清華大學天文系
Department of Astronomy, Tsinghua University

13. Galaxy Ecosystem in the Universe

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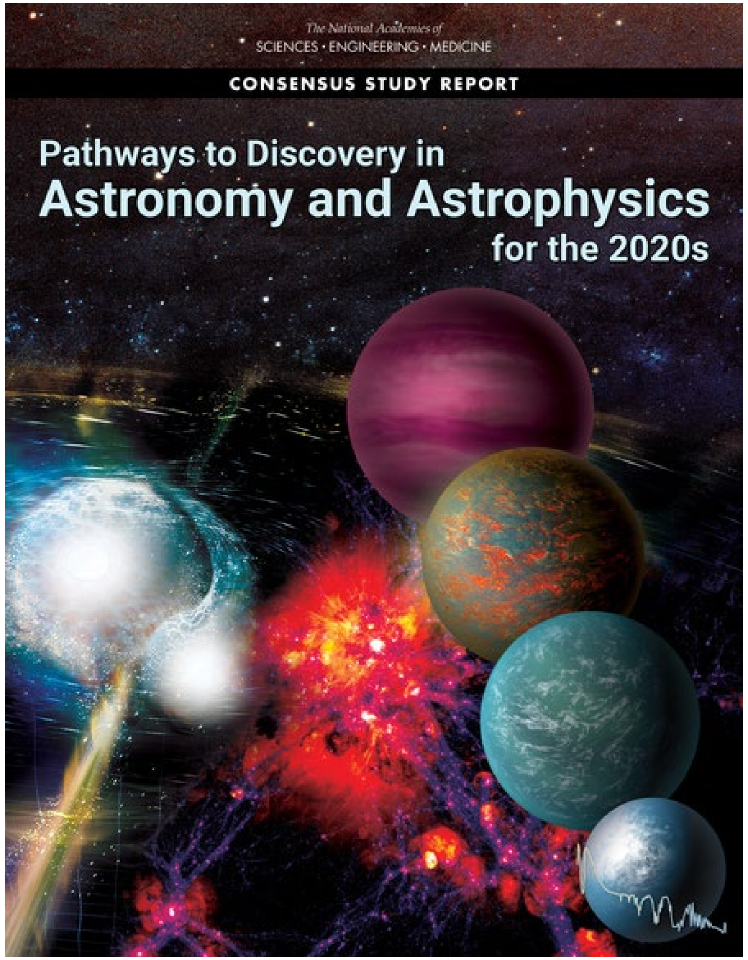
Tsinghua University

DECADAL SURVEY ON ASTRONOMY AND ASTROPHYSICS

1960s: Mid-sized ground-based optical telescopes
1970s: VLA and space programs
1980s: Chandra, Hubble, and VLBA
1990s: Space infrared telescope facility
2000s: JWST, ALMA
2010s: Roman, Rubin, LISA
2020s: GMT, TMT, LUVOIR, Lynx?

“Pathways to Discovery in Astronomy and Astrophysics for the 2020s”



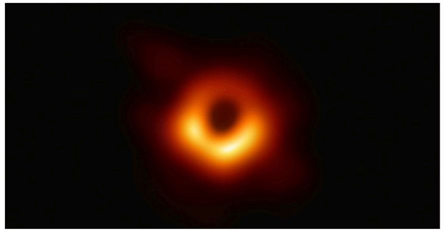
Key Scientific Challenges for the Next Decade

Worlds and Suns in Context

Priority Area: Pathways to Habitable Worlds

Understanding the connections between stars and the worlds that orbit them, from nascent disks of dust and gas through formation and evolution, is an important scientific goal for the next decade. The effort to identify habitable Earth-like worlds in other planetary systems and search for the biochemical signatures of life will play a critical role in determining whether life exists elsewhere in the universe.

KEY RECOMMENDATIONS:



New Messengers and New Physics

Priority Area: New Windows on the Dynamic Universe

Over the next decade, a range of complementary observations—from radio to gamma rays, gravitational waves, neutrinos, and high-energy particles—will enable investigations into the most energetic processes in the universe and address larger questions about the nature of dark matter, dark energy, and cosmological inflation. These growing capabilities will enable closer study of neutron stars, white dwarfs, black hole collisions, stellar explosions, and the birth of our universe.

KEY RECOMMENDATIONS:

Cosmic Ecosystems

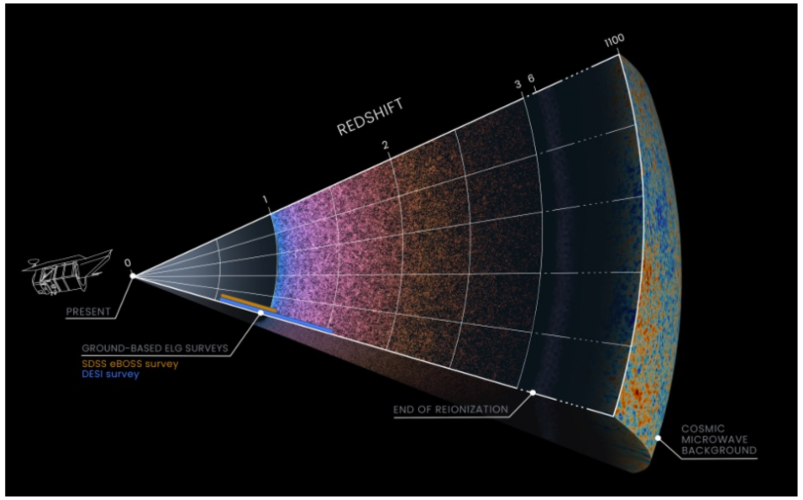
Priority Area: Unveiling the Drivers of Galaxy Growth

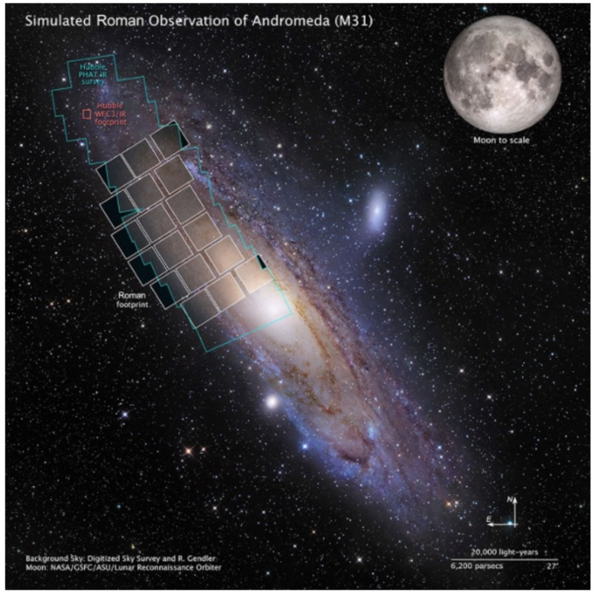
Research in the coming decade will revolutionize our understanding of the origins and evolution of galaxies, from the cosmic webs of gas that feed them to the formation of stars. New observational capabilities across the electromagnetic spectrum along with computation and theory will help resolve the rich workings of galaxies on all scales.

KEY RECOMMENDATIONS:

Cosmic Ecosystems

- **Cosmic structure**
  - How the seeds of galaxies planted during the first moments of the big bang become the structures and galaxies seen today
  - Roman's galaxy redshift survey (from the **High Latitude Wide Area Survey**) has a major role to play
- **Galaxies are ecosystems of their own**
  - Balance between formation of stars and planets and feedback from stellar winds, outflows and supernovae
  - What is the role of the supermassive black holes that reside at the center of most galaxies
  - **General Astrophysics surveys of Milkyway and nearby galaxies** will provide insight into this

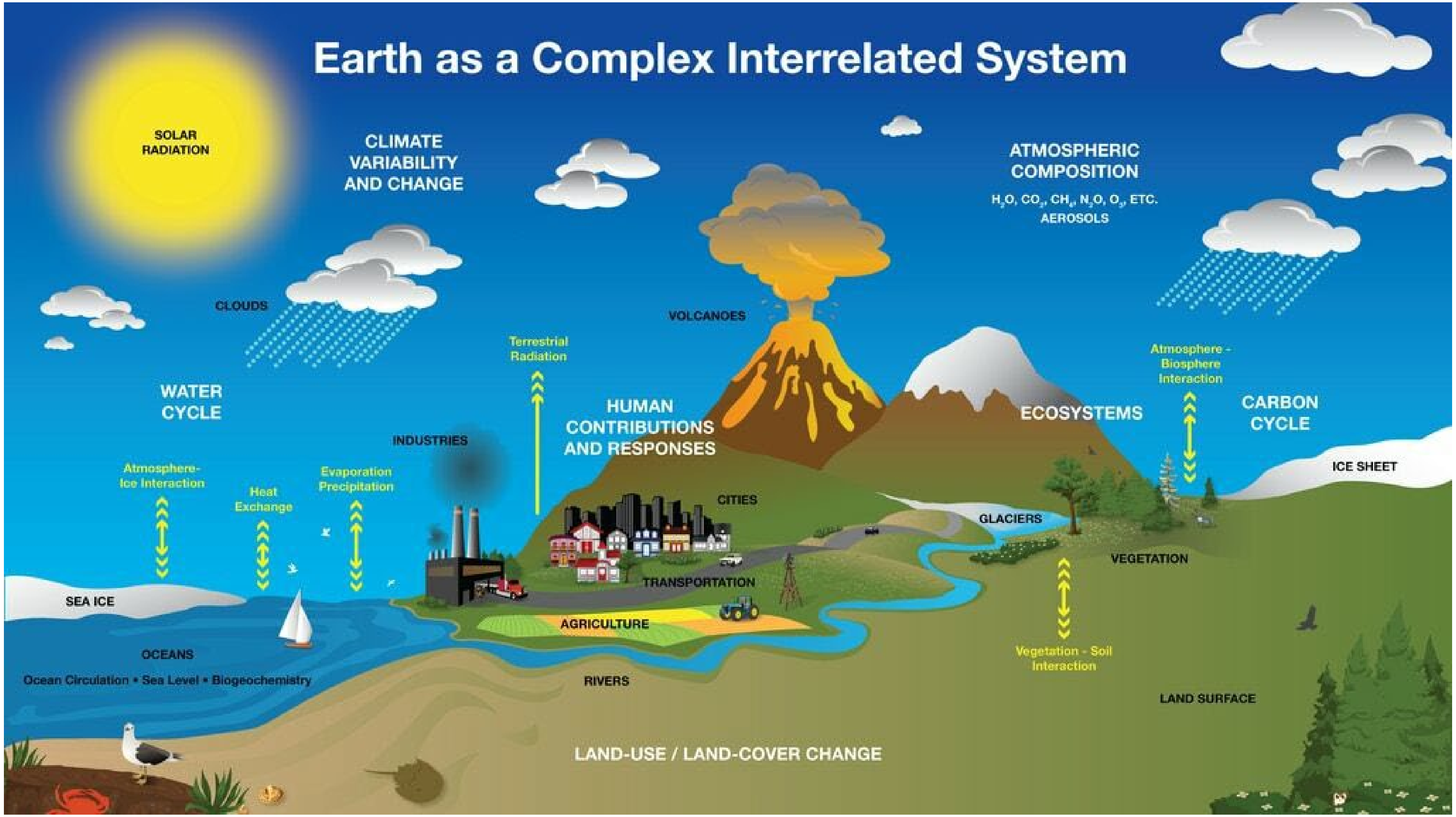




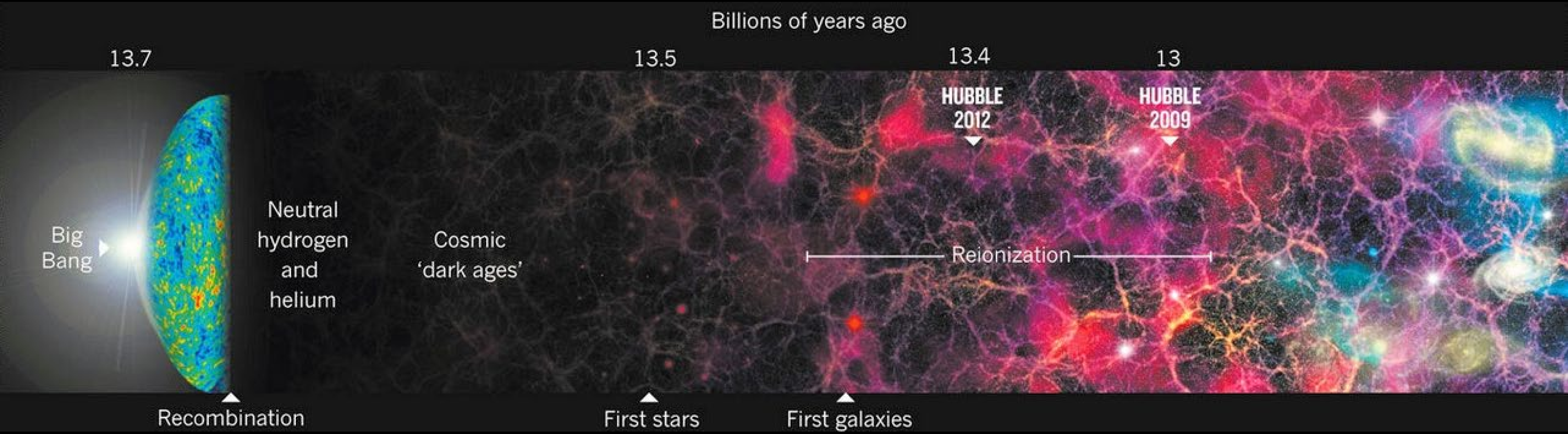
Cosmic Ecosystem

- **Priority Area: Unveiling the Drivers of Galaxy Growth**
  - Roman's **High Latitude Wide Area and High Latitude Time Domain** will greatly expand our sampling of the structure, colors and spectra of galaxies over a significant fraction of cosmic time
  - **General Astrophysics Survey of an Ultra Deep Field** would provide additional depth
  - Track the growth of normal galaxies as a function of environment
  - Enable discoveries of rare galactic objects

