# Inference of astrophysical parameters with a conditional Invertible Neural Network

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Physics Institute III A | RWTH AACHEN UNIVERSITY

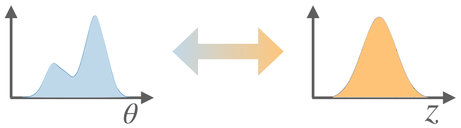
Teresa Bister[1], Martin Erdmann[1], Ullrich Köthe[2], *Josina Schulte*[1]
[1]III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
[2]University of Heidelberg, Interdisciplinary Center for Scientific Computing, Im Neuenheimer Feld 205, 69120 Heidelberg, Germany
josina.schulte@rwth-aachen.de

## Conditional normalizing flow

**normalizing flow** *(arXiv:1908.09257)*

- model complex probability distribution

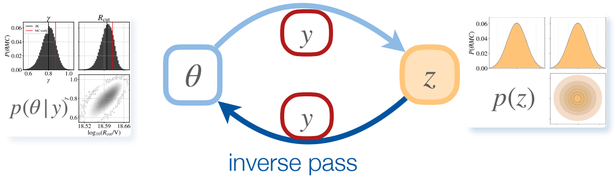
$$z = f_1 \circ \ldots \circ f_N(\theta)$$




**complex distribution** *(parameters of interest $\theta$)* **simple probability distribution** *(latents $z$)*

**conditional probability distribution** *(arXiv:2003.06281)*

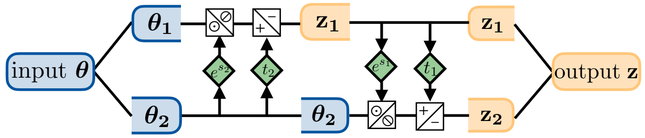
- mapping of parameters of interest $\theta$ to latents $z$ *under the condition* of observables $y$
  - posterior distributions $p(\theta \,|\, y)$ for specific observed $y$
    - quantify uncertainty, reveal correlations




## Conditional Invertible Neural Network

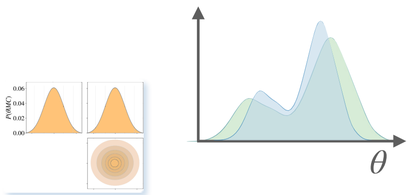
**network architecture**

- based on affine coupling layers *(arXiv:1605.08803)*
  - efficiently calculable Jacobian
  - condition: *(arXiv:1907.02392)*
    - concatenated to input of scale & translation transformations $s_i$, $t_i$




**suitable loss function**

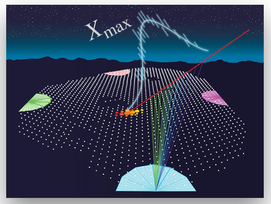
- Kullback-Leibler divergence
  - minimizes difference: true underlying posterior distribution & cINN posterior distribution
  - ensures convergence to correct posterior distributions
- enforce normal distribution for latents $z$




## Scenario from astroparticle physics

**extensive air showers**

- induced by ultra-high-energy cosmic rays
- measurement at Pierre Auger Observatory
  - energy spectrum
  - depth of shower maximum $X_{\max}$ distributions (∝ UHECR mass composition)



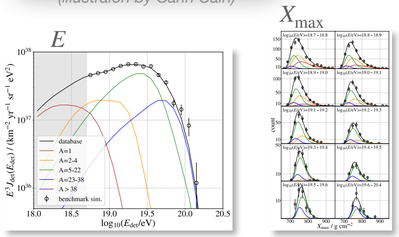

*(illustraion by Carin Cain)*

**astrophysical model**

- 7 free parameters $\theta$ in astrophysical model describing sources

*simulation of corresponding observables $y$*

- binned detected energy spectrum *(17 bins)* & binned $X_{\max}$ distributions *(10 x 24 bins)*

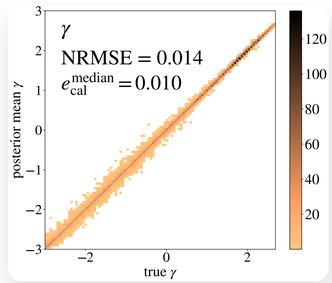


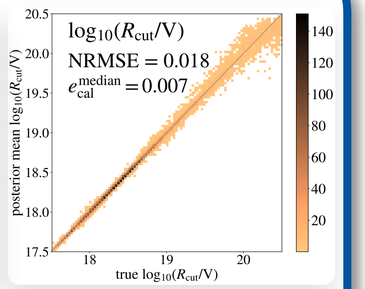

## cINN reconstruction quality

**reconstruction quality** → *arXiv:2110.09493*

- evaluation of 10,000 test datasets
- normalized root mean square error (NRMSE)
  - agreement of posterior mean with true value
- calibration error $e_{\text{cal}}$
  - estimation of correctness of widths of posterior distributions

→ good reconstruction quality & appropriate uncertainty estimation




**comparison of posterior distributions**
cINN ↔ Markov Chain Monte Carlo (*MCMC*)

- very similar posterior distributions
- evaluation with cINN computationally more efficient