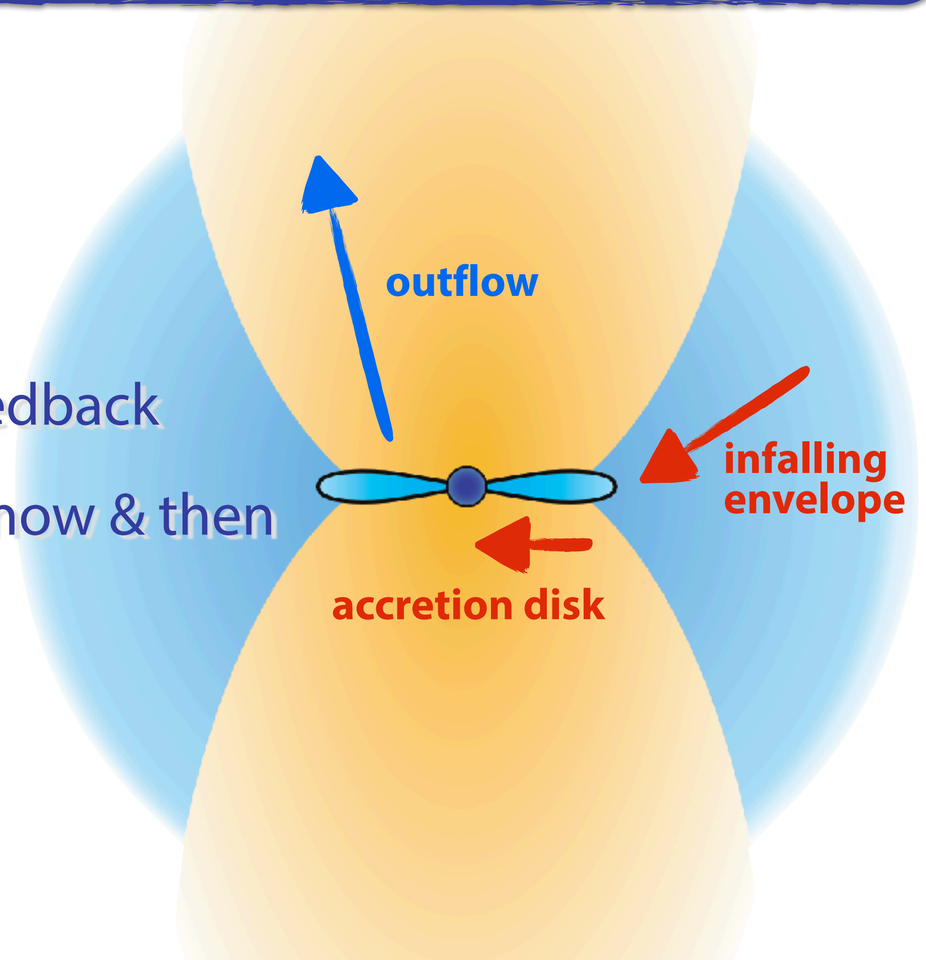
Massive Star Formation

Kei E. I. Tanaka / 田中圭 (Osaka University → NAOJ)

Contents

1. **Introduction:** massive stars & their birth
2. **Theoretical Problems:** fragmentation & feedback
3. **Metallicity Dependence:** star formation, now & then
4. **Summary**

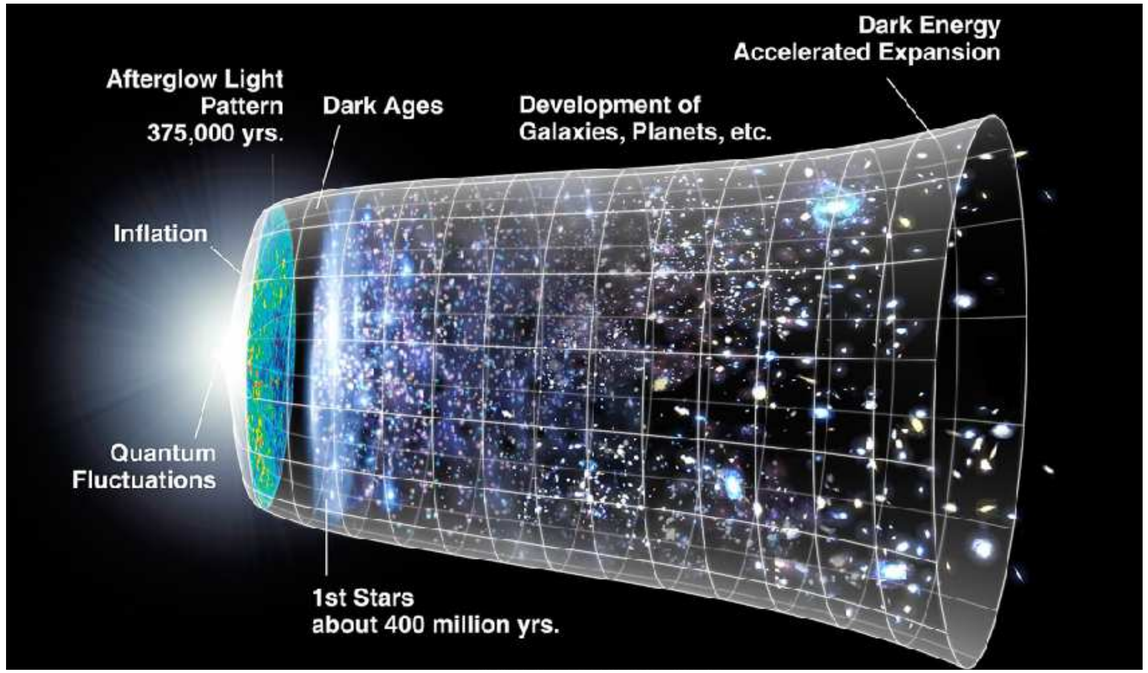


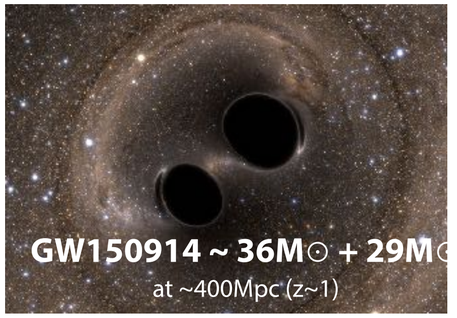
Massive Stars & Their Formation

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.









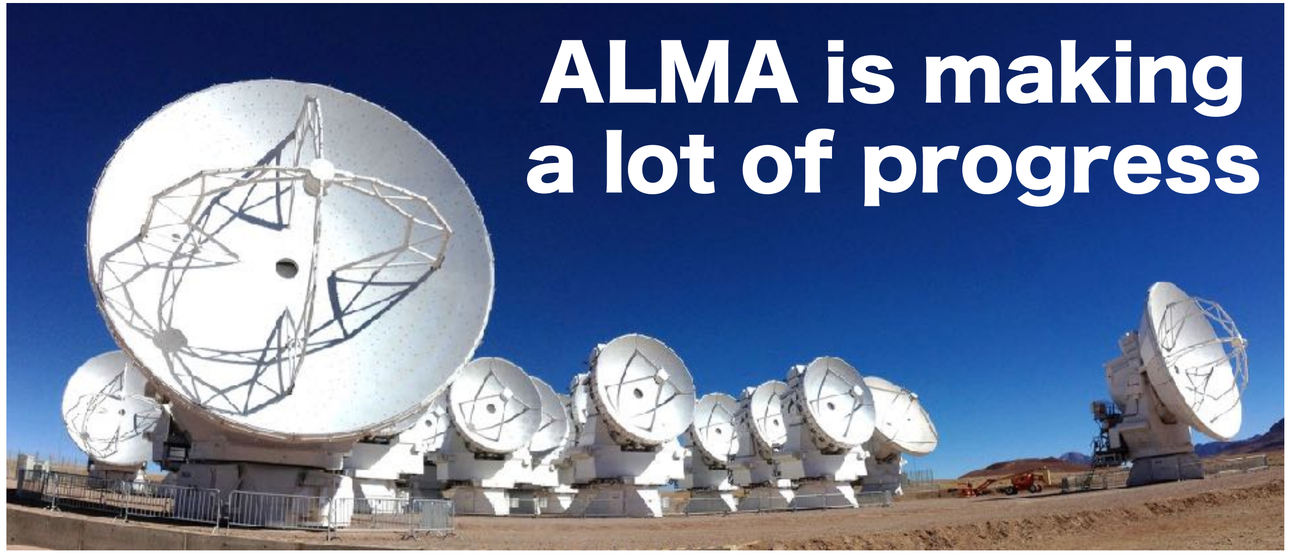
However, massive SF is poorly understood…

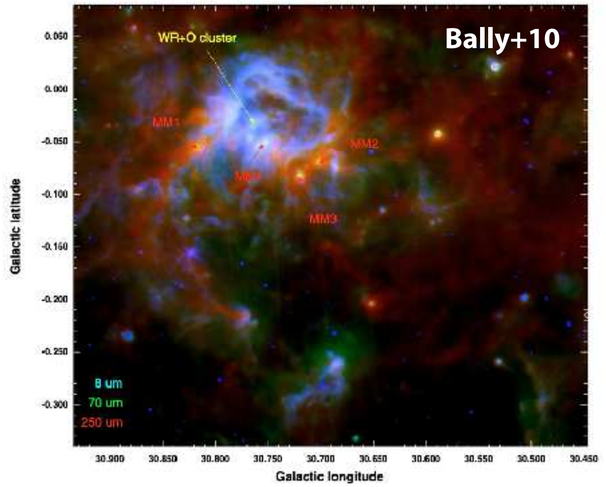
Observational Difficulties

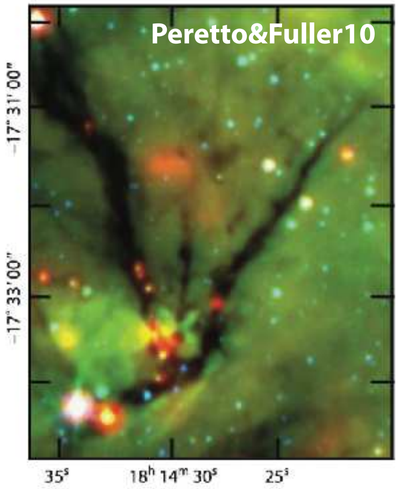
Far away
rare
short-lived

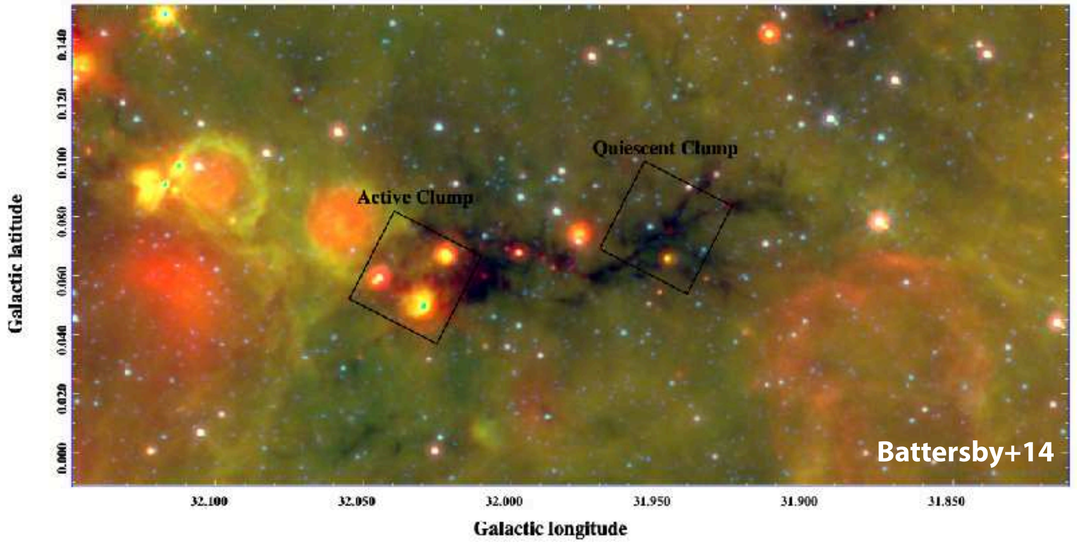
Complex
embedded
jam-packed

BUT









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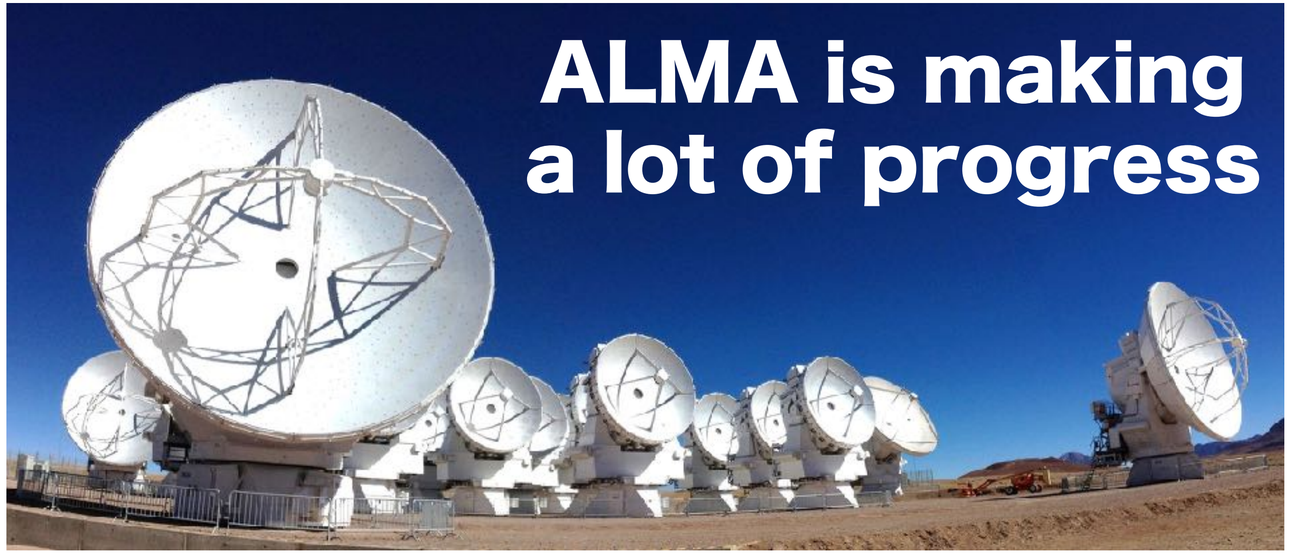

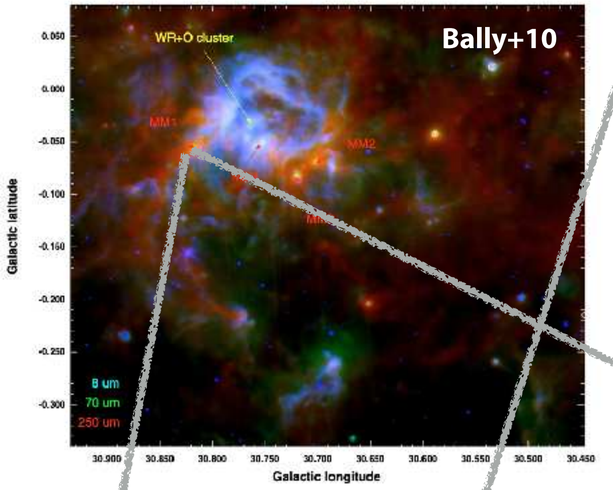

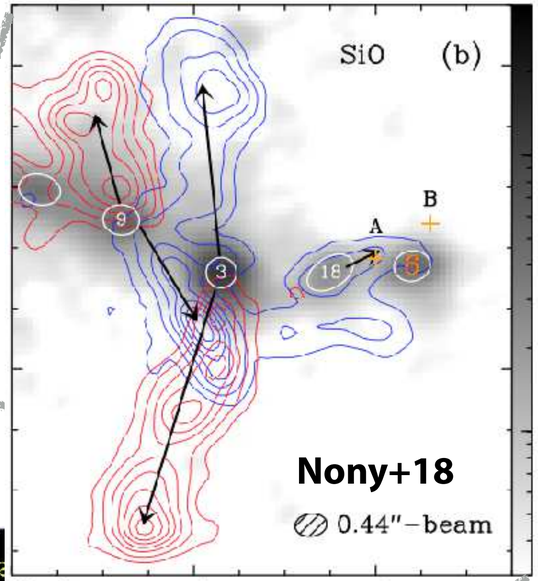

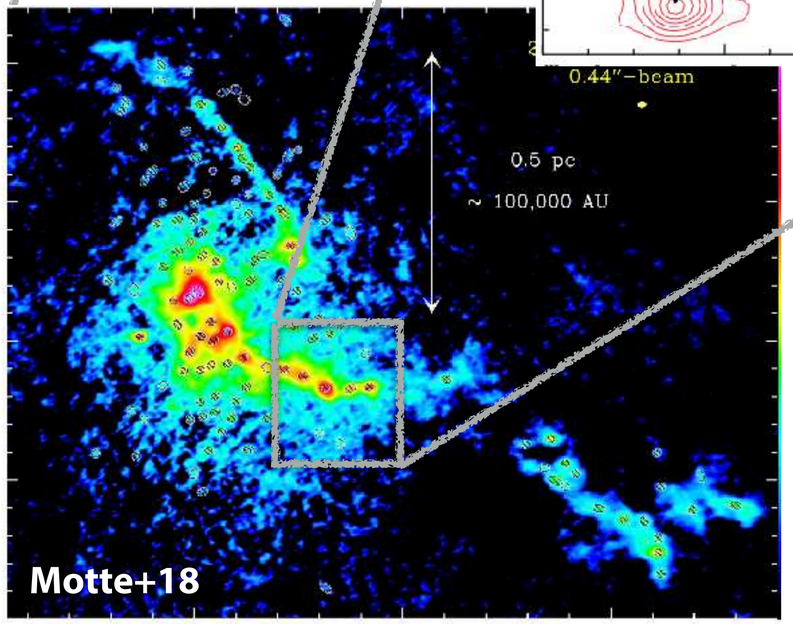

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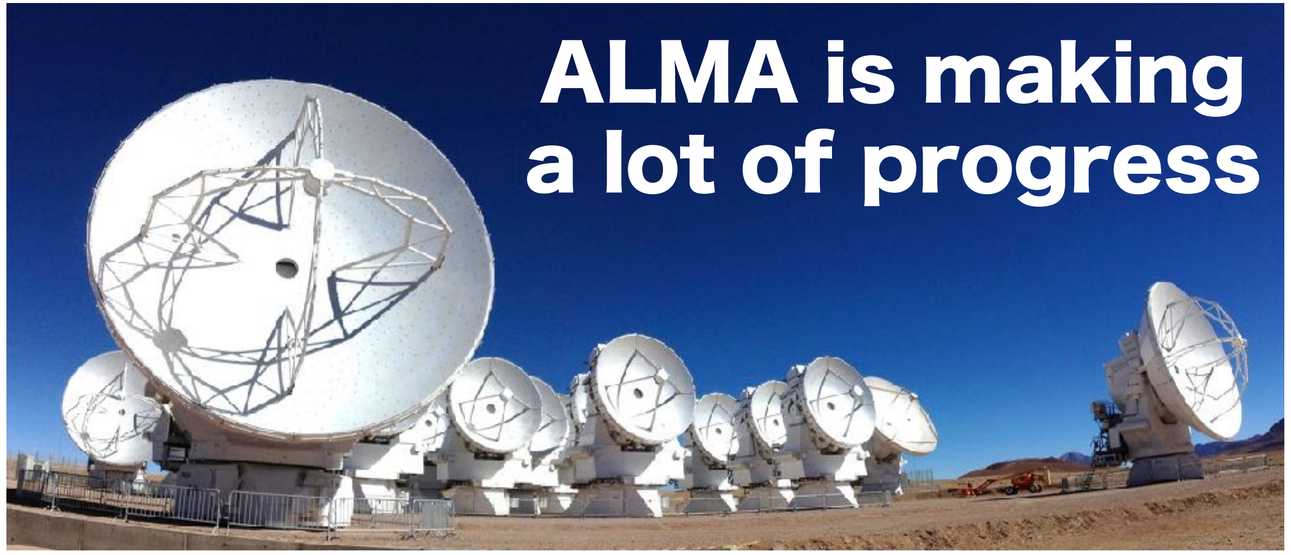
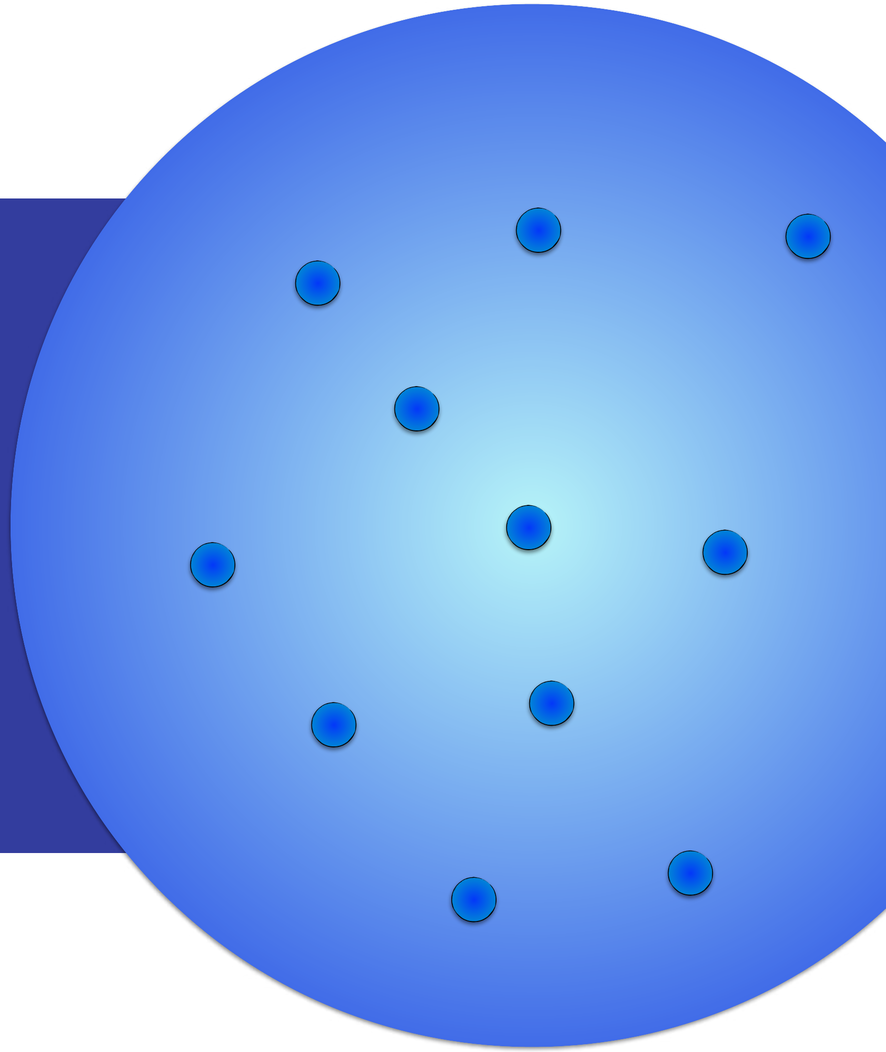




Stay tuned for the next two talks for more ALMA achievements!

