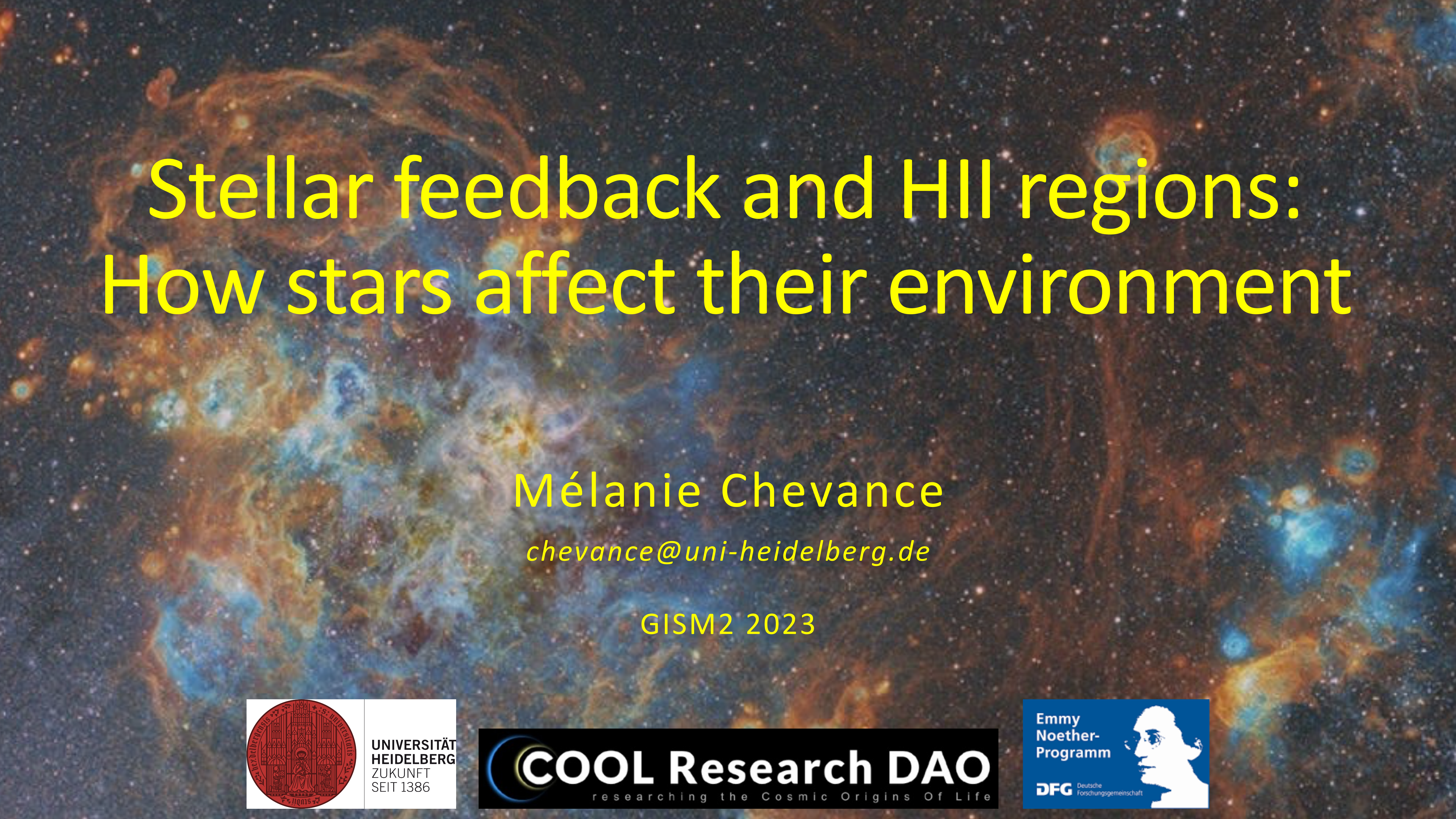

Stellar feedback and HII regions: How stars affect their environment

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GISM2 2023

UNIVERSITÄT HEIDELBERG
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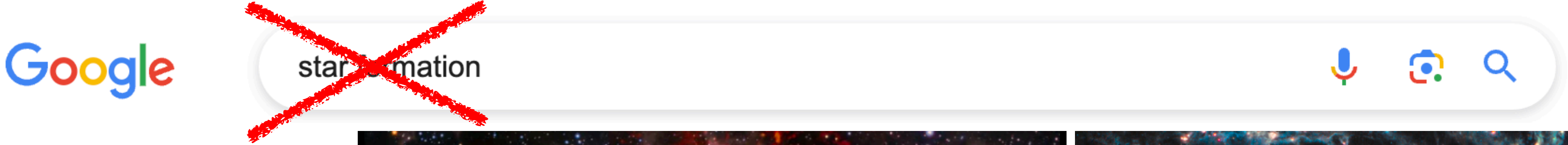
COOL Research DAO
researching the Cosmic Origins Of Life

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Outline

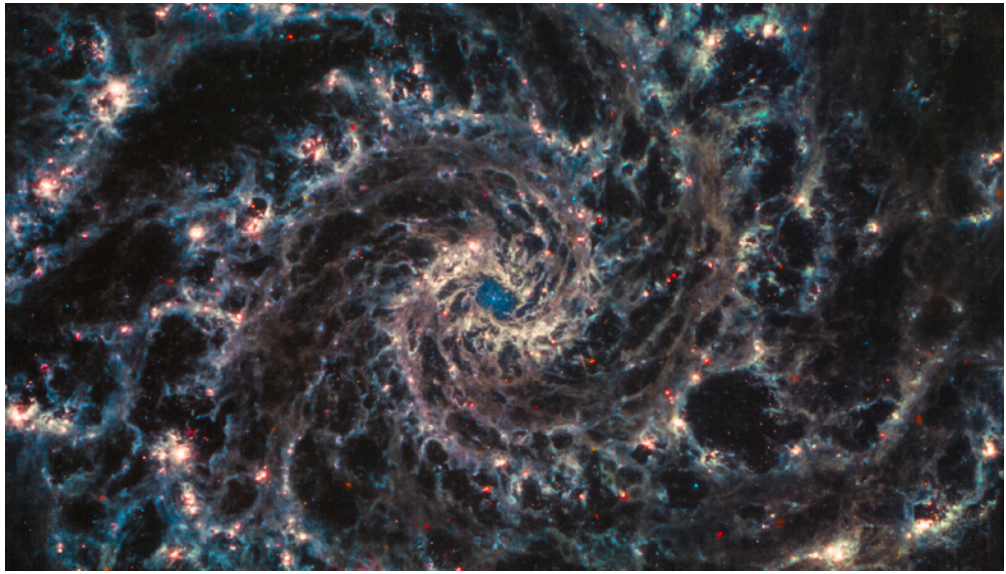
I. The importance of feedback
II. Stellar feedback mechanisms
III. Impact of feedback on GMC scales
IV. Impact of feedback on galactic scales
V. Conclusions/questions

I. The importance of feedback

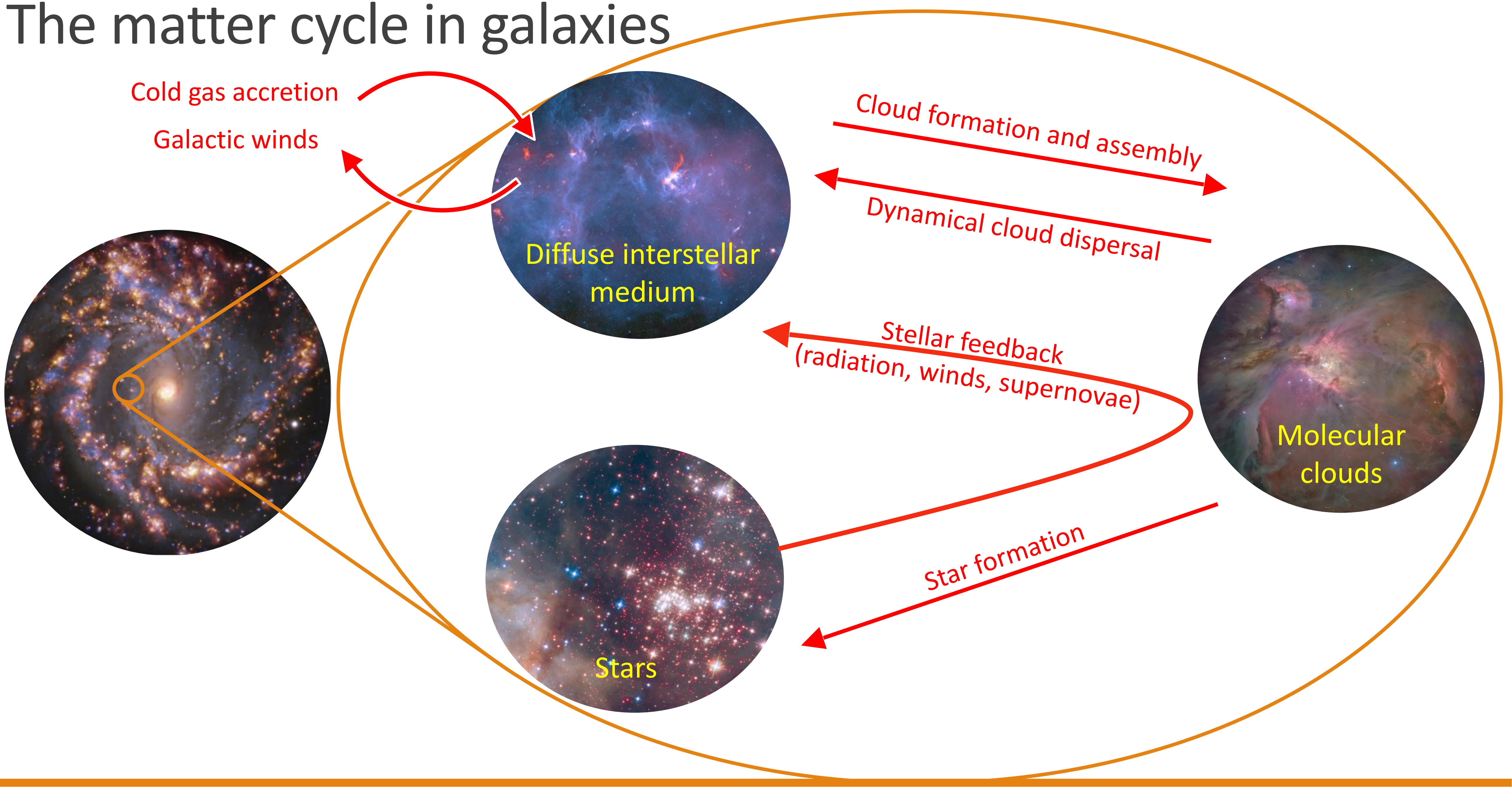


~~star formation~~

Feedback!



The matter cycle in galaxies



Cold gas accretion

Galactic winds

Diffuse interstellar medium

Cloud formation and assembly

Dynamical cloud dispersal

Molecular clouds

Stellar feedback (radiation, winds, supernovae)

Star formation

Stars

The importance of feedback

★ Turbulence dissipates ***quickly*** —> gas heating

★ Cooling time of the ISM is ***short***
Without feedback: diffuse ISM —> collapse into dense clouds —> collapse into stars

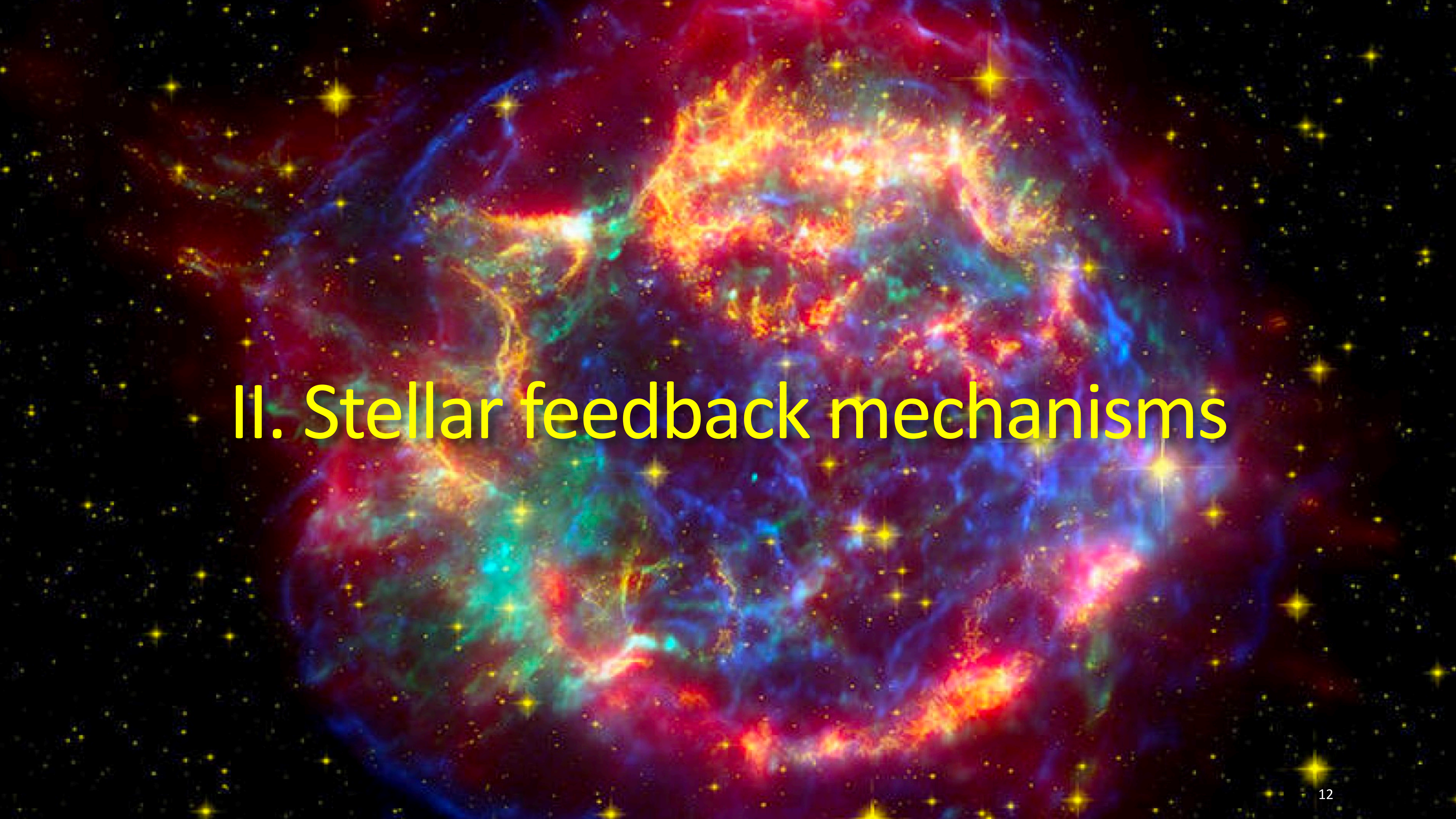
★ ***Feedback*** is the reason we are not sitting in a black hole!
With feedback: young stars inject energy and momentum in the gas —> limit/revert collapse —> ***"Self-regulation"***

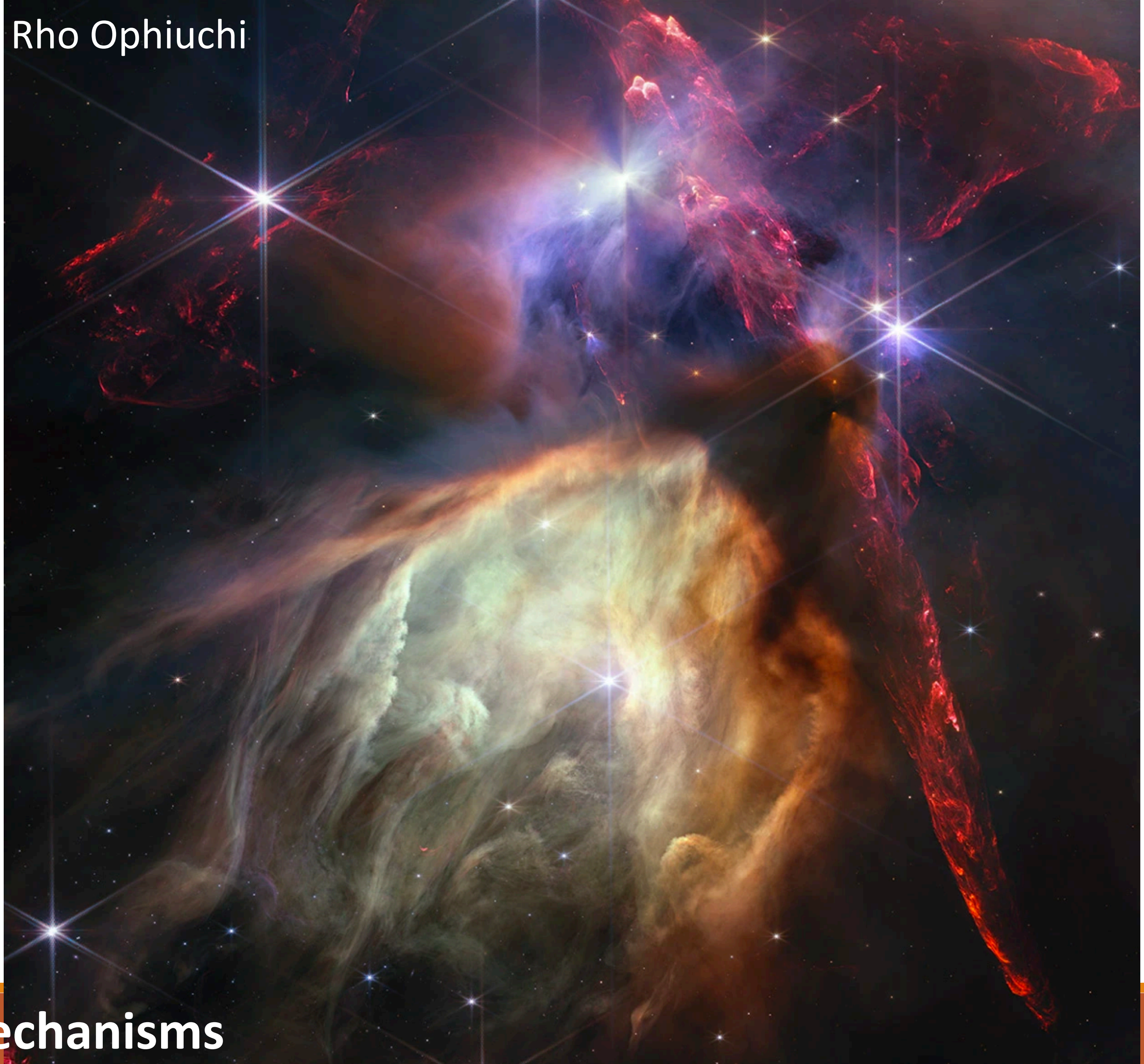
The importance of feedback

Some notes:

- ★ Turbulence creates ***structure*** in the ISM —> stars are born in a ***clustered environment***
- ★ ***Massive stars*** are important feedback sources and ***live the shortest*** —> ***fast regulation***
- ★ The effects of feedback are ***correlated in space and time***

II. Stellar feedback mechanisms





JWST/NIRCam
F187N
F200W
F335W
F444W
F470N

Stellar feedback mechanisms

- ★ ***Outflows*** disperse the natal cores of individual stars
- ★ ***Non-ionizing FUV/optical radiation*** heats the gas through the photoelectric effect
- ★ ***Ionizing EUV radiation*** photoevaporates dense material, producing high-pressure ionized gas
- ★ ***Stellar winds*** create very hot, high-pressure bubbles
- ★ ***Radiation pressure*** from (direct or indirect) momentum transfer of photons to the gas
- ★ ***Supernovae***
- ★ ***Cosmic rays*** created in SNRs

Outflows

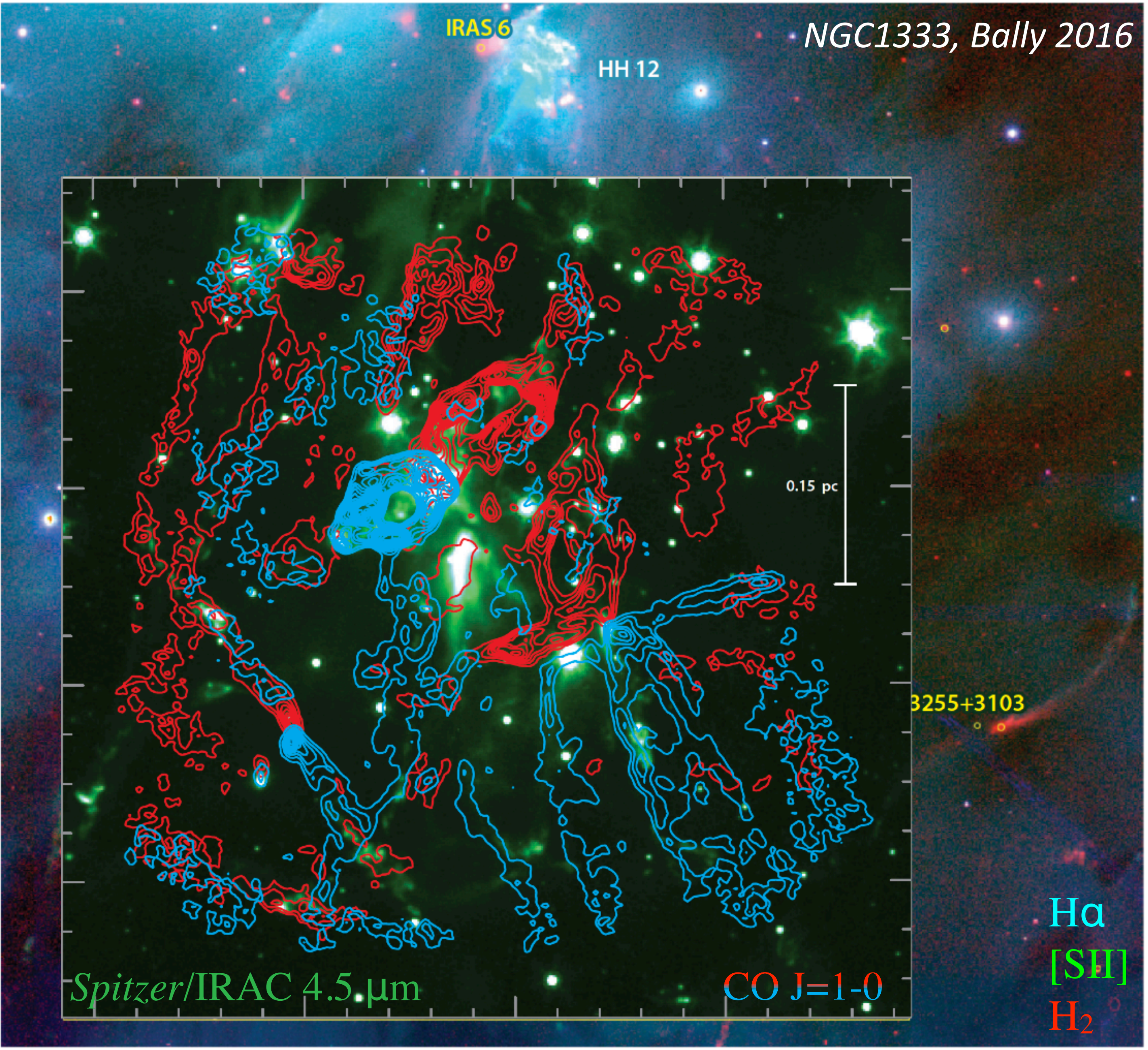
★ Accreting systems with ***rotation*** and a ***magnetic field*** tend to exhibit ***bipolar outflows or collimated jets***

★ Outflow speed for forming star: ***a few km/s to over 10^3 km/s***

★ Can generate turbulence, limit collapse rate, blow out parent cores

★ Generally ***cannot halt star formation***

★ Very complete review: see ***Bally 2016 (ARA&A)***



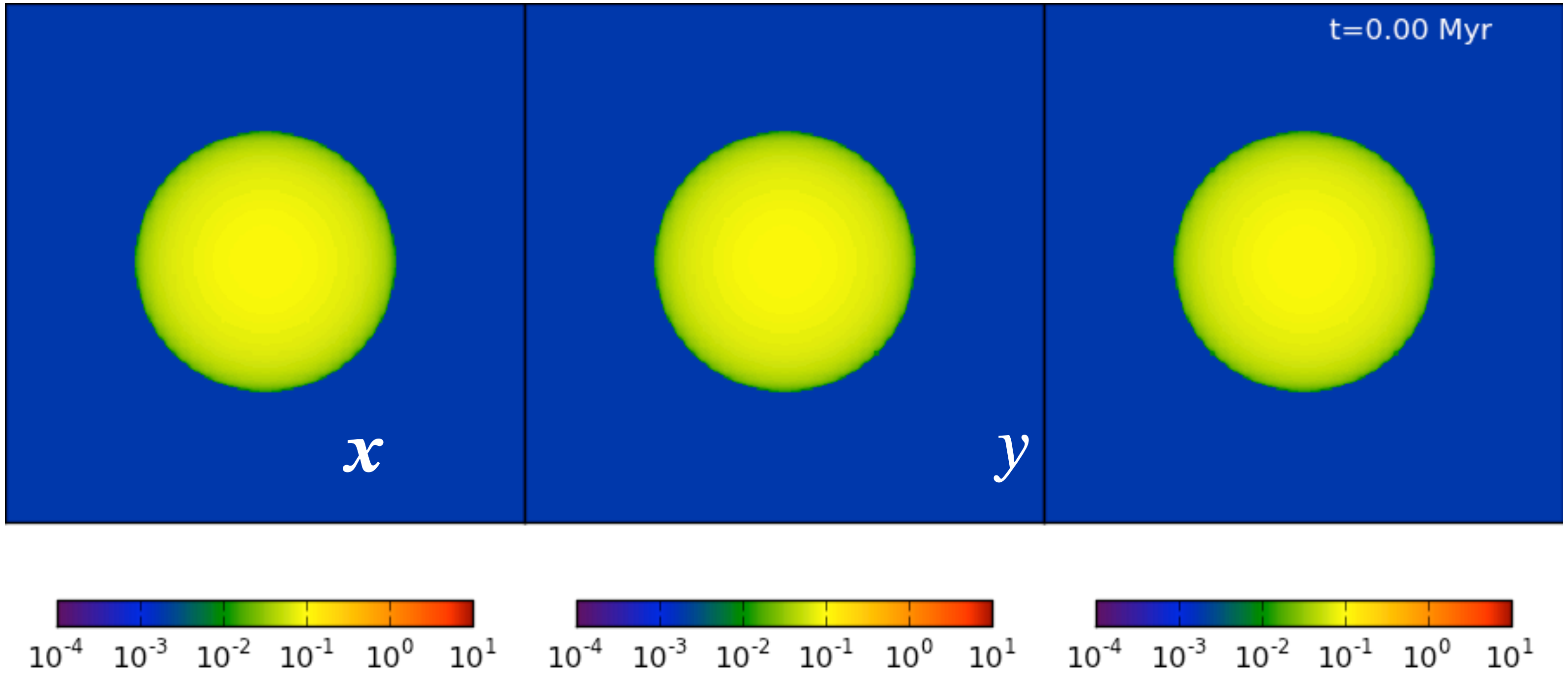
NGC1333, Bally 2016

Outflows — Simulations

“Isolated” Star Forming Core

$M_{\rm core} = 4\,{\rm M}_\odot$

$L = 0.26\,{\rm pc}$



Column Density (g cm^{-2})

