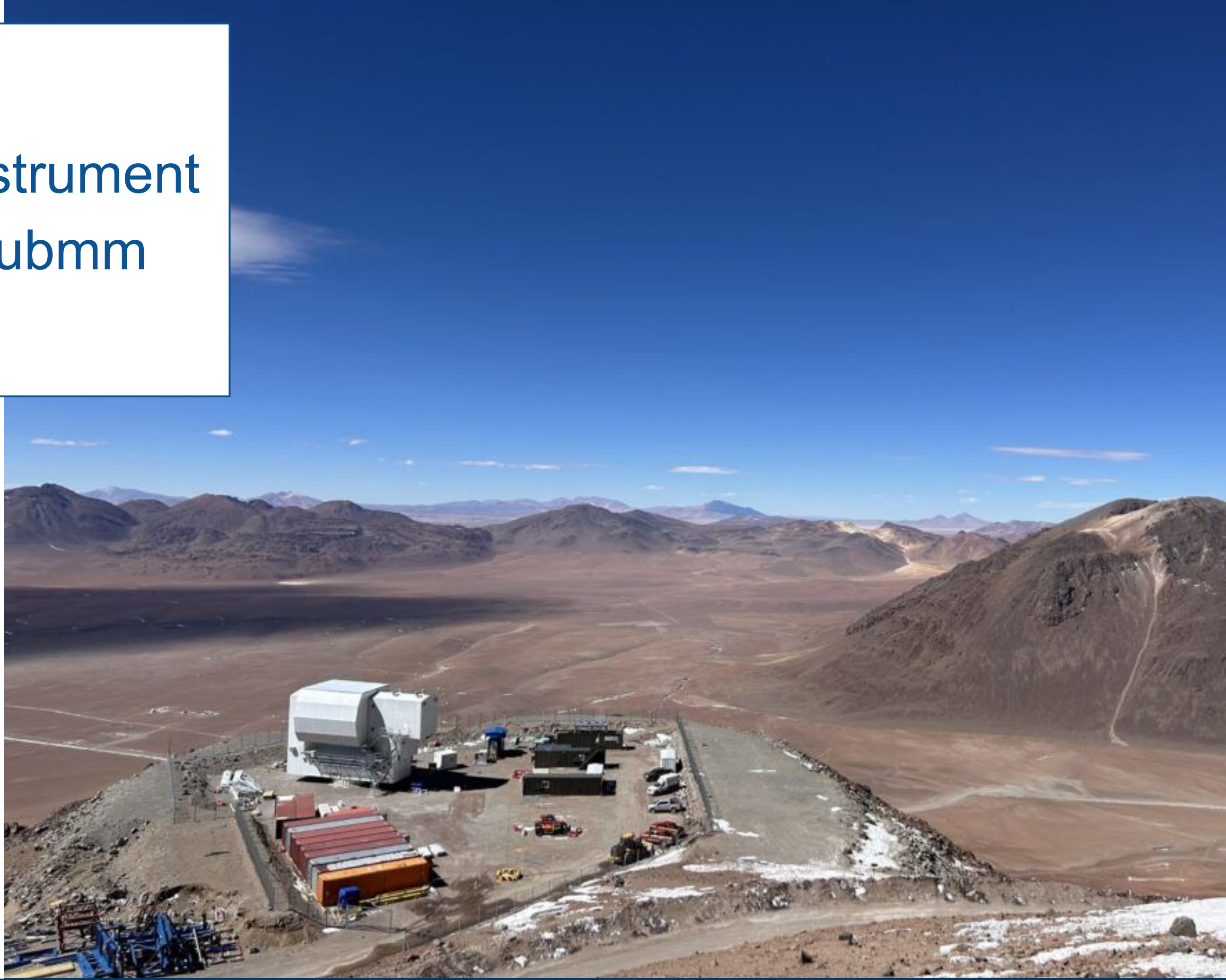
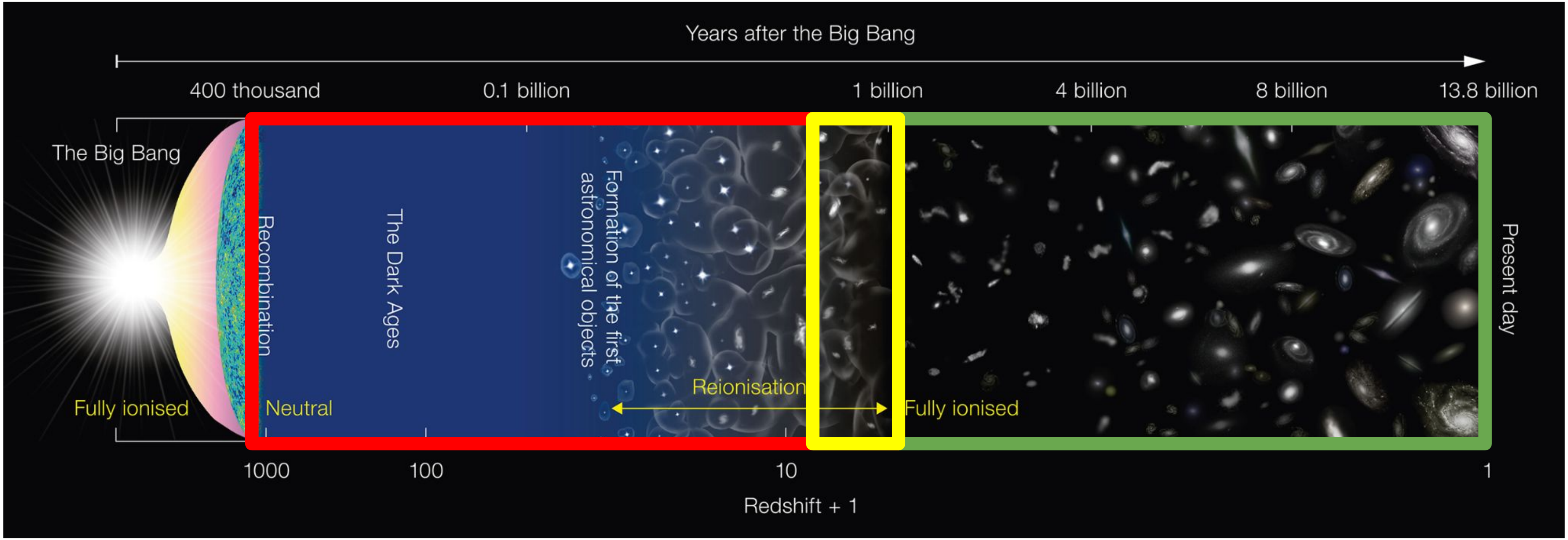
FYST/CCAT
Masking and cross-instrument cross-correlation for submm line intensity mapping

Jonathan Clarke, PhD at University of Cologne,
+ Prof. Dominik Riechers,
Dr. Christos Karoumpis, Ankur Dev,
Dr. Anirban Roy, Tejas Oak,
Himadri Saha, Yoko Okada+…



Line intensity mapping at the epoch of reionisation



NAOJ

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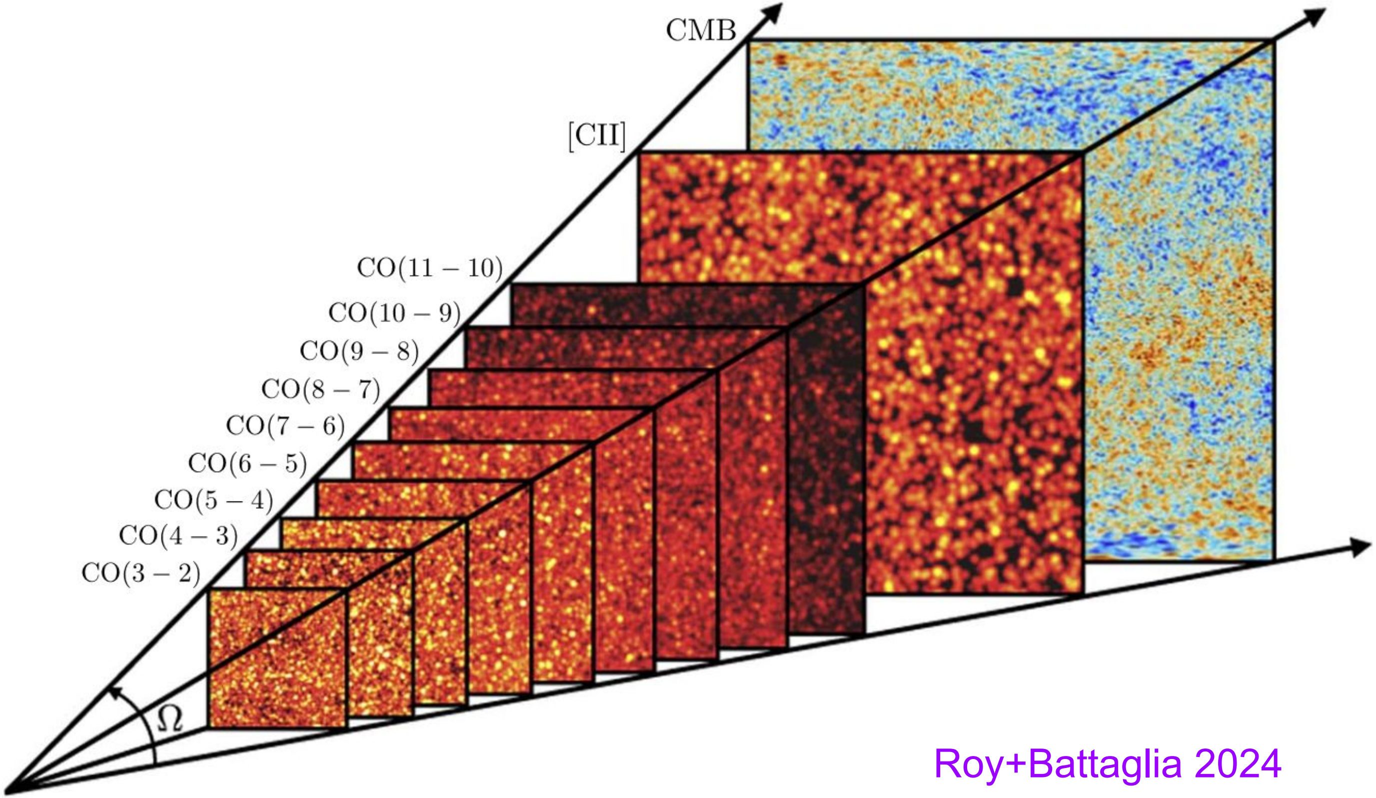
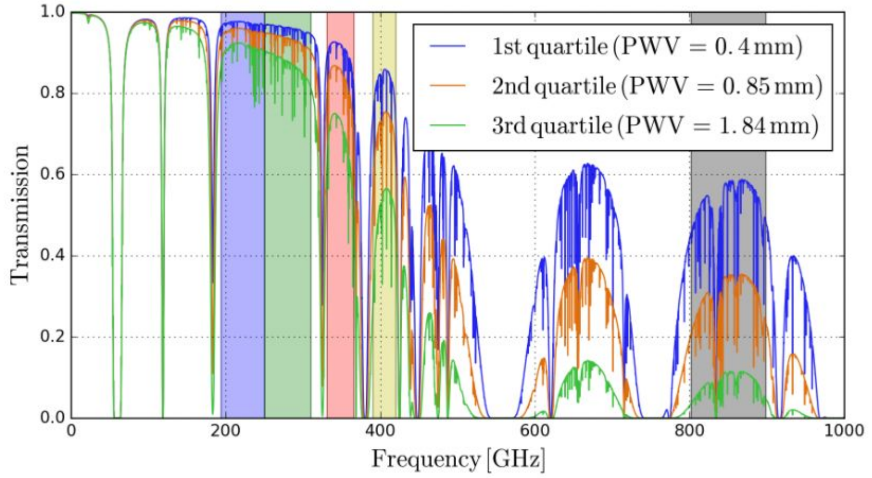
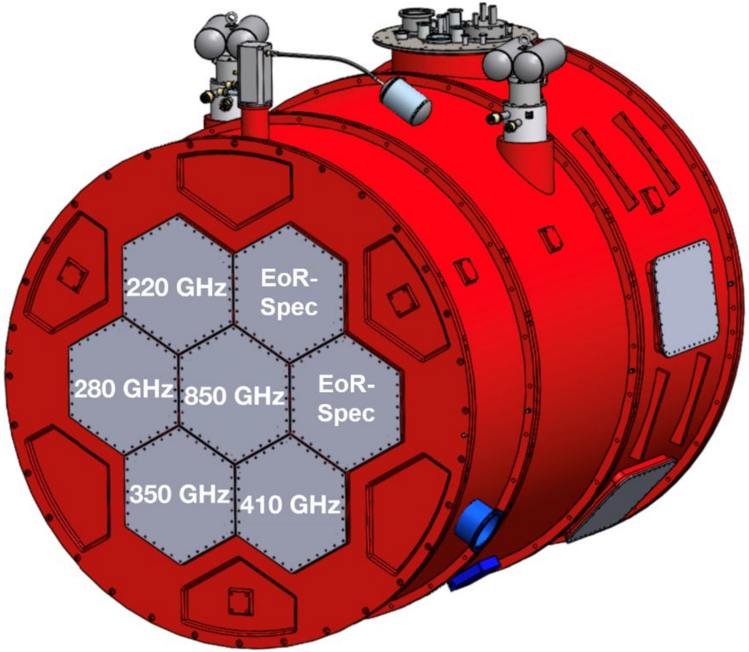


