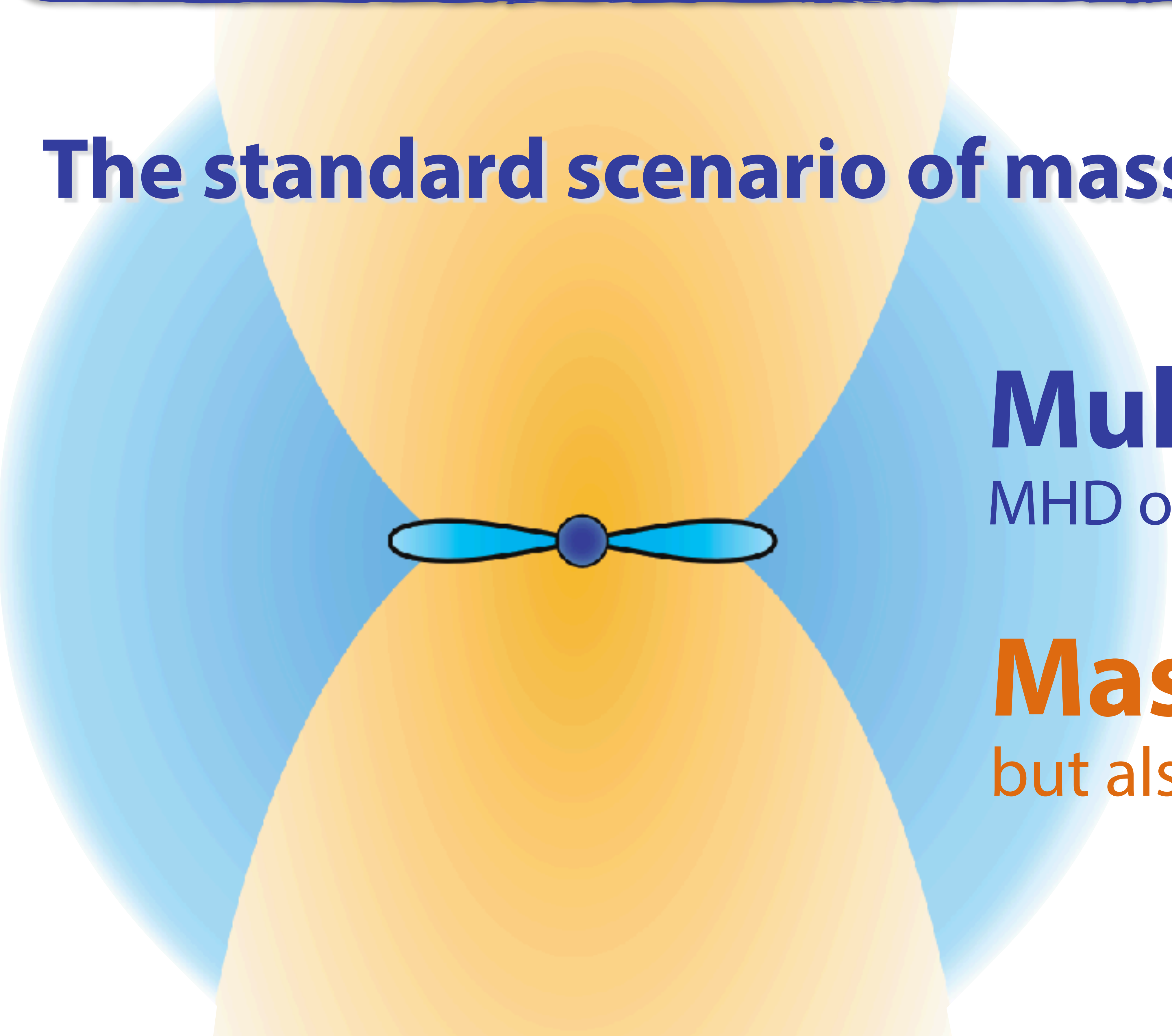
大質量星形成における複合フィードバック
とその金属量依存性

田中圭 (大阪大学 / 国立天文台)

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*



The standard scenario of massive star formation will soon be established!!

Multiple Feedback

MHD outflow, radiation pressure, ionization, stellar wind

Massive SF is similar to low-mass SF!!

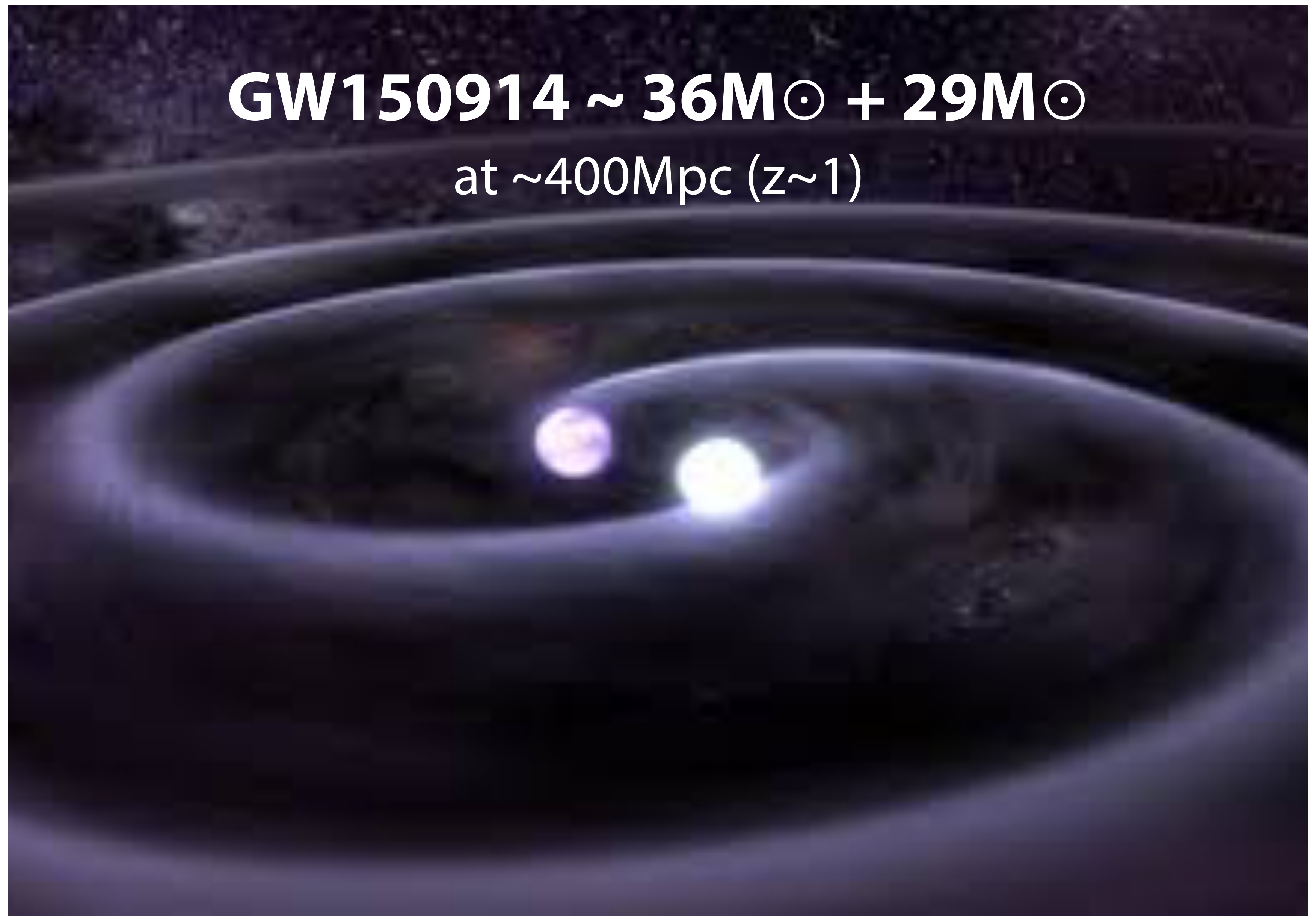
but also depends on metallicity, etc.

Massive Stars
& Their Formation

Massive Stars are Important!!

Massive stars (>10M☉) are rare (~1%)
but very bright (>10,000L☉)

UV radiation, stellar winds, SNe, metal/dust, BHs, NSs, etc.

