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ALPINE: a survey for studying teenage galaxies in the early Universe

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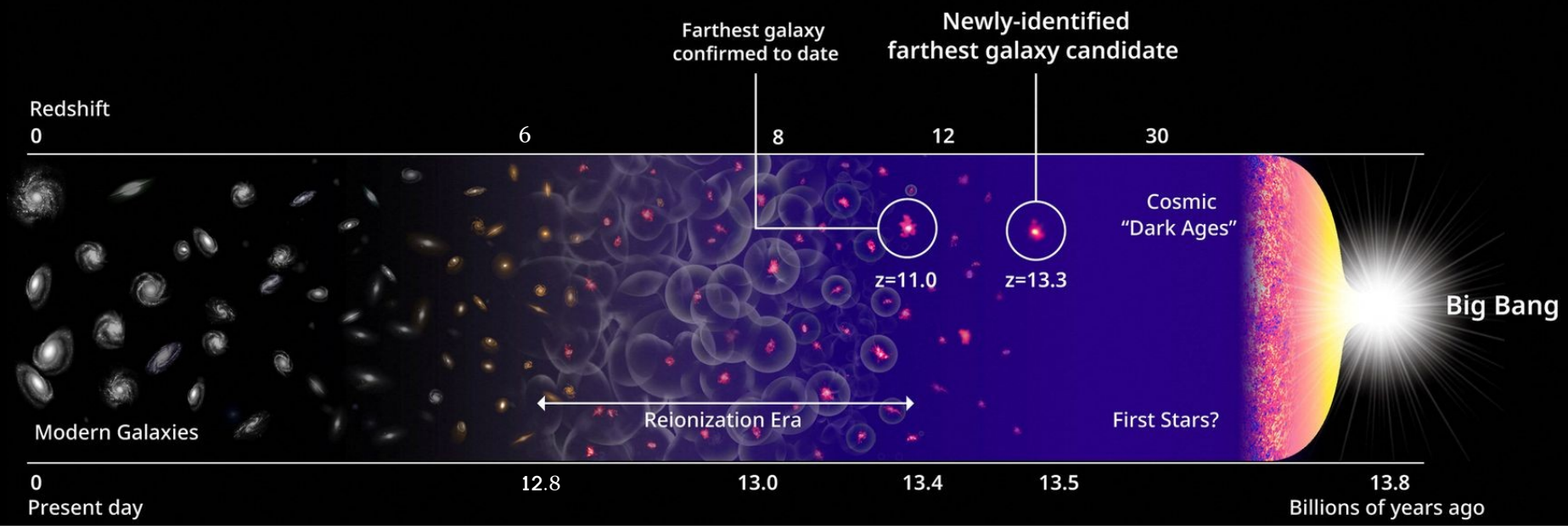
June 26, 2023 - Warsaw, Poland

Outline

- **Scientific context**
- **The ALPINE survey (an overview)**
- **A few major results from ALPINE**
- **[CII] as a star-formation tracer in the early Universe**
- **Summary and conclusions**

The history of the Universe



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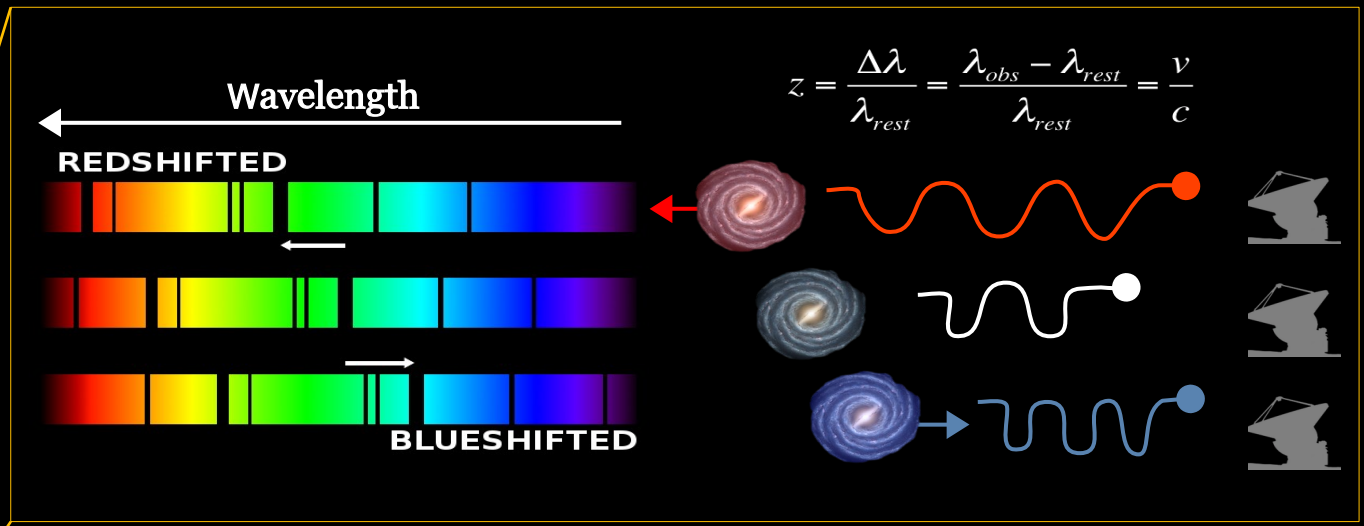

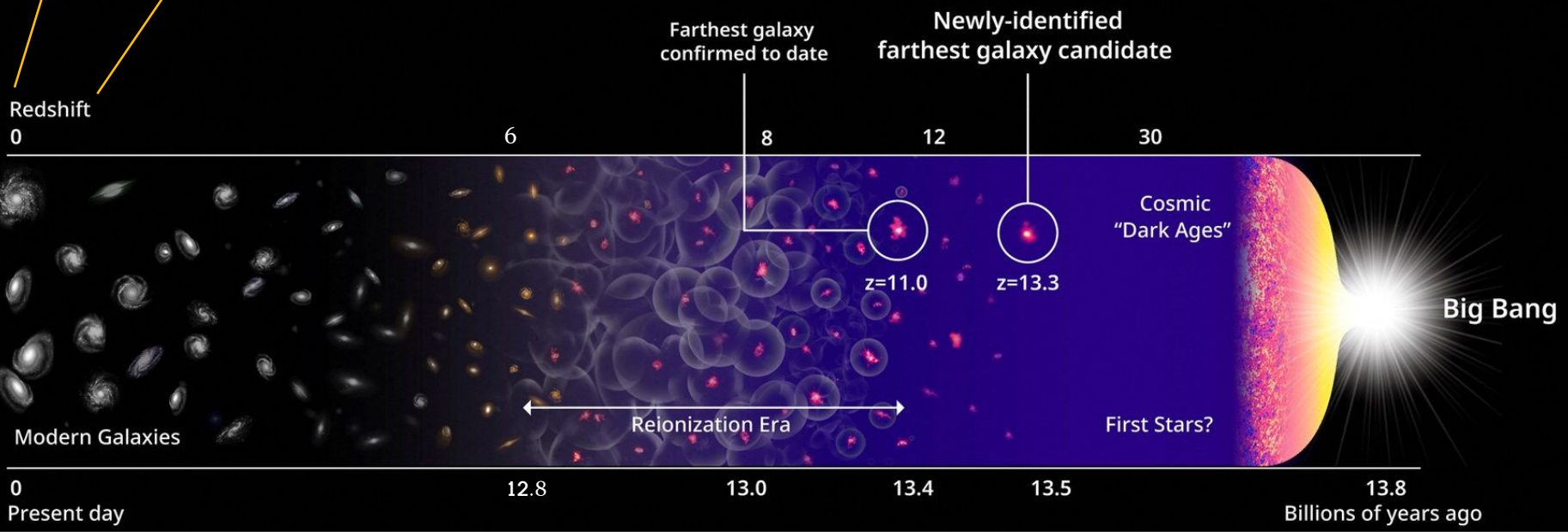

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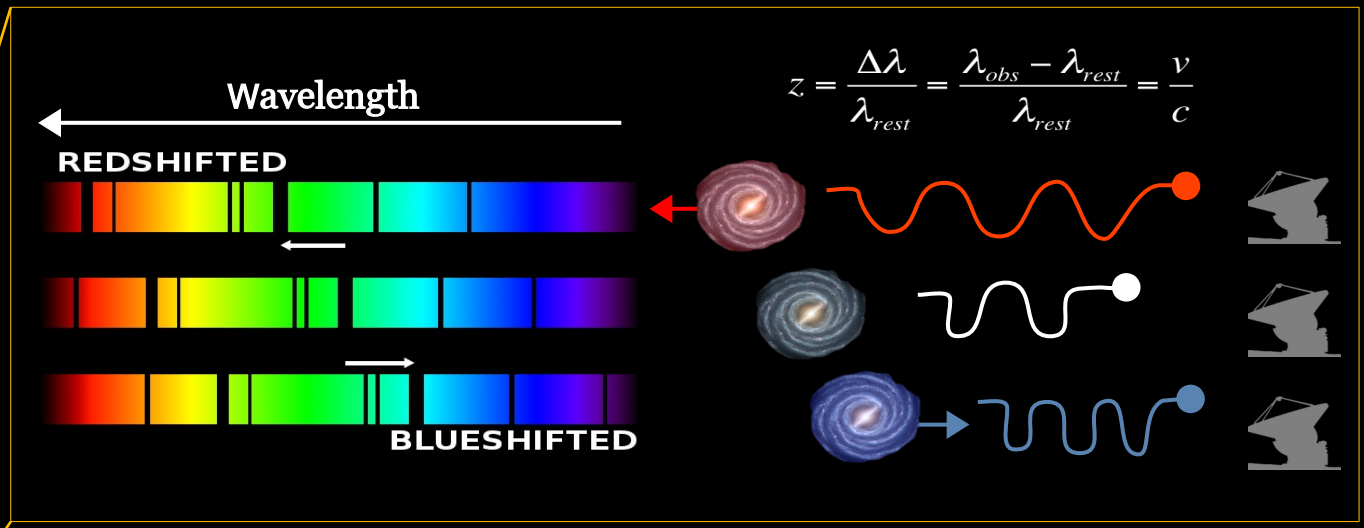
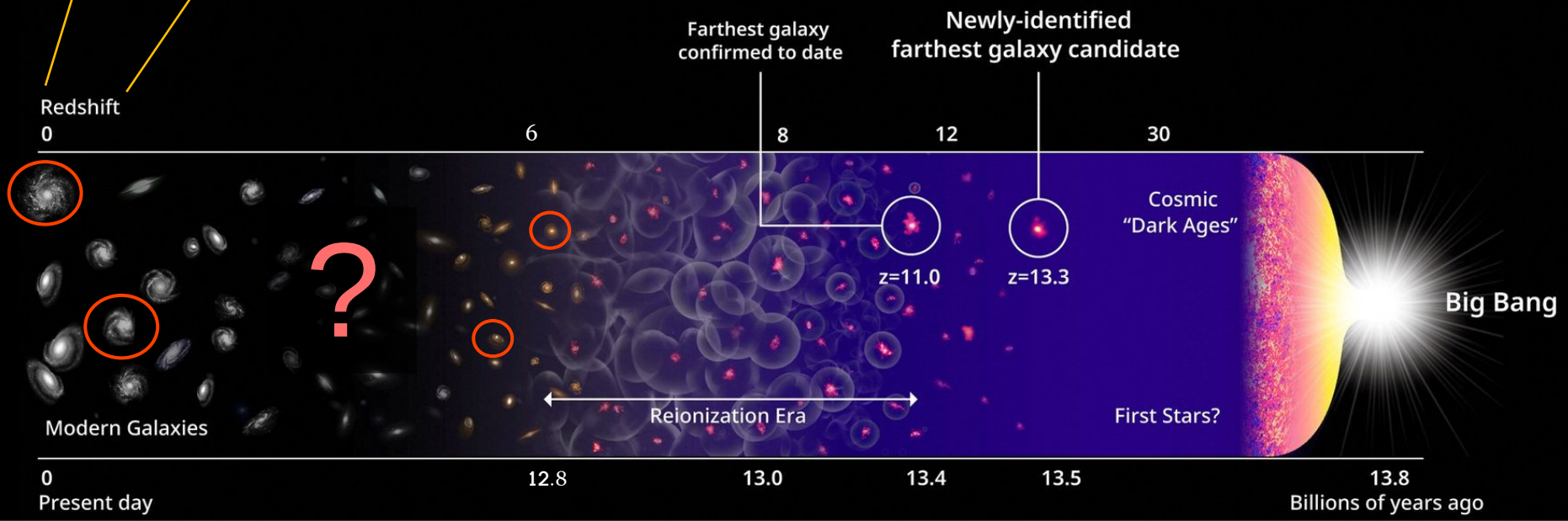
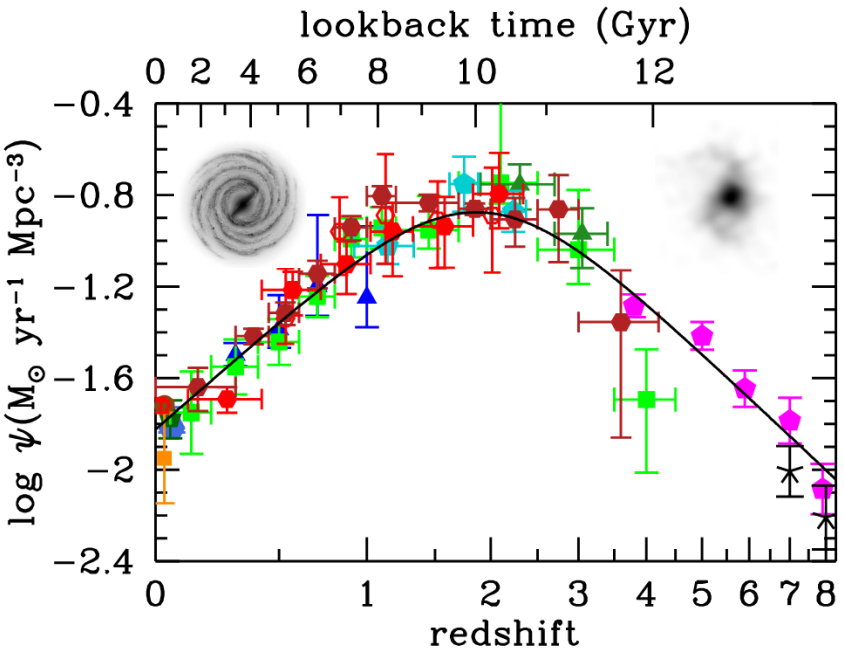




