Title: Mergers, Radio Jets, and Quenching Star Formation in Massive Galaxies: Quantifying Their Synchronized Cosmic Evolution and Assessing the Energetics

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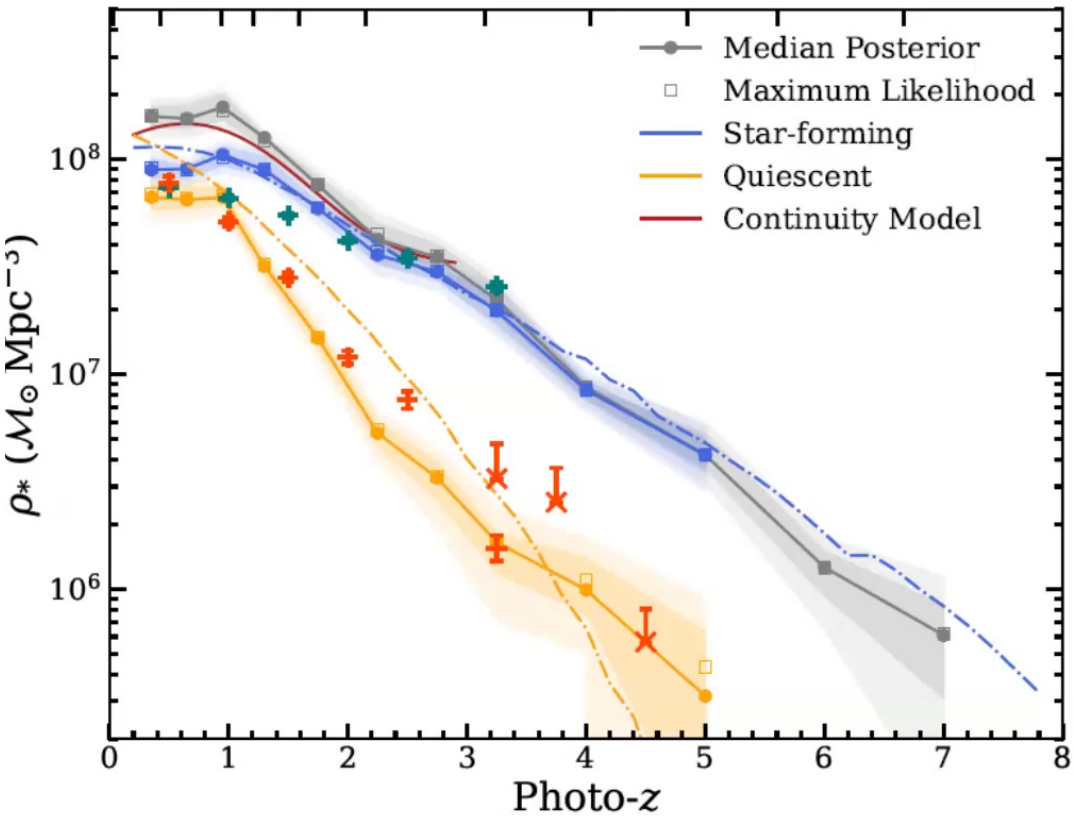
Abstract:

The existence of a population of massive quiescent galaxies with little to no star formation poses a challenge to our understanding of galaxy evolution. The physical process that quenched the star formation in these galaxies is debated, but the most popular possibility is that feedback from supermassive black holes lifts or heats the gas that would otherwise be used to form stars. In this paper, we evaluate this idea in two ways. First, we compare the cumulative growth in the cosmic inventory of the total stellar mass in quiescent galaxies to the corresponding growth in the amount of kinetic energy carried by radio jets. We find that these two inventories are remarkably well-synchronized, with about 50% of the total amounts being created in the epoch from z ≈ 1 to 2. We also show that these agree extremely well with the corresponding growth in the cumulative number of major mergers that result in massive (>10^11 M_ O) galaxies. We therefore argue that major mergers trigger the radio jets and also transform the galaxies from disks to spheroids. Second, we evaluate the total amount of kinetic energy delivered by jets and compare it to the baryonic binding energy of the galaxies. We find the jet kinetic energy is more than sufficient to quench star formation, and the quenching process should be more effective in more massive galaxies. We show that these results are quantitatively consistent with recent measurements of the Sunyaev–Zel'dovich effect seen in massive galaxies at z ≈ 1.

How is Star Formation Quenched in Massive Galaxies?

- Today there are two populations of galaxies: those rich in dense gas and actively forming new stars, and “quiescent” galaxies with little dense gas and star-formation
- The structures of quiescent and star-forming galaxies are different: spheroids vs. disks

The bi-modal populations have been around since early times

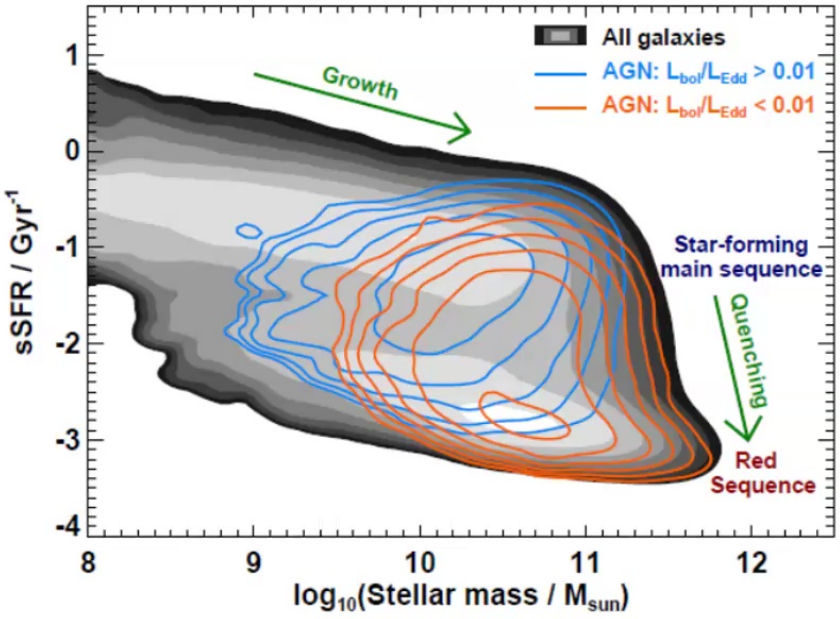


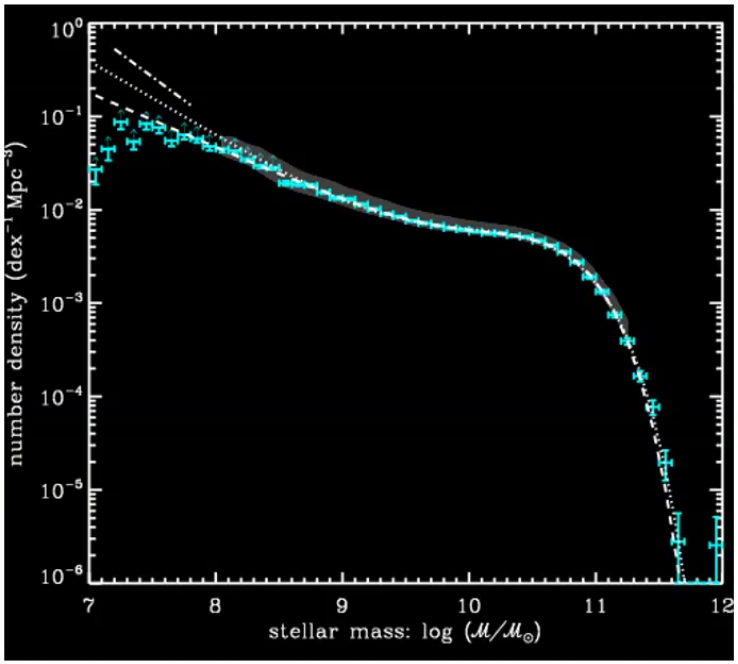
- Today nearly half of all the stellar mass is in quiescent galaxies
- At a redshift of 5 this fraction was only about 5% (Weaver et al. 2023)

How does quenching happen?

Why does the creation of quiescent galaxies "lag behind" that of star-forming galaxies?

A related issue: what sets the maximum galaxy mass?





