MODELLING STAR FORMATION AND AGN FEEDBACK IN COSMOLOGICAL SIMULATIONS

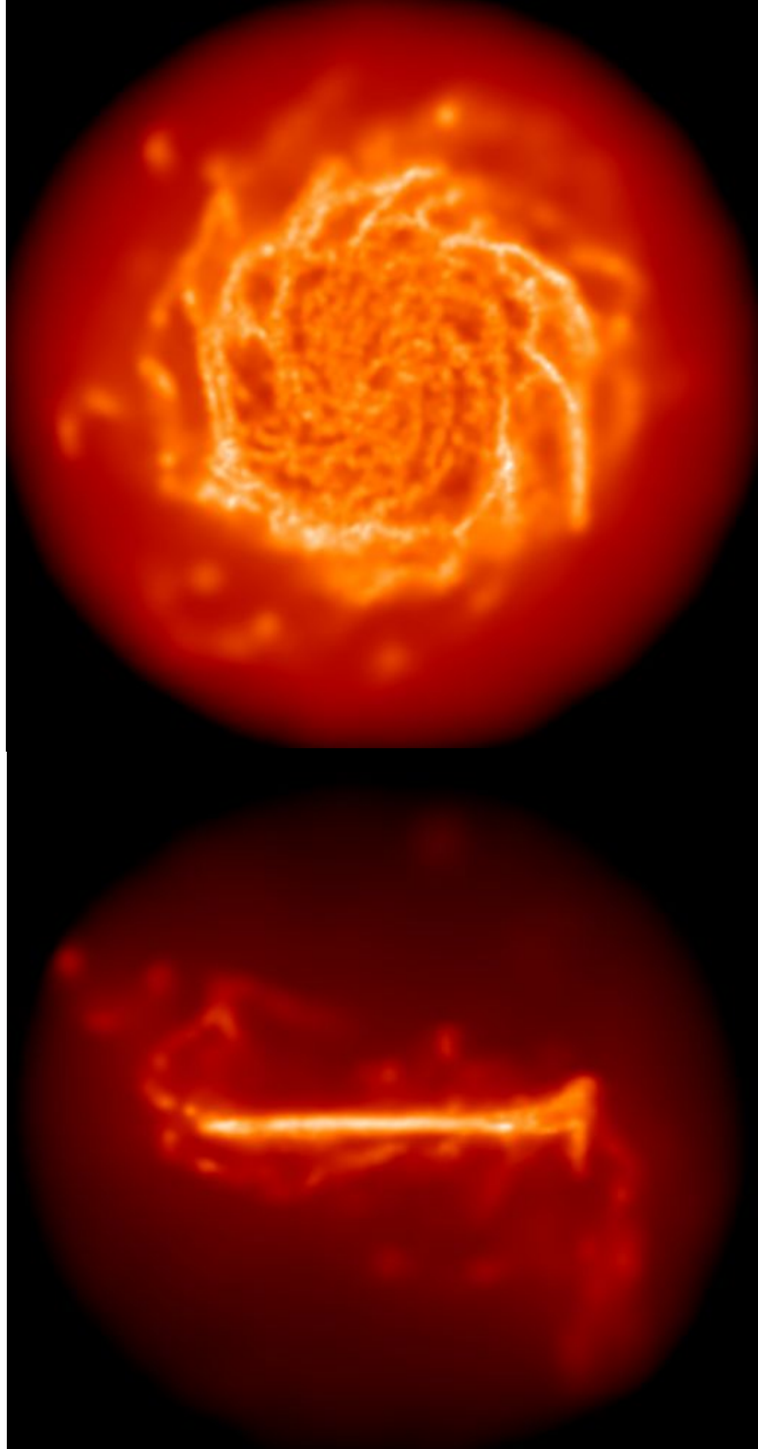
Milena Valentini

University of Trieste, Italy

milena.valentini@units.it

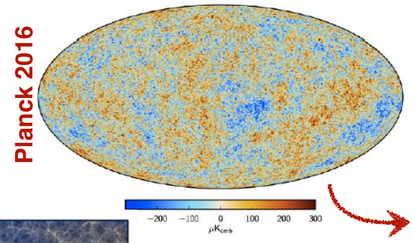
COLLABORATORS:
S. Borgani, K. Dolag, G. Murante, L. Tornatore, G.L. Granato, C. Ragone-Figueroa, A. Damiano, L. Sala

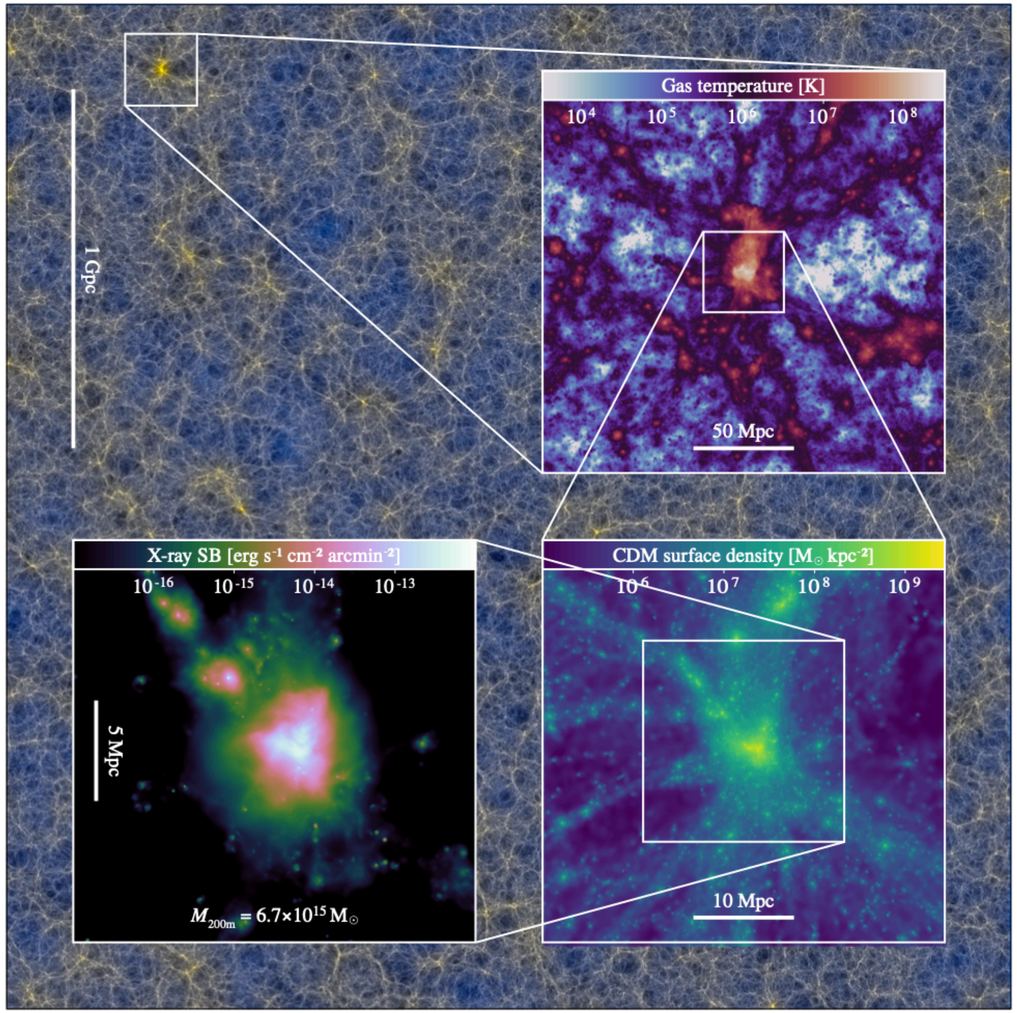
AGN Feedback and Star Formation Across Cosmic Scales and Time — Sirolo, September 2, 2024



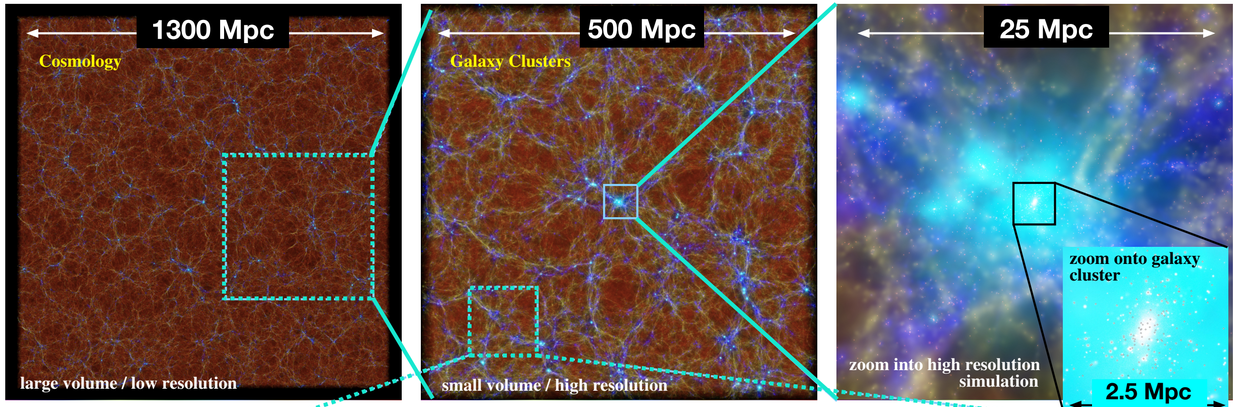
WHY SUB-RESOLUTION PHYSICS

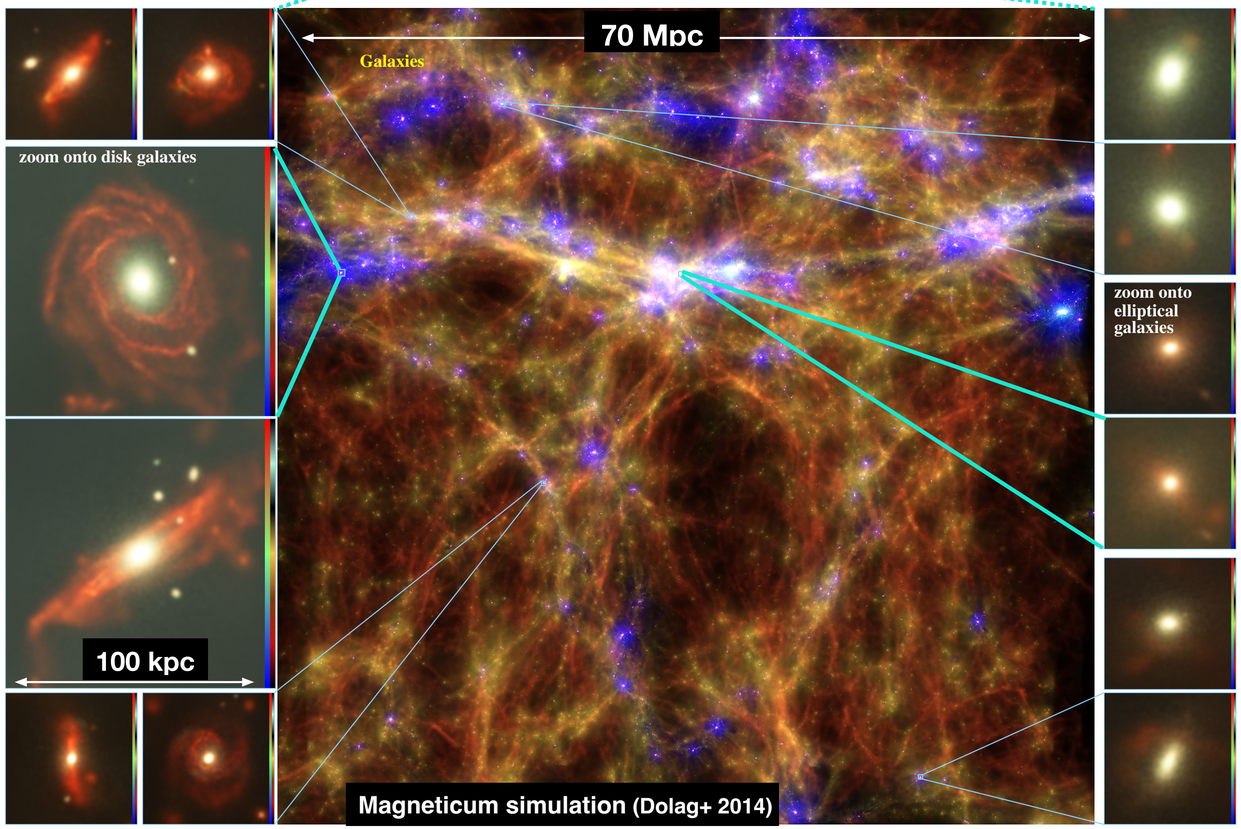
- Different physical phenomena across a **wide range of scales**: **sub-resolution models** essential





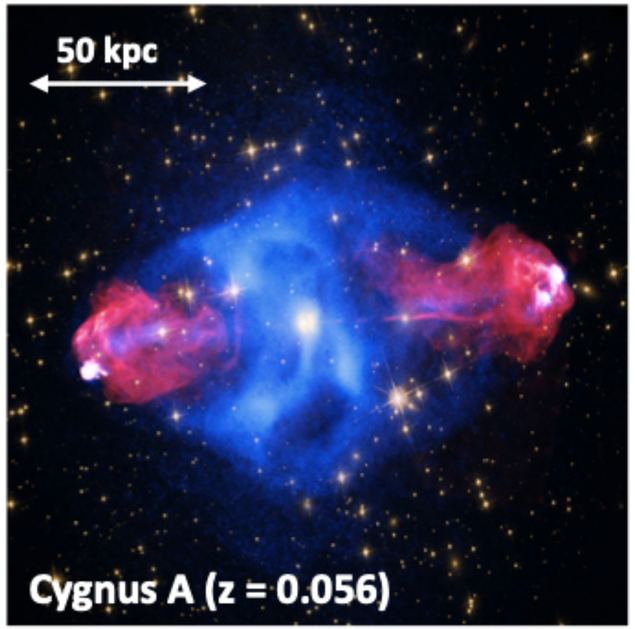
FLAMINGO simulation (Schaye+ 2023)





DYNAMICAL CHALLENGE

- **AGN feeding** described by a hierarchy of physical processes
- **AGN feedback** effects to distances way larger than sites of energy injections



Blanton+ 2011

AGN feeding:

accretion of gas from the large scale (~Mpc)

↓

inflowing, cooling gas streams (~kpc)

↓

chaotic accretion/accretion flow (~pc) and accretion disc (<0.1 pc)

↓

down to the gravitational BH radius (~10^{-5} pc)

AGN feedback:

radiation-driven accretion disc winds (~sub-pc)

↓

nuclear ultrafast outflows (~pc)

↓

relativistic, collimated jets (~pc - kpc)

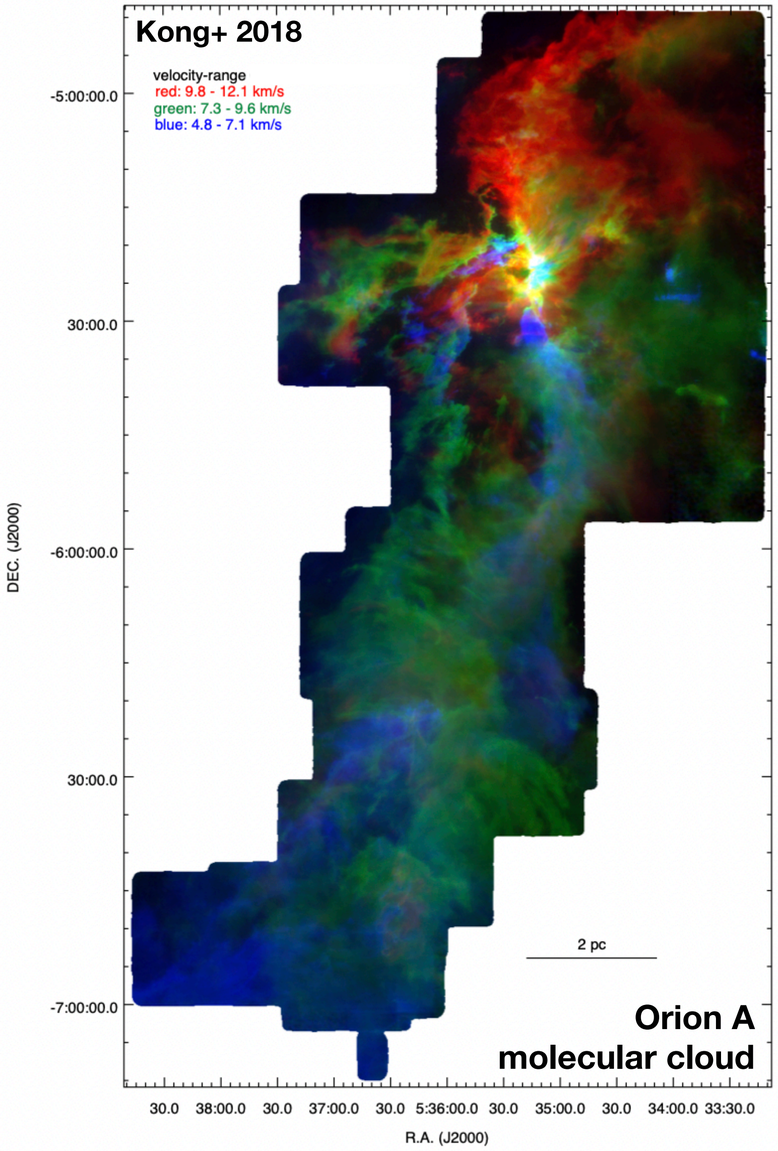
↓

(mainly energy-driven) sub-relativistic outflows (>kpc)

↓

galaxy scale, multi-phase outflows involve ISM/CGM swept-up and/or entrained by different driving mechanisms

DYNAMICAL CHALLENGE



Star formation:

accretion of gas from the large scale (~Mpc)

↓

gas cooling to form HI (~kpc)

↓

formation of molecular clouds (~10 - 100 pc)

↓

H_2 fragmentation and accretion to clumps and cores (~1 - 0.1 pc)

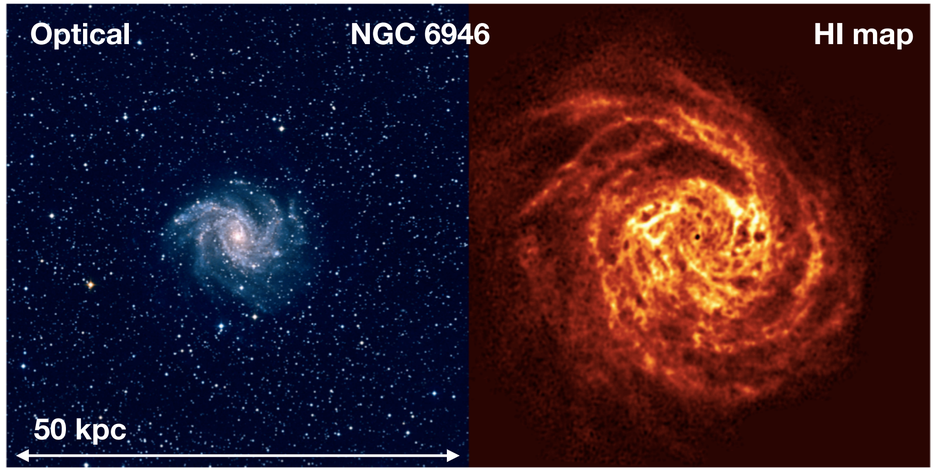
↓

subsequent contraction of cores to form stars (~10^{-8} pc)

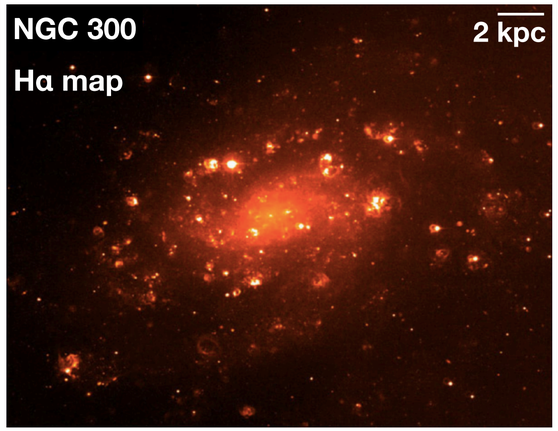
Multi-scale, multi-phase problem:

- Dynamical challenge (“coupled” physics)
- Physics on small scales is qualitatively different from physics on large scales
- Non-linear nature of galaxy formation

