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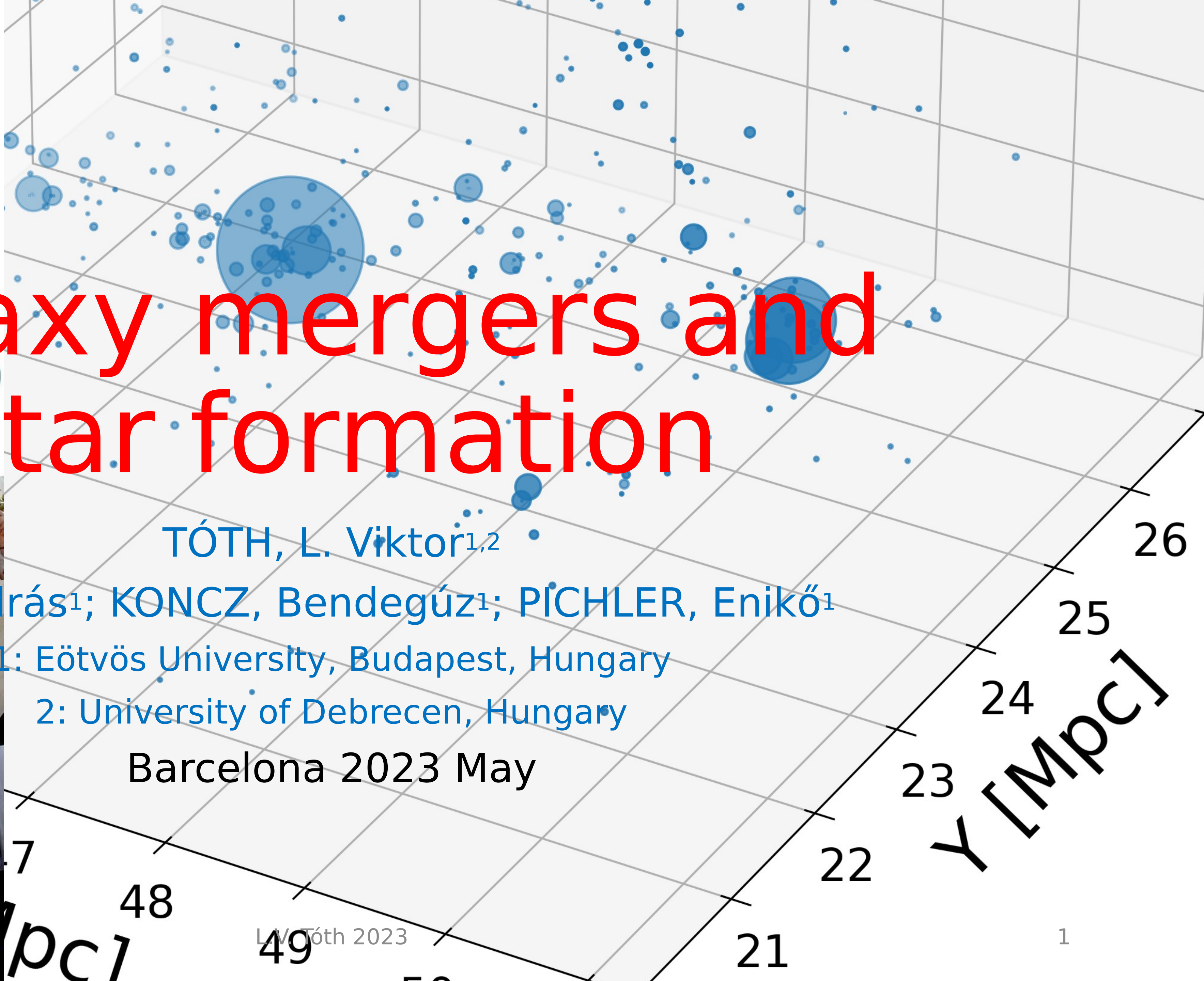

Galaxy mergers and star formation

TÓTH, L. Viktor[1,2]

JOÓ, András[1]; KONCZ, Bendegúz[1]; PICHLER, Enikő[1]

1: Eötvös University, Budapest, Hungary

2: University of Debrecen, Hungary

Barcelona 2023 May

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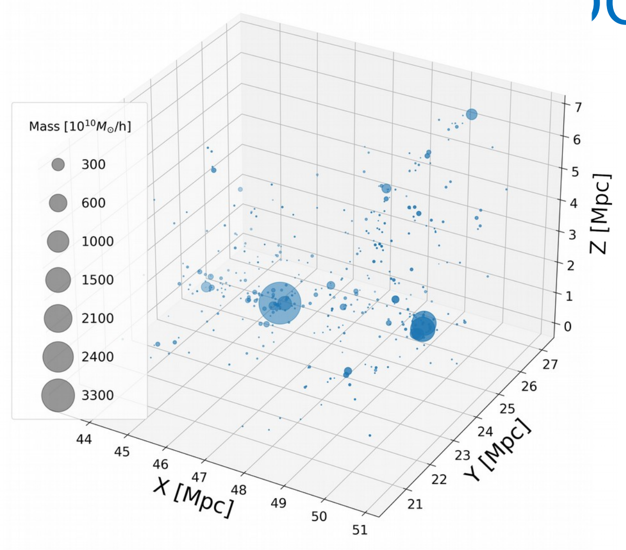


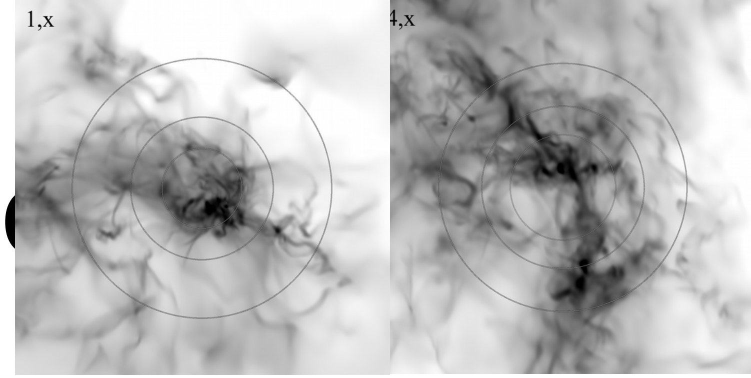
Galaxy mergers

- “peculiar galaxies” – from Arp to JWST
- types of interactions
- examples in the Local Universe
- merger models
- assumed role in galaxy evolution
- JWST tests
- the Illustris Universe model
- megers in the Illustris Universe model

Star formation

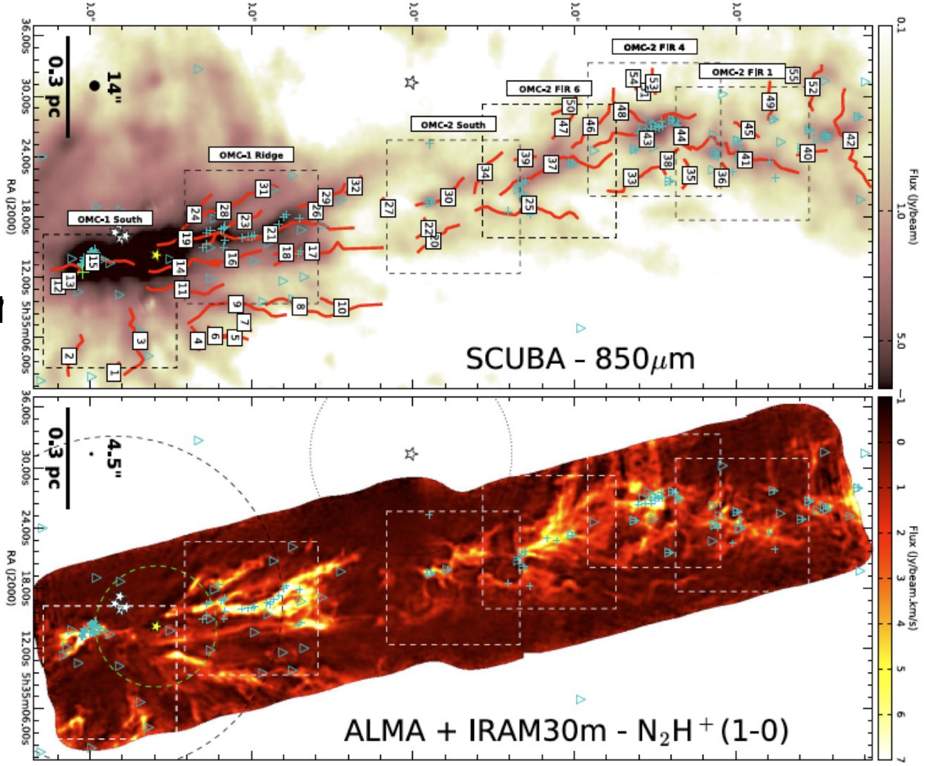
- basics, massive star formation
- tracers
- triggers
- role of SF in chemical evolution
- star formation in spiral galaxies
- infall history and star formation
- starbursts

Star formati



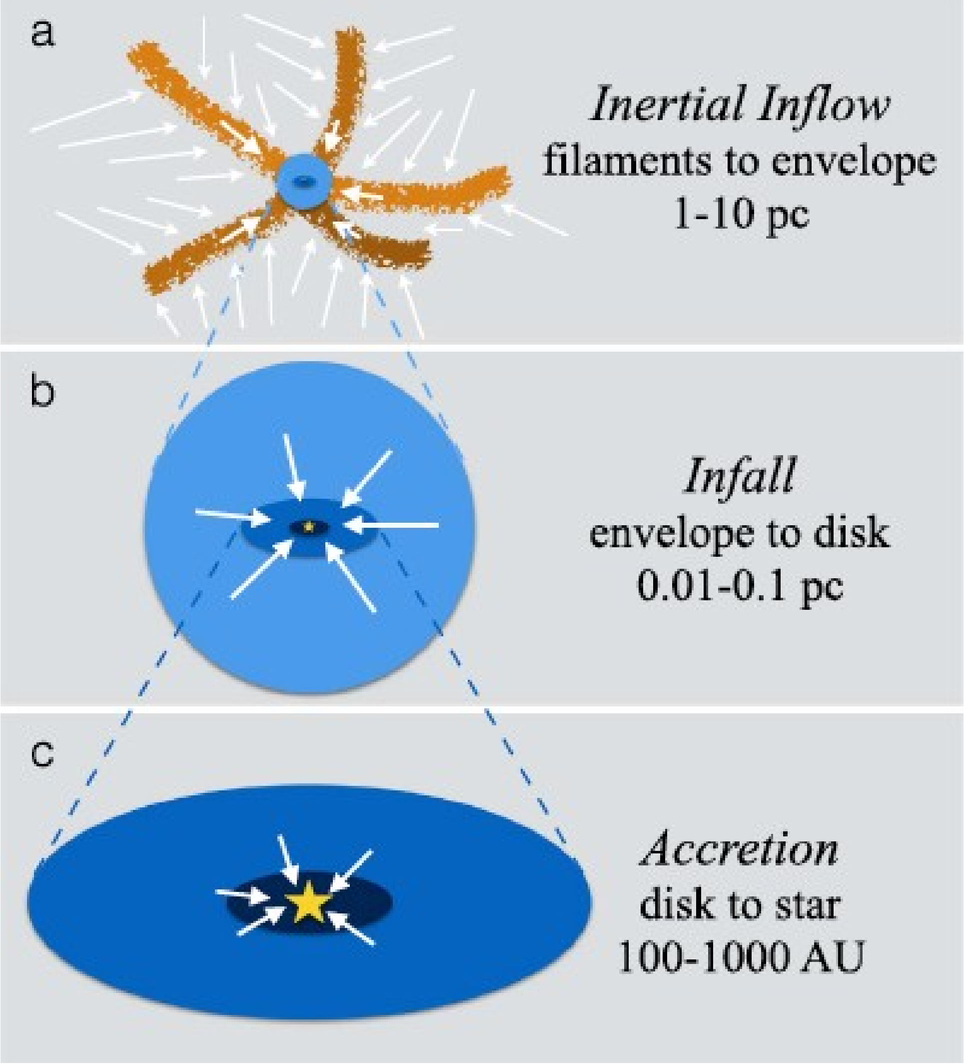
Column-density maps, snapshots at 7 and 28 Myrs from the model of Padoan+ 2023 of an ISM region of size $L_{\rm box}$ = 250 pc and total mass $M_{\rm box} = 1.9\times10^6\ M_\odot$, where the turbulence is driven by SNe alone.

