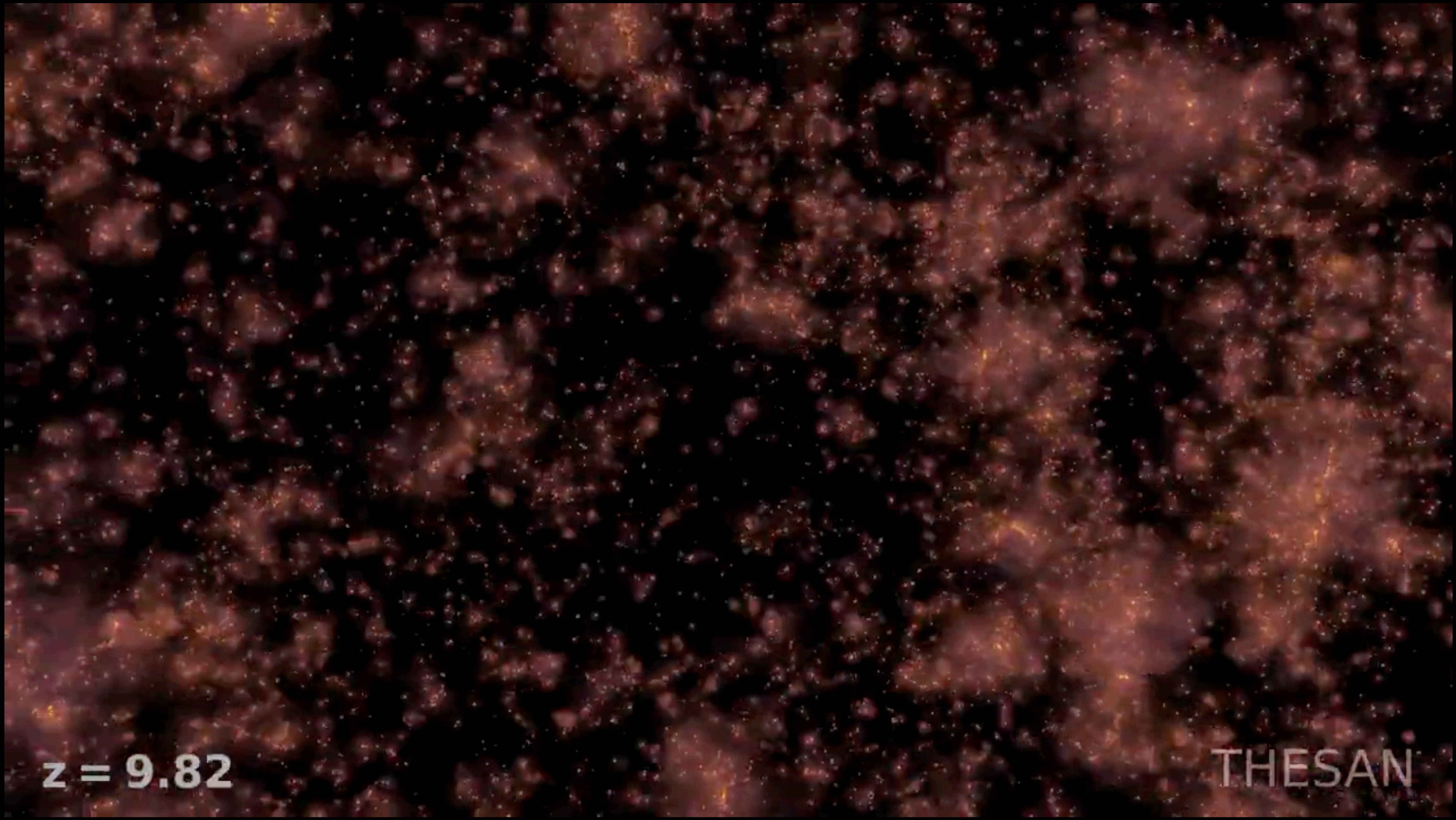
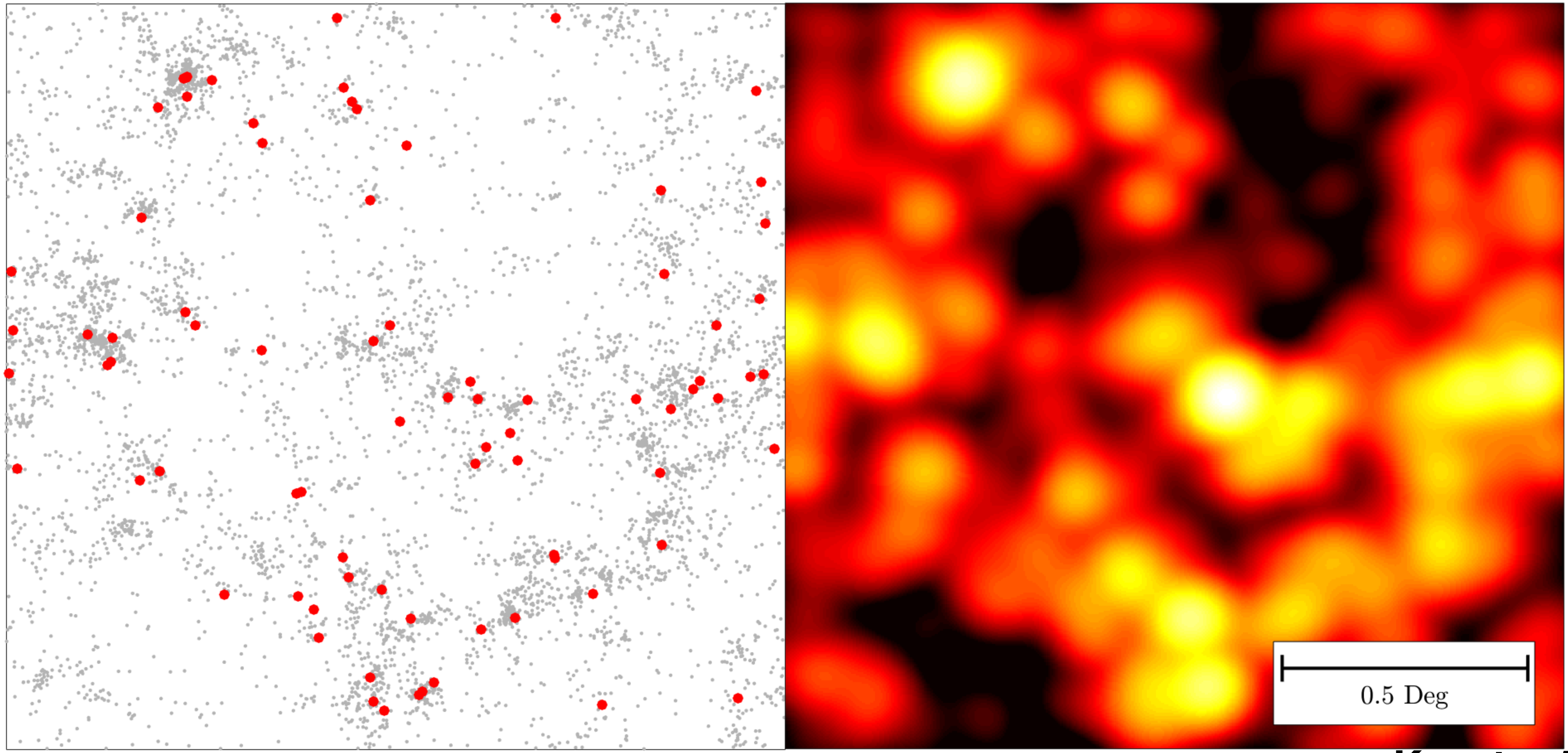
Probing the Epoch of Reionization with Line Intensity Mapping



Astronomy Seminar
University of Bologna
Feb 15, 2022

Rahul Kannan
ITC Fellow
Harvard University

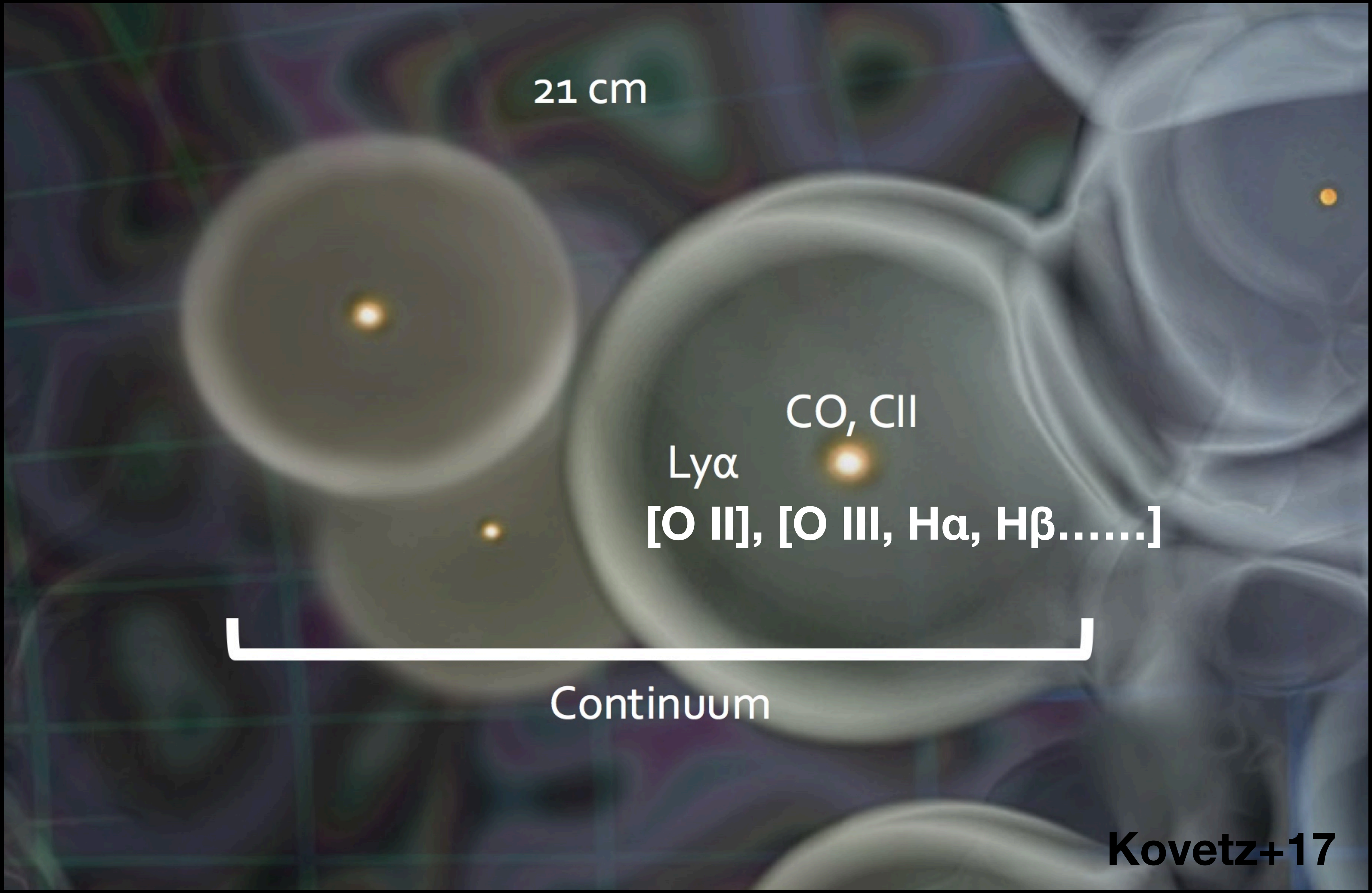
What is Line Intensity Mapping



Kovetz+17

- Measure collective spectral line emission from a large region containing multiple sources, without spatially resolving down to galaxy scales.
- Use spectral lines as tracers of structure, retain frequency resolution thus redshift information.
- The statistics of the fluctuations and the amplitude of the emission will give us information about large scale structure in the Universe

