Determining the Dark Matter distribution in galaxies with Deep Learning (2111.08725)

As part of the darkmachines projects challenges: https://darkmachines.org/

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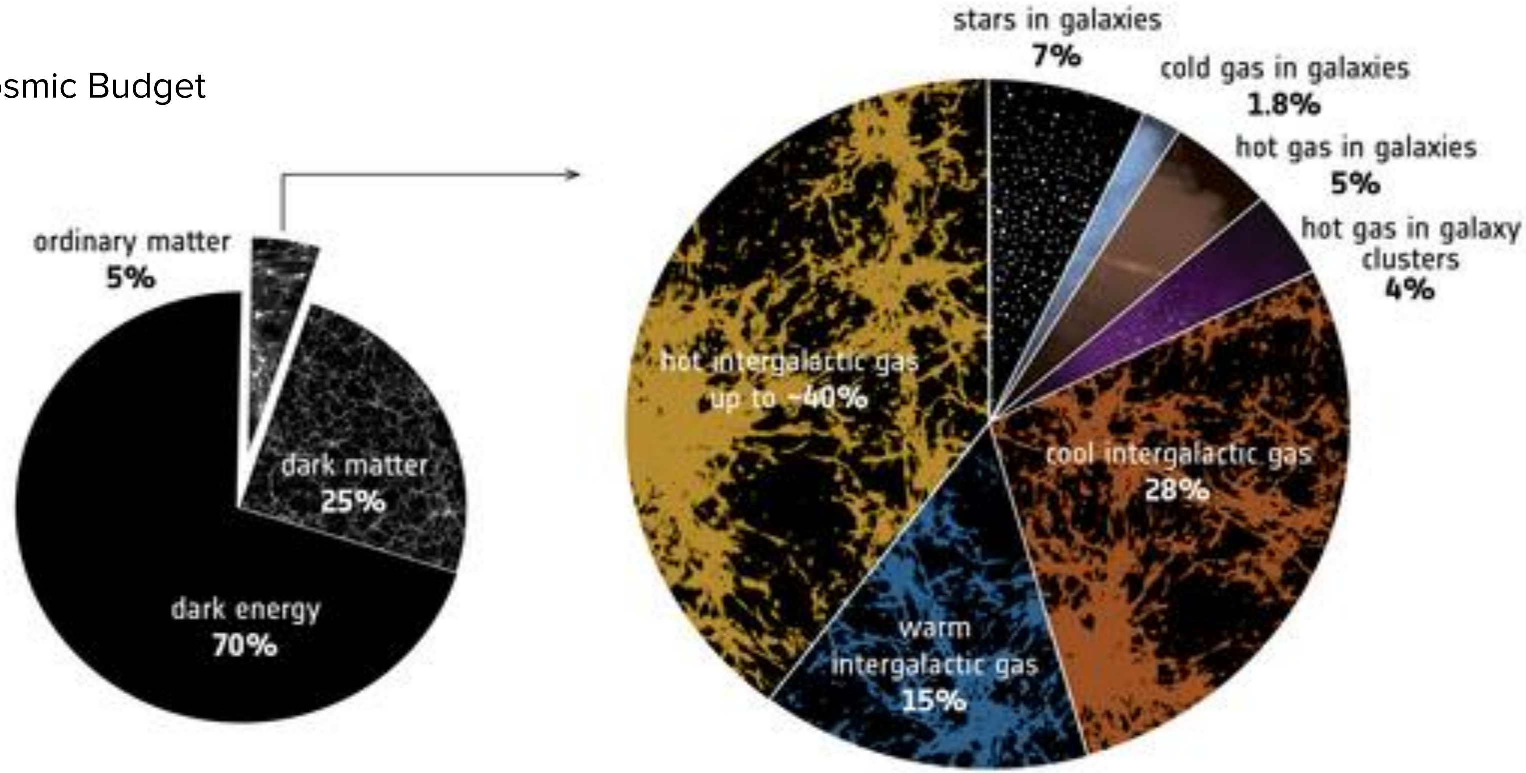
Outline

- Brief Introduction to Dark Matter
- Brief Introduction to Machine Learning
  - Supervised Learning
  - Neural Networks
  - Deep Learning
- Constructions of the dataset
  - TNG100 Simulations (1707.03401, 1707.03395, 1707.03395, ...)
  - SKIRT (2003.00721)
  - MARTINI (https://github.com/kyleaoman/martini)
- Results
  - Prediction of the Dark matter profile
  - Comparison between different architectures
  - Comparison between different inputs
  - Comparison with Rotation Curve method
- Conclusions and Future work

