The Cycle of Star Formation across Scales: Stellar Feedback as a Source of Interstellar Turbulence

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Star Formation, Stellar Feedback, and the Ecology of Galaxies ~ May 28, 2025

American Museum of Natural History

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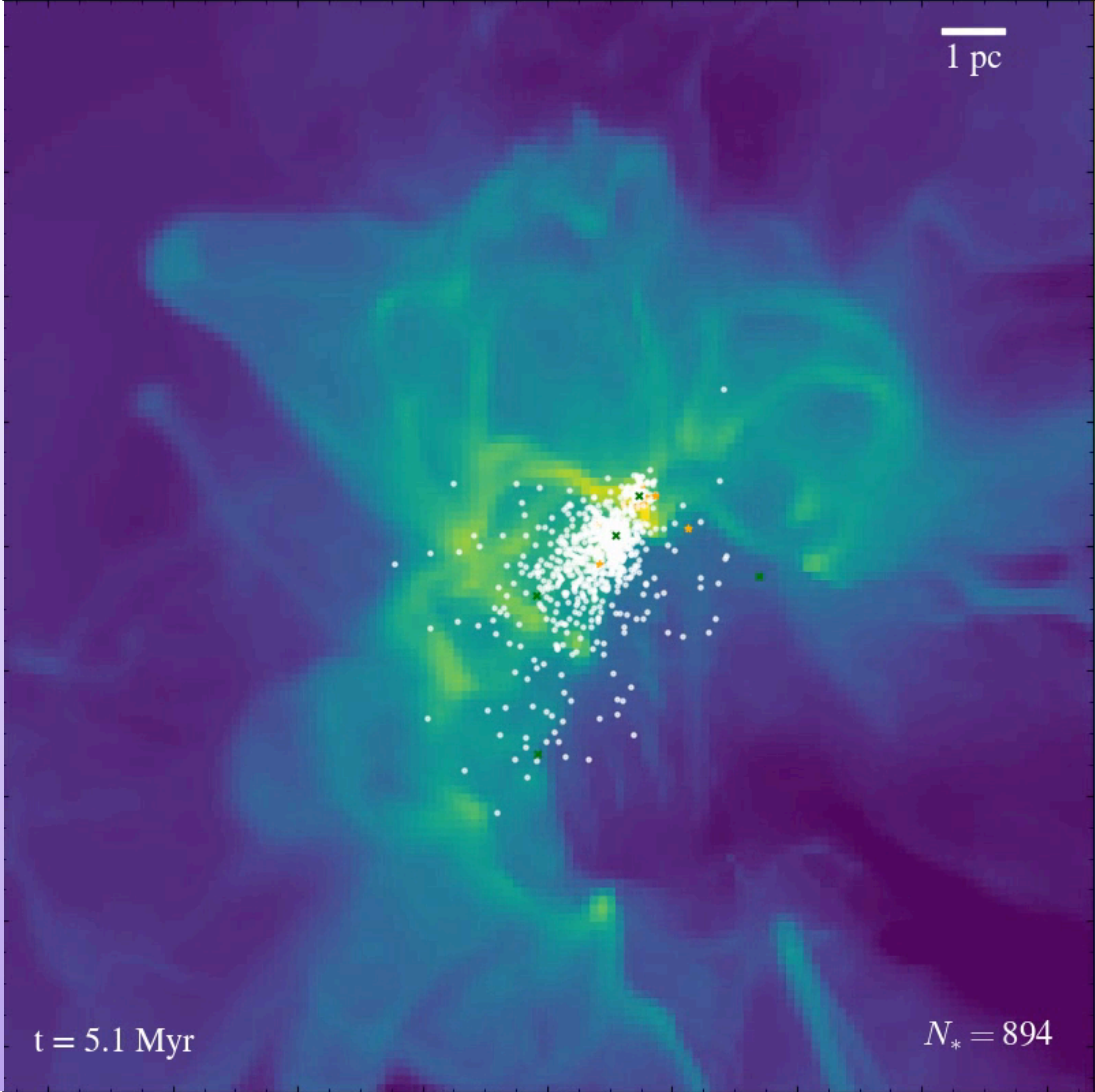
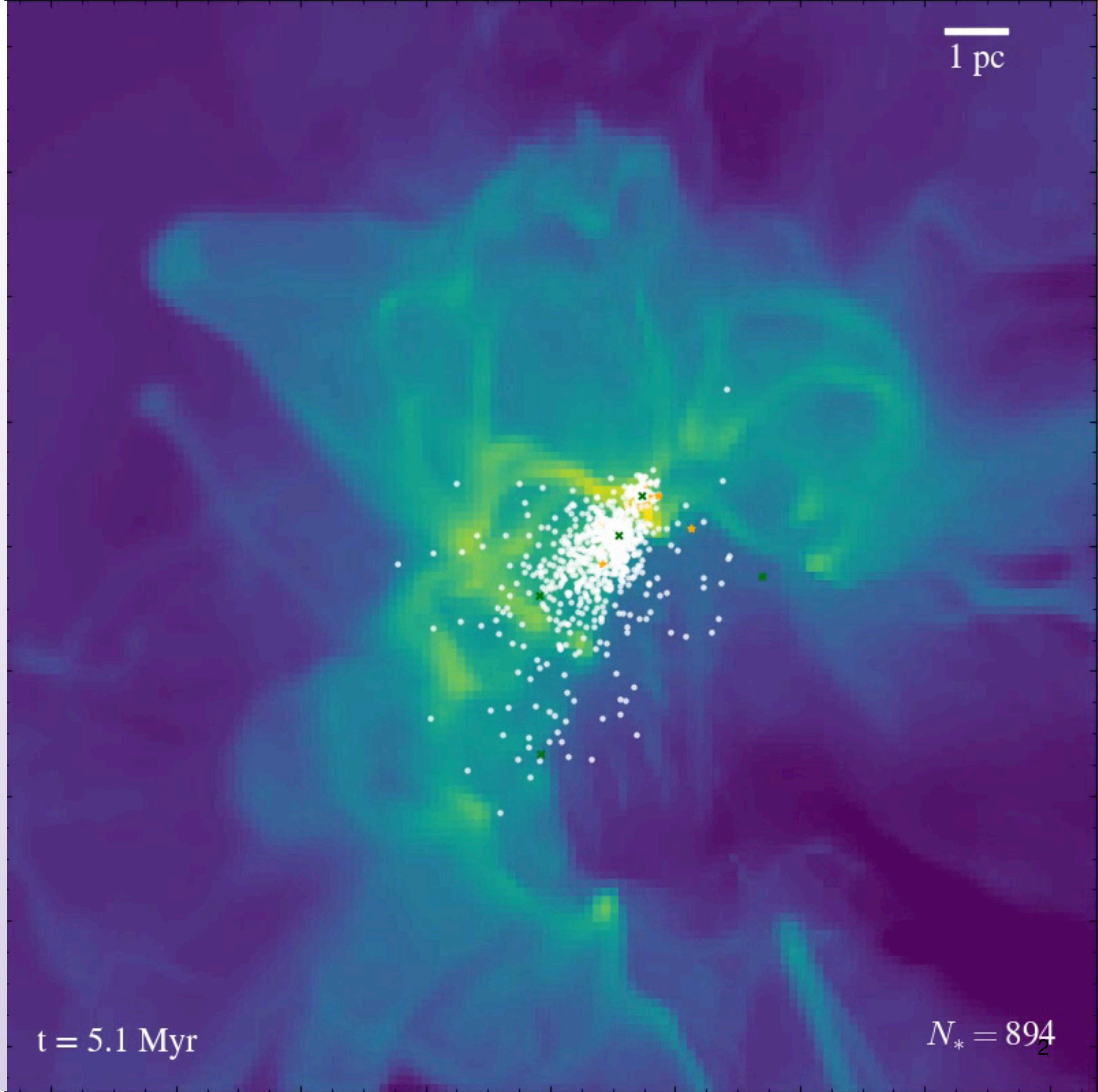


Overview of Star Formation



Appel et al. in prep.

Star Formation is a Cycle

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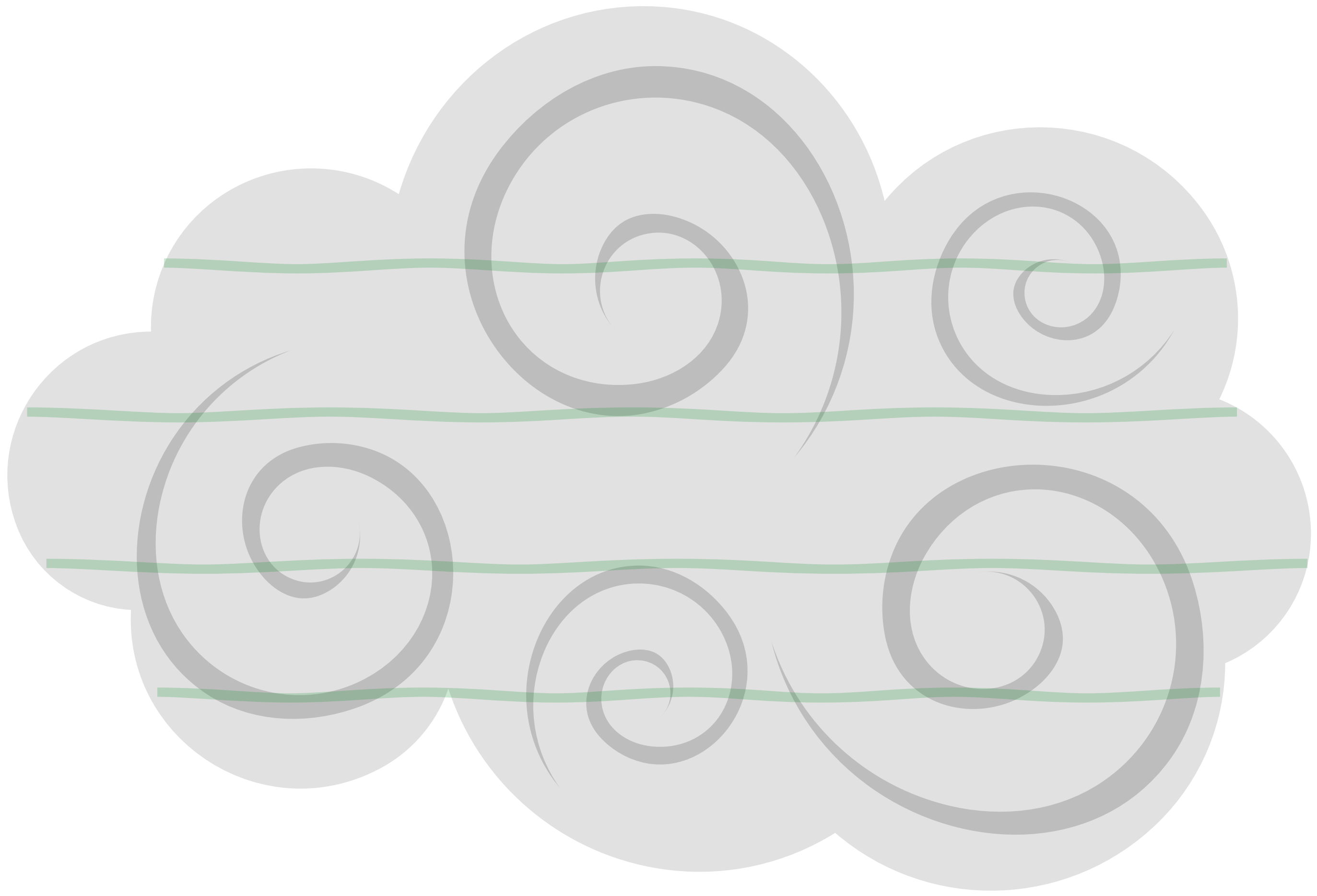
Initial turbulent, magnetized gas cloud



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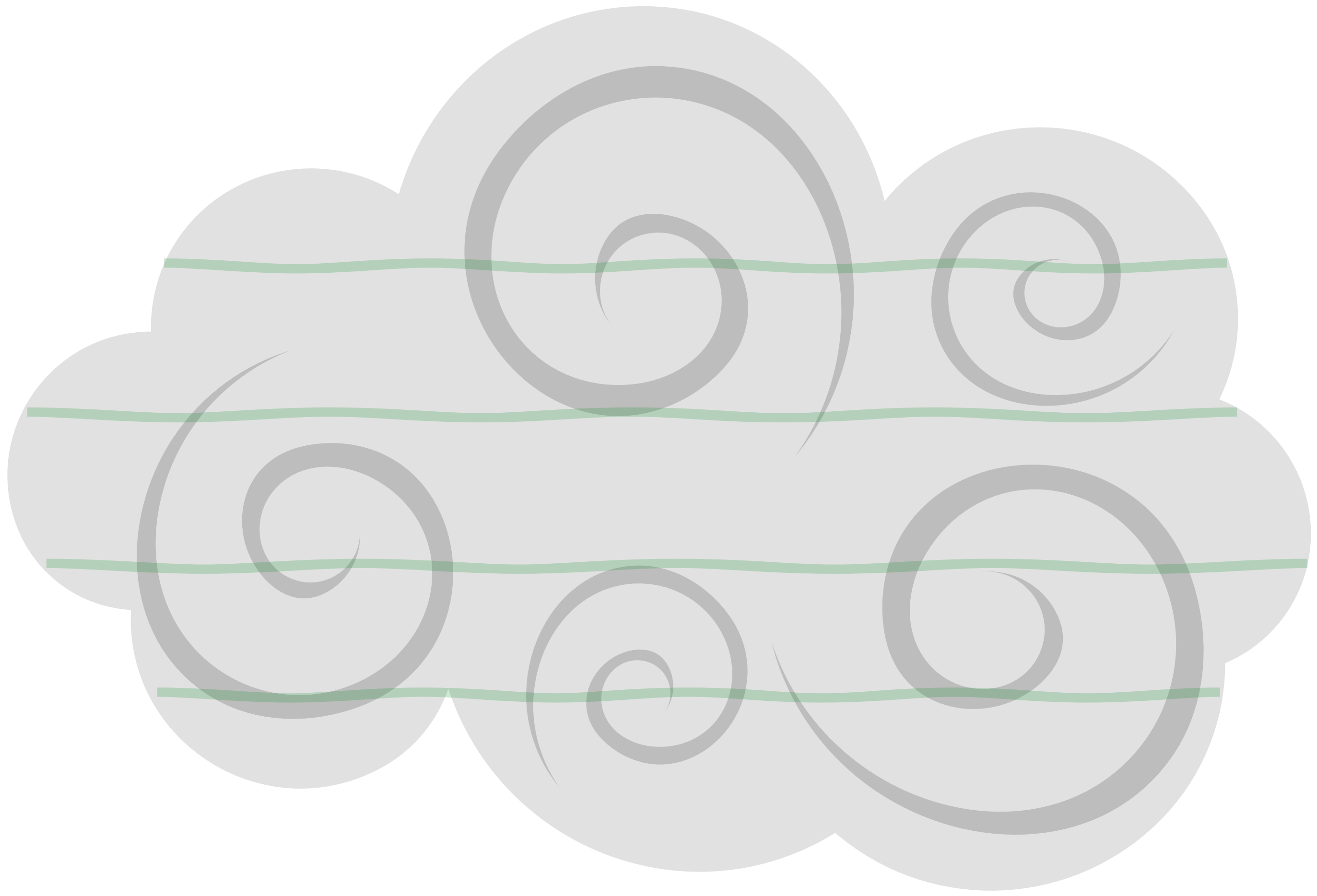
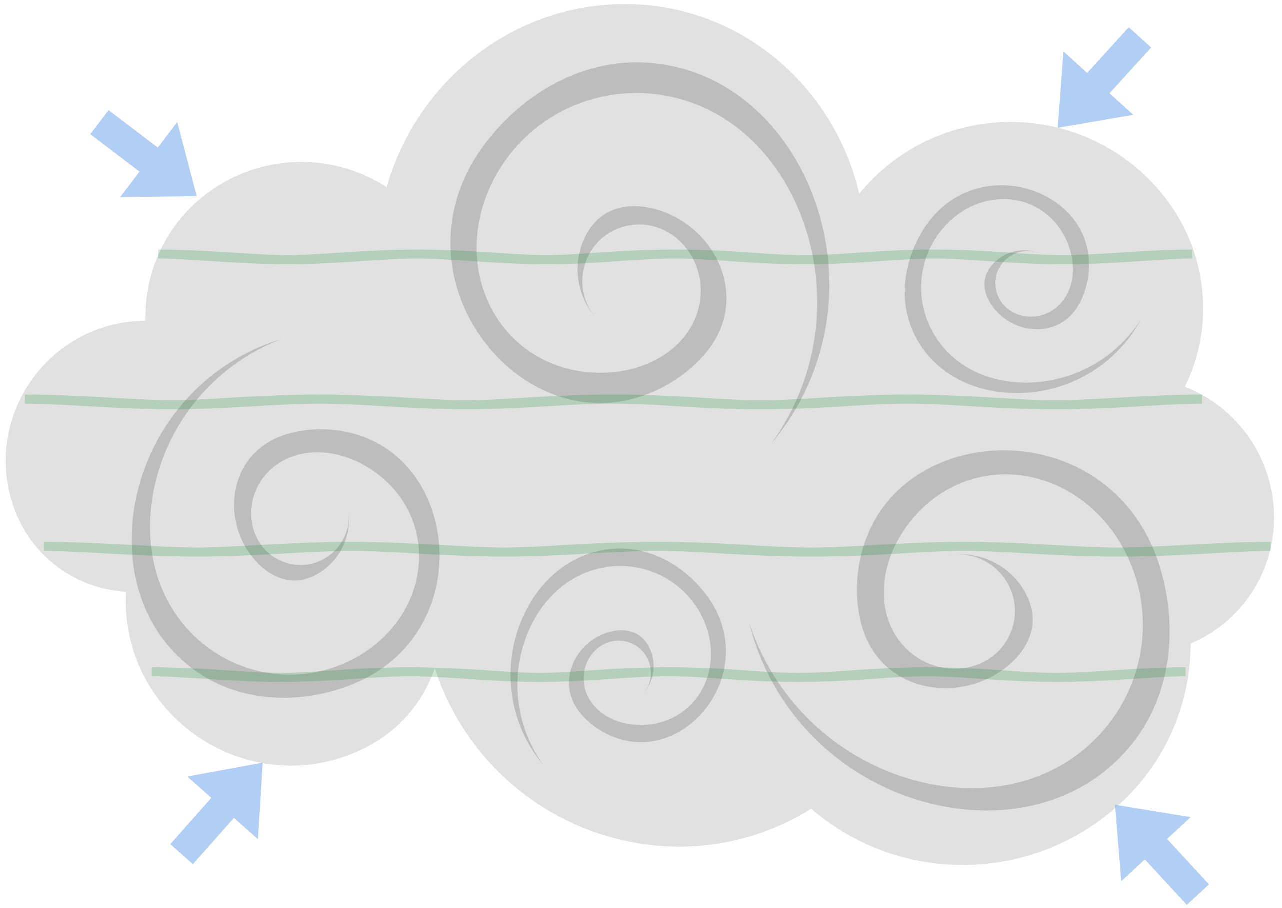


