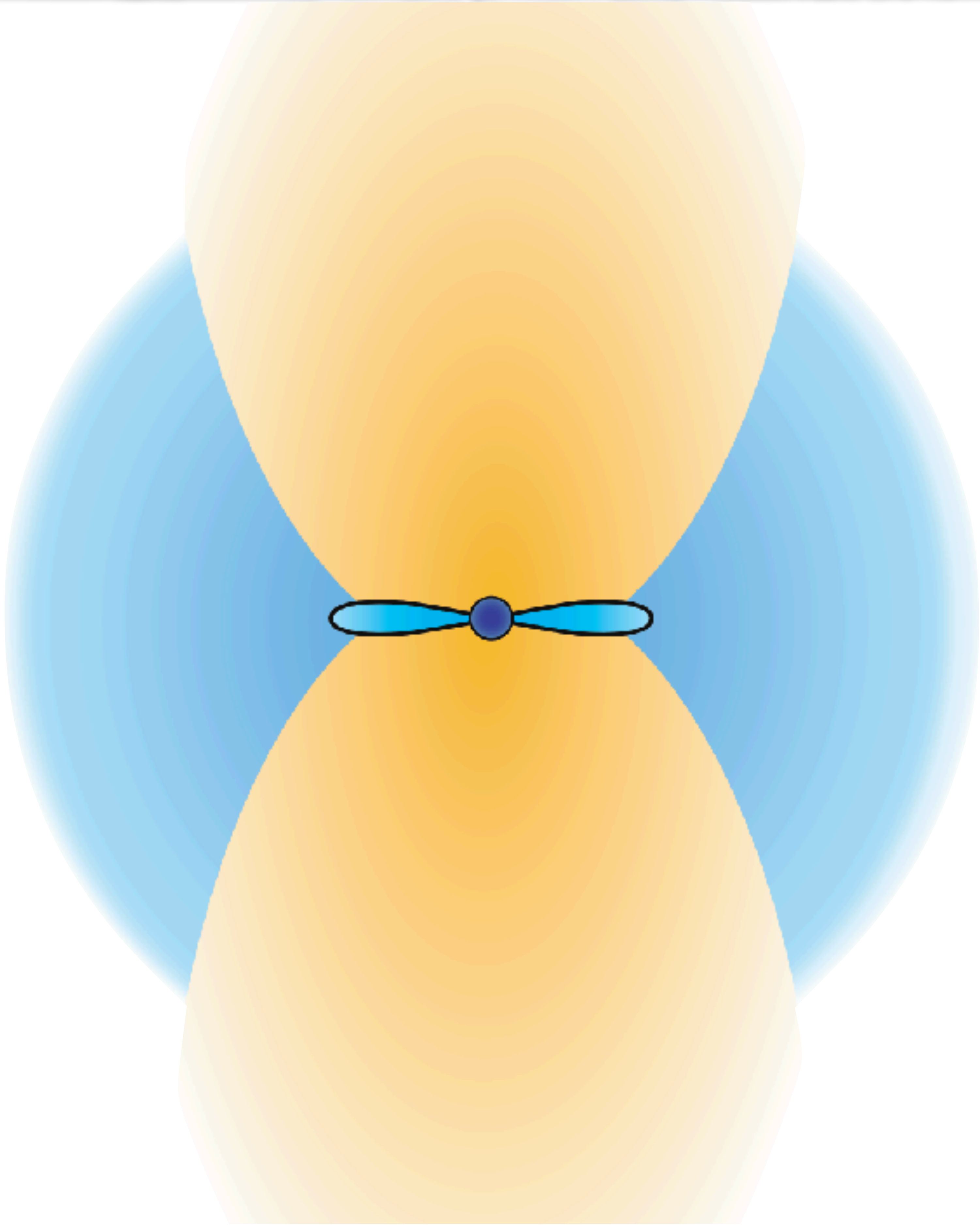
Metallicity Dependence of Multiple Feedback in Massive Star Formation

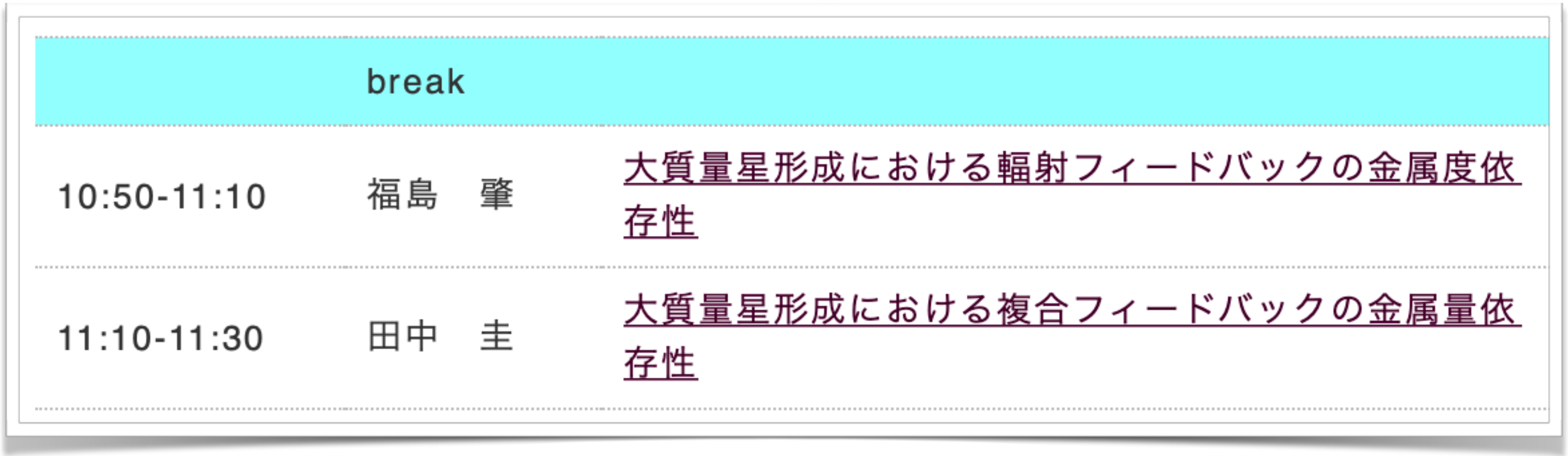
Kei E. I. Tanaka (Osaka Univ. / NAOJ)

J. C. Tan (Chalmers/Virginia), Y. Zhang (RIKEN), T. Hosokawa (Kyoto),
V. Rosero (Virginia), J. E. Staff (Virgin Islands), J. M. De Buizer (SOFIA), M. Liu (Virginia), K. Tomida, K. Iwasaki (Osaka) *and more*



Feedback Problem

Upper mass limit? Dominant feedback? Now & Then?



	break	
10:50-11:10	福島　肇	大質量星形成における輻射フィードバックの金属度依存性
11:10-11:30	田中　圭	大質量星形成における複合フィードバックの金属量依存性

(From the program of this workshop)

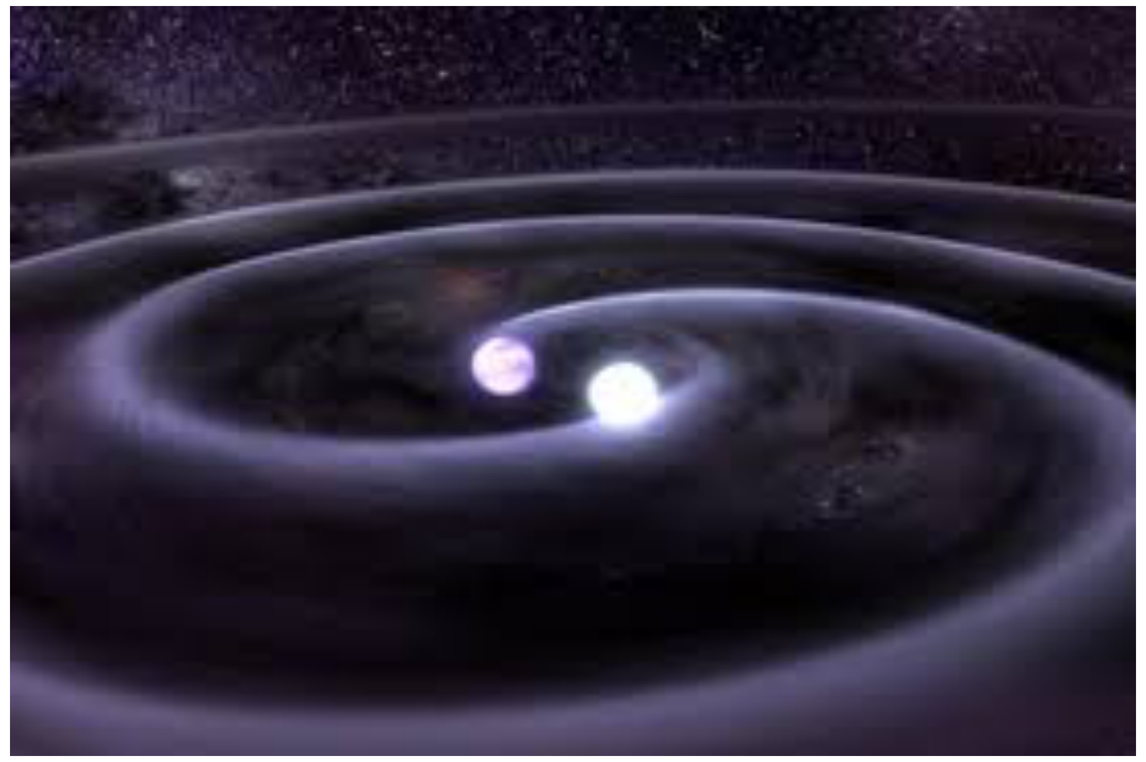
Massive Stars throughout the Cosmic History

Massive stars are important
throughout the cosmic history

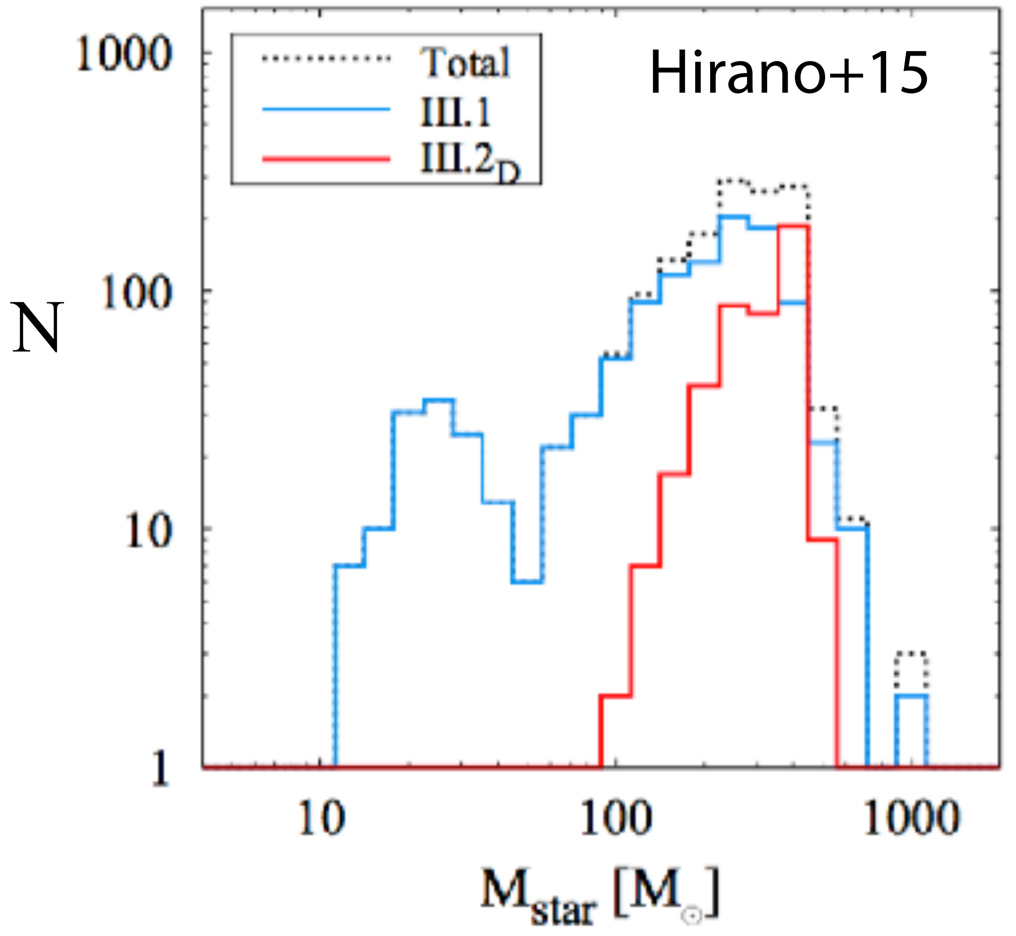
radiation, winds, SNe, metal & dust, GRBs, GW

30 Dor &
R136a ~300M⊙

GW150914 ~ 36 + 29M⊙



First Stars~10-1000M⊙



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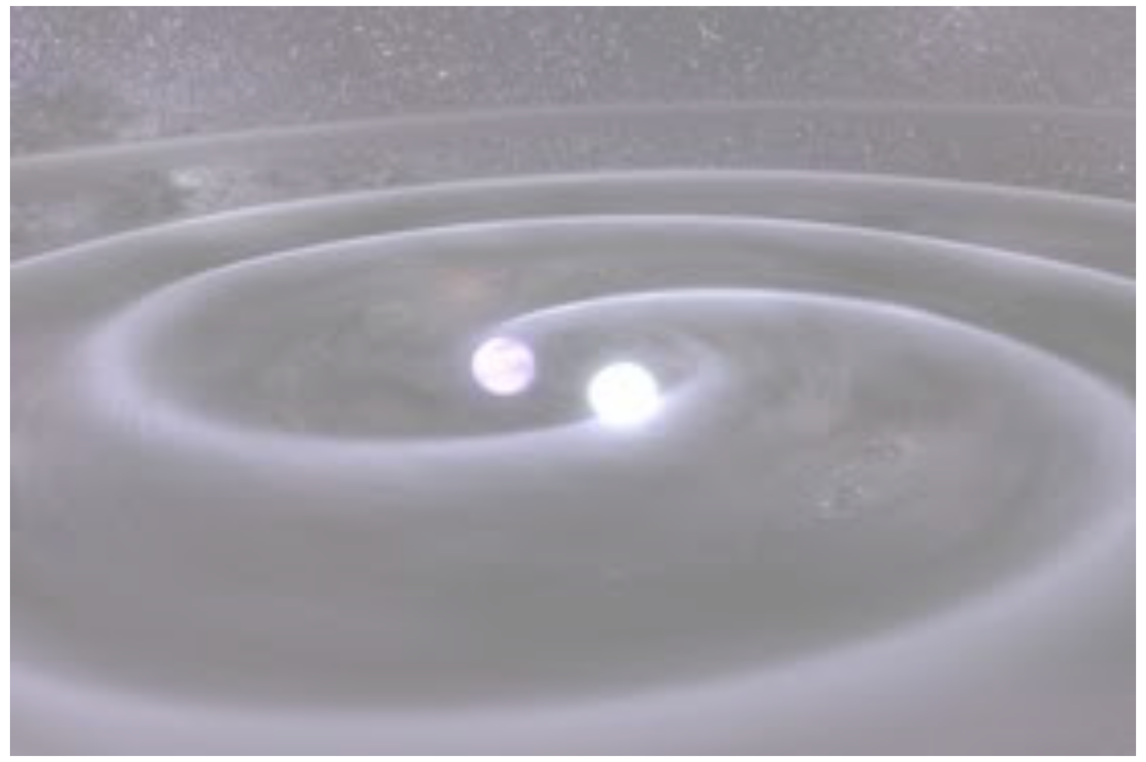

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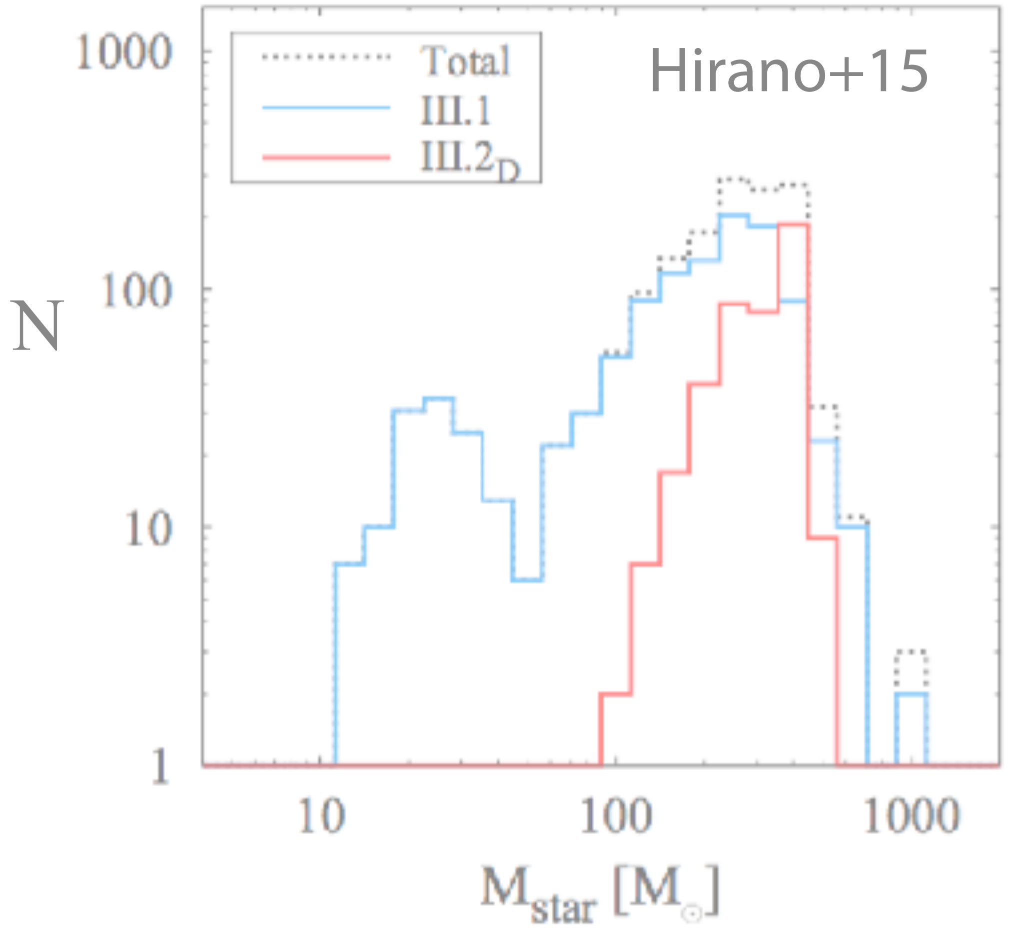

