Observatoire astronomique de Strasbourg | ObAS

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Studying star-forming galaxies through clustering and polarization with AtLAST

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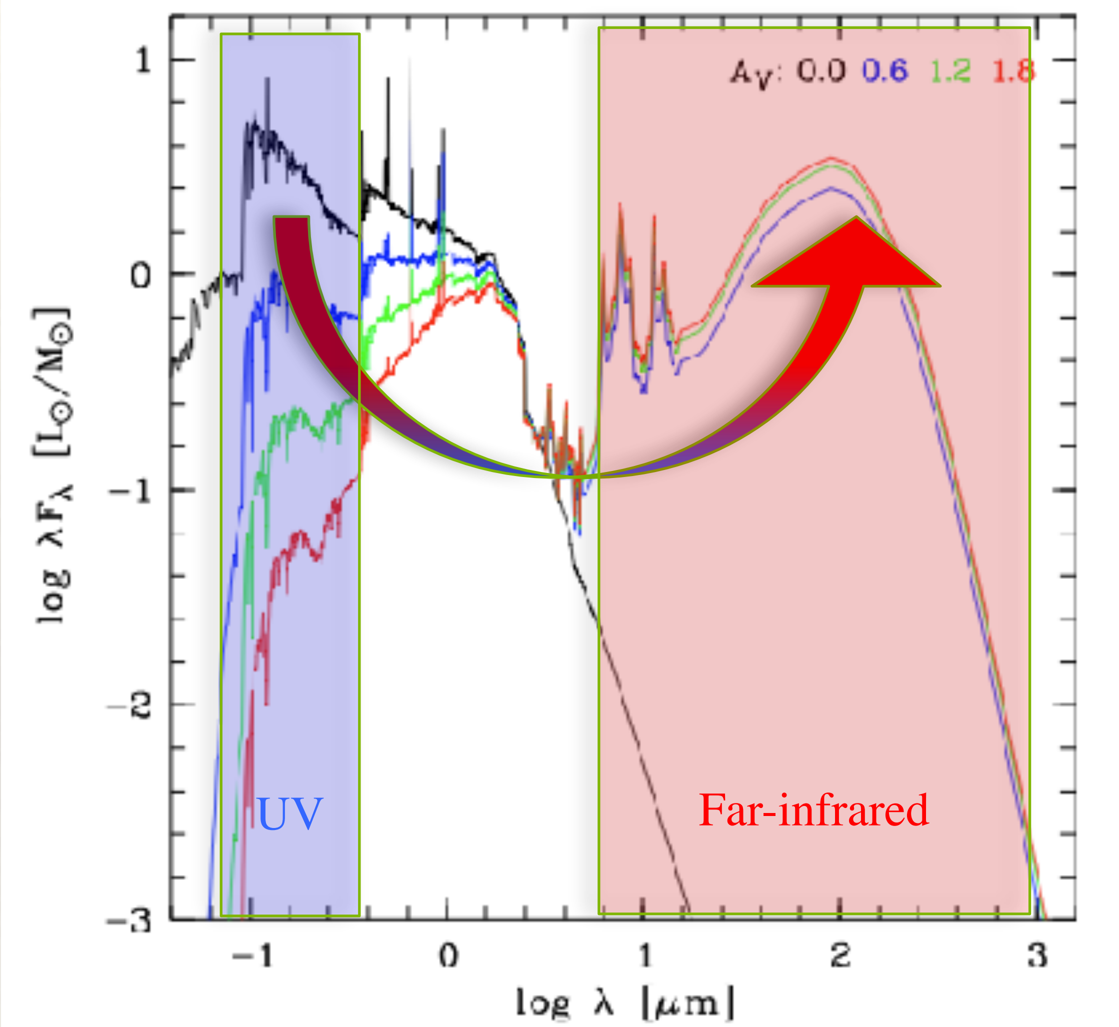
Obscured star formation rate

- Massive young short-life stars produce a strong UV emission
- BUT, this emission is very efficiently absorbed by dust
- Dusty systems: most of UV photons are absorbed by dust and re-emitted in the far IR
- We need both UV and far-IR (dust obscured) to measure SFR:

$$\mathrm{SFR_{tot}} = \mathrm{SFR_{IR}} + \mathrm{SFR_{UV}} = \kappa_{\mathrm{IR}} L_{\mathrm{IR}} + \kappa_{\mathrm{FUV}} L_{\mathrm{FUV}}$$

Obscured star formation

Unobscured star formation

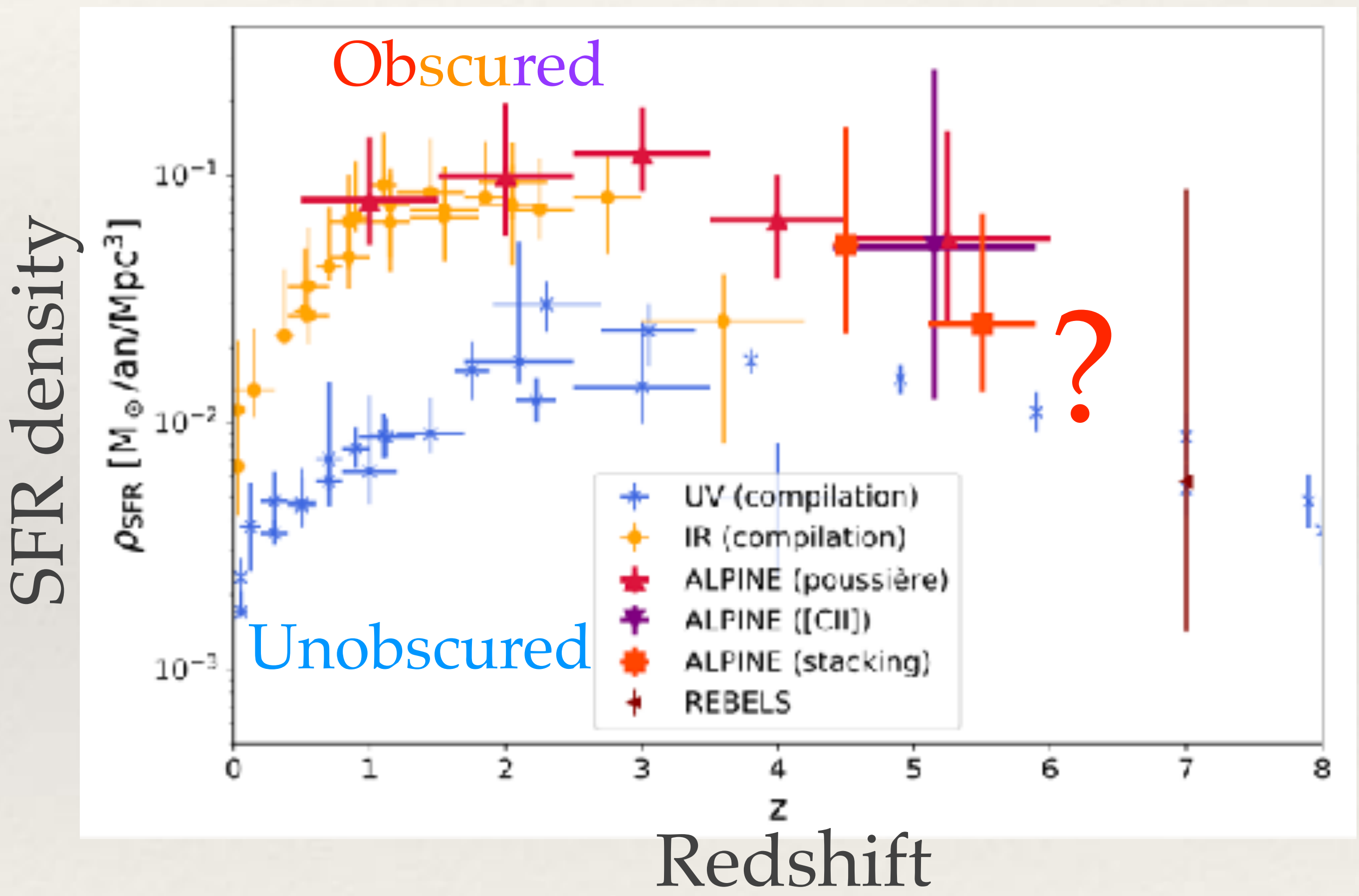


Spectral energy distribution (SED) of a galaxy (Noll+09)

The high-redshift dusty Universe

- Star formation rate density history: amount of stars per comoving volume as a function redshift (left panel).
- Up to z~5, obscured star formation (far-IR) larger than unobscured star formation (UV).
- Long wavelengths are thus key to probe the high-z star formation.

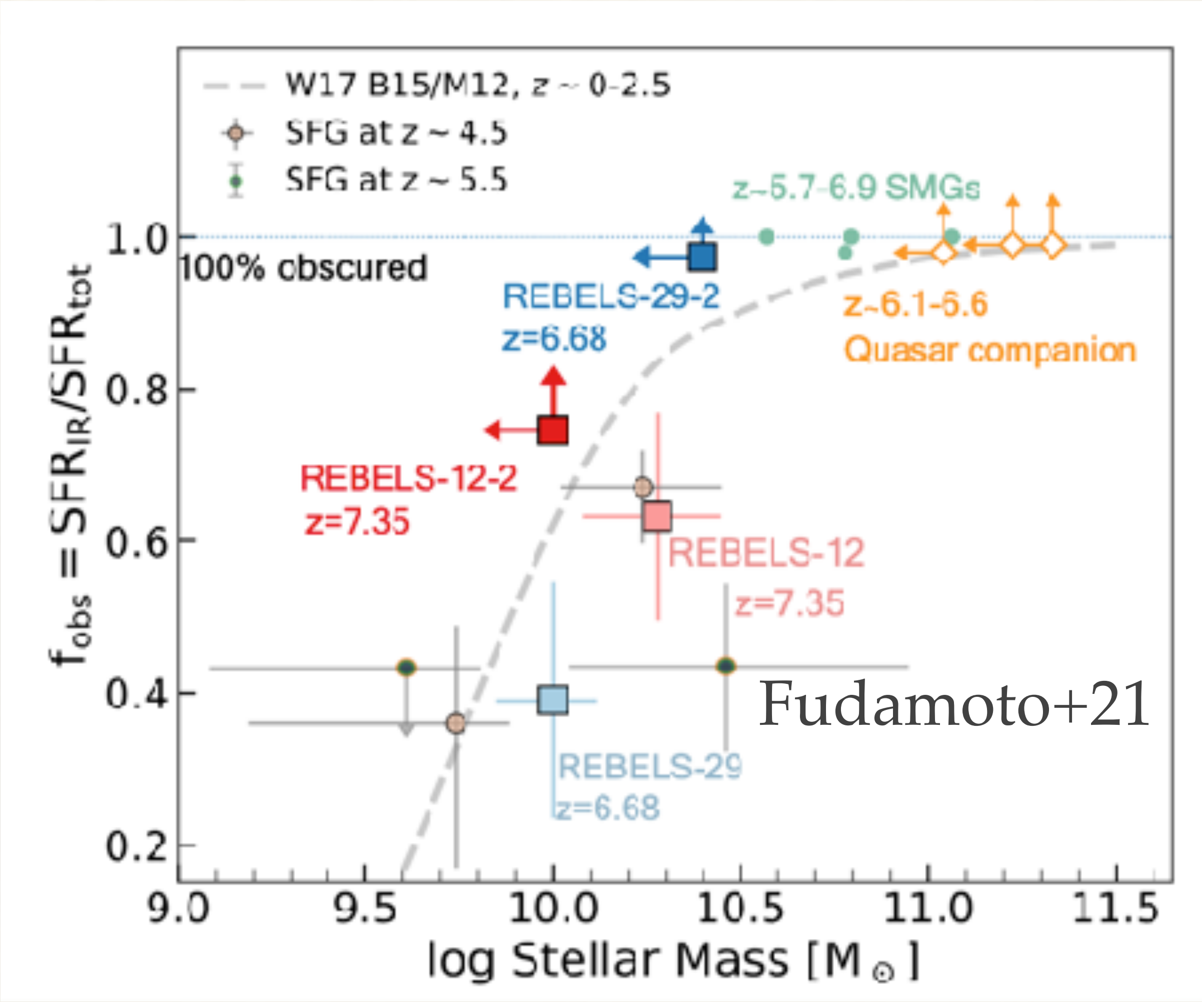
Adapted from Madau+14



Early massive galaxies are dusty…

- The mean dust-obscured fraction increases steeply with stellar mass.
- Even at high redshift, the most massive galaxies are VERY dust obscured!
- Sub-mm observations are thus essential to **understand early star formation in massive systems**.

