The evolutionary pathways of dust and cold gas in quiescent galaxies

Giuliano Lorenzon

PhD supervisor: Darko Donevski

Collaborators: K. Lisiecki, M. Romano, C. Lovell, D. Narayanan, R. Dave'

NCN founded project "Dusty giants"

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK

Narodowe Centrum Nauki

The (non?)disappearance of dust in quiescent galaxies

Are feedbacks efficient in removing dust?

Layout of the talk

Overview of the interstellar medium

Dust production / destruction channels

Galaxy quenching

Connecting ISM and QGs: observations and simulations

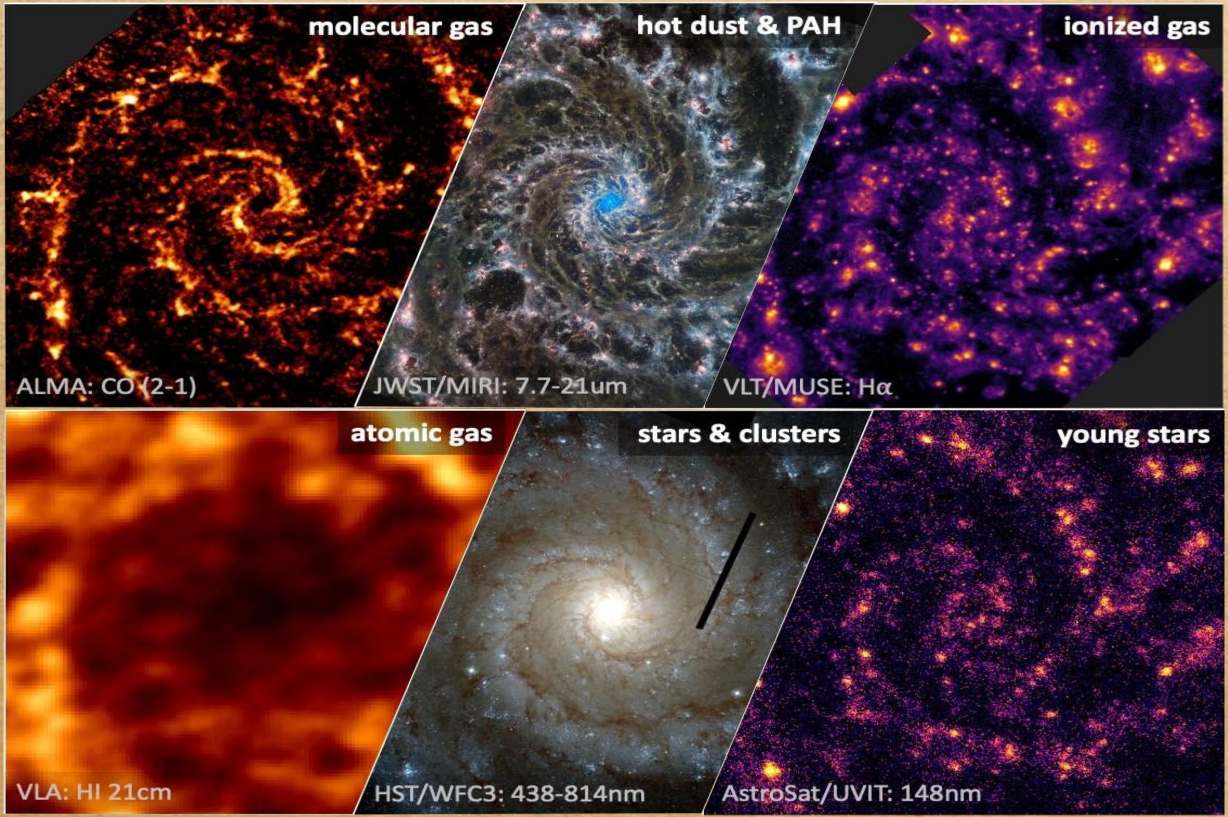
Evolution of the ISM in the SIMBA cosmological simulation

Summary and conclusions

Different phases, different tracers

Inter
Stellar
Medium

BARYONIC

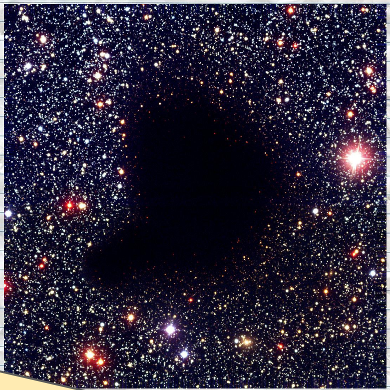


Credits: Jiayi Sun

Molecular gas: the fuel of star formation

- Distributed in clouds in the galaxy
- H_2 clouds are cold (T~10 K) and dense (T~10^4 cm^{-3})
- Collapse by self-gravity to form stars
- Associated with star formation (SF) regions
- H_2 → HII in photoionized region around young stars

Credits: ESO



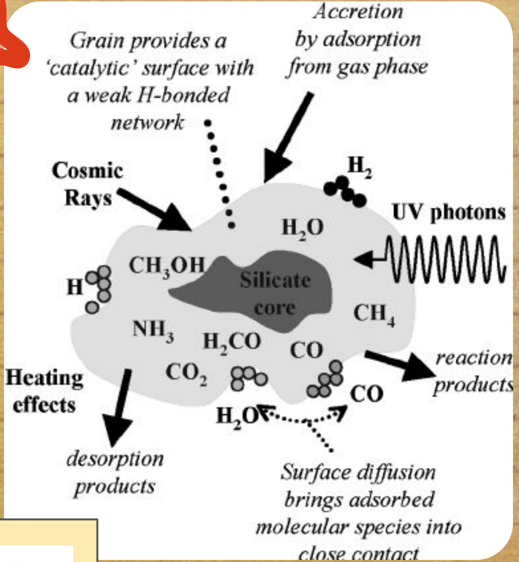
Barnard 86

H_2 lit by young stars

Dust grains: catalysts of star formation

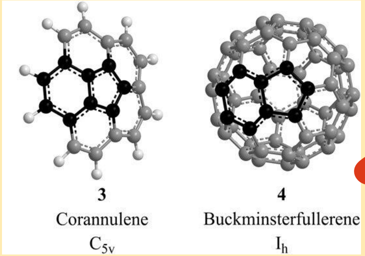
- Size from ~1 nm to ~100 μm
- Carbon / silicon composition
- T ~ 10 K up to ~100-1000 K
- Absorption law $A_\lambda \sim 1/\lambda$
- Emission peak $\lambda \sim 100\ \mu m$

Dust grain



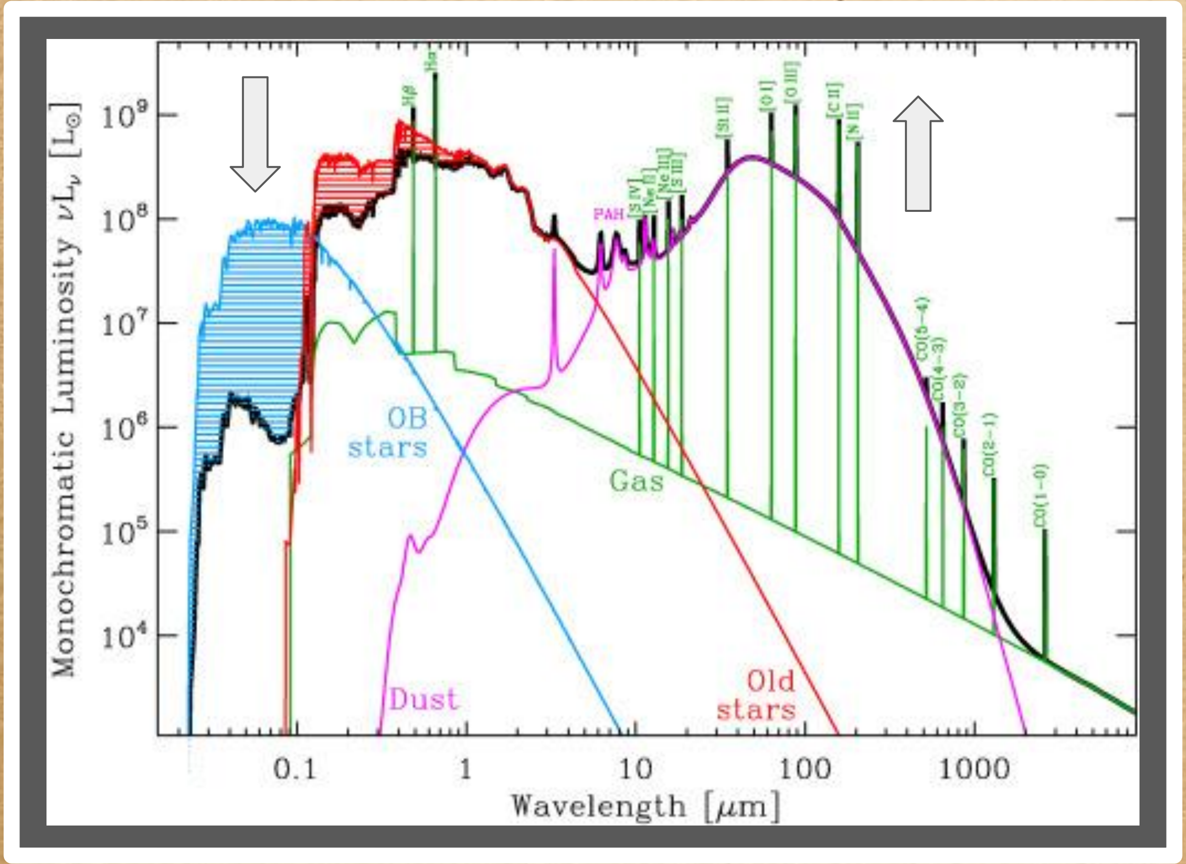
Cools down H_2 regions by absorbing UV

Catalyst for H_2 formation by H on the grain surface



PAH

Where is the dust?

