Feedback and the evolution of molecular clouds

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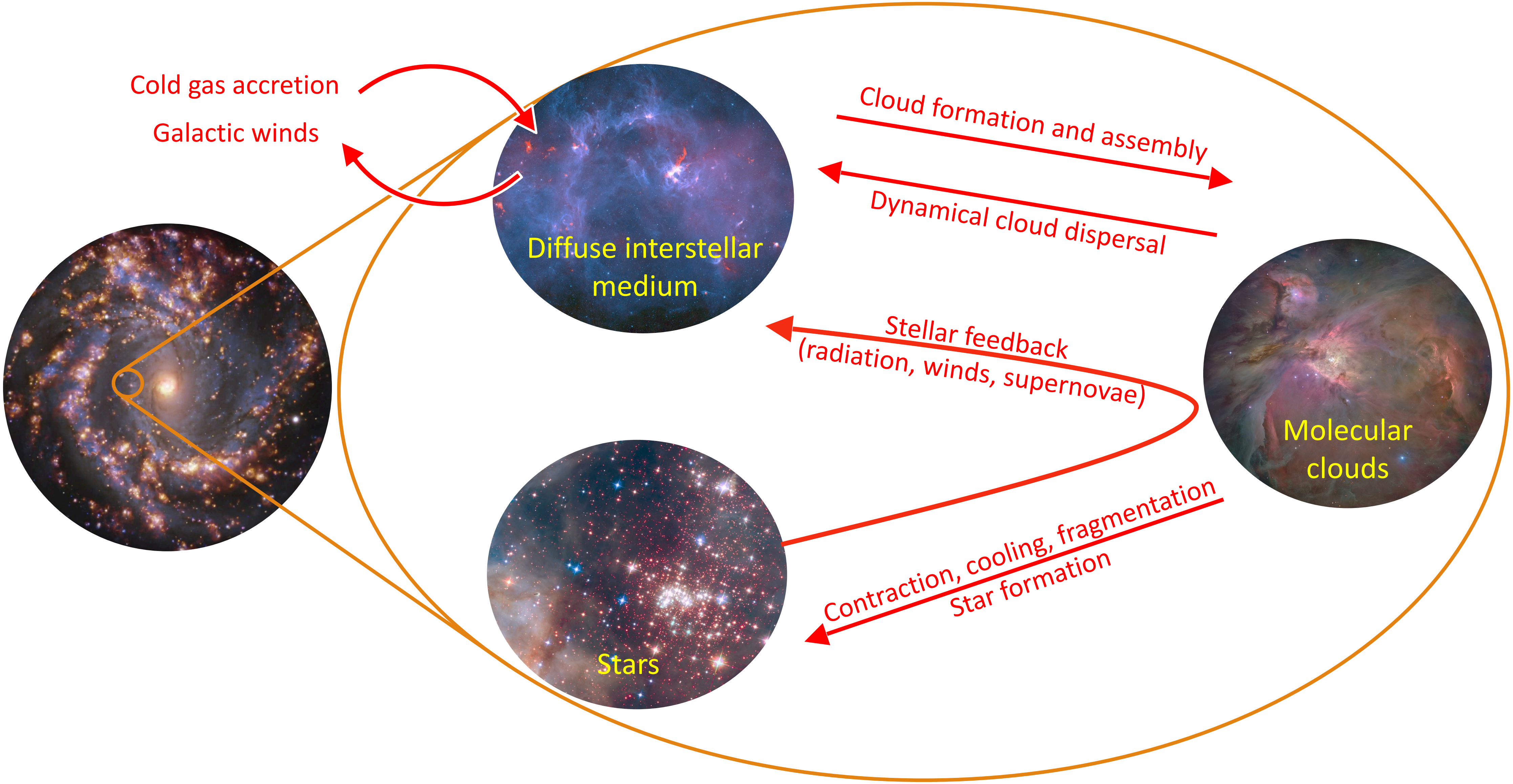
DFG Deutsche Forschungsgemeinschaft

Star Formation, Stellar Feedback, and the Ecology of Galaxies — Visegrád — May 27th 2025


Cold gas accretion
Galactic winds
Diffuse interstellar medium
Cloud formation and assembly
Dynamical cloud dispersal
Stellar feedback
(radiation, winds, supernovae)
Molecular clouds
Contraction, cooling, fragmentation
Star formation
Stars

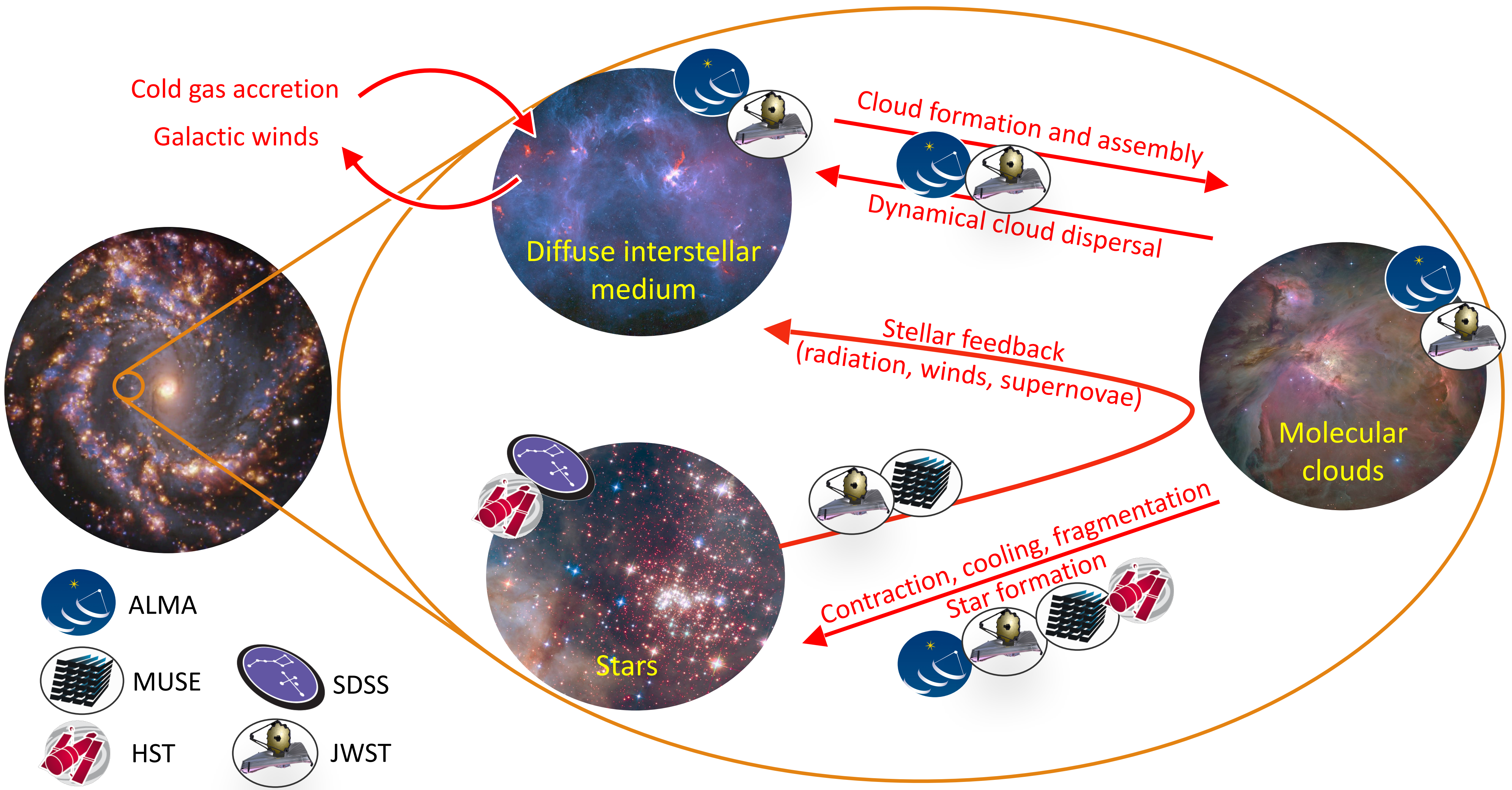
Simulation: *Keller, Kruijssen, Chevance et al. 2022*

Gas density: low – medium – high

How do galaxies turn their gas into stars?

How do the new-born stars impact the remaining gas?

How does this cycle depend on the galactic properties & environment?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ALMA
MUSE
SDSS
HST
JWST

Recent observational breakthroughs now ***enable*** addressing these challenges

Phangs

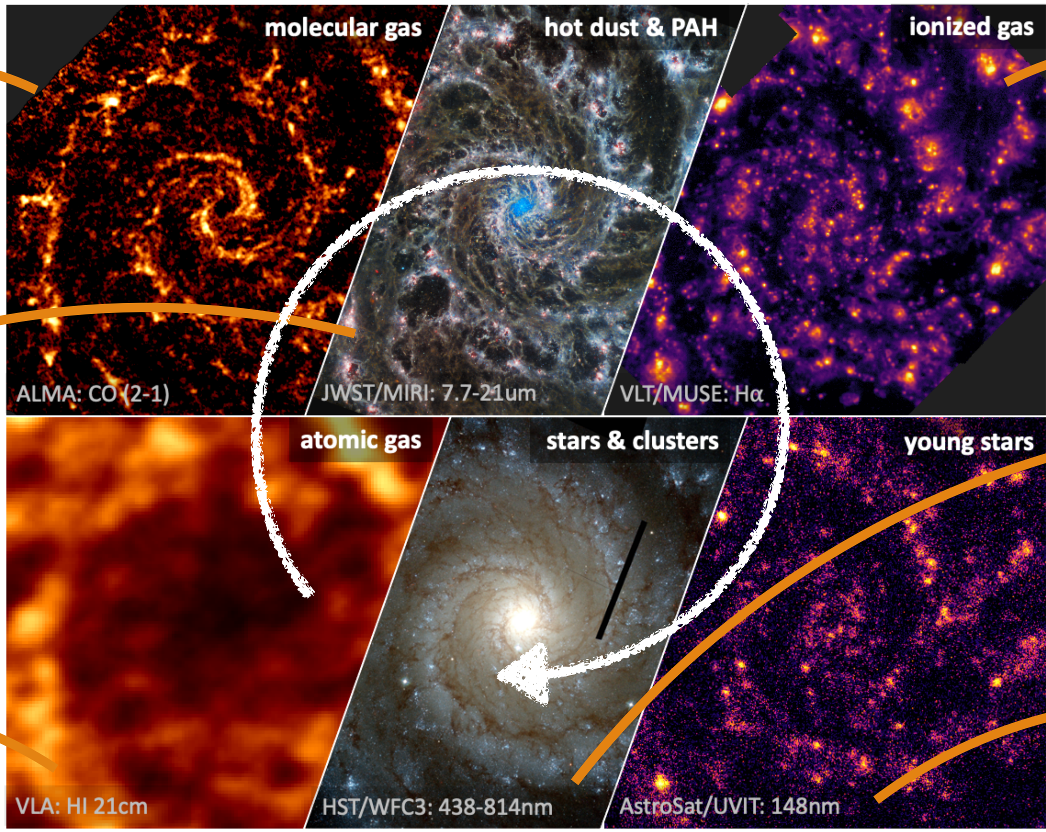
Physics at **H**igh **A**ngular resolution in **N**earby **G**alaxies

Leroy et al. 2021a, b • Lee et al. 2021 • Emsellem et al. 2022 • Lee et al. 2023 • Razza et al. to be subm.

ALMA
74 (+26) *galaxies*

JWST
74 *galaxies (Cycle 1 & 2)*

VLA
50 *galaxies*



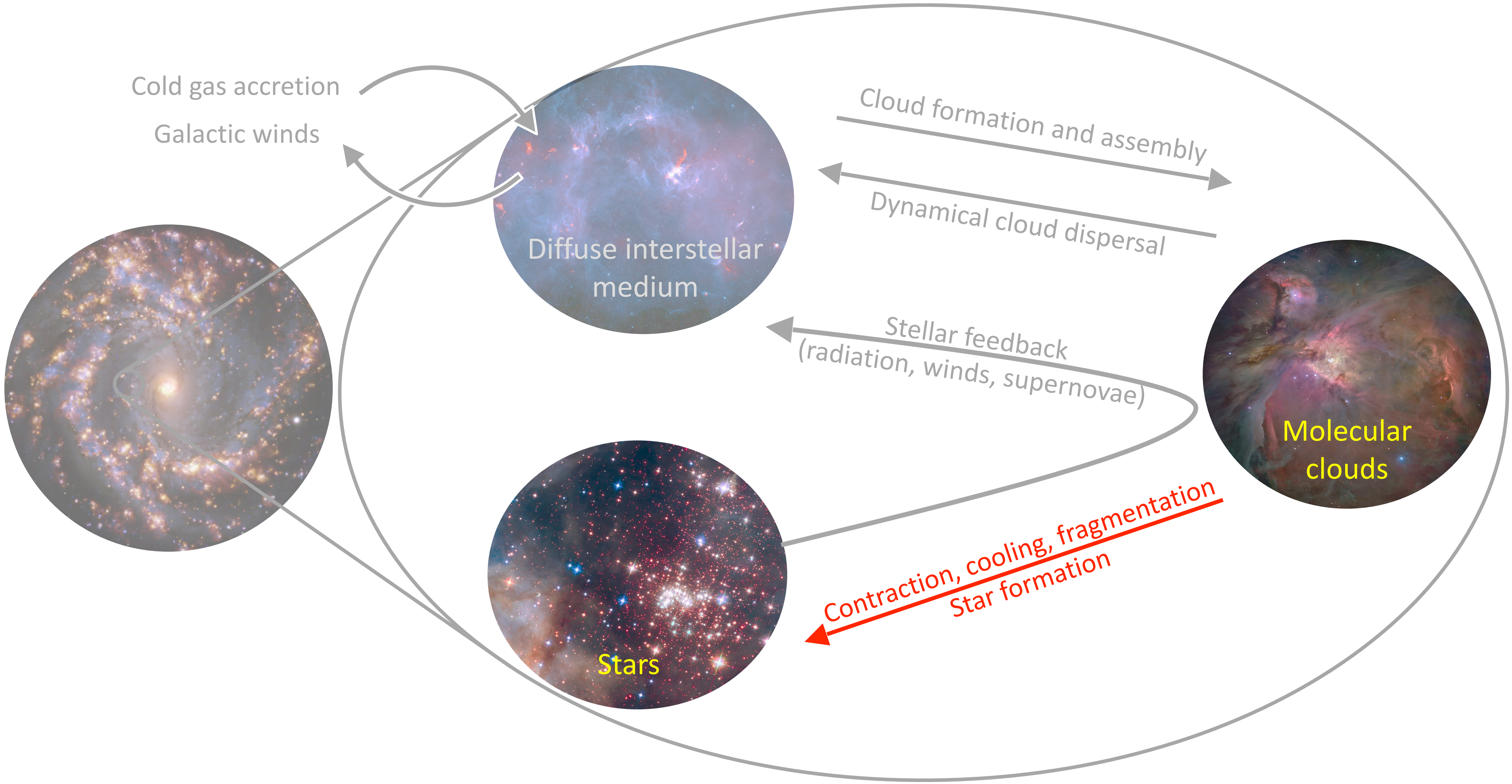
MUSE
19 *galaxies*

Other Hα surveys
74++ *galaxies*

HST
38 *galaxies*

Astrosat
35 *galaxies*

+ Complementary data with IRAM-30m, NOEMA, MeerKAT, Spitzer…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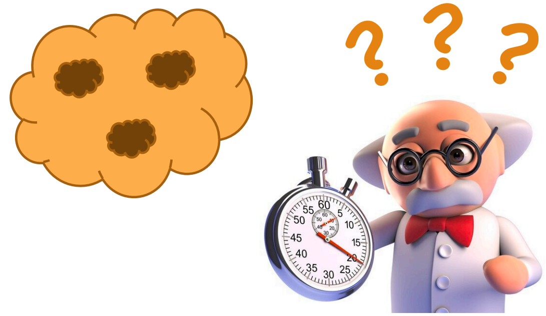
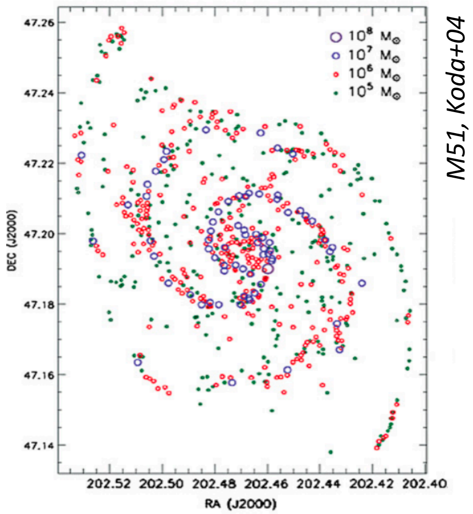
Measuring Myr timescales — How?



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

> 100 Myr?

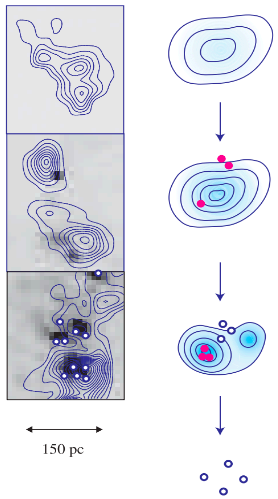


M51, Koda+04

Molecular clouds between galactic arms

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

10-50 Myr?

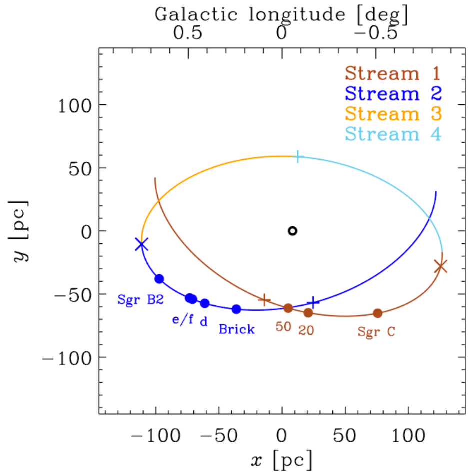


LMC, Kawamura+09

Classification of clouds

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

~ 1 Myr?



