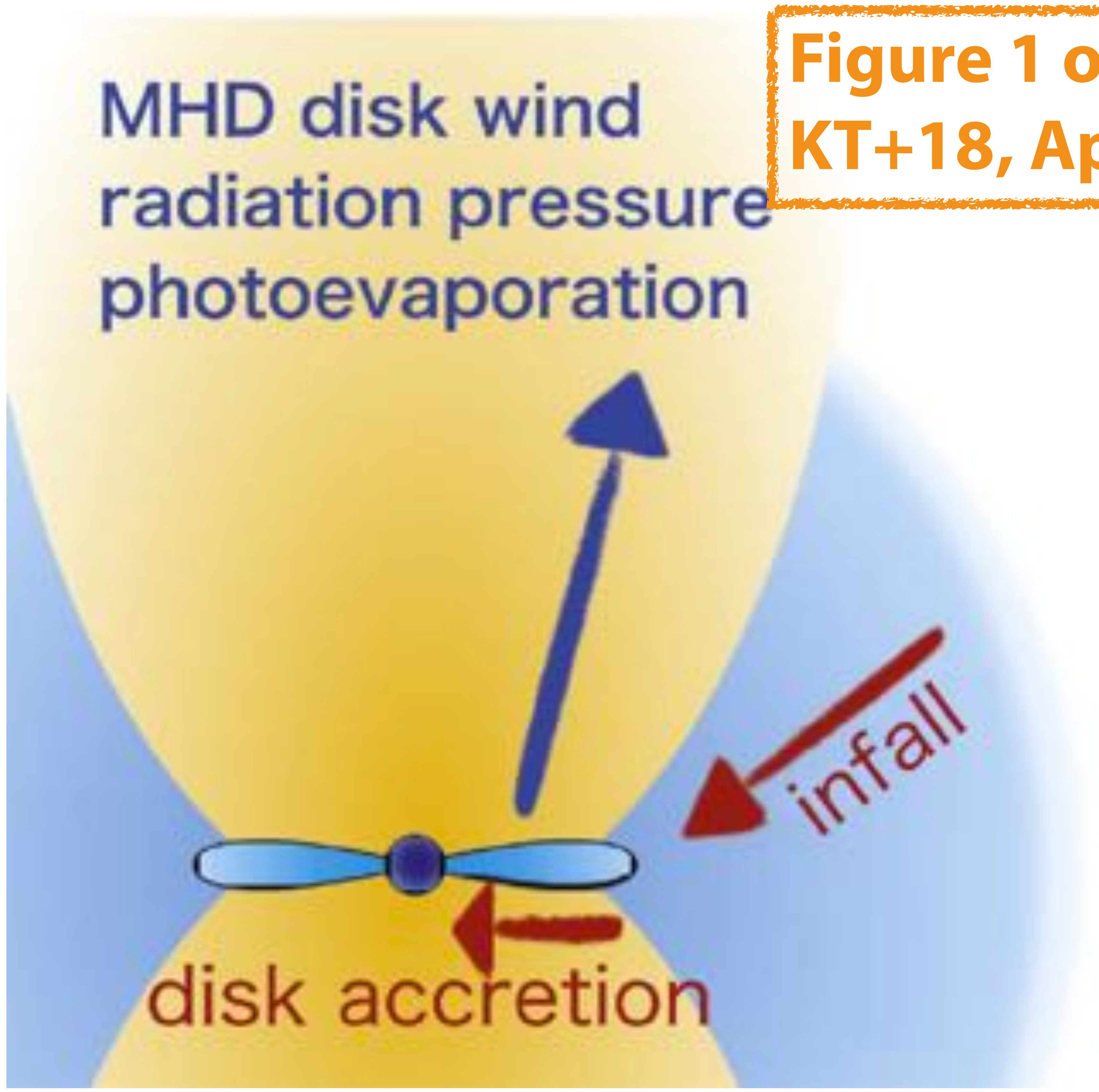
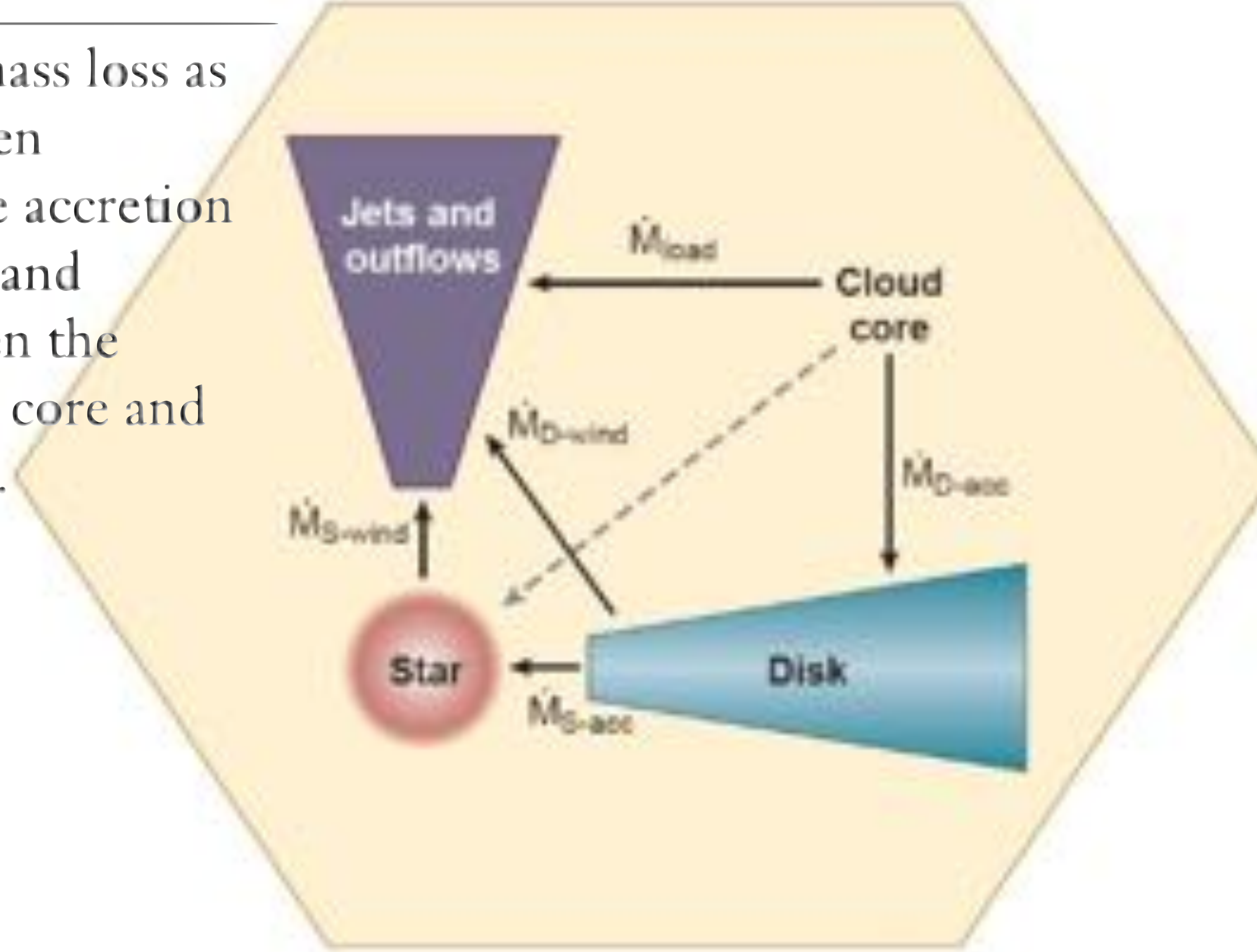


Figure 1 of KT+18, ApJ, 861, 68

Figure 1

Accretion and mass loss as exchange between components: the accretion disk is reservoir and interface between the molecular cloud core and the forming star.

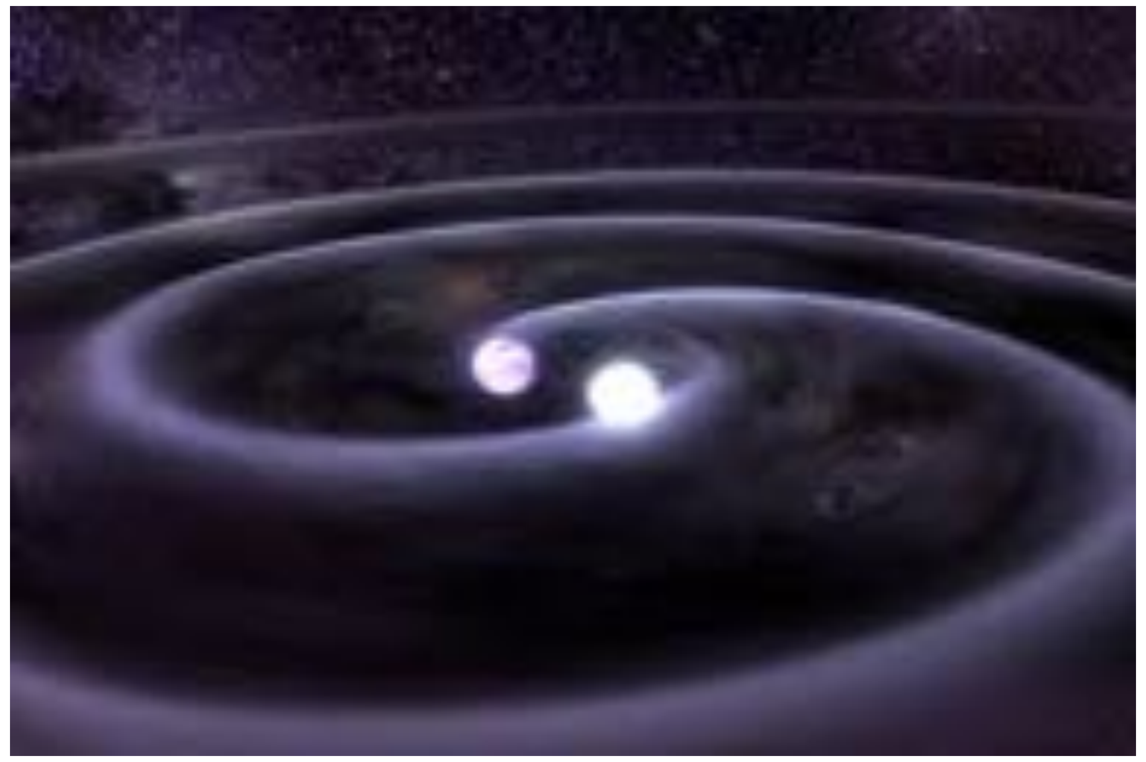


Massive Stars throughout the Cosmic History

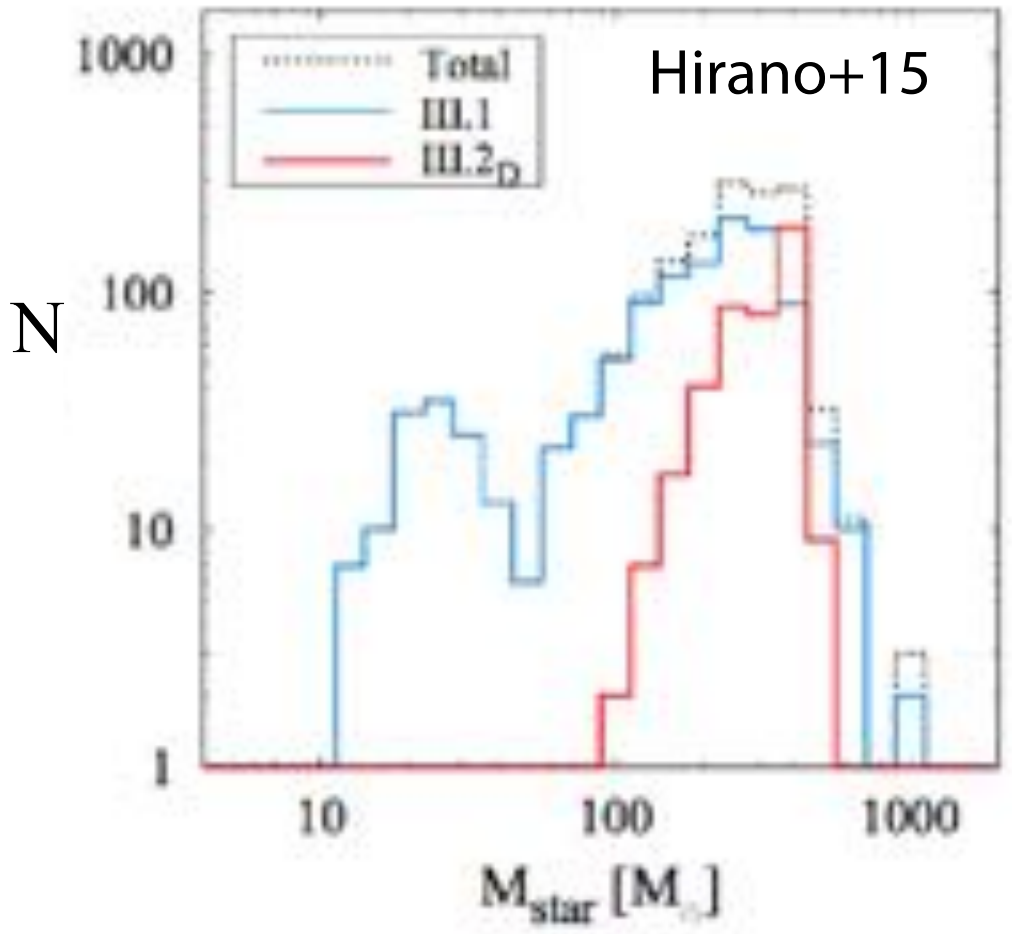
Massive stars are important
throughout the cosmic history
radiation, winds, SNe, metal & dust, GRBs, GW

30 Dor &
R136a ~300M⊙

GW150914 ~ 36 + 29M⊙



First Stars~10-1000M⊙

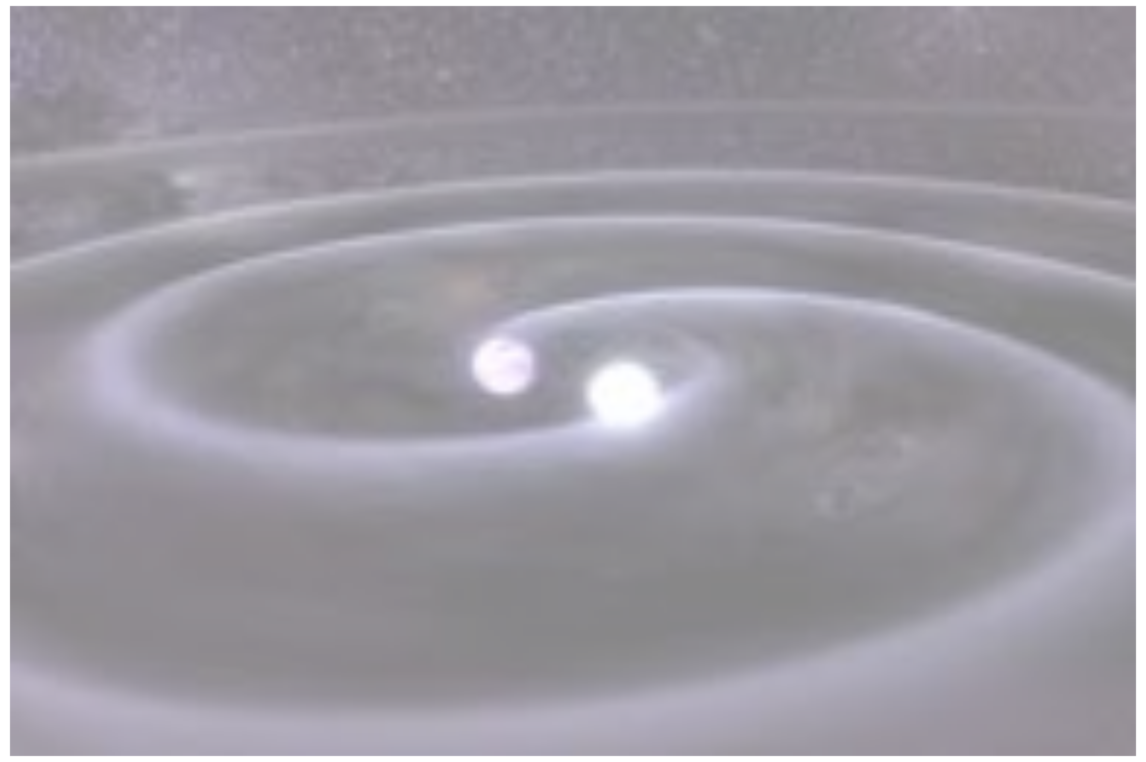


Massive Stars throughout the Cosmic History

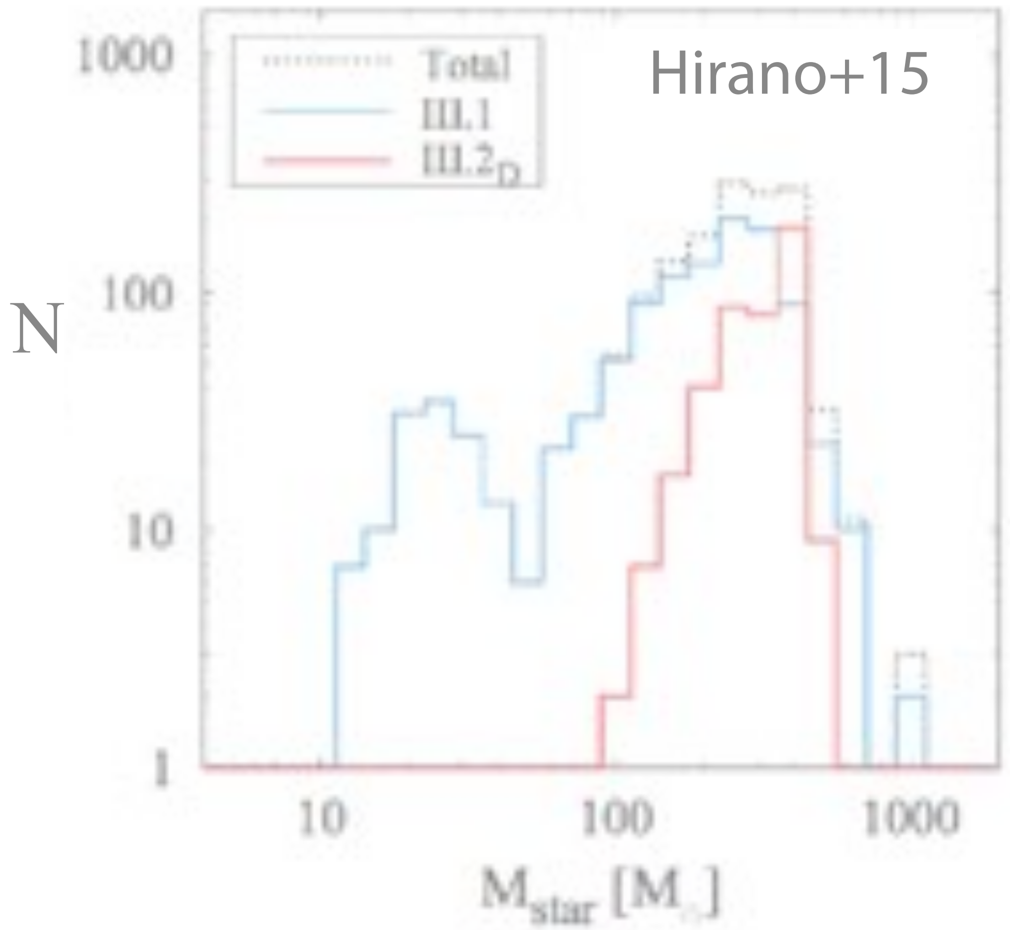
Massive stars are important
throughout the cosmic history
radiation, winds, SNe, metal & dust, GRBs, GW