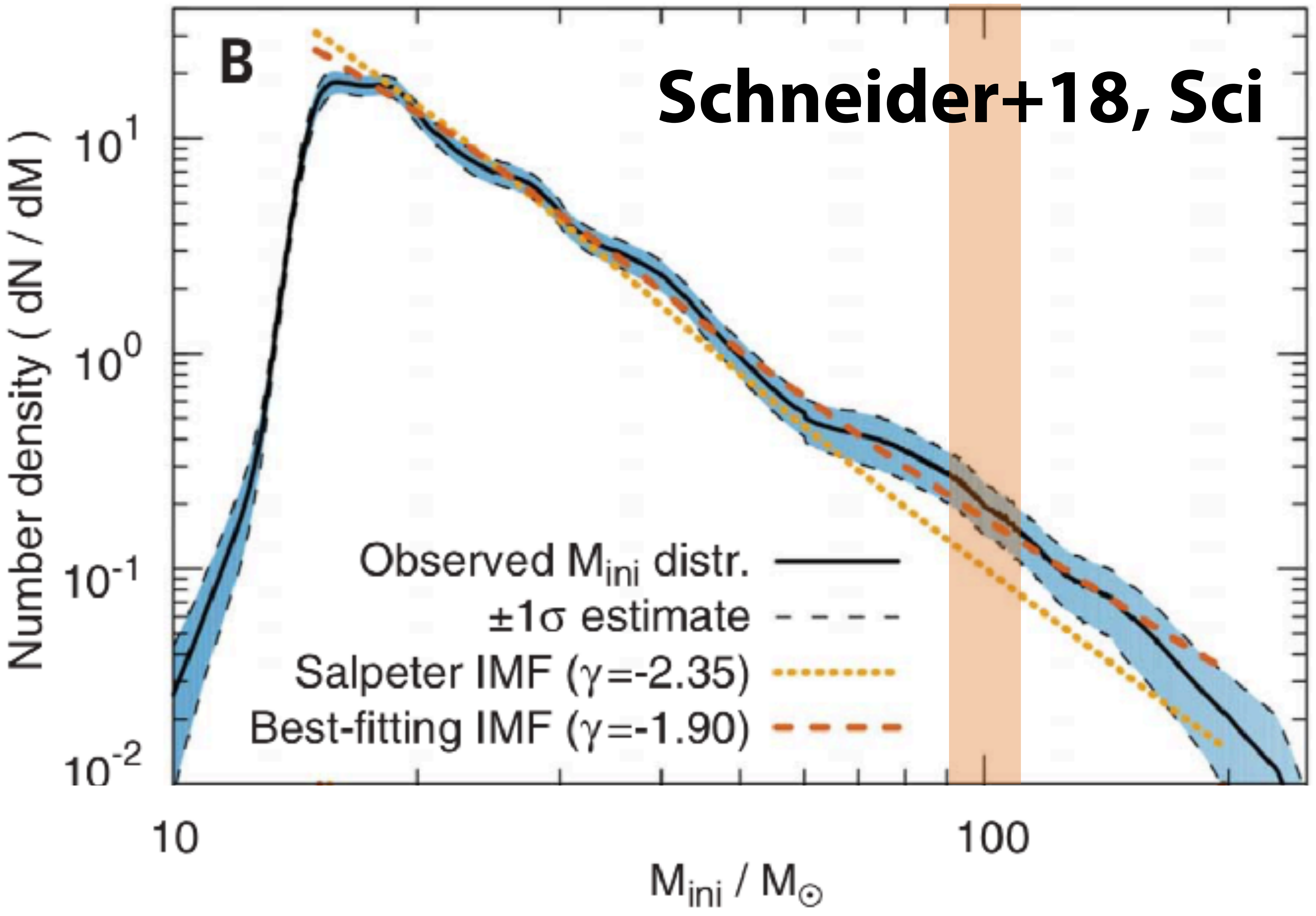

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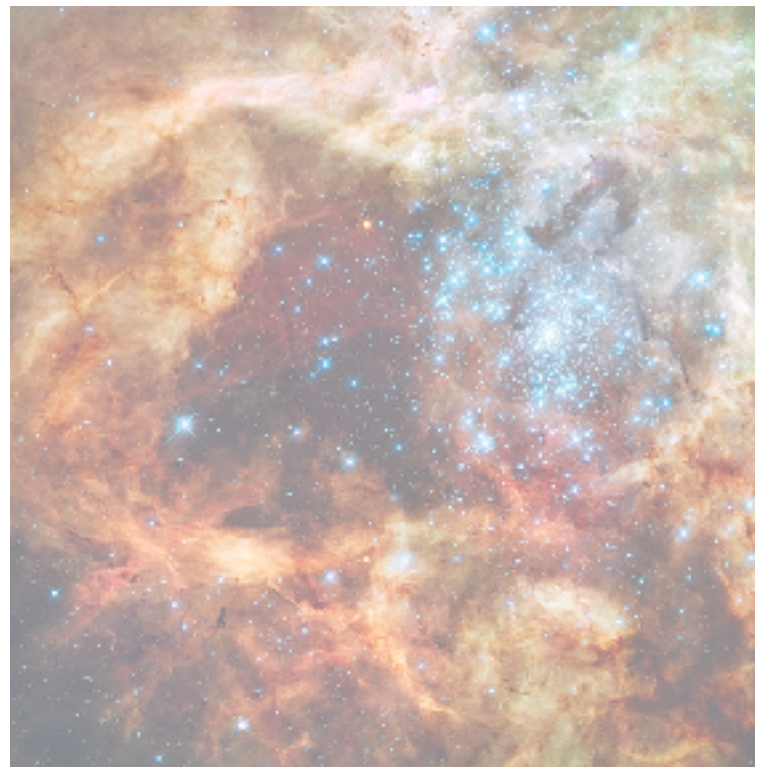

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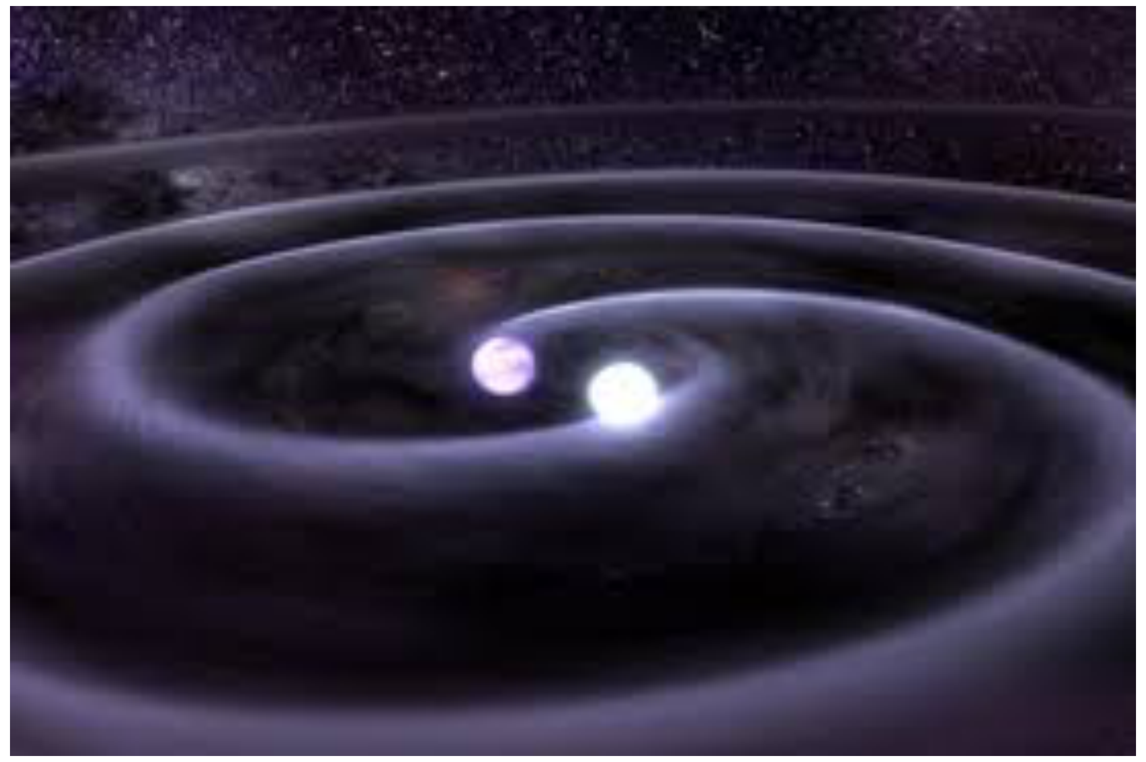

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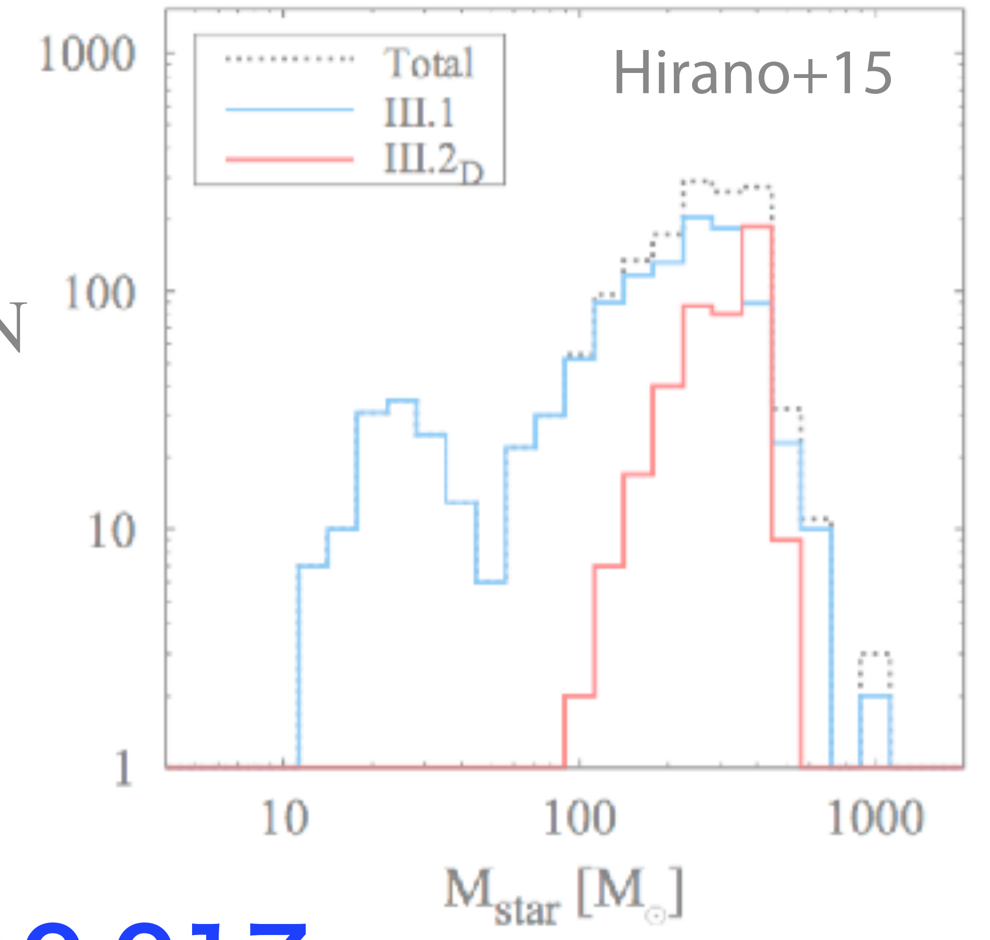
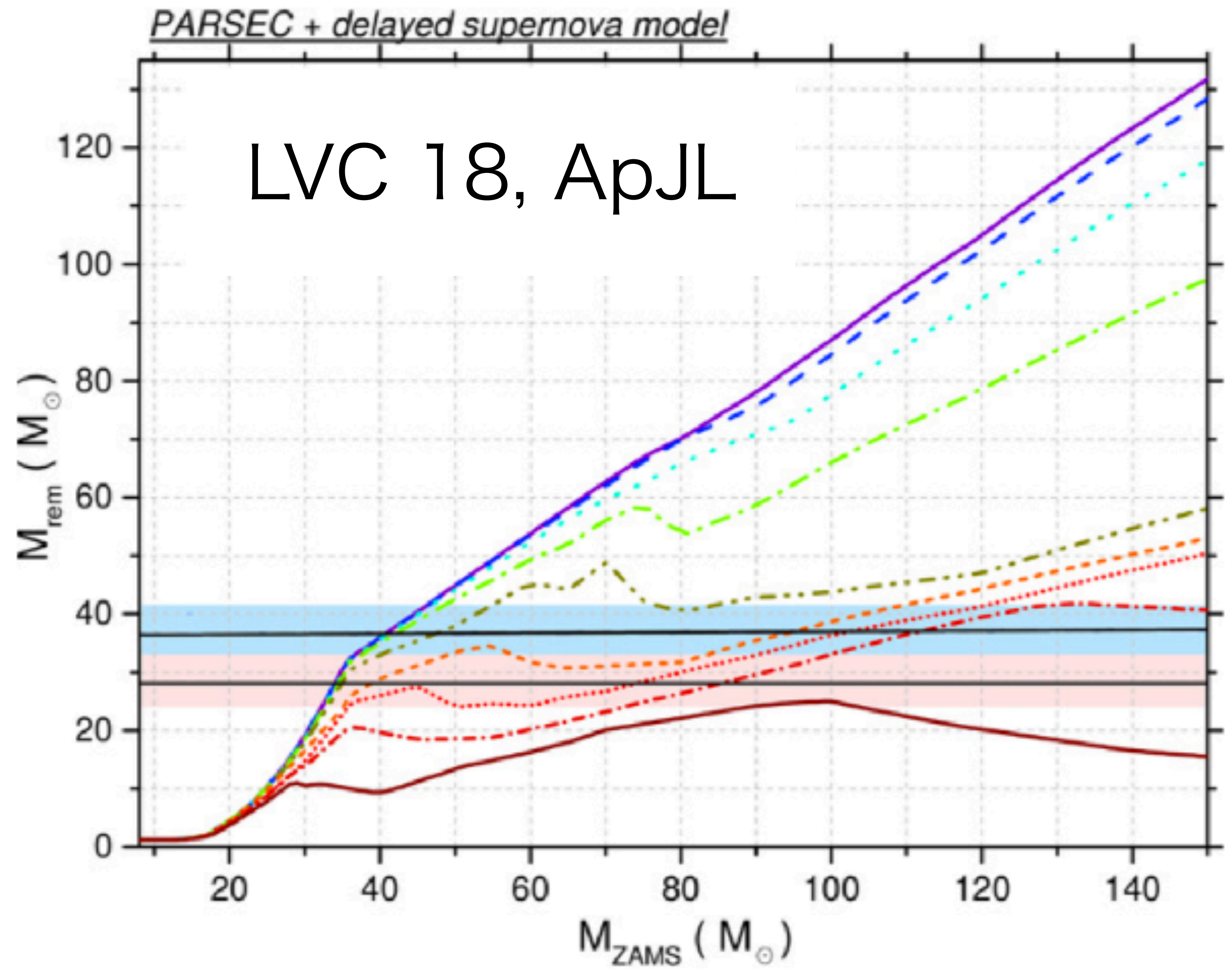

Hirano+15


PARSEC + delayed supernova model

LVC 18, ApJL

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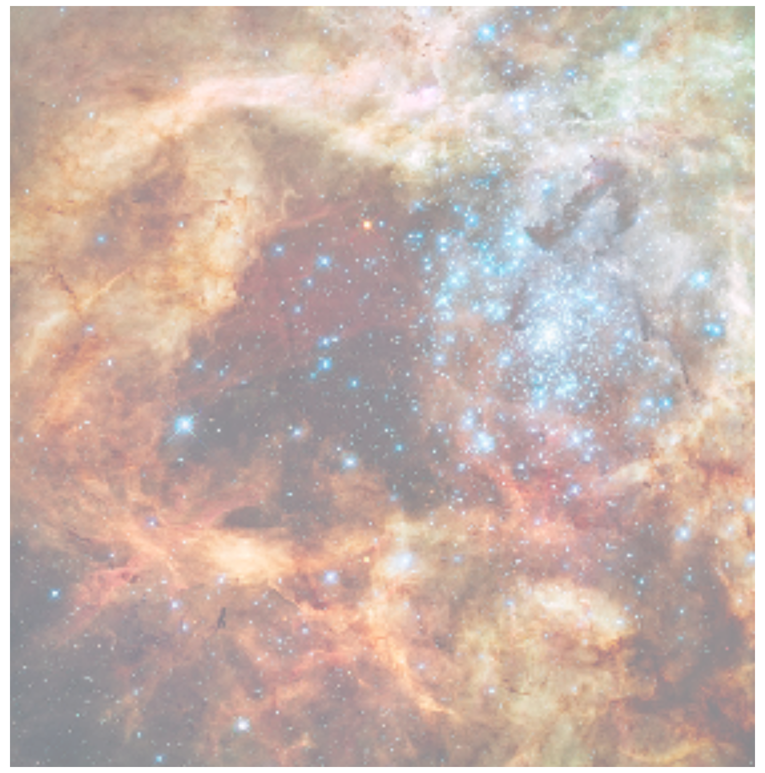

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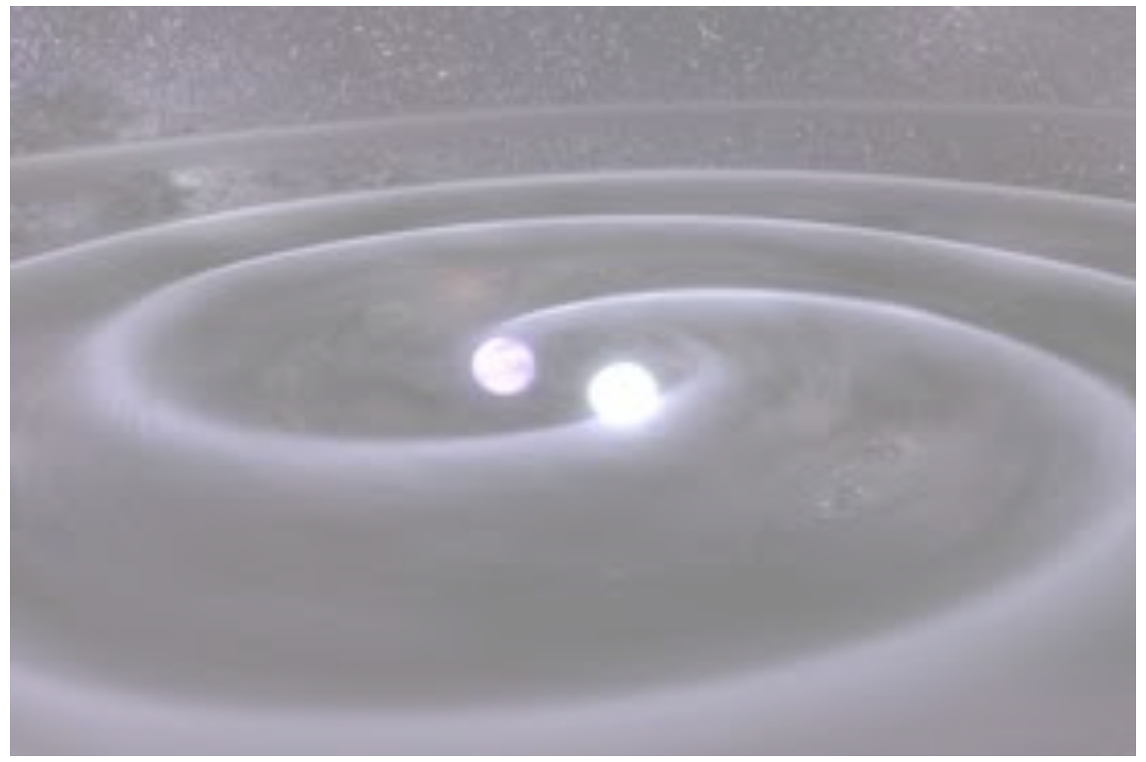