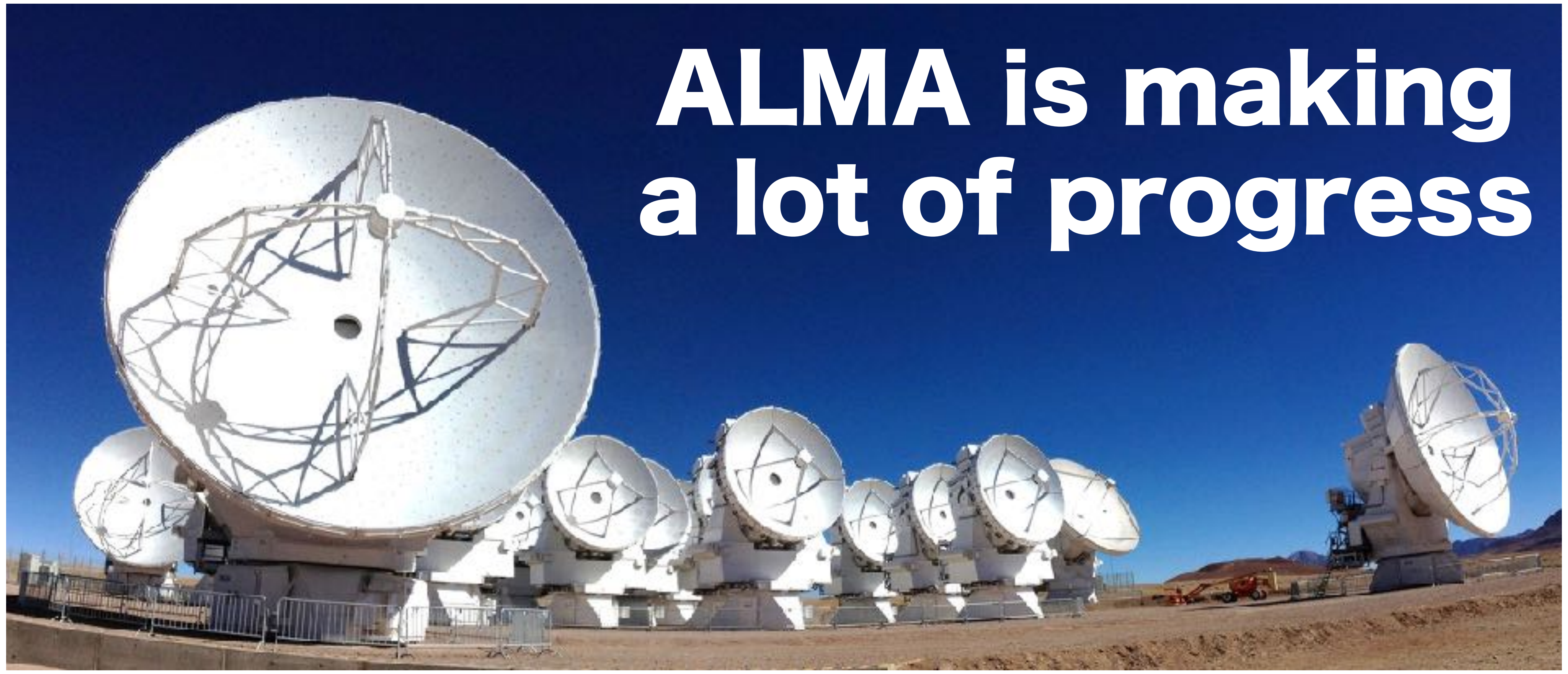


However, massive SF is poorly understood…

Observational Difficulties/Progress

Faraway	**Complex**
rare	embedded
short-lived	jam-packed

BUT



ALMA is making a lot of progress

Observational Difficulties/Progress

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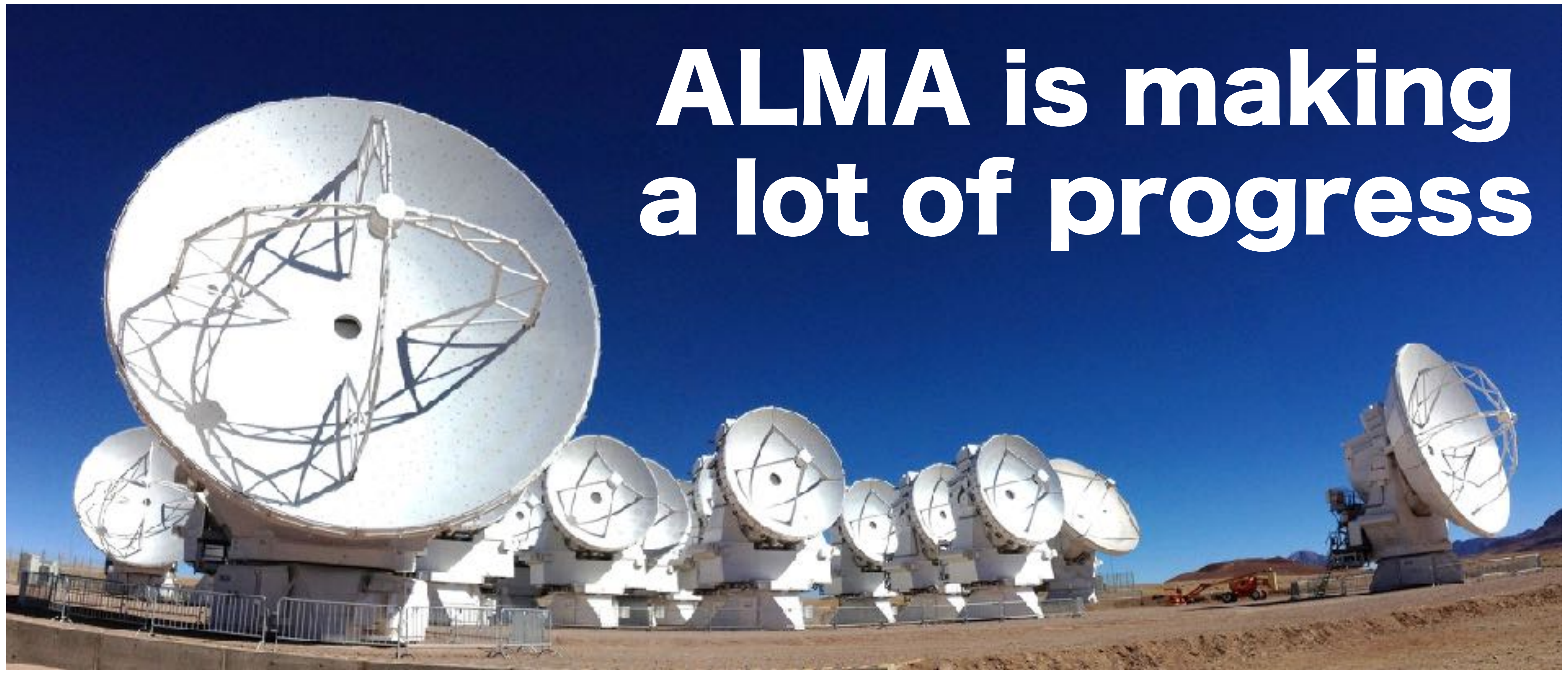
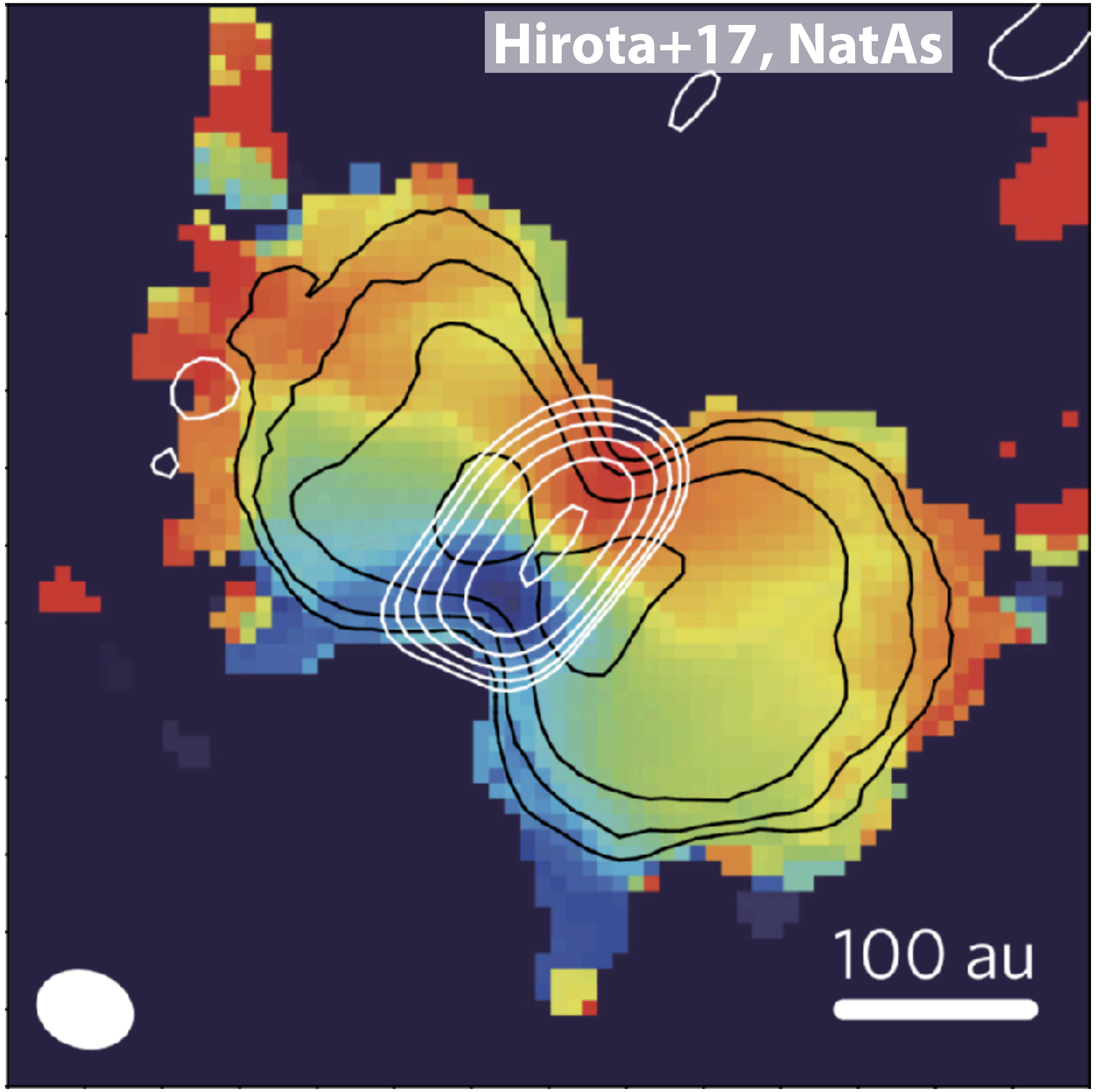

ALMA is making a lot of progress


Hirota+17, NatAs

Observational Difficulties/Progress

Faraway
- rare
- short-lived

Complex
- embedded
- jam-packed

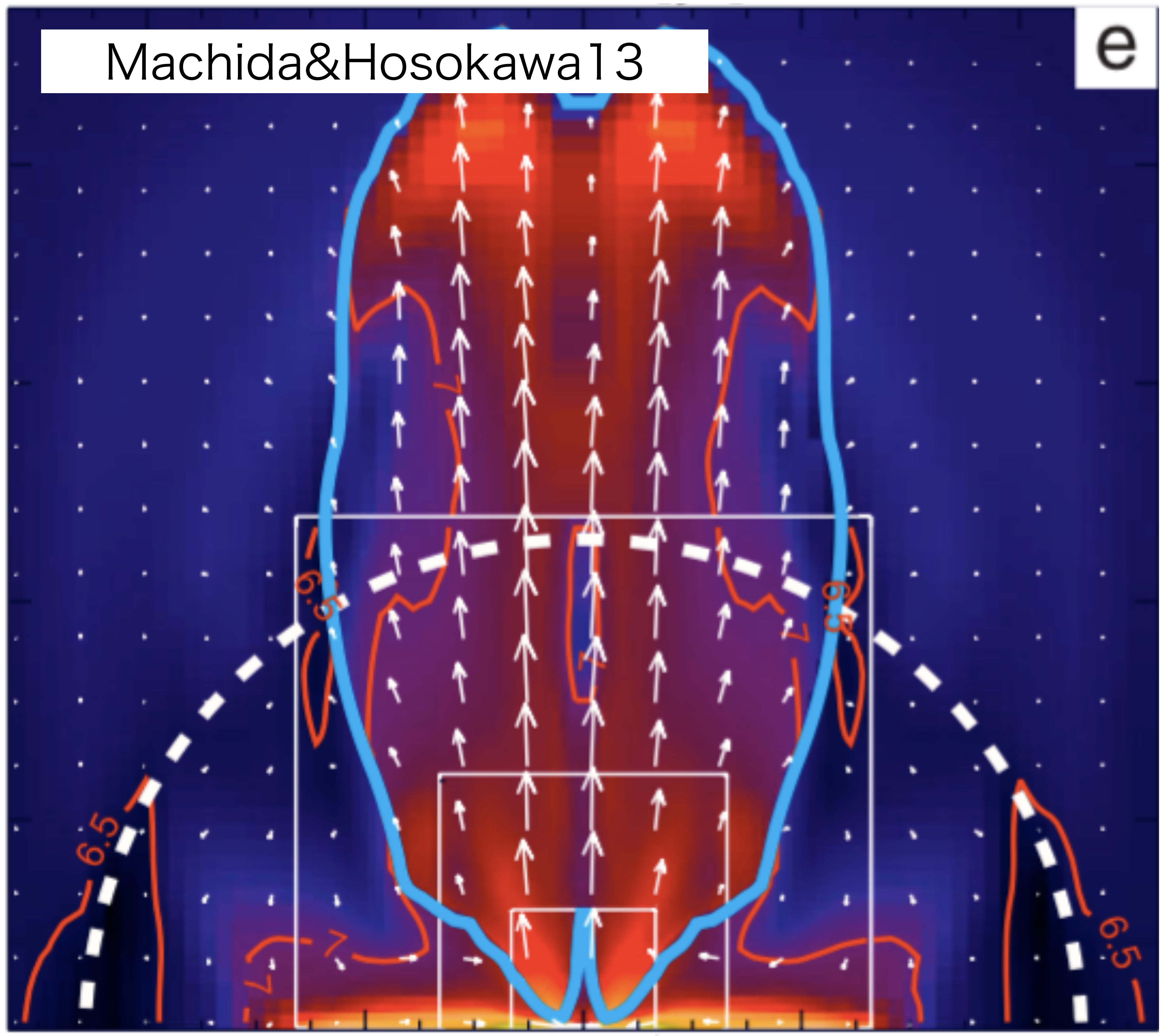
BUT

How about theories?

