Cross-correlating cosmic fields: Reionisation, star formation history and cosmological model

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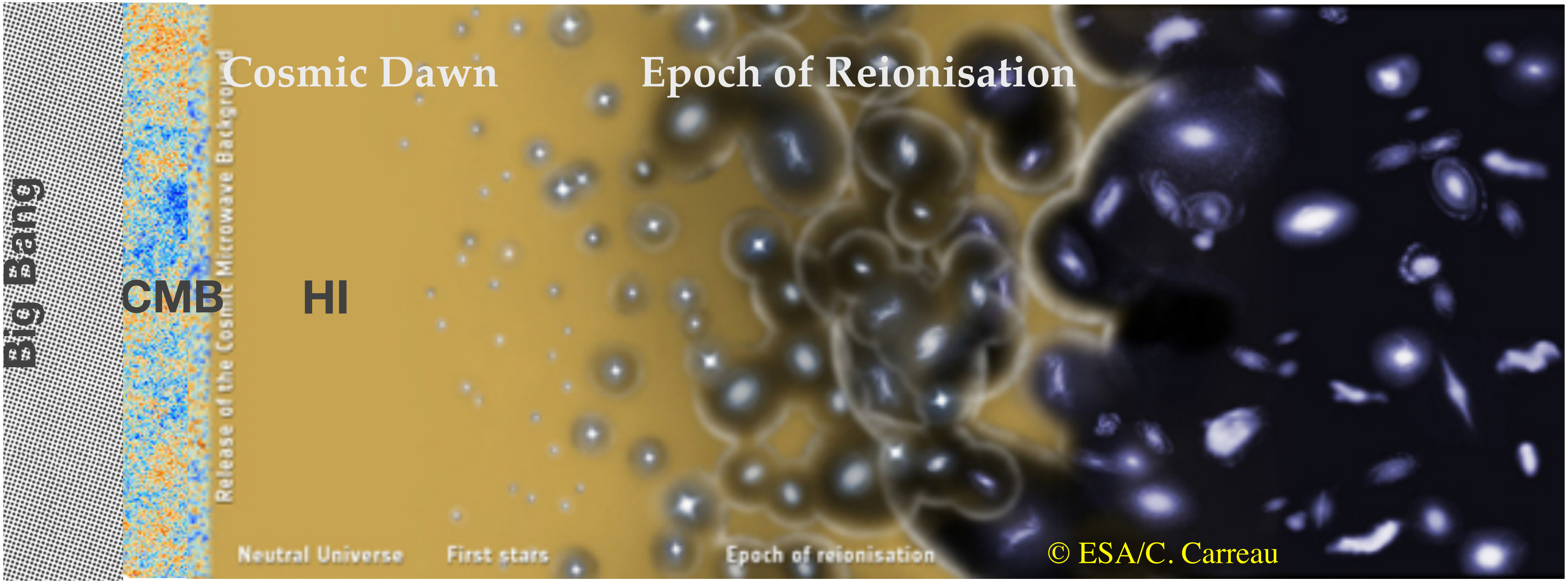
IphU WP "Cosmology and galaxies"
Marseille, Feb. 2021

Instructions:
present myself "extra-muros"
discuss at pedagogical level

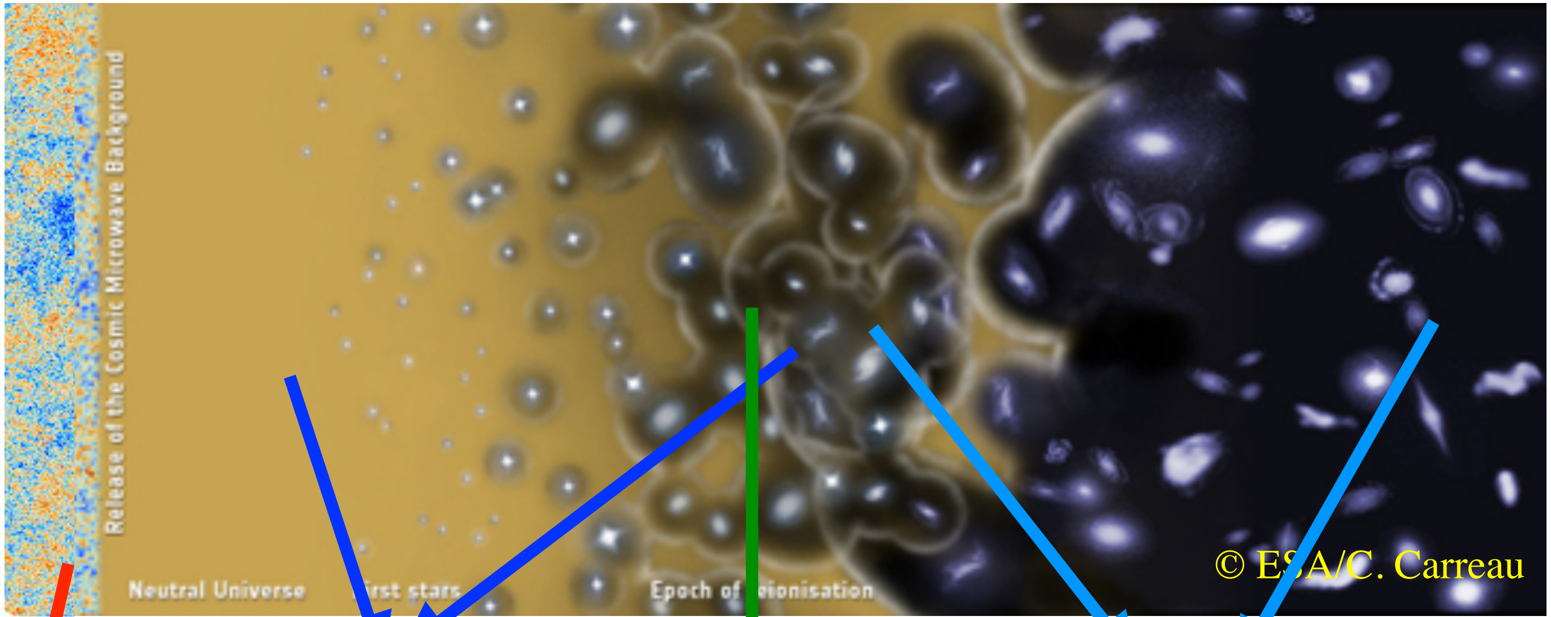
A very brief history of the Universe…

Redshifts 1200 20 10 8 6 3 0



Time 380 000 yrs 0.2 0.5 0.6 0.9 11.5 Gyrs

Probes



CMB
primary anisotropy
T, E, B

HI

[CII]
kSZ
CMB EE
(galaxies)

CIB
Dusty galaxies
[CII], CO

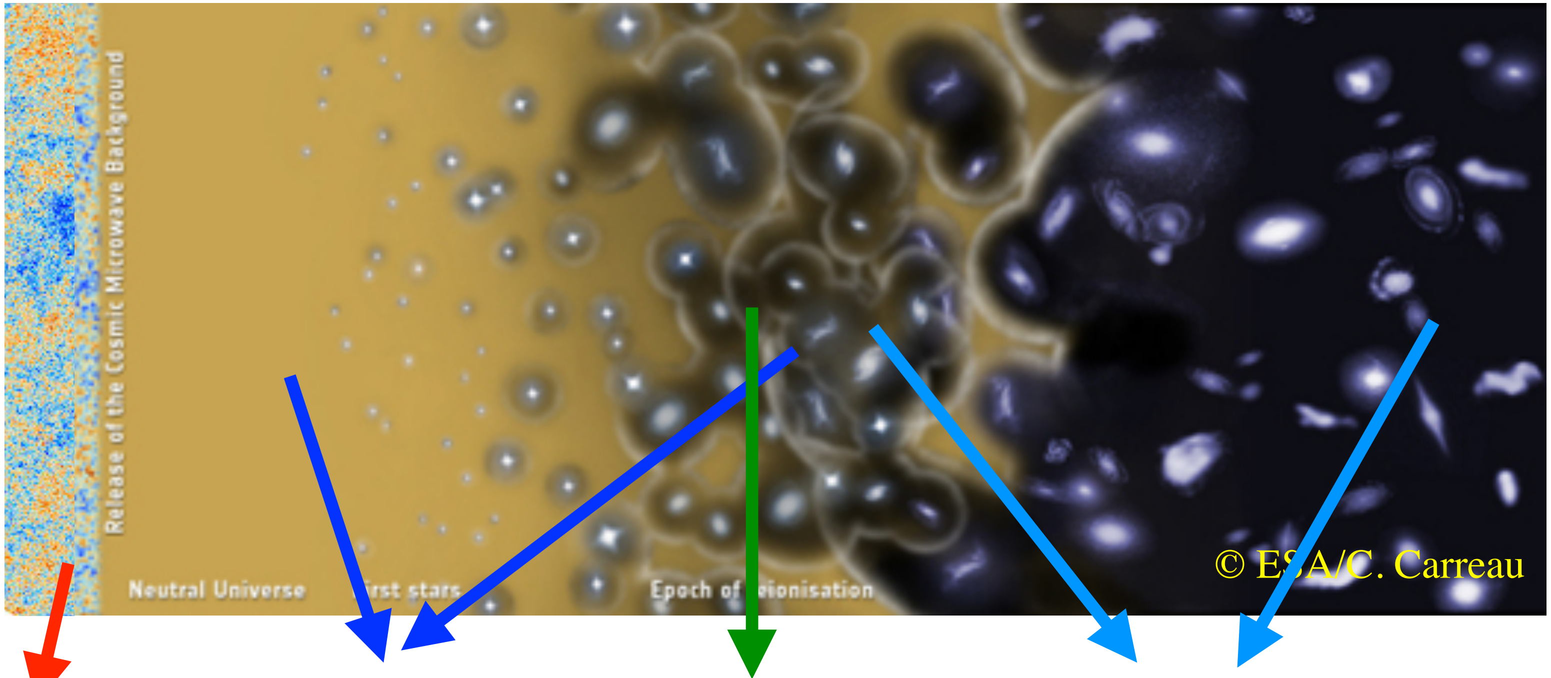
Cross-correlations:

CMBxCIB ; CIBxtSZ ; [CII]x HI and kSZxHI ; GalaxiesxCIB

Cross-analysis:

CMB+CIB+tSZ+PS => kSZ ; CIB+PS+Polar => B modes

Experiments



Planck
LiteBIRD
CMB S4

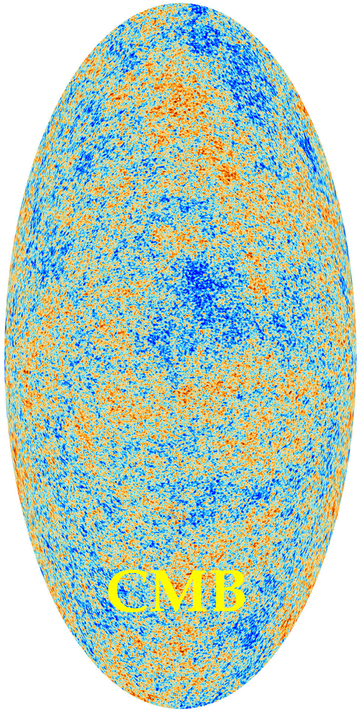
SKA

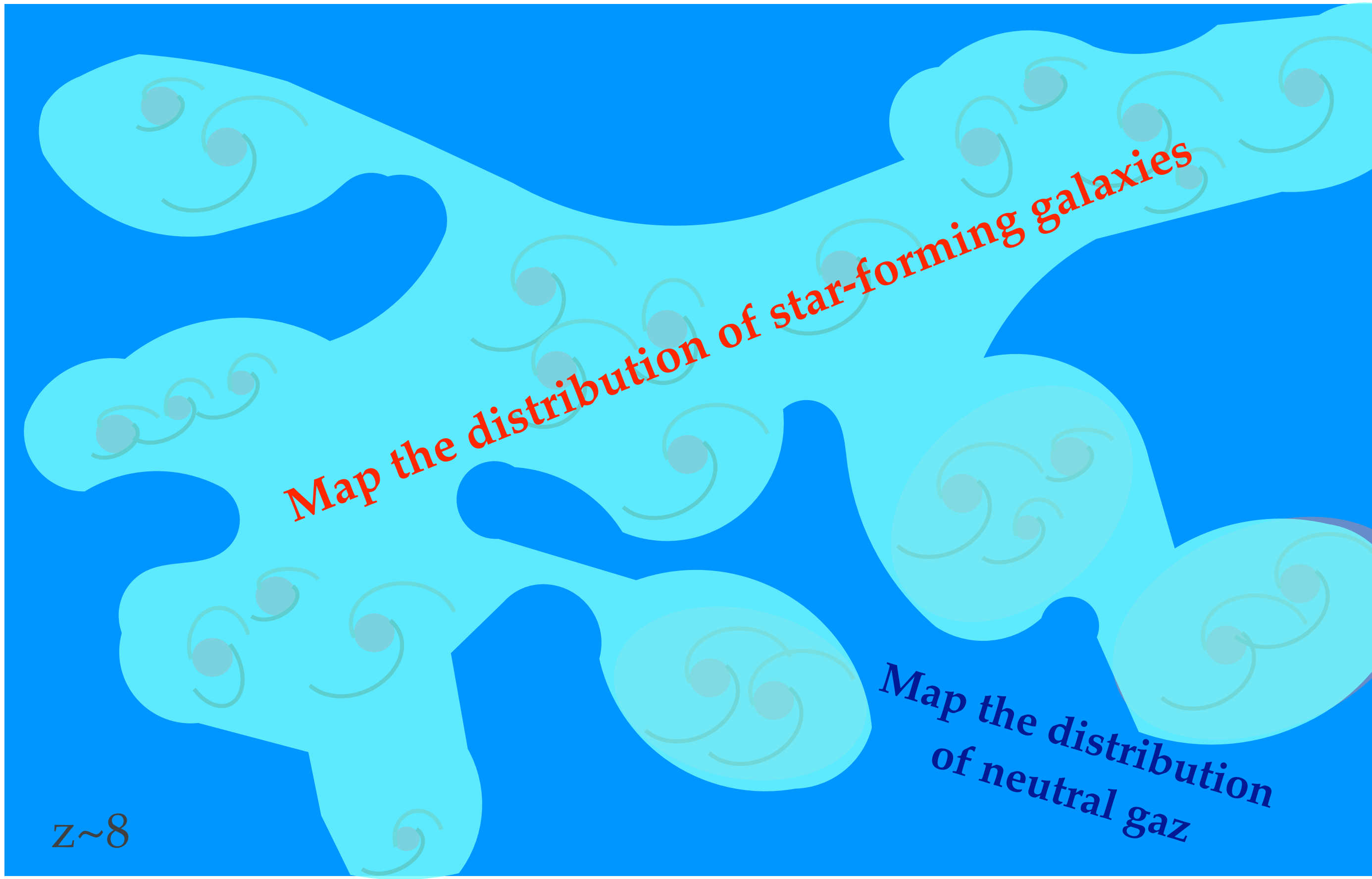
CONCERTO
Planck
LiteBIRD
CMB S4

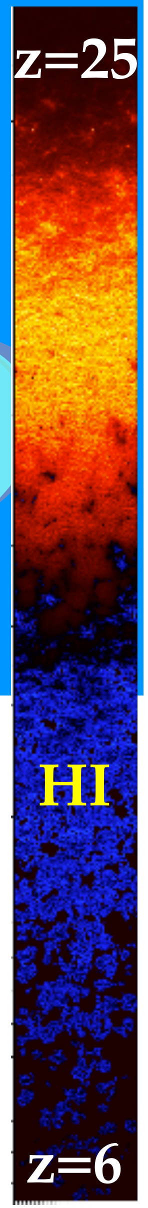
Planck, Herschel
NIKA2
CONCERTO
ALMA, NOEMA

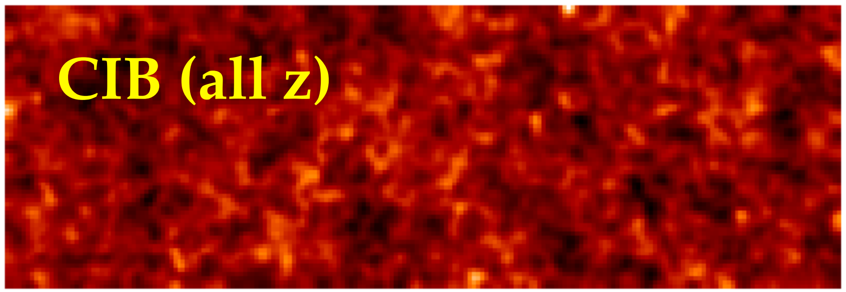
- Far-IR to mm (radio) experiments: common ground for a long time
- Data reduction pipeline (single dish), analysis, modelling
- From 2007 to 2017: Planck/HFI was a deep part of my life (operation, science, component separation, pipeline, photometric calibration and systematics, core team)
- Since then: CONCERTO and NIKA2

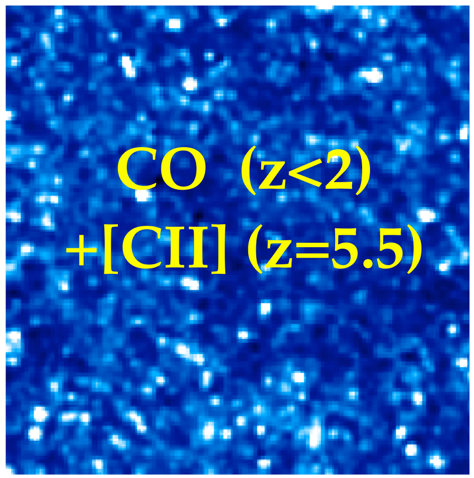
Fluctuations, anisotropies, 2/3D intensity mapping…..

