Revealing the First Billion Years of the Universe

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Group Members

UToledo PhD Students/postdoc/undergrads:

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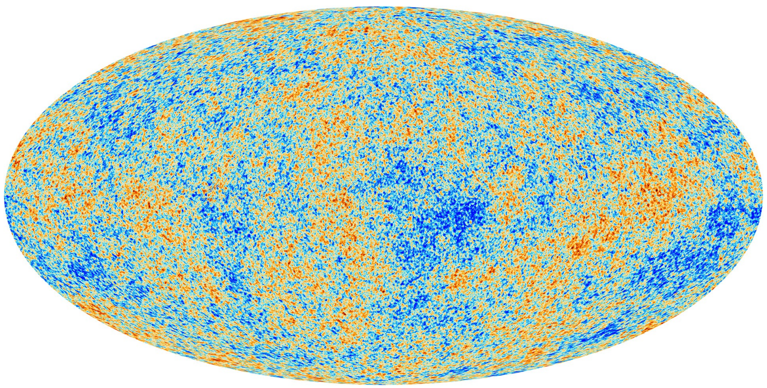
Additional key collaborators: Matthew McQuinn (U of Washington), Greg Bryan (Columbia), and Zoltan Haiman (Columbia)

Trevor Blodgett

Thomas Behling

First Billion Years

Cosmic Microwave Background from Planck



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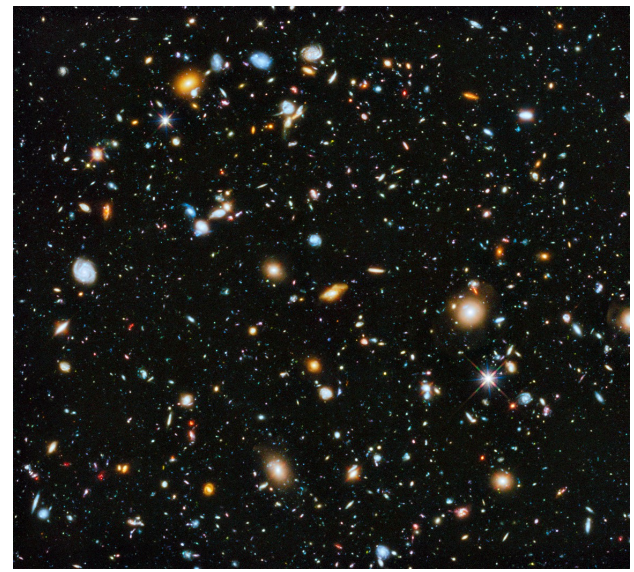
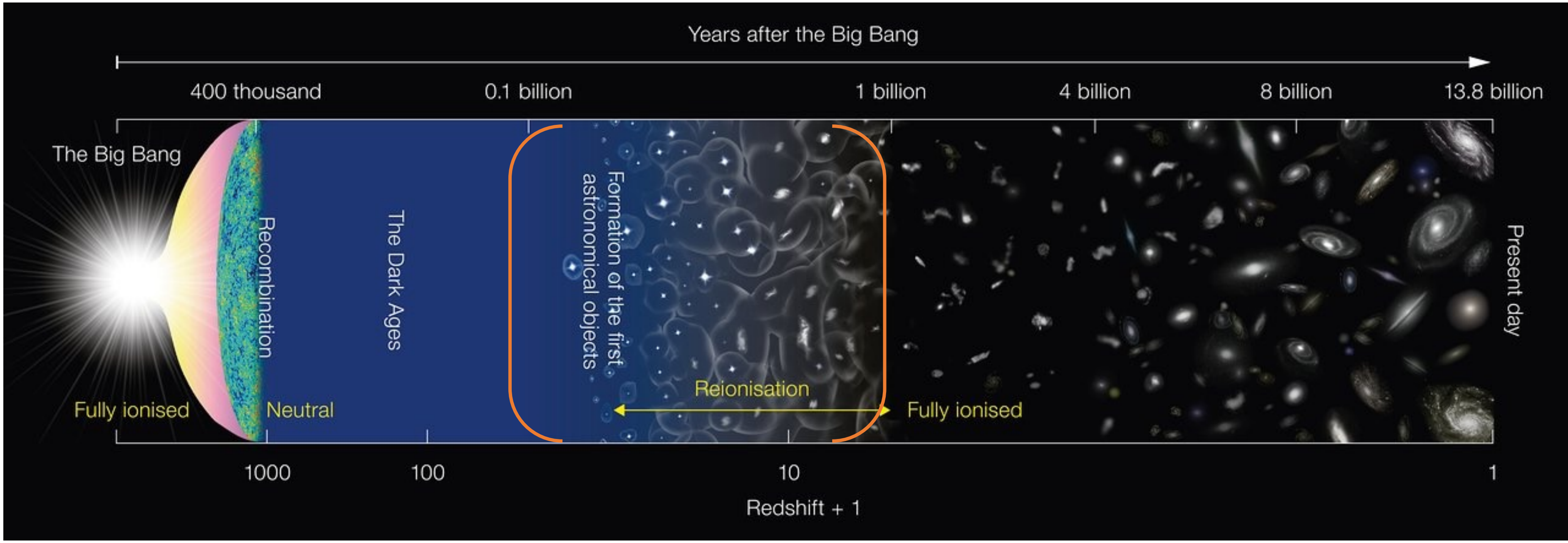
Hubble Ultra-Deep Field



- “Baby picture” of Universe (~380,000 years old)
- Very small temperature fluctuations (1 part in 100,000)
- **<u>Simple initial conditions!</u>**
  - **<u>Dark matter</u>**
  - **<u>Gas</u>**
  - **<u>Radiation</u>**

