The Empirically-Motivated Physics (EMP) simulations of galaxy formation and evolution

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Clustering of star formation & feedback determines galaxy properties

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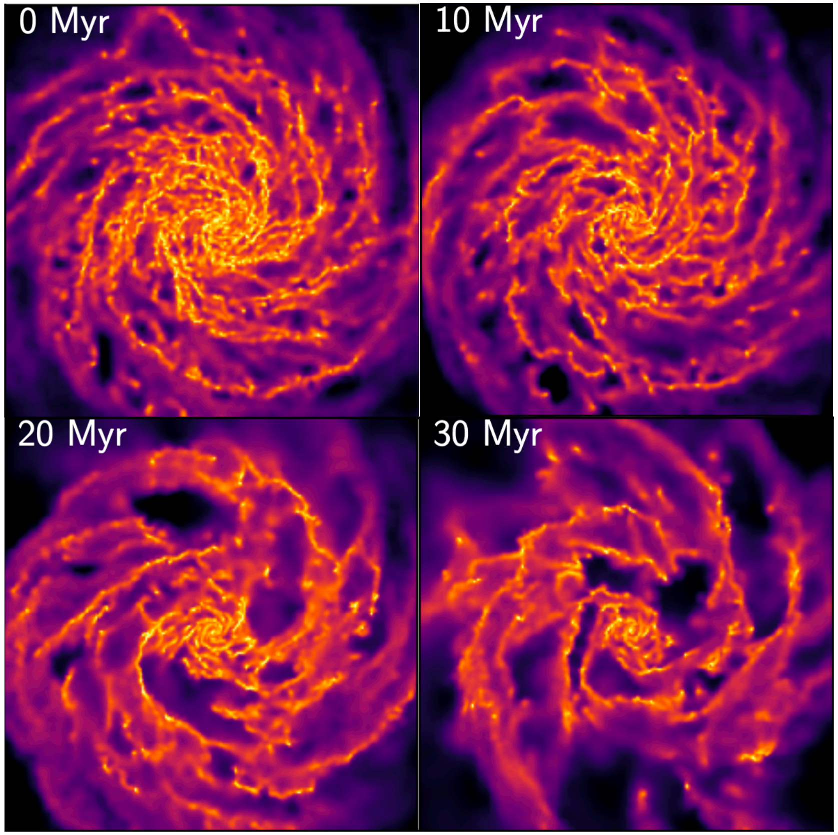
varying FB model
all else identical



Keller & Kruijssen 2021

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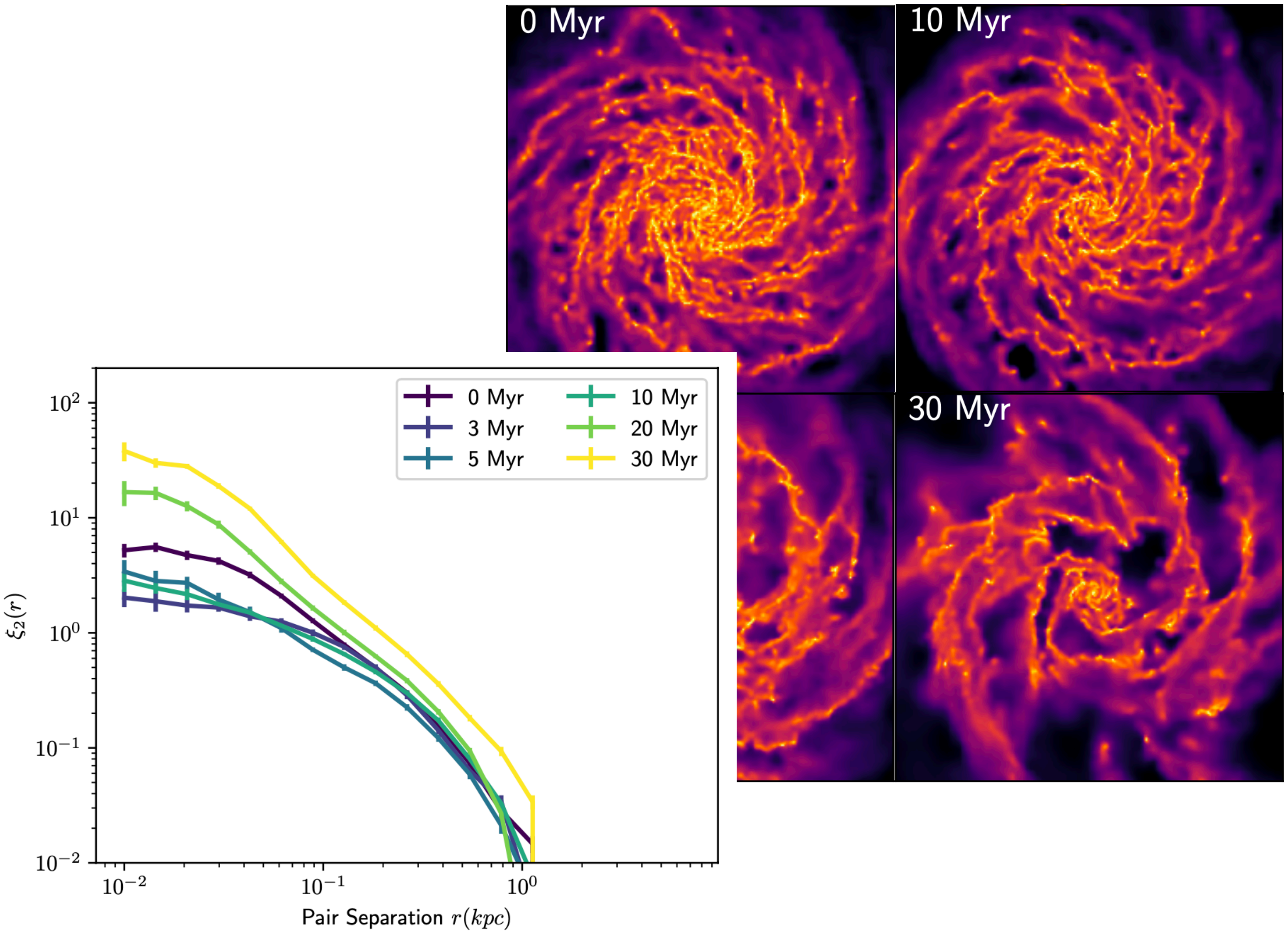

Keller & Kruijssen 2021

Modelling feedback is complex due to combination of mechanisms

- Stellar winds
- Supernovae
- Photoionisation
- Radiation pressure
- Protostellar outflows

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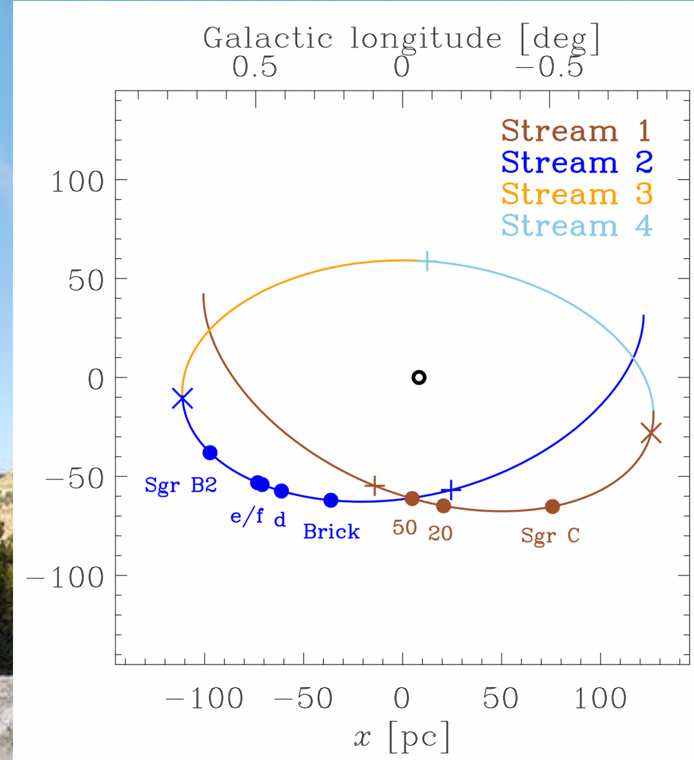
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **440,** 3370–3391 (2014) doi:10.1093/mnras/stu494

What controls star formation in the central 500 pc of the Galaxy?

J. M. Diederik Kruijssen,[1★] Steven N. Longmore,[2,3] Bruce G. Elmegreen,[4] Norman Murray,[5] John Bally,[6] Leonardo Testi[3,7] and Robert C. Kennicutt Jr[8]




x [pc]
Galactic longitude [deg]
Stream 1
Stream 2
Stream 3
Stream 4
Sgr C
Sgr B2
Brick

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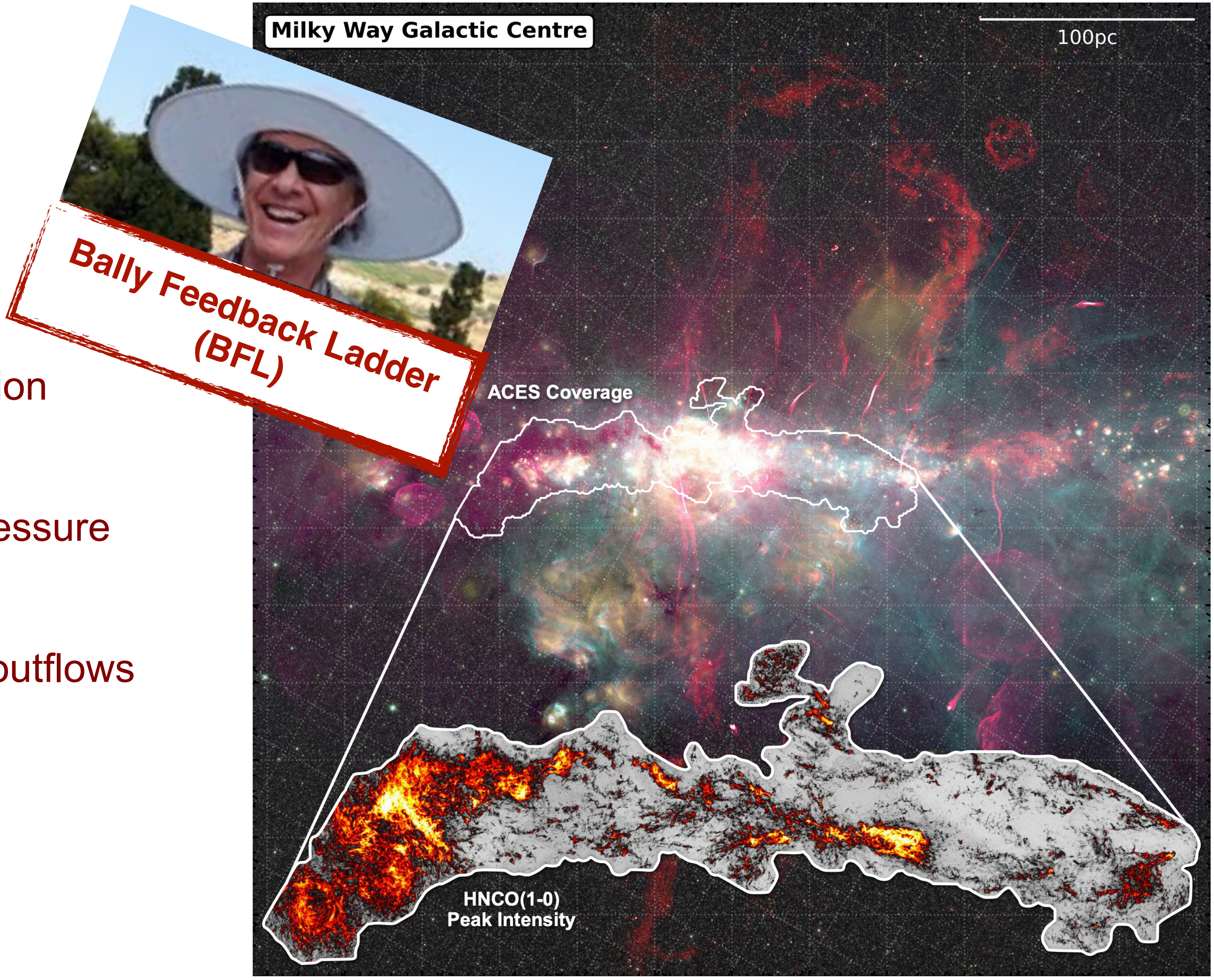

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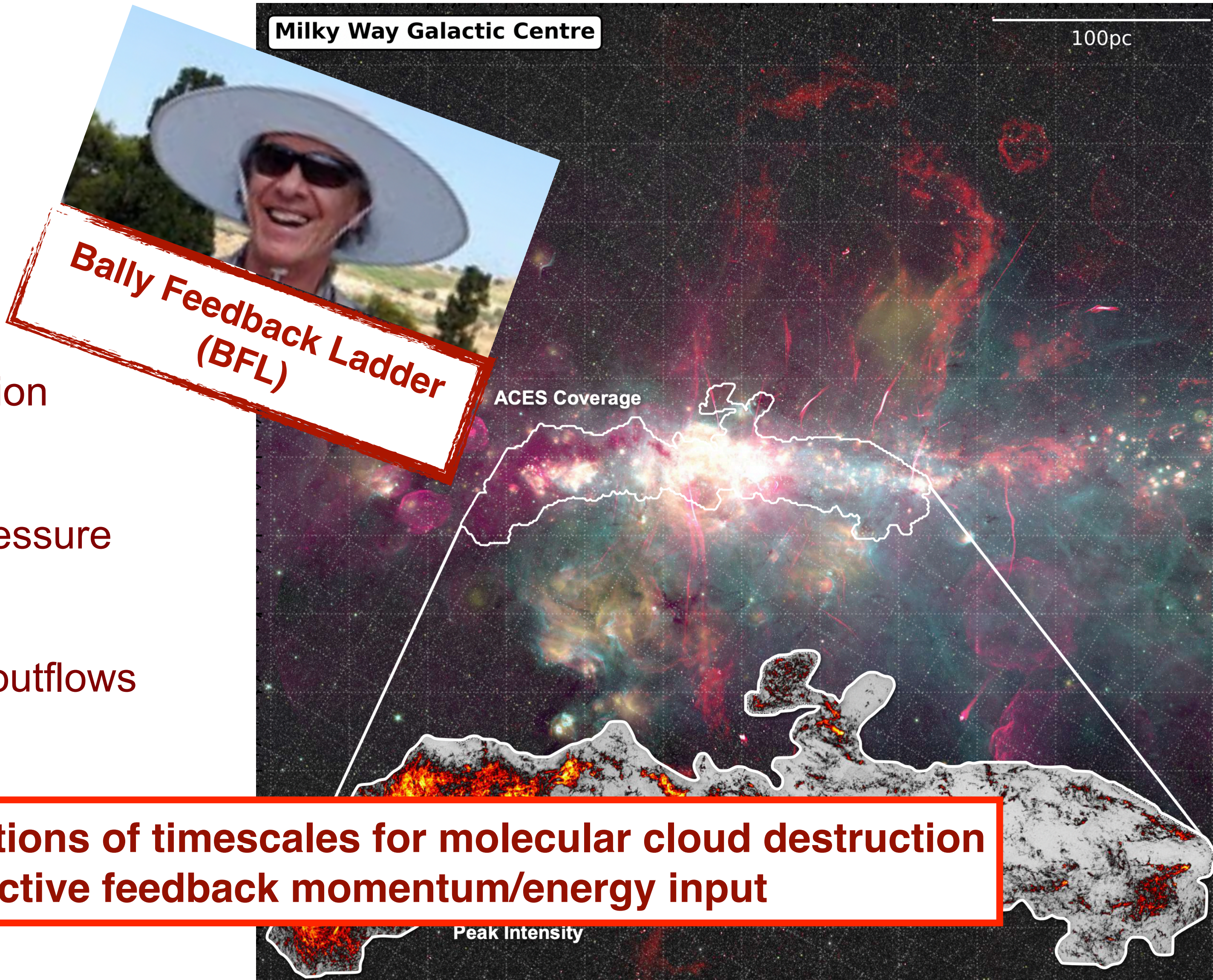
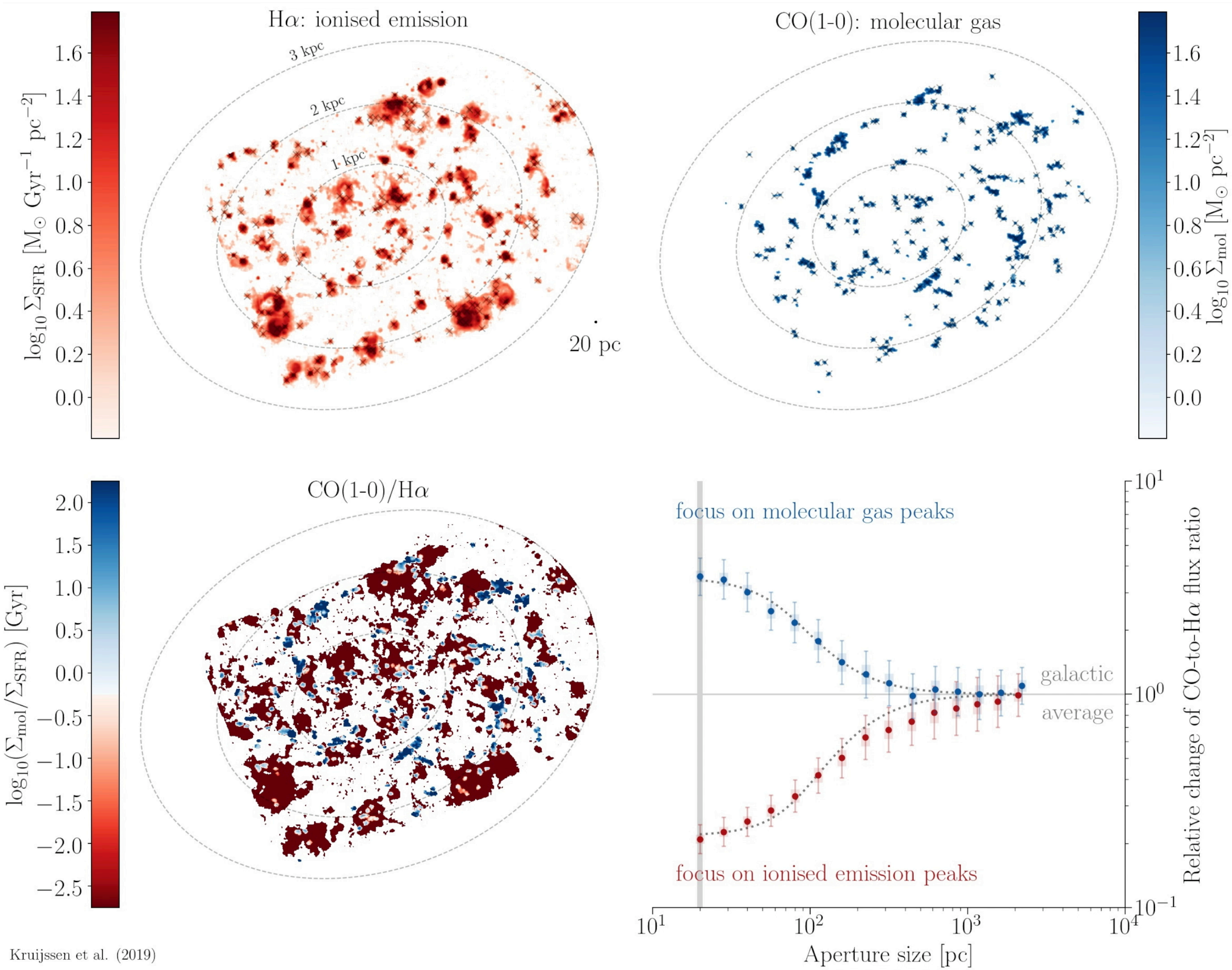