Gas undergoes gravitational collapse



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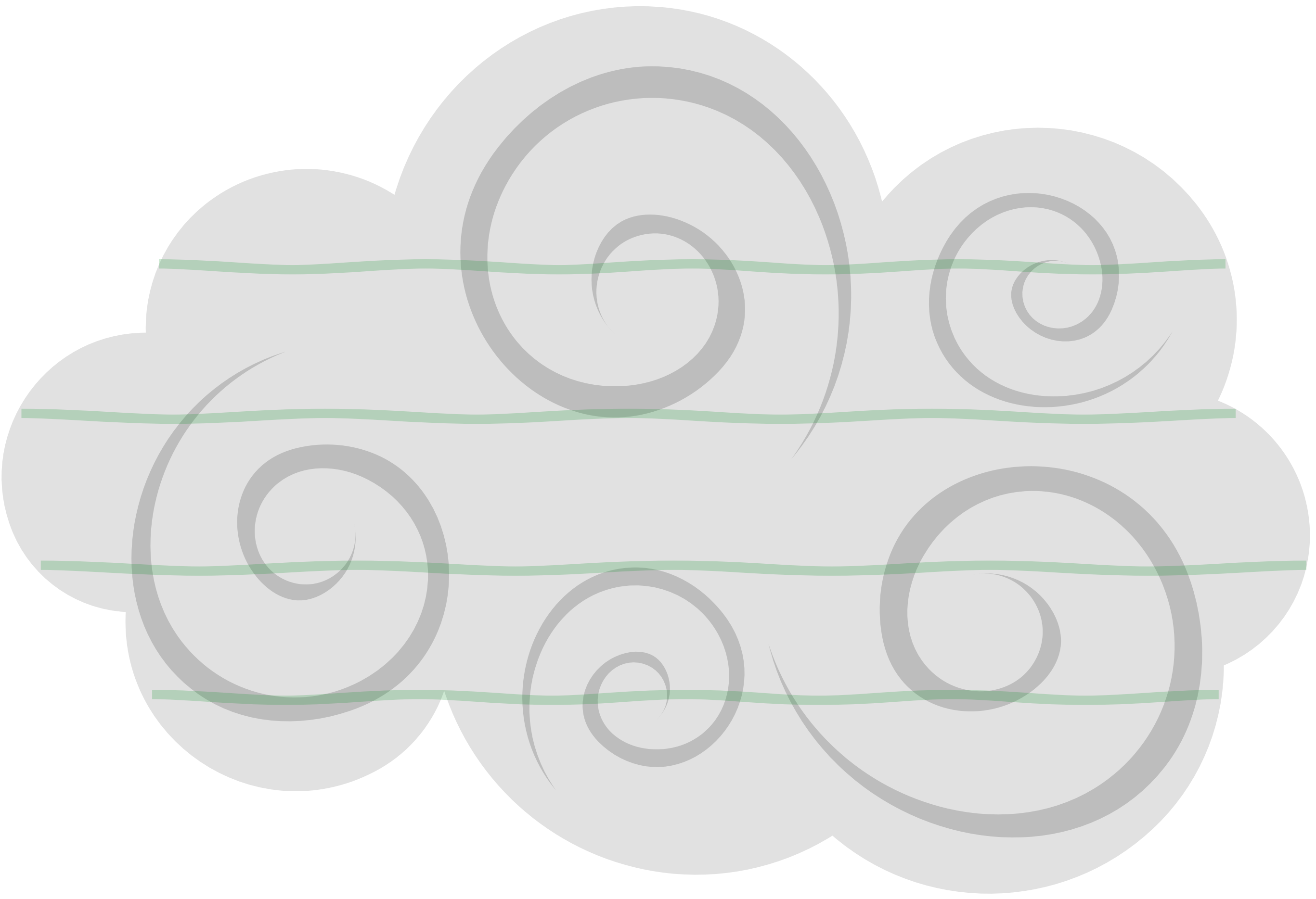

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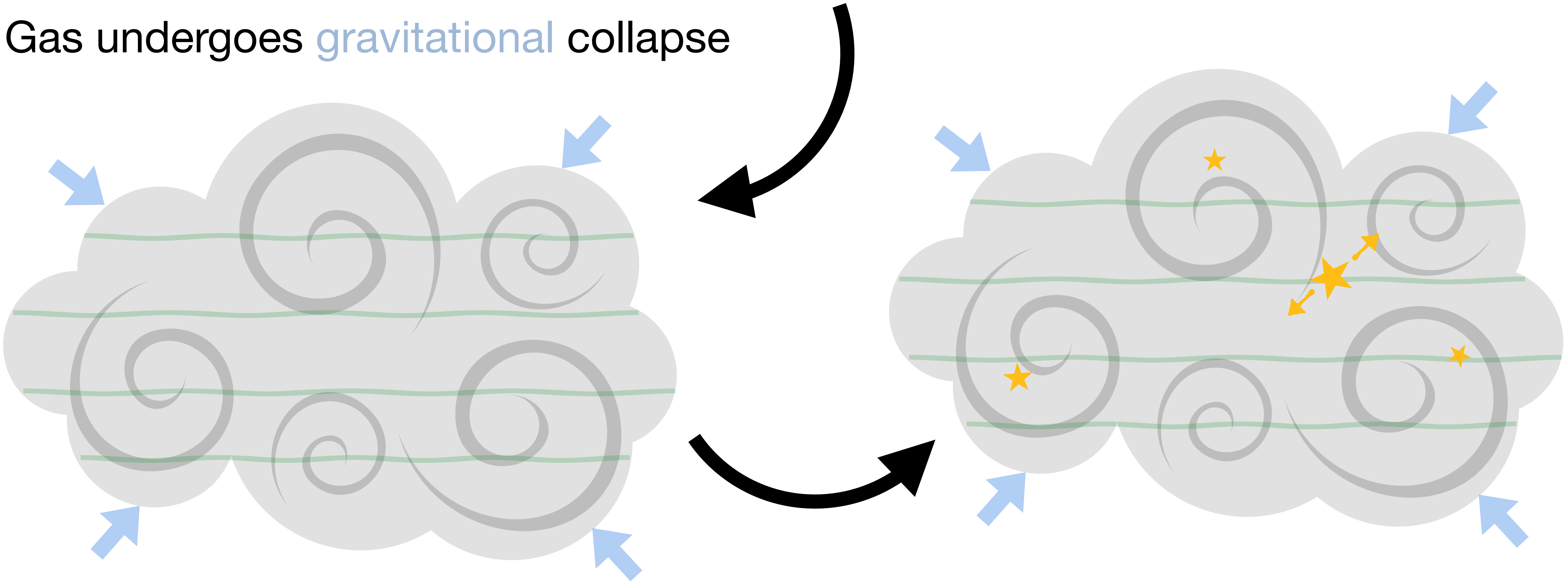

First stars form with protostellar feedback
(Jets and accretion luminosity/protostellar heating)

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Star Formation is a Cycle

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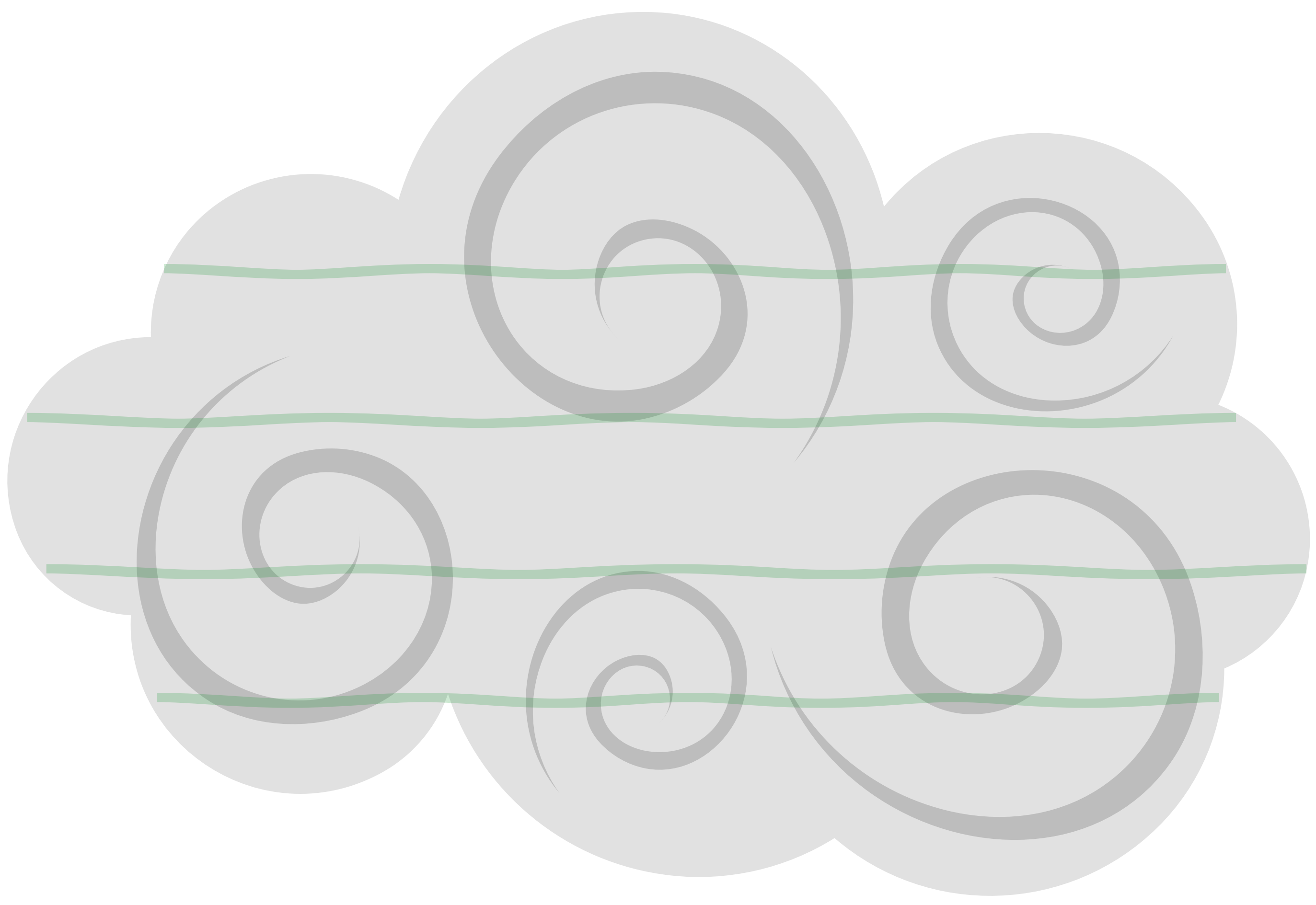

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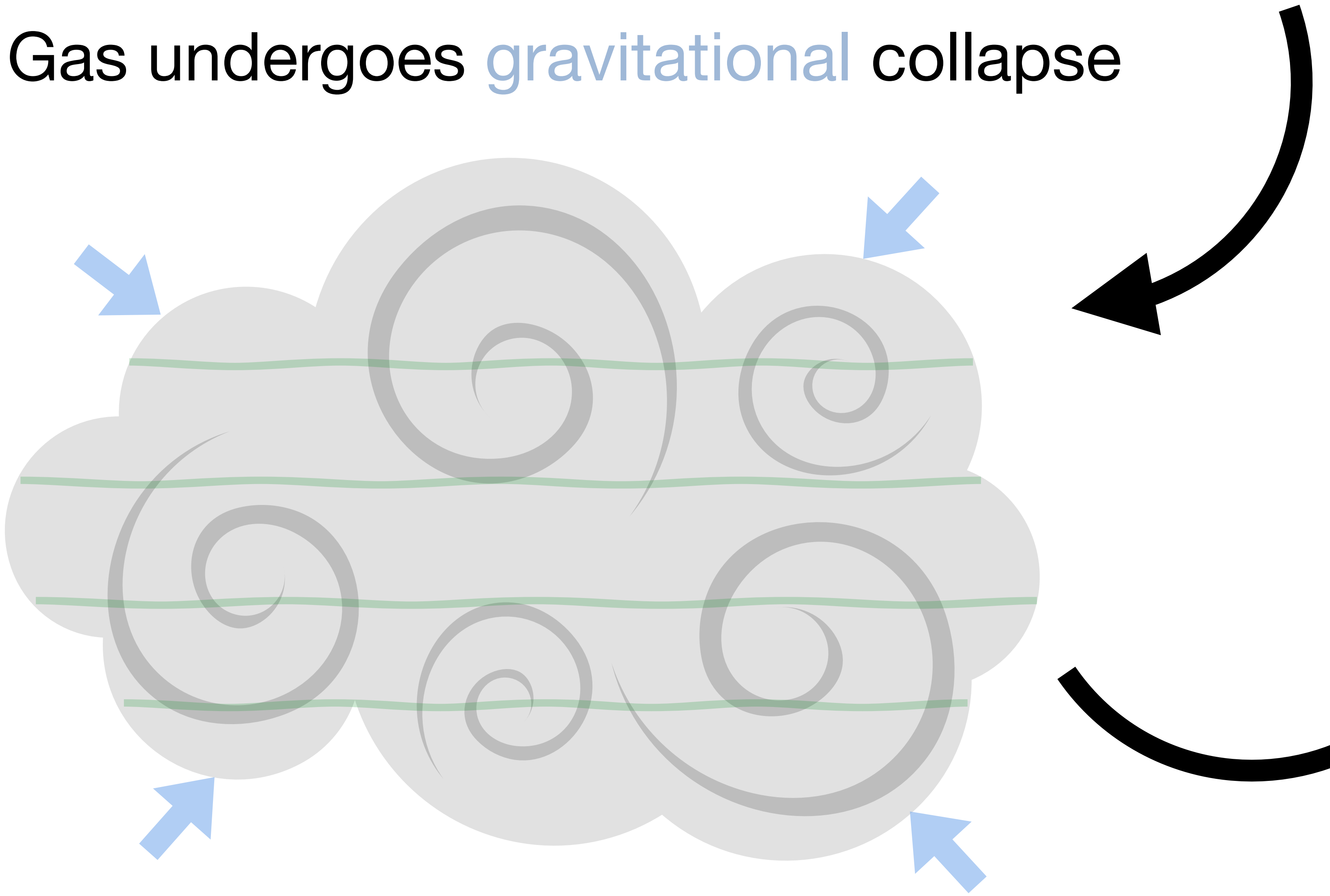
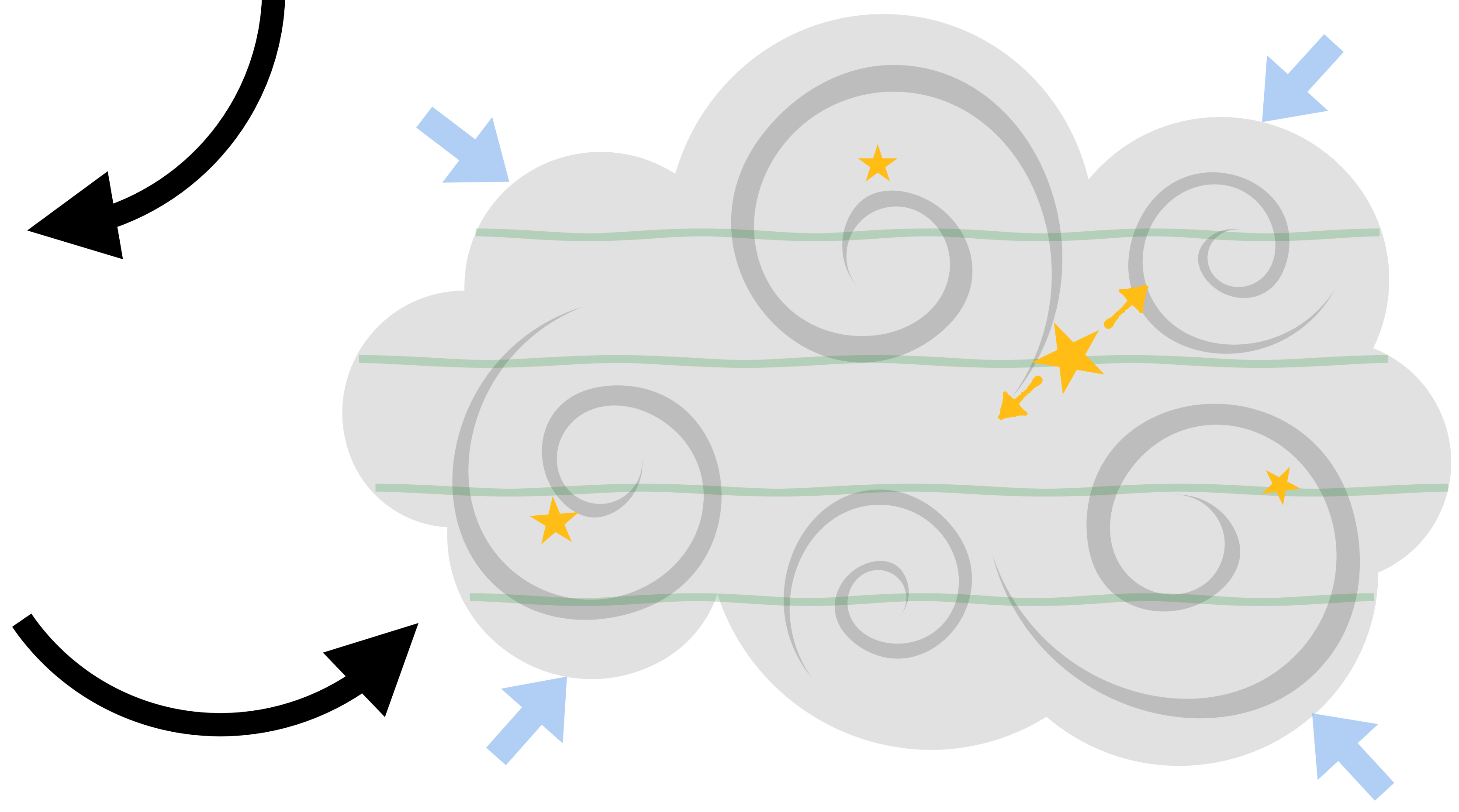
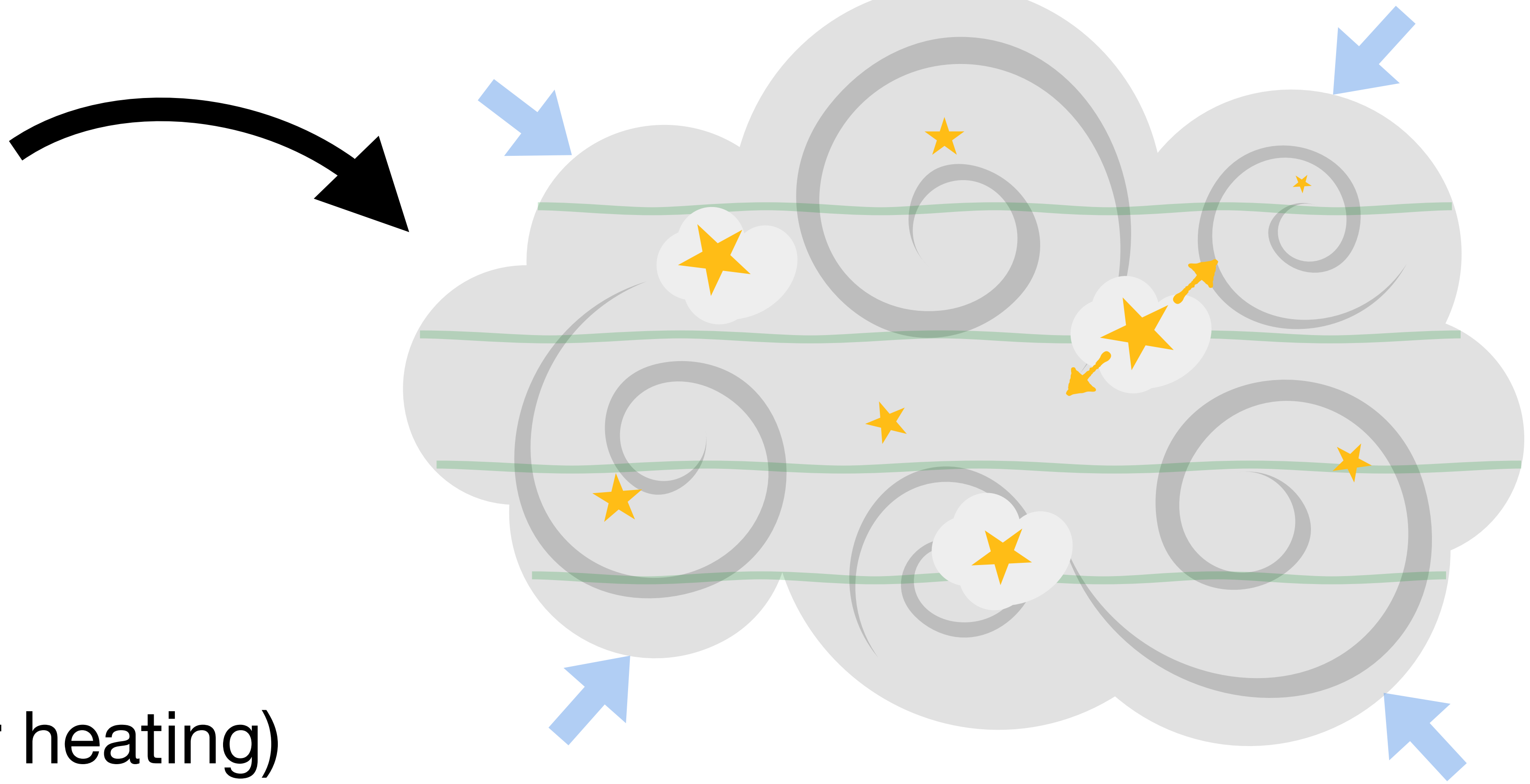




