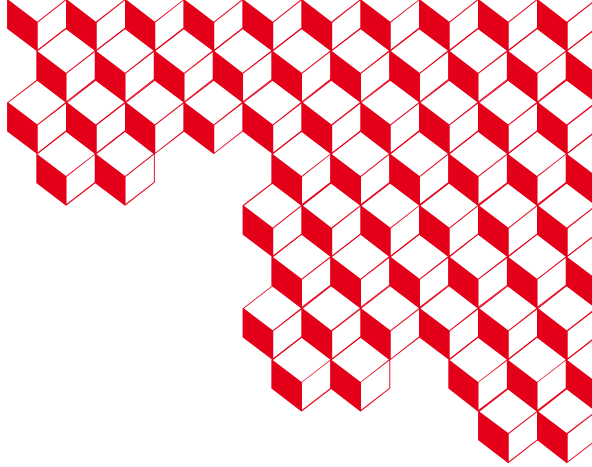


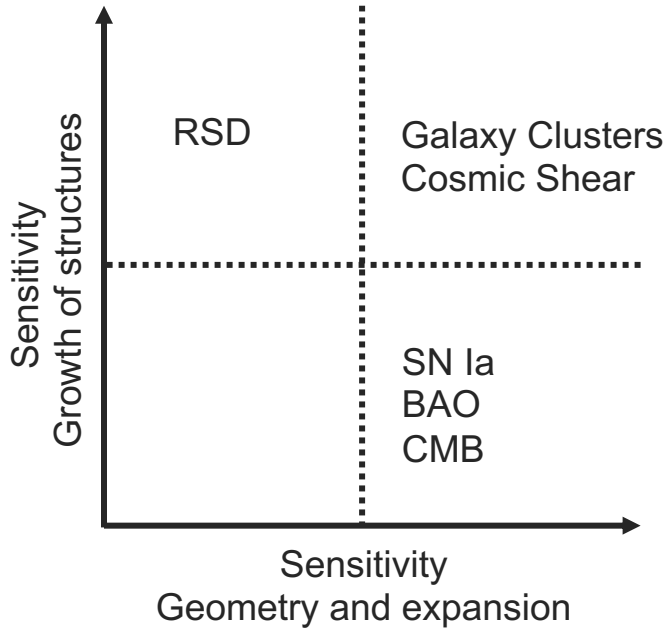
Simulation-based modelling of X-ray cluster samples

Nicolas Cerardi

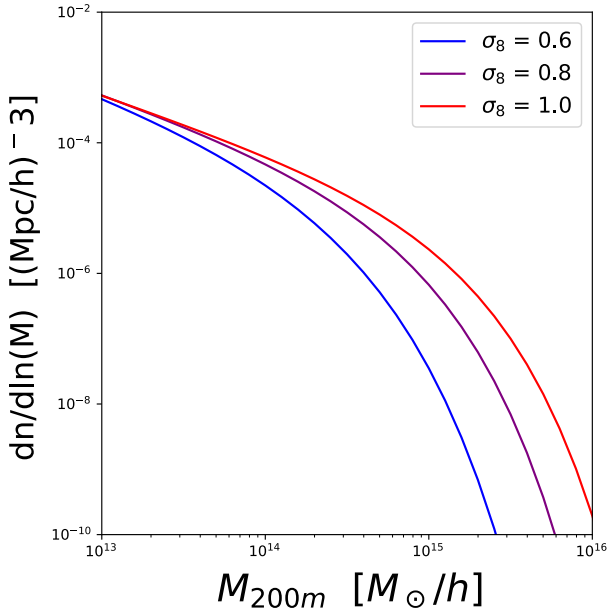
Under the supervision of Marguerite Pierre and François Lanusse

Cluster Cosmology

- Probe for the growth of structure and the geometry of the universe
- Population studies: abundancy, angular correlation…
- Standard candels: gas fraction…



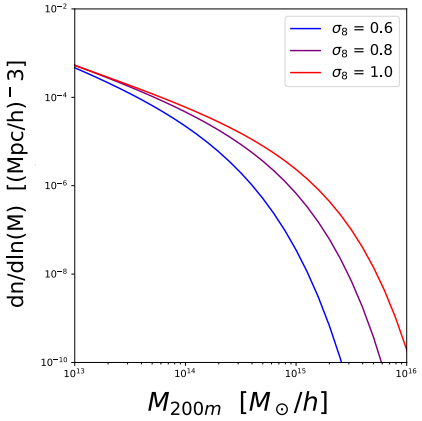
Halo Mass Function (HMF)



Cluster cosmology: link between mass and observables

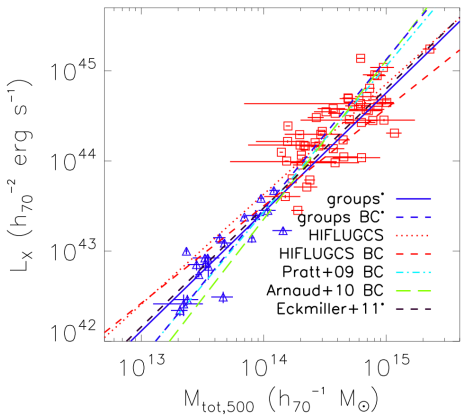
HMF

Calibrated on simulations



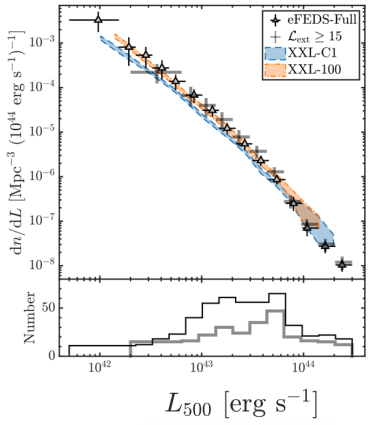
Scaling relations

Fitted on observed samples



Lovisari+2020

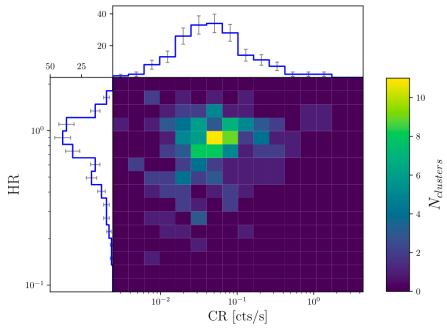
Physical properties



Liu+2021

Instrument knowledge

Observed cluster samples



3D X-ray observable diagram, Garrel+22

- Empirical fit on the scaling relations parameters $\log X = \alpha + \beta \log M + \gamma \log E(z) \quad \pm \sigma$.
- Deviation from theoretical predictions: environmental effects (triaxiality, mergers..) + baryonic processes (CC, AGN and SN retroaction, …)