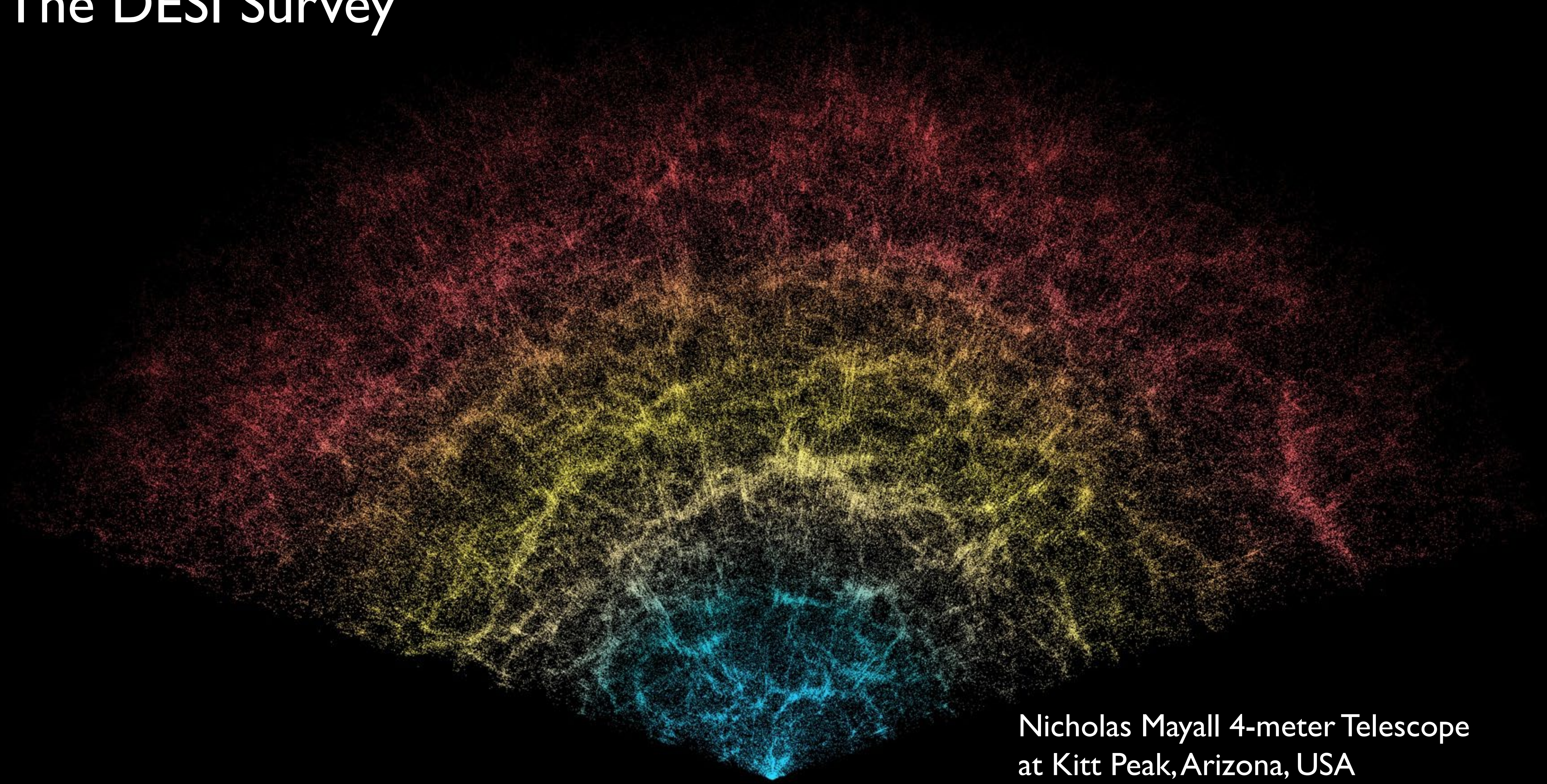
Earth Ecosystem



Timeline of the evolution of the Universe



The DESI Survey

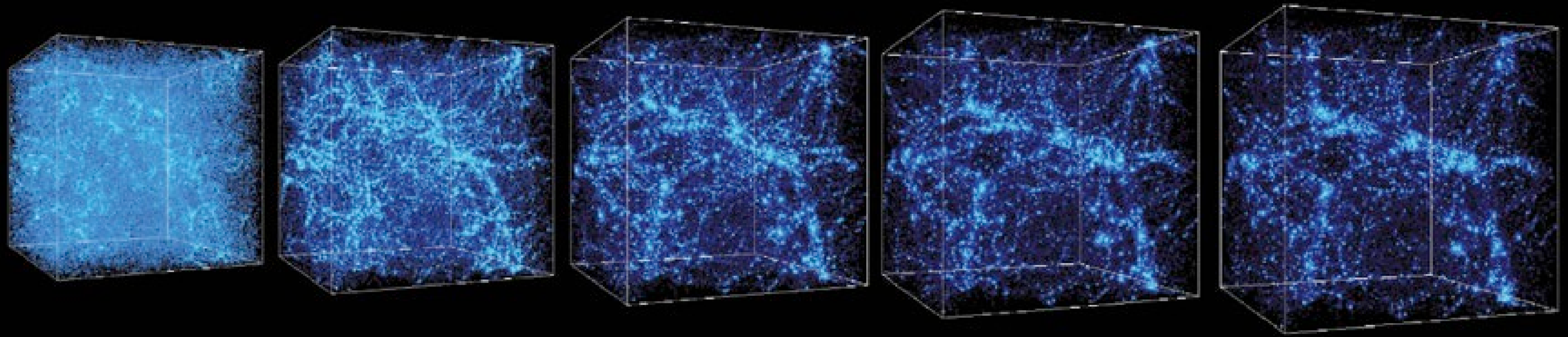


Nicholas Mayall 4-meter Telescope
at Kitt Peak, Arizona, USA

Credit: NOIRLab

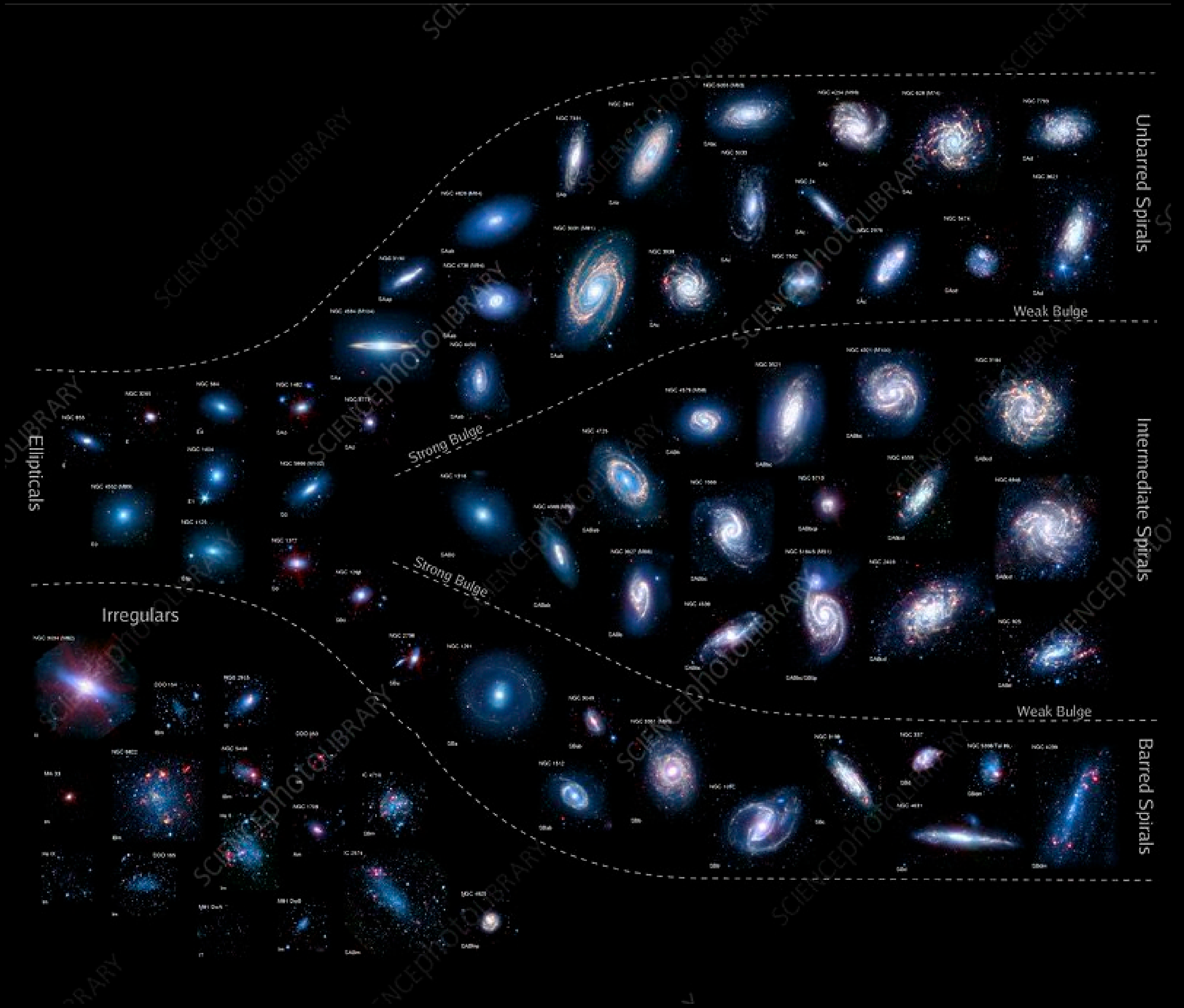
Large-scale structure of the Universe due to gravity

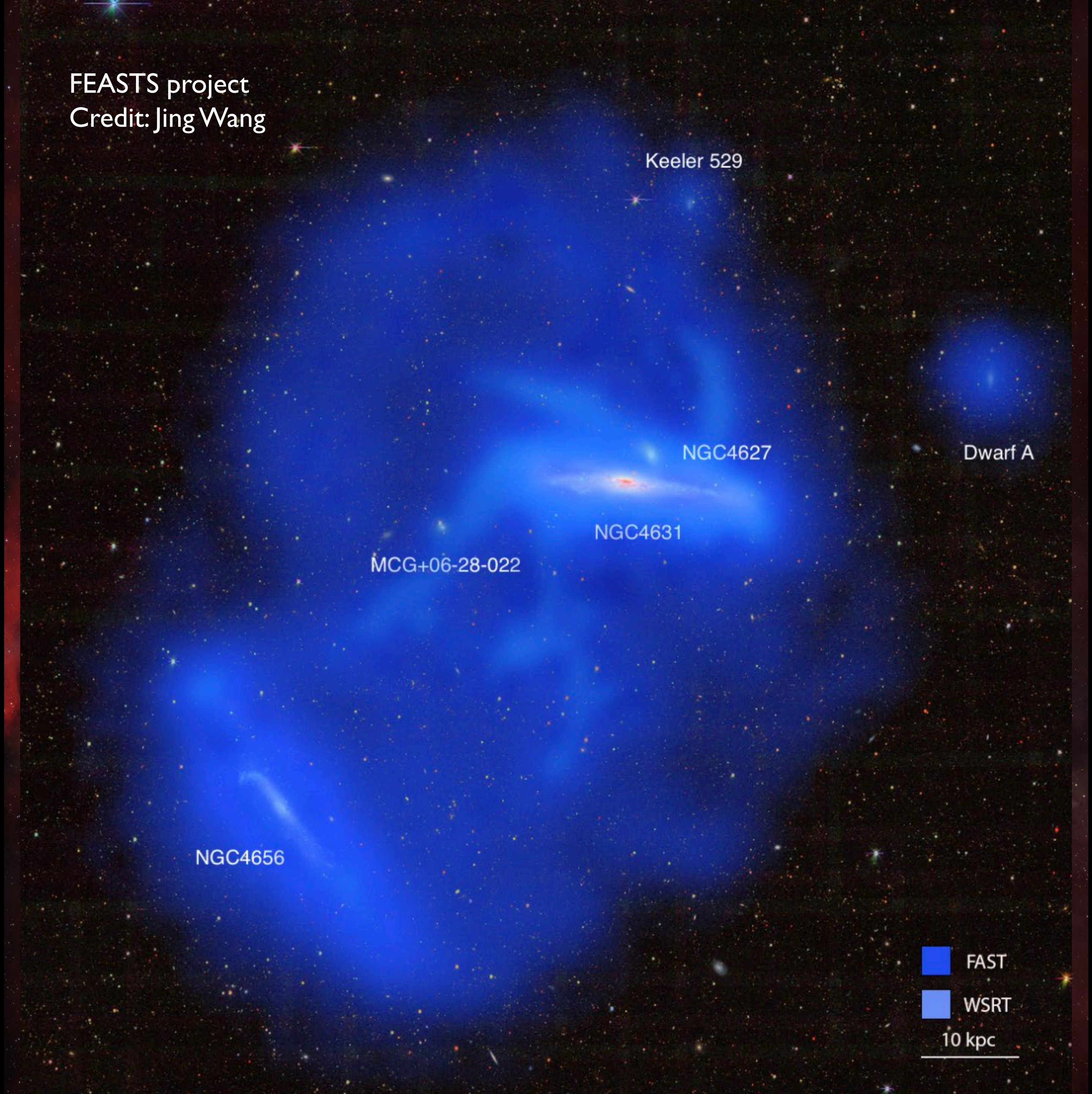
Credit: Andrey Kravtsov

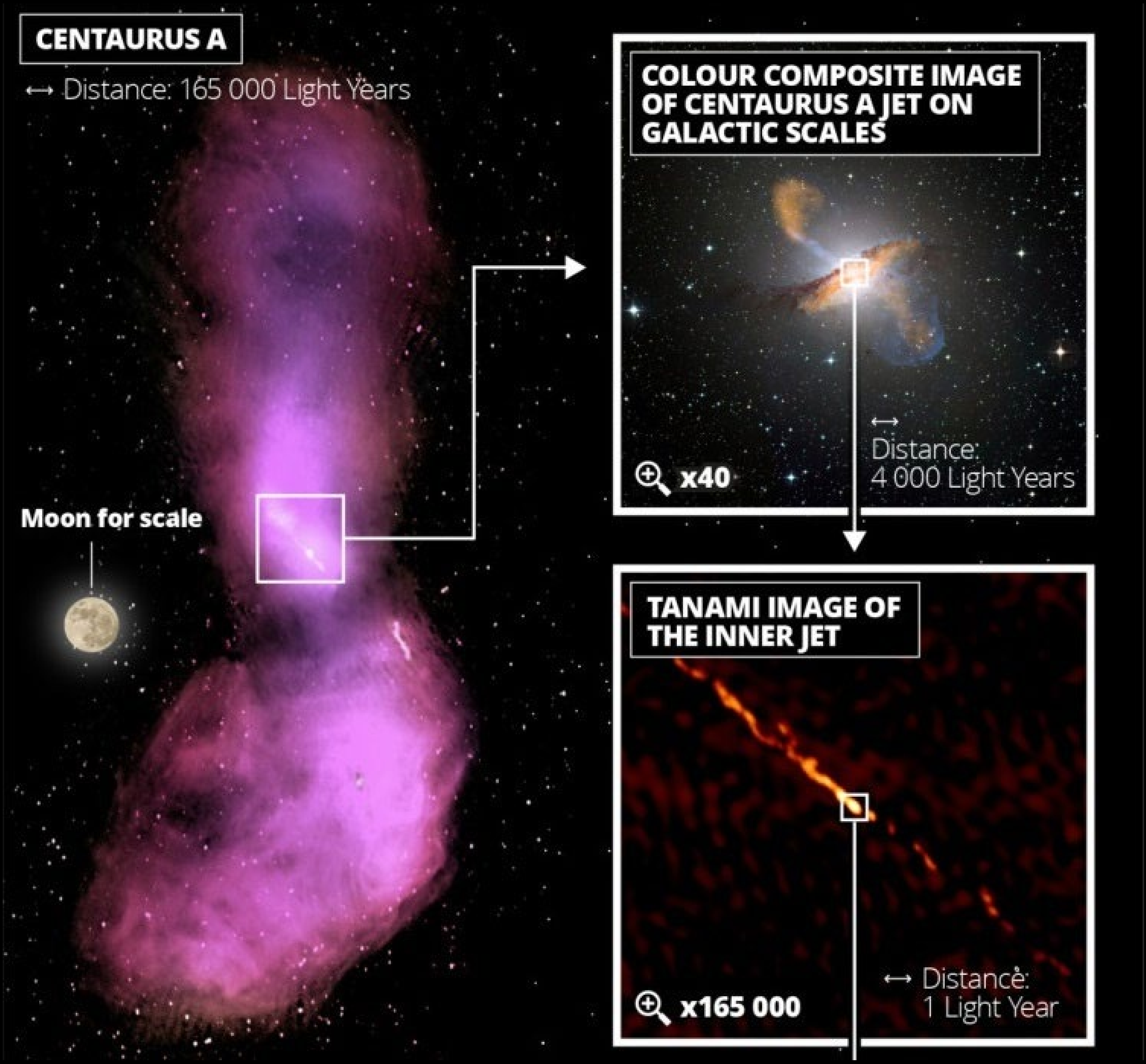


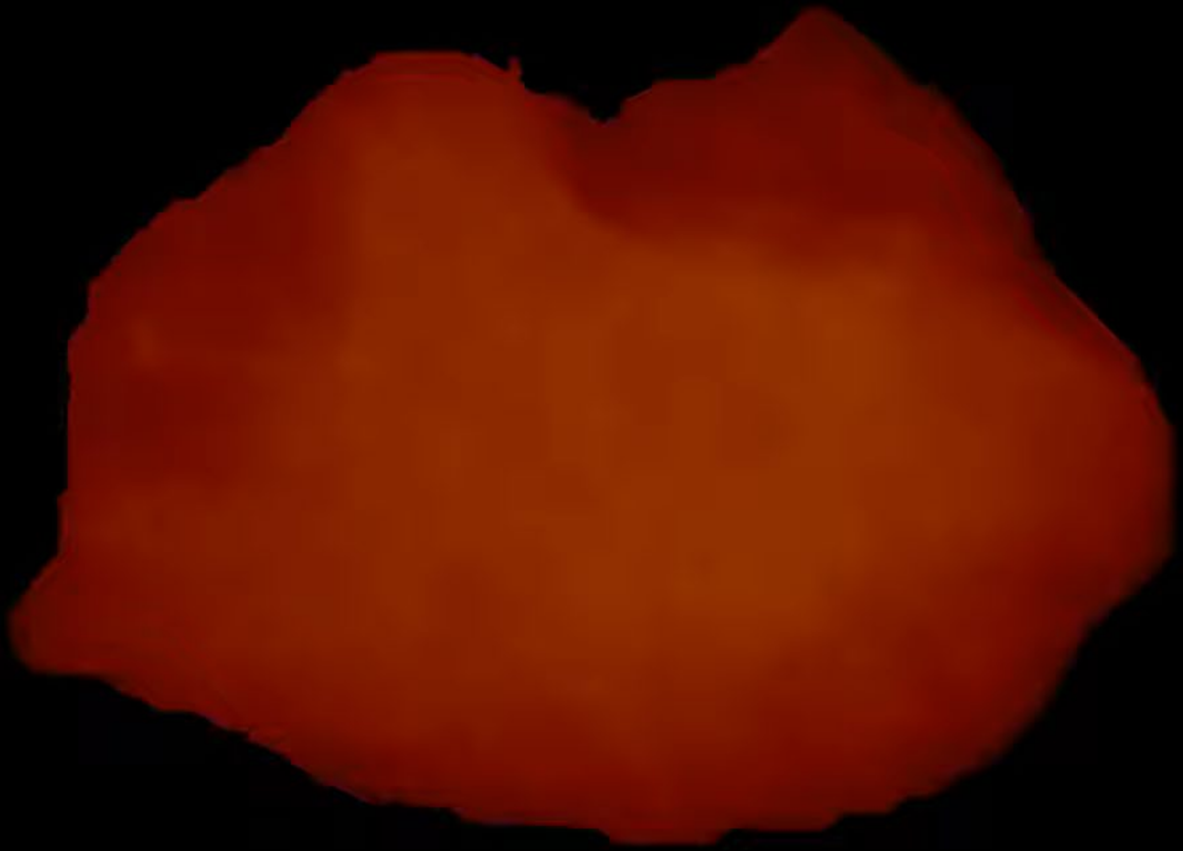
Hubble Tuning Fork

- Key question: why do galaxies exhibit such a large diversity?
- Nature vs. Nurture




FEASTS project
Credit: Jing Wang
Keeler 529
NGC4627
Dwarf A
NGC4631
MCG+06-28-022
NGC4656
FAST
WSRT
10 kpc