Dust-obscured fraction



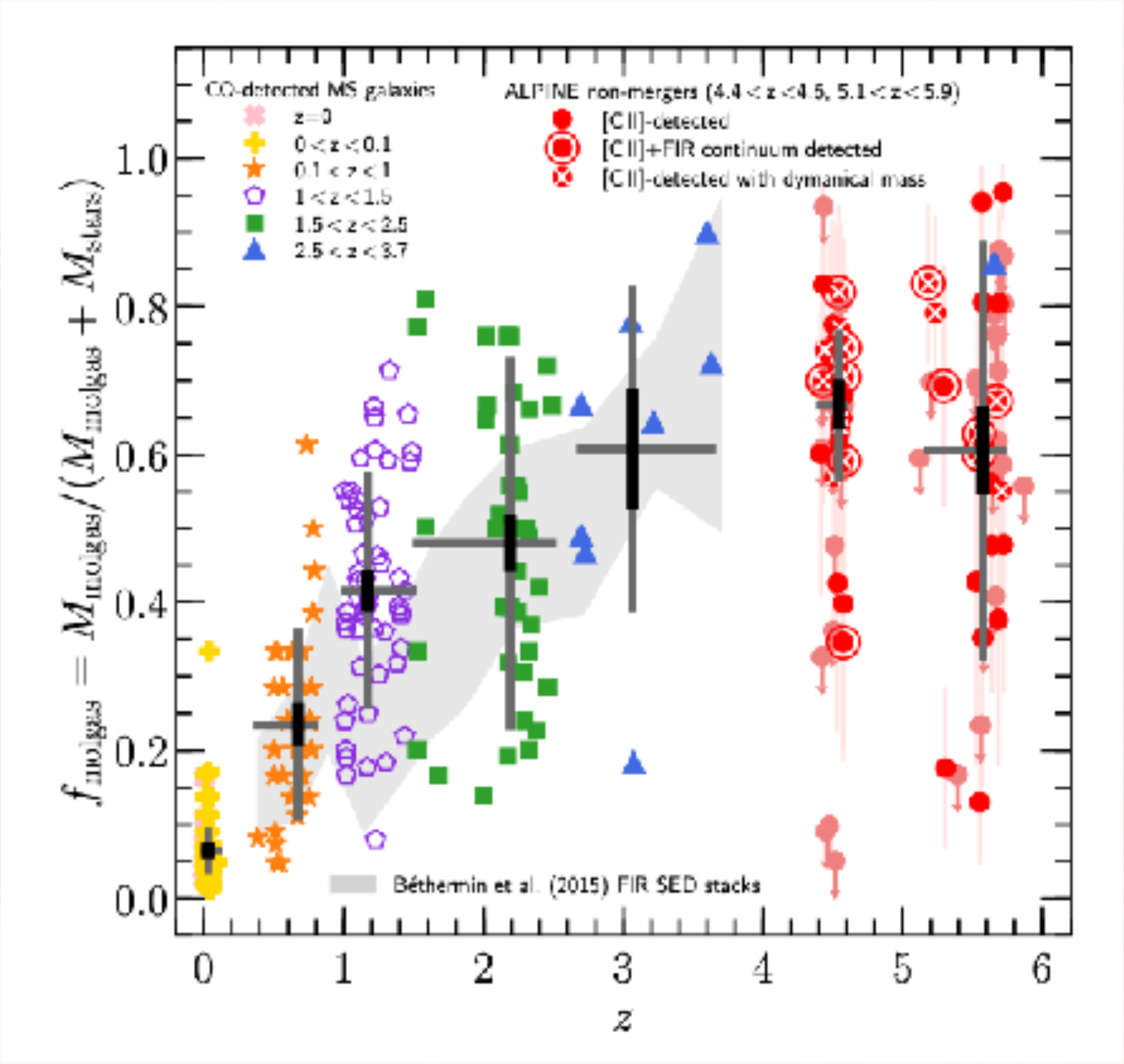
Stellar mass

… and gas rich!

Dessauges-Zavadsky+20

- Observations up to z~6: increasing gas fraction with increasing redshift.
- Large gas reservoirs drives the high star formation rates.

Gas fraction



Redshift

Observing high-z cold gas and dusty star formation with previous and current facilities

Space far-infrared telescopes

+ Peak of the dust emission up to z~5
+ Excellent mapping speed in photometry
- Limited spectroscopy at high z
- Low angular resolution (confusion)

Ground-based (sub-)mm single-dish telescopes

+ Dust emission in photometry (Rayleigh-Jeans)
+ Mapping speed in photometry
- Limited sensitivity in spectroscopy
- Low angular resolution

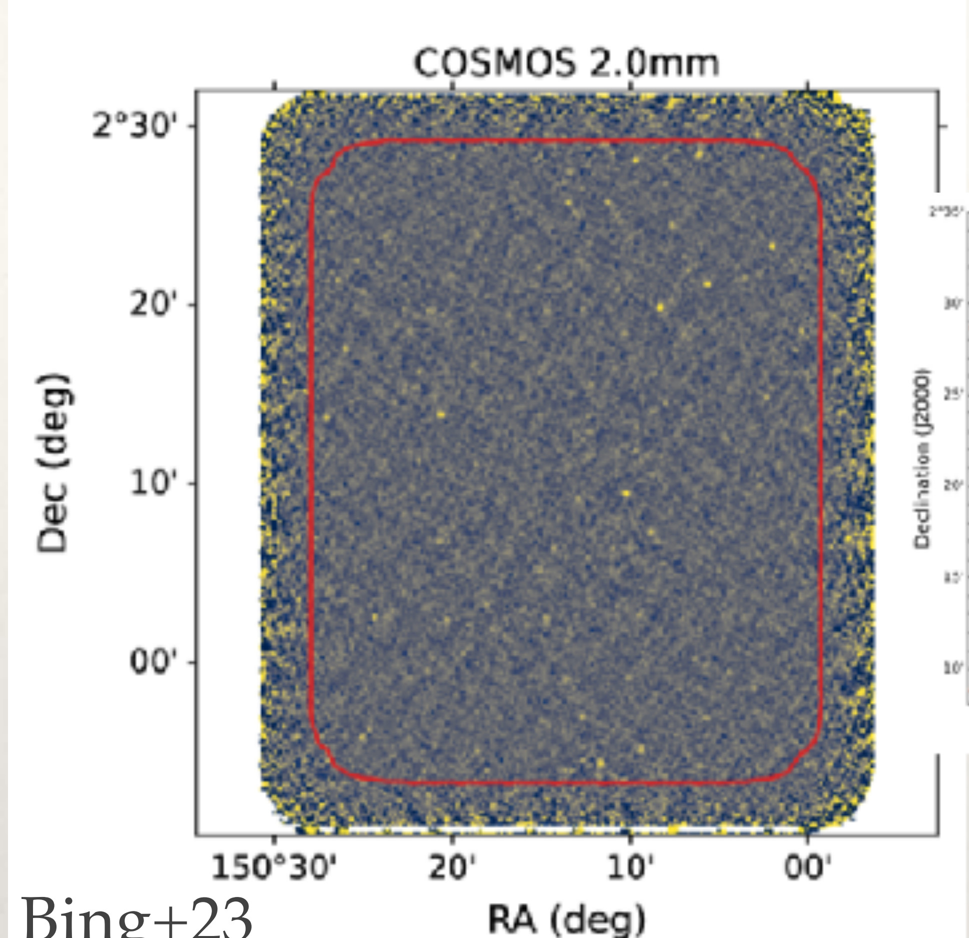
Sub-mm interferometers

+ Excellent sensitivity in both continuum and spectroscopy
+ Tunable angular resolution (antenna configuration)
- Small field of view
- Miss large angular scales

Future large ground-based single-dish telescope: strength and weaknesses

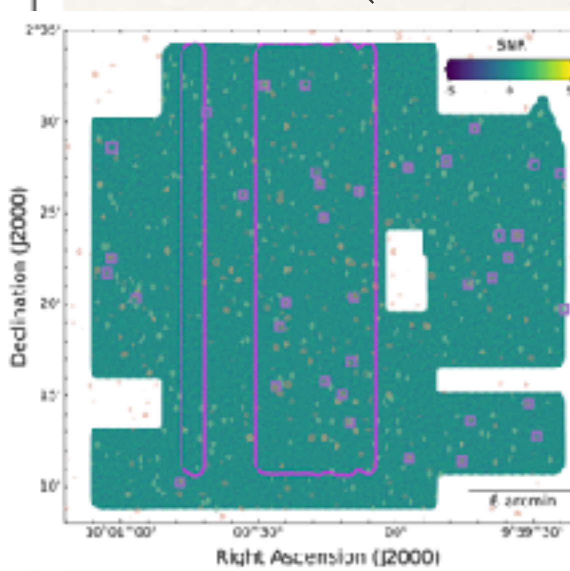
- **Strengths**:
  - mapping speed is excellent: for instance N2CLS@IRAM30m detects as many sources per hour as ALMA for a blank 2mm survey (Béthermin+ to be sub.).
  - can cover very large areas to probe large-scale structures and obtain statistic on rare massive systems.
- **Weaknesses**:
  - potential resolution effects especially for large beams (e.g., Béthermin+17, Bing+23)
  - maximal sensitivity is limited by confusion

N2CLS survey (IRAM 30m)

