A high-resolution view of the baryon cycle in local SF galaxies

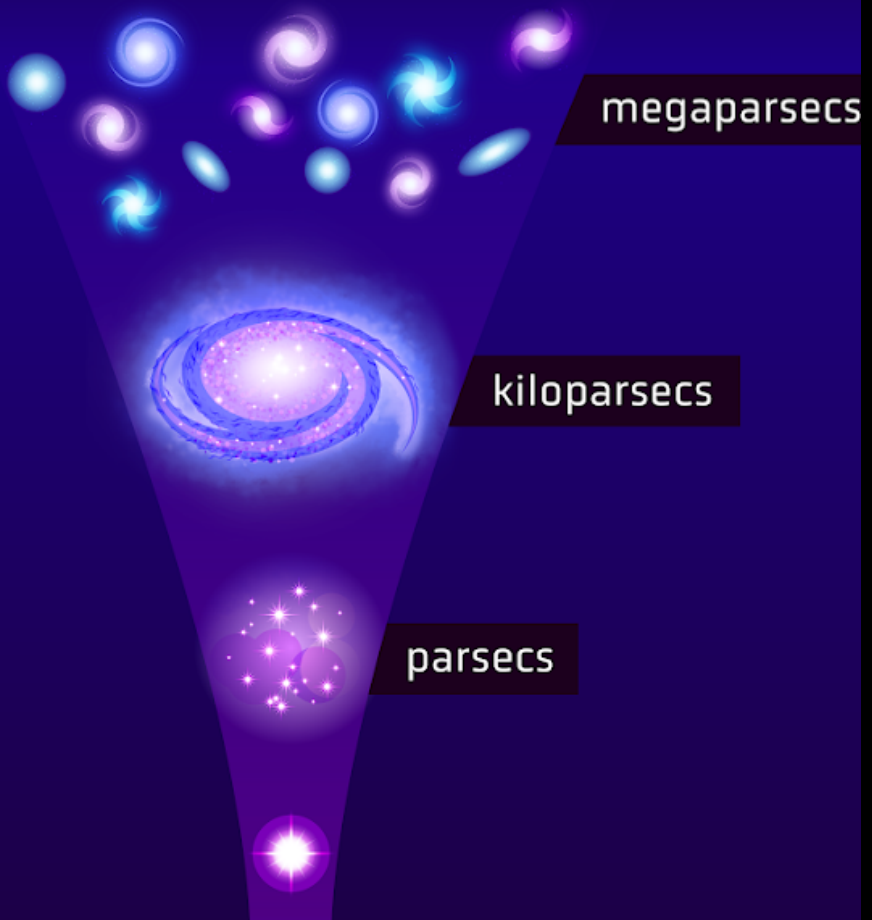
Eric Emsellem

With big thanks to:

PHANGS Team, incl. Eva Schinnerer, Adam Leroy, Janice Lee, Pierrick Verwilghen

STAR FORMATION

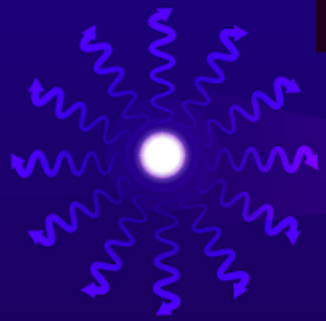
SCALES



STAR FORMATION

PHYSICAL PROCESSES

(self-) gravity



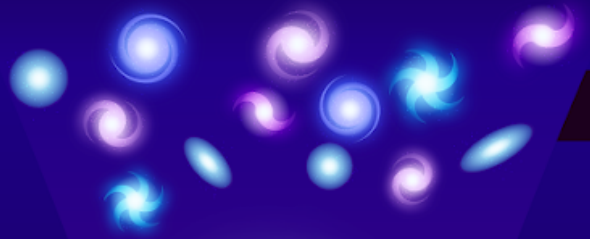
turbulence

small-scale

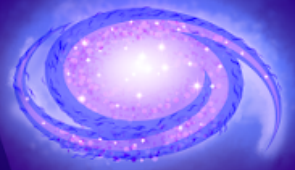
large-scale

radiation

SCALES



megaparsecs



kiloparsecs

parsecs

STAR FORMATION

PHYSICAL PROCESSES

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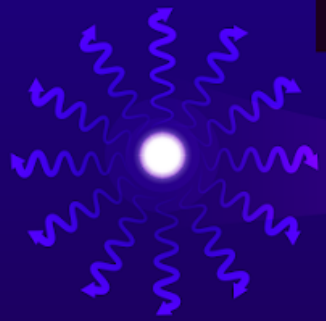

turbulence

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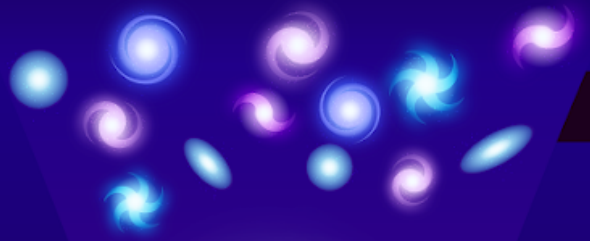
SCALES



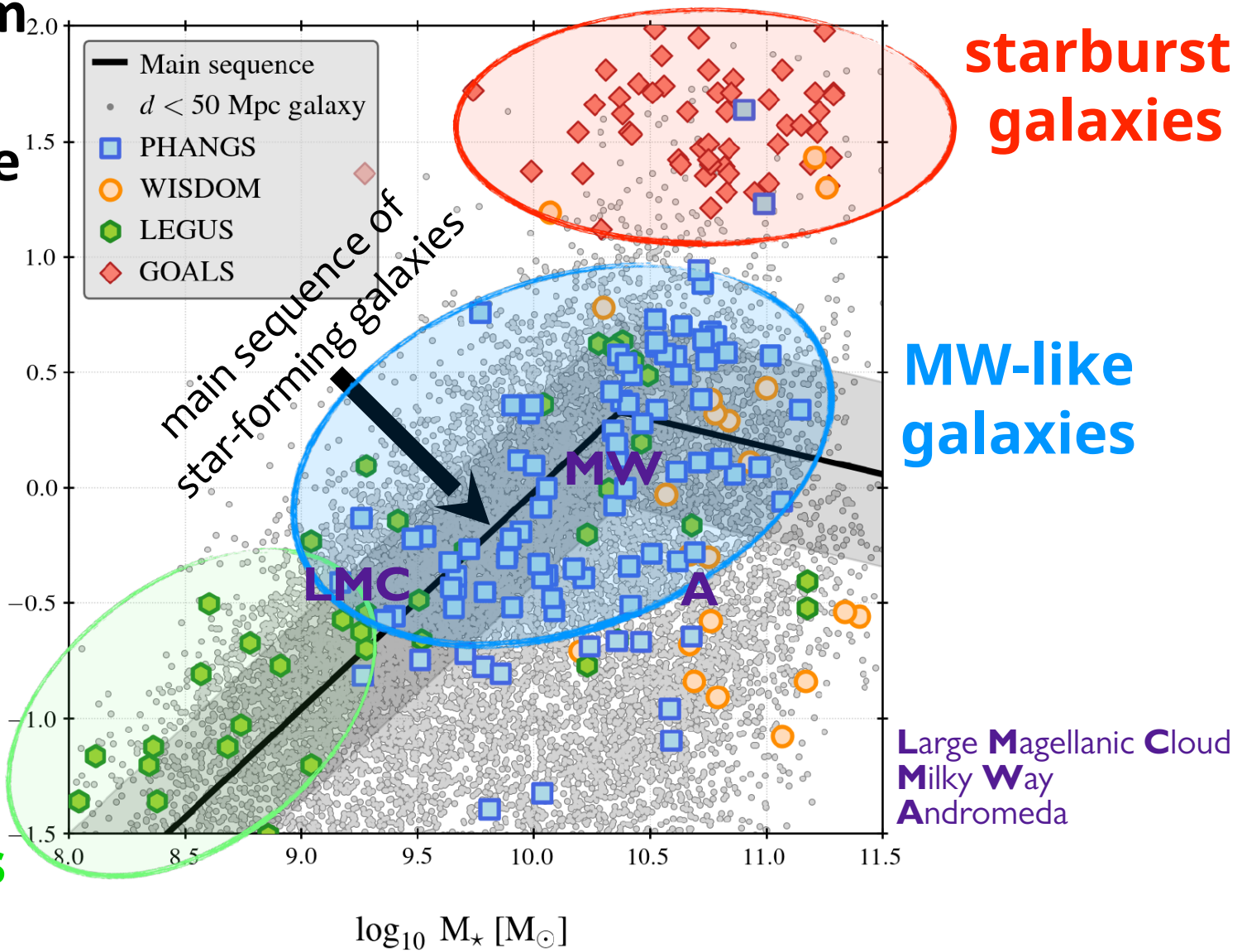
megaparsecs

kiloparsecs

parsecs

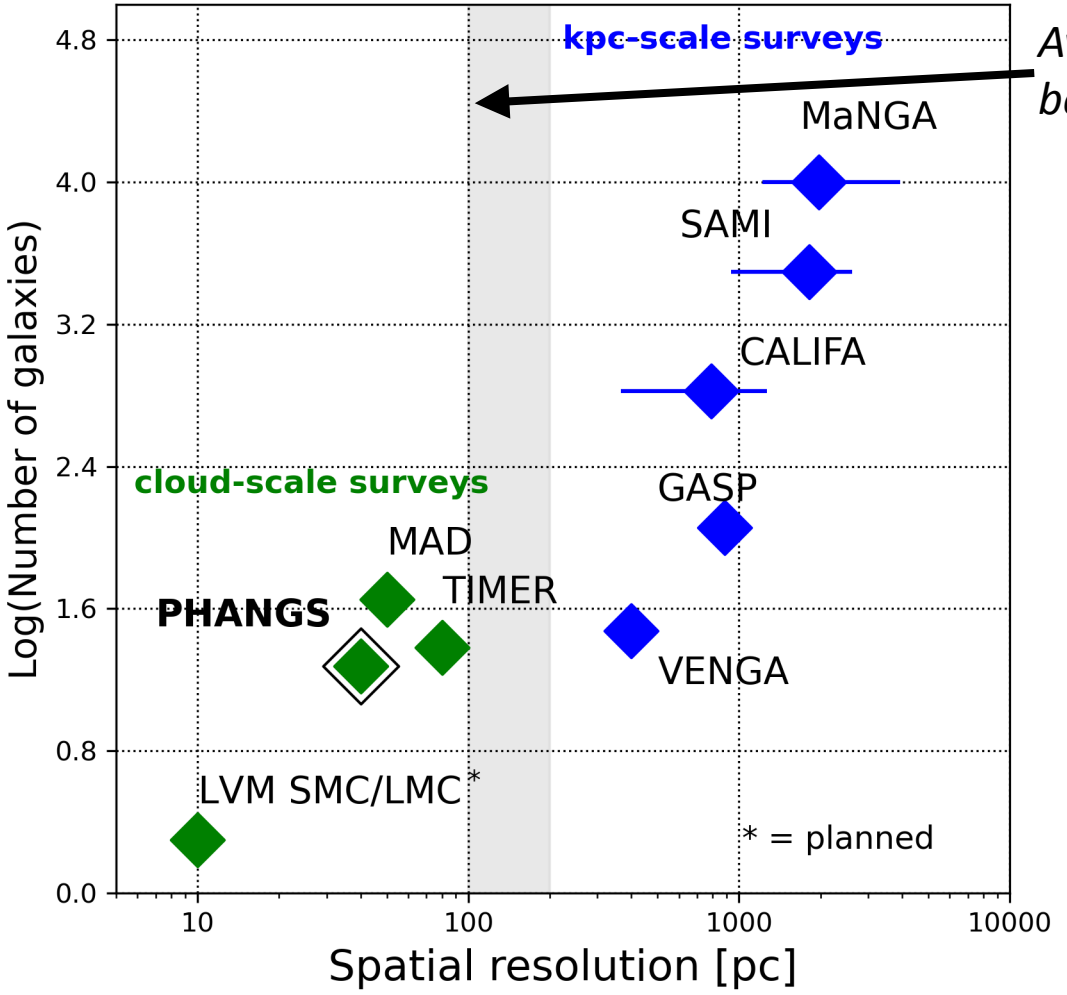
[@z=0]

Where stars form in the nearby Universe



The golden era of IFU surveys

Emsellem et al., 2022



The golden era of IFU surveys

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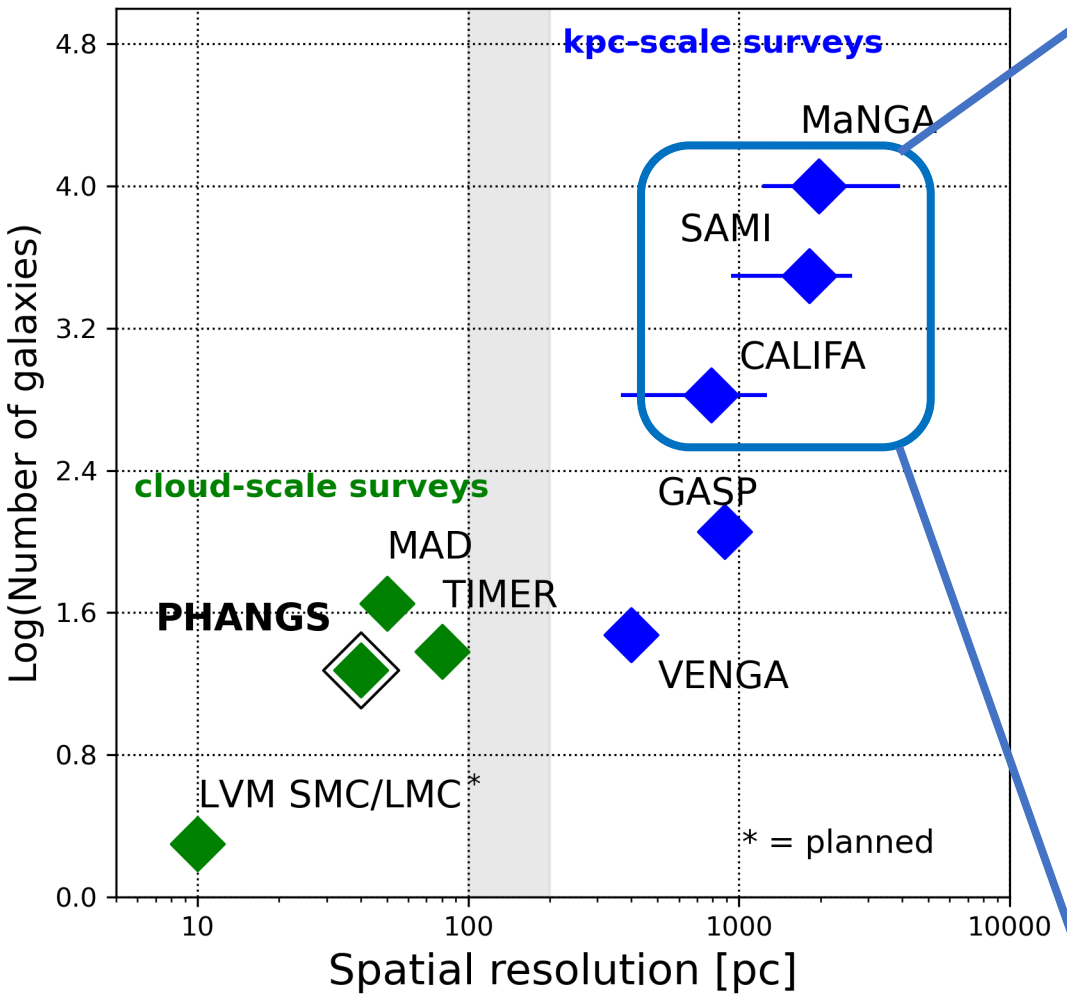
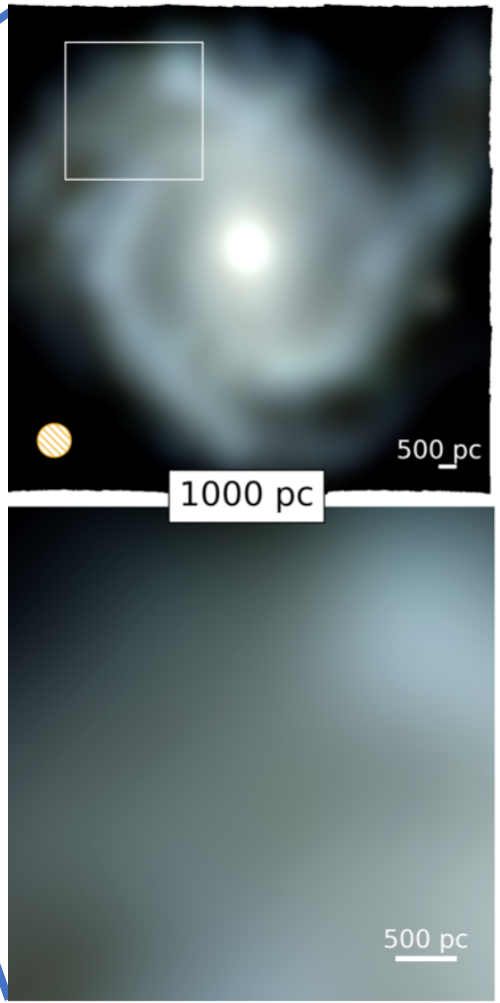
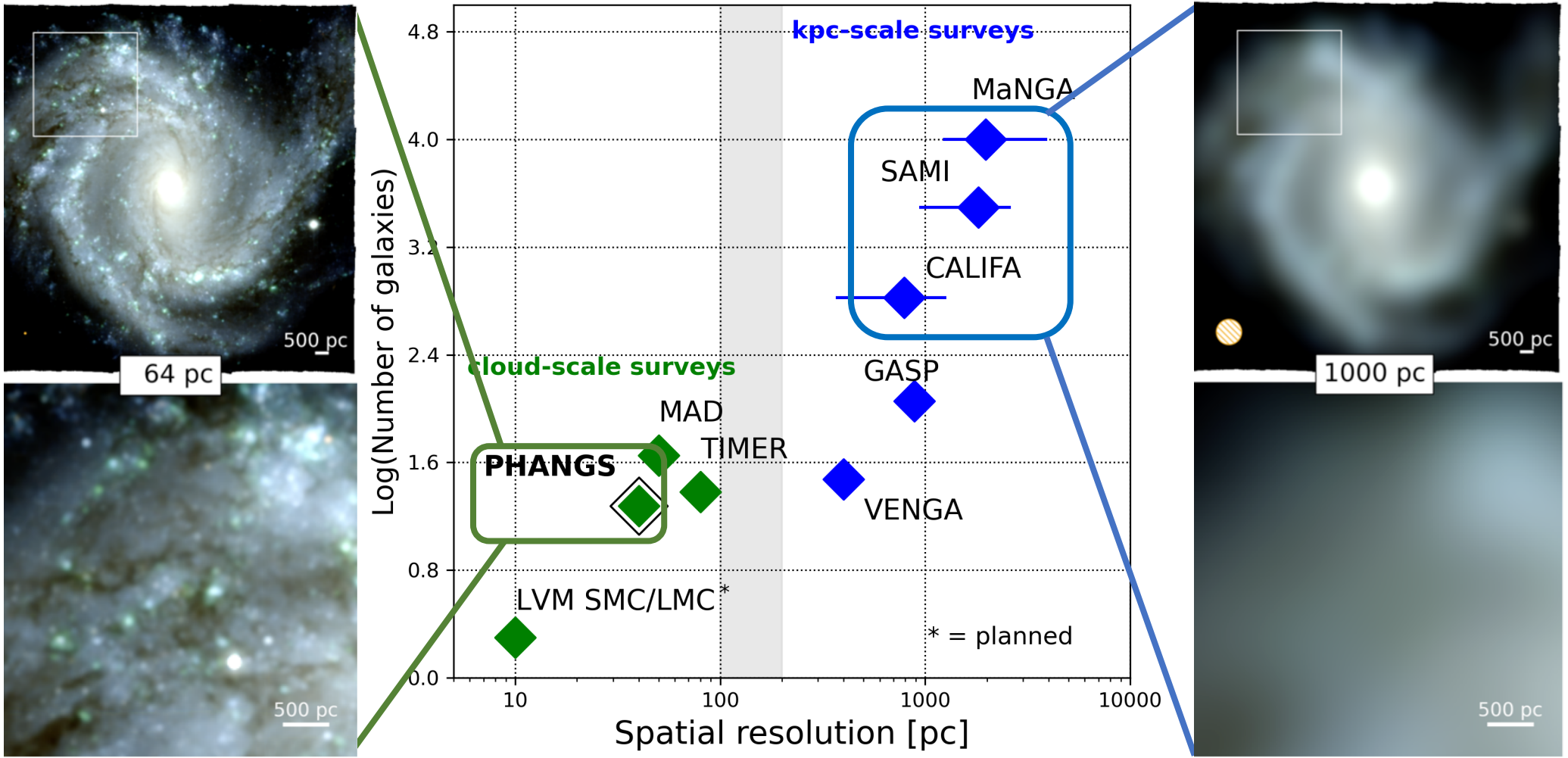