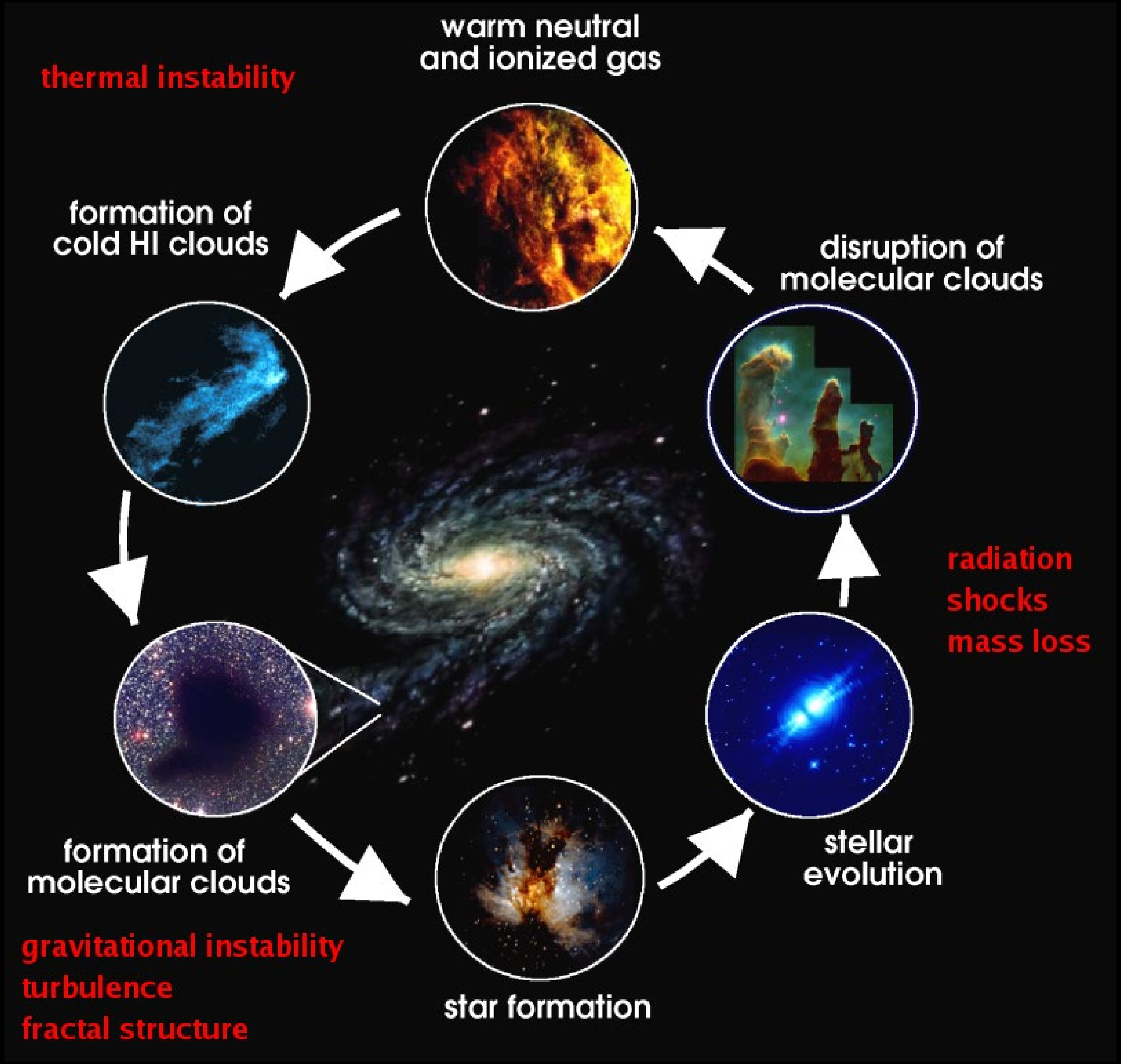

CENTAURUS A
↔ Distance: 165 000 Light Years
Moon for scale
COLOUR COMPOSITE IMAGE OF CENTAURUS A JET ON GALACTIC SCALES
x40
↔ Distance: 4 000 Light Years
TANAMI IMAGE OF THE INNER JET
x165 000
↔ Distance: 1 Light Year



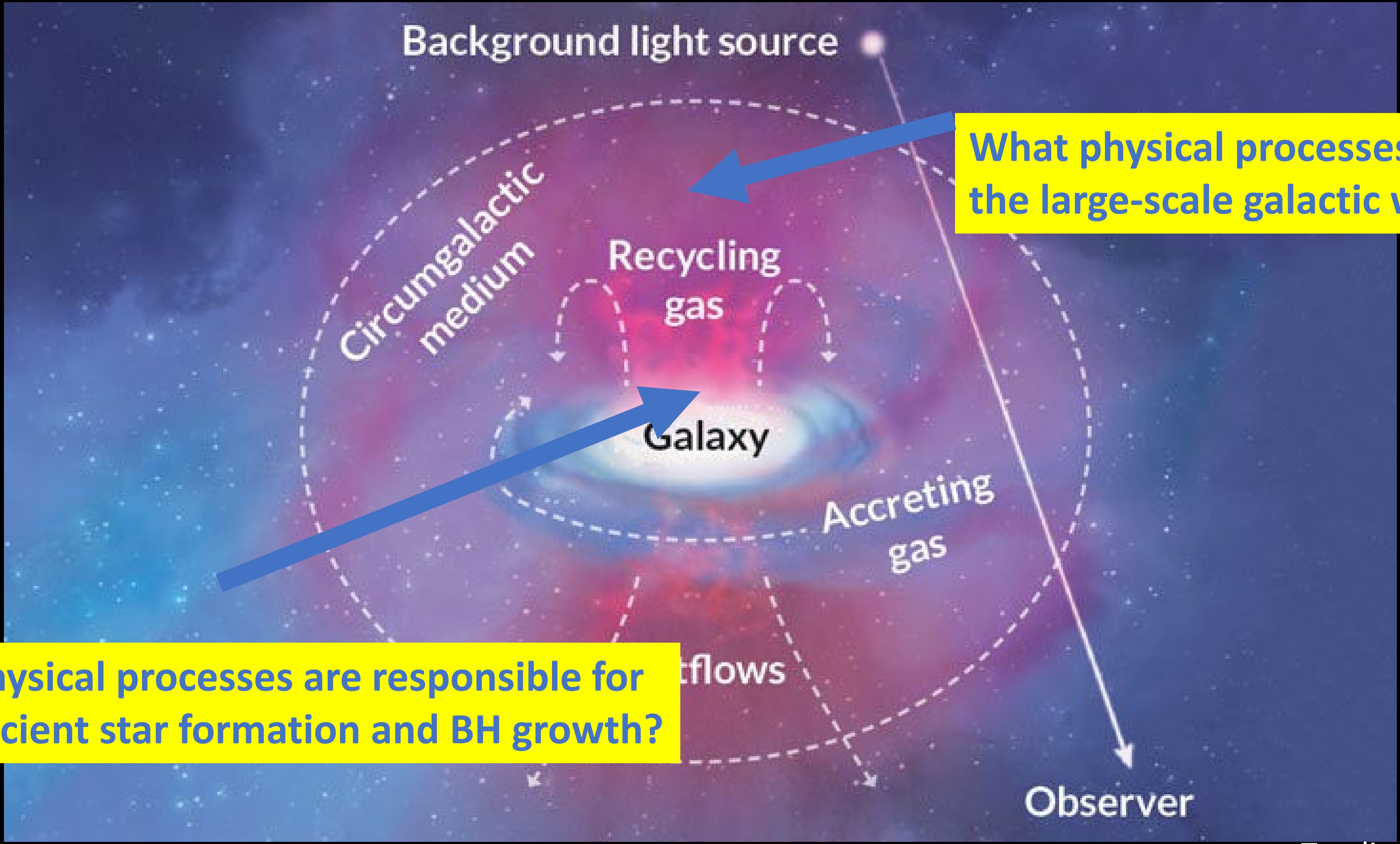
VINTERGATAN simulation
Credit: Florent Renaud

Baryonic cycle in the ISM

- The baryonic cycle in the ISM is the central engine of the baryonic cycle around galaxies, which triggers the transformation of the galaxy over cosmic time.
- Any key questions here?



Baryonic cycle in and around galaxies:
A multi-scale, multi-physics, non-linear problem



What physical processes drive the large-scale galactic winds?

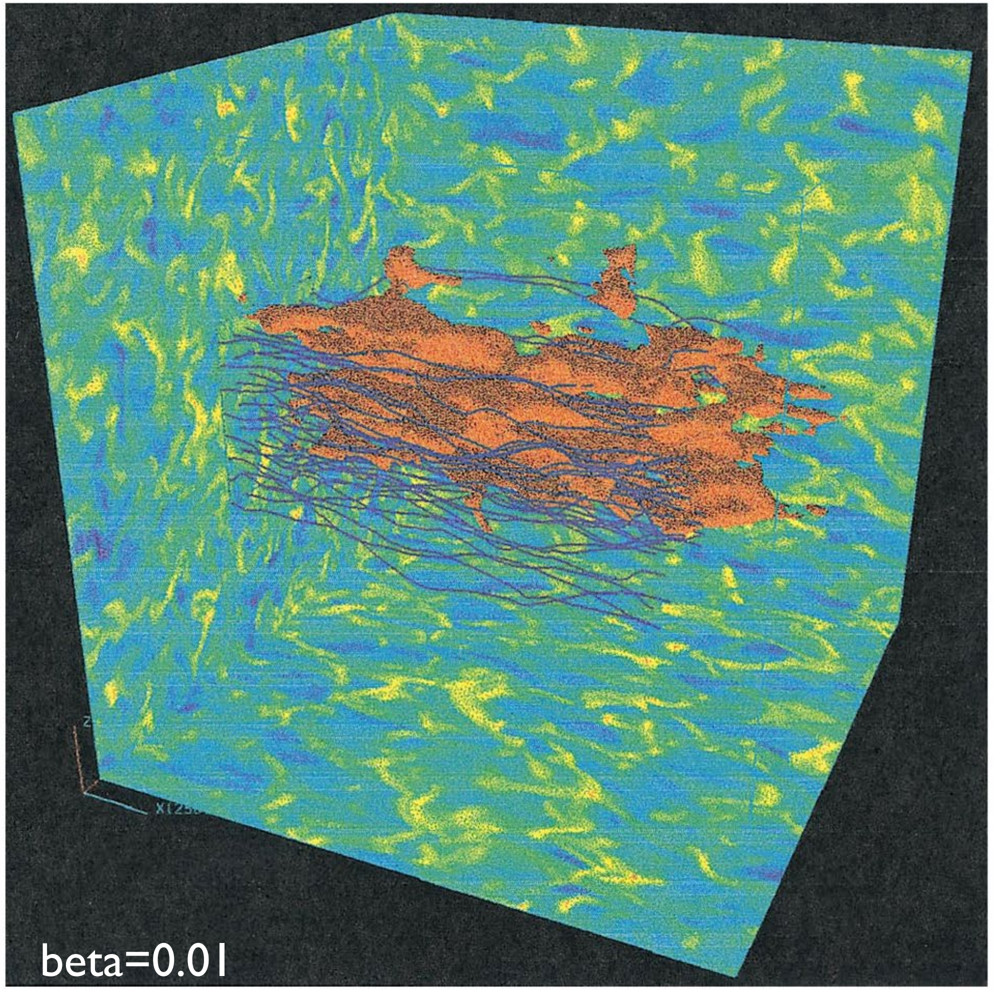
Which physical processes are responsible for the inefficient star formation and BH growth?

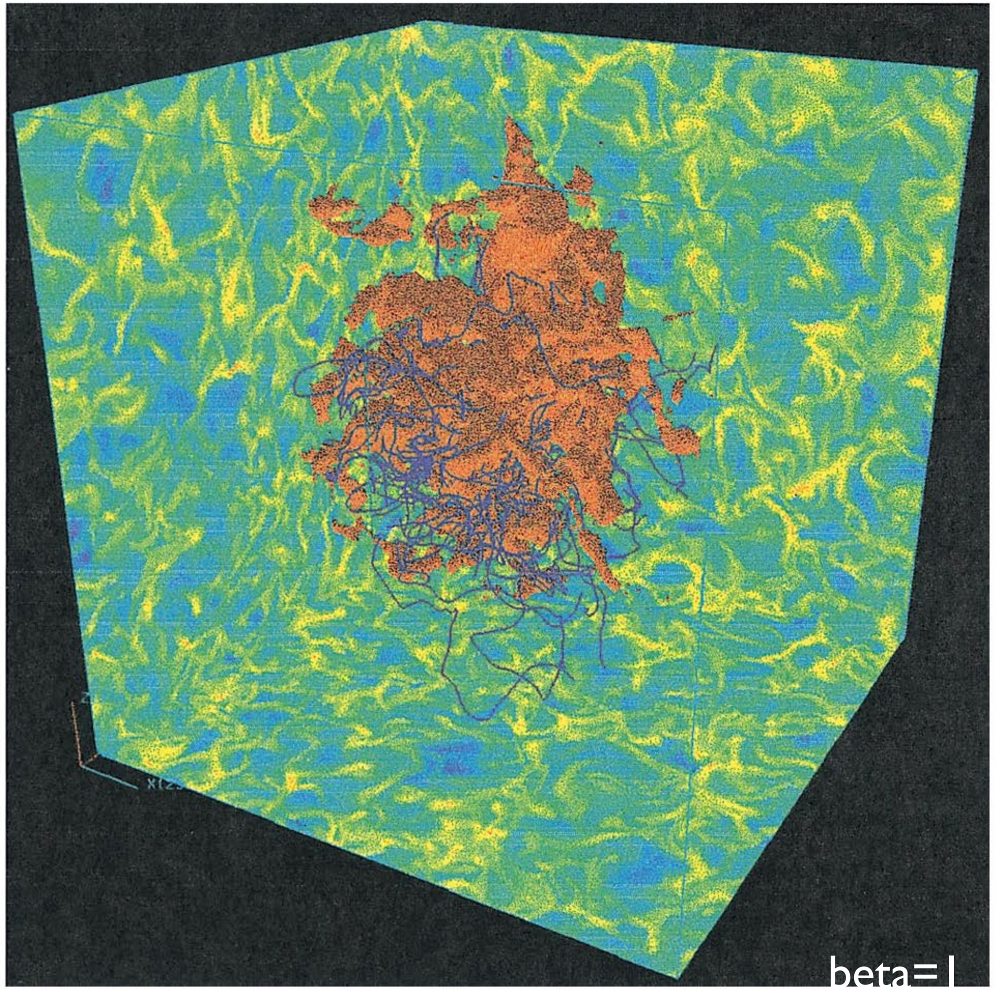
Tumlinson et al. 2017

Turbulence-regulated star formation

- The molecular clouds are self-gravitating entities permeated by magnetic fields and strongly supersonic turbulence (Blitz+93, Evans+99).
- It has long been appreciated by theorists that turbulence and magnetic fields must play a decisive role in cloud dynamics (Mestel & Spitzer 56, Shu+99; McKee+99).
- However, the dissipation time of turbulence is of the order of the crossing time or smaller, even in the presence of strong magnetic fields. (Stone, Ostriker, Gammie 98)
- About half of the dissipation occurs in shocks.