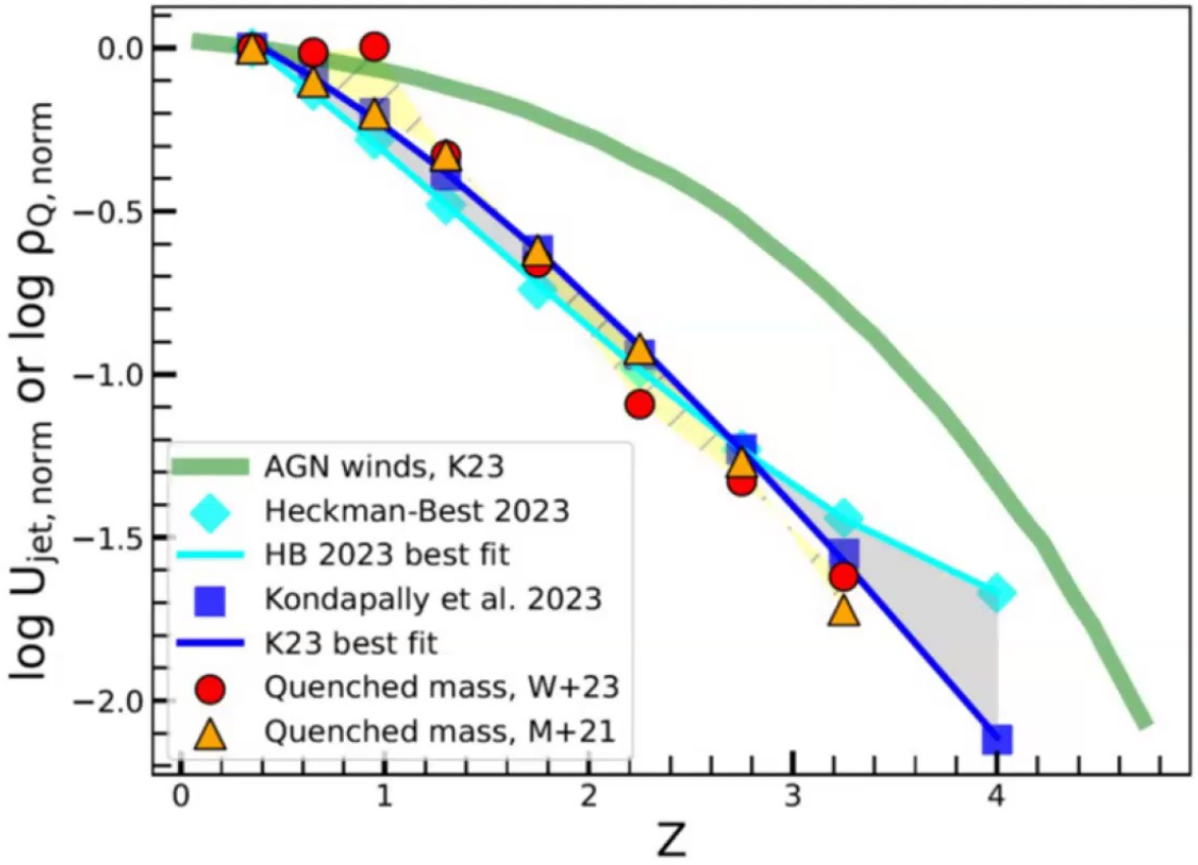
- Star formation (fueled by cold gas) occurs mainly in lower mass galaxies
- Some **quenching** process shuts down star formation above a mass ≈ 10^{11} $M_\odot$
- Commonly attributed to **"feedback" from supermassive black holes**

Pre-Emptive Summary of the Take-Away Points

- The build-up in the population of massive quenched galaxies over cosmic time is perfectly synchronized with major mergers and with the injection of energy of radio jets launched by supermassive black holes
- During the "quenching era" ($z \approx 1$ to 2), 80% of radio galaxies are star-forming (not yet quenched) and 90% are on-going mergers
- The causal connection: 1) mergers transform the galaxy structure (disk to spheroid) and 2) trigger the launching of jets that 3) then lead to quenching
- The energy delivered by jets exceeds that required for quenching

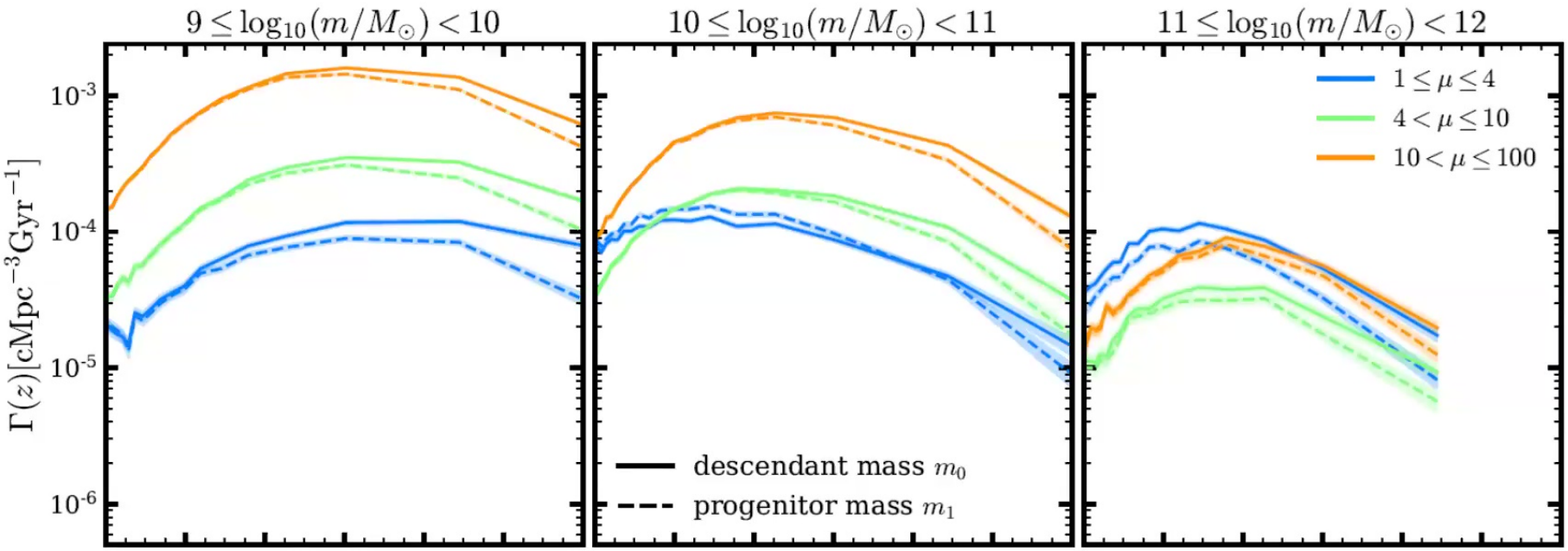
For details see Heckman & Best (2023) and Heckman et al. (2024)

