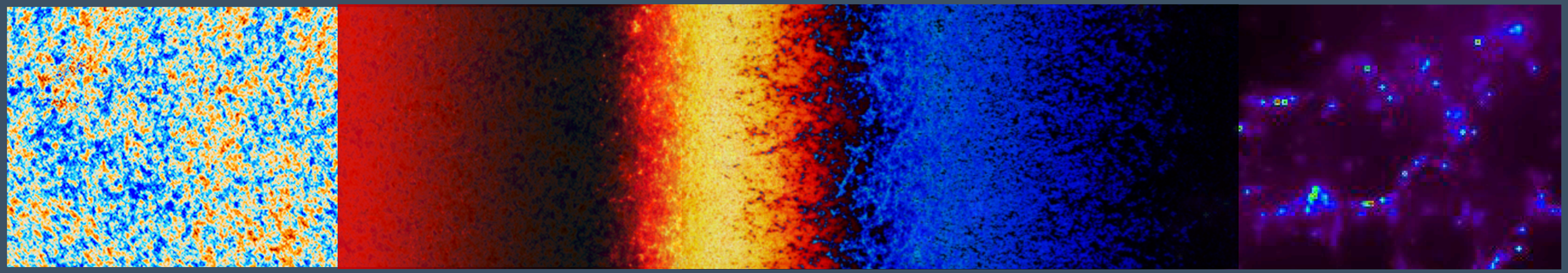


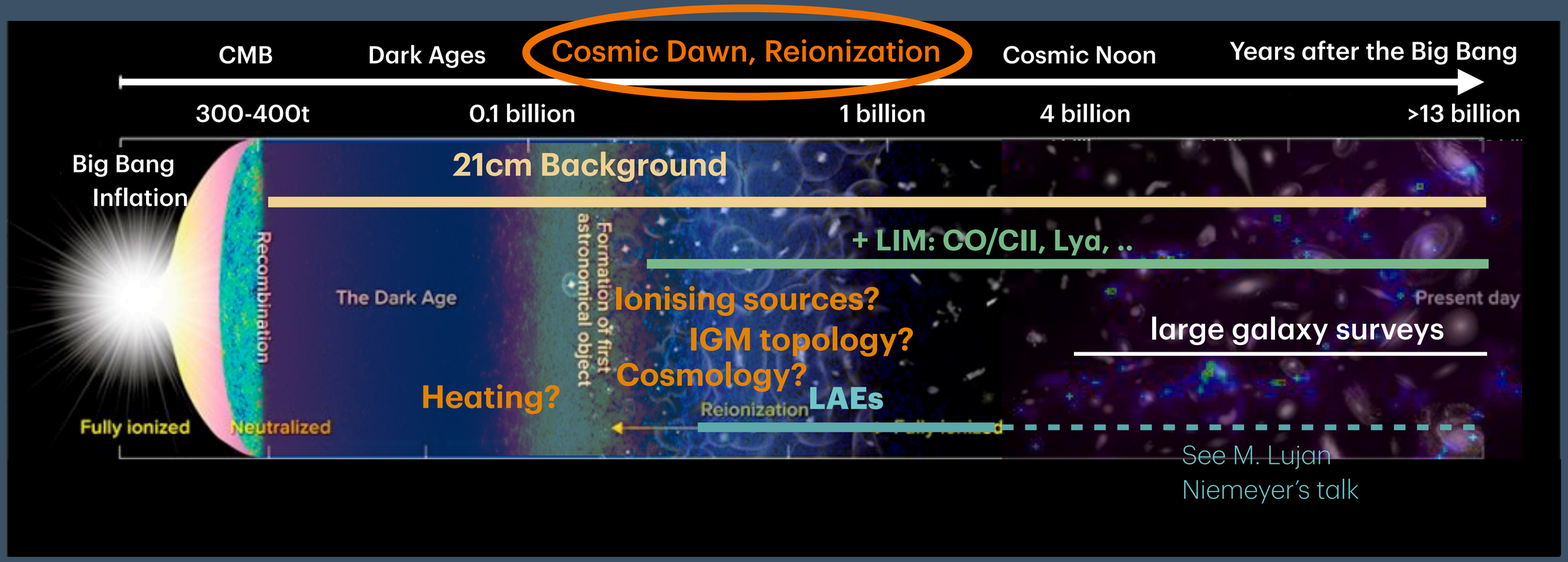
Unveiling the EoR with LIM and galaxy synergies

Caroline Heneka

Research Group Leader, Heidelberg University

LIM2025, Annecy, June 5th 2025

Closing the gap in cosmic evolution

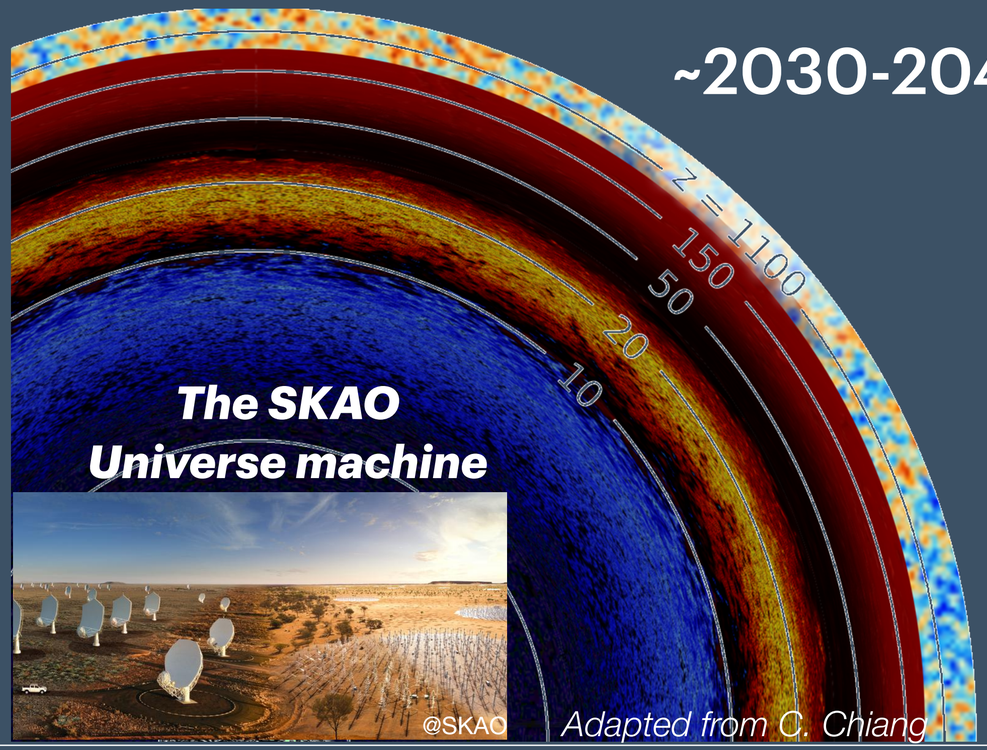


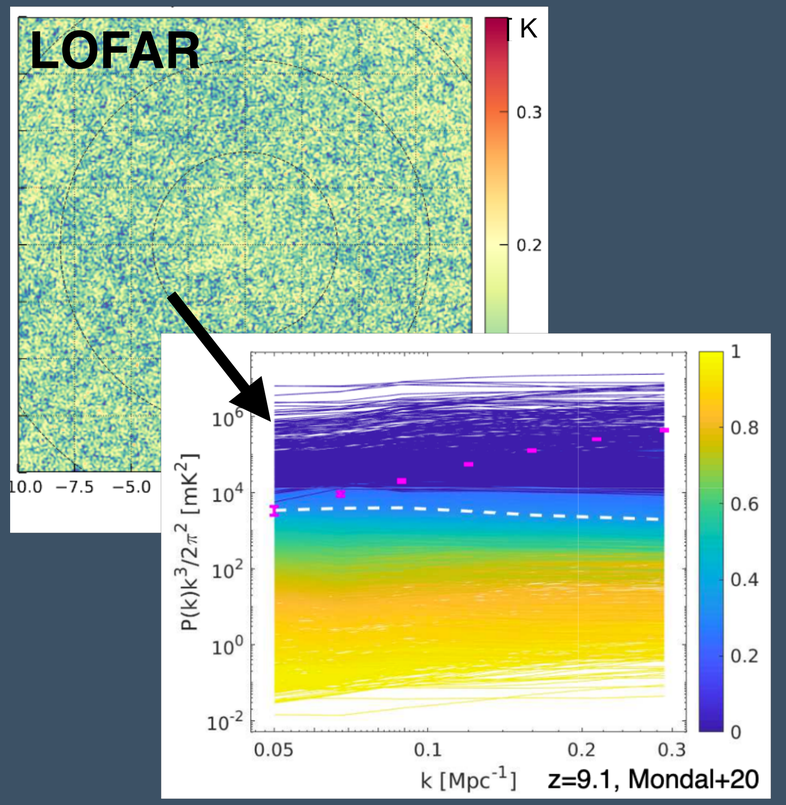
Map up to >50% of the observable Universe.

21cm Observable Universe Roadmap

High S/N map of >50% of the observable Universe

~2030-2040?





Now: upper limits on power spectra

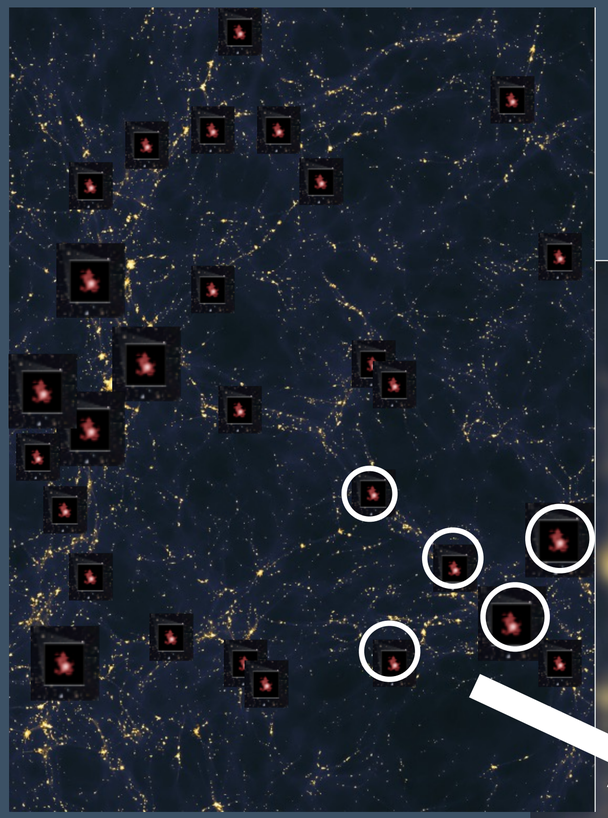
Soon: Low S/N detection, cross-correlation?