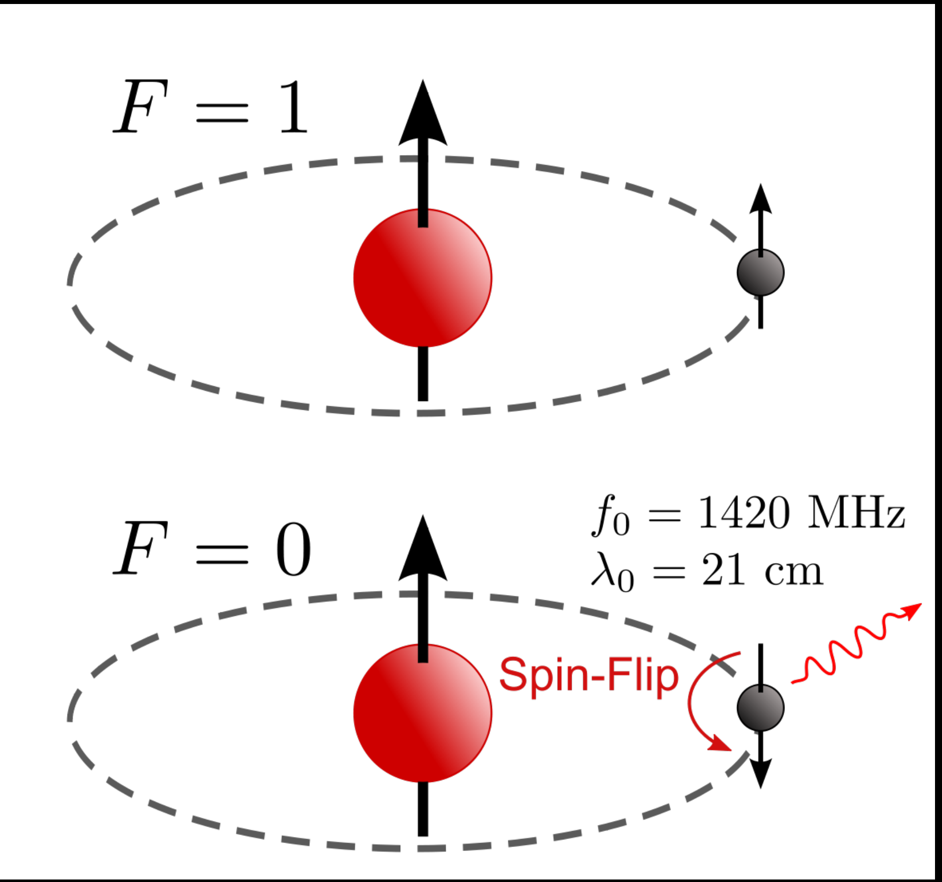
LIM during EoR



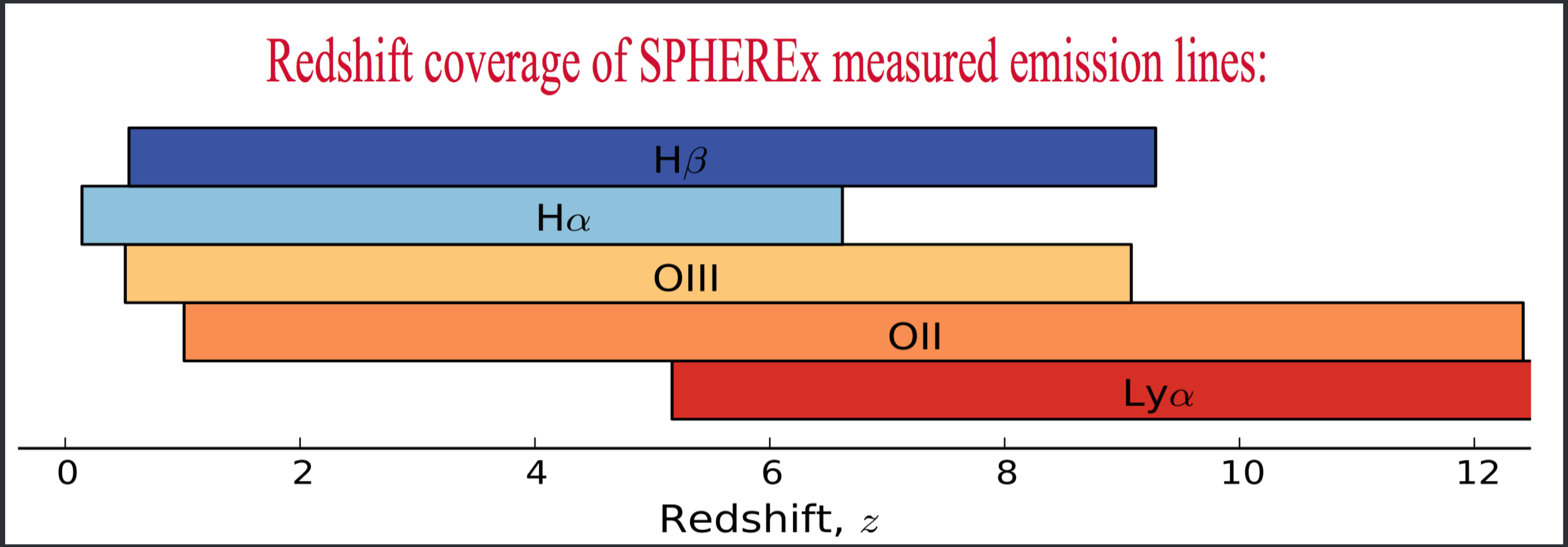
- 21 cm tells us about the reionization process
- Metal emission line (C[II], O[II], O[III]…etc) intensity mapping allows us to understand the sources responsible for it

LIM during EoR

- Intensity mapping of the Hydrogen spin flip transition provides promising way to measure neutral H at high-z
- Move from individual sight-lines to a tomographic picture
- Current and upcoming telescopes like LOFAR, SKA, HERA will provide a wealth of data soon



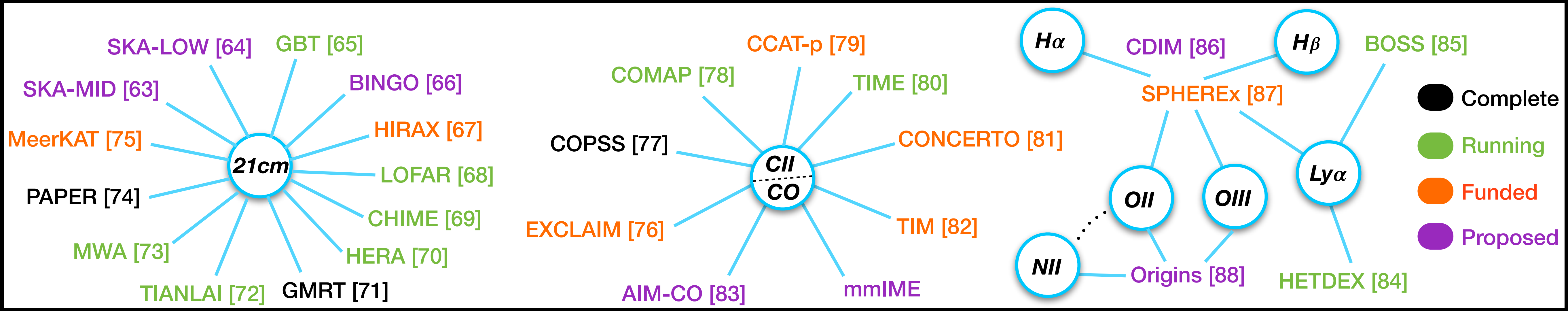
SPHEREx:
Multi-line intensity maps of the Universe



- SPHEREx will produce 96 spectral images and map 3D intensity fluctuations of multiple line tracers across redshift.
- SPHEREx has access to multiple lines at $0 < z < \sim 7$.
- Multi-line cosmology and EoR! But line deconfusion a potential issue.
- Focusing on EoR and Cosmology science cases on high-z with ~200 deg^2 deep fields for now.

Slide Credit: Tzu-Ching Chang (JPL/Caltech)

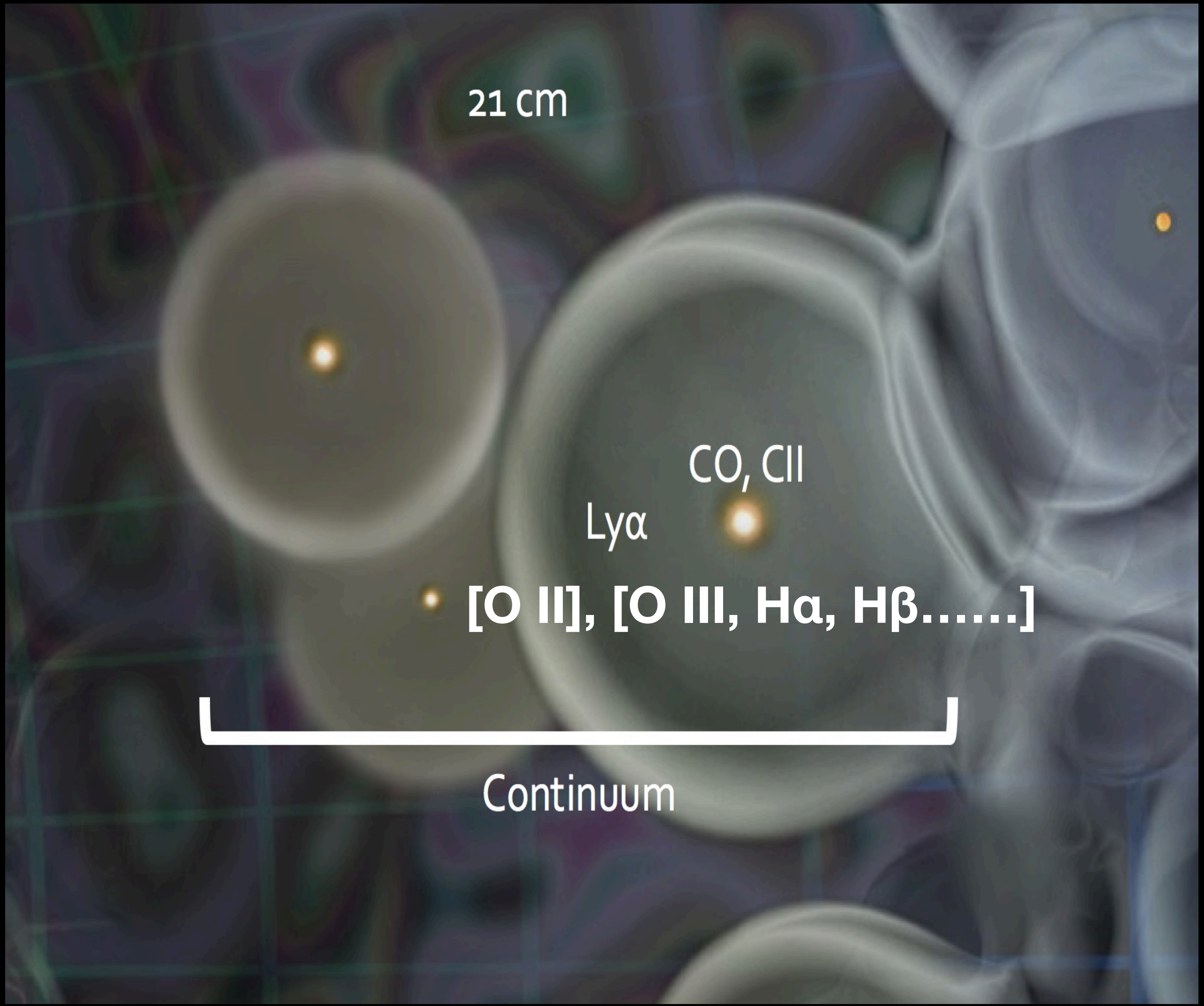
Current and Upcoming Experiments



- 21 cm tells us about the reionization process
- Metal emission line (C[II], O[II], O[III]…etc) intensity mapping allows us to understand the sources responsible for it

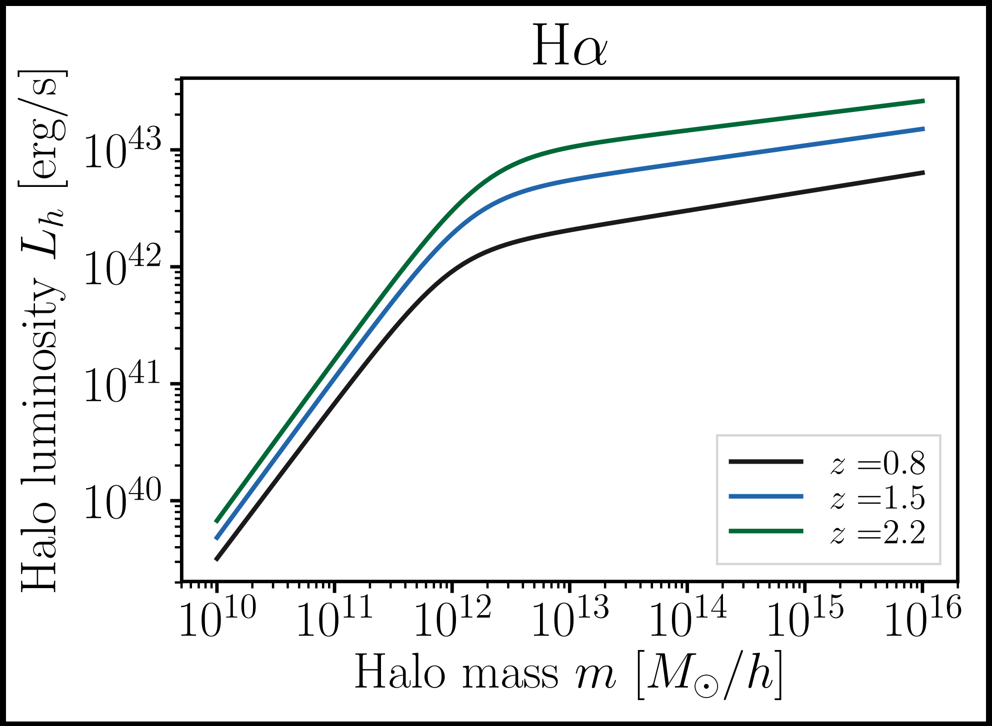
Required ingredients

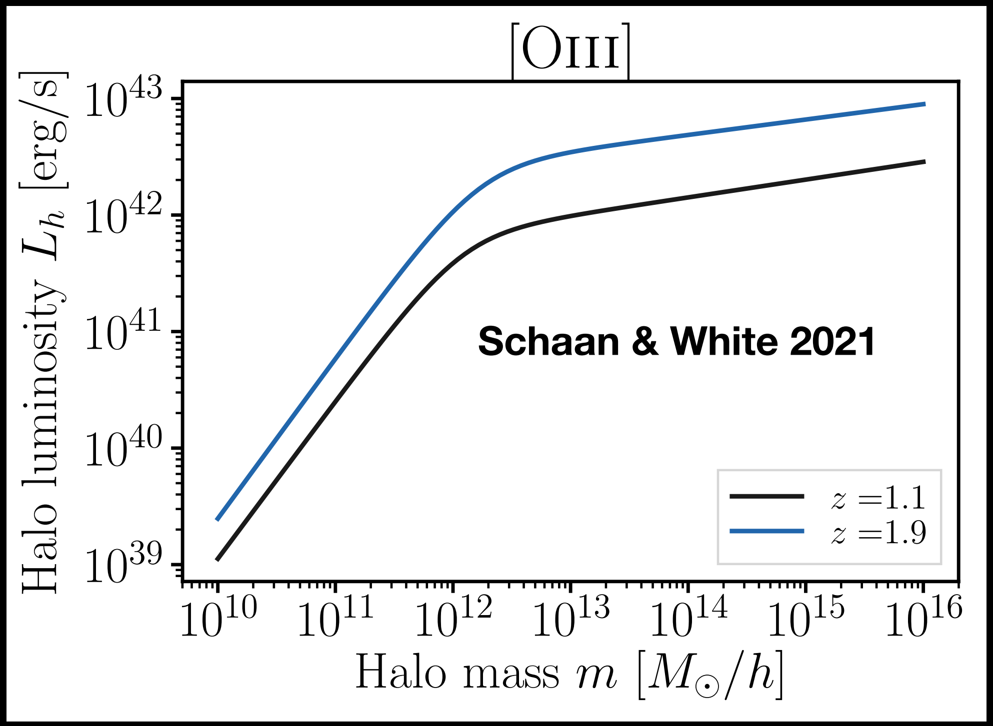
- Accurate reionization history and topology
- Accurate galaxy formation model
- Accurate interaction between the low density IGM and the sources responsible for it
- Accurate modeling of emission lines
- High dynamic range - model large scale Reionization process and the resolved properties of galaxies and BHs