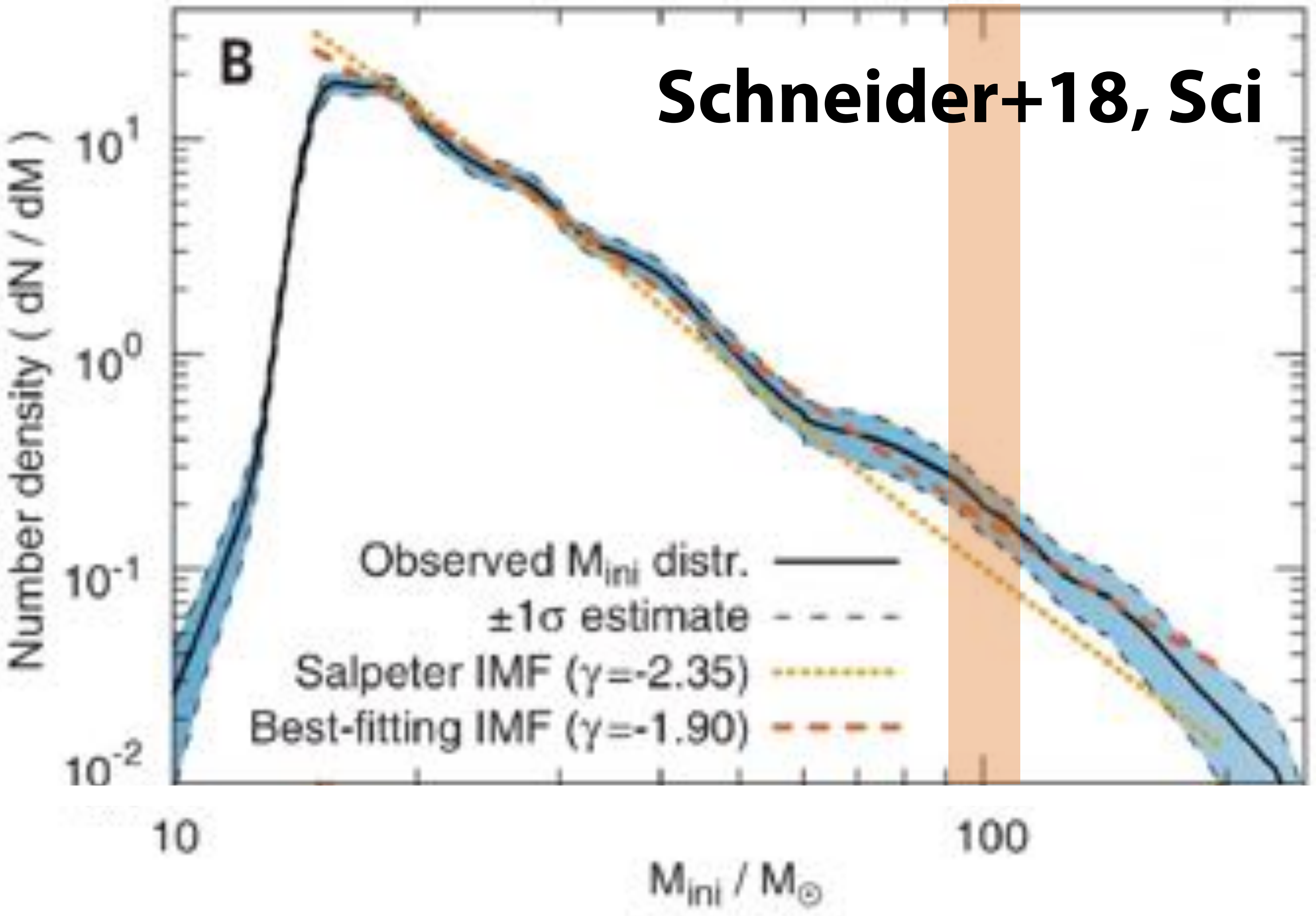
30 Dor &
R136a ~300M⊙

GW150914 ~ 36 + 29M⊙



First Stars~10-1000M⊙



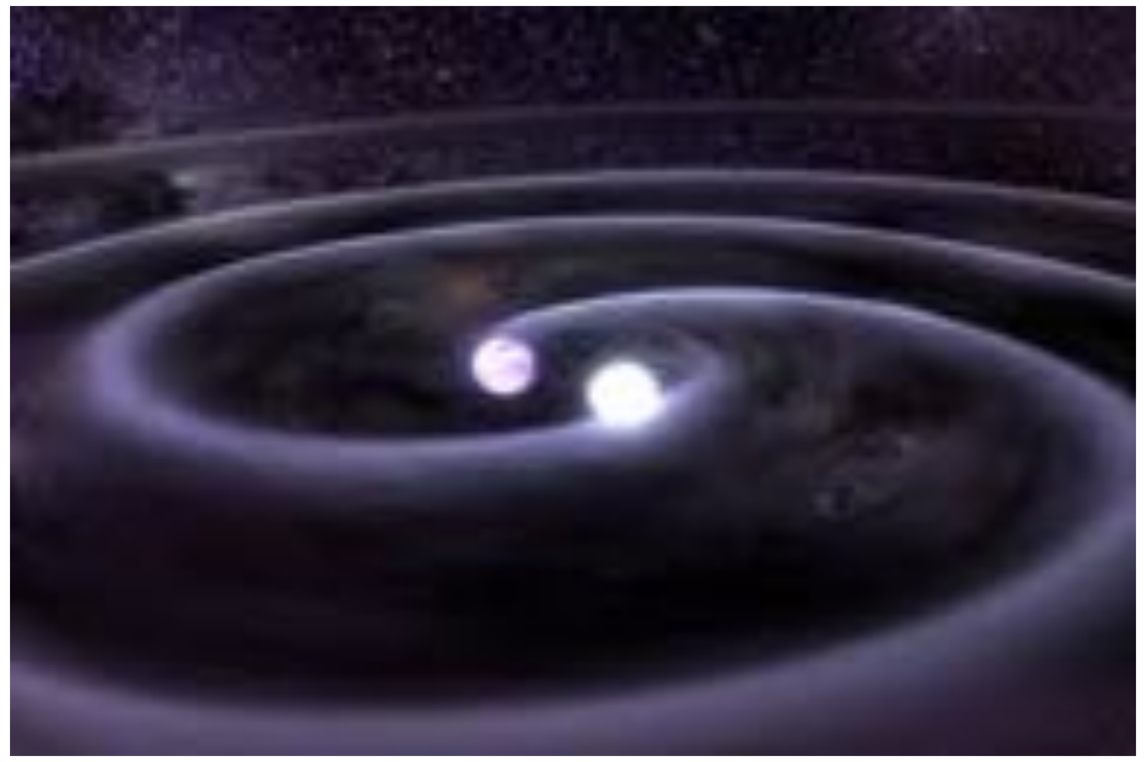


Massive Stars throughout the Cosmic History

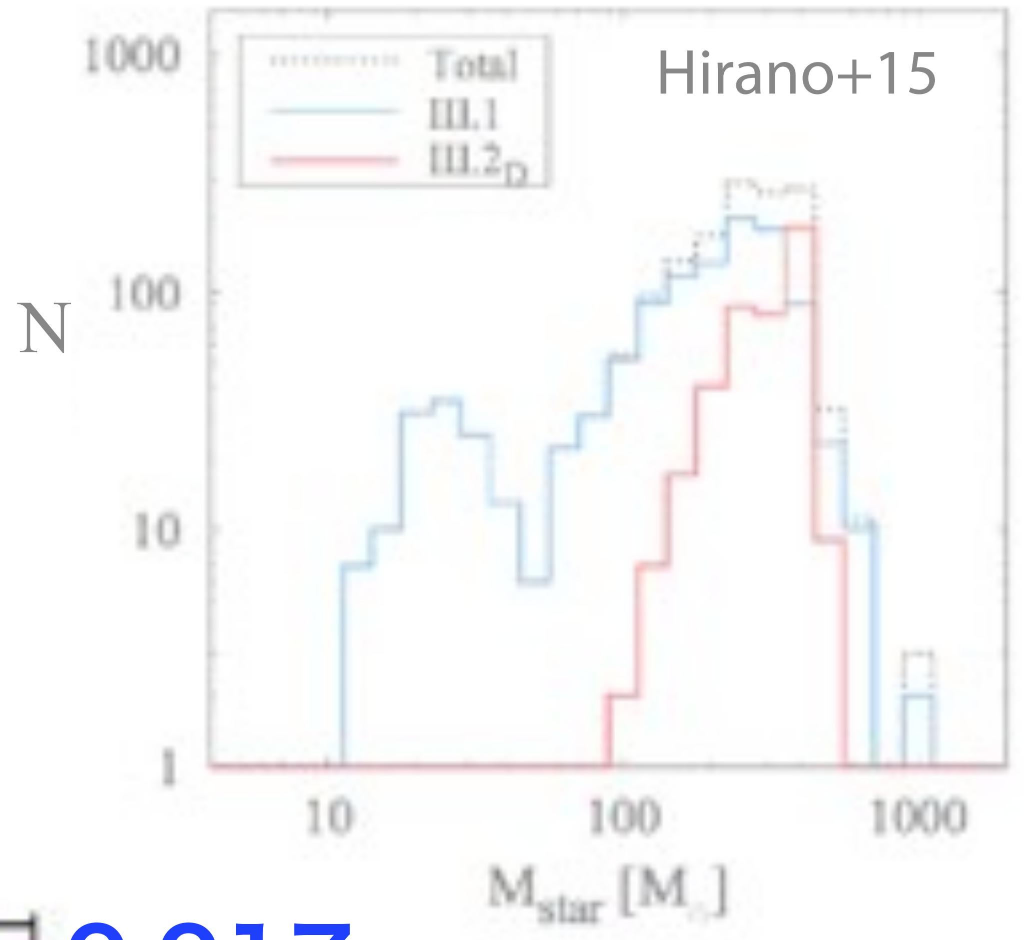
Massive stars are important
throughout the cosmic history
radiation, winds, SNe, metal & dust, GRBs, GW

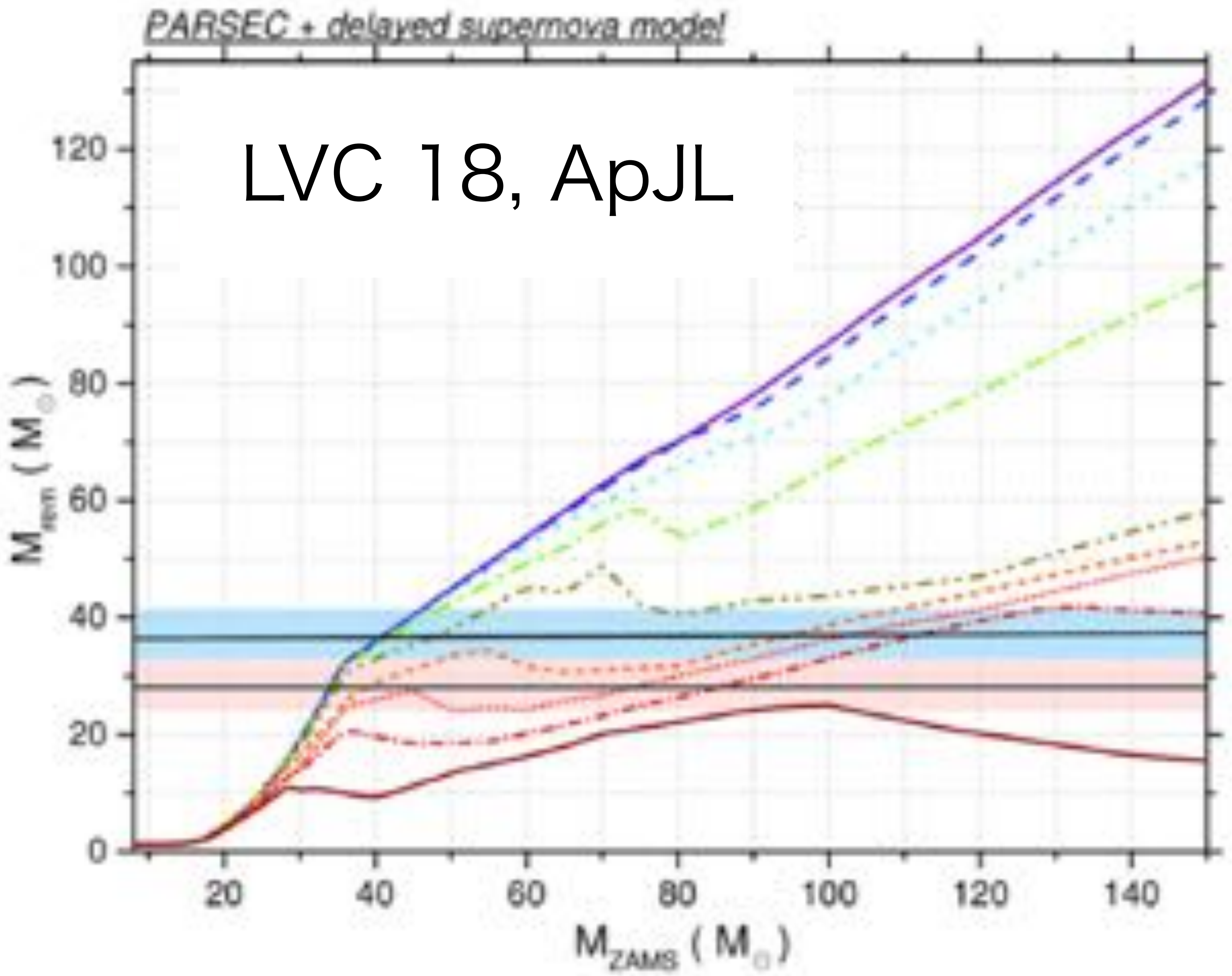
30 Dor &
R136a ~300M⊙

GW150914 ~ 36 + 29M⊙



First Stars~10-1000M⊙



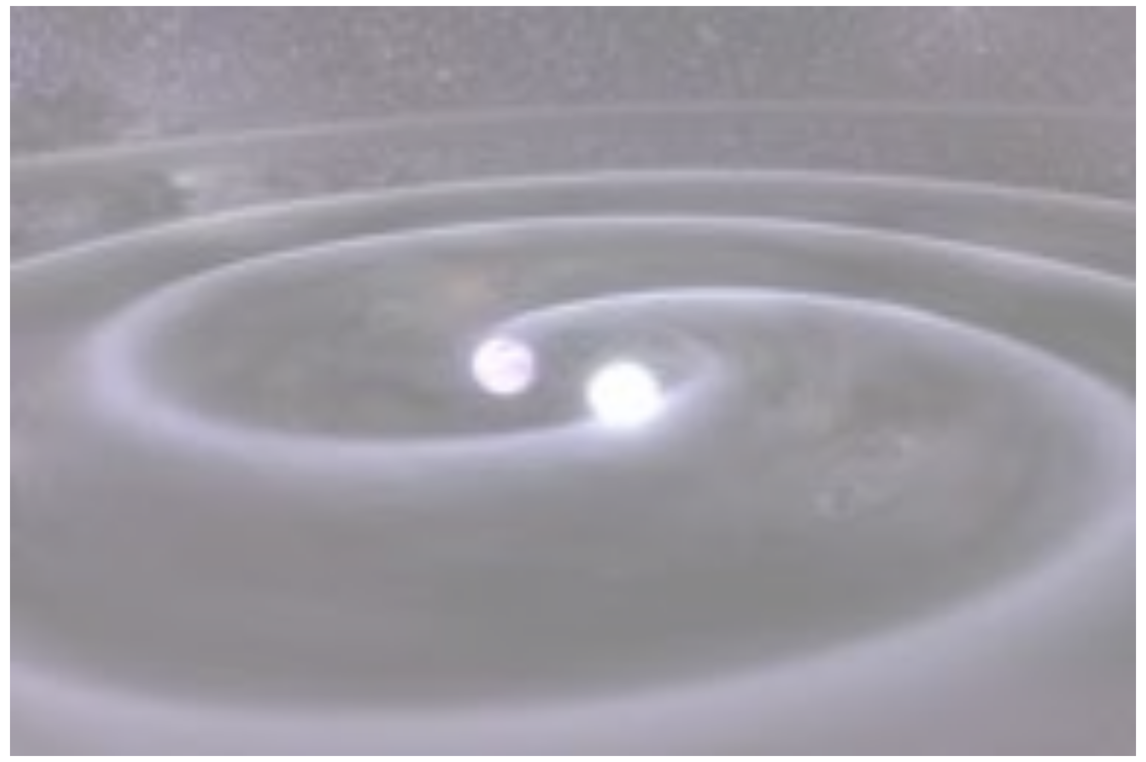


Massive Stars throughout the Cosmic History

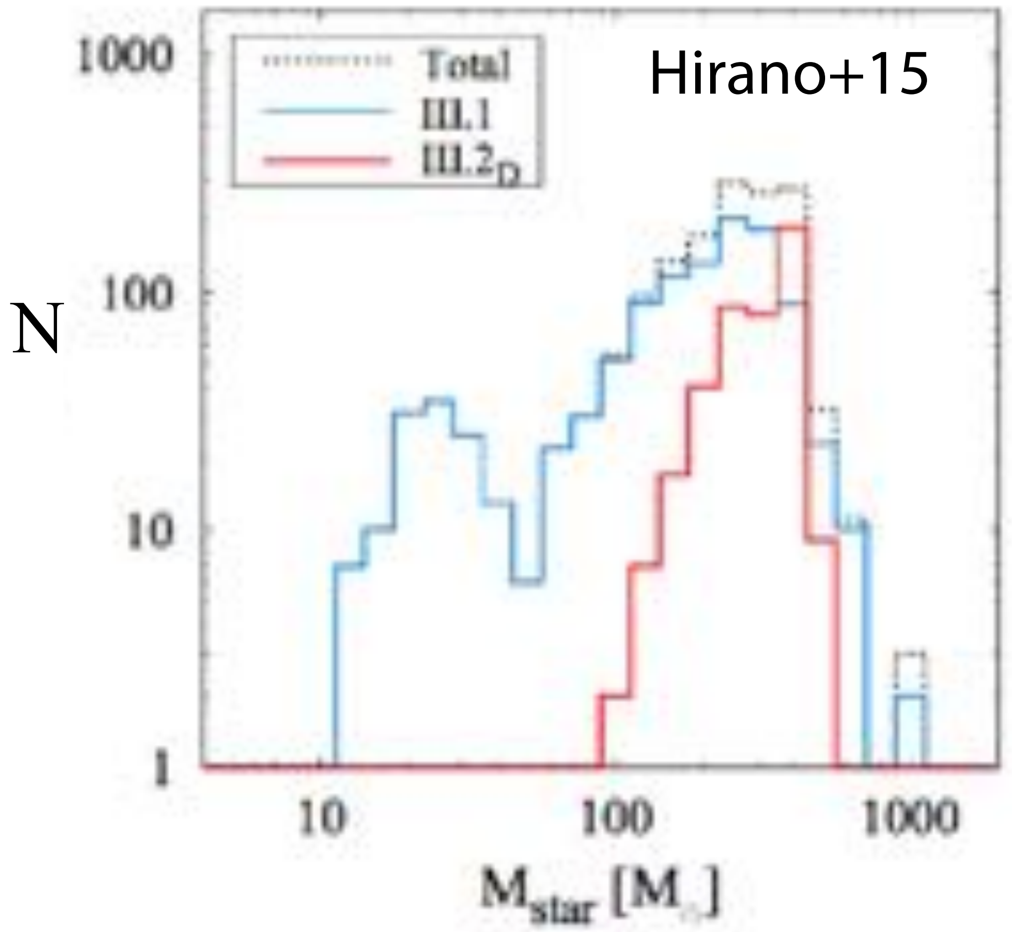
Massive stars are important
throughout the cosmic history
radiation, winds, SNe, metal & dust, GRBs, GW