Roy+Battaglia 2024

CCAT/FYST: Deep Spectroscopic Survey

- Sub-mm line intensity mapping - Cerro Chajnantor unique site with optimal atmosphere
- **EoR-Spec** modules in Prime-Cam (FYST instr.)
  - R=100, 33-58" angular resolution
  - **210-420GHz**





Choi+22, CCAT+23

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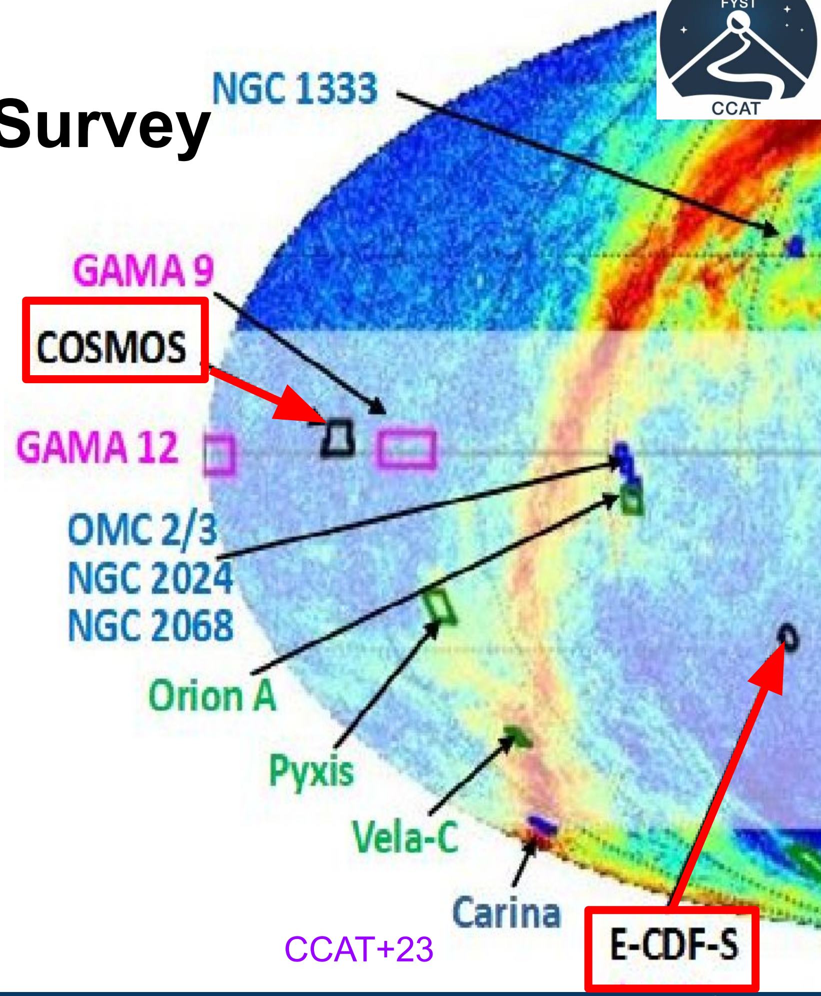
- Two fields, 4deg², 2000hrs each
  - **E-COSMOS and E-CDF-S/EDF-F**
  - Overlap with COSMOS, Euclid surveys
  - Lots of UV spectroscopic data



CCAT+23

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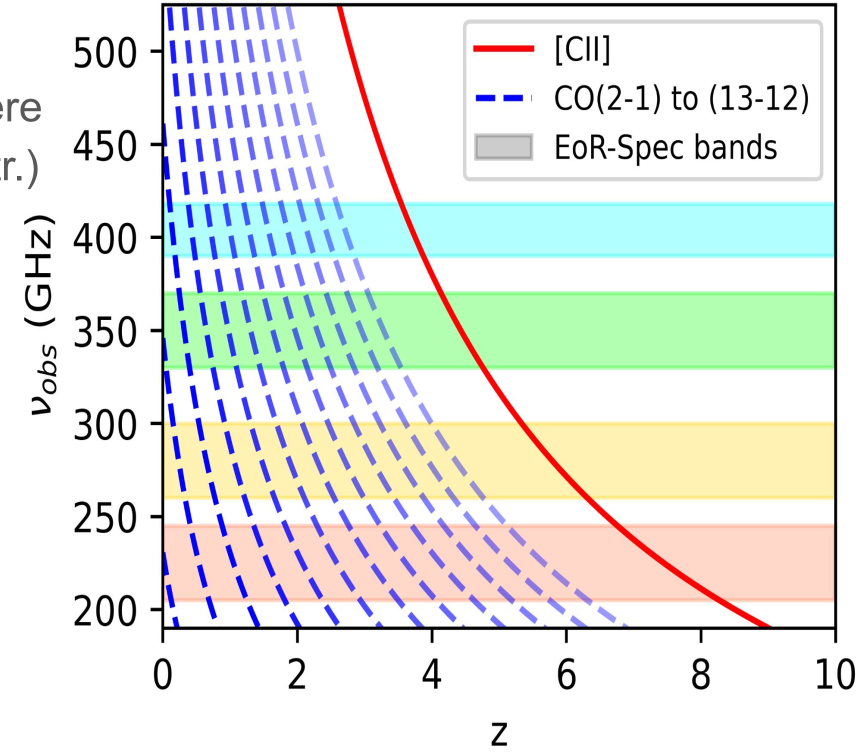
  - Overlap with COSMOS, Euclid surveys
  - Lots of UV spectroscopic data
- Noise tricky, need cleaning pipeline **(Dev+26** arxiv:2607.20404)
- **CO INTERLOPERS ARE MAJOR ISSUE**

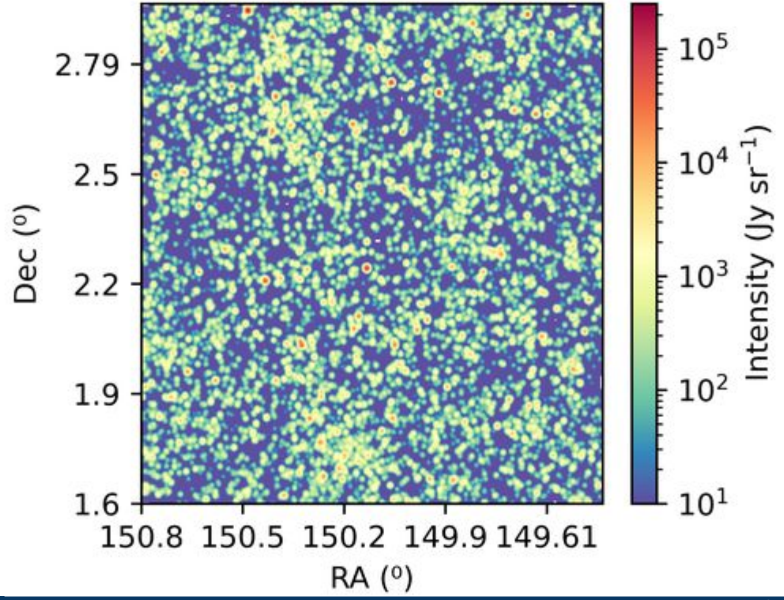


Clarke+26 [arxiv:2606.17210]

Intensity Cube Modelling: Empirical Data

Building on Clarke+24

- Sims based on COSMOS2020 data, galaxy catalogue covering 1.5deg² cube
- **Extrapolate** from known incompleteness; calibrated with CANDELS, COSMOS-Web
- Paint CO/[CII]/[OIII]/[CI] luminosity models onto cube at galaxy locations
- **Empirical basis to synthetic data**



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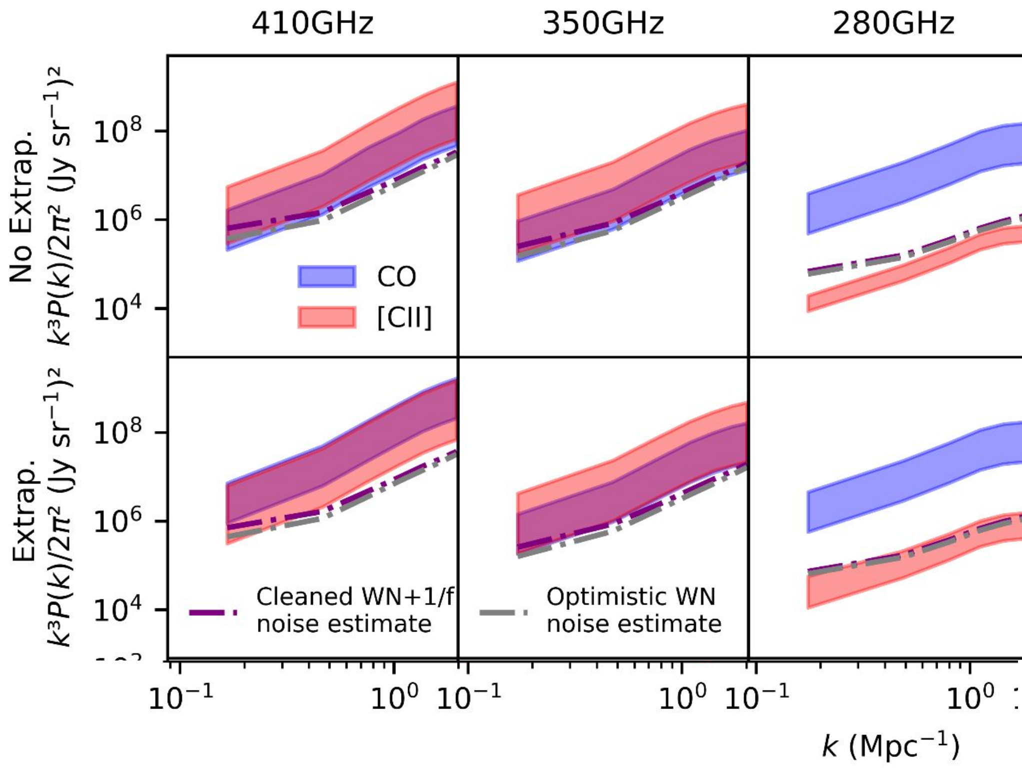
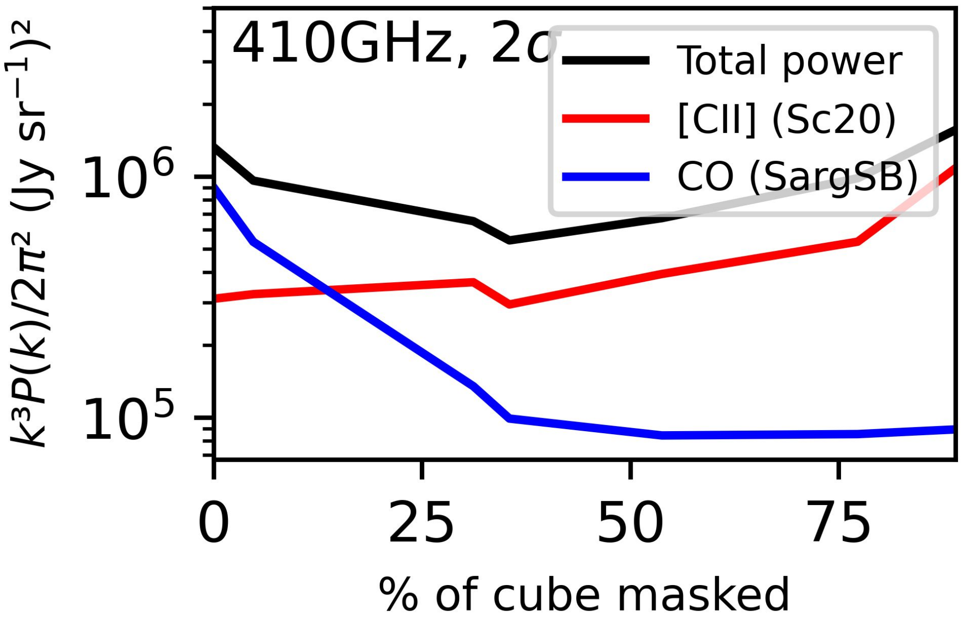