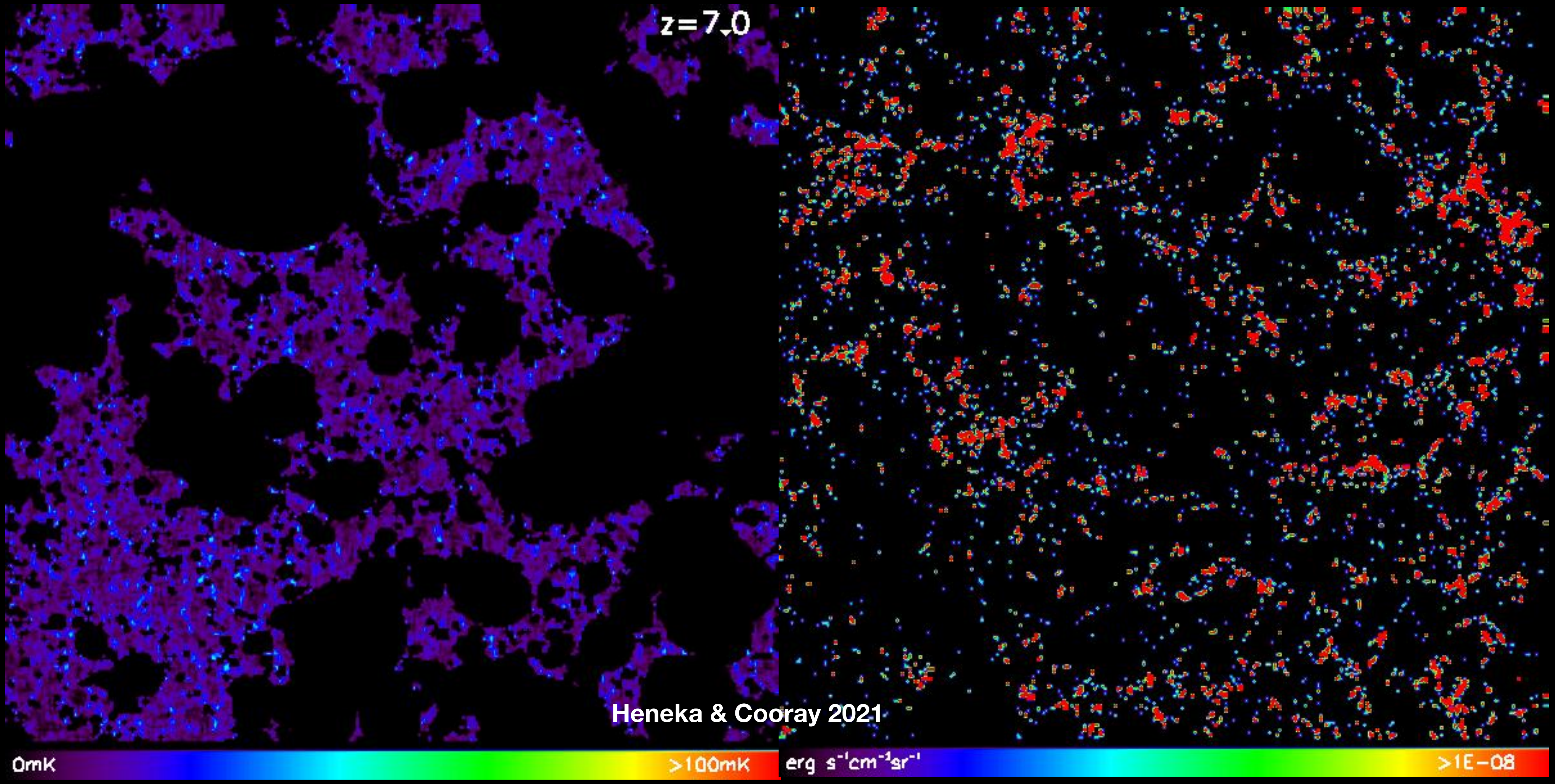


LIM using semi-numerical techniques

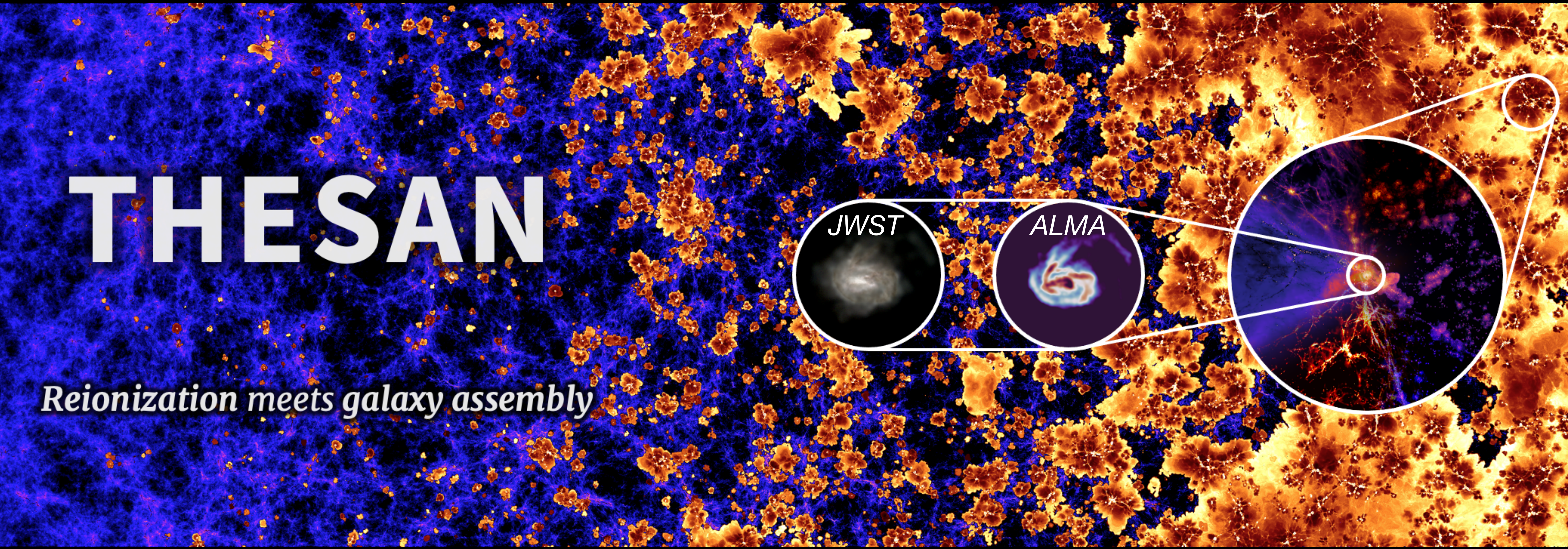
Paint on line luminosities on halos and compare with painted HII regions in the IGM







The THESAN Project

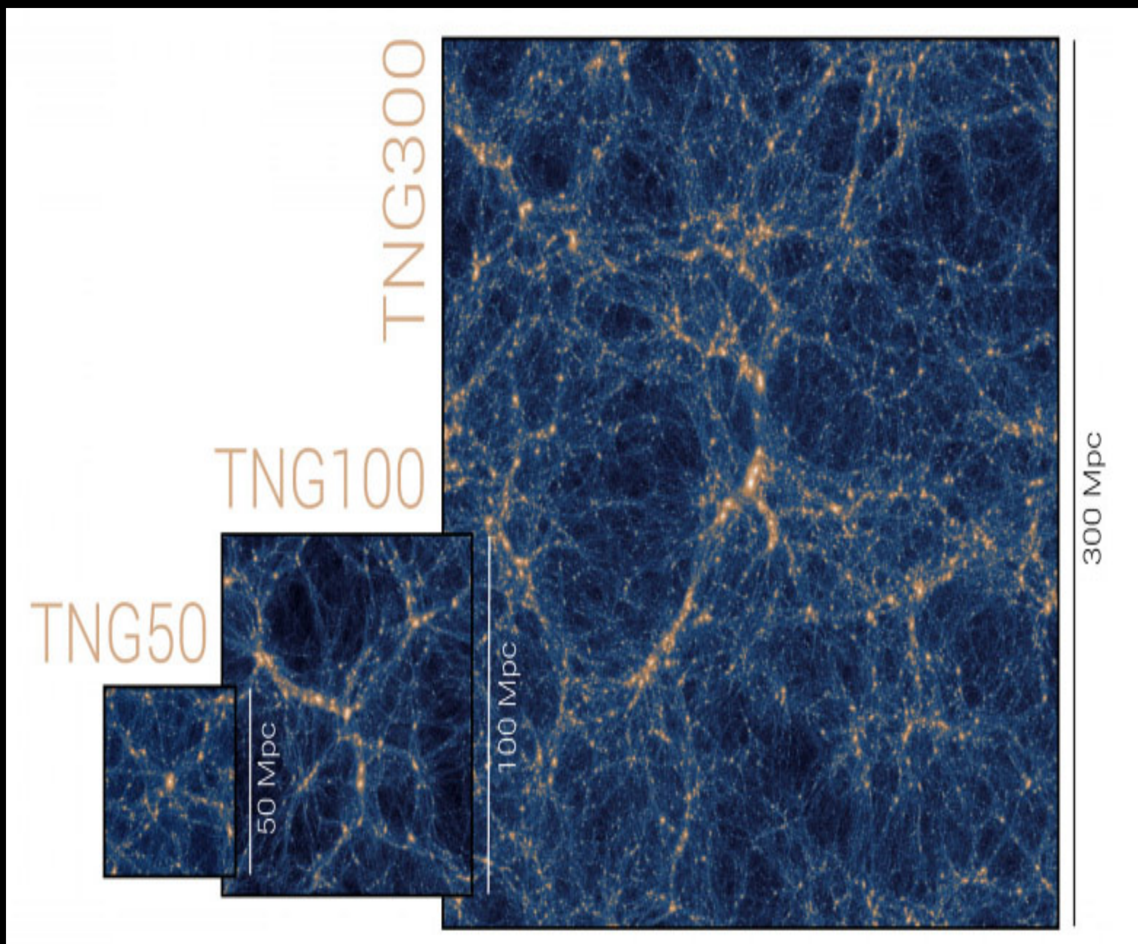


Team Members: **Rahul Kannan**

Enrico Garaldi, Aaron Smith, Rüdiger Pakmor, Volker Springel, Mark Vogelsberger & Lars Hernquist

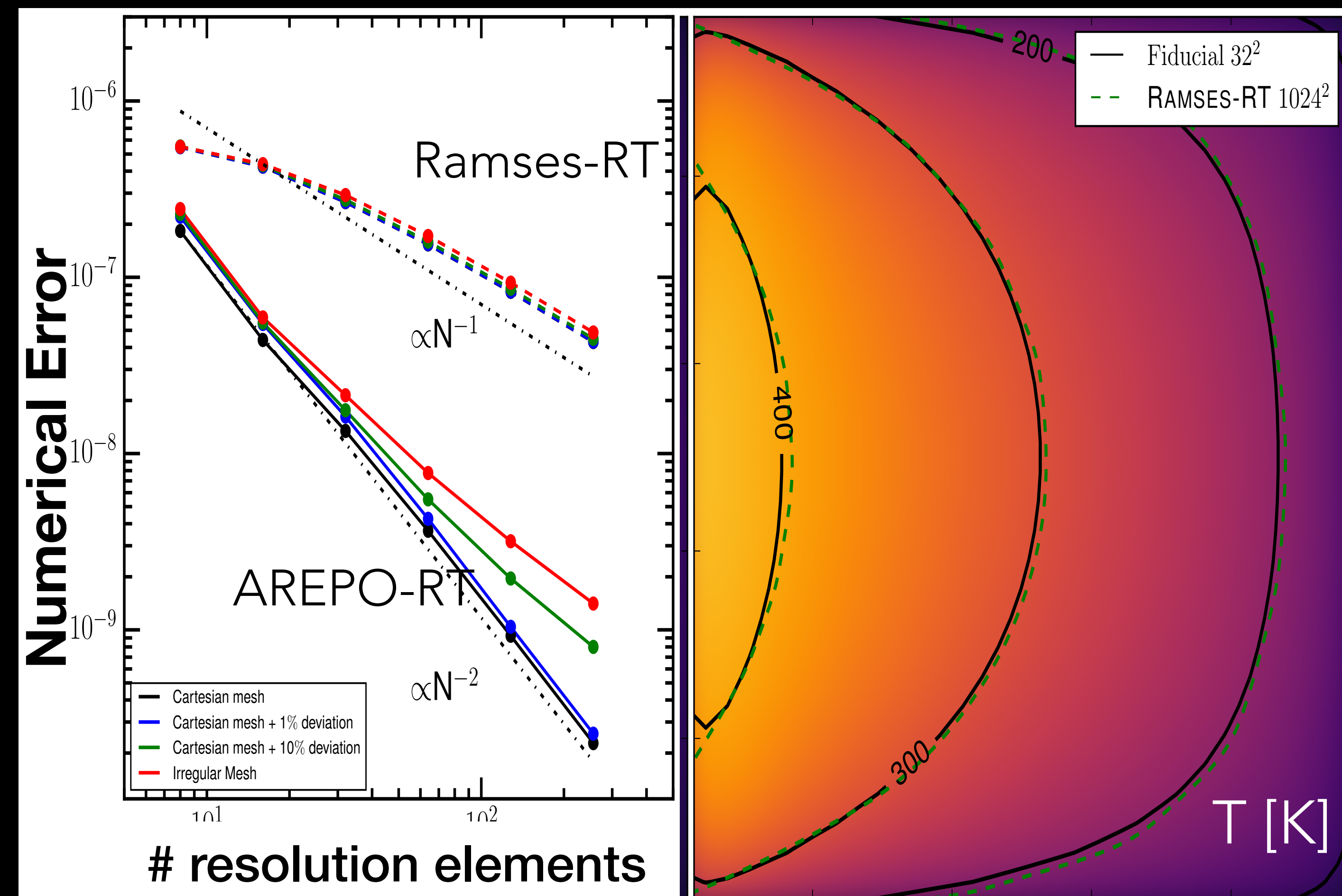
Kannan+2022 (MNRAS, Accepted)