Cosmic Inventory 1: Stellar mass in quiescent galaxies



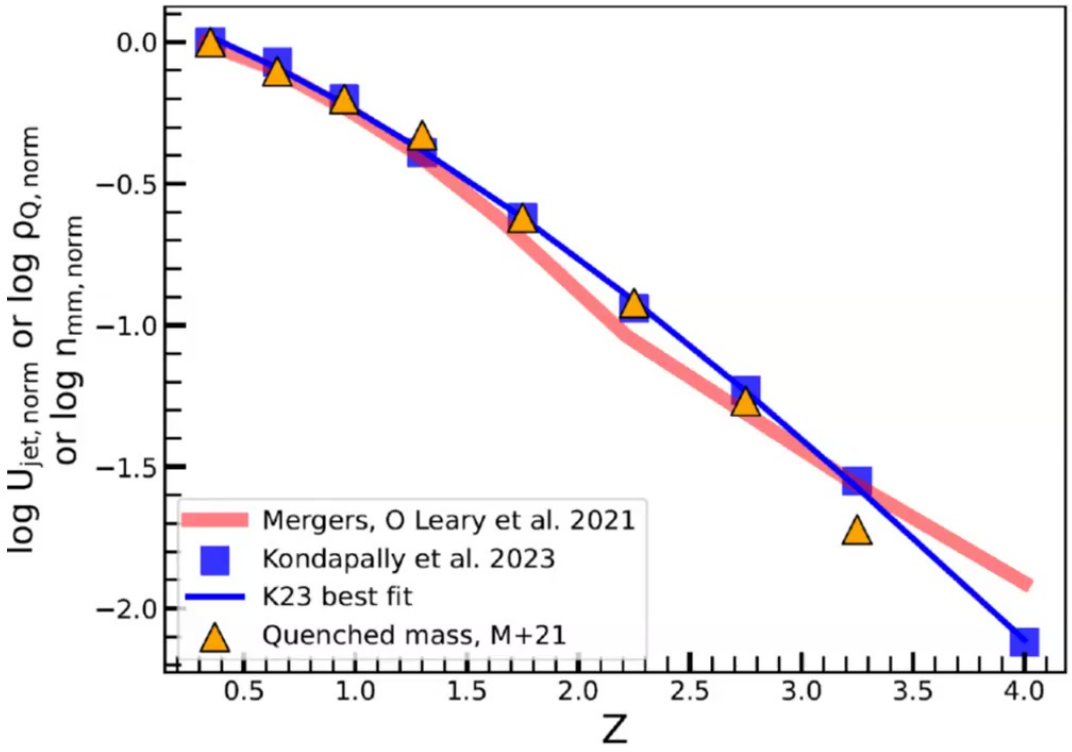
- The build-up of the population of quiescent galaxies (Yellow and Red points) is a late-time phenomenon
- Only ≈10% of present-day mass in place at z = 2
- The “quenching epoch” is z ≈ 1 to 2 (≈70% of present-day total mass is produced then)

Step 2: Comparing quenching to the growth in the number of major mergers of massive galaxies



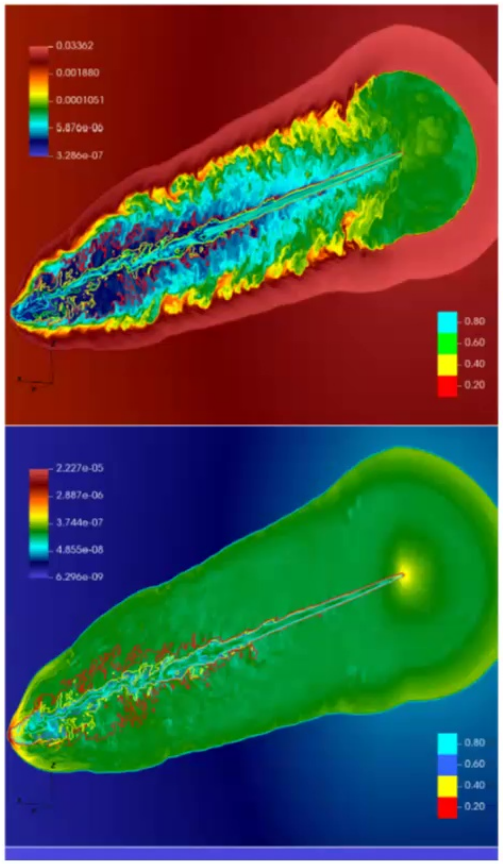
- Merger rates as a function of redshift, mass-ratio, and resulting mass (O'Leary + 21)
- Focus on major mergers (ratio < 4) and massive galaxies (≈ 10^{11} $M_\odot$): blue, right panel
- Compute the cumulative mass produced by these major mergers vs. redshift

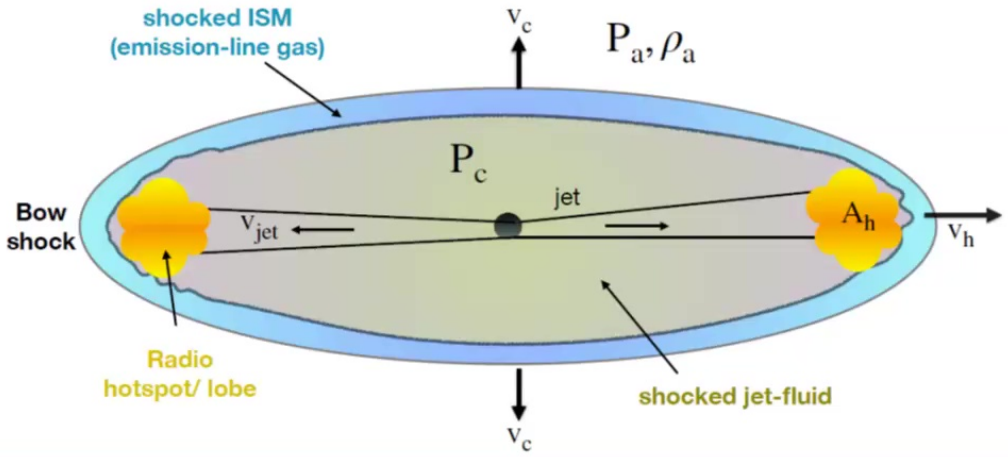
The Cosmic Inventory Part 2: The growth in the number of major mergers of massive galaxies



- ***There is near-perfect synchronization between the cumulative growth in the total number of major mergers (red line) and the stellar mass in quenched galaxies (yellow points)***
- ***The phasing of major mergers of massive galaxies is what drives the "lag" in the build-up of quiescent galaxies***

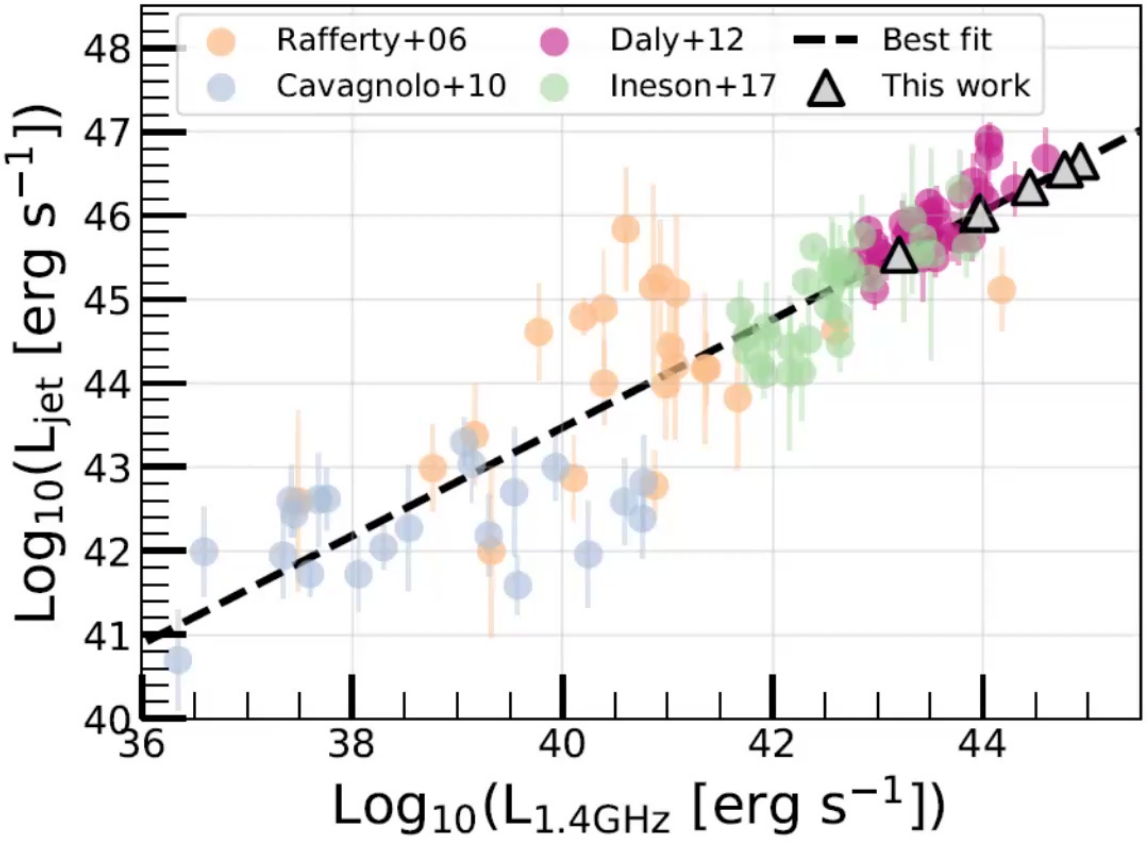
Step 3: Energy injection by radio jets and quenching