Idea: observations of timescales for molecular cloud destruction constrain effective feedback momentum/energy input

Observations help constrain feedback by measuring underlying timescales

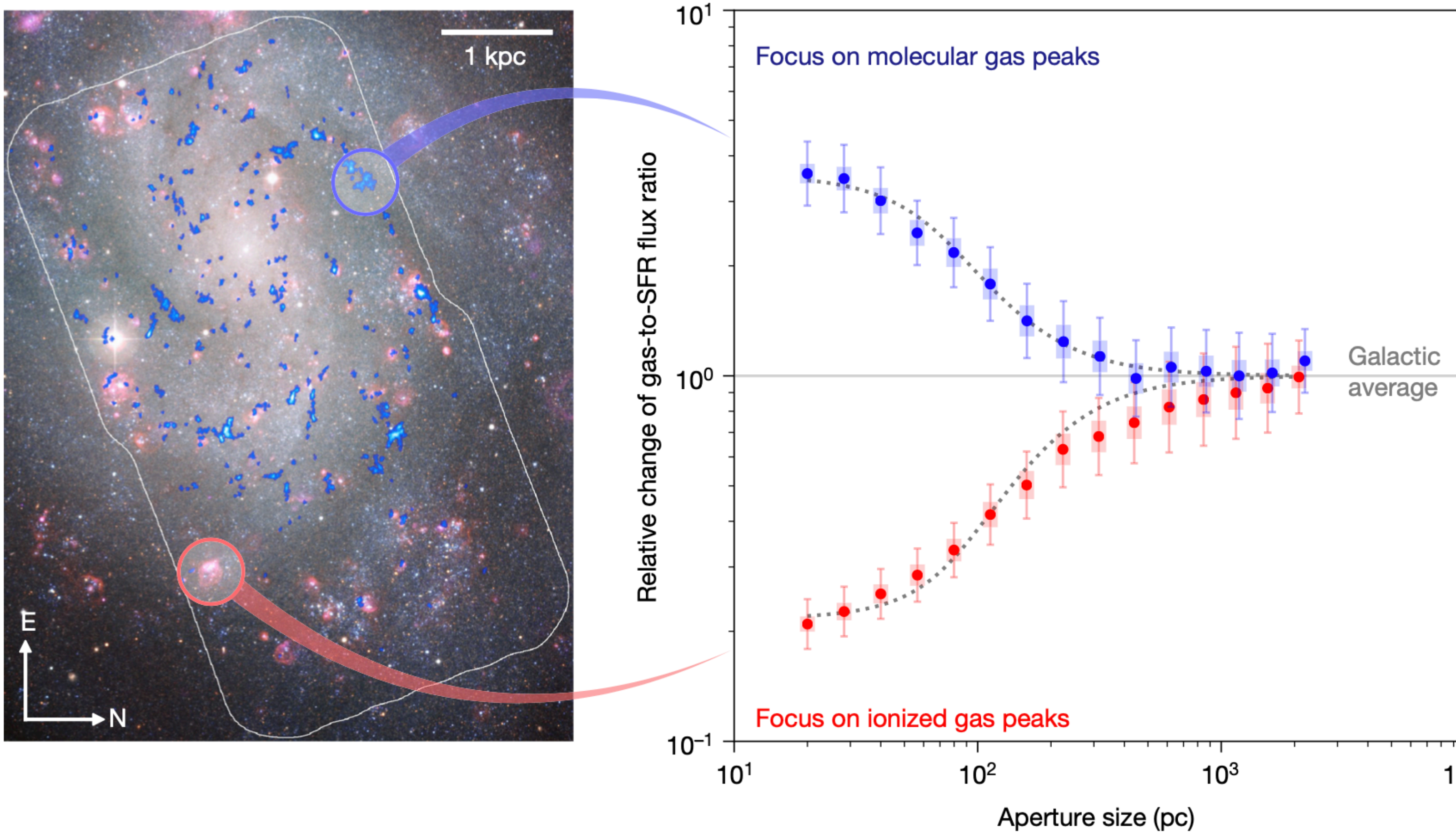
Spatially-resolved SF relation in NGC300: vigorous evolutionary cycling



Kruijssen, Schruba, Chevance, Longmore+2019, *Nature*, 569, 519

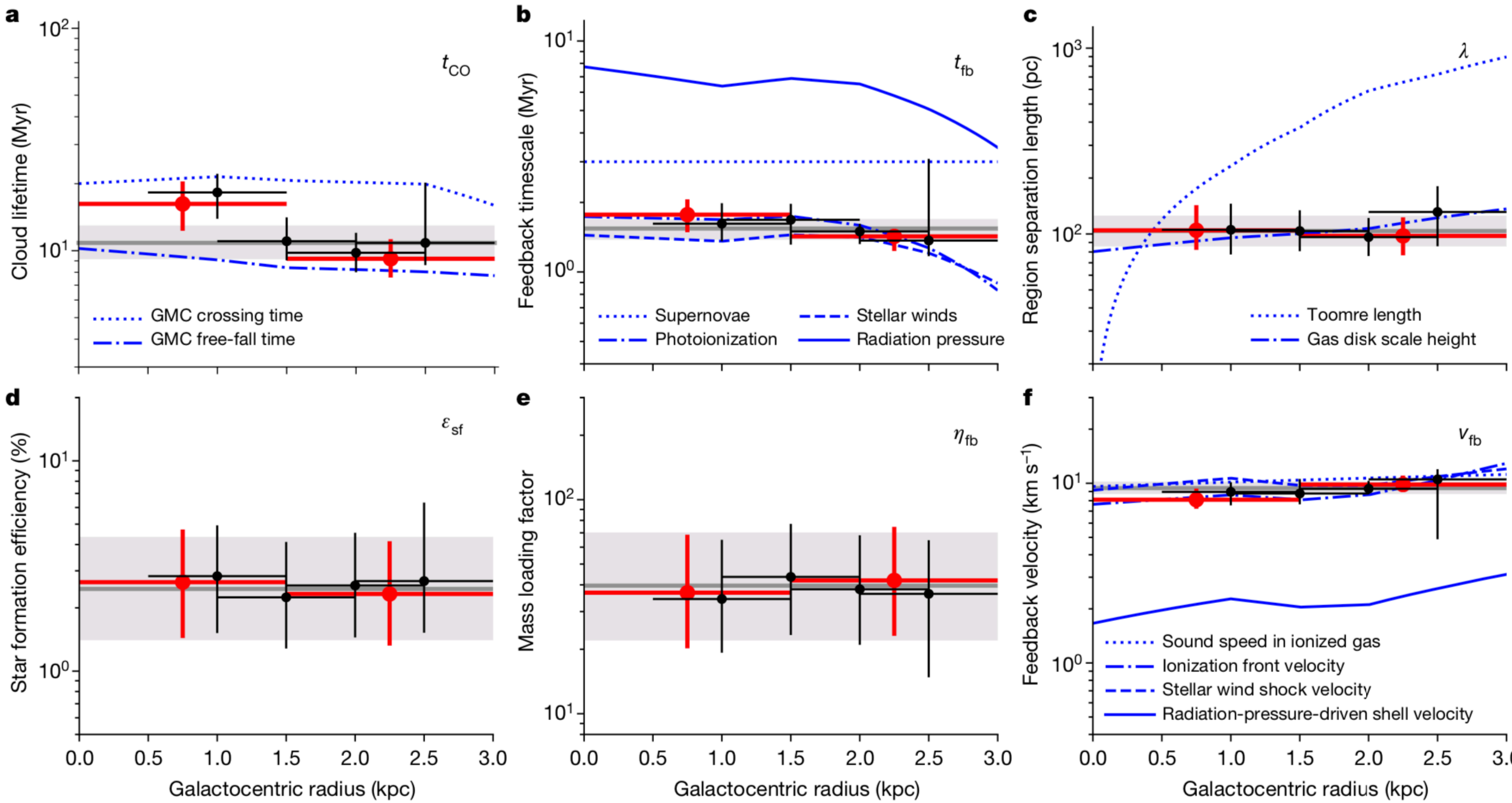
Spatially-resolved SF relation quantifies GMC lifecycle

"Uncertainty principle for star formation"; described in Kruijssen & Longmore 2014; Kruijssen+ 2018



Kruijssen, Schruba, Chevance, Longmore+ 2019, *Nature*, 569, 519

Enables simultaneous measurement of quantities describing SF & FB



Kruijssen, Schruba, Chevance, Longmore+ 2019, *Nature*, 569, 519

Spatially-resolved SF relation fundamentally rules out "long" GMC lifetimes

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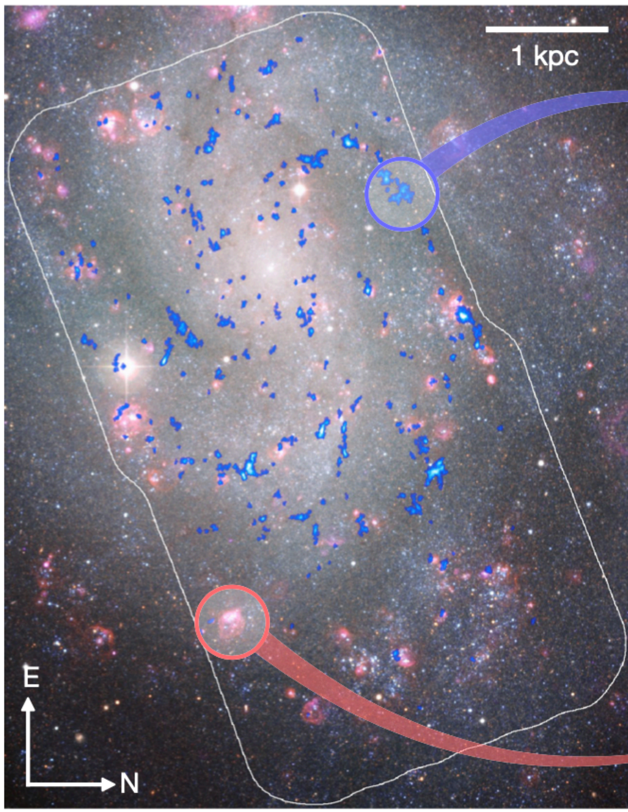

