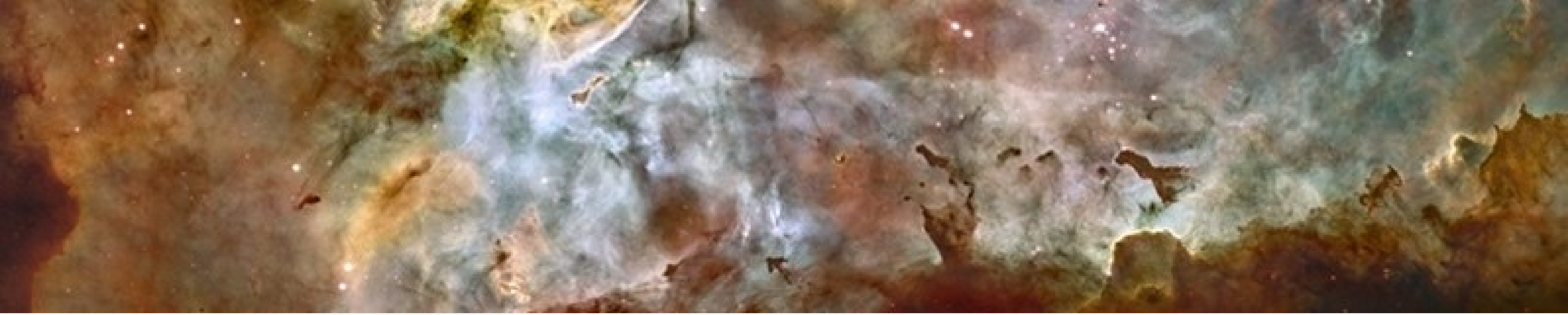
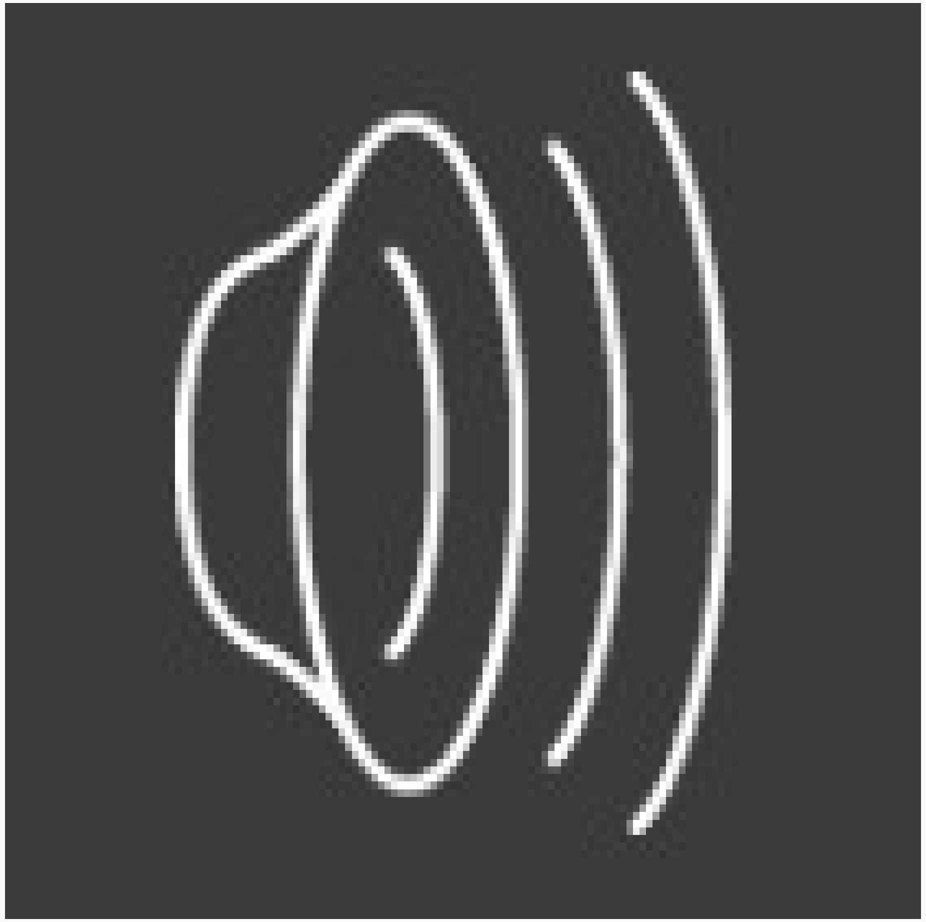


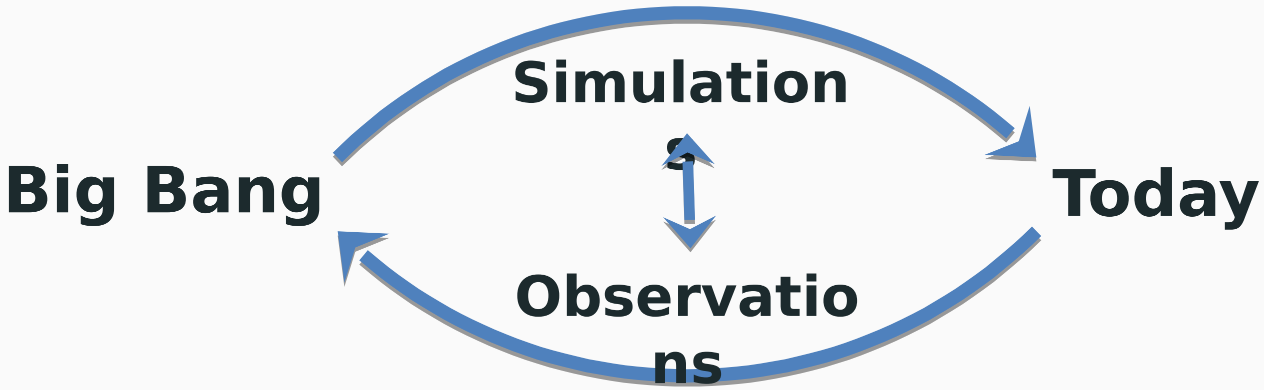
The physics of Lyman-alpha escape from high-*z* galaxies

Aaron Smith
MIT Kavli Institute
October 3, 2018

Einstein Symposium



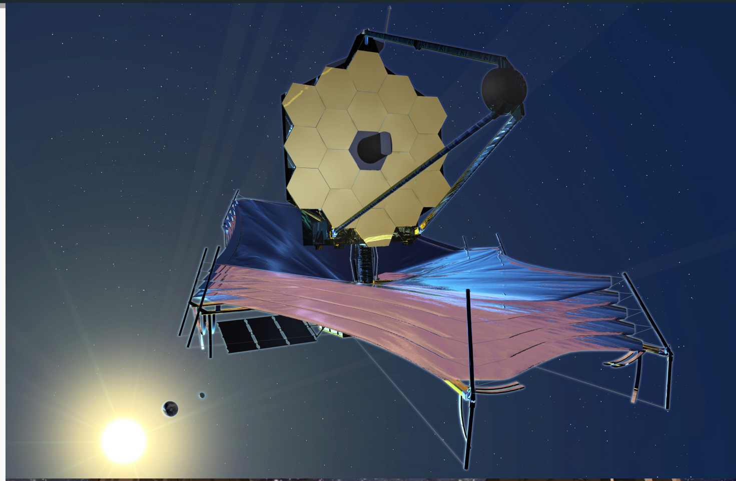
TALK OVERVIEW

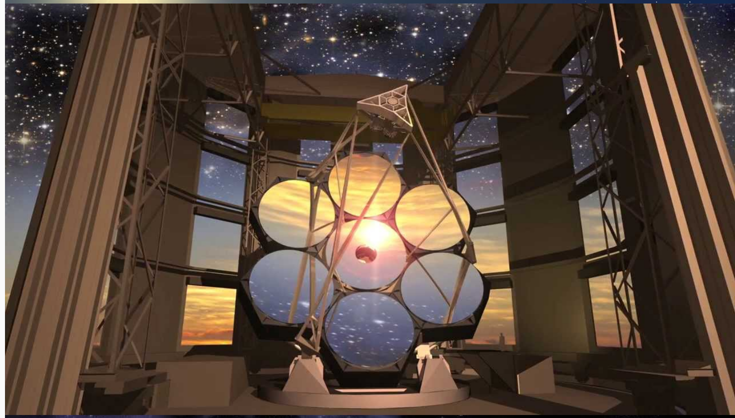


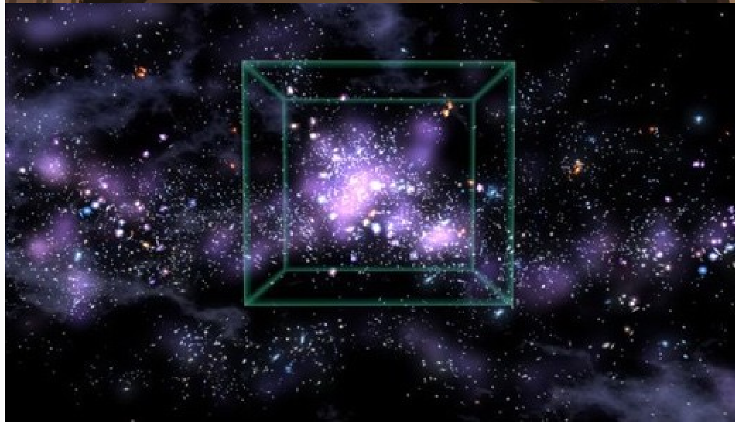
Computer simulations connect what can be directly seen with what is ultimately powering celestial sources.

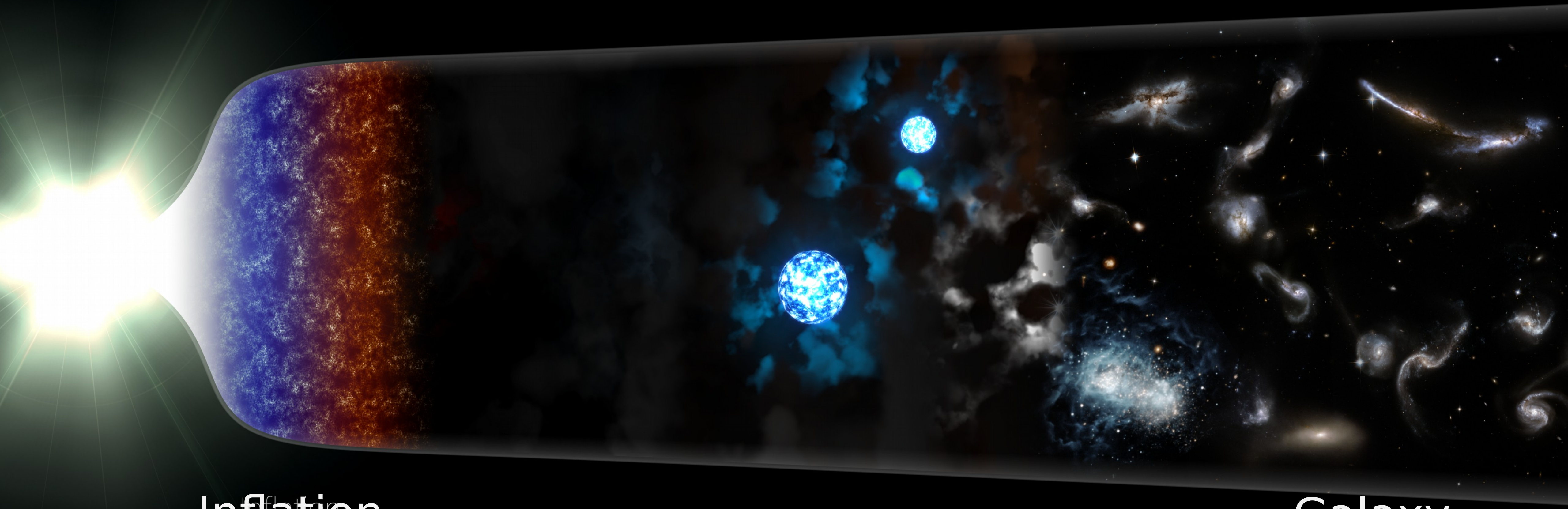
We weave the snapshots accessible to observations
into a continuous tapestry of cosmic evolution.

- Frontiers in Lyman-alpha radiative transfer
- Zoom-in simulations and radiation hydrodynamics









Big Bang

ment of creation. The Universe began as a point st infinite density and began to expand. It was almost tely smooth, but not quite - tiny variations known as m fluctuations began to cause slight variations in density.

Inflation

The early universe expanded rapidly for reasons that are not well understood. The slight variations now became "inflated" into much larger structures, which would eventually become the clusters of galaxies we see today. As it exanded, the Universe cooled. While it was still above about 3000K, no atoms could form - the Universe was made of nothing but a soup of hot, ionized gas called plasma. Photons of light are scattered by travelling through plasma, so the Universe was opaque.

Dark Ages

Once the temperature had cooled to below 3000K, the first atoms formed. The photons from the Big Bang could now travel freely - the Universe became transparent. With no stars there was no source of light, so the next 400 million years are known as the Dark Ages. The Universe was empty except for clouds of hydrogen, helium and a trace of heavier elements.

First Stars

Eventually the gas cooled and began to collapse under its own gravity. This caused the temperature to rise until nuclear fusion started and the first stars began to shine. These are believed to have been much bigger and hotter (and therefore bluer) than our own Sun, and their light caused the gas clouds to become ionized. Photons of light were now scattered off the free protons and electrons, and so the Universe became opaque once again.