Offner & Arce 2014

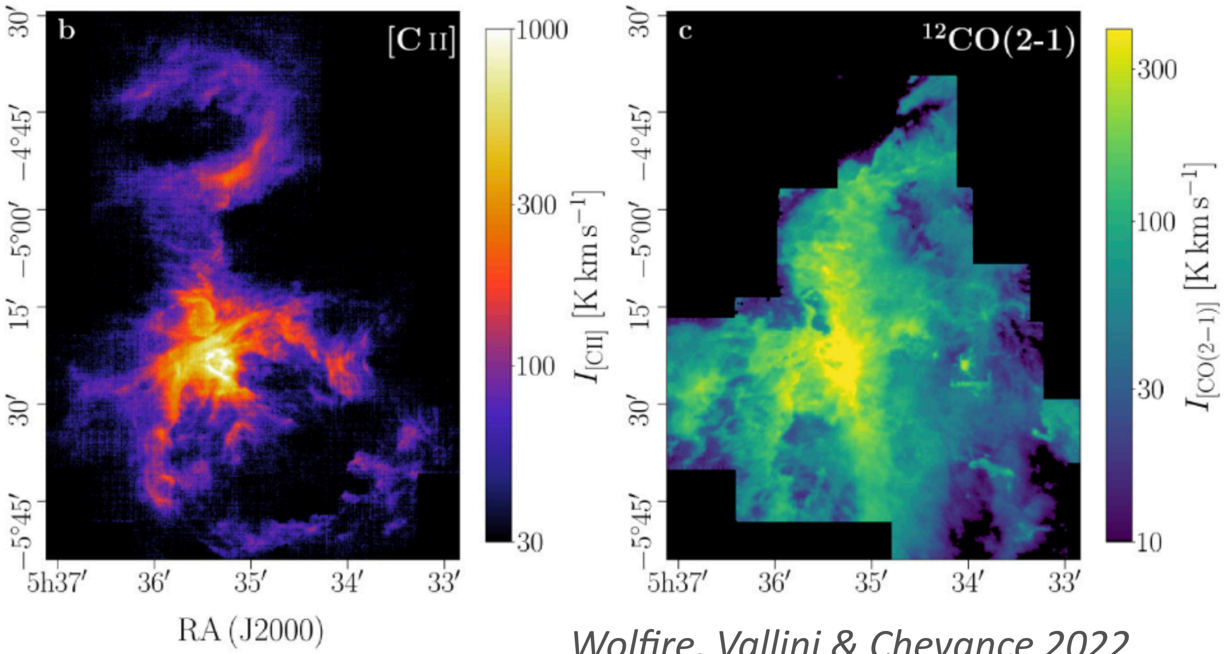
Turbulence+Radiation+Gravity+Stellar Model/Feedback

Non-ionizing radiation

★ Local UV (***non-ionizing***) photons from OB stars absorbed by small dust grains generates ***photoelectric heating***

★ Important for thermal balance and chemistry in the WNM/CNM (*T ~ 100 – 8000 K*)

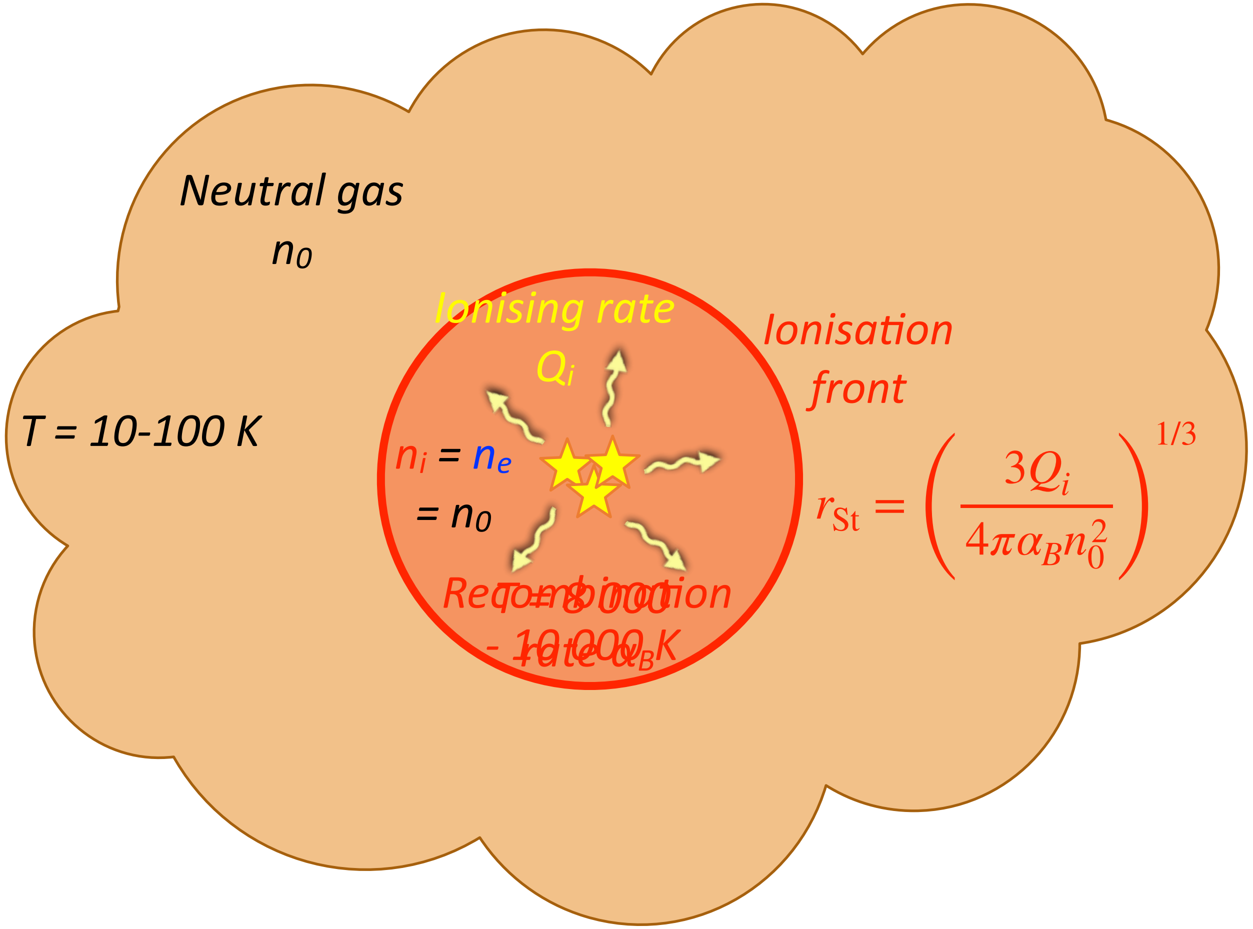
★ Deposits momentum when absorbed or scattered by dust —> ***radiation pressure***



Wolfire, Vallini & Chevance 2022

Ionising radiation

- ★ Photons > 13.6 eV from massive stars ***ionise nearby gas***
- ★ For a fully sampled IFM, ionising photon rate:
  $Q_i = \Xi M_*$ with $\Xi = 3 \times 10^{13}\,\mathrm{photons\,s^{-1}\,g^{-1}}$
- ★ Balance ***ionisation/recombination*** sets the ***Strömgren radius***: $\frac{4}{3}\pi r_{\mathrm{St}}^3 \times n_e n_i \times \alpha_B = Q_i$
- ★ Hot gas —> overpressure —> expansion
- ★ Accelerated of ~ 10–30 km/s
  via internal pressure gradients



Ionising radiation — timescale

Spitzer (1978)

Hosokawa et al. (2006)

- ★ Equation of motion of the swept-up shell: $\frac{d}{dt}\left(\frac{4\pi}{3}r_{\mathrm{IF}}\rho_0\dot{r}_{\mathrm{IF}}\right) = 4\pi r_{\mathrm{IF}}^2\rho_0 c_s^2\left(\frac{r_{\mathrm{St}}}{r_{\mathrm{IF}}}\right)^{3/2}$

mass of the swept-up shell

pressure in the HII region

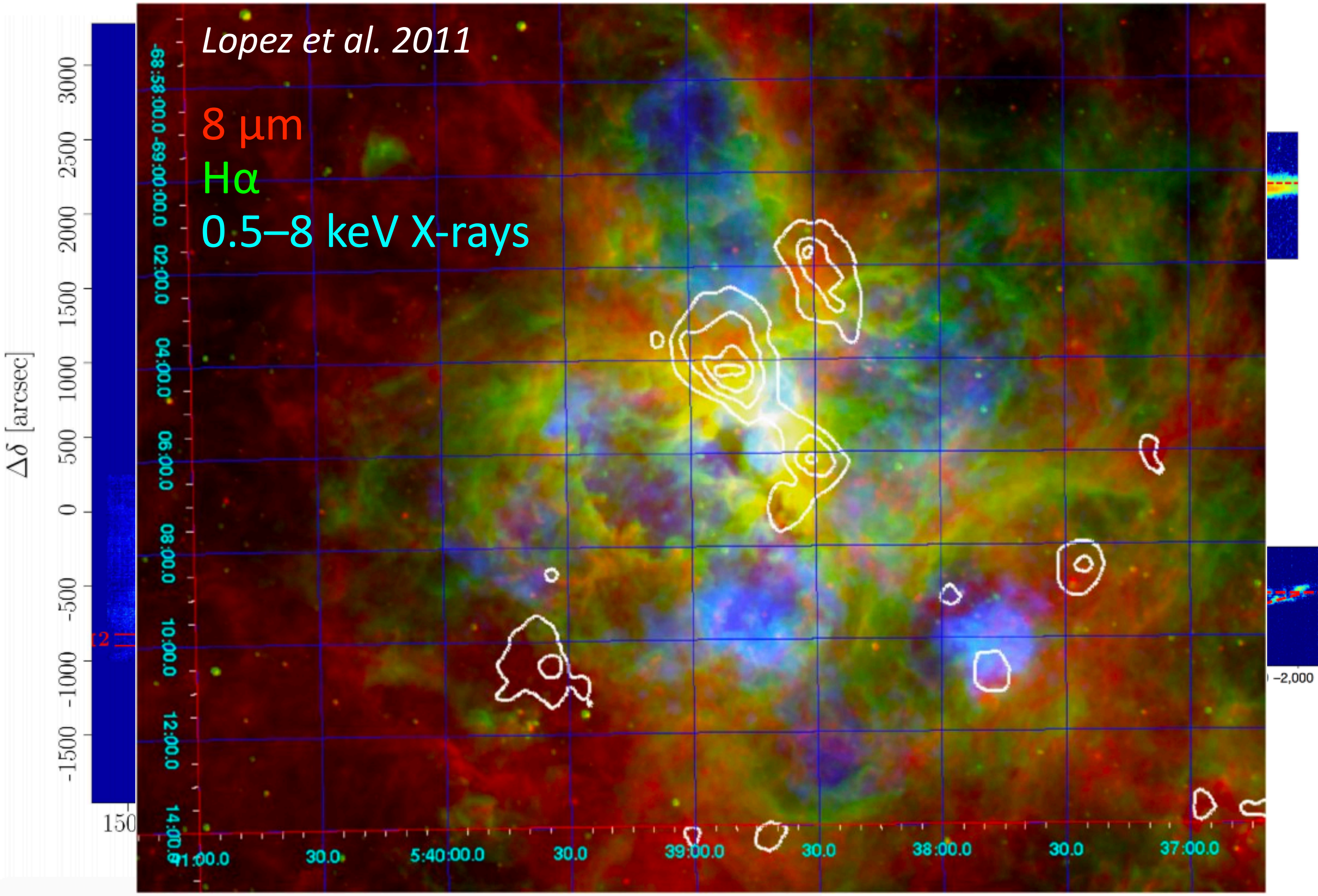
- ★ Solving to get radius expansion: $r_{\mathrm{IF}}(t) = r_{\mathrm{St}}\left(1+\frac{7}{4}\left(\frac{4}{3}\right)^{1/2}\frac{c_s t}{r_{\mathrm{St}}}\right)^{4/7}$

- ★ For $r_{\mathrm{IF}} = r_{\mathrm{GMC}}$ at $t = t_{\mathrm{phot}}$:

$$t_{phot} = \frac{4}{7}\left(\frac{3}{4}\right)^{1/2}\frac{r_{\mathrm{St}}}{c_s}\left[\left(\frac{r_{\mathrm{GMC}}}{r_{\mathrm{St}}}\right)^{7/4} - 1\right]$$

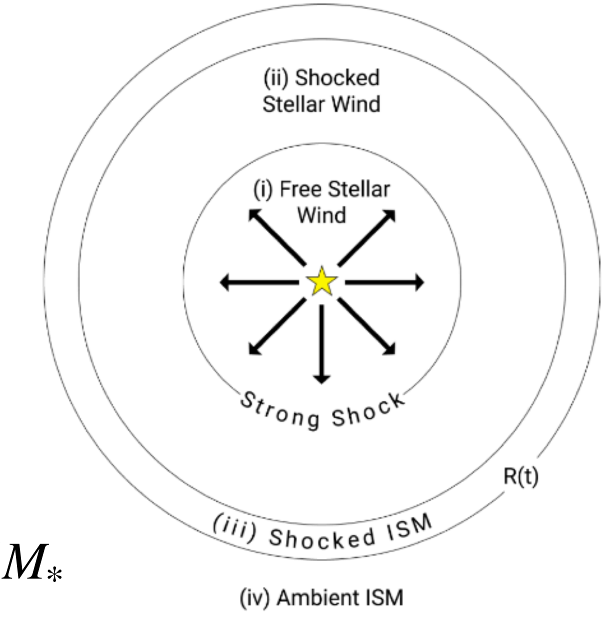
Stellar winds

- ***OB stars*** have very fast winds
- ***Shock surrounding gas*** to create a high temperature (> 10^6 K) bubble
- Mass fluxes of $10^{-5} - 10^{-4}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ at $v_0 \sim 10^3\,\mathrm{km/s}$
- See review by ***Smith 2014 (ARA&A)***



Lopez et al. 2011

Stellar winds — timescale



- ★ Energy injection rate (for a fully sampled IMF):

$$\dot{E}/M_* = L_{\rm wind}/M_* = \frac{1}{2}\dot{M}v^2_{\rm wind}/M_*$$

- ★ Radius evolution of an energy-driven shock:

$$r(t) = \left(\frac{125}{154\pi}\frac{L_{\rm wind}t^3}{\rho_{\rm GMC}}\right)^{1/5}$$

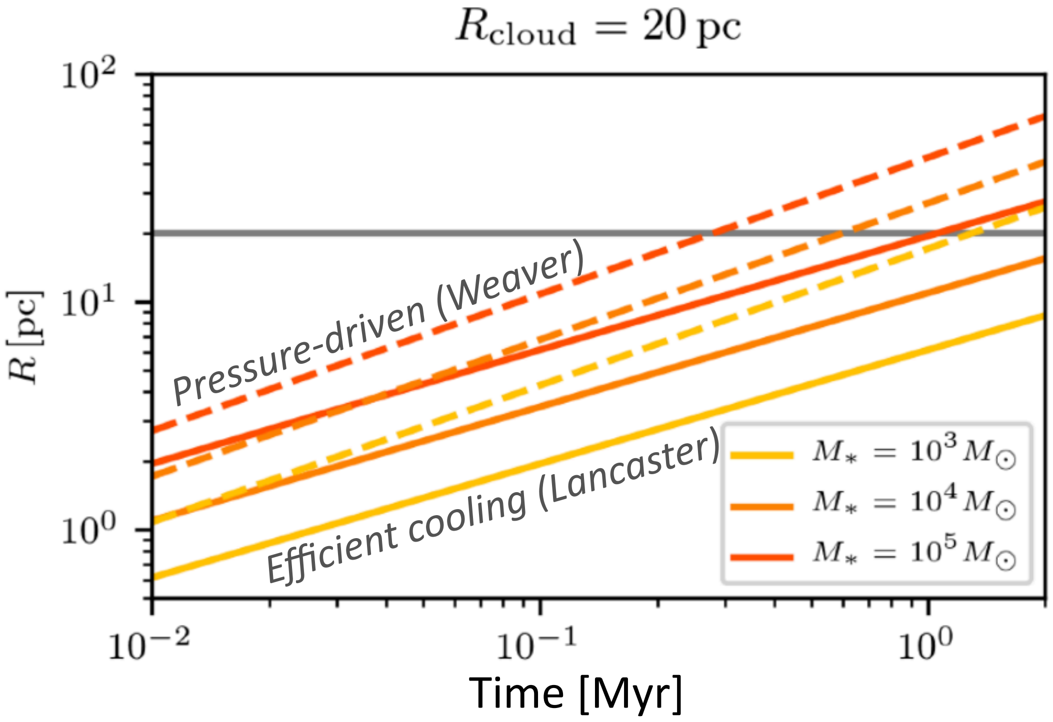
Weaver et al. (1977)

- ★ For $r = r_{\rm GMC}$ at $t = t_{\rm wind}$:

$$t_{\rm wind} = \left(\frac{154\pi}{125}\frac{\rho_{\rm GMC}}{L_{\rm wind}}\right)^{1/3} r^{5/3}_{\rm GMC}$$

Stellar winds — timescale

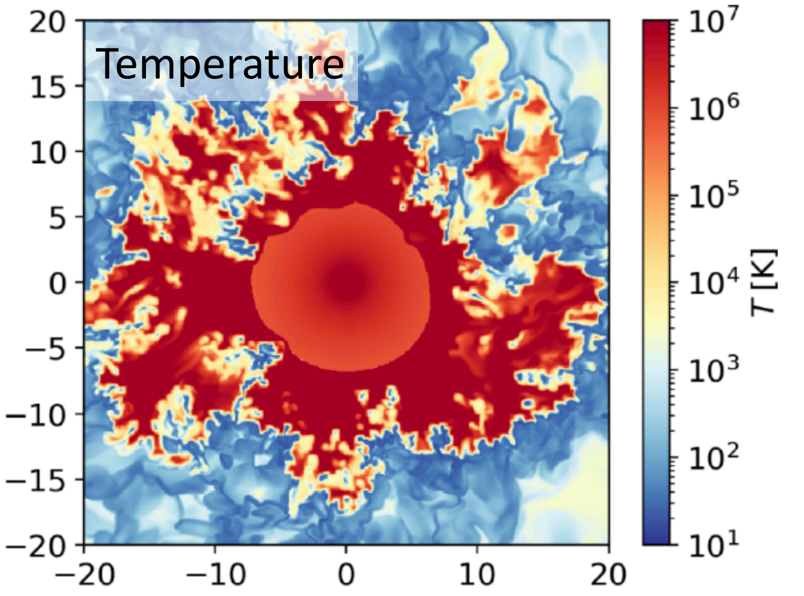
- ★ In reality, efficient turbulent mixing and cooling at the interface:



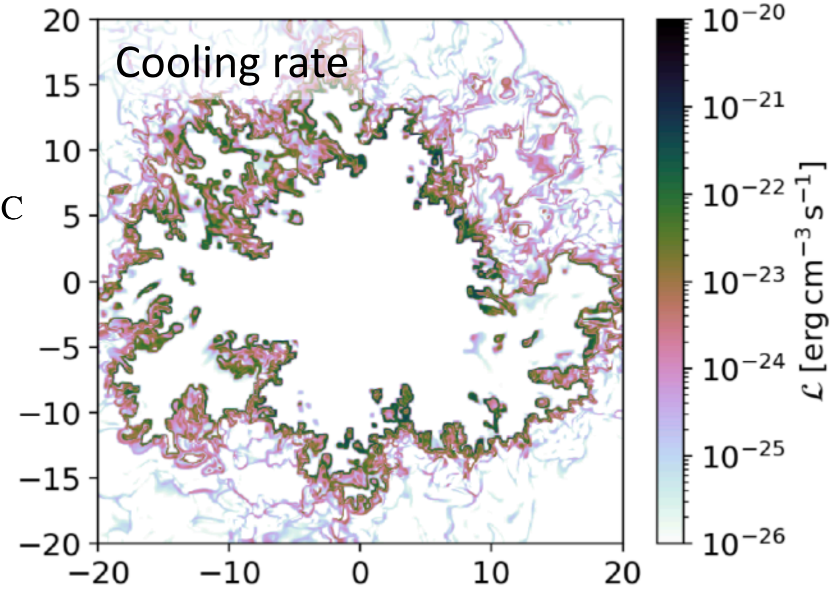
Lancaster et al. (2021a)

$$r(t) = \left(\alpha \frac{\dot{M}_{\rm wind} v_{\rm wind} t^2}{\bar{\rho}_{\rm GMC}}\right)^{1/4}$$

$$t_{\rm wind} = \left(\alpha \frac{\rho_{\rm GMC}}{\dot{M}_{\rm wind} v_{\rm wind}}\right)^{1/2} r_{\rm GMC}^2$$



Lancaster et al. (2021b)



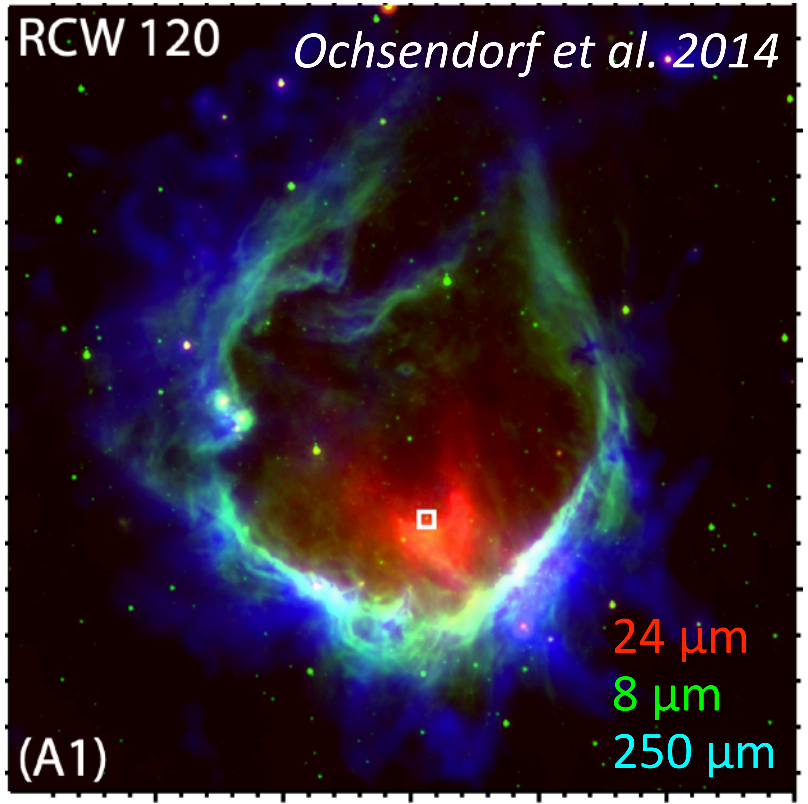
Radiation pressure

- ★ Photons transfer energy and ***momentum*** to the surrounding gas ***and dust***, with $p = h\nu/c$
- ★ ***Direct*** absorption/scattering of photons by gas or dust
  Or ***indirect*** after absorption by dust and reemission in IR
- ★ For a (point) source of luminosity L:

$$P_{\rm rad}(r) = f_{\rm trap}\frac{L}{4\pi r^2 c}$$

*how much of this momentum is **actually absorbed** by the gas (Krumholz & Matzner 2009)*

- ★ Significant ***only*** for massive stars, ***small regions with high opacity***
- ★ ***Cannot halt*** star formation



Radiation pressure — timescale

★ Radiation pressure force: $F_{\rm rad} = (1+\tau_{\rm IR})\frac{L_{\rm bol}}{c}$

bolometric luminosity

infrared optical depth

★ For a typical GMC: $\tau_{\rm IR} = 8\times10^{-5}\left(\frac{\phi_{\rm tr}}{0.2}\right)\left(\frac{T_{\rm GMC}}{20\,K}\right)^2\left(\frac{\Sigma_{\rm GMC}}{20\,{\rm M_\odot\,pc^2}}\right) \ll 1$

Fraction of IR radiation trapped at $\tau_{\rm IR} = 1$ from simulations (Krumholz et al. 2012)

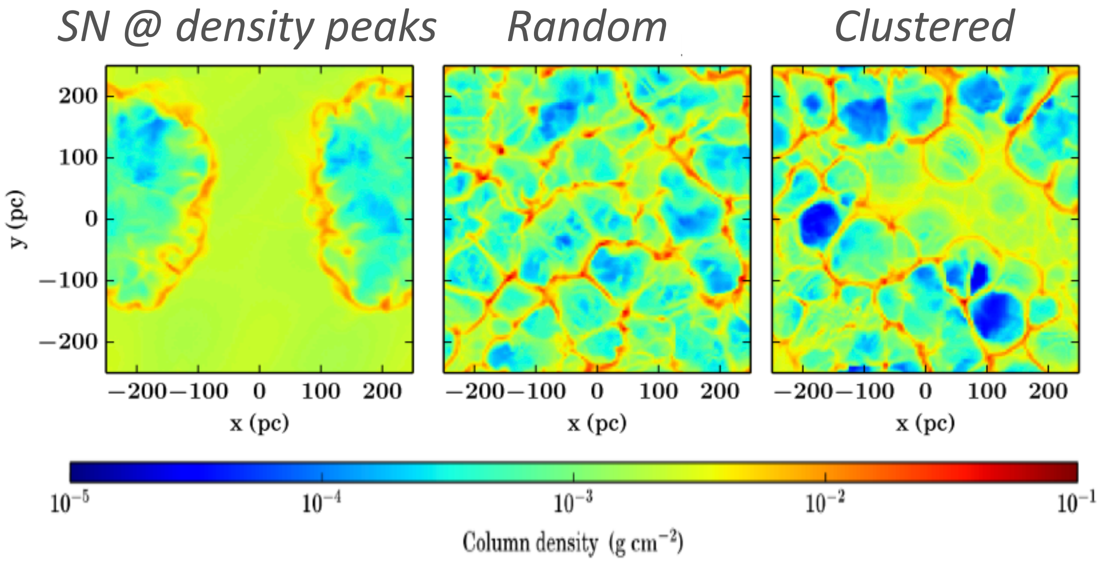
optically thin to infrared radiation

★ Solving the momentum equation for a constant volume density GMC, $r = r_{\rm GMC}$ at $t = t_{\rm rad}$

$$t_{\rm rad} = \left(\frac{2\pi c}{3}\frac{\rho_{\rm GMC}}{L_{\rm bol}}\right)^{1/2} r_{\rm GMC}^2$$

Supernovae

- ★ Largest source of ***momentum injection*** to the ISM from stellar feedback
- ★ Each supernova yields 10^{51} erg, much of which ends up as thermal energy in a hot phase with a long cooling time (hot remnant)
- ★ Drive ***turbulence*** in the molecular gas
- ★ Efficiency ***depends on the environment*** (density) and ***clustering***
- ★ ***Limited importance for halting star formation*** (time delay)

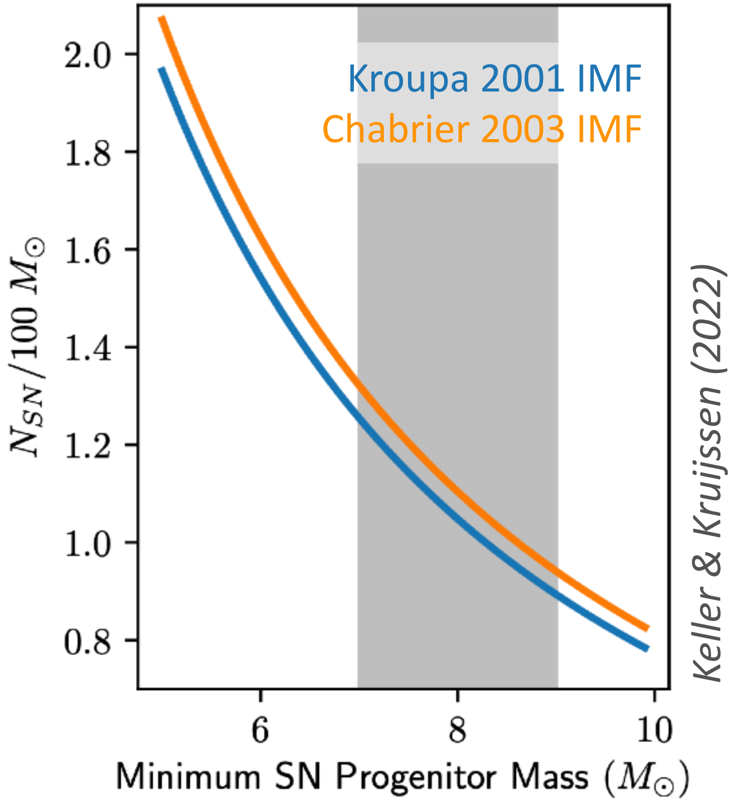


Girichidis et al. (2016)

See also: Iffrig+14, Iffrig & Hennebelle 15, C.-G. Kim & Ostriker 15, Gatte+15, Martizzi+15, Walch & Naab 15

Supernovae delay time

How many stars explode as SN and when?