EoR synergies with galaxies and LIM

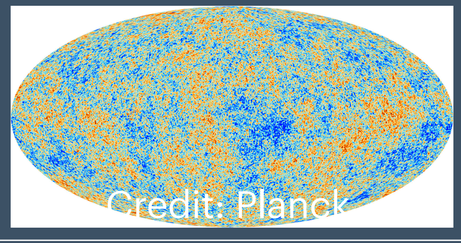
What is the Large-Scale-Structure?

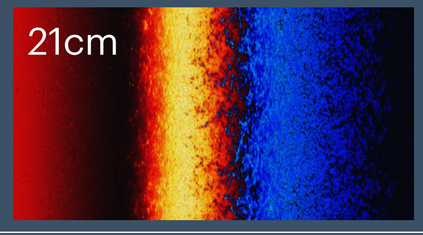
Distribution of gas + sources.

A) Individual sources
~ peaks in the DM field



Created by Uwe Kils (iceberg) and User:Wiska Bodo (sky).
CC BY-SA 3.0 <http://creativecommons.org/licenses/by-sa/3.0/>
Wikimedia Commons: https://commons.wikimedia.org/wiki/File:Iceberg.jpg

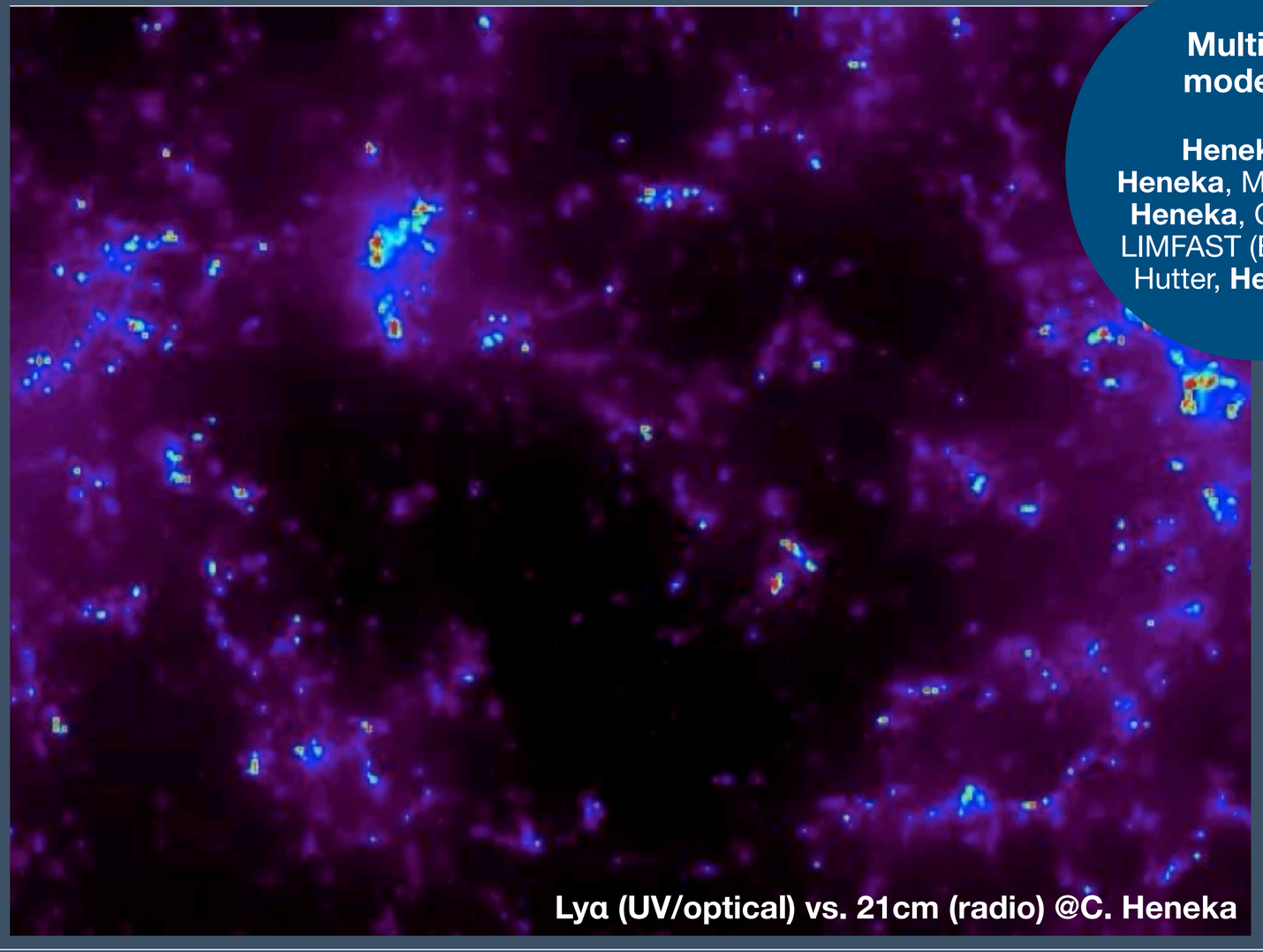




B) Intensity Mapping
~ tracer of fluctuations

The Universe is multi-colour

The multi-line signal during CD/EoR is a rich signal



Multi-line modelling

Heneka+17
Heneka, Mesinger 20
Heneka, Cooray 21
LIMFAST (Bernal+23)
Hutter, **Heneka**+23

The Universe is multi-colour

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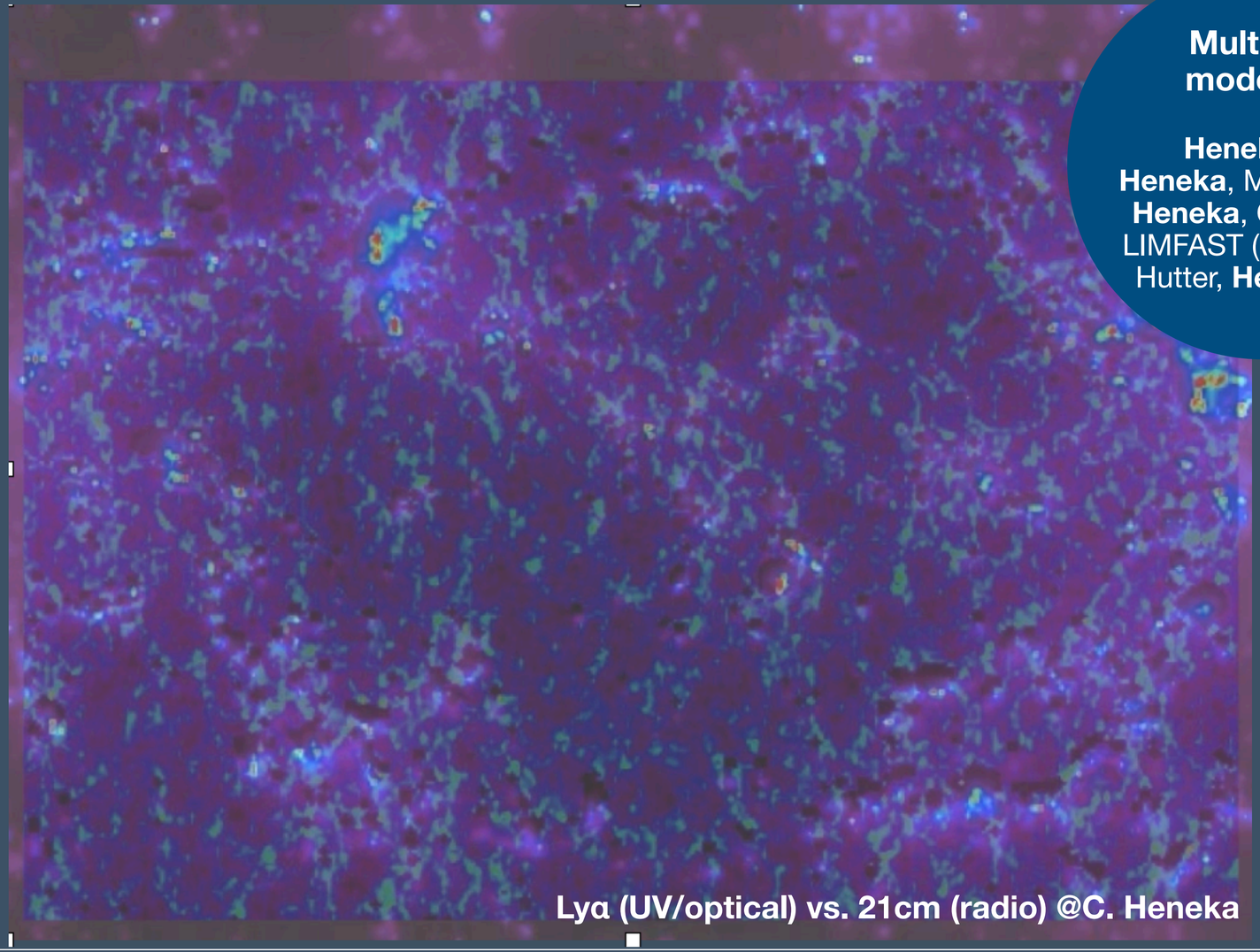

