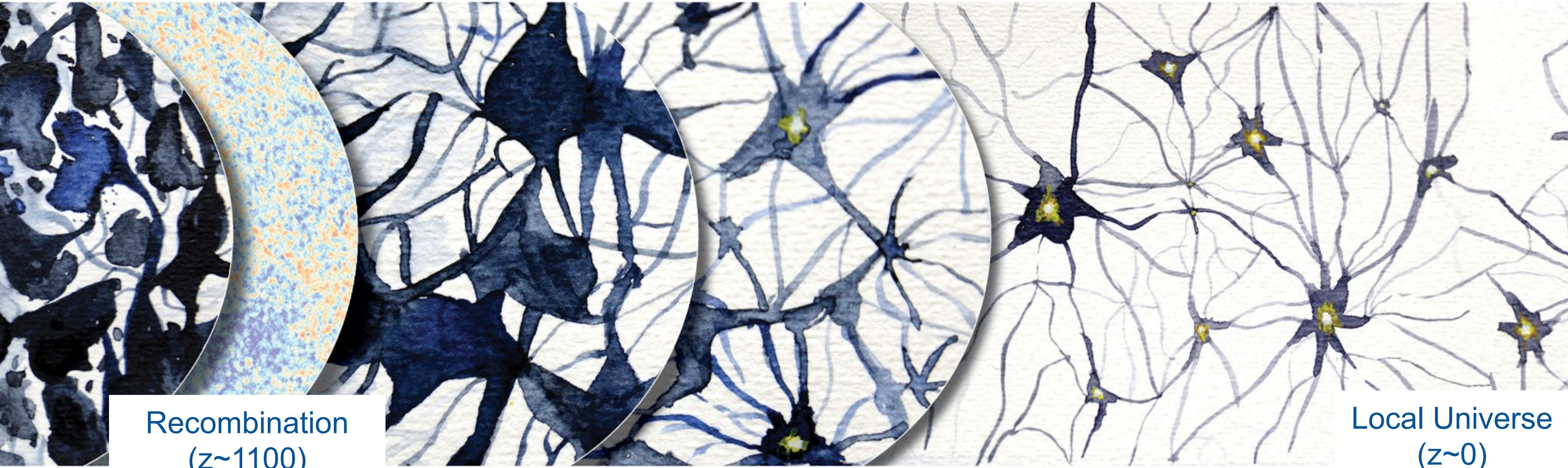
Advancing the Understanding of Neutral Hydrogen in the Post-Reionization Universe with the Upgraded GAEA Model

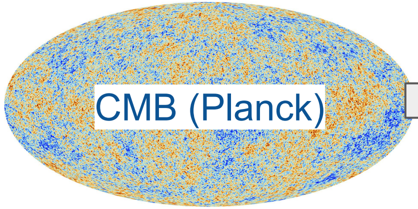
Mohammad Kamran
INAF – Osservatorio Astronomico di Trieste