- “The formation and evolution of galaxies cannot be fully understood until a universal SFR law is revealed.” [Padoan+2017]
- gravoturbulent models of massive star formation with SNe
- SFR may depend on SNe induced turbulence
- [Pelkonen+ 2021] for any individual star there is only a weak correlation between the gravitationally-bound prestellar or “progenitor” core mass and the final stellar mass
- the mass reservoir to form high-mass stars is spread over larger scales (core-collapse model is questioned)
- The inertial-inflow model [Padoan+ 2020]
- ALMA based CMF is under critics [Padoan+ 2023]
- filaments and fibers in action [Hacar+ 2013]
- Cores formed uniform density filaments? [Hoemann+ 2023]



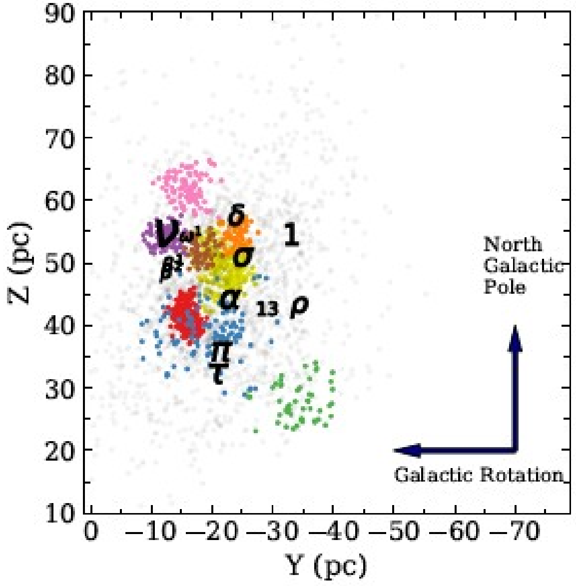
The inertial-inflow model Padoan+ 2020

- gravoturbulent models of massive star formation with SNe
- the origin and subsequent growth of a star are addressed self-consistently in the context of large-scale ISM turbulence
- mass flow of interstellar gas onto a growing star
- scales: inertial inflow, infall, and accretion
- Xu+ 2023 (in prep in ATOMS collaboration)
  - from ALMA sub-mm continuum and spectral line measurements
  - → 1000AU resolution structure and kinematics
  - → streemers of infalling gas to star forming cores



different scales and corresponding terminologies adopted in the inertial-inflow model. The infall and disk-accretion scales inherit the filamentary structure of the larger scale, but are here depicted as smooth regions for simplicity.

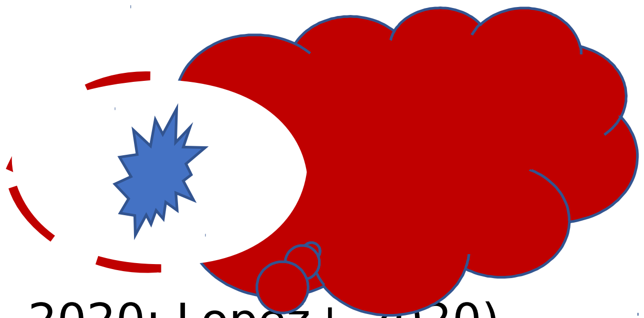
Star formation triggers – or not?



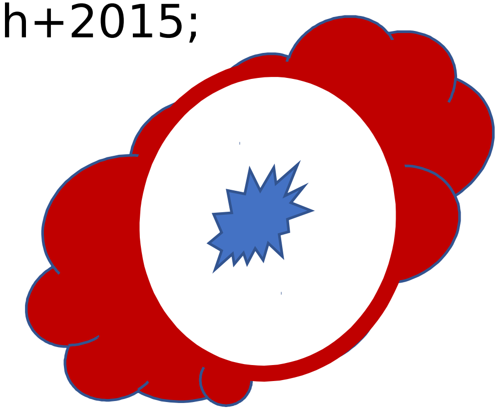
- classical approach (Elmegreen)
  - direct compression
  - accumulation of gas
  - cloud collision
- Example 1: Upper Scorpius – stellar winds and young S
  - correlation in density-age, providing an empirical expansion law to be tested in other associations,
  - correlation in tangential velocity-age, providing constrains on the dynamics of these substructures and the **position of potential past triggering events**
  - four potential supernovae events occurred in Upper Scorpius.
  - Briceño-Morales & Chanamé 2023
- Example 2: Rosette Molecular Cloud – ionizing stars – not
  - Star formation is influenced by the primordial structure of the cloud in spite of the impact of irradiation from the nearby cluster, NGC 2244
  - Bőgner+ 2022

Massive star formation – hidden or exposed? Studies in nearby star-forming galaxies

- The exact effects of SNe on giant molecular clouds (GMCs) and their parent galaxies depend
  - on the relative spatial configuration of the SNe, the gas
  - and the density distribution of that gas
- SNe in environments full of low-density gas
  - cools slowly
  - hence are efficient at heating and ejecting material out of the galaxy,
  - resulting in hot, diffuse gas outflows (e.g., Martizzi+ 2016; Andersson+ 2020; Lopez+ 2020).



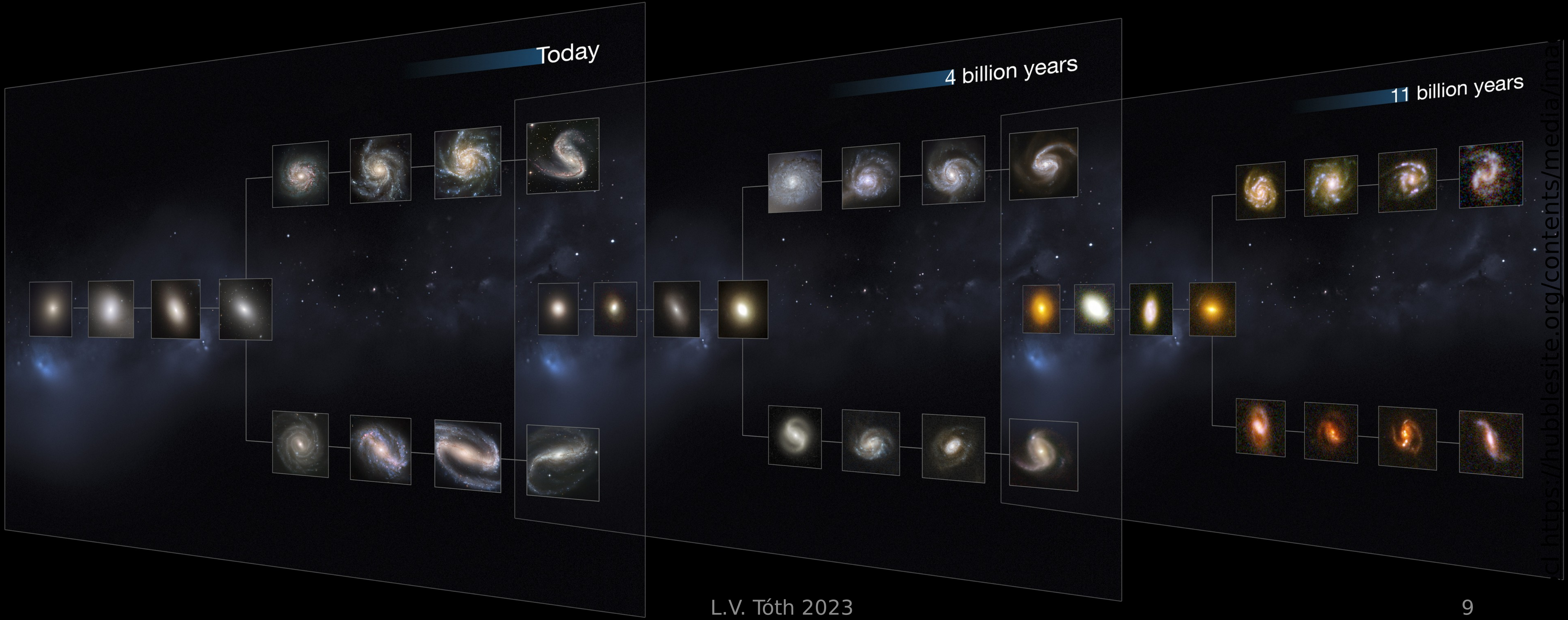
- SNe in or near dense clouds
  - can destroy GMCs & shut down star formation in these areas,
  - but they cool more rapidly hence are less effective at driving outflows (Walch+2015; Lu+2020)
- Relative distribution of SNe and GMCs must be investigated
- Chen+ 2023: PHANGS:
  - SN explosions are not restricted to only the densest gas,
  - exert feedback across a wide range of molecular gas densities



Massive SF in NGC628 – the molecular gas environment and star formation

- Results of the ~1'' or ≤150 pc resolution CO (2–1) maps from the PHANGS–ALMA survey of nearby star-forming galaxies
- the interval during which GMCs in NGC628 are devoid of young massive stars is 18 Myr.
- the embedded phase of star formation lasts for 5.1 Myr - about 20% of the total GMC lifetime
- star-forming regions are heavily obscured for 2.3 Myr, thus undetected in Hα emission
- Subsequently, the star-forming region becomes partially exposed, enabling the detection of Hα emission along with CO and 21 μm emission for 2.7 Myr
- Finally, the molecular clouds are completely dispersed by the stellar feedback, leaving behind only SFR tracers to be detected for an additional 5 Myr, without accompanying CO emission.