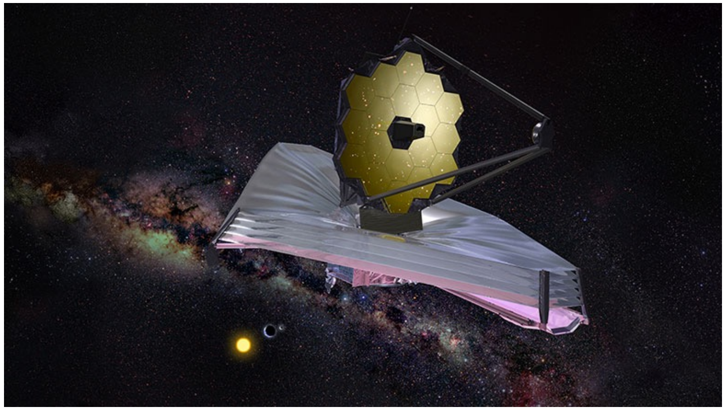
- Tiny patch of sky
- ~10,000 galaxies
- View of the past (≳billion years after Big Bang)
- **<u>Emergence of complexity!</u>**

First Billion Years



- Big Questions
  - What were the properties of the first stars?
  - How did the first supermassive black holes form?
  - How/when did reionization occur?
- Why is this interesting?
  - Gap in cosmic timeline
  - First stages of galaxy evolution
  - Possible new dark matter physics

New Windows into the Early Universe



James Webb Space Telescope

Giant Magellan Telescope, Thirty Meter Telescope

- New instruments now and in coming decade
- Deep observations → earlier times
- **Improved theoretical predictions required to maximize scientific return on investment**

Large Radio Telescopes -- 21cm cosmology

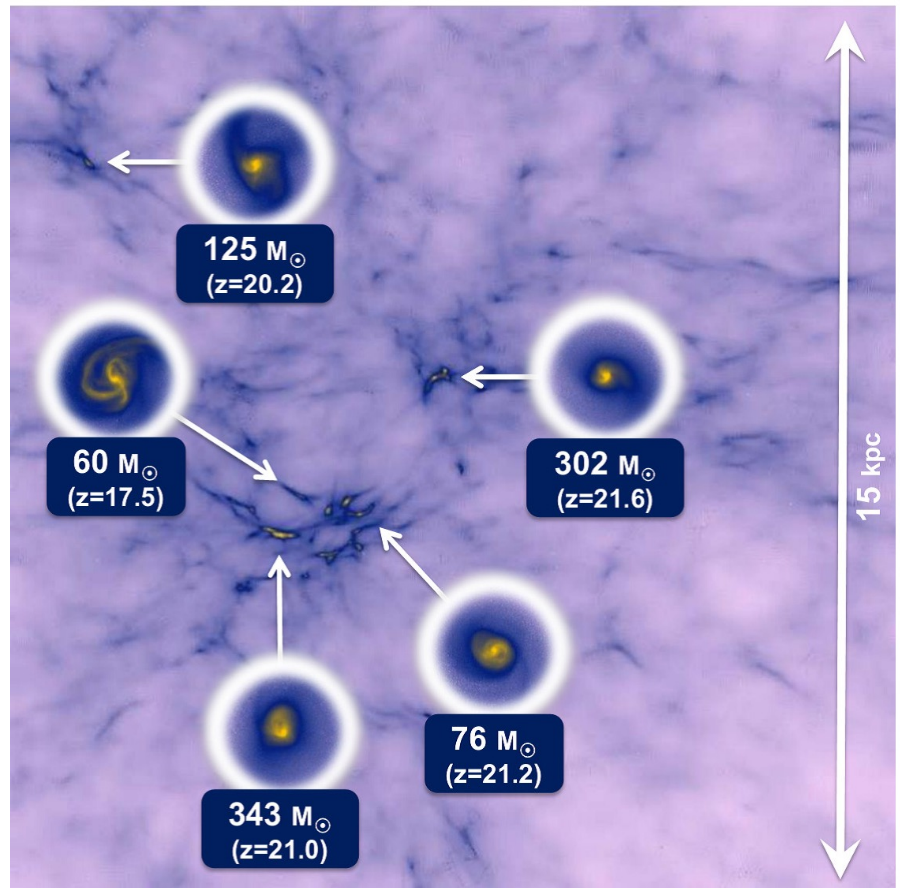
Outline

- First stars (Population III)
  - Hydrodynamical cosmological simulations
  - Semi-analytic models
- Probing Cosmic Reionization with Line-Intensity Mapping
  - Lyman-α intensity mapping observations
  - Cross correlating JWST galaxies and line-intensity maps

First Stars (Population III)

Haiman et al. (1996), Tegmark et al. (1997), Abel et al. (2002), **Visbal** et al. (2012), **Visbal** et al. (2015), Hirano et al. (2014/2015)

- Metal-free (Pop III), i.e. formed from H and He
- Theoretical Predictions
  - H_2 cooling
  - Form in $\sim 10^{5-6} M_\odot$ "minihalos"
  - Massive stars
- Open Questions
  - Initial mass function (IMF)
  - Abundance/evolution
  - Impact on IGM
- Importance
  - First stages of galaxy evolution
  - Dark matter physics