Co-authors: Gabriella De Lucia, Marta Spinelli, Fabio Fontanot

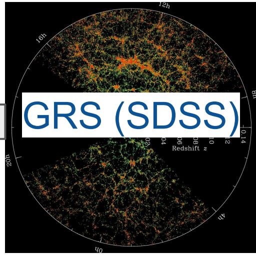
Hydrogen Across Cosmic Time

Credit: ESA



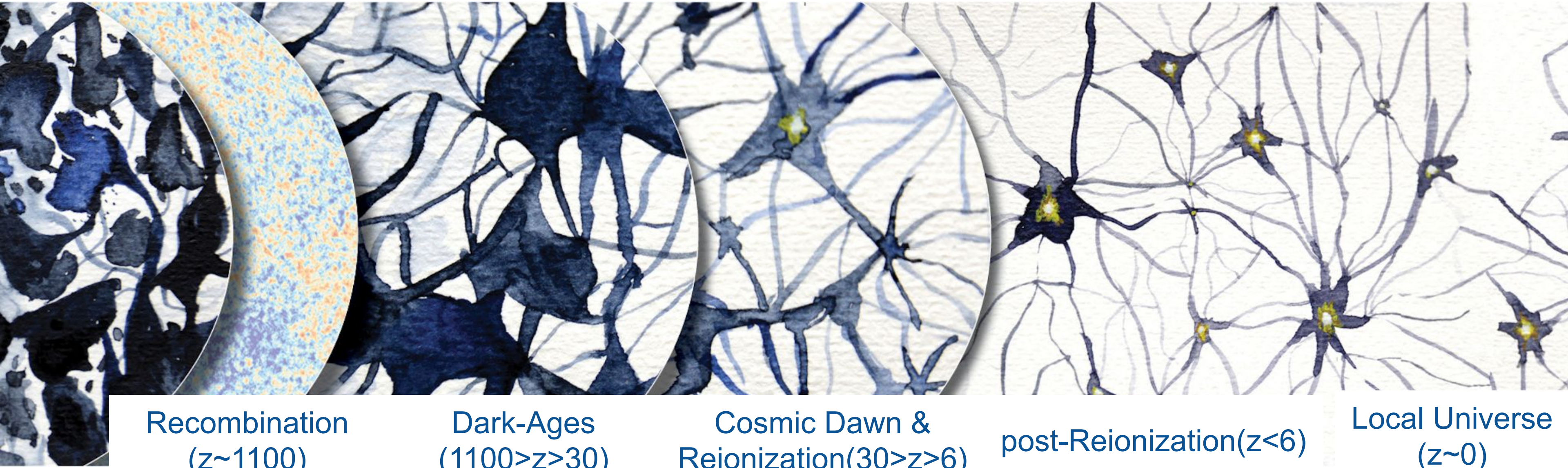


Provide clear pictures of the **LSS**

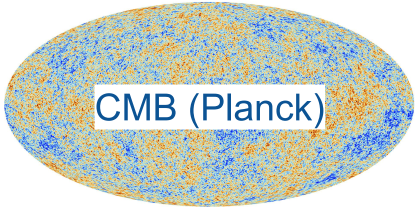


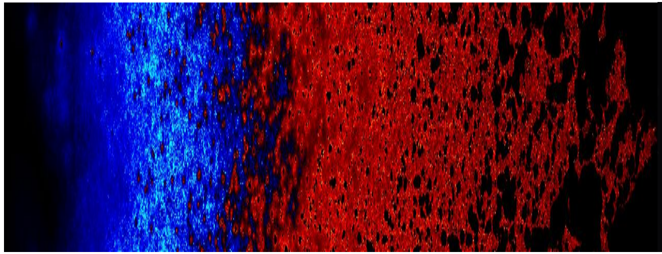
Hydrogen Across Cosmic Time

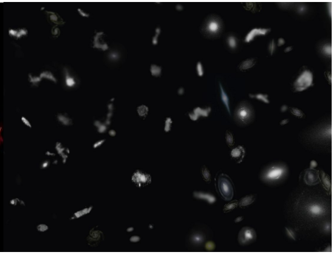
Credit: ESA

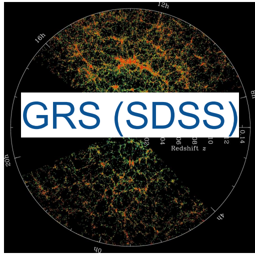


Recombination (z~1100) | Dark-Ages (1100>z>30) | Cosmic Dawn & Reionization(30>z>6) | post-Reionization(z<6) | Local Universe (z~0)





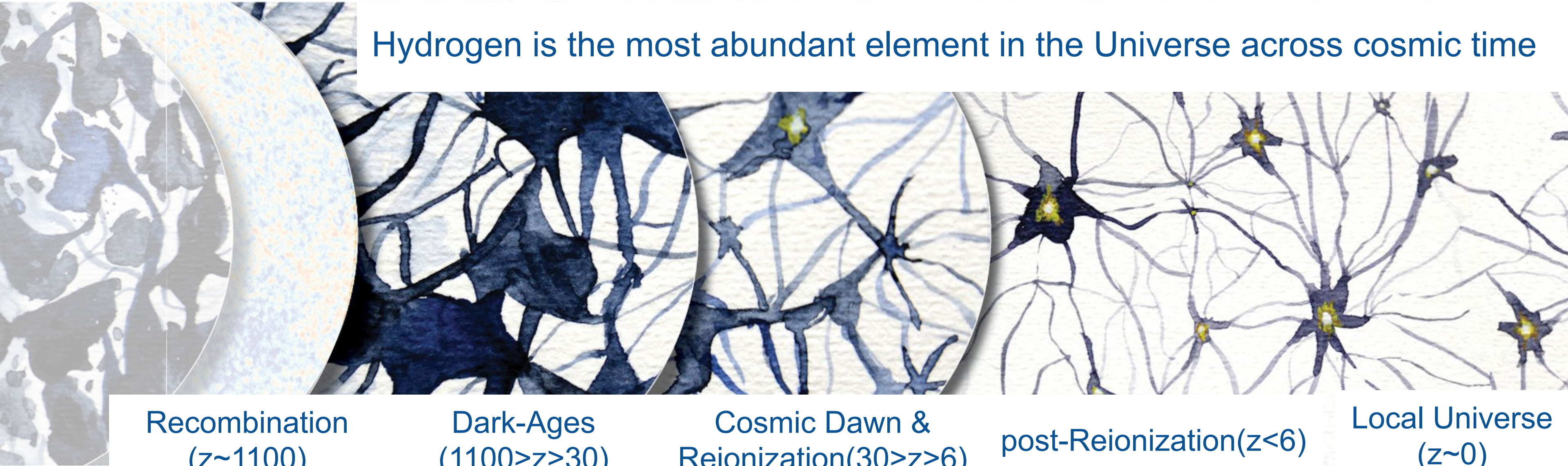




Hydrogen Across Cosmic Time

Credit: ESA

Hydrogen is the most abundant element in the Universe across cosmic time



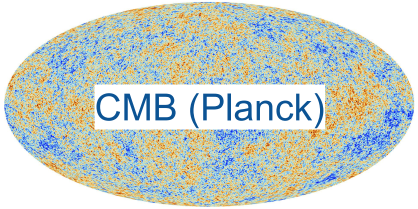
Recombination (z~1100)

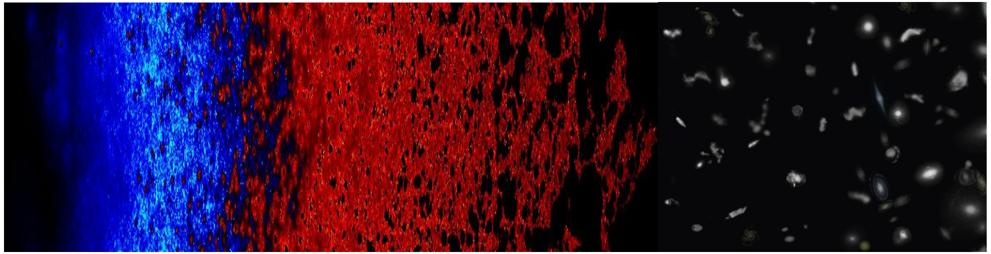
Dark-Ages (1100>z>30)

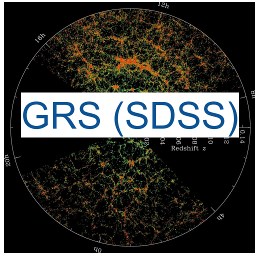
Cosmic Dawn & Reionization(30>z>6)

post-Reionization(z<6)

Local Universe (z~0)