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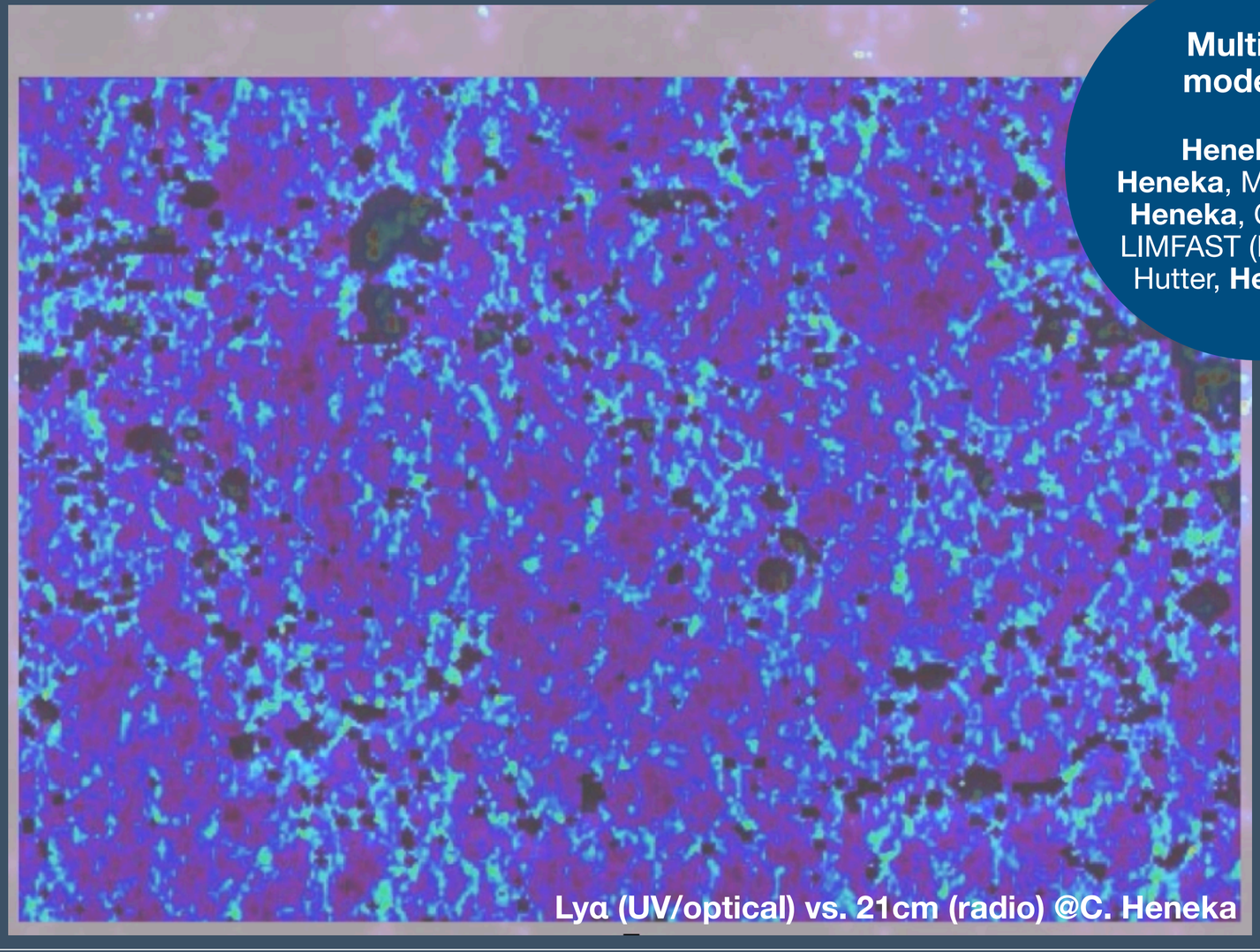

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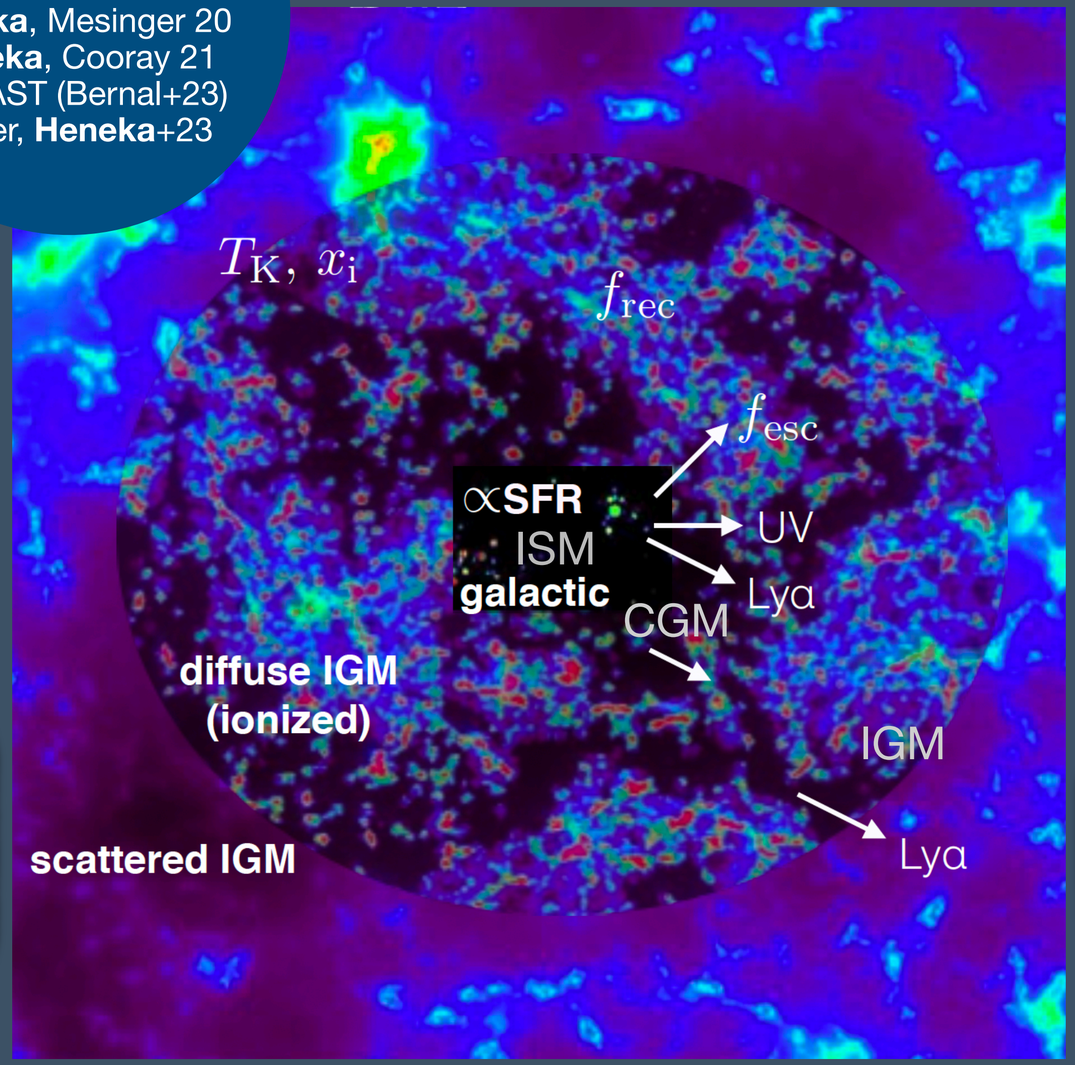
LIMFAST (Bernal+23)
Hutter, **Heneka**+23

21cmFAST

- Density/halo fields
  Velocity fields
  Ionisation fields
- Spin, gas temperature fields