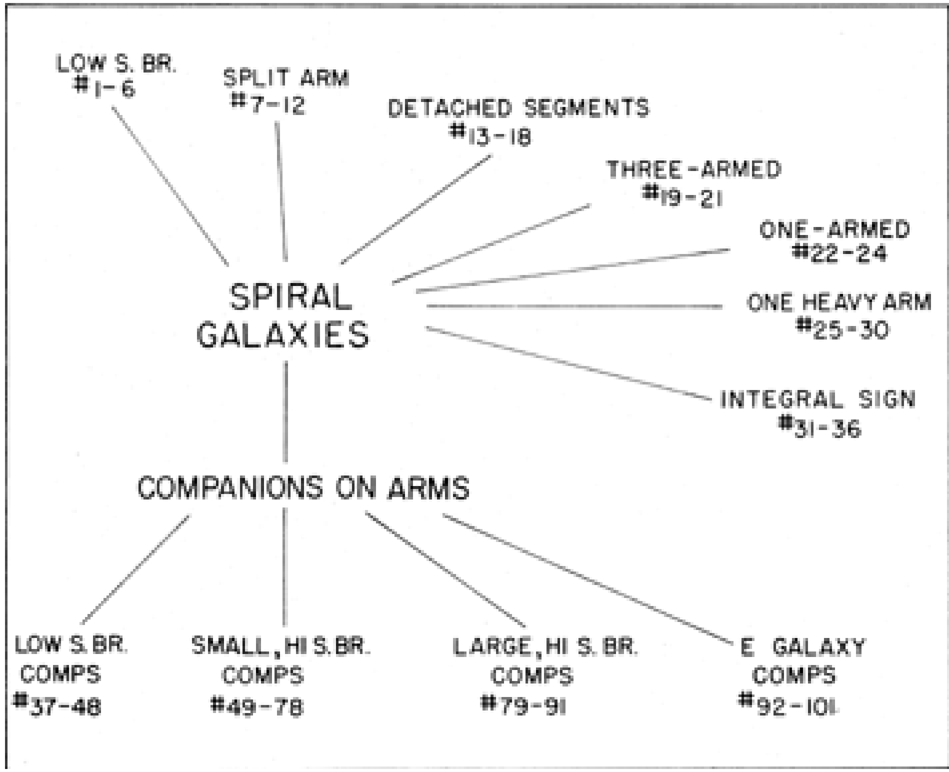
Hubble morphological classes



(https://hubblesite.org/contents/media/ima

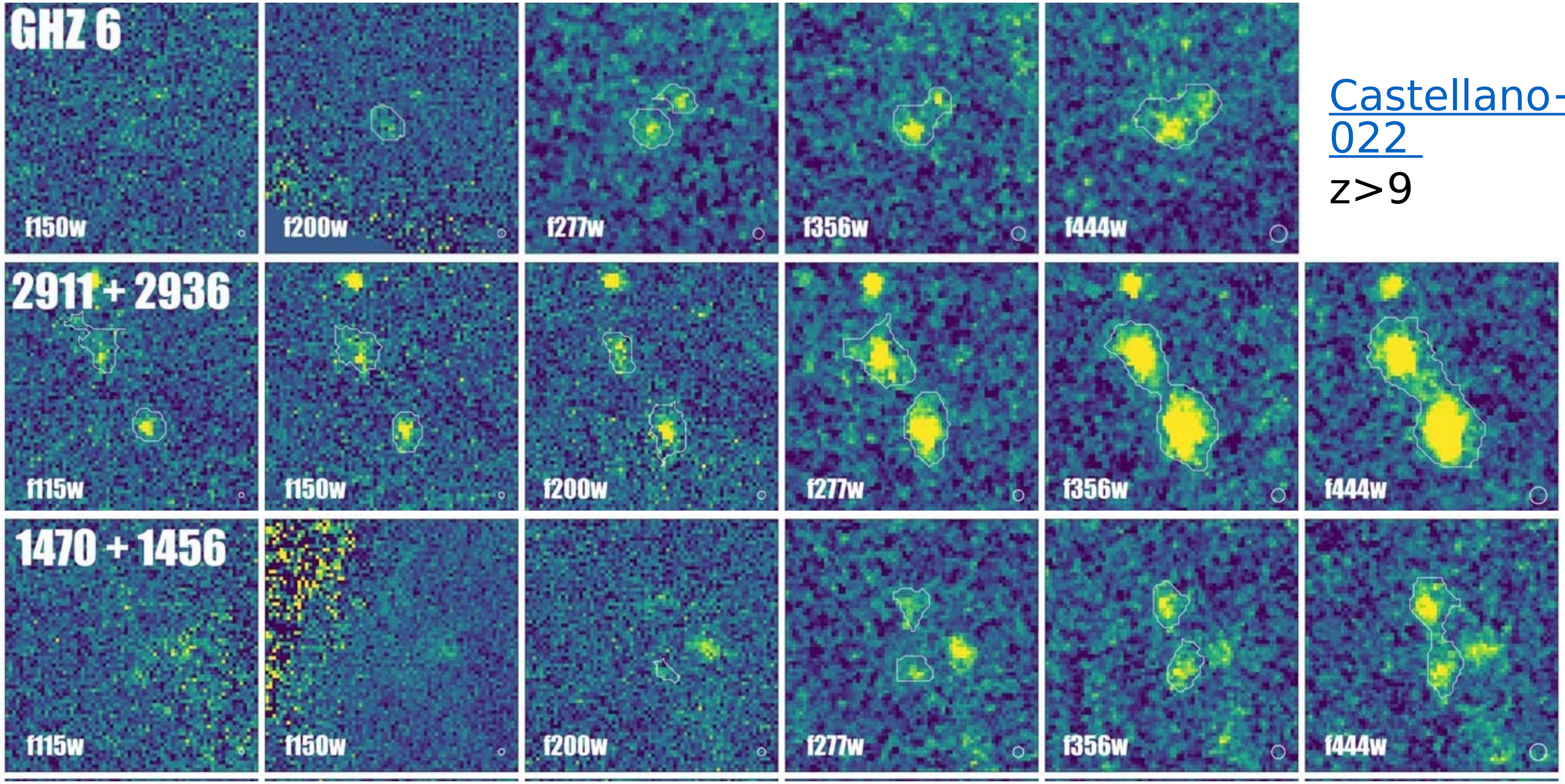
Beyond the “Hubble tuning fork”
Halton Arp – Atlas of Peculiar Galaxies (1965)

- Mt. Wilson & Palomar Observatory photographic archive – visible
- special spiral systems in 11 categories
- special elliptical galaxies in 5 categories
- another 14 categories with non-spiral or elliptical-looking galaxies
- 8 groups of binary and multiple systems that Arp for some reason did not classify in the spiral and elliptical galaxy categories
- "other" group
- “Large high surface brightness companion”



https://ned.ipac.caltech.edu/level5/Arp/Arp_figure1.html

JWST NIRCam



Castellano+ 2022
z>9

Leethochawalit+ 2022
z=6.9

Leethochawalit+ 2022
z=7.6

- Treu+ 2023: 4/19 JWST observed “re-ionozation galaxies” with signatures of mergers/interactions
- Single-band images of galaxies at z > 7 selected by Castellano+ 2022 & Leethochawalit+ 2022; in order of increasing wavelength of observation.
- Each postage stamp is 2’x2’ on a side. The images are at their native resolution.
- The white continuous lines delimitate the binary detection mask, circles in the bottom right corner of each band are representative of the PSF FWHM size.

Halton Arp – Atlas of Peculiar Galaxies (1965)

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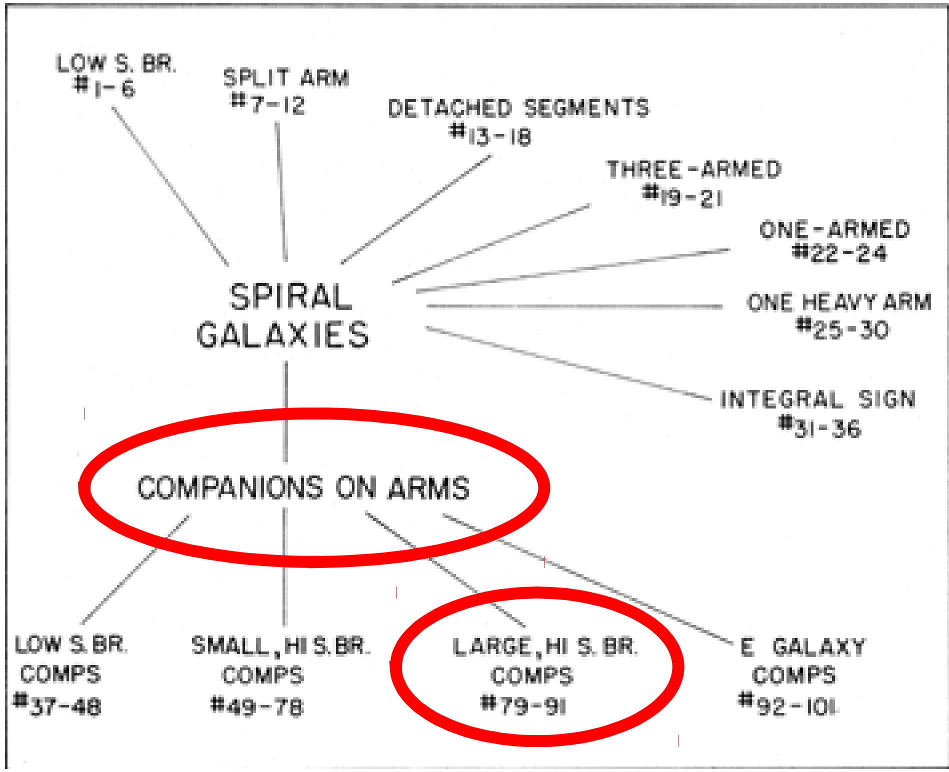
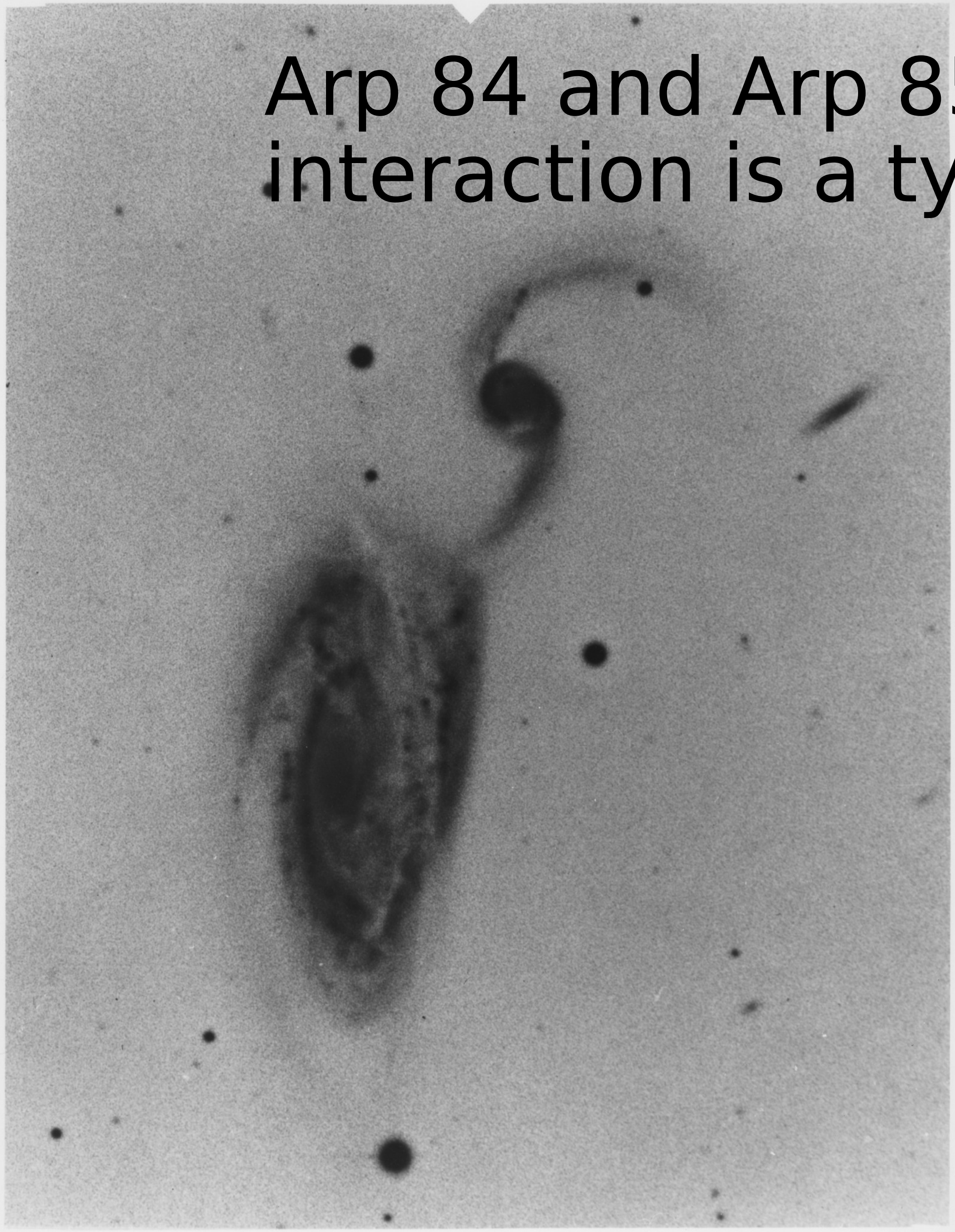