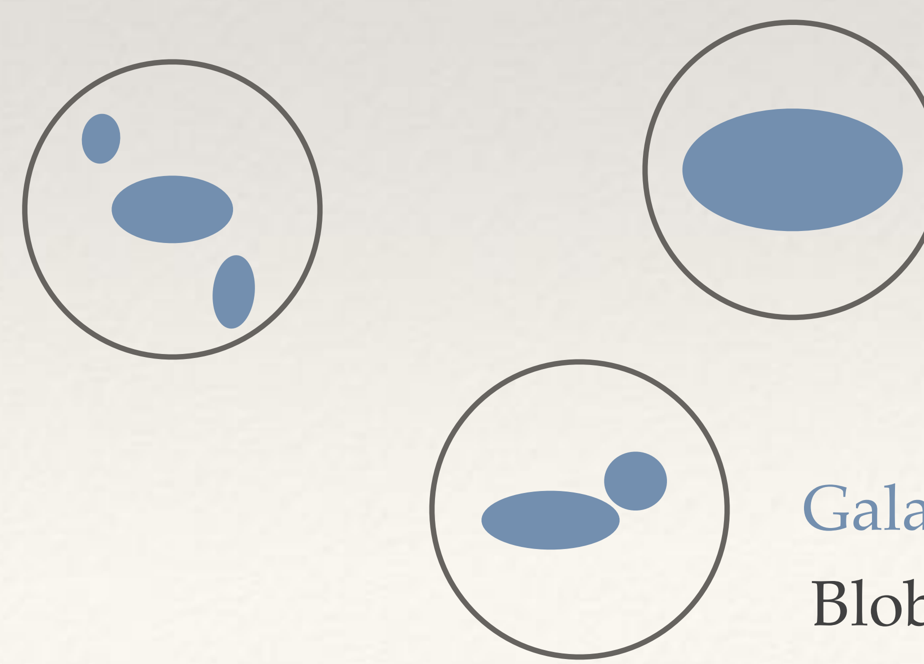


Bing+23

ExMORA (ALMA)



Long+24



Galaxies

Blobs

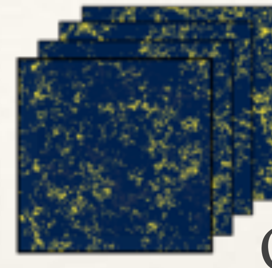
The SIDES simulation

Two light cones are available:
- SIDES-Bolshoi (2 deg², Béthermin+22)
- SIDES-Uchuu (118 deg², Gkogkou+22)

Abundance matching

Dark matter halo catalog → Galaxy catalog (Stellar masses) → Galaxy properties (passive/normal/starburst, SFR)

Observed scaling relations:
- fraction of passive galaxies
- main-sequence and scatter



[CII] emission

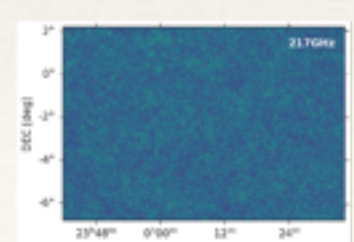
Observed SFR-luminosity relation

CO SLED templates

Line fluxes

SED templates

Continuum fluxes



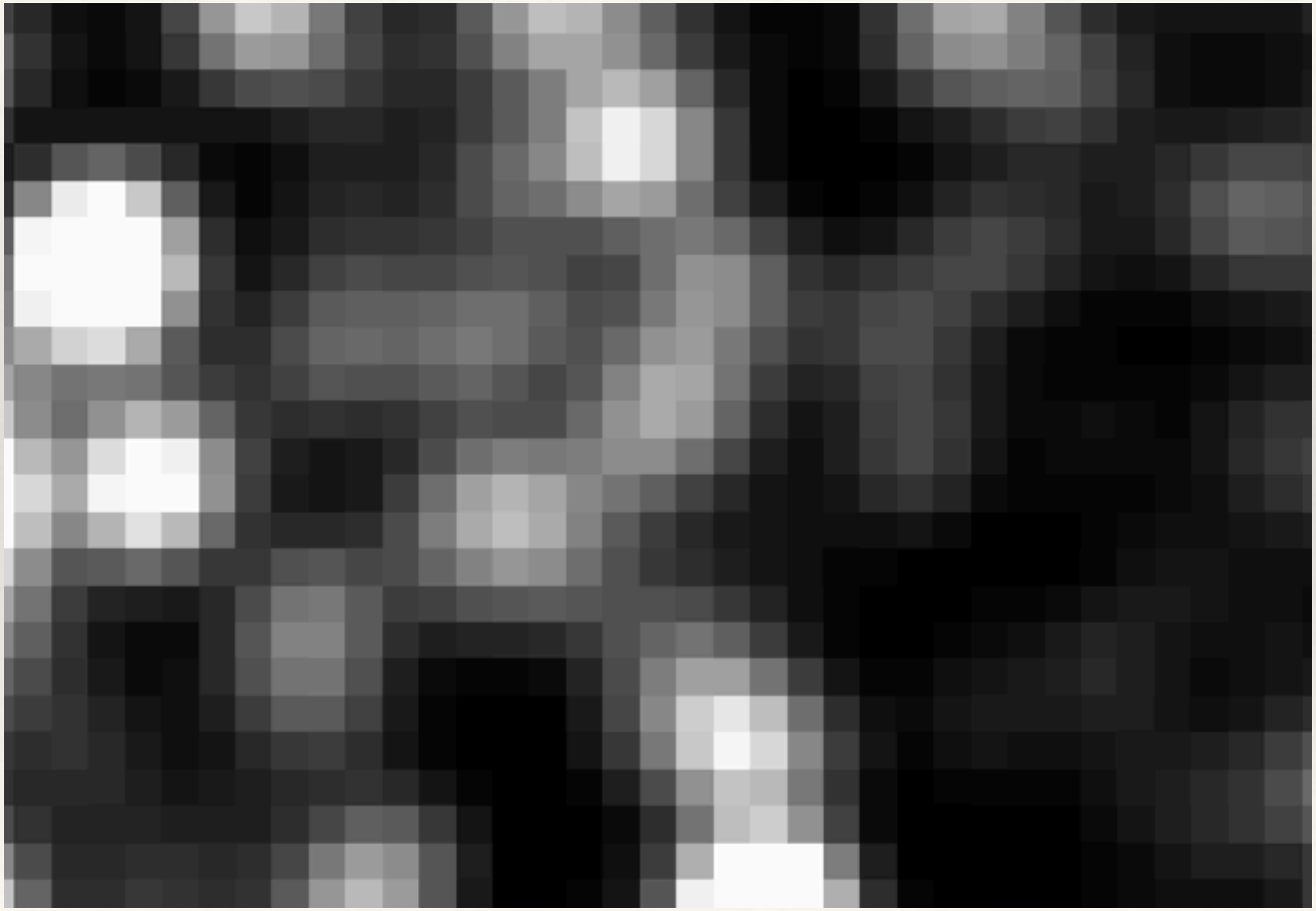
Continuum emission
Planck 217GHz

Béthermin+13, Béthermin+17, Béthermin+22, Gkogkou+22

Impact of confusion for various telescope diameters

850 microns

Simulation assuming a 25-m and no instrumental noise

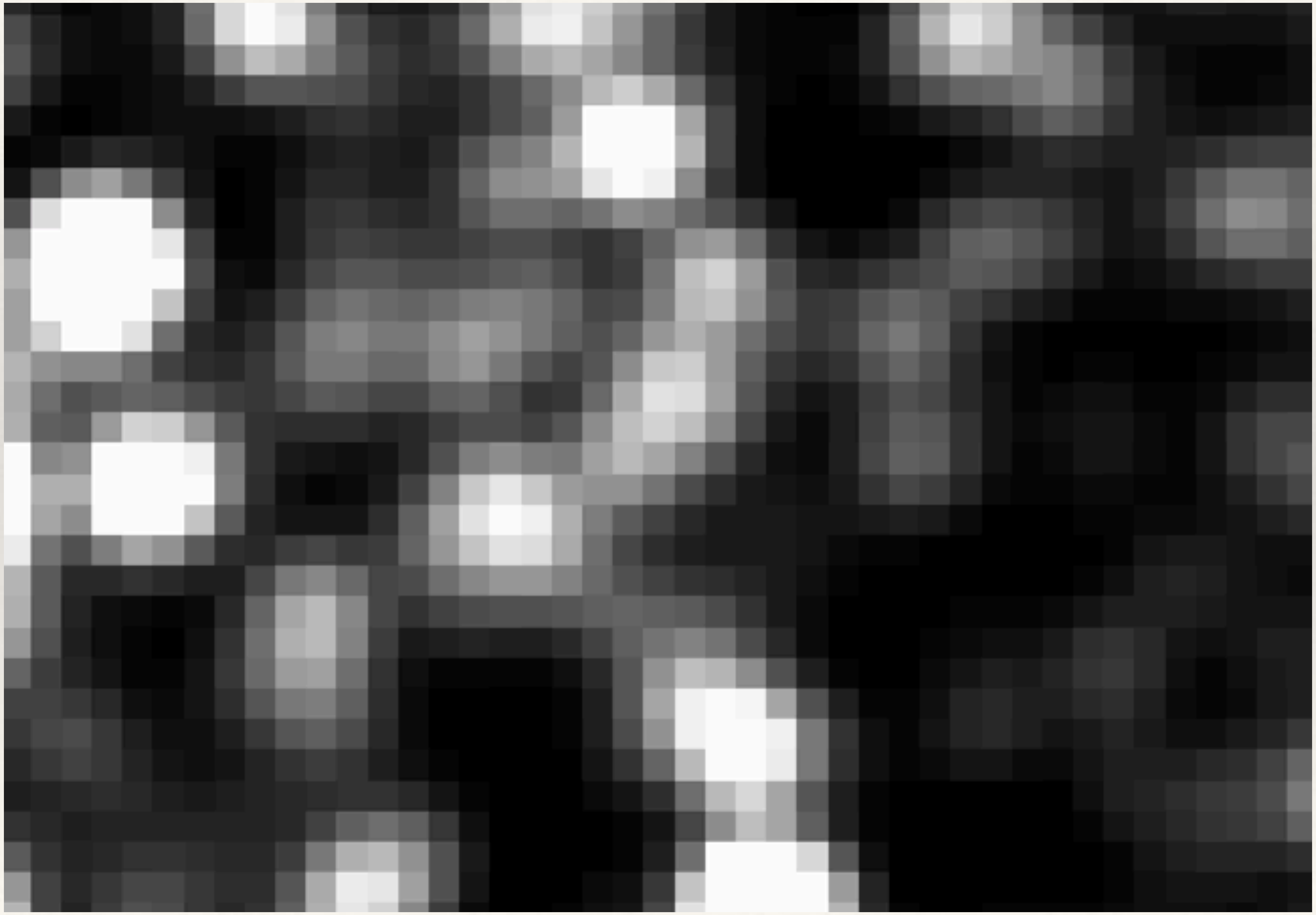


From SIDES simulations (Bethermin+2017)

