21cmCosmoSim: Simulations and inference for 21cm cosmology

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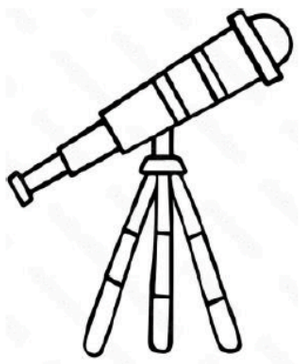
Cosmology in the Alps 2024, March 21st 2024, Les Diablerets

Based on work with: Benedikt Schosser*, Tilman Plehn, Tim Ullrich*, Steffen Neutsch*, Marcus Brüggen, Luca Amendola, Xue-Wen Liu*
+ further group members: Lara Alegre, Yannic Pietschke*, Vrund Patel*, Abdulmalik Kara*

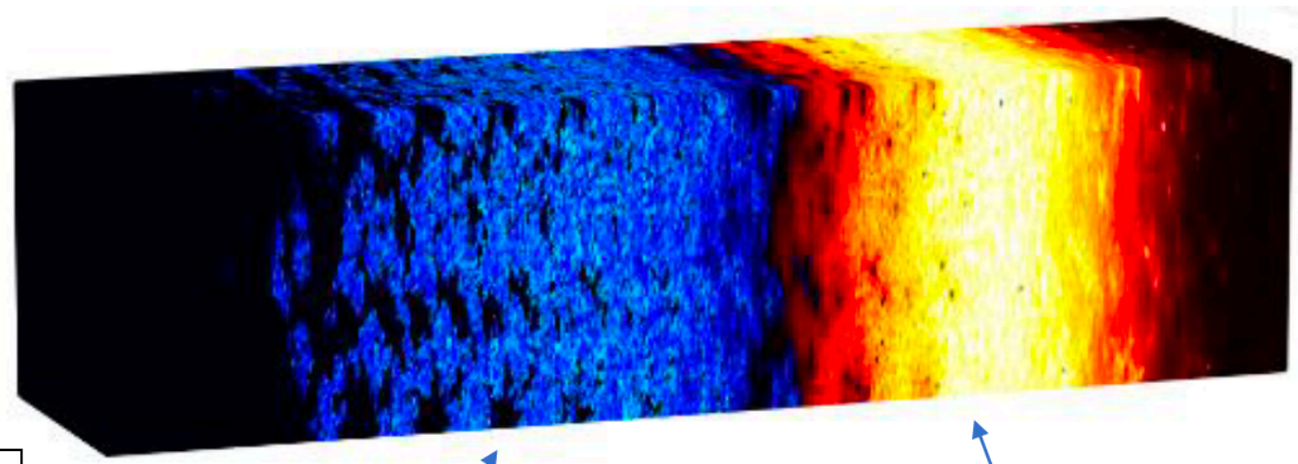
21cm high-redshift cosmology?

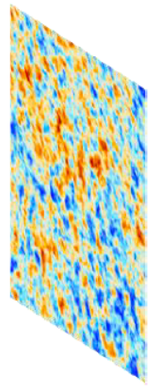


Credit: ESO

Galaxy Surveys

Redshift z





Credit: Planck, ESA

21cm Intensity Mapping

Credit: 21cmFAST

CMB

Cosmic reionisation

HI ⟶ HII

Cosmic dawn

first stars and galaxies

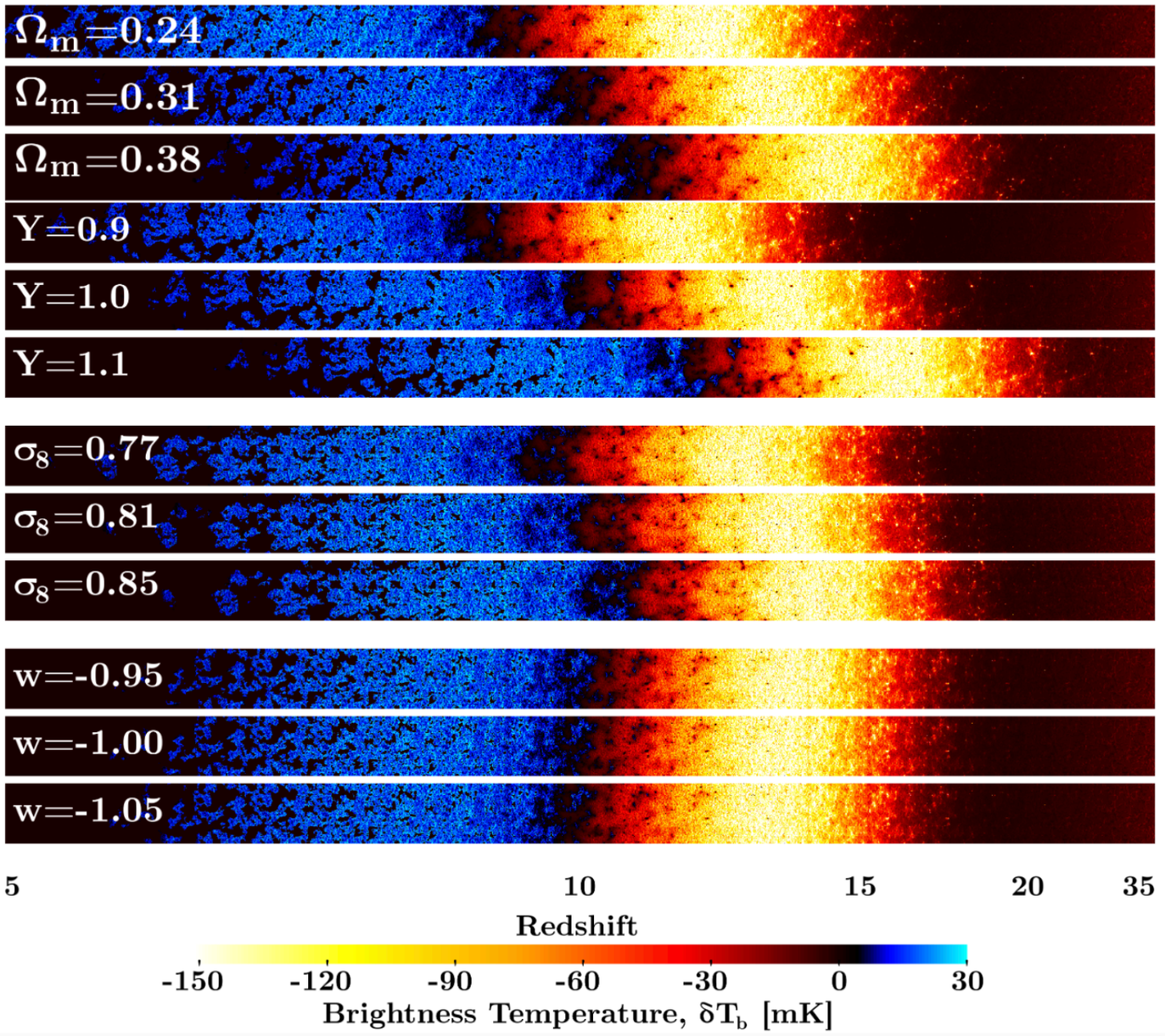
$$\delta T_{\mathrm{b}}(\nu) = \frac{T_{\mathrm{S}} - T_{\gamma}}{1+z}\left(1 - e^{-\tau_{\nu_0}}\right)$$

$$\propto x_{\mathrm{HI}}\,(1+\delta_{\mathrm{nl}})\left(\frac{H}{\mathrm{d}v_{\mathrm{r}}/\mathrm{d}r + H}\right)$$

21cmCosmoSim

Goal: Impact of cosmological models on the 21cm signal

- simulations with 21cmFAST
- custom cosmology branch
  - 15% faster computation



Examples investigated:

- wCDM + CPL (time-dependent)
- Modified gravity (Y or Geff)
- (Coupled) quintessence

Ullrich, Heneka, Brüggen (in prep)
See also: Heneka & Amendola (2018), Liu+ (2020) arXiv:1805.03629, 1910.02763

