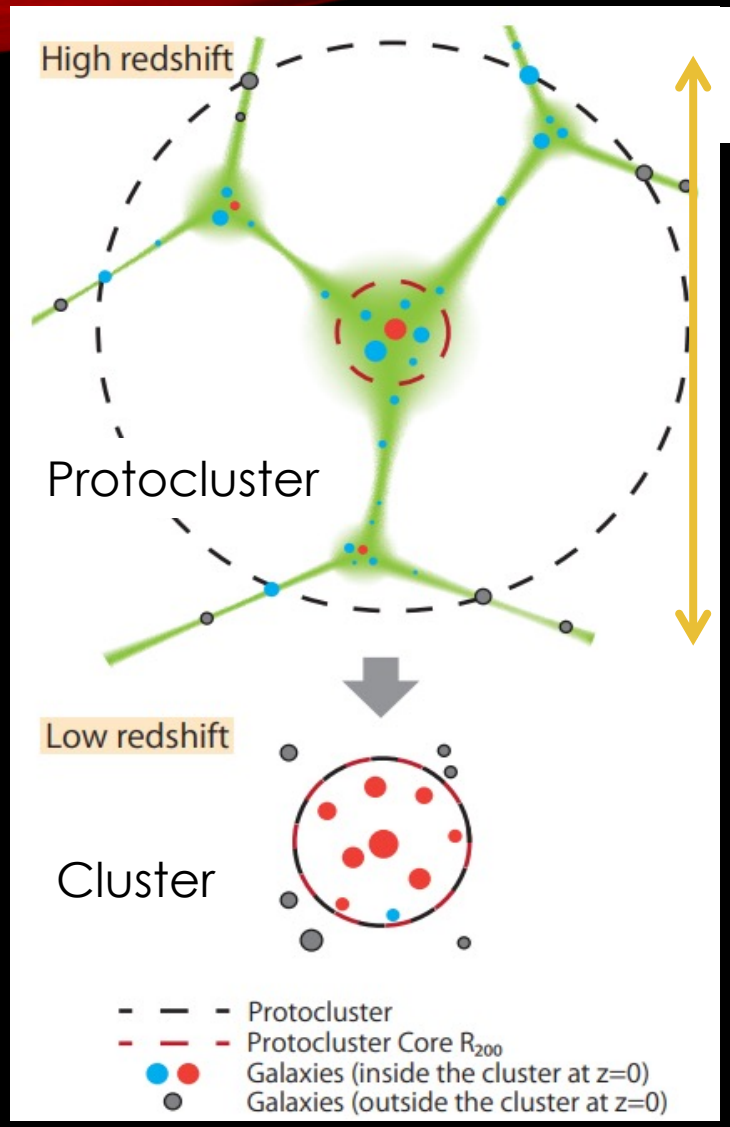
Surveying Galaxy Clusters in formation in the Distant Universe with AtLAST

Jose Perez-Martinez (IAC)

Funded by
the European Union

Cofinanciado por
la Unión Europea

Why do we care about Galaxy Protoclusters?



Studied for >20 years!

~10-100 Mpc

Fukushima+22

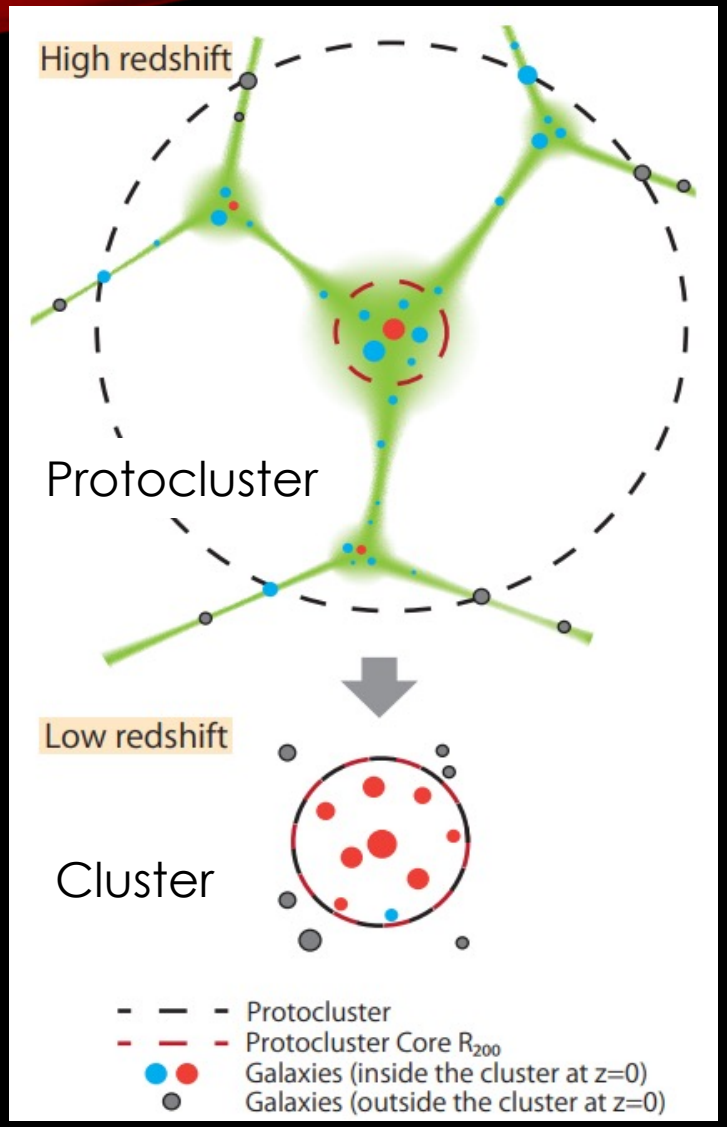
Rapid and enhanced mass build-up

- Dynamically active
- High availability of cold gas
- Frequent Interactions
- Star formation dominated