CMZ, Kruijssen+15

Gas orbiting the centre of our Galaxy

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

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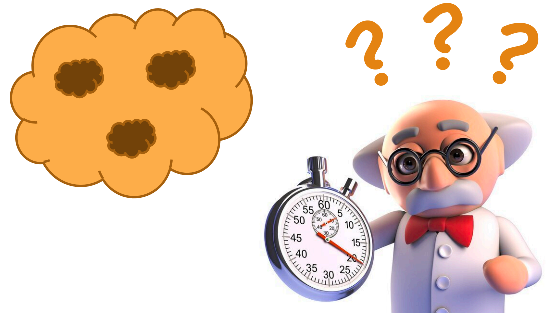

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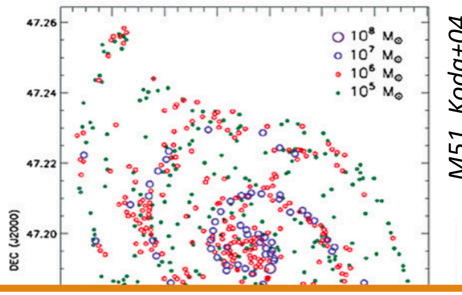

M51, Koda+04

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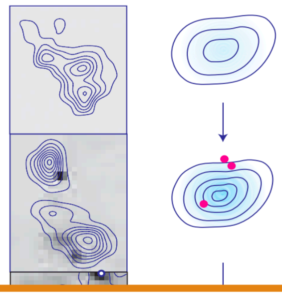

LMC, Kawamura+09

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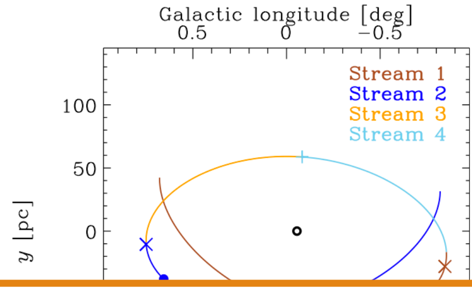


CMZ, Kruijssen+15

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

Mo … axy

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

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

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

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

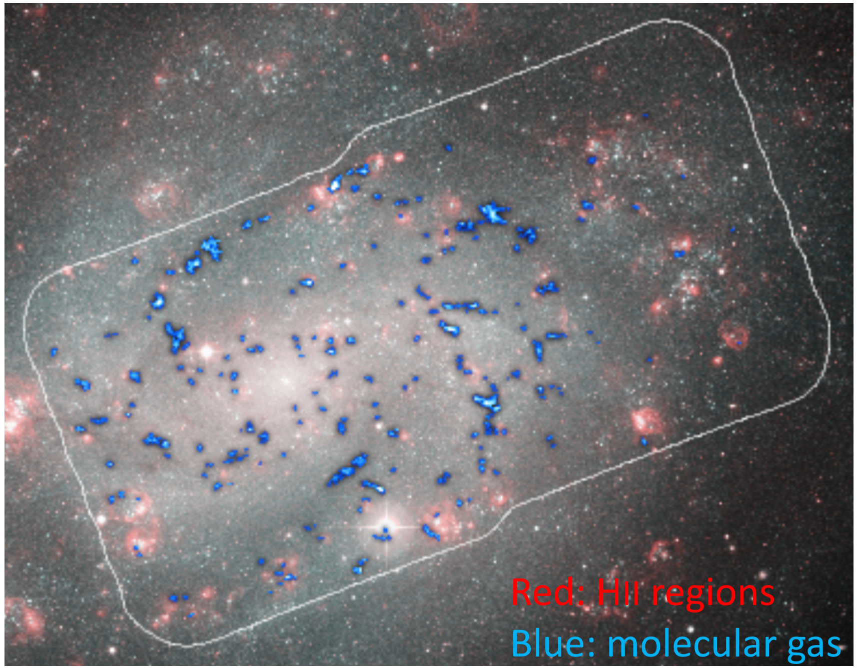
Gas and young stars ***correlated*** on small scales

Clouds are destroyed by massive stars

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?

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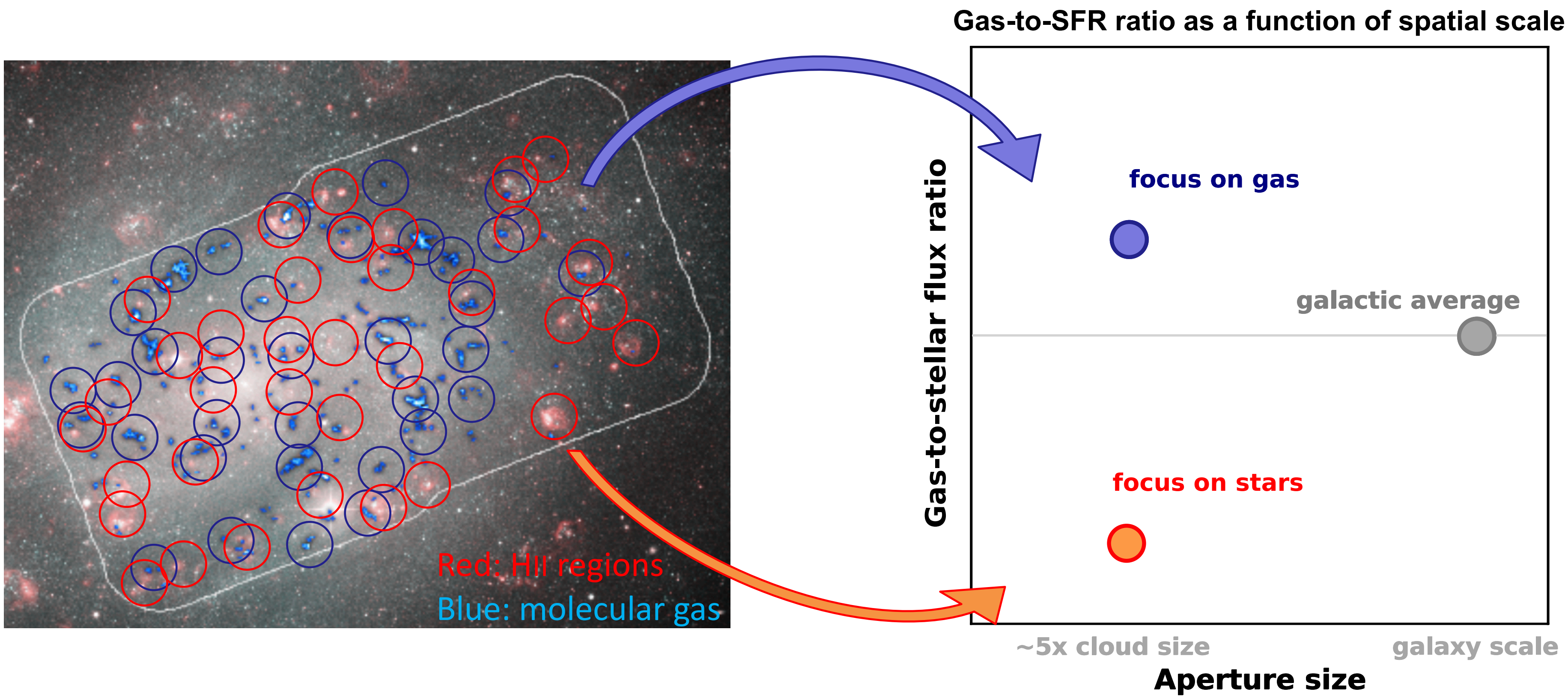

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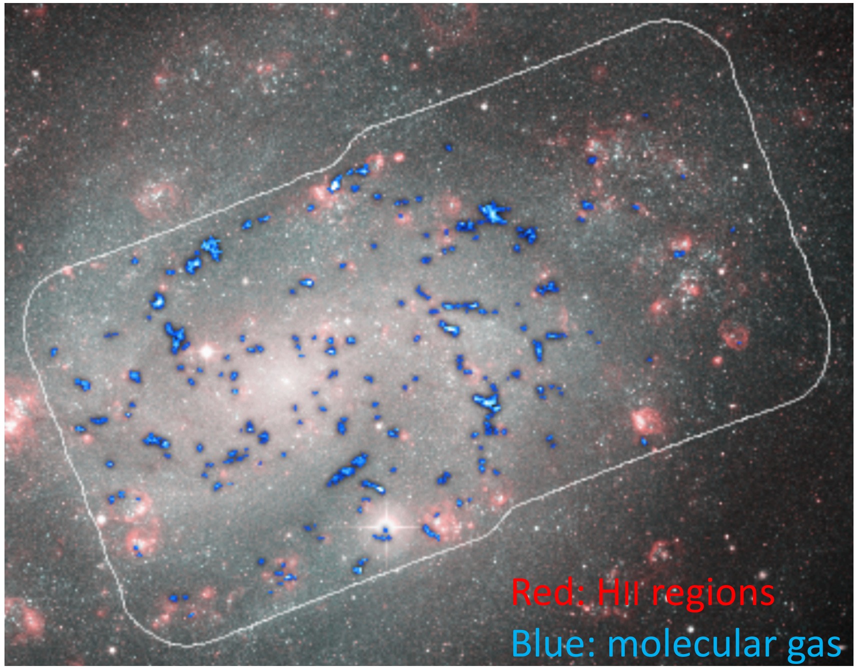
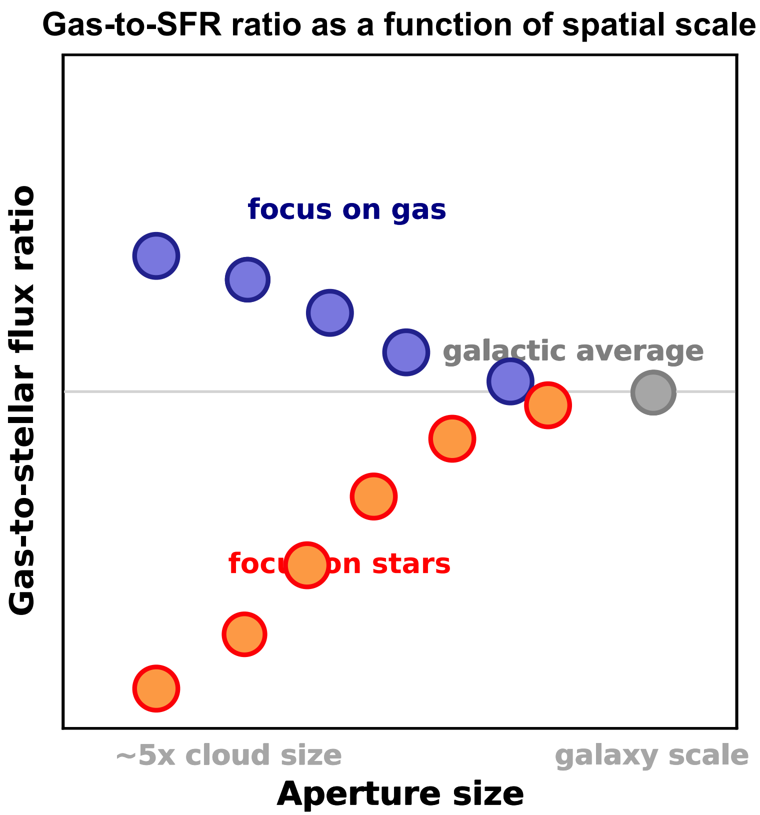
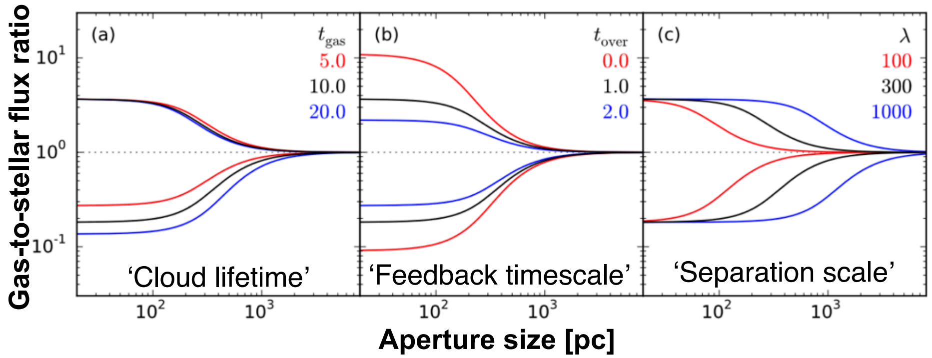


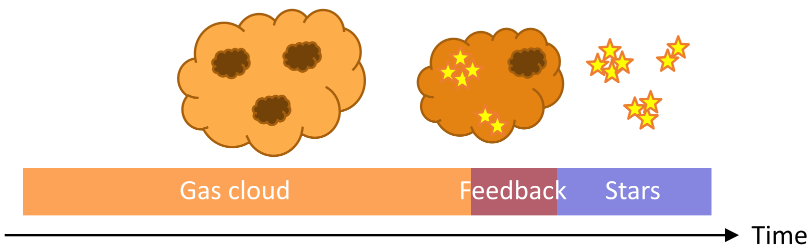


Measuring Myr timescales — How?

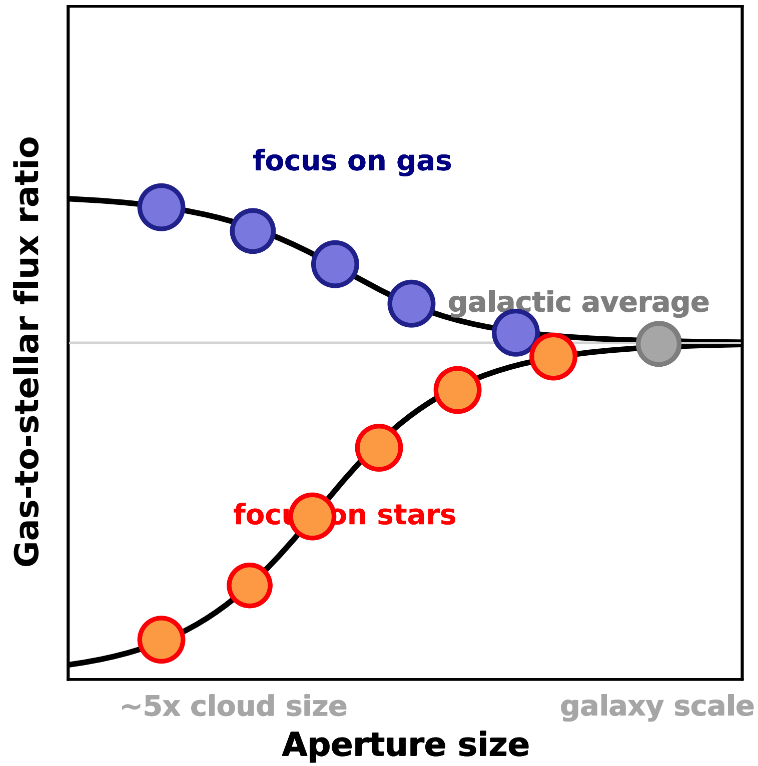
Small-scale variations of gas-to-SFR ratio reflect underlying timeline *(Kruijssen & Longmore 2014, Kruijssen et al. 2018)*

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



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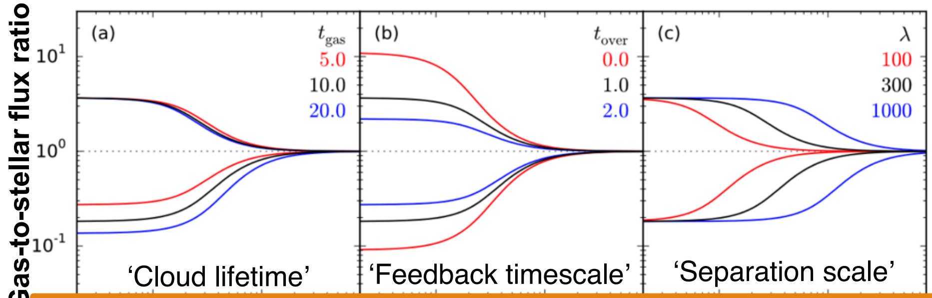

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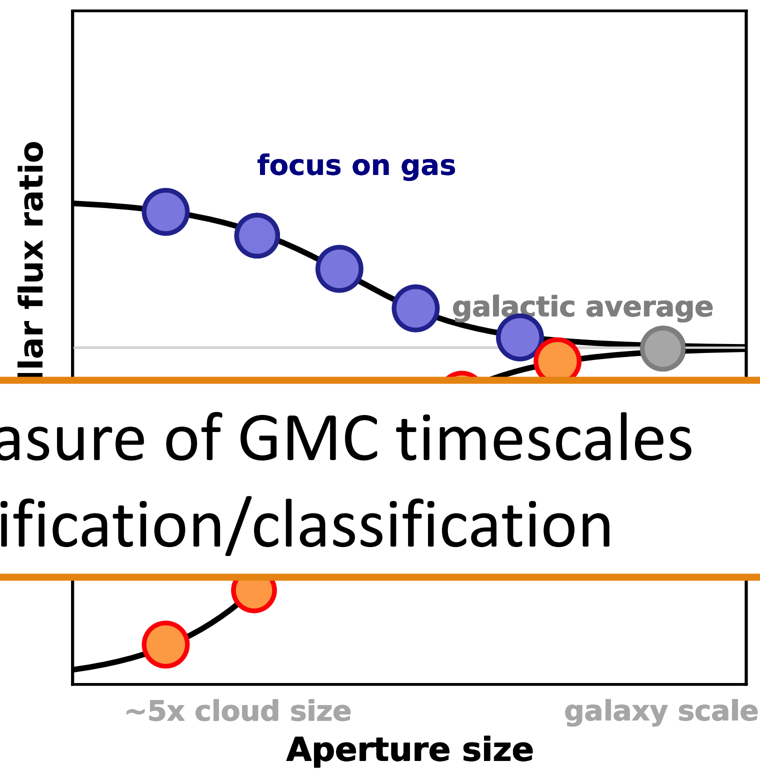
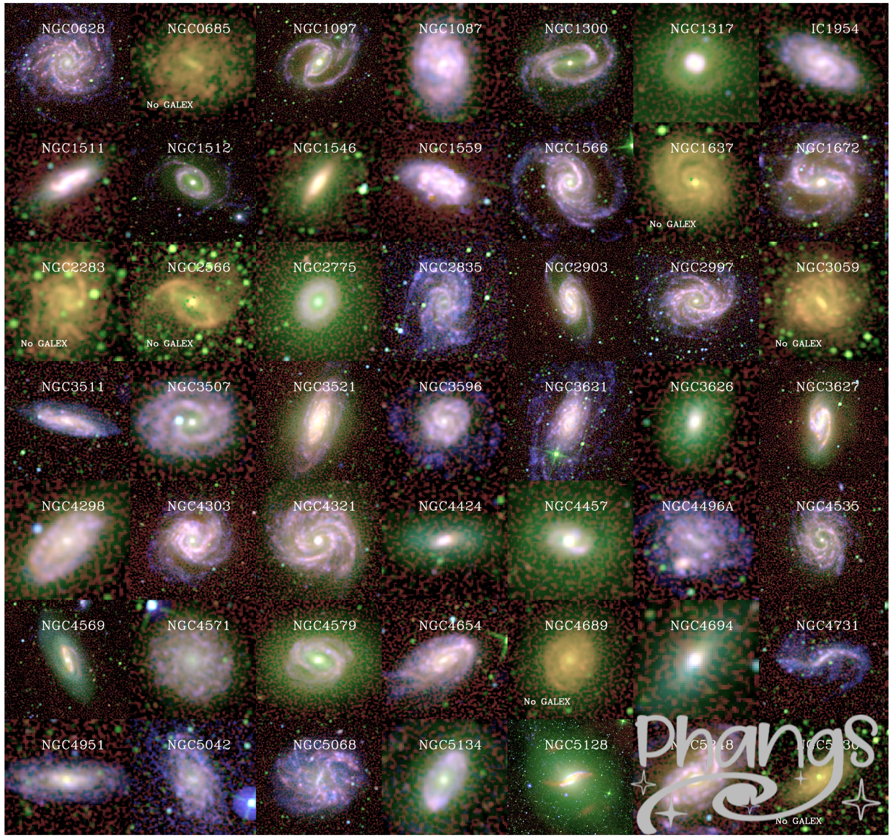