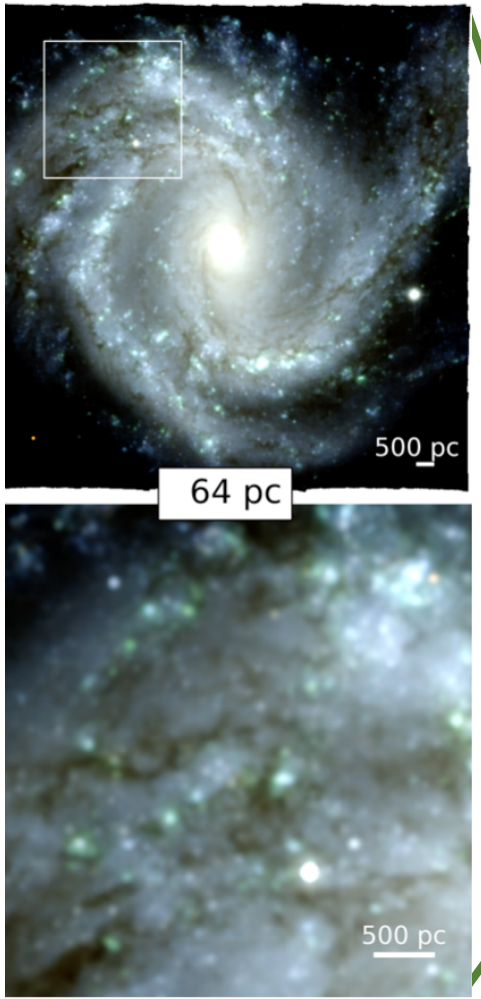


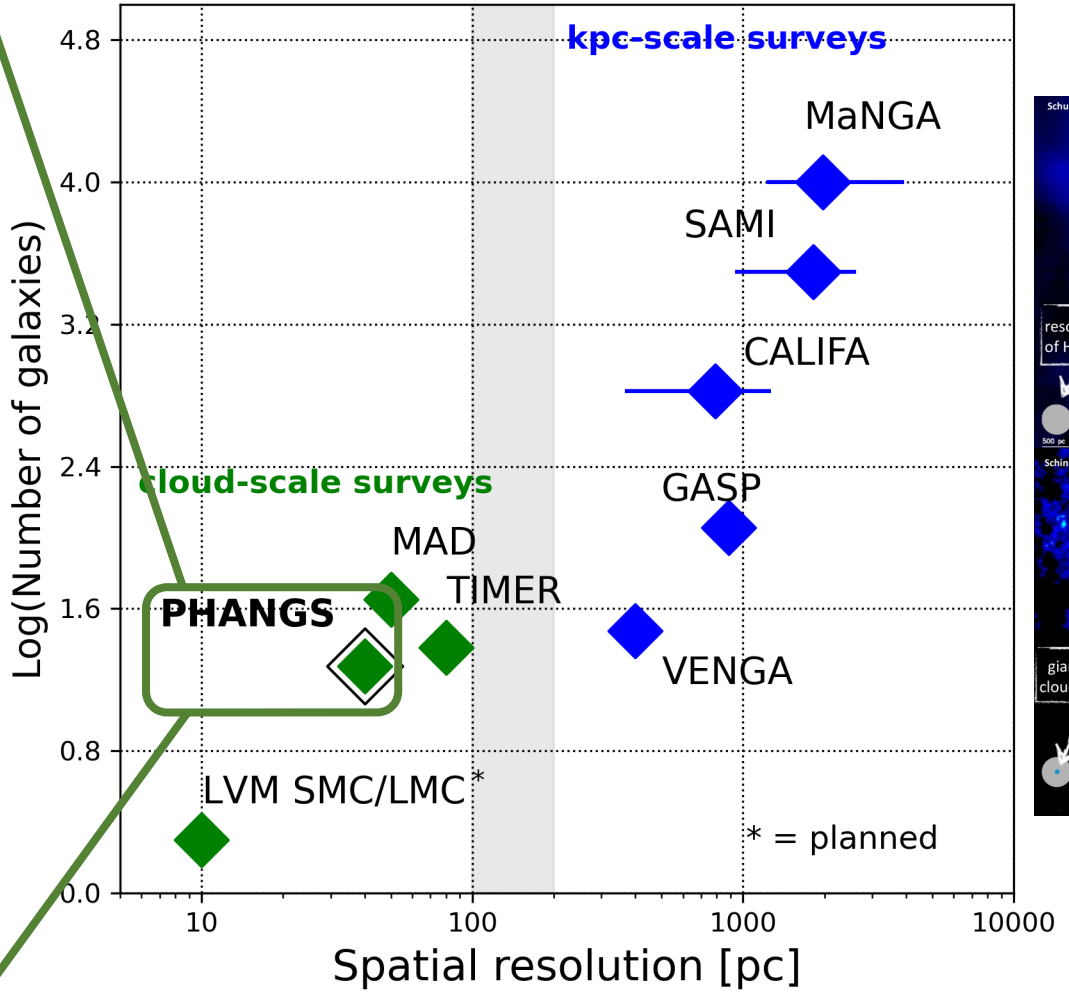
A revolution

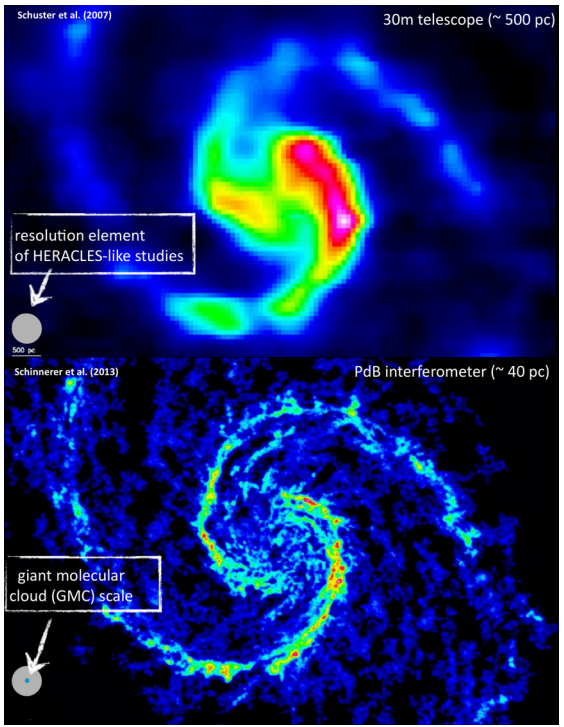
Emsellem et al., 2022



A revolution

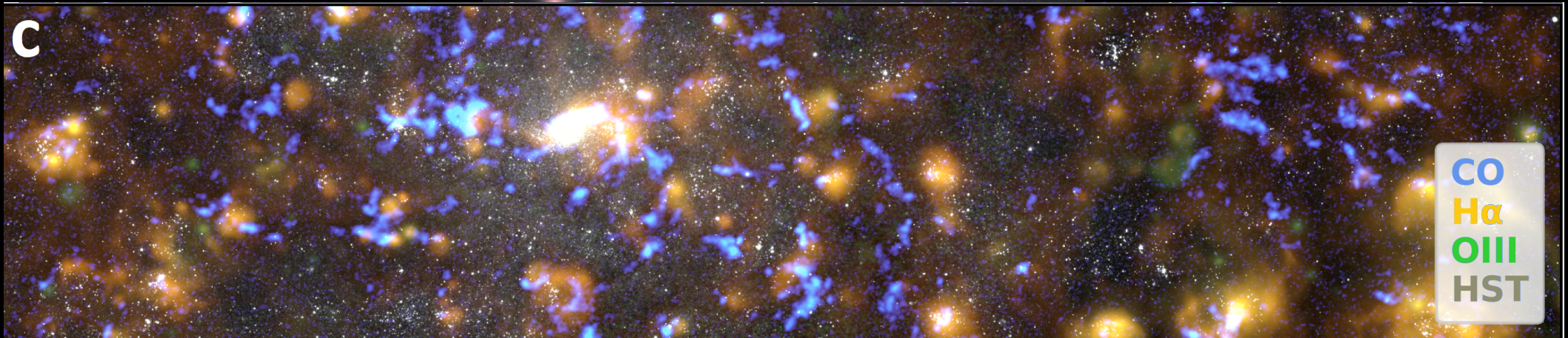






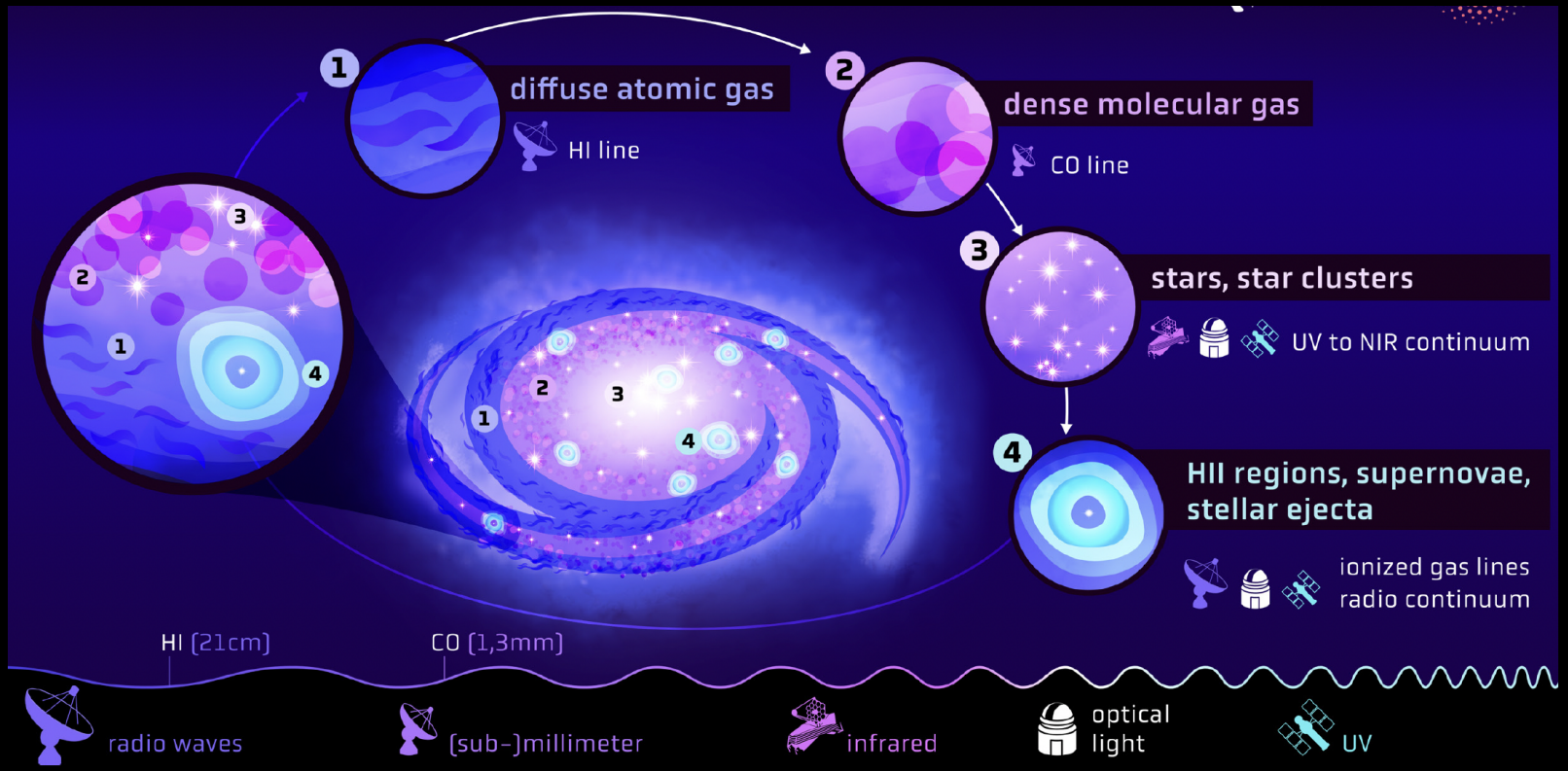
Disentangling the tracers

Image credits: Elizabeth Watkins & Ivana Beslic



How do stars form from gas… in a galactic context?

The challenge: stars, gas, & dust must be studied together from stellar (<pc) to galactic (>kpc) scales



What are the factors that control population growth?

Where, when, and how do stars form?
How efficient is star formation? Is it the same everywhere?
How long does it take or can it proceed?
What shuts off star formation?

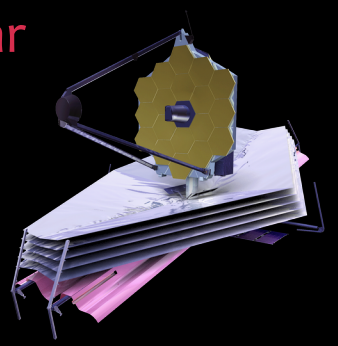
PHANGS

ALMA

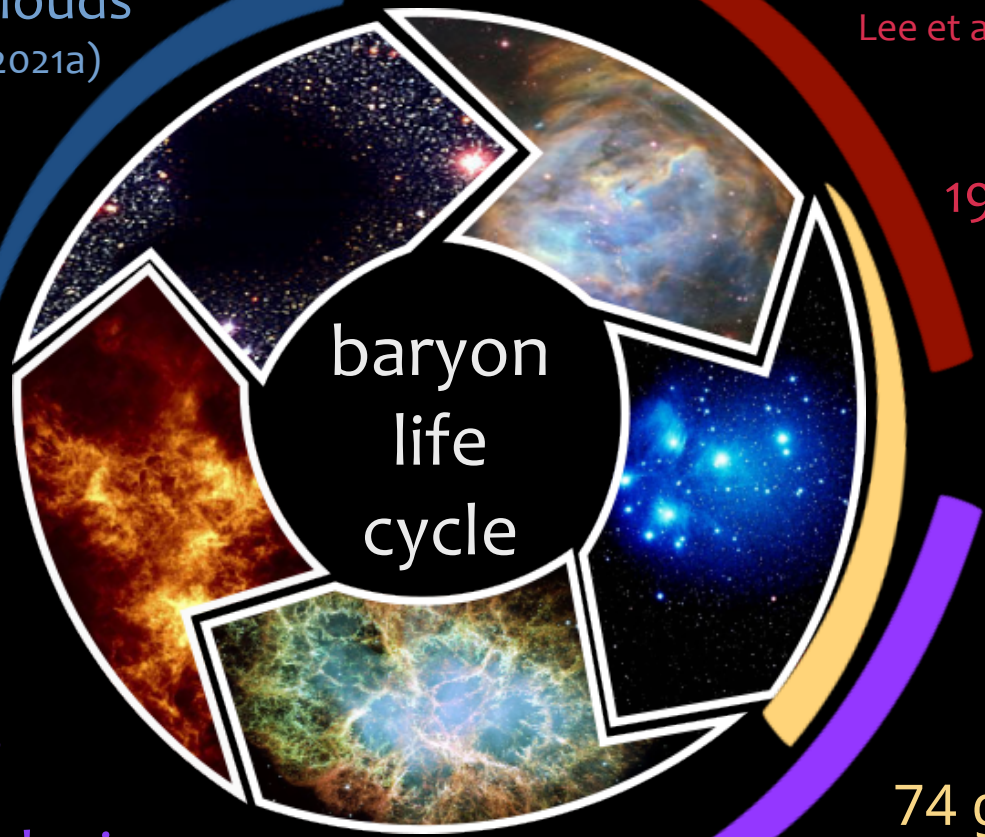
molecular gas probing ~100,000 clouds
Leroy et al. (2021a)

90+ galaxies
Pis Schinnerer; Blanc; Leroy; Faesi; Chevance

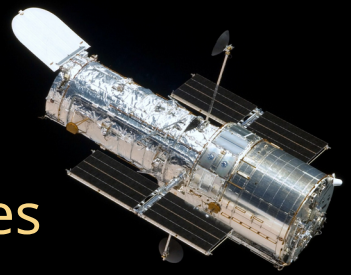
embedded star formation & dust heating
Lee et al. (2023)



19 + 55 galaxies
PI Lee + PI Leroy



~80,000 stellar clusters
Lee et al. (2022)



74 galaxies
PI Lee

stellar feedback probed by ~25,000 nebulae + stellar populations
Emsellem et al. (2022)

muse
multi unit spectroscopic explorer

19+ galaxies
PI Schinnerer

Physics at High Angular resolution in Nearby GalaxieS

PHANGS

est. 2016

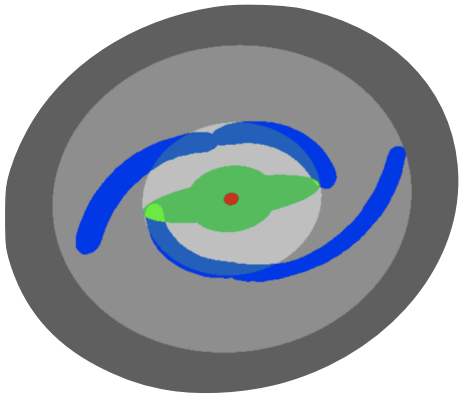
Eric Emsellem*
Adam Leroy*
(team project scientist)
Erik Rosolowsky
(team manager)
Eva Schinnerer
(team lead)

*working group leads

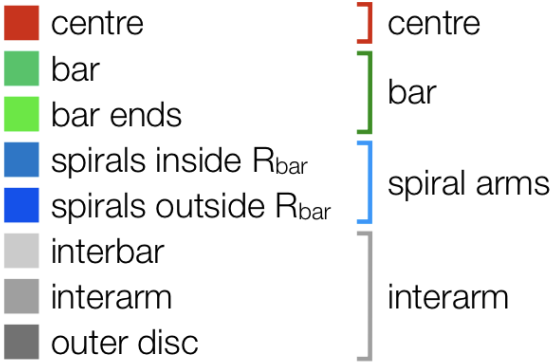
Gagandeep Anand, Ashley Barnes, Dalya Baron, Zein Bazzi, Francesco Belfiore*, Frank Bigiel, Guillermo Blanc, Ivana Bešlić, Alberto Bolatto, Mederic Bouquien*, Mathilde Brazzini, Jacob den Brok*, Yixian Cao, Rupali Chandar, Jeremy Chastenet, Melanie Chevance, I-Da Chiang, Ryan Chown, Dario Colombo, Enrico Congiu*, Danny Dale, Sinan Deger, Nelida Diaz Fernandez, Oleg Egorov, Cosima Eibensteiner*, Chris Faesi*, Francesca Frakoudi, Ina GalićSimon Glover, Oleg Gnedin, Brent Groves*, Stephen Hannon, Hamid Hassani, Hao He, Kiana Henny, Jonathan Henshaw, Annie Hughes, Remy Indebetouw, Maria Jimenez-Donaire, Hwihyun Kim, Jaeyeon Kim, Ralf Klessen, Eric Koch, Hannah Koziol, Kathryn Kreckel, Sushma Kurapati, Kirsten Larson, Janice Lee*, Jing Li, Fu-Heng Liang, Daizhong Liu, Laura Lopez, Daniel Maschmann, Smita Mathur, Ness Mayker Chen, Rebecca McClain, Sharon Meidt*, Jose Eduardo Mendez-Delgado, Eric Murphy, Lukas Neumann, Justus Neumann, Elias Oakes, Hsi-An Pan*, Debosmita Pathak, Jerome Pety*, D.J. Pisano*, Miguel Querejeta*, Lise Ramambason, Alessandro Razza, Stefan Reissl, Ryan Rickards Vaught, Jimena Rodriguez, Andrea Romanelli, Marina Riuz-Garcia, Toshiki Saito, Patricia Sanchez-Blazquez, Karin Sandstrom*, Somit Sarbahicary, Fabian Scheuermann, Rowan Smith, Mattia Sormani, Sophia Stuber, Jiayi Sun*, Jessica Sutter, Eltha Teng, David Thilker*, Mallory Thorp, Qiushi Tian, Robin Tress, Antonio Usero*, Pierrick Verwhilgen, Elizabeth Watkins, Tony Weinbeck, Brad Whitmore, Thomas Williams*, Aida Wofford*

Extragalactic cloud-scale observations

Give access to (possible) variations with galactic environment



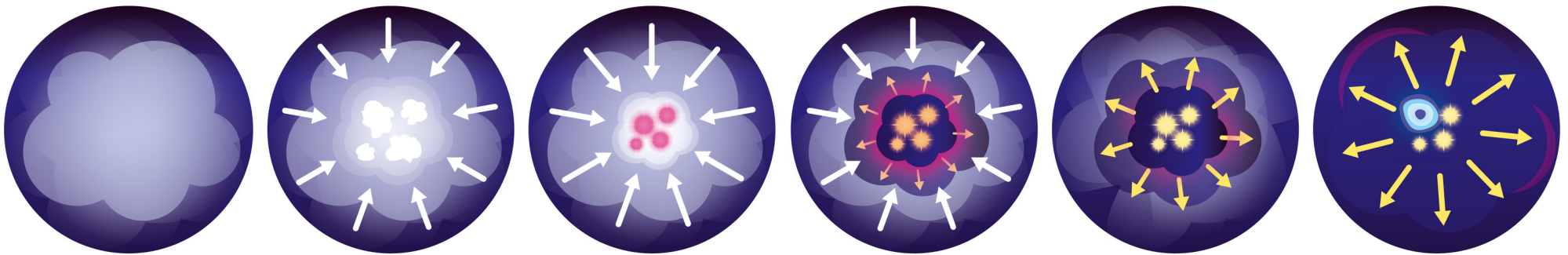
Querejeta et al. (2021)