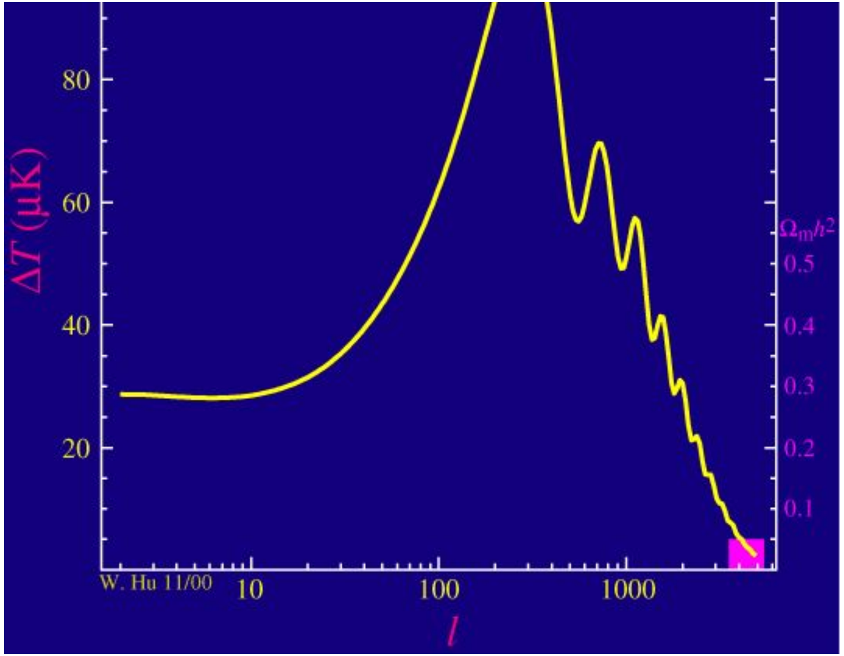
Brief Introduction to Dark Matter

Cosmic Budget

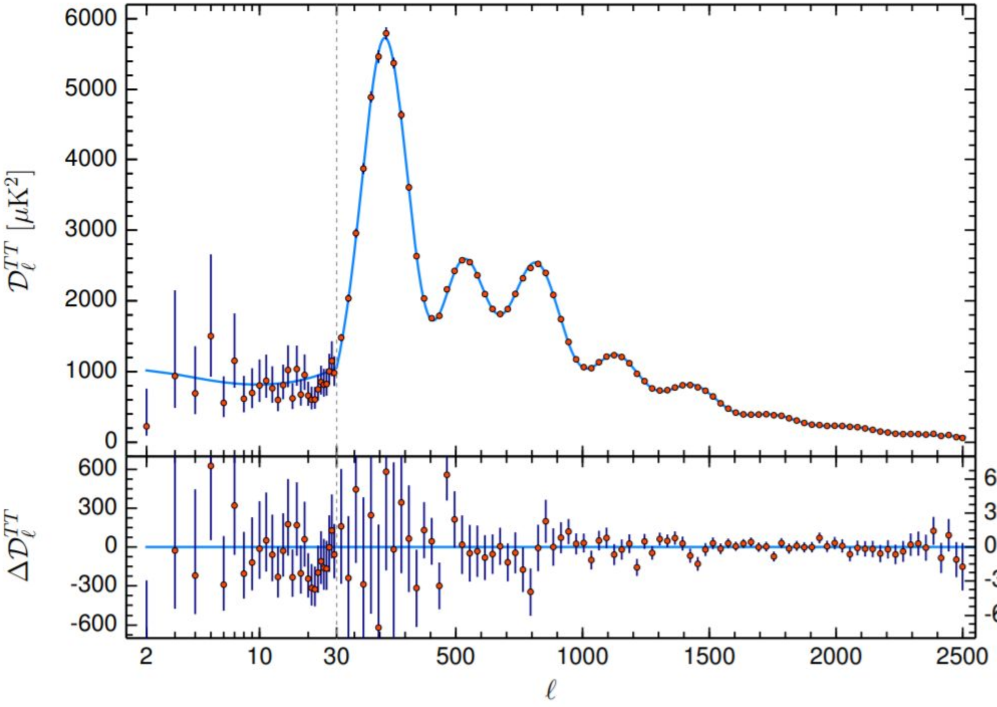


https://sci.esa.int/web/xmm-newton/-/60430-the-cosmic-budget-of-ordinary-matter

Brief Introduction to Dark Matter



http://background.uchicago.edu/~whu/animbut/anim2.html



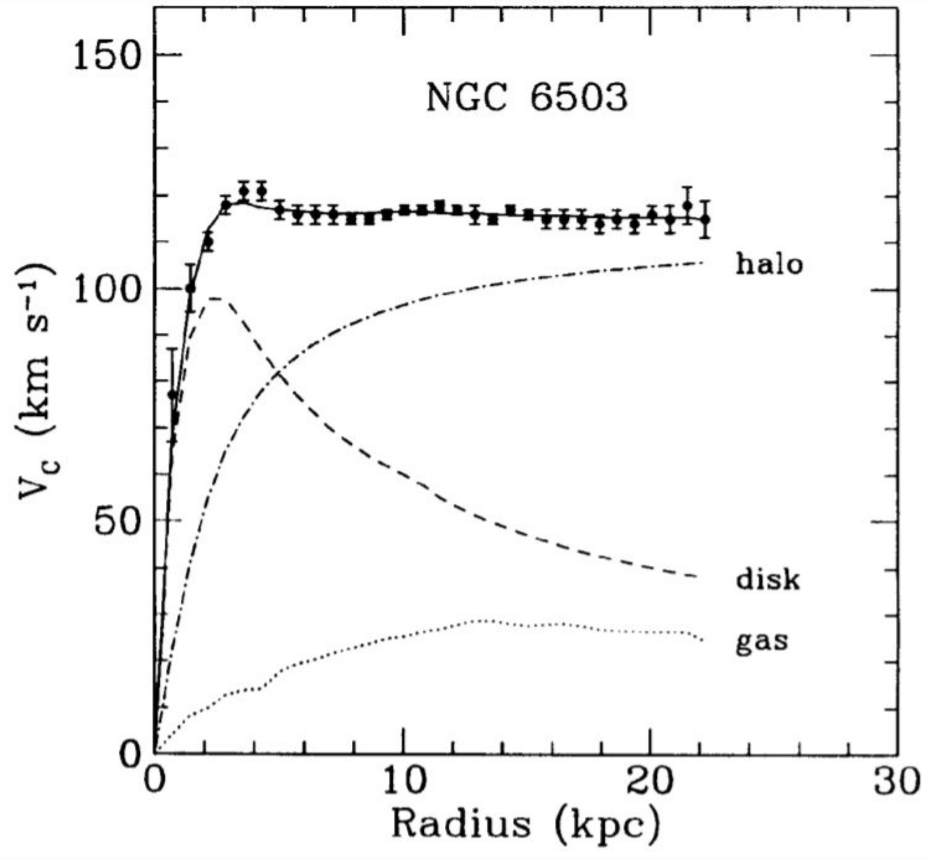
Planck Collaboration 1807.06209

Brief Introduction to Dark Matter

Bullet Cluster

Markevitch et al. 0309303

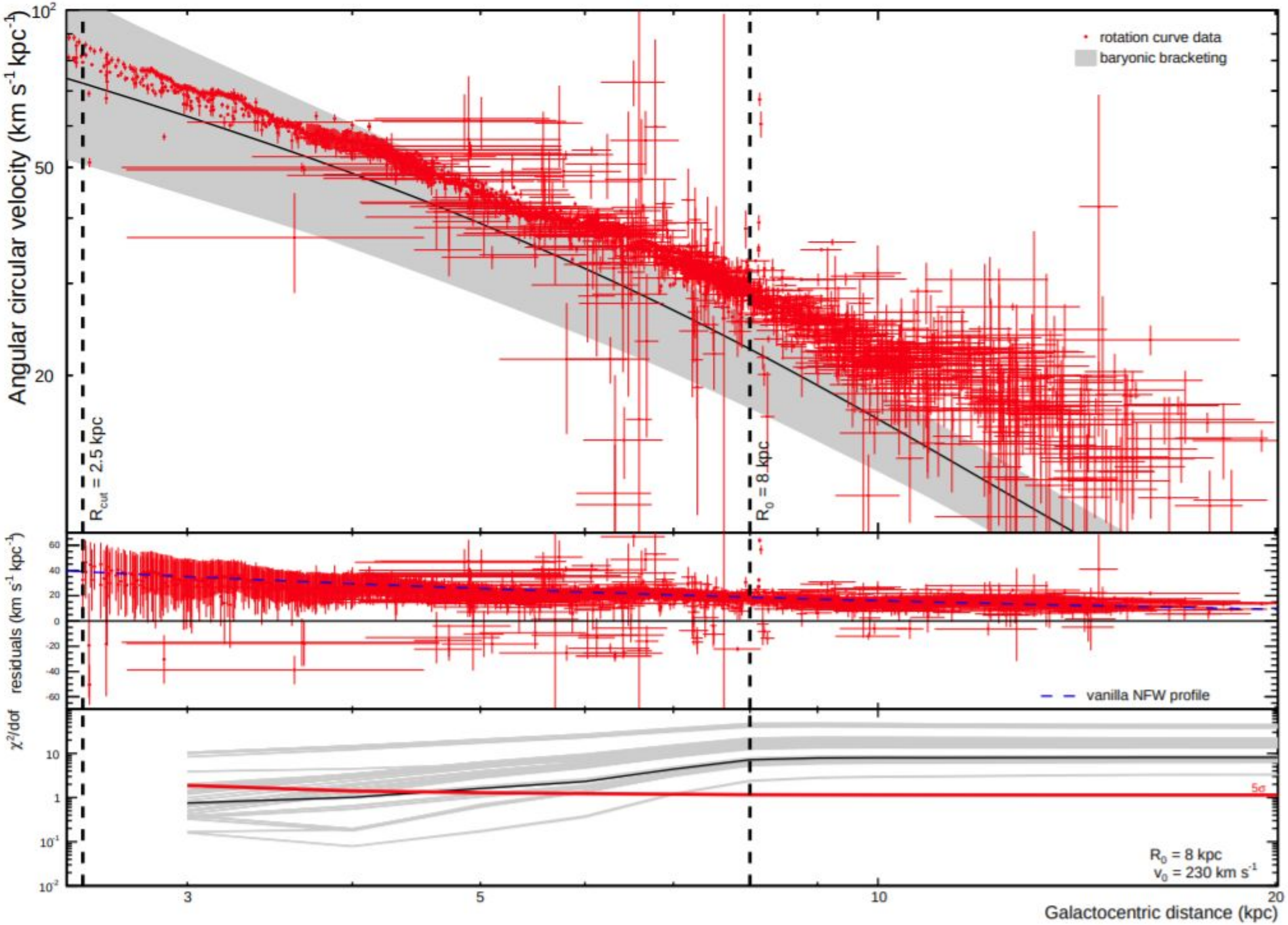
Brief Introduction to Dark Matter



NGC 6503 Rotation Curve

Katherine Freese 0812.4005

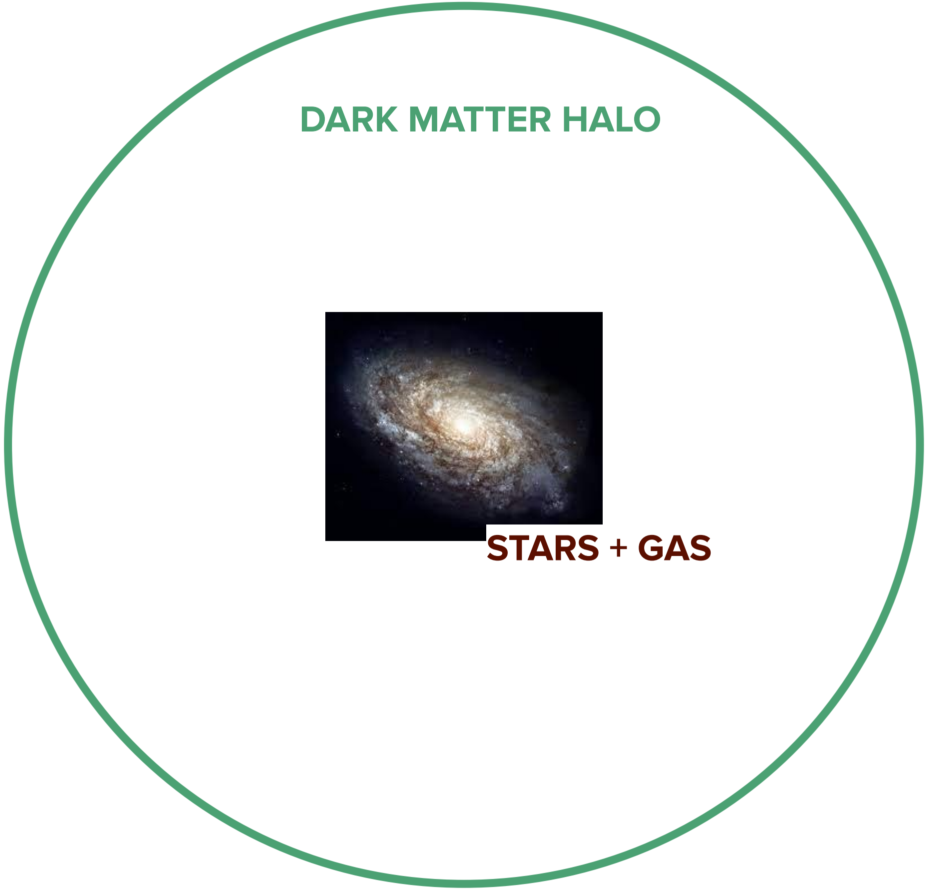
Brief Introduction to Dark Matter



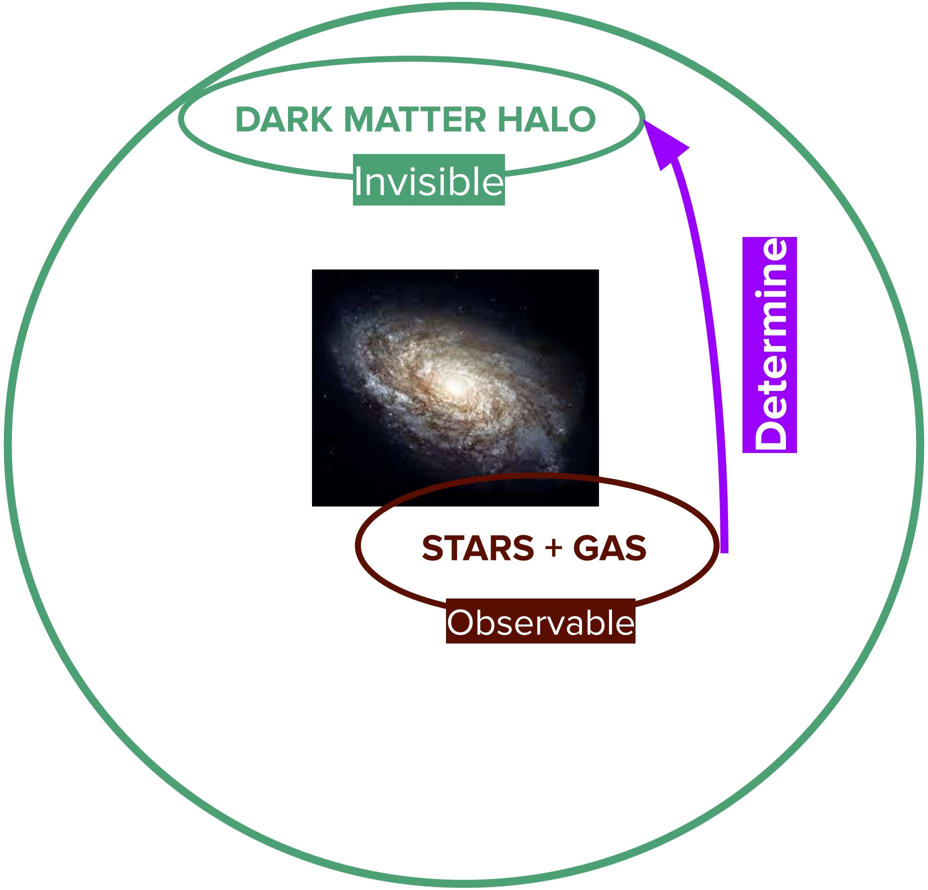
Evidence for dark matter in the inner Milky Way (1502.03821)