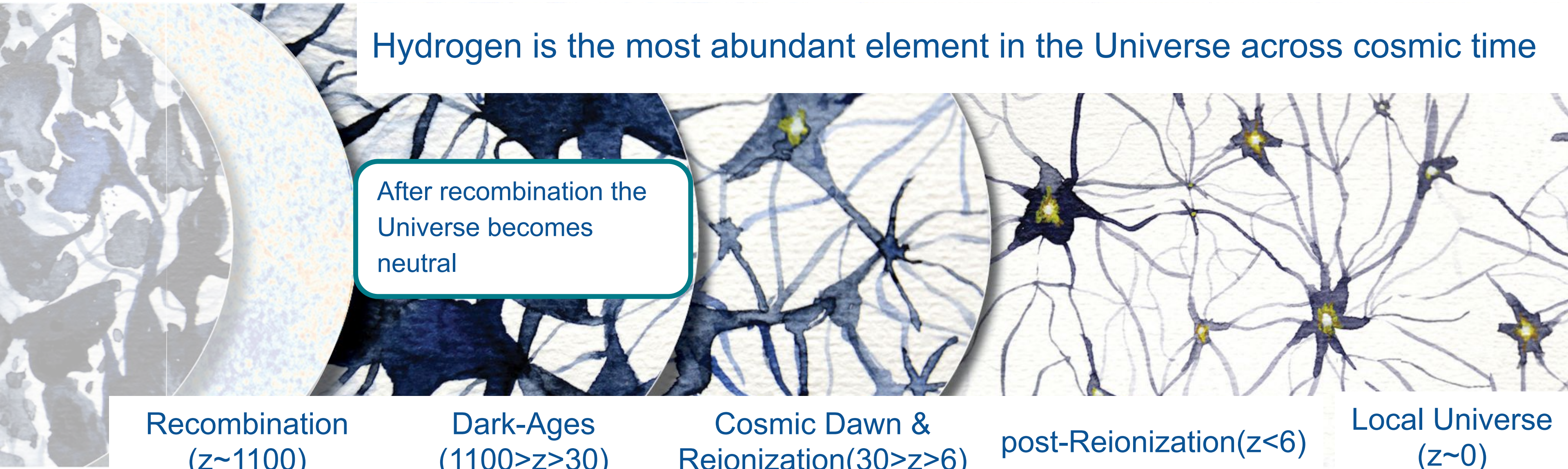






Hydrogen Across Cosmic Time

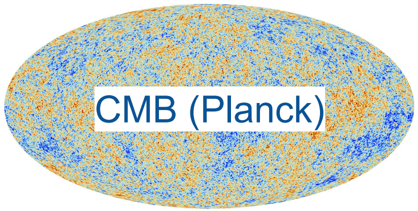
Credit: ESA

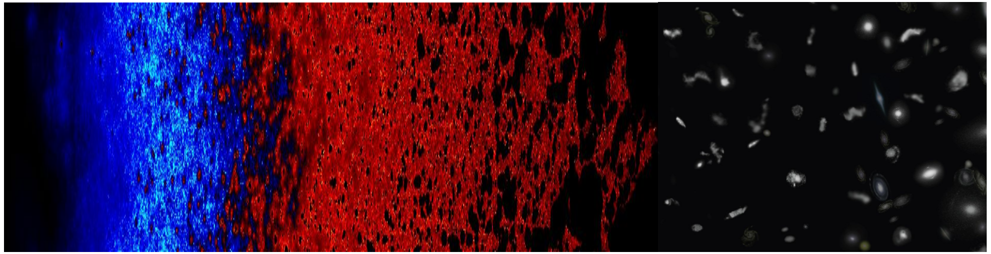


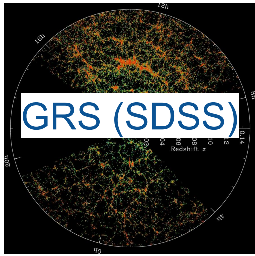
Hydrogen is the most abundant element in the Universe across cosmic time

After recombination the Universe becomes neutral

Recombination (z~1100)	Dark-Ages (1100>z>30)	Cosmic Dawn & Reionization(30>z>6)	post-Reionization(z<6)	Local Universe (z~0)

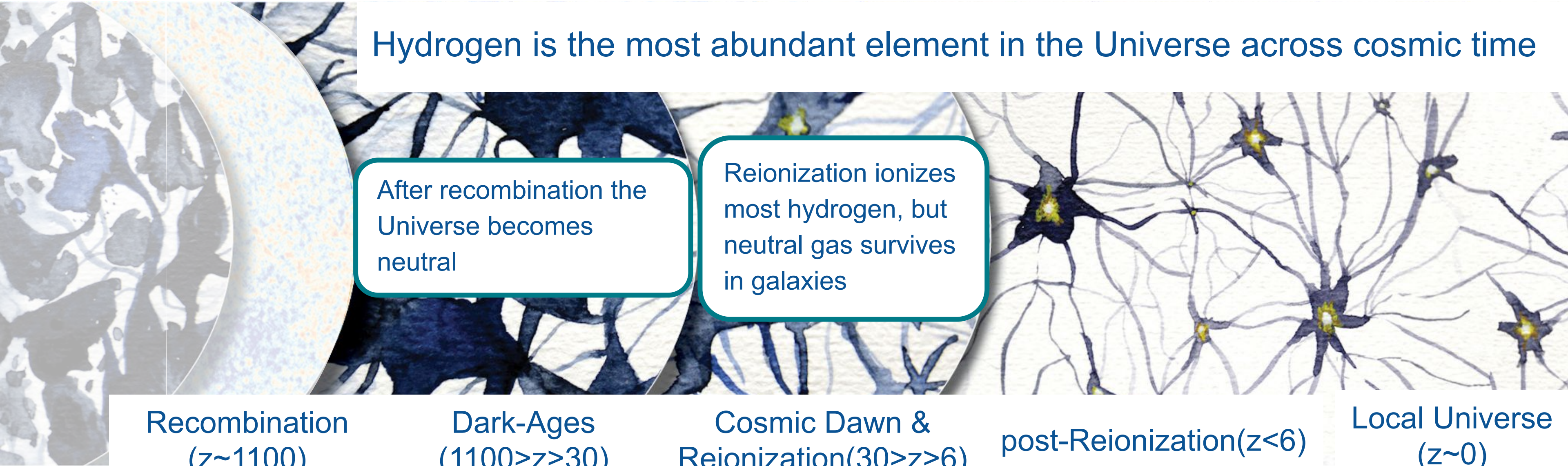






Hydrogen Across Cosmic Time

Credit: ESA



Hydrogen is the most abundant element in the Universe across cosmic time

After recombination the Universe becomes neutral

Reionization ionizes most hydrogen, but neutral gas survives in galaxies

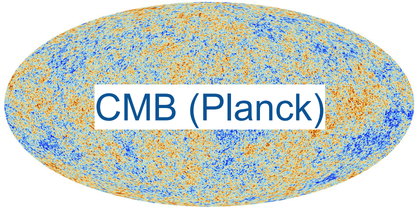
Recombination (z~1100)

