SCUOLA NORMALE SUPERIORE

Emulating 21cmFAST summary observables with 21cmEMU

Daniela Breitman[1]
Scuola Normale Superiore
Supervised by Andrei Mesinger
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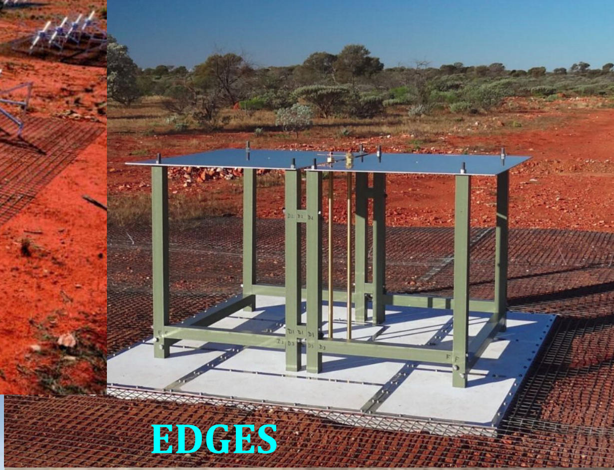
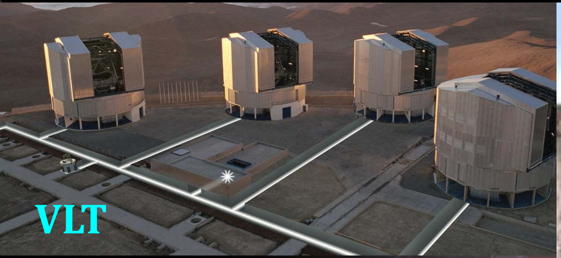
[1]daniela.breitman@sns.it