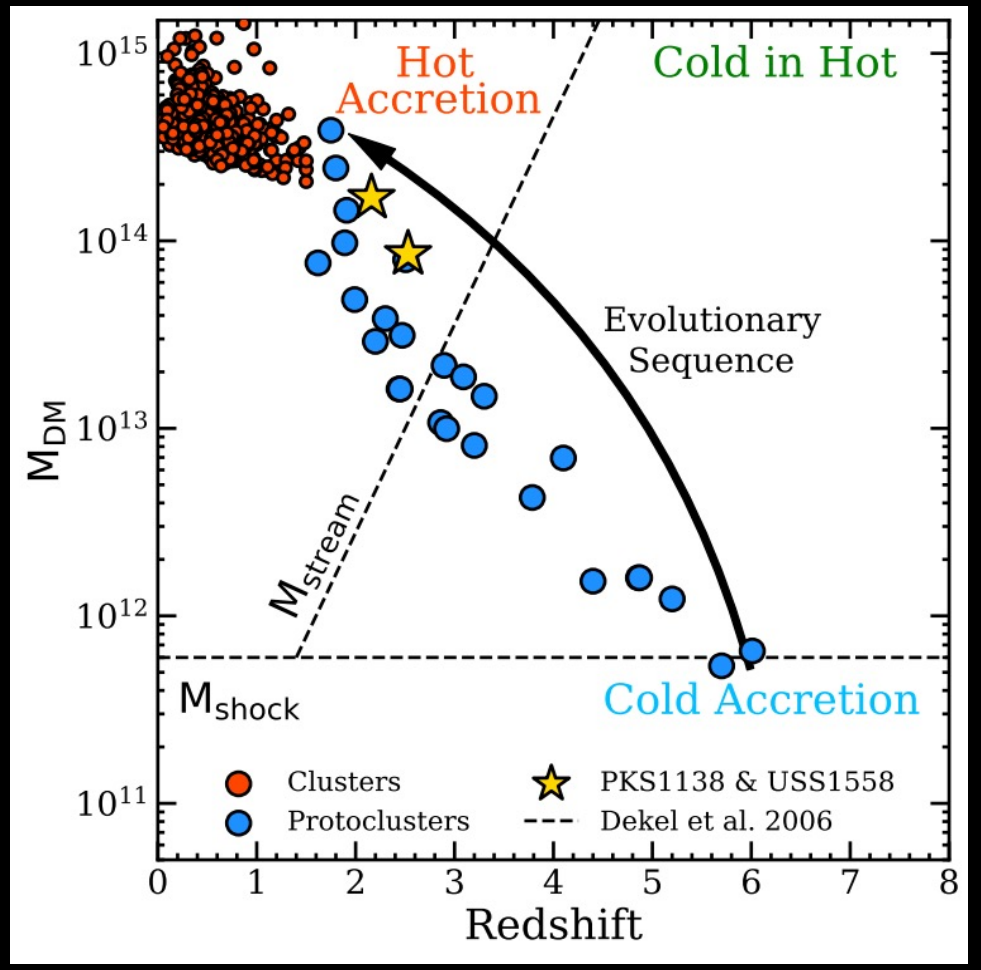
Suppressed Star-formation

- 'Virialized' systems
- Cold gas depleted
- Passive dominated

Halo growth modulates baryon accretion



Fukushima+22



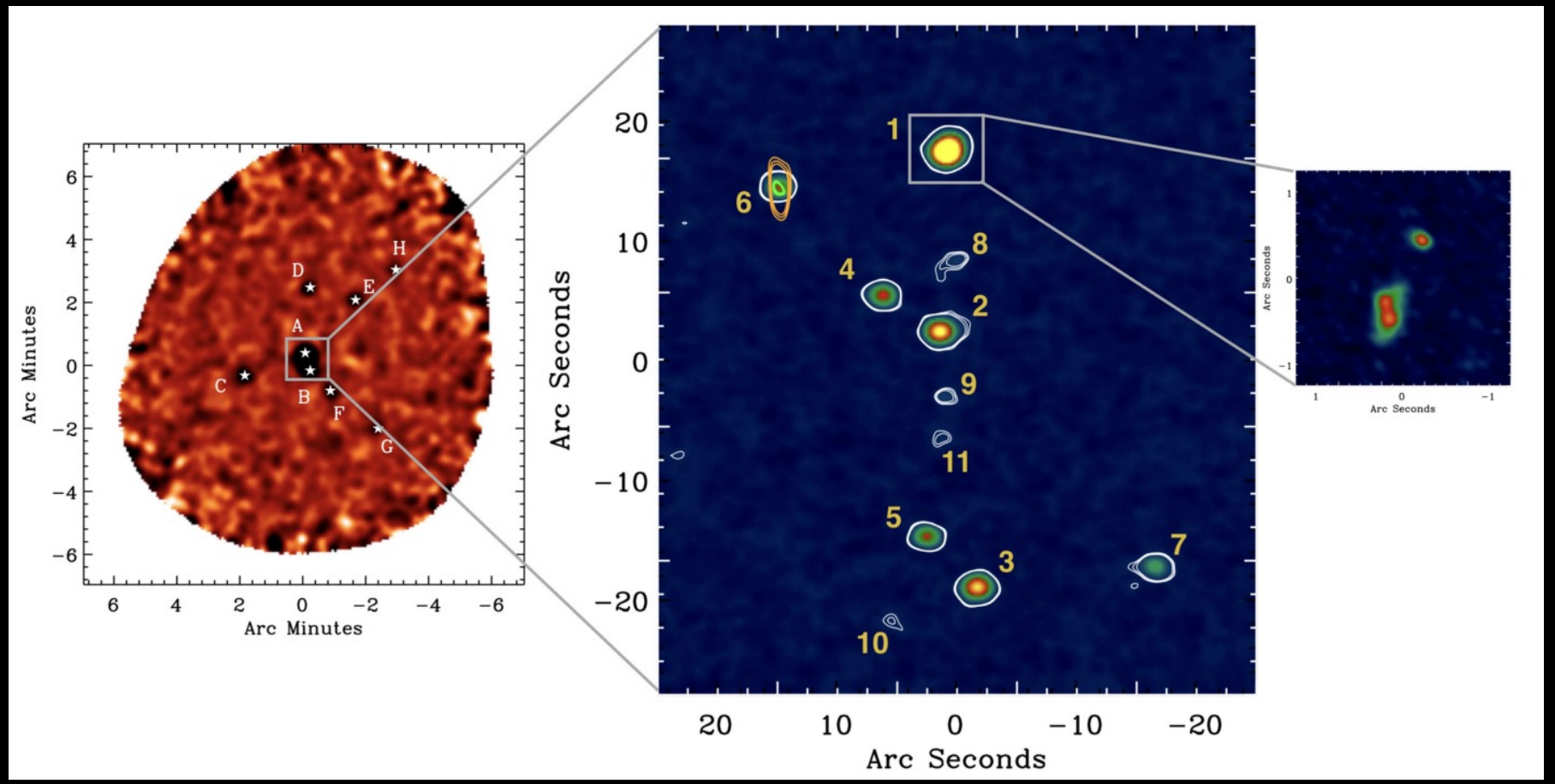
Based on Dekel+06, see also Daddi+22

Protoclusters as cosmic star formation nurseries

LABOCA 870um
27” resolution

ALMA 2mm continuum

ALMA 870um

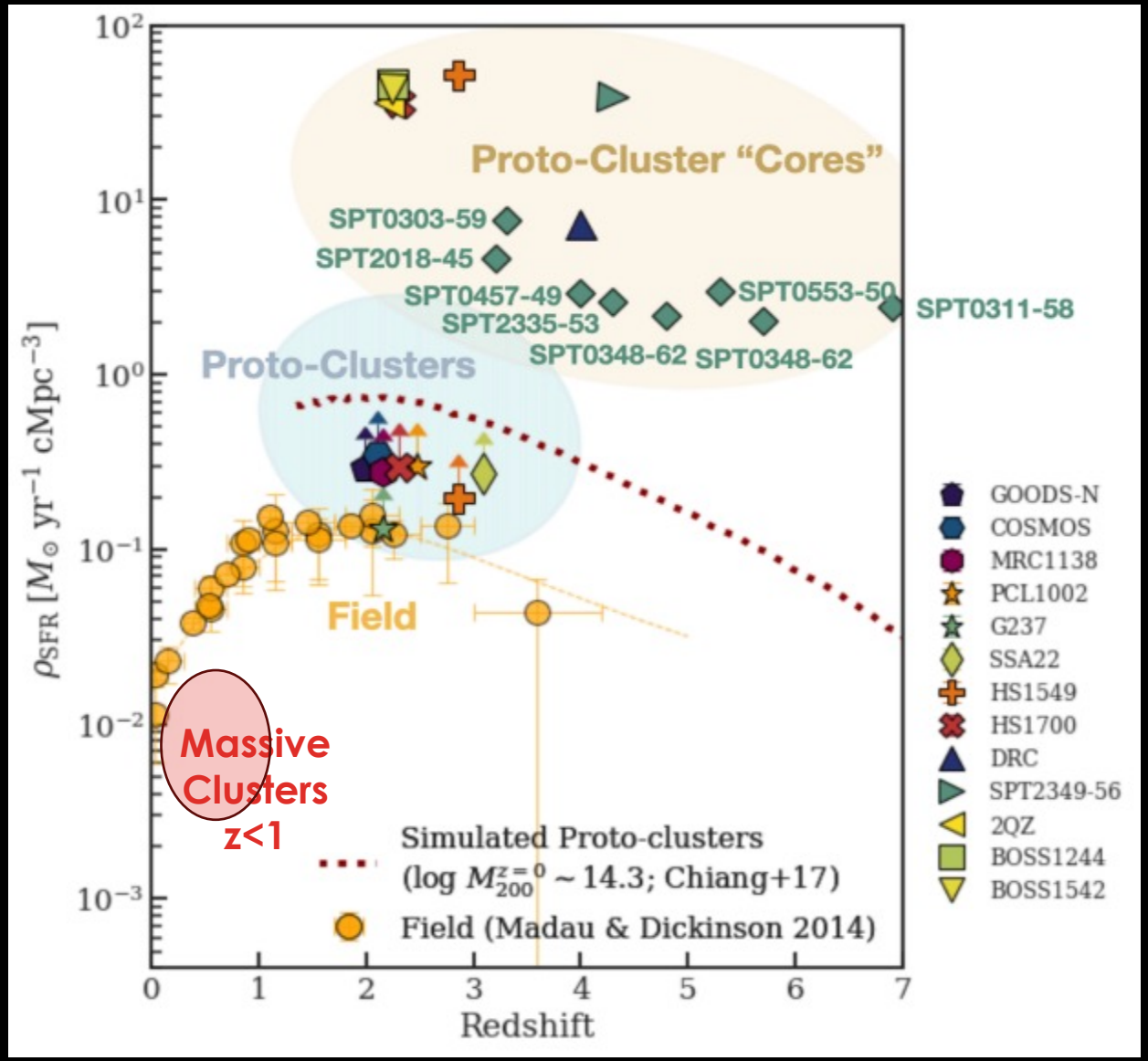


- Bright SMGs are beacons to identify protoclusters at high-z (see also Calvi+2023)

Oteo+2018, Dusty Red Core at z=4.002

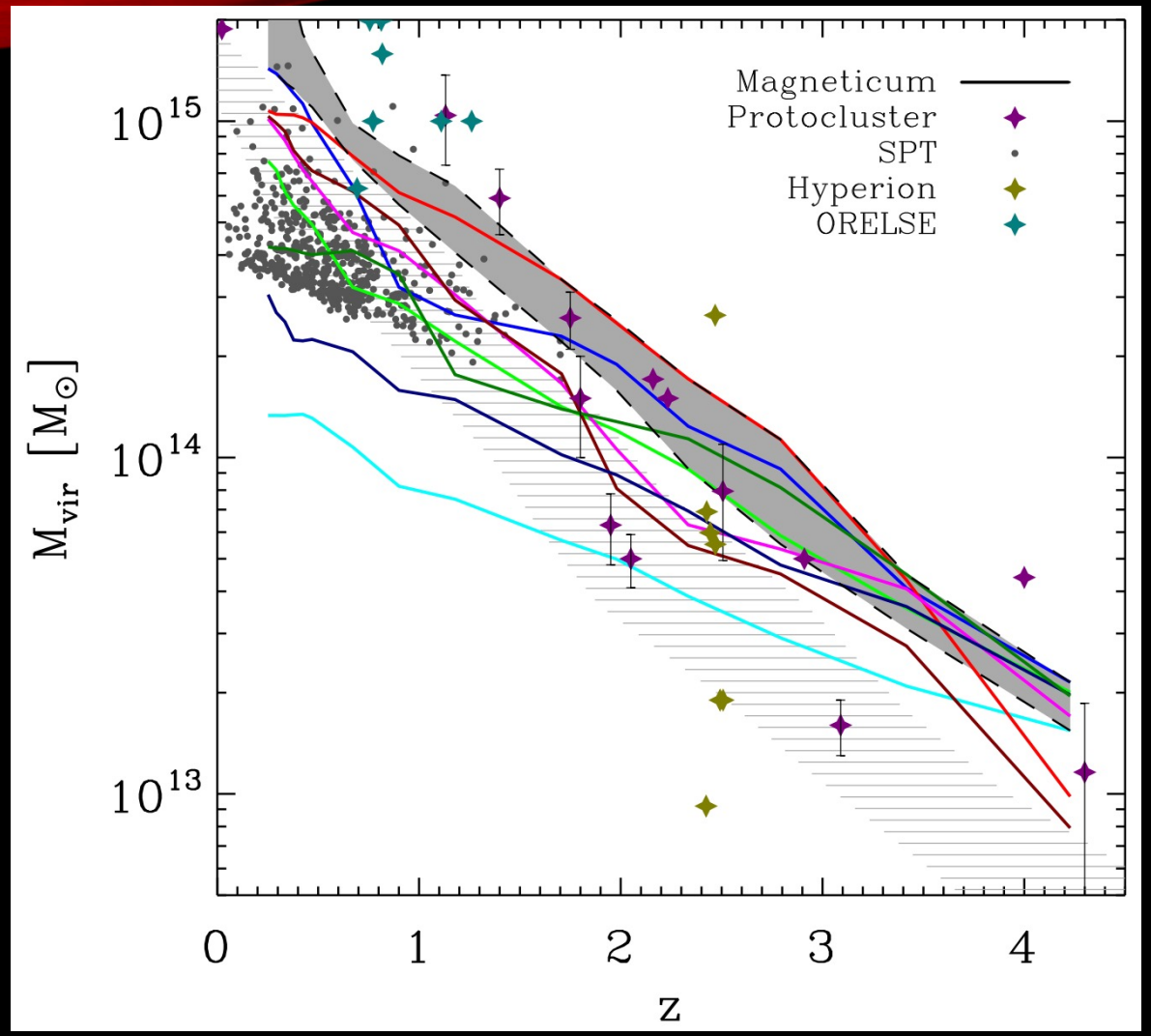
Total SFR~6500 Mo/yr

Protoclusters as cosmic star formation nurseries



Adapted from Alberts & Noble 2022

Protoclusters Fate: From Fake News to Real Clusters



- Similar PCL at z>4 evolve into very distinct structures by z=0
- Differences largely depend accretion of surrounding material (gas and galaxies) in large scales (tens of Mpc)

Remus+2022 Magneticum Simulation

Current Limitations and Key Questions

- Small sample size and volumes
- Inhomogeneous physical tracers
- Lack of protocluster statistics (Butterfly Collection)

- When and how do the first galaxy clusters assemble on Mpc scales?

  → Large Scale Structure Assembly
- How do protocluster intermediate scales (50-500 kpc) regulate galaxy growth?

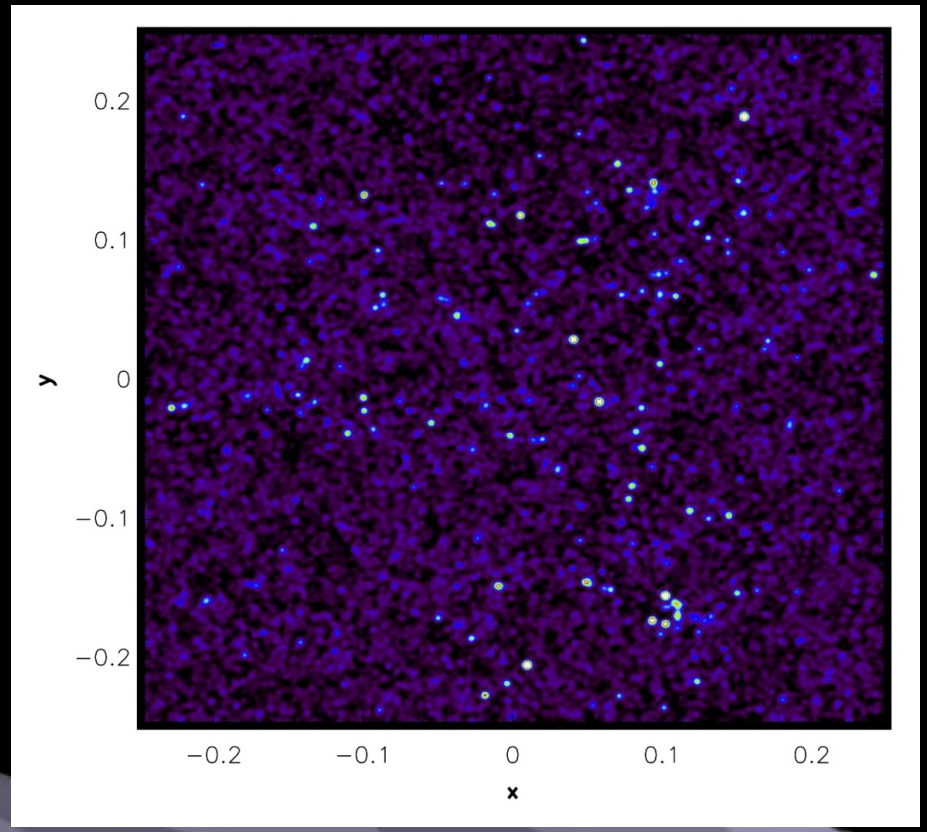
  → Diffuse and extended gas reservoirs + Nascent ICM (Helmut's talk!)
- How do dense regions influence star formation on galactic scales?

  → Baryon Cycle and accelerated galaxy evolution

See Perez-Martinez+2026 ESO Expanding Horizons White Paper arXiv:2512.14372

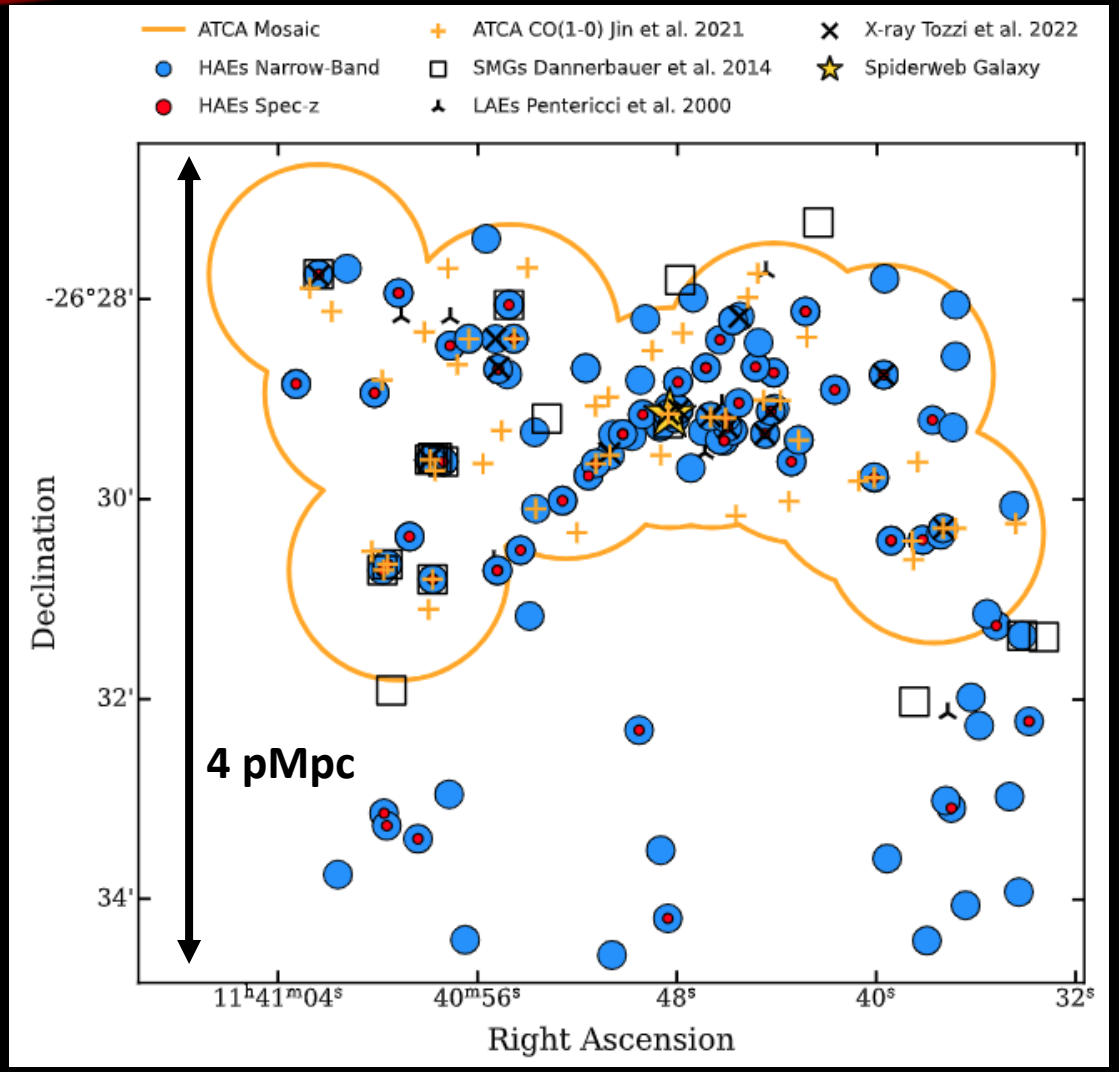
AtLAST Transformative contribution to Protoclusters