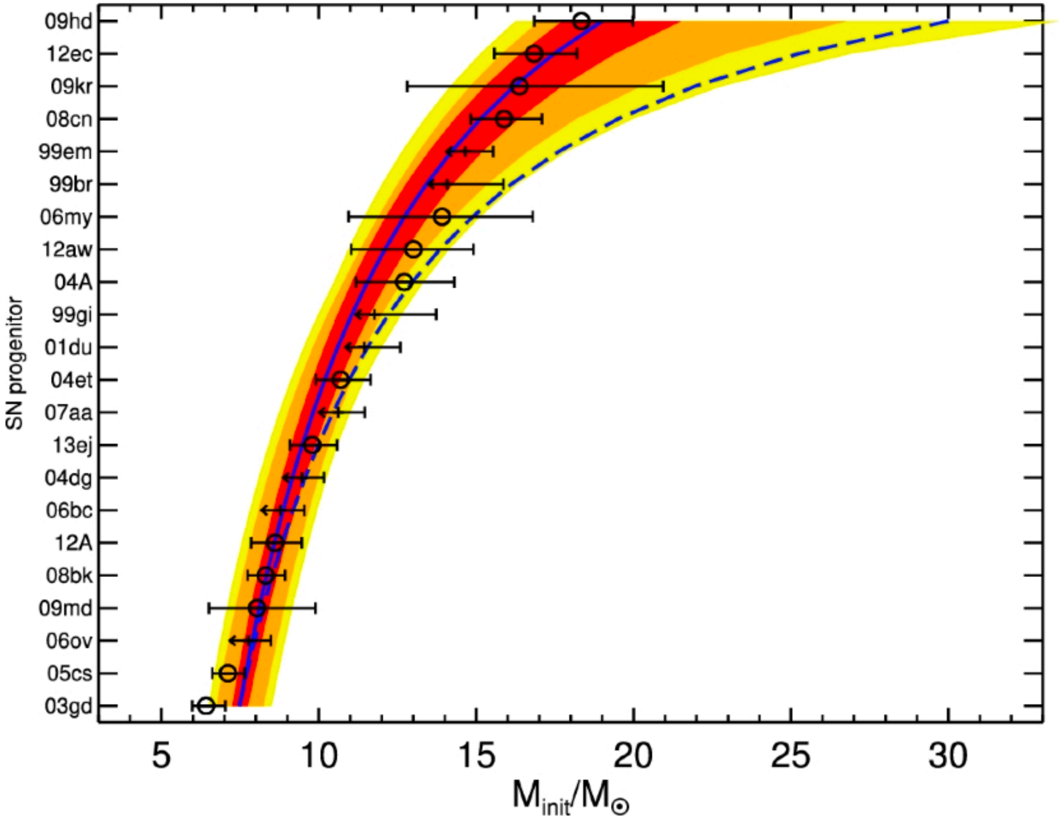
Keller & Kruijssen (2022)

★ Shape of the IMF

—> ***More SNe*** from ***low-mass*** progenitors ($\gtrsim 8\,\mathrm{M}_\odot$)

Supernovae delay time

How many stars explode as SN and when?



Davies & Beasor (2018)

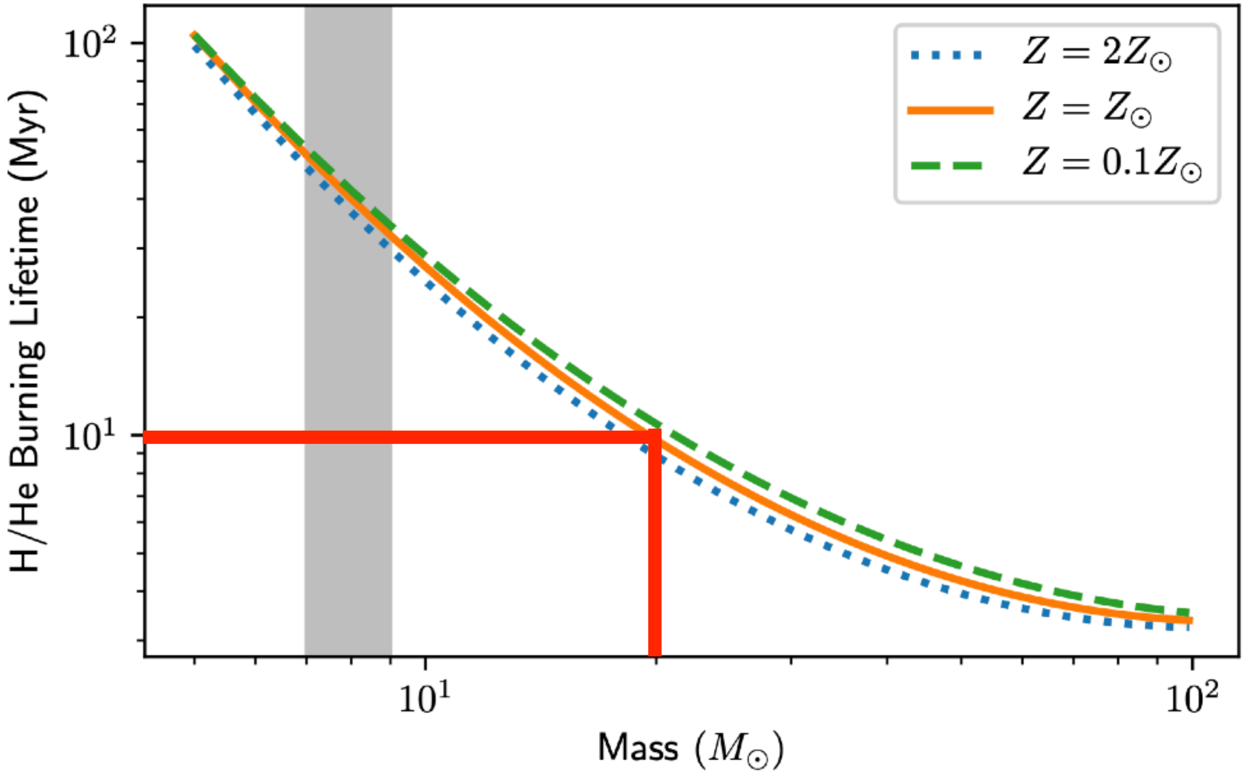
★ Shape of the IMF

—> ***More SNe*** from ***low-mass*** progenitors ($\gtrsim 8\,\mathrm{M}_\odot$)

★ ***'Failed SNe'*** for stars $\gtrsim 20\,\mathrm{M}_\odot$ —> black holes

Supernovae delay time

How many stars explode as SN and when?



Keller & Kruijssen (2022)

★ Shape of the IMF
—> ***More SNe*** from ***low-mass*** progenitors ($\gtrsim 8\,\mathrm{M}_\odot$)

★ ***'Failed SNe'*** for stars $\gtrsim 20\,\mathrm{M}_\odot$ —> black holes

★ ***First SN*** after $\gtrsim (3-)10\,\mathrm{M}_\odot$

Stellar feedback mechanisms

- ★ ***Outflows*** disperse the natal cores of individual stars
- ★ ***Non-ionizing FUV/optical radiation*** heats the gas through the photoelectric effect
- ★ ***Ionizing EUV radiation*** photoevaporates dense material, producing high-pressure ionized gas
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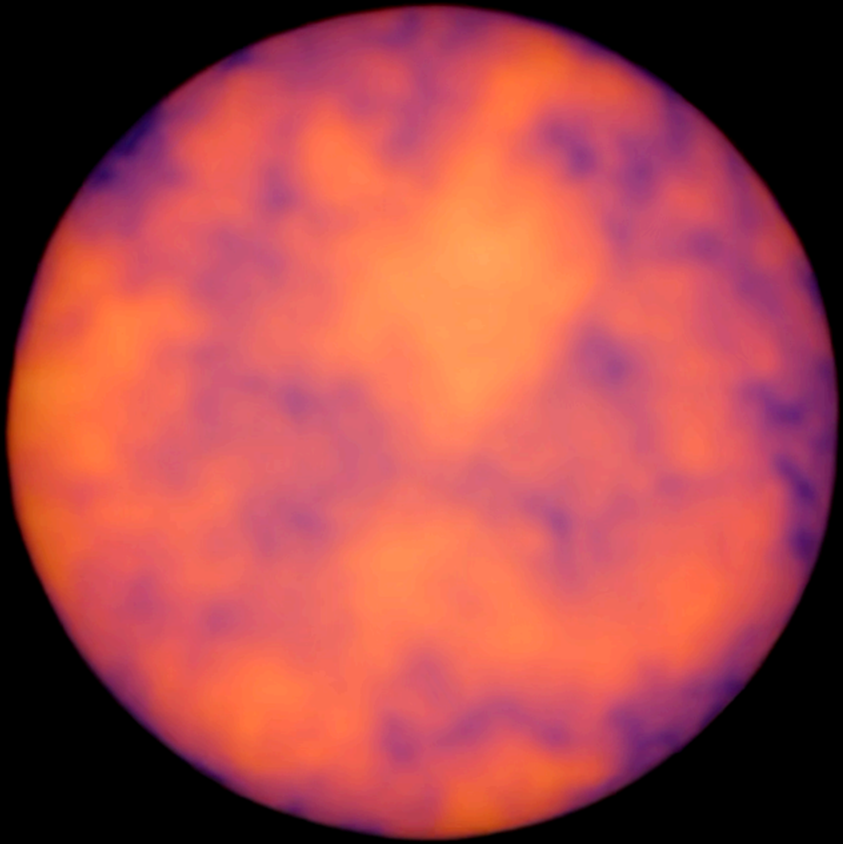
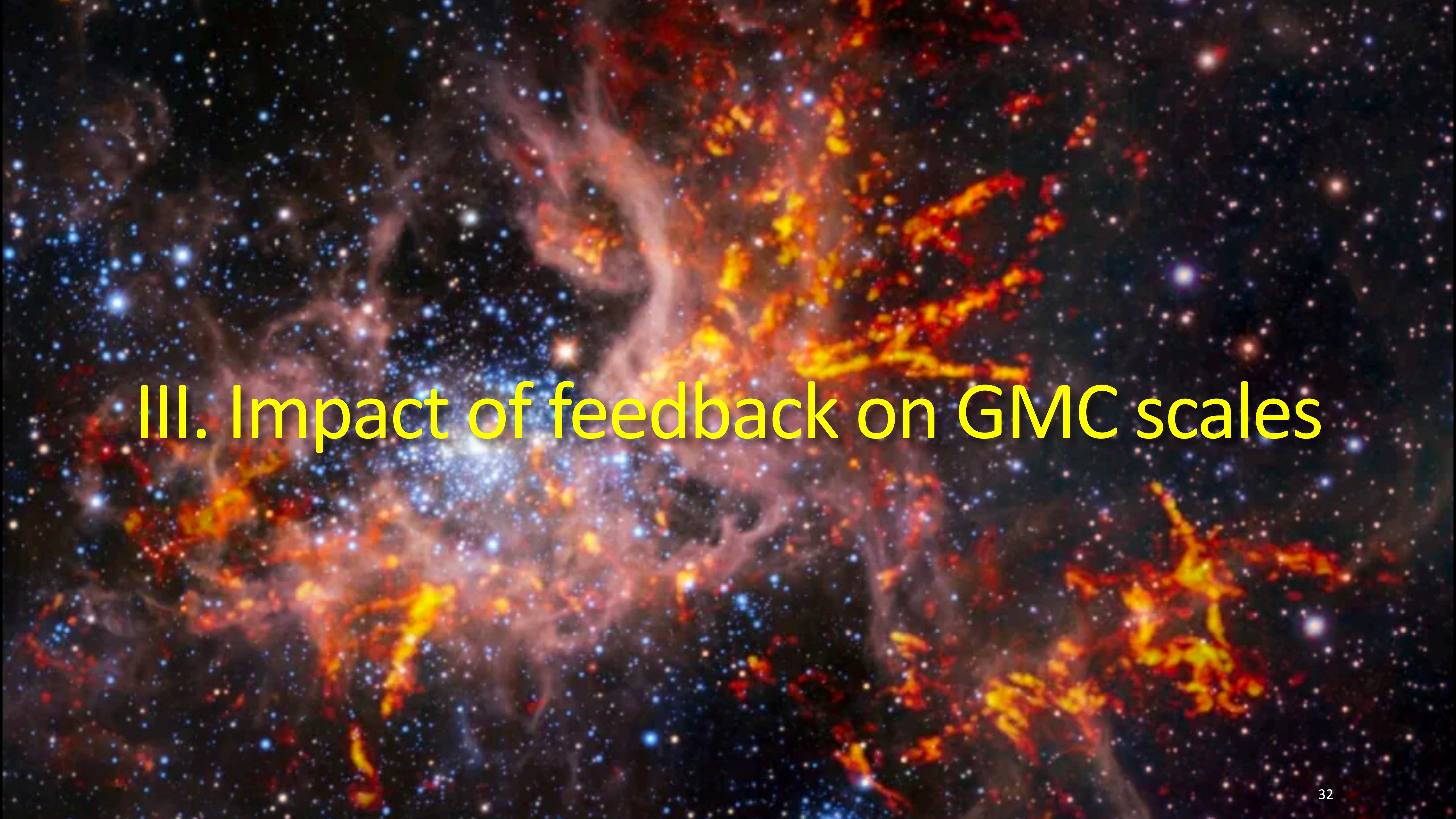
- ★ ***Cosmic rays*** created in SNRs

$M_0 = 2 \times 10^4\,\mathrm{M}_\odot$

$R_0 = 10\,\mathrm{pc}$



Credit: David Guszejnov, Mike Grudic, and the STARFORGE Project



III. Impact of feedback on GMC scales

How do (massive) stars impact their surrounding?

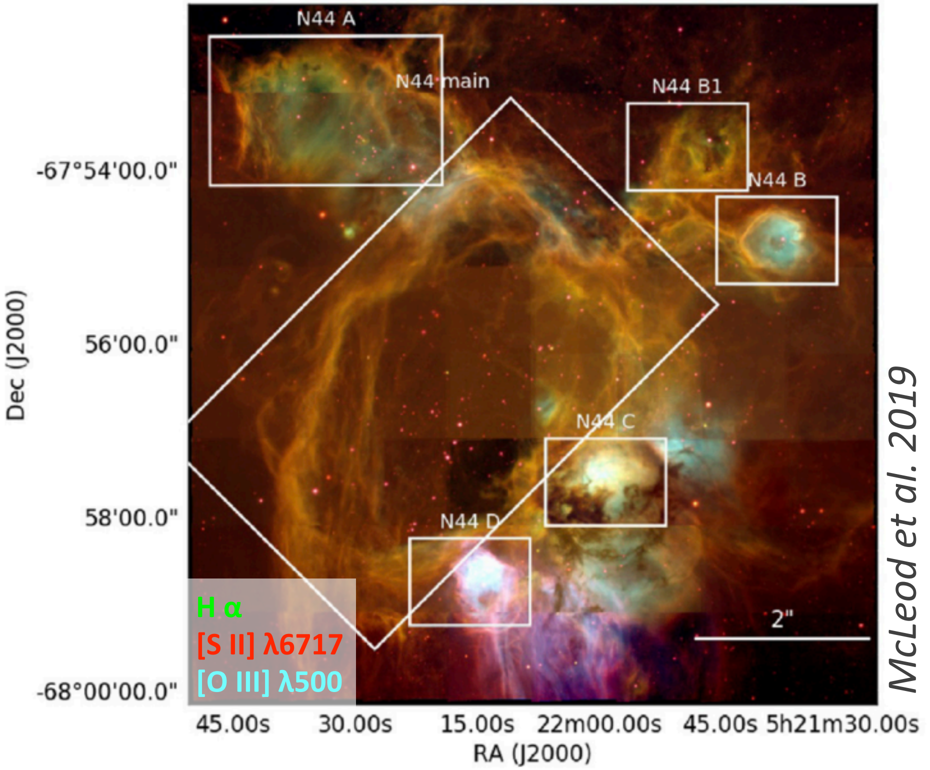
★ Heat and ionise the gas

★ Disrupt GMCs

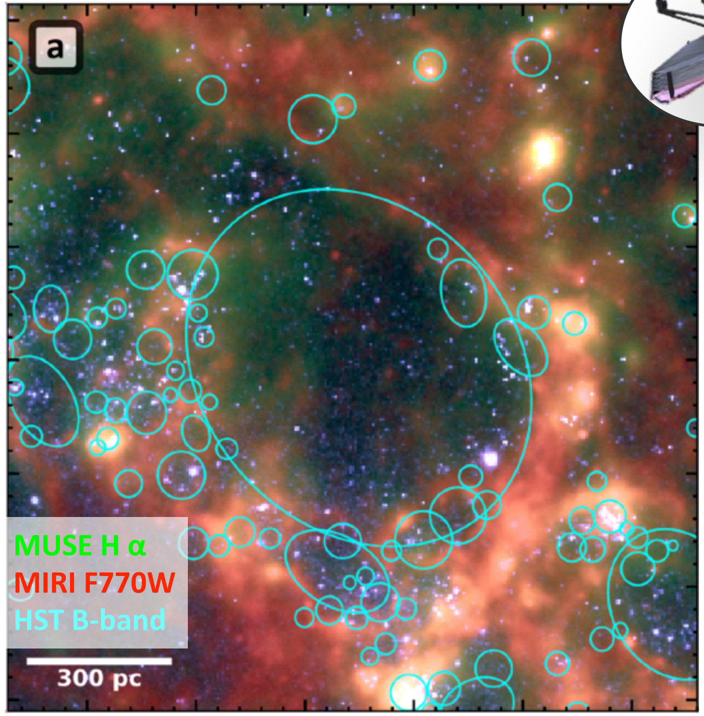
★ Limit star formation efficiency

★ Impact the IMF

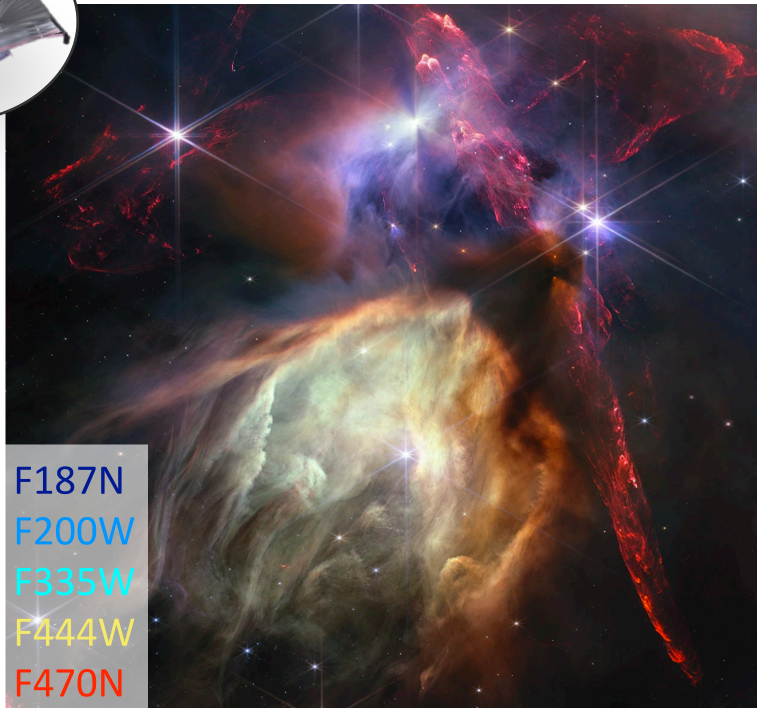
Heating, ionising and expelling the gas — Recent observations



McLeod et al. 2019



Watkins et al. 2023



NASA, ESA, CSA, STScI, Klaus Pontoppidan (STScI)

How do (massive) stars impact their surrounding?

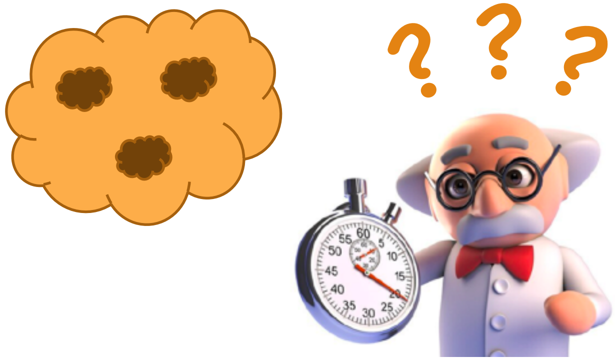
- ★ Heat and ionise the gas
- ★ Disrupt GMCs
- ★ Limit star formation efficiency
- ★ Impact the IMF

How does stellar feedback regulate star formation (efficiency) on GMC scales?

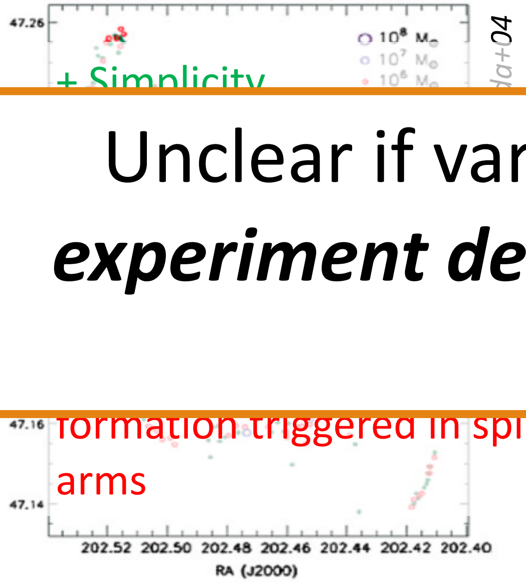
—> How ***fast*** are GMCs dispersed after star formation?

How fast are GMCs dispersed by FB?

Molecular cloud lifecycle (e.g. lifetime) is a long-standing problem:



> 100 Myr?



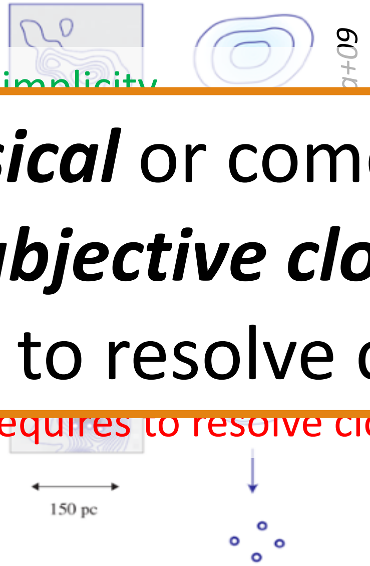
+ Simplicity

formation triggered in spiral arms

Molecular clouds between galactic arms

Scoville & Hersh 79, Scoville & Wilson 04, Koda+09

10-50 Myr?



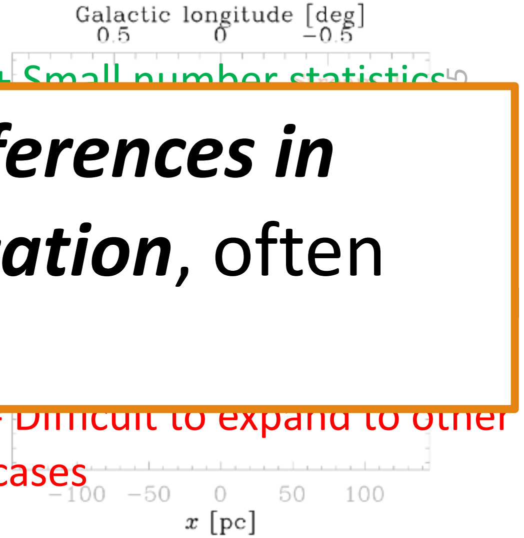
+ Simplicity

- Requires to resolve clouds

Classification of clouds

Elmegreen 00, Hartmann+01, Engargiola+03, Kawamura+09, Meidt+15

~ 1 Myr?



+ Small number statistics

- Difficult to expand to other cases

Gas orbiting the centre of our Galaxy

Kruijssen+15, Henshaw+16b, Barnes+17, Jeffreson+18b

Unclear if variety is ***physical*** or comes from ***differences in experiment design*** and ***subjective cloud classification***, often requiring to resolve clouds.

Measuring Myr timescales — How?

Do clouds live for much longer than massive stars or for a similar timescale?

Quasi-equilibrium or ***rapid cycling***?

(clouds form stars for many dynamical times)

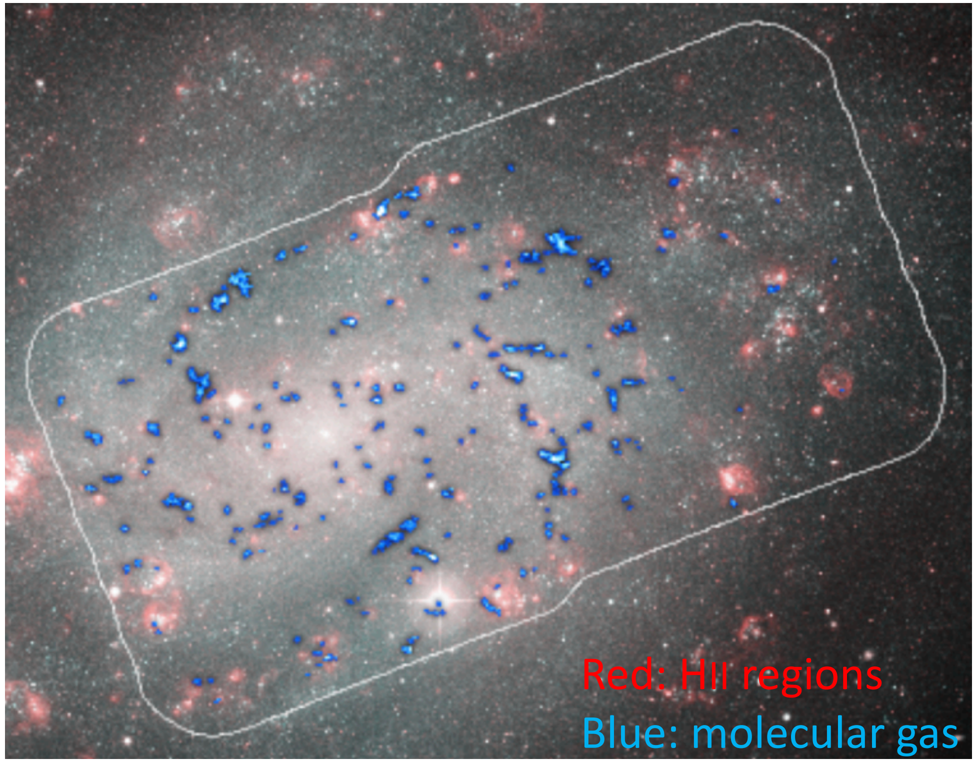
(clouds are destroyed by massive stars)

Gas and young stars ***correlated*** on small scales

Gas and young stars ***decorrelate*** on small scales

Measuring Myr timescales — How?