HST

MWA

EDGES

VLT

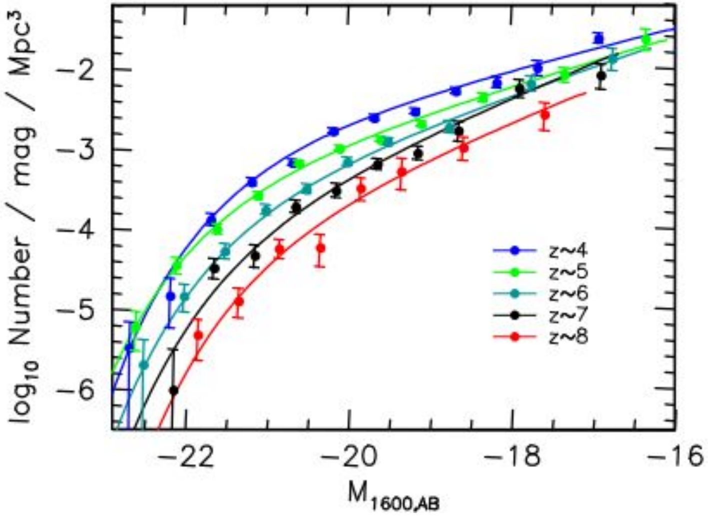
SKA low

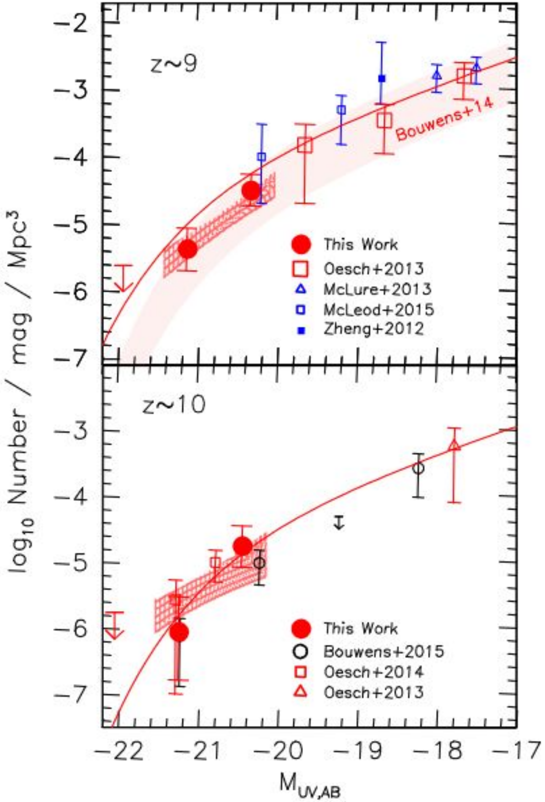
HERA

JWST

LOFAR

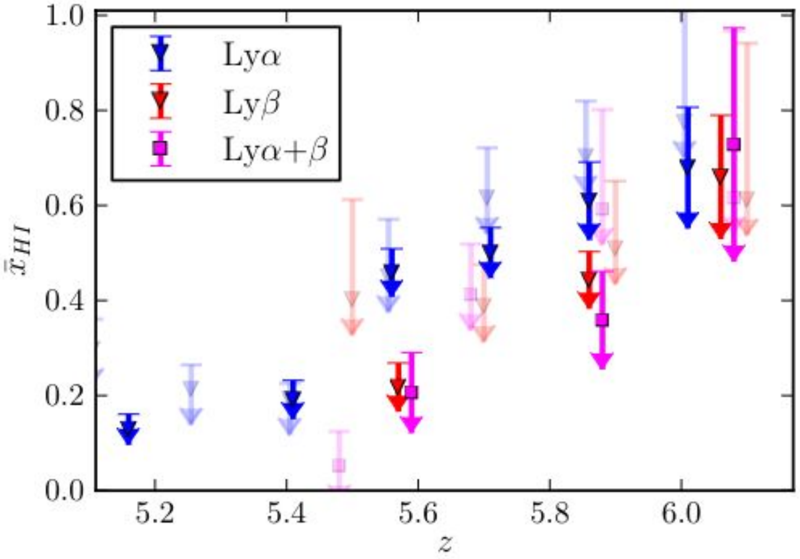
UV Luminosity Functions

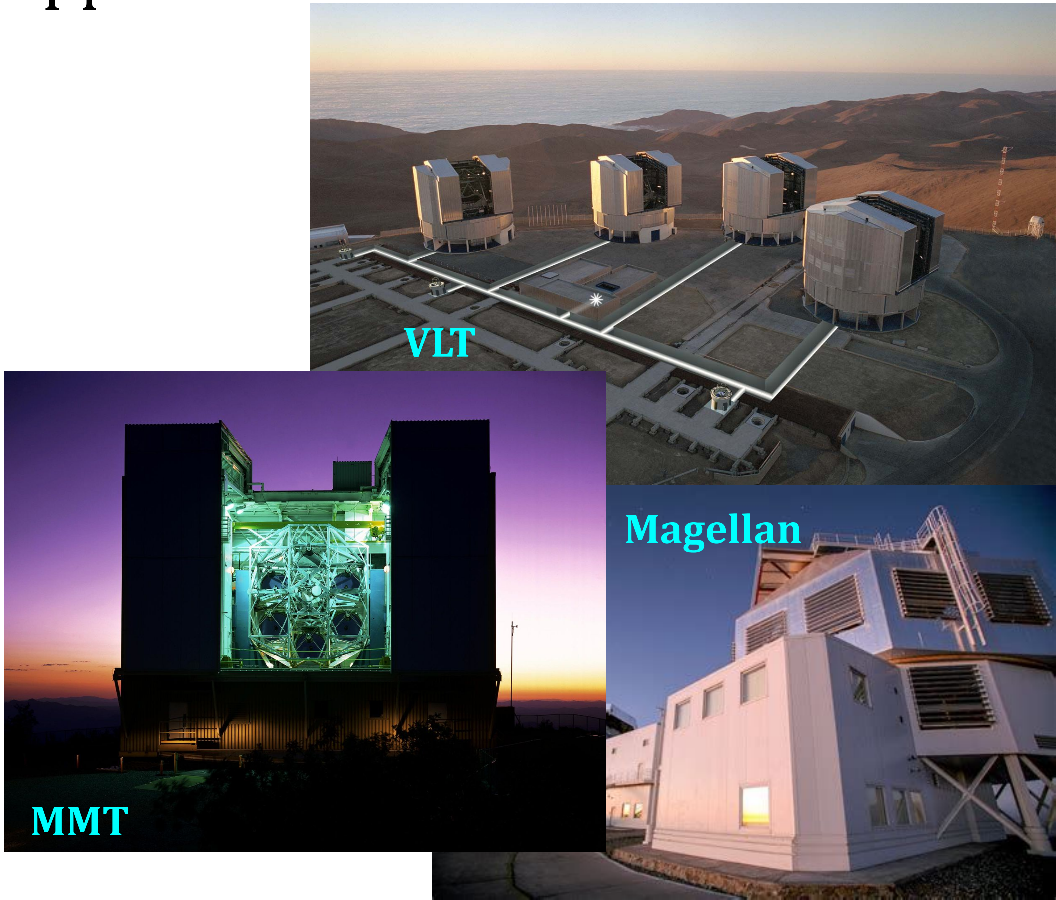




Bouwens+15, 16

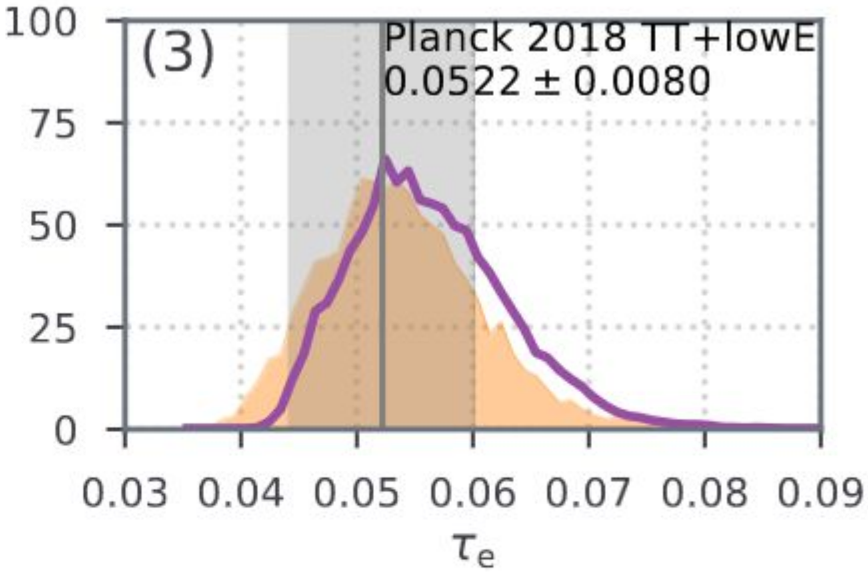
Hydrogen Neutral Fraction Upper Limit

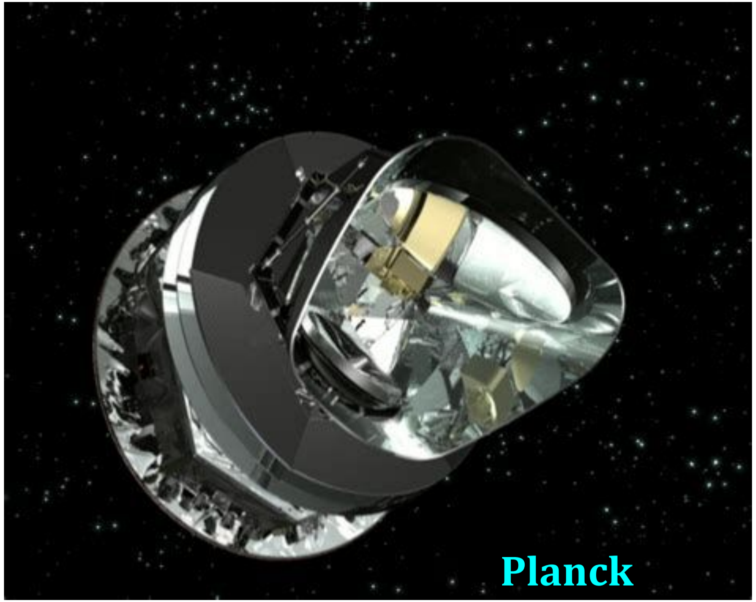




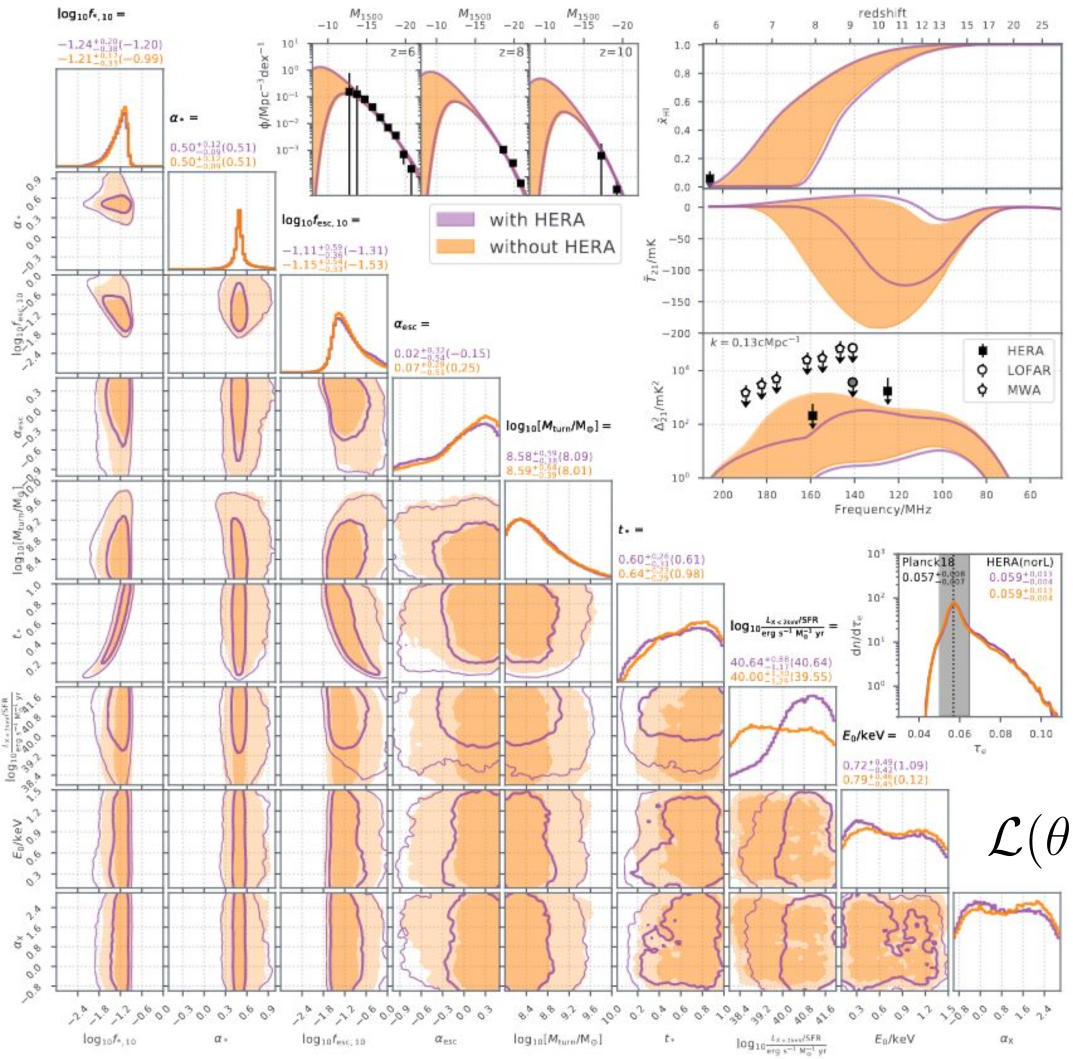
