Forward modeling the first billion years with 21cmFASTv4

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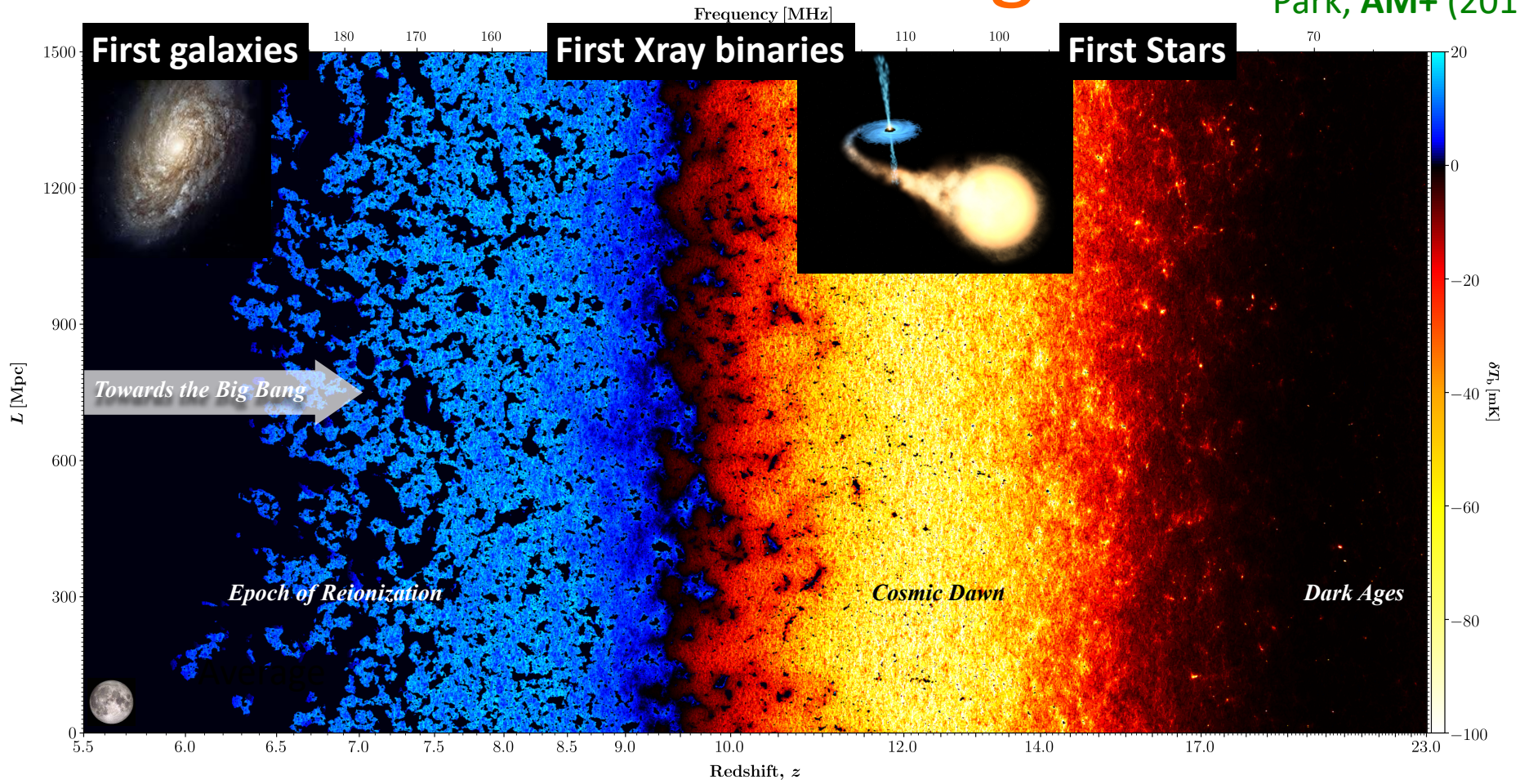
Ministero dell'Università e della Ricerca

erc
European Research Council

Cosmic 21-cm signal

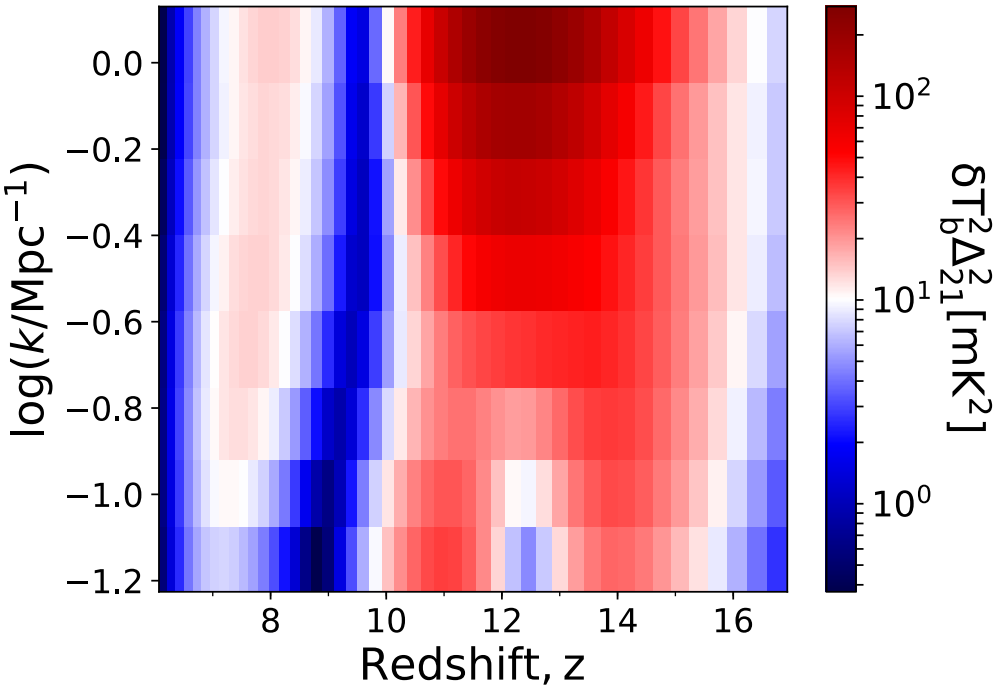
Park, **AM+** (2019)



$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) {\rm mK}$$

The SKA will detect the power spectrum of these fluctuations with very high signal to noise

1D power spectrum from "fiducial model"



characteristic "three-peak" structure of the cosmic signal

Kaur, Gillet, **AM** (2020)

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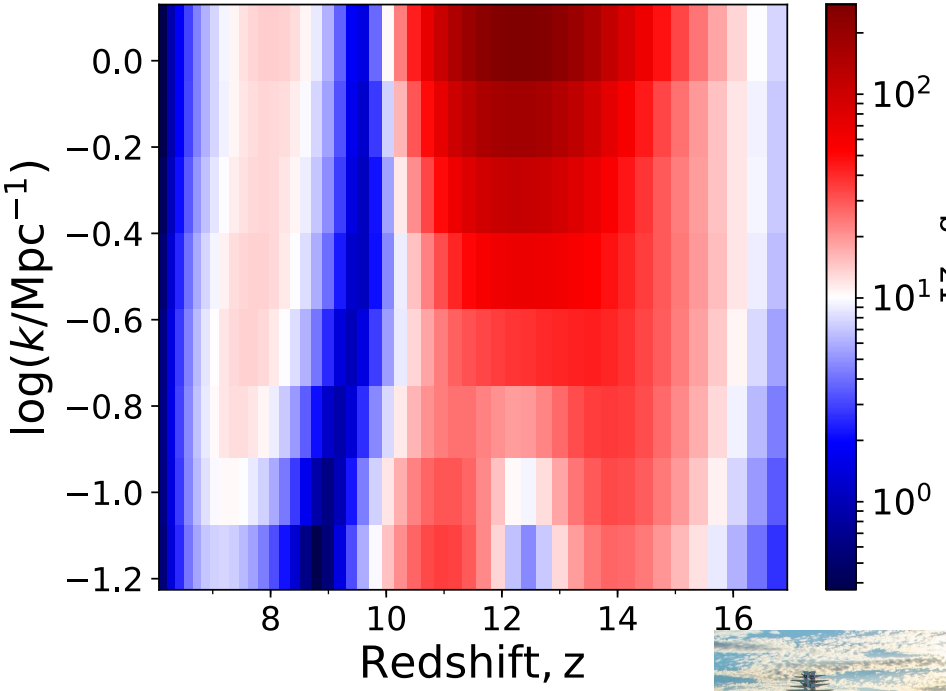
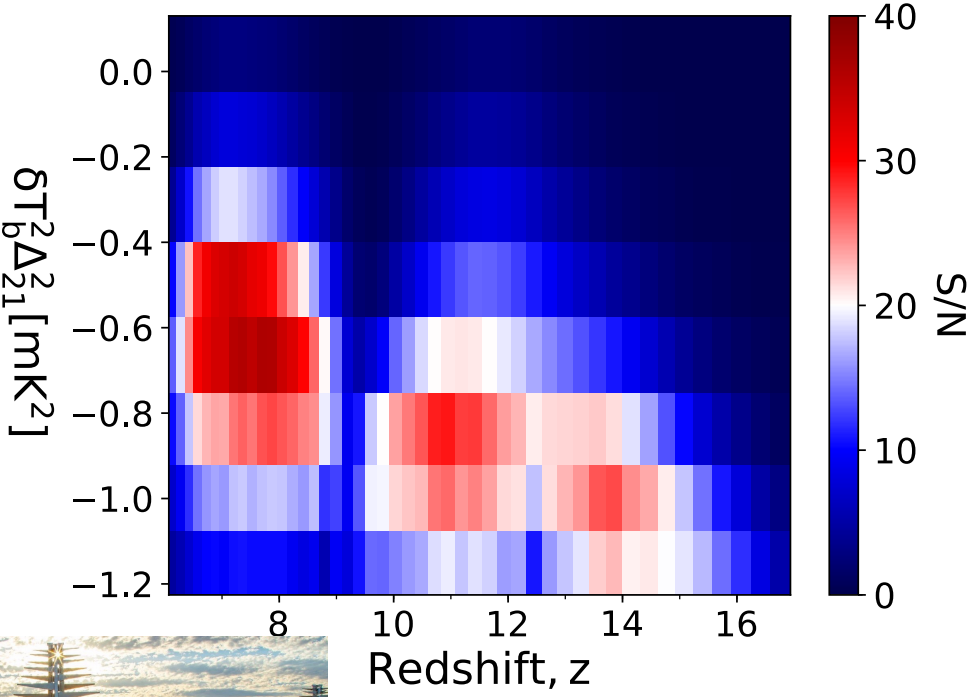
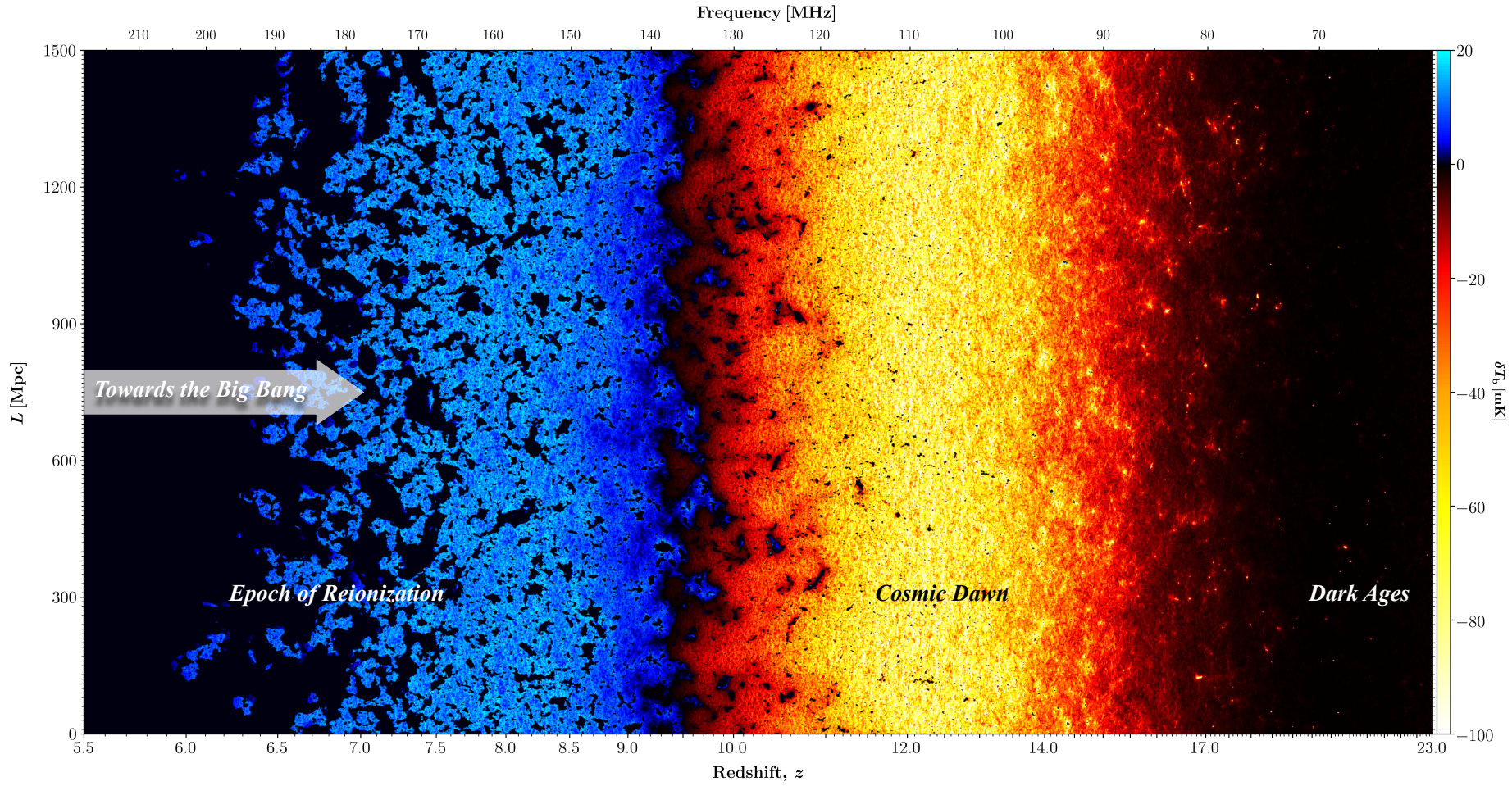


S/N from a 1000h SKA-low observation



Kaur, Gillet, **AM** (2020)

But we have a long way to go before we have a high S/N map of our Universe



Measurements are improving, but currently only upper limits on the PS

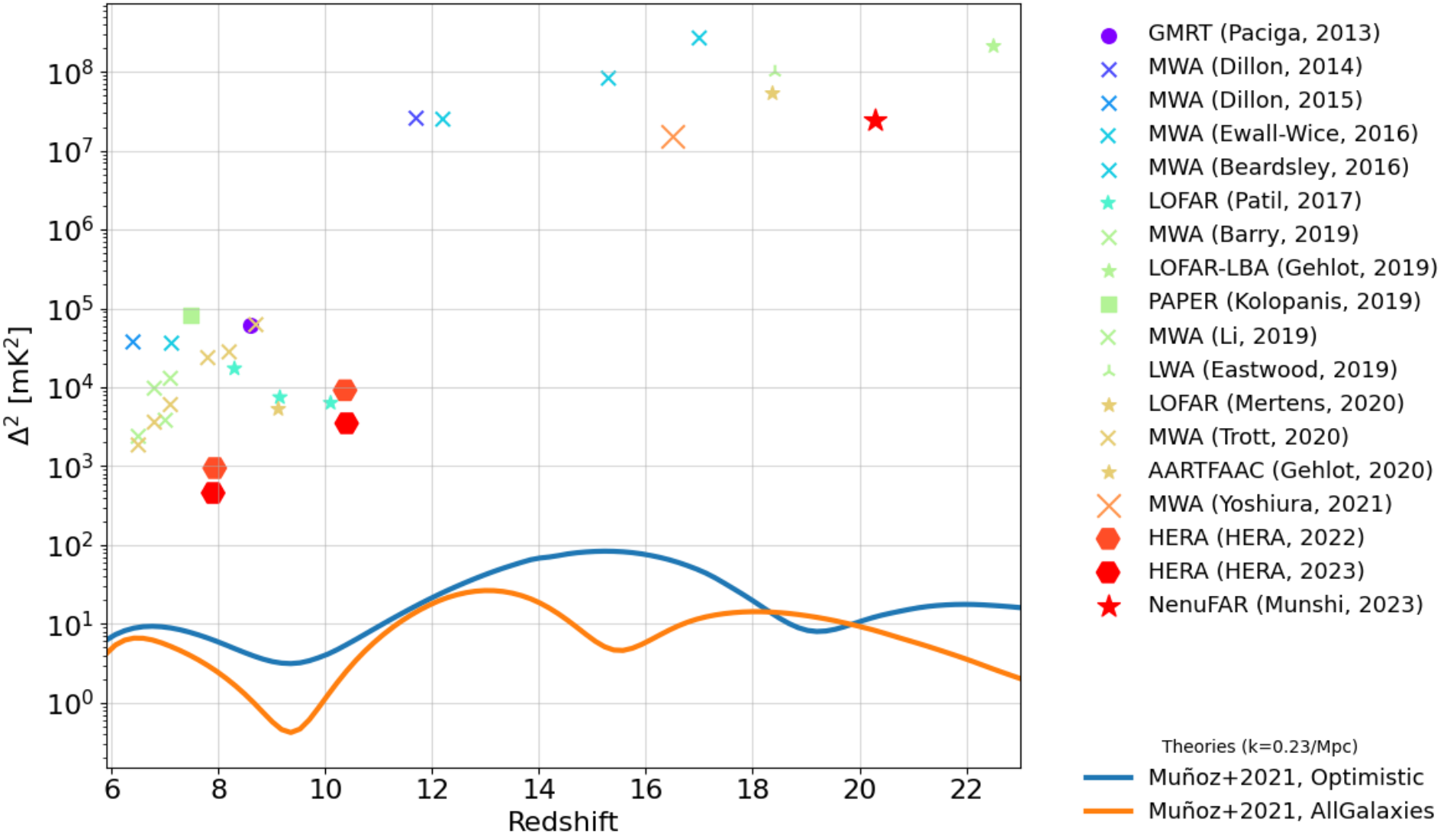
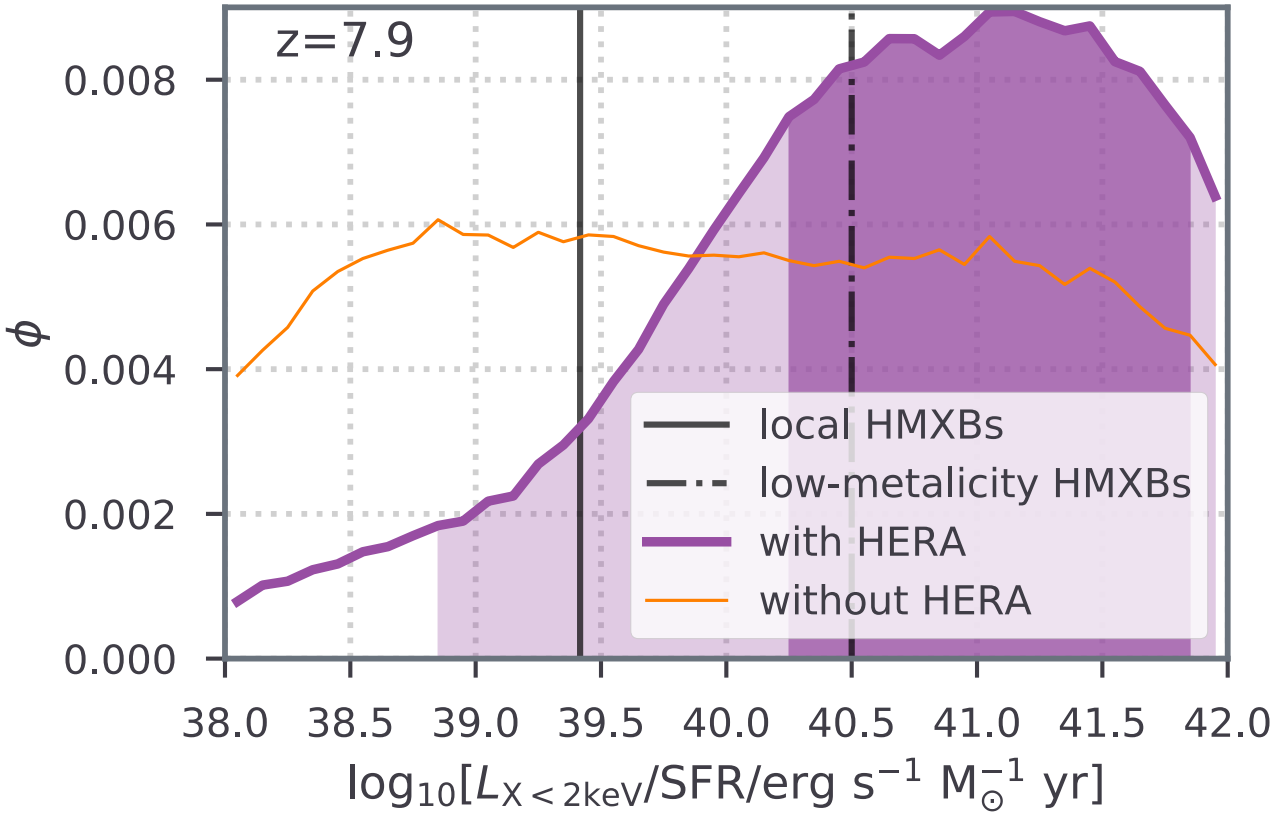


figure credit S. Murray

A multi-tracer approach will be **ESSENTIAL** for the next decade(s)

i) The only reason we learned something new from current 21cm PS upper limits is because we inform our models with **synergistic observations.**