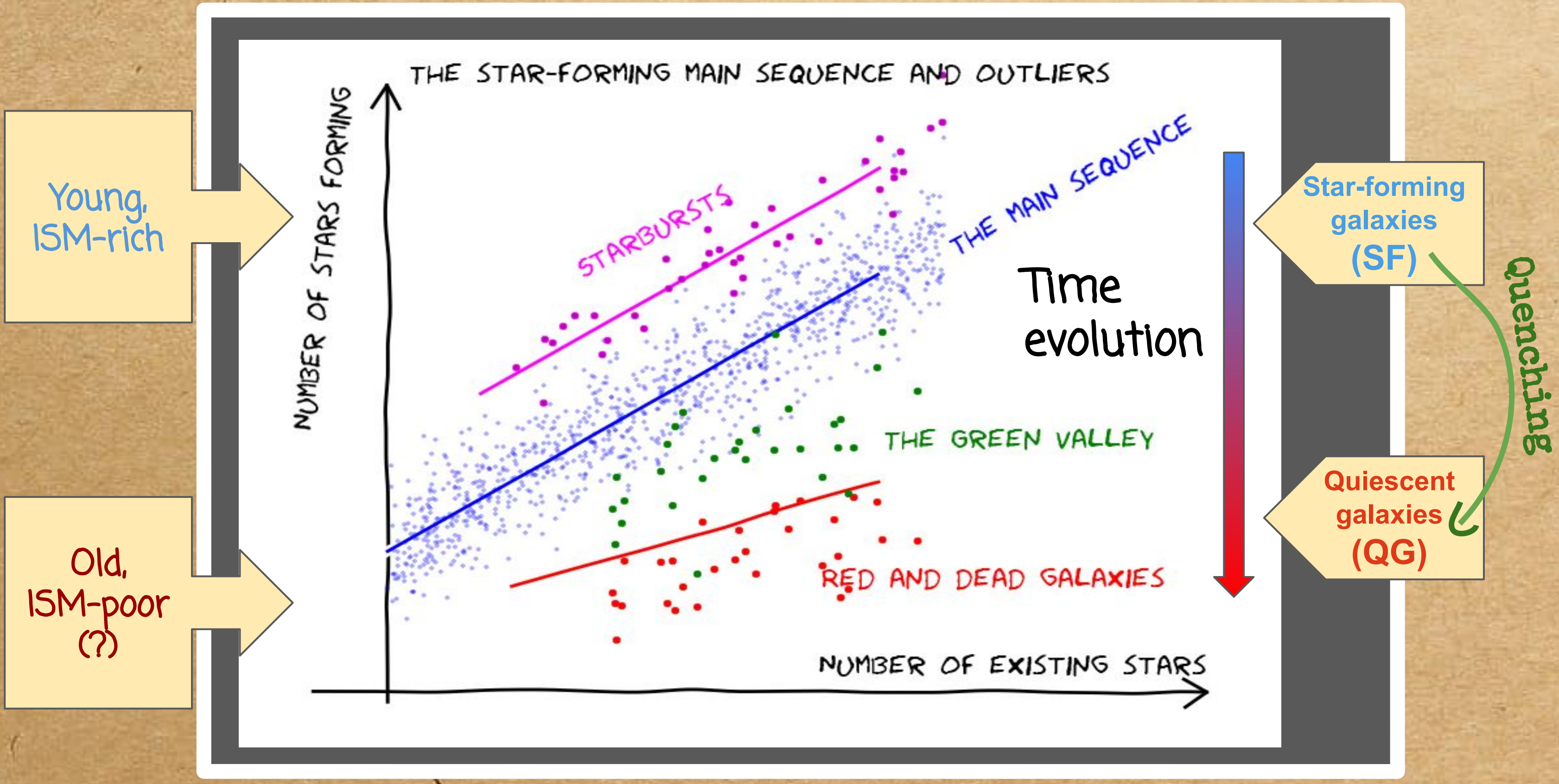


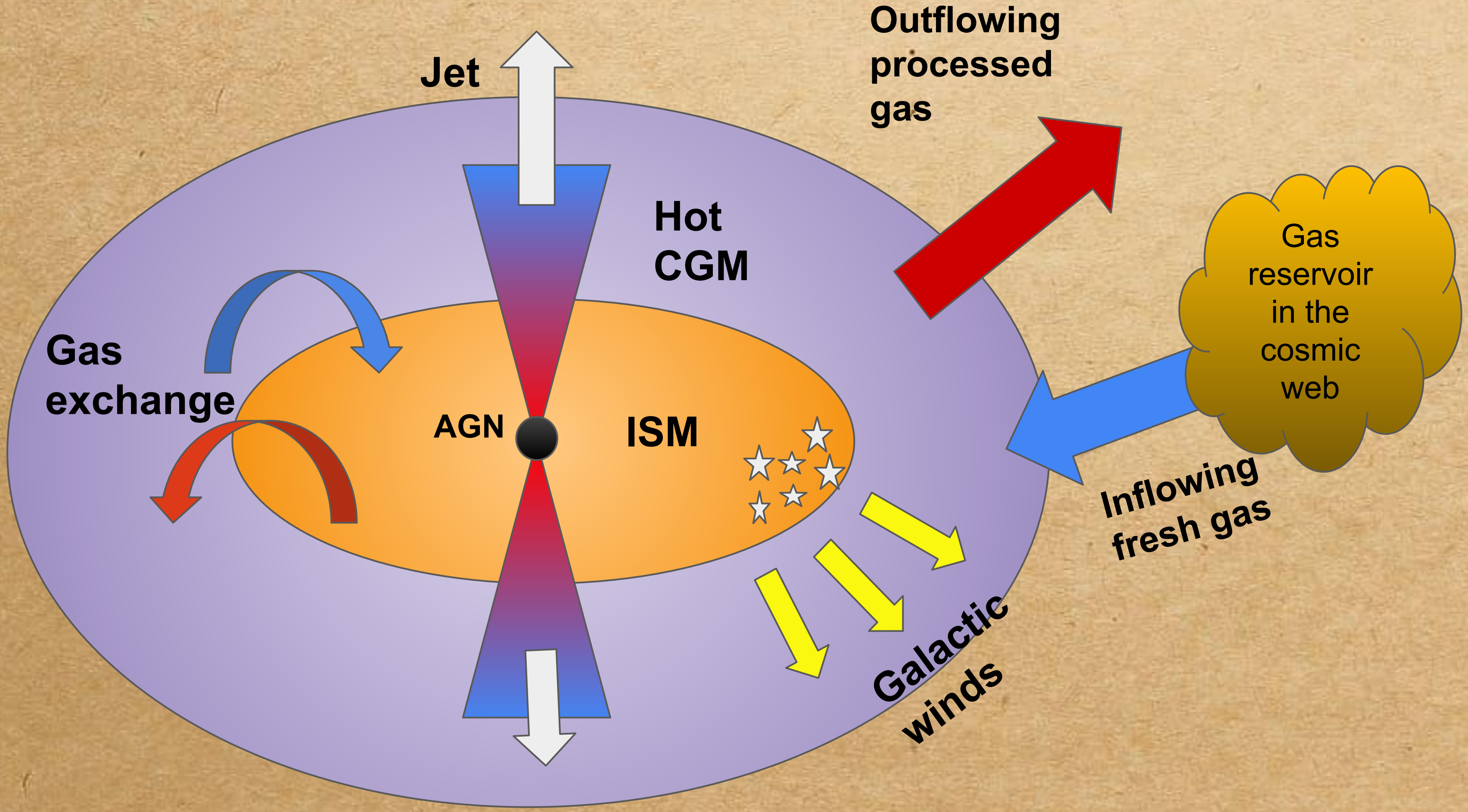
Galliano+17

A case of galaxy quenching

What is quenching and how it affects ISM

Quenching is the cessation of star formation




Outflowing processed gas
Jet
Hot CGM
Gas reservoir in the cosmic web
Gas exchange
AGN
ISM
Inflowing fresh gas
Galactic winds

A backstory of dust

Dust formation and destruction channels

Channels of dust production

- Grains form in the outer envelope of (super)giant stars ($M < 8\ M_{sun}$)
- Timescales ~ 10^8 - 10^9 yr
- Composition depends on
  - C / O > 1 → Carbon grains
  - C / O < 1 → Silicate grains

- Massive stars go supernova
- Dust forms in the expanding ejecta
- Yields depend on the mixing coefficient and physical conditions of the ejecta
- Timescale $t<10^7$ yr

$$\dot{\rho}_{\rm dust,AGB} = \int_{m_{t_{\rm age}}}^{m_{\rm up}} m_{\rm d}(m)\phi(m)\dot{\rho}_*(t_{\rm age} - \tau_m)\,{\rm d}m,$$