McGreer+15

Thomson Scattering CMB Optical Depth





Planck Collaboration 2020, Qin+20

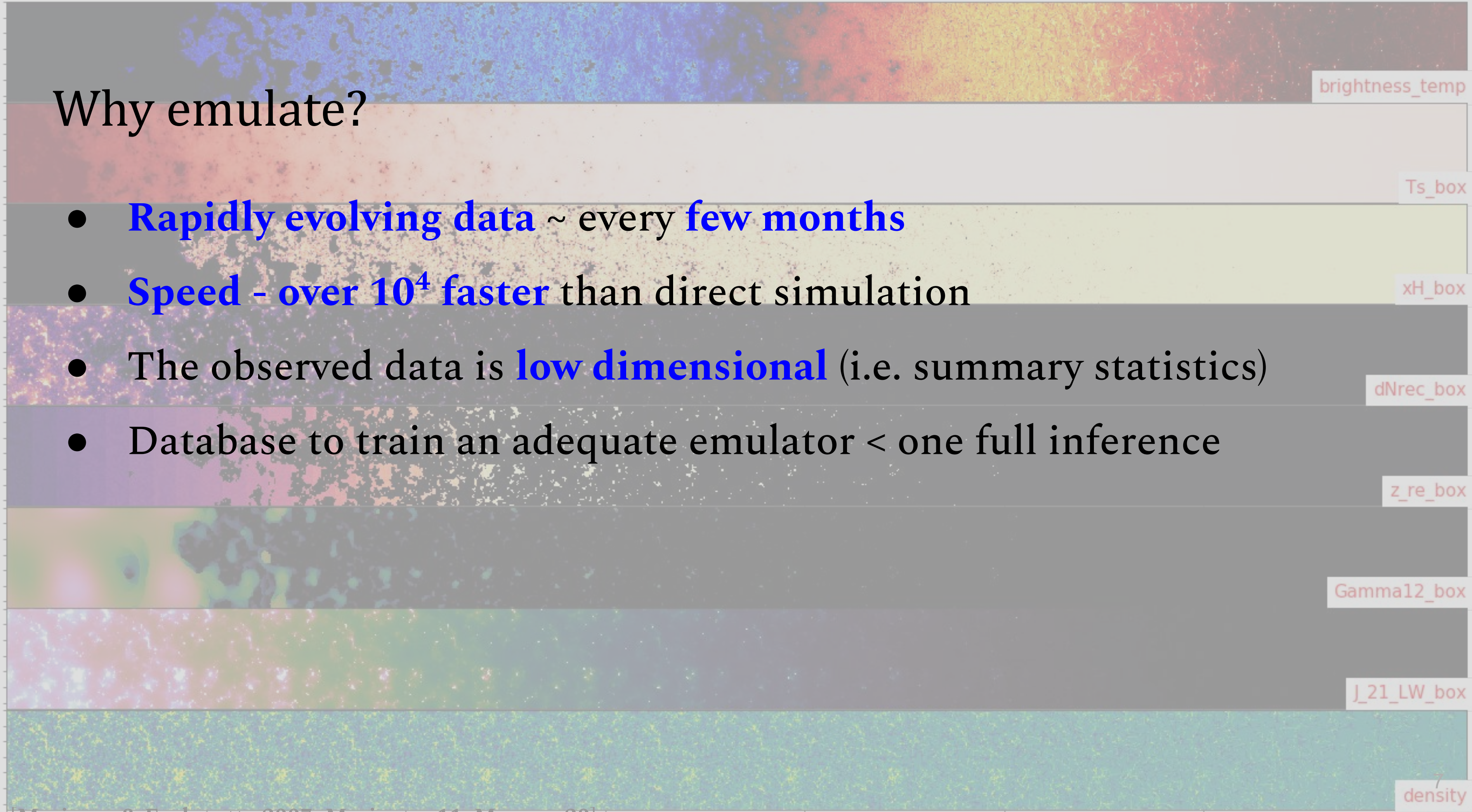


$$\mathcal{L}(\theta|\mathcal{M})_{\mathrm{total}} = \mathcal{L}_{\tau_e} \times \mathcal{L}_{\mathrm{xHI}} \times \mathcal{L}_{\mathrm{LFs}} \times \mathcal{L}_{\mathrm{PS}}$$

HERA22 takes ~400k CPU hrs to run

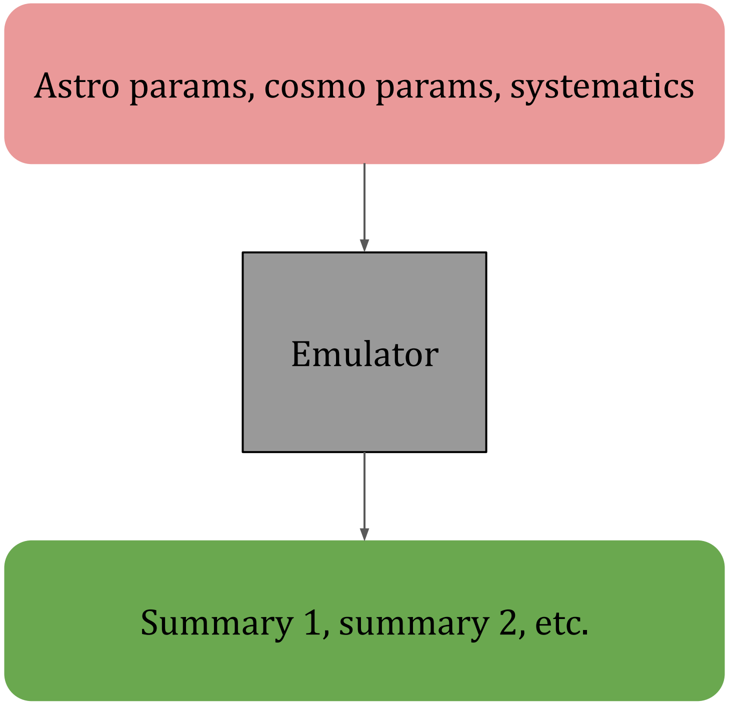
Why emulate?