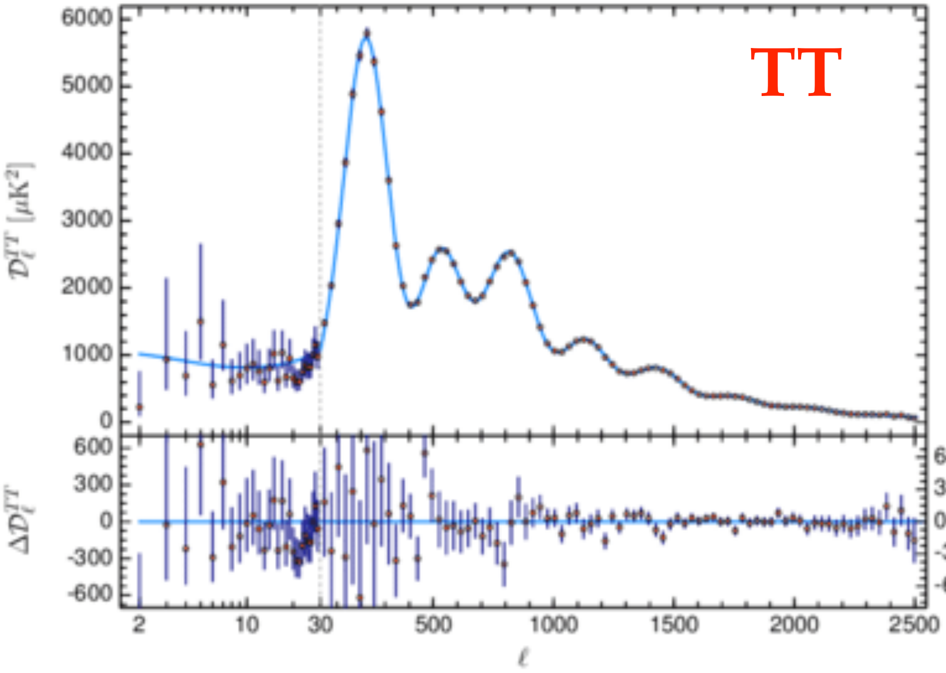


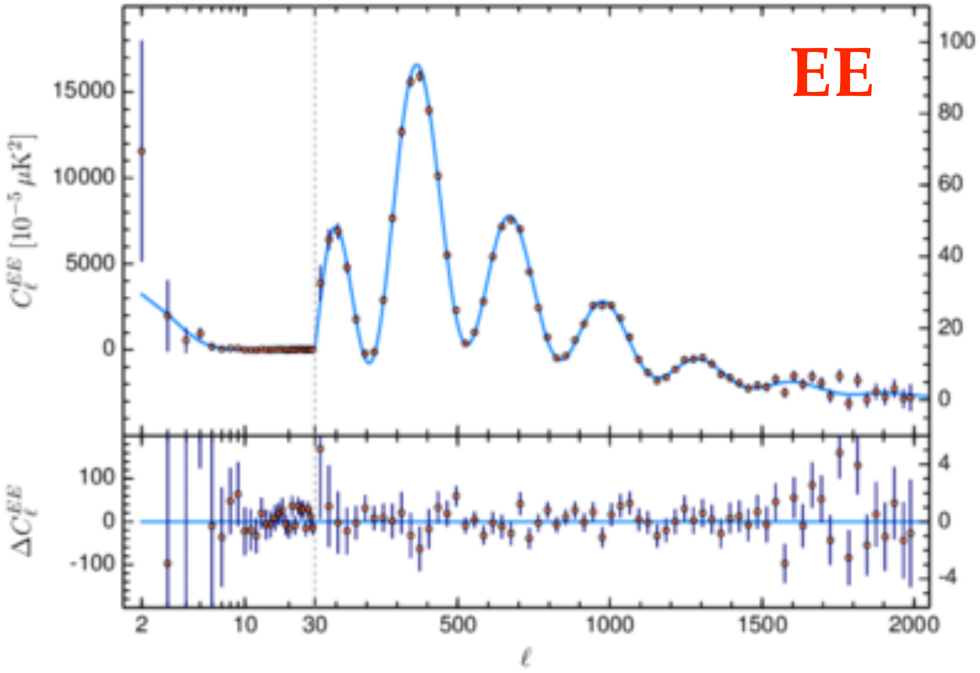


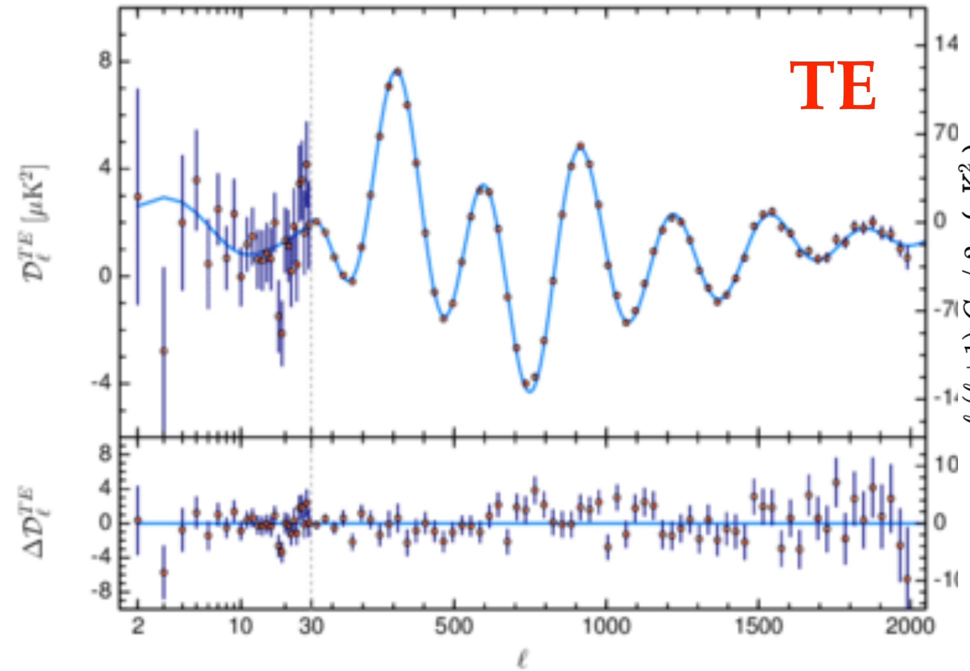


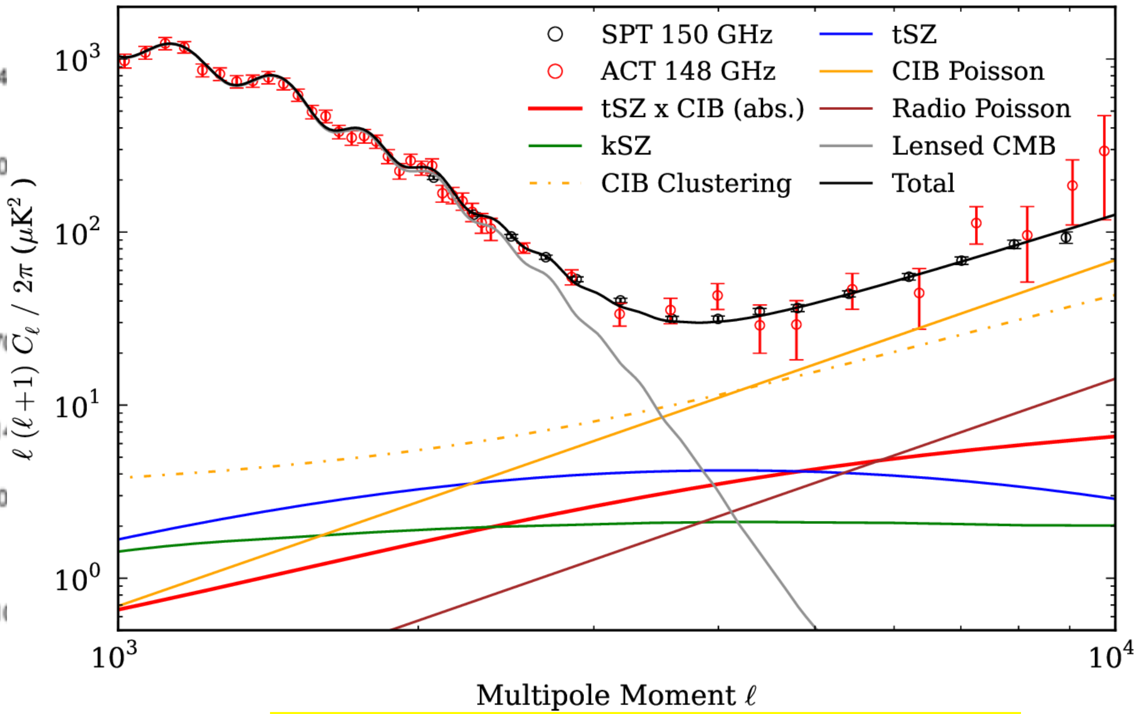










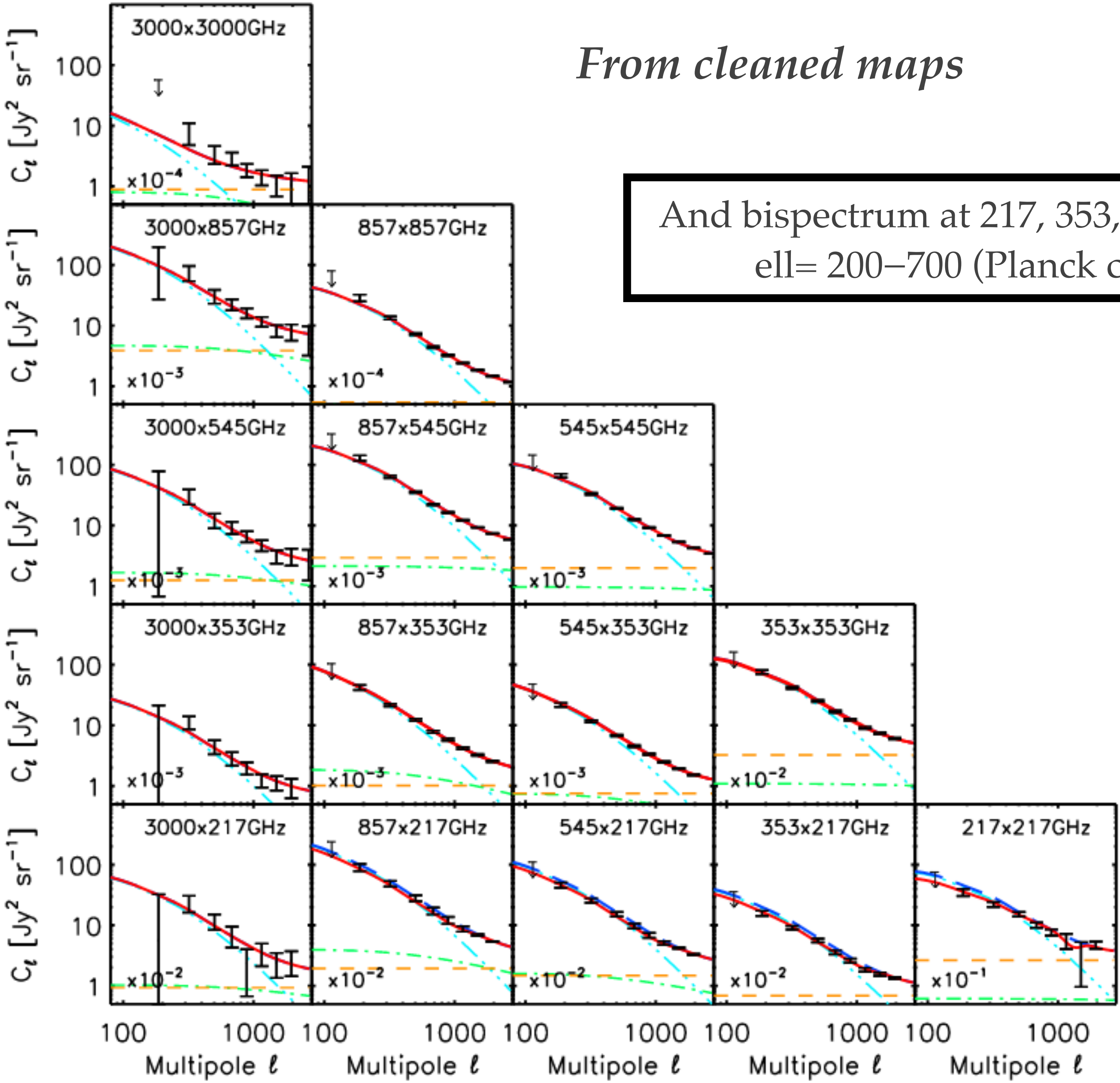


Planck collab 2018

My science is your noise!

CIB from Planck: power spectra

From cleaned maps

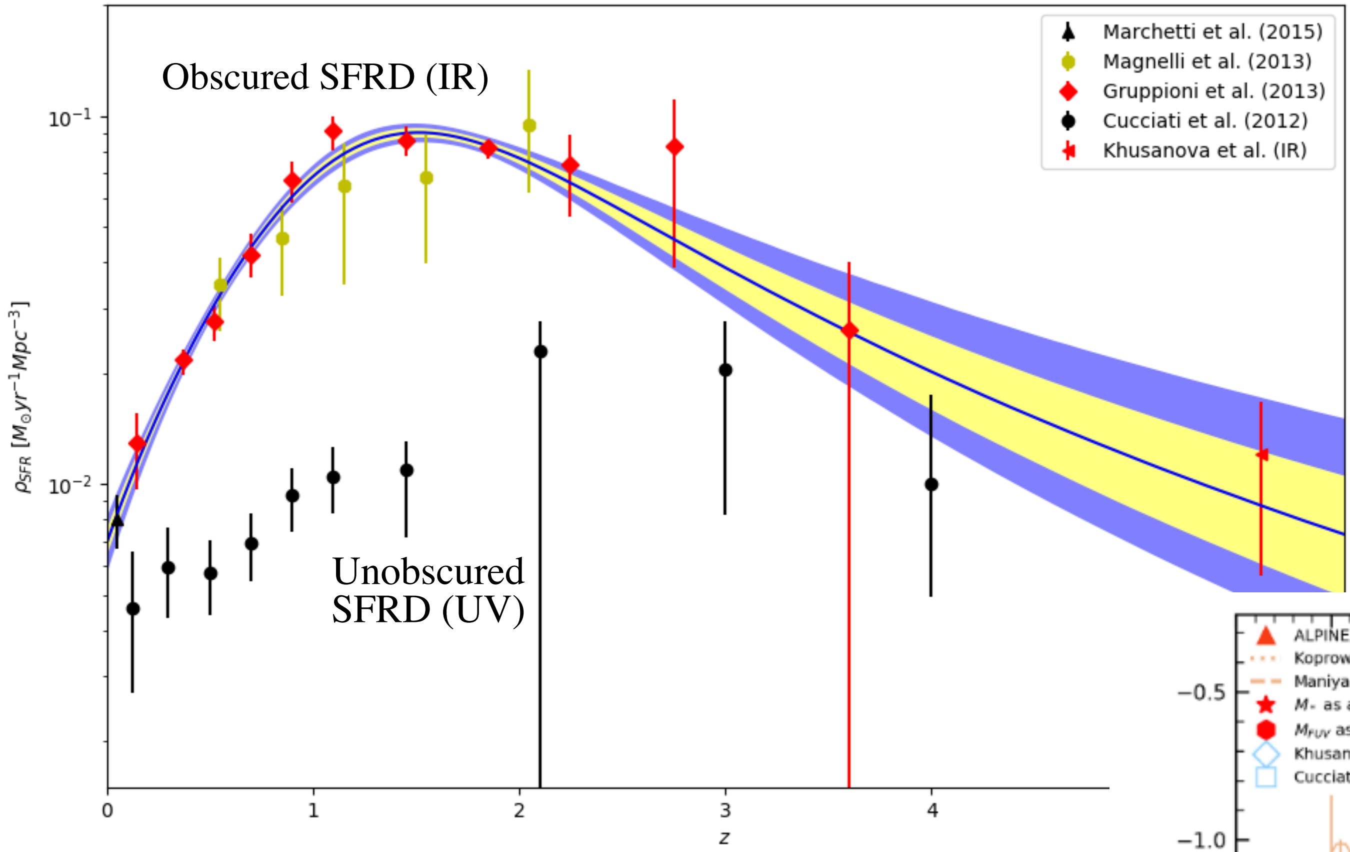


And bispectrum at 217, 353, 545 GHz in the range ell= 200–700 (Planck collab 2014 XXX)