First Galaxies

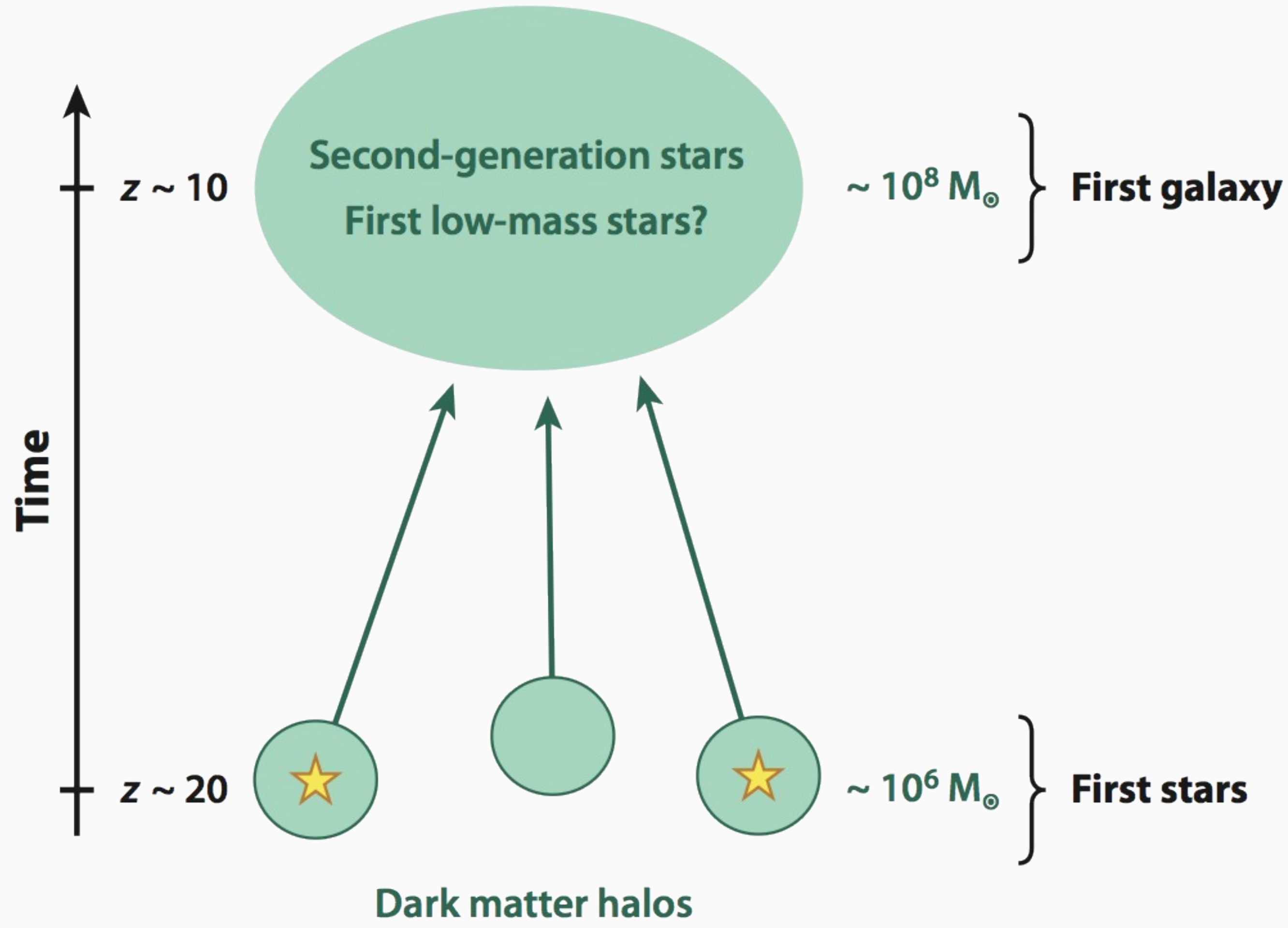
The initially tiny variations in density had now become unimaginably massive, the largest structures in the Universe. Within these huge filaments, gas began to condense in huge discs and spheres in which stars could form - the first galaxies.

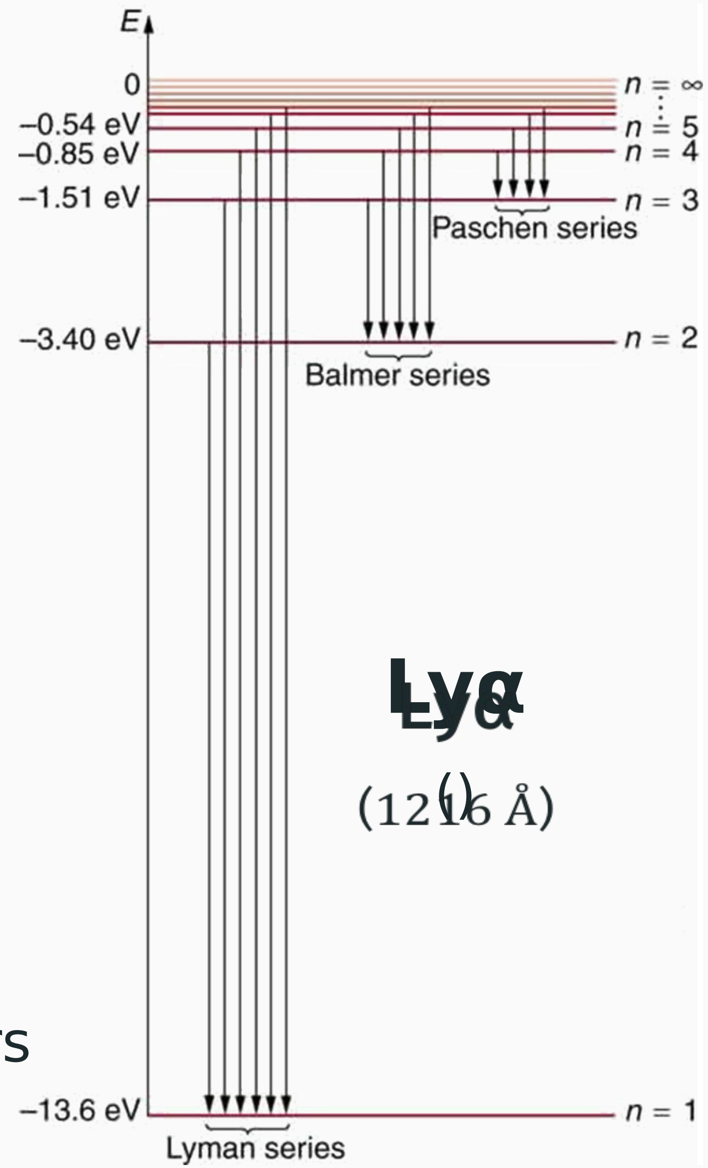
Galaxy Evolution

Galaxy Evolution

Over the next 9 billion years, continuing to the present day and beyond, the galaxies interacted with one other. Near misses can distort them into fantastic shapes, while collisons and mergers cause smaller galaxies to grow into giants. As the Universe expanded, the rate of these interactions decreased. Although interactions continue, today many galaxies are relative stable. Some are little more than giant starballs - ellipticals - while our own Milky Way is a spiral.

HIGH-REDSHIFT GALAXIES EFFICIENTLY PRODUCE LYMAN-ALPHA PHOTONS





Lyα

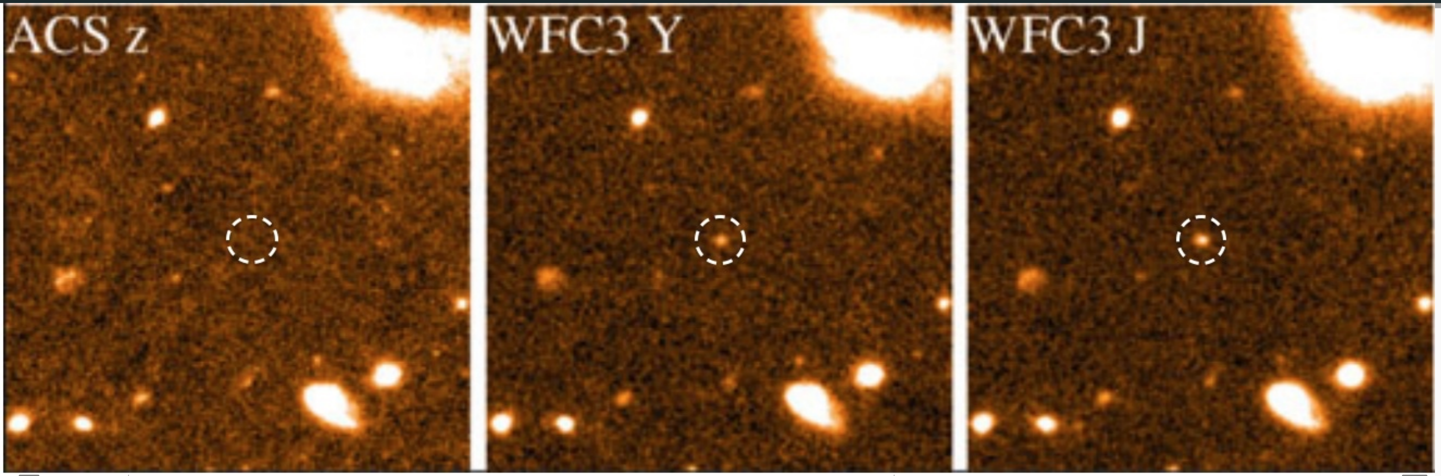
(1216 Å)

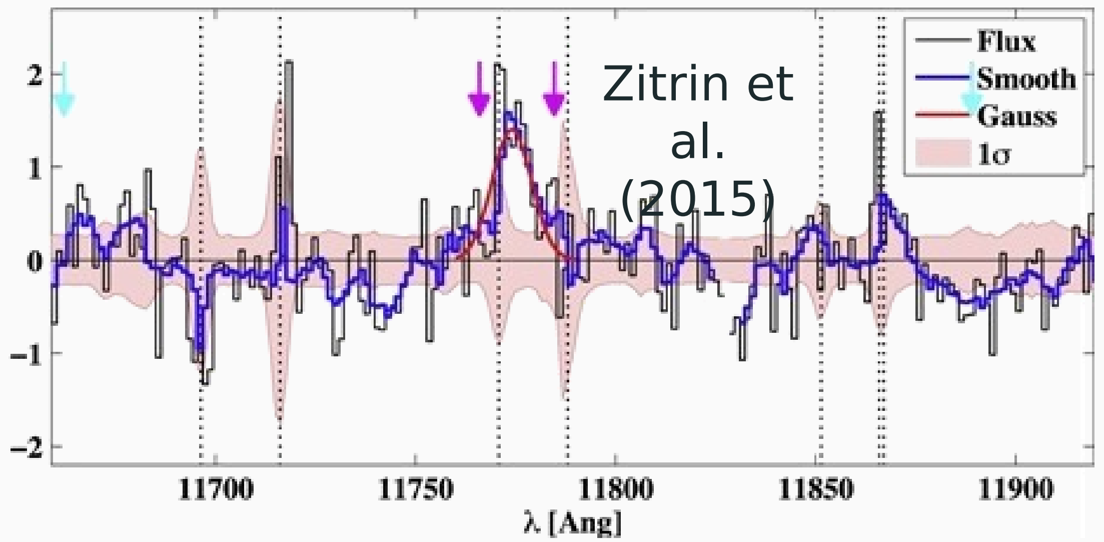
Stable against feedback mechanisms – 2nd generation stars

⇒ Atomic cooling halos ($T_{\rm vir} > 10^4$ K and $M_{\rm vir} > 10^8\,{\rm M}_\odot$)

⇒ UV radiation ⇒ Ionized gas ⇒ Case B Recombination

LYMAN-ALPHA SELECTION OF HIGH-REDSHIFT GALAXIES

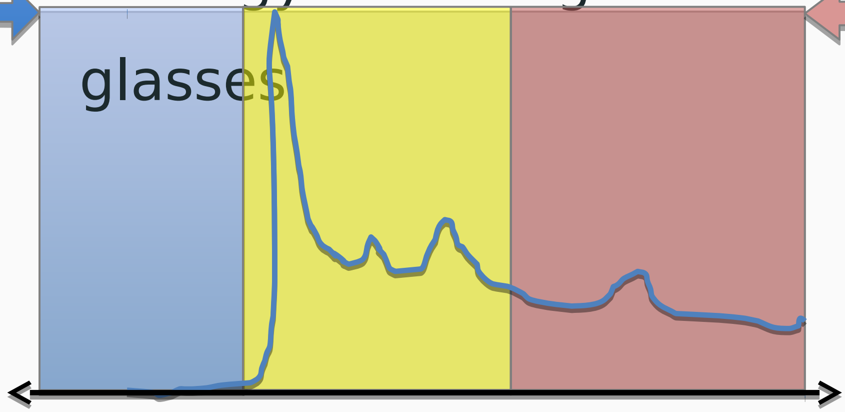




Zitrin et al. (2015)

More “Blue” ⟵ Near-Infrared ⟶ More “Red”

- “Dropouts” are missing in *HST* images
- Analogy — Red glasses vs. Blue glasses



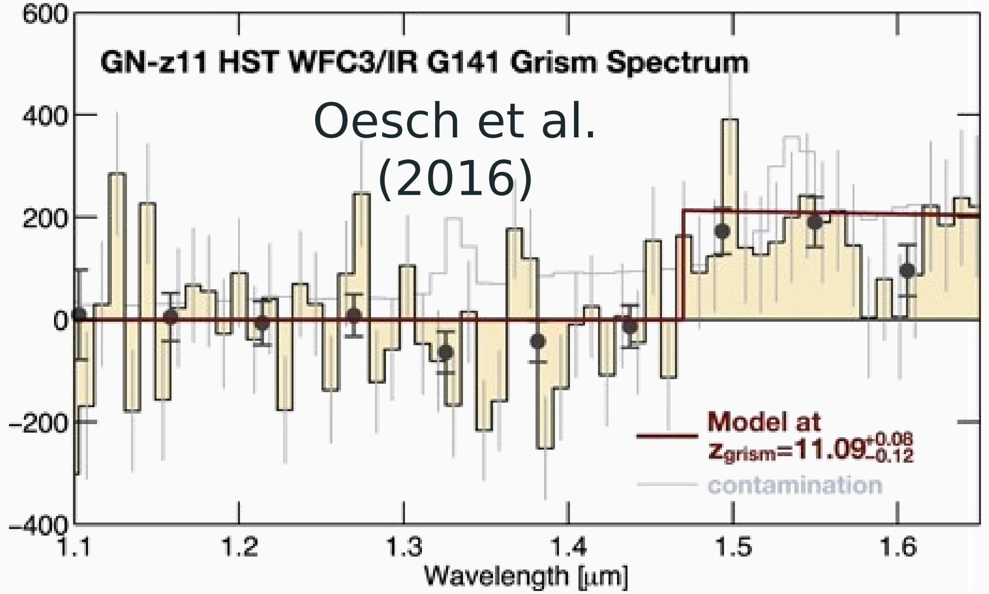
Wavelength (λ)

Find candidates.

Spectroscopic follow-up with large aperture ground-based telescopes.

Study galaxy populations and large

Several excellent targets for the *JWST* and GMT/TMT/E-ELT.



