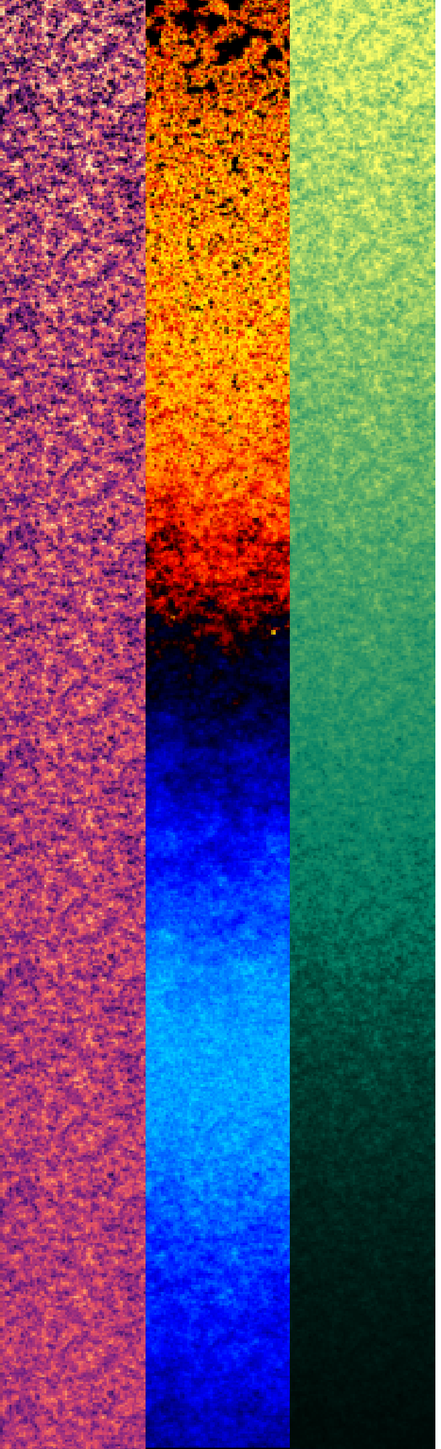


The Dawn of Multi-Line Intensity Mapping

Sarah Libanore

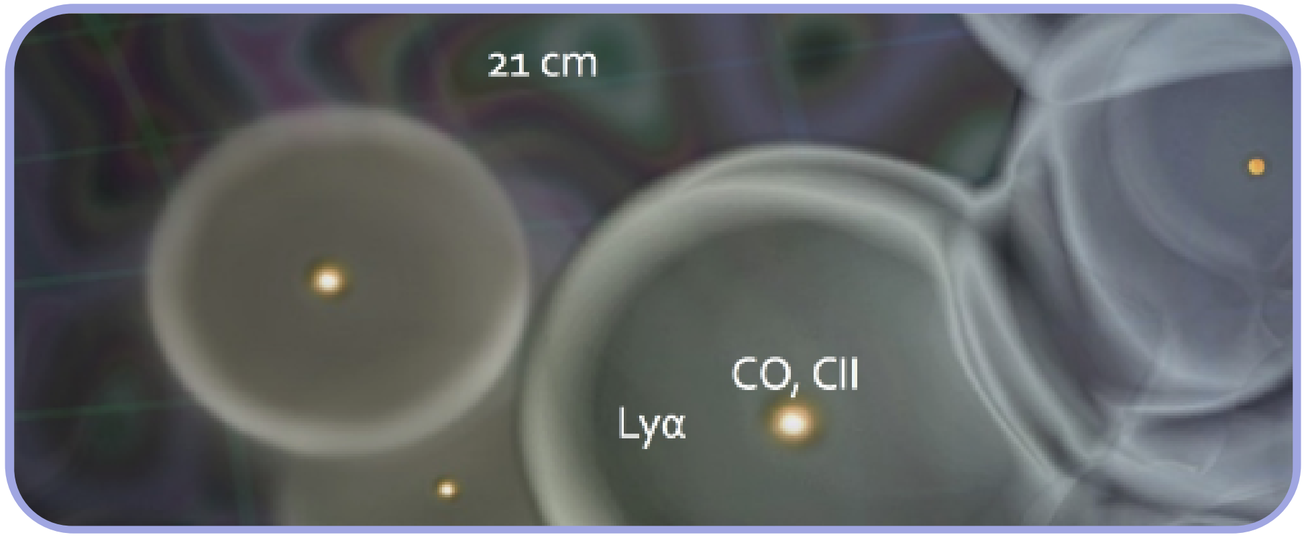
Ben Gurion University of the Negev

LIM25, Annecy, June 5th 2025

Observing Cosmic Dawn and Reionization

LIM25, Annecy, June 5th 2025

Observing Cosmic Dawn and Reionization



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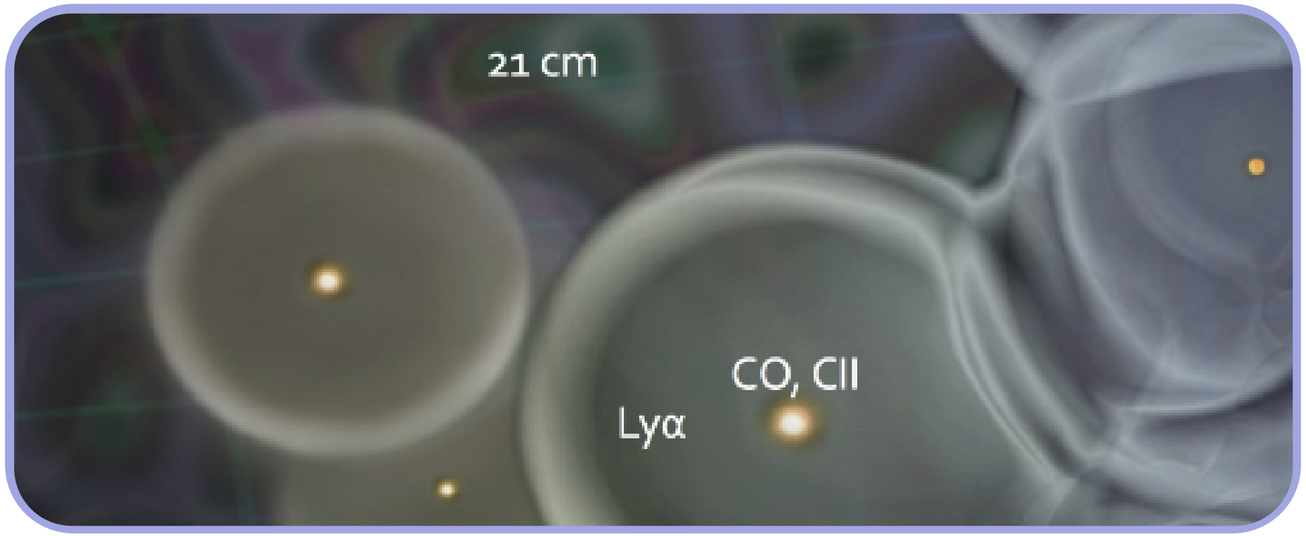

- How to probe the ***beginning*** of reionization?
- How does it depend on astrophysical and cosmological ***models***?

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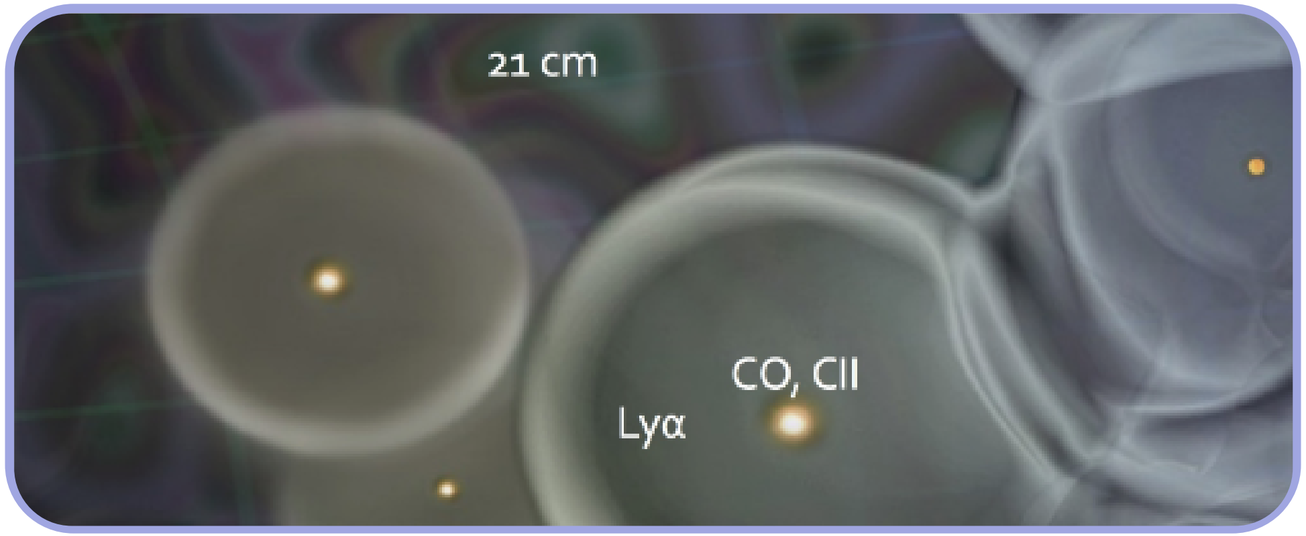