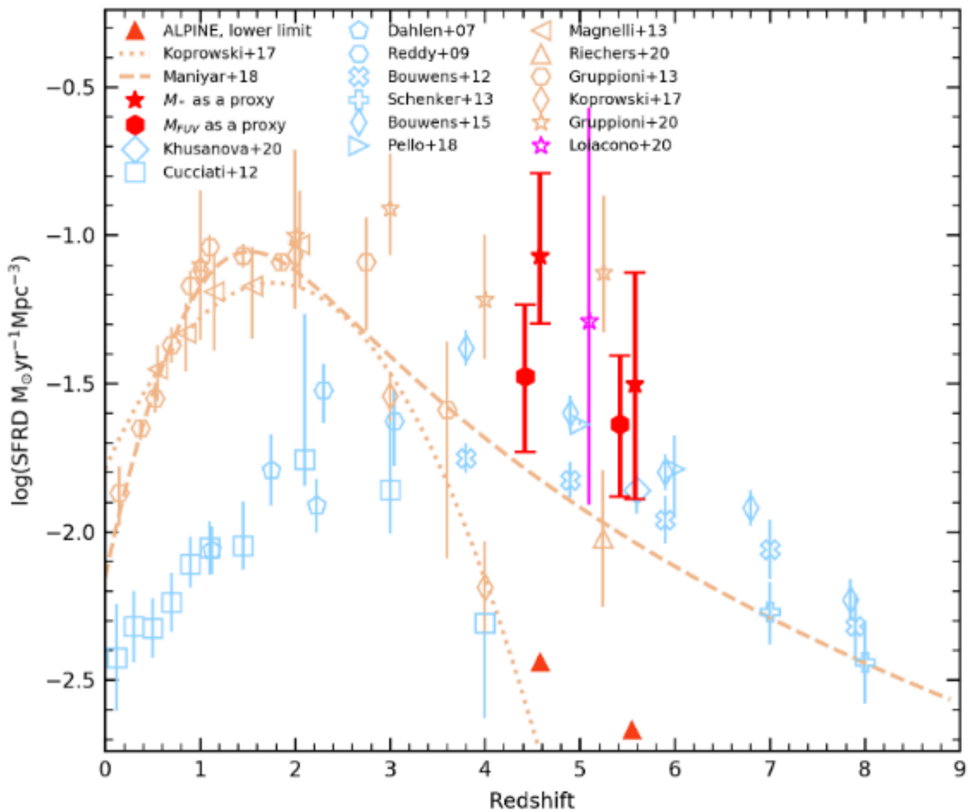
Planck collab 2014 XXX

From the CIB clustering on linear scales

CIB from Planck: SFRD



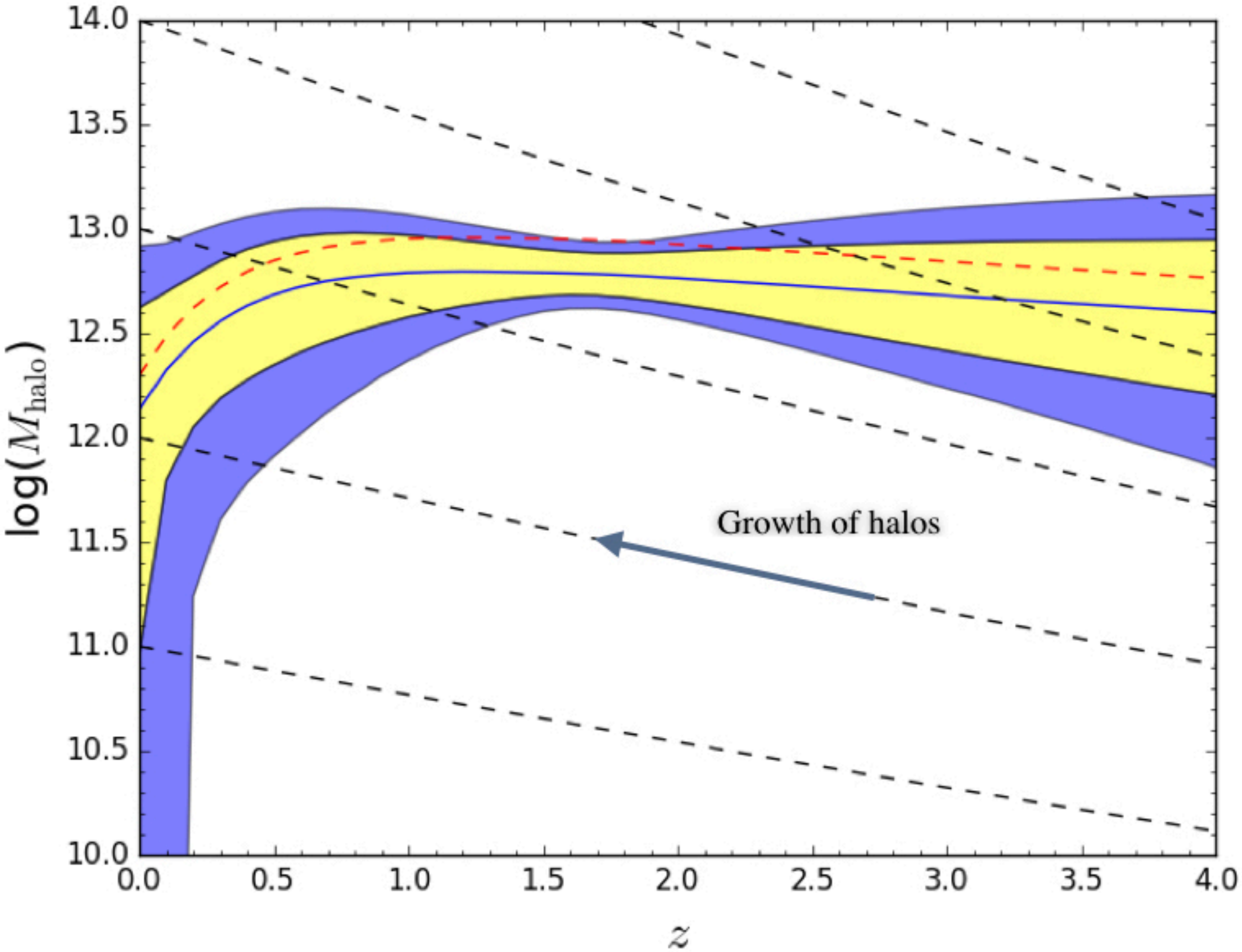
Maniyar et al. 2018



Khusanova et al. 2021

ALPINE ALMA [CII] large progam

CIB from Planck: most efficient mass halo



Mass of the dark matter halos hosting the galaxies contributing to the CIB as a function of redshift

For z > 2.5
$M_h(z=0) > 10^{13.5} M_\odot$
Progenitors of clusters

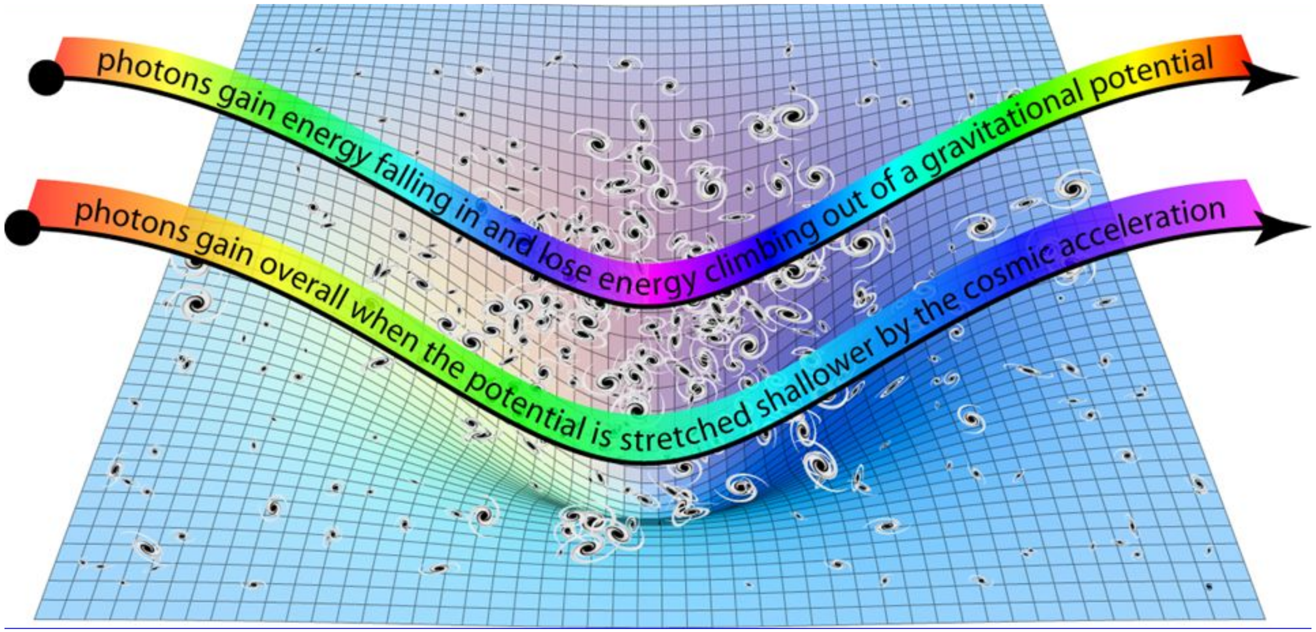
For 0.3 < z < 2.5
$10^{12.5} < M_h(z=0) < 10^{13.5} M_\odot$
Groups

For z < 0.3
$10^{12} < M_h(z=0) < 10^{12.5} M_\odot$
Milky Way like halos

Maniyar et al. 2018

CIBxCMB and Integrated Sachs Wolfe Effect

Much like gravitational lensing the ISW effect is gravitational but instead of probing the gravitational potential directly, it measures its time dependence along the line of sight.



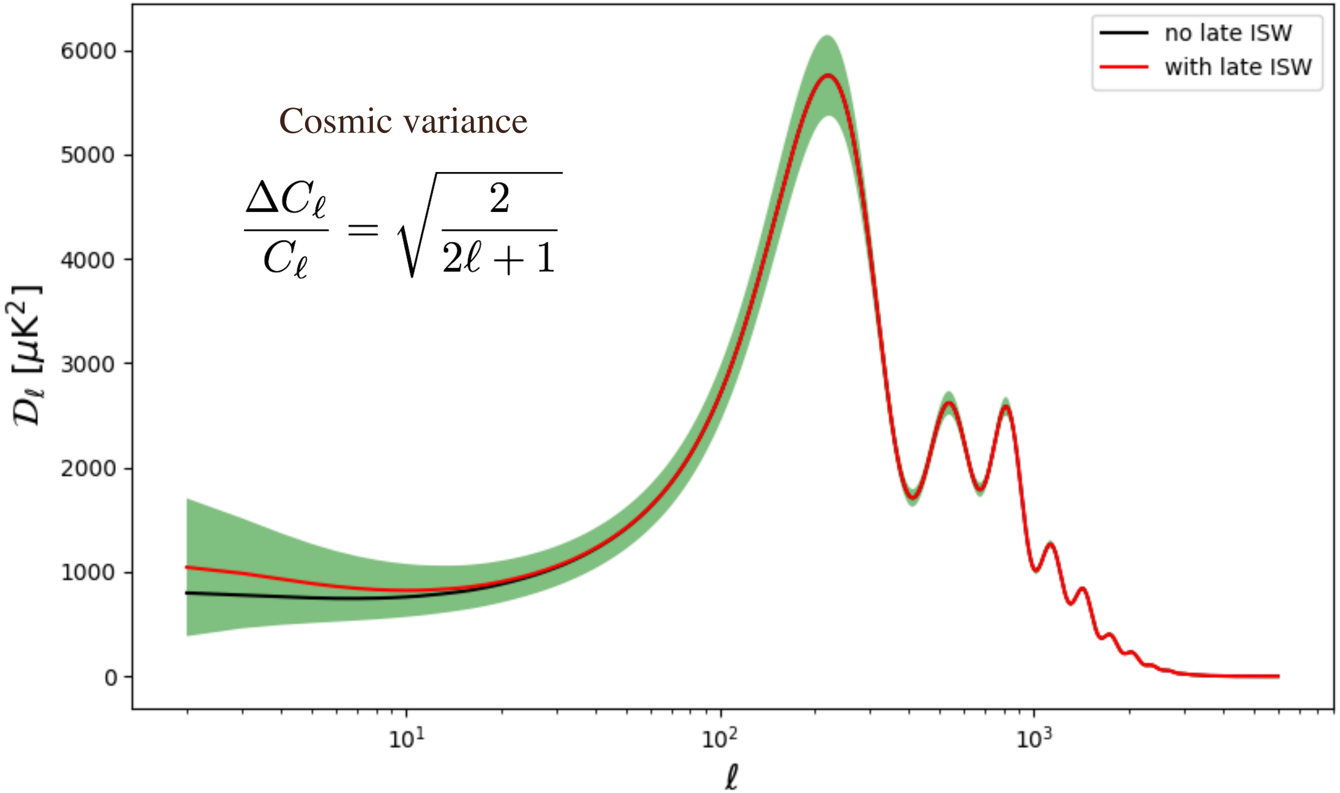
potential depth changes as CMB photons pass through

$$\frac{\delta T}{T} = -2 \int \dot{\Phi}(\tau) d\tau$$

The gravitational potential is actually constant in a matter dominated universe on large scales.

However, when the equation of state changes, so does the potential, and temperature anisotropies are created.

CIBxCMB and Integrated Sachs Wolfe Effect

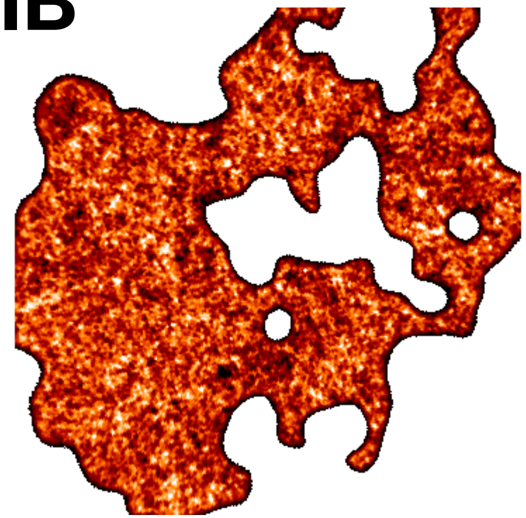


Integrated Sachs-Wolfe effect really small!