[CII] Recovery: Targeted Masking

Based on Van Cuyck+23, Karoumpis+24

- Use foreground catalogue to target brightest CO sources
- Mask in order of luminosity contribution
- Variable mask size to maximise CO removal/minimise cube masking
- More challenging if catalogue misses key CO sources
- High masking=heavy bias (K+24)

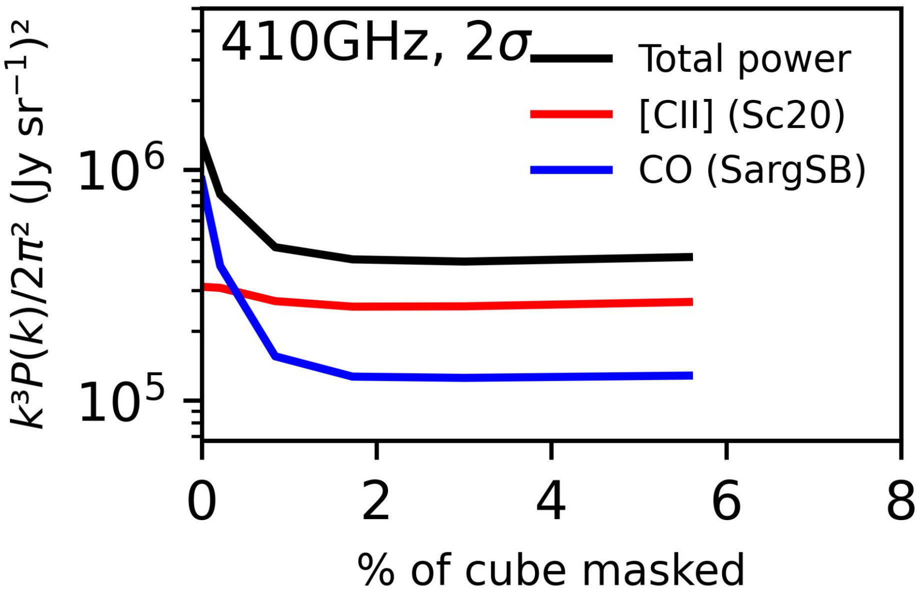


Clarke+26 arxiv:2606.17210

[CII] Recovery: Blind Masking

Based on work from Kanako Narita (NAOJ)

- Match x% brightest locations shared across frequency channels
- Use template matching to verify across frequency slices that voxels are CO
- Aided by presence of additional lower frequency channels (e.g. 150GHz). Lower % masked
- Noise can greatly impact, prevent usage of specific frequency channels



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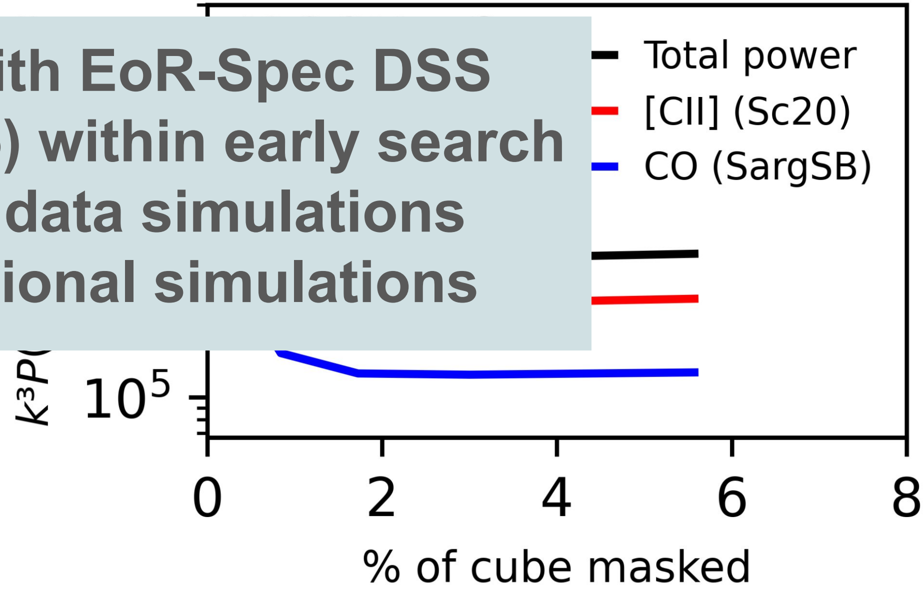
[CII] recoverable with EoR-Spec DSS above 300GHz (z<5) within early search params - empirical data simulations agree with conventional simulations



Clarke+26 arxiv:2606.17210

[CII] Recovery: Blind Masking

Testing masking effectiveness using multi-line image cubes based on COSMOS2020 for [CII] line intensity mapping at $z_{[CII]} > 3.5$

J. Clarke[1]★, C. Karoumpis[2], A. Dev[2], D. Riechers[1], T. Oak[2], Y. Okada[1], K. Narita[3,4], and F. Bertoldi[2]

[1] I. Physikalisches Institut, Universität zu Köln, Zülpicher Straße 77, D-50937 Köln, Germany
[2] Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
[3] Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 133-0033, Japan
[4] National Astronomical Observatory of Japan, National Institutes of Natural Sciences, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

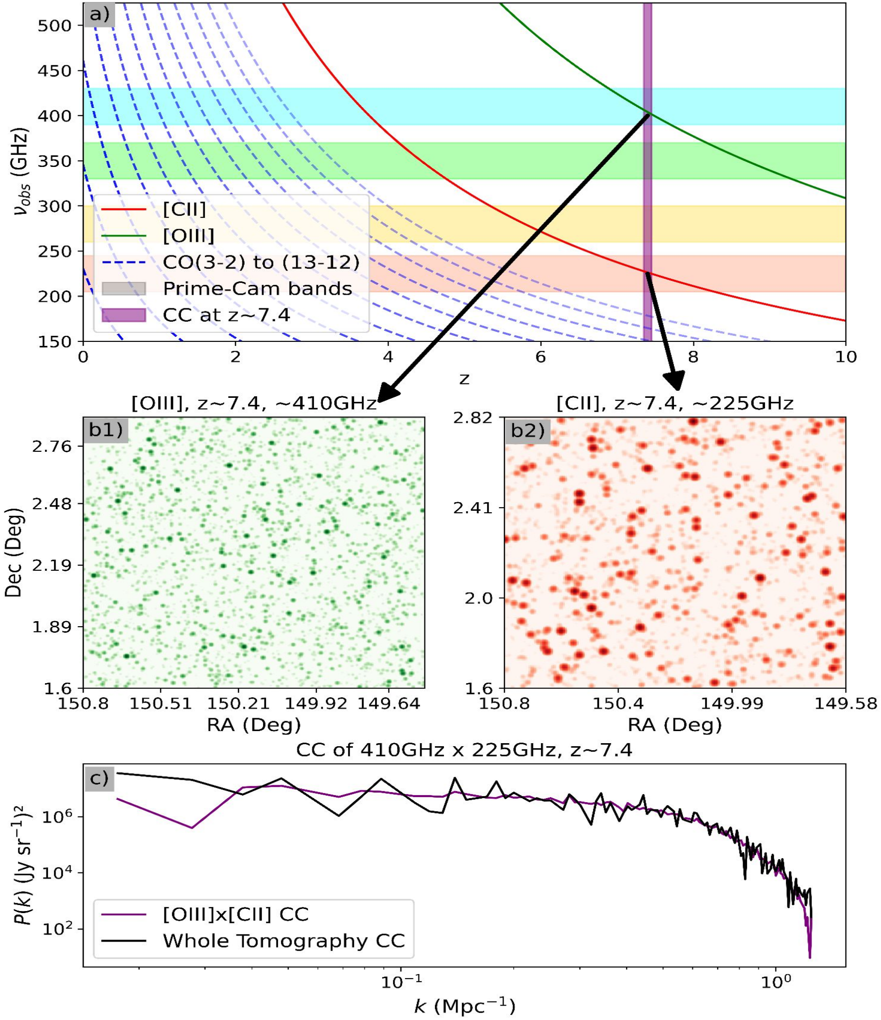
June 17, 2026

(Sub-)mm cross-correlations

Cross-correlation is less affected by these challenges - non-correlated components fall out

Past work with instruments/galaxy CCs (**Roy+24, Agrawal, Bracks, Kramer+26**), etc

Line-line options in EoR-Spec (CO, [CII]x[OIII])



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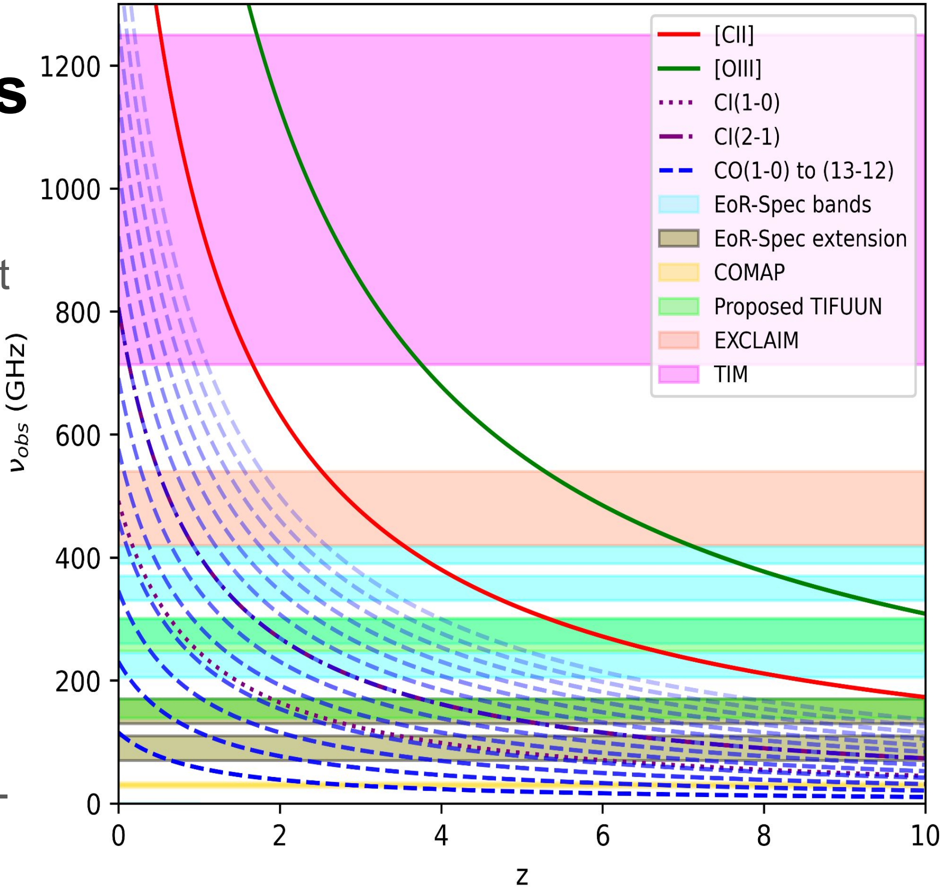
What about **cross-instrument cross-correlation** across sub-mm and mm**?**

COMAP, TIFUUN, EoR-Spec, EXCLAIM, TIM - 26-1250GHz



Best cross-correlations

Best per band pair -
NOT COMPREHENSIVE!!!!