Main punchline from 21cm upper limits is only possible thanks to other likelihood terms



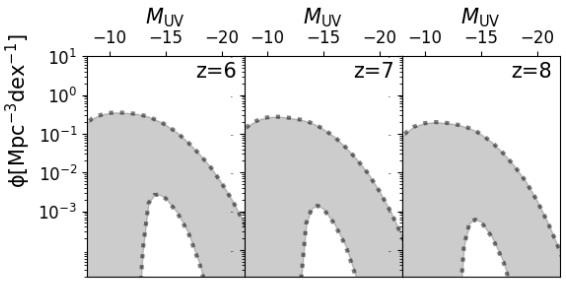
The HERA collaboration (2022)

HERA is the first observation to constrain the X-ray luminosities of Cosmic Dawn galaxies (e.g., Fragos+13), *disfavoring the values seen in local, metal-enriched galaxies*

led by Y. Qin

Contribution of different data

UV LFs

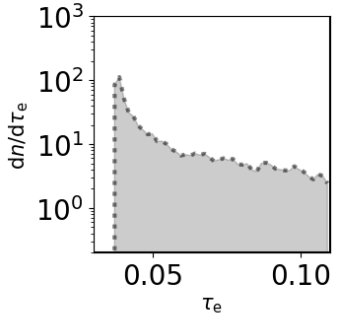


21cm PS @ k=0.1/Mpc

21cm mean

EoR history

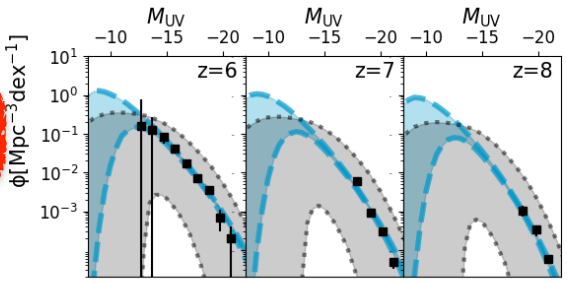
Breitman, AM+(2024)



CMB τ

Contribution of different data

UV LFs



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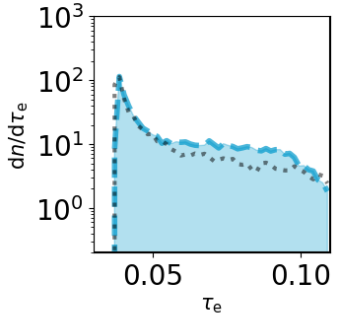

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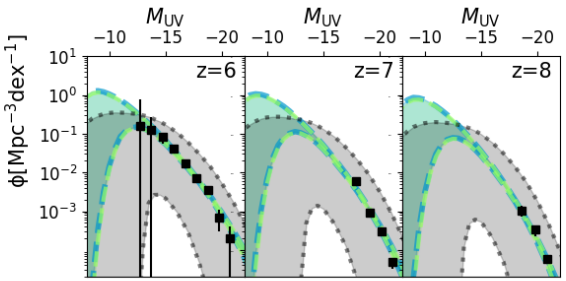

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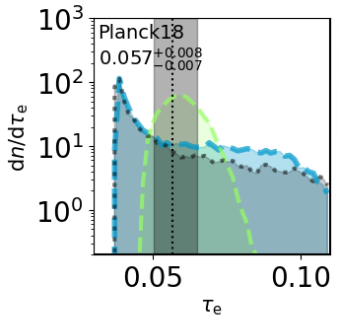

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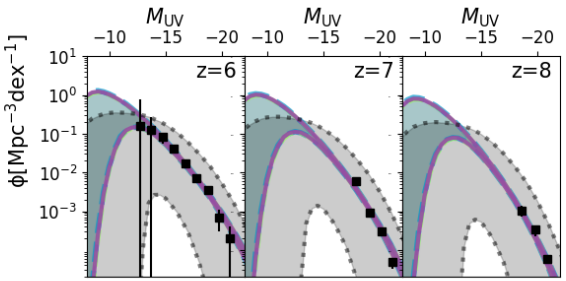

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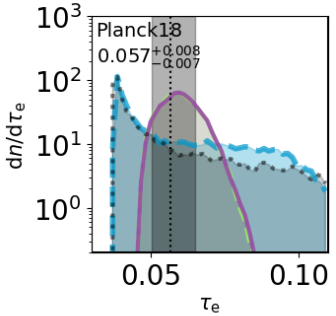

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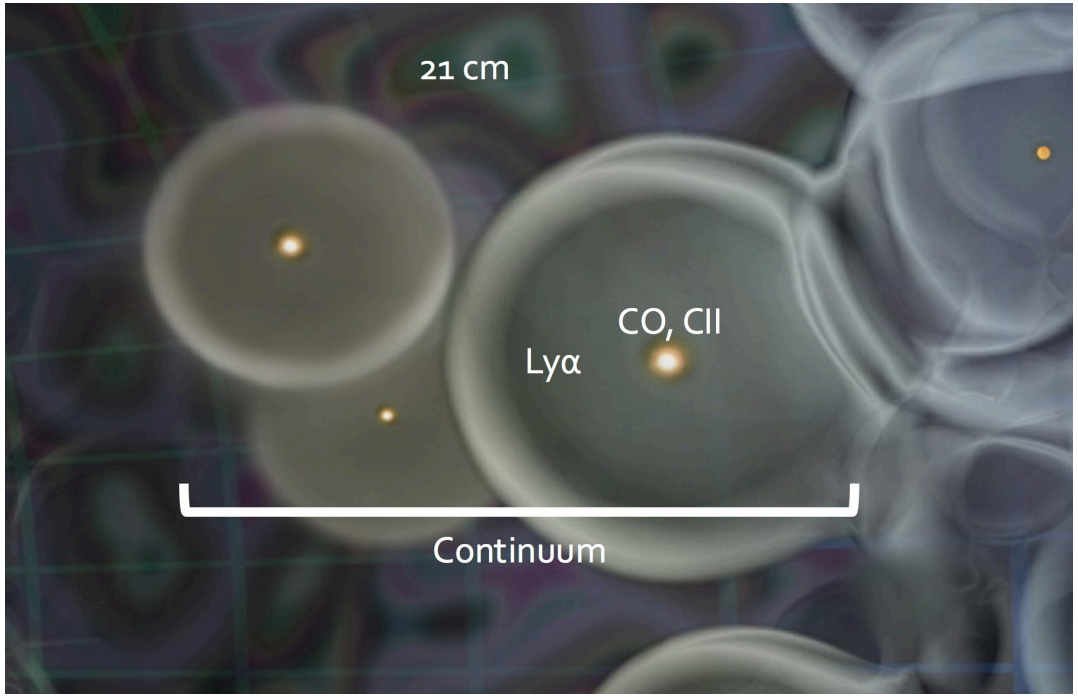
A multi-tracer approach will be **ESSENTIAL** for the next decade(s)

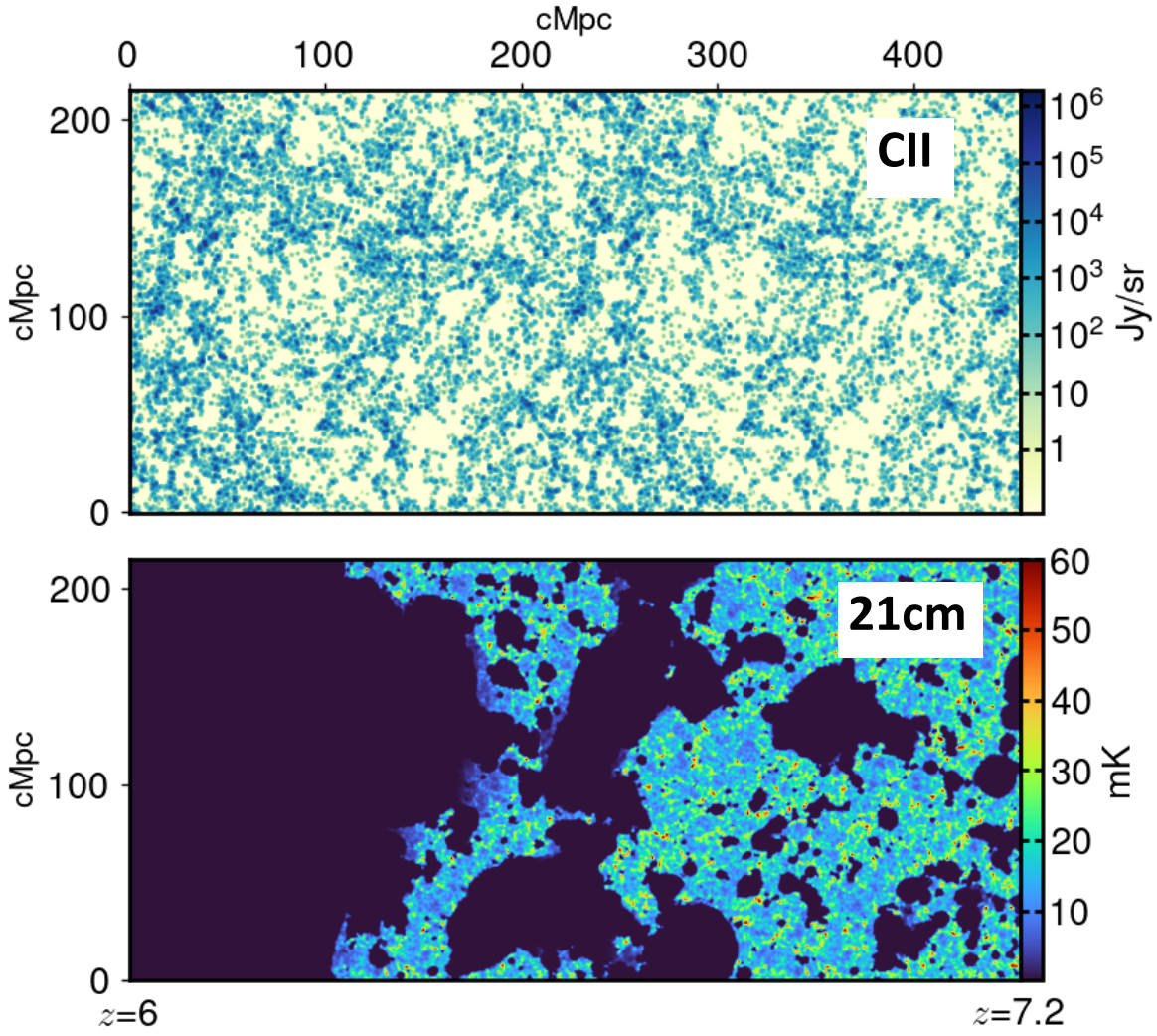
i) The only reason we learned something new from current 21cm PS upper limits is because we inform our models with **synergistic observations.**

ii) Observations *probing the same volume* yield **complimentary points of view.**



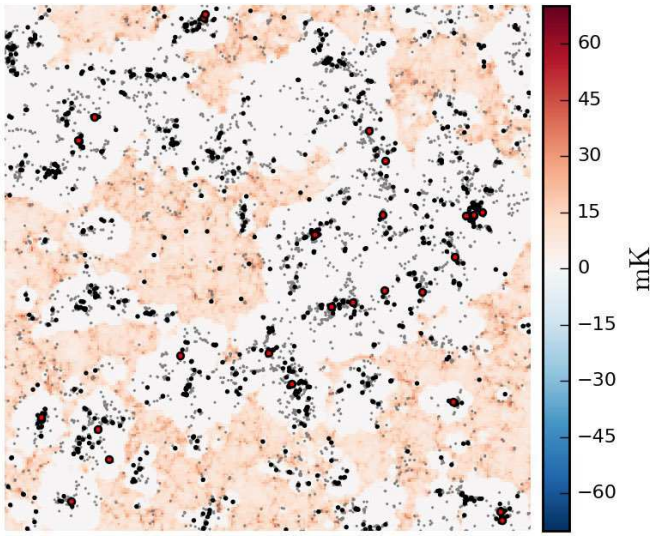
Kovetz+2017

The importance of cross-correlations



Murmu+ (2021)

OIII galaxies - 21cm



Moriwaki+2019

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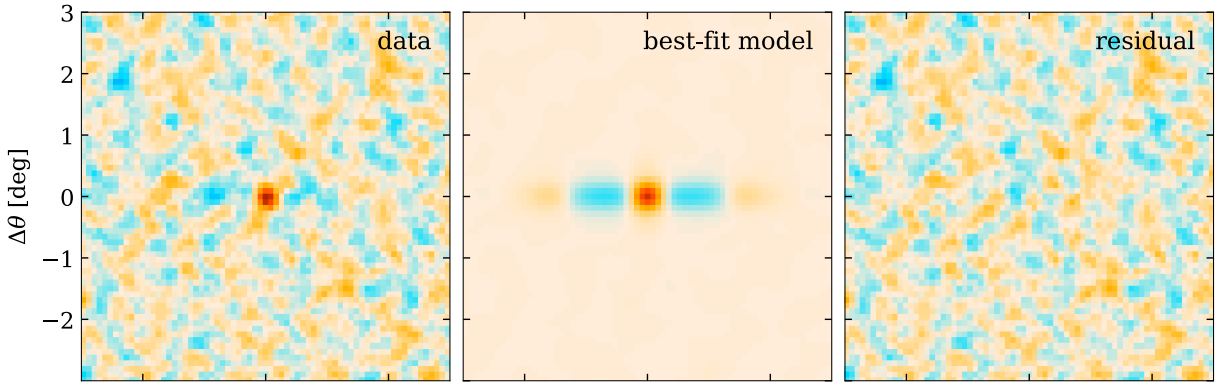
i) The only reason we learned something new from current 21cm PS upper limits is because we inform our models with **synergistic observations.**

ii) Observations *probing the same volume* yield **complimentary points of view.**

iii) Cross-correlations will be important proof that **initial claims of a 21cm detection are genuine.** Signal might even be **easier to detect** in the cross, since systematics average out to zero.



The CHIME collaboration 2022

New **21cmFASTv4**:
built for high-dimensional, multi-tracer, field-level Bayesian inference of the first billion years

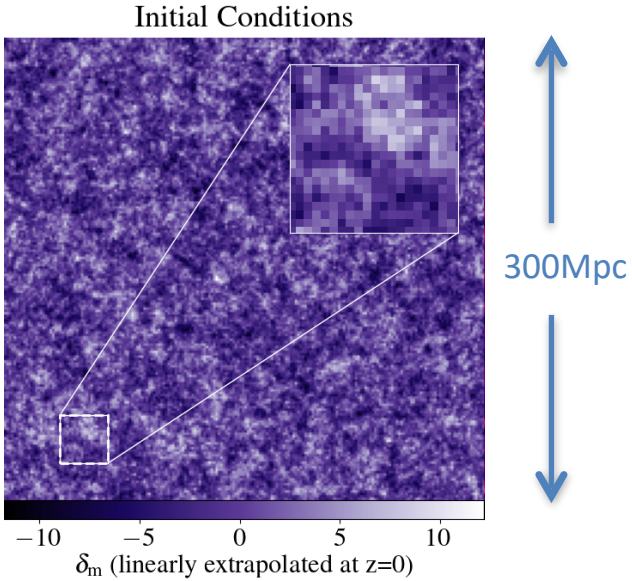
Davies, Mesinger, & Murray, in prep

21cmFASTv4

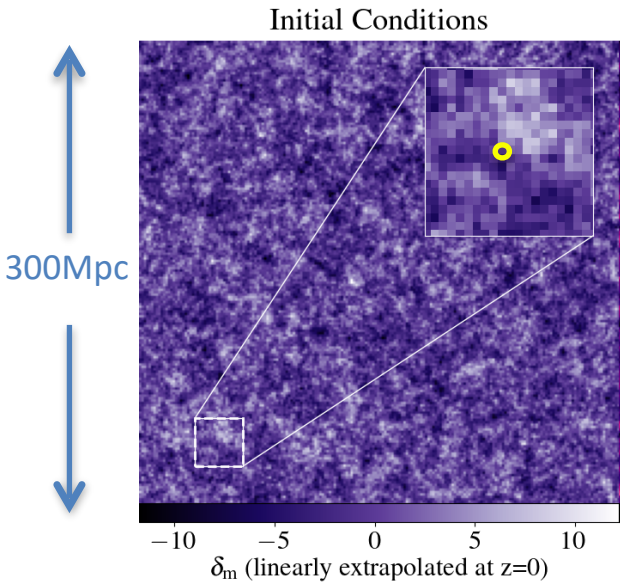
1. Sample cosmology and create initial conditions

Cosmology Parameters

$(\Omega_m \;\; \sigma_8 \;\; H_0 \;\; \ldots)$



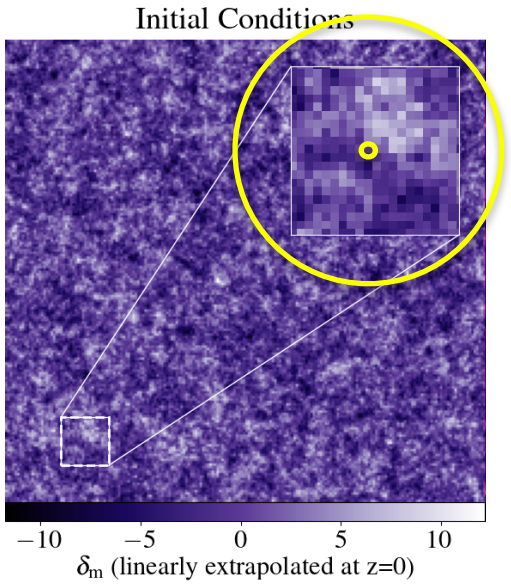
2) Efficient halo finding

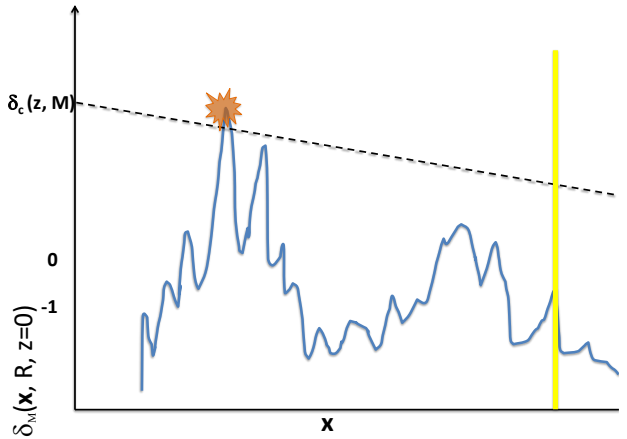


Scales > cell size

DexM excursion-set Lagrangian halo finder (AM & Furlanetto 2007; see also Monaco+2002)