Small-scale variations of gas-to-SFR ratio reflect underlying timeline *(Kruijssen & Longmore 2014, Kruijssen et al. 2018)*



Gas and young stars ***decorrelate*** on small scales

↓

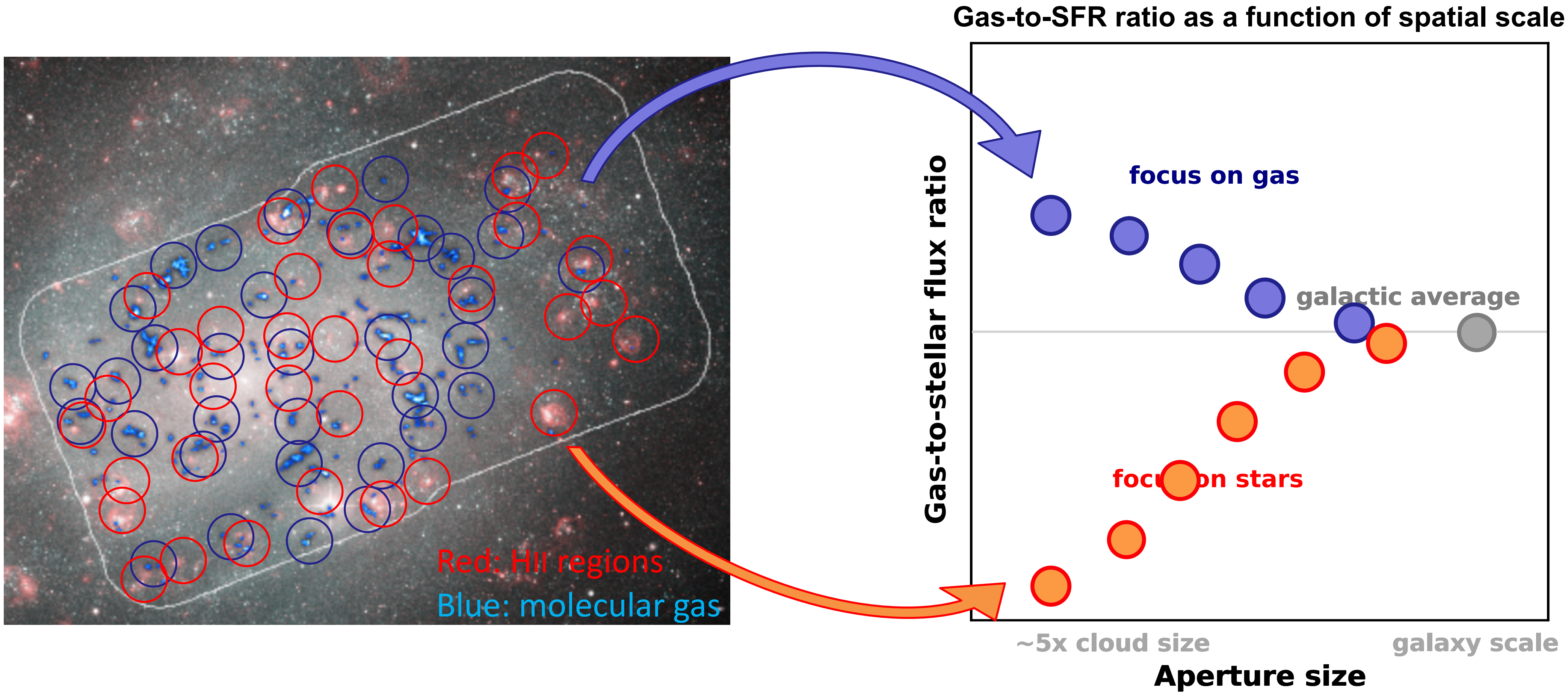
Rapid cycling

↓

How can we ***quantify***
this decorrelation/this timeline?

Measuring Myr timescales — How?

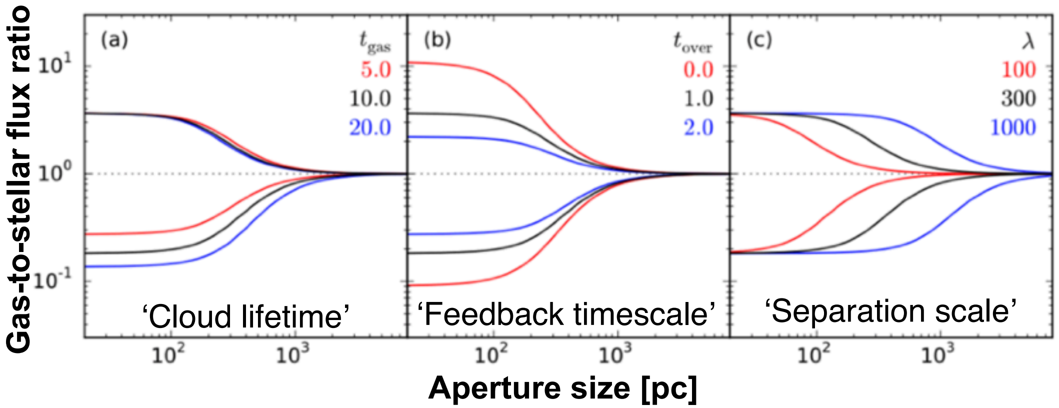
Small-scale variations of gas-to-SFR ratio reflect underlying timeline *(Kruijssen & Longmore 2014, Kruijssen et al. 2018)*

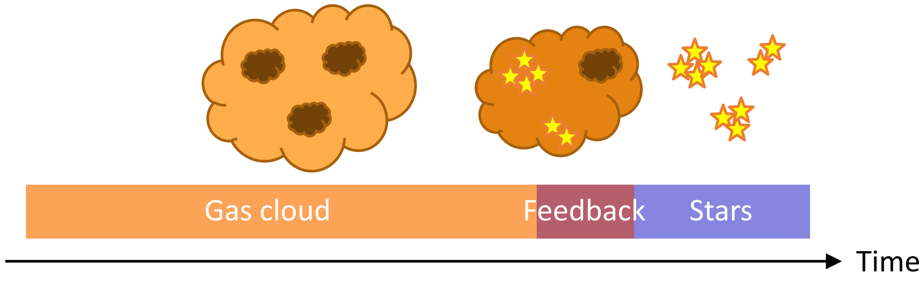


Measuring Myr timescales — How?

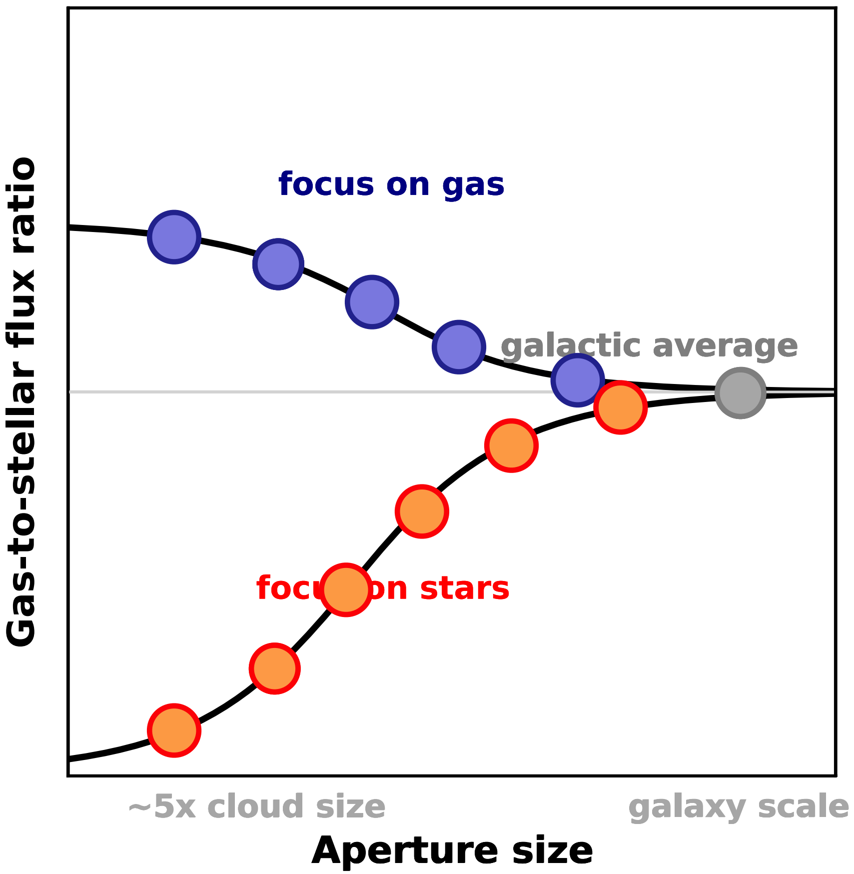
Small-scale variations of gas-to-SFR ratio reflect underlying timeline *(Kruijssen & Longmore 2014, Kruijssen et al. 2018)*

Analytical function entirely describes the decorrelation
(asymmetry, flattening, decorrelation scale)
controlled by **3 independent parameters**

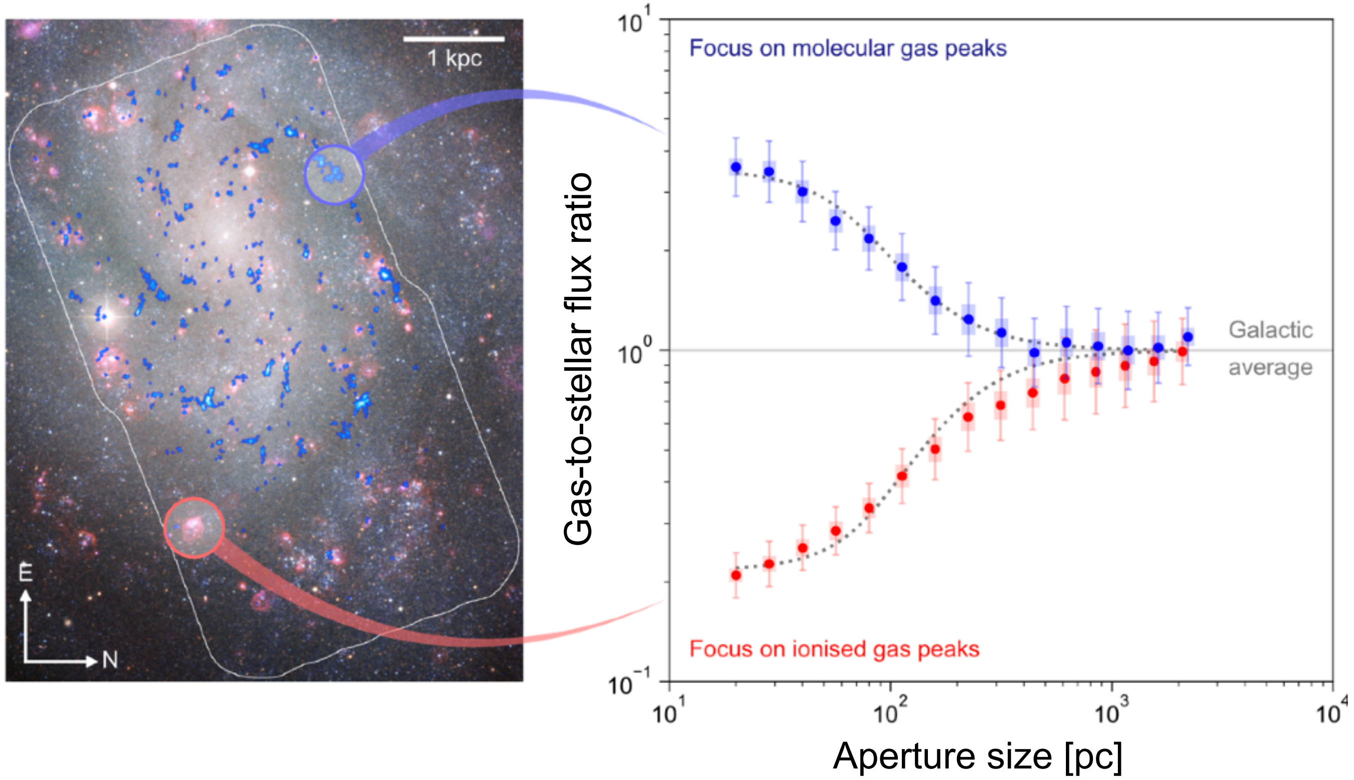


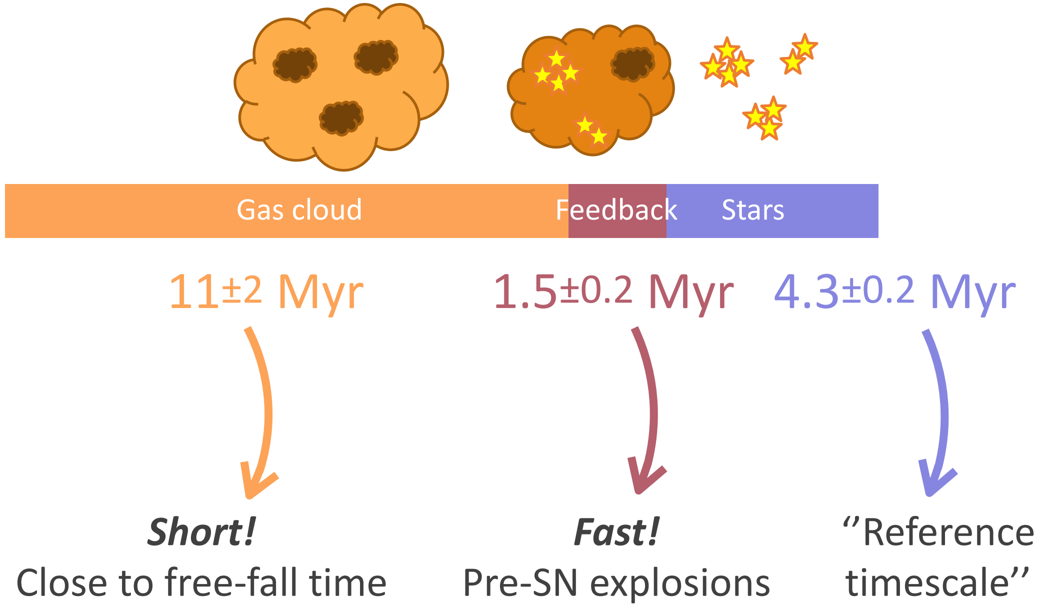


Gas-to-SFR ratio as a function of spatial scale



Application to an example — NGC300




Gas cloud
Feedback
Stars

11±2 Myr

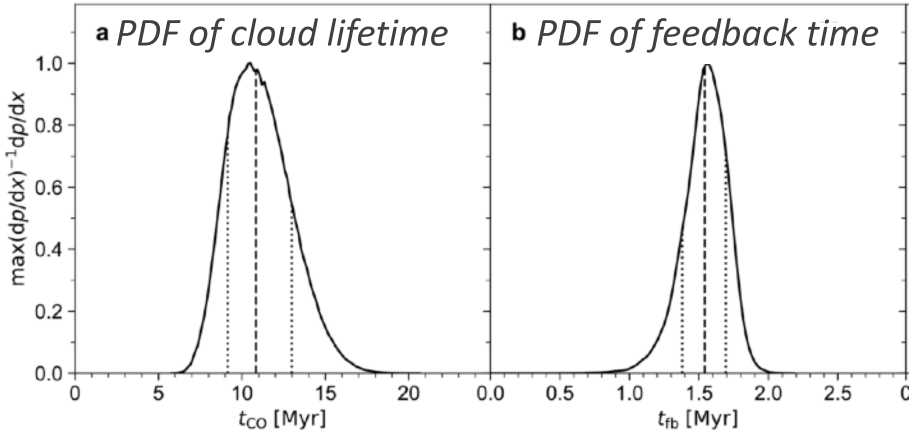
Short!
Close to free-fall time

1.5±0.2 Myr

Fast!
Pre-SN explosions

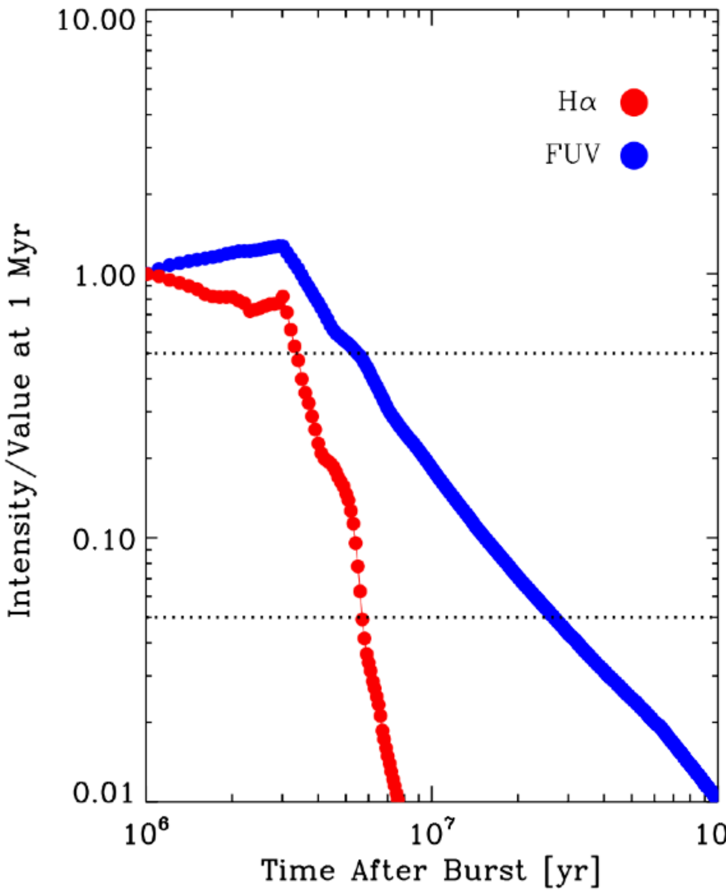
4.3±0.2 Myr

''Reference timescale''

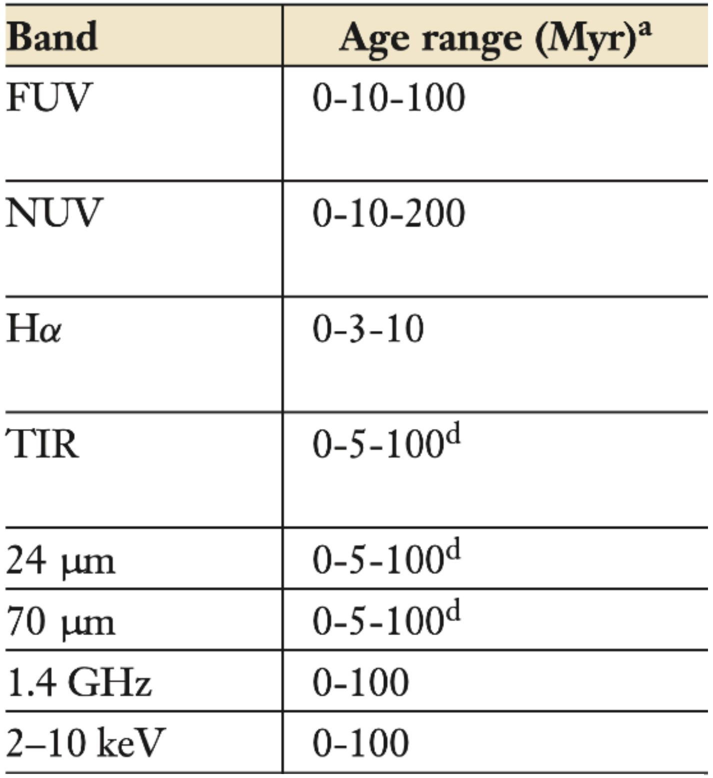


Kruijssen, Schruba, Chevance et al., 2019, Nature

Tracing *past* star formation

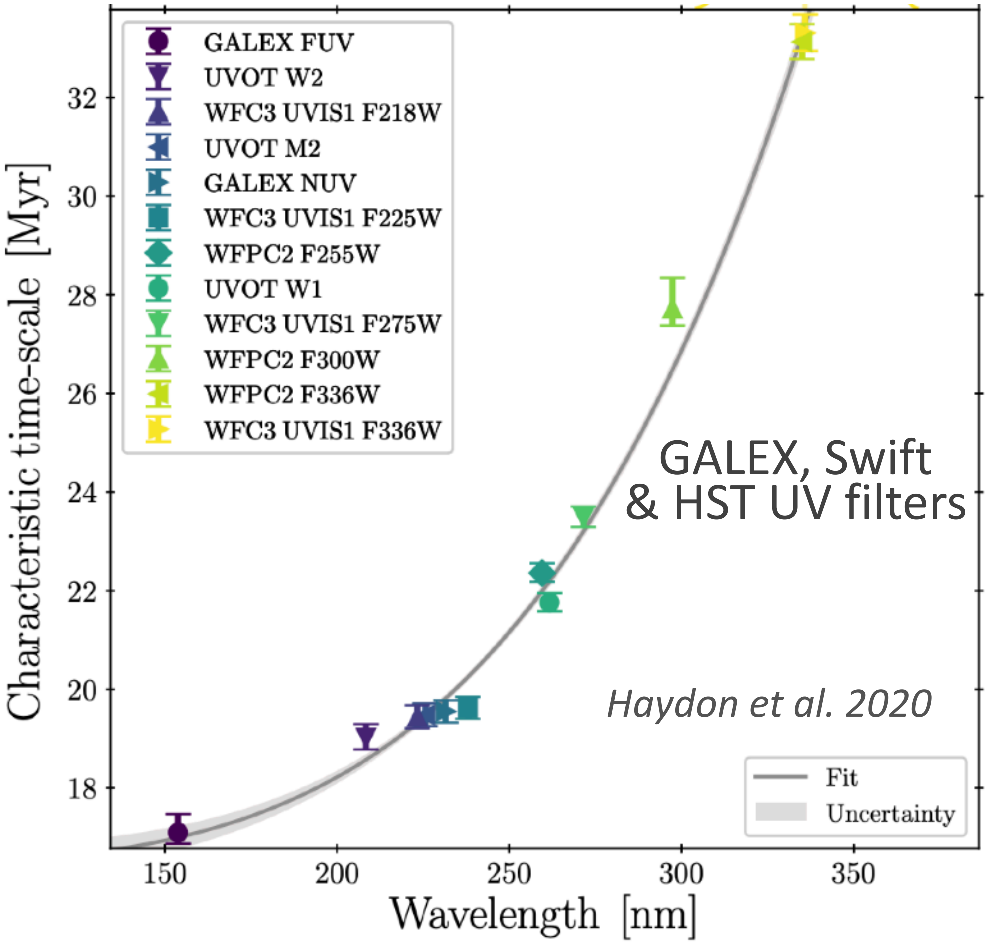


Leroy et al. 2012



Band	Age range (Myr)[a]
FUV	0-10-100
NUV	0-10-200
Hα	0-3-10
TIR	0-5-100[d]
24 μm	0-5-100[d]
70 μm	0-5-100[d]
1.4 GHz	0-100
2–10 keV	0-100

Kennicutt & Evans 2012



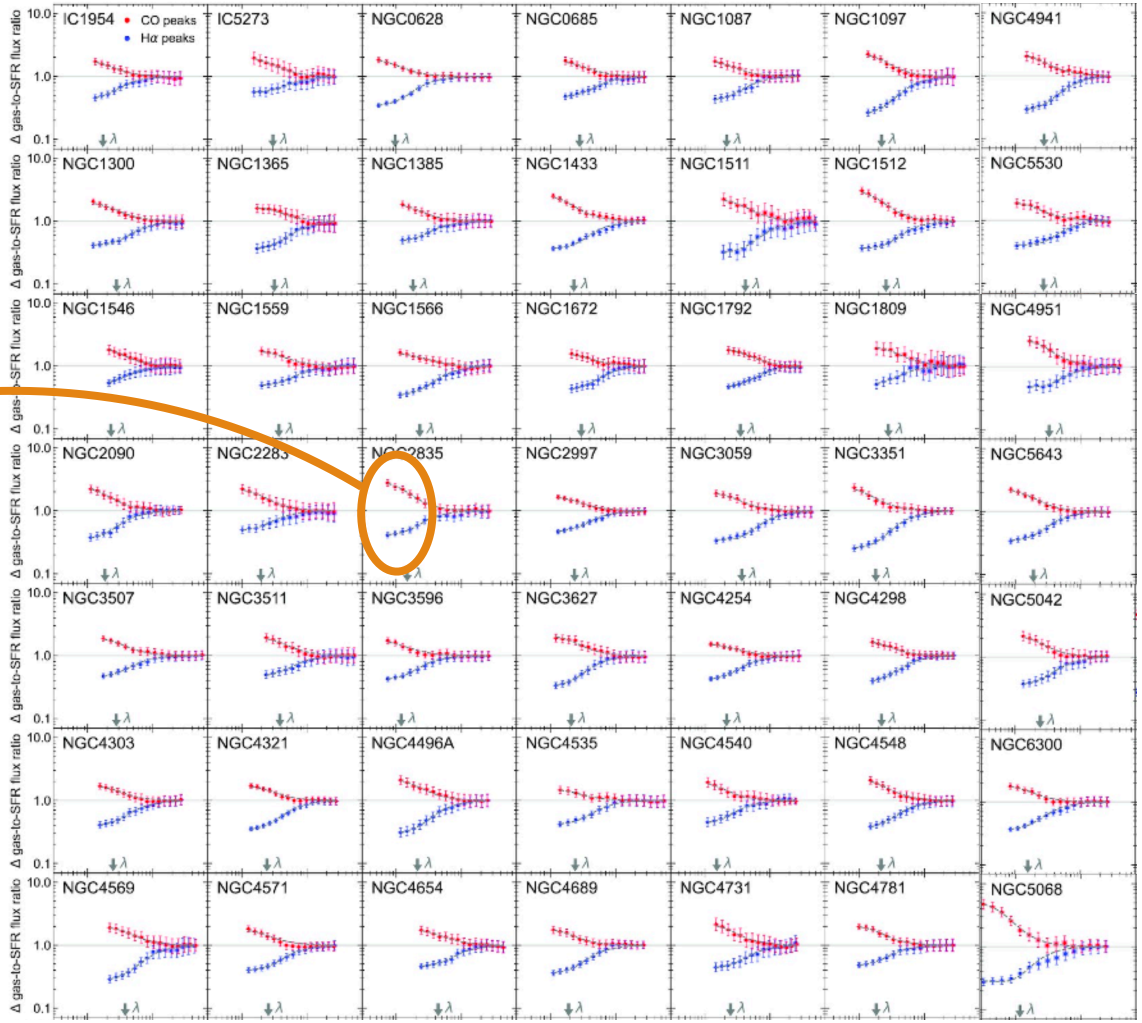
GALEX, Swift & HST UV filters

Haydon et al. 2020

How do (massive) stars impact their surrounding?