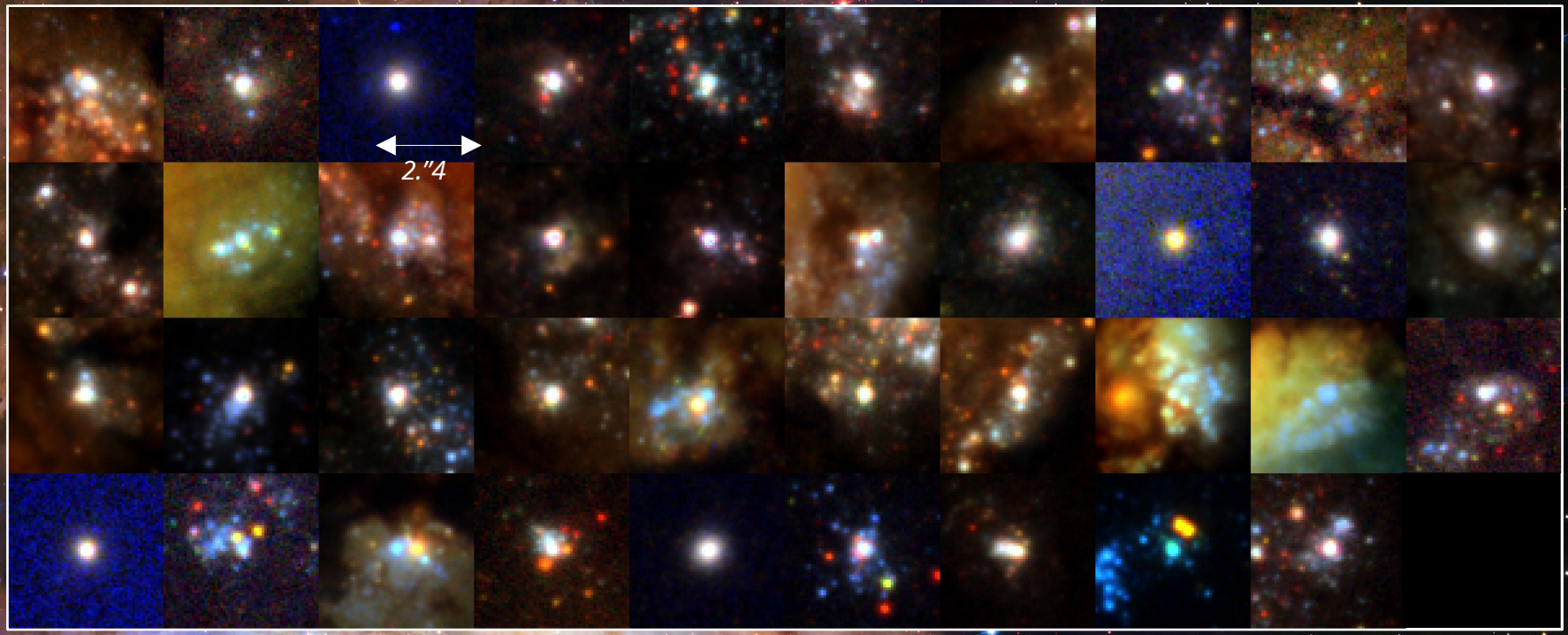
- galactocentric radius
- (molecular) gas surface density
- stellar mass surface density
- SFR surface density
- dynamical equilibrium pressure
- …

Time evolution of cloud & star formation via statistics

Schinnerer & Leroy (2024)



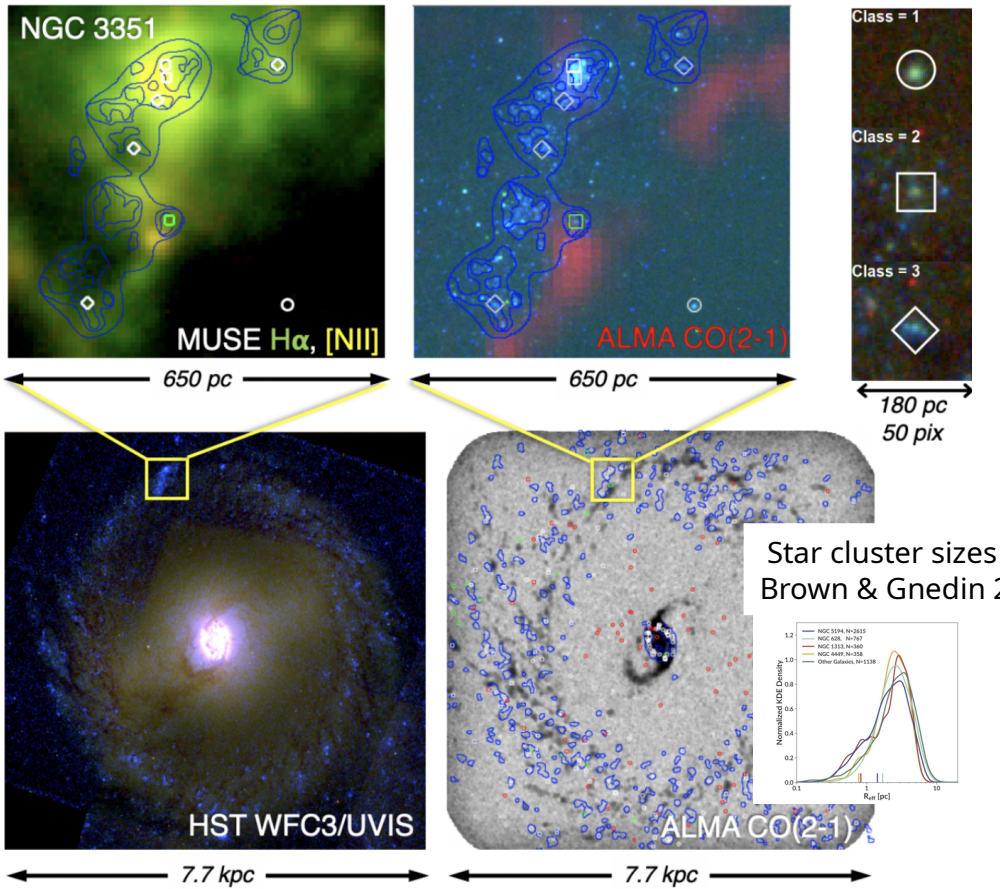
Hubble imaging of star clusters in PHANGS galaxies (5-23 Mpc)

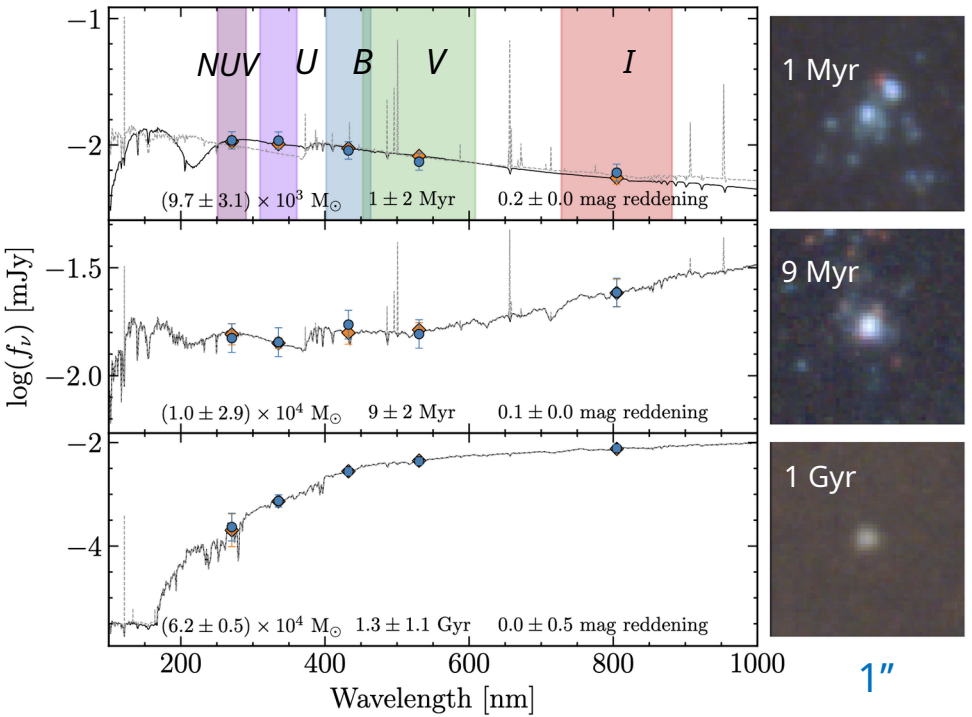


Brightest star cluster in each of the 38 PHANGS galaxies.
Postage stamps span 50-270 pc.
Are these preferentially formed in certain environments (e.g., Ali&Dobbs+23)?

Hubble census of star cluster and stellar associations

Lee+22





Boquien 2019, Thilker+ sub

A reference sample: stellar, cluster, galaxy evolution

~15,000 Human classified clusters across 38 galaxies

3 principal features observed

Young cluster locus (YCL)
Middle-aged plume (MAP)
Old globular cluster clump (OGC)

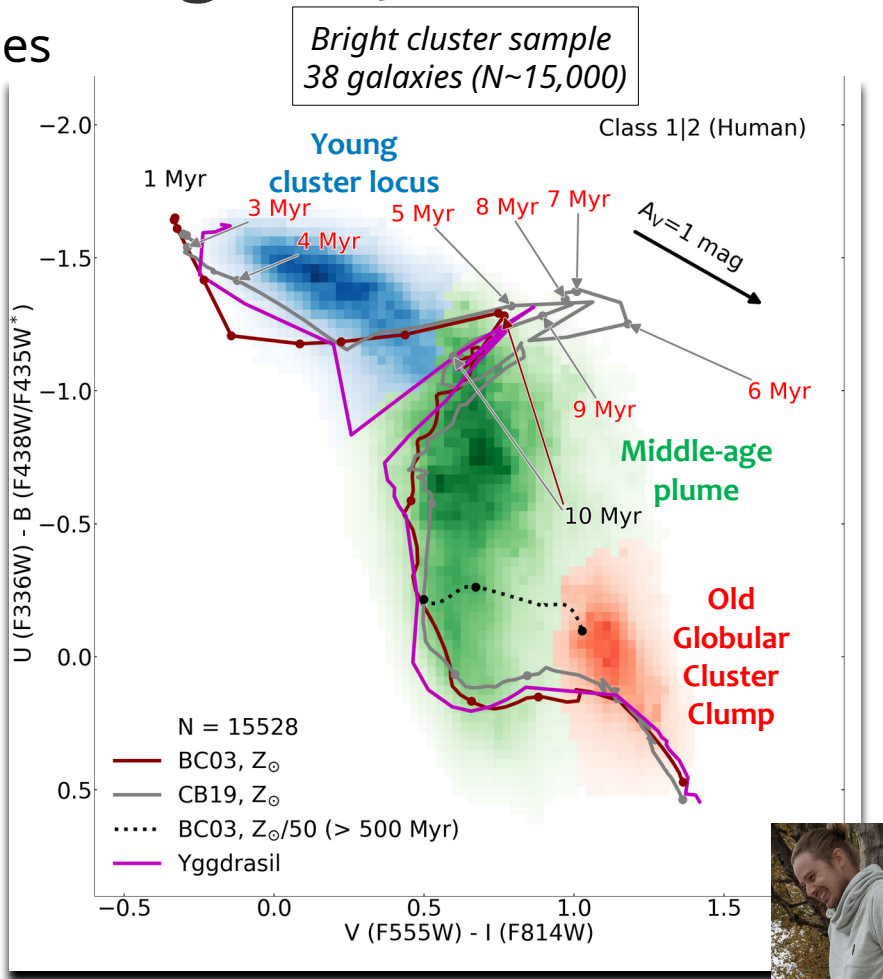
*Slope of the **YCL** consistent with reddening vector*

***MAP** left edge remarkable consistent with Zsun SSP*

***OGC =** distinct clump, consistent metal-poor nature*

Provides a key test of SSP models

Ages, M, E(B-V) SED fits - CIGALE*
(Boquien+19; Thilker+ submitted)

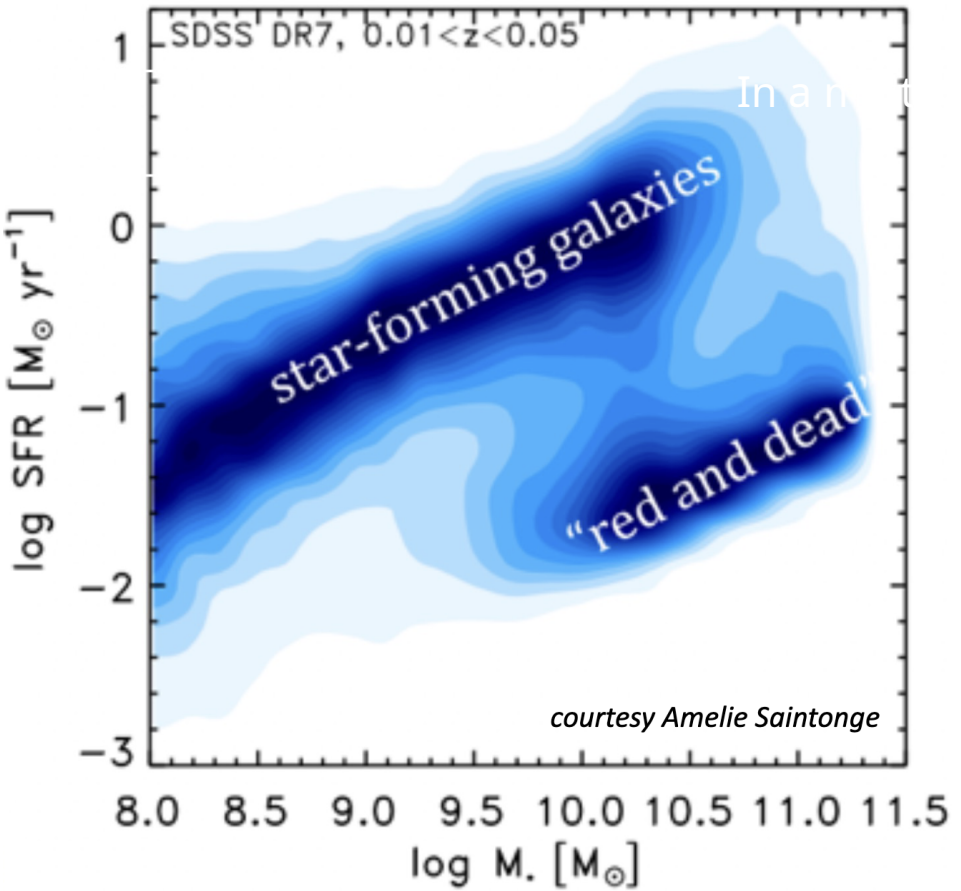


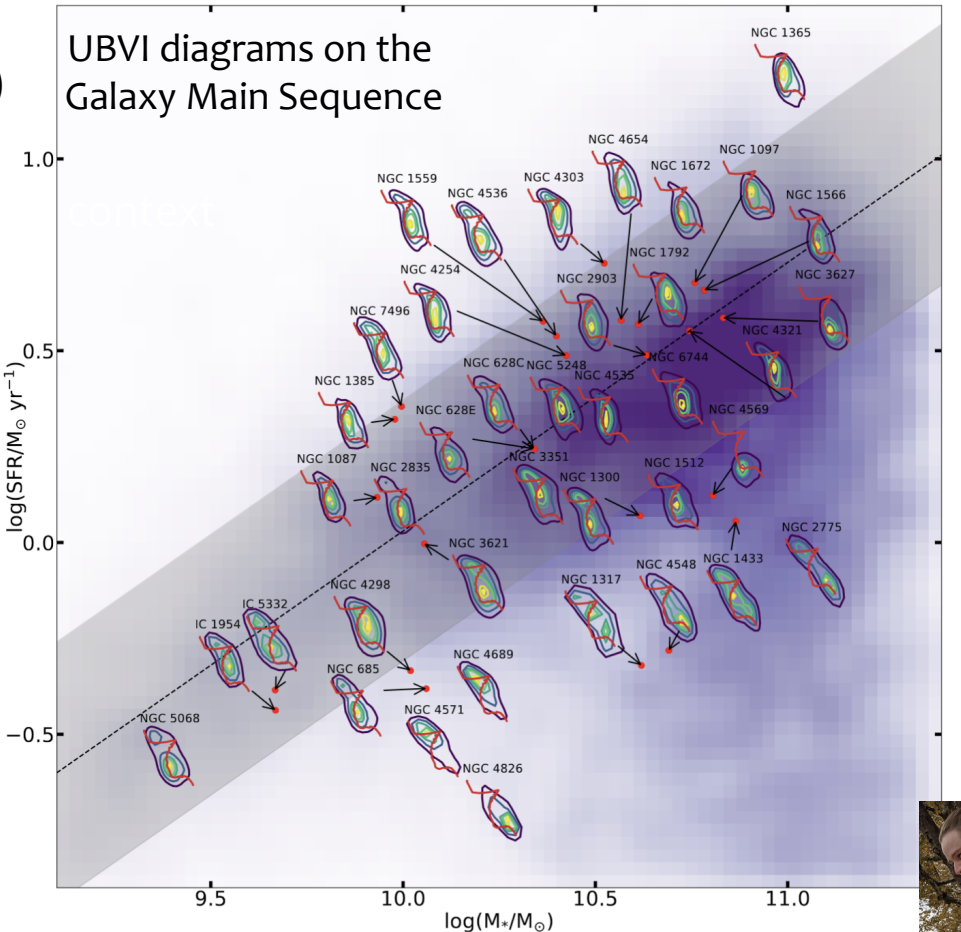
Daniel Maschmann, JCL+24

In a multi-scale context

~15,000 Human classified clusters

Extended sample of ~100,000 clusters (NN)



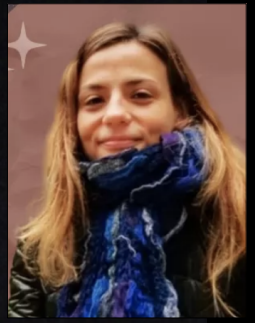


Daniel Maschmann, JCL+24

Dust embedded star clusters

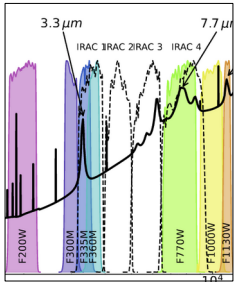
(in NGC 7496)

MJ Rodriguez, Lee, Whitmore+23

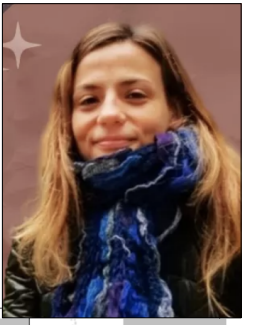


MIRI + HST
Image Credit: NASA / ESA / CSA / Judy Schmidt

PAH compact sources across 19 galaxies
(preliminary)

