Synergizing IM surveys at the EoR

— [OIII] and [CII] from the sky —

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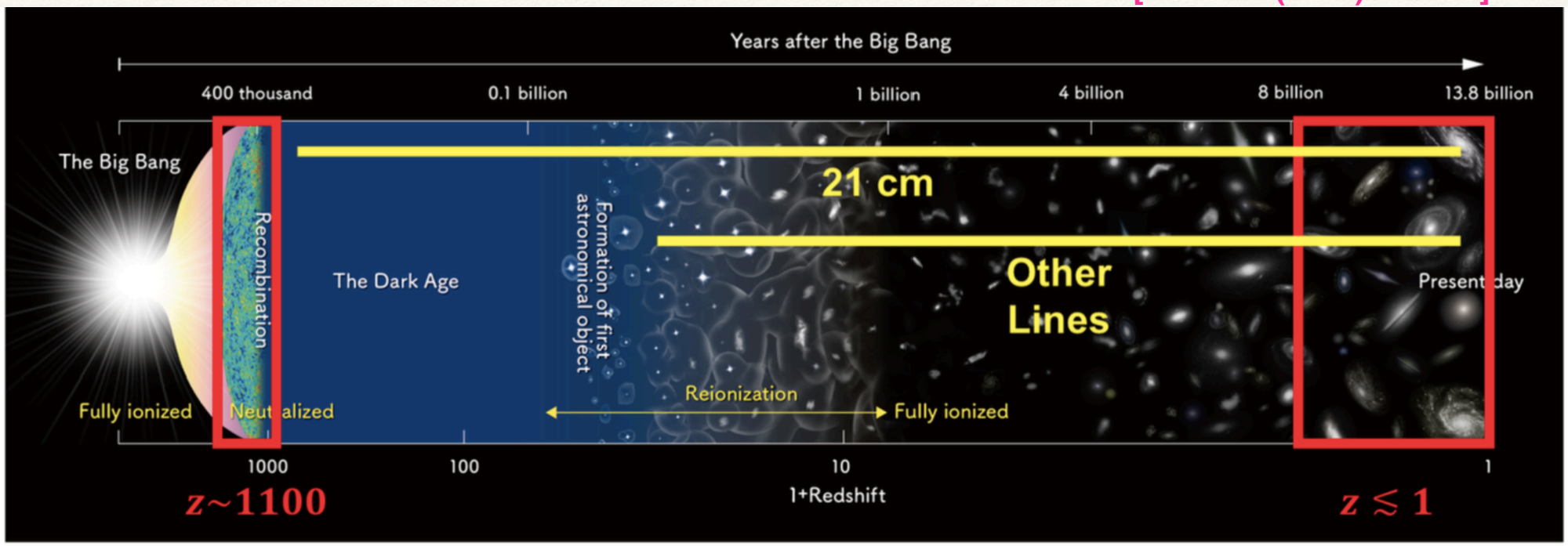
Based on https://arxiv.org/abs/2105.12148
with Patrick Breysse, Adam Lidz and Eric. R. Switzer

The sub-millimetre regime

[Kovetz+ (2017) / NAOJ]



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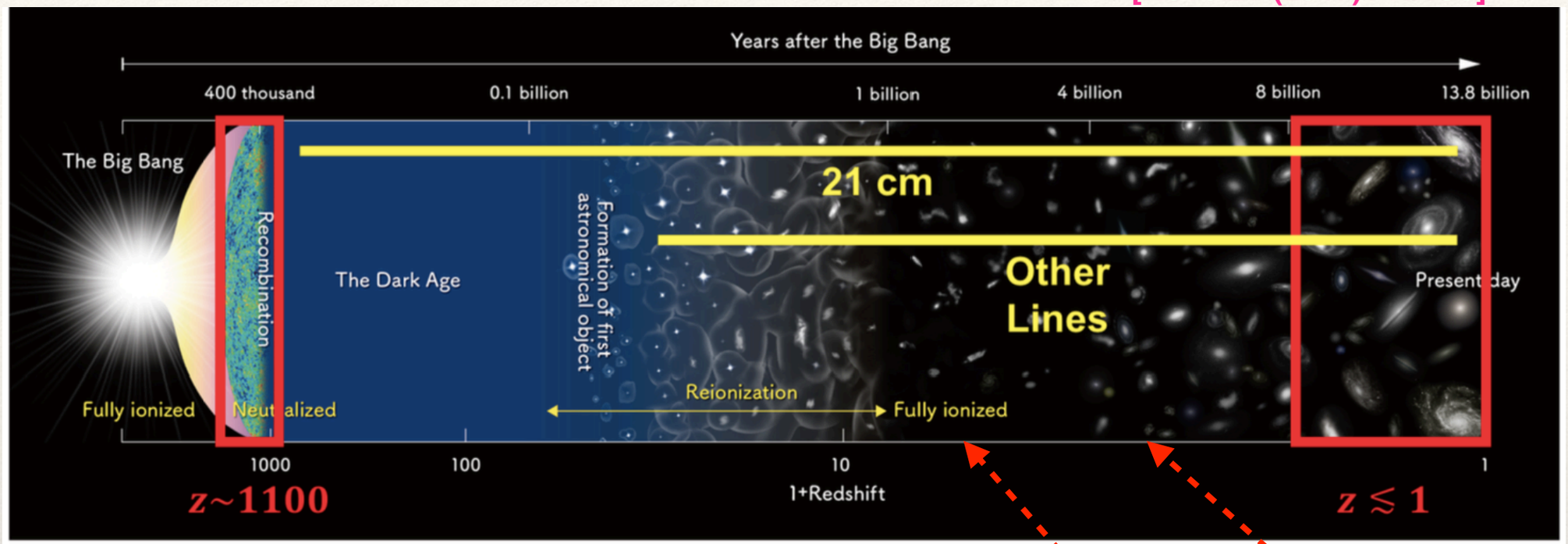
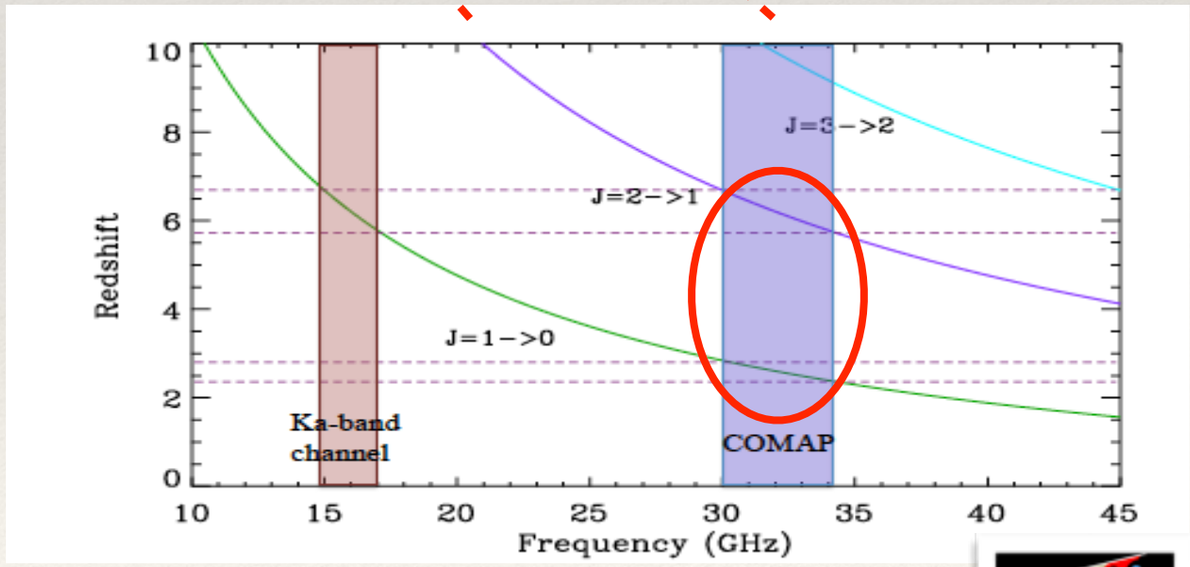
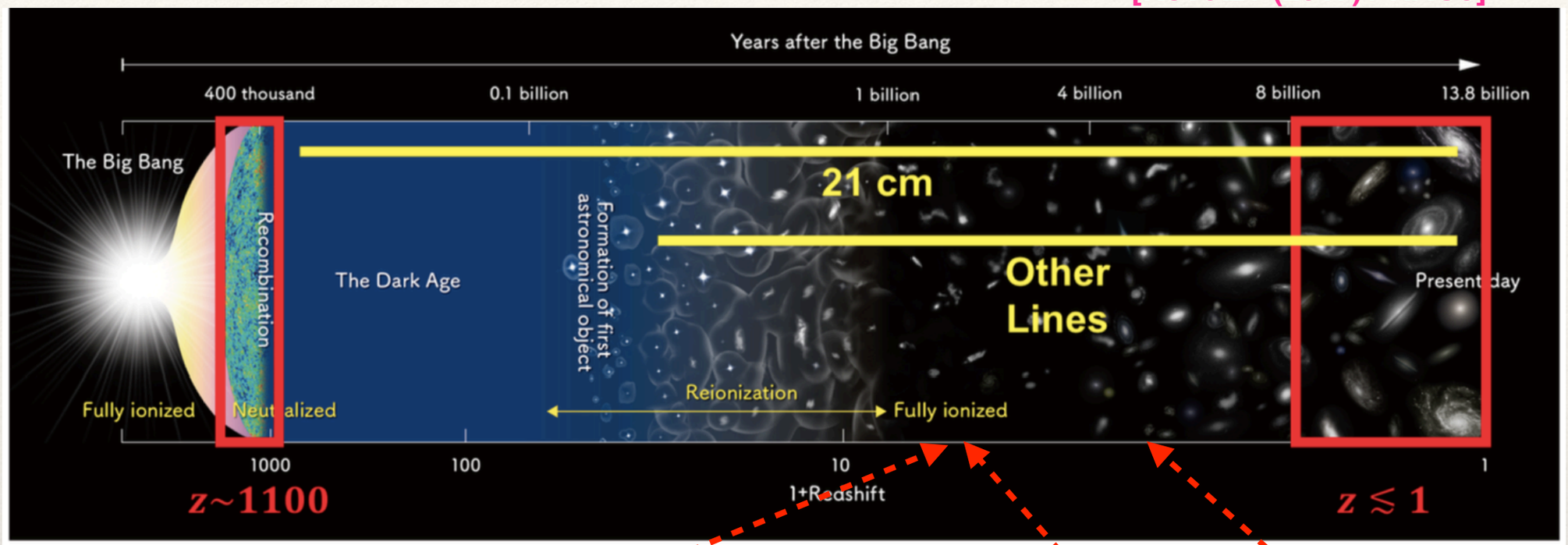