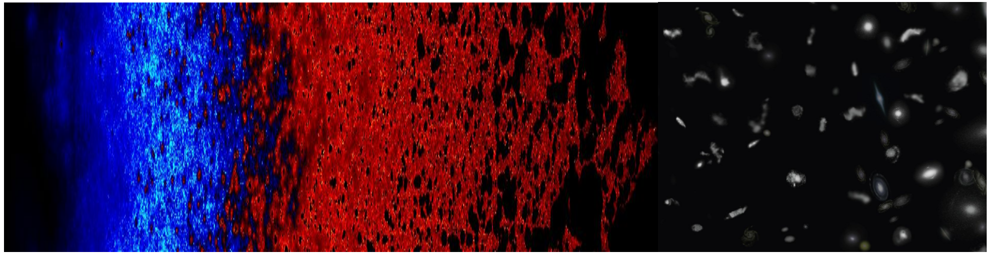
Dark-Ages (1100>z>30)

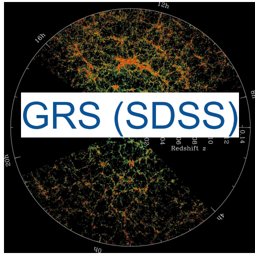
Cosmic Dawn & Reionization(30>z>6)

post-Reionization(z<6)

Local Universe (z~0)

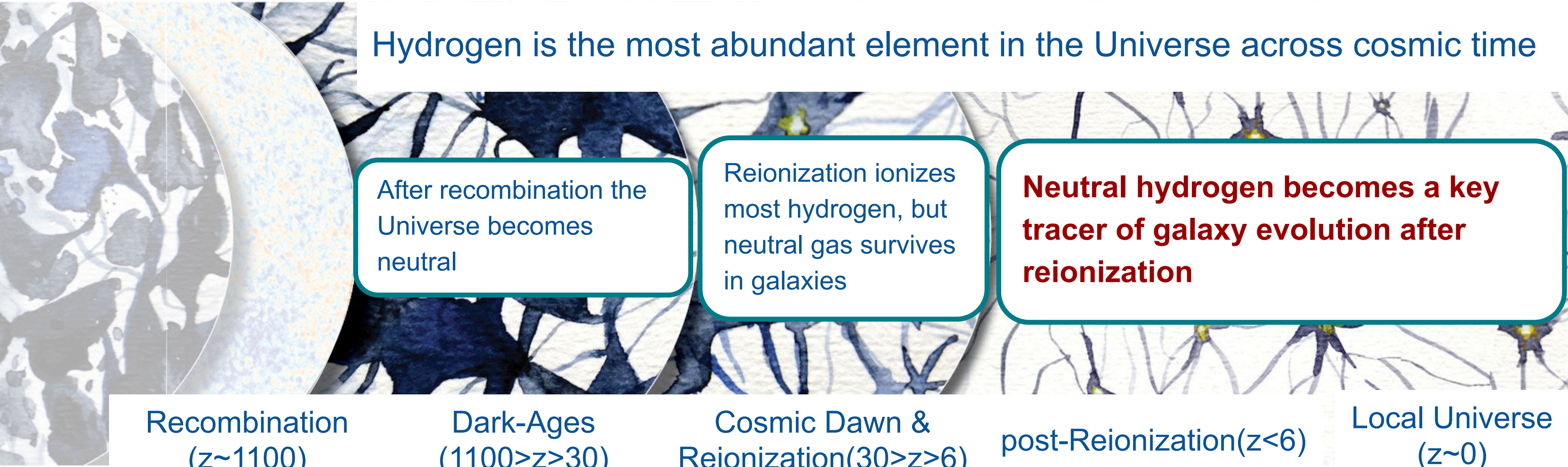






Hydrogen Across Cosmic Time

Credit: ESA



Hydrogen is the most abundant element in the Universe across cosmic time

After recombination the Universe becomes neutral

Reionization ionizes most hydrogen, but neutral gas survives in galaxies

Neutral hydrogen becomes a key tracer of galaxy evolution after reionization

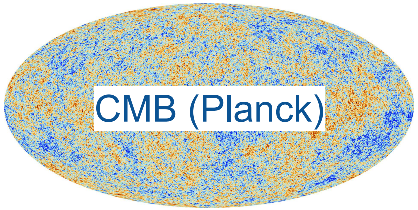
Recombination (z~1100)

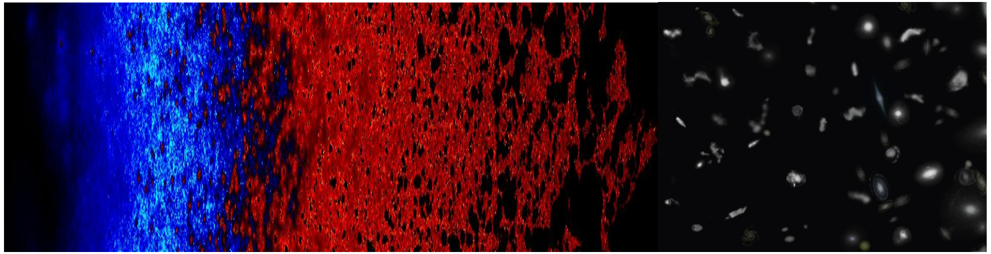
Dark-Ages (1100>z>30)

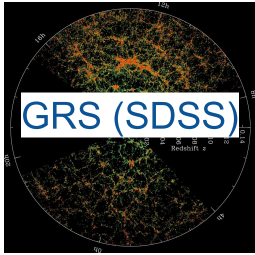
Cosmic Dawn & Reionization(30>z>6)

post-Reionization(z<6)

Local Universe (z~0)