- **1-2 deg^2 FoV** to capture **entire** protoclusters
- **Resolving power (1-2”) and high sensitivity** to identify “ordinary” SFGs.
- **High multiplexity, and multiband/multiline** capabilities (CO sled, [CI], [CII], dust…)
- **Fast Mapping Speed** for PCL statistics
- Strong Synergies with Wide Sky Surveys



Mock image at 2.4mm of the CO(3-2) line for galaxies in and around a simulated z=1.74 cluster in formation (Van Kampen+24)

The Spiderweb protocluster at z=2.16



Perez-Martinez+25

MAHALO (Kodama+13):

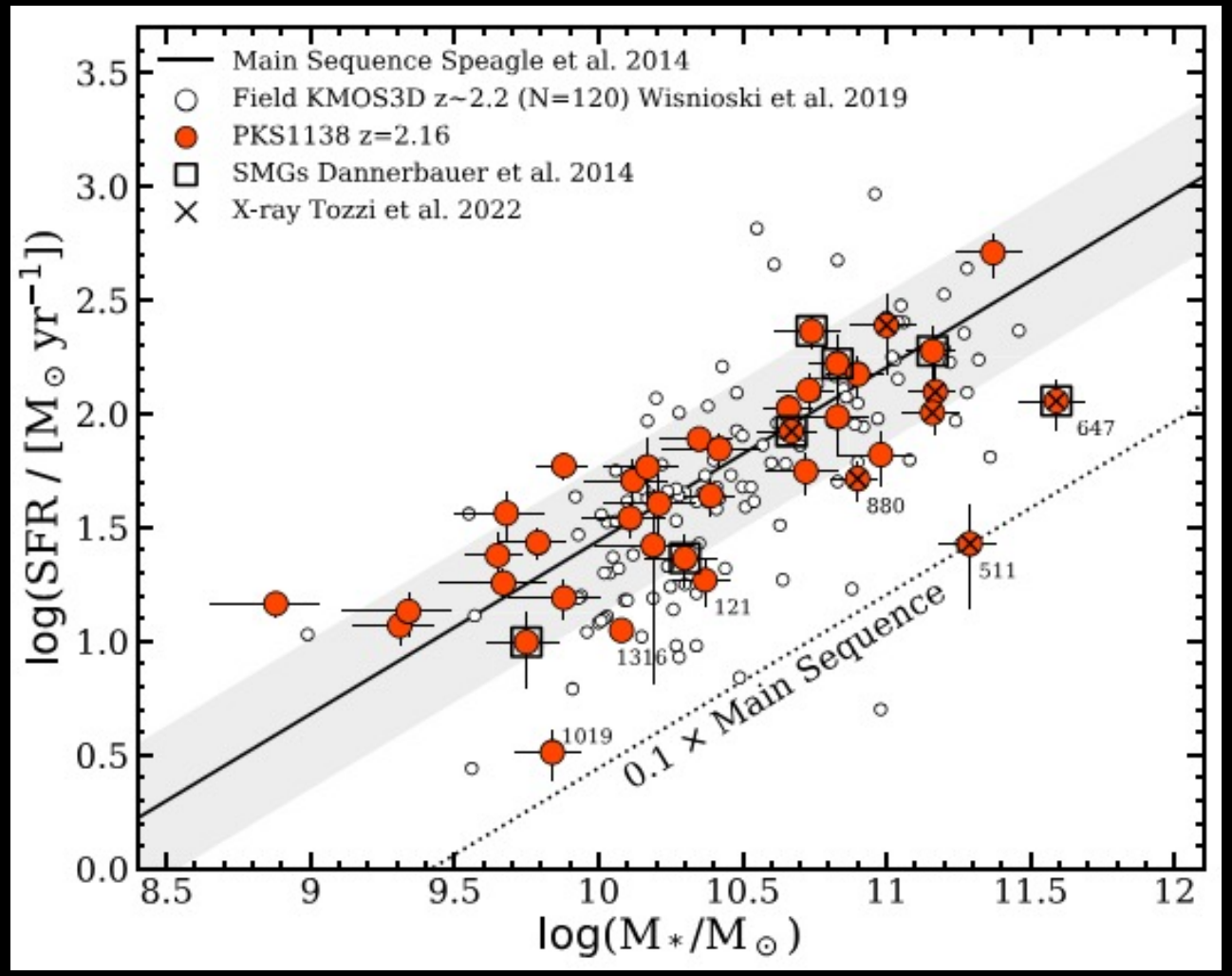
- **Blind search for Ha** NB emitters in the SW
- Trace **current star formation.**

COALAS (Jin+21):

- **Blind search for CO(1-0)** emission in the SW
- CO(1-0) best tracer for **cold molecular gas**

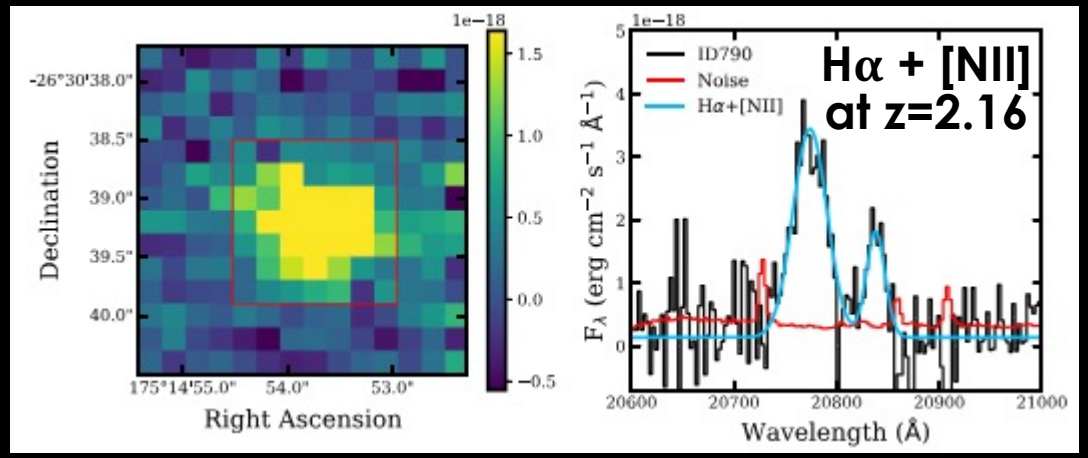
HAEs represent the backbone population in the Spiderweb Protocluster

The Main Sequence of Star Formation



Perez-Martinez+23

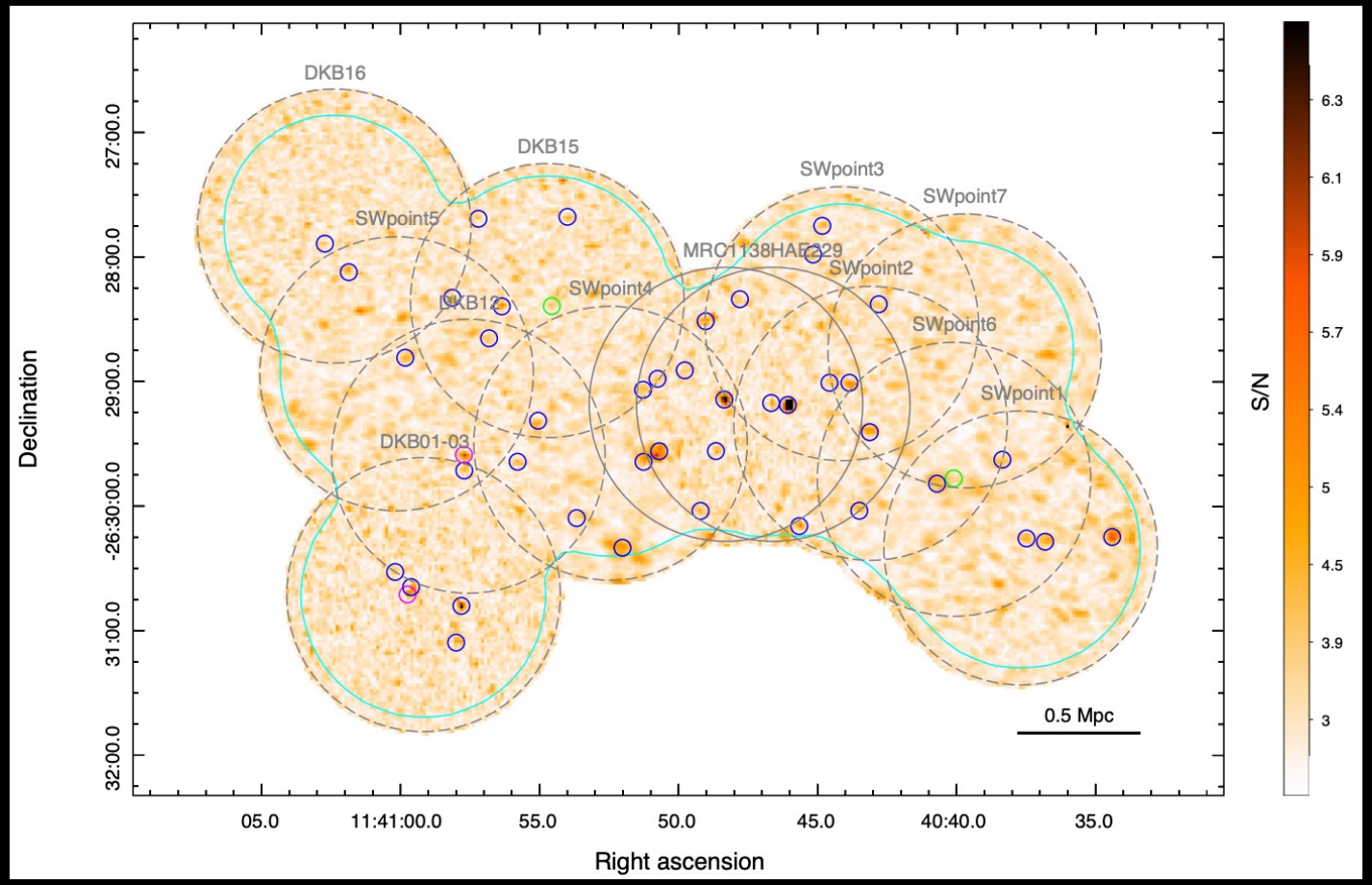
VLT/KMOS for 39 protocluster HAEs



HAEs (bulk of population) consistent with the Main Sequence.

<u>In contrast,</u> SF enhancement in other PCL (e.g., Perez-Martinez+24a, Daikuhara+24, etc) and higher-z PCL-cores.