Scientific context

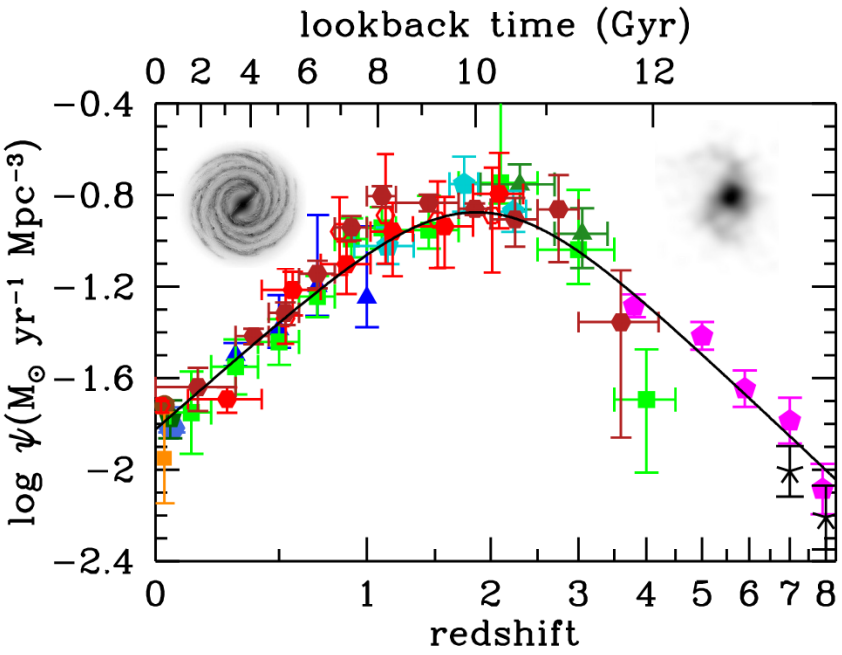


Madau & DIckinson 2014, ARA&A, 52, 415

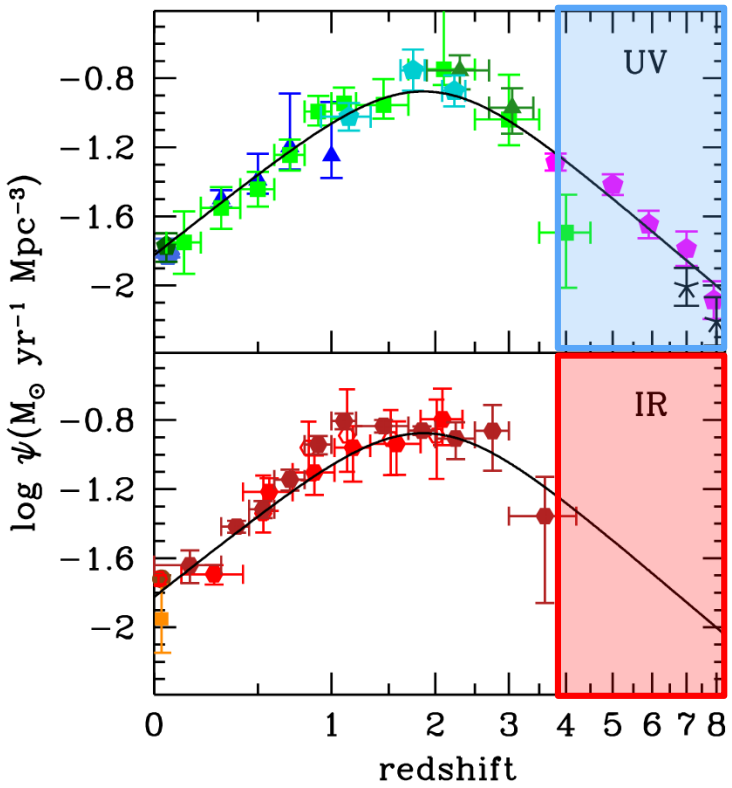
Scientific context

Data at z>4 are almost exclusively based on
UV measurements

IR observations are needed



Madau & DIckinson 2014, ARA&A, 52, 415



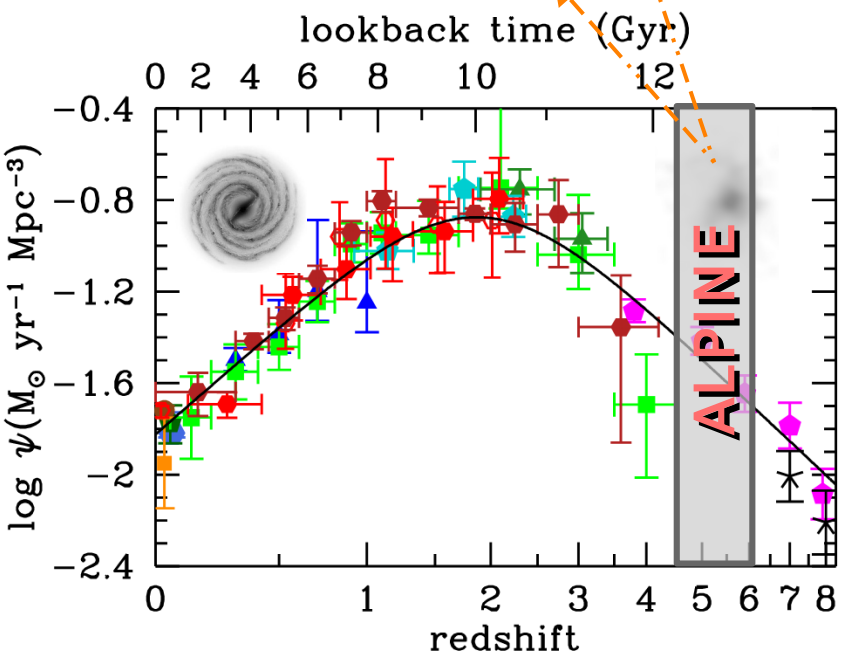
Young stars

Dust

Scientific context

What is the amount of dust-obscured star formation at z>4?

Which are the processes molding the shape of the cosmic star-formation rate density (SFRD)?



Madau & DIckinson 2014, ARA&A, 52, 415

Data at z>4 are almost exclusively based on UV measurements

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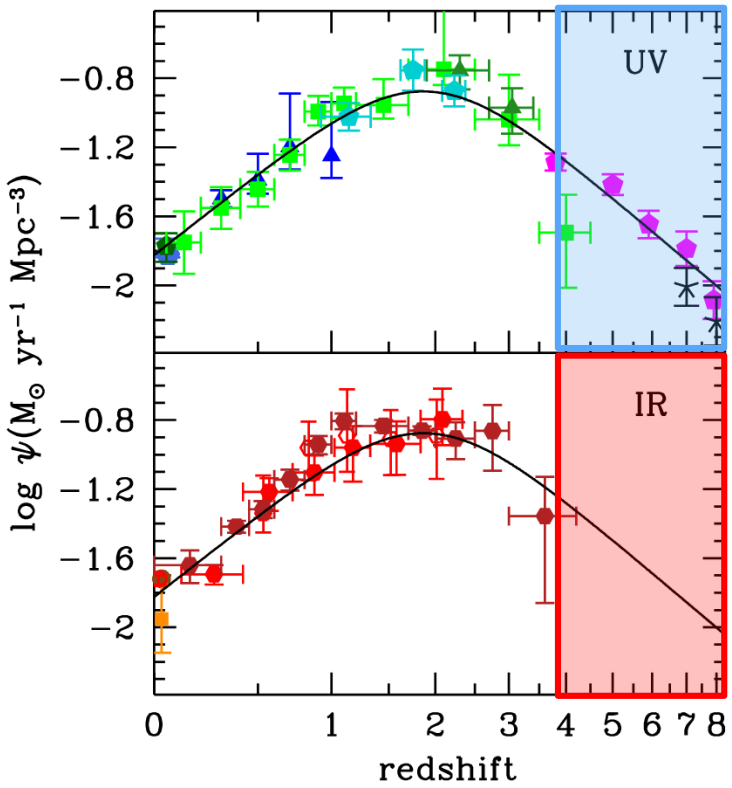
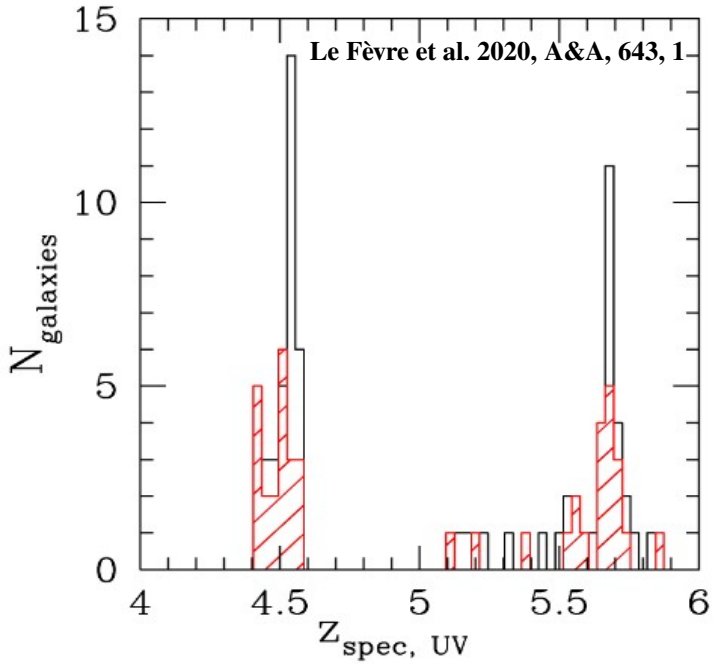