Impact of confusion for various telescope diameters

850 microns

Simulation assuming a 30-m and no instrumental noise

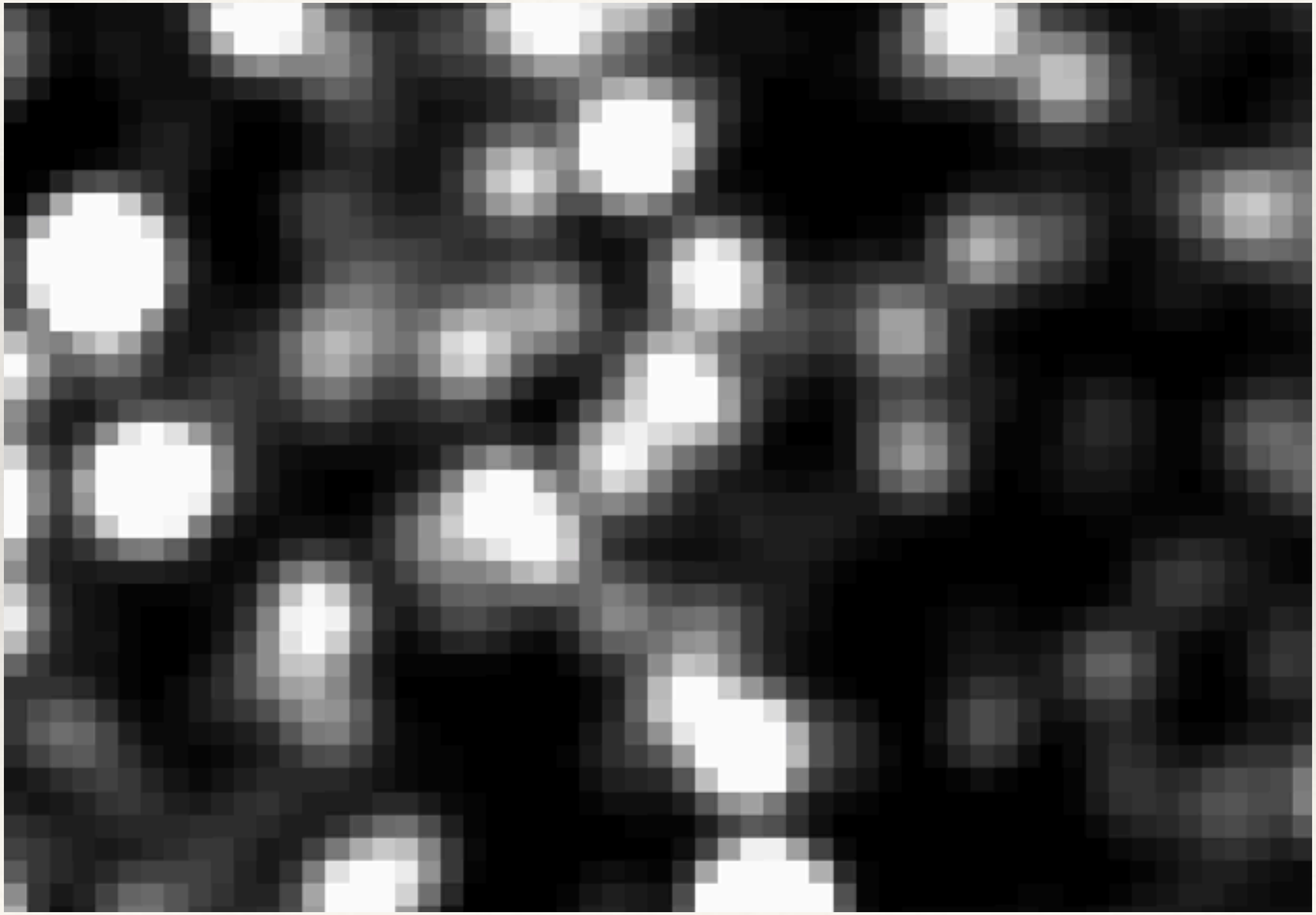


From SIDES simulations (Bethermin+2017)

Impact of confusion for various telescope diameters

850 microns

Simulation assuming a 40-m and no instrumental noise

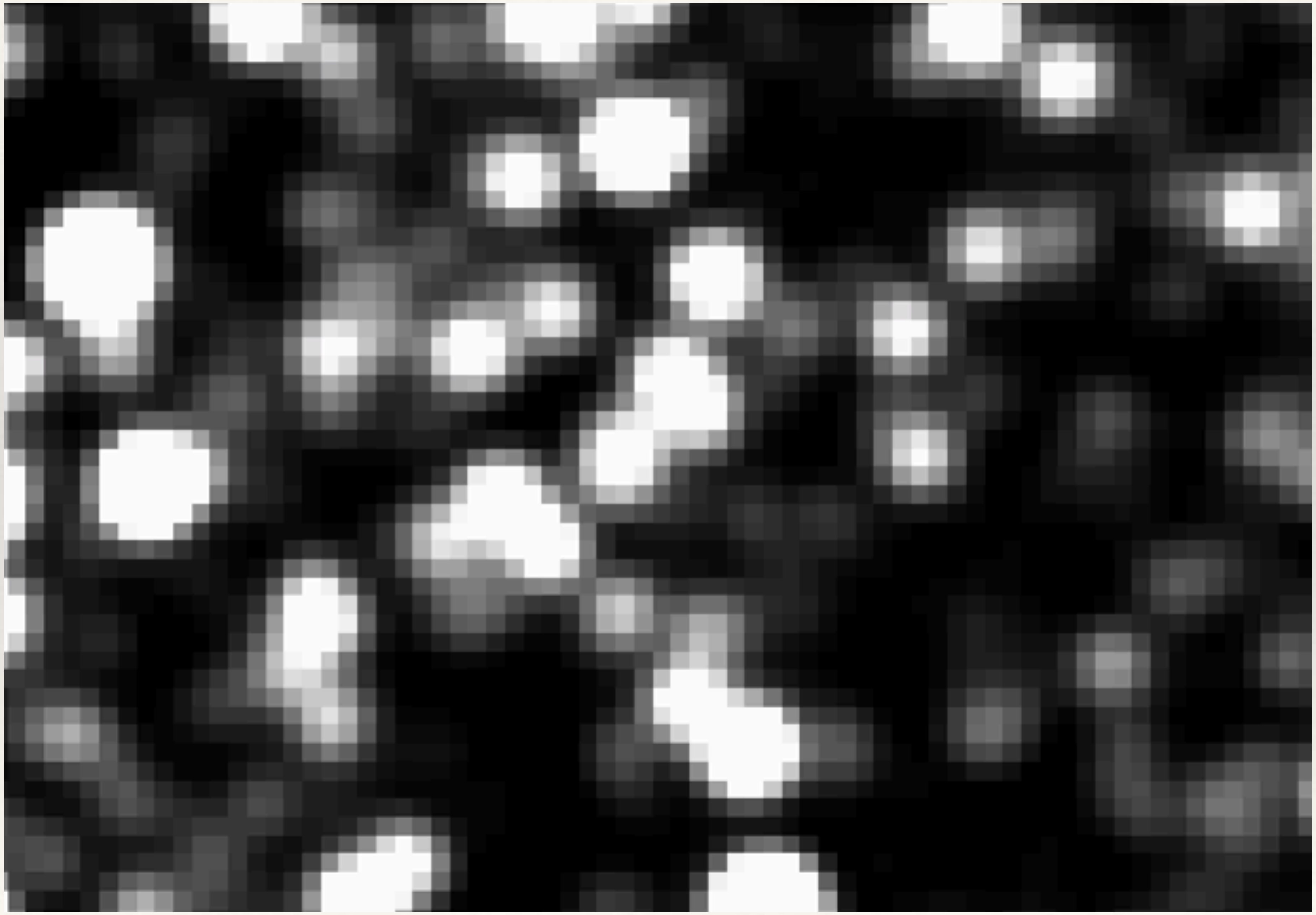


From SIDES simulations (Bethermin+2017)

Impact of confusion for various telescope diameters

850 microns

Simulation assuming a 50-m and no instrumental noise



From SIDES simulations (Bethermin+2017)

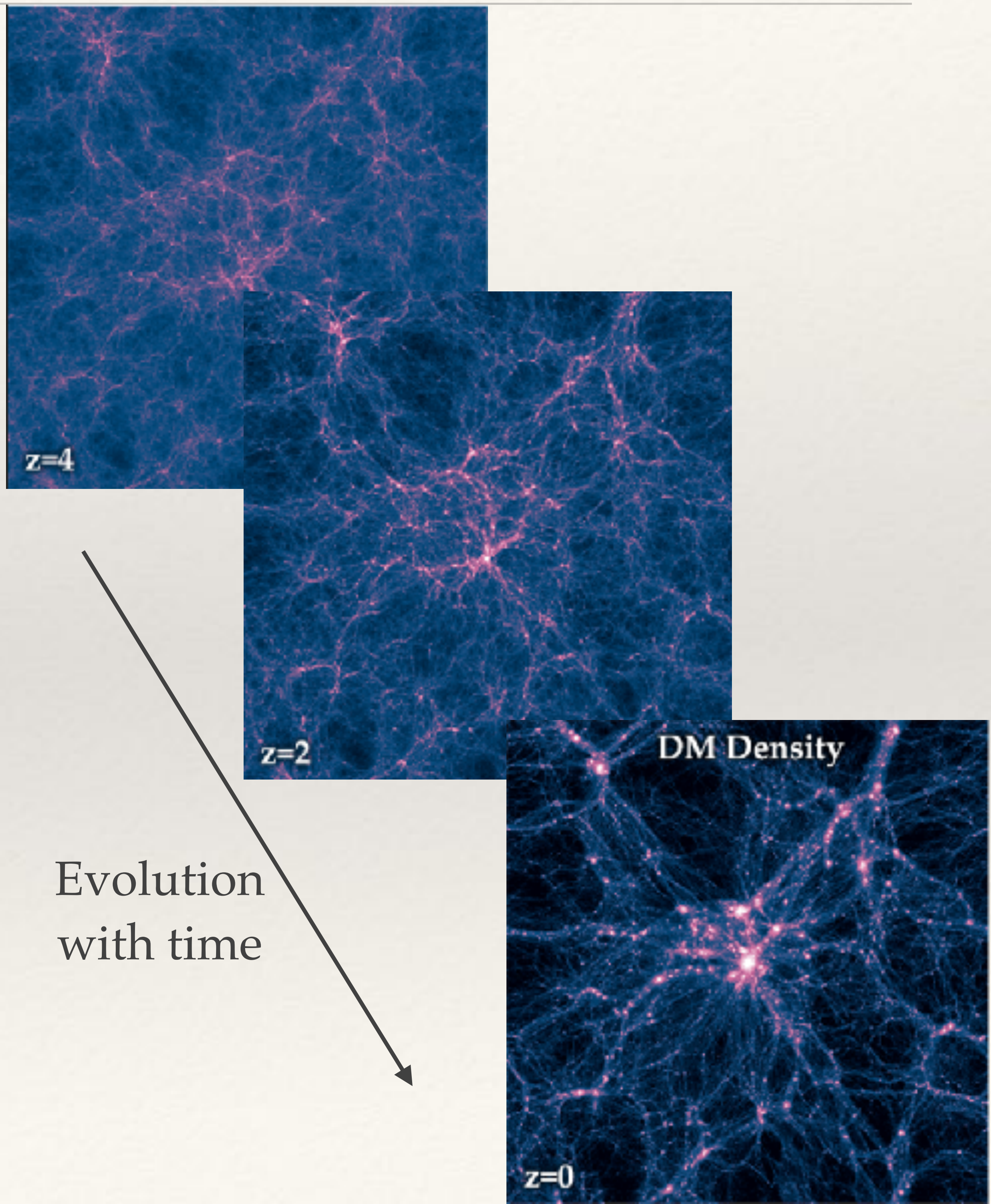
SFR limit versus telescope size (for a 850 μm survey)

- Negative K-correction: similar SFR limit for z=2-6.
- From 25m to 50m: confusion limit 5 times lower => diameter is essential to beat confusion
- >40m: able to detect the obscured SFR of the typical «M-star» high-z galaxies (a few tens of $M_\odot$/yr)

	25 m	30 m	40 m	50m
1σ confusion μJy/beam	152	107	57	32
5σ SFR limit at z=2 ($M_\odot$/yr)	80	56	30	17
5σ SFR limit at z=6	108	76	40	22

Dusty galaxies and LSS

- Large baryonic mass necessary to form a massive galaxy.
- Since structures grow with time, massive halos are rare at high z.
- We expect massive dusty galaxies to be formed in the most overdense regions of the Universe.