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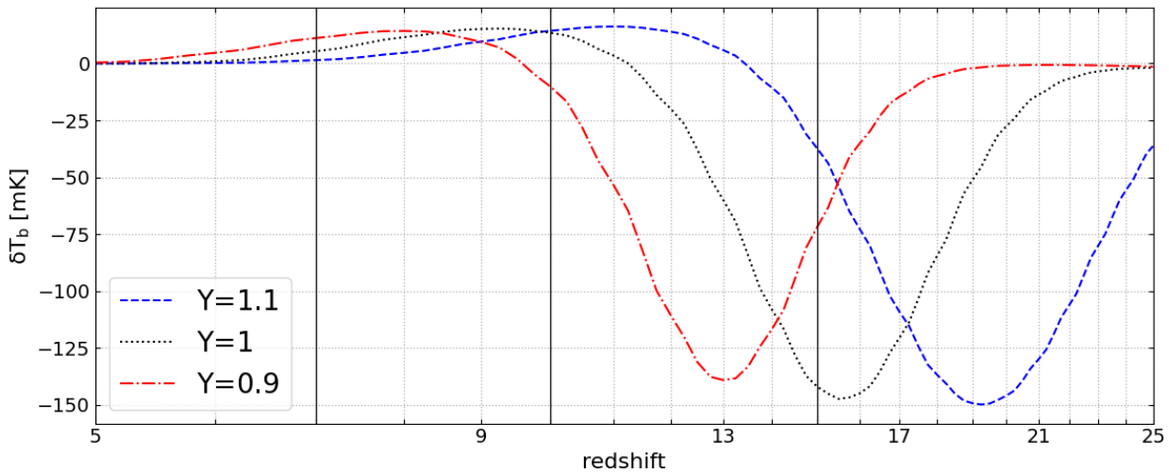
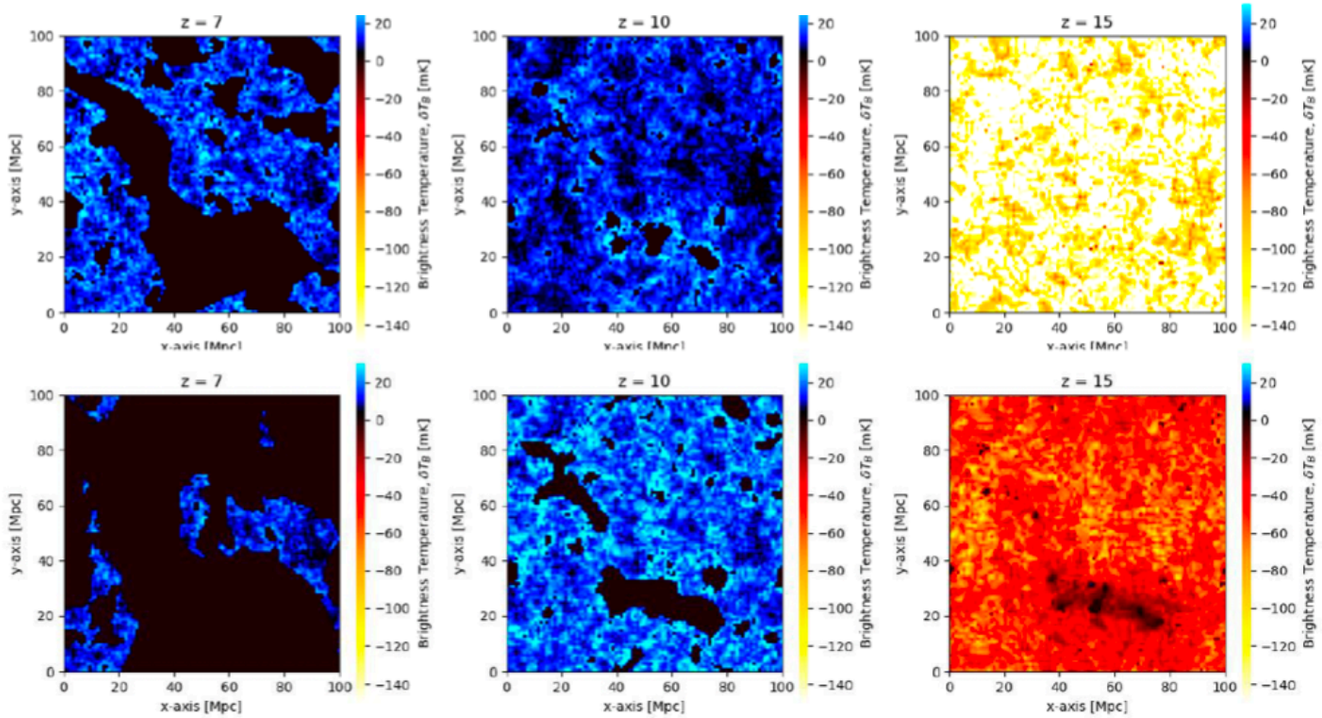


Example Modified Gravity:

- fiducial model:
  Y = 1
- stronger gravity:
  Y = 1.1



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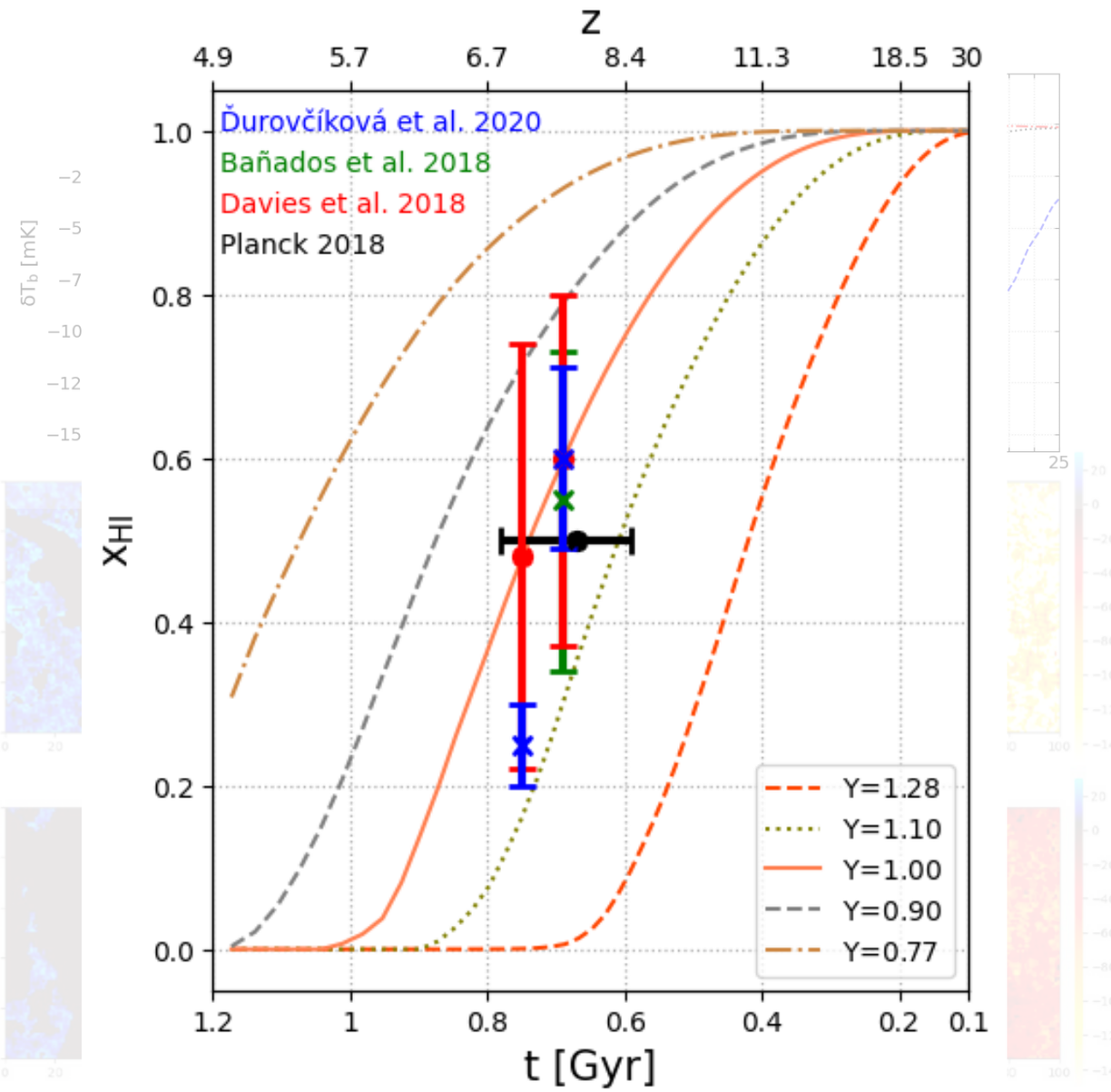