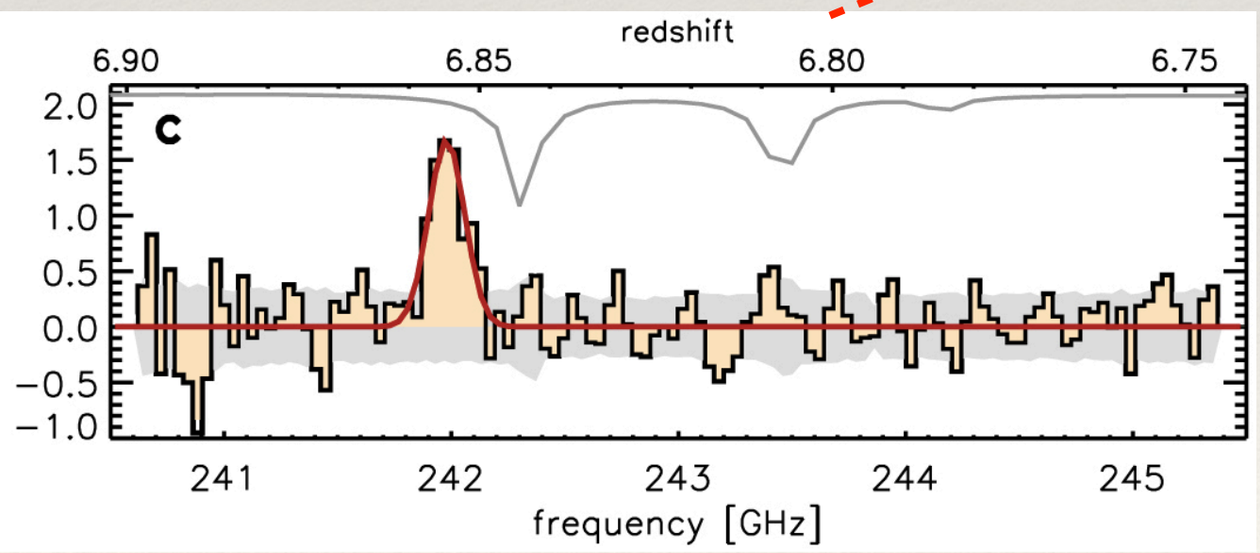


CO transitions

The sub-millimetre regime

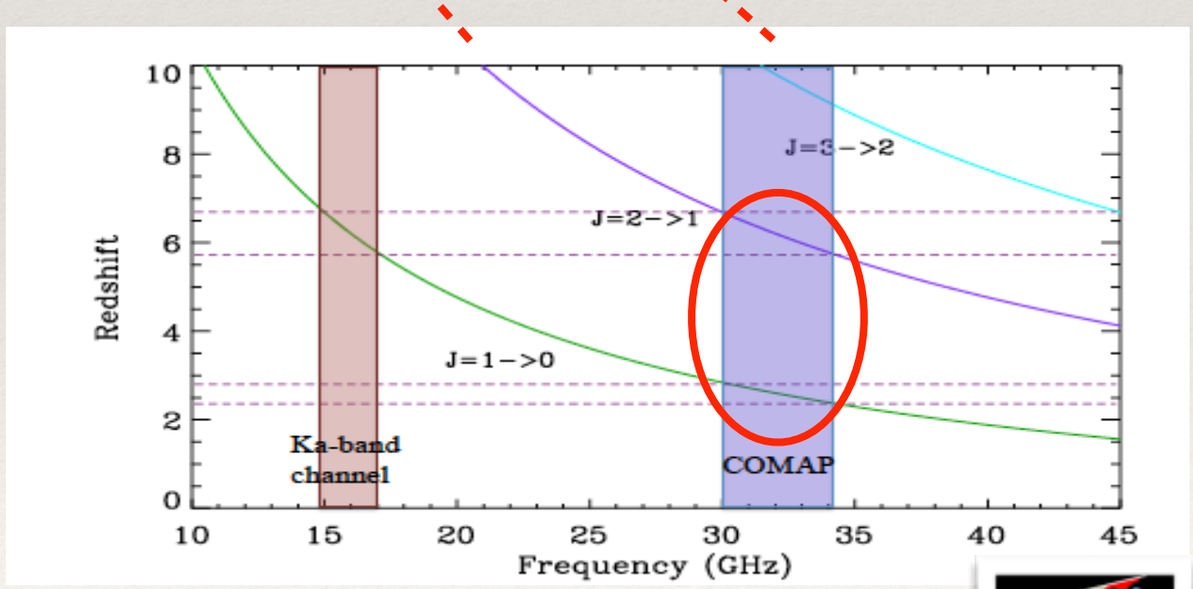
[Kovetz+ (2017) / NAOJ]





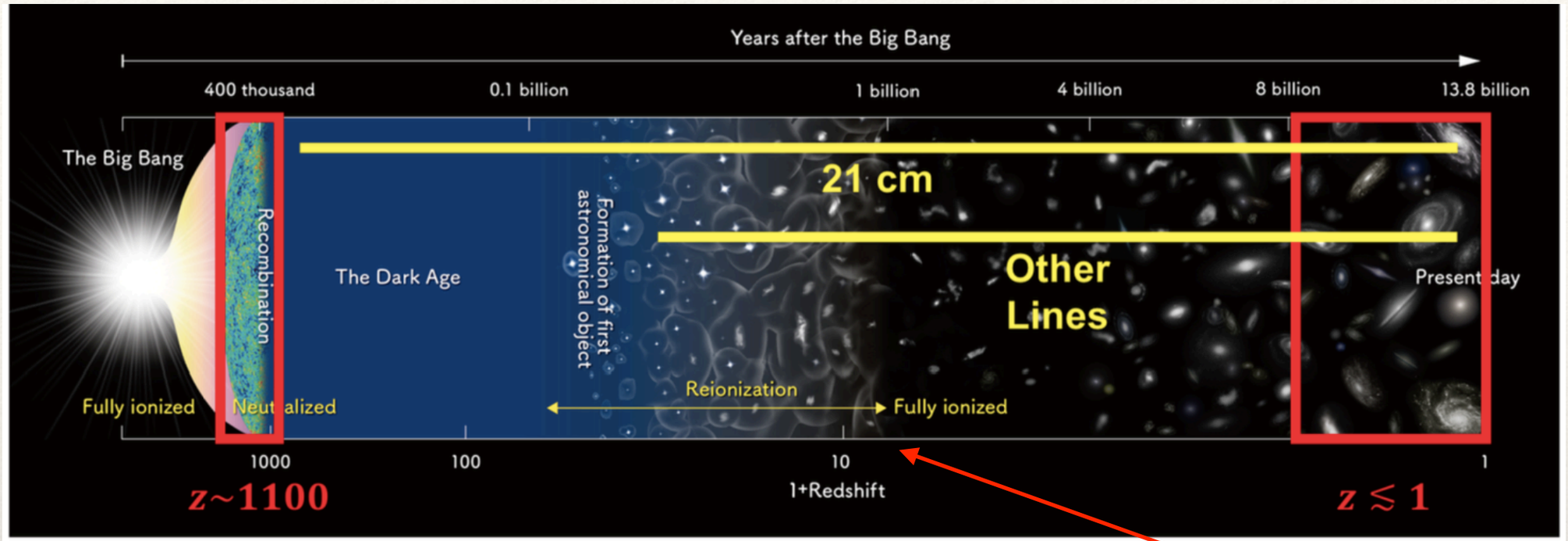
CII, 158 micron

[Smit+ (2018), Pentericci+ (2017)]



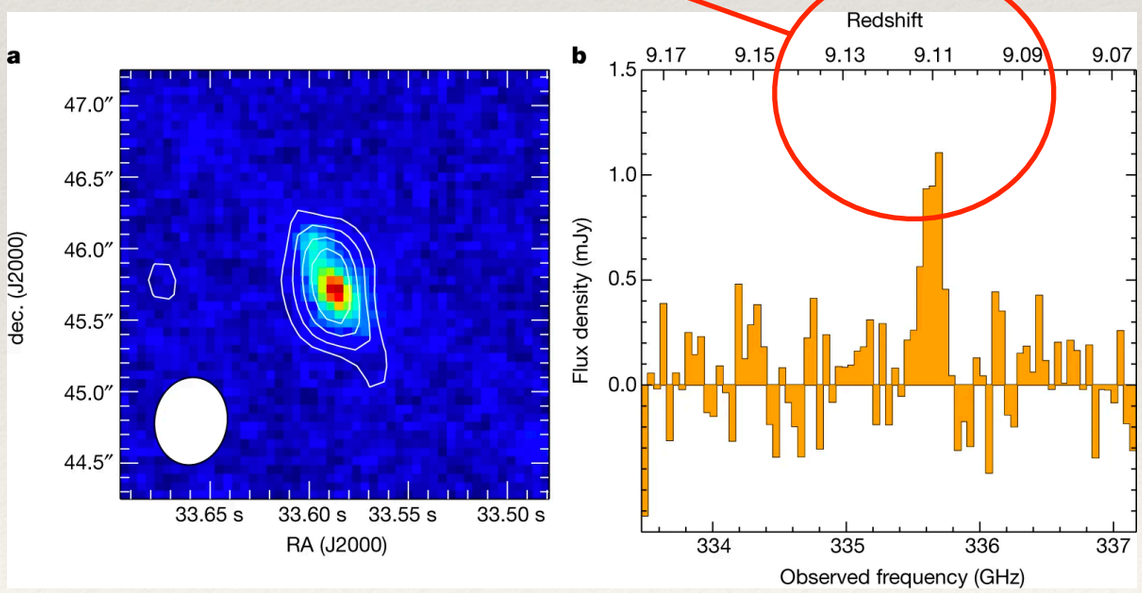
CO transitions

The [OIII] fine structure lines



[OIII] 88 micron

[Hashimoto+ (2018, 2019),
Laporte+ (2017, 2019), Harikane+ (2020)]