IMF

Galaxy age

Produced dust mass

SFR density

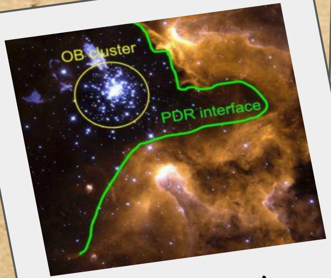
Stellar lifetime

Yields are tabulated and based on observations

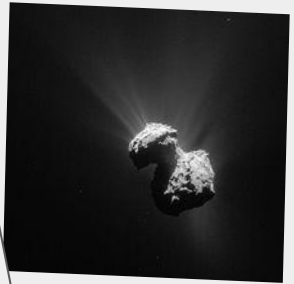
Mechanisms of dust destruction

Thermal Sputtering

Different mechanisms affect dust depending on environmental conditions

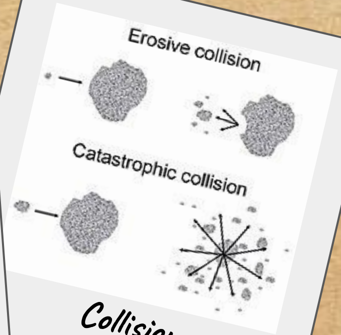


Photoionization



Sublimation

Chemisputtering



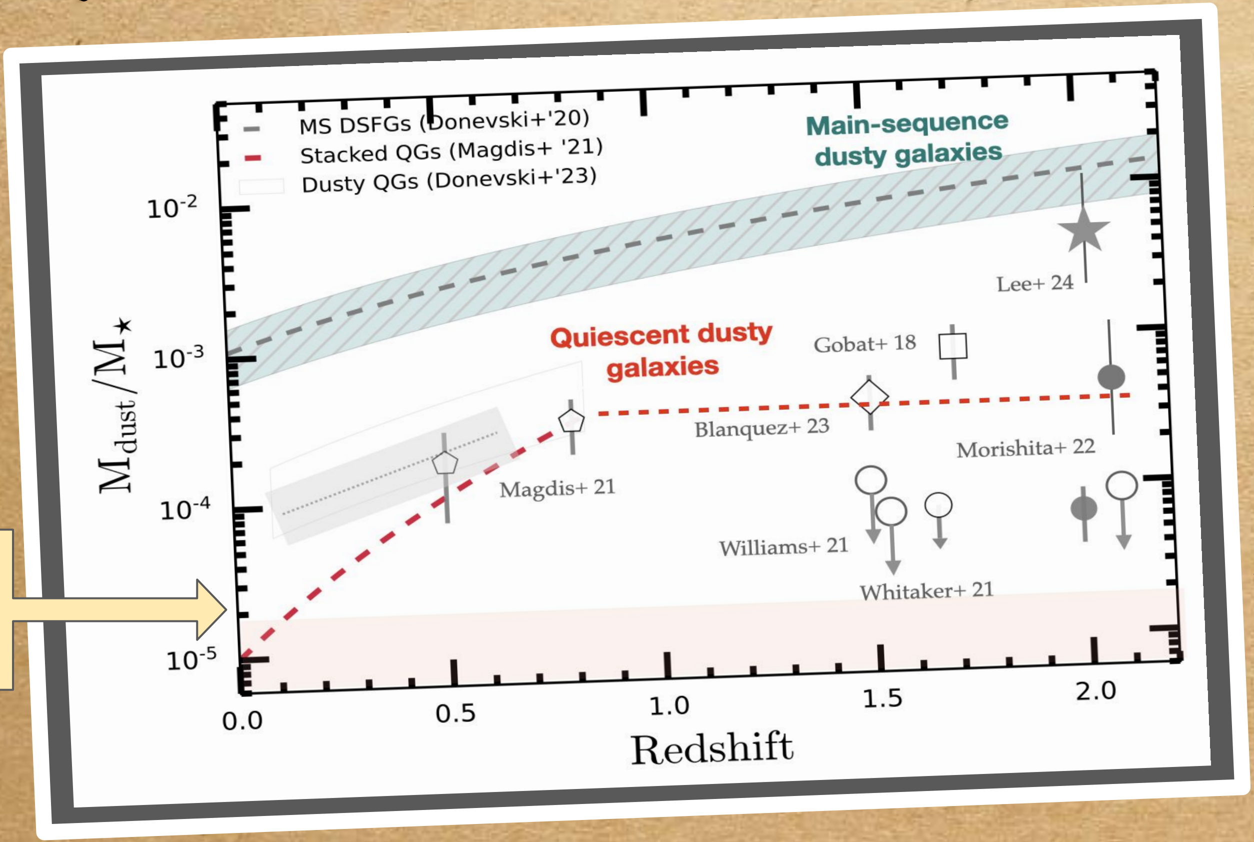
Collision

Hot sputtering requires high temperature and density of ionized gas

$$\tau_{\rm sput} \simeq \frac{a}{\bar{h}\mu n_{\rm H}} \simeq 7.1 \times 10^5 \left(\frac{a}{1\ \mu m}\right)\left(\frac{n_{\rm H}}{1\ {\rm cm}^{-3}}\right)^{-1} {\rm yr}.$$

Short timescale

Different evolutionary scenarios: is dust destroyed or not?

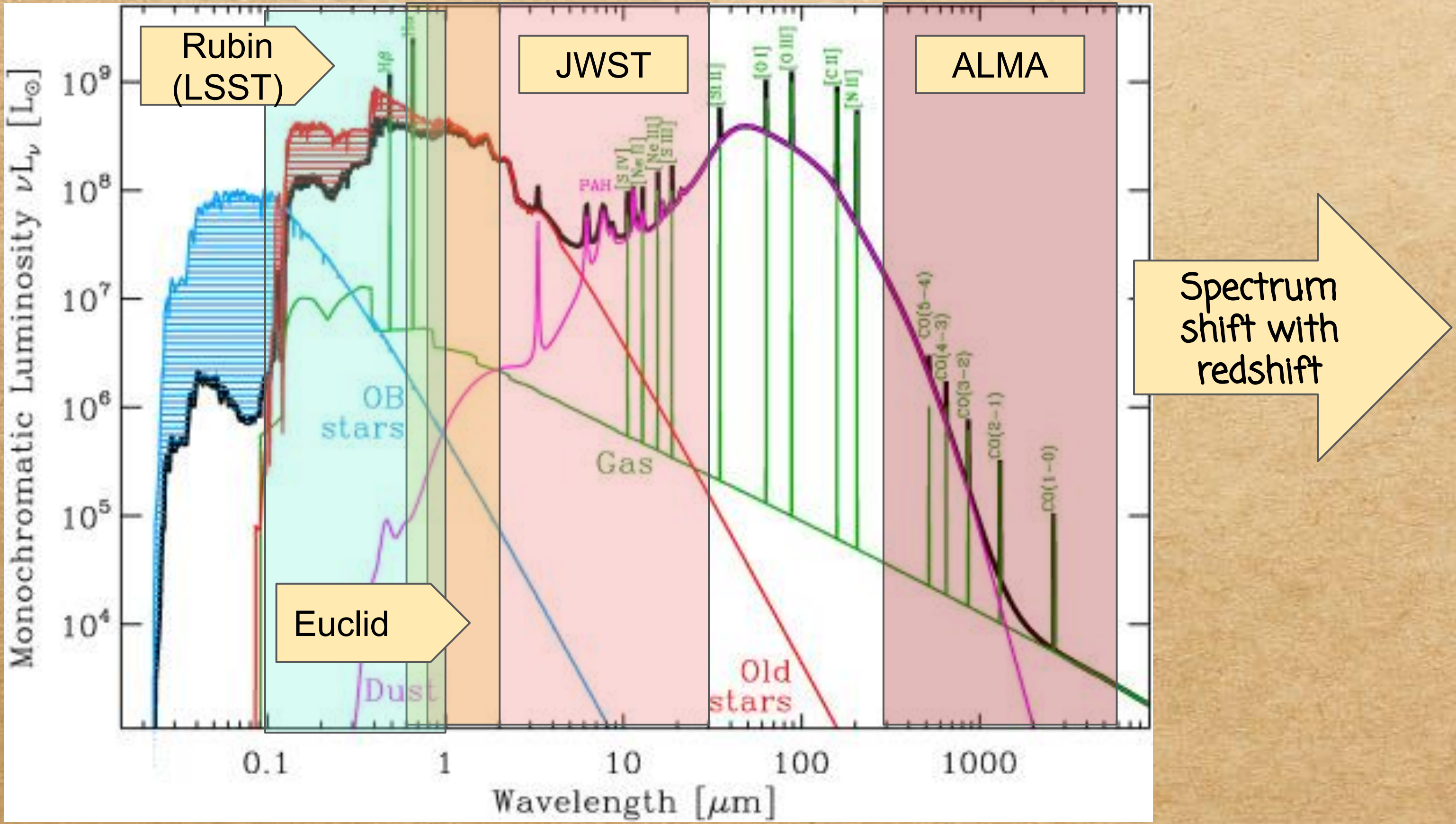


Limit for individual detection

Big scatter in the dust fraction: are feedbacks efficient or not?

The investigation tools

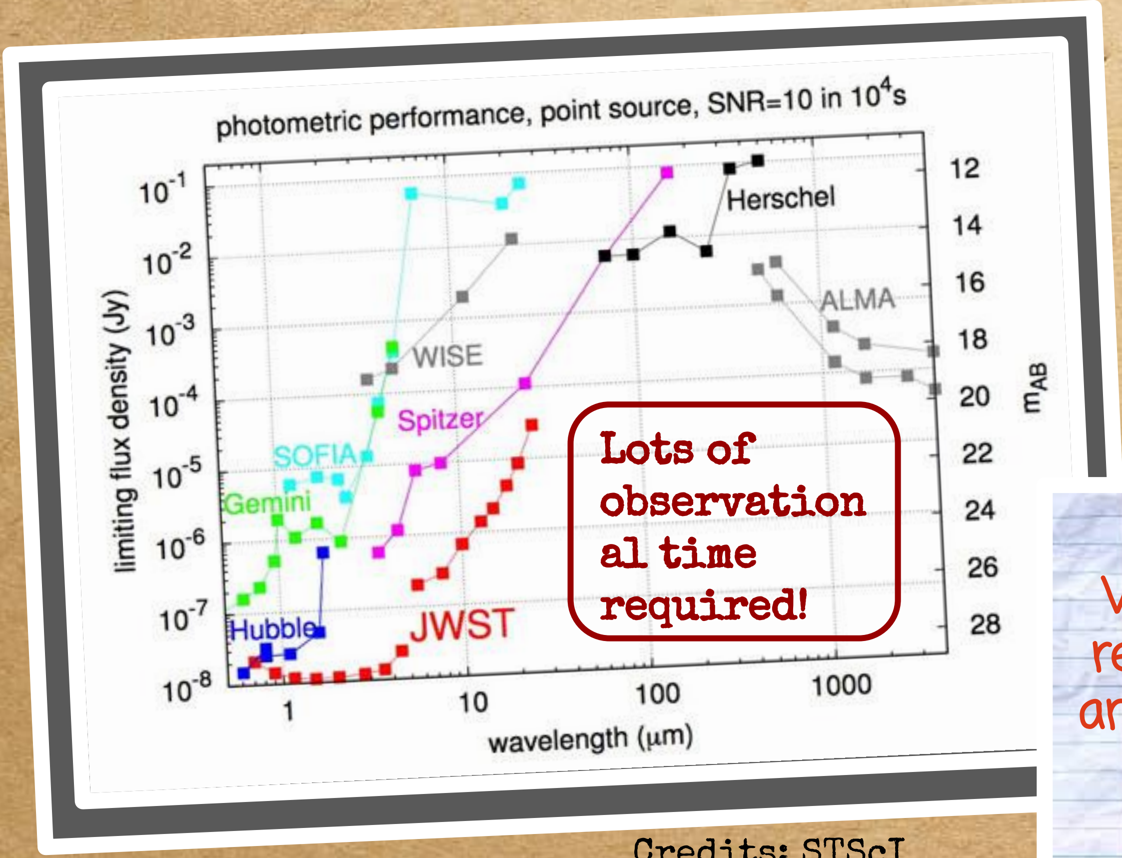
Limitations of ISM observations in QGs and the help of simulations



Measuring SF

Measuring dust

Observations are hard



Credits: STScI

Small FOW:

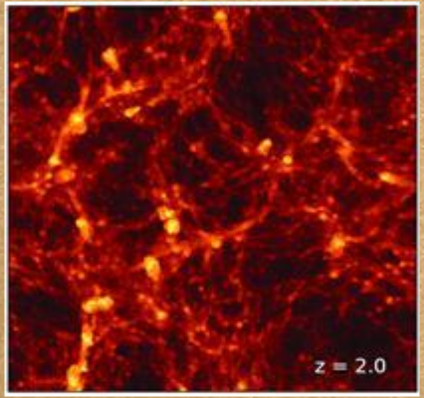
- JWST ~ 130"
- ALMA ~ 30"
- Euclid ~ 2700"

(Moon d ~ 1900")

We need to balance resolution, sensitivity and coverage for large statisitcs

Simulations mean more statistics and a way to guide observation towards interesting targets

Mimicking feedbacks: the SIMBA simulation



100 cMpc

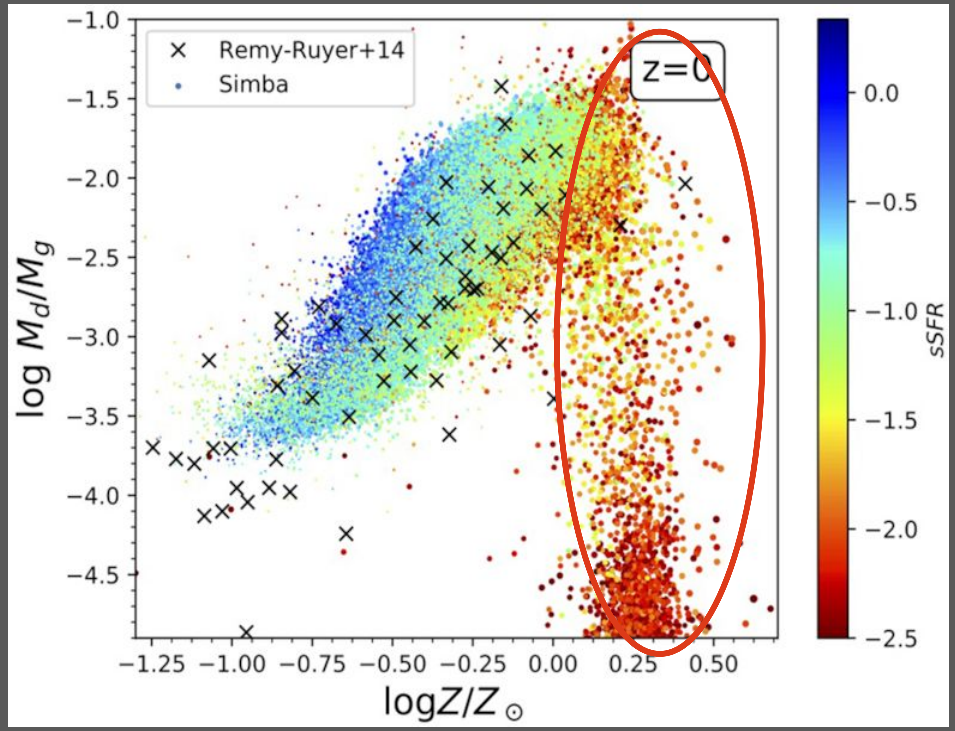
cosmological galaxy formation simulation with meshless finite mass hydrodynamics

- Self consistent evolution of baryonic together with dark matter
- Dust destroyed / created / growth on-the-fly
- Black hole hot gas Bondi accretion, cold gas torque-limited accretion
- Well reproduces dust mass function and CGM properties
- Non-constant dust-to-metal ratio
- Number counts of sub-mm sources is consistent with observations thanks to high SFR and dust masses

Linking ISM and stars

□$_{DGR}$ = M_{dust} / M_{H2}

- Allows to directly **compare** the 2 main components of the ISM
- Constant if the dust follows the H_2 gas
- Gas phase metallicity serves as proxy for the galaxy mass / age

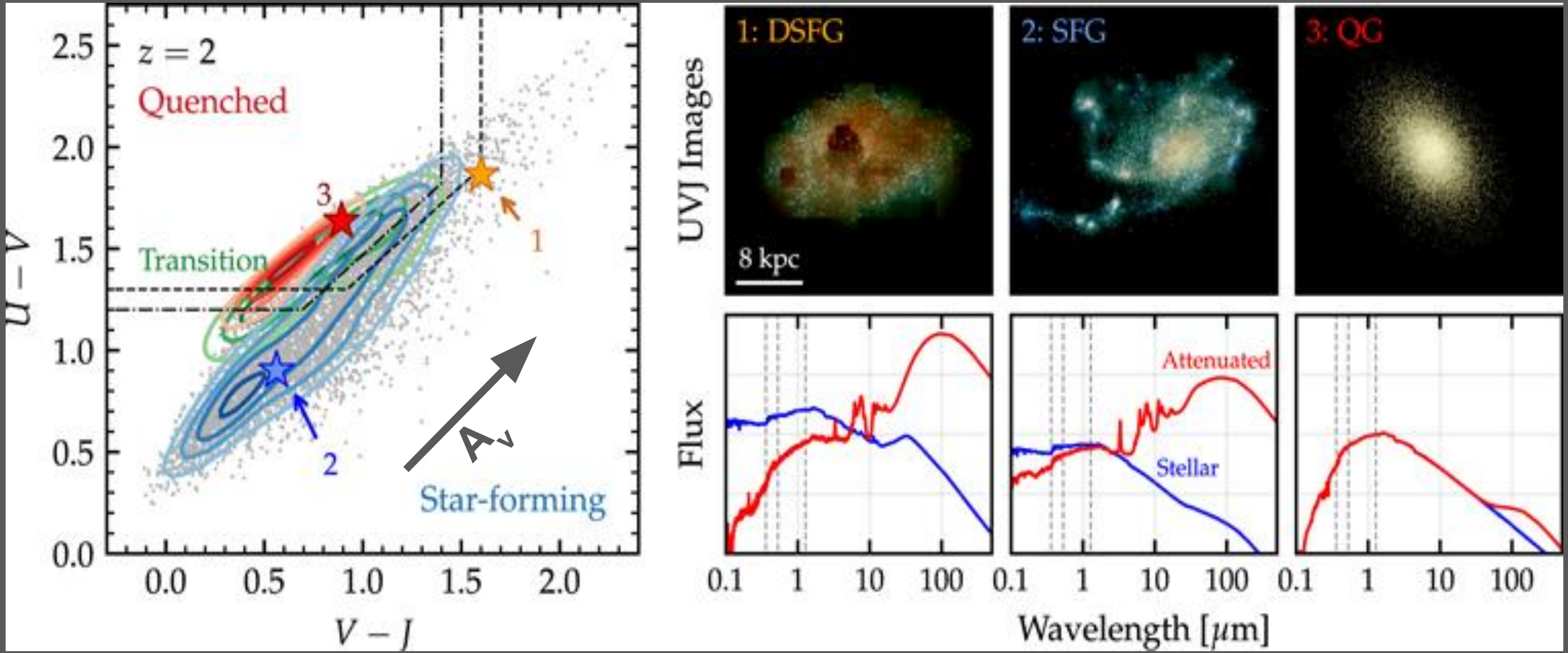


Scatter in dust fraction due to QGs with anomalous properties (high dust or high H_2)

Now

Big Bang

Photometric selection of QGs depends on dust content!



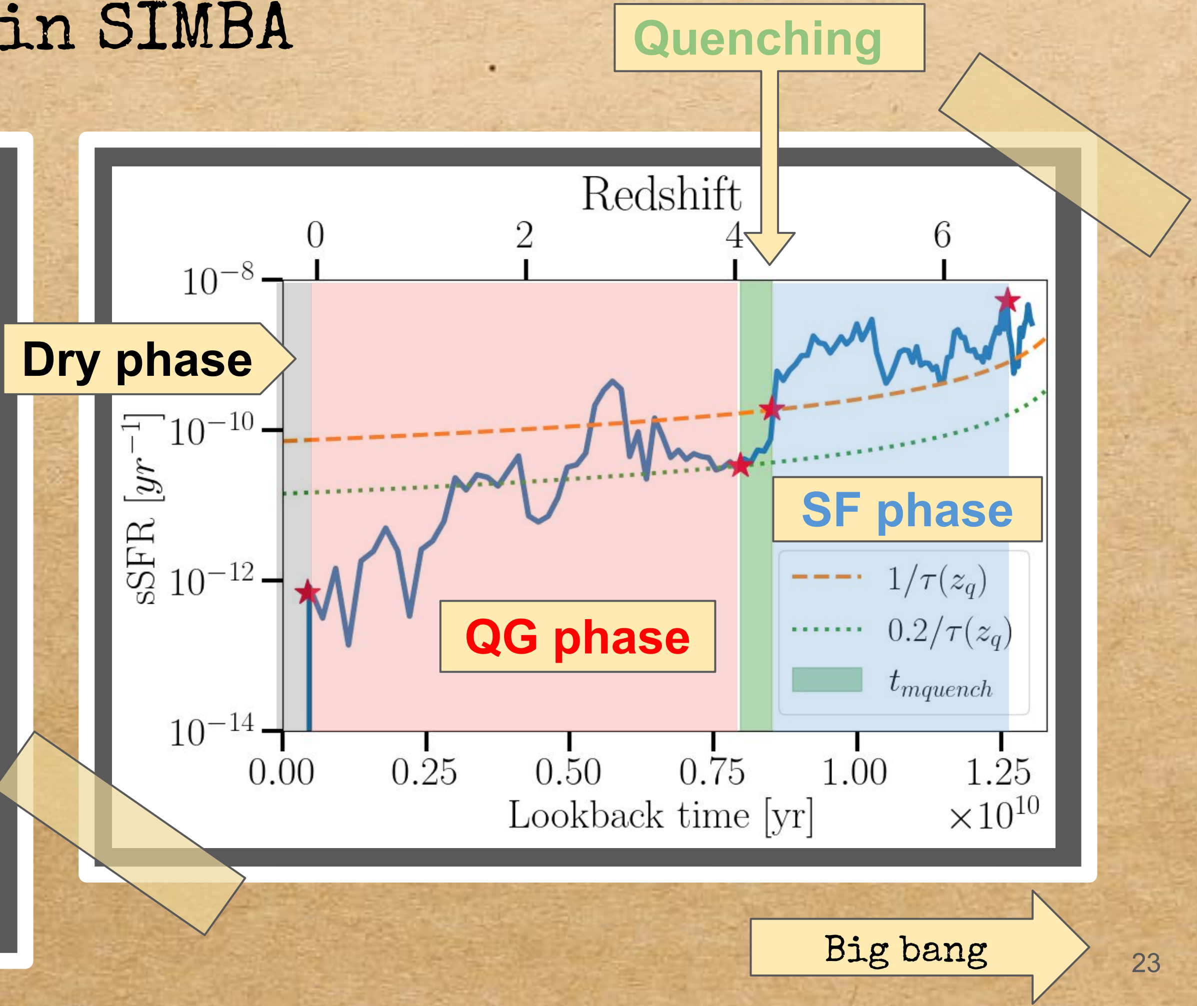
Akins+22

The data sample

- SIMBA full-physics 100 $cMpc^3$ ($3x1024^3$ particles)
- $0 < z < 2$
- ~ 2400 QGs in clusters ($M_{halo} > 10^{14}$ M_{sun})
- ~ 7500 QGs in field
- $10^9 < M_{star} < 10^{12}$ M_{sun}

