Stellar feedback on different scales: Simulations

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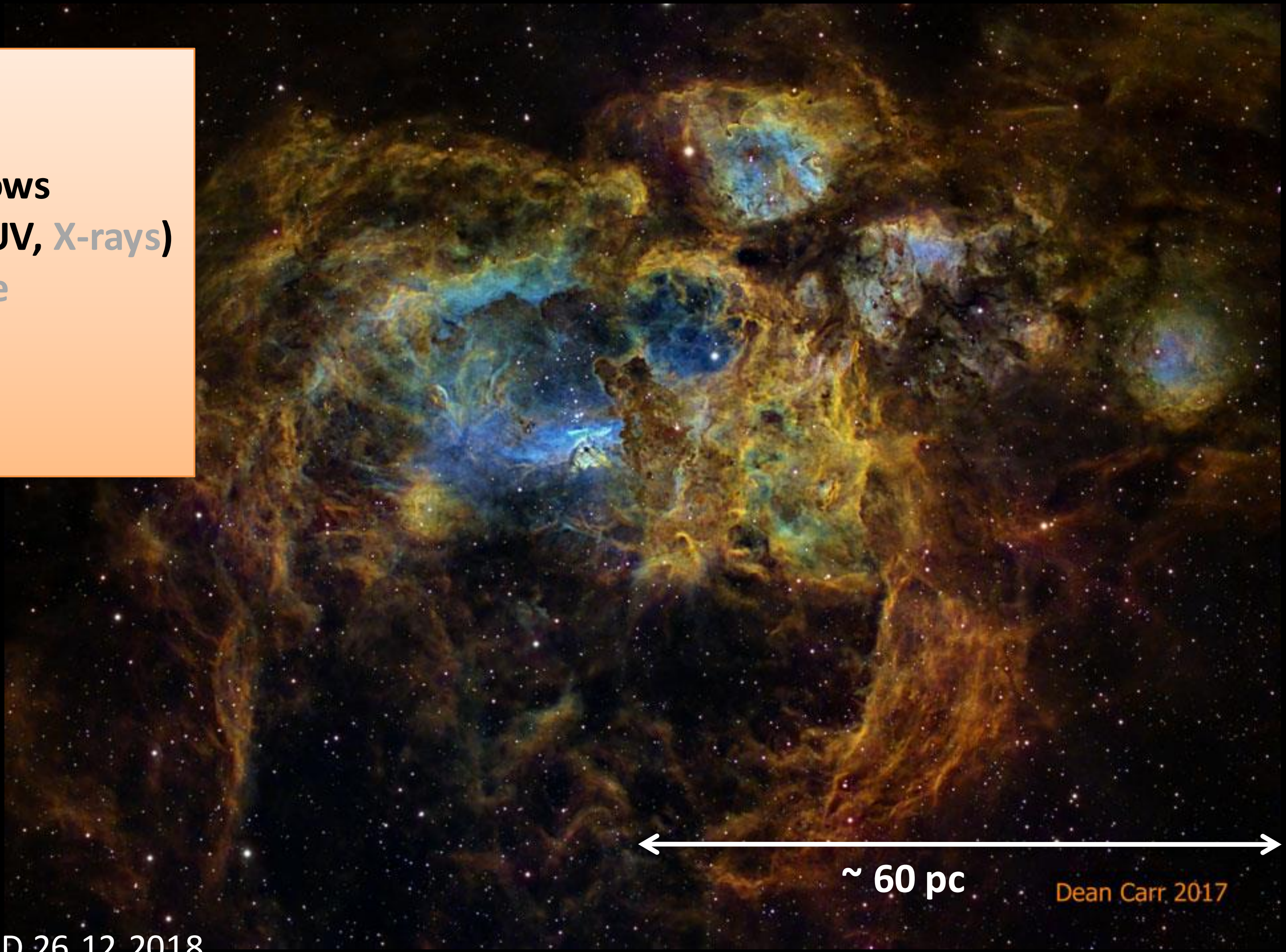
Ballyfest, Visegrad - 27.5.2025

The impact of (massive) star formation: The signatures of stellar feedback are ubiquitous in the Interstellar Medium (ISM)

Stellar feedback driven bubbles in the Lobster Nebula (NGC 6357)

Stellar feedback:

- Protostellar outflows
- Radiation (FUV, EUV, X-rays)
- Radiation pressure
- Stellar winds
- Supernovae
- Cosmic Rays



Blue: ionized gas
Red: dust
Image taken from: APOD 26.12.2018

The role of stellar feedback in galaxies

- What is the origin of the stellar initial mass function (IMF)?
- Why is star formation inefficient on galactic scales?

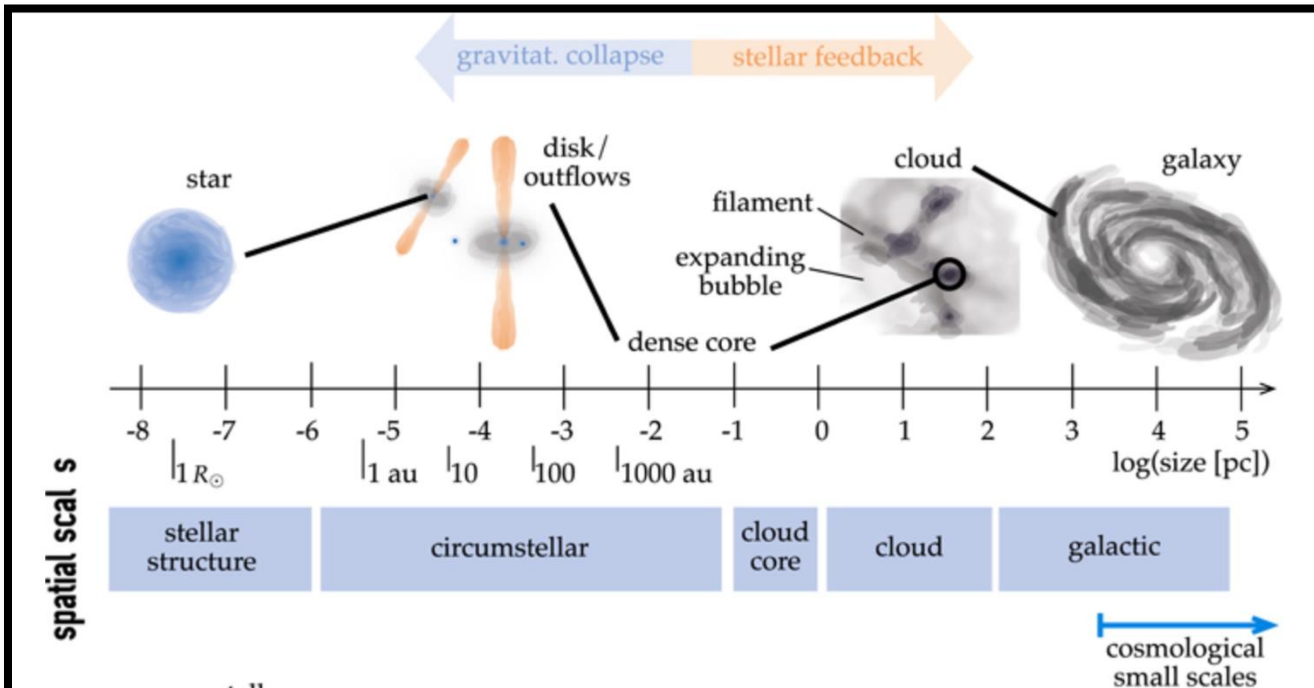
⇒ Molecular cloud formation, **stellar feedback**, and N-body dynamics

- What shapes galaxies over time?

⇒ How do stars and their feedback affect the ecology of galaxies?

- Feedback is so interesting (and difficult) because it couples the small scales of individual stars with scales of ~100 pc and beyond

⇒ Individual galaxies (or regions in them) -> down to stars -> back up



From Geen+2023, PASP 135

Motivation and Key Questions

- Stellar masses / stellar initial m
- Inefficient star formation

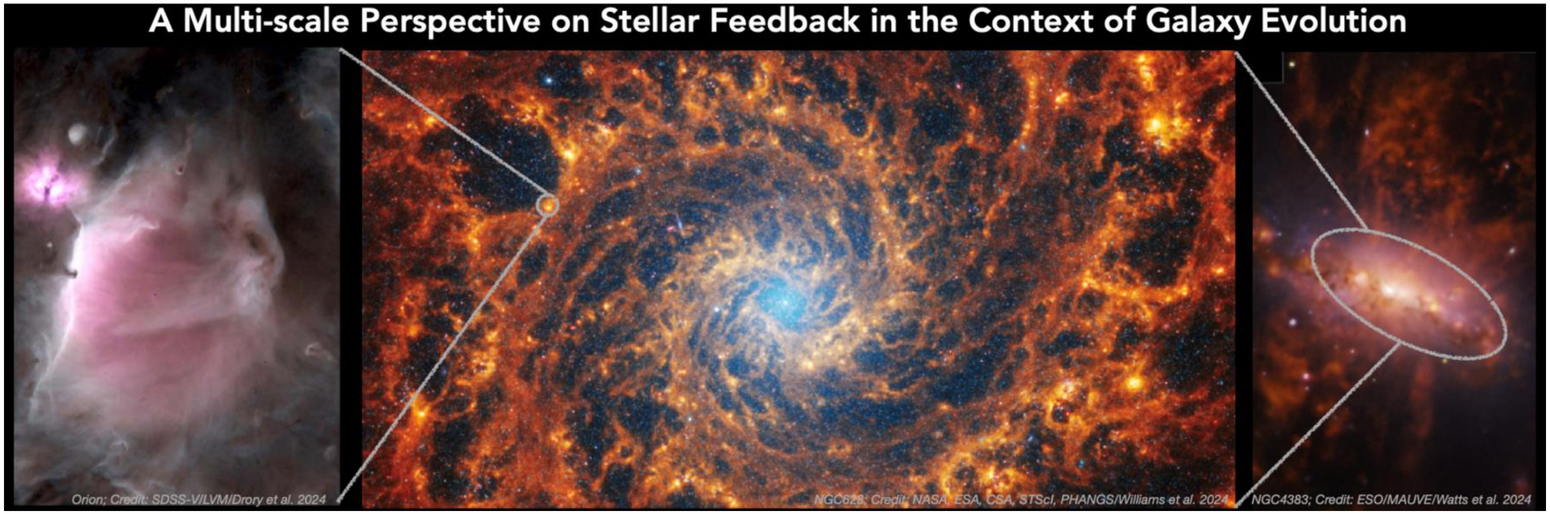
⇒ Molecular cloud formation, **ste**

- What shapes galaxies over time

⇒ How do stars and their feedbac

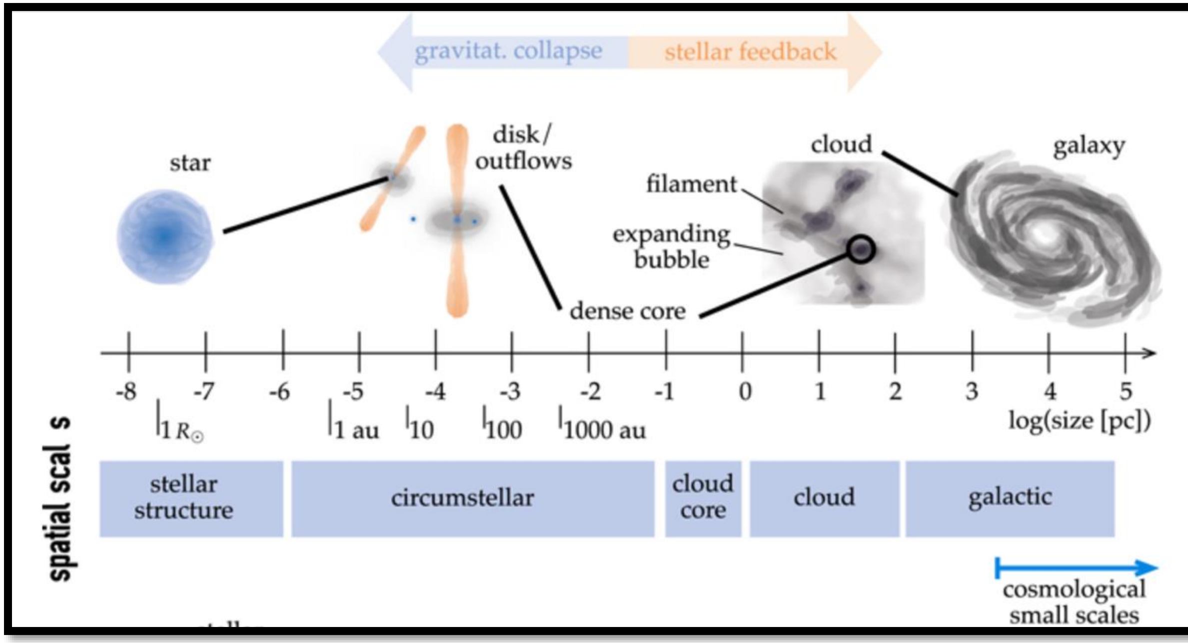
- Feedback is so interesting (and individual stars with scales of ~
- Individual galaxies (or regions i

- Simulations allow us to connect scales (spatial and temporal)
- Dynamic range! A major challenge for numerical simulations!



From EAS 2025, SS30

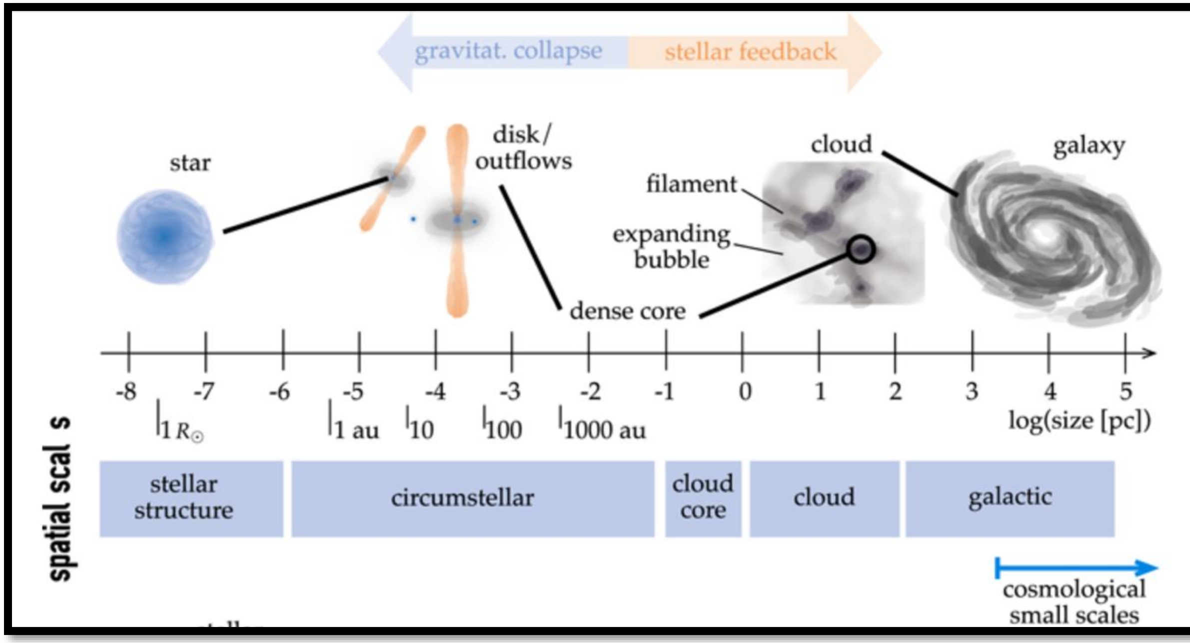
Types of Simulations



- Isolated (massive) cloud cores ($\lesssim$ 1 parsec)
- Isolated molecular cloud (few 10 parsec)
- Zoom into single molecular cloud (few 100 parsec)
- Multi-phase ISM (few hundred parsec)
- Galaxy-scale zoom-ins (few kilo-parsec)
- Cosmological volumes (few mega-parsec)