	TIM High Freq	TIM Low Freq.	EXCLAIM	FYST 410GHz	FYST 350GHz	FYST 280GHz	FYST 225GHz	TIFUUN 275GHz	TIFUUN 155GHz	FYST Ext. 150GHz	FYST Ext. 90GHz	COMAP 30GHz
TIM High Freq.												
TIM Low Freq	CO(10-9)x [CII] z~0.567											
EXCLAIM	[CII]x [OIII] z~2.55	[CII]x [OIII] z~2.69										
FYST 410GHz	CO(4-3)x CO(10-9= z~0.143	[CII]x [OIII] z~3.33	CO(4-3)x [CI](1-0) z~0.138									
FYST 350GHz	CO(6-5)x [CII] z~0.942	CO(7-6)x [CII] z~1.31	CO(5-4)x CO(6-5) z~0.602	CO(5-4)x CO(6-5) z~0.702	CO(4-3)x [CI](1-0) z~0.366							
FYST 280GHz	CO(5-4)x [CII] z~0.966	CO(4-3)x CO(11-10 z~0.654	CO(4-3)x CO6(5-4) z~0.592	CO(3-2)x CO(4-3) z~0.167	CO(4-3)x CO(5-4) z~0.652	CO(4-3)x [CI](1-0) z~0.71						
FYST 225GHz	CO(4-3)x [CII] z~0.946	CO(5-4)x [CII] z~1.51	CO(8-7)x [CII] z~2.53	[CII]x [OIII] z~7.41	CO(3-2)x CO(5-4) z~0.624	CO(3-2)x CO(4-3) z~0.615	CO(4-3)x [CI](1-0) z~1.13					
TIFUUN 275GHz	CO(5-4)x [CII] z~0.962	CO(4-3)x CO(11-10 z~0.653	CO(3-2)x CO(6-5) z~0.575	CO(3-2)x [CI](1-0) z~0.221	CO(4-3)x CO(5-4) z~0.652	CO(4-3)x [CI](1-0) z~0.75	CO(4-3)x CO(3-2) z~0.61	CO(4-3)x [CI](1-0) z~0.74				
TIFUUN 155GHz	CO(4-3)x [OII] z~2.02	CO(3-2)x [CII] z~1.26	CO(2-1)x CO(5-4) z~0.364	CO(2-1)x CO(5-4) z~0.428	CO(2-1)x CO(5-4) z~0.609	CO(2-1)x CO(4-3) z~0.600	CO(2-1)x CO(3-2) z~0.535	CO(2-1)x CO(4-3) z~0.596	CO(4-3)x [CI](1-0) z~2.11			
FYST Ext. 150GHz	CO(4-3)x [OIII] z~2.13	CO(5-4)x [OIII] z~3.01	CO(2-1)x CO(5-4) z~0.364	CO(2-1)x CO(5-4) z~0.428	CO(2-1)x [CI](1-0) z~0.423	CO(2-1)x CO(4-3) z~0.654	CO(2-1)x CO(3-2) z~0.550	CO(2-1)x CO(4-3) z~0.651	CO(4-3)x [CI](1-0) z~2.22	CO(4-3)x [CI](1-0) z~2.22		
FYST Ext. 90GHz	CO(2-1)x [OIII] z~2.00	CO(4-3)x [OIII] z~3.47	CO(1-0)x [CI](1-0) z~0.122	CO(1-0)x [CI](1-0) z~0.221	CO(1-0)x CO(4-3) z~1.31	CO(1-0)x CO(3-2) z~0.241	CO(2-1)x CO(5-4) z~1.58	CO(1-0)x CO(3-2) z~0.272	CO(3-2)x CO(5-4) z~2.77	CO(1-0)x CO(2-1) z~0.502	CO(3-2)x CO(4-3) z~3.57	
COMAP 30GHz	CO(1-0)x [OII] z~2.49	CO(1-0)x [OIII] z~3.00	CO(1-0)x [CII] z~2.66		CO(1-0)x CO(10-9) z~2.44	CO(1-0)x CO(9-8) z~2.65	CO(1-0)x CO(7-6) z~2.62	CO(1-0)x CO(11-10 z~3.32	CO(1-0)x CO(5-4) z~2.99	CO(1-0)x CO(5-4) z~2.61	CO(1-0)x CO(3-2) z~3.13	

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Hashed - no field overlap
Blue - significant noise issues
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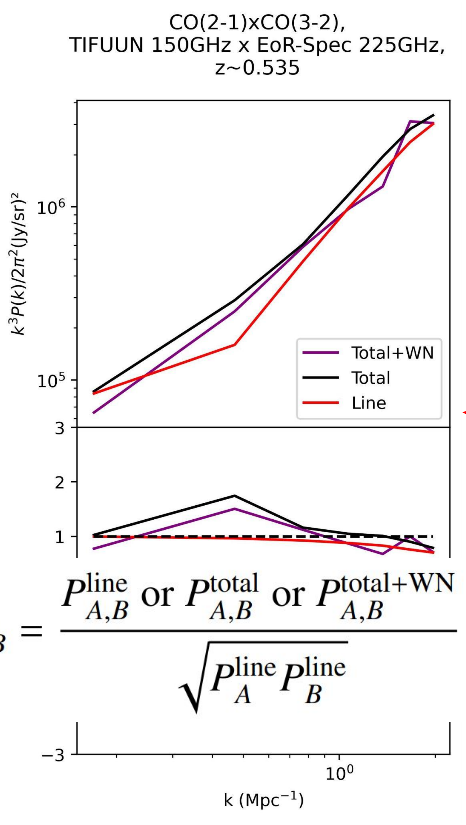
Purple - both
Yellow - minor noise/signal issues
Green - good!

*modified

Best cross-correlations



$$r^{\mathrm{alt}}_{A,B} = \frac{P^{\mathrm{line}}_{A,B} \text{ or } P^{\mathrm{total}}_{A,B} \text{ or } P^{\mathrm{total+WN}}_{A,B}}{\sqrt{P^{\mathrm{line}}_{A} P^{\mathrm{line}}_{B}}} \approx 1$$

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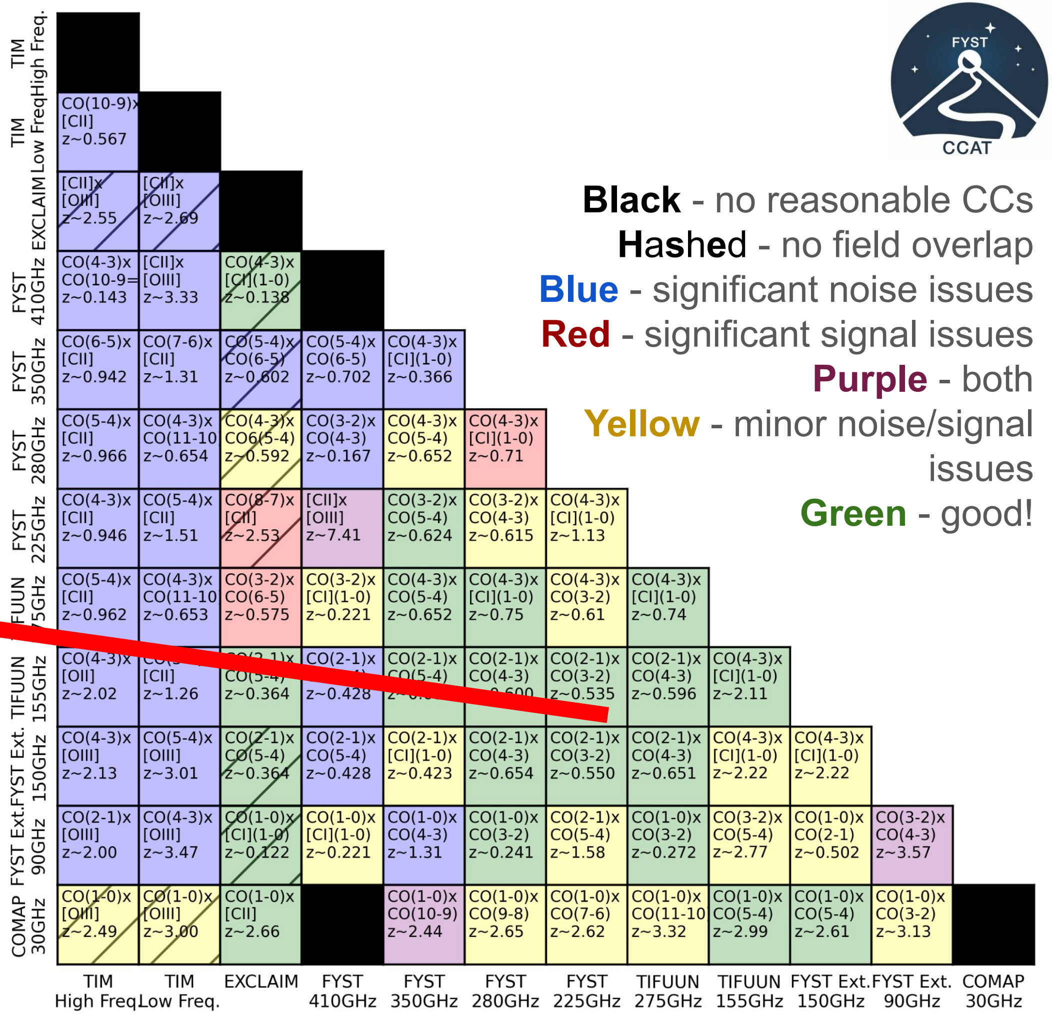

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ETA OCTOBER-NOVEMBER

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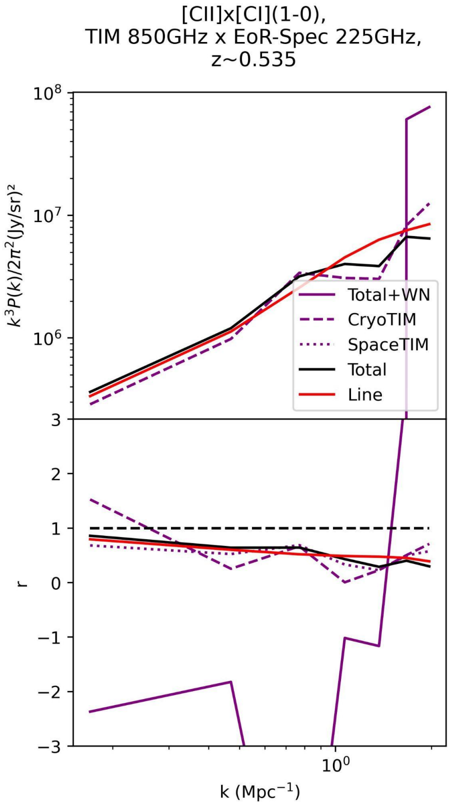