The Spiderweb protocluster at z=2.16

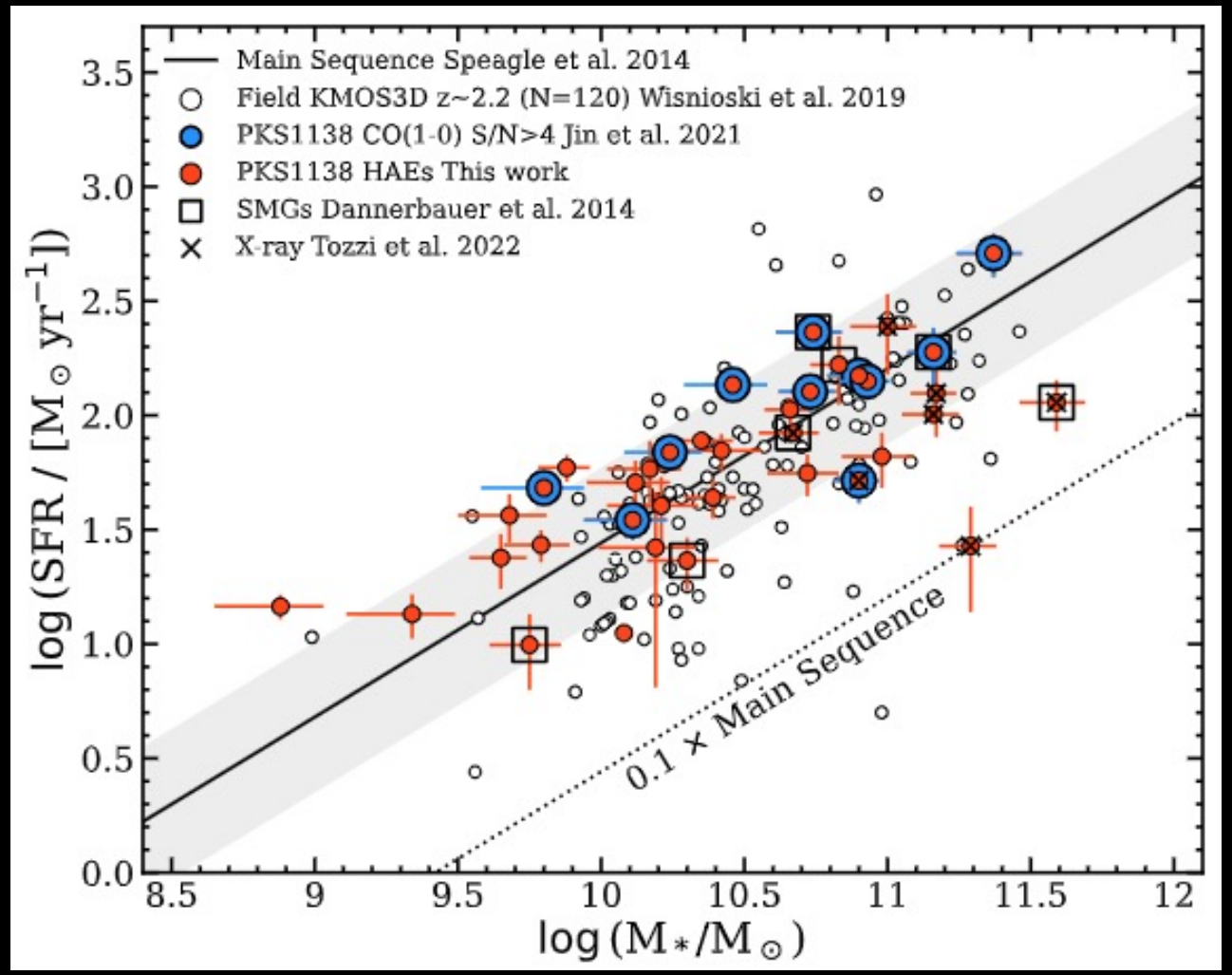


Jin+21

COALAS (PI: Dannerbauer):

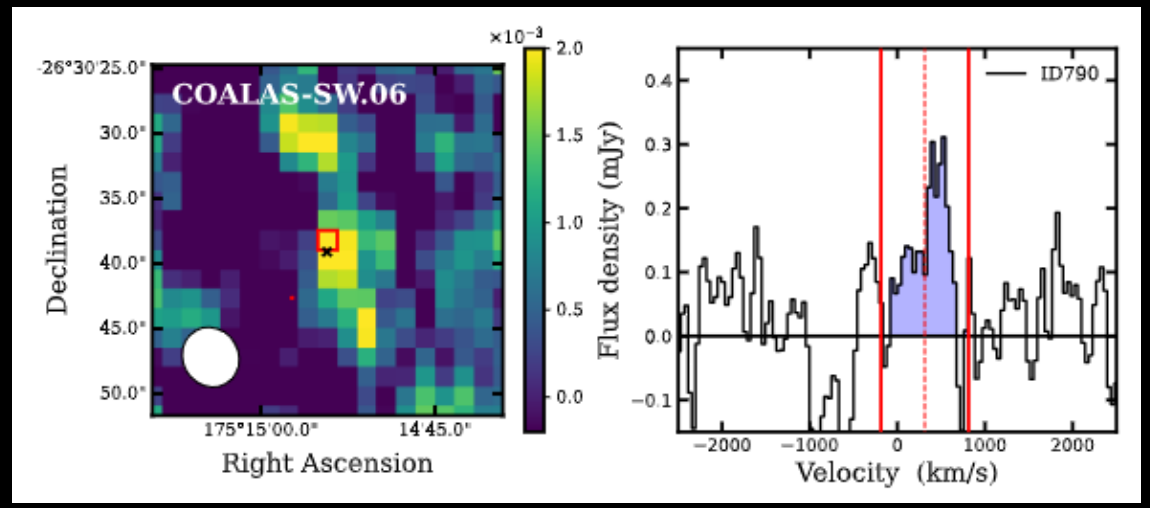
- **Blind search for CO(1-0)** emission in the SW
- CO(1-0) best tracer for **cold molecular gas**

Cold molecular gas from CO(1-0) in COALAS



Perez-Martinez+25

COALAS: Mosaic with 450h integ. time for **CO(1-0)** (Jin+21), **best molecular gas tracer!**

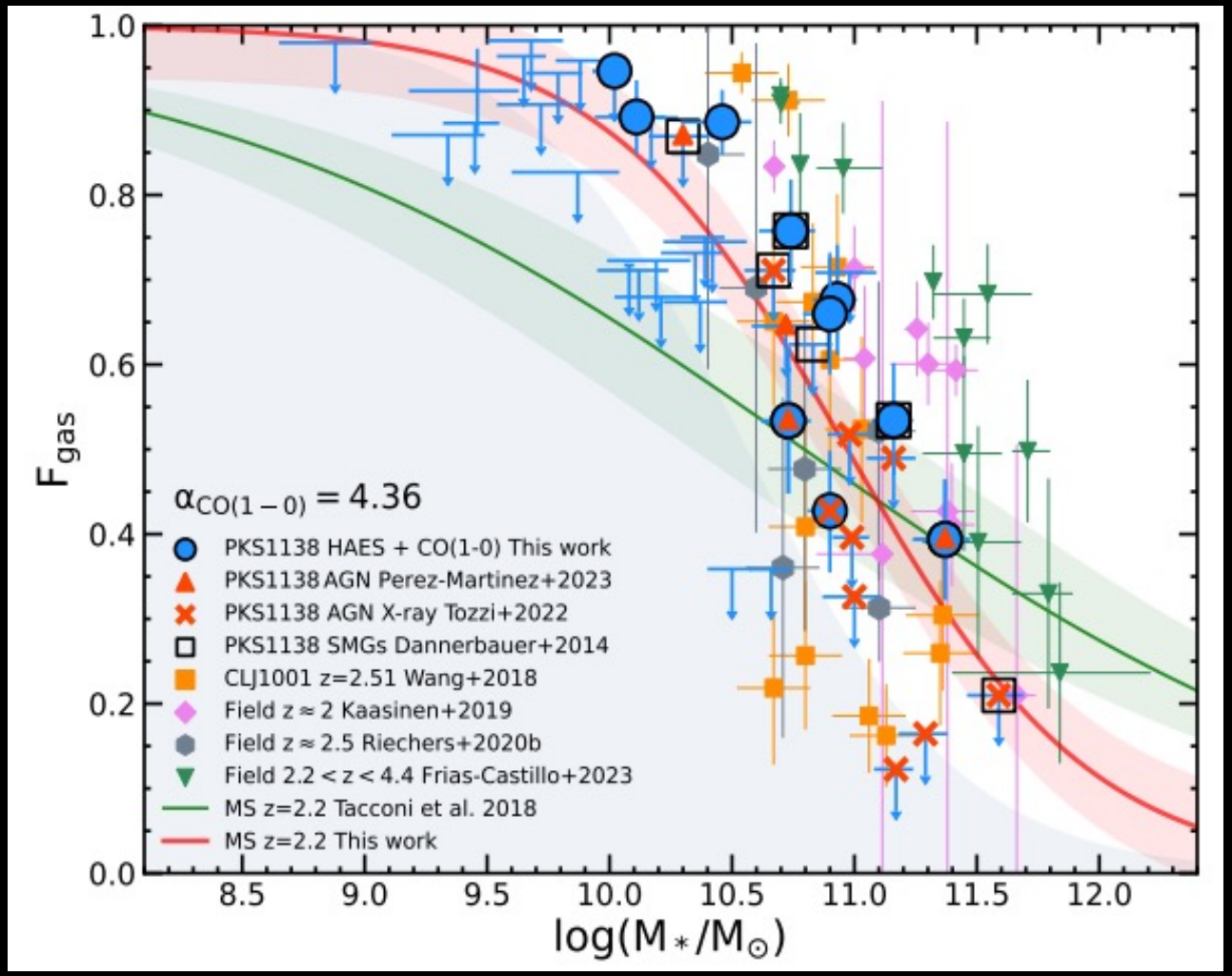


11 CO(1-0) detections at S/N>4 and 26 upper lim.

Investigate Gas Fraction and Depletion time!

Molecular gas fraction

Only CO(1-0) samples!



Perez-Martinez+25

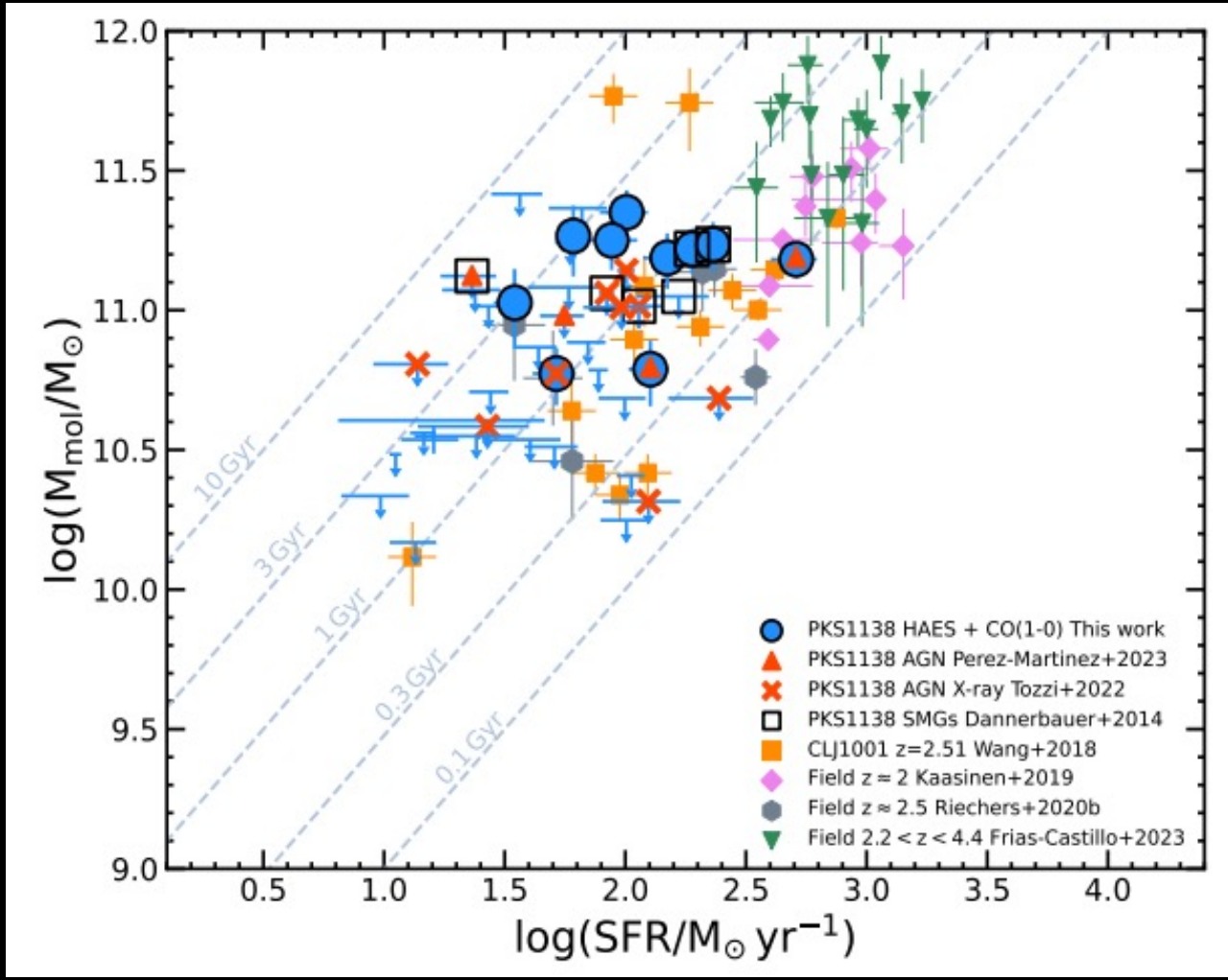
Gas fraction: $F_{gas} = M_{mol}/(M_* + M_{mol})$

Two F_{gas} regimes at low and high M_* :

- Sharp transition at $M_* > 10^{10.5} M_\odot$
- High AGN fraction (~50%) in massive end