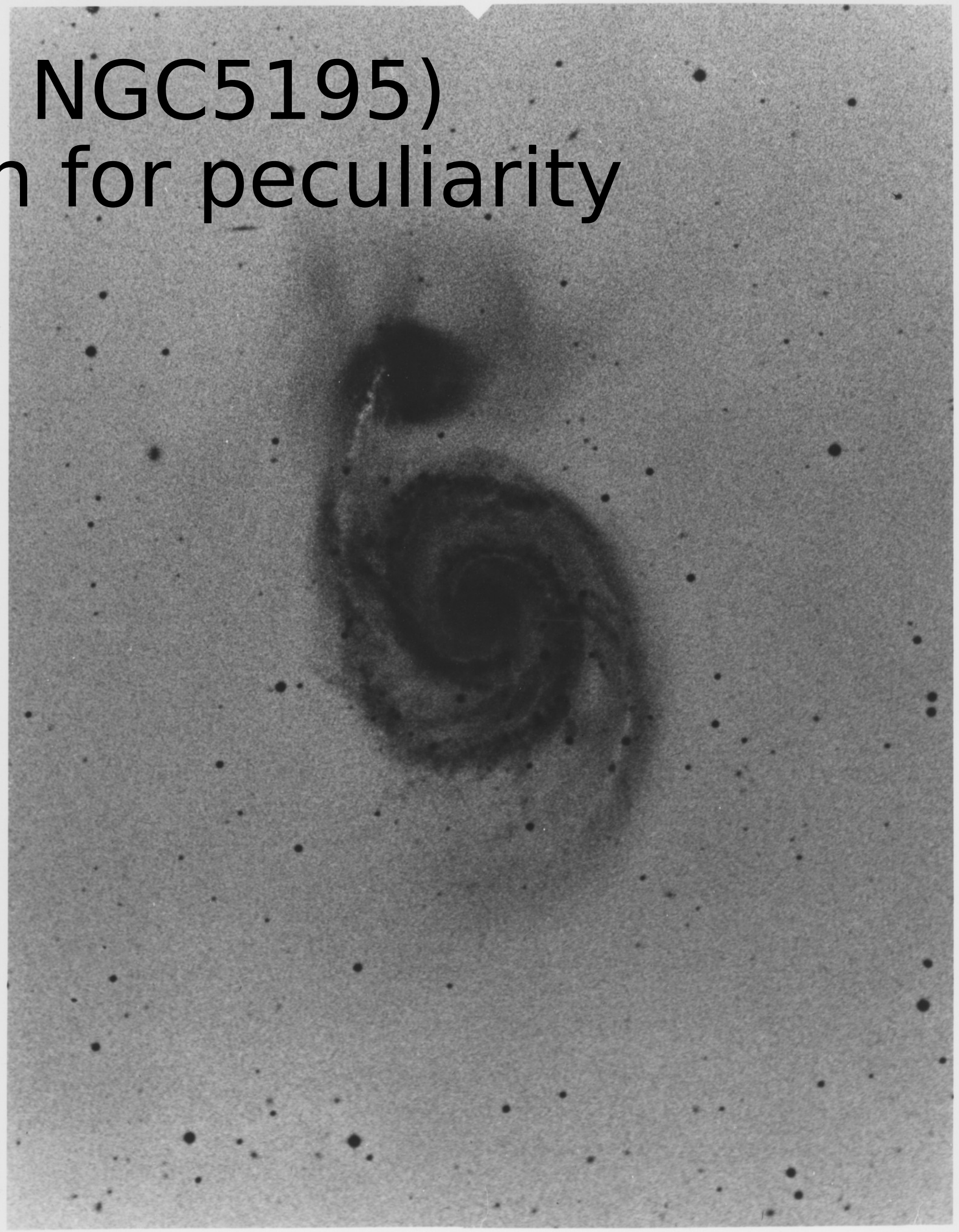
https://ned.ipac.caltech.edu/level5/Arp/Arp_figure1.html

Arp 84 and Arp 85 (M51 with NGC5195) interaction is a typical reason for peculiarity



84

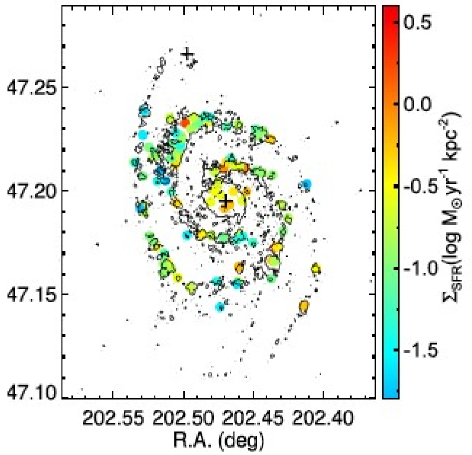
L.V. Tóth 2023

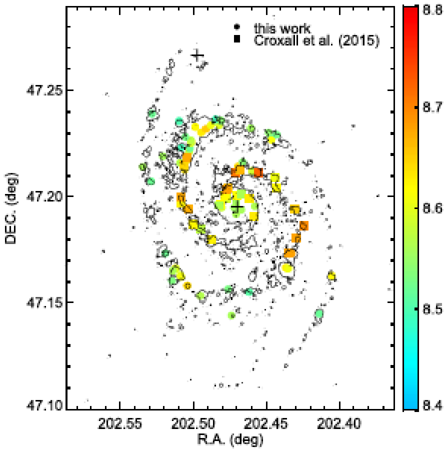


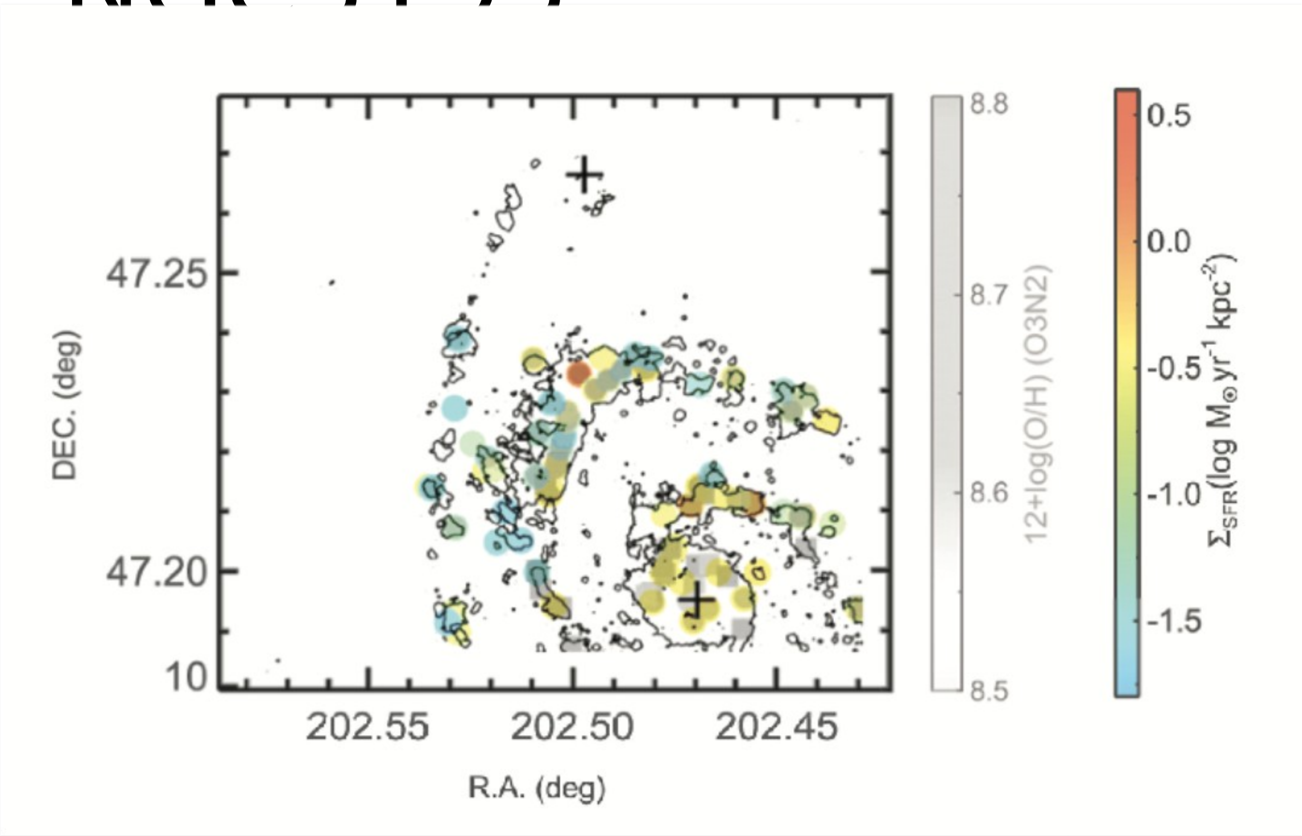
85

Arp 85: M51 with NGC5195

- H II regions in M51 were observed using the 2.16 m telescope of the National Astronomical Observatories of the Chinese Academy of Sciences and the 6.5 m Multiple Mirror Telescope with spatial resolution of less than ~100 pc
- H II regions have the stellar age between 50 and 500 Myr, consistent with the recent interaction history
- distribution of ΣSFR is shown in logarithmic scale with the isophotal contours of the Hα emission
- let's compare it to the metallicity





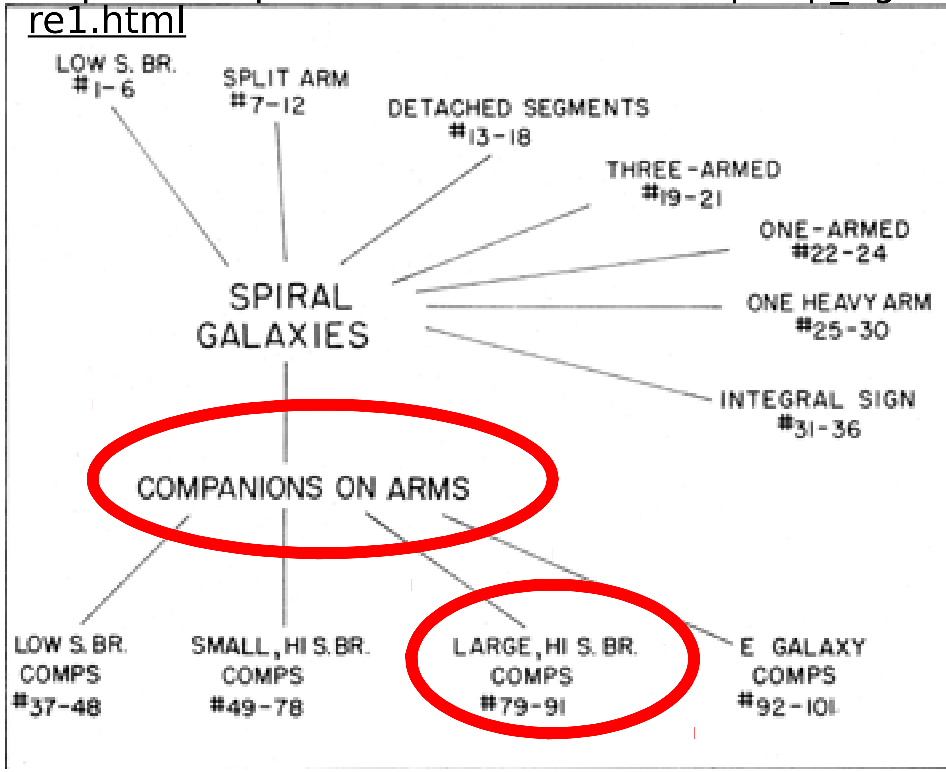


region around the high ΣSFR area at 202.50 +47.23. Bottom layer in greyscale shows the metallicity
Wei+ 2020