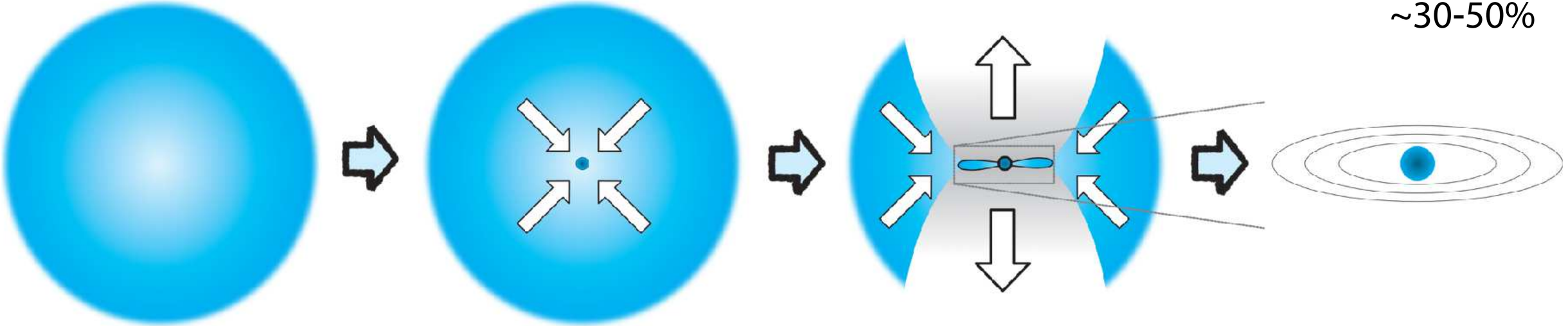
Fragmentation



Standard Scenario of Low-Mass SF

e.g. Shu, Adams & Lizano 87

prestellar "core" → collapse → disk & outflow → SFE = m_*/M_c ~30-50%



established in 80s
based on theories
and observations

mass: $M \sim 1 M_\odot \left(\frac{T}{10\mathrm{K}}\right)^{3/2} \left(\frac{n}{10^4\,\mathrm{cm}^{-3}}\right)^{-1/2}$

acc. rate: $\dot{M} \sim 10^{-6} M_\odot \mathrm{yr}^{-1} \left(\frac{T}{10\mathrm{K}}\right)^{3/2}$

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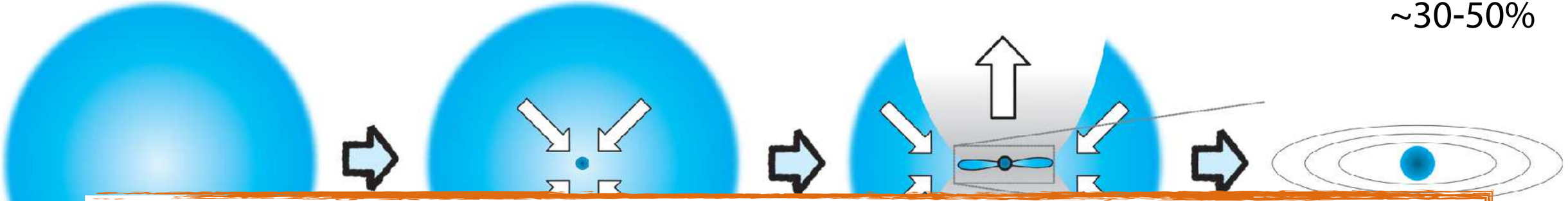


Other formation scenarios are suggested for massive SF, such as ***Stellar Mergers*** *or* ***Competitive Accretion***

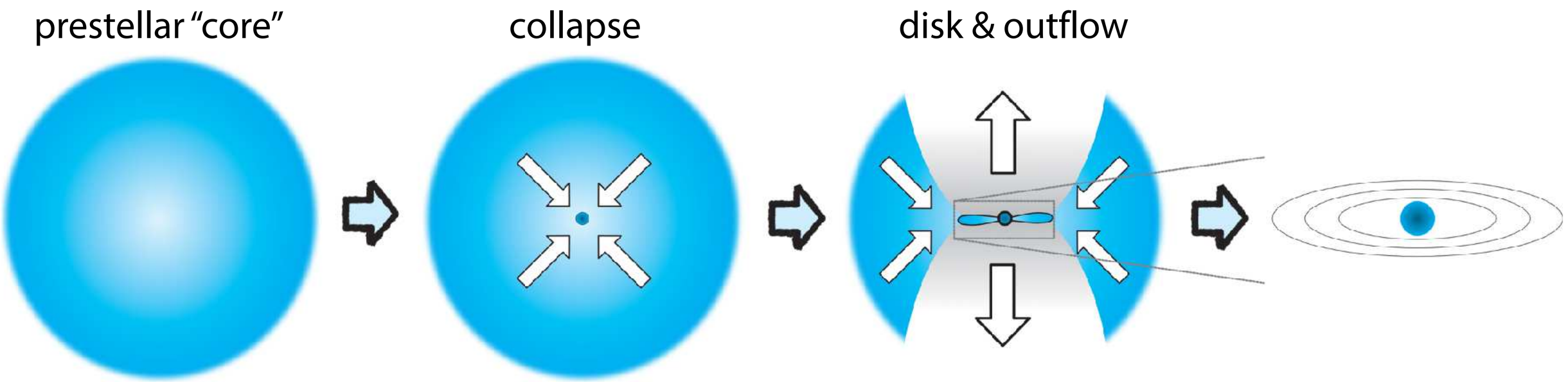
established in 80s
based on theories
and observations

mass: $M \sim 1 M_\odot \left(\frac{T}{10\mathrm{K}}\right)^{3/2} \left(\frac{n}{10^4\,\mathrm{cm}^{-3}}\right)^{-1/2}$

acc. rate: $\dot{M} \sim 10^{-6} M_\odot \mathrm{yr}^{-1} \left(\frac{T}{10\mathrm{K}}\right)^{3/2}$

Massive SF by Core Accretion

e.g. McKee & Tan 03



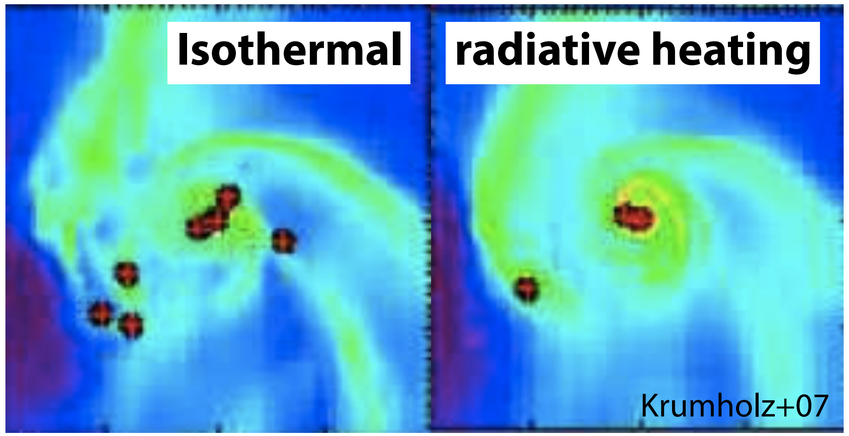
Scale-up!
Turbulence
& B-filed

$$M \sim 100 M_\odot \left(\frac{c_s^2 + \mathrm{v}_{\mathrm{turb}}^2 + \mathrm{v}_{\mathrm{A}}^2}{1 \mathrm{km}^2\ \mathrm{s}^{-2}} \right)^{3/2} \left(\frac{n}{10^4 \mathrm{cm}^{-3}} \right)^{-1/2}$$

$$\dot{M} \sim 10^{-4} M_\odot \mathrm{yr}^{-1} \left(\frac{c_s^2 + \mathrm{v}_{\mathrm{turb}}^2 + \mathrm{v}_{\mathrm{A}}^2}{1 \mathrm{km}^2\ \mathrm{s}^{-2}} \right)^{3/2}$$

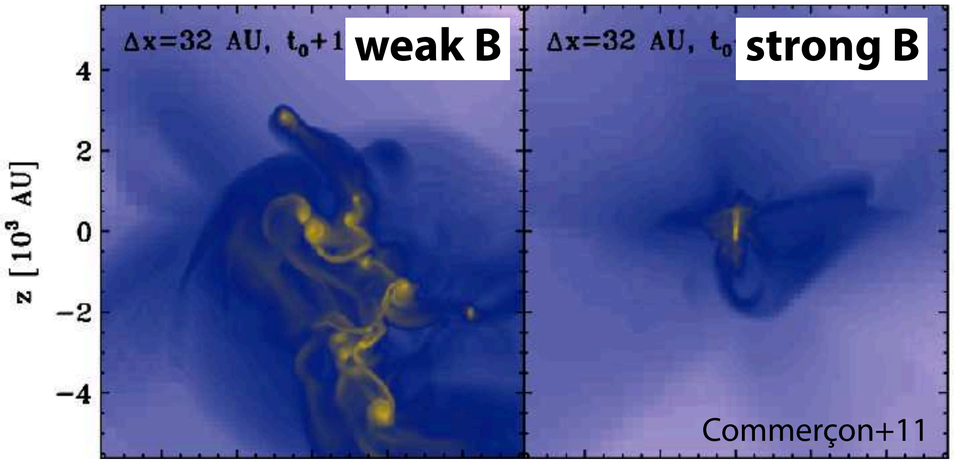
Suppression of Fragmentation

Rad. MHD simulations confirmed suppression of fragmentations [Krumholz+07,11, Commerçon+11, Myers+13, etc.]



accretion heating

High accretion rate provides effective radiative heating increasing Jeans mass scale



magnetic braking

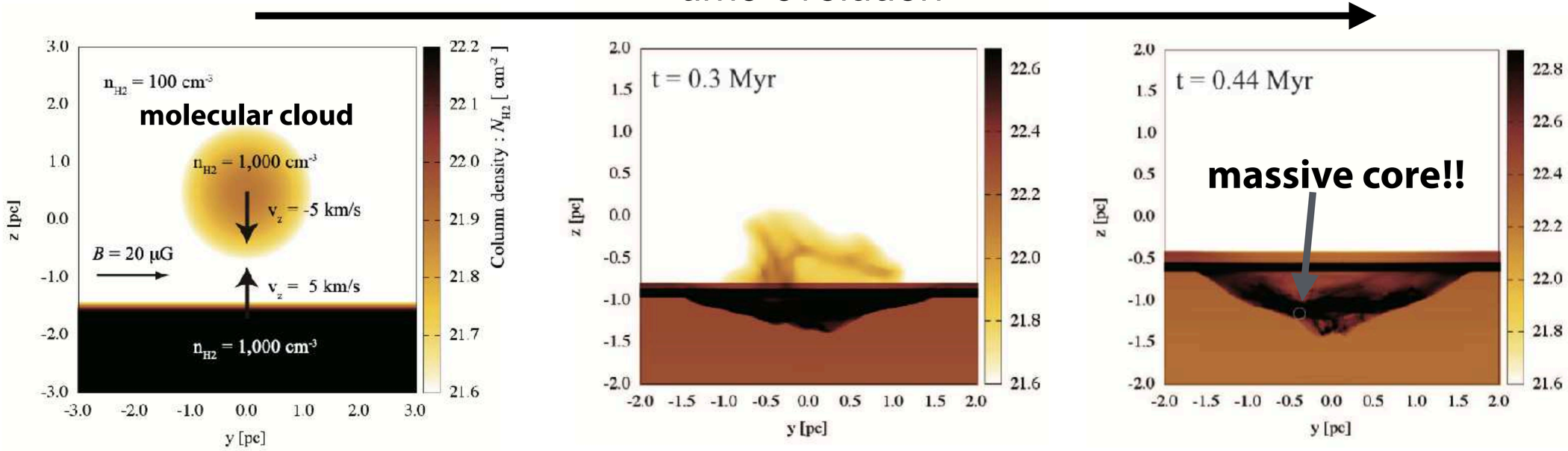
Magnetic fields transfer angler momentum efficiently enhancing accretion heating

Those studies normally assume *"massive cores"* as initial conditions…

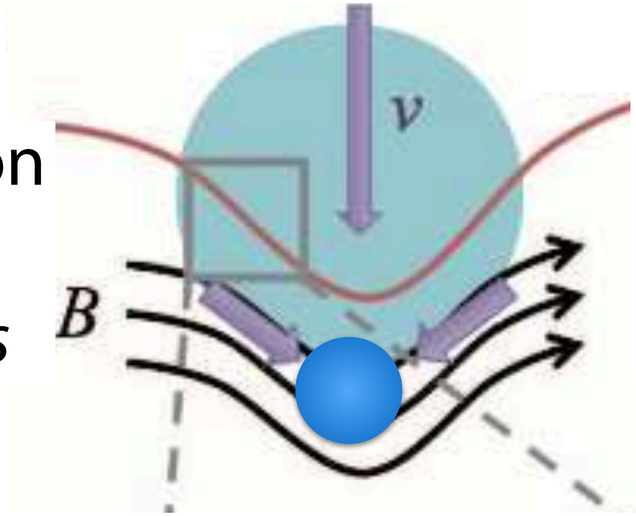
Cloud-Cloud Collision as Massive Core Formation

e.g., Inoue&Fukui13, Inoue+18

time evolution



Shock by could-cloud collision enhances B-field strength, which supports *massive cores*



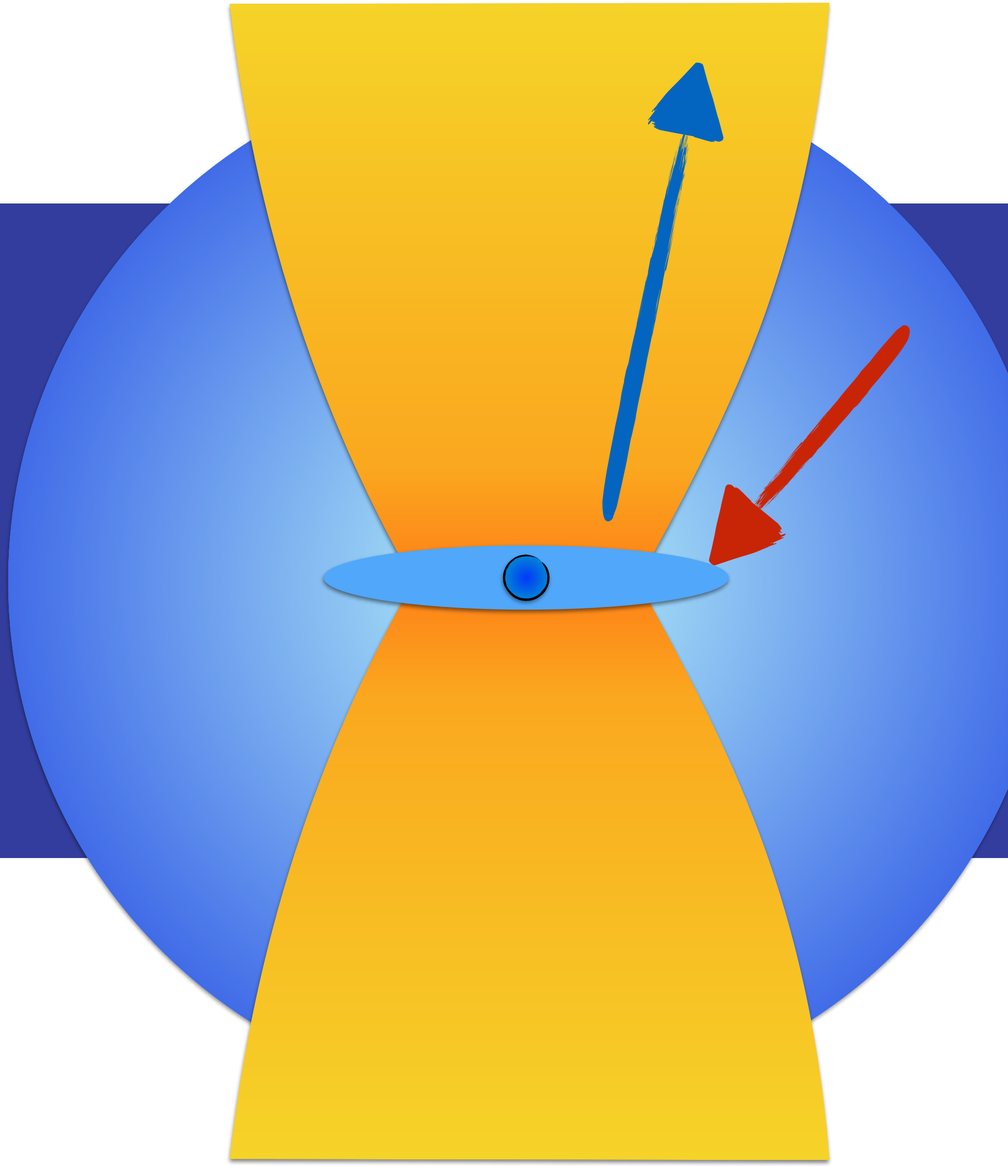
Are collisions of clouds or similar colliding flows **required for massive core formation?**

How is this type of event ubiquitous?

What do observations suggest?

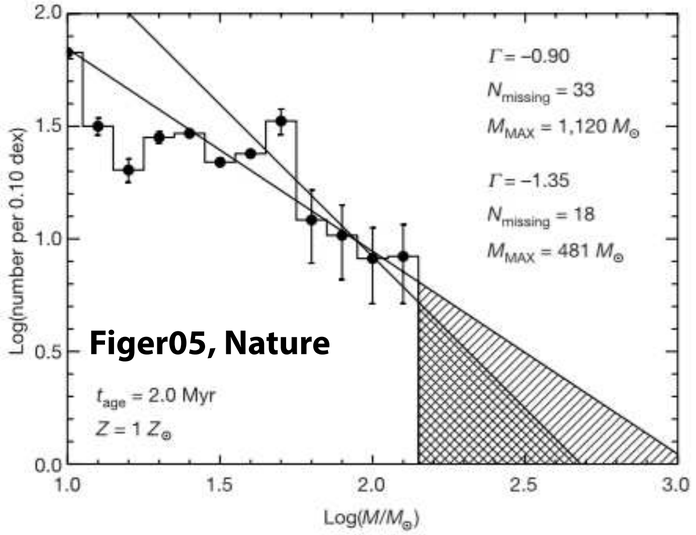
→ ***Tokuda-kun's talk***

Feedback



How massive can stars be?