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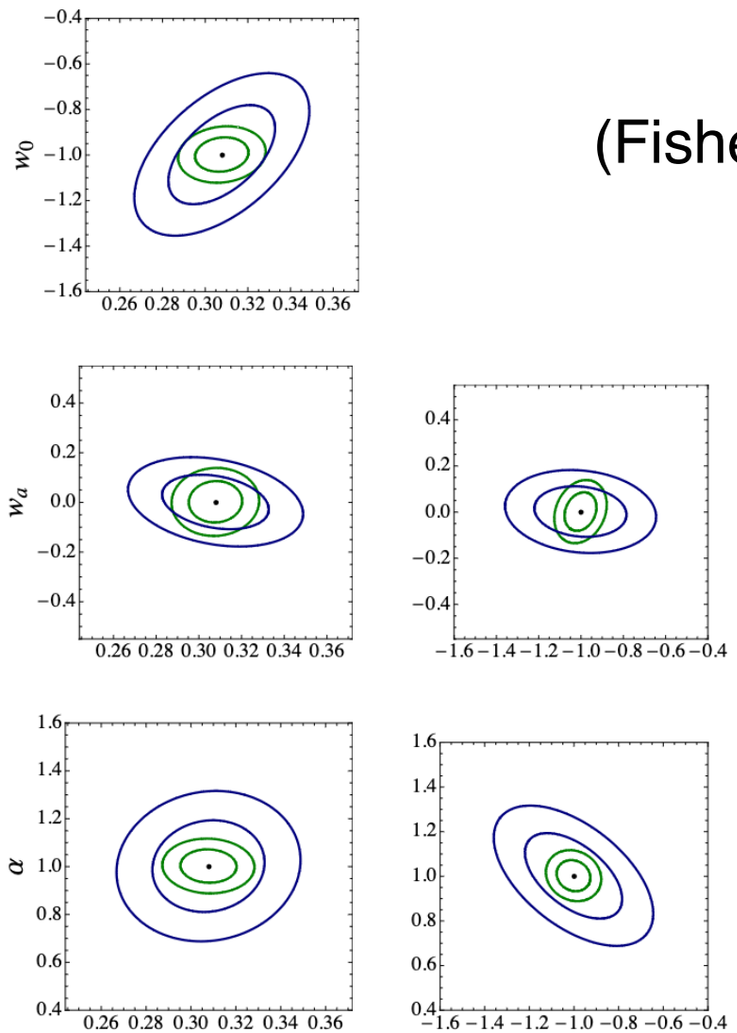
21cmCosmoSim: High-redshift cosmology!



(Fisher) forecasting has shown us:

- %-precision also for extended models reachable
- Tomography lifts (in large part) degeneracy with astrophysics
- Important to model (mildly) non-linear scales

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

[Example: 5 z-bins z=6 to z=10, SKA-Low, marginalised over EoR + CD parameters]

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More lessons learned:

- Global signal improves IM constraints on $\Omega_{\rm m}$
- Both global and IM similarly constrain couplings
- Sensitive to shape of quintessence potential

$$\nabla_\mu T^\mu_{\nu(\phi)} = -I_{\rm int}$$
$$\nabla_\mu T^\mu_{\nu(m)} = +I_{\rm int}$$
$$I_{\rm int} = Q T_{\rm m} \nabla_\nu \phi$$
$$V(\phi) = V_0 e^{-\lambda\phi}$$

[Example: 6 z-bins z=15 to z=20, SKA-Low

⟶ Avenue to constrain cosmology during EoR and CD

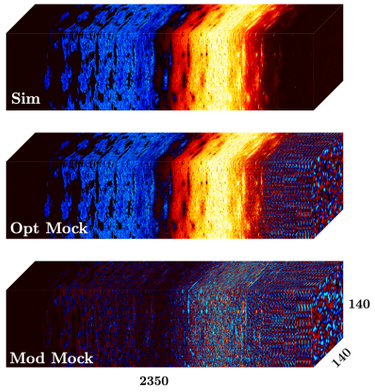
21cmCosmoSim: Simulation and Analysis Pipeline

For example:

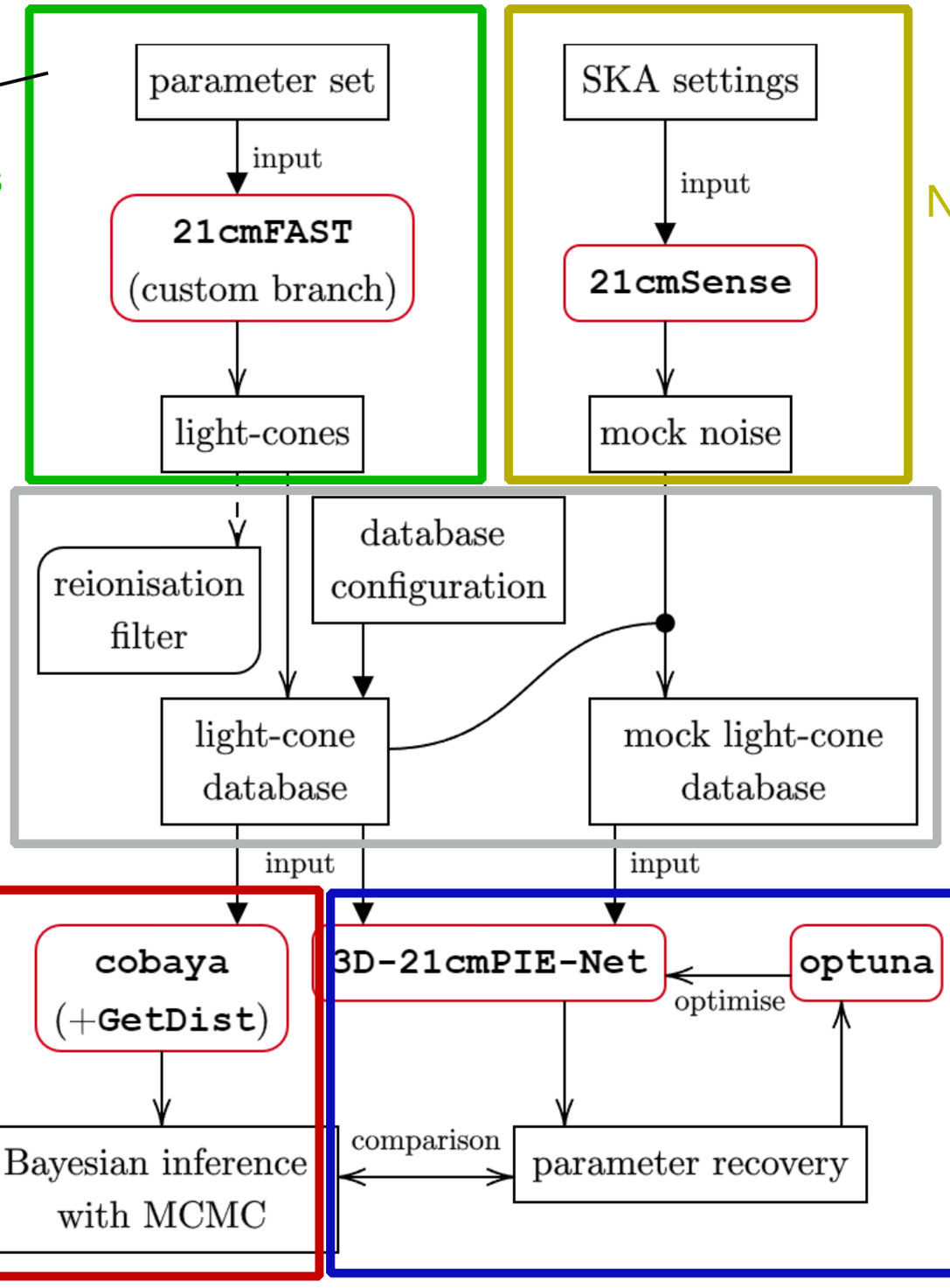
$Y, \Omega_m, T_{\rm vir}, L_X, E_0, \zeta$