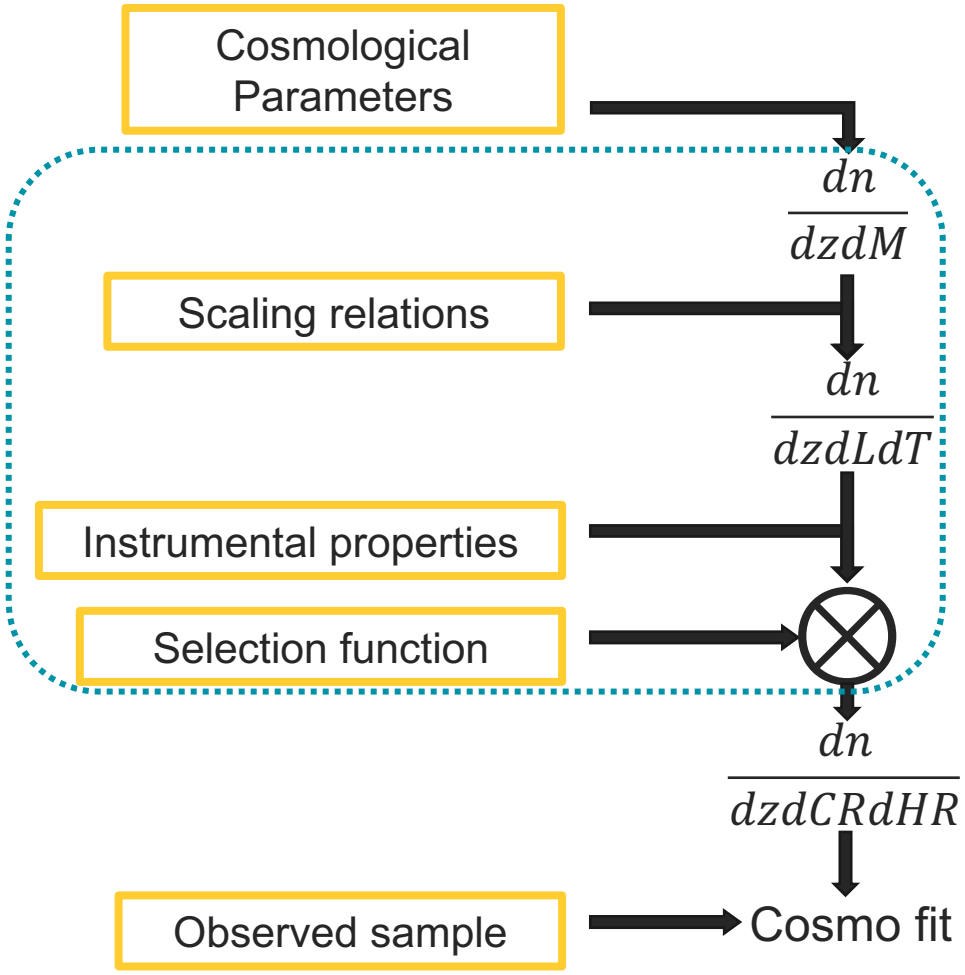
Goal : model cluster populations without empirical, explicit scaling relations

Modelling without scaling relations ?

Simulation-based model:

- Directly models physical processes that affects clusters properties.
- Computationally too expensive.
- Hydro simulation acceleration/emulation with ML

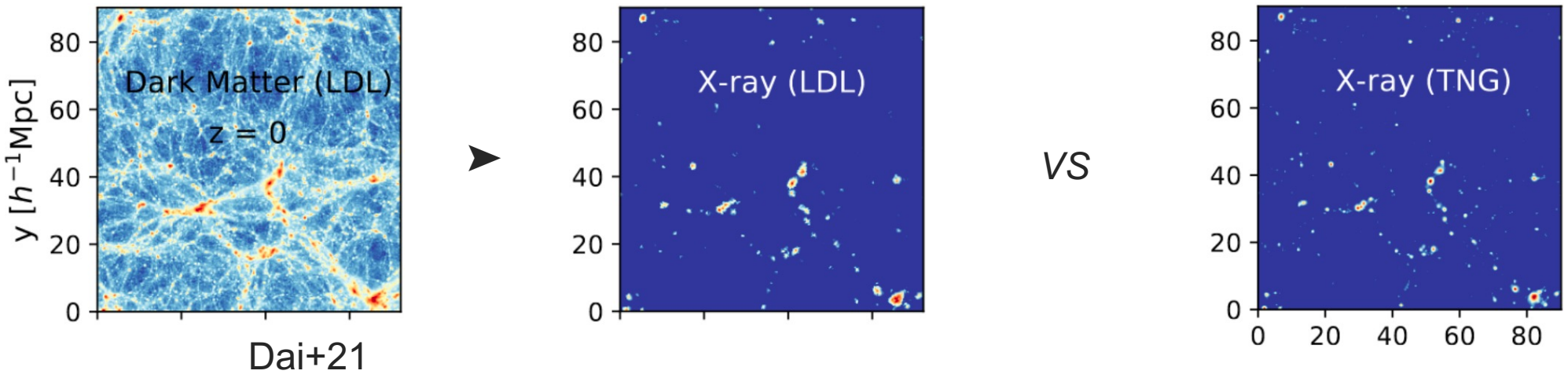
1. **Can we learn a fast and accurate (relatively to simulations) baryon pasting model ?**
2. **What advantage during inference ?**



Baryon pasting

Lagrangian Deep Learning (LDL): Baryon pasting on DMO simulations

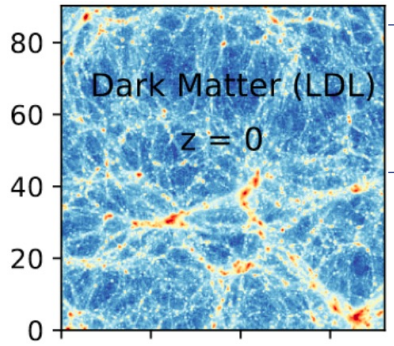
- Fast emulation of full 3D baryonic property
- For Xray emission: electron number density n_e and temperature T.



Dai+21

Baryon pasting

Lagrangian Deep Learning (LDL): Peinture baryonique sur un champ de DMO



Dai+21

$\mathbf{x}$

$f(\delta) = (1+\delta)^{\gamma}$
Potential (Fourier space)

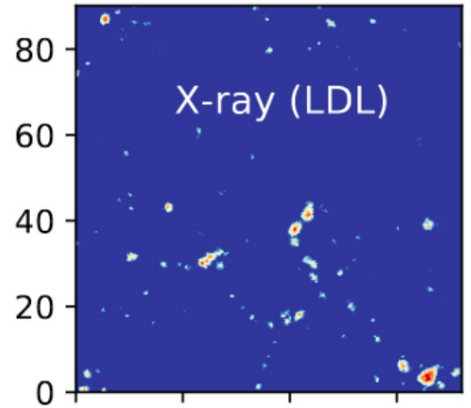
Corrected Potential (Fourier Space)

$\mathcal{S}_{\varphi}(k)$
1D Fourier filter

$\mathrm{d}\mathbf{x} = \alpha \nabla \mathcal{F}^{-1}(\mathcal{S}_{\varphi}(k) f(\delta))$
Displacement field

$\delta'(\mathbf{x} + \mathrm{d}\mathbf{x})$
Updated field

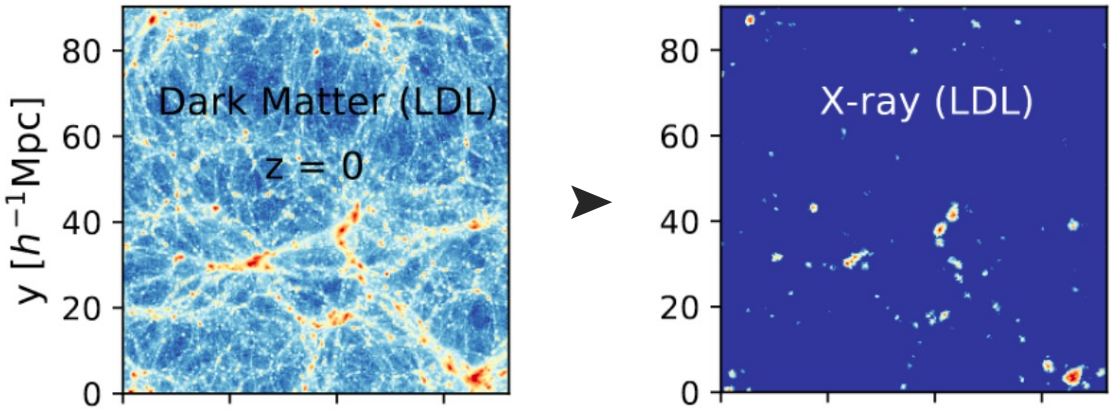
$F(\mathbf{x}) = \mathrm{ReLU}(b_1(1+\delta')^{\mu} + b_0)$
Non-linear activation



Advantages

- Adopts physical principles.
- Lighter model than deep generative models.