Arches in Galactic Center



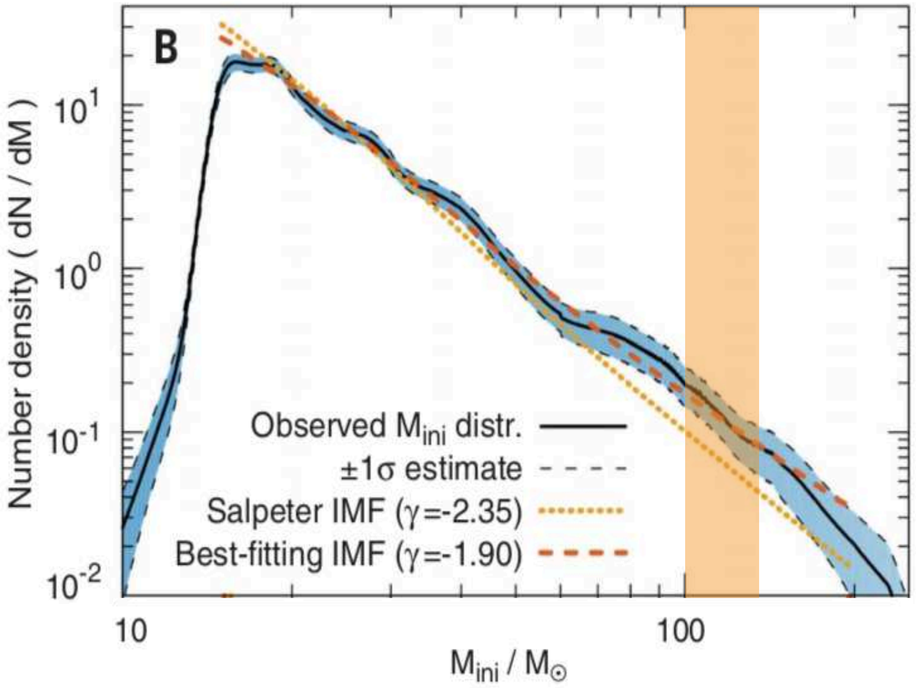
150M⊙ limit?

however

30 Doradus in LMC



Schneider+18



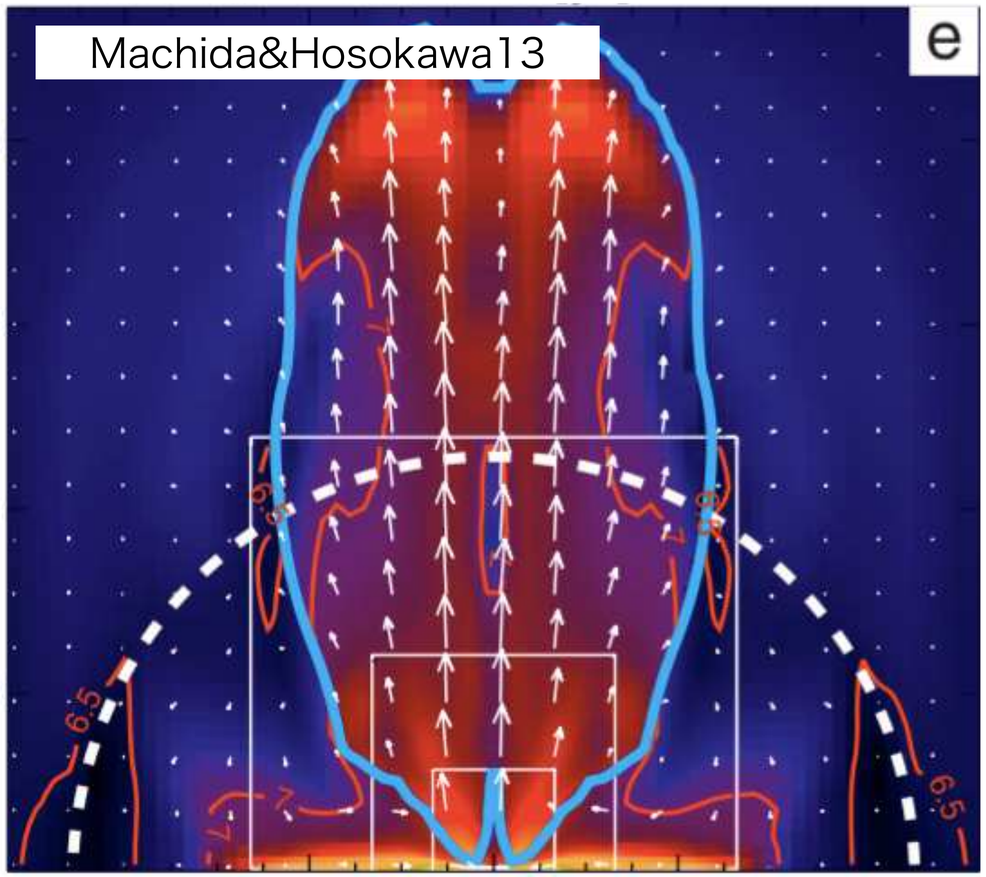
No mass limit? Or environmental effect, such as *metallicity*?

What physical processes can make the limit?

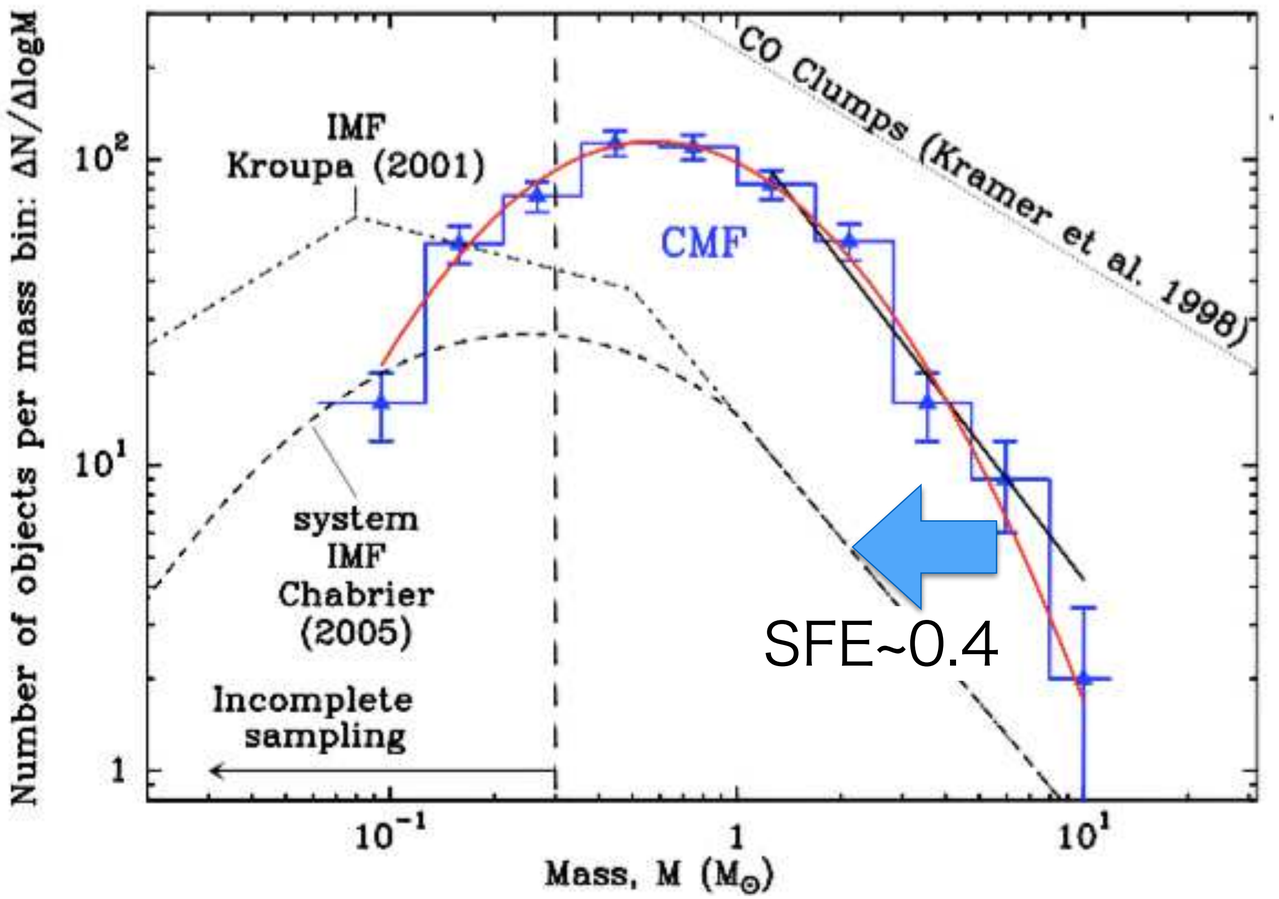
→ **FEEDBACK!!**

MHD Disk Wind in Low-Mass SF

SFE ~ 0.4



Andre+10



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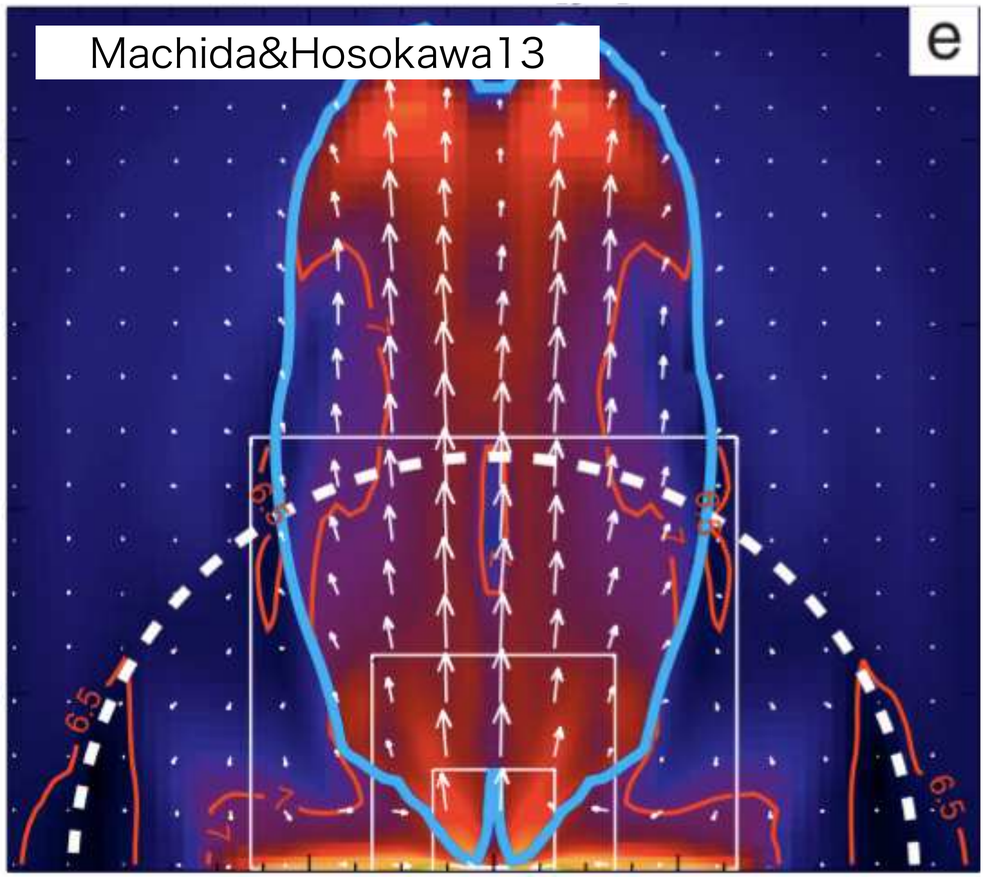
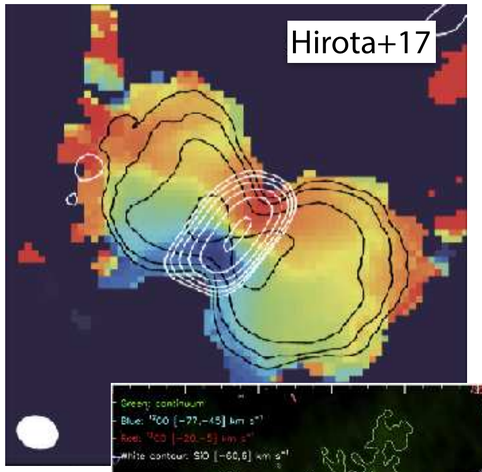
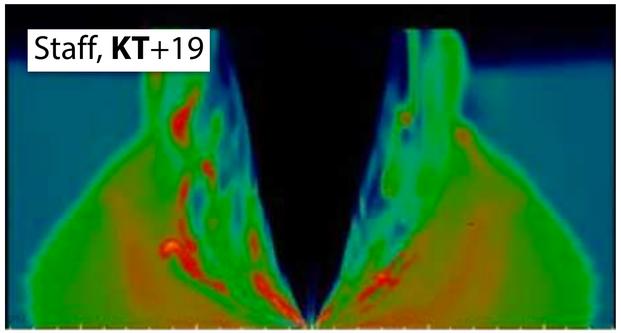
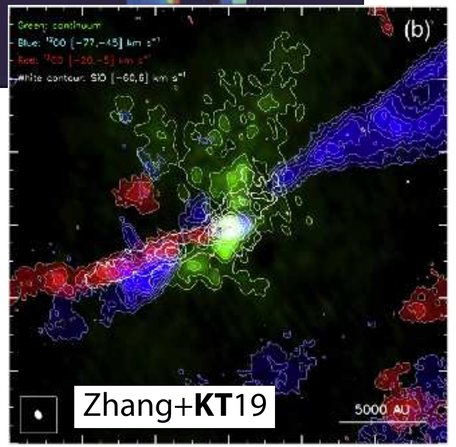


also in massive SF!!



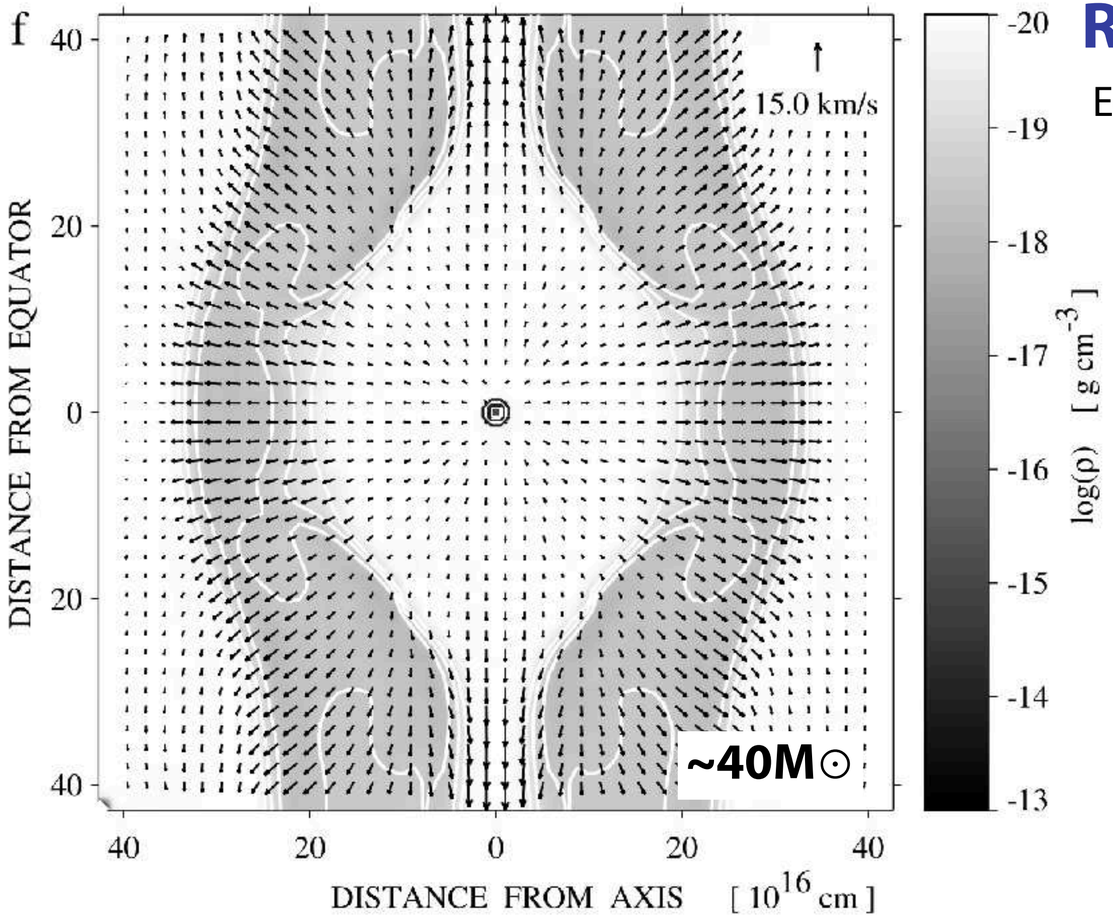






Radiation Pressure in Massive SF

Yorke&Sonnhalter02



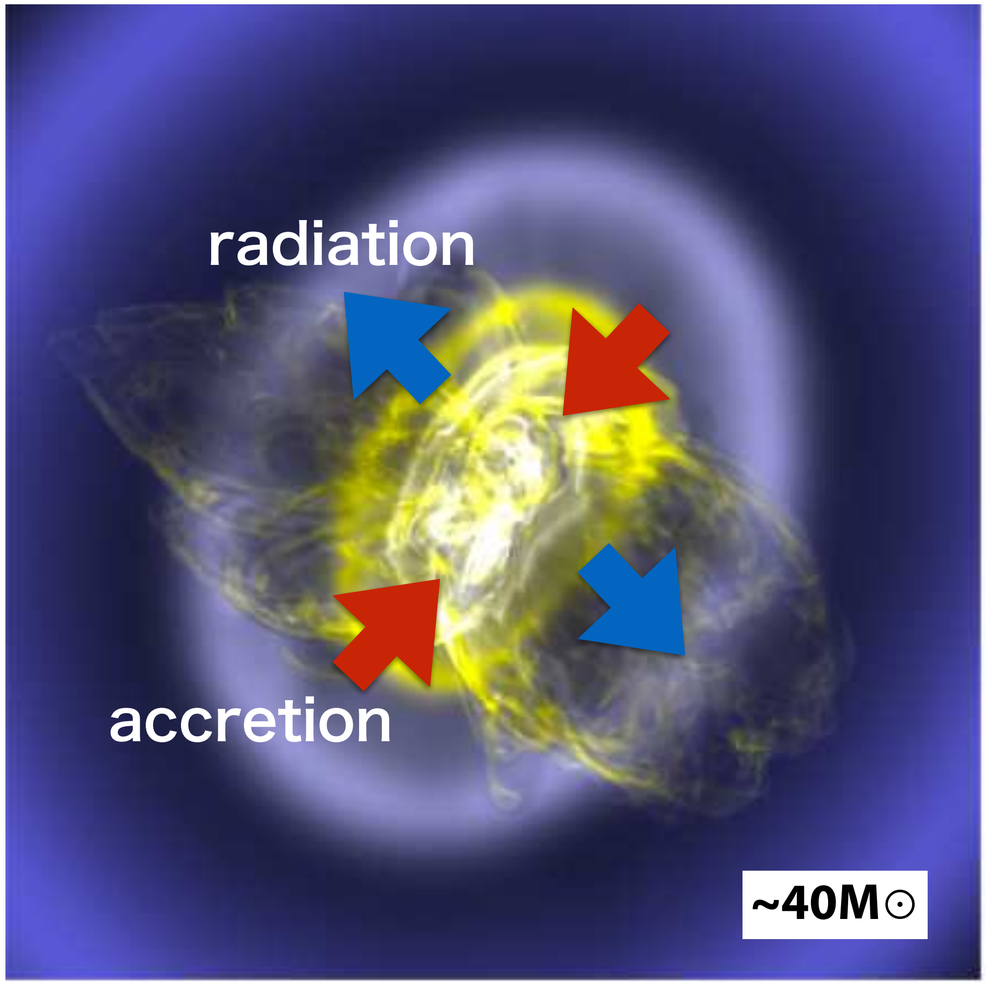
Radiation pressure problem [e.g., Kahn1974, Wolfire&Cassinelli84]

Eddington limit by stellar radiation onto dusty envelope

$$\frac{Gm_*}{r^2} \ll \frac{\kappa_{\rm dust} L_*}{4\pi c r^2}$$ for >20M⊙

Radiation Pressure in Massive SF

Rosen+16



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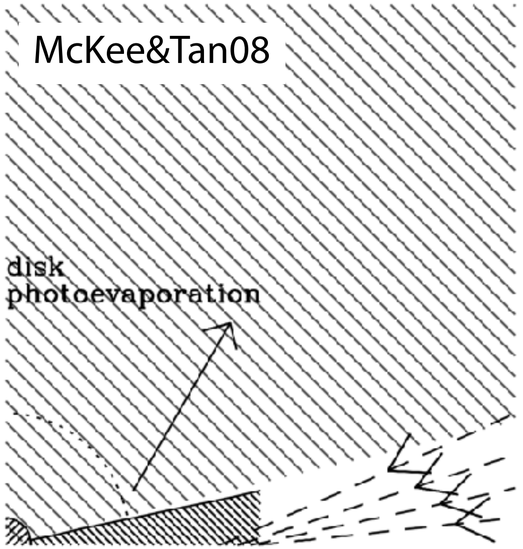
Eddington limit by stellar radiation onto dusty envelope

$$\frac{Gm_*}{r^2} \ll \frac{\kappa_{\rm dust} L_*}{4\pi c r^2}$$ for >20M⊙

Disk accretion overcomes the radiation pressure barrier!

Krumholz+09, Kuiper+10, Peters+10, KT+11, Rosen+16, etc.