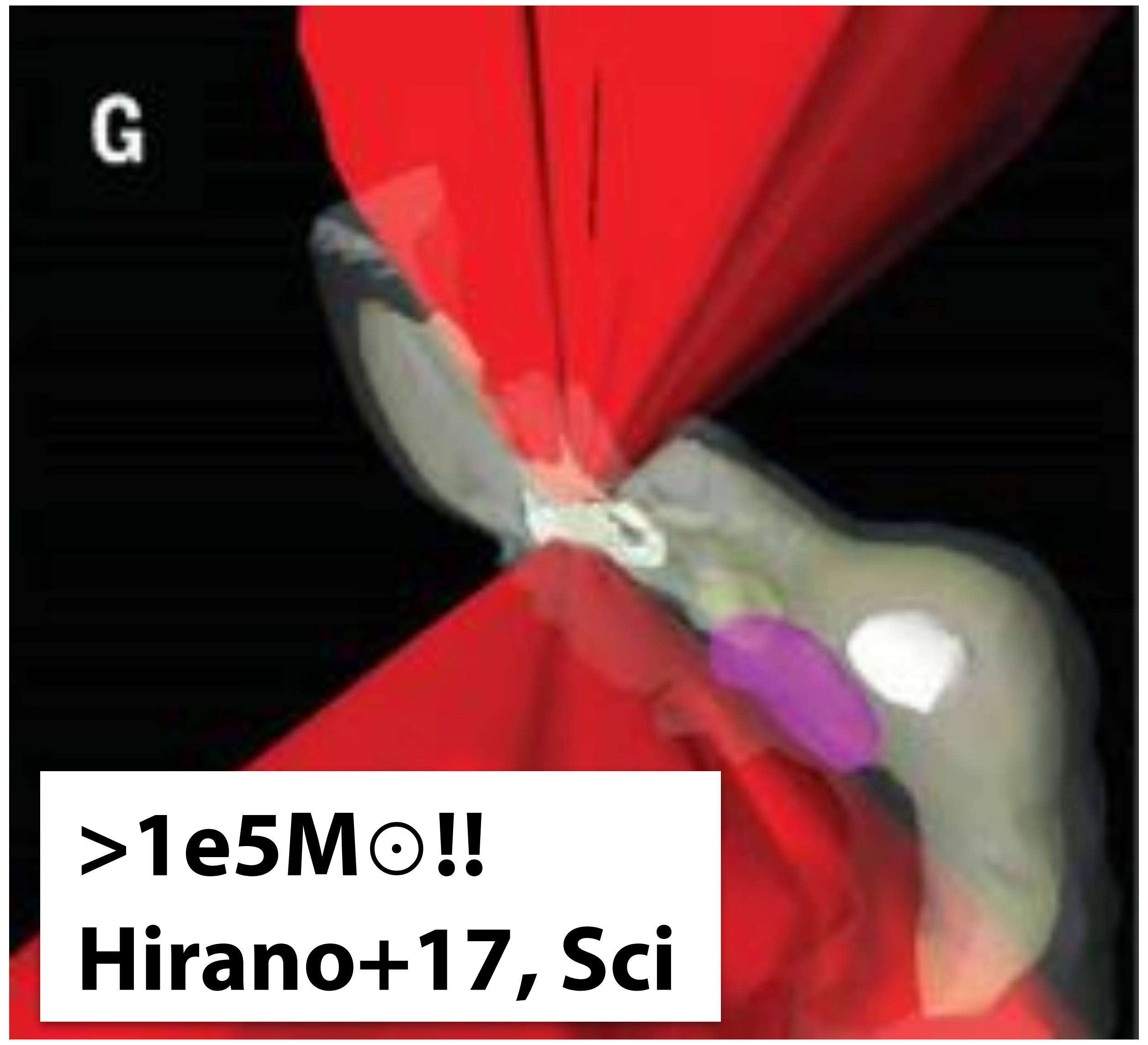
30 Dor &
R136a ~300M⊙

GW150914 ~ 36 + 29M⊙



First Stars~10-1000M⊙



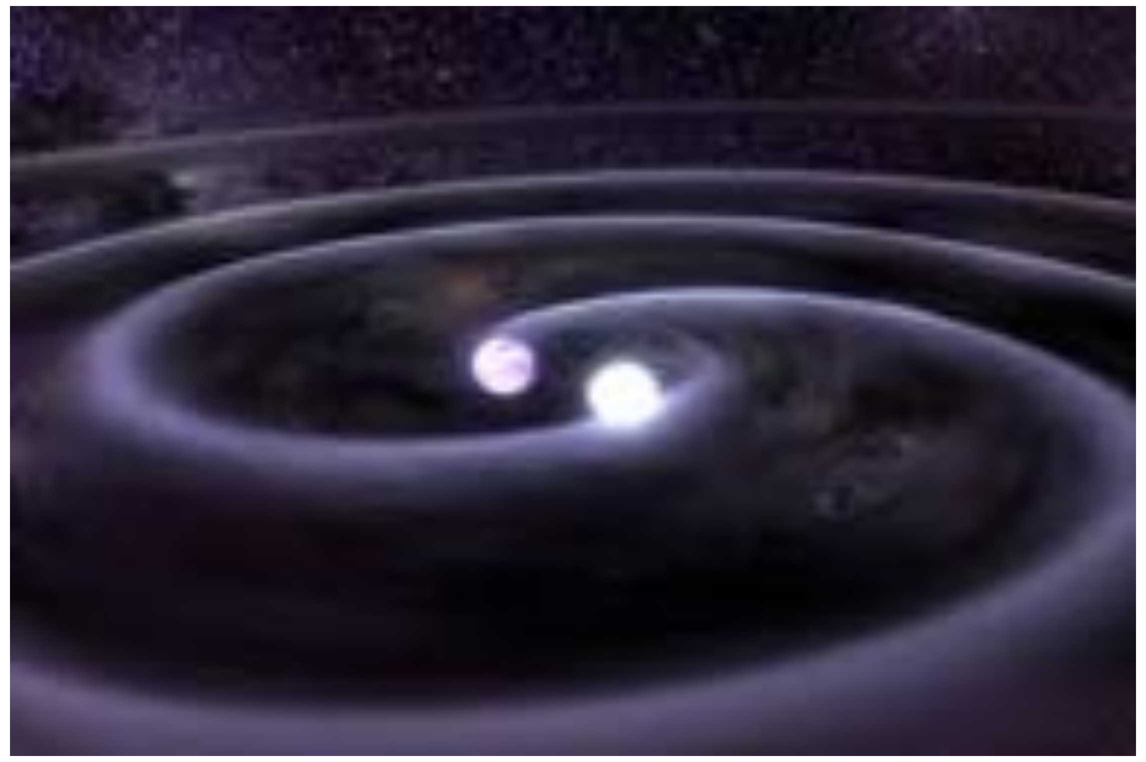


Massive Stars throughout the Cosmic History

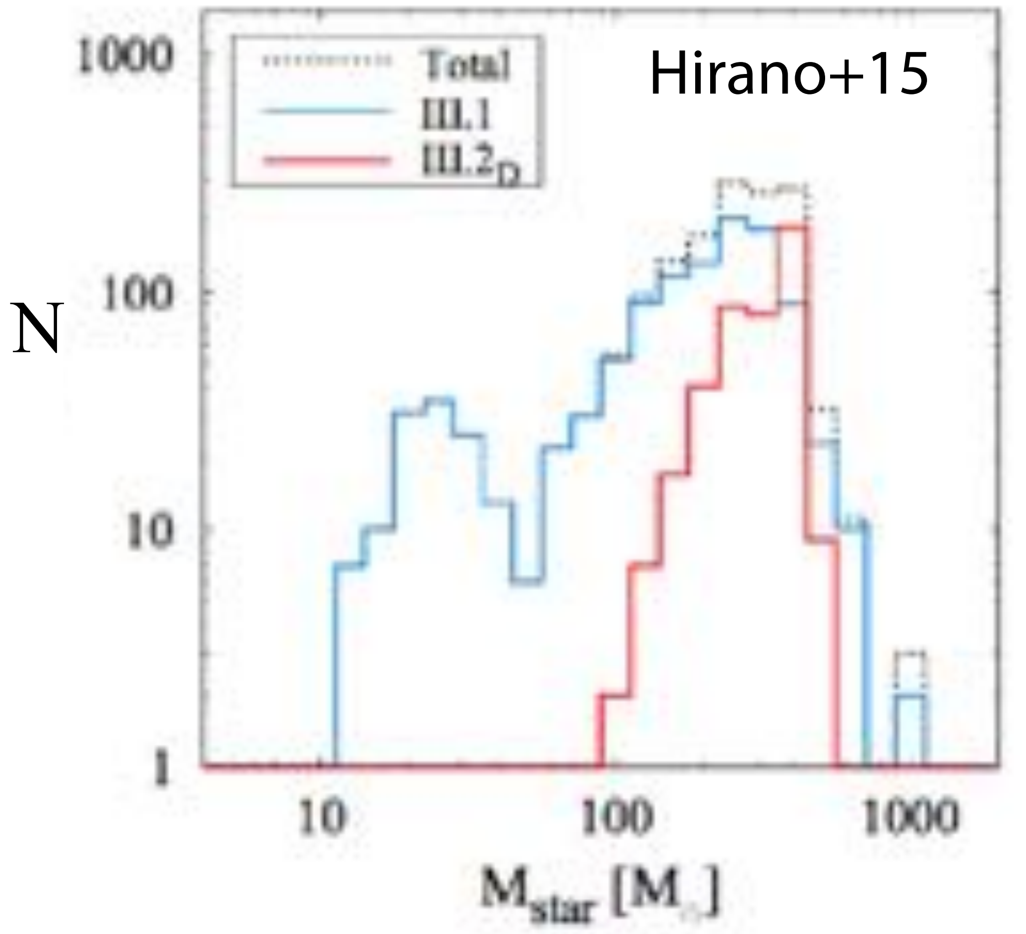
Massive stars are important
throughout the cosmic history
radiation, winds, SNe, metal & dust, GRBs, GW

30 Dor &
R136a ~300$M_\odot$

GW150914 ~ 36 + 29$M_\odot$



First Stars~10-1000$M_\odot$

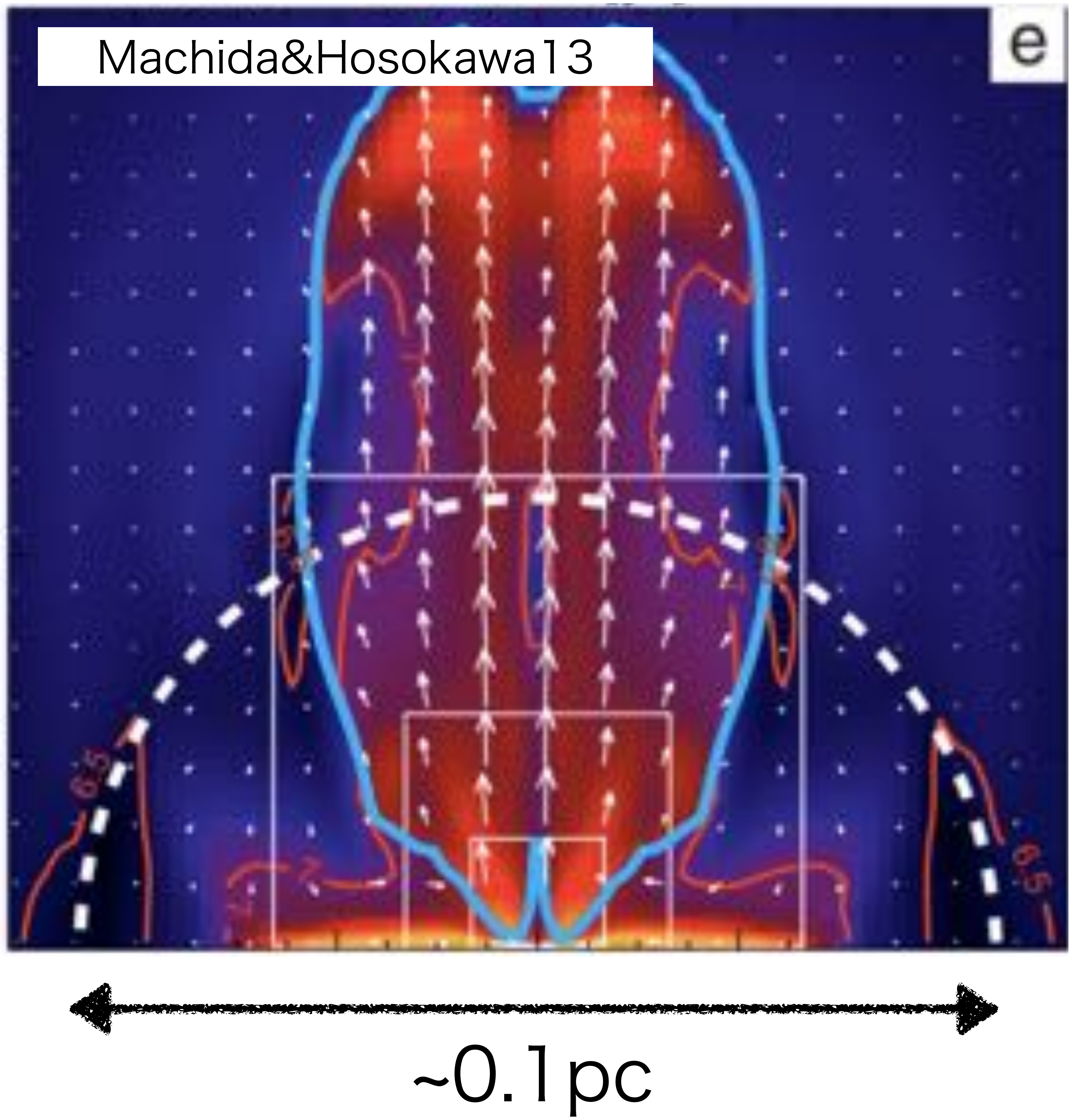


The key to connect the present & early Universe!!

We study the impact of *multiple feedback processes* in massive SF at *various metallicities*