Baryon pasting



Dai+21

Conditioning the baryon pasting model on simulation parameters
Meta-learning LDL parameters with fully-connected NN.

$$\Omega_m, \sigma_8, A_{feedback} \xrightarrow{NN} \gamma, \varphi, \alpha, b_0, b_1, \mu$$

Training simulations

CAMELS dataset

- Thousands of simulated volumes.
- HD Codes : **IllustrisTNG** / SIMBA / Astrid / Magneticum.
- Fiducial simulations: 27x(50 Mpc/h)^3
- Varied simulations: 500x(25 Mpc/h)^3

  Cosmology : Ω_m , σ_8.

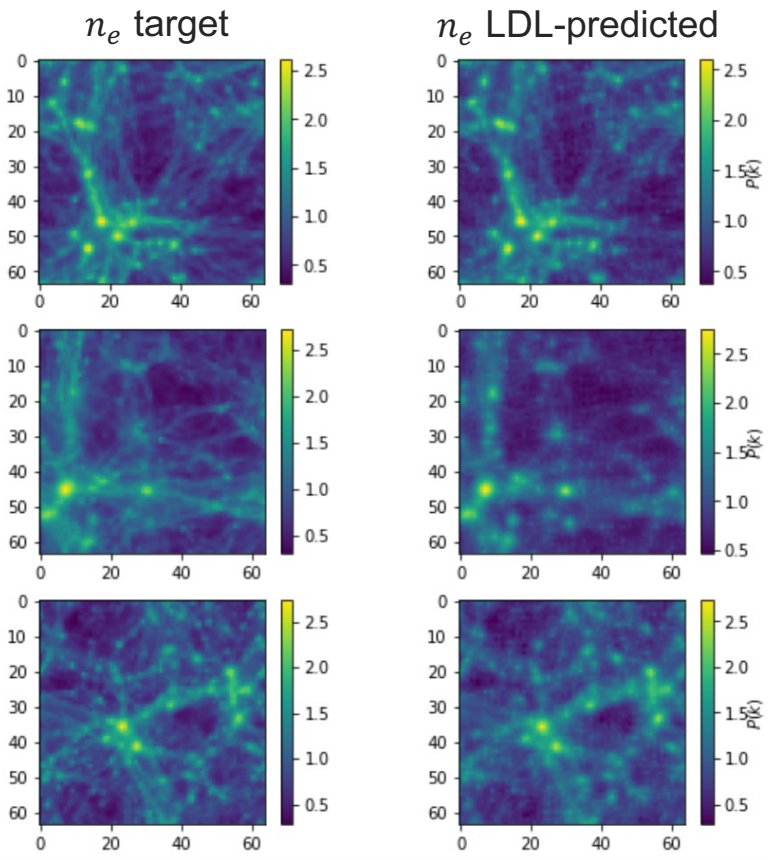
  SN : A_{SN1}, A_{SN2}, energy and speed of galactic winds.

  AGN : A_{AGN1}, $A_{AGN2,}$ power and burstiness of kinetic mode / low accretion rate.