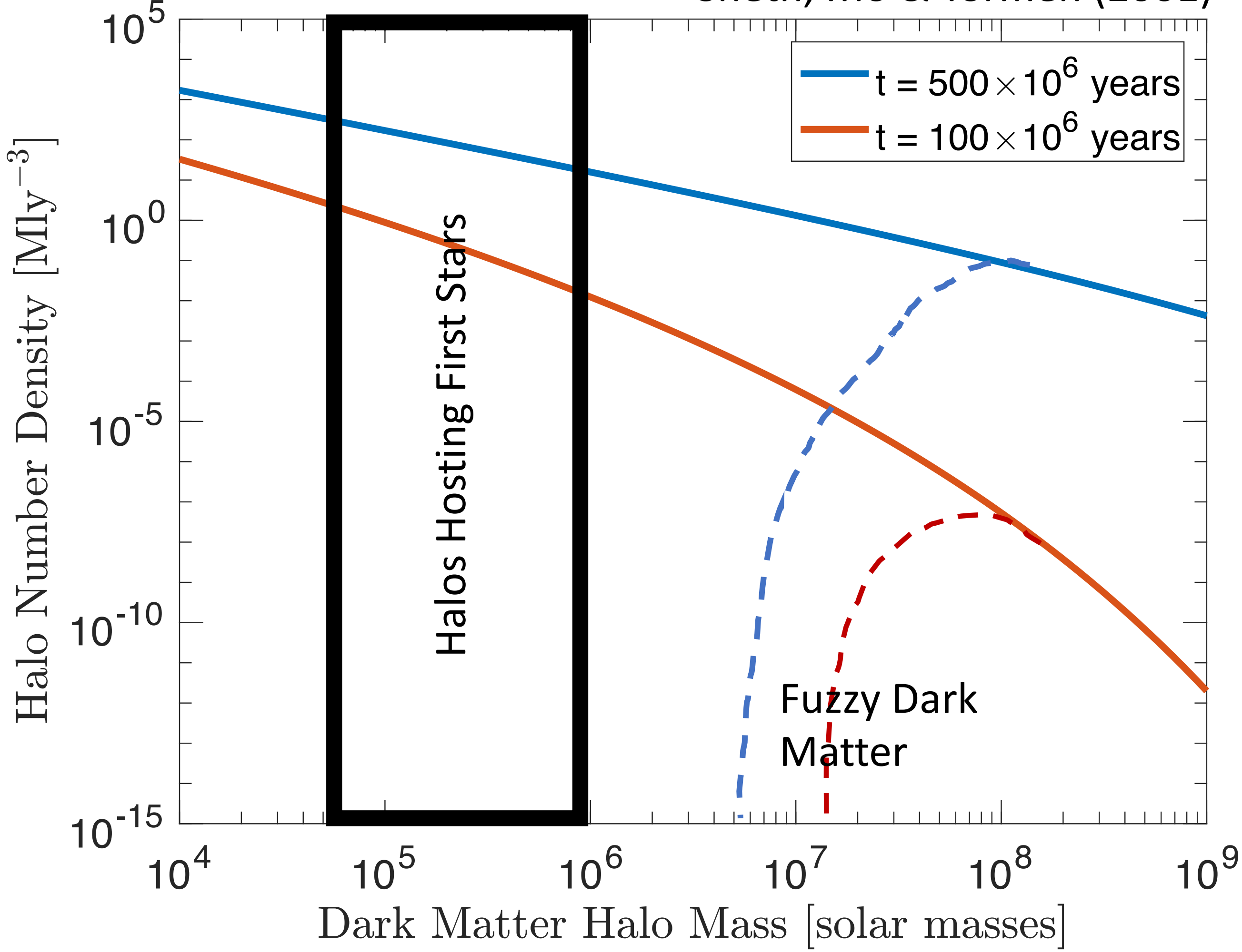


Pop III Star Formation in Cosmological Simulations, Hirano et al. (2014)

Mass Distribution of Dark Matter Halos

- Many low-mass halos, fewer high-mass
- More at late times
- **Sensitive to dark matter particle physics**
  - **"Fuzzy" dark matter (Hu et al. 2000)**
  - **Warm dark matter**
- **First stars can constrain dark matter models!**

Sheth, Mo & Tormen (2001)



Observational Probes

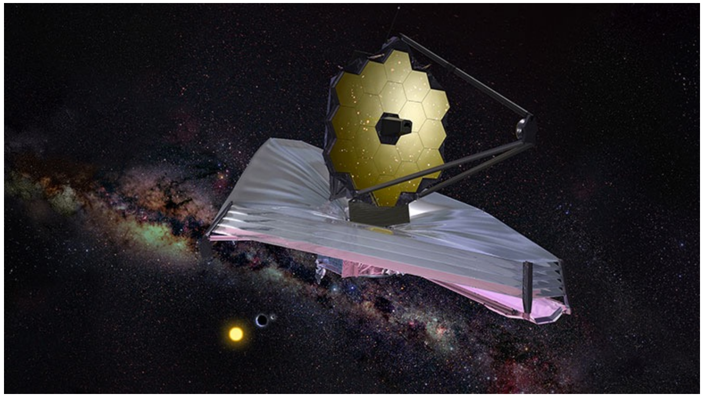
- Supernovae (JWST/WFIRST)

[e.g., Whalen et al. (2013), Magg et al. (2016)]

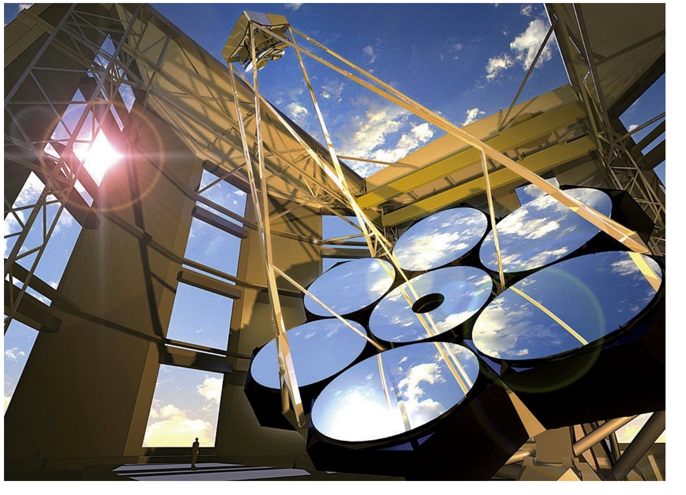
- Gravitational waves from BH remnants (Advanced LIGO)

  [e.g., Inayoshi et al. (2015)]

- Low-Mass High-Redshift Galaxies (JWST)
  [e.g., **Visbal** et al. (2017); Kulkarni, **Visbal** & Bryan (2019)]
- Stellar archaeology (GMT/TMT)
  [see Frebel & Norris (2015)]
- 21cm observations (HERA)
  [e.g., **Visbal** et al. (2012); Fialkov et al. (2014)]