First stars form with protostellar feedback
(Jets and accretion luminosity/protostellar heating)

Stellar feedback ramps up - now including:
Winds + Radiation + Supernovae



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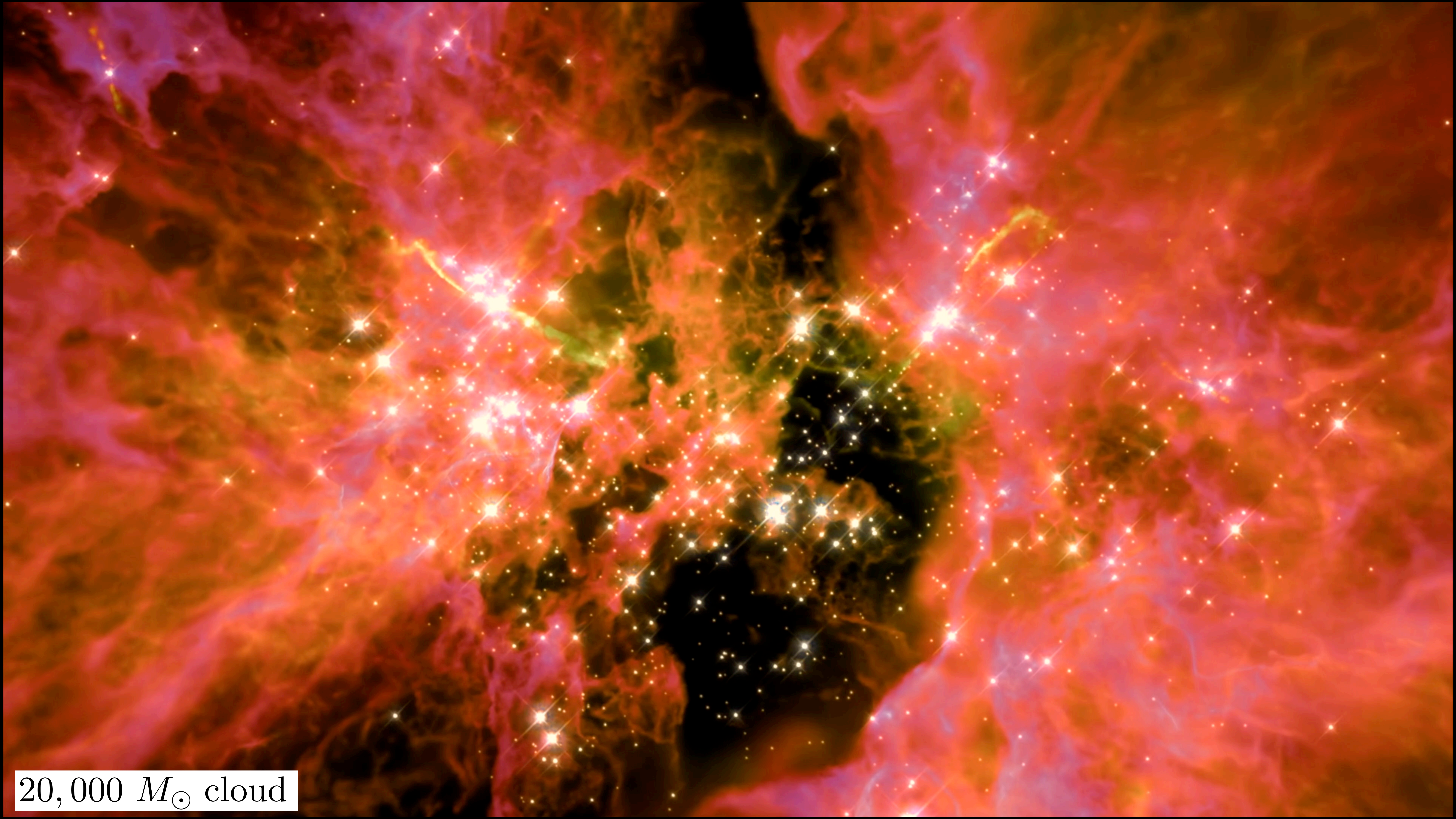
30 Doradus / Tarantula Nebula - JWST NIRCam

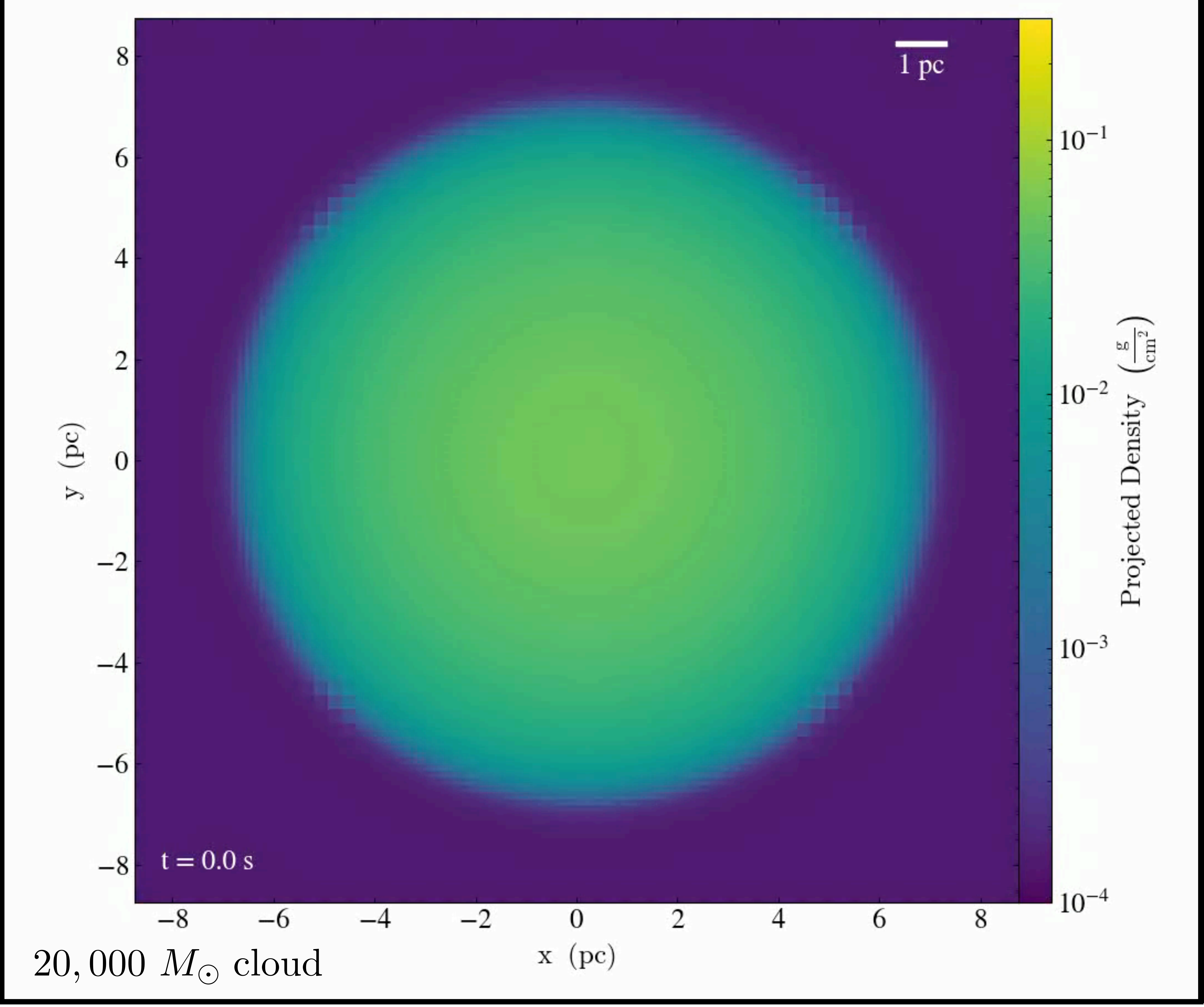
Image Credit: NASA, ESA, CSA, STScI, Webb ERO Production Team



STARFORGE: The Anvil of Creation simulation

Appel

Movie Credit: Mike Grudić & Dávid Guszejnov; Grudić et al. 2021; https://starforge.space/



Torch simulation with protostellar jets

Appel

Movie Credit: Simulation and movie by S. Appel; Appel et al. in prep.

Modes of Feedback

Image Credit: NASA, ESA, CSA, STScI, Webb ERO Production Team

Protostellar jets

HST image of the Carina Nebula

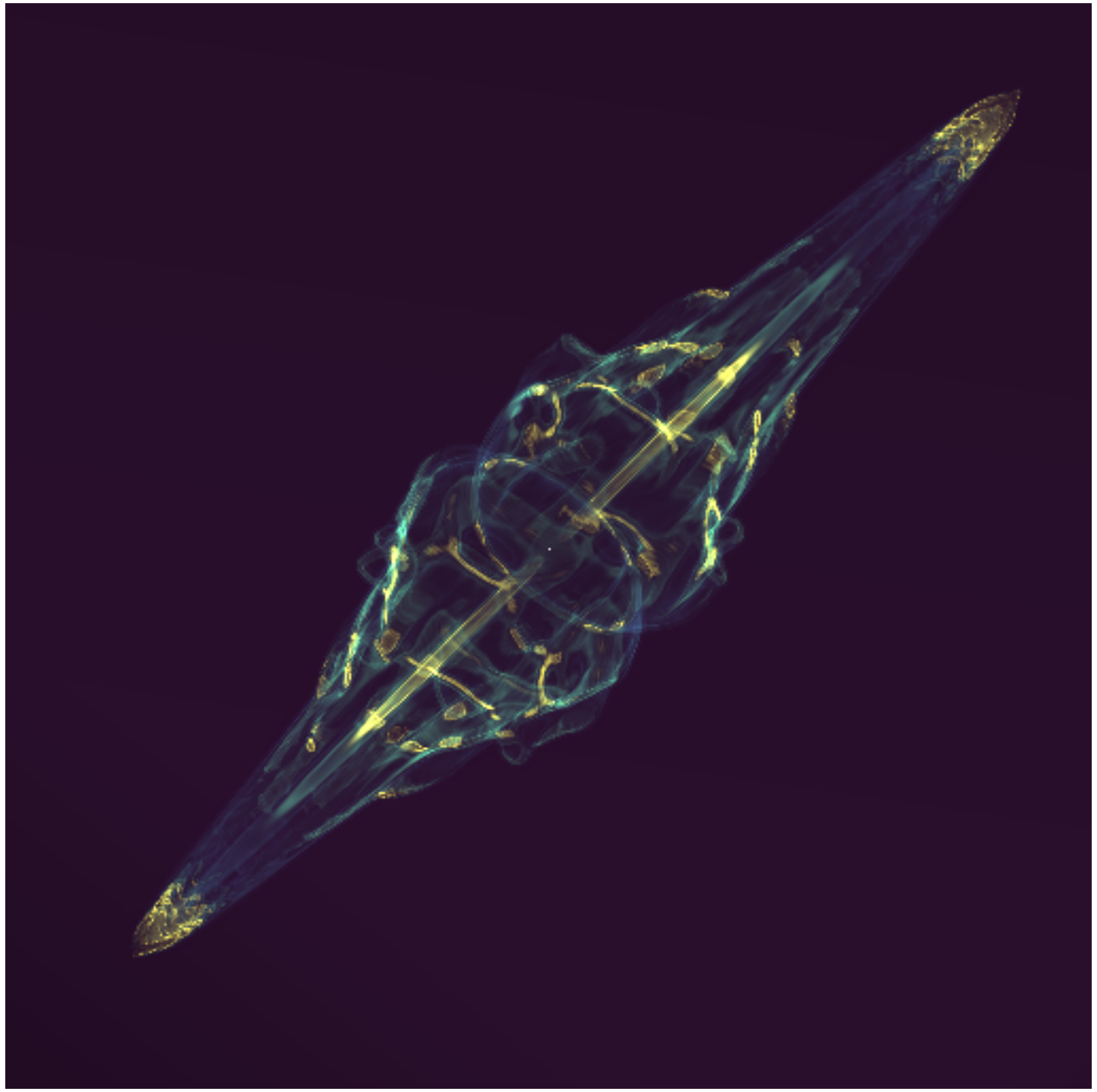
JWST image of ρ-Ophiuchus

Bally 2024

Protostellar jets

JWST NIRCam image of HH 211

Ray et al. 2023; Bally 2024



Simulation of a protostellar jet

Appel et al. in prep.