Similar trend for coeval field samples

Depletion times



Perez-Martinez+25

Depletion time: $\tau_{dep} = M_{mol}/SFR$

τ_{dep}=1-3 Gyrs (in the absence of inflows)

Concurrent with surge of Red Sequence in massive clusters (1<z<1.6)

Other processes may hasten or delay τ_{dep}

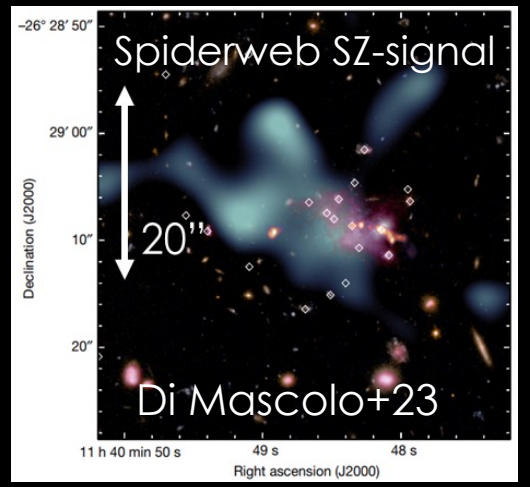
→ **Inflow vs Outflow/Consumption (un)balance?**

Three main scenarios

A) Starvationn through Intracluster Medium (X)

- Small extent of nascent ICM + only in center (Di Mascolo+23)

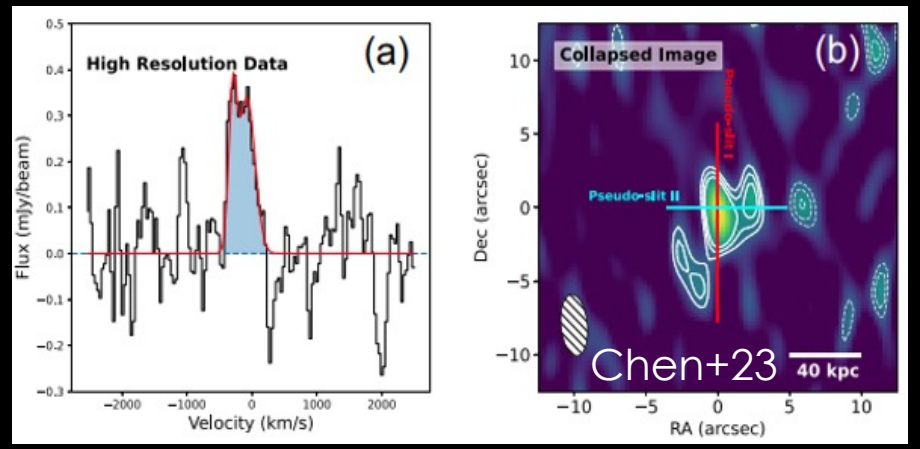
- Typical cold BAR can fuel SF for long times (Daddi+22)



B) Gas removal through Ram Pressure Stripping (X)

- Small extent of nascent ICM + only in center (Di Mascolo+23)

- Widespread large (>40kpc) molecular reservoirs (Chen+23)

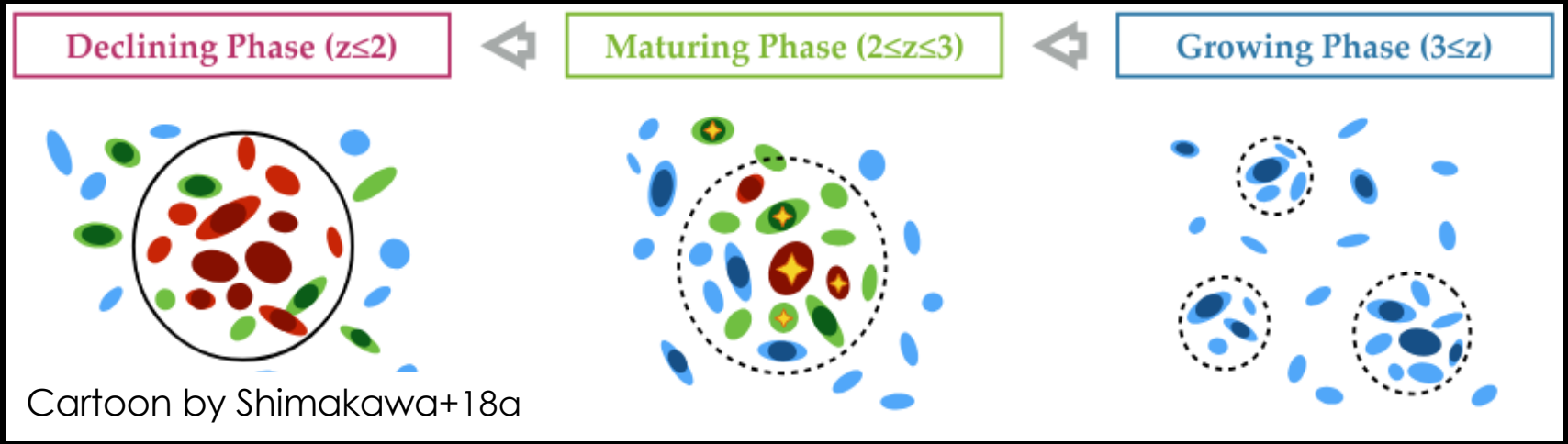


C) AGN feedback + Overconsumption (👍)

- High AGN rate (9/17) in massive end (PM+24b).

- Perhaps enough to quench some galaxies, but could they rekindle? (Remus+23, Kimmig+23b).

Interpretation



Cartoon by Shimakawa+18a

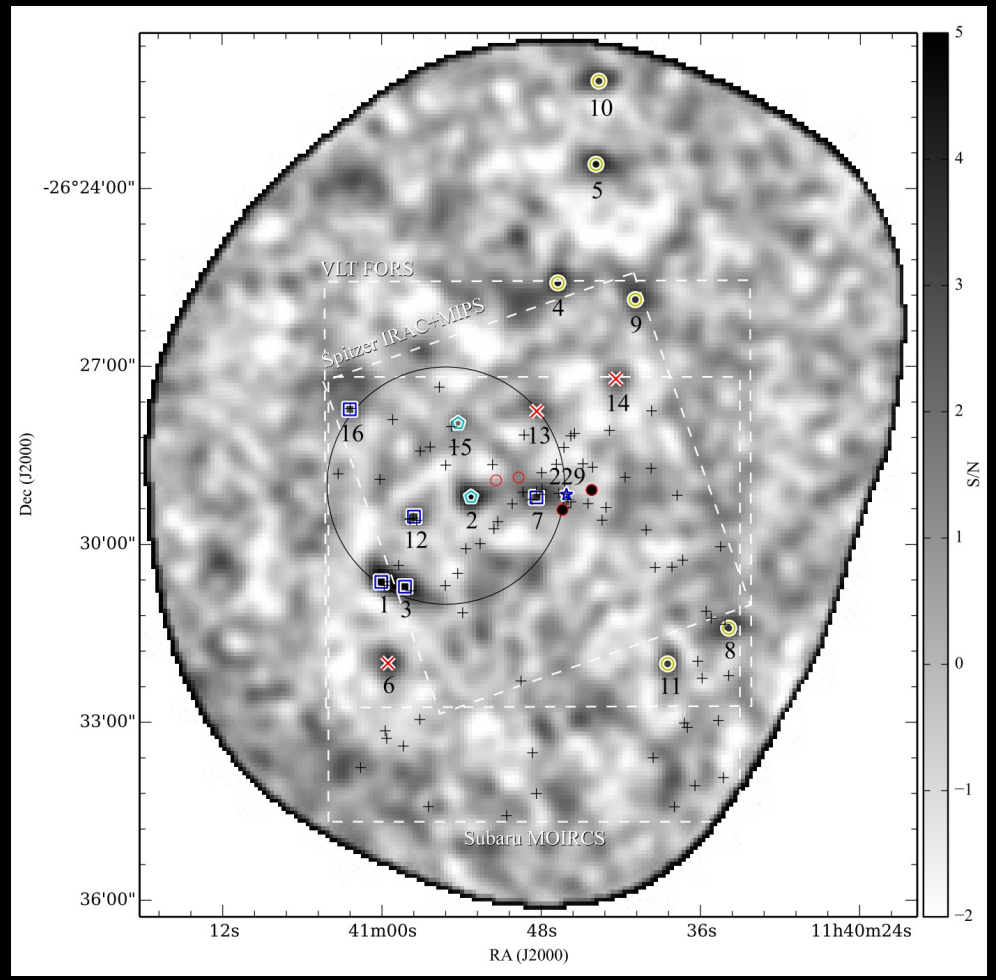
Declining Phase (z≤2)	Maturing Phase (2≤z≤3)	Growing Phase (3≤z)
No Accretion	Accret. Modulation	Isotr. Gas Accretion
Cluster Virialization	PCL-Core Virialized	In situ SMGs
SF only in Outskirts	Growth of HAEs	High merging Rates
Quenched Core	First quenched Gals.	Merging Haloes
Classical Env. Effects	Nascent ICM	Small volumes

Spiderweb Protocluster

z=2.16

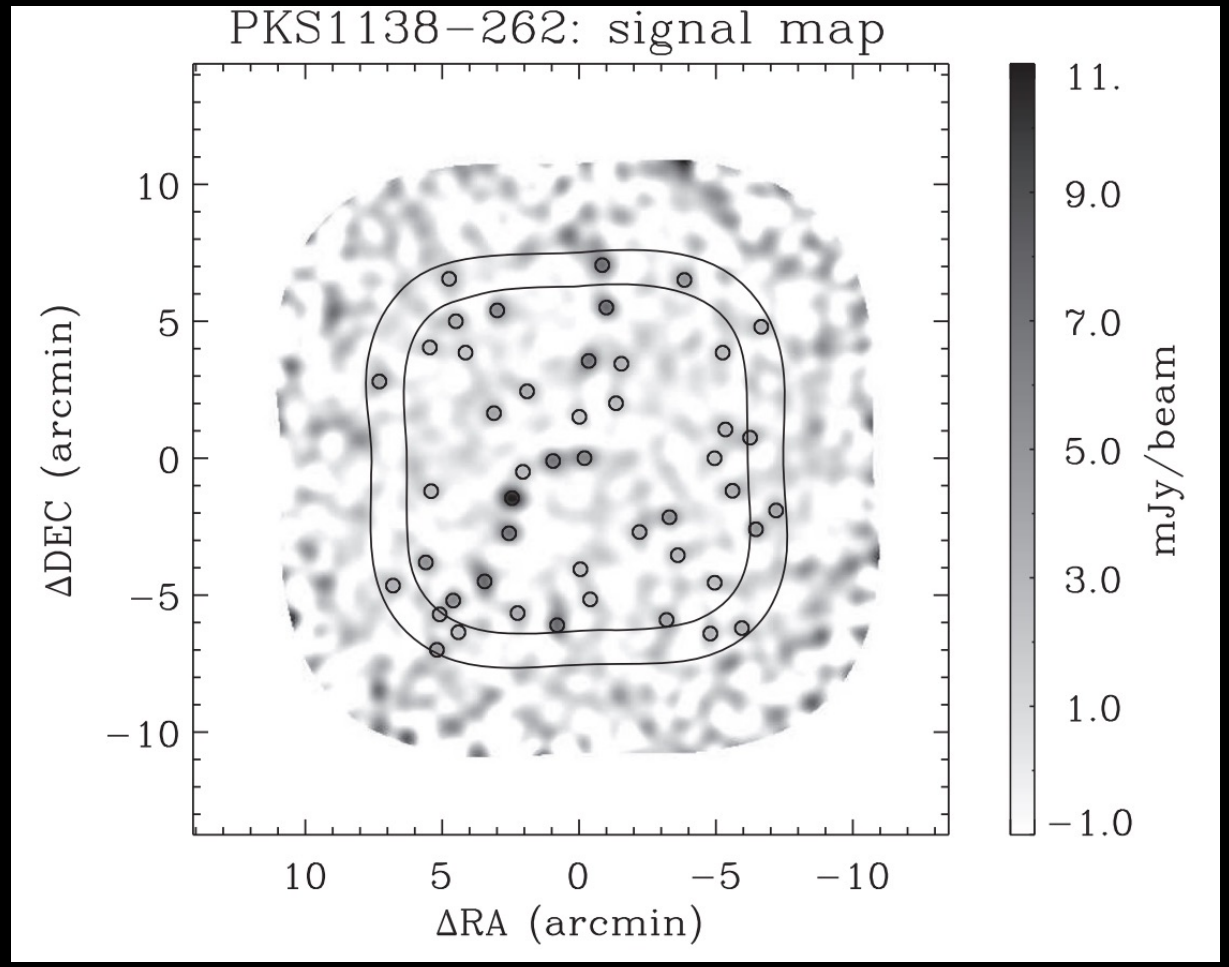
Single Dish Spiderweb Campaigns

870um APEX LABOCA; FWHM~19”