2) Efficient halo finding





e.g. Sheth+1999

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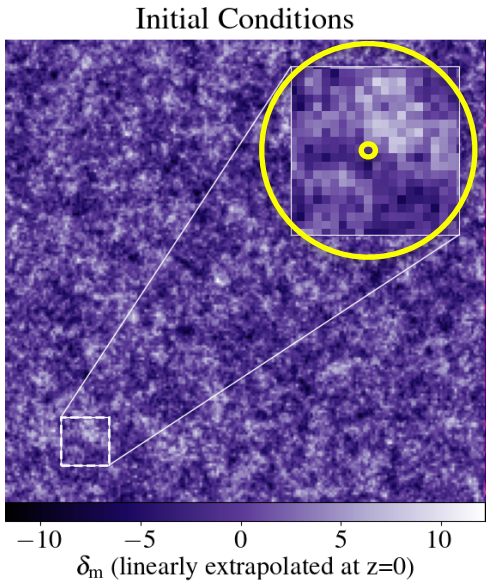

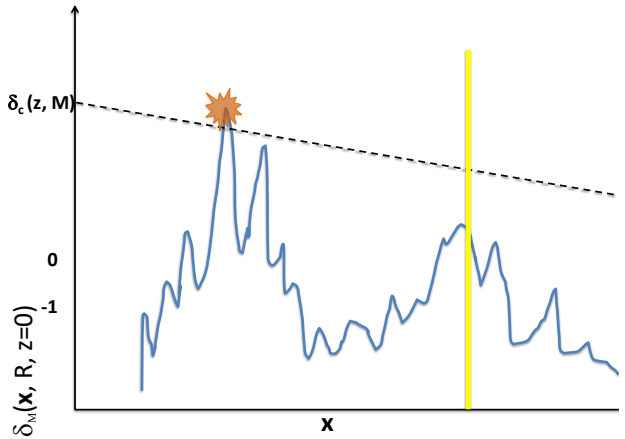

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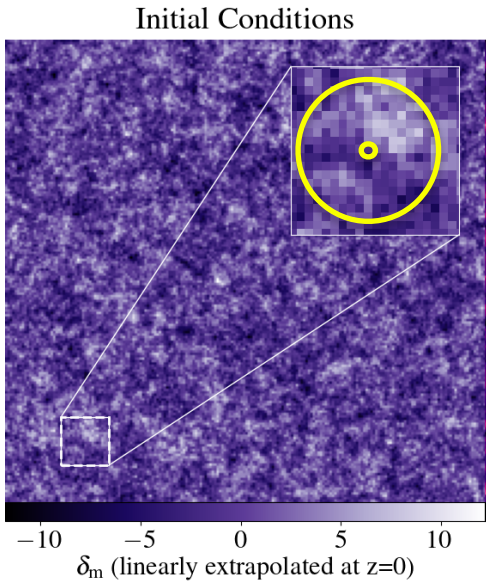

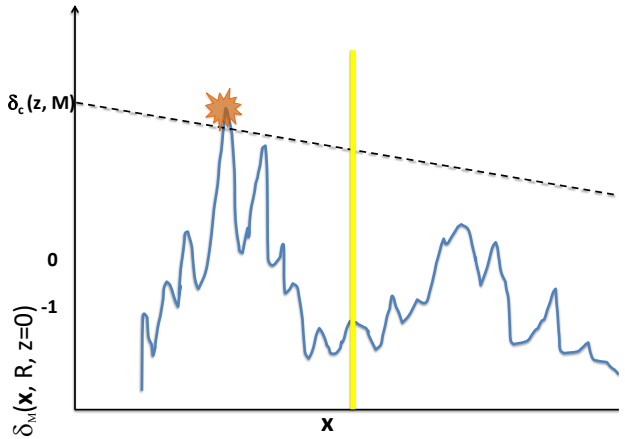

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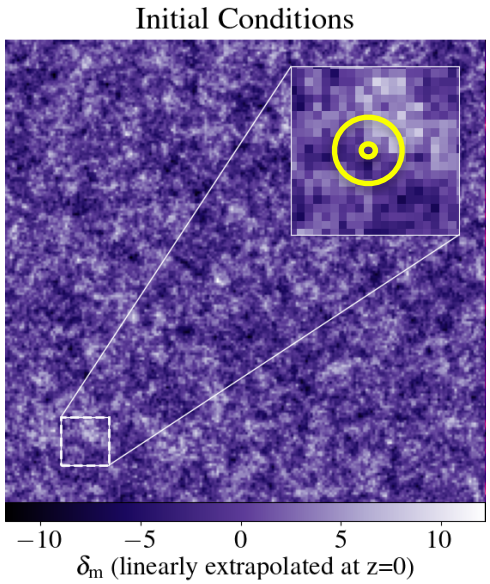

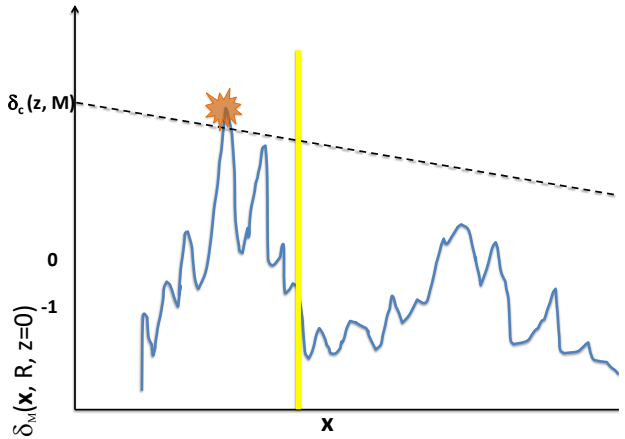

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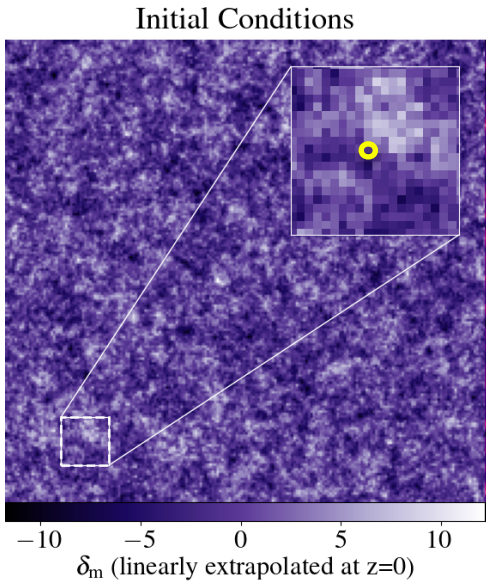

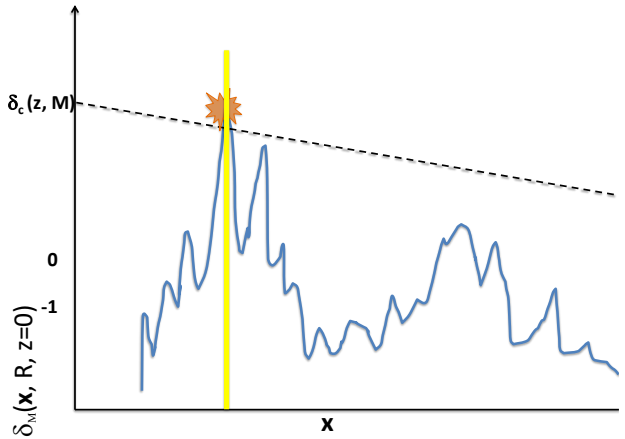

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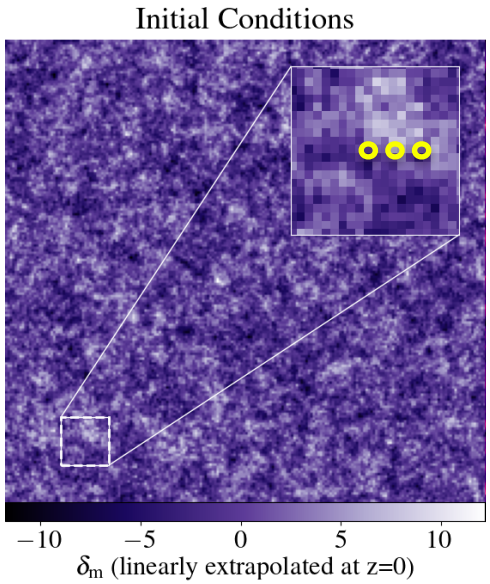


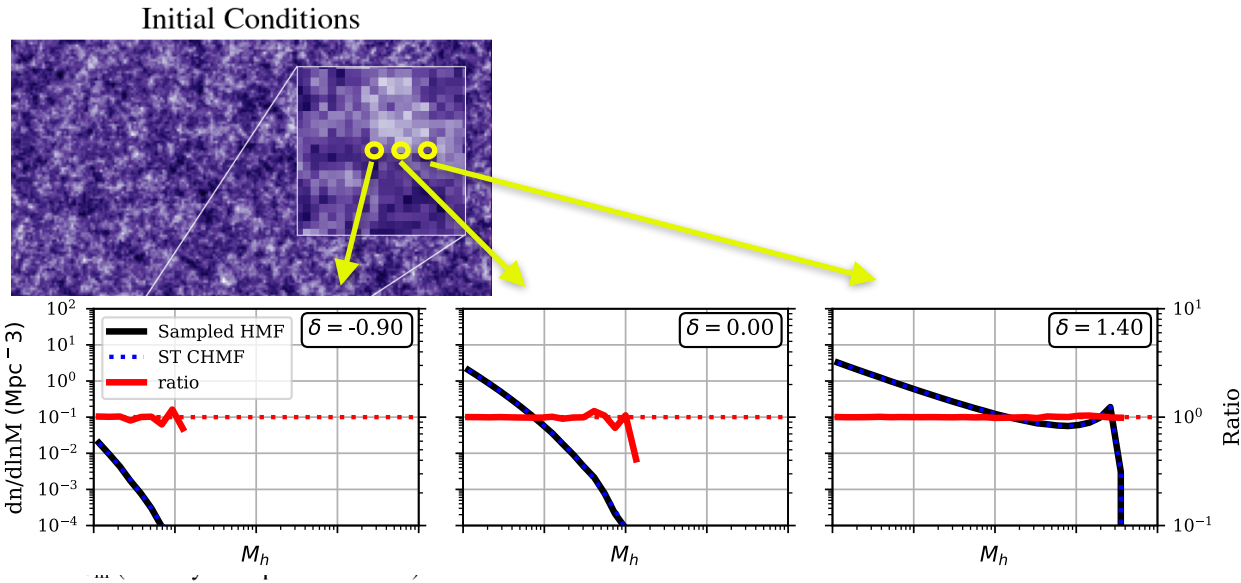
Scales > cell size

DexM excursion-set Lagrangian halo finder (AM & Furlanetto 2007)

Scales < cell size

New, coarse-time step merger trees (Davies, AM, Murray, in prep;
see also McQuinn+2007; Nasirudin+2020; Meriot & Semelin 2024)

2) Efficient halo finding



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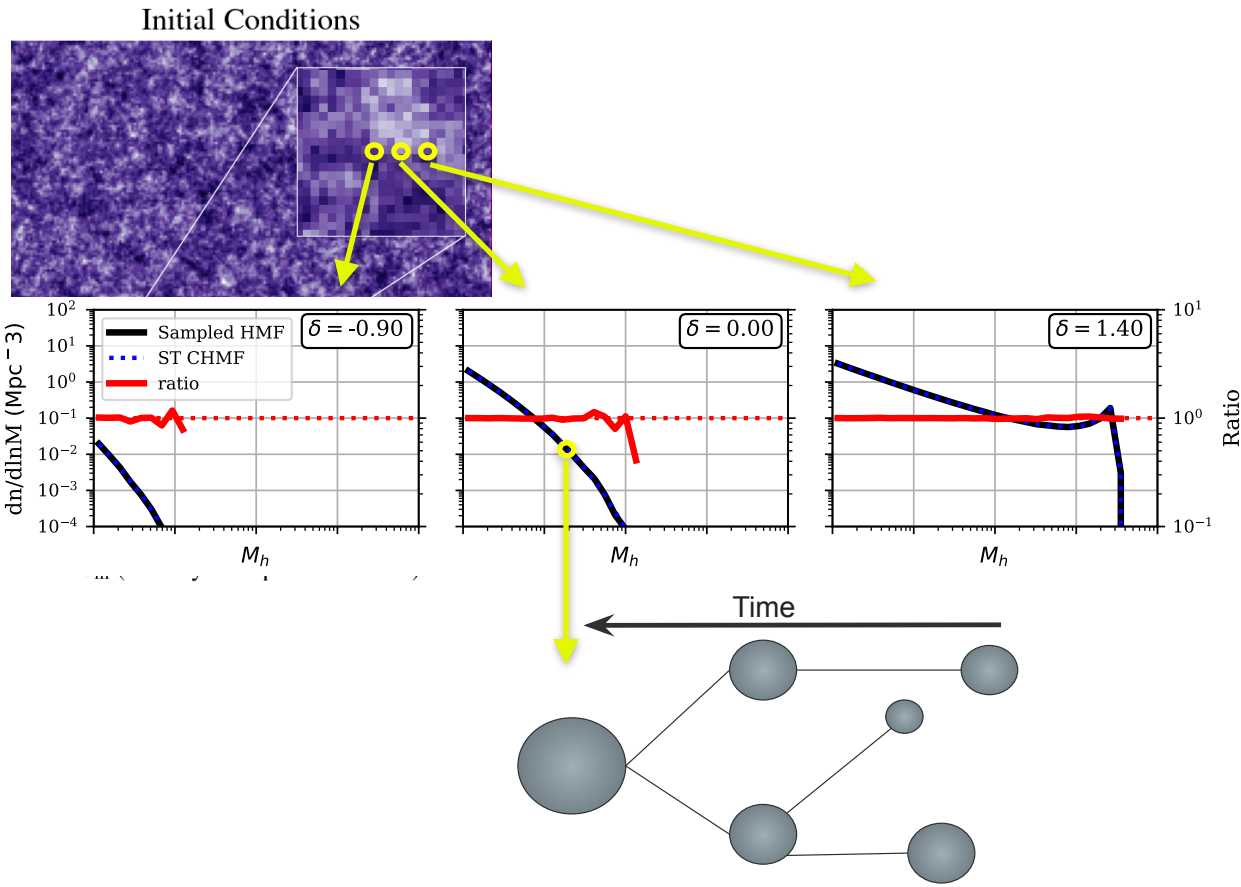

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Scales < cell size

DexM excursion-set Lagrangian halo finder (AM & Furlanetto 2007)

New, coarse-time step merger trees (Davies, AM, Murray, in prep)

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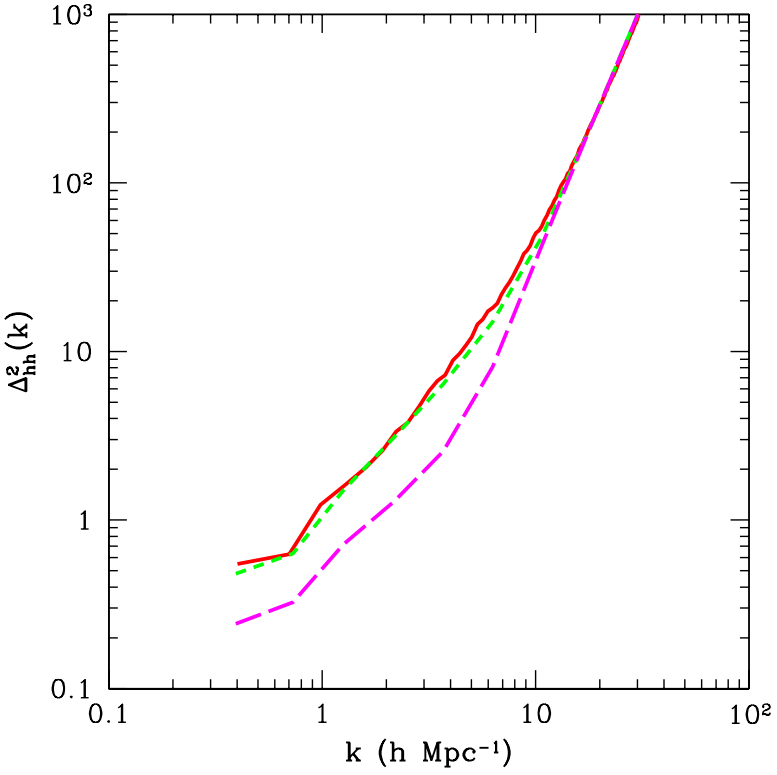
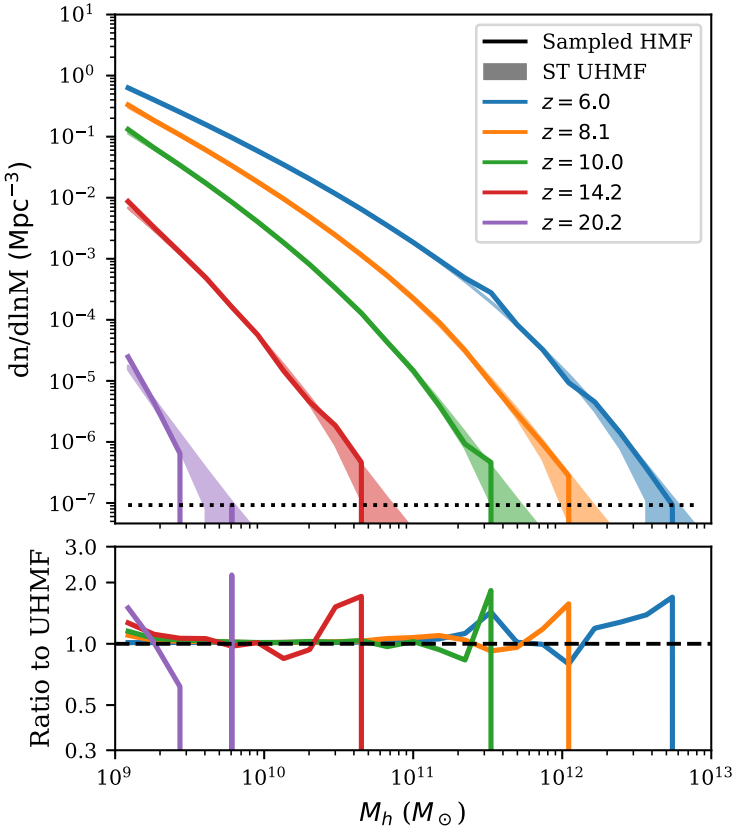
halo power spectra