Photoionization in First Star Formation



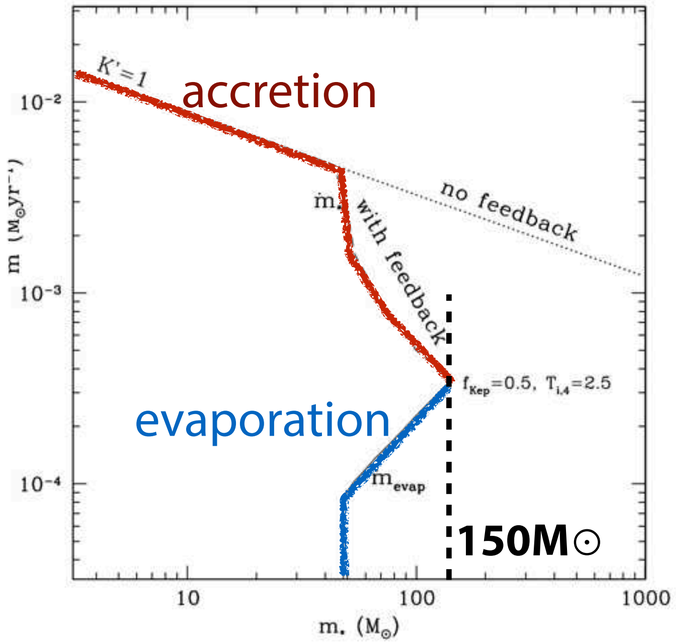
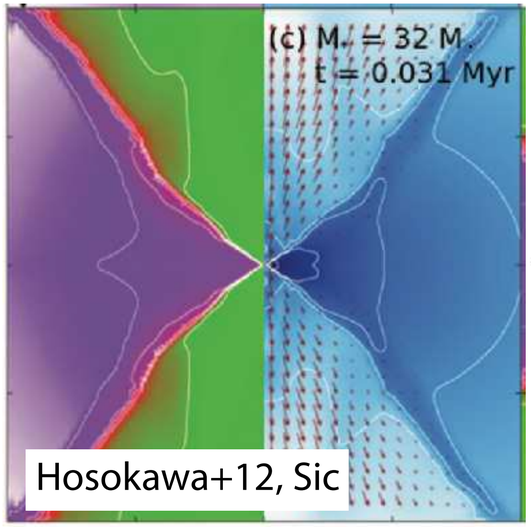
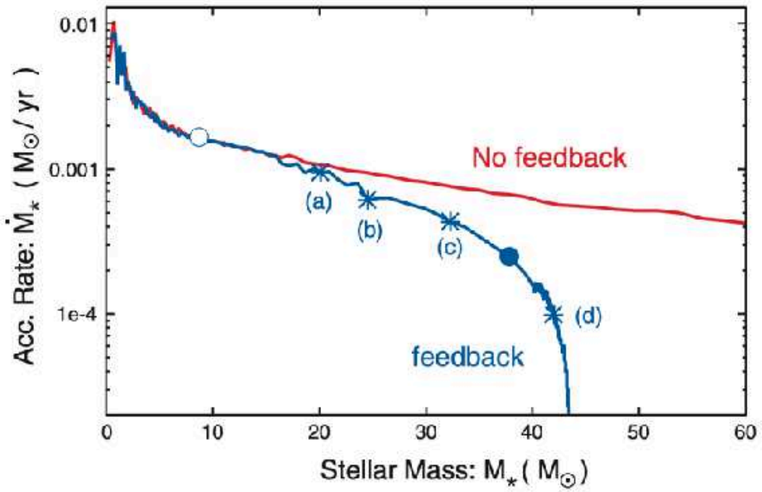


Photo-evaporation rate

$$\dot{M}_{\rm evp} > 10^{-4} M_\odot \ {\rm yr}^{-1}$$ for ~50-100M⊙ in first SF

McKee&Tan08, Hosokawa+12,16, Stacy+13, KT+13, Hirano+15, etc.

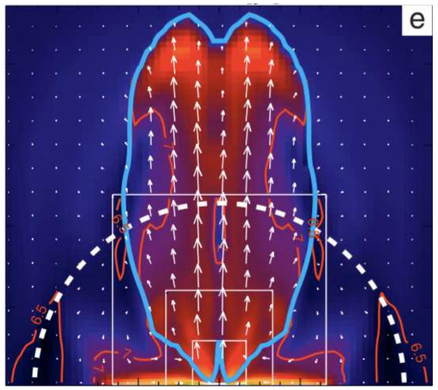


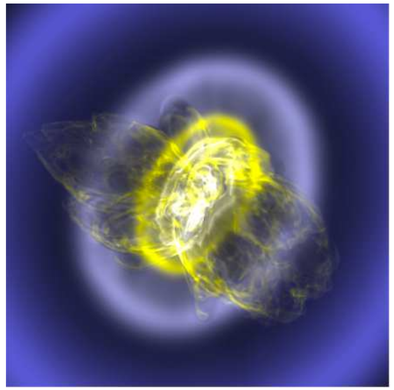


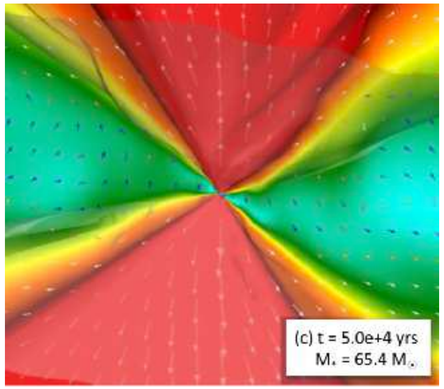
Even at zero metallicity, radiation feedback can be strong enough to stop mass accretion

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?
Are they universal throughout cosmic history? (metallicity etc.)

Multiple Feedback in Massive SF

KT+17,18, ApJ

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

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

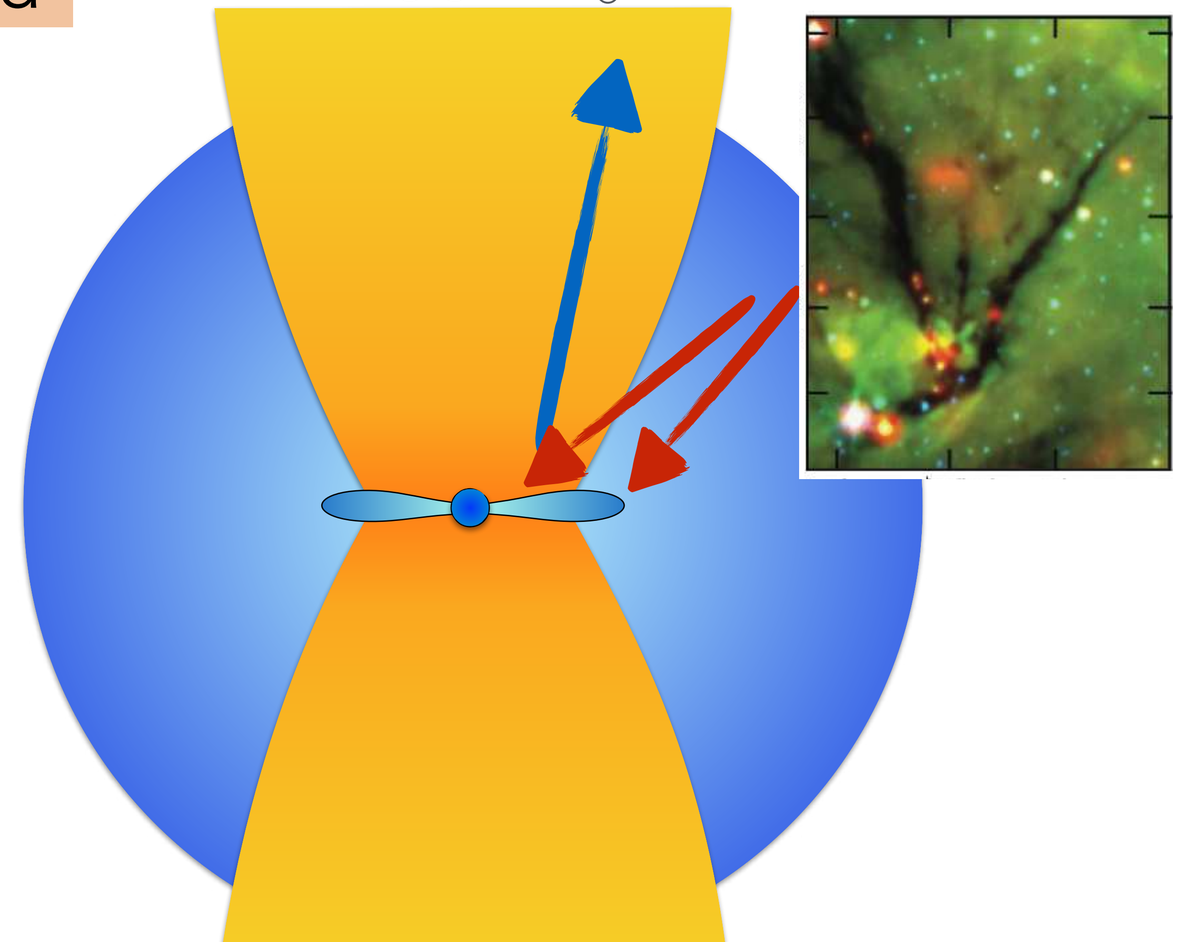
We solve the evolution of protostars,
accretion flow structures,
and feedback processes self-consistently
until the end of accretion.