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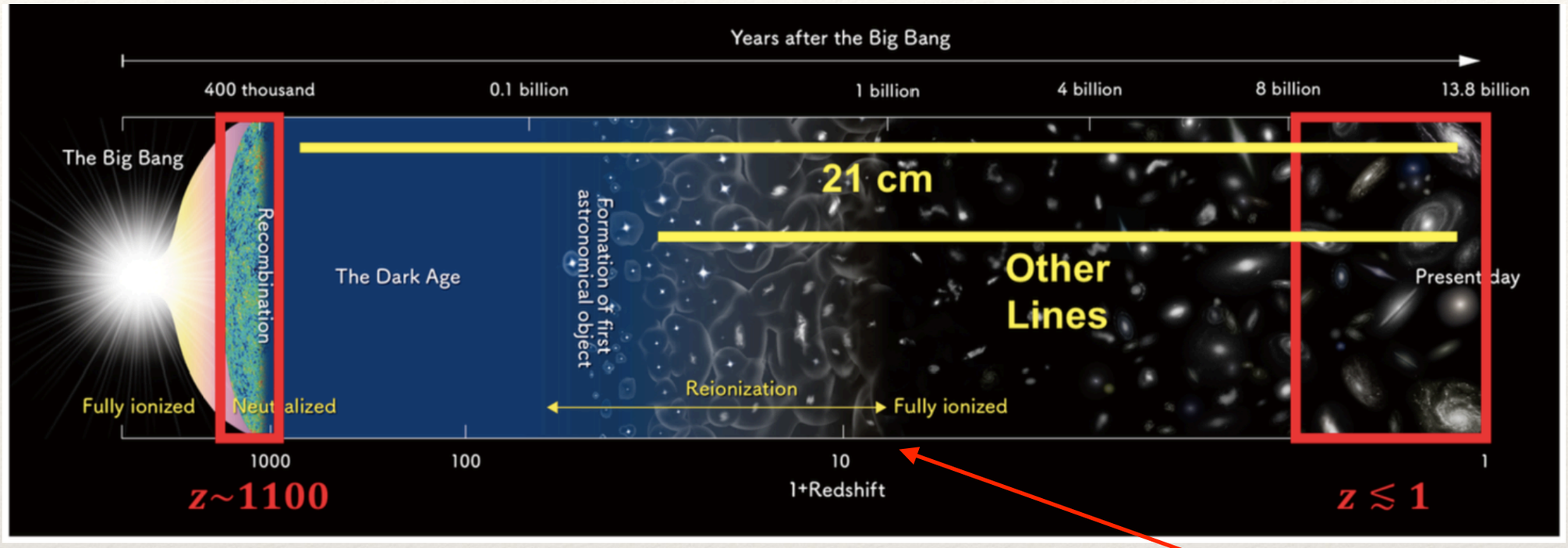
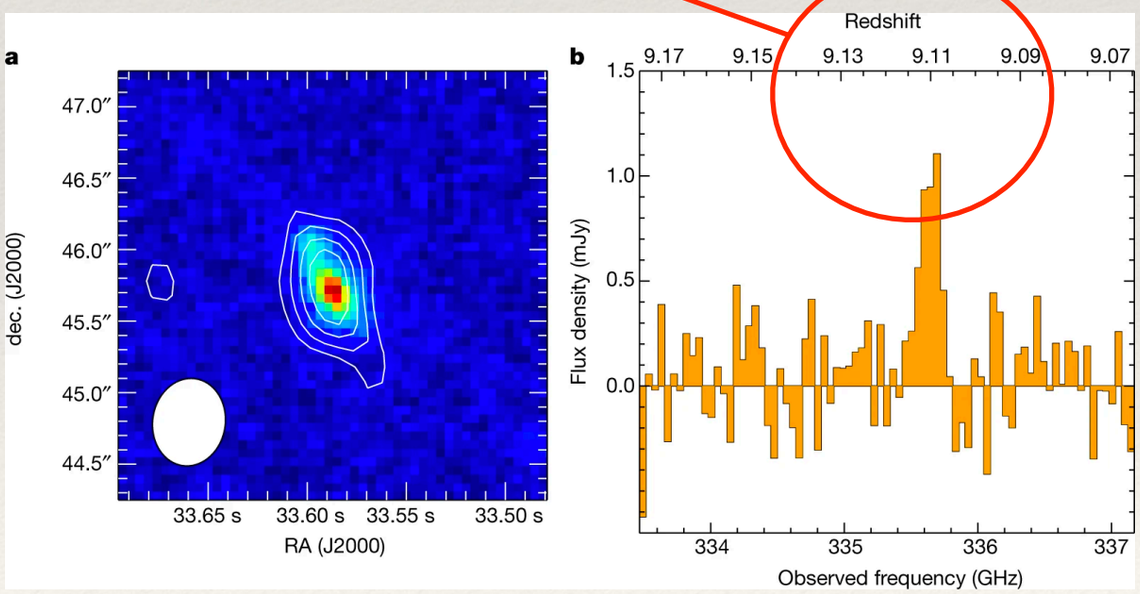


[OIII] 52 micron forecasts

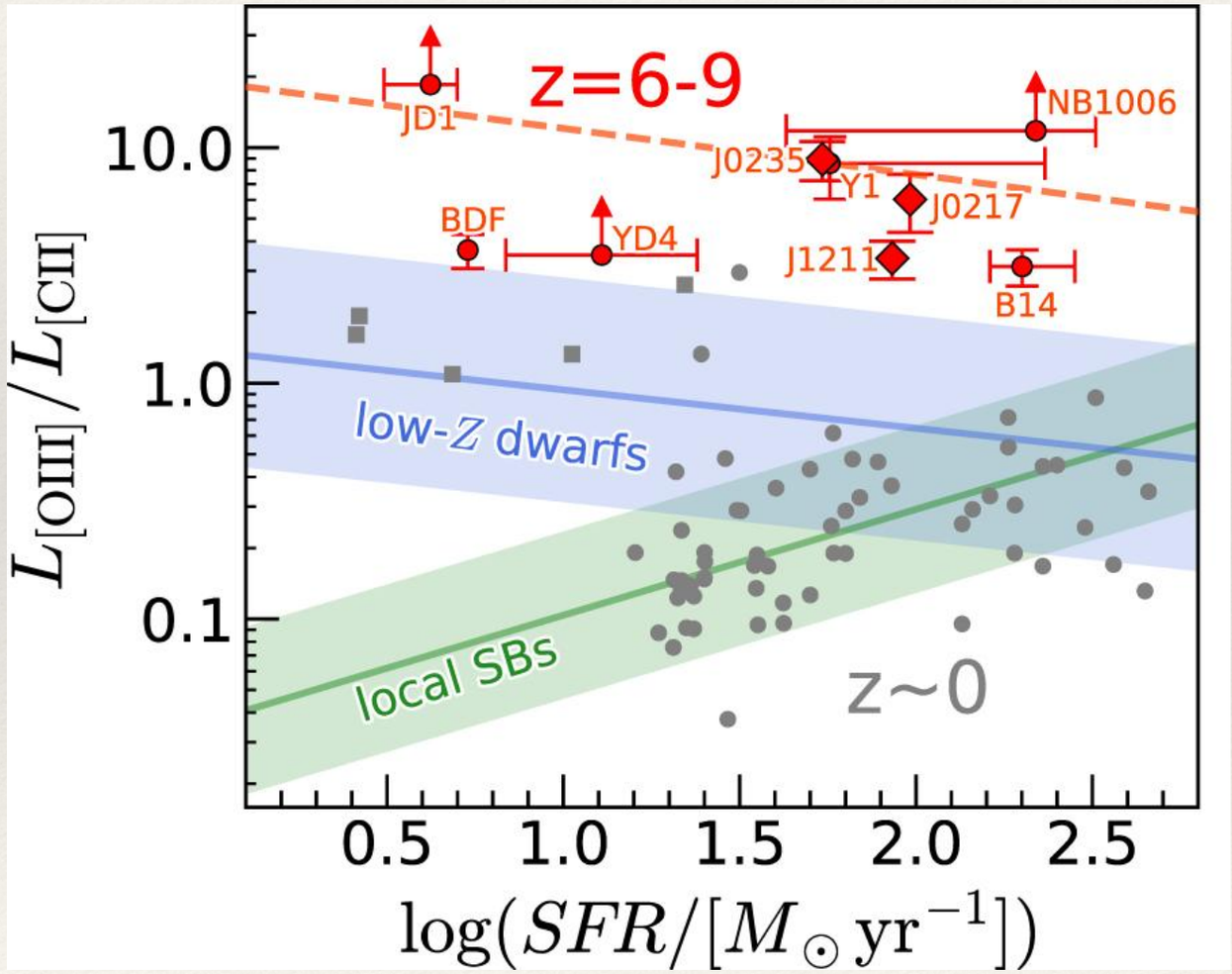
[Yang & Lidz (2020),
Yang+ (2021), Jones+ (2020)]



[OIII] in high redshift galaxies

[OIII]: > 35 eV; HII regions

ALMA observations: [CII] ‘deficit’ at high-z; if confirmed by IM, indicates hard ISM field and/or larger HII regions



[Harikane+ (2020), see also Laporte+ (2019)]

EXCLAIM-like survey probing [OIII] at z ~ 7?