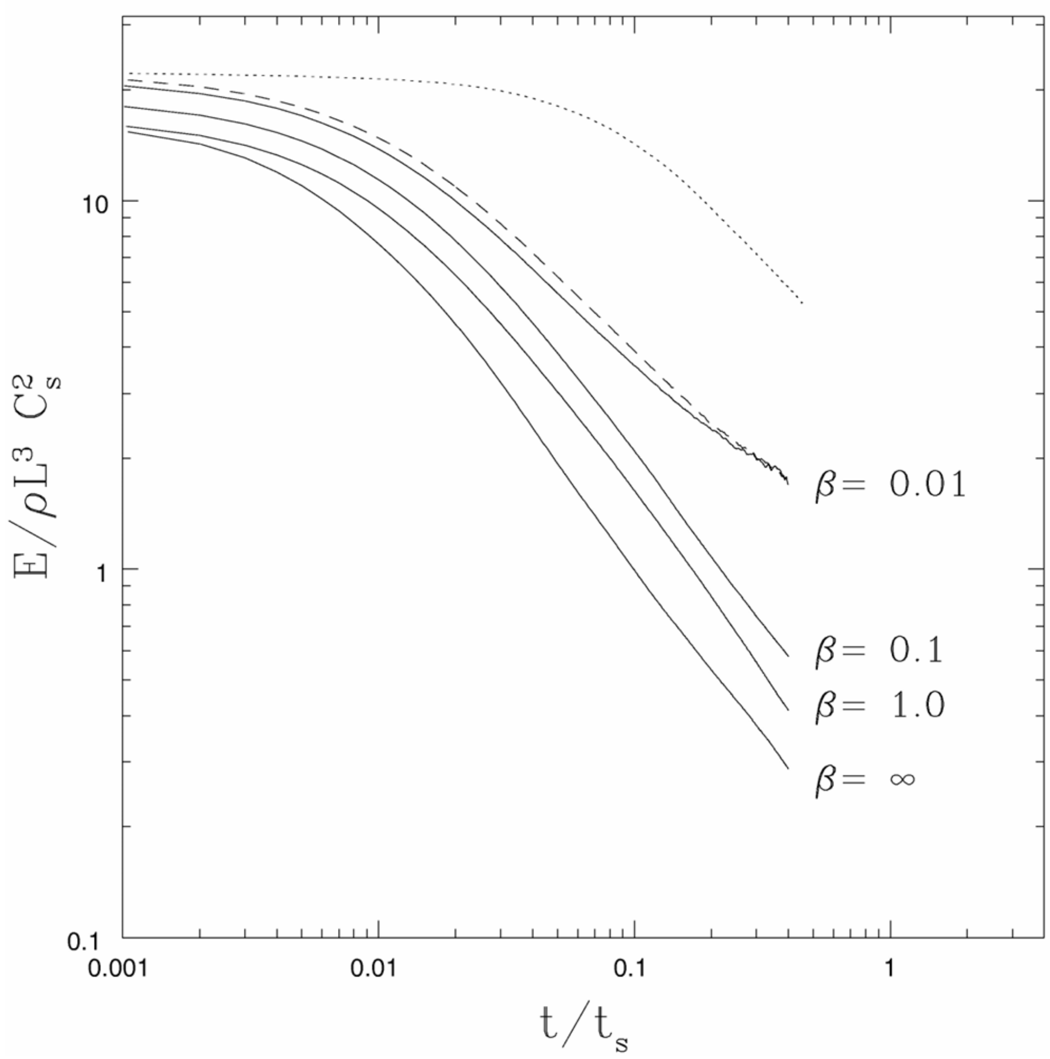
Dissipation in compressible magnetohydrodynamic turbulence



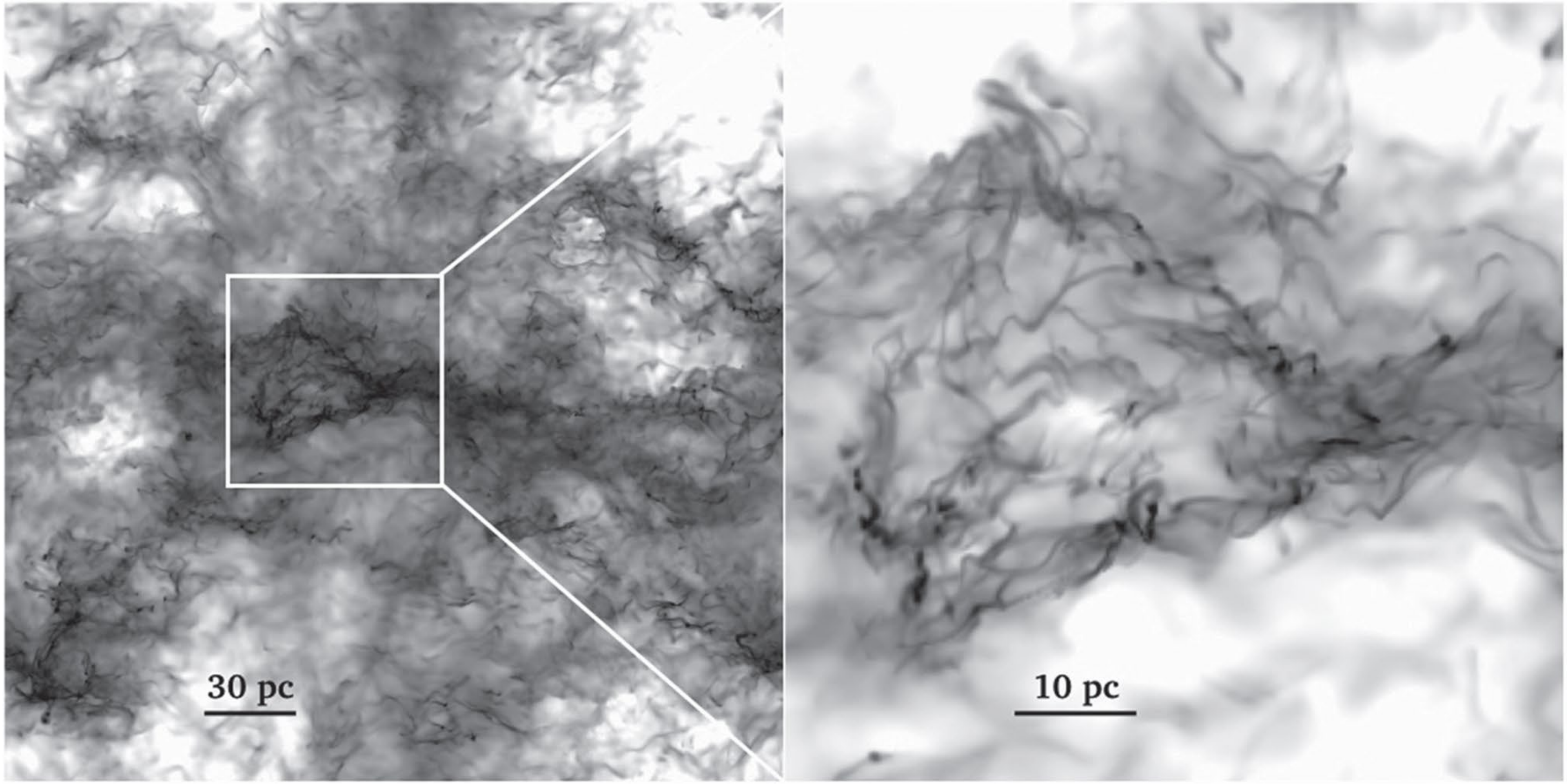


Stone, Ostriker, Gammie 98

Dissipation in compressible magnetohydrodynamic turbulence



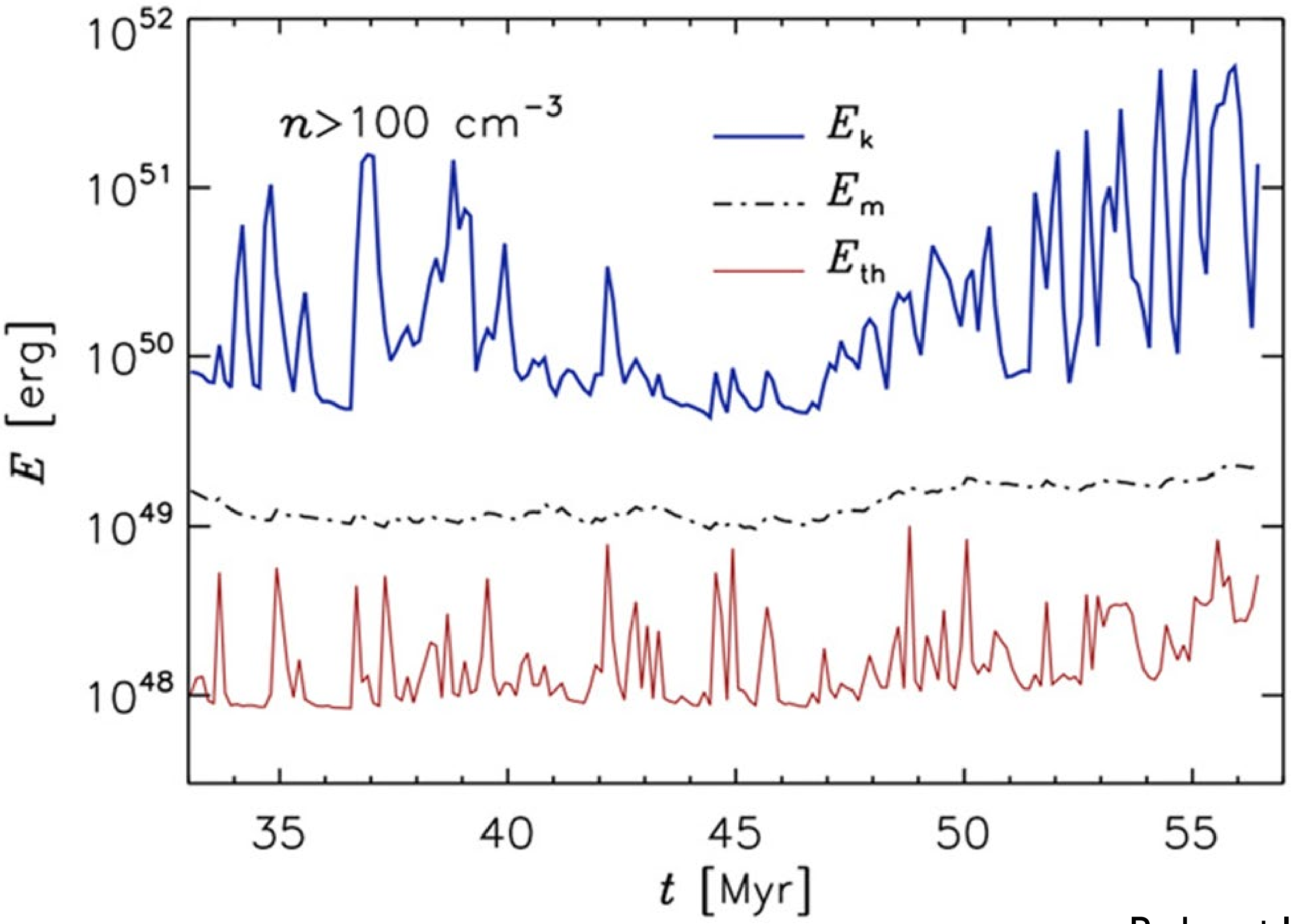
SNe-driven turbulence in the giant molecular clouds



Padoan+16

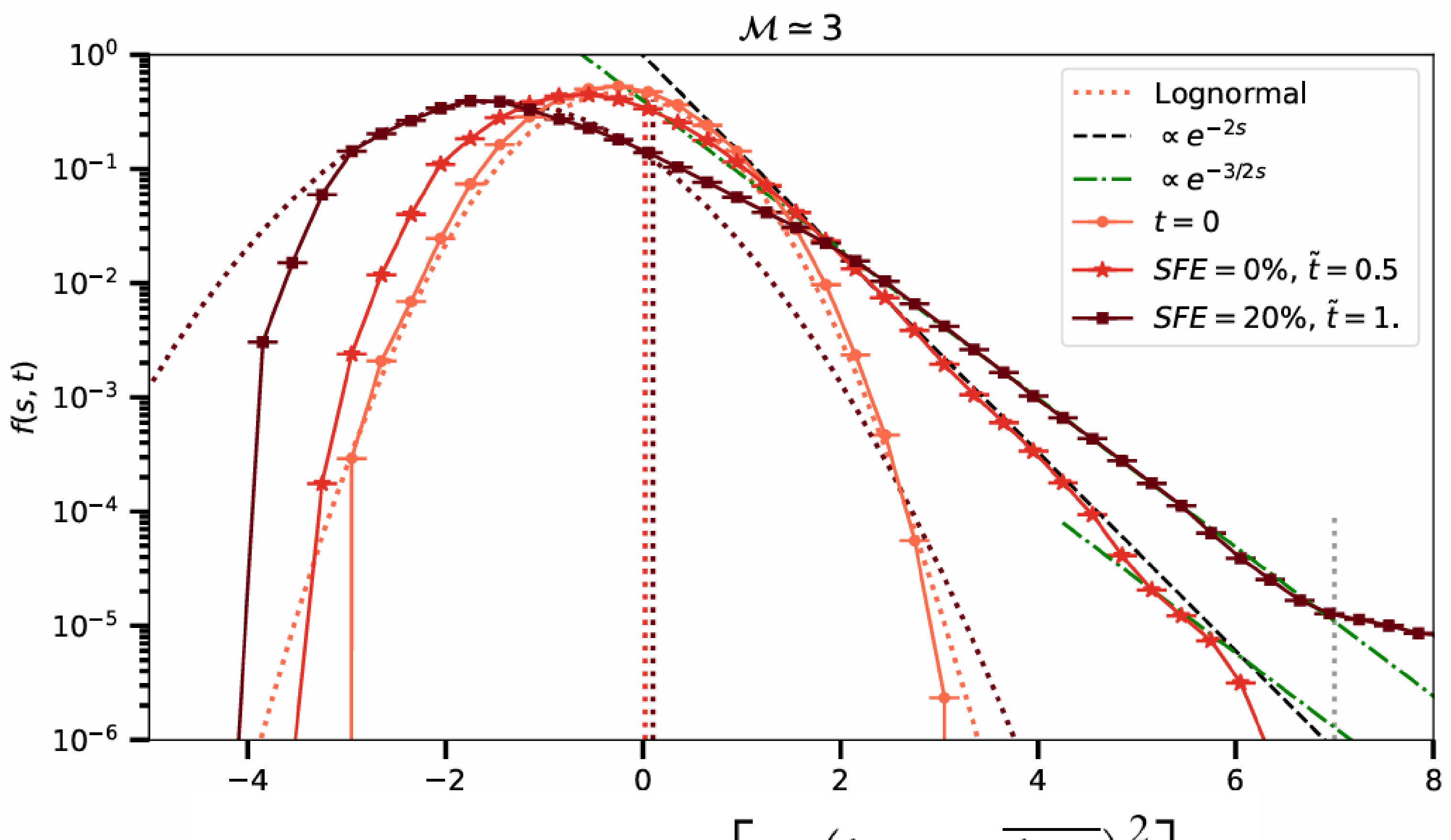
SNe-driven turbulence in the giant molecular clouds

- There is a clear energy separation in the dense gas, with the lowest kinetic energy values being approximately an order of magnitude larger than the mean magnetic energy.
- Two orders of magnitude larger than the lowest values of the thermal energy.
- The turbulence in the dense gas is both supersonic and super-Alfvénic.

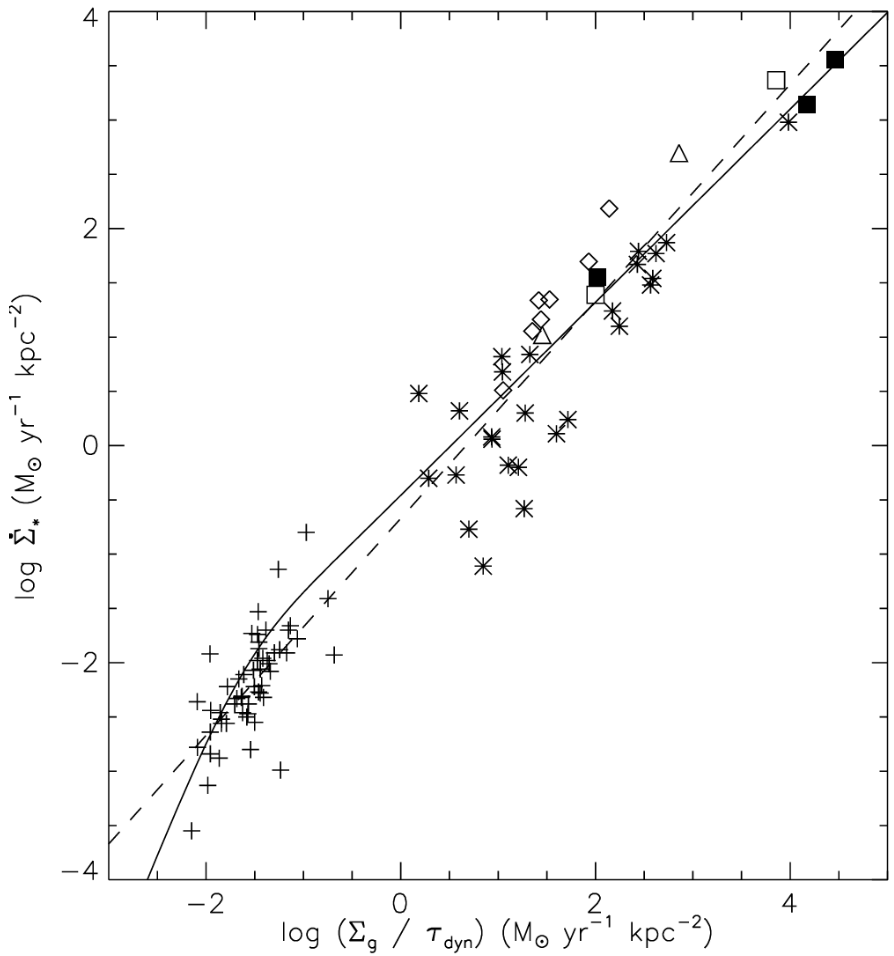


Padoan+16

Krumholz & McKee 2005 star-formation model

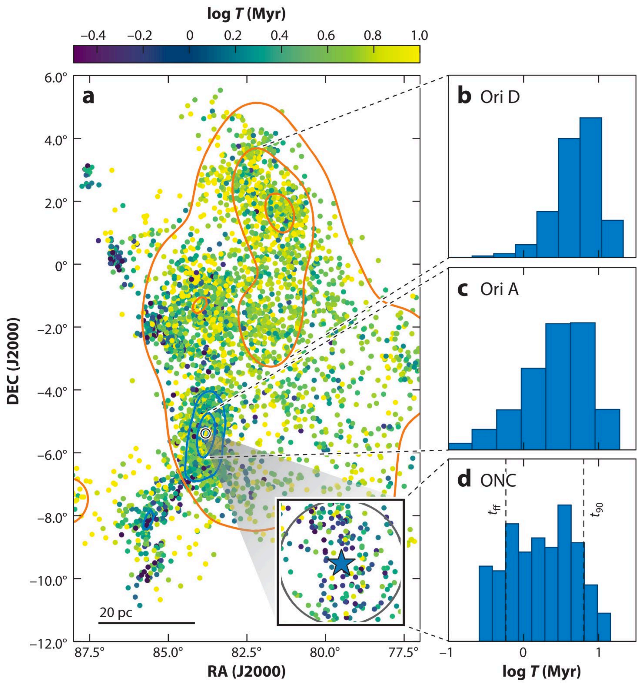


$$dp(x) = \frac{1}{\sqrt{2\pi\sigma_\rho^2}} \exp\left[-\frac{(\ln x - \overline{\ln x})^2}{2\sigma_\rho^2}\right] \frac{dx}{x}$$



Timescale problem of the KM05 model:

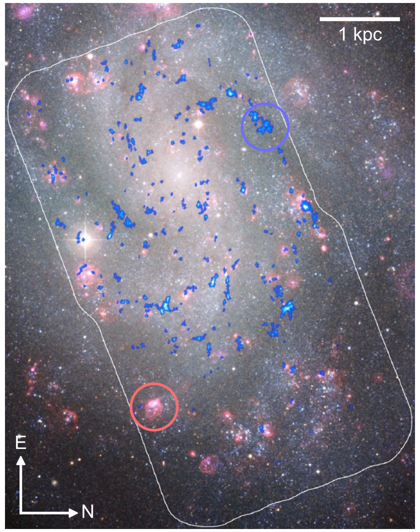
Star formation is rapid on cloud scales!