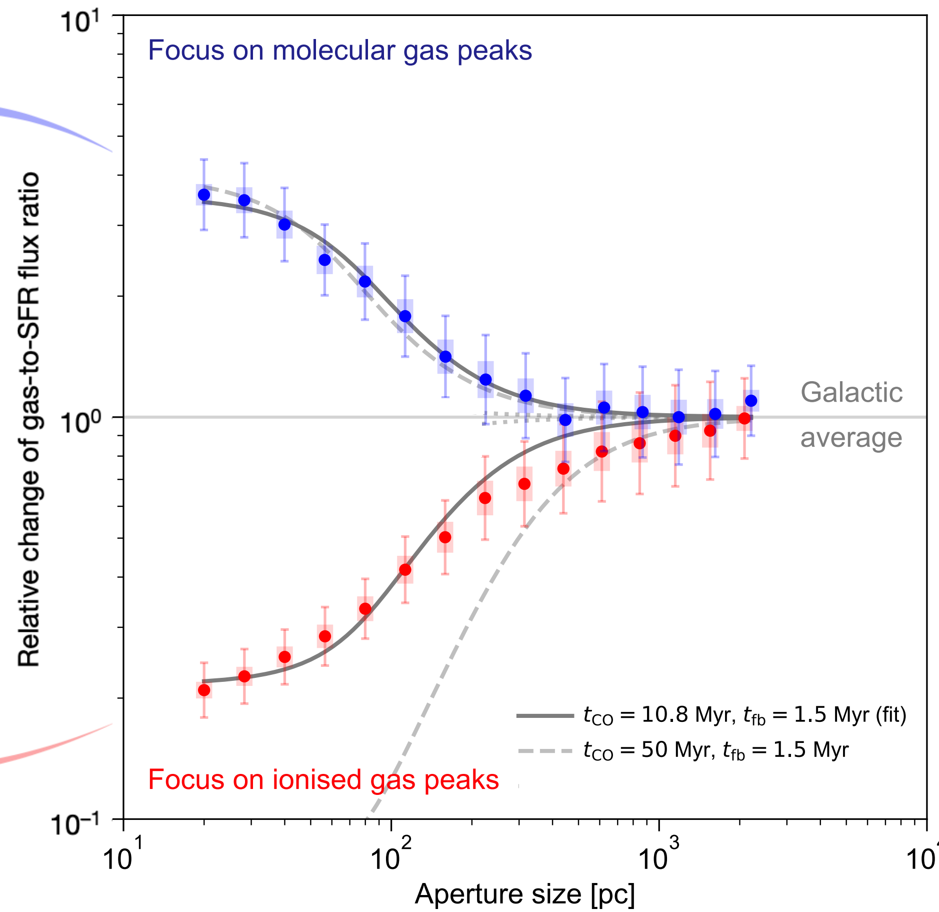

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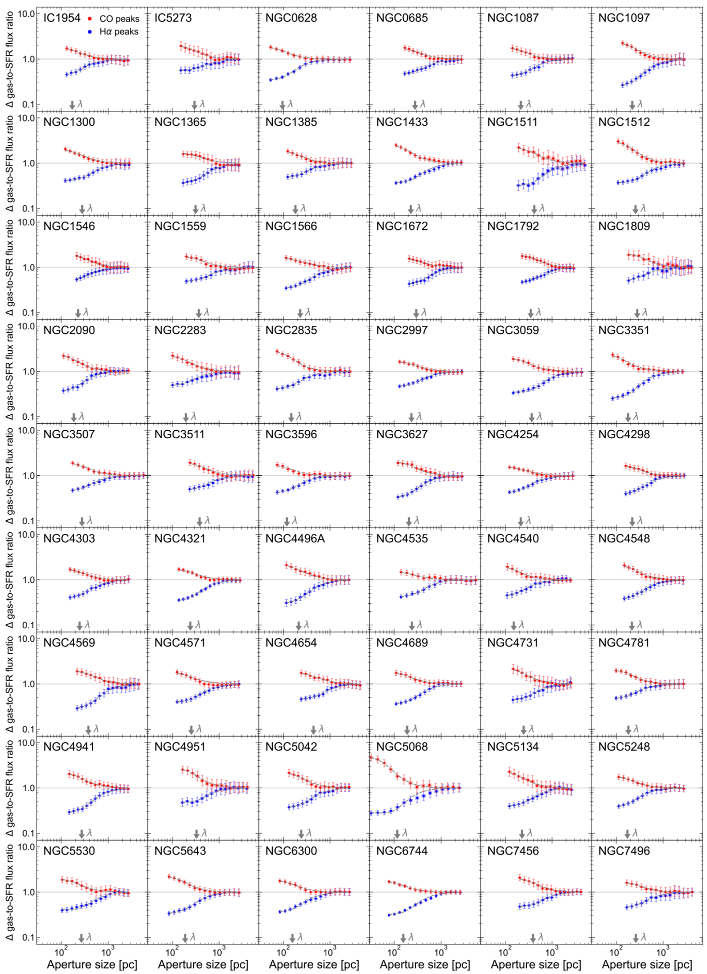
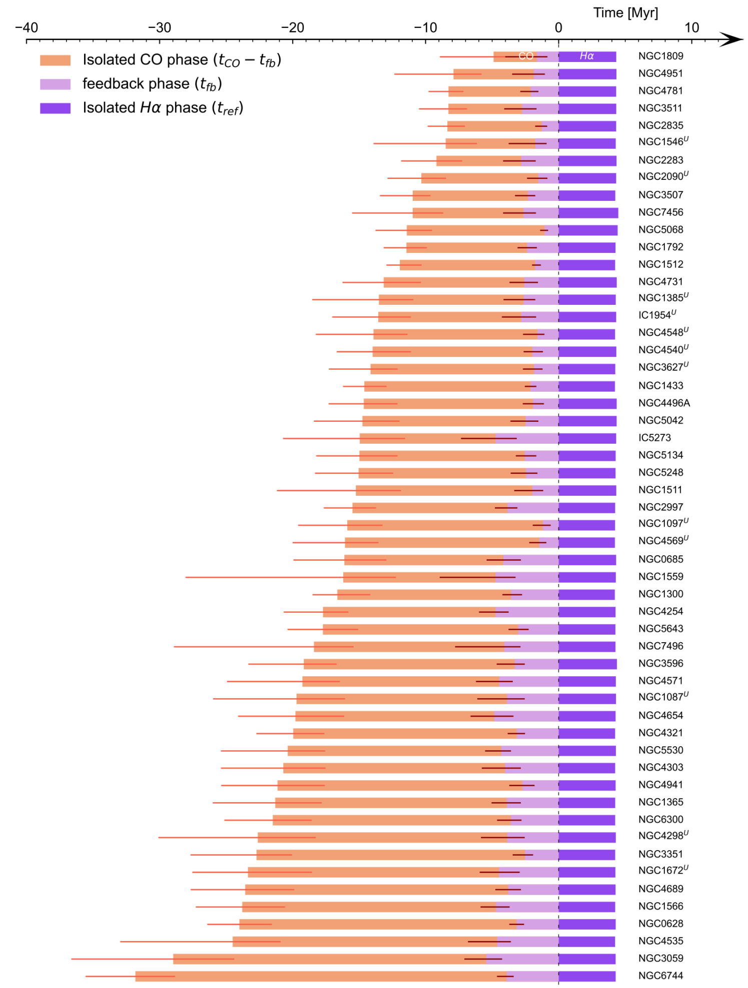
Universal de-correlation: ubiquitous GMC destruction by pre-SN feedback

Kim+ 2022





These measurements can motivate a subgrid model for pre-SN feedback

Keller, Kruijssen & Chevance 2022

- Specific terminal momentum from feedback timescale, cloud radius, and SFE

$$\hat{p}(t_{FB}) = \alpha\left(\frac{(1-\epsilon_{SF})\,r_{cl}}{\epsilon_{SF}\,t_{FB}}\right)$$

These measurements can motivate a subgrid model for pre-SN feedback

Keller, Kruijssen & Chevance 2022

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

$$\hat{p}(t_{FB}) = \alpha\left(\frac{(1-\epsilon_{SF})\,r_{cl}}{\epsilon_{SF}\,t_{FB}}\right)$$

$$\boxed{\hat{p}(t) = \alpha\left(\frac{(1-\epsilon_{SF})\,r_{cl}}{\epsilon_{SF}\,t_{FB}}\right)(t/t_{FB})^{4\alpha-1}}$$

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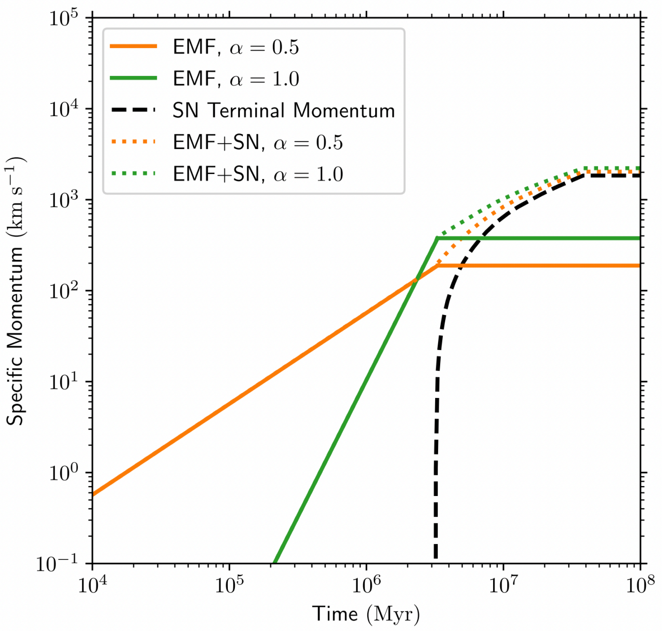
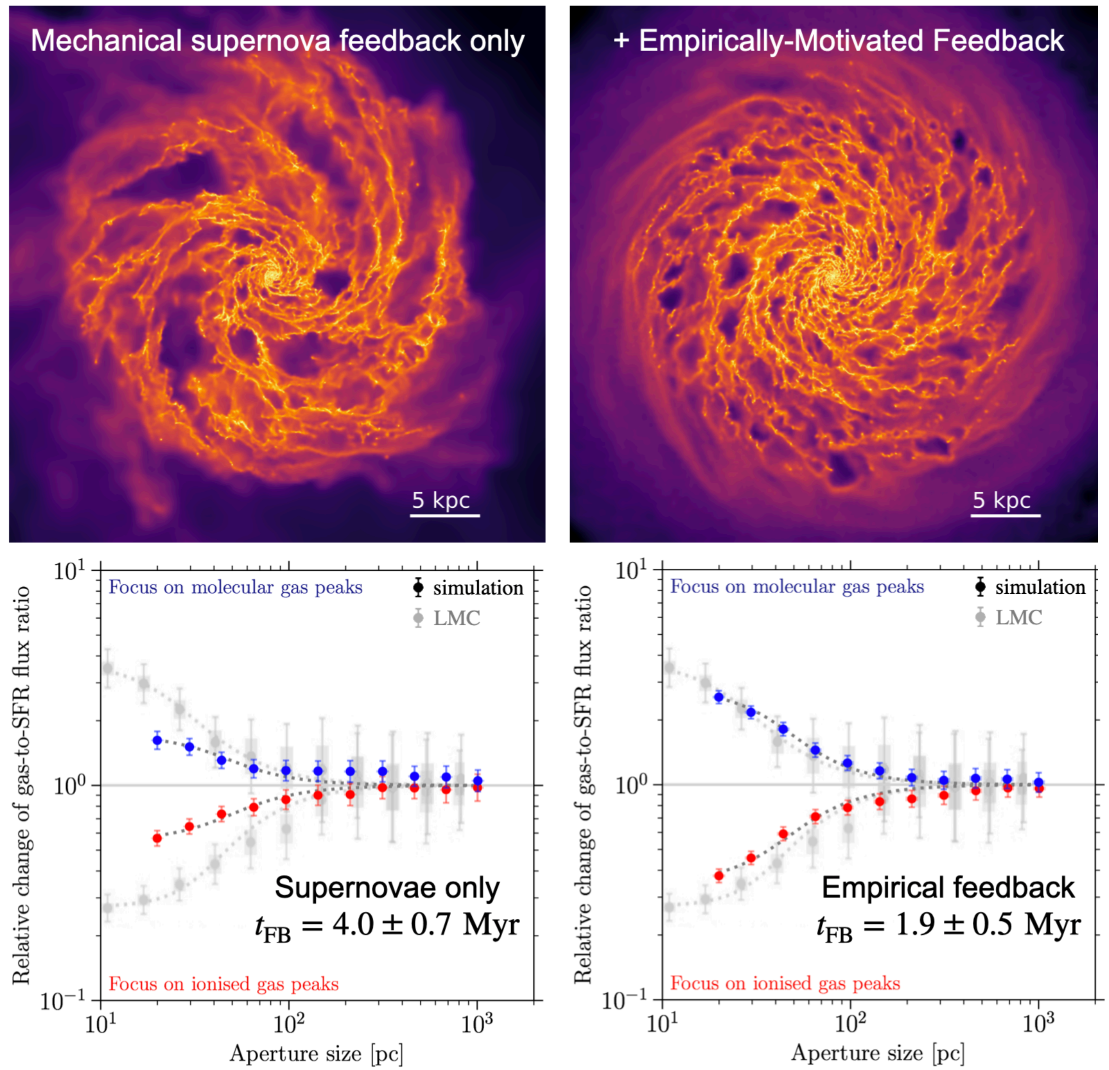
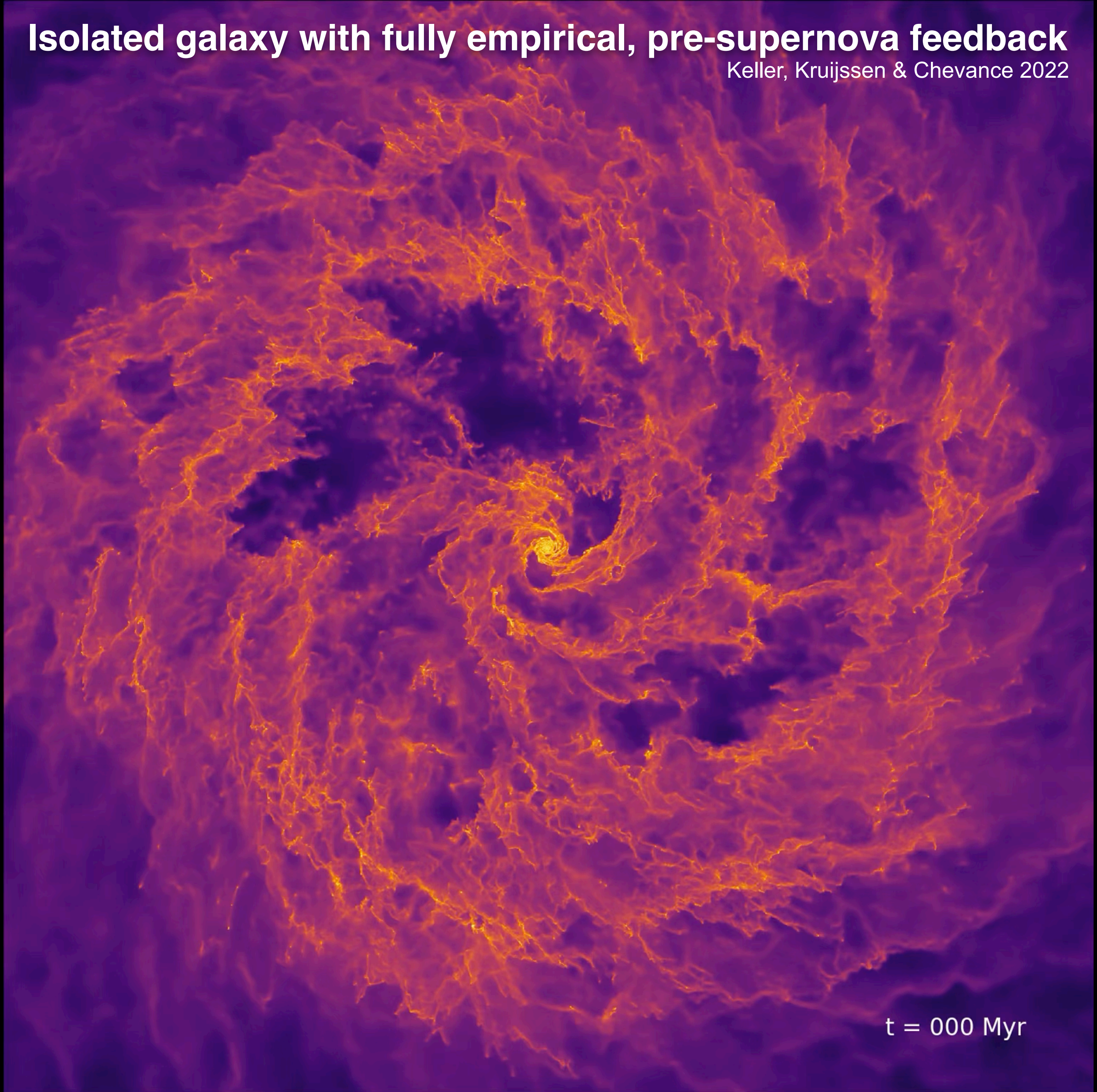


Empirically-motivated FB reproduces observed de-correlation in simulations

Keller, Kruijssen & Chevance 2022

- ✦ Reproduces the observed GMC lifecycle by construction
- ✦ Changes galaxy-scale baryon cycle




Isolated galaxy with fully empirical, pre-supernova feedback
Keller, Kruijssen & Chevance 2022
t = 000 Myr

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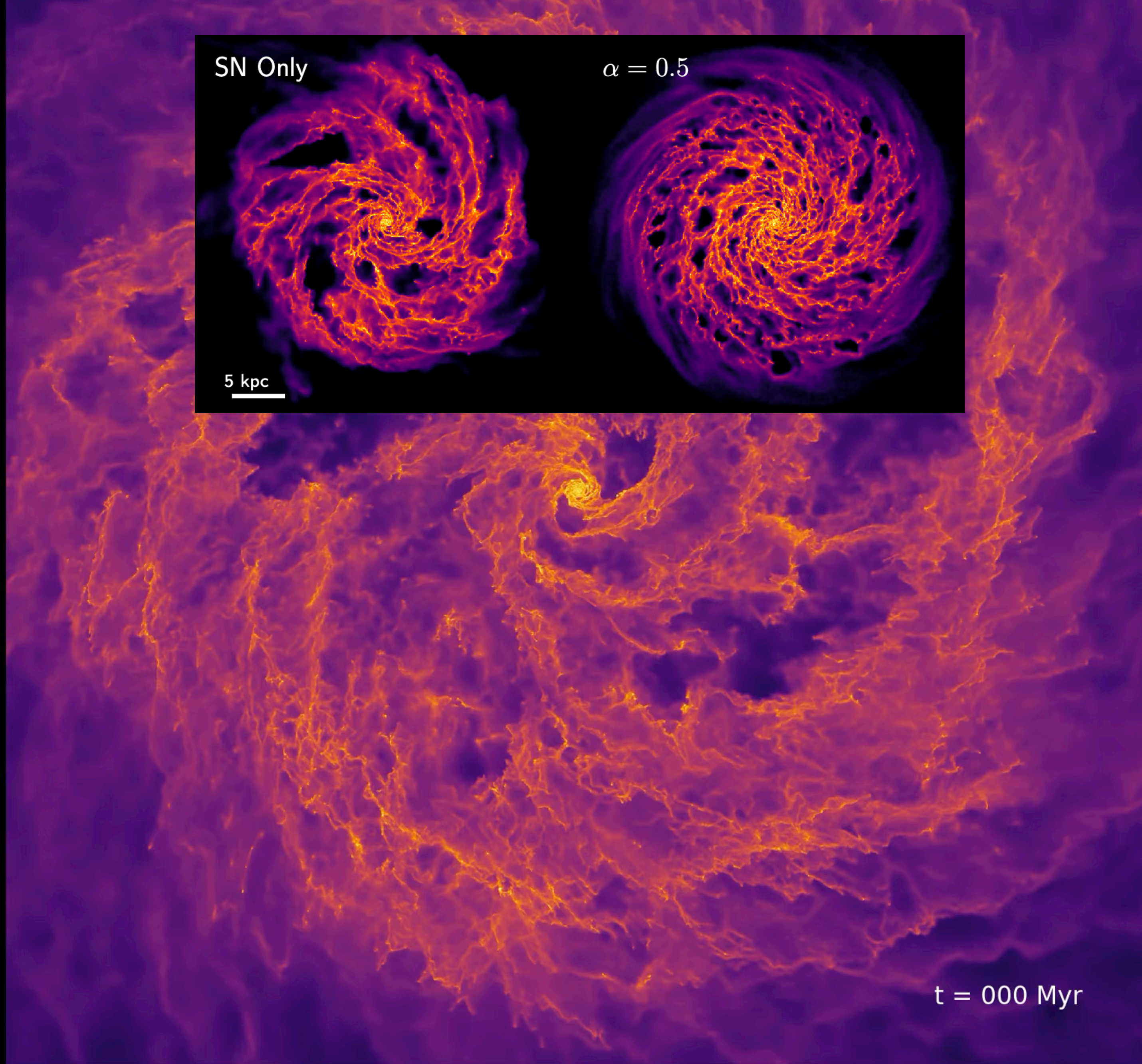