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

Infrared Dark Clouds

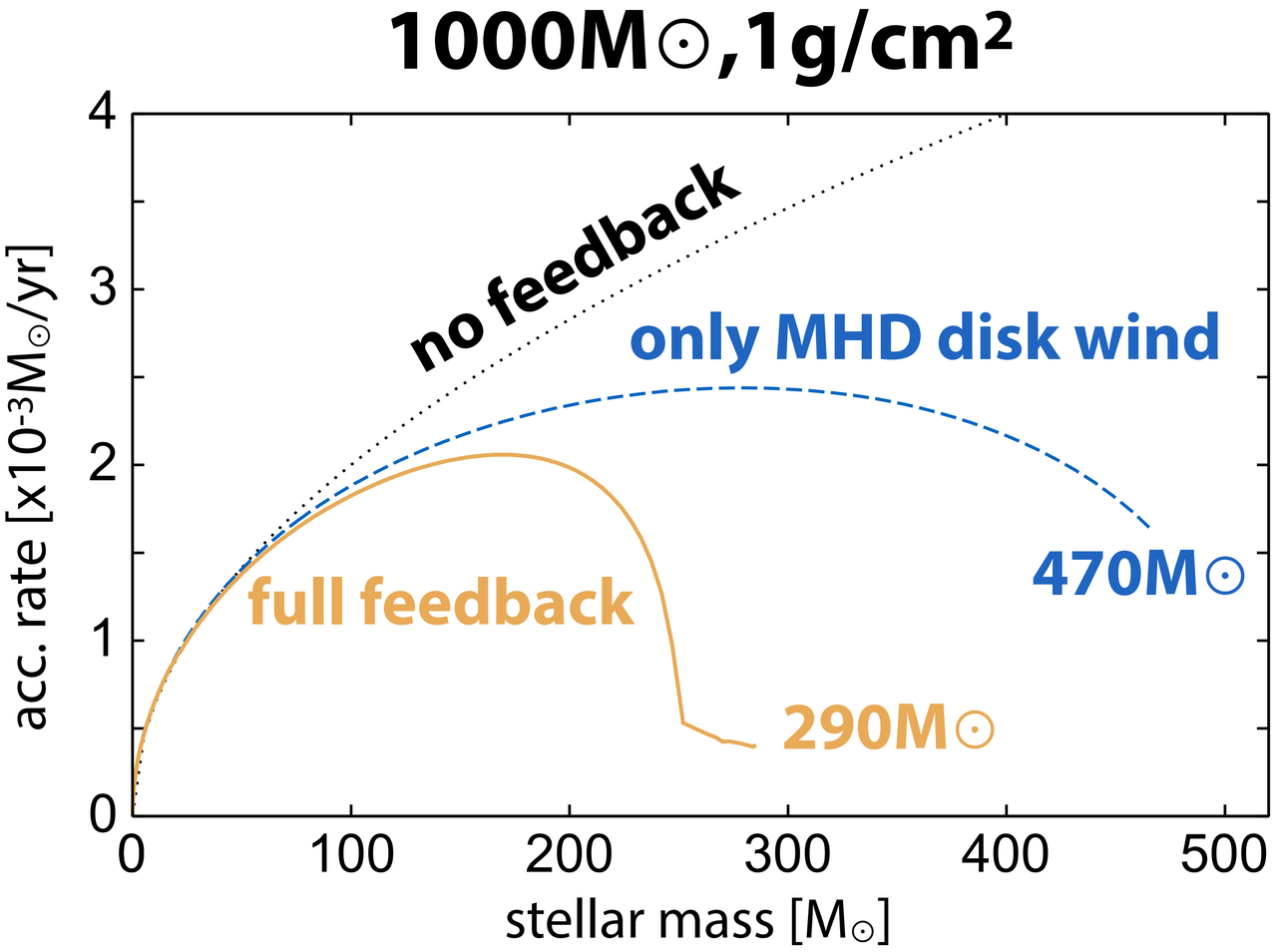


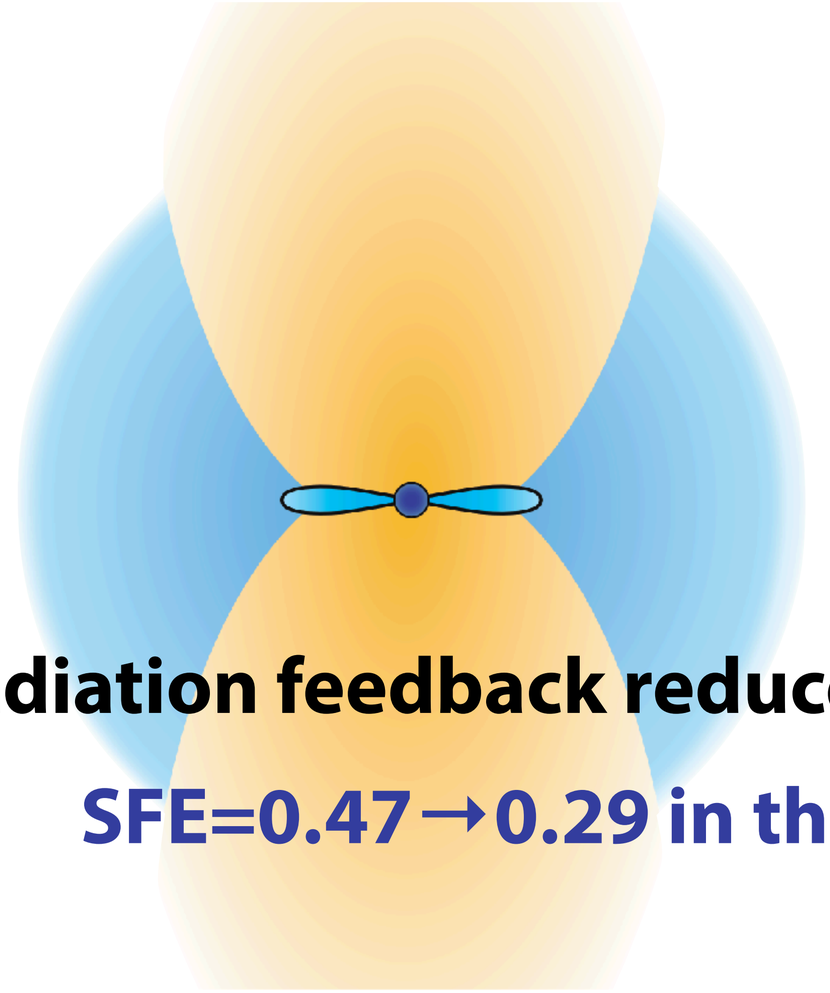
Impact of Multiple Feedback

at $Z_\odot$

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

Accretion History

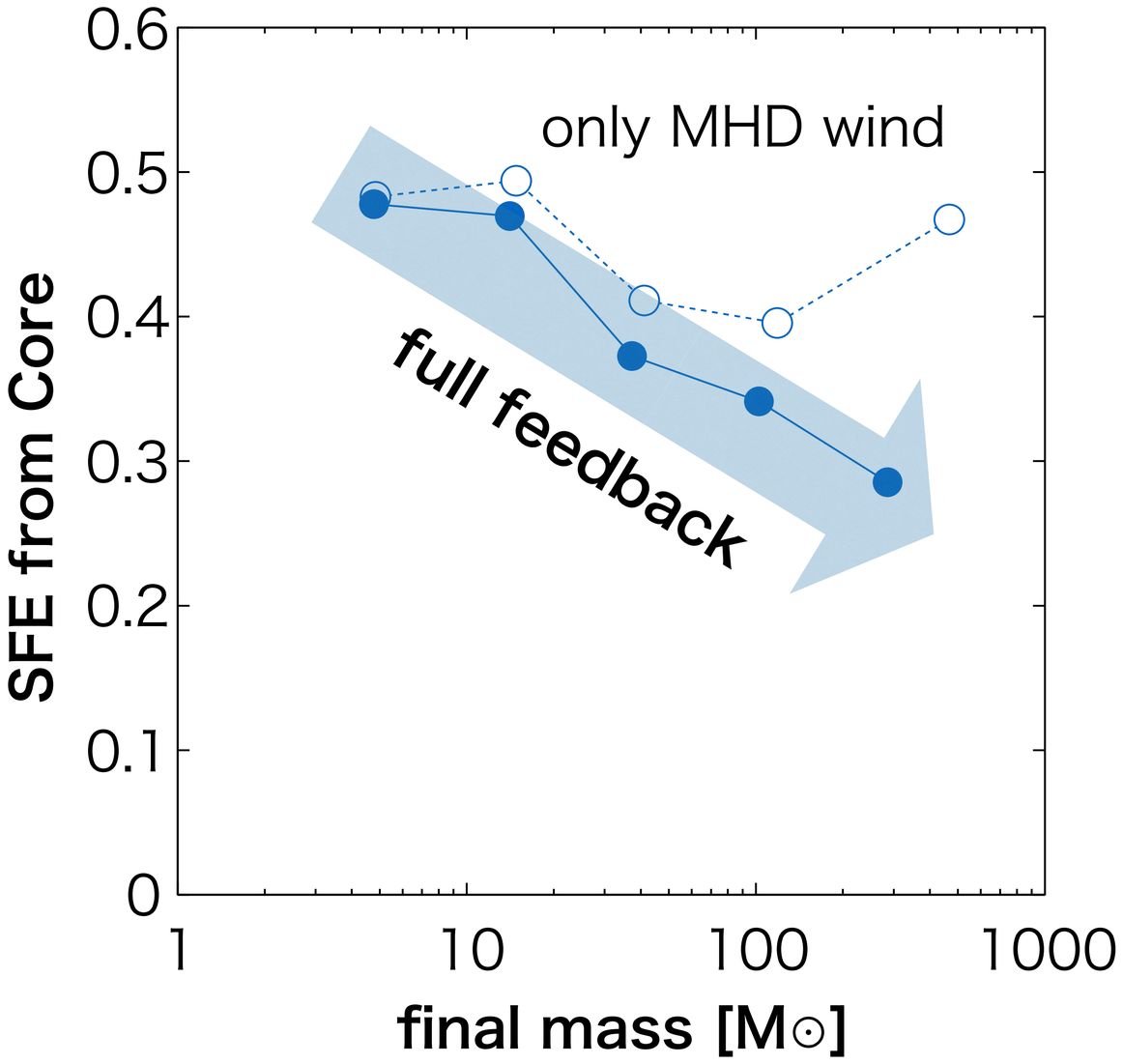




Radiation feedback reduces SFE

SFE=0.47→0.29 in this case

Star Formation Efficiencies

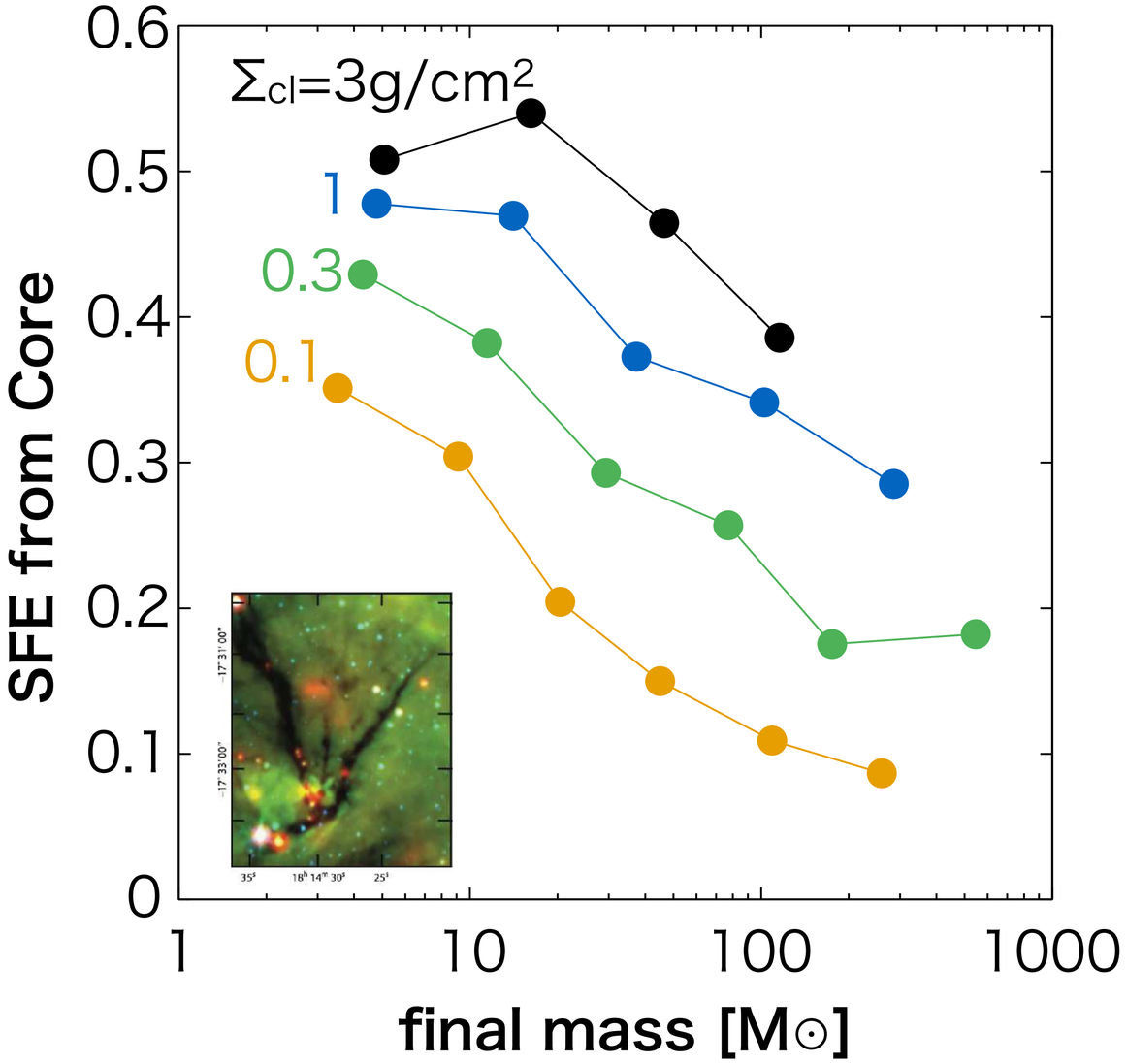


lower SFE in higher-mass SF
due to radiation feedback

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

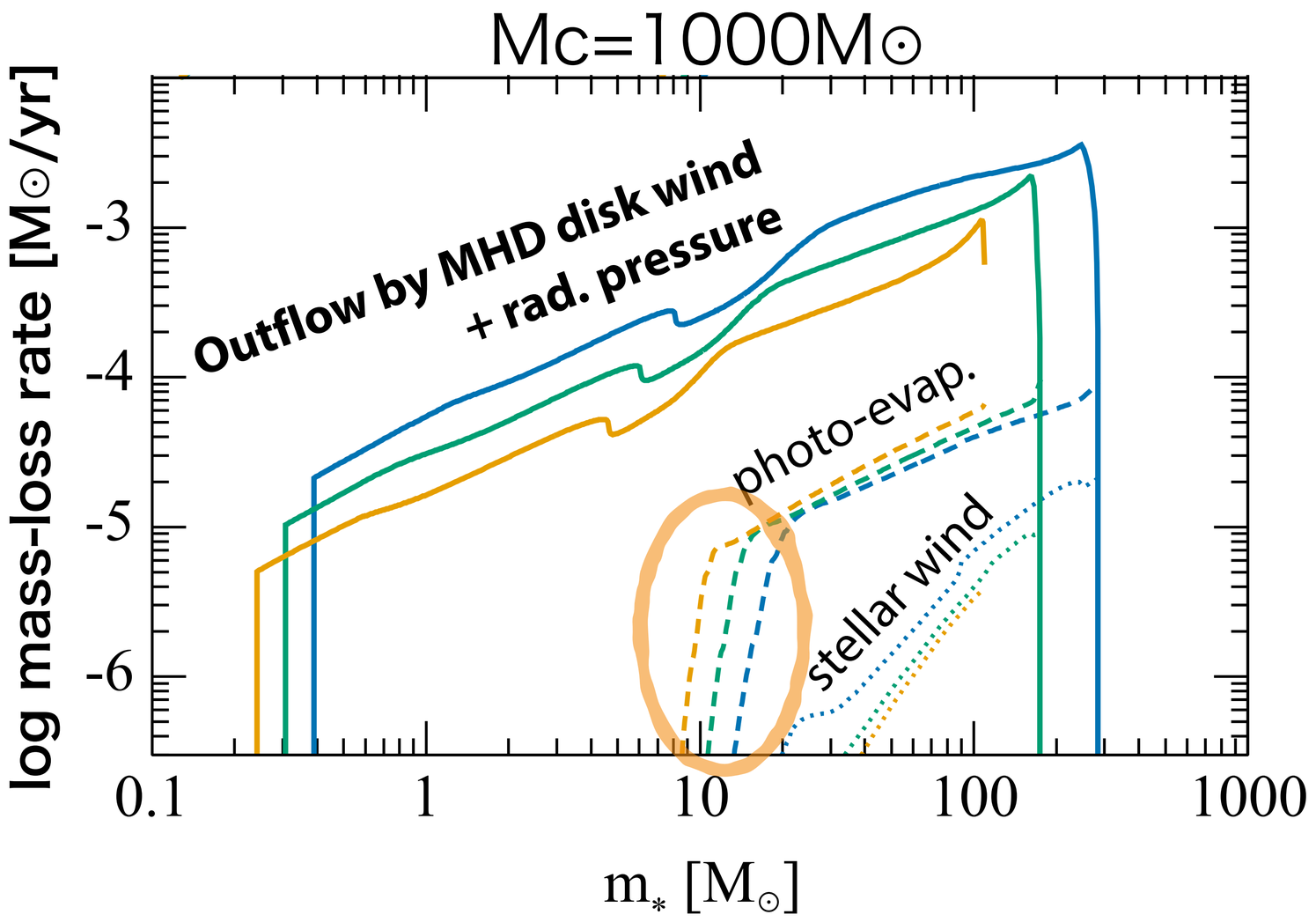
lower SFE at lower Σ

difficult to form very-massive stars

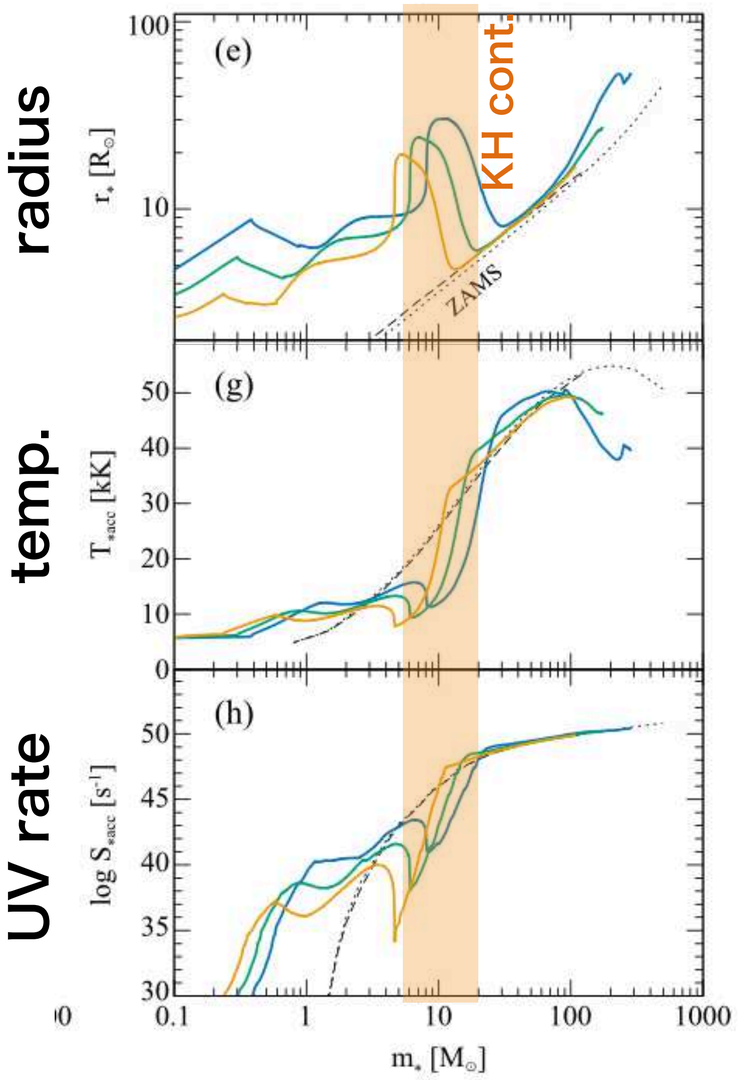
without dense massive cores

(maybe not competitive accretion?)

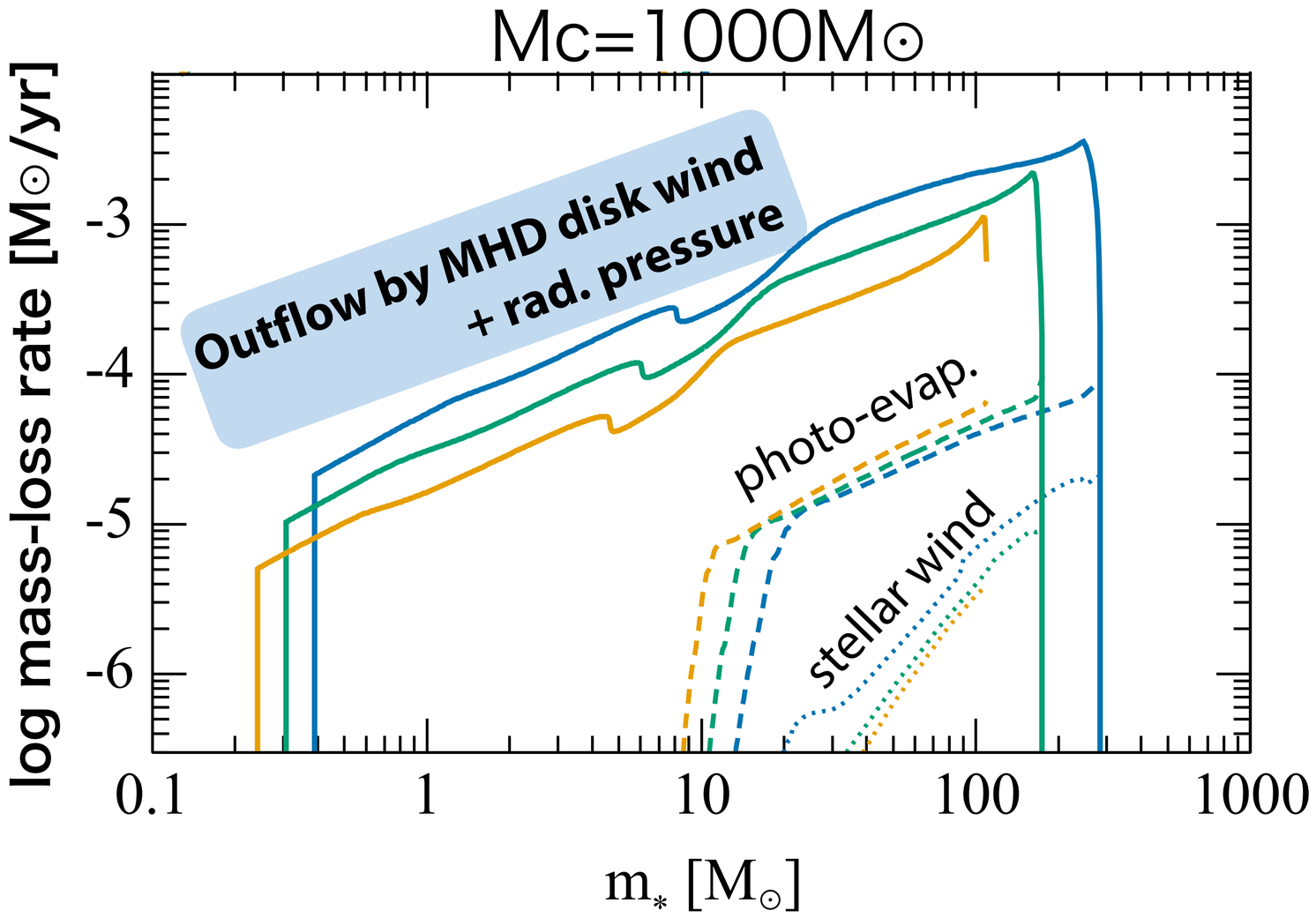
Which is the dominant feedback?



proto-stellar properties



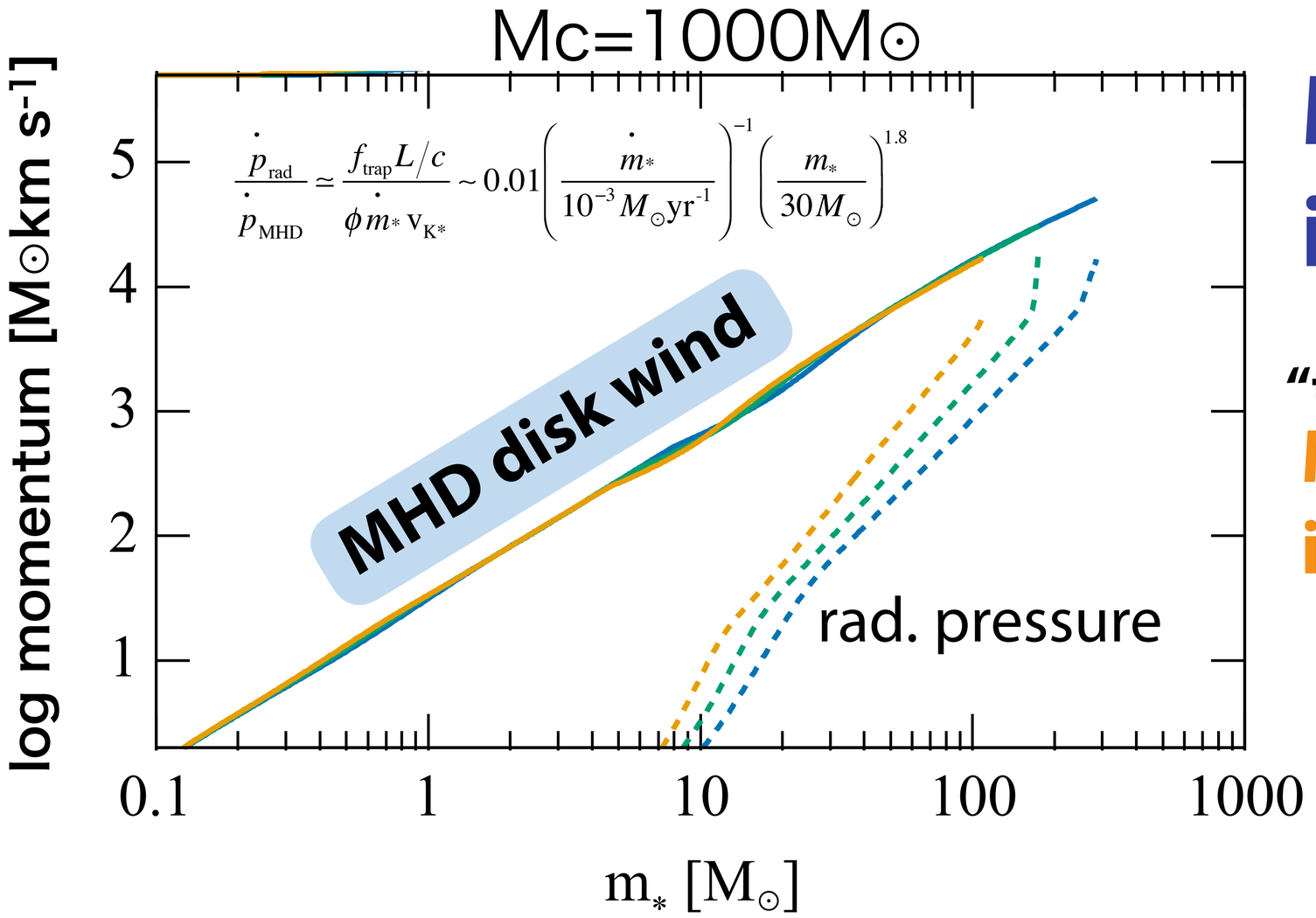
Which is the dominant feedback?



Momentum-driven outflow is dominant

MHD disk wind?
or
Radiation pressure?

Which is the dominant feedback?



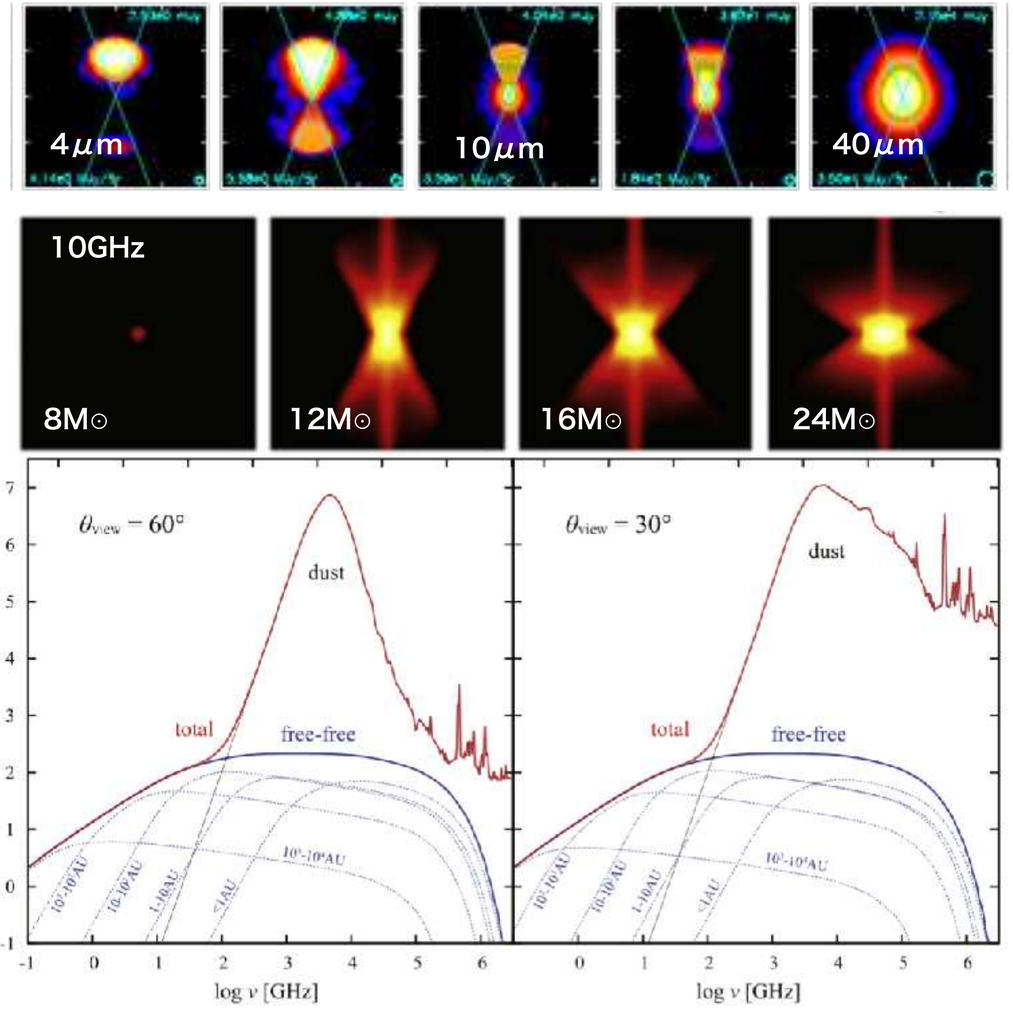
MHD disk wind is dominant!!