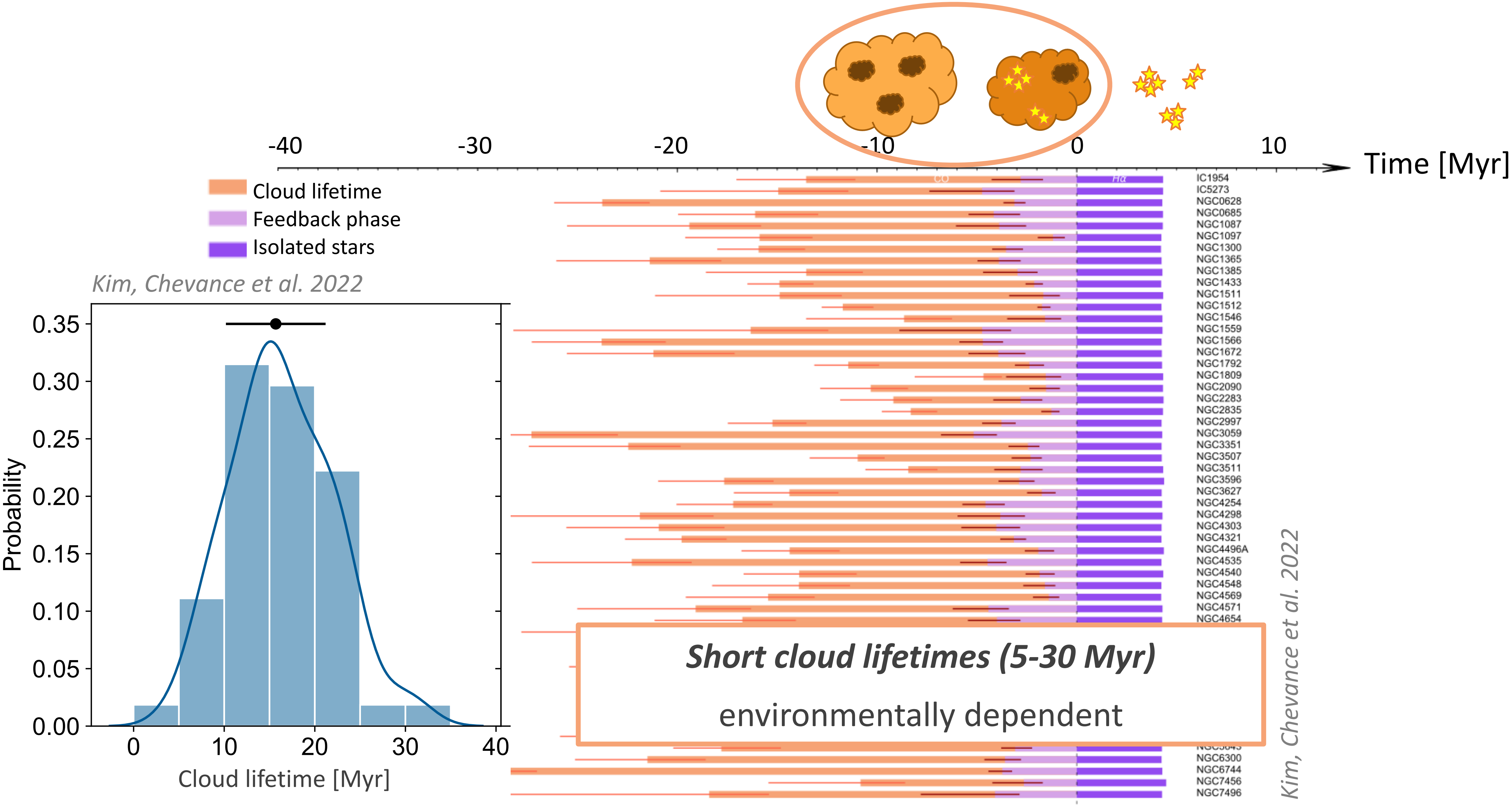
- ★ Heat and ionise the gas
- ★ Disrupt GMCs
- ★ Limit star formation efficiency
- ★ Impact the IMF

Cloud evolutionary cycle in the Phangs galaxies



Universal decorrelation:
Rapid cycling between
cold gas and young stars

Kim, Chevance et al. 2022



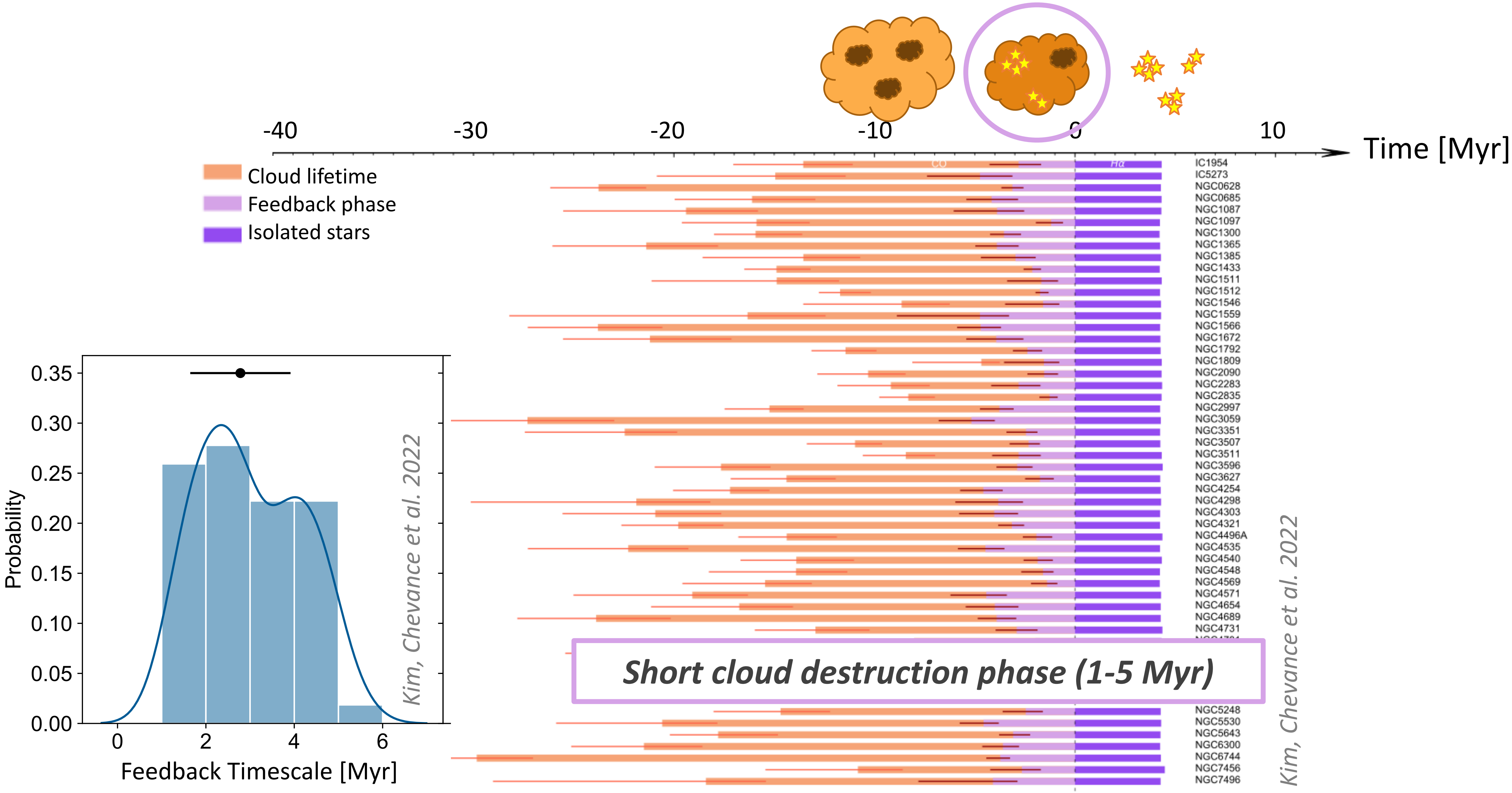
🟧 Cloud lifetime
🟪 Feedback phase
🟪 Isolated stars

Kim, Chevance et al. 2022

Short cloud lifetimes (5-30 Myr)

environmentally dependent

Kim, Chevance et al. 2022

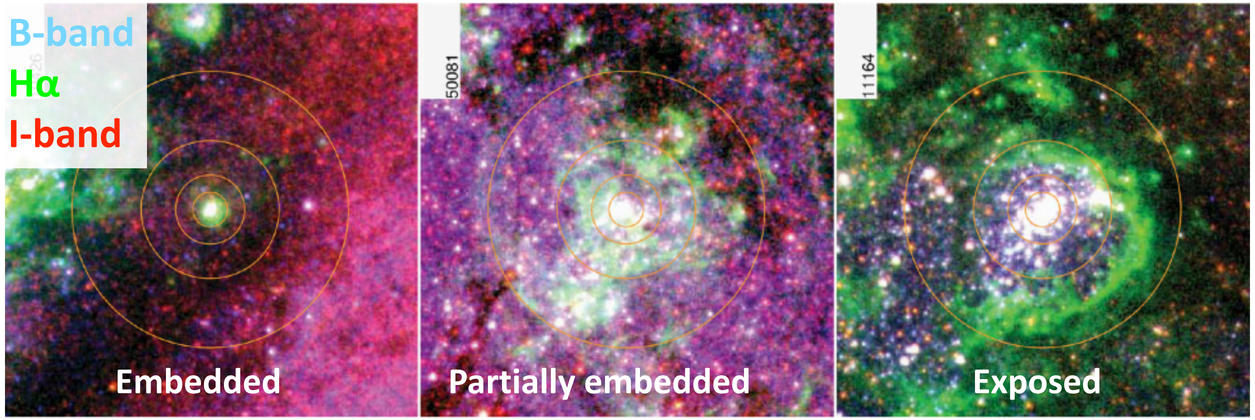


Short cloud destruction phase (1-5 Myr)

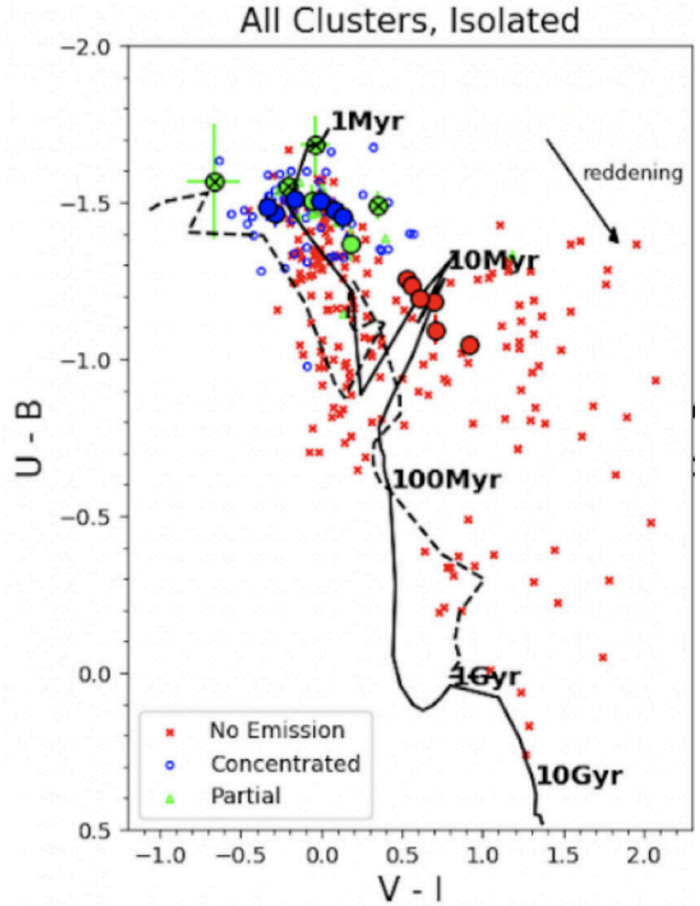
III. Impact on GMC scales

Rapid cloud destruction

From resolving young stellar clusters



Hollyhead et al. 2015



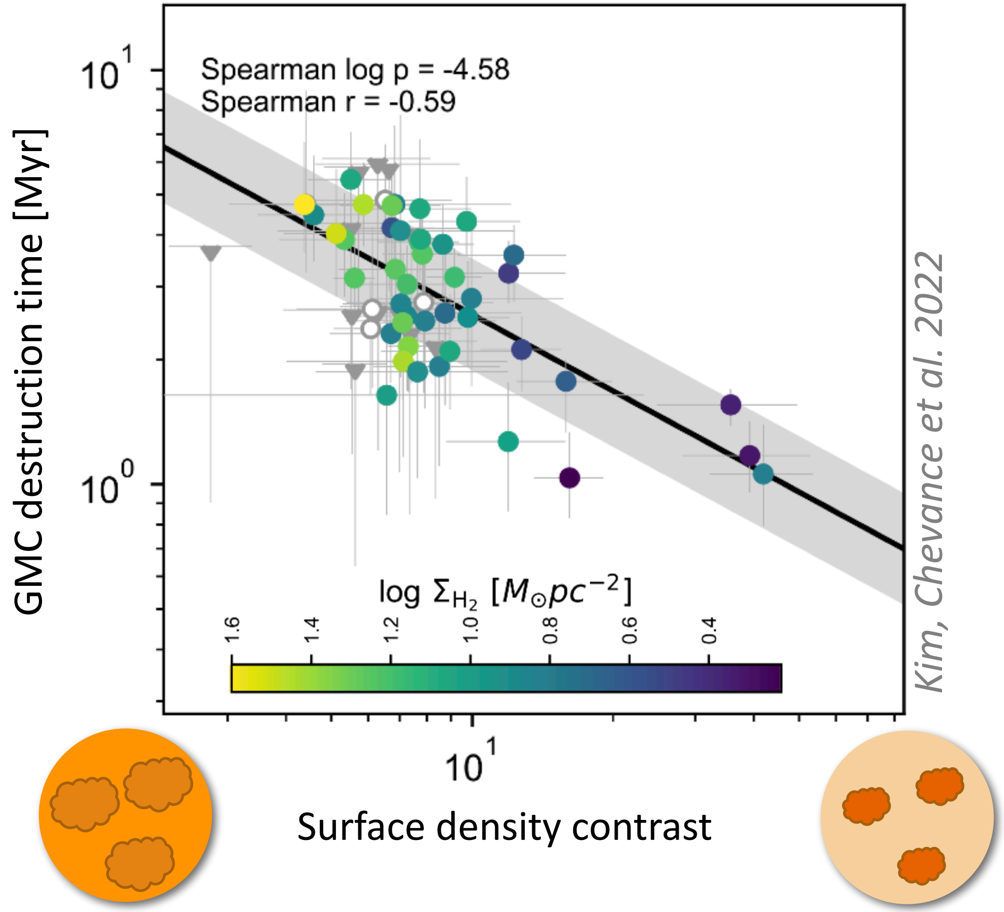
Hannon et al. 2019

★ Young clusters are found to be ***gas-free after 3-5 Myr***
Whitmore et al. 2014, Hollyhead et al. 2015, Grasha et al. 2018, 2019, Hannon et al. 2019, Messa et al. 2021

⚠ Requires ***resolving and age dating young clusters***: limited sample
Antennae, M83, NGC 7793, M51, NGC 4395, NGC 1313

Rapid cloud destruction by stellar feedback

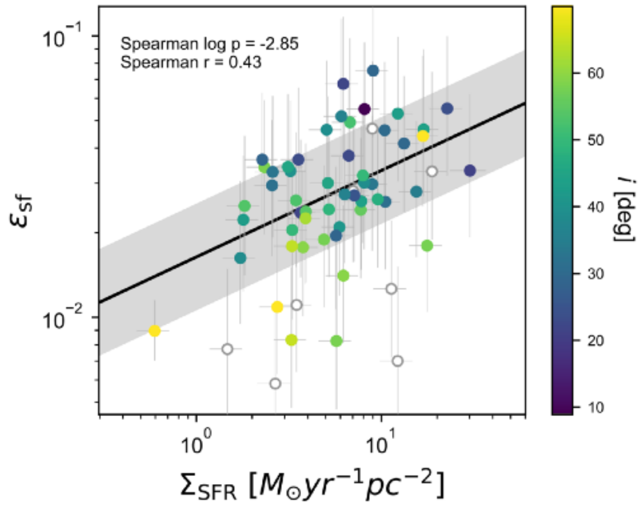
- Molecular cloud disrupted within 1-5 Myr (pre-
- Environmentally dependant timescale



Kim, Chevance et al. 2022

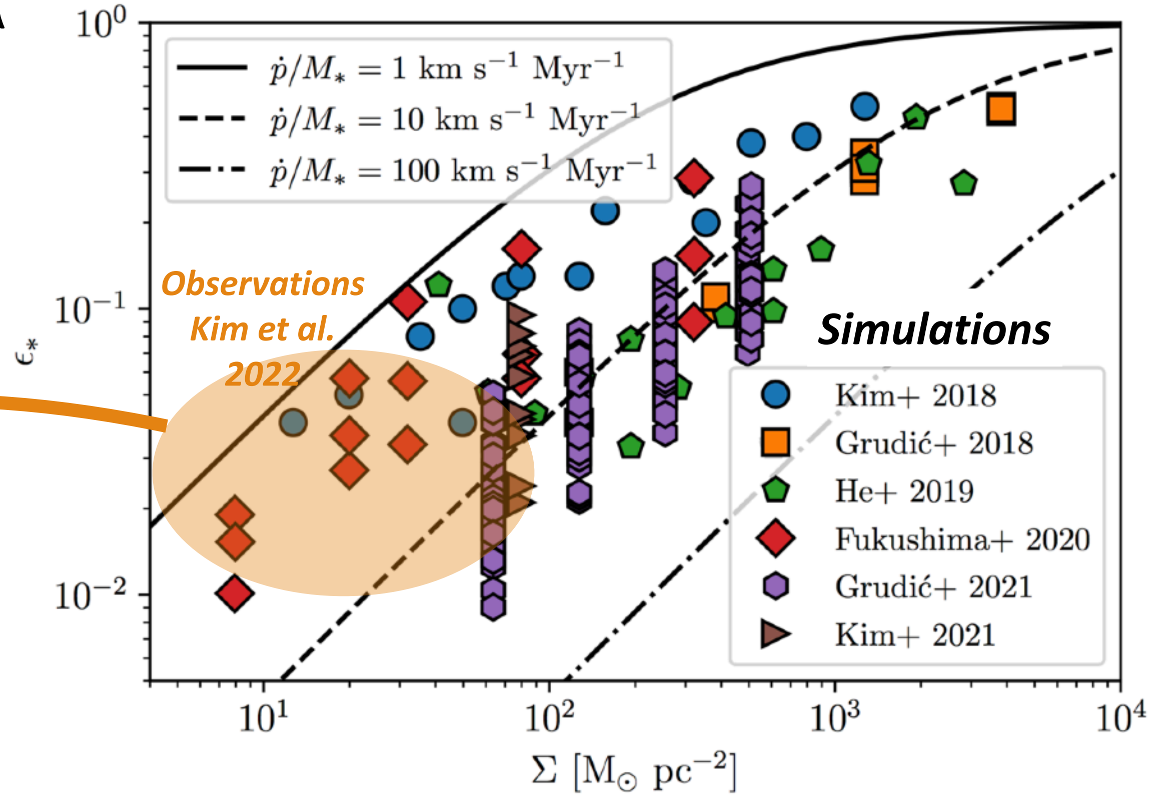
Rapid cloud destruction by stellar feedback

- ★ Molecular cloud disrupted within 1-5 Myr (pre-s
- ★ Environmentally dependant timescale
- ★ Limits star formation efficiency



Kim, Chevance et al. 2022

Chevance, et al. 2023, PPVII review chapter

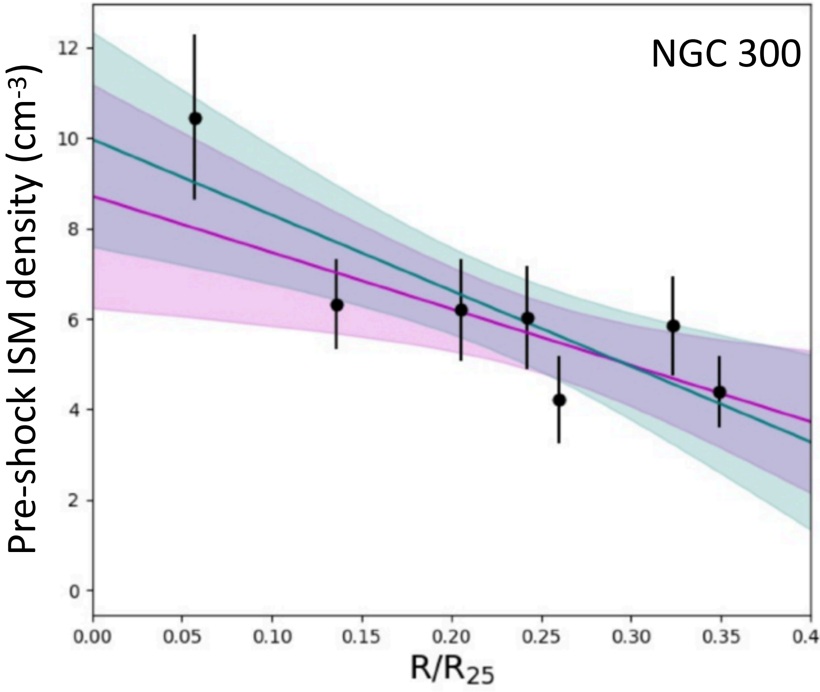


Observations Kim et al. 2022

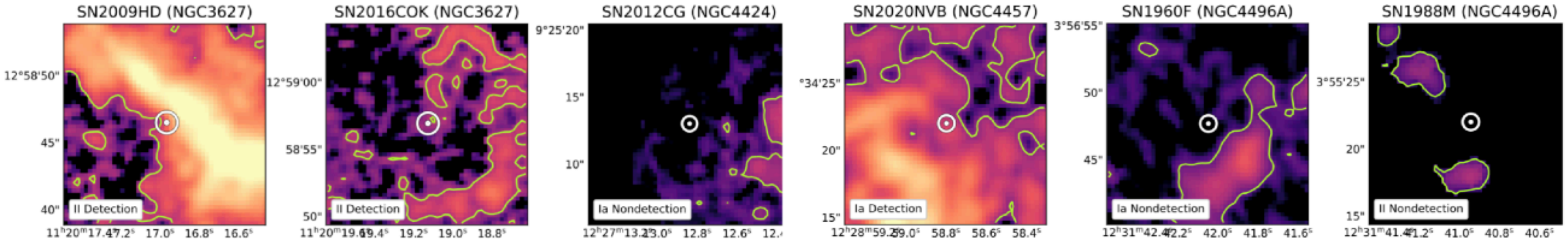
Simulations

Rapid cloud destruction by stellar feedback

- ★ Molecular cloud disrupted within 1-5 Myr (pre-SN)
- ★ Environmentally dependant timescale
- ★ Limits star formation efficiency
- ★ Early (pre-SN) feedback pre-processes the medium



McLeod et al. 2021



Mayker et al. (2023)

63 SNe in 31 galaxies

—> rarely correspond to the CO peak

What limits the star formation efficiency?

What feedback mechanisms can disperse the gas so quickly?

- Jets and outflows (disperse ***cores***, not GMCs)

Act on different timescales

- Supernovae

  ~ 3 - 15 Myr

- Ionizing EUV radiation

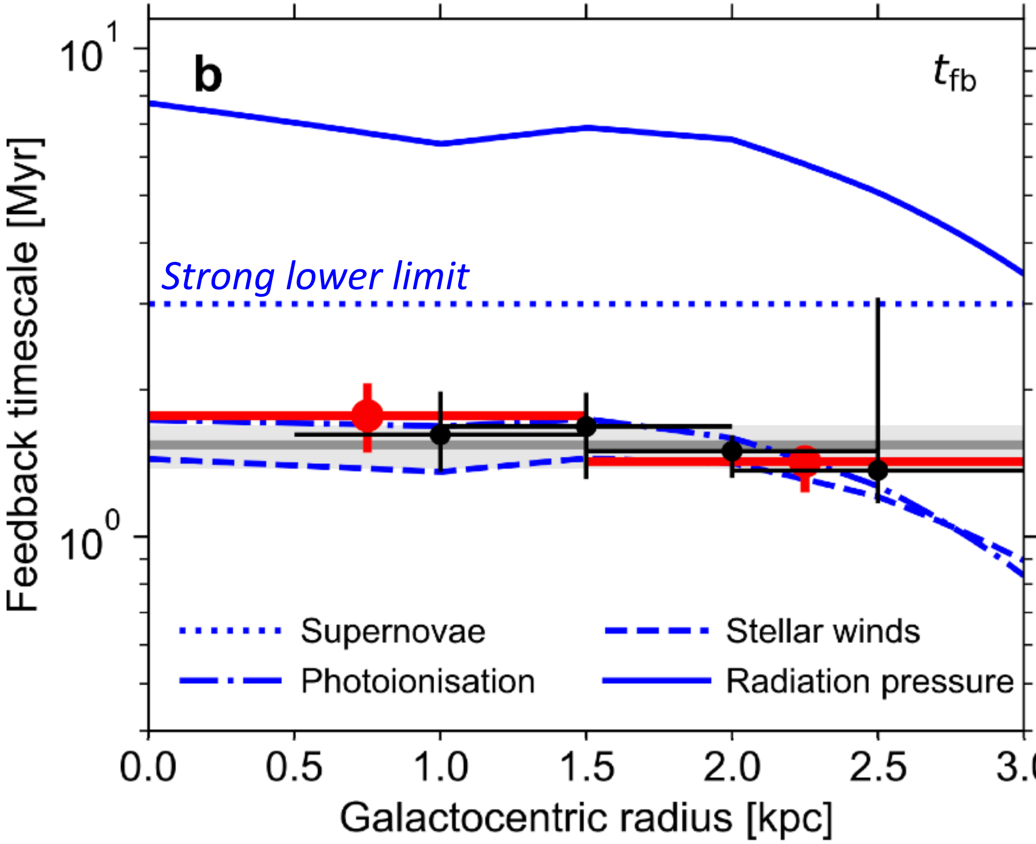
$$t_{phot} = \frac{4}{7}\left(\frac{3}{4}\right)^{1/2}\frac{r_{Strömgren}}{c_s}\left[\left(\frac{r_{GMC}}{r_{Strömgren}}\right)^{7/4} - 1\right]$$

- Stellar winds

$$t_{wind} = \left(\frac{154\pi}{125}\frac{\rho_{GMC}}{L_{wind}}\right)^{1/3} r_{GMC}^{5/3}$$

- Radiation pressure

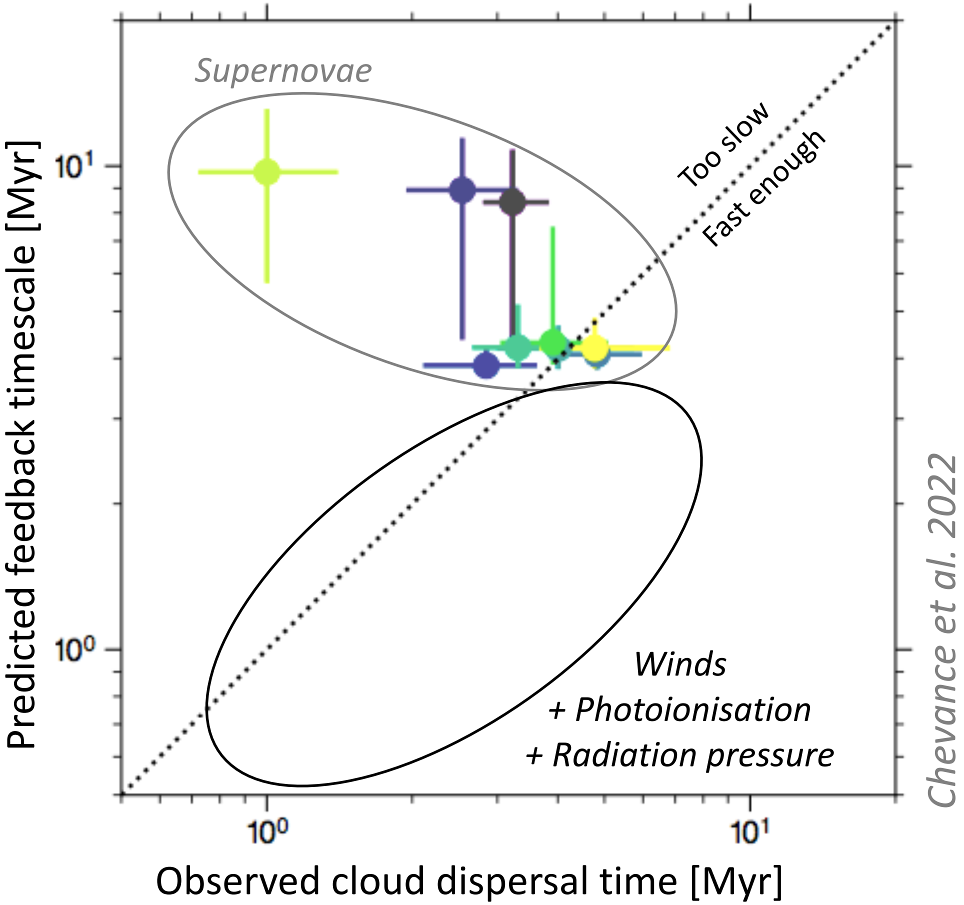
$$t_{rad} = \left(\frac{2\pi c}{3}\frac{\rho_{GMC}}{L_{bol}}\right)^{1/2} r_{GMC}^{2}$$



Kruijssen, Schruba, Chevance et al., 2019

What limits the star formation efficiency?