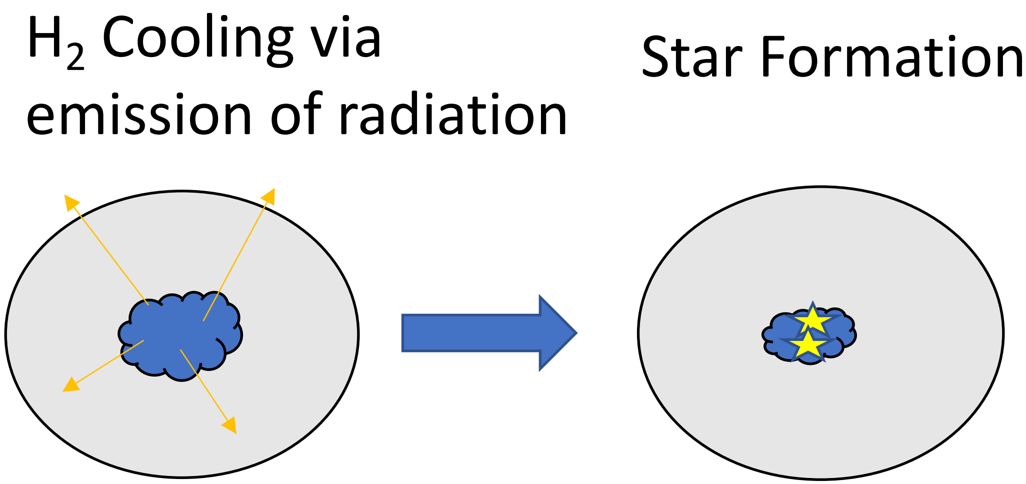


James Webb Space Telescope



Giant Magellan Telescope

Key Question: Critical Halo Mass For Pop III Star Formation

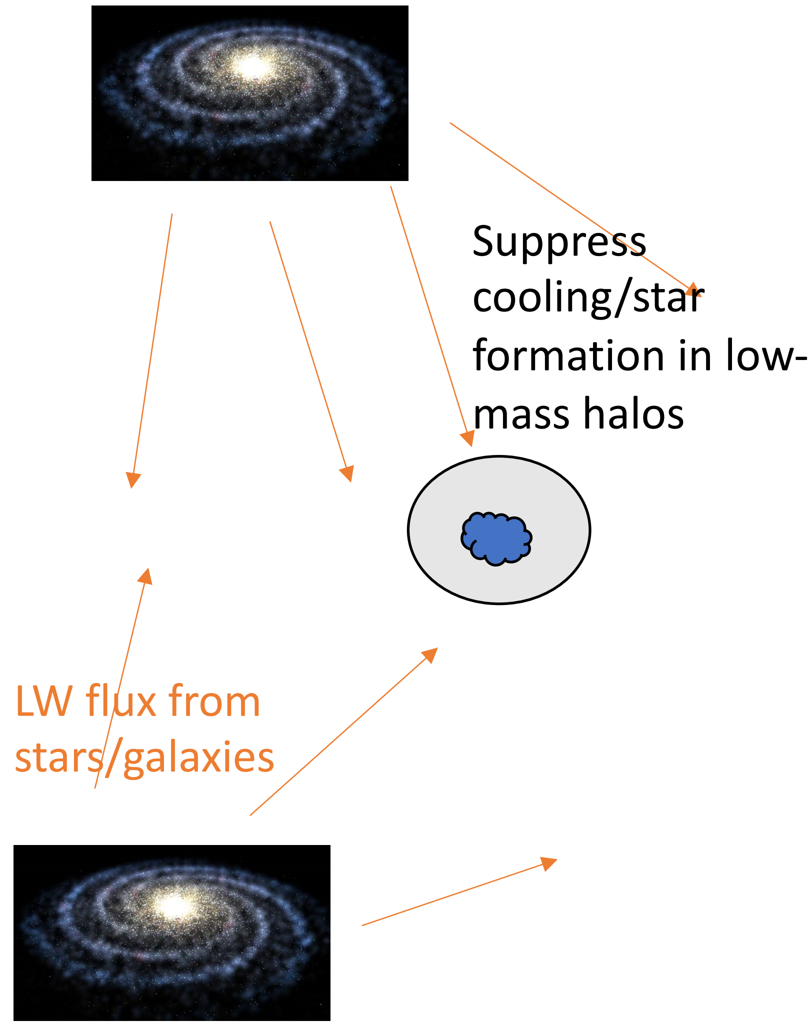


- Gas cools → collapses to high density → star formation
- Cooling via H_2 rotational/vibrational transitions
- $\sim 10^6$ solar mass dark matter halos (e.g., Machacek et al. 2001)
  - Sufficient density for significant H_2 formation
  - Virial temperatures of hundreds of Kelvin → excite H_2 transitions
- Precise mass crucial, but not previously predicted with all relevant physics included
- Strongly impacts the abundance of Pop III stars