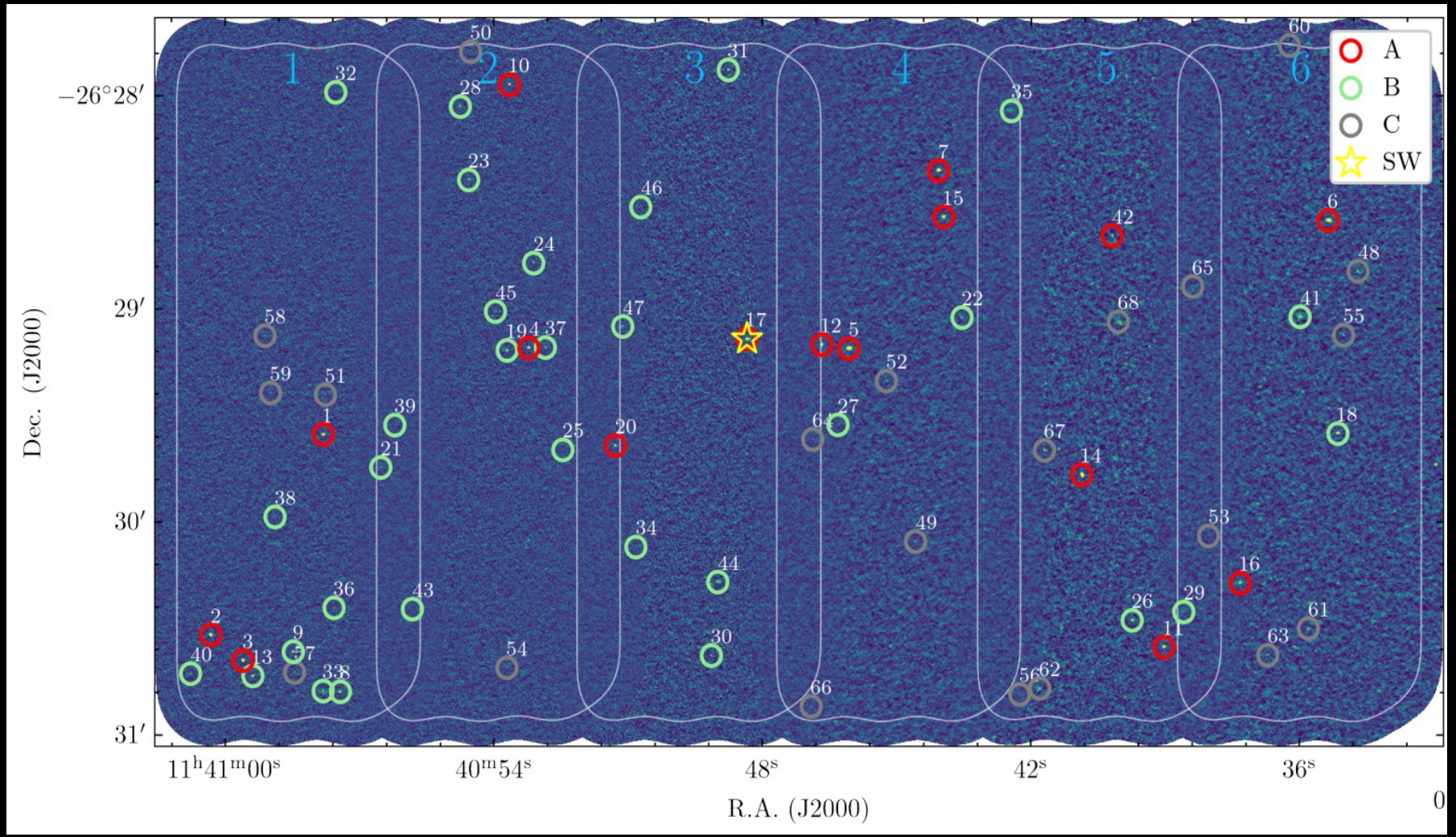
Dannerbauer+2014

1.1mm AzTEC, visiting @JCMT; FWHM~18”



Zeballos, Aretxaga+2018

ALMA 1.1mm Dust Continuum follow-up

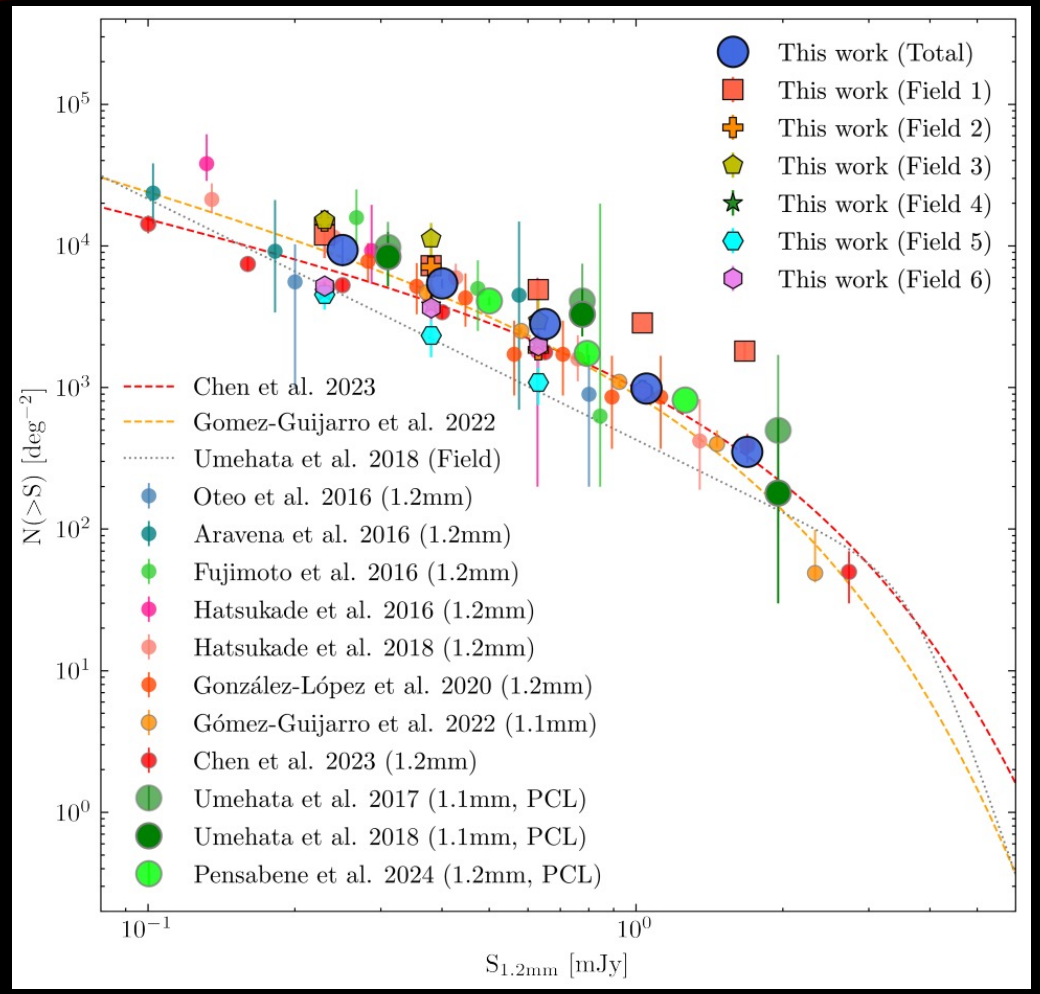


- PIs: Koyama, Dannerbauer
- Mosaic ~3x6 arcmin²
- 0.5-0.9" resolution
- ~80 Mo/yr Depth
- Det. Codes:

  SoFiA, SEP, AEGEAN, eyes
- 47 DSFGs at SNR>4 (A+B)

Zhang, Dannerbauer, Perez-Martinez +2024

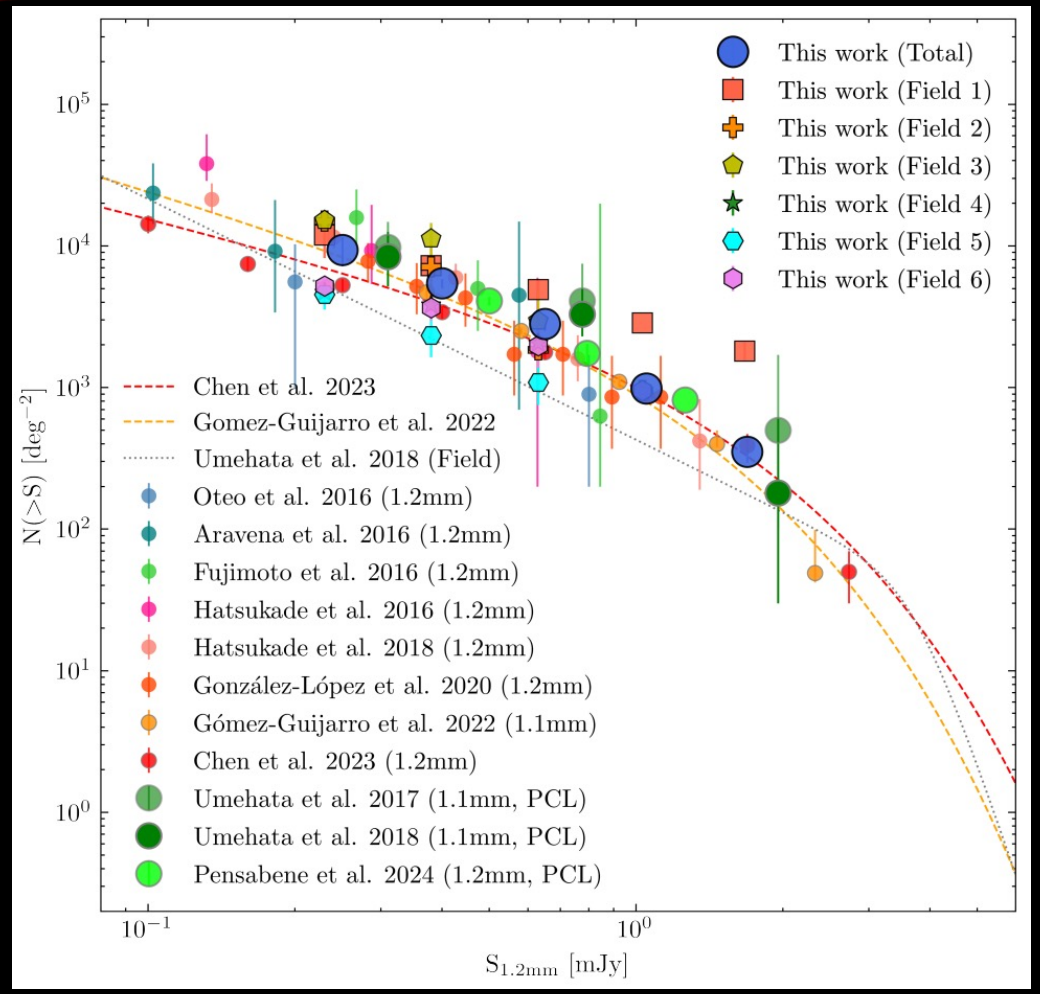
Number counts

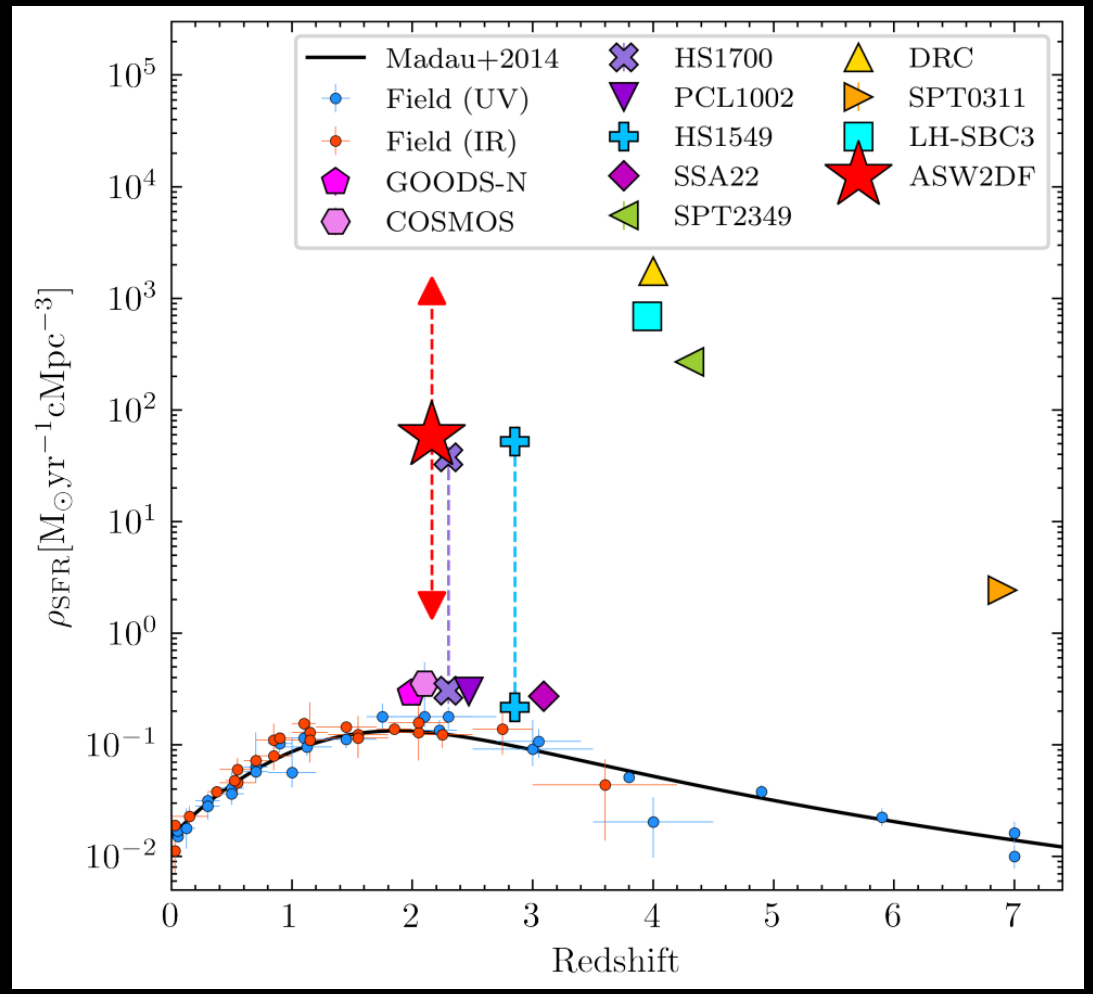


Zhang, Dannerbauer, Perez-Martinez +2024

Spiderweb PCL is 2-4 times more overdense in ALMA-detected DSFGs than field samples