Protostellar jets

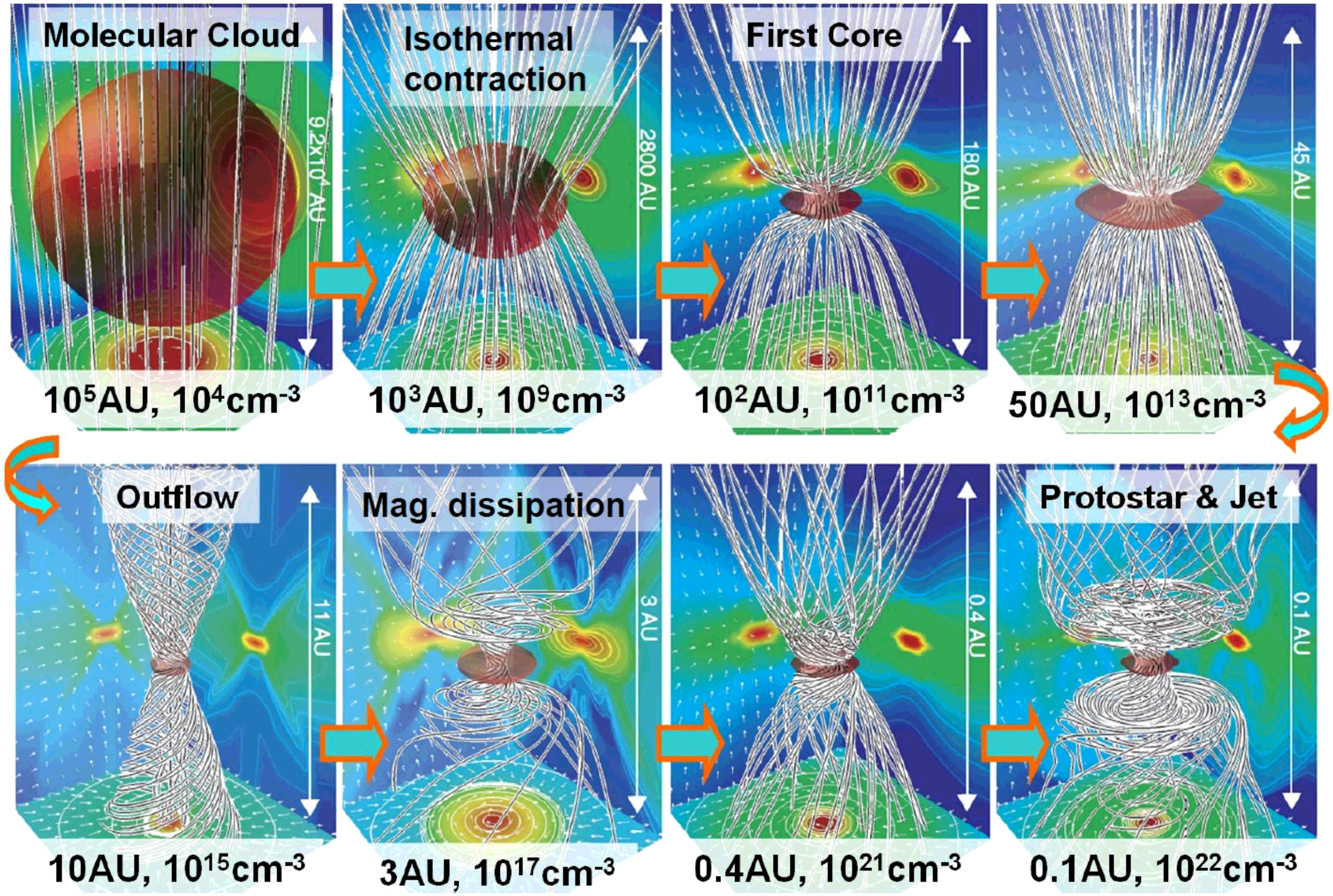
Protostellar jets are the earliest mode of feedback — launched during the accretion phase

Injected by protostars of all masses
e.g., Shepherd & Churchwell 1996

Jets drive turbulence in the cloud
e.g., Nakamura & Li 2007

Significantly alter SFE, IMF, etc.
e.g., Federrath 2015, Guszejnov et al. 2021, Appel et al. 2022,

Insufficient to disperse GMCs
e.g., Chevance et al. 2023



Machida 2017, Bally 2024

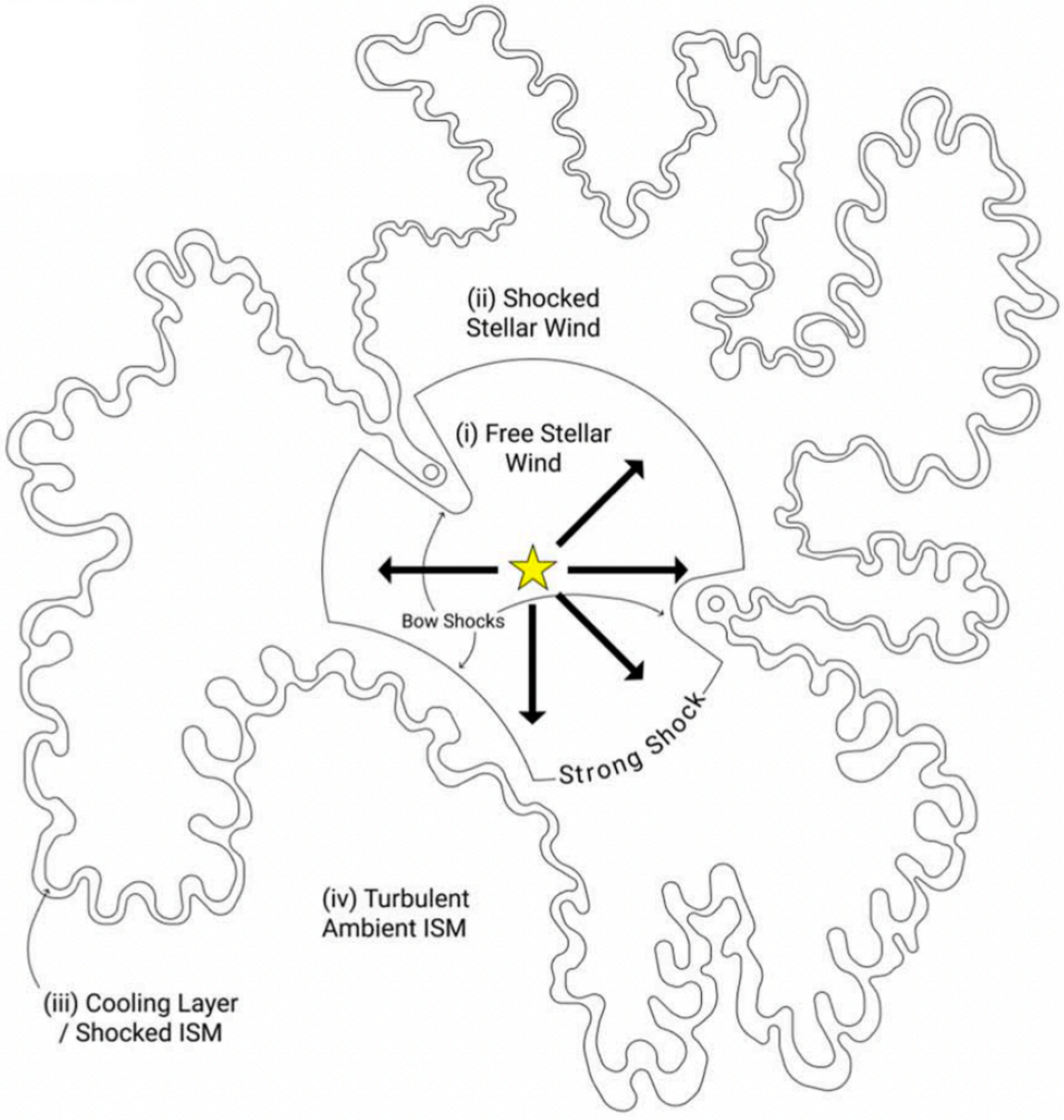
Stellar Winds

Winds inject high velocity material into the gas

Spherical* injection of high velocity gas, creating bubbles of hot gas
e.g., Rosen et al. 2014; Lancaster et al. 2021a,b,c, 2024

Inject turbulence into the gas; drive gas out of star-forming regions
e.g., Rosen et al. 2014; Geen et al. 2023

Winds deposit enriched material
e.g., Lancaster et al. 2021a



Lancaster et al. 2021c

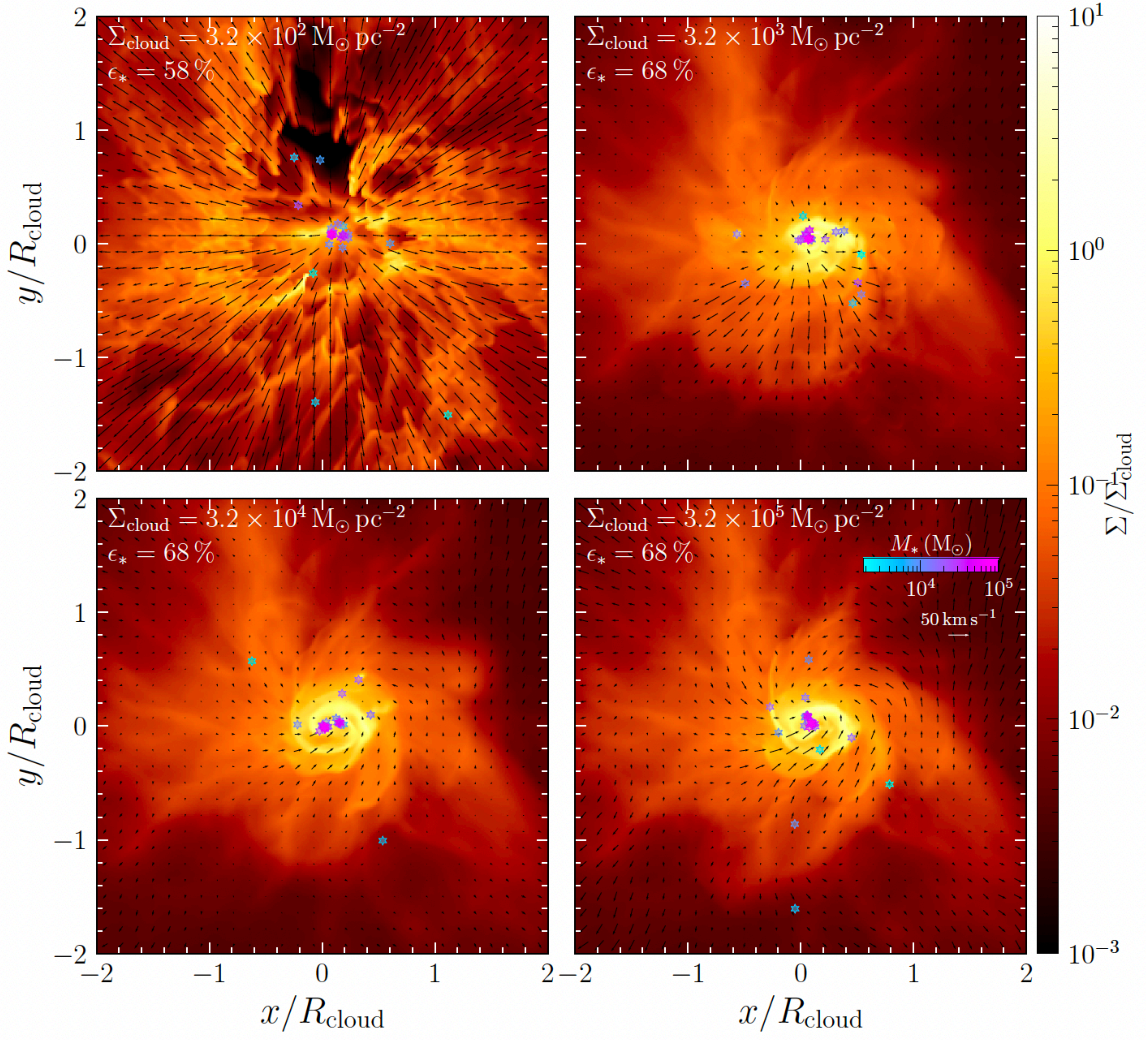
Radiative feedback

Photoionization heating (EUV), Photoelectric heating (FUV), & Radiation pressure

Ionizing radiation produces HII regions of expanding, ionized gas

This alters the gas morphology; drives turbulence in the ISM; and can drive outflows from clusters
e.g., Menon et al. 2021, 2023; Habart et al. 2024

Radiative feedback shapes the IMF and limits the SFE of dense cores
e.g., Guszejnov et al. 2016; Rosen & Krumholz 2020; Menon et al. 2024

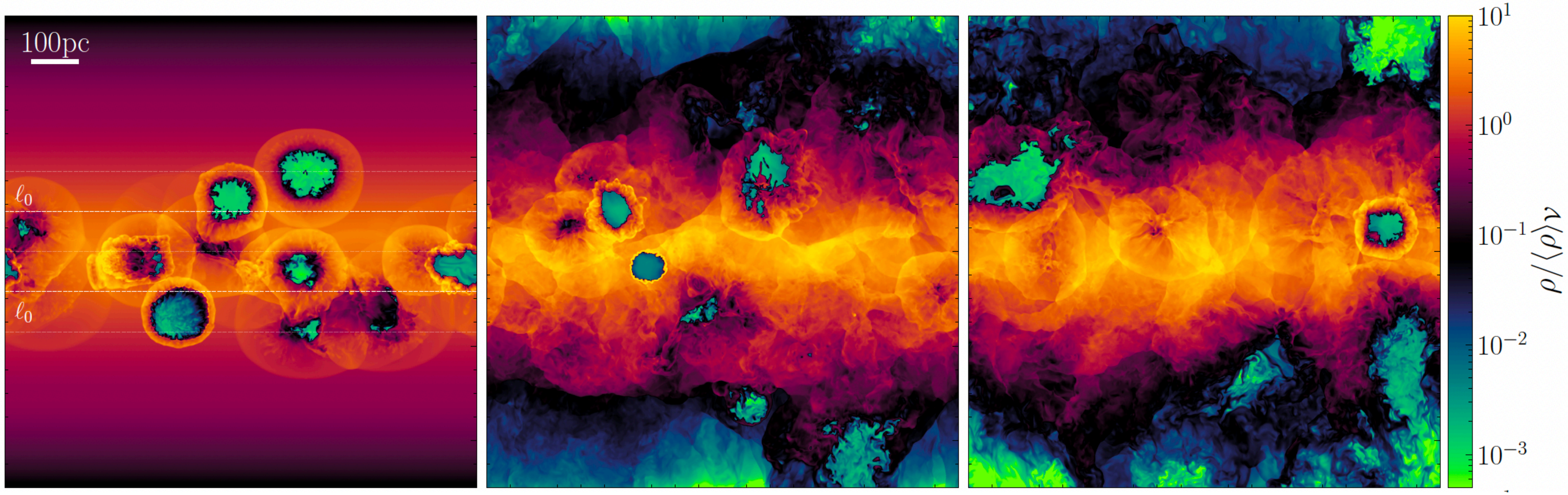


Menon et al. 2023

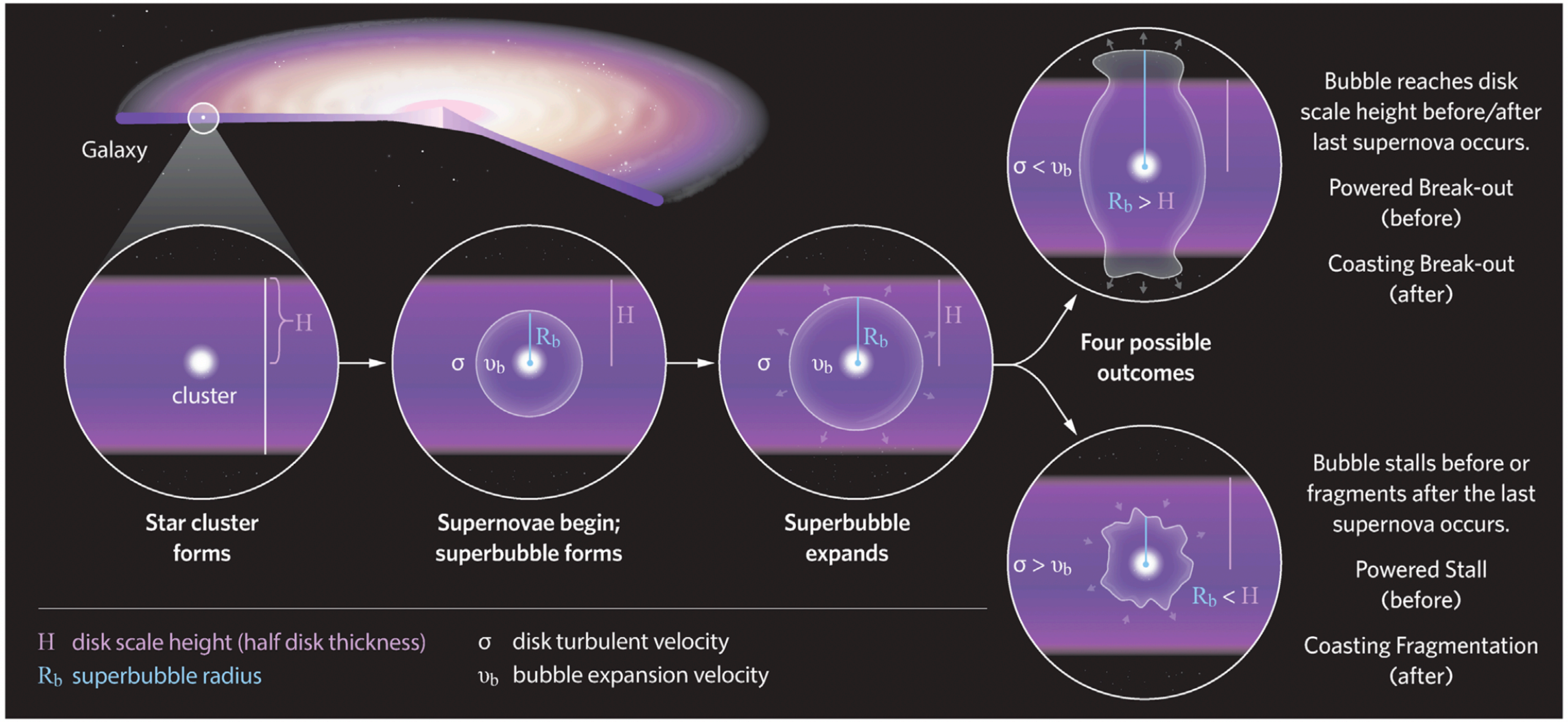
Supernovae

SNe occur late in star formation

SNe inject large amounts of energy and momentum at the largest scales



Beattie et al. 2025



Orr et al. 2022

Drives turbulence on the galactic scale
e.g., Beattie et al. 2025

Clustered SNe drive superbubbles which drive: galactic-scale turbulence, galactic morphology, and outflows into the local CGM
e.g., Mac Low & McCray 1988; Mac Low & Ferrara 1999; Orr et al. 2022