Consistent Modeling of Multi-Line Cross-Correlations

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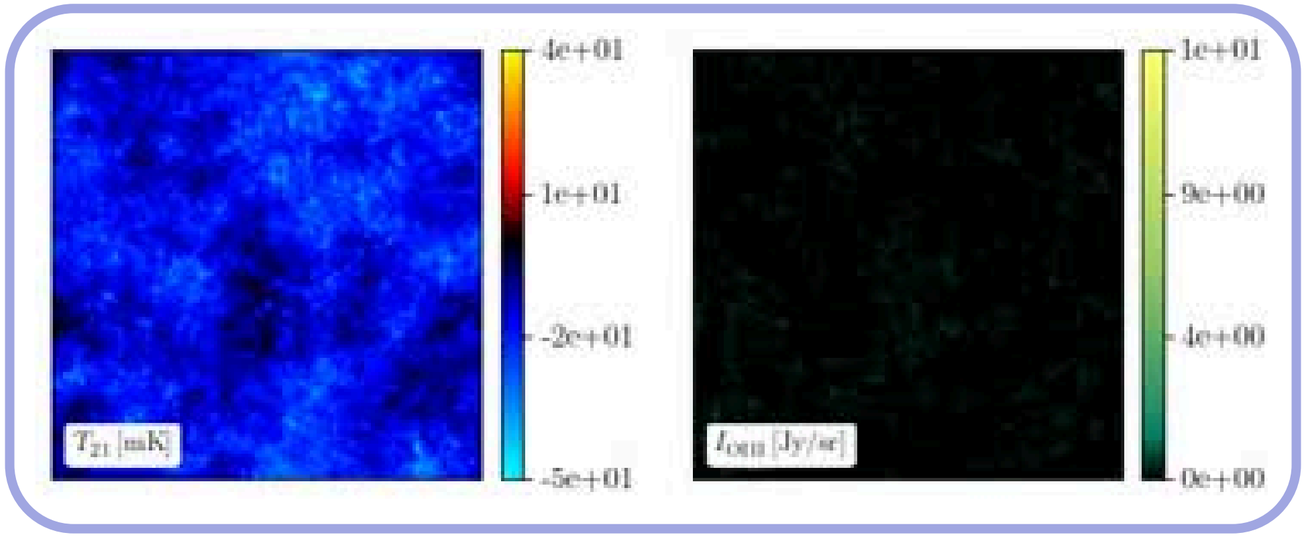

Consistent Modeling of Multi-Line Cross-Correlations

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Two compelling techniques

Simulations
Physical models

Analytics
Empirical models

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- Physical modeling

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- Approximations
- Usually calibrated at low z

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- Multi scale problem
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LIMpus

Effective LIM Spectra at Reionization

Libanore, Munoz, Kovetz, 2506.xxxxx

LIM25, Annecy, June 5th 2025

- Effective Model for Cosmic Dawn 21cm

Munoz, MNRAS 523 (2023)
Cruz, Munoz et al., 2407.18294 (2024)

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COSMOLOGY

- Interfaced with CLASS
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$$P_m(k,z),\ \frac{dn}{dM_h}(\delta_R)$$

STAR FORMATION RATE

- Computed from SFR-halo mass relation
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- Easy to customize

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Zeus21
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- LIM Power Spectra for Star Forming Lines
- Cross-Power Spectra with 21cm (*)
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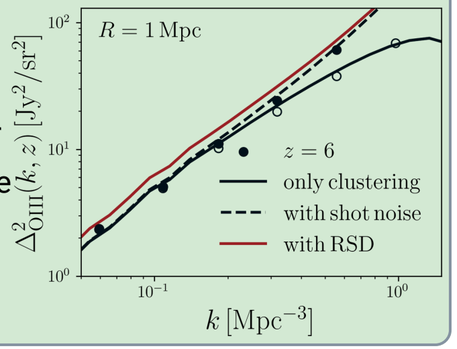
- Include linear redshift space distortions



LIM25, Annecy, June 5th 2025

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Sklanski, Munoz et al (in prep)

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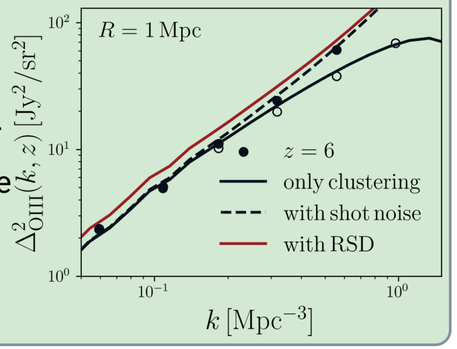

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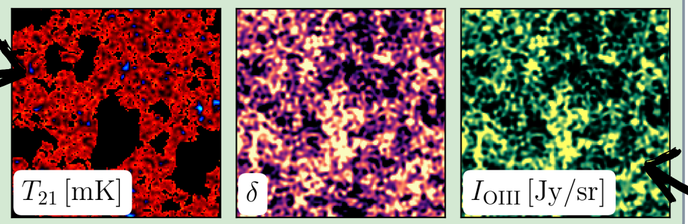
COEVAL BOXES & LIGHTCONES

- Star forming lines and 21cm (*)
- Option 1: Gaussian field from analytical non-linear power spectrum
- Option 2: Cell-by-Cell computation



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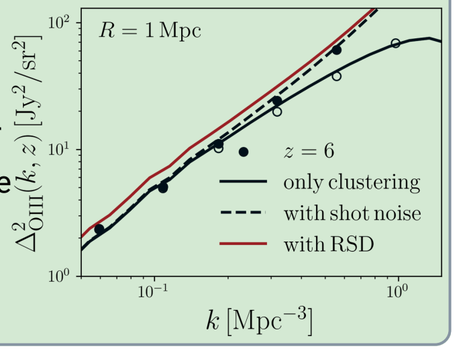

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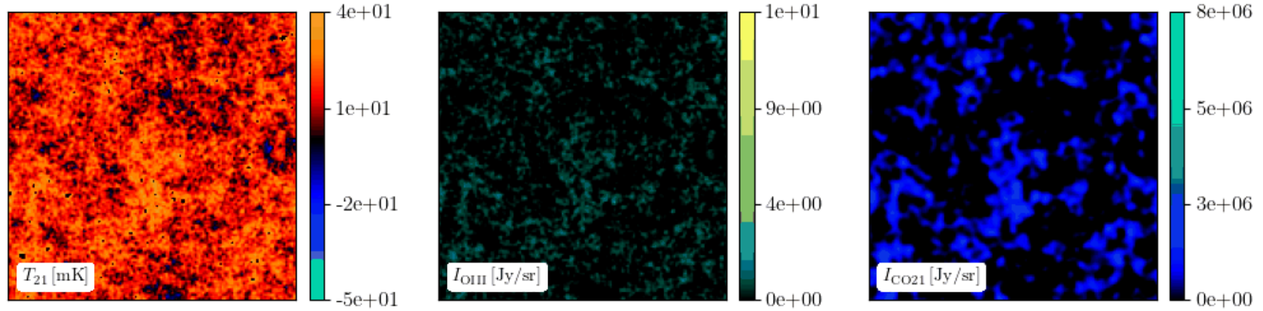
PRELIMINARY!



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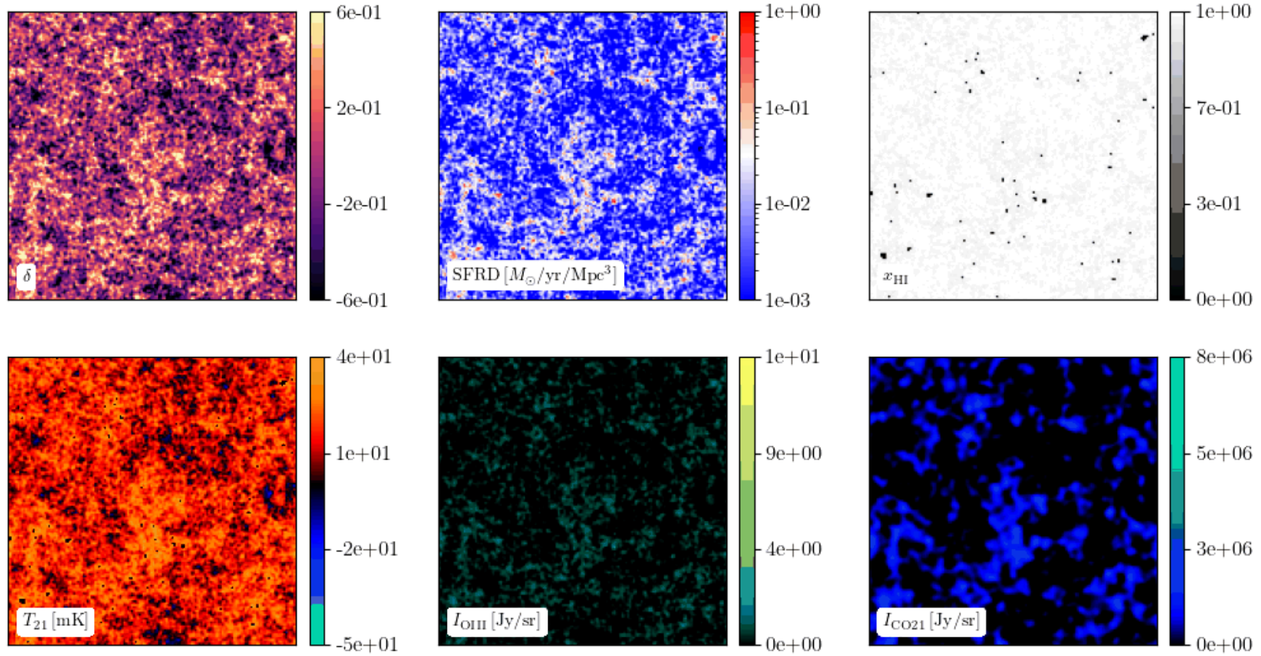
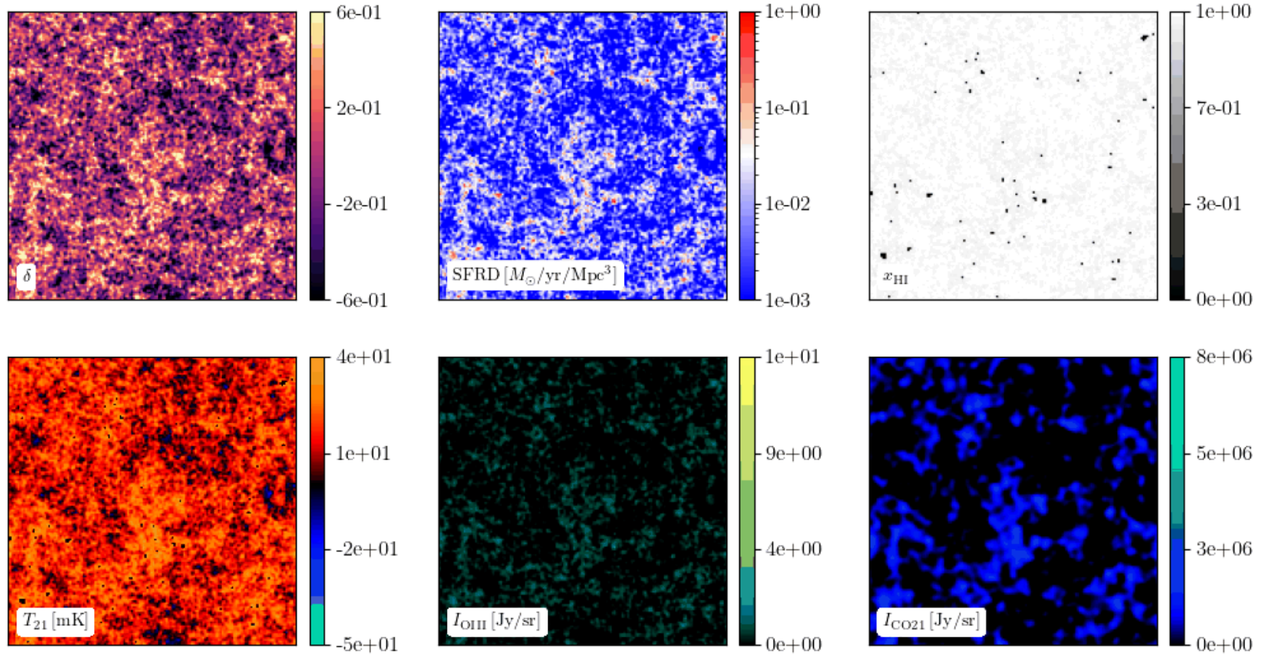