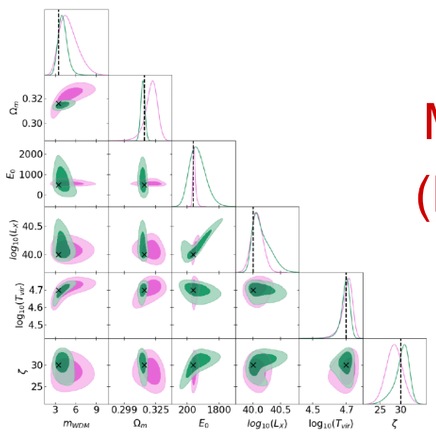
$\sigma_8, \Omega_m, T_{\rm vir}, L_X, E_0, \zeta$

Simulations



(Database, Filtering)

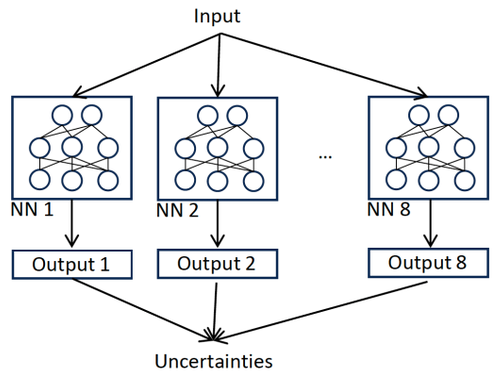




Ullrich, Heneka, Brüggen (in prep)

21cmCosmoSim: First inference steps

Estimates with MCMC as well as network ensembles



	Y	Ω_m	L_X	E_0	T_{vir}	ζ
Fiducial value	1	0.31	40	500	4.7	30
Ensemble	$0.97(\pm 3.4\%)$	$0.291(\pm 4.8\%)$	$39.9(\pm 0.4\%)$	$536(\pm 37\%)$	$4.69(\pm 4.8\%)$	$31(\pm 52\%)$
MCMC	$1.03(^{+12.4\%}_{-11.4\%})$	$0.307(^{+27.4\%}_{-14.0\%})$	$40.5(^{+1.3\%}_{-1.6\%})$	$772(^{+94\%}_{-87\%})$	$4.65(^{+11.9\%}_{-8.4\%})$	$127(^{+46\%}_{-76\%})$

- Perfect recovery of gravitational strength Y-only
- Remaining degeneracies, e.g. between $T_{\rm vir},\ \Omega_{\rm m},\ Y$
- Ensemble better recovers E_0

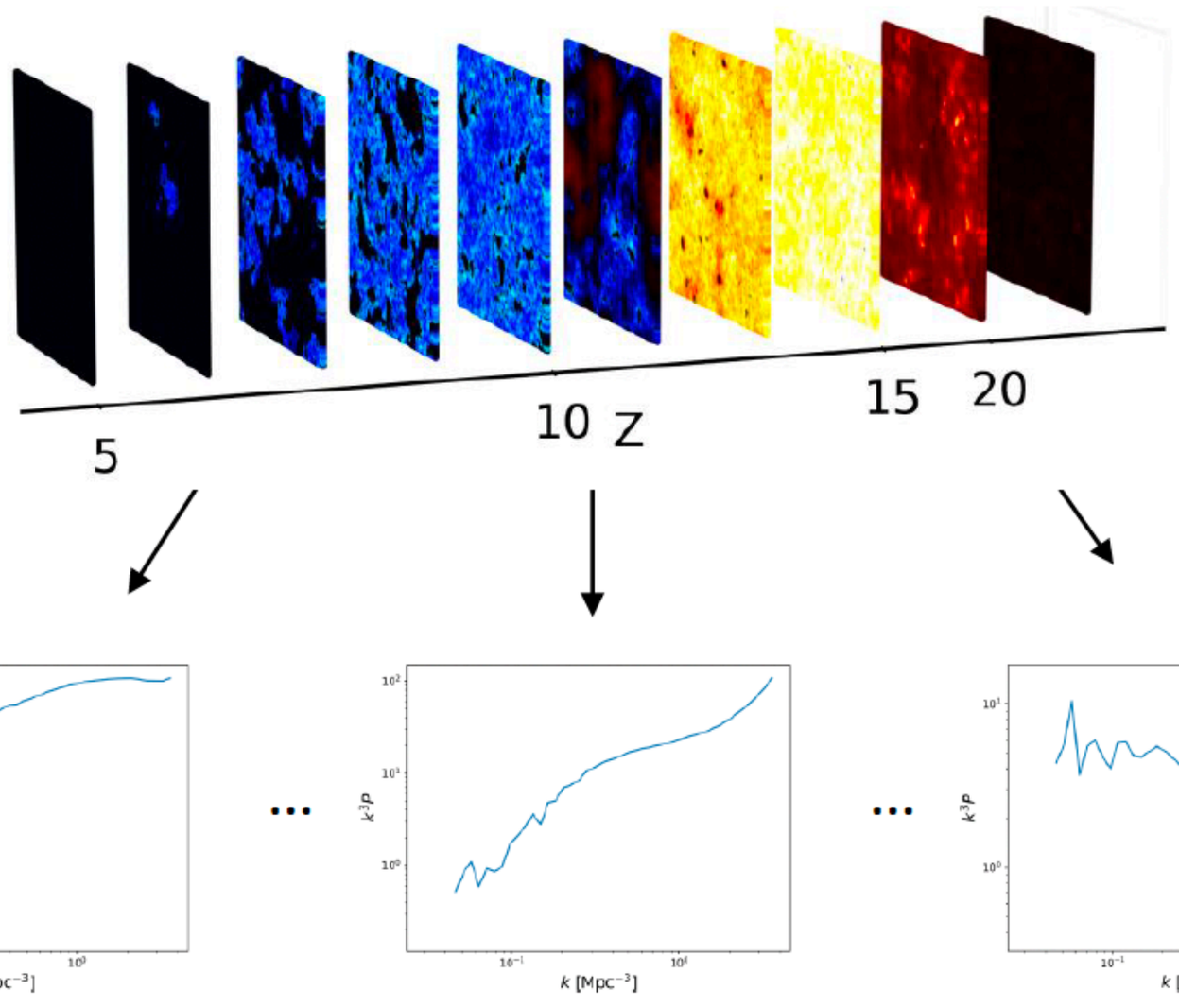
→ Move to full likelihood inference with networks

Ullrich, Heneka, Brüggen (in prep)
Neutsch, Heneka, Brüggen (2022), arXiv:2201.07587

21cmCosmoSim: Simulation-based Inference

What summary do we chose?

21cm lightcone:
2D spatial + 1D frequency



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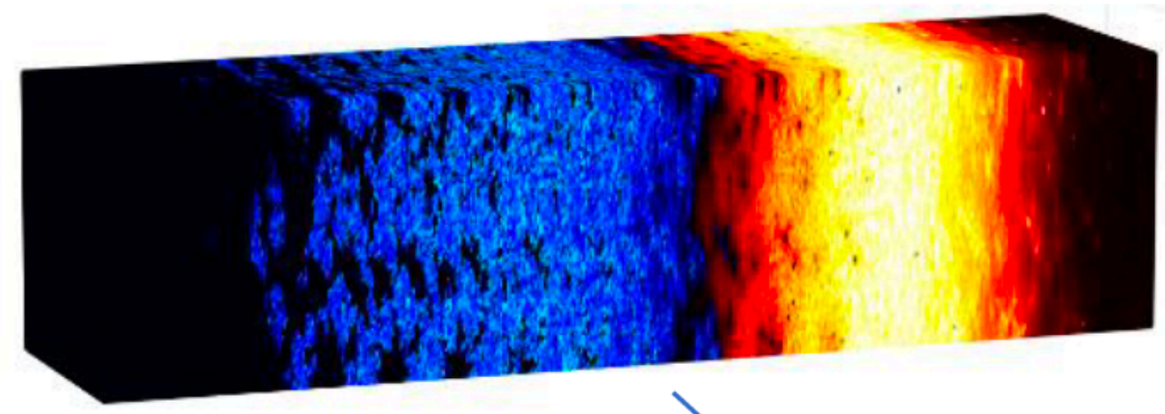
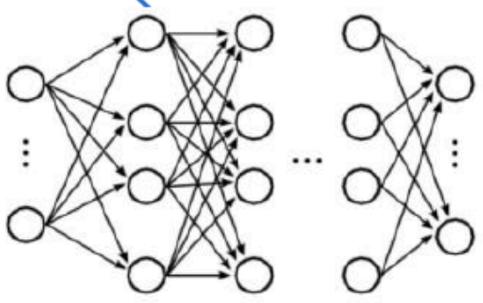
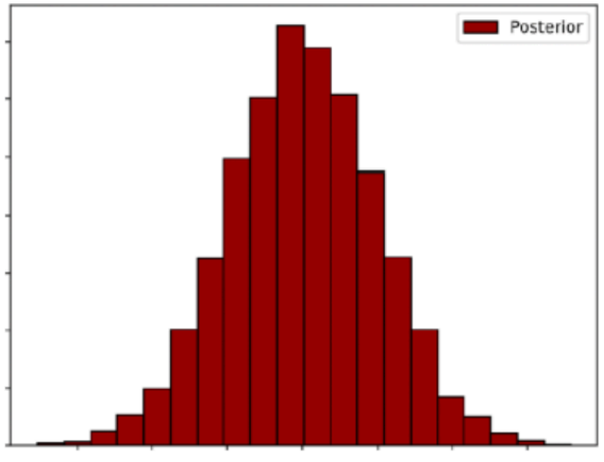