Other feedback: interacting binaries, post main sequence stars

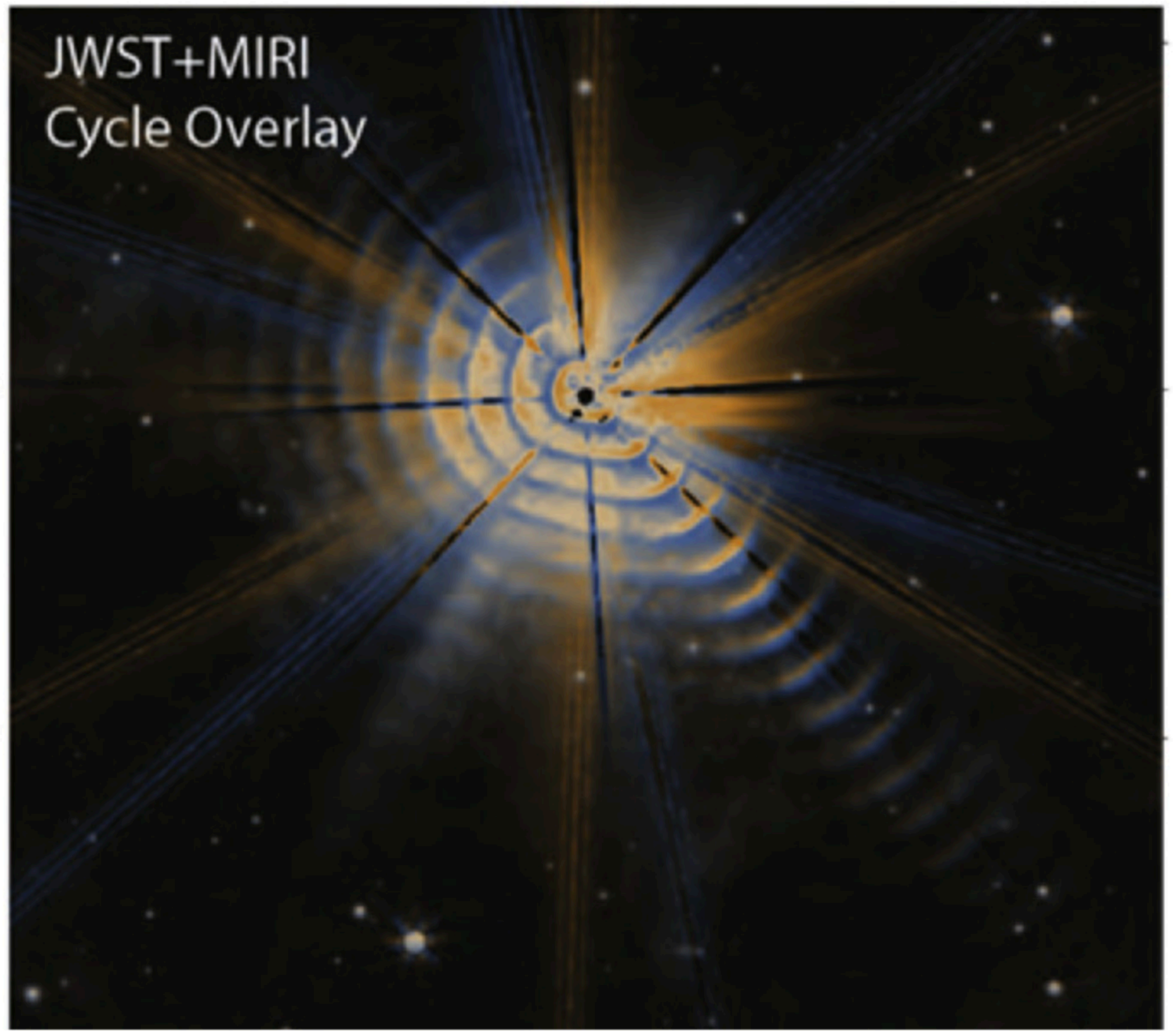
Stellar evolution is complicated!
This will contribute to stellar feedback

Most stars are in multiple systems:
Binary interactions enhances winds and radiation
e.g., Cournoyer-Cloutier et al. 2021; 2024 (incl. SMA); submitted (incl. SMA)

Movie from Claude Cournoyer-Cloutier

Post main sequence evolutionary stages can introduce new ejecta modes and strengths
e.g., Crowther 2007; Ventura et al. 2020; Fitchner et al. 2022

Example: WR binary stars



Lieb et al. 2025

Look out for a paper on arXiv in ~month:
Cournoyer-Cloutier et al. (incl. SMA) 2025 (submitted)

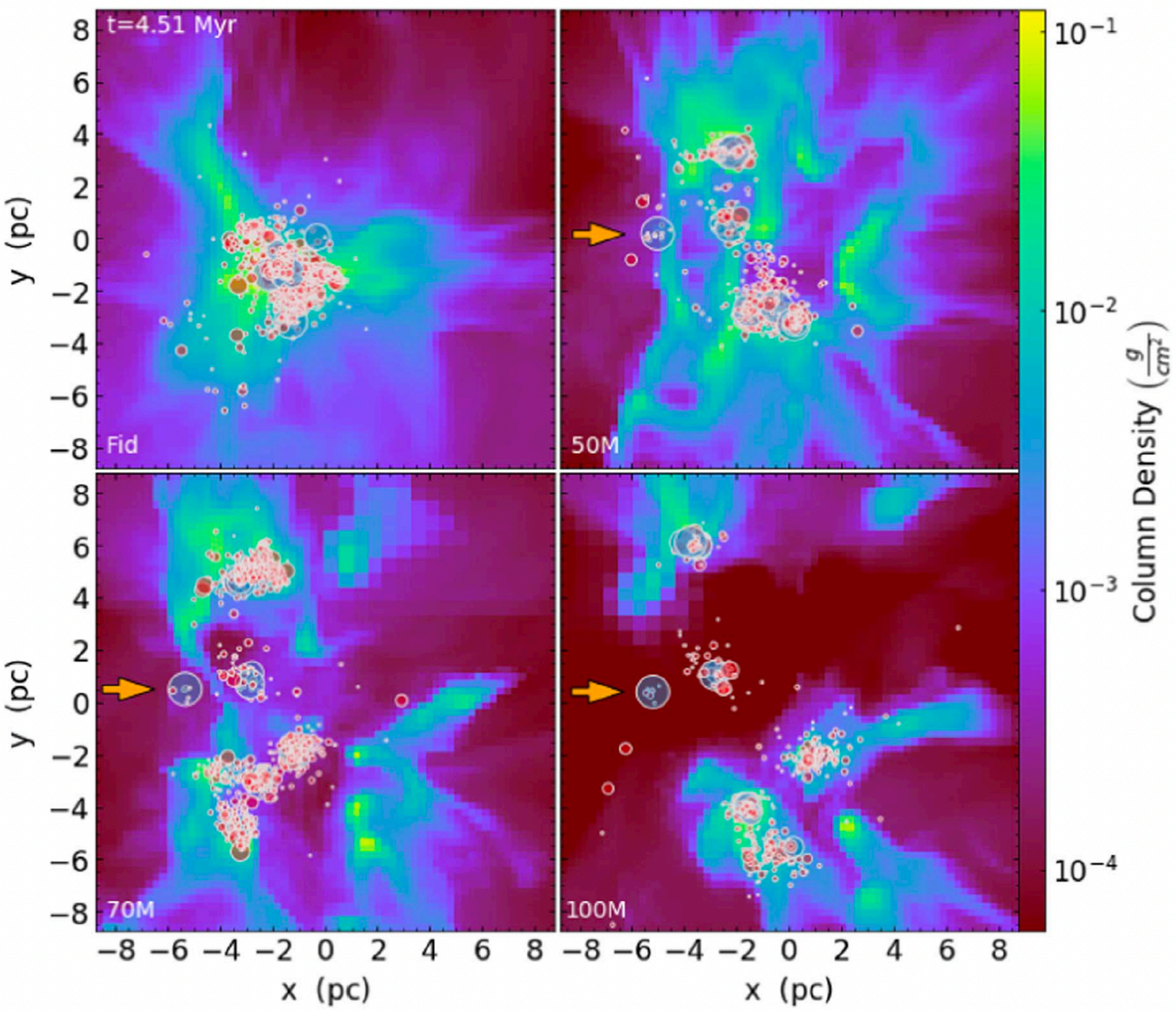
Other considerations: timing and interactions between modes

Early forming massive stars can halt star formation, alter cluster properties
e.g., Lewis et al. 2023

Interactions between feedback modes can alter the impact

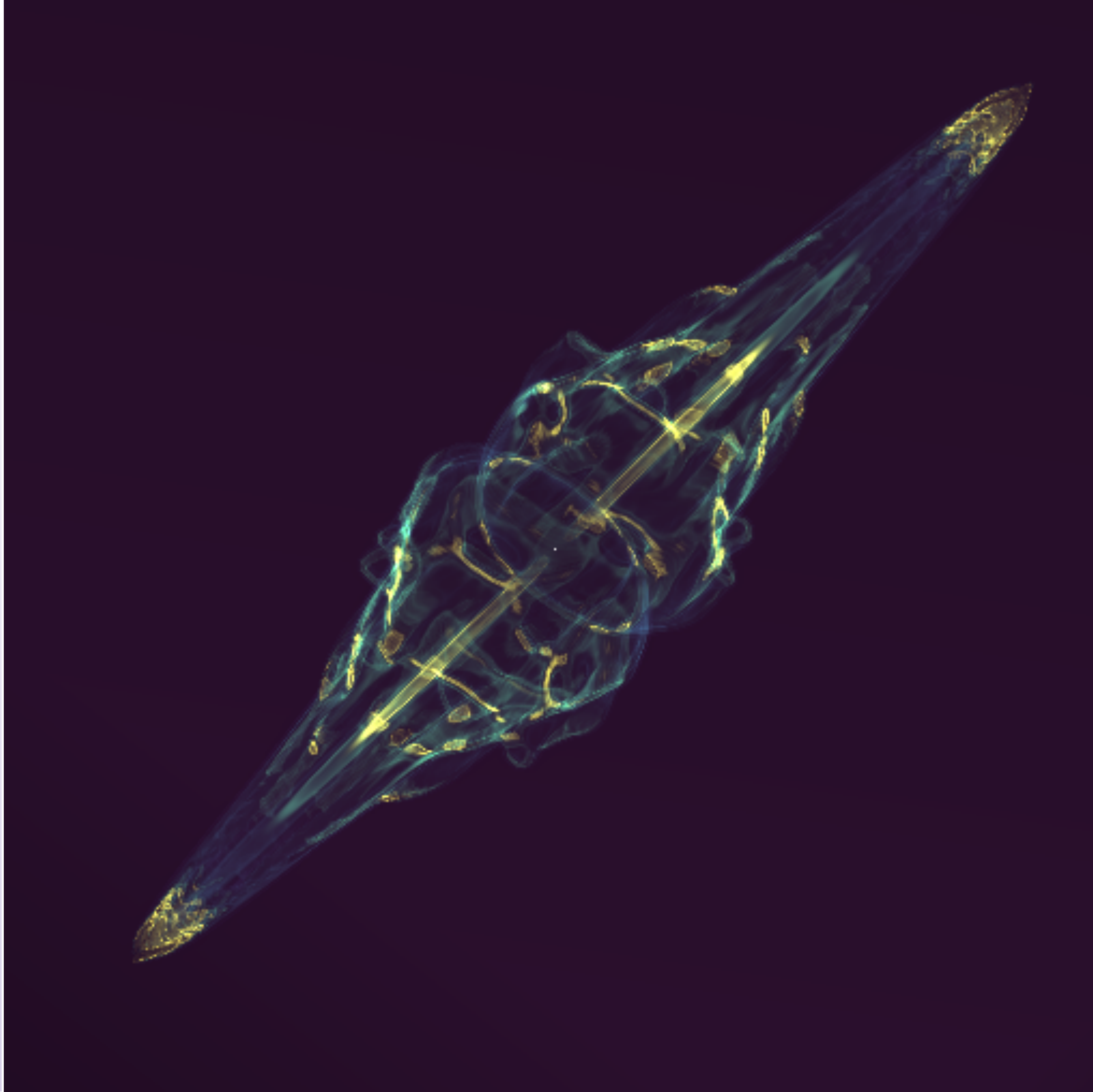
Jets can allow radiation to escape more efficiently
e.g., Rosen & Krumholz 2020

Pre-SN feedback alters the role of SNe!
e.g., yesterday's talks!



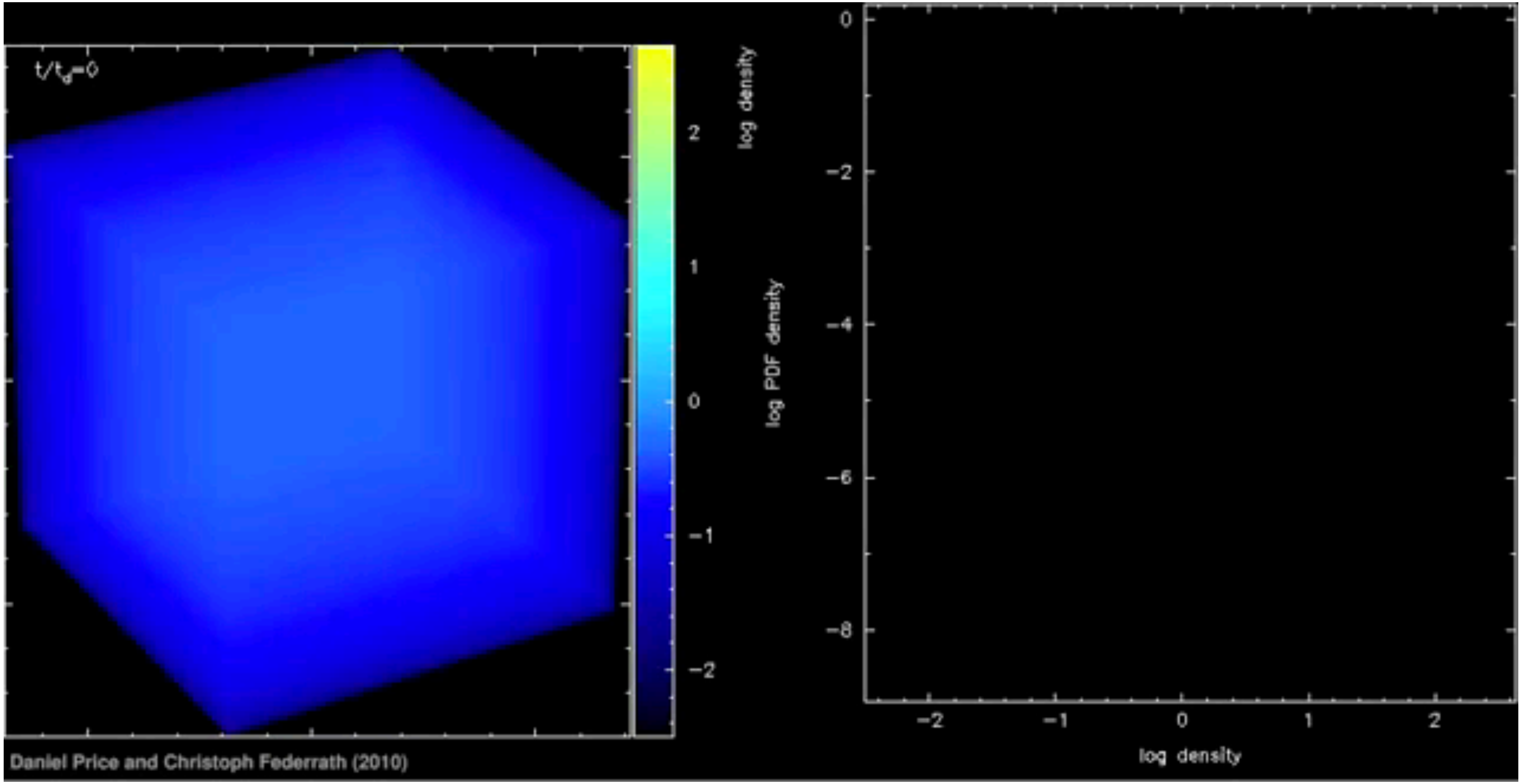
Lewis et al. 2023

Stellar Feedback and Star-forming gas



Appel et al. in prep.

The statistics of supersonic turbulence predict a lognormal density PDF



Price & Federrath 2010

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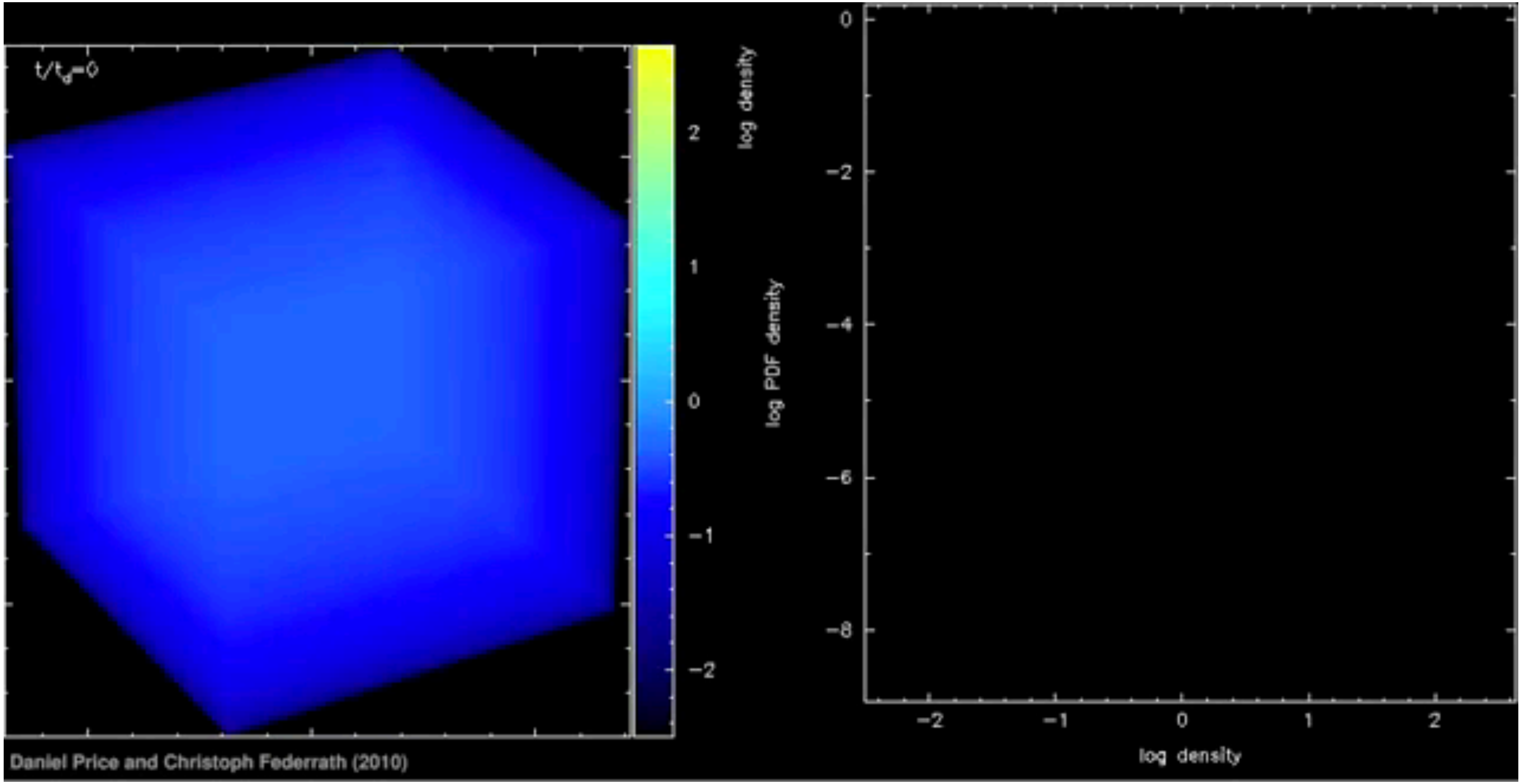