PRELIMINARY

Cross-Correlation Coefficients



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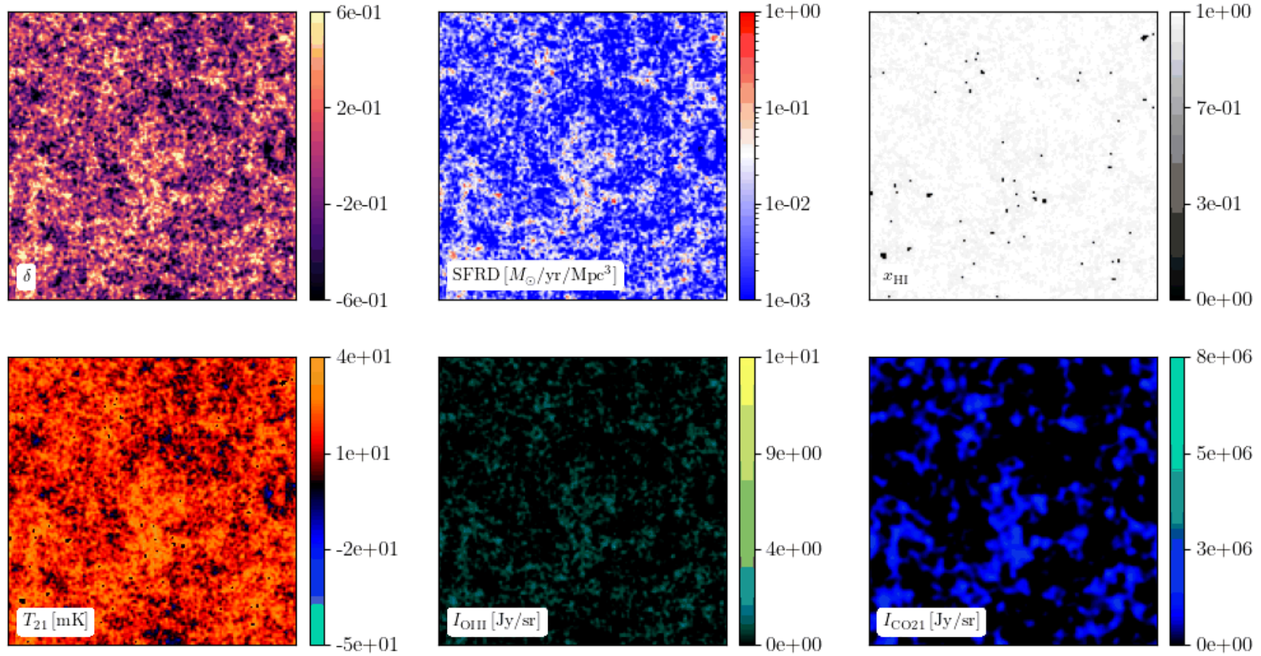

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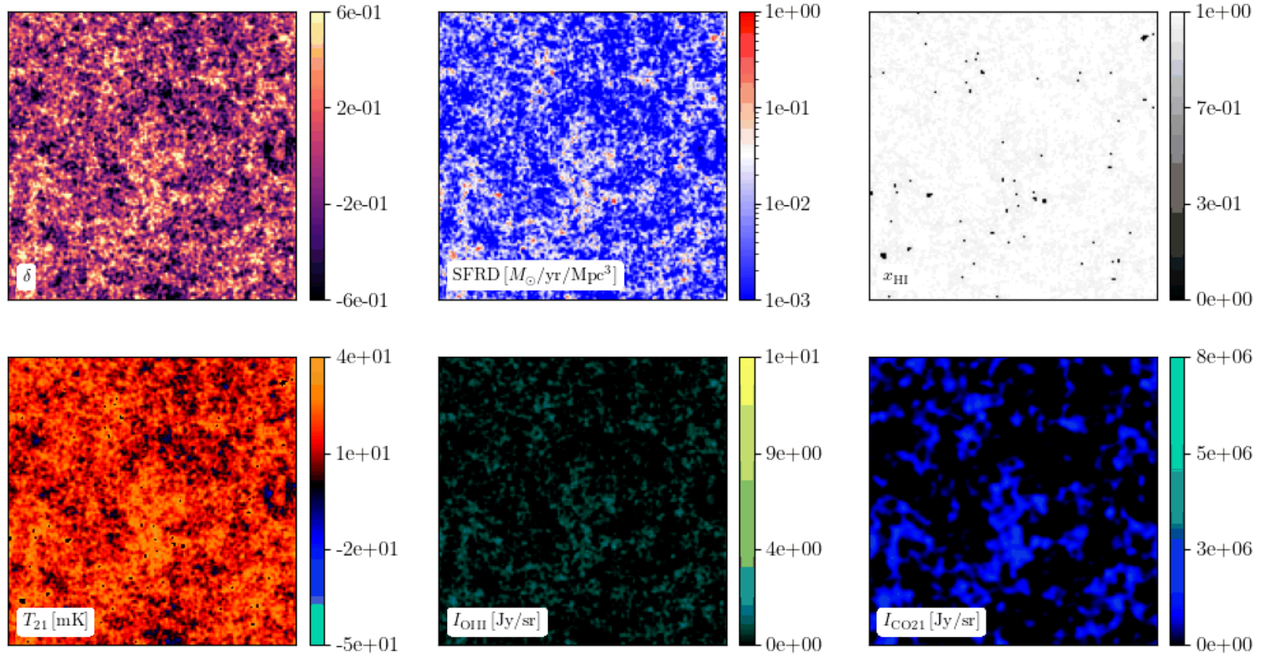