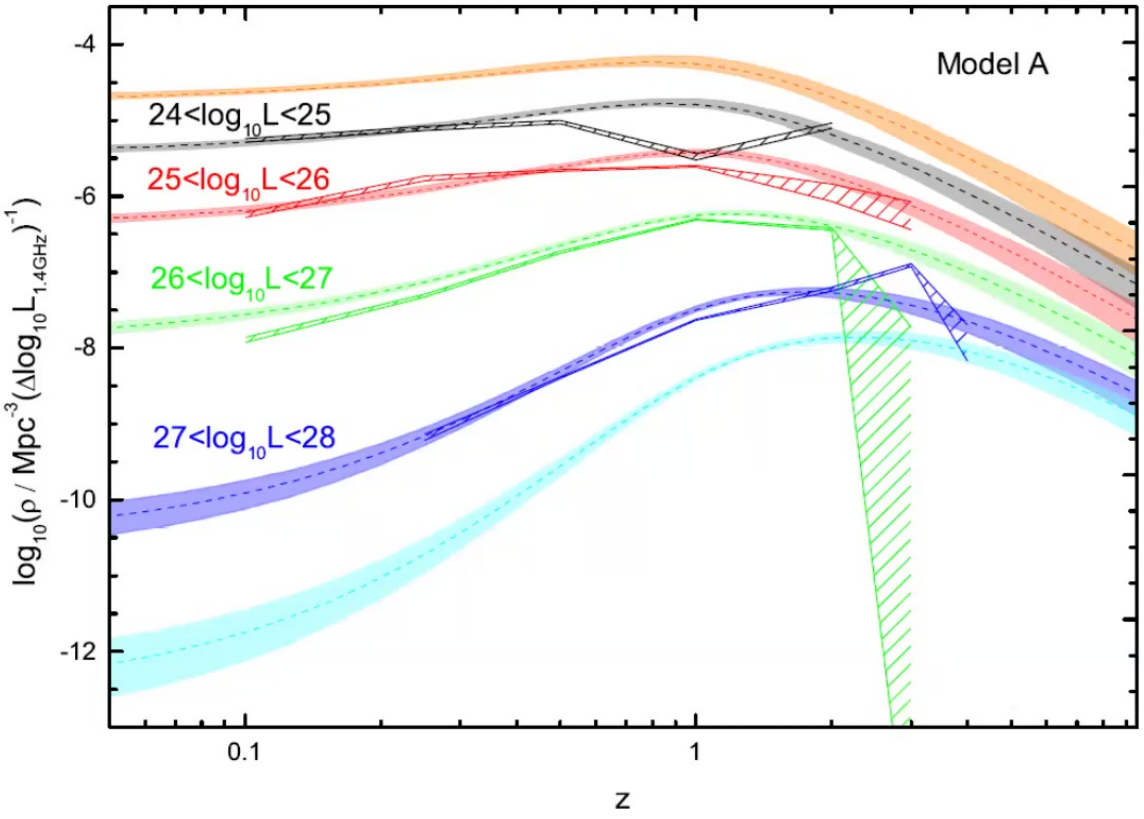
- Kinetic energy is transported from the supermassive black hole by jets
- The jets terminate in strong shocks (bright “hot spots” of radio synchrotron emission).
- This shocked jet fluid has a very high pressure and it expands laterally and then “backflows” creating an expanding cocoon
- This cocoon creates an expanding cavity in the gas surrounding the galaxy (Begelman & Cioffi 1989)
- This delivers energy to this gas (Roy +24; Perucho+22). Quenching?

How much energy do jets actually carry? Three methods



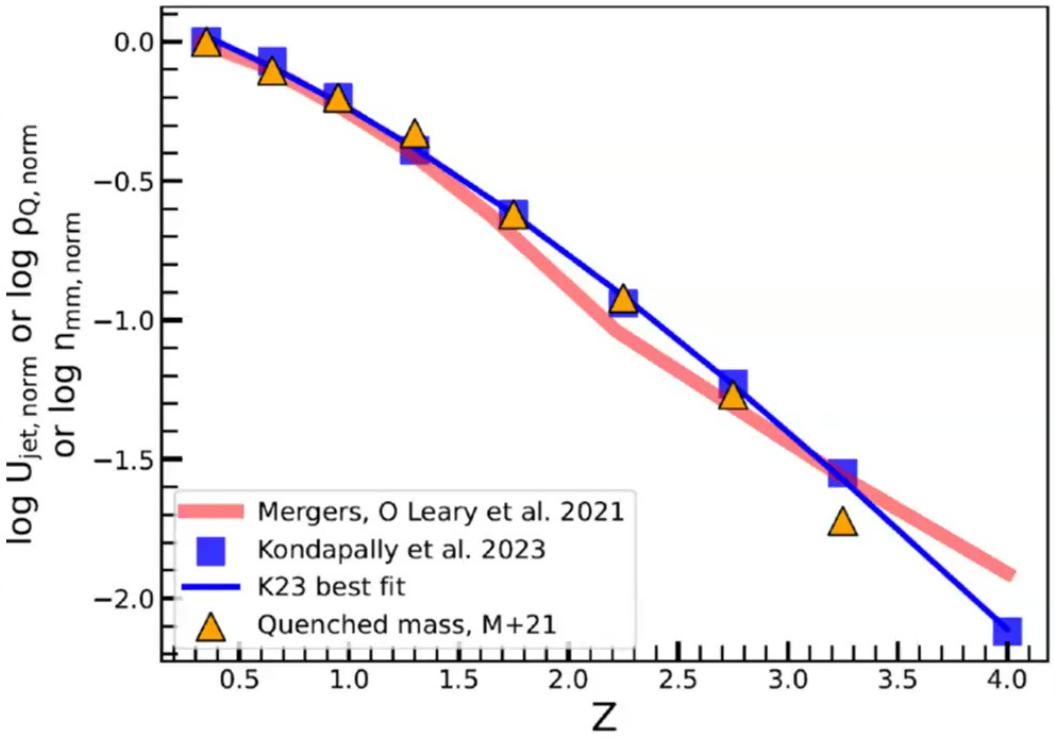
1. Energy needed to excavate X-ray cavities (Rafferty+06; Cavagnolo+10)
2. Energy content of radio plasma from synchrotron plus inverse Compton (Ineson+17) $\langle z \rangle \approx 0.3$
3. Measurements of A x P x v for the radio lobe (Daly+12; O'Dea+09) $\langle z \rangle \approx 1$

Now use the radio luminosity function vs. z and convert luminosity to jet power per unit volume



- Integrate energy injection rate per unit volume over time (z) to measure how the cumulative amount of jet energy per unit volume grows with cosmic time
- Yuan et al 2017 RLFs