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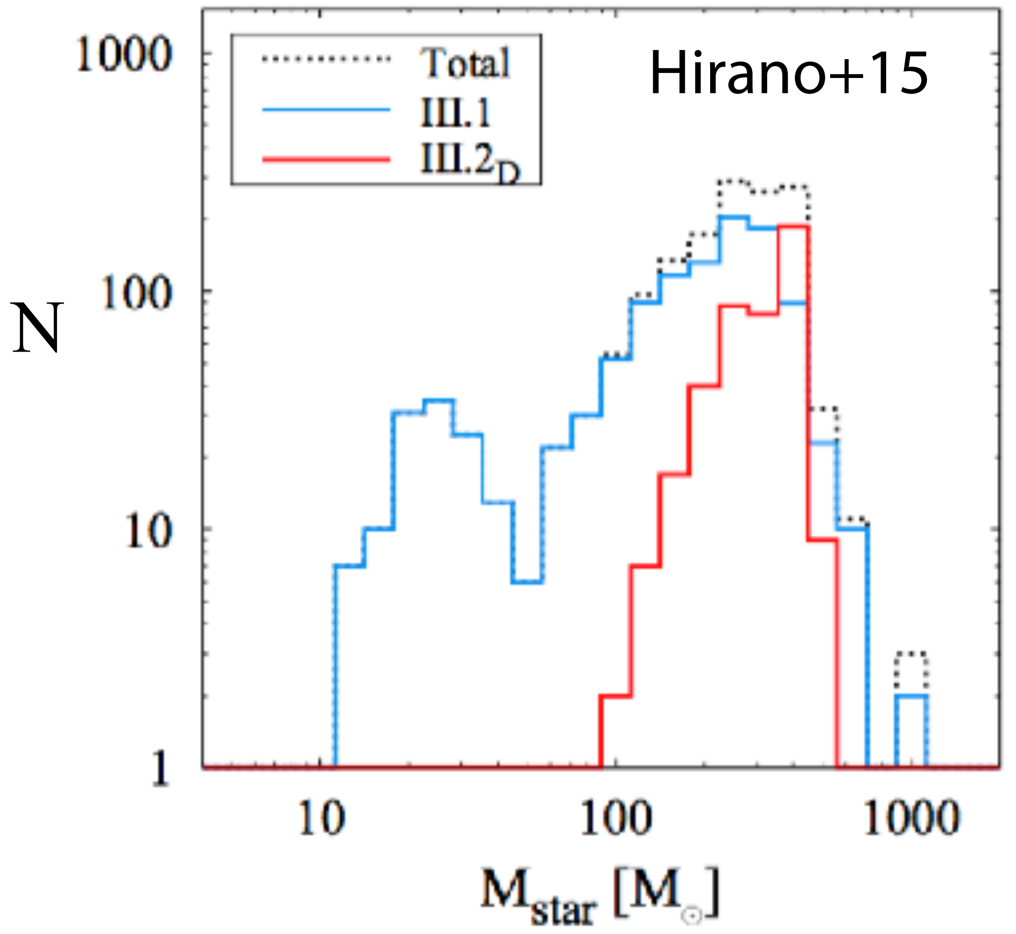

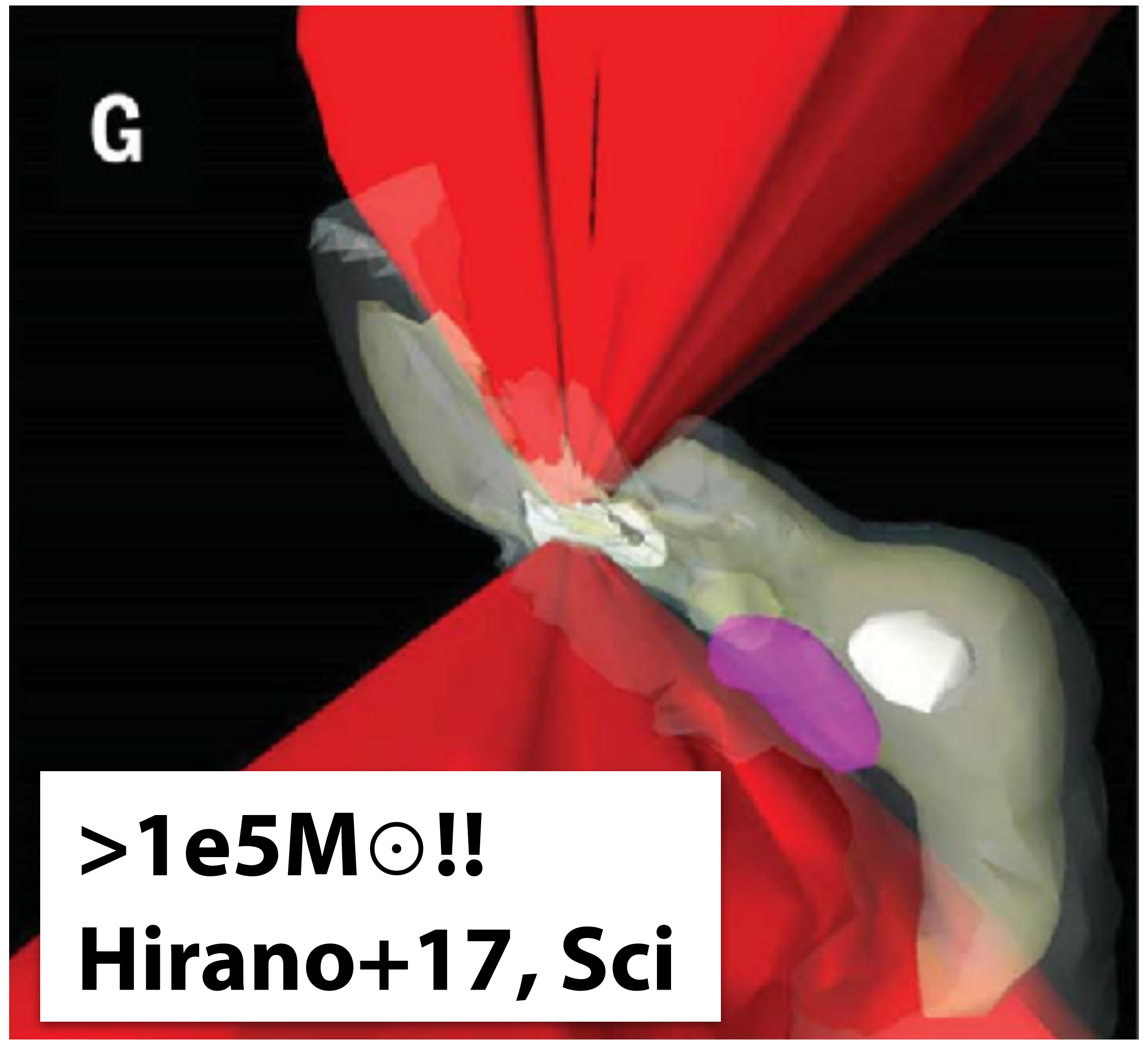

>1e5M⊙!!
Hirano+17, Sci

Massive Stars throughout the Cosmic History

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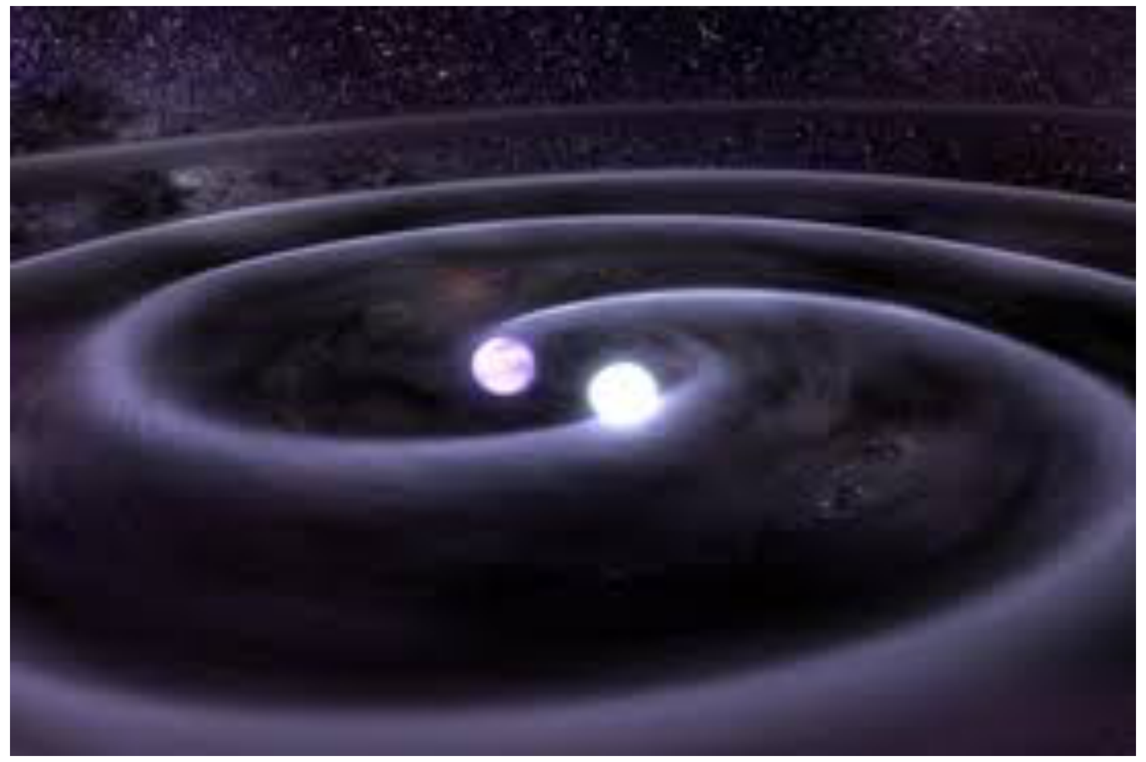

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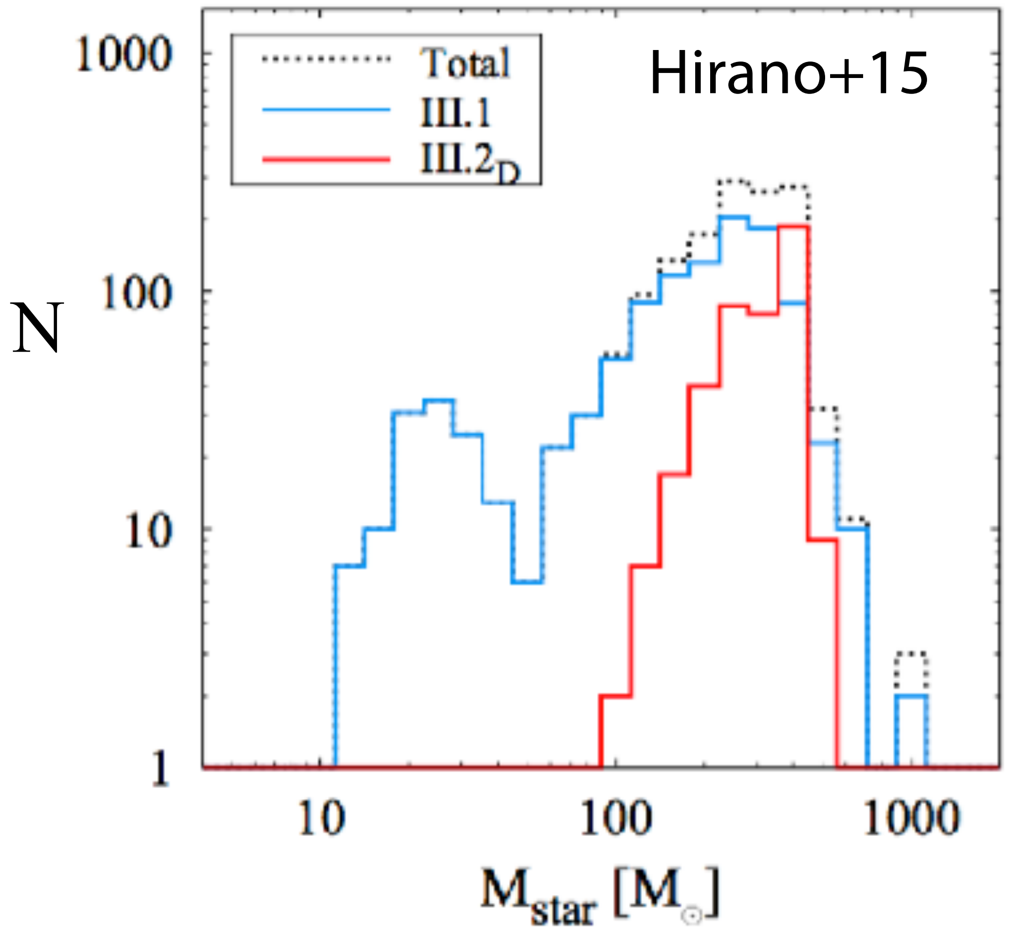
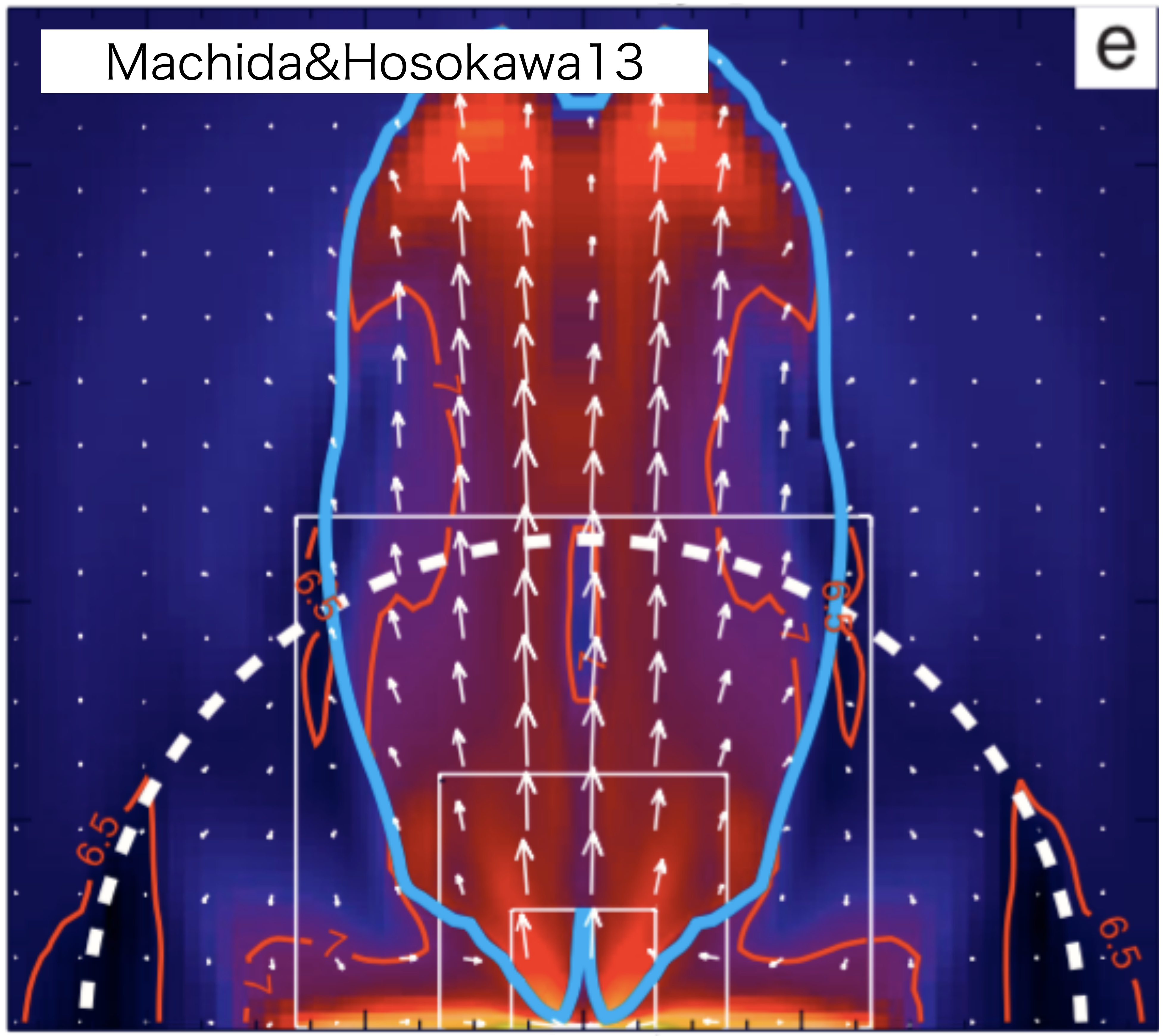


The key to connect the present & early Universe!!