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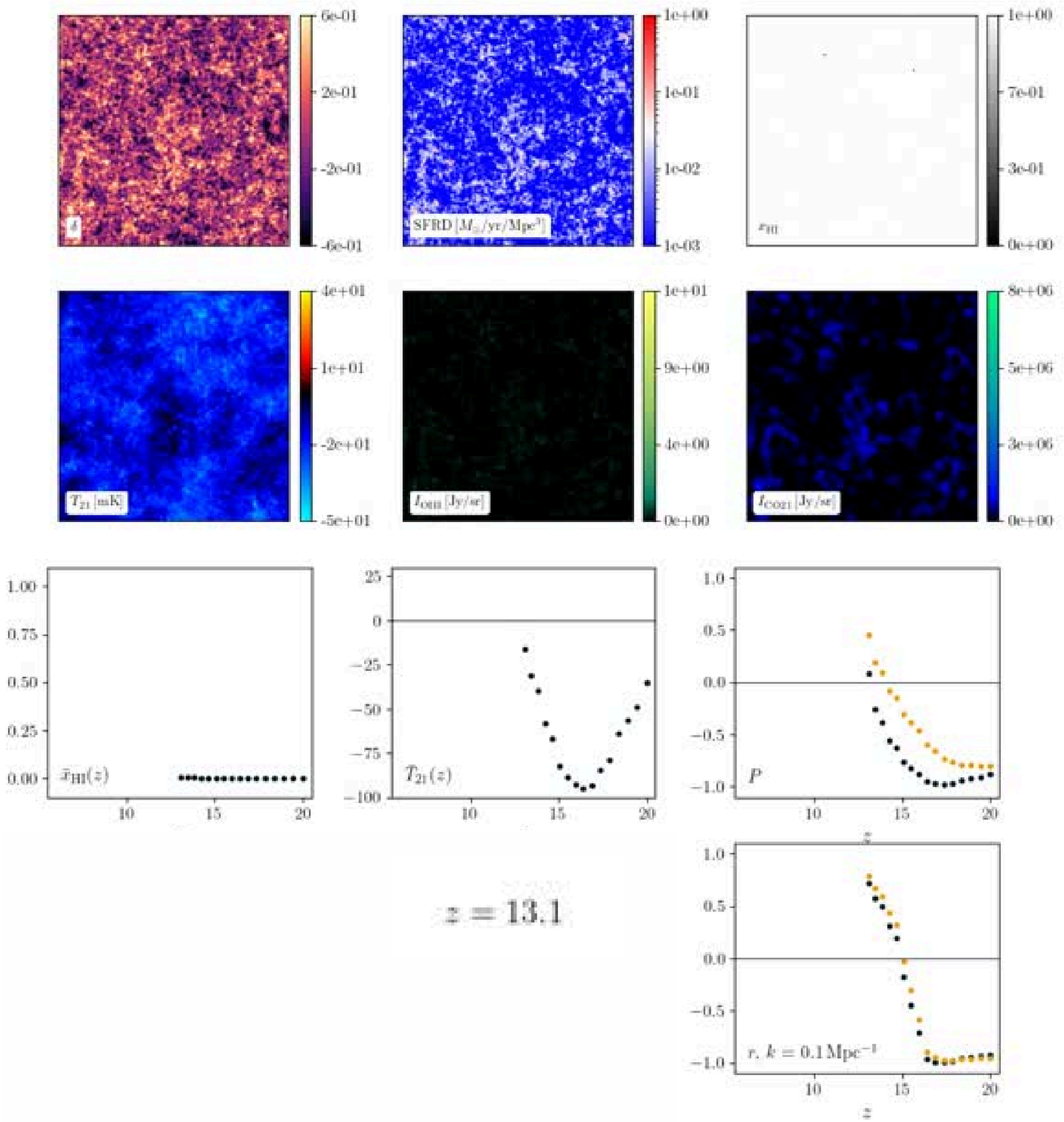

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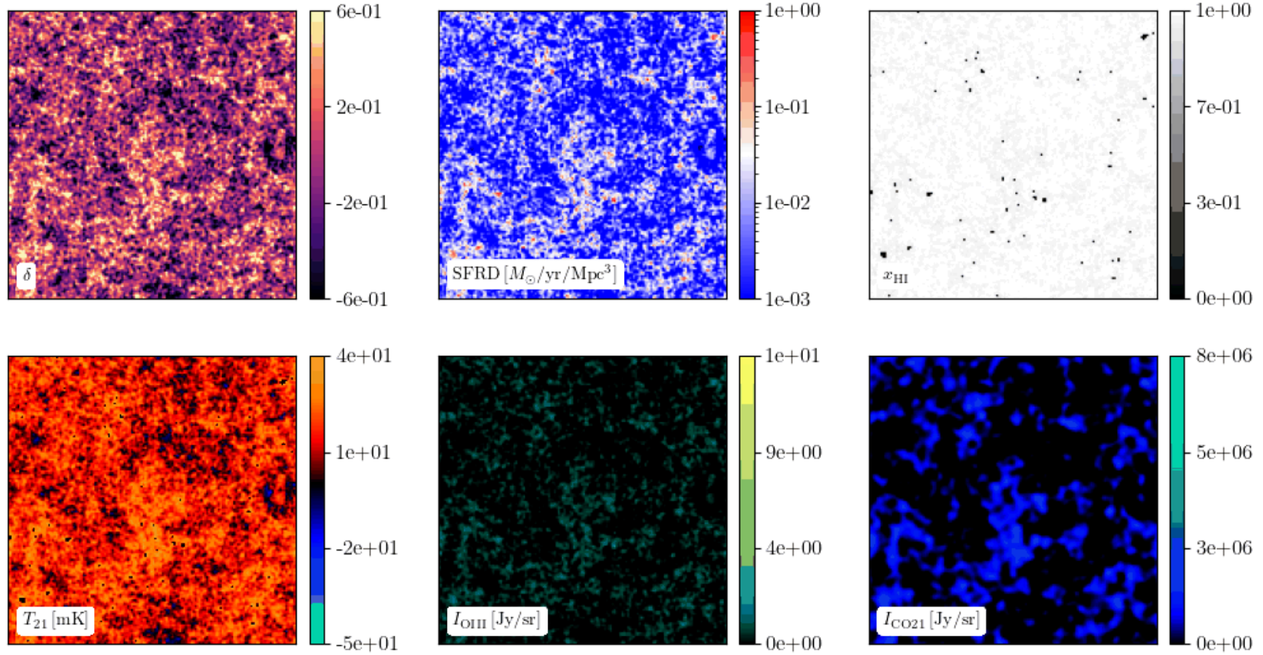