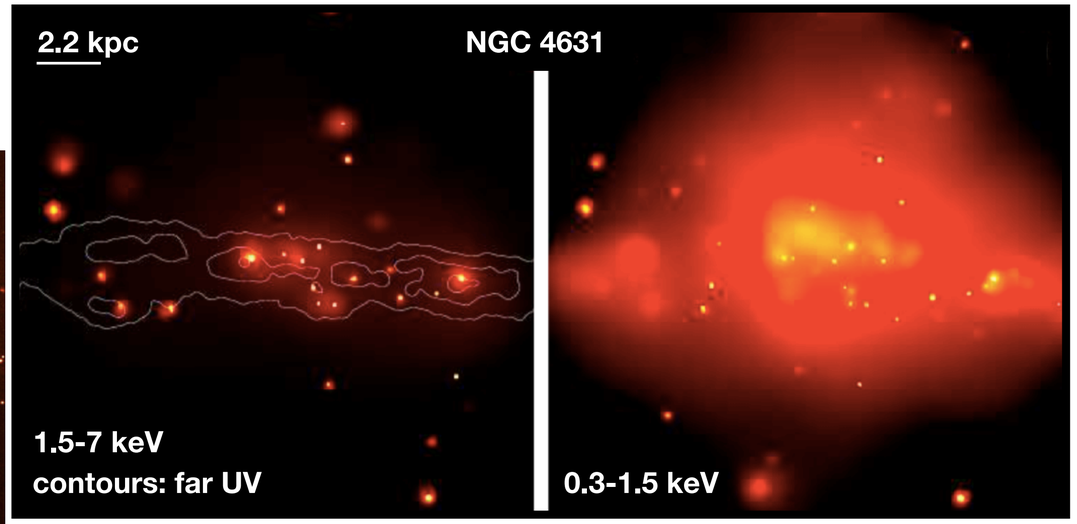
THE MULTI-PHASE ISM/CGM/ICM



Boomsma+ 2008

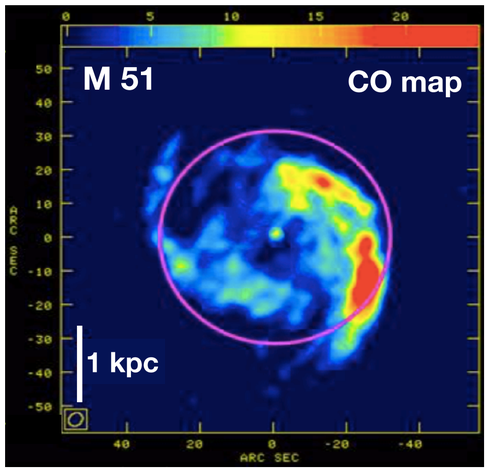


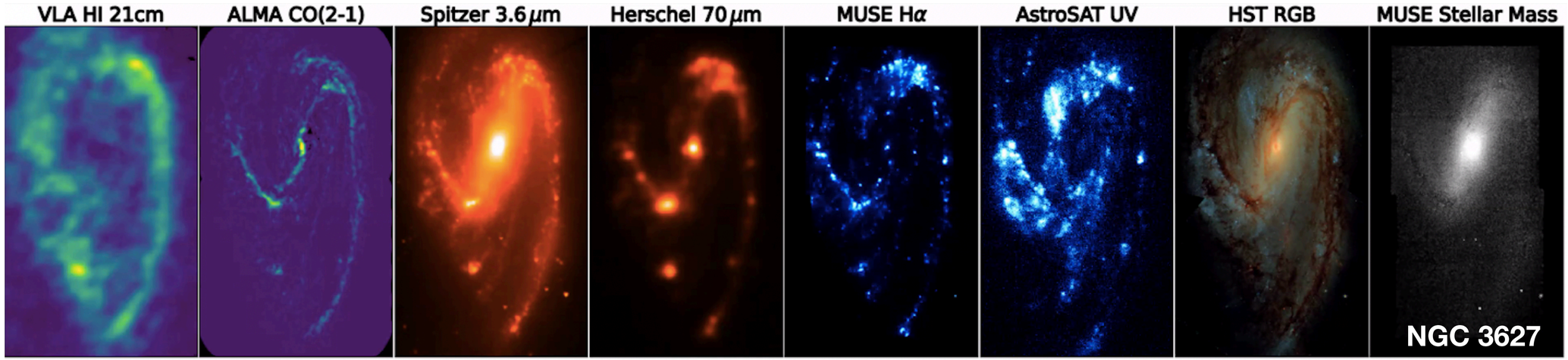
Bresolin+ 2009



Wang+ 2001

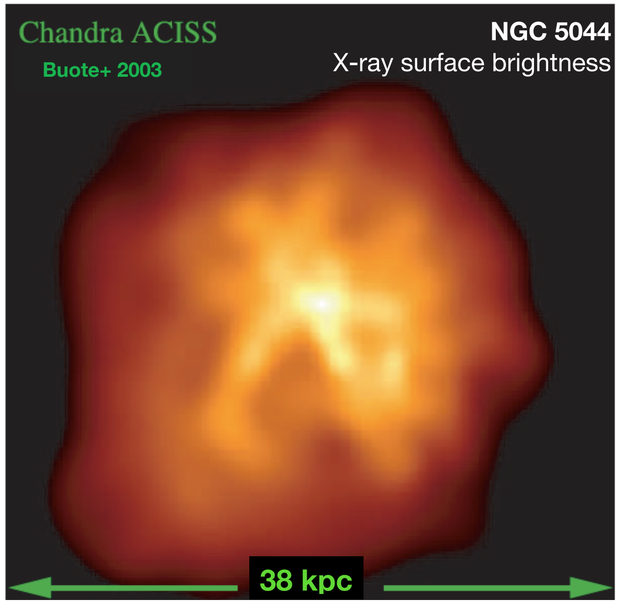
Sakamoto+ 1999

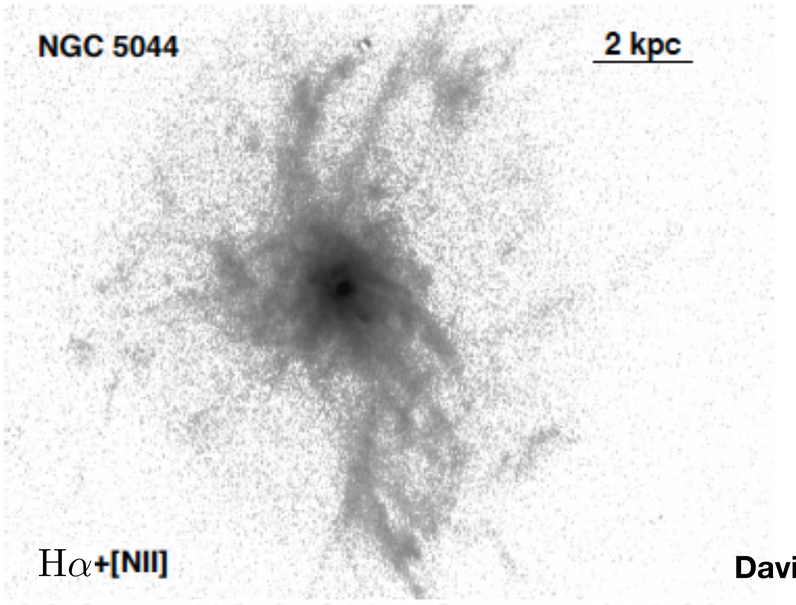


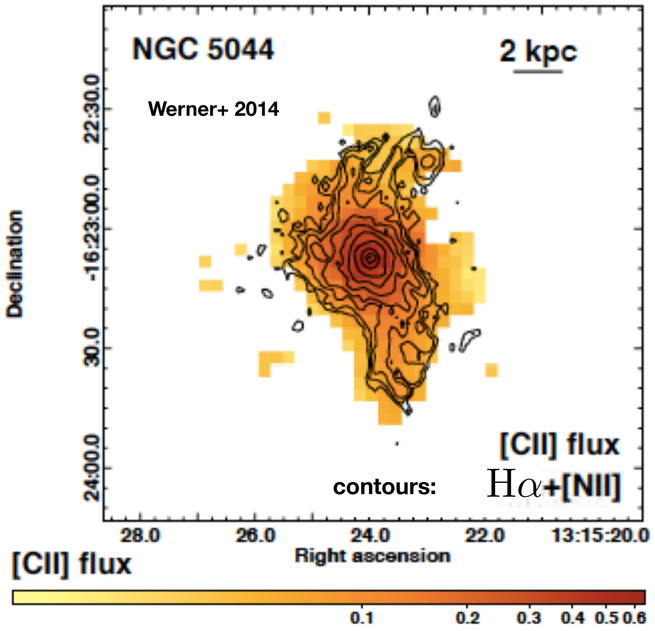


Credits: Phangs Survey

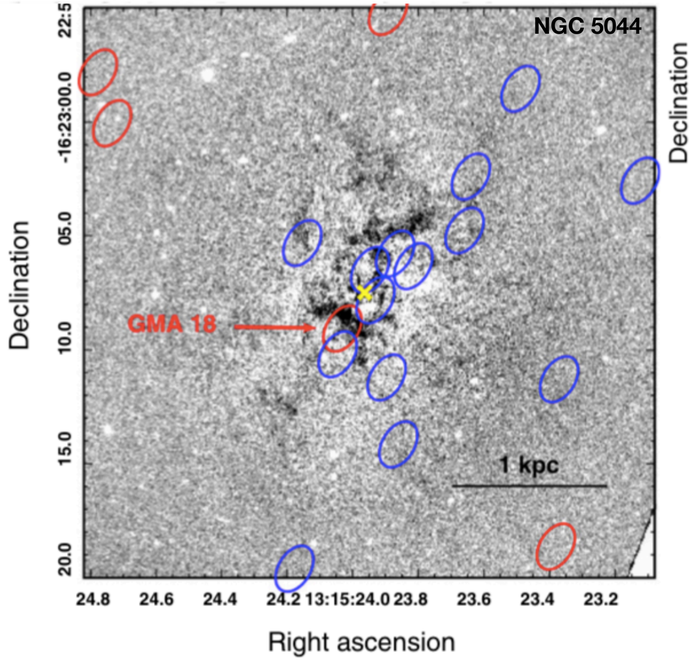
THE MULTI-PHASE ISM/CGM/ICM

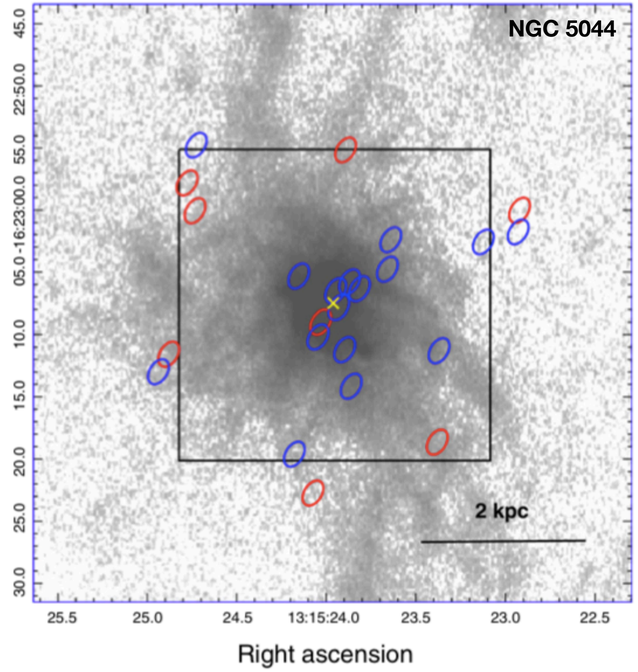






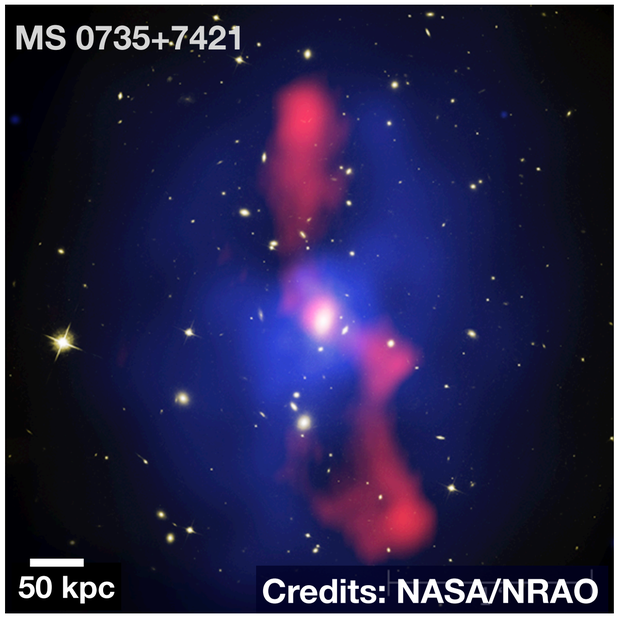
David+ 2014





Molecular associations on $H\alpha$ image and on HST dust extinction map

AGN FEEDBACK EVIDENCE



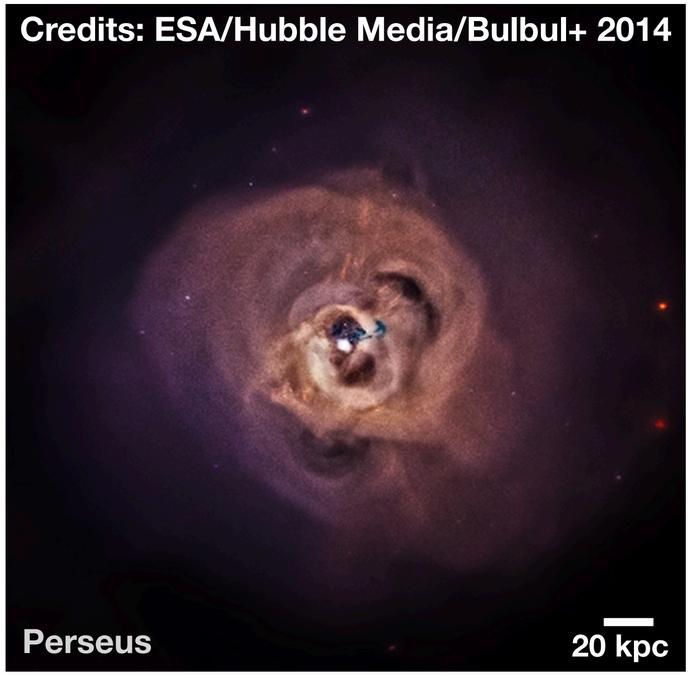
Multiphase gas in the innermost regions of galaxies and

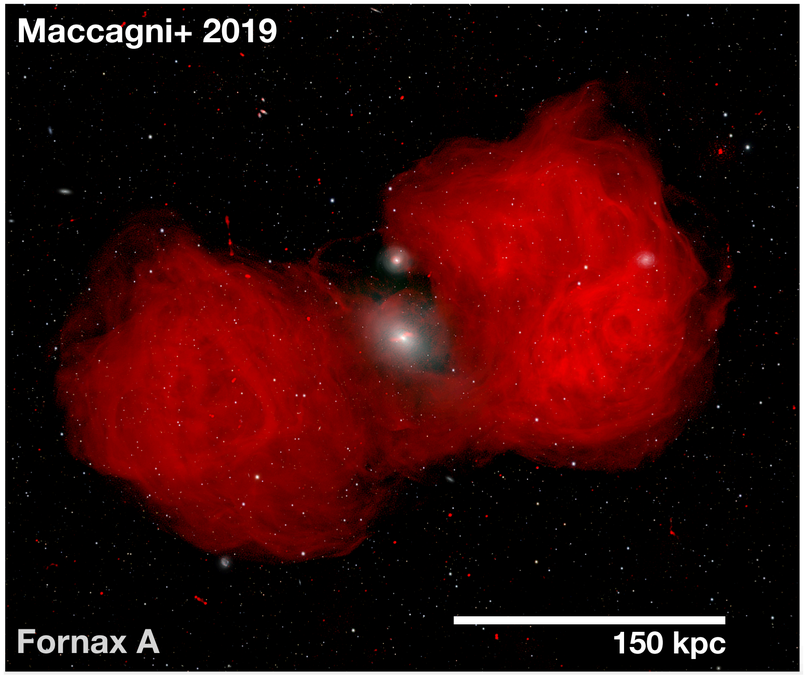
multiphase outflows powered by AGN (plus stellar feedback driven galactic outflows)

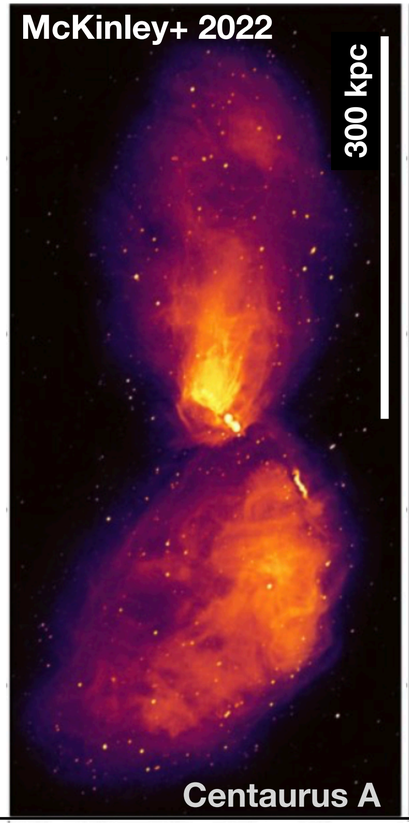
e.g. Chartas+ 2003, Rupke and Veilleux 2011, Cicone+ 2014, Feruglio+ 2015, Tombesi+ 2015, Morganti+ 2016, Russell+ 2019, Zanchettin+ 2023, …

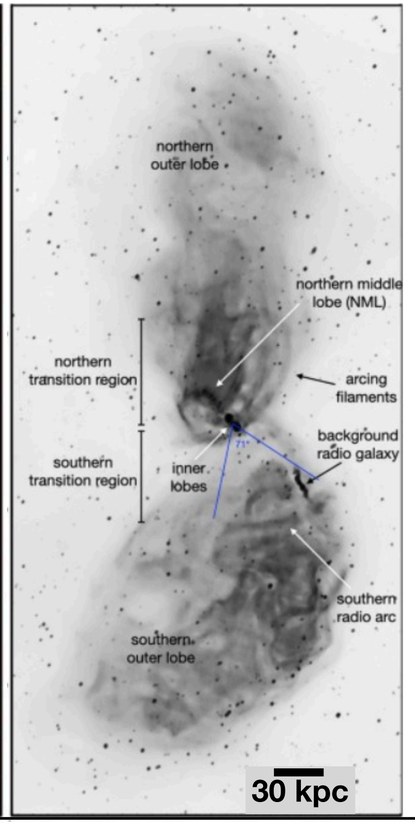
→ How do accreting BHs transfer **feedback energy** to the surrounding **multiphase ISM**?

→ How does **AGN feedback energy coupling** with the ISM set BH and host galaxy properties?