Feedback Problem

Feedback in Low-Mass Star Formation

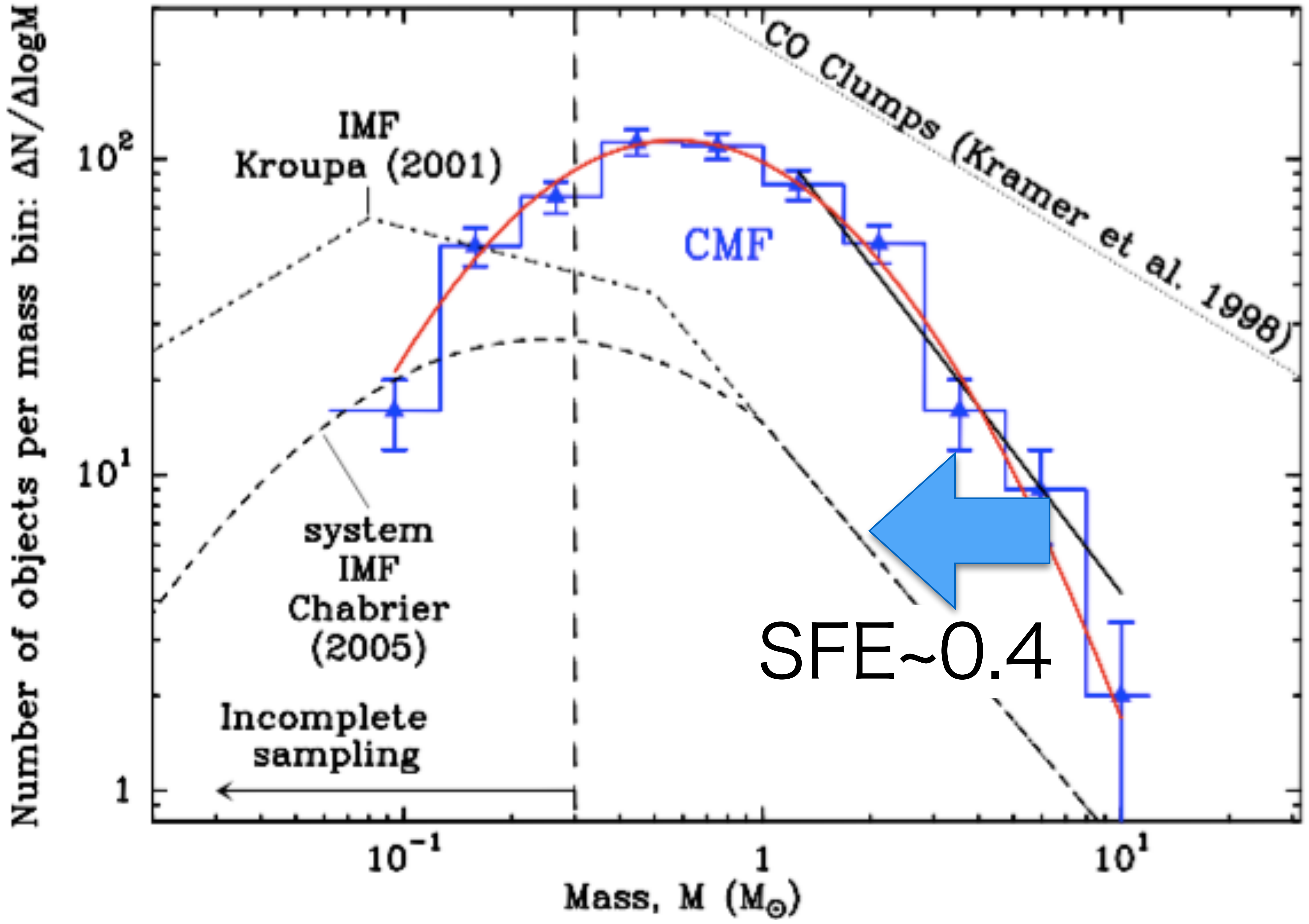
SFE ~ 0.4



low-mass SF

MHD Disk Wind

Andre+10



Feedback in Low-Mass Star Formation

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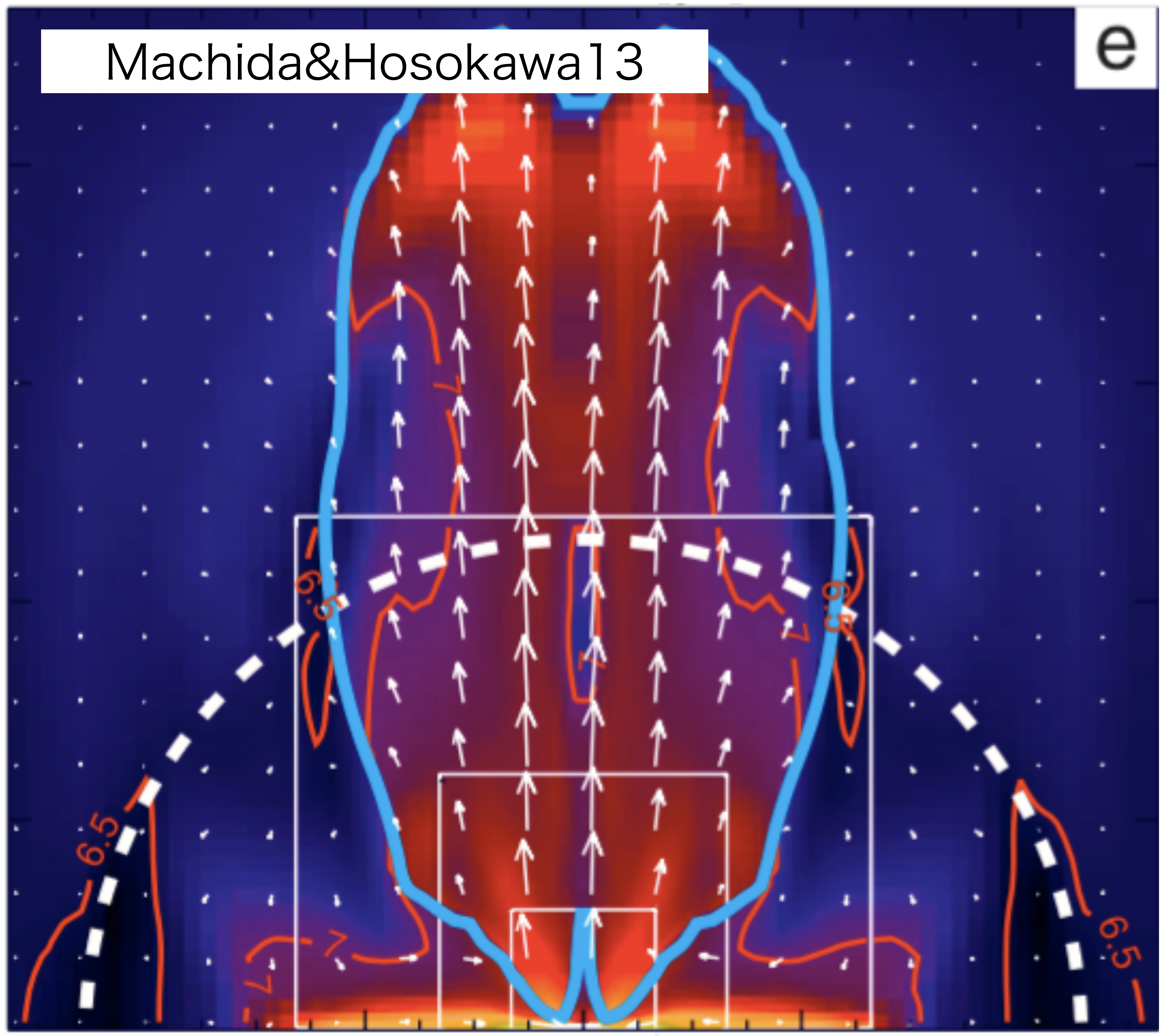
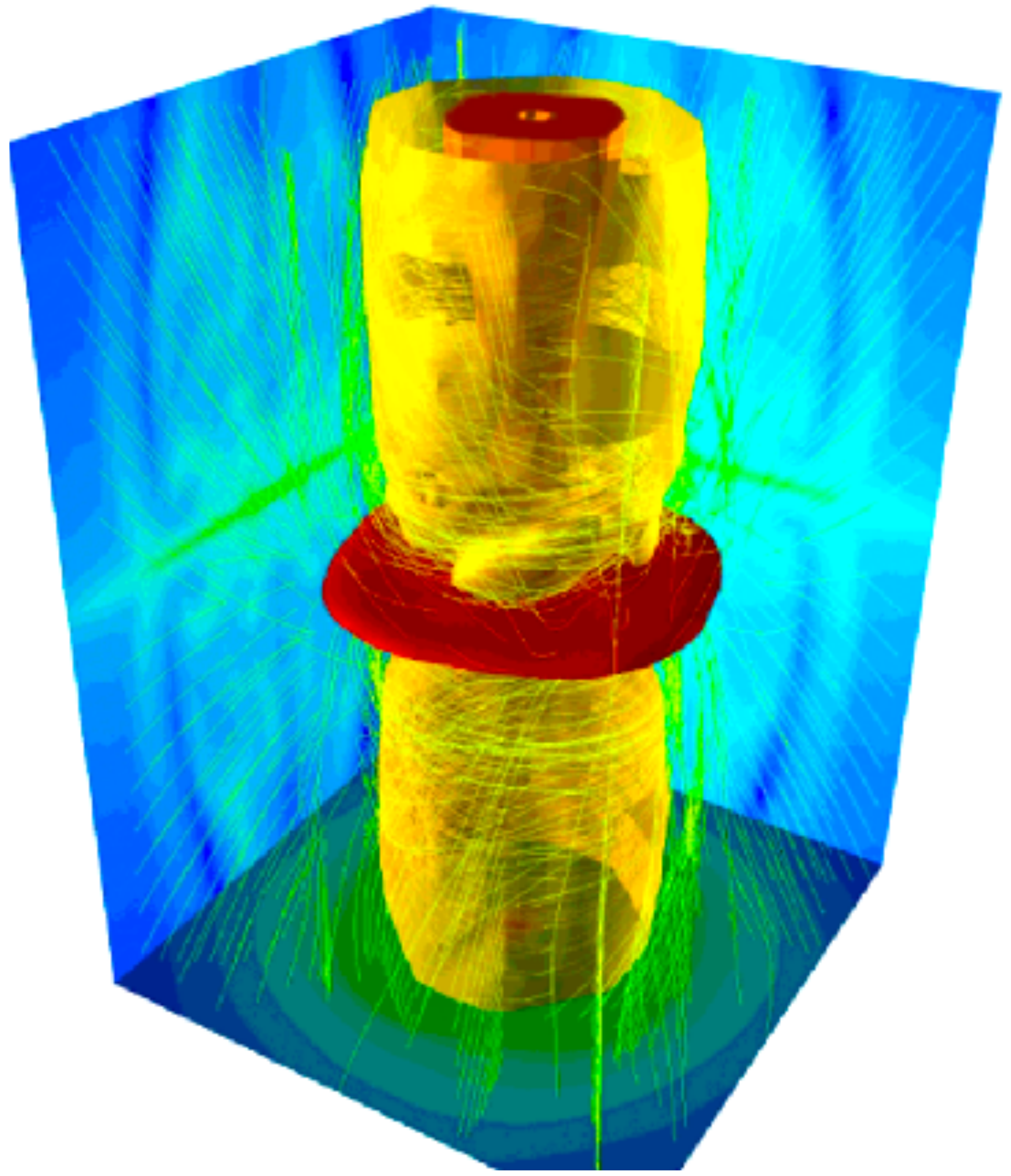


low-mass SF

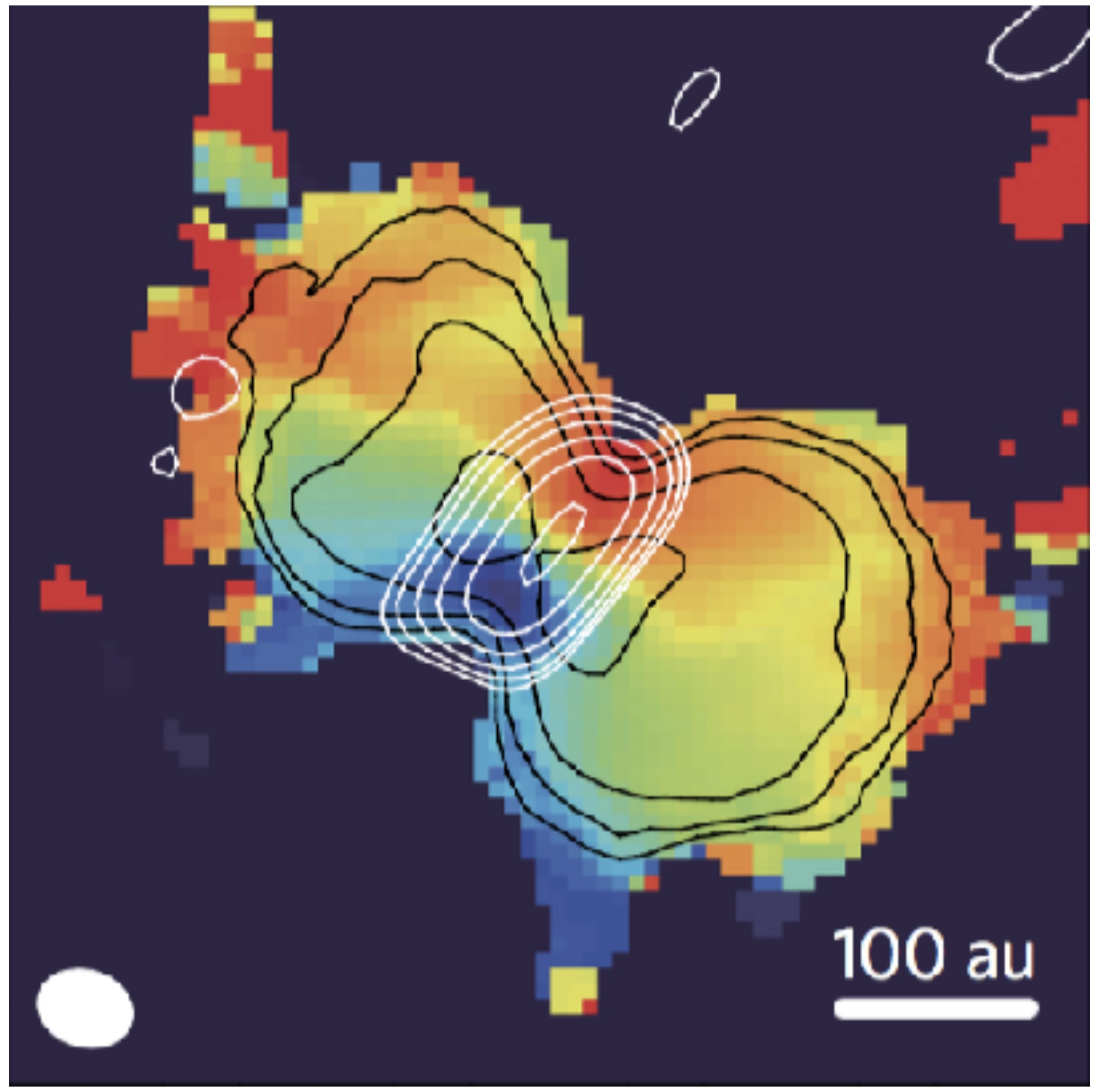
MHD Disk Wind

also in massive SF!!