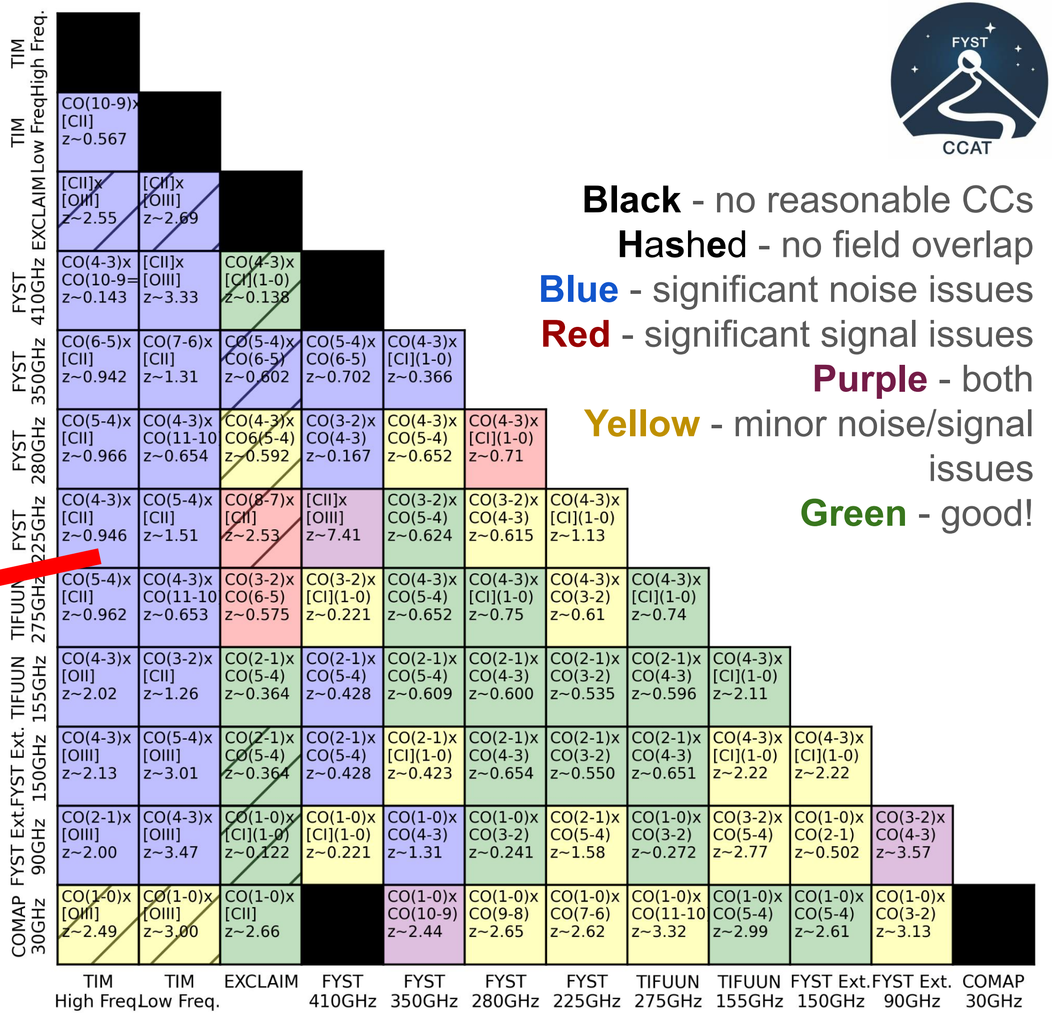

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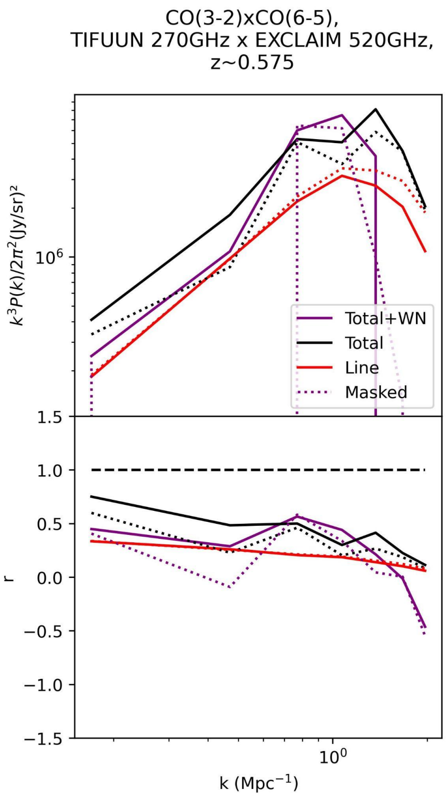

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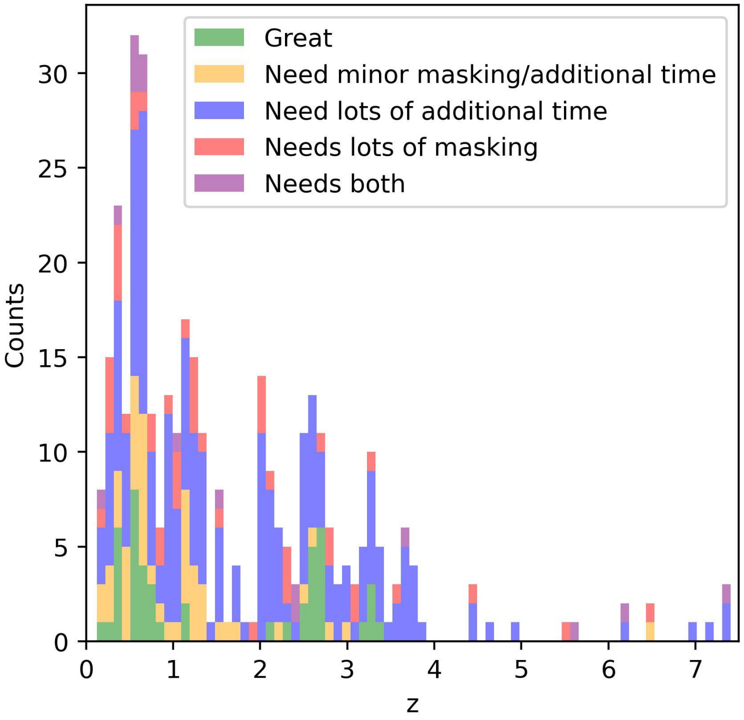
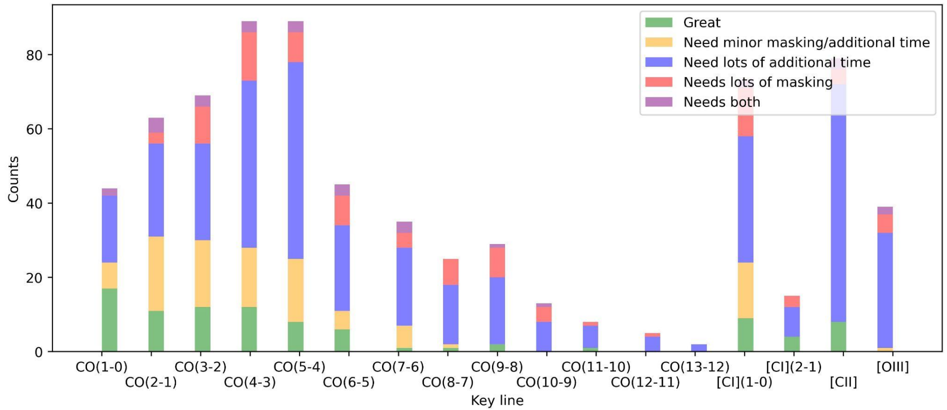
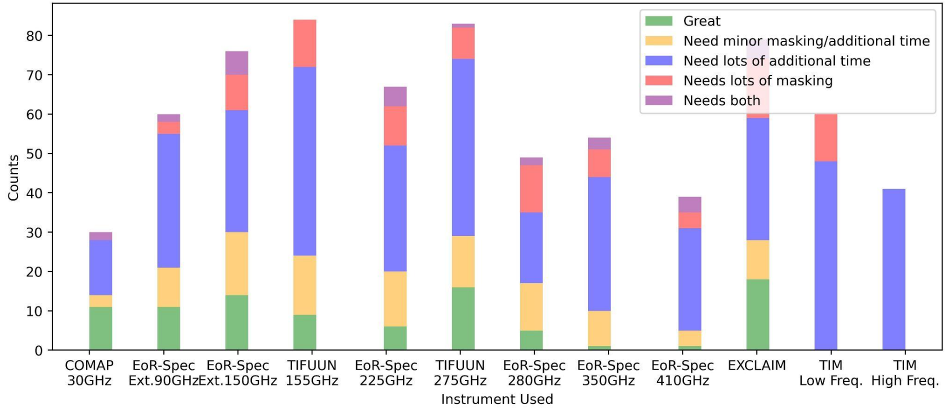
CC Distribution

Stacked histograms: see trends across CCs





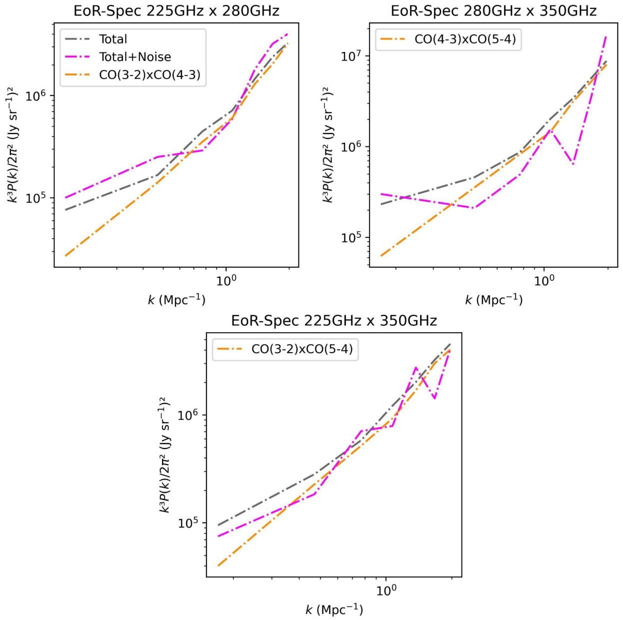


Cross-correlation triplet possibilities

Three cross-correlations can recover auto-spectra (Beane+19, McBride+Liu 2023). Noise limited. Best at z<1

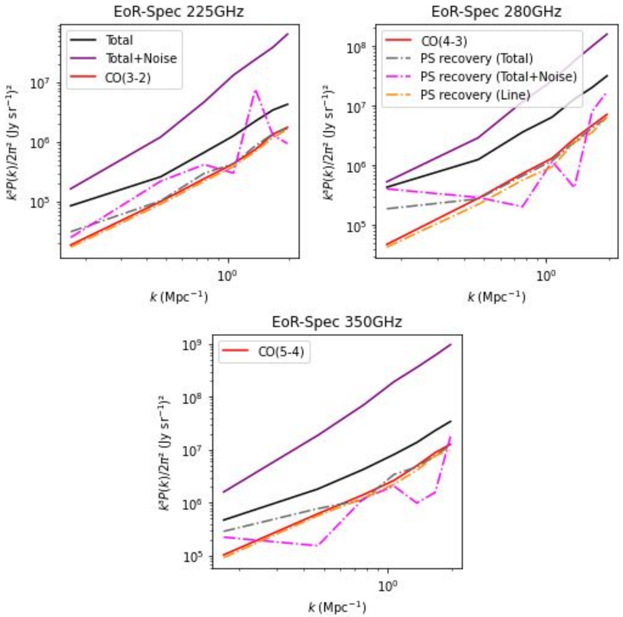
$$P_{i,i} = (\langle I_i \rangle b_i)^2 P_{\rm lin} = \frac{r_{j,k}}{r_{i,j} r_{k,i}} \frac{P_{i,j} P_{k,i}}{P_{j,k}} \equiv R_{i,j,k} P_{i,j,k},$$

Cross-spectra



(z~0.61)

Auto-spectra



Conclusions

- Masking for EoR-Spec makes [CII] recovery possible for >300GHz ($z_{[CII]}<5$)
- Sub-mm line CC is challenging, but feasible **and helpful** for multiple cases
  - Noise is often limiting factor for higher freq.
  - Lack of shared field footprint limits applicability AT PRESENT
- Current CCs provides case for next-gen field share - **should consider for future!**

Graduating early next year - looking for postdocs, interested in continuing LIM work!