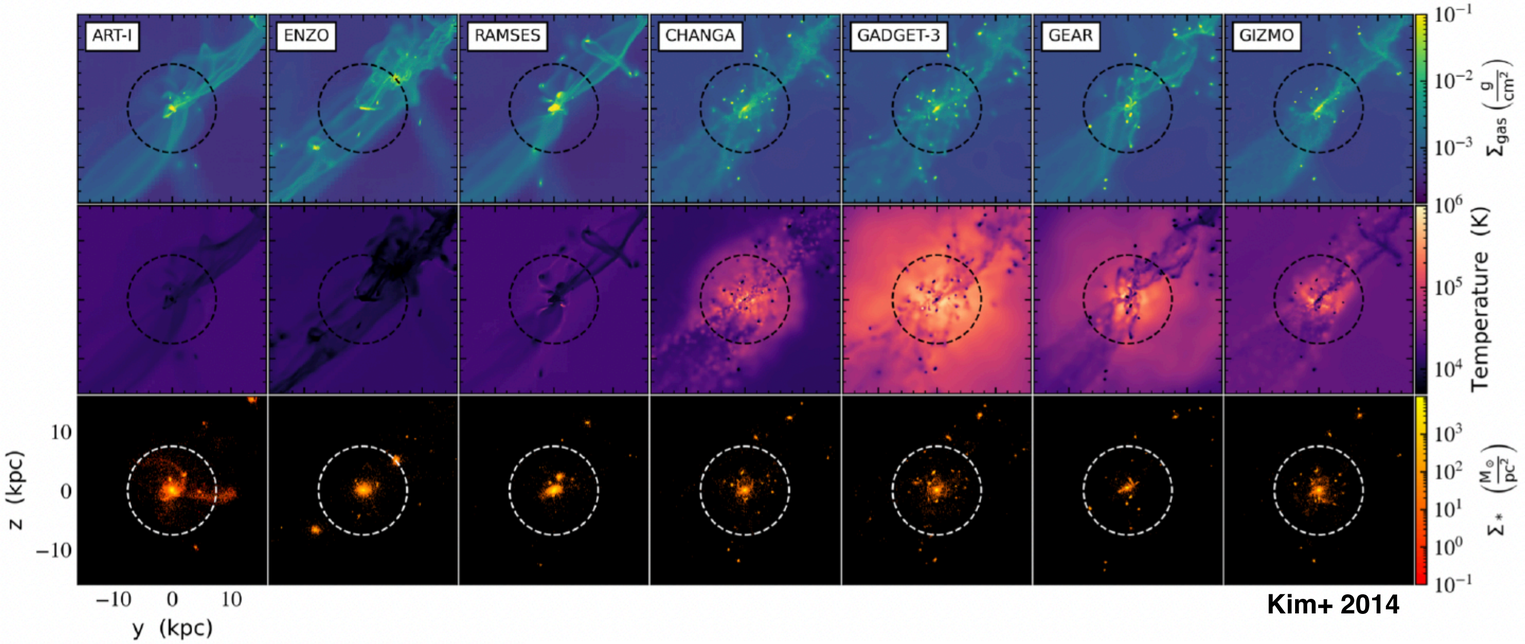




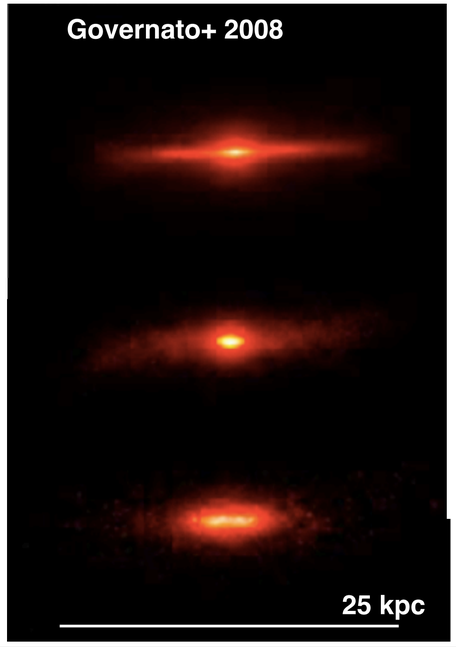




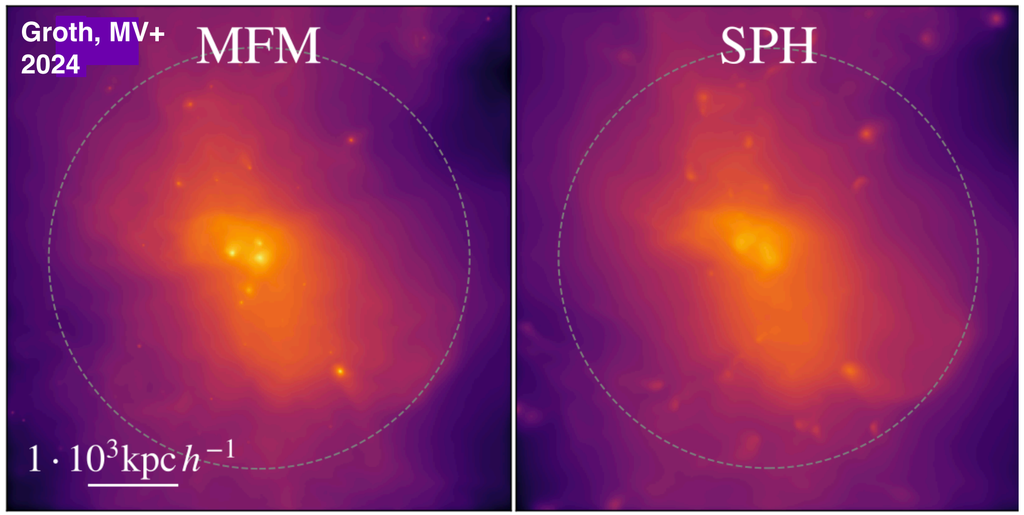
IMPACT OF NUMERICS AND SUB-GRID PHYSICS

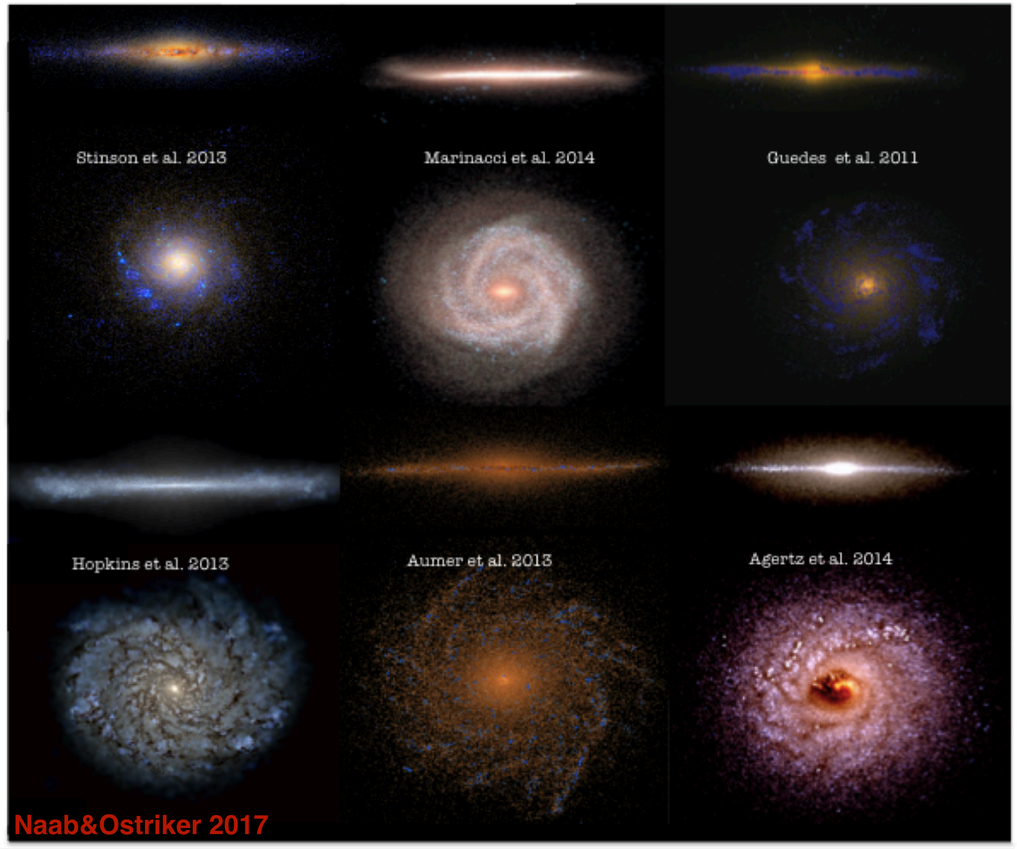


- **Sub-resolution physics modelling** is crucial
- **Resolution** and the **hydrodynamic scheme** play a significant role
- **Effective** description of **star formation, BH growth and feedback** processes



Resolution





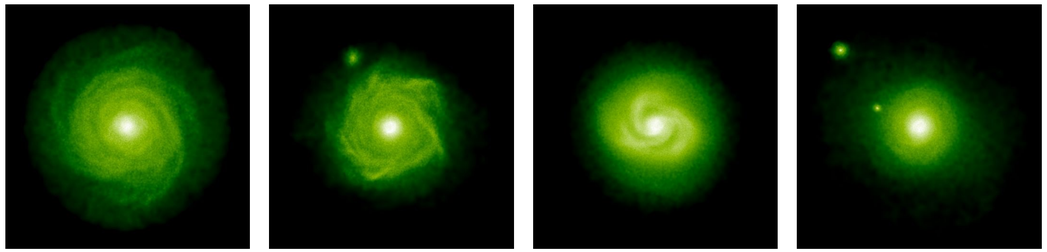
IMPACT OF SUB-GRID PHYSICS: A CASE STUDY

Effect of stellar feedback modelling on the formation of a disc galaxy

GOAL: Explore different feedback models to highlight the **variation in final results by modifying only the description of galactic outflows**.

1. How sensitive are the **properties** of a **galaxy** to **different galactic outflow models**?

2. Which are the requirements for a galactic outflow model that lead to the formation of a disc galaxy?



- Zoom-in simulations: halo of $M_{\rm vir} \simeq 2 \cdot 10^{12}\,{\rm M}_{\odot}$
- Box size: $L = 100\,h^{-1}\,{\rm Mpc}$
- Resolution:
  - mass of DM particles: $1.6 \cdot 10^{6}\,h^{-1}\,{\rm M}_{\odot}$
  - mass of gas particles: $3.0 \cdot 10^{5}\,h^{-1}\,{\rm M}_{\odot}$
  - softening length: $325\,h^{-1}\,{\rm pc}$

Valentini, Murante, Borgani+ 2017

COSMOLOGICAL SIMULATIONS

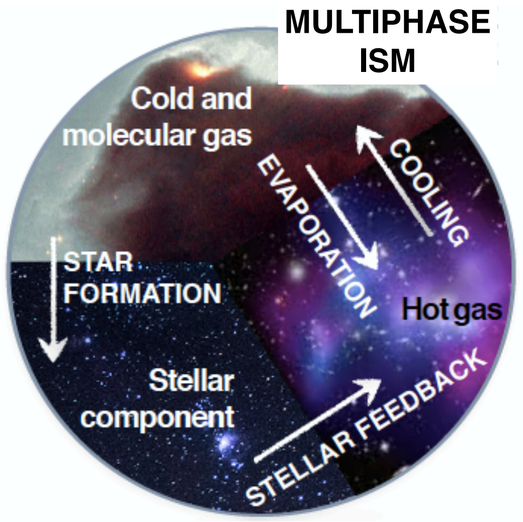
Code: GADGET-3 (TreePM+SPH, Springel 2005, Beck+ 2016)

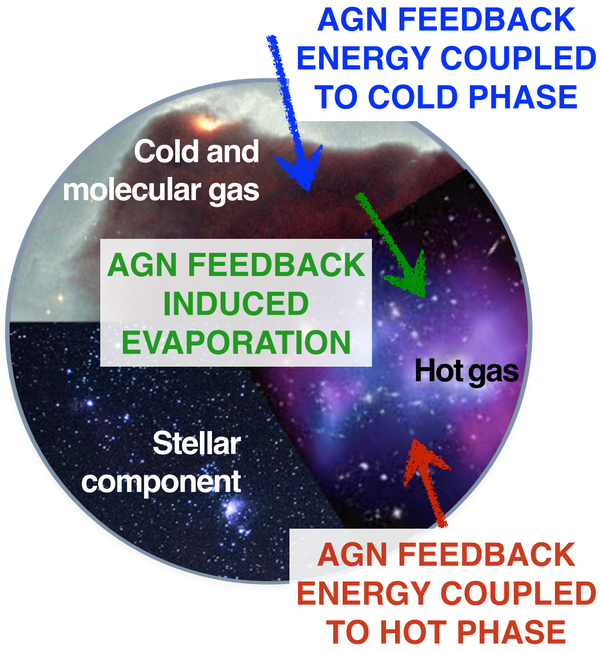
→ Sub-resolution model: MUPPI (Murante+ 2010, 2015, Valentini+ 2017-2023)

- Multiphase gas particles: **hot, cold** and **stellar** components
- Mass and energy flows between components
- Dust formation and evolution (Granato+ 2021, Parente+ 2022)
- H_2-based star formation (Valentini+ 2023, Ragone-Figueroa+ 2024)

→ Thermal and kinetic + low-metallicity stellar feedback

→ Metal-dependent cooling and chemical enrichment (Tornatore+ 2007)





AGN feedback (Valentini+ 2020)

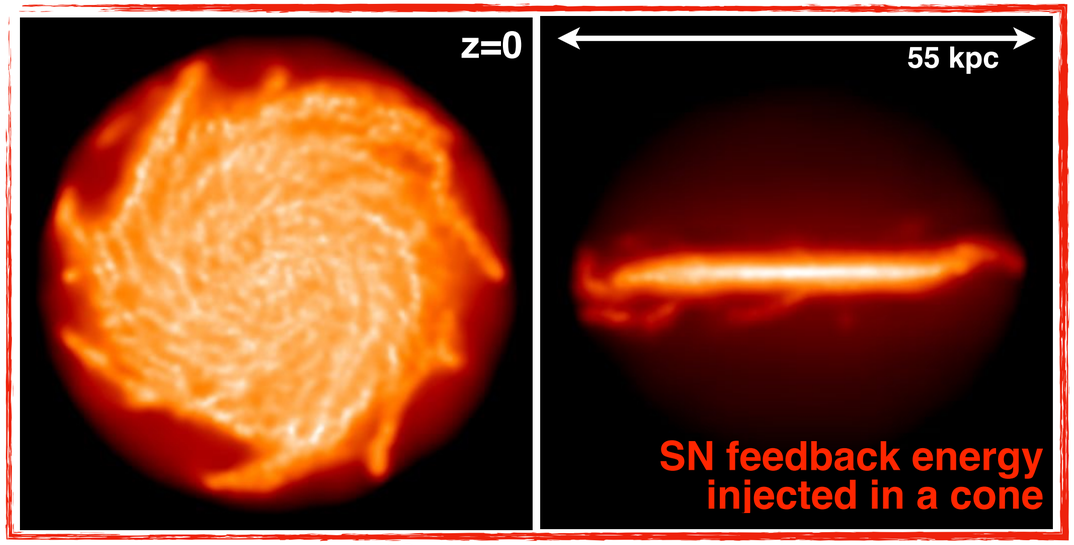
→ Refined description of the gas accretion process

- AGN feeding: angular momentum dependent, Eddington-limited, hot and cold gas accretion

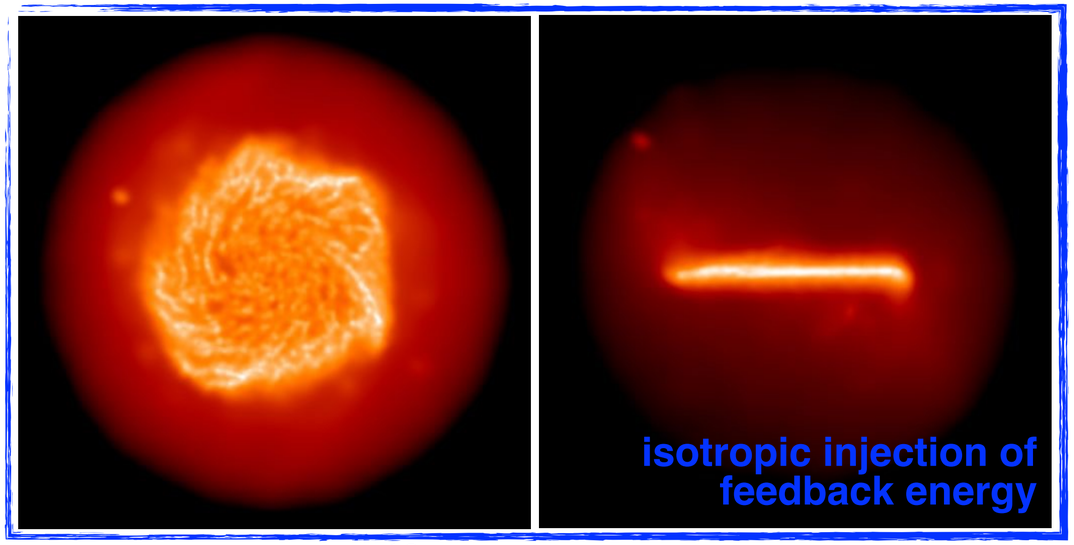
→ Accurate modelling of AGN feedback energy distribution among the gas phases

- AGN feedback coupled to hot and cold gas depending on their physical properties (i.e. covering factor)

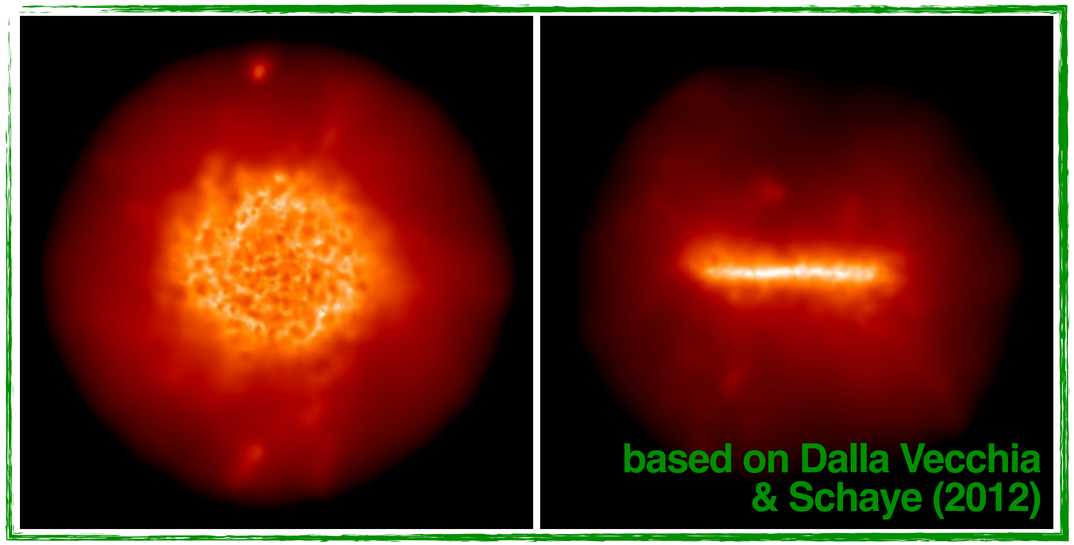
STELLAR FEEDBACK: IMPACT ON GALAXY MORPHOLOGY



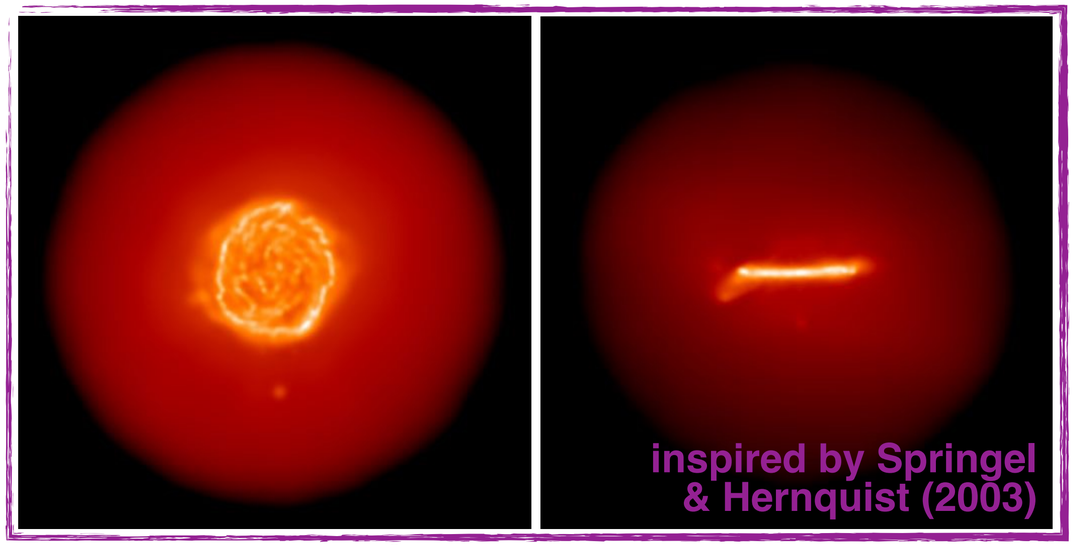
$M_{gas} = 2.91 \cdot 10^{10}\, M_\odot$