Matsushita+17

Staff, KT & Tan, arXiv:1811.00954

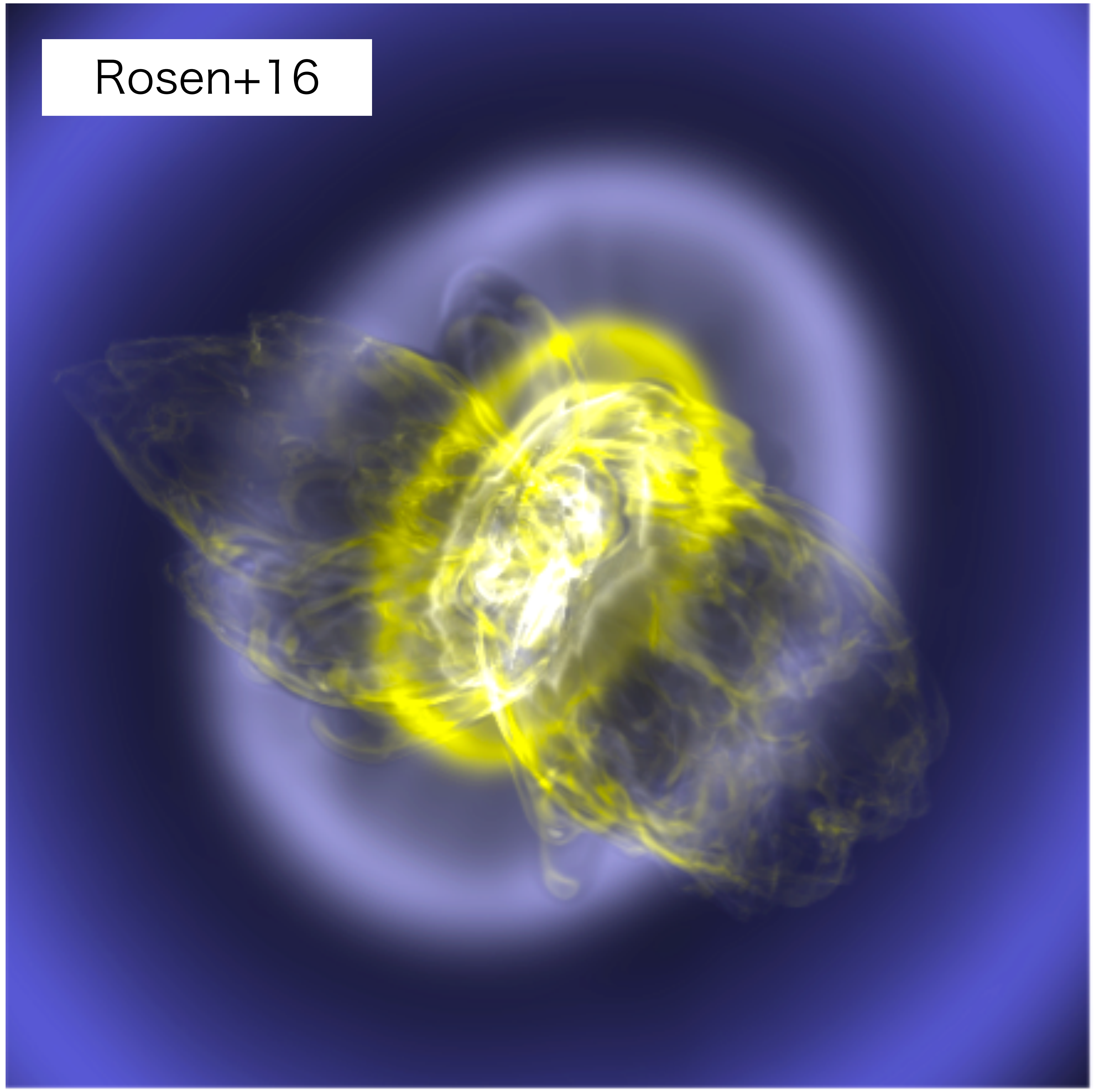


Hirota+17

Zhang, Tan, KT+, arXiv:1811.04381

Feedback in Massive Star Formation

Disk Accretion



low-mass SF

MHD Disk Wind

also in massive SF!! Matsushita+17, Hirota+18

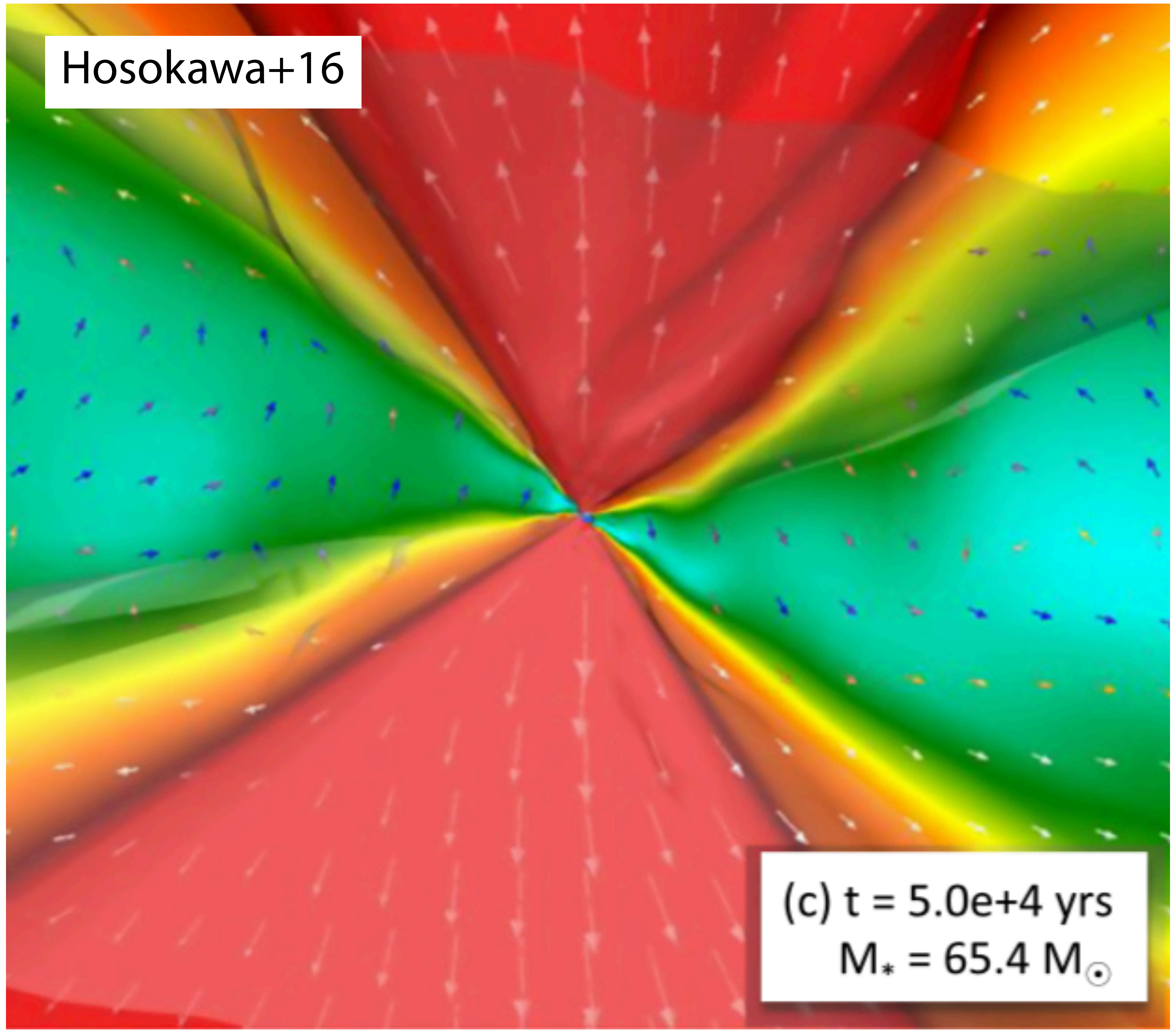
massive SF

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!! Matsushita+17, Hirota+18

massive SF

Radiation Pressure

Krumholz+09, Kuiper+10, etc

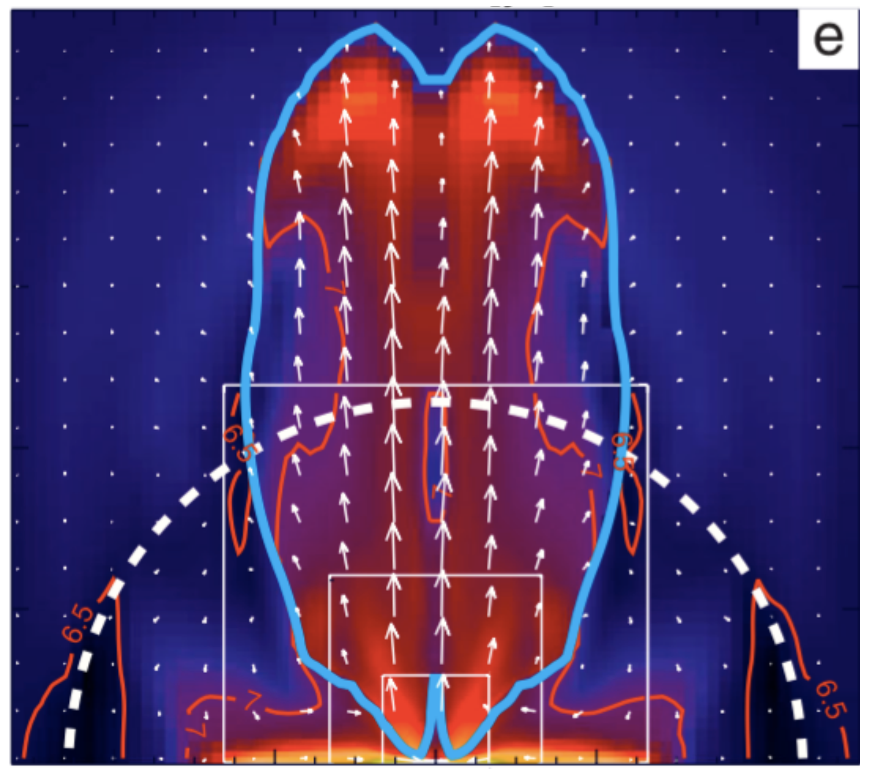
First SF in the early universe

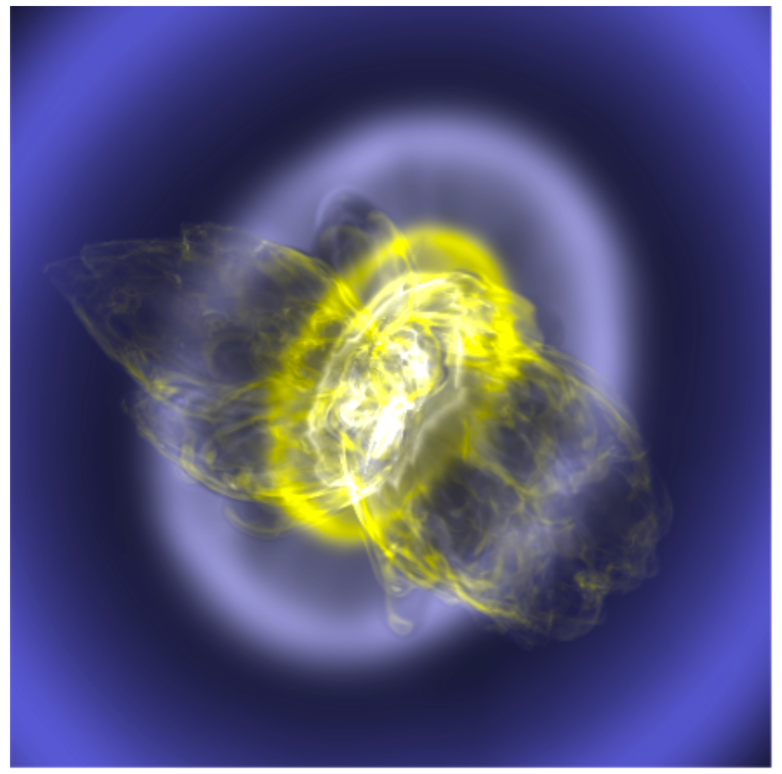
Photoevaporation

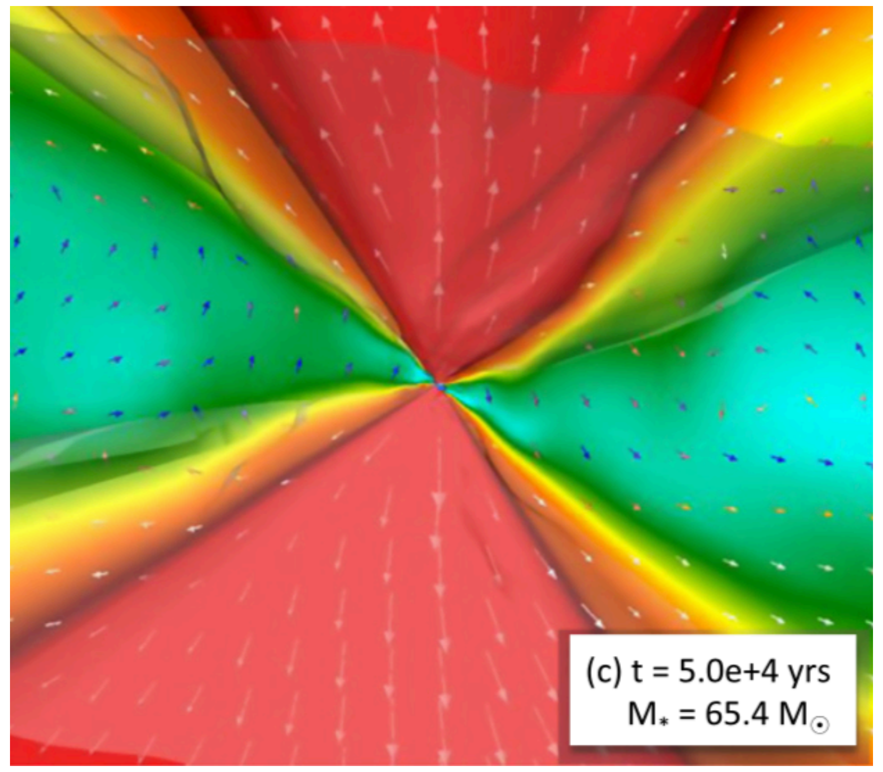
McKee&Tan08, Hosokawa+11, etc

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

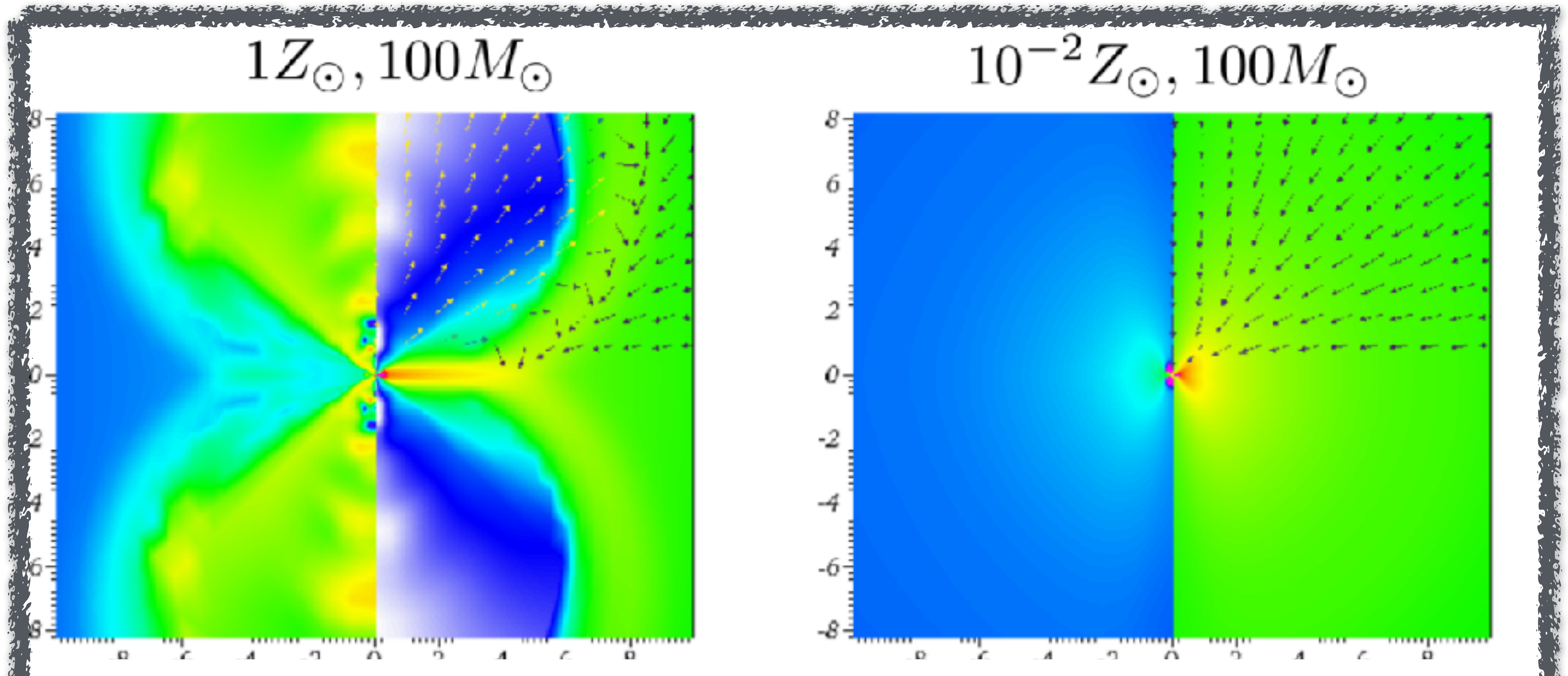
How do all feedback mechanisms work together?

Which is the dominant feedback?

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

How do they depend on metallicity and clump density?

Multiple Feedback in Massive SF



recall Fukushima-kun's talk

low-mass SF

MHD Disk Wind

massive SF

Radiation Pressure + **Stellar Wind**

First SF

Photoevaporation

How do all feedback mechanisms work together?

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

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Model

Overview of Our Semi-Analytic Model

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

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

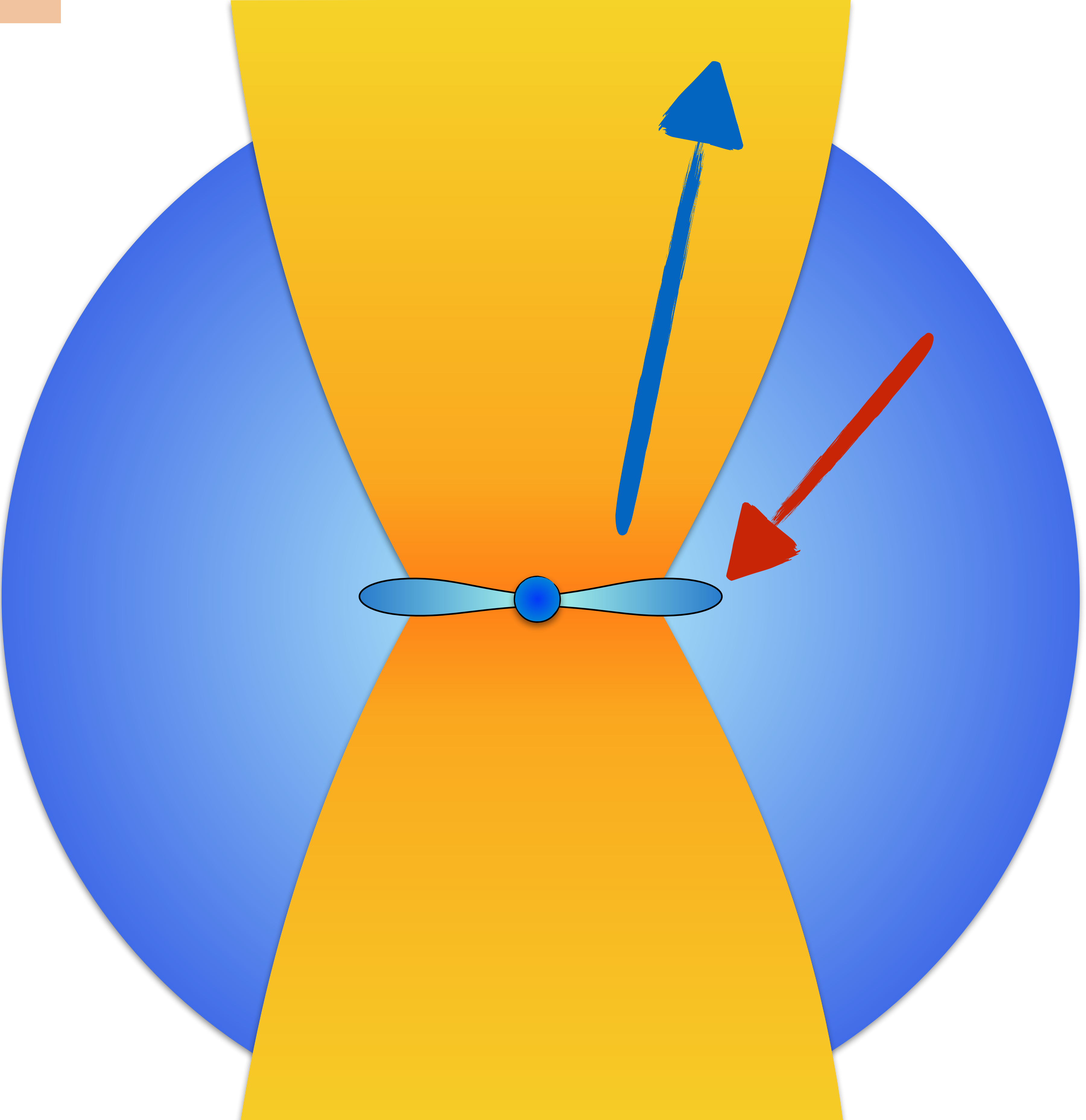
We solve the evolution of protostars,
accretion flow structures,
and feedback processes self-consistently
until the end of accretion.