Halton Arp – Atlas of Peculiar Galaxies (1965) ApJS 14, 1

- special spiral systems in 11 categories (largest class)
- special elliptical galaxies in 5 categories
- another 14 categories with non-spiral or elliptical-looking galaxies
- 8 groups of binary and multiple systems that Arp for some reason did not classify in the spiral and elliptical galaxy categories
- "other" group
- interaction is not always obvious from Arp's images

https://ned.ipac.caltech.edu/level5/Arp/Arp_figure1.html



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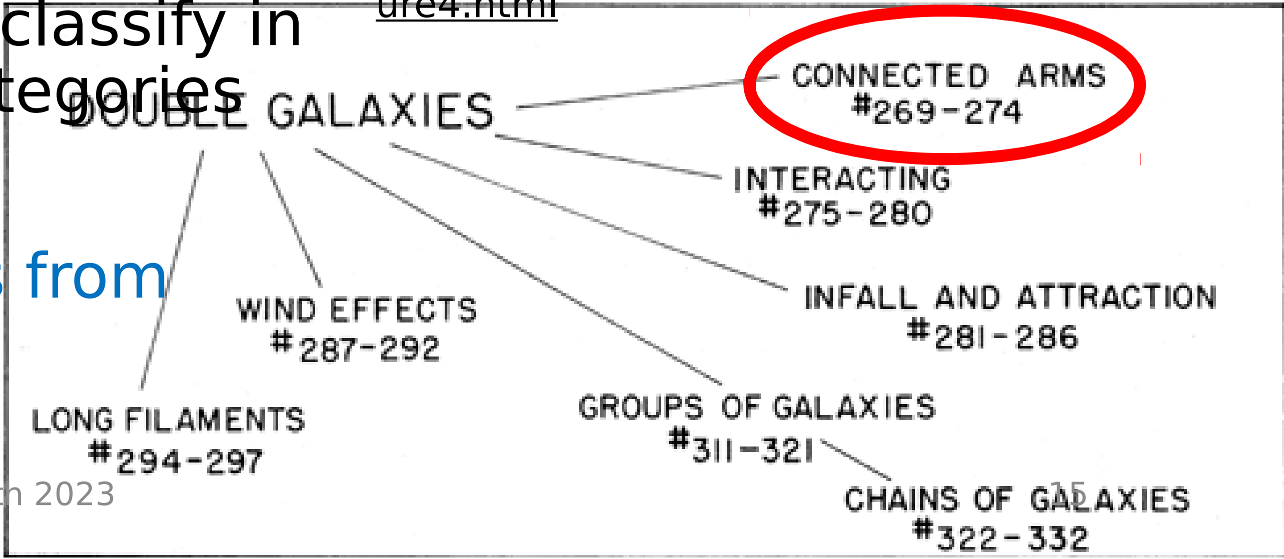
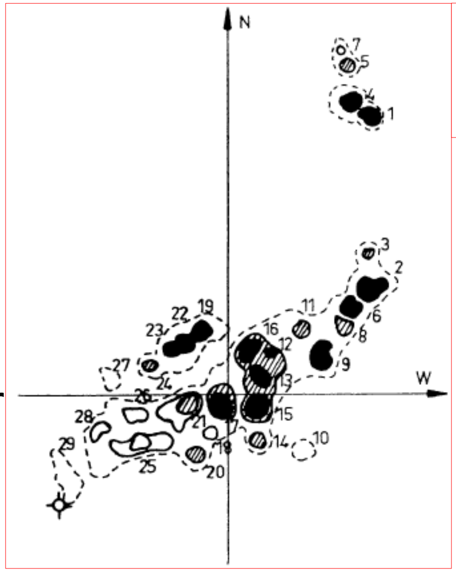
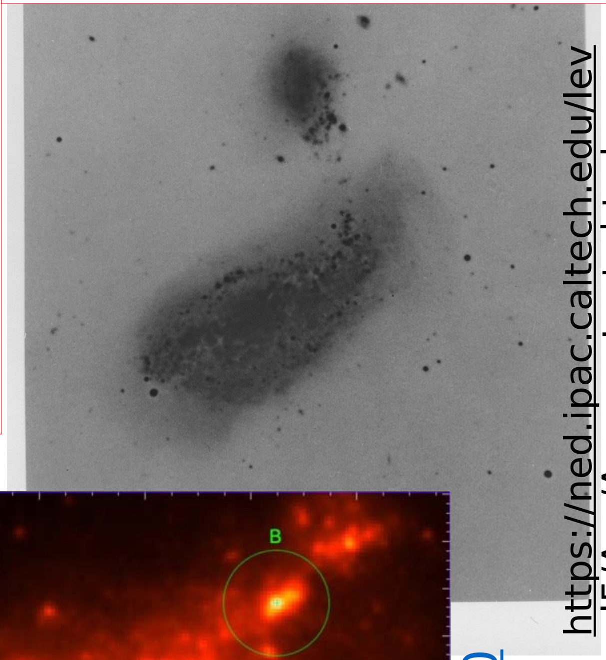
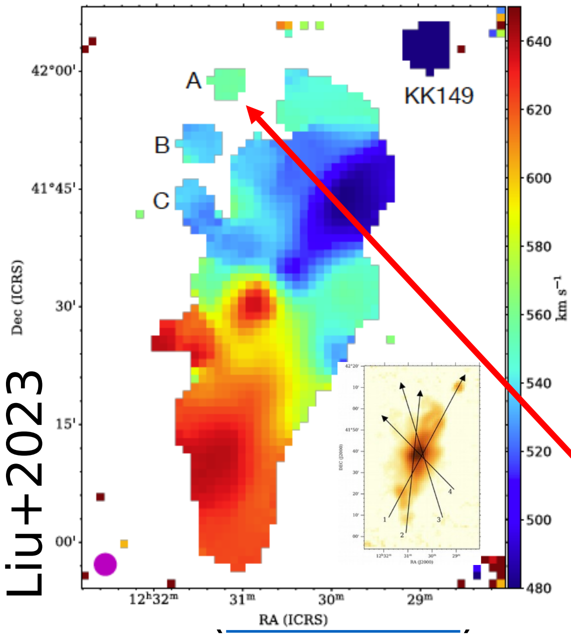


Arp 269: NGC 4490 & NGC 4485

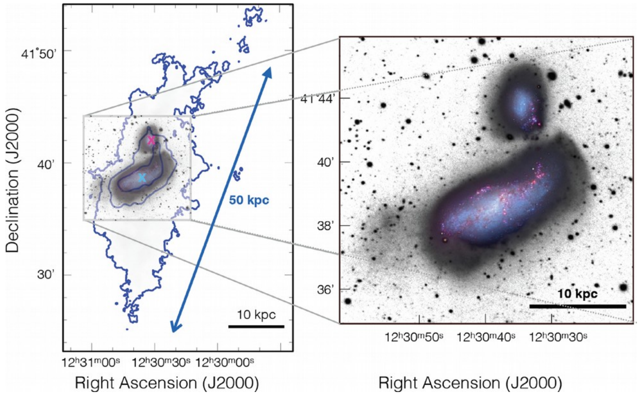
- 29 HII regions (Hα) Véron & Sauvayre (1965)
- HI tidal tail (Clemens+1998; Pearson+ 2019; Liu+ 2023)
- NGC4490 double nucleus (Lawrence+ 2020): optical & IR+r
- recent 1:8 merger and former (-2,3Ga) merger





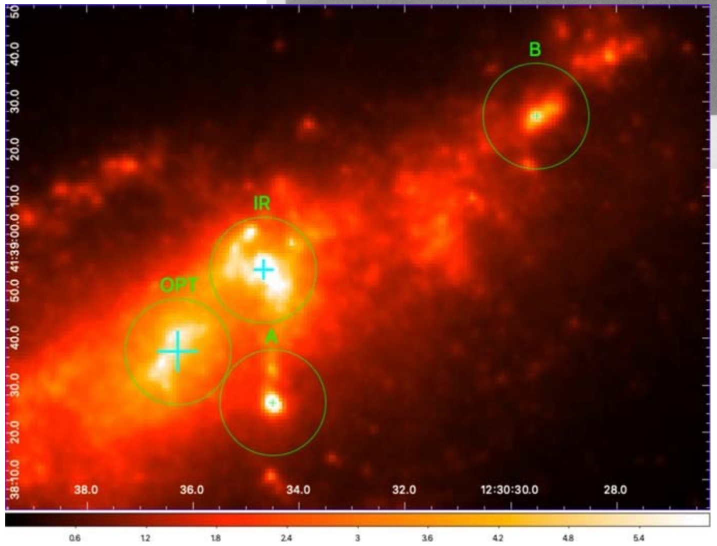


FAST v(HI) by Liu+2023



HI envelope N(HI) = 0.7, 7, 35 × 10^{20}cm^{-2} (Clemens+1998)

- ...nger tidal arms & probably 4 arms (see insert!)
- low metallicity starburst dwarf galaxy MAPS 1231+42 (Clump A) is also connected with the gas envelope (see: C-B-A clump chain)
- interaction trigged the intense star formation in it

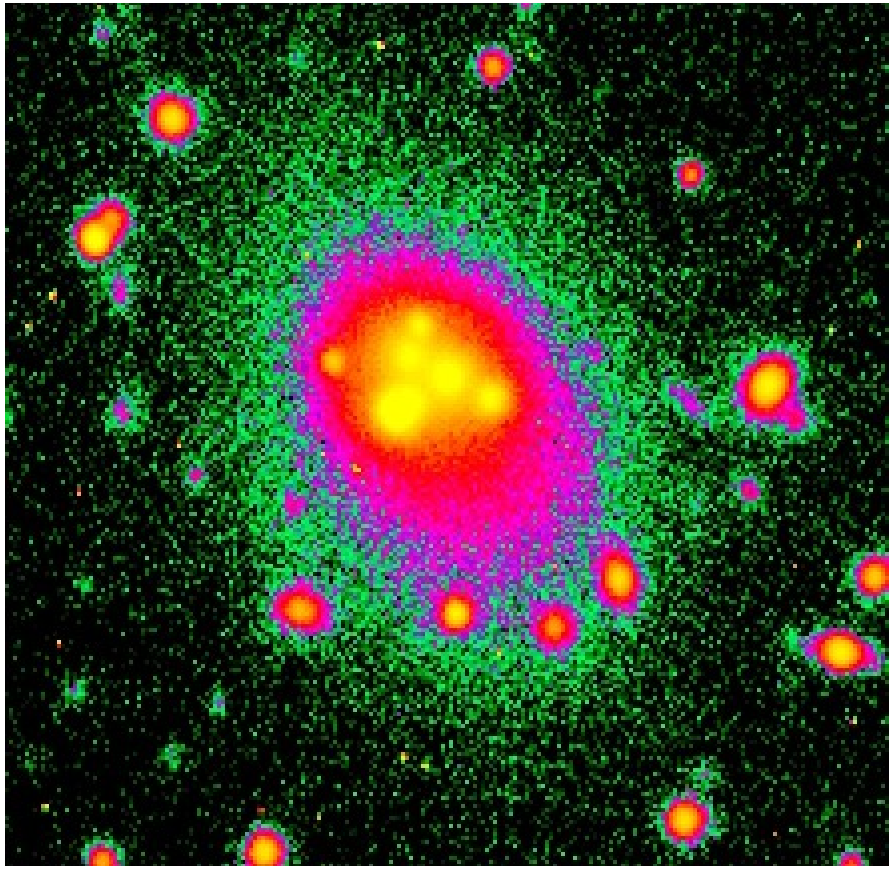


Lawrence+ 2020

Apertures (500 pc) are shown surrounding the optical nucleus (OPT), infrared nucleus (IR), and the giant HII regions A and B.