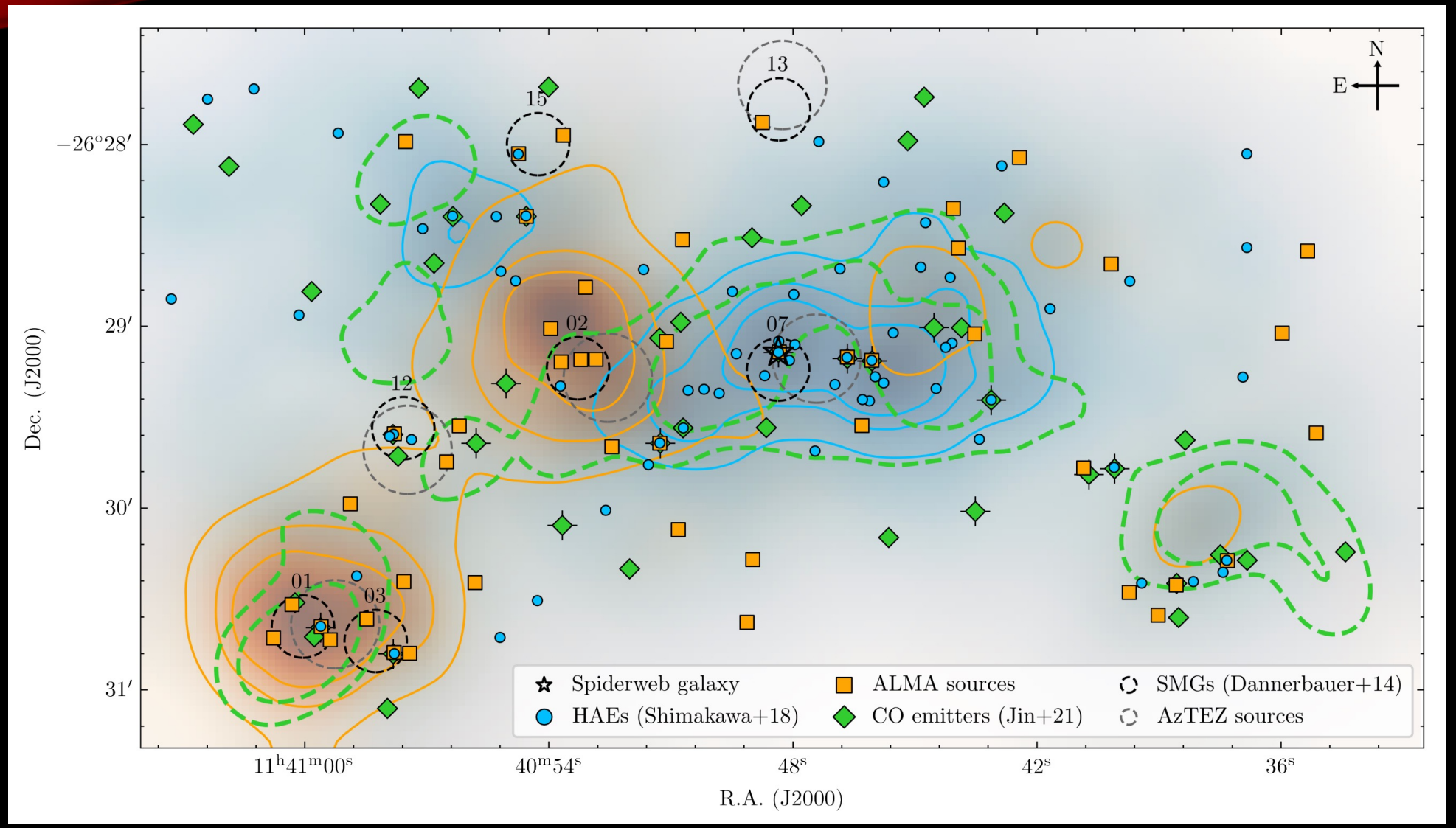
Number counts and Cosmic SFRD





Zhang, Dannerbauer, Perez-Martinez +2024

Spatial distribution of gaseous and dusty populations

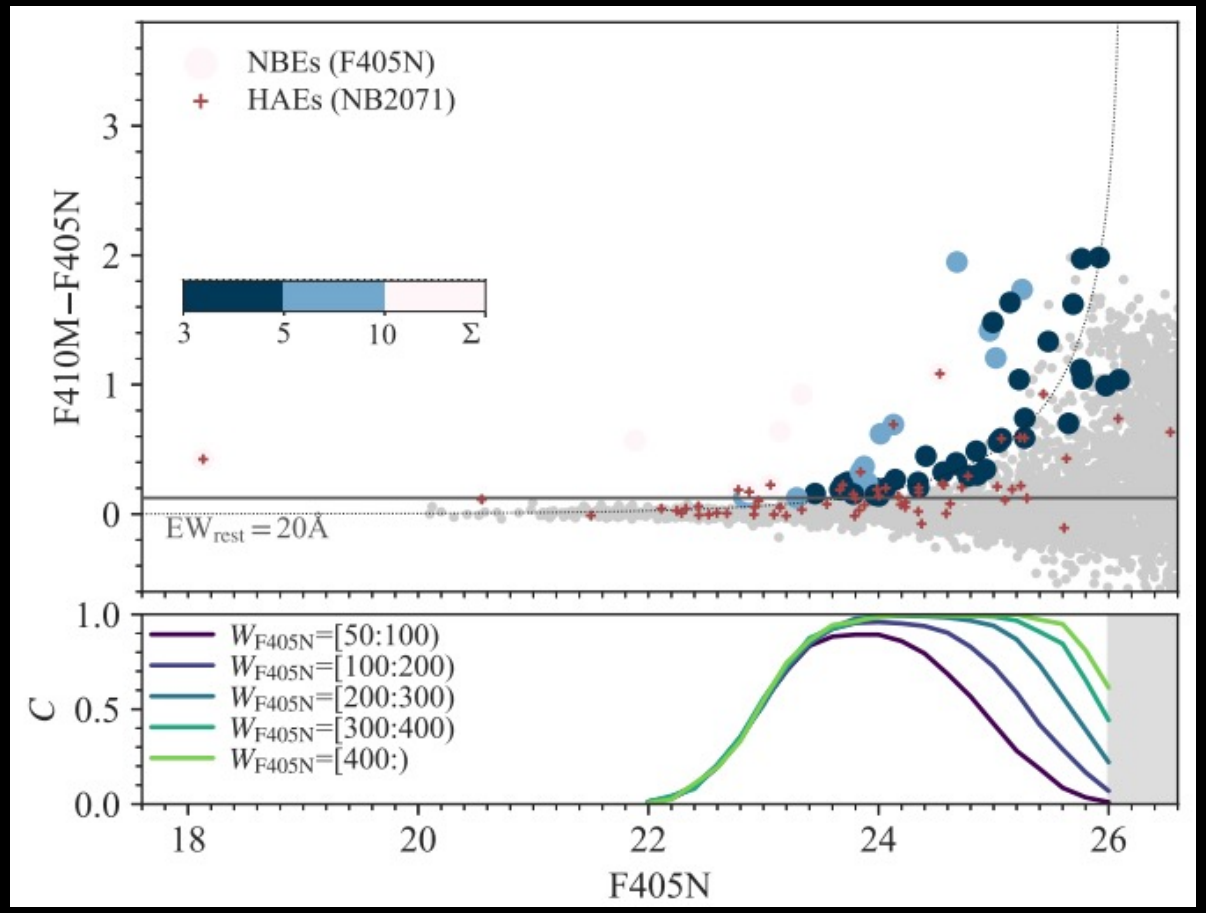


Zhang, Dannerbauer, Perez-Martinez +2024

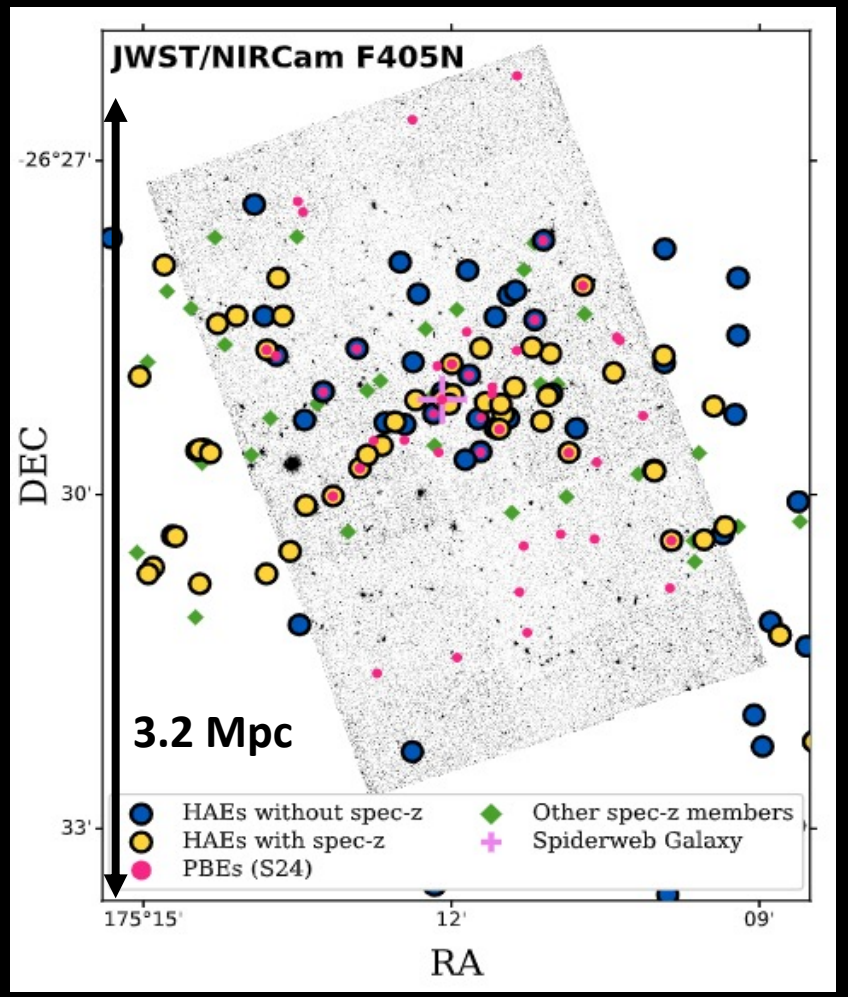
Cycle 1 JWST/NIRCam in the Spiderweb

JWST/NIRCam F115W, F182M, F410M, F405N ~4h exp. Time. **PIs: H. Dannerbauer + Y. Koyama.**