$M_{gas} = 2.07 \cdot 10^{10}\, M_\odot$



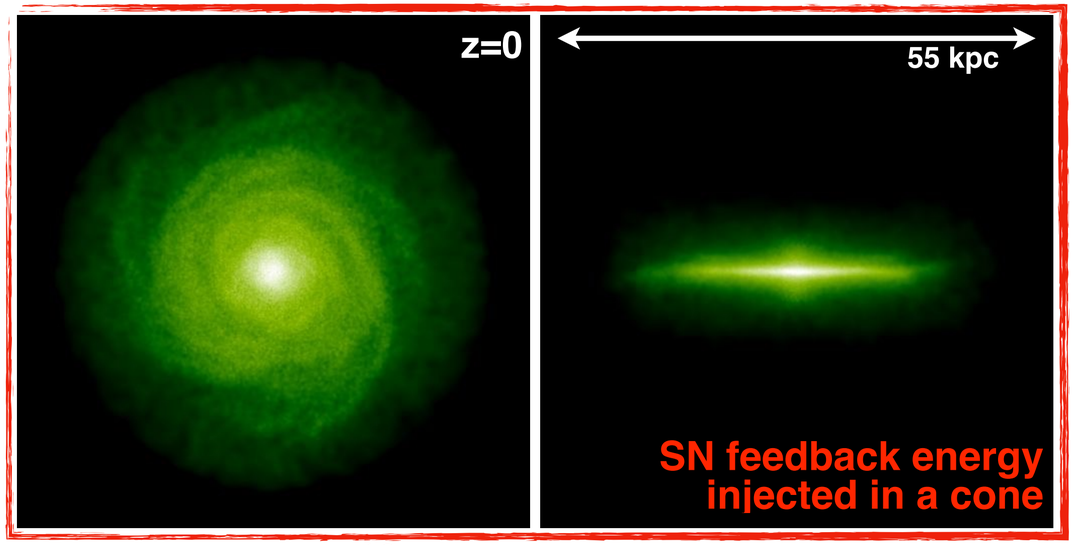
$M_{gas} = 3.33 \cdot 10^{10} M_\odot$



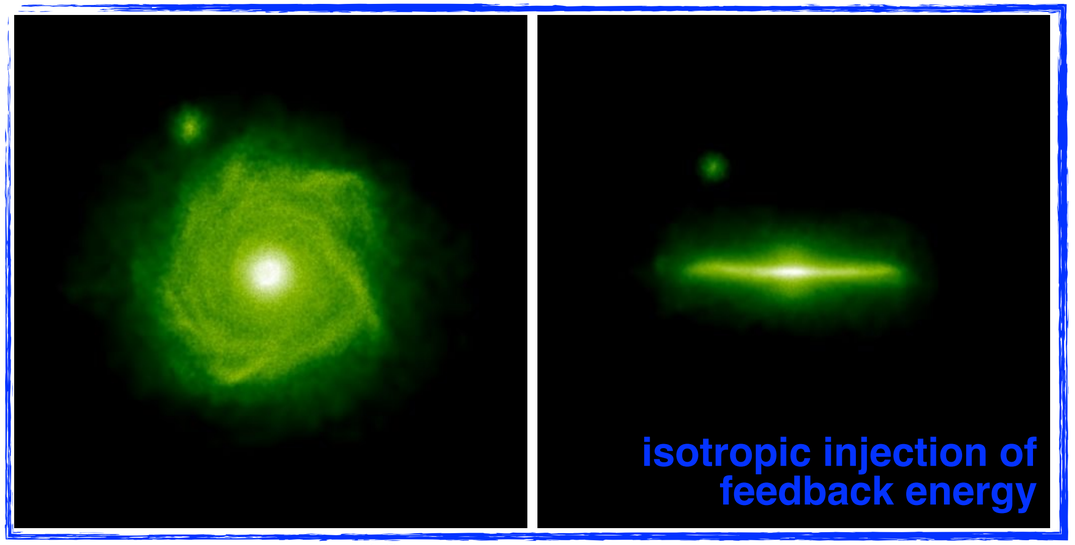
$M_{gas} = 8.82 \cdot 10^{9}\, M_\odot$

Valentini, Murante, Borgani+ 2017

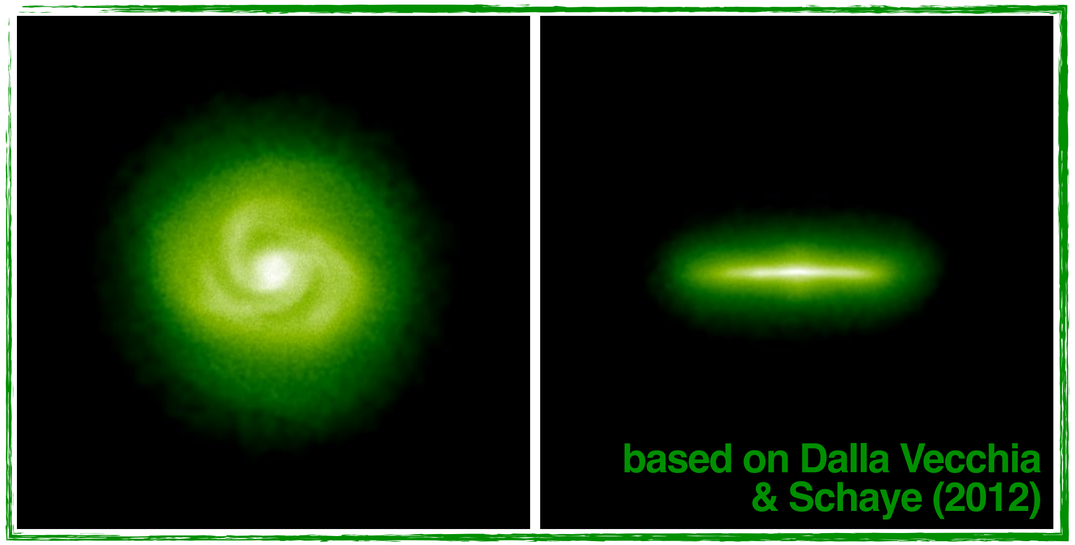
STELLAR FEEDBACK: IMPACT ON GALAXY MORPHOLOGY



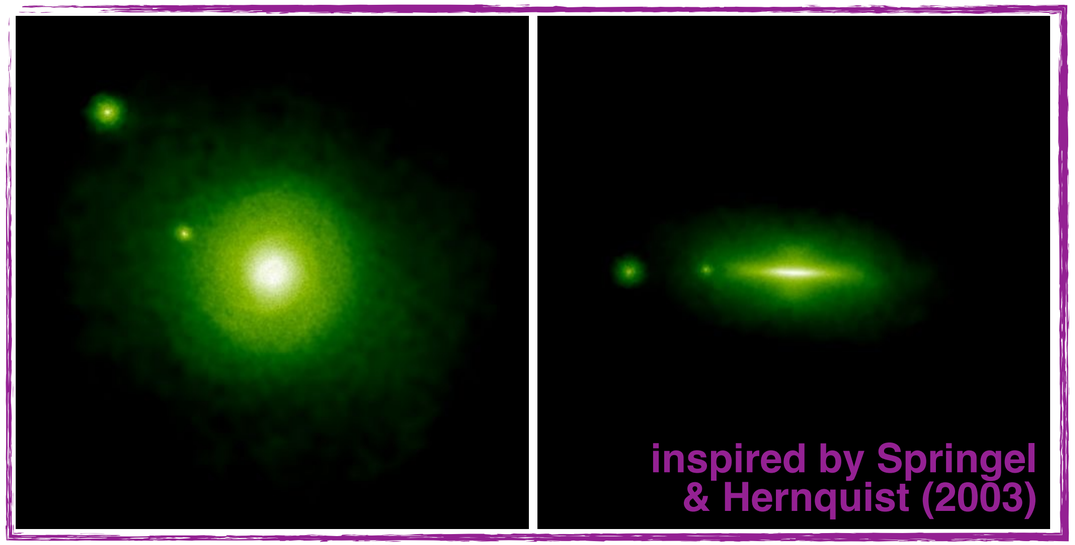
$M_* = 4.74 \cdot 10^{10}\,M_\odot$



$M_* = 3.29 \cdot 10^{10}\,M_\odot$



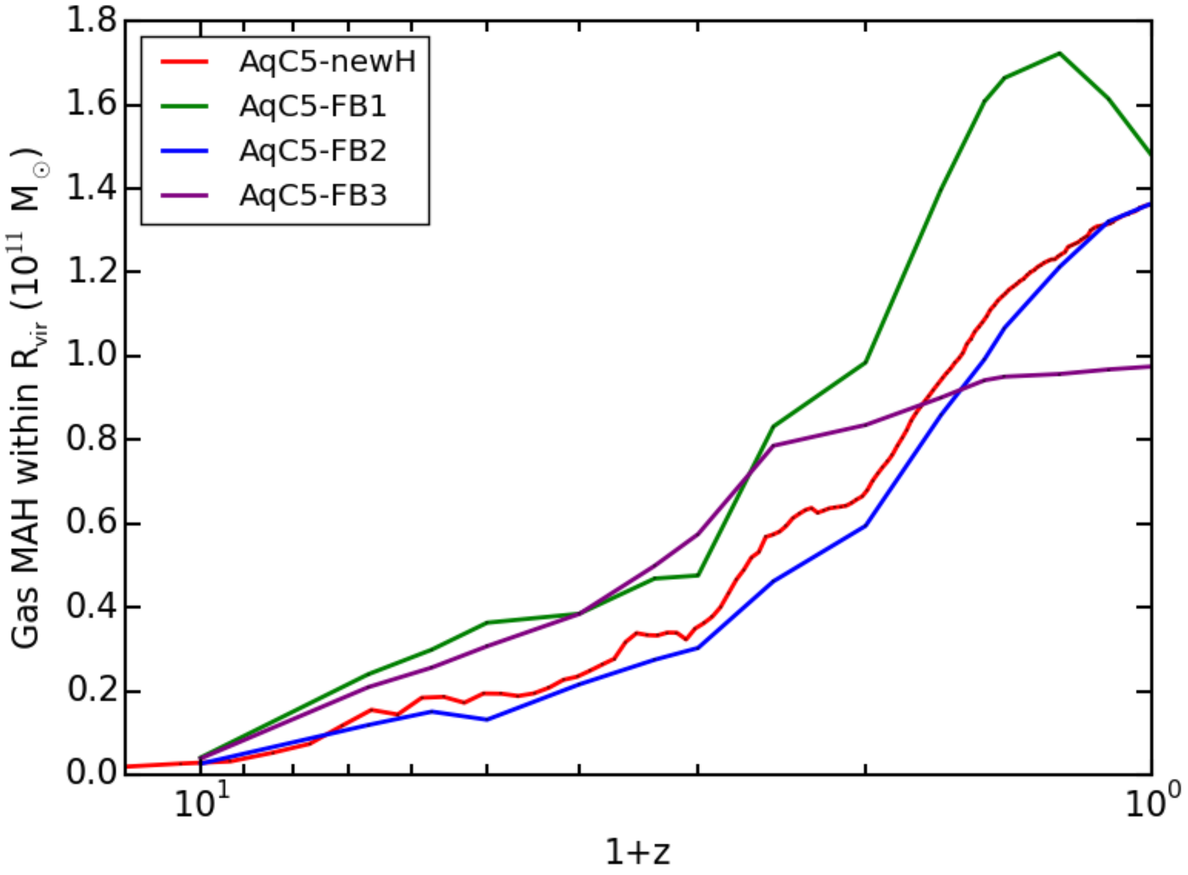
$M_* = 9.34 \cdot 10^{10} M_\odot$



$M_* = 2.94 \cdot 10^{10}\,M_\odot$

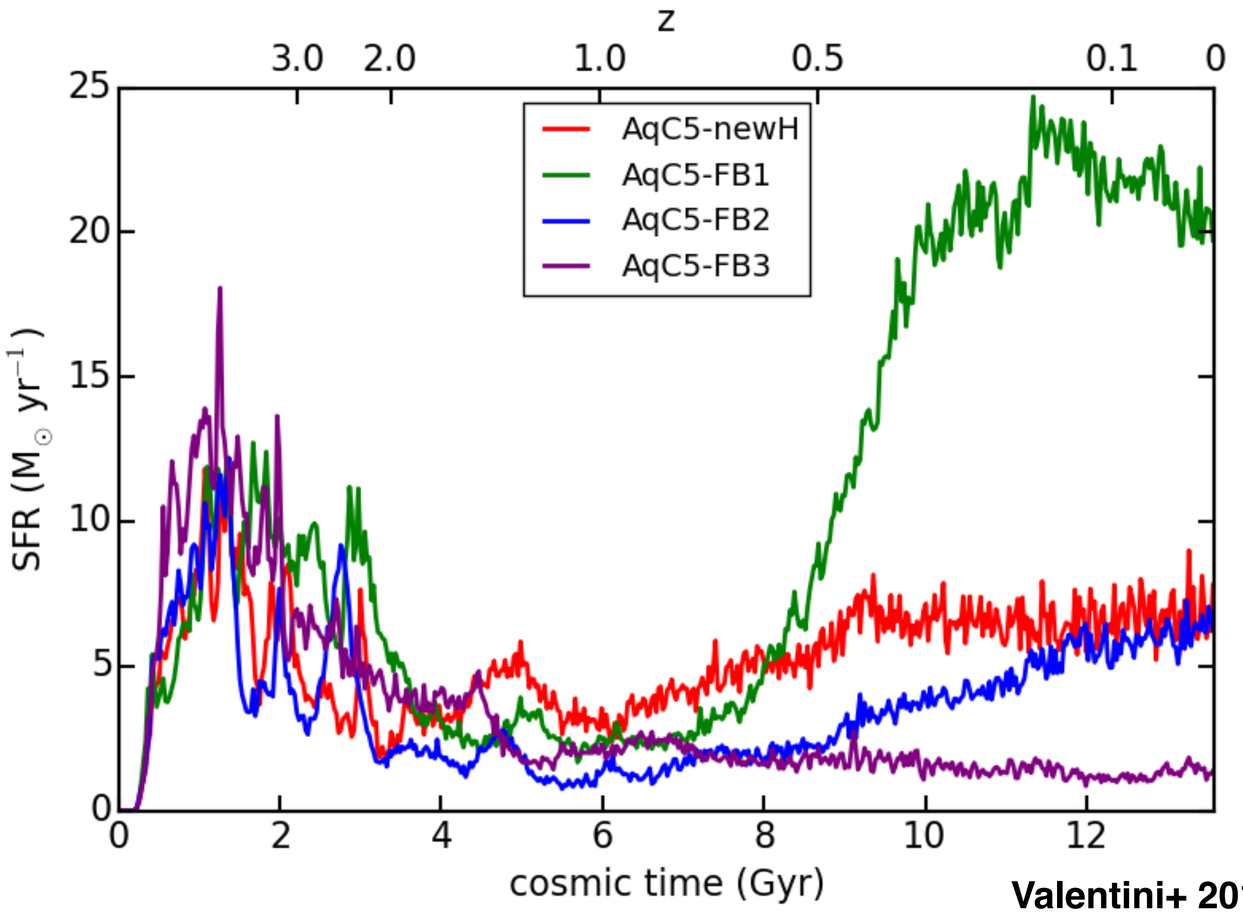
Valentini, Murante, Borgani+ 2017

STELLAR FEEDBACK: IMPACT ON GALAXY MORPHOLOGY



Gas mass accretion history

Effect of different outflow models on the regulation of gas accretion: key differences in **galaxy stellar mass** at low z