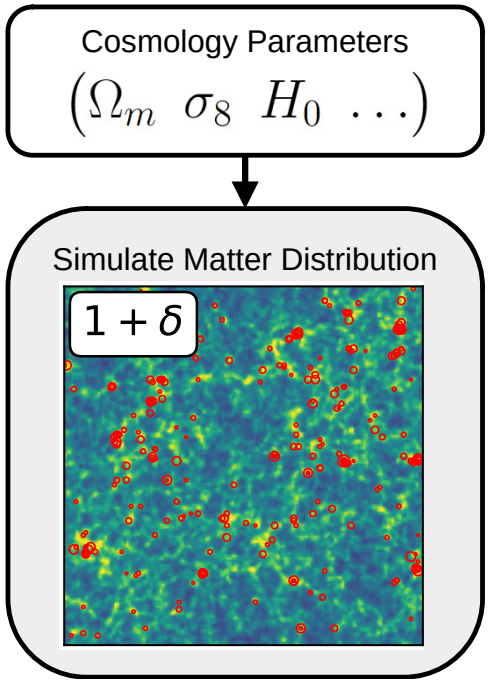


halo mass function



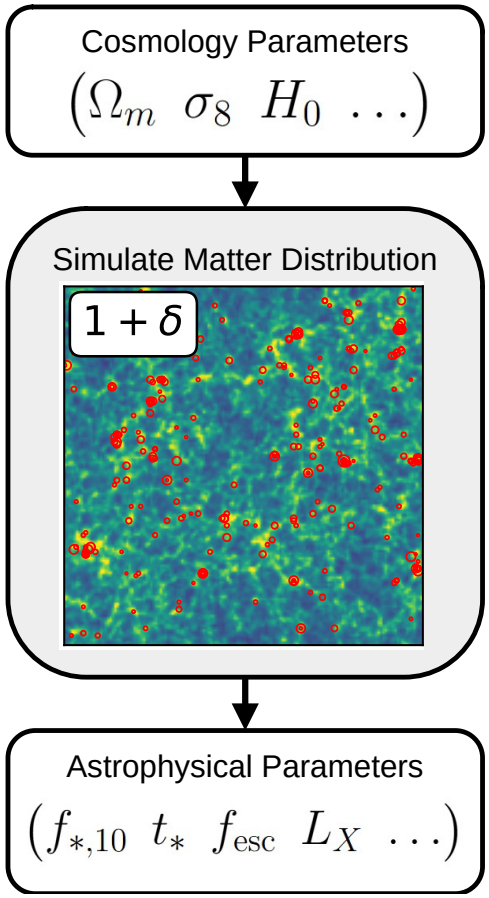
AM & Furlanetto 2007

Davies, AM, Murray, in prep



21cmFASTv4

1. Sample cosmology and create initial conditions
2. Create DM halo field, moving both DM and matter field w. 2LPT



21cmFASTv4

1. Sample cosmology and create initial conditions
2. Create DM halo field, moving both DM and matter field w. 2LPT
3. Sample astrophysics and populate halos with galaxies

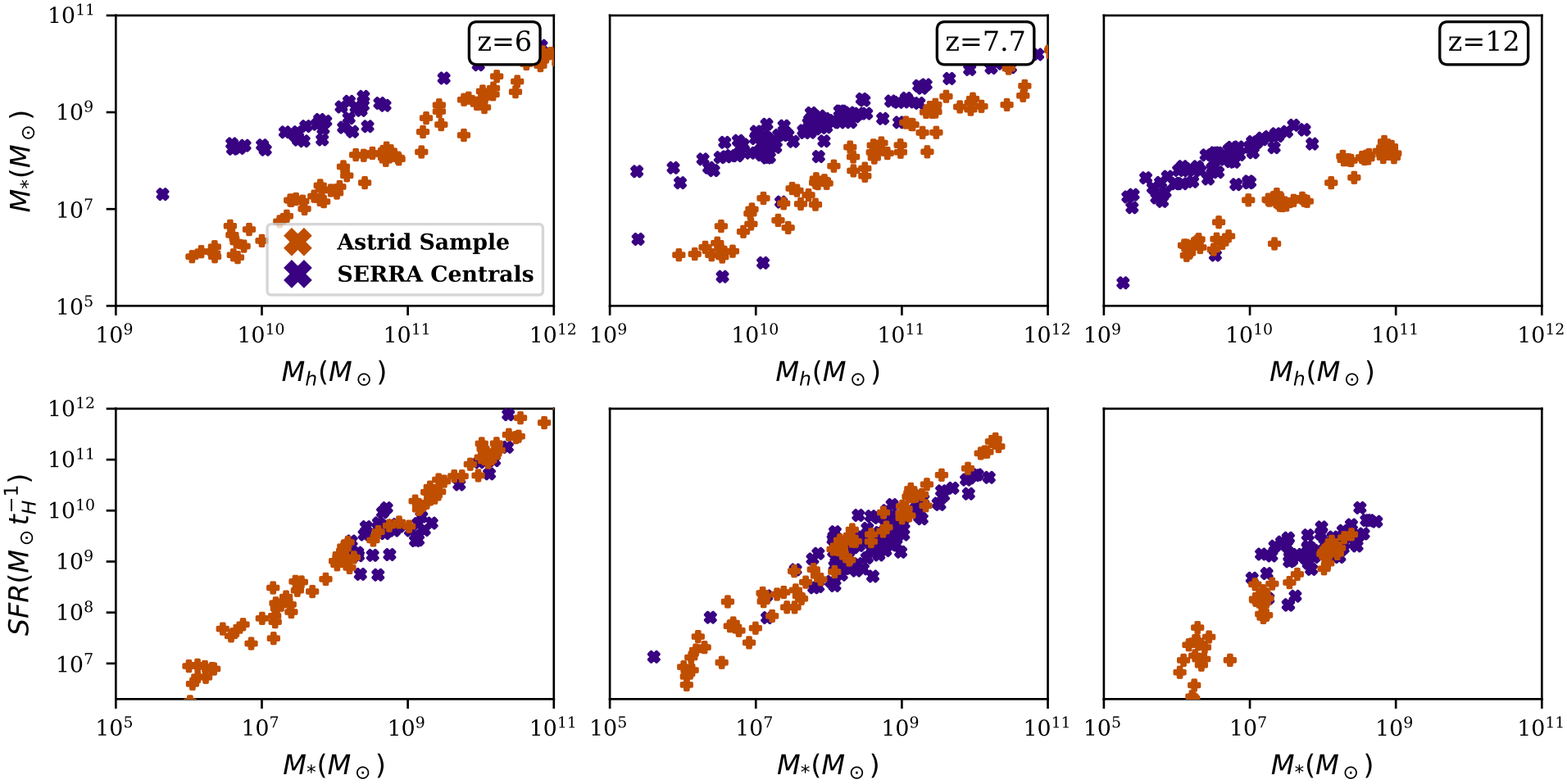
Relate galaxies to DM halos with semi-empirical scaling relations: a *"universal language"*

Galaxies sit in DM halos —>

We "know" how DM halos are spatially-distributed —>

Semi-empirical relations tying emissivities to DM halos prove a sort of "universal language"

Relate galaxies to DM halos with semi-empirical scaling relations: a *"universal language"*



SERRA; Pallottini+2022

ASTRID; Ni+2022

Davies, AM+ in prep

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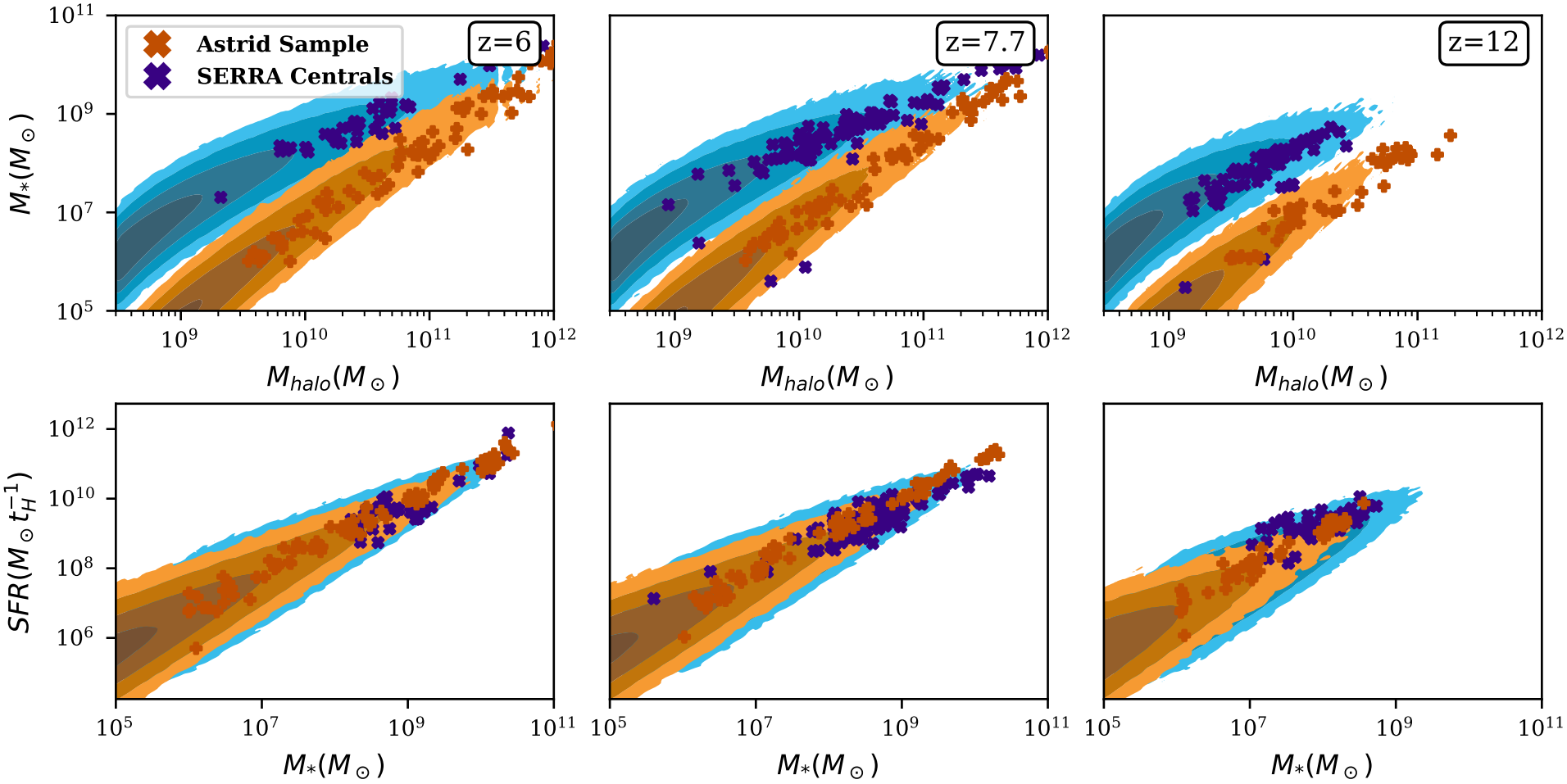
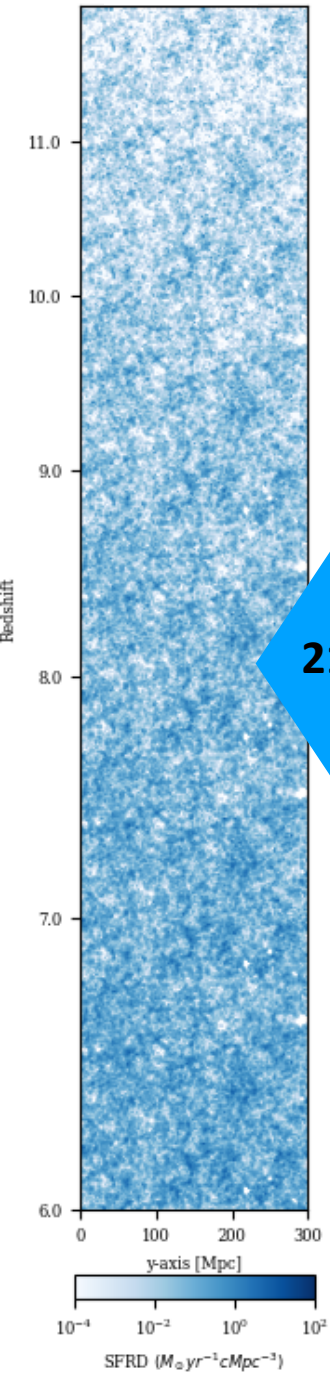


Davies, AM+ in prep

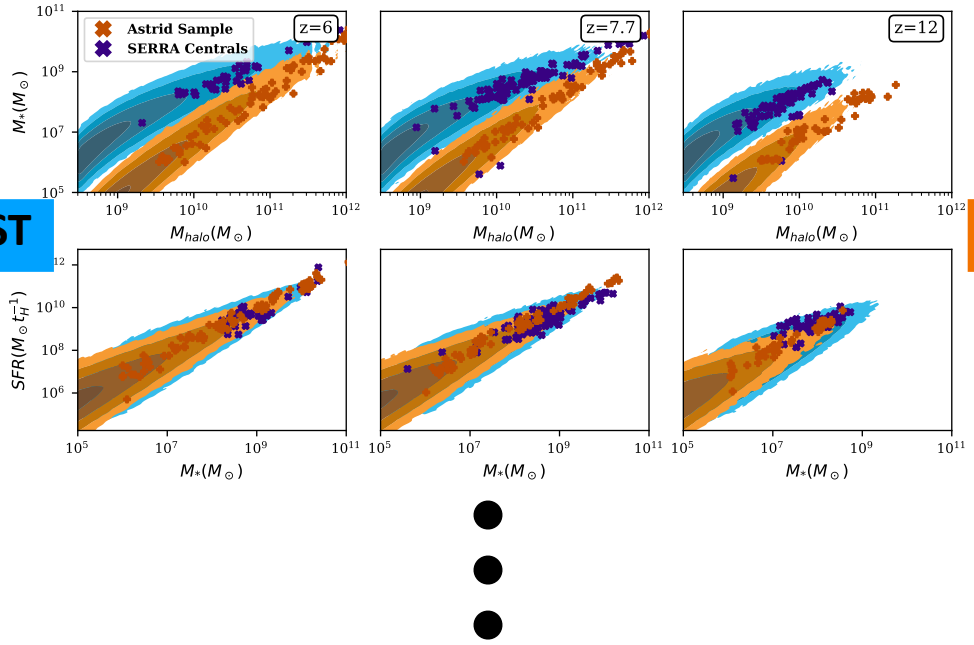
SFRD



$\theta^1_{\rm gal}$

21cmFAST

Galaxy properties

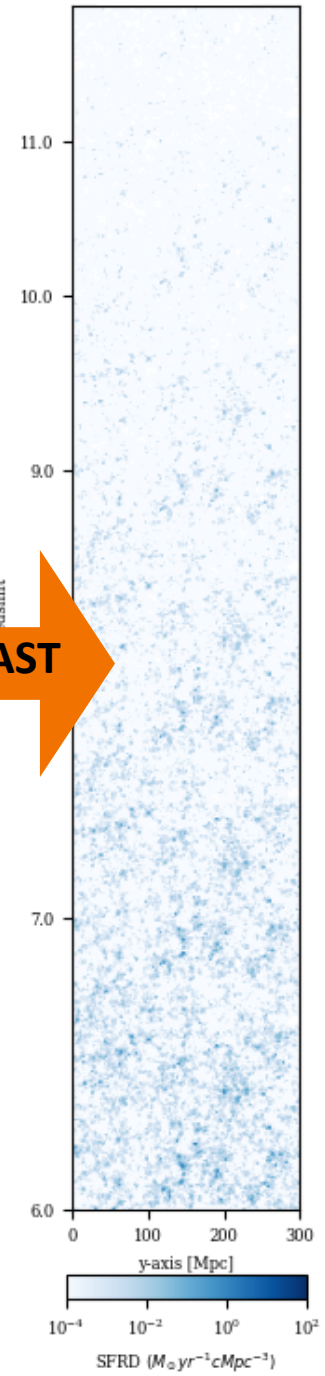


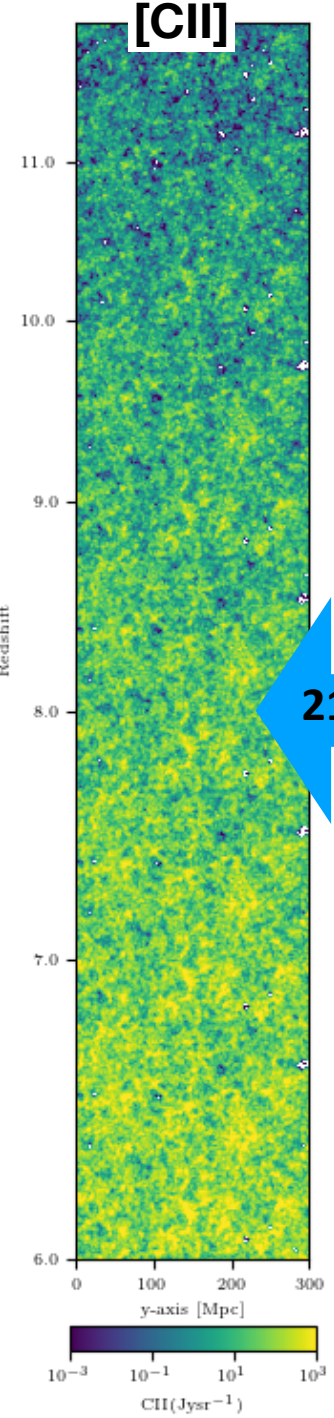
Computed with new
21cmFast v4
(Davies, AM+ in prep)

$\theta^2_{\rm gal}$

21cmFAST

SFRD





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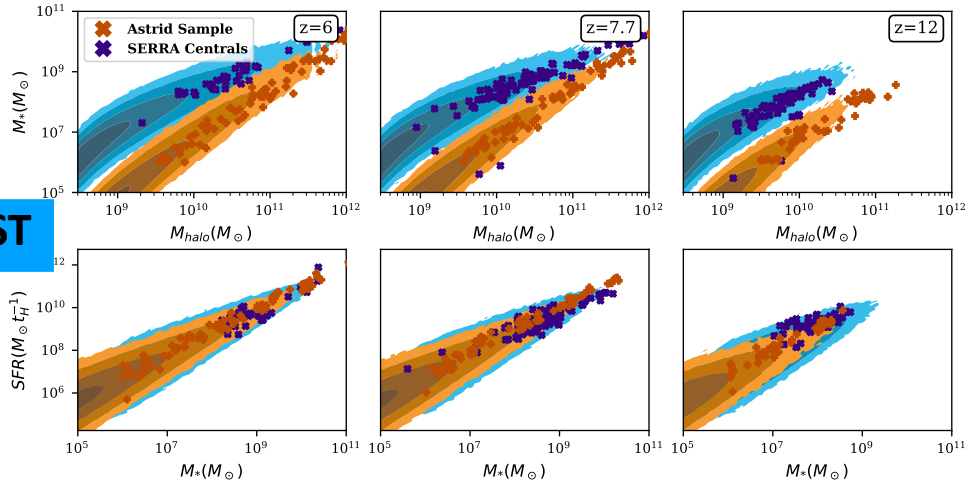
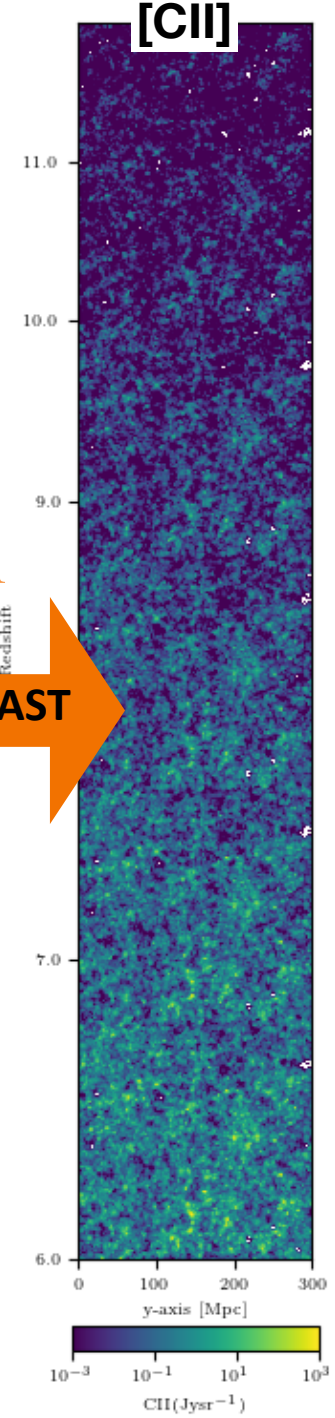