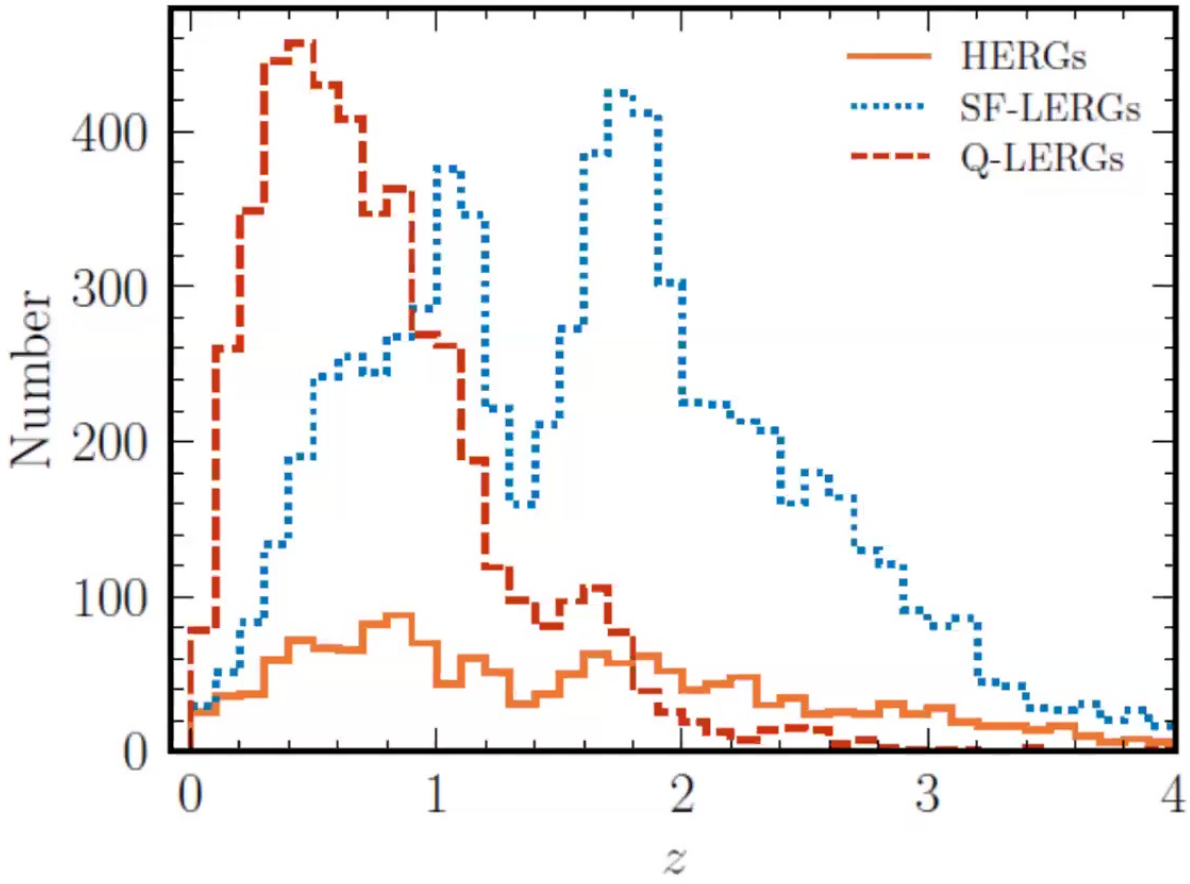
The Cosmic Inventory Part 3: The cumulative amount of jet kinetic energy injected per co-moving volume



- There is near-perfect synchronization in the cumulative growth of injected jet energy (Blue), of the mass in quenched galaxies (Yellow) and major mergers of massive galaxies (Red)

But what is the causal connection?

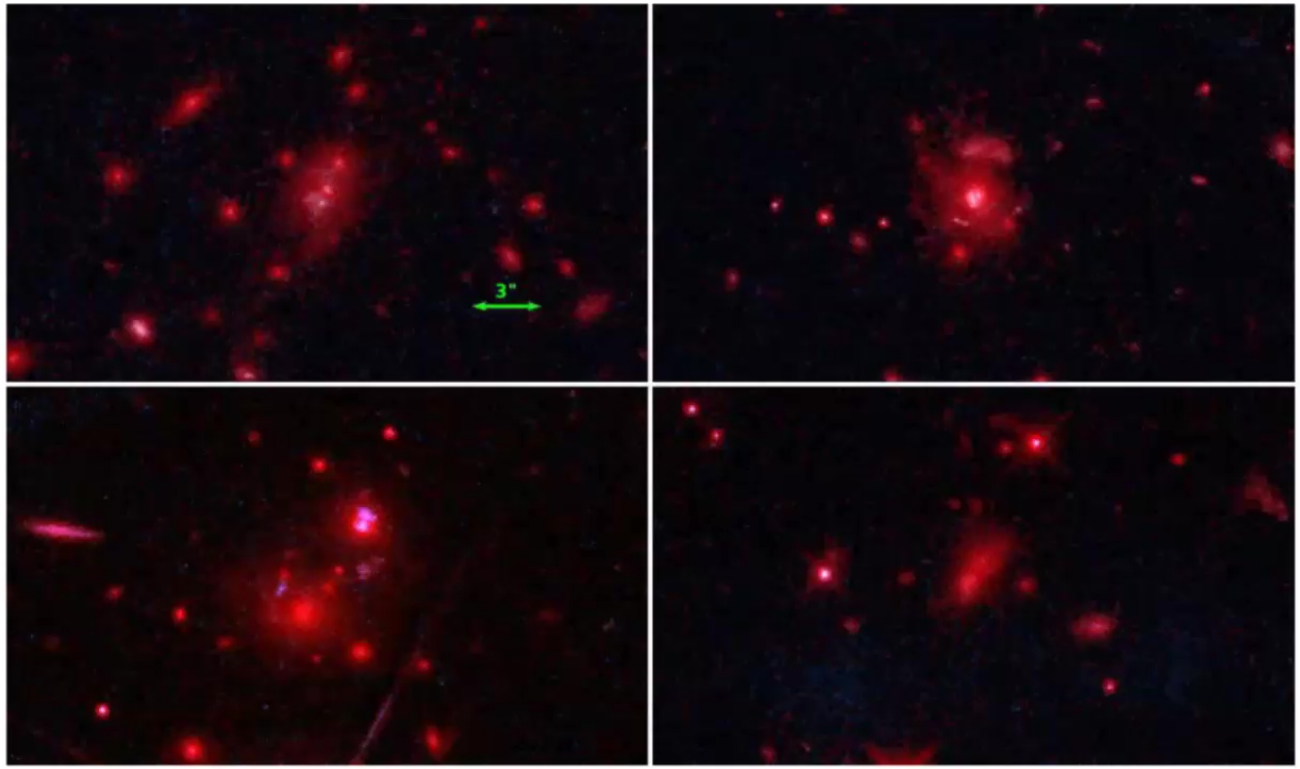
One possibility – mergers lead to quenching and quenching later leads to jet launching



This is inconsistent with the fact that over 80% of radio galaxies during the epoch of quenching are star-forming galaxies (Kondapally + 2022)

They have not already been quenched

A more plausible scenario: mergers trigger jets and jets later quench star-formation



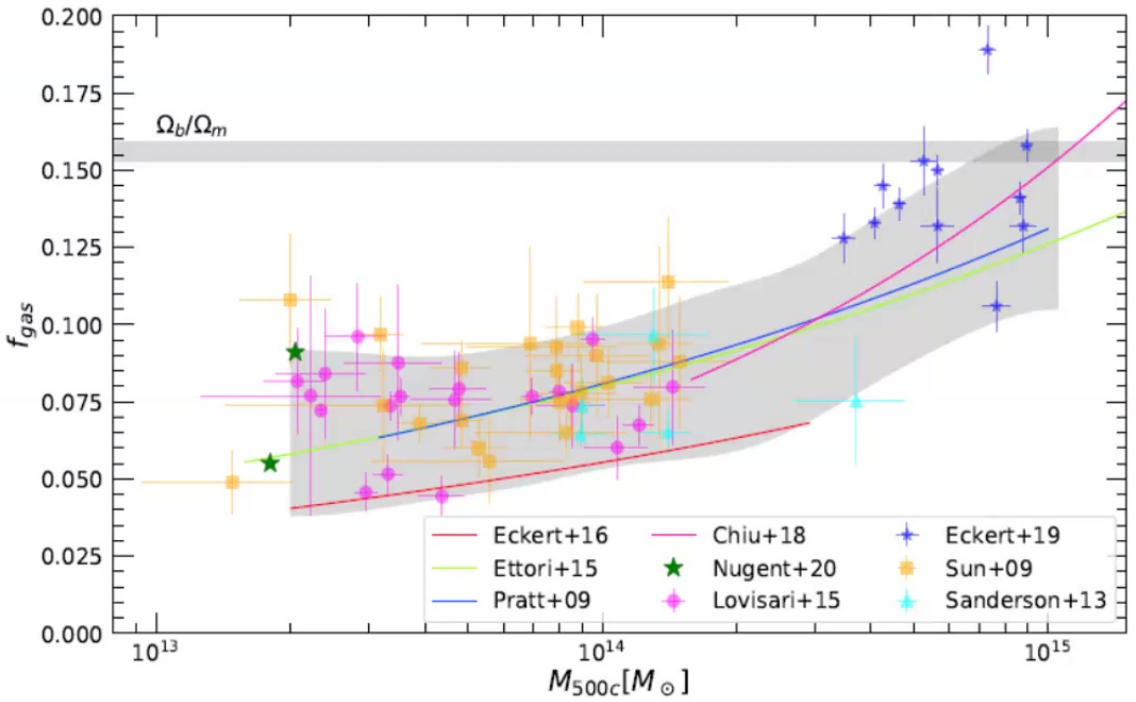
- HST imaging of these star-forming radio galaxies at z ≈ 1 – 2 shows that over 90% are on-going or recent mergers (Chiaberge et al 2016; Breiding et al. 2024)

Do jets carry enough energy to do the job?