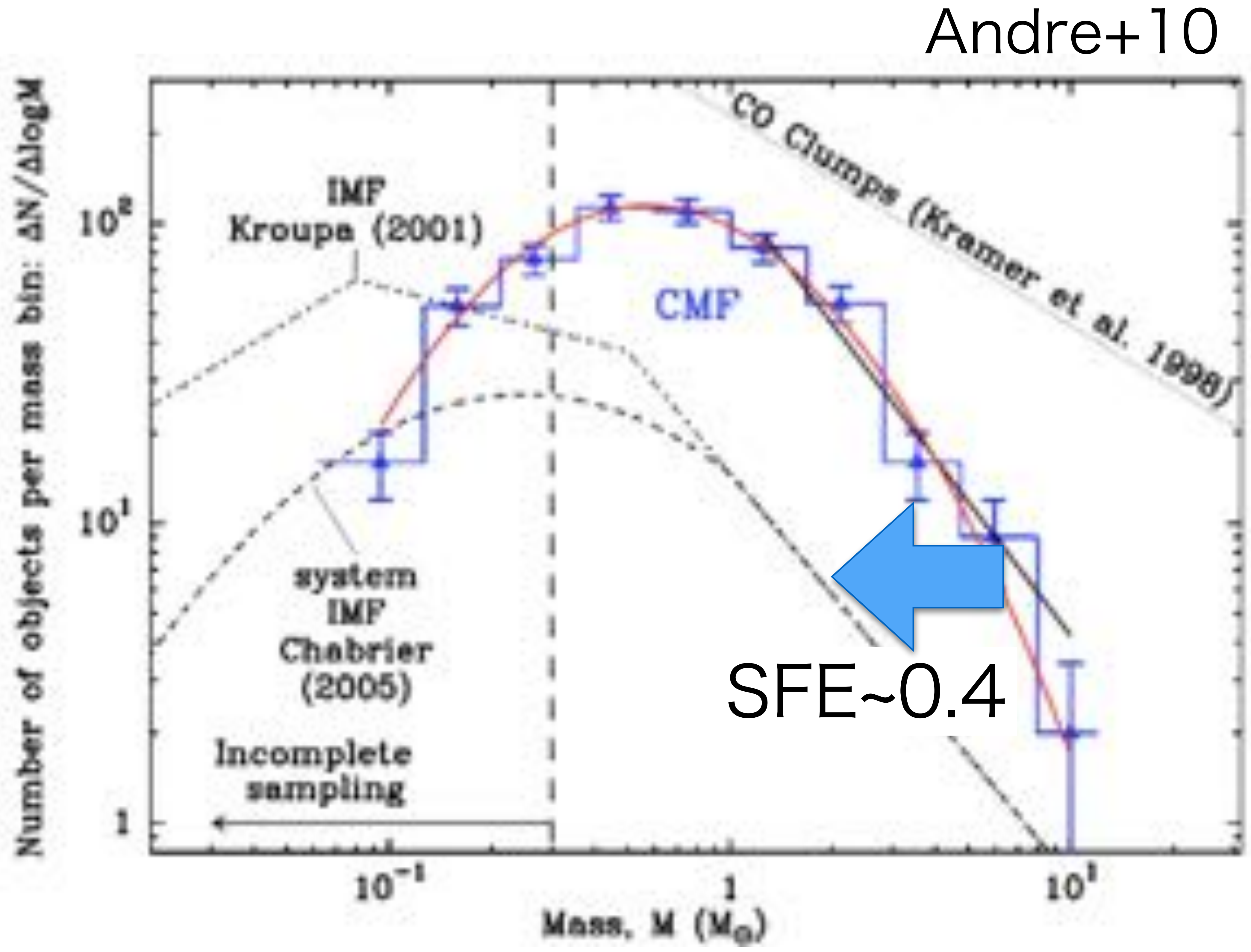
Feedback in Low-Mass Star Formation

SFE ~ 0.4



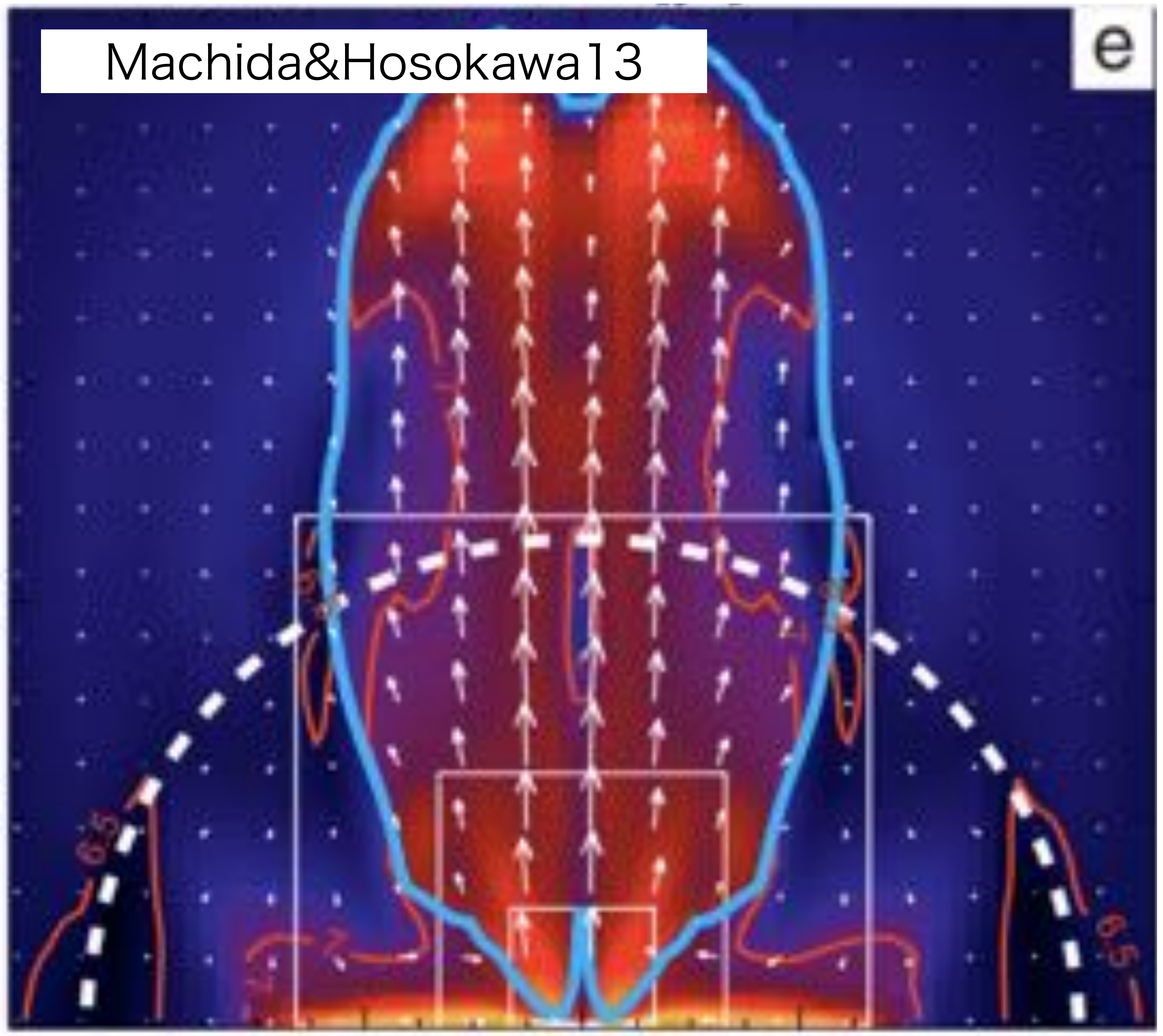
low-mass SF

MHD Disk Wind



Feedback in Low-Mass Star Formation

SFE ~ 0.4

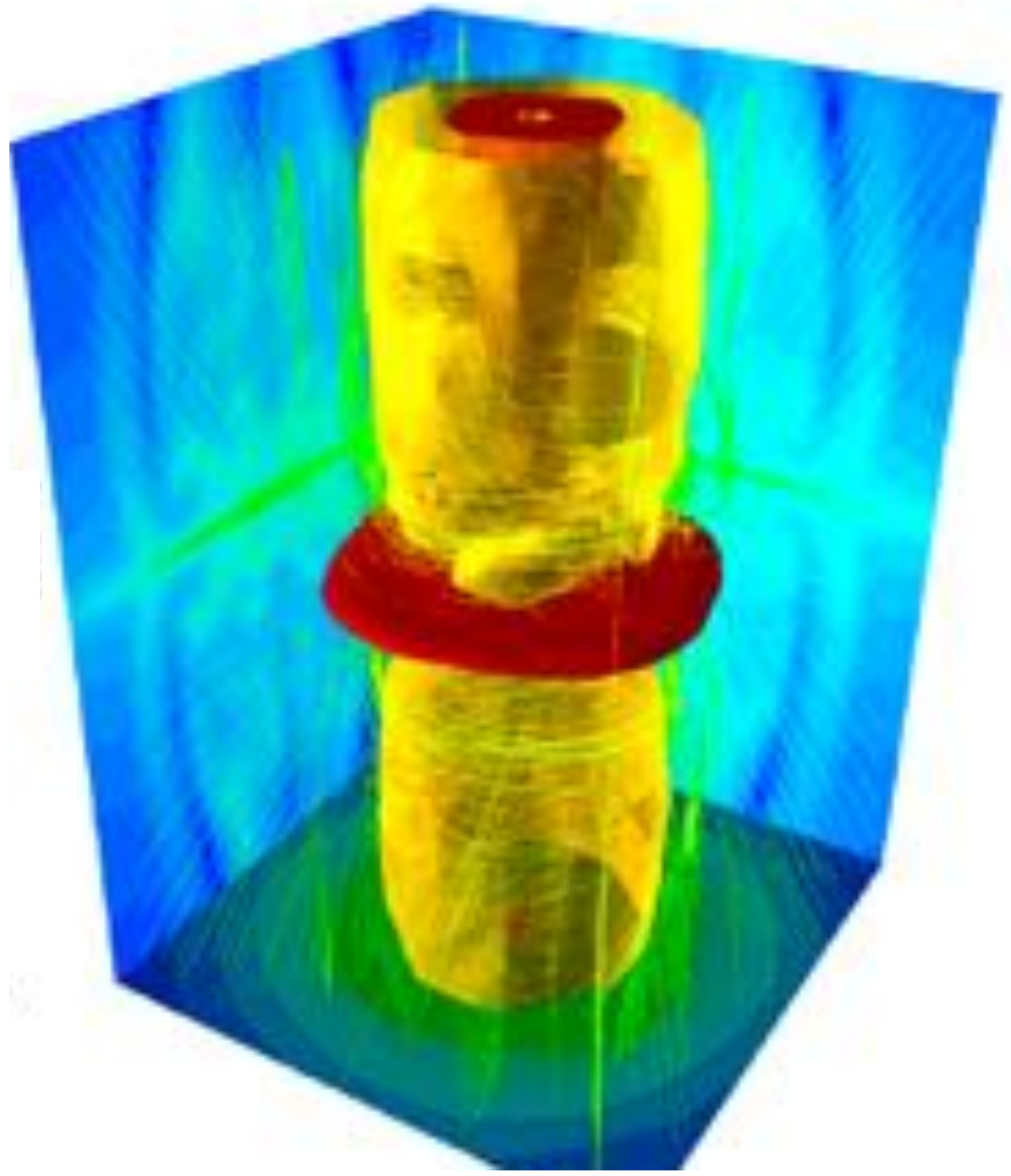


~0.1pc

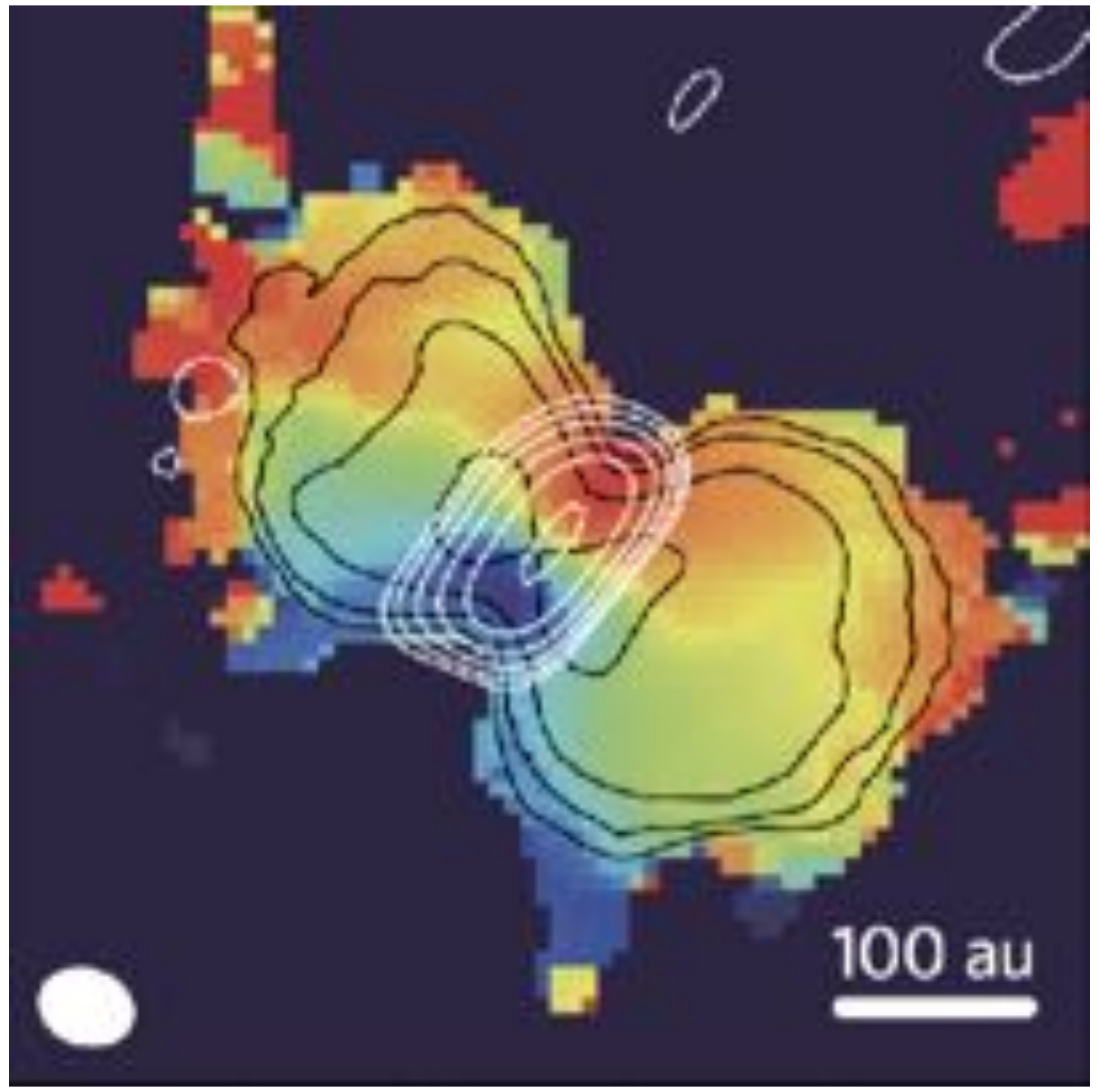
low-mass SF

MHD Disk Wind

also in massive SF!!