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

Feedback in Low-Mass Star Formation

SFE ~ 0.4

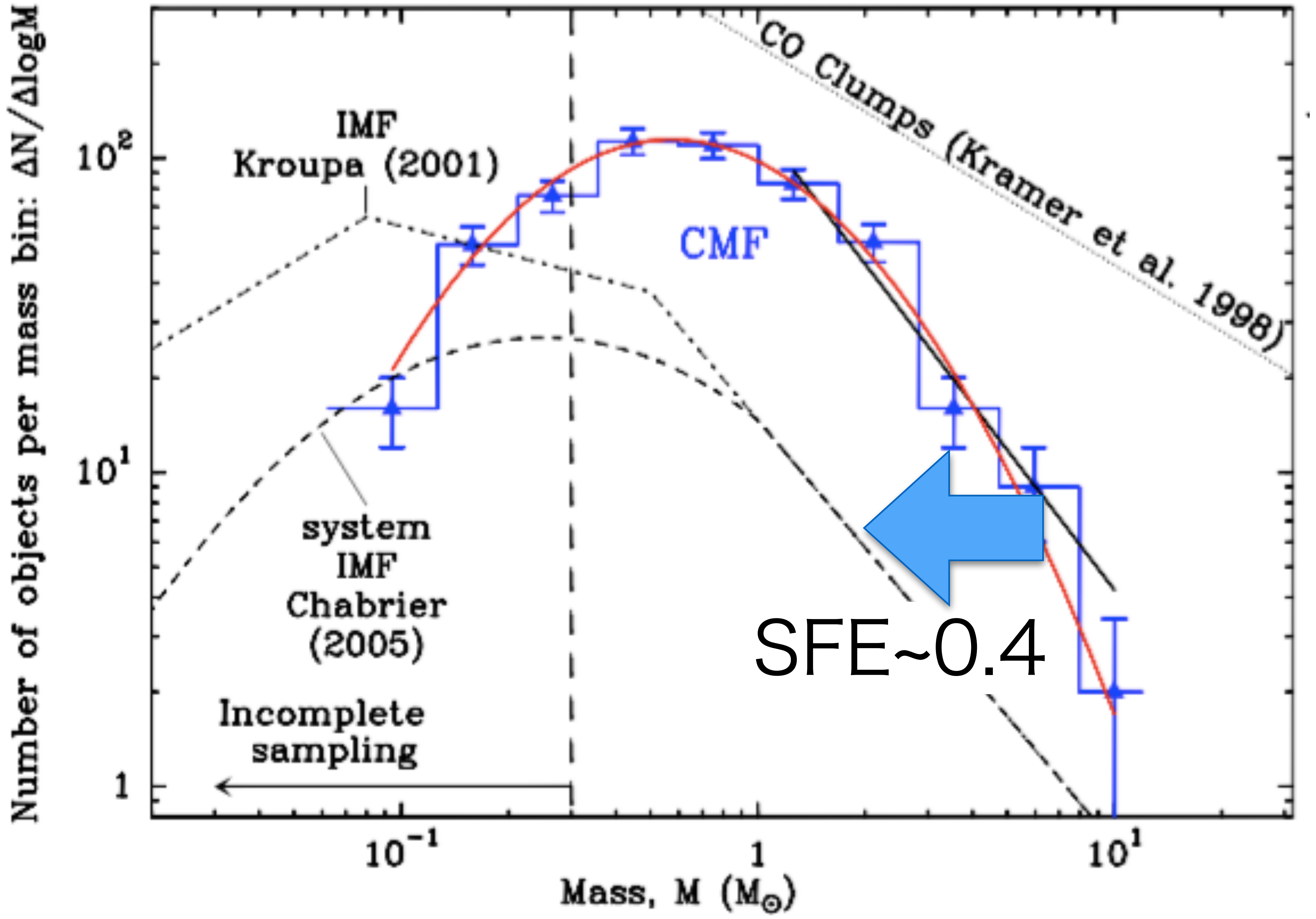


Machida&Hosokawa13

low-mass SF

MHD Disk Wind

Andre+10



SFE~0.4

Feedback in Low-Mass Star Formation

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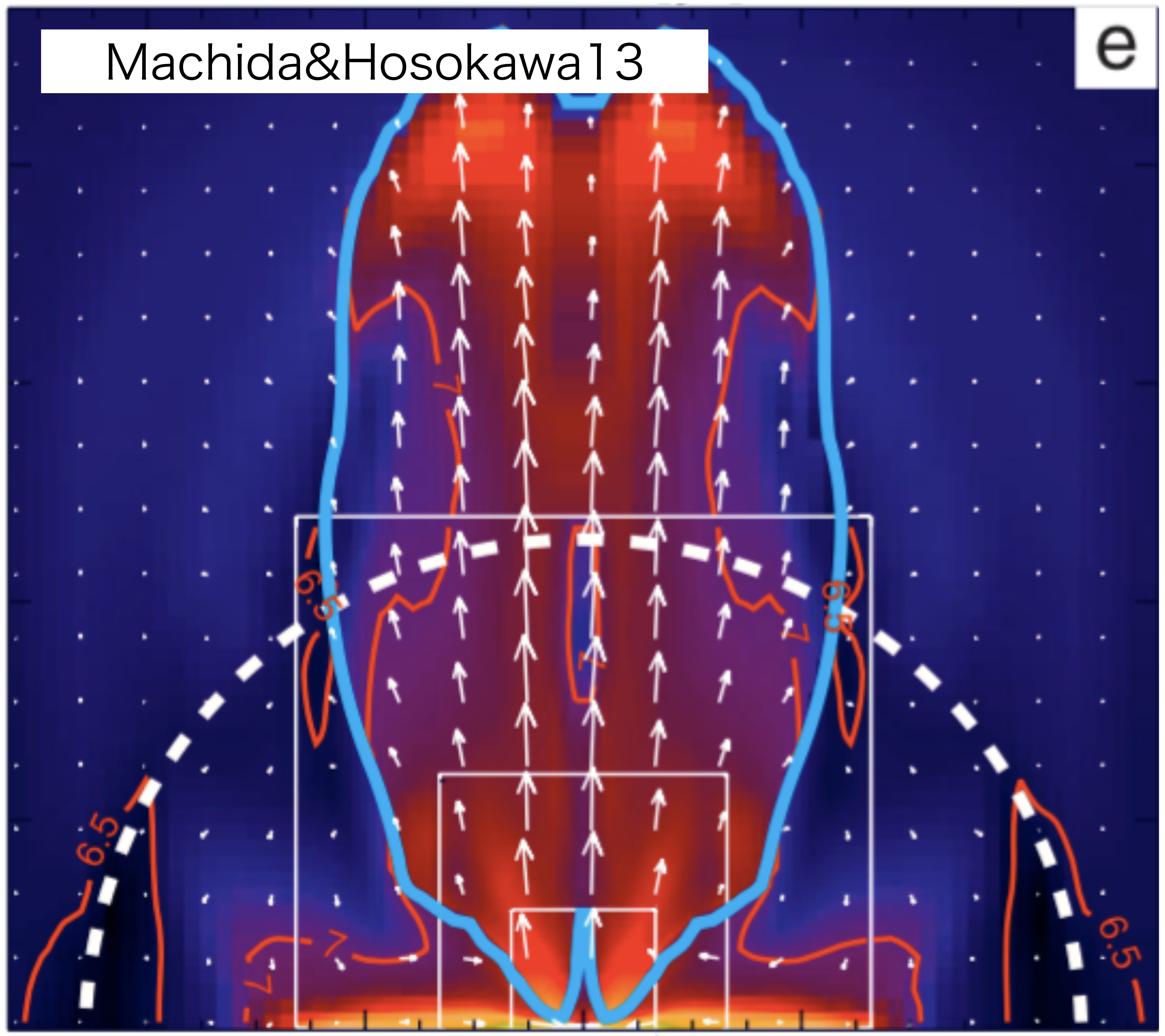
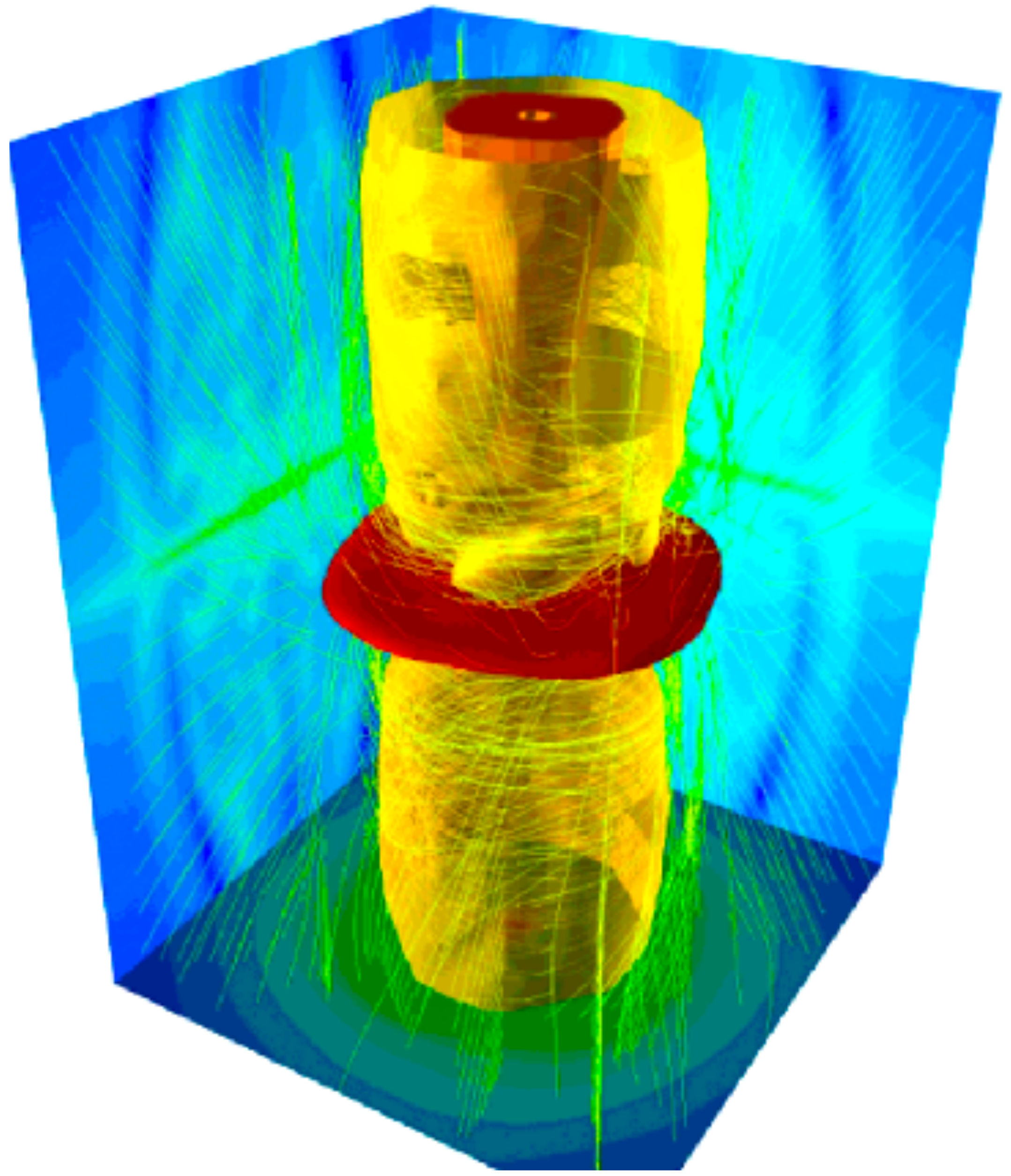
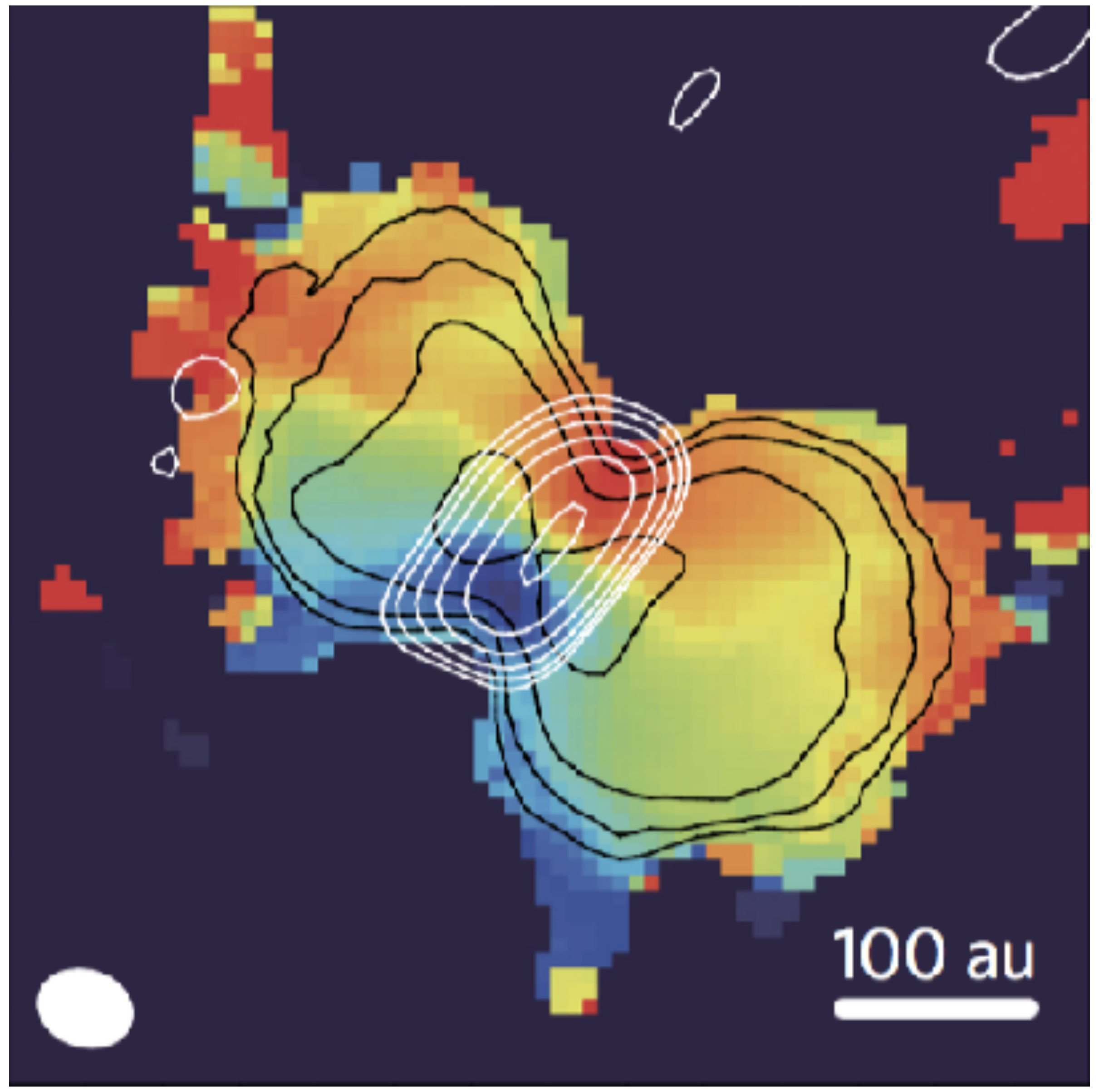


low-mass SF

MHD Disk Wind

also in massive SF!!