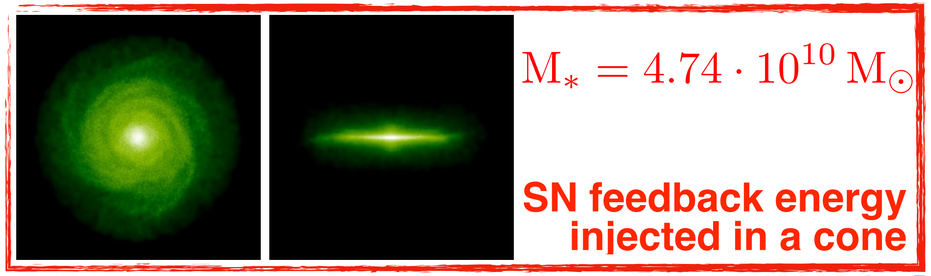


Star formation history

Galactic outflow models determine the galaxy star formation rate

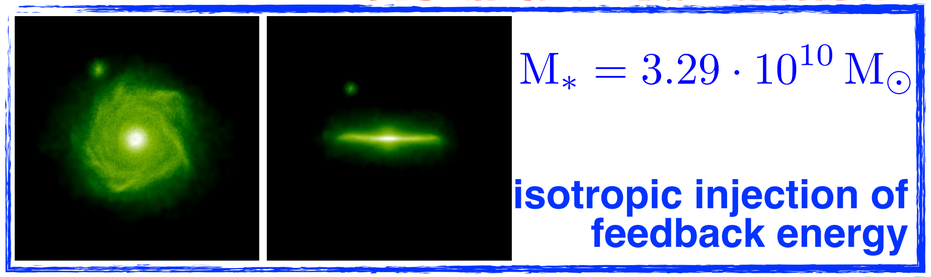
Valentini+ 2017

STELLAR FEEDBACK: IMPACT ON GALAXY MORPHOLOGY



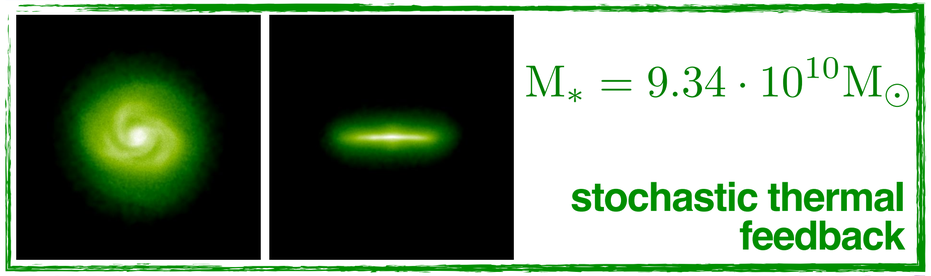
$M_* = 4.74 \cdot 10^{10}\, M_\odot$

SN feedback energy injected in a cone



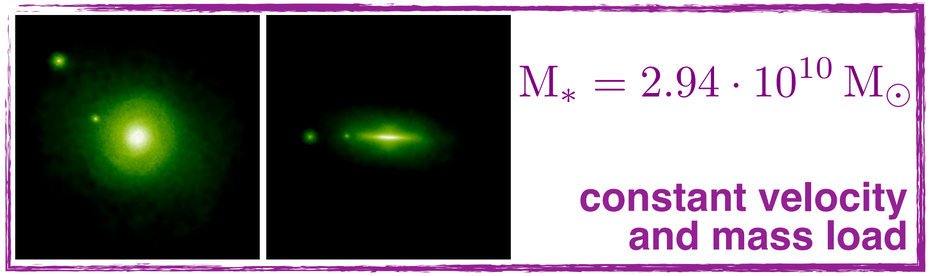
$M_* = 3.29 \cdot 10^{10}\, M_\odot$

isotropic injection of feedback energy



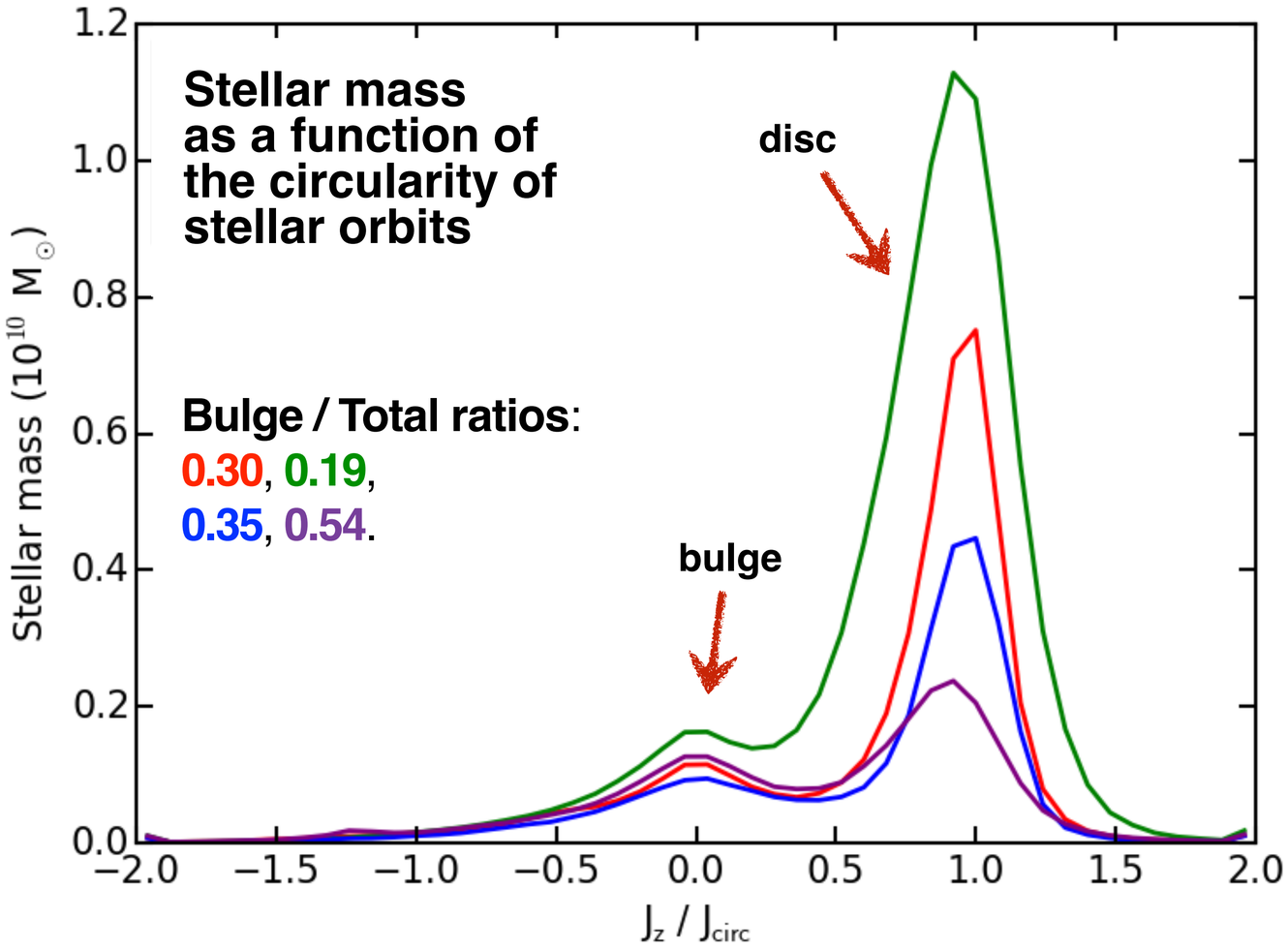
$M_* = 9.34 \cdot 10^{10} M_\odot$

stochastic thermal feedback



$M_* = 2.94 \cdot 10^{10}\, M_\odot$

constant velocity and mass load



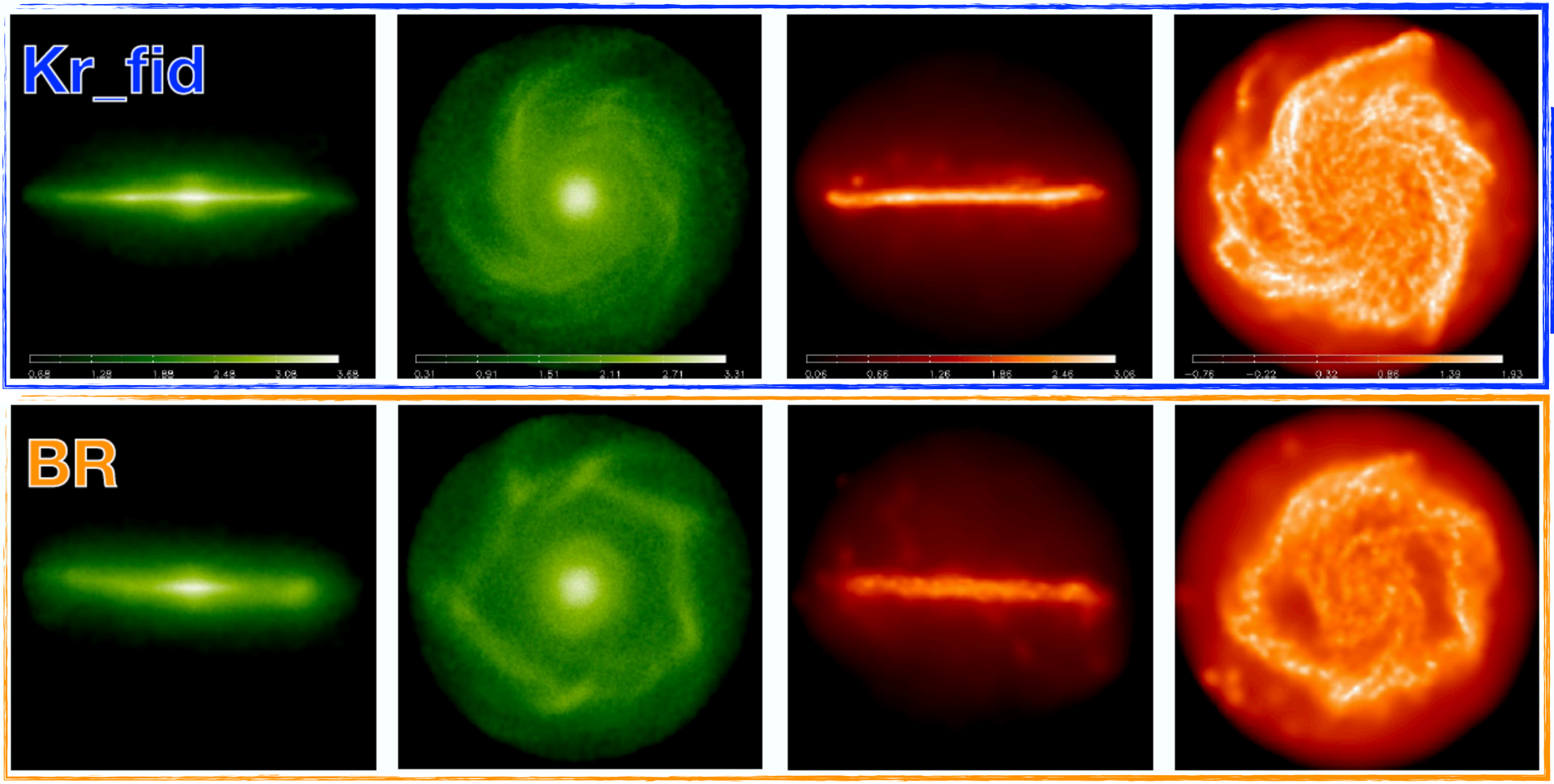
Prominence of the bulge component: sensitive dependence on the adopted stellar feedback model

Valentini, Murante, Borgani+ 2017

STAR FORMATION: NUMERICAL MODELLING OF MOLECULAR GAS

→ Different assumptions on the modelling of the molecular gas fraction affect the instantaneous SFR and galaxy properties

$$\dot{M}_{\rm SF} = \epsilon_{\rm SF} \frac{f_{\rm H2} M_{\rm cold}}{\tau}$$



Valentini, Dolag, Borgani+ 2023

$$f_{\rm H2}(\Sigma, Z) = 1 - \left(1 + \left(\frac{3}{4}\frac{s}{1+\delta}\right)^{-5}\right)^{-1/5}$$

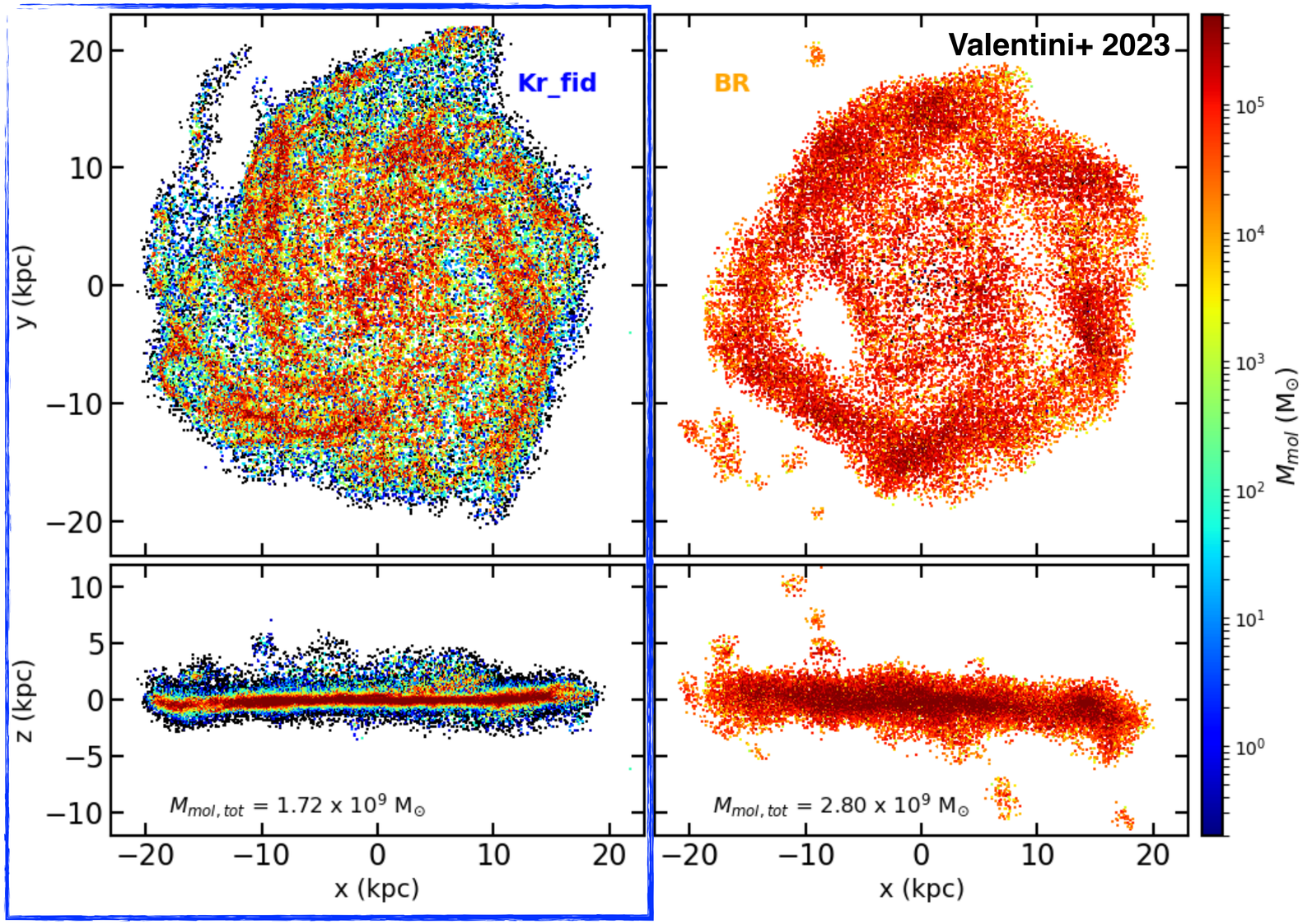
$$s \propto \frac{\ln(1+\chi)}{\Sigma Z} \qquad \chi \propto Z^{0.365} \qquad \delta \propto s^{2.8}$$

Krumholz+ 2009 theoretical model

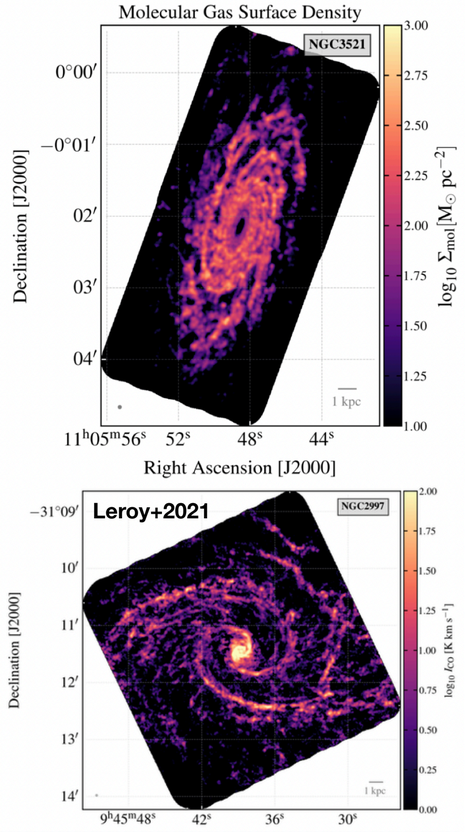
$$f_{\rm H2}(n) = \frac{1}{1 + P_0/P}$$

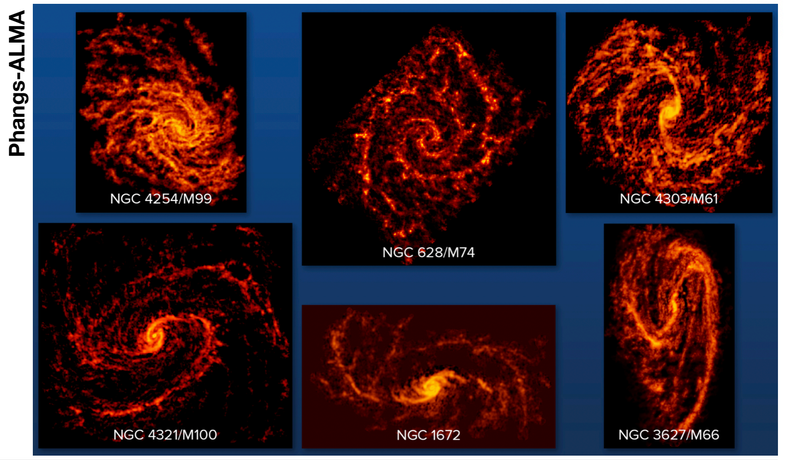
Blitz&Rosolowsky 2006 phenomenological prescription

STAR FORMATION: NUMERICAL MODELLING OF MOLECULAR GAS



Galaxies simulated adopting the Krumholz model to estimate the molecular gas have a clumpier ISM and a morphology in better agreement with observations

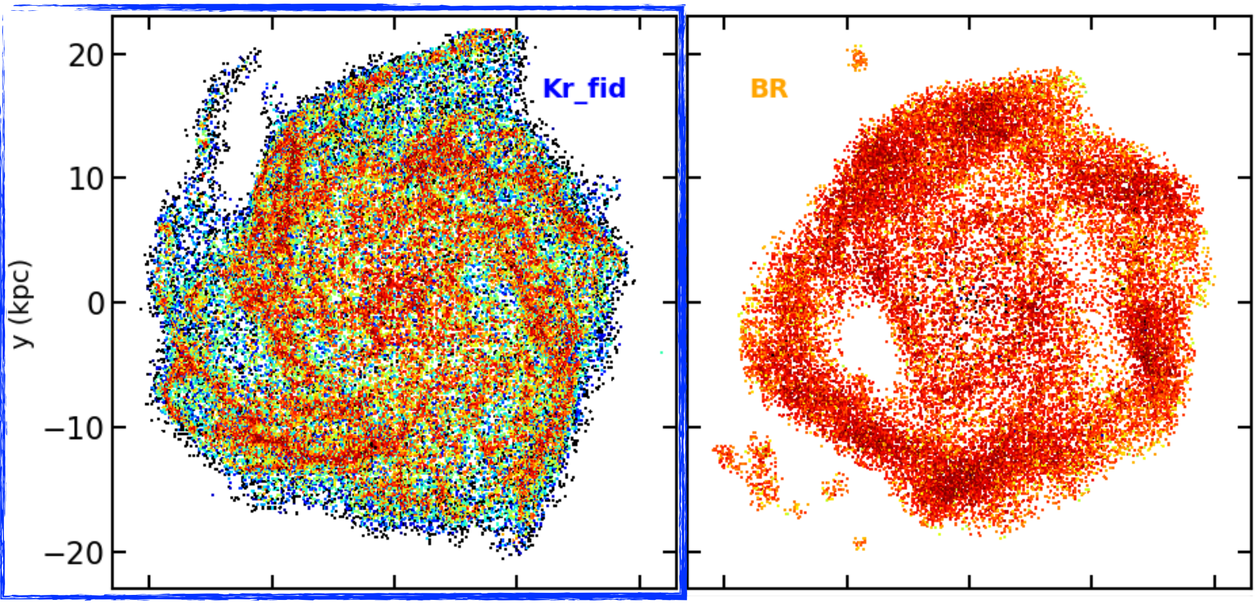




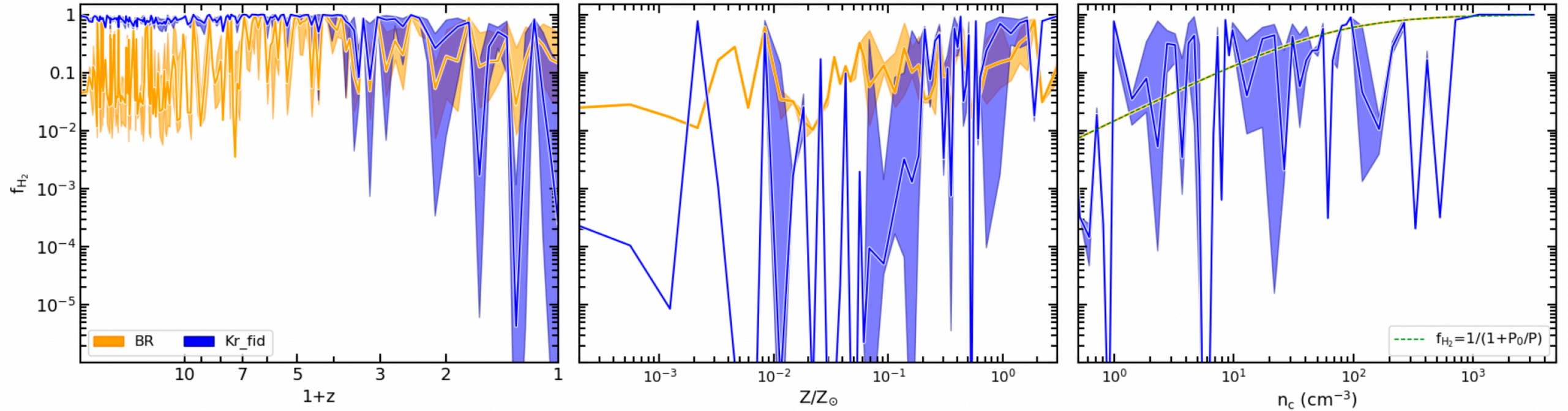
→ Final properties (e.g. morphology) of simulated galaxies help in supporting or disfavouring different models to estimate the SFR