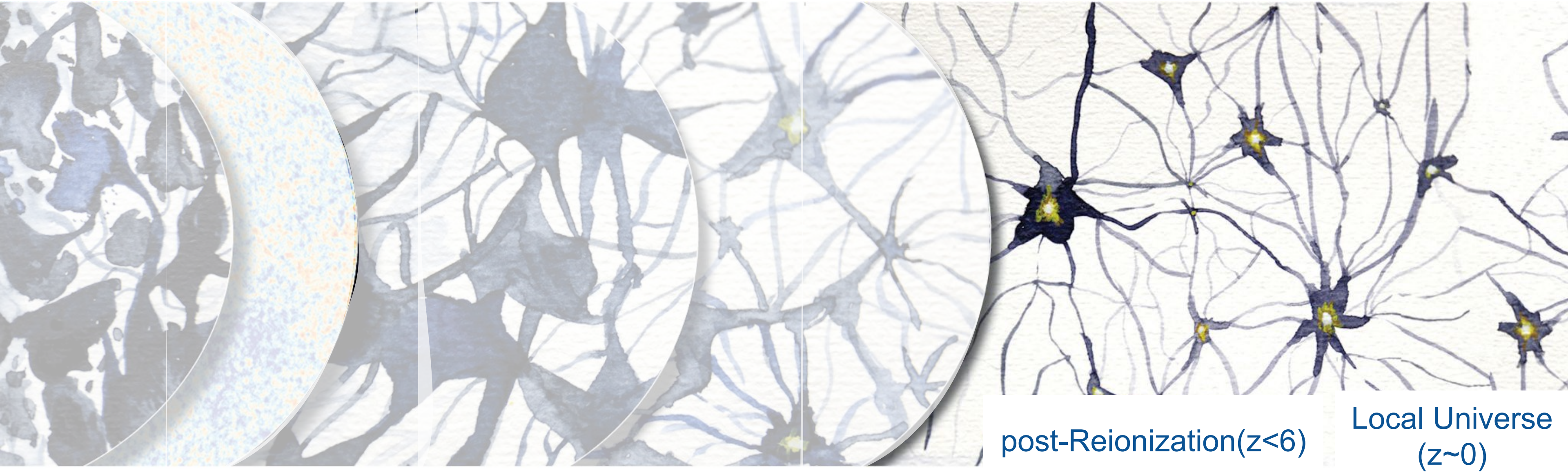






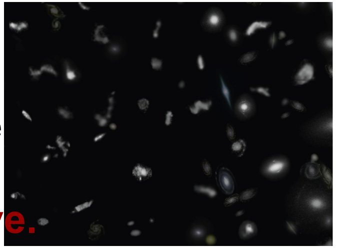
Neutral Hydrogen After Reionization

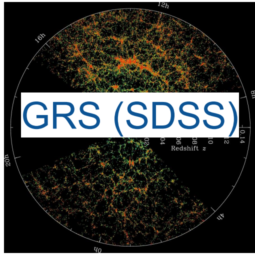
Credit: ESA



post-Reionization(z<6)

Local Universe (z~0)



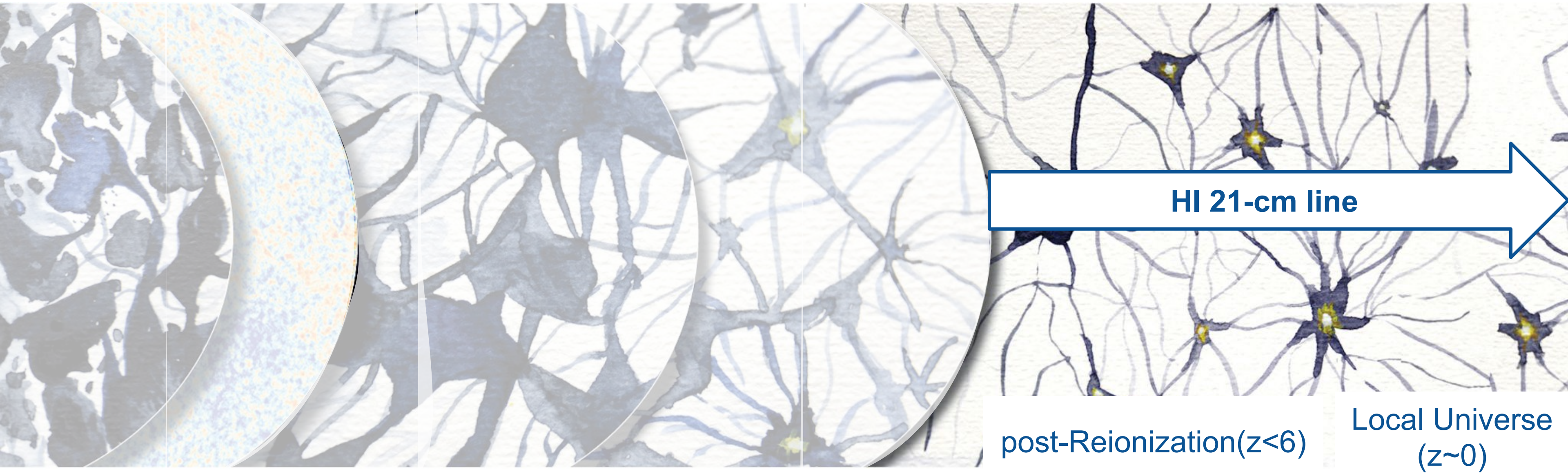


- Neutral hydrogen resides mainly inside galaxies
- It fuels star formation
- It is the biased tracer of the distribution of matter in the Universe

Studying HI tells us how galaxies and large-scale structure evolve.