- SFR, L-SFR/M-SFR relations
- Escape fraction
- (UV) Luminosity function

LINE BRIGHTNESS

COSMOLOGY

IGM EVOLUTION

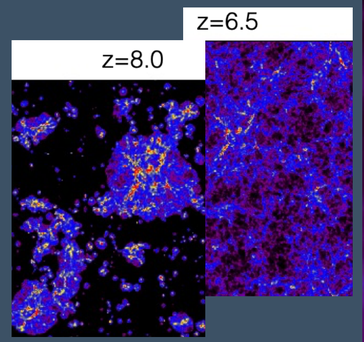
SOURCE (GALAXY) PROPERTIES

+ available: Hα, PAH

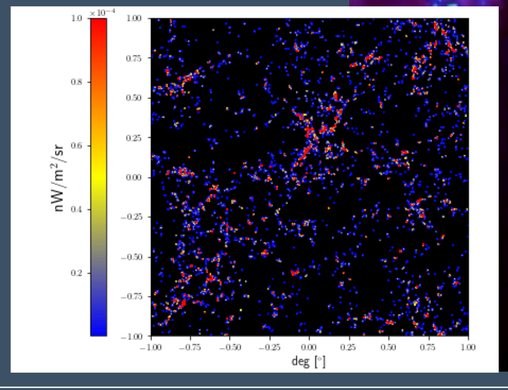
The Universe is multi-colour

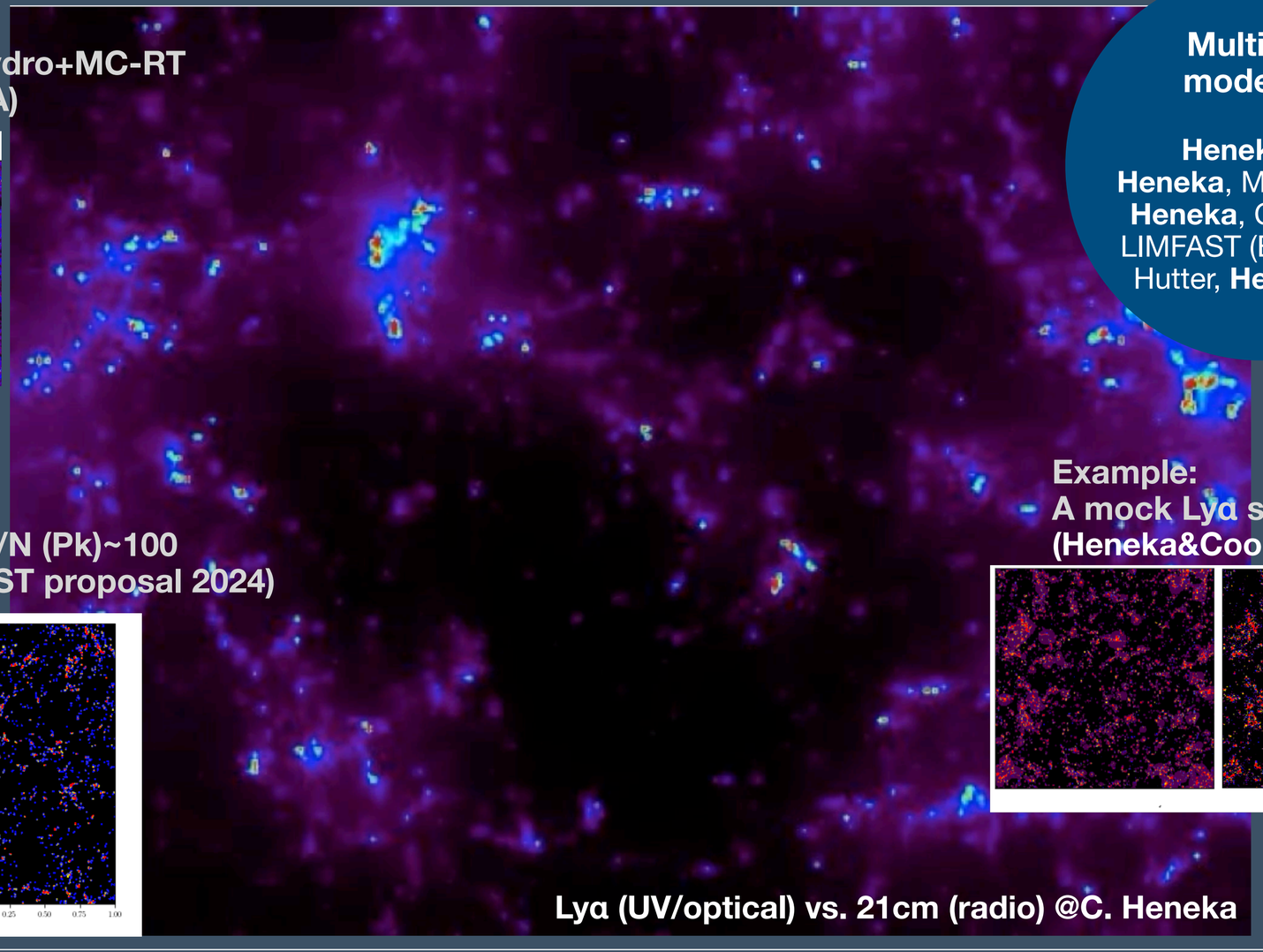
The multi-line signal during CD/EoR is a rich signal

Example:
Comparison with hydro+MC-RT
(with B.Ciardi@MPIA)



Example:
PAH 11.3μm at z~6, S/N (Pk)~100
(with A. Cooray, FIRSST proposal 2024)



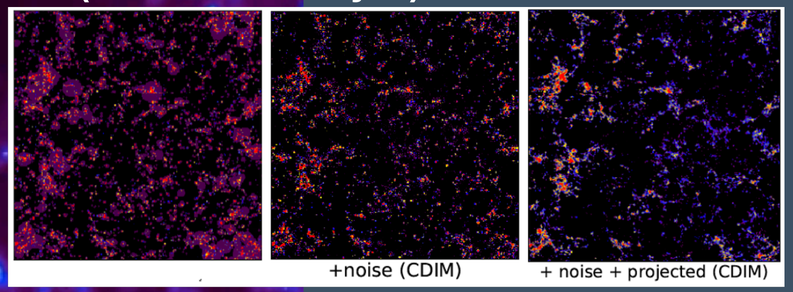


Lyα (UV/optical) vs. 21cm (radio) @C. Heneka

Multi-line modelling

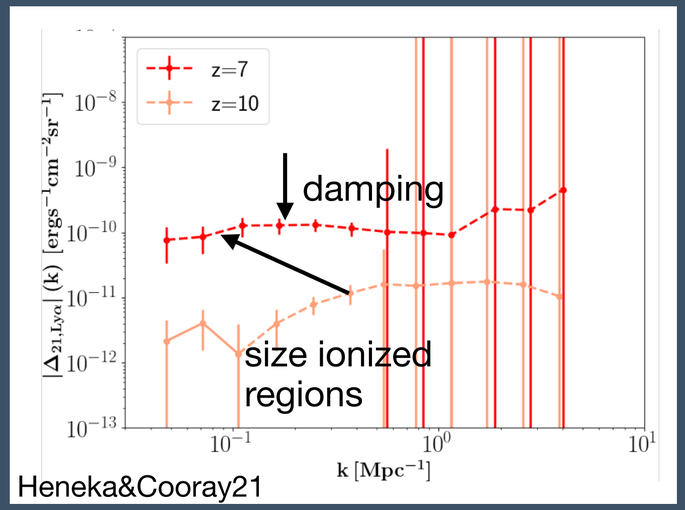
Heneka+17
Heneka, Mesinger 20
Heneka, Cooray 21
LIMFAST (Bernal+23)
Hutter, **Heneka**+23

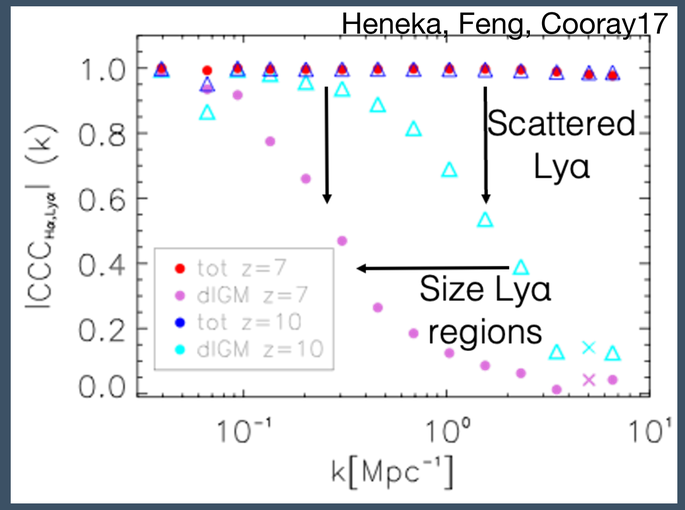
Example:
A mock Lyα sky with wide-field surveys
(Heneka&Cooray21)

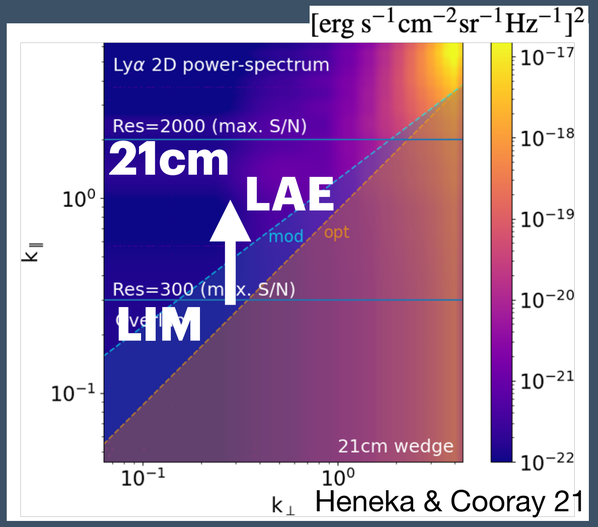


Synergies: LIM cross-correlations

Cross-power encodes additional information:







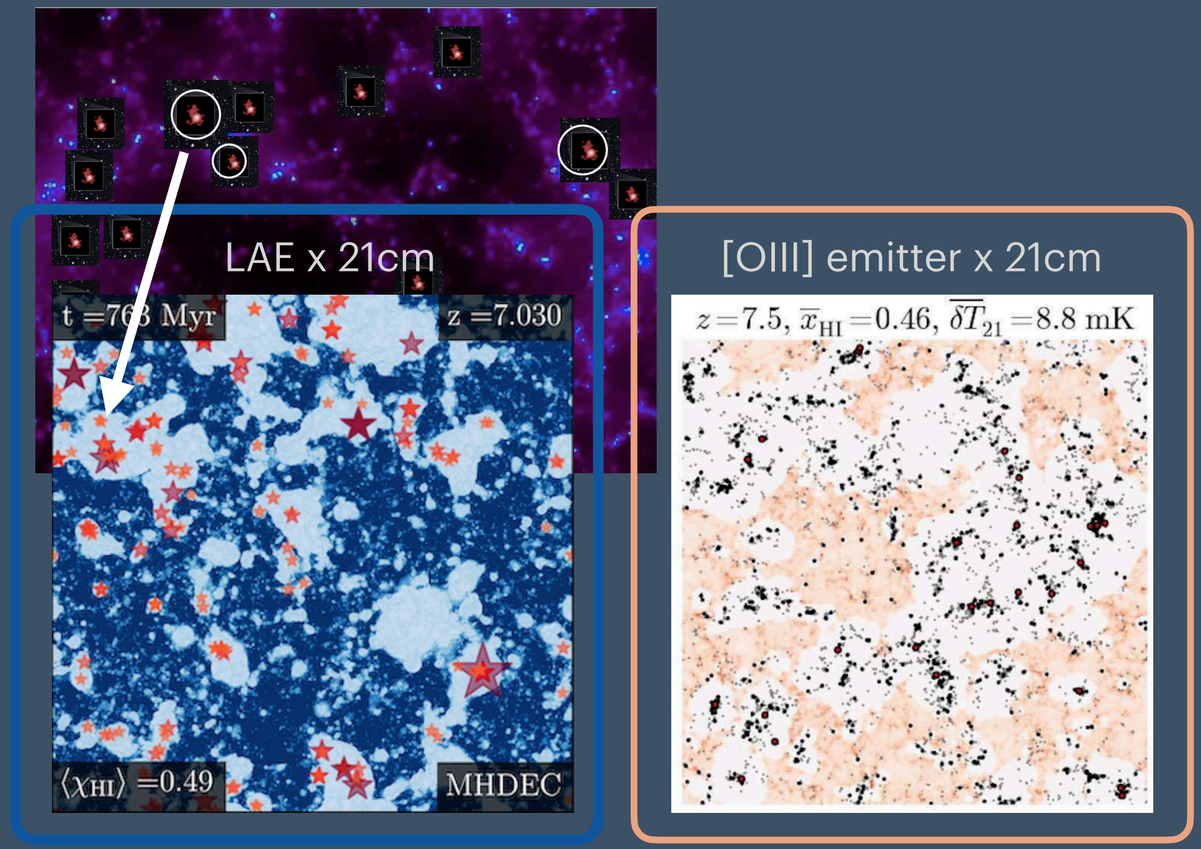
21cm x Lyα
Size distribution of ionised regions

Lyα x Hα
Size of Lyα regions
Radiative escape

Lyα-IM vs. LAE
Scales probed vs. signal-to-noise

+ damping is important!