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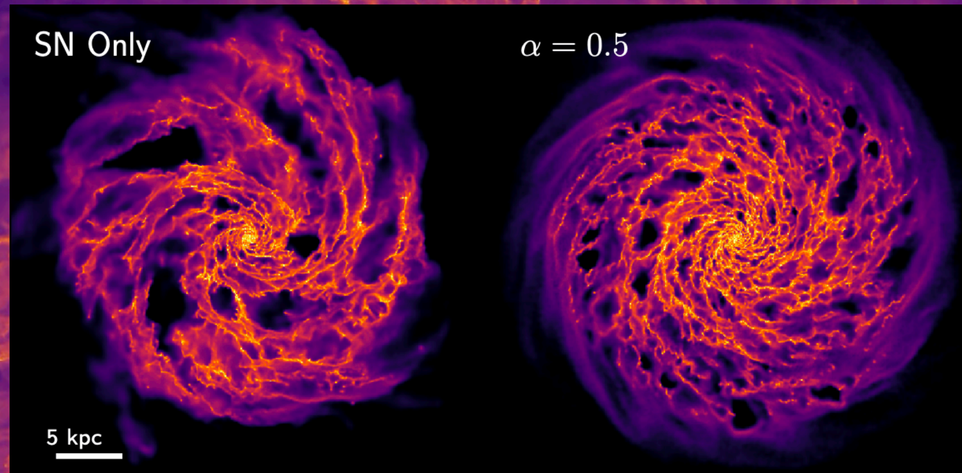

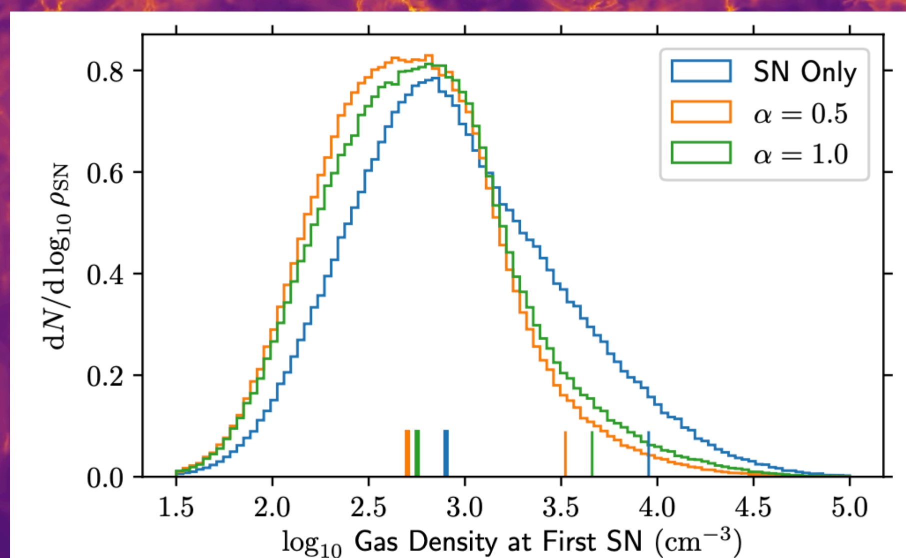

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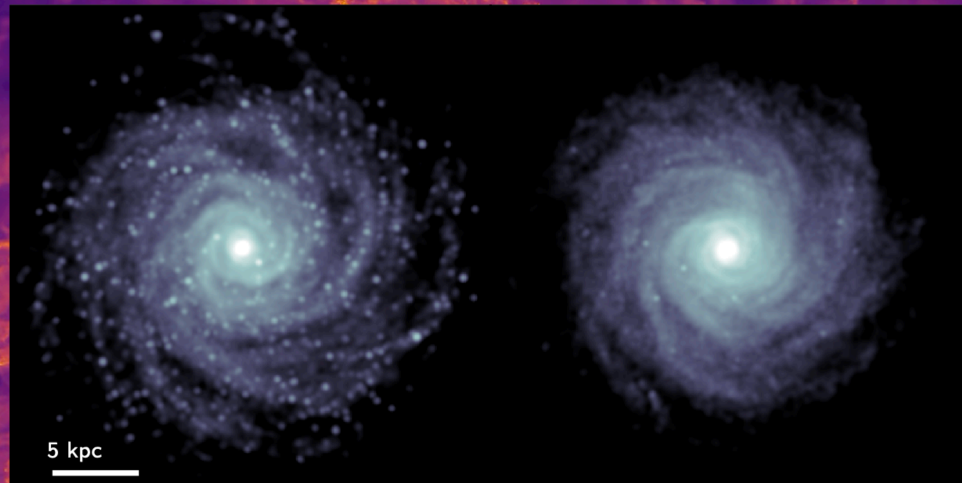

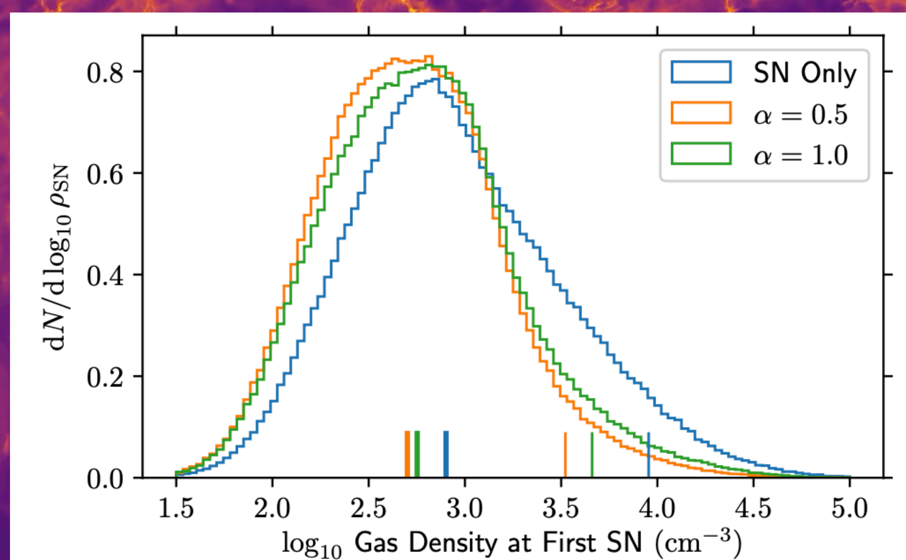

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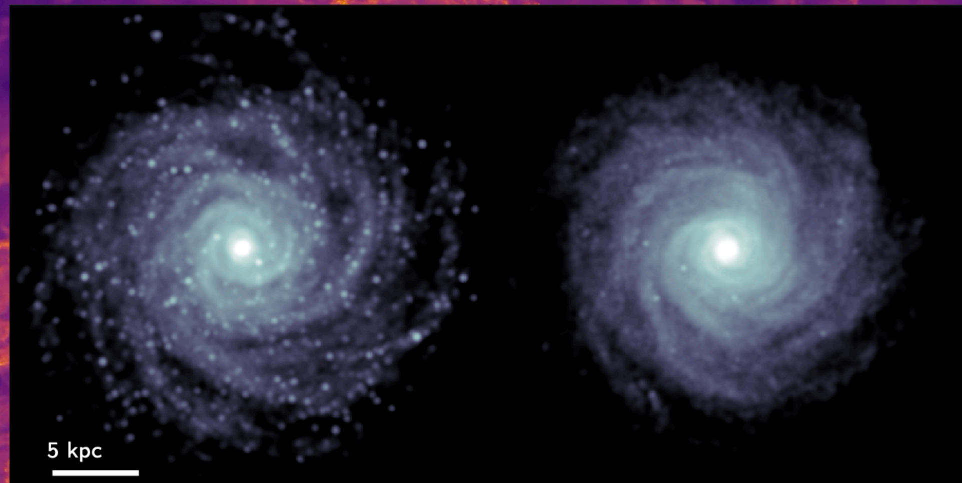

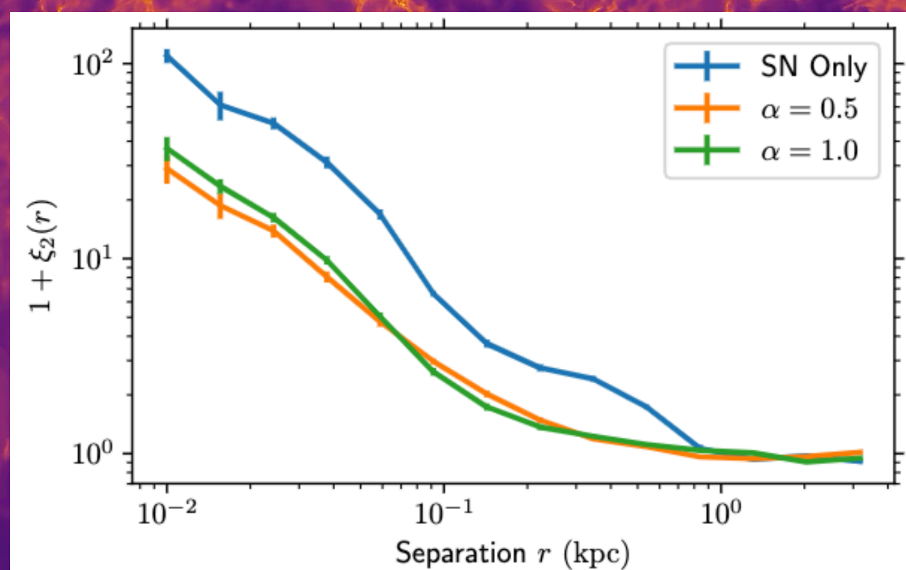

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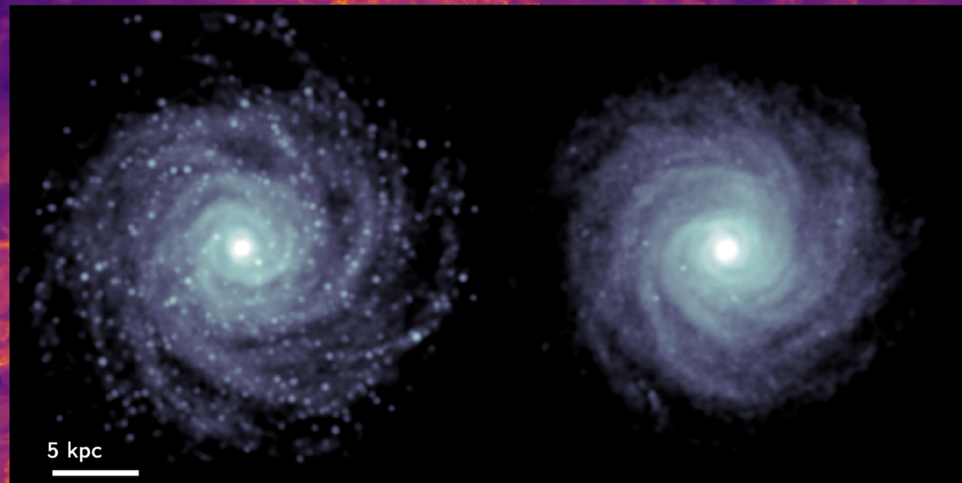
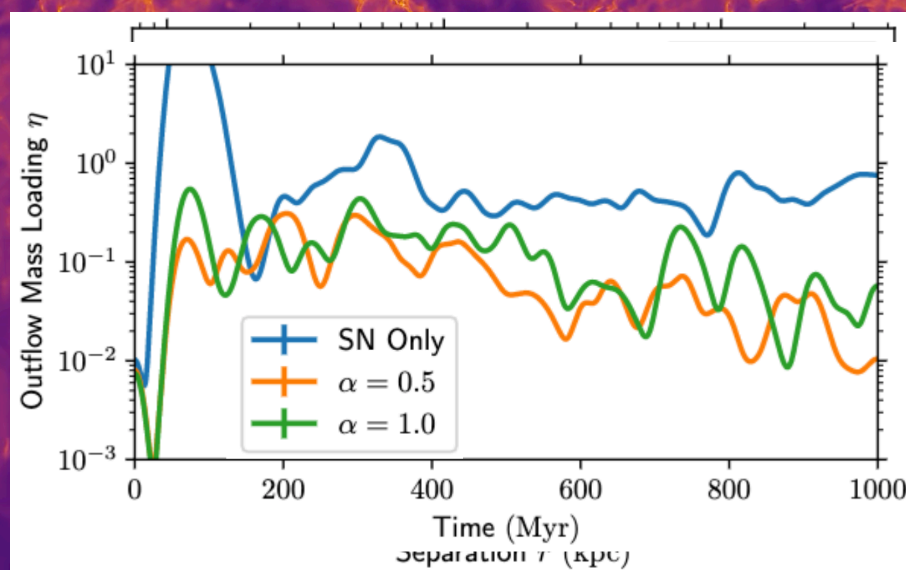




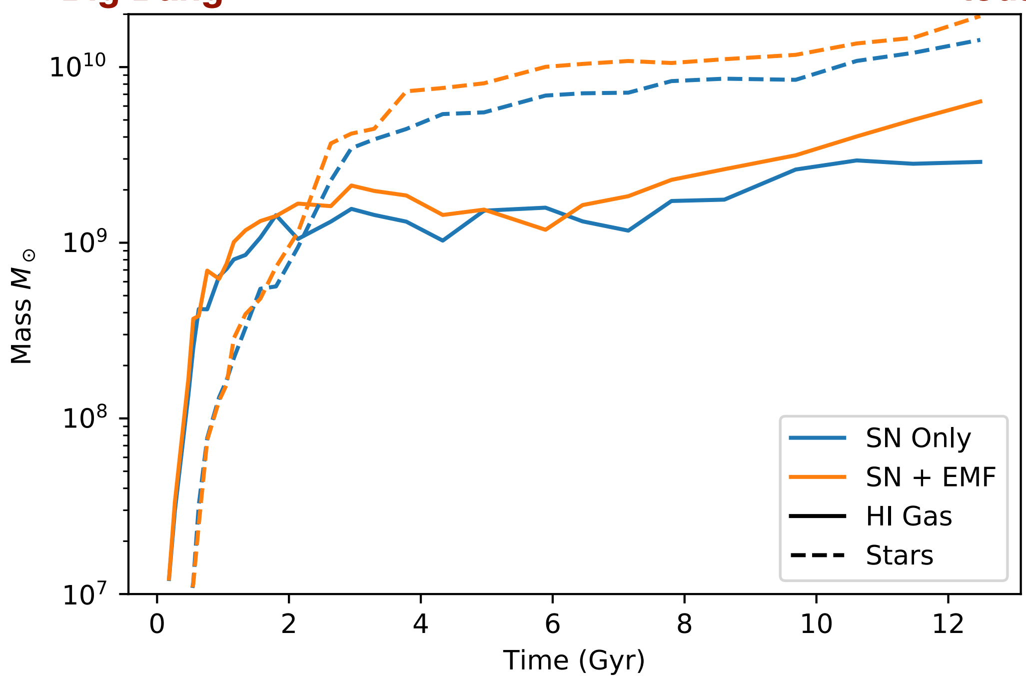
Applied in cosmological context: significant change in gas mass histories

Kruijssen+ in prep.
Keller+ in prep.