→ Different scales, different strengths

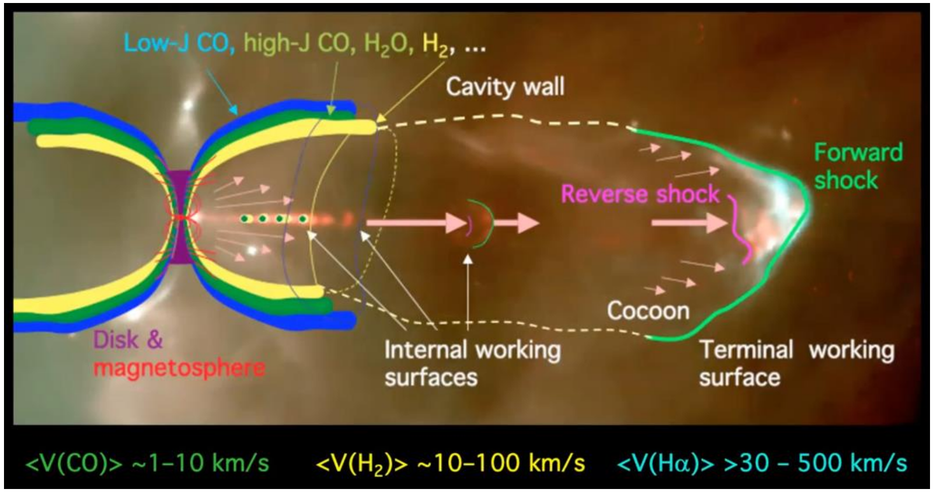
Types of Simulations

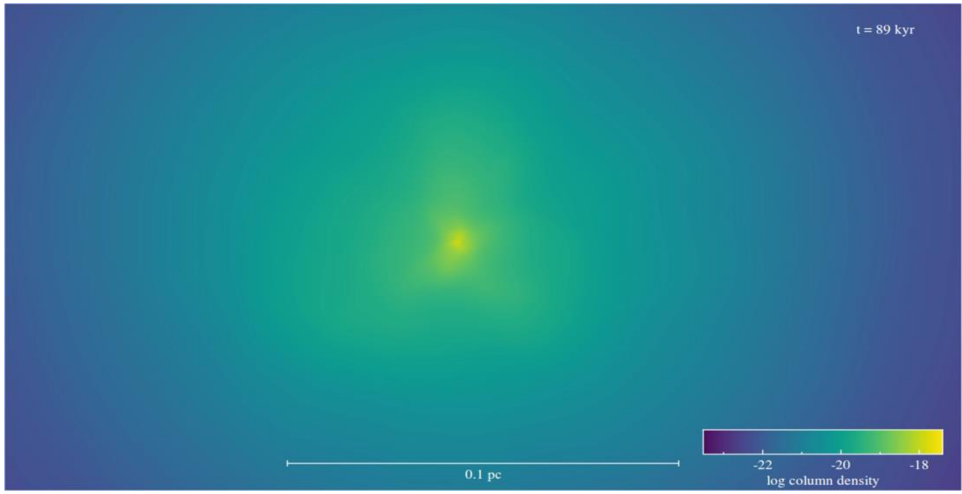


- Isolated (massive) cloud cores ($\lesssim$ 1 parsec) => Talk by Anna Rosen
- Isolated molecular cloud (few 10 parsec)
- Zoom into single molecular cloud (few 100 parsec) => Talks by Sabrina Appel, Enrique Vazquez-Semadeni, Cheryl Lau
- Multi-phase ISM (few hundred parsec)
- Galaxy-scale zoom-ins (few kilo-parsec) => Talks by Natalia Lahén, Mattia Sormani, Eric Andersson, Matt Orr
- Cosmological volumes (few mega-parsec) => Talk by Diederik Kruijssen

→ Different scales, different strengths

Protostellar jets & outflows





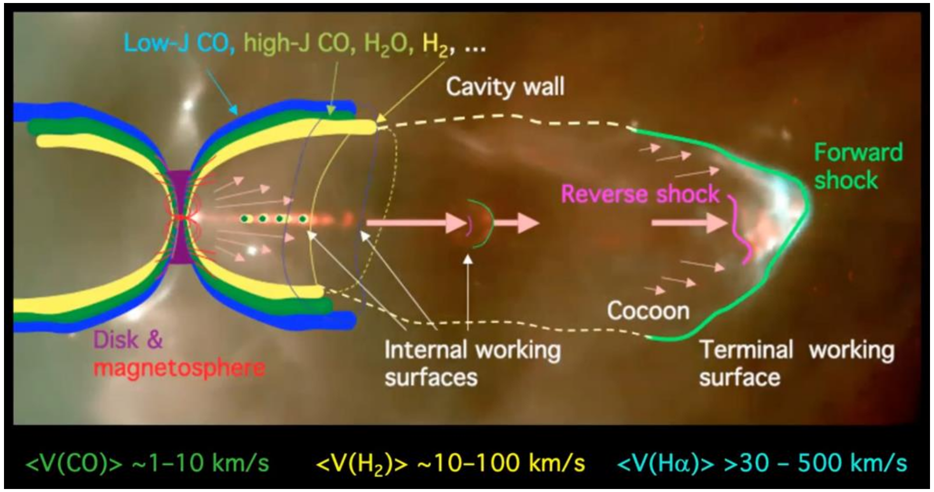
"Couple P, E directly into the parental cloud" - John Bally
Recent review by Bally+2024

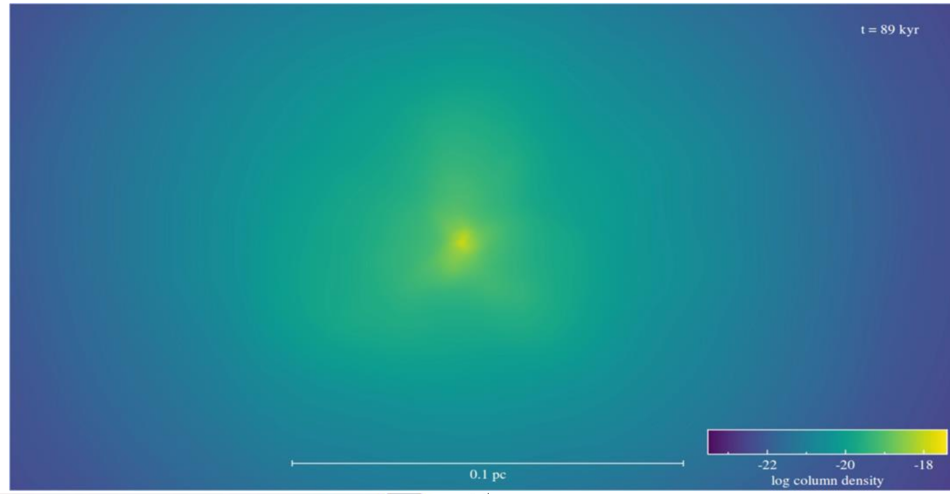
Most YSOs have them…

They affect:

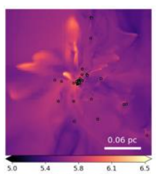
- Star formation efficiency (SFE) in star-forming cores
- Stellar multiplicity
- The peak of the stellar IMF (see later)

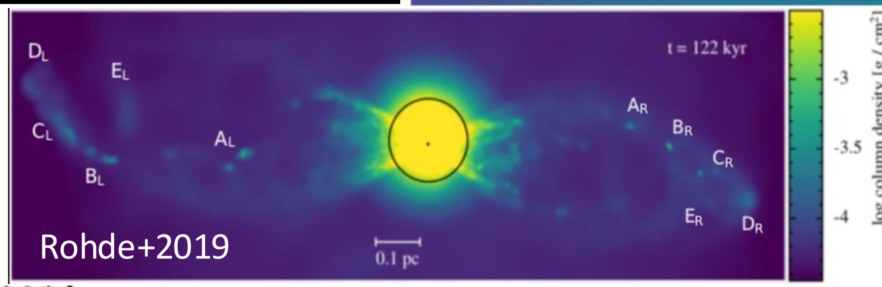
Protostellar jets & outflows



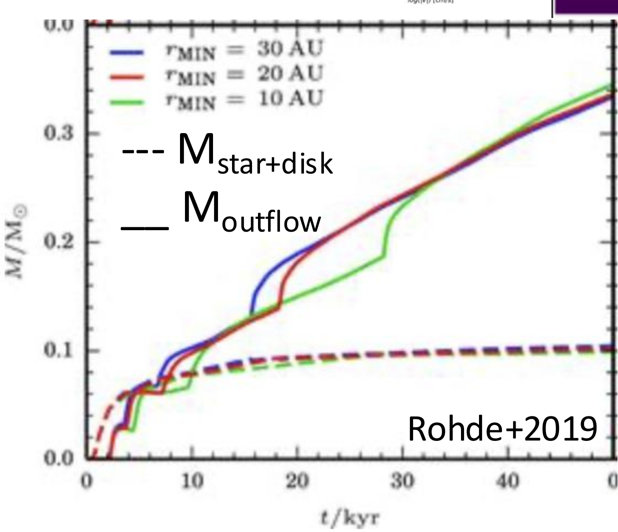


Effect on **stellar multiplicity**:
Rohde+2021
Verliat+2022
Lebreuilly +2023



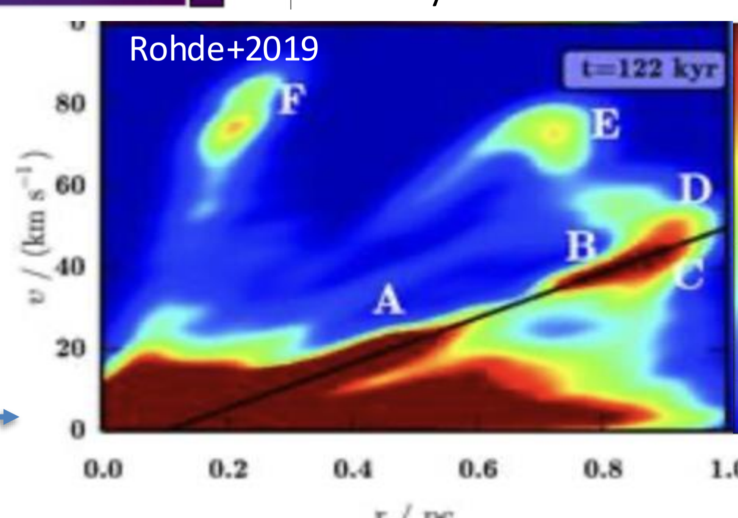


Rohde+2022:
Bullets can be used to **trace the age and energetics of the outflow**
Also Dunham+2024;
Talk by H.Arce



Outflows entrain a substantial amount of mass!
SFE reduced by ~factor 2
(see also Cunningham+2011; Rosen & Krumholz+2020; Guszejnov+2020)

Hubble flow recovered in the simulations

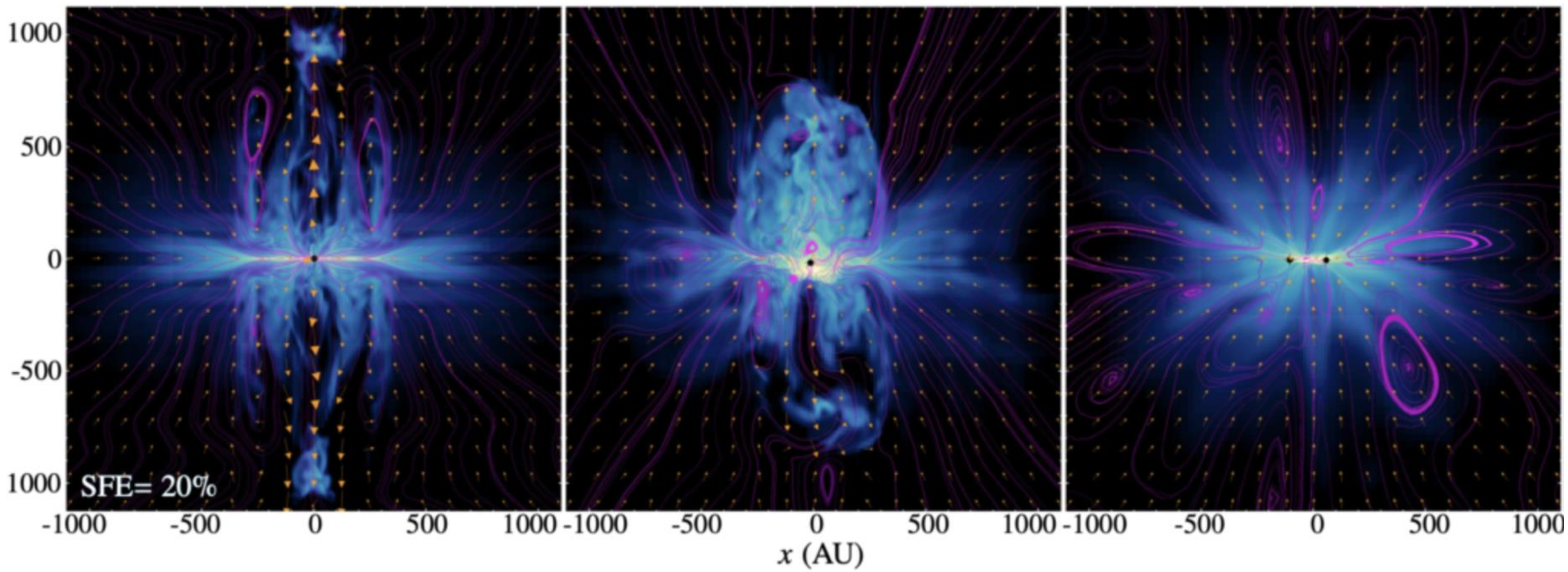


Protostellar jets & outflows

What about magnetic fields?

Gerrard, Federrath, Kuruwita 2019:

Effect of turbulent magnetic fields on the structure of protostellar outflows:



Uniform B

Low turbulence

High turbulence

No clear outflow structure in fully turbulent case

Feedback from massive stars

Massive stars (> 8 $M_\odot$) are rare!
~ 1 massive star per 100 $M_\odot$ of gas that forms stars

Massive stars are special!

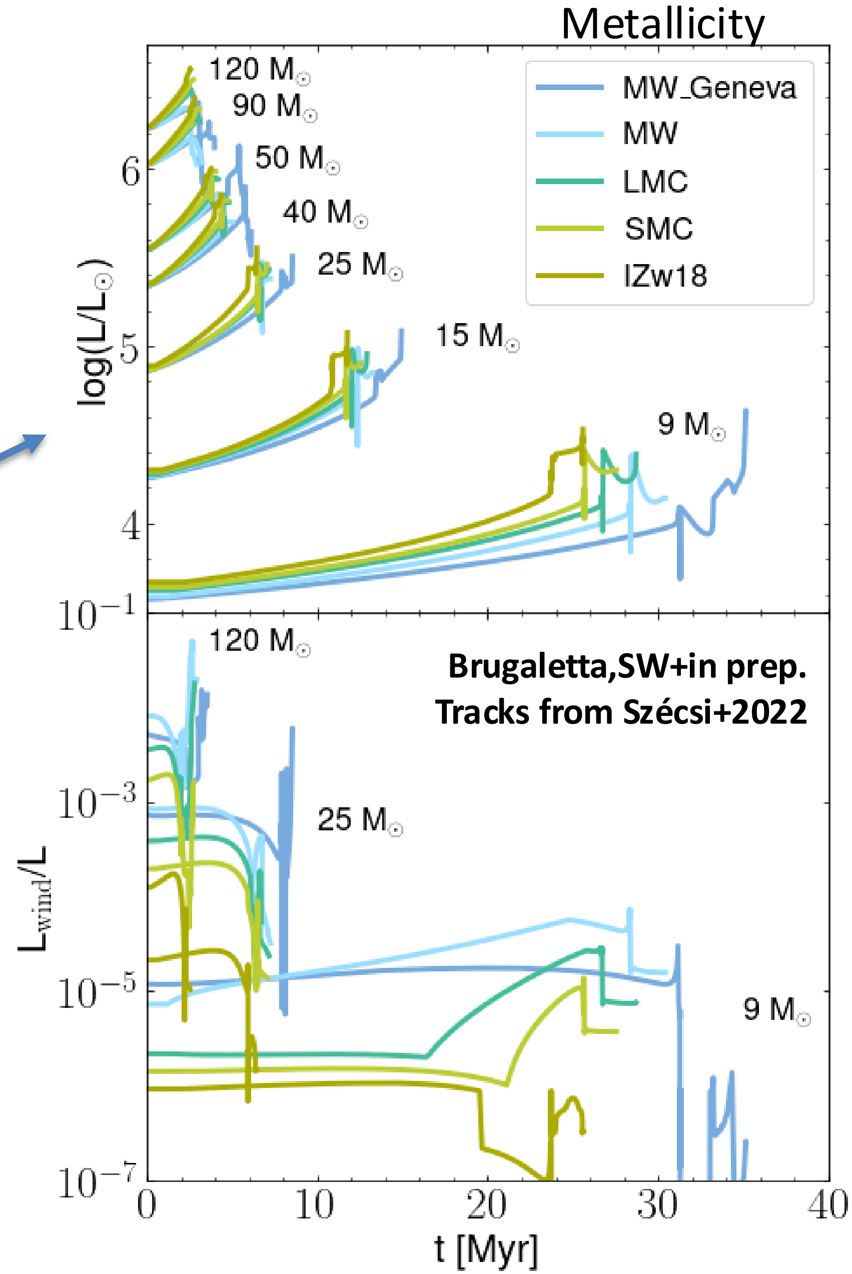
- **They have short lifetimes (few Myr)**
- **They die as a Supernova Type II**

(Blast wave, E_{SN}= 10^{51} erg)