Synergies: Galaxy cross-correlations



Modelling framework should be:

- **Fast**

  Suitable for forward-modelling & model exploration

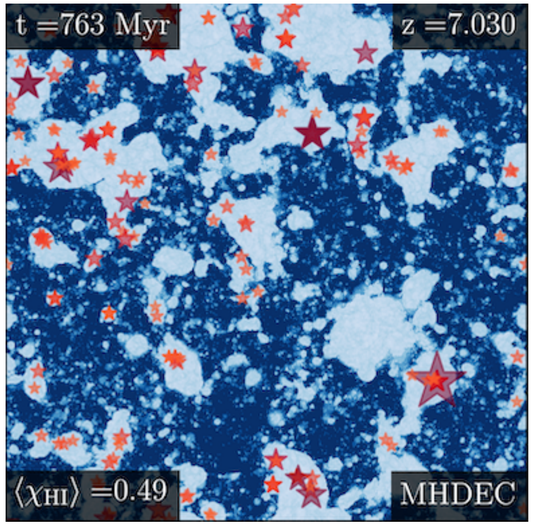
- **Consistent**

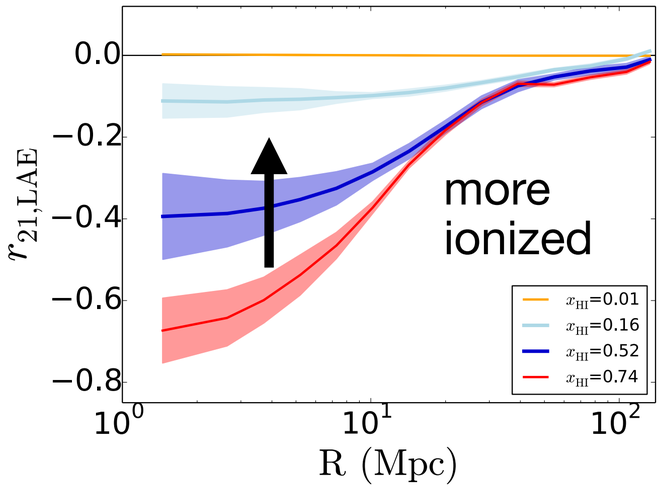
  Model lines, galaxies & intensity maps (mocks) alongside

Upcoming new SKA Red Book: Synergies for the Epoch of Reionization and Cosmic Dawn

Synergies: Galaxy cross-correlations

LAE x 21cm





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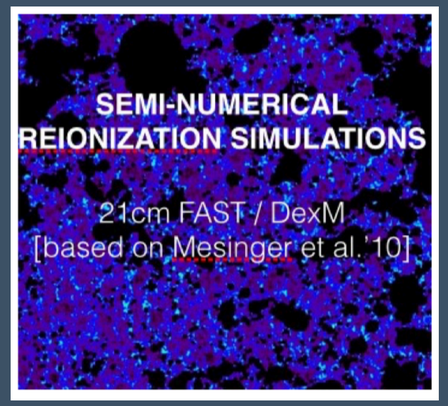
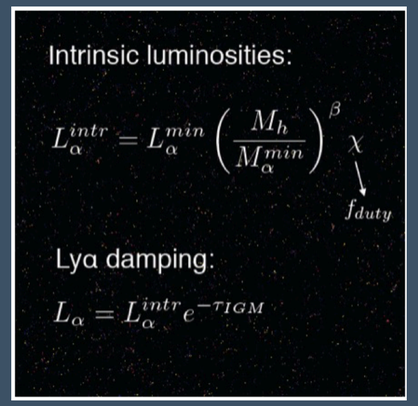
Upcoming new SKA Red Book: Synergies for the Epoch of Reionization and Cosmic Dawn

Synergies: Galaxy cross-correlations



+

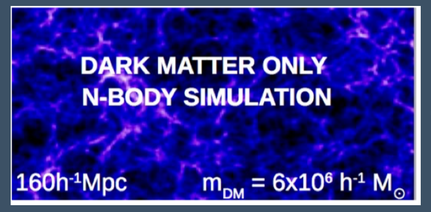


2 setups:

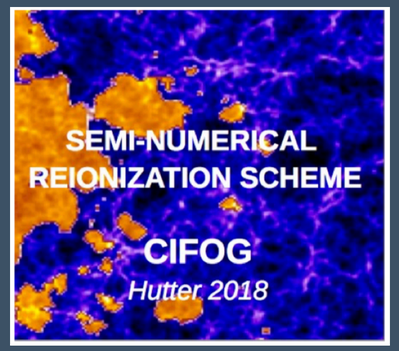
A. ‘Semi-numerical’

Semi-numerical simulations
21cmFAST (Mesinger+10, Murray+20, Davies+25)

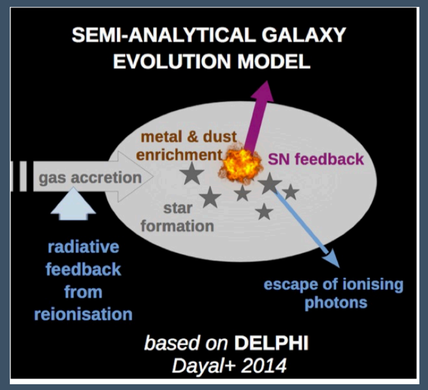
+ galaxy properties calibrated
with observations
(e.g., Heneka&Mesinger20, Gagnon-Hartman+25)



+



+



B. ‘Hybrid’

N-body + semi-numerical (CIFOG)

+ analytical galaxy evolution model

= Astraeus (I. Hutter+20 - X. Hutter+25)

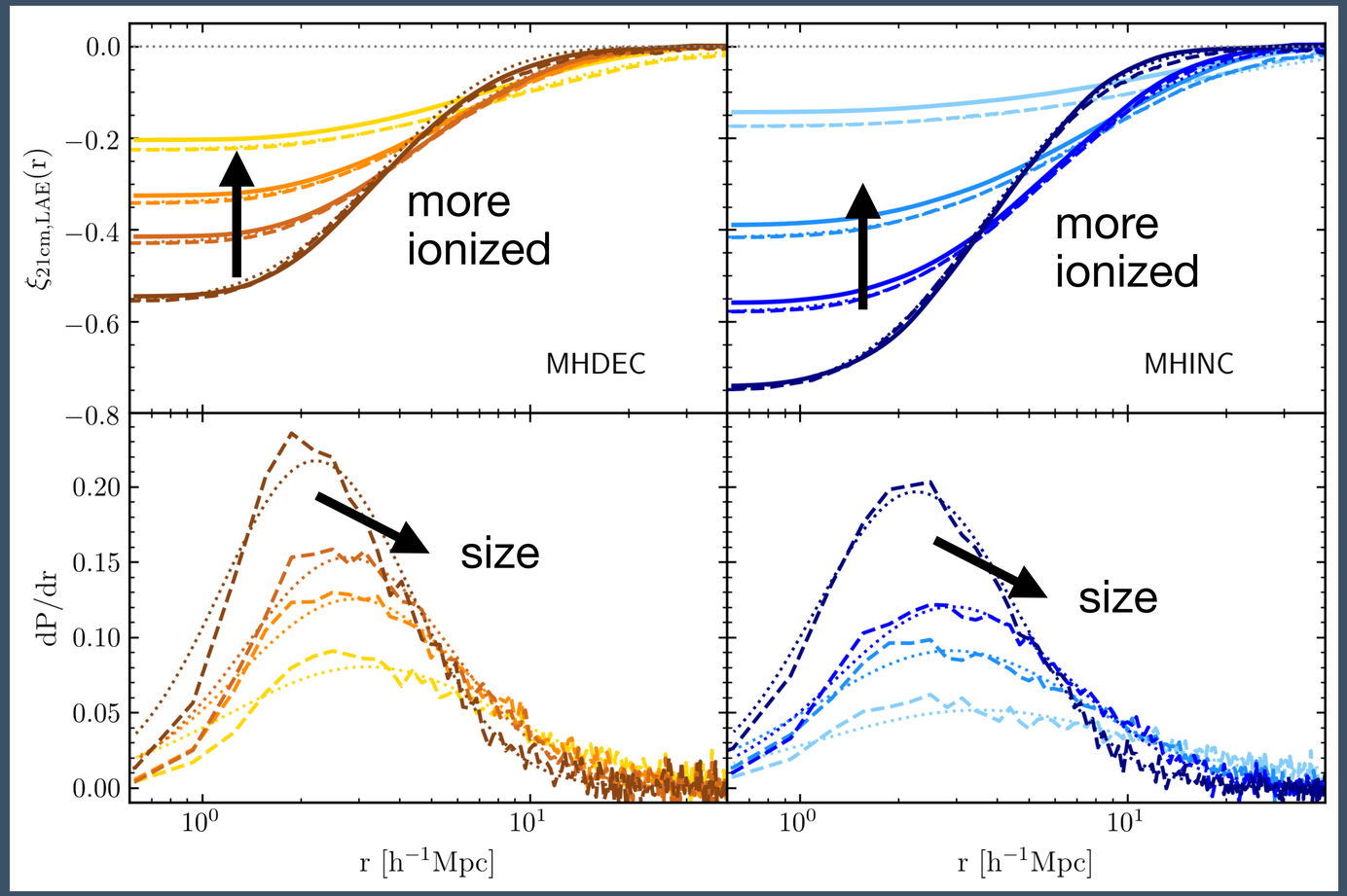
Do these setups agree?