Cross-Correlation with LSS tracers

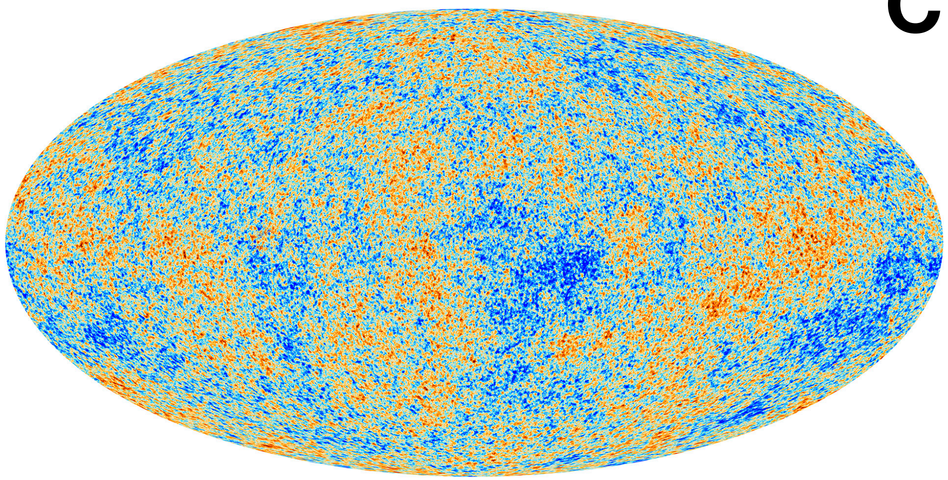
SNR going up to 4

CIB



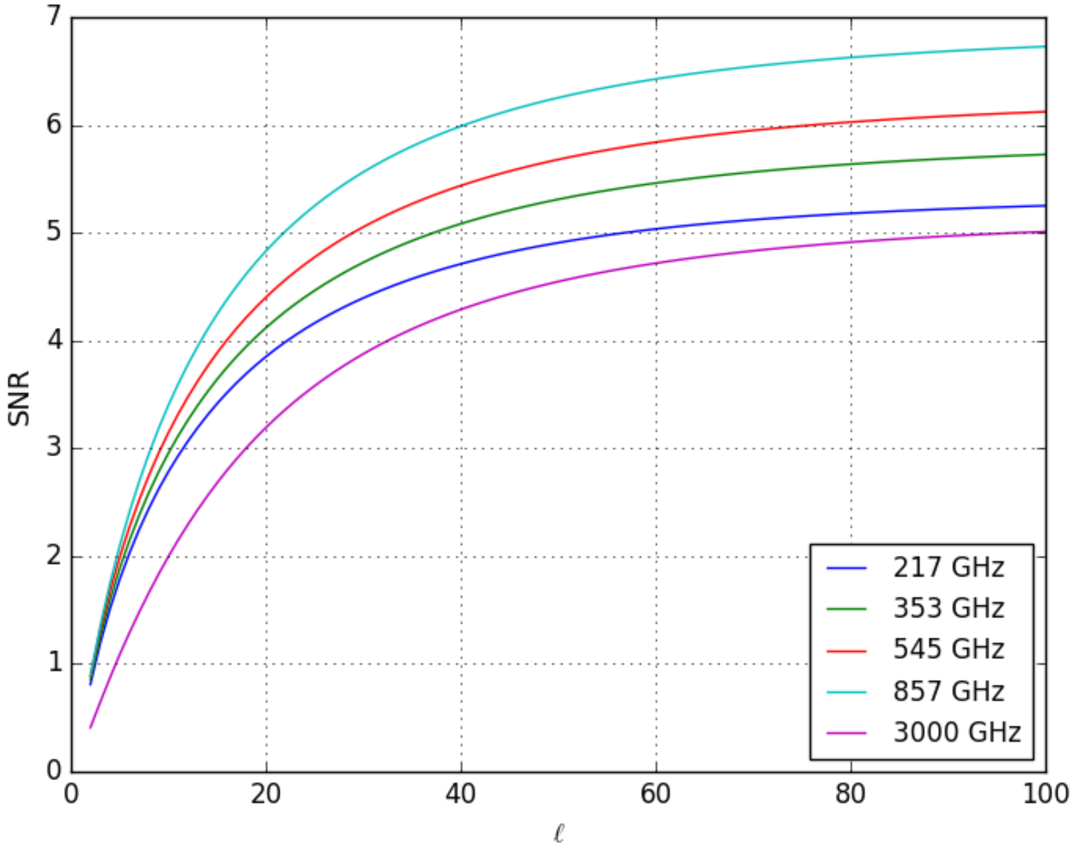
X

CMB



CIBxCMB and Integrated Sachs Wolfe Effect

Cumulative SNR for CIB-ISW cross-correlation

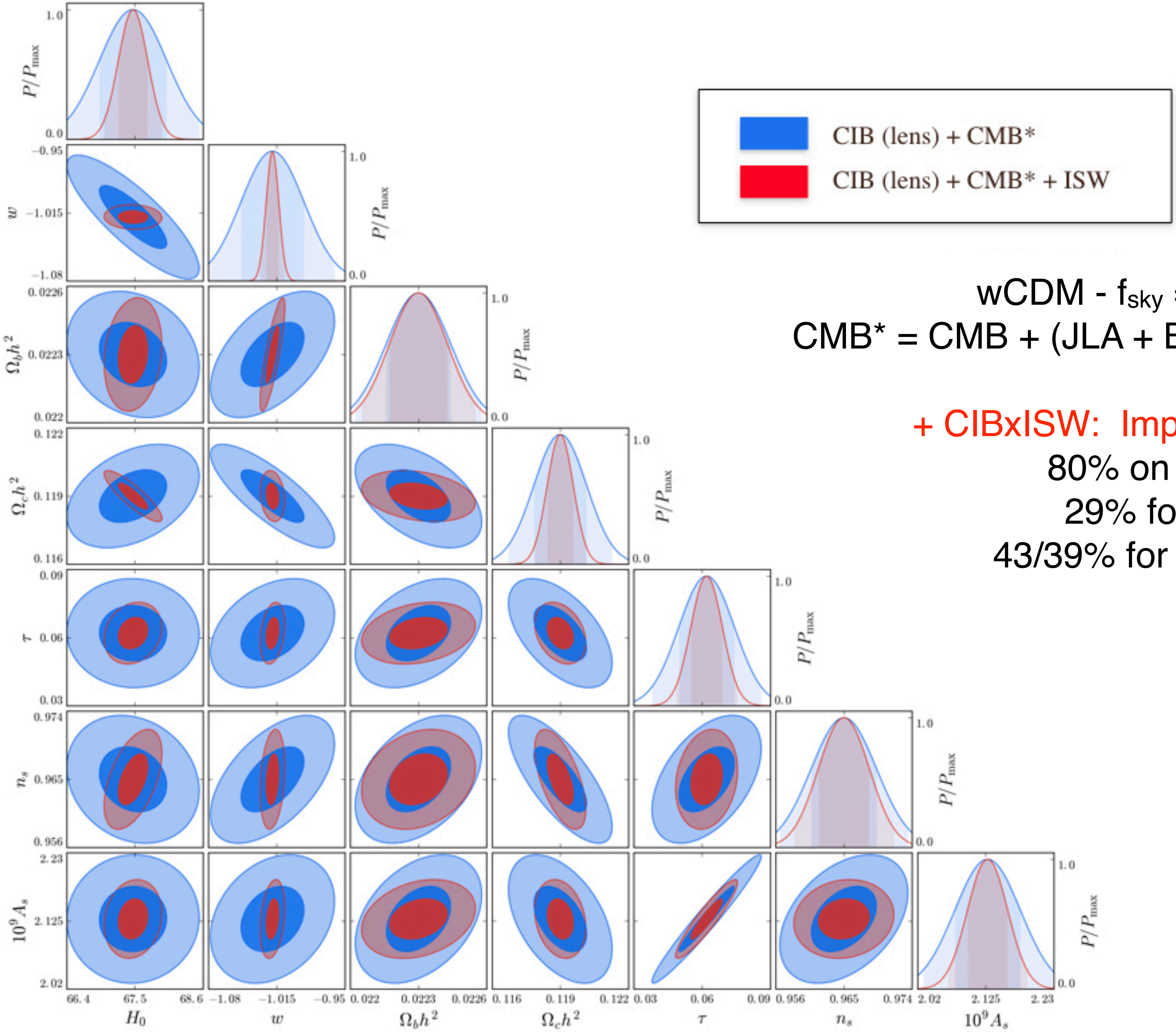


Freq. (GHz)	217	353	545	857	3000
SNR 100% f_{sky}	5.25	5.73	6.12	6.73	5.01
SNR 40% f_{sky}	3.32	3.62	3.87	4.26	3.17

Maniyar et al. 2019

With CIB: The best SNR for a single tracer!

CIB from Planck: ISW

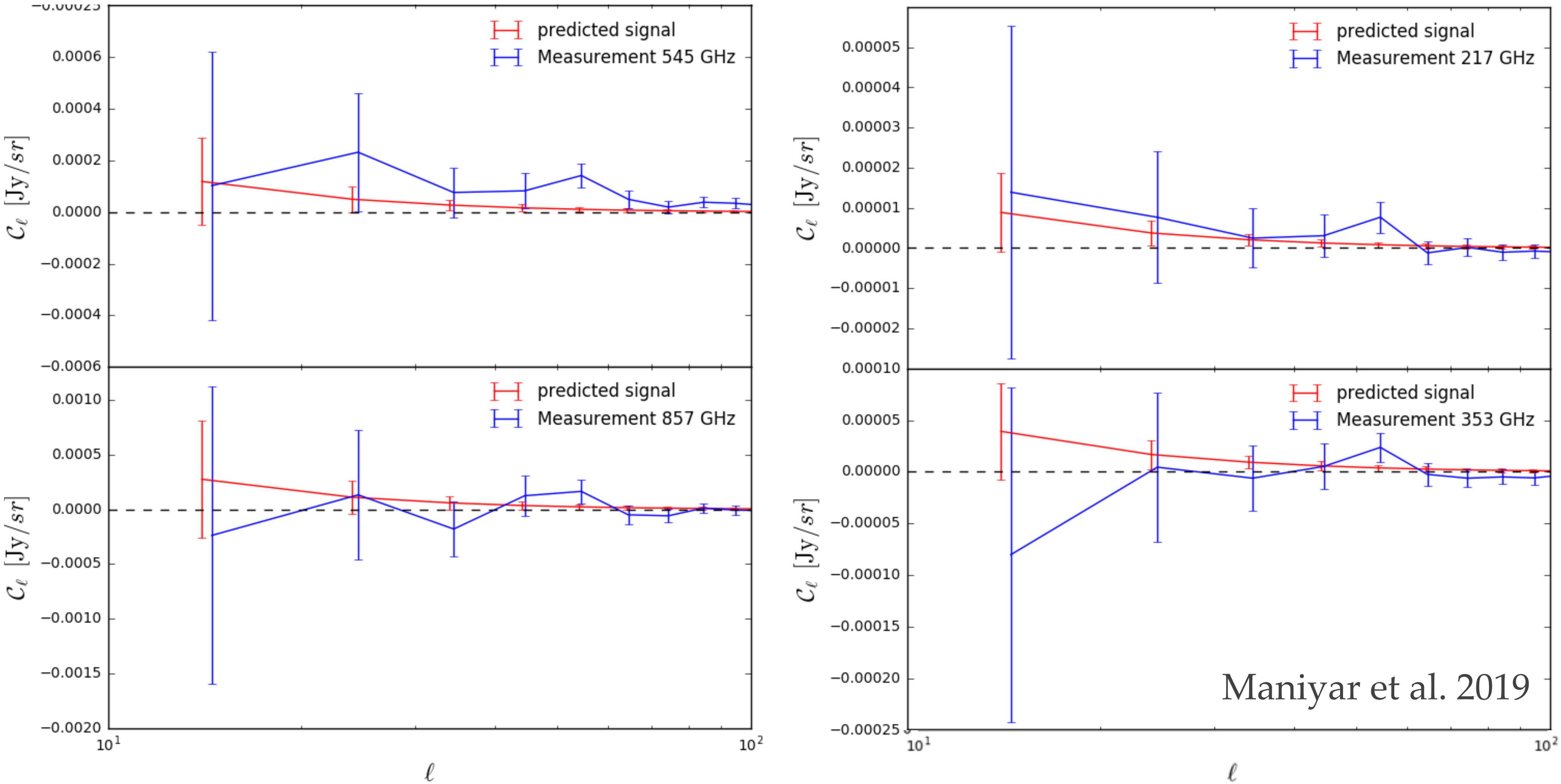


wCDM - f_{sky} = 70%
CMB* = CMB + (JLA + BAO and H0 prior)

+ CIBxISW: Improvement:
80% on w
29% for Ω_Λ
43/39% for τ/As

Maniyar et al. 2019

CIB from Planck: ISW

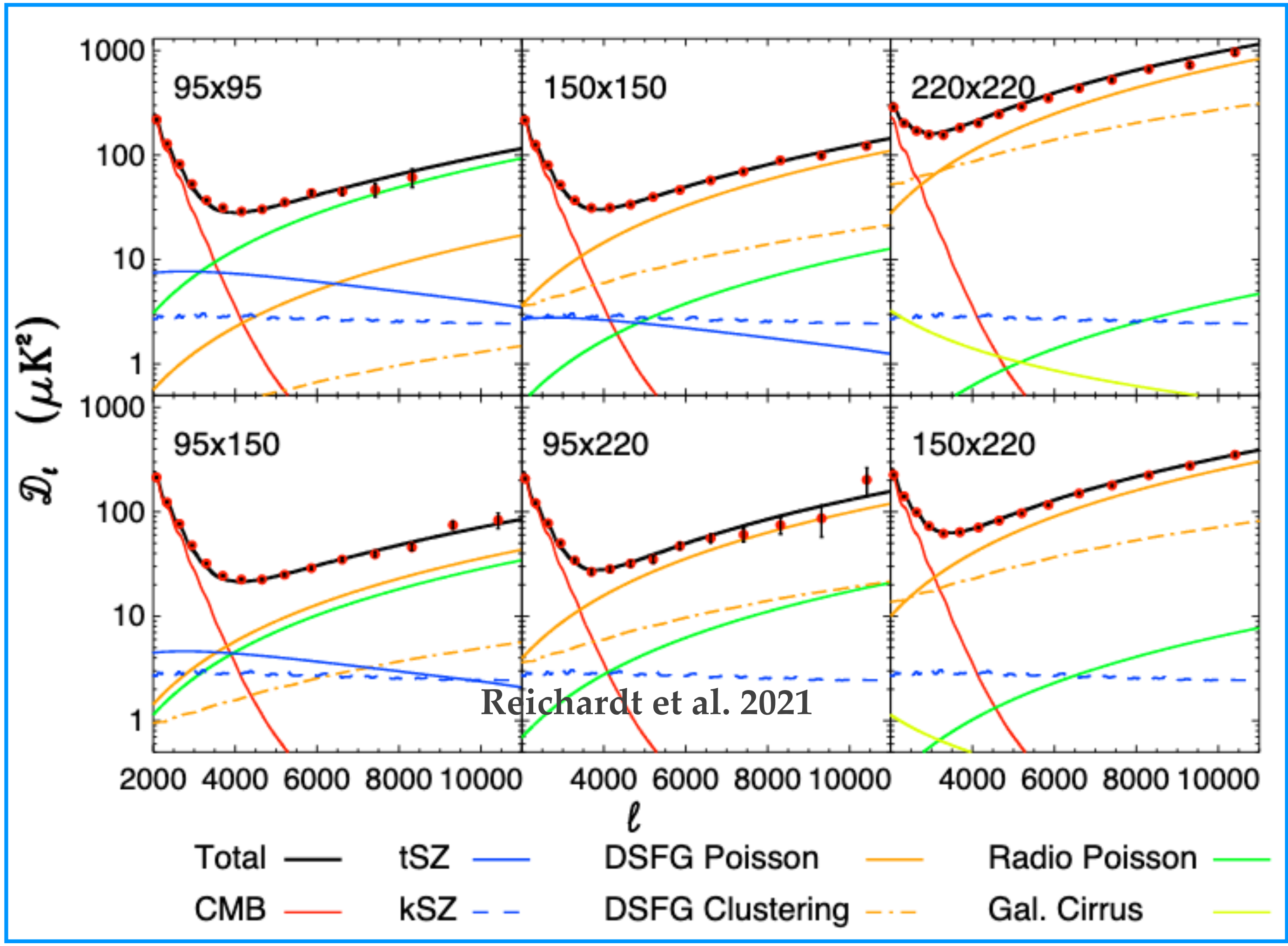


Measurement in the GASS CIB field

Degrade the S/N on the measurements by less than 10% on 40% of the sky =>
clean the dust up to the 0.01% level on the power spectrum!

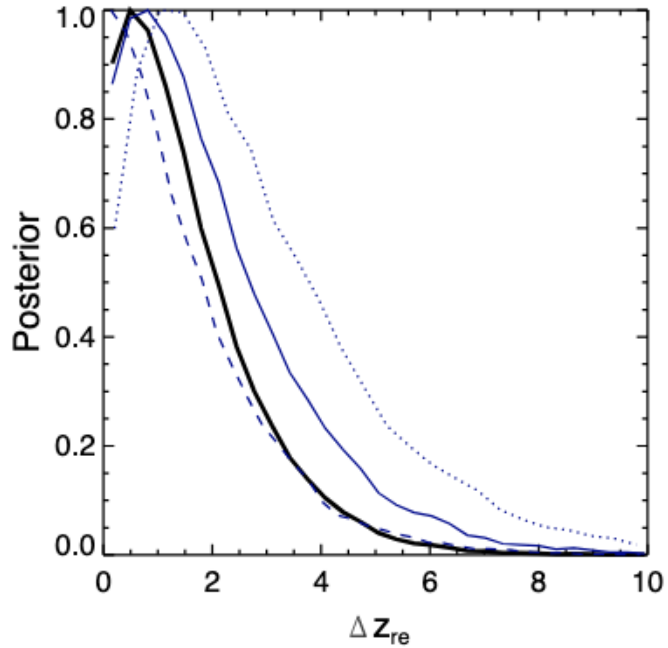
On small scales

Towards kSZ



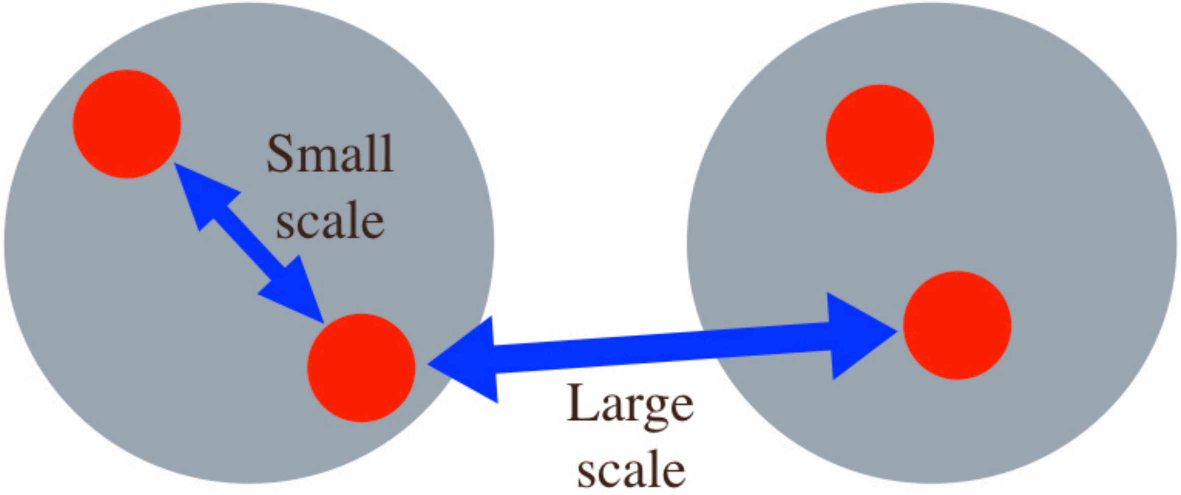
$$D_{3000}^{\mathrm{kSZ}} = 3.0 \pm 1.0\,\mu\mathrm{K}^2$$