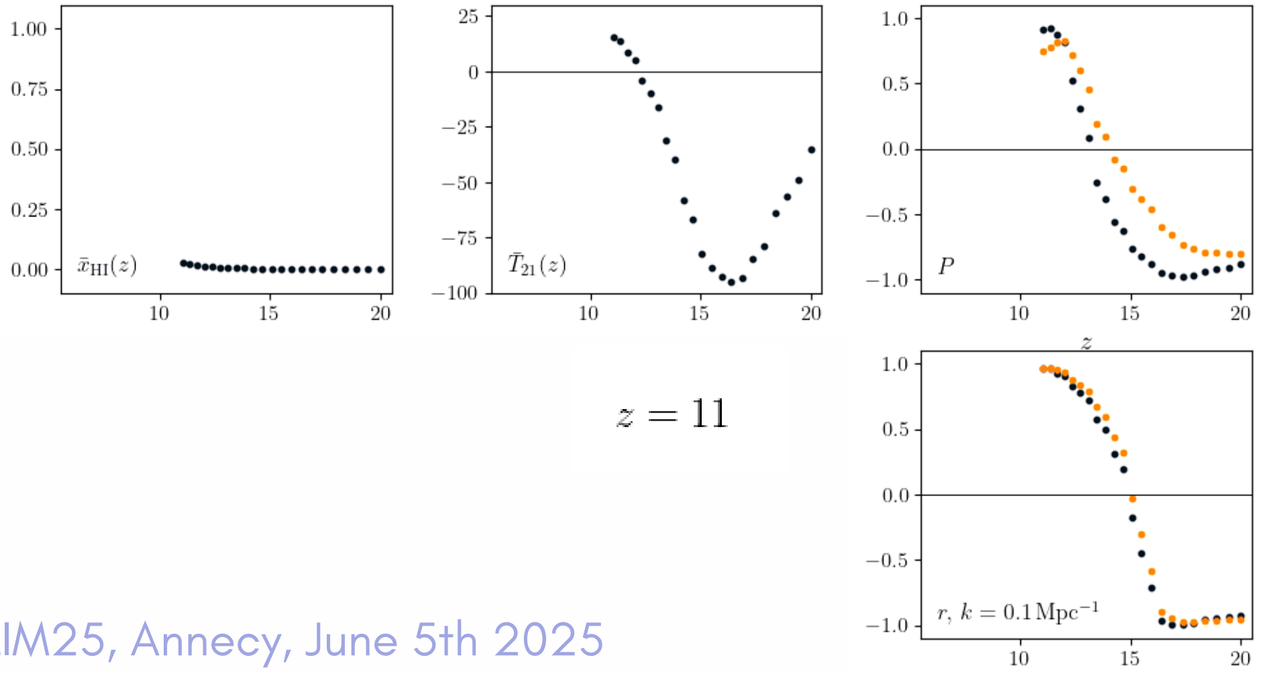

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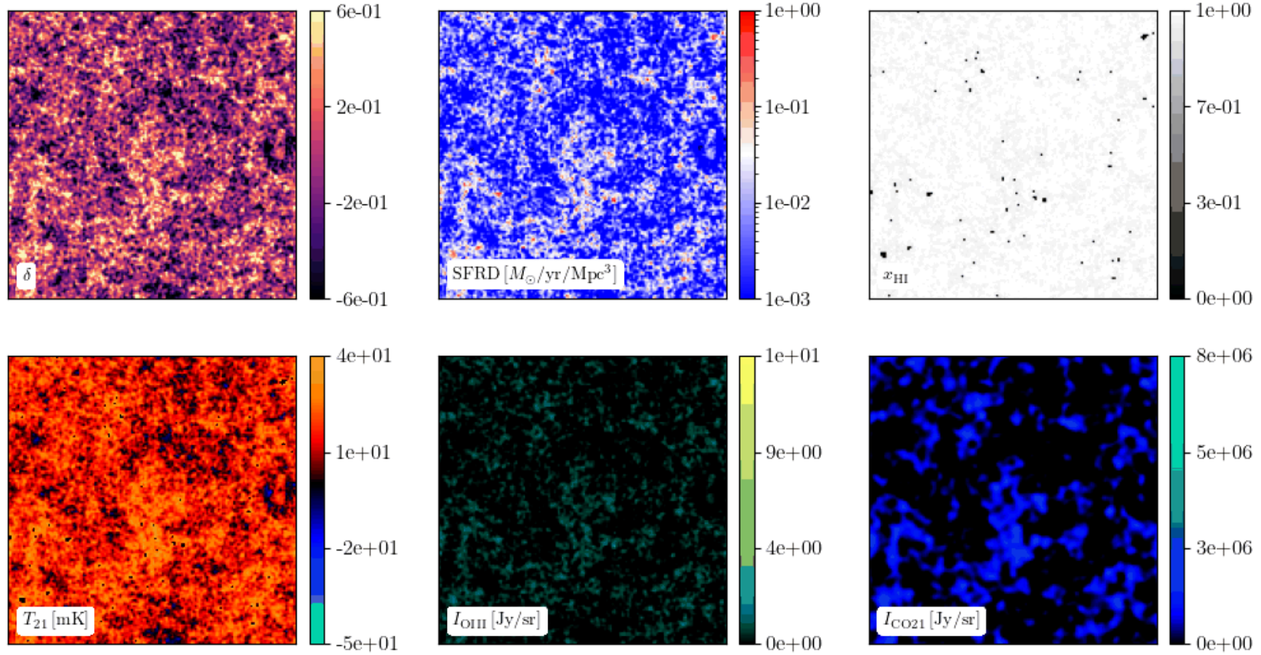
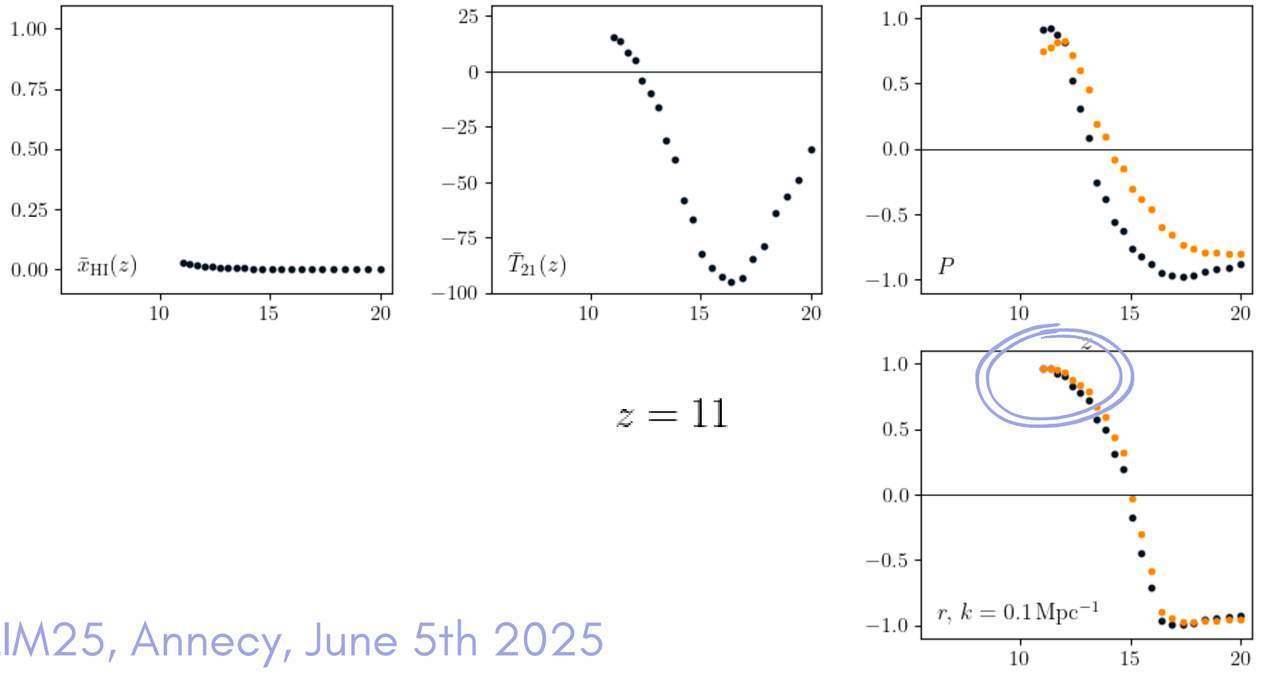
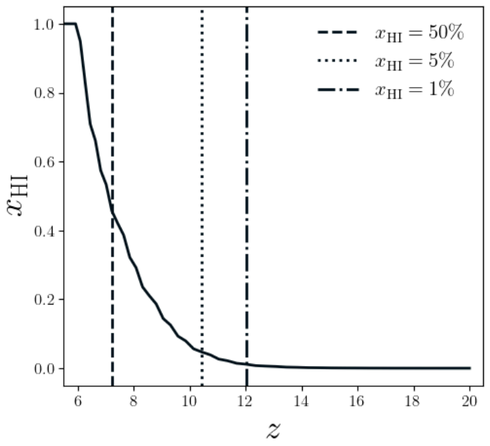


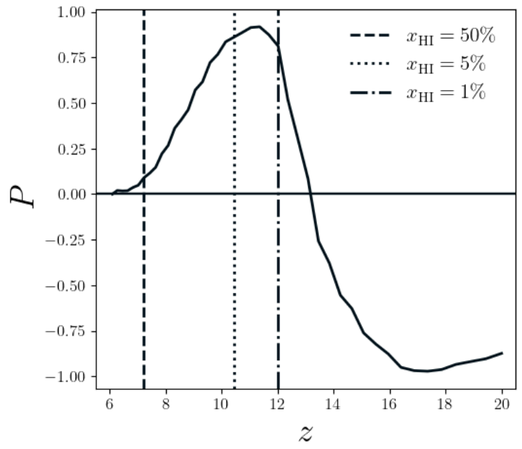


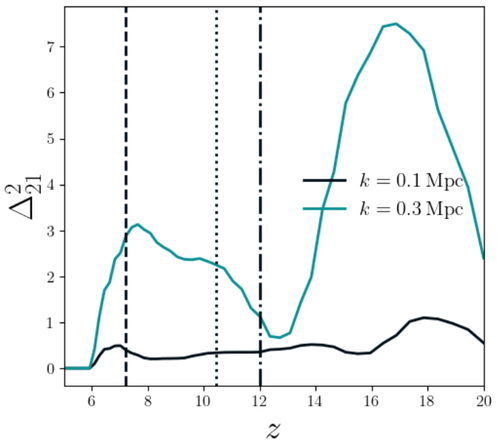
$z = 11$

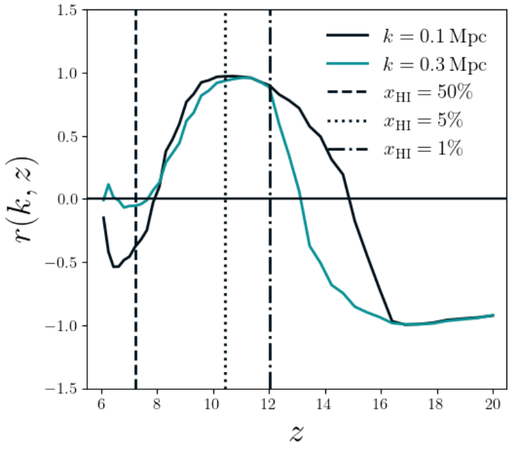
PRELIMINARY!

Probing the beginning of reionization ...with oLIMpus!









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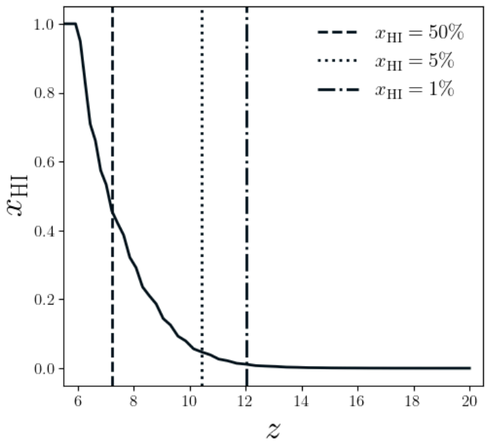