“theoretically”

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

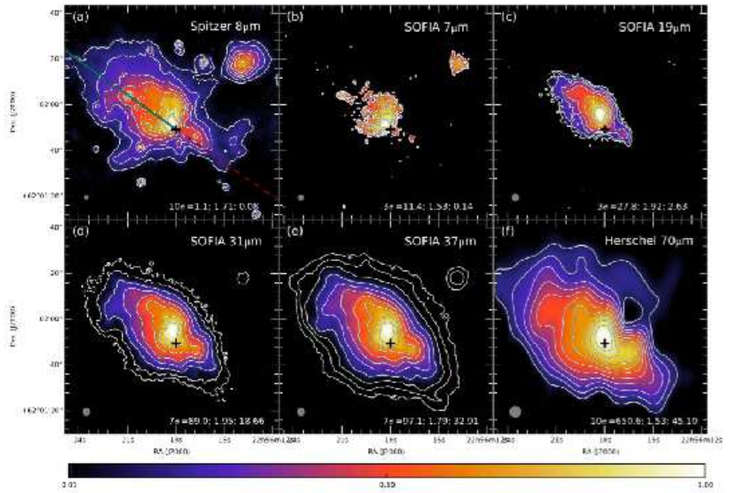
Synthetic Observations

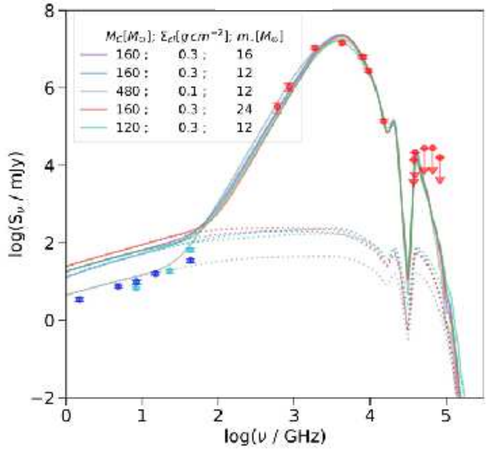
Synthetic Observations Zhang+18; KT+16,17b



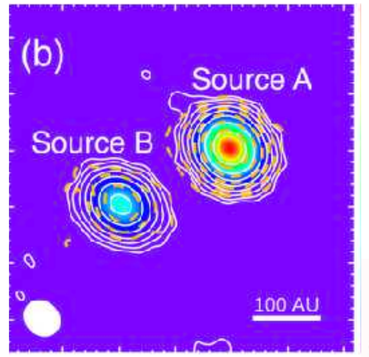
Liu+KT19; Rosero, KT+19; etc

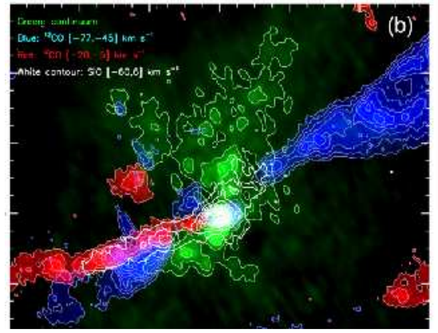
IR by SOFIA

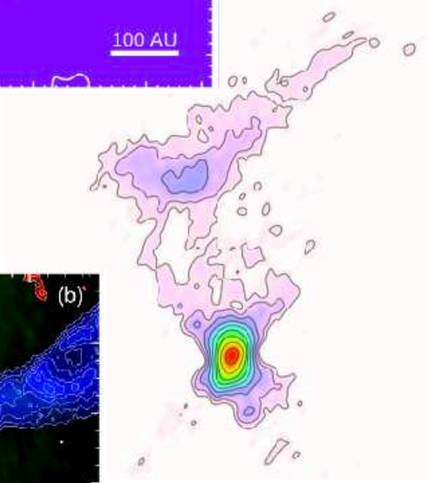




mm & radio by ALMA & VLA



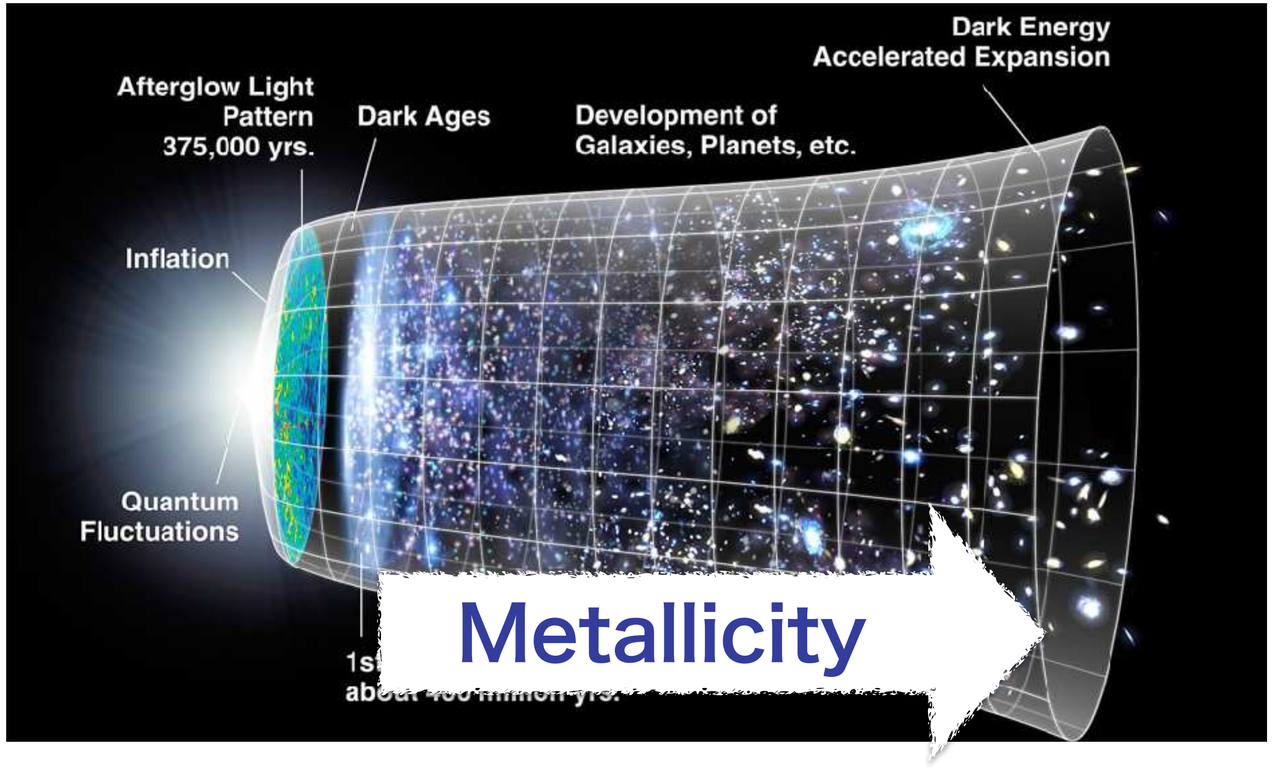




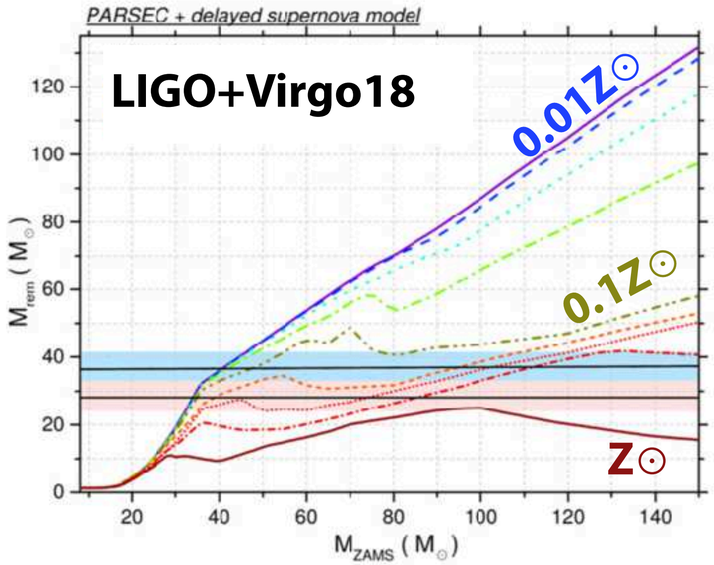
→ *Yichen Zhang's talk*

Metallicity Dependence

(Massive) Star Formation at Low Metallicity

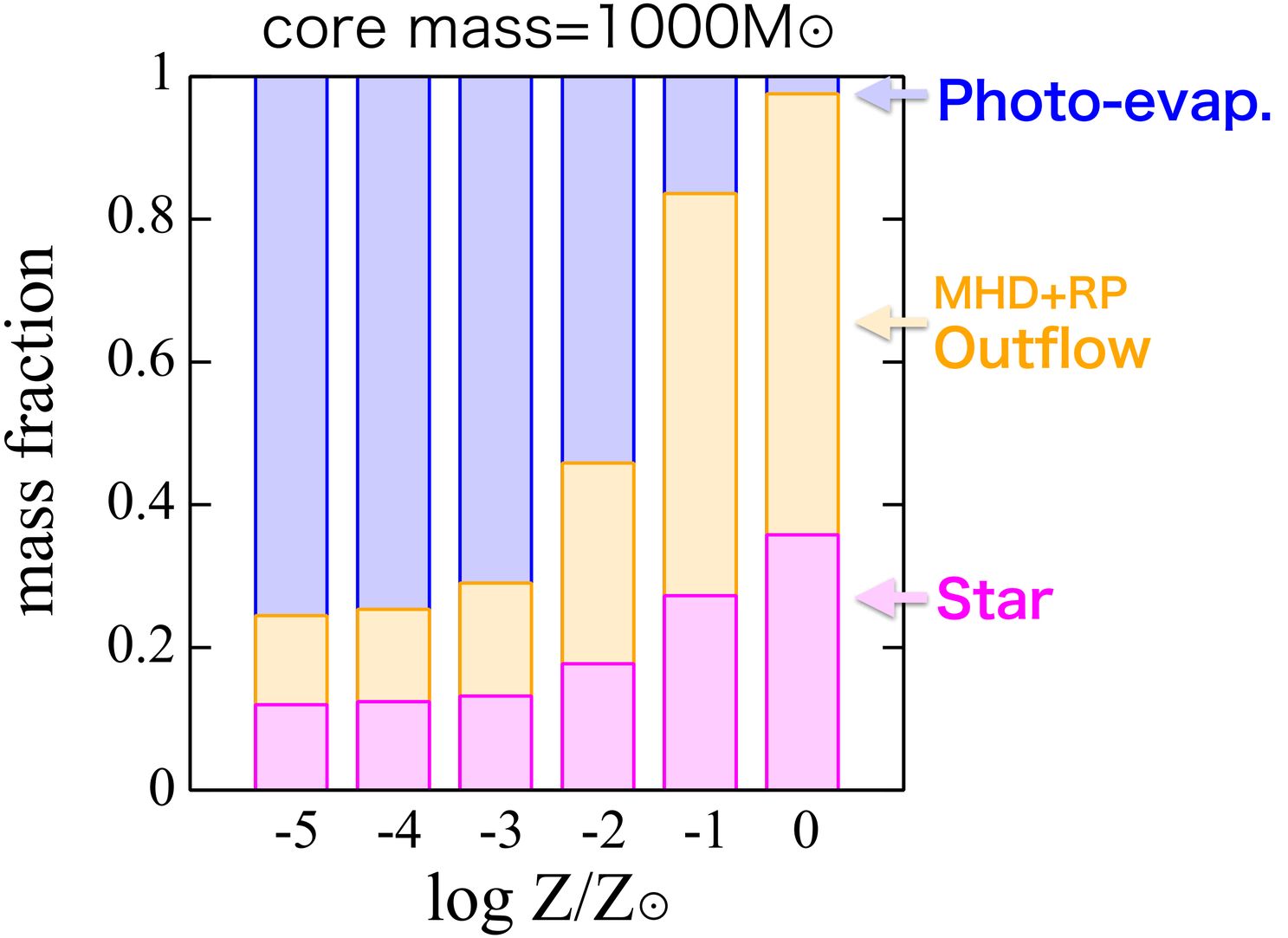


The most massive star on record in LMC [Crowther+10]
Progenitors of BH-BH mergers [LIGO+Virgo18,19]
Progenitors of GRBs [recall 1st-day talks; Woosley & Heger 06]
First stars were 100-1000$M_\odot$ [Hirano+15]



Is SF process universal or not?

Feedback at Low Metallicities



At Z⊙,
outflow is strongest

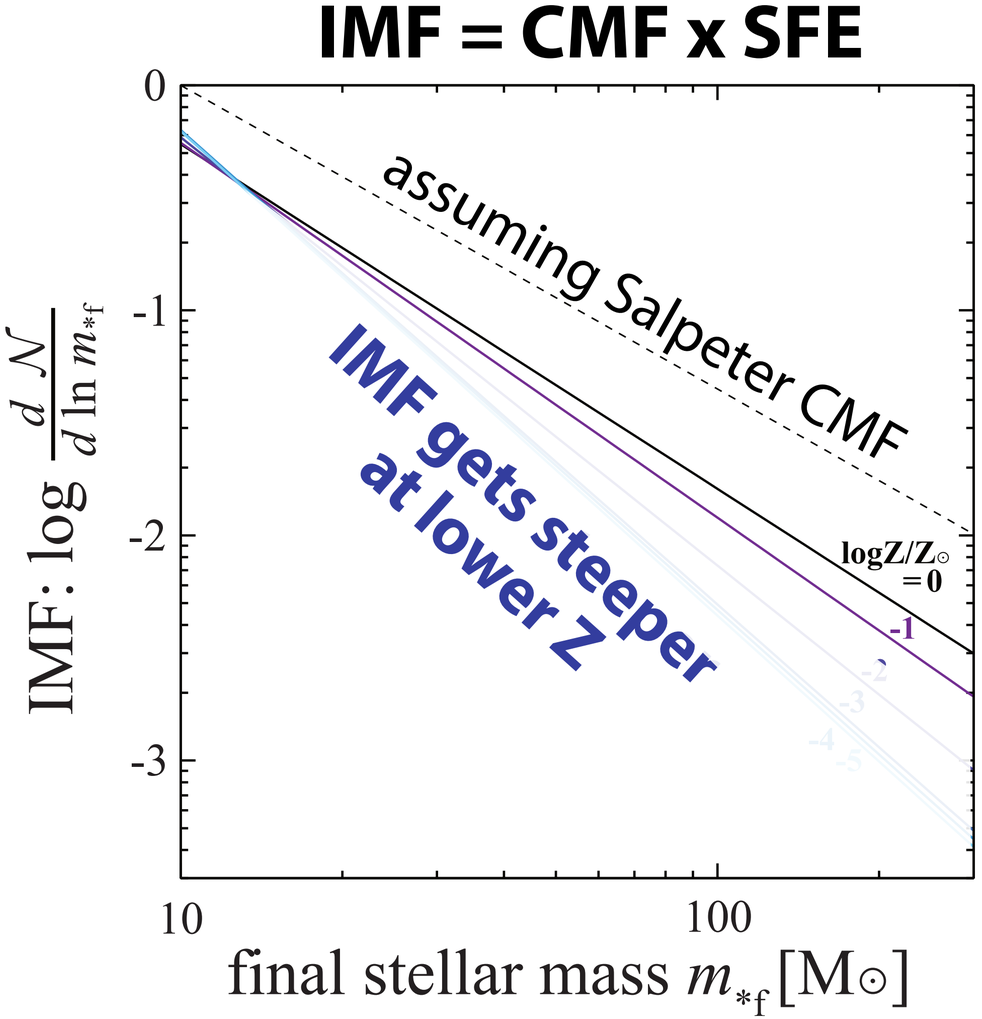
At <0.01Z⊙,
PE becomes dominant

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⊙

Non-Universal IMF?

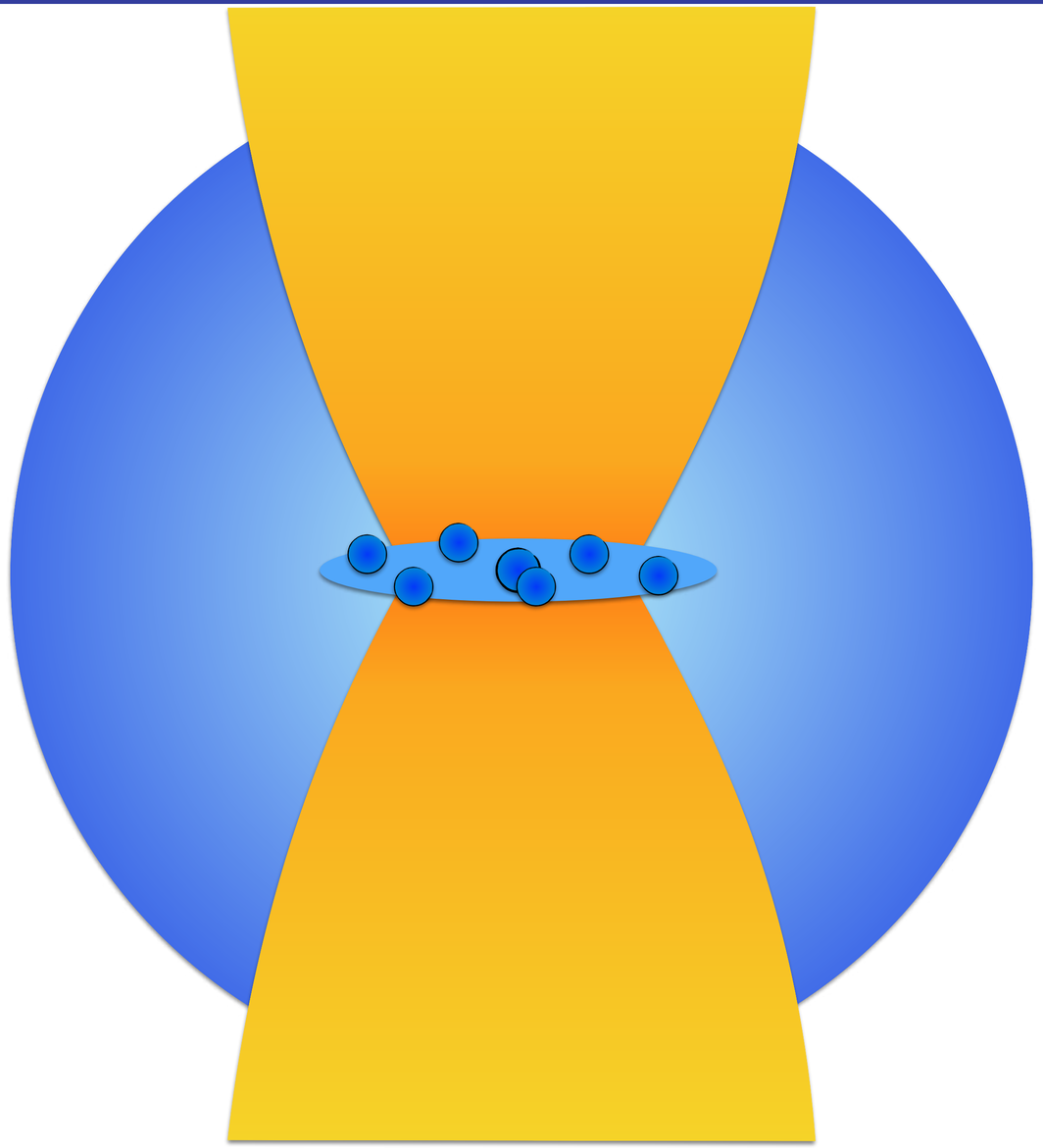


At sol to sub-sol metal of 1– $0.1Z_{\odot}$,
Z dependence is not apparent.
Σ_{cl} dependence is more significant

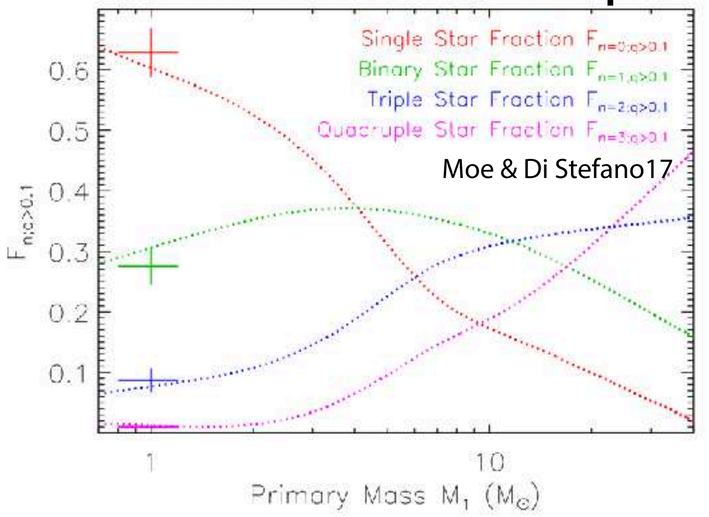
At extremely low Z case of 10^{-5}– $10^{-3}Z_{\odot}$,
massive stars would be rarer

Typical metallicity of 2nd stars (Chiaki+18)

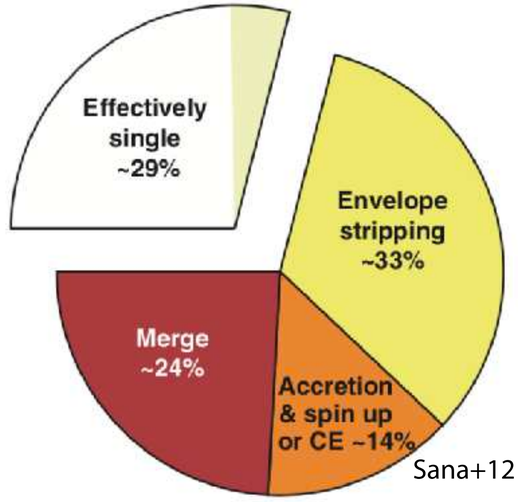
What about Close Binaries/Multiples?