Accurate galaxy formation model + RHD



IllustrisTNG
(Springel+18)

+

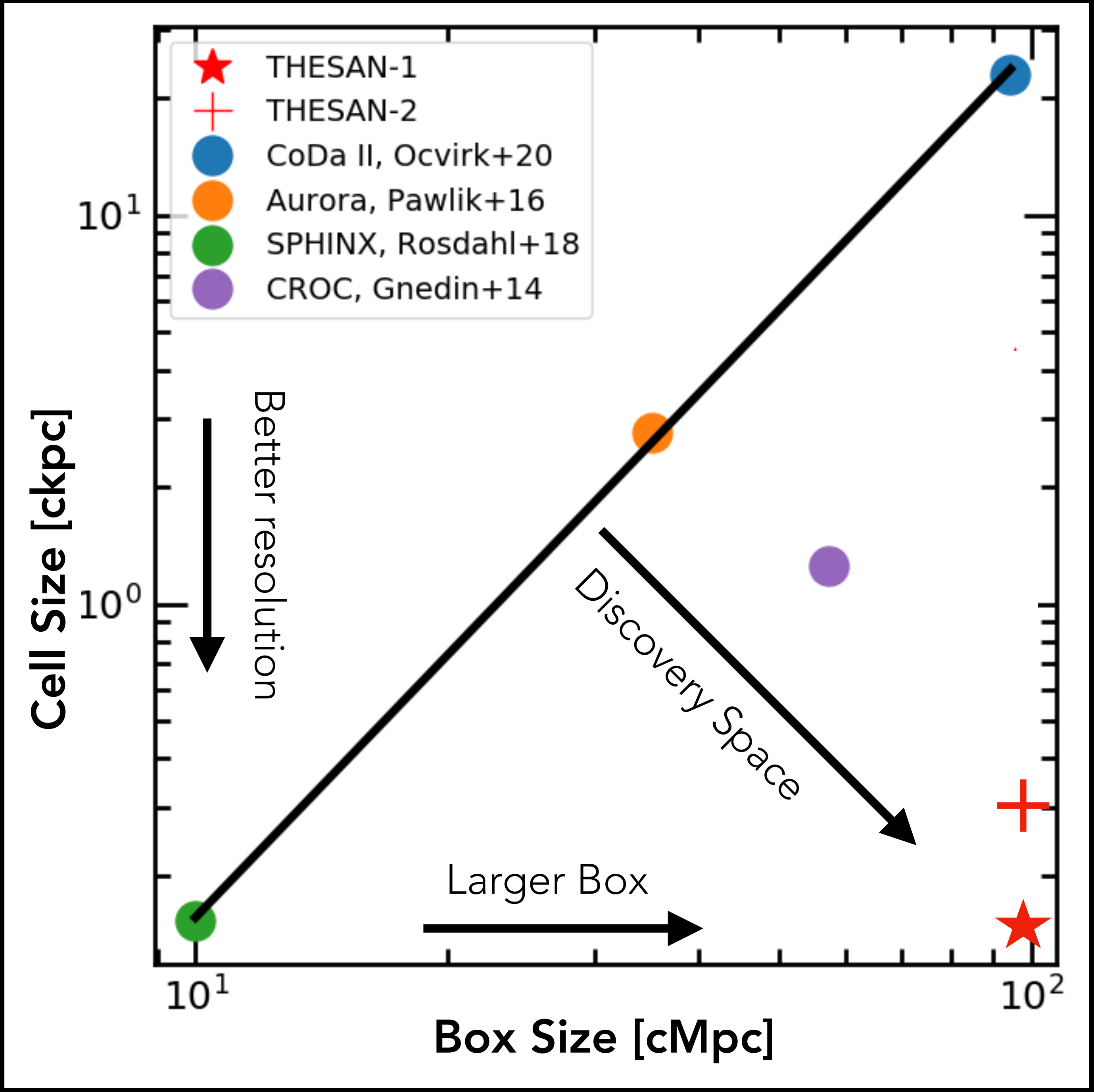


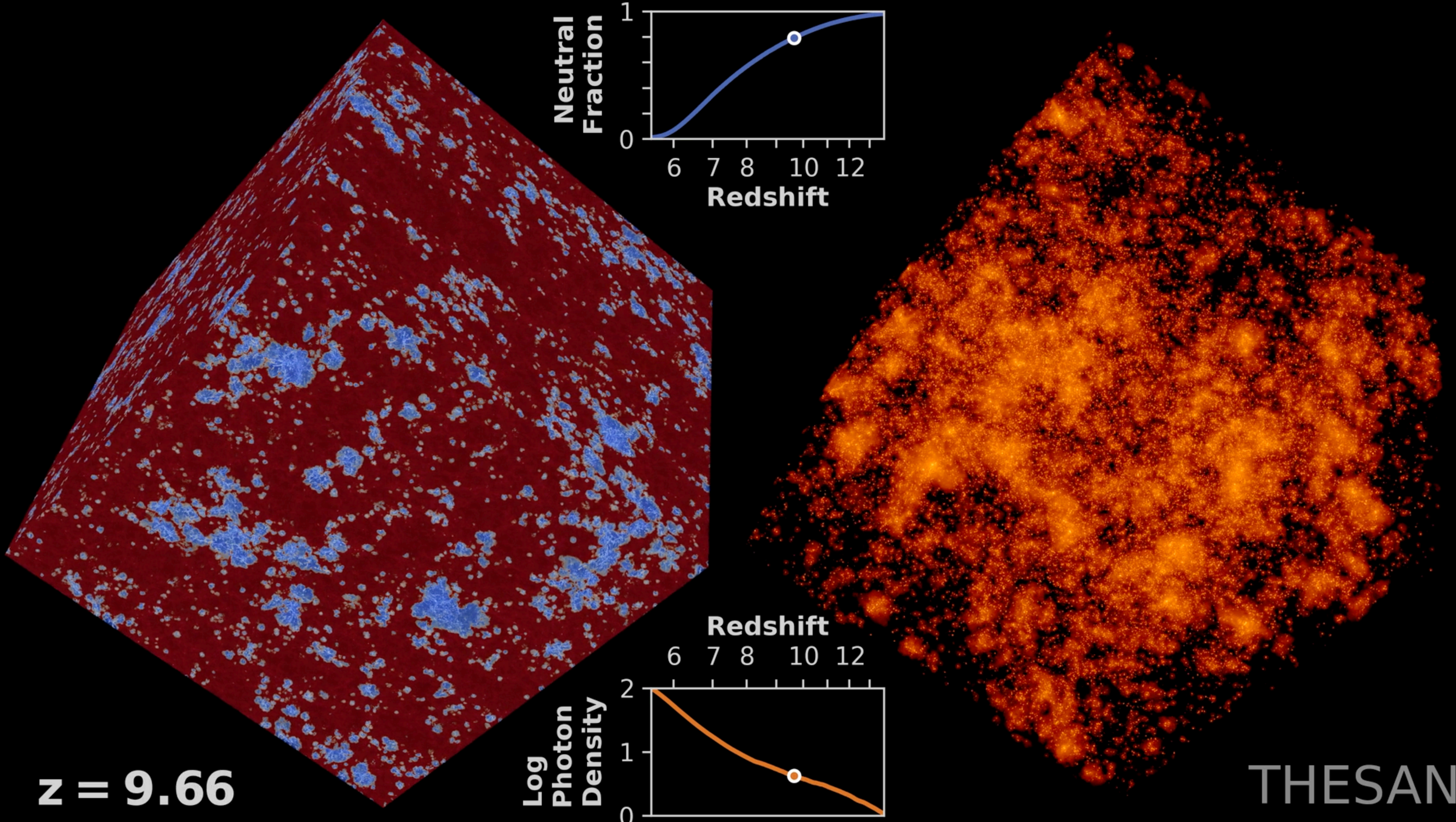
AREPO-RT
(Kannan+19)

- Well tested galaxy formation model, works extremely well down to z=0
- Efficient and highly scalable radiation hydrodynamics module that solves the RT equations on the native Voronoi Mesh

The THESAN Project

- Large volume simulations
- 95.5 cMpc, N=2100^3
- Spatial resolution of 1.4 ckpc ~ 0.2 pkpc (at z=6), minimum gas cell size ~ 10 pc
- Gas Mass resolution ~ 5 x 10^5 M_{sun}
- Performed on 57, 600 cores on SuperMUC-NG
- Resolves atomic cooling halos throughout the simulation volume
- Additional low resolution runs test the convergence, escape fractions and alternative DM models
- Different sims with different escape fractions and underlying DM models.
- Is a significant step forward in modeling EoR