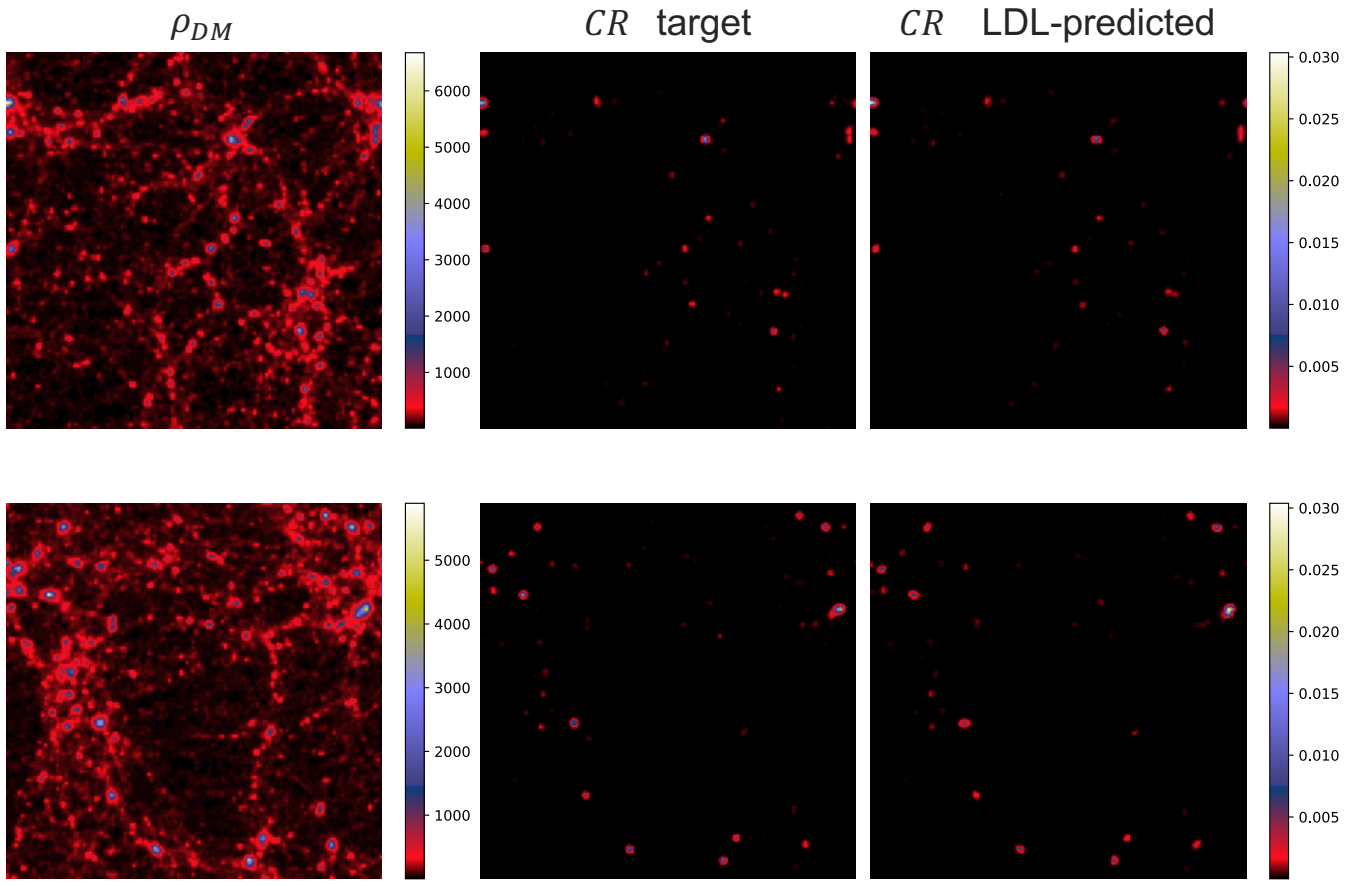
K. Wong

Emulated fields

Baryonic properties, CAMELS/LH

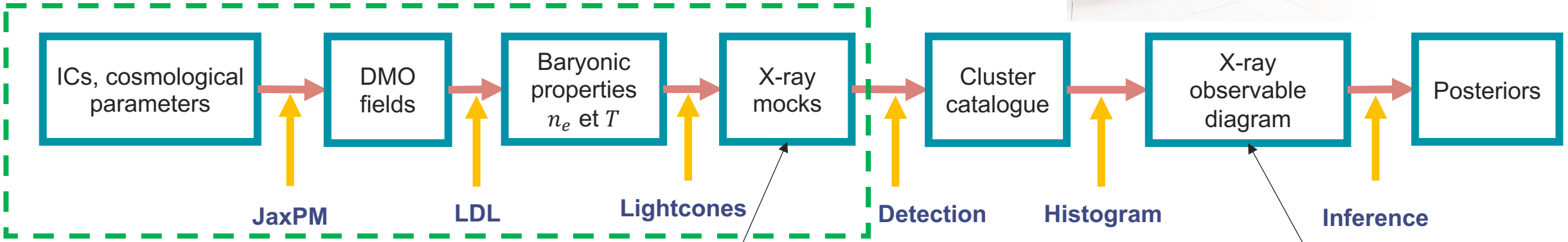


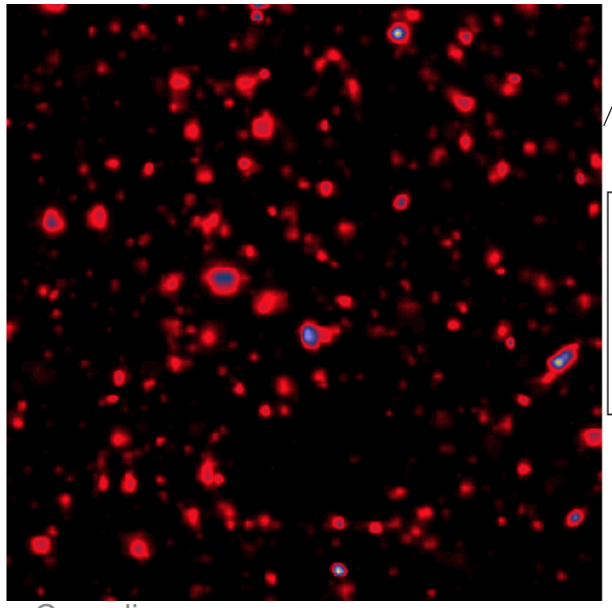
X-ray emission, CAMELS/CV50



End-to-end pipeline

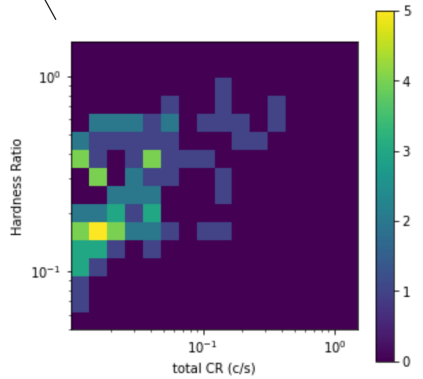
Compiled on GPUs: ~30s to make a mock X-ray map!





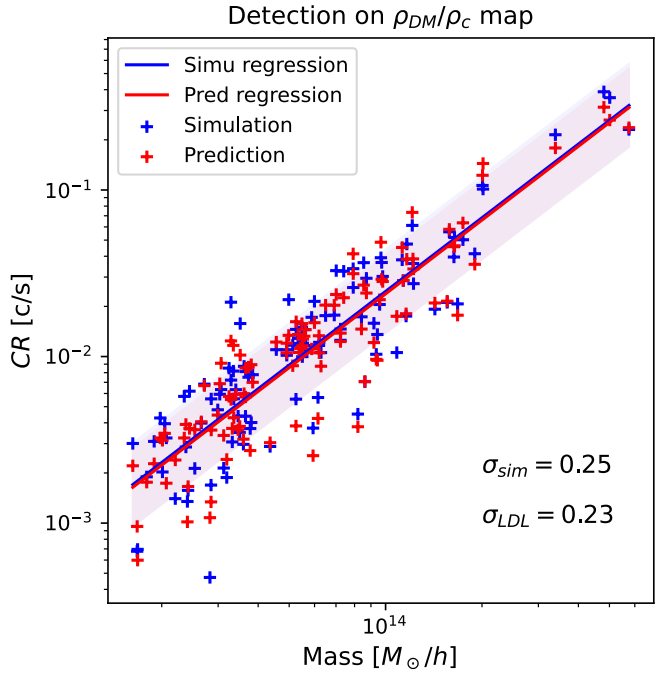
Simplified detection

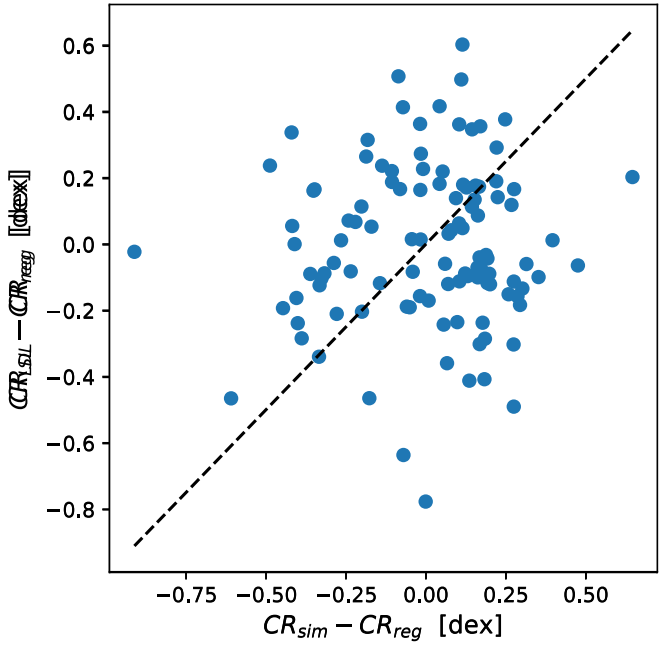
- Simplifications: no AGNs, no galactic absorption
- Detection SExtractor-like on unnoised CR maps
- Measures of clusters' CR and HR



Emulated scaling relations

- Reproduction of CR-M relation from the fiducial model @ z=0.21.
- Correlated deviations : LDL benefits from the 3D information on each halo environments.