- Empirical feedback does not regulate SF by blowing gas out of galaxy globally, but locally by disrupting GMCs and putting the gas in a non-star-forming state

Big Bang

today



lines: average of 10 simulations

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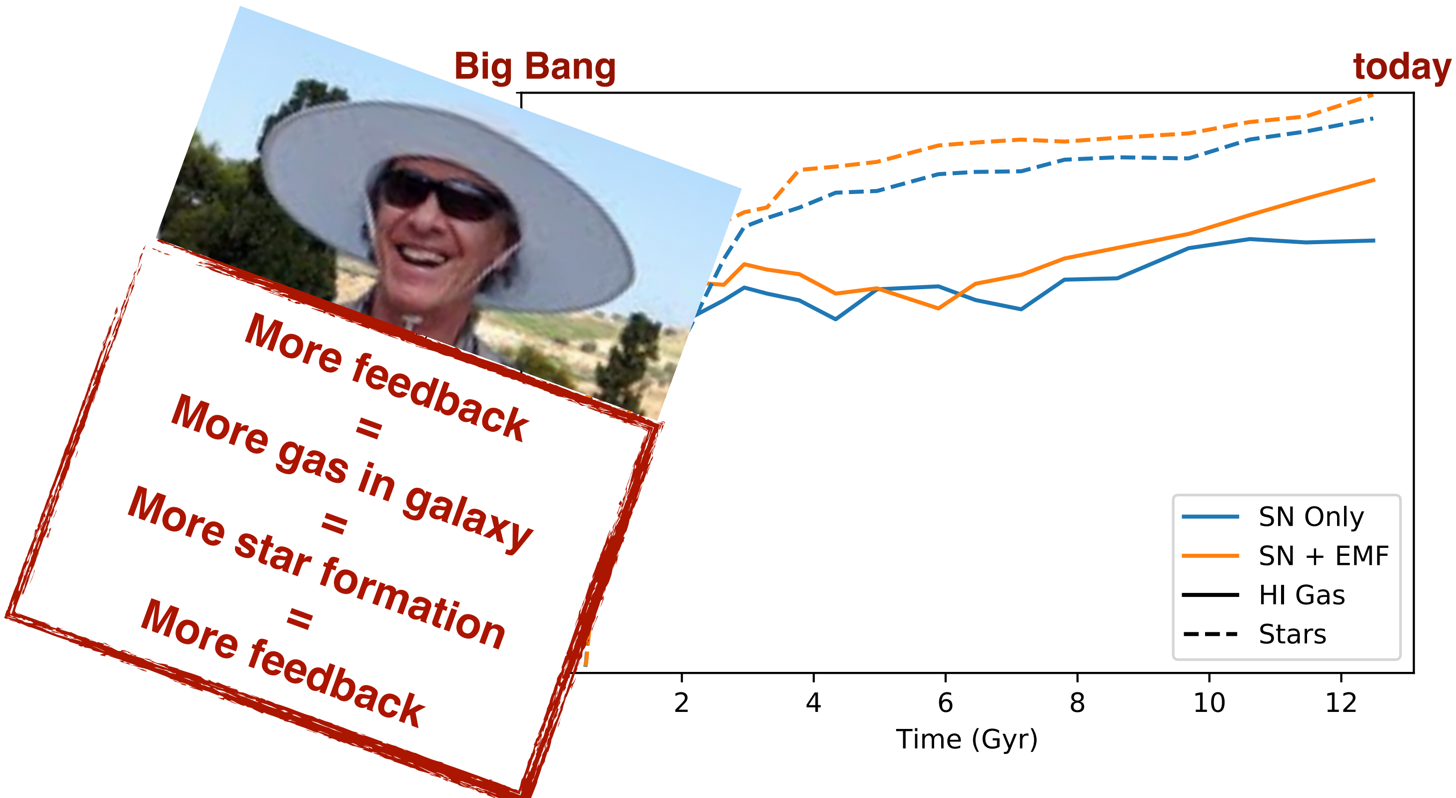

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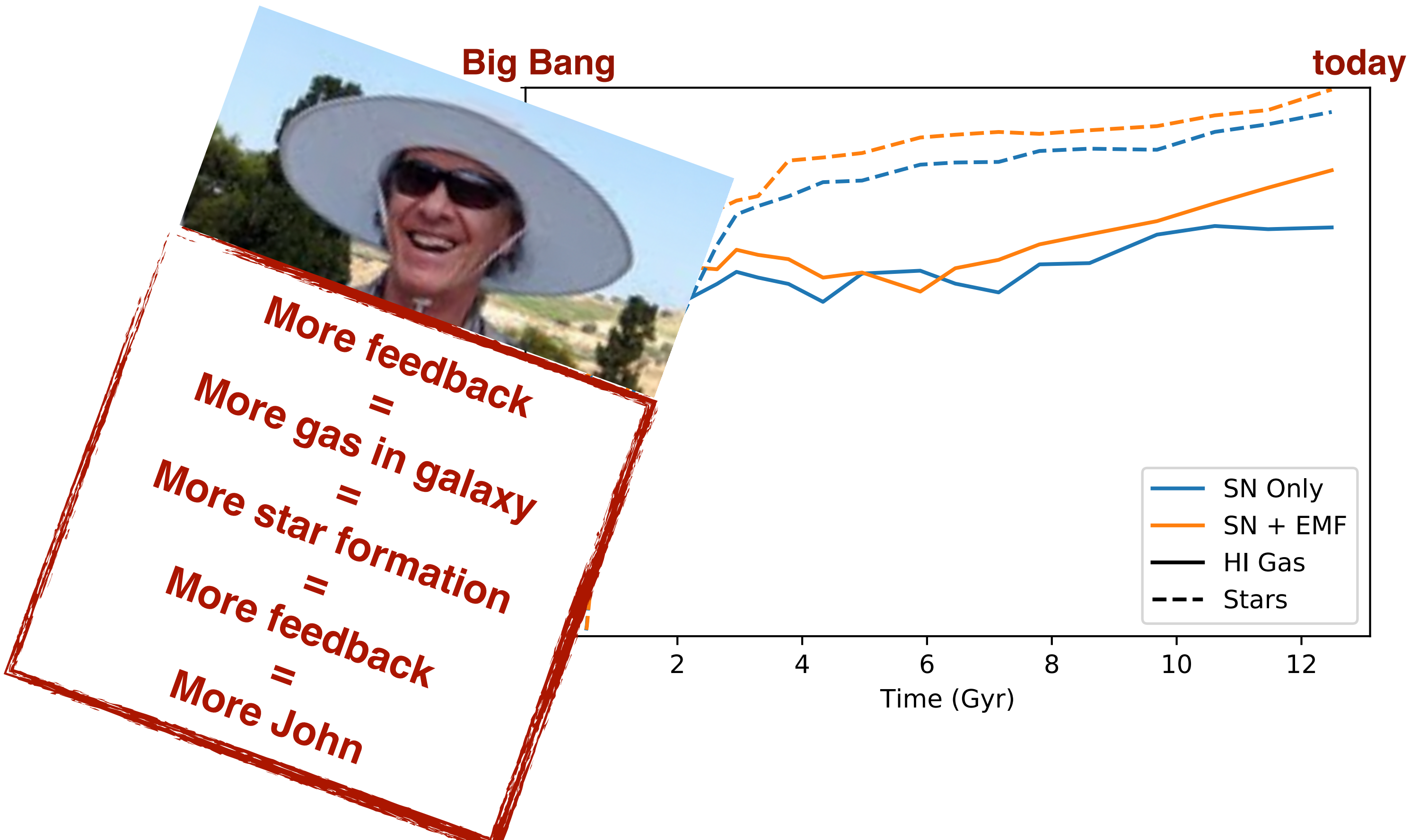


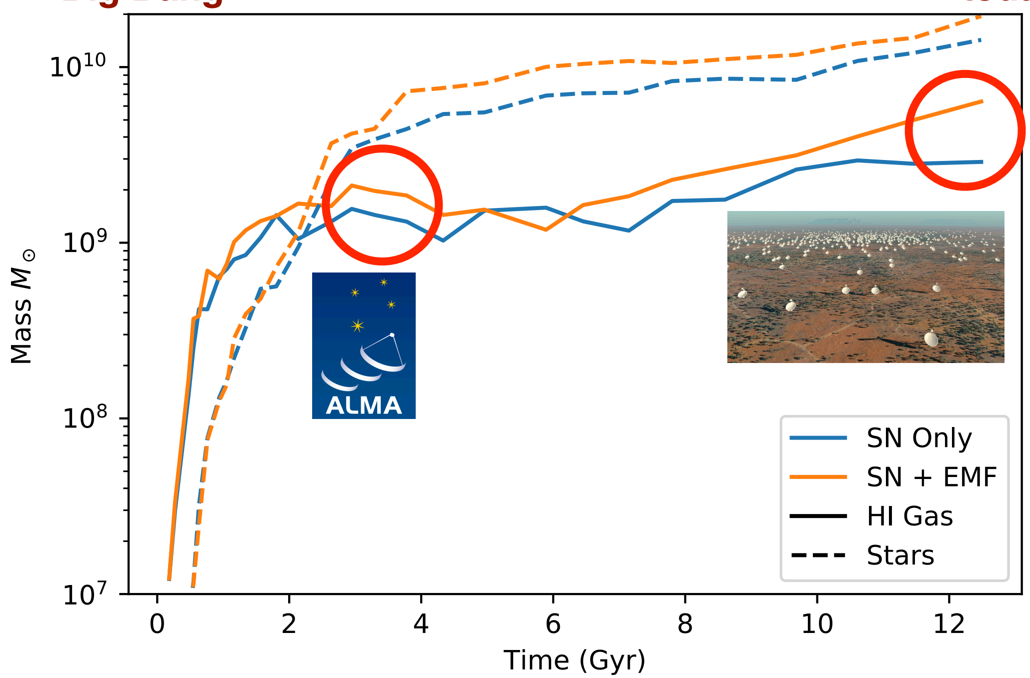
lines: average of 10 simulations

Phase of the excess gas depend on moment in cosmic history

Kruijssen+ in prep.
Keller+ in prep.

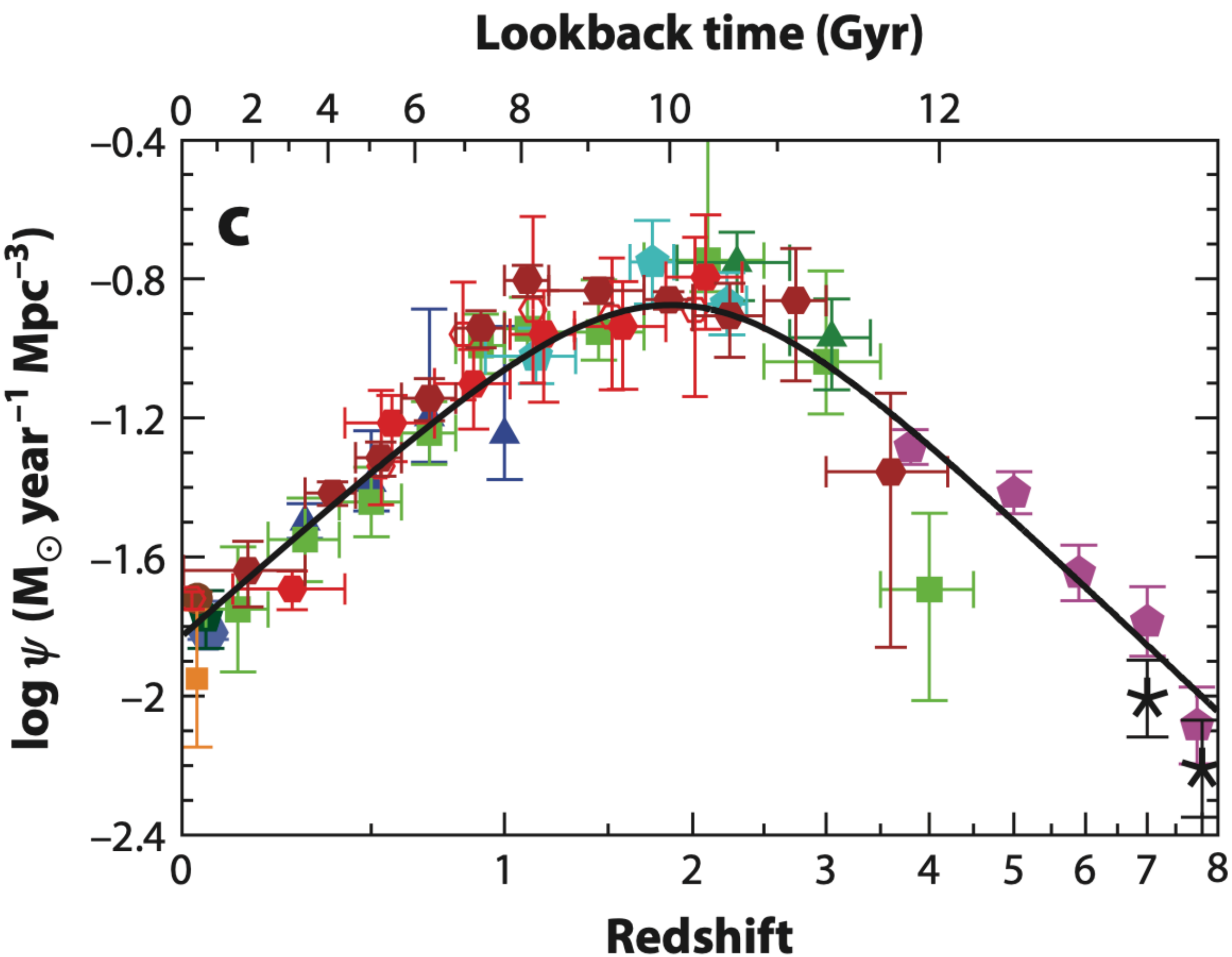
- ✦ Excess gas mass in local Universe should be mostly HI => SKA
- ✦ Excess gas mass at z ~ 2 should be mostly CO-bright => ALMA

Big Bang
today



lines: average of 10 simulations

How does this generalise to the environments where cosmic SFR peaked?



Madau & Dickinson 2014

How did globular clusters form?

How did globular clusters form?

Kruijssen 2025 in press, arXiv:2501.16438

The formation of globular clusters

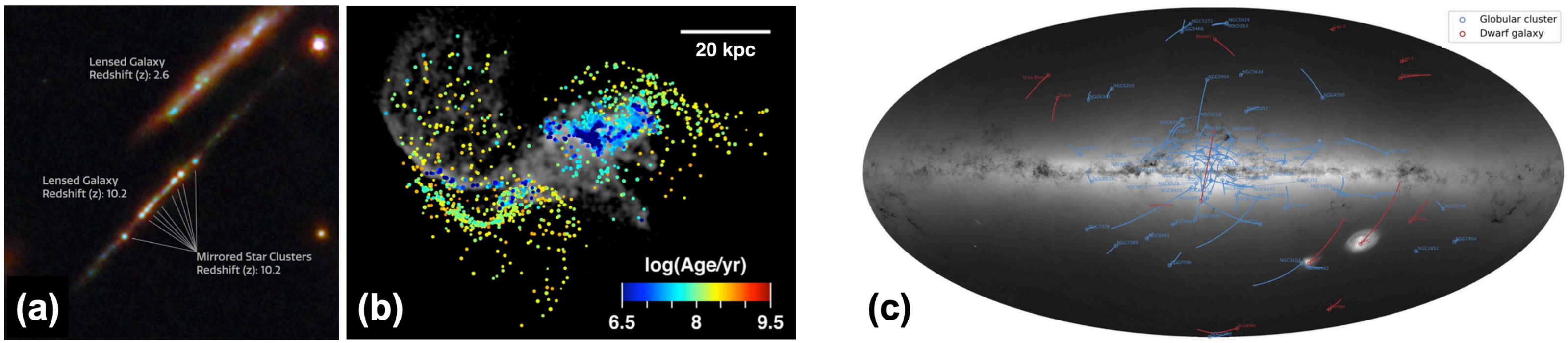
J M Diederik Kruijssen[a,b,*], [a]Department of Aerospace and Geodesy, Chair of Remote Sensing Technology, Technical University of Munich, Munich, Germany; [b]Cosmic Origins Of Life (COOL) Research DAO