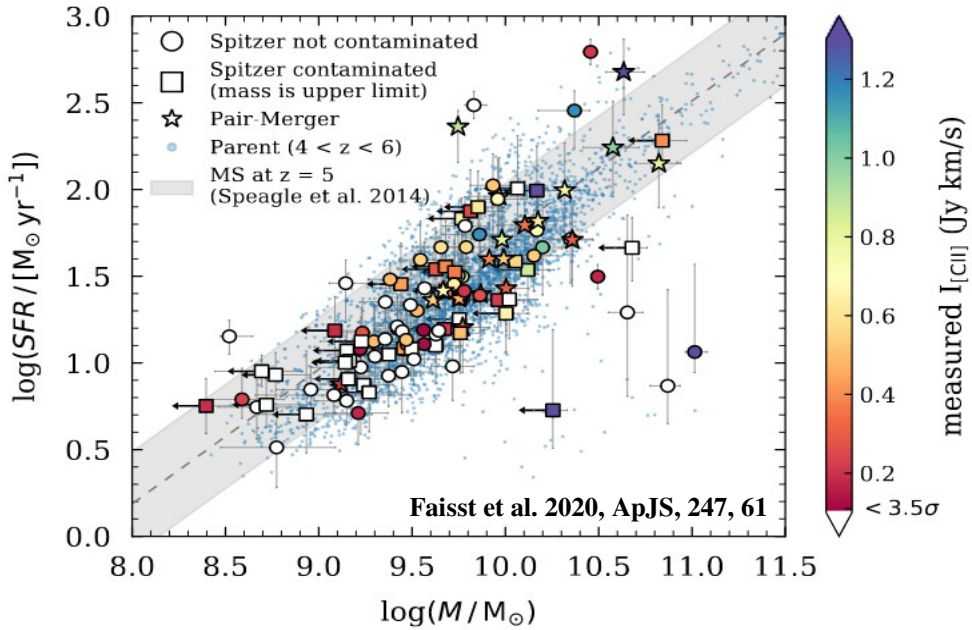
Young stars

Dust

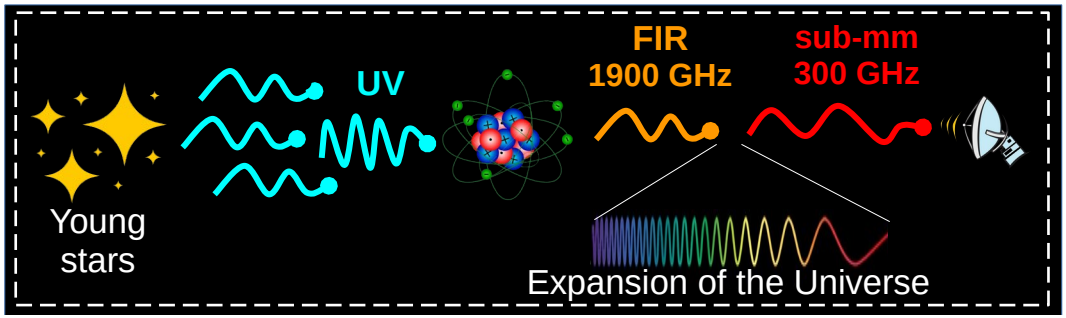
ALPINE: the ALMA Large Program to INvestigate [CII] at Early times

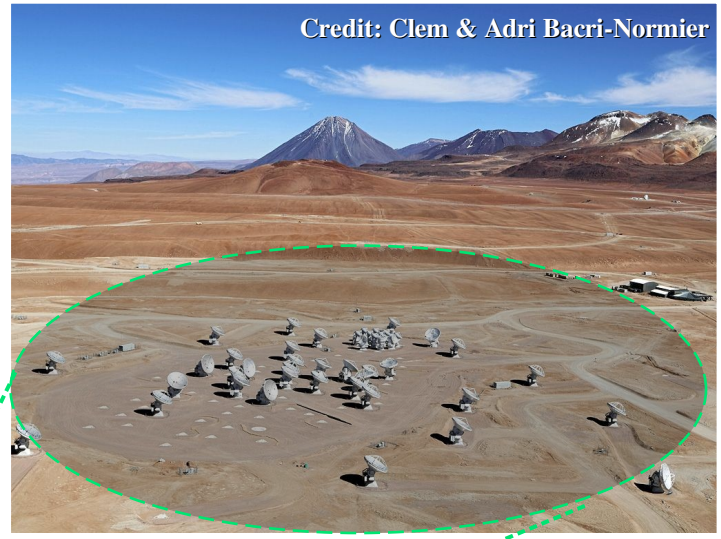
- PI: Olivier Le Fèvre
- 70h of **[CII] + continuum observations** in ALMA Band 7 (275 – 373 GHz)
- **118 normal star-forming galaxies** (SFGs) drawn from the COSMOS and Extended Chandra Deep Field South (E-CDFS) fields
- $4.4 < z_{spec} < 5.9$ with VUDS and DEIMOS 10K
- "main-sequence" galaxies SFR > 10 $M_\odot$/yr & $9 < \log(M_*/M_\odot) < 11$