What feedback mechanisms can disperse the gas so quickly?



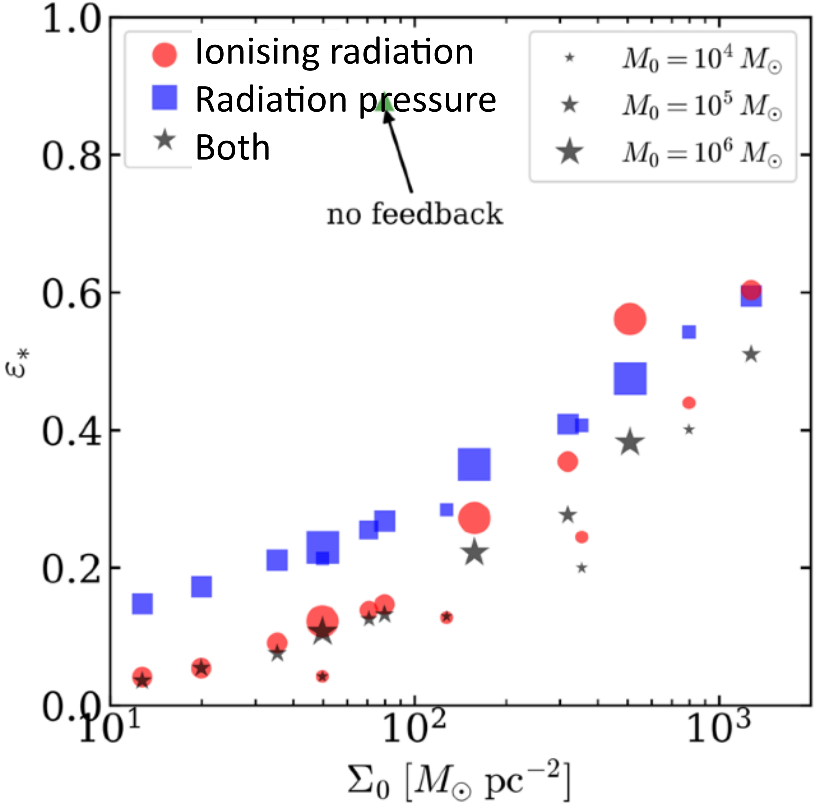
Chevance et al. 2022

- ***Pre-supernova*** mechanisms play an important role in dispersing the clouds.
- Their ***coupling efficiency*** with the surrounding gas is ***not 100%***.

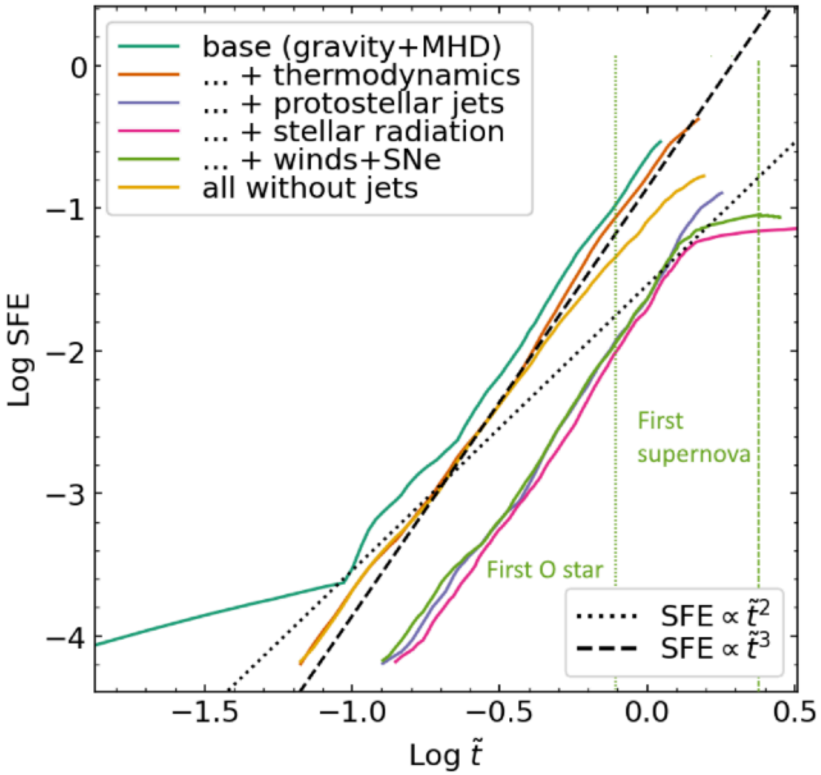
What limits the star formation efficiency?

What feedback mechanisms can disperse the gas so quickly?

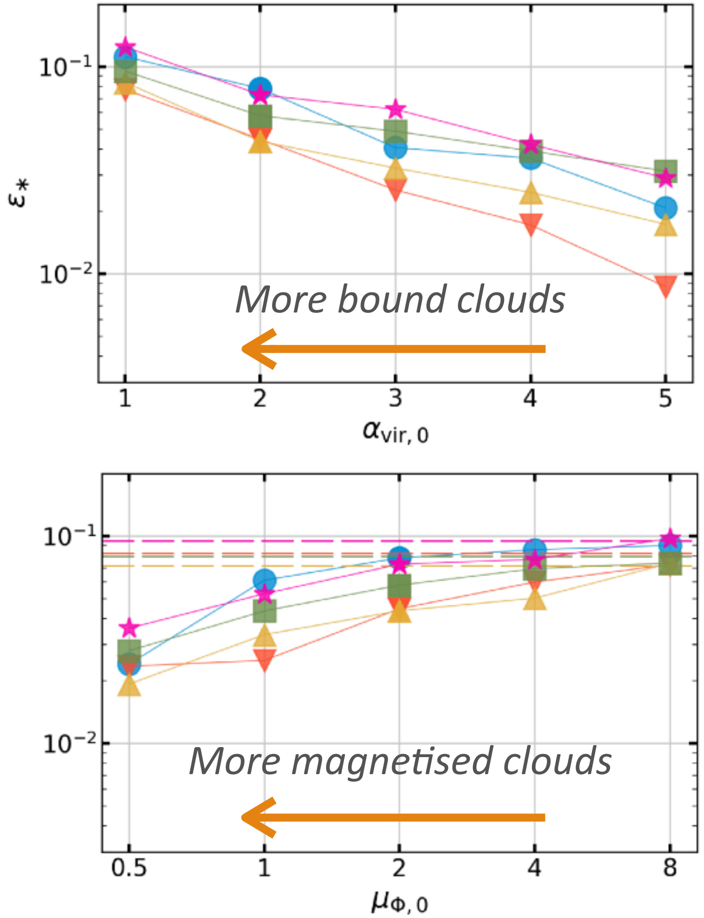
Kim, Kim & Ostriker 2018



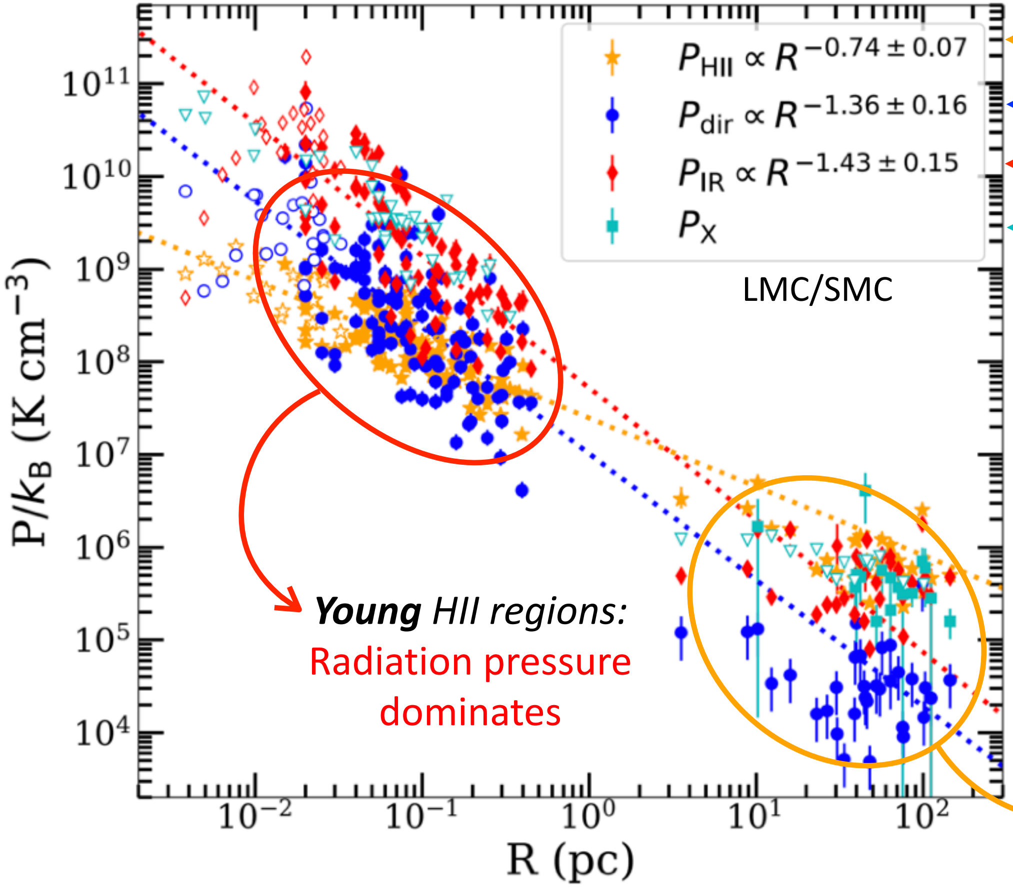
Guszejnov et al. 2022



Kim, Ostriker & Filippova 2021



Dominant feedback mechanism depends on ***evolutionary stage*** and ***environment***



Olivier et al. 2021

Photoionised gas pressure

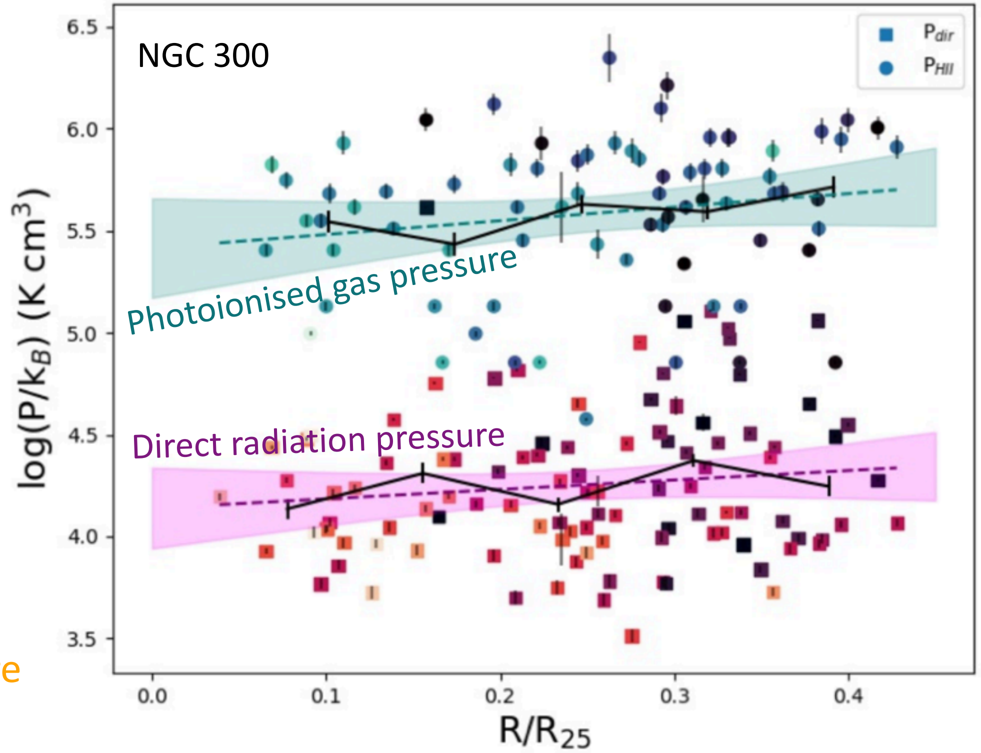
Direct radiation pressure

Dust-processed radiation pressure

Hot gas pressure

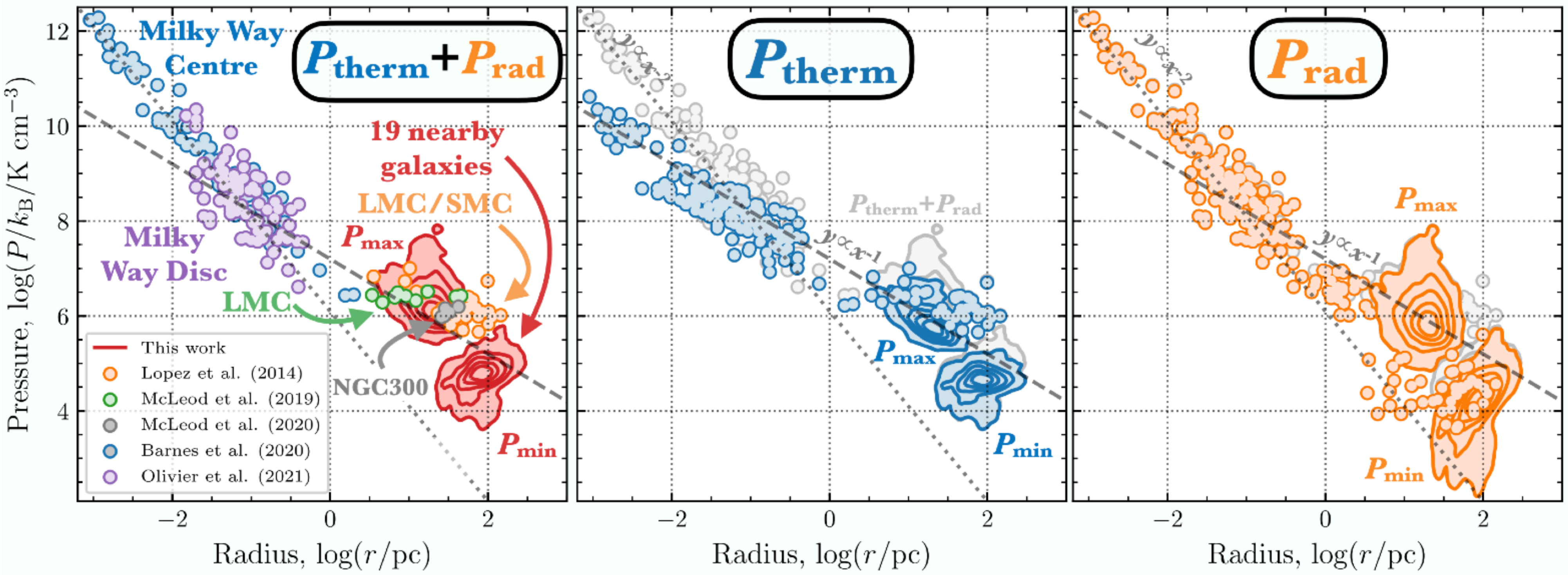
Young *HII regions:*
Radiation pressure
dominates

Evolved *HII regions:*
Photoionisation pressure
dominates



McLeod et al. 2021

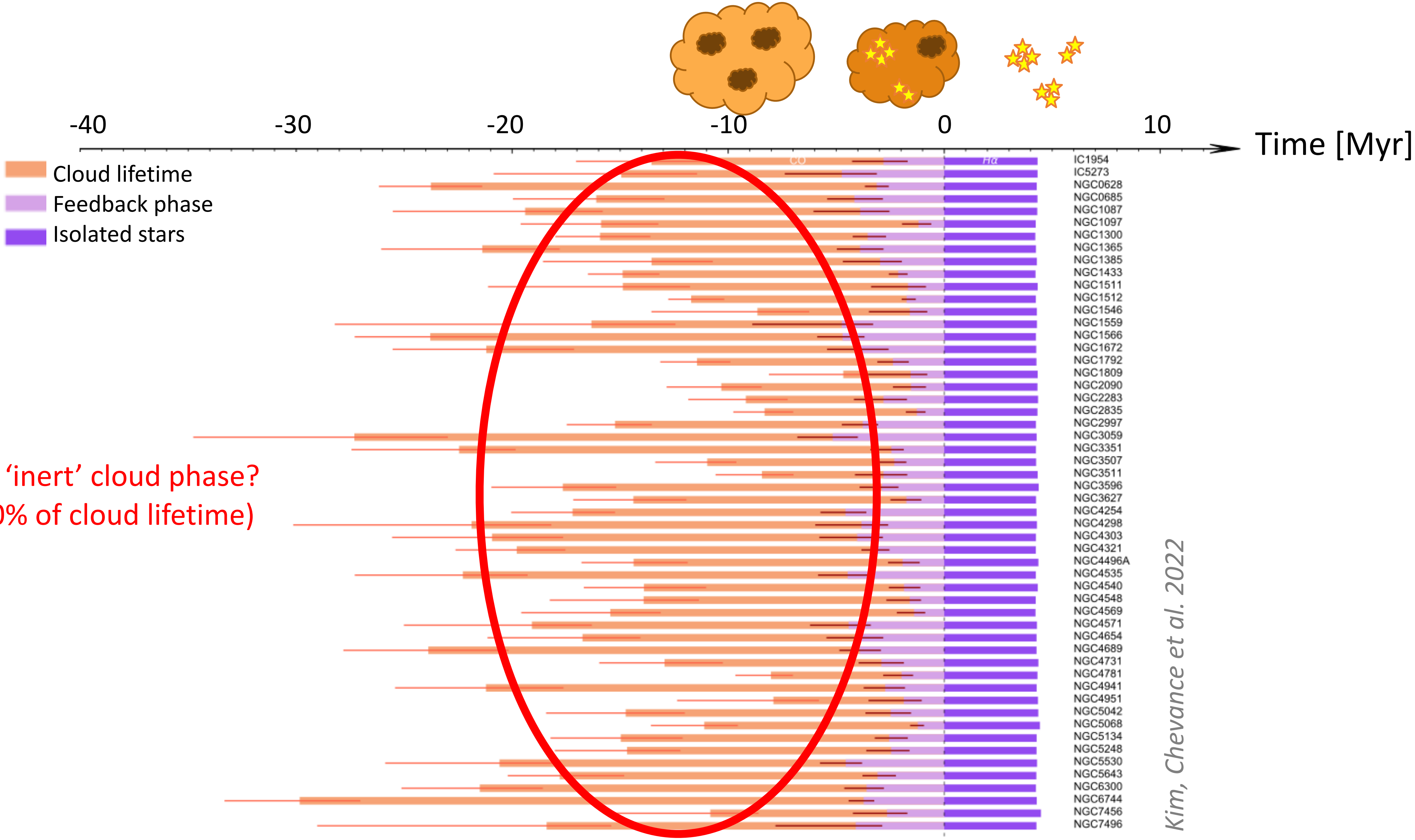
Dominant feedback mechanism depends on ***evolutionary stage*** and ***environment***



Barnes et al. 2021

Caveats:

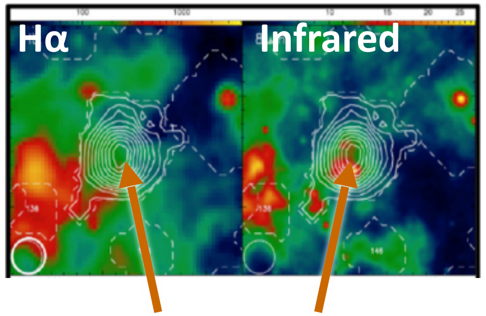
- Different observational tracers in different studies/environments
- Unresolved HII regions in nearby galaxies
- JWST for heated dust pressure in nearby galaxies



A long ‘inert’ cloud phase?
(70-90% of cloud lifetime)

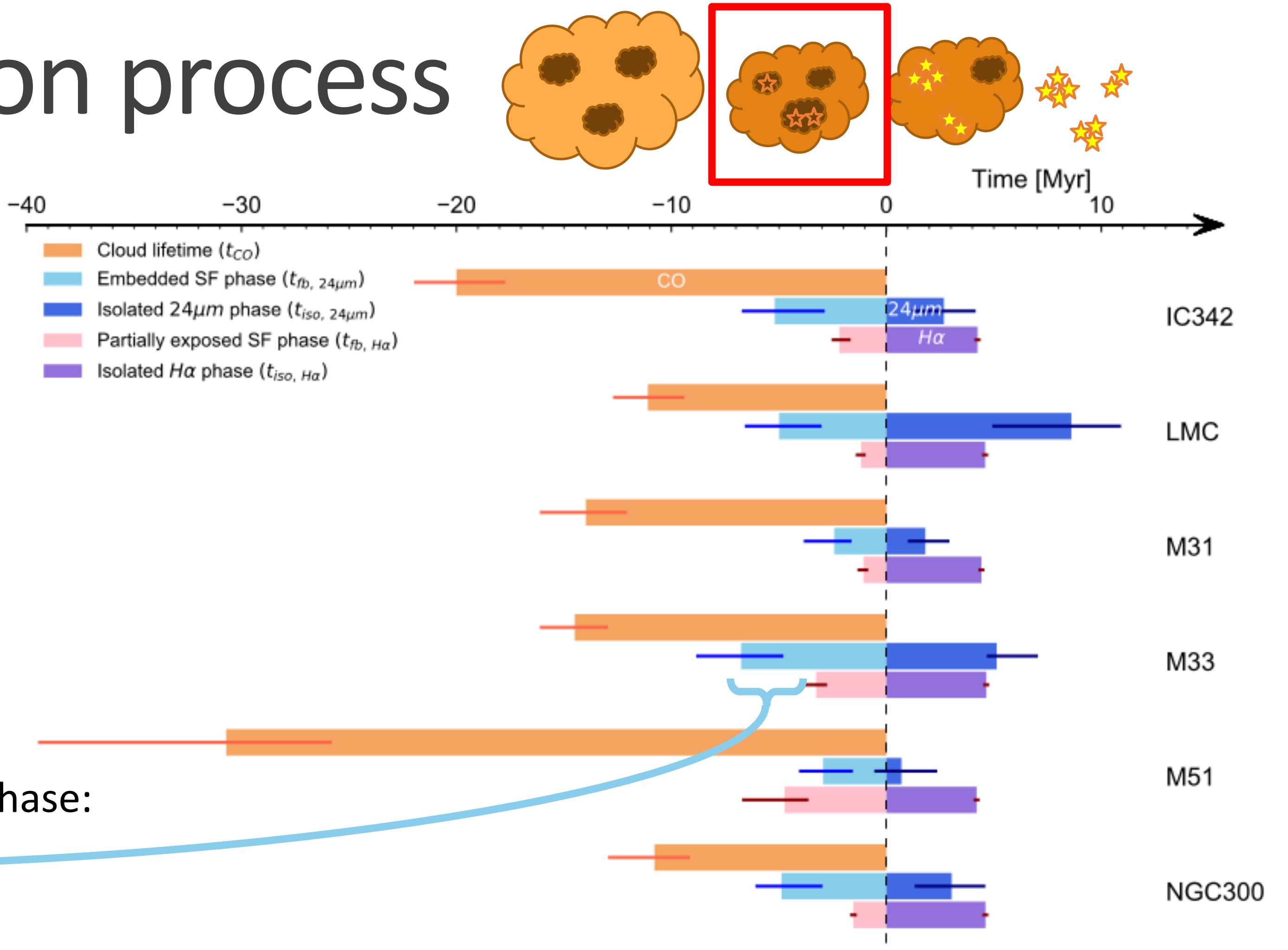
Kim, Chevance et al. 2022

Refining the gas expulsion process



Embedded young stars

Corbelli et al. 2017

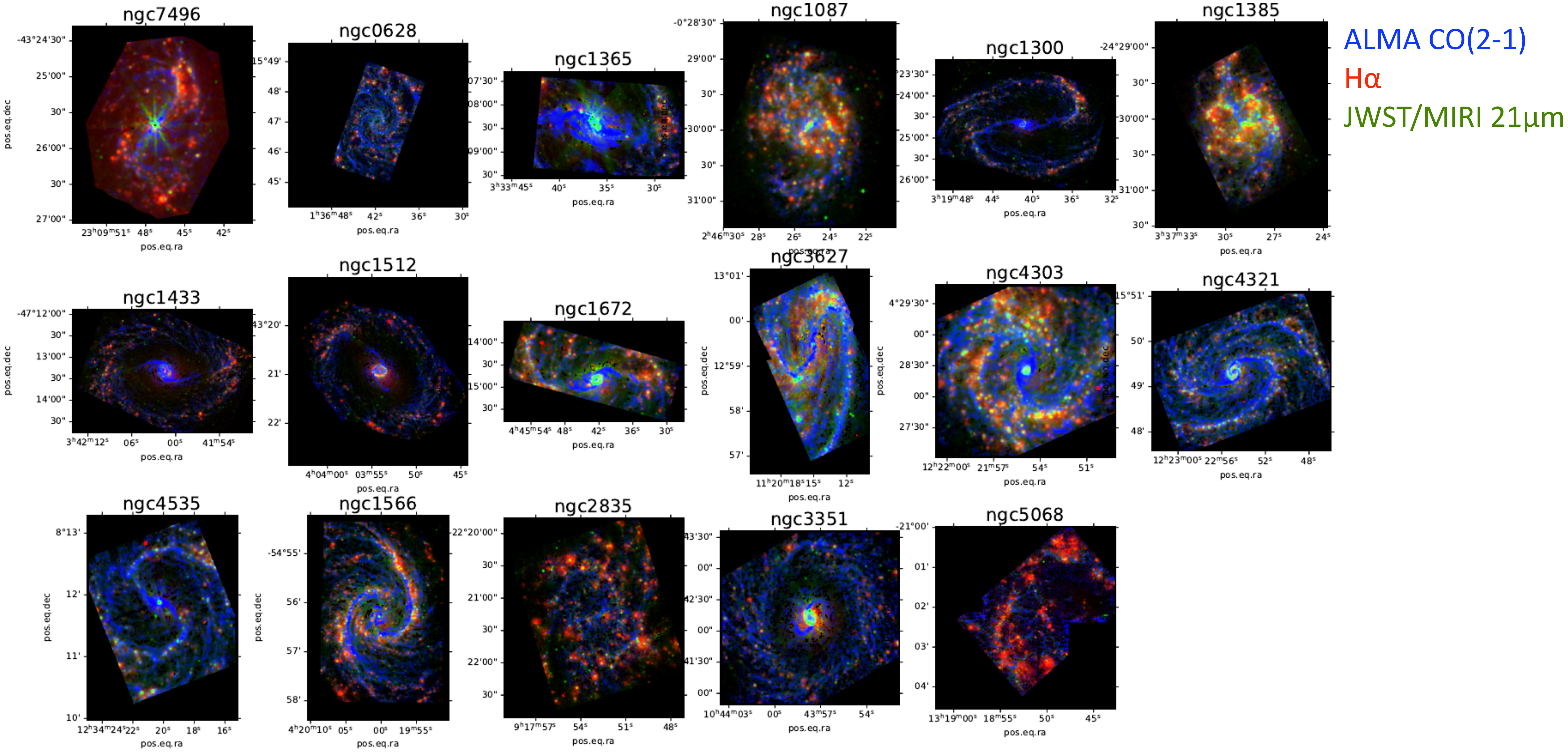


Heavily obscured star formation phase:

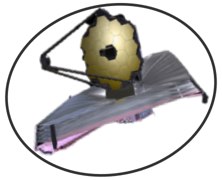
1.4-3.8 Myr

Kim, Chevance et al. 2021

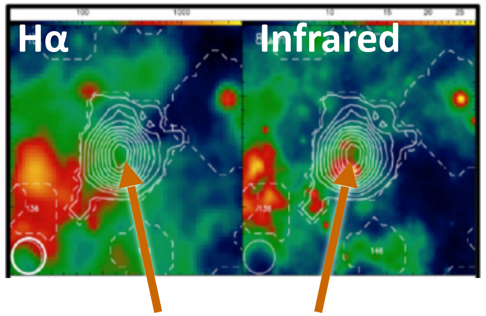
- ➢ Pre-*James Webb Space Telescope*: 6 galaxies



- Pre-*James Webb Space Telescope*: 6 galaxies
- Now: ongoing *JWST* Large Programme for **19 additional galaxies**
  approved *JWST* Large Programme for **55 additional galaxies**

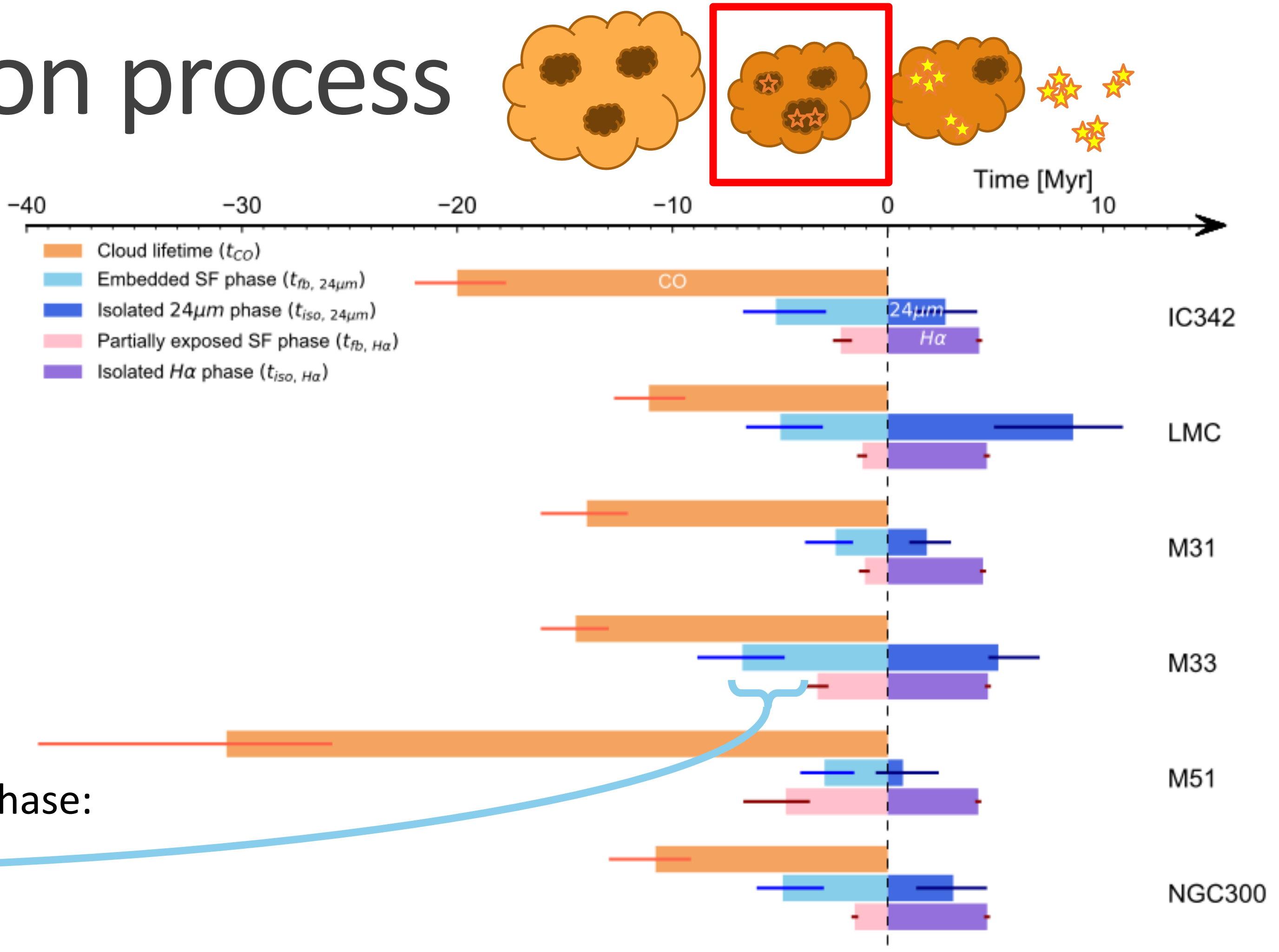


Refining the gas expulsion process



Embedded young stars

Corbelli et al. 2017



Heavily obscured star formation phase:

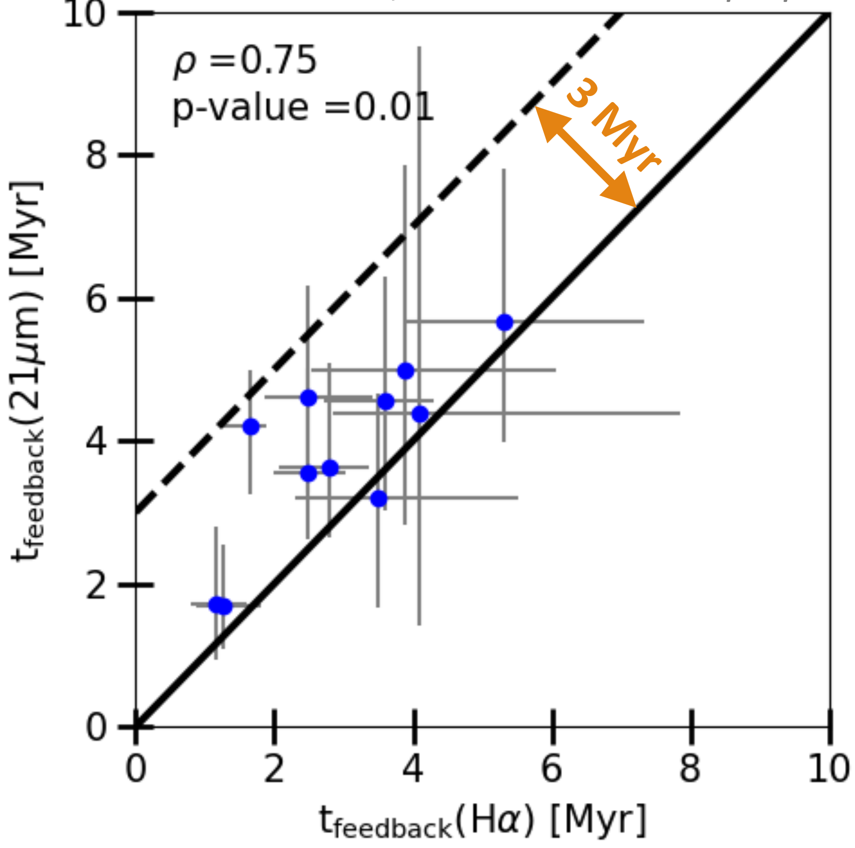
1.4-3.8 Myr

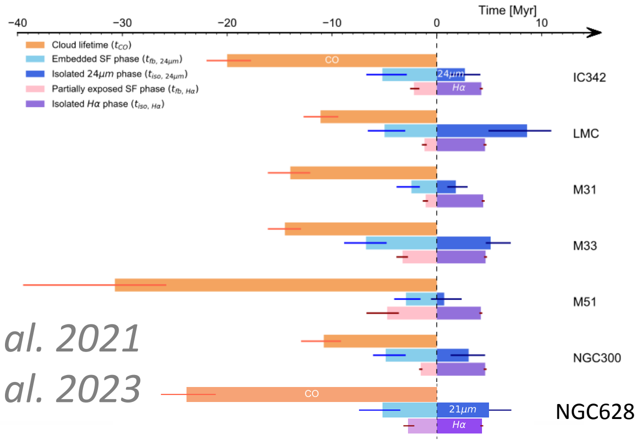
Kim, Chevance et al. 2021

- ➢ Pre-*James Webb Space Telescope*: 6 galaxies

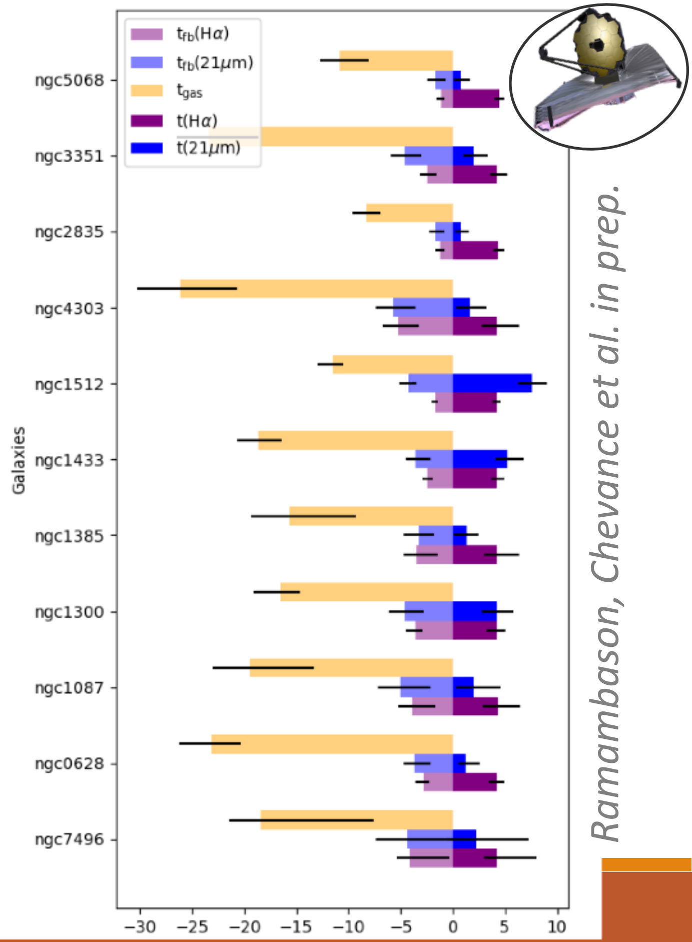
Refining the gas expulsion process

Ramambason, Chevance et al. in prep.





Kim, Chevance et al. 2021
Kim, Chevance et al. 2023

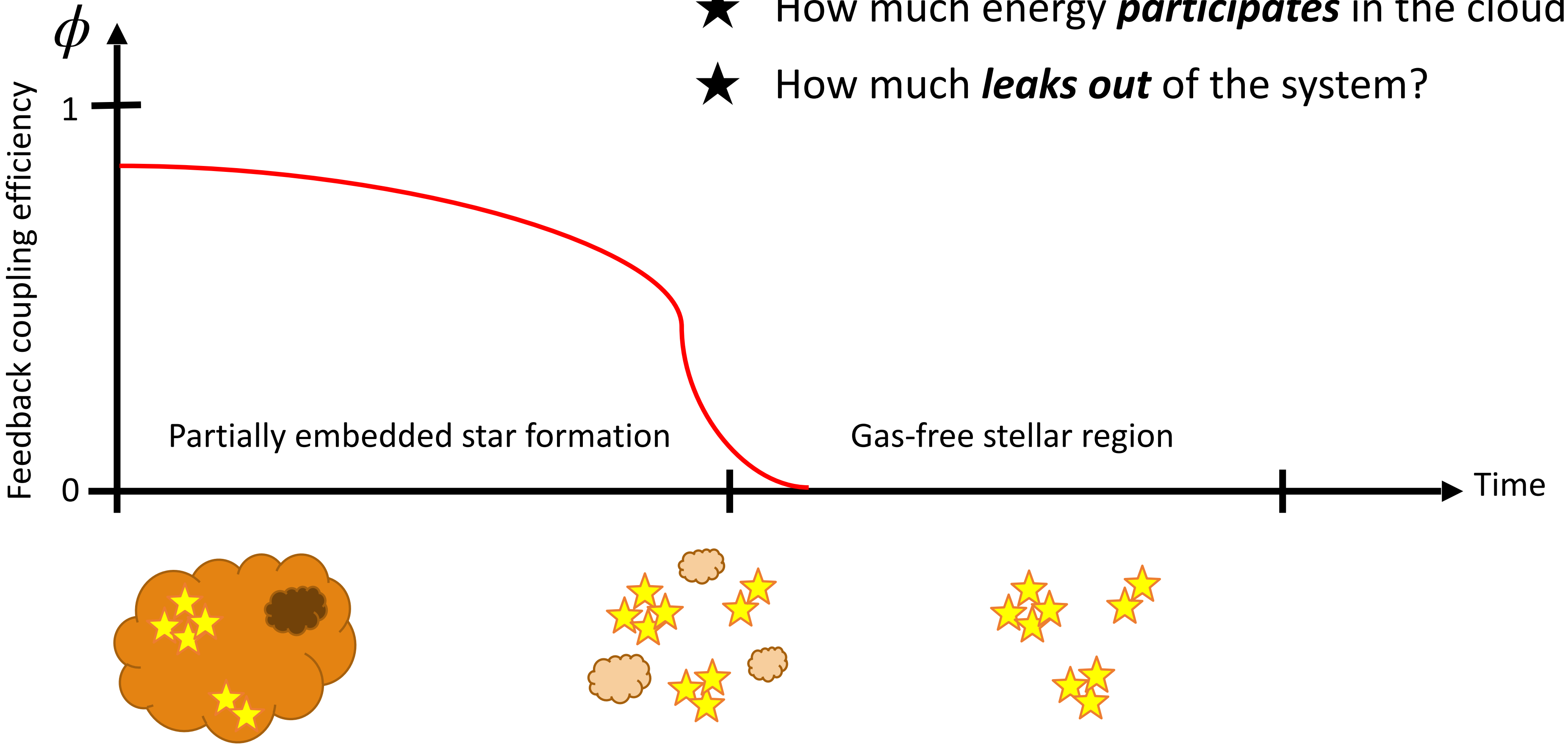


Ramambason, Chevance et al. in prep.

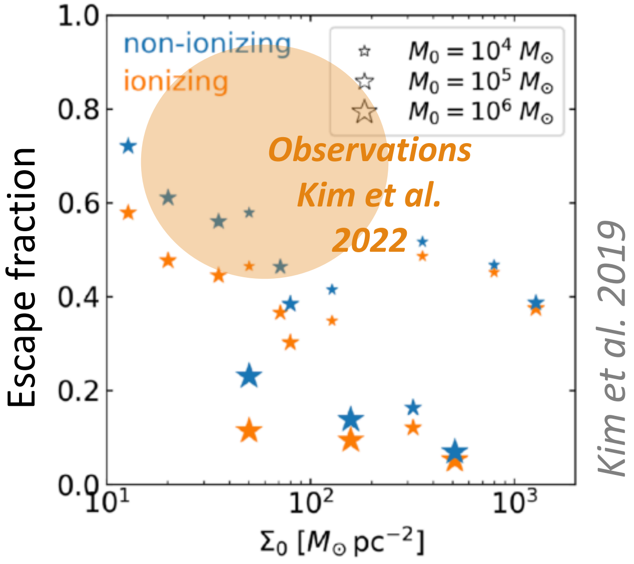
★ Deeply embedded stars (invisible in Hα) for ***at most 3 Myr***

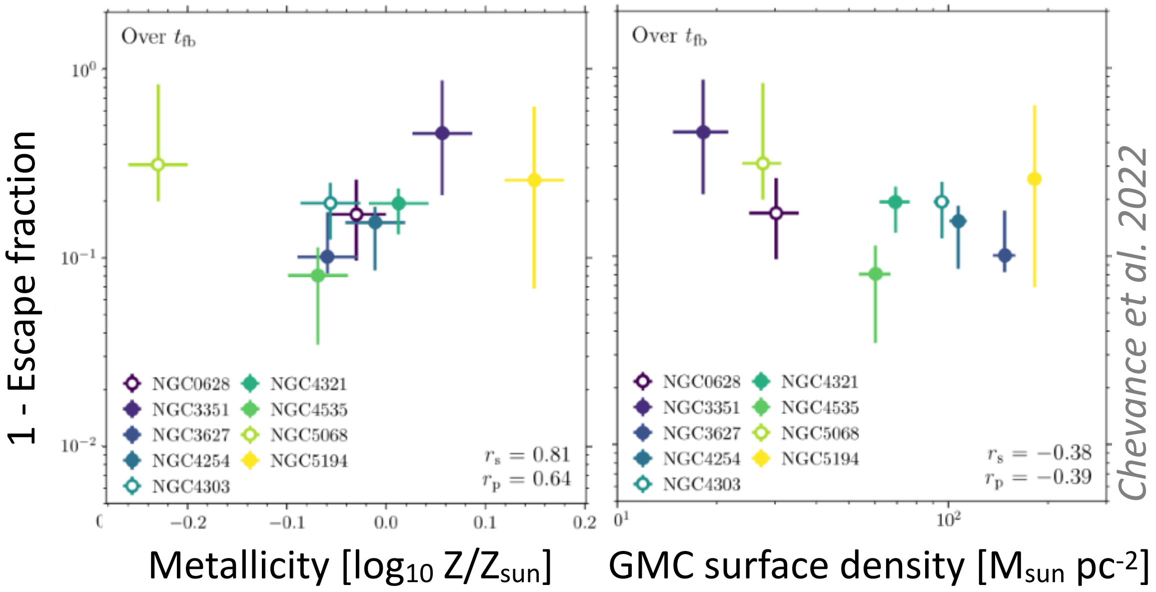
Feedback coupling efficiency — Escape fraction

- ★ How much energy ***participates*** in the cloud dispersal?
- ★ How much ***leaks out*** of the system?



Feedback coupling efficiency — Escape fraction



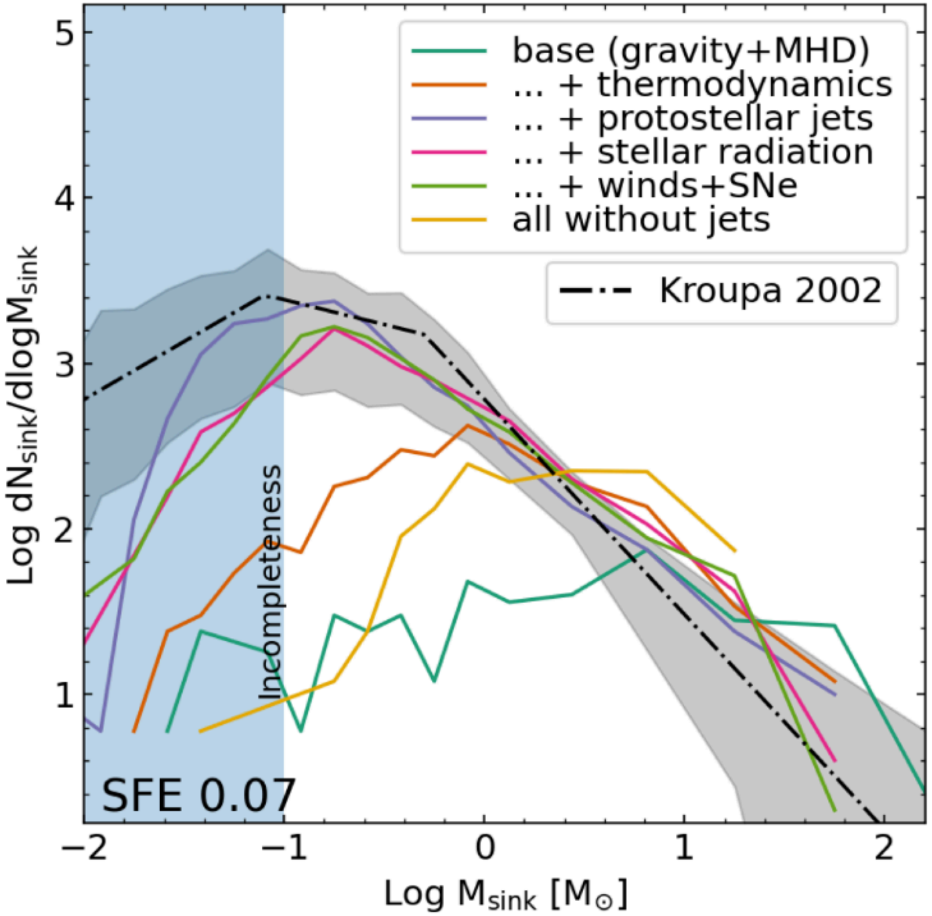


- ★ **Feedback coupling efficiencies of a few %,** qualitatively similar to simulations *(e.g. Howard et al. 2018, Kim et al. 2019, Rahner et al. 2019, Pellegrini et al. 2020)*
- ★ Explain (at least partially) **observed diffuse ionised hydrogen emission** throughout galaxies *(e.g. Poetrodjojo et al. 2019, Lucas et al. 2020)*
- ★ Environmental dependence: **more porous gas at low metallicities** *(e.g. Petitpas & Wilson 1998; Lebouteiller et al. 2012; Cormier et al. 2015; Chevance et al. 2016; Kimm et al. 2019, Ramambason et al. submitted)*
- ★ Energy losses: **photon leakage** (rather than radiative cooling) likely dominates

How do (massive) stars impact their surrounding?

- ★ Heat and ionise the gas
- ★ Disrupt GMCs
- ★ Limit star formation efficiency
- ★ Impact the IMF

Impact on the IMF



Guszejnov et al. 2022

★ ***Protostellar jets*** reduce stellar mass scales by:

- directly removing accreted material
- disrupting the accretion flow around stars

★ They cannot prevent the most massive stars from undergoing runaway accretion

★ ***Radiation, winds and SN*** have little direct effect on the IMF (prevent runaway accretion of massive stars)

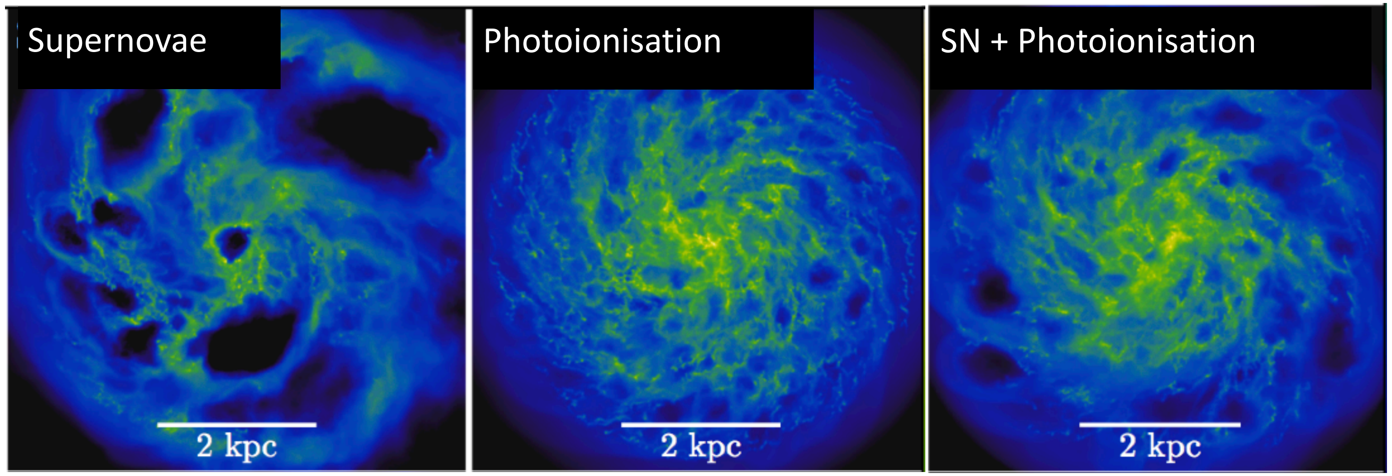
IV. Impact of feedback on galactic scales

Is the galaxy at large modified by these small-scale feedback mechanisms? *(i.e. do we care?)*

Yes!