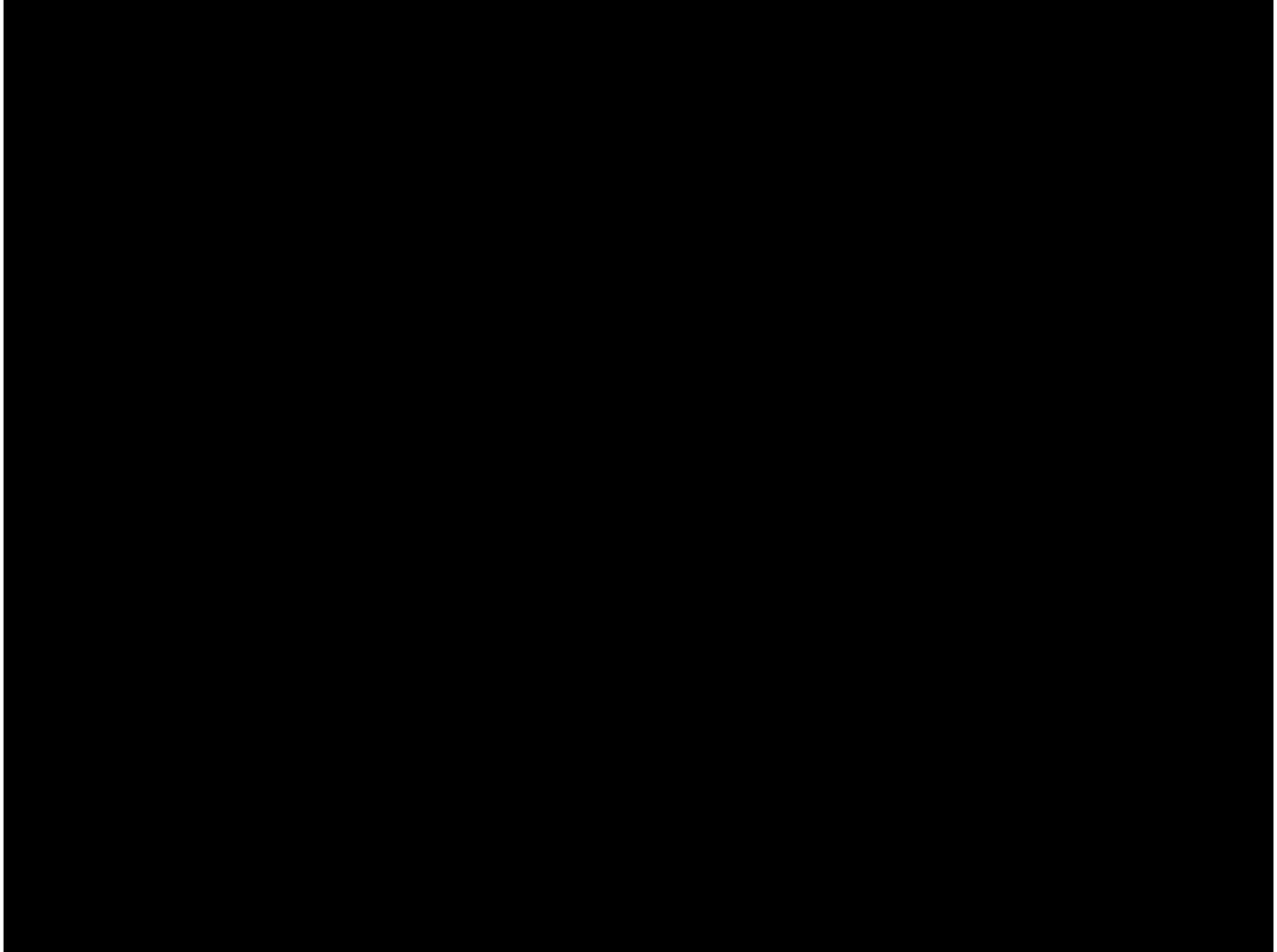
- **Rapidly evolving data** ~ every **few months**
- **Speed - over 10^4 faster** than direct simulation
- The observed data is **low dimensional** (i.e. summary statistics)
- Database to train an adequate emulator < one full inference



[Mesinger & Furlanetto 2007; Mesinger+11; Murray+20]

Ideal Emulator





[See it here]

Summary Statistics

- **xHI** (**z**): Global fraction of neutral hydrogen
- $\mathbf{T_S}$(**z**): Global neutral IGM spin temperature

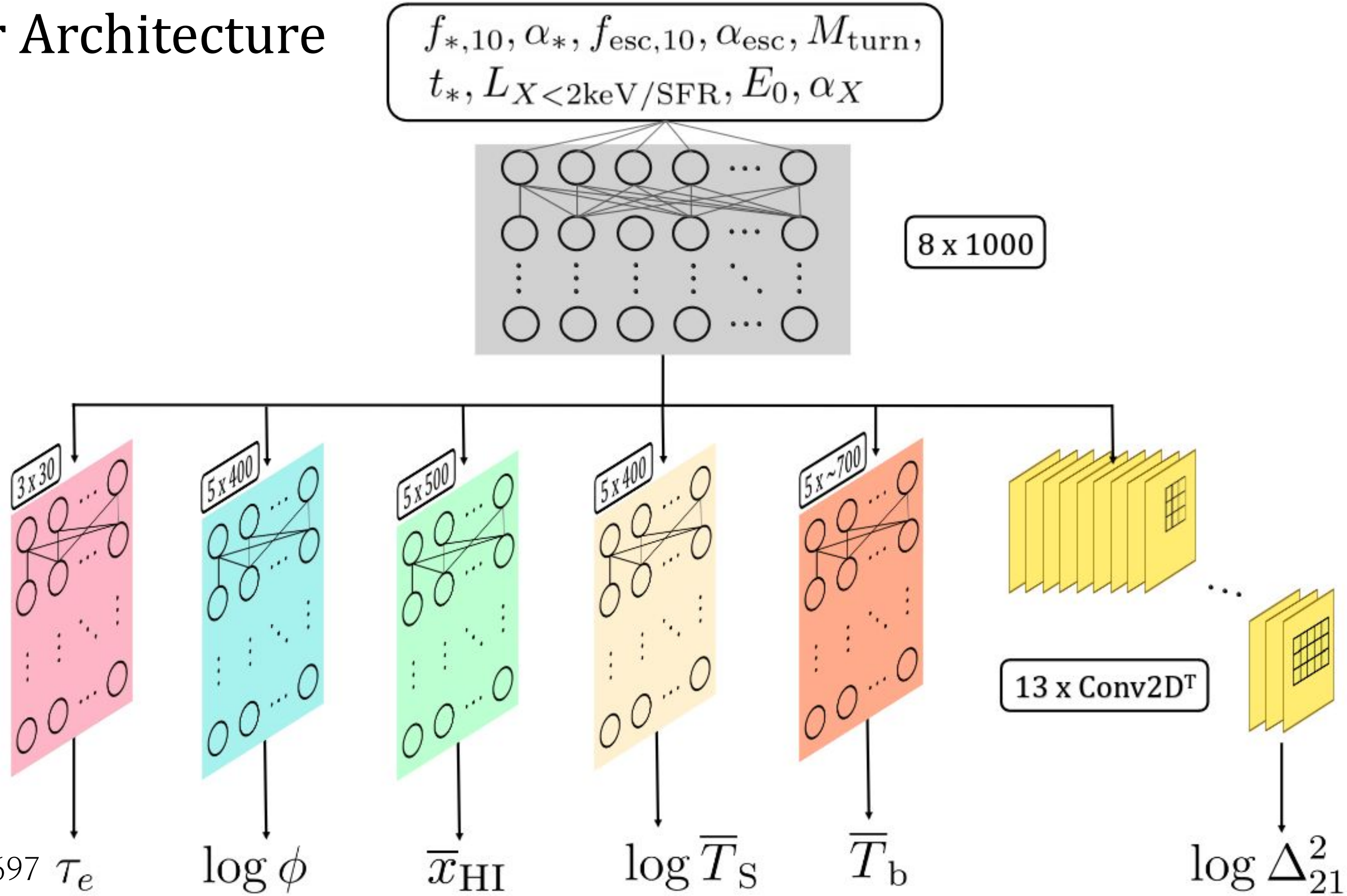
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