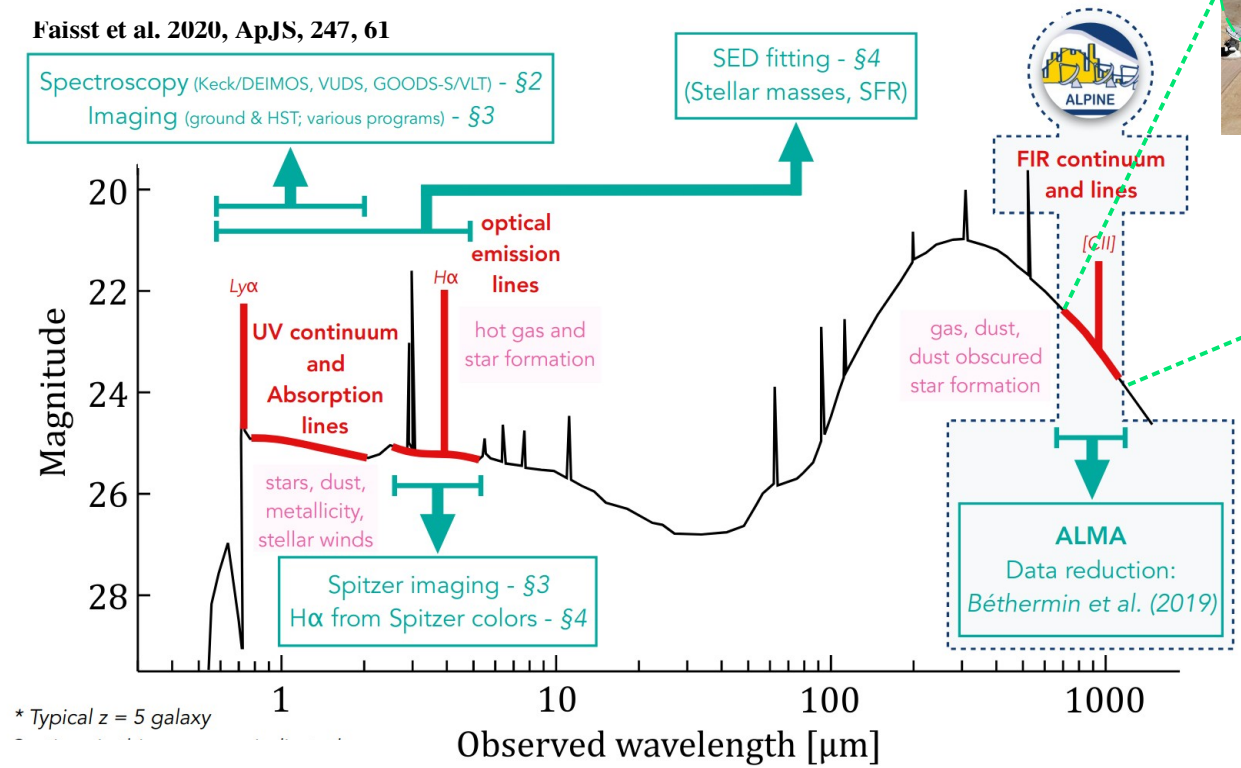




ALPINE: the ALMA Large Program to INvestigate [CII] at Early times







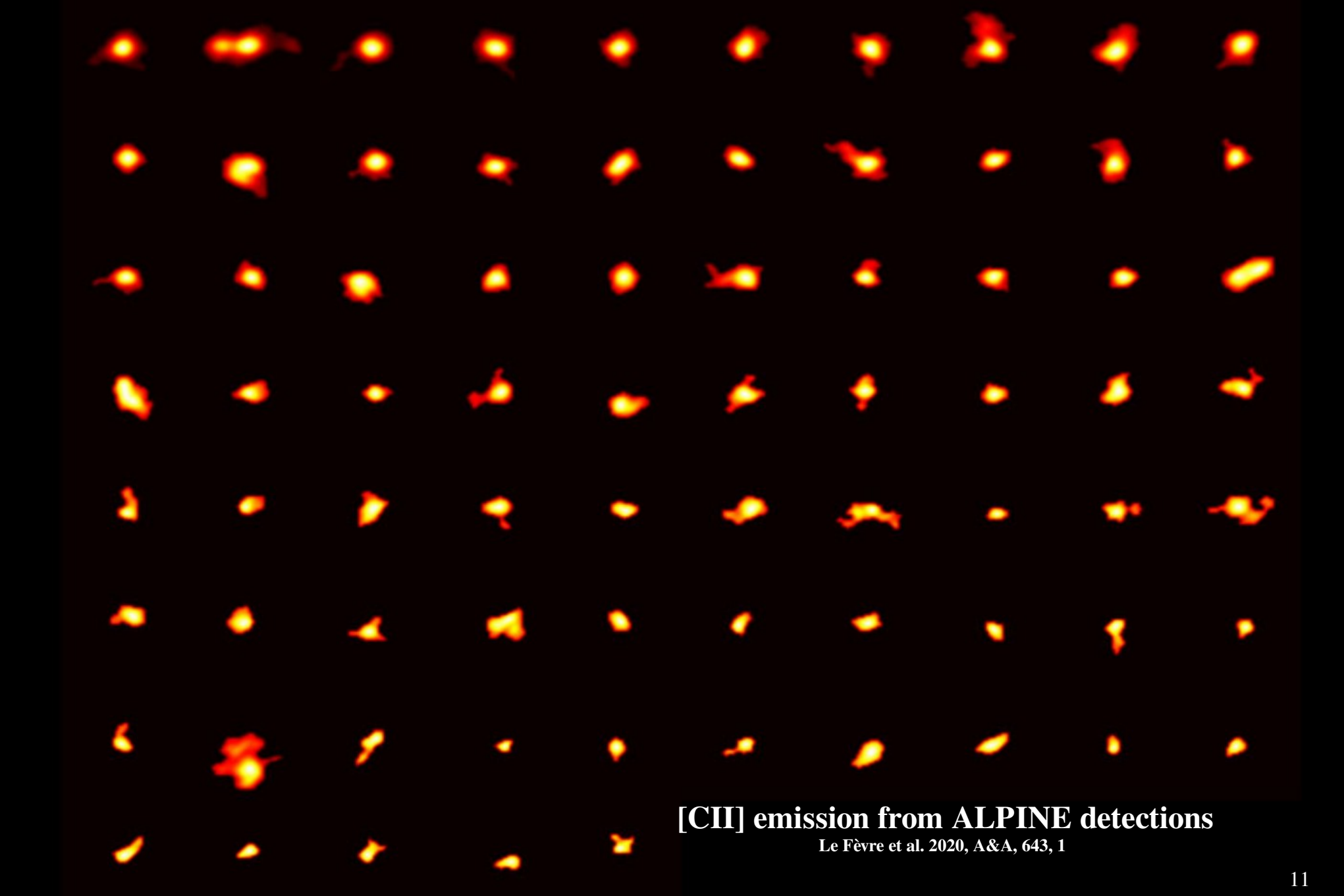
[CII] line @ 158 μm rest-frame:

one of the strongest FIR line;

mainly excited in photo-dissociation regions (PDRs);

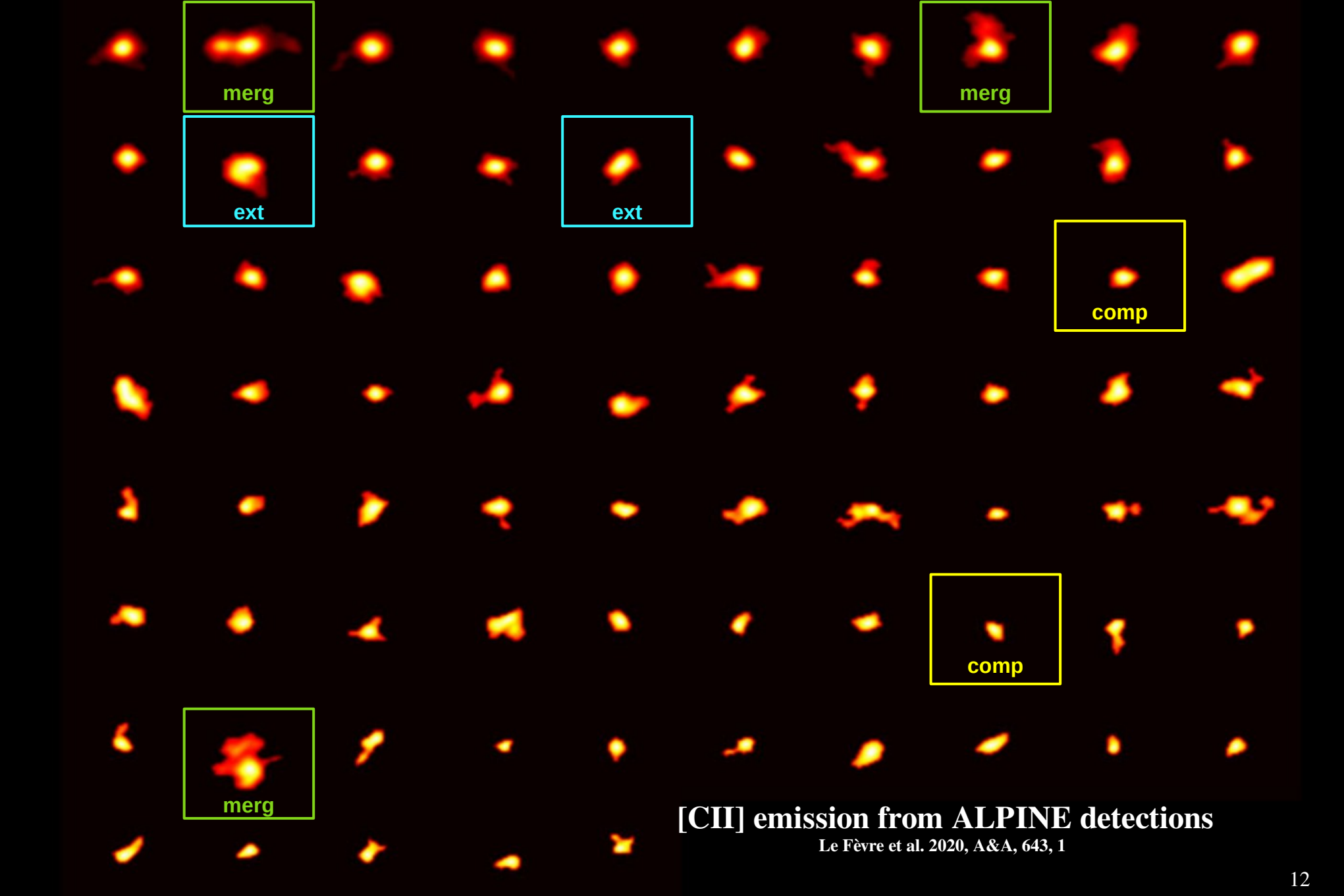
poorly affected by dust;

near the peak of FIR emission



[CII] emission from ALPINE detections

Le Fèvre et al. 2020, A&A, 643, 1



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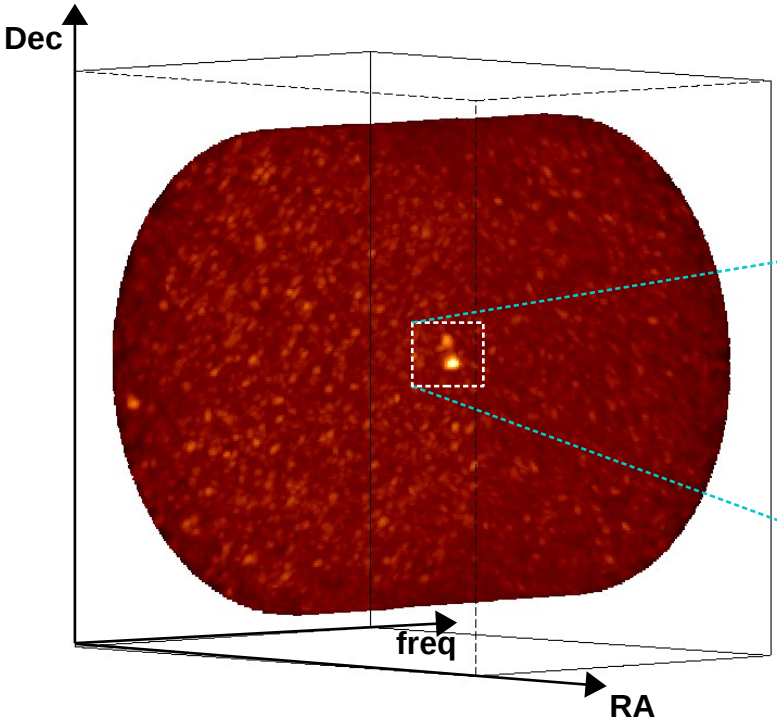
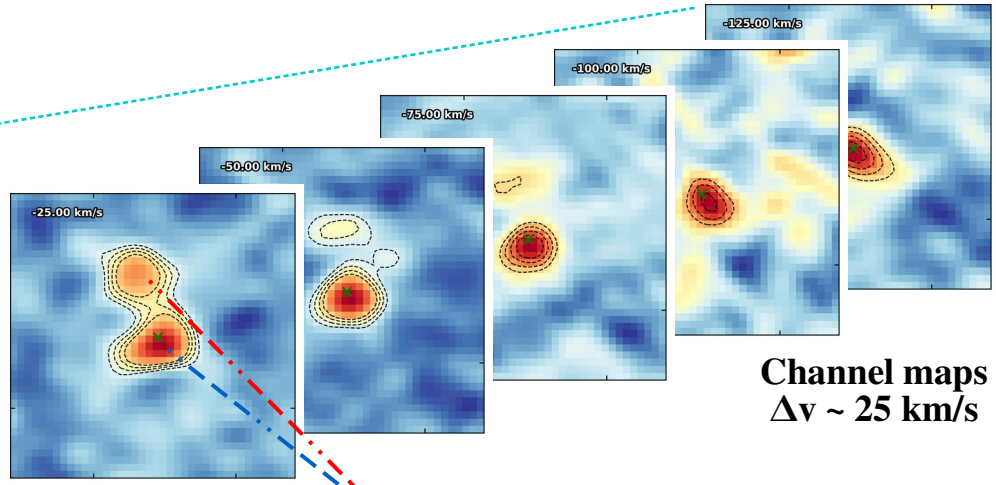