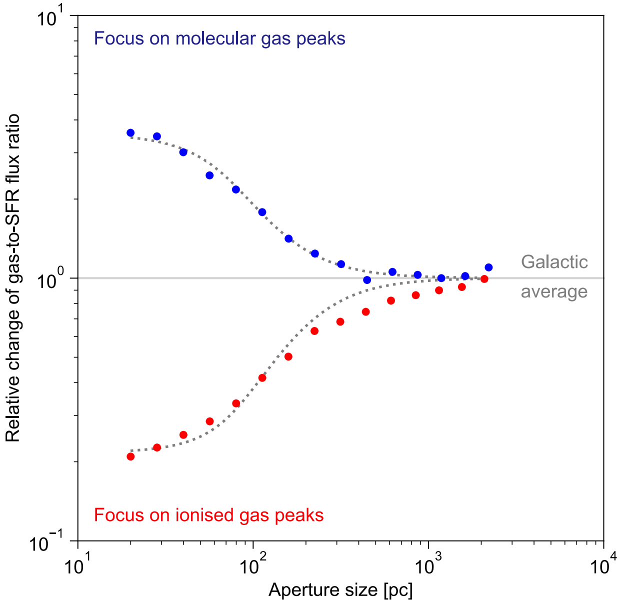


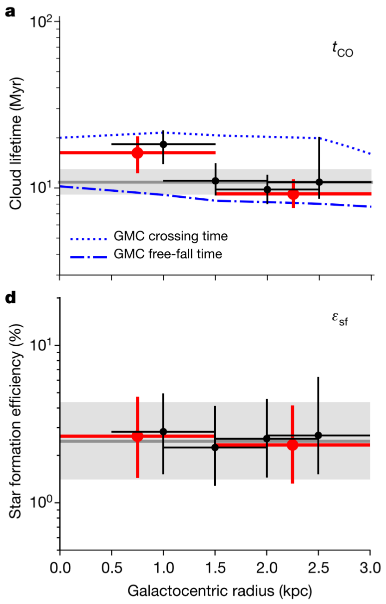
By matching the spatial (de)correlation between CO and Ha emission over different spatial smoothing scales, Kruijssen+18 concluded 1) cloud lifetime is sh formation efficiencies is small.

$$\epsilon_* = \epsilon_{ff} \frac{t_{sf}}{t_{ff}}$$

Stellar age distribution across ONC provided by Kounkel+18. Age spread is on the order of dynamical time of the whole regions, but the densest regions show age spread that are longer than free-fall time.







RIGEL: Realistic Ism modeling in Galaxy Evolution and Lifecycles

Physical ingredients:

Gravity: BH tree, Hydrodynamics: Arepo (Springel 10)

Radiative transfer: M1 method (Kannan+19, Deng+24)

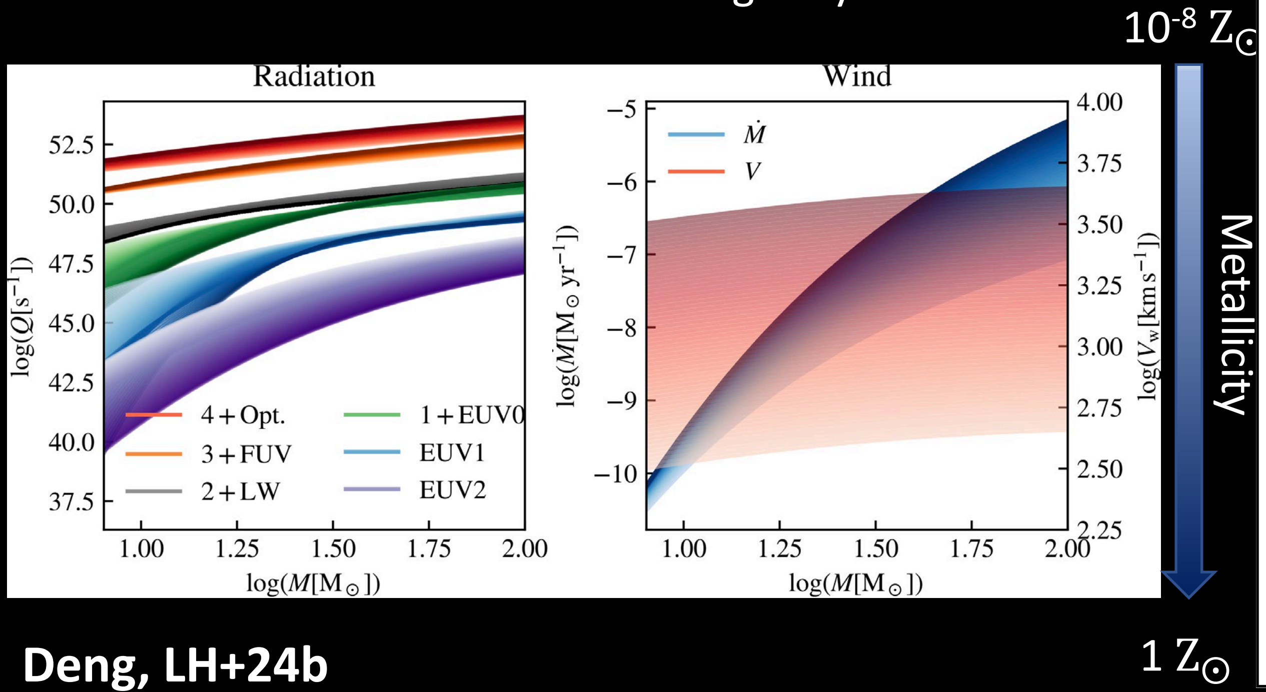
Non-equilibrium H, He chemistry (Kannan+19, Kannan+20)

Equilibrium C/O chemistry and Cooling

Star formation: resolving individual massive stars

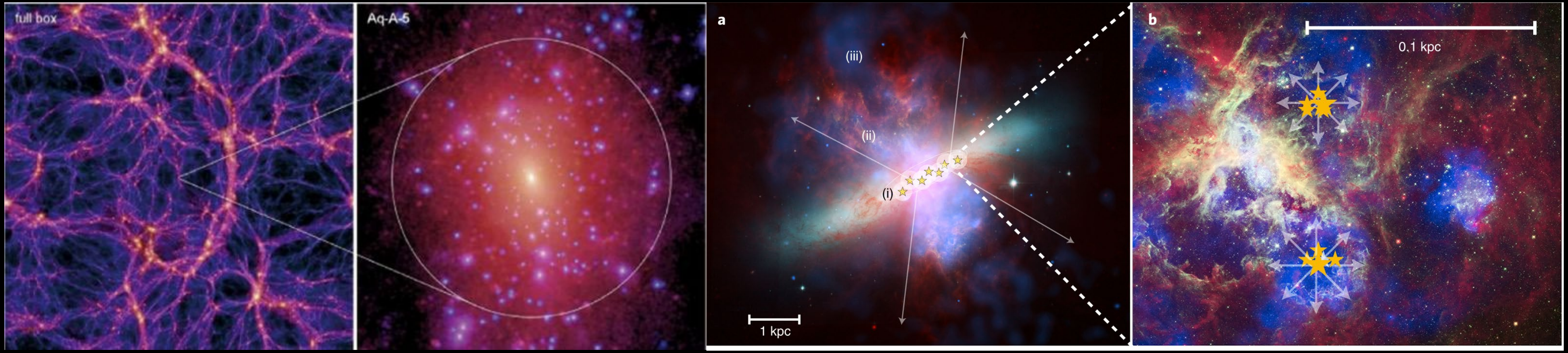
Stellar feedback model: from individual massive stars based on their masses and metallicity.

Resolution: 1 Msun resolution in galaxy simulations.



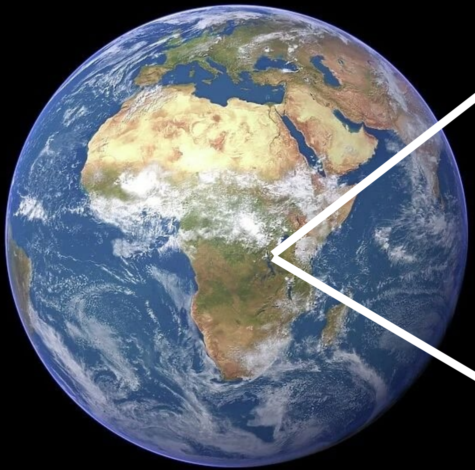
Deng, LH+24b

Numerical challenges: huge dynamical range, non-linear interaction

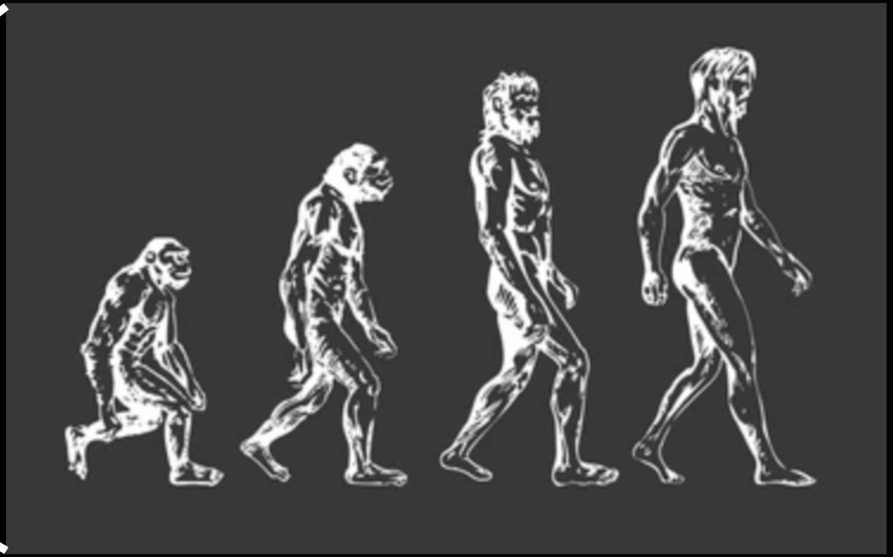


RIGEL

> 10Mpc | Mpc | kpc | 10pc | < 0.1 pc

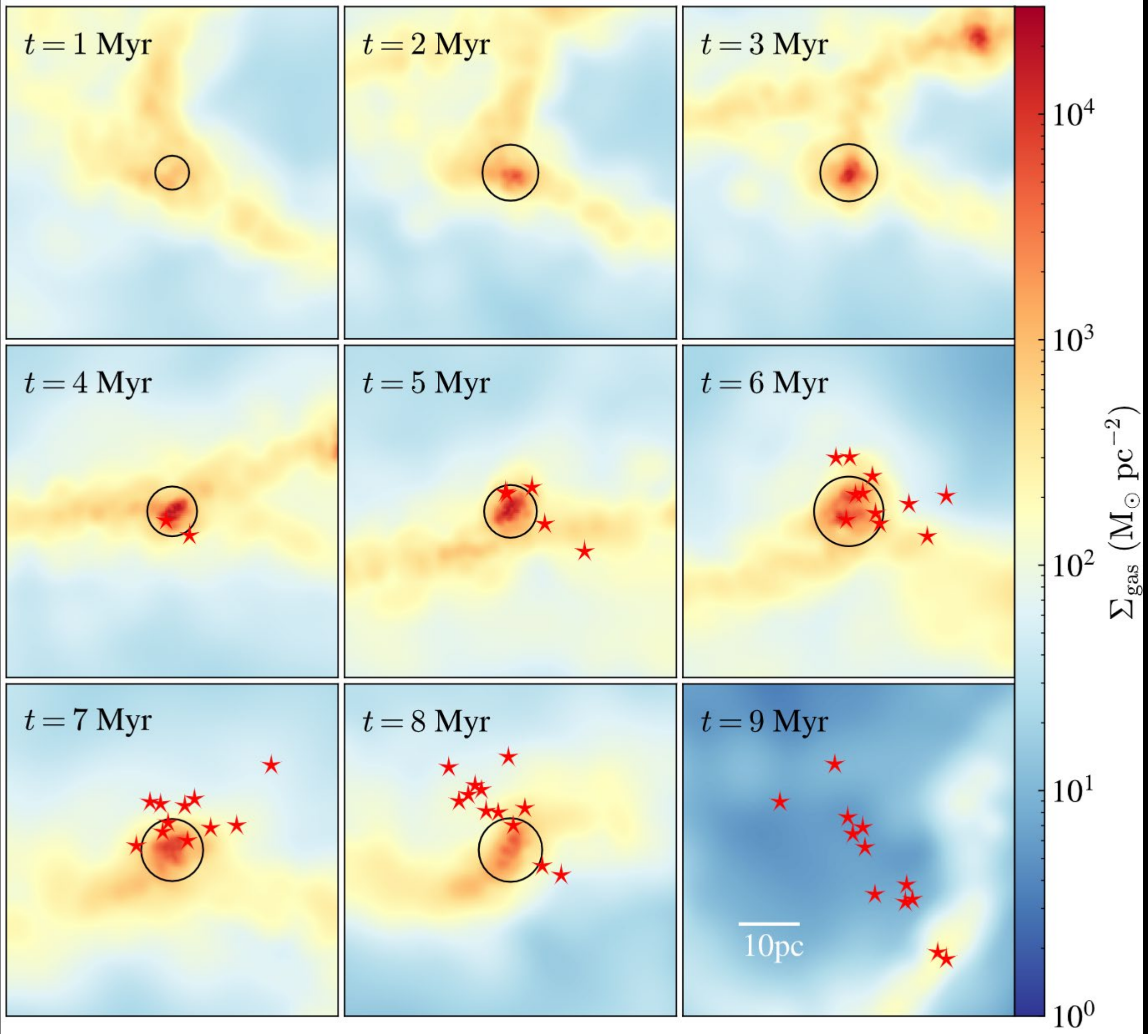


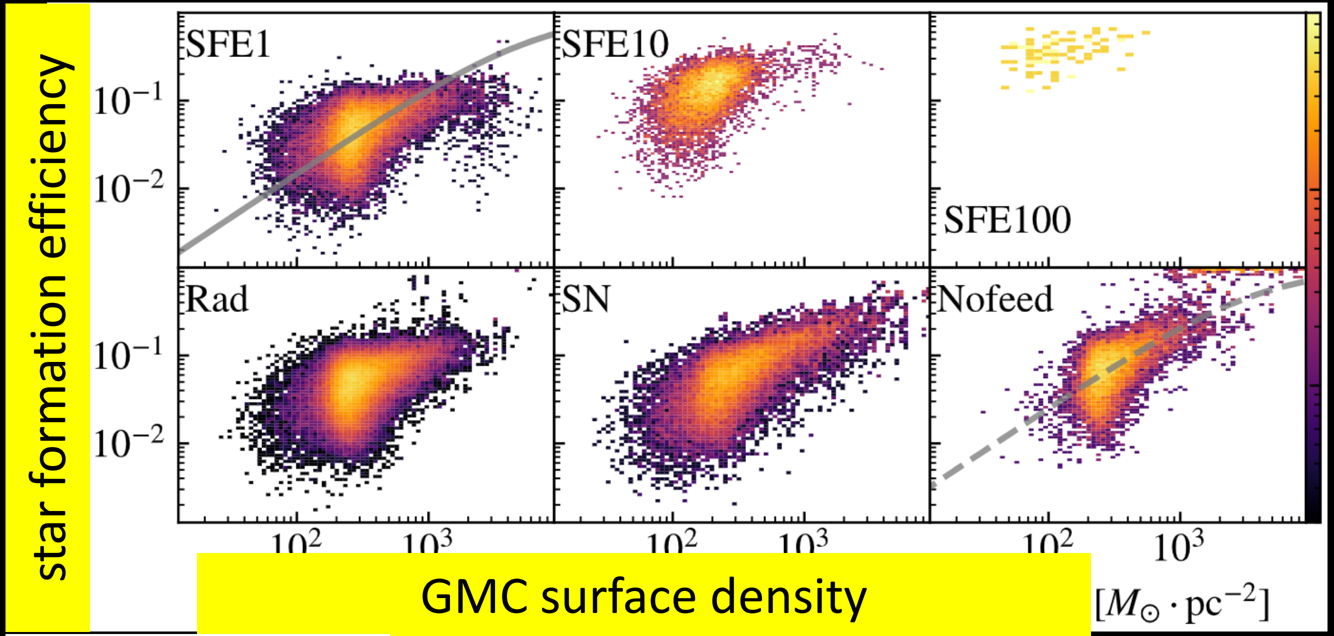
数千万米



米

Tracing the baryonic cycles in GMC level: on the variability of star formation efficiency in different galactic environments