- $\mathbf{T_b}$(**z**): Global 21-cm brightness temperature [e.g. Bye+22, Bevins+21, Cohen+19]

$$\delta T_b \approx 27 x_{HI} (1+\delta_b) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10}\right)^{1/2} \times \left(\frac{T_S - T_R}{T_S}\right) \left[\frac{\partial_r v_r}{(1+z)H(z)}\right] \mathrm{mK}$$

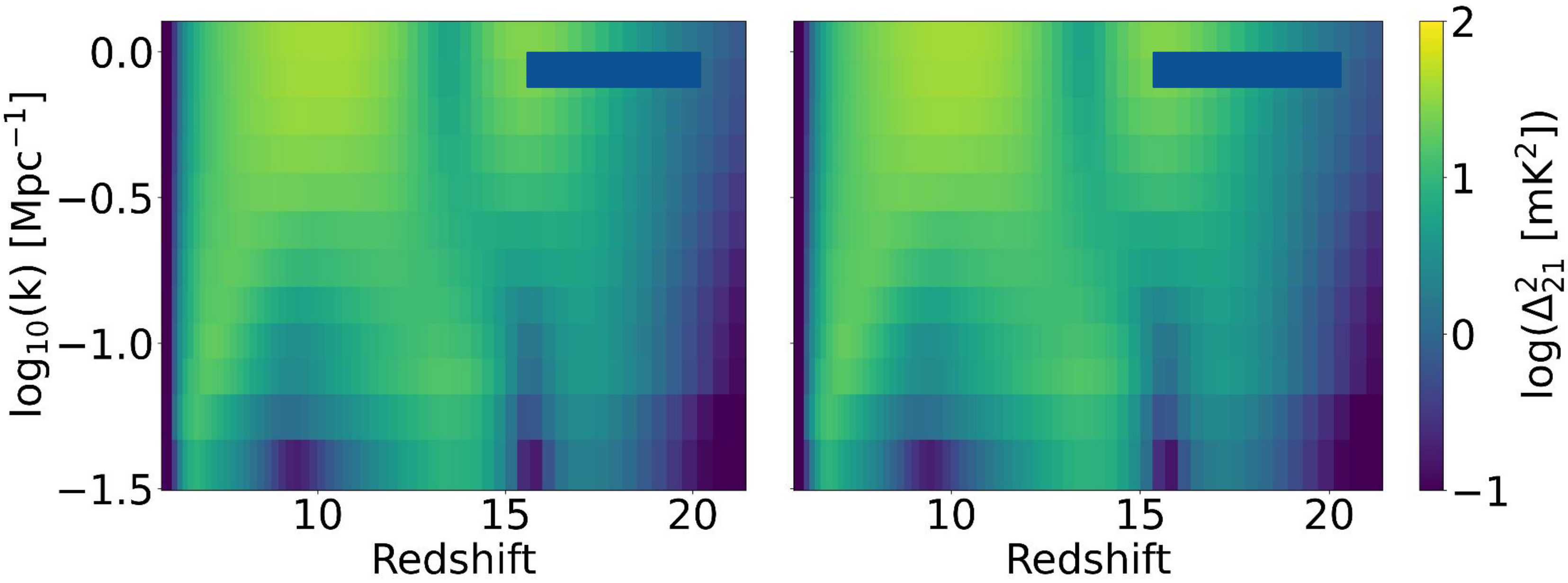
- **21-cm power spectrum** (**k, z**): e.g. Kern+17, Schmit & Pritchard 18, Ghara+20, Mondal+21
- **UV luminosity function:** Source number density per magnitude vs z [Bouwens+15, 16]
- $\boldsymbol{\tau_e}$: Thomson scattering optical depth of CMB photons

Emulator Architecture



Breitman+ 2309.05697

Power Spectrum



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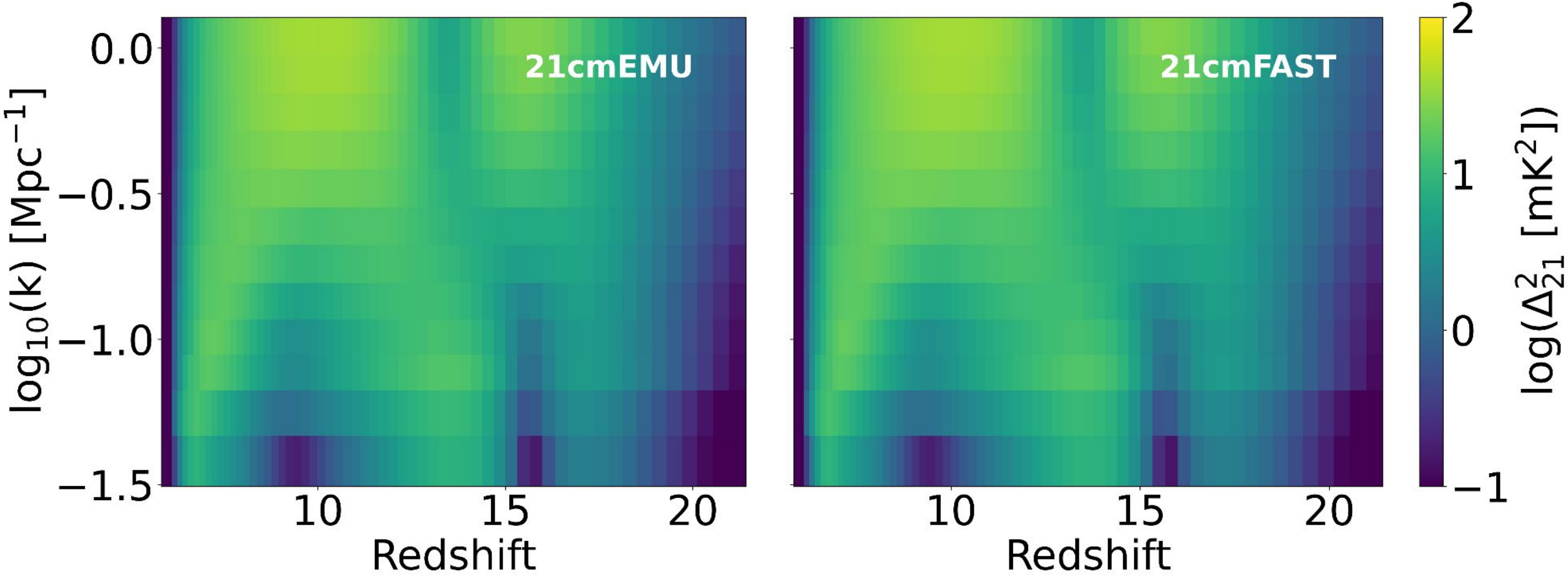
Power Spectrum