EXCLAIM bandwidth : 420 - 540 GHz

Captures [OIII] 88 micron at ***z* ~ 5.3 - 7.1!**

Caveat: The nominal mission may not be sensitive enough …

Solution: Near next-gen version, and cross-correlate!

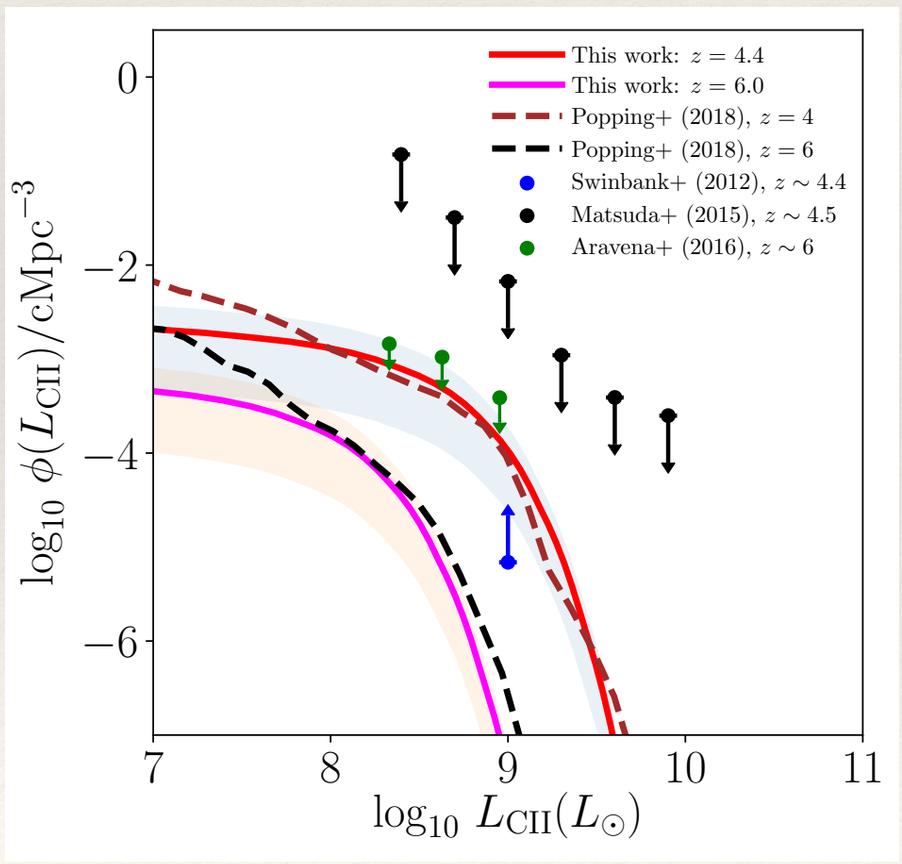
Most promising to cross-correlate with [CII] from FYST

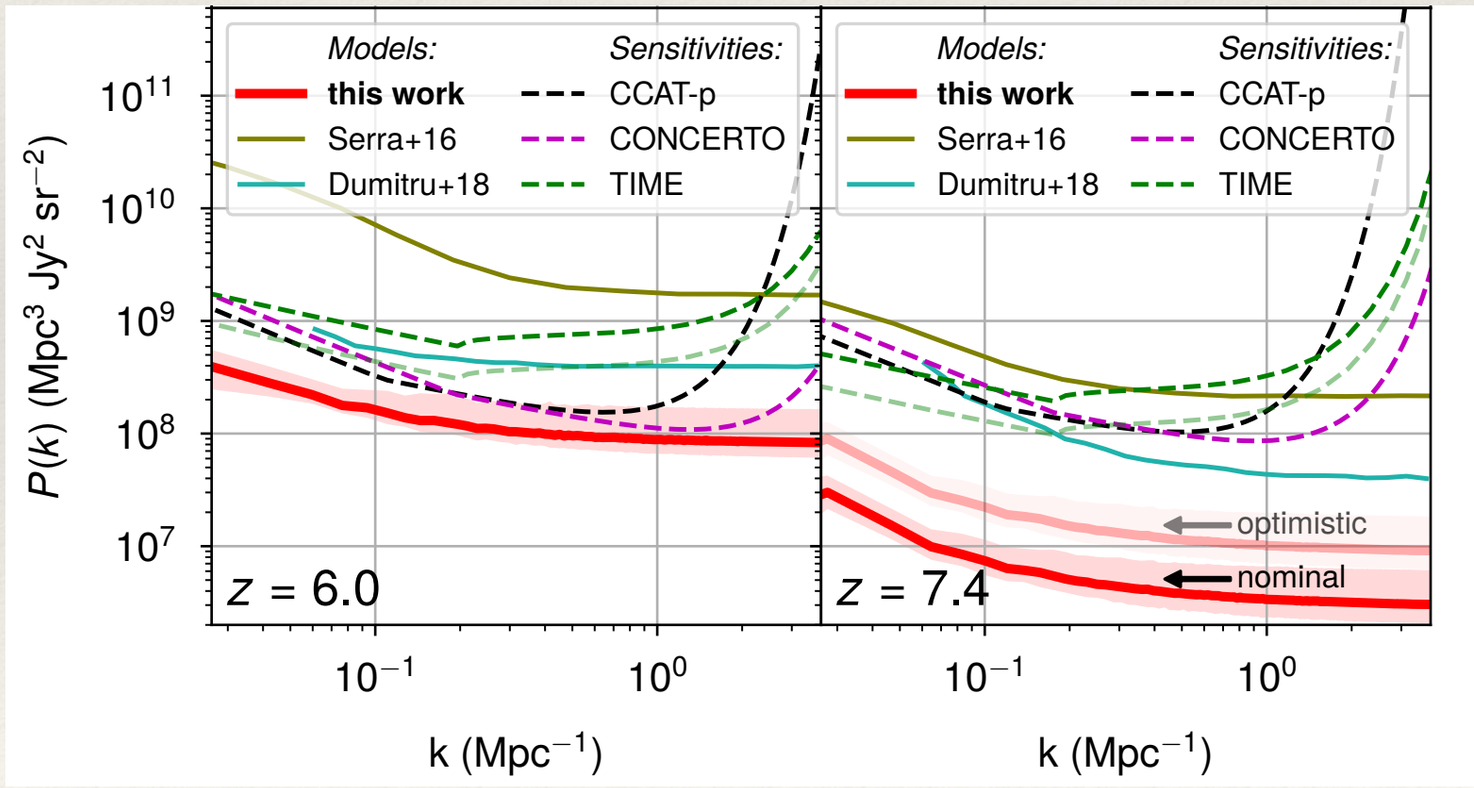
[CII] power spectra

$$L_{\rm CII}(M,z) = \left(\frac{M}{M_1}\right)^{\beta} \exp(-N_1/M) \left(\frac{(1+z)^{2.7}}{1+[(1+z)/2.9)]^{5.6}}\right)^{\alpha}$$

$$M_1 = (2.39 \pm 1.86) \times 10^{-5};\ N_1 = (4.19 \pm 3.27) \times 10^{11};$$
$$\beta = 0.49 \pm 0.38;\ \alpha = 1.79 \pm 0.30$$

[HP (MNRAS 2019), arXiv:1811.01968]





[Chung+ (2020)]

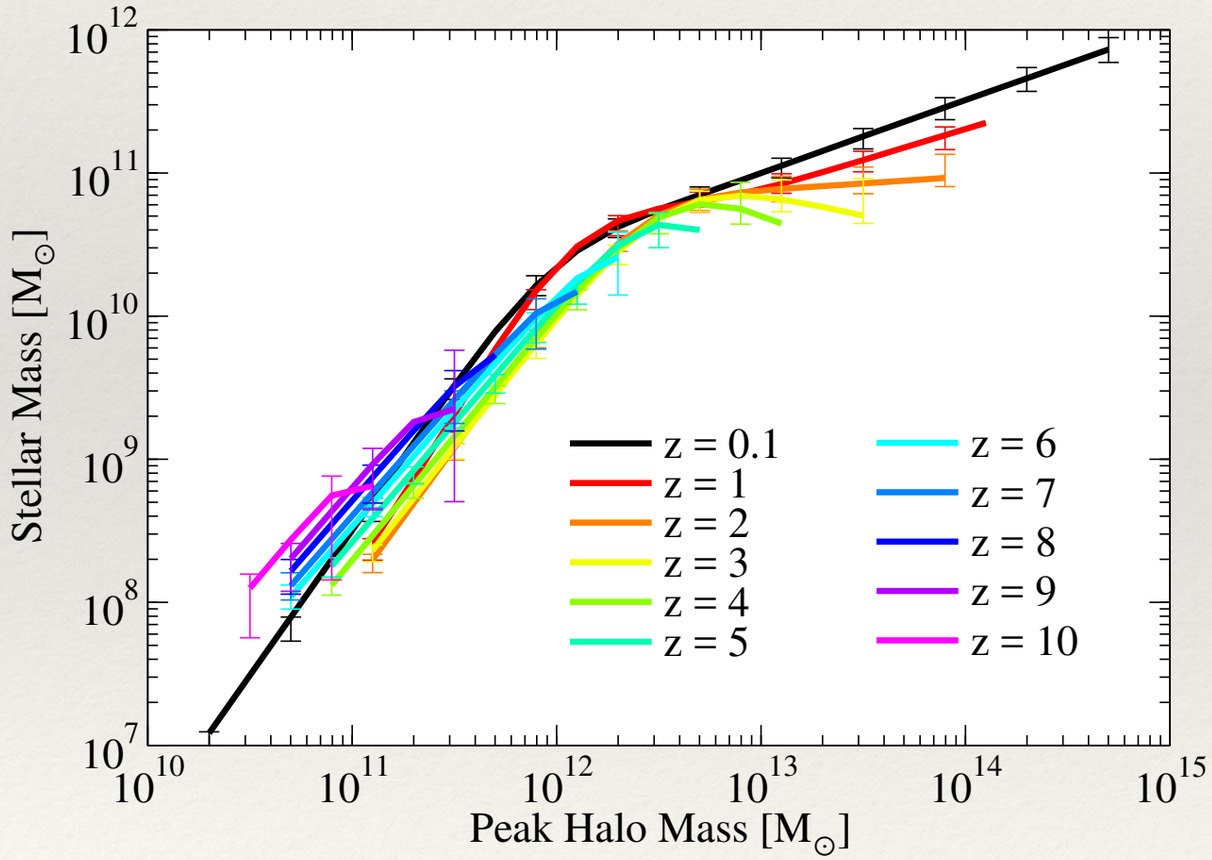
[OIII] power spectra

[Early work: Visbal & Loeb (2010), Gong+ (2016), Visbal+ (2011) …]