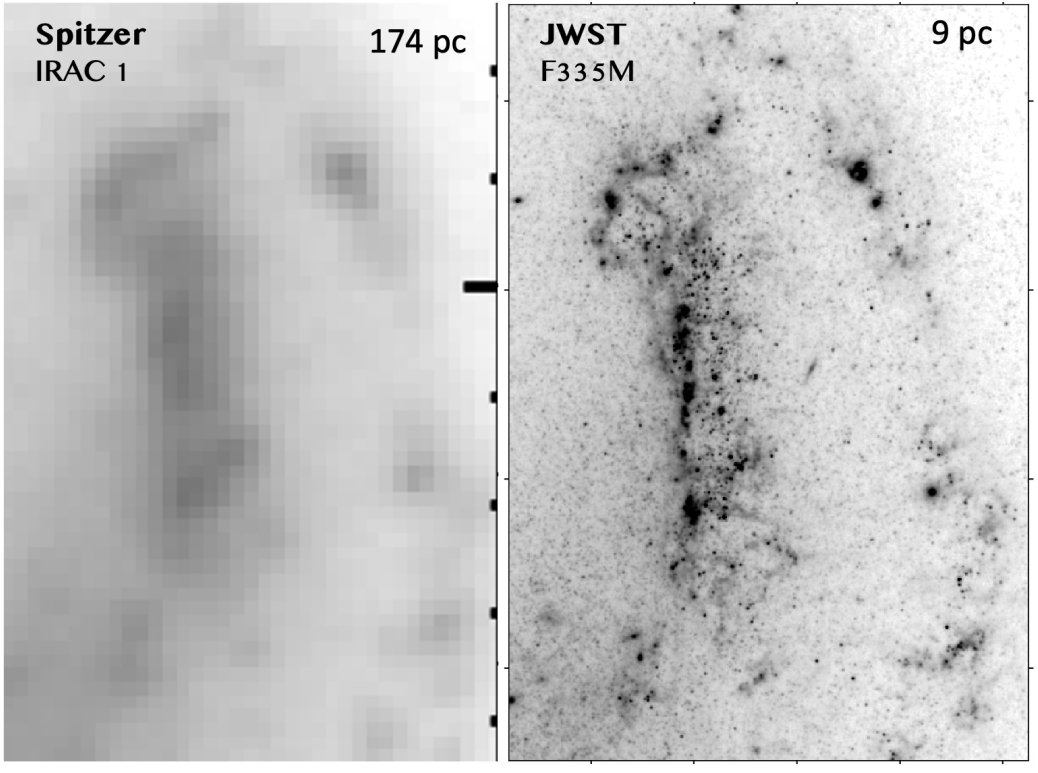


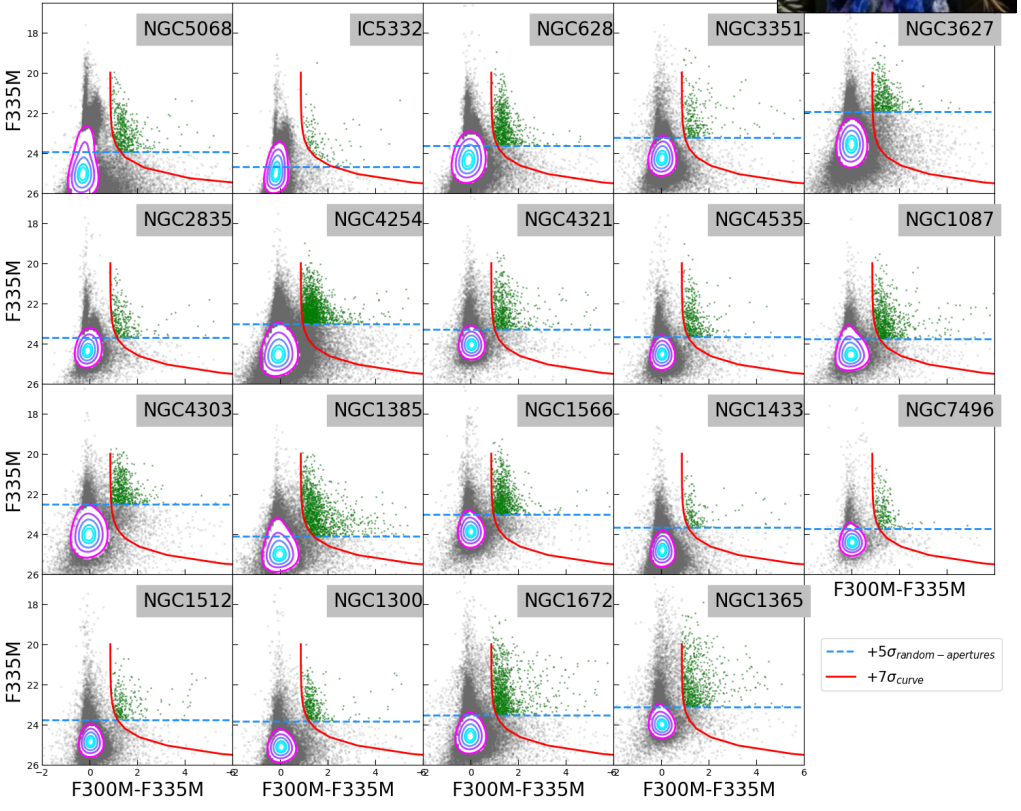
High resolution tracer of embedded clusters & SF



MJ Rodriguez, Lee, Whitmore+23

Spitzer & JWST 3.3μm Comparison





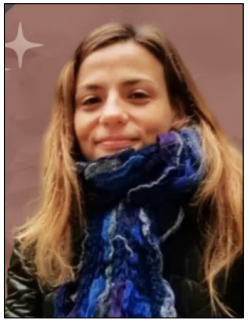
Color-mag selection across 19 galaxies

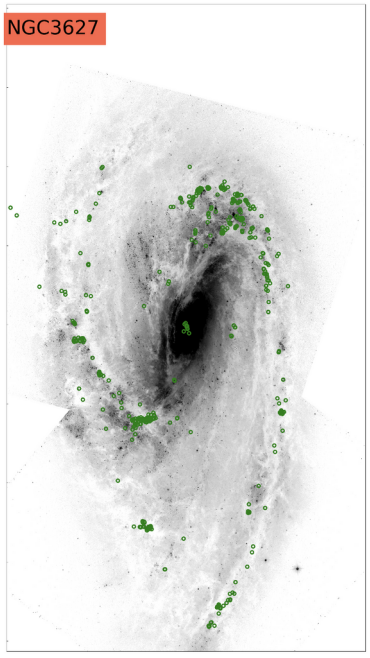
PAH compact sources across 19 galaxies

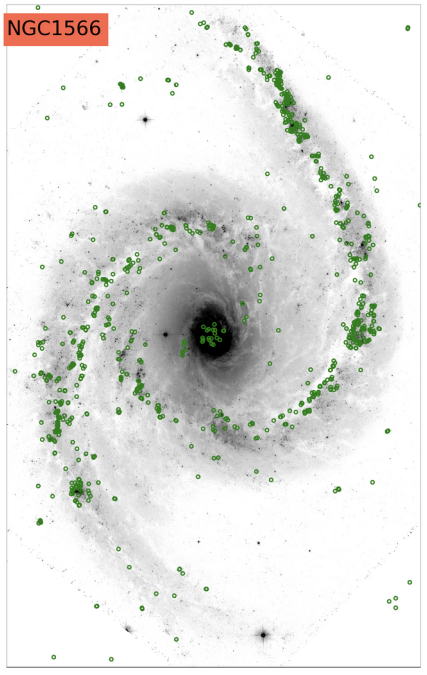
(preliminary)

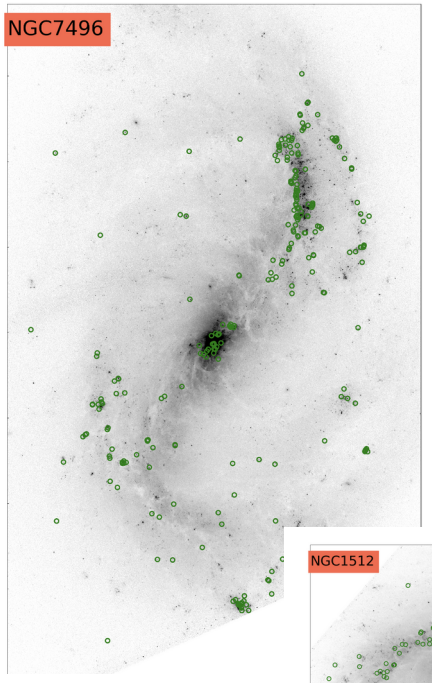
MJ Rodriguez, Lee, Indebetouw

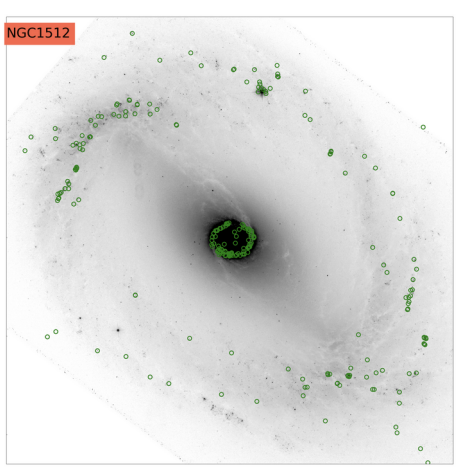
In prep

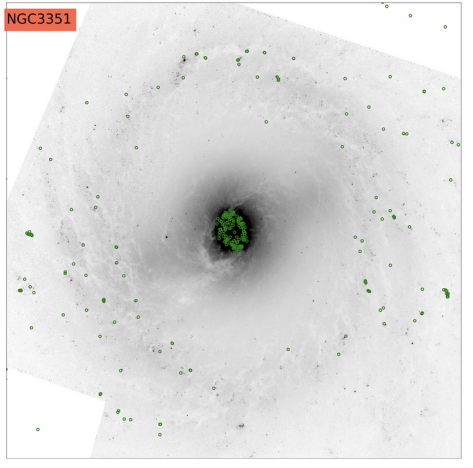








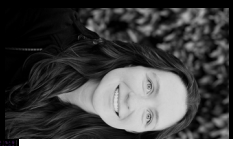




➔ Primarily located in dust lanes along spiral arms & rings

➔ Avoid bars

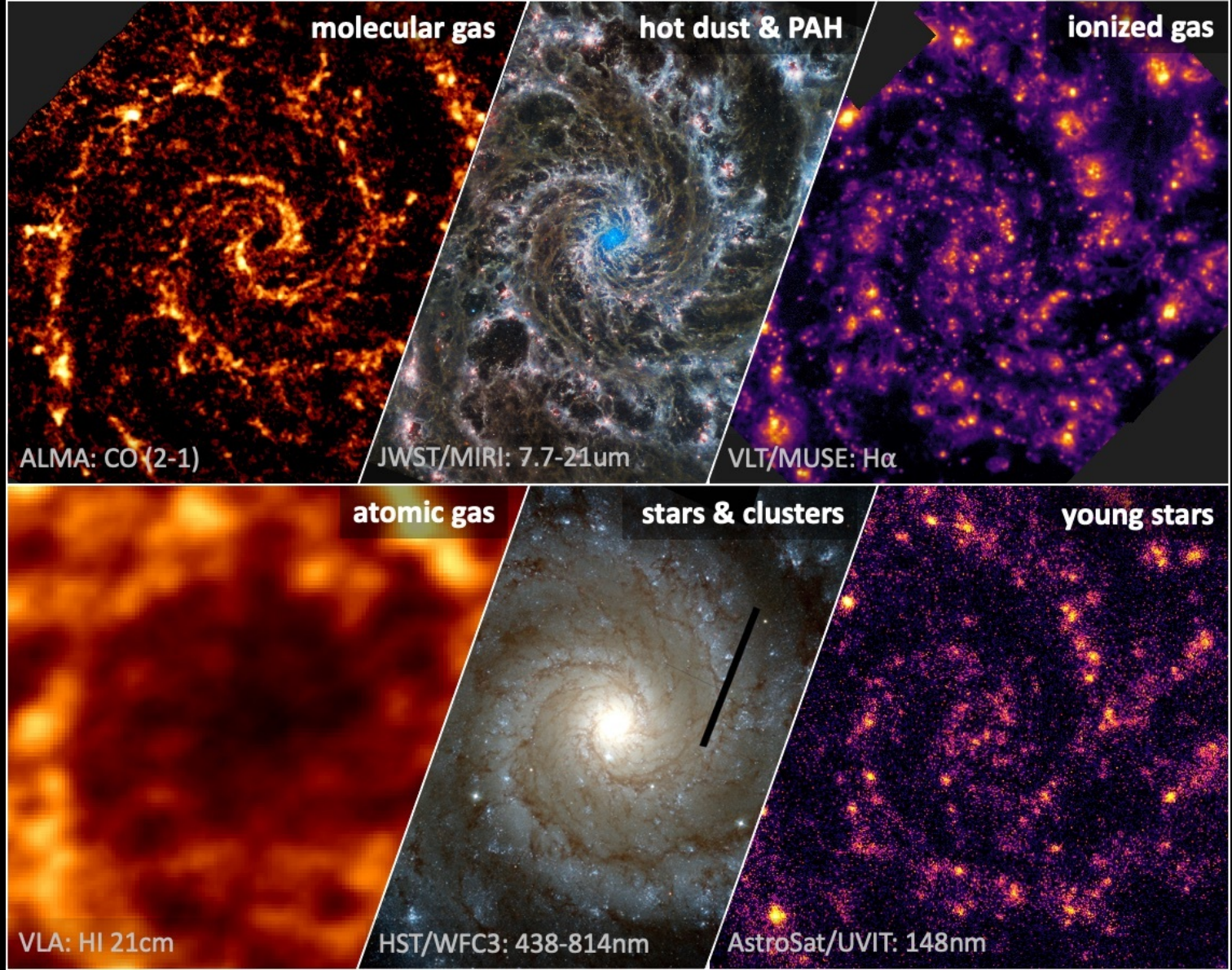
CO density map in PHANGS Galaxies



The Zoology

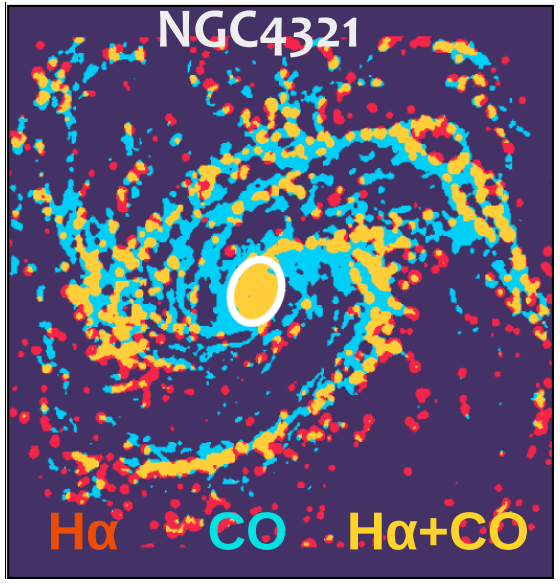
Credit: PHANGS/Stuber

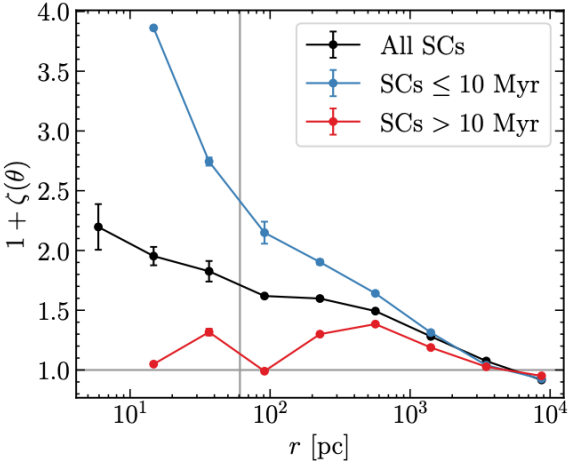
Spirals...



Credit: Jiayi Sun

Pan, Schinnerer et al. (2022)

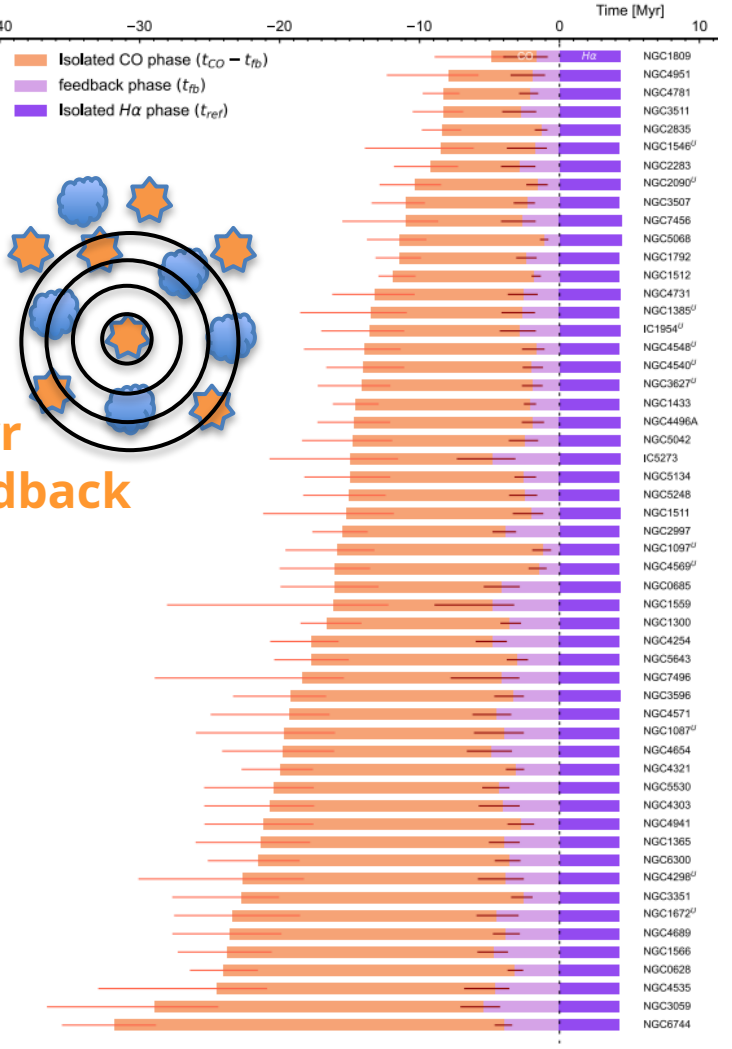




Turner, Dale et al. (2022)

Molecular clouds : ~10 Myr disrupted by pre-SN feedback

Feedback phase: ~ 3Myr



Kim et al. (2021, 2022, 2023)
Chevance et al. (2020)

Dedicated simulations

Emsellem et al. 1994, 2013/2015

Input pyMGE

Parametric (1-3D) & profiles / images

Modules

Projection/deprojection

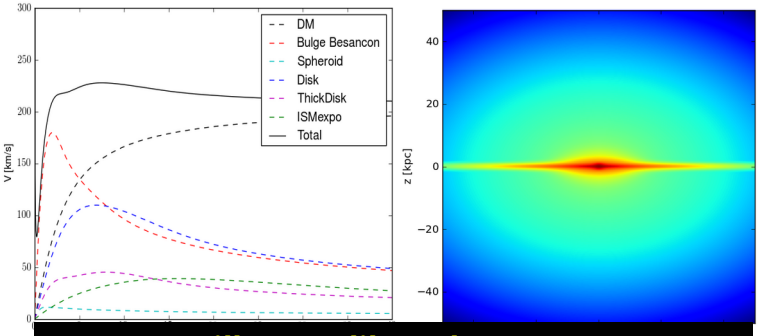
Gravitational Potential, epicycles, etc

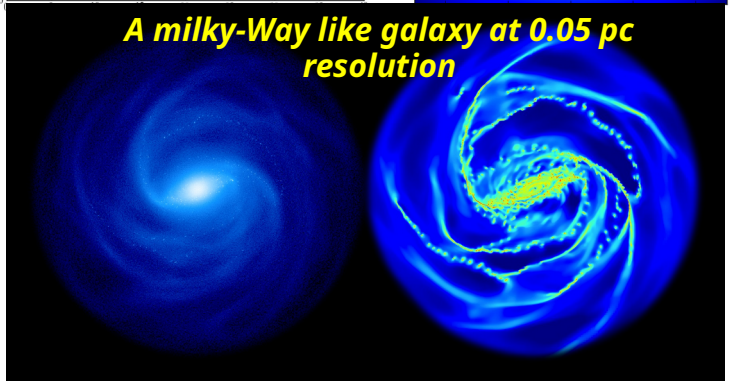
Fully generalised Jeans Eqs

IC for N-body

Particle-based model (varying masses)