Galaxy interaction types

- Quantities that control the interaction
  - The mass ratio of the galaxies:
  - The relative velocity of the galaxies:
  - How close is it to a direct hit?
- Major mergers
  - nearly equal mass
  - small relative velocities
  - very close pass or central hit
- Cannibalism
  - massive and low mass (central+satellite)
  - small relative velocities
  - very close
  - central galaxy can disrupt and then absorb
- Galaxy Harassment
  - massive and low mass
  - high relative velocities
  - close passing by
  - alters the shape & some mass is striped off



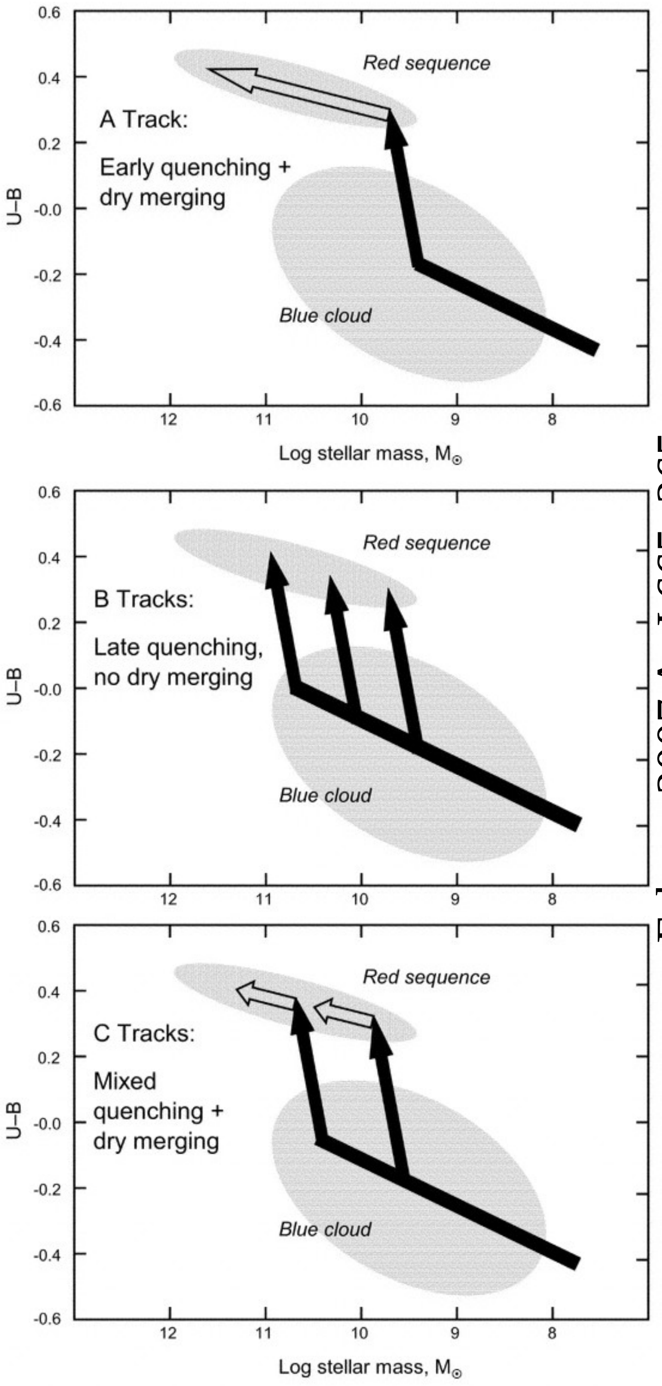
https://apod.nasa.gov/apod/ap980831.html

cD galaxy in the Abell 3827 cluster with remnants of 6 massive galaxies & 4 more to be cannibalised

Credit: Michael J. West (St. Mary's U.), ESO 1-m Telescope

Mergers and galaxy evolution

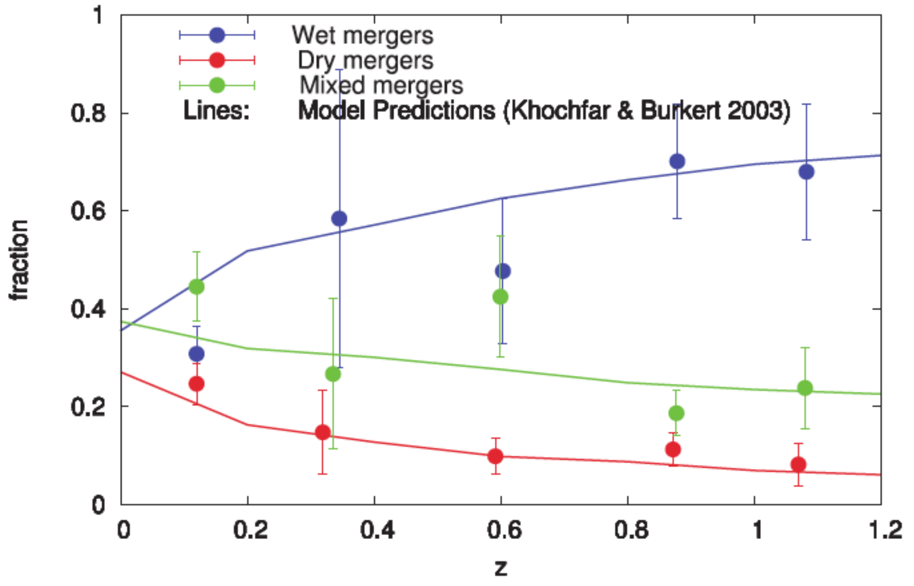
- **very early quenching** while the fragments of the galaxy are still small, most mass assembly occurs in dry mergers along the red sequence
- **maximally late quenching**, galaxies assemble most of their mass while still blue and then merge once to become red with no further dry merging
- **"mixed" scenario** with contributions from both mechanisms
- the gas supply of some disks may simply be choked off or stripped out without mergers, to produce disky S0s (tracks would be vertical)
- kinematic pairs from the DEEP2 Redshift Survey + other surveys at lower redshifts
  - wet mergers dominate merging at 0.2<z<1.2
  - the relative importance of dry and mixed mergers increases over time.
  - 22%-54% of present-day L galaxies have experienced major mergers since z=1.2, depending on the definition of major mergers.



Faber+ 2007 ApJ 665, 265

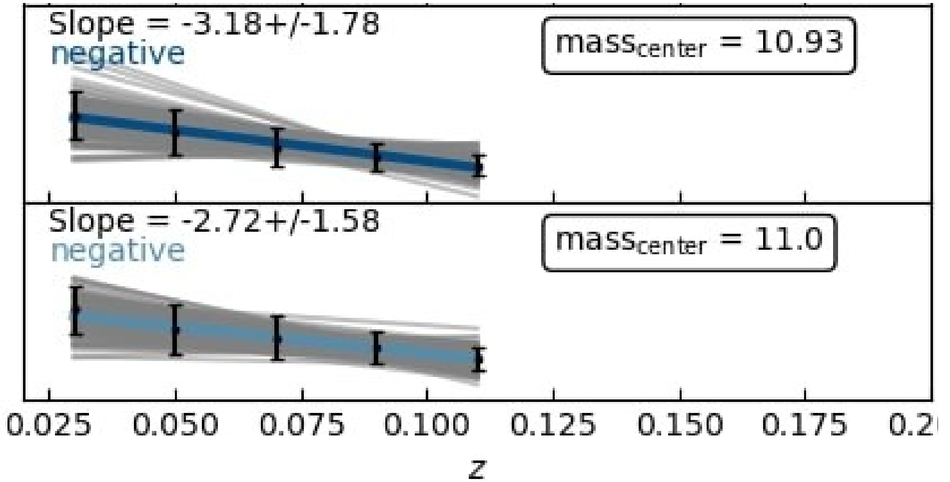
Mergers and galaxy evolution

- Fraction of major mergers for wet (blue), dry (red), and mixed mergers (green) as a function of redshift.
- Data points: results from DEEP2, TKRS, CNOC2, & MGC surveys
- The three lines show the semi-analytical predictions of Sp-Sp, E-E, and E-Sp mergers by Khochfar & Burkert (2003)
- ⬆ fraction of dry (E-E) & mixed (E-Sp) mergers with ⬇ redshift



Lin+ 2008, ApJ 681, 232

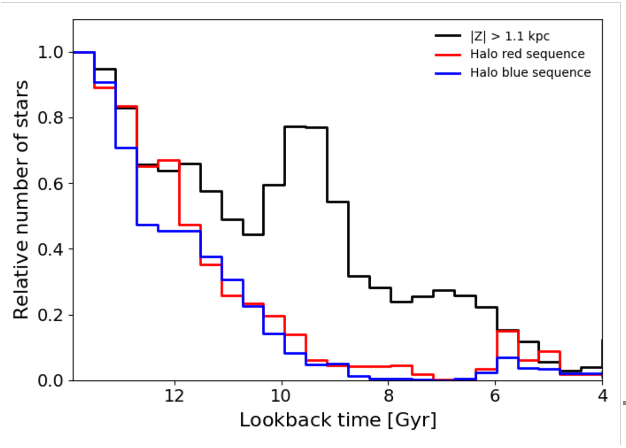
- 1.3 million galaxies from the SDSS DR16 photometric catalog
- major or minor merger galaxy, splitting the classifications by merger stages (early, late, post-coalescence)

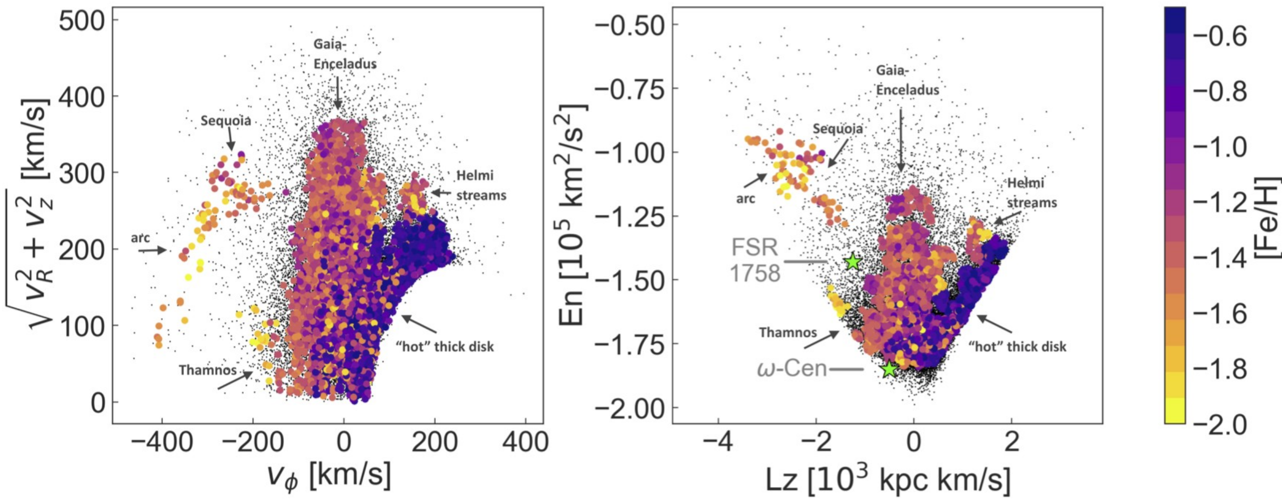


Nevin+ 2023, MNRAS 522, 1

Last major merger of the Milky Way galaxy: Gaia-Enceladus probably completed at z~2 (10 Gyr ago)

- giant spiral galaxies, like Milky Way, form hierarchically through mergers with less massive galaxies at z < 1, satellite quenching becomes more important (Behroozi+ 2019)
- most of the merging stellar populations are tidally disrupted during infall, and form various structures in today’s Milky Way stellar halo (Cooper et al. 2010)
- stars with metallicities typical of the thick disk but with halo-like kinematics: the **Gaia-Enceladus**
- a starburst in the thick disk appears to have been triggered 10 Gyr ago (Helmi 2020)