Oesch et al. (2016)

LYMAN-ALPHA PHOTONS UNDERGO RESONANT SCATTERING

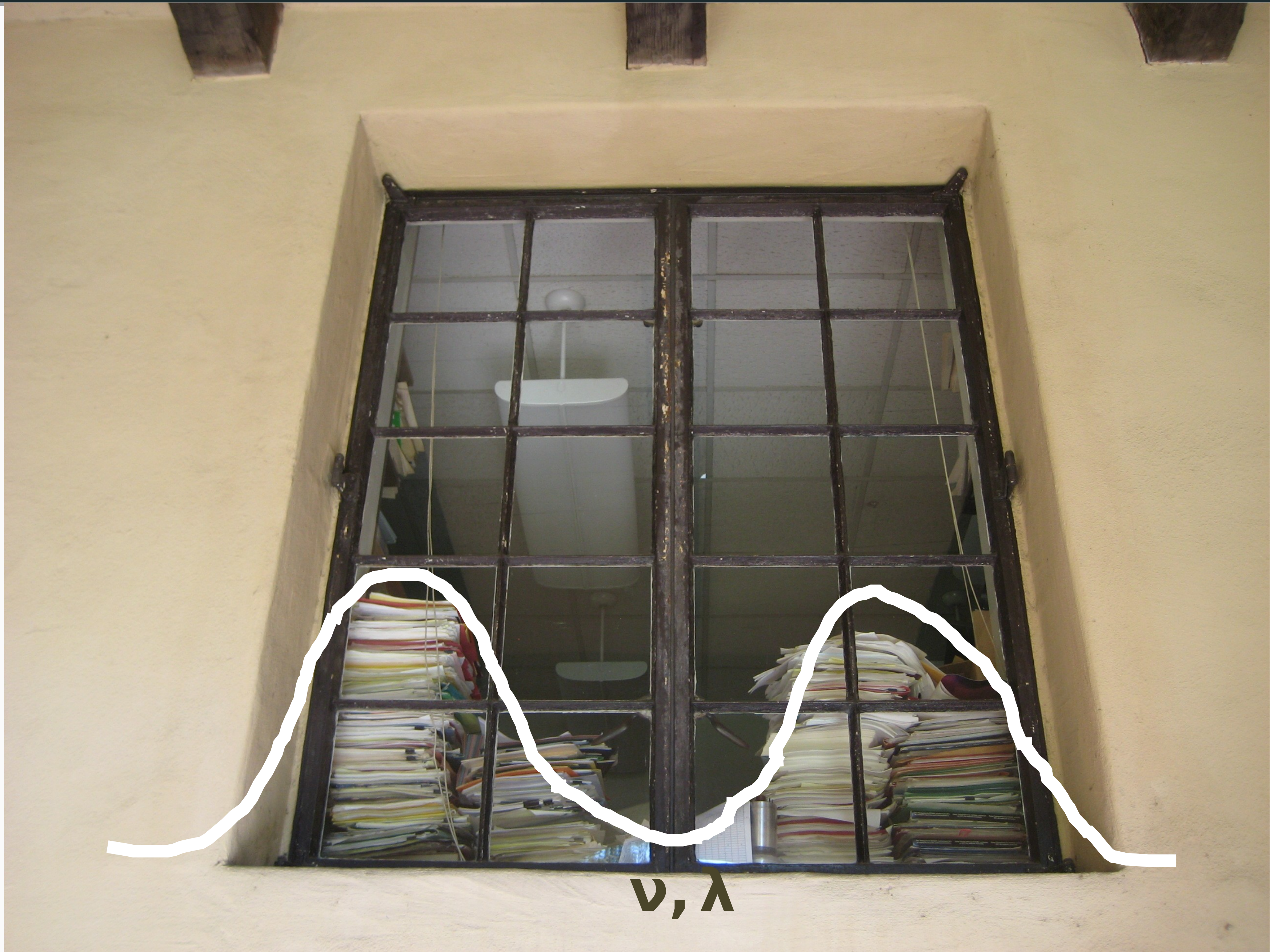
Scattering Analogy: Papers within reach cannot escape

Standard Picture: Lyα photons escape in the wings ()

Double-peaked line profiles

Major Caveats: Density & velocity gradients, dust, IGM transmission

Scattering Analogy: Papers within reach cannot escape
Standard Picture: Lyα photons escape in the wings ($\tau \ll 1$) → Double-peaked line profiles
Major Caveats: Density & velocity gradients, dust, IGM transmission, 3D geometry, etc.



GALACTIC OUTFLOW MODELS

- Central source drives an outflow or “wind” & the Lyα line is redshifted.

- A partially neutral IGM:

  → Reduces the visibility of LAEs

- Spherical symmetry

  → 1D approx. for comp. feasibility & simplicity

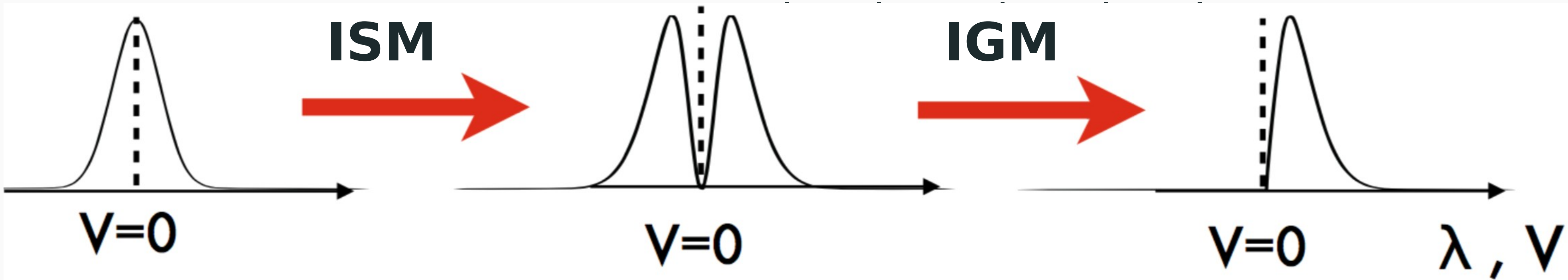
- Reality:

  → 3D geometry

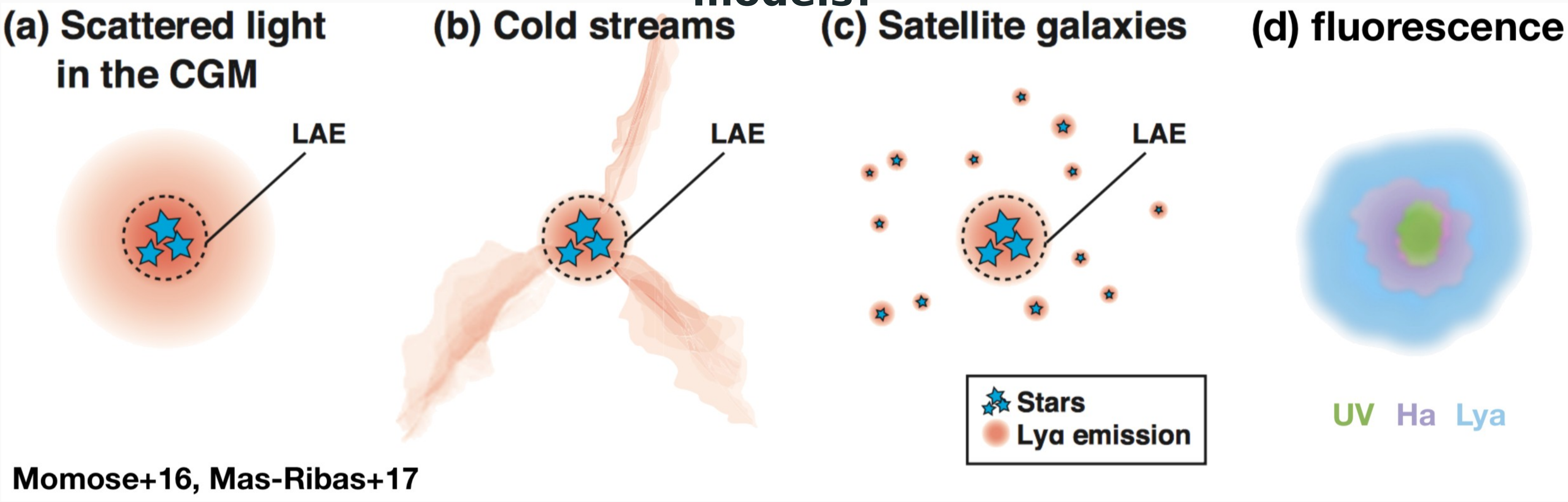
  → Multi-scale

  → Multi-phase

  → Multi-physics



What is the origin of Lyα halos? Can we discriminate between models?

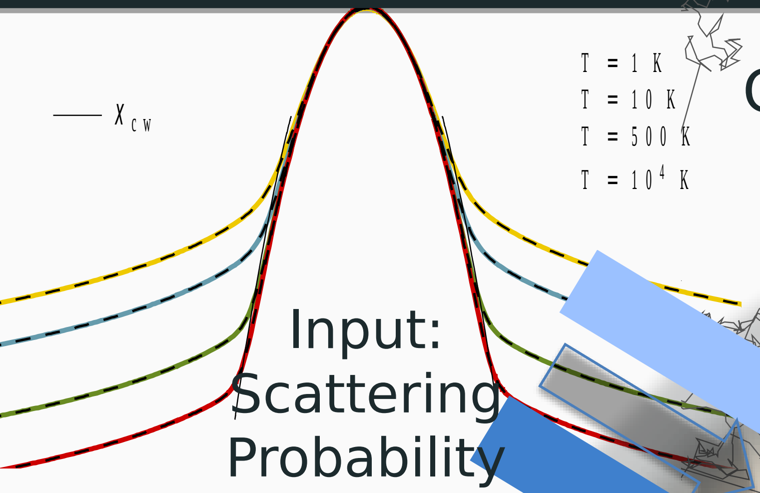


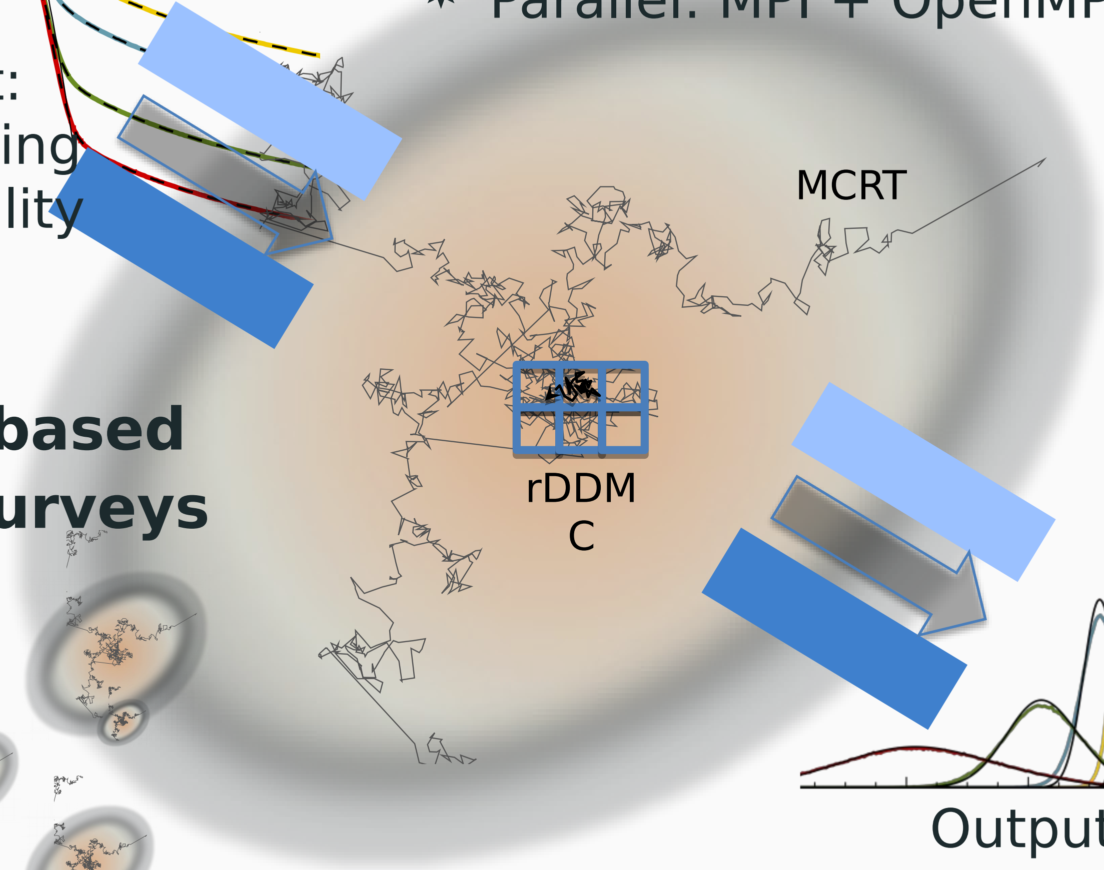
Quantitative theories for each scenario could constrain feedback models and provide additional clues about the nature of the circumgalactic medium (CGM).

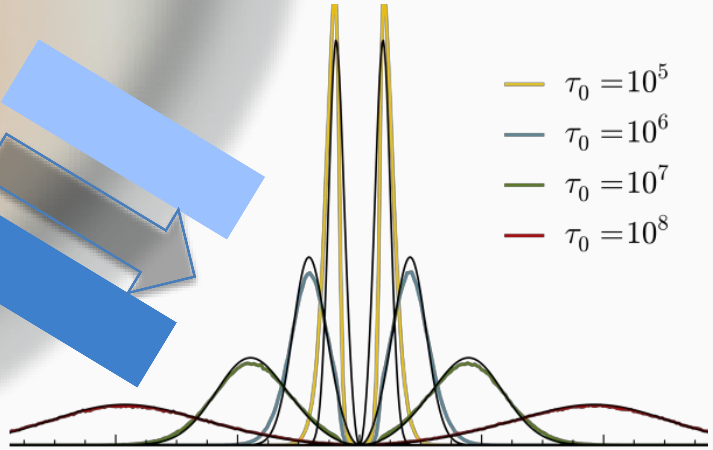
(SOME!) FRONTIERS IN MULTI-SCALE LYMAN-ALPHA RADIATIVE TRANSFER

Cosmic Lyα Transfer code (COLT)

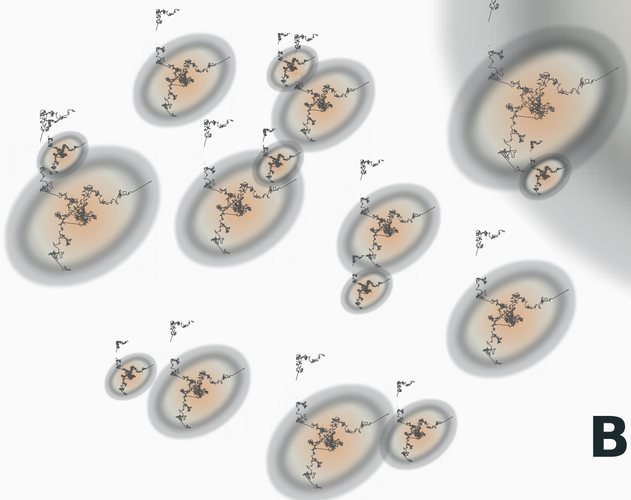
- Monte Carlo Methodology
- Parallel: MPI + OpenMP







Simulation-based high-z LAE surveys



Empirical Models (Shells/Clumps)