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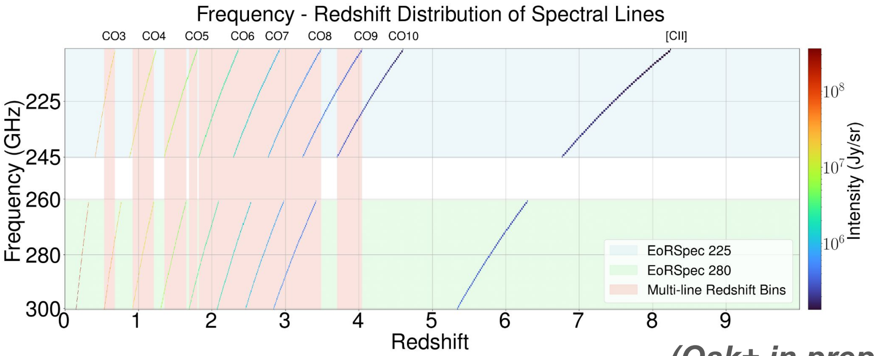
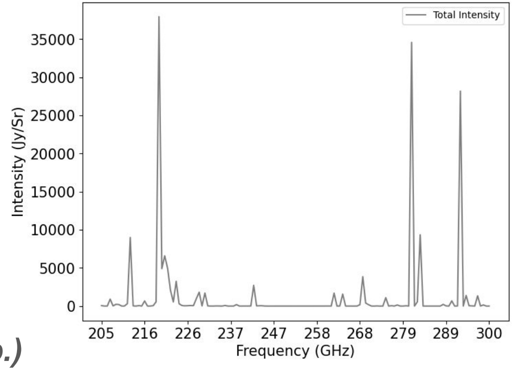
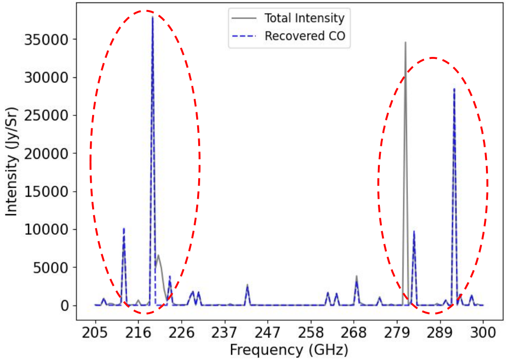
https://ccat.uni-koeln.de/team/jonathan-clarke/
jclarke@ph1.uni-koeln.de

Backup slides

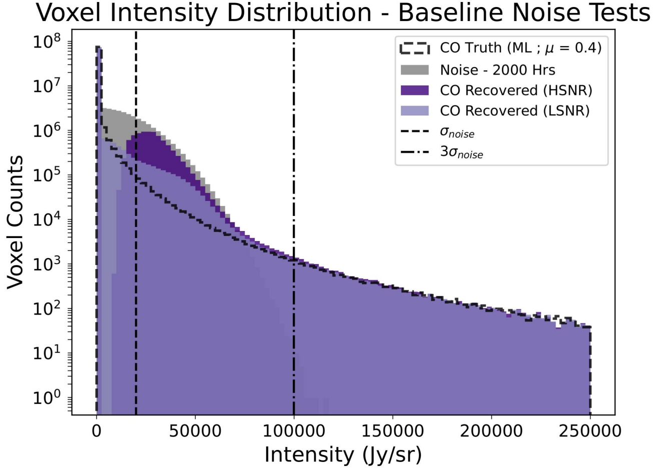
CO Cleaning: Line deconfusion







(Oak+ in prep.)



- <300 GHz, CO highly dominates [CII] and arises from large no. of sources: harder to mask
- Line deconfusion is more effective: subtracting repeating spectral structure by fitting templates ***(Cheng+20)***
- Recovery can be further enhanced by using ancillary foreground catalog

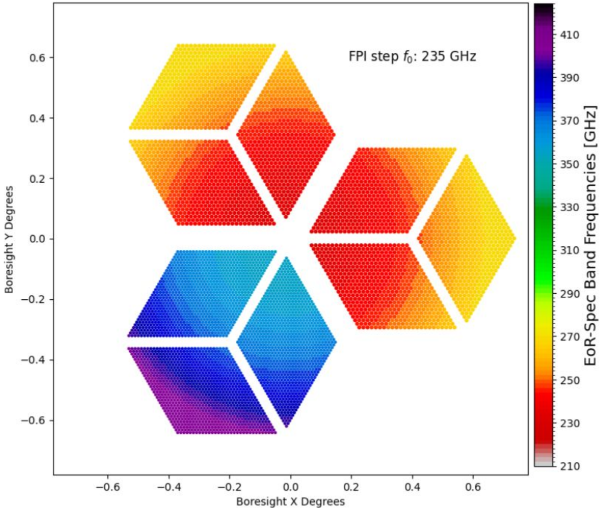
Tejas Oak
PhD at Bonn

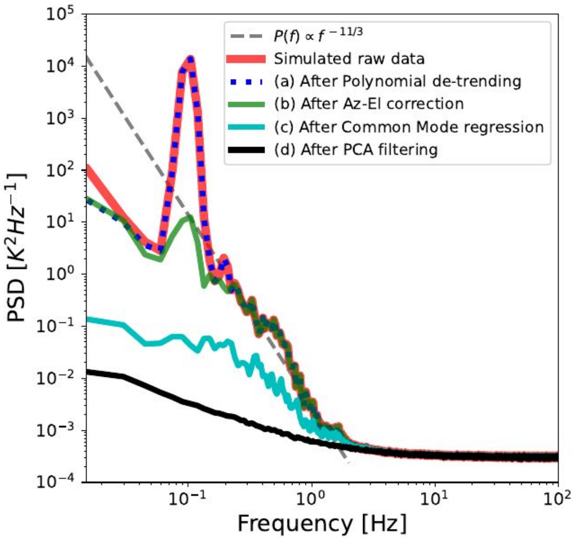
Effect of correlated atmospheric noise

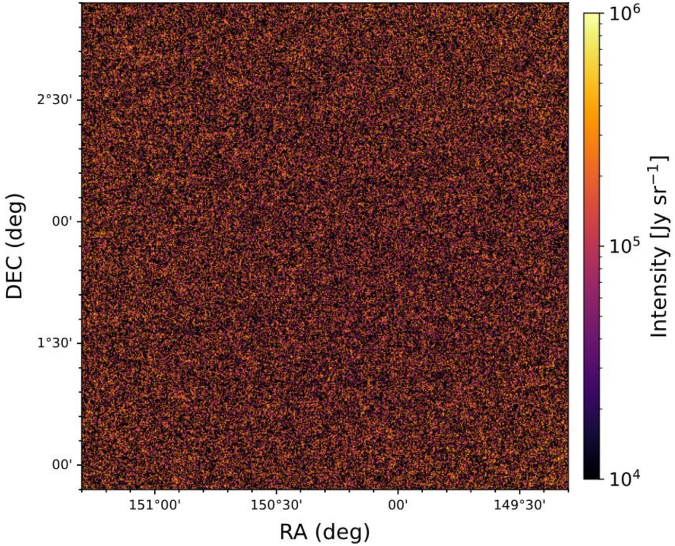
Dev+26 (arxiv:2607.20404)

Soon postdoc at Cornell!!!

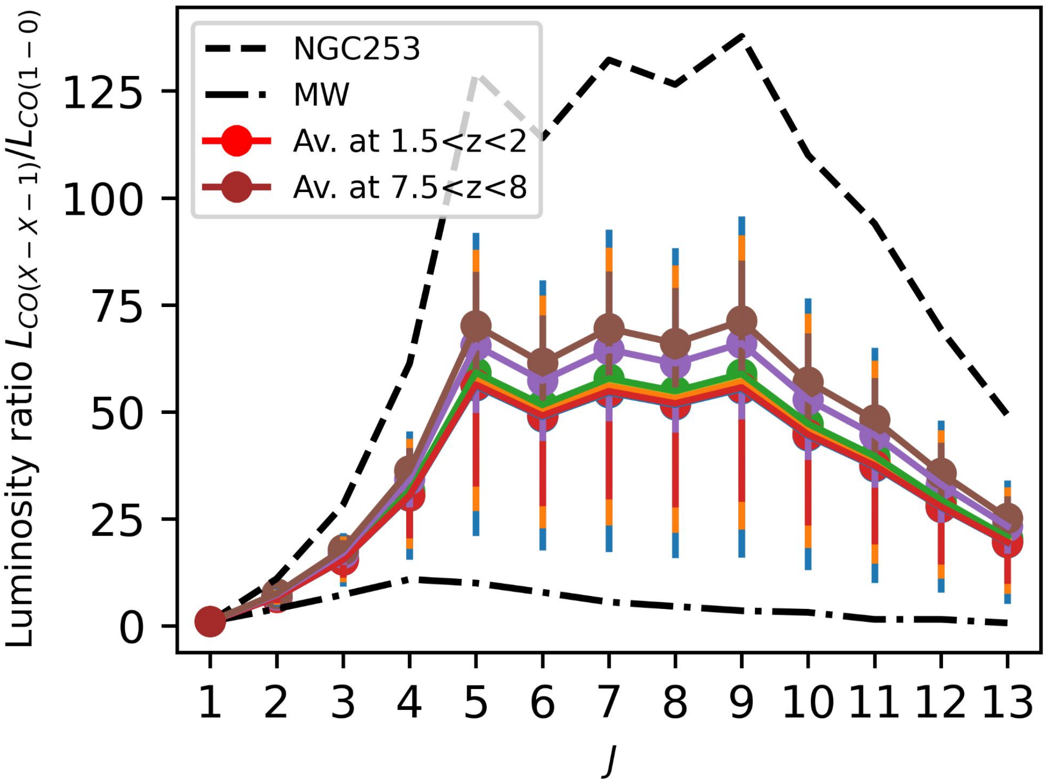
- Simulated realistic EoR-Spec detector timestreams with all noise terms → mock dataset
- Tested effectiveness of the data reduction pipeline in removing correlated 1/f noise
- Created maps using the reduction pipeline on mock dataset → Can reach white-noise level
- Effect of the filtering pipeline on the LIM signal measurement → Transfer Function analysis