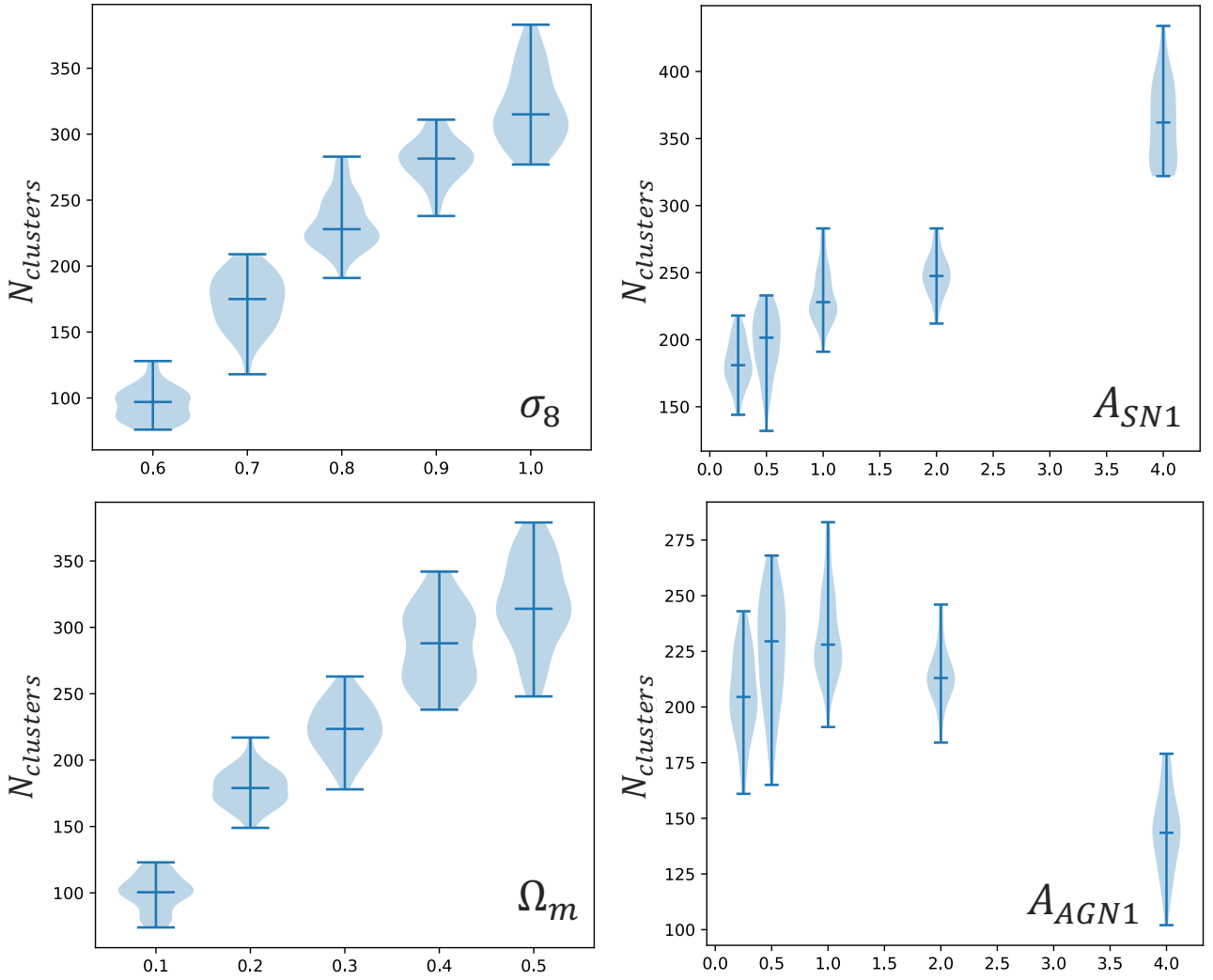


- Too few clusters in CAMELS/LH to conduct the same test

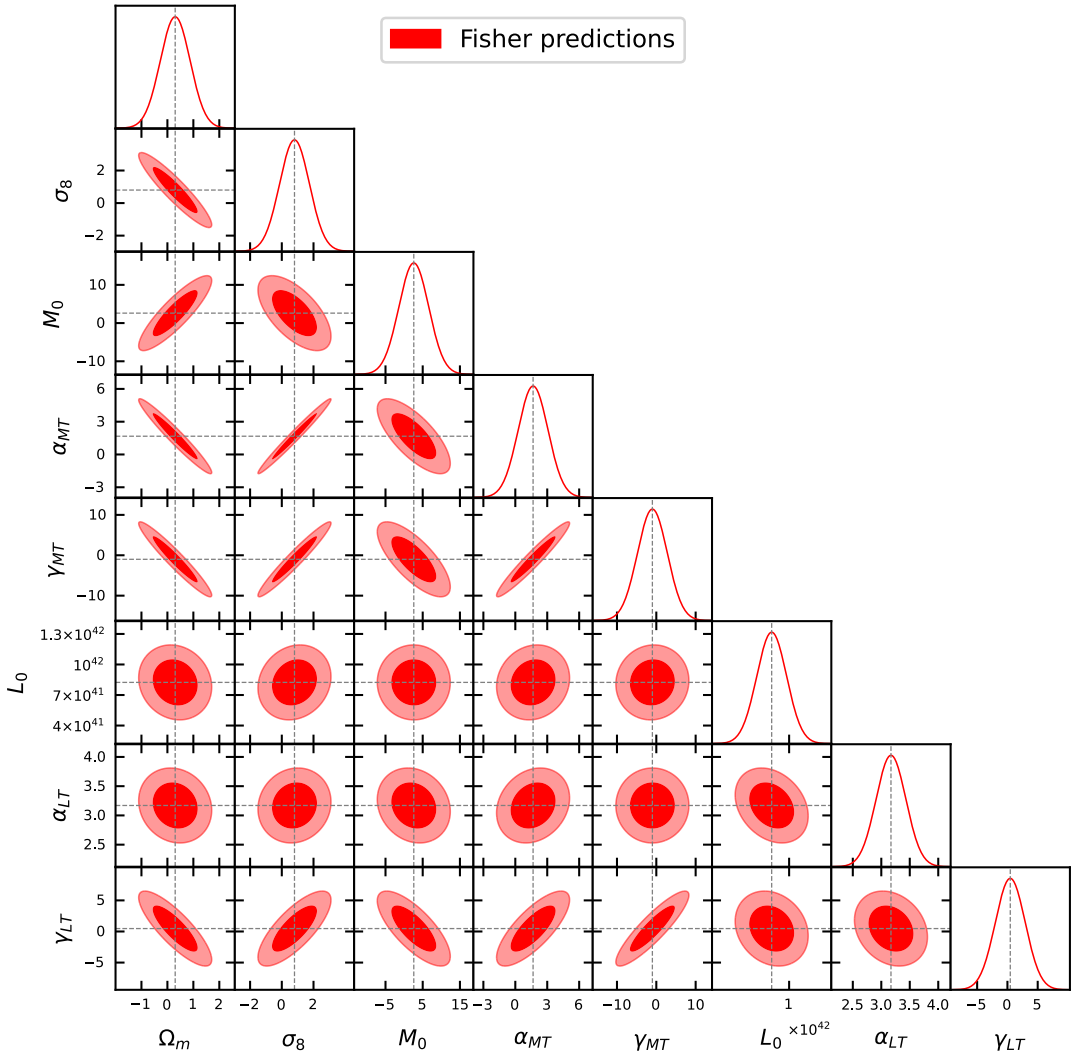
Pipeline sensitivity

Individual variation of each parameter

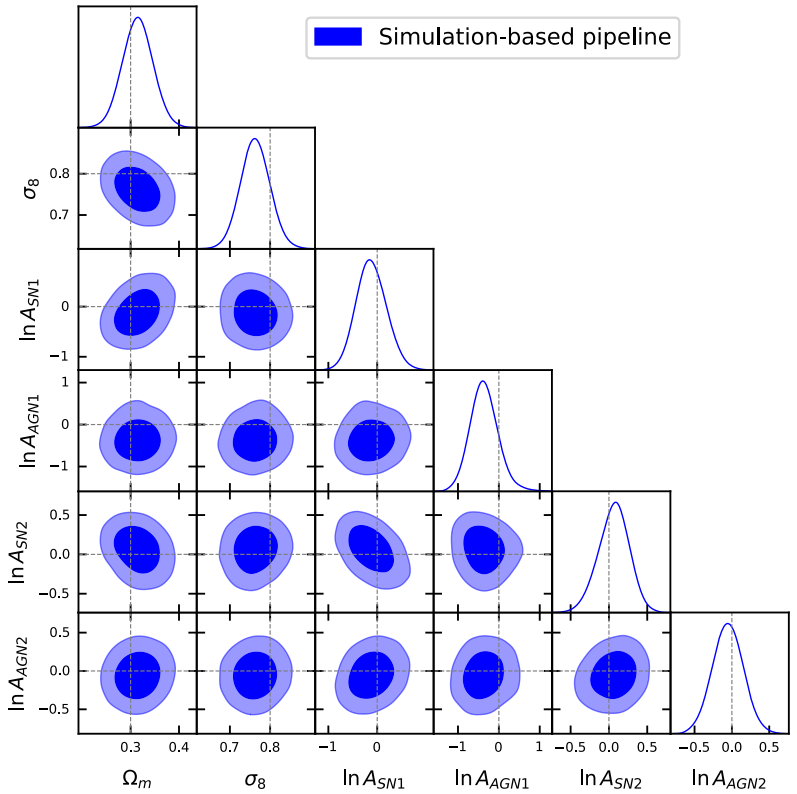
- 48 surveys of 50 deg^2 for each parameter value
- Strong sensitivity to cosmological parameters (full pipeline)
- Strong response to SN retroaction but weak to AGN parameters (extended LDL)



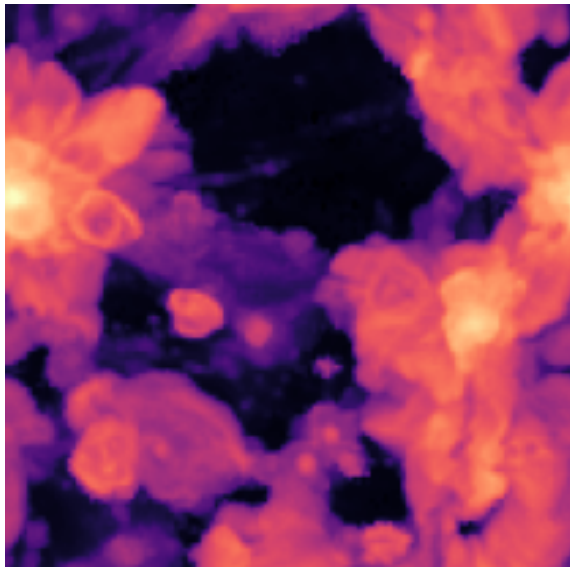
Degeneracies in each model



- Full posteriors for explicit model (empirical scaling relations) and simulation-based model.
- Less degeneracies with simulation-based model.