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**
$Z = 1e\text{-}5 - 1\ Z_\odot$

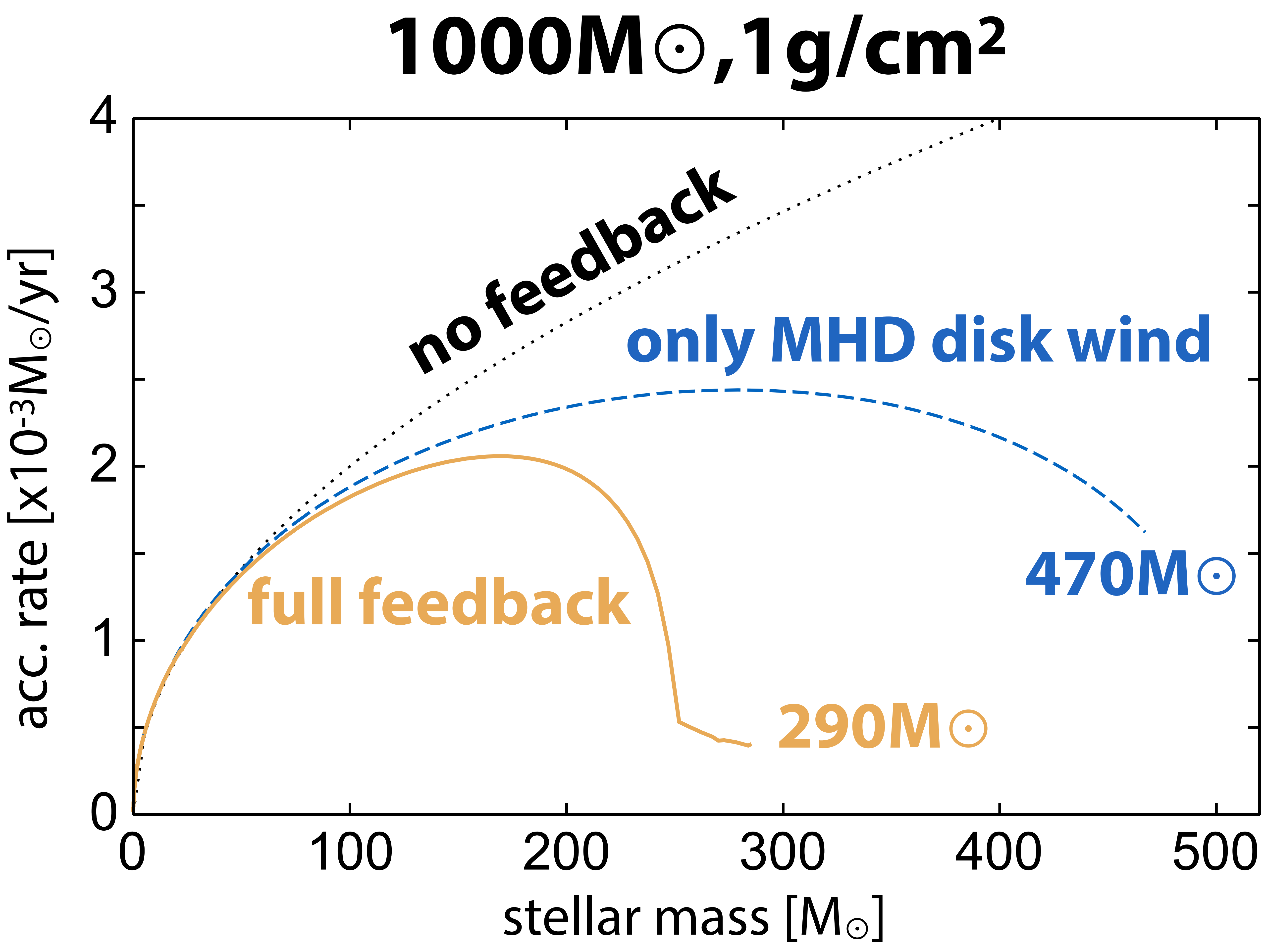


Impact of Multiple Feedback

at $Z_\odot$

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

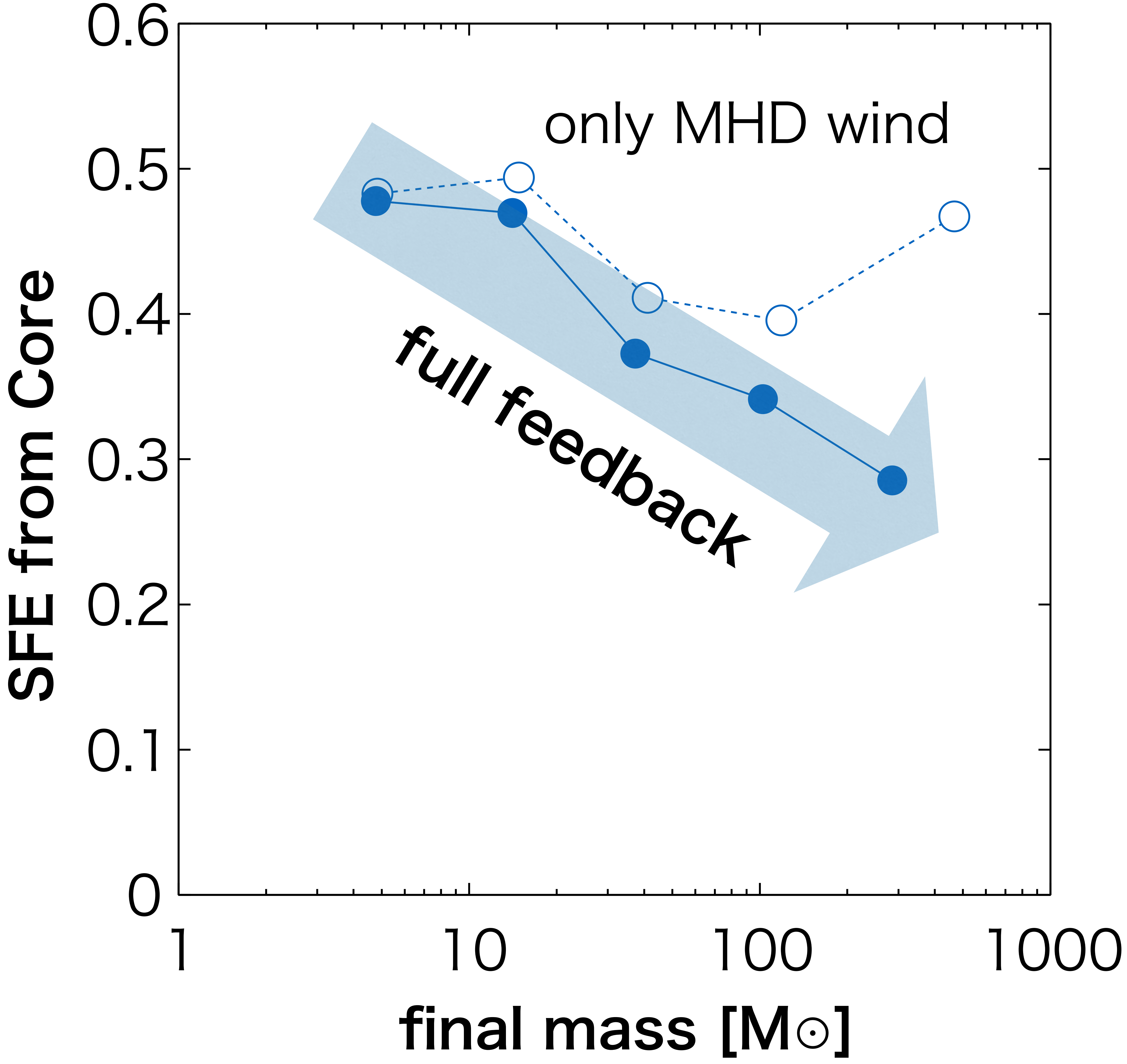
Accretion History



Radiation feedback reduces SFE

SFE=0.47→0.29 in this case

Star Formation Efficiencies



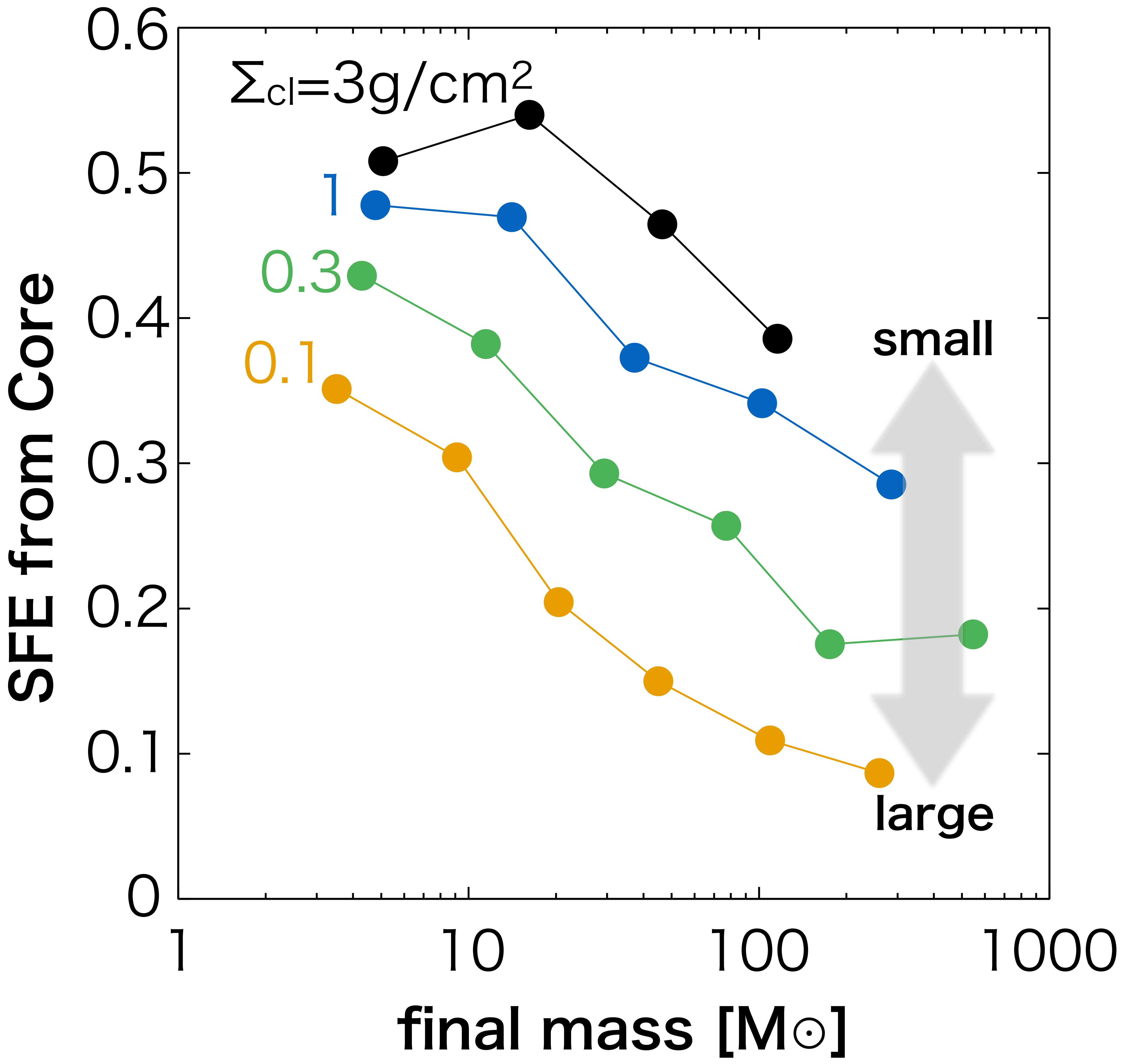
lower SFE in higher-mass SF

due to radiation feedback

No upper limit by feedback

Unlike models with a truncation at 100M⊙
cf. stars with >100M⊙ in 30 Dor

Star Formation Efficiencies



lower SFE in higher-mass SF