Dark matter + stars + gas ⇒ Gadget, RAM

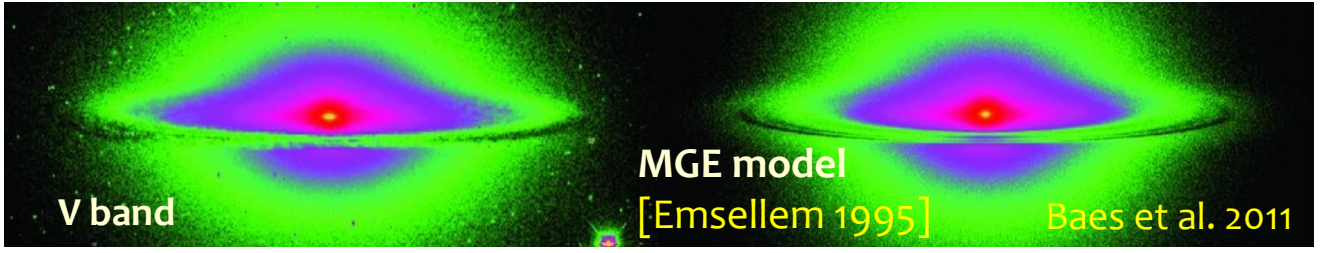




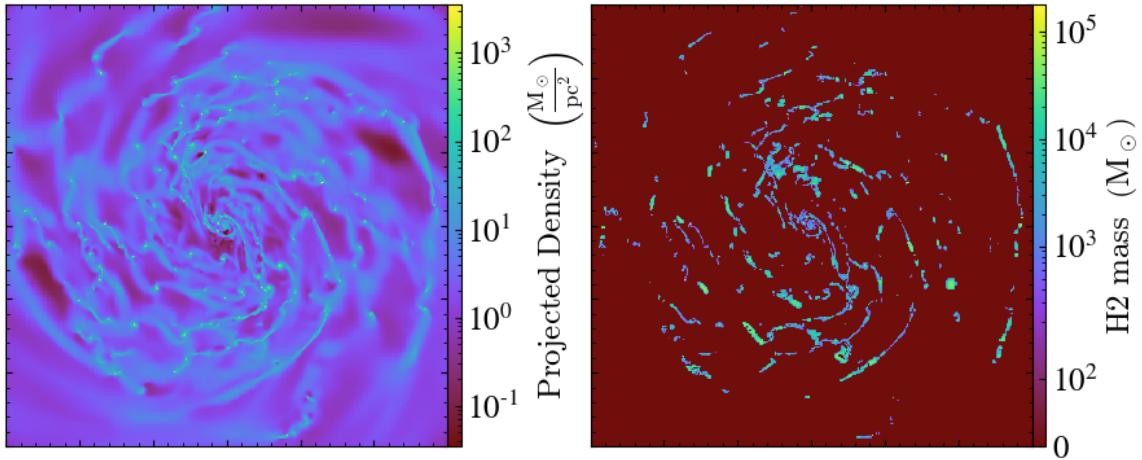
Mocks

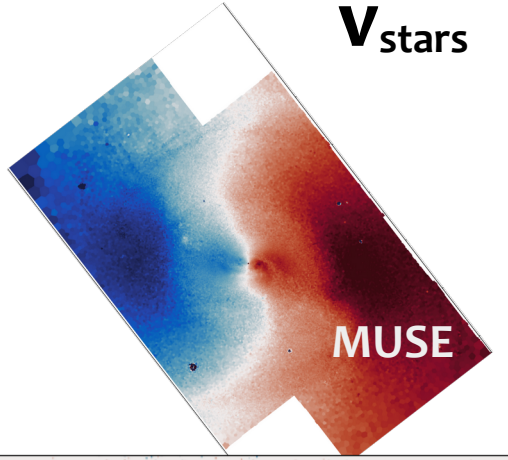
Stellar libraries ⇒ 3D cubes

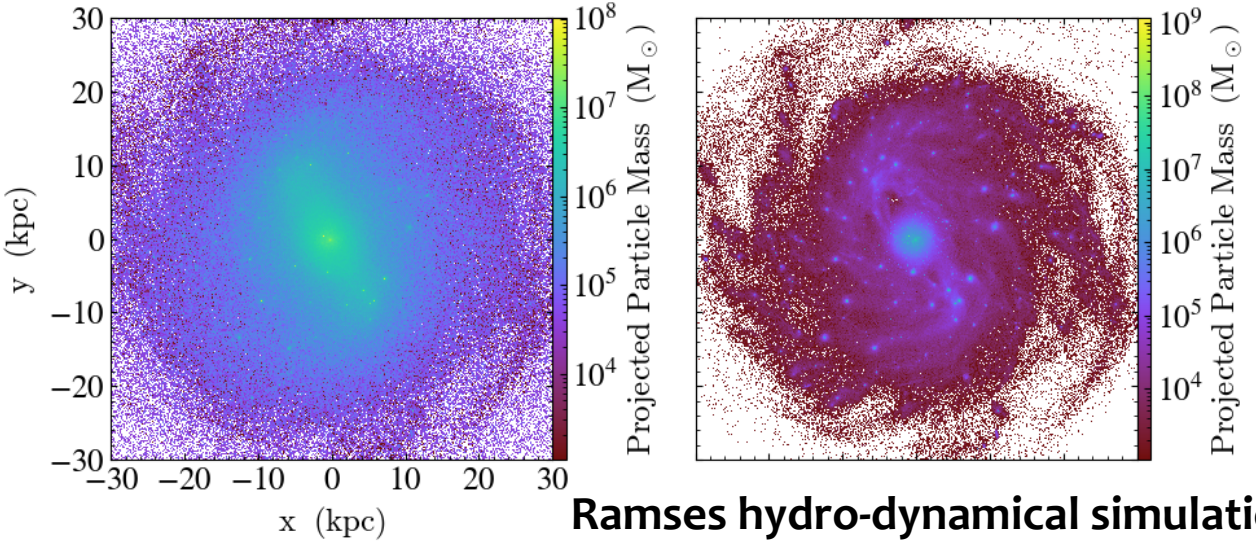
RT to come

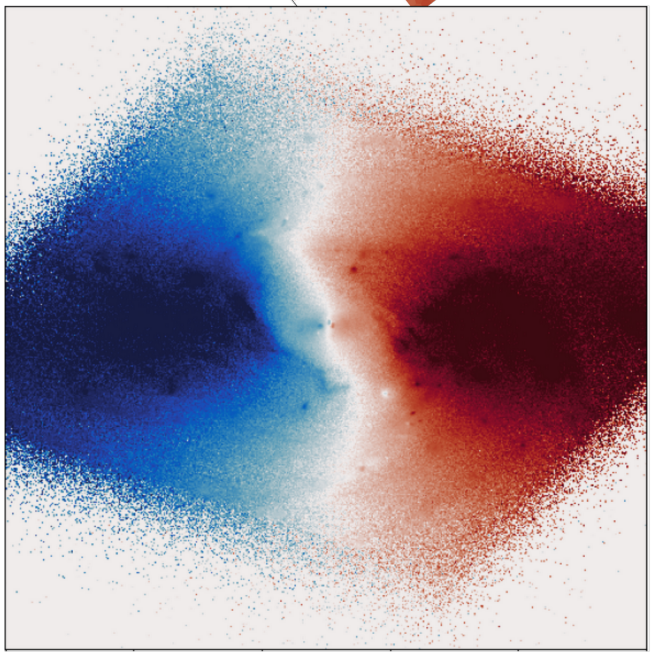


NGC 1365

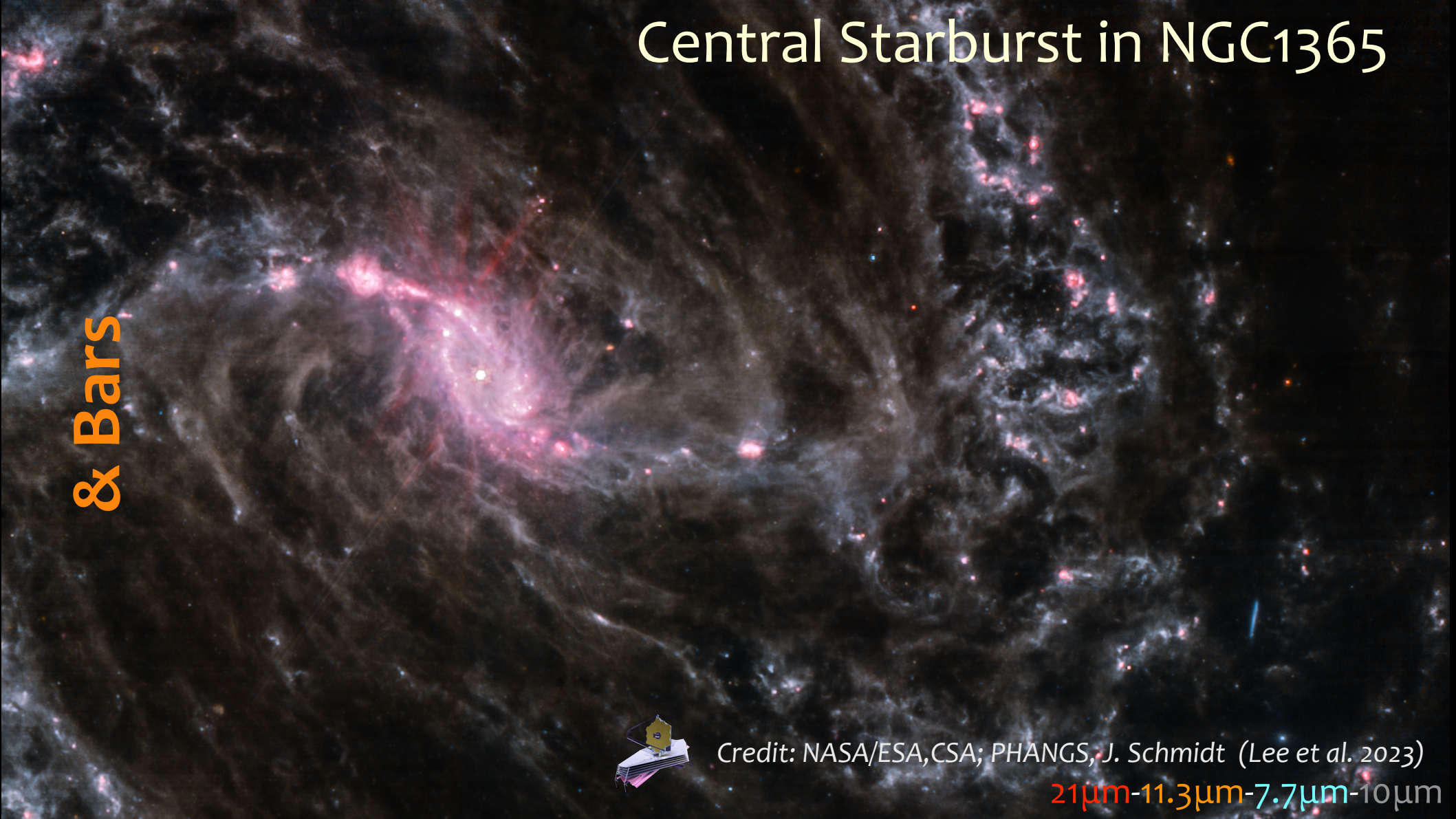




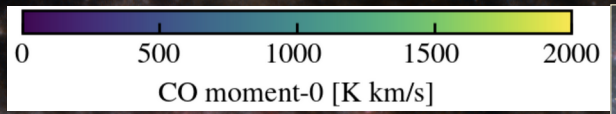


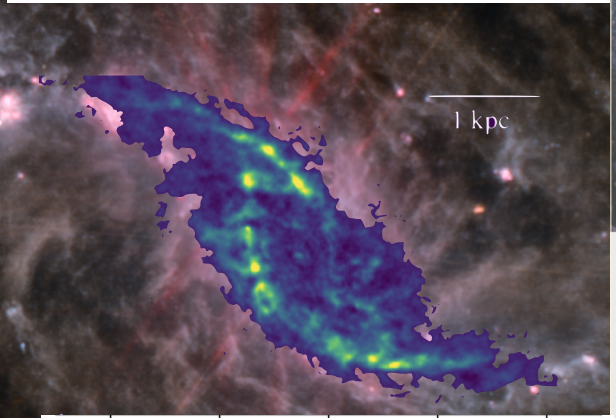


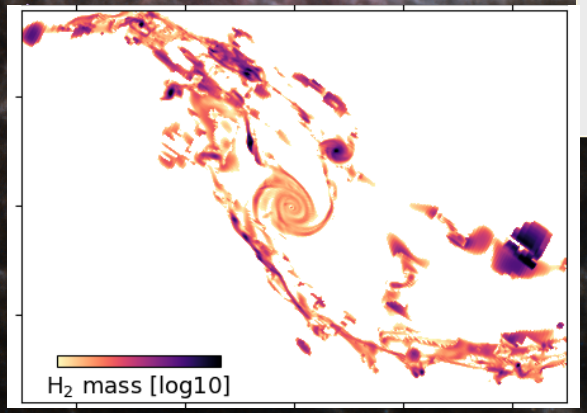
Ramses hydro-dynamical simulation (Emsellem+ in prep)


Central Starburst in NGC1365
& Bars
Credit: NASA/ESA,CSA; PHANGS, J. Schmidt (Lee et al. 2023)
21µm-11.3µm-7.7µm-10µm

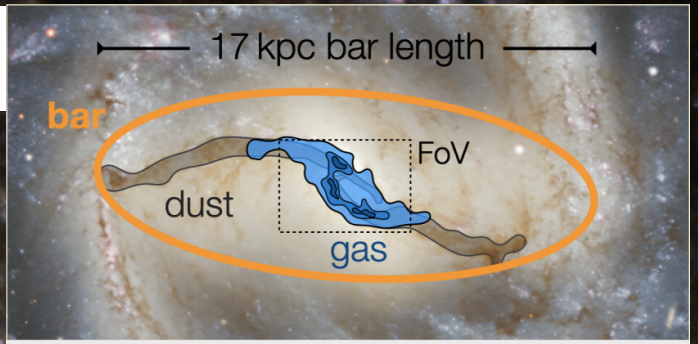
Central Starburst in NGC1365

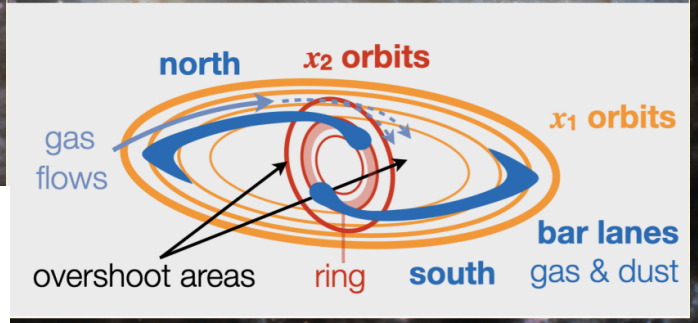






Hydro-dynamical simulation





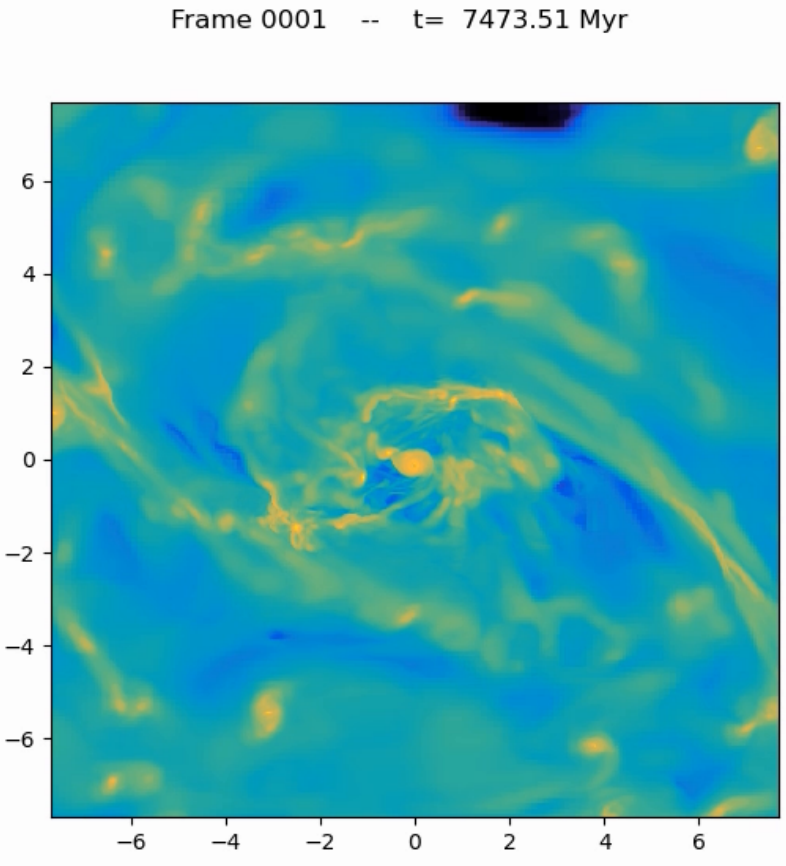
Schinnerer et al. (2023)

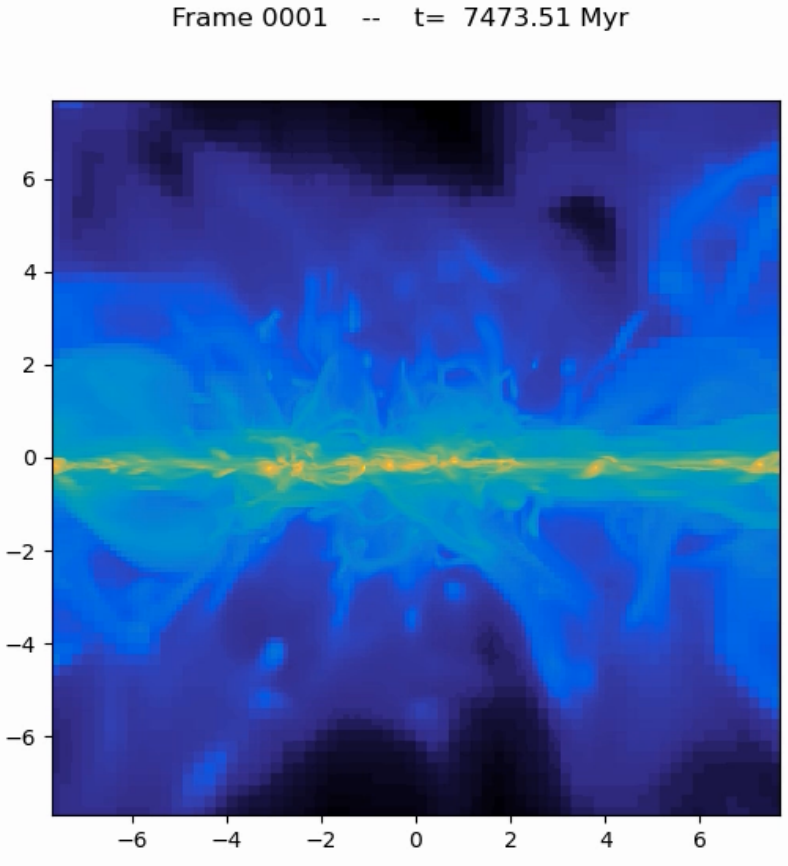
21μm-11.3μm-7.7μm-10μm

Time evolution

Emsellem in prep.