Galaxy correlation function

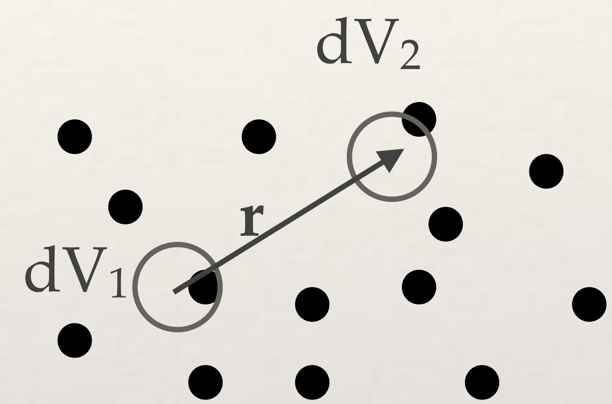
Mean number density   Correlation function

$$dP(\vec{r}) = \bar{\rho}^2(1+\xi(\vec{r}))dV_1 dV_2$$

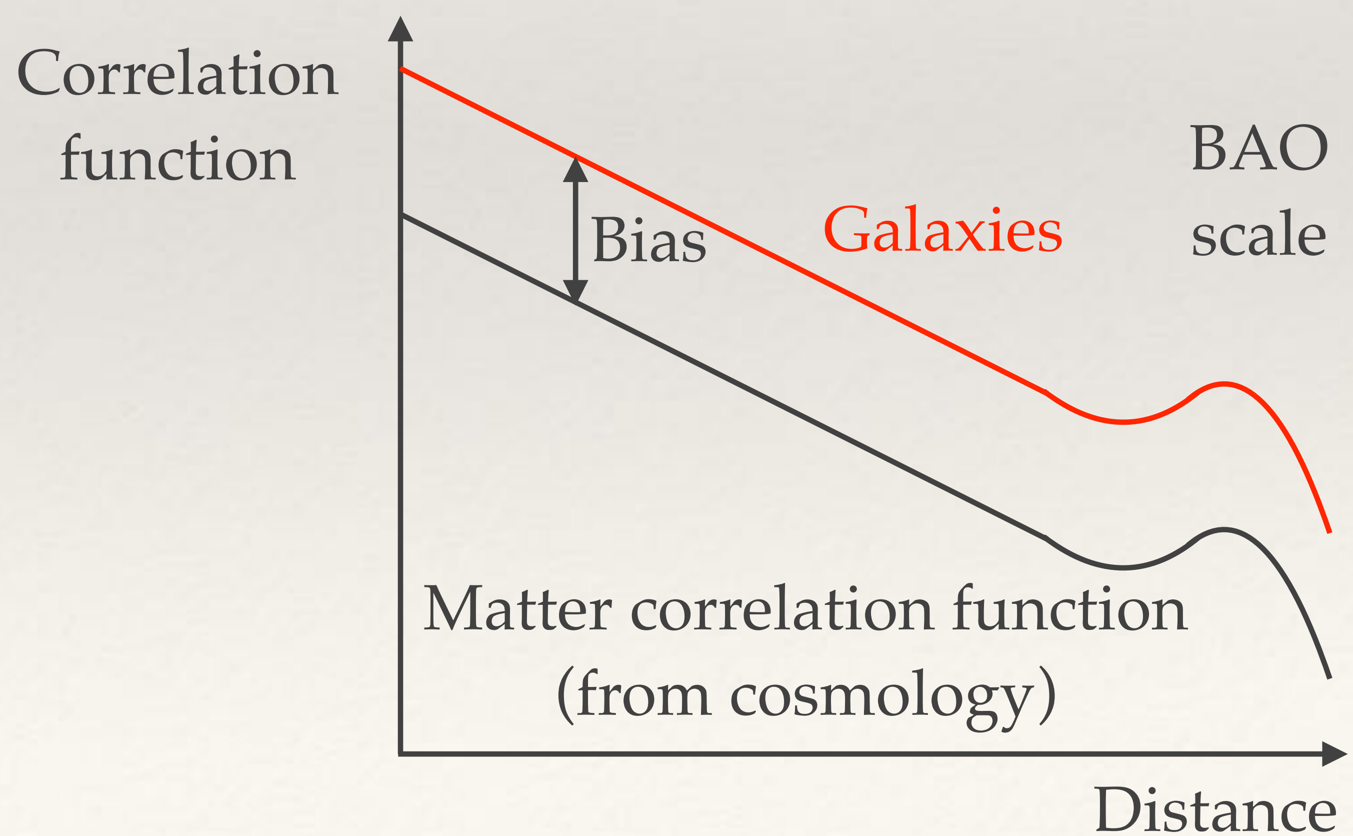
Probability to find two objects separated by a vector **r** from each other.

Differential volume elements

When null, the probability is linked to the number density squared, i.e. the Poisson case.



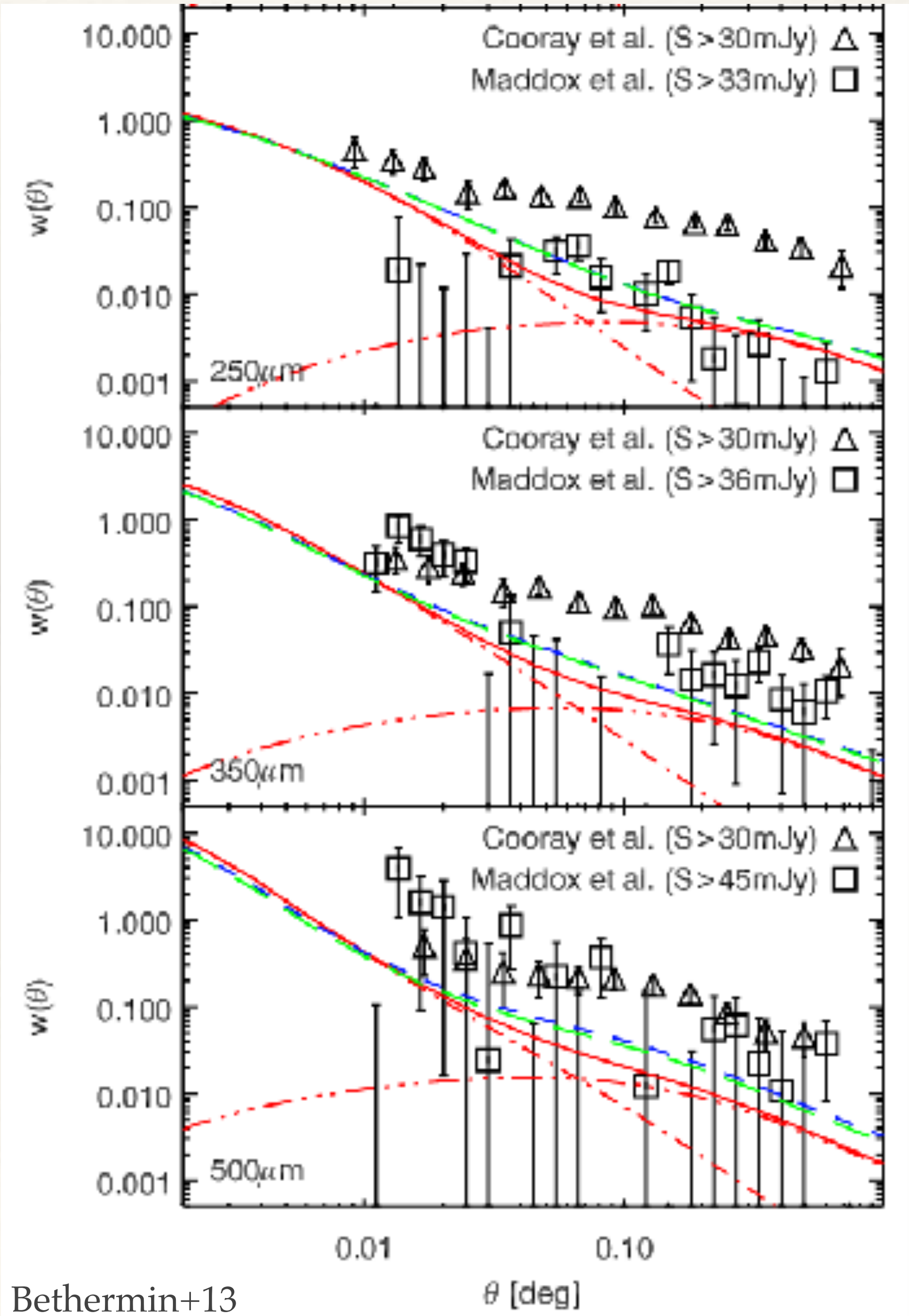
- The galaxy and matter correlation function are linked through a scaling factor called the bias.
- More massive halos are more clustered (relation between bias and halo mass)
- The bias provides **information on the host halo mass** of a galaxy population.



Limitation of previous sub-mm surveys

- Confusion and resolution effects biases the clustering measurements from single-dish instruments (e.g., Cowley+17)
- Too few objects from interferometric surveys to have enough statistics to perform a measurement.