$\theta^2_{\rm gal}$

21cmFAST



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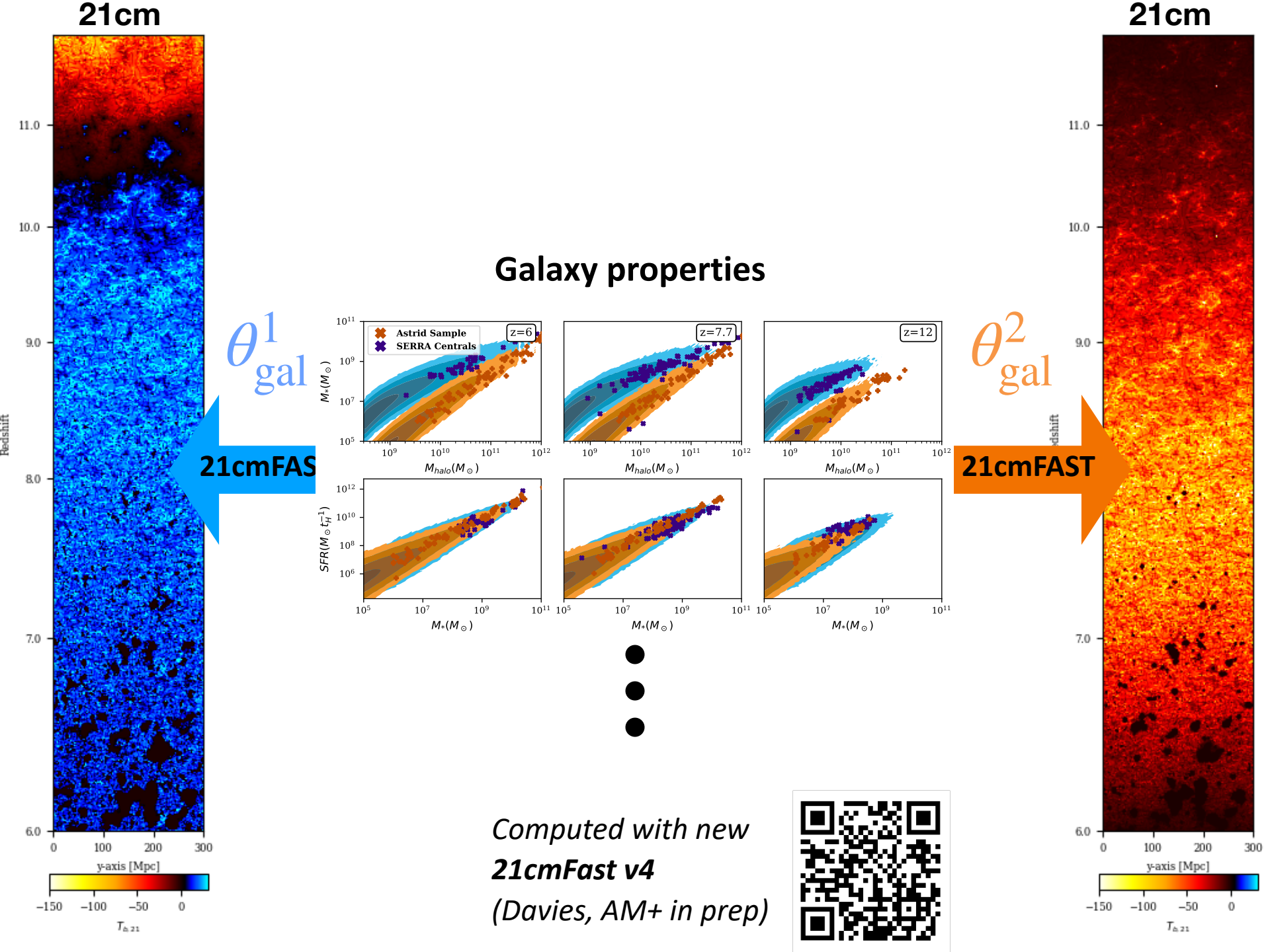
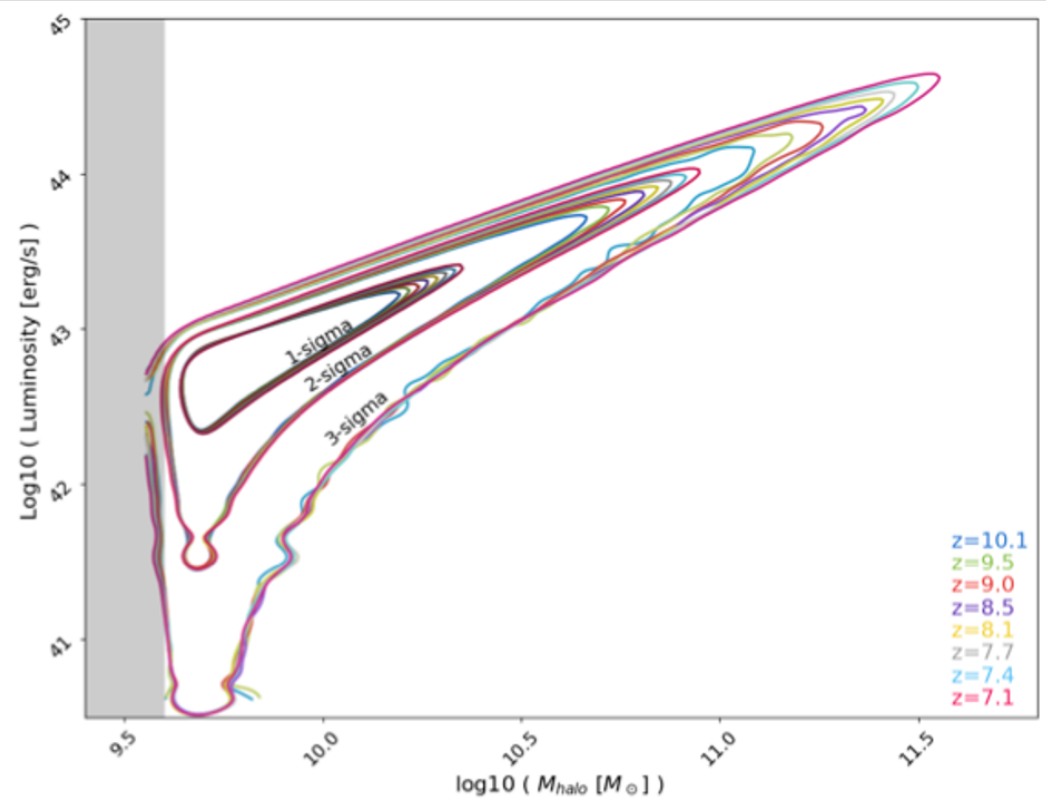
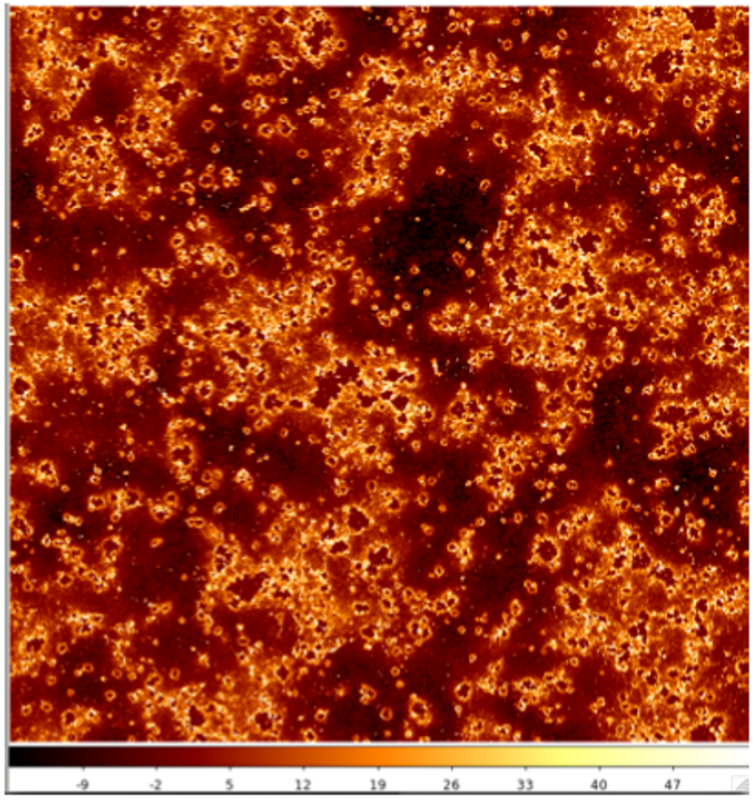

21cm
21cm
Galaxy properties
$\theta^1_{\rm gal}$
$\theta^2_{\rm gal}$
21cmFAS
21cmFAST
Astrid Sample
SERRA Centrals
z=6
z=7.7
z=12
$M_*(M_\odot)$
$M_{halo}(M_\odot)$
$SFR(M_\odot\, t_H^{-1})$
Redshift
y-axis [Mpc]
$T_{b\,21}$
Computed with new
21cmFast v4
(Davies, AM+ in prep)

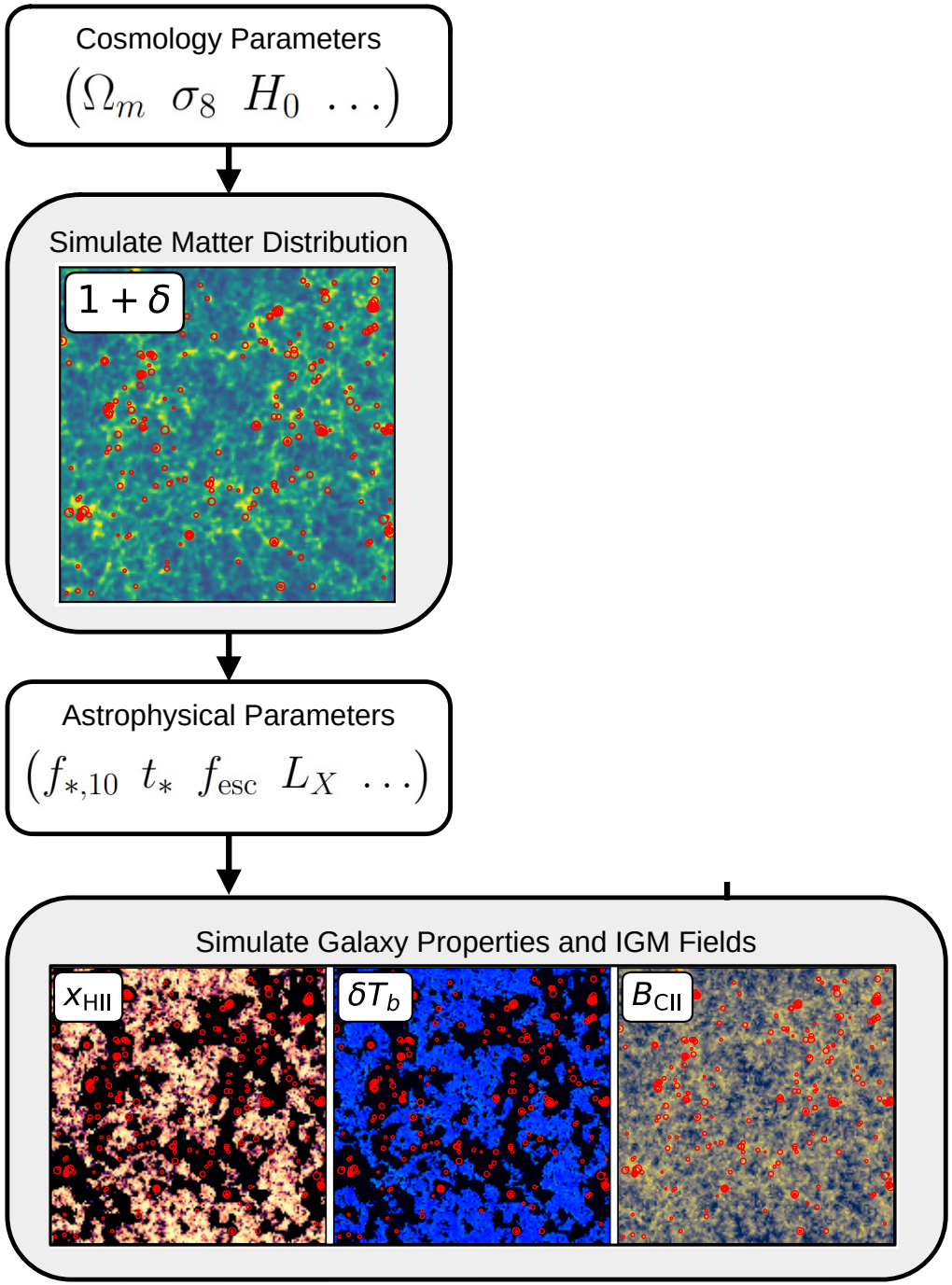
Relate galaxies to DM halos with semi-empirical scaling relations: a *"universal language"*



p(L_{ion} ,M_h | z) from LICORICE (Semelin+)



21cm field

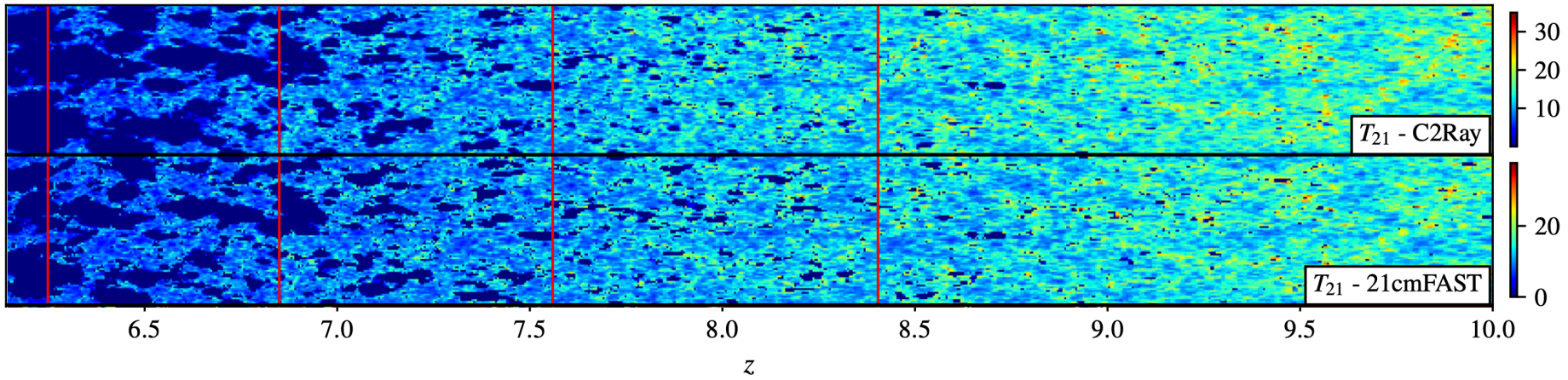


21cmFASTv4

1. Sample cosmology and create initial conditions
2. Create DM halo field, moving both DM and matter field w. 2LPT
3. Sample astrophysics and populate halos with galaxies
4. Using approximate RT, compute corresponding IGM evolution

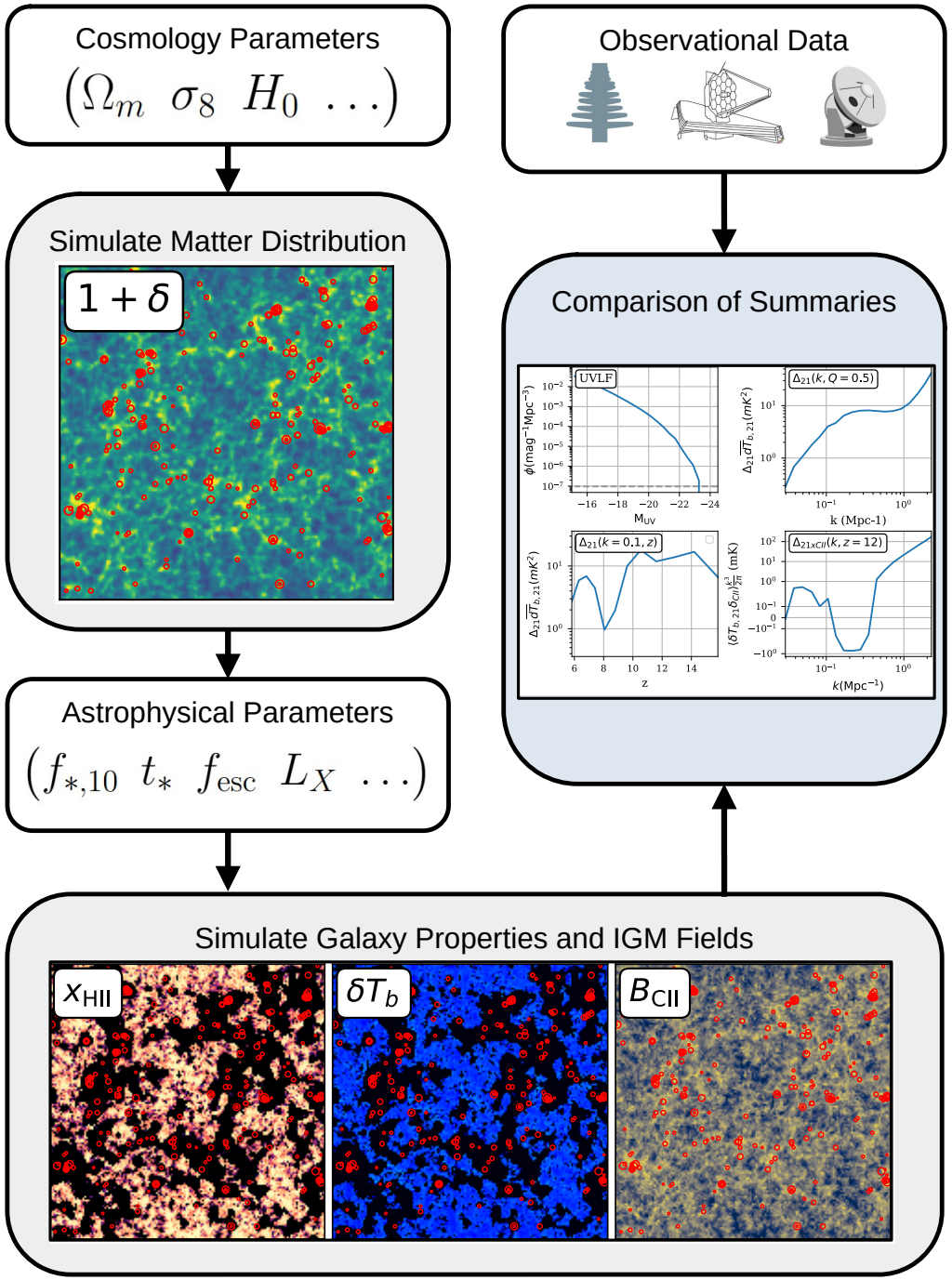
4) Using approximate RT, compute corresponding IGM evolution