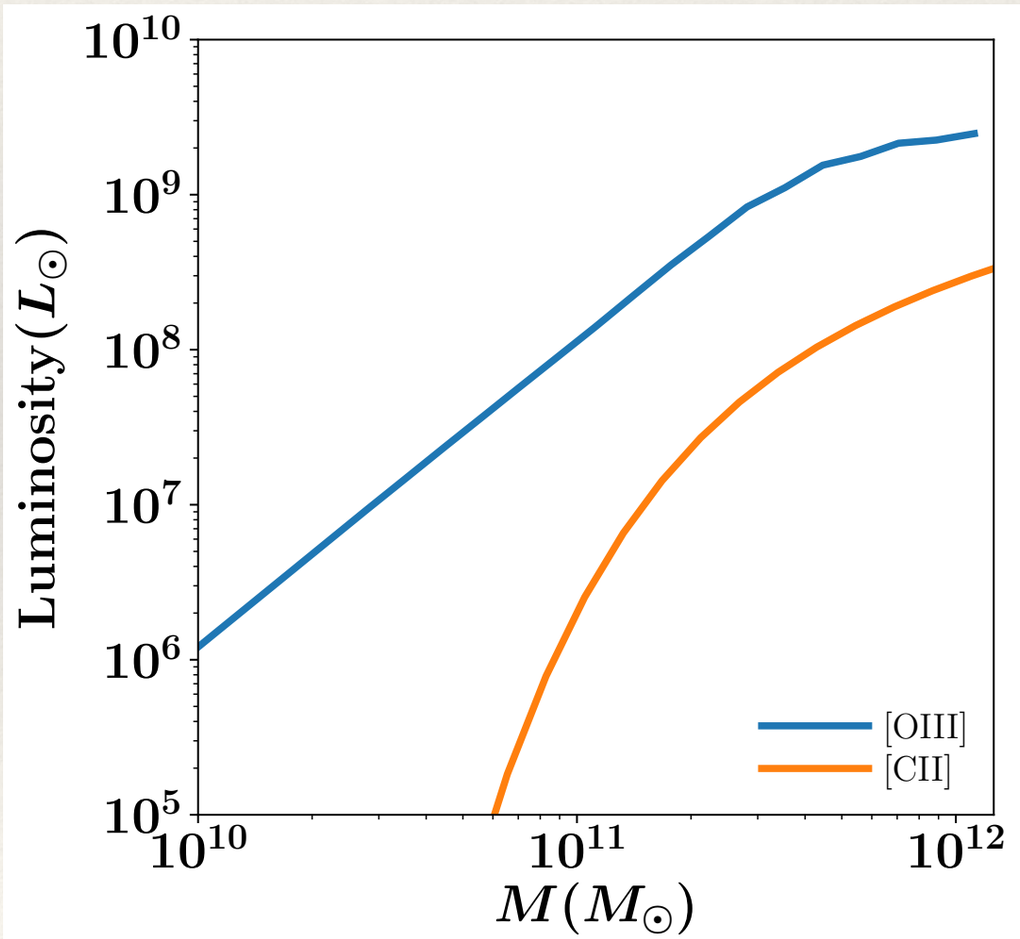
$$\log\left(\frac{L_{\rm OIII}}{L_\odot}\right) = 0.97 \times \log\frac{\rm SFR}{[M_\odot {\rm yr}^{-1}]} + 7.4$$

[Harikane+ (2020)]

[Behroozi+ (2018)]



[HP+ (2021), arXiv:2105.12148]



Improved versions of current architecture

EXCLAIM

$$D_{\rm dish} = 0.74 \text{ m}$$
$$\Delta\nu = 1000 \text{ MHz}$$
$$N_{\rm spec,eff} = 6$$
$$S_{\rm A} = 400 \text{ sq.deg.}$$
$$\sigma_{\rm N} = 600000 \text{ Jys}^{1/2}/\text{sr}$$
$$B_\nu = 40 \text{ GHz}$$
$$t_{\rm obs} = 8\text{h}$$
$$\text{Bandwidth} = 420 - 540 \text{ GHz}$$

FYST

$$D_{\rm dish} = 6 \text{ m}$$
$$\Delta\nu = 2500 \text{ MHz}$$
$$N_{\rm spec,eff} = 20$$
$$S_{\rm A} = 8 \text{ sq.deg.}$$
$$\sigma_{\rm N} = 500000 \text{ Jys}^{1/2}/\text{sr}$$
$$B_\nu = 40 \text{ GHz}$$
$$t_{\rm obs} = 4000\text{h}$$
$$\text{Bandwidth} = 212 - 428 \text{ GHz}$$

[e.g., HP+ (2019), Chung+ (2020), Breysse+ (2021)]

Improved versions of current architecture

EXCLAIM++

$$D_{\rm dish} = 0.74 \text{ m}$$
$$\Delta\nu = 1000 \text{ MHz}$$
$$N_{\rm spec,eff} = 30$$
$$S_{\rm A} = 100 \text{ sq.deg.}$$
$$\sigma_{\rm N} = 100000 \text{ Jys}^{1/2}/\text{sr}$$
$$B_\nu = 40 \text{ GHz}$$
$$t_{\rm obs} = 8\text{h}$$
$$\text{Bandwidth} = 420 - 540 \text{ GHz}$$

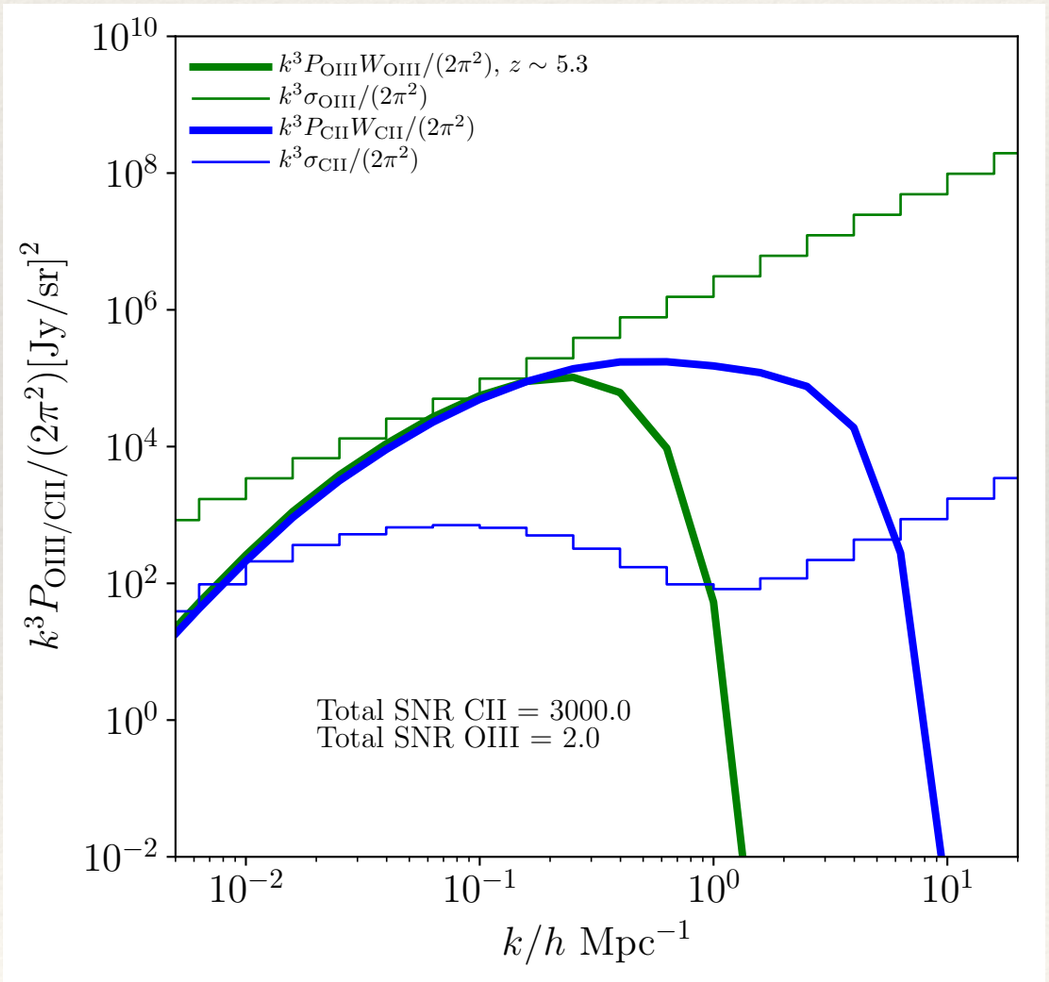
FYST++

$$D_{\rm dish} = 9 \text{ m}$$
$$\Delta\nu = 400 \text{ MHz}$$
$$N_{\rm spec,eff} = 16000$$
$$S_{\rm A} = 100 \text{ sq.deg.}$$
$$\sigma_{\rm N} = 210000 \text{ Jys}^{1/2}/\text{sr}$$
$$B_\nu = 40 \text{ GHz}$$
$$t_{\rm obs} = 2000 \text{ h}$$
$$\text{Bandwidth} = 212 - 428 \text{ GHz}$$