Price & Federrath 2010

Width given by: $\sigma_s^2 = \ln\left[1 + b^2 \mathcal{M}_s^2\right]$

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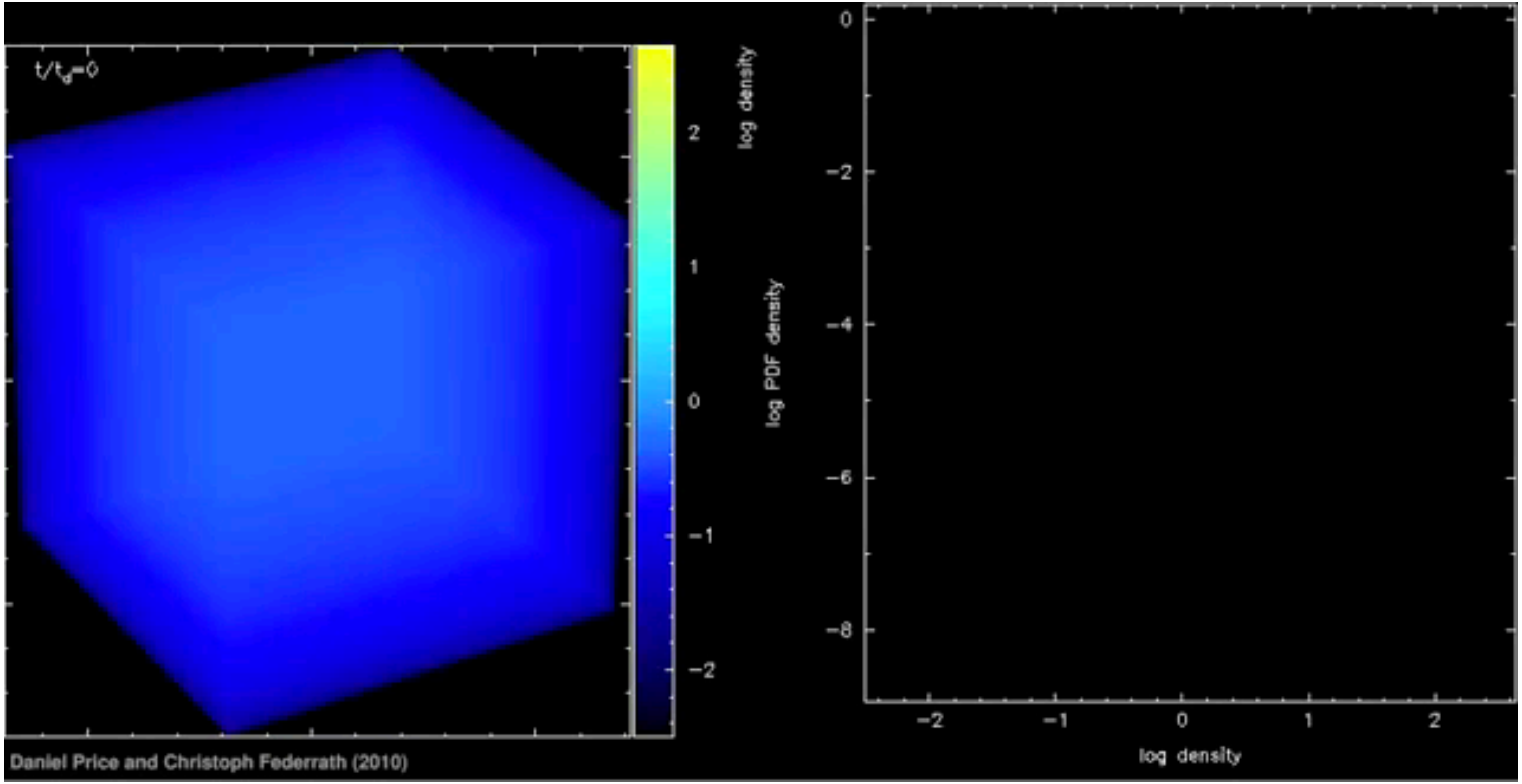


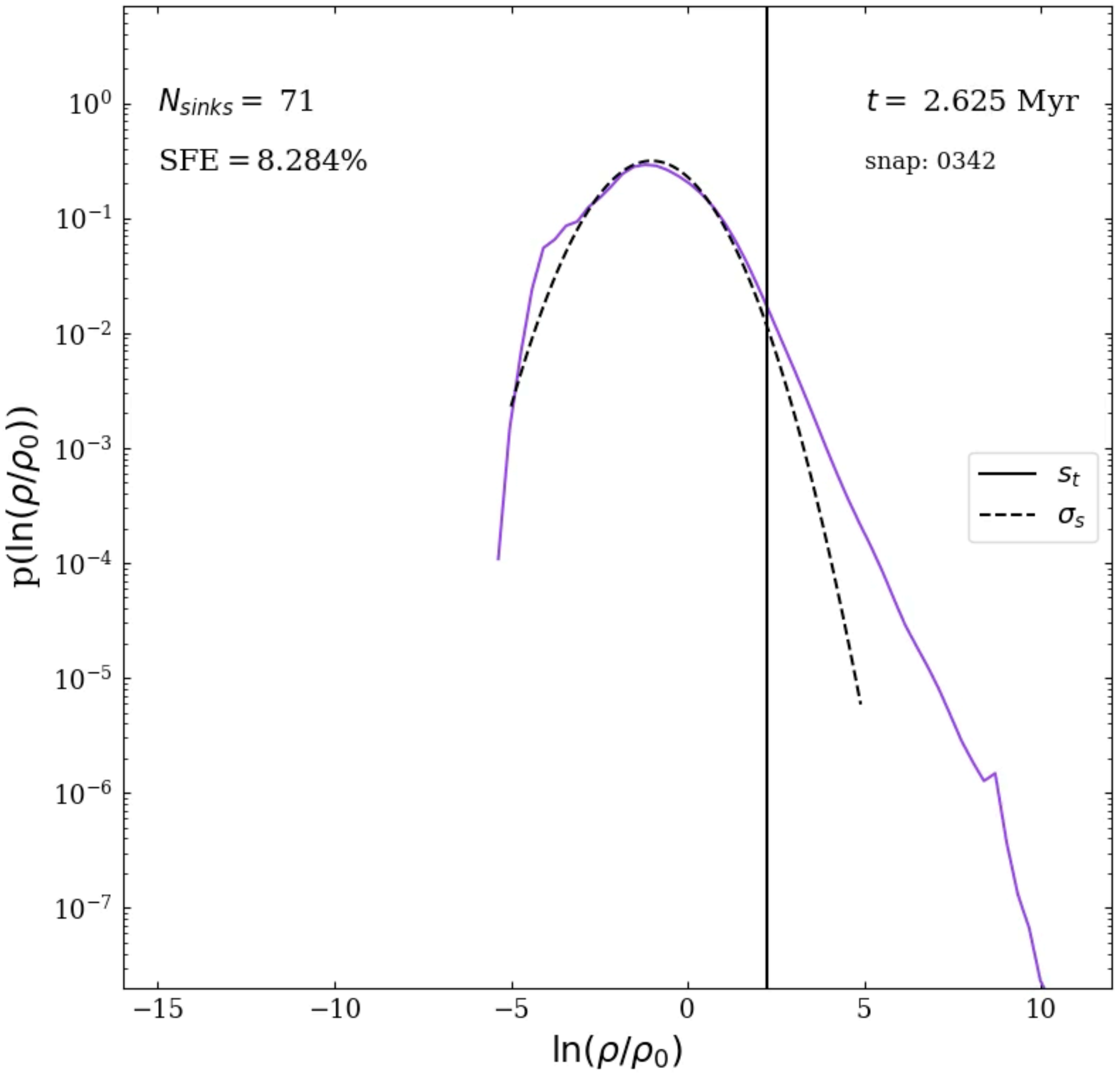
Price & Federrath 2010

Gravity produces a power-law distribution!

The piecewise density PDF

Turbulence produces a lognormal distribution

$$\sigma_s^2 = \ln\left[1 + b^2\mathcal{M}_s^2\right]$$



The piecewise density PDF

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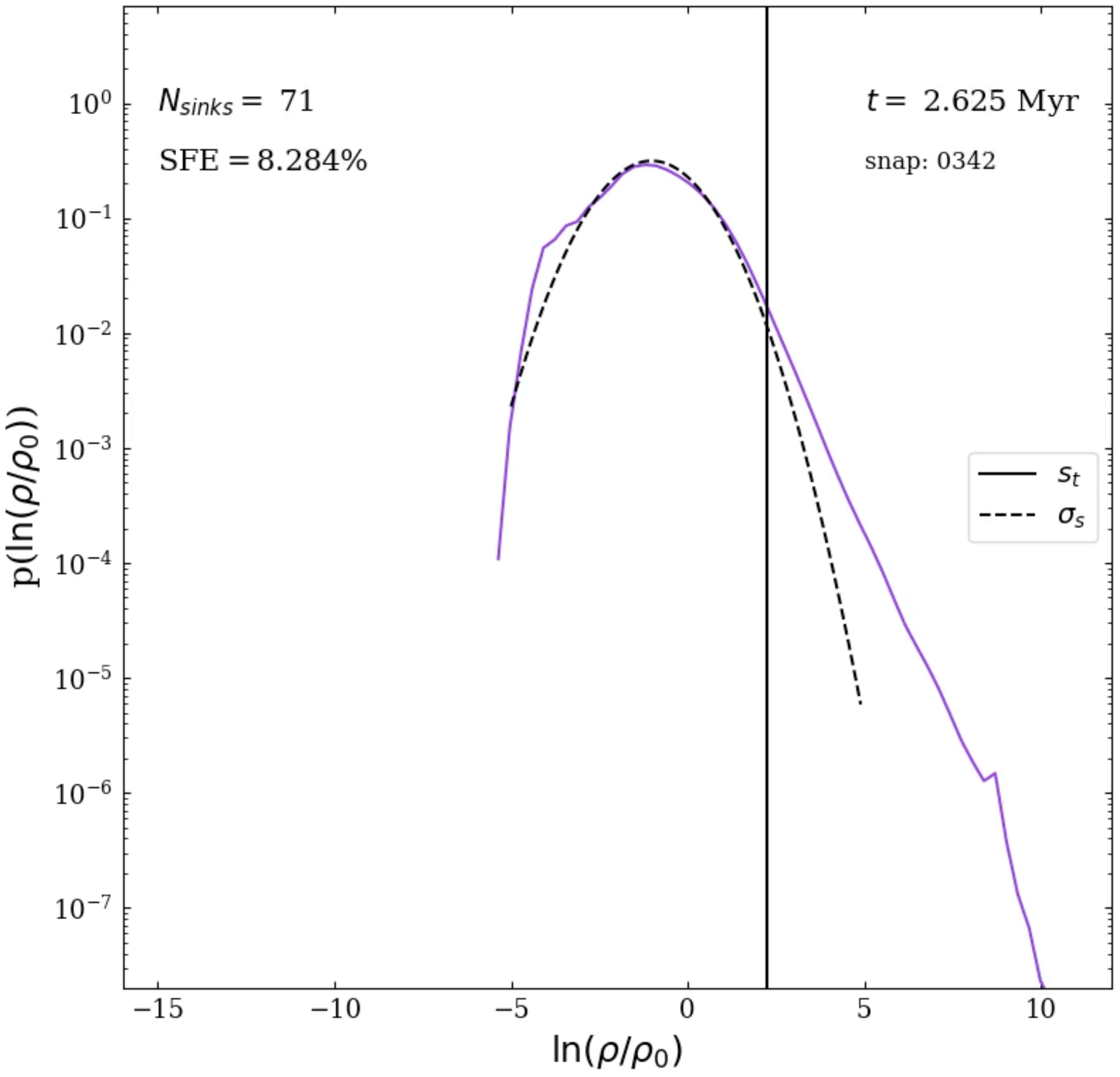
Gravity produces a power-law distribution

$$p(s) \propto \alpha\, s$$



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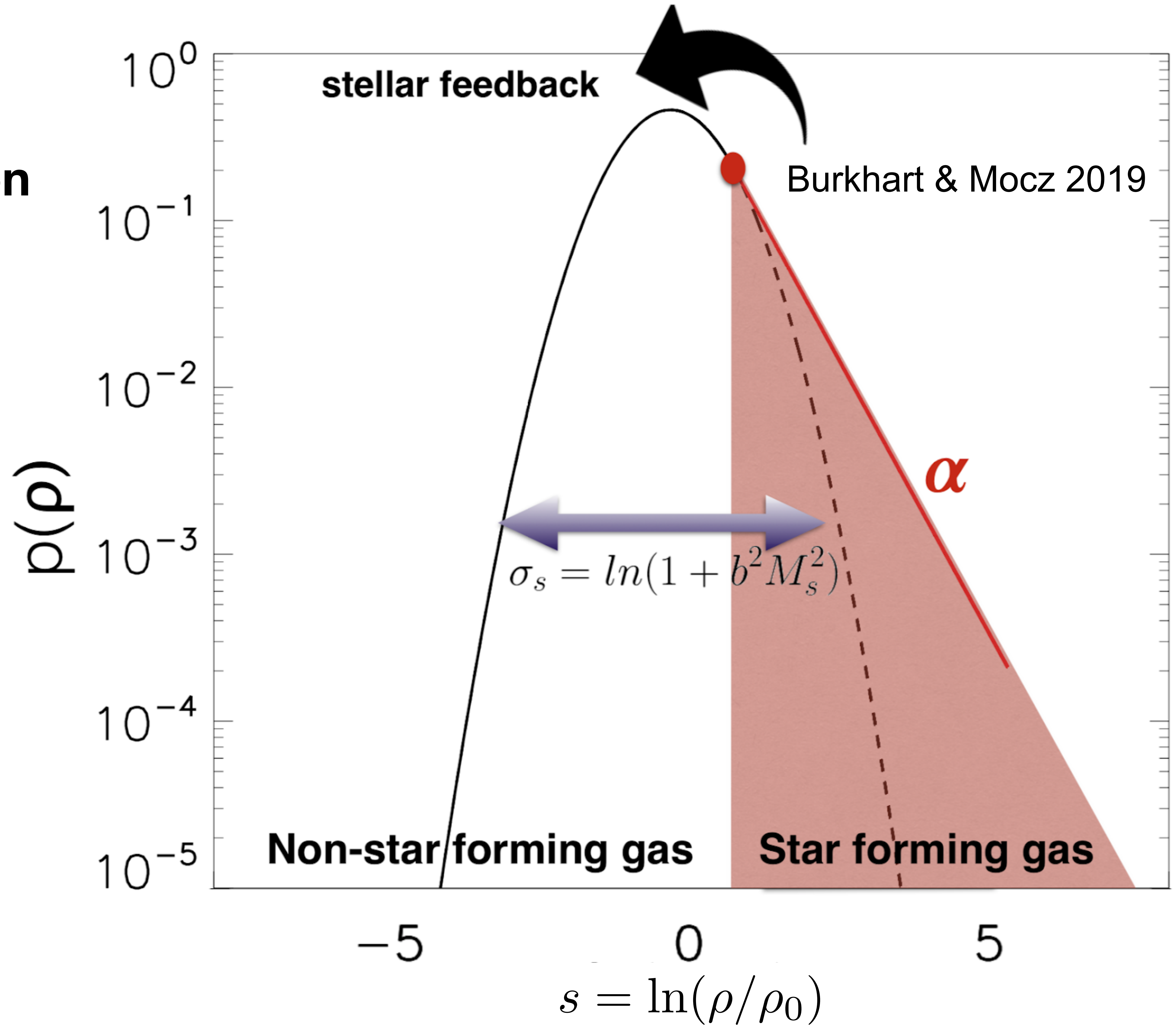