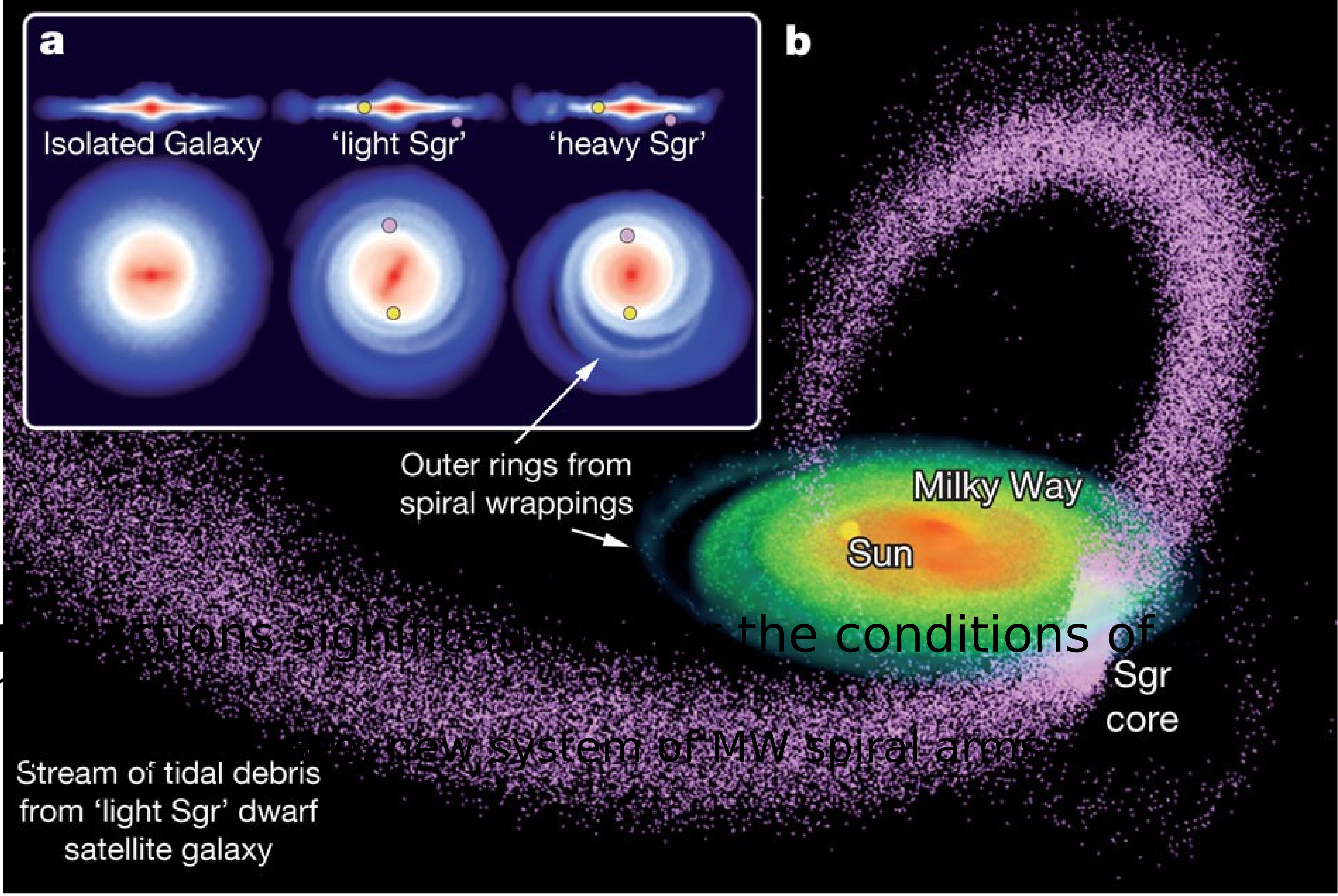
Distribution of halo stars selected kinematically

Other merger events discovered in wide-field photometric surveys:

- Helmi streams: local over-densities
- Sequoia: high energy retrograde structure Myeong+ 2019
- Thamnos: part of the local retrograde halo Koppelman et al. (2019a)
- Sagittarius streams

Sagittarius dE merger

- Galaxy i… ctions significa… the conditions of star form…
  - even d… new system of MW spiral arms



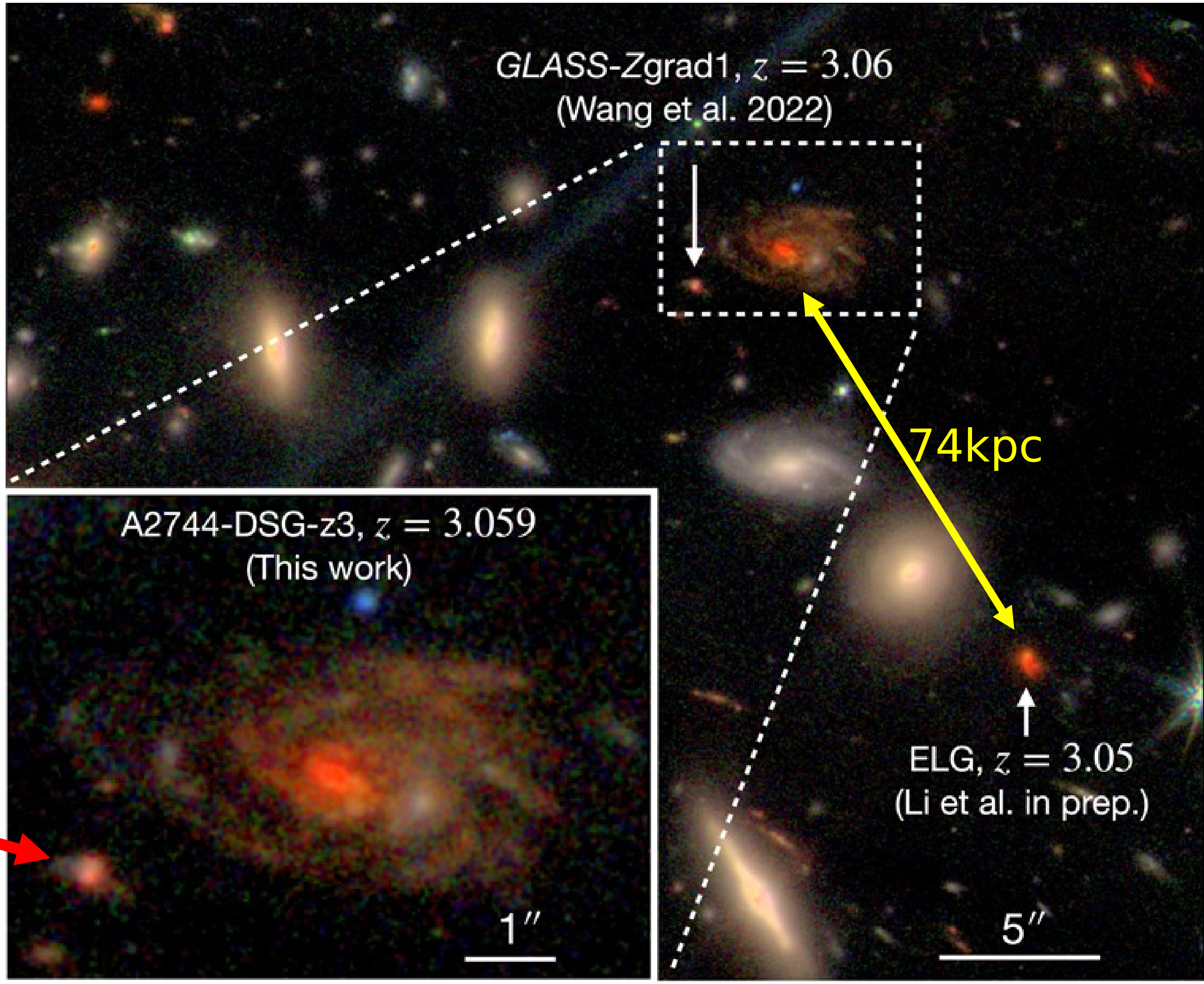
Dust obscured galaxies – a need for JWST

can't be detected in HST rest-frame ultraviolet imaging

- Barrufet+ 2023 studied (heavily dust-obscured i.e. $A_V \sim 2$ mag) HST-dark galaxies
- very deep, high-resolution NIRCam imaging from the Early Release Science Program CEERS.
- 30 HST-dark sources
- massive ($\log(M/M_\odot) \sim 10$), star-forming galaxies at $z \sim 2 - 8$, on the main sequence of gx
- observed surface density of ~ 0.8 arcmin^{-2} suggests that an important fraction of massive galaxies may have been missing from our cosmic census at $z > 3$ all the way into the Reionization epoch.
- add an obscured star formation rate density (SFRD) of $3.2 \times 10^{-3}\ M_\odot \mathrm{yr}^{-1} \mathrm{Mpc}^{-3}$ at $z \sim 7$ showing likely presence of dust in the Epoch of Reionization.

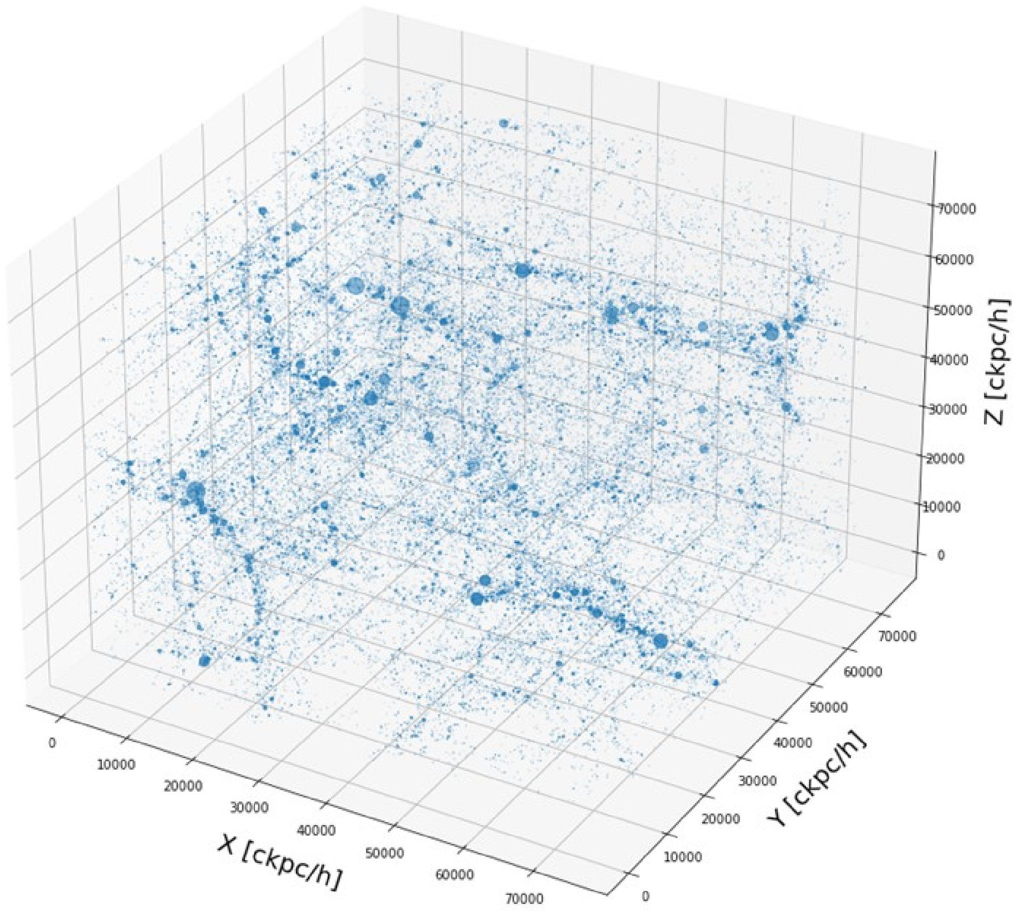
A z=3 flocculent spiral galaxy is relaxing after a merger?