Objective **and** ***systematic*** measure of GMC timescales
No subjective 'cloud' identification/classification

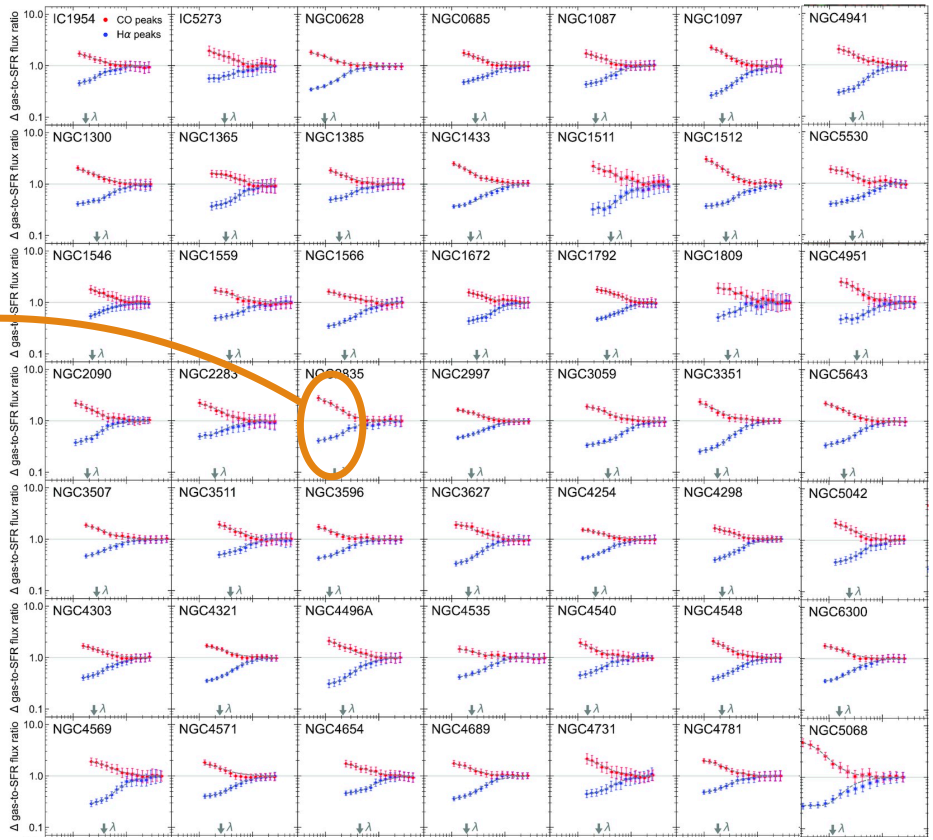
Molecular cloud lifecycle



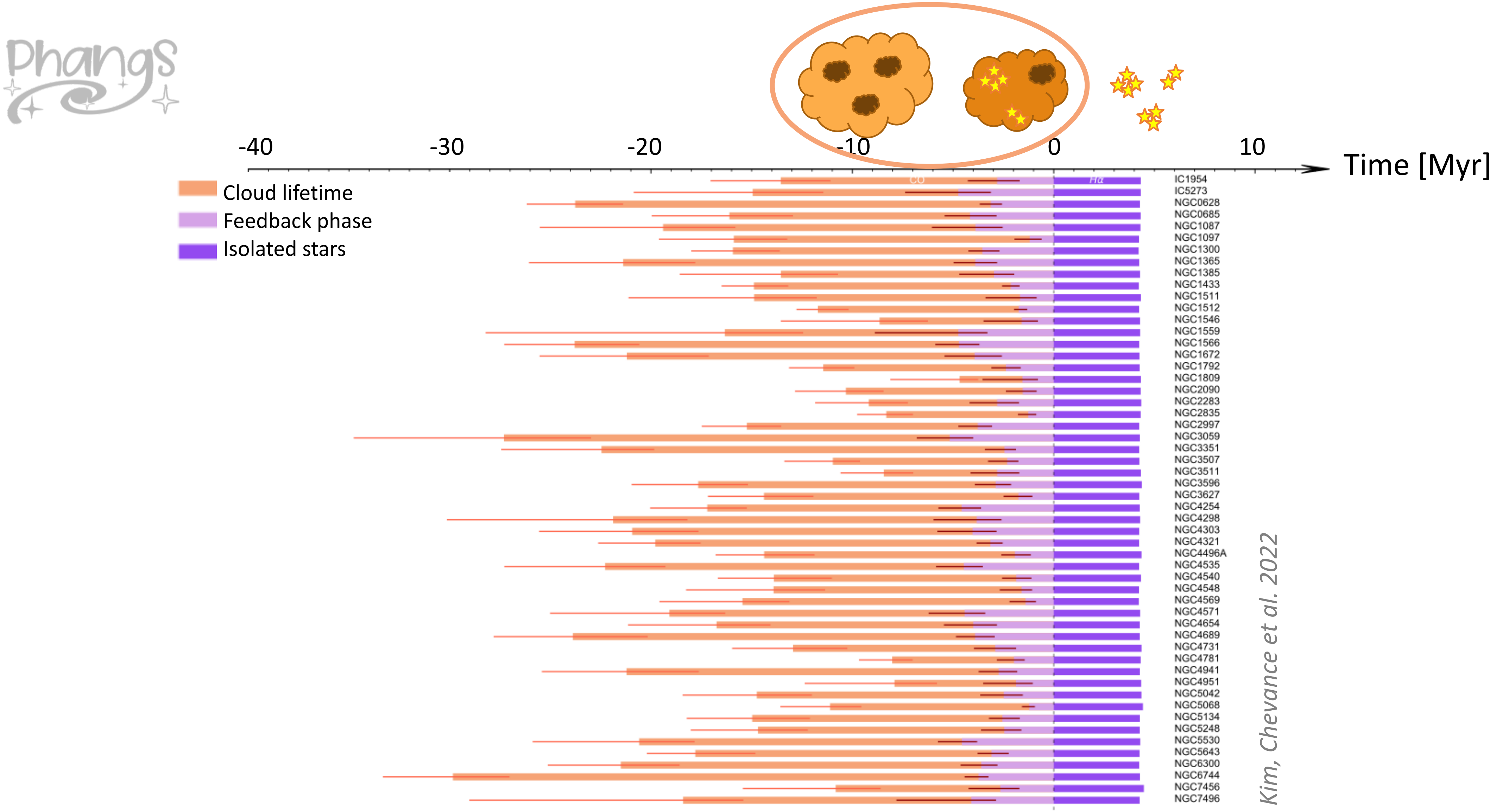
Kim, Chevance et al. 2022

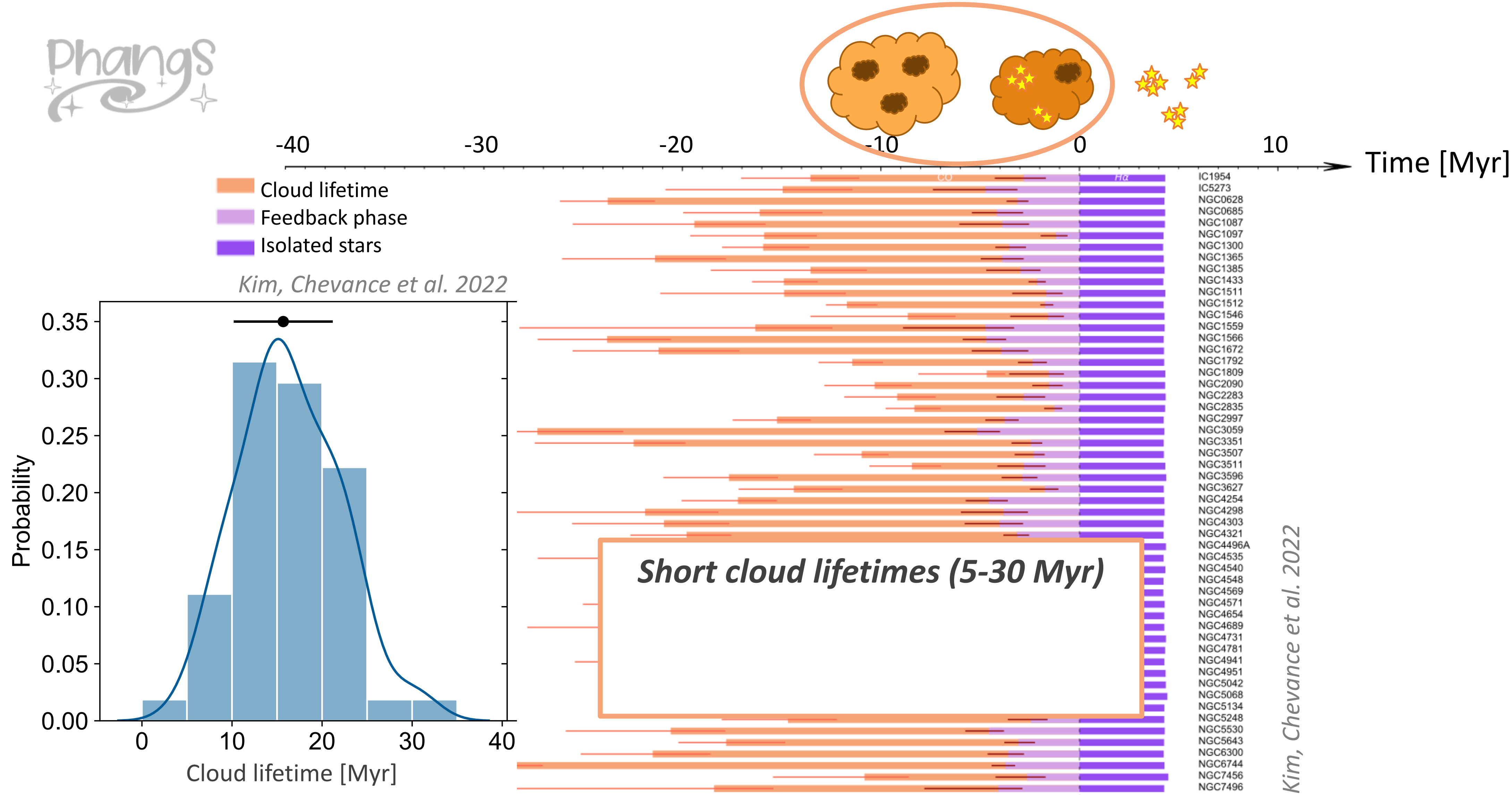
Molecular cloud lifecycle

Universal decorrelation:
Rapid cycling between
cold gas and young stars



Kim, Chevance et al. 2022


Phangs
-40
-30
-20
-10
0
10
Time [Myr]
Cloud lifetime
Feedback phase
Isolated stars
IC1954
IC5273
NGC0628
NGC0685
NGC1087
NGC1097
NGC1300
NGC1365
NGC1385
NGC1433
NGC1511
NGC1512
NGC1546
NGC1559
NGC1566
NGC1672
NGC1792
NGC1809
NGC2090
NGC2283
NGC2835
NGC2997
NGC3059
NGC3351
NGC3507
NGC3511
NGC3596
NGC3627
NGC4254
NGC4298
NGC4303
NGC4321
NGC4496A
NGC4535
NGC4540
NGC4548
NGC4569
NGC4571
NGC4654
NGC4689
NGC4731
NGC4781
NGC4941
NGC4951
NGC5042
NGC5068
NGC5134
NGC5248
NGC5530
NGC5643
NGC6300
NGC6744
NGC7456
NGC7496
Kim, Chevance et al. 2022


-40
-30
-20
-10
0
10
Time [Myr]
Cloud lifetime
Feedback phase
Isolated stars
Kim, Chevance et al. 2022
Probability
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
Cloud lifetime [Myr]
IC1954
IC5273
NGC0628
NGC0685
NGC1087
NGC1097
NGC1300
NGC1365
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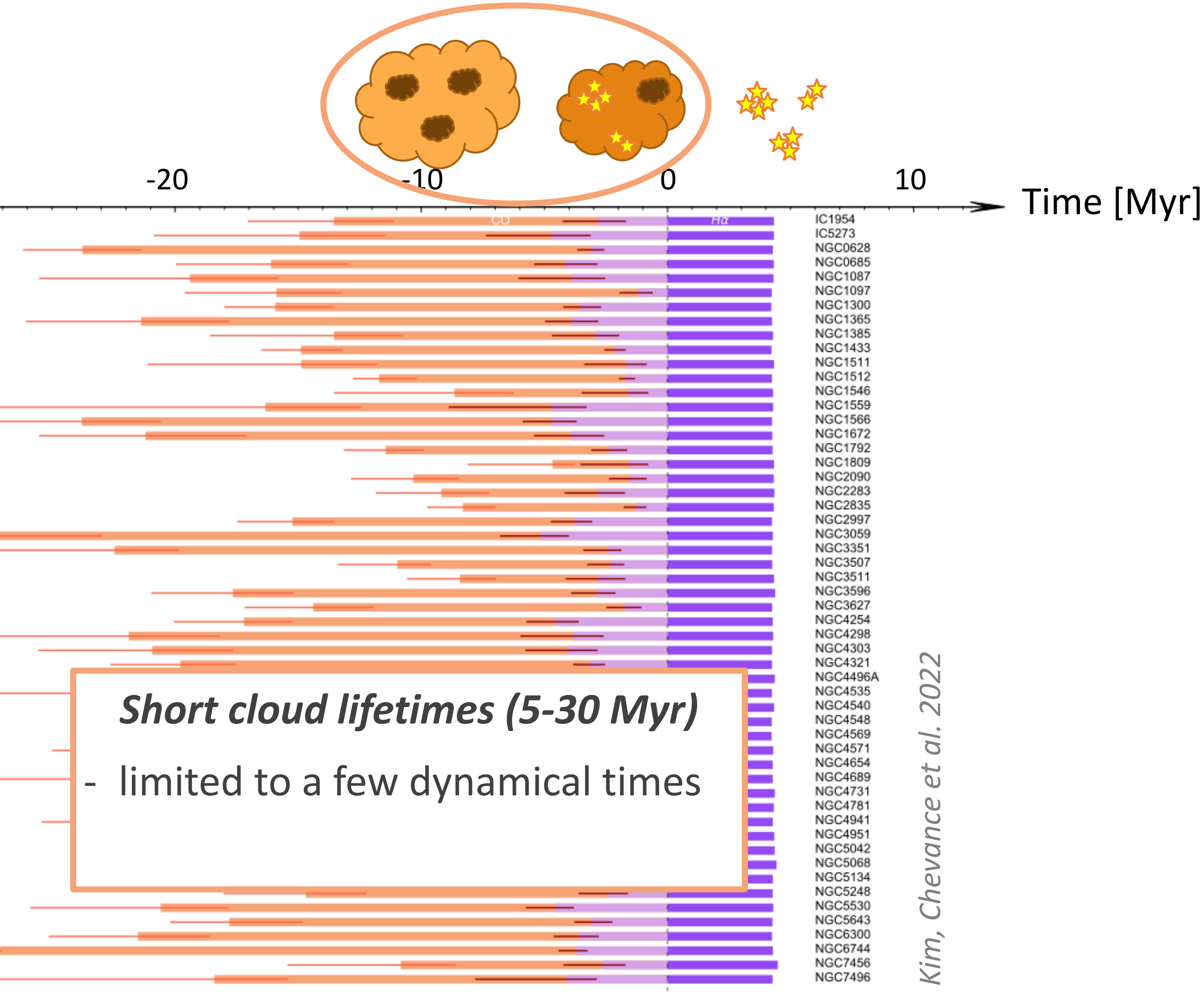
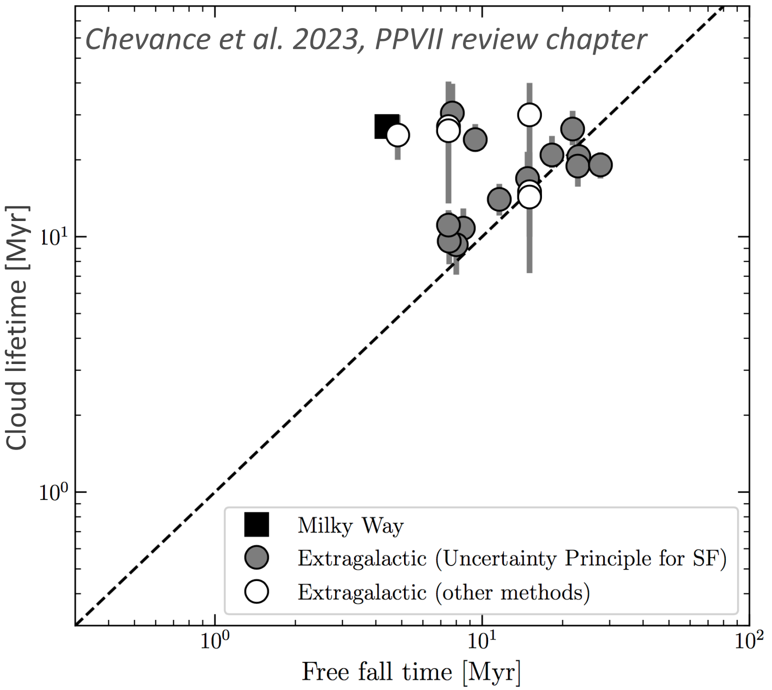
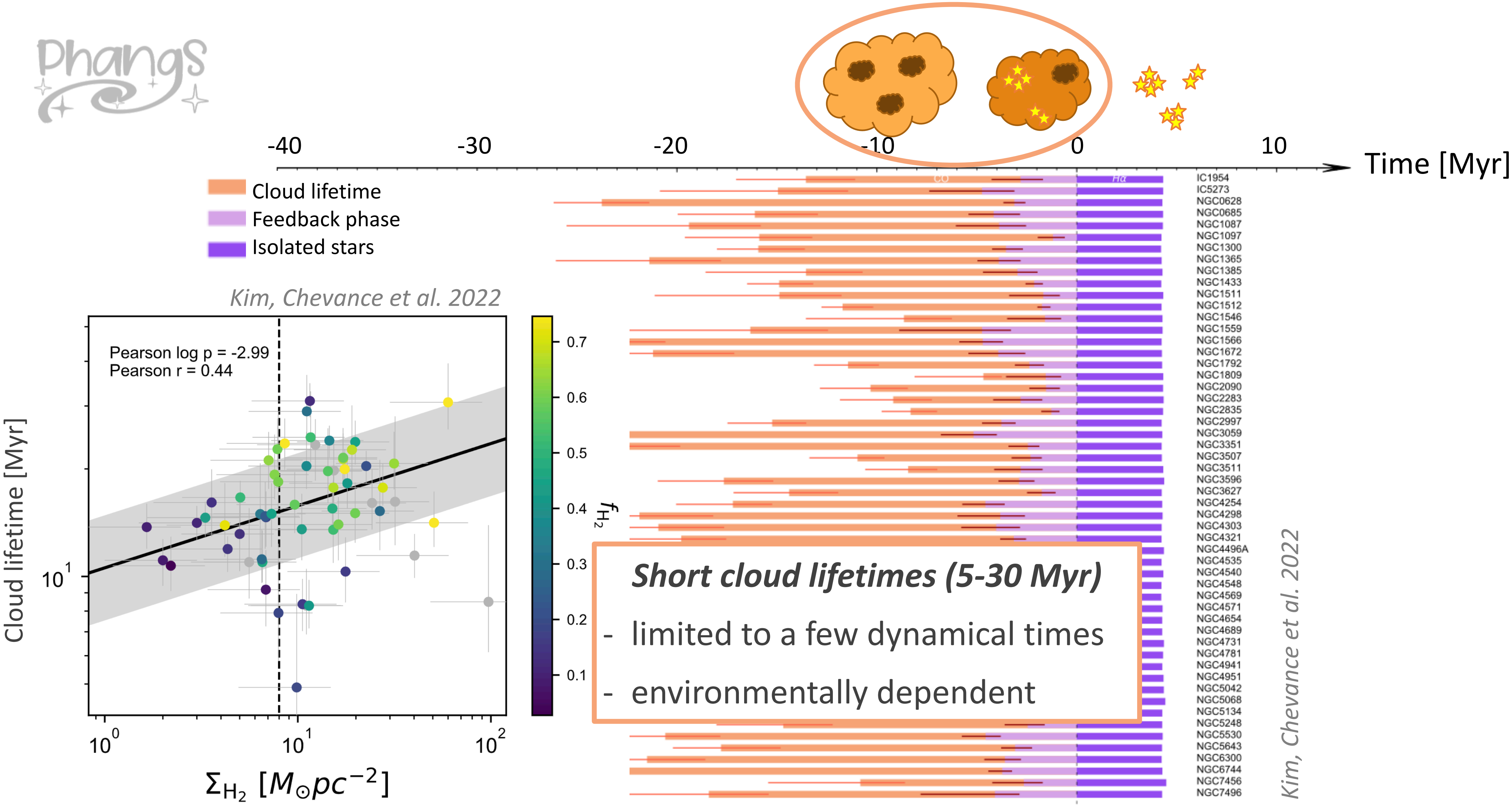
Short cloud lifetimes (5-30 Myr)
Kim, Chevance et al. 2022