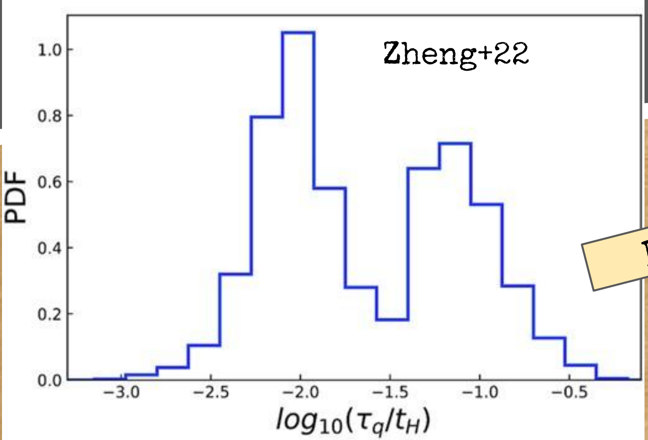
Selecting the QGs in SIMBA

- Quenching based on empirical relations
- Star formation: sSFR > 1/τ(z)
- Quenching: sSFR < 0.2/τ(z)
- Follows the z-evolution of the main sequence scatter
- Evolutionary points depending on sSFR and f_{H2} :
  - SF peak
  - Start / end quenching
  - f_{H2} < 1% (gas fraction)

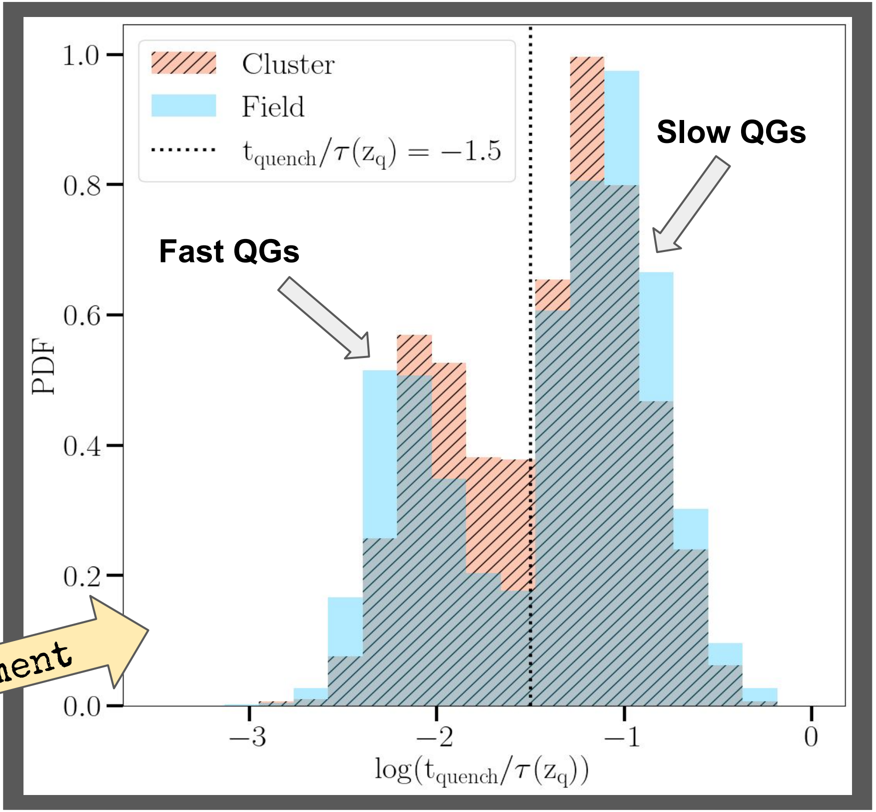


Effect of the environment on quenching?

- Quenching time (t_{quench}) normalized by the cosmic time τ(z)
- Striking bimodality in SIMBA
- No significant difference with the environment



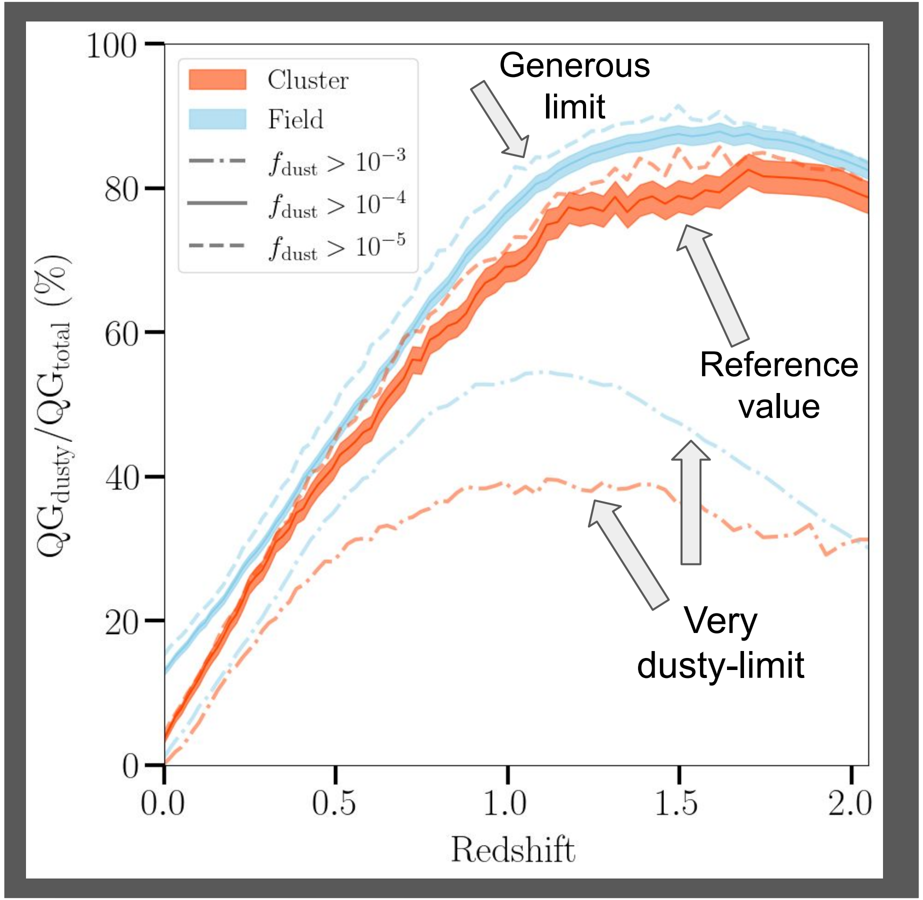
Environment



Lorenzon et al. in prep

- Fraction of dusty QGs with redshift and environment
- Different definitions of "dusty" using $f_{dust} = M_{dust}/M_{H2}$ thresholds
- Dusty QGs are abundant at higher redshift!

Lorenzon et al. in prep



Evolution

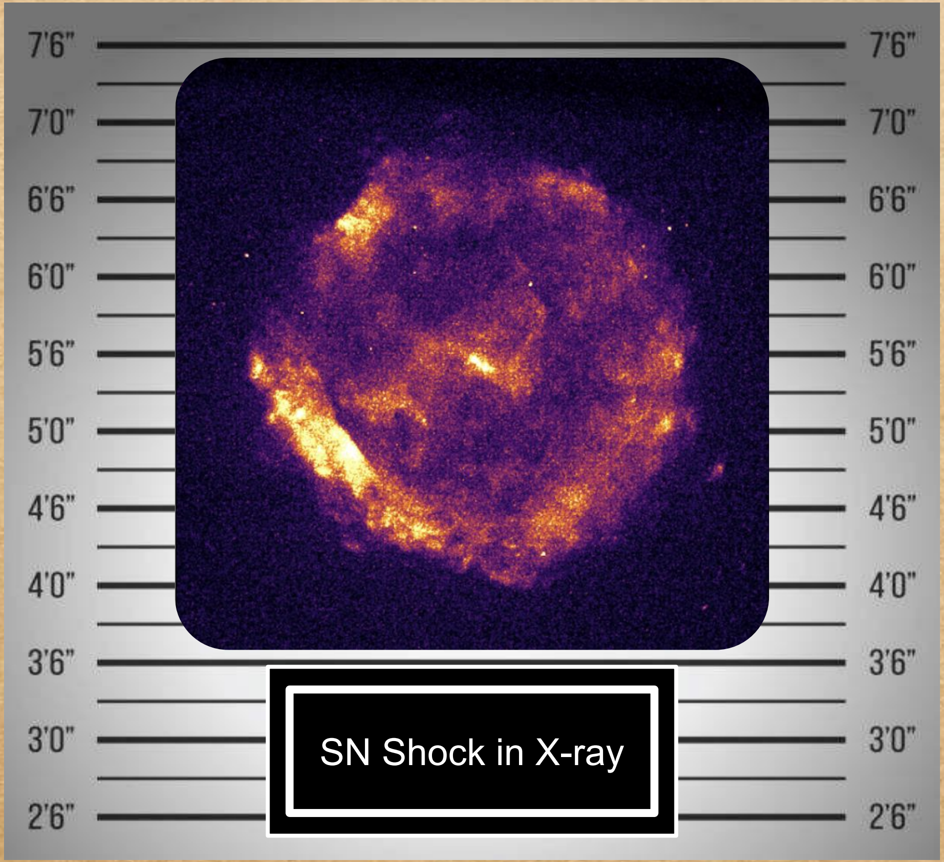
Investigating the usual suspects

Exploration of the different mechanisms of dust sputtering in SIMBA

Stellar activity

- Winds remove dust
- UV from young stars heat dust and gas
- High density in SNe shocks
- Efficient sputtering by H_2
- Short timescales ($t<10^8$ yr)