due to radiation feedback

No upper limit by feedback

Unlike models with a truncation at 100M⊙

cf. stars with >100M⊙ in 30 Dor

lower SFE at larger core

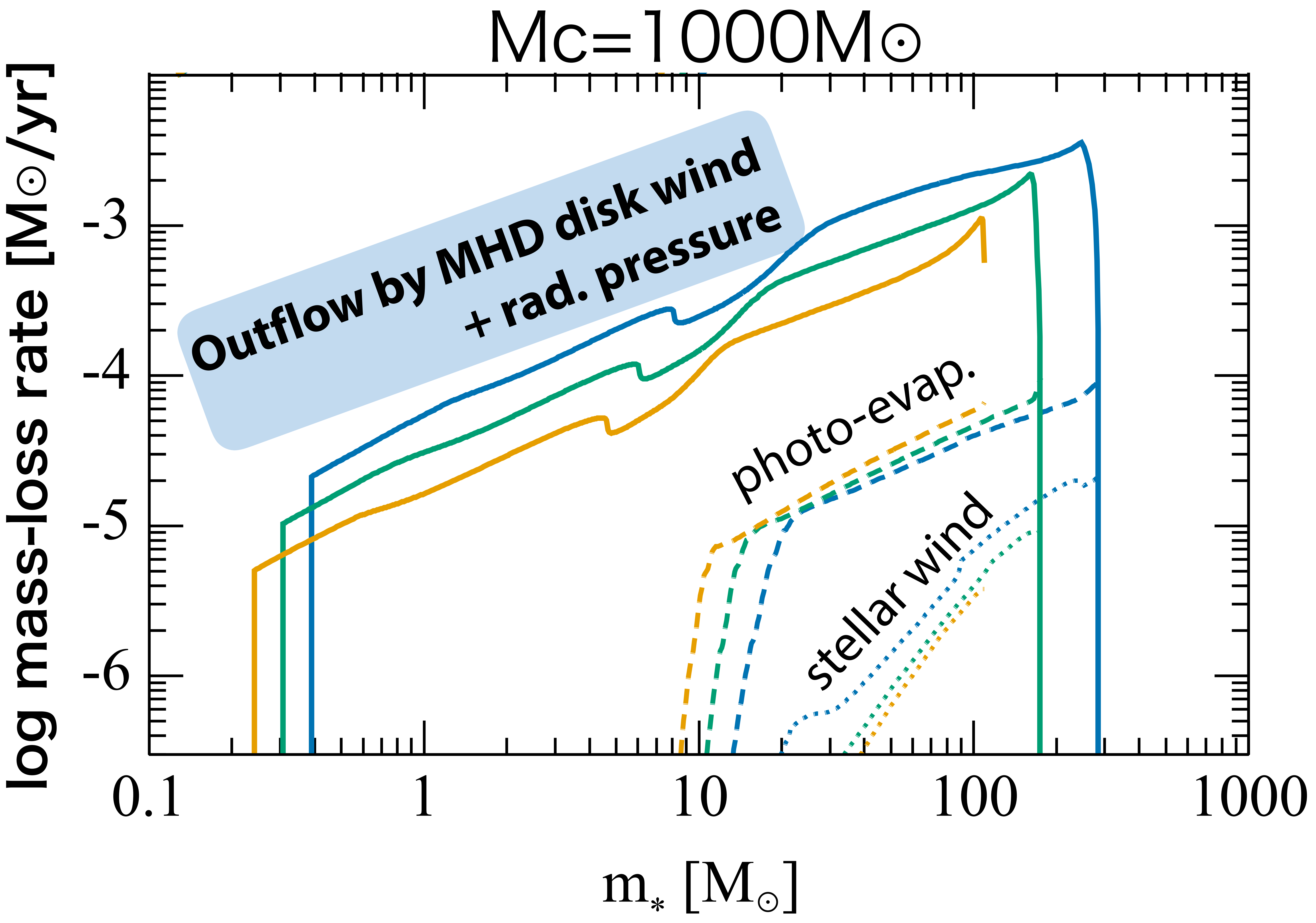
difficult to form very-massive stars

by the competitive accretion

reasonable agreement with recent sims

by Kuiper & Hosokawa 2018

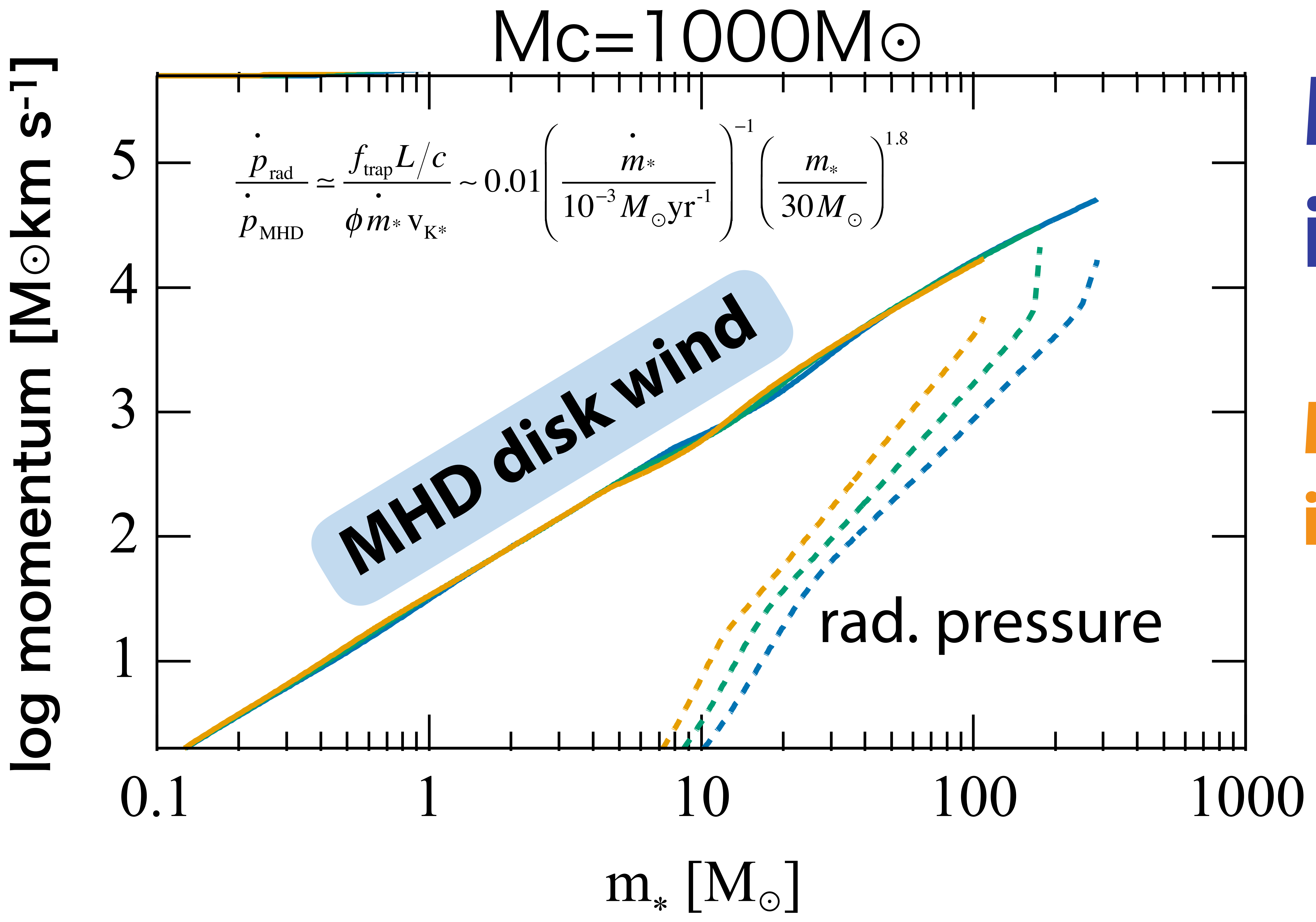
Which is the dominant feedback?



Momentum-driven outflow is dominant

MHD disk wind?
or
Radiation pressure?

Which is the dominant feedback?



MHD disk wind is dominant!!

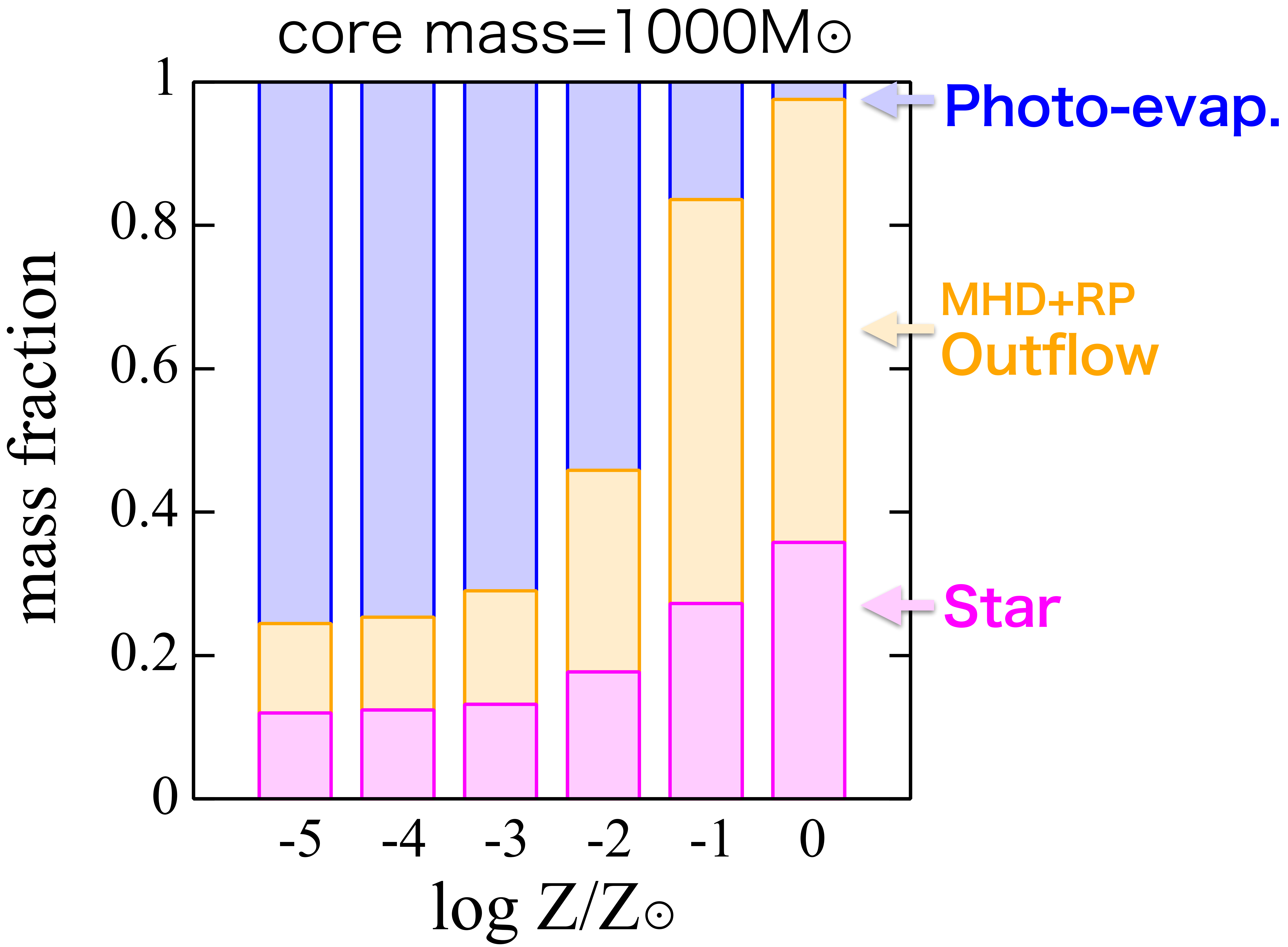
Massive star formation is similar to low-mass SF!!