Fabio Iocco, Miguel Pato & Gianfranco Bertone

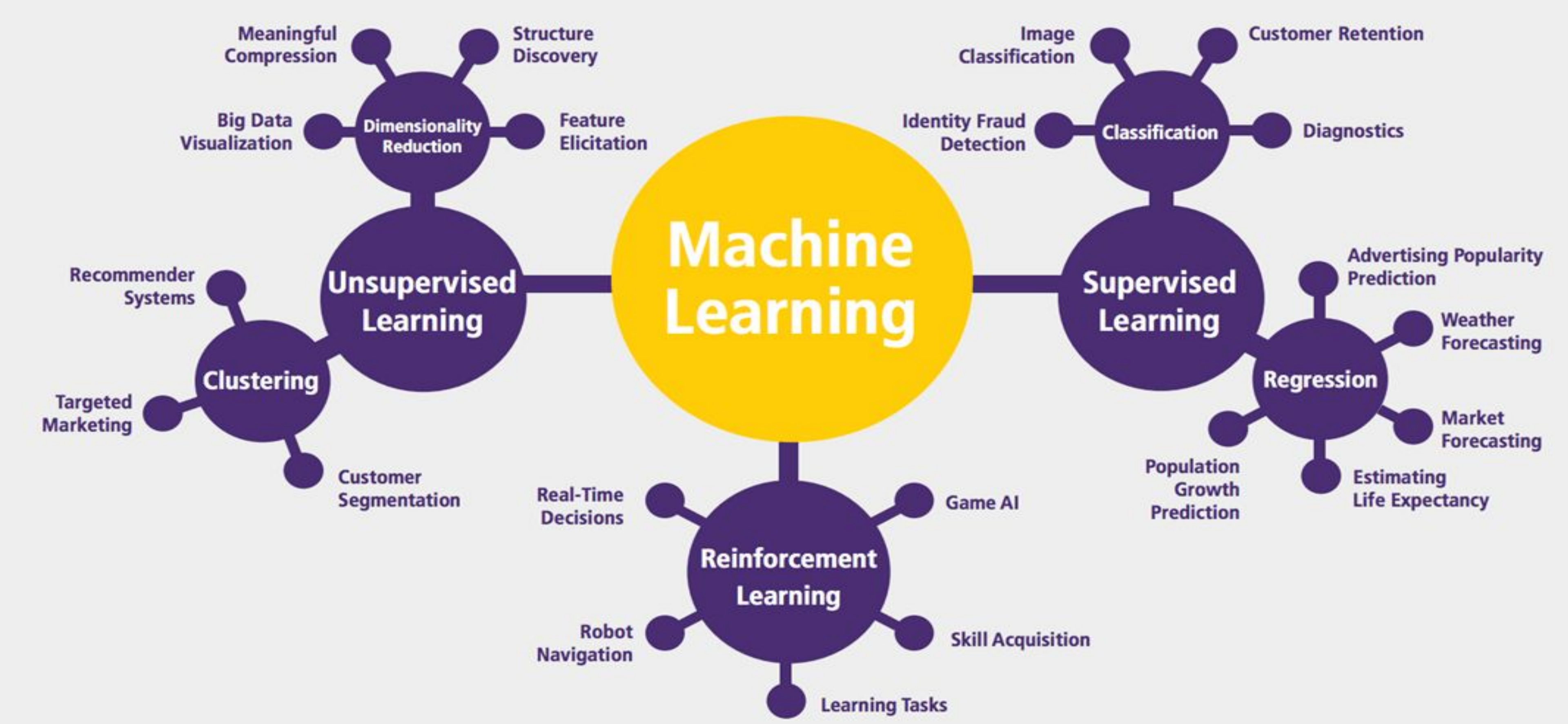
Brief Introduction to Dark Matter



Motivations and previous works

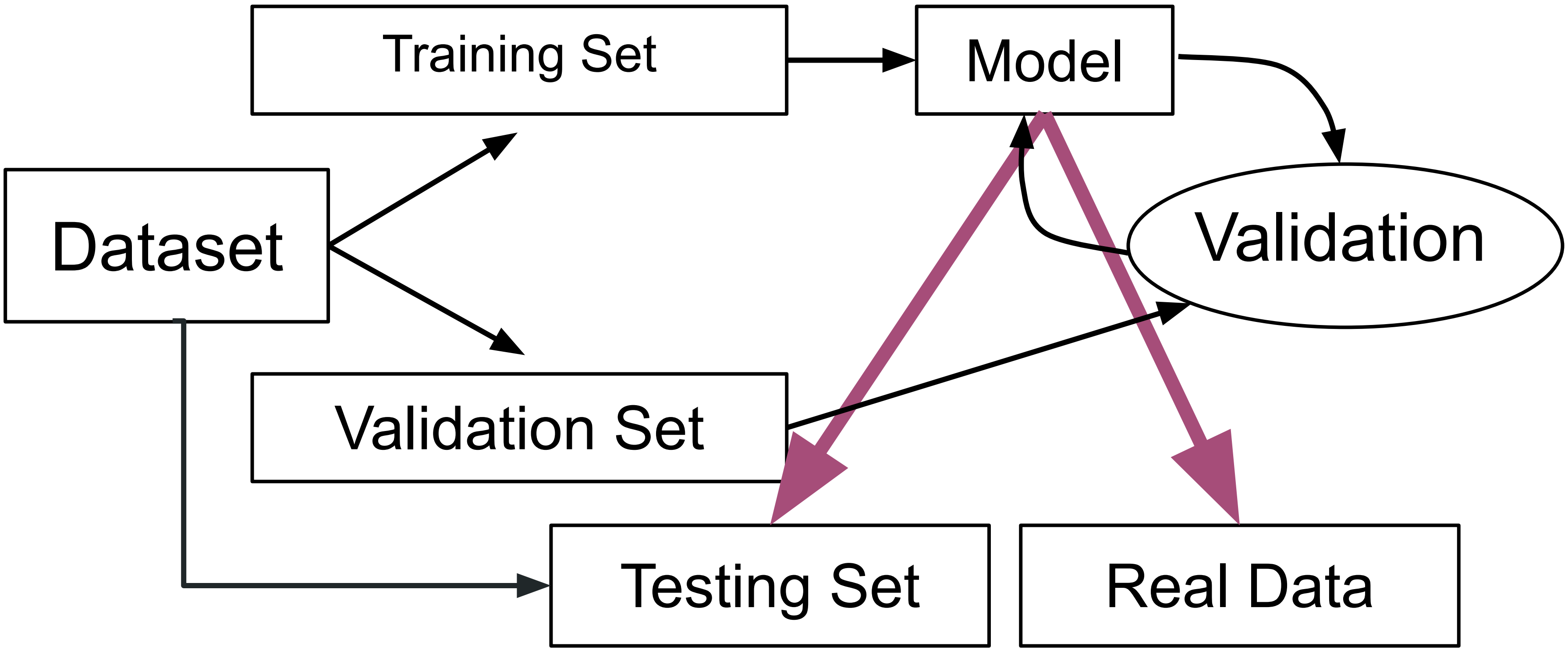


Brief introduction to Machine Learning



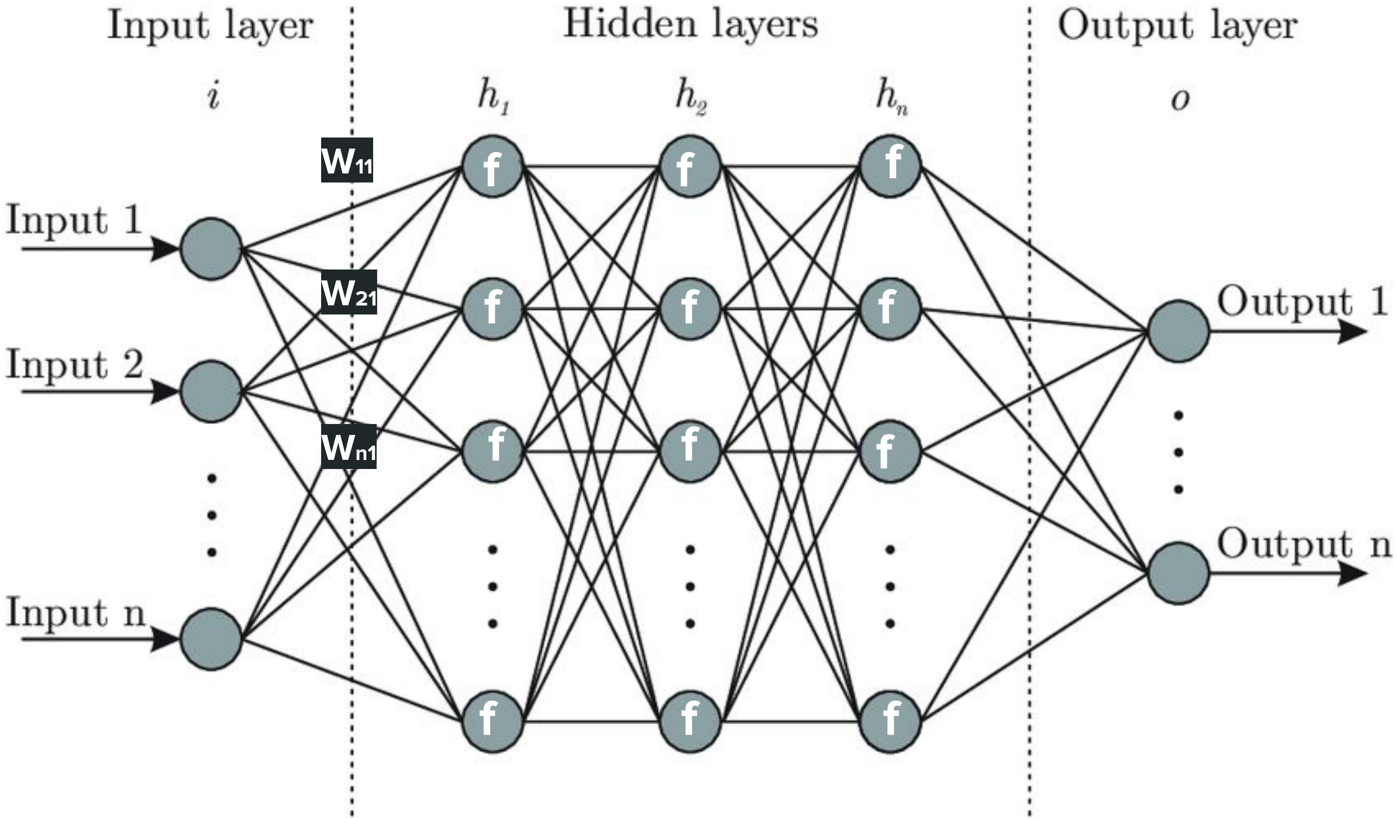
Brief introduction to Machine Learning

Supervised Learning



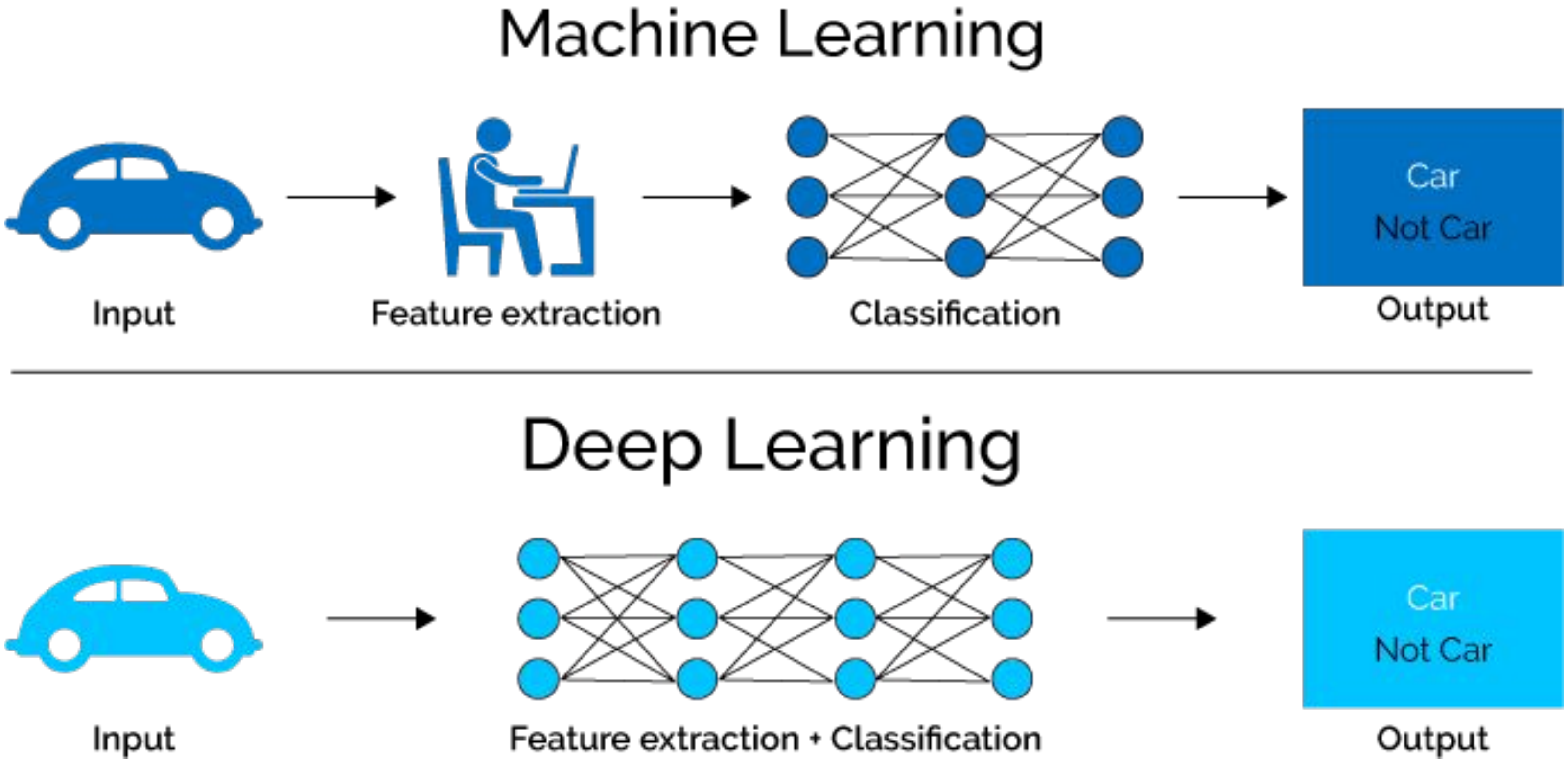
Brief introduction to Machine Learning

Neural Networks

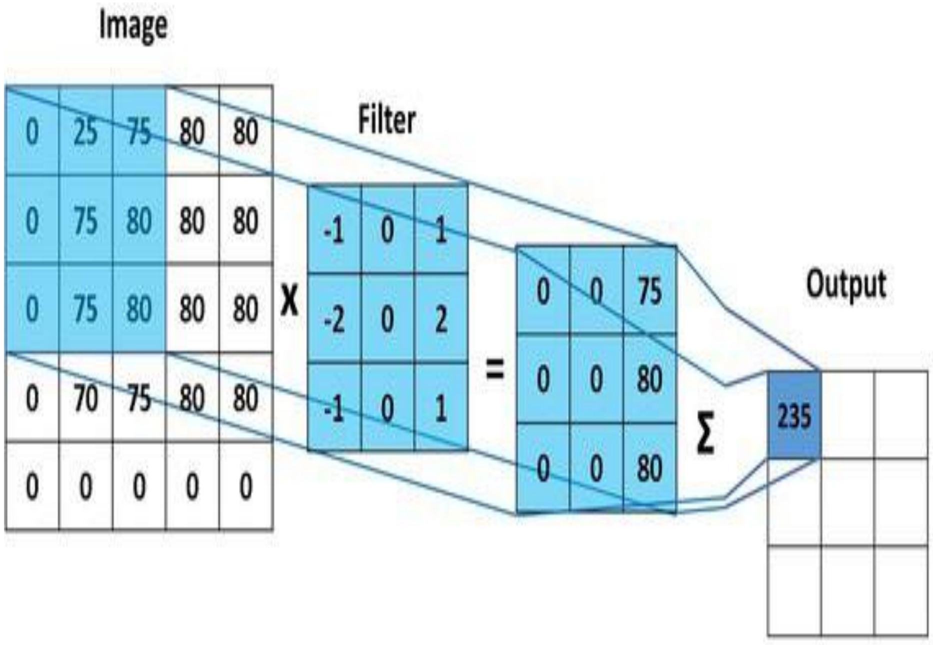


Brief introduction to Machine Learning