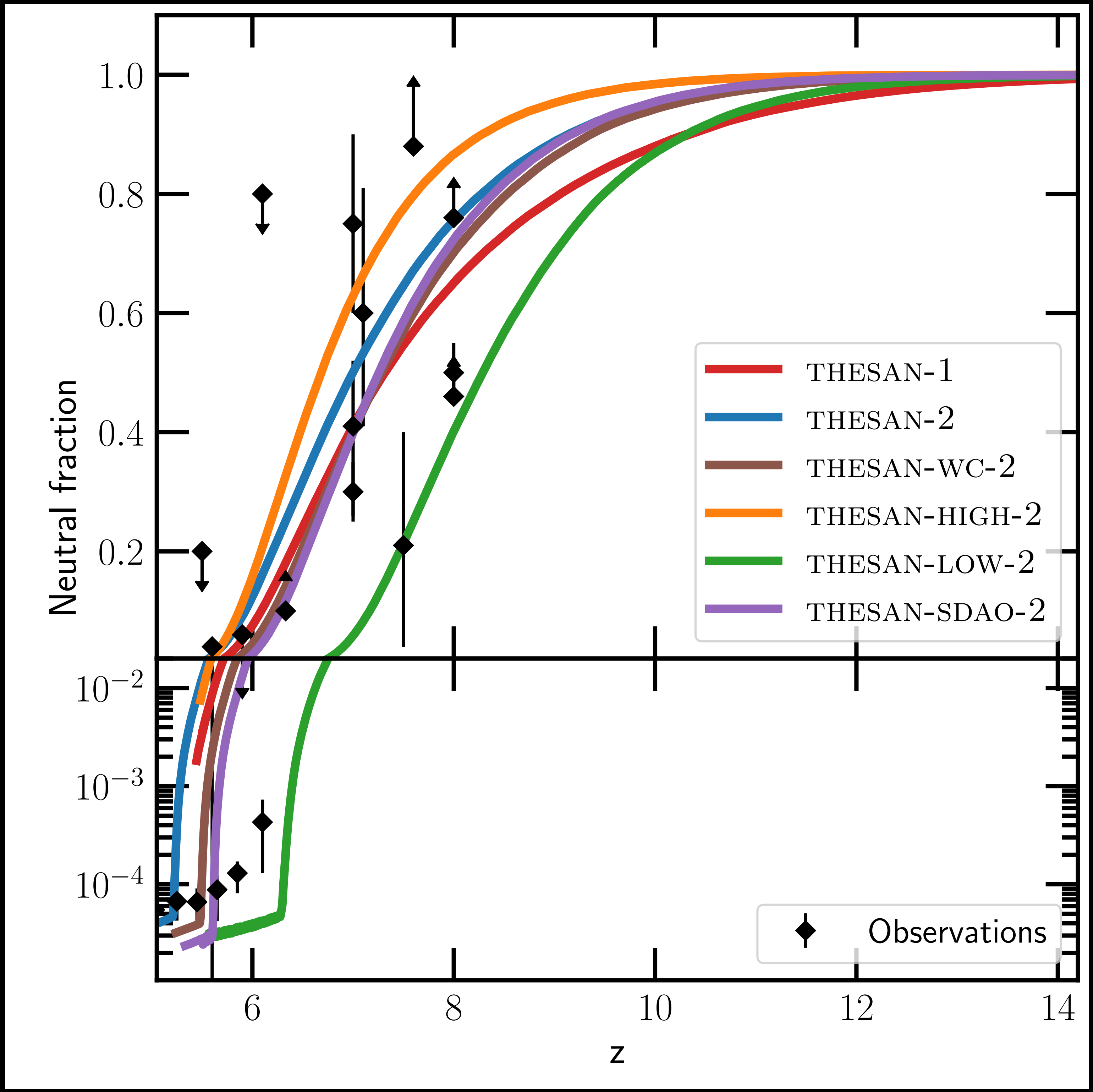


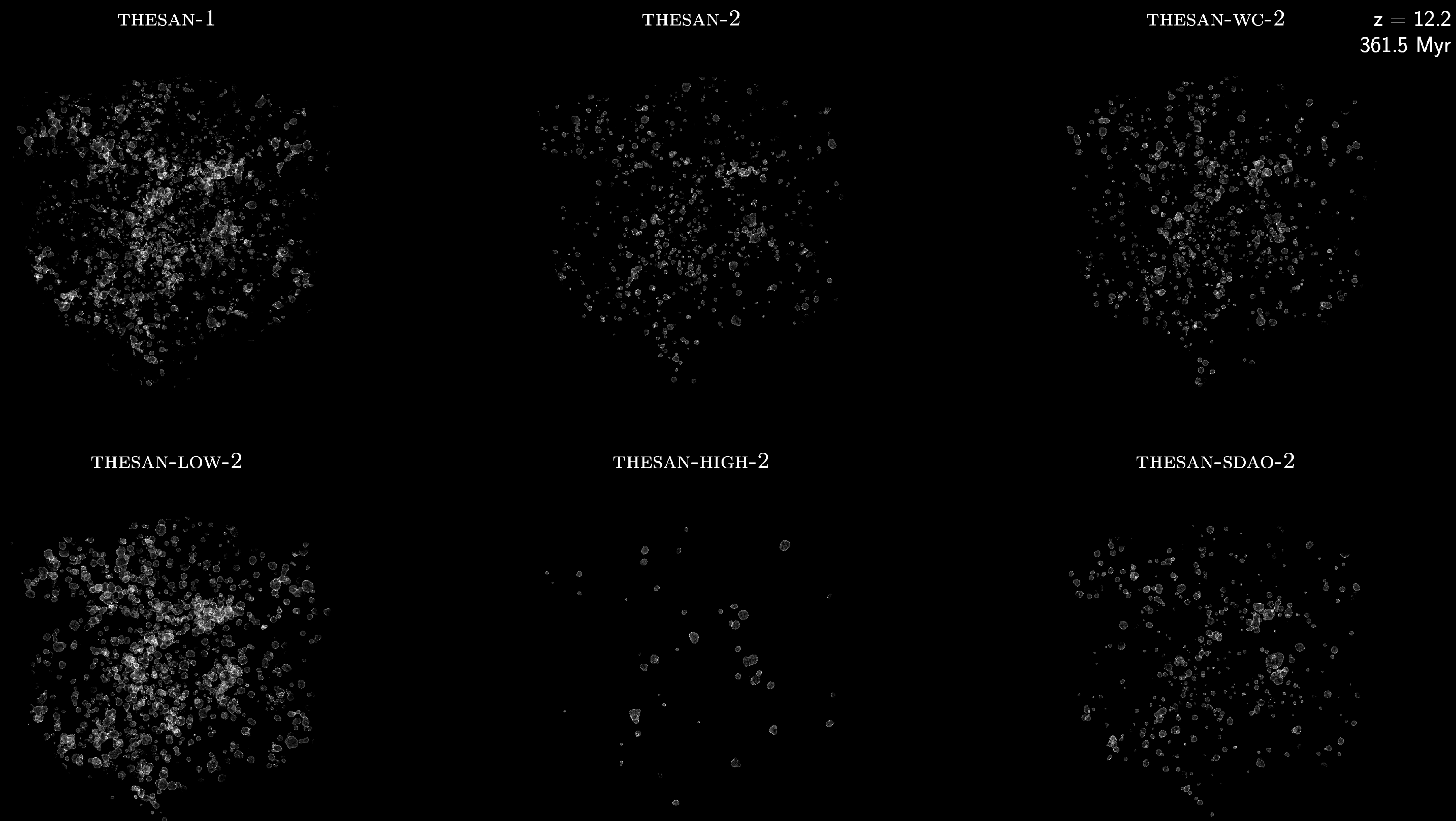

Neutral Fraction
1
0
6 7 8 10 12
Redshift
Redshift
6 7 8 10 12
2
1
0
Log Photon Density
z = 9.66
THESAN

Kannan+22

CORRECT NEUTRAL FRACTION EVOLUTION

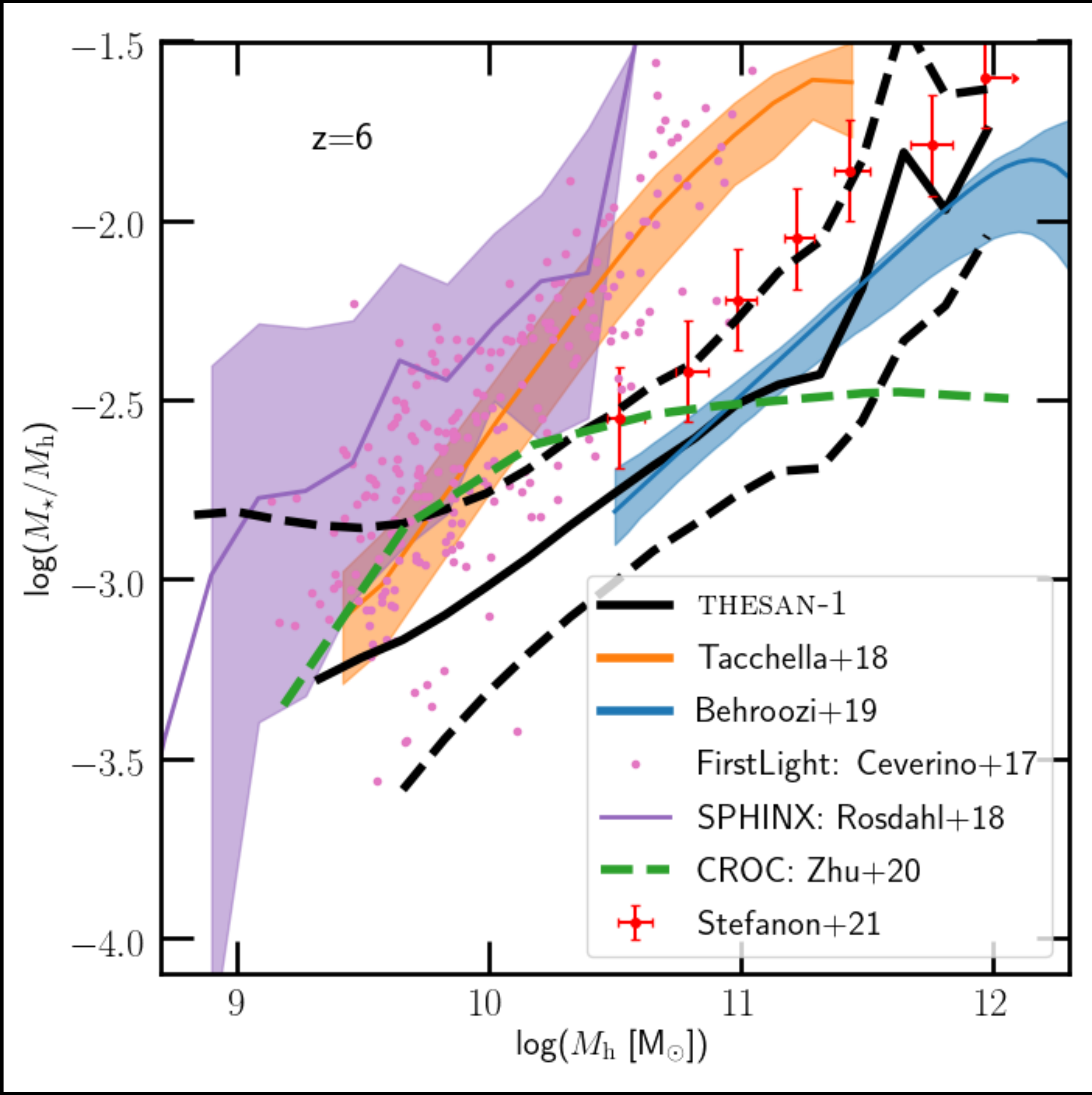
- Thesan-1 fiducial high resolution run
- Thesan-2/Thesan-WC-2 lower resolution counterpart
- Thesan-High-2/Thesan-Low-2 only high/low mass halos (> 10^{10}/< 10^{10}) contribute photons
- Thesan-sDAO-2 alternative DM model



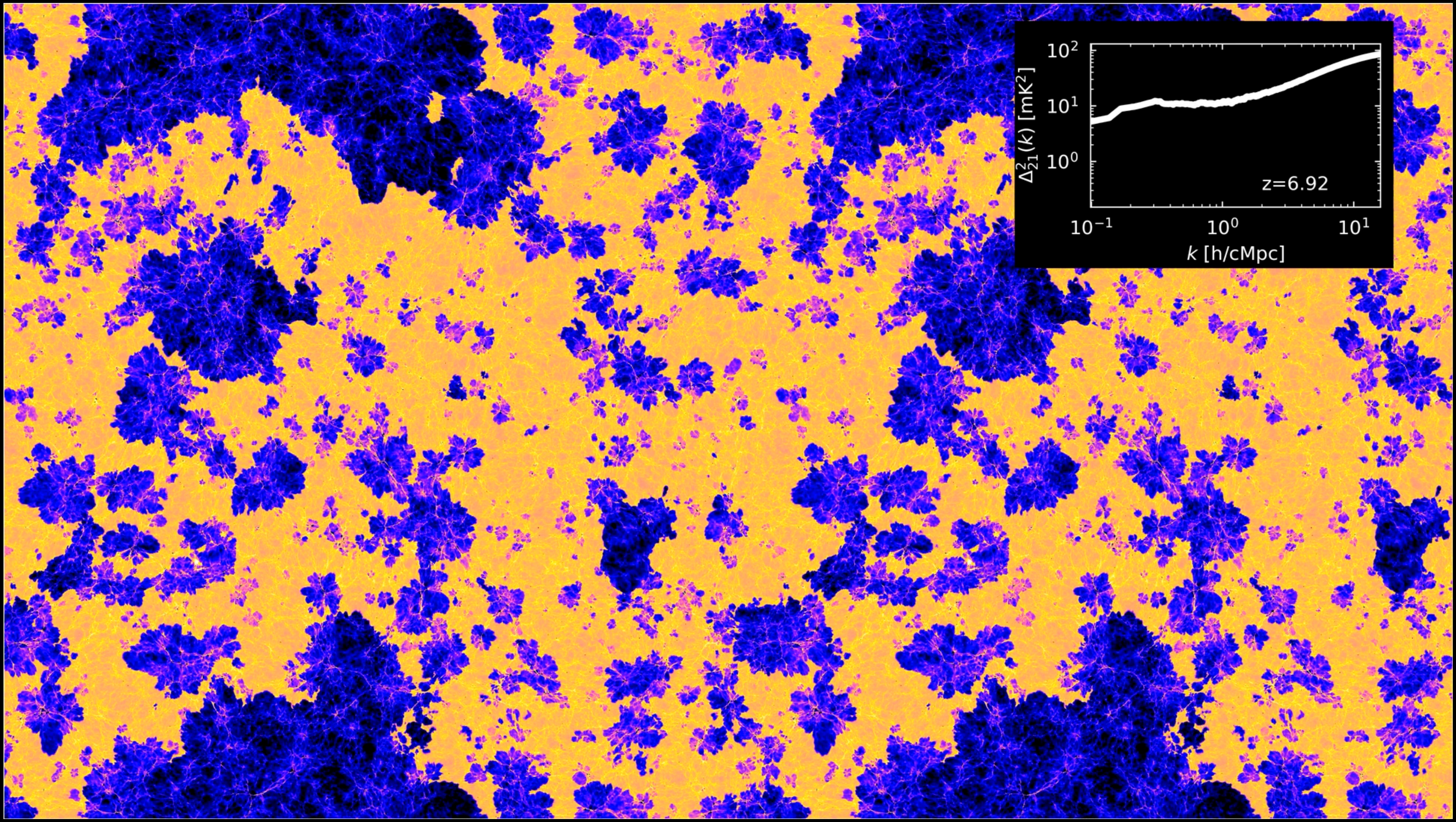

THESAN-1
THESAN-2
THESAN-WC-2
z = 12.2
361.5 Myr
THESAN-LOW-2
THESAN-HIGH-2
THESAN-SDAO-2

ACCURATE STELLAR MASSES

- THESAN predicts the right amount of stars in a halo
- Matches Behroozi+19 abundance matching estimates and broadly in agreement with recent observational estimates from Stefanon+21
- Other simulations either predict a baryons conversion efficient that is either too high (SPHINX / FirstLight) or too low (CROC)