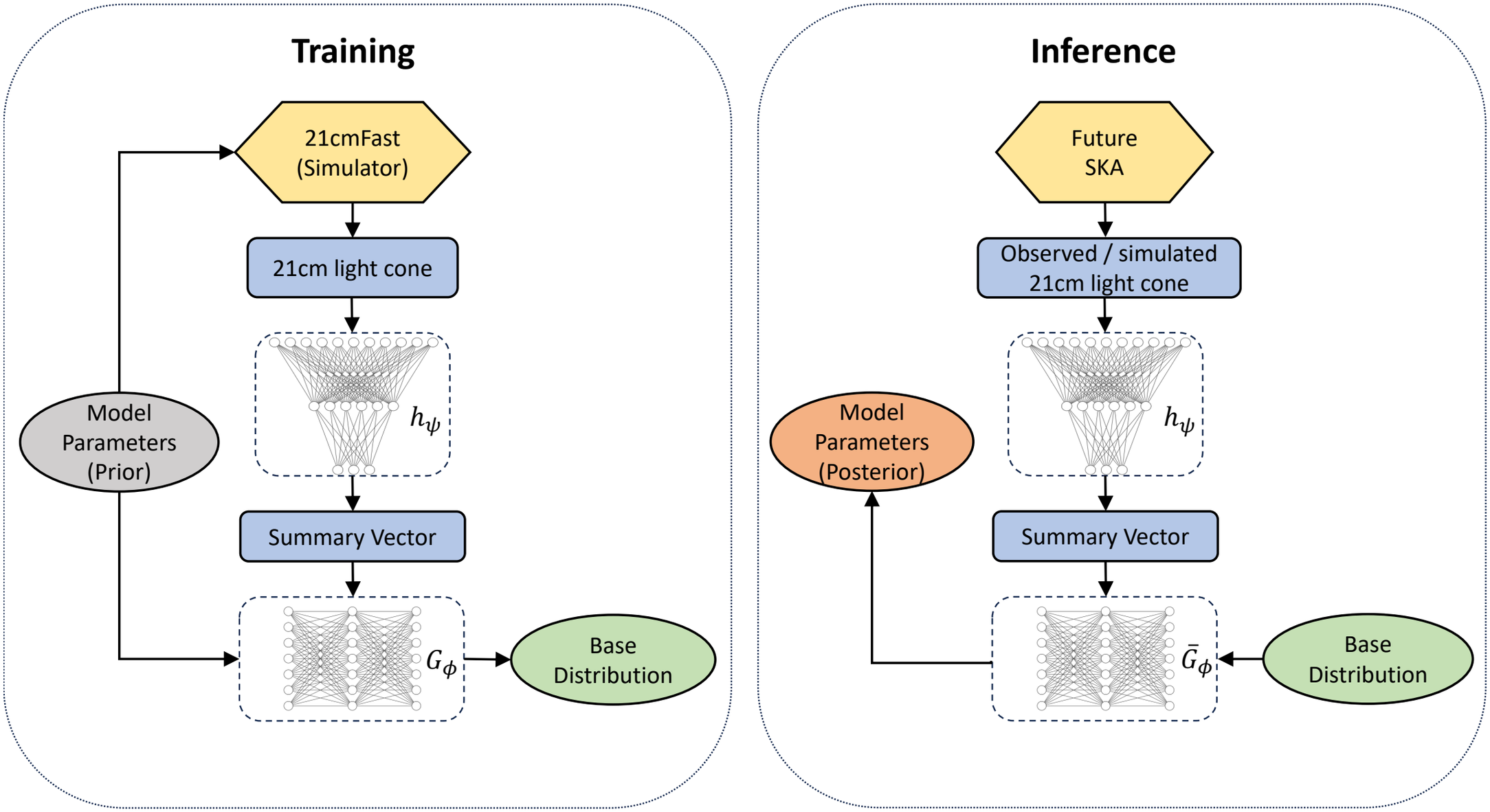


However, want

- non linearities
- fast Inference
- no hand-crafted summary statistic
- …

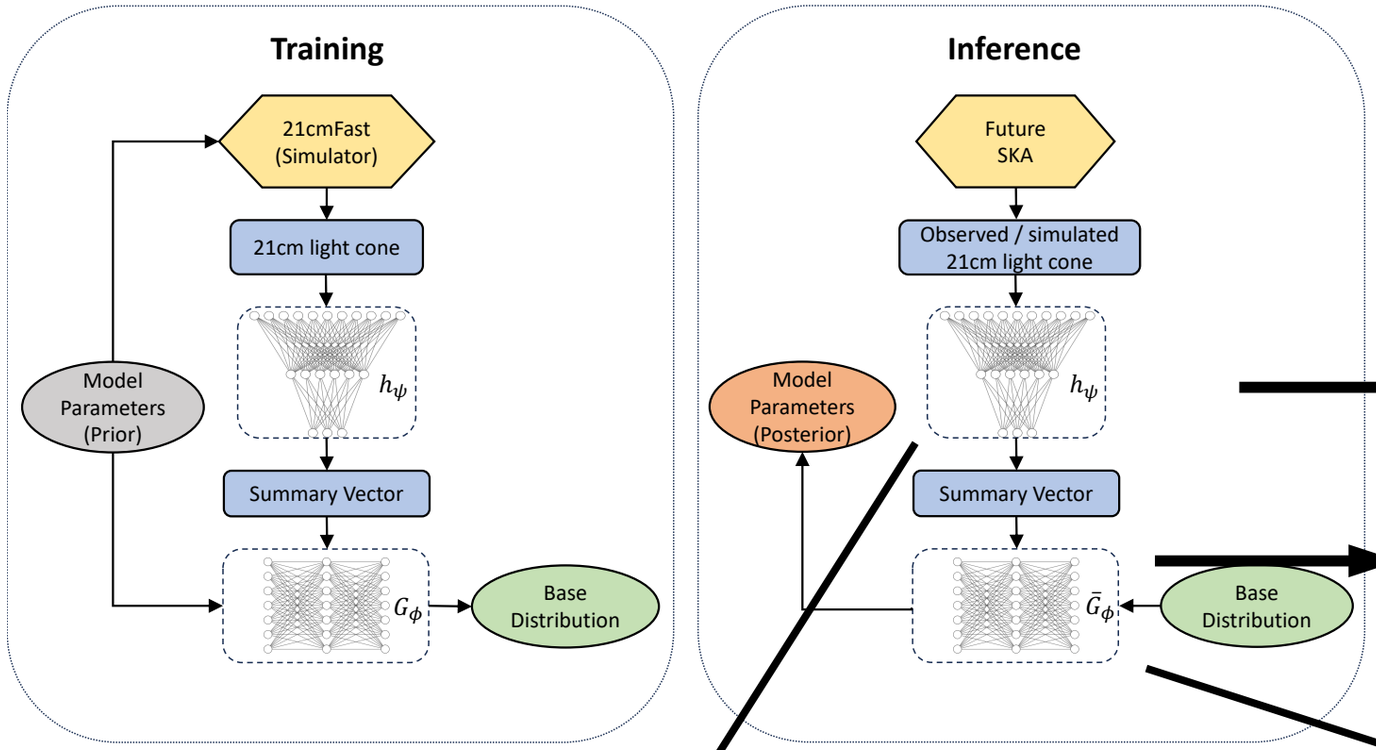


Simulation-based Inference: Concept



BayesFLow: Learning complex stochastic models with invertible neural networks, arXiv:2003.06281v4