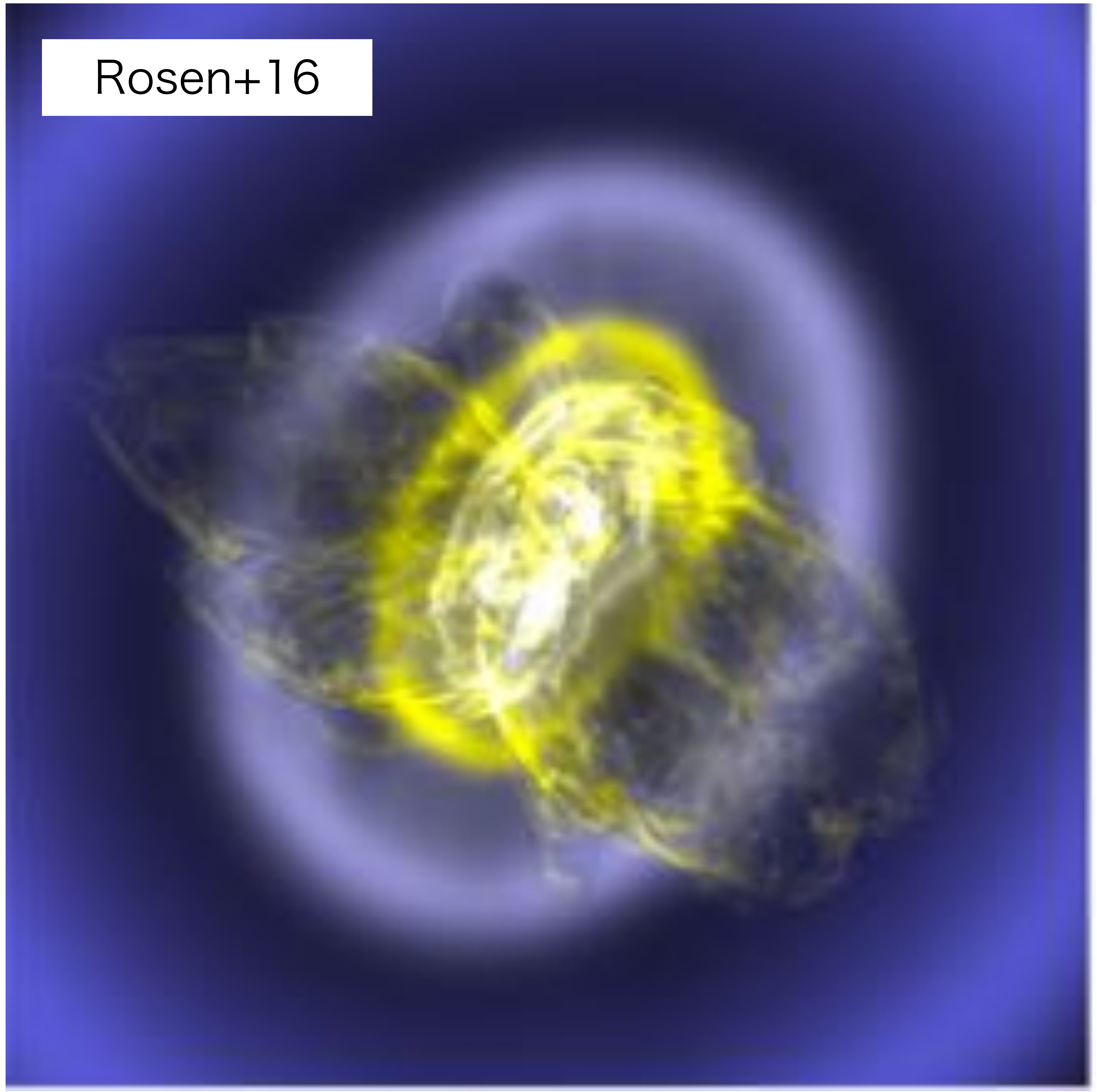
Matsushita+17



Hirota+17

Feedback in Massive Star Formation

M_{max}=40$M_\odot$ in spherical case



low-mass SF

MHD Disk Wind

also in massive SF!! KT+17, Matsushita+17

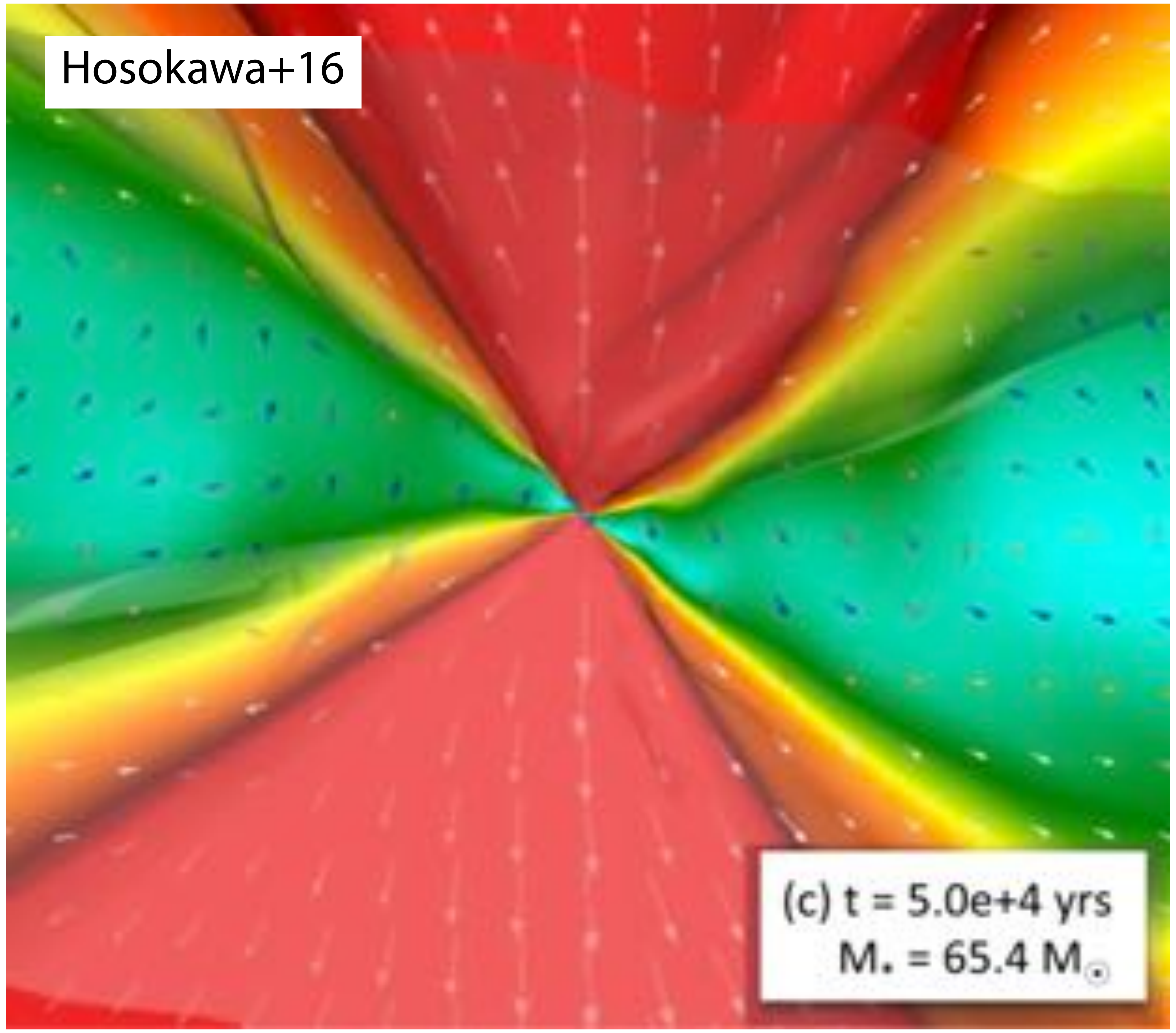
massive SF

Radiation Pressure

Krumholz+09, Kuiper+10, etc

Feedback in First Star Formation

typically ~50-100M⊙
from 1000M⊙ core



low-mass SF

MHD Disk Wind

also in massive SF!! KT+17, Matsushita+17

massive SF

Radiation Pressure

Krumholz+09, Kuiper+10, etc

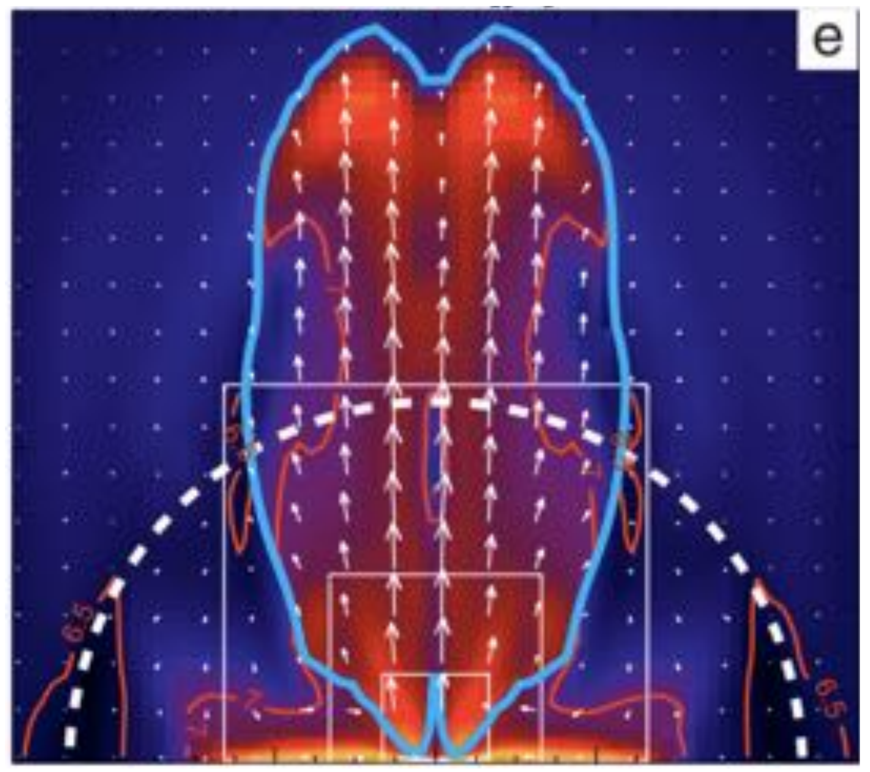
First SF in the early universe

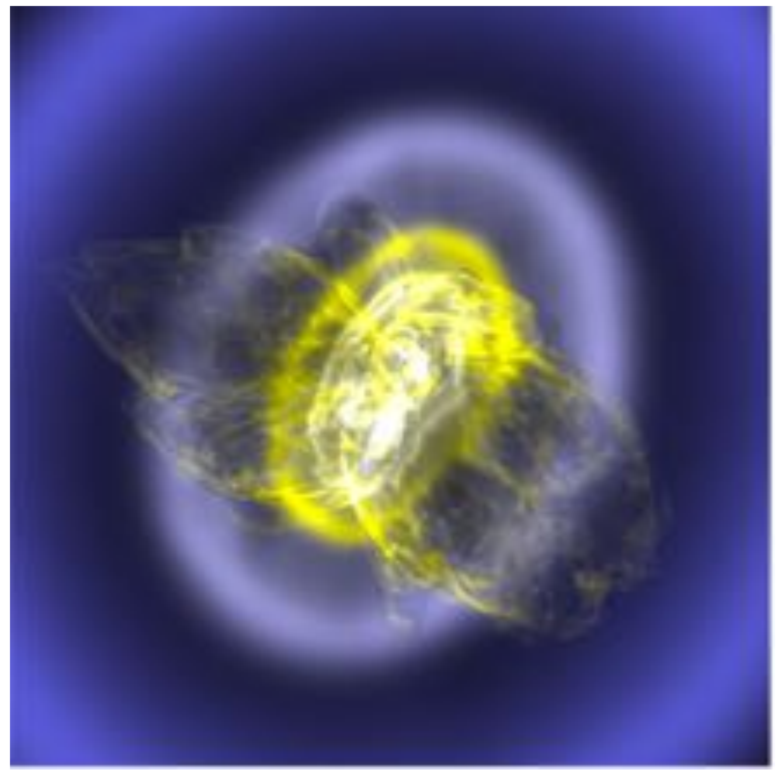
Photoevaporation

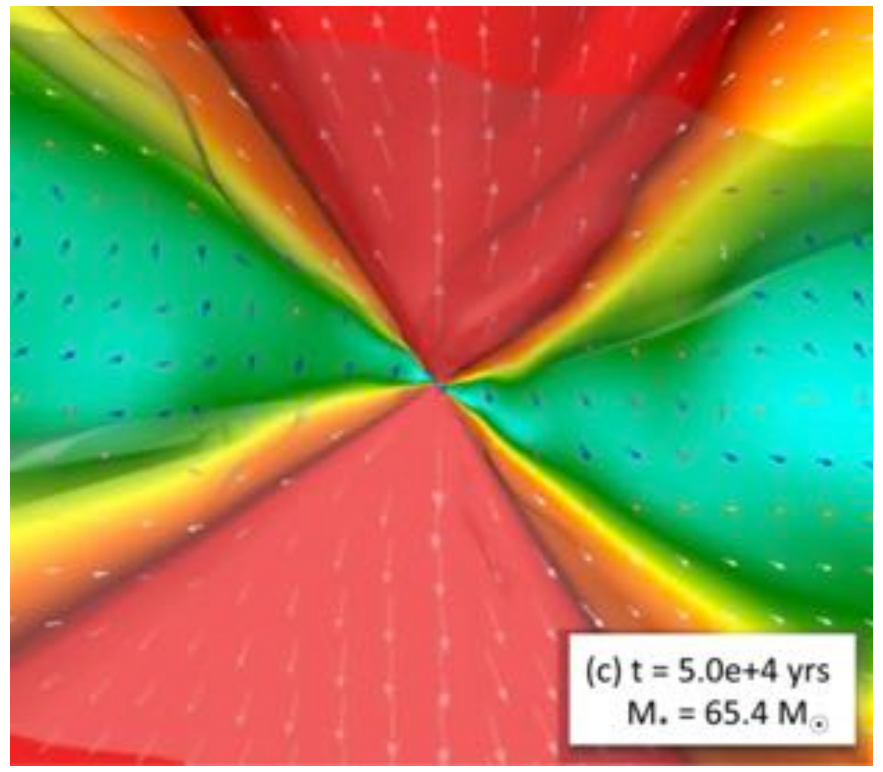
McKee&Tan08, Hosokawa+11, etc

Multiple Feedback in Massive SF

Those processes were studied separately, but
all feedback acts together in reality







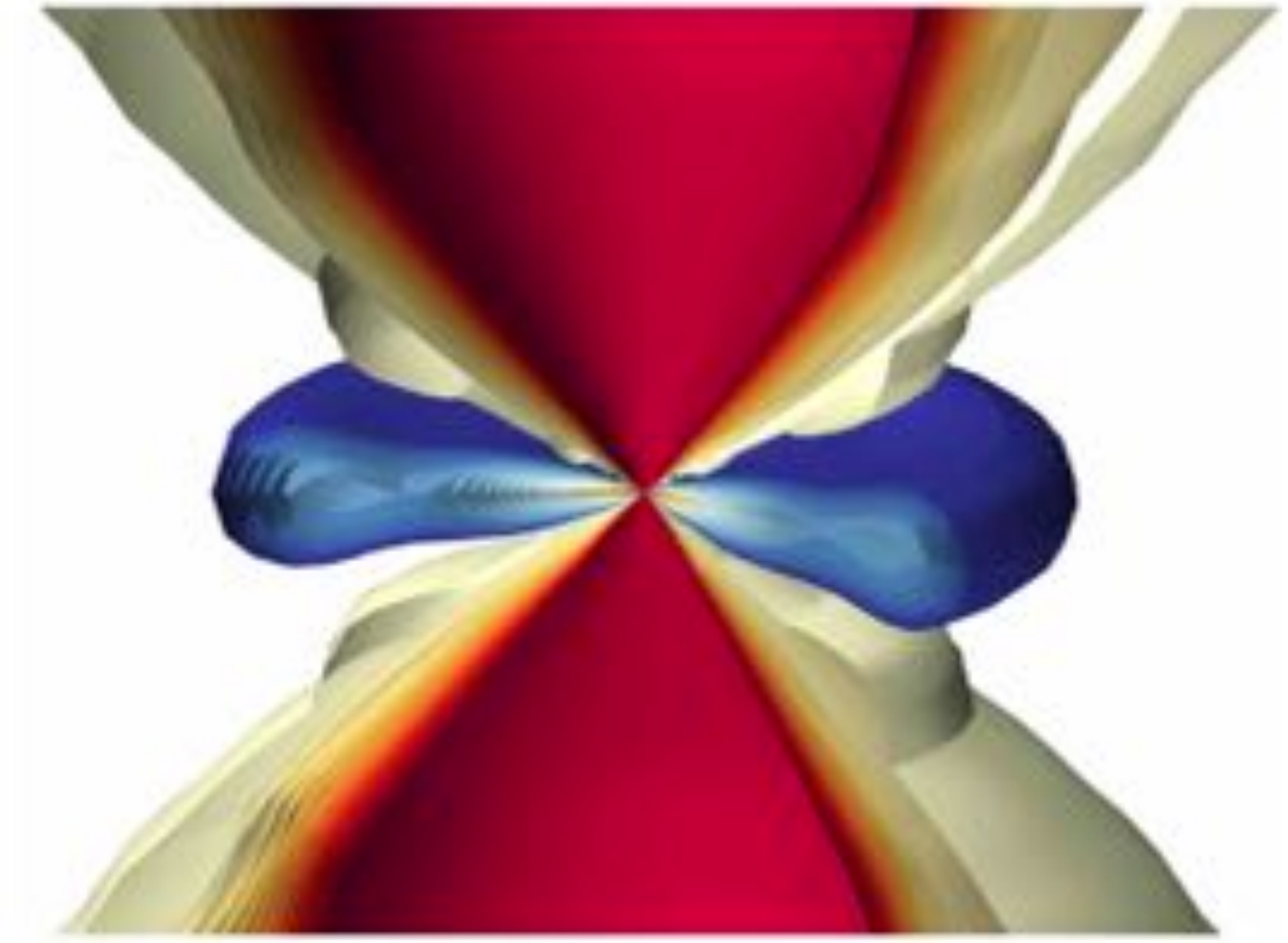
low-mass SF
MHD Disk Wind

massive SF
Radiation Pressure + Stellar Wind

First SF
Photoevaporation

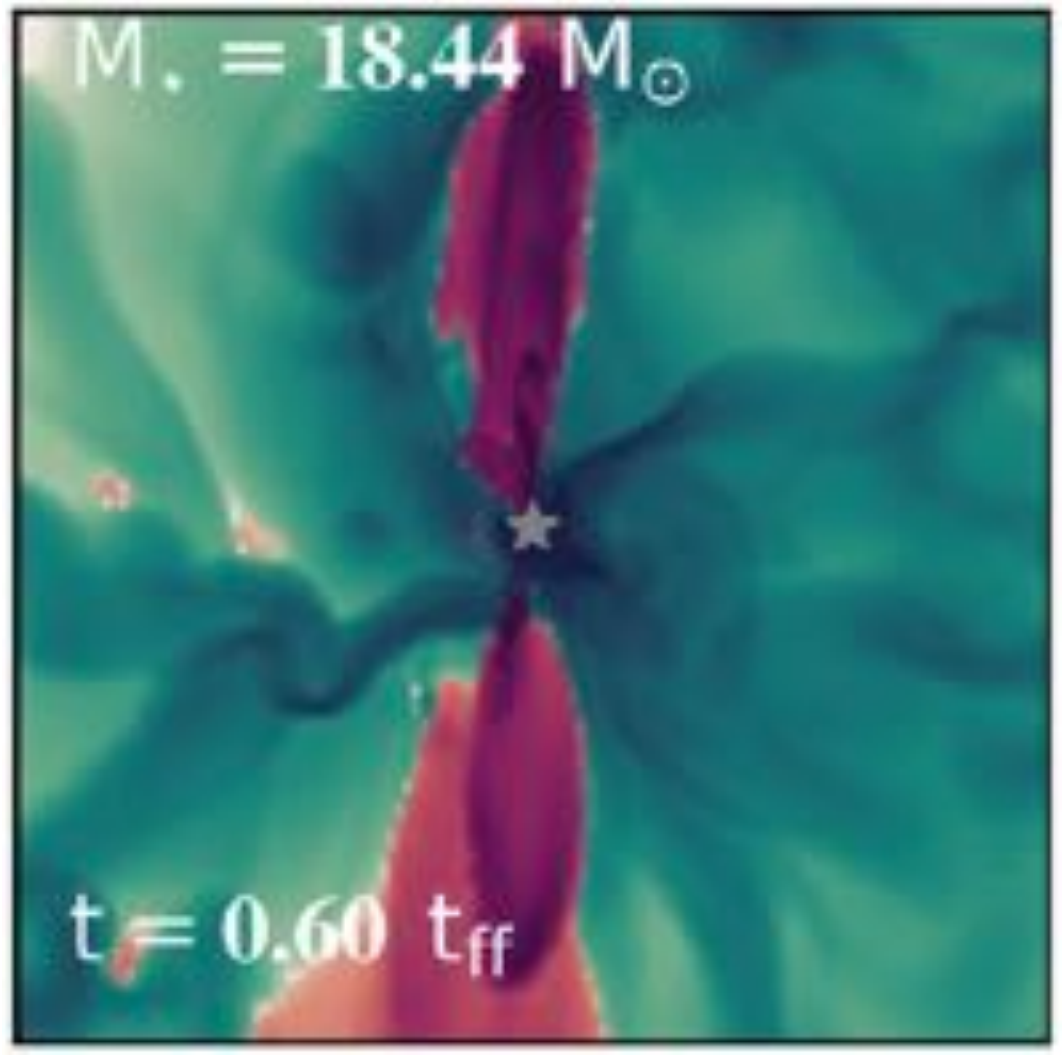
How do all feedback mechanisms work together?
Which is the dominant feedback?
Does feedback set the upper mass limit? or shape IMF?

Multiple Feedback in Massive SF



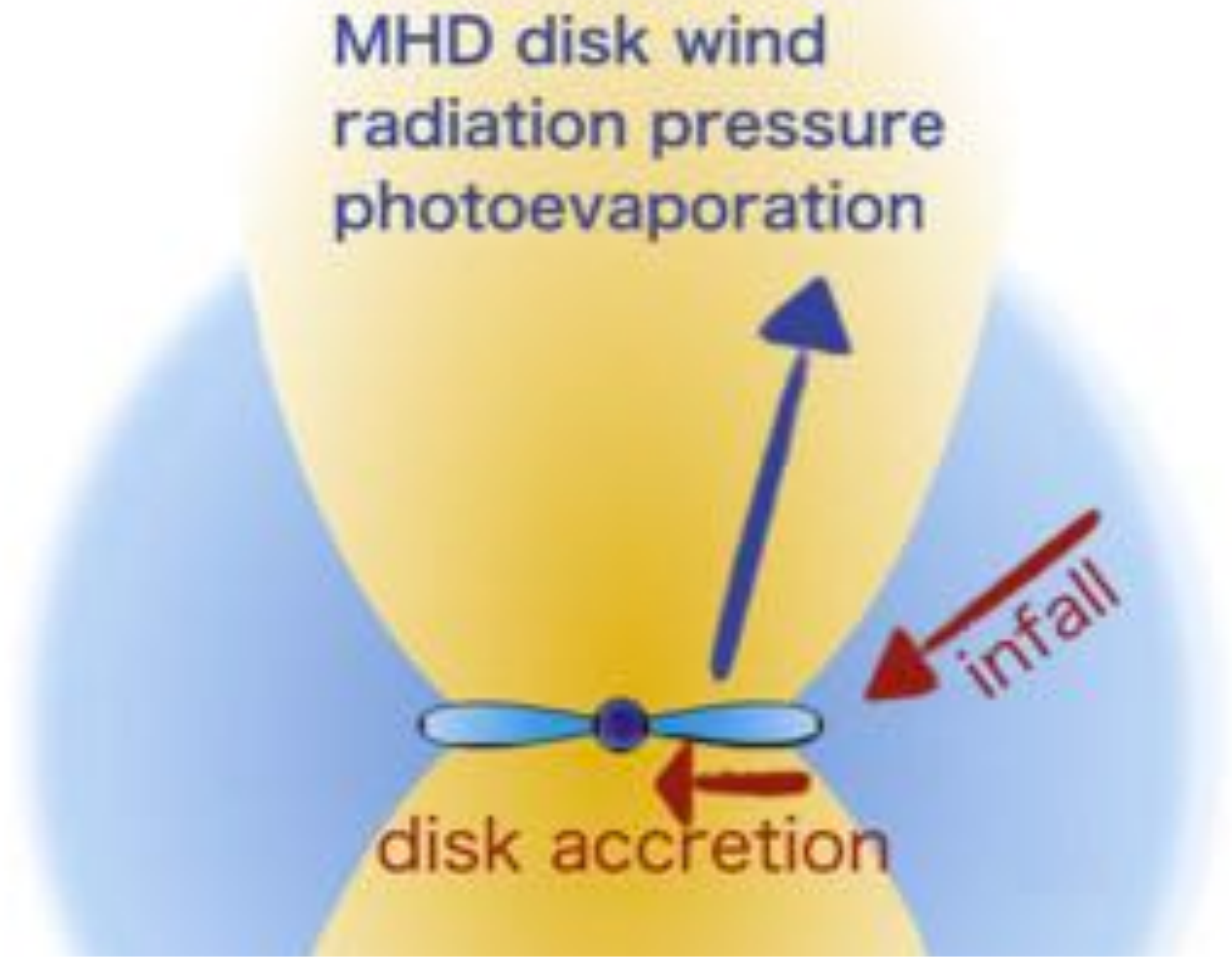
Rolf did!!

Kuiper & Hosokawa, accepted by A&A



Anna also!!

Rosen+, in prep.



Us too!!

KT+17,18, ApJ

How do all feedback mechanisms work together?

Which is the dominant feedback?

Does feedback set the upper mass limit? or shape IMF?

How do they depend on metallicity and clump density?