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21cmEMU Performance

Summary	Median FE (%)	68% CL (%)
$\log \Delta^2_{21}$	0.55	2.4
$\overline{T}_{\mathrm{b}}$	0.25	0.82
$\log \overline{T}_{\mathrm{S}}$	0.032	0.13
$\overline{x}_{\mathrm{HI}}$	0.0073	0.10
τ_{e}	0.11	0.26
$\log \phi$	0.50	2.1

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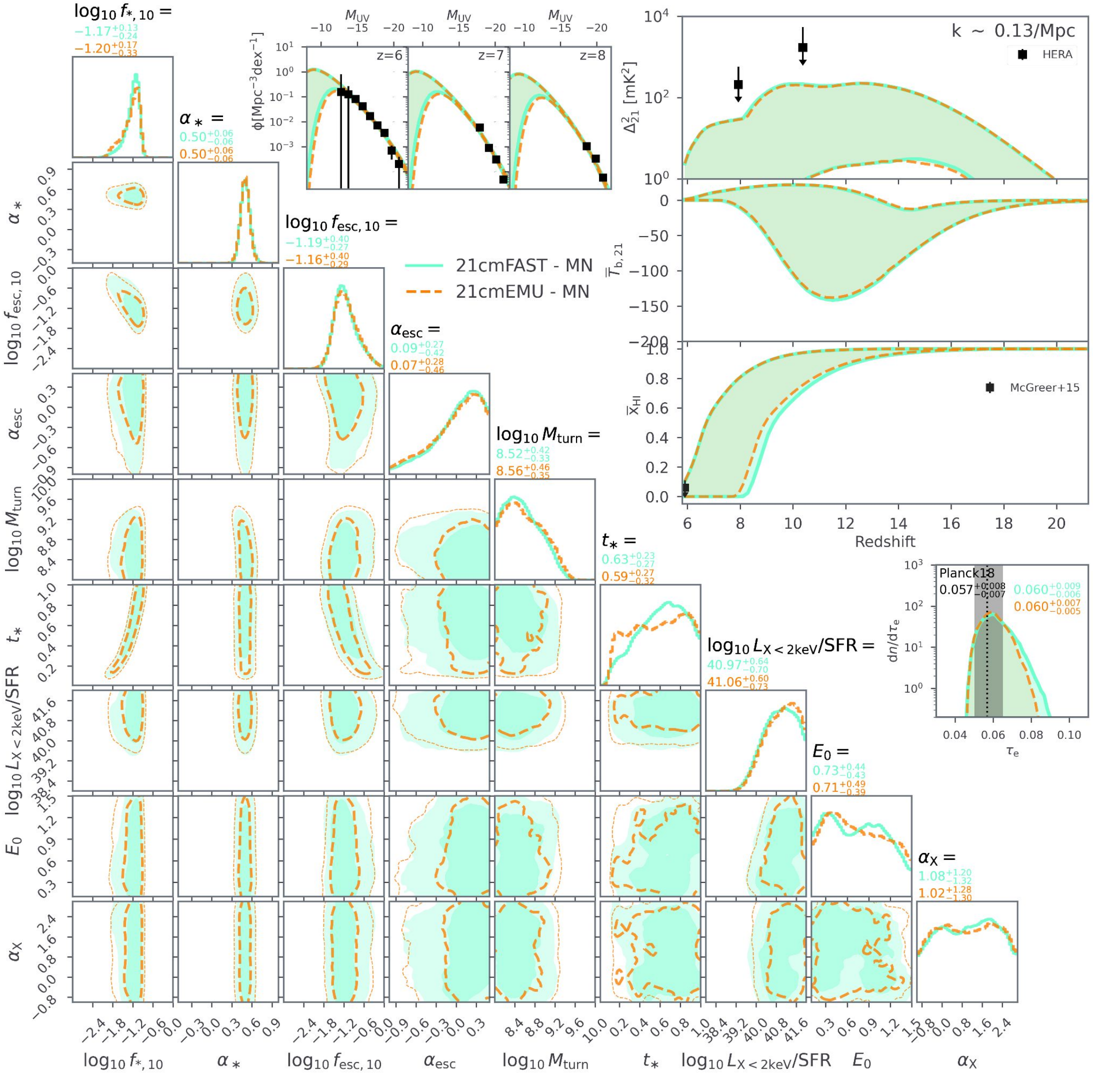
Small errors, but do they impact the inference?

21cmEMU can reproduce 21cmFAST results.