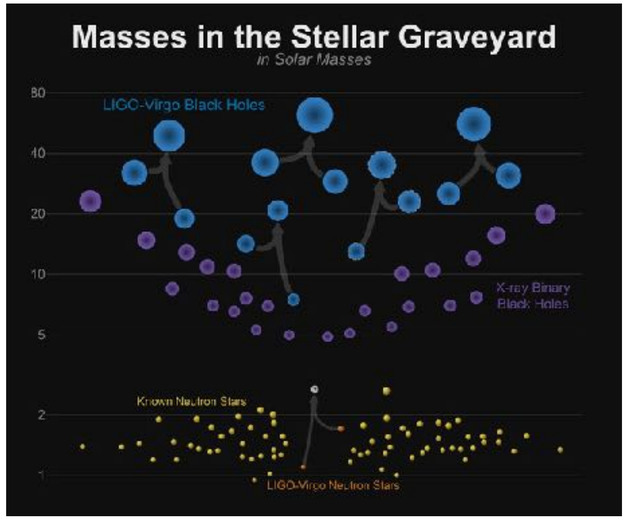


all massive stars form in multiples

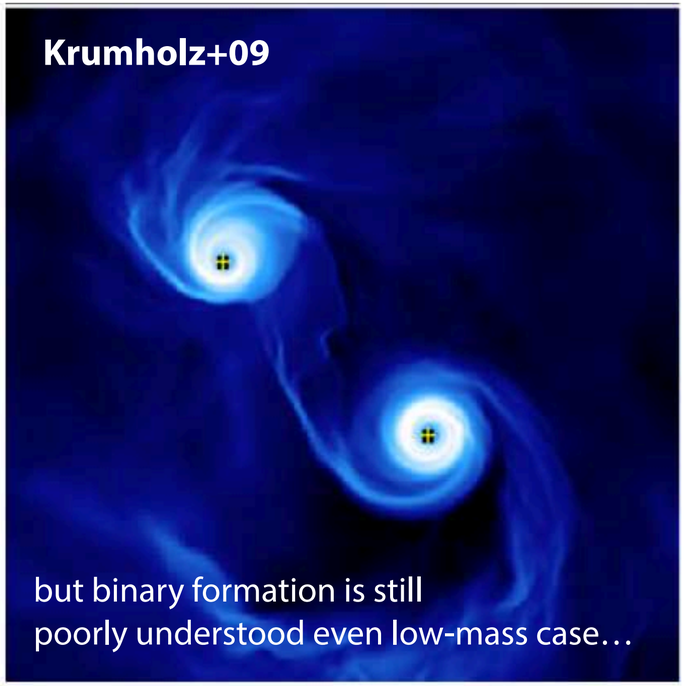


normally close companions





What about Close Binaries/Multiples?



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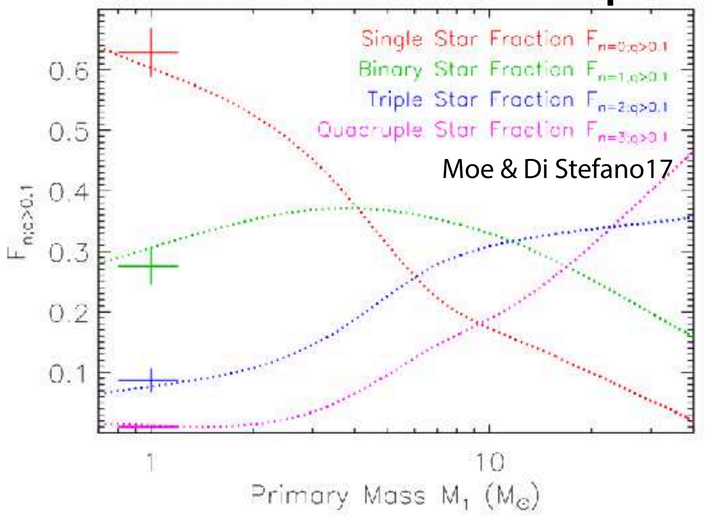
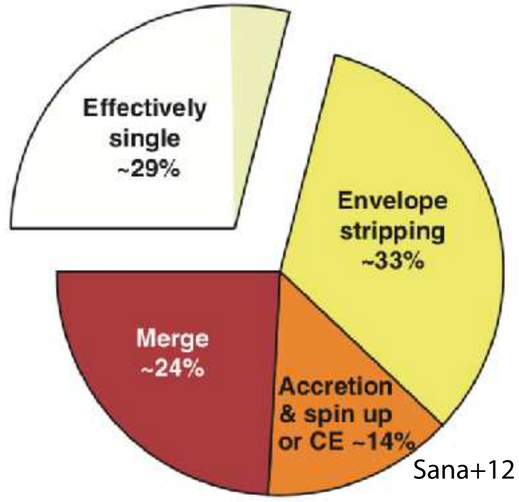


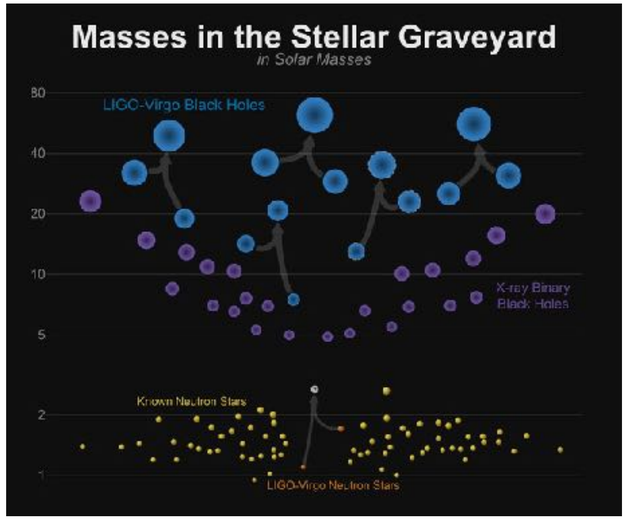
normally close companions



In massive SF, due to high-Mdot, disks likely to become unstable (Q<1)

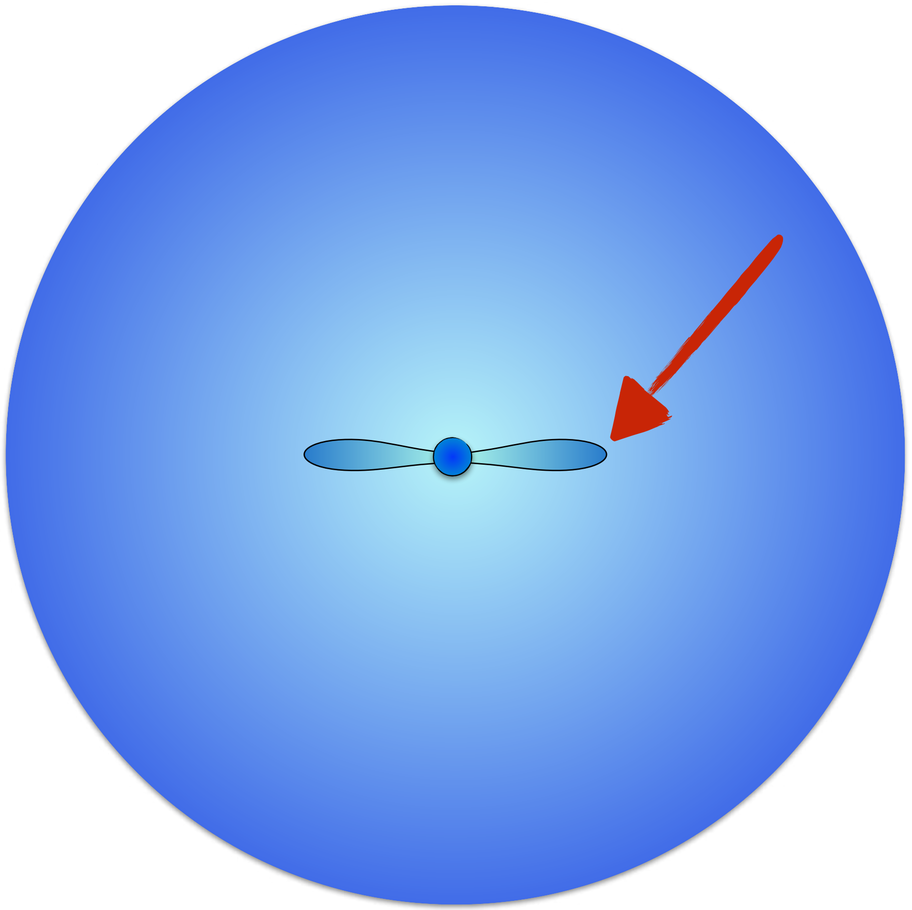
[e.g., Kratter10]

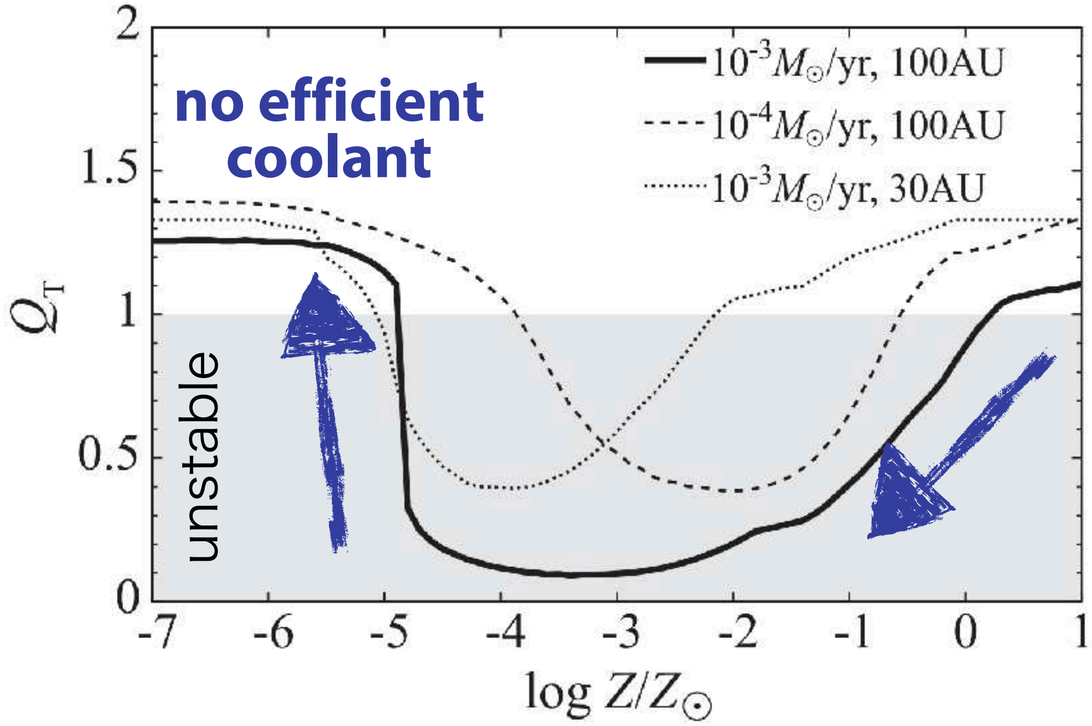
What about metallicity dependence?
Progenitors of GRBs & BH binaries



Stability of Protostellar Disk

KT&Omukai14





blanket effect is weaker

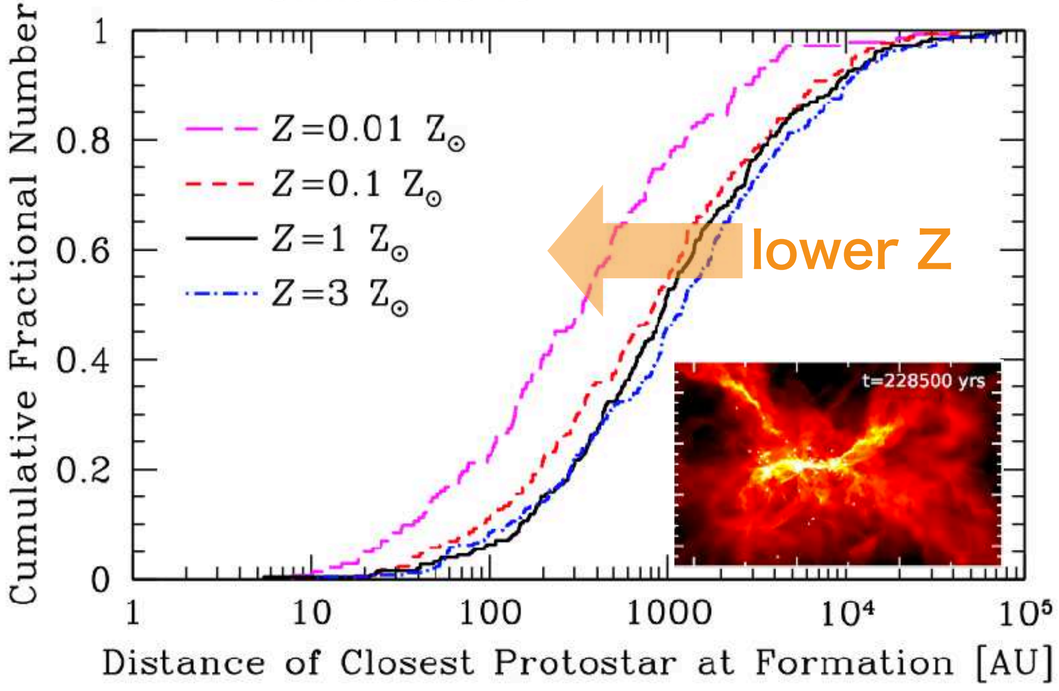
Catastrophic disk fragmentation is expected at low metallicity

→ close binary/multiple formation

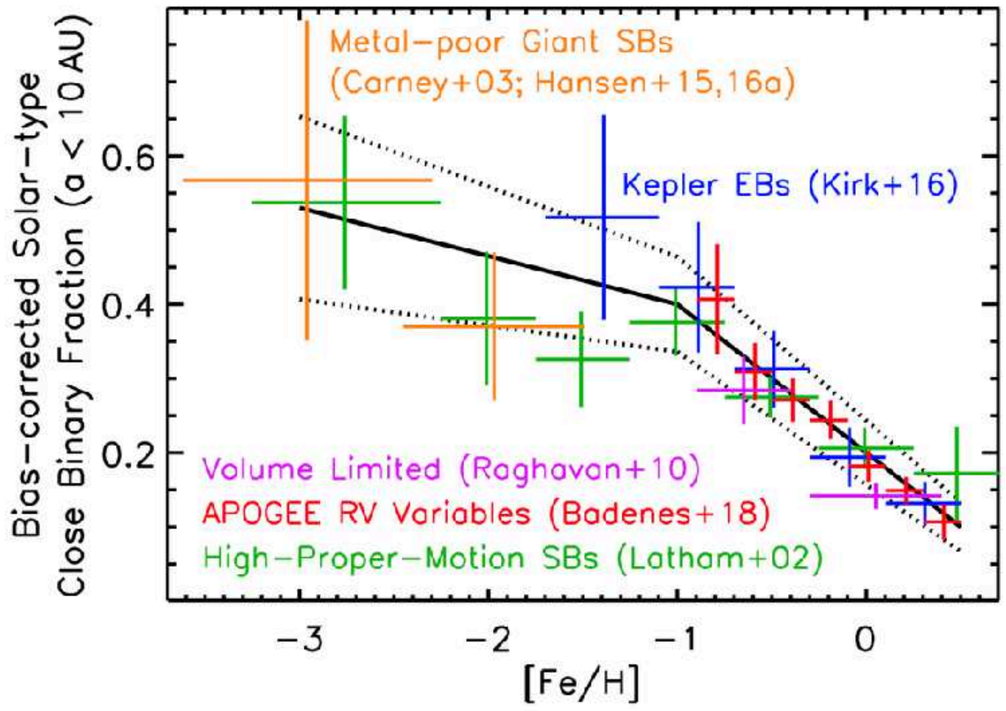
Formation of Close Binaries/Multiples

consistent with recent simulations & observations

Sim: Bate 19 see also Machida&Nakamura14



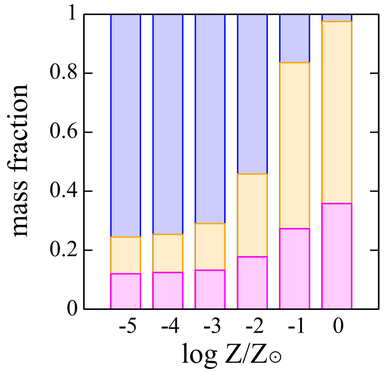
Obs: Moe+19 see also Schlaufman+18



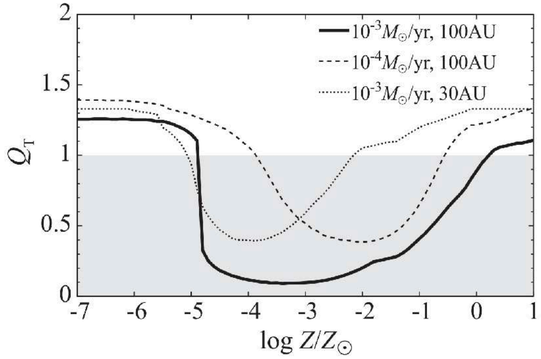
Those new results support our theoretical prediction

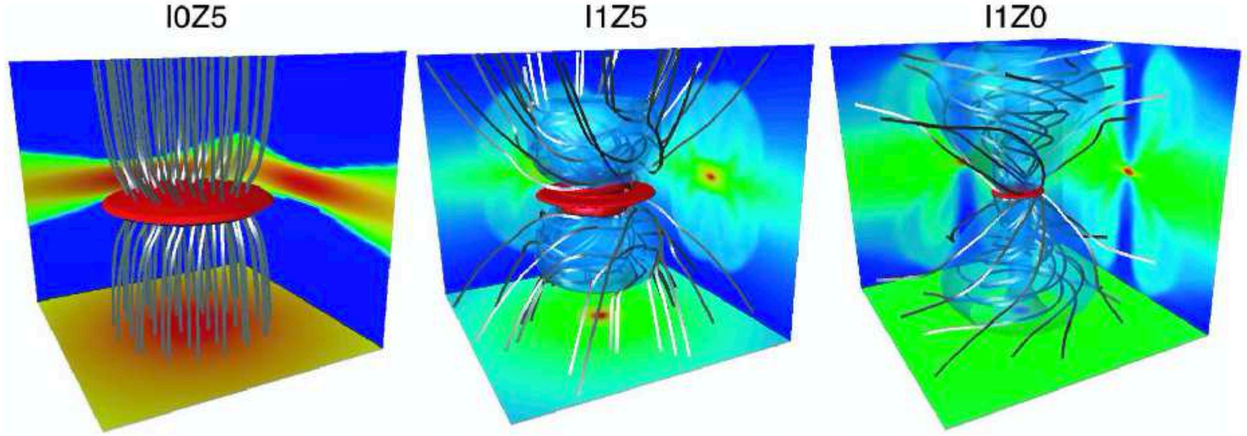
Universality of Star Formation Dynamics?

Feedback [KT+18]



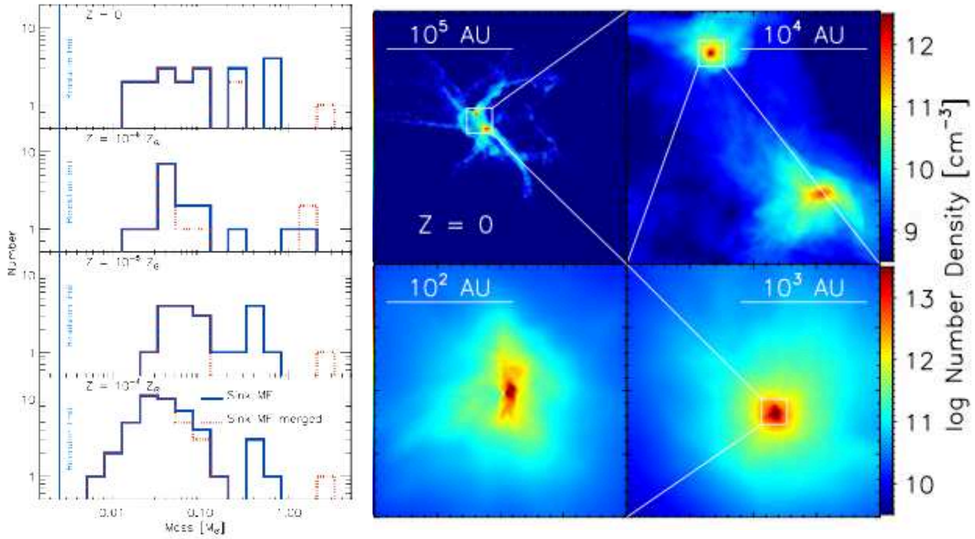
Disk stability [KT&Omukai14]





MHD disk wind [Higuchi+19]

fragmentation [Dopcke+13]

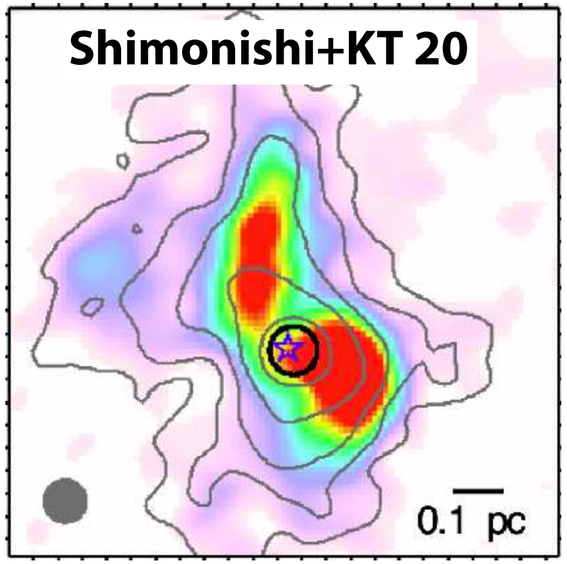


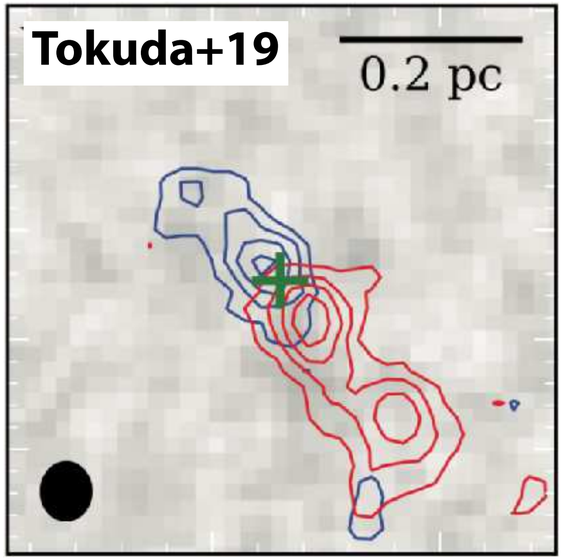
Some *theoretical studies* have proposed metallicity (or other environmental) **dependences of star formation dynamics.**

How can we test them?
Observations are mostly limited in Milky Way so far…

Outflow Survey in Magellanic Clouds

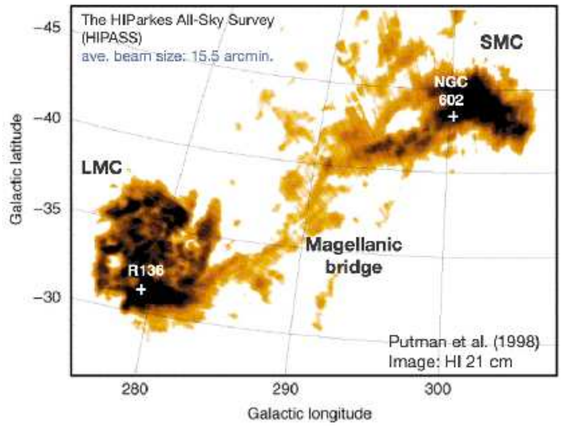
KT+ in prep.