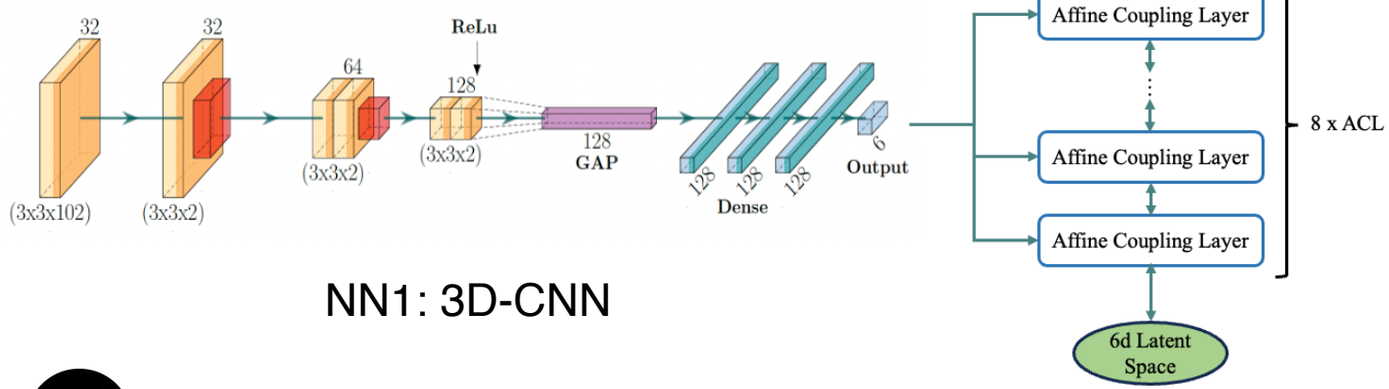
Simulation-based Inference: Model



NN1: Dimension reduction

NN2: Learning of distribution

Network Model:



NN1: 3D-CNN

Small networks,
comparably few parameters
= fast training and convergence

3D-21cmPIE-Net (public)

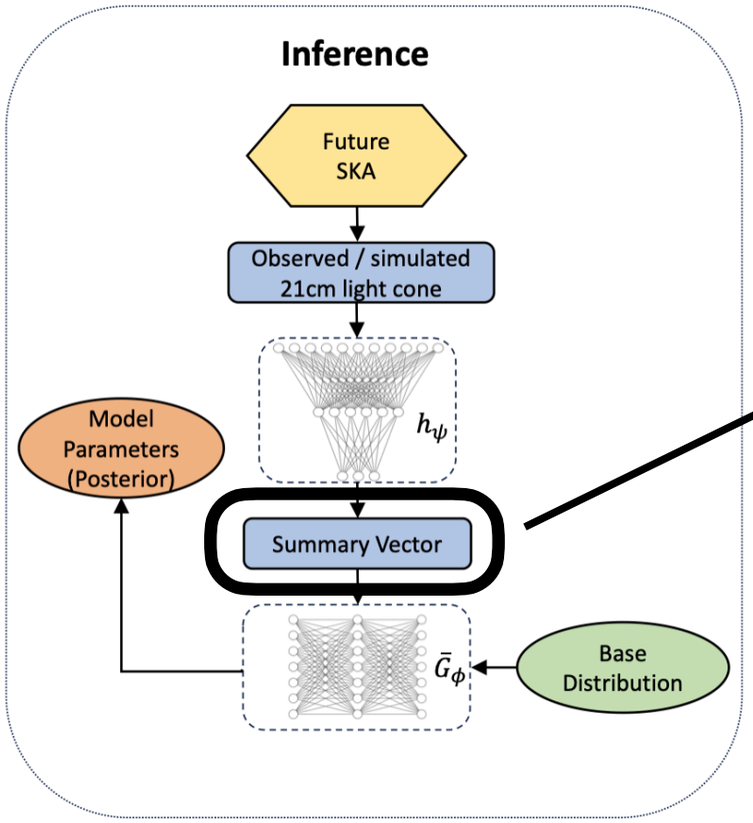
Neutsch, Heneka, Brüggen (2022)
arXiv:2201.07587

NN2: Invertible Network

21cm-cINN (private till published)

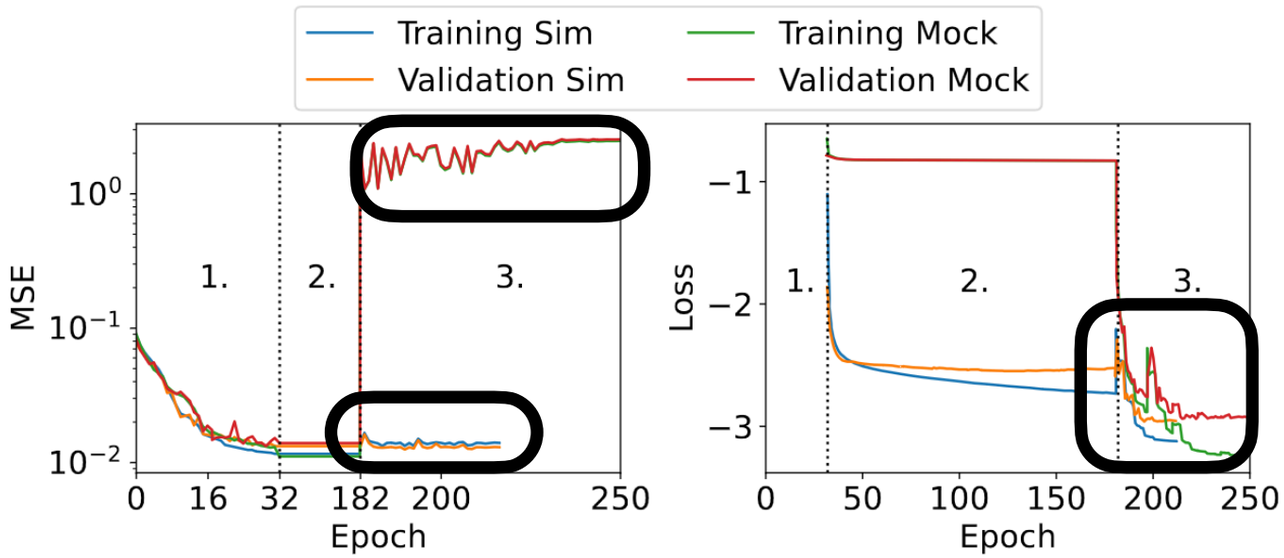
Schosser, Heneka, Plehn, arXiv:2401.04174

Lessons learned on Summaries



Summary vector versus summary statistics:
Free adjustment with scheduled training
= move away from ‘parameter interpretation’ of vector

Key difference between Sim and Mock:



We profit from learned summary in presence of noise (more).