Model

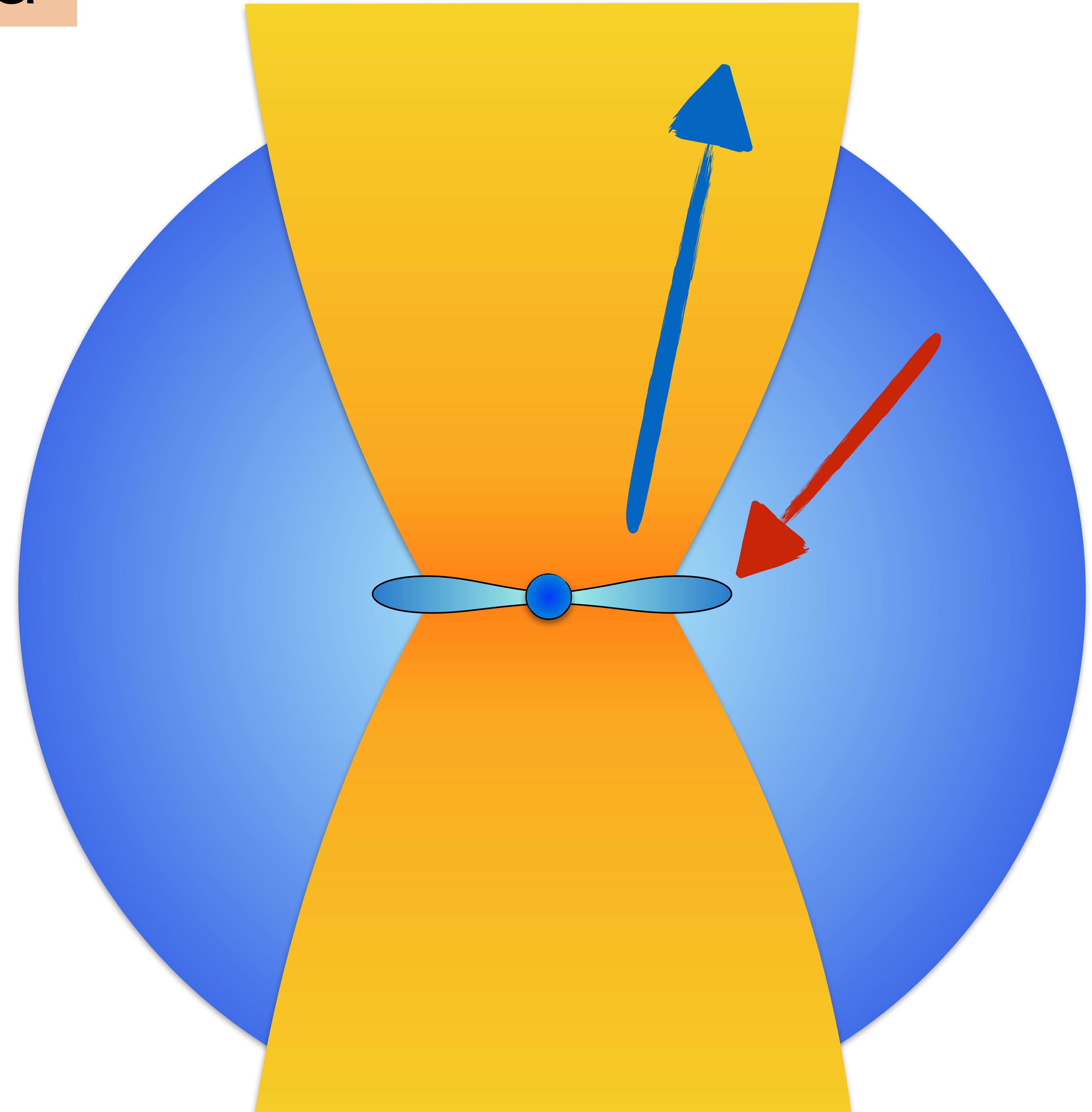
Overview of Our Semi-Analytic Model

core collapse
+ disk form. + MHD wind + photo-evap.
+ star evol. + rad press. + stellar wind

acc. rate: $\dot{m}_* = \dot{M}_{\rm env}\cos\theta_{\rm esc} - \dot{m}_{\rm dw} - \dot{m}_{\rm pe} - \dot{m}_{\rm sw}$

Pre-stellar cloud core

M_c = 10 - 1000 $M_\odot$
Σ_{cl} = 0.1 - 3 g/cm^2 ← **Infrared Dark Clouds**
Z = 1e-5 - 1 $Z_\odot$



We solve the evolution of protostars,
accretion flow structures,
and feedback processes self-consistently
until the end of accretion (mdot=0)

and evaluate SFEs from initial cores

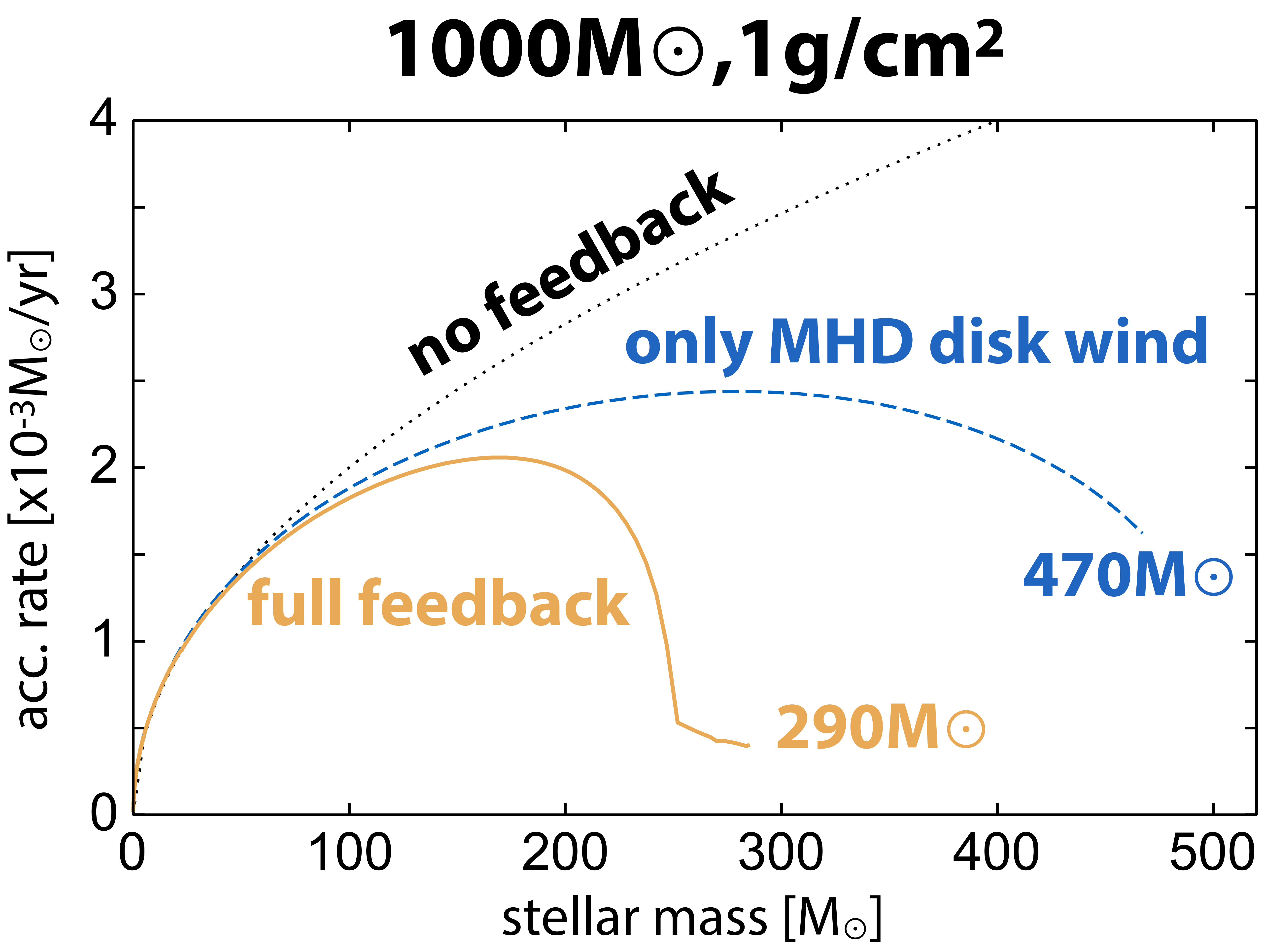
The dominant feedback?
The upper-mass limit by feedback?
The metallicity dependence?

Impact of Multiple Feedback

at $Z_\odot$

KT, Tan, & Zhang, 2017, ApJ, 835, 32

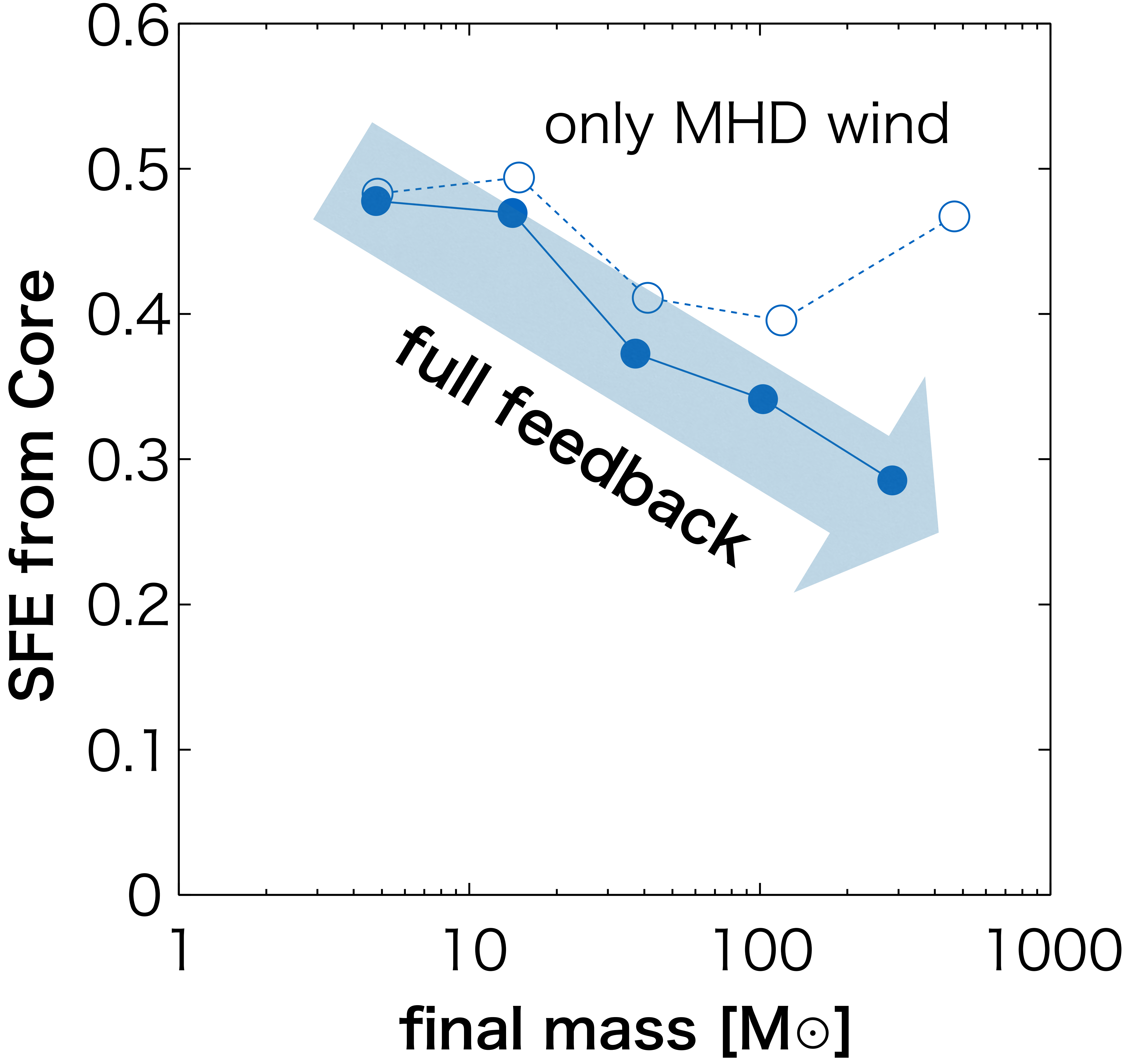
Accretion History



Radiation feedback reduces SFE

SFE=0.47→0.29 in this case

Star Formation Efficiencies



lower SFE in higher-mass SF

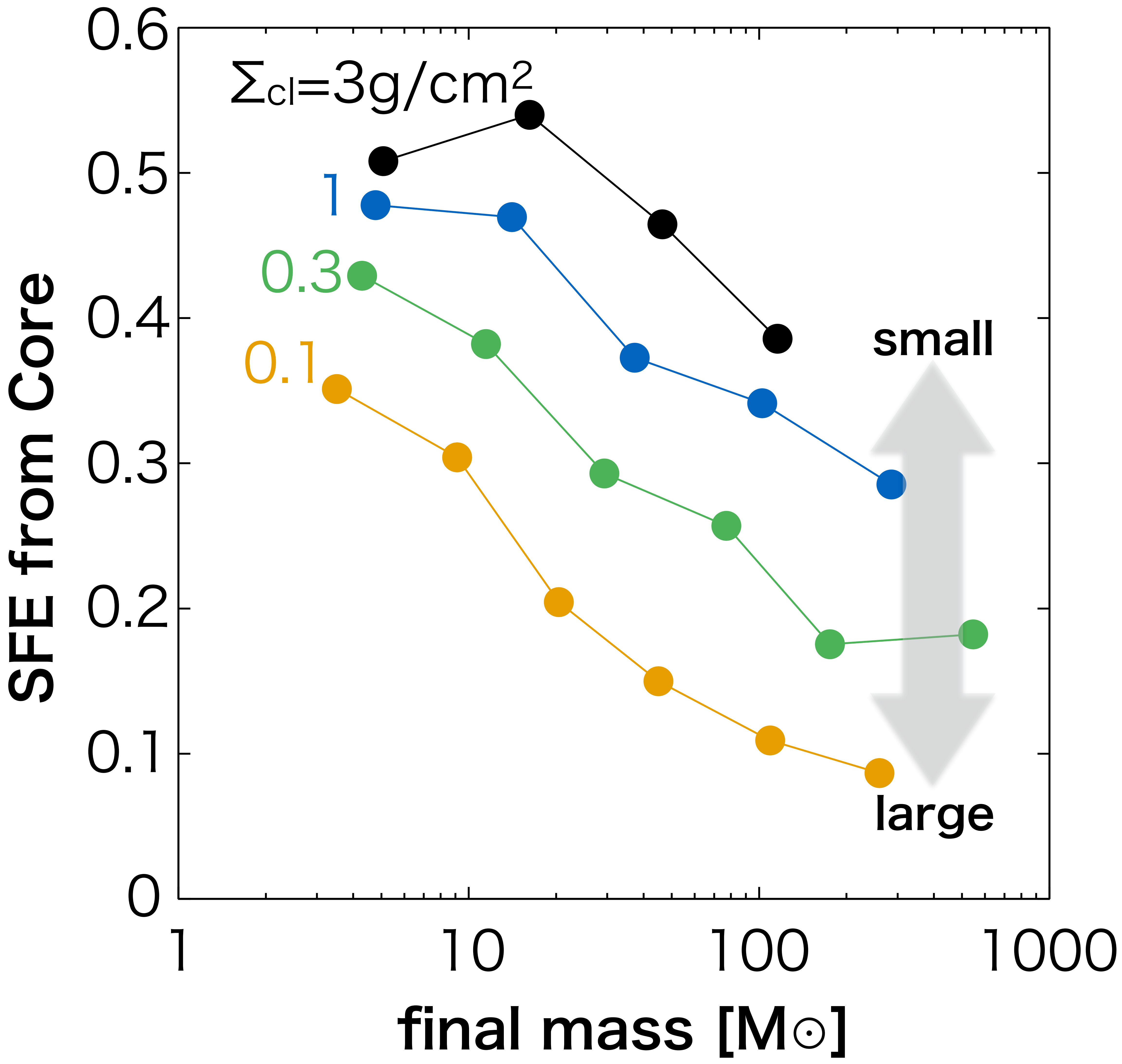
due to radiative feedback

No upper limit by feedback

Unlike models with a truncation at100M⊙

cf. stars with >100M⊙ in 30 Dor

Star Formation Efficiencies



lower SFE in higher-mass SF

due to radiative feedback

No upper limit by feedback

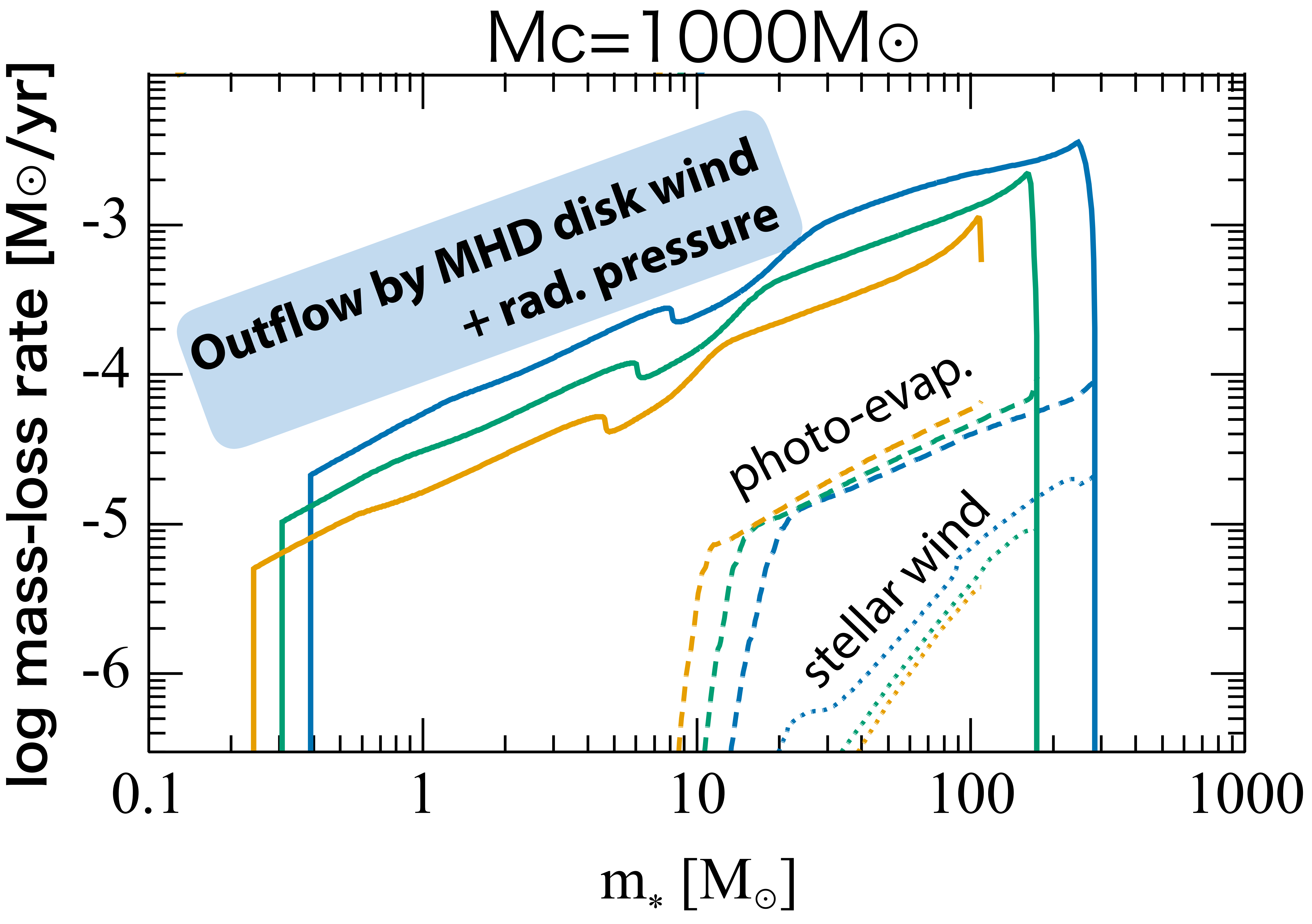
Unlike models with a truncation at100M⊙

cf. stars with >100M⊙ in 30 Dor

lower SFE at larger core

recall Rolf Kuiper's talk!