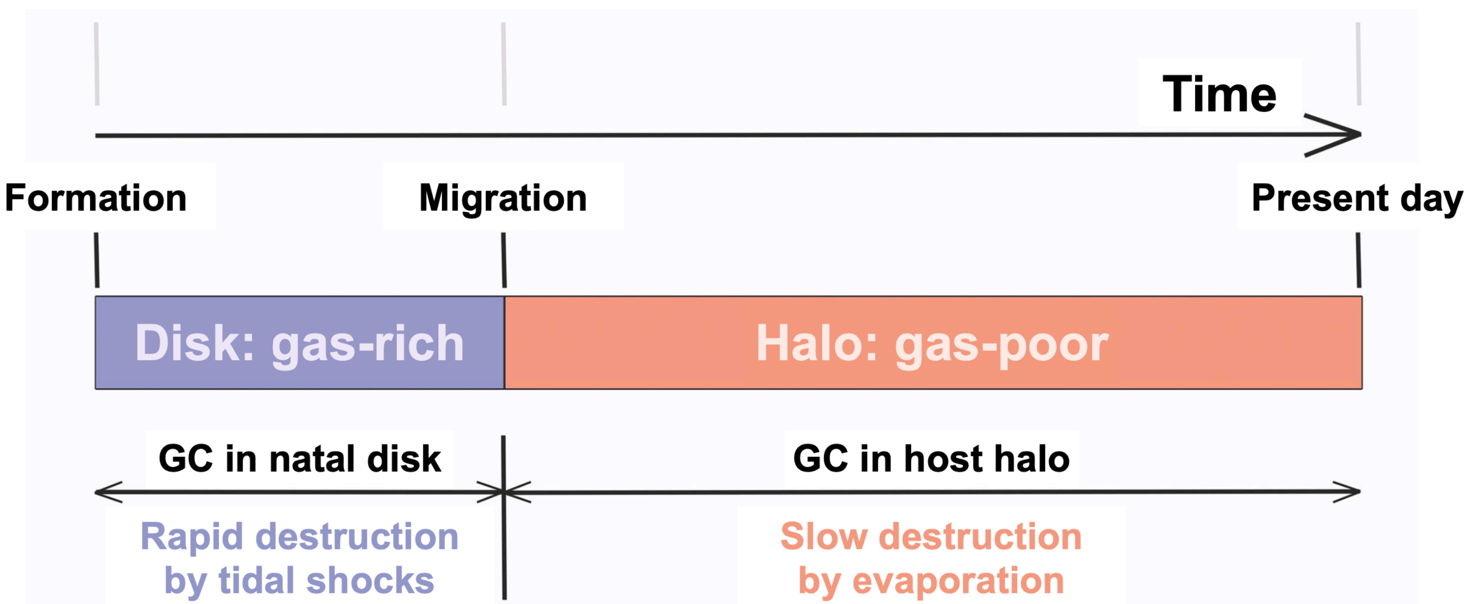
Abstract

Globular clusters (GCs) are among the oldest and most luminous stellar systems in the Universe, offering unique insights into galaxy formation and evolution. While the physical processes behind their origin have long remained elusive, major theoretical and observational developments in the past decade have led to a new understanding of GCs as the natural outcome of high-pressure star formation in high-redshift galaxies. This review synthesizes recent advancements in our understanding of GC formation and aims to provide a comprehensive point of reference for leveraging the revolutionary capabilities of the current and upcoming generation of telescopes. The latest generation of GC models combines our understanding of their formation and destruction with advanced galaxy formation simulations. The next decade will provide the first-ever opportunity to test such models across their full evolutionary history, from GC formation at high redshift as seen with the James Webb Telescope to snapshots of GC demographics at intermediate redshifts obtained with 30 m-class telescopes, and eventually to the well-characterized GC populations observed at the present day. We identify the major questions that we should expect to address this way.

Current paradigm: GCs are natural outcome of high-pressure SF at high z

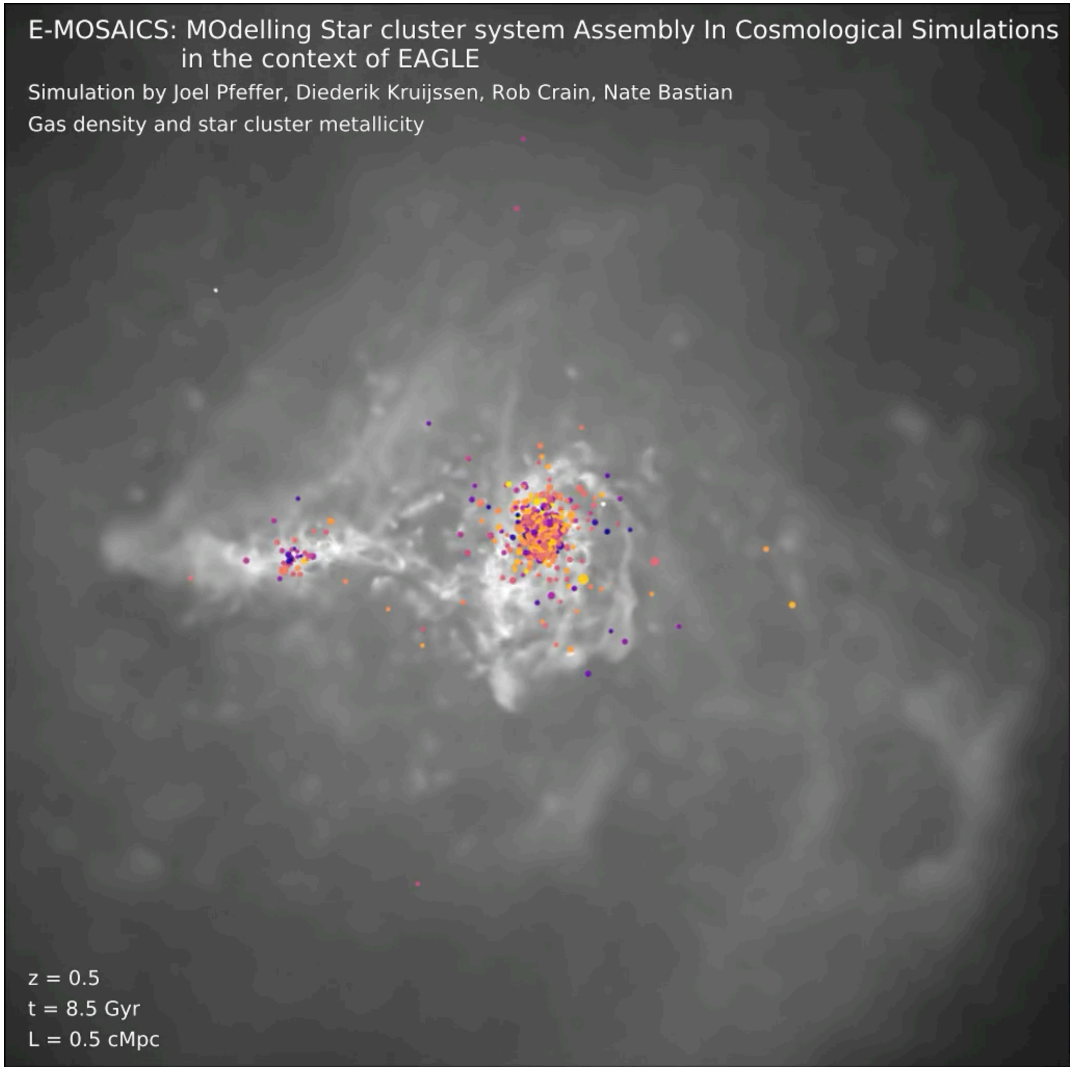
Kruijssen 2025 in press, arXiv:2501.16438





The co-formation of galaxies & GC populations: the *E-MOSAICS* project

Pfeffer+ 2018; Kruijssen+ 2019d

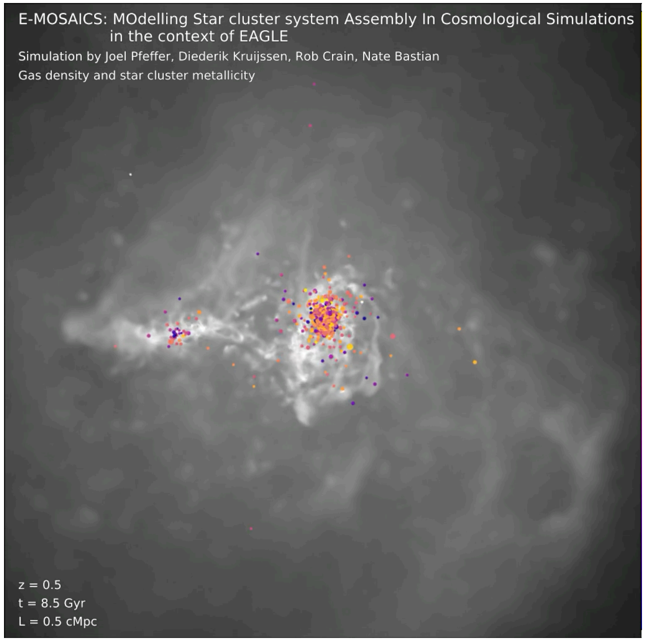


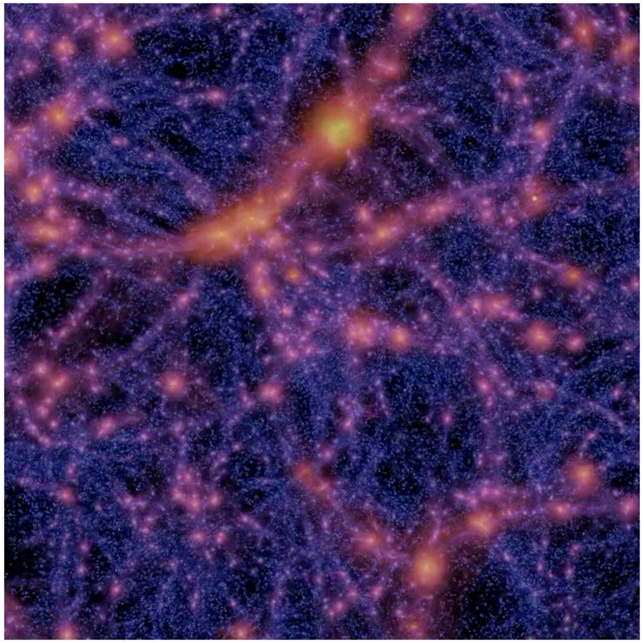
- Couple Kruijssen+11,12 "MOSAICS" cluster formation/evolution models to the EAGLE simulations Schaye+ 2015 Crain+ 2015
- First time that the formation and evolution of the entire cluster population is modelled self-consistently across cosmic history

The co-formation of galaxies & GC populations: the *E-MOSAICS* project

Pfeffer+ 2018; Kruijssen+ 2019d

- 25 cosmological zoom-in simulations of Milky Way-mass galaxies + satellites
- >200 of simulations run with different physical ingredients
- 34^3 Mpc^3 periodic volume: 80 MWs, 1 Fornax Cluster





E-MOSAICS: two main results

Pfeffer+ 2018; Kruijssen+ 2019d

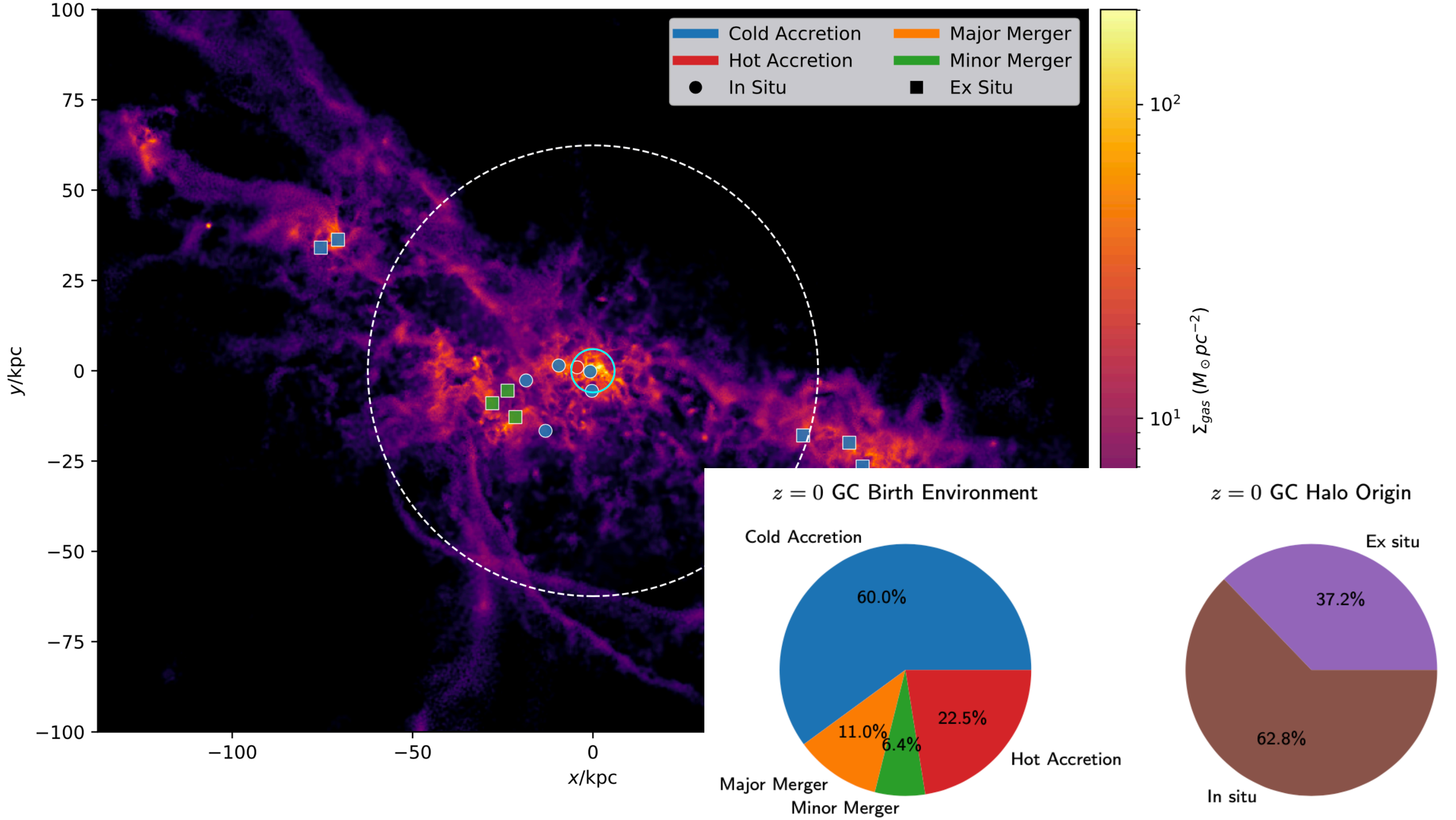
- ✦ GC properties today follow naturally from regular cluster formation at high z
- ✦ GCs can be used to reconstruct galaxy formation and assembly