Soon also the ability to chose your RT algorithm



Bianco+, in prep

21cmFASTv4



1. Sample cosmology and create initial conditions
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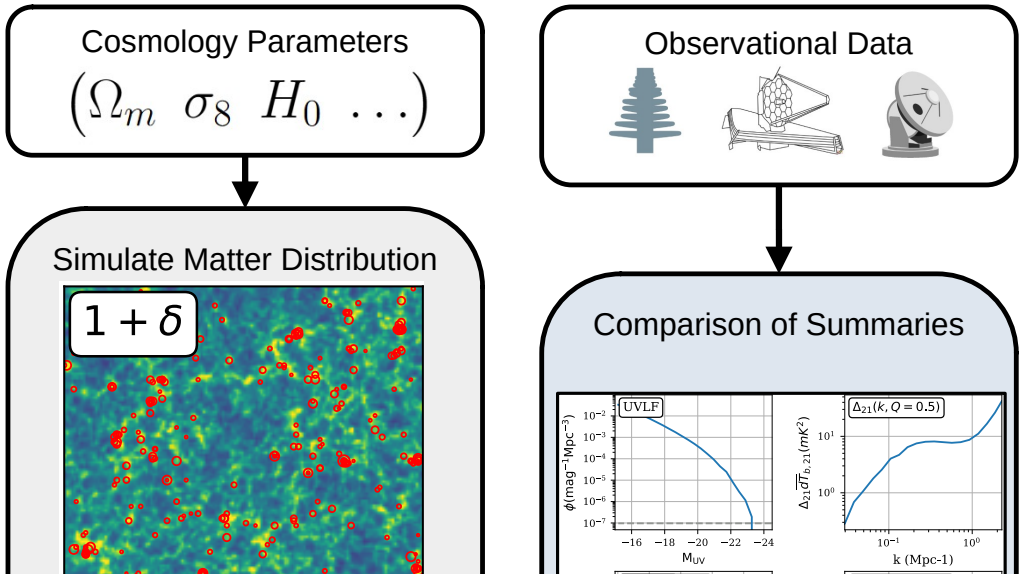
5. Compute summaries and compare to observations

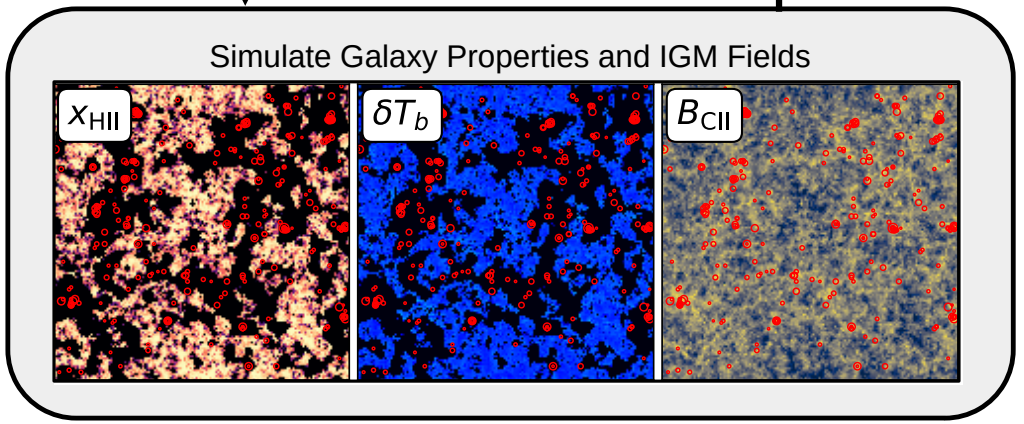


21cmFASTv4

1. Sample cosmology and create initial conditions
2. Create DM halo field, moving both DM and matter field w. 2LPT
3. Sample astrophysics and populate halos with galaxies
4. Using approximate RT, compute corresponding IGM evolution
5. Compute summaries and compare to observations
6. Repeat sampling and map out posterior

~2 core hours

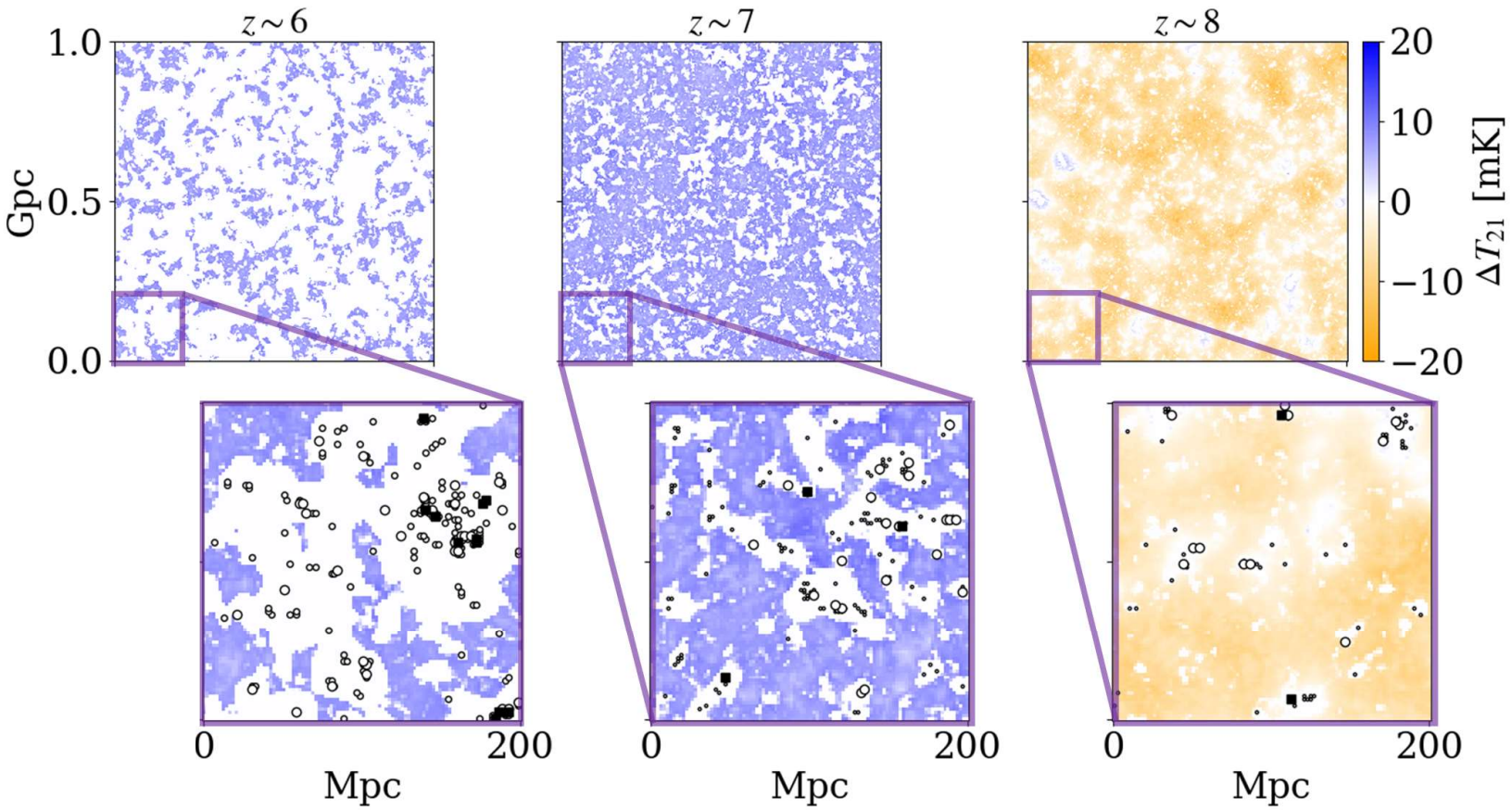
repeat 10^4 - 10^6 times



Some usage cases….

Which galaxy surveys are optimal to cross-correlate with 21cm?

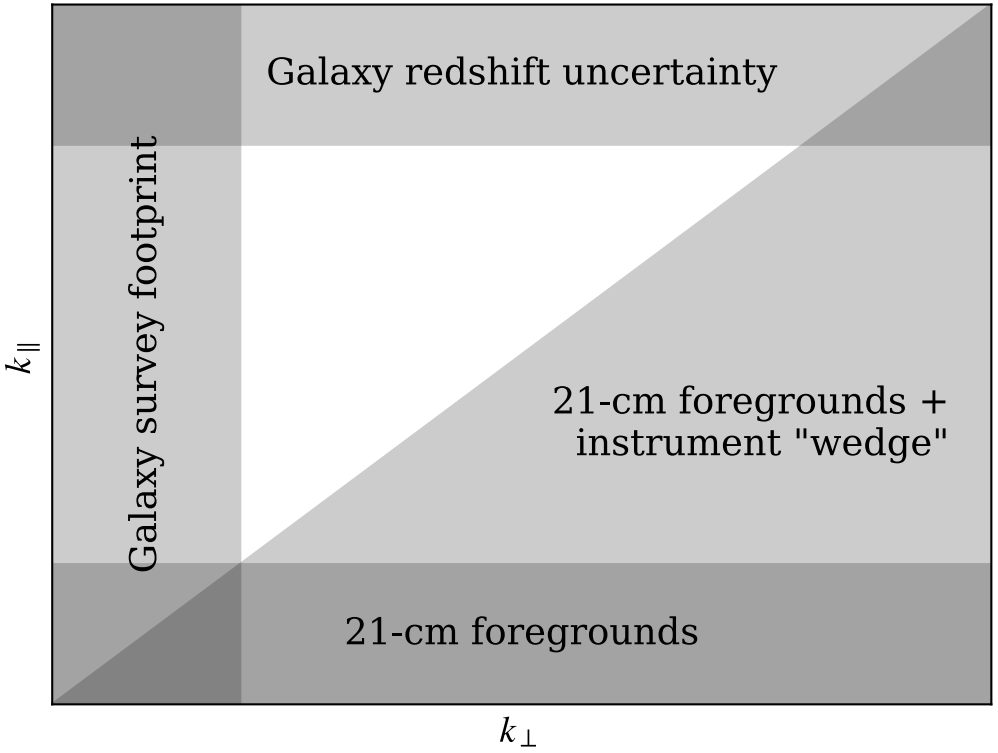
Gagnon-Hartman, Davies, AM (2025)



Which galaxy surveys are optimal to cross-correlate with 21cm?

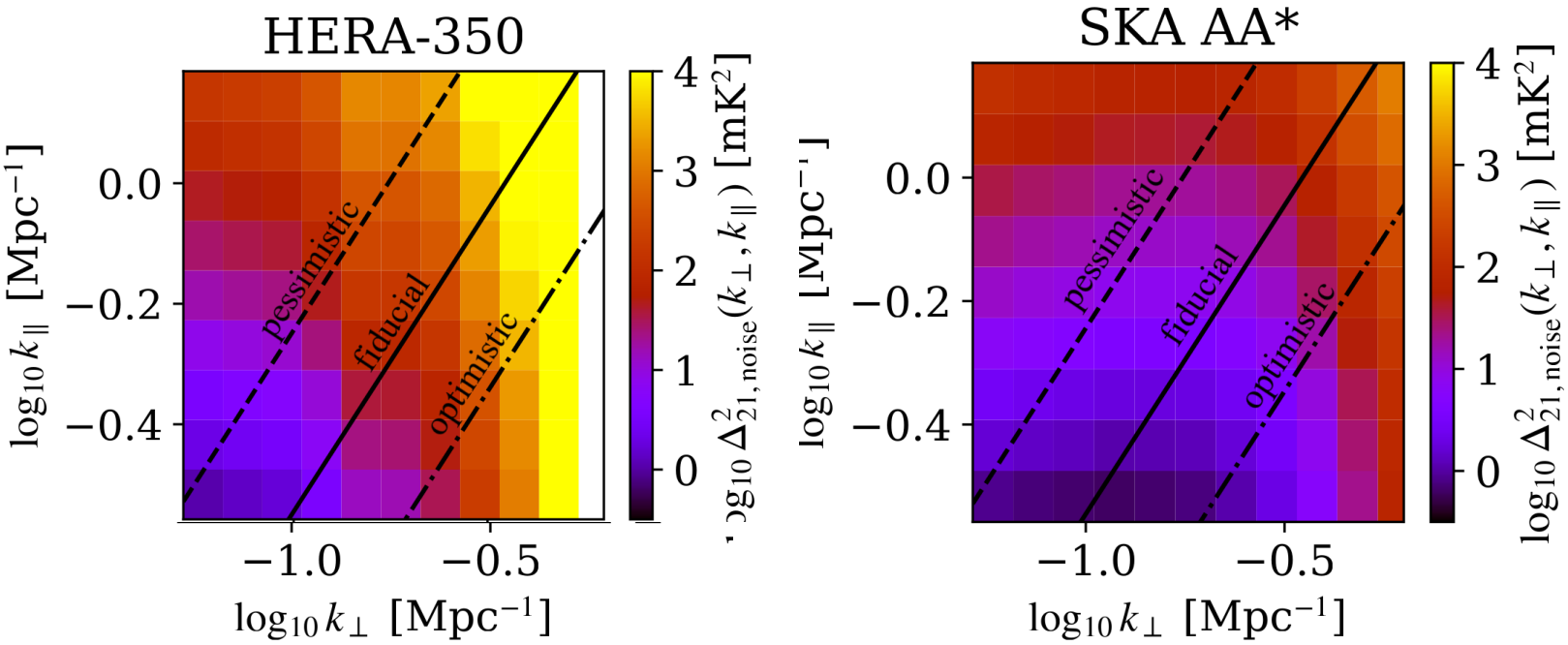
Varied:

- Galaxy survey depth
- Galaxy survey footprint
- Line targeted
- Instrument (galaxy and 21cm)
- 21cm foreground contamination



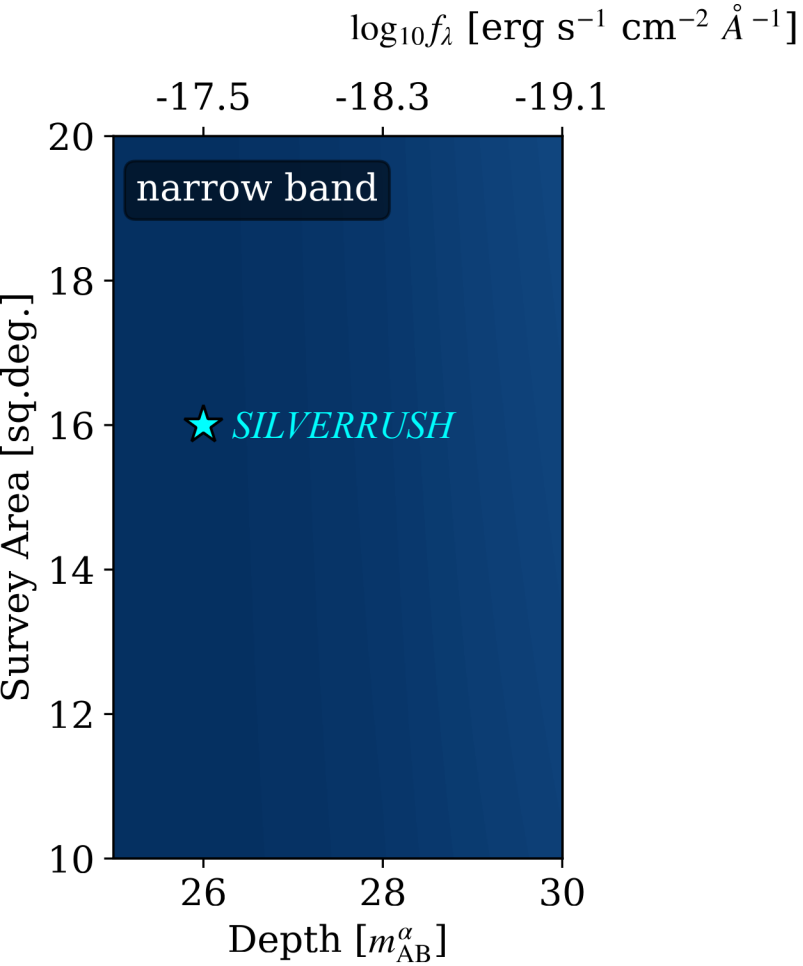
Interferometer	Detection Type	Line Targeted	δz	Footprint Range	Depth Range (m_{AB})
SKA-low	Narrow-band dropout	Ly-α	$5 \cdot 10^{-2}$	10 – 20 sq. deg.	25.5 – 30
SKA-low	Grism $z > 7.2$	Ly-α	10^{-2}	0 – 25 sq. deg.	25 – 27
SKA-low	Spectroscopy	Ly-α	10^{-3}	0 – 4 sq. deg.	24 – 27
HERA	Narrow-band dropout	Ly-α	$5 \cdot 10^{-2}$	10 – 20 sq. deg.	25.5 – 30
HERA	Grism $z > 7.2$	Ly-α	10^{-2}	0 – 120 sq. deg.	25 – 27
HERA	Spectroscopy	Ly-α	10^{-3}	0 – 4 sq. deg.	24 – 27
SKA-low	Grism	Hα/[OIII]	10^{-2}	0 – 350 sq.arcmin.	27 – 30

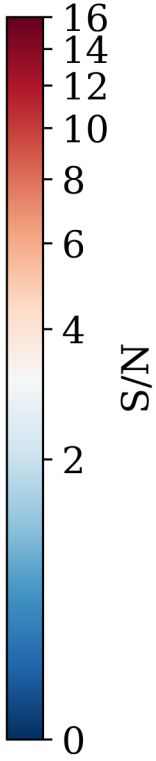
Interferometer noise



Gagnon-Hartman, Davies, AM (2025)