- The amount of jet kinetic energy per unit volume integrated over cosmic time is $U_{jet} \approx 2 \times 10^{57}$ erg Mpc^{-3}
- The amount of stellar mass in quenched galaxies today is $\rho_Q \approx 1.2 \times 10^8\ M_\odot$ Mpc^{-3}
- This corresponds to 1.1×10^{16} erg/gm
- Example: galaxy with $M_* = 10^{11}\ M_\odot$ would have received 2.2×10^{60} ergs in jet KE
- The binding energy of the baryons is $E_{bind} \approx \frac{1}{2} M_{baryon} v_{cir}^2 \approx 2 \times 10^{59}$ ergs
- **$KE_{jet} \approx 10\ E_{bind}$**
- Jets can indeed do great damage, at least in principle

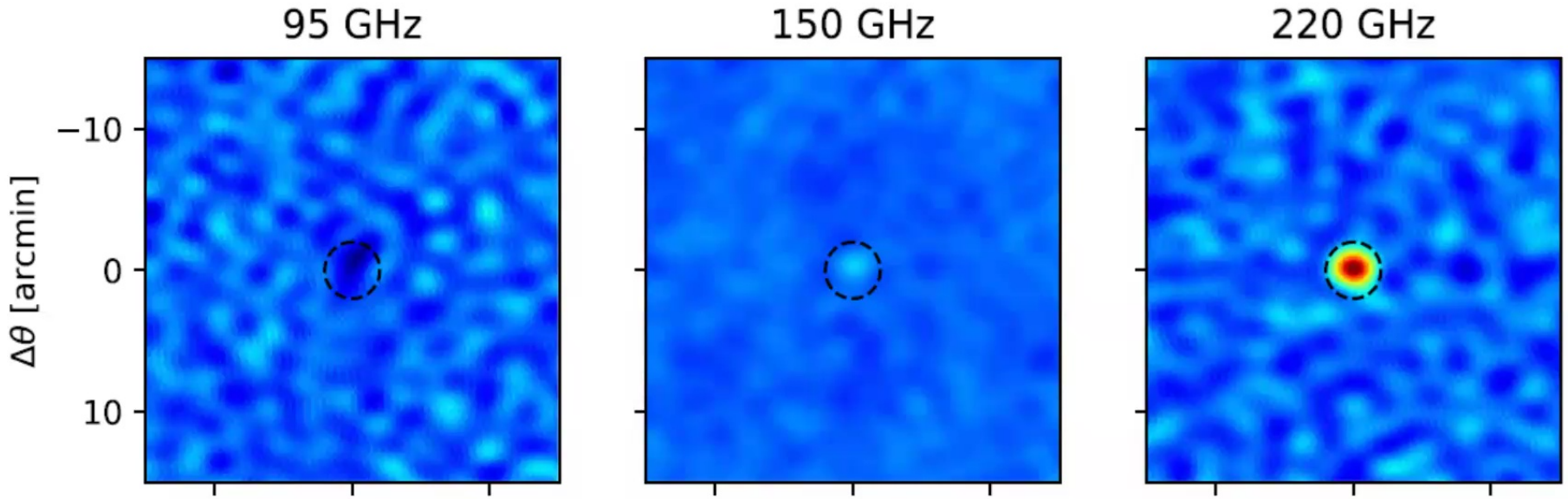
Jet energetics and the baryon fraction in groups, clusters

- Consider cluster with $M_{halo} = 10^{14}\ M_\odot$
- It has lost about 50% of its gas (a mass of $7.5 \times 10^{12}\ M_\odot$)
- Given $v_{Vir} \approx 600$ km/s, removing this gas would take about 3×10^{61} ergs
- The total mass of quenched galaxies in this cluster is $\approx 1.6 \times 10^{12}\ M_\odot = 3.2 \times 10^{45}$ gm
- The accumulated jet energy for this mass is 3.5×10^{61} ergs
- Q.E.D!



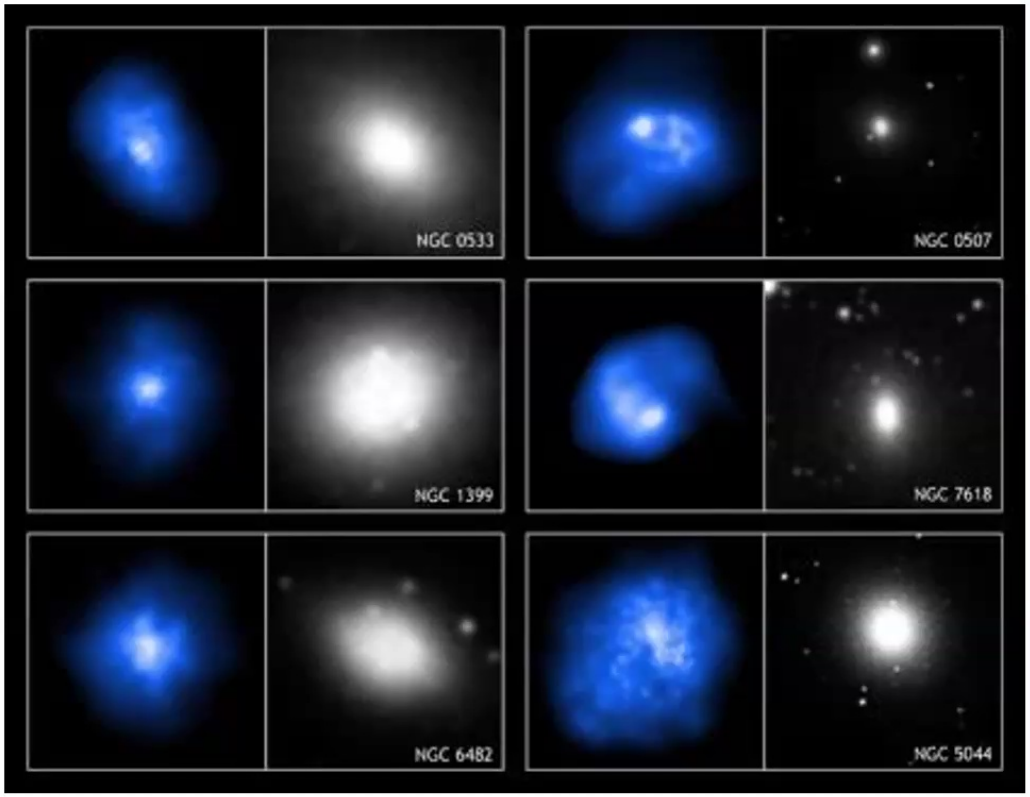
Donahue & Voit 2022

Further Sanity Check on Jet Energetics:



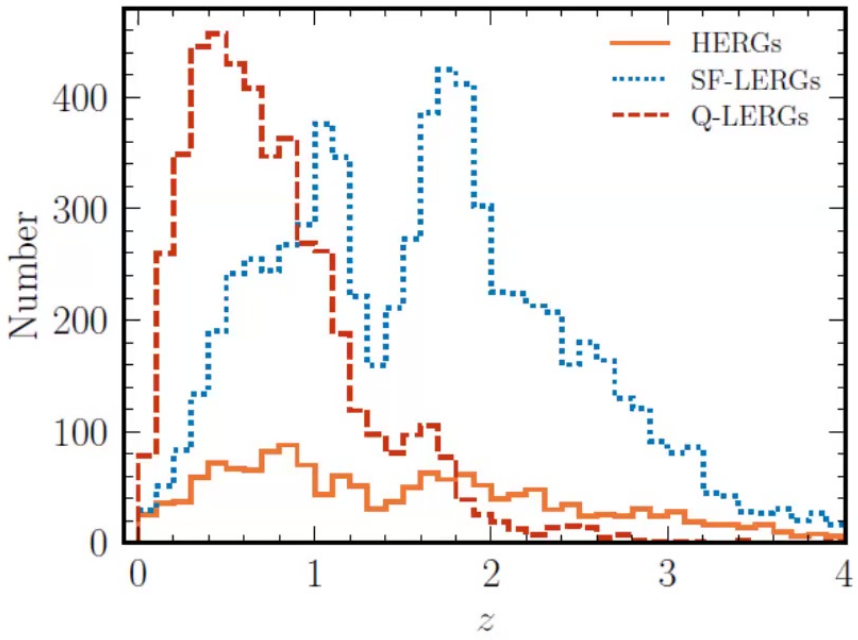
- Thermal SZ Effect in very massive ($\langle M_* \rangle = 2.5 \times 10^{11}\ M_\odot$) galaxies at $\langle z \rangle \approx 1$ (Meinke+21)
- Total energy required is $\approx 8 \times 10^{60}$ ergs per galaxy
- The cumulative amount of jet energy at z = 1 is $9 \pm 3 \times 10^{60}$ ergs per very massive galaxy
- Excellent agreement!