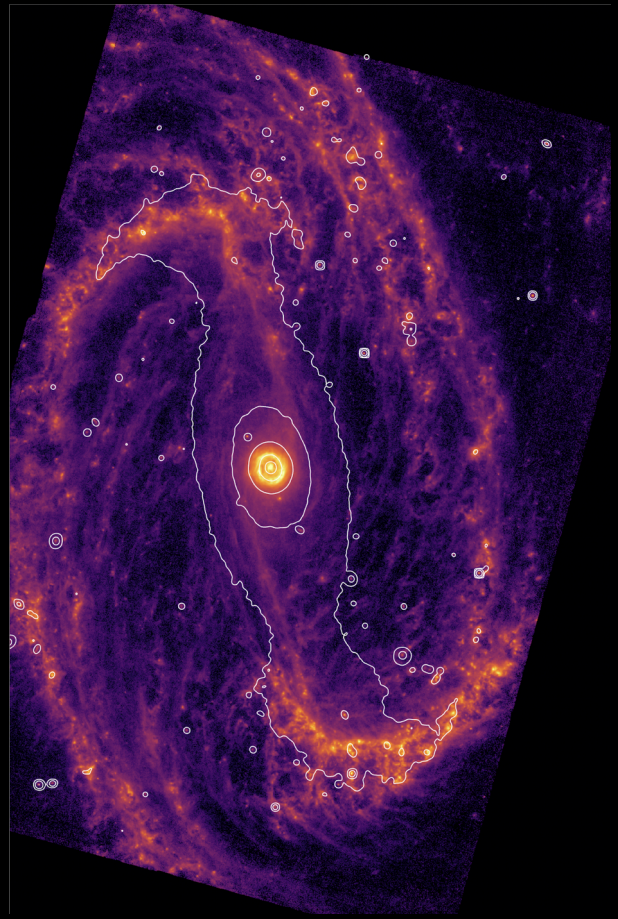
Time varying / Star formation regimes



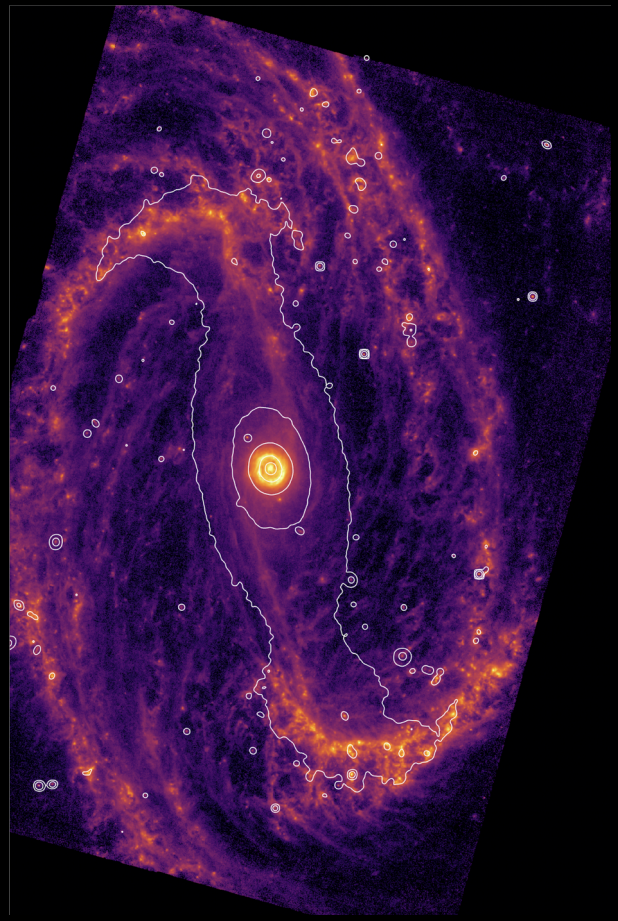


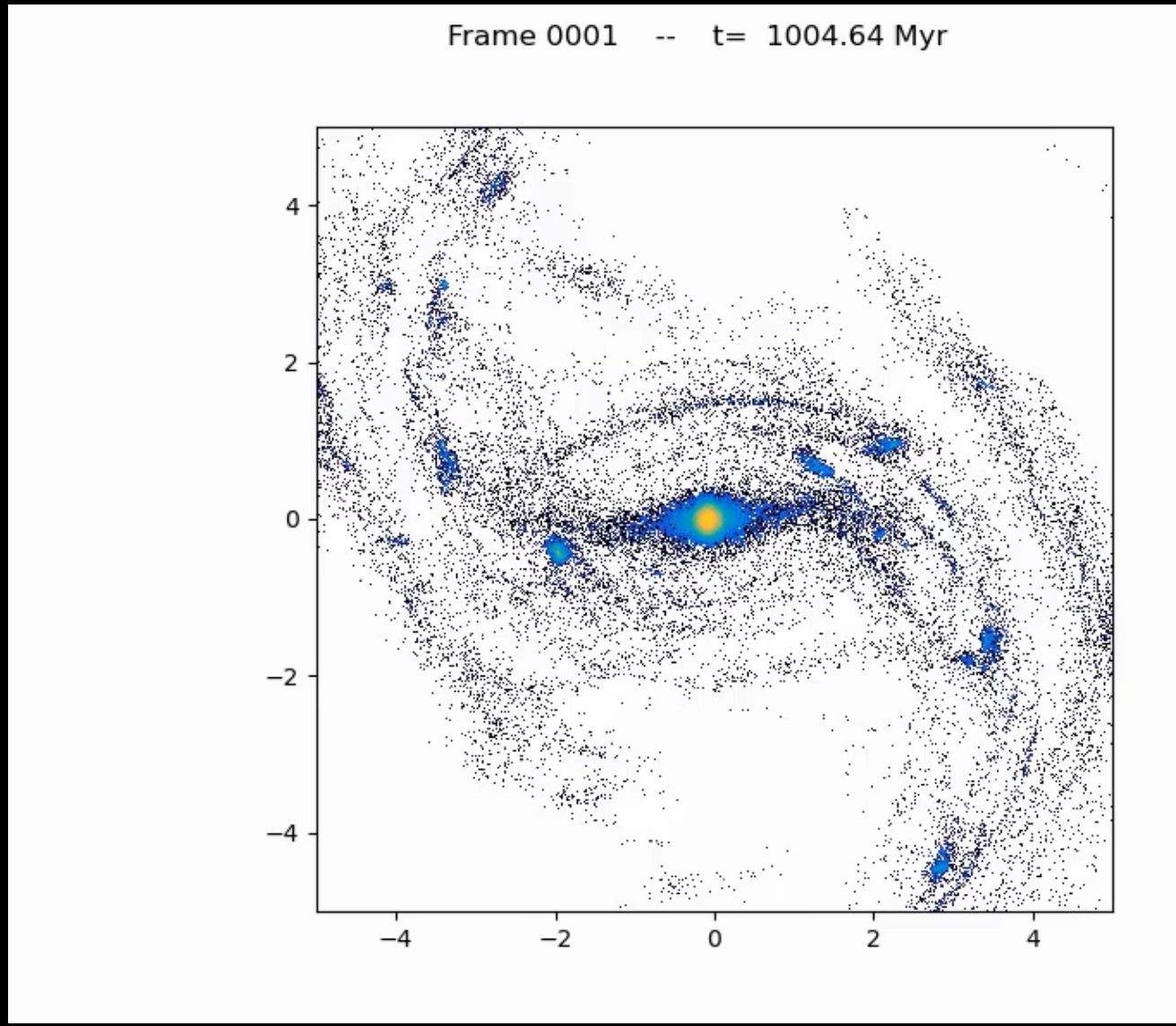

Credit: NASA/ESA,CSA; PHANGS
©Jessica Sutter
Orbital skeleton
11.3µm-10.0µm-2µm

The orbital skeleton



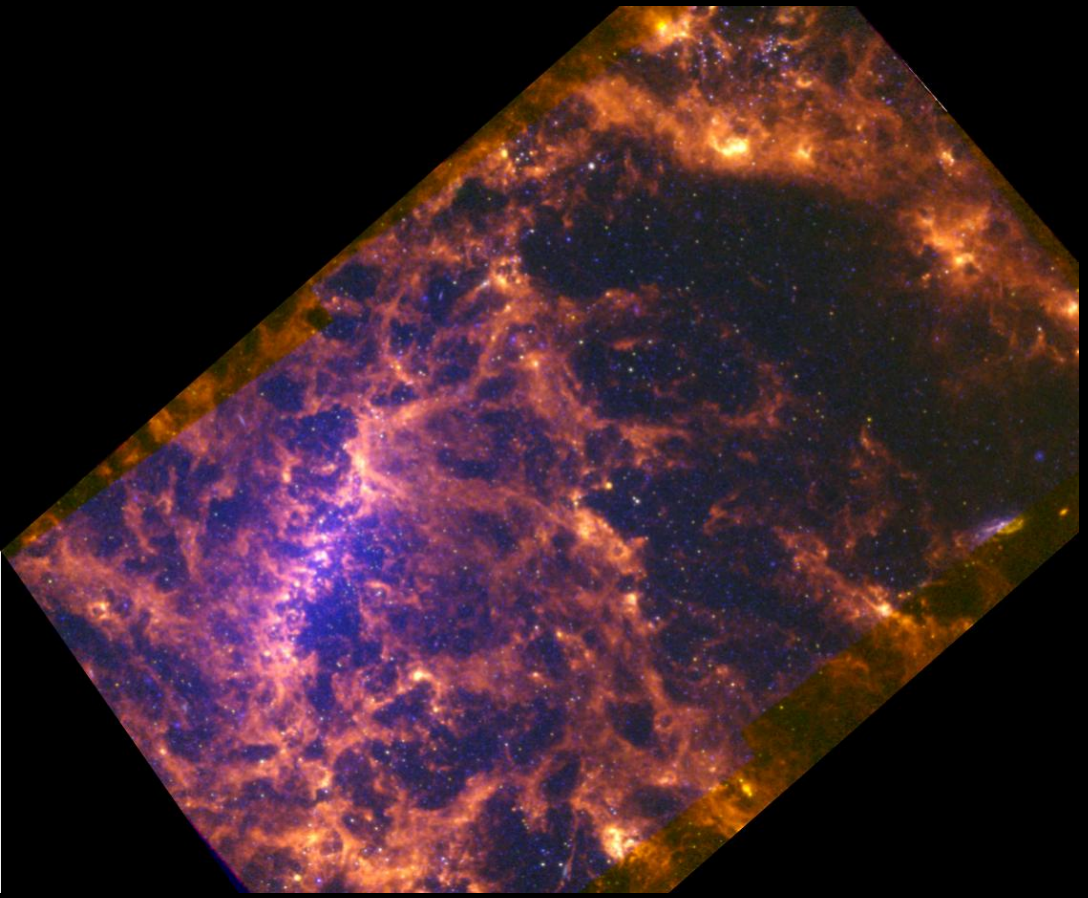
The orbital skeleton

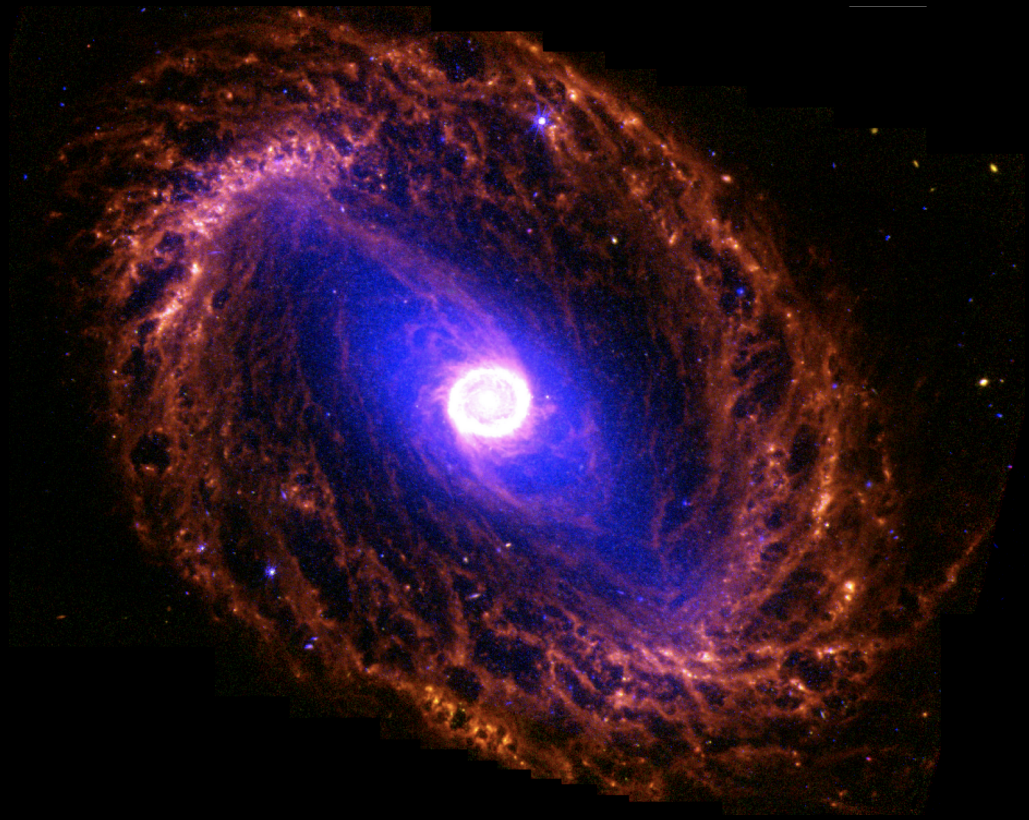




Emsellem in prep.

Credit: NASA/ESA,CSA; PHANGS





Orbital skeleton

11.3µm-10.0µm-2µm

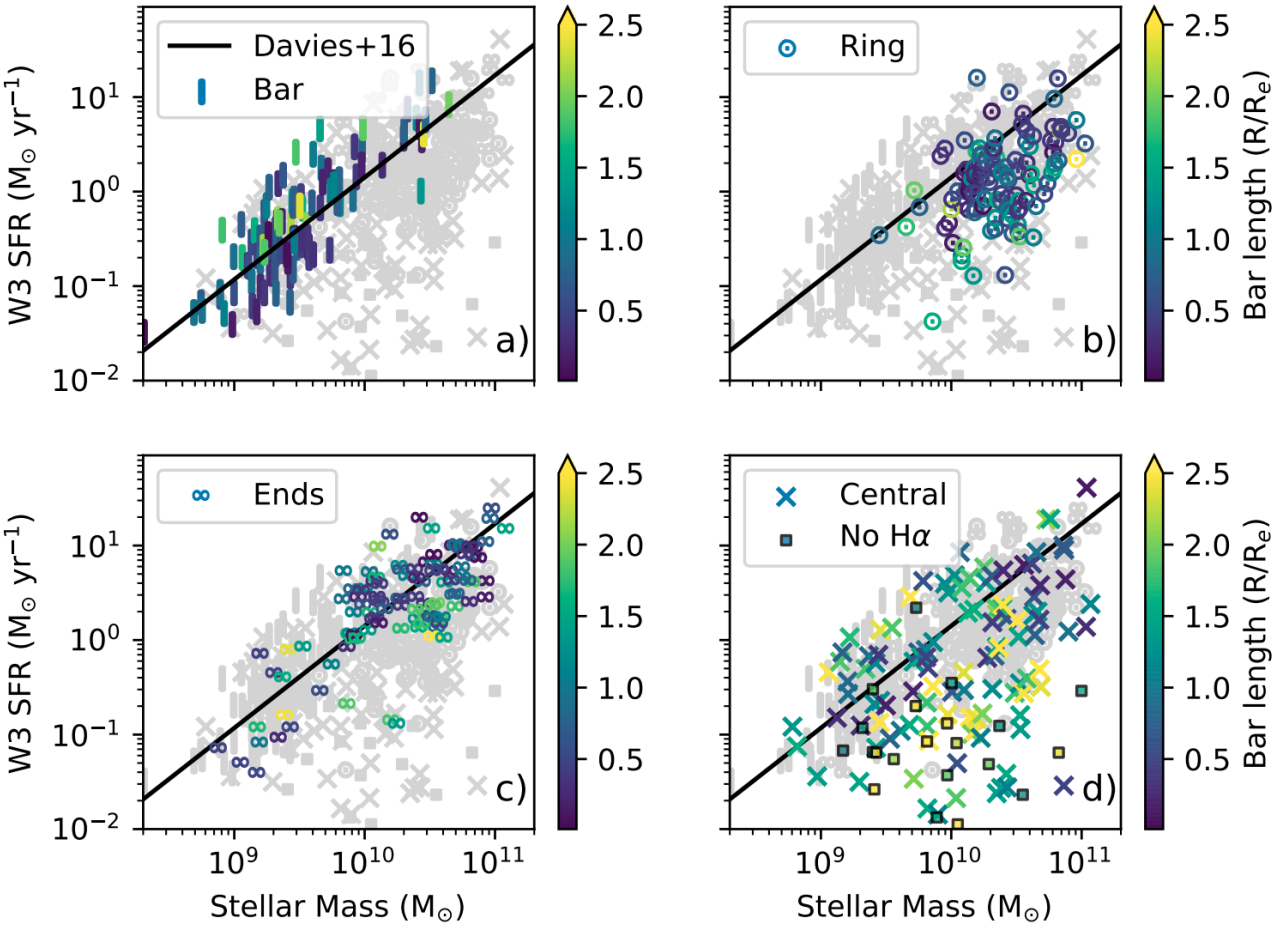
Where do stars form / Why ?

Fraser-McKelvie et al. 2020

Dependence of SF on stellar mass

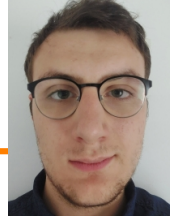
⇒ lower-mass = bar

⇒ higher mass = rings



Generic Simulations of isolated discs

Verwilghen+ 2024



Time evolution ⇒ hydro-dynamical simulations

MGE ICs + **AMR RAMSES** (Teyssier 2002)

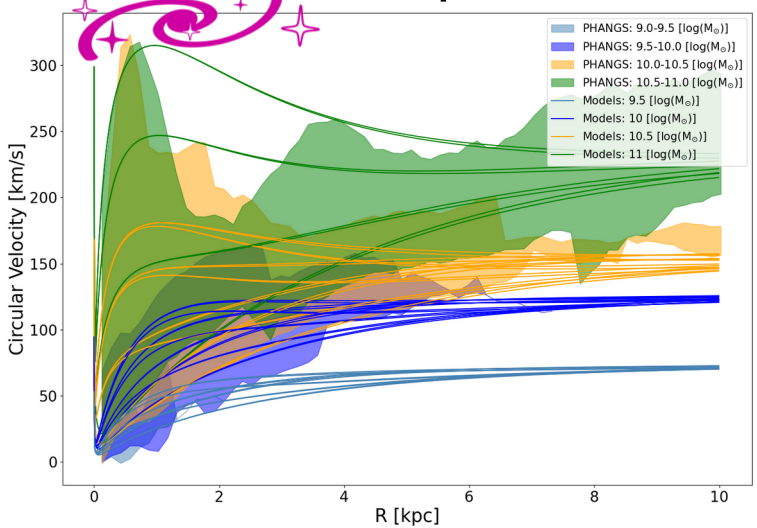
⇒ Gas, Stars, Dark Matter

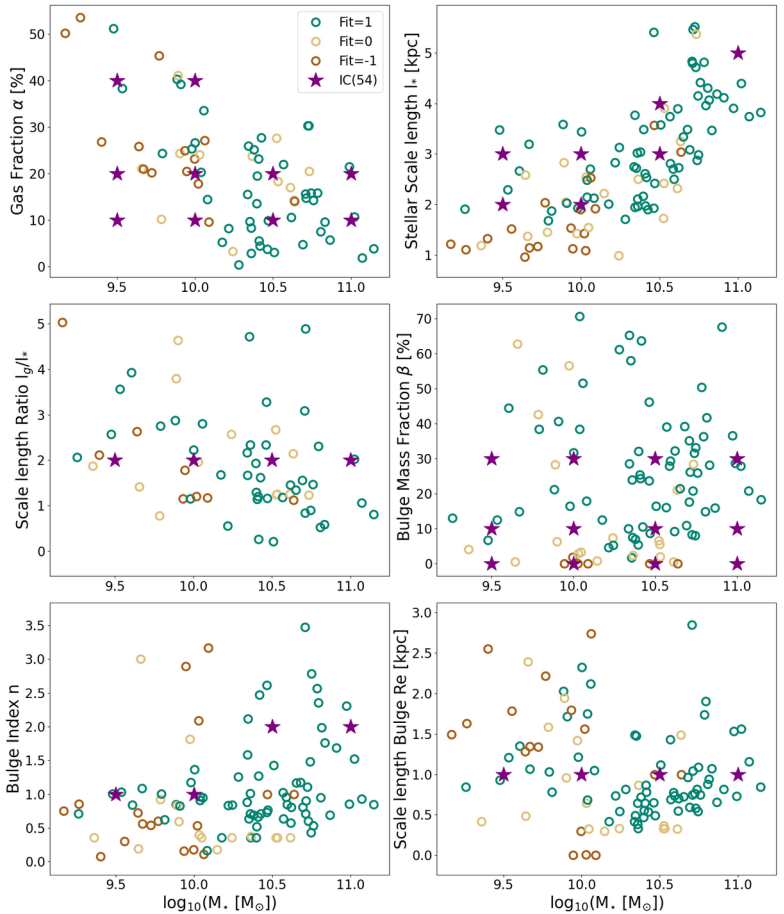
⇒ Star formation, feedback (winds, SN, …)

⇒ ~12 pc cells, 3Gyr evolution

⇒ **Grid of 54 models spanning**

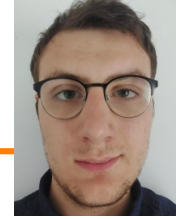
the Phangs sample





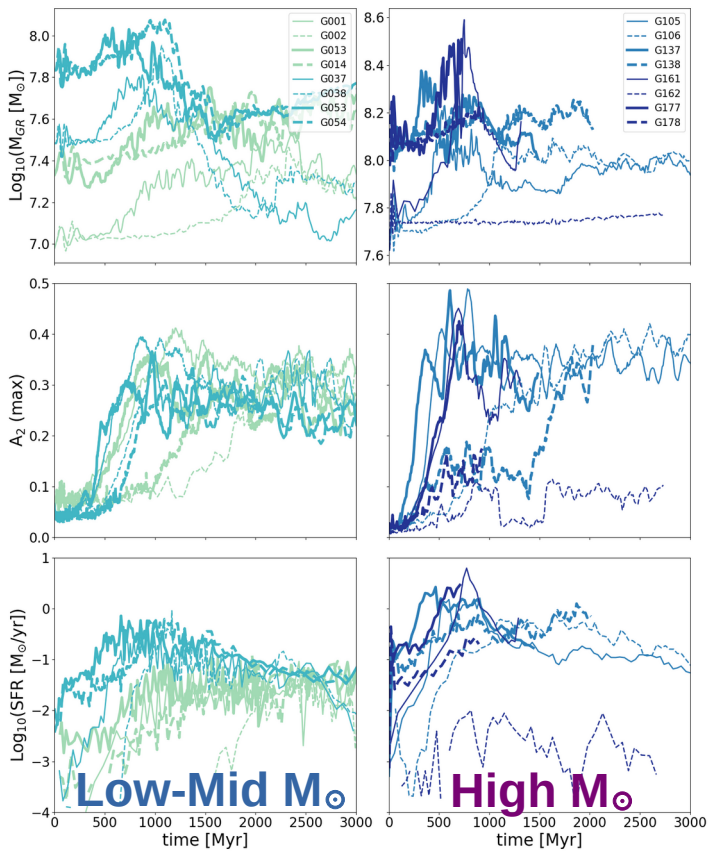
Bar Dynamical coupling

Verwilghen+ 2024



⇒ Low vs High mass systems → different **depletion times** ?