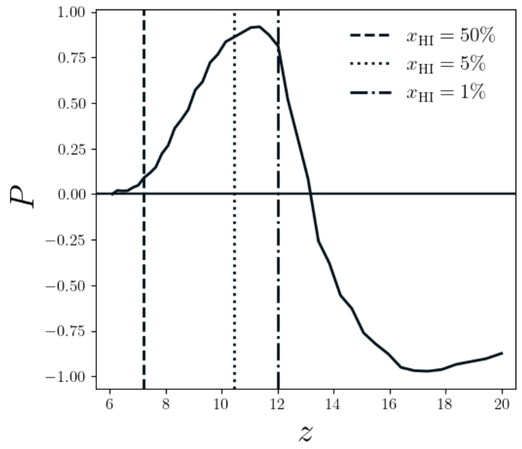

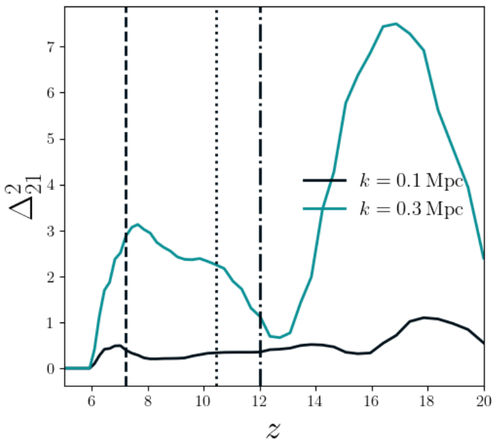

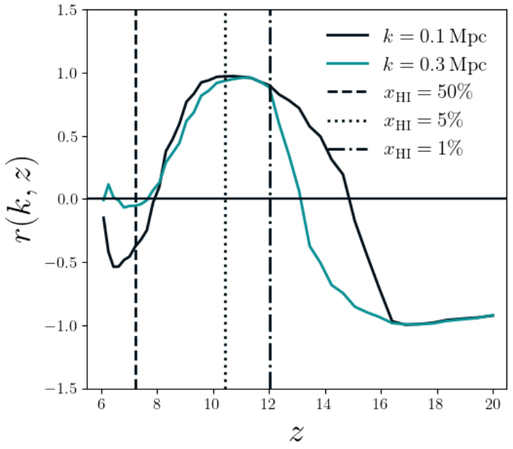

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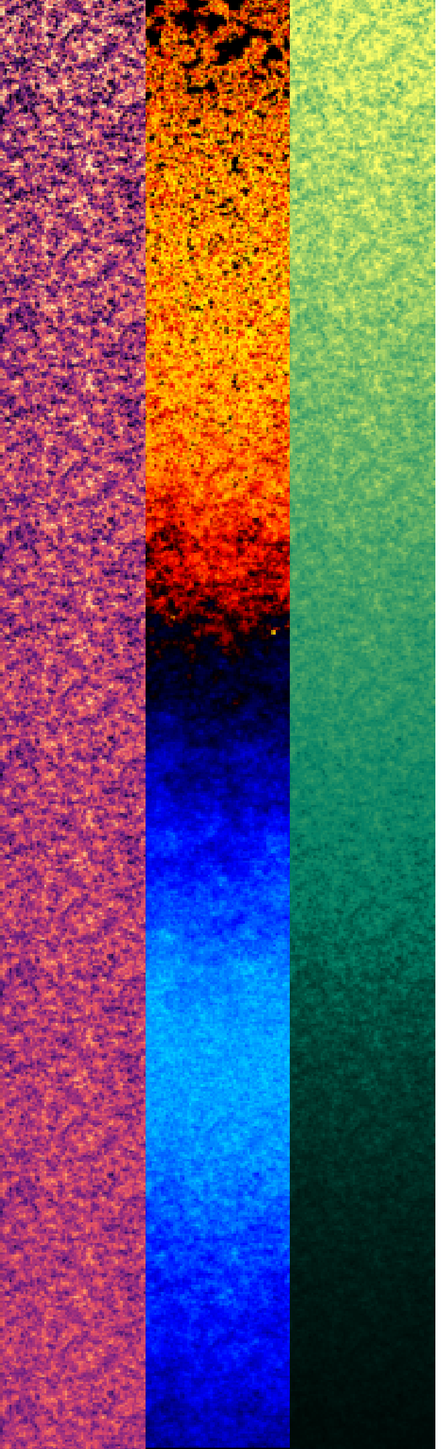

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slibanore/oLIMpus

Thank you for your attention & keep an eye on the arXiv!

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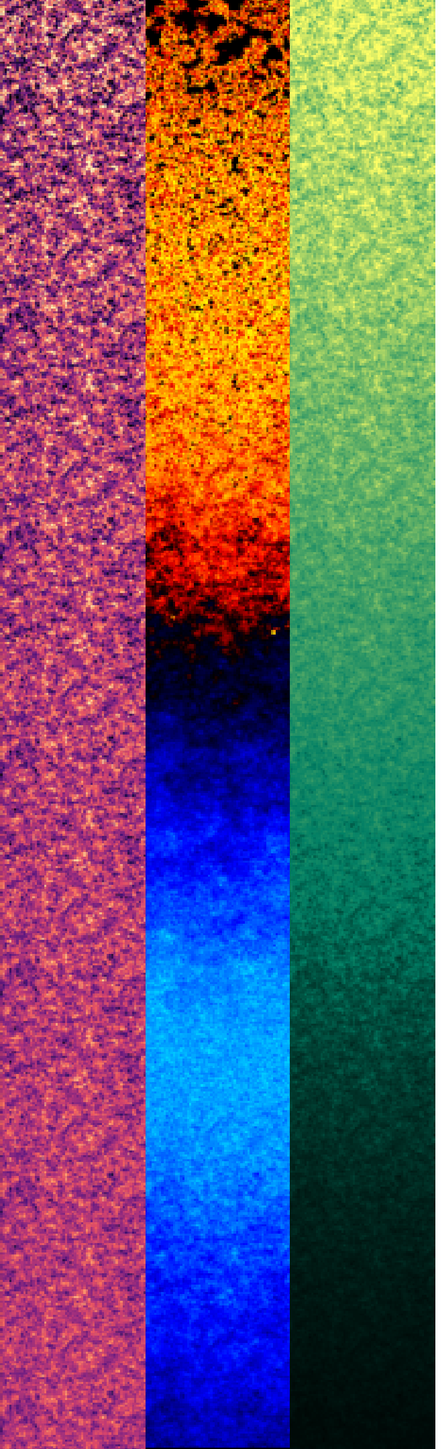
קרן עזריאלי
Azrieli Foundation
תוכנית עמיתי עזריאלי
Azrieli Fellows Program

אוניברסיטת בן-גוריון בנגב
Ben-Gurion University of the Negev

LIM25, Annecy, June 5th 2025



Backup Slides

An Effective Model for the 21-cm Signal

$$\langle e^{\gamma_{R_1}\delta_{R_1}} e^{\gamma_{R_2}\delta_{R_2}} \rangle = e^{\gamma_{R_1}\gamma_{R_2}\xi_{R_1R_2}(r,z)} - 1$$

$$T_{21} = T_0(z)\,(1+\delta-\delta_v)\left(\frac{x_\alpha}{1+x_\alpha}\right)\left(1-\frac{T_{\rm CMB}}{T_k}\right)x_H$$

$$x_\alpha \propto J_\alpha(x,z)$$

Model the Lyman-α flux:

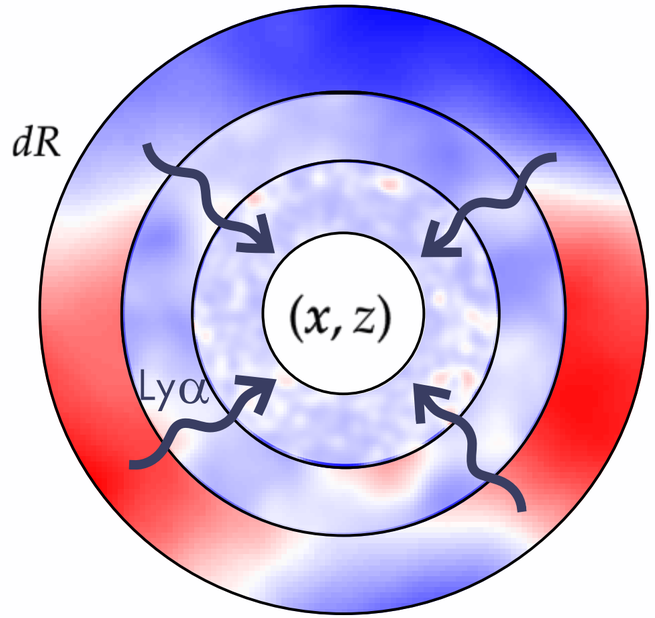
$$J_\alpha(x,z) = \frac{(1+z)^2}{4\pi}\int dR\,\mathrm{SFRD}(\delta_R(x),R)\,\epsilon_\alpha(\nu')$$

$$x_\alpha = c_{1,\alpha}(z)\sum_R c_{2,\alpha}(z,R)e^{\gamma_R\delta_R}$$

$$\xi_\alpha(r,z) = c_{1,\alpha}^2(z)\sum_{R_1,R_2} c_{2,\alpha}(z,R_1)c_{2,\alpha}(z,R_2)\left[e^{\gamma_{R_1}\gamma_{R_2}\xi_{R_1R_2}(r,z)}-1\right]$$

Munoz, Mon.Not.Roy.Astron.Soc. 523 (2023)
Cruz, Munoz et al., 2407.18294 (2024)
Sklansky, Munoz, in prep. (2025)
Libanore, Munoz, Kovetz, in prep. (2025)

Zeus21
with Population II and III stars



An Effective Model for the 21-cm Signal

Munoz, Mon.Not.Roy.Astron.Soc. 523 (2023)
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$\Delta^2_{21}(k,z)$

$\xi_{21}(r,z)$ during cosmic dawn

?

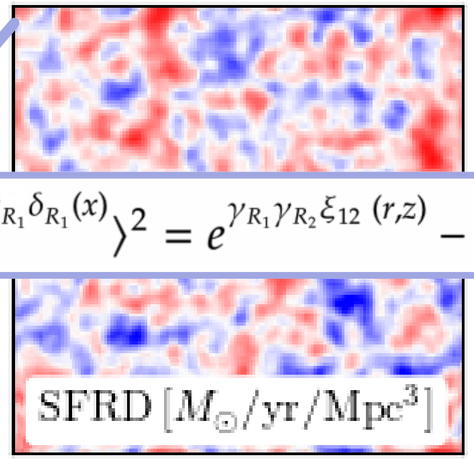
$$T_{21} = T_0(z)\,(1+\delta-\delta_v)\left(\frac{x_\alpha}{1+x_\alpha}\right)\left(1-\frac{T_{\rm CMB}}{T_k}\right)x_H$$

SFRD

$$\overline{\rm SFRD}(z) = \int dM_h\,\frac{dn(z)}{dM_h}\dot{M}_*(M_h,z)$$

$$\langle e^{\gamma_{R_1}\delta_{R_1}(x_1)}e^{\gamma_{R_2}\delta_{R_2}(x_2)}\rangle - \langle e^{\gamma_{R_1}\delta_{R_1}(x)}\rangle^2 = e^{\gamma_{R_1}\gamma_{R_2}\xi_{12}\,(r,z)} - 1$$

$$\mathrm{SFRD}(\delta_R,z) = (1+\delta_R)\int dM_h\,\frac{dn_{\rm EPS}(\delta_R,z)}{dM_h}\,\mathrm{C_{EPS}}\,\dot{M}_*(M_h,z)$$