Effect I: Lyman-Werner Feedback

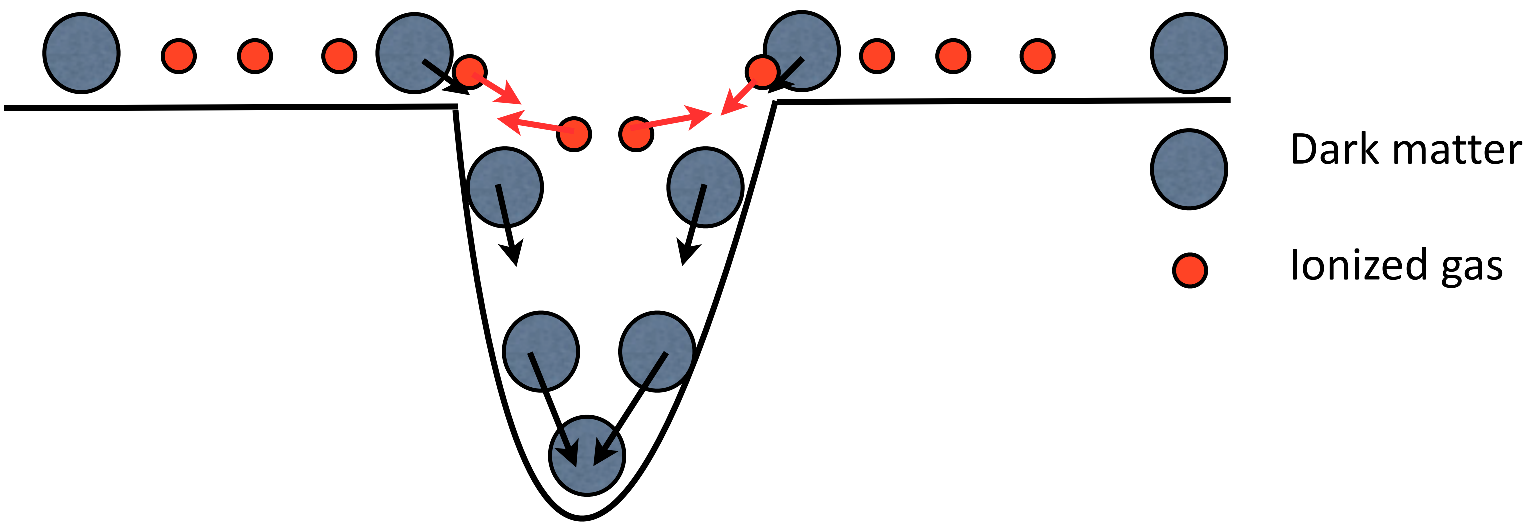
Haiman et al. (1997); Machacek et al. (2001); O'Shea & Norman (2008); EV et al. (2014)

- LW photons: 11.2 - 13.6 eV
- LW photons dissociate H_2
- LW background produced by stars suppresses star formation in small minihalos
- Higher LW flux → higher minimum mass for star formation
- Self-regulation of first stars



Effect II: Streaming Velocity

Tseliakhovich & Hirata (2010)

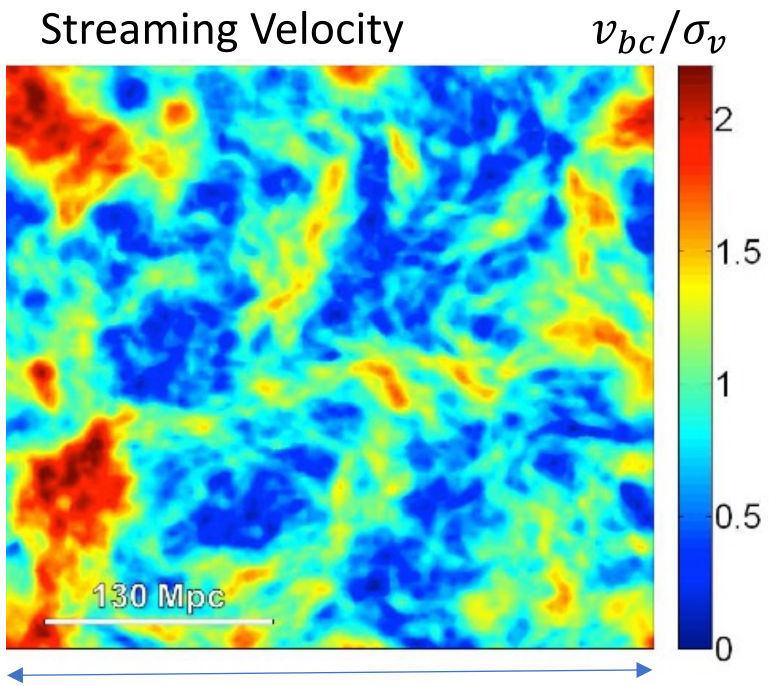


Gravitational potential well

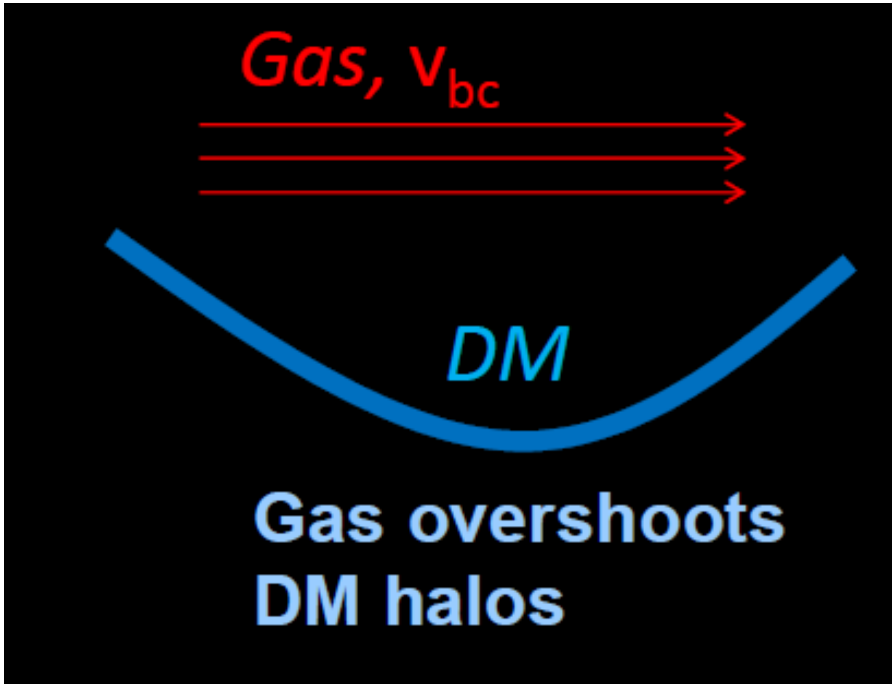
- Before ~380,000 years – ionized gas coupled to radiation
- Dark matter falls into gravitational potential wells
- Gas supported by radiation pressure
- Results in relative velocity between dark matter and gas