Synergies: Galaxy cross-correlations

Analytical function: $\xi_{21,\mathrm{LAE}}(r) = -\langle \chi_{\mathrm{HI}} \rangle \langle 1+\delta \rangle_{\mathrm{HI}} \; [1 - \mathrm{CDF}(r)]$

Hutter, Heneka+24
arXiv:2306.03156

21cm-LAE cross-correlation fct.



21cm x LAE
Size distribution of ionised regions

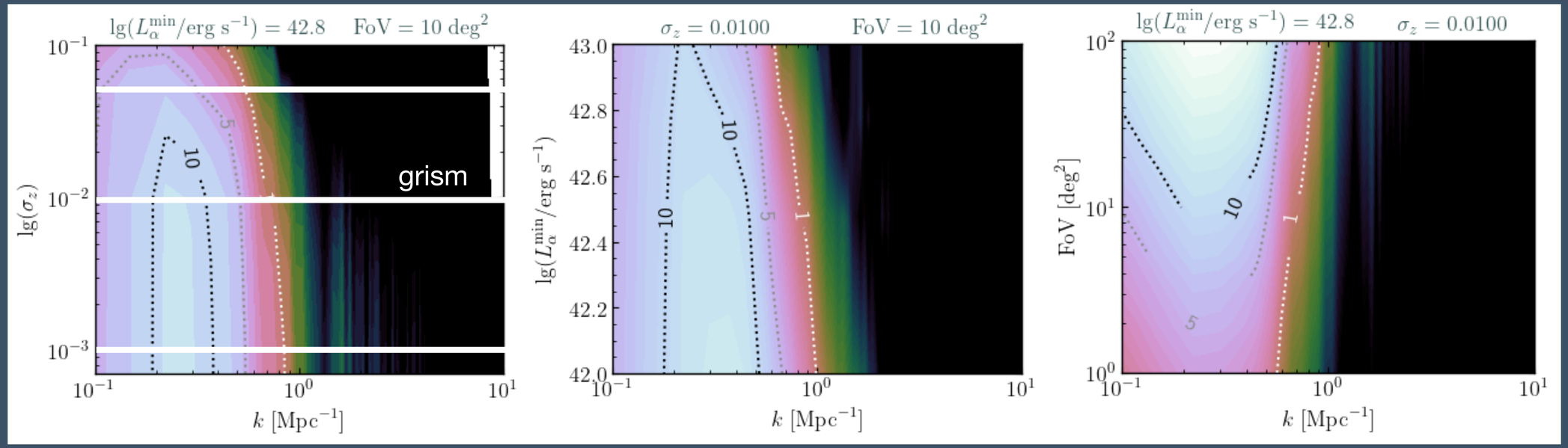
Analytic formalism allows to ‘standardise’ different models (simulators).

Synergies: Galaxy cross-correlations

Redshift uncertainty

Luminosity threshold

Field-of-view



narrow-band (Subaru/HSC)
grism (Roman, JWST NIRCam)
spectroscopic (VLT/ELT)

Depth m_{AB} >25

> few 100 arcmin fields

Upcoming new SKA Red Book: Synergies for the Epoch of Reionization and Cosmic Dawn

21cm lessons: More information with Intensity Mapping

Challenges:

- Data volume (>TB/s for radio)
- Number of modes (>10^9)
- Noise, foregrounds, systematics
- Non-Gaussian signal

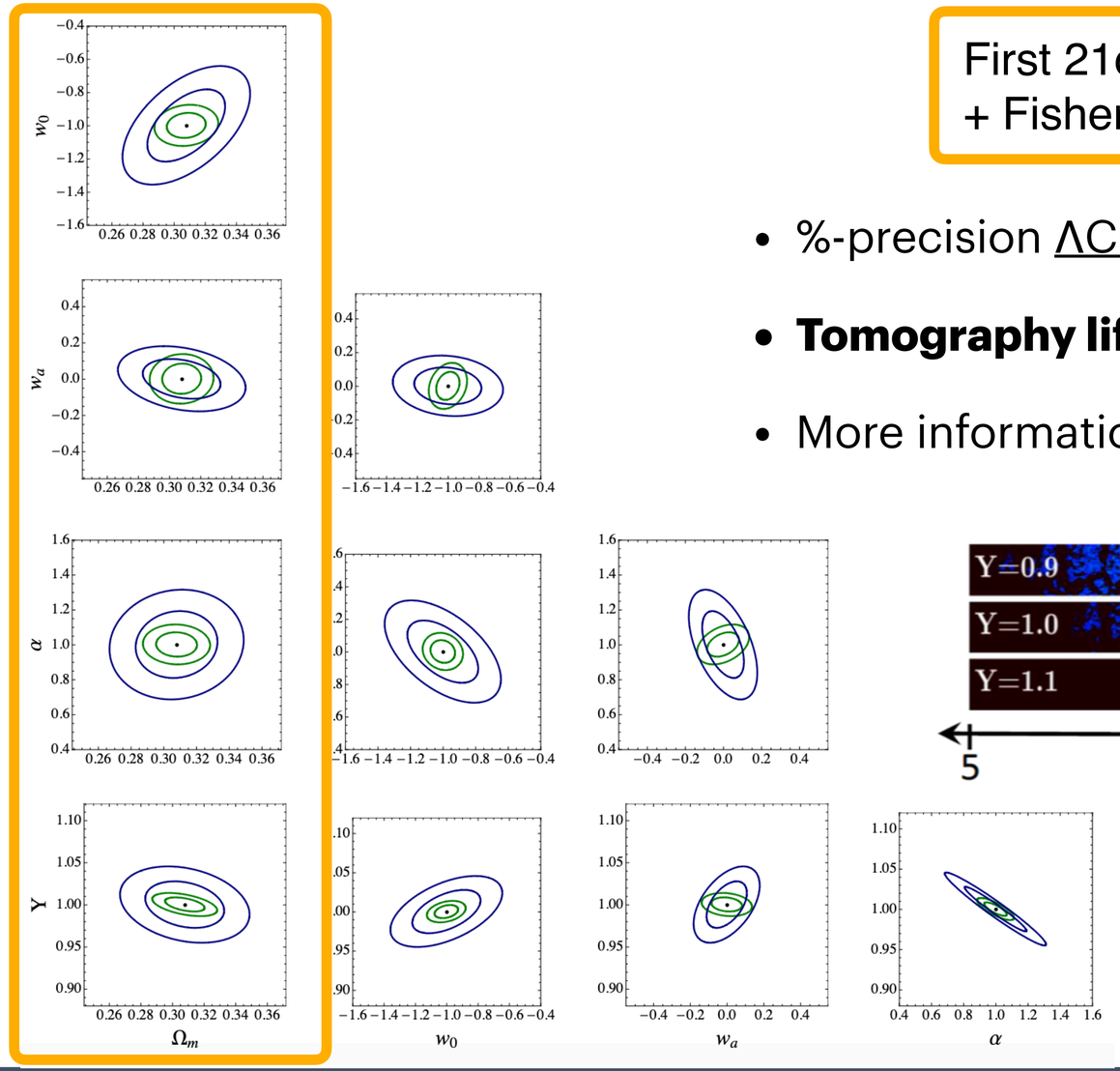
Are we up for the challenge?

The SKAO Universe machine

- Solutions (non-exhaustive list, Credit: Adélie Gorce):
  - Minkowski functionals & topology Giri+2020, Thélie+2022
  - Higher-order statistics, bispectrum Watkinson+19, Hutter+20
  - Scattering transforms Greig+22, Hothi+22, Prelogovic+24
  - AI/ML techniques Neutsch, **Heneka**+22, Schosser, **Heneka**+25

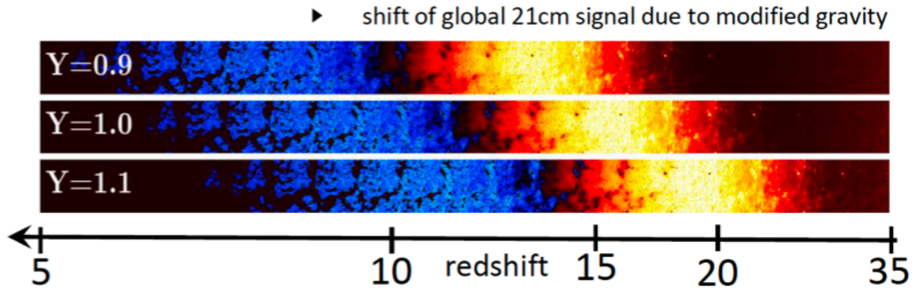
Adapted from C. Chiang

21cm lessons: Cosmology at z > 6



First 21cm beyond-ΛCDM simulations
+ Fisher forecast

- %-precision <u>ΛCDM + beyond</u>
- **Tomography lifts degeneracy astro + cosmo**
- More information via (mildly) non-linear scales

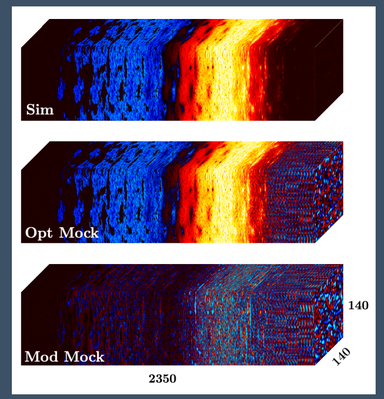


Heneka & Amendola (2018) arXiv:1805.03629
Liu, **Heneka**, Amendola (2020) 1910.02763
See also: 1805.11044, 1903.03144, 1903.03629, 1903.11744, 2104.12739

21cm lessons: Unbiased inference

Likelihood-free inference from intensity maps

21cm light cone



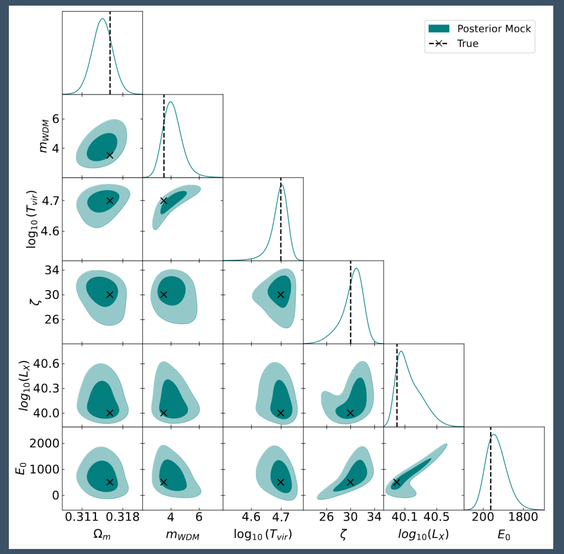
mocks

Data Compression

Summary

Parameter Estimation

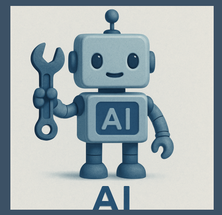
Astro + Cosmo



~~POWER SPECTRUM~~

Gaussian, MCMC biased

OTHER?