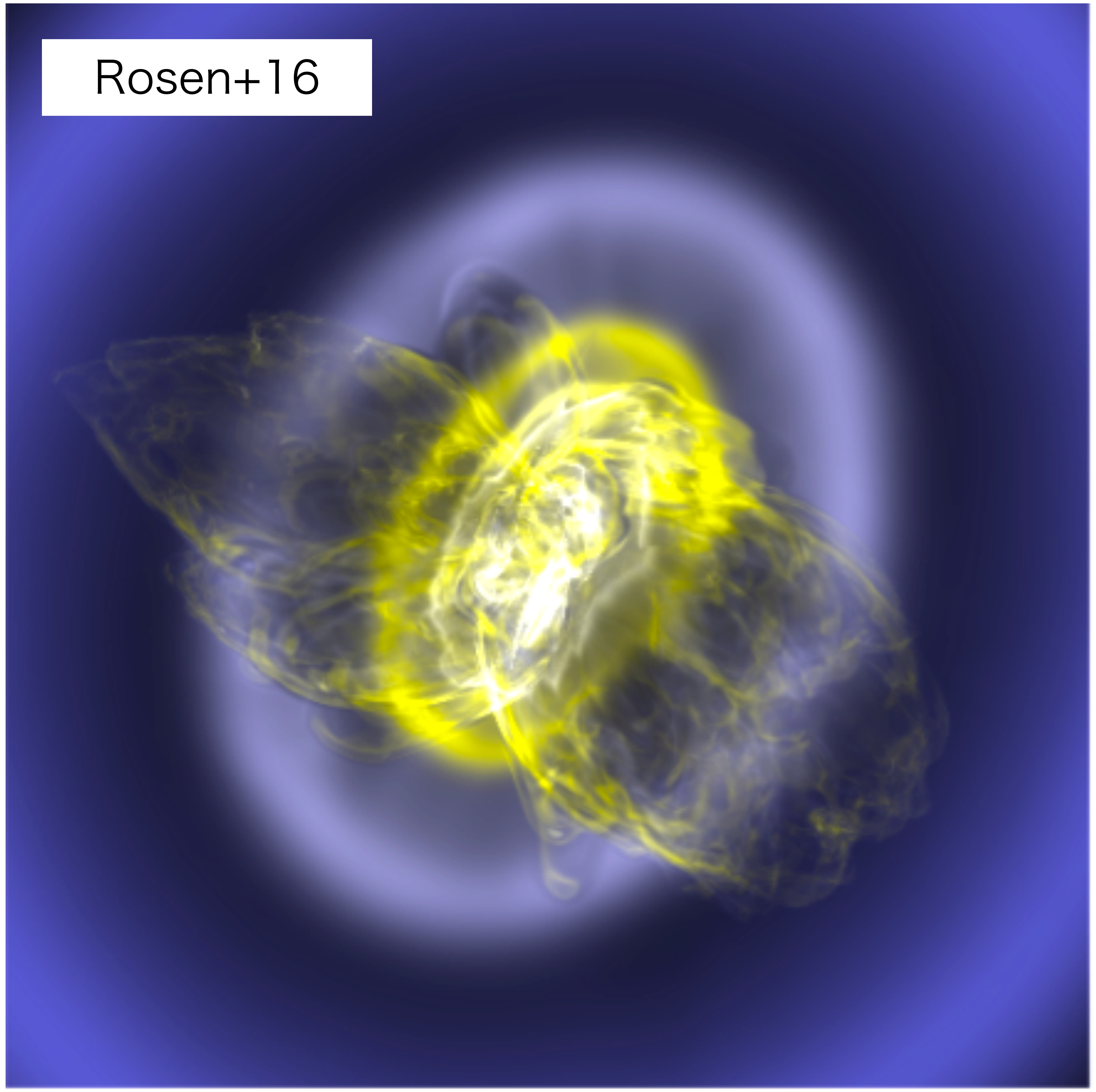
Matsushita+17

Hirota+17

Staff, KT & Tan, arXiv:1811.00954

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

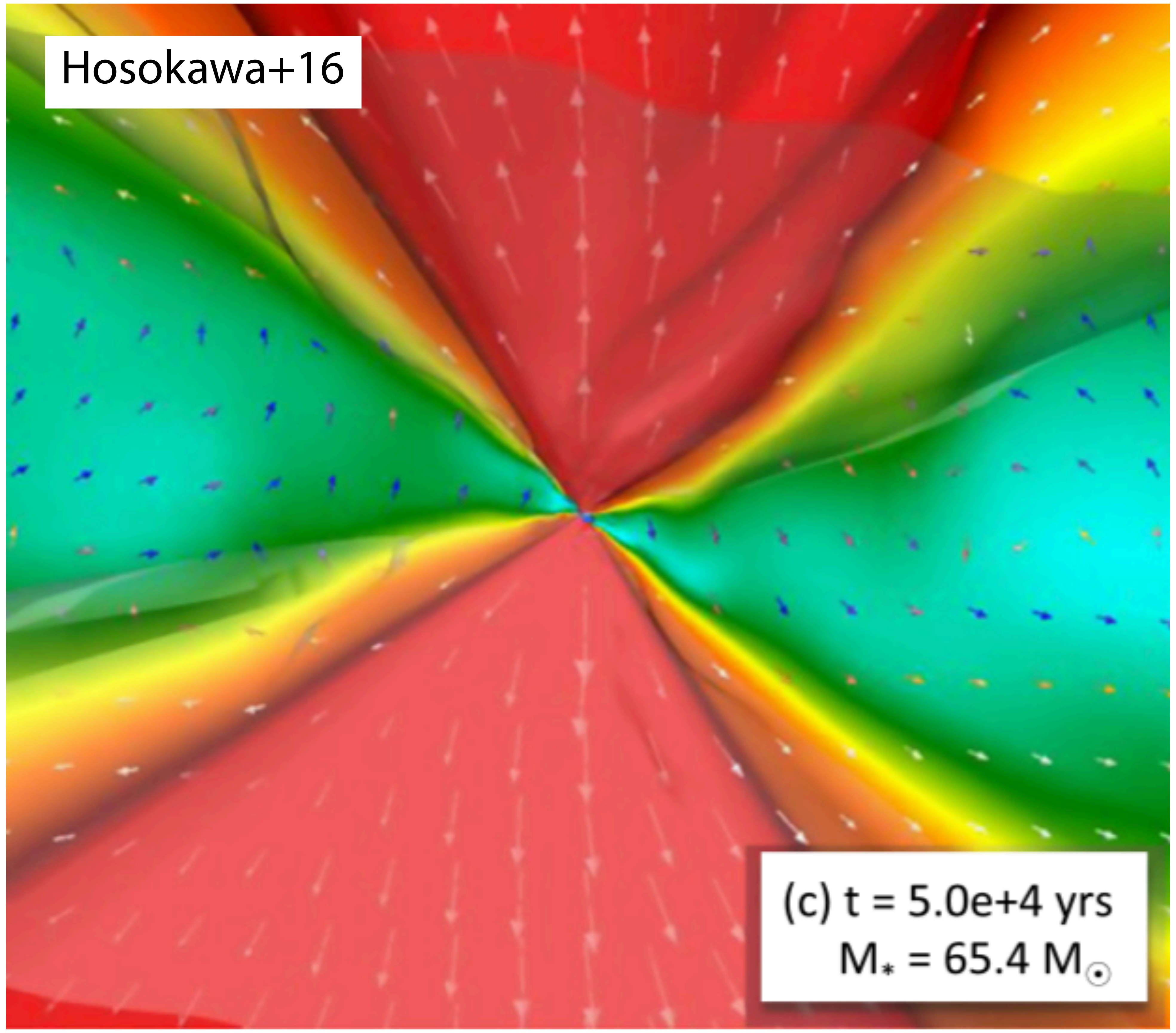
massive SF

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

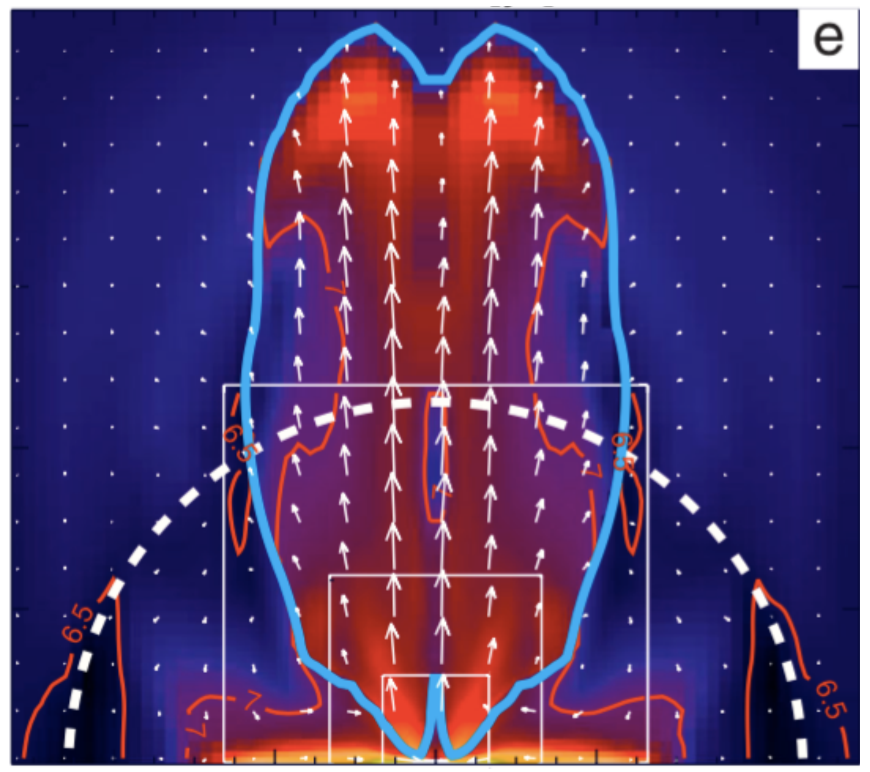
First SF in the early universe

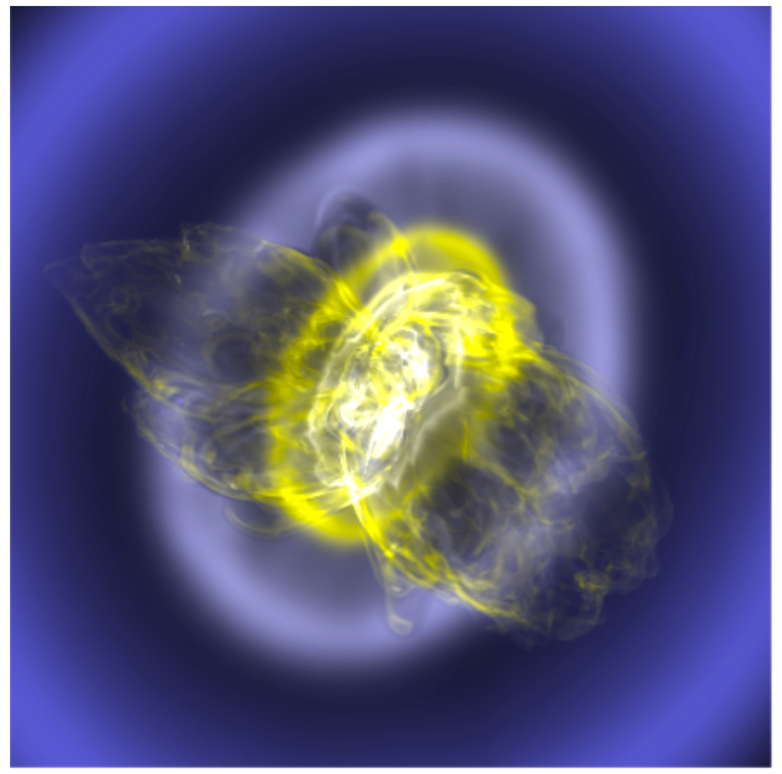
Photoevaporation

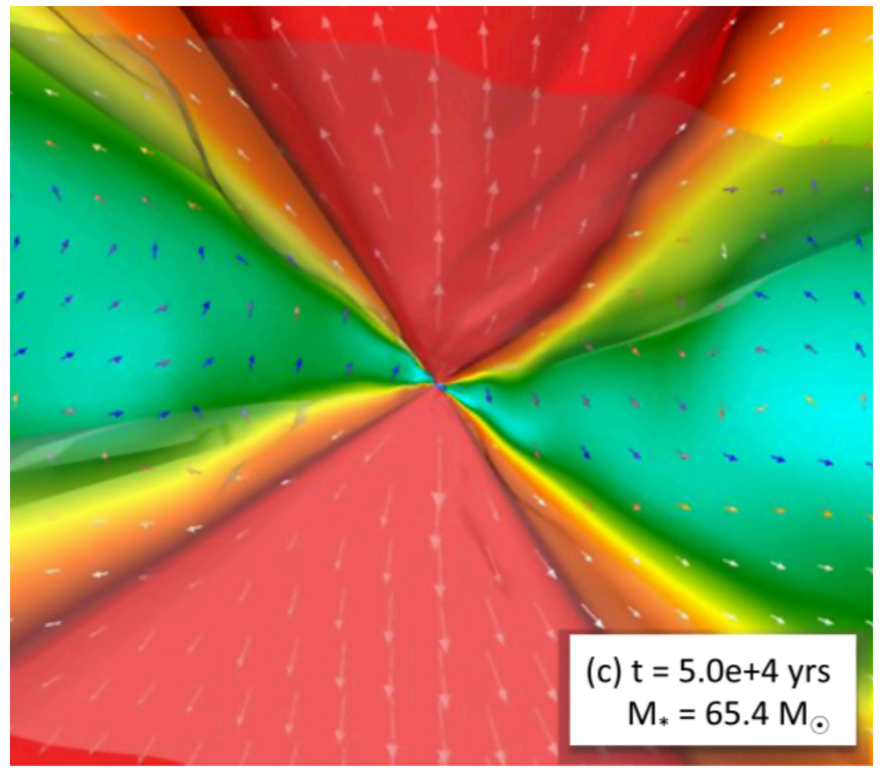
McKee&Tan08, Hosokawa+11, etc

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

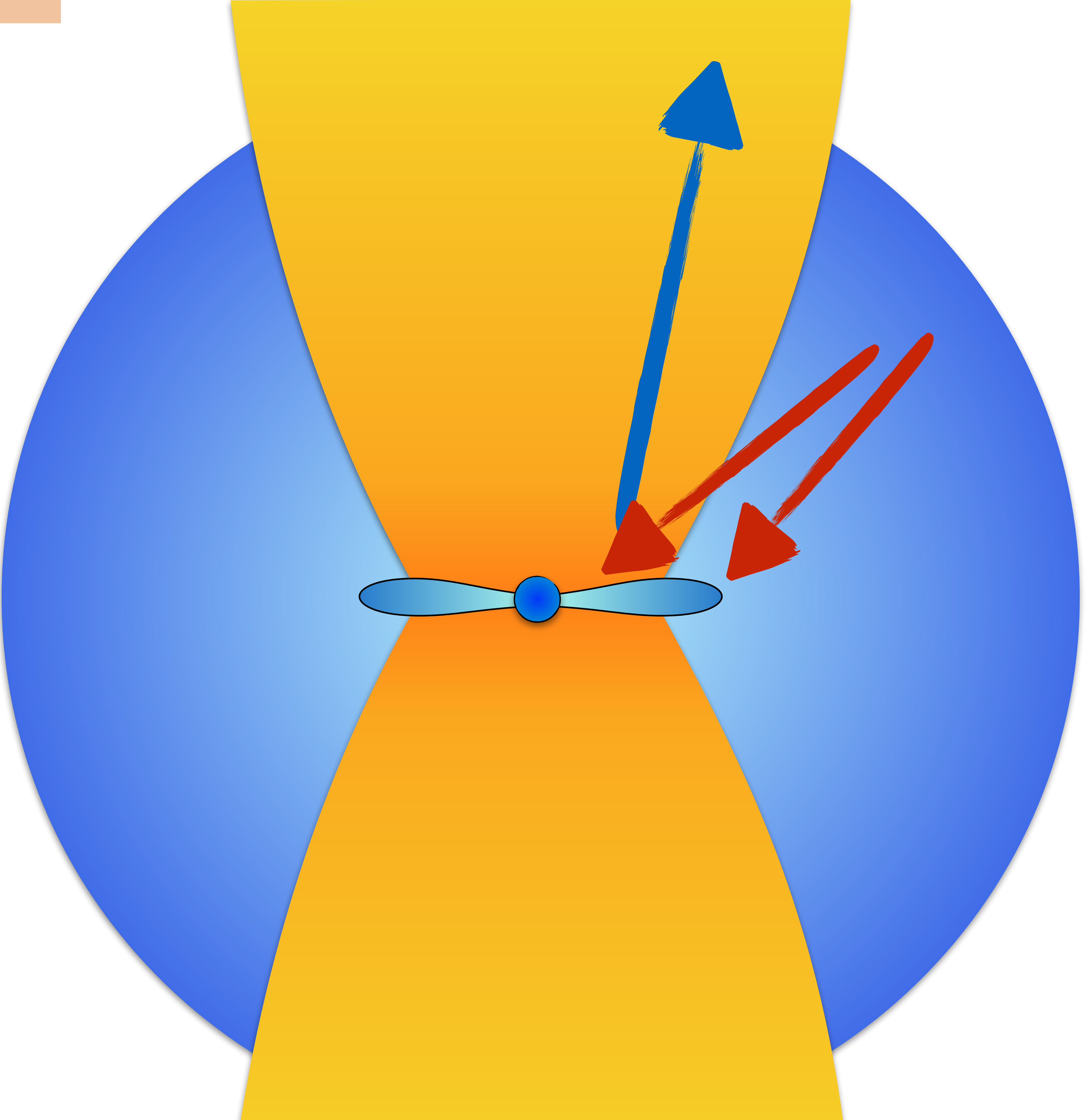
We solve the evolution of protostars,
accretion flow structures,
and feedback processes self-consistently
until the end of accretion (mdot=0)

and evaluate SFEs from initial cores

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

Pre-stellar cloud core

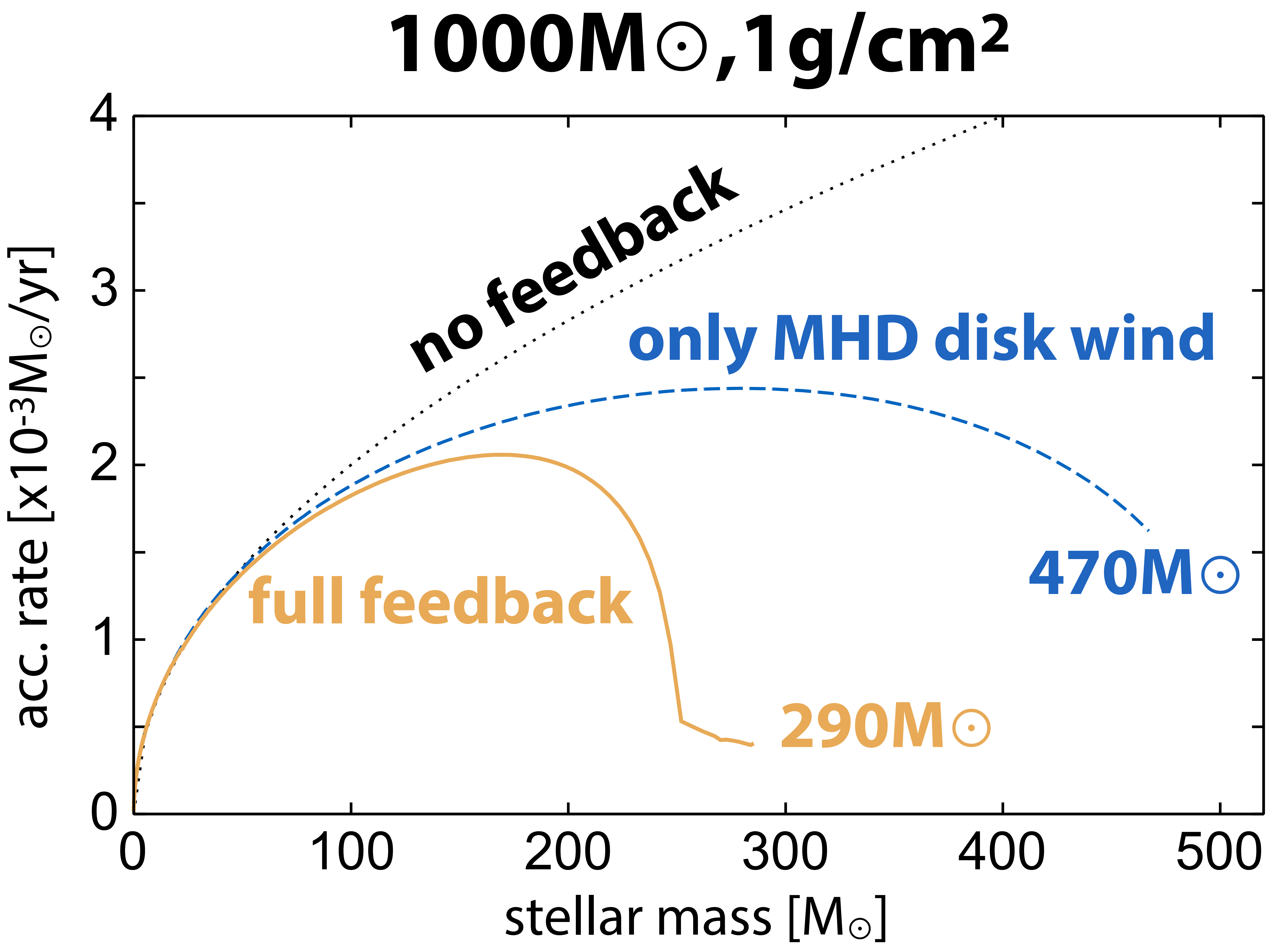
$M_c = 10 - 1000 M_\odot$
$\Sigma_{cl} = 0.1 - 3$ g/cm^2 ← **Infrared Dark Clouds**
$Z = 1e\text{-}5 - 1\ Z_\odot$