They are in **the Large Magellanic Cloud**!!

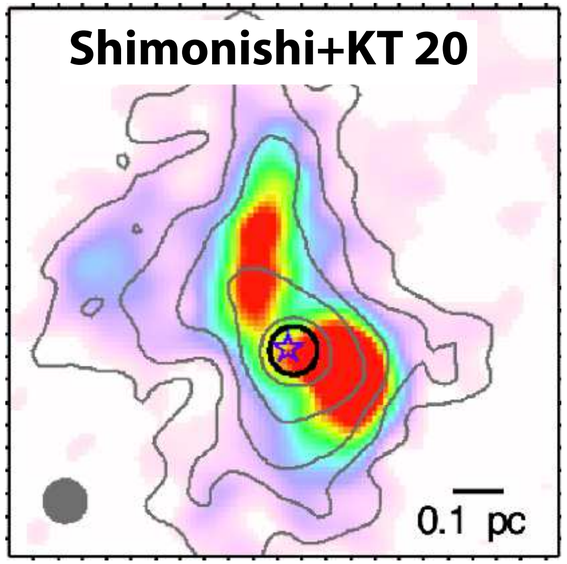


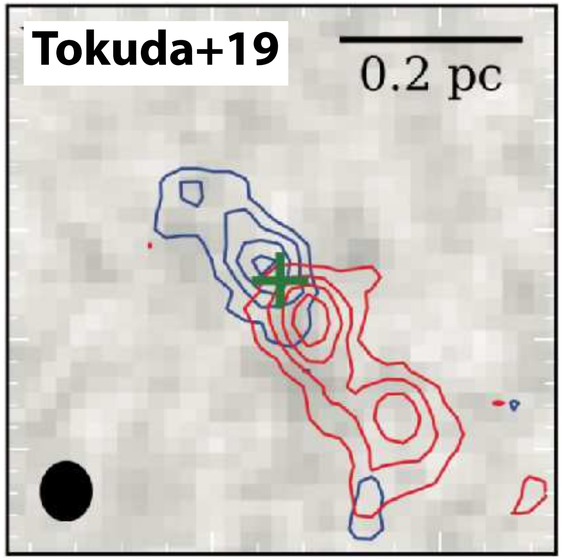


Thanks to the power of ALMA,
protostellar outflows in LMC start to be found

Outflow Survey in Magellanic Clouds

KT+ in prep.





Thanks to the power of ALMA,
protostellar outflows in LMC start to be found

The first outflow survey in LMC (~1/2$Z_\odot$) & SMC (~1/5$Z_\odot$)

[2019.1.01770.S, PI: KT]

This survey will let us to examine the (non-)universality of the star formation processes throughout cosmic history

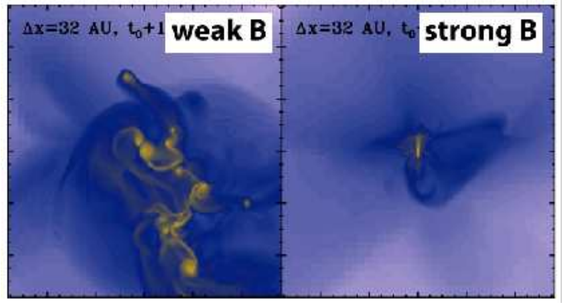


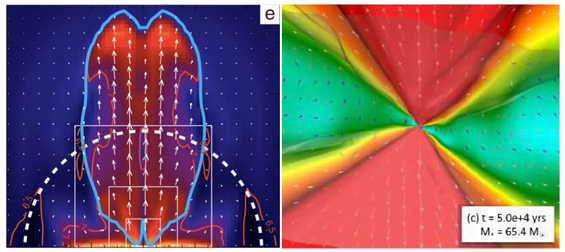


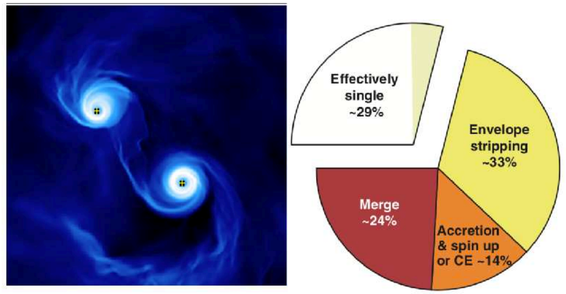
Summary

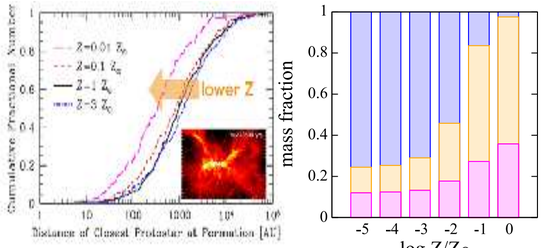
Massive Star Formation

in my view









Fragmentation

radiation heating & magnetic braking suppress fragmentation

(but low-mass stars should also form together)

Collision of clouds can creates such massive cores with strong B-filed

Feedback

Multiple feedback does not limit the upper mass

MHD disk wind is strongest feedback, i.e., scale-up of low-mass SF

Close Companions

Most of massive stars have close companions due to disk fragmentation

Properties cloud depends on metallicity

Environmental Dependence

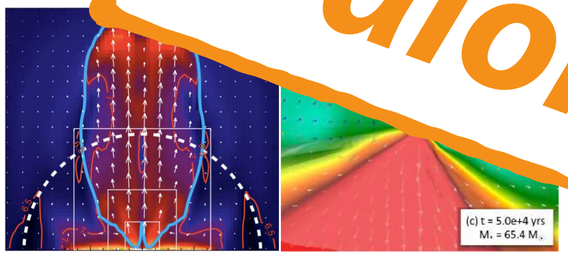
Some metallicity dependences have been proposed

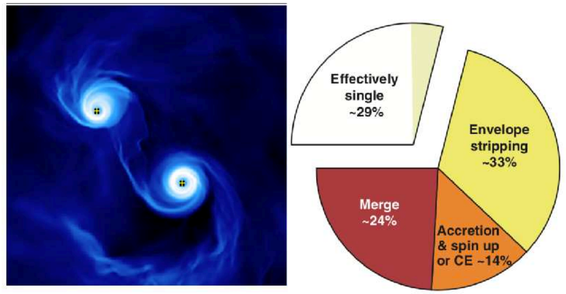
What about ∑, UV, CRs, B-field, etc..?

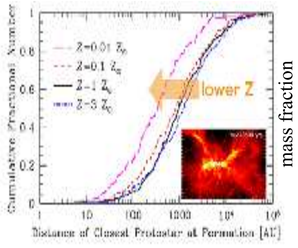
Massive Star Formation

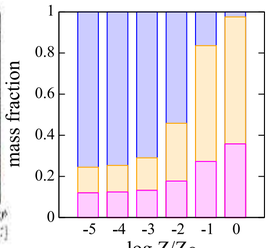
in my view











Fragmentation

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…r mass

…n of low-mass SF

Close Comp…

Most of massive stars ha…

Properties cloud depends on ne…

…ation

Environmental Dependence

Some metallicity dependences have been proposed

What about ∑, UV, CRs, B-field, etc..?

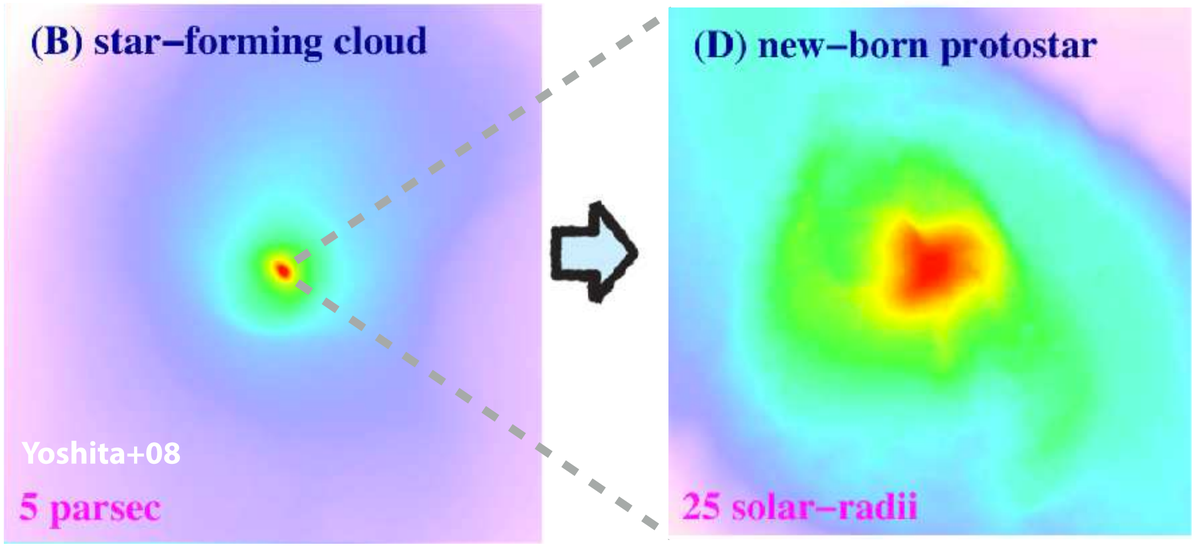
Necessary to investigate alongside observations!

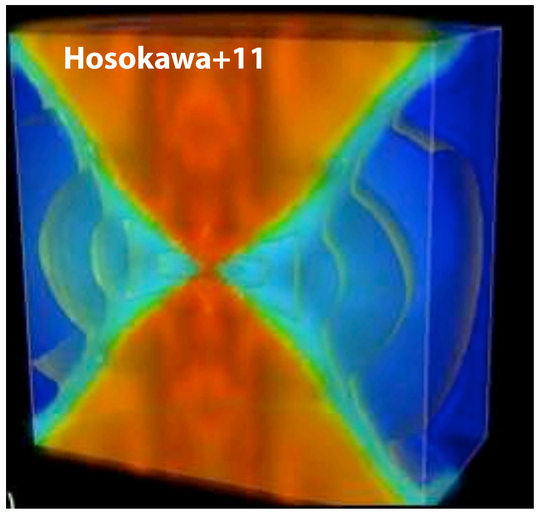
interestingly

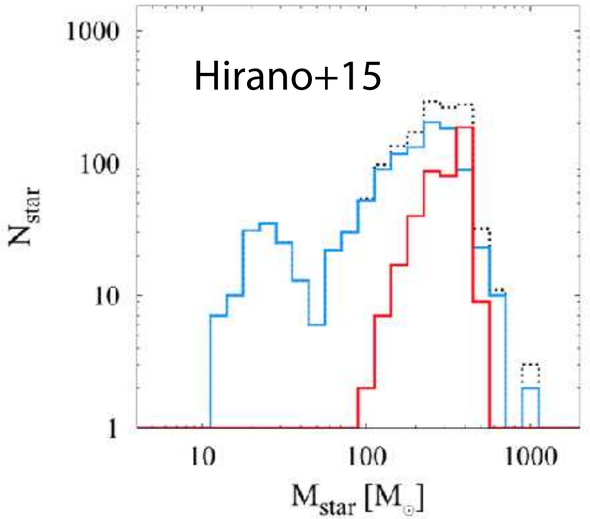
First Star Formation

e.g. Bromm&Larson04, Glover13

prestellar "core" → collapse → disk & outflow







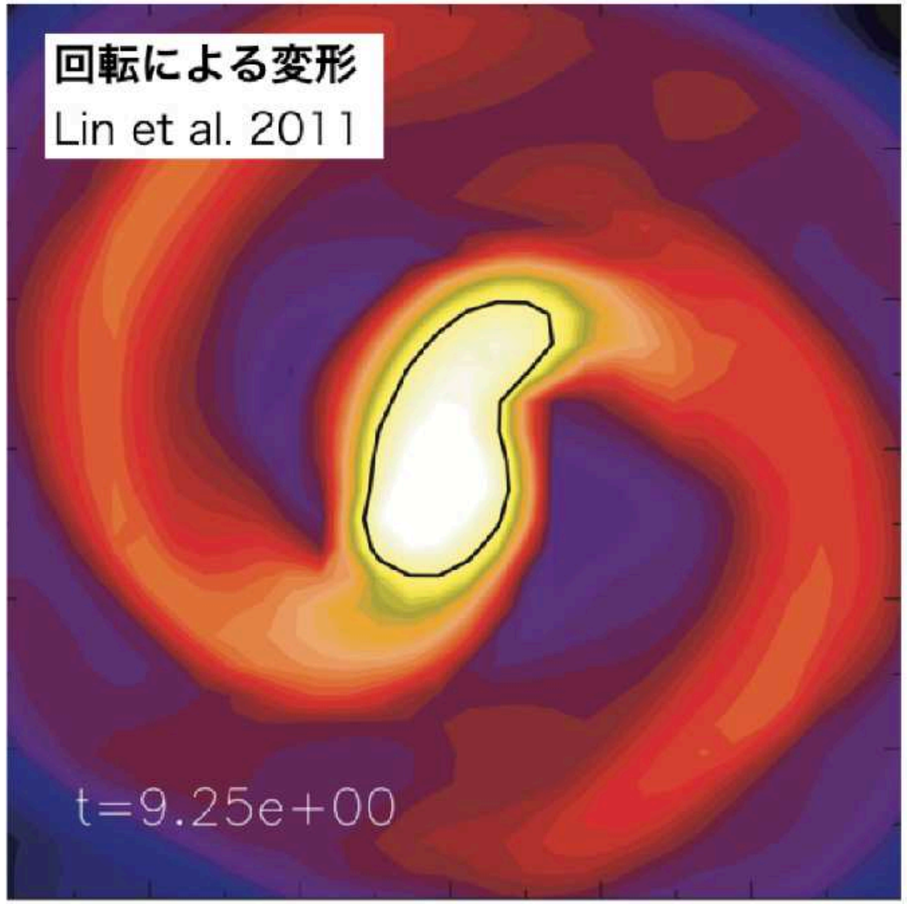
Zero metal.
→ inefficient cooling

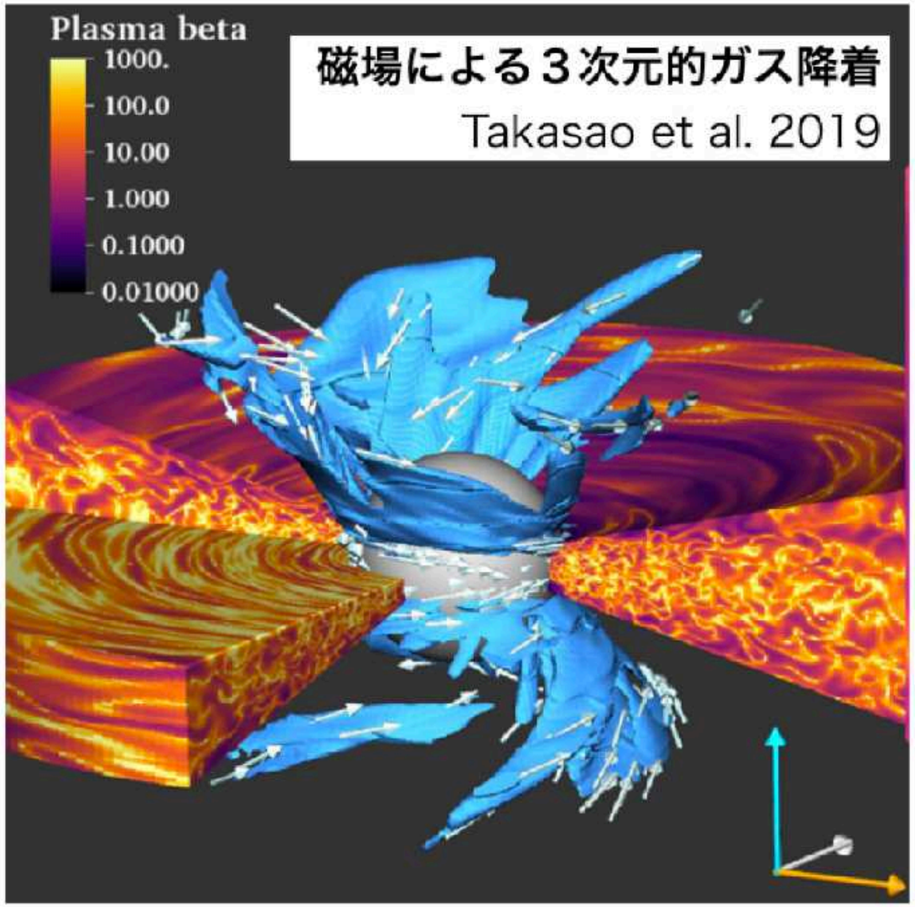
$$M \sim 1000 M_\odot \left(\frac{T}{500\mathrm{K}}\right)^{3/2} \left(\frac{n}{10^4 \mathrm{cm}^{-3}}\right)^{-1/2}$$

$$\dot{M} \sim 10^{-3} M_\odot \mathrm{yr}^{-1} \left(\frac{T}{500\mathrm{K}}\right)^{3/2}$$

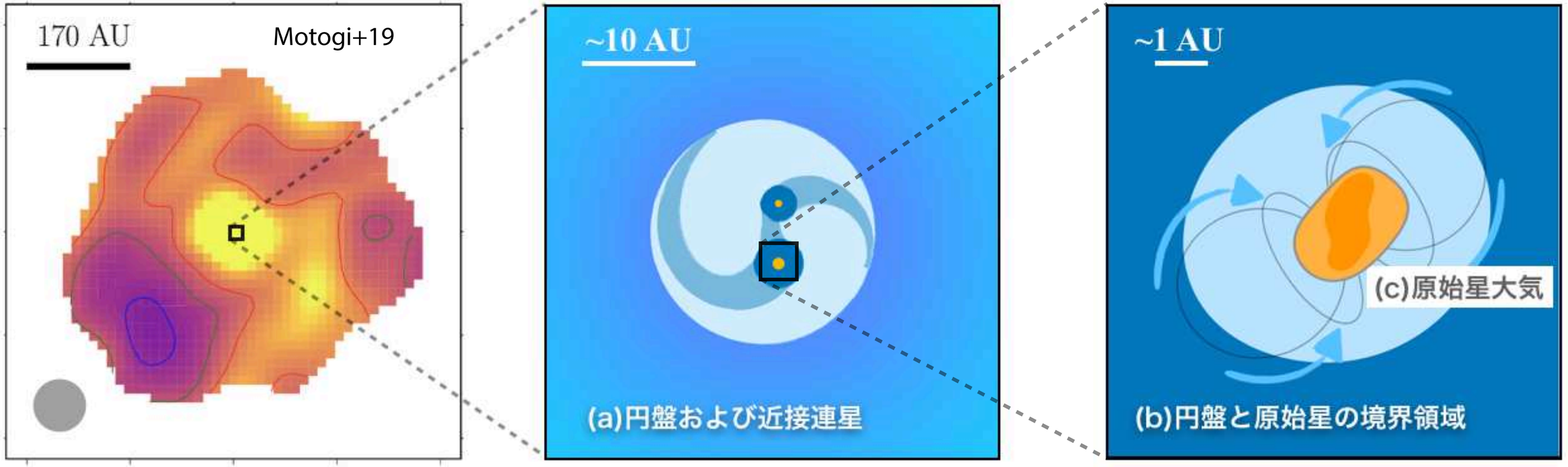
What determines stellar spin at birth?

Accretion onto stellar surfaces!!





ngVLA & SKA: True Faces of Protostars



Massive protostars could be as big as ~AU scale via high accretion rate

(e.g. Hosokawa&Omukai09)

Next generation radio telescopes might be able to directly observe protostellar surfaces!!