Effect II: Streaming Velocity

Tseliakhovich & Hirata (2010), Fialkov et al. (2012), **Visbal** et al. (2012)



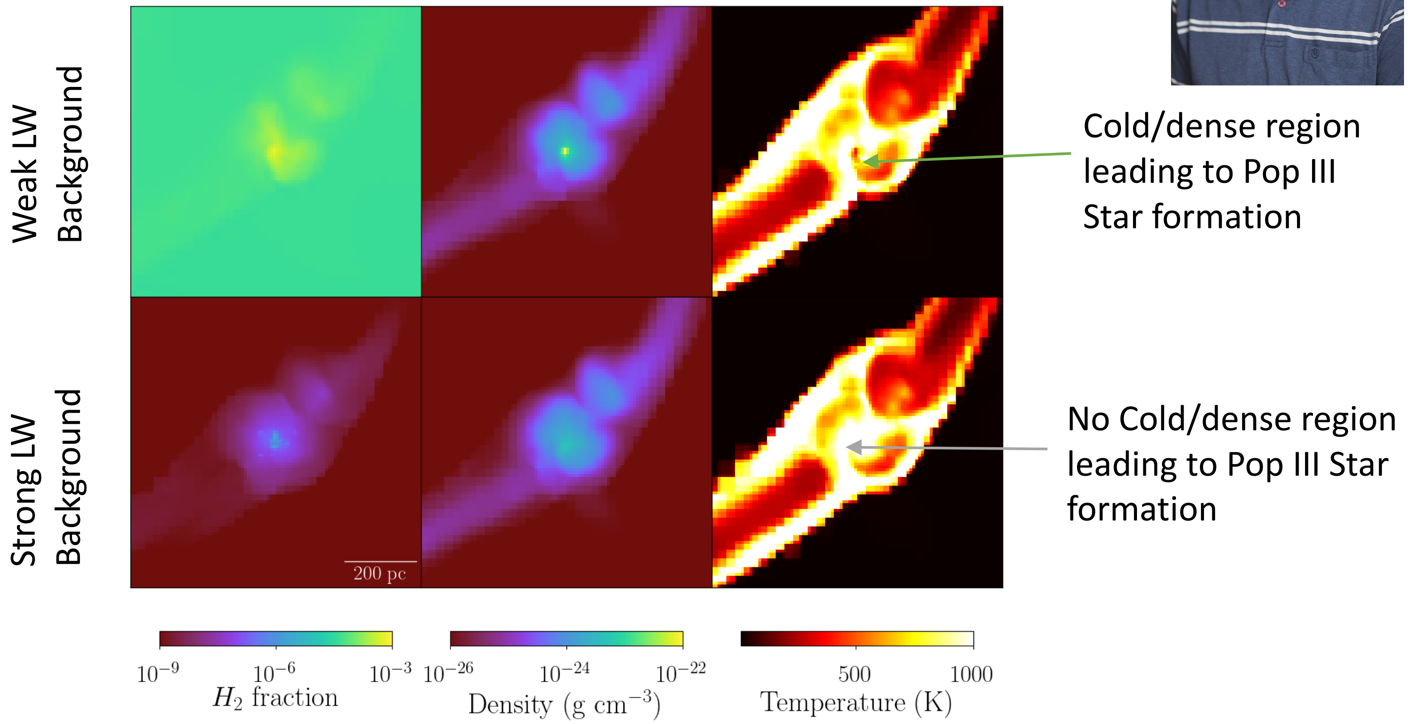
~billion light years
$\sim 10^{25}$ meters



- Velocity varies spatially
- High velocity regions – star formation suppressed in low mass dark matter halos

Simulations of Critical Halo Mass Kulkarni, EV, Bryan (2021), see also Schauer et al. (2021)