Duration of reionisation from kSZ



- Power law/best fit templates for the CIB, tSZ, and CIB x tSZ
- Different frequency channels assumed to be perfectly correlated for the CIB
- Inconsistencies between the CIB, tSZ and CIB x tSZ templates
- Cosmology dependance

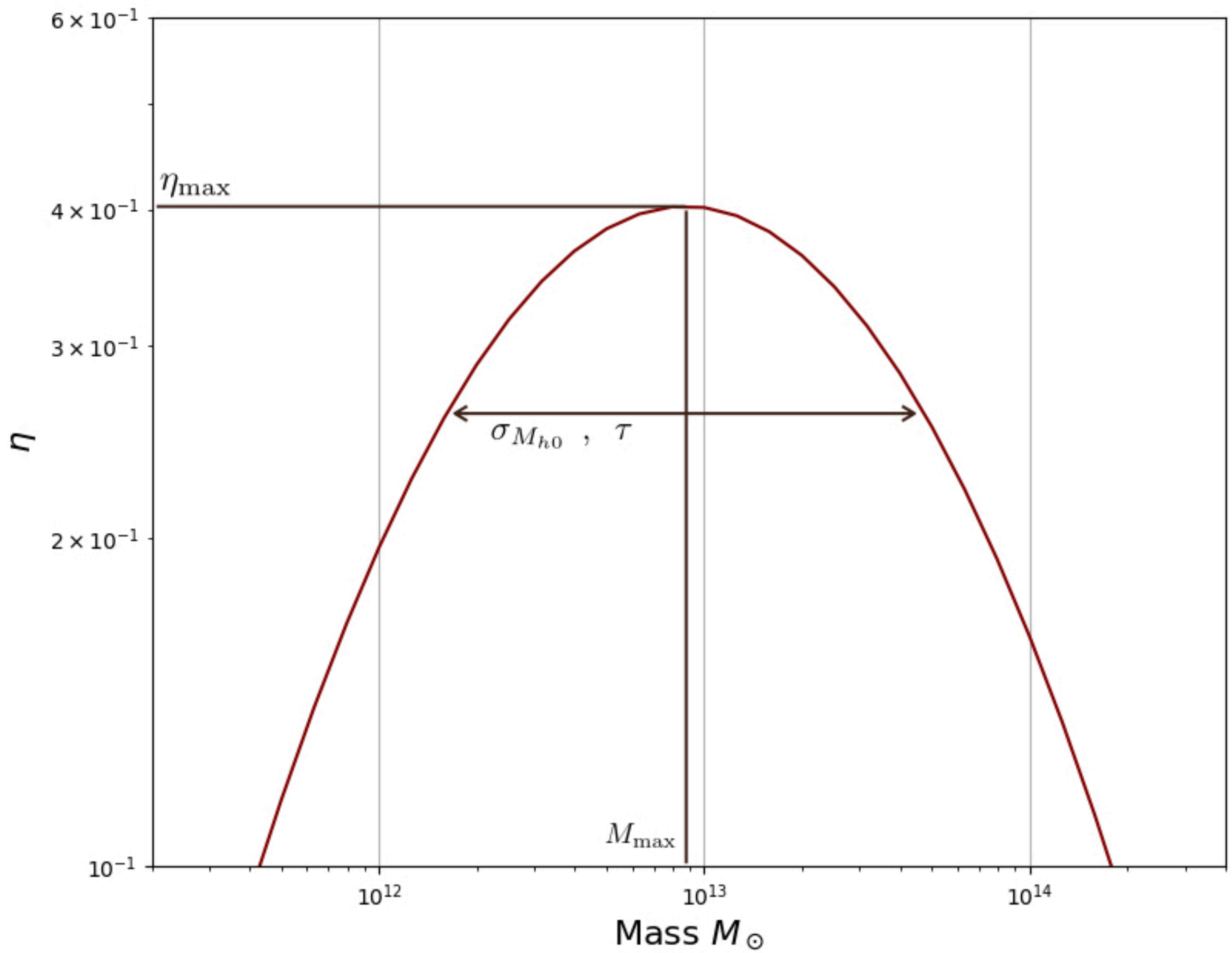
A new halo model for CIB



Previous halo models:

- L-M relation
- High number of parameters
- Results not consistent with linear models/data => SFRD

A new halo model for CIB



Baryonic Accretion Rate

$$\mathrm{BAR}(M,z) = \langle \dot{M}_h(M,z)\rangle \times \Omega_b(z)/\Omega_m(z)$$

Efficiency to convert accreted baryons into stars

$$\frac{\mathrm{SFR}}{\mathrm{BAR}} = \eta = \eta_{\max}\, e^{-\frac{(\log M_h - \log M_{\max})^2}{2\sigma^2_{M_h}}}$$

Calculating SFR

$$\mathrm{SFR}(M_h,z) = \eta(M_h,z) \times \mathrm{BAR}(M_h,z)$$

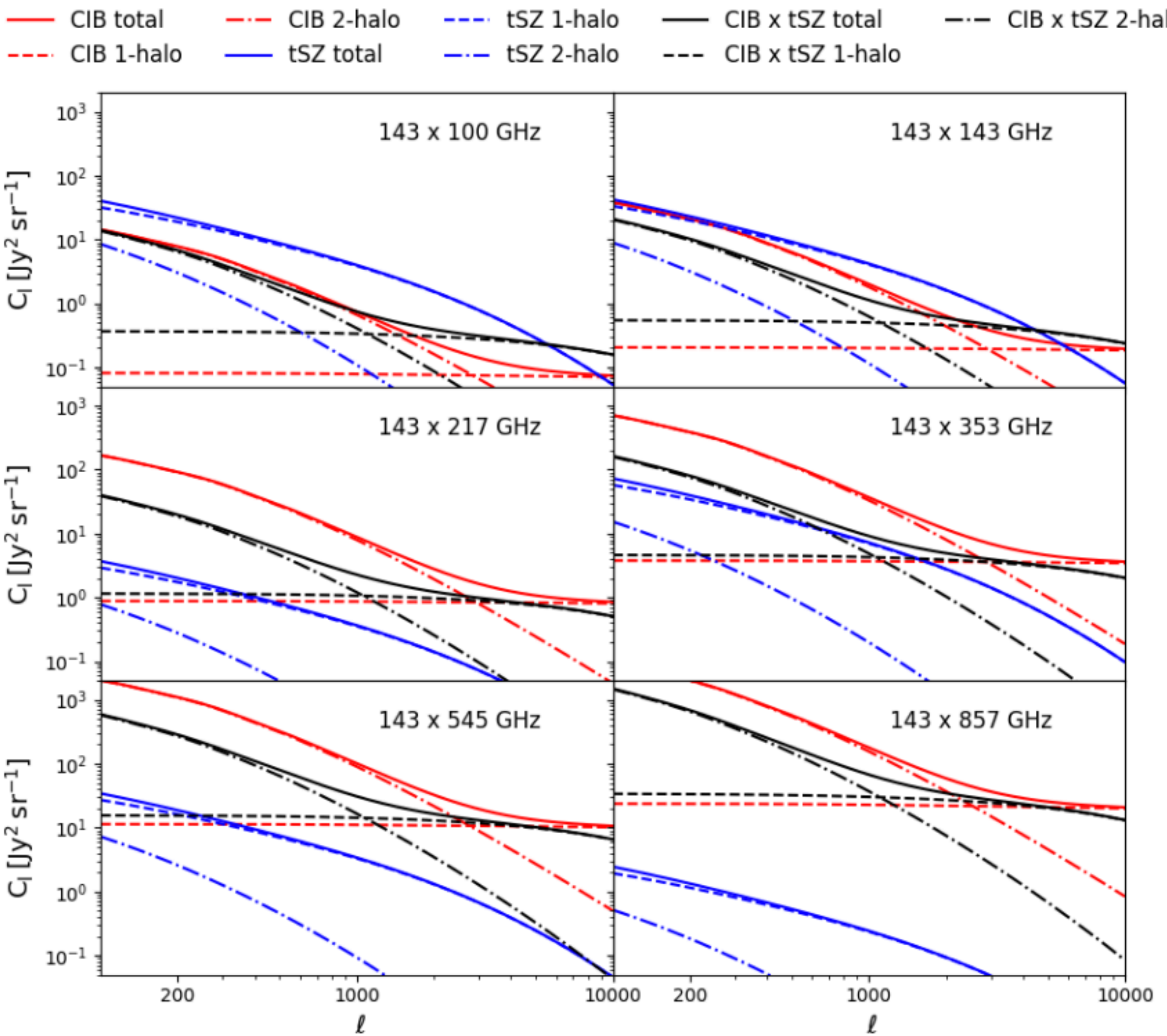
$$\mathrm{SFR} \Rightarrow \frac{dj_\nu}{d\log M}(M,z) \Rightarrow C_\ell^{\nu,\nu'}$$

And evolution in width+shape of the lognormal with redshift

Only 4 parameters

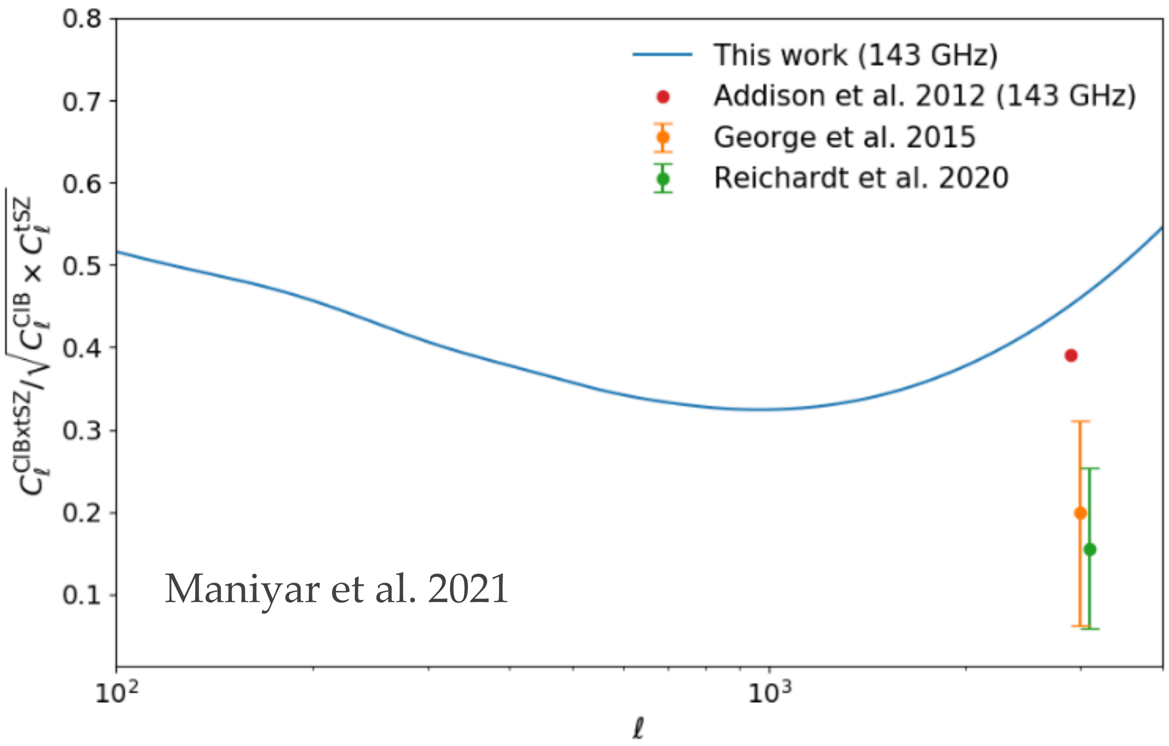
Maniyar et al. 2021

CIBxtSZ



Maniyar et al. 2021

CIBxtSZ: towards kSZ



In collaboration with
M. tristram and Xavier Garrido

- ✓ High-l Likelihood on Polarized Power spectra (HiLLiPOP) likelihood
- ✓ Combining different frequency data (Planck and SPT for the CMB; Herschel/Spire, Planck/HFI for the CIB)
- ✓ Replacing old templates for foregrounds with halo models
- ✓ Cosmology dependance of all the foregrounds explicitly considered at every step

Stay tuned!

Epoch of Reionization: When?

- The Planck breakthrough (Planck collaboration 2016, XLVI & XLVII; 2018 VI):
  - Scattering optical depth due to free electrons:

$$\tau(z) = \int_{t(z)}^{t_0} n_e \sigma_T \, c\,dt$$

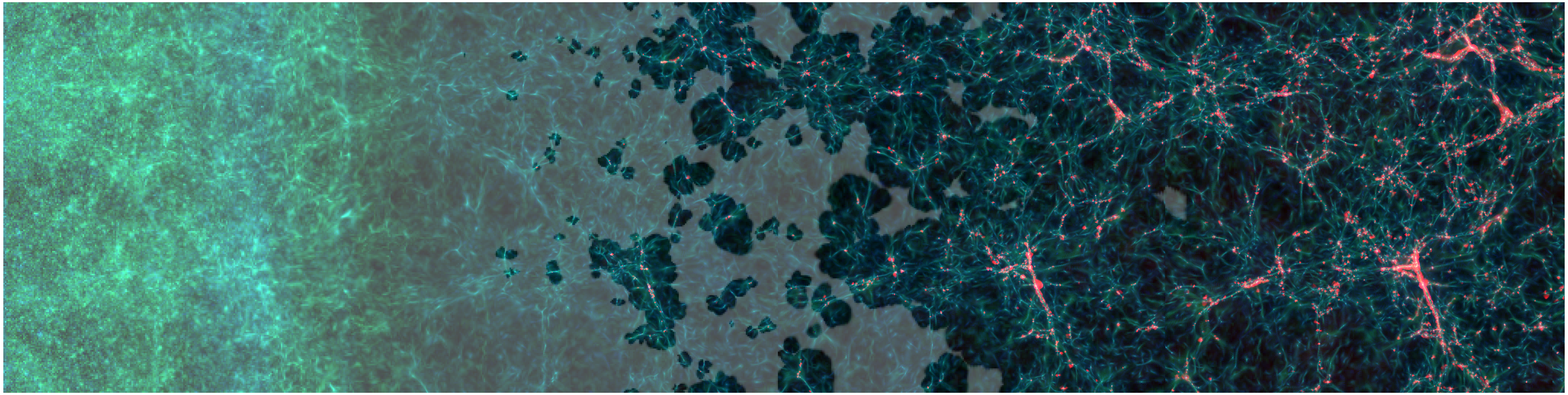
n_e is the number density of free electrons
σ_T is the Thomson scattering cross section

  - $\tau = 0.054 \pm 0.007$ (Previously WMAP: 0.089 ± 0.014)
  - Average redshift of reionization: z~8
  - Universe is ionized at less than the 10% level at z>10.
- From the quasars absorption along the LoS: reionization ends at z~6

=> Reionization is extremely rapid and at our fingerprints!

We have now a reasonable handle of when….

The Epoch of Reionisation: what and how?



EMMA simulation, D. Aubert & N. Deparis

… But what and how?…… we don't really know!

Stellar populations vs black holes, IMF in first galaxies, role of supernovae and radiative feedback, metal pollution, efficiency of star formation, IGM structures, UVB evolution etc..

Galaxy candidates have been found out to z~10. Are these the stellar populations responsible for the Cosmic Dawn and reionization?

The Epoch of Reionisation: galaxy candidates

@ z=8

Hubble limit

JWST limit

Hidden population of faint and abundant galaxies?