at $Z_\odot$

Metallicity Dependence

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

Feedback at Low Metallicities



At Z⊙,
outflow is strongest

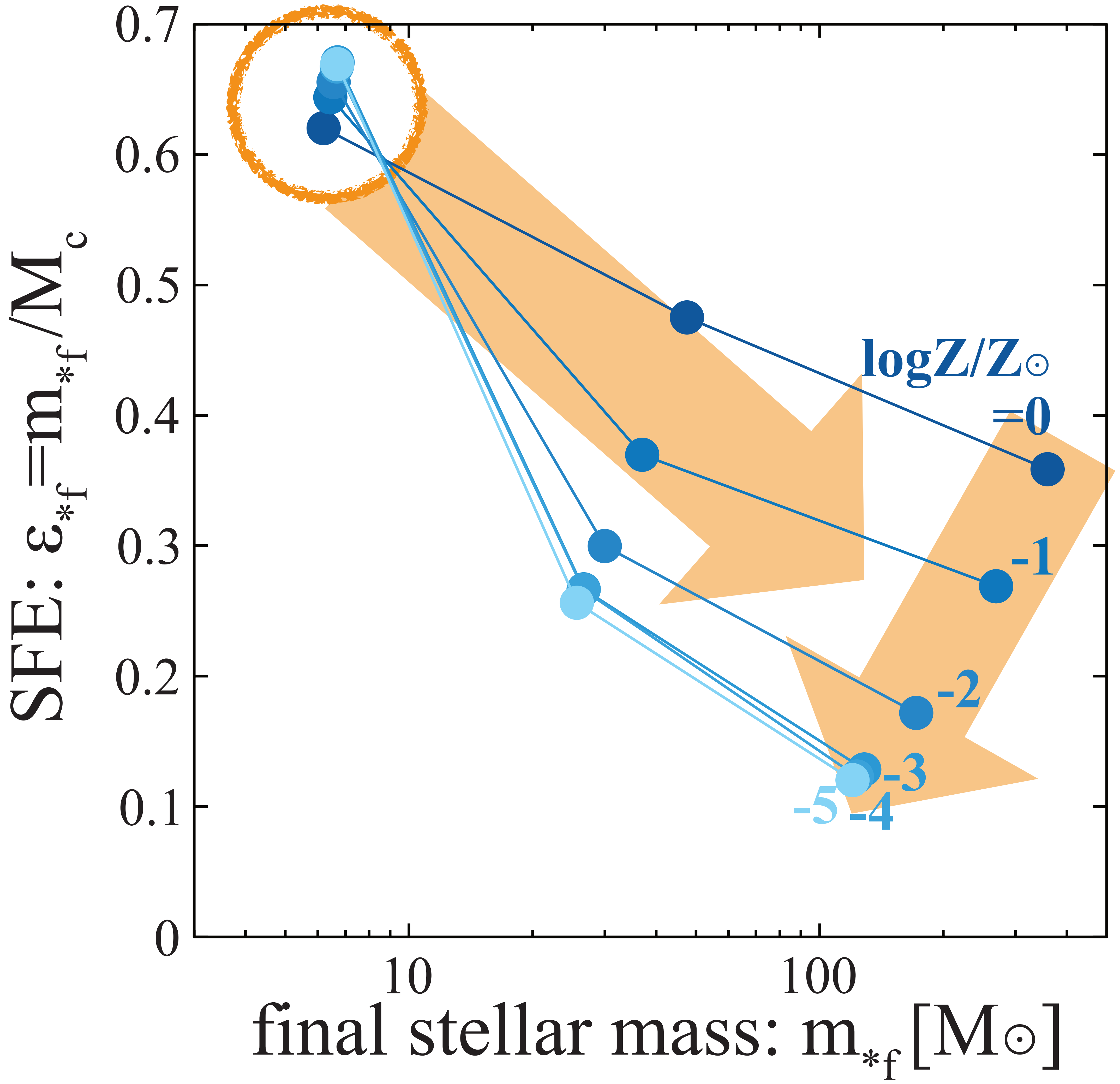
At <0.01Z⊙,
PE becomes dominant

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 $Z<1e\text{-}3Z_\odot$

SFEs at Various Metallicities



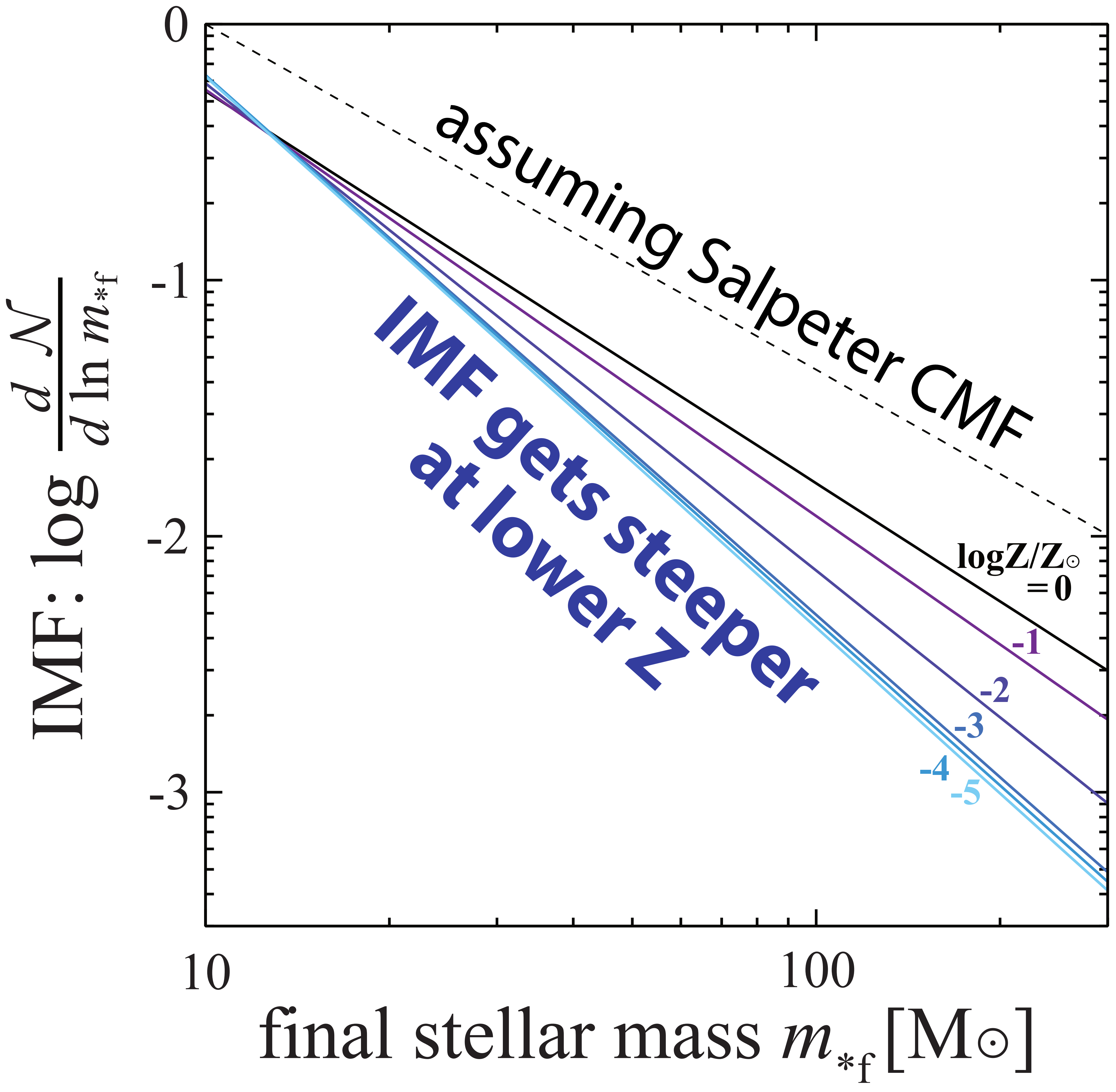
Feedback does not set the upper-mass limit!

lower SFE in higher-mass SF
due to stronger feedback

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

Non-Universal IMF?

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)

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;

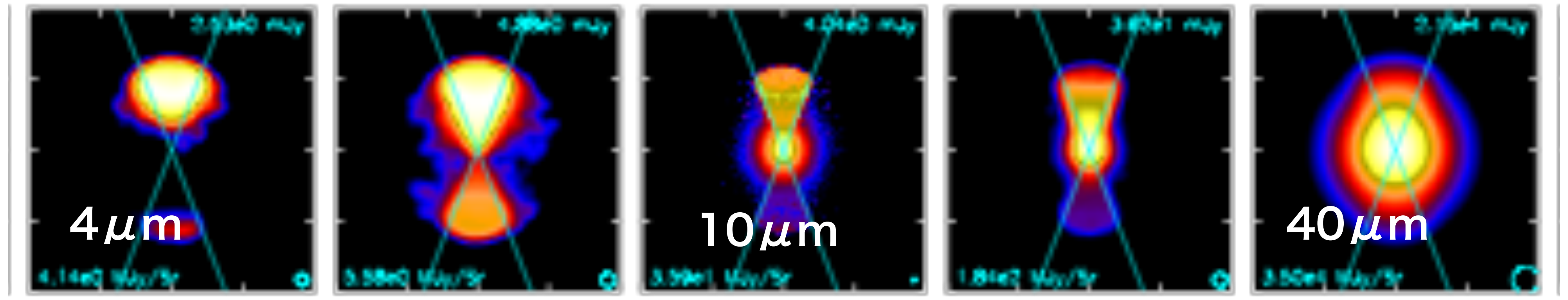
Rosero, **KT**+, *submitted* to ApJ, arXiv:1809.01264;

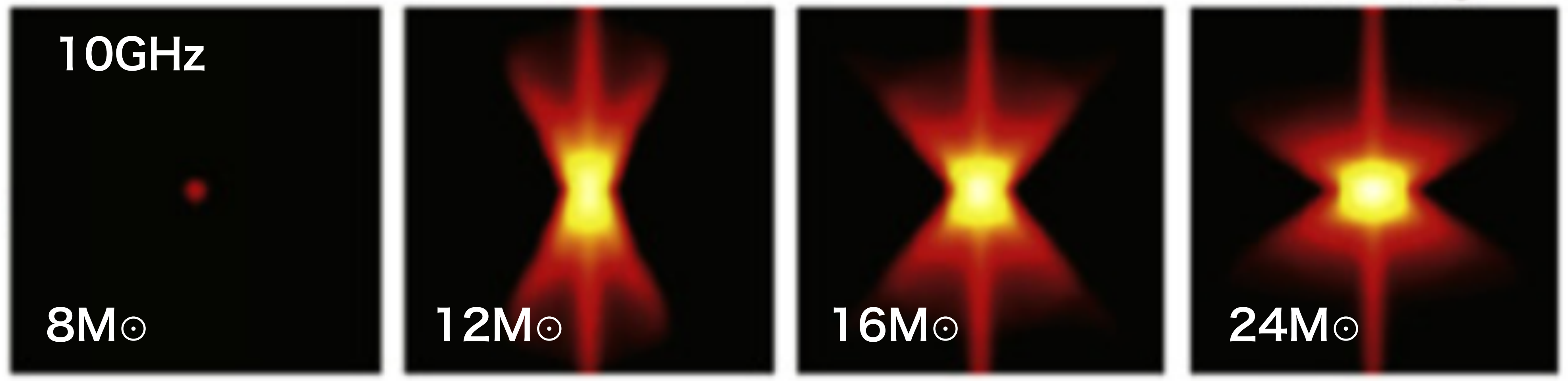
Zhang, Tan, Sakai, **KT**+, *submitted* to ApJ, arXiv:1811.04381;

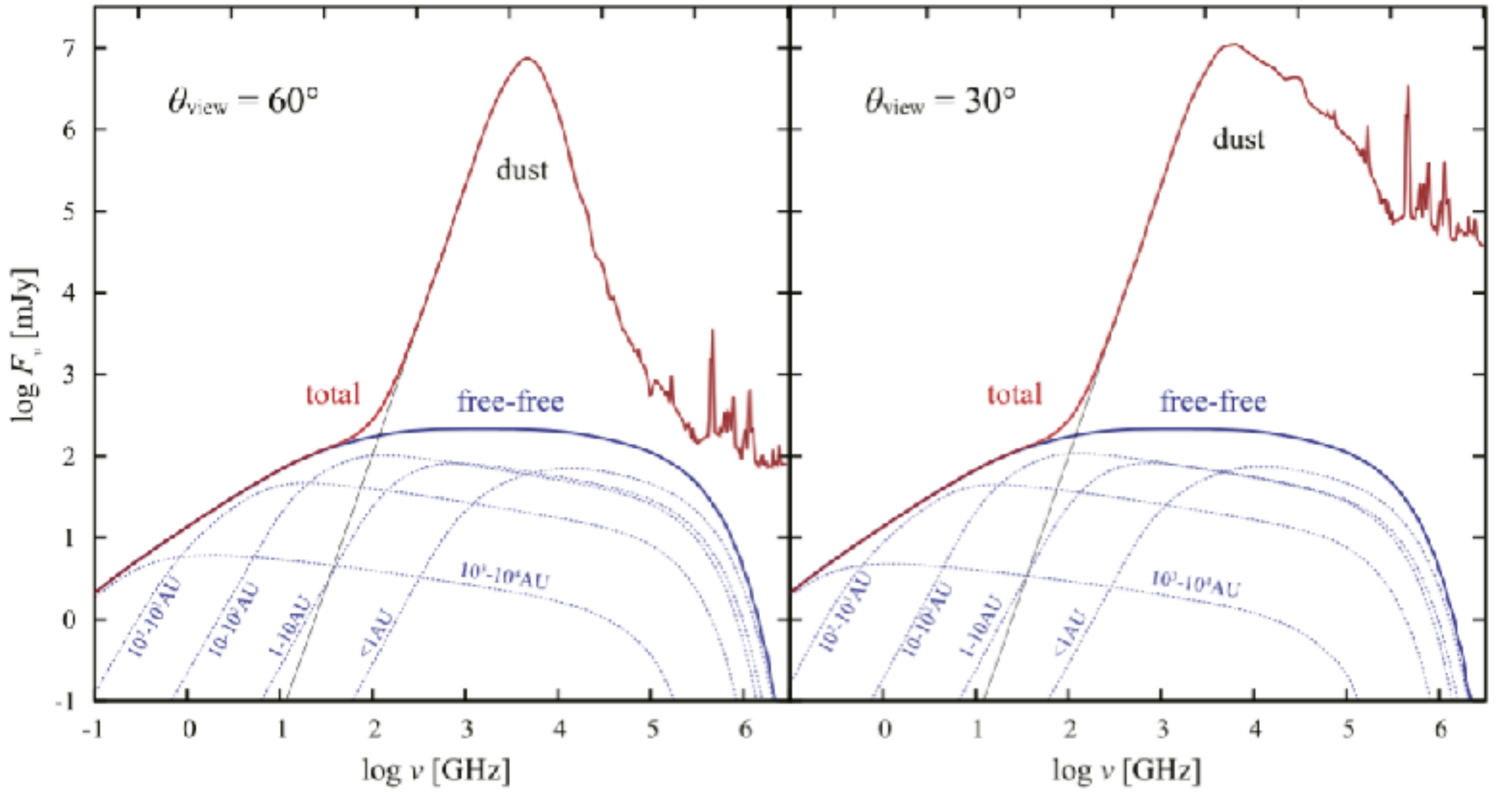
Zhang, Tan, **KT**+ *submitted*; etc.