Short cloud lifetimes (5-30 Myr)

- limited to a few dynamical times



Time [Myr]
-40
-30
-20
-10
0
10
Cloud lifetime
Feedback phase
Isolated stars
IC1954
IC5273
NGC0628
NGC0685
NGC1087
NGC1097
NGC1300
NGC1365
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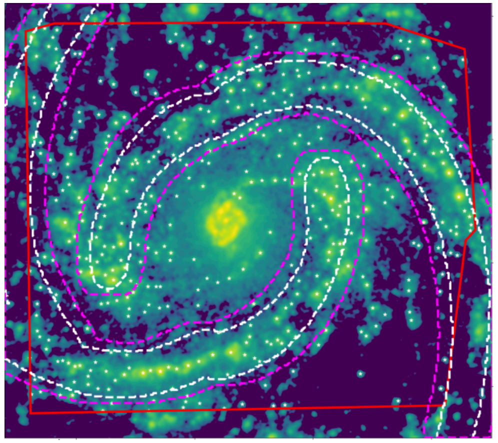
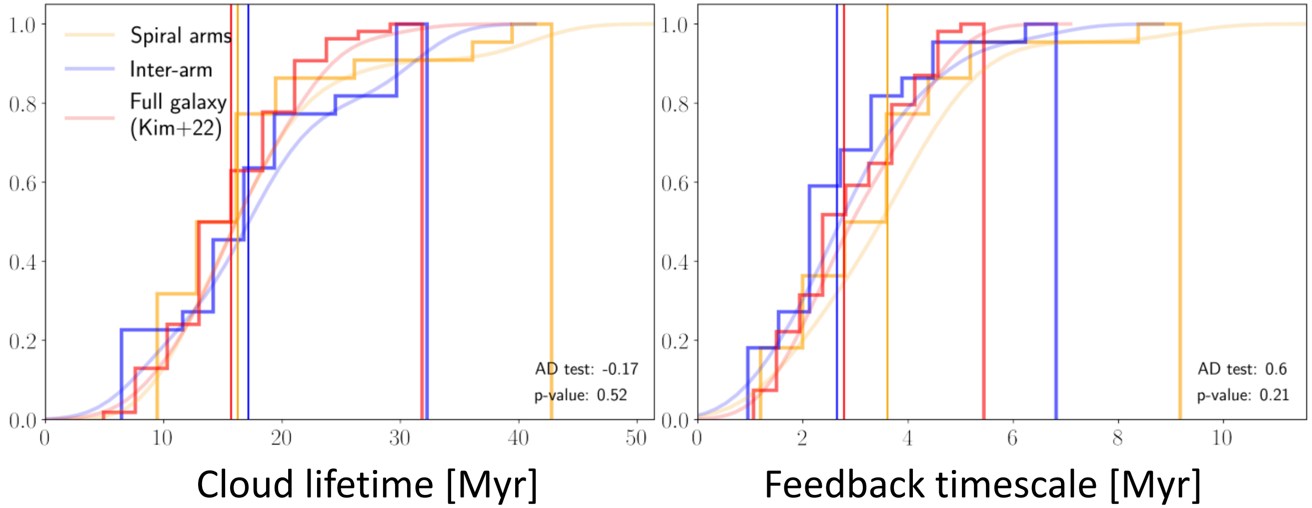
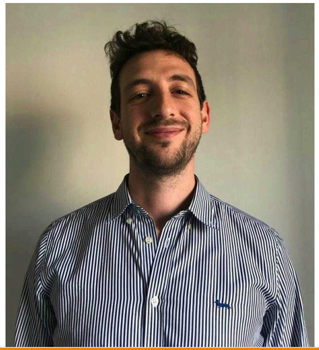
NGC5134
NGC5248
NGC5530
NGC5643
NGC6300
NGC6744
NGC7456
NGC7496
Kim, Chevance et al. 2022
Kim, Chevance et al. 2022
Pearson log p = -2.99
Pearson r = 0.44
Cloud lifetime [Myr]
Σ_{H_2} $[M_\odot pc^{-2}]$
f_{H_2}
Short cloud lifetimes (5-30 Myr)
- limited to a few dynamical times
- environmentally dependent



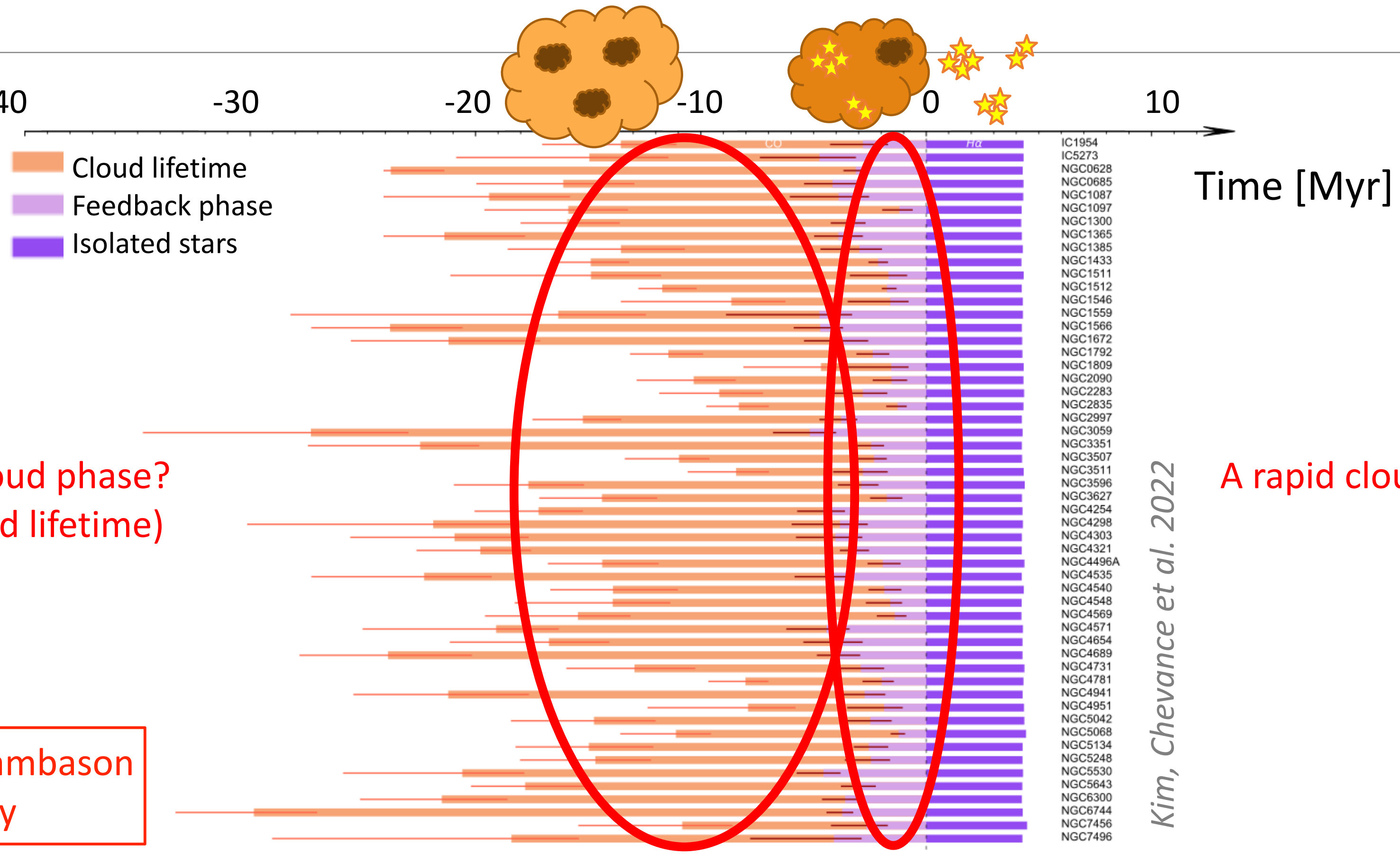




Andrea Romanelli

- No statistical difference for the cloud evolutionary timeline between ***arms and inter-arm regions*** *(Romanelli, Chevance et al., 2025)*
- Dependance of the cloud evolutionary timeline with ***galactocentric radius and cloud properties*** *(Romanelli, Chevance et al., in prep.)*