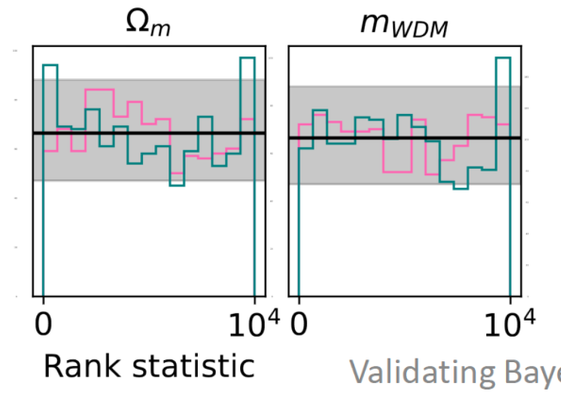
Sim: Summary stays close to original
Mock: Heavy adjustment of summary vector

Schosser, Heneka, Plehn, arXiv:2401.04174

Simulation-based Inference: Likelihood

Performance validation via:

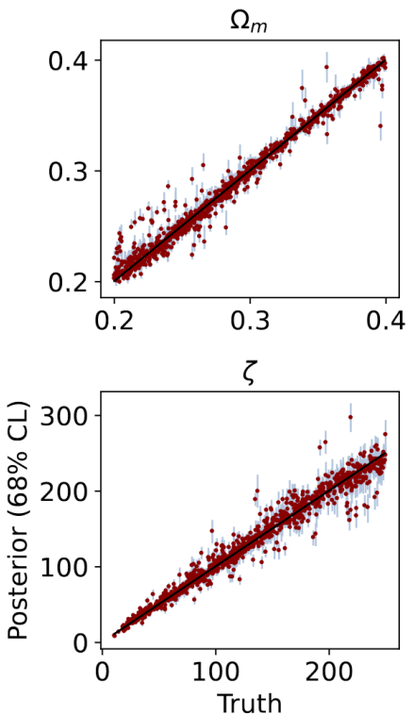
- Distribution of latent variables
- Simulation-based calibration
- Parameter recovery



Uniform distribution

Self-consistent sampling

Validating Bayesian Inference Algorithms with Simulation-Based Calibration, arXiv:1804.06788



Check Posterior vs. True label

Schosser, Heneka, Plehn, arXiv:2401.04174

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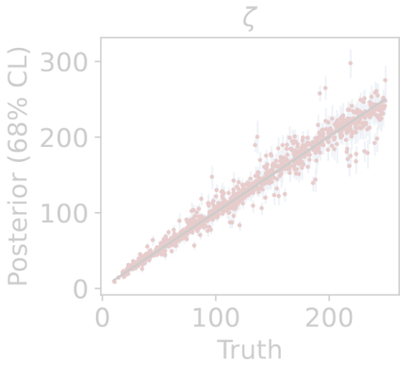

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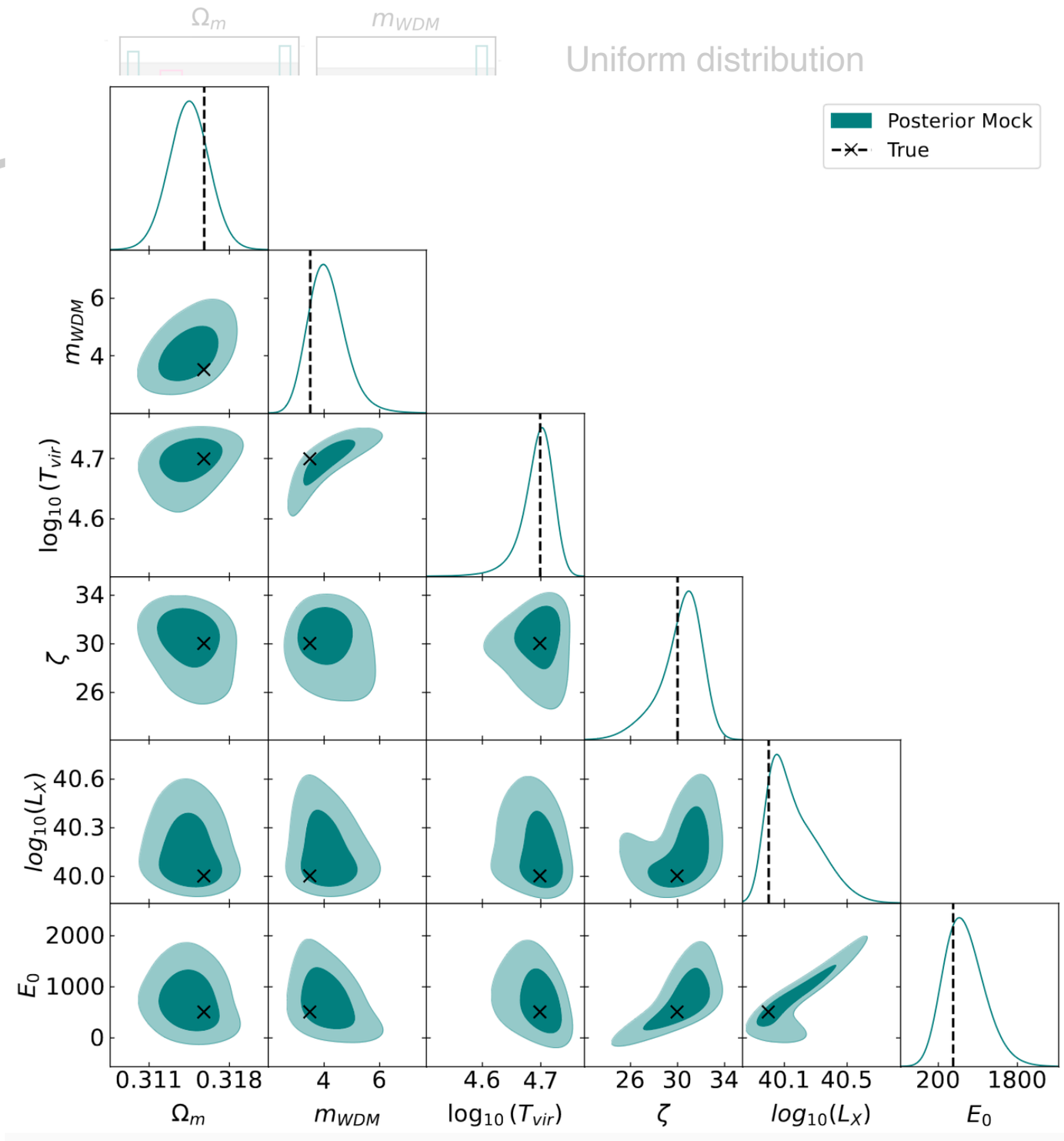
<u>Likelihood contours:</u>

Explore any model in prior range!

+ similar performance
  Mock vs. Sim
  (except for E_0)



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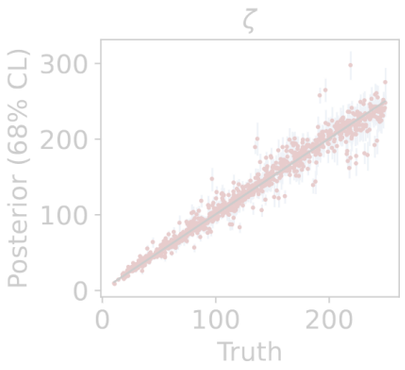

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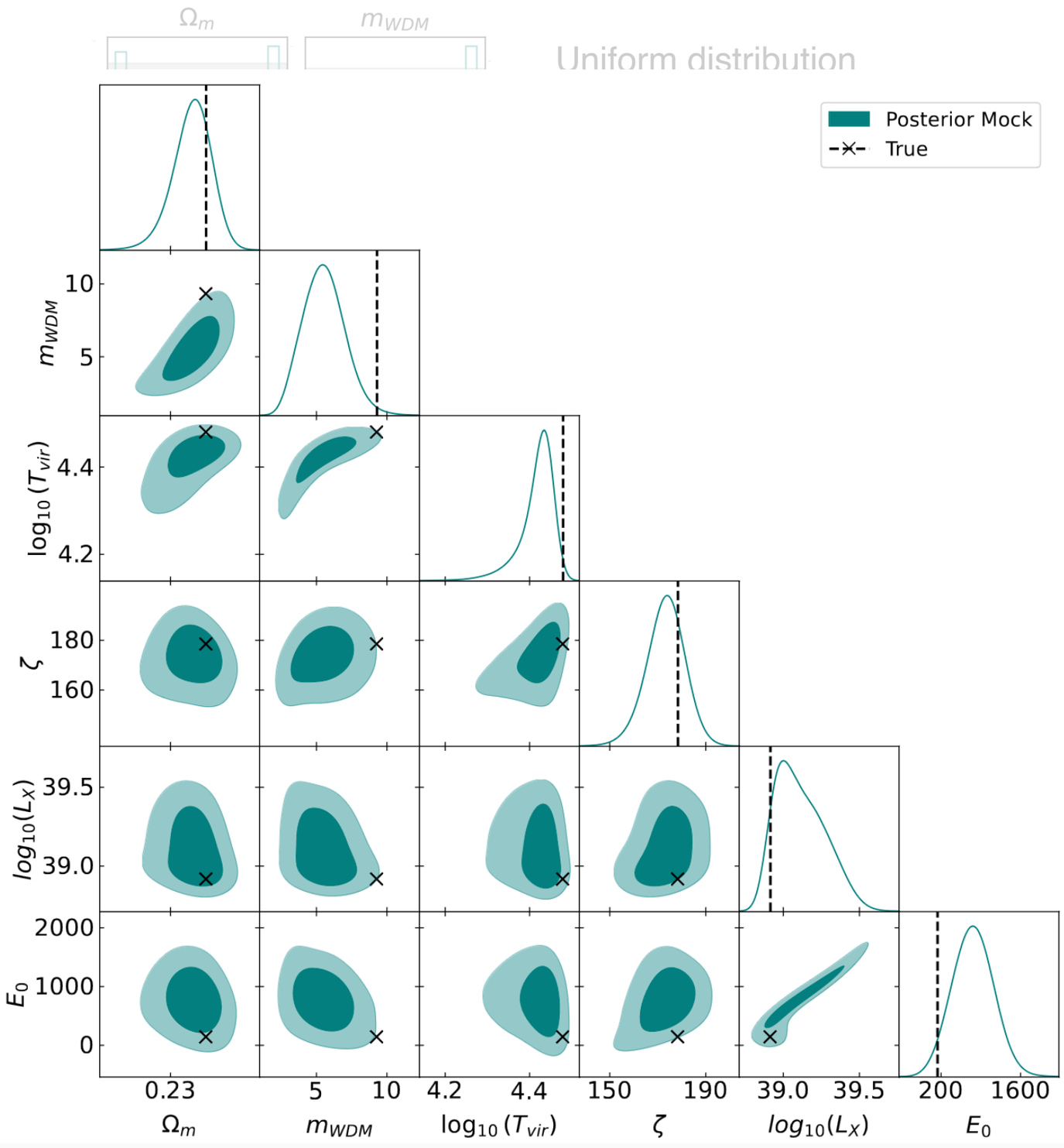