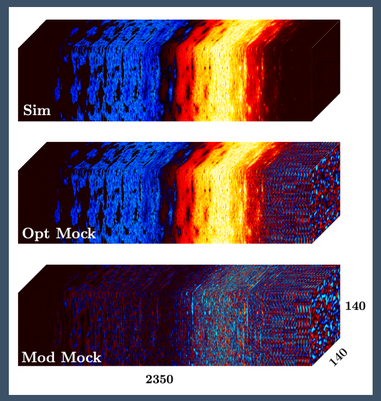


Created with AI

21cm lessons: Unbiased inference

Likelihood-free inference from intensity maps

Data x



mocks

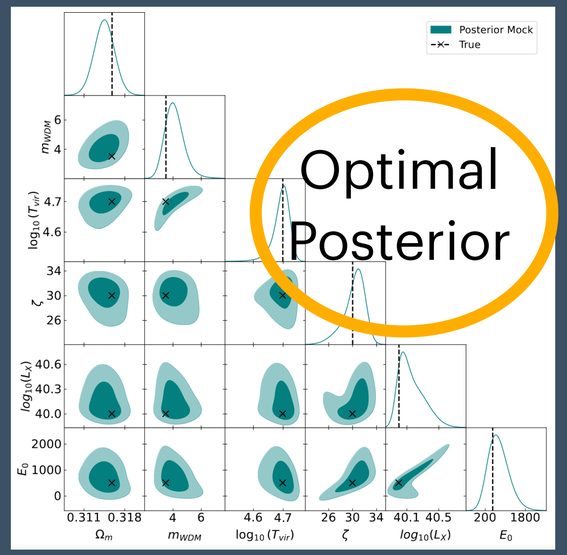
Robust to noise!

+ Unbiased

+ optimal calibrated posterior

IF joint estimate of optimal summary

Unbiased Parameter θ



21cm lessons: Unbiased inference

1 frame = 1 MCMC

For any model in prior range

21cm_pie Public

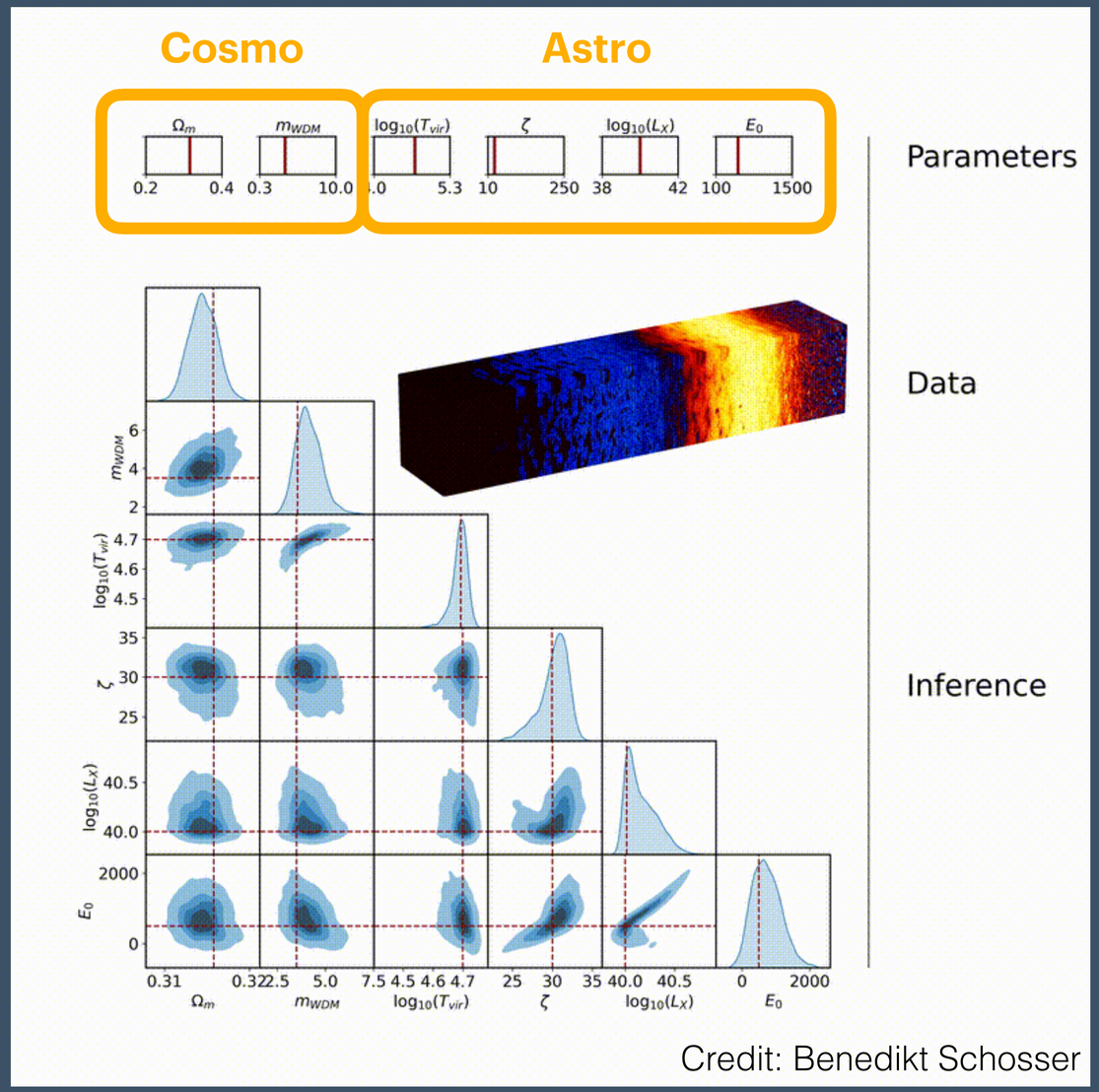
3D-21cmPIE-Net Public

'Optimal, fast, and robust inference of reionization-era cosmology with the 21cmPIE-INN'

Schosser, **Heneka**, Plehn 2025

Neutsch, **Heneka**, Brüggen 2022

See also new SKA Red Book: Machine Learning for the SKA



Credit: Benedikt Schosser

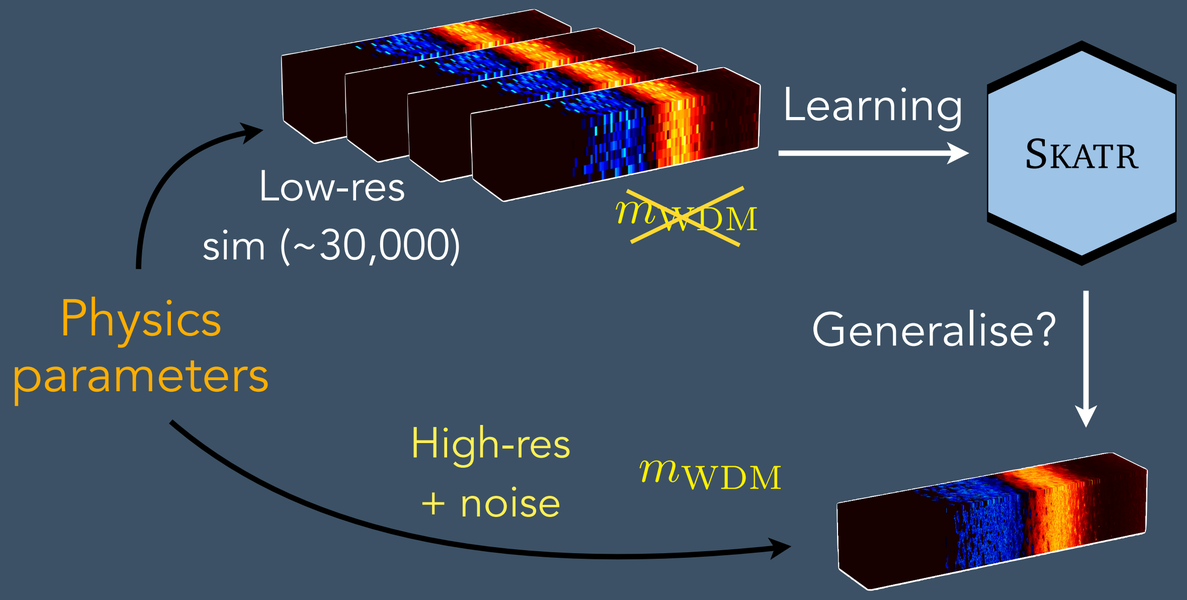
21cm lessons: Transfer (model + noise)

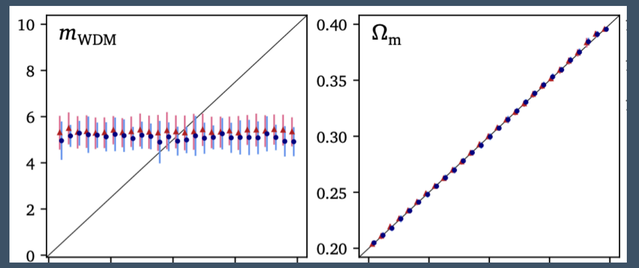
→ ***Self-supervised learning:***

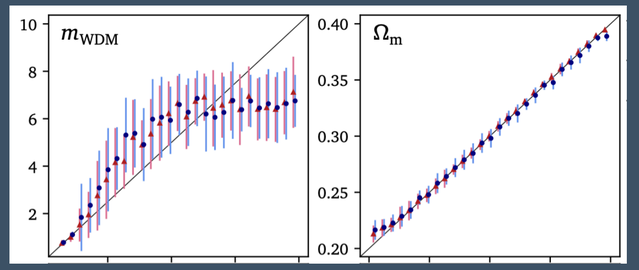
Train a network to produce informative representations without using labels (physics parameters)