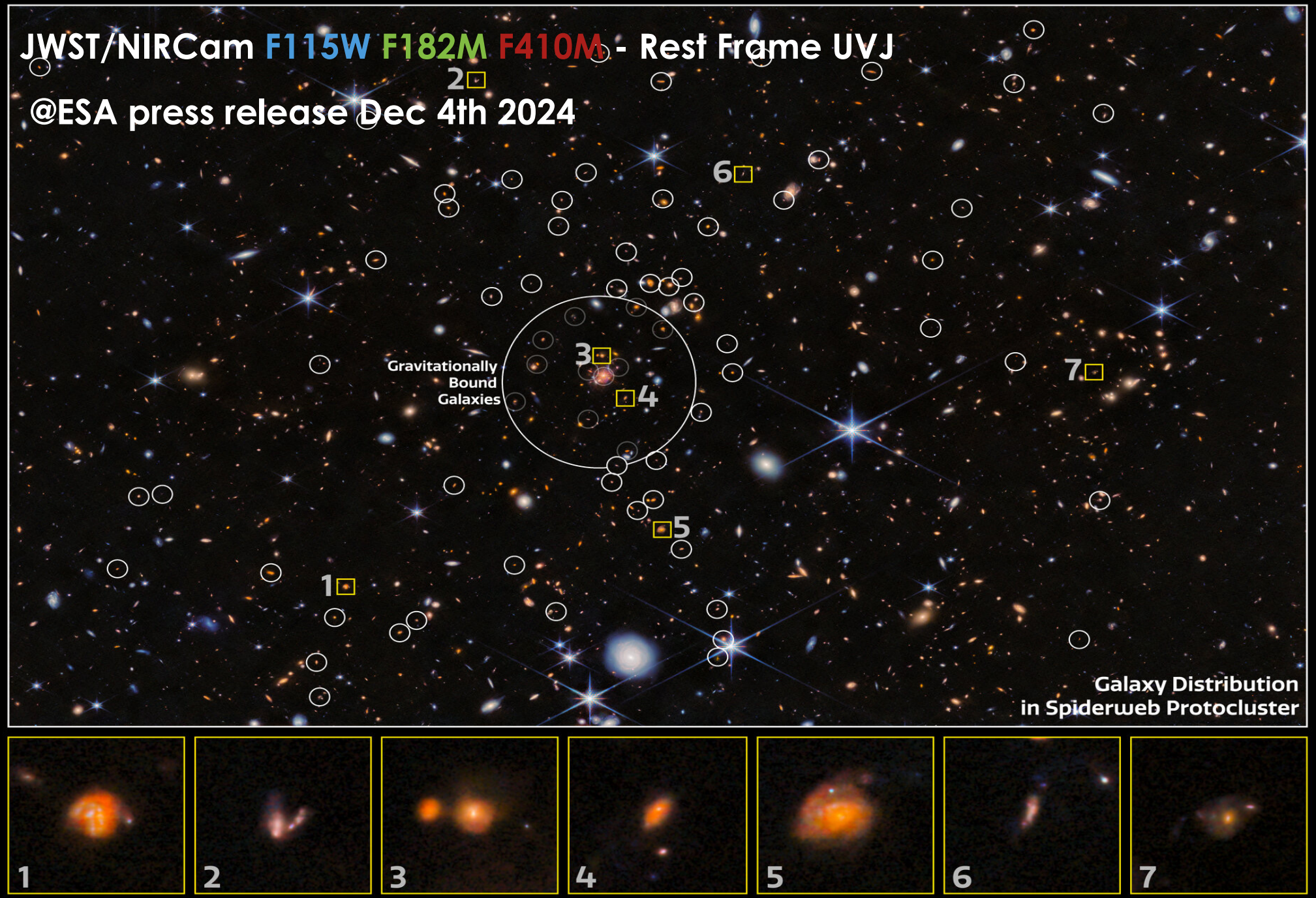
Blind search for Paβ emitting galaxies (rest-frame 12821 Å)



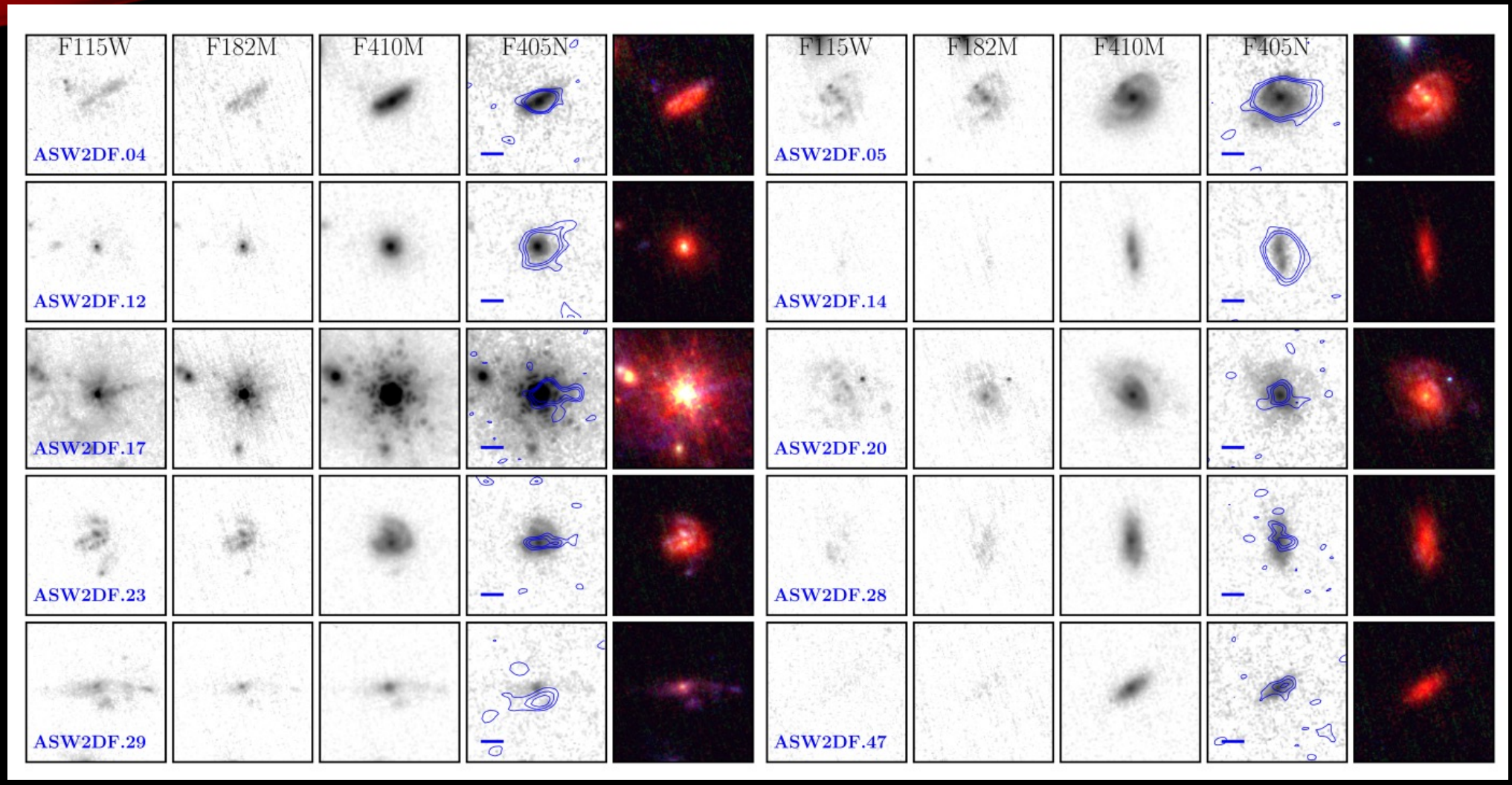
Shimakawa, Perez-Martinez+24b (Paβ detection)



Perez-Martinez+24b (Hα + Paβ analysis)

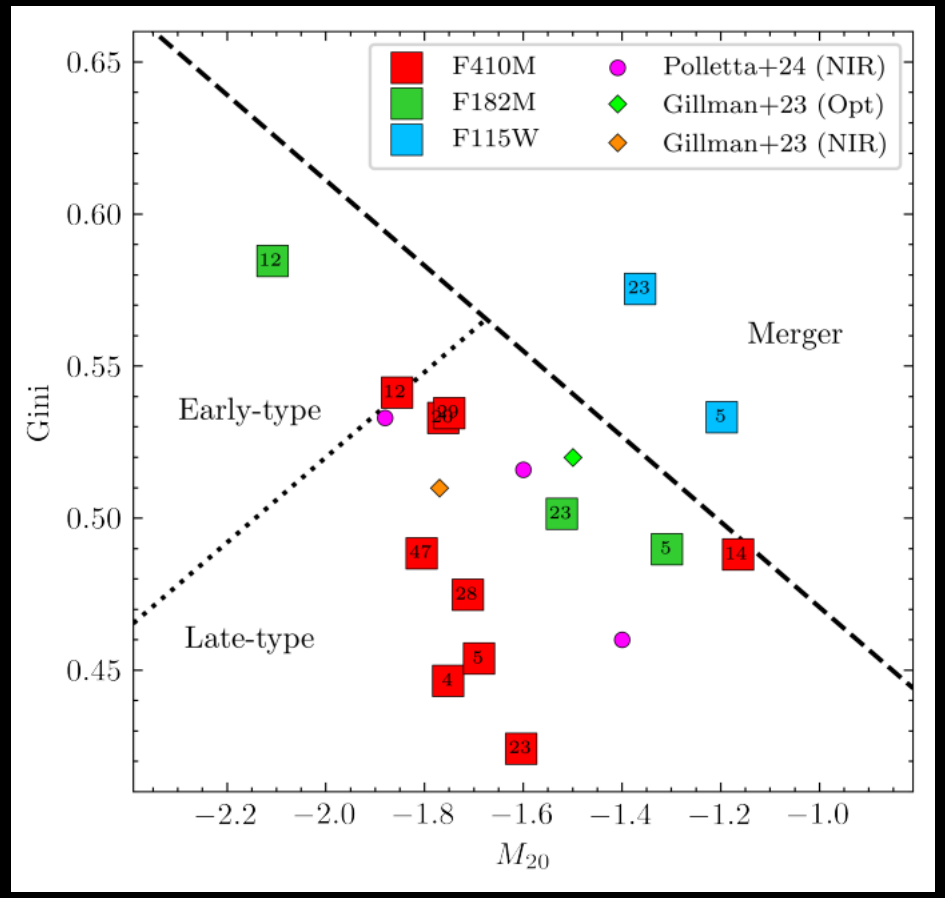

JWST/NIRCam F115W F182M F410M - Rest Frame UVJ
@ESA press release Dec 4th 2024
2
6
Gravitationally
Bound
Galaxies
3
4
7
5
1
Galaxy Distribution
in Spiderweb Protocluster
1
2
3
4
5
6
7

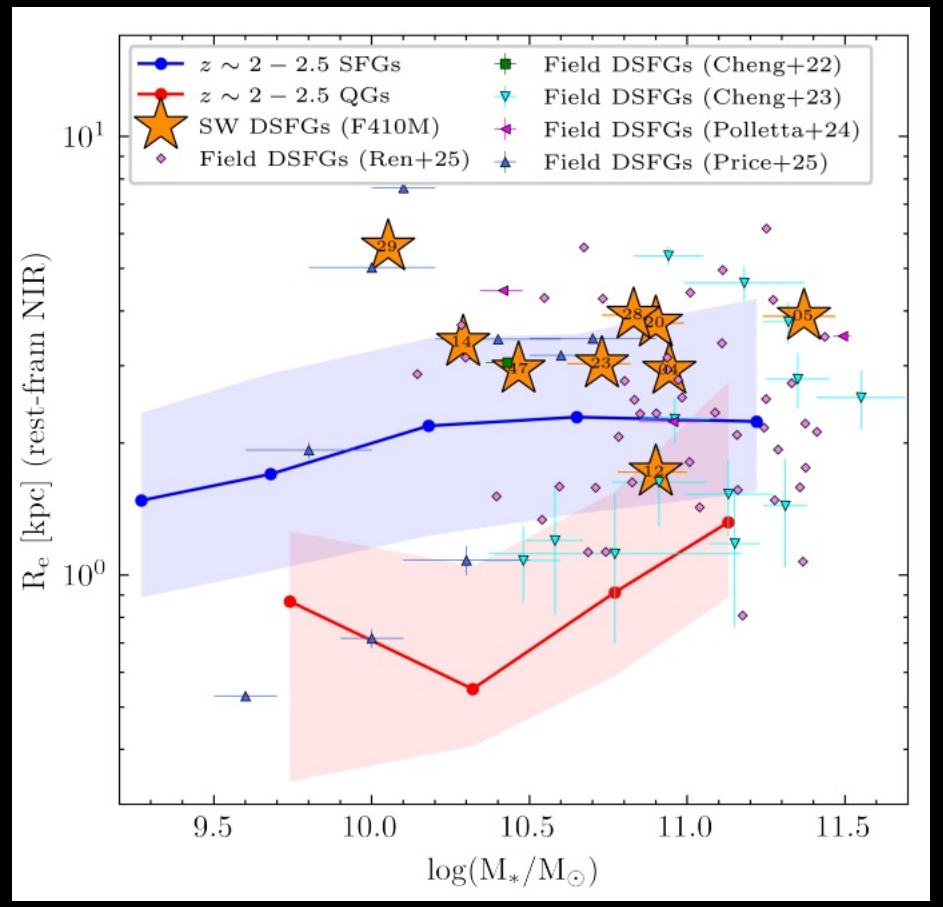
ALMA + JWST DSGs Morphologies



Zhang, Dannerbauer, Perez-Martinez +2026

ALMA + JWST DSGs Morphologies





Regular and Extended Stellar disks for ALMA bright DSFGs in the Spiderweb Protocluster

Zhang, Dannerbauer, Perez-Martinez +2026

Takeaway Messages

1) Galaxy Protocluster Science remains an Emerging Field (tip of the iceberg + lack of statistics)

2) Heavily dominated by gas-rich, dusty and highly star-forming galaxies, but baryon cycle for most members remain poorly understood (small biased simples).

3) **AtLAST** will overcome such limitations in a **multiscale way, from Mpc to individual members**

4) Synergies with present and future Wide Sky Surveys and Facillities (Euclid, LSST, Roman, etc)

S5: "Diverse Eyes, shared vision: Euclid, LSST, SKA, Roman and CSST join forces to explore the early Universe"
Chairs: J.M. Pérez-Martínez + H. Dannerbauer

SS26: "Planning the future of large-scale (sub-)mm astrophysics"
Chairs: E. Hatziminouglou