STAR FORMATION: NUMERICAL MODELLING OF MOLECULAR GAS

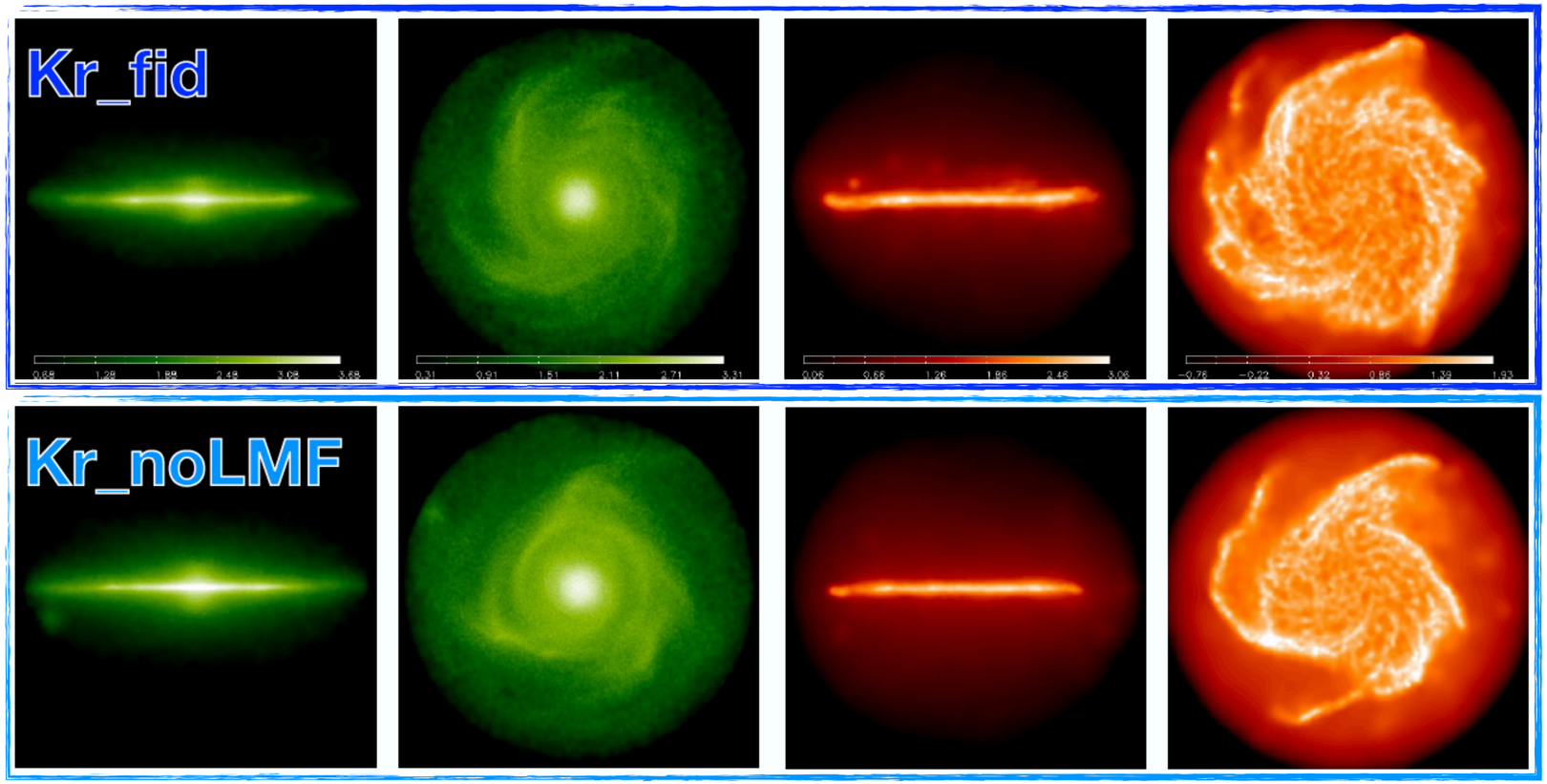
Valentini, Dolag, Borgani+ 2023



Fraction of H_2 as a function of redshift, metallicity and density



EFFECT OF LOW-METALLICITY FEEDBACK

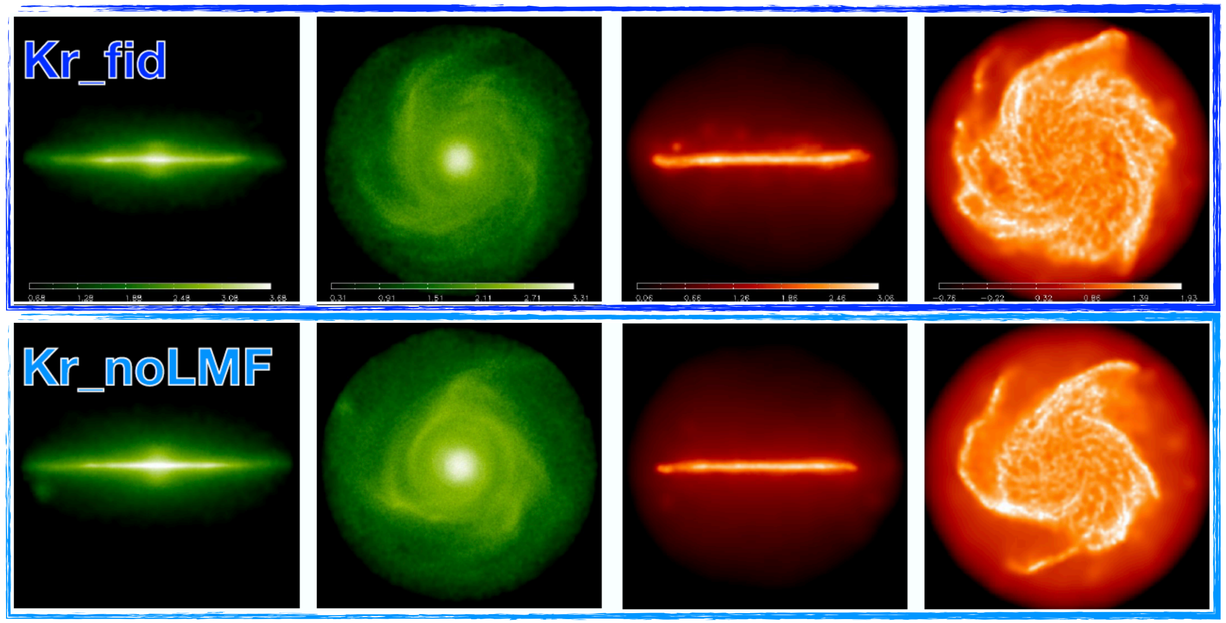


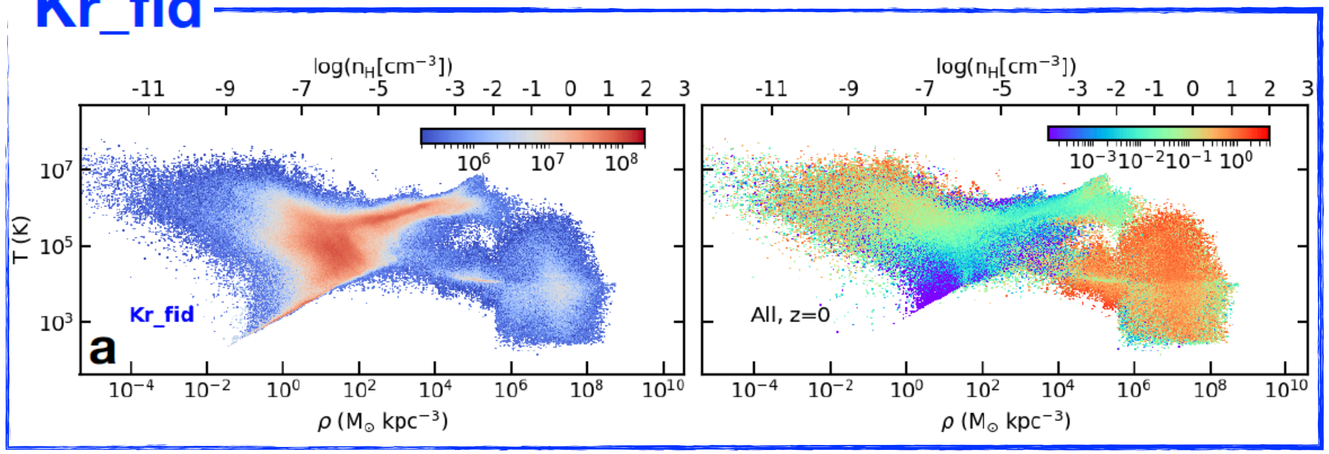
- Stellar feedback from low-metallicity environments (LMF): larger amount of feedback energy from SNe exploding in pristine ISM, mimicking Pop III stars

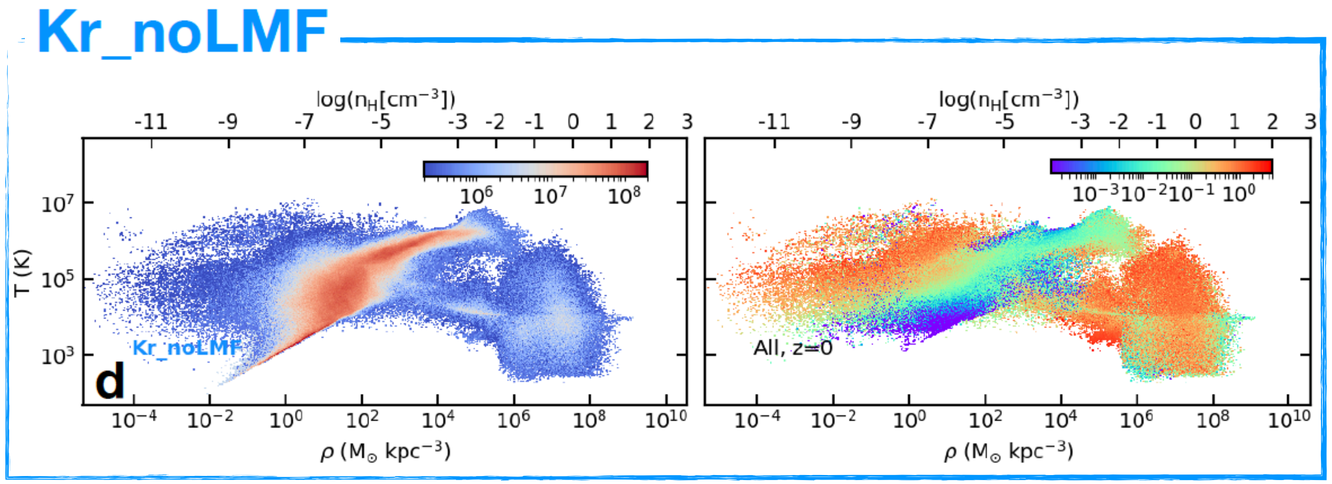
- Impact at all redshifts: LMF promotes a long-lasting modification of gas cooling properties

Valentini, Dolag, Borgani+ 2023

EFFECT OF LOW-METALLICITY FEEDBACK



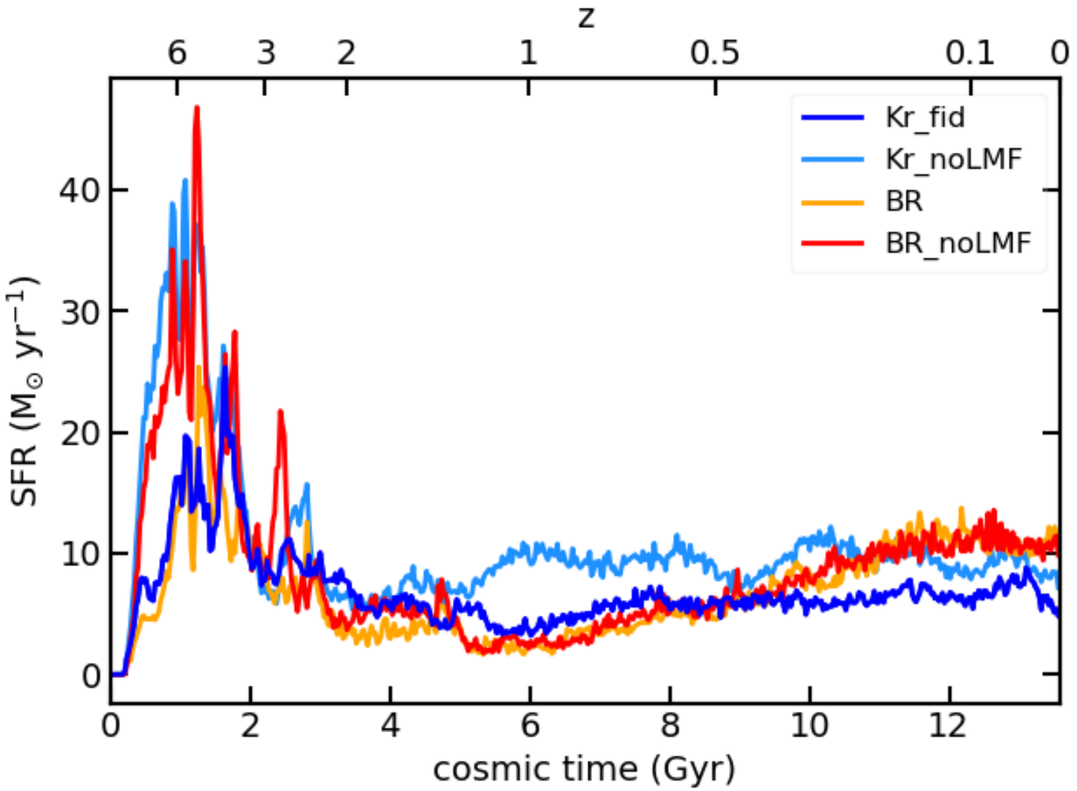


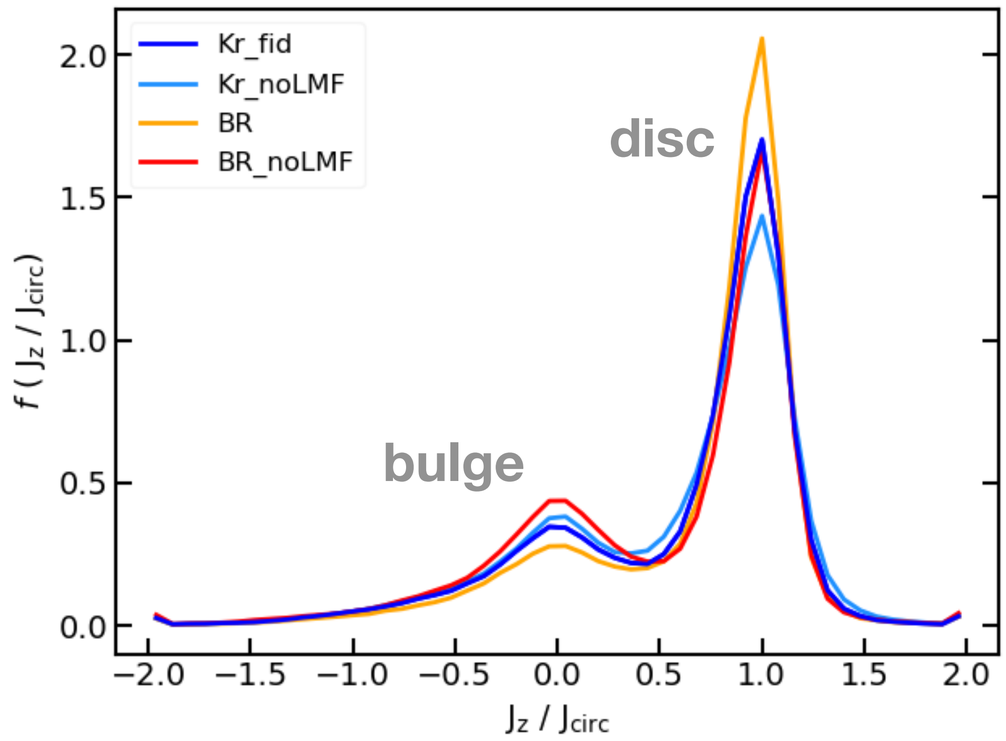


→ Impact at all redshifts:
LMF promotes
a long-lasting modification
of gas cooling properties

Valentini, Dolag, Borgani+ 2023

IMPACT OF H_2 AND LOW-METALLICITY FEEDBACK MODELLING

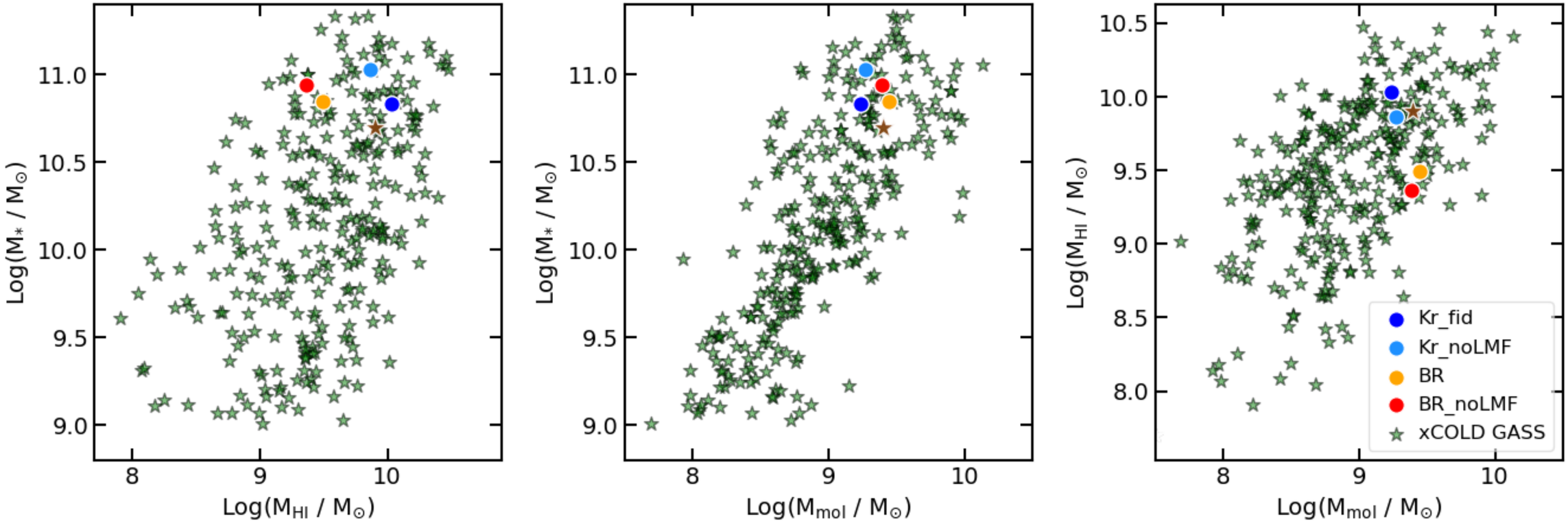




Simulation	r_{vir} (kpc)	M_{gas} (10^{11} $M_\odot$) $r < r_{vir}$	M_{gas} (10^{11} $M_\odot$) $< r_{gal}$	M_{HI} (10^{10} $M_\odot$) $< r_{gal}$	M_{mol} (10^{9} $M_\odot$) $< r_{gal}$	M_* (10^{10} $M_\odot$) $< r_{gal}$	B/T	r_s (kpc)
Kr_ fid	240.8	1.18	0.24	1.07	1.72	6.84	0.36	4.1 ± 0.1
Kr_noLMF	243.8	1.37	0.21	0.73	1.87	10.69	0.38	4.1 ± 0.1
BR	240.8	1.23	0.14	0.31	2.80	7.02	0.29	4.4 ± 0.2
BR_noLMF	242.7	1.42	0.12	0.23	2.45	8.69	0.43	4.3 ± 0.2

Valentini, Dolag, Borgani+ 2023

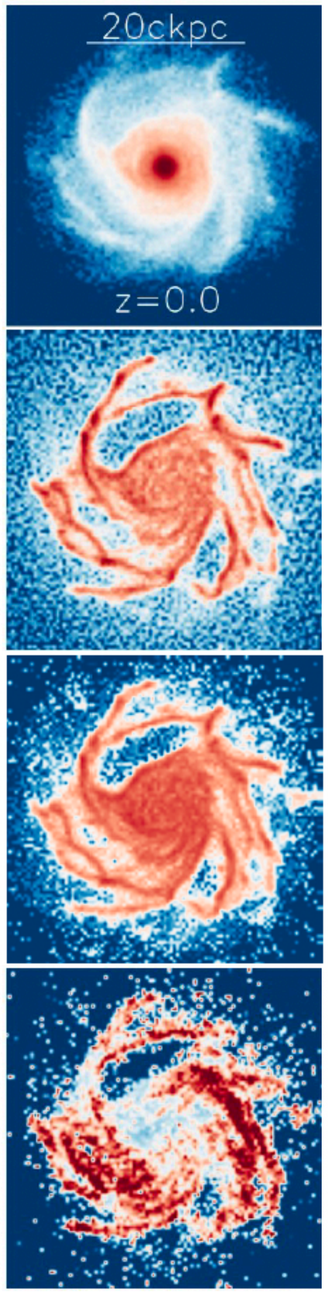
IMPACT OF H_2 AND LOW-METALLICITY FEEDBACK MODELLING



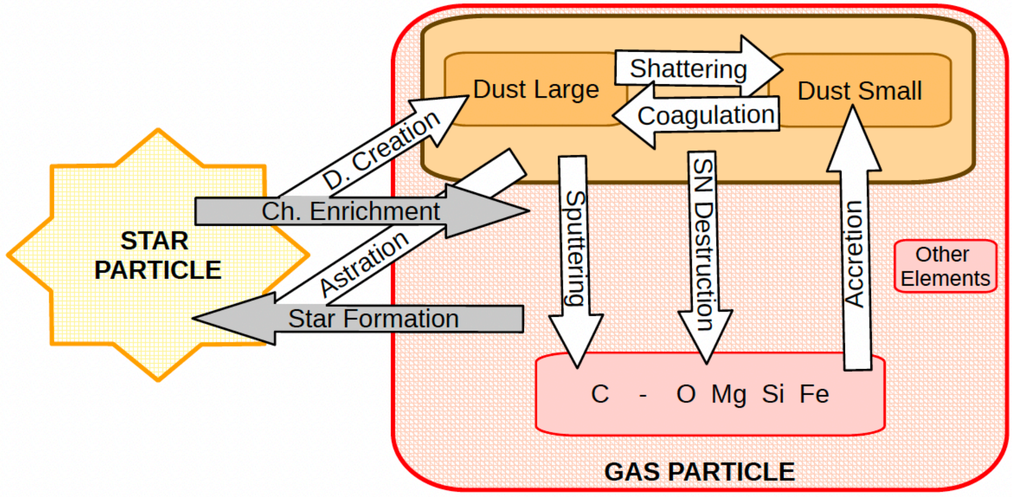
Simulation	r_{vir} (kpc)	M_{gas} (10^{11} $M_\odot$)		M_{HI} (10^{10} $M_\odot$)	M_{mol} (10^{9} $M_\odot$)	M_* (10^{10} $M_\odot$)
		$r < r_{vir}$	$< r_{gal}$	$< r_{gal}$	$< r_{gal}$	$< r_{gal}$
Kr_ fid	240.8	1.18	0.24	1.07	1.72	6.84
Kr_noLMF	243.8	1.37	0.21	0.73	1.87	10.69
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Valentini, Dolag, Borgani+ 2023