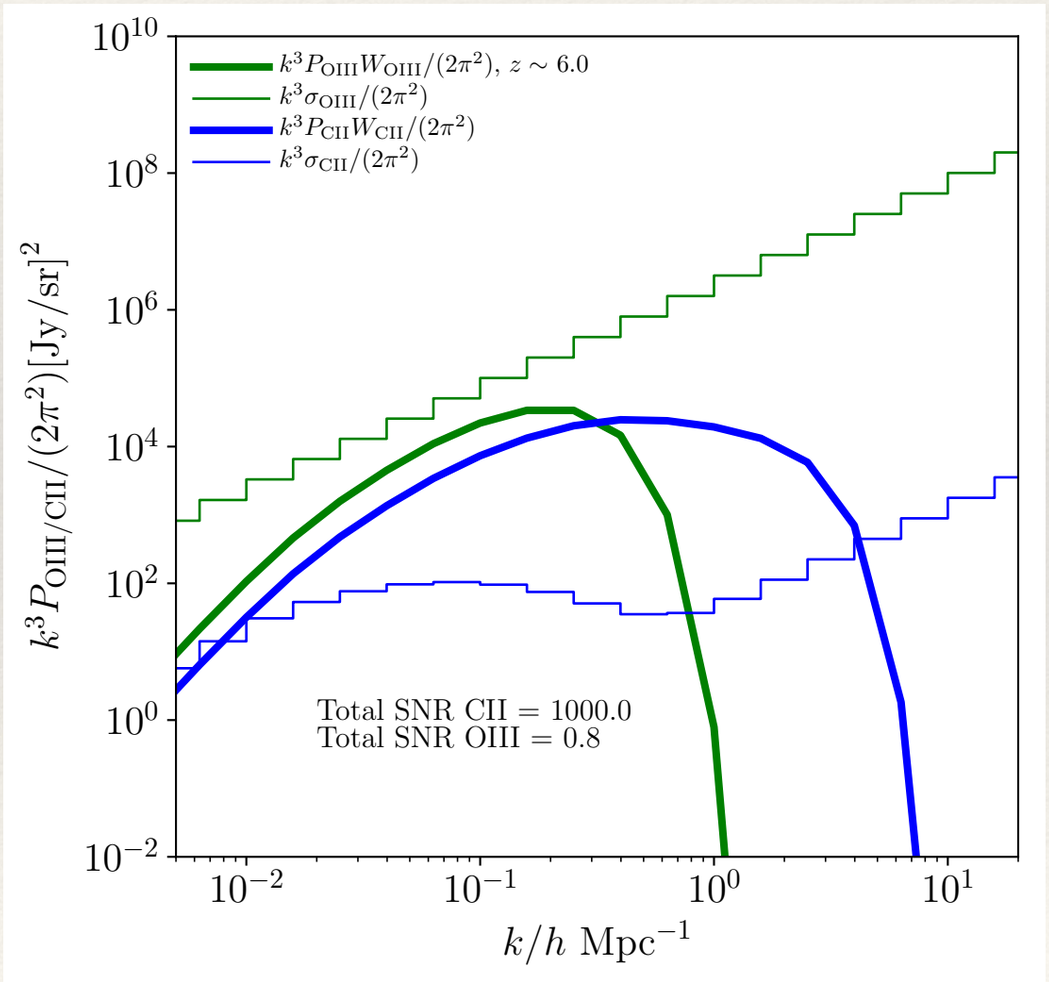
Auto-correlation forecasts

FYST++, EXCLAIM++

z ~ 4.9 - 5.7, [CII] 158, [OIII] 88



z ~ 5.5 - 6.5, [CII] 158, [OIII] 88



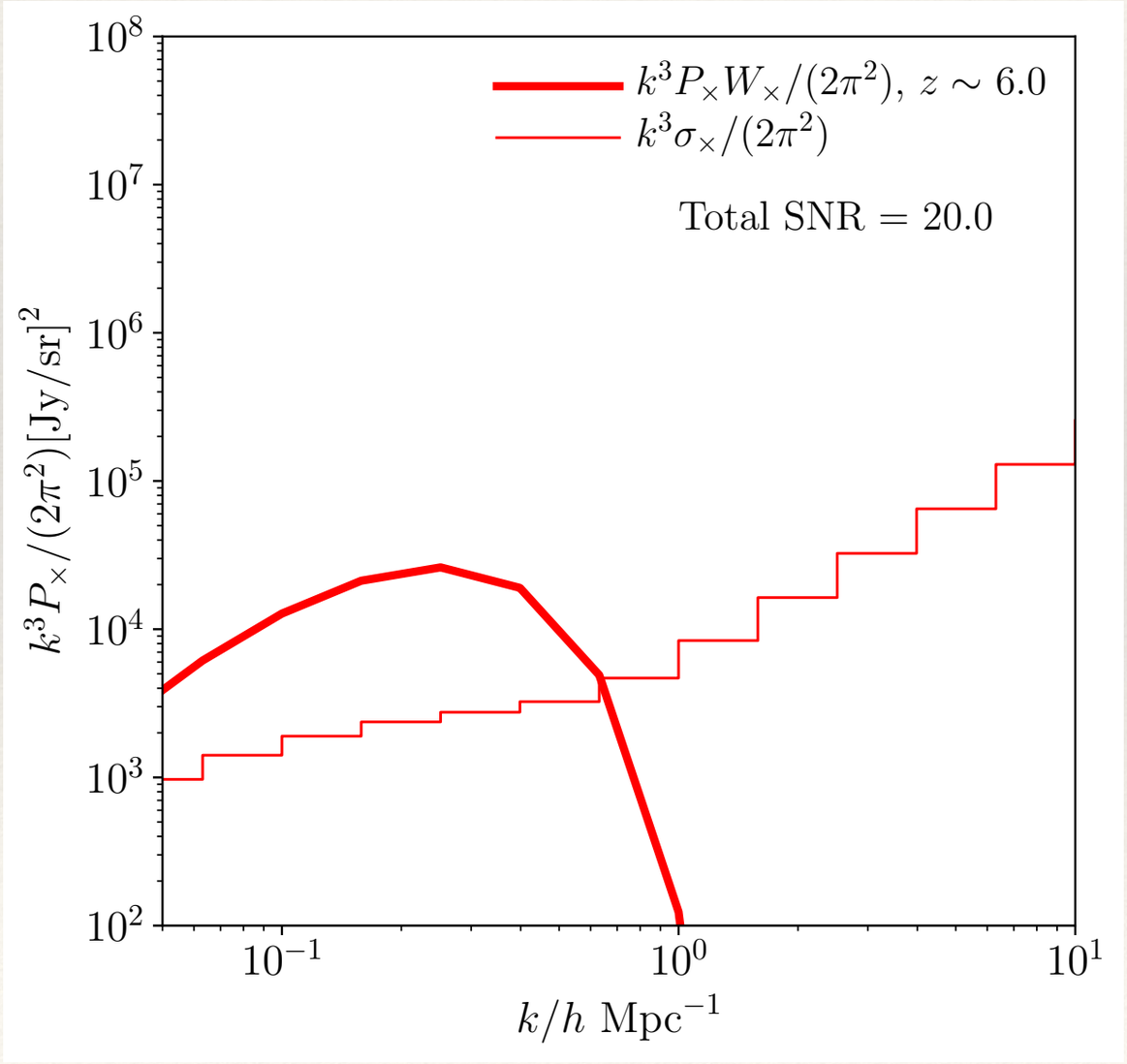
[HP+ (2021), arXiv:2105.12148]