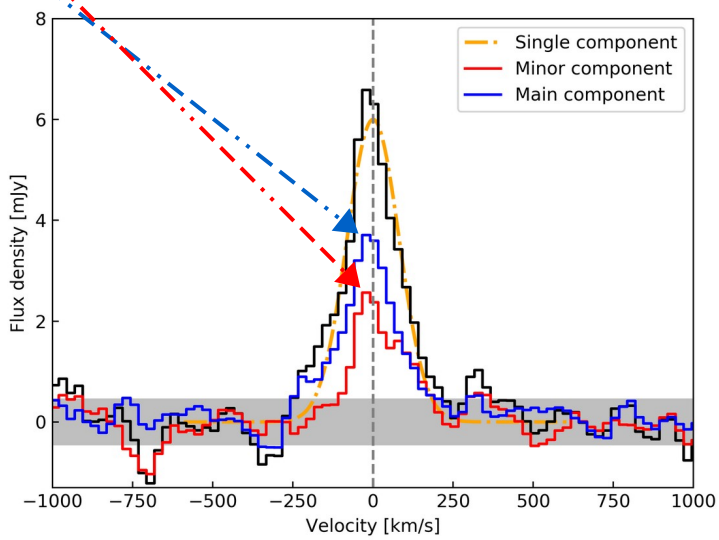


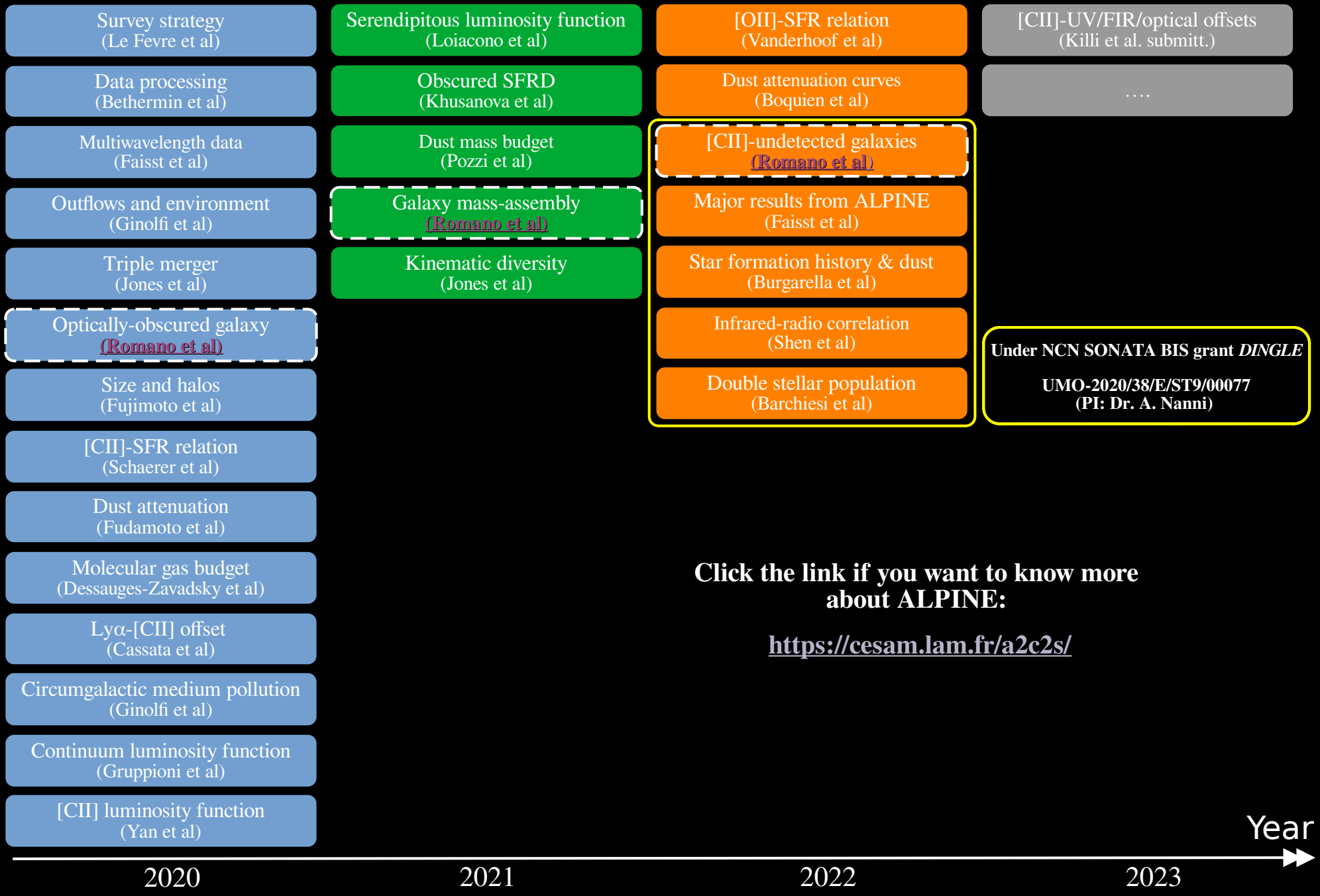
Channel maps
Δv ~ 25 km/s

118 ALPINE targets

75 [CII] detections (S/N > 3.5)

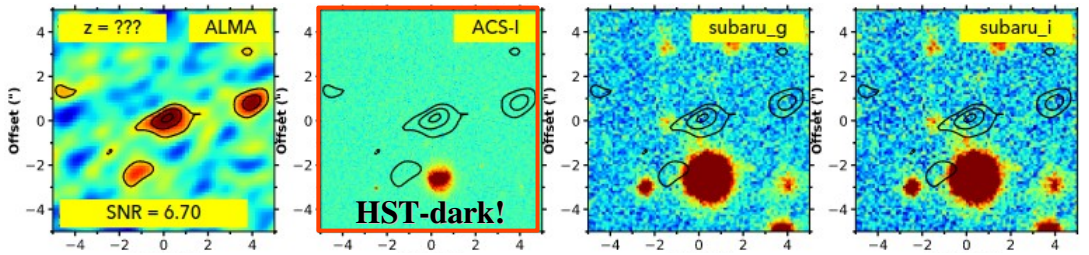
43 [CII] non-detections



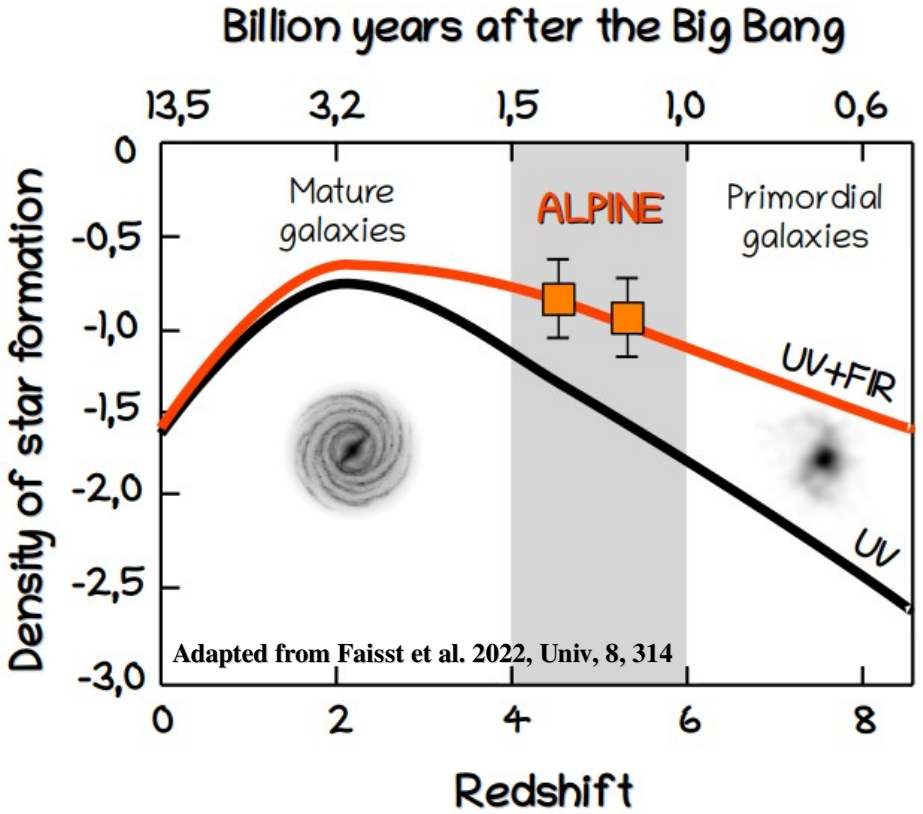

Survey strategy
(Le Fevre et al)
Data processing
(Bethermin et al)
Multiwavelength data
(Faisst et al)
Outflows and environment
(Ginolfi et al)
Triple merger
(Jones et al)
Optically-obscured galaxy
(Romano et al)
Size and halos
(Fujimoto et al)
[CII]-SFR relation
(Schaerer et al)
Dust attenuation
(Fudamoto et al)
Molecular gas budget
(Dessauges-Zavadsky et al)
Lyα-[CII] offset
(Cassata et al)
Circumgalactic medium pollution
(Ginolfi et al)
Continuum luminosity function
(Gruppioni et al)
[CII] luminosity function
(Yan et al)
Serendipitous luminosity function
(Loiacono et al)
Obscured SFRD
(Khusanova et al)
Dust mass budget
(Pozzi et al)
Galaxy mass-assembly
(Romano et al)
Kinematic diversity
(Jones et al)
[OII]-SFR relation
(Vanderhoof et al)
Dust attenuation curves
(Boquien et al)
[CII]-undetected galaxies
(Romano et al)
Major results from ALPINE
(Faisst et al)
Star formation history & dust
(Burgarella et al)
Infrared-radio correlation
(Shen et al)
Double stellar population
(Barchiesi et al)
[CII]-UV/FIR/optical offsets
(Killi et al. submitt.)
....
Under NCN SONATA BIS grant DINGLE
UMO-2020/38/E/ST9/00077
(PI: Dr. A. Nanni)
Click the link if you want to know more about ALPINE:
https://cesam.lam.fr/a2c2s/
Year
2020
2021
2022
2023

General results: more dust than expected!