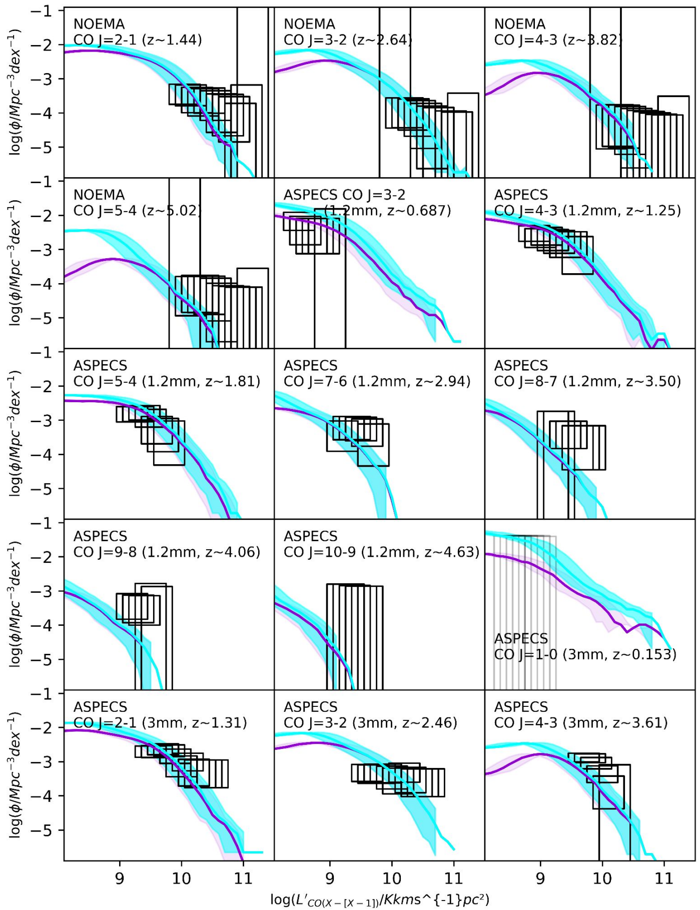




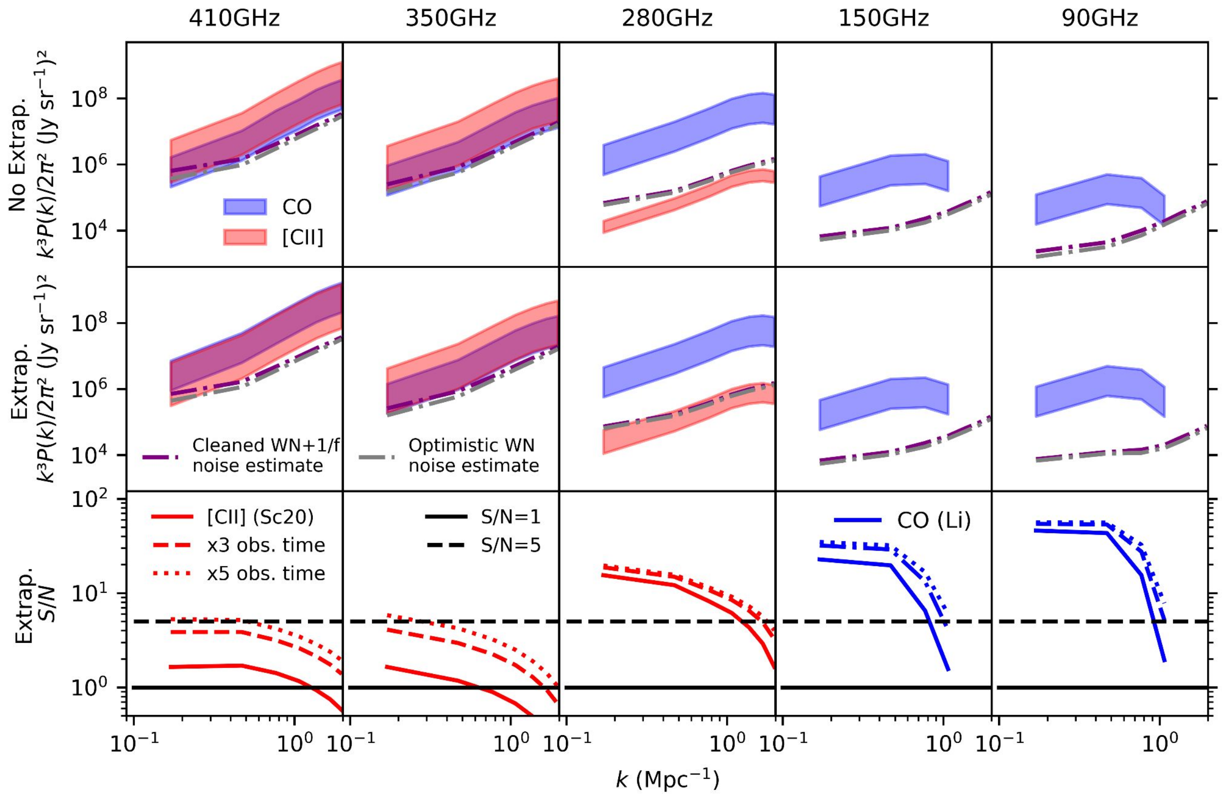


CO Modelling within COSMOS2020



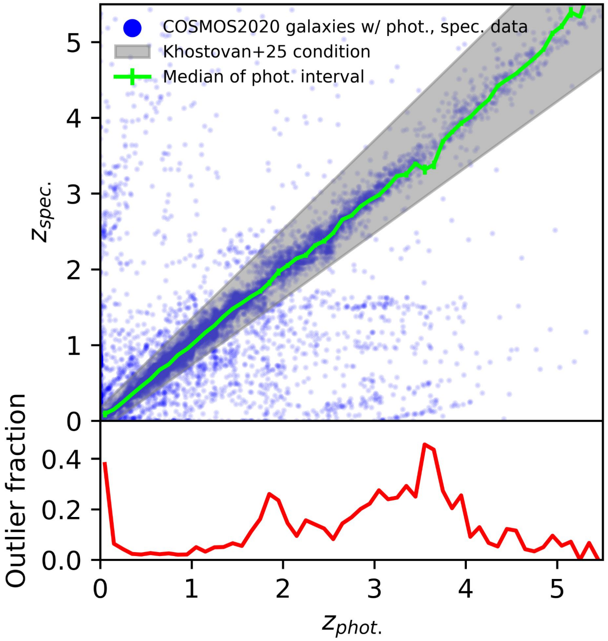


COSMOS2020 signal predictions

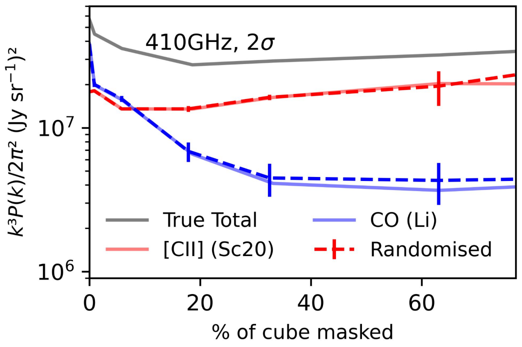


Other masking

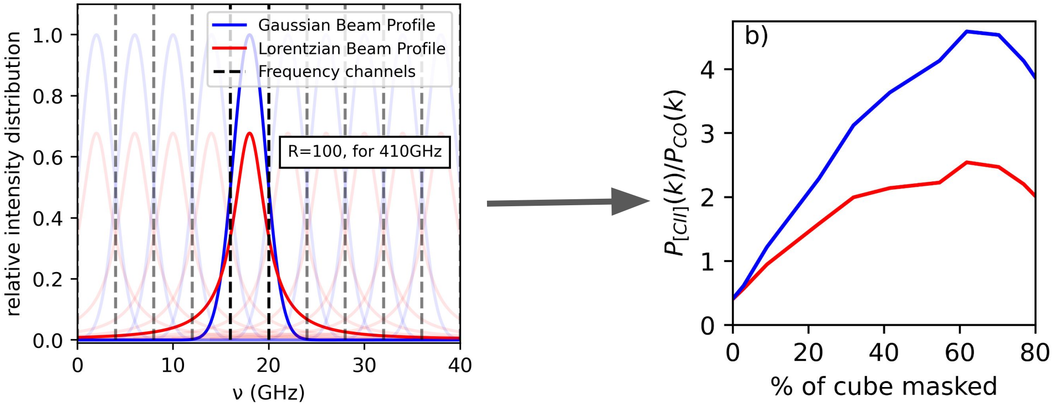
Phot. vs spec. Is difficult in certain redshift ranges



Catalogue uncertainty not an issue



Beam size can affect masking

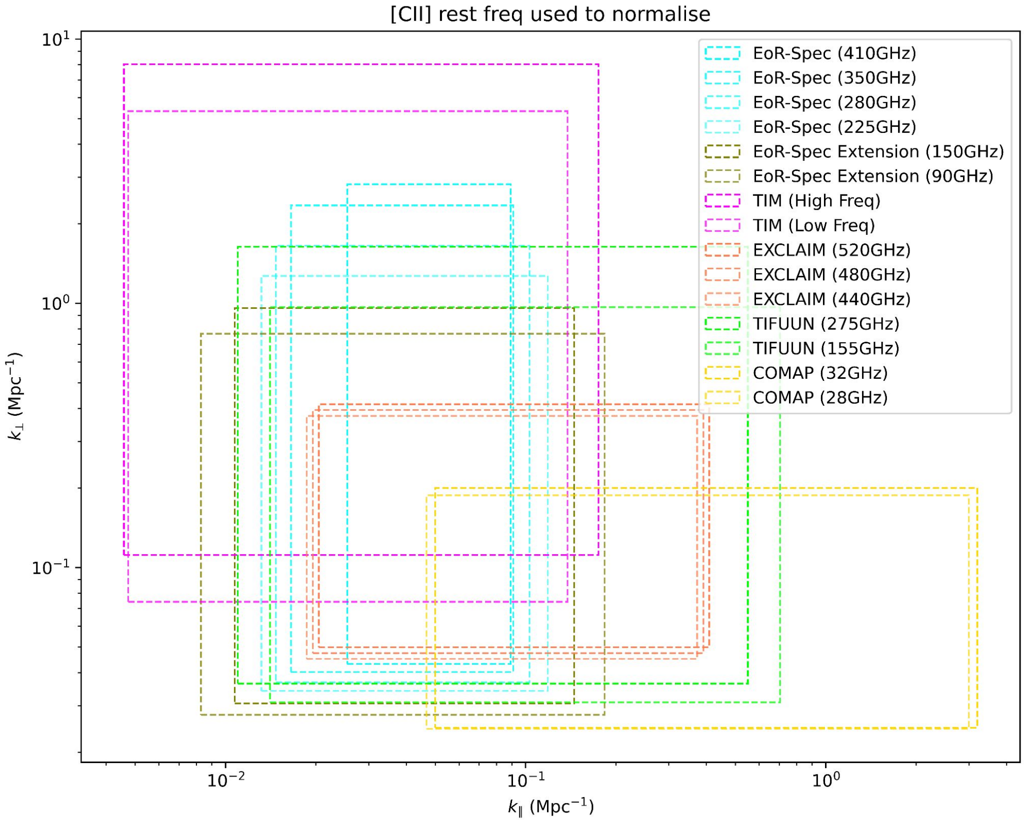


Available k modes

Kmin, kmax depend on shared area coverage, beam width, and frequency channel range

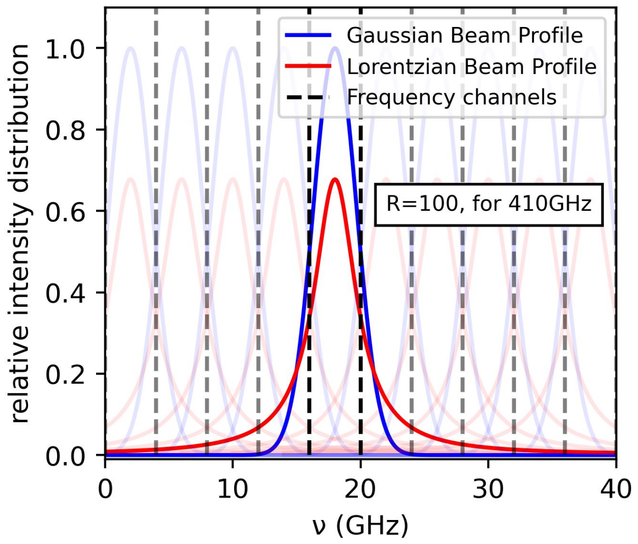
For a given redshift range, instrument coverage vastly differs

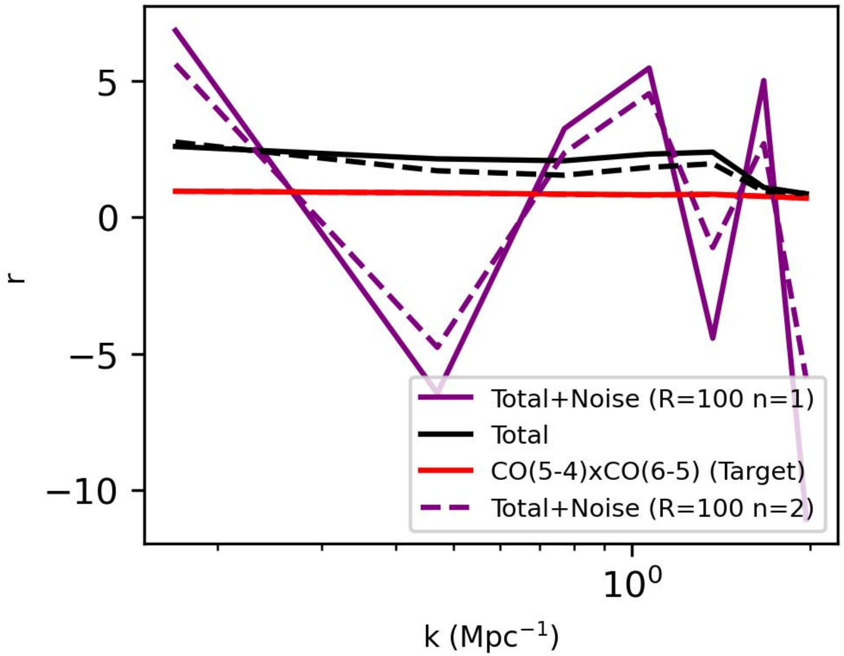
For COMAP/EXCLAIM, need to rely on largest k modes