Cross-correlation forecasts*

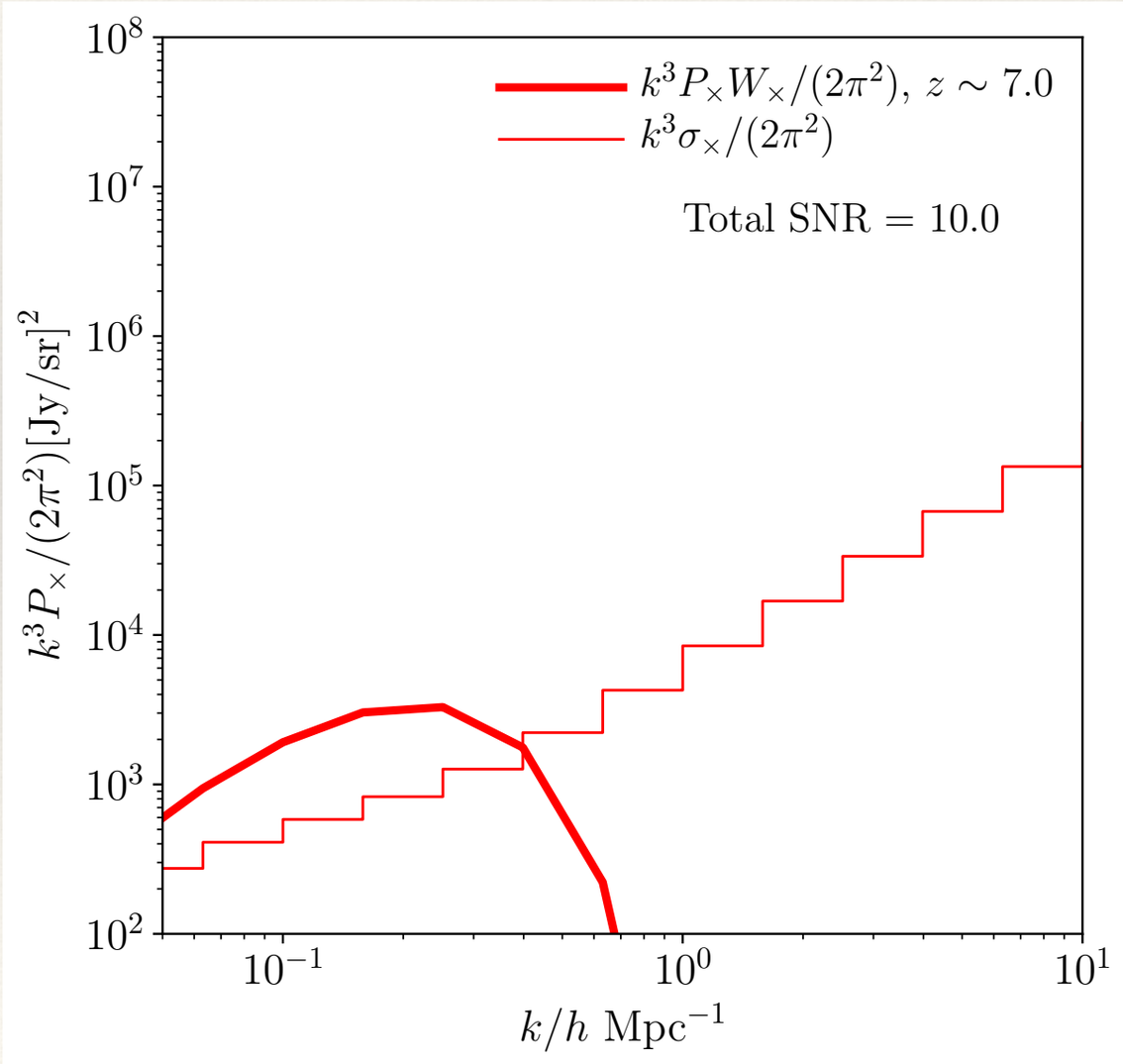
**Assumes complete overlap*

(FYST++) x (EXCLAIM++)

z ~ 5.5-6.5, [CII] 158 x [OIII] 88



z ~ 6.3-7.8, [CII] 158 x [OIII] 88



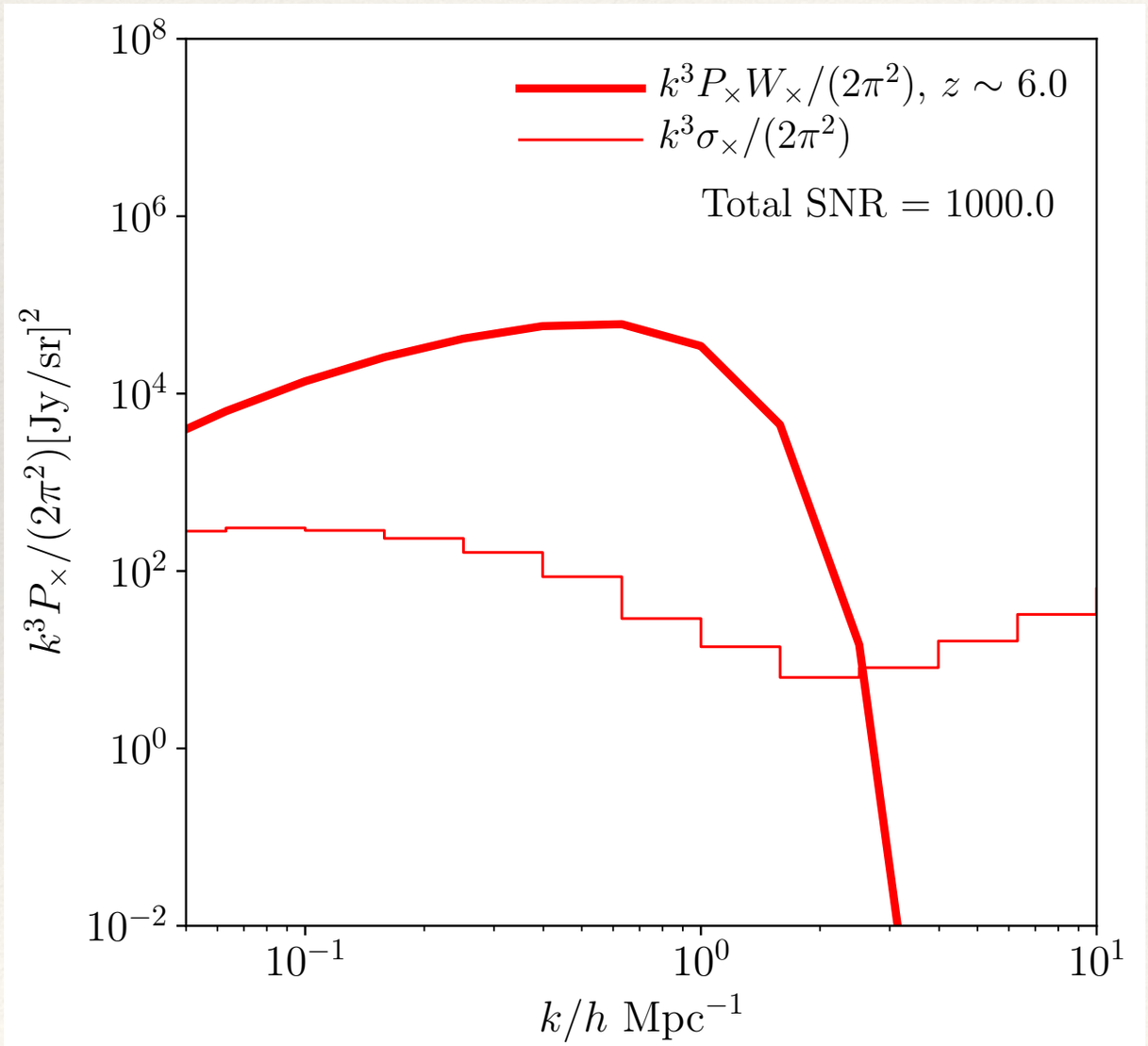
A ‘design’ [OIII] and [CII] intensity mapping survey

- A future space mission, background limited -

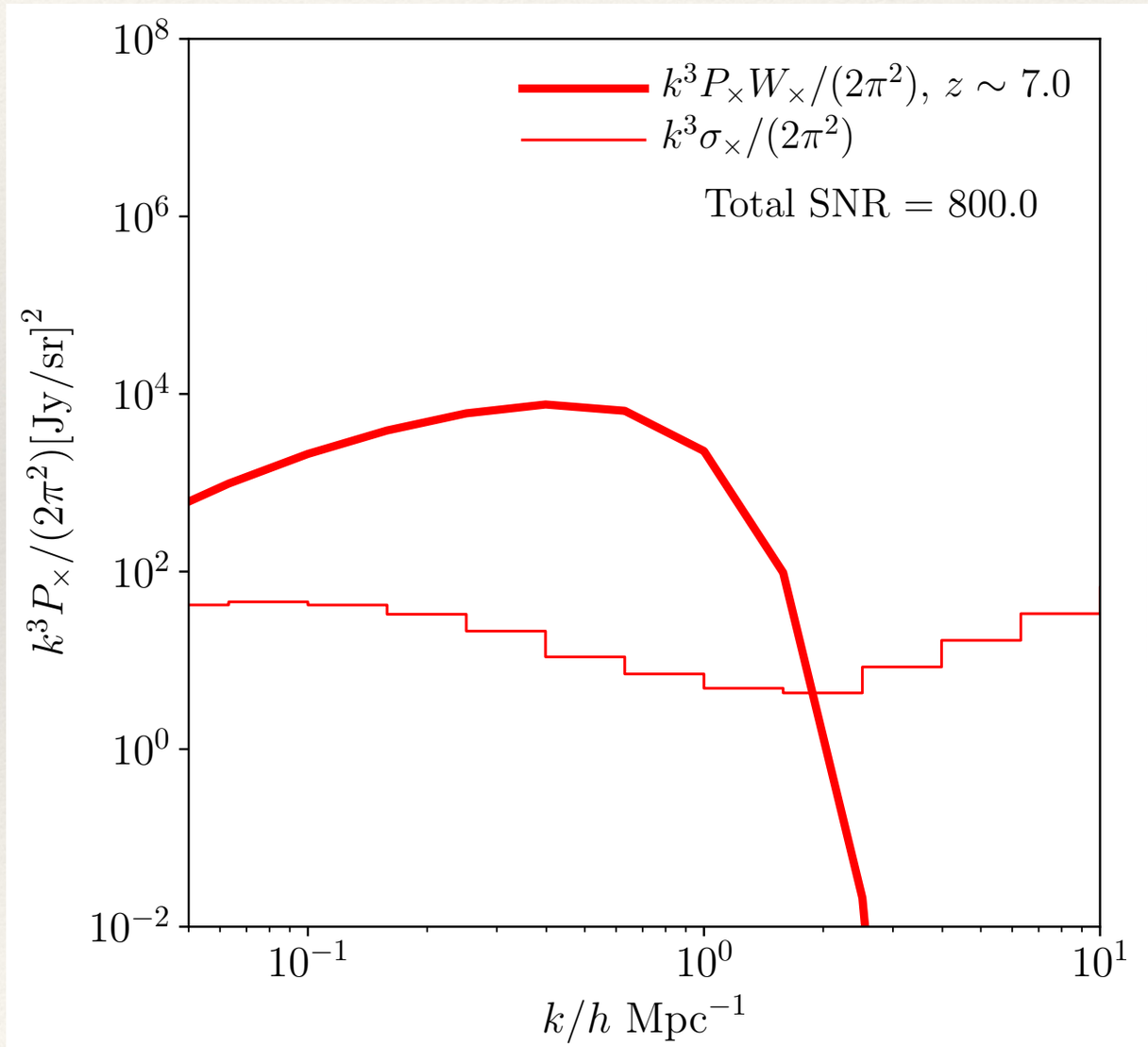
Design	**EXCLAIM++**	**FYST++**
$D_{\rm dish} = 3$ m	$D_{\rm dish} = 0.74$ m	$D_{\rm dish} = 9$ m
$\Delta\nu = 300$ MHz	$\Delta\nu = 1000$ MHz	$\Delta\nu = 400$ MHz
$N_{\rm spec,eff} = 50$	$N_{\rm spec,eff} = 30$	$N_{\rm spec,eff} = 16000$
$S_{\rm A} = 16$ sq.deg.	$S_{\rm A} = 100$ sq.deg.	$S_{\rm A} = 100$ sq.deg.
$\sigma_{\rm N} = 10000$ Jys$^{1/2}$/sr	$\sigma_{\rm N} = 100000$ Jys$^{1/2}$/sr	$\sigma_{\rm N} = 210000$ Jys$^{1/2}$/sr
$B_\nu = 100$ GHz	$B_\nu = 40$ GHz	$B_\nu = 40$ GHz
$t_{\rm obs} = 4000$ h	$t_{\rm obs} = 8$h	$t_{\rm obs} = 2000$ h
$250 - 900$ GHz	$420 - 540$ GHz	$212 - 428$ GHz