$$SFR_{TOT} = SFR_{UV} + SFR_{FIR}$$

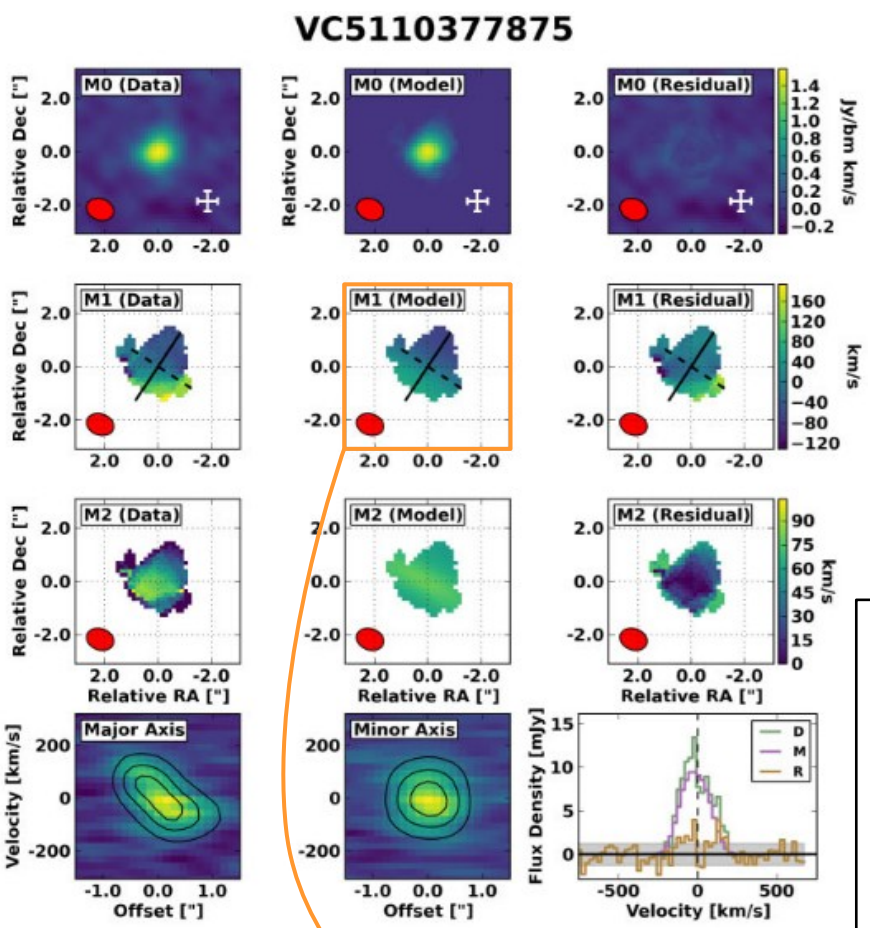


Gruppioni et al. 2020, A&A, 643, 8

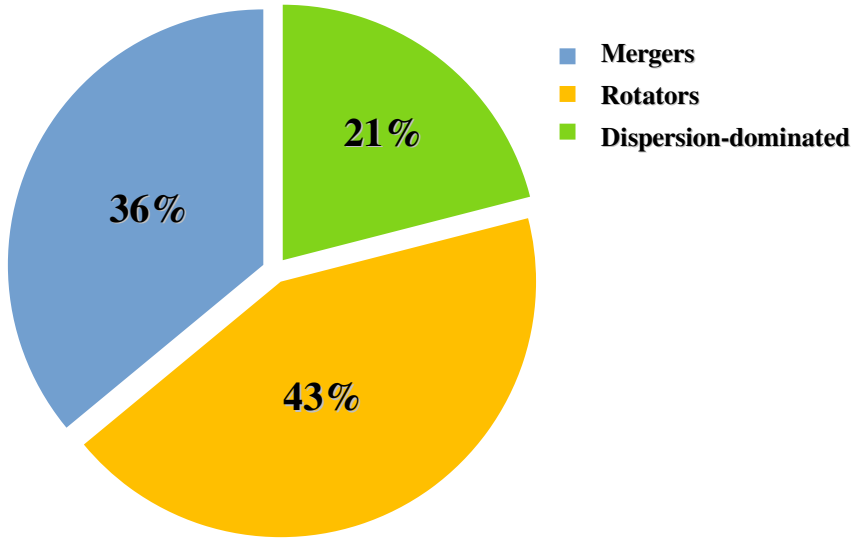


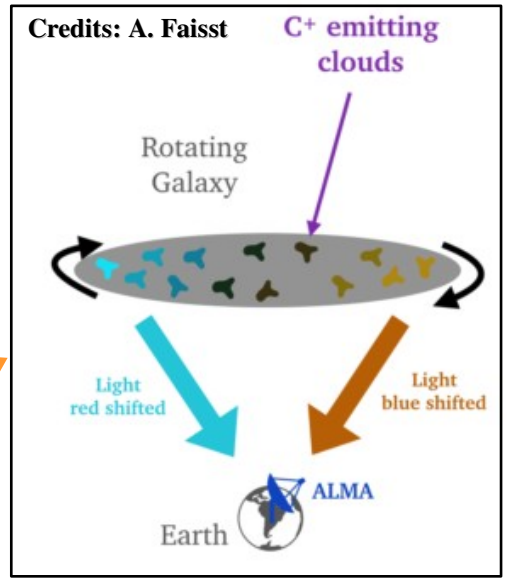
- Discovery of optically-dark galaxies missed by previous UV/optical surveys
- HST-dark galaxies contribute ~17% to the total SFRD at z>3
- SFRD almost constant between redshift 2 and 6
- Large difference between ALPINE and UV/optical data, reaching a factor of 10 at z~6
- Need to revise galaxy formation models and simulations which are not able to predict such a high amount of SFR in dusty galaxies at high-z

General results: morpho-kinematic diversity of primordial galaxies



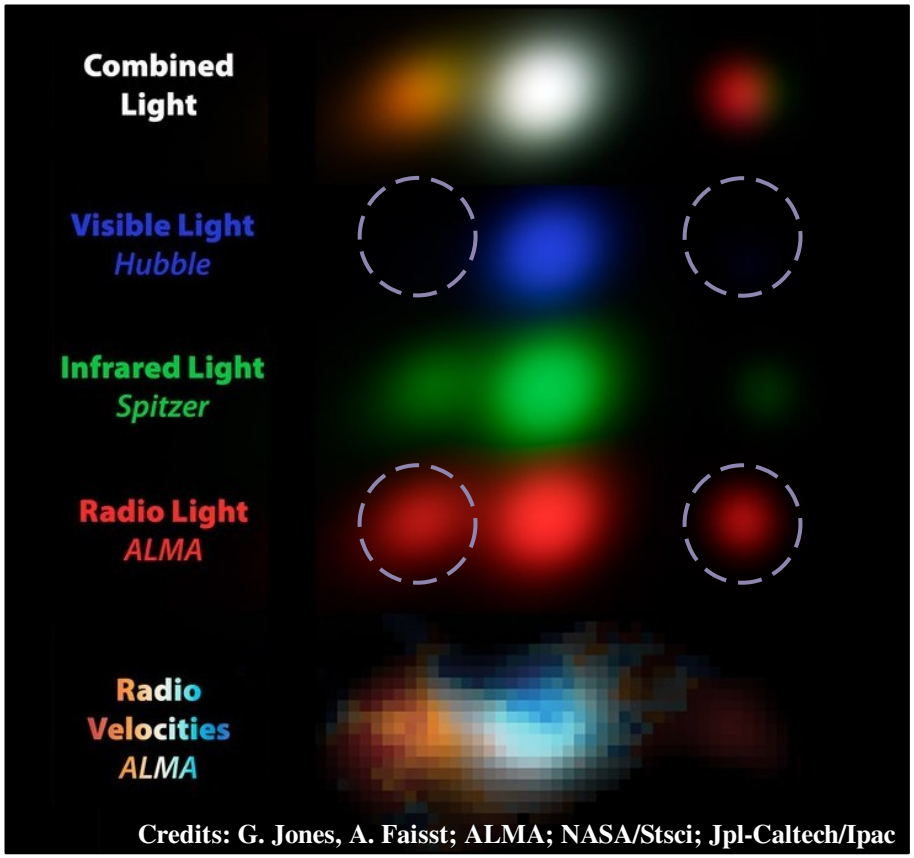
Jones et al. 2021, MNRAS, 507, 3540

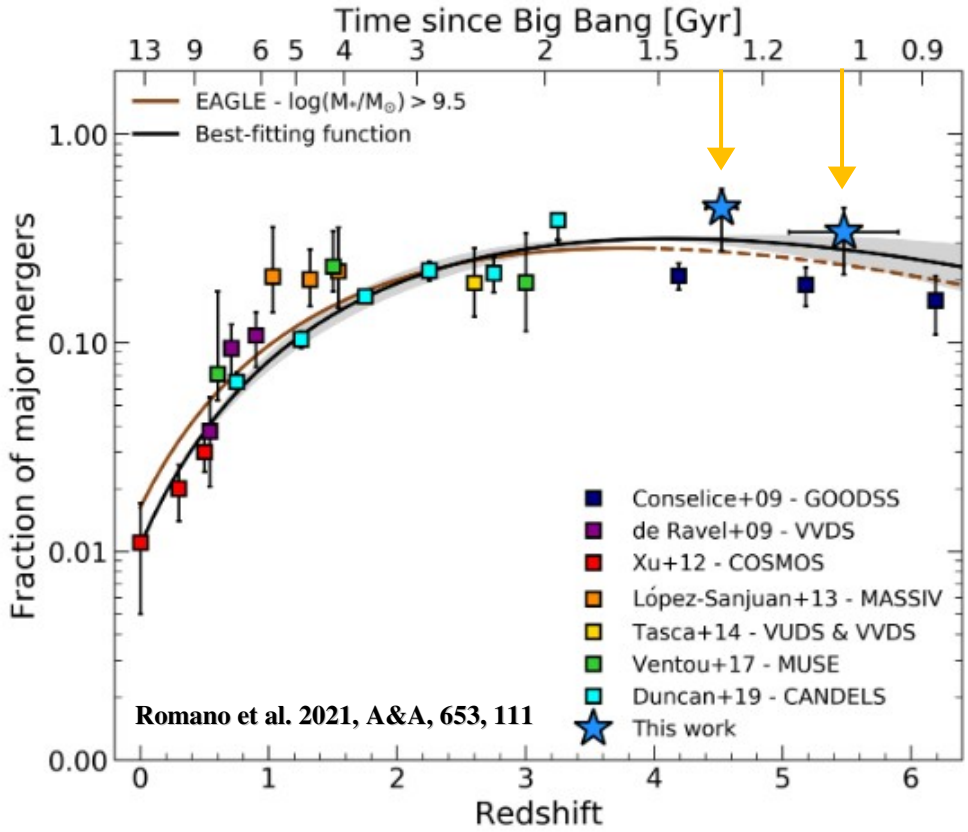




- Evidence of morpho-kinematic diversity in primordial galaxies, at only 1-1.5 Gyr after the Big Bang
- High number of mergers as compared to local Universe
- More rotating galaxies than expected

General results: mergers as a mechanism of galaxy mass-assembly





- A large fraction (~40%) of major mergers is found in ALPINE (two times higher than at z~2 by using optical data)
- Hints that optical survey could miss dust-obscured meerger components, which are bright in the sub-mm
- The contribution of major mergers to the cosmic star-formation rate density varies from 5% to 30%, depending on the assumed merger timescale

[CII] as a star-formation tracer in the early Universe

$$\log(L_{[CII]}/L_{\odot}) = a + b \times \log(SFR/M_{\odot}\ yr^{-1})$$

$a = 7.06 \pm 0.33$, $b = 1.00 \pm 0.04$ ⇢ **Local**

De Looze et al. 2014, A&A, 568, 62

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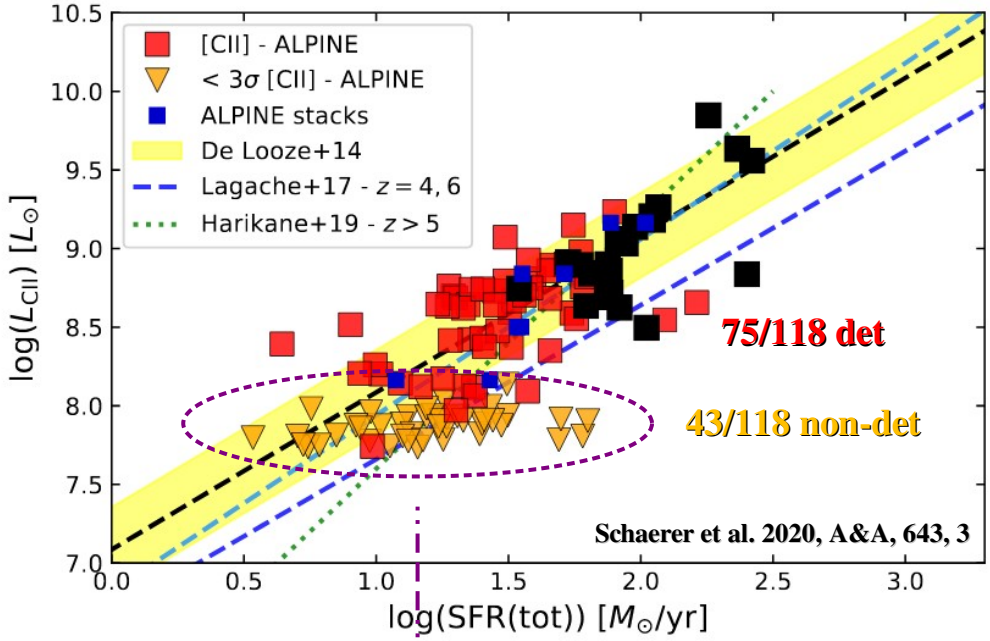
De Looze et al. 2014, A&A, 568, 62

$a = 6.61 \pm 0.20$, $b = 1.17 \pm 0.12$ ⇢ **ALPINE**
Schaerer et al. 2020, A&A, 643, 3