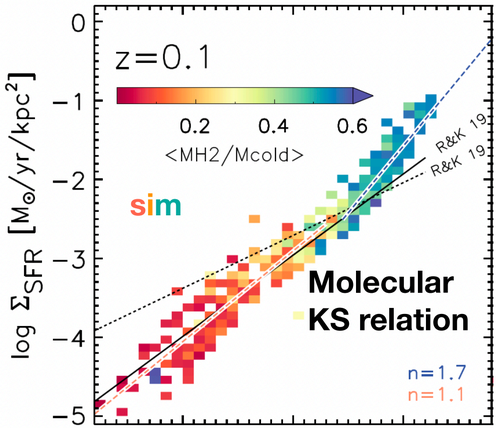
IMPACT OF H_2 MODELLING: FORMING H_2 ON DUST GRAINS

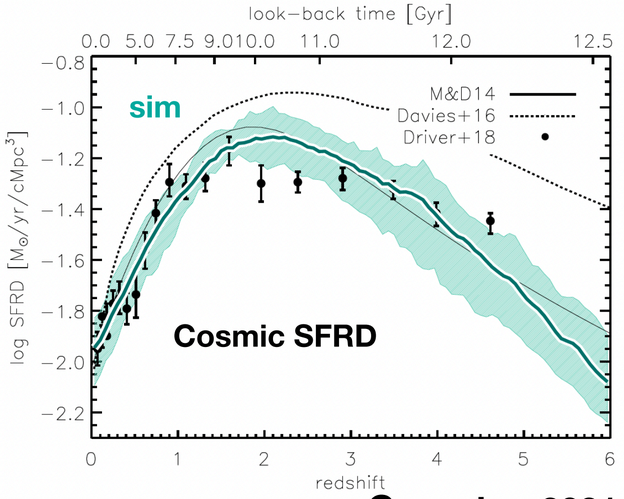


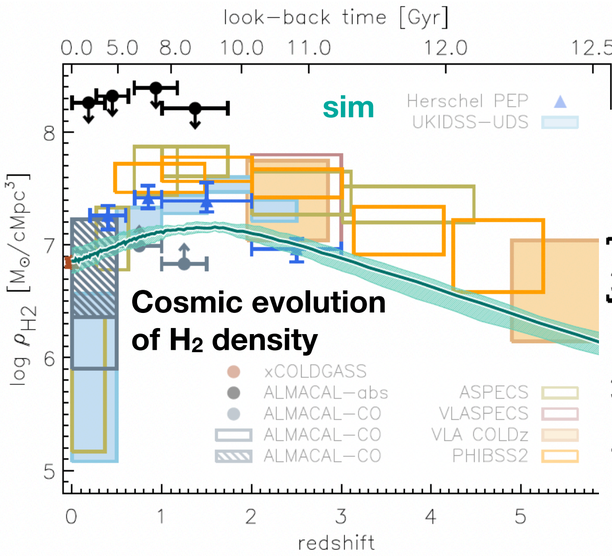
- Model for dust formation and evolution (two grain-size approach), plus dust-assisted cooling

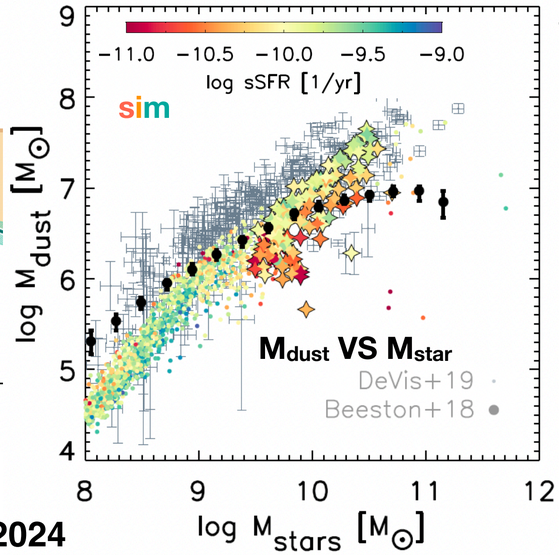


- Sub-grid modelling of H_2 formation on dust grain surface, with H_2 destruction by UV radiation, and dust + H_2 self shielding



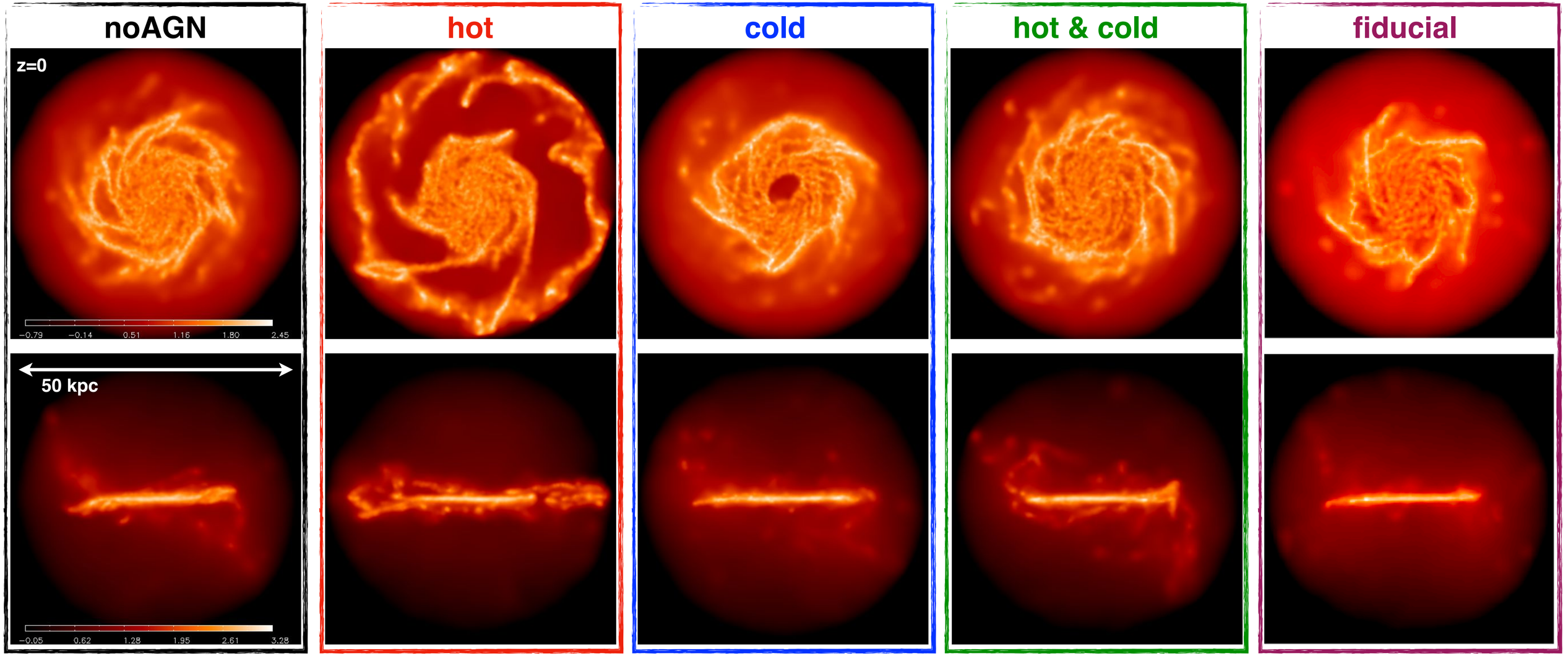






Granato+ 2021, Parente+ 2022, Ragone-Figueroa+ 2024

DISTRIBUTING AGN FEEDBACK TO THE DIFFERENT PHASES OF THE ISM

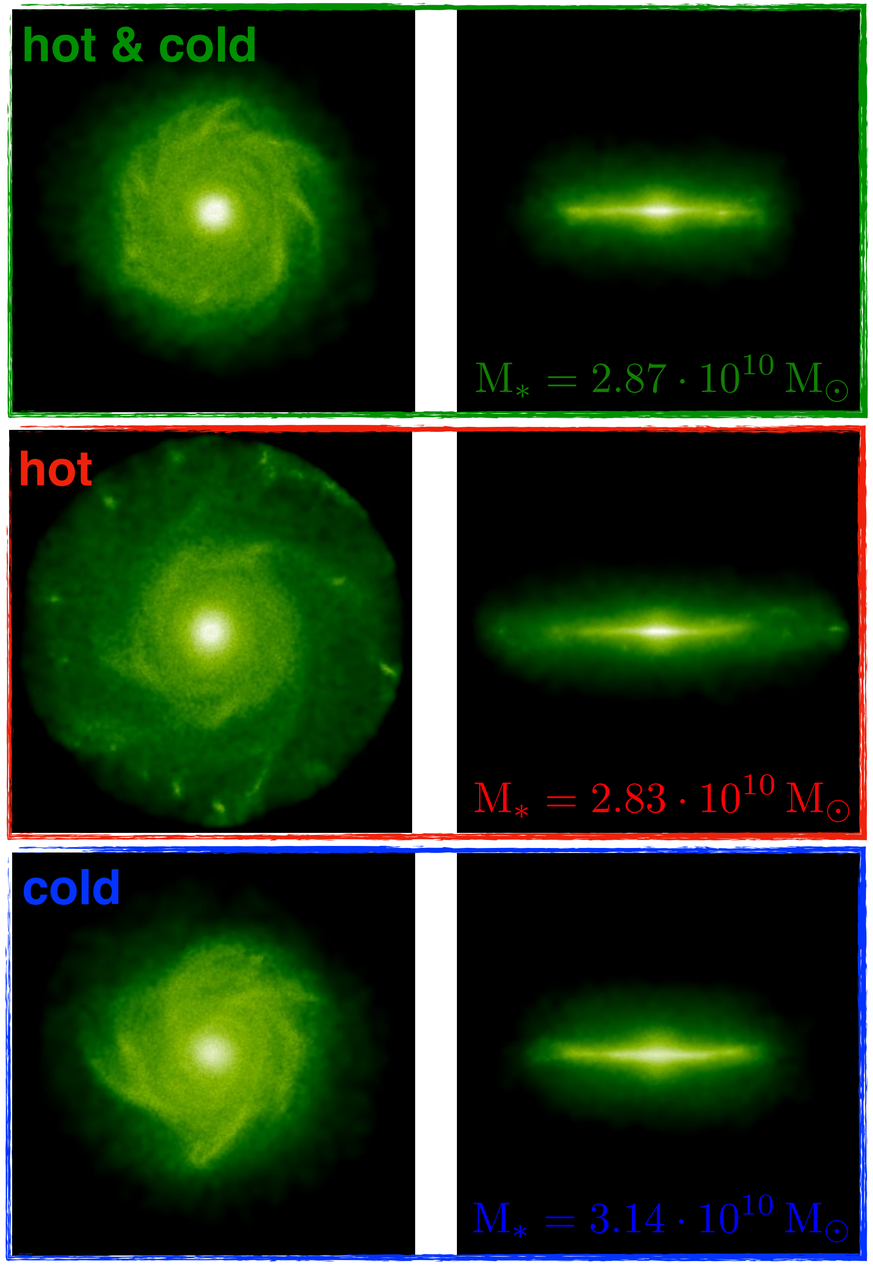


$\mathbf{M}_{\mathrm{gas}} = 2.34 \times 10^{10}\ \mathbf{M}_{\odot}$ $\mathbf{M}_{\mathrm{gas}} = 2.55 \times 10^{10}\ \mathbf{M}_{\odot}$ $\mathbf{M}_{\mathrm{gas}} = 2.56 \times 10^{10}\ \mathbf{M}_{\odot}$ $\mathbf{M}_{\mathrm{gas}} = 2.54 \times 10^{10}\ \mathbf{M}_{\odot}$ $\mathbf{M}_{\mathrm{gas}} = 2.32 \times 10^{10}\ \mathbf{M}_{\odot}$

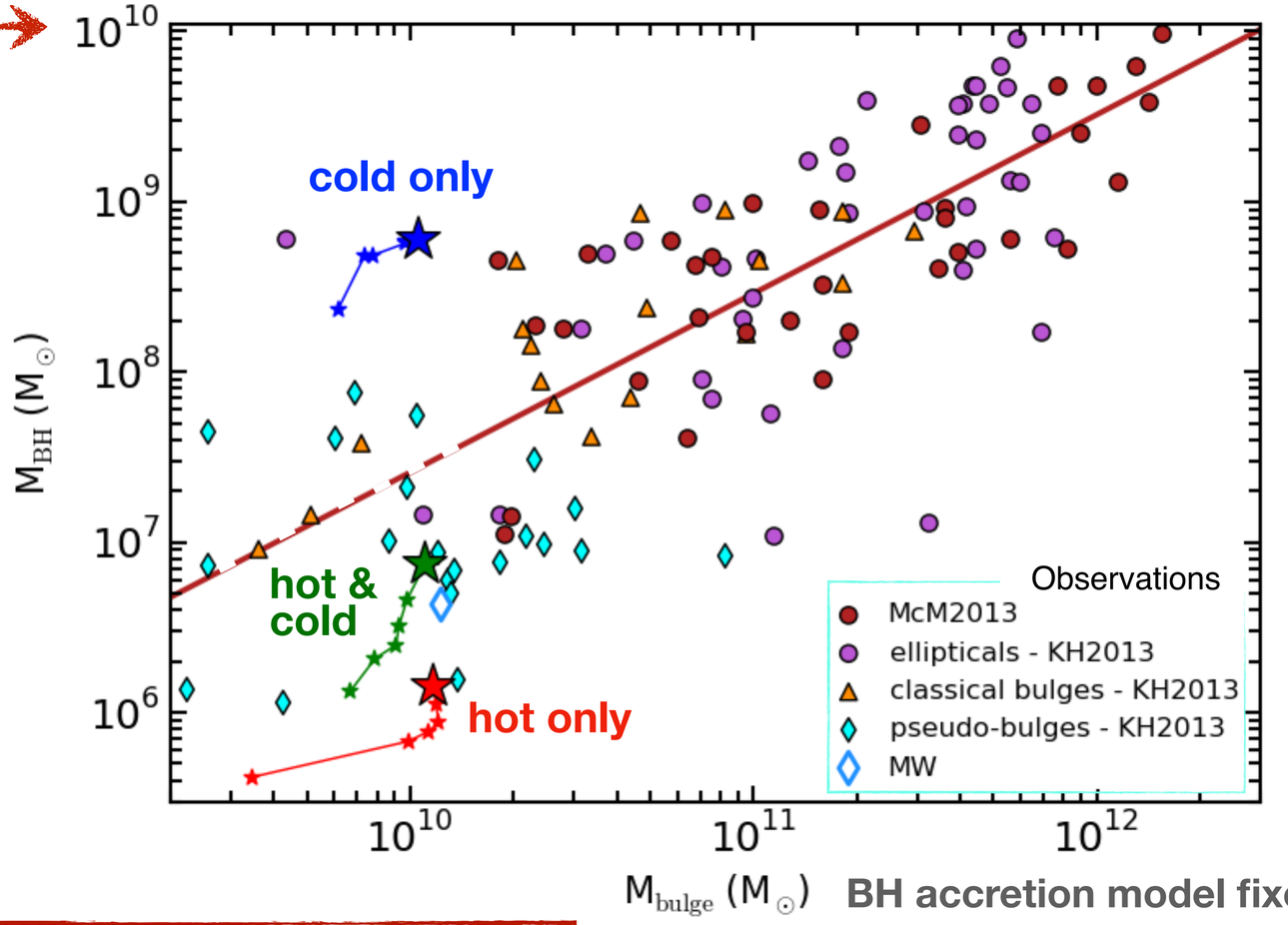
Cosmological simulations of a MW-size halo

Valentini, Murante, Borgani+ 2020

DISTRIBUTING AGN FEEDBACK TO THE DIFFERENT PHASES OF THE ISM



$M_{bulge} - M_{BH}$ relation



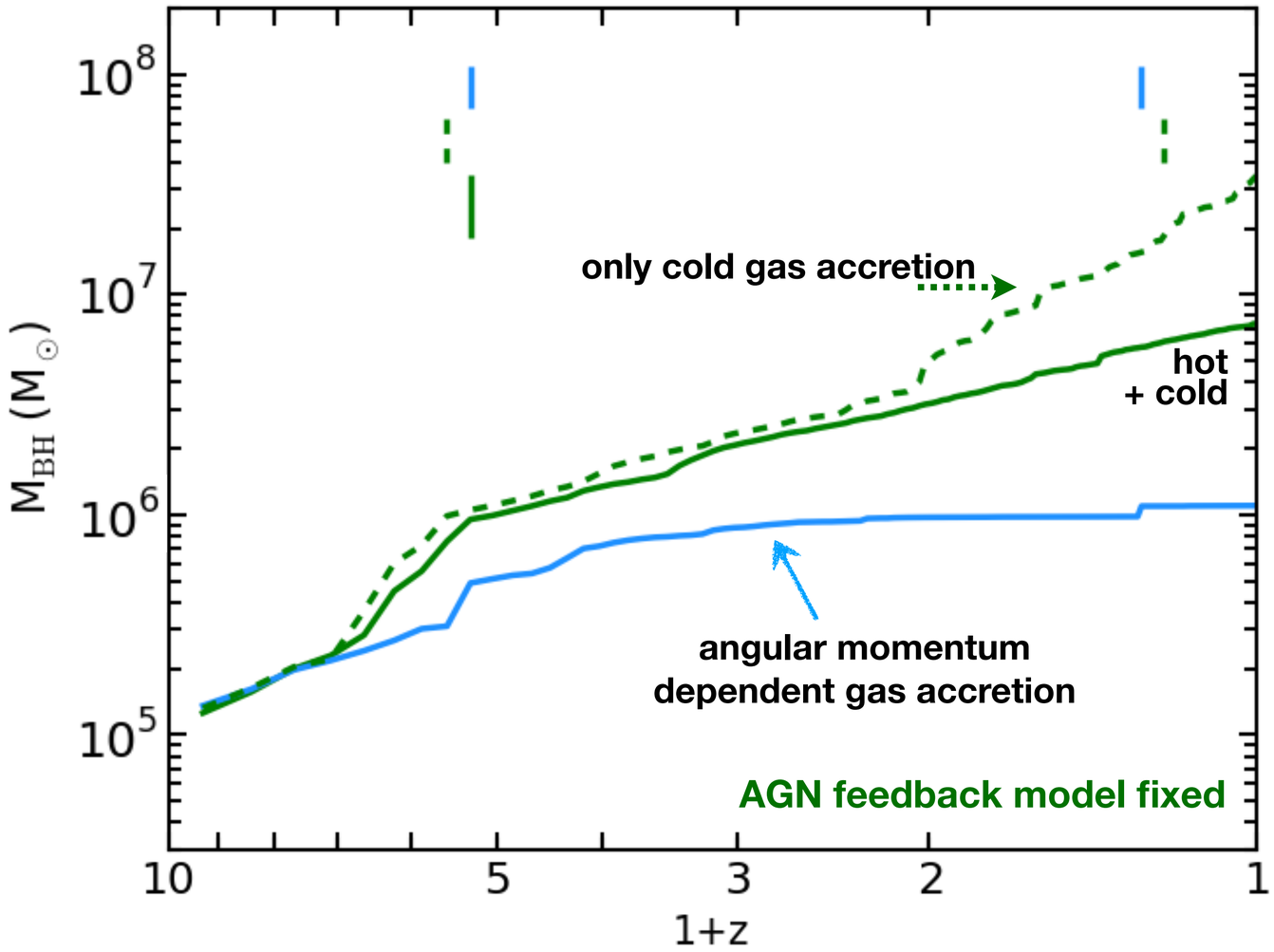
BH accretion model fixed

A fraction of **AGN feedback energy to be coupled with hot gas** to avoid excessive BH growth

Valentini, Murante, Borgani+ 2020

BH ACCRETION MODELLING

Cosmological simulations
of a MW-size halo



Cold gas accretion only
→ faster BH growth at low z

Limiting accretion by rotationally supported cold gas → suppression of the BH growth at low z

→ Different **models of gas accretion** impact on the connection between **BH growth - galaxy formation**

→ **Angular momentum-dependent BH accretion** key to reproduce observed **correlation BH-bulge properties**