Complete reionisation

M_{AB}=-22

M_{AB}=-18

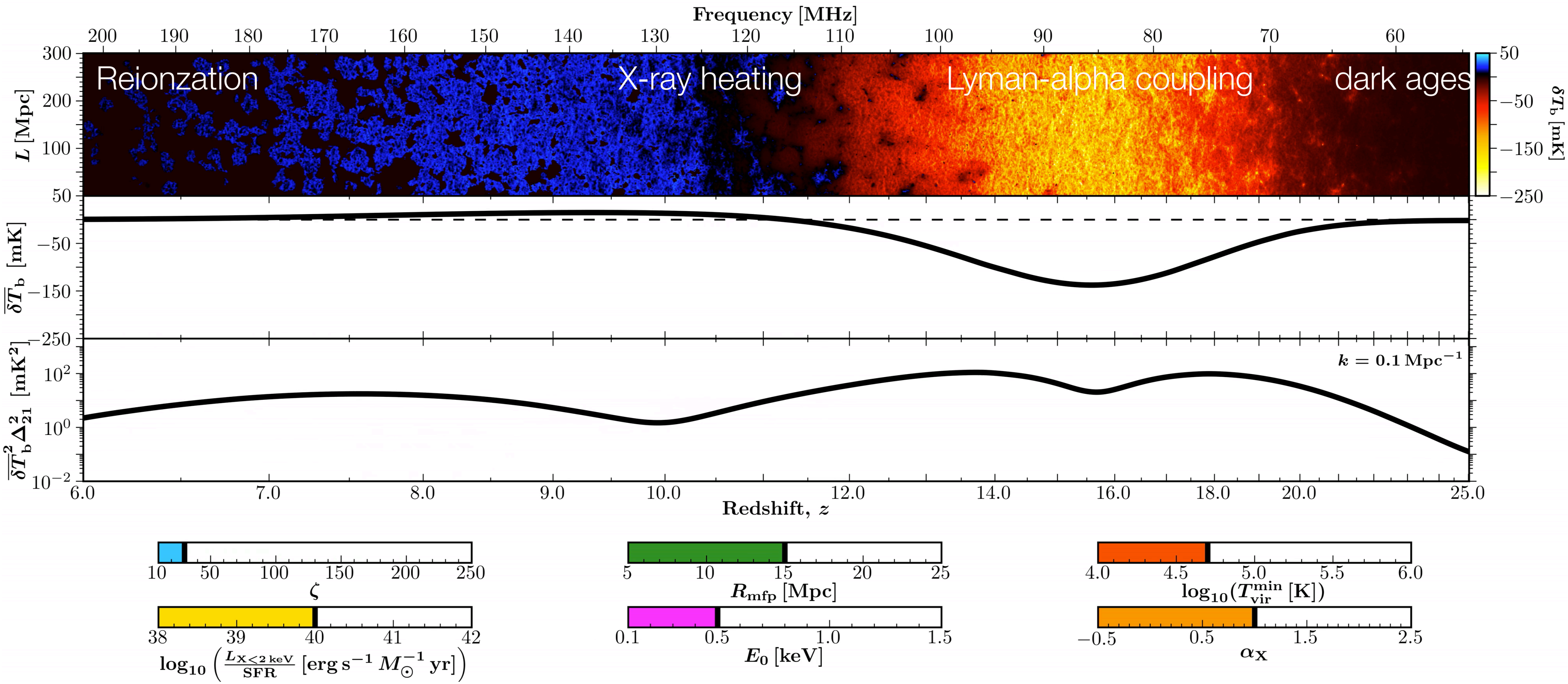
M_{AB}=-14

M_{AB}=-10

Idea: Mesinger

HI in the EoR: difficult to predict

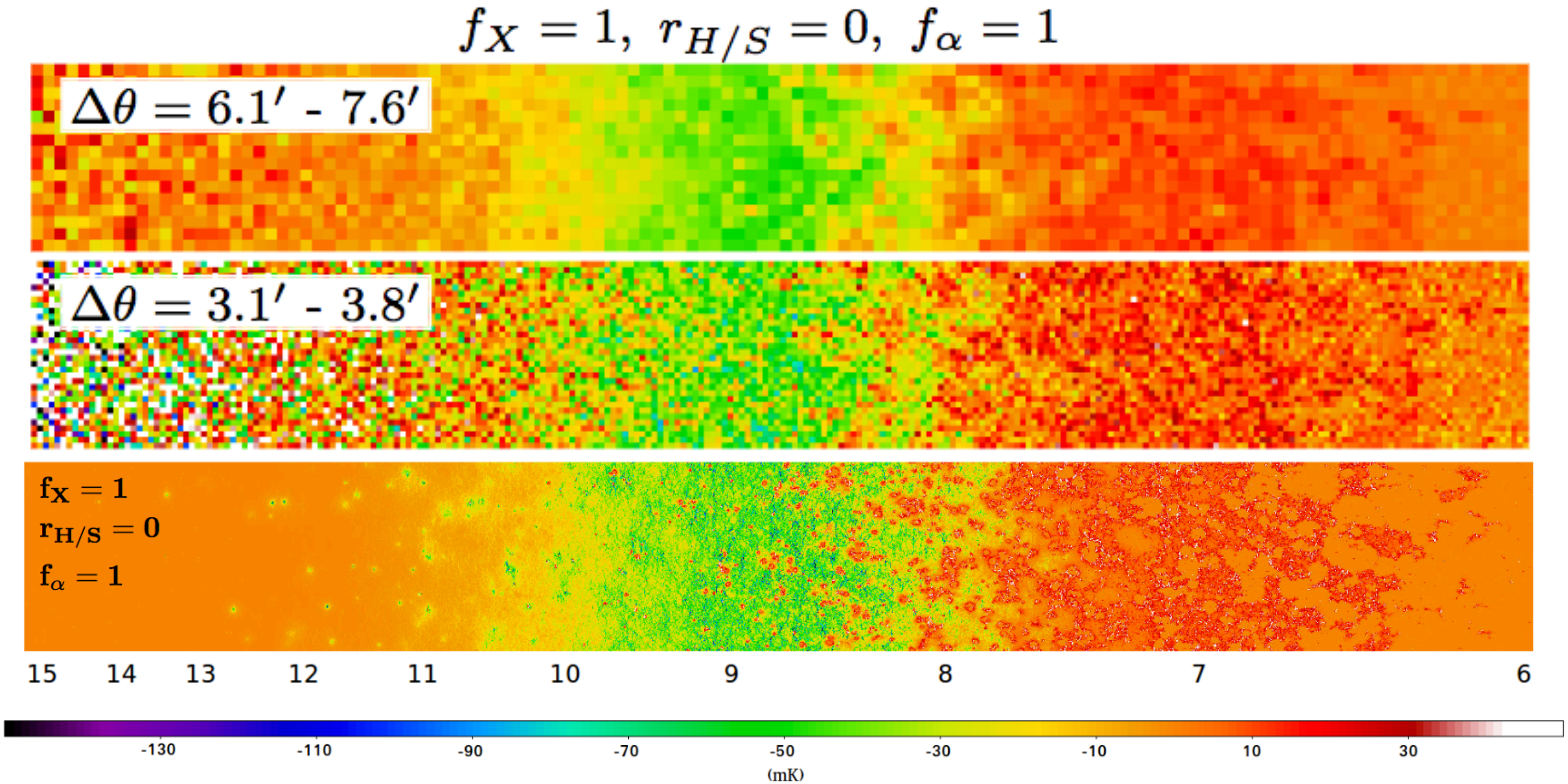
Movie from Bradley Greig, Greig & Mesinger, 2015, 2017….. in the case of faint galaxies…..



Different astrophysical models of galaxies and the IGM show different 21-cm power spectra
A lot of degeneracies

Variation is up to a factor of ~10, at a fixed cosmic epoch…

HI in the EoR: difficult to detect

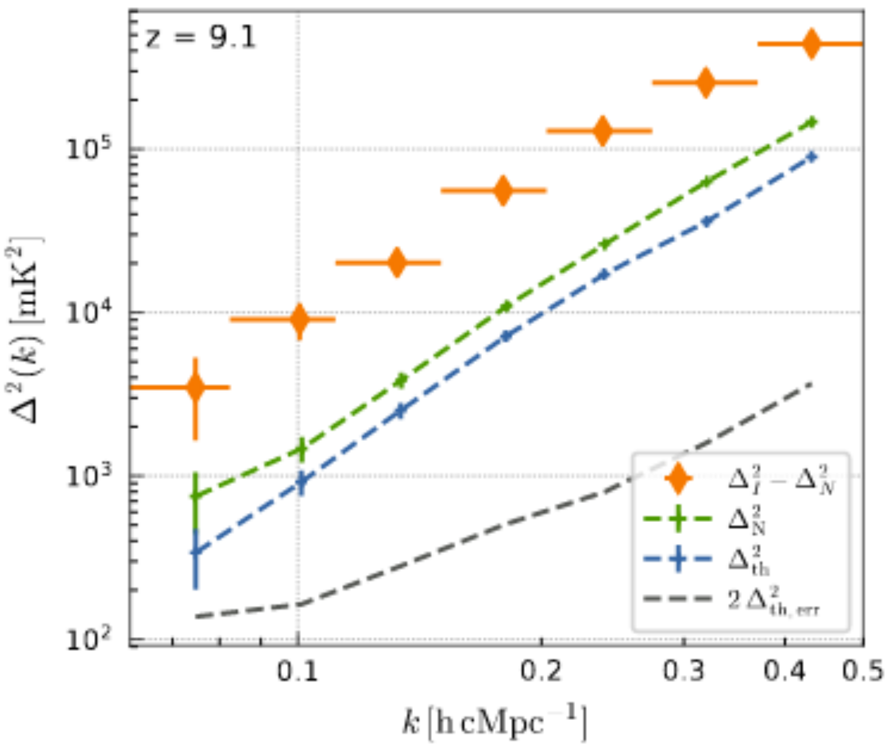


Tomography becomes difficult at z > 10

From Semelin et al. 2017, assuming 1000hr of SKA

First results

LOFAR EoR KSP (upper limits)



Mertens+2020

- Excess noise that is not solved yet.
- Results with only 141 hours are published (extrapolation to 1700h => EoR signal could be detected).
- Ghara+2020: constraints on the thermal and ionization states of the intergalactic medium (IGM): can rule out some extreme models

+ Gehlot+19 (for an upper limit at z~20) + Li, Pober+19 (MWA, z~7)

SKA

- The signal is faint but our future is bright
  - SKA1 and SKA will be the most sensitive radio telescopes to explore the cosmological dawn when the first galaxies formed

- SKA will trace the reionization of the intergalactic medium, but will not observe the young stars /black holes responsible for it.

=> Cross-correlation and joint analysis:

  - Get information on the nature of the sources, the statistical measure of average reionisation bubble size and ionisation fraction, redshift and duration of reionisation
  - Advantageous since the measurable statistics do not suffer in the same way from foregrounds and systematic effects as is the case of auto-correlation function measurements

Virtual Meeting LAM — 10th of March, 10am-12 — SKA, LOFAR and Nenuphar
Registration: https://doodle.com/poll/yru83gp49wetgz93

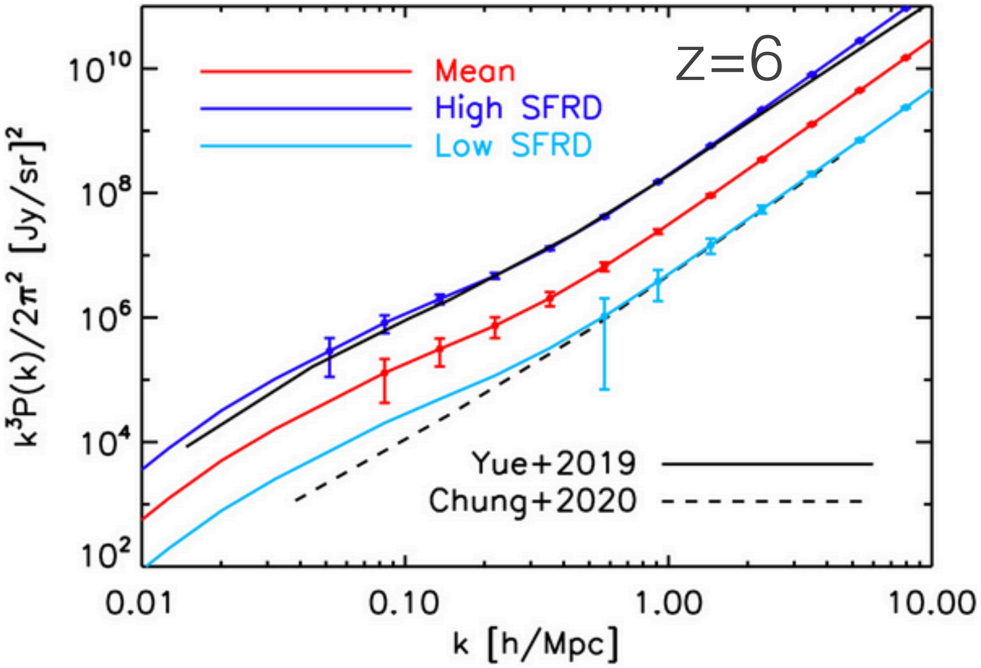
CONCERTO

A new spectrometer to map the intensity fluctuations of the [CII] line at z>5.2

LAM, Institut Néel, LPSC, IPAG
And European partners (science)

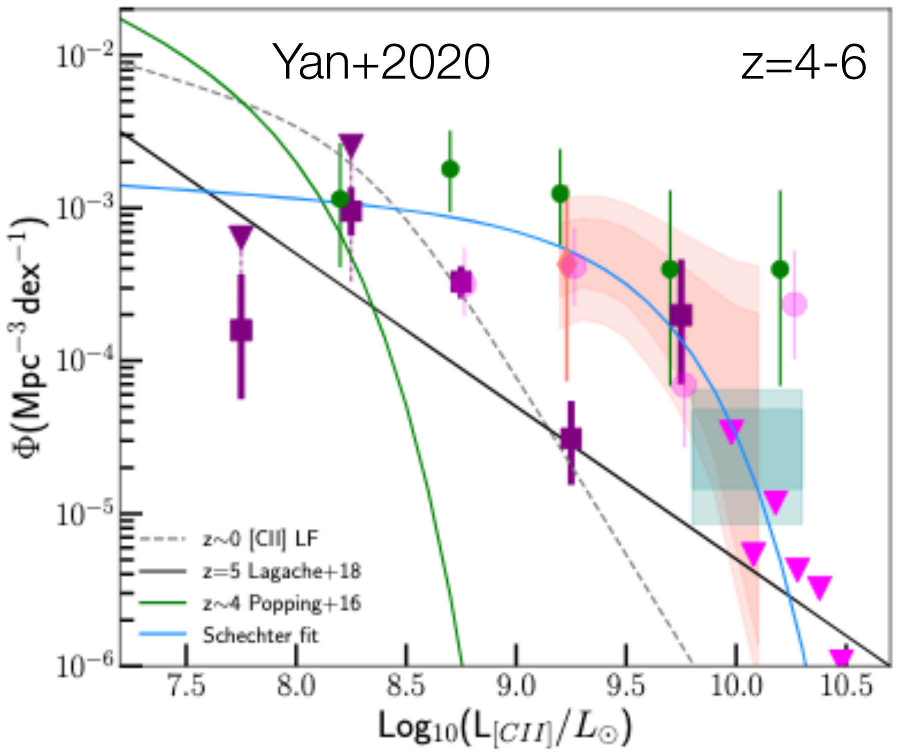
https://mission.lam.fr/concerto/

CONCERTO: scientific objectives



Survey of 1.4 Sq. deg. - COSMOS field
1,200h of observations (840h on field)

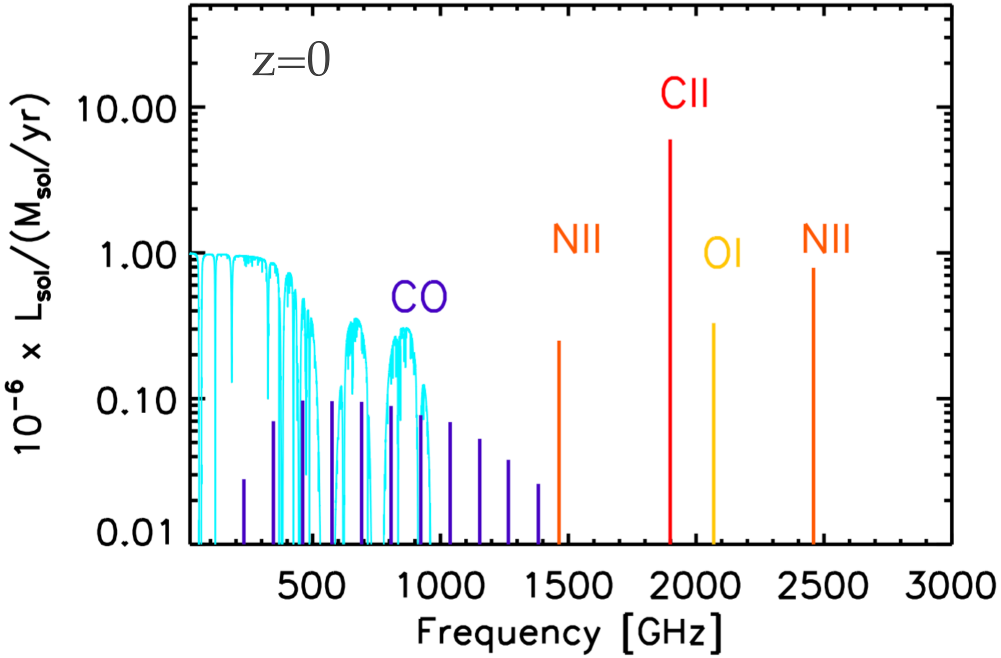
ESO LP + Chilean + Swedish time

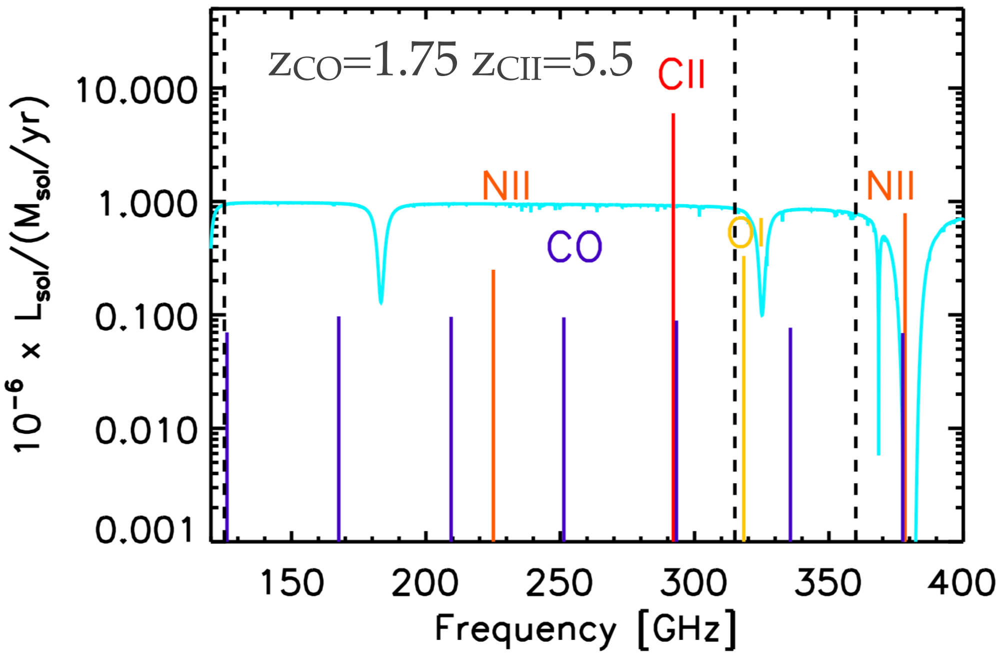


- « Dusty» SFRD for z>5.2
- [CII] luminosity- Mh relation, typical halo mass scale of SF galaxies
- Weighted dark-matter halo mass integral of the [CII] luminosity function
- Number counts of [CII]-emitters as a function of z.
- Average ISM conditions in high-z galaxies: Cross-power spectra of the [CII] line with the [OI] and the [NII] lines.