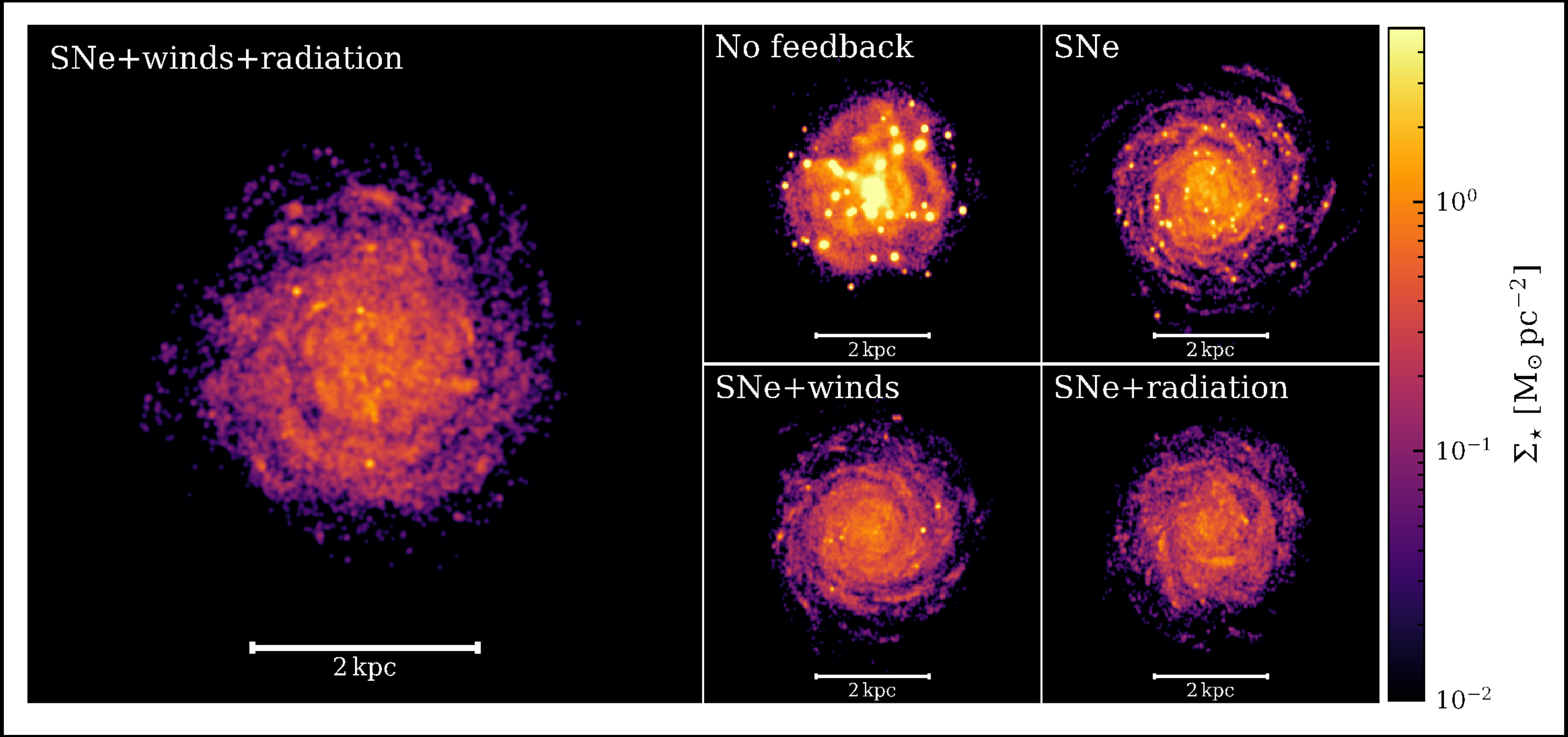
$$\epsilon_{\rm int} = \frac{M_\star(t = t_{\rm termination})}{\mathrm{MAX}\{M_{\rm baryon}(t)\}}$$

- Integrated star formation efficiency in cloud scale is far from a small constant as previous turbulence/magnetic field-regulated model predicted. Instead, it shows huge variation from 0.1% to ~50%.
- Efficiency increases as the GMC surface density increases.
- Effects of early feedback is important for clouds with high gas surface density.

- Identify GMCs and star clusters
- Build merger trees of GMCs
- Track the evolution of individual GMCs

Ni, LH+ to be submitted

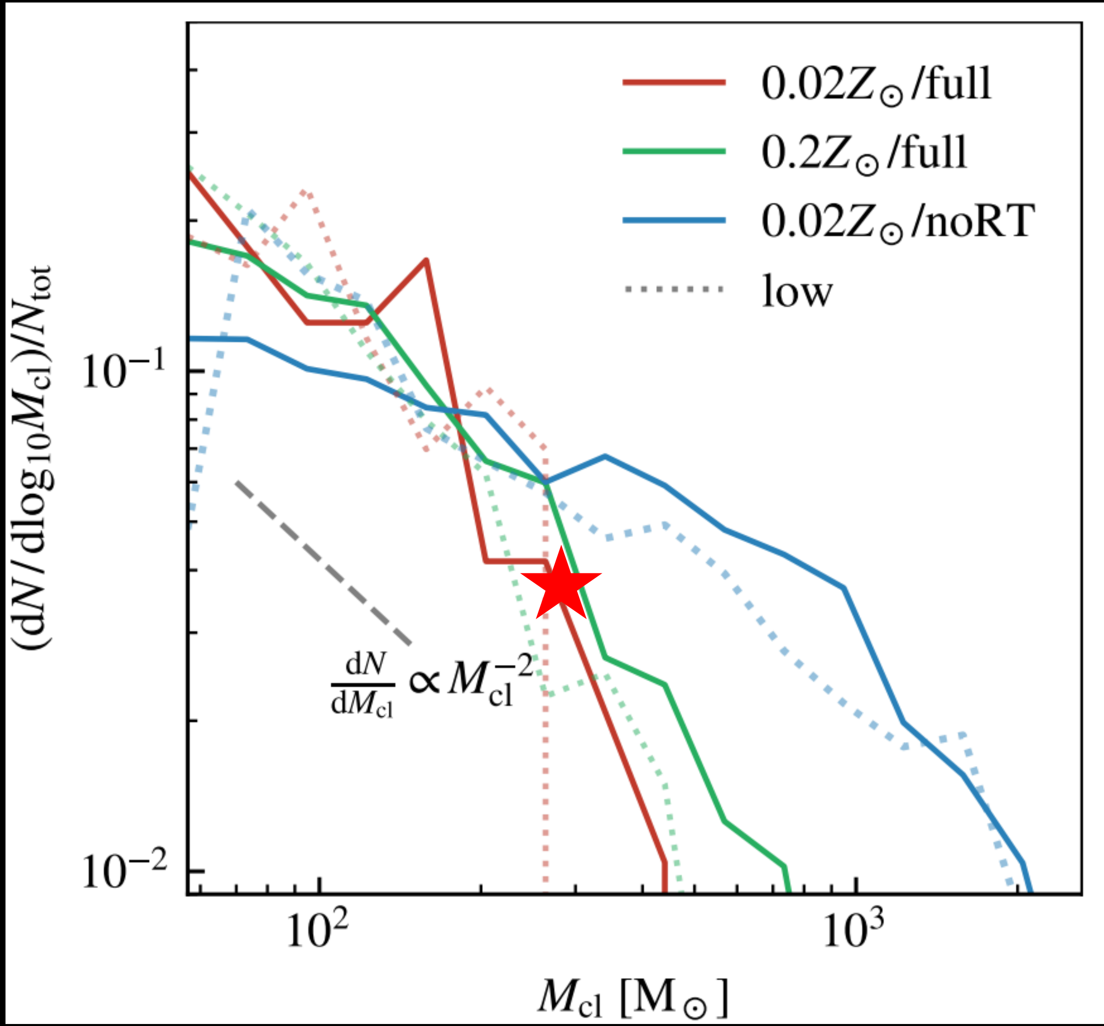
Cluster formation efficiency is significantly reduced with radiation feedback



Andersson, **w/LH+23, Deng, LH+24b**


Wolf–Lundmark–Melotte (WLM)
a lonely galaxy in the local Universe

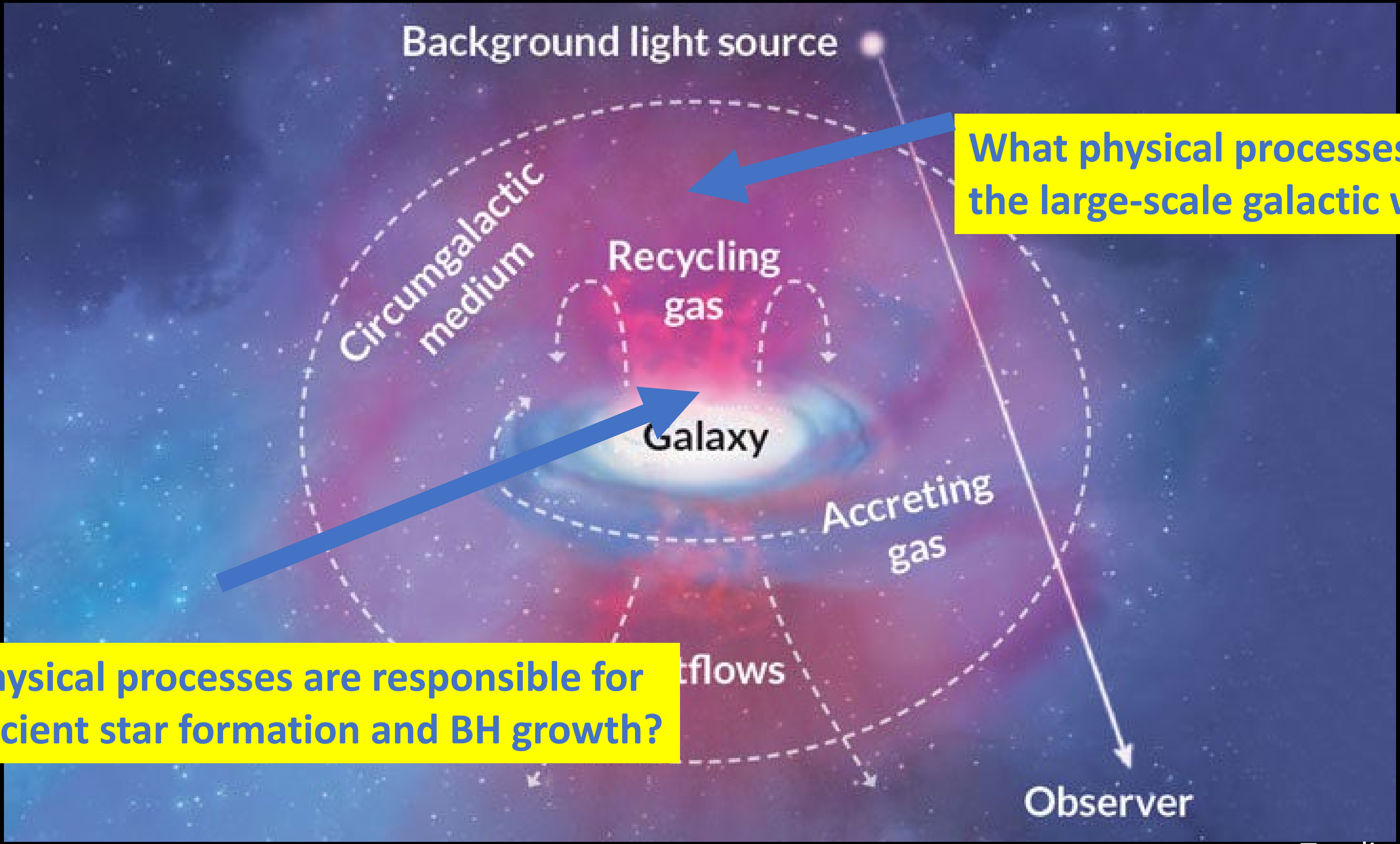
Radiation feedback matters on small-scale cluster formation



- SN-only feedback cannot destroy GMCs because it has to wait until the first massive star to explodes.
- Radiation feedback, especially photo-ionization, destroys GMCs early, reduces the mass of the star clusters emerged from GMCs.
- Radiation feedback also helps to reproduce the observed slope of the cluster initial mass function.

Deng, LH+24b

Baryonic cycle in and around galaxies:
A multi-scale, multi-physics, non-linear problem

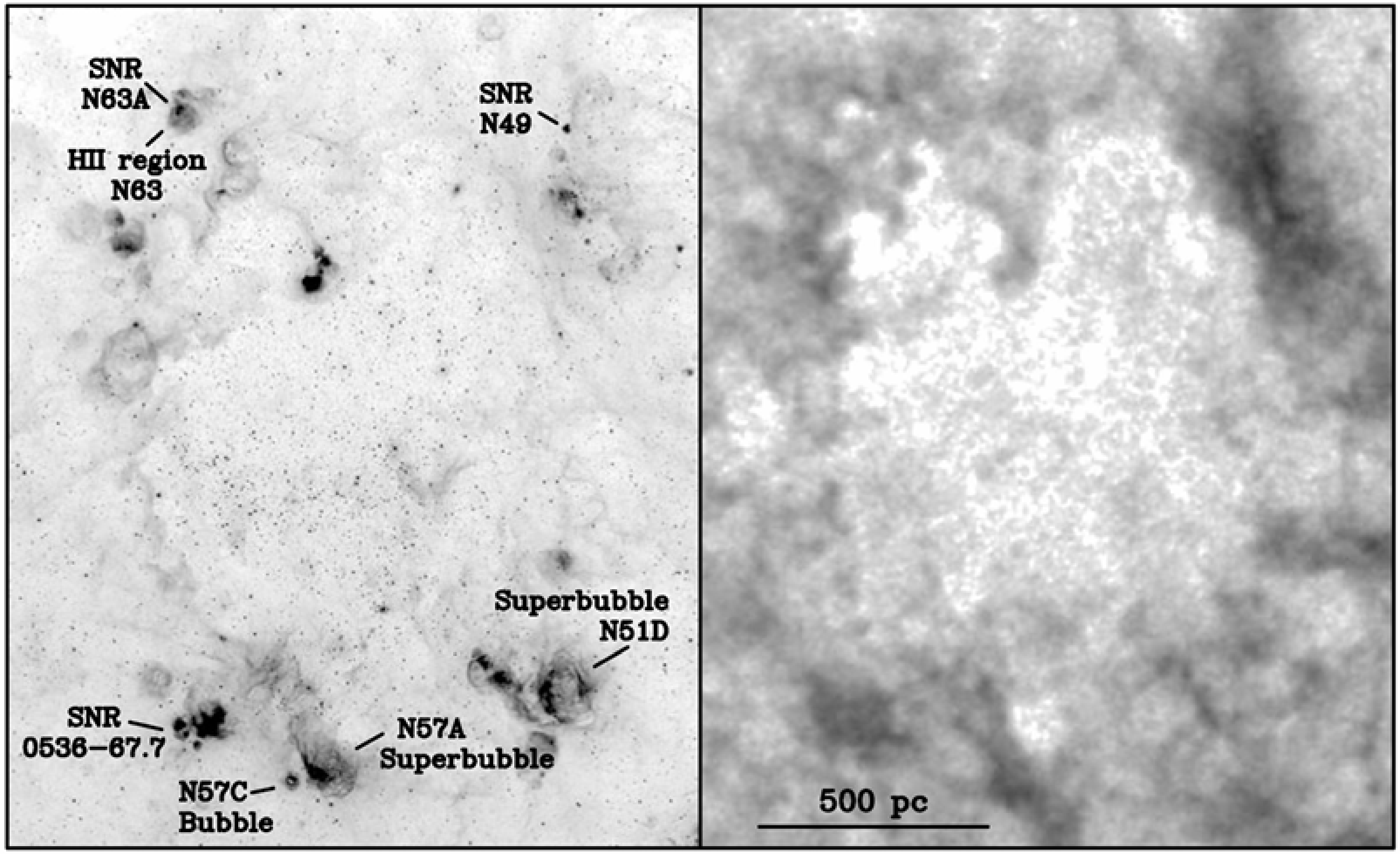


What physical processes drive the large-scale galactic winds?