↕

Hybrid Methods (Subgrid/Approx)

↕

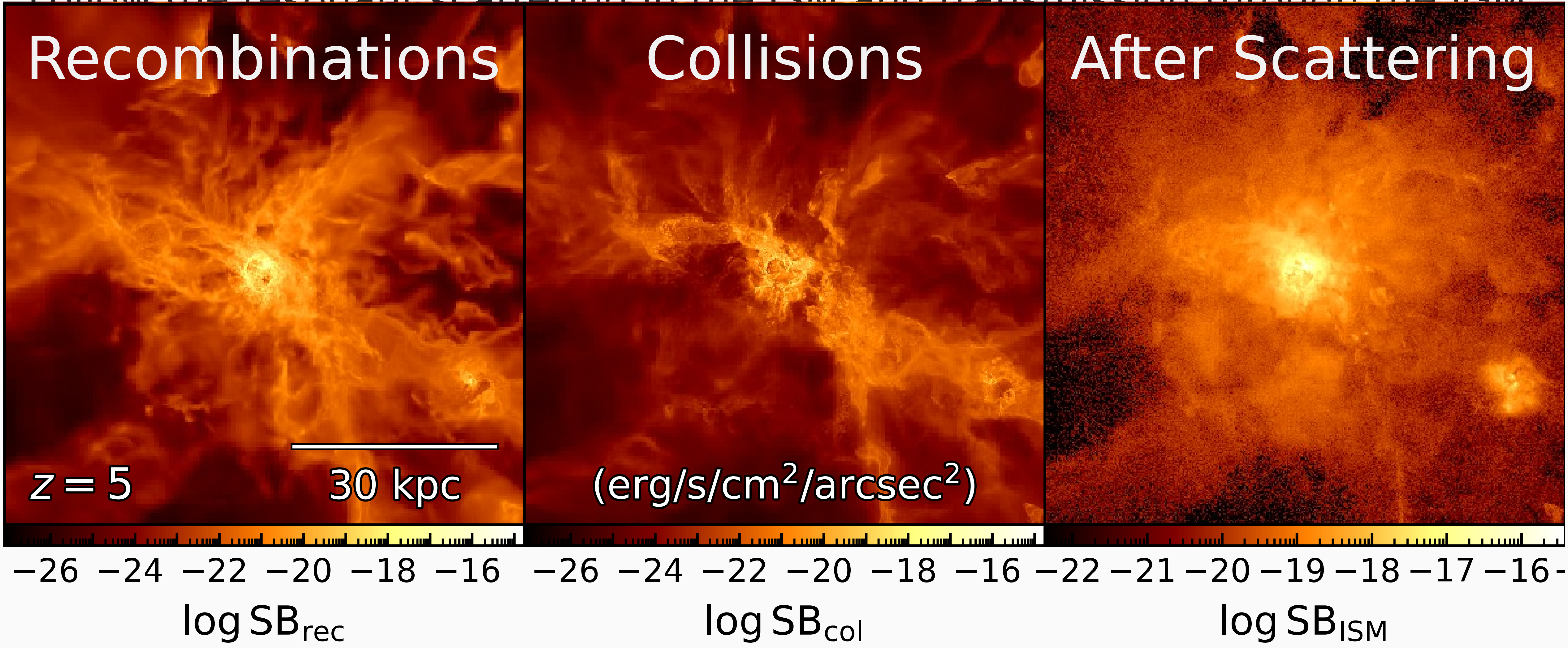
Ab Initio Approach (Cosmological etc. Galaxy Simulations)

Breaking the MCRT efficiency barrier with my new resonant DDMC method

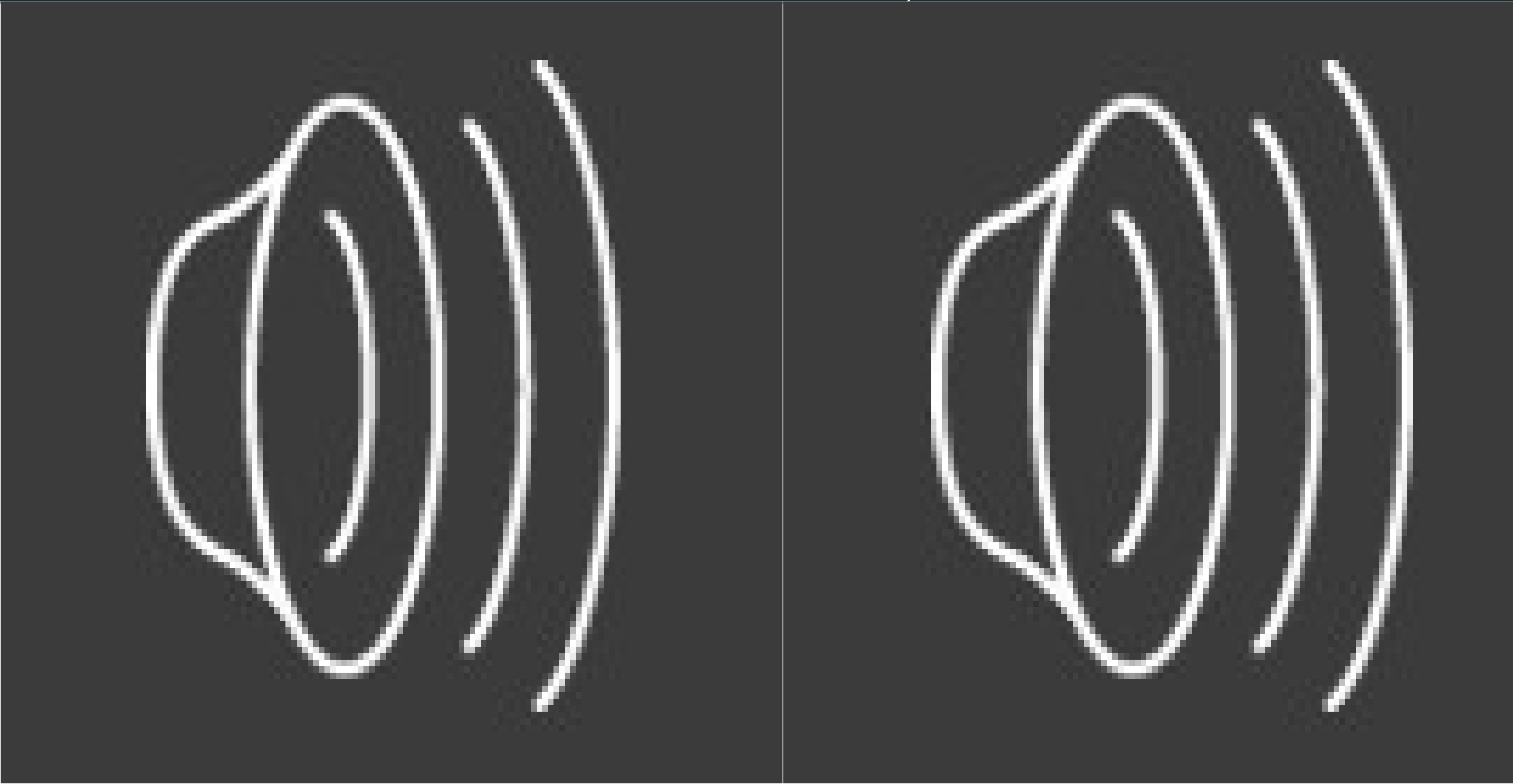
COSMOLOGICAL "ZOOM-IN" SIMULATION OF A REDSHIFT 5 GALAXY (GIZMO/FIRE, Ma et al. 2017)

Accurately model the ionizing radiation for the recombination/collisional emission.

Follow the resonant scattering in the ISM and transmission through the IGM



ROTATING CAMERA REVEALS NONTRIVIAL SIGHTLINE DEPENDENCE (CLOUDS, DOPPLER SHIFTS)