Observing HI: The 21-cm Line

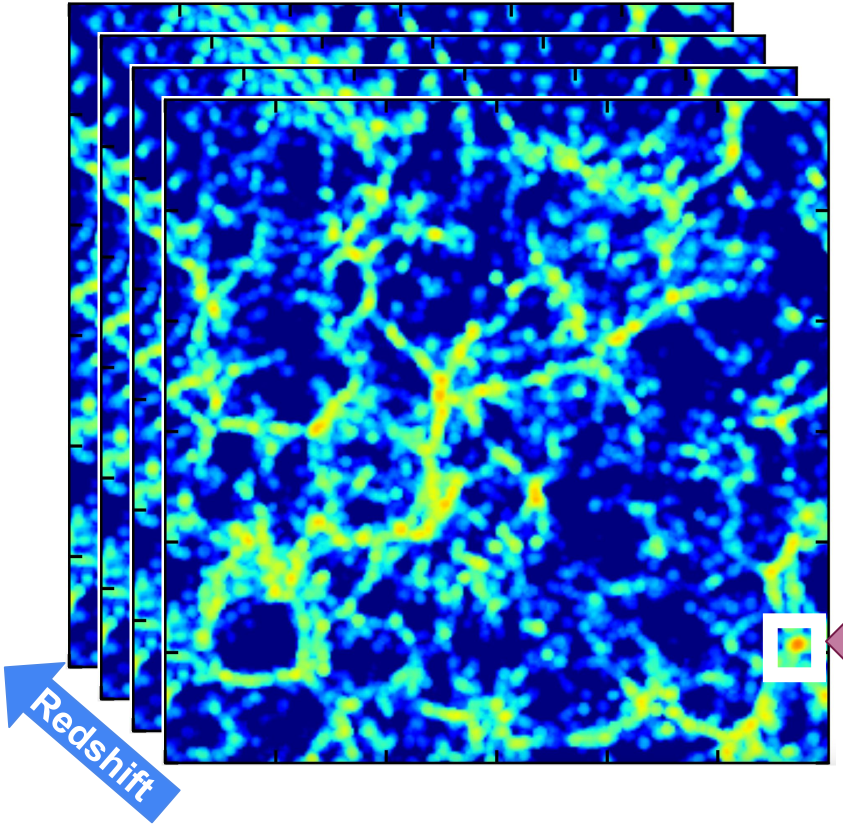
Credit: ESA



- HI emits radiation at 21 cm
- **Nearby Universe ($z \ll 1$):** 21-cm emission is reliable probe of the HI content of the individual galaxies in terms of HI mass function and HI density parameter (Ω_{HI})

Detecting HI galaxies individually becomes difficult at high z.

Intensity Mapping



- **At high z:** We cannot identify individual galaxies in 21-cm → We integrate the flux of the 21-cm radiations from the emitters. This integrated flux appears as a diffuses background radiation.

- The fluctuations in the intensity in this diffused background provide us the probe of the LSS during post-EoR.

Intensity Mapping:

- Measure the total HI emission from large regions
- Allows mapping very large cosmic volumes

Intensity mapping enables cosmological measurements of HI.

Future HI Experiments: SKAO

Credit: skatelescope.org

- ❖ Among several upcoming HI surveys with different telescopes, the most powerful will be the SKA
- ❖ These surveys will measure the large-scale distribution of HI

Future HI Experiments: SKAO

Credit: skatelescope.org

- ❖ Among several upcoming HI surveys with different telescopes, the most powerful will be the SKA
- ❖ These surveys will measure the large-scale distribution of HI

Why Do We Need Models?

- There are different methods that can be used to construct "mock" catalogues
- HOD or subhalo abundance matched techniques are certainly faster than theoretical models of galaxy formation
- They are also a faithful representation of data, by construction

Limitations:

- We need data to build them and we do have HI data only at z=0
- Also, they rely on the assumption that halo baryon content depends only on halo mass which we know is incorrect and more so when it comes to low-mass halos (assembly bias).

That is why it is important to develop more complicated galaxy formation models and use them in this context

Semi-Analytic Models

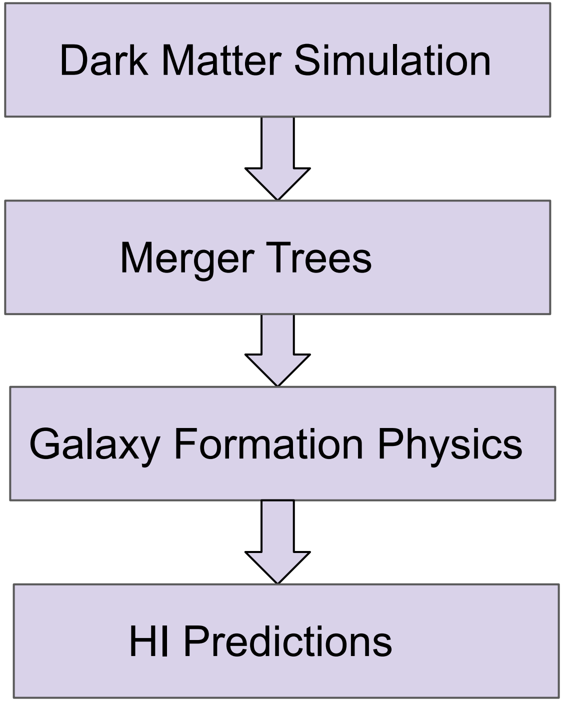
- Uses dark matter merger trees
- Adds galaxy physics with analytic recipes
- Computationally efficient for large volumes

Models:

- GAEA2017 (Spinelli+2020)
- GAEA2023 (Kamran+2026, in progress…)

In this work we use the upgraded GAEA model: GAEA2023.

Upgraded GAEA Model



Updated version: GAEA2023

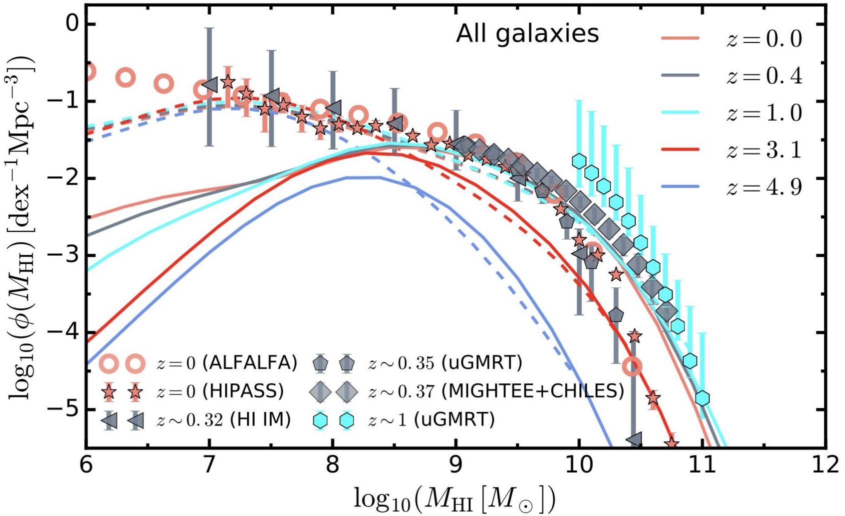
Self-consistent treatment of the partition of cold gas in atomic and molecular hydrogen (Xie+2017)