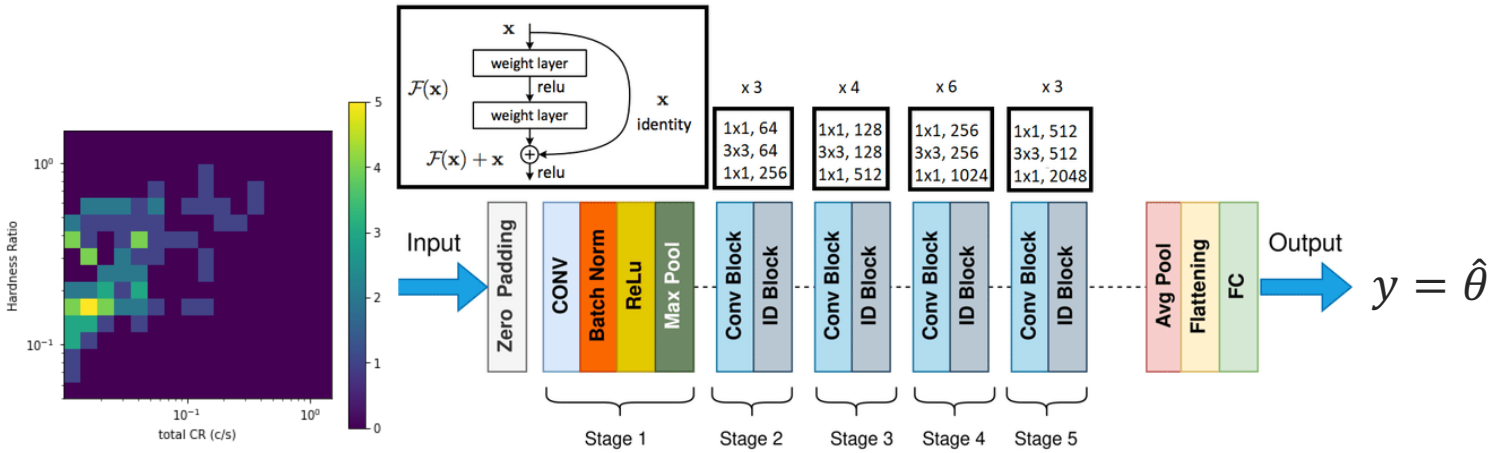


Thank you !

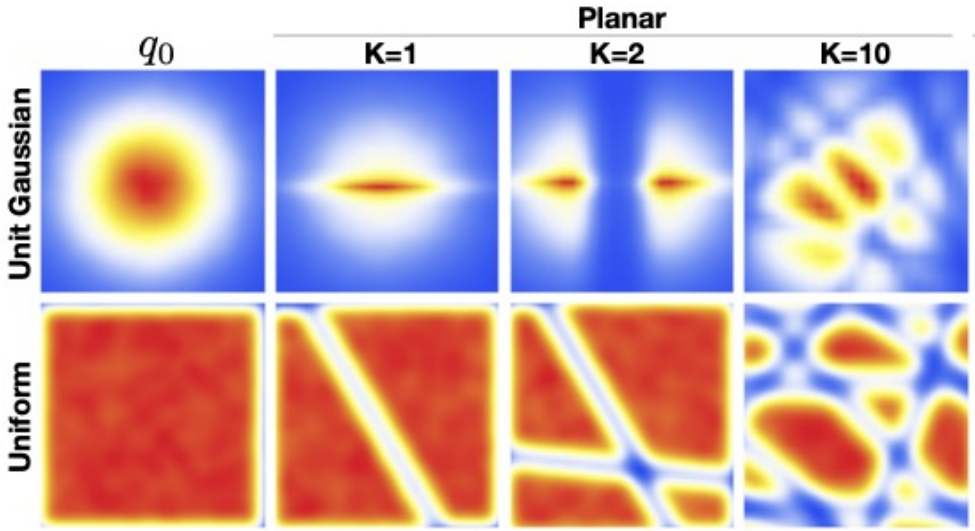


Simulation-based inference

- Compression of cluster counts into low dimension statistics



- Direct neural posterior estimation with density estimators

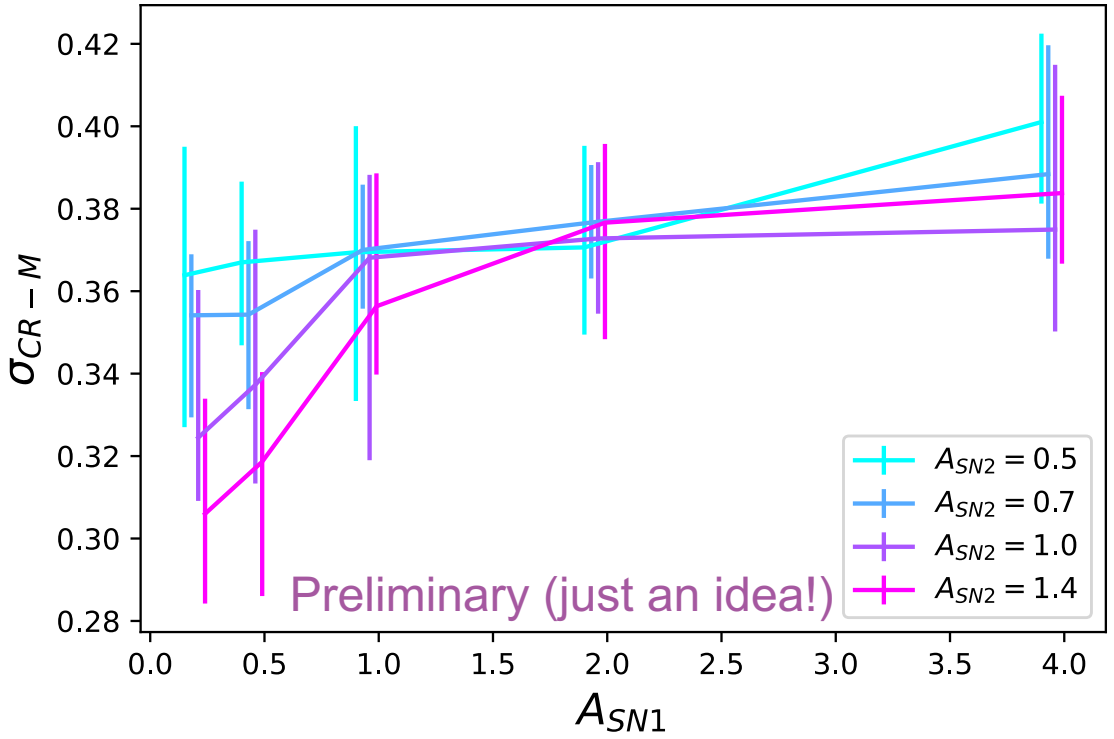


Rezende+2016

Alternative idea: simulation-based scaling relations ?

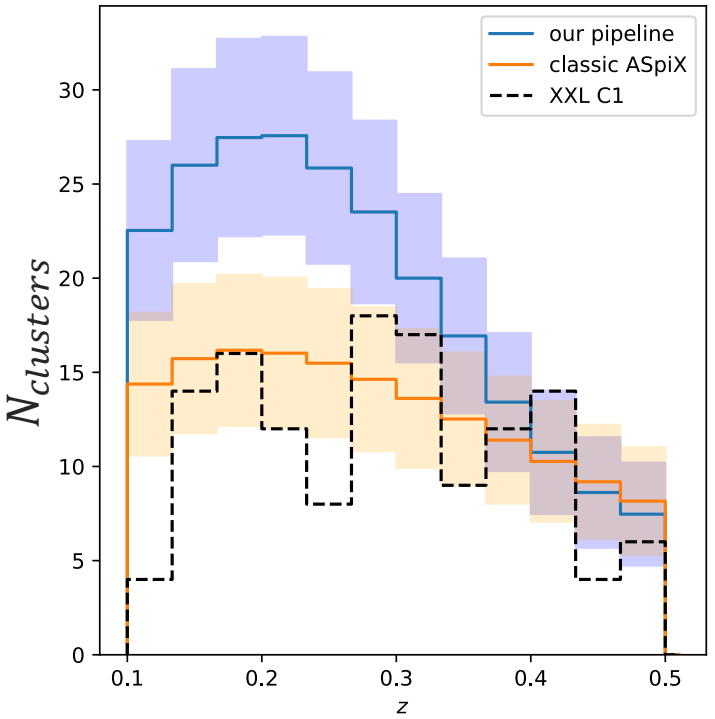
Explicit model with scaling relations sampled from extended LDL simulations ?