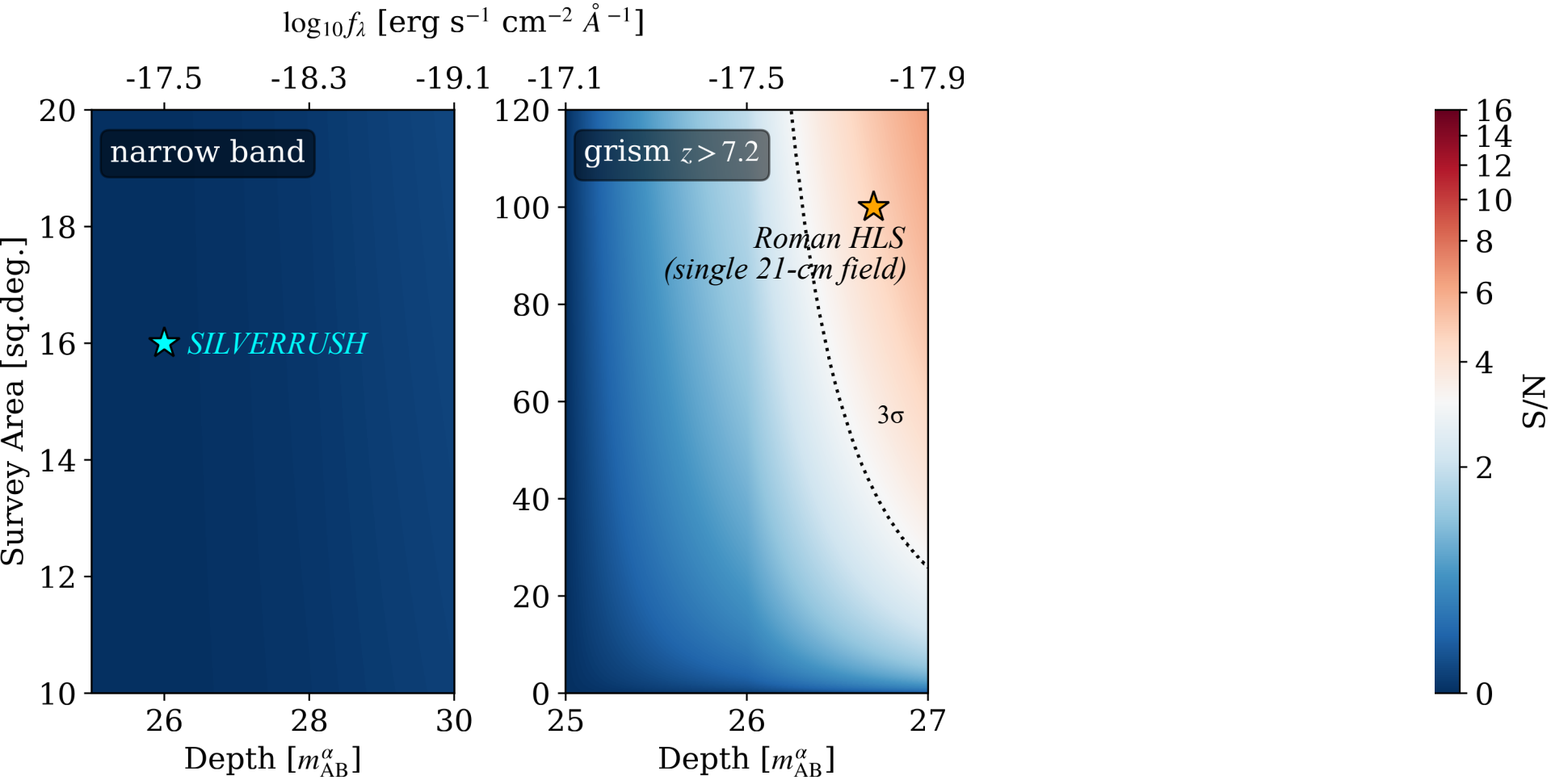
HERA 350 combined with…





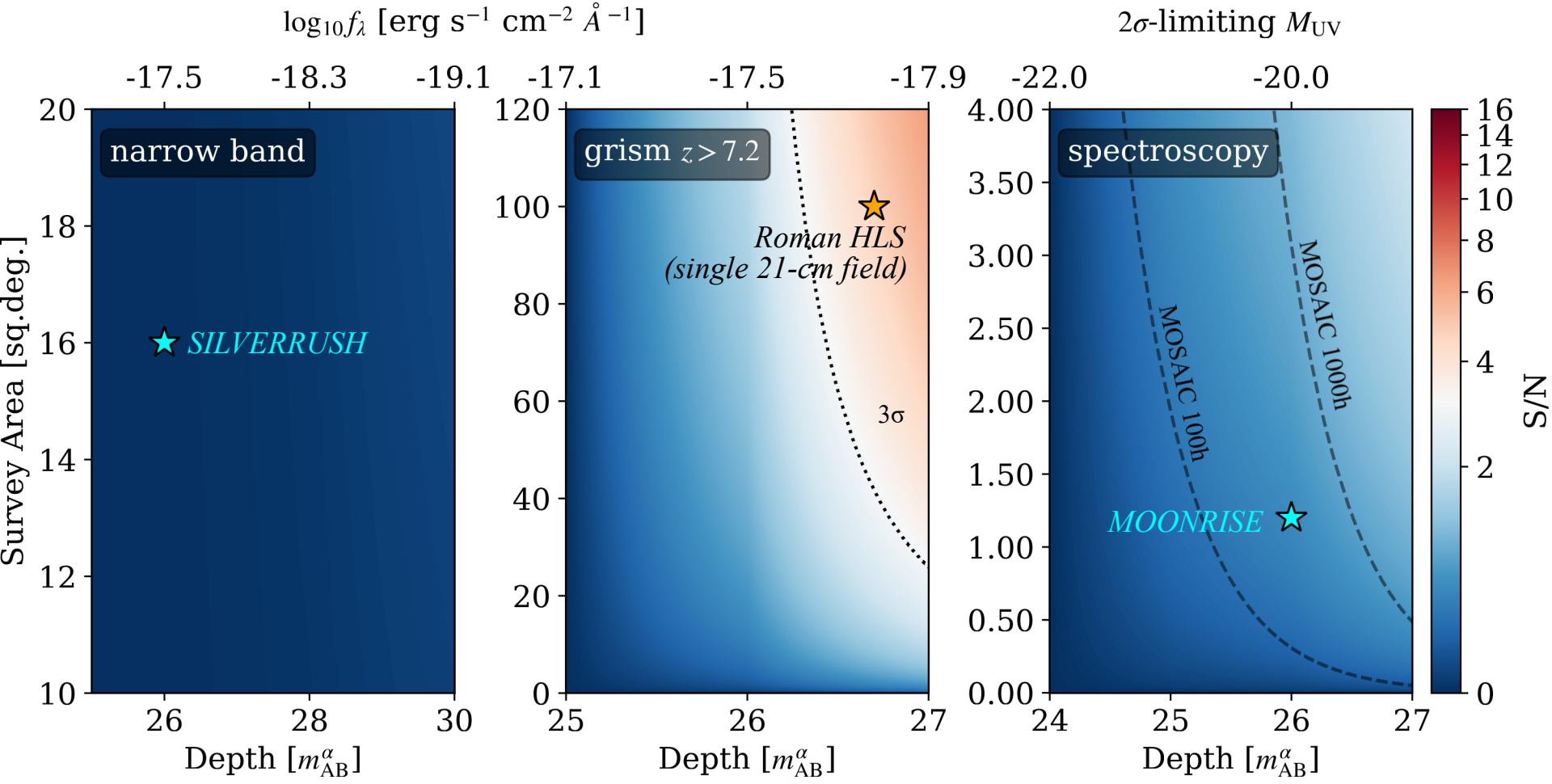
Gagnon-Hartman, Davies, AM (2025)

HERA 350 combined with…



Gagnon-Hartman, Davies, AM (2025)

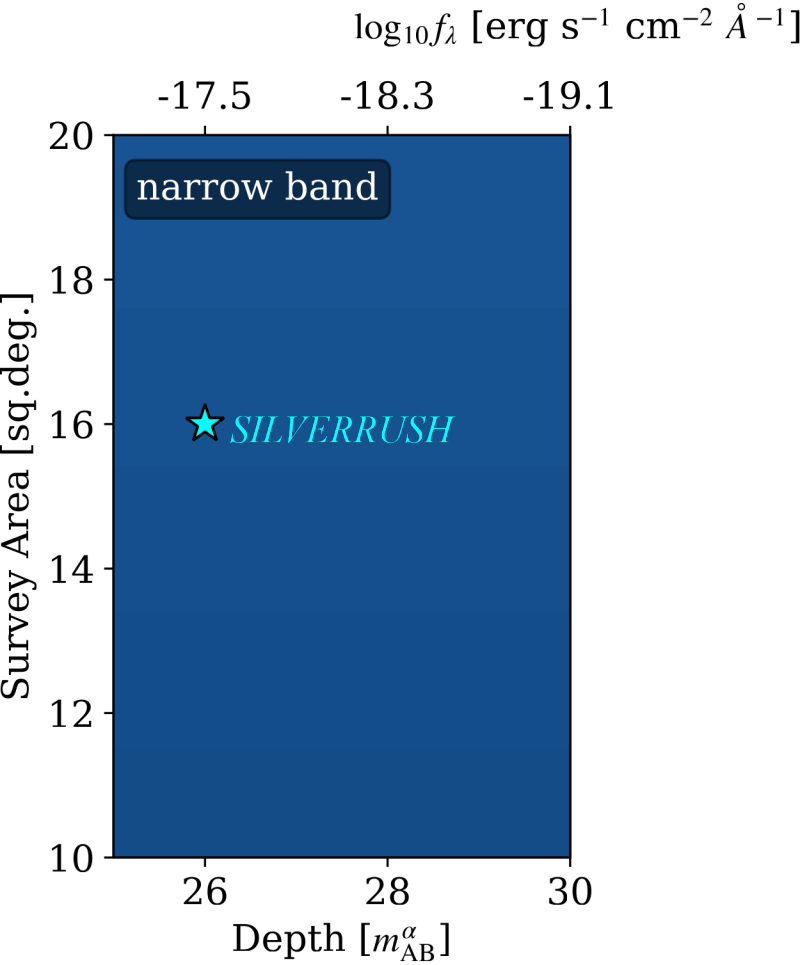
HERA 350 combined with…

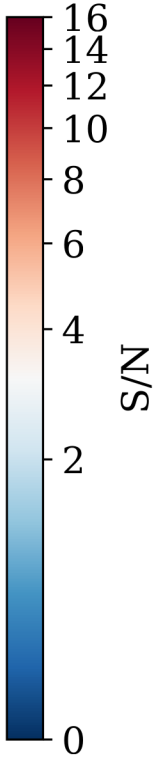


Only hope is HERA - wide field grism (e.g. ROMAN; c.f. La Plante+2023)

Gagnon-Hartman, Davies, AM (2025)

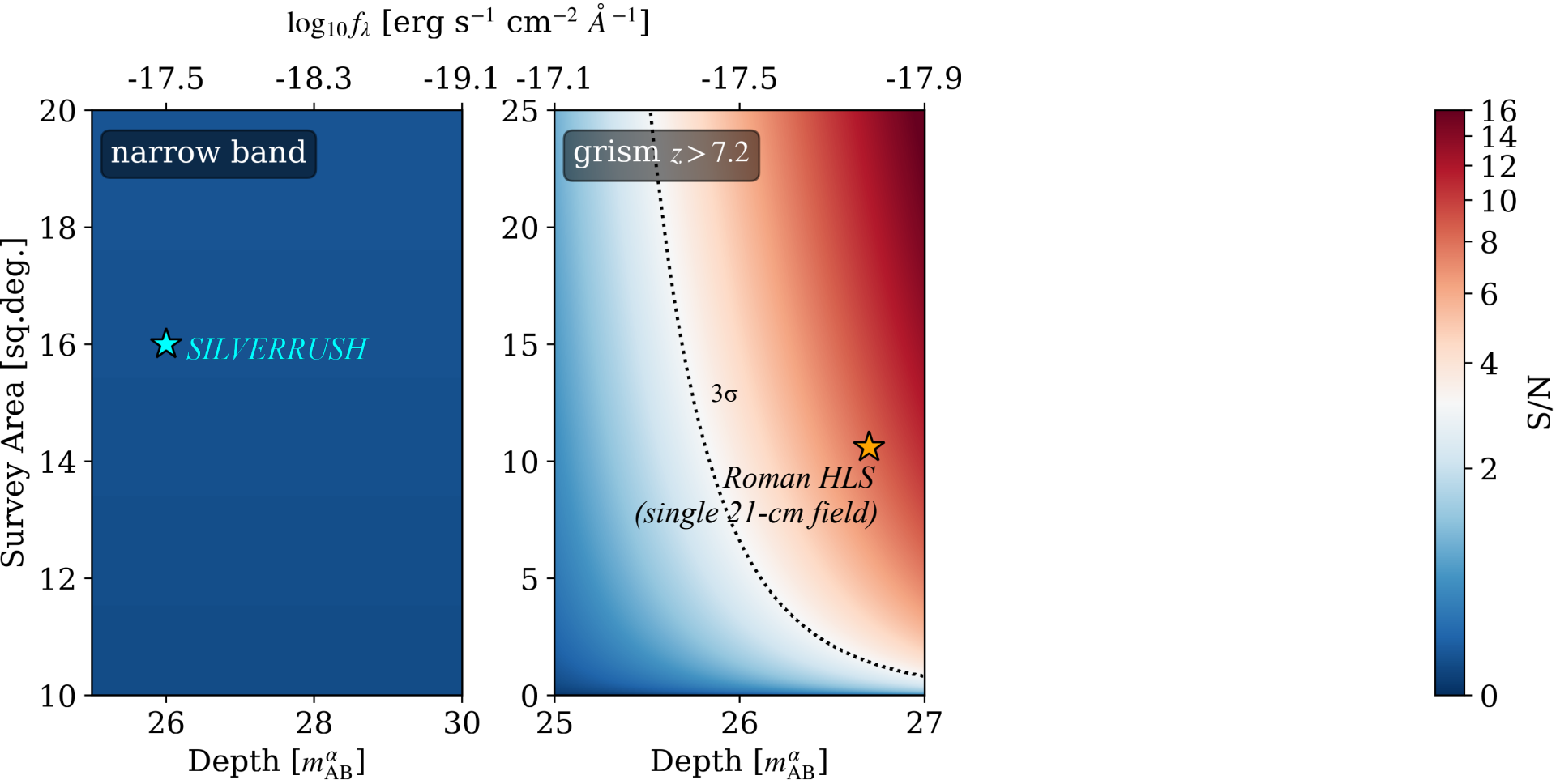
SKA AA* combined with…





Gagnon-Hartman, Davies, AM (2025)

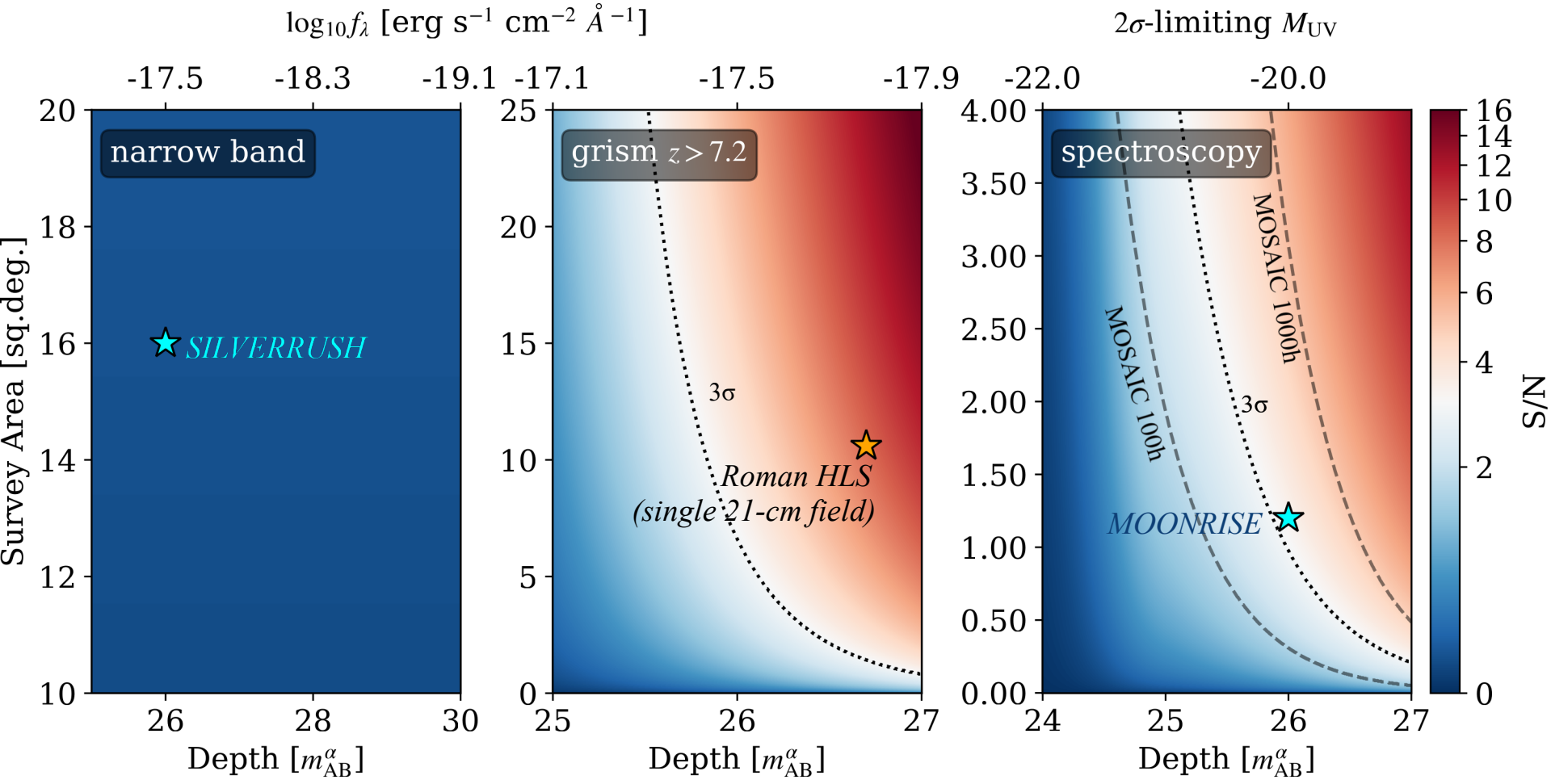
SKA AA* combined with…



SKA can have high S/N detection with
wide-field grism

Gagnon-Hartman, Davies, AM (2025)

SKA AA* combined with…

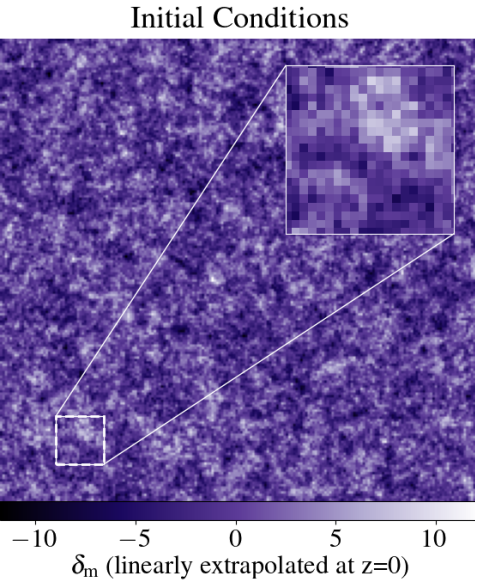


SKA can have high S/N detection with EITHER
wide-field grism OR **deep, narrow-field spectroscopy**

Gagnon-Hartman, Davies, AM (2025)

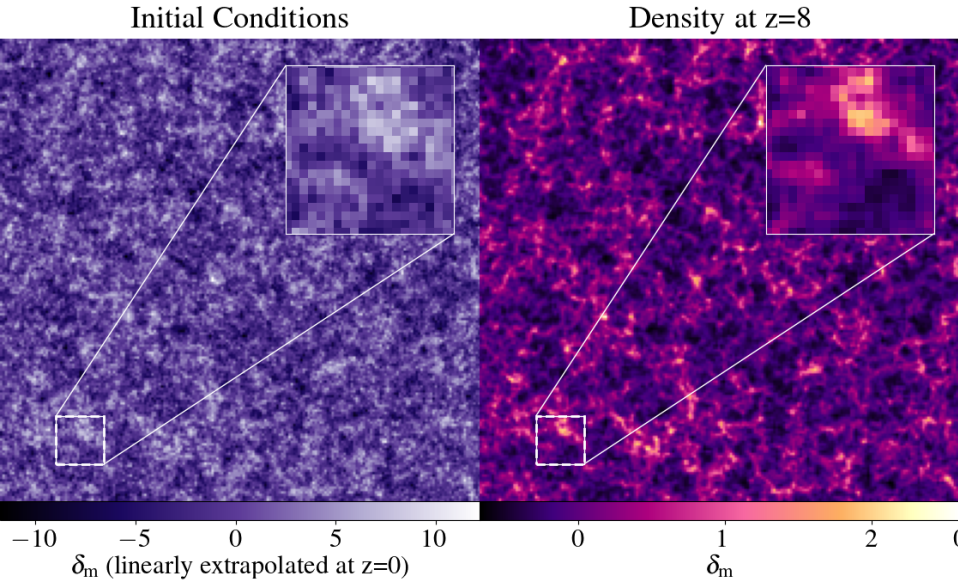
Inferring initial conditions from galaxy and 21cm surveys