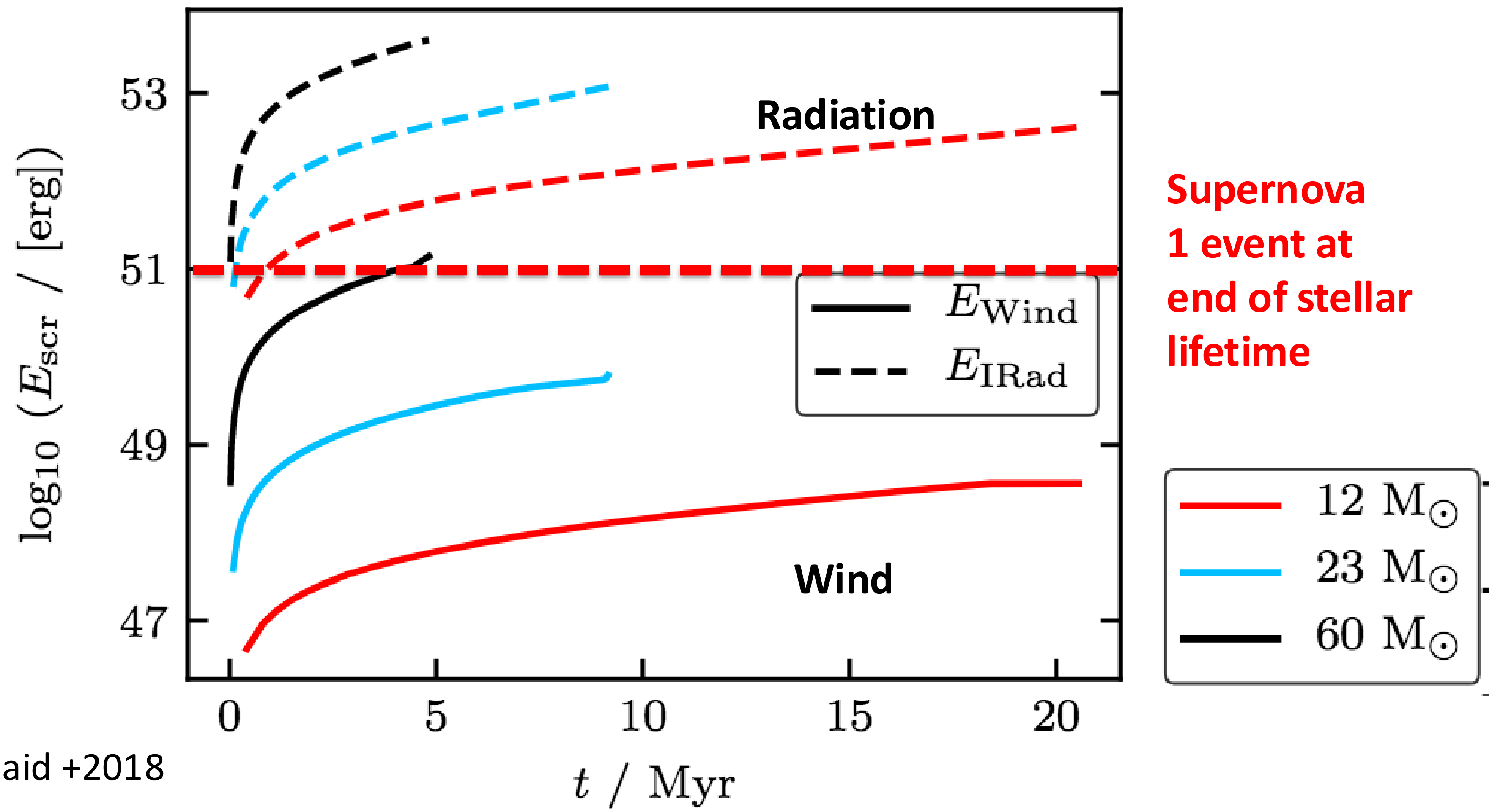
During their life they emit:

- **Ionising radiation (UV):**
  - **⇒ionizes and**
  - **⇒heats up the environment to 10^4K**
  - **⇒disperses the surrounding gas**
- **Fast stellar winds:**
  - **⇒v_{wind}~few 1000 km/s,**
  - **⇒dM/dt~10^{-6} $M_\odot$/yr**
  - **⇒Additional momentum input**

$L_{wind} = ½\, v_{wind}^2\, (dM/dt)_{wind}$



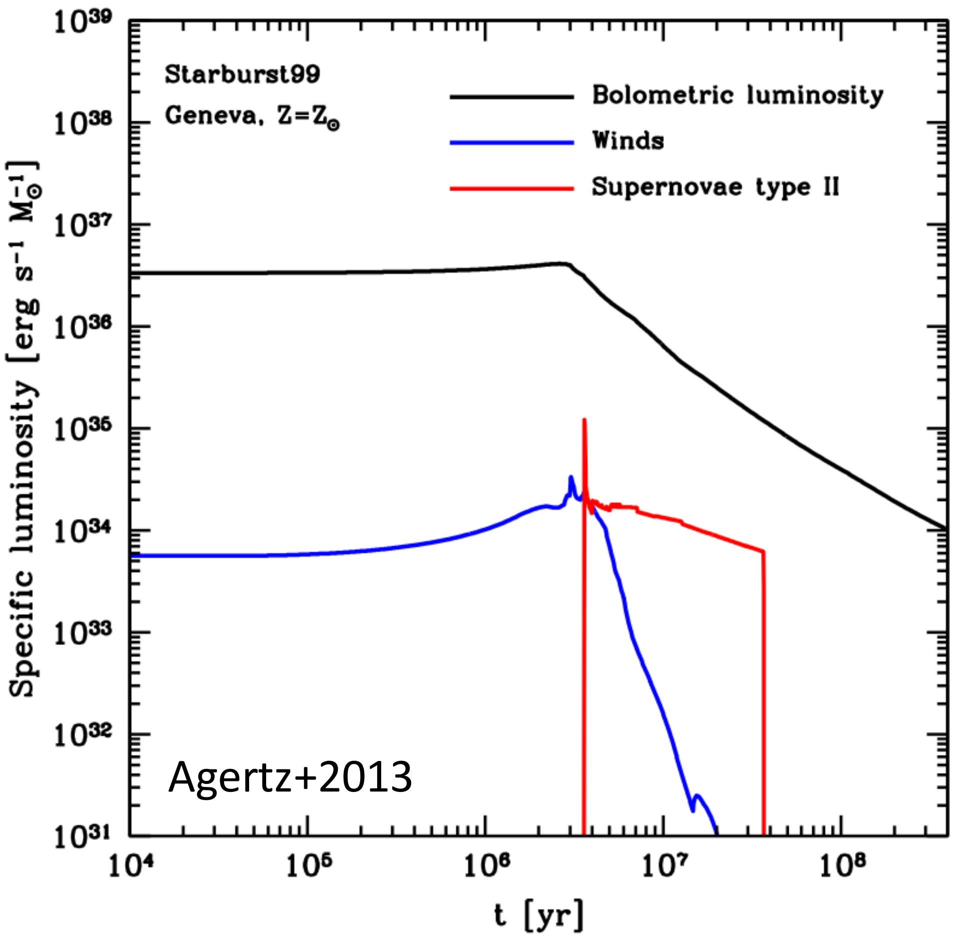
Energy input from massive stars:
Stellar winds, ionizing radiation & Supernovae:



Supernova 1 event at end of stellar lifetime

see Haid +2018

Energy input from massive stars: Stellar winds, ionizing radiation & Supernovae:



How is this energy coupled to the ISM?

$\Rightarrow$ How is radiative energy converted into kinetic and thermal energy of the surrounding gas?

$\Rightarrow$ Apart from the momentum delivered by winds and supernovae: how much energy is delivered **depends on radiative cooling, i.e. depends on the conditions in the ISM environment**

Summary of observational assessment of pre-supernova feedback:
e.g., Schinnerer & Leroy,2024

Why radiative cooling is important

Beautiful images means: gas is radiating!
Photons are lost => **radiative cooling**

The **input momenta** (wind and supernovae) **are much smaller than the actual momentum** associated with the expansion of evolved bubbles

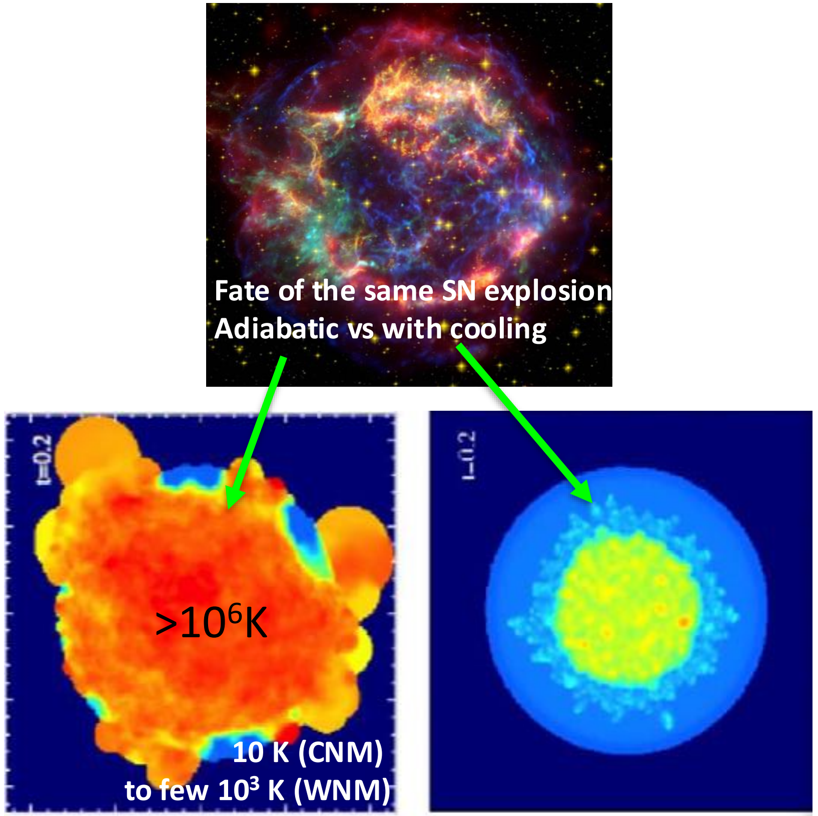
=> Most of the work done on the ambient medium **is PdV work** => hydrodynamic effect!

The longer the gas stays hot, the longer a **pressure gradient across the bubble interface** can be sustained => more **acceleration**

- $\Rightarrow$ **Radiative cooling is key** to understanding the dynamics of the surrounding gas
- $\Rightarrow$ We call this "coupling" of energy to the surrounding gas (ISM)
- $\Rightarrow$ **How much thermal E is transformed into kinetic E of the surrounding ISM?**

Momentum equation of ideal MHD + gravity,
No viscosity

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}=\frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{4\pi}-\nabla P_{\rm tot}+\rho\mathbf{g},$$



Supernova remnant simulation:
Without cooling (left), with cooling (right)
Walch & Naab 2015

Energy-driven vs. momentum-driven winds

Energy-driven wind

Assumes energy conservation

$\Rightarrow$ No (or very small) losses due to radiative cooling

$\Rightarrow$ **Upper limit** for the impact of stellar winds!

Energy-driven winds (remember, NO COOLING), could unbind up to 100 times the mass of formed stars, hence reducing the star formation efficiency to just 1%

Uncertainty:

$\varepsilon_w \leqq 1$ Cooling efficiency

Momentum-driven wind

Assumes momentum conservation

$\Rightarrow$ Most extreme case assumes maximum cooling, i.e. no additional momentum-driving by the expanding hot wind bubble

$\Rightarrow$ **Lower limit** for the impact of stellar winds!

Momentum-driven winds (MAXIMUM COOLING), cannot unbind significant cloud mass, hence the SFE could be as high as 90%

Uncertainty:

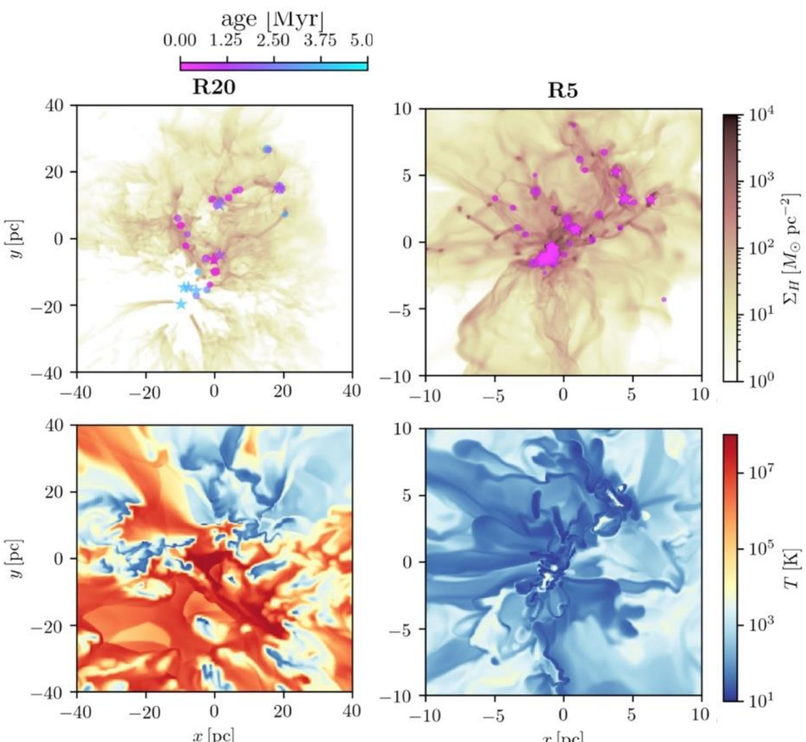
$\varepsilon_{mom} \geqq 1$ Momentum boost (hydro effect)

Walch+2023 (pcsf.conf, 97W)

=> See also Anna Rosen's talk

Unclear how much energy is lost by cooling in turbulent mixing layers: Determines whether winds are "energy-driven" or "momentum-driven"

State-of-the-art simulations of molecular cloud evolution with stellar winds



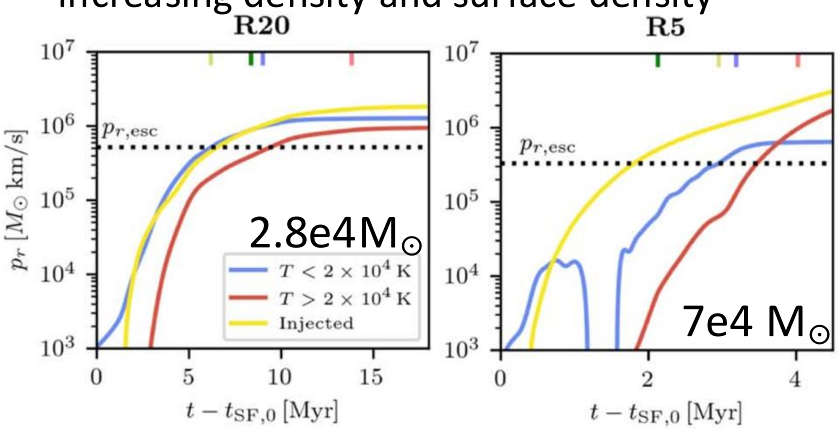
Lancaster +2021a/b

Study the impact of stellar winds in isolated turbulent clouds with 10^5 $M_\odot$ and different sizes and develop an analytical model to describe the cooling of turbulent mixing layers

In simulations, cooling efficiency $\boldsymbol{\varepsilon_w}$ varies depending on environment!

=> Cumulative radial momentum delivered by the winds is similar despite much higher SFE in different runs: R5 (~70%) vs. R20 (~28%)

Increasing density and surface density



Feedback yield as an essential quantity

$$\Upsilon_{\mathrm{fb}} \equiv P_{\mathrm{DE}}/\Sigma_{\mathrm{SFR}}$$

Ostriker & Kim, 2022

Specific momentum delivered by feedback

Typical values ~1000 – 3000 [($M_\odot$ km/s)/ $M_\odot$]

Here (from wind): only ~100 km/s

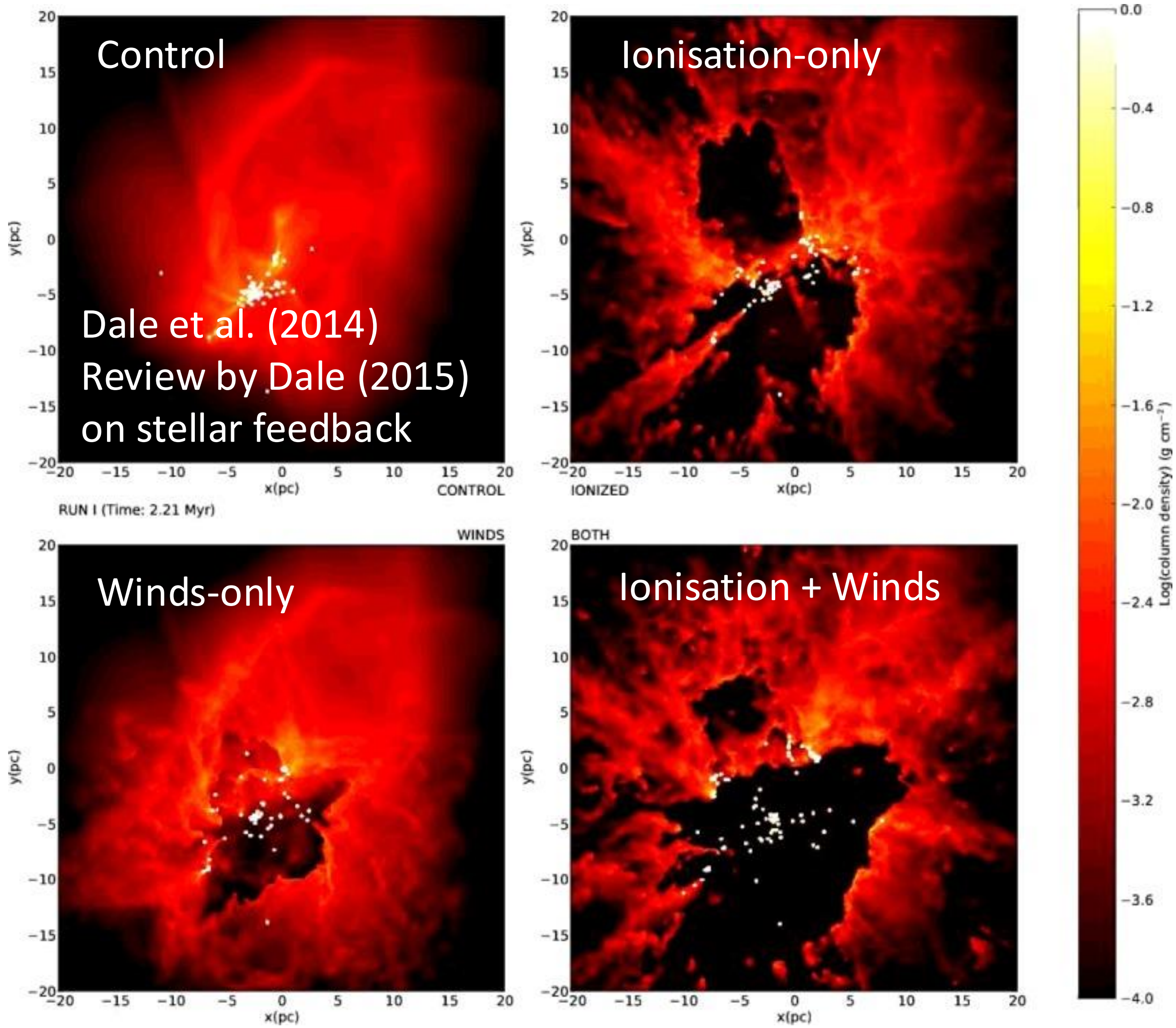
Winds vs. Ionizing radiation in simulations of star cluster formation