Molecular cloud lifecycle

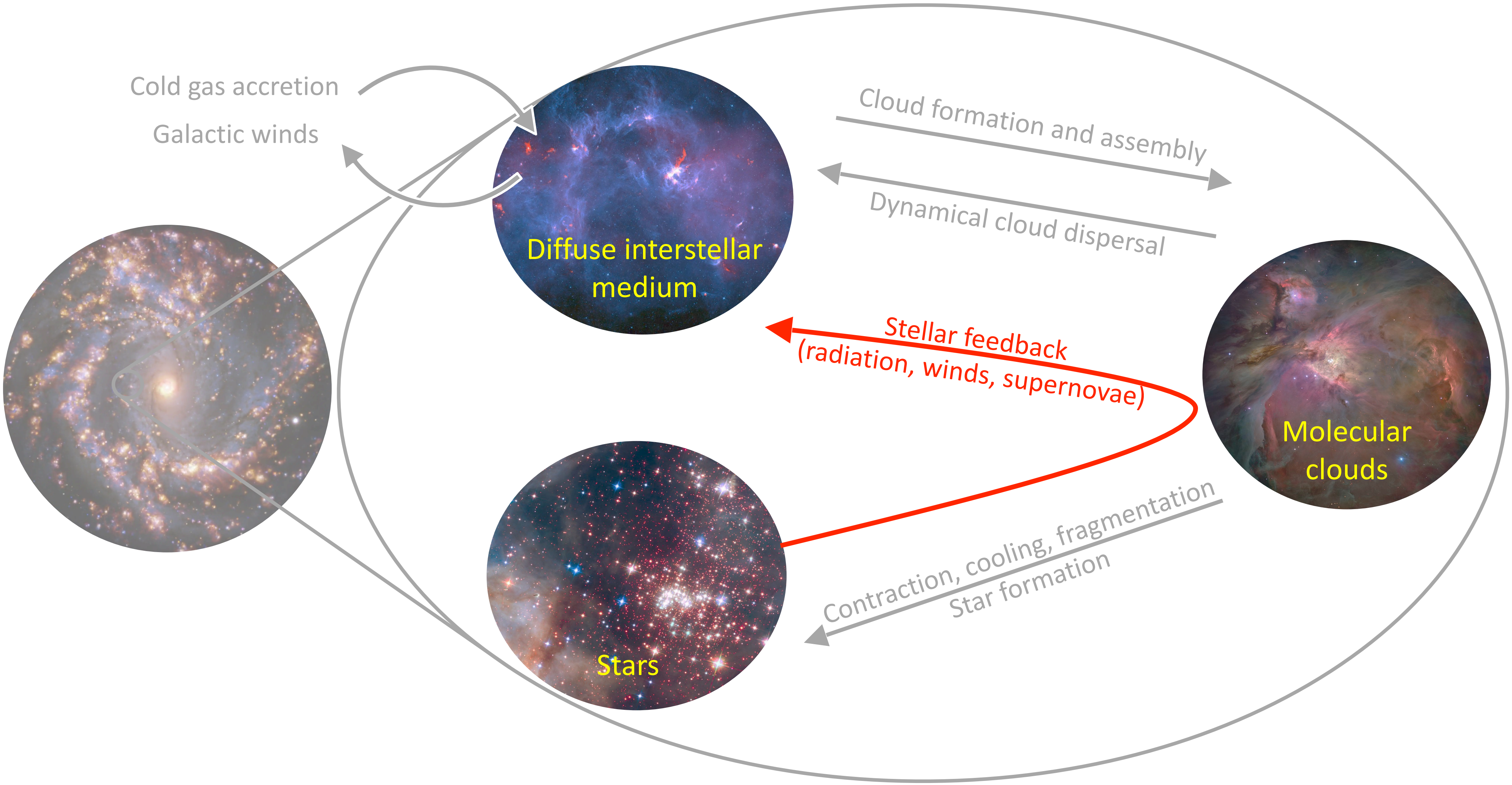


Kim, Chevance et al. 2022

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

See talk by Lise Ramambason on Wednesday

A rapid cloud dispersal phase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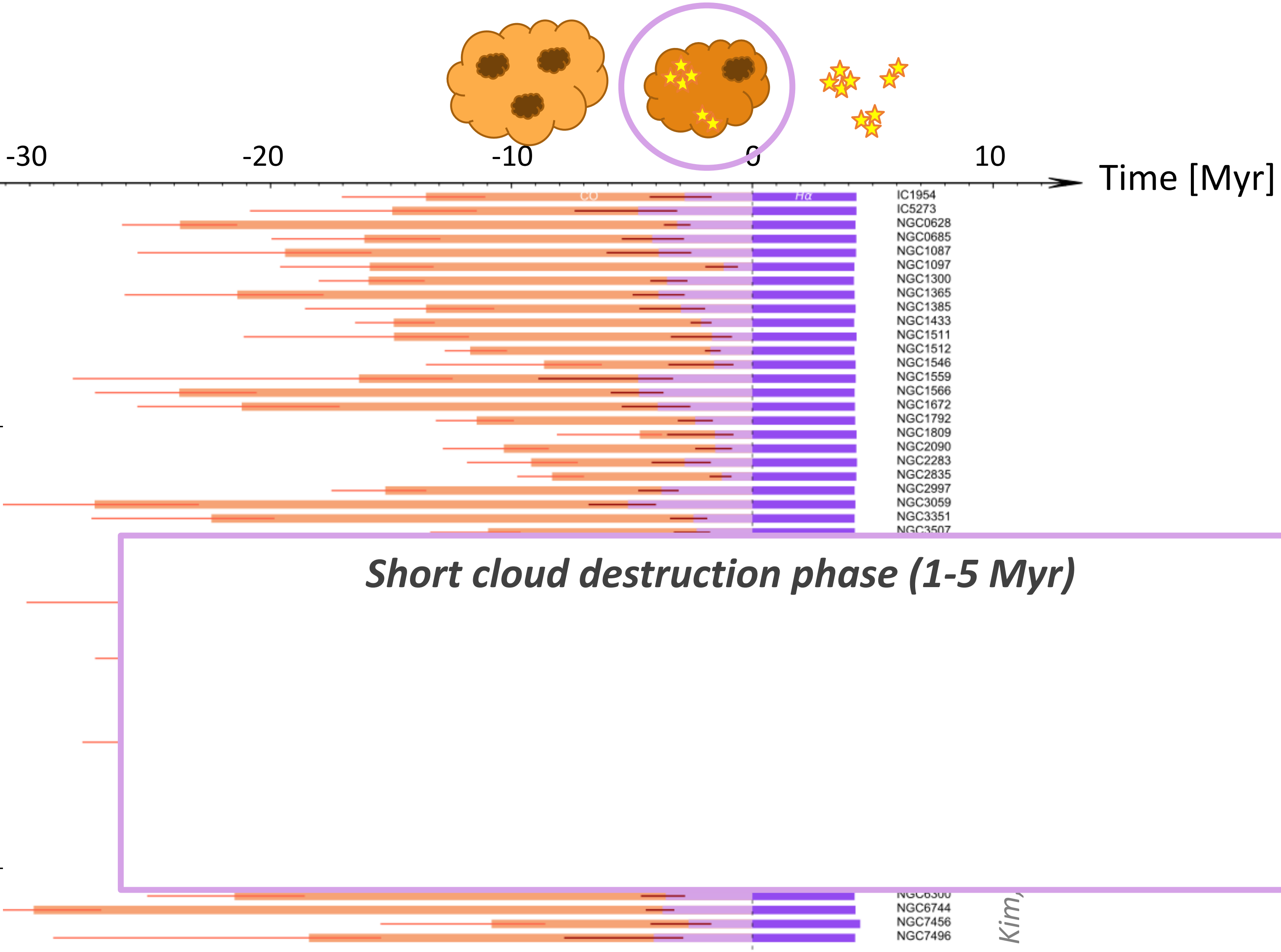
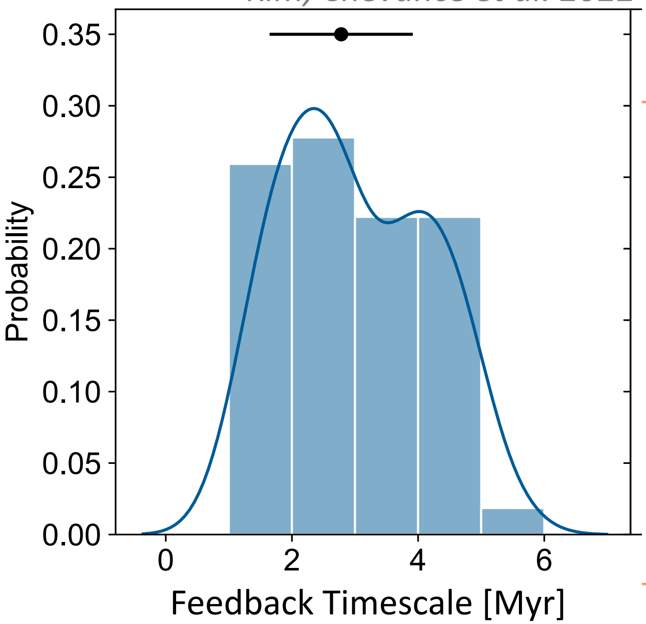
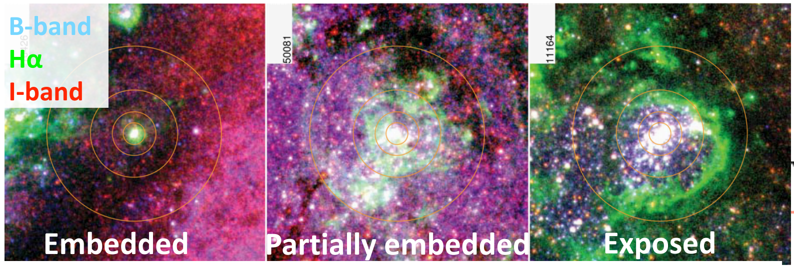


Kim, Chevance et al. 2022



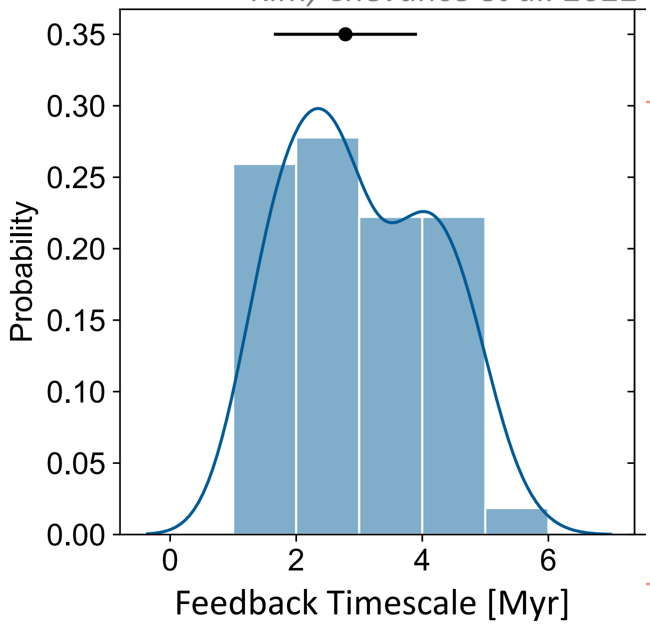
Short cloud destruction phase (1-5 Myr)

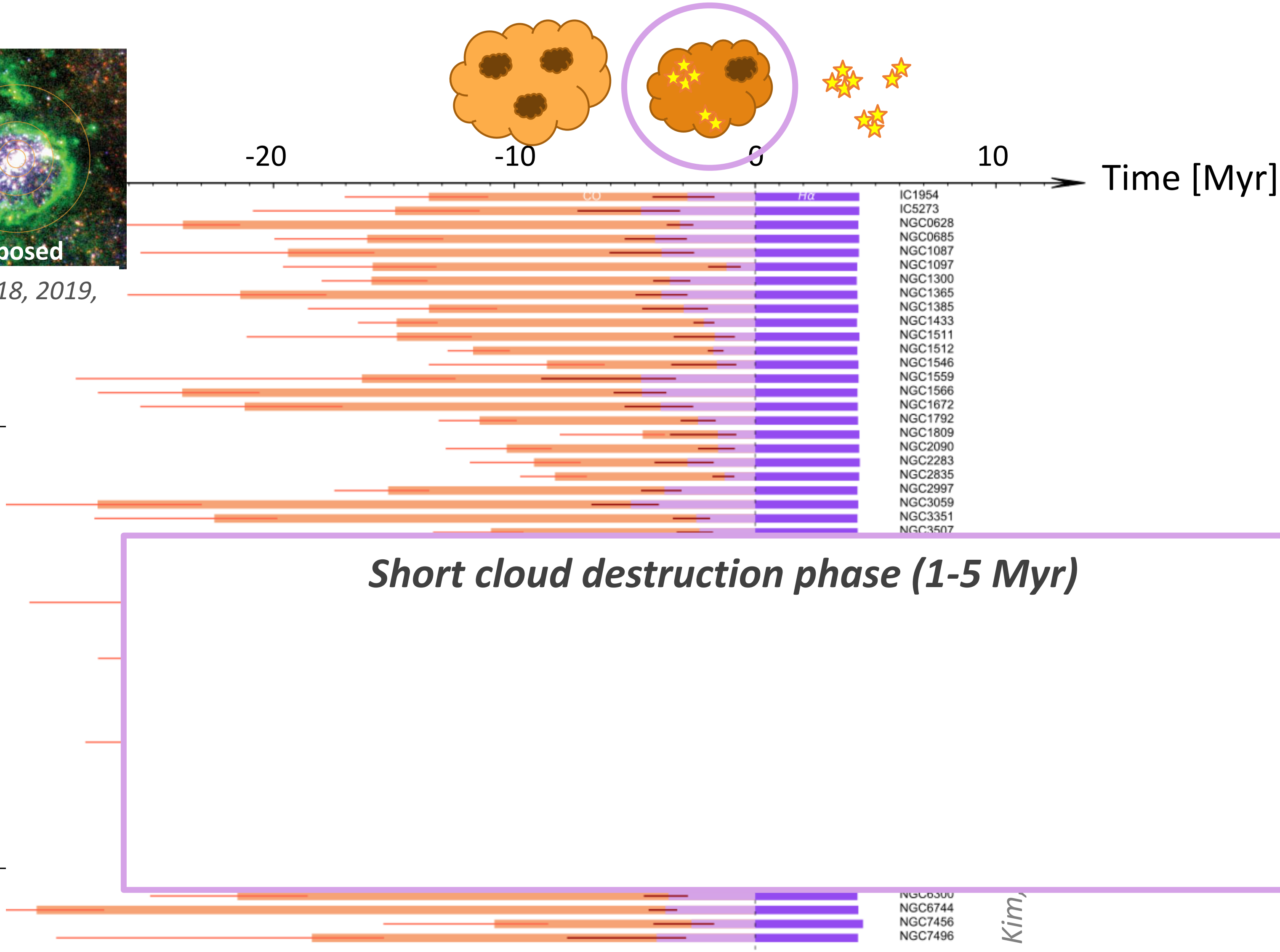
Hollyhead et al. 2015



See also Whitmore et al. 2014, Grasha et al. 2018, 2019, Hannon et al. 2019, Messa et al. 2021

Kim, Chevance et al. 2022





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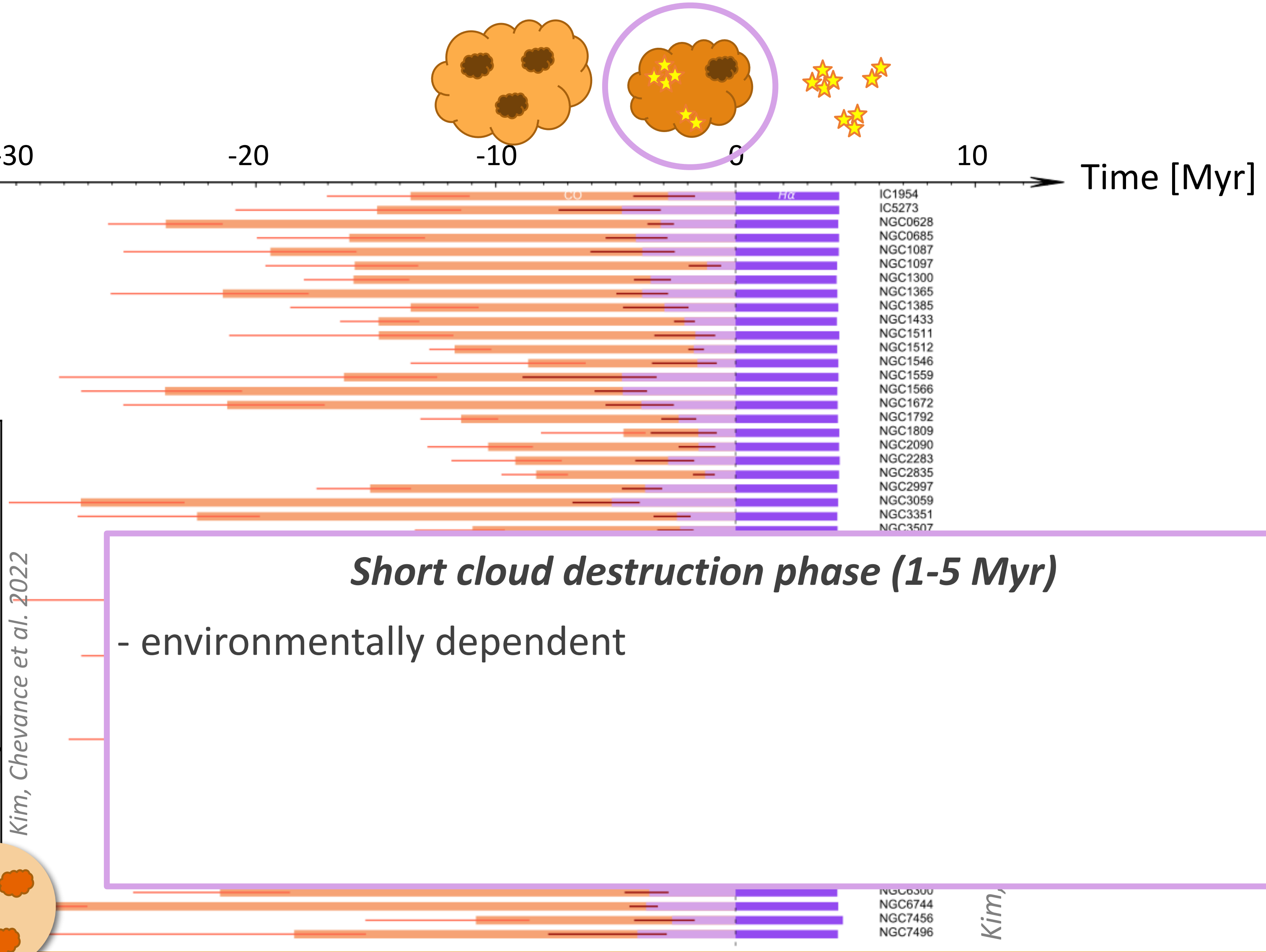
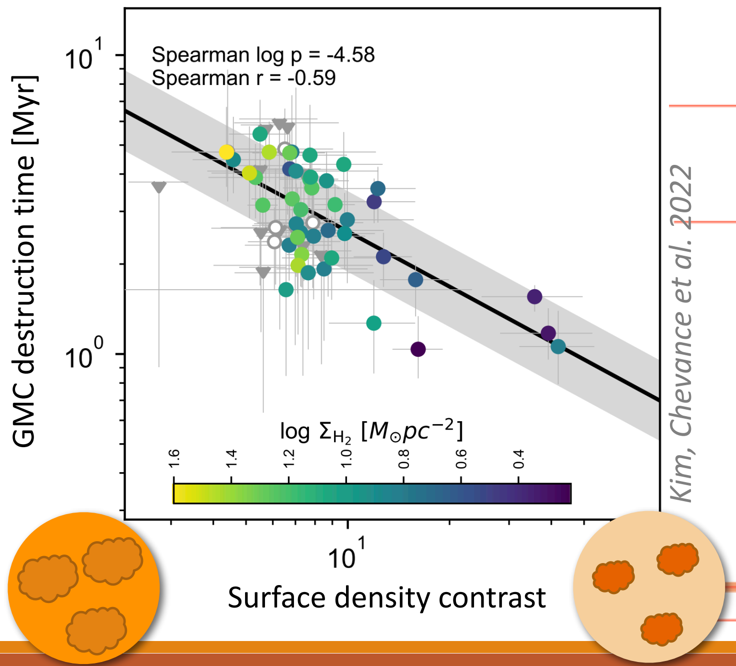
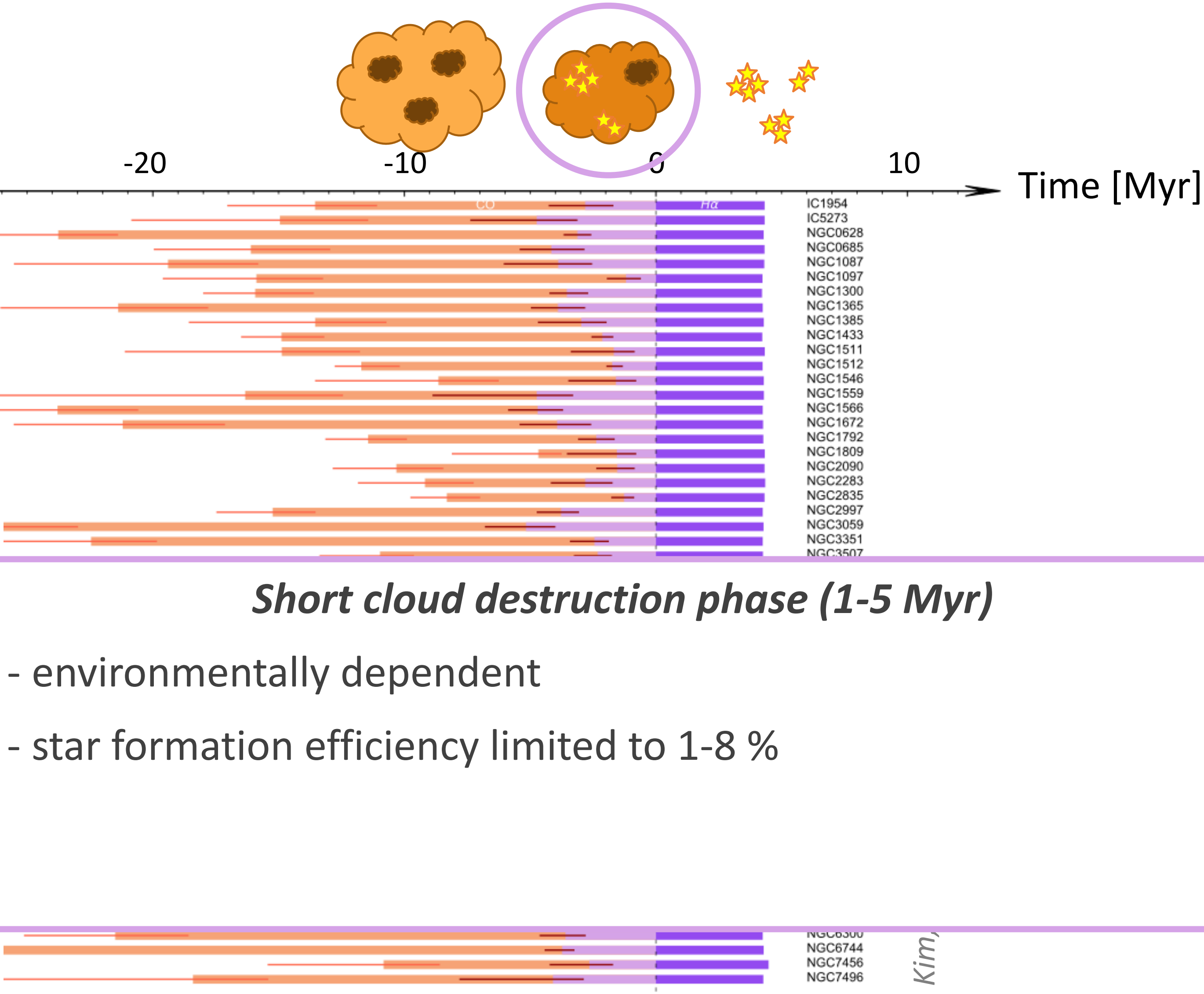