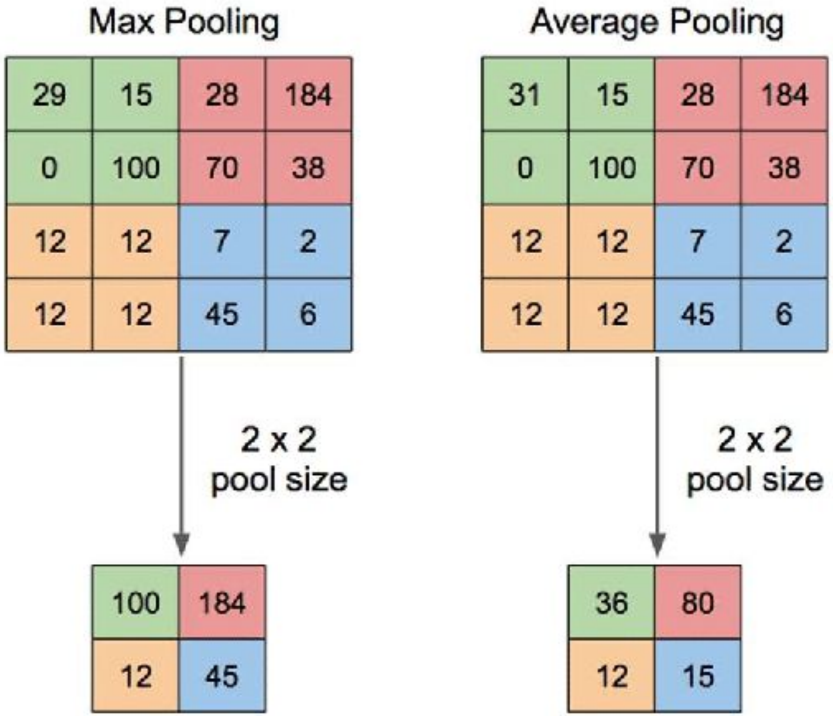
Deep Learning

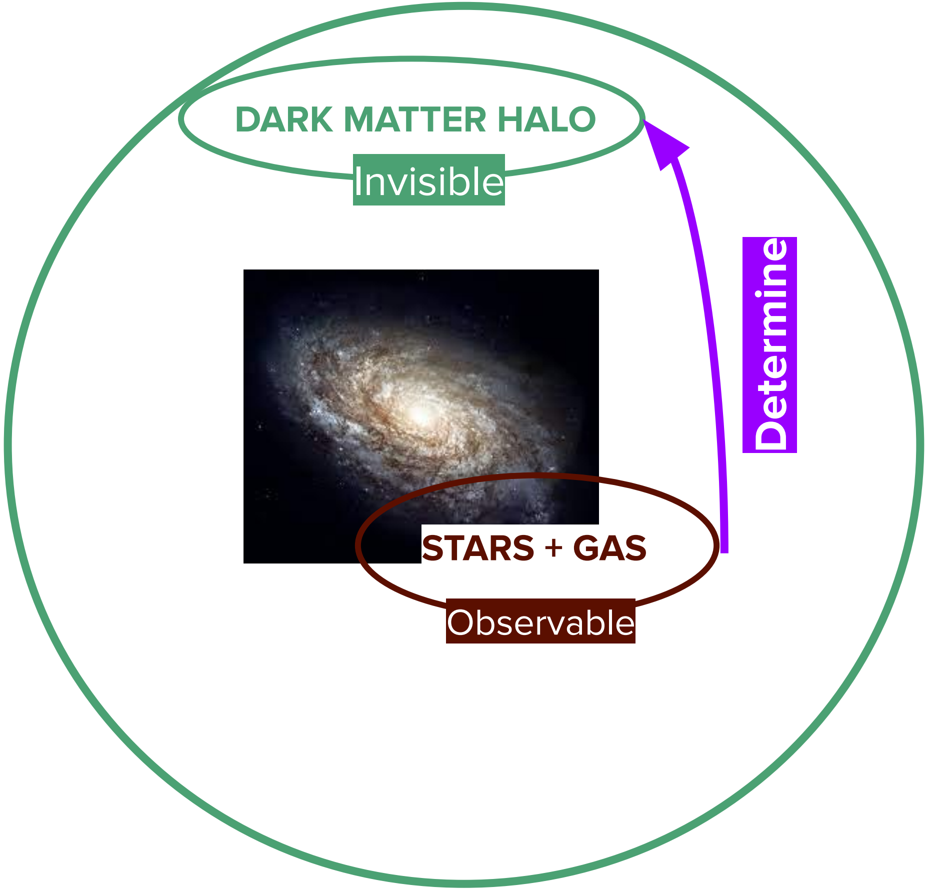


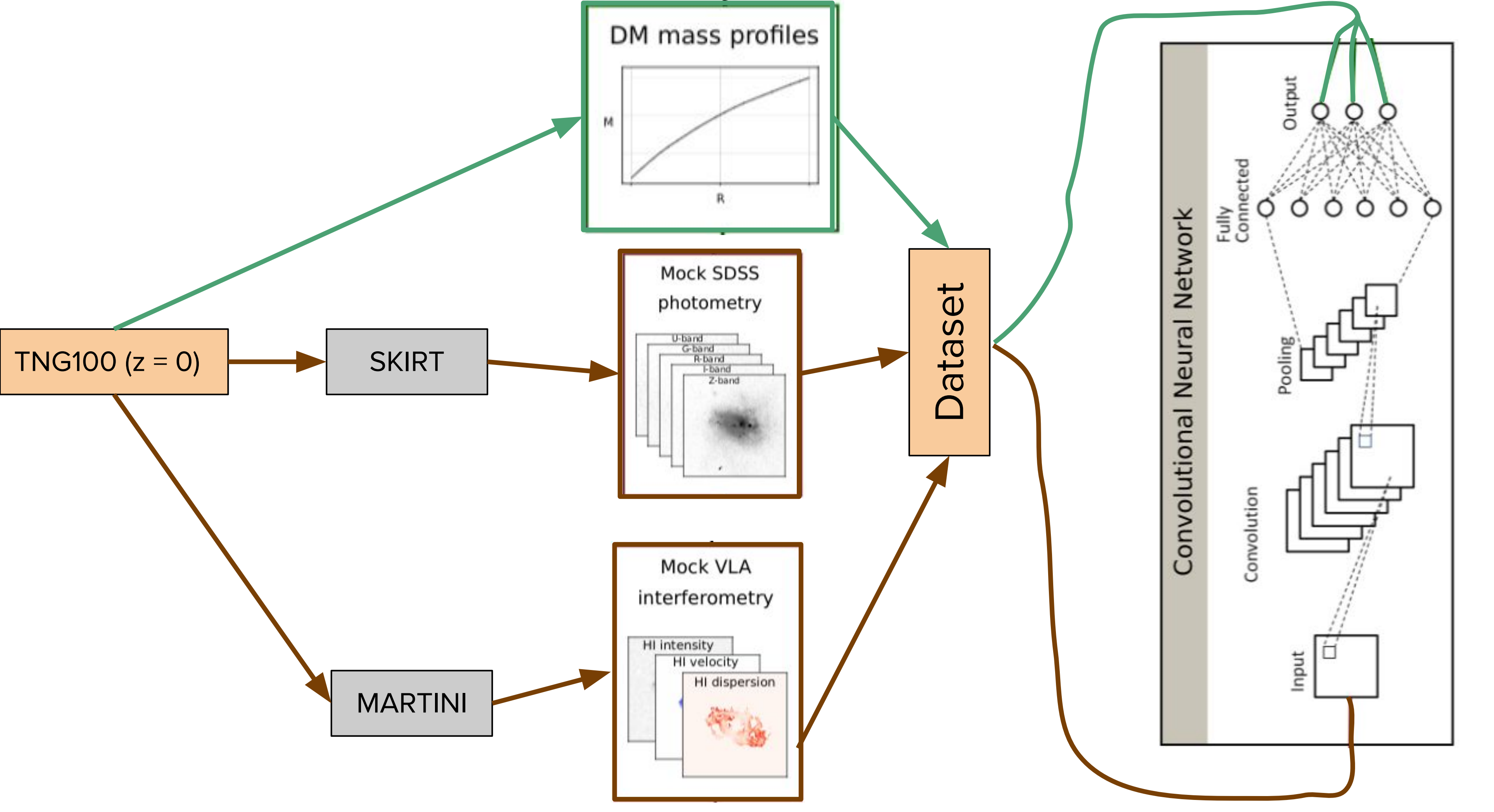
Convolutional layers



Pooling layers




DARK MATTER HALO
Invisible
STARS + GAS
Observable
Determine



DM mass profiles
M
R
TNG100 (z = 0)
SKIRT
Mock SDSS
photometry
U-band
G-band
R-band
I-band
Z-band
MARTINI
Mock VLA
interferometry
HI intensity
HI velocity
HI dispersion
Dataset
Convolutional Neural Network
Output
Fully Connected
Pooling
Convolution
Input

Construction of the dataset