Galaxy simulations with identical initial conditions

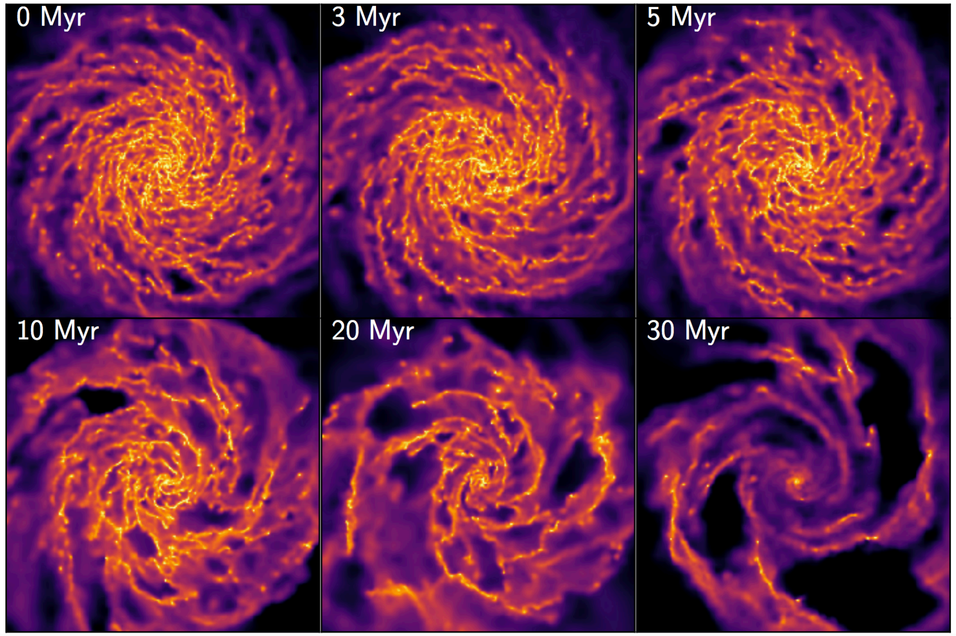
different feedback mechanisms



Gas density: low – medium – high

Smith et al. 2021

different SN delay time



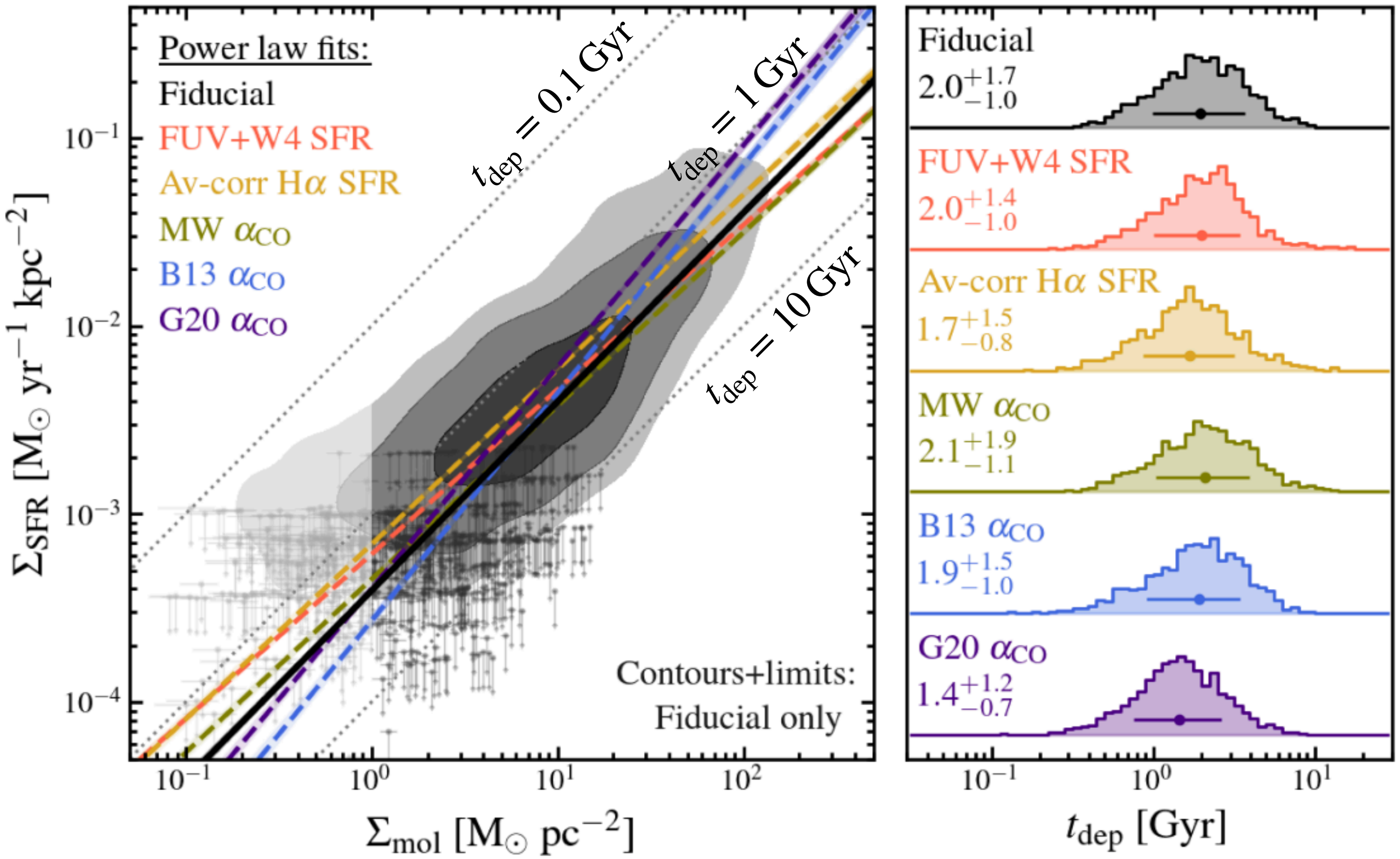
Keller & Kruijssen 2020

Impact of feedback on galactic scales

- ★ Limits SF efficiency —> ***regulates SFR***
- ★ Changes the ***morphology*** of galaxies at large
- ★ Regulates ***galactic outflows***

Self-regulated star formation model

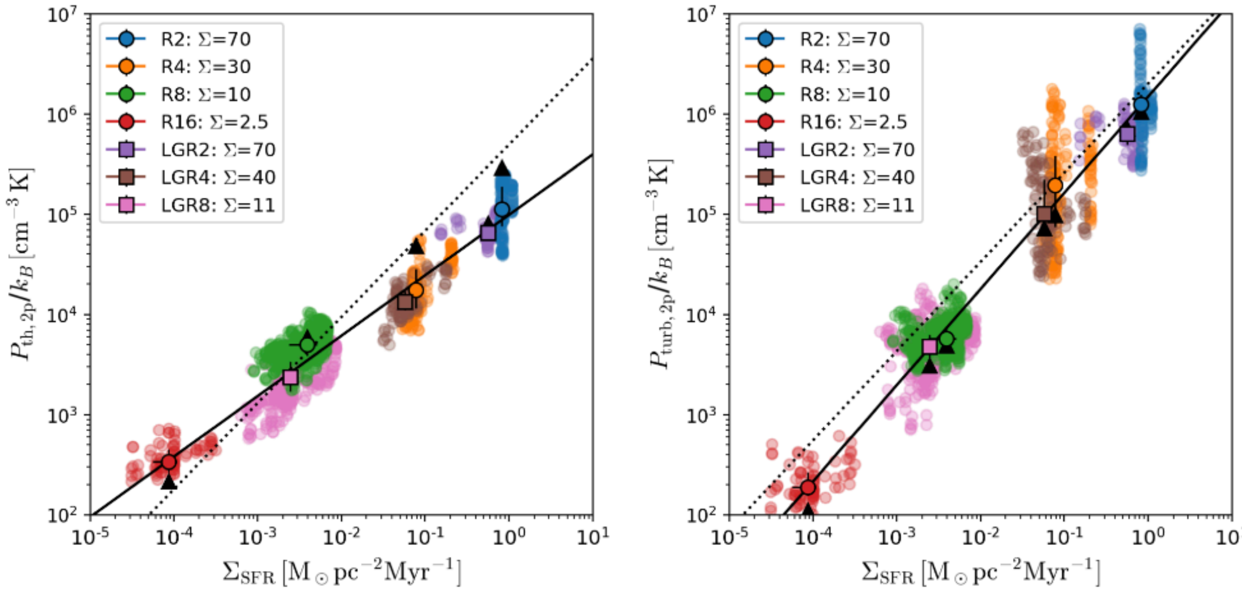
Molecular Schmidt-Kennicutt relation



Sun et al. 2023

Self-regulated star formation model

- ★ Galactic disk = system in equilibrium *(Ostriker et al. 2010, Ostriker & Shetty 2011)*
—> sum of **turbulent**+**thermal**+magnetic (+cosmic ray+radiation) terms balance ISM weight
- ★ Turbulence dissipation and radiation cooling ***must to be compensated***
- ★ Star formation is a ***source of energy and momentum*** via stellar and supernovae feedback
—> prevents collapse



Ostriker and Kim 2022

Self-regulated star formation model

★ Galactic disk = system in equilibrium *(Ostriker et al. 2010, Ostriker & Shetty 2011)*
—> sum of **turbulent**+**thermal**+magnetic (+cosmic ray+radiation) terms balance ISM weight

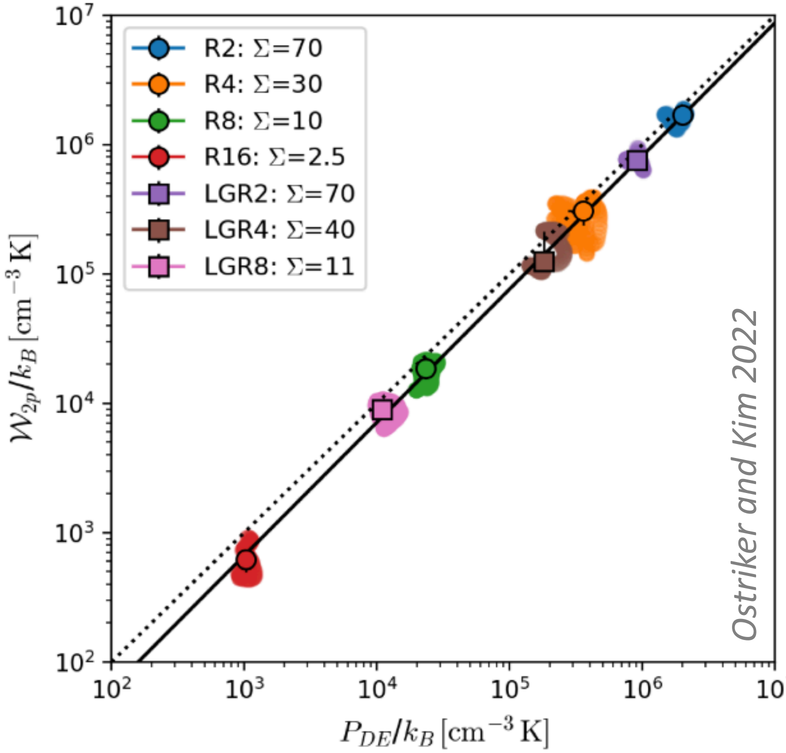
★ Turbulence dissipation and radiation cooling ***must to be compensated***

★ Star formation is a ***source of energy and momentum*** via stellar and supernovae feedback
—> prevents collapse

★ Local SFR ***required*** to keep the ISM in a long-term equilibrium set by the weight of the ISM
—> $\Sigma_{\rm SFR} \propto$ weight of the ISM per unit area (= ***dynamical equilibrium pressure*** $P_{\rm DE}$)

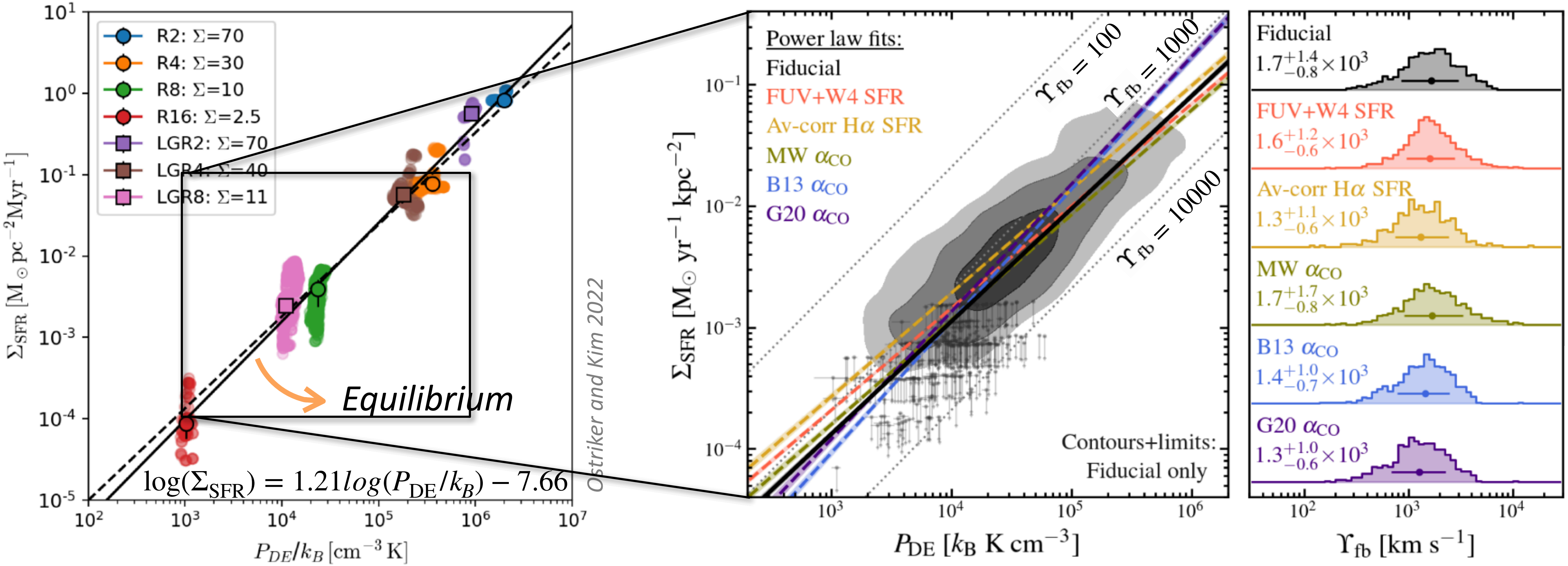
★ ***Feedback yield***: $Y_{\rm FB} = P_{\rm DE}/\Sigma_{\rm SFR}$

(also see Ostriker & Kim 2022)



Ostriker and Kim 2022

Self-regulated star formation model



Simulations

Observations

Ostriker and Kim 2022

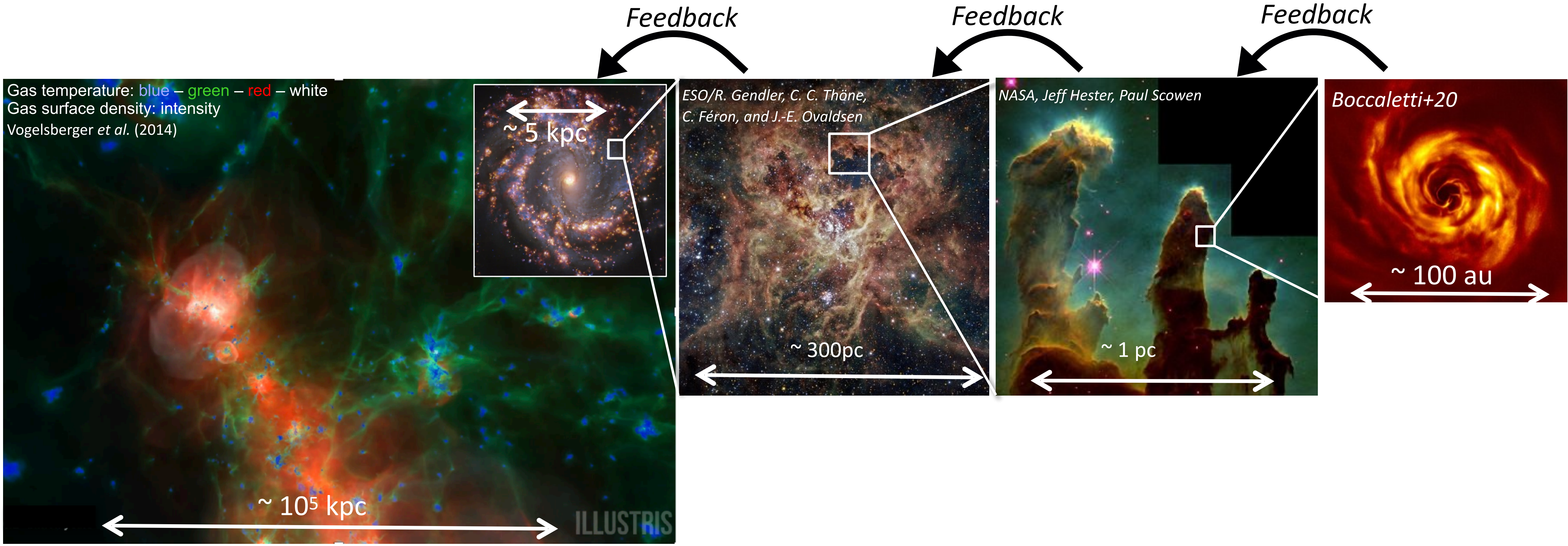
Sun et al. 2023

Impact of feedback on galactic scales

- ★ Limits SF efficiency —> ***regulates SFR***
- ★ Changes the ***morphology*** of galaxies at large
- ★ Regulates ***galactic outflows***

Including stellar feedback in galaxy formation and evolution simulations

Challenge: The range of ***temporal and spatial scales is so large***, that models and simulations require ***sub-resolution prescriptions***



Vogelsberger *et al.* (2014)

ESO/R. Gendler, C. C. Thöne, C. Féron, and J.-E. Ovaldsen

NASA, Jeff Hester, Paul Scowen

Boccaletti+20

Duration ←

Galaxy formation and evolution
~ Gyr

Molecular clouds
Stellar evolution
~ Myr

Prestellar cores
~ kyr

Supernovæ
~ yr

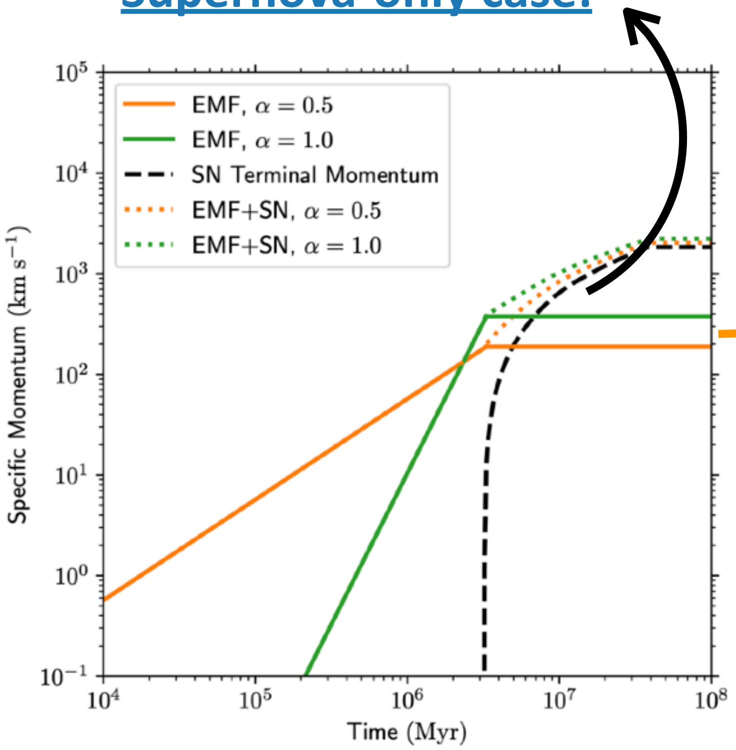
Including stellar feedback in galaxy formation and evolution simulations

- ★ Tuning the (*many*) free parameters
- ★ Using the results of small-scale simulations
- ★ Using empirical results from observations

Impact of the details of stellar feedback modelling on global galactic properties

The '*Empirically Motivated Physics*' suite of simulations adopts an **empirically-motivated feedback model**

Supernova-only case:



Empirically-motivated feedback case:

Early stellar feedback:

Specific terminal momentum set by measured quantities:

$$\mathbb{P}(t_{FB}) = \alpha \frac{r_{cl}(1-\varepsilon_{SF})}{\varepsilon_{SF} t_{FB}} \qquad \alpha \in [0.5;1]$$

Injected momentum as a function of time follows from self-similarity:

$$\mathbb{P}(t) = \alpha \frac{r_{cl}(1-\varepsilon_{SF})}{\varepsilon_{SF} t_{FB}} \left(\frac{t}{t_{FB}}\right)^{4\alpha-1}$$

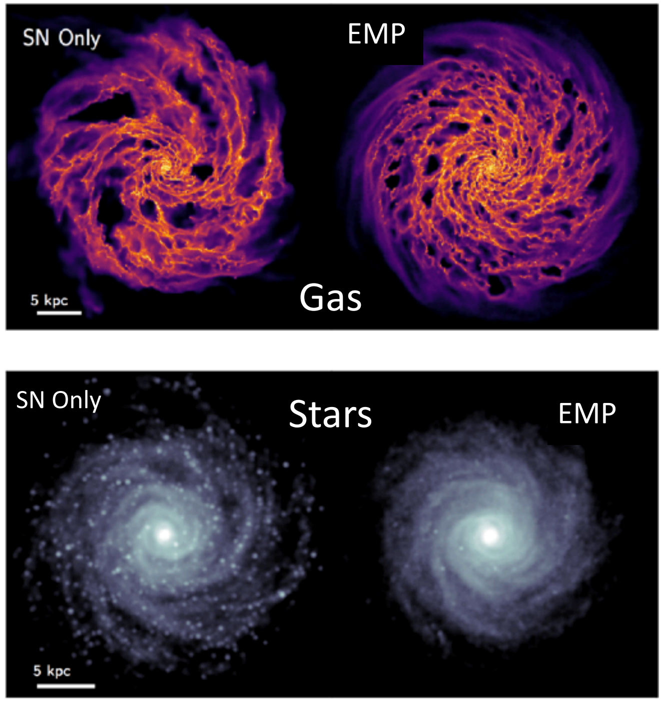
Keller, Kruijssen & Chevance 2022

Impact of the details of stellar feedback modelling on global galactic properties

The ‘*Empirically Motivated Physics*’ suite of simulations adopts an **empirically-motivated feedback model**

Supernova-only case:

Empirically-motivated feedback case:



Smoother discs in the *EMP model* compared to *SN-only model*

Keller, Kruijssen & Chevance 2022

Impact of the details of stellar feedback modelling on global galactic properties

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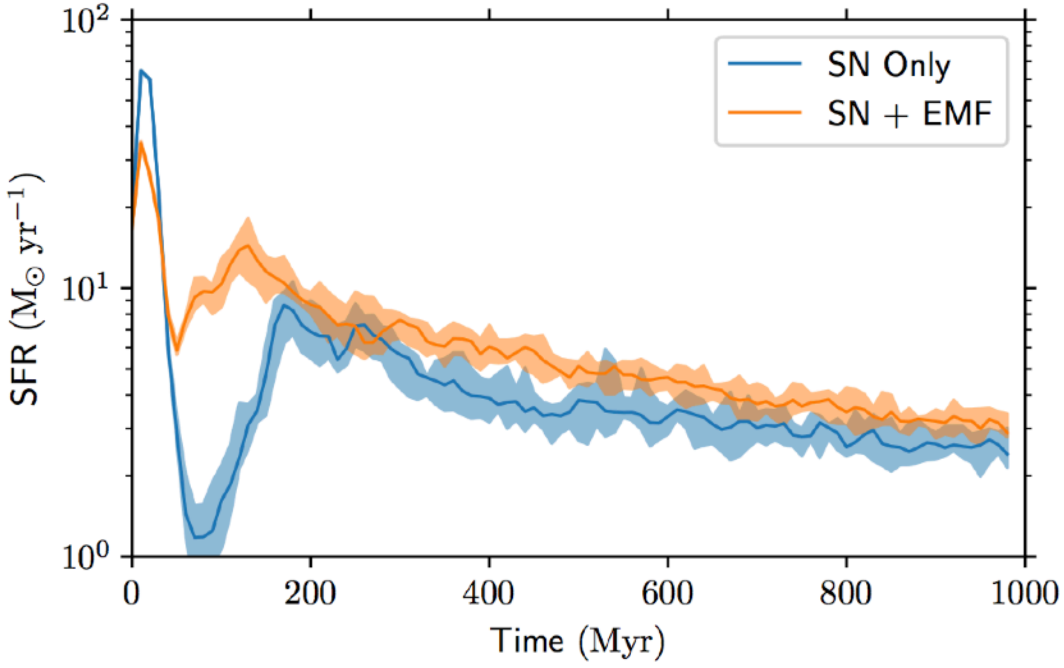
Supernova-only case:

Empirically-motivated feedback case:



SFR and Schmidt-Kennicutt relation consistent with observations

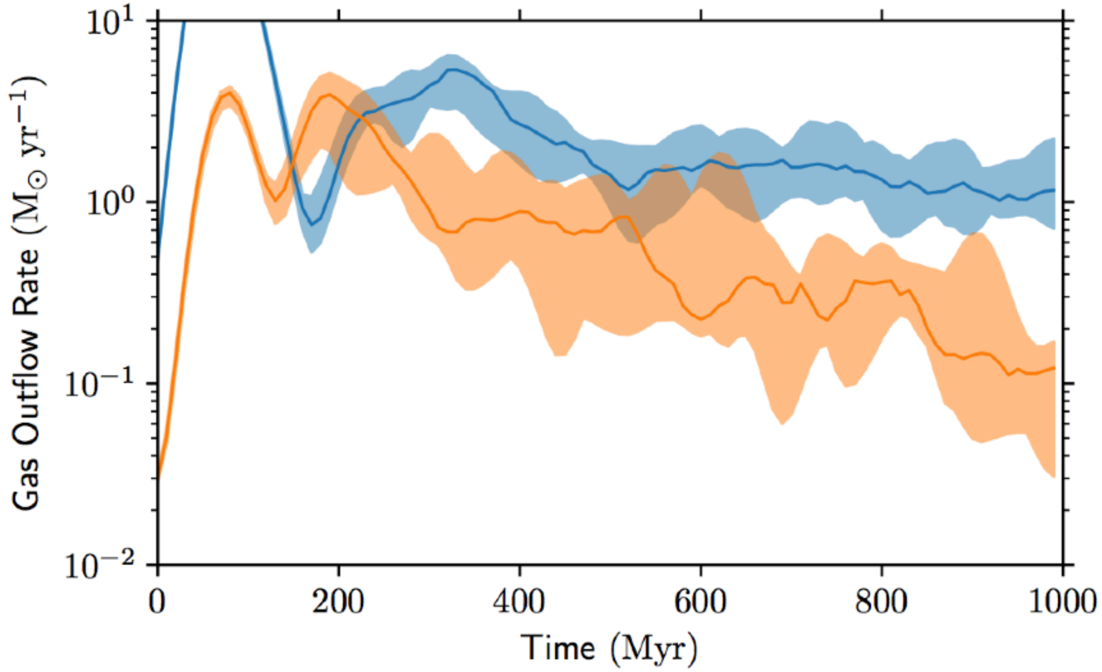
Keller, Kruijssen & Chevance 2022

Impact of the details of stellar feedback modelling on global galactic properties

The ‘*Empirically Motivated Physics*’ suite of simulations adopts an **empirically-motivated feedback model**

Supernova-only case:

Empirically-motivated feedback case:



Weaker outflows in the *EMP model* compared to *SN-only model*

Keller, Kruijssen & Chevance 2022

Impact of feedback

On GMC scales:

- ★ Heat and ionise the gas
- ★ Disrupt GMCs
- ★ Limit star formation efficiency
- ★ Impact the IMF

On galactic scales:

- ★ Limits SF efficiency —> ***regulates SFR***
- ★ Changes the ***morphology*** of galaxies at large
- ★ Regulates ***galactic outflows***

Major open questions

Fundamental physics question:

★ ***What is the deposition rate of mass, energy and momentum by feedback as a function of time, space and environment?***

Steps needed to address this overarching question:

★ What is (are) the dominant feedback mechanism(s) as a function of evolutionary age and environment?

★ How do the different feedback mechanisms interact with each other?

★ How do feedback mechanisms couple across all spatial scales, from single star formation to entire galaxies?

★ How do we capture all of these processes in simulations? Is there a theory of everything or will we always need multiple models?

★ How do magnetic fields affect the deposition of mass, energy and momentum by feedback?

References

Books and General Reviews:

- **Krumholz** et al., *PPVI*, 2014
- **Dale**, *New Astronomy reviews*, 2015
- **Krumholz**, *Star Formation* (esp. Chapter 7), 2017
- **Girichidis** et al., *Space Science Reviews*, 2020
- **Rosen** et al., *Space Science Reviews*, 2020
- **Chevance** et al., *PPVII*, 2023