Forecasting with the design configuration

z ~ 6, [CII] 158 x [OIII] 88



z ~ 7, [CII] 158 x [OIII] 88



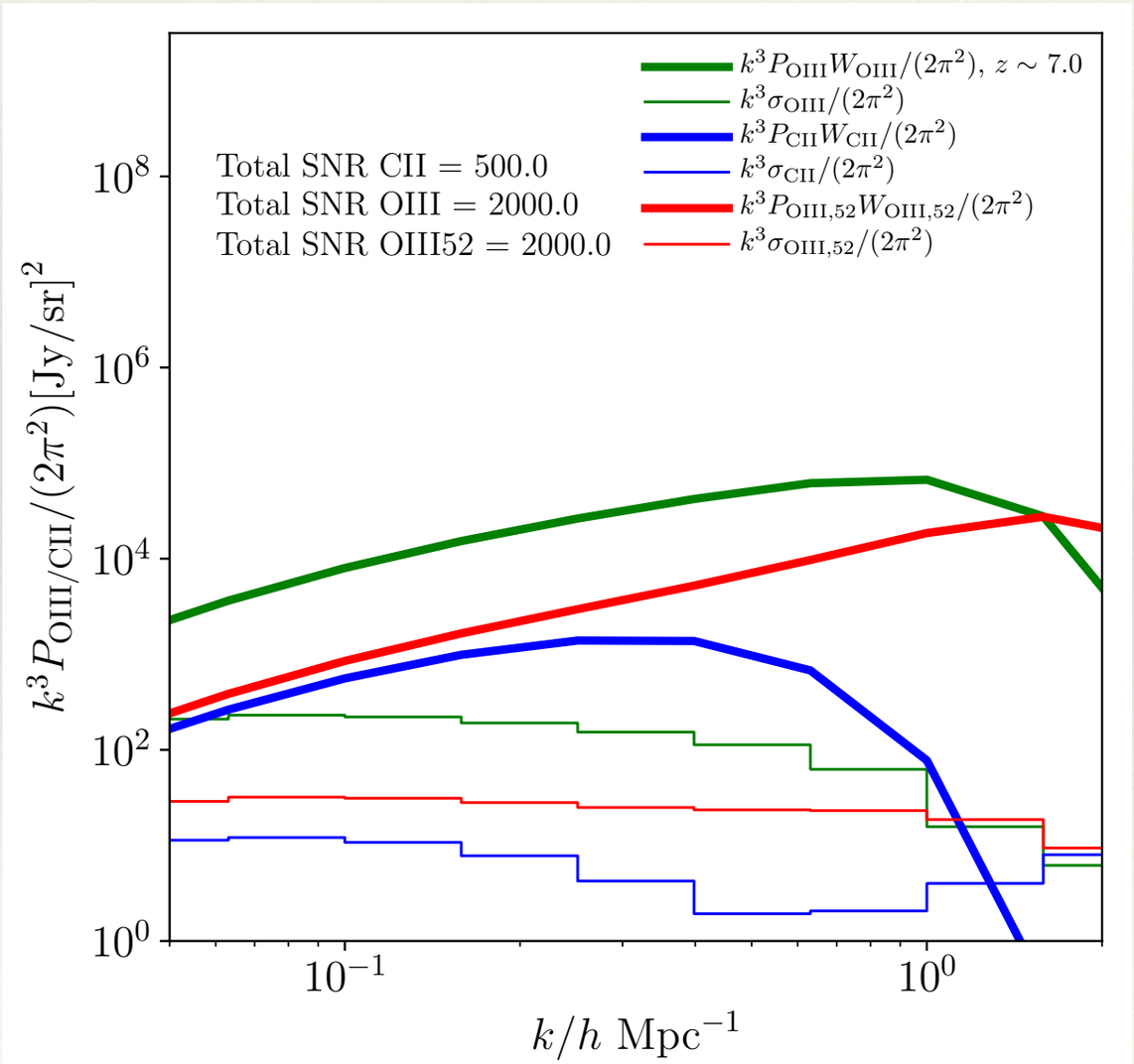
[HP+ (2021), arXiv:2105.12148]

Ability to observe [OIII] 52 μm

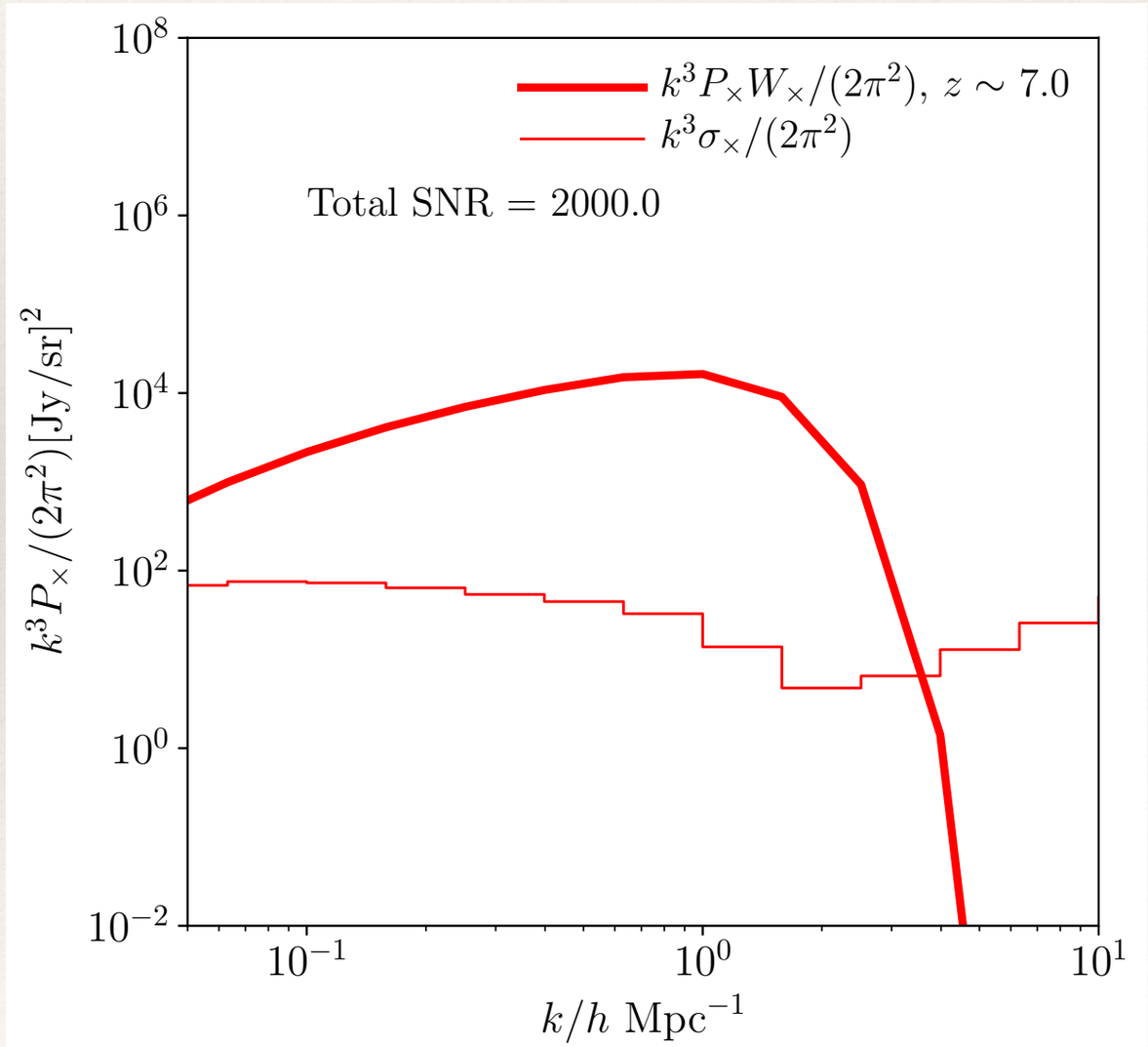
Ratio depends on electron density

$$L_{[\mathrm{OIII}]52}/L_{[\mathrm{OIII}]88} \sim 0.55 - 10$$

z ~ 7, auto



z ~ 7, [OIII] 88 x [OIII] 52



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Summary

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- [OIII] is a key species of IM interest for the EoR
- [CII] ‘deficit’ observed in high-z star forming galaxies (physical?)
- Cross correlation with [CII]: reduce systematics and foregrounds, remove line interlopers
- Improved versions of current architecture (EXCLAIM, FYST) reach ***several 10 sigma detection*** in cross-correlation at $z \sim 5$-7
- A ‘design’, or space-based configuration can reach ***several 100 to 1000 sigma*** in both auto and cross-correlation modes
- Additionally probes [OIII] 52 — rejecting interlopers, cleaner interpretation …
- Future: synergies with AtLAST, ngVLA …

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Thank you!