- Winds only have a weak impact

- Combination of wind + ionization is more effective than only ionization

- Momentum-driven winds are not effective (e.g. Ngoumou+13)

⇒ But that is not surprising (see before)

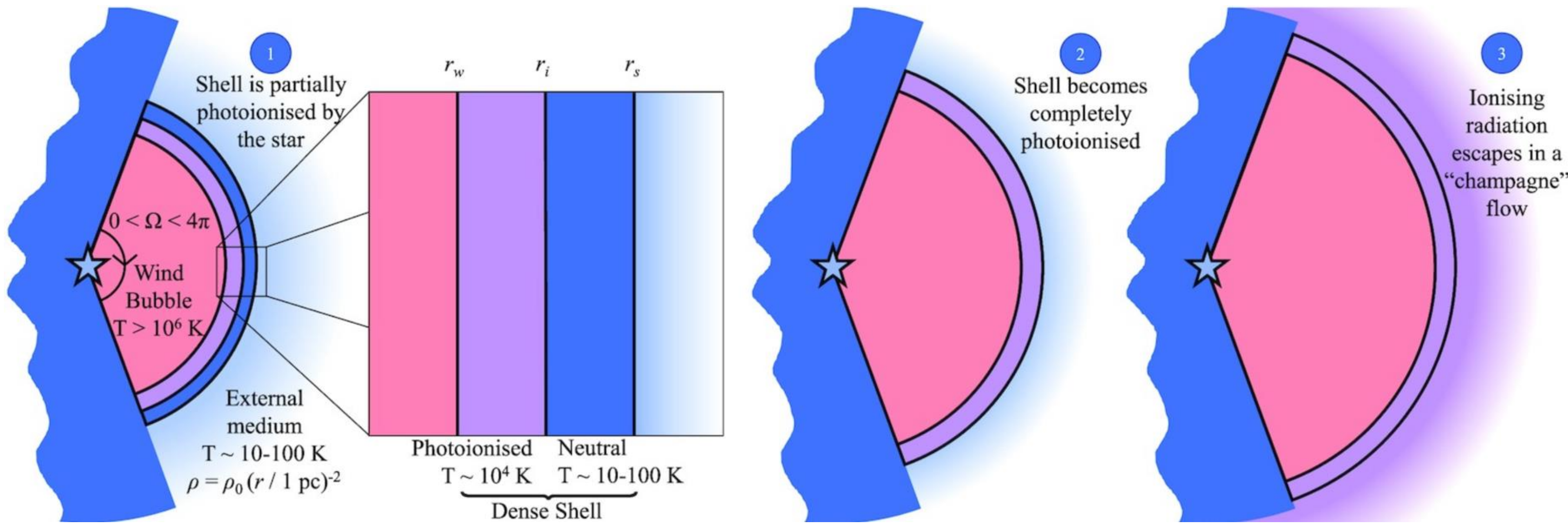


Winds vs. Ionizing radiation in simulations of individual bubbles

- Need high resolution to capture trapping: currently only possible in dedicated simulations
- Geen & deKoter, 2022: analytical solution to wind dominating over radiation:

Steep density profile (powerlaw -2) needed to enable trapping and wind domination

=> Fast (faster-than-Spitzer) bubble expansion



Geen & deKoter, 2022

$$v_{w,2} = 13.5\ \mathrm{km/s} \left(\frac{L_w}{10^{36}\ \mathrm{erg/s}}\right)^{1/3} \left(\frac{n_0}{1000\ \mathrm{cm}^{-3}}\right)^{-1/3}$$

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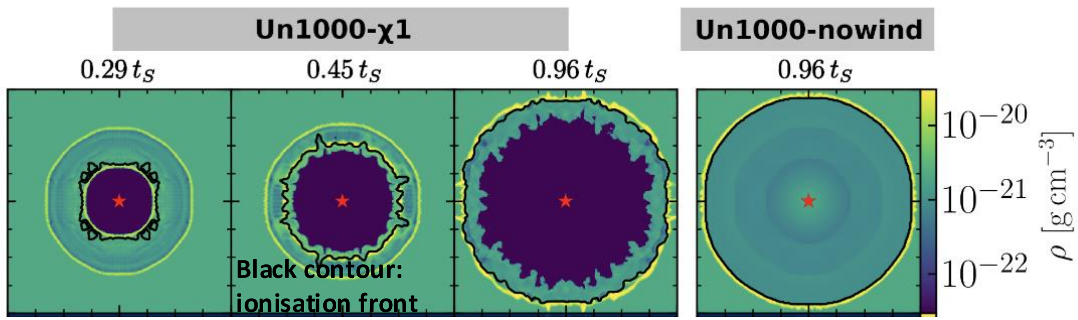
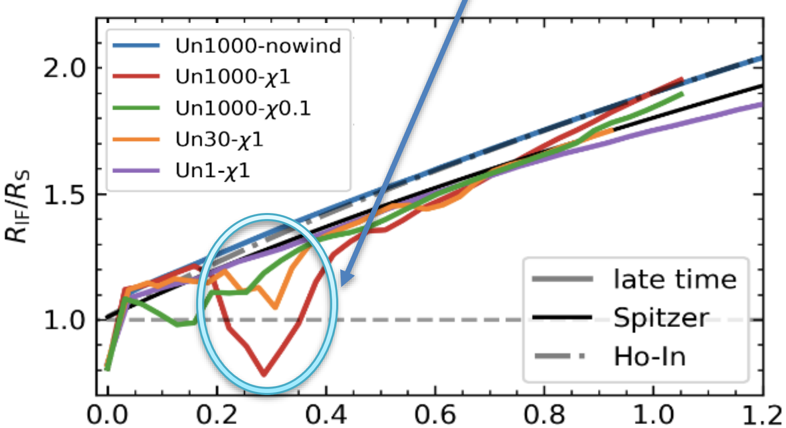
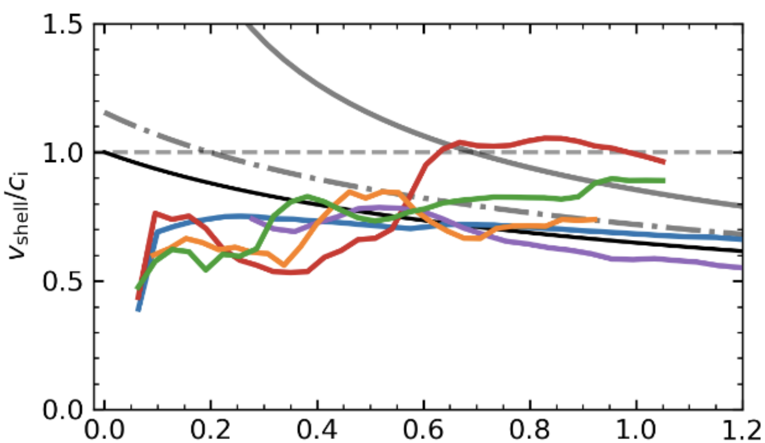
- Vider et al., in prep.: Trapping **is only a temporary effect** due to instabilities;

⇒ Expansion with wind is slightly faster, but not substantially faster







HII region+ wind in different density environments: n=1, 30, 1000 cm^{-3}

c_i ~ 10 km/s

Vider et al., in prep.

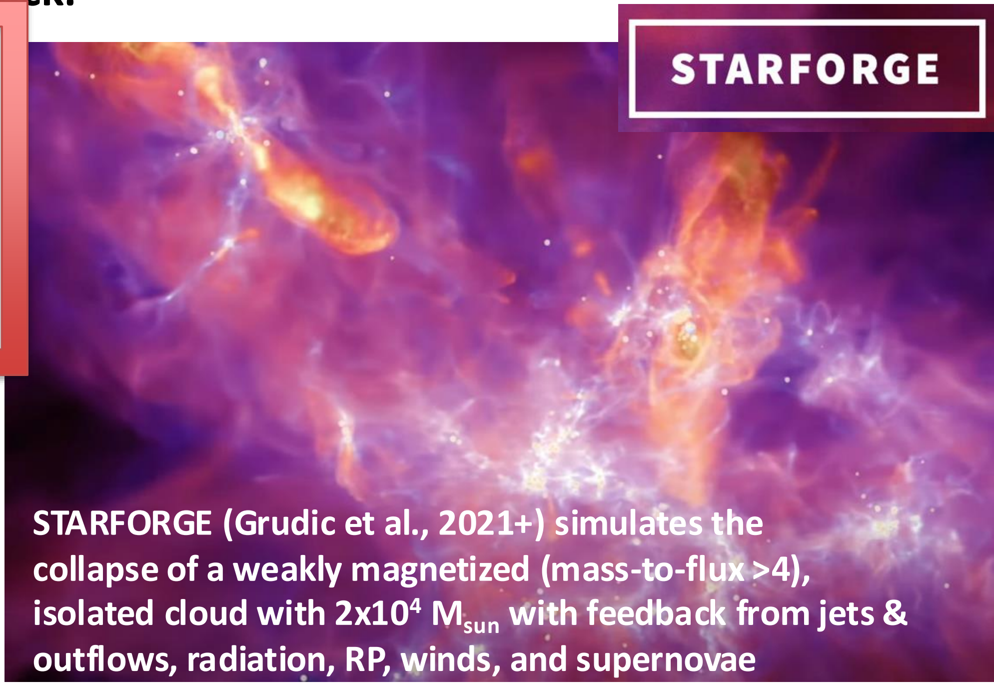
Combination of feedback processes

Examples with varying combinations of feedback:

High-resolution simulations:

Isolated clouds or clumps / periodic boxes

- Bate+ (improvement throughout the years)
- Federrath+2015
- Cunningham+2018
- Starforge: Grudic+2021, etc.

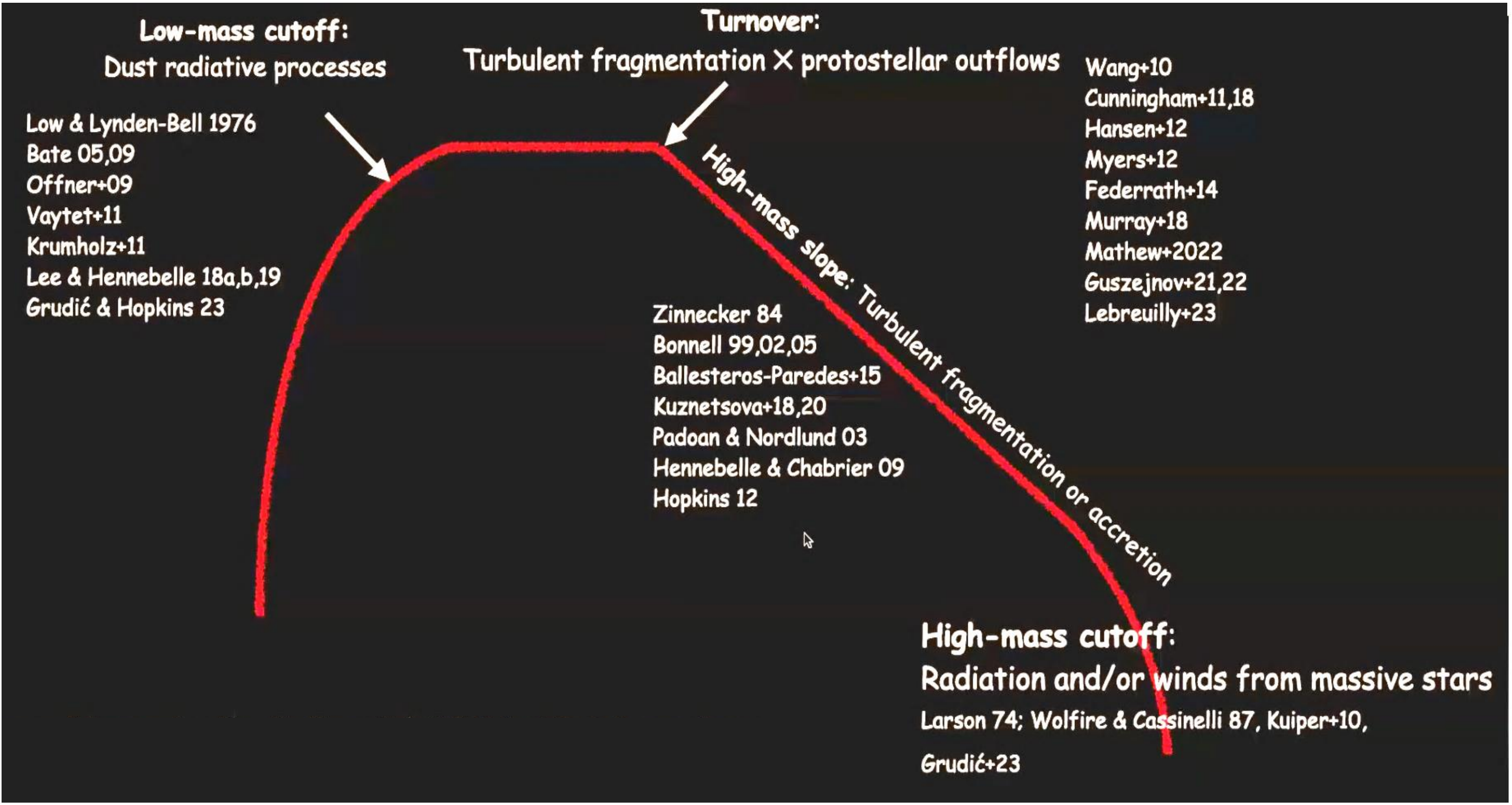


Global GMC simulations that do not resolve individual stars:

- Dale+2013, etc.
- Walch+2013
- Skinner & Ostriker+2015
- Geen+2017
- Kim+2018
- Grudic+2018
- Haid+2019
- Li+2019
- Decaltado+2020
- Fukushima+2020
- He+2022

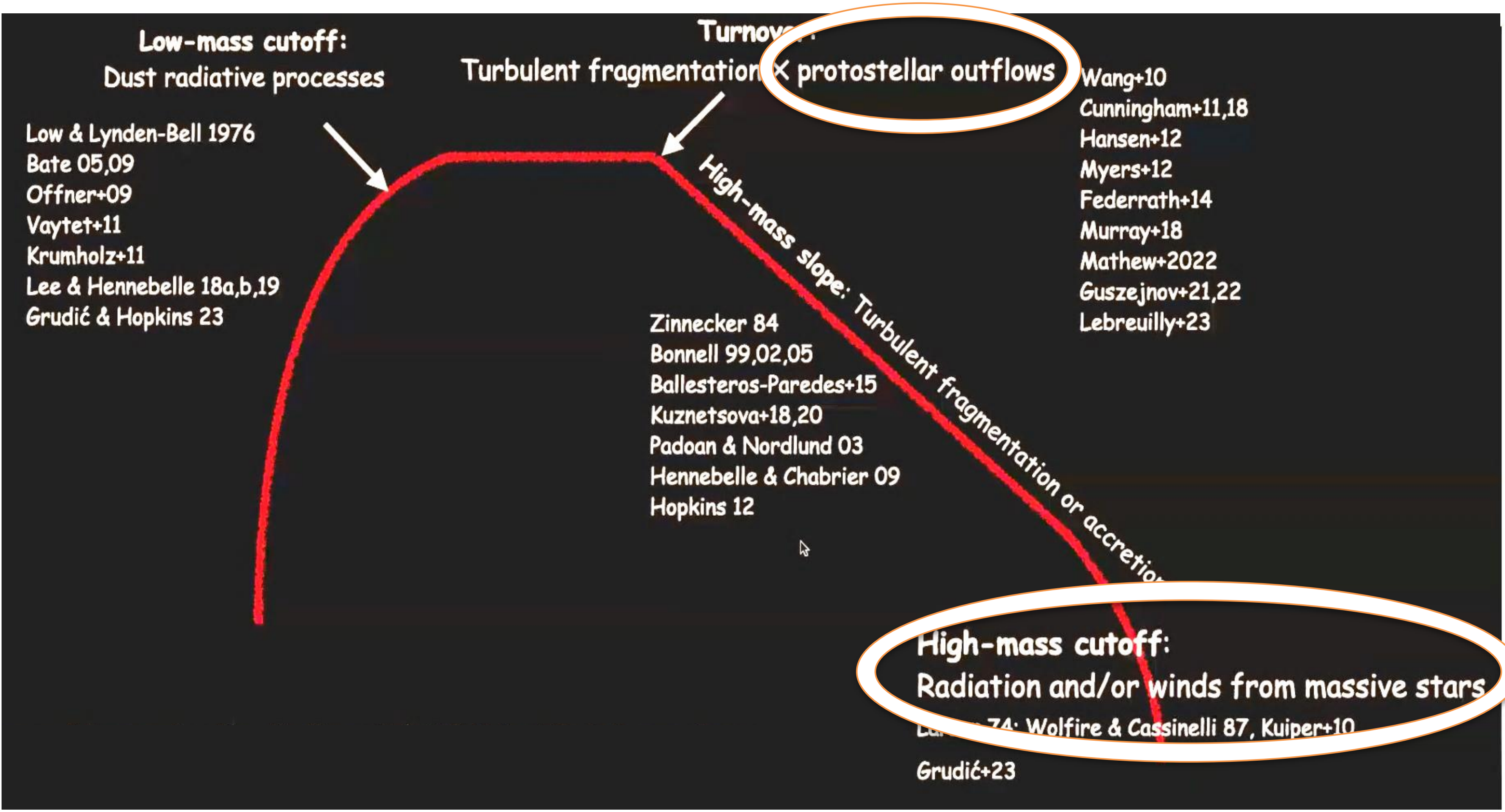
=> Need to include supernovae!