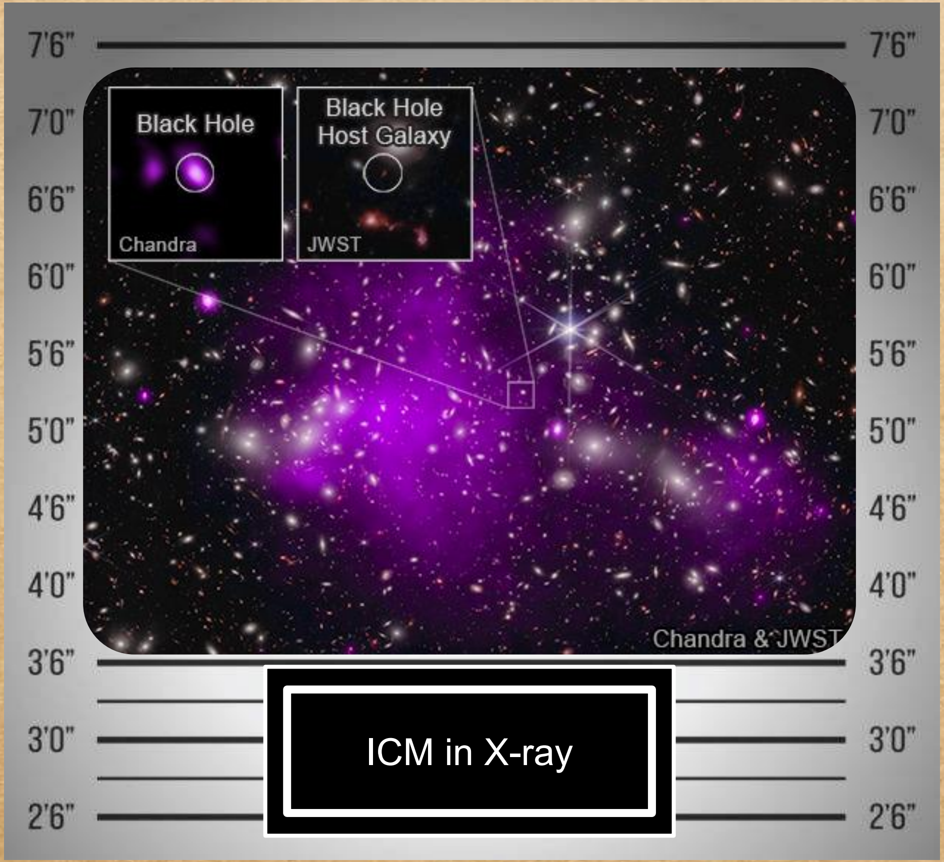
Side note: SNe inject dust with the ejecta, but the shock destroys the dust in the surrounding ISM



Hot halos

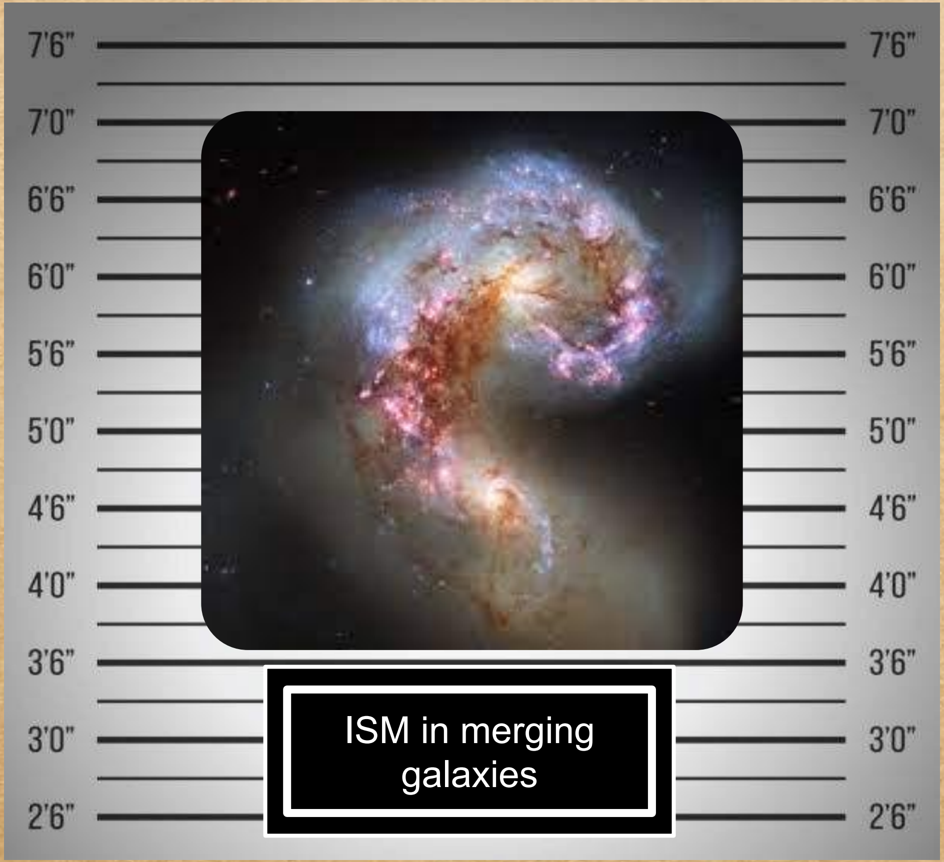
- Coronal emission around massive galaxies
- Intra-Cluster Medium (ICM) emits in X-ray
- Gas temperature $T \sim 10^7$ K
- Density $\rho \sim 10^{-4}$ cm^{-3}

The effect is a decrease of the fraction of dusty QGs in cluster with respect to the field (as observed)

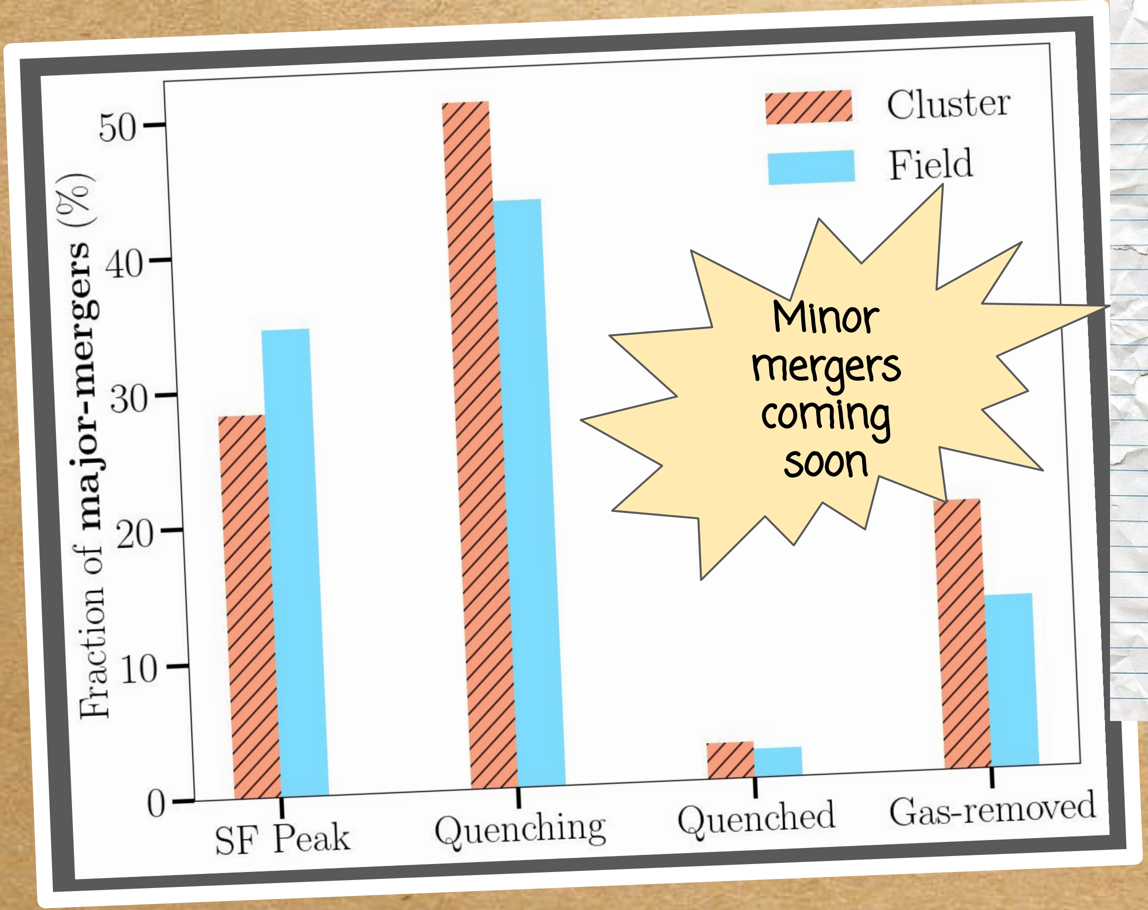


Galaxy mergers

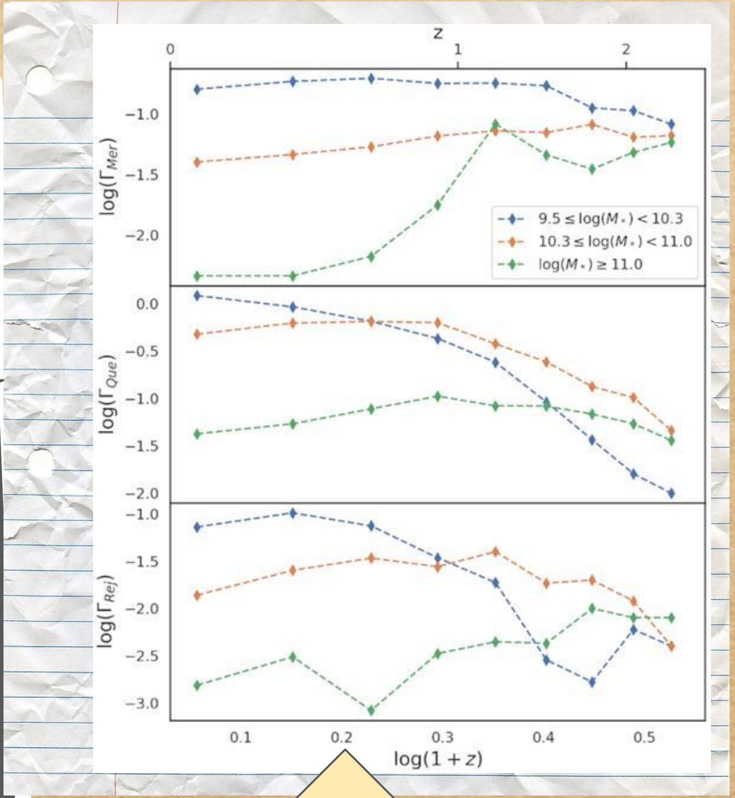
- Dust-poor (dry) mergers cause dilution
- Dust survive in dust-rich (wet) merger
- Gravitational instability → cool flows →Rejuvenation
- Possible AGN activation