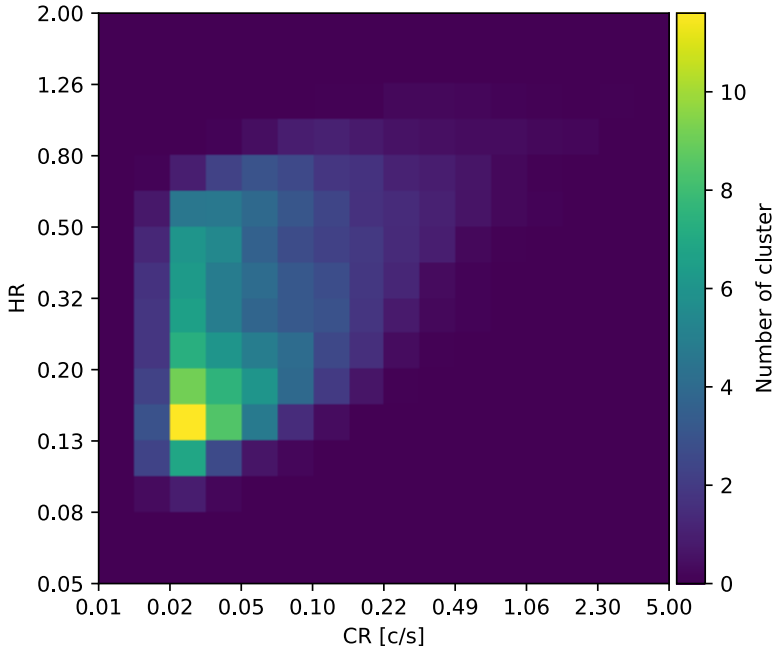
1. Use the extended LDL to generate mock X-ray cluster catalogues.
2. Fit scaling relations on it.
3. Train a scaling relation emulator, with physicial insights from HD simulations !



Comptages d'amas

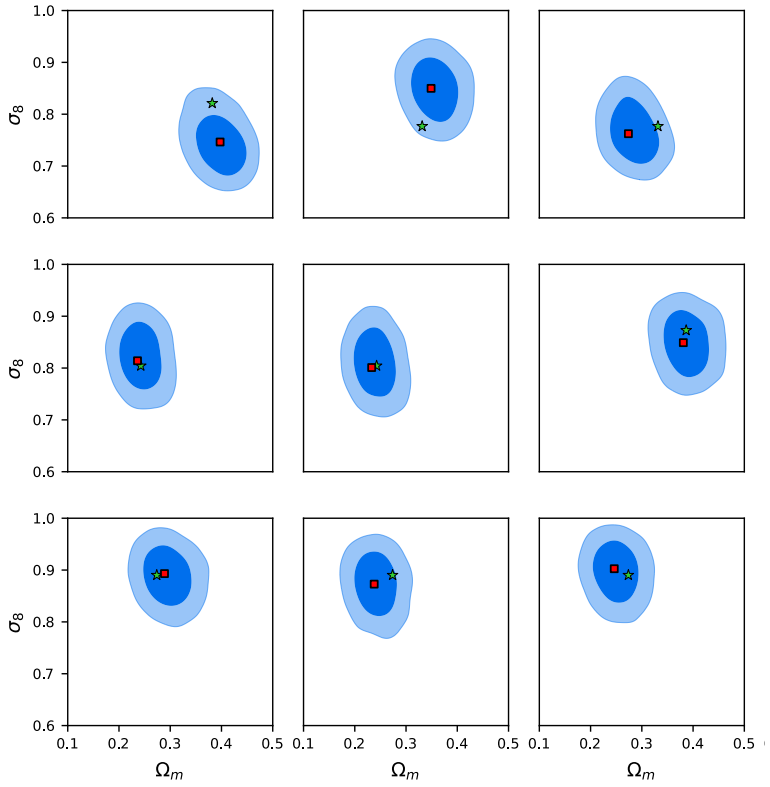
- Comptages moyennés sur 48 relevés de 50 deg2 – modèle fiduciel
- 40% d'amas supplémentaires pour notre pipeline



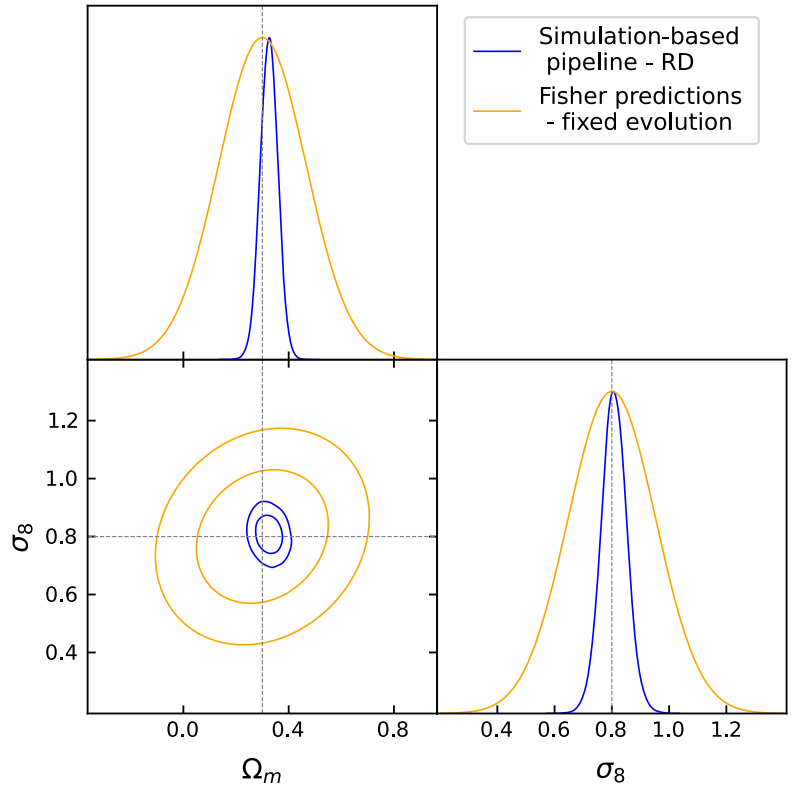


Posterior cosmologiques

- Inférence NPE sur les diagrammes simulés



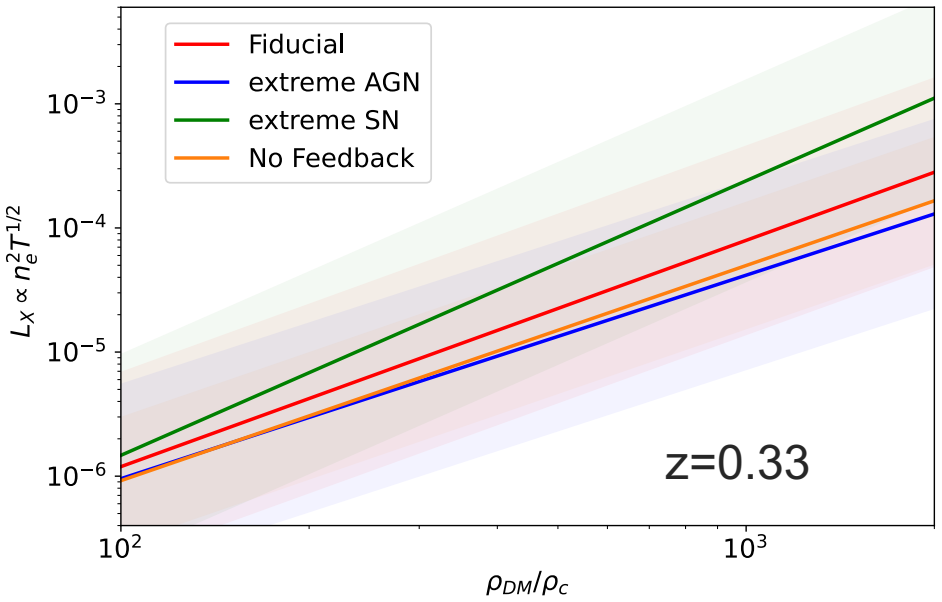
- Comparaison avec la modélisation classique (analyse de Fisher)