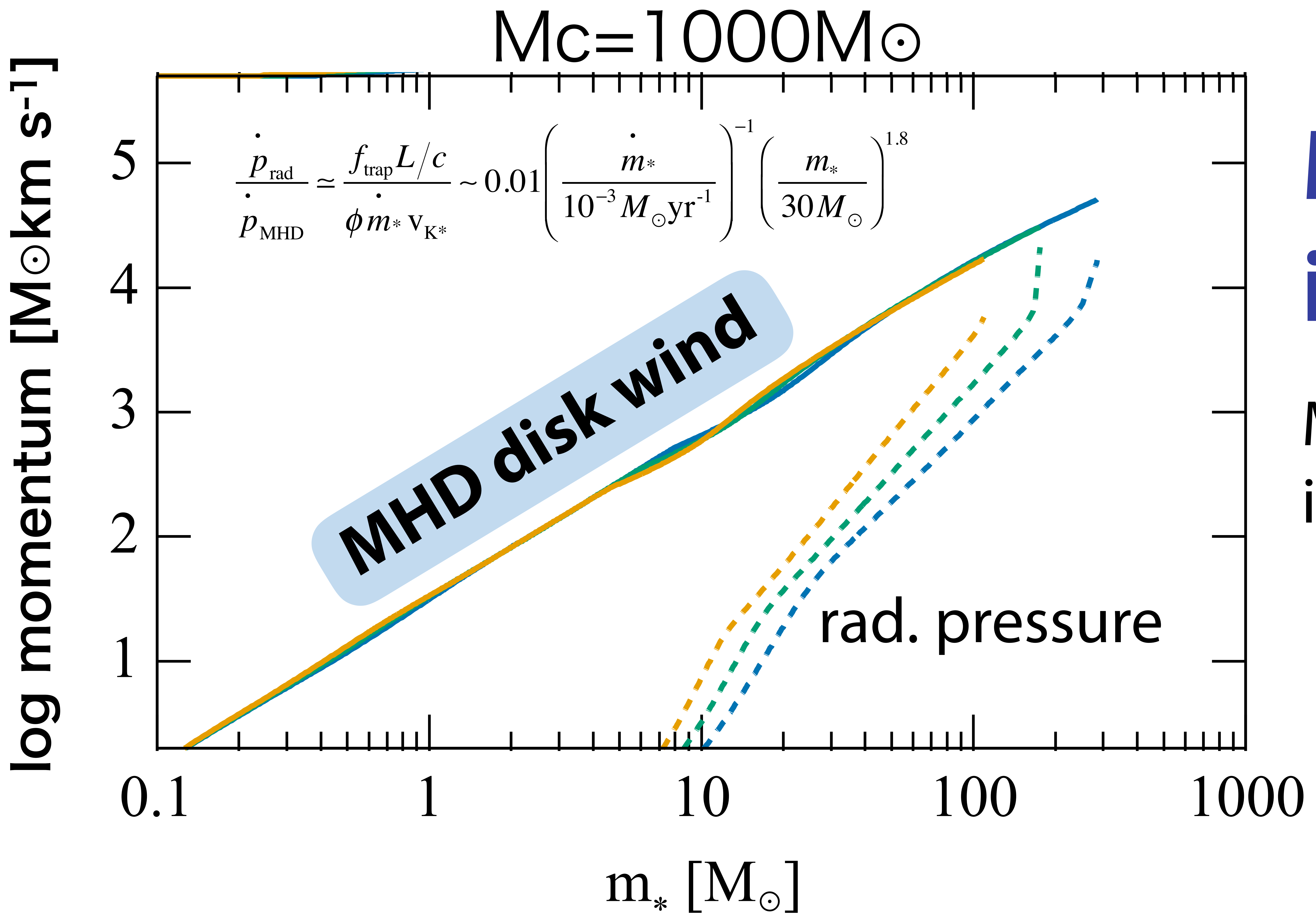
Which is the dominant feedback?



Momentum-driven outflow is dominant

MHD disk wind?
or
Radiation pressure?

Which is the dominant feedback?



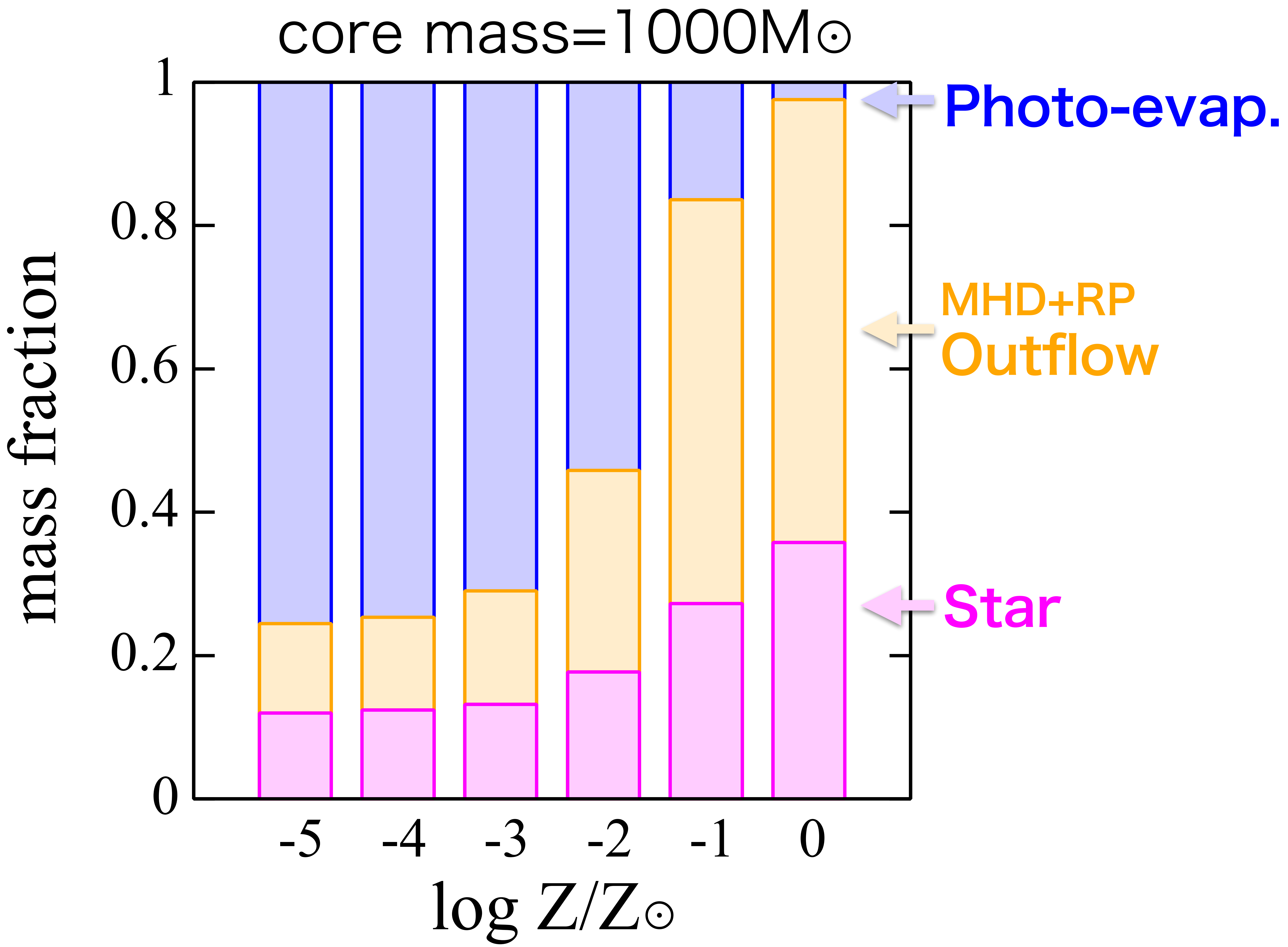
MHD disk wind is dominant!!

Massive star formation is similar to low-mass SF.

Metallicity Dependence

KT, Tan, Zhang, & Hosokawa, 2018, ApJ, 861, 68

Feedback at Low Metallicities



At Z⊙,
Outflow is strongest

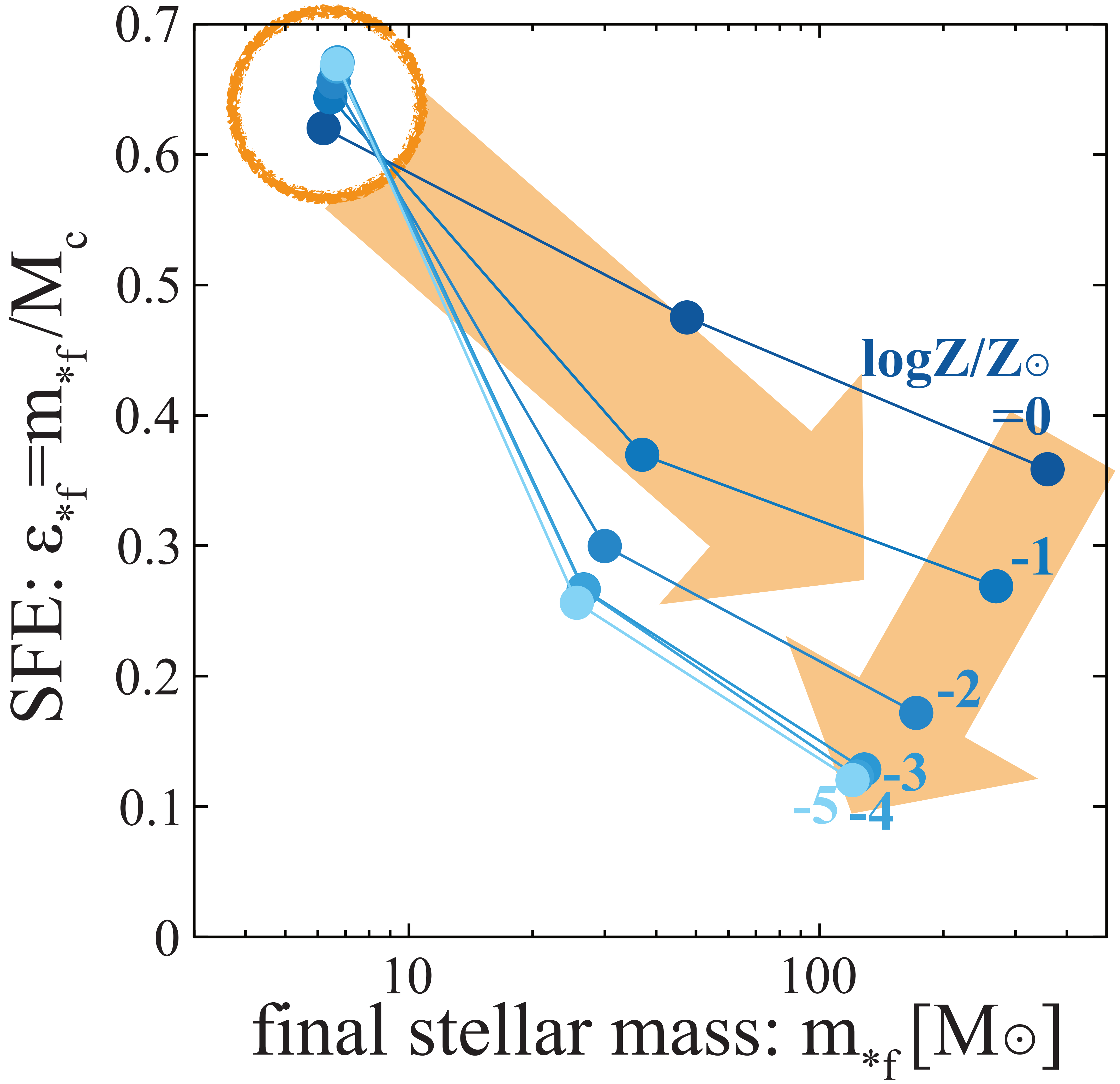
At <0.01Z⊙,
PE becomes dominant

Dust attenuation regulates PE rate

$$\dot{M}_{\rm evp} \sim \frac{\dot{M}_{\rm evp,Z=0}}{1+\tau_d}$$

$\tau_d \ll 1$ at Z<1e-3Z⊙

SFEs at Various Metallicities



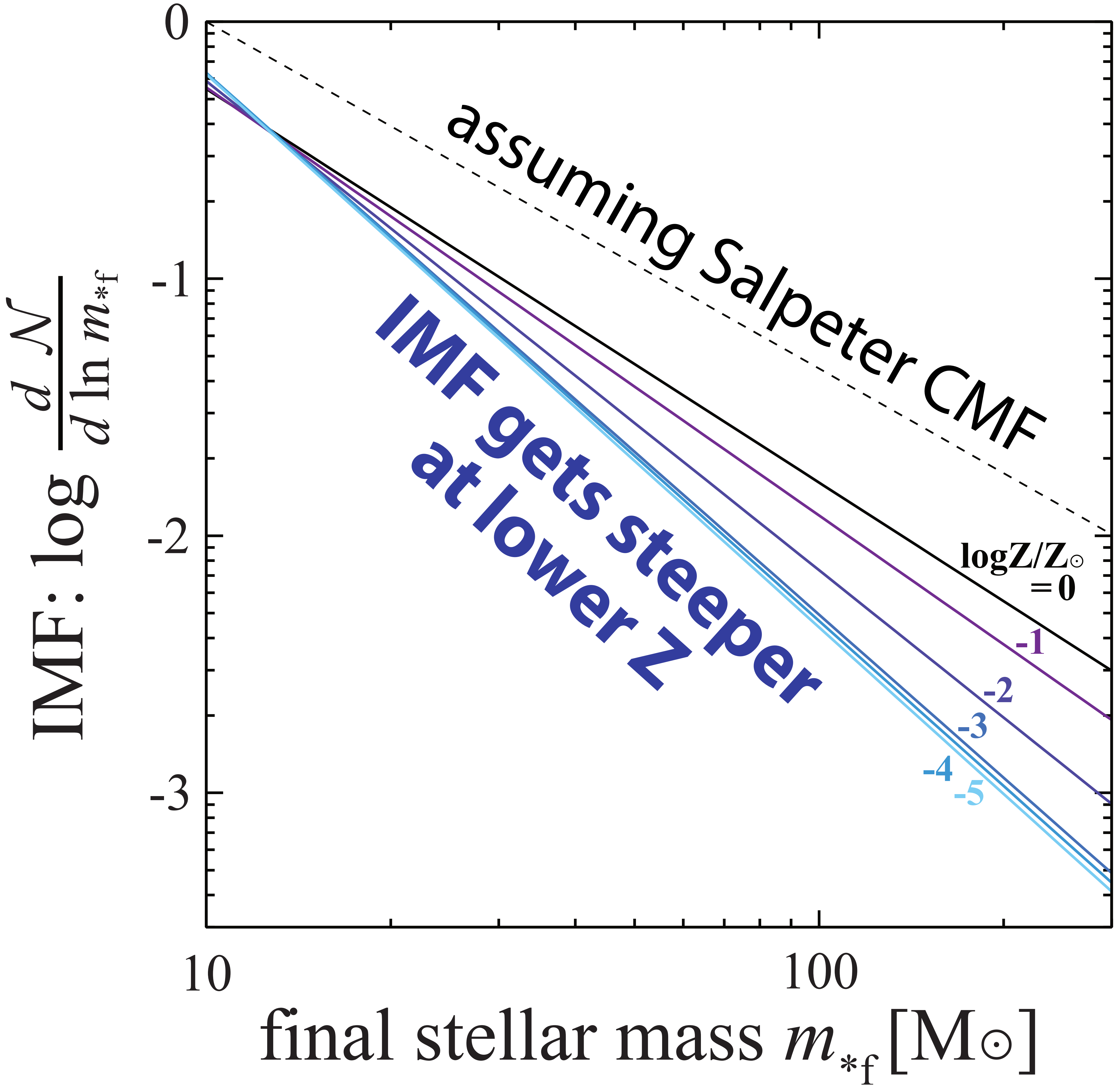
Feedback does not set the upper-mass limit!

lower SFE in higher-mass SF
due to stronger feedback

lower SFE at lower Z
due to efficient photo-evap.

Non-Universal IMF?

IMF = CMF x SFE



At sol to sub-sol metal of 1– 0.1Z⊙,
Z dependence is not apparent.
Σ_{cl} dependence is more significant

At extremely low Z case of 10^{-5}– 10^{-3}Z⊙,
massive stars would be rarer

Typical metallicity of 2nd stars (Chiaki+18)

NOTE: CMF should also depend on environments

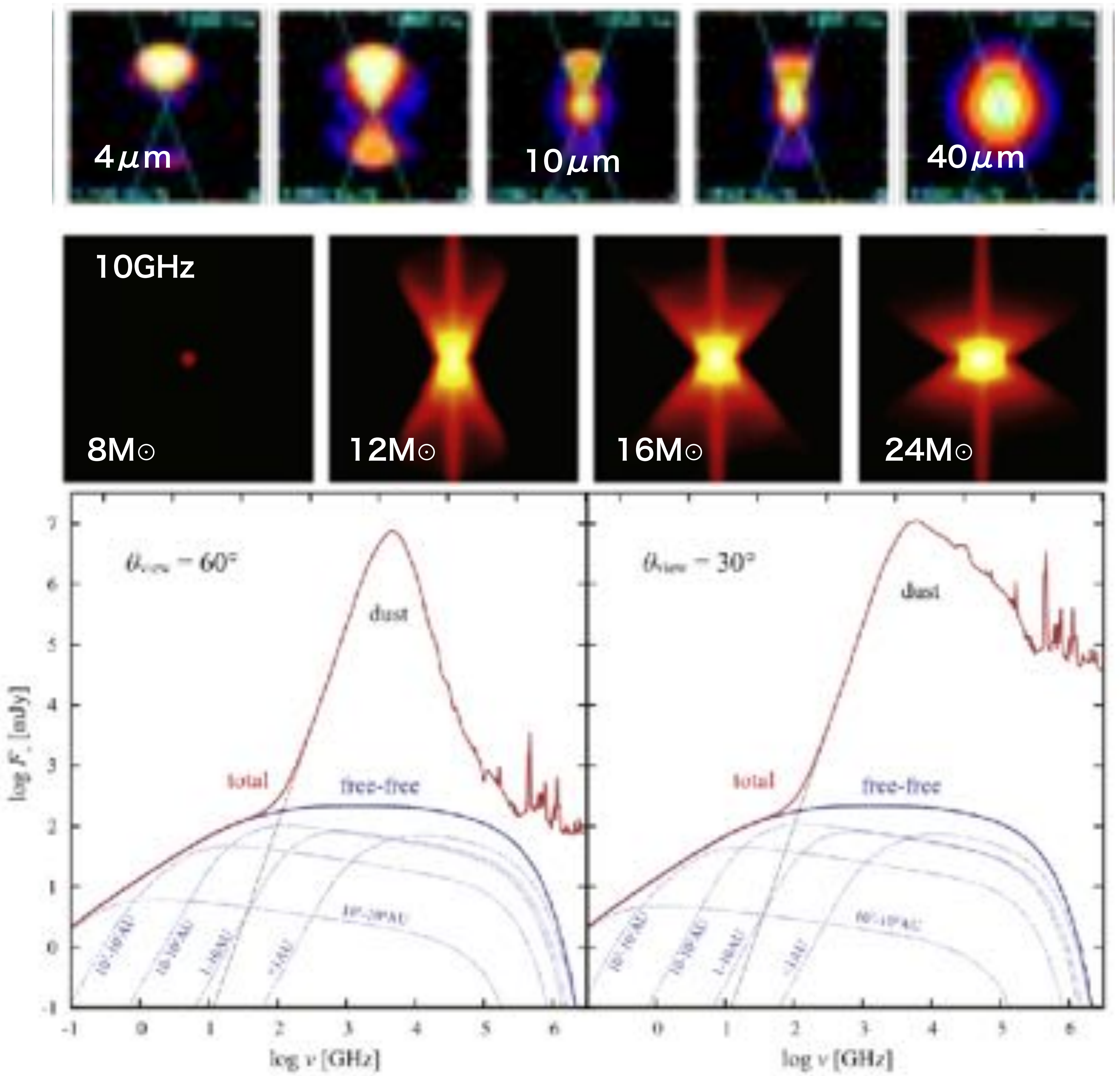
Massive cores are rare at ≳1e-5Z⊙
(Omukai&Tsuribe05)