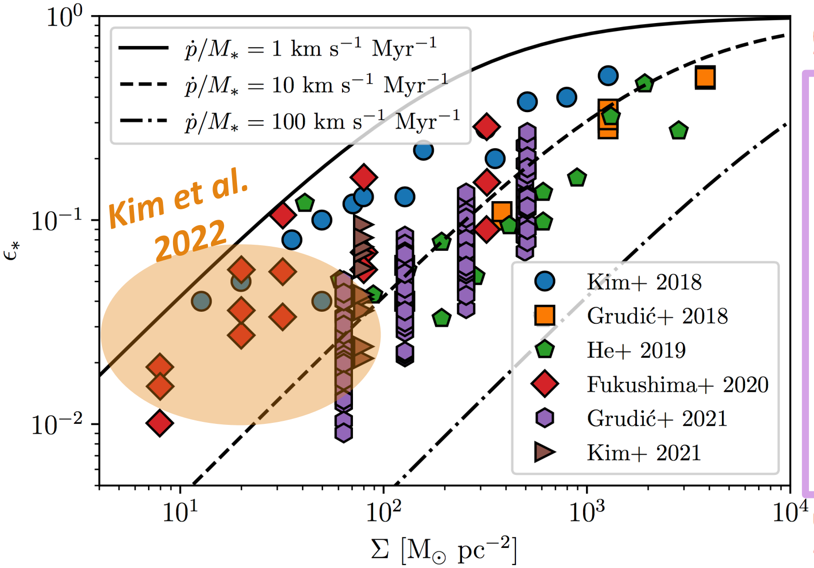


Short cloud destruction phase (1-5 Myr)

- environmentally dependent



Chevance, et al. 2023, PPVII review chapter



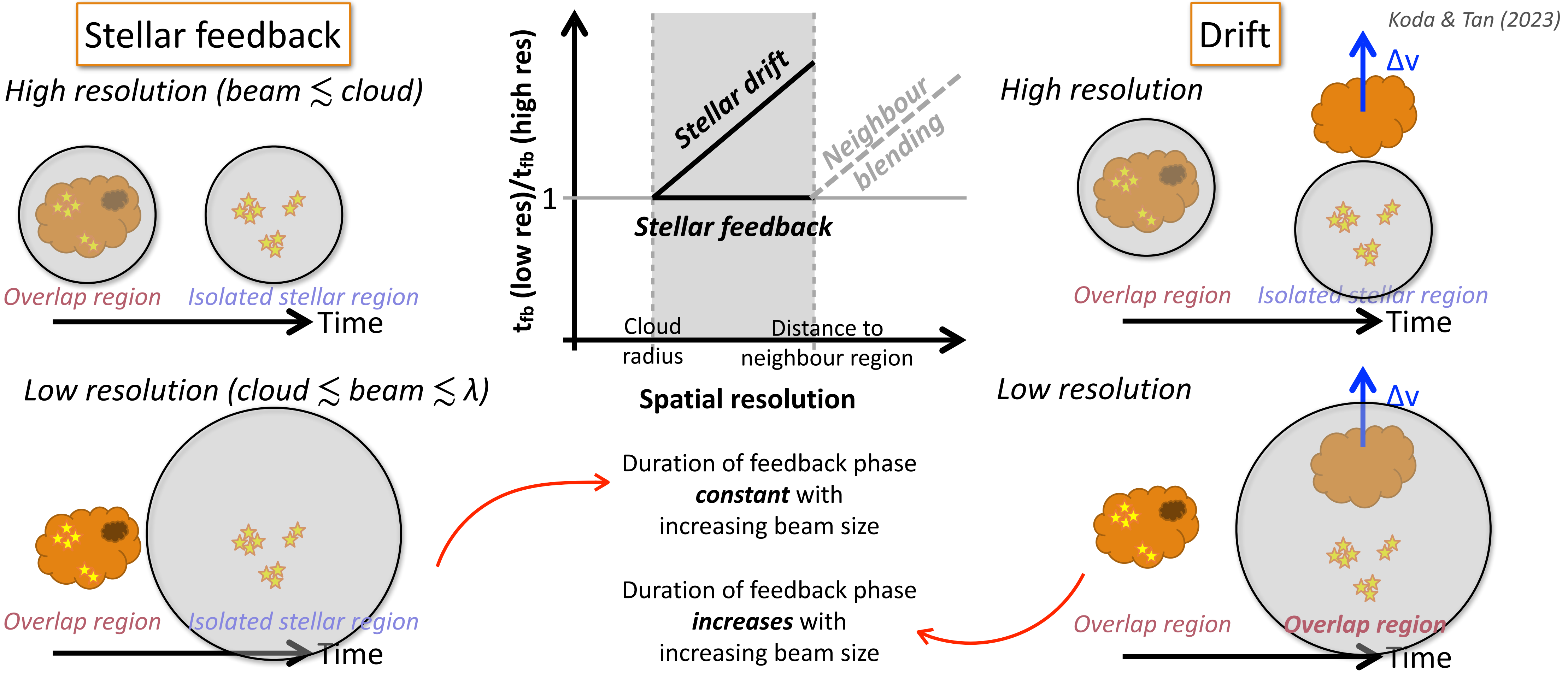
Short cloud destruction phase (1-5 Myr)

- environmentally dependent
- star formation efficiency limited to 1-8 %

Rapid cloud dispersal

Or are the stars just drifting away?

Kruijssen, Chevance, Longmore et al. (subm., arXiv:2404.14495)



Rapid cloud dispersal

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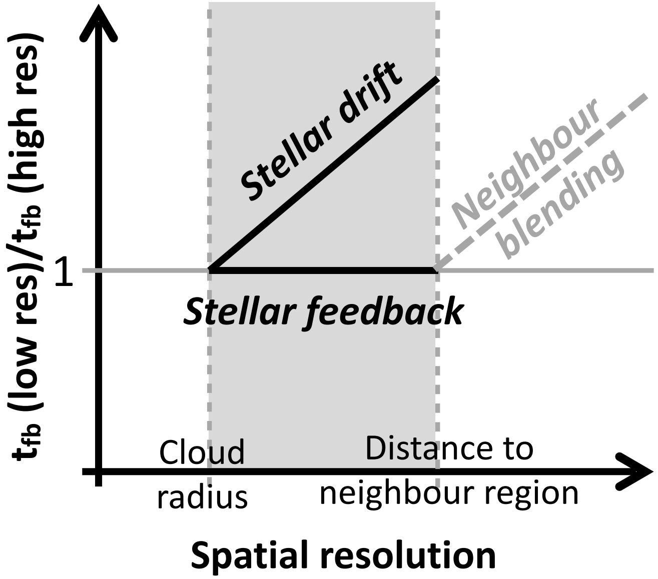
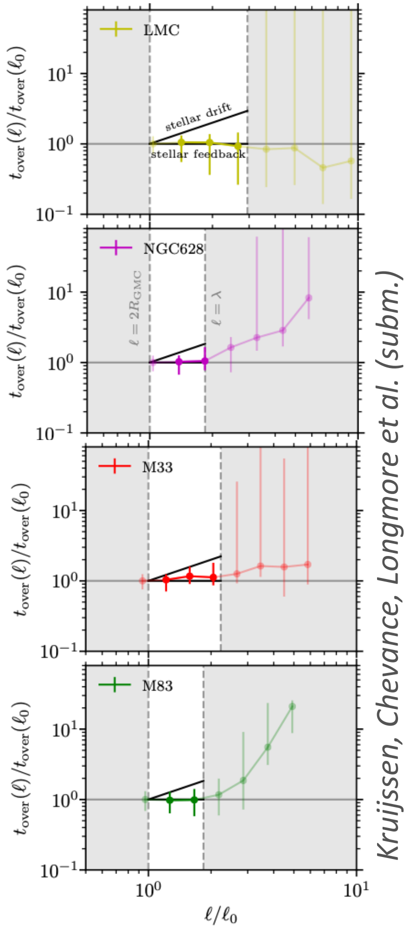
Koda & Tan (2023)

Stellar feedback

Duration of feedback phase ***constant*** with increasing beam size





Drift

Duration of feedback phase ***increases*** with increasing beam size

Dispersal scenario is highly favoured over drift scenario (globally and for individual galaxies)

Rapid cloud dispersal: *What stellar 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

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

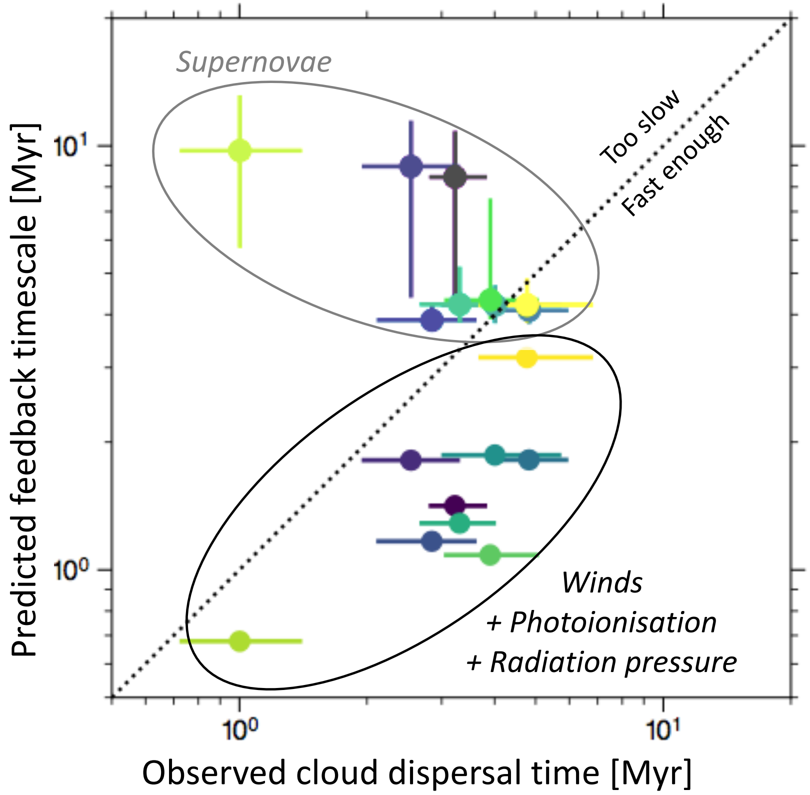
- Stellar winds *(energy driven or energy+momentum driven)*

$$t_{wind} = \left(\frac{154\pi}{125}\frac{\rho_{GMC}}{L_{wind}}\right)^{1/3} r_{GMC}^{5/3} \qquad t_{wind} = \left(\frac{154\pi}{125}\frac{\rho_{GMC}}{L_{wind}}\right)^{4/5} t_{cool}^{-7/5} r_{GMC}^{4}$$

- Radiation pressure

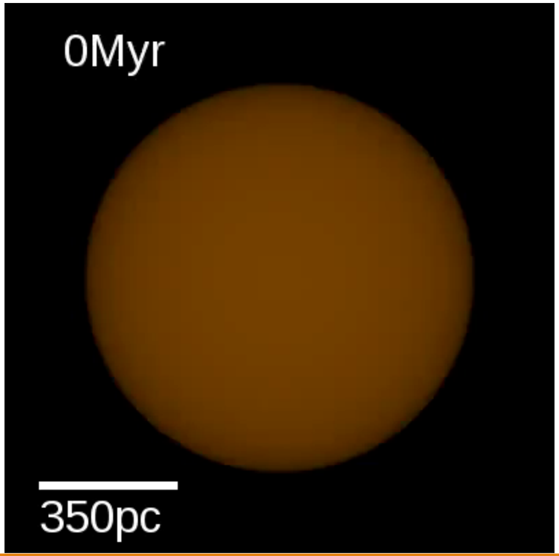
$$t_{rad} = \left(\frac{2\pi c}{3}\frac{\rho_{GMC}}{L_{bol}}\right)^{1/2} r_{GMC}^{2}$$

Rapid cloud dispersal: *What stellar feedback mechanisms can disperse the gas so quickly?*



Chevance et al. 2022

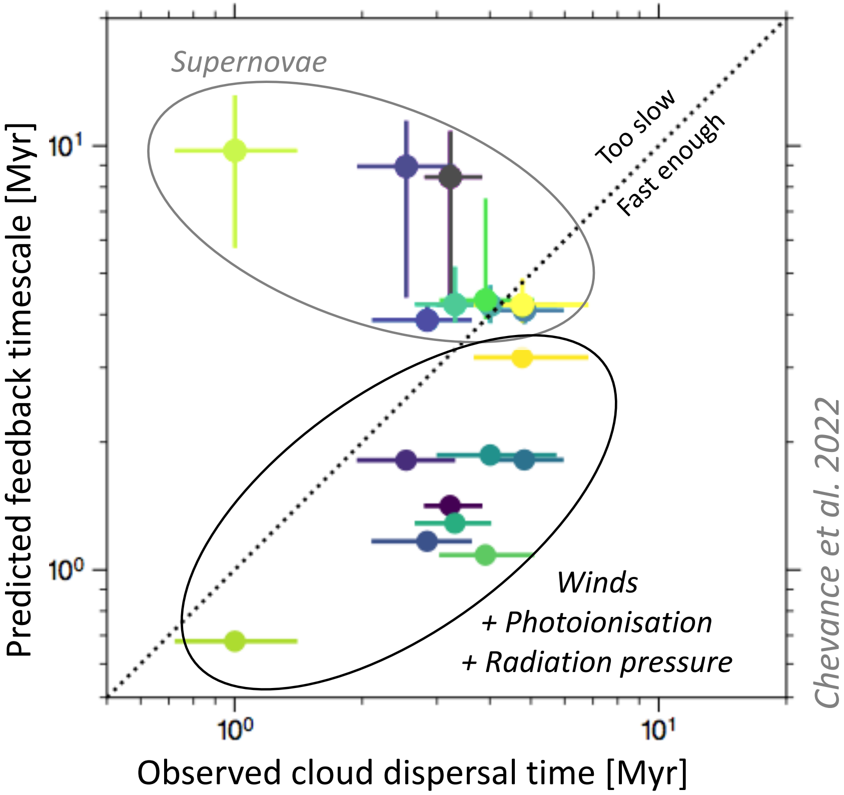
- ➢ ***Pre-supernova*** mechanisms play an important role in dispersing the clouds.
- ➢ Their ***coupling efficiency*** with the surrounding gas is ***not 100%***.



Grudić et al. 2018a

See also Kim et al. 2019, Grudić et al. 2022

Rapid cloud dispersal: *What stellar feedback mechanisms can disperse the gas so quickly?*



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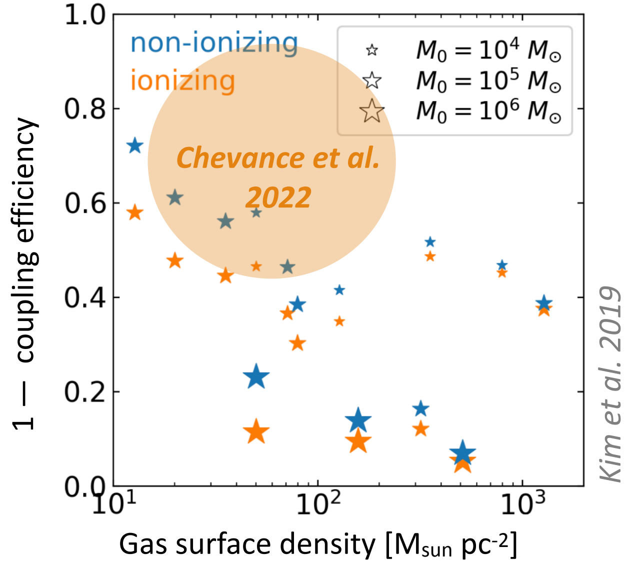
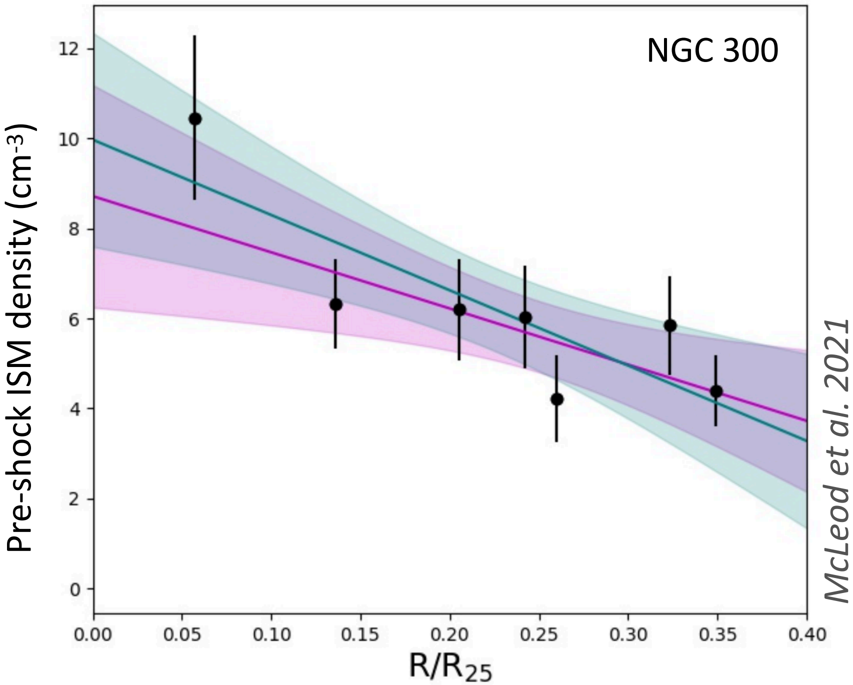


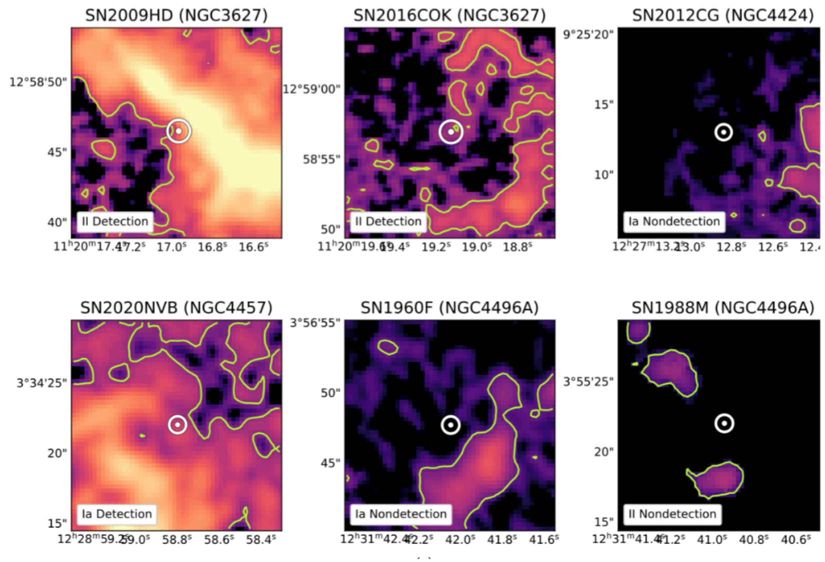
Impact of feedback on nearby MCs?