Major Mergers



Minor mergers coming soon

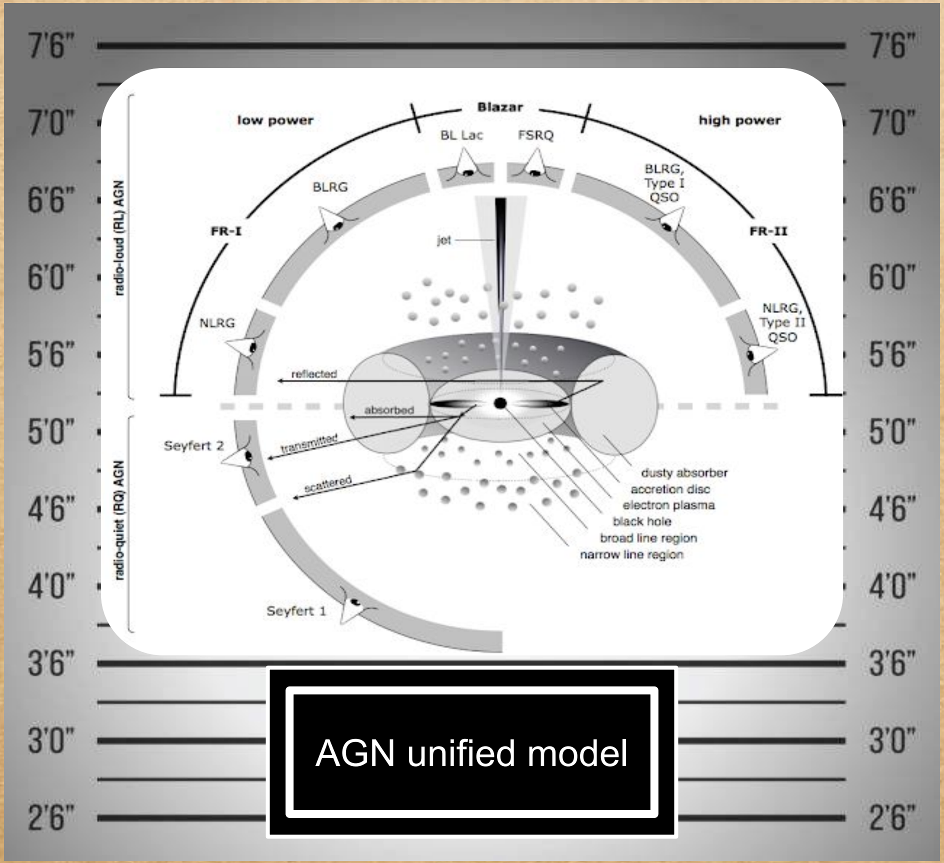


Montero+19

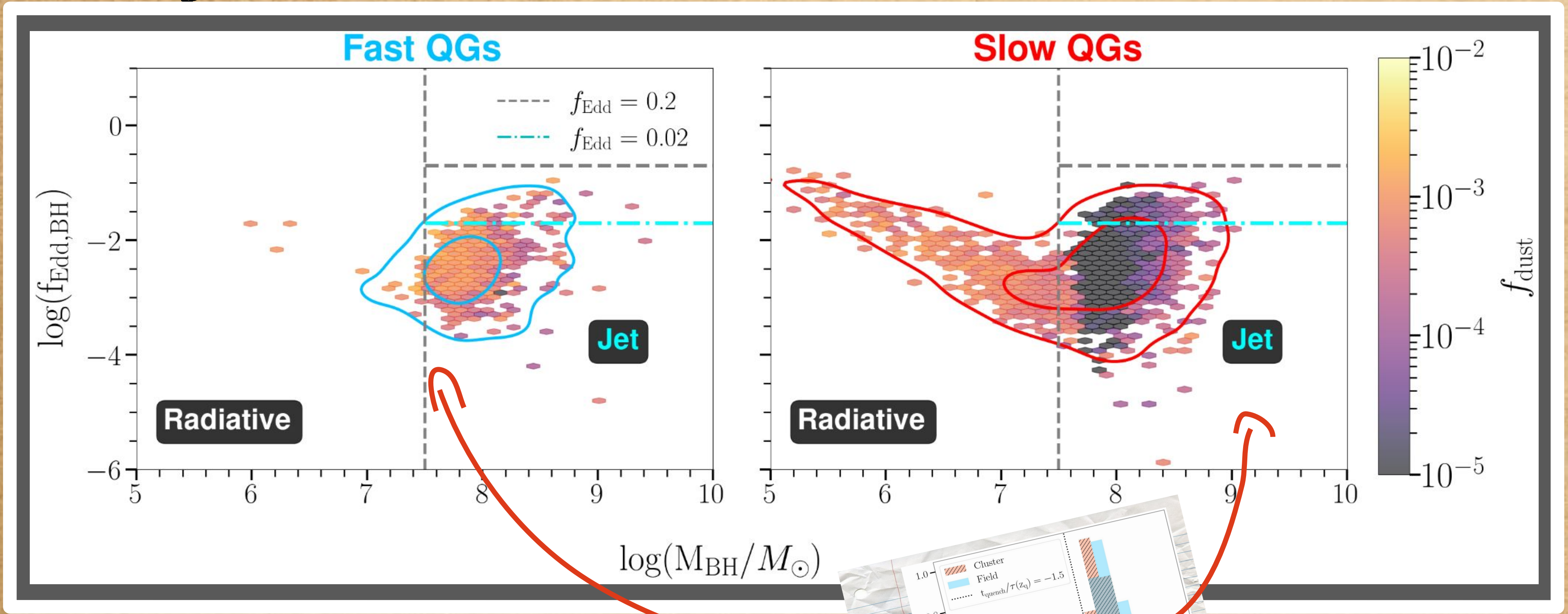
No direct correlation between mergers and quenching in SIMBA

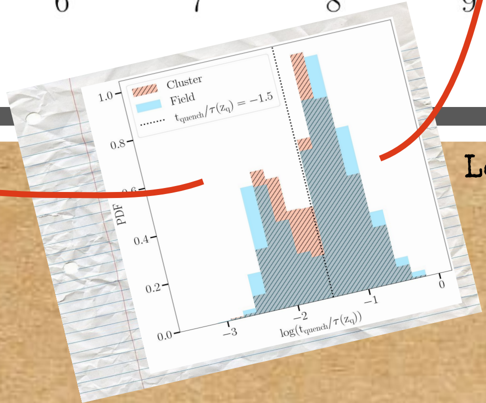
AGN activity

- X-ray radiation from accretion disk
- Accretion causes powerful winds
- Collimated jets can expel ISM far from the galactic plane