See also Burkhart 2018

The piecewise density PDF

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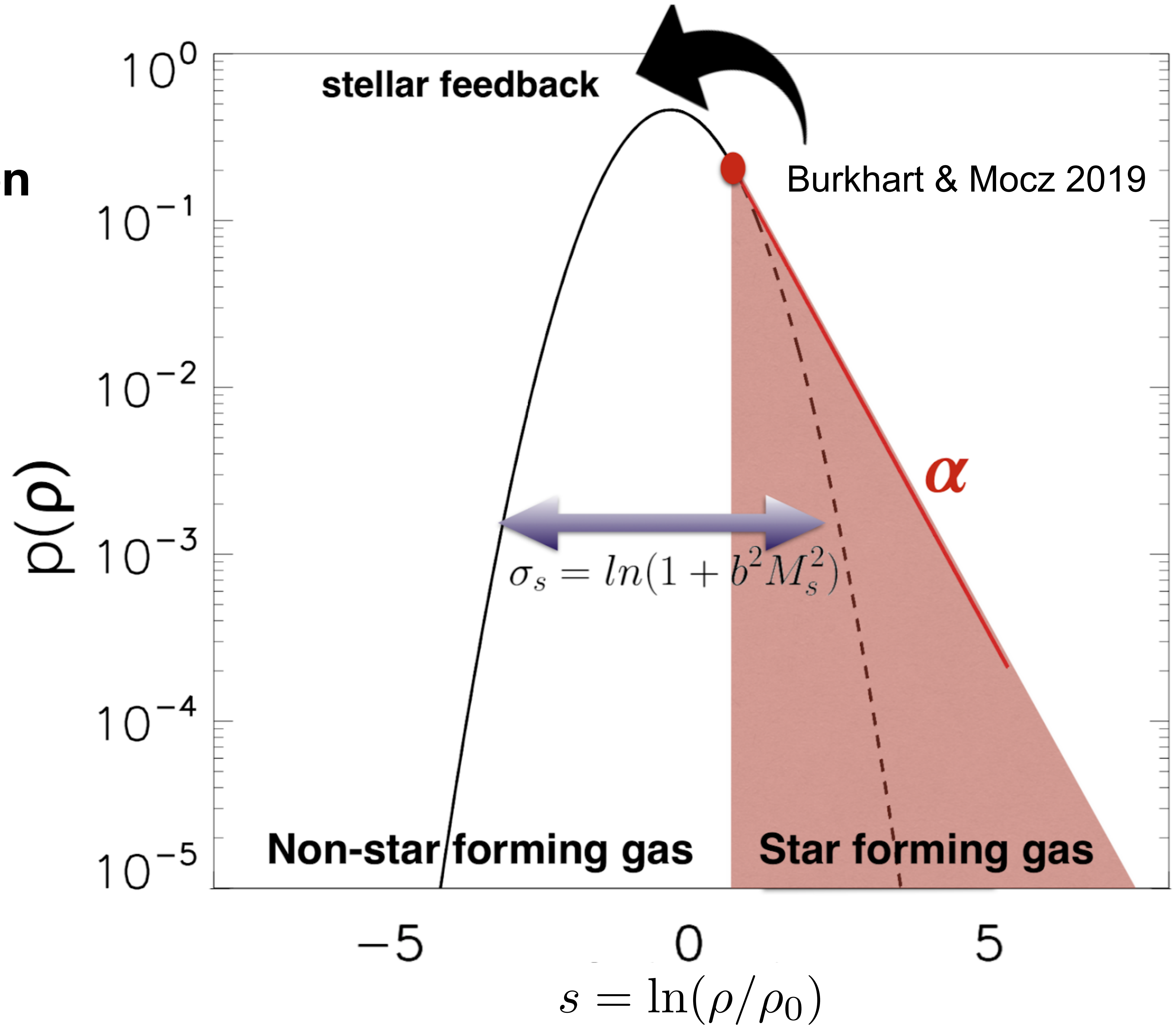
Theoretical Transition Density:

$$s_t = (\alpha - 1/2)\,\sigma_s^2$$



See also Burkhart 2018

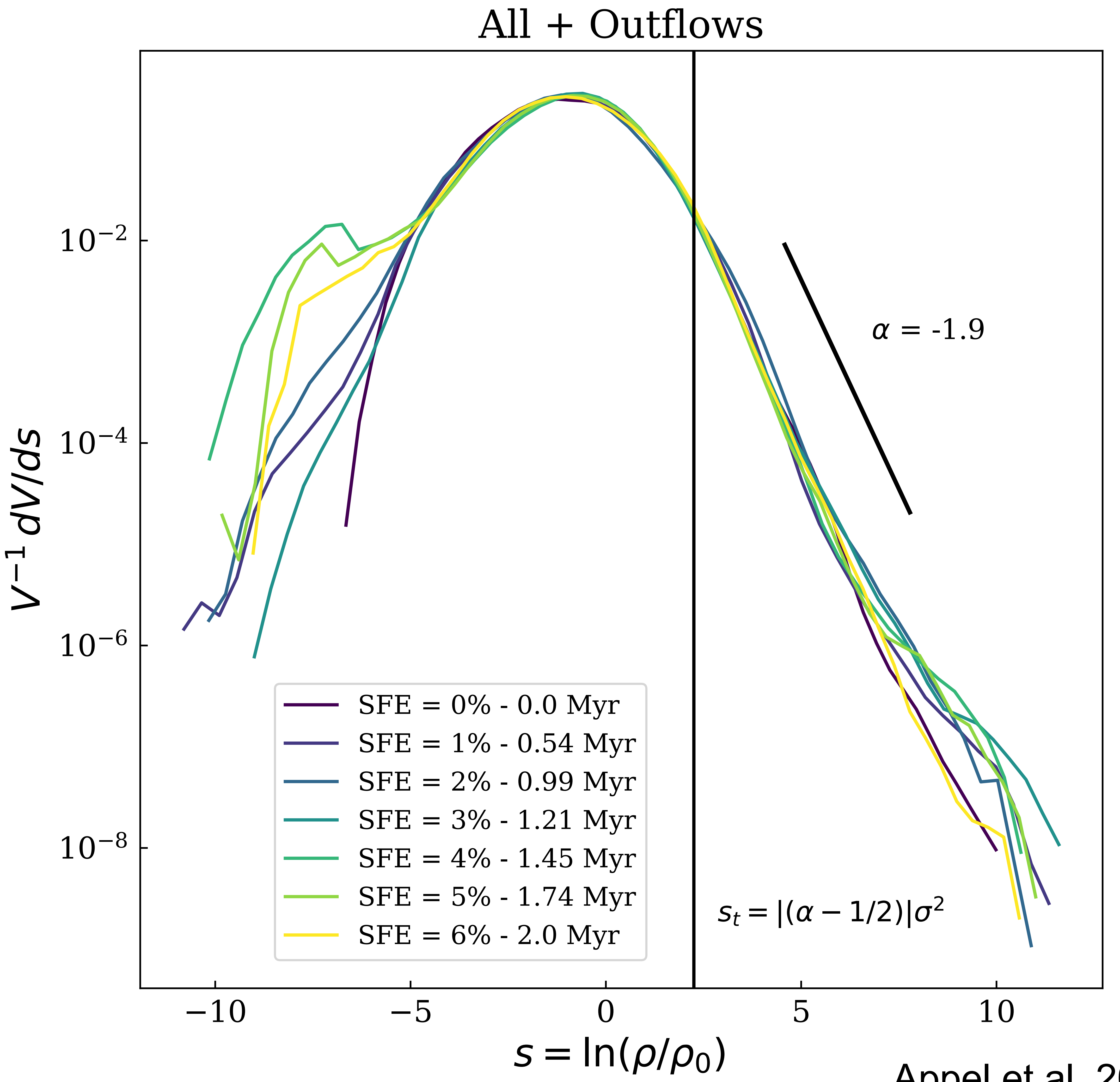
Analytic models of star formation: the density PDF and feedback

Stellar feedback alters the shape of the density PDF

Clear lognormal peak

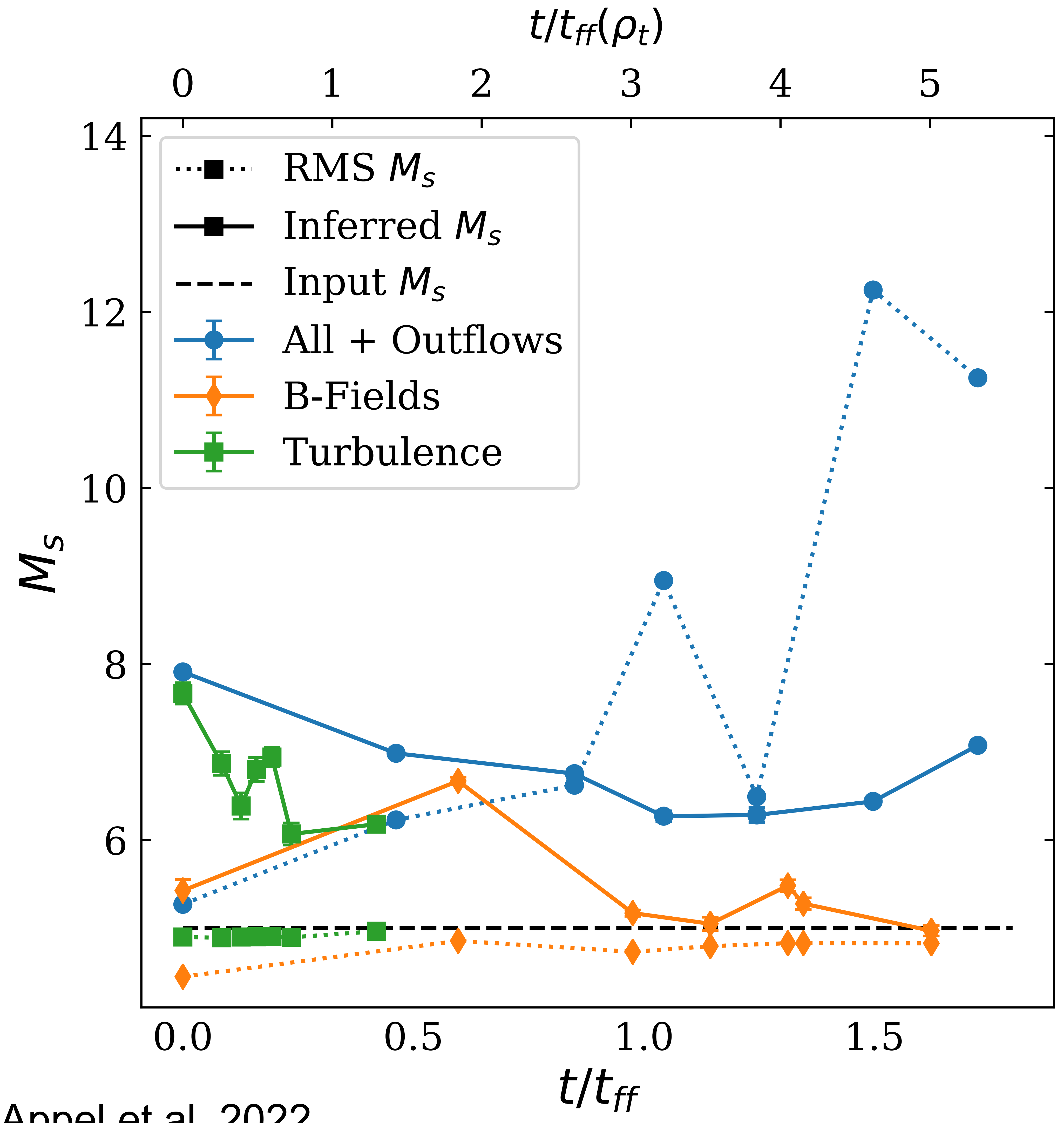
Power law tail due to self-gravity

Non-lognormal, time-varying features

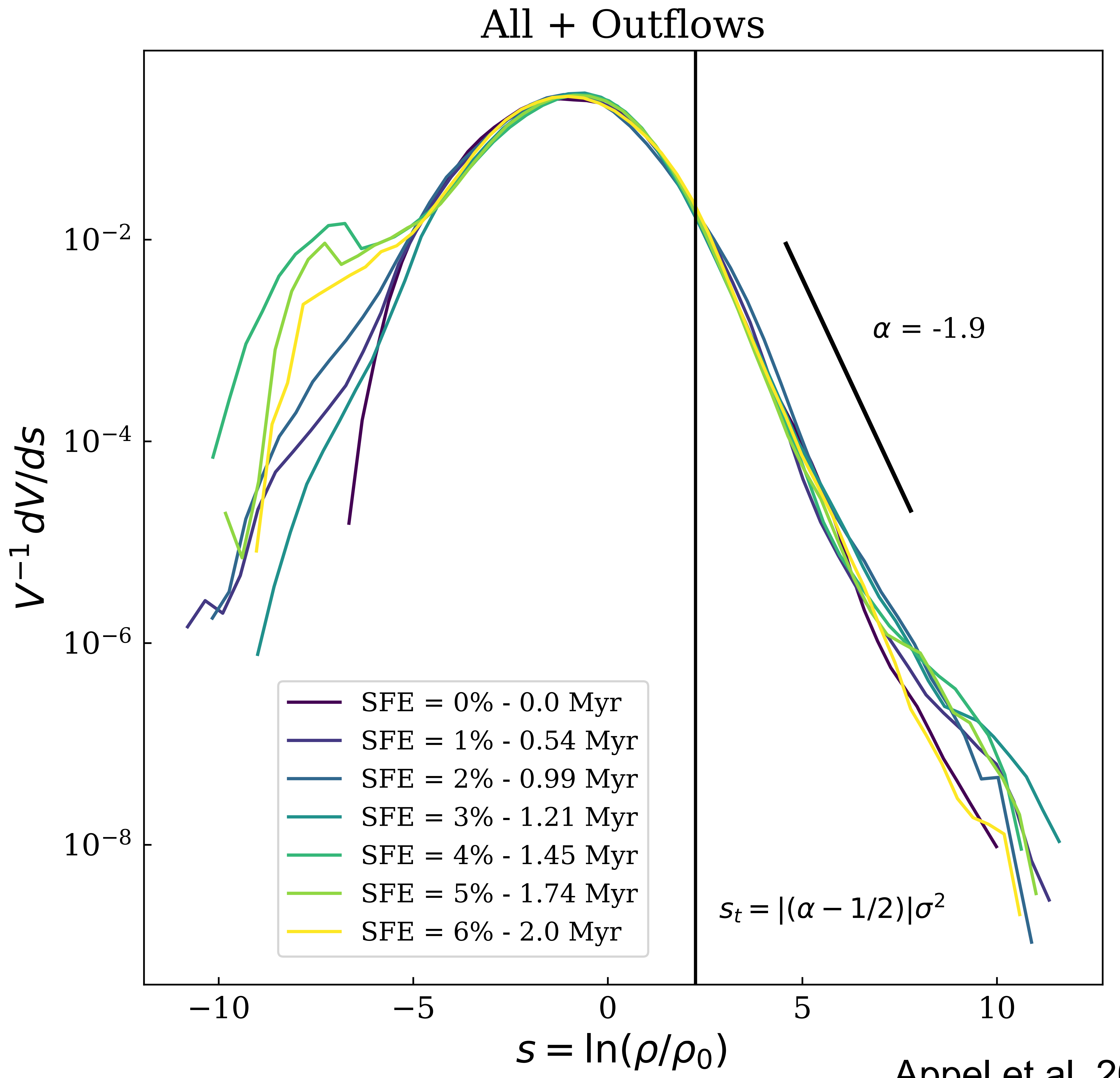


Appel et al. 2022

Analytic models of star formation: the Mach number



Appel et al. 2022



Appel et al. 2022

Stellar feedback increases the sonic Mach number

Torch (AMUSE + FLASH) is optimized to simulate star cluster formation and evolution

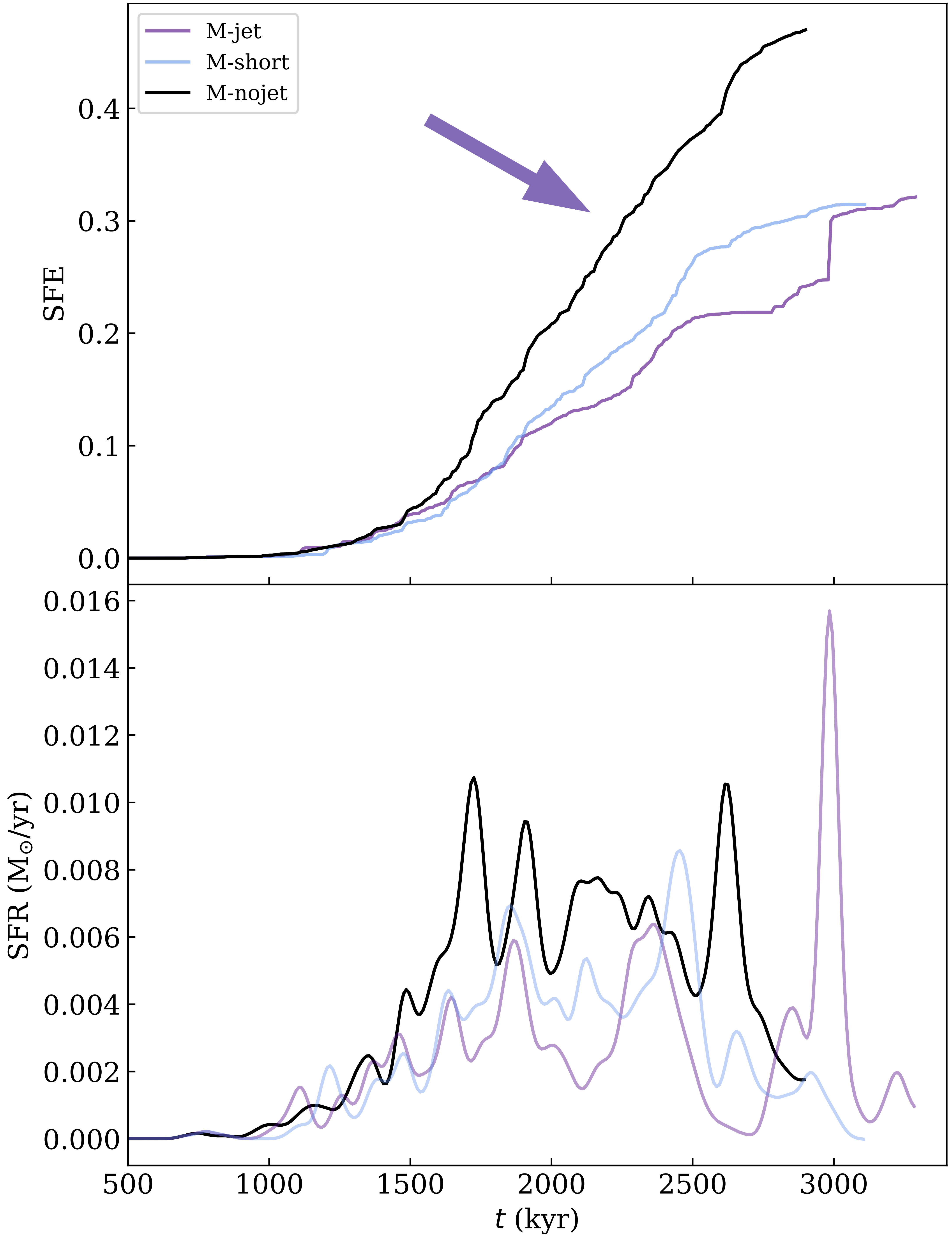
Larger clouds (2e4 Msun)

Appel et al. in prep.