$L_{[CII]}$-SFR relation from ALPINE is comparable to the local one

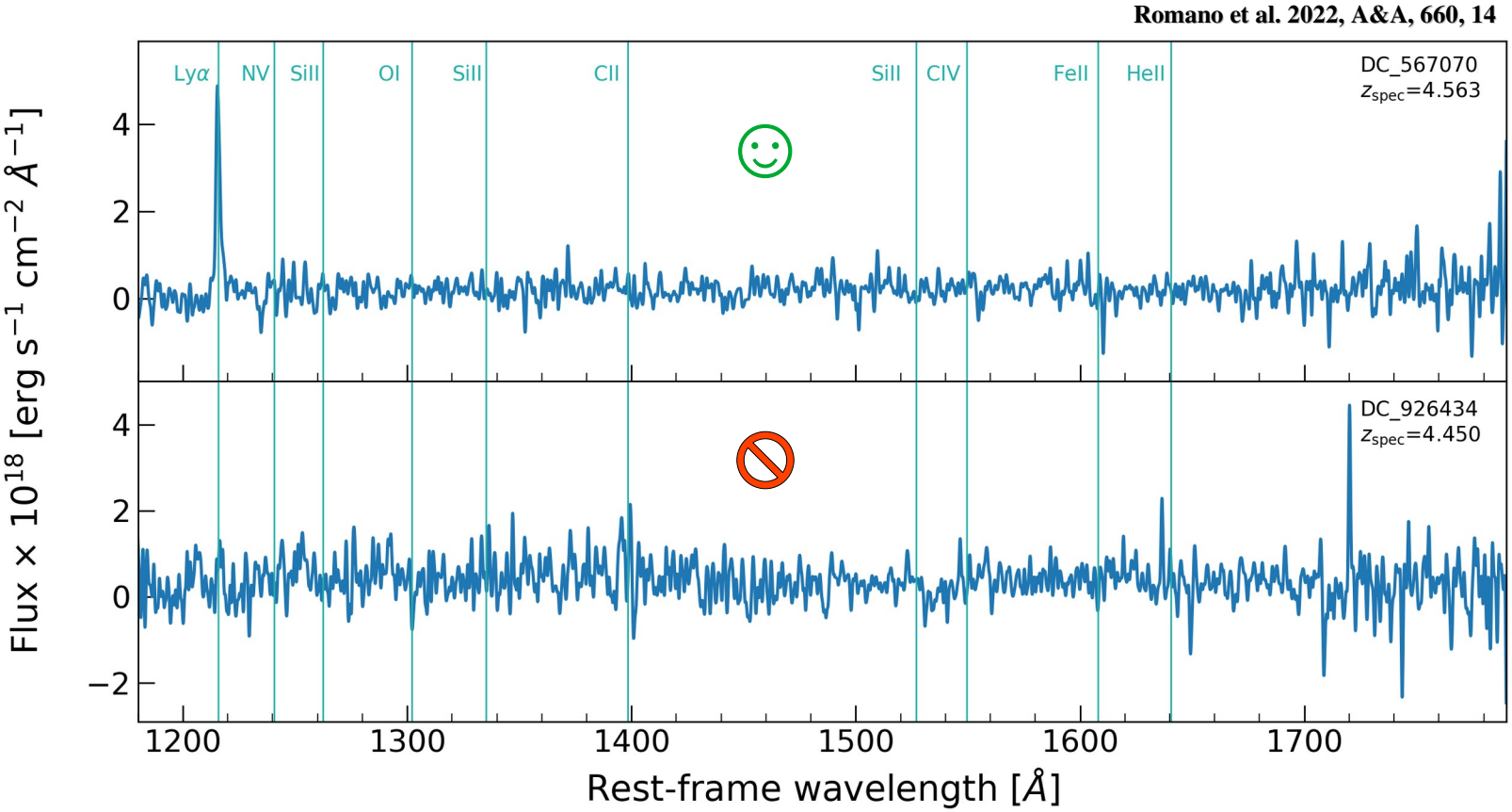
↓

[CII] is a good tracer of SFR up to z~6



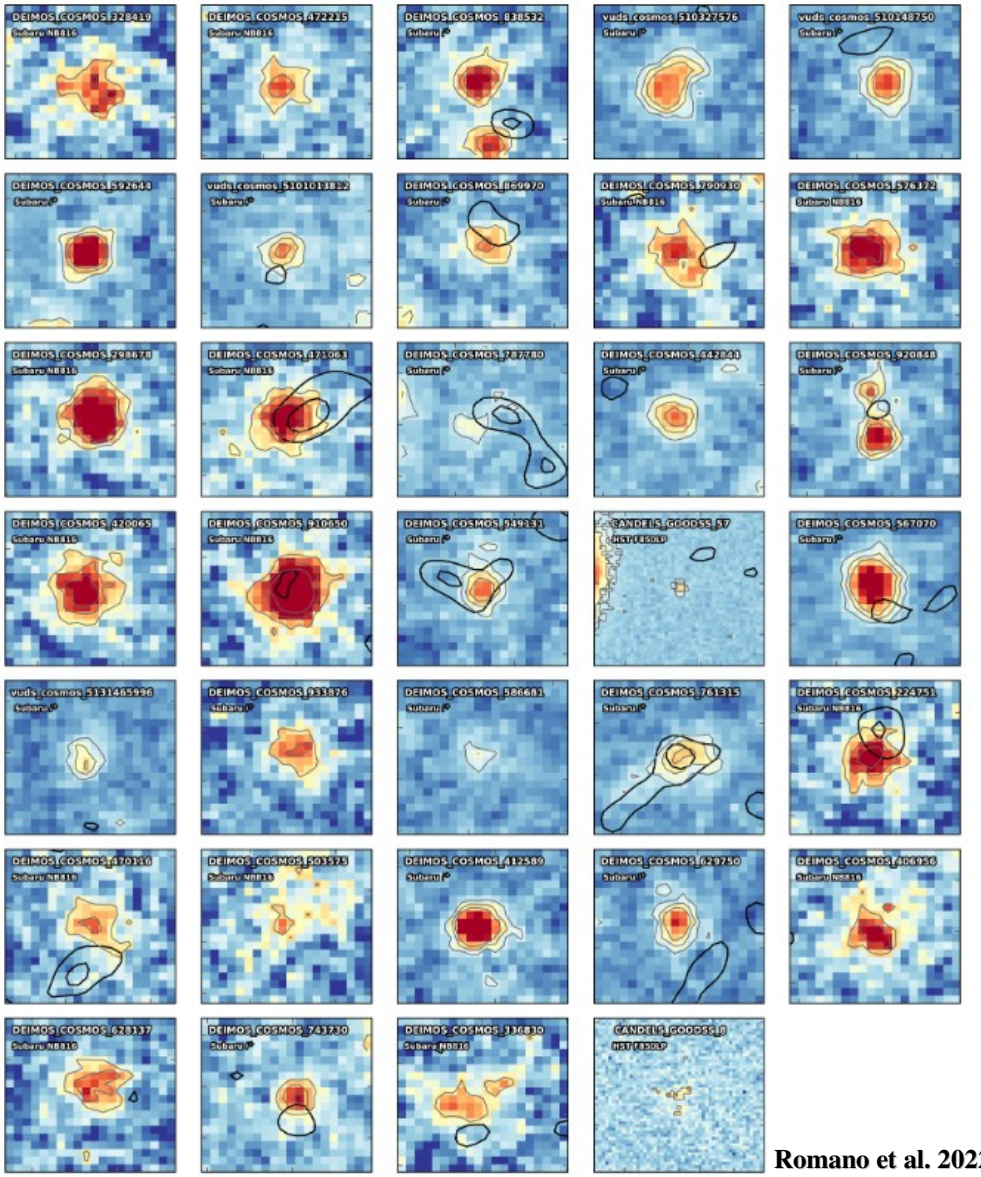
Uncertainties deriving from [CII] non-detections...what about these sources?