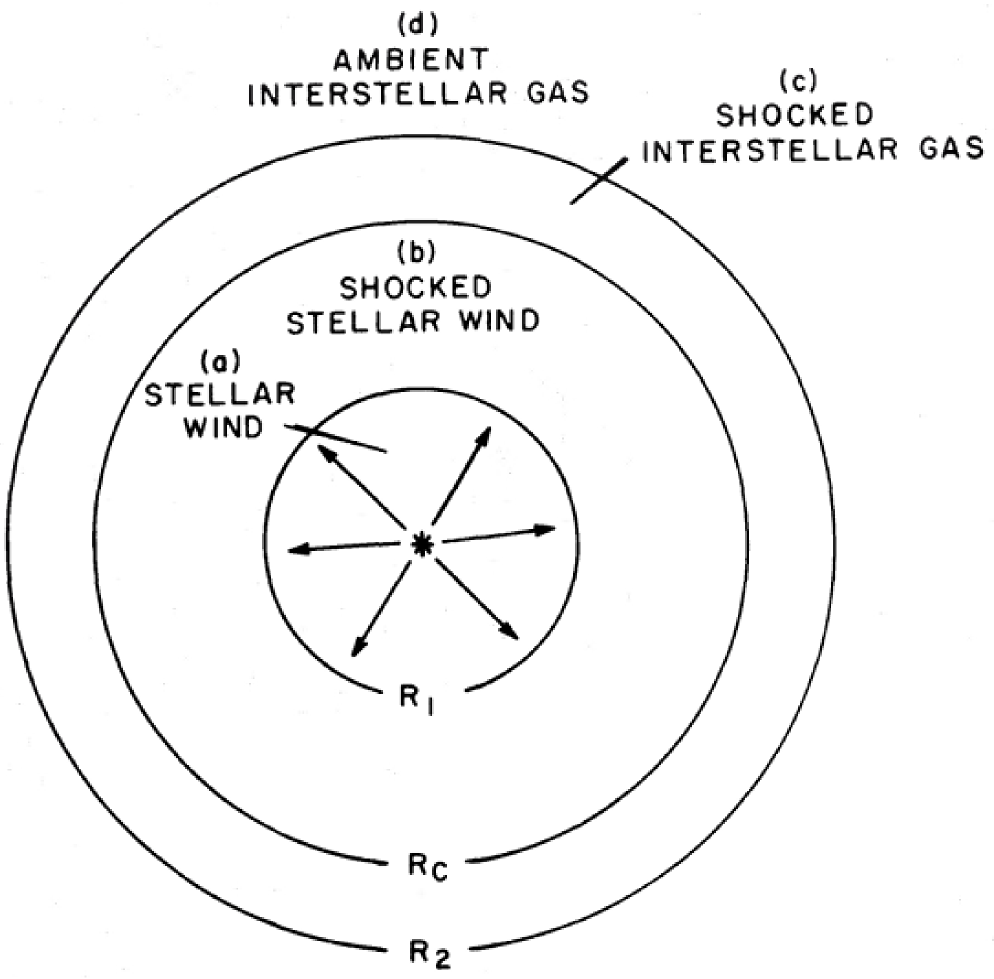
Which physical processes are responsible for the inefficient star formation and BH growth?

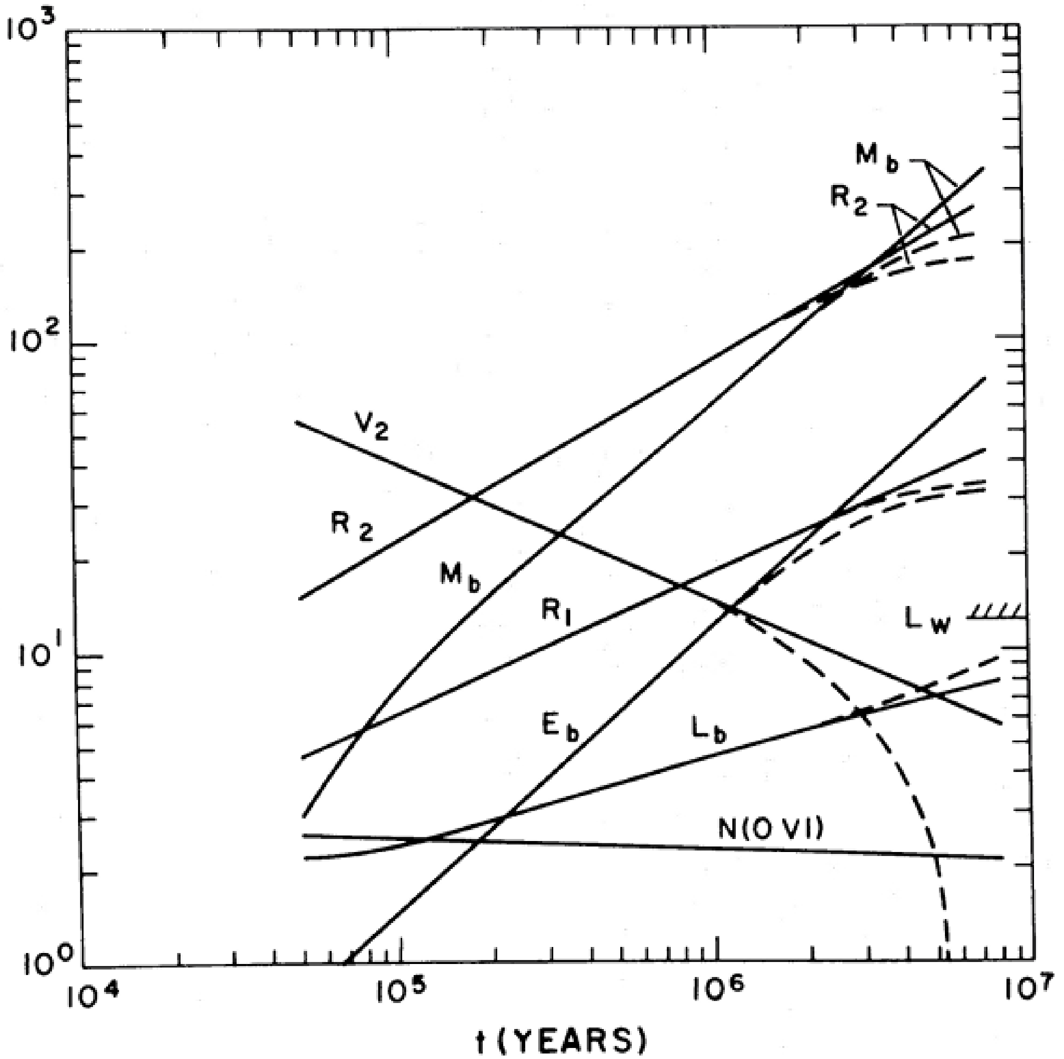
Tumlinson et al. 2017

Superbubbles by recent star formation activities

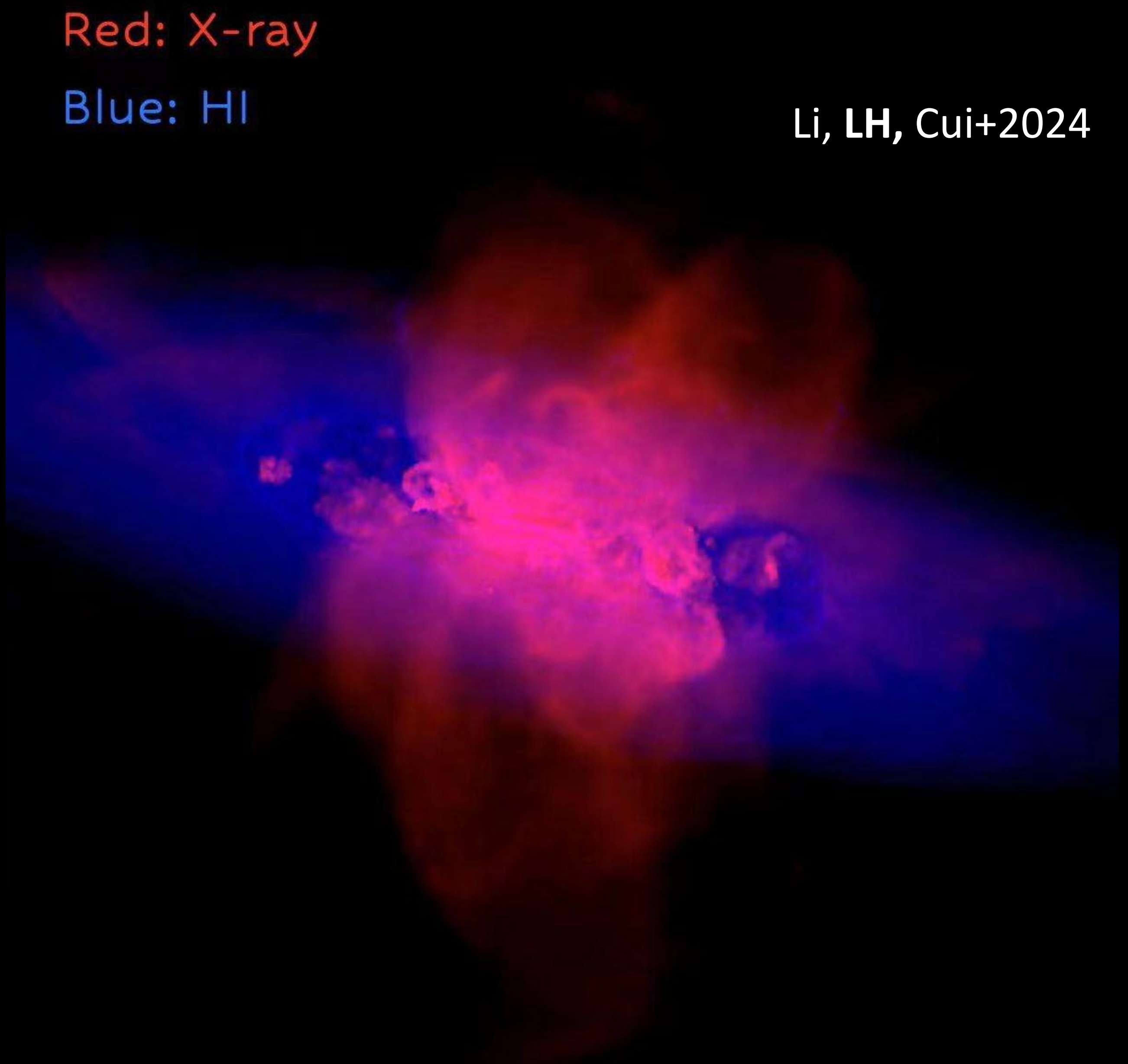


SNe-driven galactic winds: superbubble!



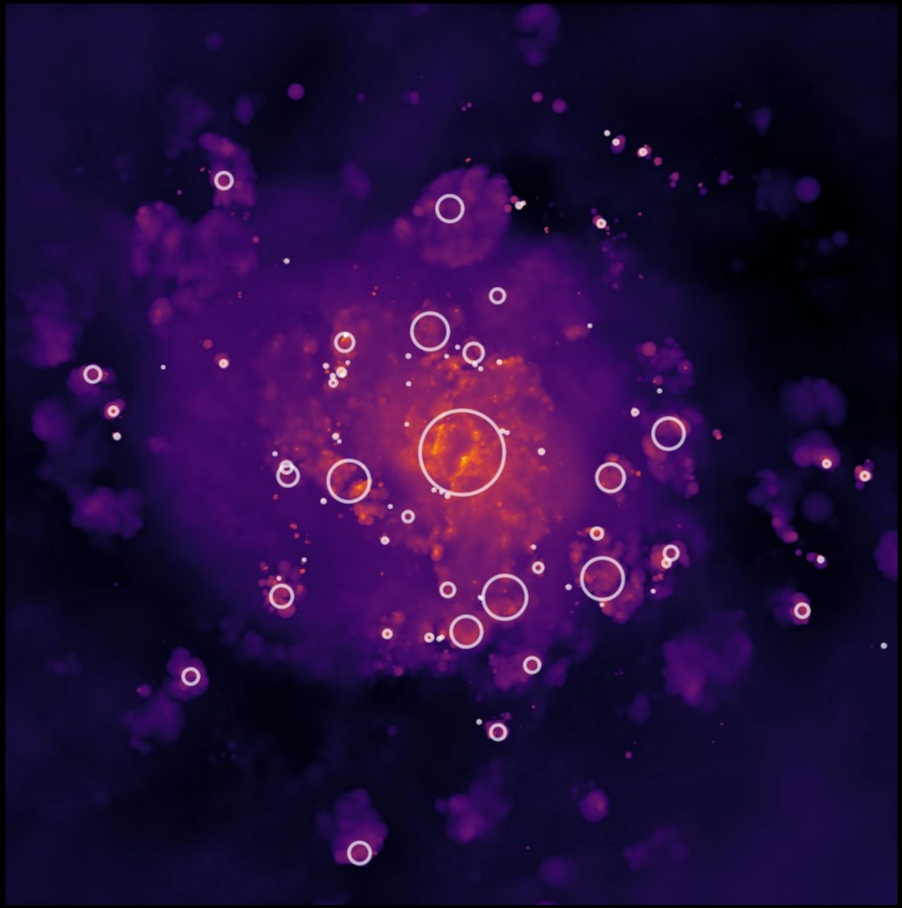


Disk-halo interface connects star-forming regions and CGM

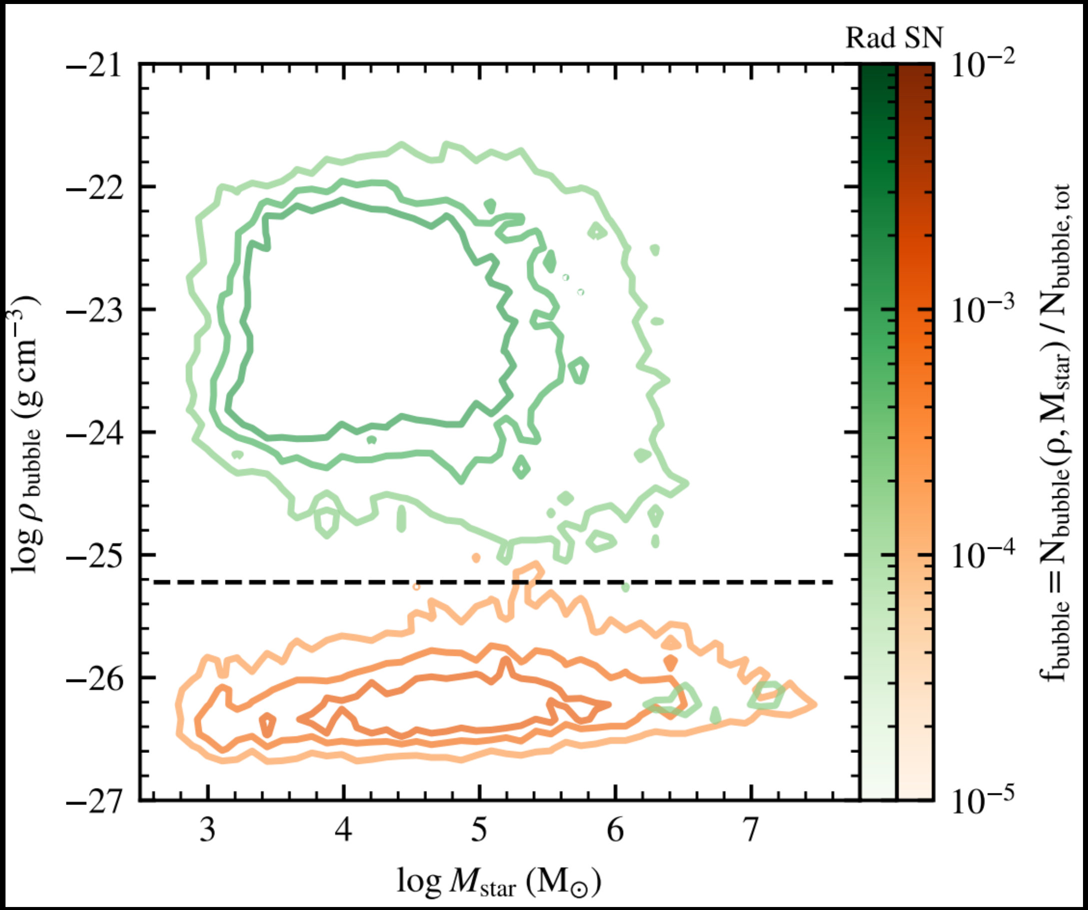


Li, **LH,** Cui+2024

A tale of two bubbles: Early feedback reduces the size of superbubbles



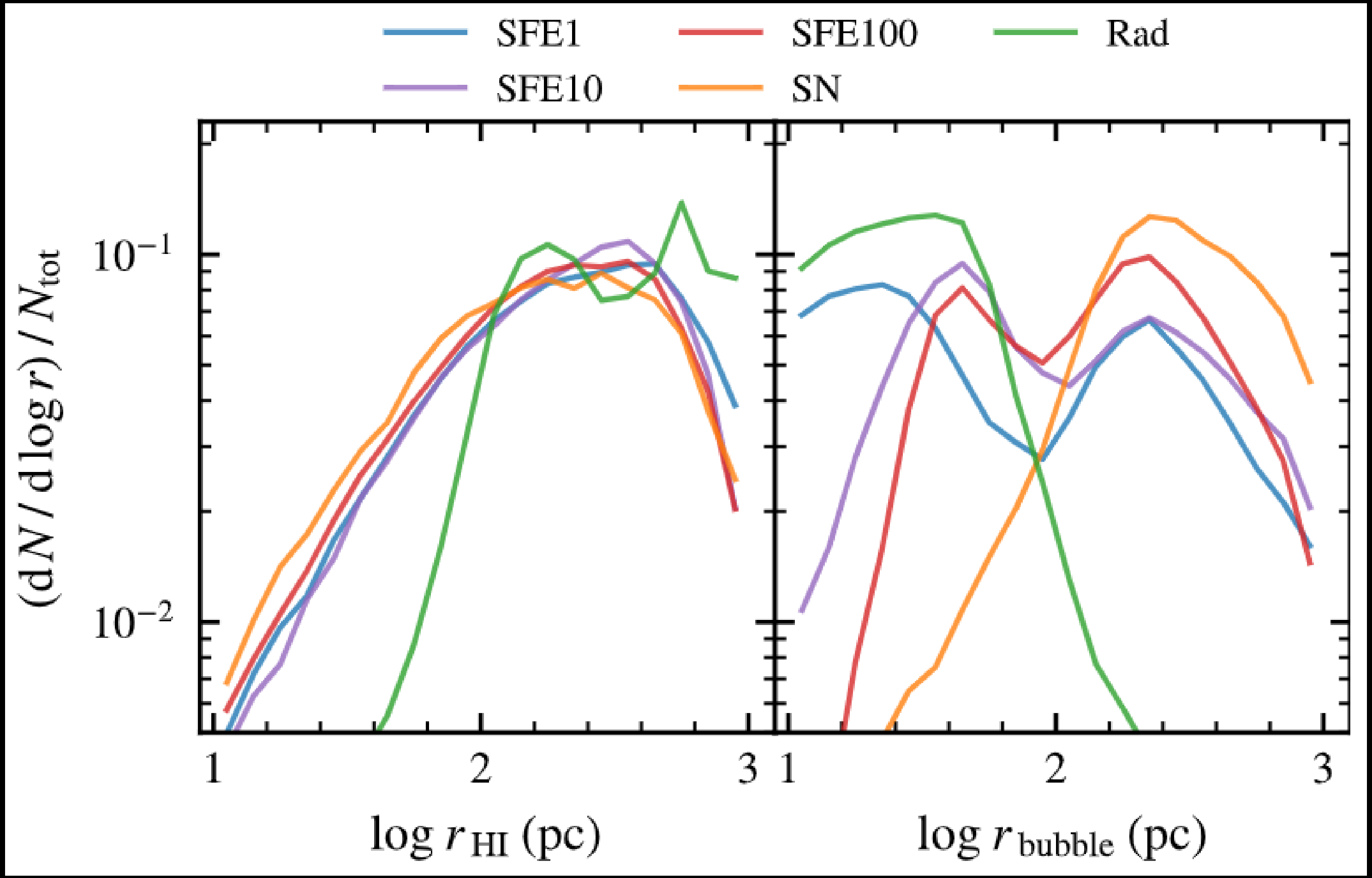
Superbubbles identified from mock X-ray emissivity maps. The bubble size and X-ray luminosity in our fiducial run are consistent with the X-ray observations of nearby superbubbles.