The role of feedback for the anatomy of the IMF



Hennebelle & Grudic, ARAA review, 2024
Slide from Mike Grudic

The role of feedback for the anatomy of the IMF



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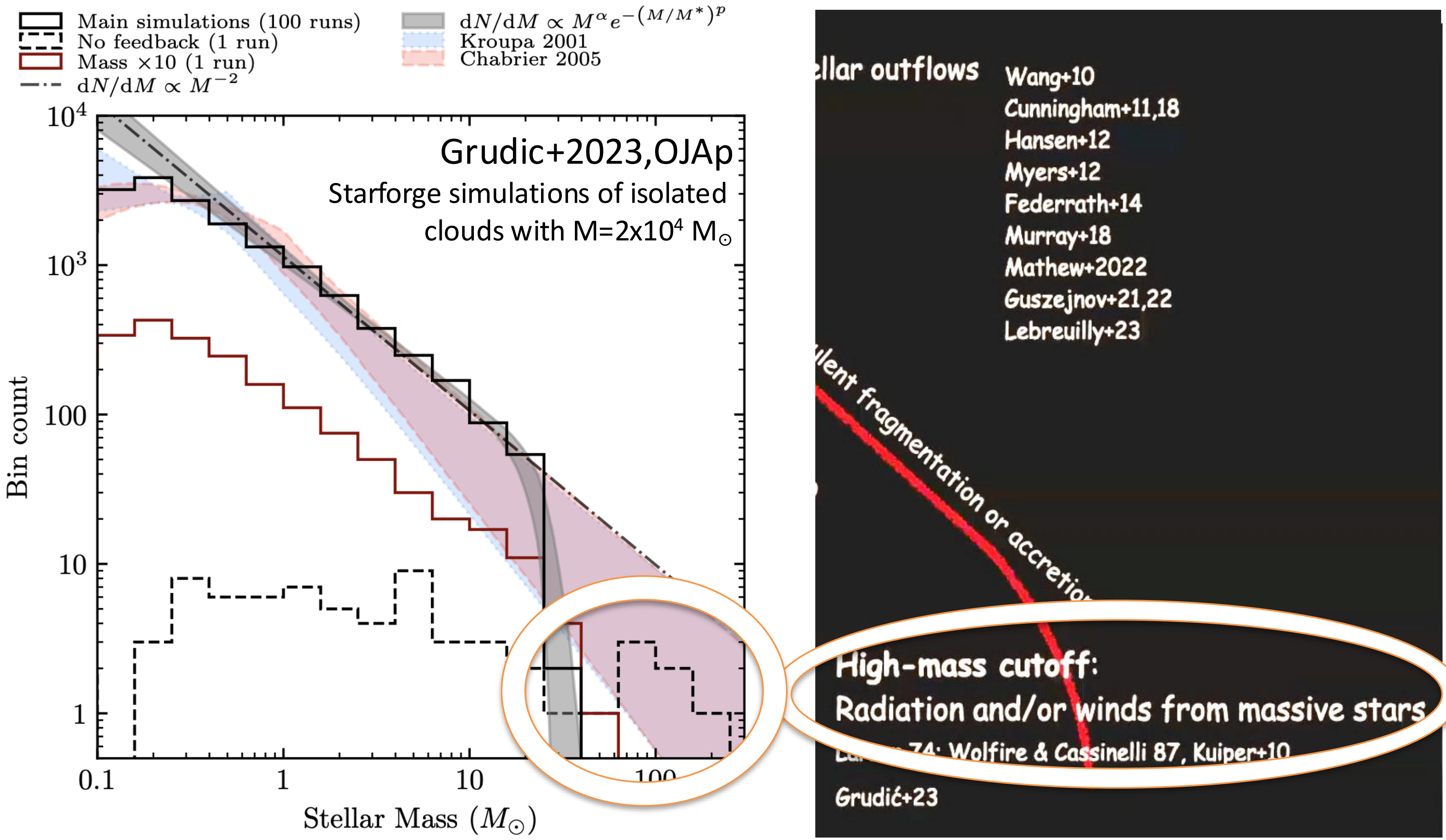
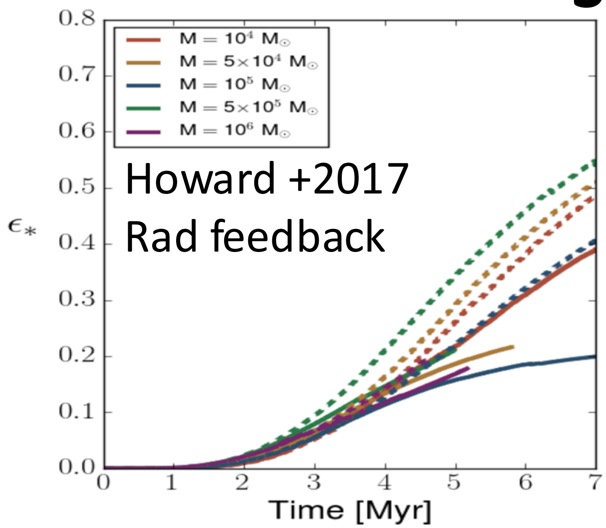
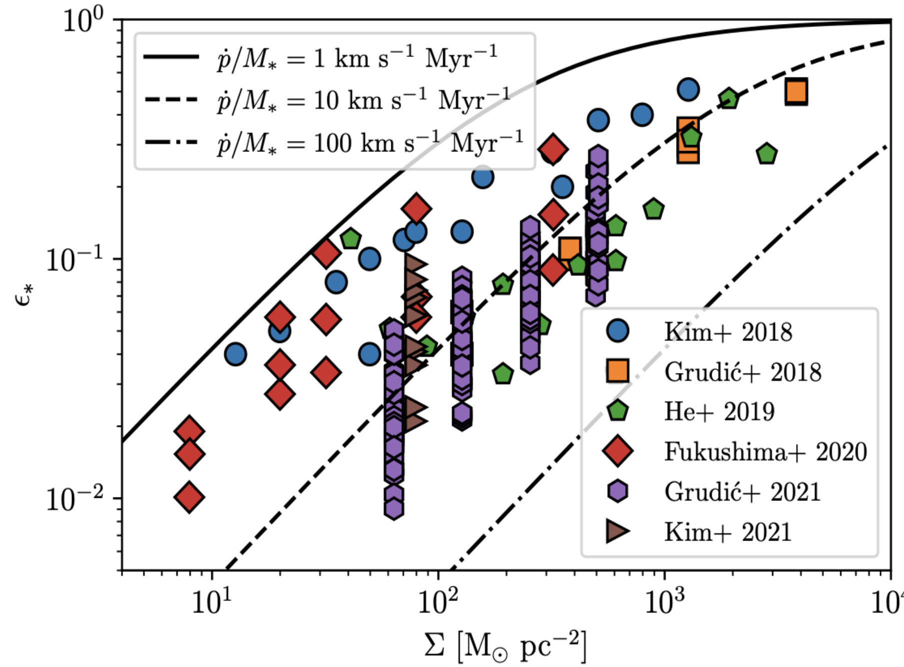
The role of feedback for the anatomy of the IMF



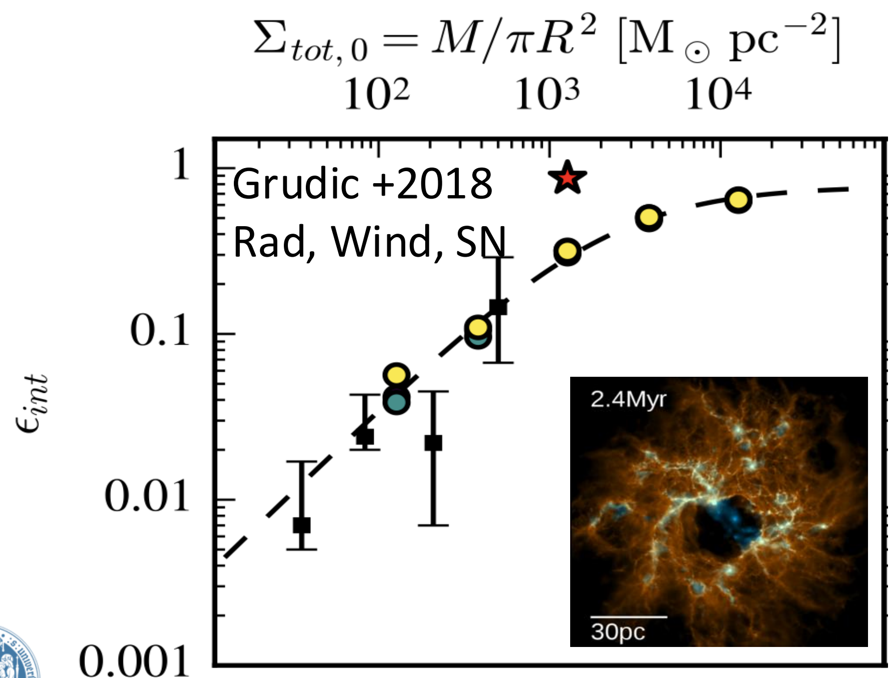
High-mass cutoff set by feedback physics,
and depends on cloud properties (M, Z, Σ, grav. boundedness, etc)

Star formation efficiency for different cloud surface densities





Chevance+2022, PPVII



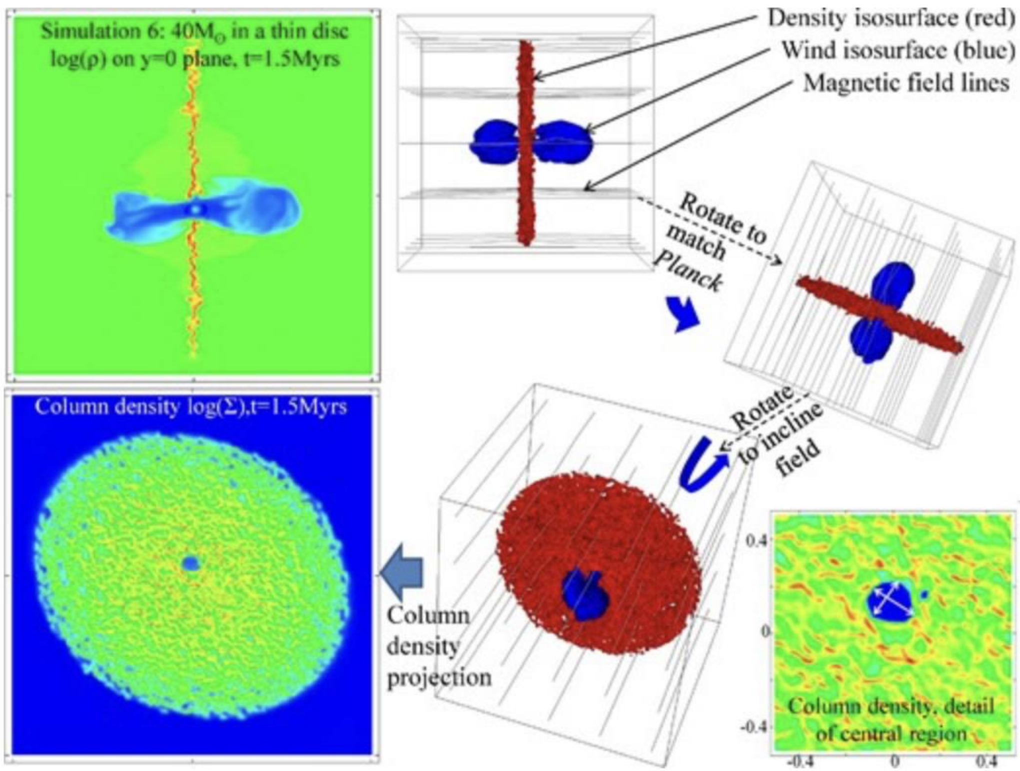
Very high SFE in clouds with high initial gas surface density!

Radiation pressure seems to help here.

Geometry matters

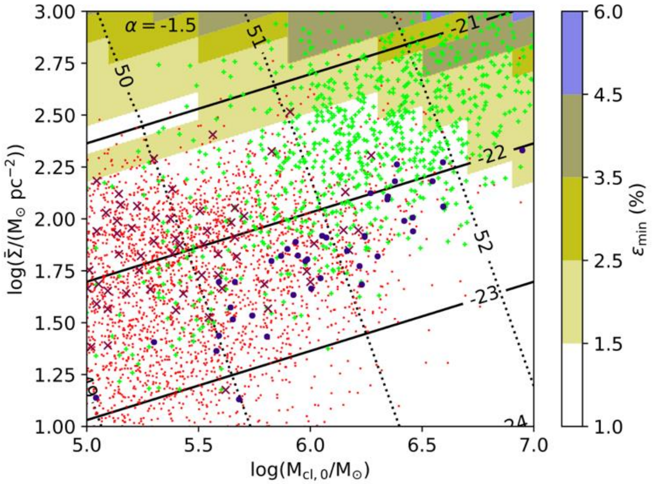
How many photons are escaping?
How much hot gas is just venting out?

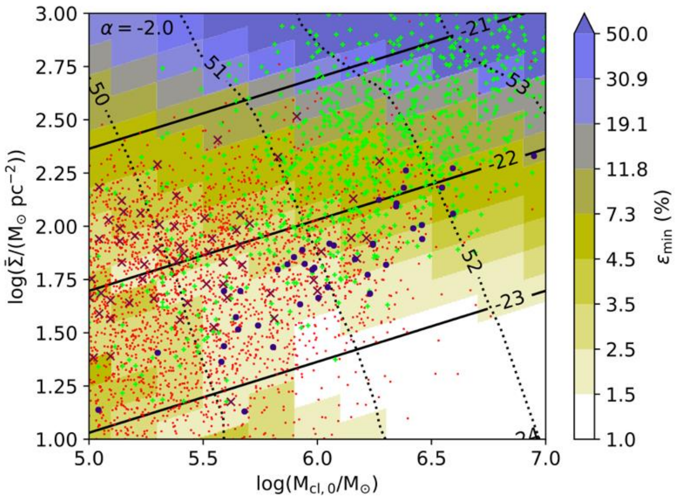
Wareing 2018: Rosette Nebula model



Dannhauer in prep:
Diamond Ring model (see talk later)

Rahner+2019: 1D Warpfield models:
SFE sensitive to initial cloud density profile

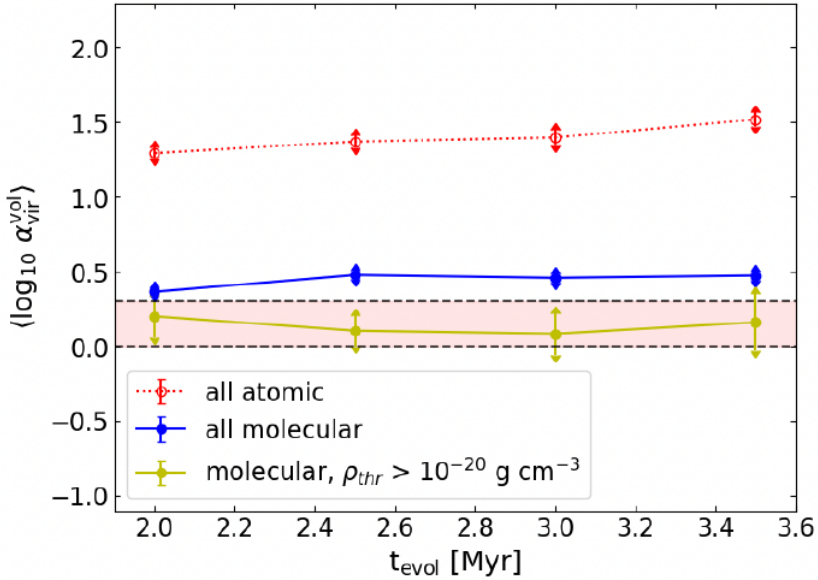




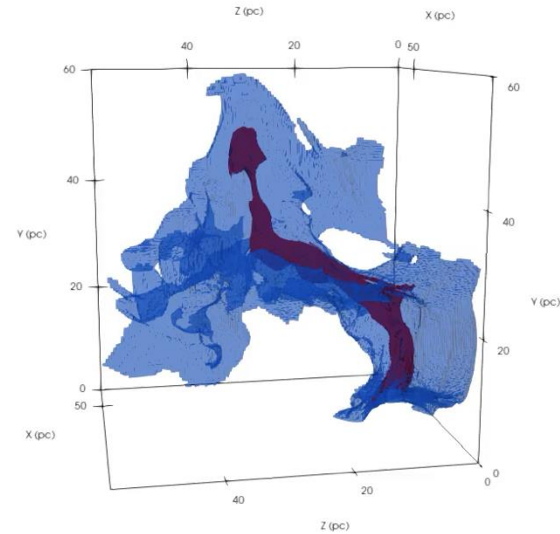
Steeper density profile => higher SFE

Connecting scales matters:
The environment of star-forming clouds

Ganguly, SW+ 2024
Atomic structures: supervirial in all cases
Molecular structures: slightly supervirial
Dense molecular structures ($n>10^4\ cm^{-3}$):
could be gravitationally bound