Synthetic & Actual Observations

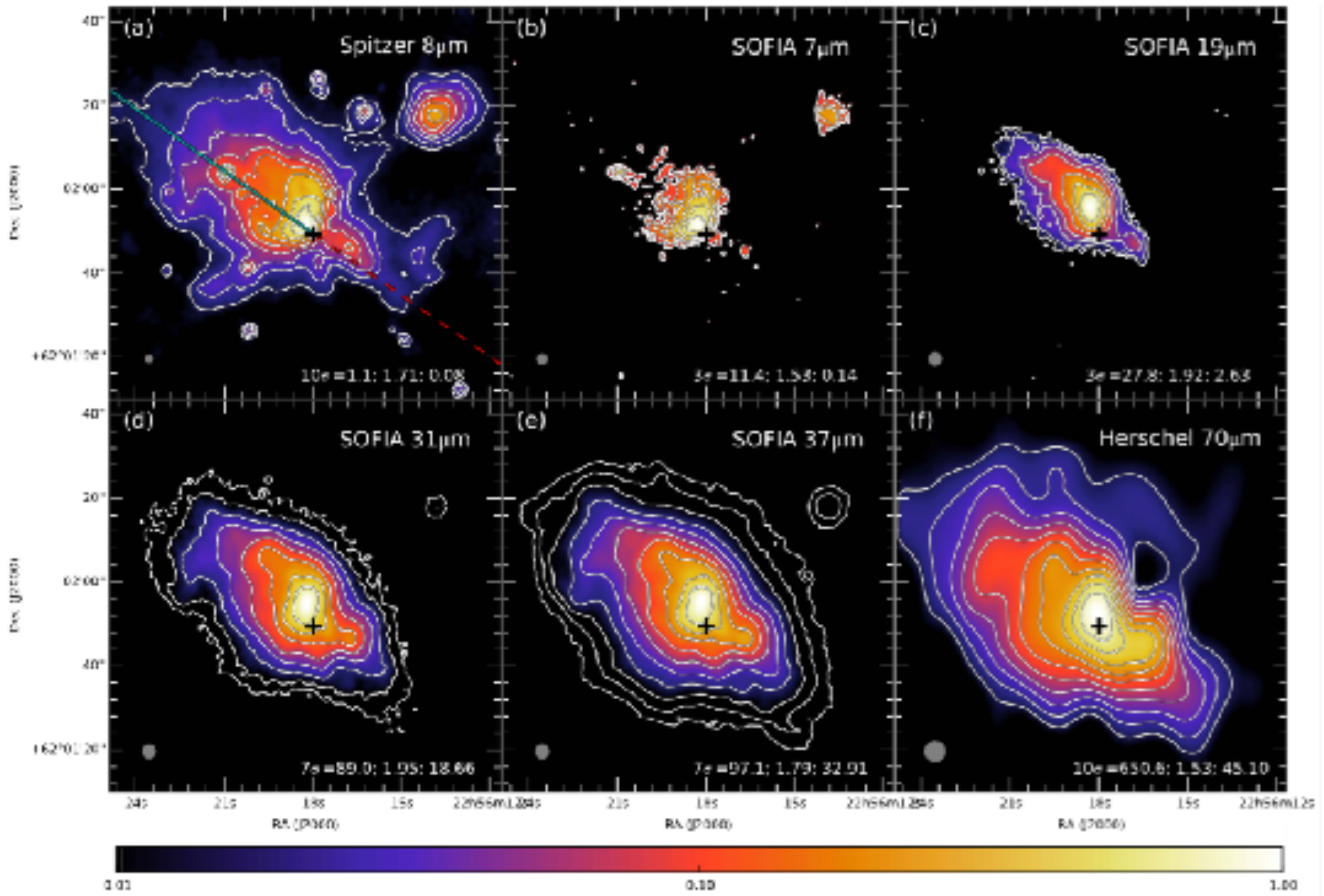
Synthetic Observations

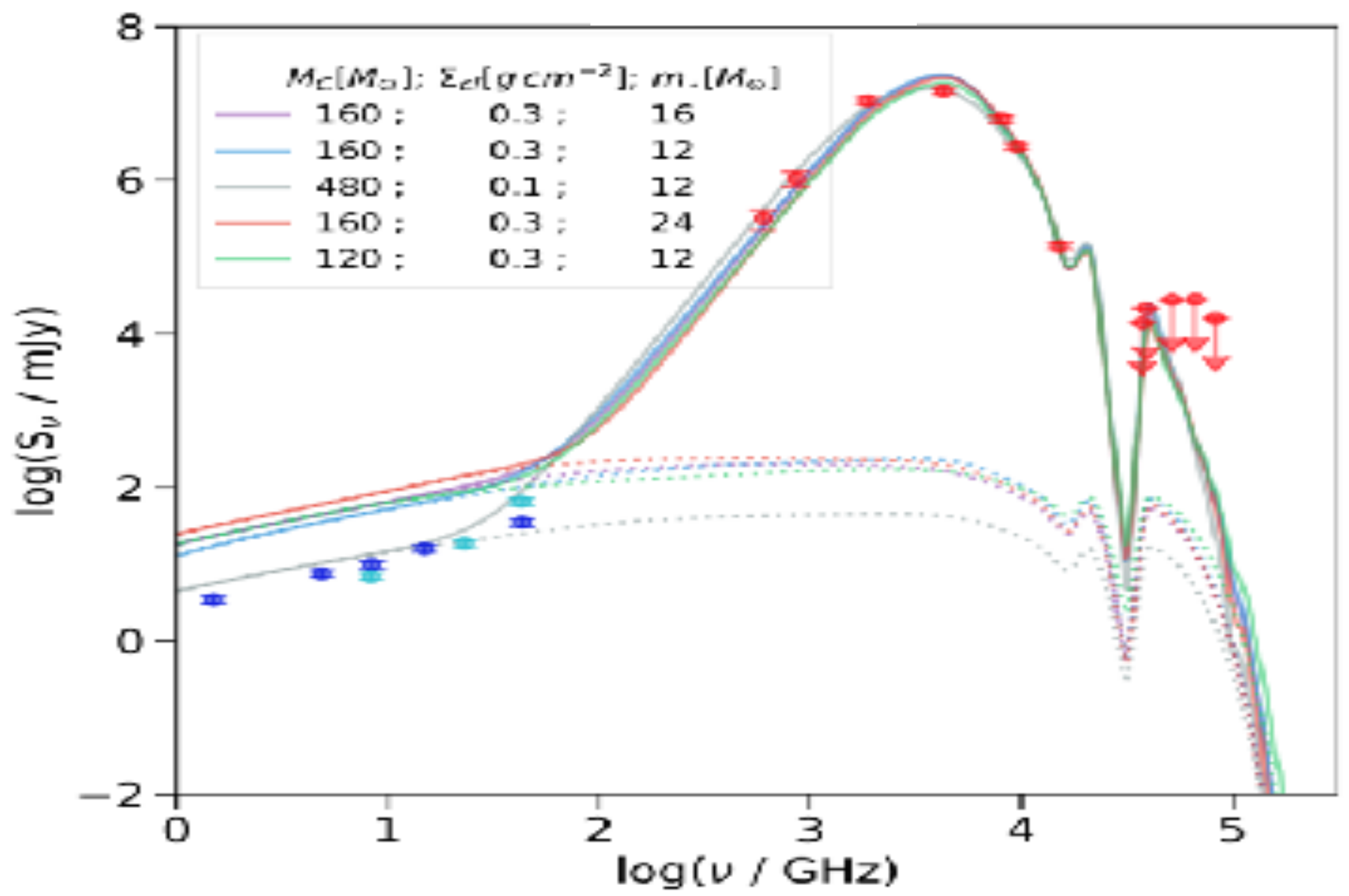




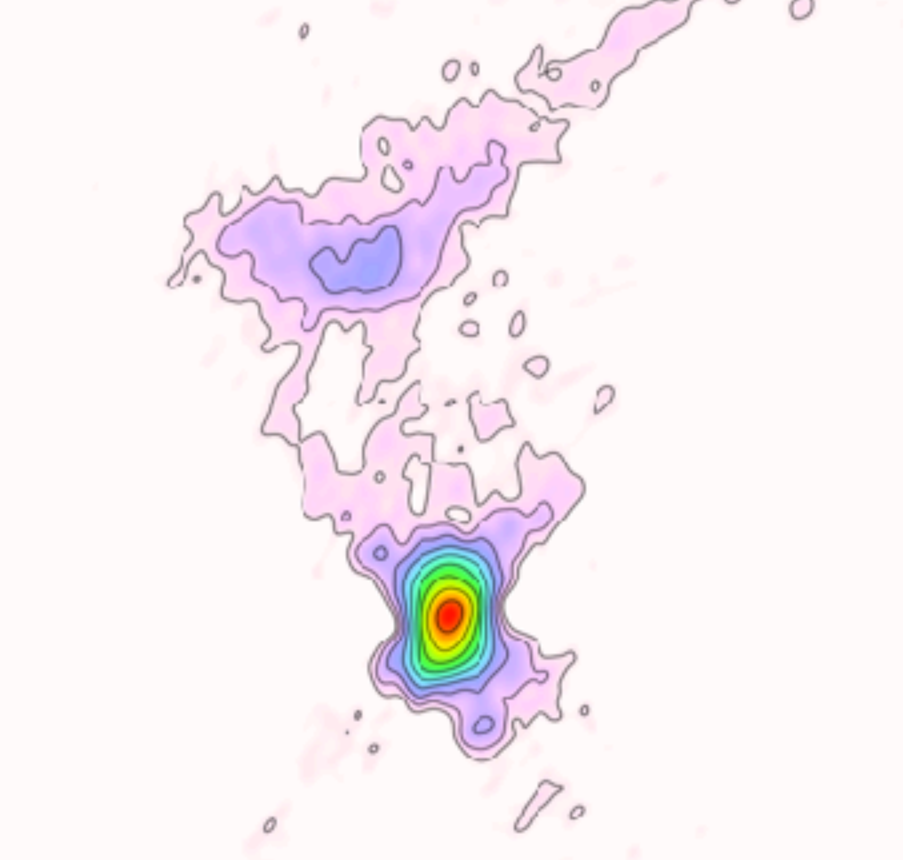


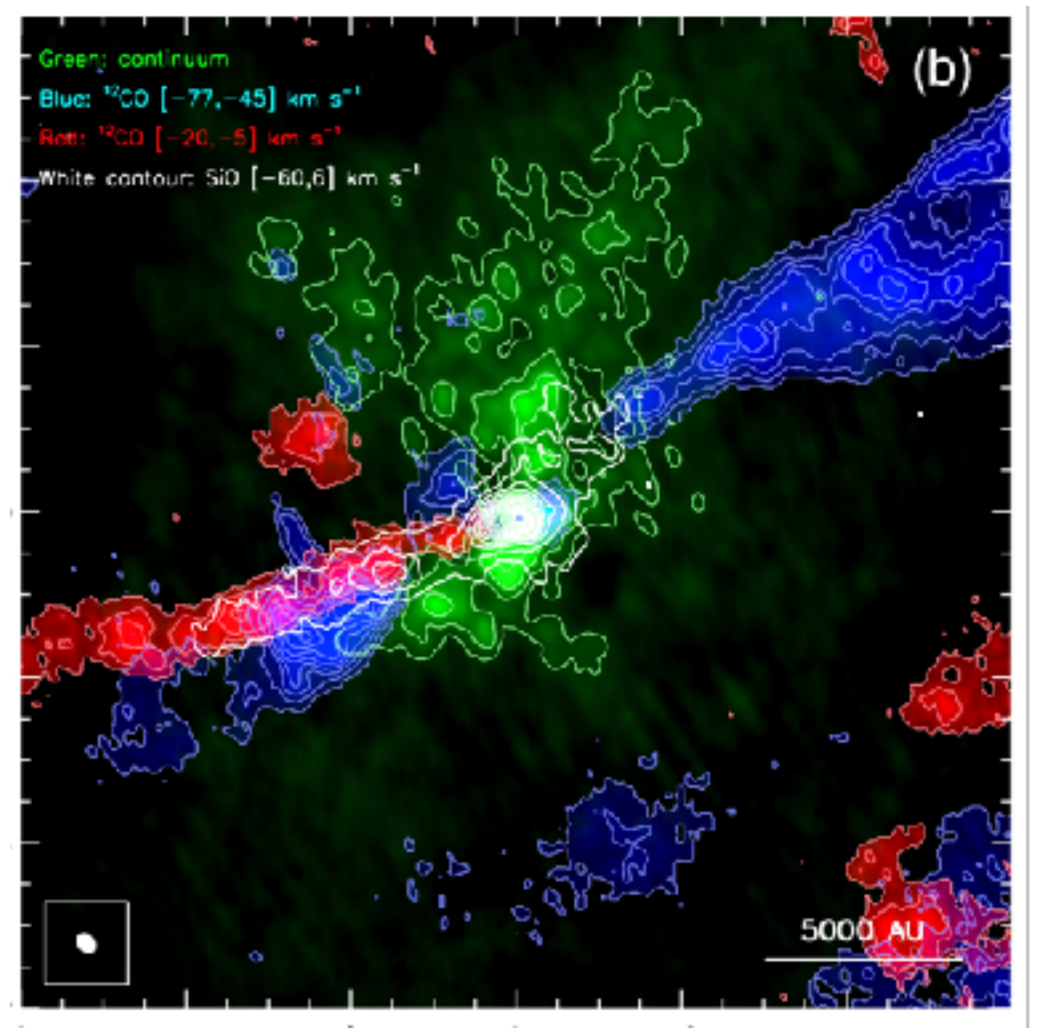
IR survey by SOFIA





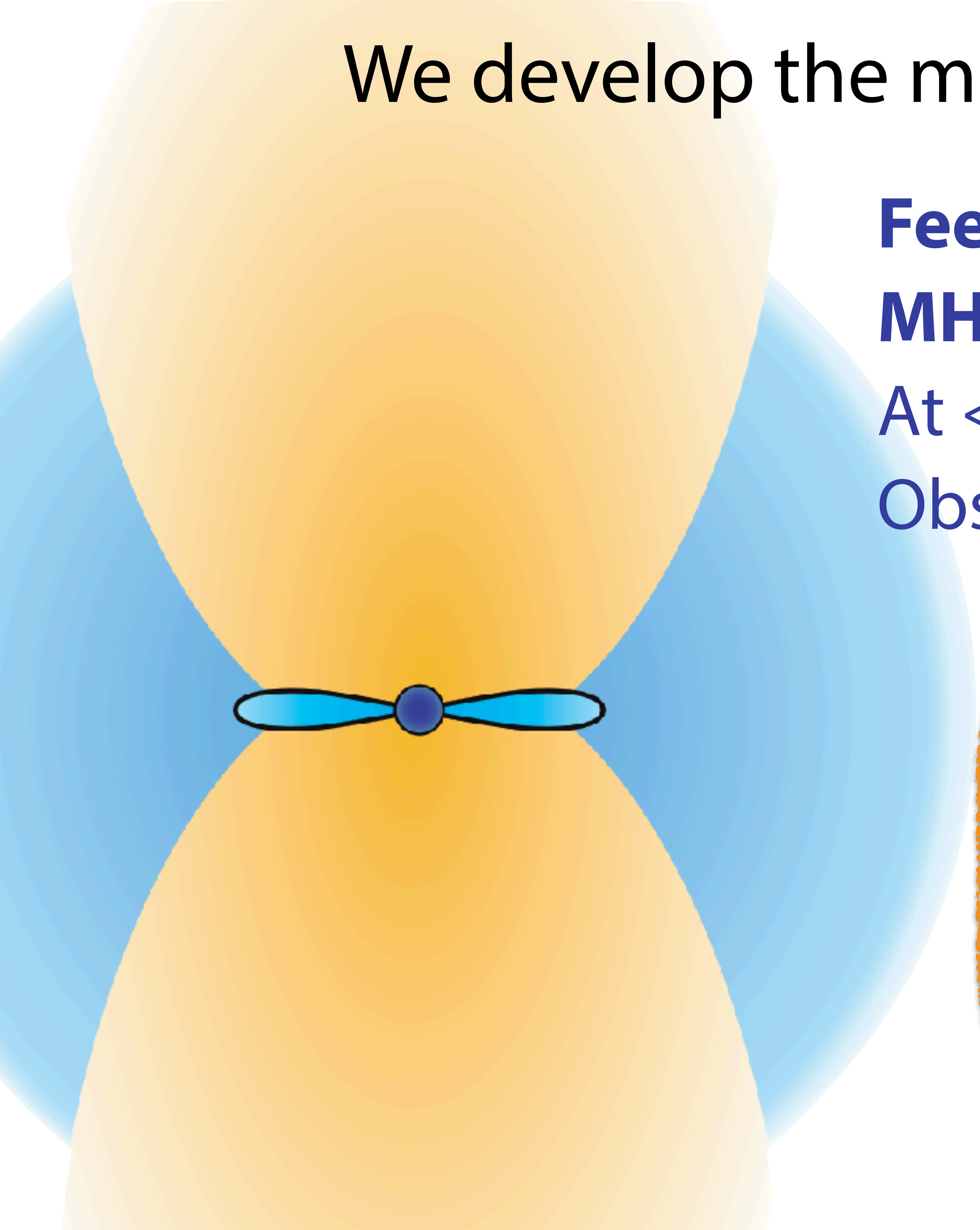
follow-up by ALMA & VLA





Summary

Multiple Feedback in Massive SF



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

Feedback does not set the upper mass limit

MHD disk wind is dominant = similar to low-mass SF!!

At $<0.01Z_\odot$, SFE is lower due to effective PE

Observation projects are also on-going

The standard scenario of massive star formation will soon be established!!