TNG100 Simulation

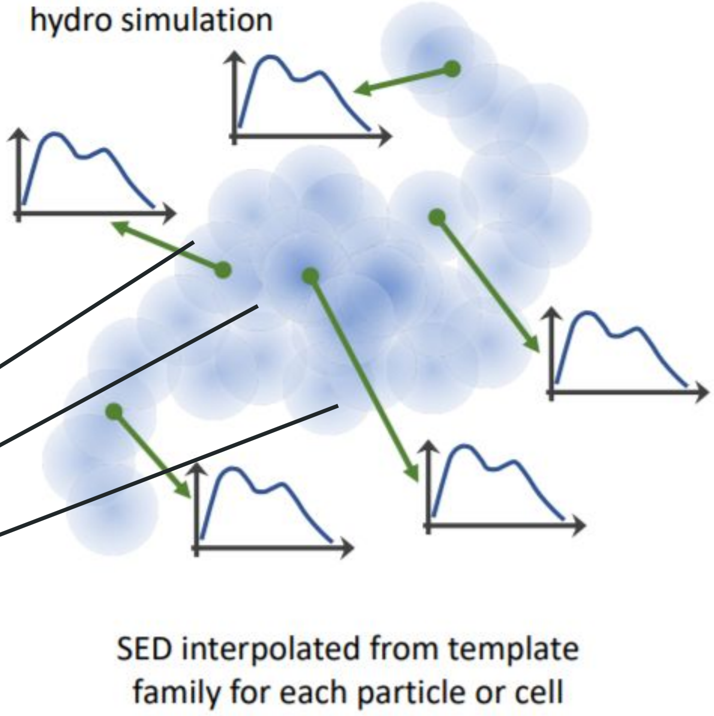
- Planck cosmology
- 106.5 Mpc by side
- 1820^3 DM particles
- 1820^3 hydrodynamic cells
- DM resolution 7.5 *10^6 M☉
- Baryon resolution 1.4*10^6 M☉
- 136 snapshots from z=127 to z=0

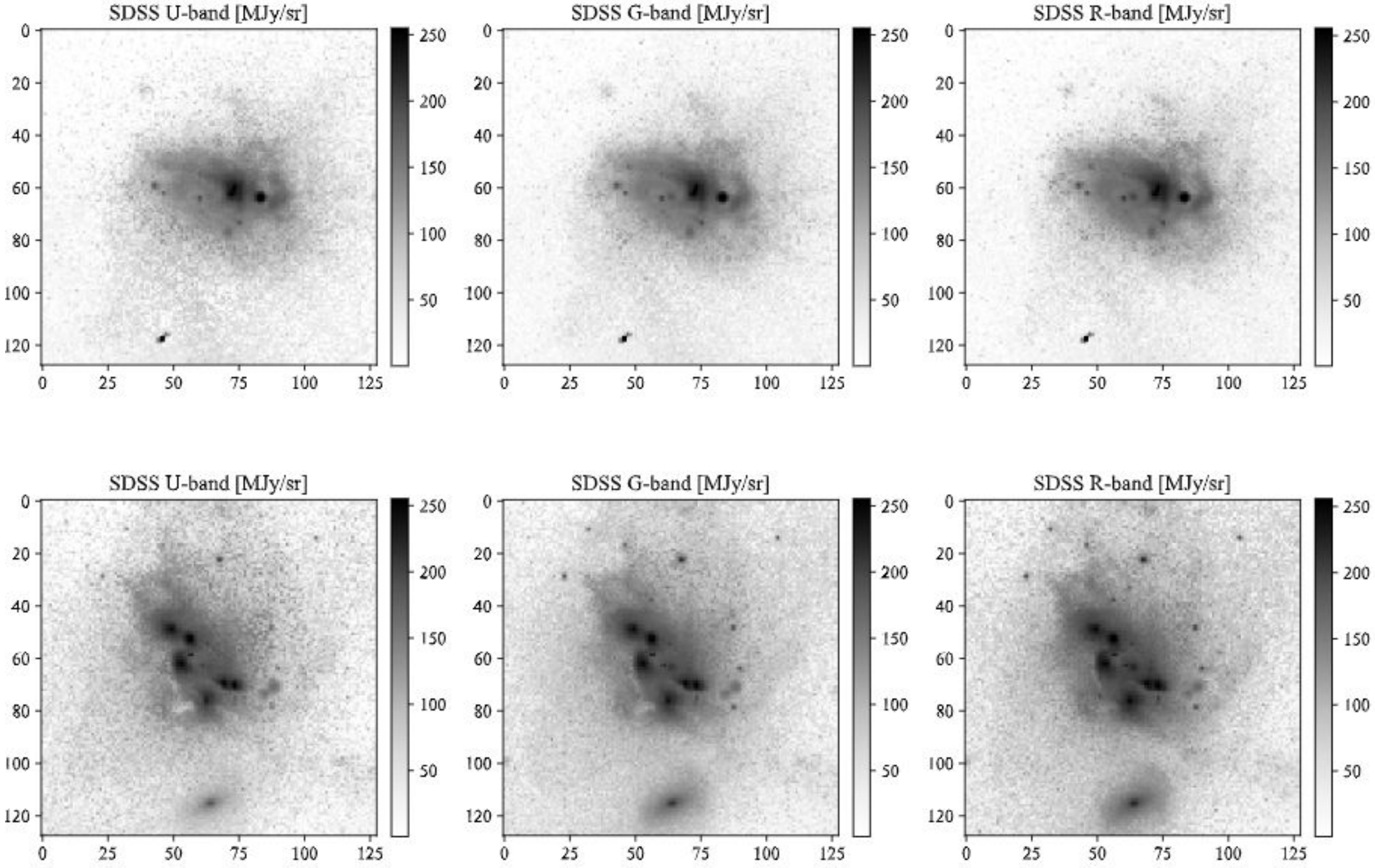
Property	Criterium
Simulation snapshot	99 ($z = 0$)
Stellar mass	$10^{10}\ M_\odot \leq M_\star \leq 10^{12}\ M_\odot$
Star formation rate	SFR $\geq 0.1\ M_\odot/\mathrm{yr}$
Central galaxy	SubhaloParent = 0
Cosmological origin	SubhaloFlag = 1