Inferring initial conditions from galaxy and 21cm surveys



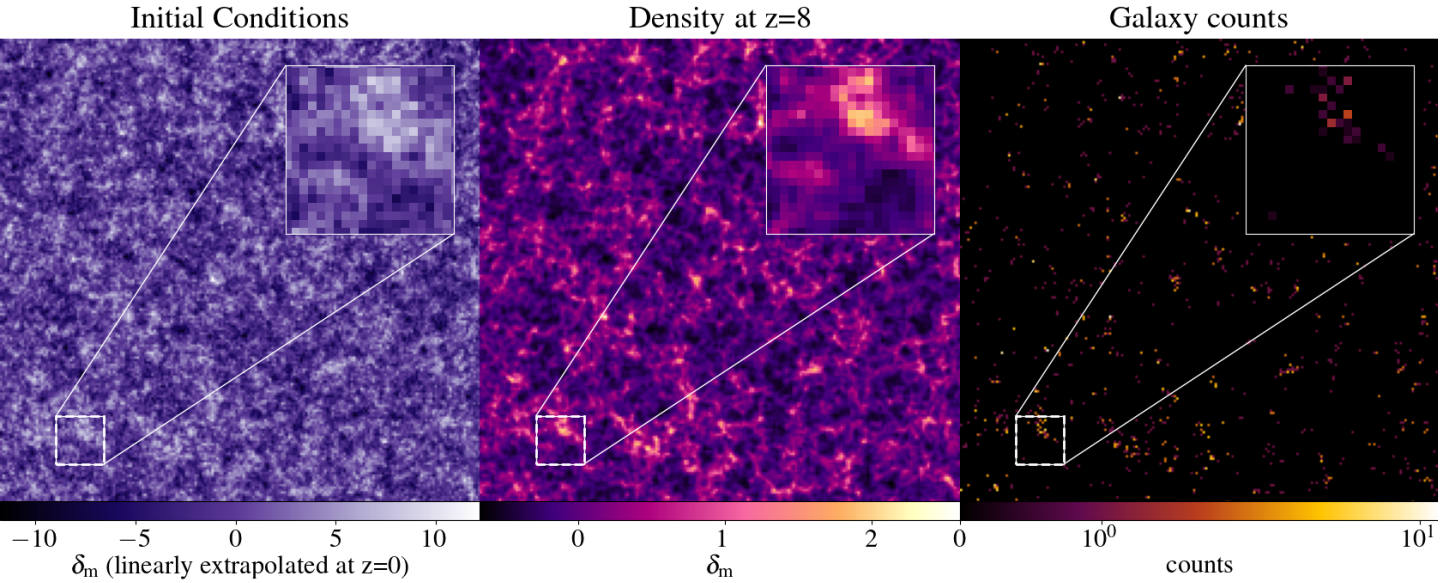
Triantafyllou, AM+ in prep

Inferring initial conditions from galaxy and 21cm surveys



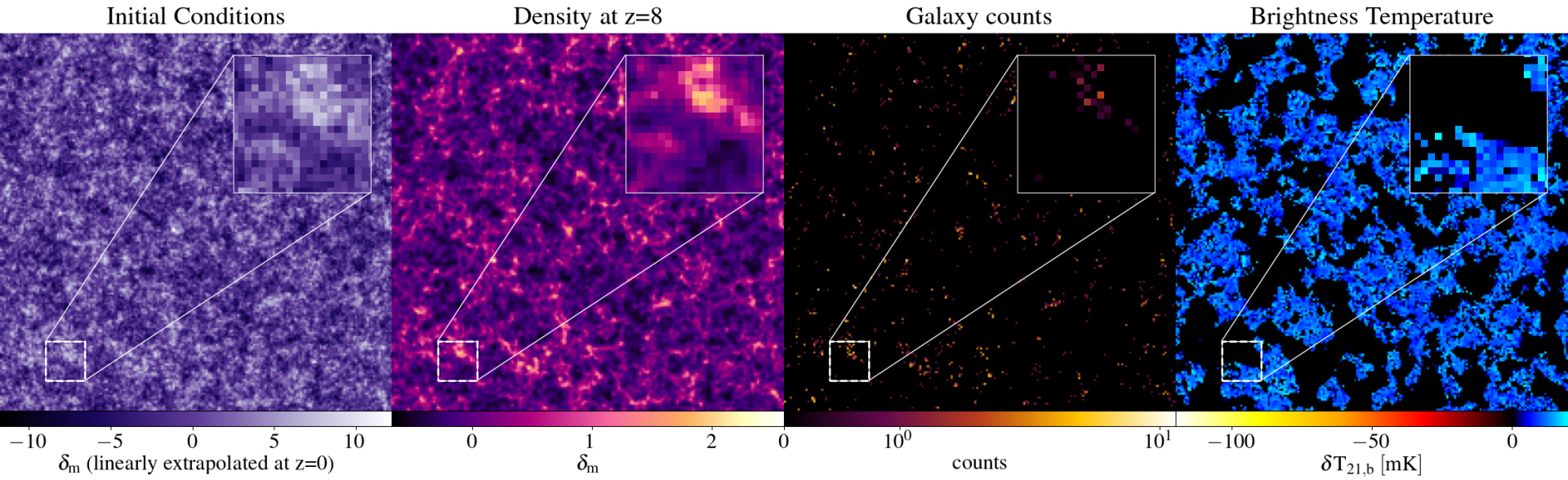
Triantafyllou, AM+ in prep

Inferring initial conditions from galaxy and 21cm surveys



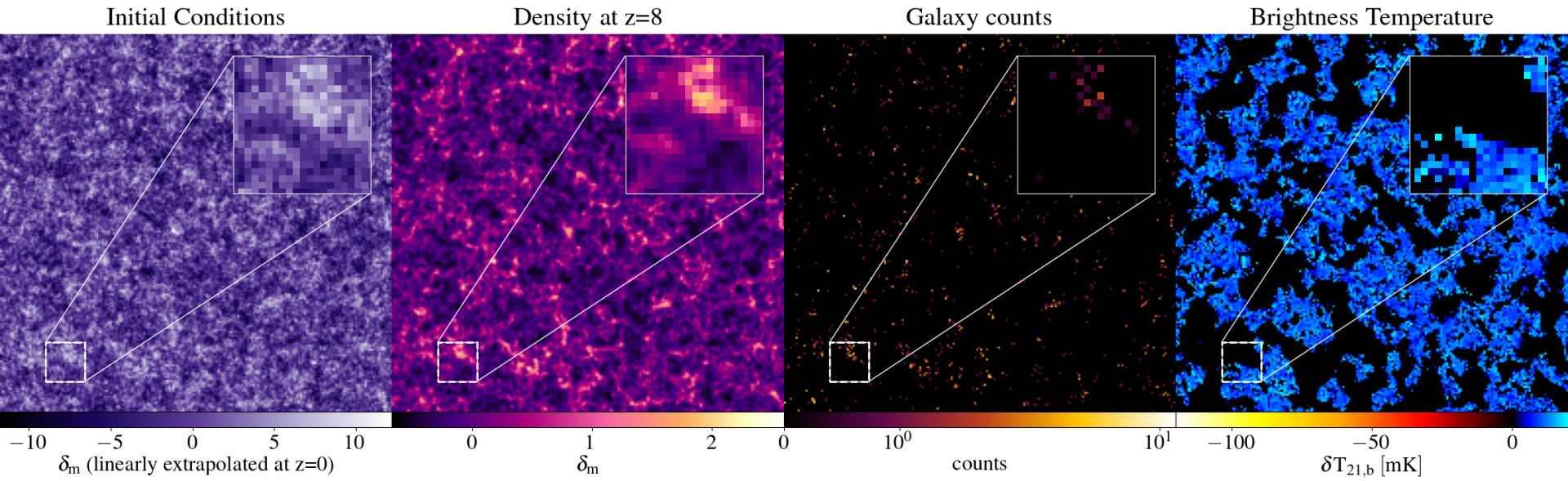
Triantafyllou, AM+ in prep

Inferring initial conditions from galaxy and 21cm surveys



Triantafyllou, AM+ in prep

Inferring initial conditions from galaxy and 21cm surveys

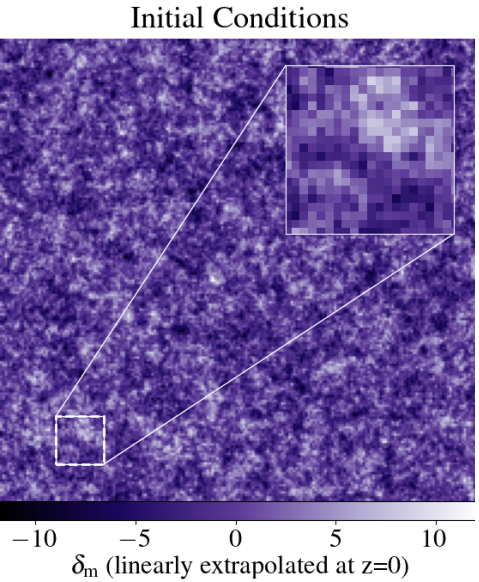


Cosmology **Astrophysics**

Triantafyllou, AM+ in prep

Inferring initial conditions from galaxy and 21cm surveys

Triantafyllou, AM+ in prep



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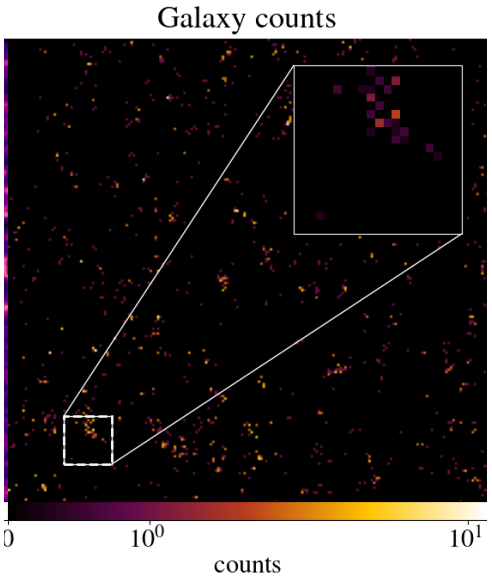
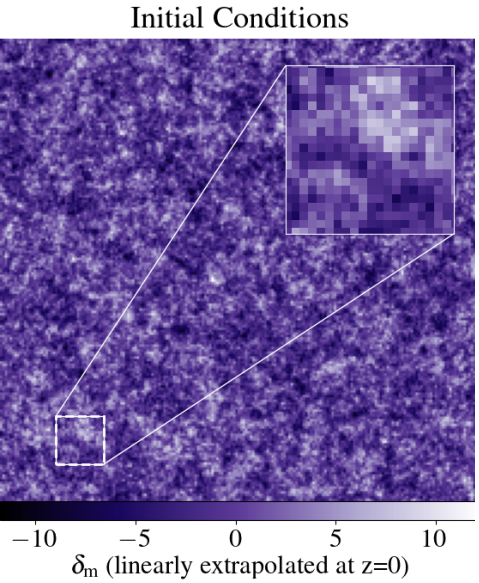


Learn cosmology as well as the history of observed galaxies and their environment (e.g. unseen faint neighbors)

Inferring initial conditions from galaxy and 21cm surveys

Triantafyllou, AM+ in prep



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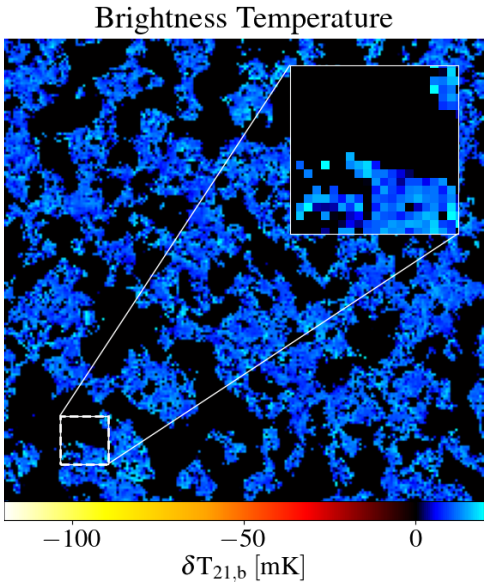
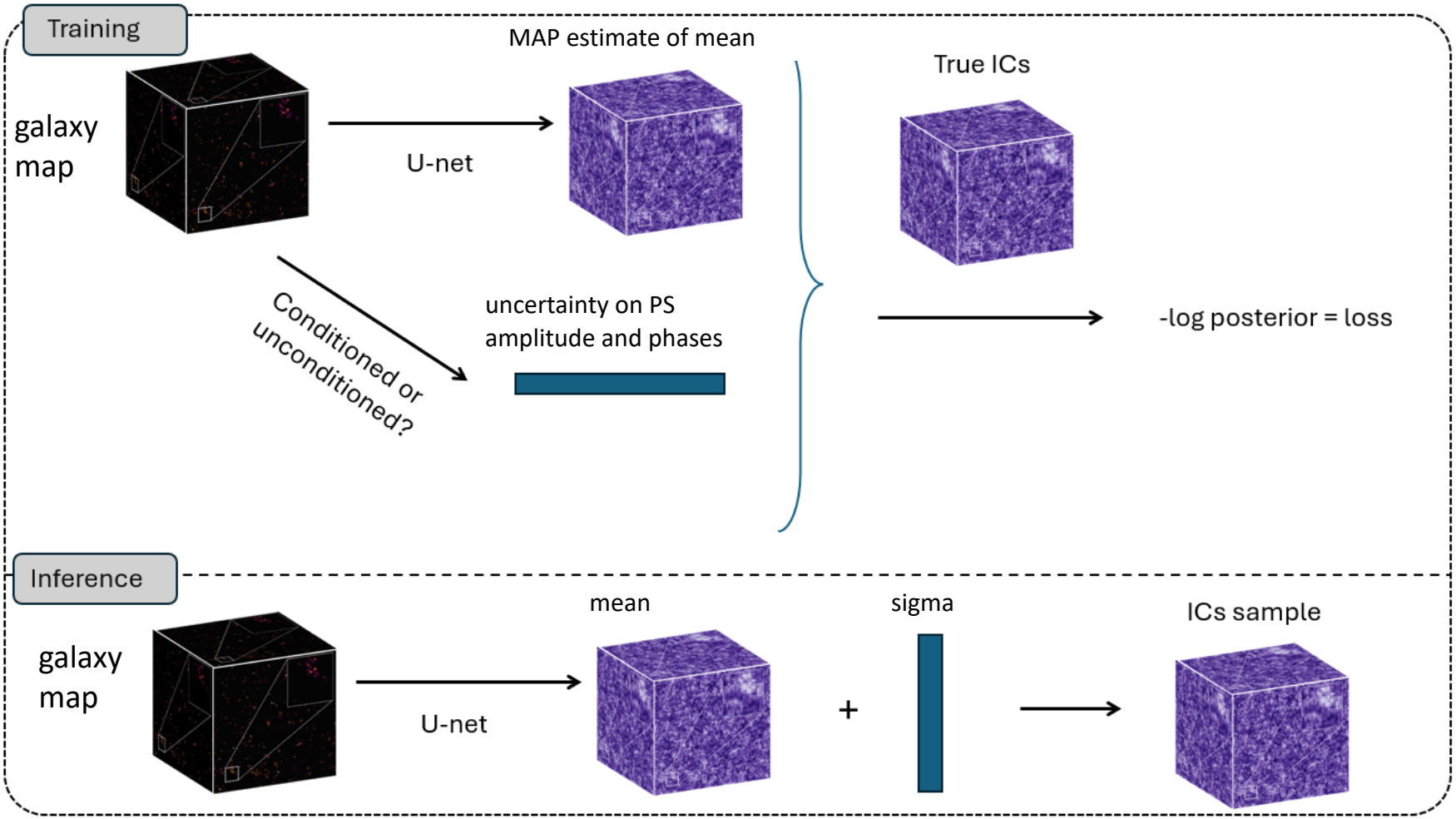


Learn galaxy <—> IGM connection and improve priors for 21cm inference.

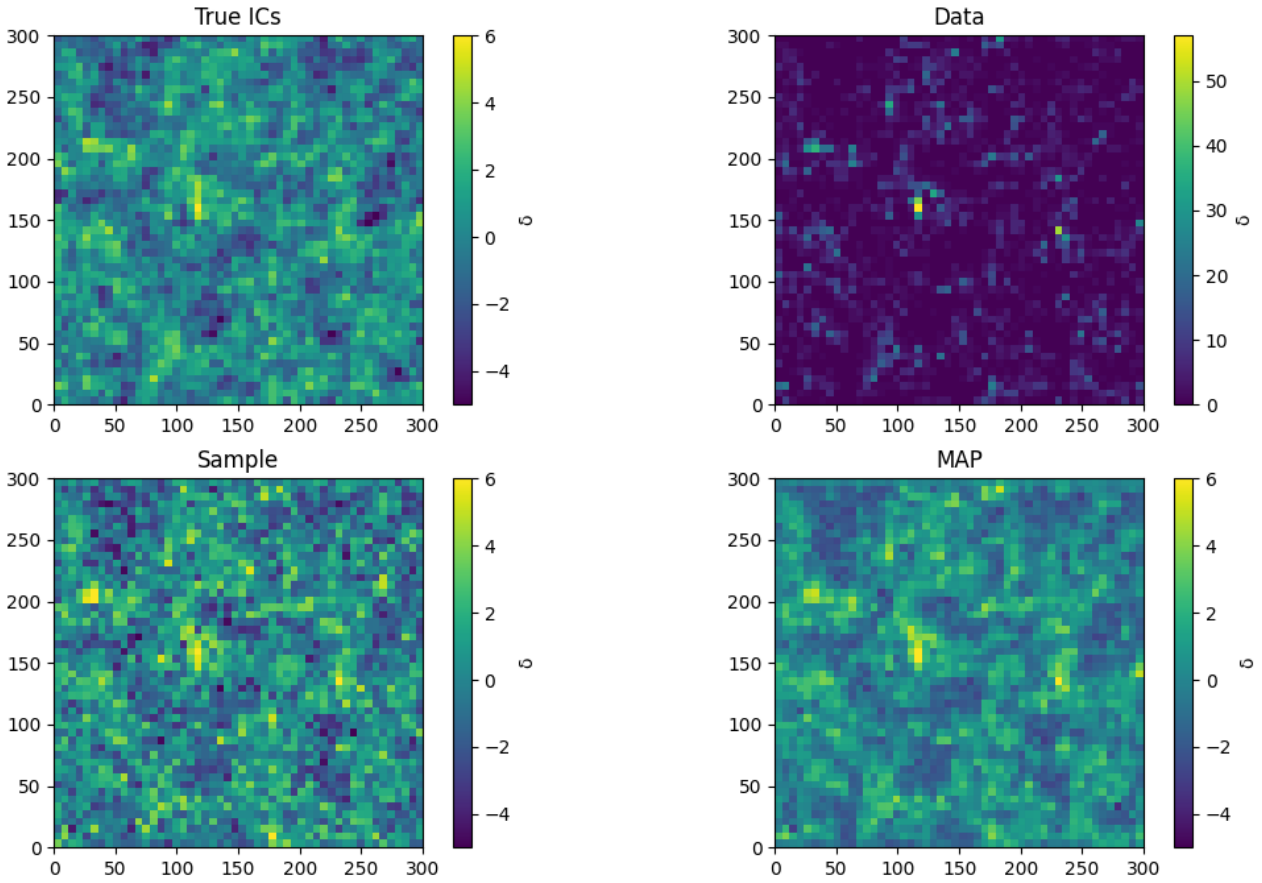
Inferring initial conditions from galaxy and 21cm surveys



modified U-net + SBI of Savchenko+ 2024

Triantafyllou, AM+ in prep

Inferring initial conditions from galaxy and 21cm surveys



Triantafyllou, AM+ in prep

Conclusions

- We need a **multi-tracer** approach to complement preliminary 21cm observations, and provide a sanity check for initial detection claims.

- New **21cmFASTv4** includes a discrete source model based on stochastic sampling of conditional mass functions and semi-empirical galaxy relations —> **universal language** for 21cm simulations. We can **learn** these relations from synergistic, multi-tracer data.

- SKA can obtain **high S/N cross-power** with wide-field grism galaxy surveys OR deep, slit spectroscopy —>
  ROMAN, MOONS (VLT), MOSAIC (ELT)