Impact of Multiple Feedback at $Z_\odot$

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

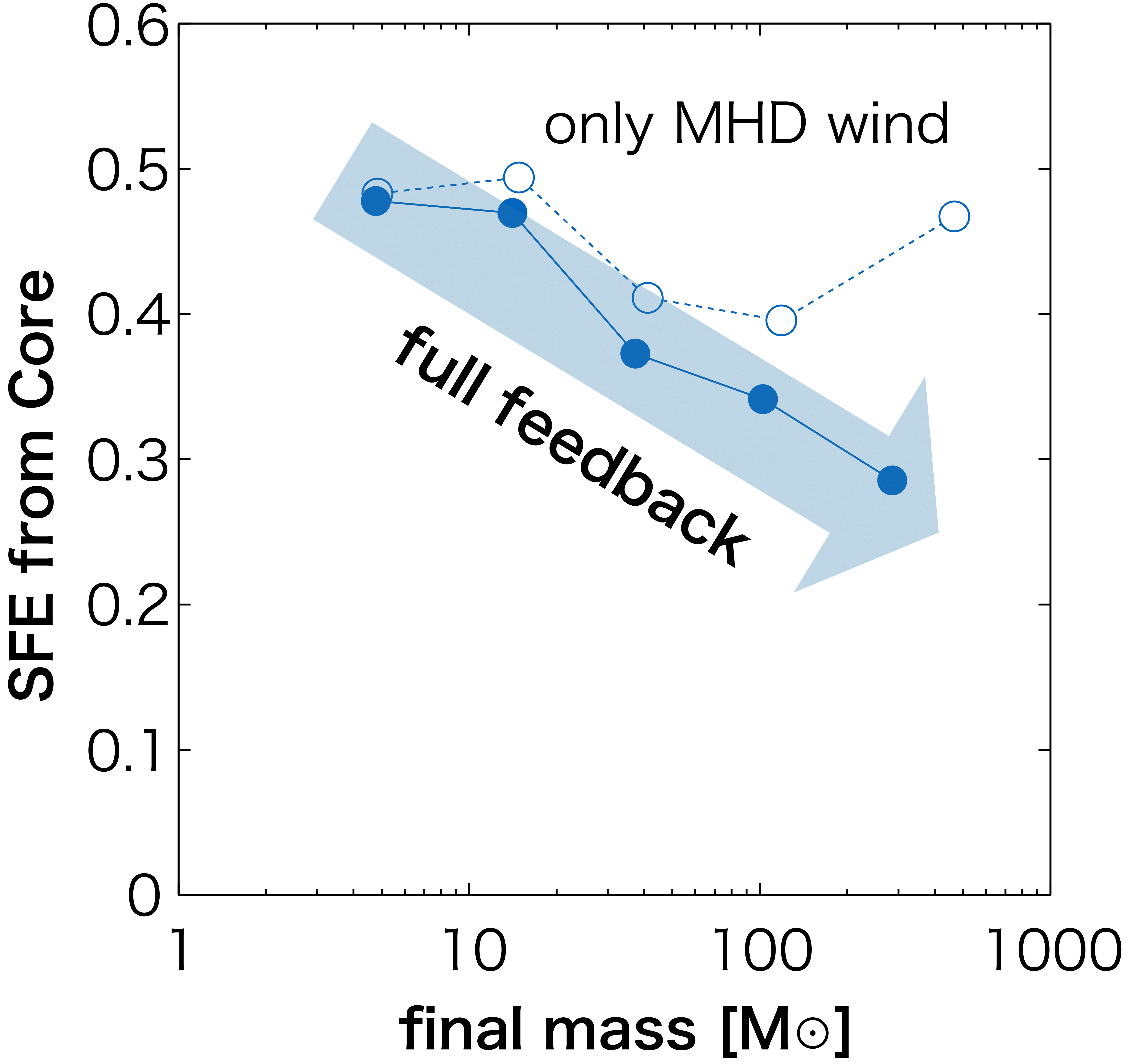
Accretion History



Radiative feedback reduces SFE

SFE=0.47→0.29 in this case

Star Formation Efficiencies



lower SFE in higher-mass SF

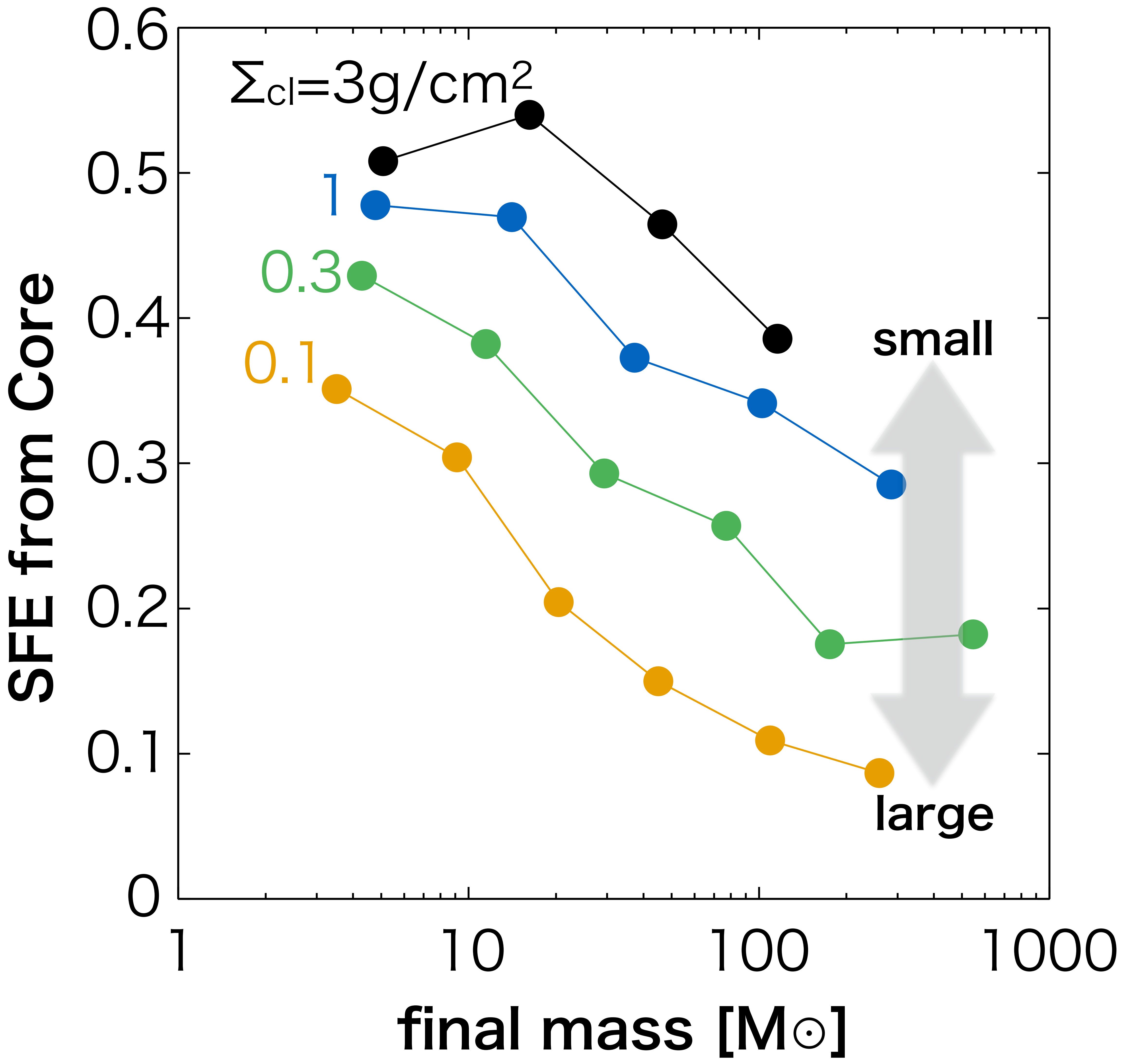
due to radiative feedback

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⊙

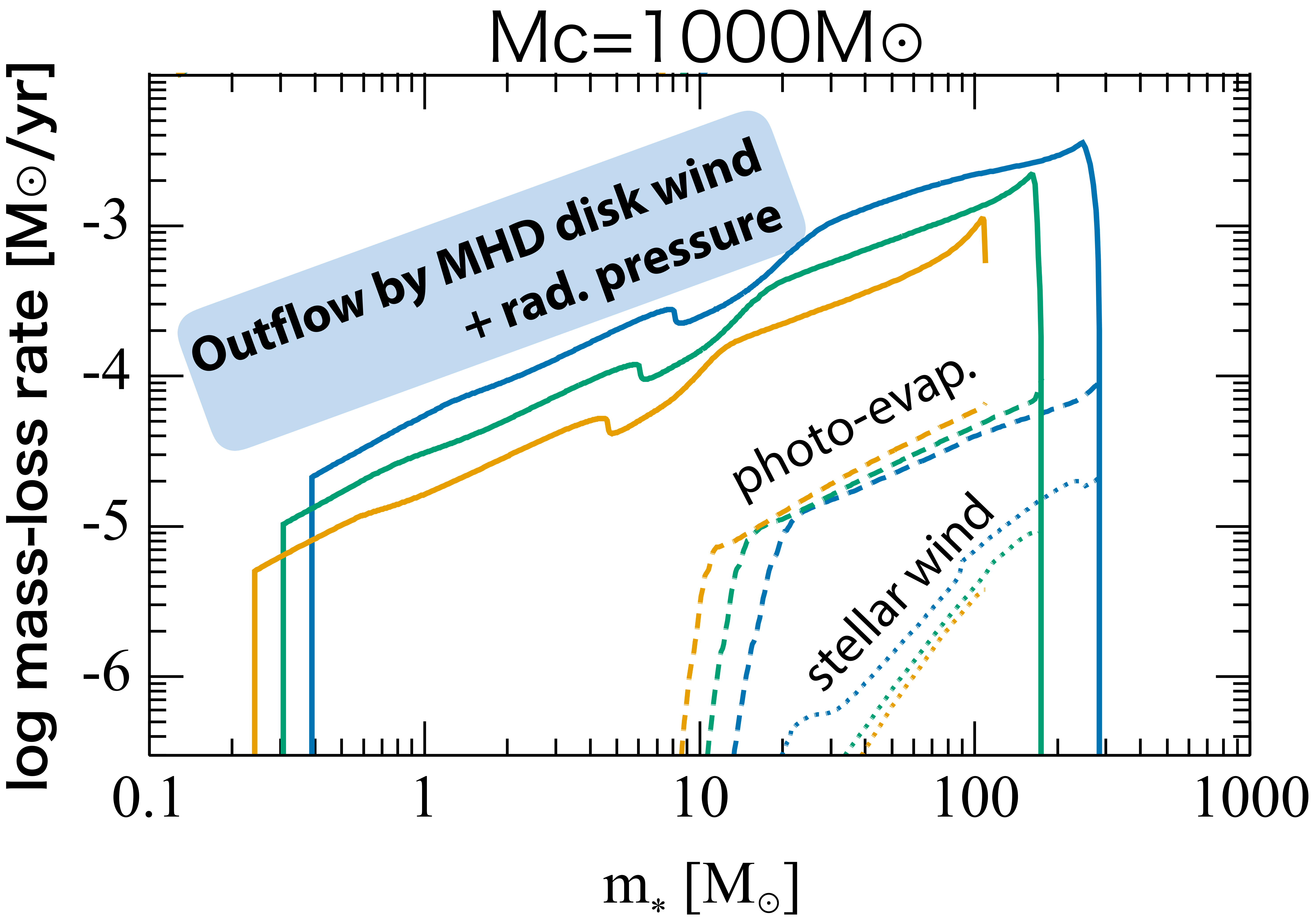
cf. stars with >100M⊙ in 30 Dor

lower SFE at larger core

difficult to form very-massive stars
by the competitive accretion

reasonable agreement with recent simulations
by Kuiper & Hosokawa 2018

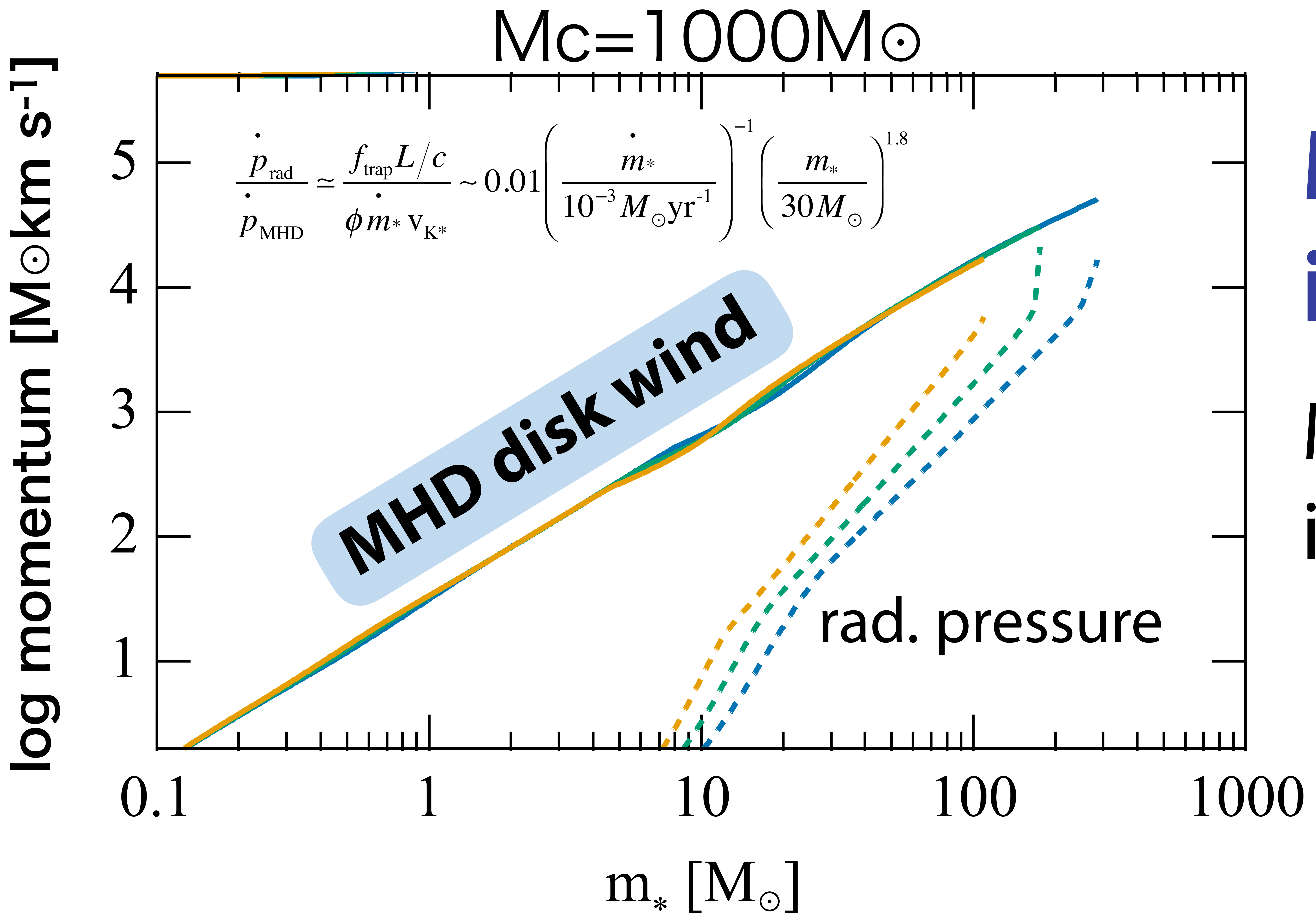
Which is the dominant feedback?



Momentum-driven outflow is dominant

MHD disk wind?
or
Radiation pressure?

Which is the dominant feedback?



Mc=1000M⊙

$$\frac{\dot{p}_{\rm rad}}{\dot{p}_{\rm MHD}} \simeq \frac{f_{\rm trap} L/c}{\phi \dot{m}_* {\rm v}_{\rm K*}} \sim 0.01 \left(\frac{\dot{m}_*}{10^{-3} M_\odot {\rm yr}^{-1}}\right)^{-1} \left(\frac{m_*}{30 M_\odot}\right)^{1.8}$$

MHD disk wind is dominant!!

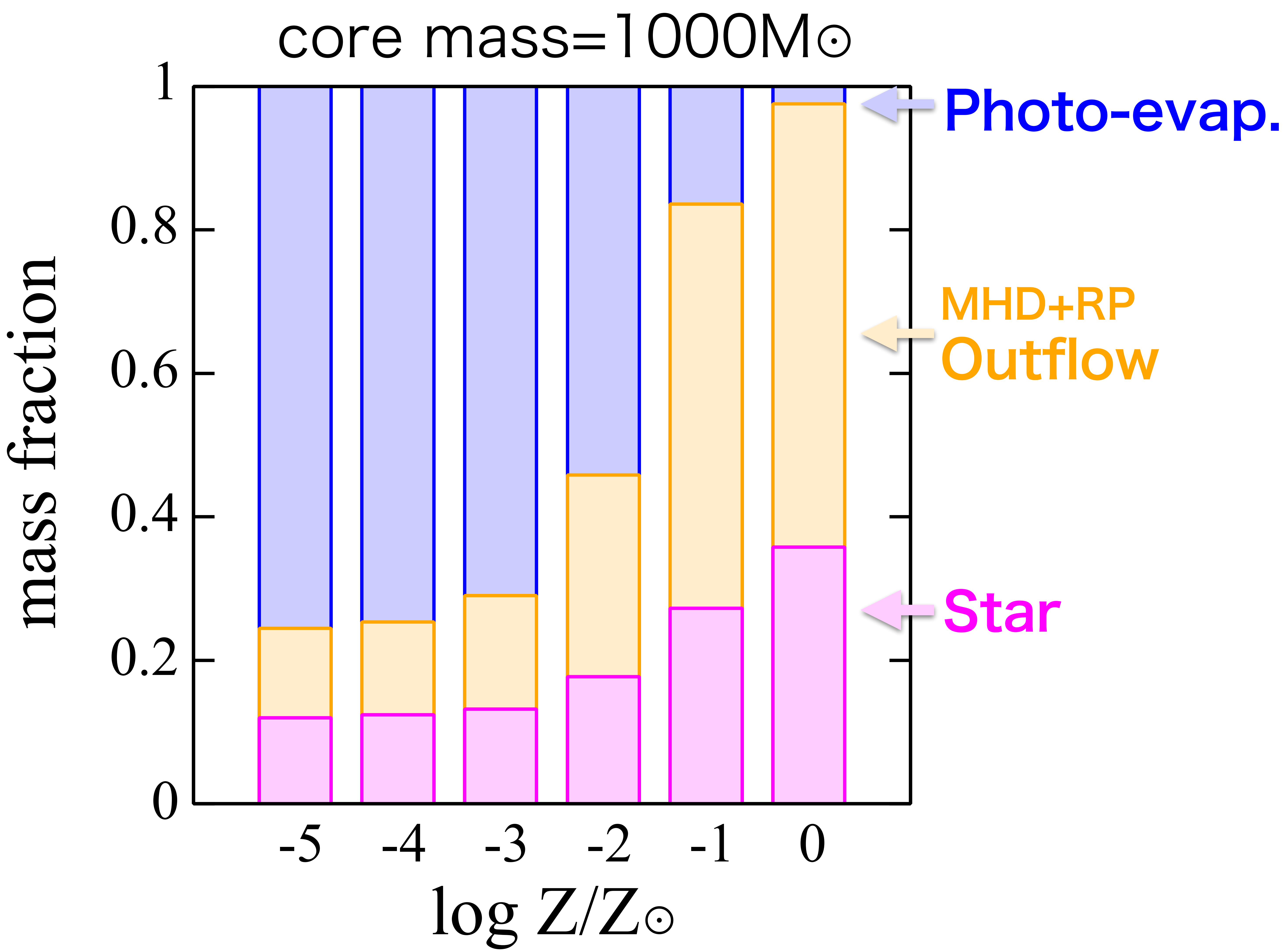
Massive star formation is similar to low-mass SF.

at Z⊙

Metallicity Dependence

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

Feedback at Low Metallicities



At Z⊙,
Outflow is strongest

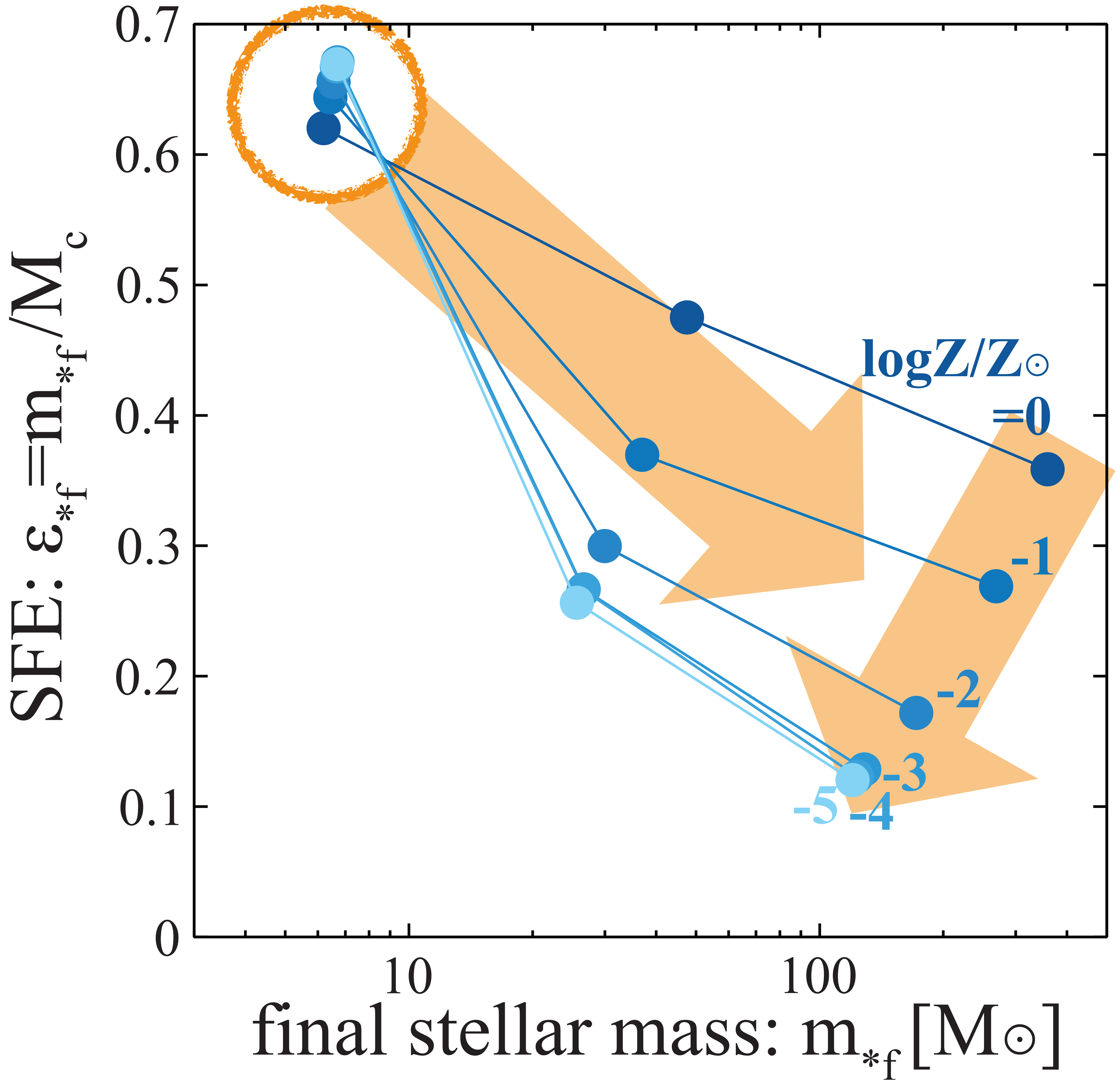
At <0.01Z⊙,
PE becomes dominant

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 $Z<1e-3Z_\odot$

SFEs at Various Metallicities



Feedback does not set the upper-mass limit!

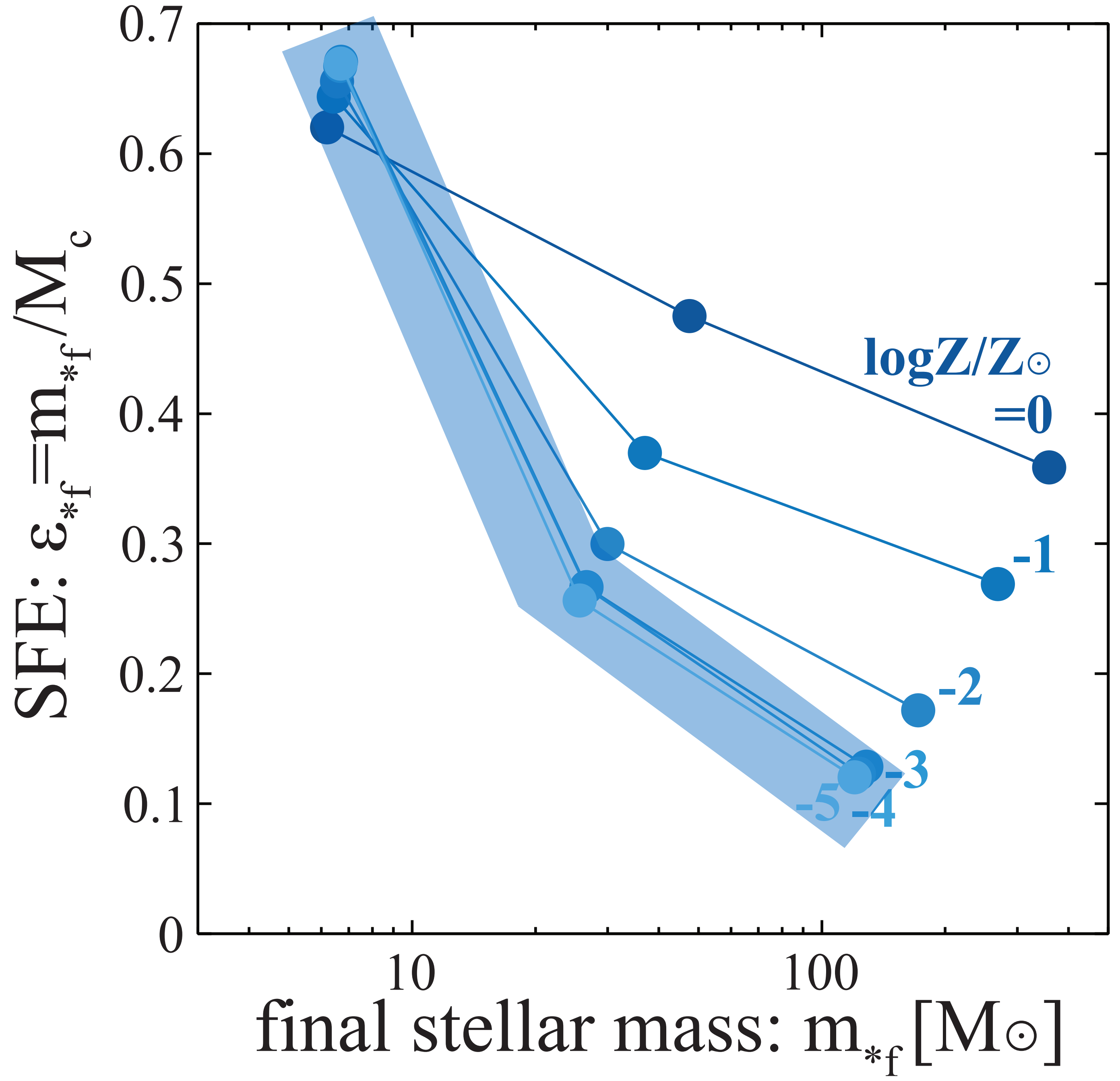
lower SFE in higher-mass SF
due to stronger feedback

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

Non-Universal IMF?