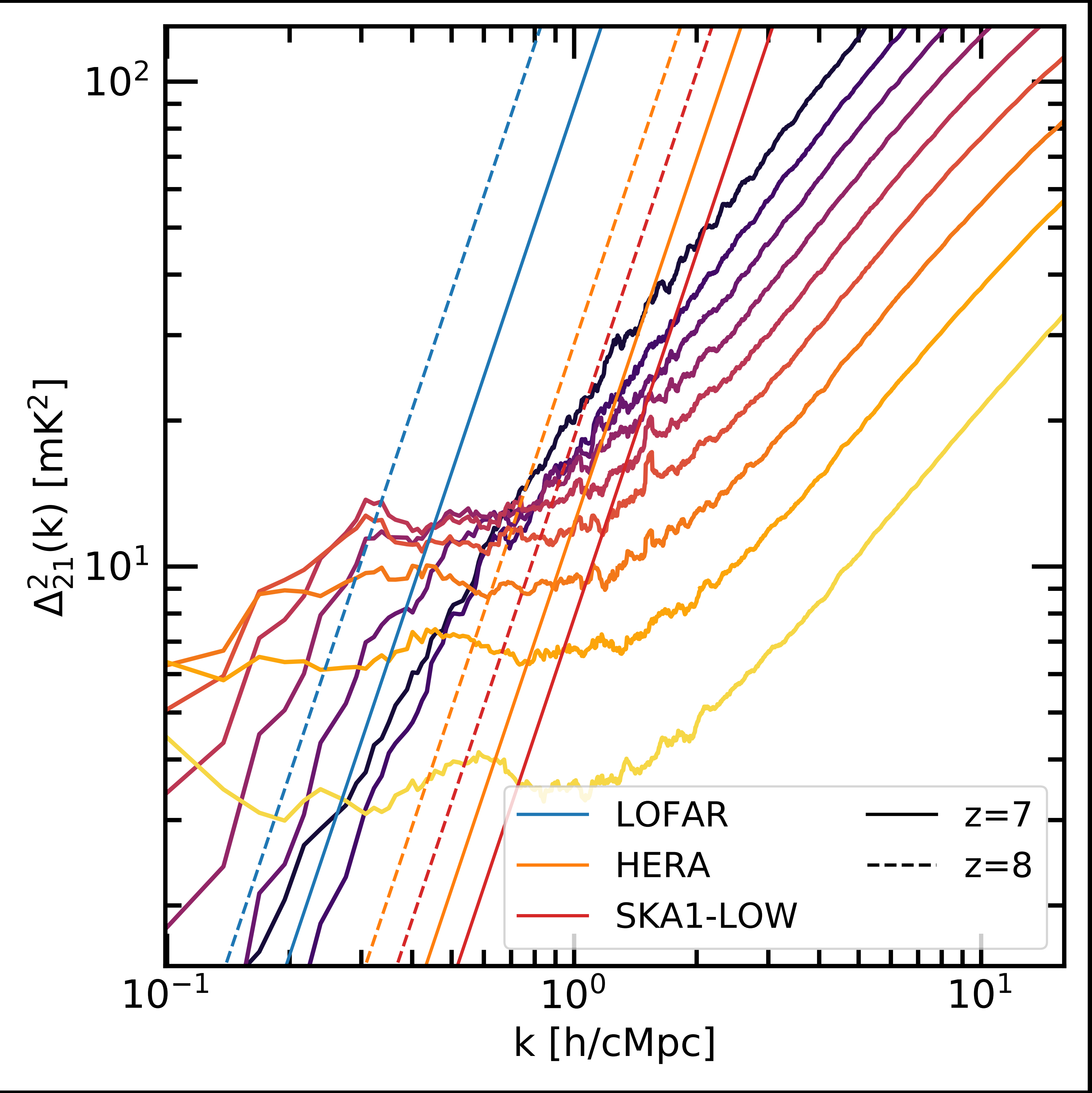
PREDICTIONS FOR 21CM EMISSION



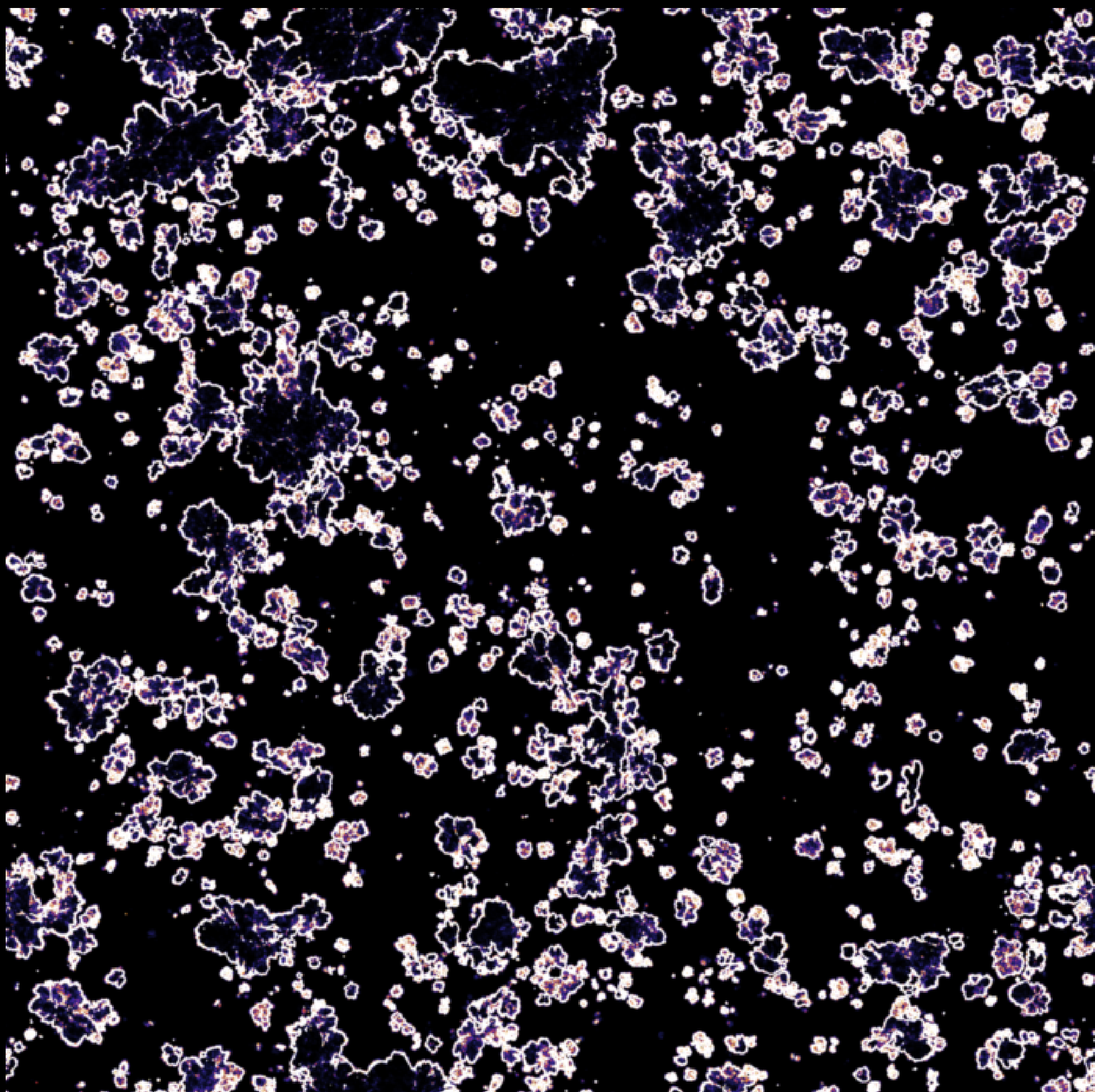
BUBBLE SIZE DISTRIBUTION IN THE 21CM SIGNAL

- The 21 cm signal is a convolution of the neutral fraction and the underlying gas density field
- The shift of power to larger spatial scales is still visible
- The change is amplitude is a combination of changing brightness temperature and the increase in gas clustering with lower redshifts

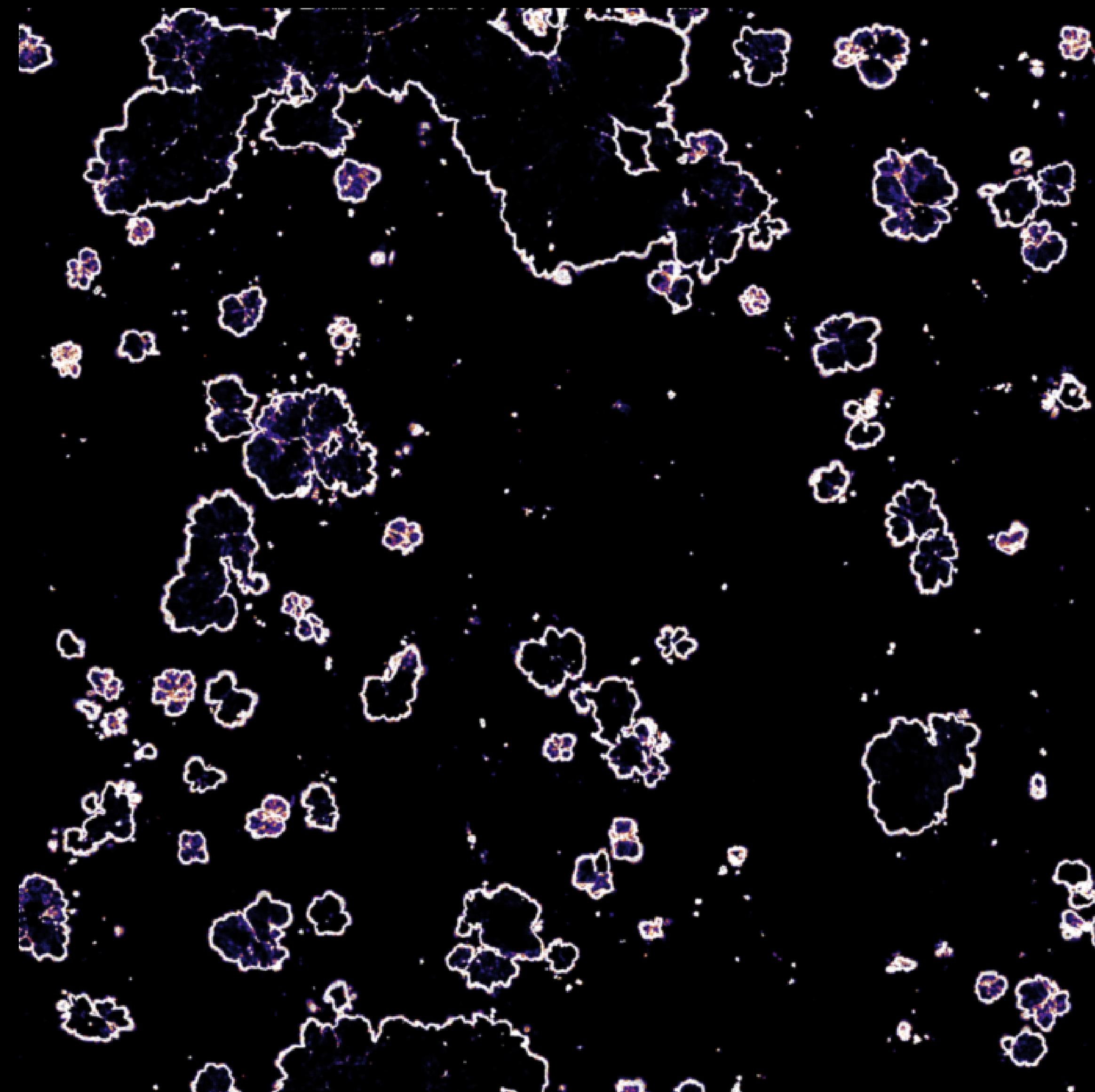
$$T_b \sim \tilde{T}_b(z) x_{HI} (1+\delta) \frac{1+z}{H(z)} \frac{dv_{||}}{dr}$$