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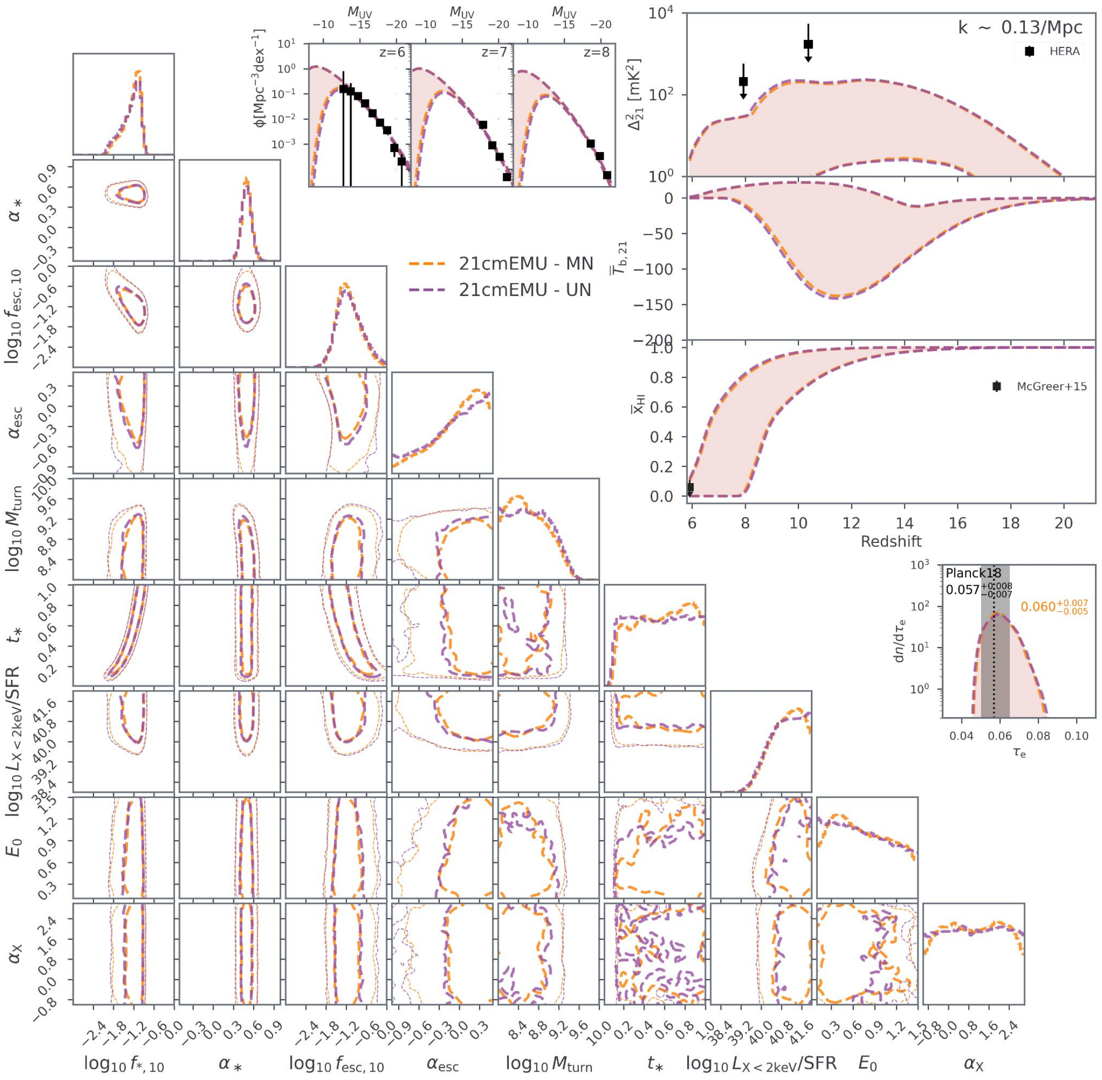
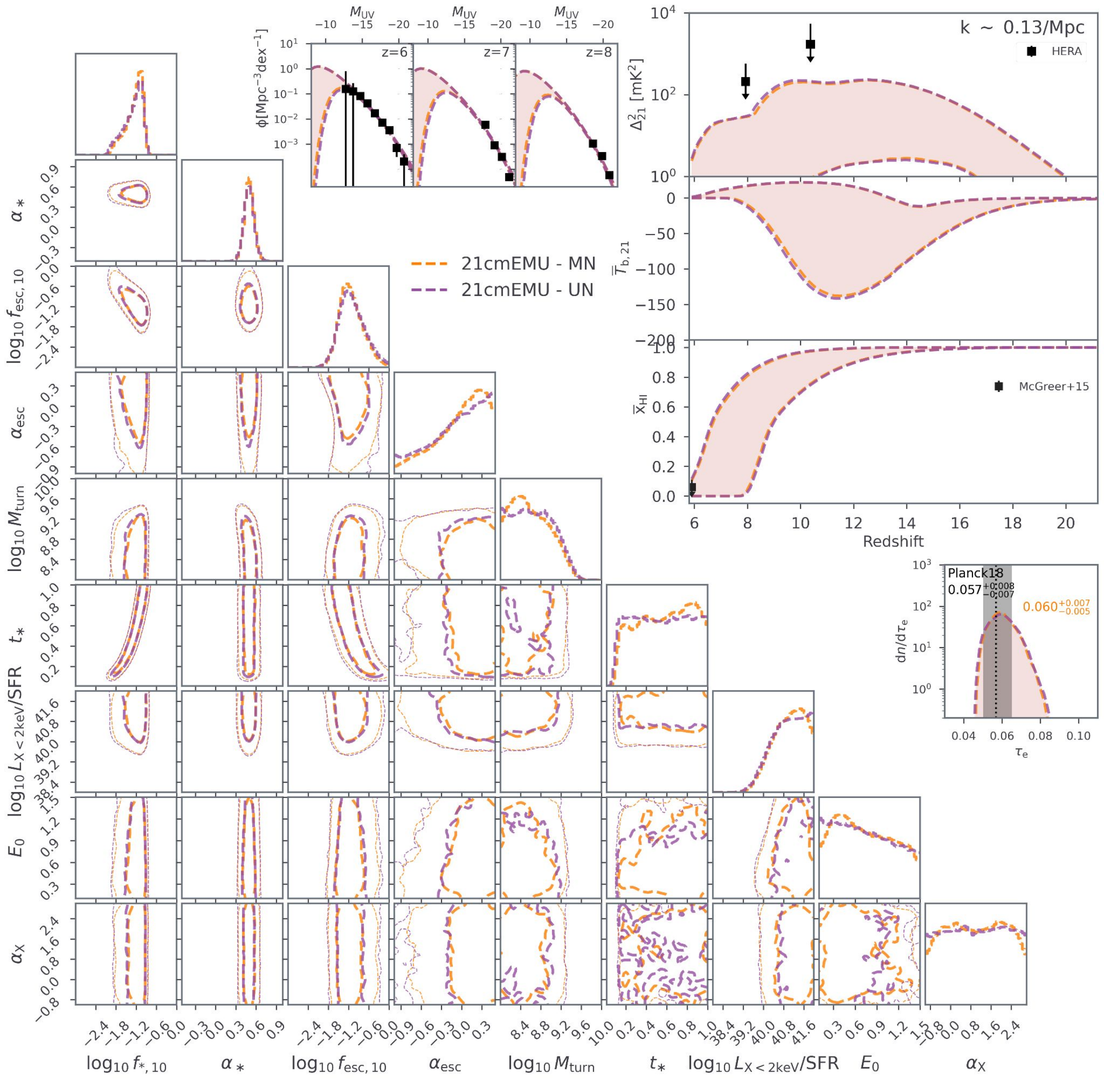
MultiNest Sampler vs UltraNest Sampler