Construction of the dataset

SKIRT* (2003.00721, skirt.ugent.be)

Radiative transfer code which emulates the stellar emissions and subsequent light-ray propagation to the observer, taking into account the absorption and re-emission by dust.

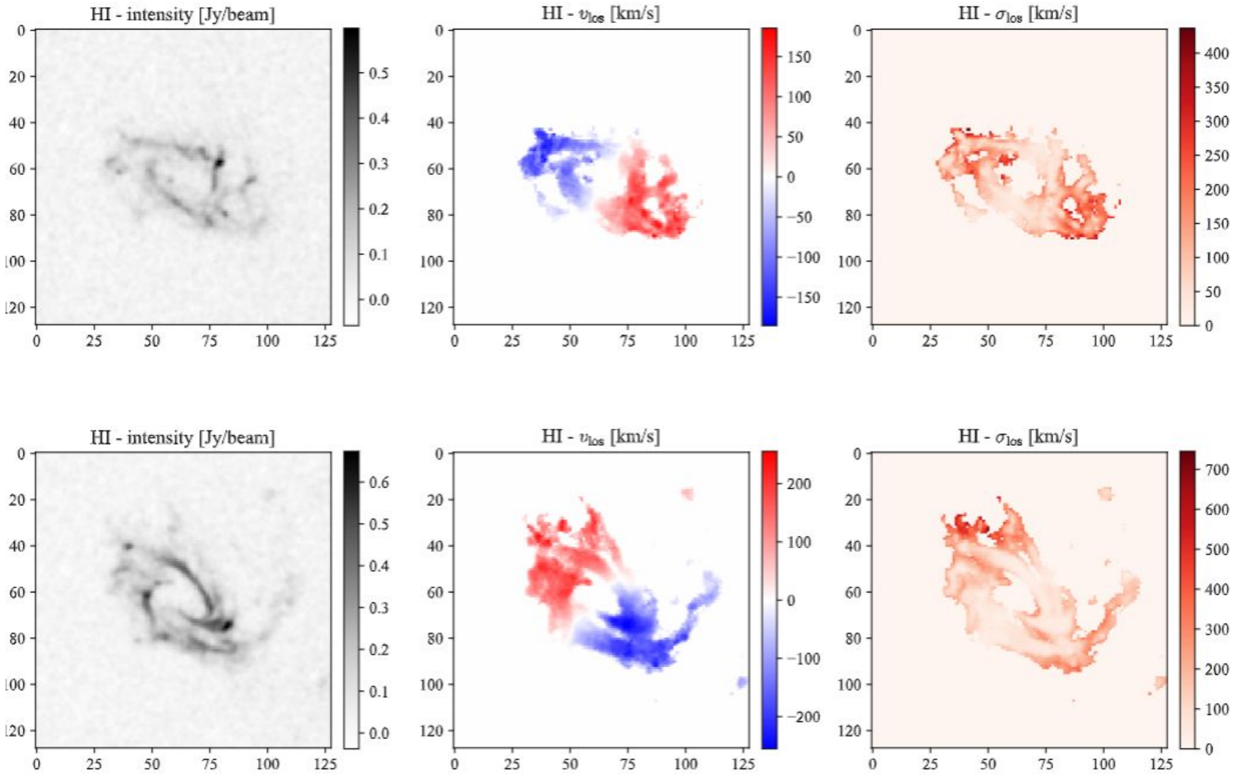



SDSS U-band [MJy/sr]
SDSS G-band [MJy/sr]
SDSS R-band [MJy/sr]
SDSS U-band [MJy/sr]
SDSS G-band [MJy/sr]
SDSS R-band [MJy/sr]

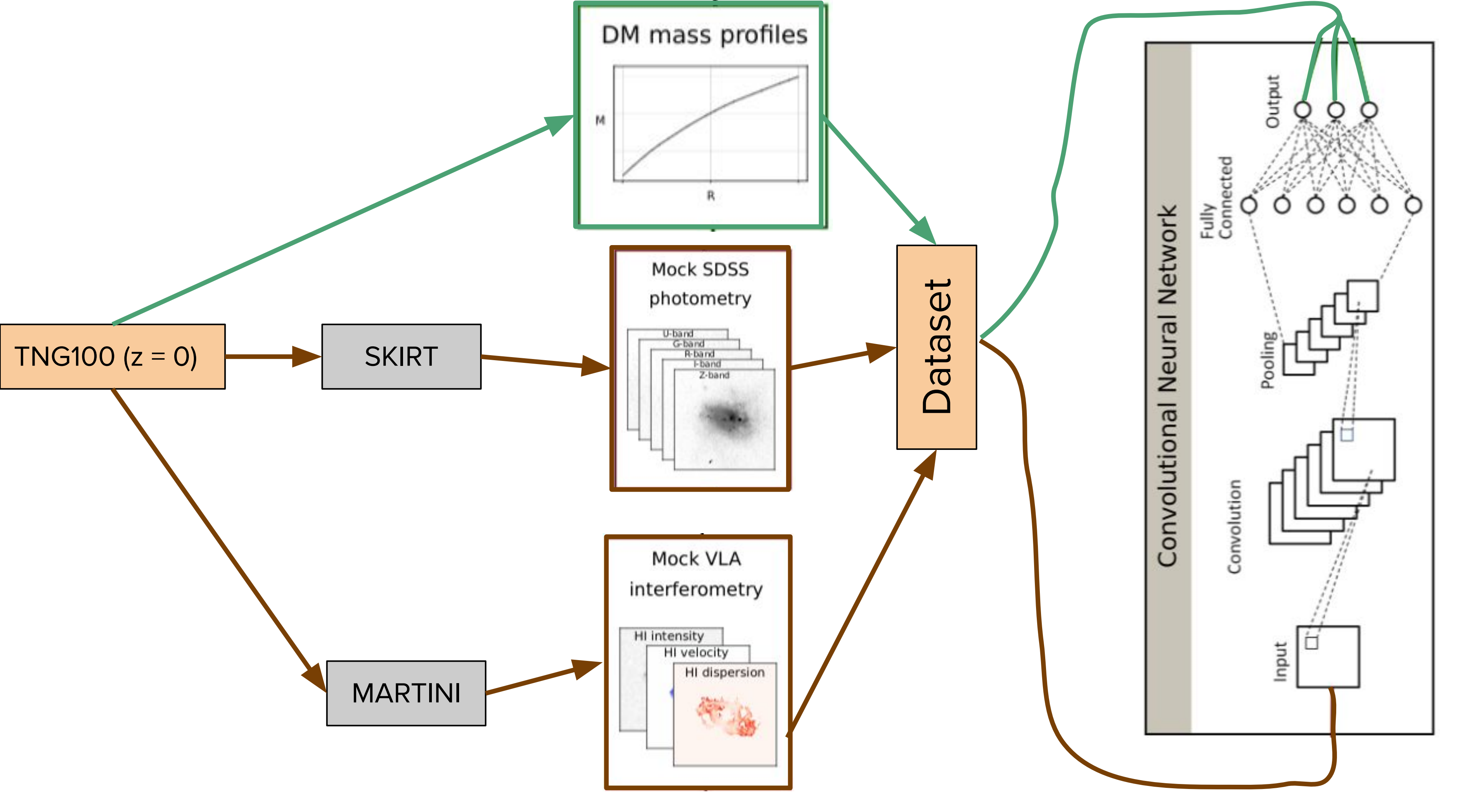
Construction of the dataset

MARTINI

Allows for the creation of synthetic resolved HI line observations (i.e. data cubes) directly from the snapshot of a hydrodynamic simulation, and its posterior analysis.