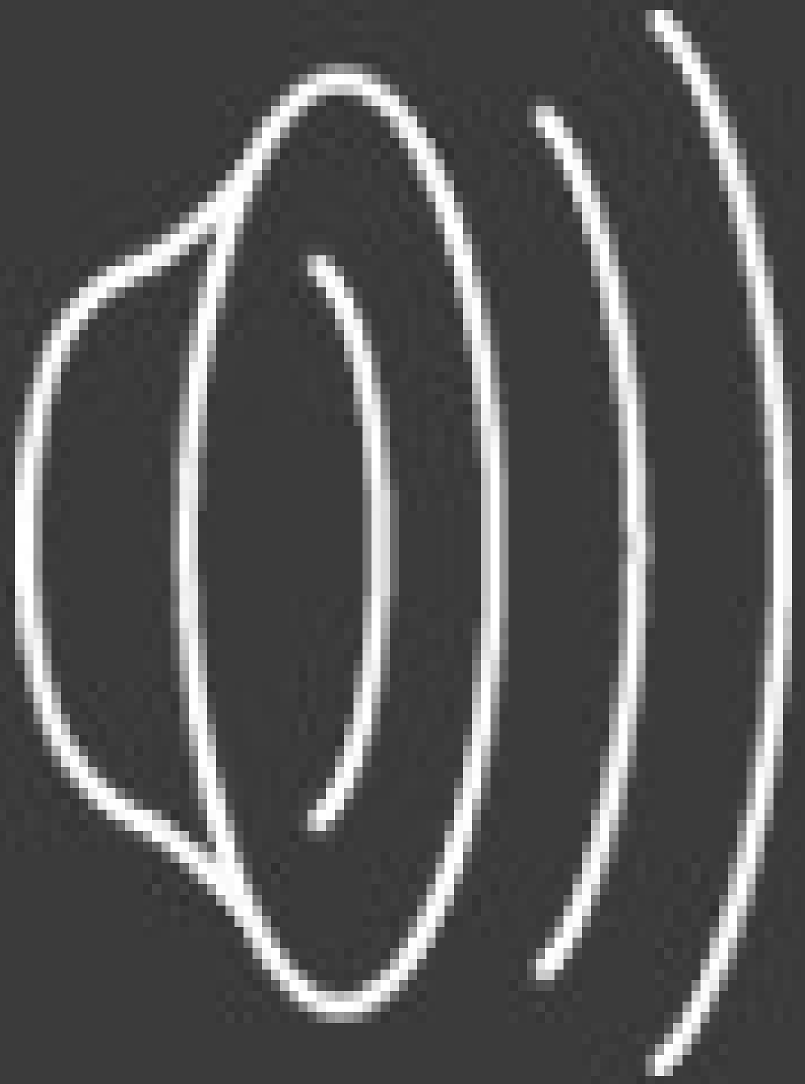


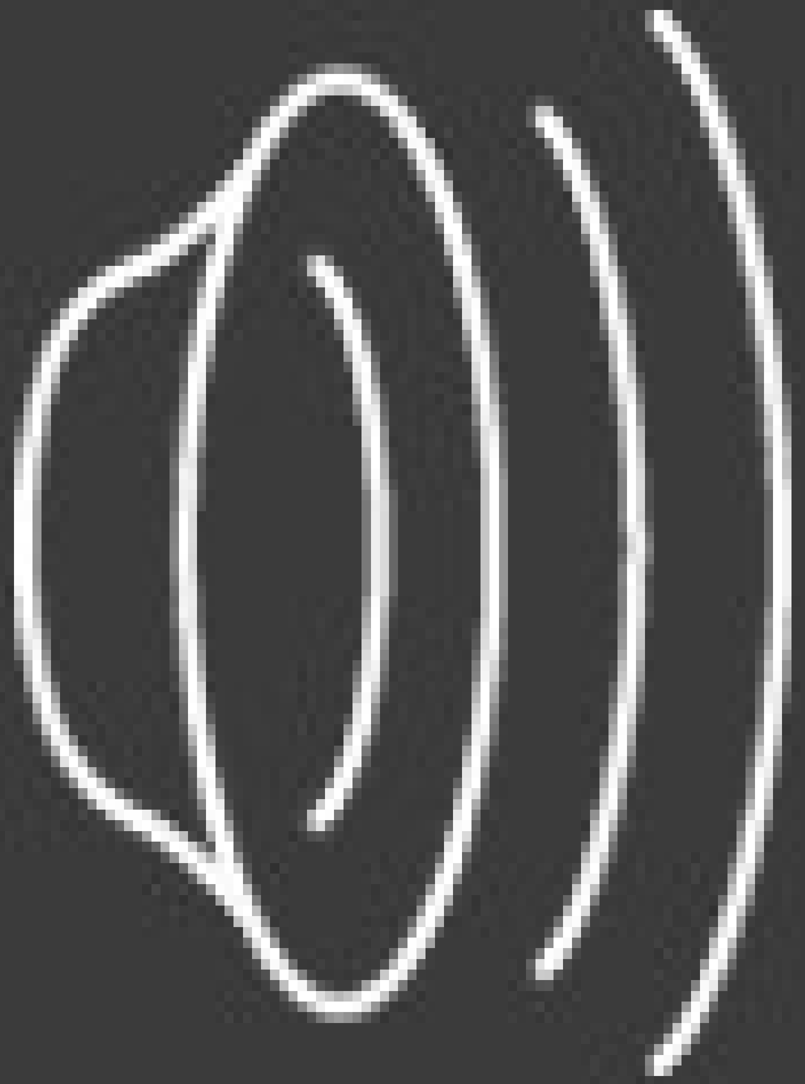
MORPHOLOGICAL DIFFERENCES IN THE LYMAN-ALPHA ENERGY DENSITY

z = 6.6

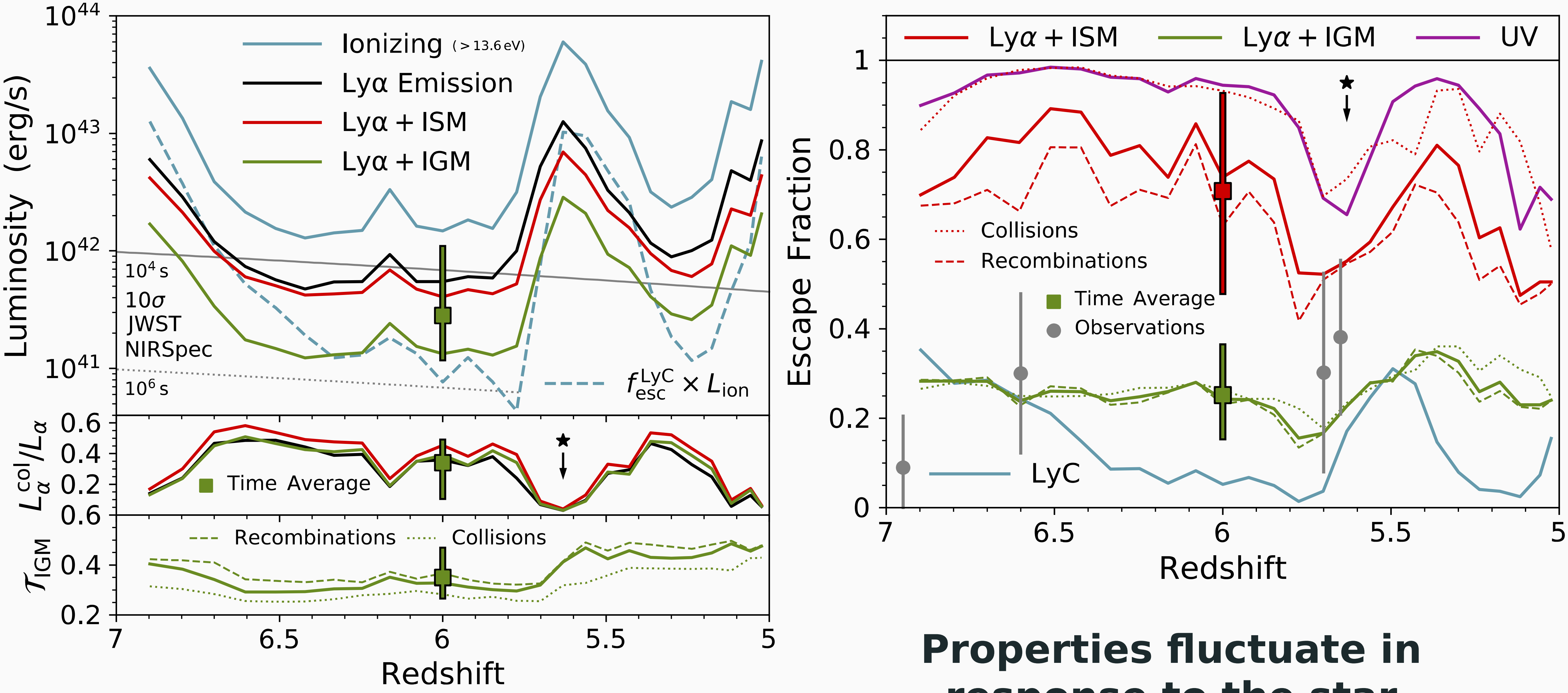
z = 5

TIME-DEPENDENCE OF LYMAN-ALPHA PROPERTIES



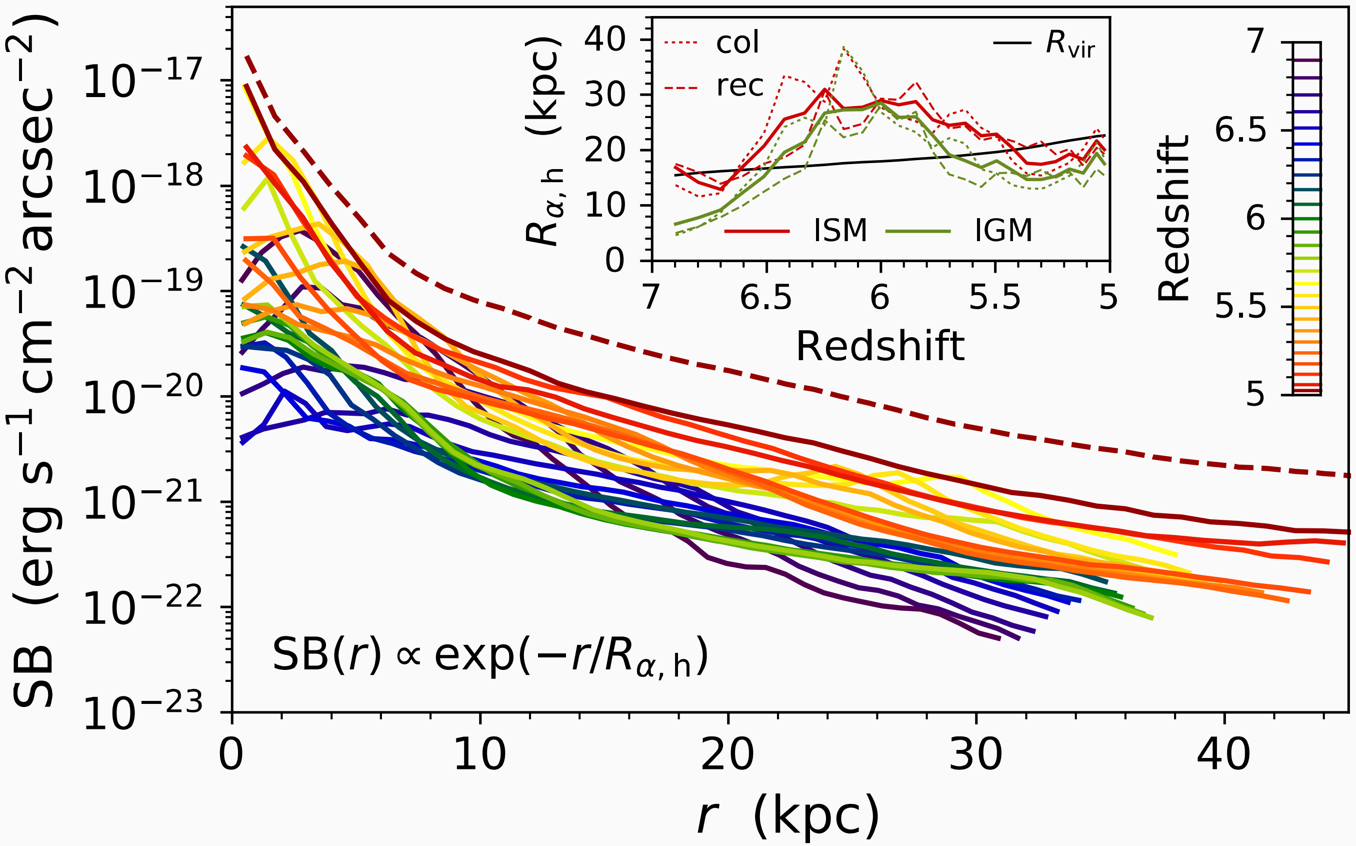


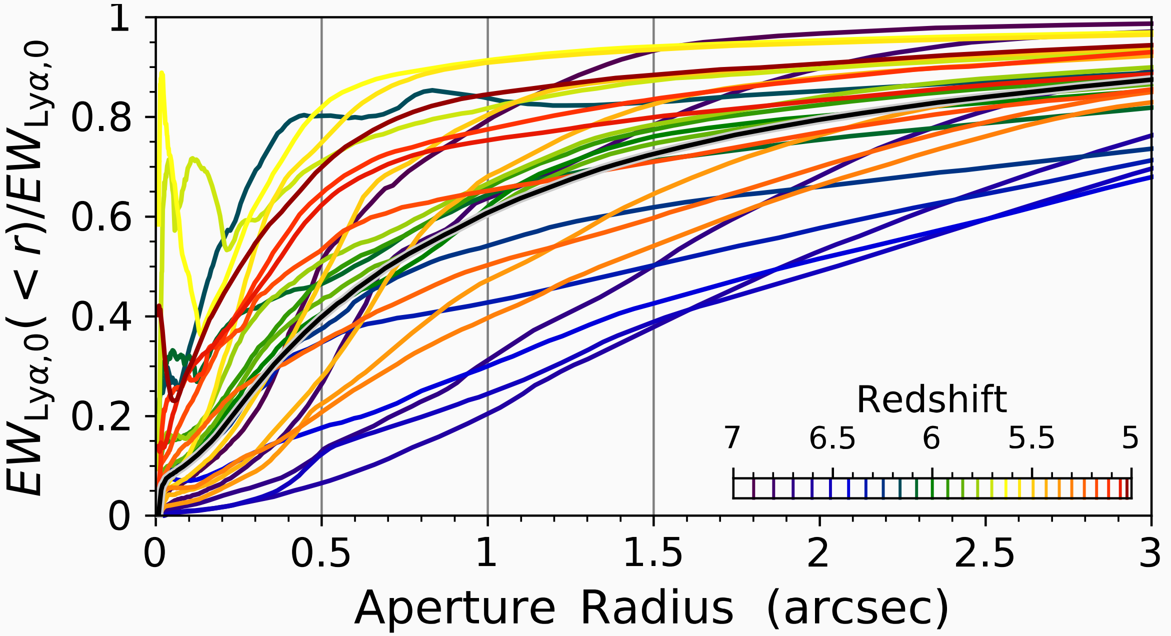
PROPERTIES OF THE EMERGENT Lyα LINE



Properties fluctuate in response to the star formation activity.

PROPERTIES OF THE EMERGENT Lyα LINE





The Lyα radial surface brightness is reasonably fit with an exponential.

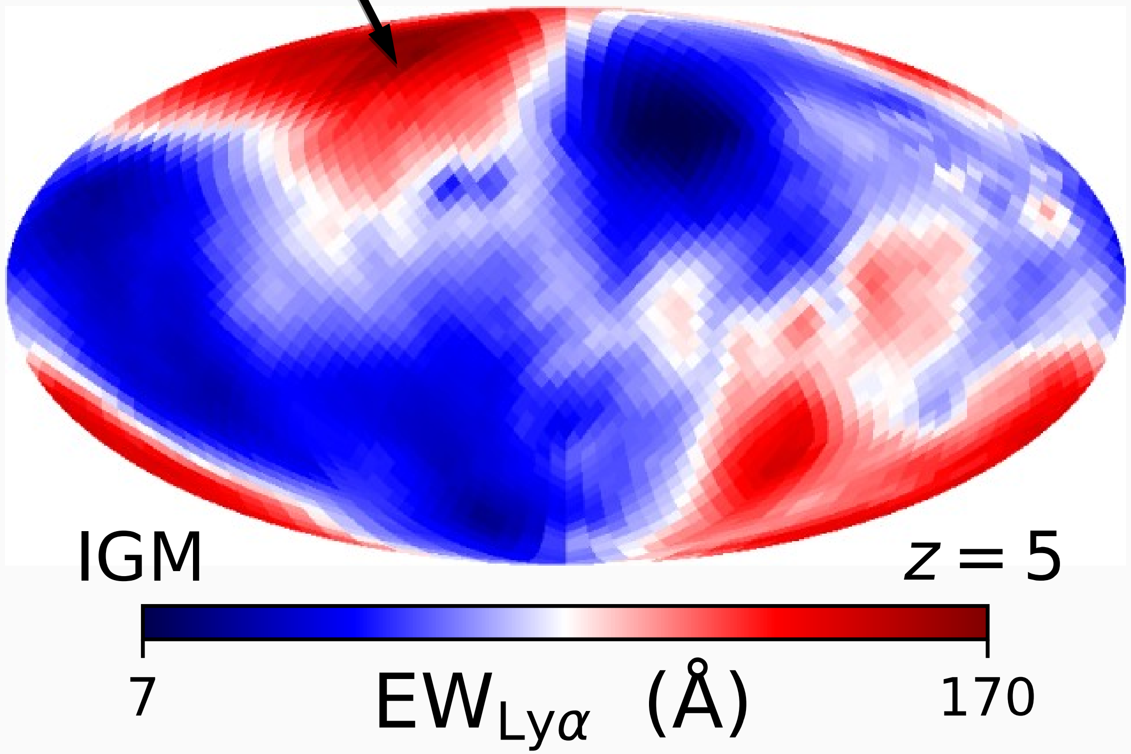
Comparison with observations requires stacking multiple

The Lyα equivalent width can be very sensitive to the telescope aperture size.

We must be careful when comparing to observations.

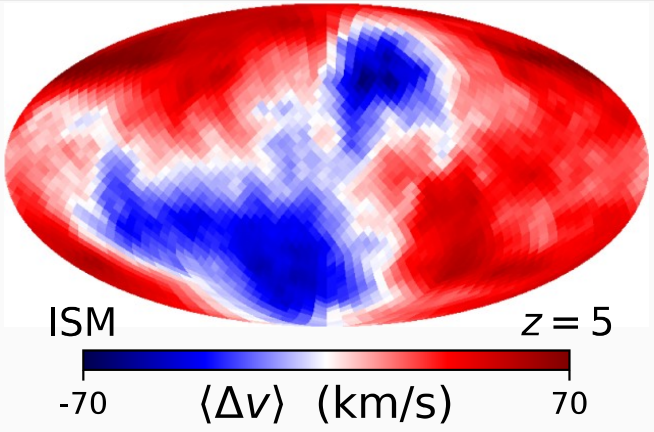
Lyα EQUIVALENT WIDTH BOOSTING (Direction and Time)

The highest EW sightlines have:



Redshifted Lyα (outflows)

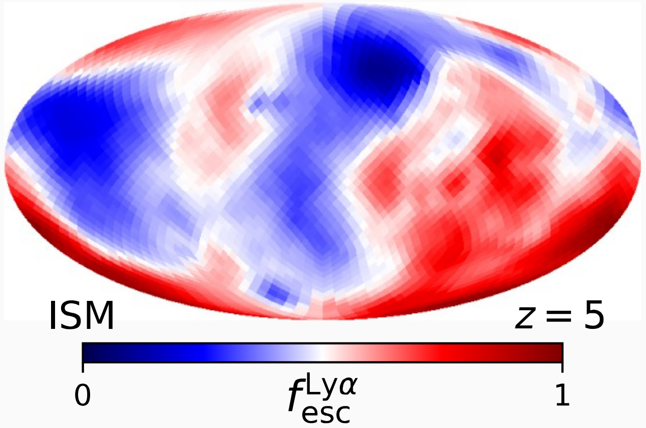
(Higher IGM transmission)



+

Allow escape channels

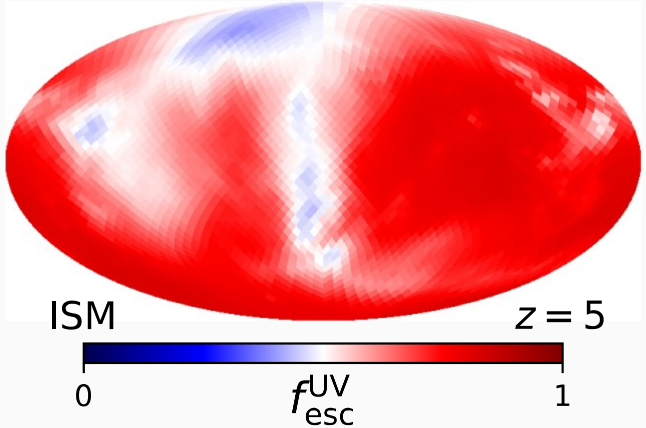
(Lower HI column density)



+

Higher coincident UV absorption by dust

(Higher IGM transmission)