Appel

Jets slow star formation

The inclusion of jets significantly slows star formation



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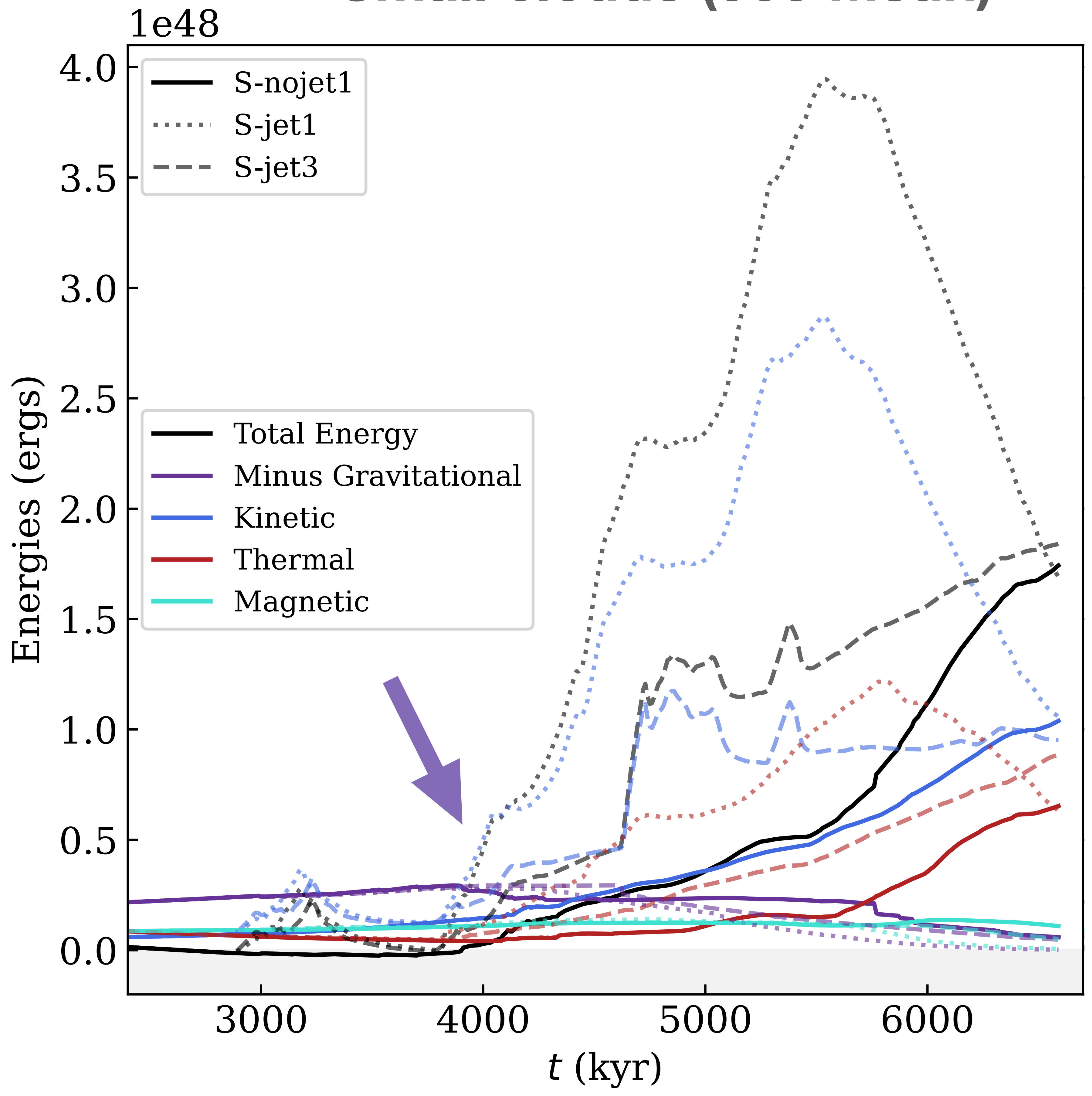
Analytic models of star formation: the gas energetics

Stellar feedback increases the energy of the gas (esp. the kinetic energy)

Small clouds (5e3 Msun)



Jets increase the energy right away

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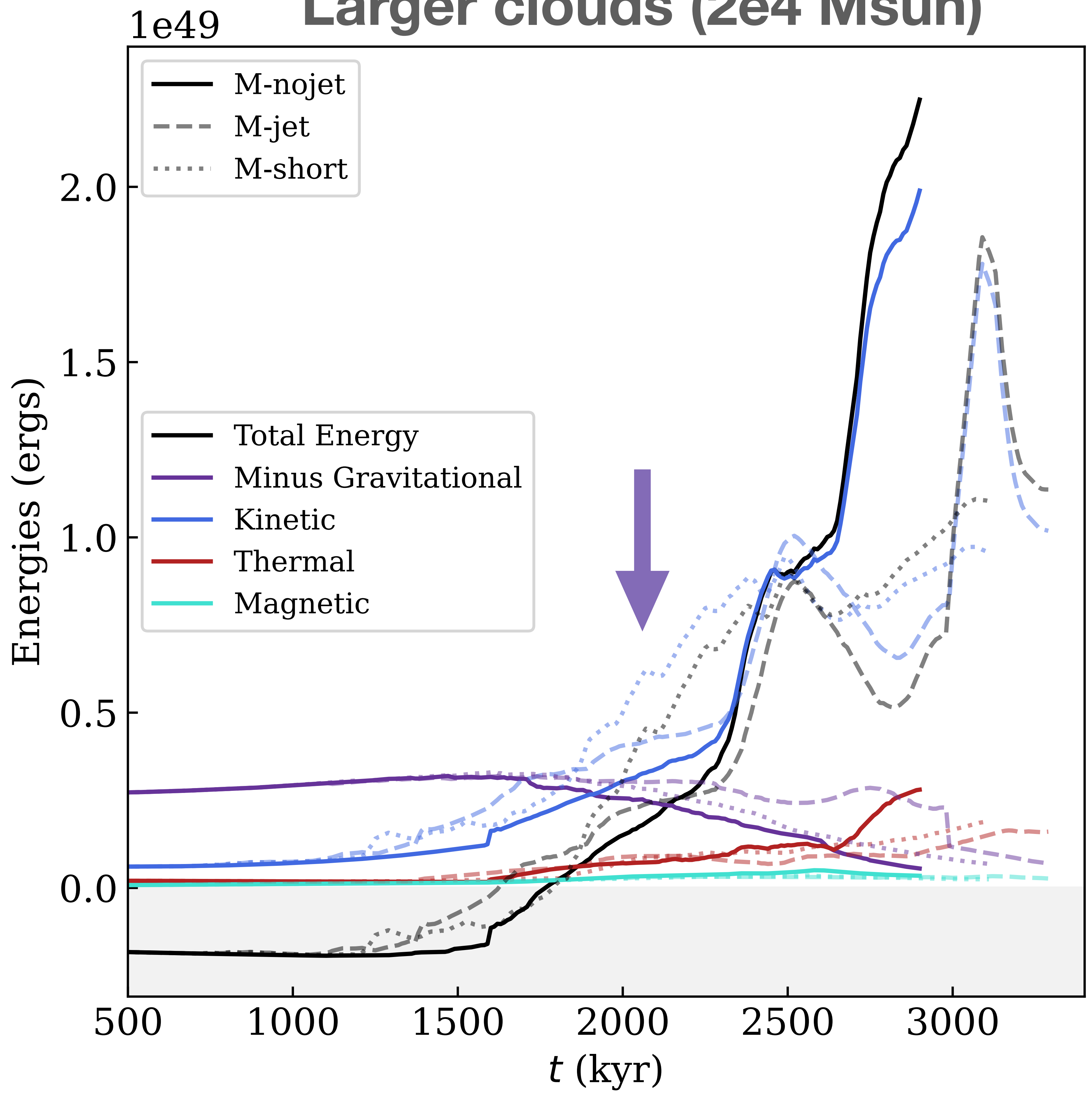

Solid lines —> without jets
Dash/dotted lines —> with jets

Appel et al. in prep.

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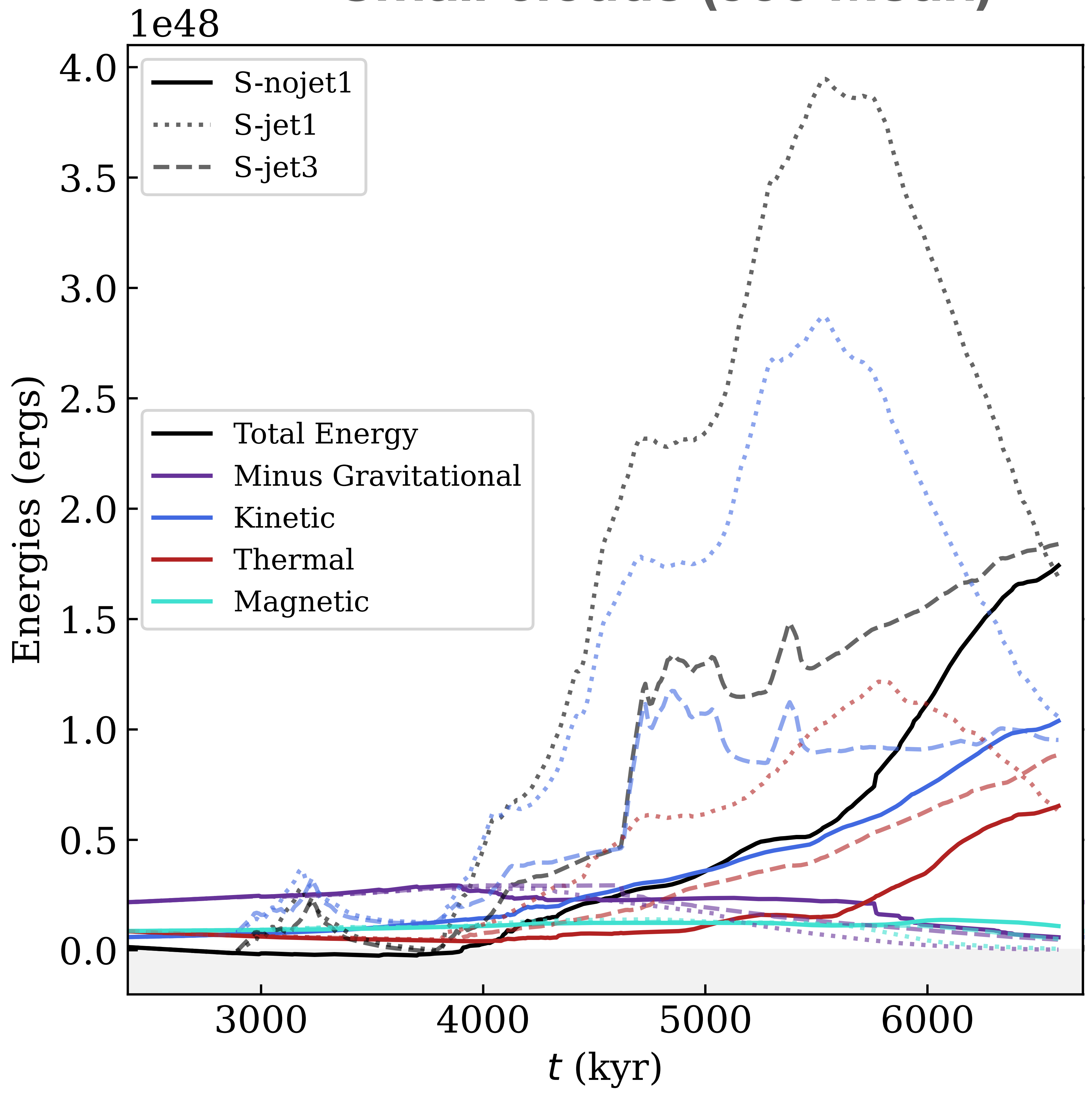
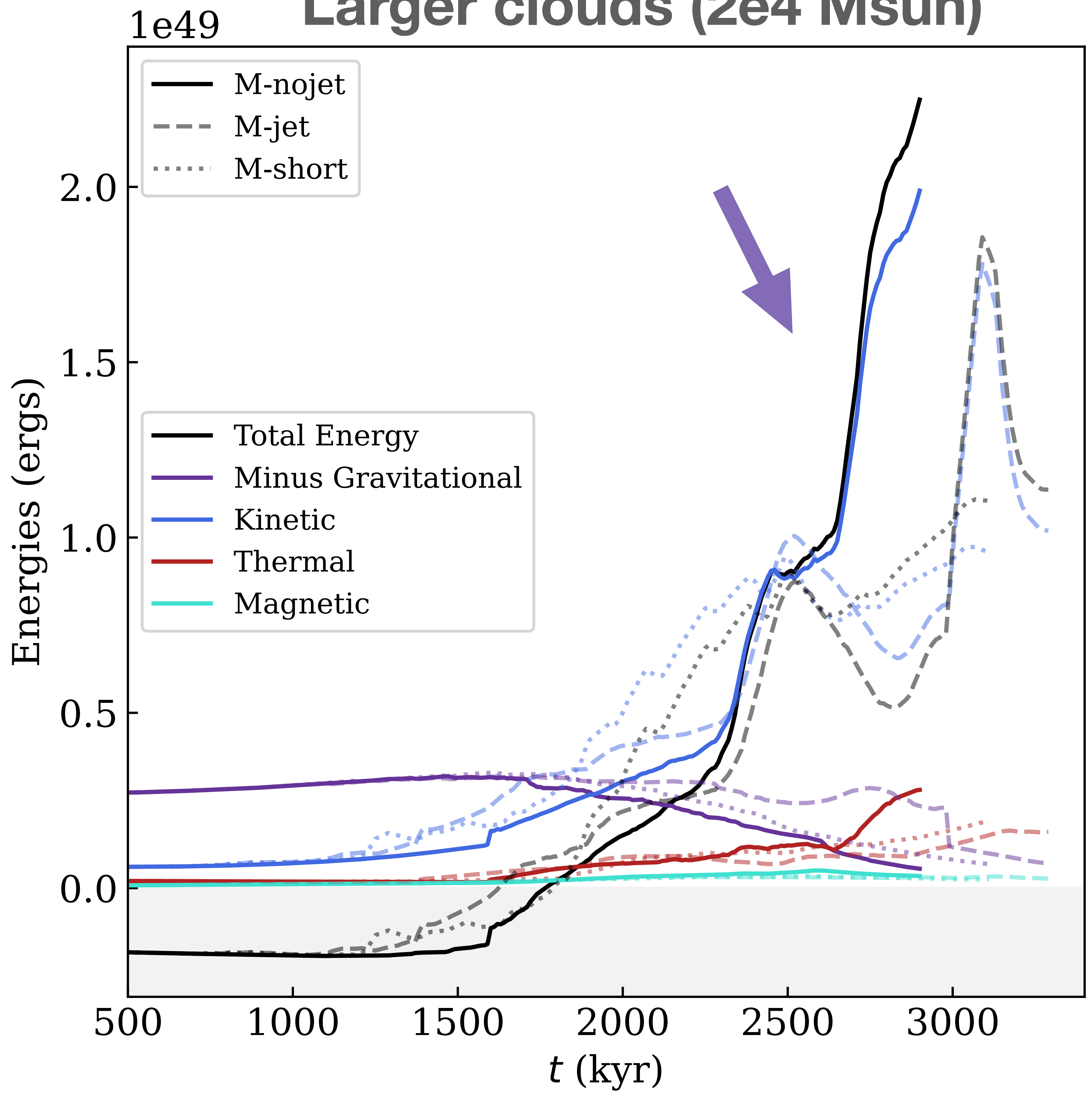


Jets increase the energy right away

Other modes of feedback act at slightly later times

Solid lines —> without jets
Dash/dotted lines —> with jets

Larger clouds (2e4 Msun)



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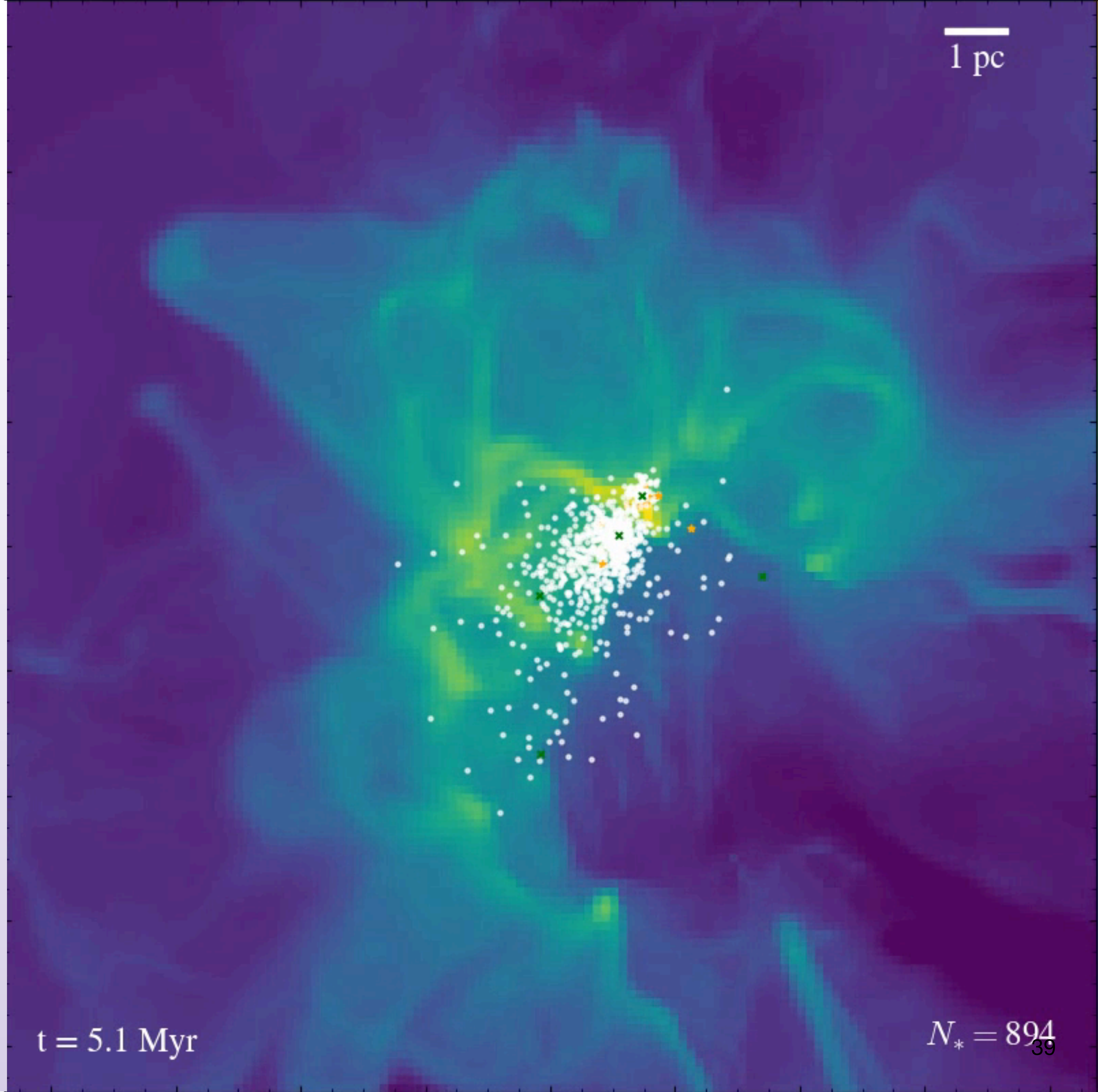
Summary

✦ Star formation is a cycle — stellar feedback influences the gas and the gas influences star formation

✦ There are many modes of feedback, each of which act at different scales and interact with each other

✦ Protostellar jet feedback:

- Alters the gas distribution (density PDF)
- Increases the sonic Mach number
- Decreases the SFE
- Increases the total energy of the gas at early times



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