- Dusty spiral galaxy A2744-DSG-z3 at z = 3.059
- A2744-ID33 lensed sub-mm galaxy (Sun+ 2022)
- composite JWST/NIRISS RGB map (blue: F115W, green: F150W, red: F200W)
- stellar mass $M_* \sim 10^{10.6}\ M_\odot$ (Sun+ 2022)
- spiral arms are resolved $\Delta l \approx 290$ pc
- de-lensed star formation rate: 85 ± 30 $M_\odot\ yr^{-1}$
- there are 2 companion (star-forming) galaxies in the same field that could be related
- *GLASS-Z* grad1 with $M_* \sim 10^9\ M_\odot$
- the spiral arms may be triggered by minor-merger events at $z \gtrsim 3$



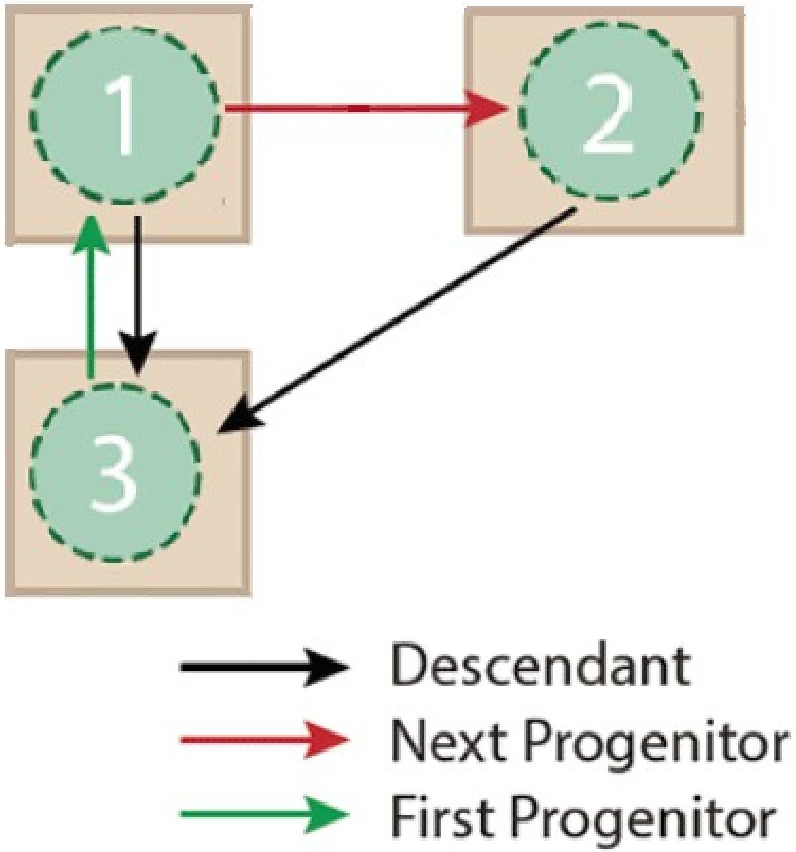
IllustrisTNG simulation

- Cosmological magneto-hydrodynamical simulation
- Galaxy formation and evolution
- ΛCDM cosmology
- Dark matter + gas dynamics
- TNG 100-1 Pillepich+ 2017, Springel+ 2017, Nelson+ 2017 , Naiman+ 2017,Marinacci+ 2017:
  - Planck2015 cosmological parameters
  - 110.7 Mpc side lenght volume
  - 100 Snapshots from the Universe between z=20.05 and z=0.00
- Galaxy mergers: Merger Tree ✉ galaxy parameters (mass, star formation rate)



Merger Tree

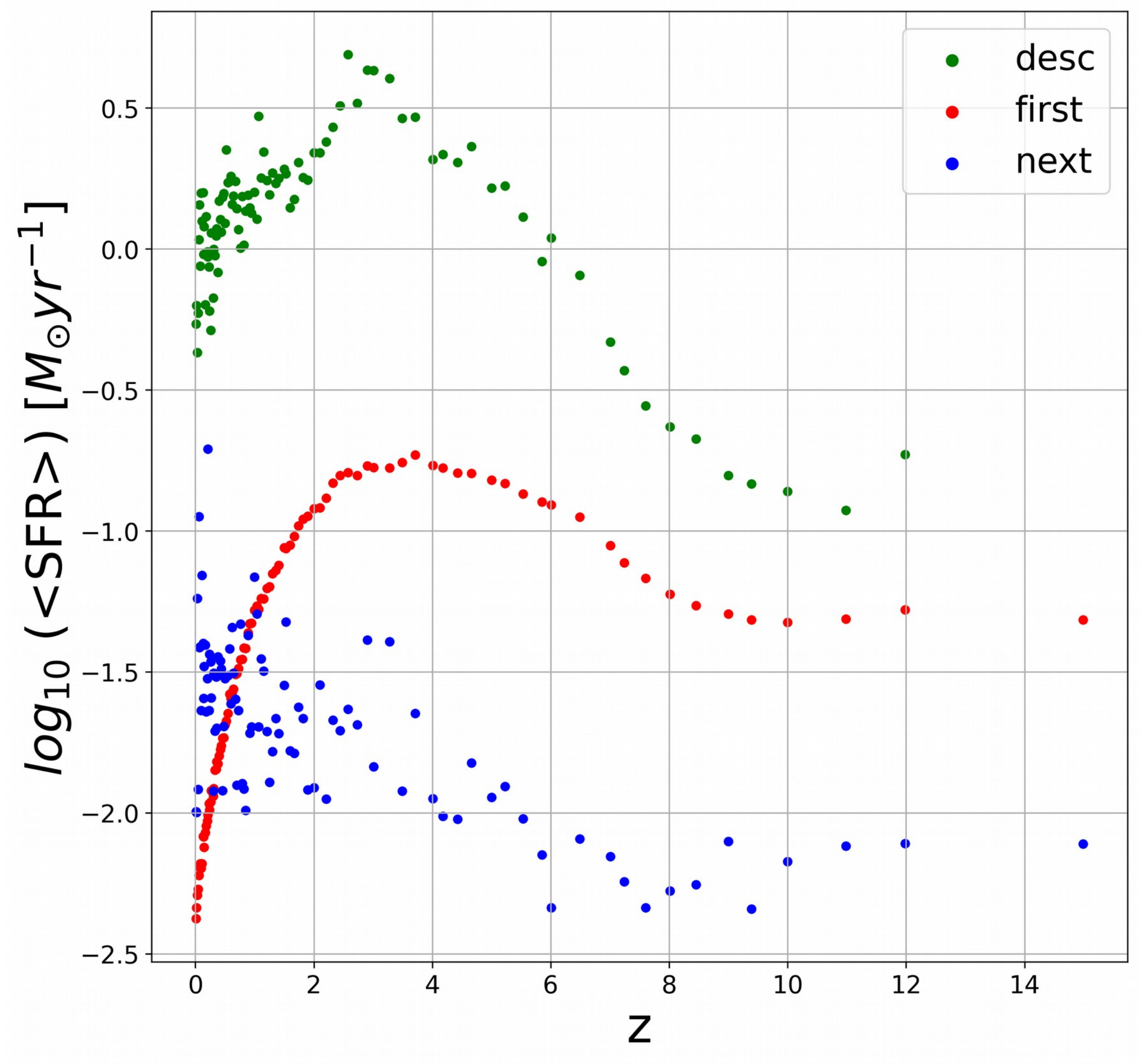
- Data structure with galaxy evolution
- Sublink algorithm Rodriguez-Gomez+ 2015 for descendant search
  - 1. Candidates identification for each subhalo (galaxy): subhalos in the following snapshot with common particles
  - 2. Candidates scored: based on a merit function ✉ binding energy rank of each particle
  - 3. Unique descendant = descendant with the highest score
- 20 Merger Trees completely independent from each other
- In general progenitors are in the same snapshot, descendant in the following (not really)
- Is there any difference?



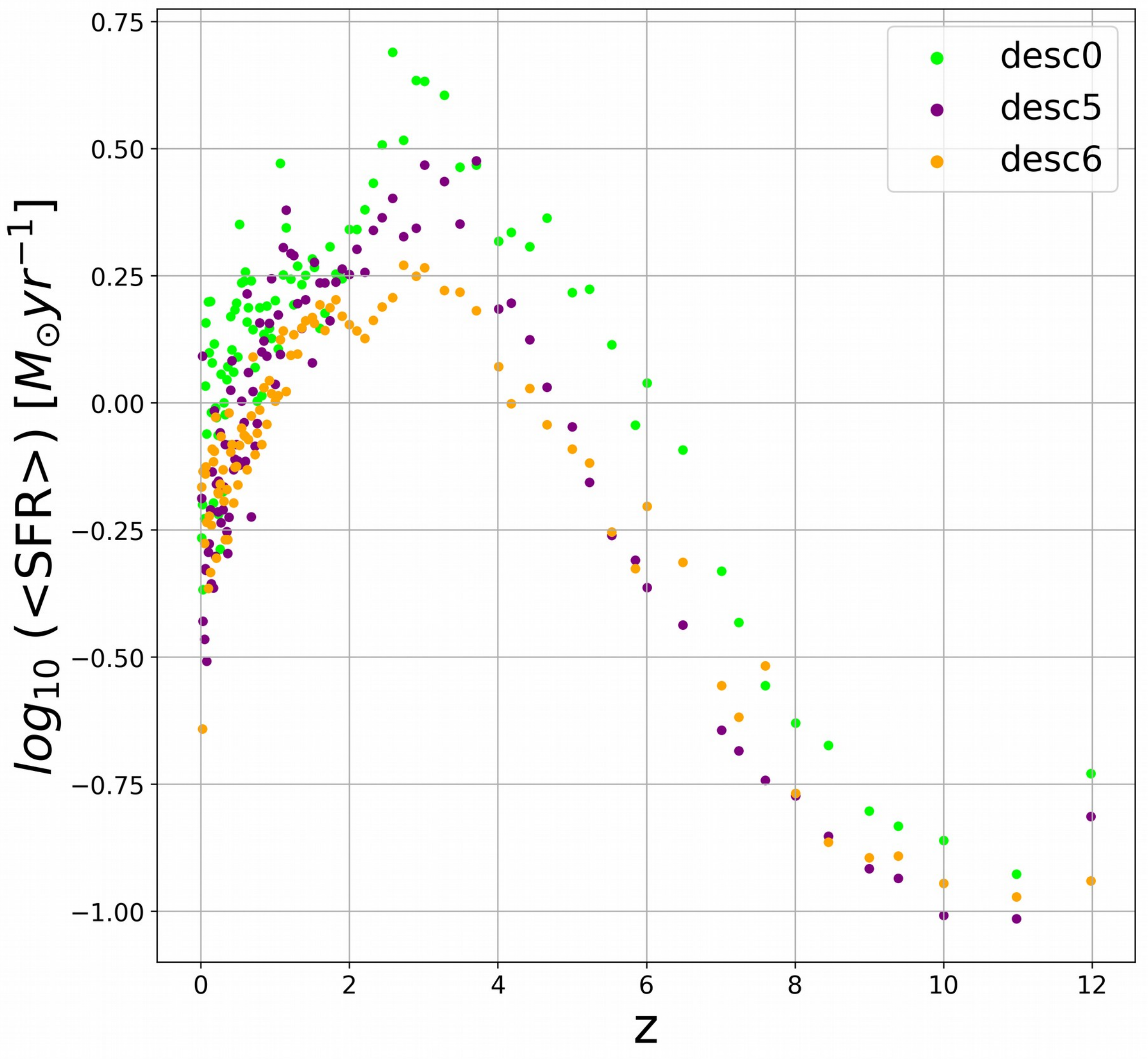
- 0. Merger tree
- Mean SFR on logarithmic scale versus redshift
- Significant increase for every z
- Descendant maximum at z = 3
- More than 1 order of magnitude difference at the peak

Star formation rate

- 0. Merger tree
- Mean SFR on logarithmic scale versus redshift
- Significant increase for every z
- Descendant maximum at z = 3
- More than 1 order of magnitude difference at the peak



Star formation rate



- Comparing three merger trees (0.,5.,6.)
- Descendant galaxies mean SFR versus redshift
- Similar results ✉ peak at around z=3

Important questions

- large scales:
  - typical galaxy interactions in given space time
  - the ways these are set/influenced
  - starburst periodes
- small scales:
  - relative distribution of ISM and young massive stars
    - conditions influencing it
      - from galaxy interactions down to star forming filaments and cores
  - timescales of cloud evolution
    - start and duration of massive star formation
    - GMC lifetimes
  - timescales of SF

Galactic cold cores research activities

- observation based description of massive SF
- models of SF
- investigations in the Local Universe – including mergers
- utilising Universe models
- including low metallicity galaxies