McLeod et al. 2021

SNe detonate in moderate to low density environments

Recent SNe rarely correspond to the CO peak



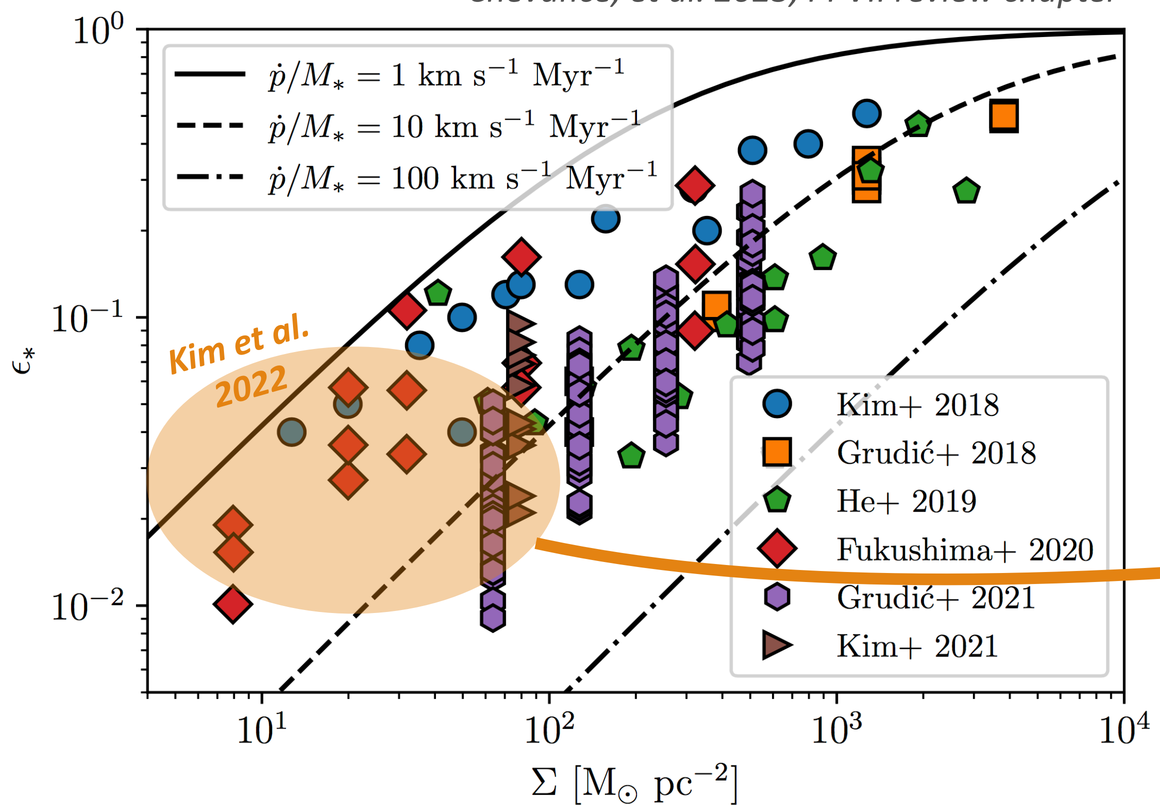
Mayker Chen et al. 2023

➢ **Large scale impact of SNe on galaxy structure** (e.g. stellar clustering and ISM structure) **and properties** (e.g. outflows)

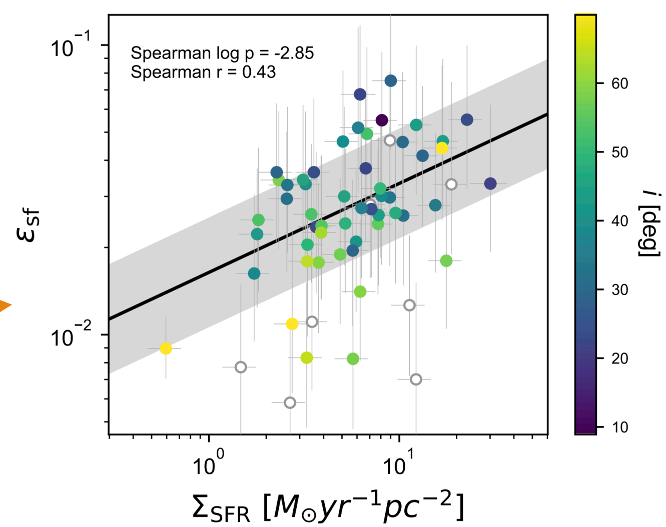
Rapid cloud dispersal — II

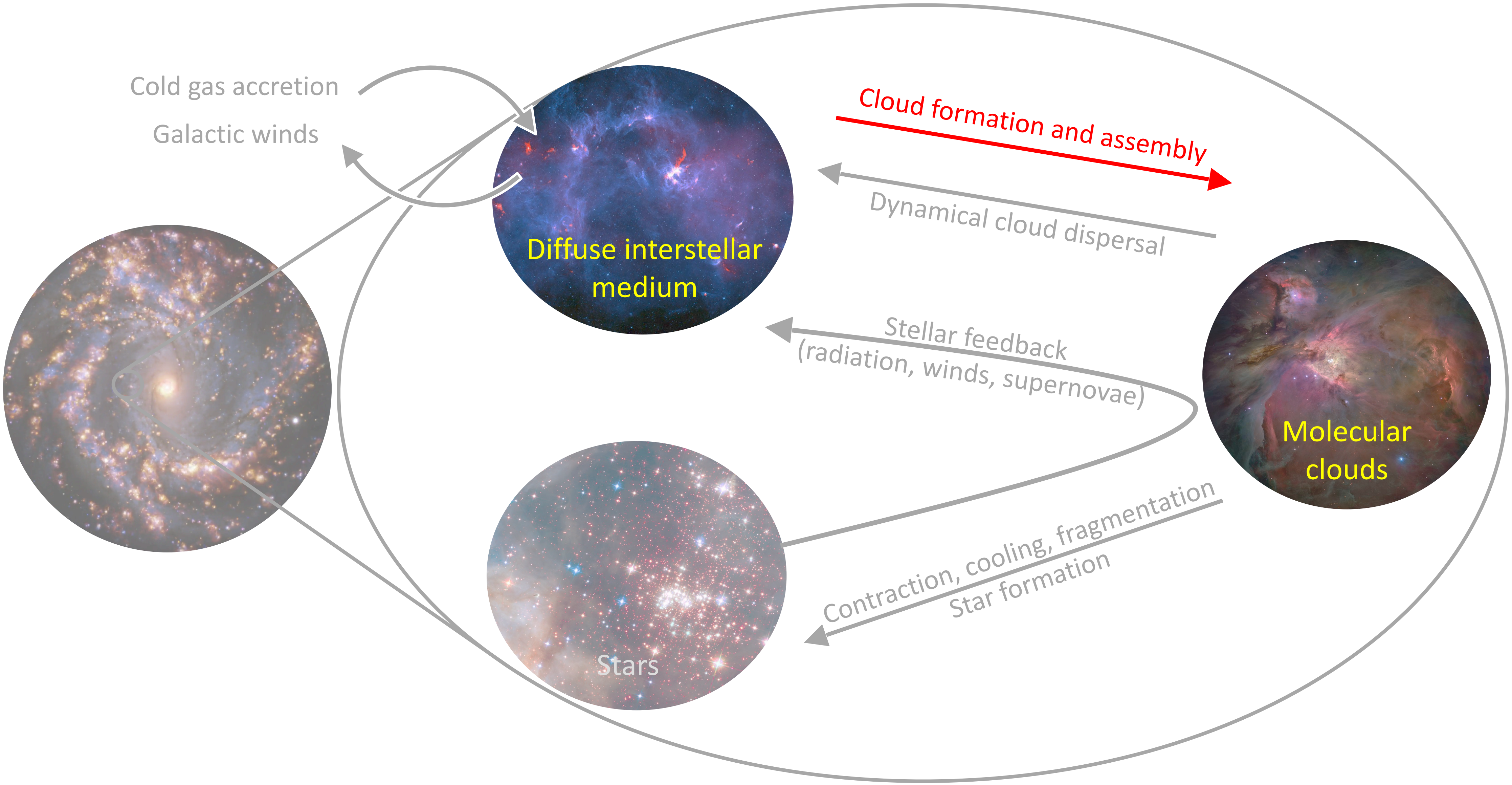
Integrated SFE limited to a few percent

Chevance, et al. 2023, PPVII review chapter



Kim, Chevance, et al. 2022a

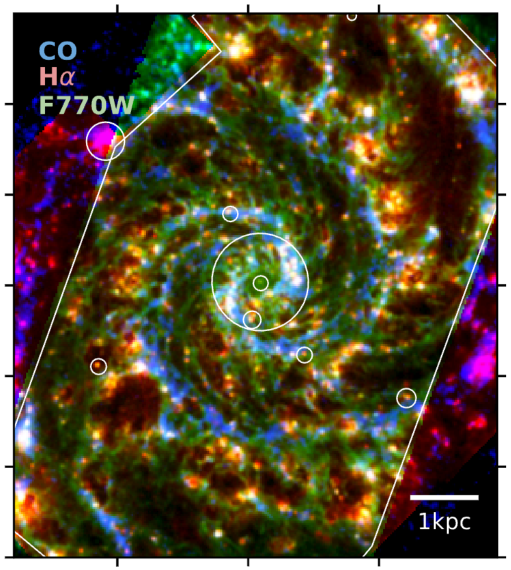


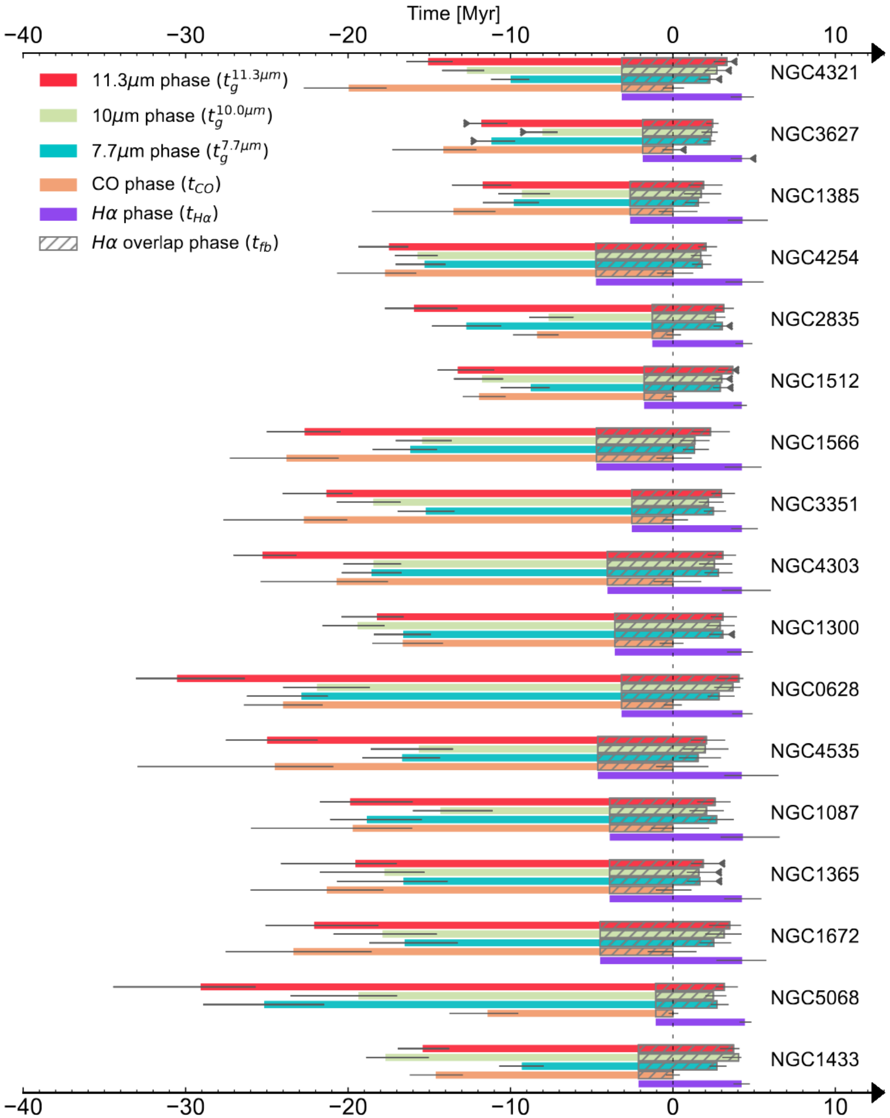

Cold gas accretion
Galactic winds
Cloud formation and assembly
Dynamical cloud dispersal
Diffuse interstellar medium
Stellar feedback
(radiation, winds, supernovae)
Molecular clouds
Contraction, cooling, fragmentation
Star formation
Stars

PAH and dust timescale

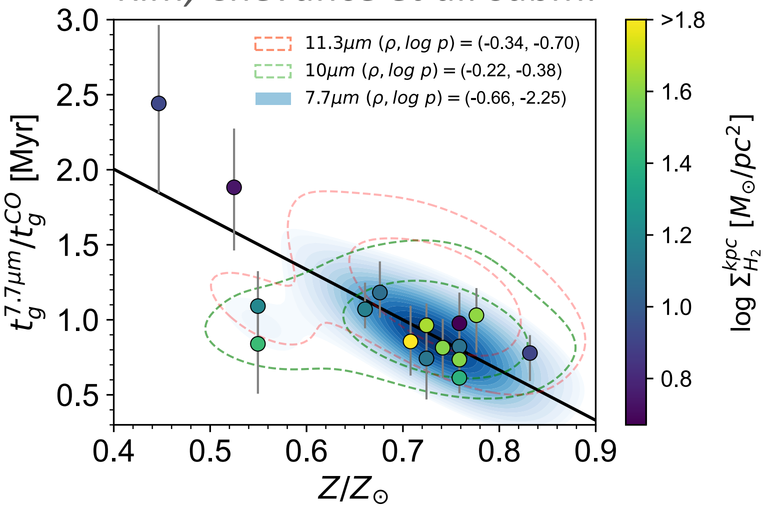
Kim, Chevance et al. subm.

NGC 0628



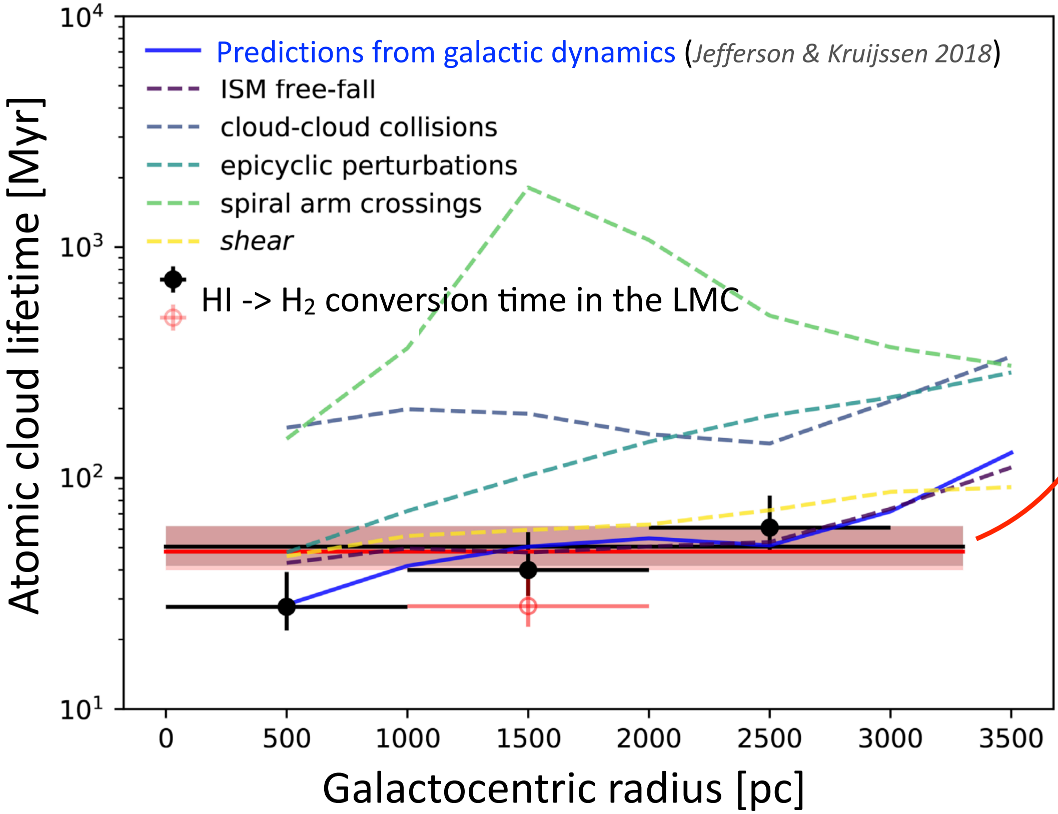


Kim, Chevance et al. subm.



- Fast conversation atomic-to-molecular gas?
- Molecular cloud lifetime limited by CO detection at low-metallicity?