Valentini, Murante, Borgani+ 2020

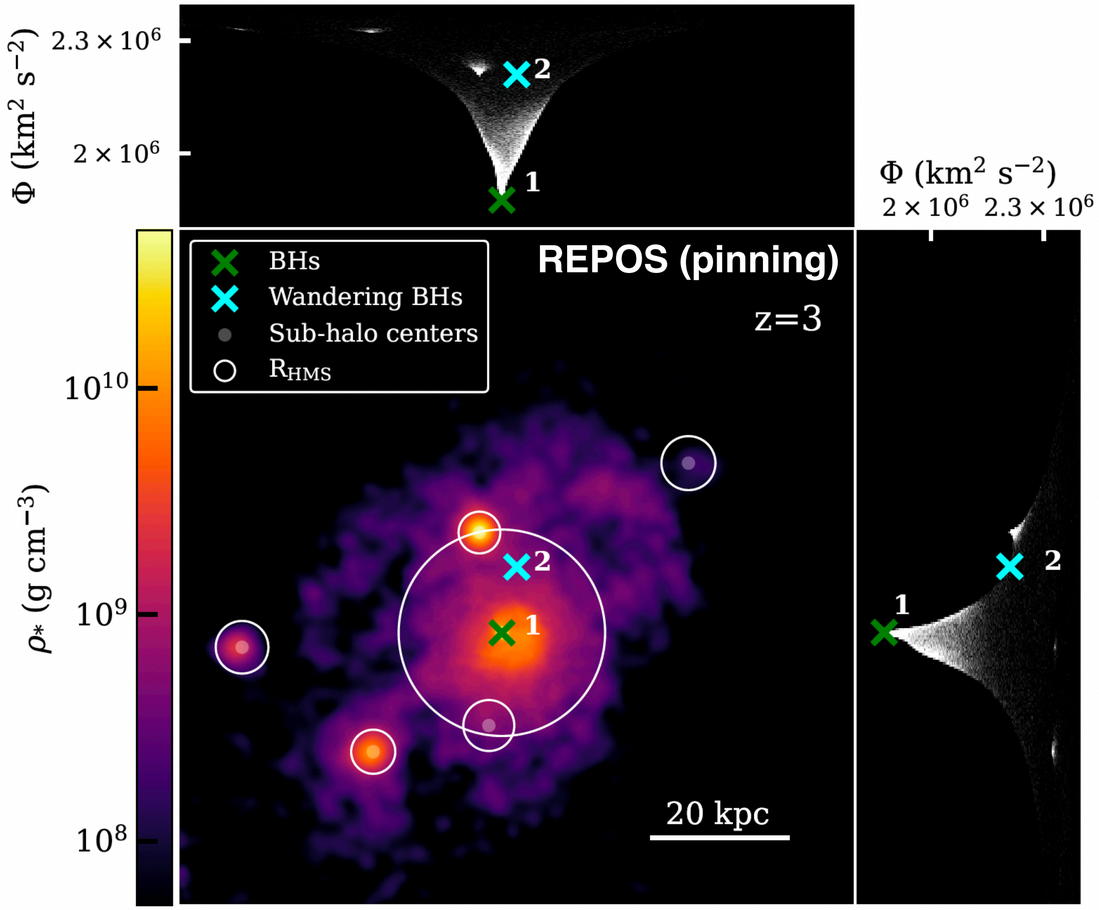
CONCLUSIONS

- **Key connection** between evolution of **star formation**, **BH** accretion rate, availability and depletion of **cold and molecular gas across cosmic time**
- **Cosmological** hydrodynamical **simulations** are a key tool to study galaxy formation and evolution, but different **sub-resolution prescriptions** affect final results

As for the **formation and evolution of disc galaxies**, simulations suggest that:

- In late-type galaxies, the **prominence of the disc** with respect to the total stellar mass is highly **sensitive to the stellar feedback model**
- **Angular momentum-dependent BH accretion** is crucial to reproduce observed **correlations between BH and bulge properties**
- Different prescriptions adopted to estimate the **molecular gas** fuelling star formation have a strong impact on galaxy morphology and final properties

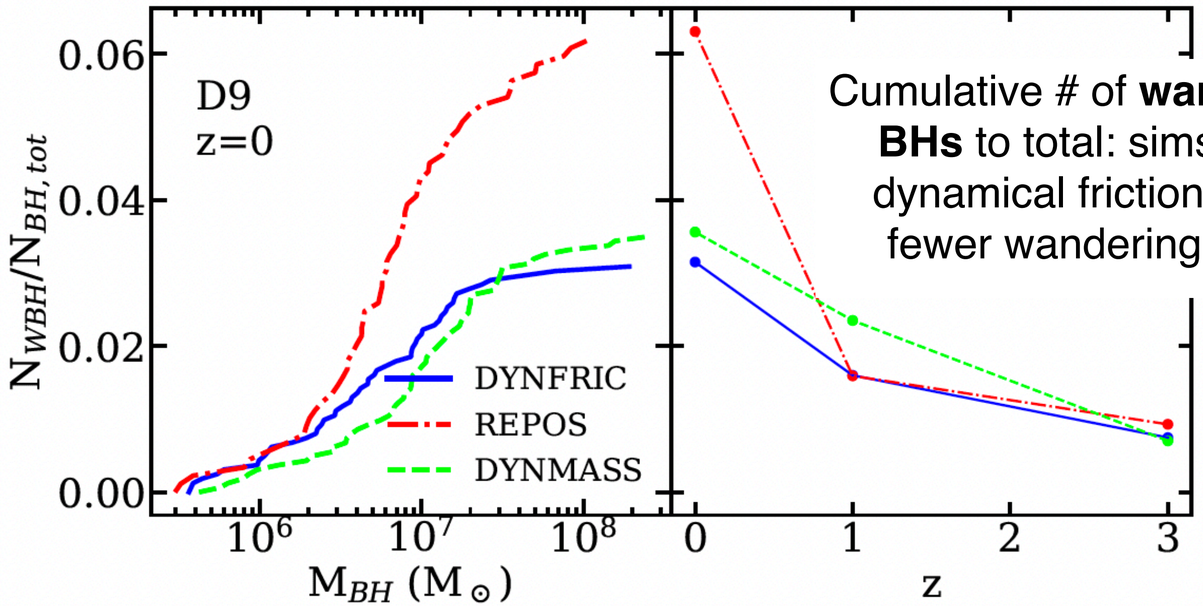
BH DYNAMICS AND THE IMPACT OF REPOSITIONING



BH2 wanders due to a close encounter between two sub-halos (**BH1** in a deeper potential well)

New approach to correct for the effect of **unresolved dynamical friction** on the orbits of BH in cosmological sims

→ the gravitational acceleration of the BH is corrected by the dynamical friction acceleration contributed by stellar and DM particles within the BH softening

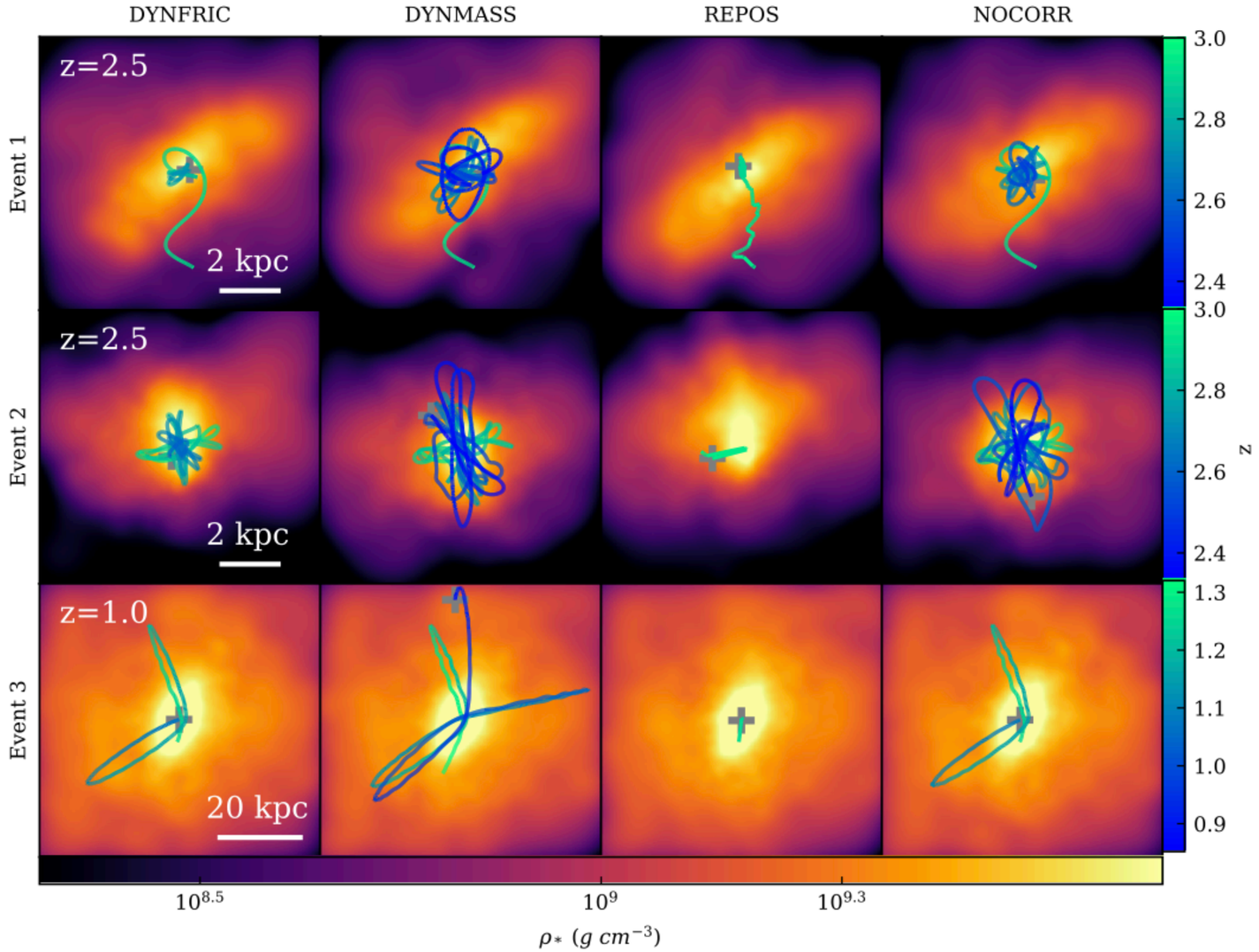


Cumulative # of **wandering BHs** to total: sims with dynamical friction have fewer wandering BHs

Adopting different numerical prescriptions for BH re-positioning has an impact on BH dynamics, AGN feedback, BH-BH mergers

Damiano, Valentini, Borgani+ 2024

BH DYNAMICS AND THE IMPACT OF REPOSITIONING



→ Dynamical friction model:
increased efficiency in centering BHs and accurate spiraling of BH orbits during mergers

Correcting for unresolved dynamical friction provides good BH centering, reduces wandering BHs, captures fairly BH-BH mergers

Adopting different numerical prescriptions for BH re-positioning has an impact on BH dynamics, AGN feedback, BH-BH mergers

Damiano, Valentini, Borgani+ 2024

MODELLING THE EVOLUTION OF THE BH SPIN

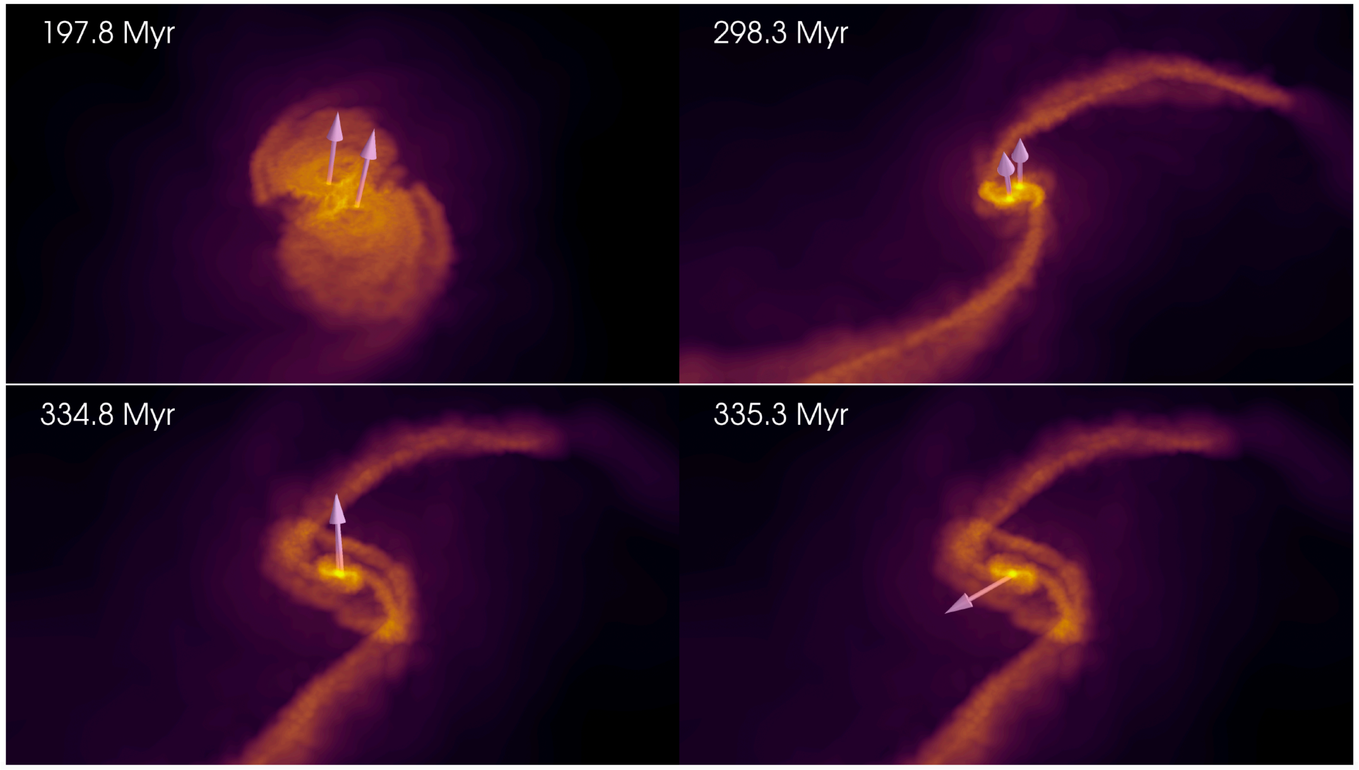
Sub-resolution accretion disc links BH accretion on resolved scales to BH spin evolution

BH accretion rate → disc mass → accretion episodes

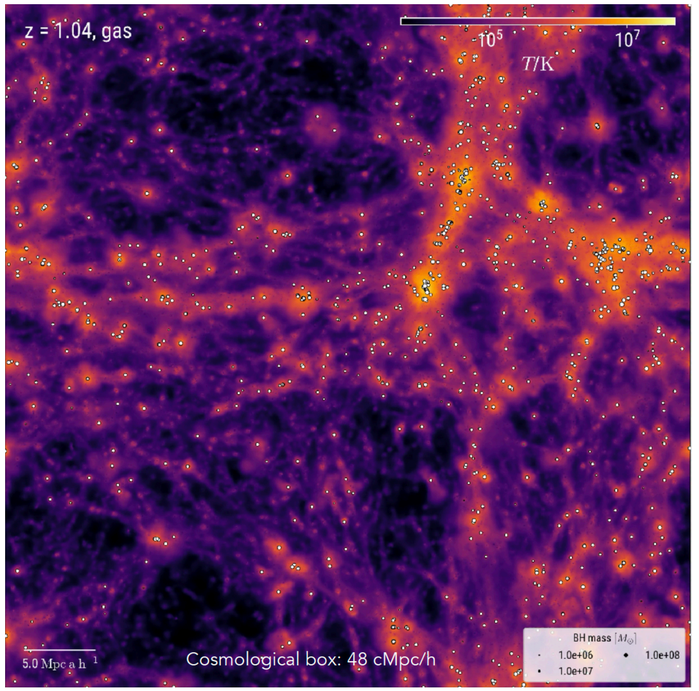
BH spin direction and magnitude defined by angular momentum of accreting gas

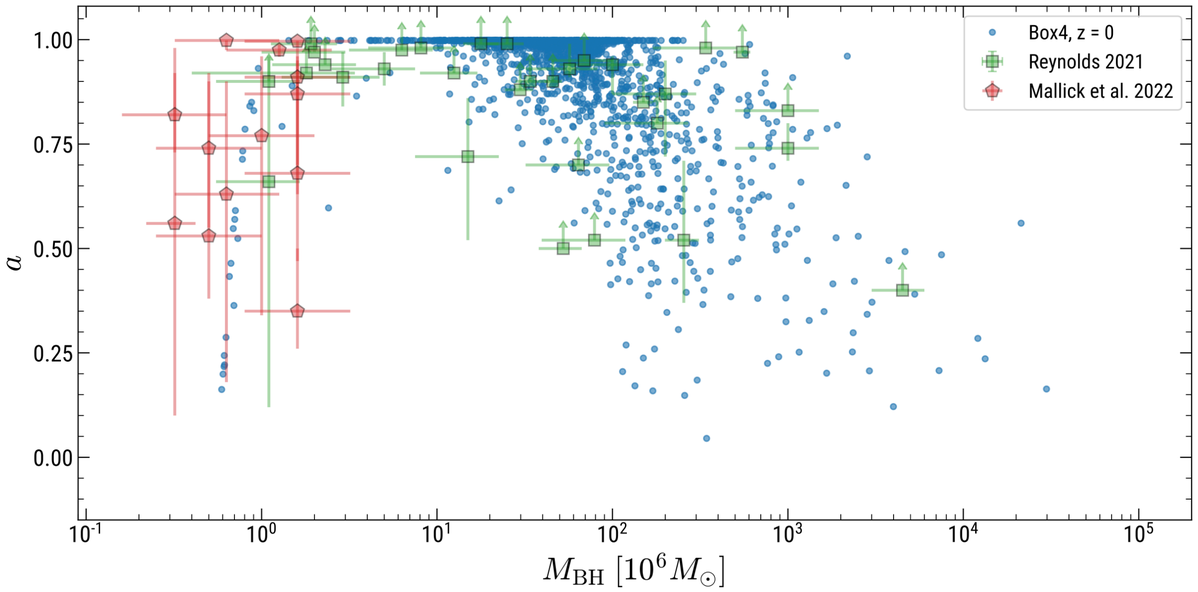
Given initial BH spin and mass → post-merger BH spin vector

BH radiative efficiency dependent on BH spin

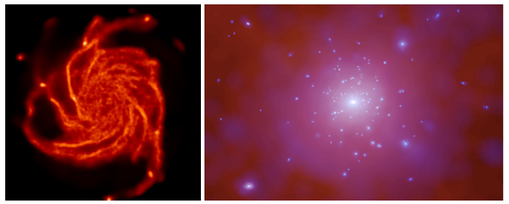


Sala, Valentini+ 2024



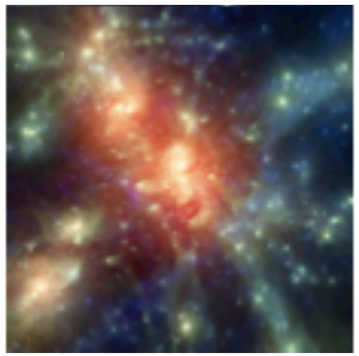


OUTLOOK AND NEXT SIMULATION CAMPAIGNS



From MW-like galaxy, to Ellipticals and small boxes,

to galaxy clusters and large volumes



The OpenGadget3 code

- **TreePM+SPH code**
- Descendant of a non-public evolution of GADGET-3 code
- **Highly optimised code:** MPI parallelised + OpenMP
- **Two hydro solvers:** improved SPH formalism or MFM
- **Two sub-grid models** (Muppi, and one based on Springel&Hernquist 2003)
- **Several modules for sub-resolution physics:** star formation, stellar feedback, BH accretion and feedback, chemical enrichment, dust evolution, magnetic fields, cosmic rays
- **Runs on CPUs and GPUs**

- MUPPI (Murante+ 2010, 2015, Valentini+ 2017-2023, Granato+ 2021, Ragone-Figueroa+ 2024), featuring:
  - description of a multi-phase ISM with H_2-based star formation
  - thermal and kinetic stellar feedback
  - stellar feedback from low-metallicity environments + improved cooling table interpolation
  - stellar evolution and chemical enrichment

star formation

  - angular-momentum-dependent gas accretion, dynamical friction and BH spin evolution
  - isotropic, thermal AGN feedback + mechanical AGN feedback

BH

  - formation and evolution of dust, and dust-assisted cooling

dust

Thank you!