Massive stars might be rarer at 1e-3-1e-5Z⊙?

KT+18

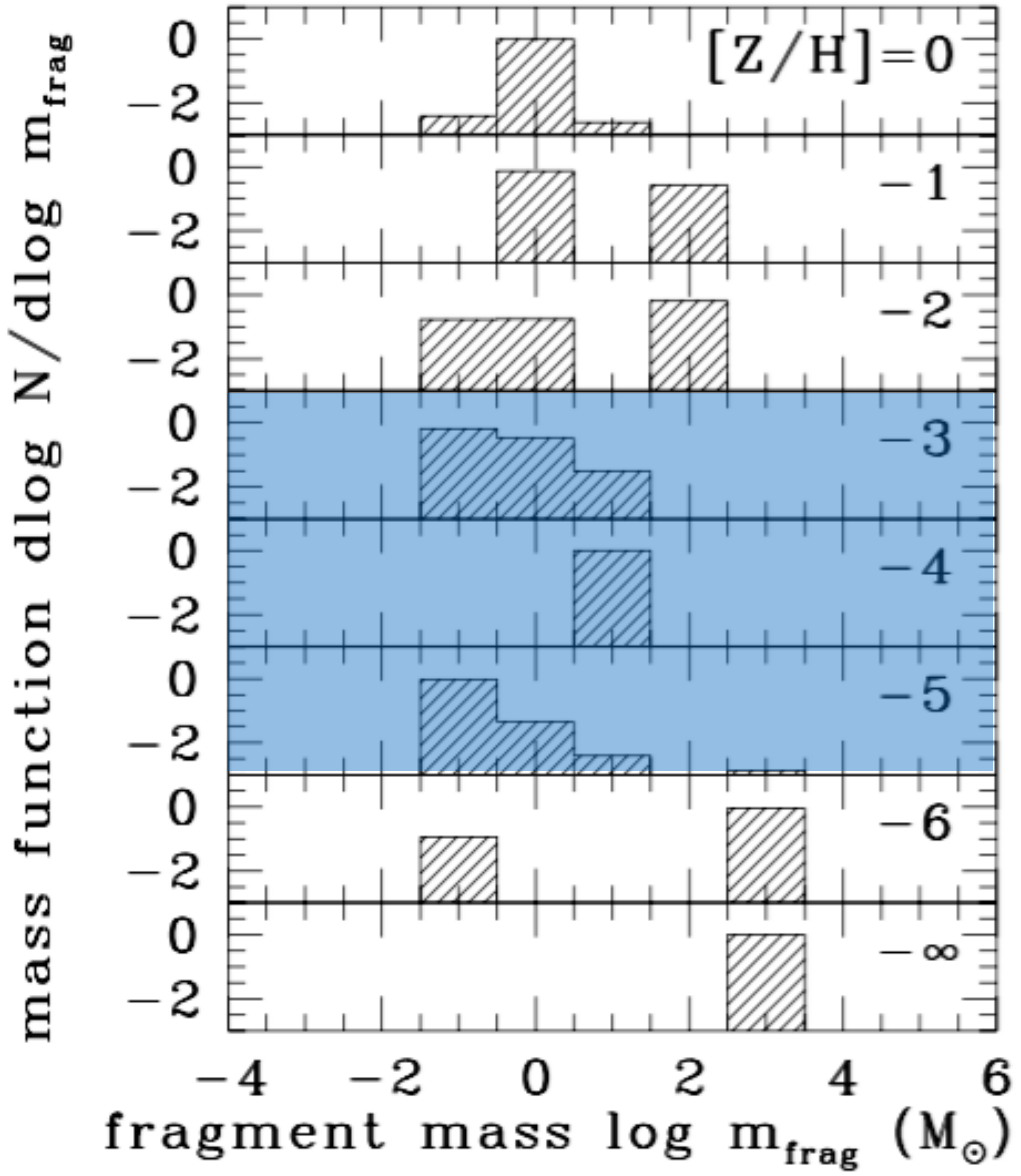


Feedback is strong

efficient PE

If CMF is Salpeter with -1.35,
IMF slope is ~ -2.1!!

Omukai&Tsuribe05

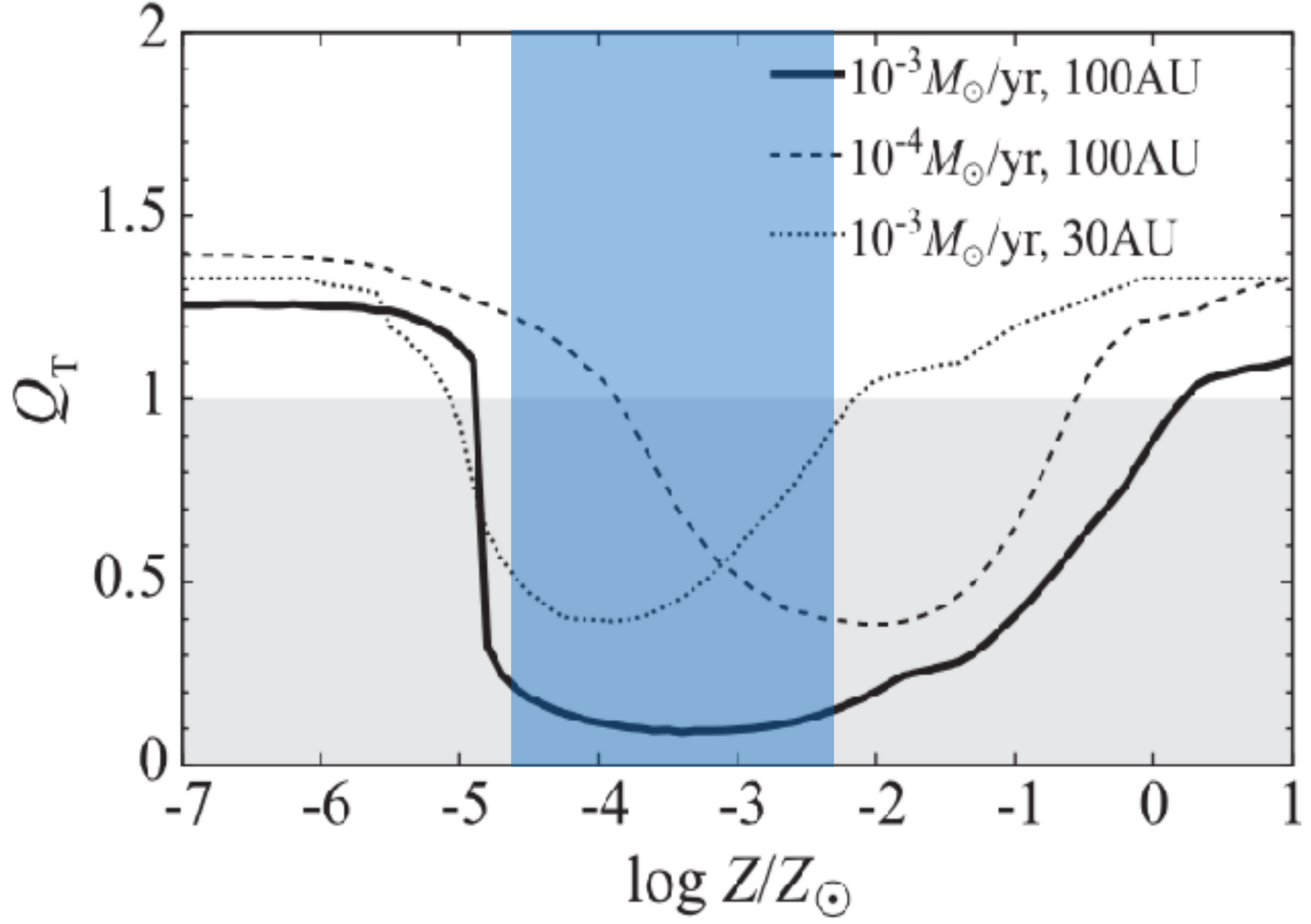


Massive core is rare

by dust cooling

low-mass core is common

KT&Omukai14



Disk is strongly unstable

due to efficient cooling (τ~1)

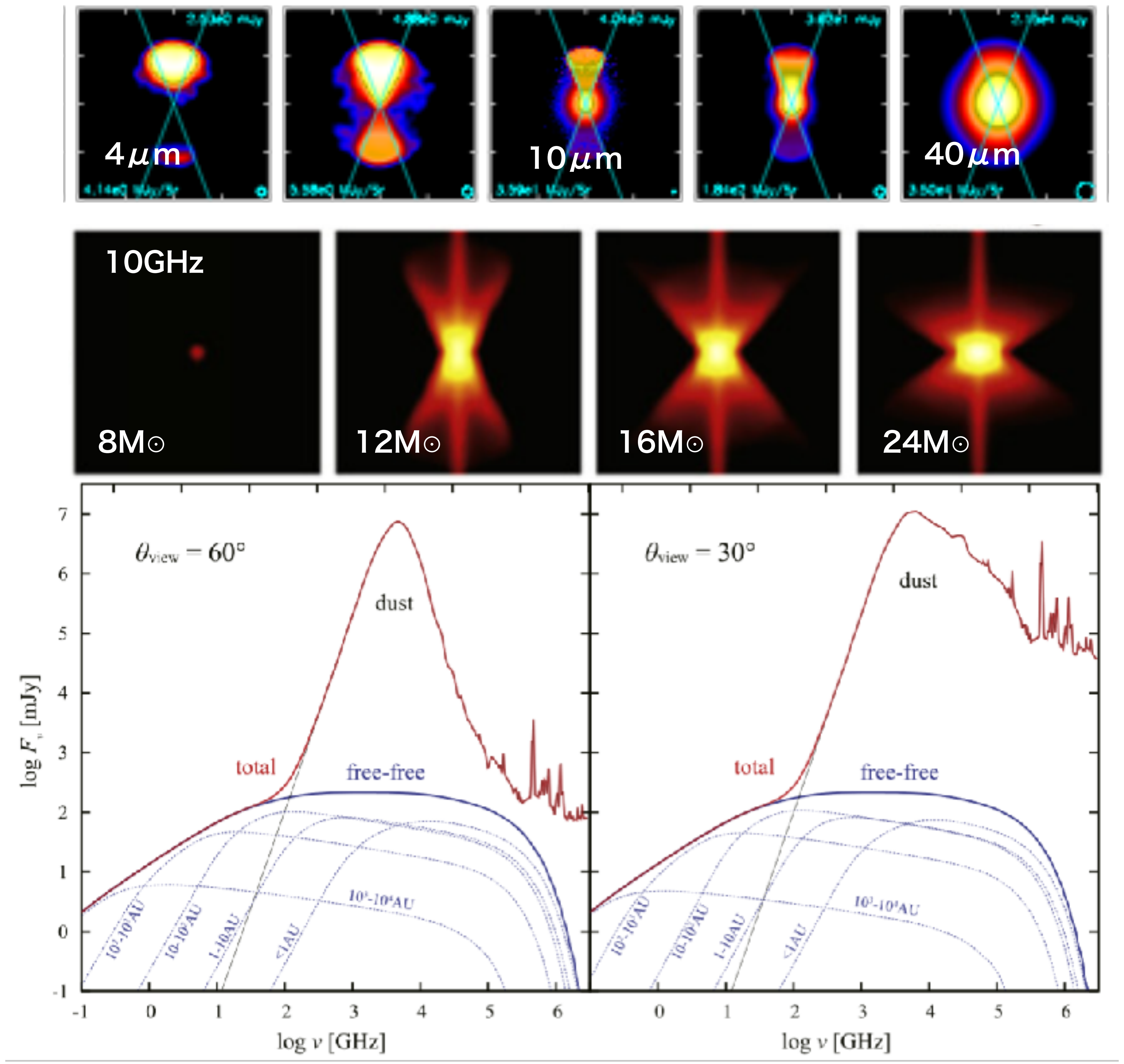
cf. close binary fraction is
higher at lower Z (Moe+18)

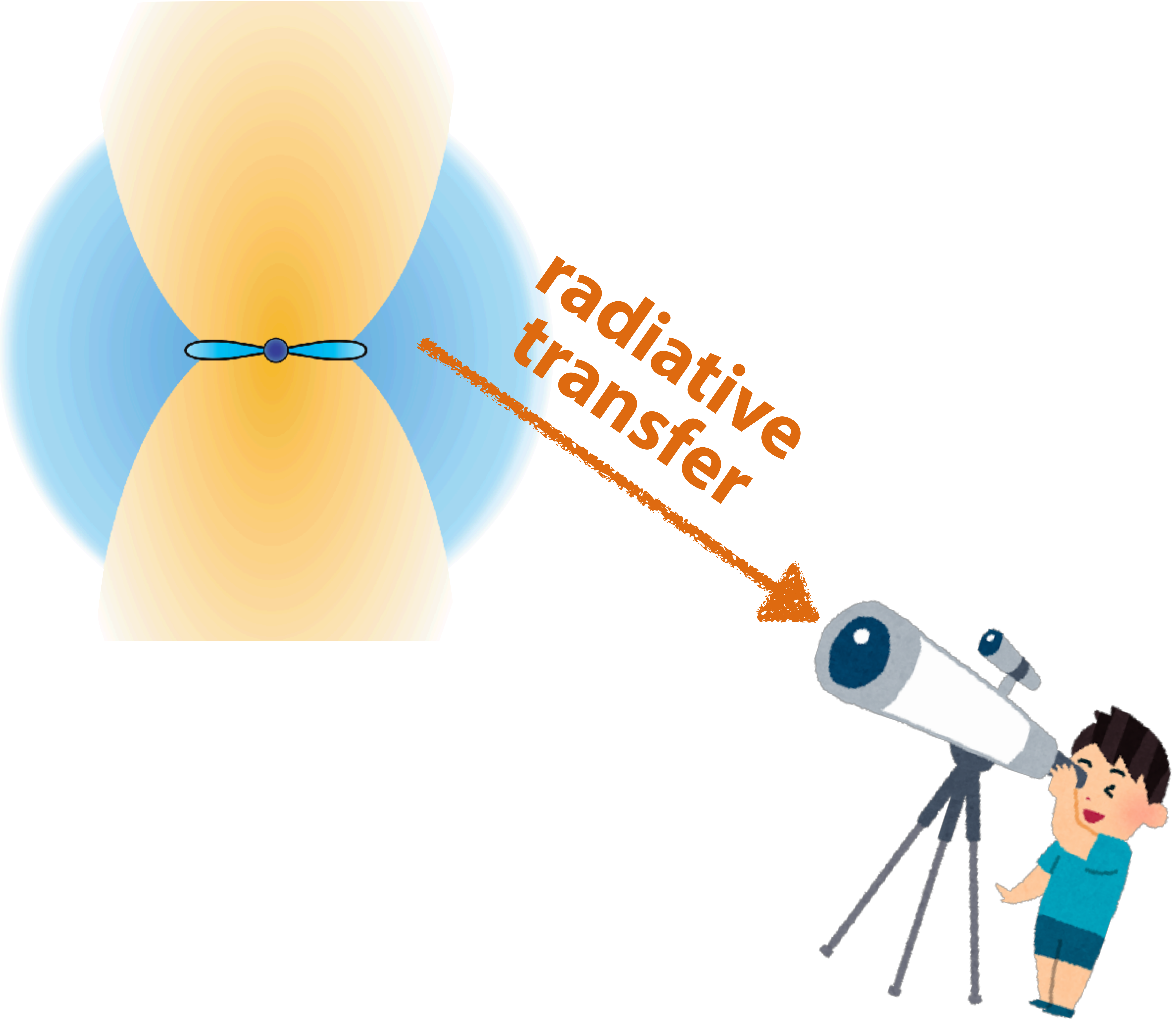
Synthetic & Actual Observations

synthetic observation:
KT+16, ApJ, 835, 32; **KT**+17, ApJ, 849, 133; etc.
actual observation:
De Buizer+**KT**17, ApJ, 843, 33;
Rosero, **KT**+, *submitted* to ApJ, arXiv:1809.01264;
Zhang, Tan, Sakai, **KT**+, *submitted* to ApJ, arXiv:1811.04381;
Zhang, Tan, **KT**+ *submitted*; etc.