Cross-correlation - instrument improvement

Signal overlap between channels can give some contribution towards “total” CC





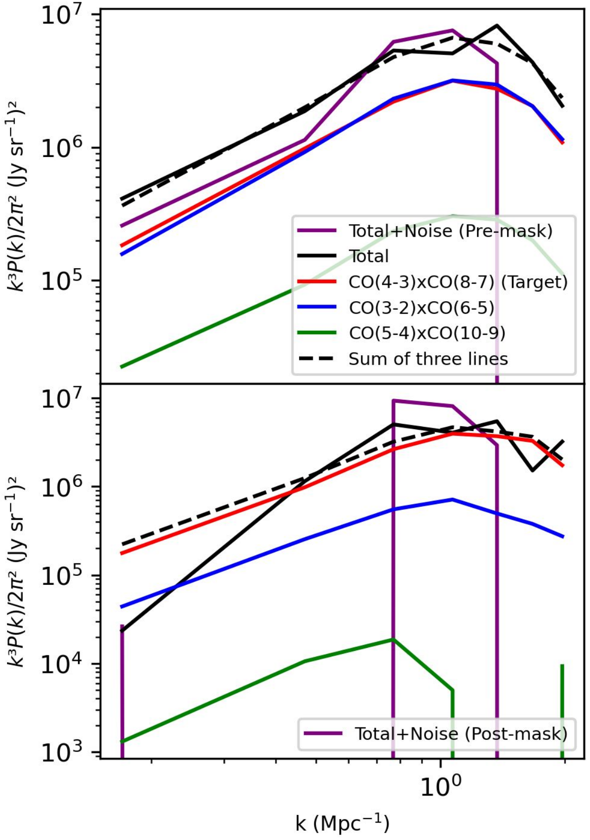
Cross-correlation - masking

EXCLAIM x TIFUUN

Total cross-correlation within a given frequency range includes two correlations

Masking key contributors to one line greatly reduces influence - works even if masking sample is incomplete!

Need to be VERY careful around volume normalisations



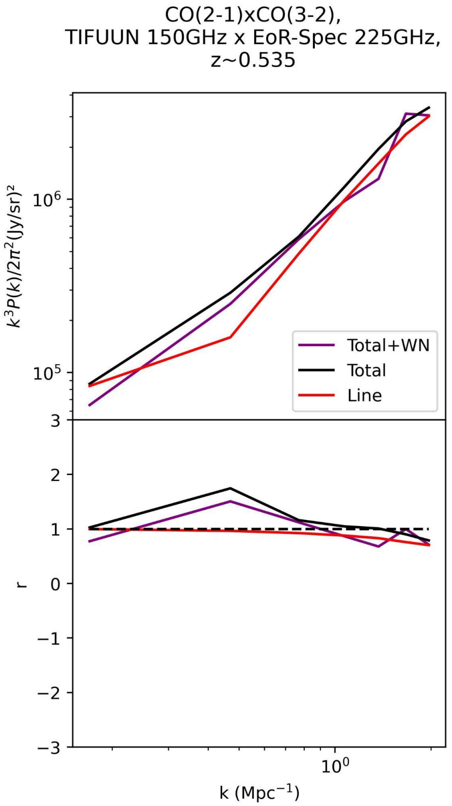
CC Examples

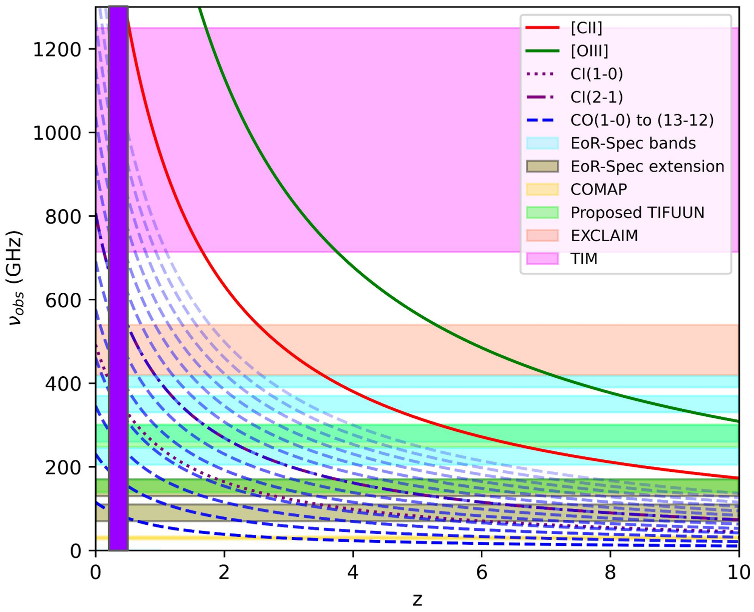
$$r_{A,B} = \frac{P^{\text{line}}_{A,B} \text{ or } P^{\text{total}}_{A,B} \text{ or } P^{\text{total+WN}}_{A,B}}{\sqrt{P^{\text{line}}_{A} P^{\text{line}}_{B}}} \approx 1$$

Good CC!

Observed CC (total+WN, purple) aligns with target line within factor 2 for all k modes (using Δk=0.3Mpc^{-1})

Best mostly at z<1





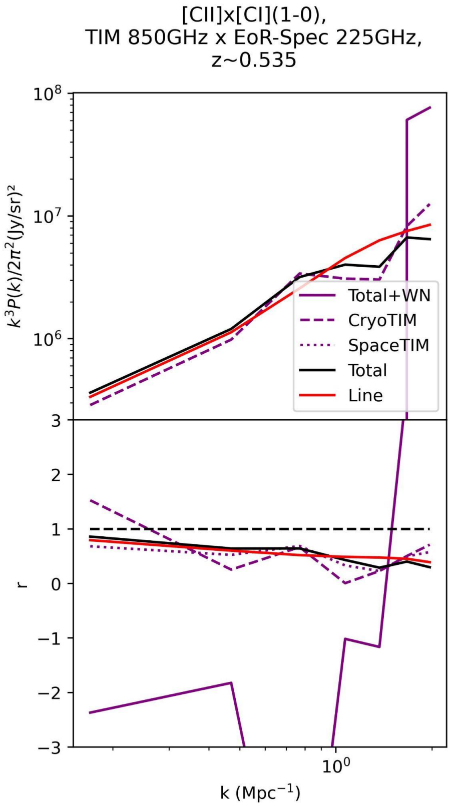
CC Examples

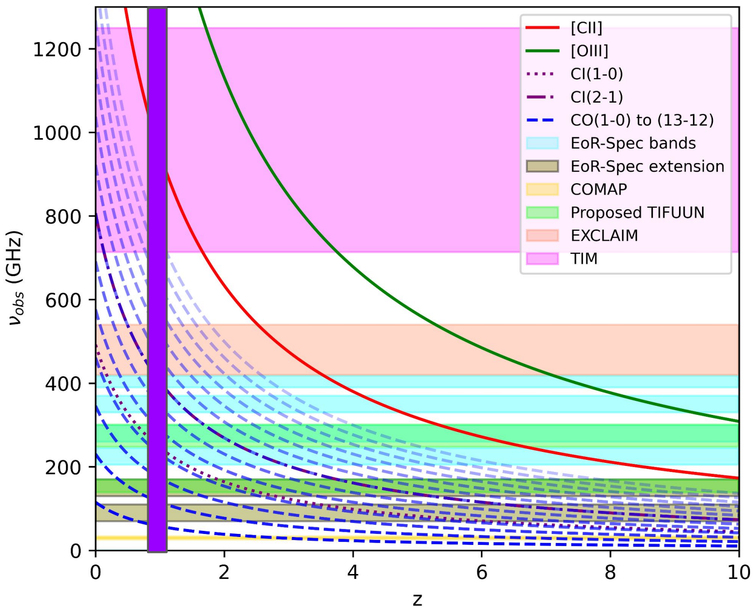
$$r_{A,B} = \frac{P^{\mathrm{line}}_{A,B} \text{ or } P^{\mathrm{total}}_{A,B} \text{ or } P^{\mathrm{total+WN}}_{A,B}}{\sqrt{P^{\mathrm{line}}_{A} P^{\mathrm{line}}_{B}}} \approx 1$$

Noise issues!

TIM, higher frequency EoR-Spec, often need more effective observing time to better align

Also problematic for weaker lines with other instruments





(modelling SpaceTIM - Agrawal+26)

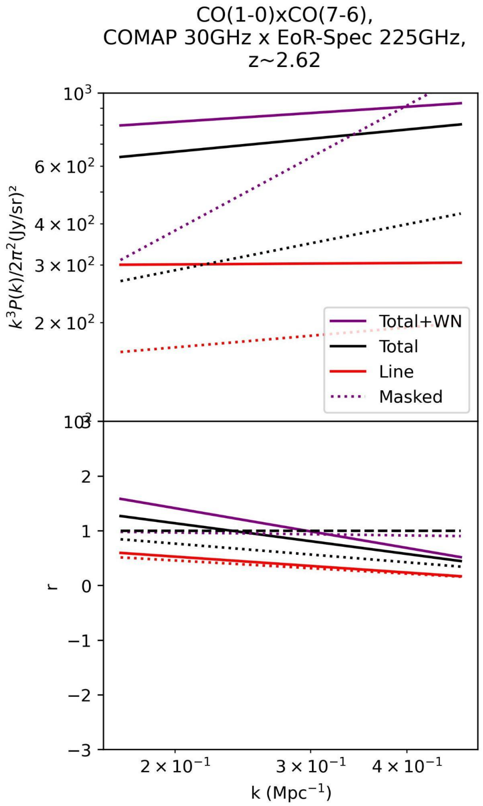
CC Examples

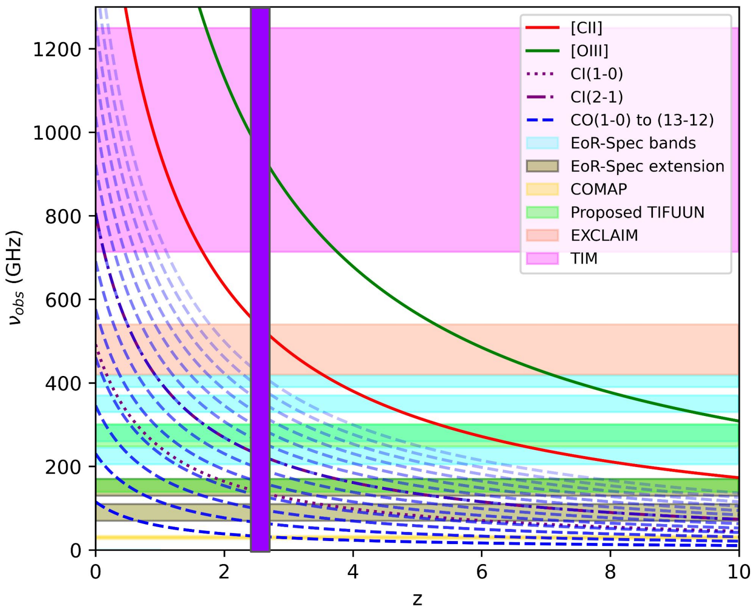
$$r_{A,B} = \frac{P^{\rm line}_{A,B} \text{ or } P^{\rm total}_{A,B} \text{ or } P^{\rm total+WN}_{A,B}}{\sqrt{P^{\rm line}_{A} P^{\rm line}_{B}}} \approx 1$$

Signal issues!

Other cross-correlations existing in same freq. range, or signal leakage, mean key line doesn't dominate

Masking techniques, when limited, help





(masking interlopers in 225GHz band)