CONCERTO: scientific objectives

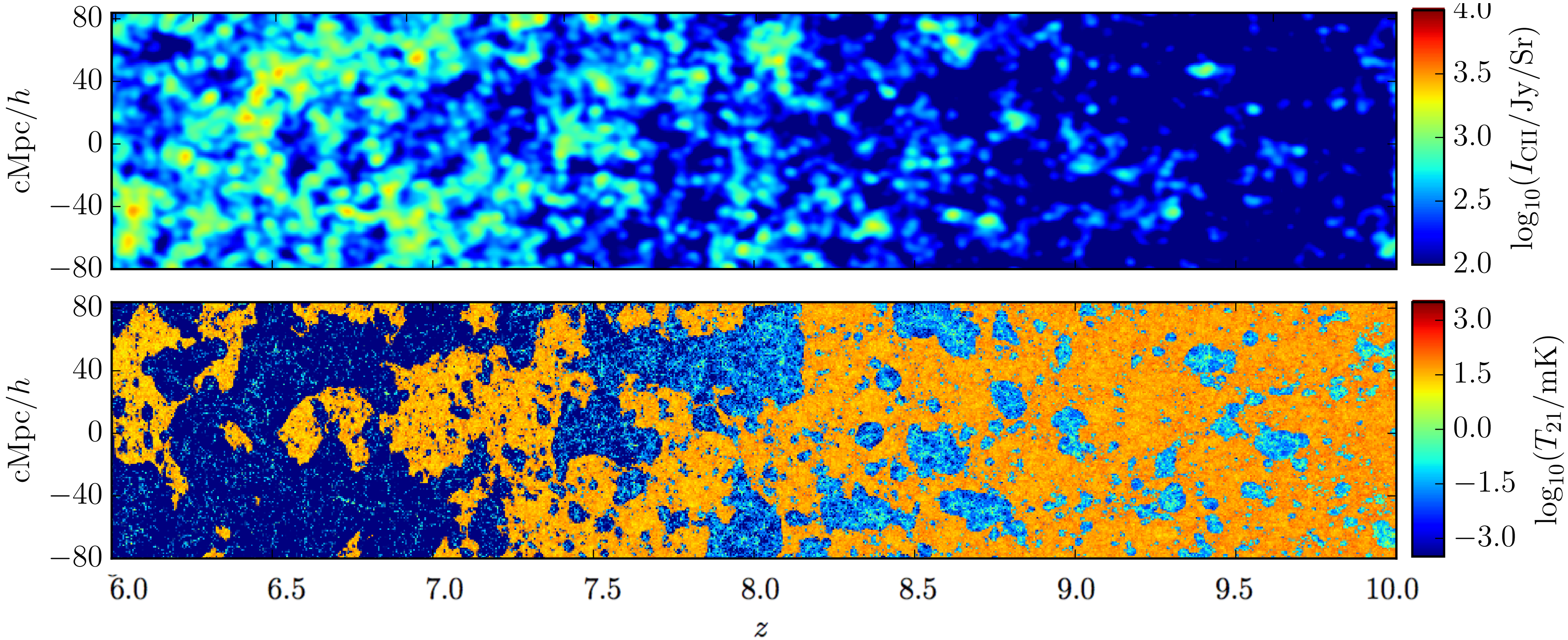
- CO emission at $z<1.9$ (for the rotational levels up to J=5):



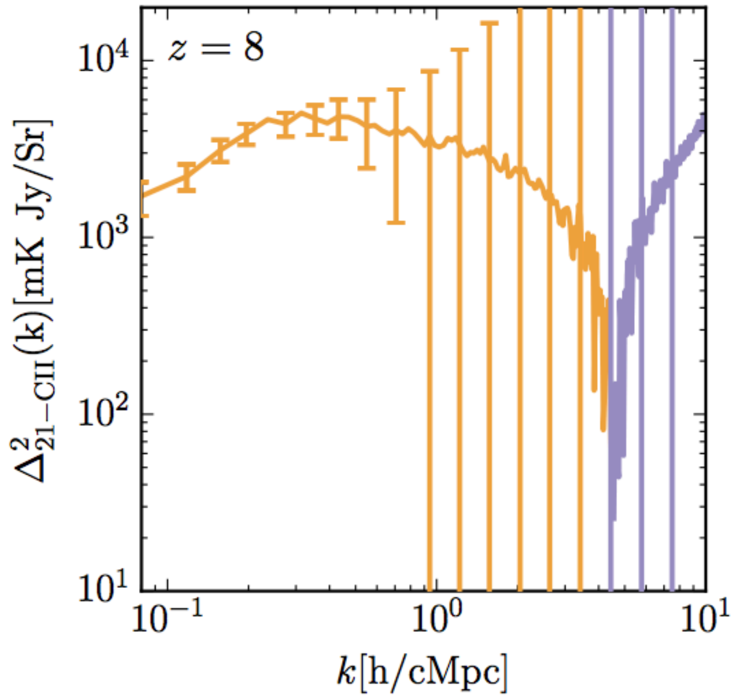


- Cross-correlation with galaxies: gas content in galaxies (up to z~2)
- Cross-power spectrum of two CO lines at the same redshift, within CONCERTO:
  - A measure of the 3D clustering of undetected galaxies

HI x [CII] intensity mapping



Dumitru et al, 2019



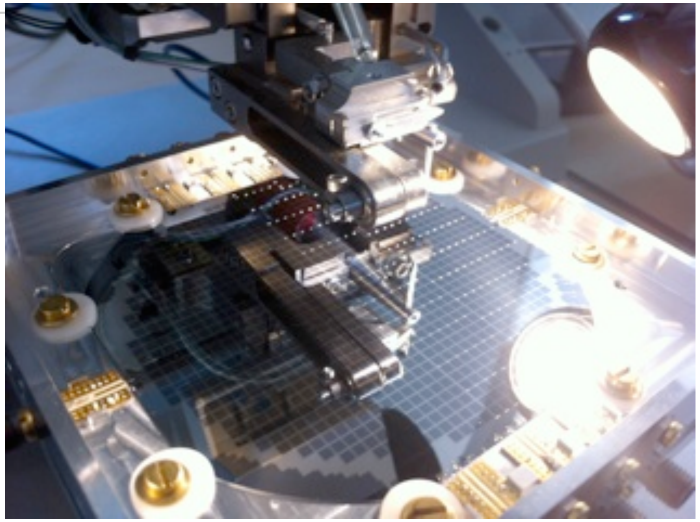
Galaxy-dominated late reionisation model

HI (LOFAR) x CONCERTO (CII - 16 Sq. Deg.)

=> Nature of sources

=> ionized bubbles growth during reionization

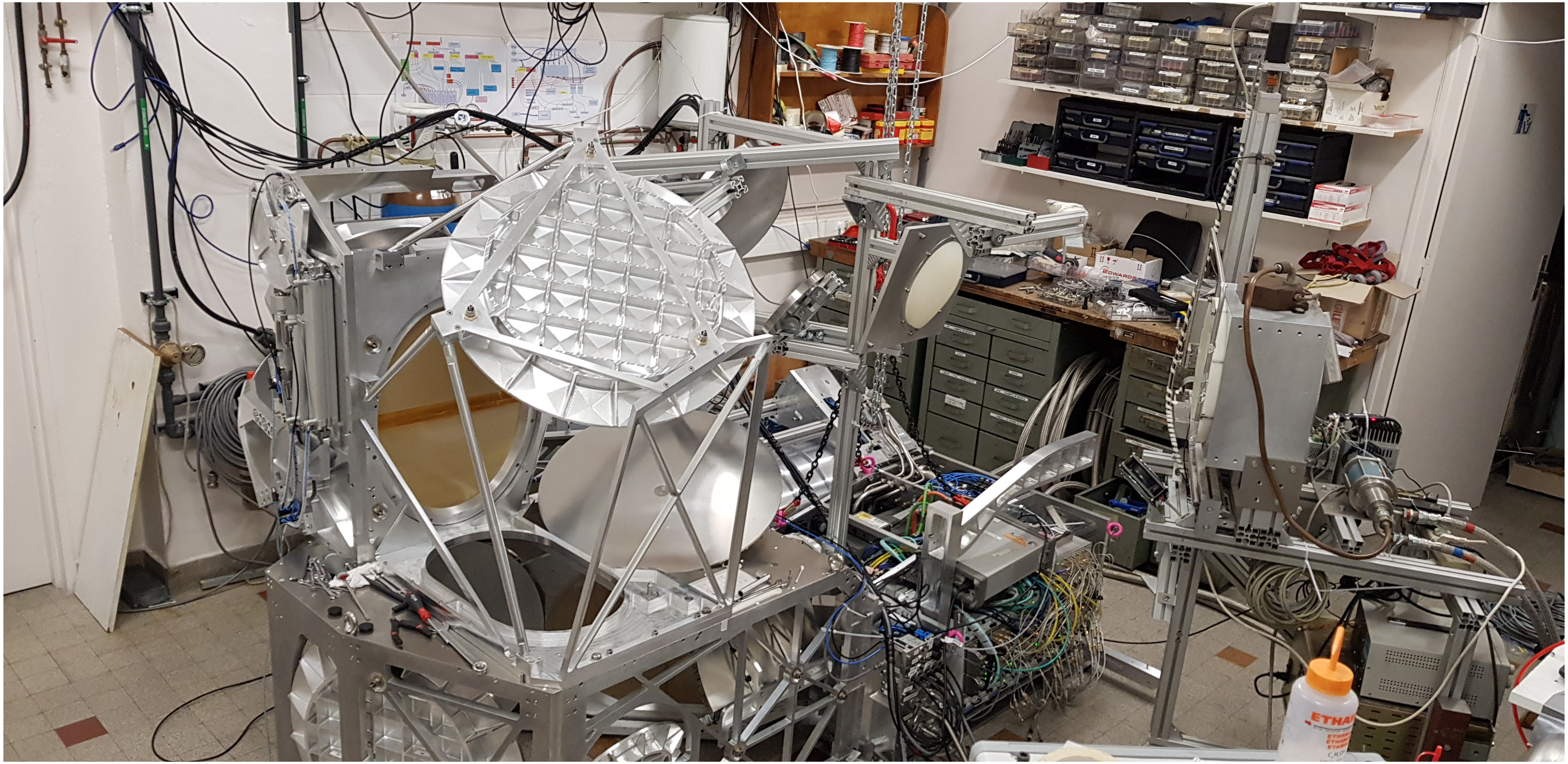
CONCERTO: instrument



- Focal plane:
  - Kinetic Inductance Detectors (KID)
  - Success of the NIKA2 IRAM camera
  - FOV D>15’, fλ sampling => arrays of 2,000 pixels
- Cryostat:
  - Closed-circle 3He-4He dilution - 150mK
  - The 4K stage (required for initiating the 3He-4He dilution) is achieved using a standard two-stages pulse-tube
- Martin-Puplet interferometer (like a Michelson interferometer but with a movable mirror)
  - Outside the cryostat
  - Spectral resolution (ν/δν): R=100 to 300
  - Perform continuously path interferograms at a frequency of few Hertz or more (2-5Hz)
    - Faster than most of the sky noise - only possible with KIDS
  - At least one spectrum for all pixels of the matrix every second
- A « sub-mm » antenna:
  - Frequency range: two sub-bands — 125 - 305 GHz
  - APEX telescope, in a very dry area, θ=15” at 350 GHz

CONCERTO: instrument is complete!

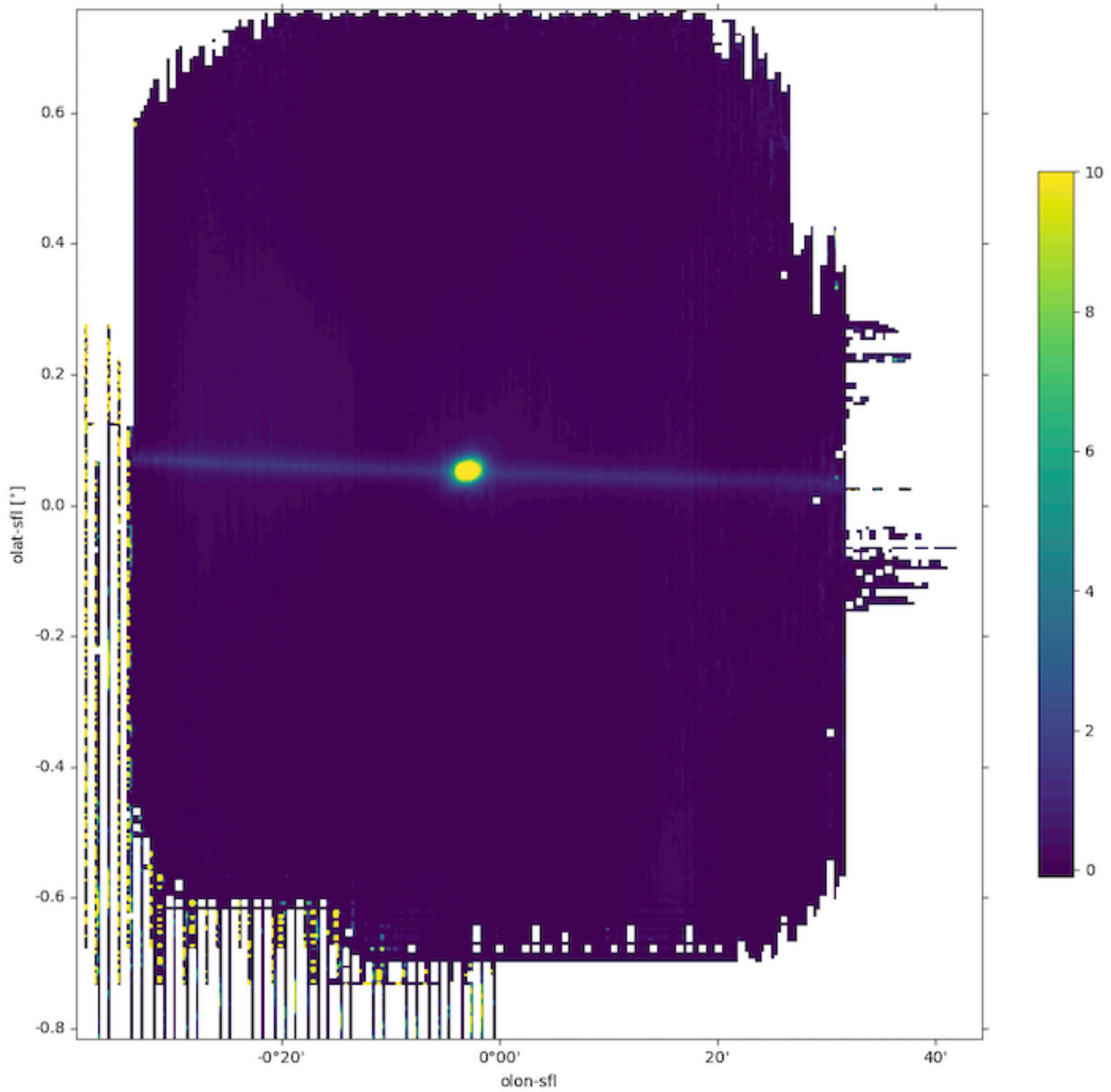
ERC approval: Feb 2018 — PDR: Feb 2019 — FDR: Feb 2020 — Installation: Avril 2021



“A wide field-of-view low-resolution spectrometer at APEX: Instrument design and scientific forecast”

The CONCERTO collaboration, A&A 642, 2020

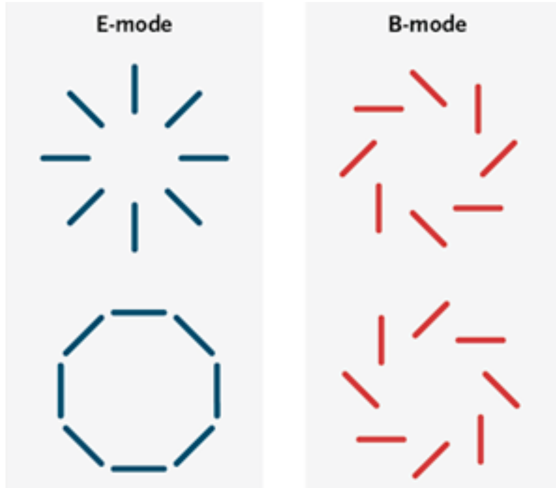
CONCERTO: First light in lab!