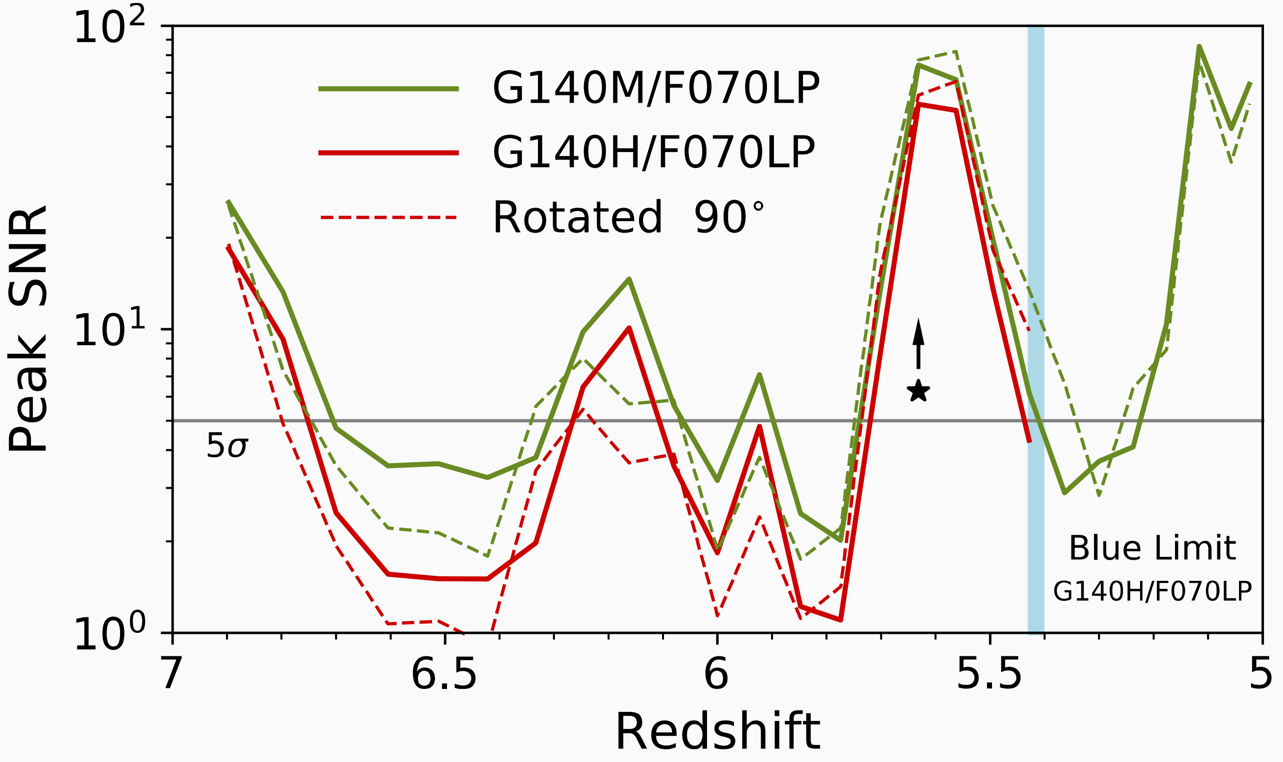
PROSPECTS FOR THE *JAMES WEBB SPACE TELESCOPE* (*JWST*)

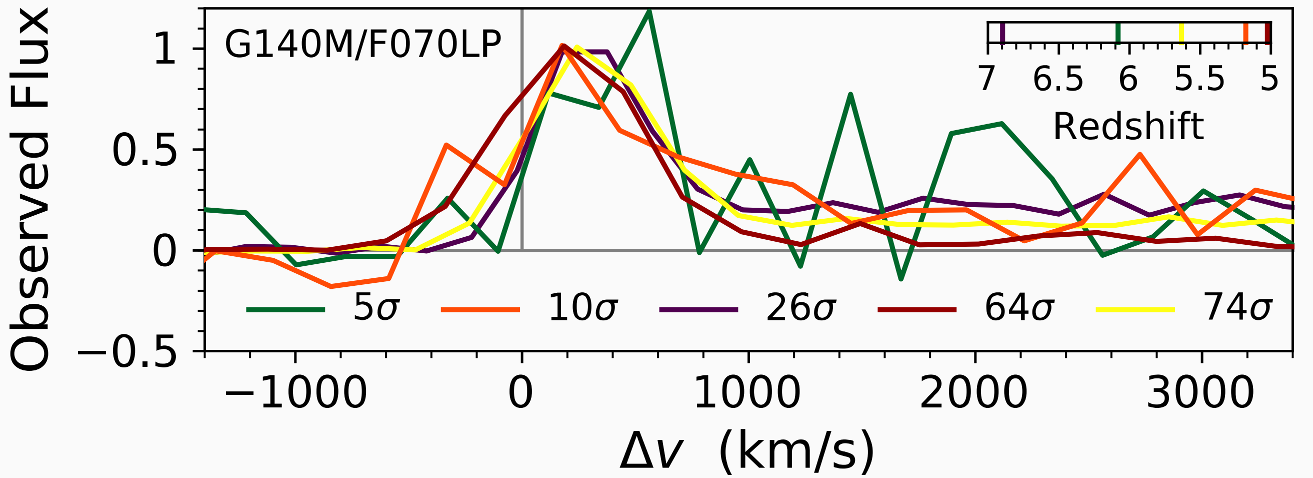
Individual sources come in and out of visibility during their lifetimes.

(We use a 10^4 second exposure time.)

NIRSpec multi-object spectroscopy achieves Δv ~ 300 km/s (R ~ 1000), the same order as the observed line widths after severe IGM reprocessing.

Diagnostics from other lines and cross-correlation studies may be necessary to unravel the detailed properties of high-z Lyα





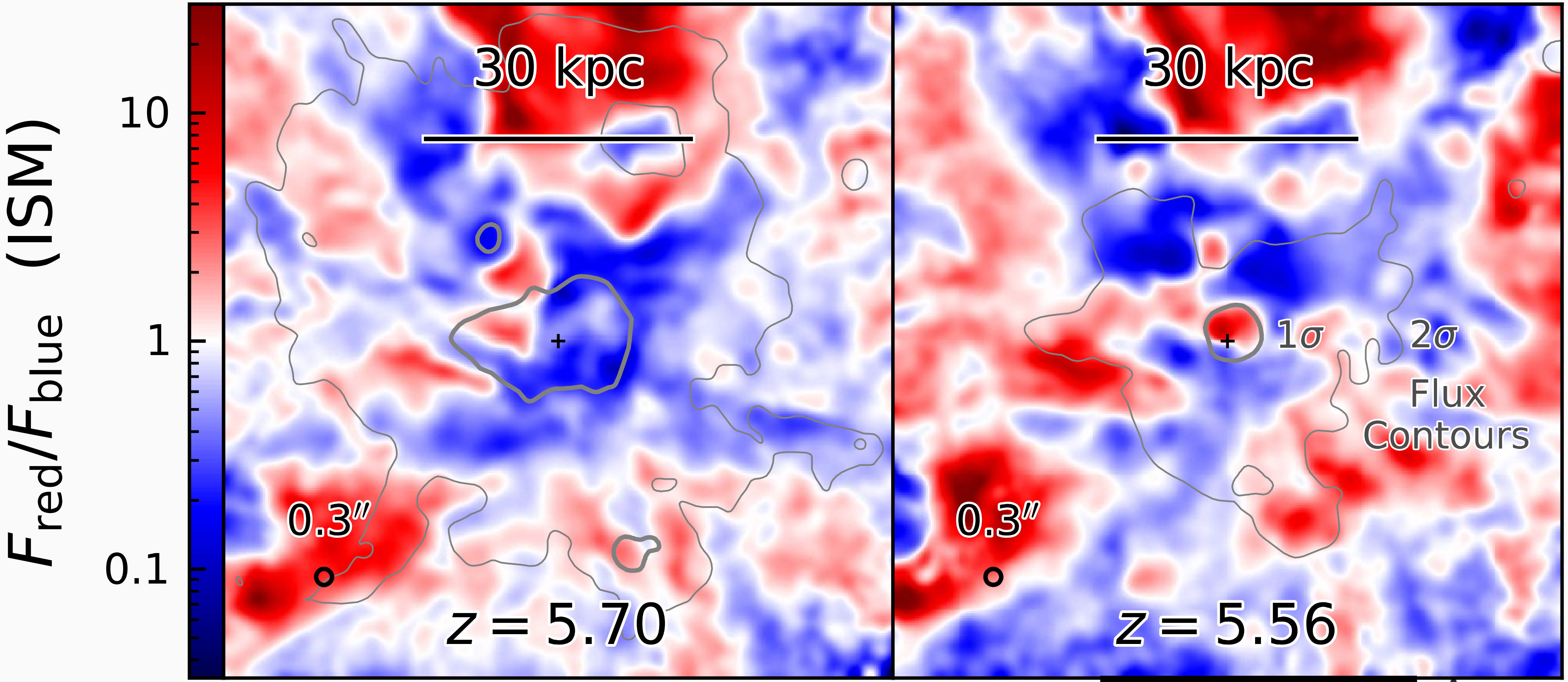
QUICK NOTE ABOUT KINEMATICS

Pre-starburst:

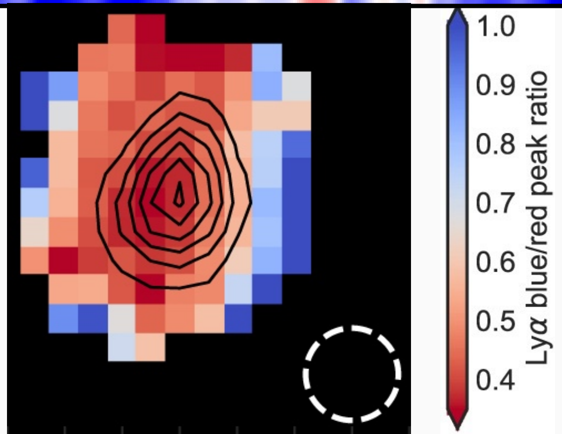
Blue infall signature

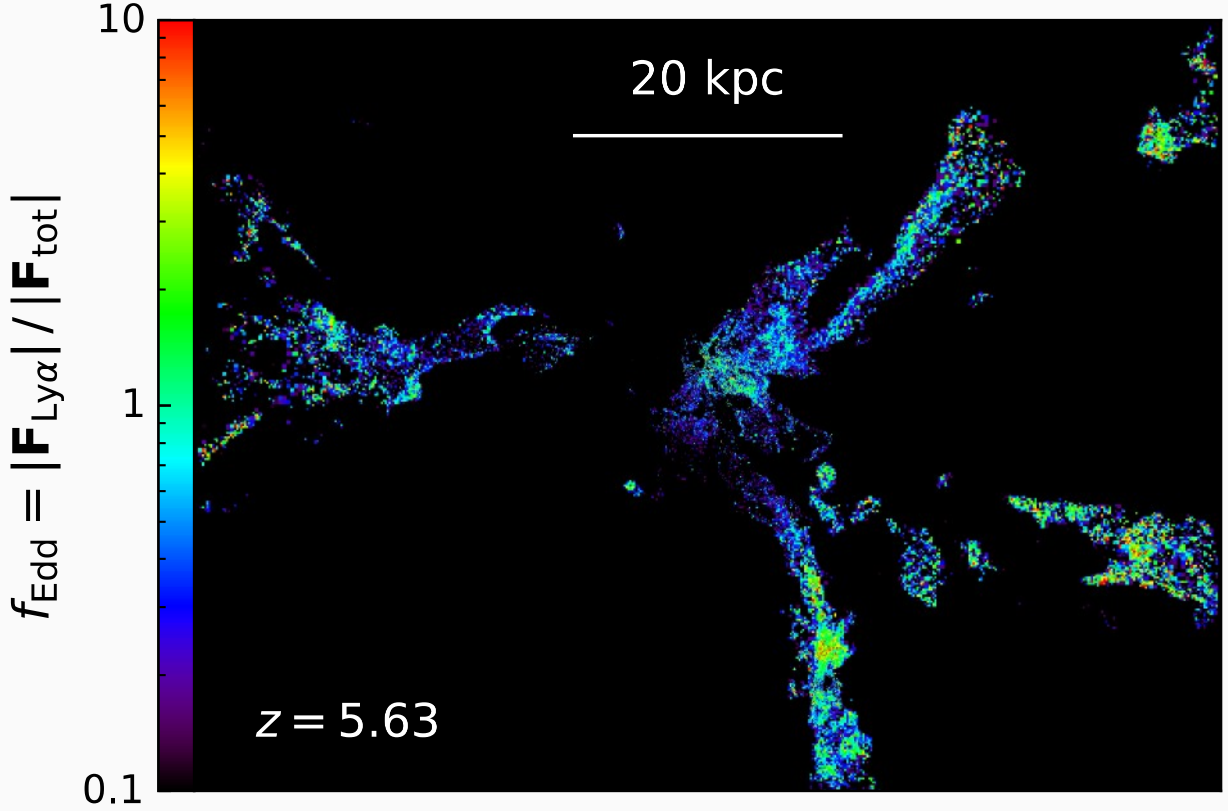
Post-starburst:

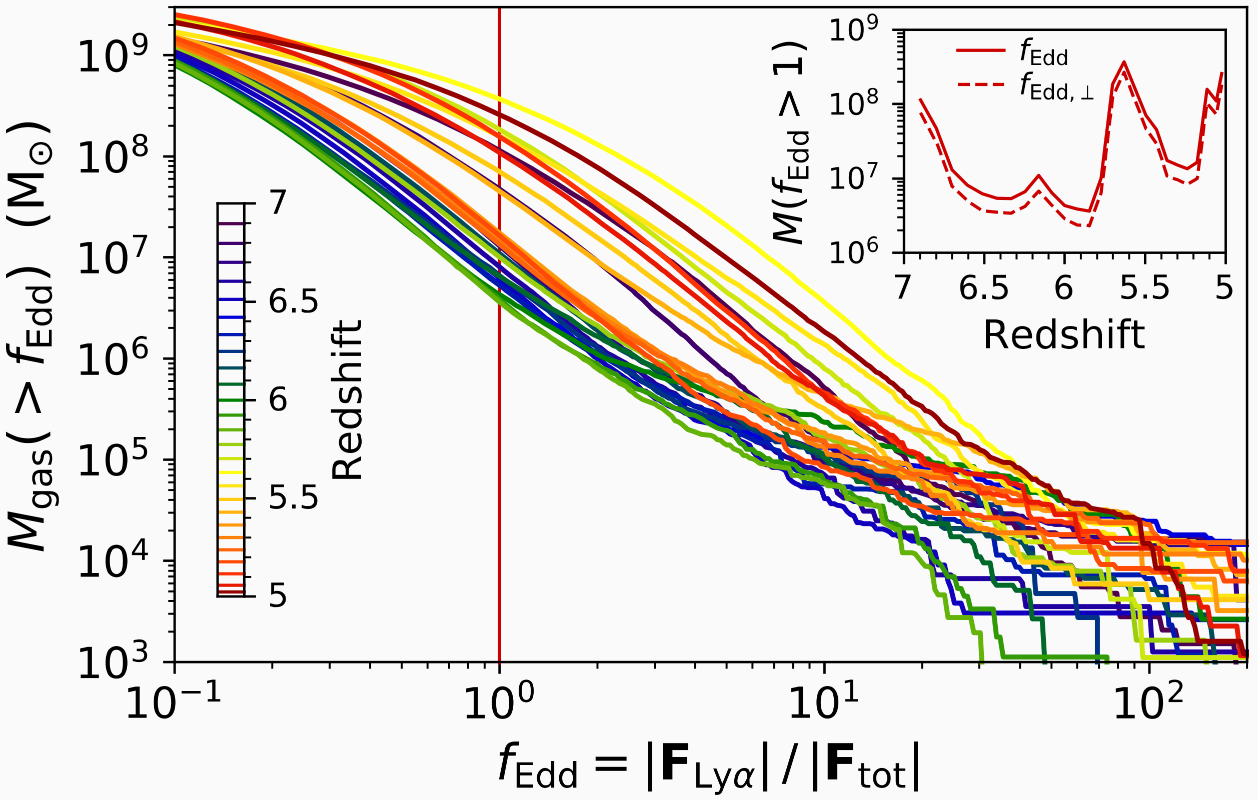
Red outflow signature



Erb et al. (2018) show the spatially-resolved kinematics of a LAE at z = 2.3, which we link to post-starburst galactic winds.