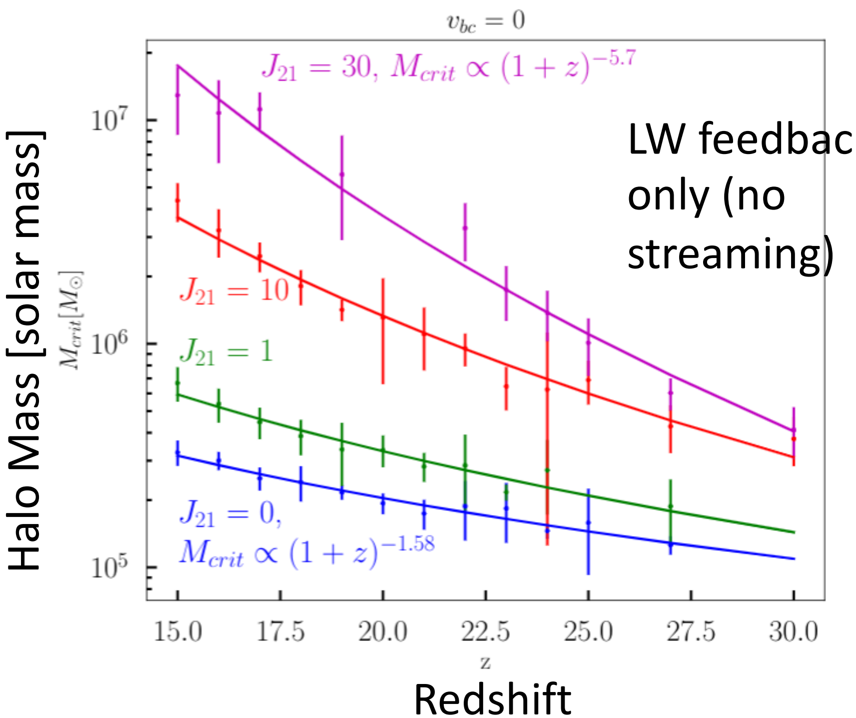
Mihir Kulkarni

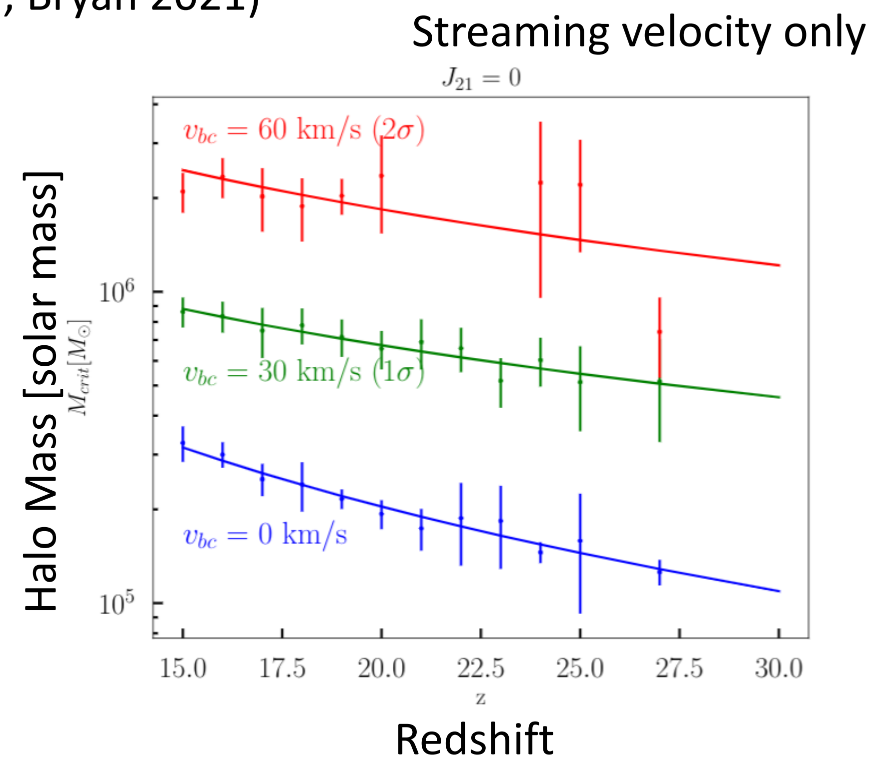


- Adaptive mesh refinement code ENZO (Bryan et al. 2014)
  - 0.5 Mpc/h box, 22 pc maximum spatial resolution
  - ~900 halos above $\sim 10^5 M_\odot$ at z=15
- Initial conditions with streaming velocity (McQuinn & O'Leary 2012), include primordial chemistry and cooling, LW radiation + H_2 self shielding
- Grid of different Lyman-Werner intensities and streaming velocities (9 combinations)

Pop III Critical Halo Mass Results

(Kulkarni, EV, Bryan 2021)



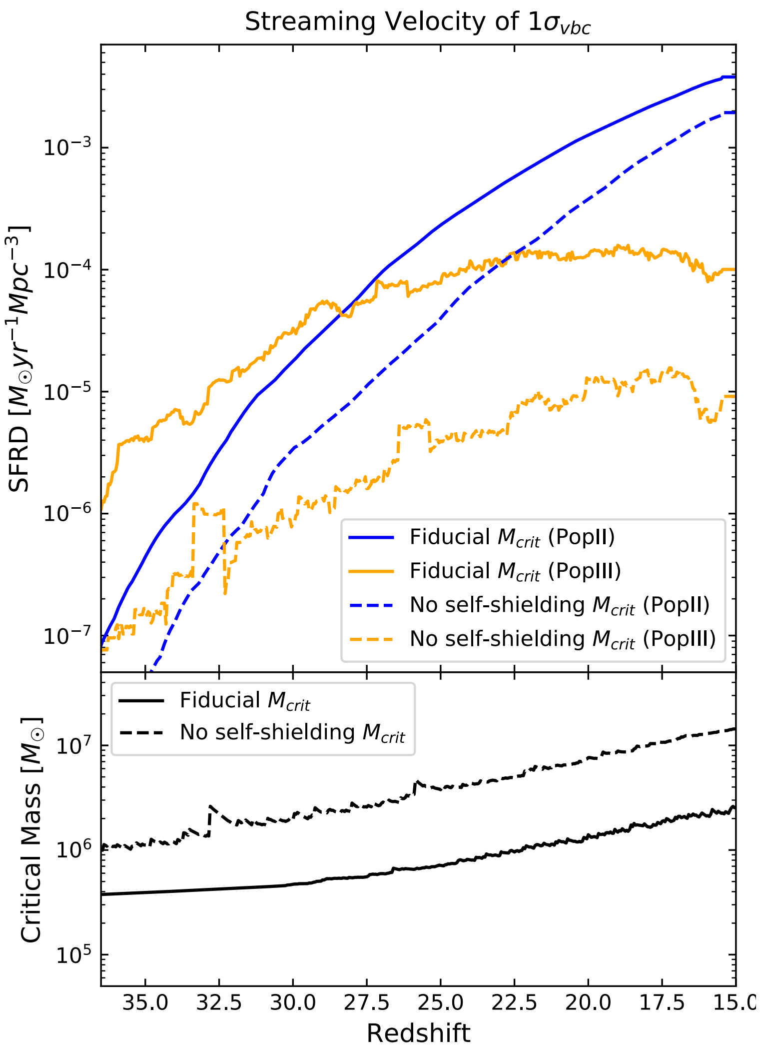


- Lower critical halo mass than previous results (e.g., Machacek et al. 2001) due to H_2 self-shielding (Wolcott Green & Haiman, 2019)
- LW + v_{bc} combine for stronger effect, but not in simple multiplicative manner as previously assumed
- <u>Analytic fitting function for $M_{crit}(v_{bc}, J_{LW}, z)$ available</u>