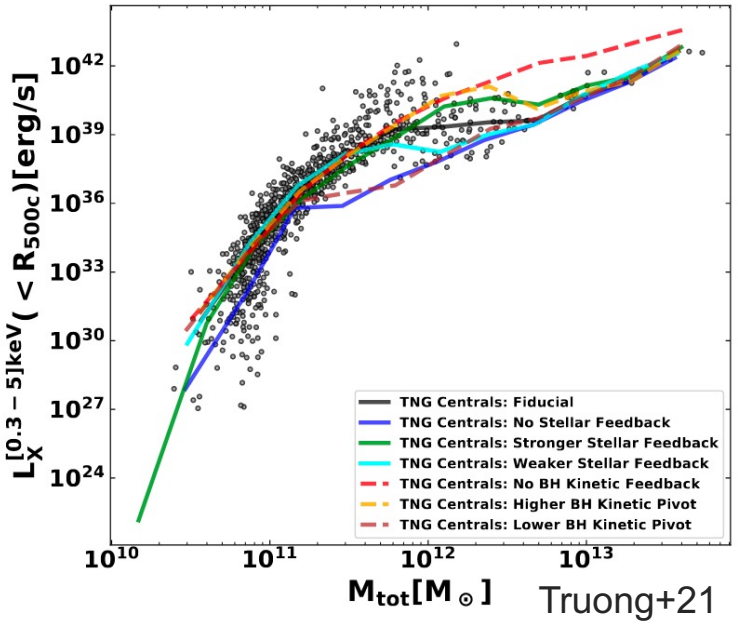


Sensibilité CAMELS/IllustrisTNG

Pertinence des paramètres variés

- Impact SN > AGN pour le gaz intra amas, étonnant !
- Consistent avec la réponse du LDL étendu.
- CAMELS fixe plusieurs paramètres importants pour la rétroaction AGN (Truong+21).

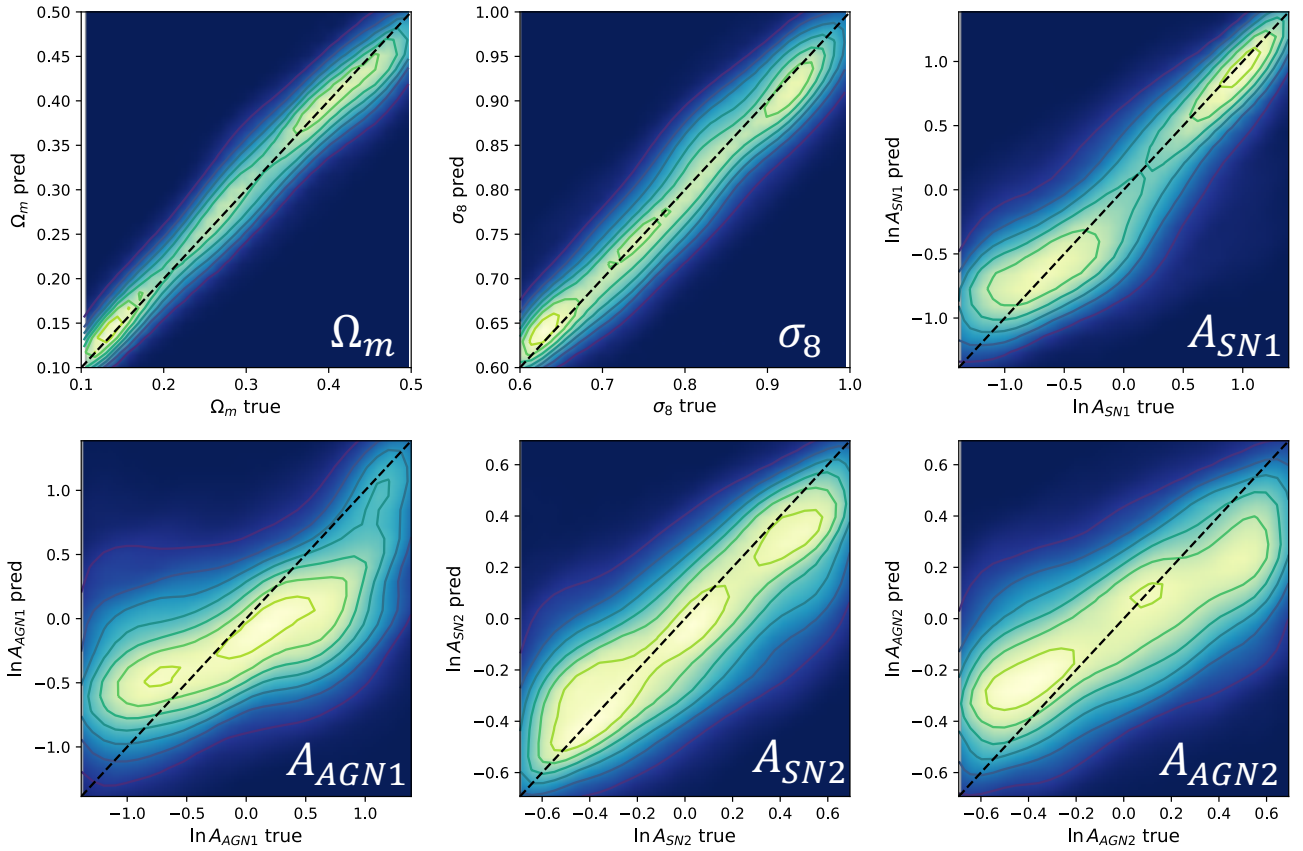




Inférence implicite avec le pipeline de simulations

- Reprise des mêmes méthodes (ResNet + NPE)
- Comparaison avec une analyse de Fisher (même modèle analytique que Kosiba, Cerardi+24)
- Création de 48000 cônes de lumière $\sim p_{CAMELS}(\theta_{sim})$, 2000h GPU.

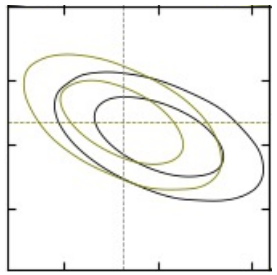
Figures de regression



Conclusion

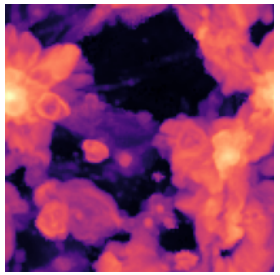
Cosmologie par amas avec ATHENA

Interêt de la cosmologie par amas pour contraindre l'équation d'état d'énergie noire avec des échantillons haut z



Inférence sans relation d'échelle

Analyse cosmologique d'échantillon d'amas avec inférence sans vraisemblance.



Modélisation sans relation d'échelle

Modèle de baryonification conditionné sur des simulations hydrodynamiques, et sur leurs paramètres de rétroaction.
Pipeline de simulation générant fausses cartes X et diagrammes d'observables X.
Inférence basée sur des simulations

Perspectives

- Nouvelles simulations CAMELS : plus grands volumes simulés, plus de paramètres variés.
- Réalisme de la partie détection $\Longrightarrow$ fonction de détection similaire à un vrai relevé.
- Effet de la résolution de la baryonification ? Code GPU parallélisé, méthodes de super résolution ?
- Emulation d'observations d'amas dans d'autres longueur d'ondes (SZ) ?