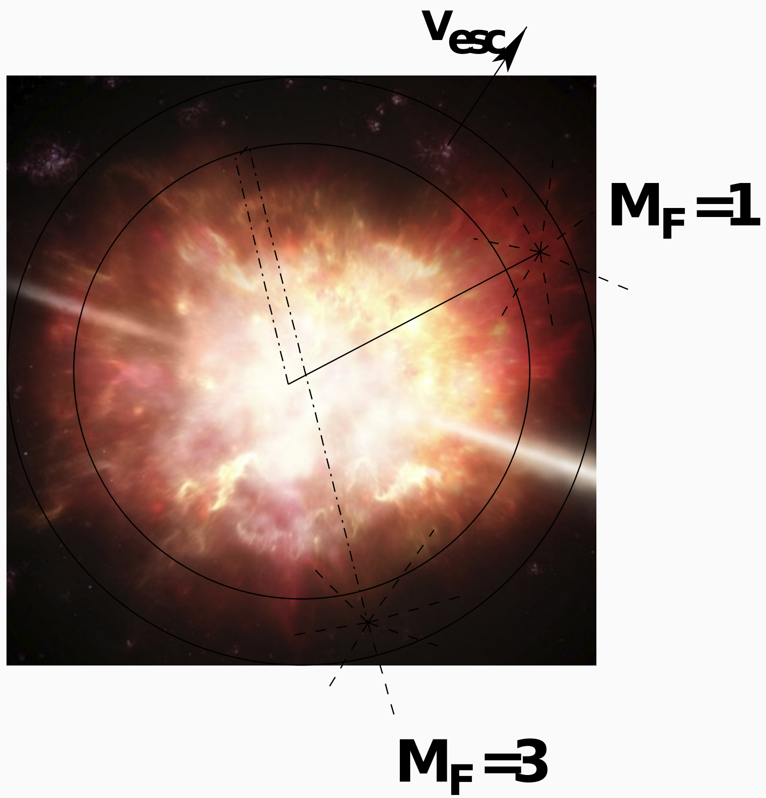


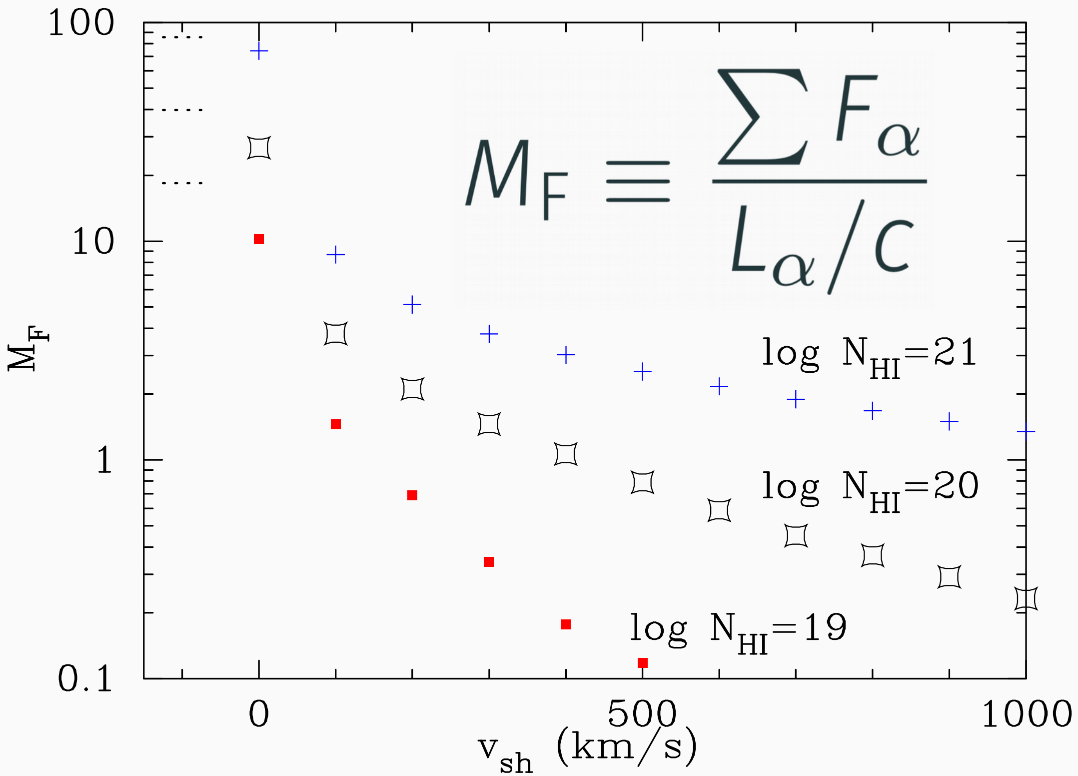


- Lyα pressure is likely to play only a minor role in the overall galactic dynamics.
- However, we find high Eddington factors in the neutral, low-metallicity filaments.

MULTIPLE SCATTERING ACTS AS A FORCE MULTIPLIER

Example: Lyα trapping in the expanding shell model based on MCRT calculations (Dijkstra & Loeb 2008,2009).

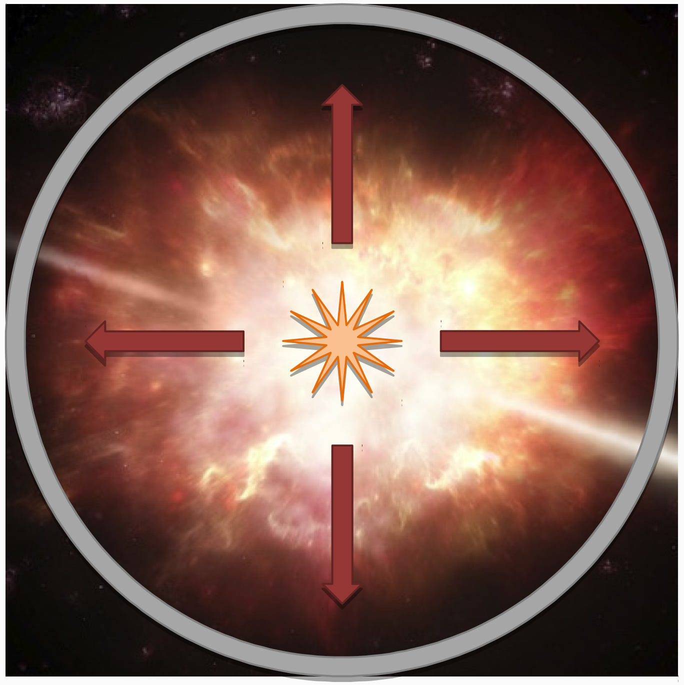




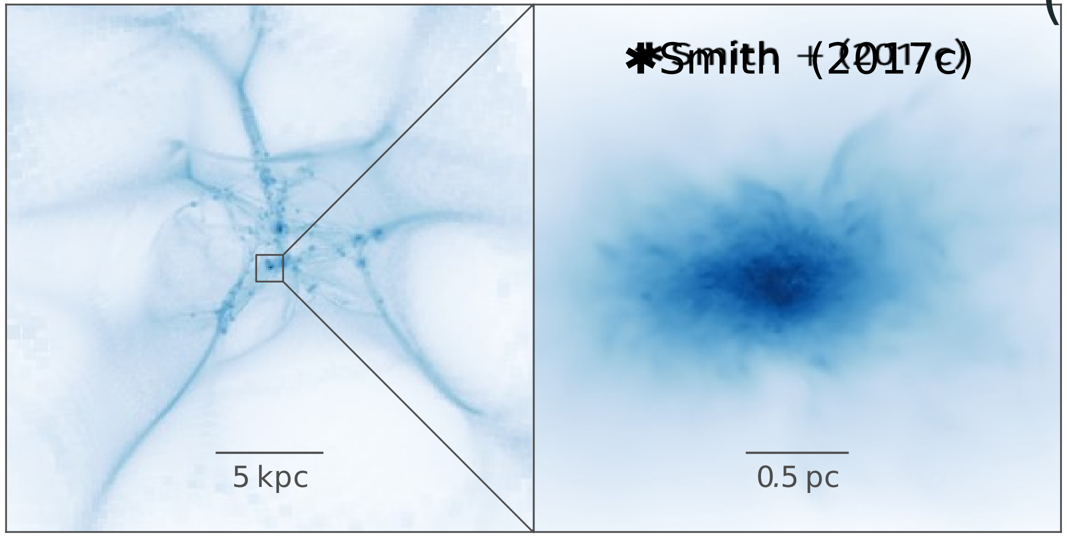
$$M_{\rm F} \equiv \frac{\sum F_\alpha}{L_\alpha / c}$$

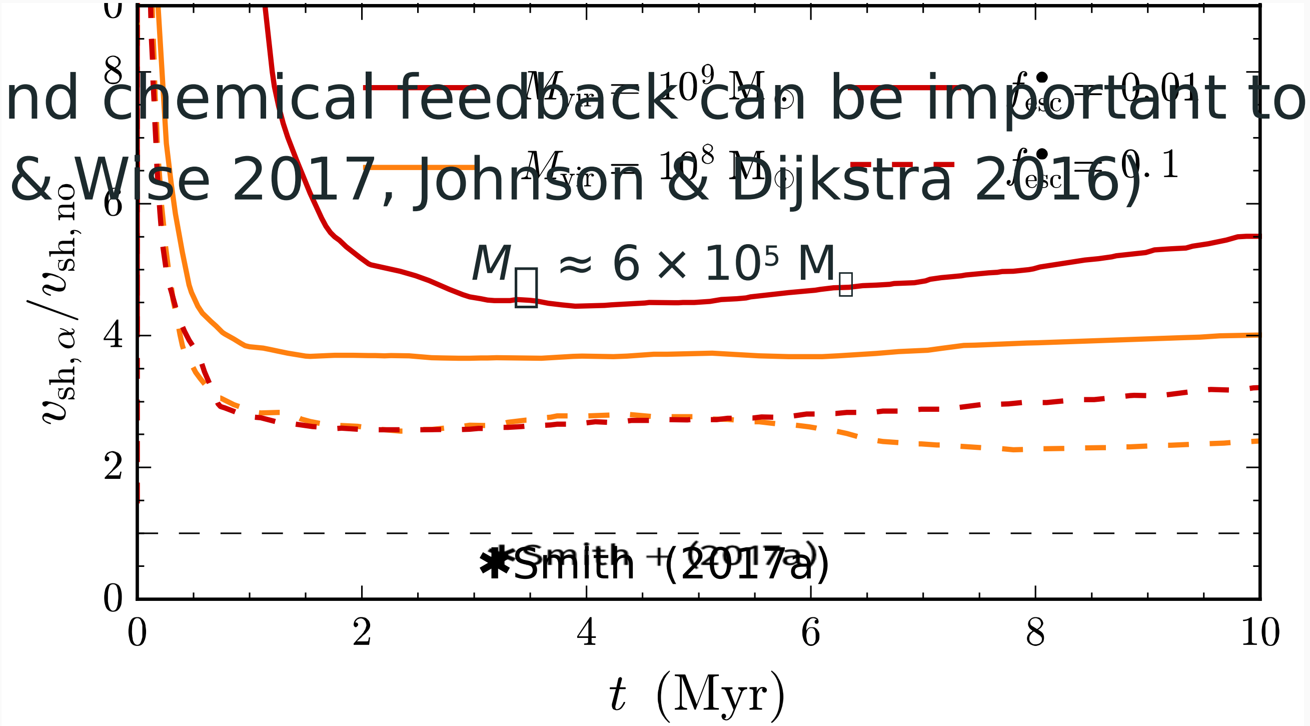
- Other works use order of magnitude estimates based on idealized Lyα RT:
  Cox (1985), Bithell (1990), Haehnelt (1995), Henney & Arthur (1998), Oh & Haiman (2002), McKee & Tan (2008), Milosavljević et al. (2009), Wise et al. (2012).

Lyα RADIATION PRESSURE IS DYNAMICALLY IMPORTANT FOR DCBHs



- First radiation hydrodynamics simulations with Lyα pressure
- Radiation-driven winds can be accelerated by Lyα trapping
- 3D post-processing analysis of a Direct Collapse Black Hole
- Thermal and chemical feedback can be important too. (Ge & Wise 2017, Johnson & Dijkstra 2016)

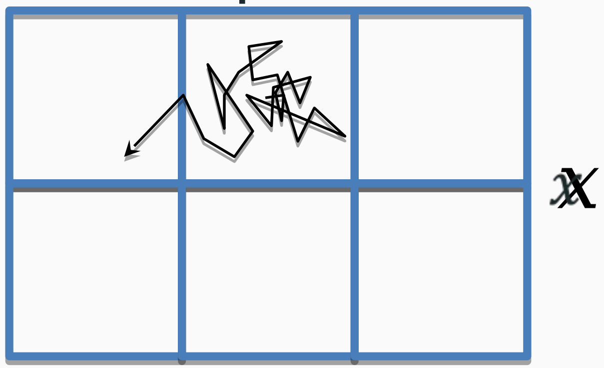




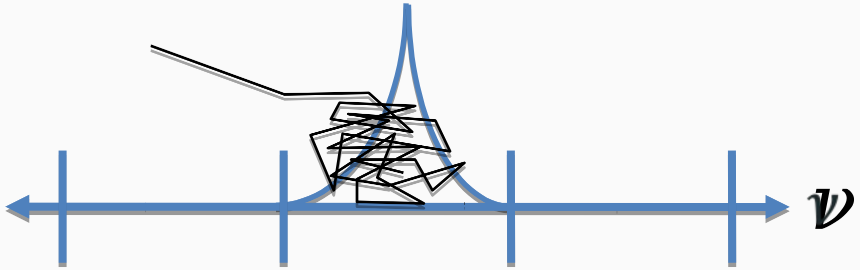
RESONANT DISCRETE DIFFUSION MONTE CARLO (rDDMC)

Discretized transfer equation leads to a Monte Carlo interpretation.