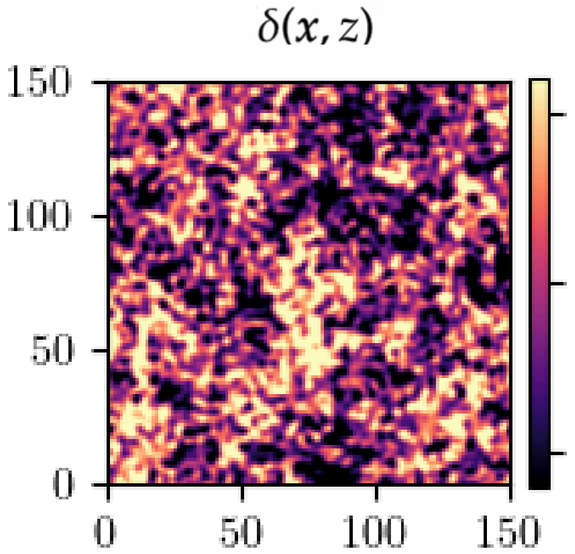


Key approximation: $\mathrm{SFRD}(\delta_R,z) = \overline{\rm SFRD}(z)e^{\gamma_R\delta_R}$

Zeus21
with Population II and III stars

Maps from Zeus21

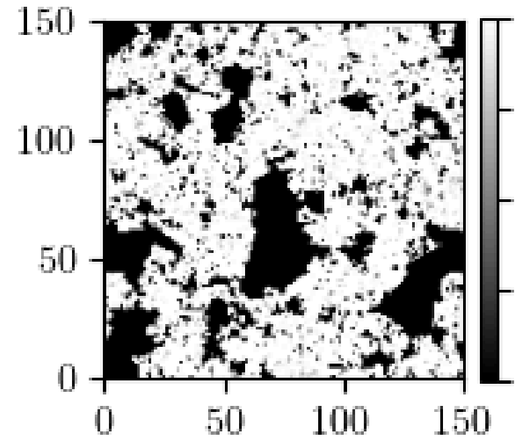
Epoch of Reionization: bubble model on maps (for now!)

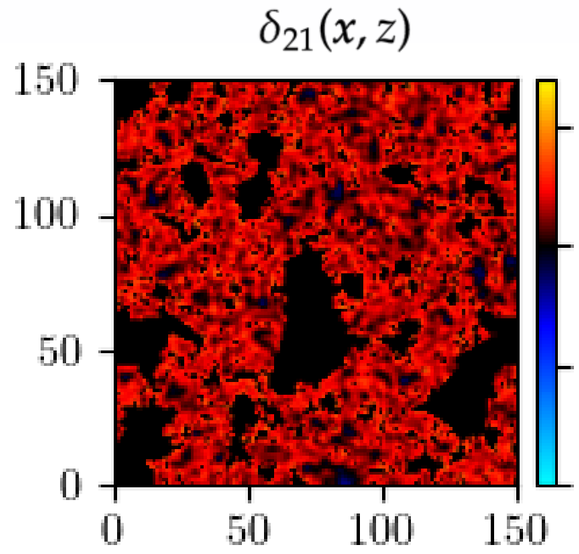


$$\overline{T}_{21}(z) + \mathrm{IFT}\left[\frac{P_{21\Delta}(k,z)}{P_{\Delta\Delta}(k,z)}\,\mathrm{FT}[\delta(x,z)]\right]$$

$$\delta(x,z) > \delta_B(z)$$

$$\delta_B = \min \delta : n_\gamma(\delta) - (1 + n_{\mathrm{rec}}(\delta)) = 0$$



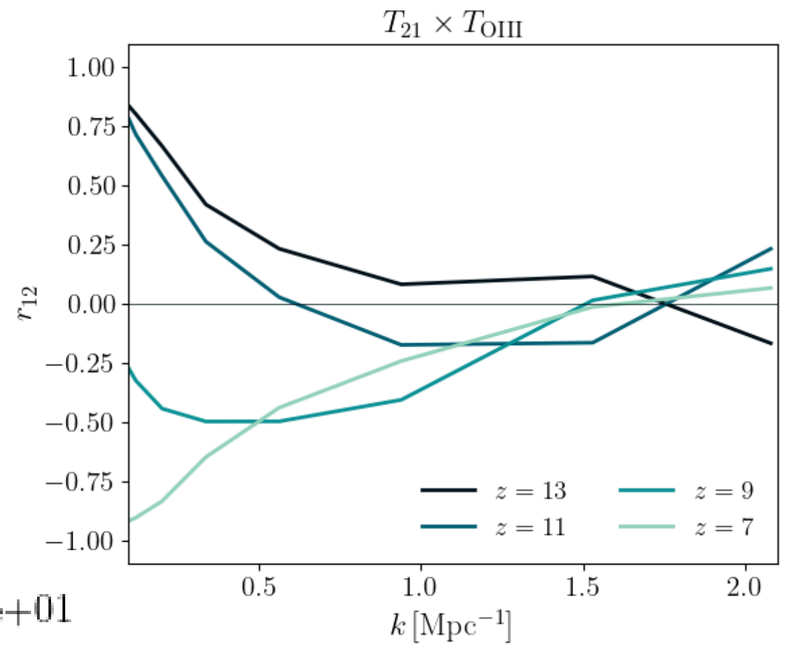


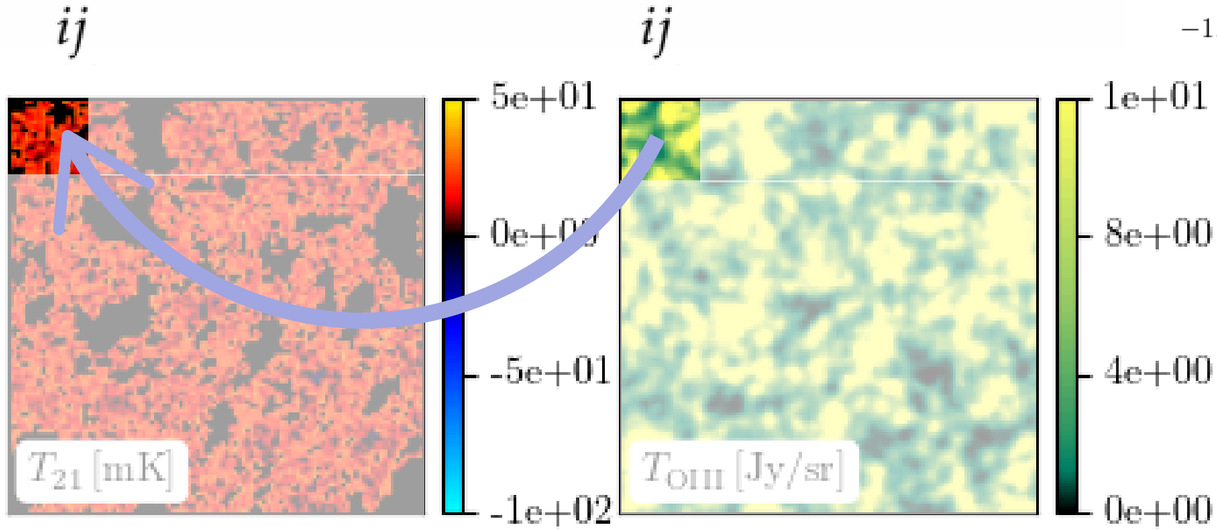
Sklansky, Munoz, in prep. (2025)

Maps and Cross Correlation Study

Correlation Coefficient

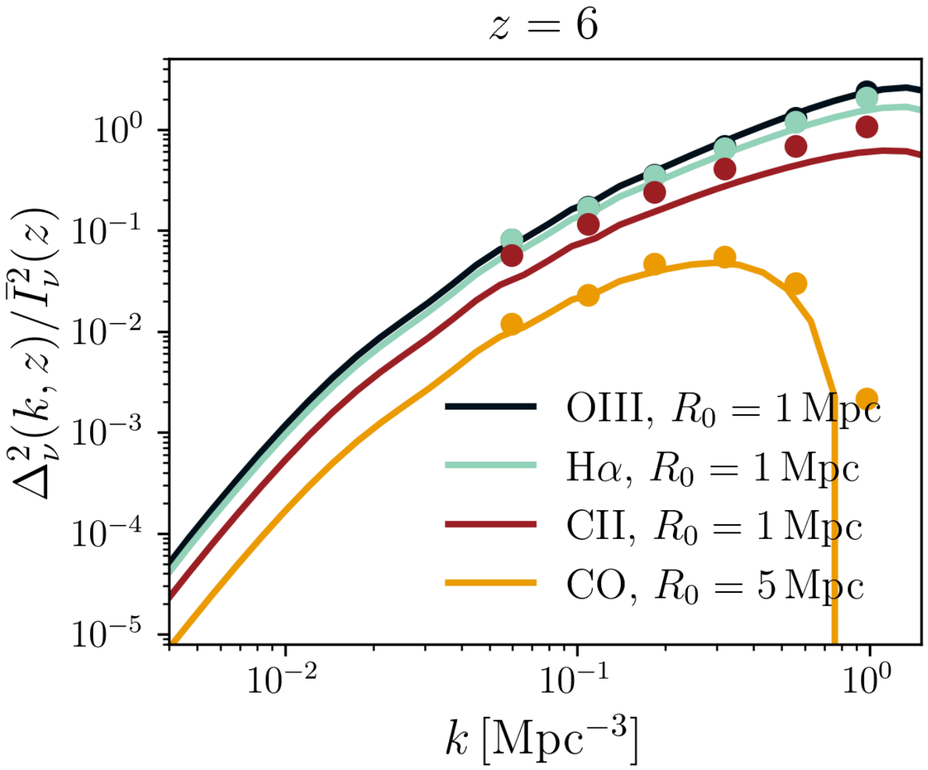
$$r = \frac{\Delta^2_{21,\mathrm{LIM}}(k,z)}{\sqrt{\Delta^2_{21}(k,z)\Delta^2_{\mathrm{LIM}}(k,z)}}$$