AGN jet-mode as cause for the scatter

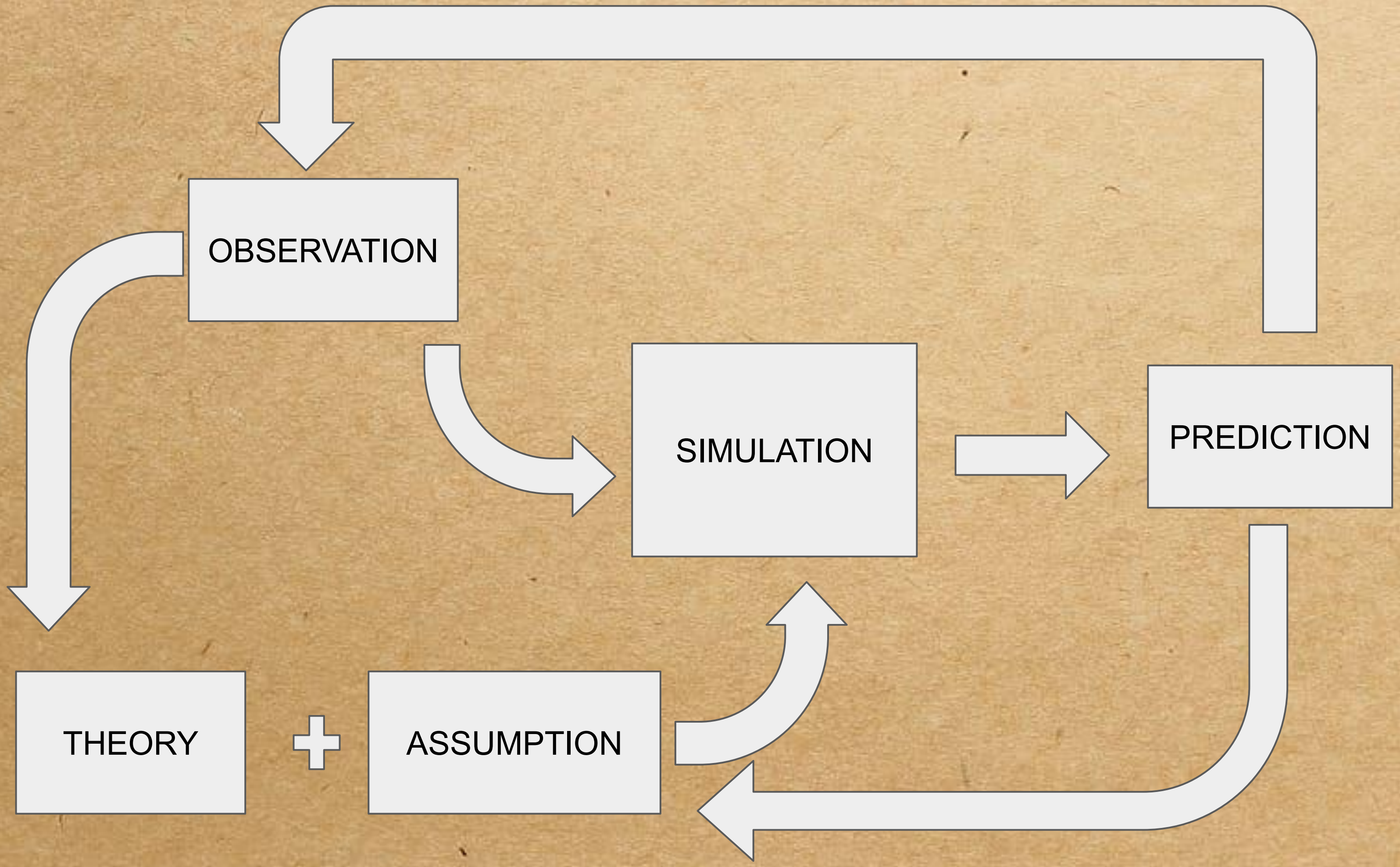




Lorenzon et al. in prep

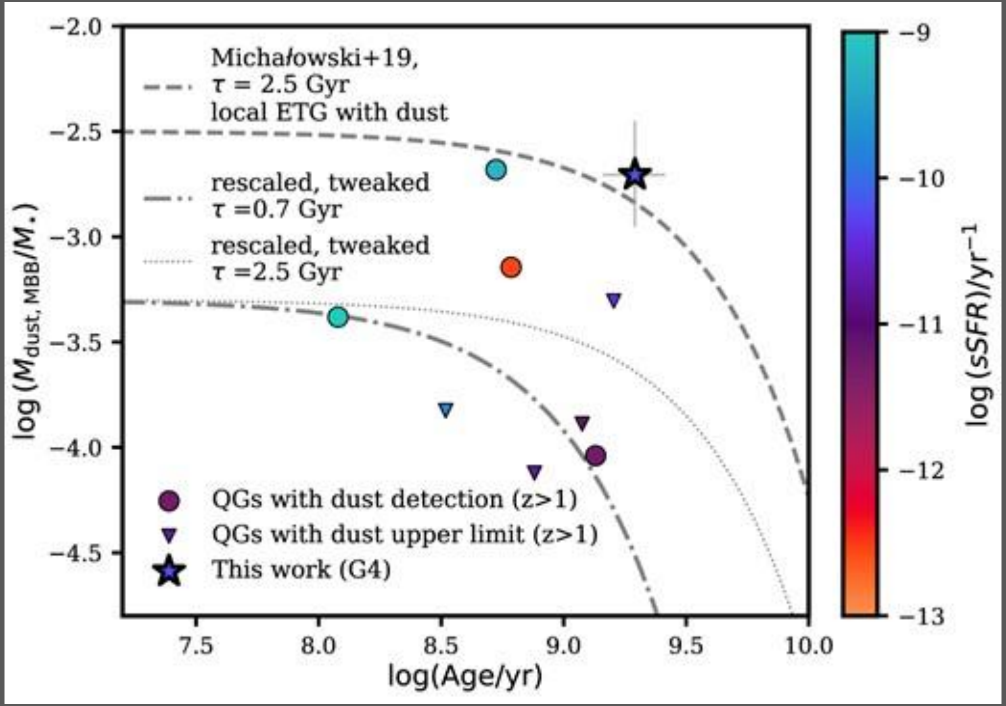
Back on the crime scene

A comparison of SIMBA predictions and current observations


OBSERVATION
SIMULATION
PREDICTION
THEORY
ASSUMPTION

ISM evolution in observations: long timescales?

1. Large scatter of f_{dust} for ~QGs
2. Very different timescales for dust destruction observed
3. Is destruction inefficient or is there something else?
4. Is dust following stellar evolution (and thus the gas component)?

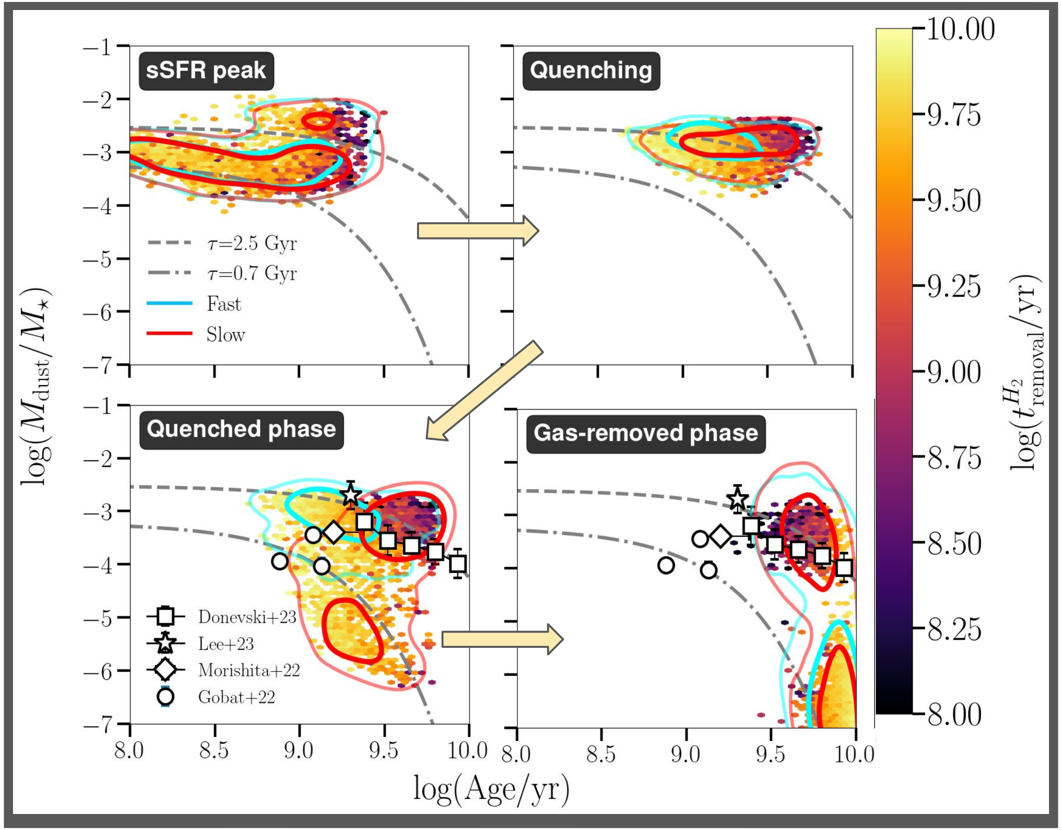


Lee+23

Exploring the dust-age plane

Lorenzon et al. in prep

- f_{dust} does not evolve before quenching
- The scatter happens during the quenching phase.
- A group of old galaxies shows large f_{dust} long after the quenching
- Gas removal timescale not directly related to f_{dust}



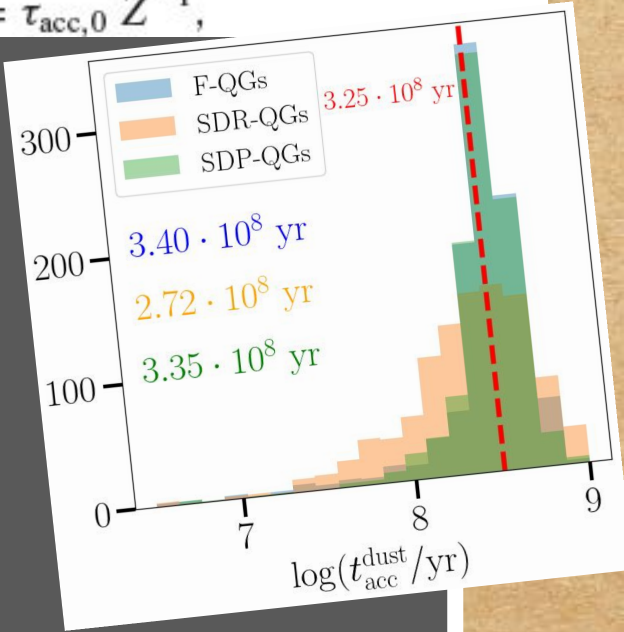
The culprit

Dust growth in SIMBA and its effect on future observations

Dust re-growth in the ISM

$$\tau_{acc} \approx 2.0 \times 10^7 \times \left(\frac{\bar{a}}{0.1\,\mu\mathrm{m}}\right)\left(\frac{n_H}{100\,\mathrm{cm}^{-3}}\right)^{-1} \times \left(\frac{T}{50\,\mathrm{K}}\right)^{-\frac{1}{2}}\left(\frac{Z}{0.02}\right)^{-1} [\mathrm{yr}] = \tau_{acc,0}\, Z^{-1},$$

- Dust growth by condensation of metals
- Short typical dust formation timescale
- Depends on T and density of the hot gas
- Most efficient for super-solar metallicity
- Efficient grain growth allows dust grains to withstand sputtering
- If $\tau_{sp} > \tau_{acc}$ dust can survive!



But probably dust is just very resilient

Both simulation and observations point to the same scenario:

The complexity of the problem must increase, with the inclusion of prolonged dust growth in ISM

Summary

- SIMBA predicts high fractions (>60%) of dusty QGs around z~2 in both cluster and field
- t_{quench} bimodality independently of the environment
- δ_{DGR} reaches similar values to MS galaxies
- In cluster environment the fraction of dusty QGs is smaller
- The large scatter in f_{dust} is due to slow QGs having both a jet and radiative mode AGN
- Dust-removal and H_2-removal timescales can be significantly different, providing clue for dust re-growth

There is a lot more coming in

- New SIMBA-C will include a new chemical enrichment model with additional grain-size distribution —> lots of new physics to explore!
- Zoom-in simulations can help resolving what happens around the dry-phase —> detailed analysis of specific targets!
- We are waiting for JWST observational time! (hopefully) —> confirmation of SIMBA results?
- We have Gemini observations coming up —> protocluster candidate to better test the environment
- Dust is hiding insight ALMA archives —> time to scavenge