Two types of bubbles co-exists: early feedback-driven bubbles vs. SNe driven bubbles.

Li, **LH,** Cui et al. 2024

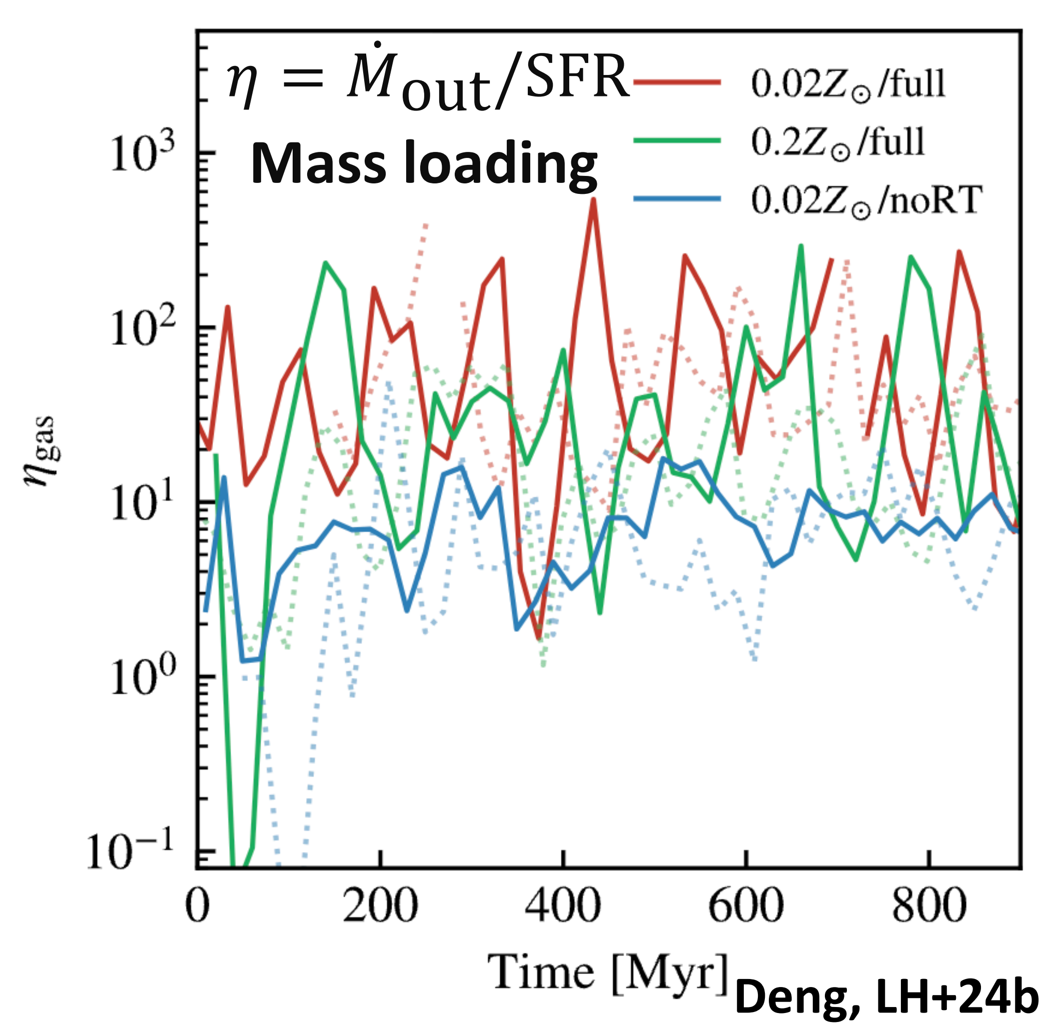
A tale of two bubbles: Early feedback reduces the size of superbubbles



Early feedback-driven bubbles are typically small in size compared to the SNe-driven bubbles.
Simulations without early-feedback (SN only run) tend to over-predict the size distribution of bubble because SNe only is not able to reduce the clustering of star formation and therefore the clustering of SNe.

Li, **LH,** Cui et al. 2024

Isolate dwarf galaxy: Outflow and mass loading



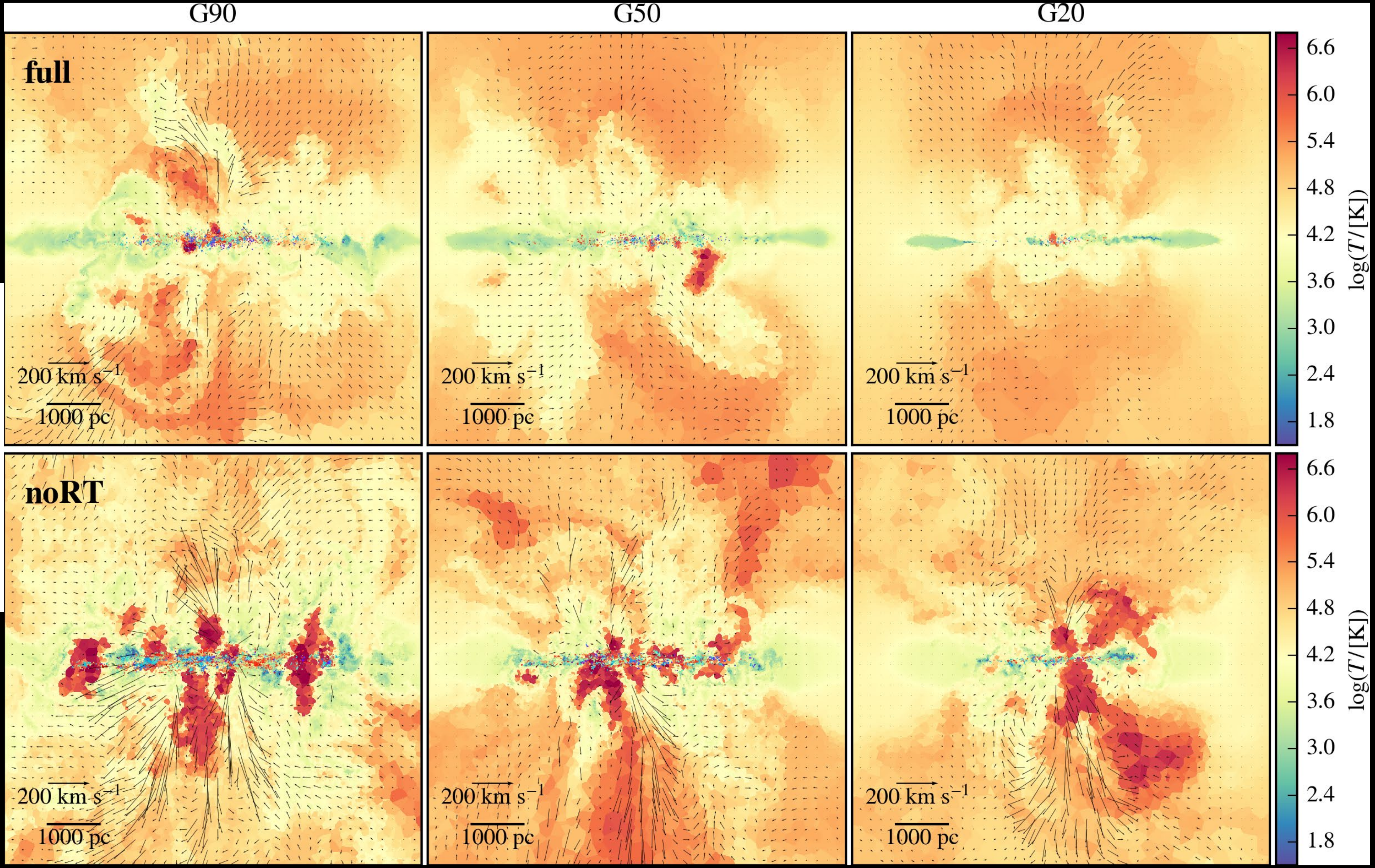
Radiation feedback enhances the mass/energy loading of the galactic winds: 1) higher feedback energy output due to photo-ionization and radiative pressure; 2) reduce the SN explosion density by pre-processing the ambient medium.

Outflow vs gas fraction: New simulation suite

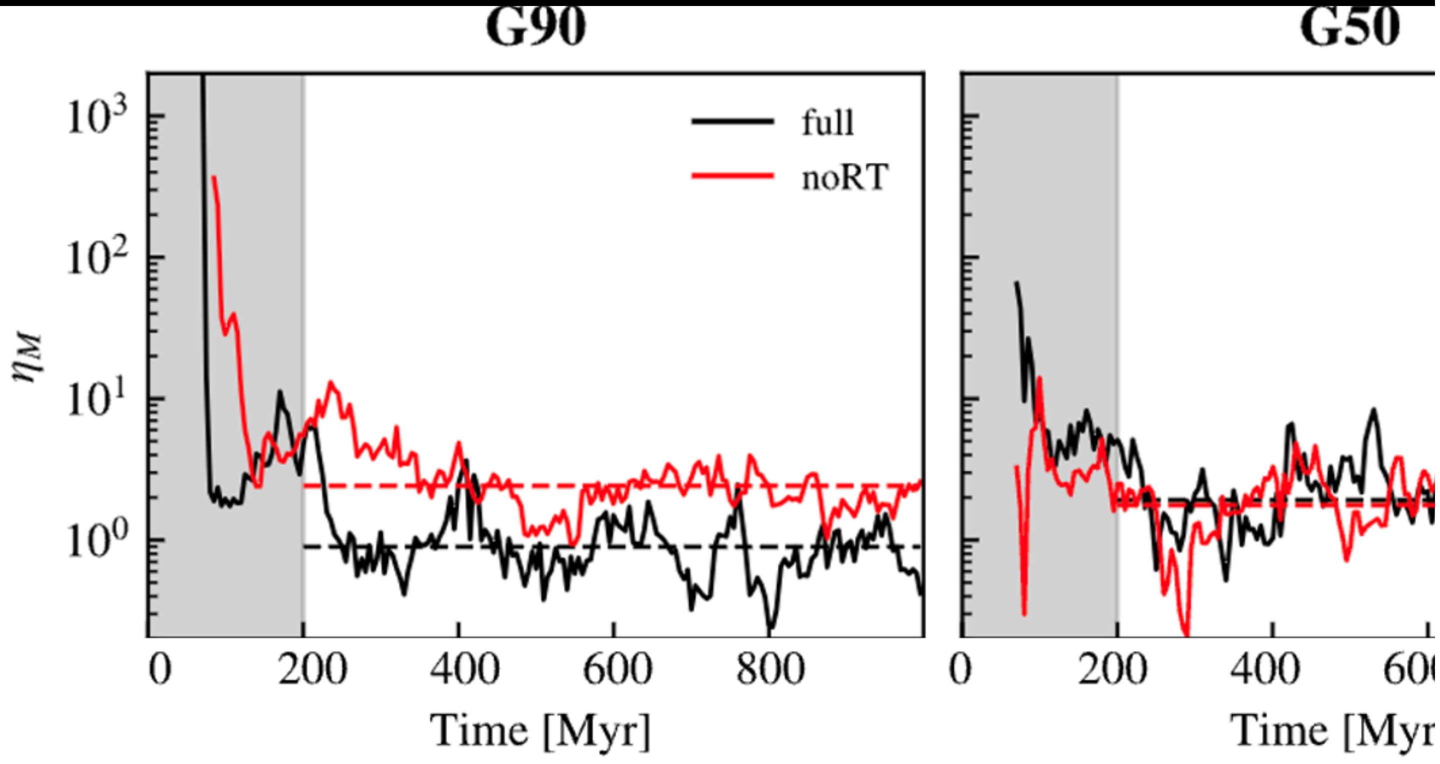
Fixed baryon & DM mass
Gas : Star

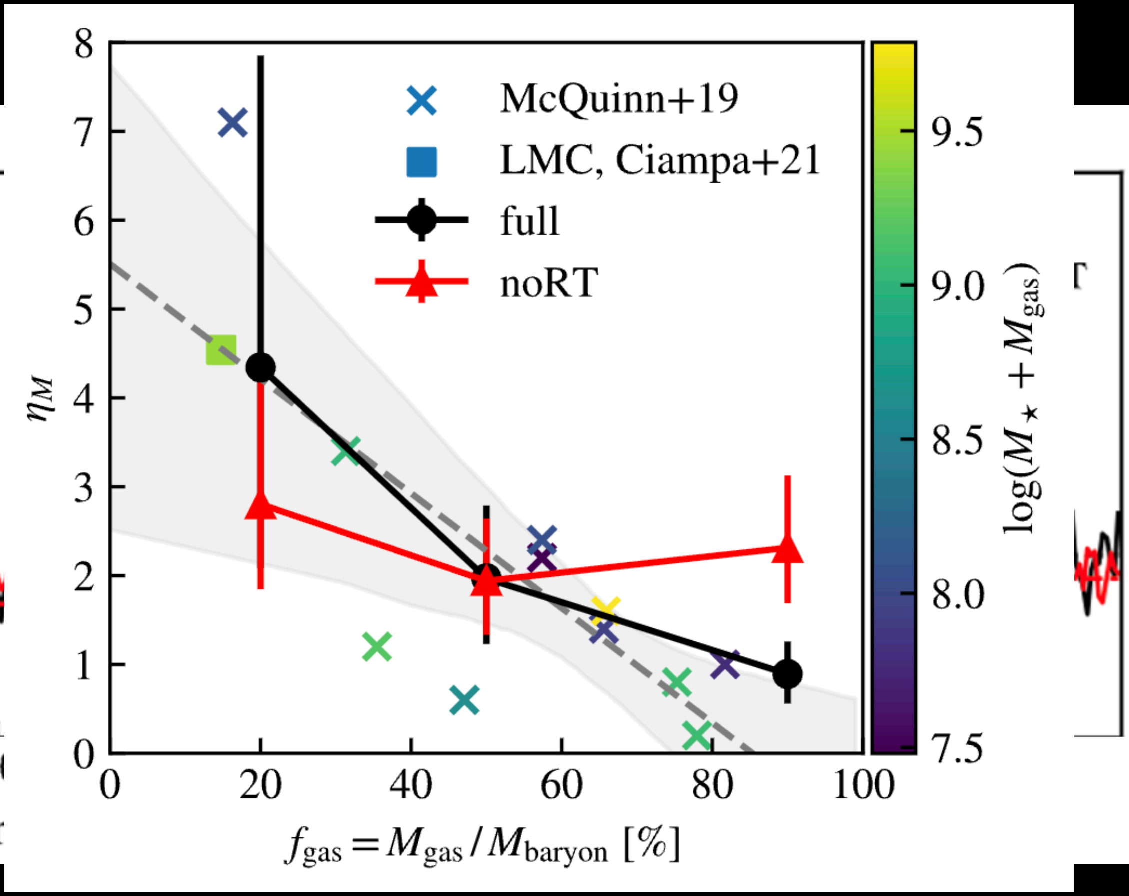
G90 9 : 1
G50 1 : 1
G20 1 : 4

Properties	Value (G20/G50/G90)
Virial mass ($M_{\rm vir}$)	1×10^{10} M$_\odot$
Concentration factor (c)	15
Spin parameter (λ)	0.04
Gas mass ($M_{\rm g,init}$)	$\{1.6, 4.0, 7.2\} \times 10^7$ M$_\odot$
Disc mass ($M_{\star,\rm init}$)	$\{6.4, 4.0, 0.8\} \times 10^7$ M$_\odot$
Gas scalelength	1100 pc
Disc scalelength	1100 pc
Scaleheight	700 pc
DM mass resolution ($m_{\rm DM}$)	1×10^3 M$_\odot$
gas mass resolution ($m_{\rm gas}$)	10 M$_\odot$
DM softening length	29 pc
Max. baryon softening length	0.3 pc
Min. baryon softening length	0.004 pc



Loading factors of galactic winds are determined by the non-linear combination of early and SNe feedback from clustered star formation





Simulations and observations:
Loading factor decrease with gas fraction