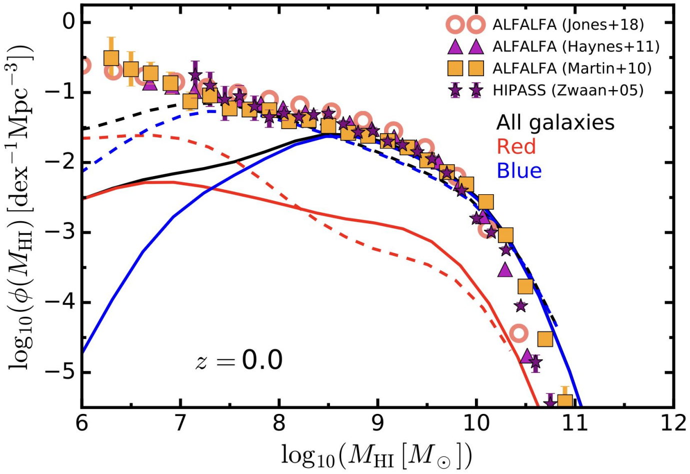
Improvements:

- ❖ Refined angular momentum evolution for gas and stellar discs, together with gradual ram-pressure stripping of satellite gas reservoirs (Xie+2020)
- ❖ Improved modeling of cold gas accretion onto supermassive black holes and associated AGN-driven outflows (Fontanot+2020)

Results: HI Evolution with Redshift

Kamran+2026 (In Progress…)



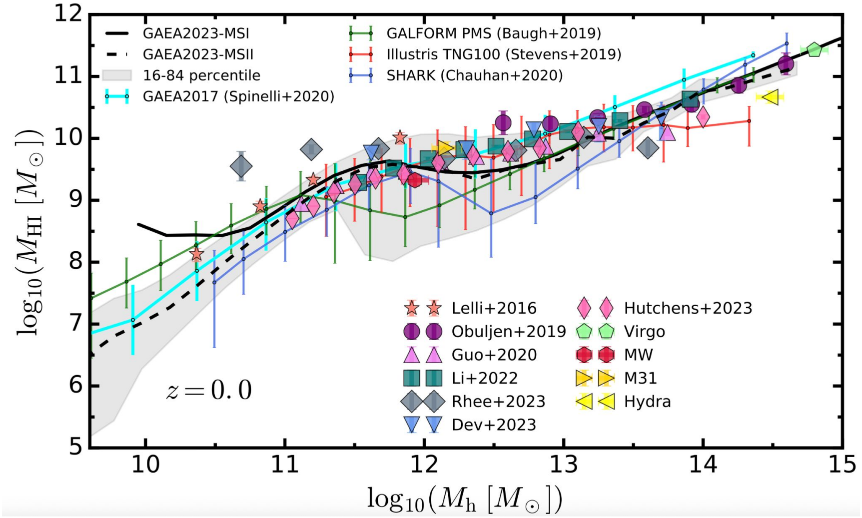


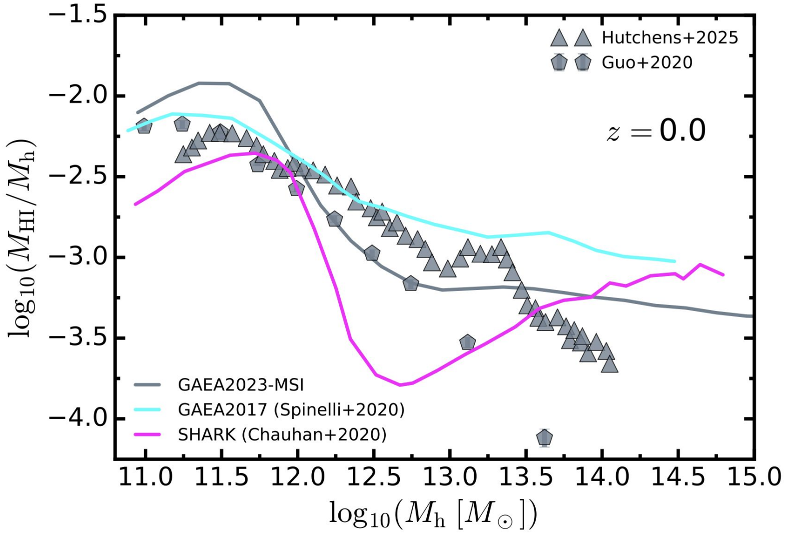
- ❖ hierarchical growth of structures
- ❖ Red vs Blue with a cut in sSFR

Blue star forming dominates HI content

Results: HI-Halo Mass Relation

Kamran+2026 (In Progress…)