- Not all gas in molecular clouds is gravitationally bound!
  - The largest bound scale is typically (much) smaller than the cloud scale!
  - Potentially bound mass fraction is typically <50%
  - Definitely bound mass fraction is typically below 10%



Feedback from massive stars: Supernovae

Typical momentum from ejecta:
few 10^4 $M_\odot$km/s

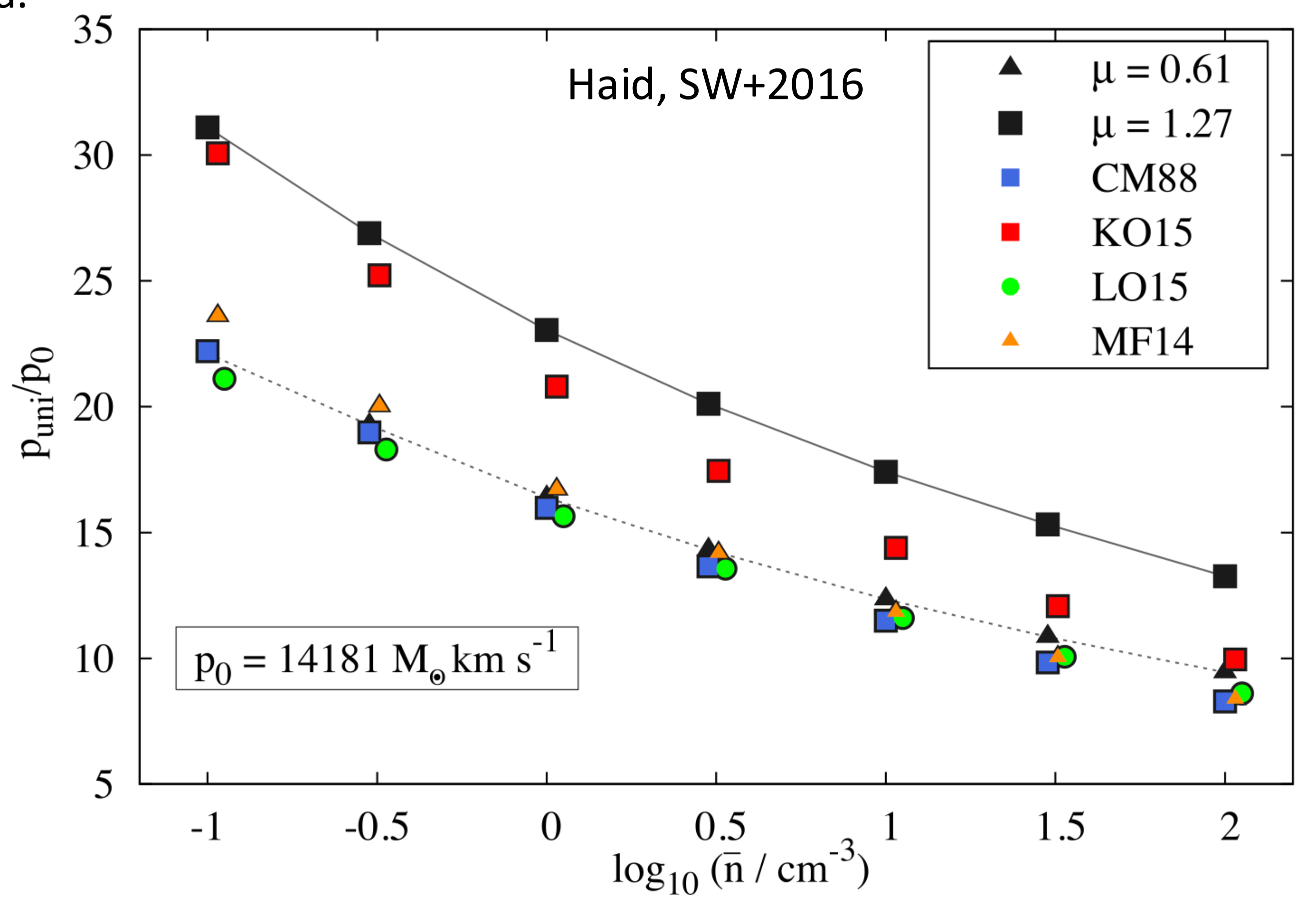
Typical final momentum input:
few 10^5 $M_\odot$km/s

Radiative cooling of the surrounding gas is essential

Feedback yield Υ_{fb} from supernovae:
1 SN / 100 $M_\odot$
$\Rightarrow$ ~1000 – 3000 km/s (without leakage)

Generally, SNe act to late to efficiently regulate SF (e.g. see Rathjen+2021; Schinnerer & Leroy, 2024)

However, they drive galactic fountains and outflows
$\Rightarrow$ see SILCC

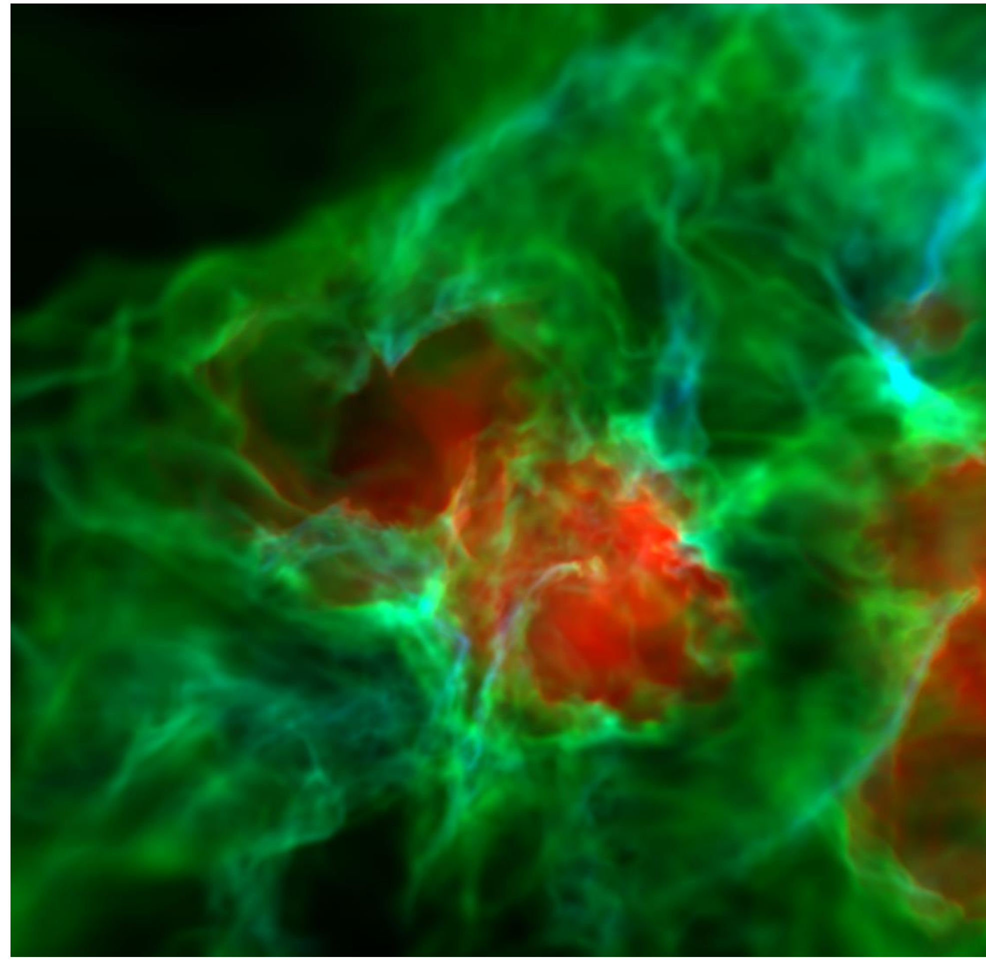


See also:
Gatto,SW+15; Walch & Naab 2015; Ostriker+2015; Hennebelle & Iffrig 2015

$\Rightarrow$ In high-density environments, the Sedov-Taylor phase could be inhibited and the reverse shock could be suppressed (Jiménez, Tenorio-Tagle, Silich, 2019)

Simulating the multi-phase ISM

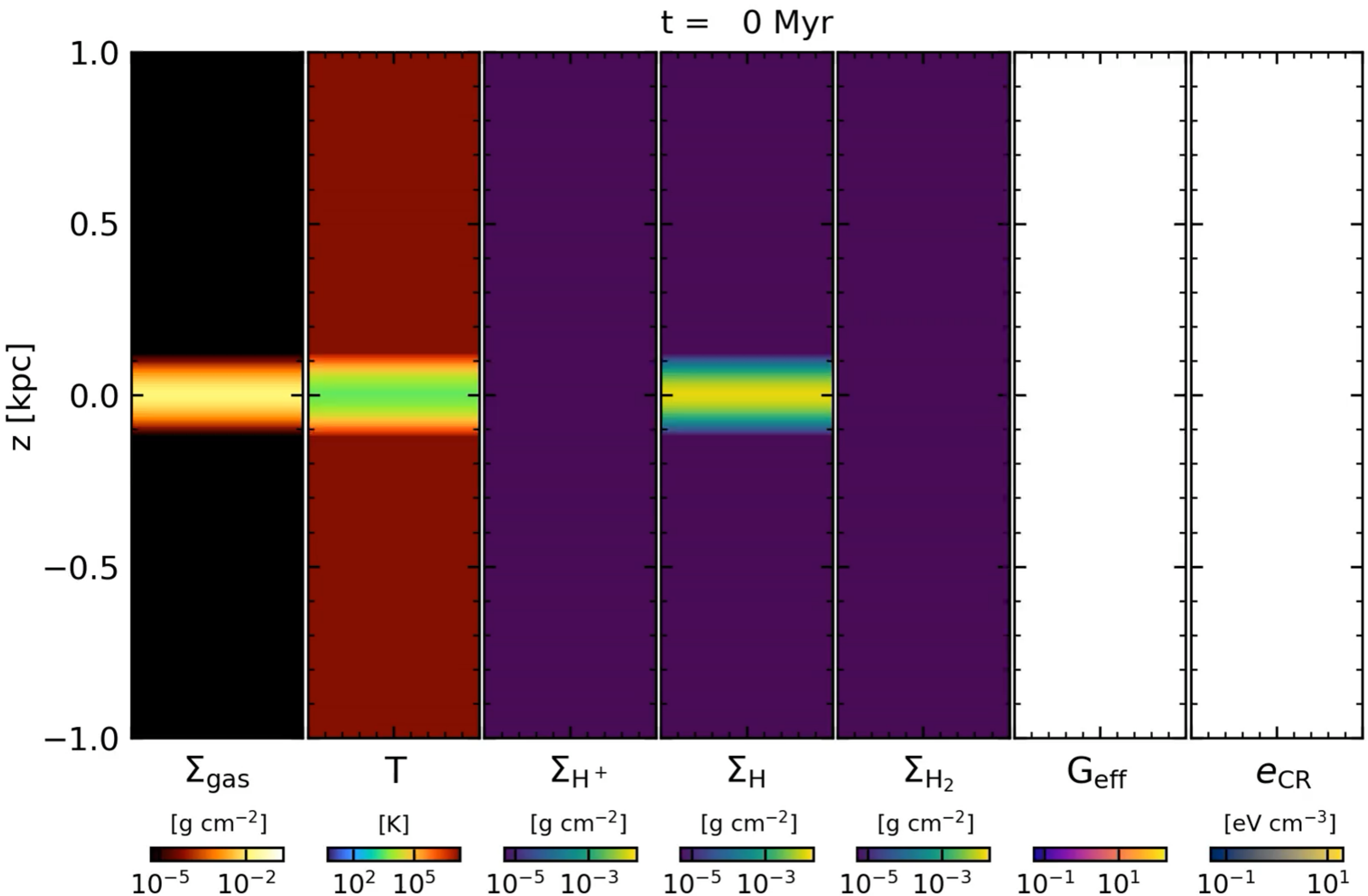
See also:
Kim & Ostriker (2018, 2017, 2022, 2023 TIGRESS),
Hill +2018, Hennebelle+2014,
Iffrig & Hennebelle (2017),
Safranek-Shrader +2017, Martizzi +2016,
Sur+2016, Gent +2013a, +2013b,
Hill & MacLow (2006),
deAvillez & Breitschwerdt (2005),
SILCC: Walch+2015, Girichidis+2016, Gatto+2017,
Peters+2017,…, Rathjen+2021, Rathjen+2023,
Brugaletta+2024, astro.uni-koeln.de/~silcc
etc.



In SILCC, we have an on-the-fly chemical network, and different forms of feedback incl. radiation transport (FUV, EUV), stellar winds, supernovae, and cosmic rays

SILCC simulations: multi-phase ISM in a stratified environment

Feedback: winds + ionizing radiation + supernovae + Cosmic Rays



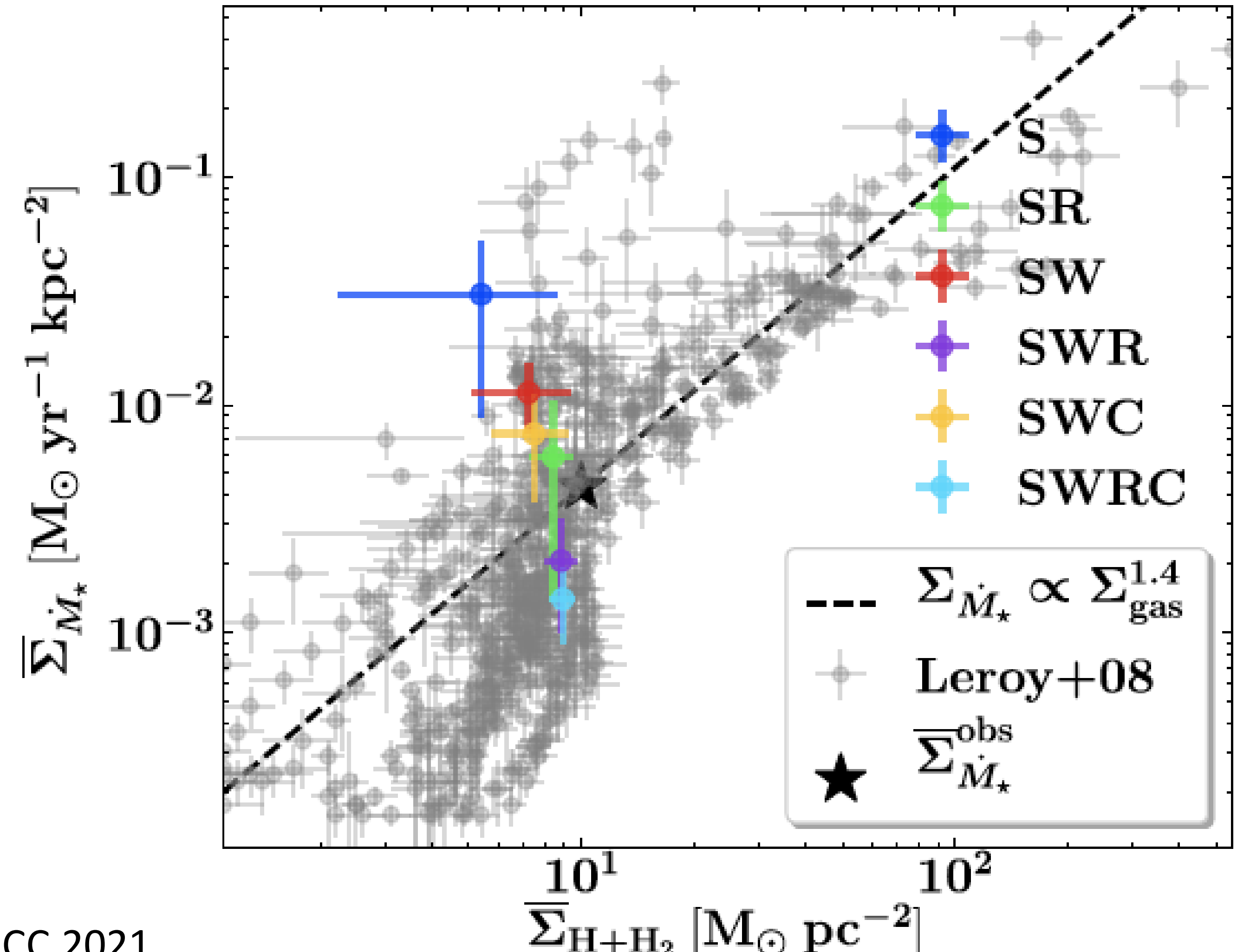
Cluster mass:

- 10^2 $M_\odot$
- 10^3 $M_\odot$
- 10^4 $M_\odot$

Brugaletta+2025
Rathjen+ 2021, +2023
CR description: Girichidis +2016, Girichidis +2018

What regulates star formation in the multi-phase ISM? Comparison of different stellar feedback processes

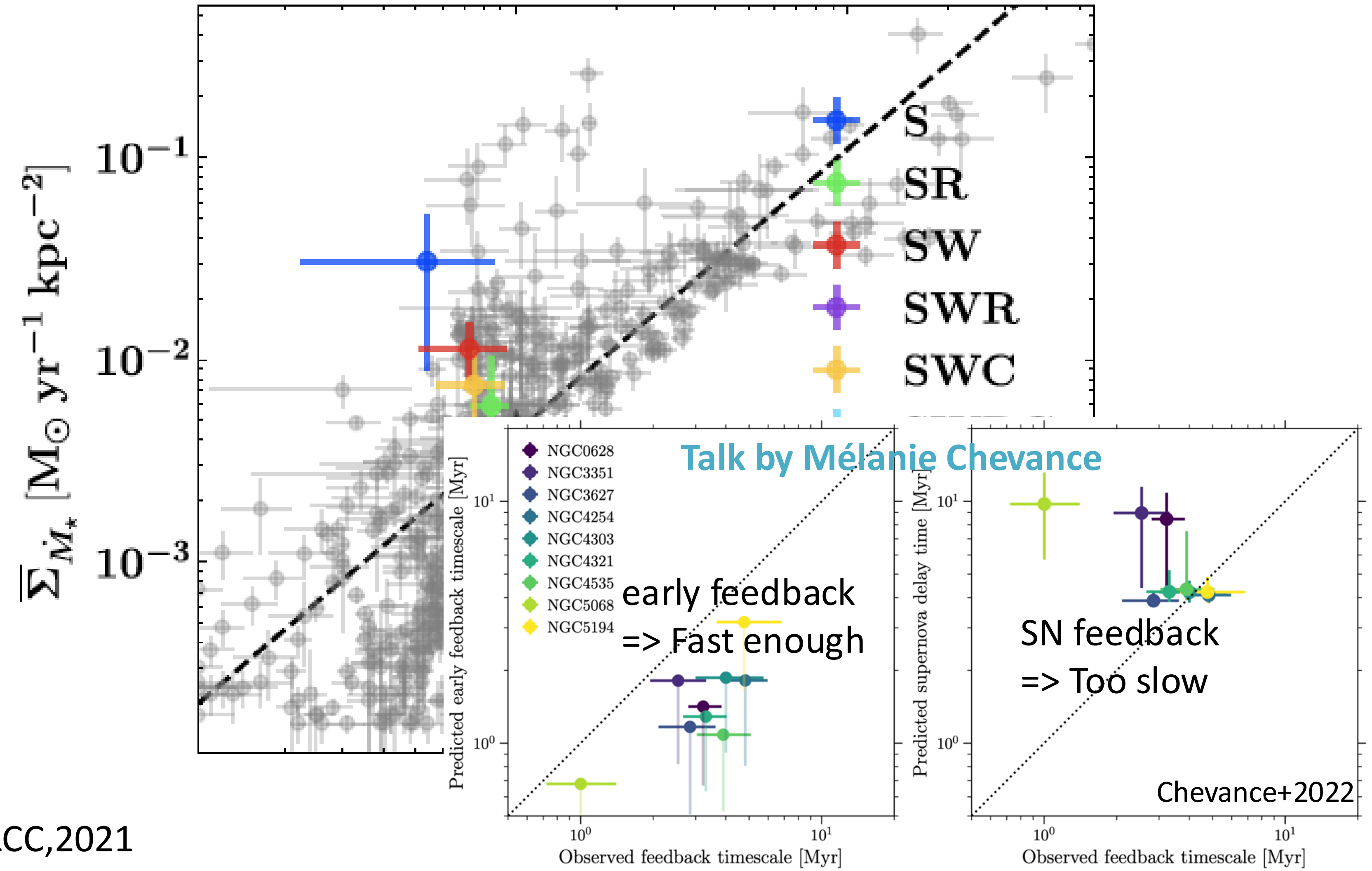
In case of supernova feedback alone, the star formation rates are too high
$\Rightarrow$Stellar radiation and winds are needed to regulate star formation



Rathjen+SILCC,2021

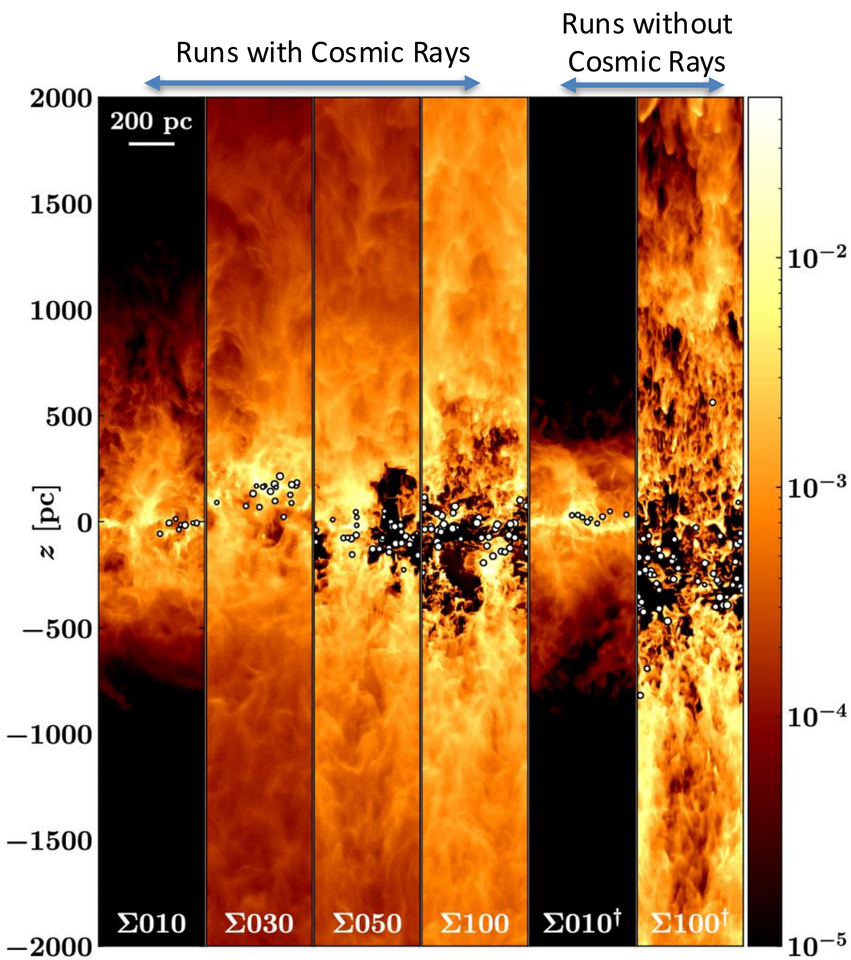
What regulates star formation in the multi-phase ISM? Comparison of different stellar feedback processes

In case of supernova feedback alone, the star formation rates are too high
⇒Stellar <u>radiation</u> and winds are needed to regulate star formation



Rathjen+SILCC,2021

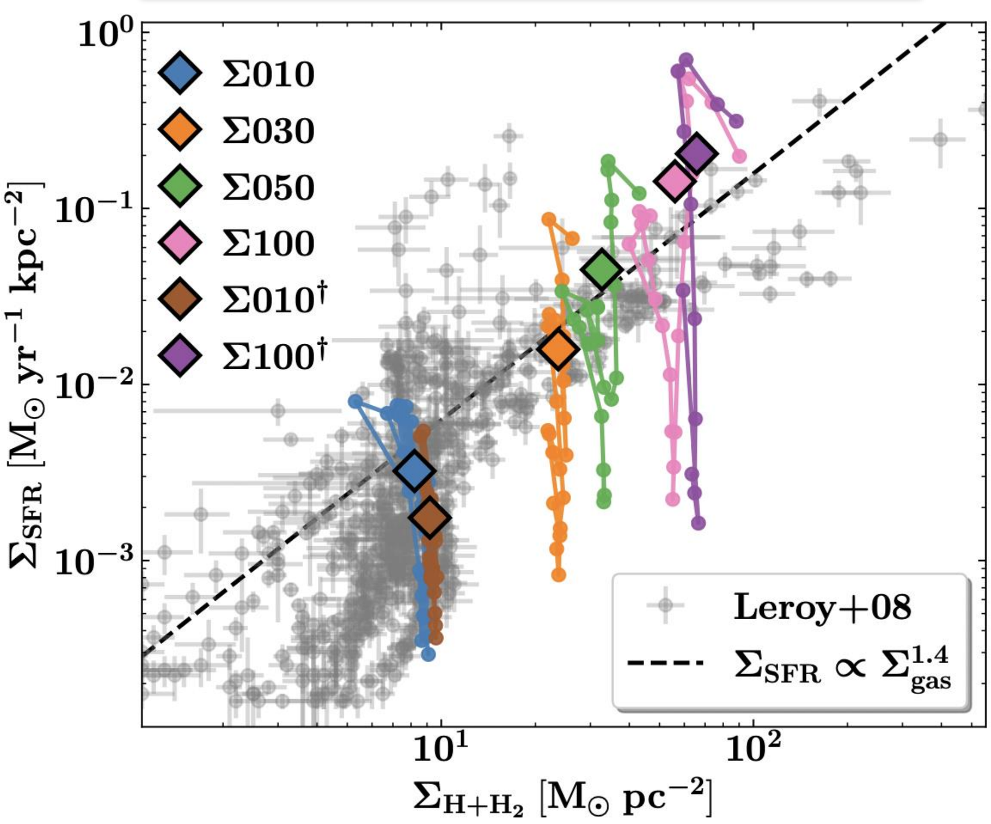
Different surface densities, Σ_{gas}=10-100 $M_\odot/pc^2$



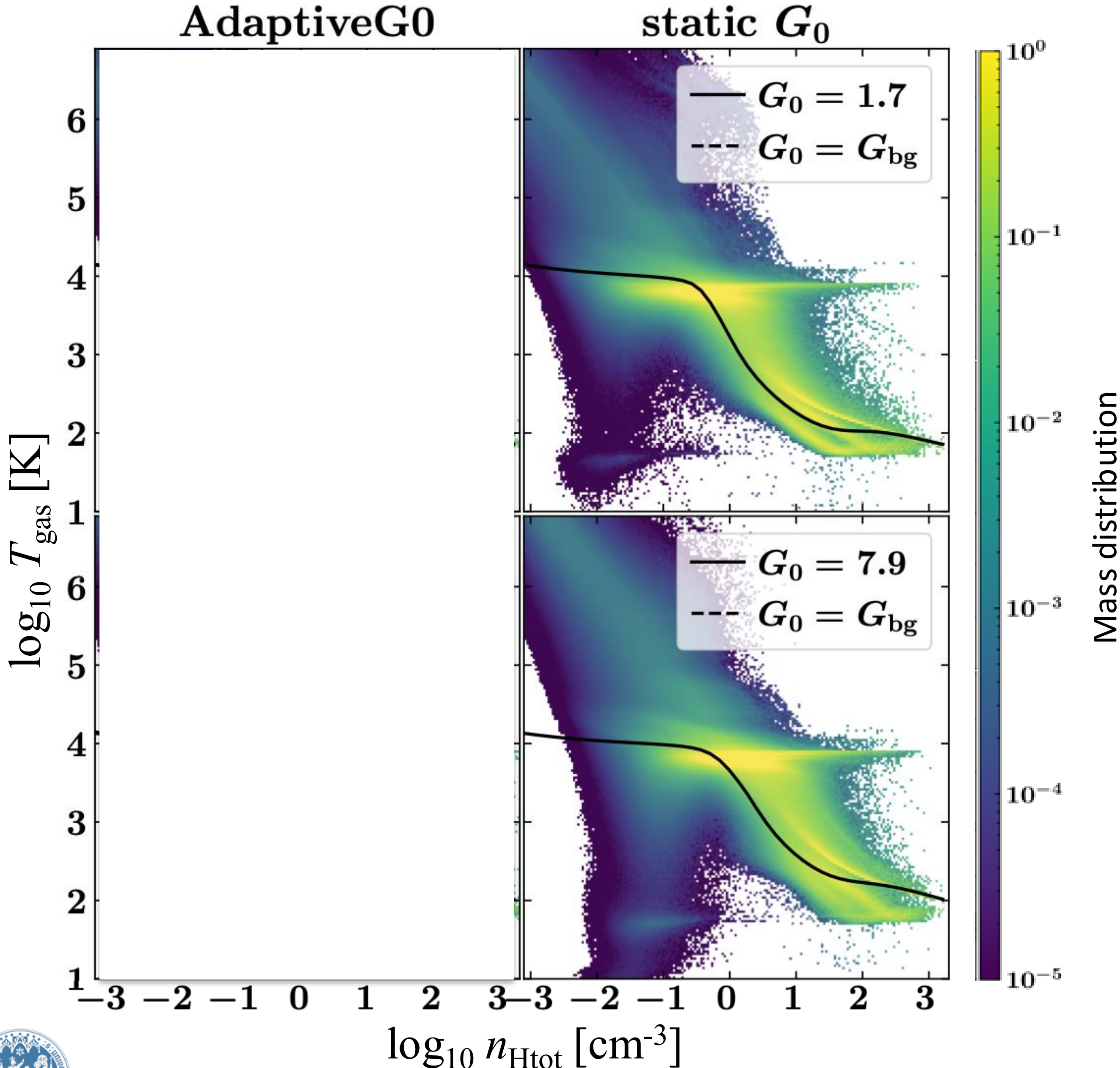
Rathjen+23
Simulations with ionization, winds, supernovae and cosmic rays

Different gas surface density:

- Scale height changes significantly
- Time average follows KS relation
- Large variation in time: bursty
- Cosmic Rays don't regulate SF on small scales at solar metallicity



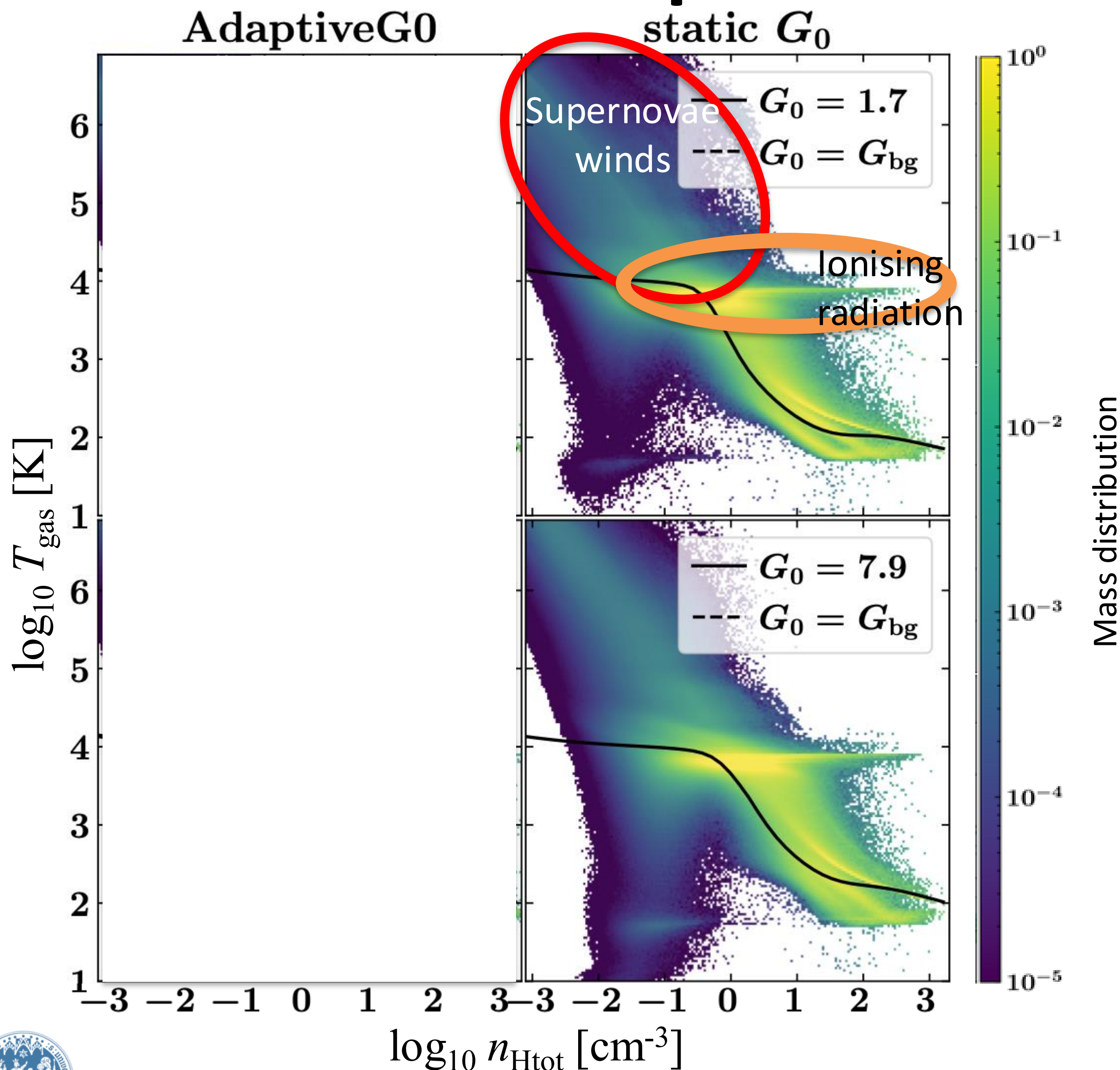
How feedback shapes the multi-phase ISM



- Gas distributed over very broad temp / dens range
- "equilibrium curves" (heating – cooling balance) for different interstellar radiation field shown as lines
- Most gas mass in warm (ionised) and cold ISM, with a significant fraction in the "thermally unstable" regime