CONCERTO @ APEX

The future of CMB science: B modes

Inflation predicts the existence of a stochastic background of gravitational waves that then induce a specific "B-mode" pattern in the polarization of the CMB



- **According to single field, slow-roll inflationary scenario, quantum vacuum fluctuations excite cosmological scalar and tensor perturbations**

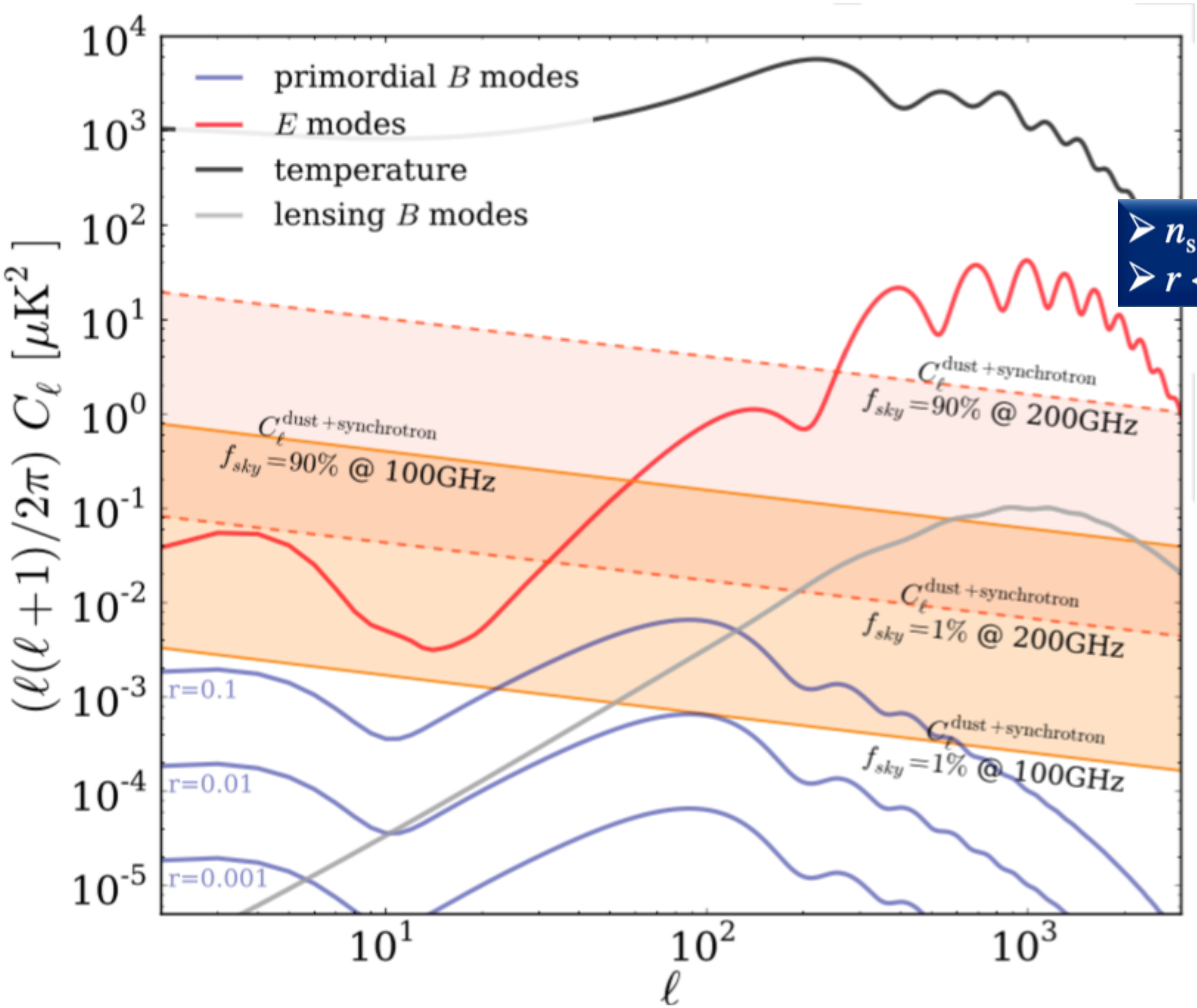
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1} \quad \text{scalar}$$

$$\mathcal{P}_{\mathcal{T}}(k) = A_t \left(\frac{k}{k_0}\right)^{n_t} \quad \text{tensor}$$

- **with the definition of the tensor-to-scalar ratio "r"** $r = A_t / A_s$

which characterises the amplitude of GW and gives direct constraints on the shape of the potential

The future of CMB science: B modes



- $n_s = 0.967(4)$
- $r < 0.07$ (95%CL)

CMB B-mode contamination by polarised Xgalactic sources

Predict the polarisation level of:
- the radio shot noise
- the dusty galaxy shot noise
- the CIB clustering

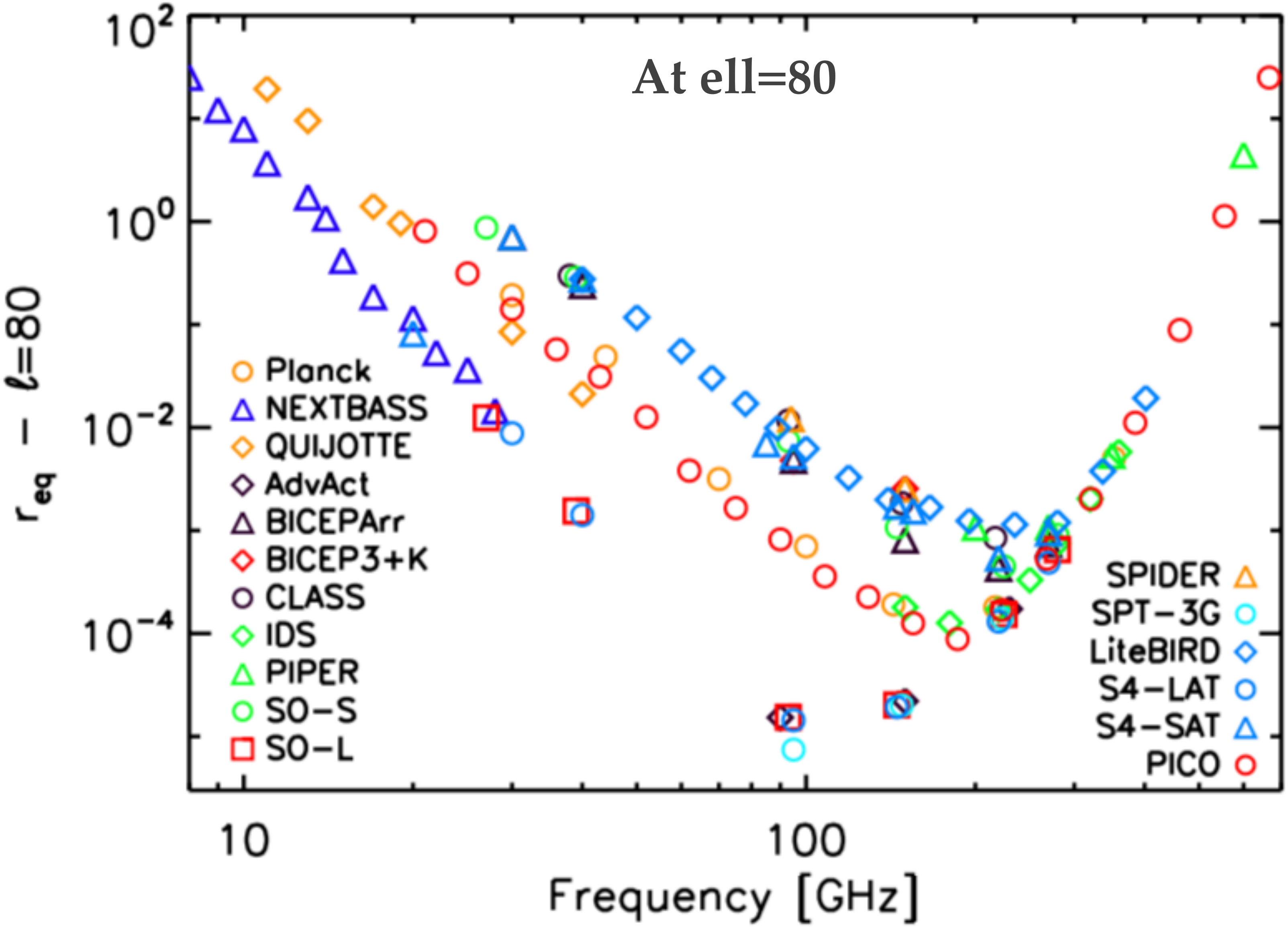
using new models.

To compute the shot noises, we use for each experiment its noise level and compute the confusion noise using the experiments characteristics (e.g. FWHM).

Ground-based experiments:
C-BASS, NEXT-BASS, QUIJOTE, AdvACTPOL, BICEP3+Keck, BICEPArray, CLASS, Simons Observatory, SPT3G, and S4

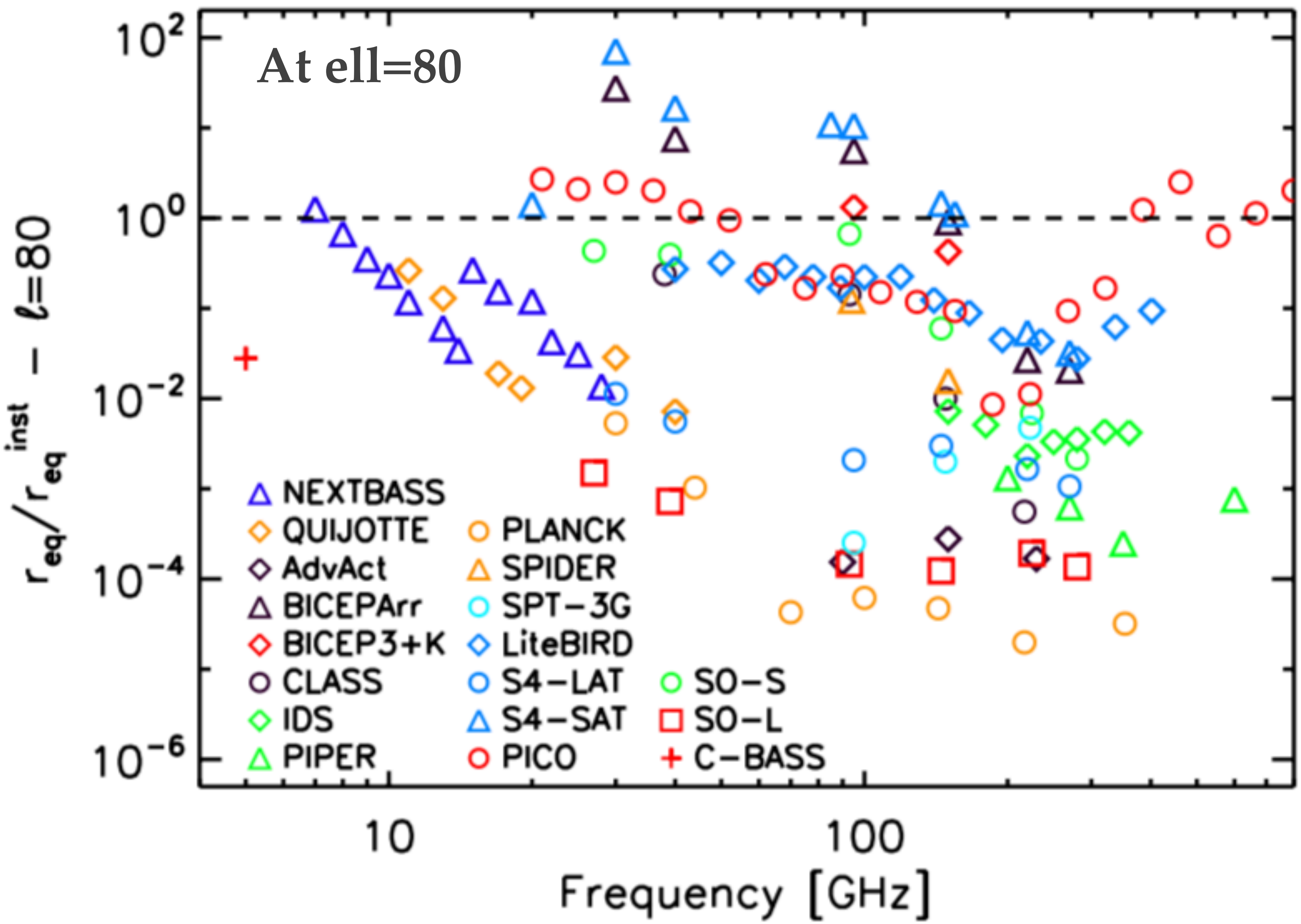
Space-based or balloon-borne experiments:
IDS, PIPER, SPIDER, LiteBIRD, and PICO

CMB B-mode contamination by polarised Xgalactic sources

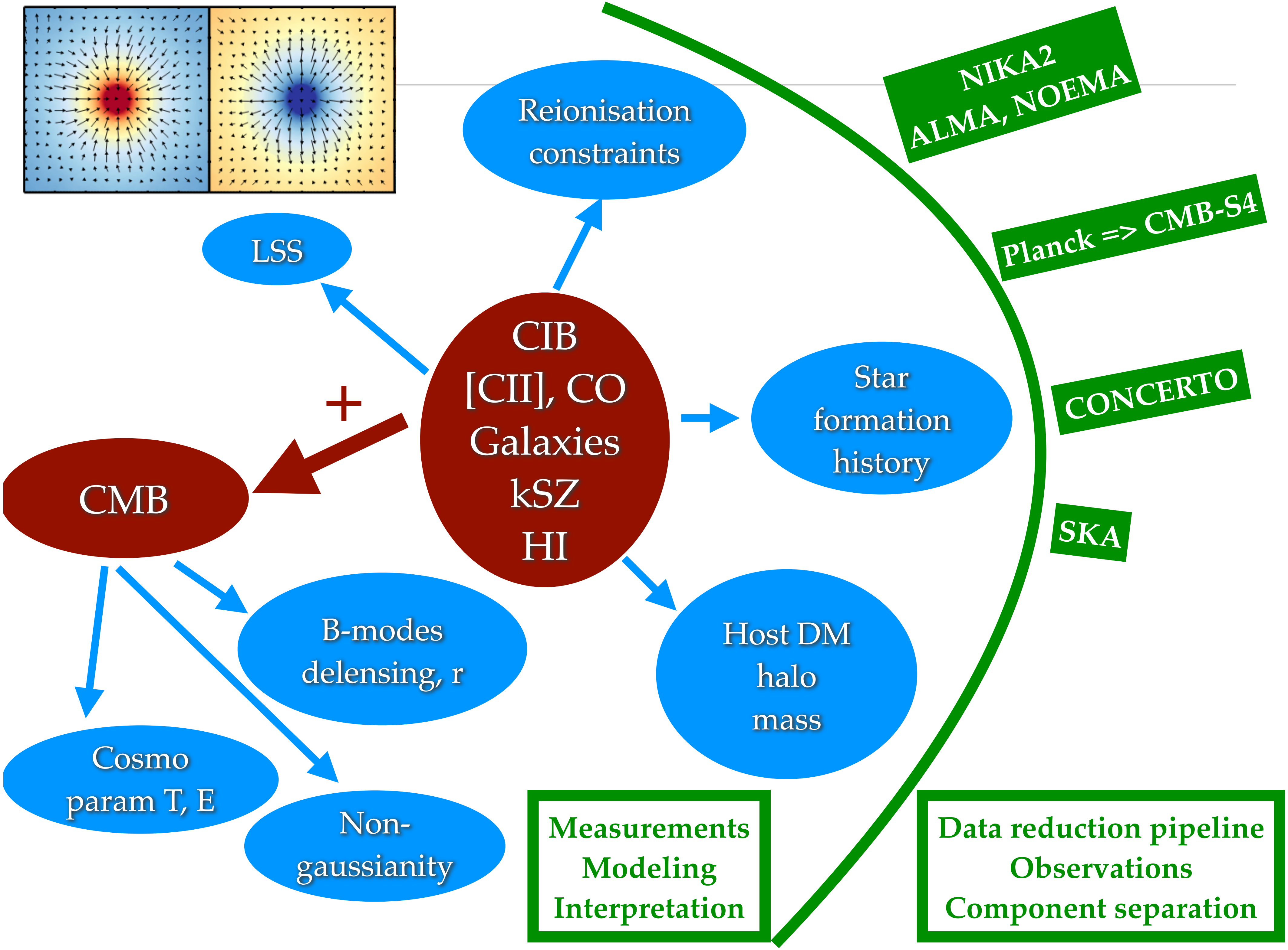


Lagache et al., A&A 2020

CMB B-mode contamination by polarised Xgalactic sources



Lagache et al., A&A 2020


NIKA2
ALMA, NOEMA
Planck => CMB-S4
CONCERTO
SKA
Reionisation constraints
LSS
CIB
[CII], CO
Galaxies
kSZ
HI
+
CMB
Star formation history
Host DM halo mass
B-modes delensing, r
Cosmo param T, E
Non-gaussianity
Measurements
Modeling
Interpretation
Data reduction pipeline
Observations
Component separation