Ayodele Ore, Heneka, Plehn 2025

arXiv: 2410.18899

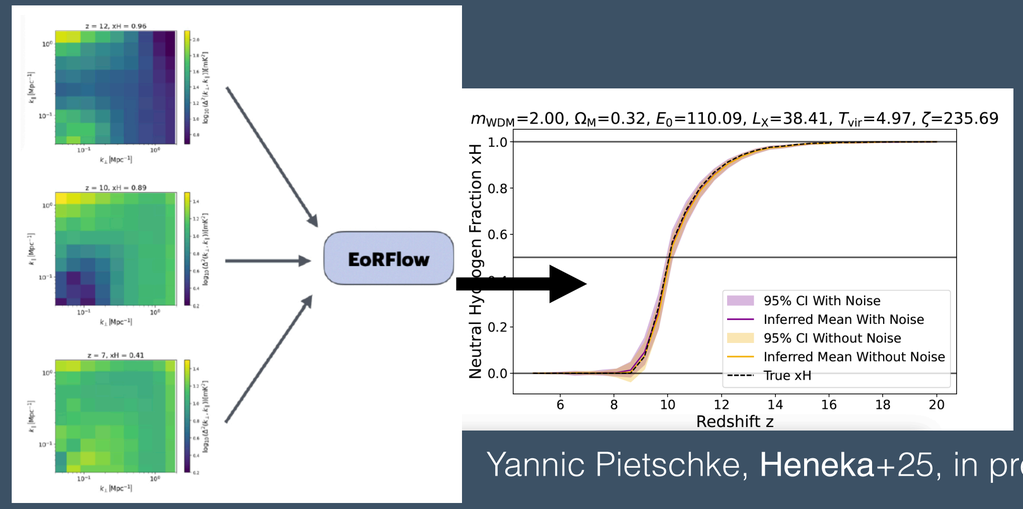






SKATR *— A self-supervised summary transformer for the Square Kilometre Array*

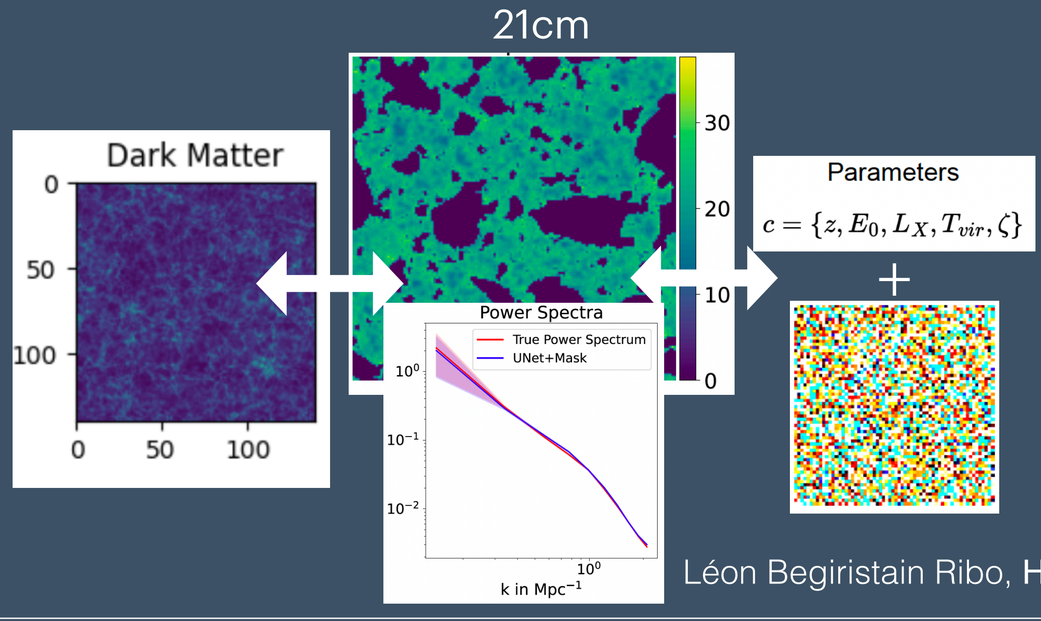
More 21cm highlights: Reconstructions & fast simulators



Global xHI history

Yannic Pietschke, **Heneka**+25, in prep.

Diffusion-based simulators



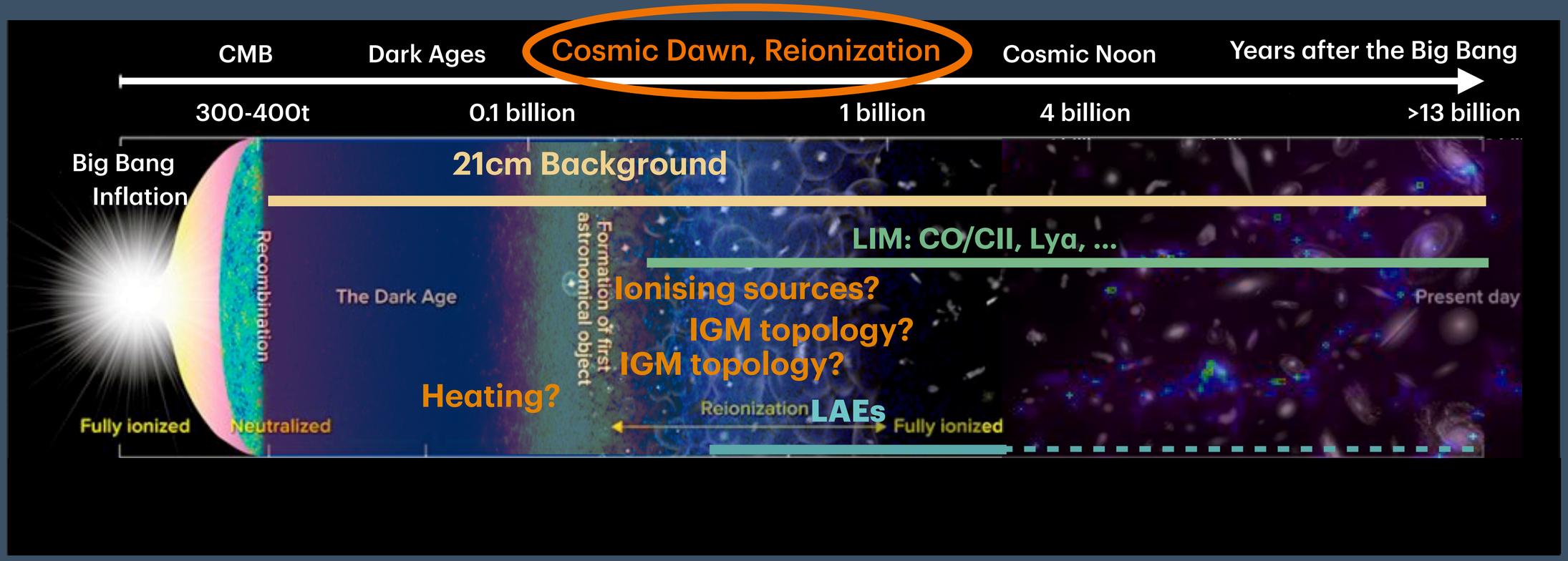
Léon Begiristain Ribo, **Heneka**+, in prep.

The EoR with LIM and galaxy synergies

1) Cross-correlations add information, e.g. on size distribution of ionized regions, radiative escape

2) Galaxy and LIM correlations are complementary goals.

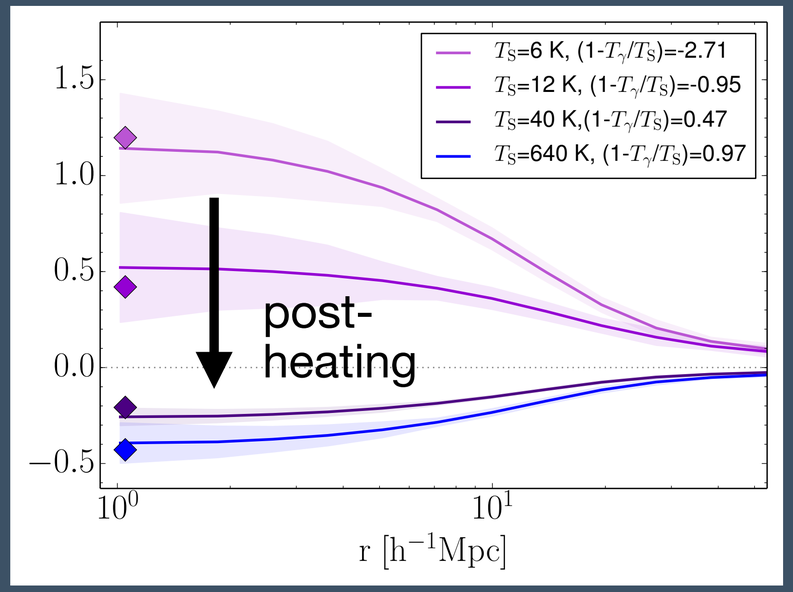
3) Exploiting the EoR 21cm signal: correlate, correlate + ML



Synergies: Galaxy cross-correlations

Analytical limit: Also holds for positive 21cm-LAE correlation during heating.

Hutter, Heneka+24
arXiv:2306.03156



$$\xi_{21,\mathrm{LAE}}(r=0) \simeq -\langle \chi_{\mathrm{HI}} \rangle \langle 1+\delta \rangle_{\mathrm{HI}}$$

$$0.5 \lesssim \langle 1+\delta \rangle_{\mathrm{HI}} \lesssim 1.0$$

Small-scale amplitude traces reionization topology

$$\xi_{21,\mathrm{LAE}}(r=0) \simeq -\langle \chi_{\mathrm{HI}} \rangle \langle (1-\frac{T_\gamma}{T_s})(1+\delta) \rangle_{\mathrm{HI}}$$

+ Heating state of the IGM