But don’t we know that jets just maintain low SFR in previously quenched galaxies? *Only true at low-z!*



- Low-z quenched massive galaxies (white, right panels) are surrounded by ample reservoirs of hot (X-ray-emitting) gas (blue, left panels)
- The radiative cooling times of this gas are short (≈ Gyr)
- This gas should produce cool dense gas that forms stars
- But (almost) no star formation is seen
- Feedback from jets is heating the gas, preventing it from cooling
- **AKA “Maintenance Mode”**

The *two* modes of jet feedback: maintenance vs. quenching. Strong cosmic evolution.



- **At z ≈ 0, 90% of radio galaxies are *already quenched ("Q-LERGS")***
- **Radio jet feedback *keeps them quenched* ("Maintenance Mode")**
- **At z > 0.8, most radio galaxies are blue and star-forming ("SF-LERGs" + "HERGs")**
- **Radio jets will quench their star-formation (over few hundred Myr timescale)**
- R. Kondapally + 2022

Summary

- ***There is a remarkable synchronization in the build-up over cosmic time of three "inventories": 1) The number of major mergers of massive galaxies 2) The amount of stellar mass in quiescent ("dead") galaxies, and 3) The amount of kinetic energy carried by radio jets created by supermassive black holes***
- This can be most naturally explained if major mergers both lead to the structural transformation of galaxies (disks to spheroids) and the triggering of radio jets
- The jets then disrupt the gas supply in their host galaxy, leading to the quenching of star-formation
- Direct evidence links mergers to radio jet launching
- Simple energetic argument suggests that jets can quench star-formation
- Present day: jets primarily operate in "maintenance mode"
- Over most of cosmic time jets operated in "quenching mode"

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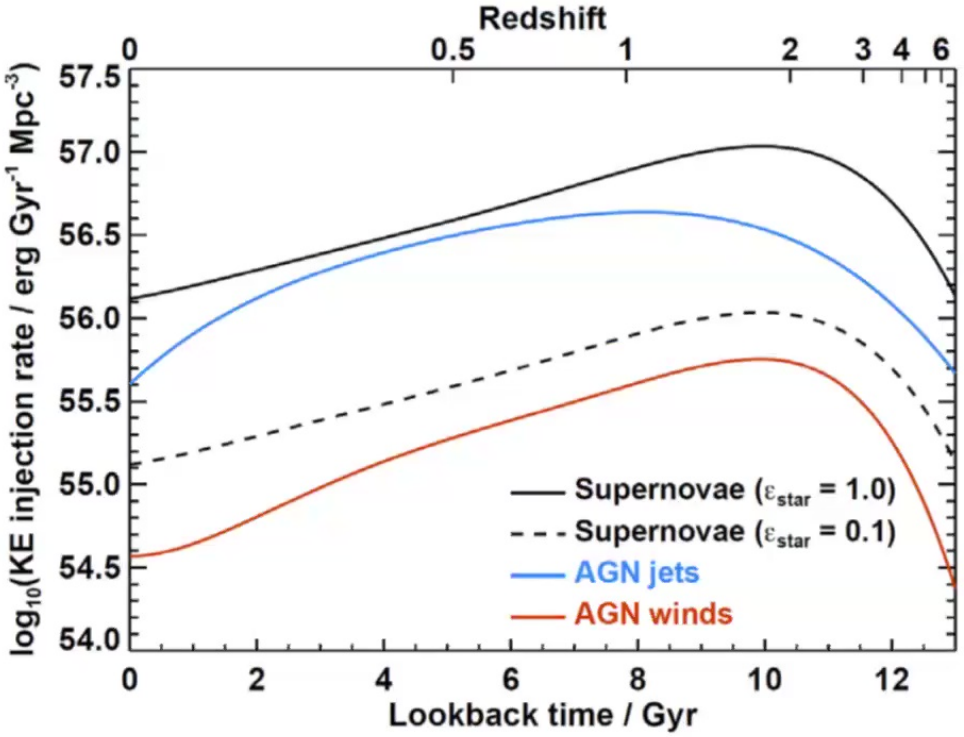
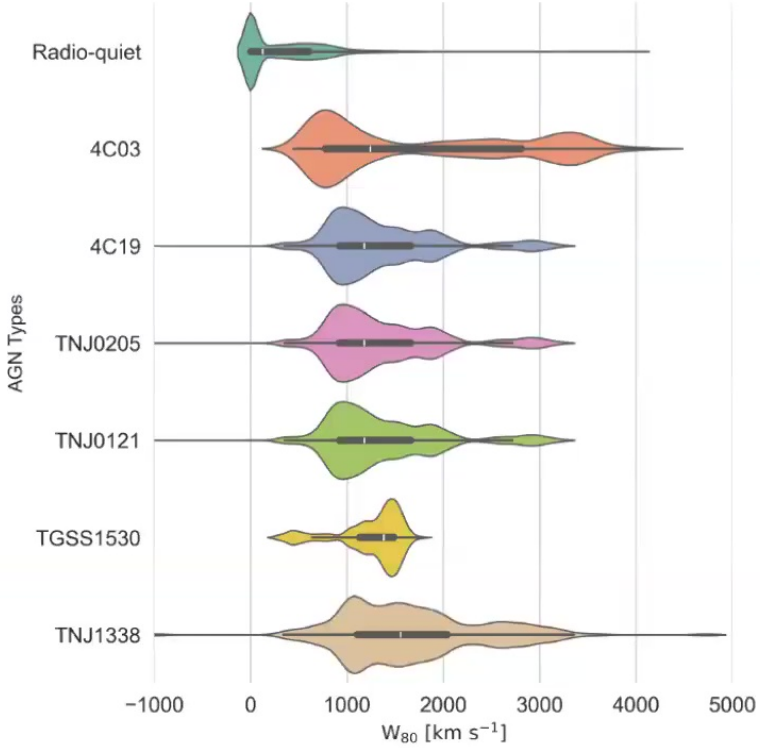
AGN Winds: Too Weak and Too Early

Heckman & Best 2023



N. Roy et al 2025



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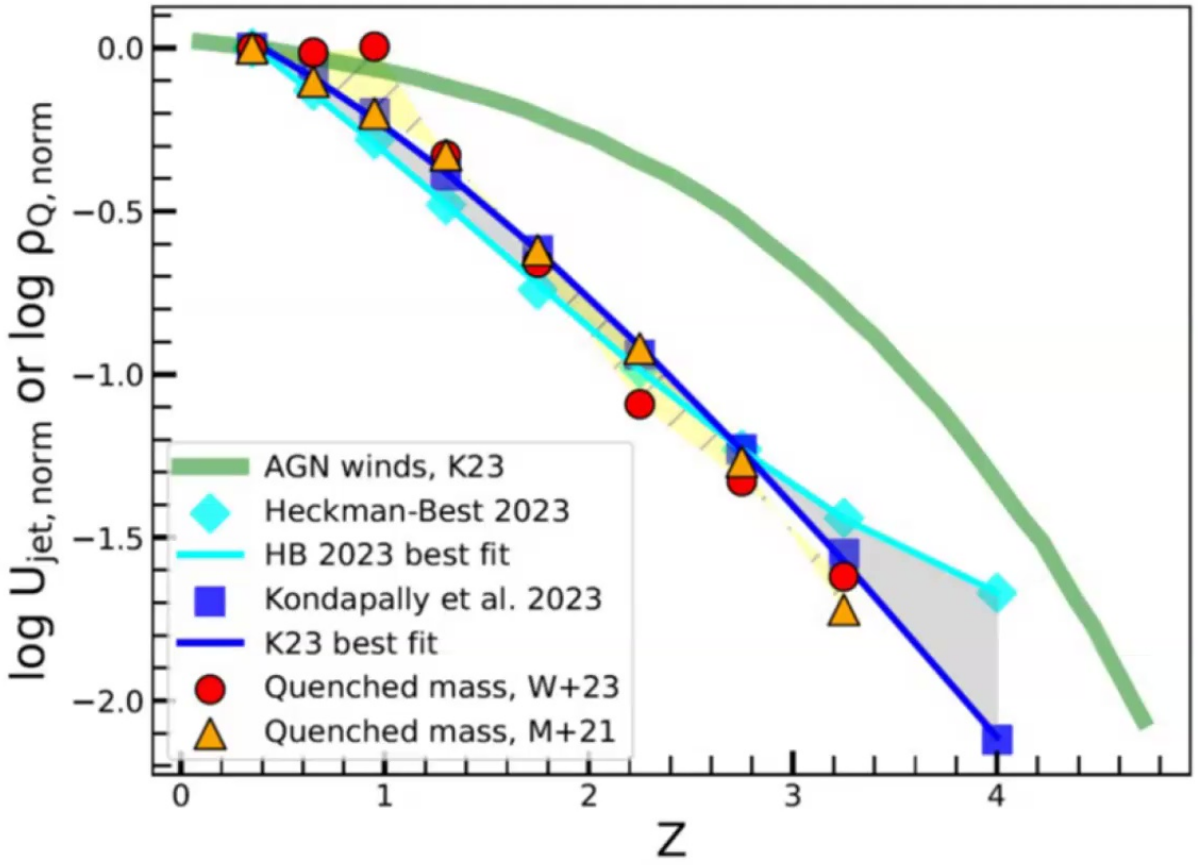