BUBBLE SIZE DISTRIBUTION IN THE 21CM SIGNAL



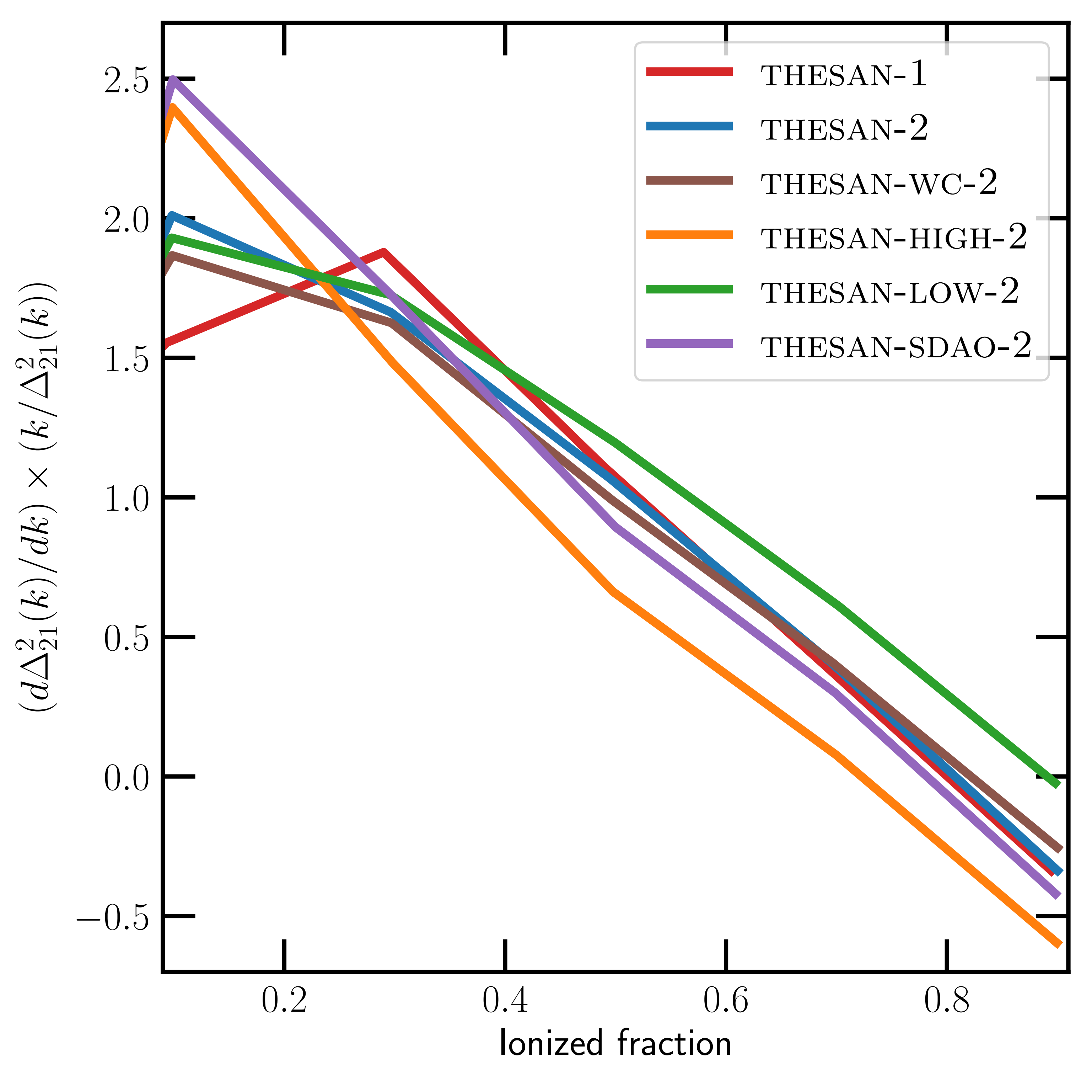
THESAN-1



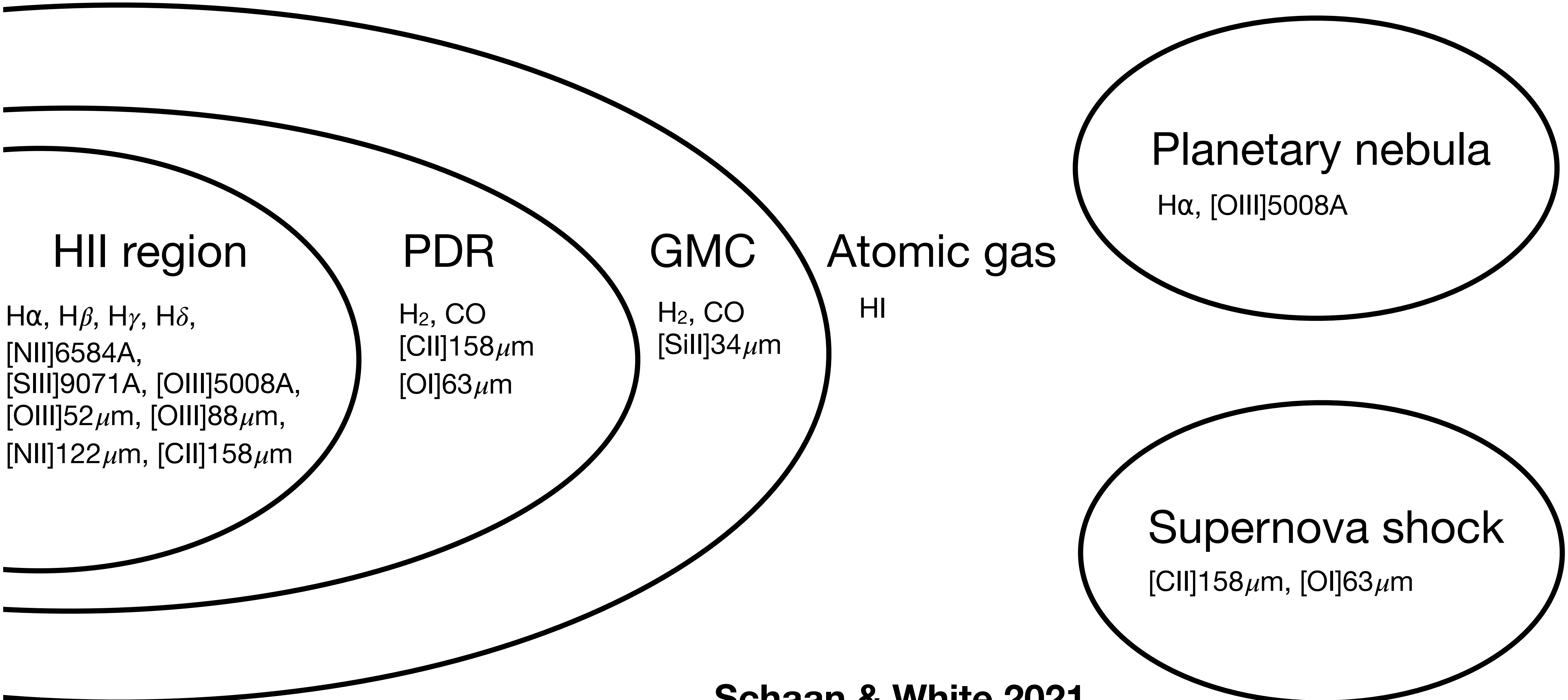
THESAN-HIGH-2

21CM EMISSION ENCODES INFORMATION THE SOURCES RESPONSIBLE FOR REIONIZATION

- Thesan-High-2 - model with highest contribution from large bubbles show shallowest slopes
- ….. and vice-versa



Modeling emission lines

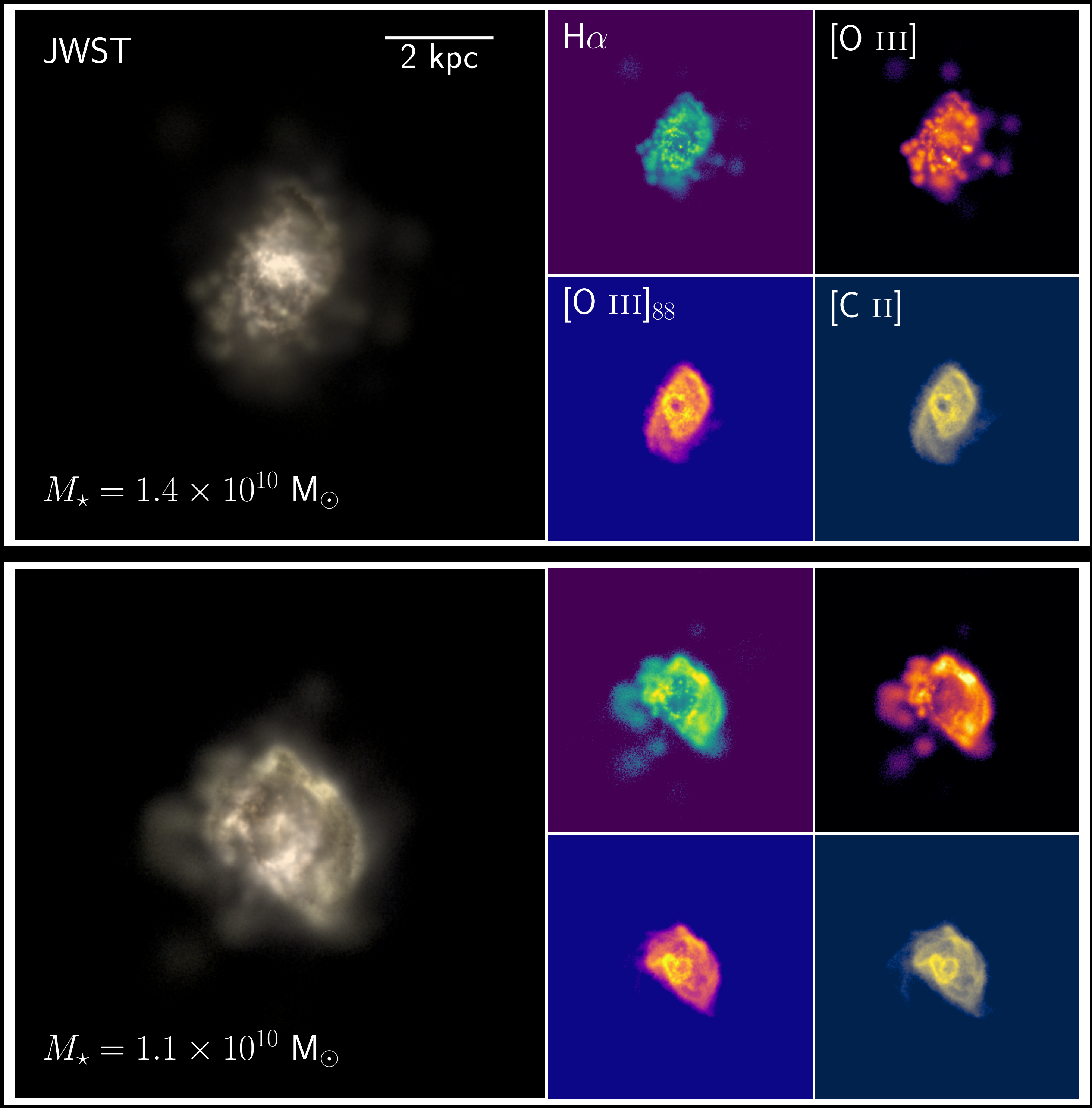


Schaan & White 2021

Need to model, HII and PDR regions in order to get emission line luminosities

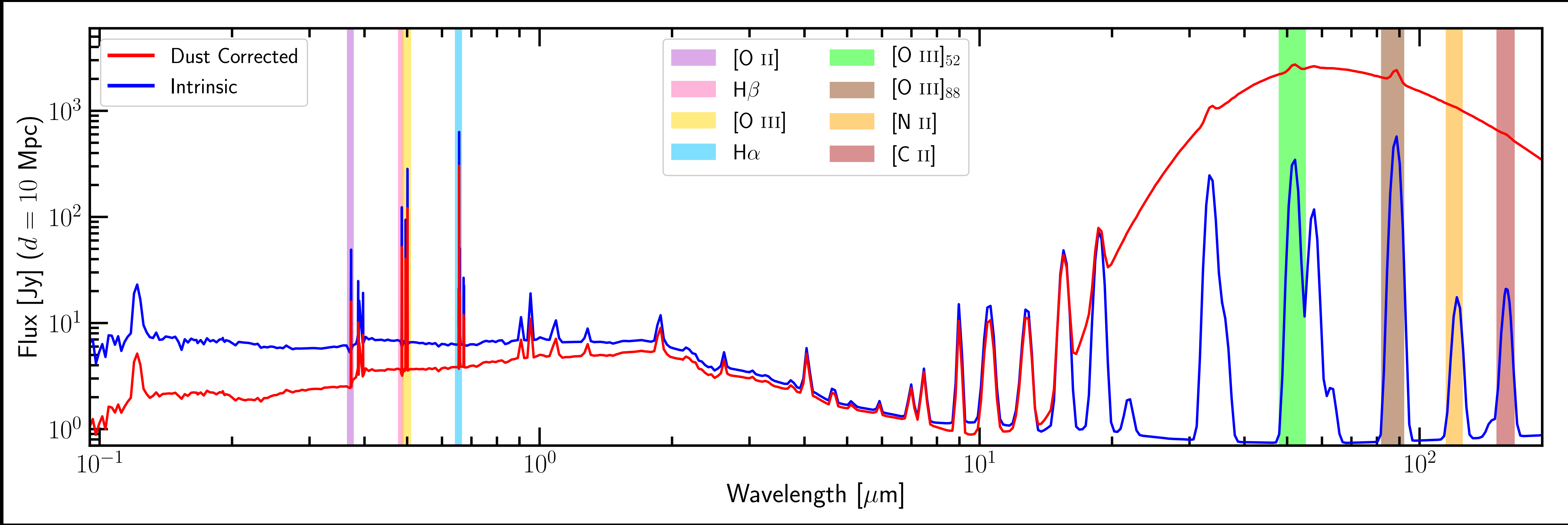
Modeling emission lines

- Paint HII regions onto THESAN galaxies
- Stellar ages and metallicities modeled self-consistently
- So is the gas metal and dust content
- Use grid of Cloudy models to predict emission line properties from nebular regions (Byler+17)
- Use the Monte Carlo Radiative transfer code SKIRT to simulate affect of dust attenuation (Baes & Camp 2020)



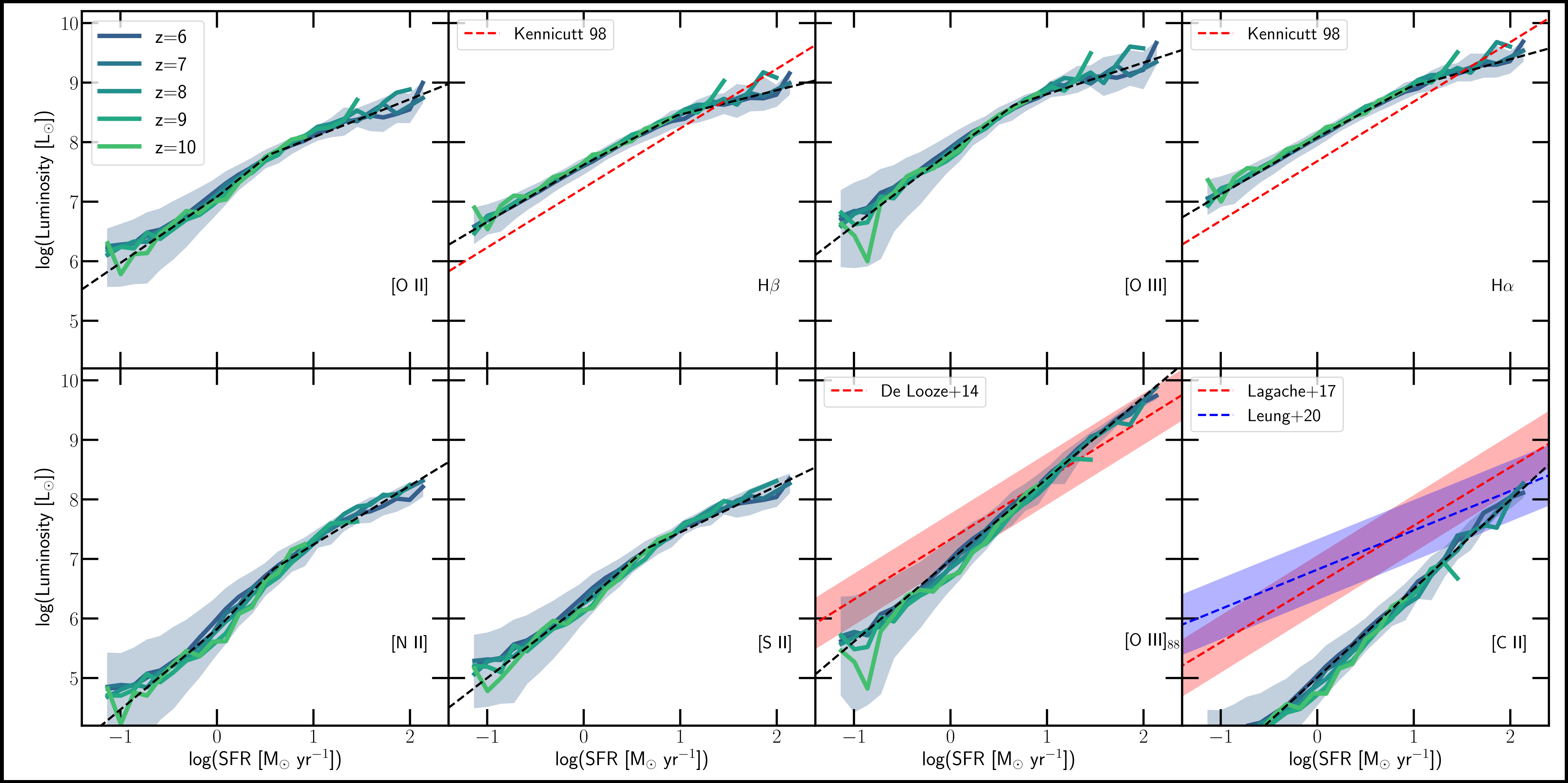
Kannan+21b

Modeling emission lines



Output is a high resolution - dust attenuated SED of all *resolved* galaxies in the volume