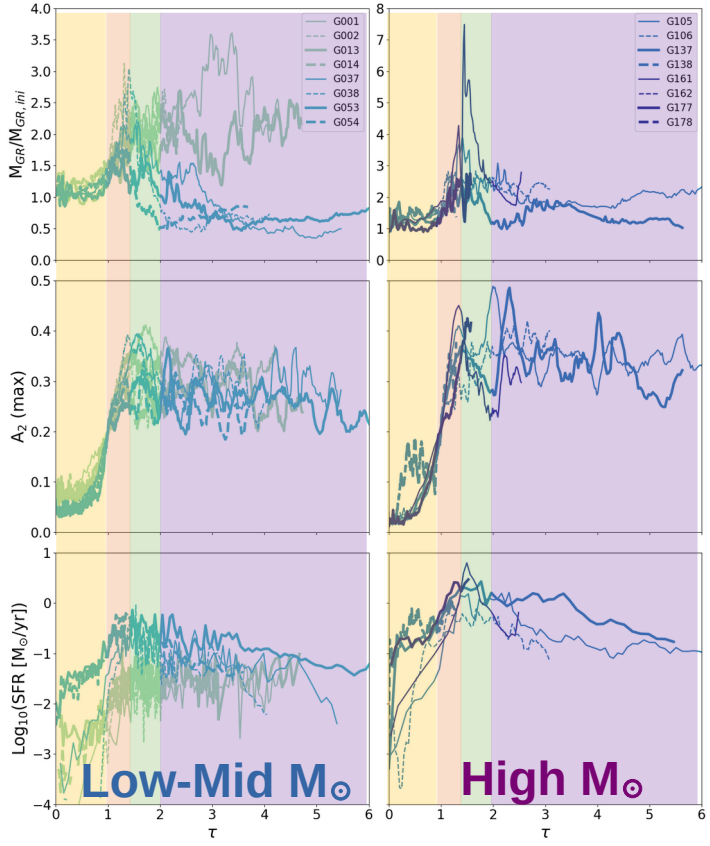
⇒ **Phases** : formation, burst, depletion → central concentration



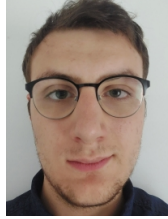
Mgas

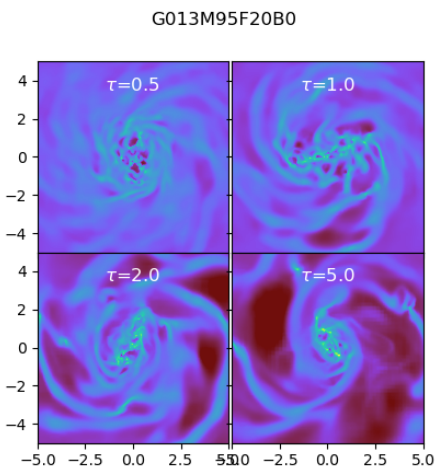
Bar strength

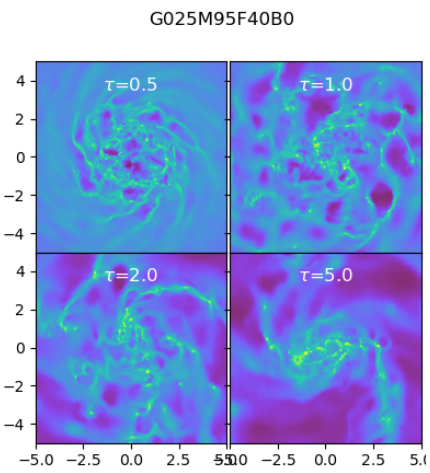
SFR

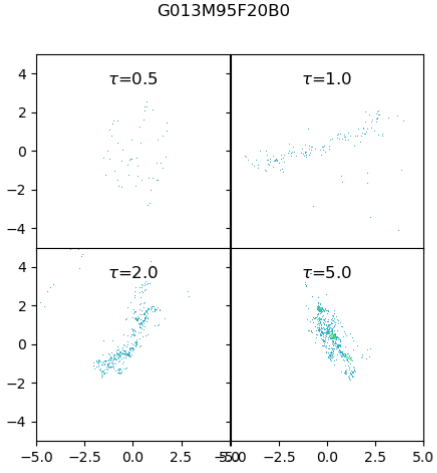


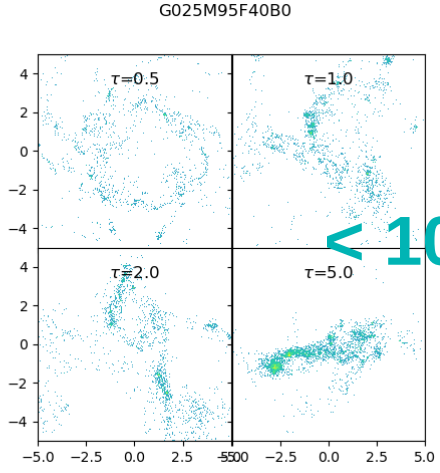
Verwilghen+ 2024, in prep.



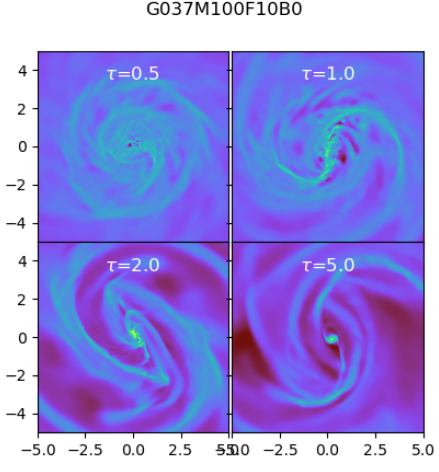


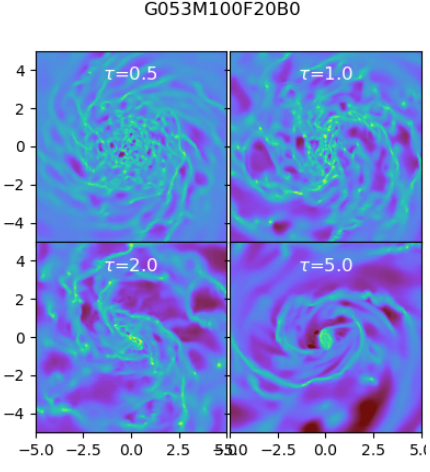


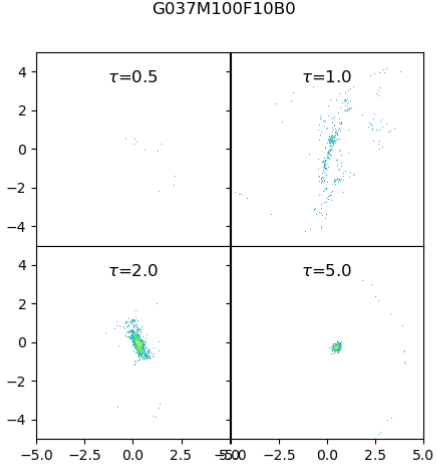


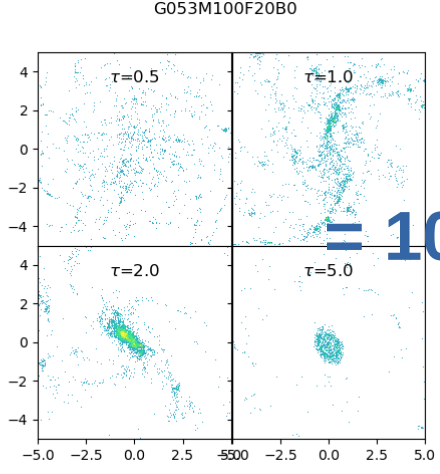


$< 10^{10}$ M⊙

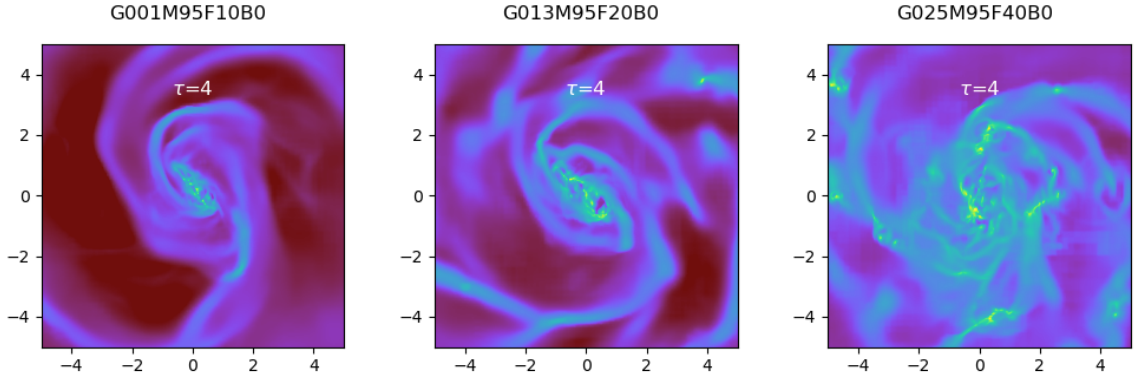


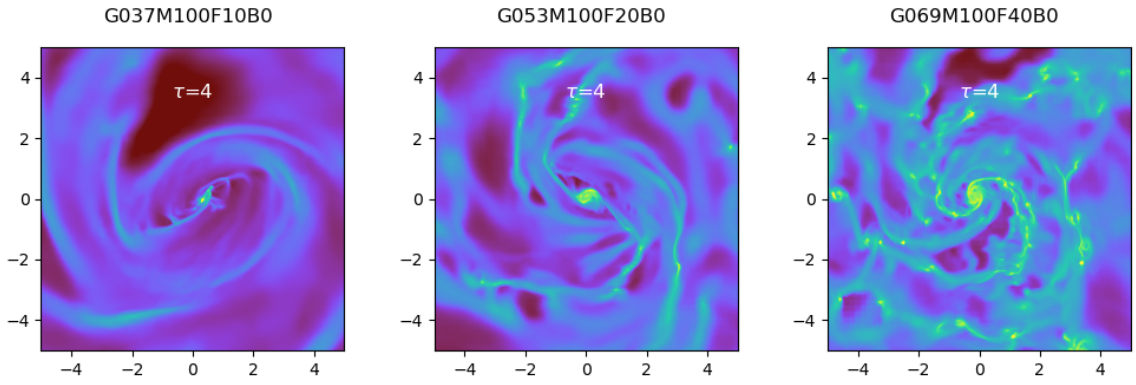


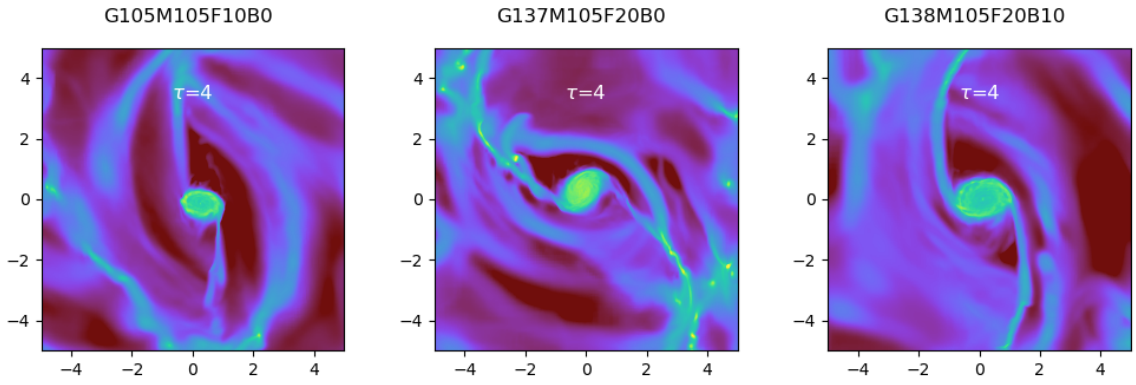




$= 10^{10}$ M⊙







Verwilghen+ 2024, in prep.

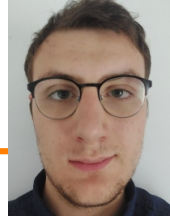
Low M⊙

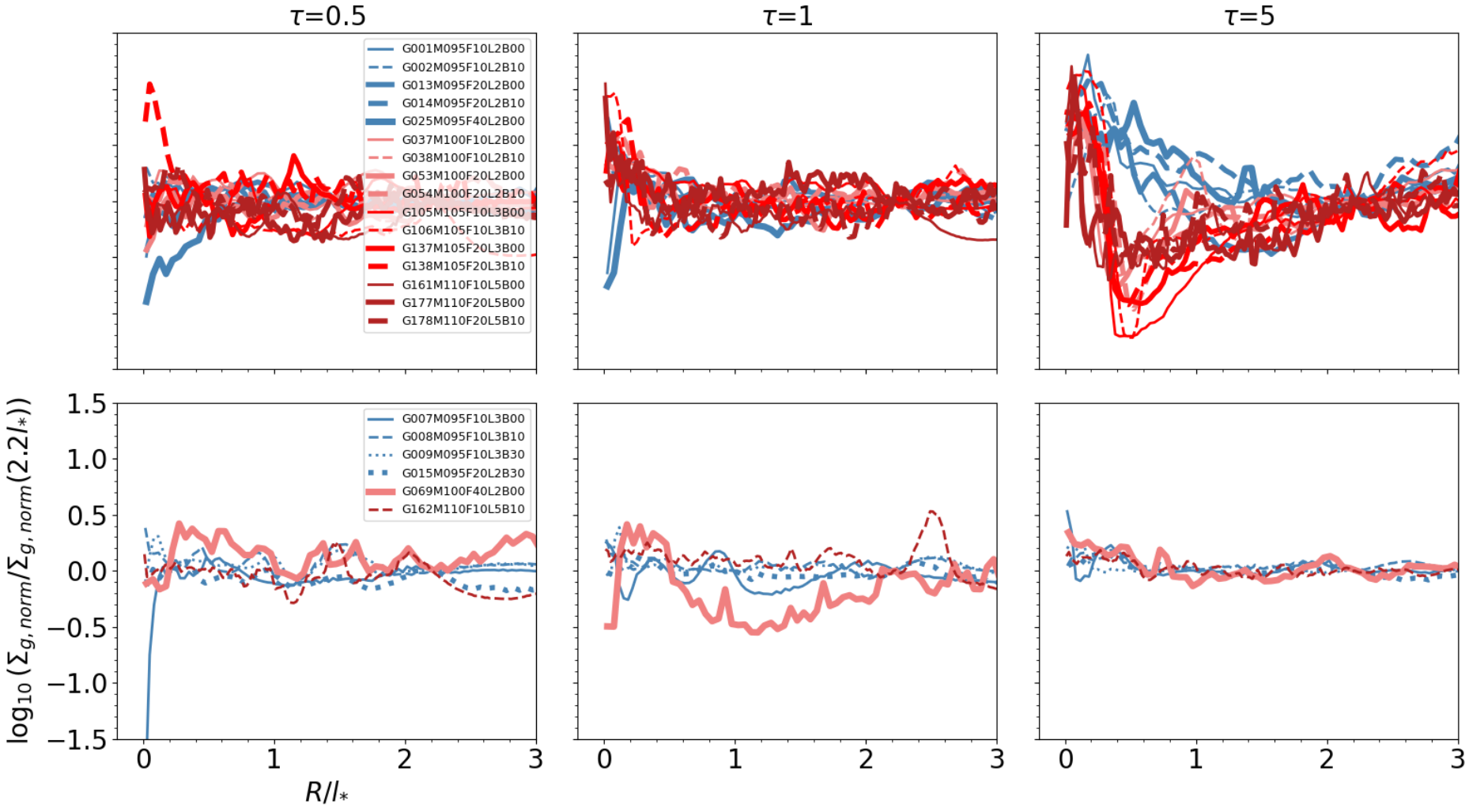
Mid M⊙

High M⊙

Bar-driven evolution

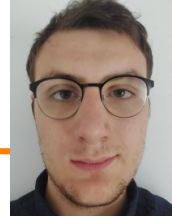
Verwilghen+ 2024, in prep.





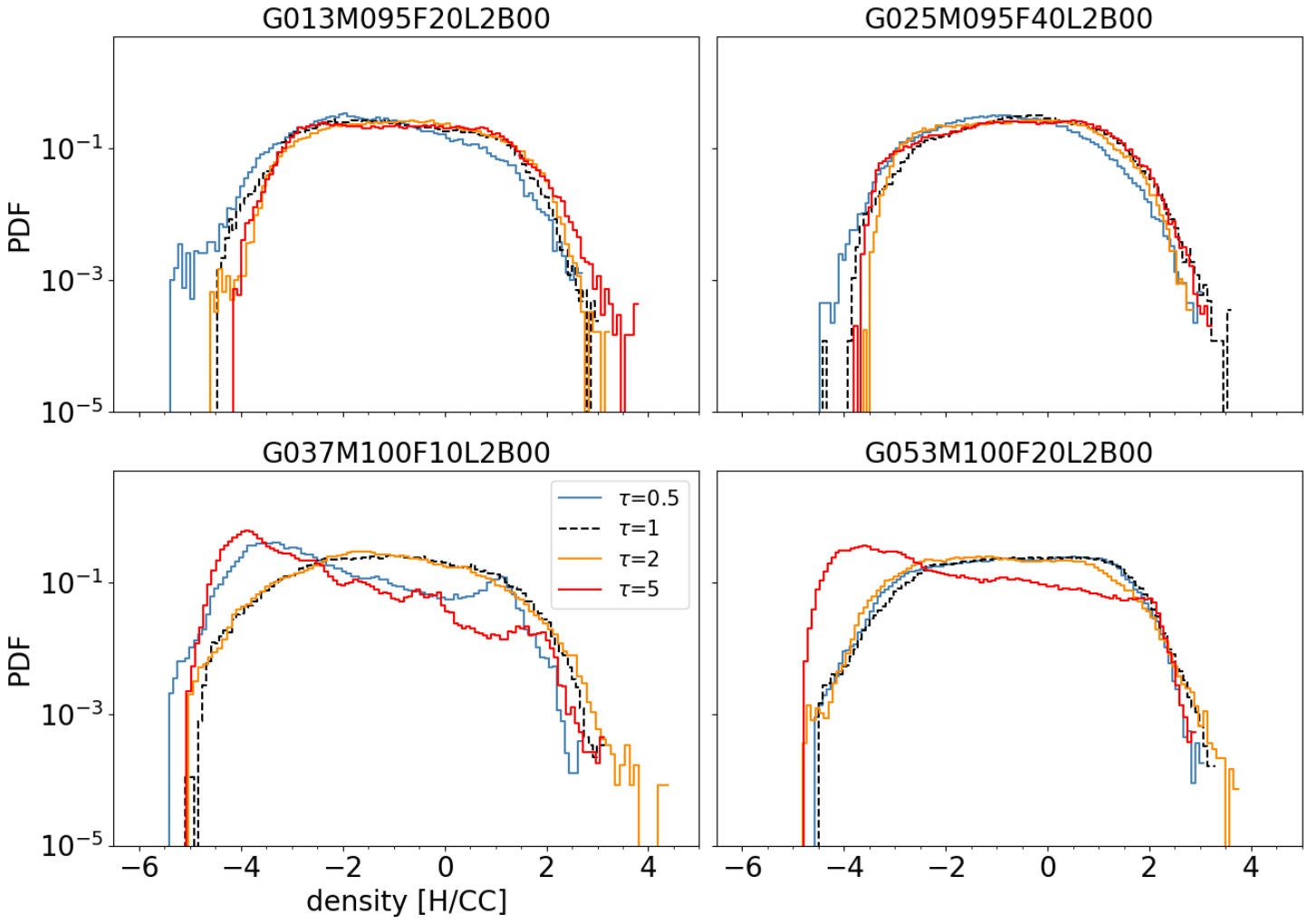
PDF (gas)

Verwilghen+ 2024, in prep.



$< 10^{10}\ M_\odot$

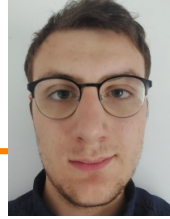
$= 10^{10}\ M_\odot$

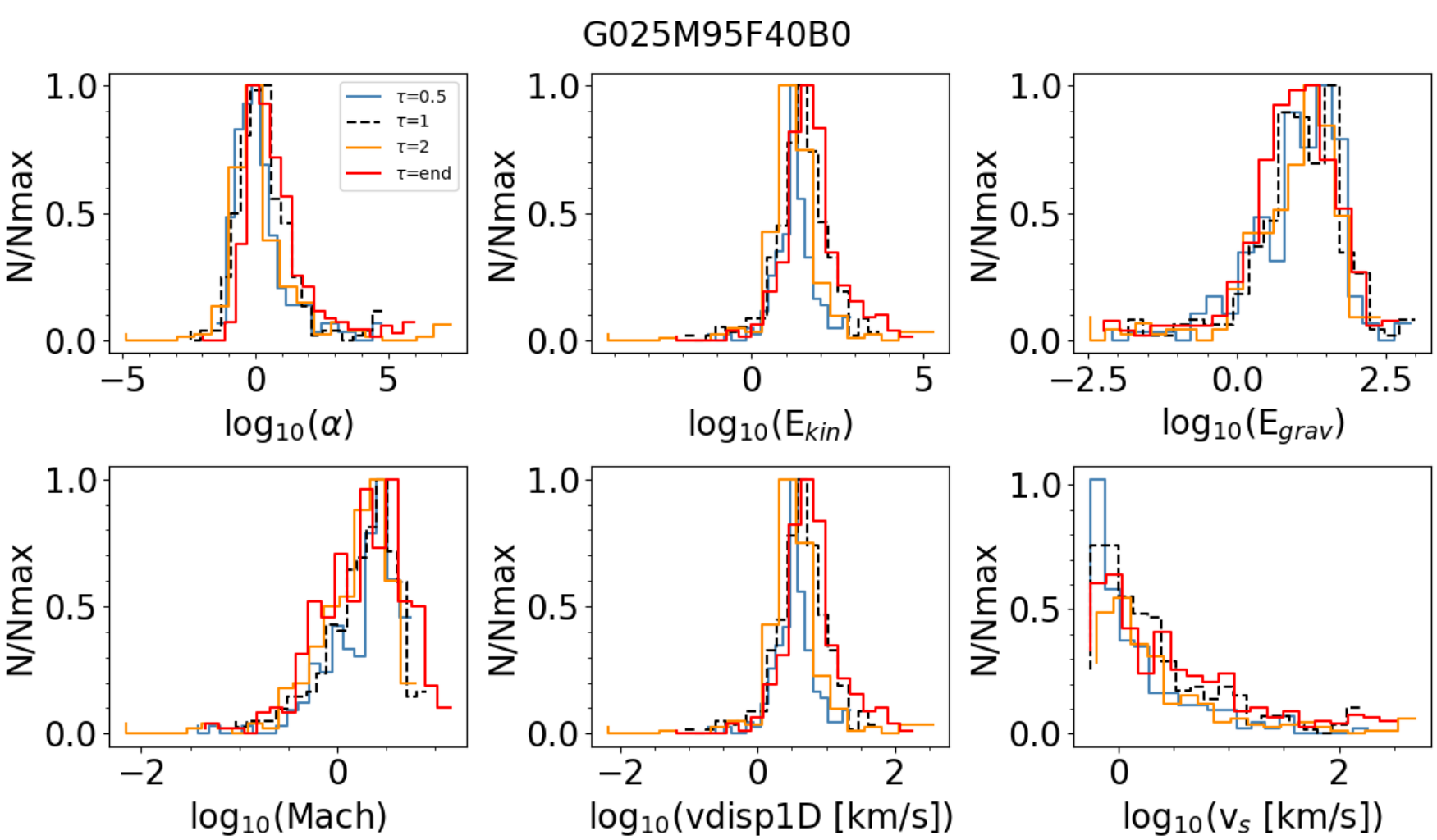


Evolution

$< 10^{10}\ M_\odot$

Verwilghen+ 2024, in prep.