E-MOSAICS: GCs formed as products of regular cluster formation at high z

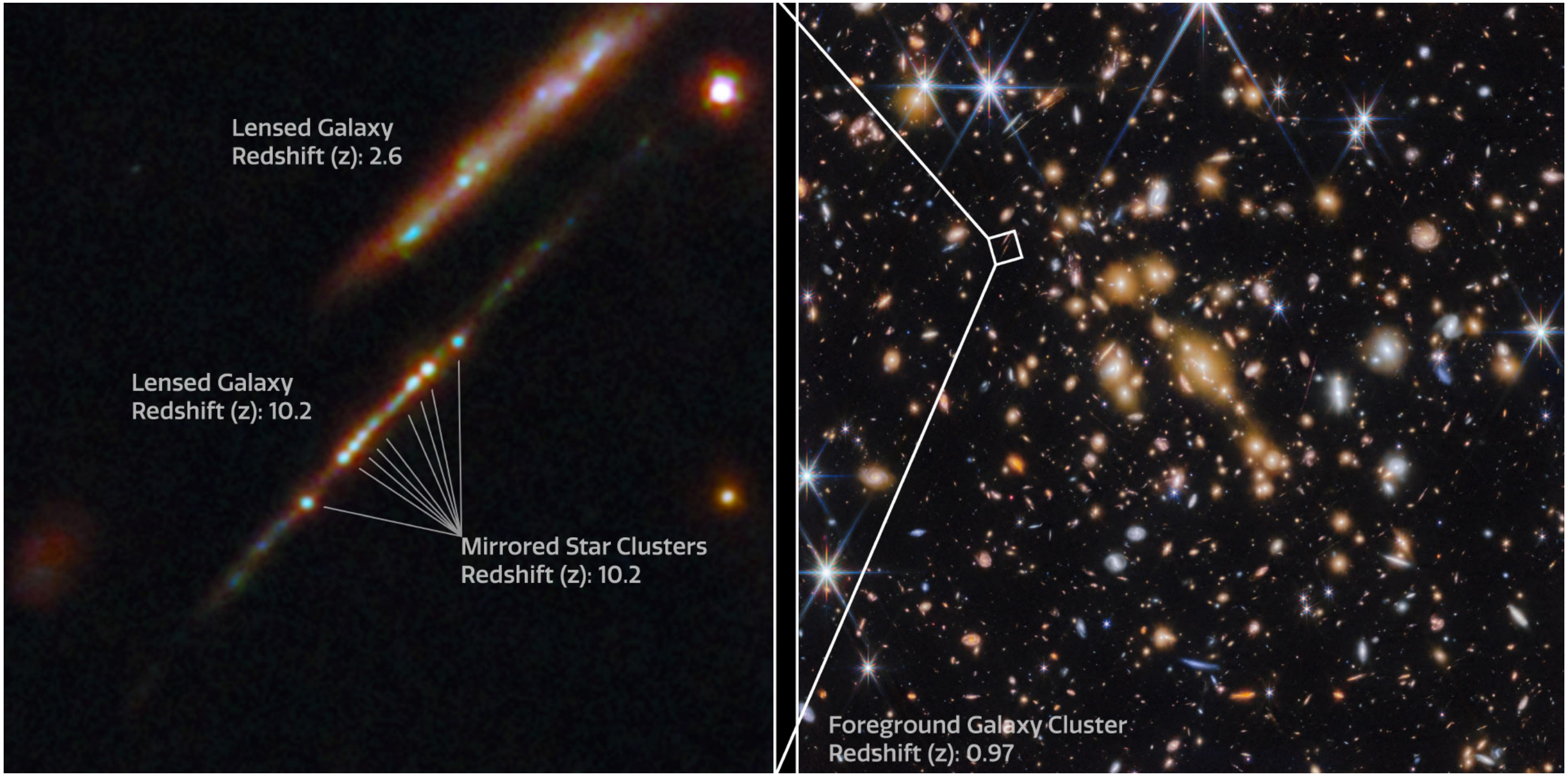
Pfeffer+2018; Kruijssen+2019d

- Simulations can be used to predict where and how globular clusters formed

Keller+ 2020



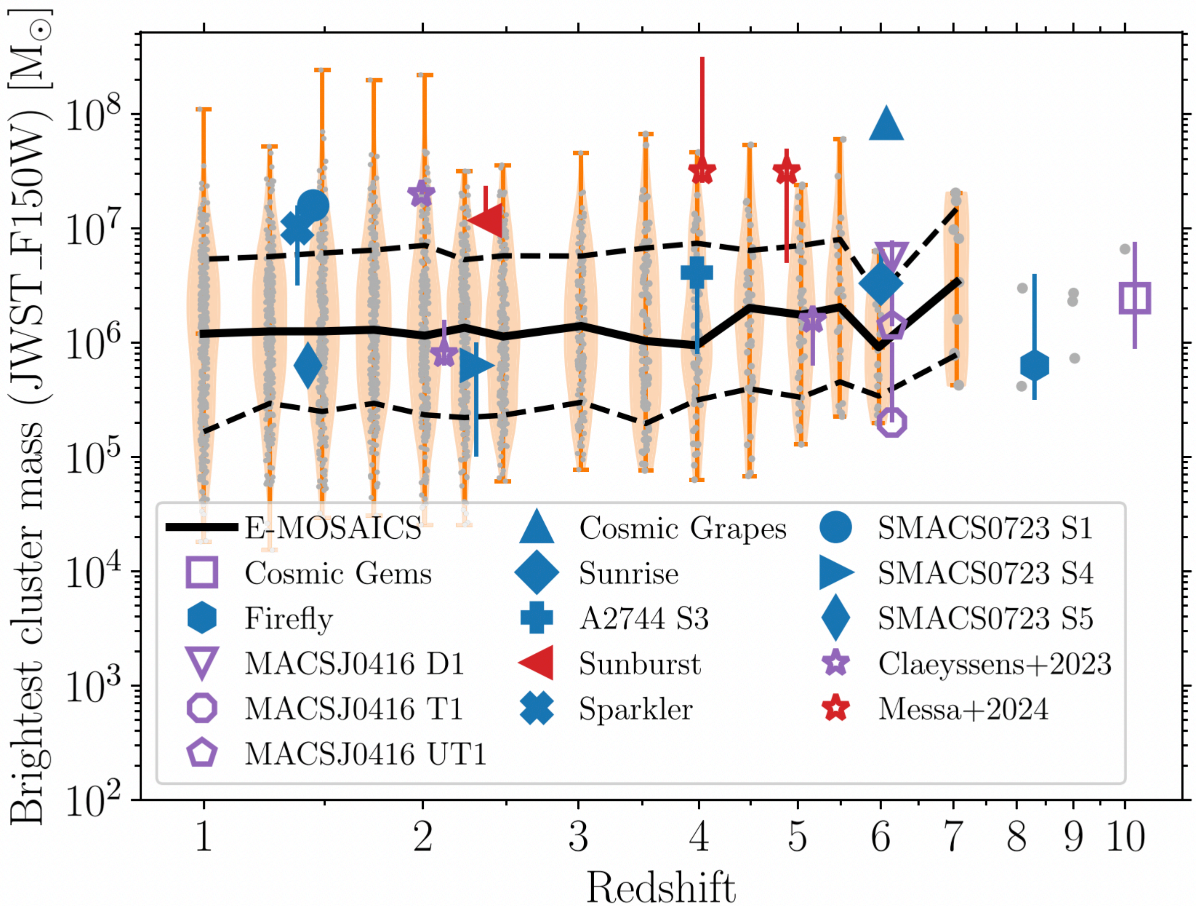
With gravitational lensing proto-GCs can be observed at high resolution



Adamo+ 2024; also see e.g. Vanzella+ 2017a,b; 2022a,b; 2023; Mowla+ 2022; 2024; Claeyssens+ 2023; Fujimoto+ 2024

Predicted masses of brightest (proto-)GCs in a galaxy versus redshift

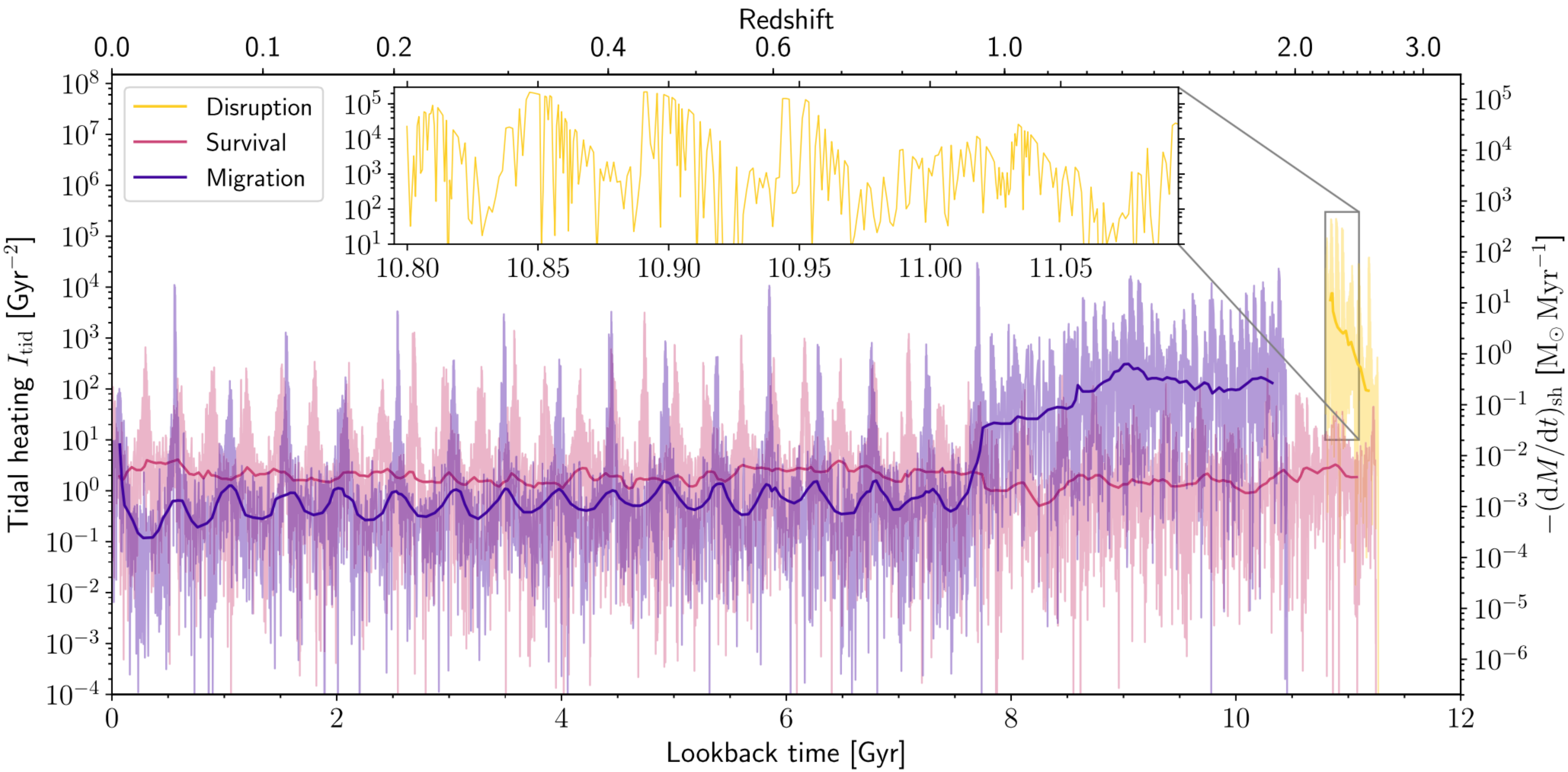
Pfeffer+ 2025



Do these proto-GCs survive until the present day?

Pfeffer+ 2018

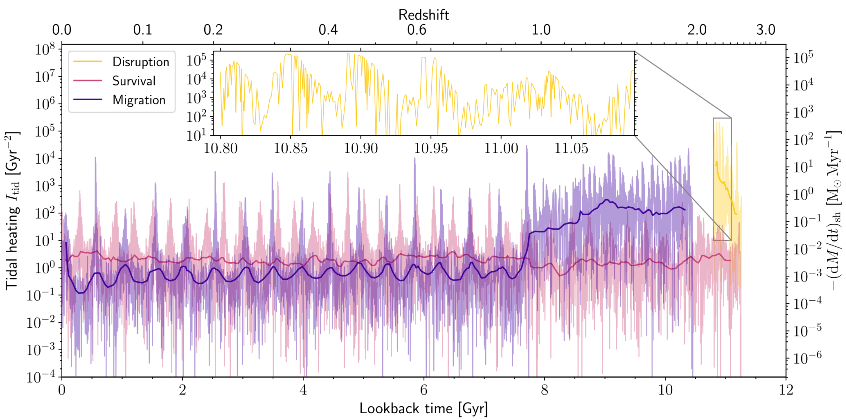
- Cluster mass loss dominated by the graininess of the gravitational potential on scales of GMCs → requires on-the-fly modelling + realistic ISM

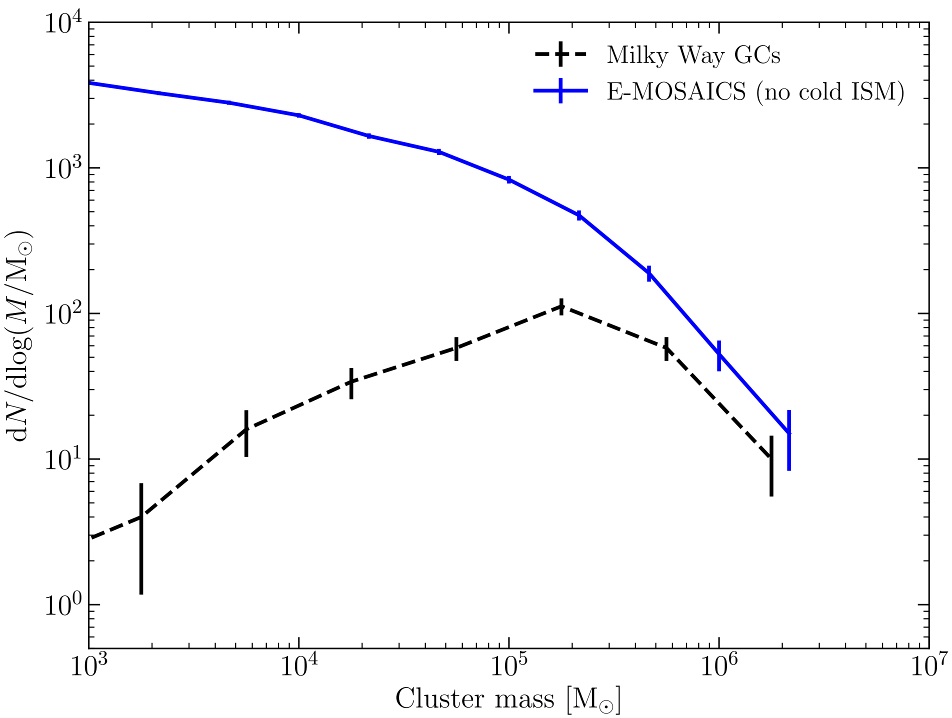


E-MOSAICS **has been quite successful, but (!):**
accurate ISM model is crucial to get a realistic cluster population

✦ The EAGLE galaxy formation model does not include a cold ISM

✦ E-MOSAICS underpredicts cluster disruption → must get baryonic physics right





The Empirically-Motivated Physics simulations of galaxy evolution

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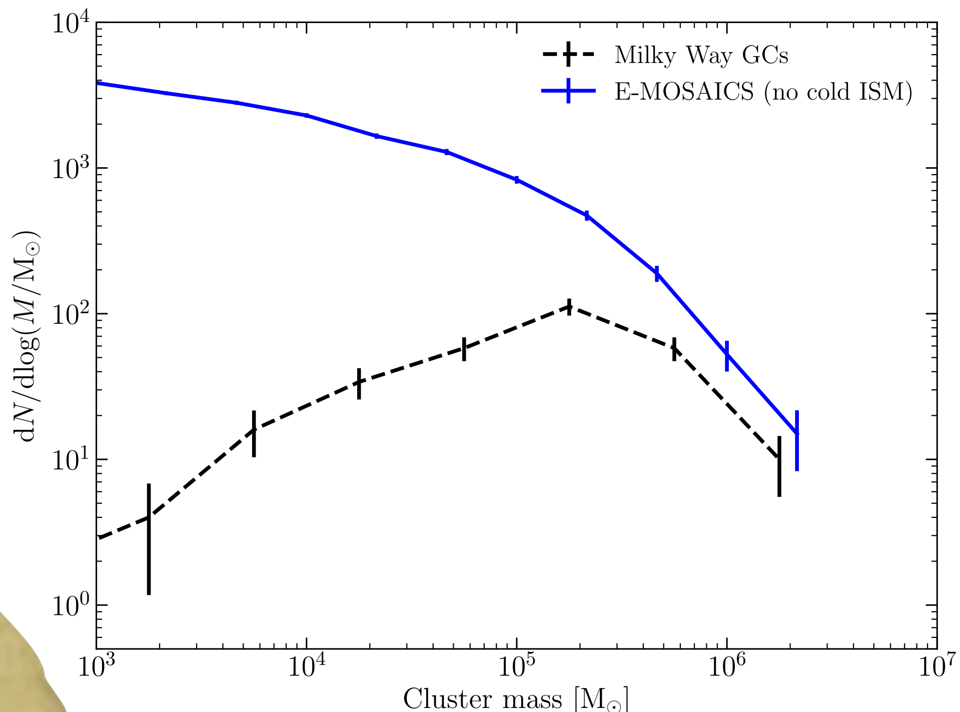
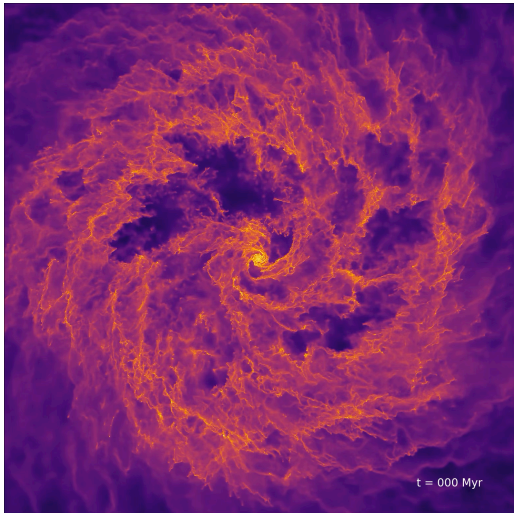