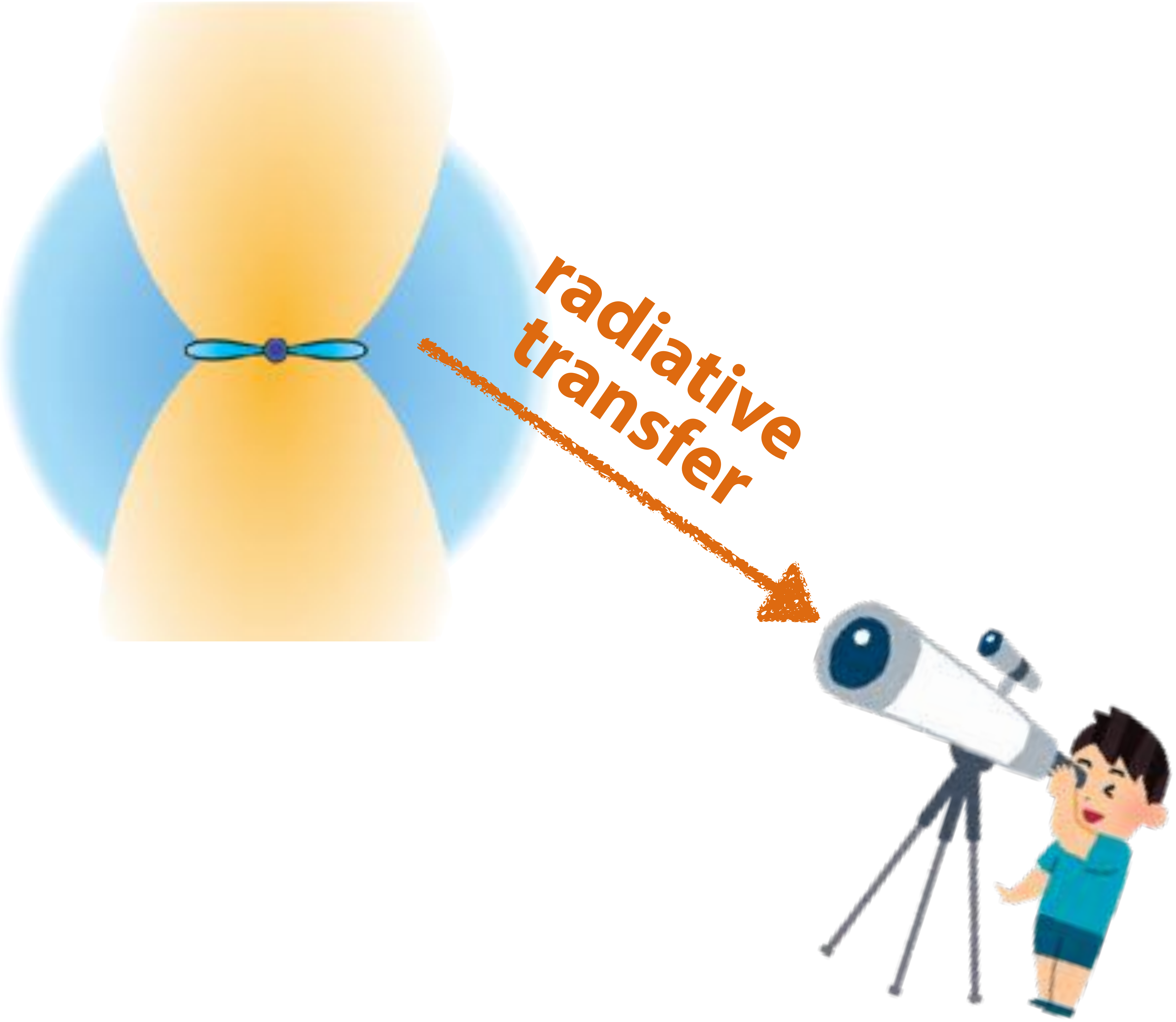
Synthetic & Actual Observations

synthetic obs: KT+16, ApJ, 835, 32; KT+17, ApJ, 849, 133; Zhang&Tan 2018, etc
actual obs: De Buizer+KT17, 843, 33; Rosero, KT+submitted, arXiv:1809.01264; Zhang, Tan, KT+submitted

Synthetic & Actual Observations

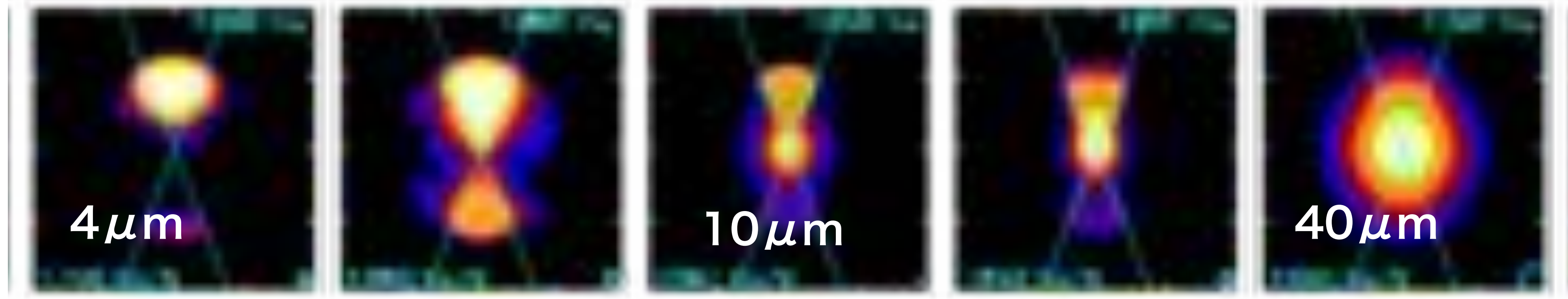
Synthetic Observations

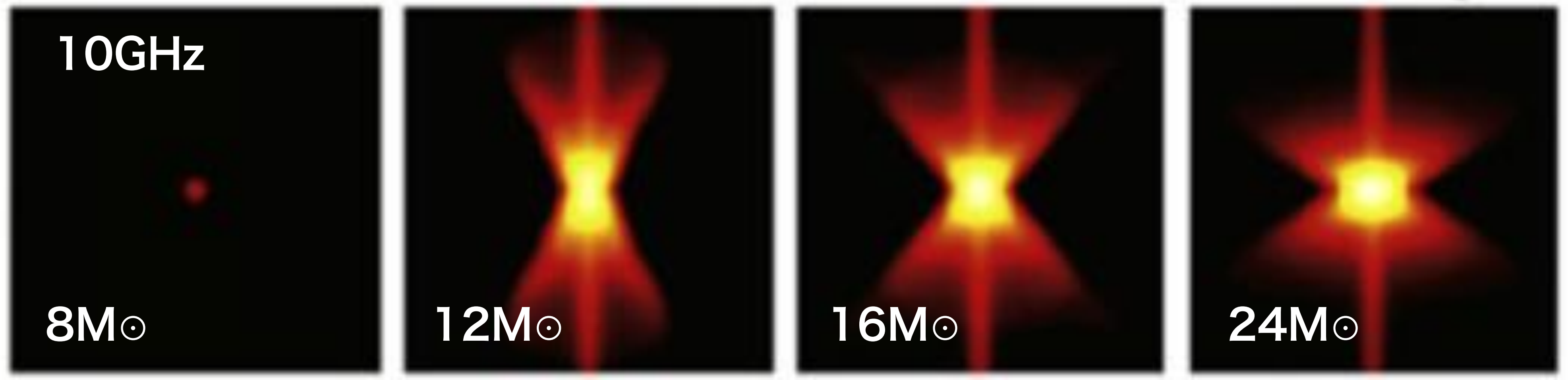


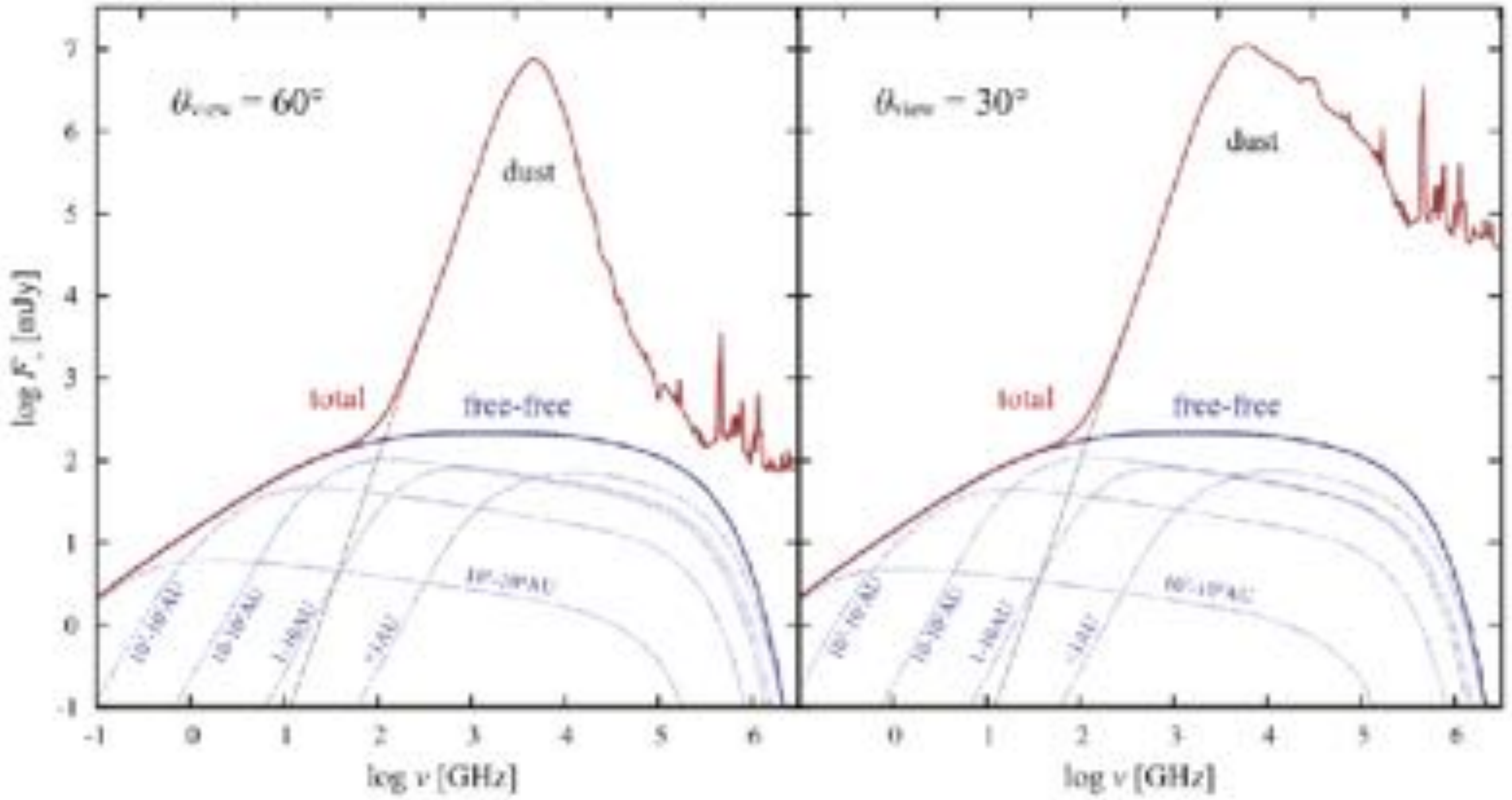


Synthetic & Actual Observations

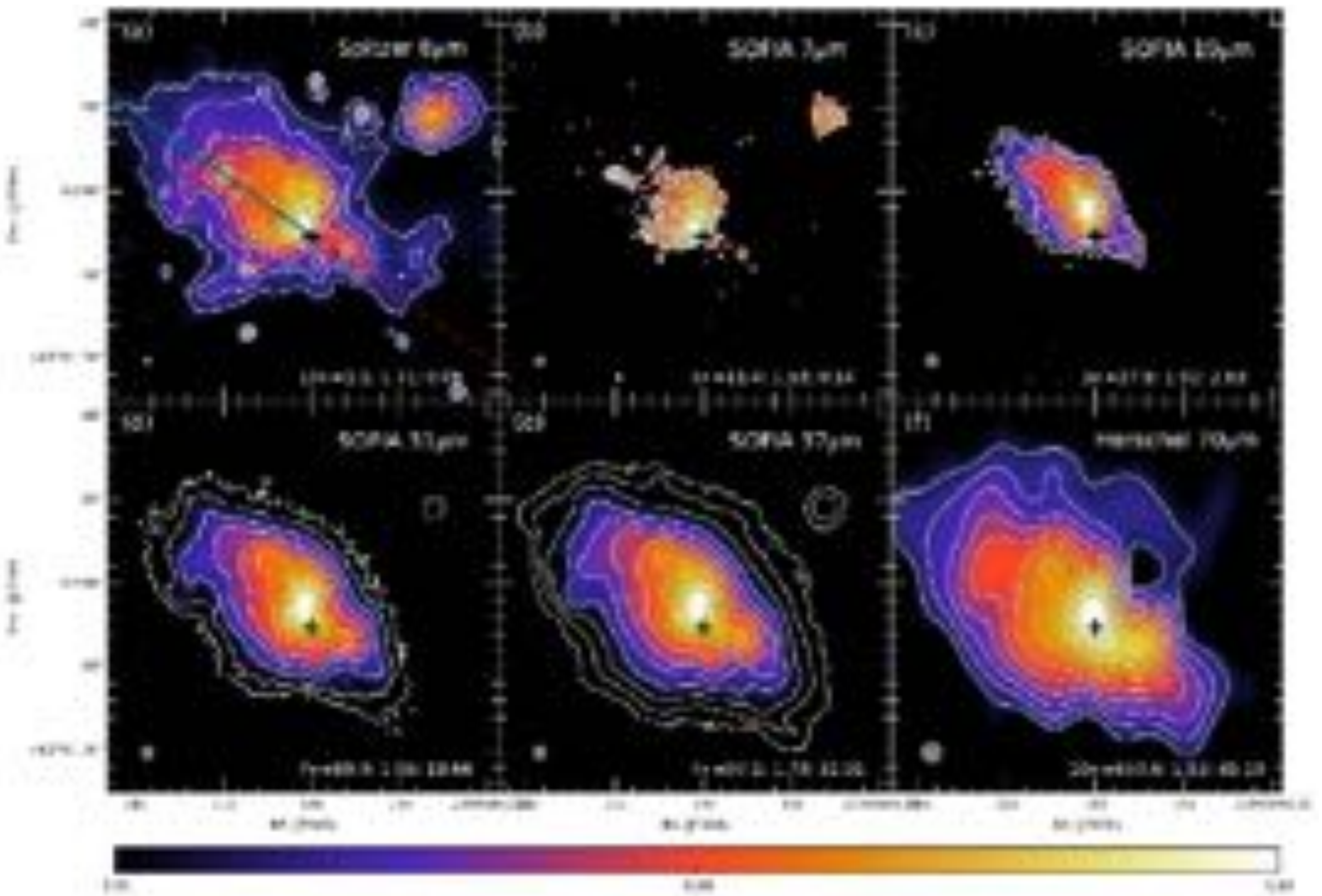
Synthetic Observations

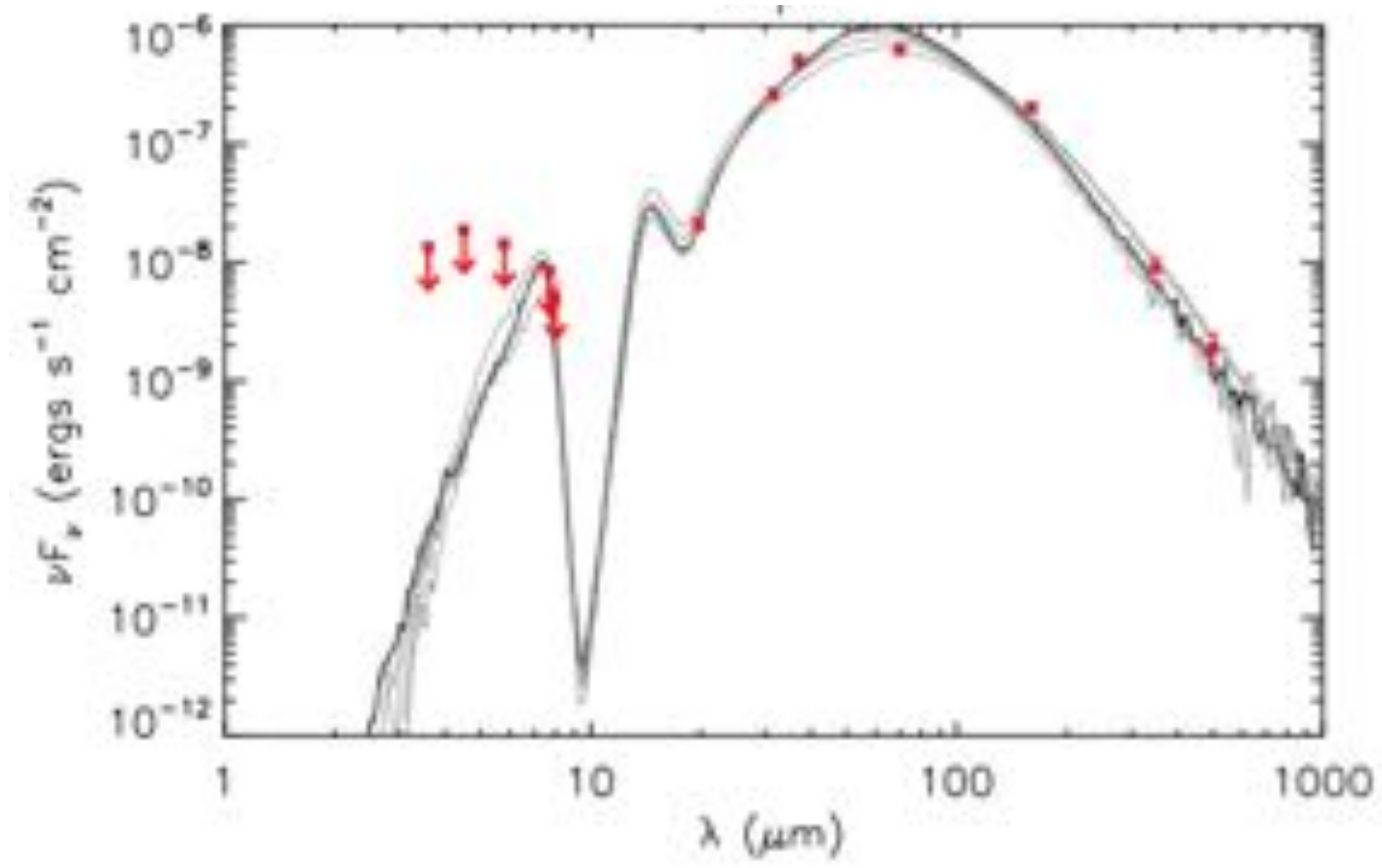






IR survey by SOFIA





follow-up by ALMA & VLA

Summary

Multiple Feedback in Massive SF

We develop the model of **massive SF with multiple feedback**

Feedback does not set the upper mass limit

SFE is lower at lower Σ_{cl}

MHD disk wind is dominant at >0.1Z⊙

SFE is lower due to effective PE at <0.01Z⊙

Real observations are also on-going