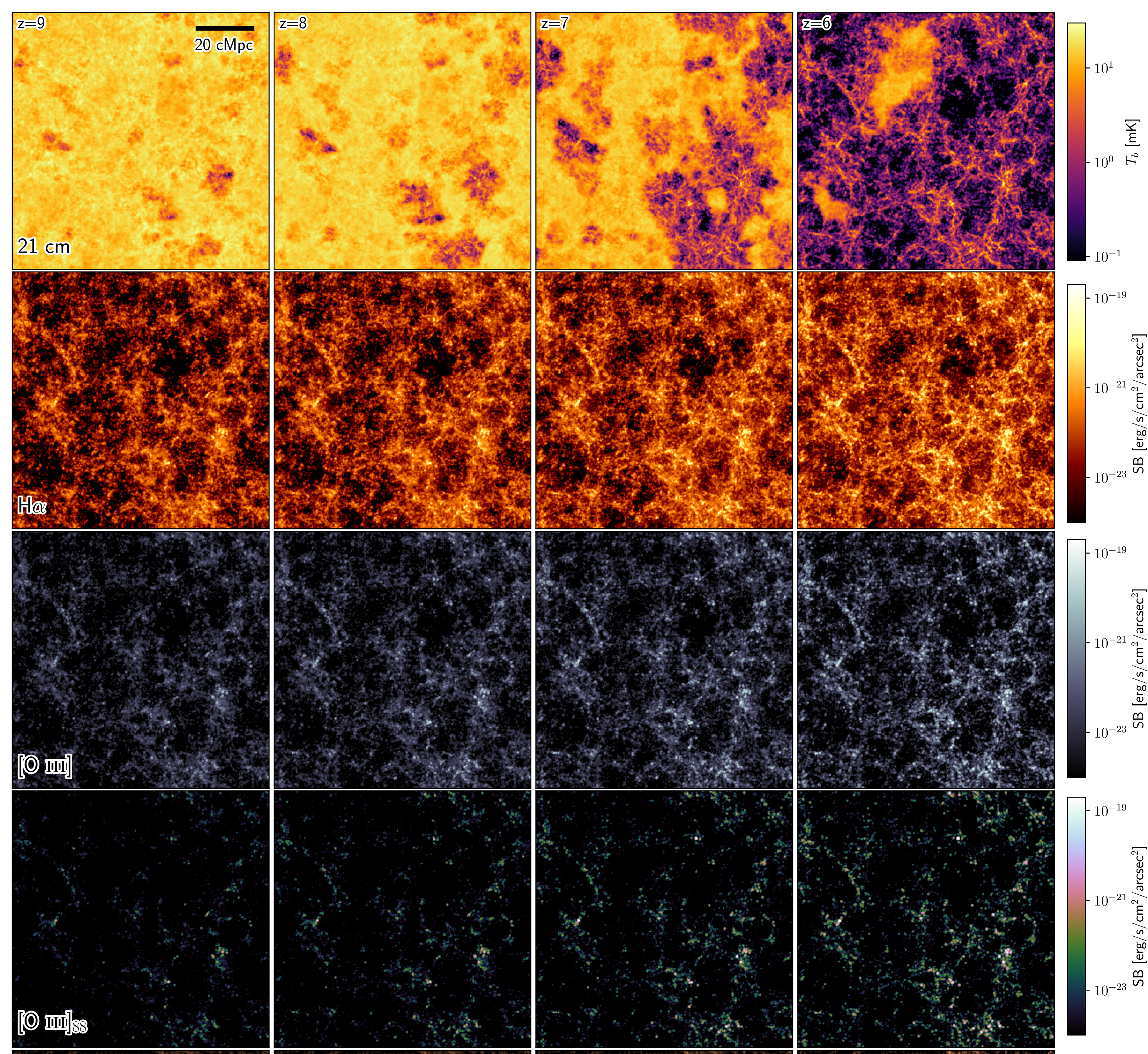
Modeling emission lines



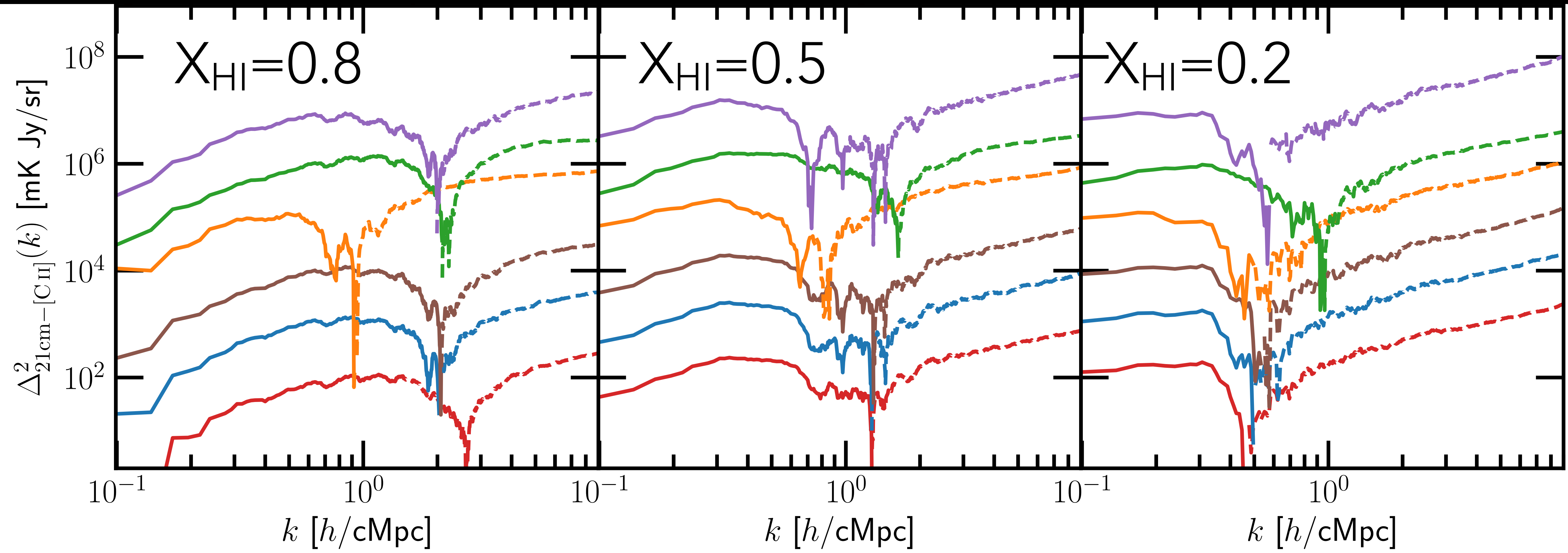
High-z relations differ from low-z ones due to difference in metallicity of ISM

Intensity Maps

- In the late stages of reionization 21cm signal dominated by high density filaments
- Low res/coarse grained RT will not capture this feature (e.g. Iliev+14, Hassan+21)
- Ha has a diffuse component
- Metal emission lines are more clustered

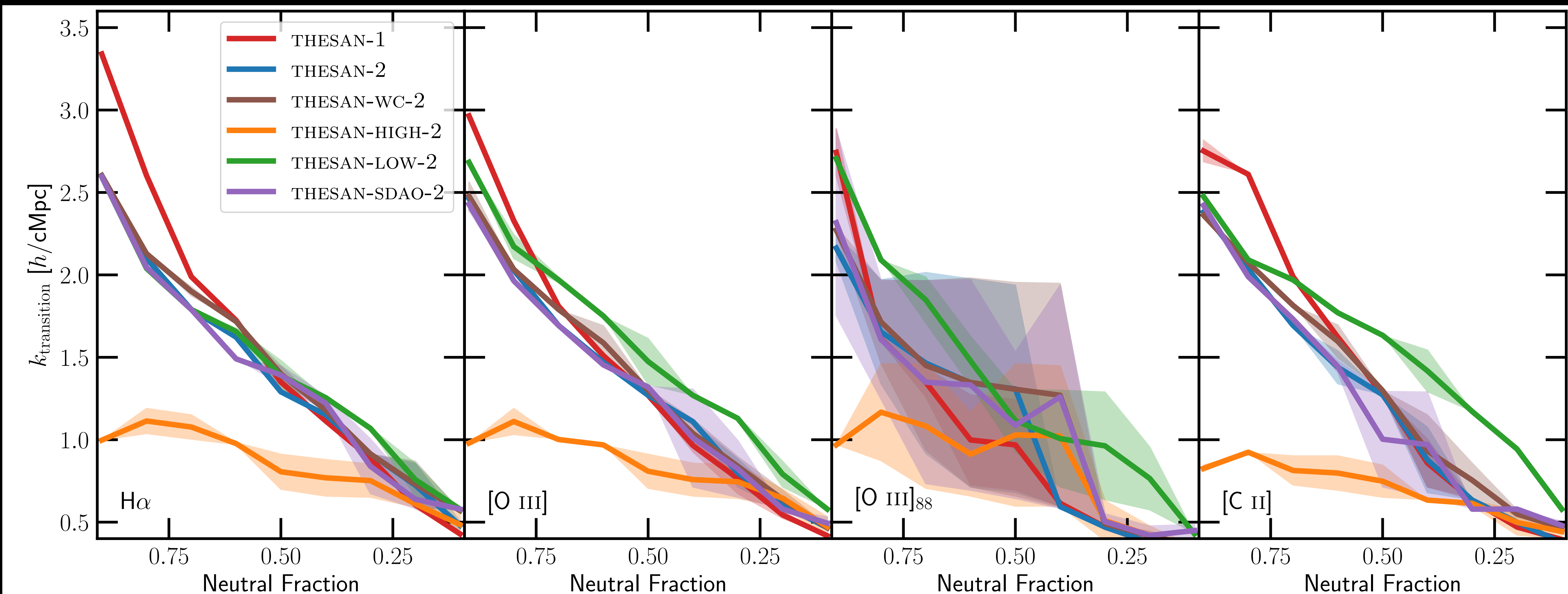


Constraining Reionization with 21cm + nebular emission lines



- Cross correlation functions
- On large scales 21 cm and nebular emission lines are negative correlated
- On small scales they are positively correlated
- The wavenumber at which this transition happens is quite informative

Constraining Reionization with 21cm + nebular emission lines

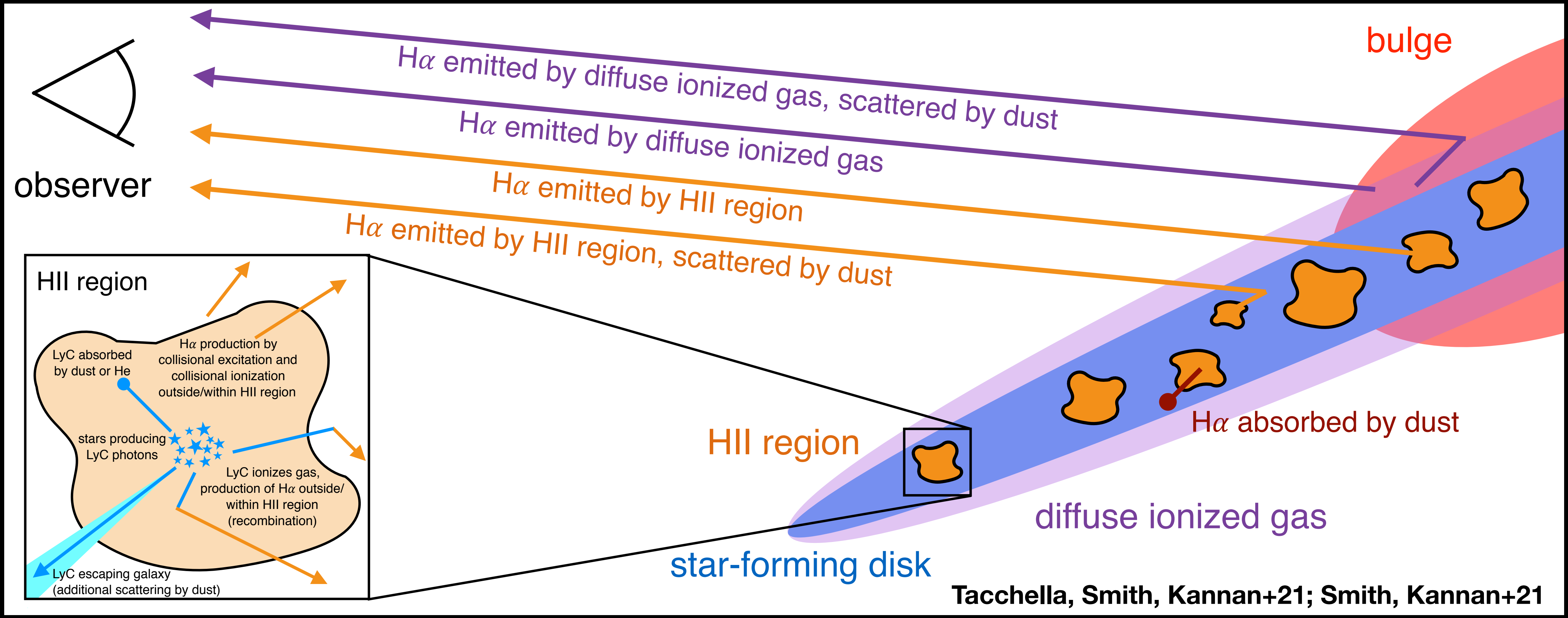


- THESAN-HIGH-2 — High mass halos dominate the photon budget
- THESAN-LOW-2 — Low mass halos dominate the photon budget
- $k_{transition}$ will help constrain the sources of Reionization

CONCLUSIONS

- THESAN simulations : Large volumes allow us to predict the large scale reionization observables and the sources responsible for it in great detail
- Accurate predictions for galaxy properties like stellar mass, UVLF, metallicity distribution
- Accurate LIM predictions of the 21 cm + nebular emission lines and the effect of varied source distribution on LIM observables
- Possible to constrain both astrophysics and cosmology using this new technique

Future work



- Currently most LIM instruments target [C II], Lyα and CO lines - unable to model these lines properly.
- [C II] retires modeling of PDRs and CO of molecular gas.
- Lyα requires accurate resonant-line RT calculations through the ISM, difficult to do because of EoS. Moreover, neutral IGM will provide opacity to Lyα unlike other optical this lines.
- Modeling of emission lines from first principles with accurate ISM models that can model the cold phase of the ISM