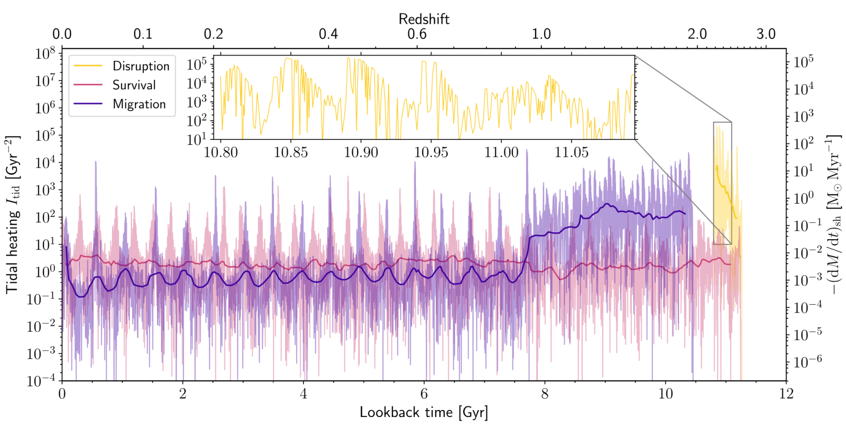
The EMP (Empirically-Motivated Physics) cosmological zoom-in simulations of galaxy formation and evolution

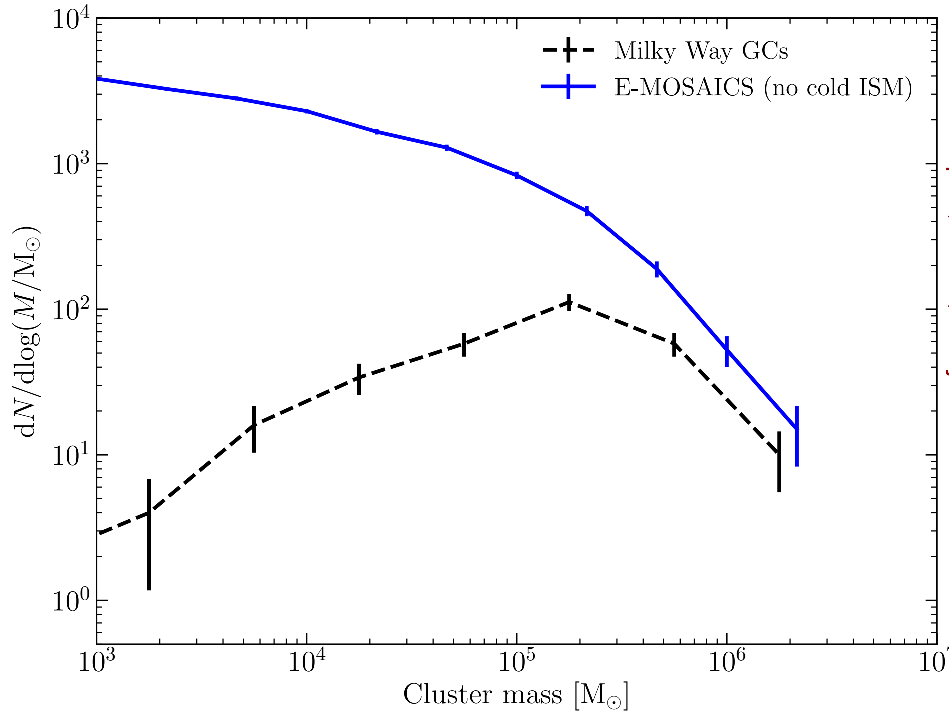
Kruijssen+ in prep.
Keller+ in prep.

- Multi-phase ISM and abundance tracking of 36 elements + their isotopes
  Reina-Campos, Keller, Kruijssen+ 2022
- SFE model: constant or depending on cloud dynamics
  Gensior+ 2020, 2021
- Empirically-motivated (early) feedback model based on observed cloud lifecycle (+ individual supernovae)
  Keller, Kruijssen & Chevance 2022
- Sub-grid model for star cluster formation and disruption
  Kruijssen+ 2011; Pfeffer, Kruijssen+ 2018; Reina-Campos, Keller, Kruijssen+ 2022
- On a moving mesh (Arepo)
  Springel 2010



Resolving the cold ISM with EMP is essential for modelling GC population



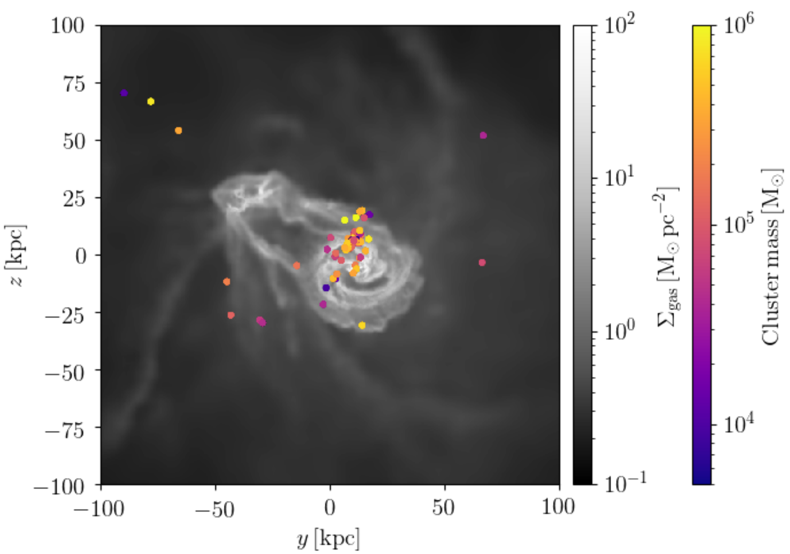


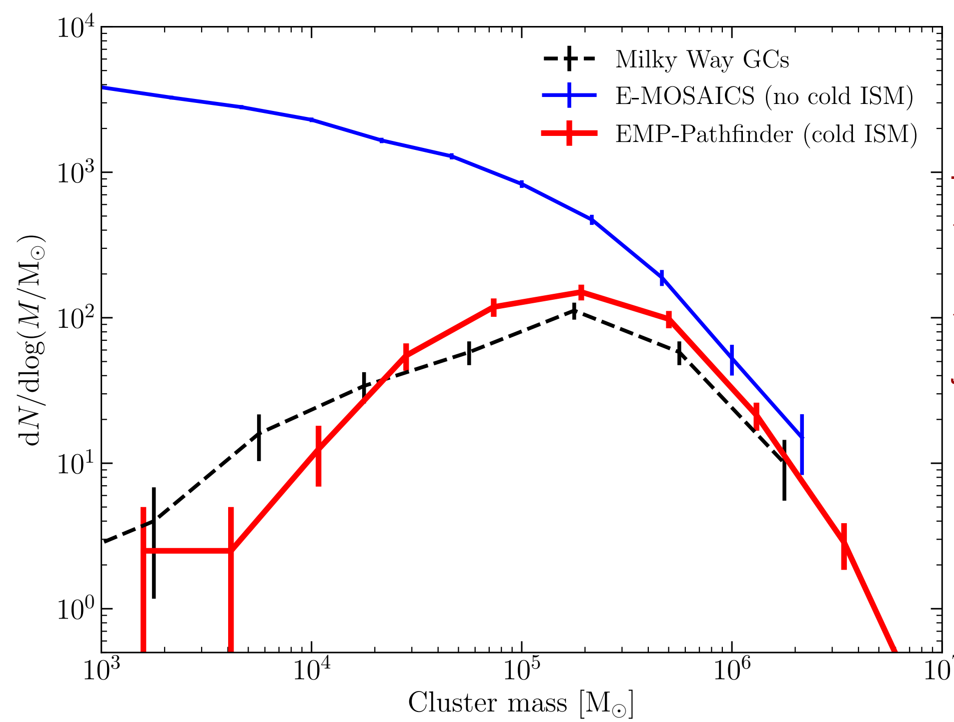
Reina-Campos, Keller, Kruijssen+ 2022

Resolving the cold ISM with EMP is essential for modelling GC population

- Thanks to cold ISM, tidal shocks disrupt GCs sufficiently quickly

- EMP reproduces the shape of the GC mass function for the first time in a cosmological simulation

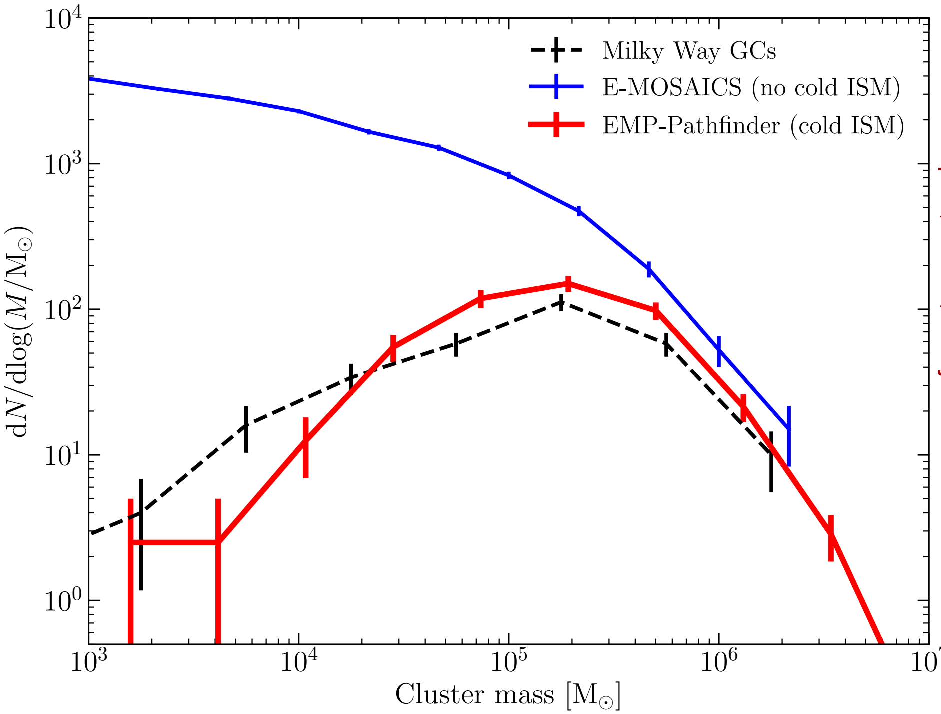




Reina-Campos, Keller, Kruijssen+ 2022

Resolving the cold ISM with EMP is essential for modelling GC population

- Thanks to cold ISM, tidal shocks disrupt GCs sufficiently quickly
- EMP reproduces the shape of the GC mass function for the first time in a cosmological simulation
- Globular cluster demographics at z = 0 are set by ISM structure, and thus by stellar feedback
- GCs are the natural byproduct of “normal” star formation at z = 2-4; no need for exotic formation mechanisms



Reina-Campos, Keller, Kruijssen+ 2022

Major open questions: quite some

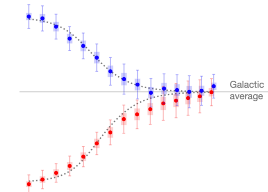
Kruijssen 2025 in press, arXiv:2501.16438

1. **Improve our fundamental understanding of star cluster formation and destruction.** The physical descriptions of these processes have been advancing, but these must reach the point where they become an unambiguous basis on which to build models of GC formation and evolution. The big revolution will be to think in terms of scale-free hierarchies rather than in terms of categorizations. Key questions that we will then be able to address are:
   a. What are the typical age spreads of star clusters, and do these vary with the cluster mass?
   b. How can we best exclude gravitationally unbound clusters from extragalactic cluster samples, to obtain a more robust CFE?
   c. How can we accurately infer the low- and high-mass truncation masses of the ICMF, given the observational challenges in terms of completeness and low-number statistics, respectively?
   d. How can we explain the origin of light element abundance variations within GCs in a way that is consistent with our understanding of star formation and stellar feedback, e.g. without invoking multiple generations of star formation?
   e. Which physics set the comparatively poorly characterized (initial and final) cluster mass-radius relation?
   f. How can the infinite number of possible tidal histories be standardized to a single framework that enables their systematic study?
   g. How can we empirically quantify the relative contributions of the two main cluster destruction mechanisms (tidal shocks and tidal evaporation) to the mass loss experienced by clusters throughout cosmic history?
2. **Construct a comprehensive theory for the formation and evolution of GCs.** How do the physics of star cluster formation and destruction in the context of galaxy formation and evolution explain the existence of the observed GC population? This is an absolute prerequisite for considering GC formation a solved problem. Key questions that we should address are:
   a. What fraction of GCs did *not* form as the product of 'normal' cluster formation in high-redshift galaxies?
   b. Are there other formation mechanisms and if so what are they?
   c. What physical processes enable the formation of massive GCs with metallicities below the metallicity floor, i.e. $[Fe/H] < -2.5$?
   d. If multiple formation mechanisms generated the current GC population, can GC ages measured at high redshift distinguish these?
   e. What was the shape of the initial GC mass function?
   f. How did proto-GCs escape the destructive environment of their host galaxy disk?
   g. What fraction of GCs was destroyed by dynamical friction?
3. **Obtain a complete census of proto-GCs demographics at high redshift, and of the subsequent emergence of the GC population.** This is the step change enabled by the next generation of telescopes, which will allow us to obtain statistically representative samples of (proto-)GCs across the redshift range needed to achieve an end-to-end understanding of GC formation. This will result in a synthesis of the GC population across cosmic time, with potential major implications for star formation, black holes, and gravitational waves. Key questions that we should address are:
   a. Given our current understanding of GC formation, can we predict the demographics of the population of (proto-)GCs across the redshift range that will be seen by JWST, Euclid, and 30m class telescopes such as the ELT?
   b. At what redshift did the formation rate of proto-GCs peak?
   c. At what redshift did the formation rate of GCs that eventually survive peak?
   d. Can the unusual chemical properties of multiple populations in GCs generate unusual abundance patterns in high-redshift galaxies, possibly aided by a high CFE or an ICMF with an elevated minimum cluster mass?
   e. How many times more massive were GCs at birth, and how many proto-GCs were there that did not survive to become GCs?
   f. At what redshift were the demographics of the current GC population in place, and how does this depend on the host galaxy mass and assembly history?
   g. Are initial (and final) GC demographics affected by cosmic variance, i.e. do we observe the same statistics if we consider fields that fall outside of each others' light cones?
4. **How do GCs trace the assembly histories of their host galaxies?** This major step is unlocked by a comprehensive theory for the formation and evolution of GCs, and our current understanding has enabled the first successful applications of GCs as tracers of galaxy assembly in the Milky Way. The big next step is to industrialize this potential and use GCs to reconstruct the merger trees of external galaxies and perform a fundamental test of cold dark matter cosmology. Key questions that we should address are:
   a. How can we further improve the accuracy of GC age measurements from integrated light?
   b. What are the key observables that we need to trace a galaxy's growth and merger history using its GCs?
   c. What are the merger trees of nearby galaxies, as traced by their GCs, as a function of galaxy mass and galaxy clustering?
   d. How do these GC-inferred merger trees compare to the predictions of cold dark matter cosmology?

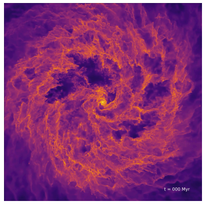
This is a highly ambitious set of questions, but it is certainly not beyond the realm of possibility to answer them over the next 10-20 years.

Empirically-motivated feedback controls the formation of GCs and galaxies

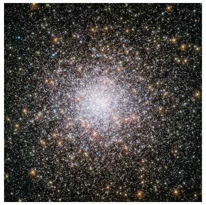
- Resolved sub-mm observations of galaxies yield the timescales that govern the molecular cloud lifecycle, solving one of the biggest problems in resolved SF



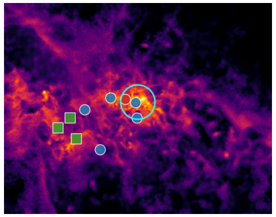
- The SF-FB cycle in galaxies is fast and inefficient: cold, star-forming gas is dispersed *gently* by pre-SN FB, changing how simulated galaxies grow over a Hubble time



- Globular clusters != archaeology; GCs are natural outcomes of high-z star/cluster formation in normal disc galaxies, the physics of which can now be resolved



- Globular cluster demographics at $z = 0$ are set by the structure of the interstellar medium, which itself is shaped by stellar feedback, which can be expressed empirically



Big step: abstracting away the BFL into a single empirical model

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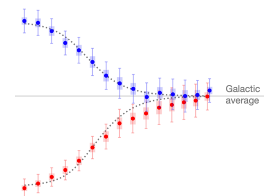

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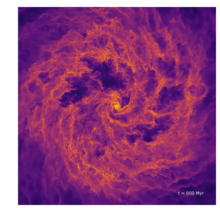

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