Discrepancy between measurements of the correlation function with Herschel



Bethermin+13

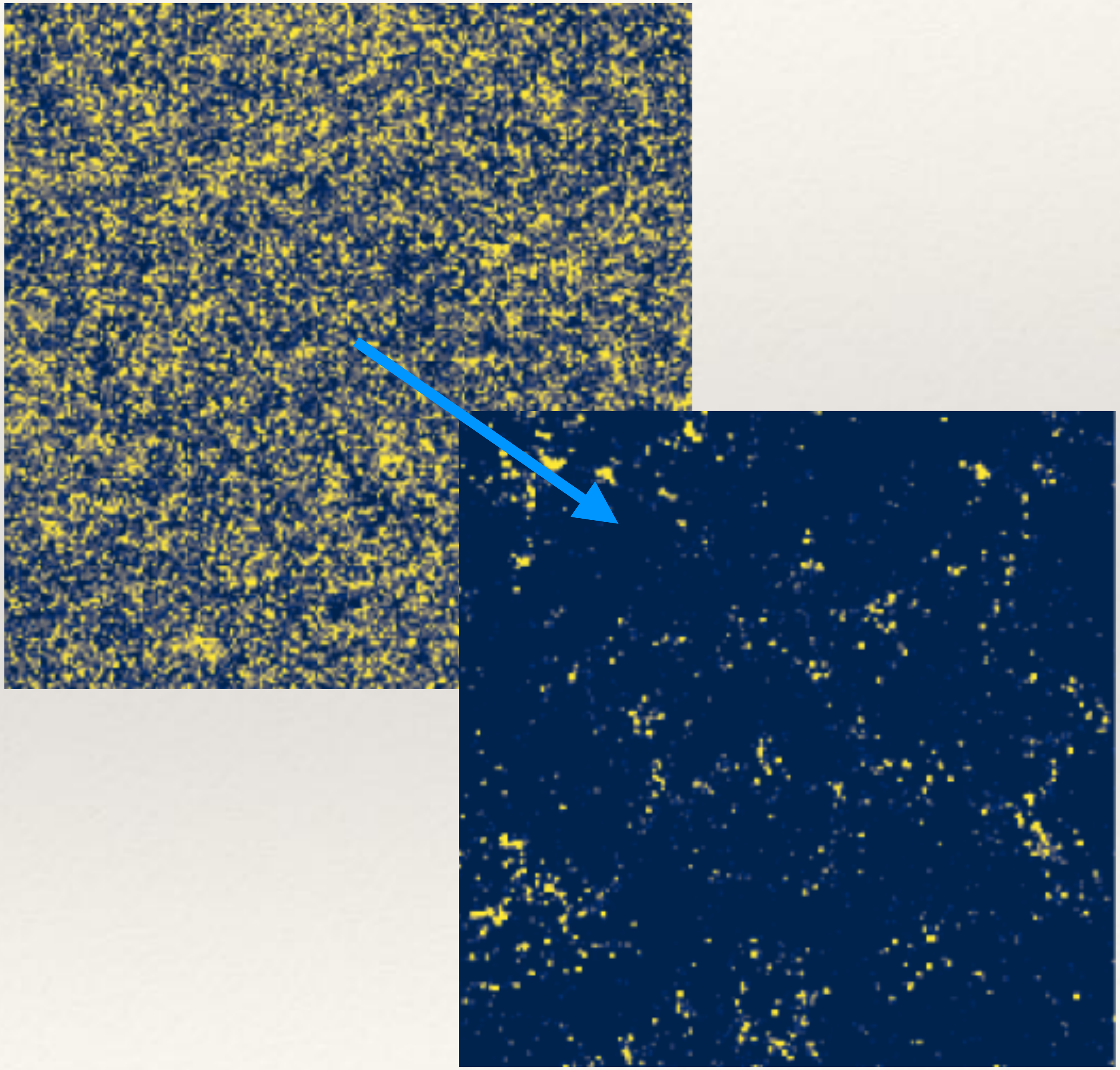
AtLAST perspectives

- Angular clustering from photometric surveys:
  + lots of statistics and easy to probe a large volume
  + selections can be reasonably simple (but potentially biased)
  - signal can be diluted if the redshift distribution is very broad
  - need to know very well the redshift distribution for the modeling
- 3D clustering through spectroscopic surveys through targeted surveys with a sub-mm MOS:
  or 3D spectrograph
  + direct measurement
  + stronger signal for the same amount of sources (no dilution)
  - harder to build large samples
  - line misidentification can be a big problem for interpretation

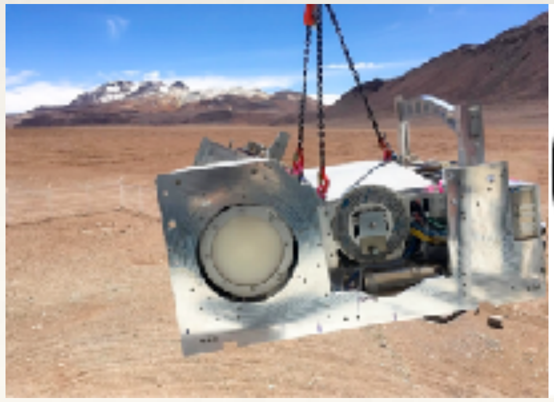
Spatial SFR distribution with line intensity mapping

- CIB (continuum of all galaxies) is limited by redshift degeneracies
- [CII]: dominant line in the far-IR and correlated with SFR (Schaerer+20)
- [CII] in a narrow frequency slice => SFR distribution at a given z
- CONCERTO (2020-2023, PI: Lagache): APEX experiment to map wide sub-mm field using low-resolution spectroscopy (R~300)

Cosmic infrared background

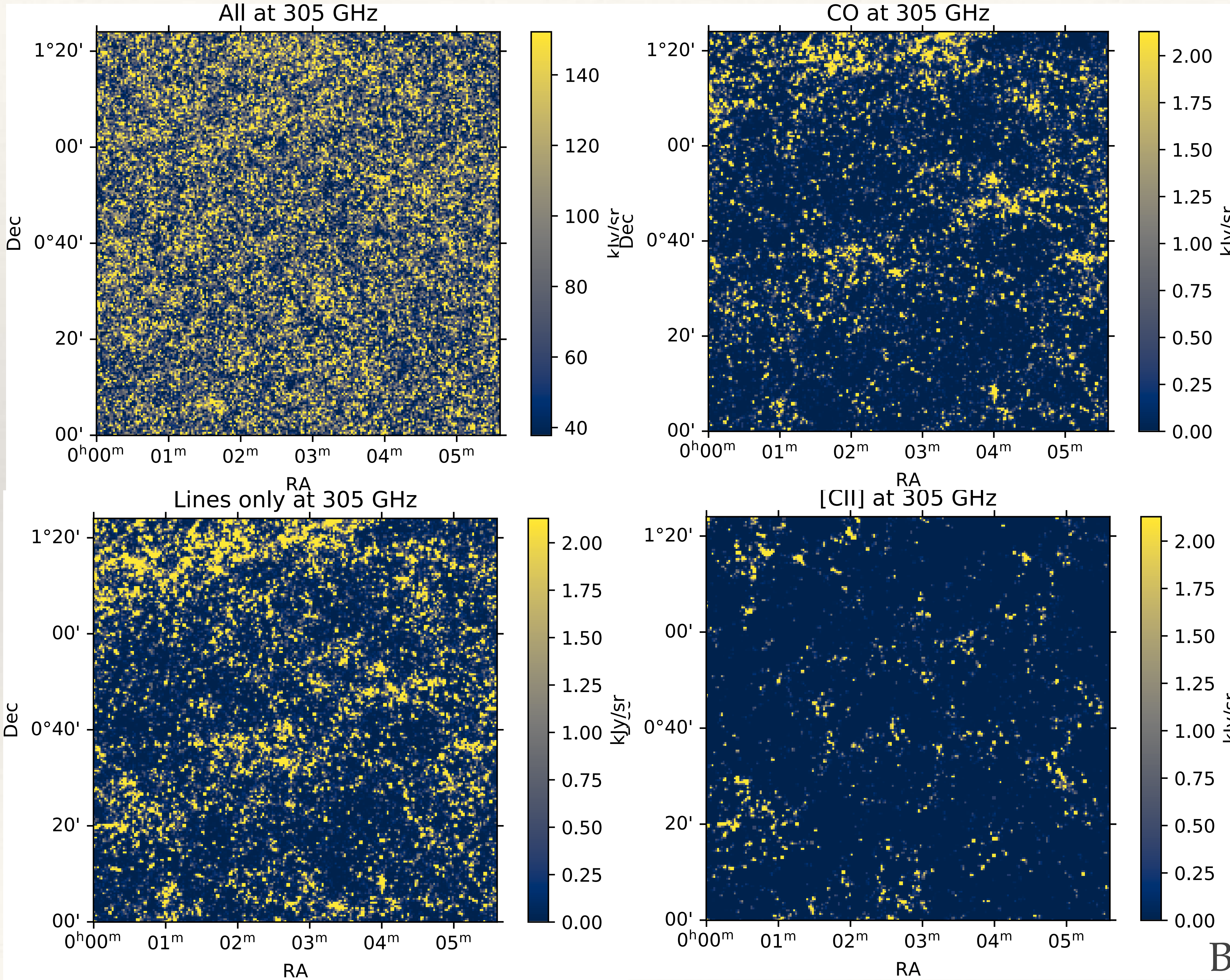


[CII] @ z~5 in a 1GHz channel



Simulated intensity mapping cube slices

All (simulated CONCERTO cube slice of 1GHZ)



CO

Lines only

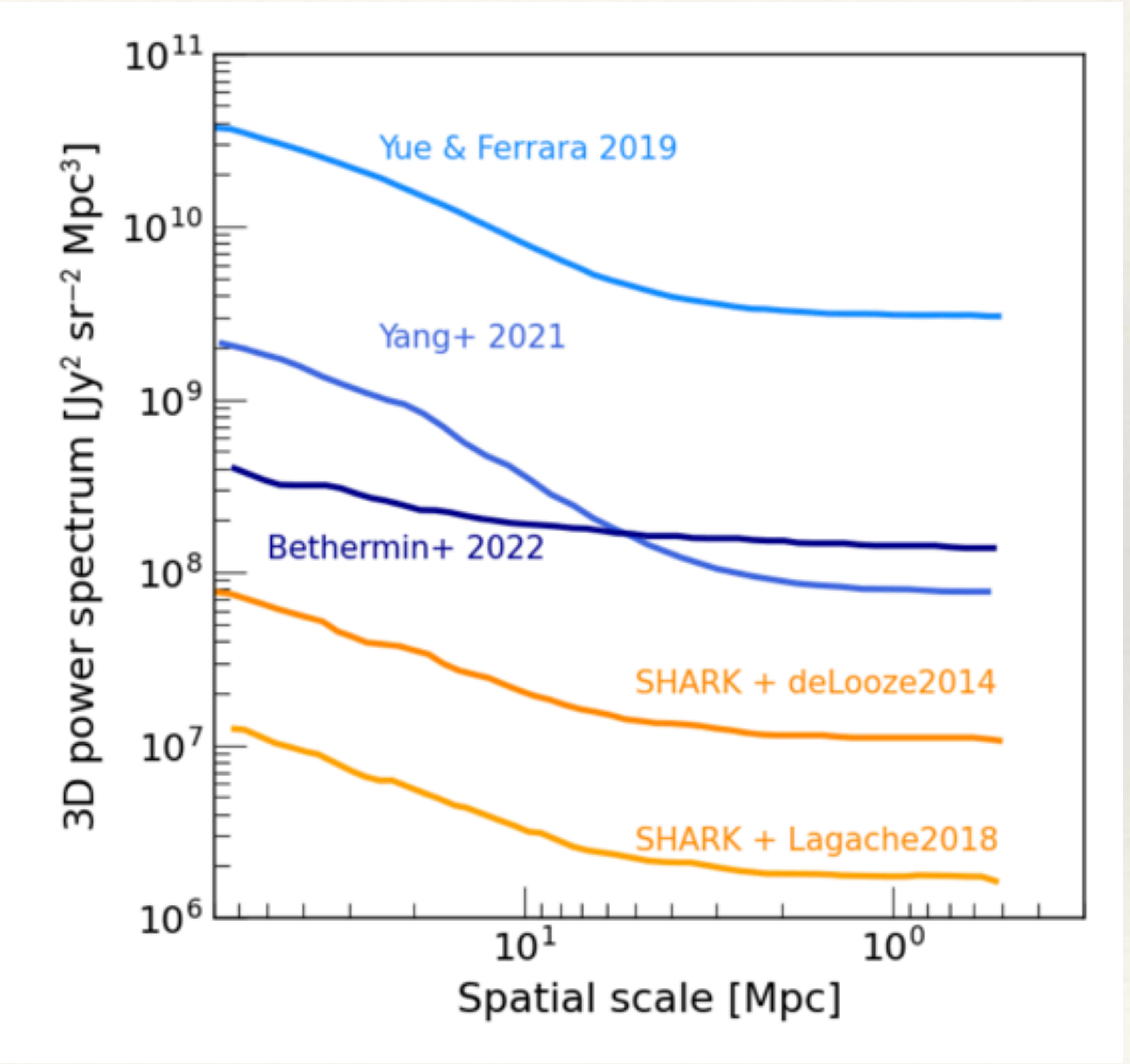
[CII]

Béthermin+22

[CII] power spectrum

- Power spectrum: distribution of the fluctuations at the various scales
- Large scale: amplitude linked to the LSS, rather similar to correlation function measurements
- Small scale: shot noise caused by source below the detection threshold
- Wide spread between models => important constraints for galaxy evolution models!