Synthetic & Actual Observations

Synthetic Observations





Synthetic & Actual Observations

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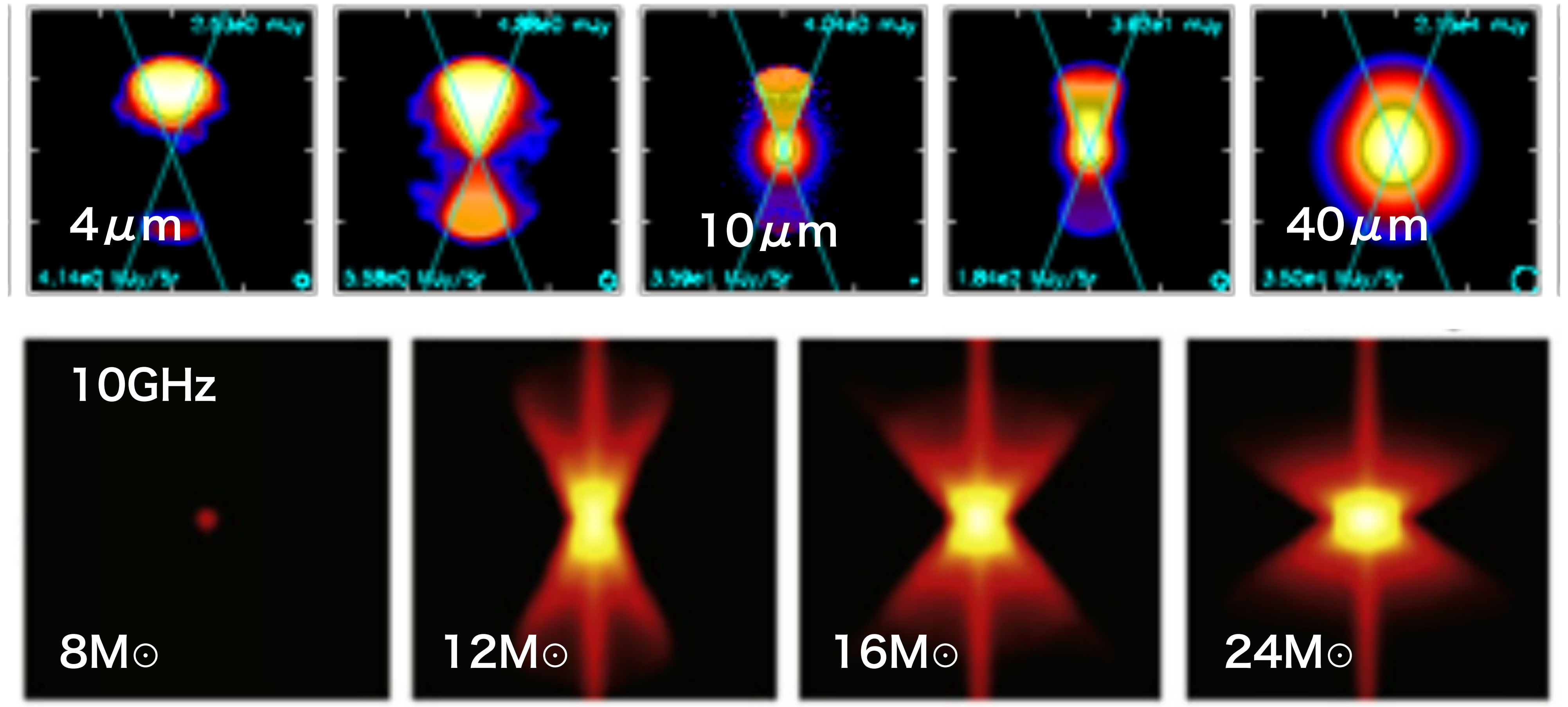
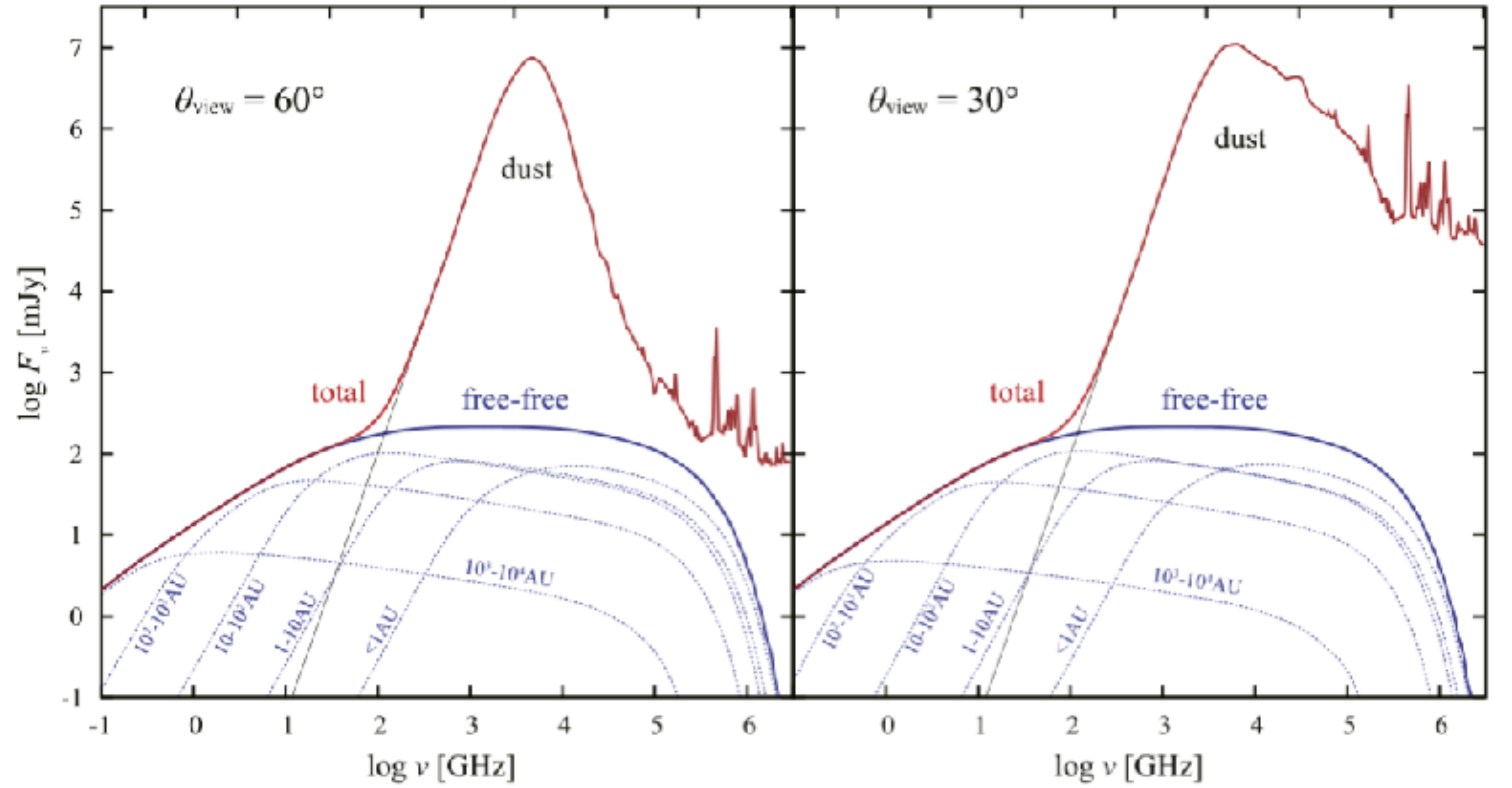
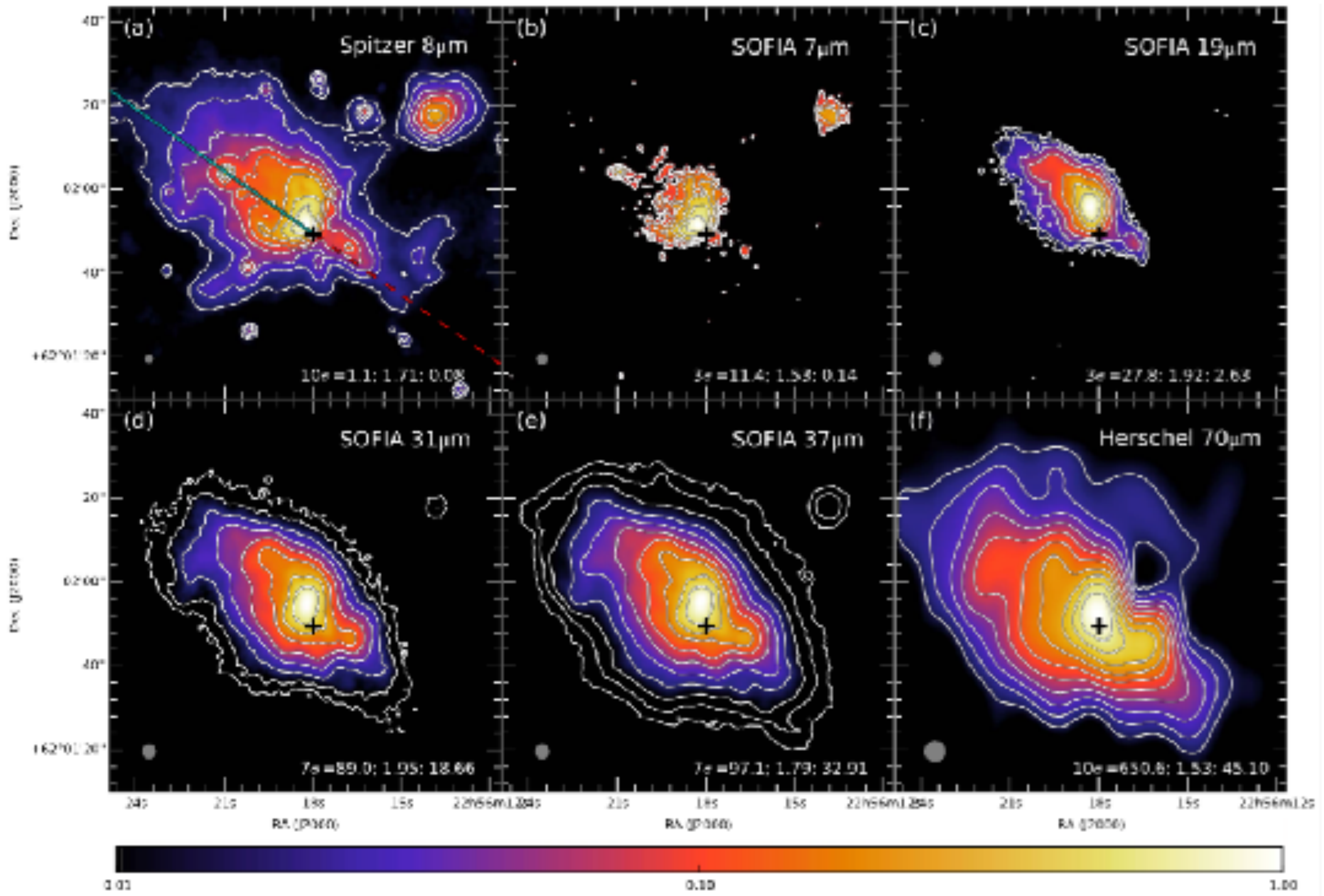
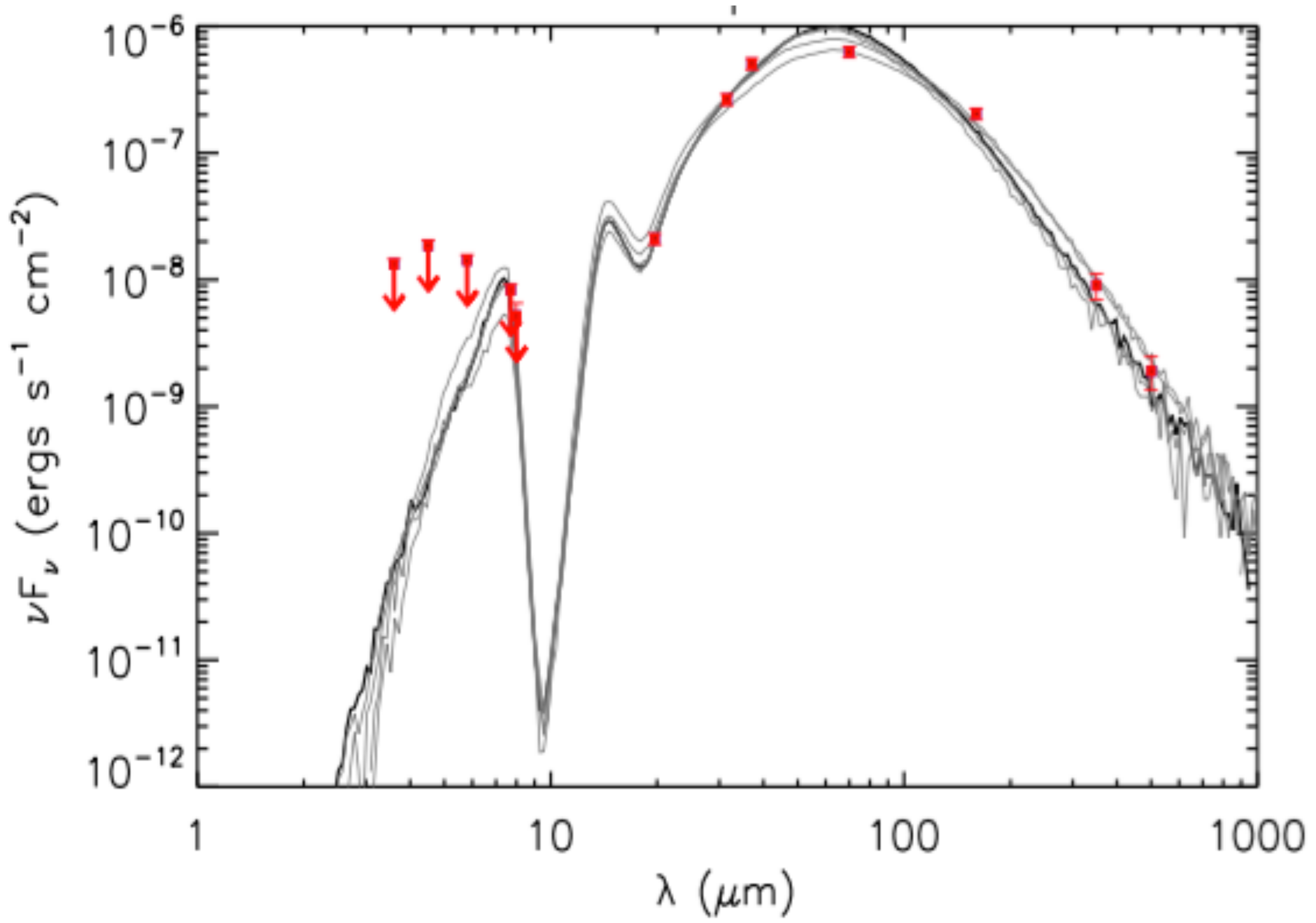


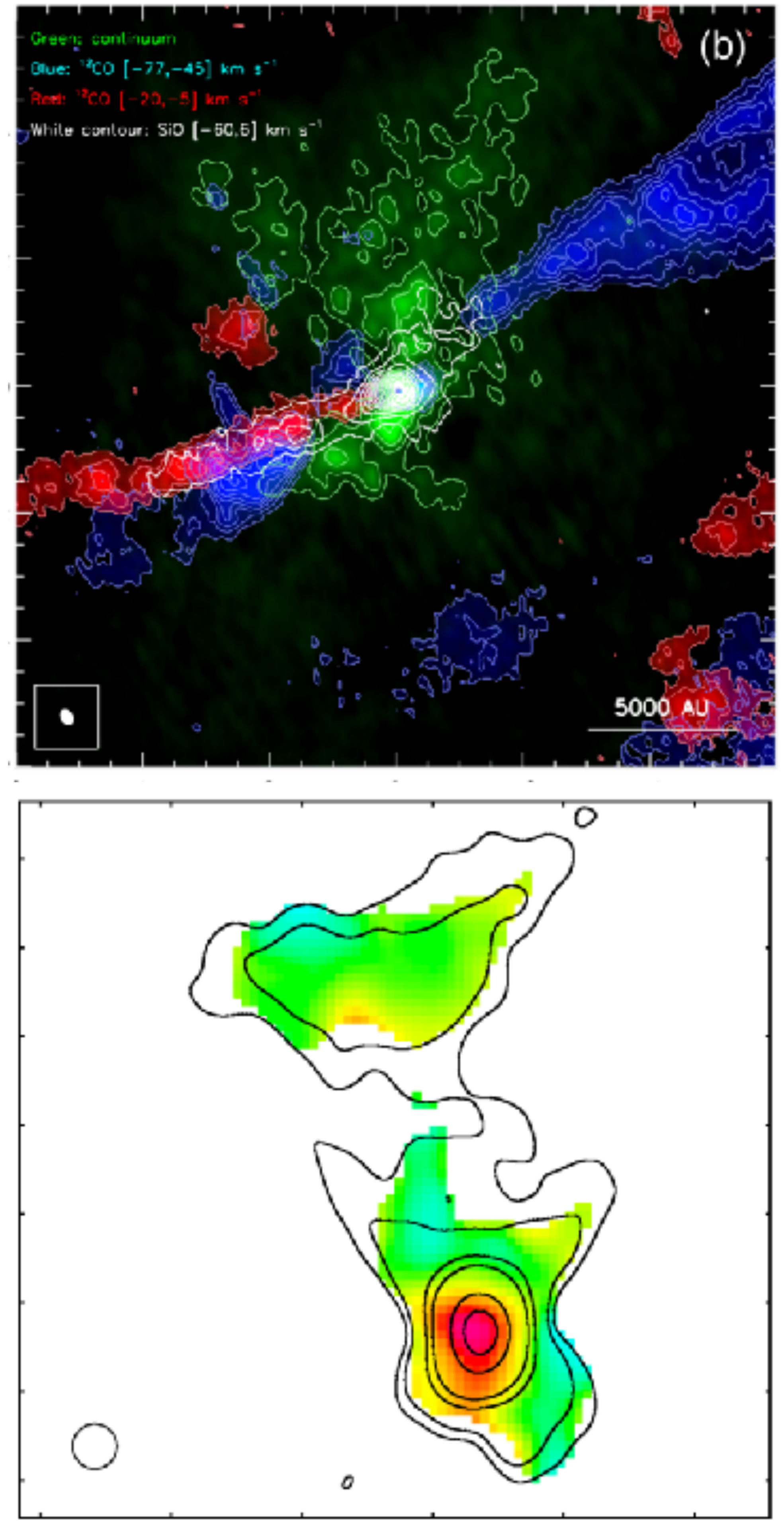


IR survey by SOFIA





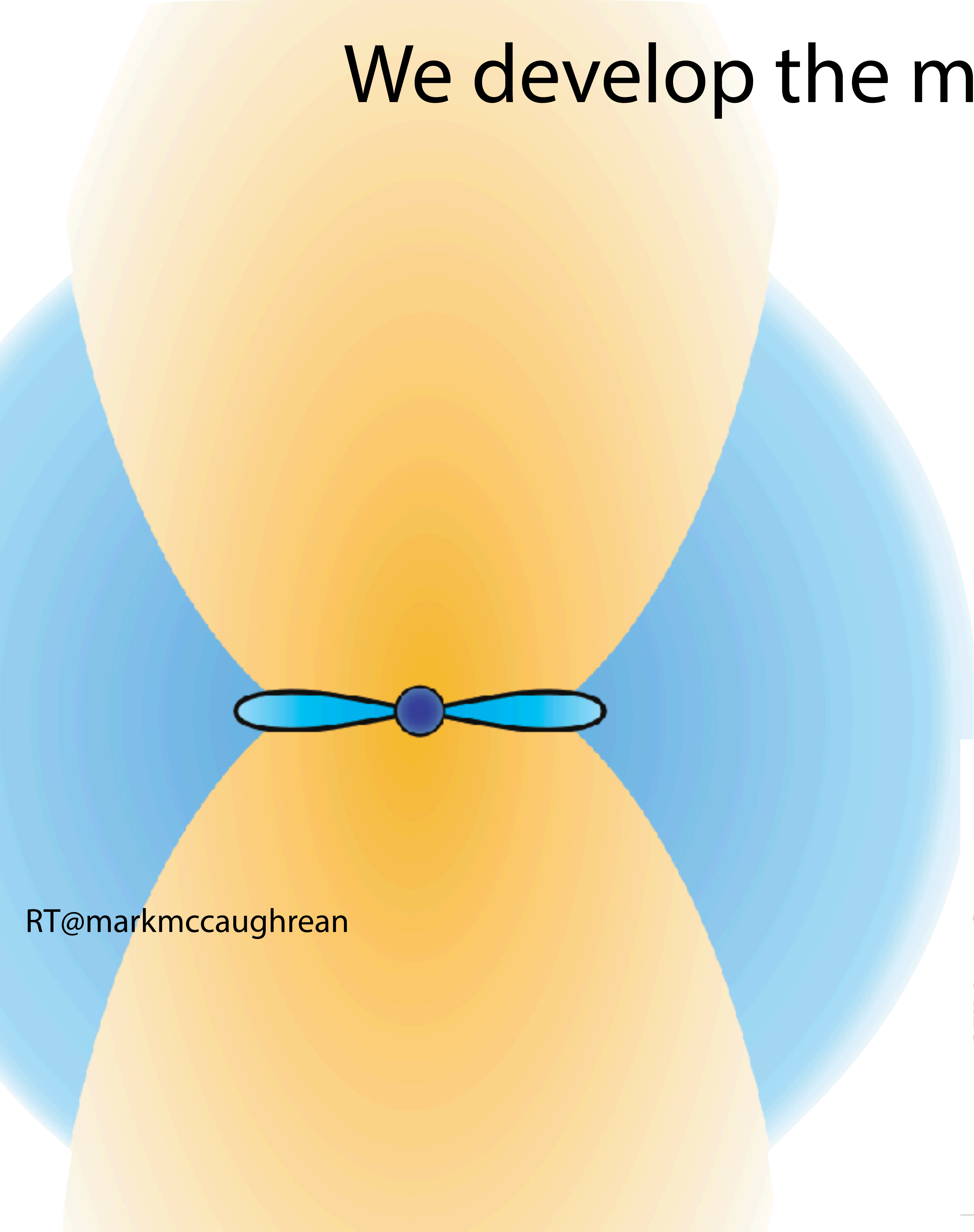
follow-up by ALMA & VLA



Summary

Multiple Feedback in Massive SF

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


RT@markmccaughrean

Feedback does not set the upper mass limit

MHD disk wind is dominant at >0.1Z⊙

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

→ ***Massive stars are rarer at 1e-3-1e-5Z⊙?***

Observations are also on-going