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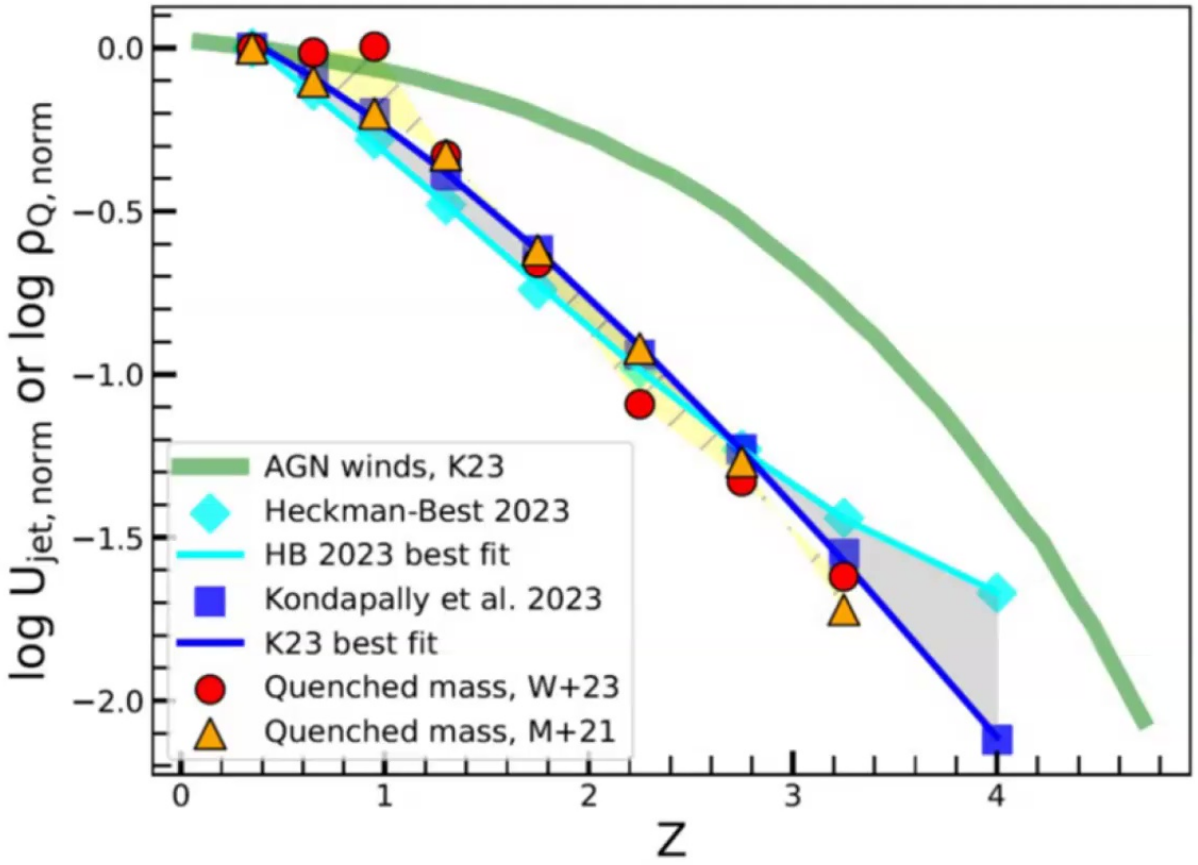

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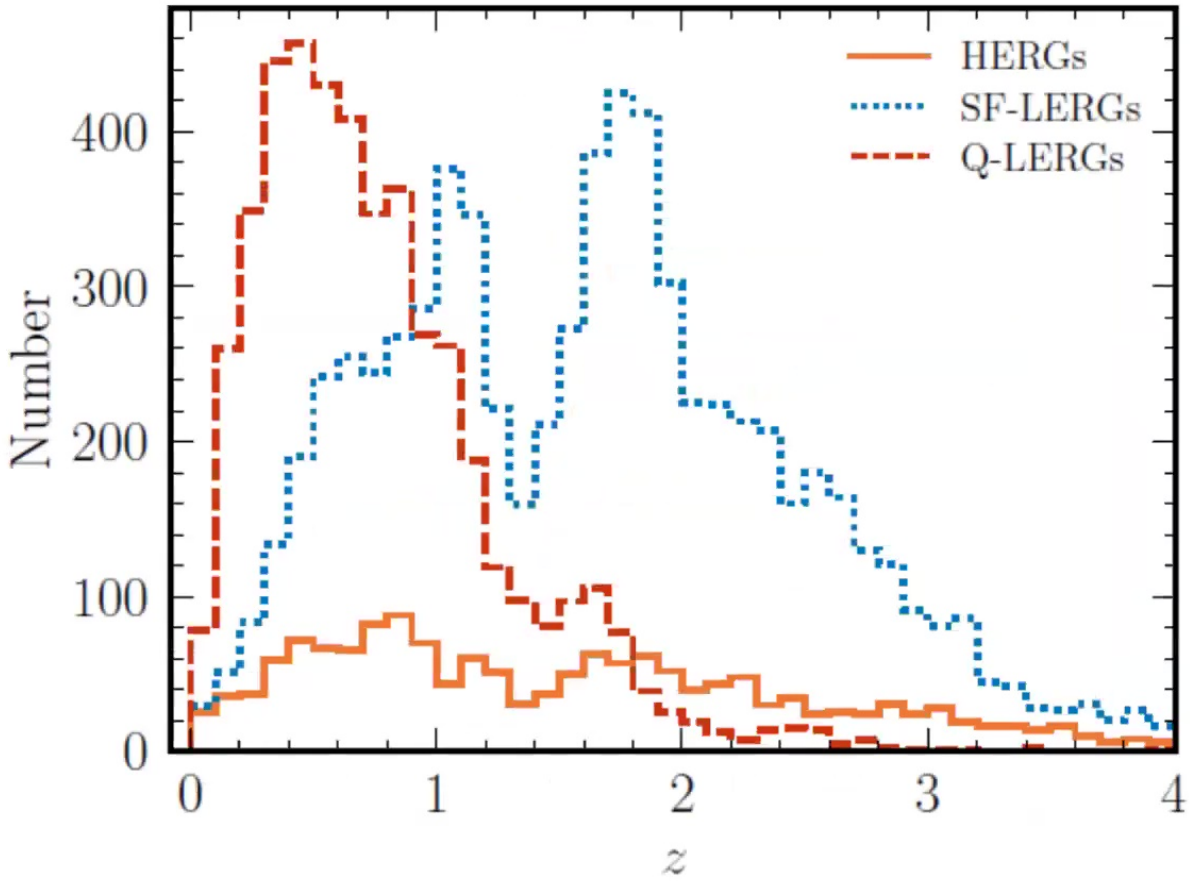

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They have not already been quenched