Rathjen+2025

How feedback shapes the multi-phase ISM



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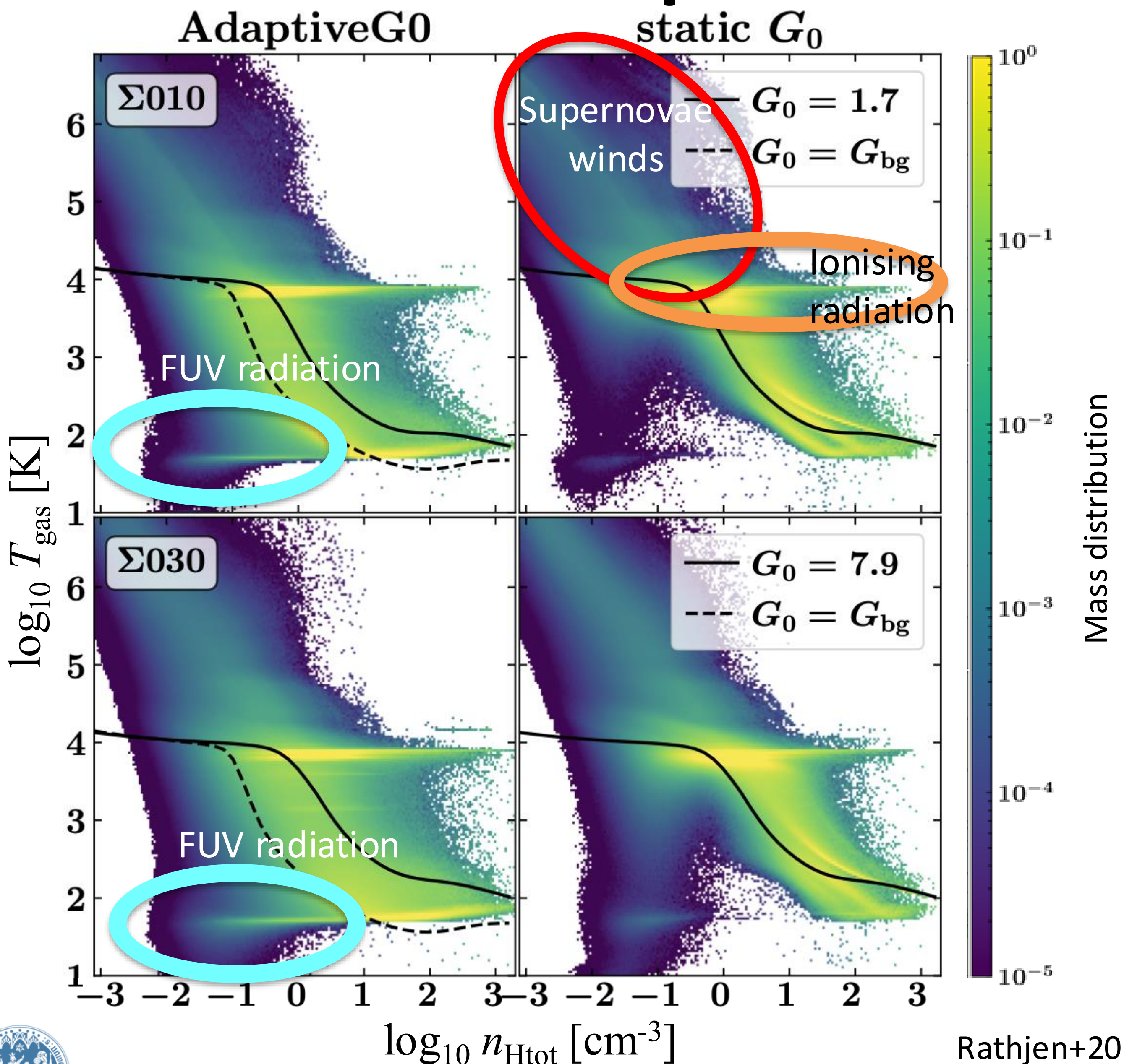
Rathjen+2025

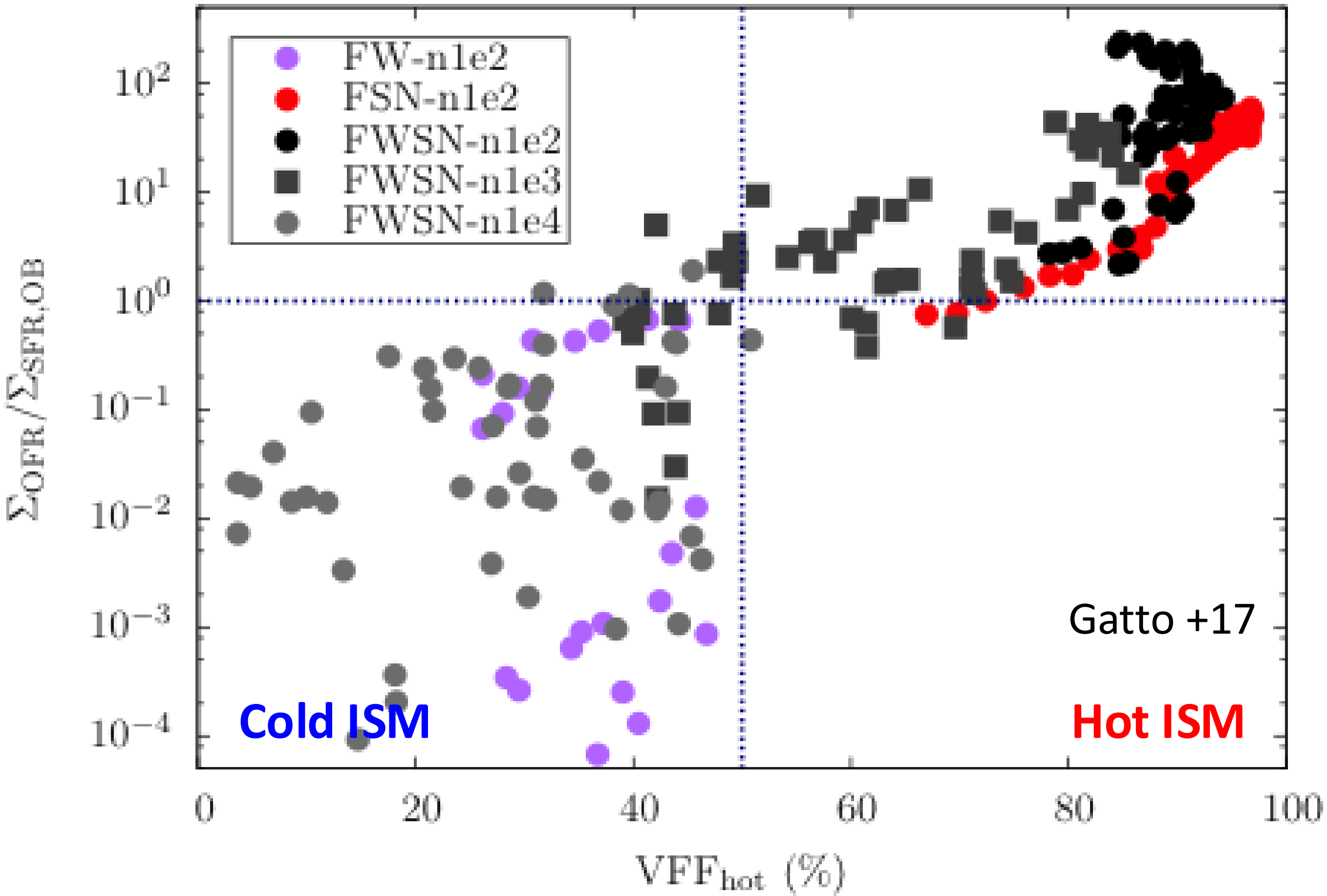
How feedback shapes the multi-phase ISM



Rathjen+2025

- Gas distributed over very broad temp / dens range
- "equilibrium curves" (heating – cooling balance) for different interstellar radiation field shown as lines
- Most gas mass in warm (ionised) and cold ISM, with a significant fraction in the "thermally unstable" regime
- **DIFFUSE molecular gas with FUV rad.**

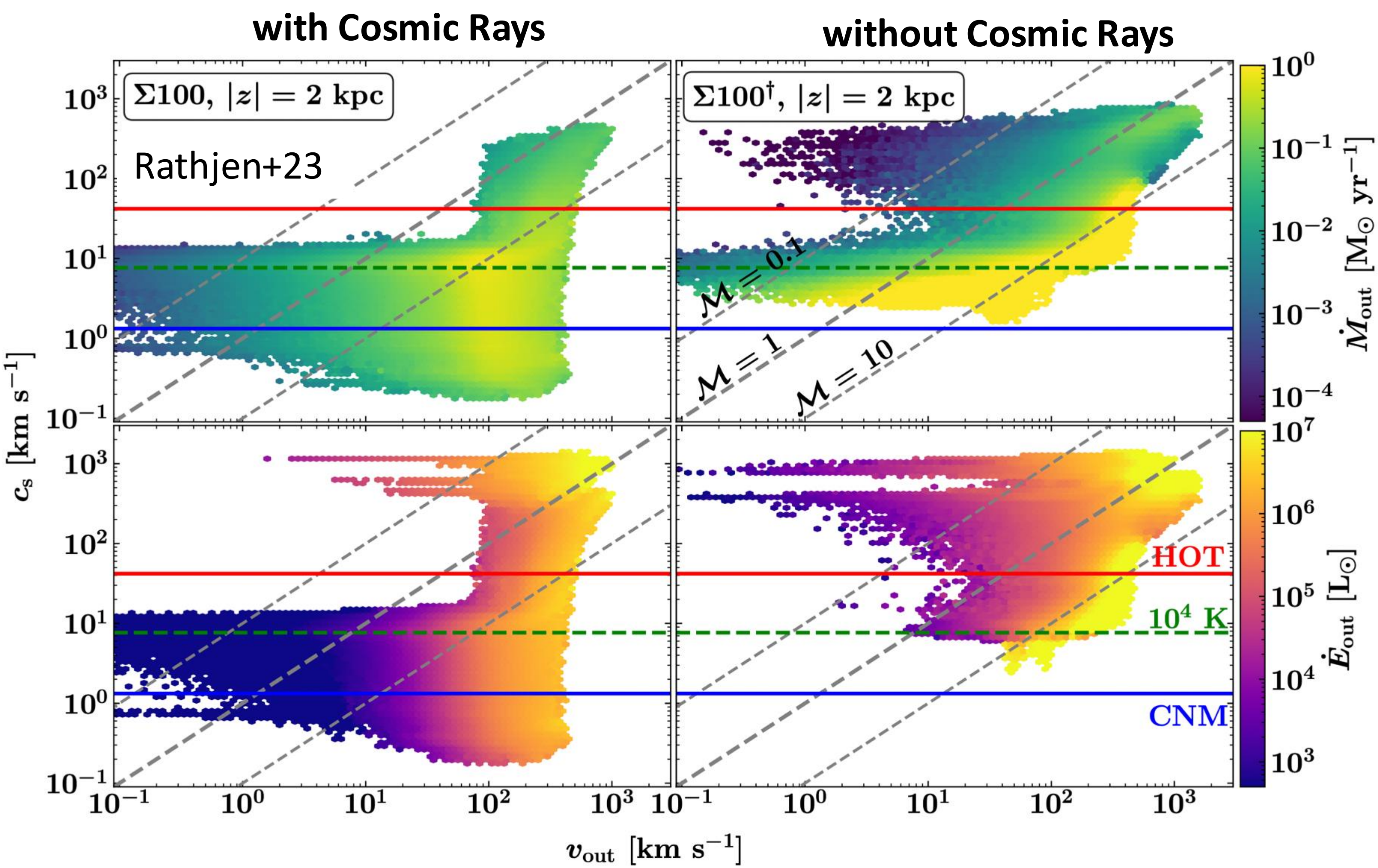
How to drive outflows? Massloading vs. hot gas VFF



Correlation of Mass loading (measured at z=± 1 kpc) with the hot gas volume filling factor in the galactic midplane
=> fountain/outflow regulated by thermal feedback

See also:
Fielding +2018, Li, Bryan & Ostriker (2017), Creasey +2013, Tomisaka & Ikeuchi (1986)

Sound speed of the outflowing gas vs. outflow velocity with/without cosmic rays



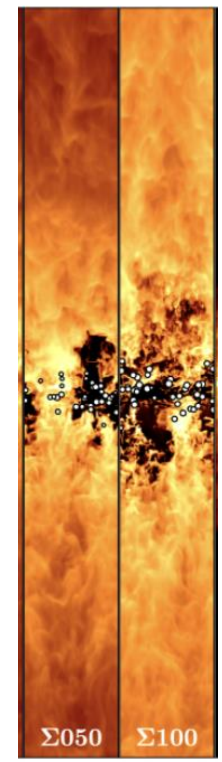
With CRs: outflowing gas is slower and cooler

Conclusions

Stellar feedback is essential to galaxy evolution

- **Protostellar outflows** set the peak of the IMF and impact stellar multiplicity; they regulate the SFE in lower-mass star-forming cores
- **Radiation** is most important for regulating star formation on galactic scales
- **Stellar wind** bubbles are not energy-driven, but not purely momentum-driven either (it's a little bit better than that)
- **Geometry matters** and not all gas in clouds is gravitationally bound
- **FUV radiative feedback** causes diffuse molecular gas component
- **Supernovae** act too late to efficiently regulate star formation
- But, Supernovae determine the gas pressure near the midplane and drive **galactic fountains / outflows**
- **Cosmic Rays** lift gas on longer time scales, outflowing gas is cooler and multi-phase

Exciting time ahead of us – simulations bridging spatial scales, going from kilo-parsec scales to individual stars!




Upcoming
Habitats of massive stars
across cosmic time
August 17-21, 2026
Cologne

Energy-driven vs. momentum-driven winds

Spherical, virialized molecular cloud with escape velocity v_{esc}~10 km/s

Energy-driven wind

$$\dot{E}_{\mathrm{w},\star} = \frac{1}{2}\dot{M}_{\mathrm{w}} v_{\mathrm{w}}^2$$ **Wind energy input**

$$\eta_{\mathrm{w}} = 0.01\,\mathrm{M}_{\odot}^{-1}$$ **#massive stars formed per M_{sun}**

$$E_{\mathrm{fb,w}} = \epsilon_{\mathrm{w}} \eta_{\mathrm{w}} \bar{E}_{w} M_{\star}$$ **Total energy provided by winds**

$$E_{\mathrm{fb,ej}} = \frac{1}{2} v_{\mathrm{esc}}^2 M_{\mathrm{fb,ej}}$$ **Total energy needed to unbind gas from the molecular cloud**

$$\frac{M_{\mathrm{fb,ej}}}{M_{\star}} = 2\epsilon_{\mathrm{w}}\eta_{\mathrm{w}}\frac{\bar{E}_{w}}{v_{\mathrm{esc}}^2} = \epsilon_{\mathrm{w}} \times 0.02\mathrm{M}_{\odot}^{-1}\frac{10^{49}\,\mathrm{erg}}{10^{12}\,\mathrm{cm}^2 s^{-2}} = 100\epsilon_{\mathrm{w}}$$

Energy-driven winds (remember, NO COOLING), could unbind up to 100 times the mass of formed stars, hence reducing the star formation efficiency to just 1%

Uncertainty: $\varepsilon_w \leqq 1$ Cooling efficiency

Walch+2023
(pcsf.conf, 97W)

Energy-driven vs. momentum-driven winds

Spherical, virialized molecular cloud with escape velocity v_{esc}~10 km/s

Momentum-driven wind

$$\dot{p}_{\rm fb,w} = \dot{p}_{\rm fb,ej}$$

Equating the wind momentum and the momentum needed to unbind the gas

$$\eta_{\rm w} = 0.01\,{\rm M}_\odot^{-1}$$

#massive stars formed per M_{sun}

$$\dot{p}_{\rm fb,w} = \dot{M}_{\rm w} v_{\rm w} \eta_{\rm w} M_\star \epsilon_{\rm mom}$$

Momentum input by IMF-averaged massive star pop

$$\dot{p}_{\rm fb,ej} = \dot{M}_{\rm fb,ej} v_{\rm esc}.$$

Momentum required to unbind gas

$$\frac{\dot{M}_{\rm fb,ej}}{\dot{M}_{\rm star}} \approx \epsilon_{\rm mom} 0.01\,{\rm M}_\odot^{-1} \frac{100\,{\rm M}_\odot {\rm km s}^{-1}}{10\,{\rm km s}^{-1}} = 0.1\epsilon_{\rm mom}$$

Compare with Matzner (2002), who give an even lower average momentum input for stellar winds of just 38 M_{sun} km/s

Momentum-driven winds (MAXIMUM COOLING), cannot unbind significant cloud mass, hence the star formation efficiency could be as high as 90%

Uncertainty: $\varepsilon_{mom} \geqq 1$ Momentum boost

Walch+2023 (pcsf.conf, 97W)