Layer	Details
2D convolution	64 kernels, 5×5 px kernel size, 2 px stride, ReLU activation
2D max pooling	2 px pooling
Dropout	50% dropout fraction
Batch normalization	
2D convolution	128 kernels, 5×5 px kernel size, 2 px stride, ReLU activation
2D max pooling	2 px pooling
Dropout	50% dropout fraction
Batch normalization	
2D convolution	256 kernels, 5×5 px kernel size, 2 px stride, ReLU activation
Batch normalization	
Dense	256 units, ReLU activation
Dropout	50% dropout fraction
Batch normalization	
Dense	128 units, ReLU activation
Dropout	50% dropout fraction
Batch normalization	
Dense	64 units, ReLU activation
Dropout	50% dropout fraction
Batch normalization	
Dense (output)	20 units, linear activation



DM mass profiles
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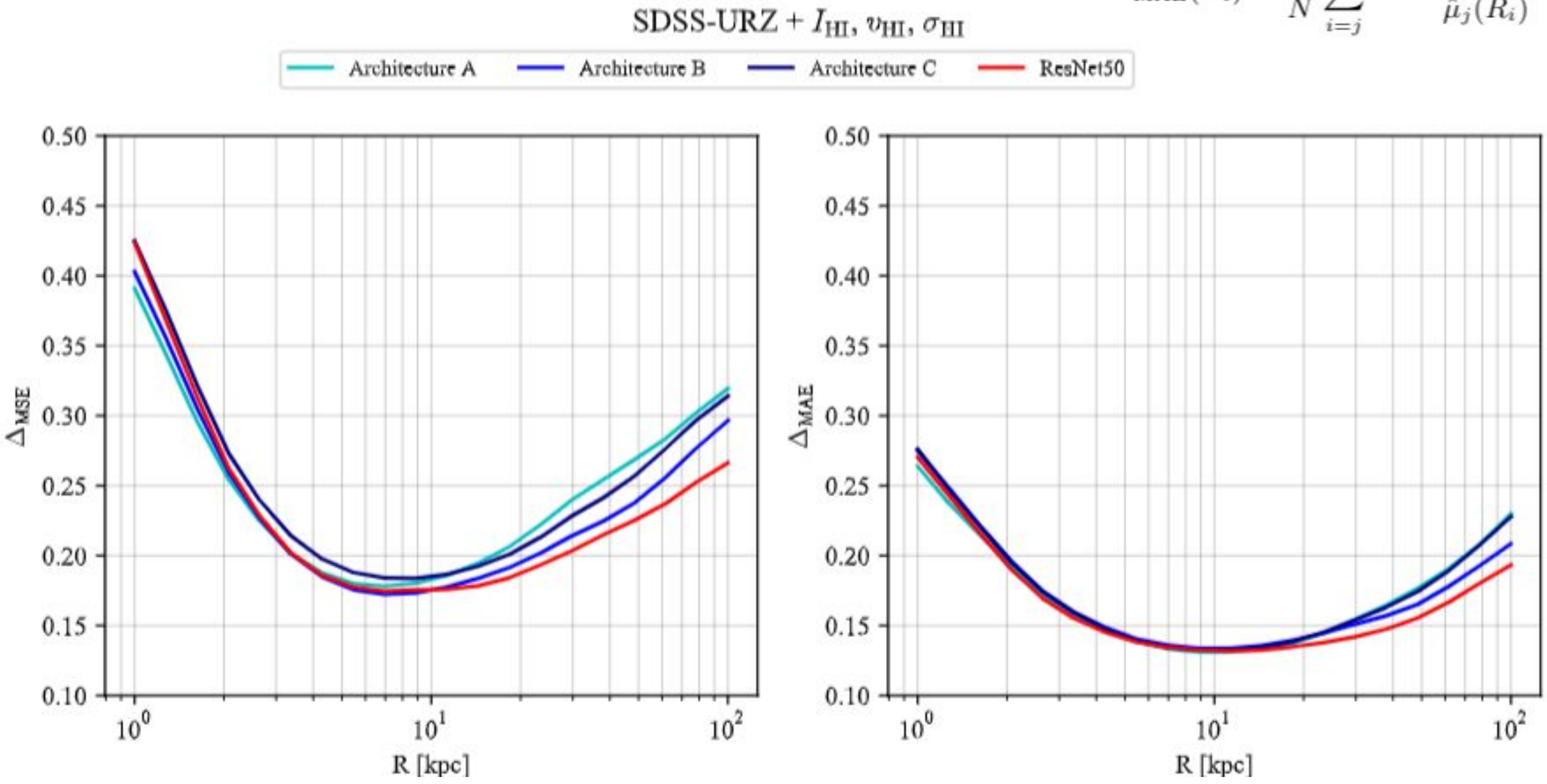
Mock VLA
interferometry
HI intensity
HI velocity
HI dispersion
Dataset
Convolutional Neural Network
Output
Fully Connected
Pooling
Convolution
Input

Results

Comparison between different architectures

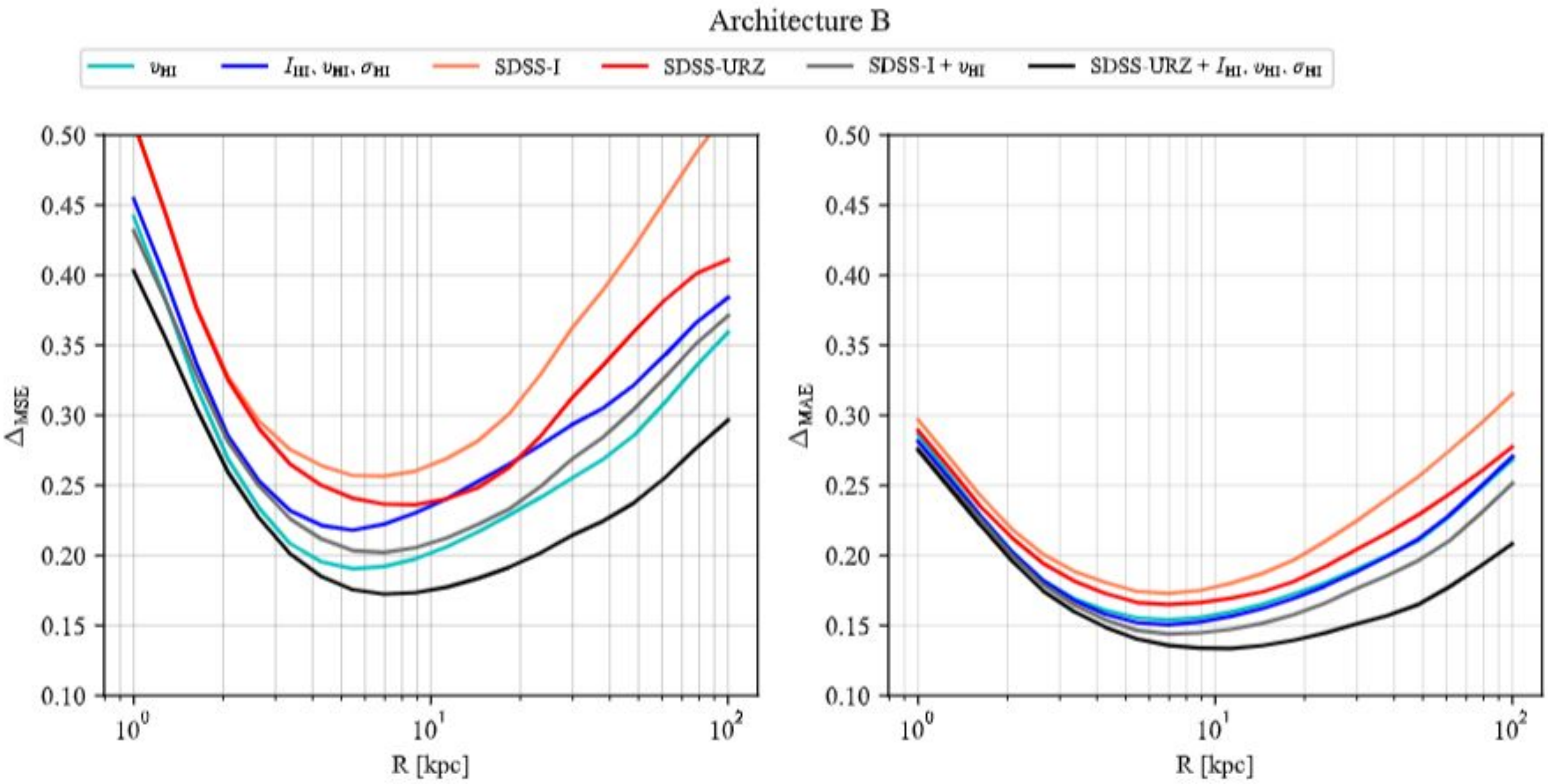
$$\Delta_{\mathrm{MSE}}(R_i) = \left[\frac{1}{N}\sum_{j=1}^{N}\left(\frac{\mu_j(R_i) - \hat{\mu}_j(R_i)}{\hat{\mu}_j(R_i)}\right)^2\right]^{1/2}$$

$$\Delta_{\mathrm{MAE}}(R_i) = \frac{1}{N}\sum_{i=j}^{N}\frac{|\mu_j(R_i) - \hat{\mu}_j(R_i)|}{\hat{\mu}_j(R_i)},$$