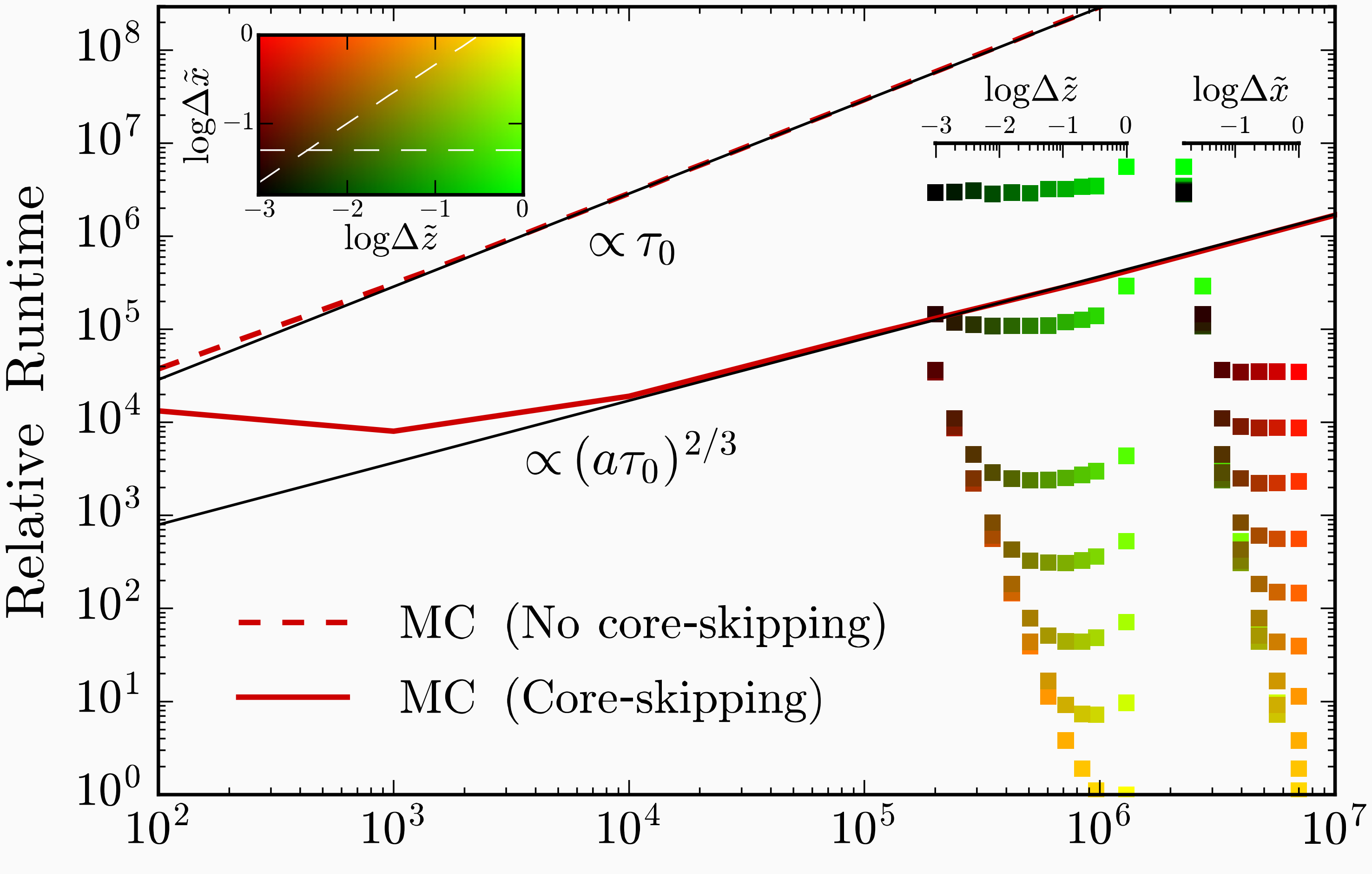
$$\frac{1}{c}\frac{\partial J}{\partial t} = \nabla \cdot \left(\frac{\nabla J}{3k} \right) + \frac{\partial}{\partial \nu} \left(\frac{k}{2} \frac{\partial J}{\partial \nu} \right)$$



Skips scatterings if $\lambda_{\rm mfp} \ll \Delta x$



Diffusion in Space & Frequency



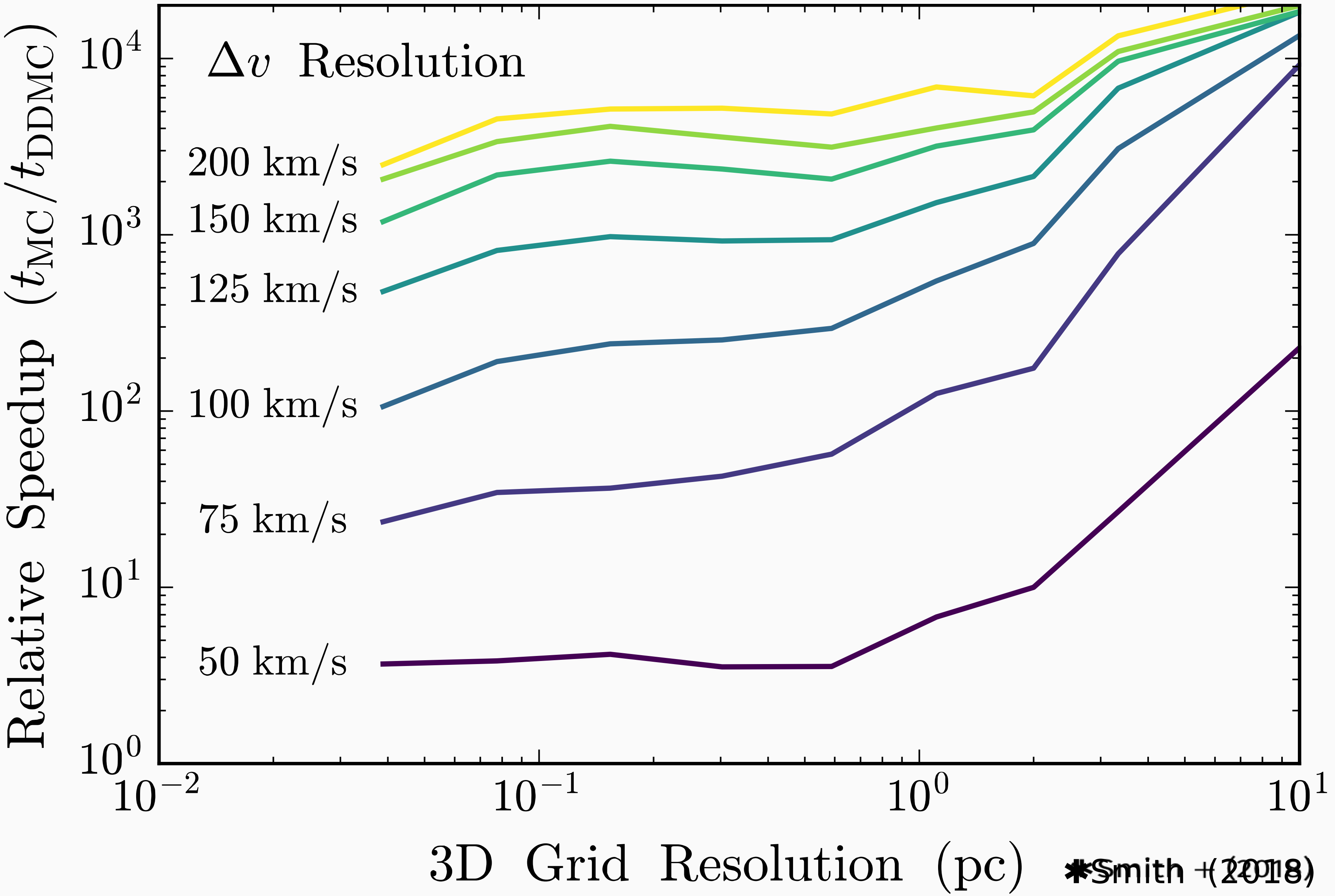
*Smith + (2018)

rDDMC SPEEDUP FOR 3D SIMULATIONS

We show that rDDMC also outperforms MCRT in more realistic setups (for example DCBHs).

Many subtle issues and promising solutions.

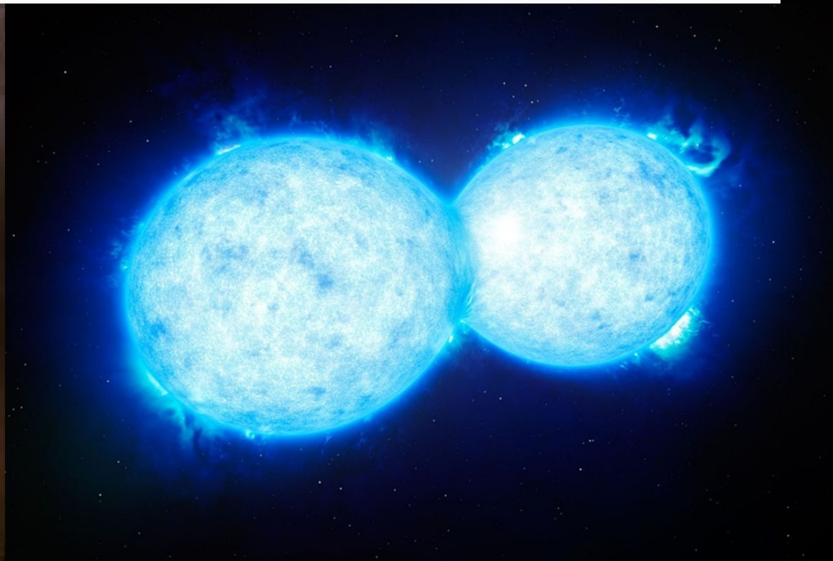
We are continuing to develop the rDDMC method and apply it to galaxies, black holes, & stellar



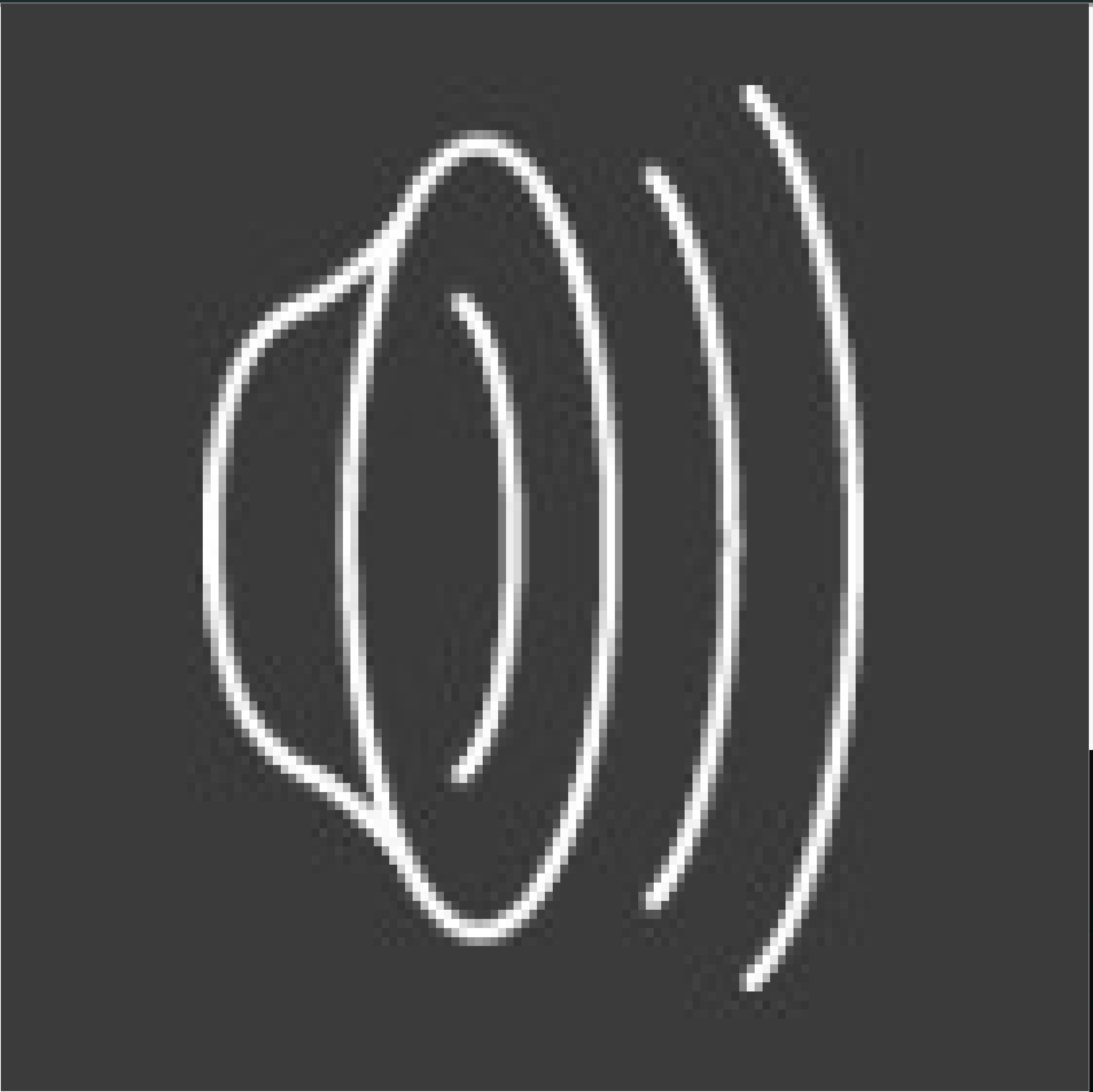
*Smith +(2018)

APPLYING RADIATION HYDRODYNAMICS TO RESONANCE LINES

- On the fly 3D Lyα radiation hydrodynamics is feasible with my new resonant discrete diffusion Monte Carlo method.
- Initial collapse of massive seed black holes, e.g. DCBHs.
- Line driven winds, e.g. massive stellar systems and the circumstellar environments of binary neutron-star mergers.



SUMMARY



- Lyα sources provide clues about galaxy formation and evolution, CGM/IGM, large-scale structure, and the epoch of reionization.
- JWST/GMT/TMT/E-ELT will extend our view into the high-z frontier.
- 3D Lyα RHD will further our