MultiNest Sampler vs UltraNest Sampler

Difference between different samplers > difference between 21cmEMU and 21cmFAST



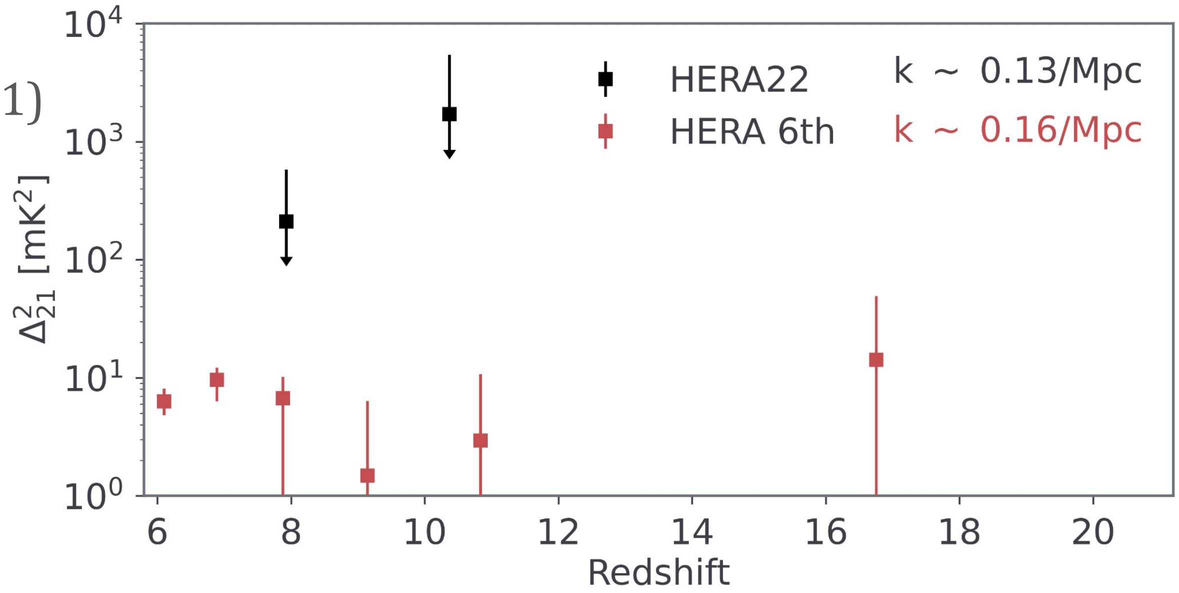
21cmEMU Application - HERA 6th Season Phase II Forecast

- HERA Phase II
  - 50-230 MHz (omitting the FM band, 90-110 MHz),
    - expanding coverage to Cosmic Dawn and late reionization with respect to Phase I (in HERA22).
- Known characteristics of observation:
  - **~1300 hours** of unflagged data over **~150 nights**, with an average of **~148 un-flagged antennas per night**
  - **HERA's most sensitive data release to date**

HERA22 (Phase I) vs HERA 6th Season (Phase II) Forecast

Mock data: EOS2021 (Muñoz+21)

Sensitivity forecasted with `21cmSense` (Pober+14,15)



Likelihood Choice

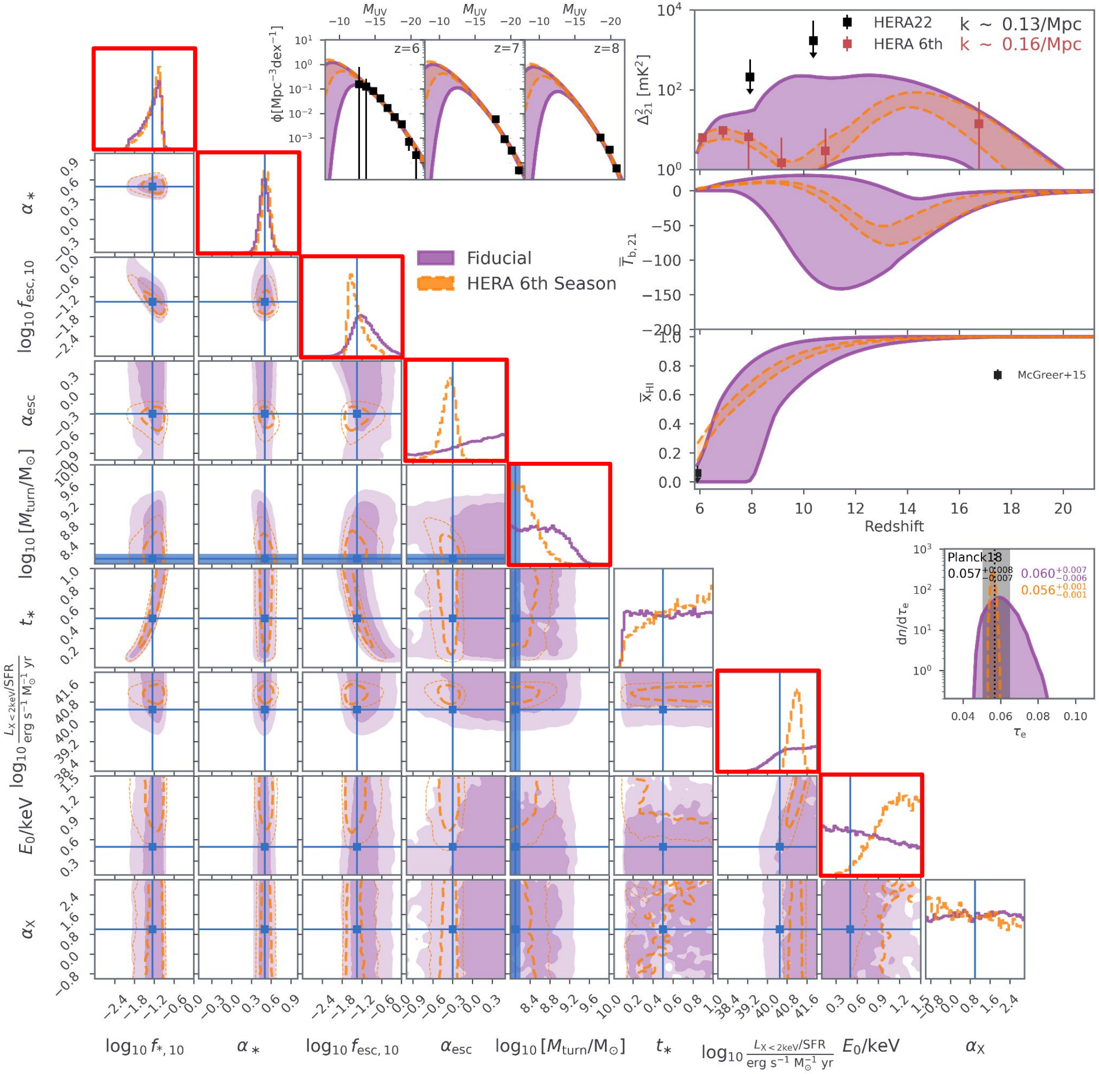
- Two-sided Gaussian (***detection***) rather than an error function (***upper limit***)

$\Rightarrow$ **Optimistic likelihood** since it assumes no residual systematics in the mock data

$\Rightarrow$ **(effectively) tighter prior on systematics**

Forecast for HERA Phase II 6th-Season Observations

New HERA data + tighter prior on systematics significantly improve the constraints for almost all astrophysical parameters



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Conclusions

- **Goal: Emulate summaries required for inference using 21cmFAST data**
  - Emulate: **PS, T_b, T_S, xHI + τ_e and UV LF**
  - **FE 68% CL ≲ 2% for all quantities**
  - This error is **much smaller than expected instrument error**
  - Major improvement in runtime: ~**ms vs** ~**hr per parameter combination** ⇒ **~10k x faster**
- **Application:**
  - **Inference with HERA 6th season somewhat optimistic forecast**
    - **Upcoming HERA data dramatically improves our understanding of the EoR: e.g. at z ~ 8:**
      - **Infer xHI to within ± 0.05 (95% C.I.): factor of ≳ 7 better than current limits**
      - **Infer Δ^2_{21} to within ± 1.29 mK^2 (95% C.I.): factor of ≳ 11 better than current limits**
- **Limitations: including new physics** e.g. minihalos will require re-running 21cmFAST + retraining

Now available!!

pip install py21cmemu

https://github.com/21cmfast/21cmemu

ArXiv 2309.05697

21 cm