Large scale Small scale

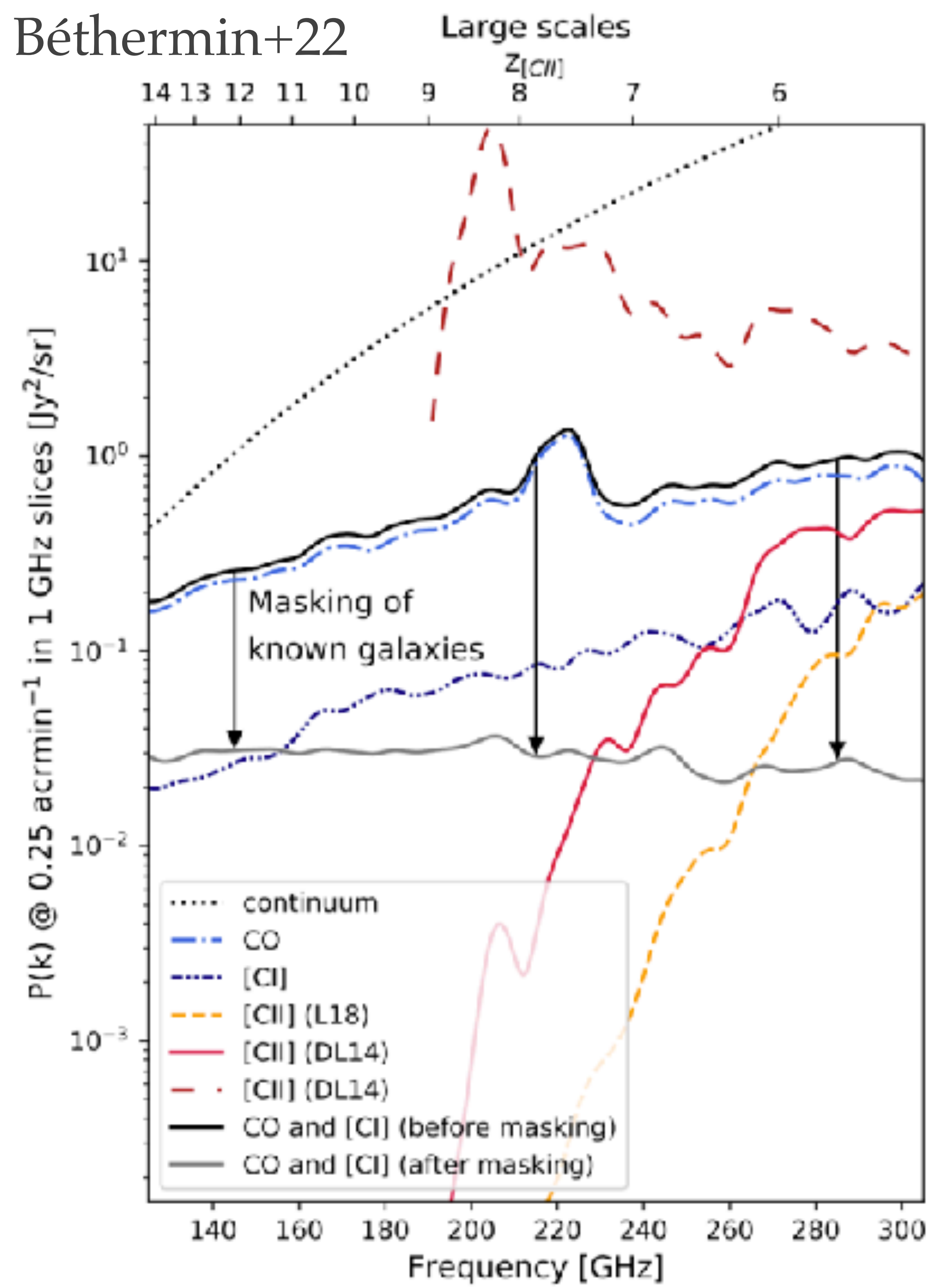


AtLAST extragalactic paper (Van Kampen+23)

What contributes to sub-mm intensity mapping signal?

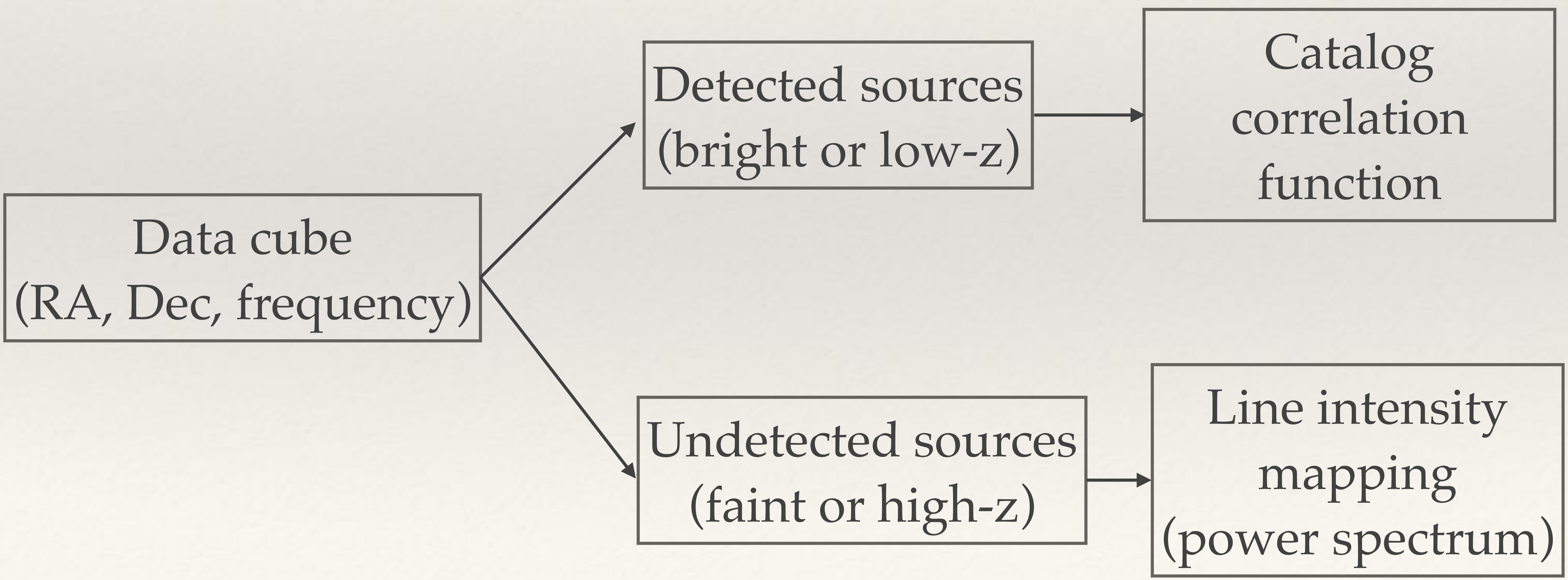
- The contribution of the various components (continuum, CO, [CI], [CII]) varies with frequency
- [CII] will be easier to detect at higher frequency
- Even at 300 GHz, CO is brighter than [CII]
- Masking technique can be used to remove the continuum and the low-z lines (Van Cuyck+23)

Béthermin+22



Synergy between clustering and LIM

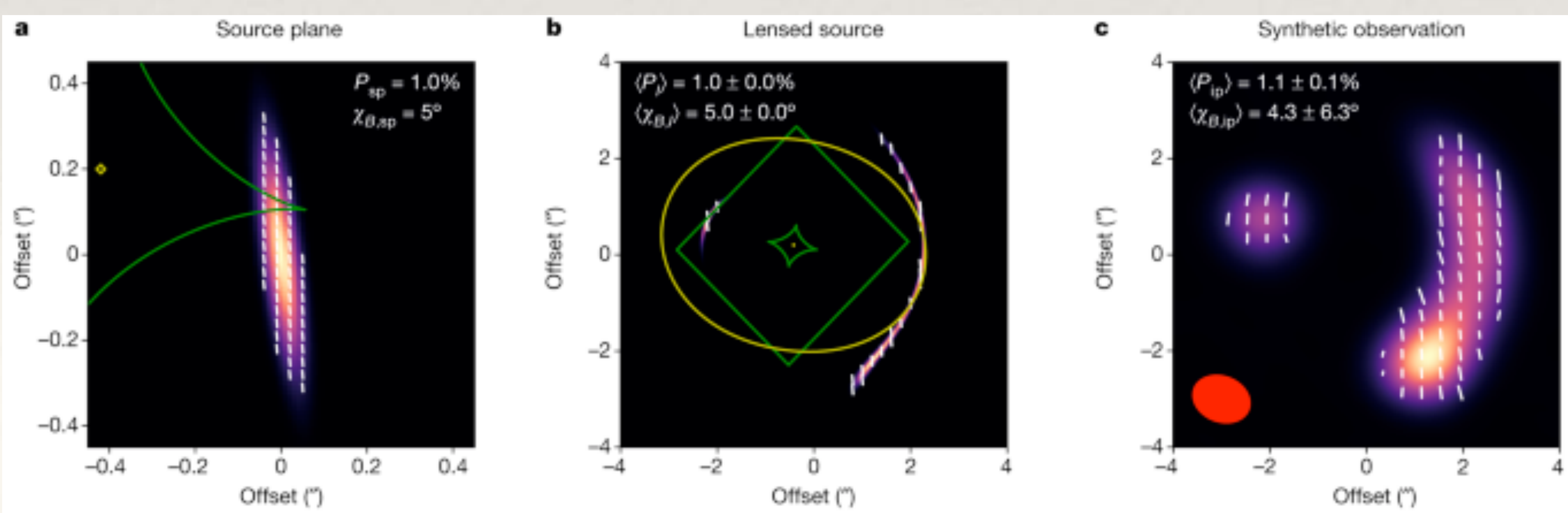
- Clustering of detected system and LIM are complementary, especially for 3D surveys.
- Bright sources can be studied in catalog space, while faint objects are studied through LIM. Allow to extract a global information on all populations.