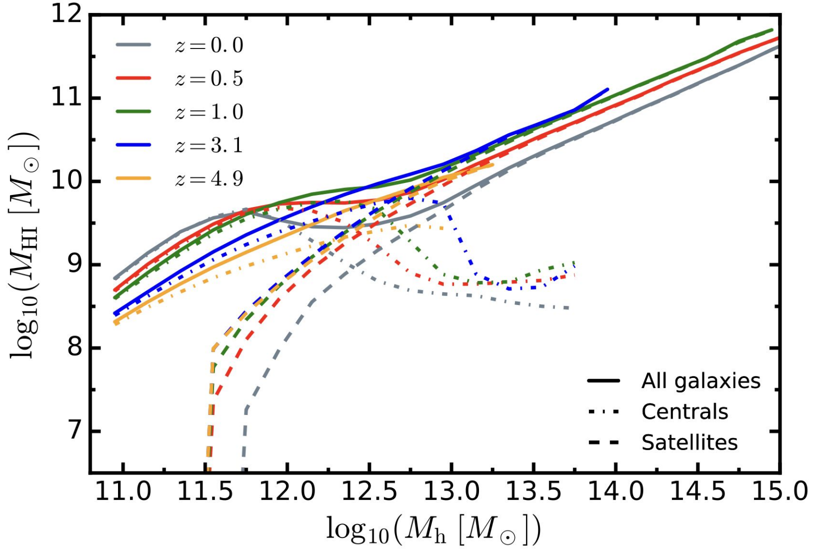


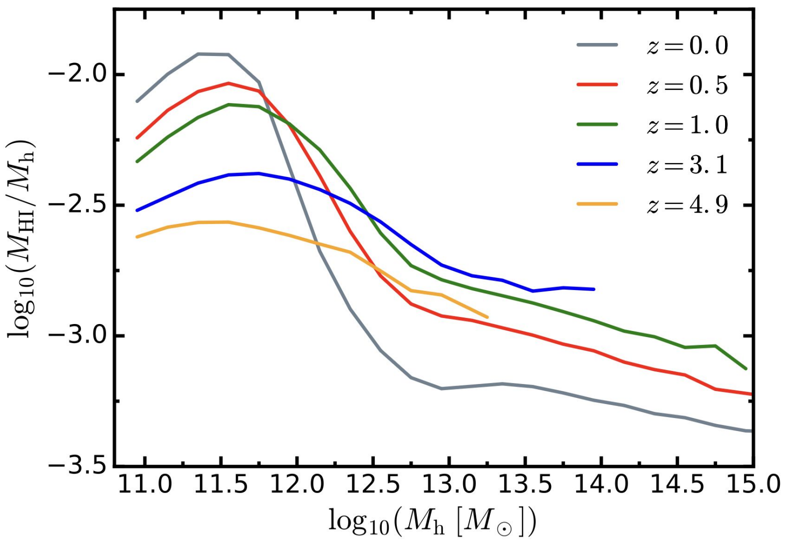


- ❖ HI content increases with halo mass at low masses: Gas accretion and cooling dominate in this regime
- ❖ HI efficiency peaks around halo masses ~10^{11}–10^{12} $M_\odot$
- ❖ Massive halos show declining HI fraction: Feedback processes and environmental effects reduce neutral gas

Results: Redshift Evolution of the HI–Halo Mass Relation

Kamran+2026 (In Progress…)

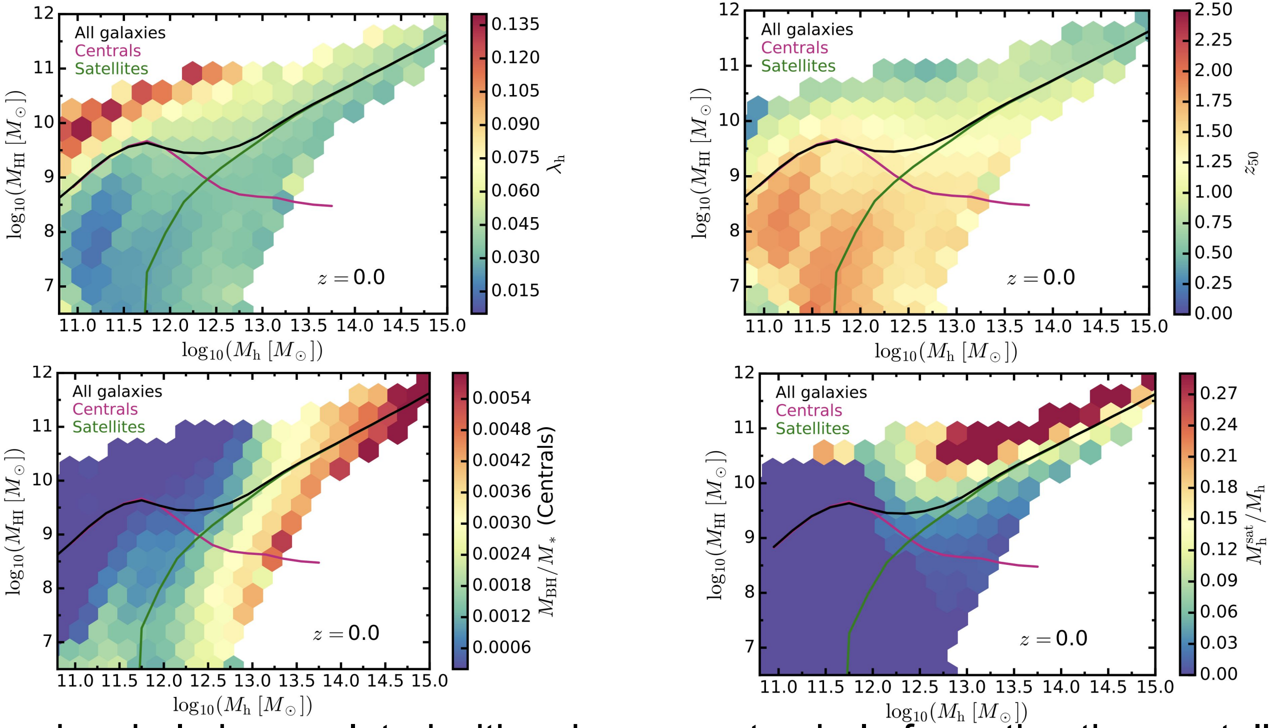




- ❖ The overall shape of the relation remains similar across redshift
- ❖ The peak shifts slightly and the HI fraction evolves gradually

Neutral hydrogen is most efficiently hosted by halos around ~10^{11}–10^{12} M⊙, while massive halos are increasingly HI-poor due to feedback and environmental processes.

Results: Physical Drivers



- HI mass in a halo is correlated with spin parameter, halo formation time, satellite fraction etc..
- HI distribution depends on both halo mass and galaxy evolution.
- Scatter in the HI–halo relation is driven by halo assembly and feedback processes.

Implications for SKA

- **Predicts HI distribution for intensity mapping**
- **Enables mock catalogs:** add SKAO-like instrumental effects
- **Helps interpret SKA measurements**

Conclusions

- **SKAO and its precursors will be crucial for 21cm Cosmology**
- GAEA has most of the fundamental ingredients (HI mass, galaxy properties, …)

  - Upgraded GAEA predicts HI evolution across cosmic time
  - Model reproduces observed HI mass function
  - HI–halo relation shows strong physical regulation: Establishing a new Mh-MHI relation just started!
  - Results provide inputs for SKA cosmology