[CII] as a star-formation tracer in the early Universe

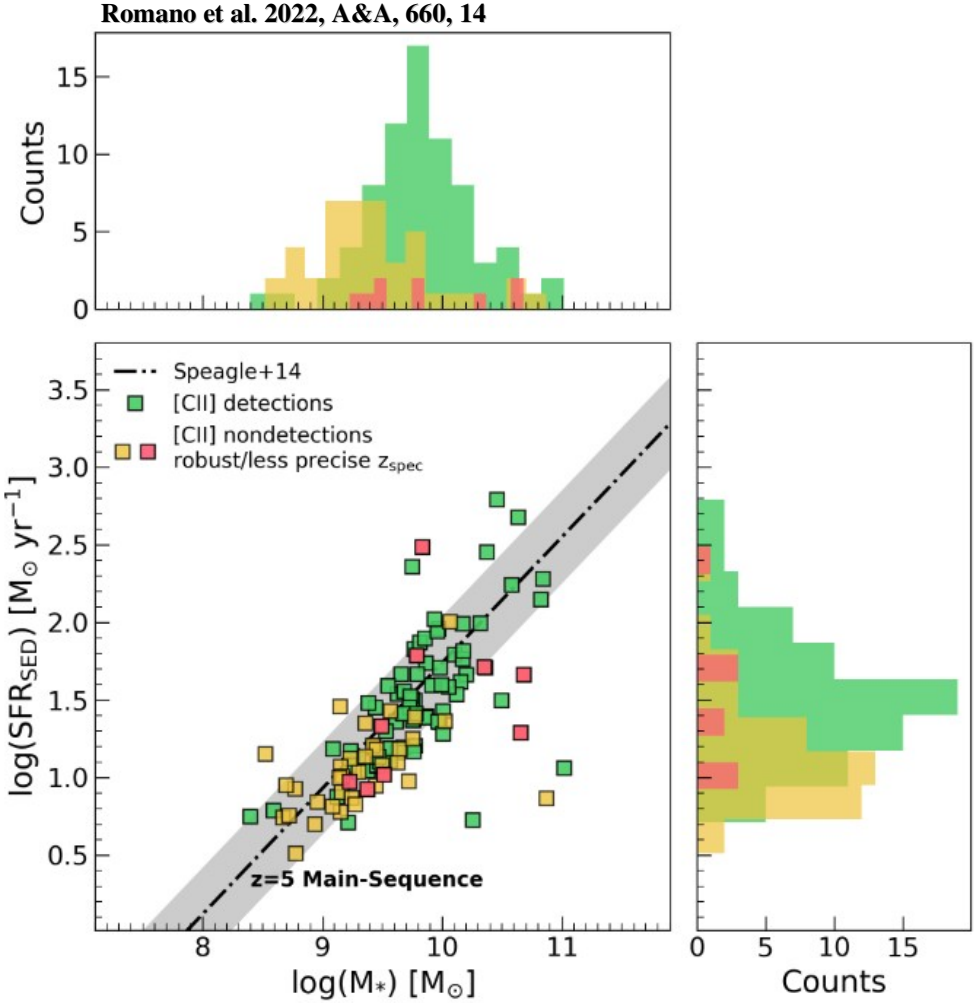


Rest-frame UV spectra

[CII] as a star-formation tracer in the early Universe



Romano et al. 2022, A&A, 660, 14



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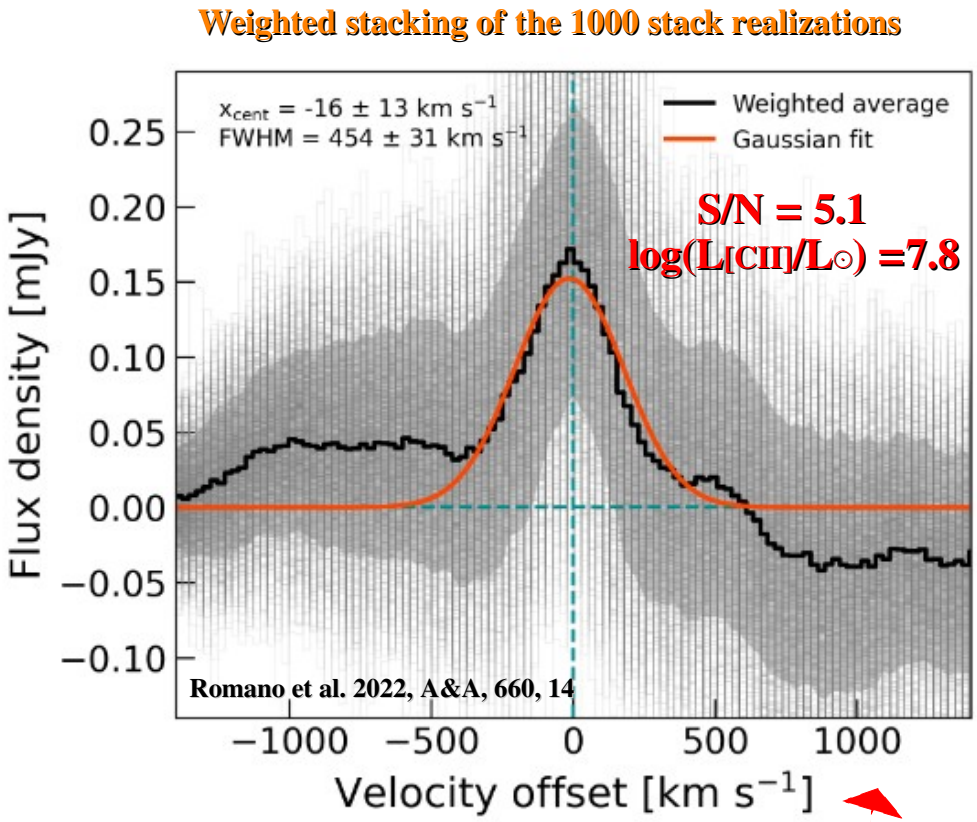
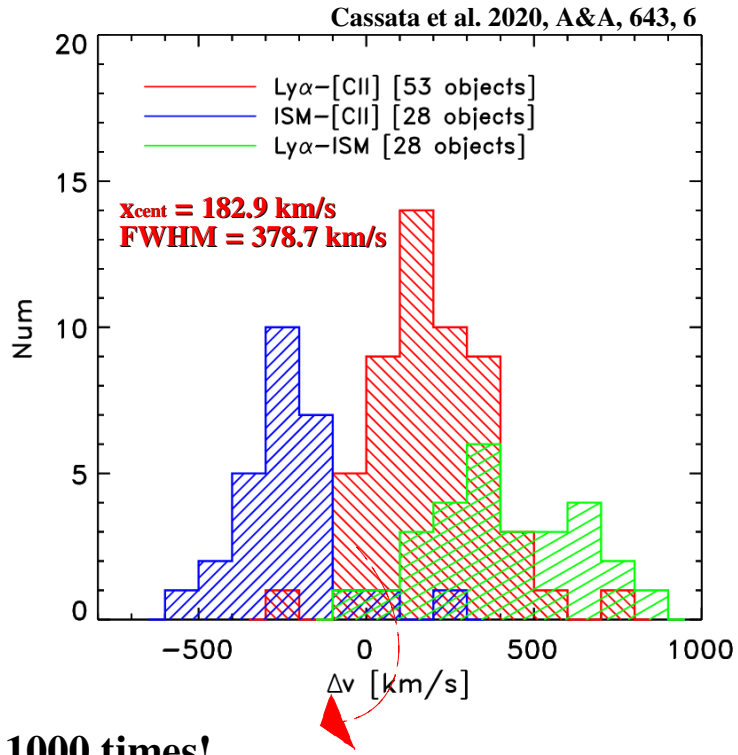




$$L_{[CII]} = 1.04 \times 10^{-3} S_{[CII]} \Delta v D_L^2 \nu_{obs} [L_\odot]$$

0. Do it 1000 times!

1. $\Delta v_{Ly\alpha}$ random extraction for each spectrum

2. Mean stack

3. If FWHM < 400 km/s:

ok

Else:

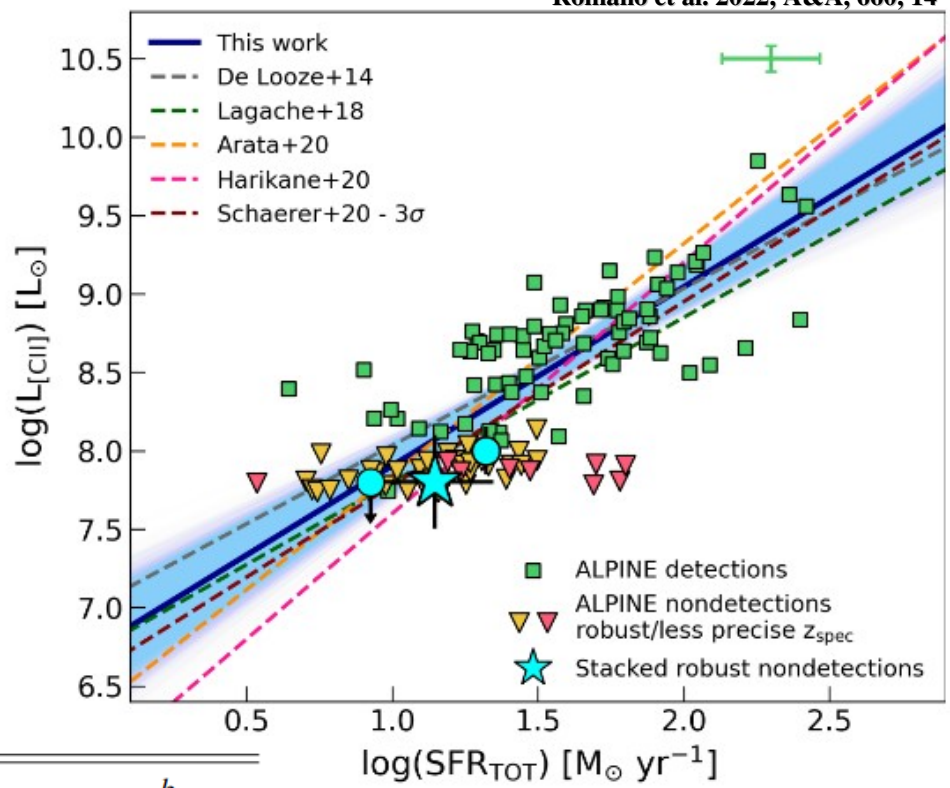
repeat

[CII] as a star-formation tracer in the early Universe

$$\log\left(L_{[CII]}/L_{\odot}\right) = a + b \times \log\left(SFR/M_{\odot}yr^{-1}\right)$$

[CII] luminosity as a function of SFR

Romano et al. 2022, A&A, 660, 14



Literature (1)	Sample (2)	Redshift (3)	a (4)	b (5)
De Looze et al. (2014)	HII/starburst	<0.5	7.06 ± 0.33	1.00 ± 0.04
Lagache et al. (2018)	G.A.S. + CLOUDY	4 – 6	6.75 ± 0.07	1.05 ± 0.07
Arata et al. (2020)	GADGET-3 + ART^2	>6	6.38	1.47
Harikane et al. (2020)	LBGs/SMGs	6 – 9	6.00	1.60
Schaerer et al. (2020)	ALPINE (3σ limits)	4 – 6	6.61 ± 0.20	1.17 ± 0.12
This work	ALPINE det + stacked non-det	4 – 6	6.76 ± 0.17	1.14 ± 0.11

Summary

ALPINE has opened a new window on the study of the high-z Universe

- **Lot of dust in the early Universe, more than what expected**
- **A large population of dust-obscured galaxies at z>4 is being now observed in the sub-mm regime → large contribution to global SFRD**
- **Mergers could provide a significant contribution to the galaxy mass assembly at all epochs**
- **[CII] can trace the star formation up to z~6**

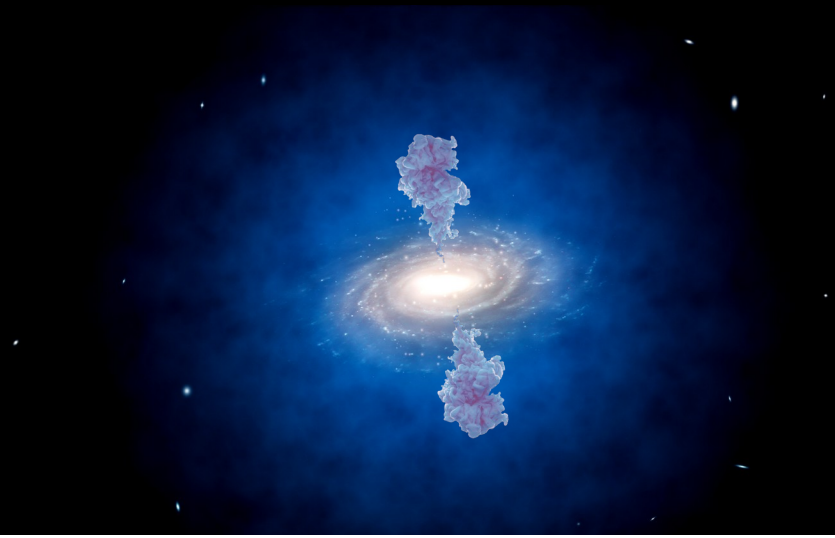
New results are coming…


Thanks for the attention!

EXTRAS

Galactic outflows in local galaxies

Further constraints on the baryon cycle and IGM enrichment of high-z galaxies by studying their analogs in the local universe, e.g. dwarf low-metallicity galaxies



Herschel Space Observatory

Astronomy & Astrophysics manuscript no. aanda
June 21, 2023

Star-formation driven outflows in local dwarf galaxies as revealed from [CII] observations by *Herschel*⋆

M. Romano⋆⋆[1,2], A. Nanni[1,3], D. Donevski[1,4,5], M. Ginolfi[6], G. C. Jones[7], I. Shivaei[8], Junais[1], D. Sa[illegible][10], and P. Sawant[1]

Coming soon...

APPLICATION FOR OBSERVING TIME

Principal Investigator: Michael Romano

ID: *110.2417* · **Type:** Normal · **Cycle:** P110 · **Status:** Valid

TITLE: **Probing the dust and metal content of primordial star-forming galaxies through rest-frame UV-to-FIR spectroscopy**

Scheduling and Feasibility Comments (per run)

Run	Instrument	Obs. Mode	Rank Class	From - To Noon	Feasibility Comment	Scheduling Comment	Final Outcome
Run A	KMOS	SM	B	-		In period 110 the number of requested nights on UT1 exceeded the available time by a factor of 5.0. Ranking: This run has been ranked in the 2nd quartile of all runs at this telescope (250) and in the 2nd quartile of all non-triaged runs requested in this period (1562).	APPROVED

[OII] observations in a sample of ~90 SFGs at z~4.5 with the K-band Multi Object Spectrograph (KMOS) at the Very Large Telescope at Cerro Paranal (Chile):

Approved in ESO Cycle 110 (110.241; PI: M. Romano) for a total of 22 hours of observation.

Main objectives:

- Star formation, dust attenuation, & metal enrichment
- Systemic redshift
- Environment