High-z polarized dust emission

- Recently, ALMA detected the polarized dust emission of two lensed dusty star-forming galaxies at high z.
- This demonstrates that this signal can be detected, but it opens complex questions on how to interpret it.

Polarized observation of a lensed galaxy at z=2.6

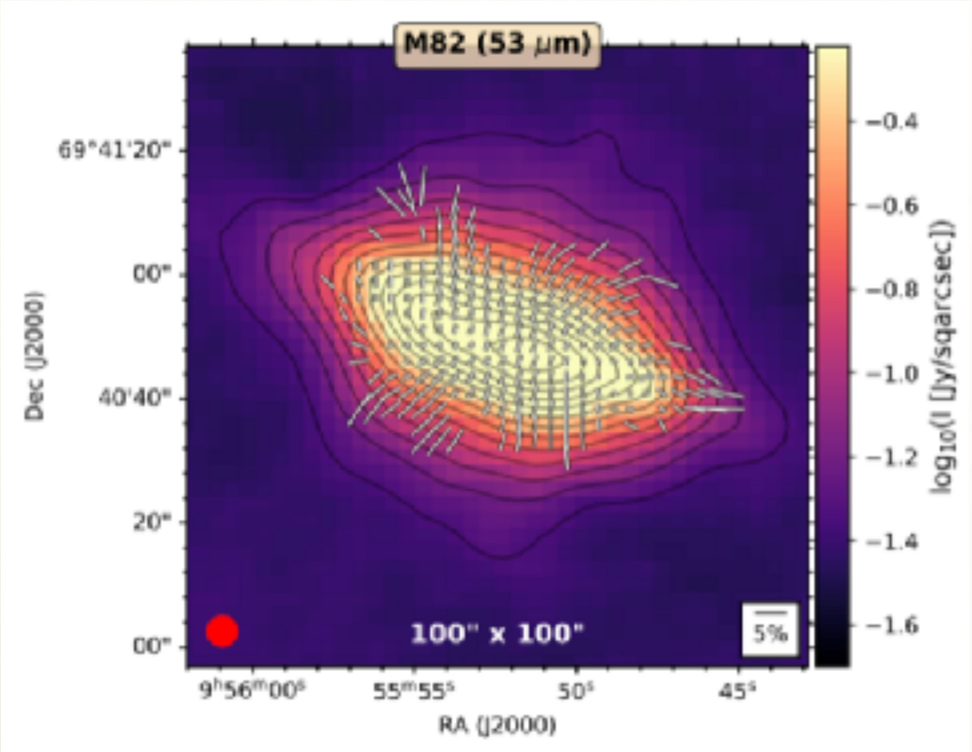


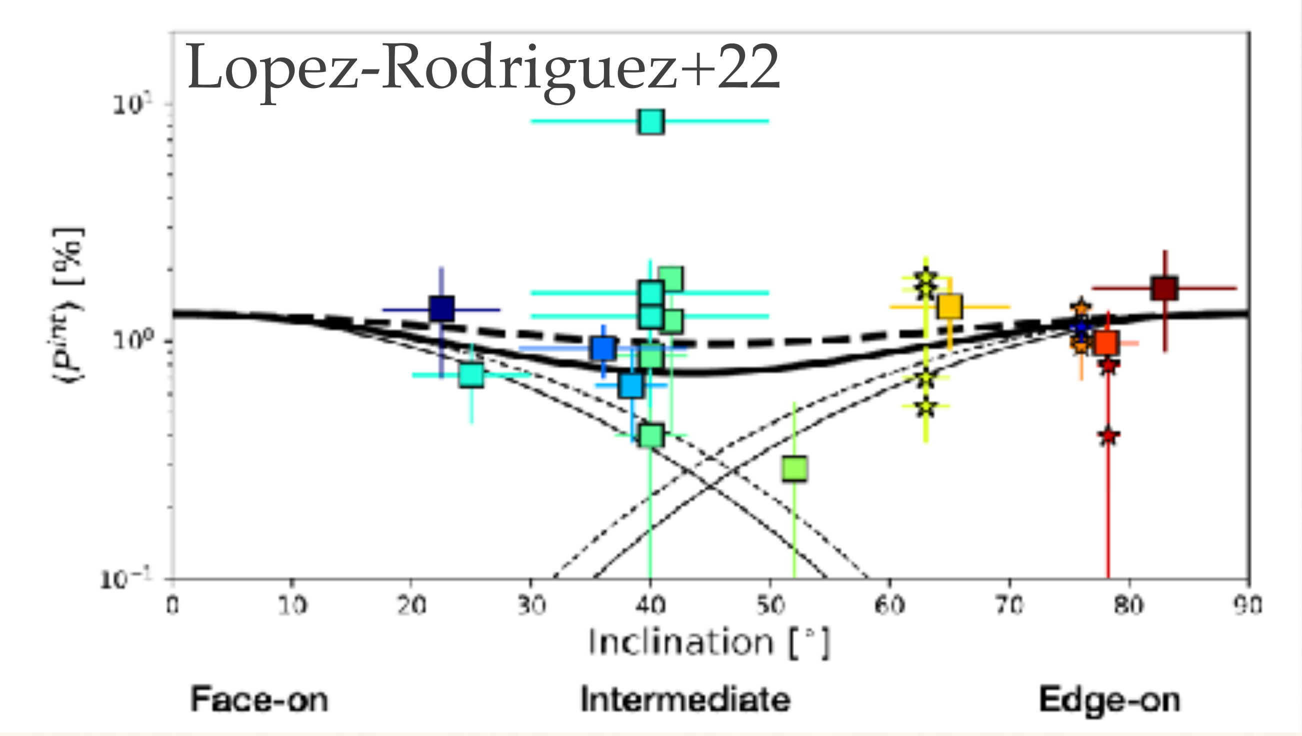
Geach+23

Lessons from the local Universe

- Polarized observations of nearby galaxies (SOFIA / SALSA) showed ordered polarization at galactic scale.
- Integrated emission is polarized at the percent level.
- Several mechanism contributes:
  - ordered magnetic fields in the disk
  - outflows
  - AGN

Dust polarization of M82

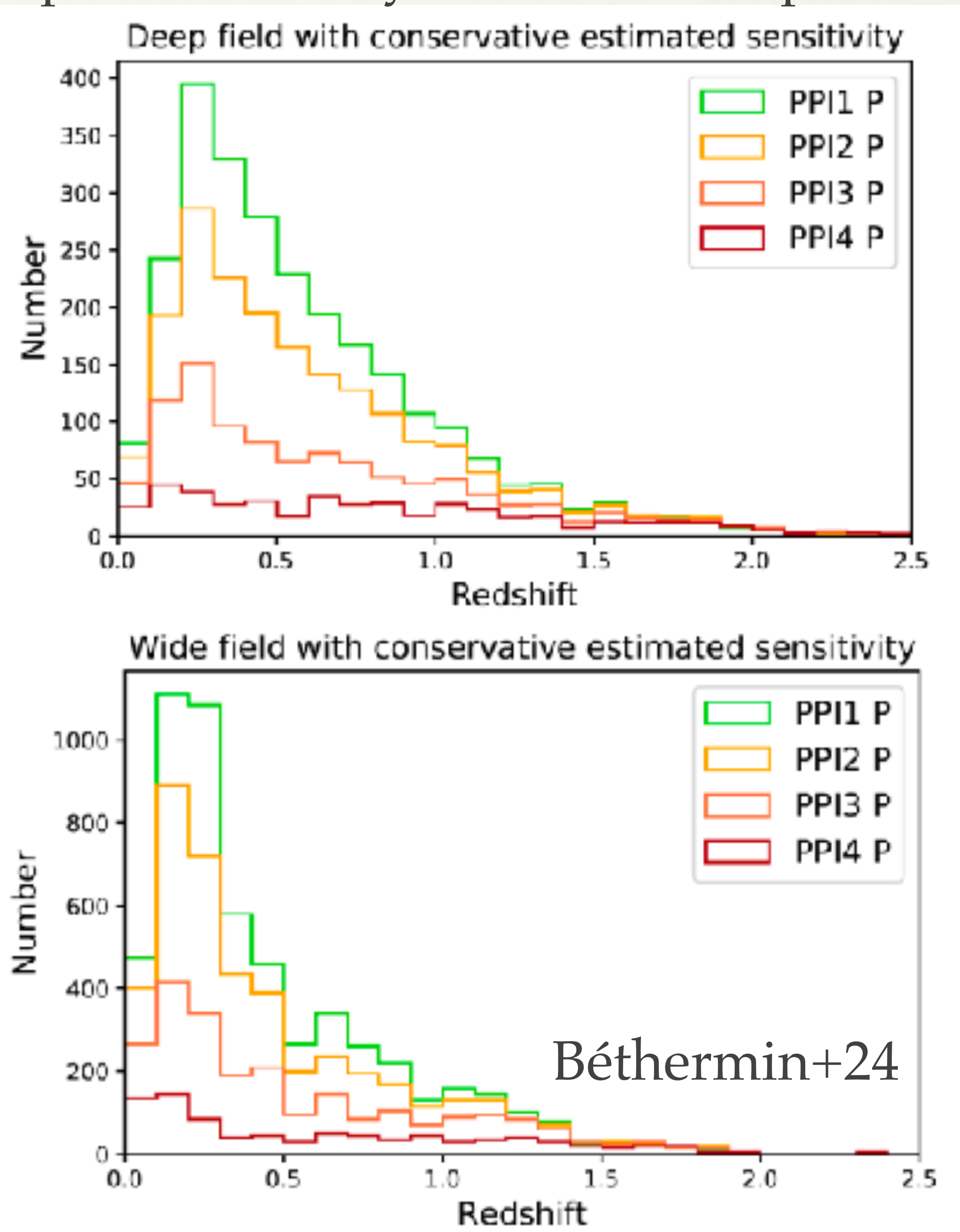




Towards high-z polarization surveys with next-gen instruments

- At high-z, single-dish telescope can only see the integrated polarization.
- Deep surveys are feasible with future far-IR telescope as PRIMA (Béthermin+24) with thousands of detections expected.
- What about the sub-mm with AtLAST? **Easy to adapt SIDES for AtLAST polarization when instrumental forecasts are ready.**

Expected redshift distribution in polarization by PRIMA far-IR probe



Conclusion

- A large single-dish sub-mm telescope offers new possibilities by beating the confusion and mitigating resolution effects.
- Clustering studies (photometric and spectroscopic selections) will allow us to constrain the host halos of the bright objects.
- In complement, line intensity mapping will provide information on fainter population.
- High-z polarization could be explored, but feasibility has to be assessed.