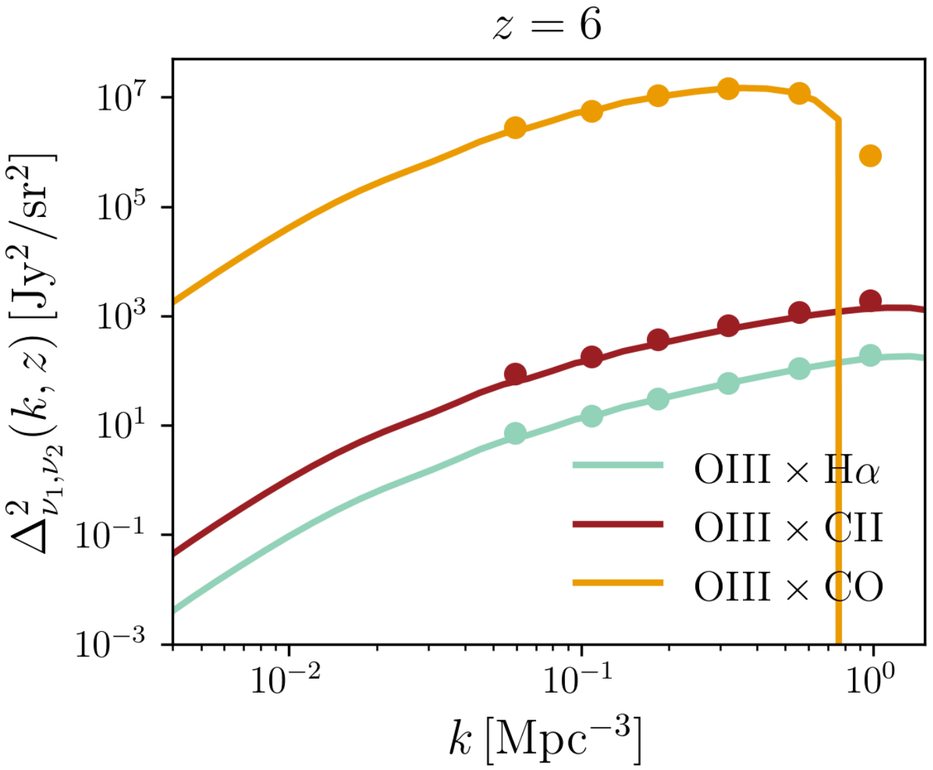




PRELIMINARY!

Main Outputs



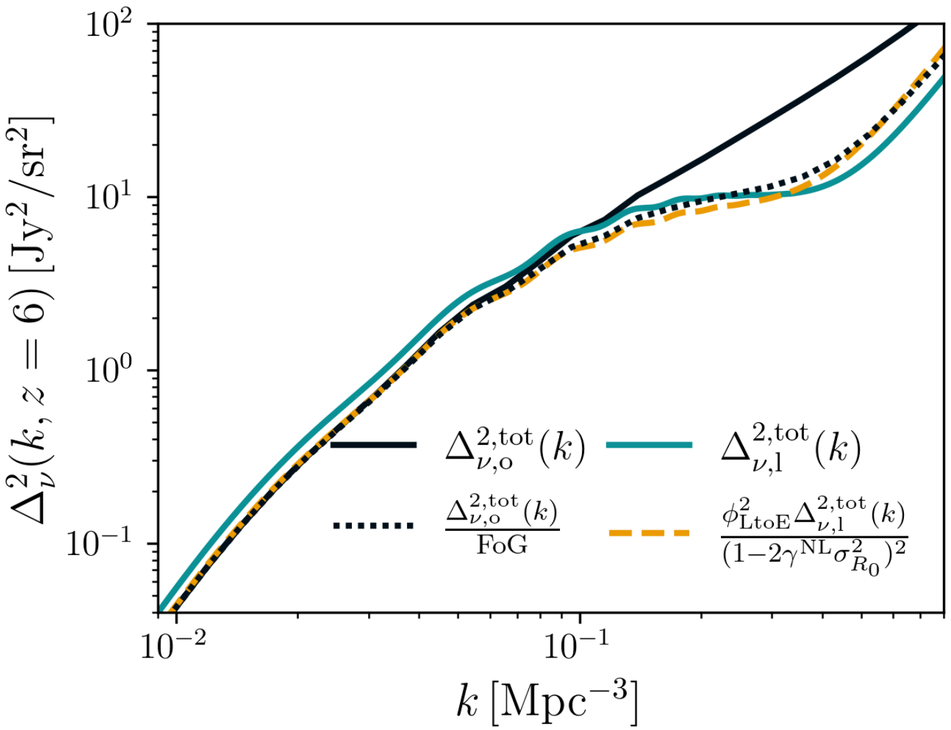


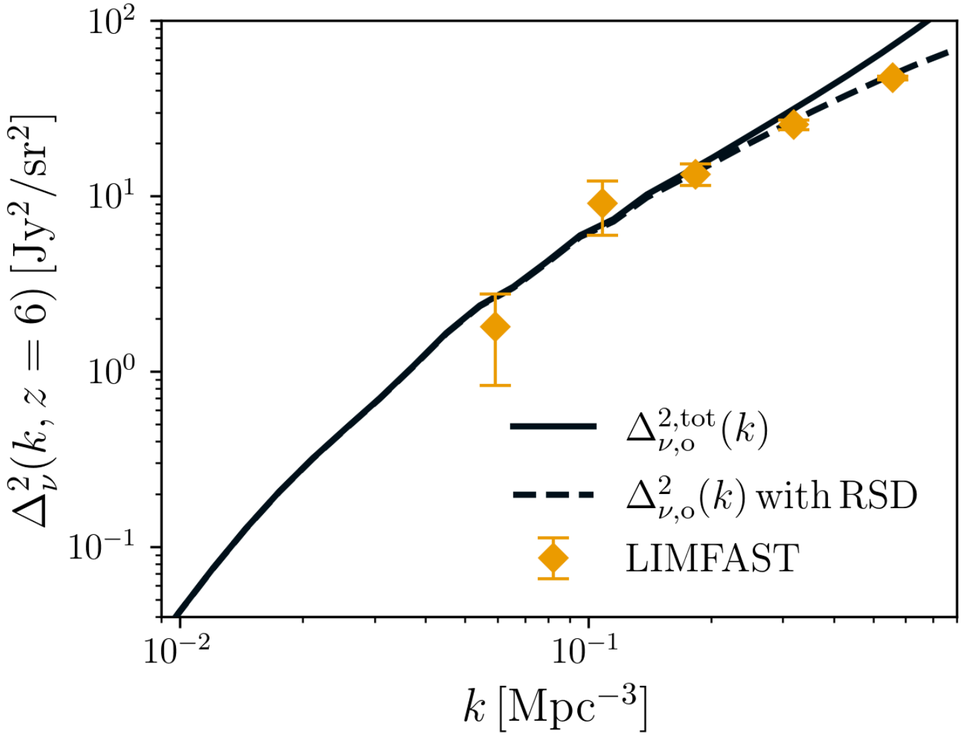
LIMpus
Effective LIM Spectra at Reionization

Libanore, Munoz, Kovetz, 2506.xxxxx

- Analytical and in-box auto-power spectra
- Analytical and in-box cross-power spectra

Comparison with other codes





LIMpus
Effective LIM Spectra at Reionization

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Applications?

Analysis of current / upcoming LIM surveys

SPHEREx
Coherent treatment of multiple lines and multiple channels

Anti-Correlation with 21-cm

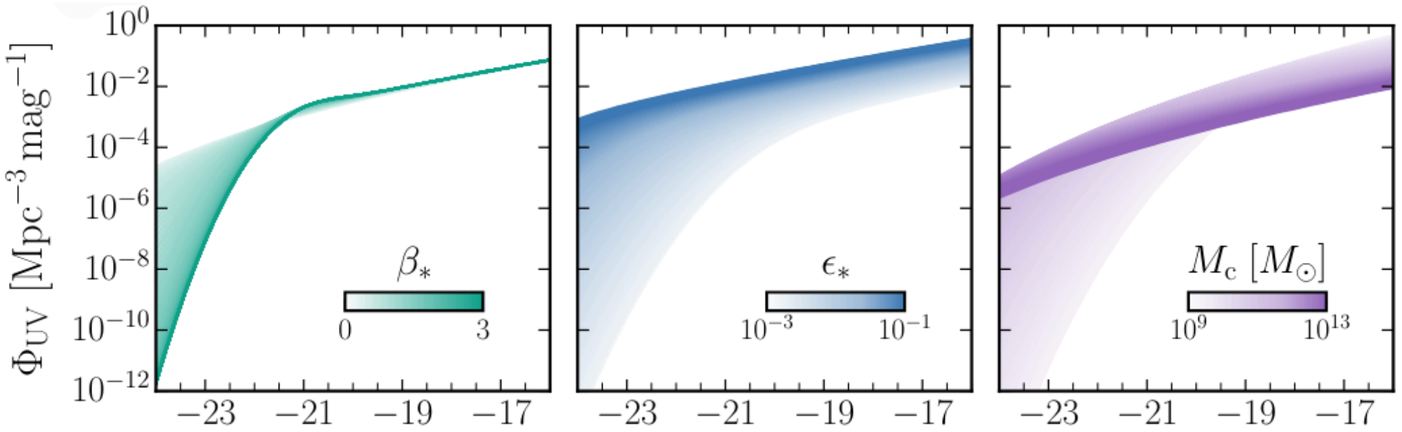
Probe of Reionization

Bridge with more complex, simulation-based models

Reach out for new ideas!

Variability on astro and cosmo models?

Sabti, Munoz, Blas, Phys.Rev.D 105 (2022) 4, 043518



Star Formation Efficiency

$$\widetilde{f}_* = \frac{\dot{M}_*}{\dot{M}_{\rm h}} = \frac{\epsilon_*}{\left(\frac{M_{\rm h}}{M_c}\right)^{\alpha_*} + \left(\frac{M_{\rm h}}{M_c}\right)^{\beta_*}}$$

Libanore, Munoz, Kovetz, arXiv:2506.xxxxx