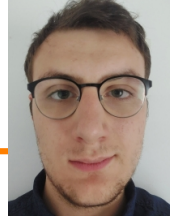


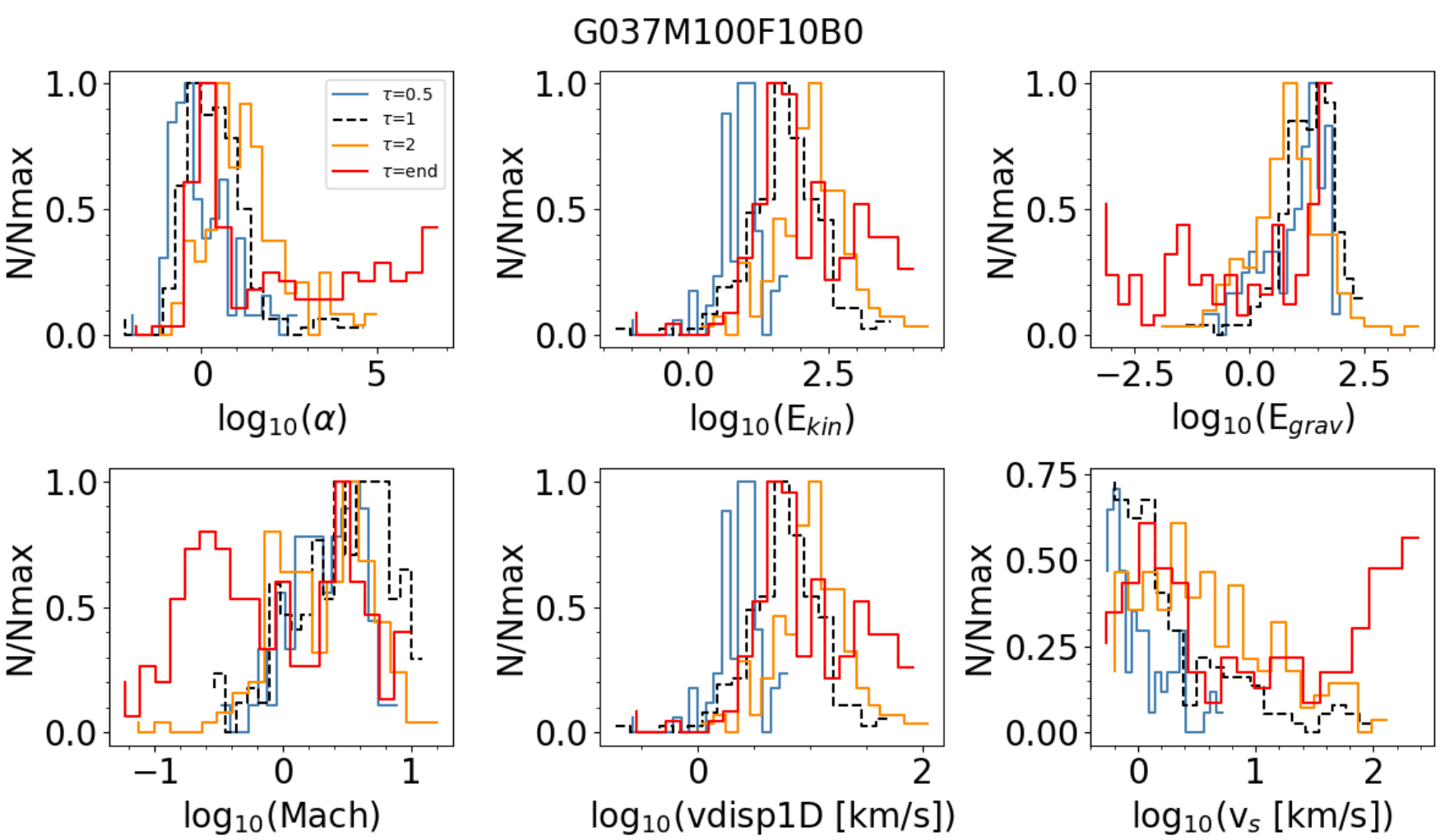


Evolution

$= 10^{10}\ M_\odot$

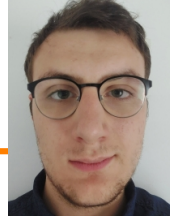
Verwilghen+ 2024, in prep.

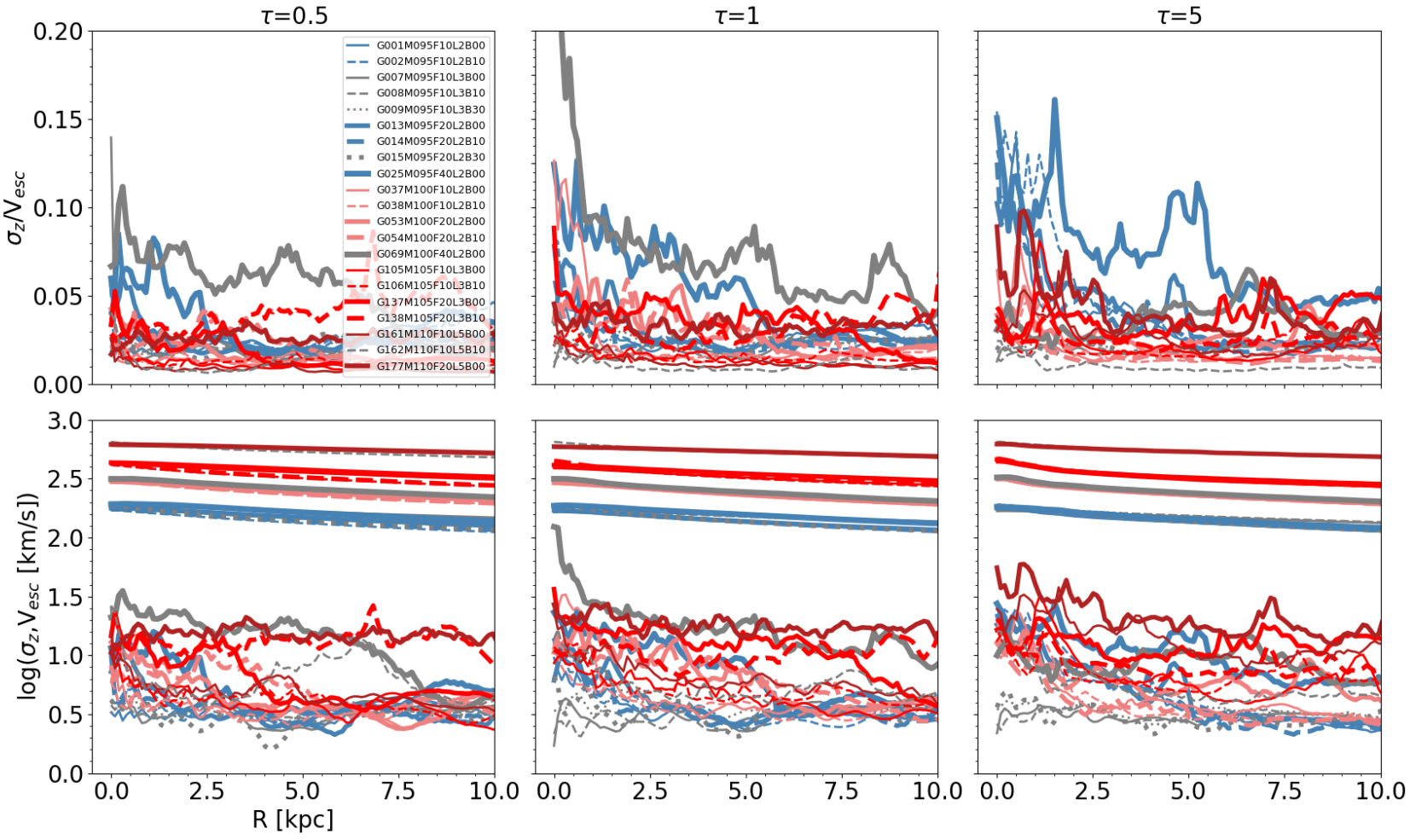


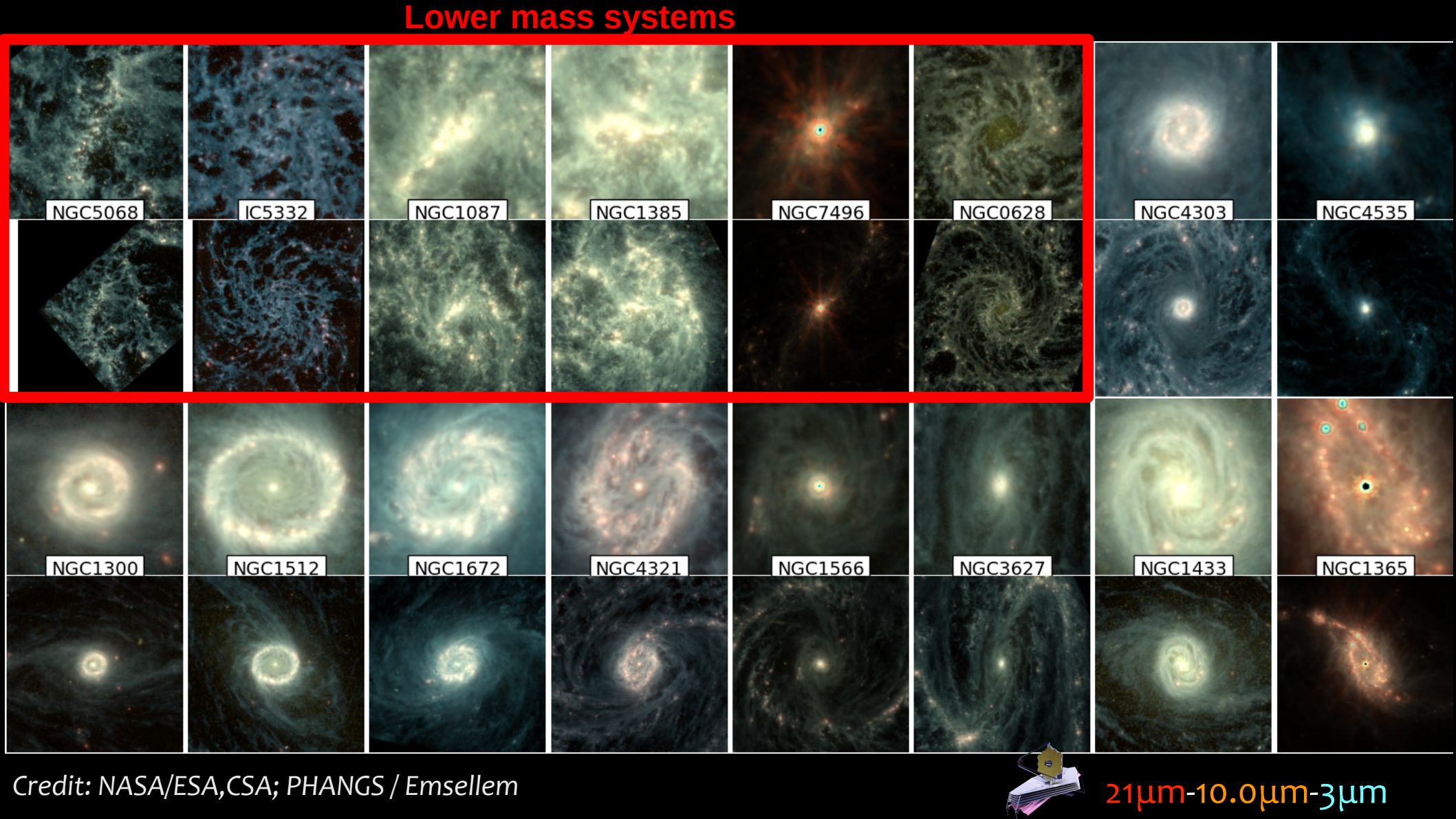


Evolution

Verwilghen+ 2024, in prep.






Lower mass systems
NGC5068
IC5332
NGC1087
NGC1385
NGC7496
NGC0628
NGC4303
NGC4535
NGC1300
NGC1512
NGC1672
NGC4321
NGC1566
NGC3627
NGC1433
NGC1365
Credit: NASA/ESA,CSA; PHANGS / Emsellem
21µm-10.0µm-3µm

Take home messages

Large-scale potential / dynamical structures

- Constrain the orbital skeleton & drive the organisation of the ISM
  - even from ***weak*** perturbations (in stars)
  - Have multiple pattern speeds + are time-varying

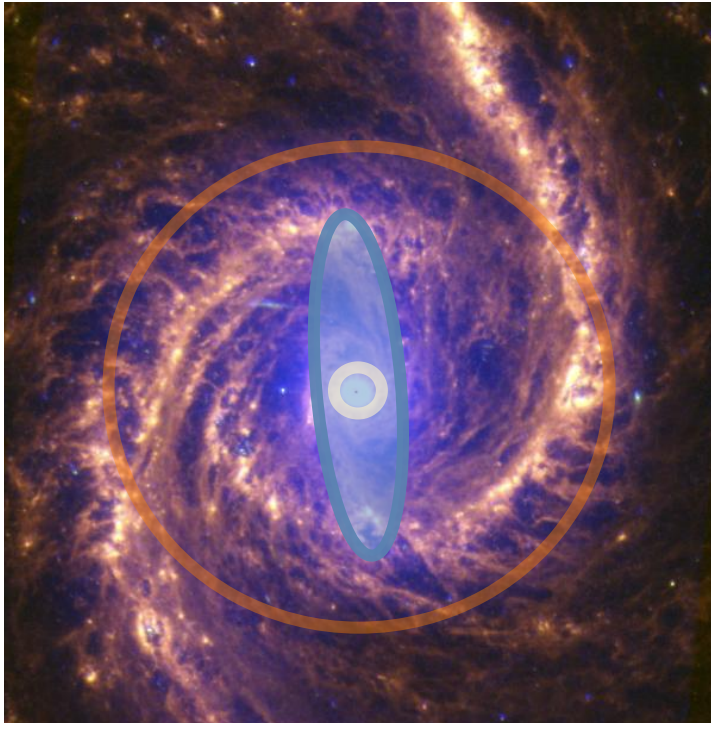
Local (dynamical) conditions

- triggering or inhibiting SF : collisions, shear

⇒ defines a complex, rapidly varying regional set of timescales and regimes

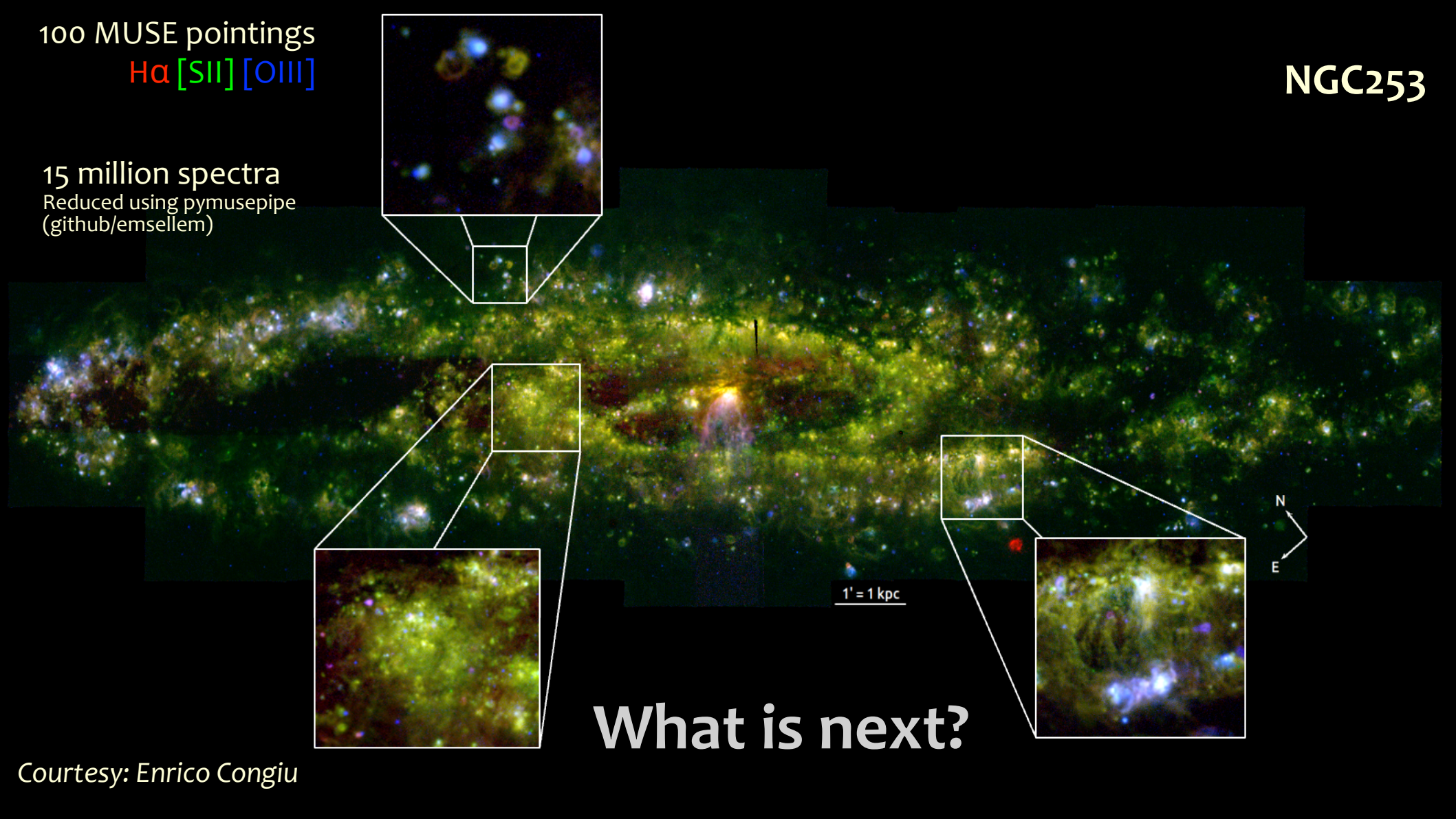
Low versus High mass galaxy ⇒ regime change ?

- Self-gravity, gas fraction vs feedback
- Mass loading factor (see Hayward & Hopkins 2017)



100 MUSE pointings
Hα [SII] [OIII]

15 million spectra
Reduced using pymusepipe
(github/emsellem)



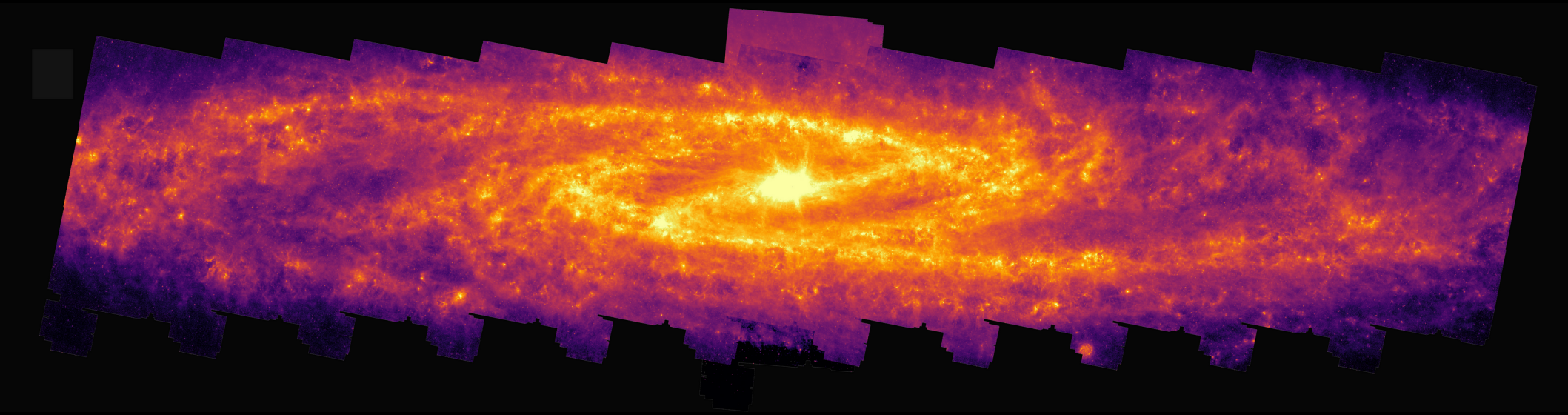
What is next?

Courtesy: Enrico Congiu

Full galaxy JWST 7.7 micron PAH mosaic

Erik Rosolowsky

NGC253



What is next?

A Legacy "Baryon life cycle"[in galaxies] community effort

To understand star formation : *Where / How it proceeds*

⇒ Need for a community-wide effort to conduct

- A high spatial resolution (10-100pc)
- Multi-λ « **using all eyes** » on the sky

⇒ **Survey of the local galaxy population**

⇒ ***To connect with*** resolved physics (e.g., Milky-Way) & unresolved high(-er) z surveys

⇒ ***To improve theory***
⇒ ***To guide simulations***

SKA : 1 arcsec atomic + radio-continuum imaging (synchrotron/thermal)
ESO instrumentation
e.g., Euclid, Roman will give imaging in optical/NIR
(other facilities, WST ?)

⇒ Can we, as a community, deliver the missing link ?