MC assembly in the Large Magellanic Cloud



Ward et al. 2020

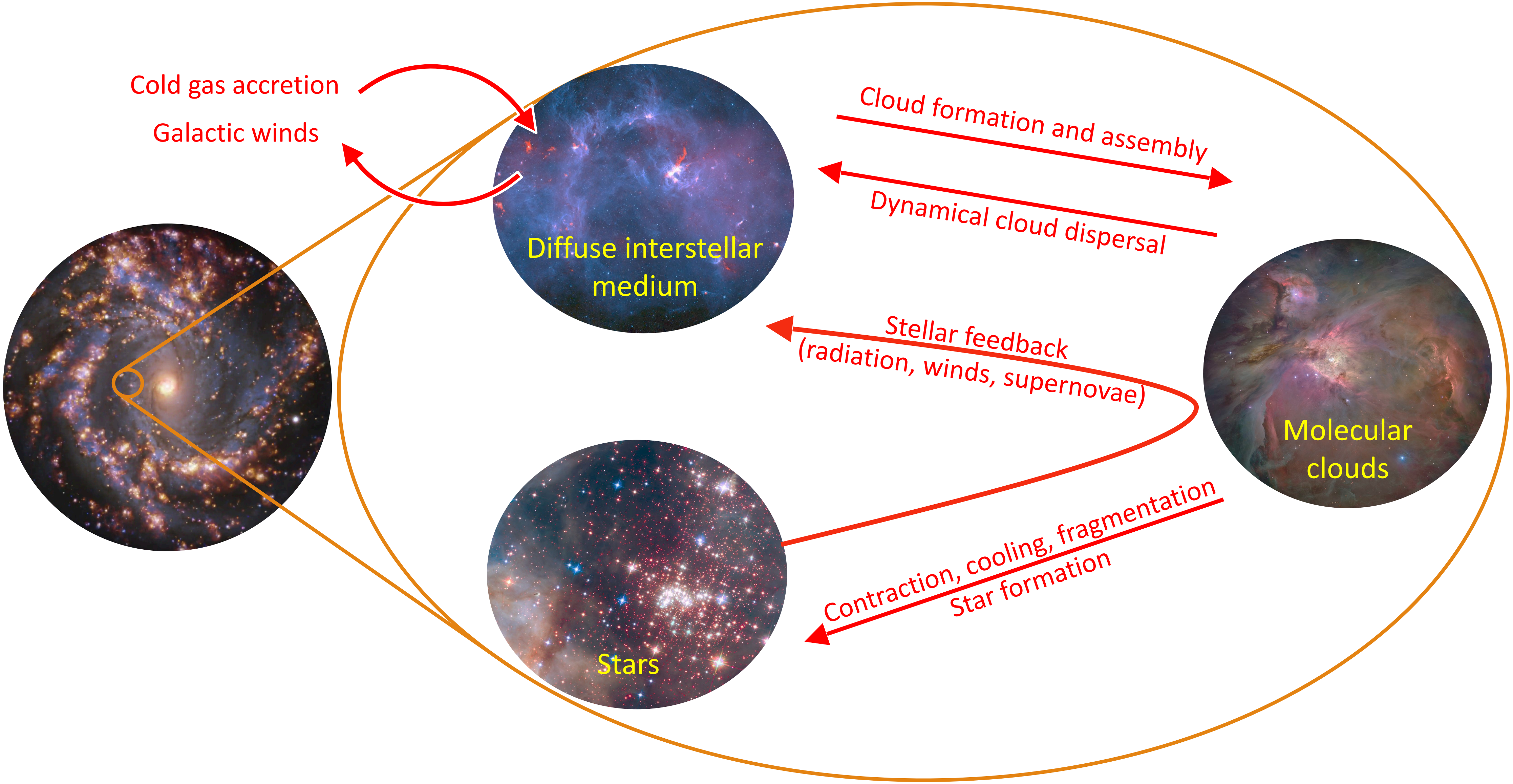
Atomic cloud lifetime:

$t_{HI} = 48\ ^{+13}/_{-8}$ Myr

consistent with predictions from galactic dynamics

With the future SKA:

—> high resolution HI observations for many more galaxies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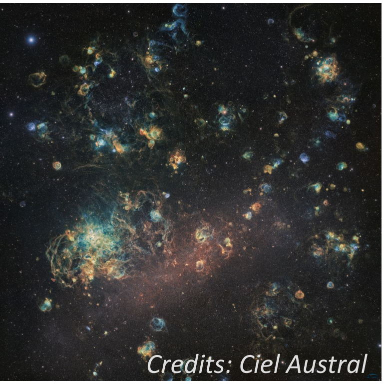
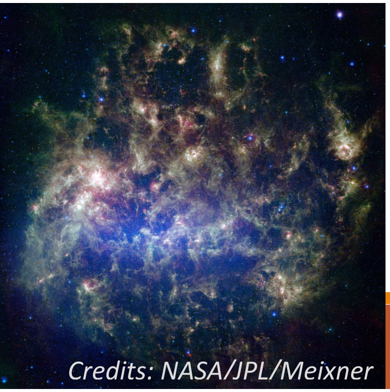


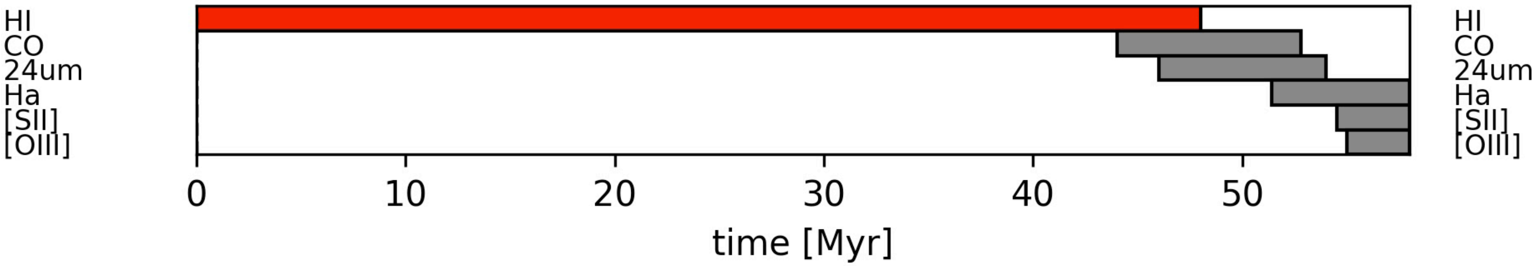


- Distance: 50 kpc
- Observed at more wavelengths than any other external galaxy
- High spatial resolution
- Full galaxy coverage

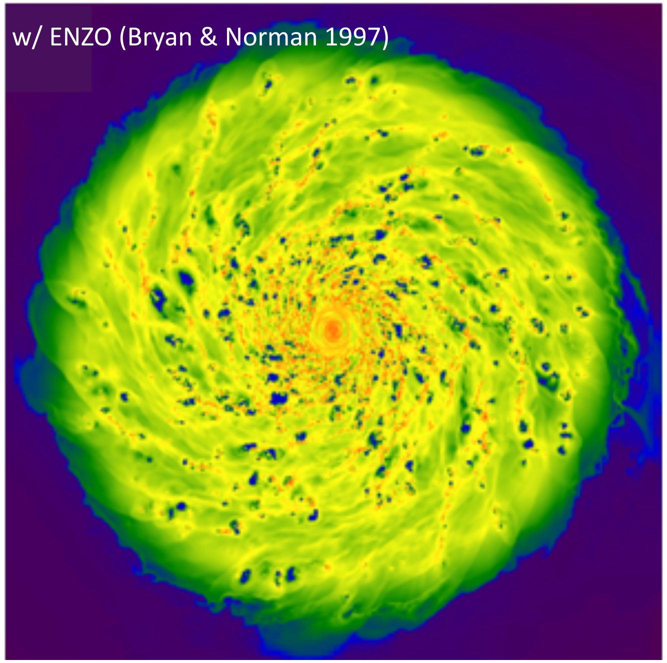
R= HI, G=N/A, B=N/A

Courtesy of Jacob Ward
Ward, Chevance et al. 2020, 2022
Kim, Chevance et al. in prep.

See poster by Xinyue Liang **before Wednesday!**

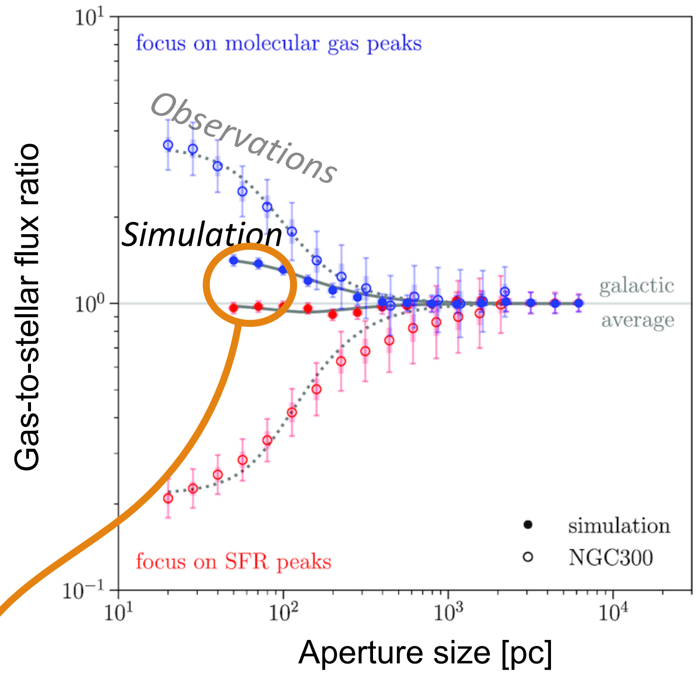


De-correlation of gas & SF: a fundamental test of simulations



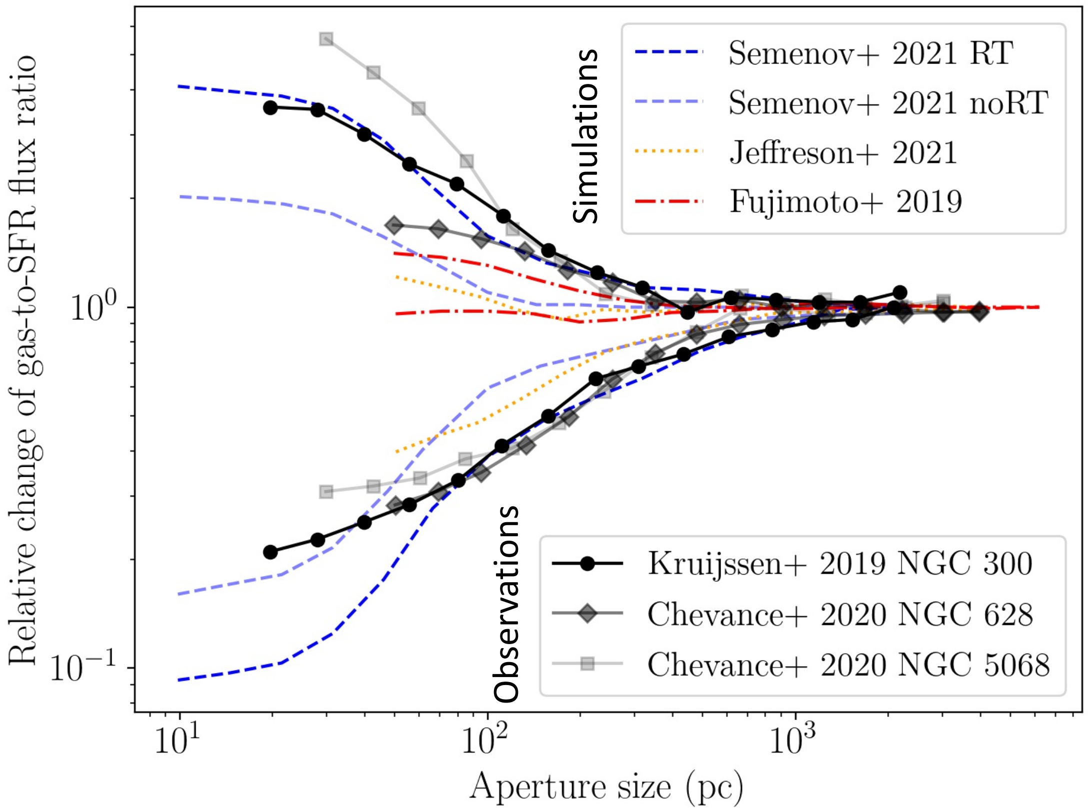
Fujimoto, Chevance et al. 2019

- Simulation including feedback from supernovae and photoionisation
- All macroscopic quantities of this simulation and its cloud properties are ***consistent with observations***
- But the matter cycle ***is not!*** ***(We get some answers right, but for the wrong reasons)***



No decorrelation:
No rapid cycling between cold gas and young stars

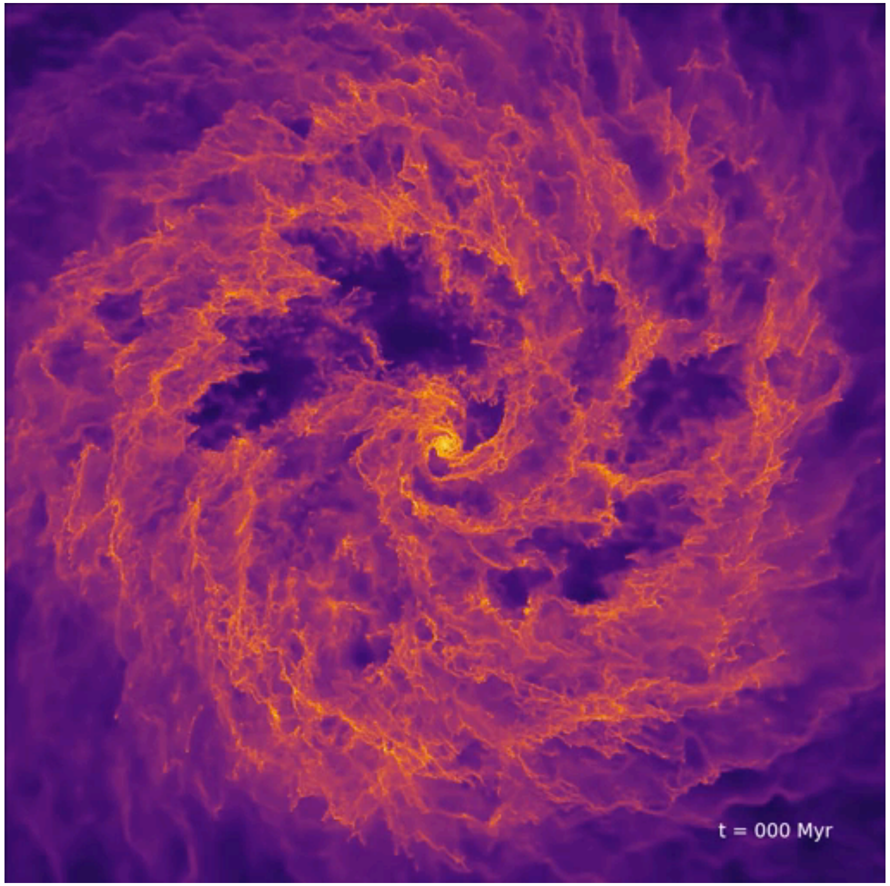
De-correlation of gas & SF:
a fundamental test of simulations



Chevance et al. 2023, PPVII review chapter

A new approach to stellar feedback modelling

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



Keller, Kruijssen and Chevance 2022

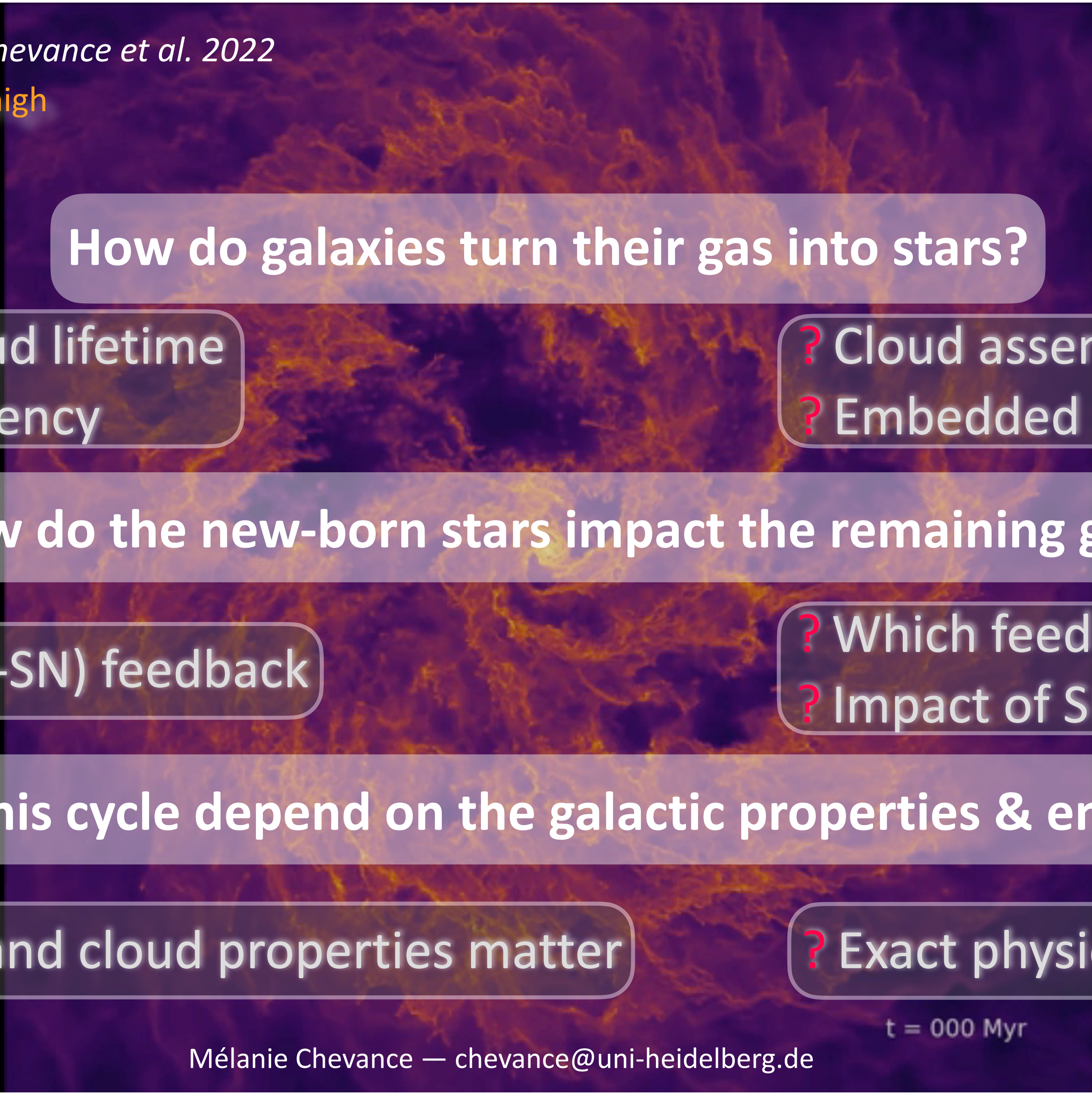
Gas density:
low – medium – high

effect of **early feedback** added as an **additional momentum** based on the observational measurements

See talk by Diederik Kruijssen on Thursday

Simulation: *Keller, Kruijssen, Chevance et al. 2022*

Gas density: low – medium – high



How do galaxies turn their gas into stars?

✓ Short cloud lifetime

✓ Low efficiency

? Cloud assembly time

? Embedded stellar phase

How do the new-born stars impact the remaining gas?

✓ Early (pre-SN) feedback

? Which feedback, when

? Impact of SN

How does this cycle depend on the galactic properties & environment?

✓ Galactic and cloud properties matter

? Exact physical mechanisms

Upcoming observational facilities

➢ ***Finer time resolution*** to identify the individual physical mechanisms at play: ***multi-wavelength observations***