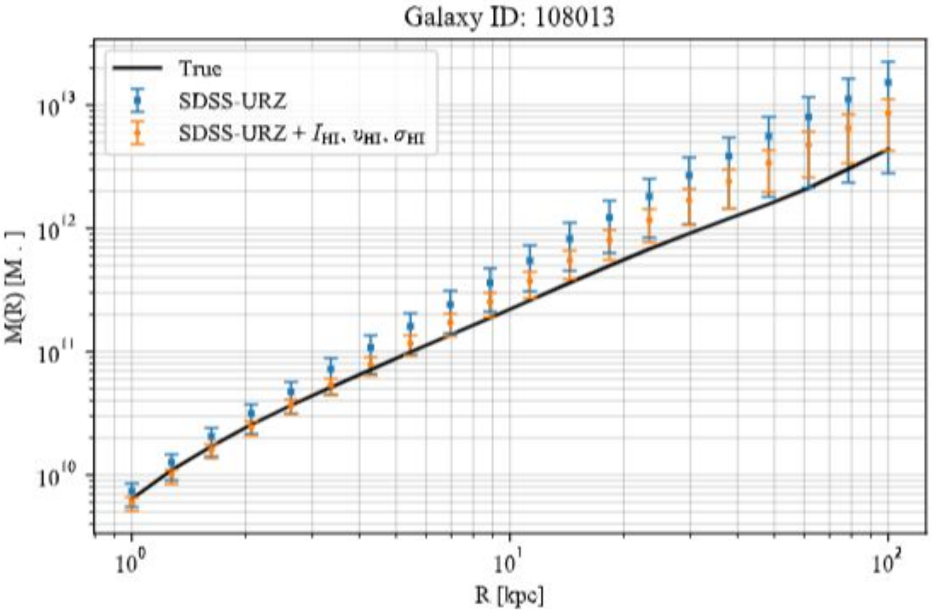
Results

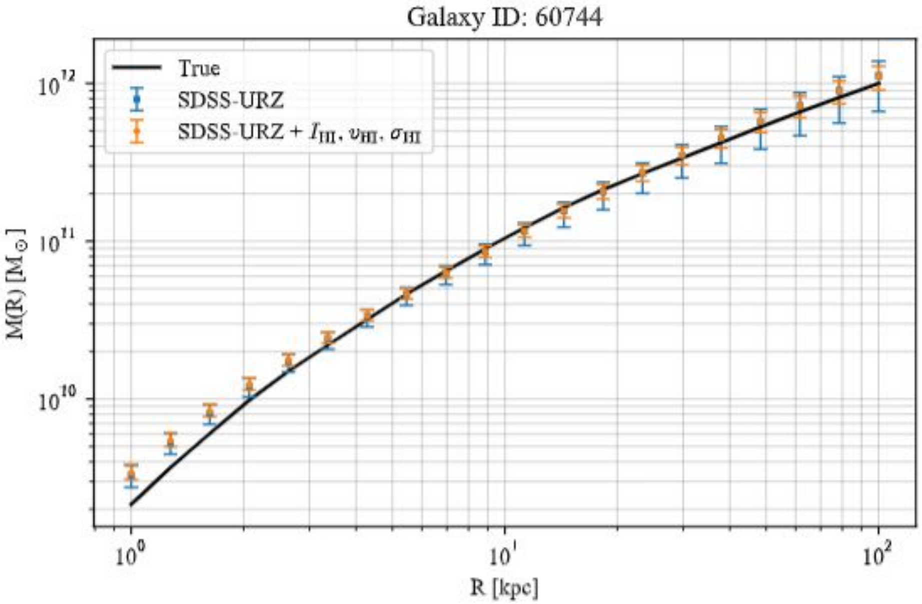
Comparison between different inputs



Results

Prediction of the dark matter profile

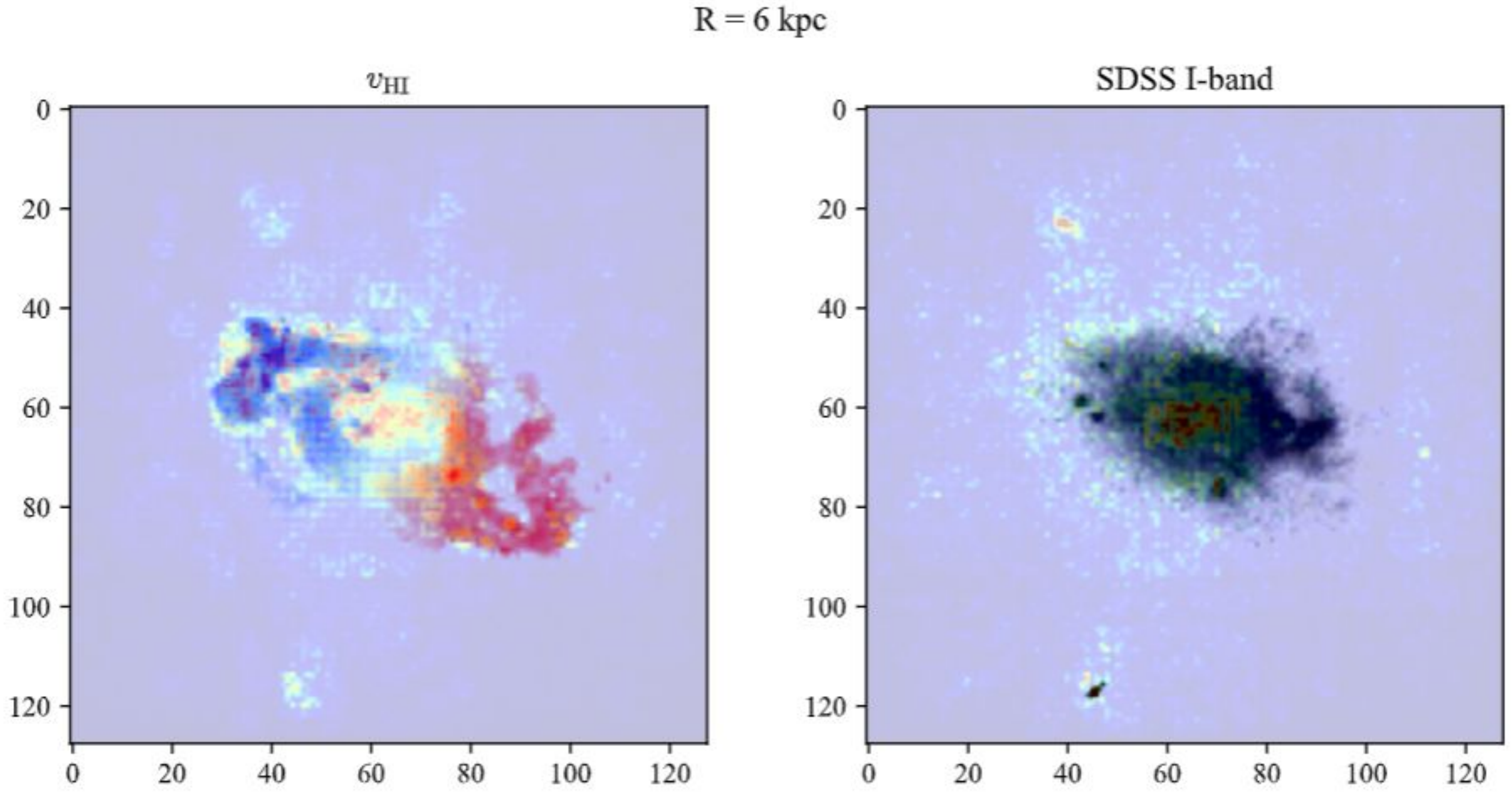




Results

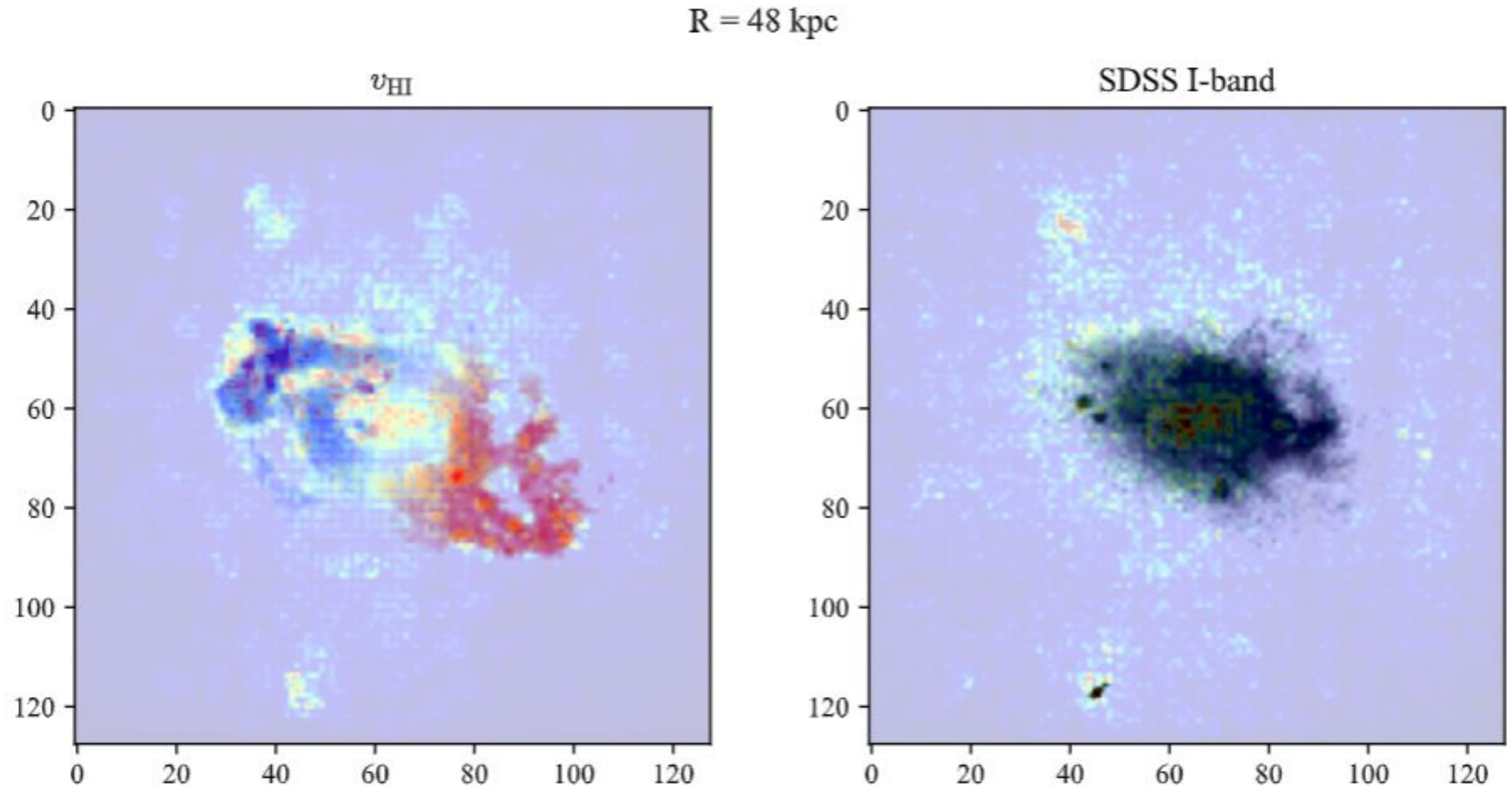
Understanding the results

$$S_{ij} \equiv \frac{\partial y}{\partial x_{ij}}$$



Results

Understanding the results



Conclusions and Future work

- Our algorithm is able to reconstruct the DM distribution profile with high performance throughout the extension of the galaxy.
- The highest performance is achieved in the intermediate regions with a mean square error below 0.2 using all the photometric and spectroscopic information.
- Even in the absence of spectroscopic information, our method is able to recover the dark matter profile with a mean square error below 0.3 in the intermediate regions.
- Our reconstruction of the DM distribution is completely data-driven, and does not need any assumption on the shape nor the functional form of the DM profile.
- The method developed here is applicable to different types of galaxies since it does not rely on explicit physical assumptions regarding the dynamical state of the system.
- The results achieved have been obtained for galaxies with masses in the range ~10^{10}-10^{12} M⊙ but the methodology can be extended to a broader mass range.

Conclusions and Future work

- We will make a comparison with the dark matter profile obtained through the traditional rotation curve analysis for the simulated galaxies.

- Study the robustness of our results to the hydrodynamical cosmological simulation.

- Apply our method to real galaxies and compare the results with other estimations.

THANK YOU