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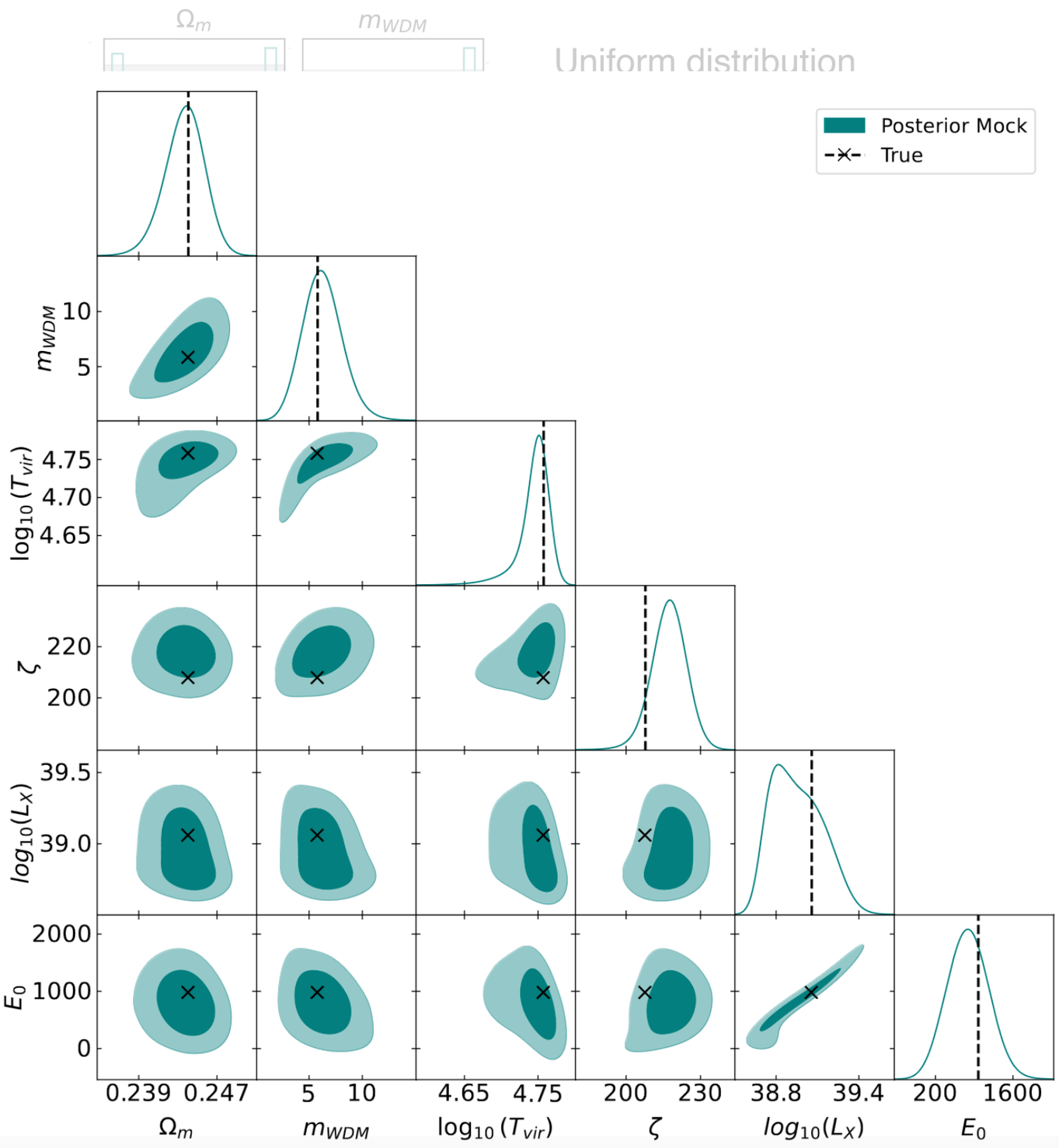

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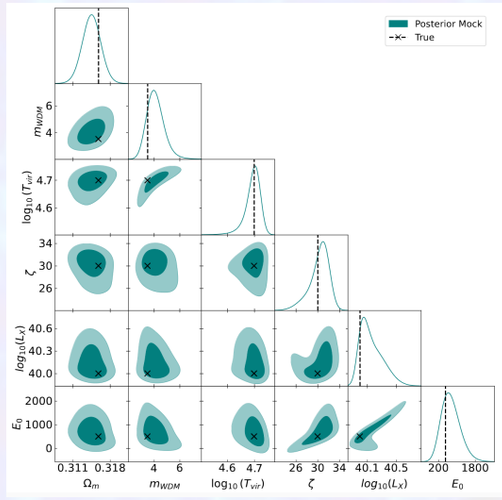
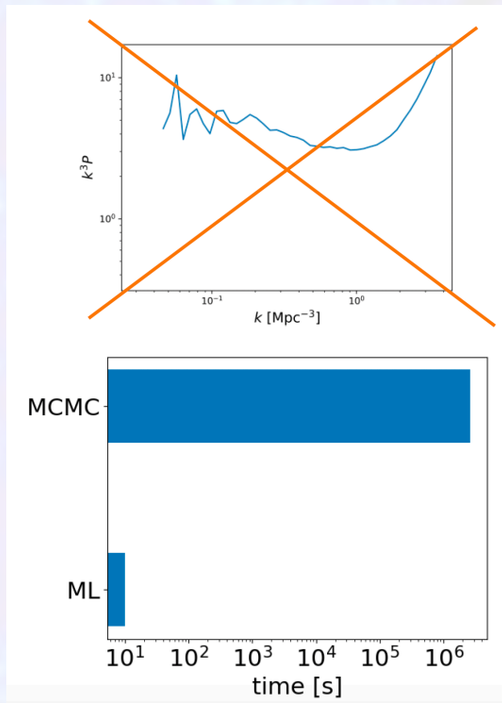
Summary and conclusions

- 21cmCosmoSim: Simulate 21cm light-cones in extended models
- 21cm data gives (also in extended models) joint constraints on Cosmology, Reionization, and Cosmic Dawn Astrophysics
- No need for hand-crafted summary statistics
- ML avenue to optimal, fast and robust inference





21cmCosmoSim: Continuous effort!

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Forschung

Beitritt zu internationalem Radioteleskop-Projekt

Abbildung einer Prototypschüssel des „Square Kilometre Array"-Observatorium auf dem südafrikanischen Standort (picture alliance / abaca | ABACA)

Liveübertragung: Donnerstag, 21. März, 19.15 Uhr

Thank you for your attention!