Implications of New M_{crit}

- Monte Carlo Merger Tree Based Semi-analytic Model
- Self-shielding of H_2 → lower critical halo mass needed for Pop III star formation
- <u>**Orders of magnitude more Pop III stars in early universe**</u>

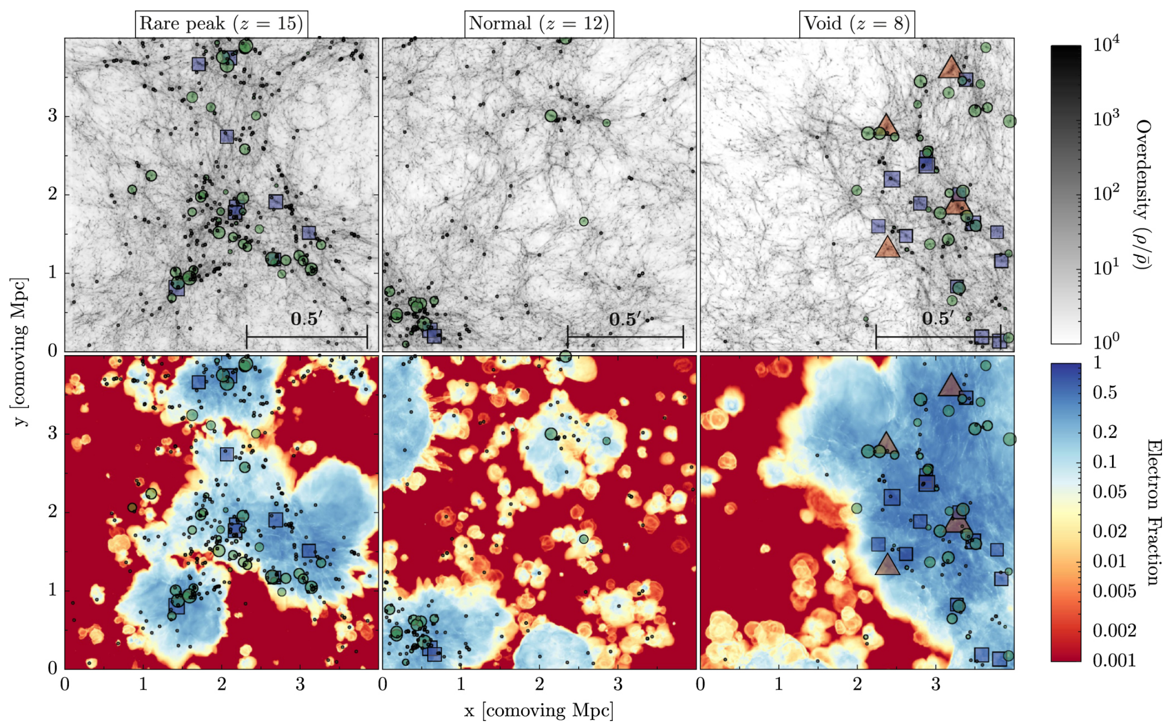
Colton Feathers



Feathers, EV+, (2024)

Key Challenge: Computational Cost

- Need to model abundance vs time including feedback (e.g., ionization and metal enrichment) for observational predictions
- Hydrodynamical cosmological simulations
  - Detailed treatment of physical processes
  - Computationally expensive (millions of CPU-hours)
  - Restricted in volume
  - Free parameters
    - Pop III/Pop II IMF
    - Critical metallicity for Pop III
- Alternative, faster approach is complementary



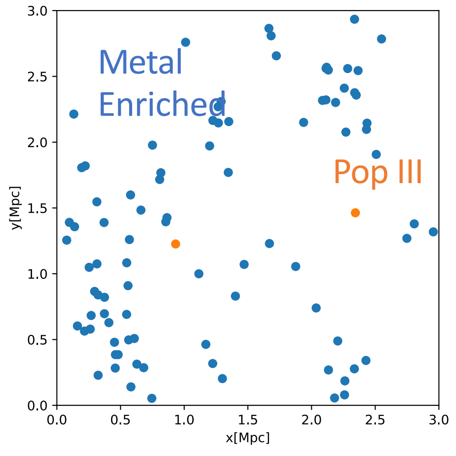
Renaissance Simulations; O'Shea et al (2015)

Faster Approach: Semi-analytic Model of First Stars/Galaxies

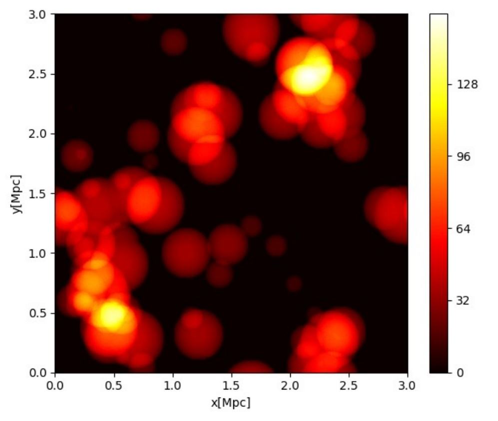
Visbal et al. (2018, 2020). See also: Trenti et al. (2009), Agarwal et al. (2012), Crosby et al. (2013), Griffen (2016), Magg et al. (2018)

- Based on cosmological N-body simulations (Springel et al. 2001, Behroozi et al. 2013)
- Analytic prescriptions for Pop III and metal enriched star formation (calibrated with hydro sims)
- New model with main 3D feedback processes
  - Hydrogen ionization
  - Intergalactic medium metal enrichment
  - LW feedback/streaming velocity
- Computationally efficient to compute cosmic abundance of first stars → can scan parameter space for observational prescriptions

First Stars and Galaxies in 3 Mpc box at z=8.6 (Visbal et al. 2020)

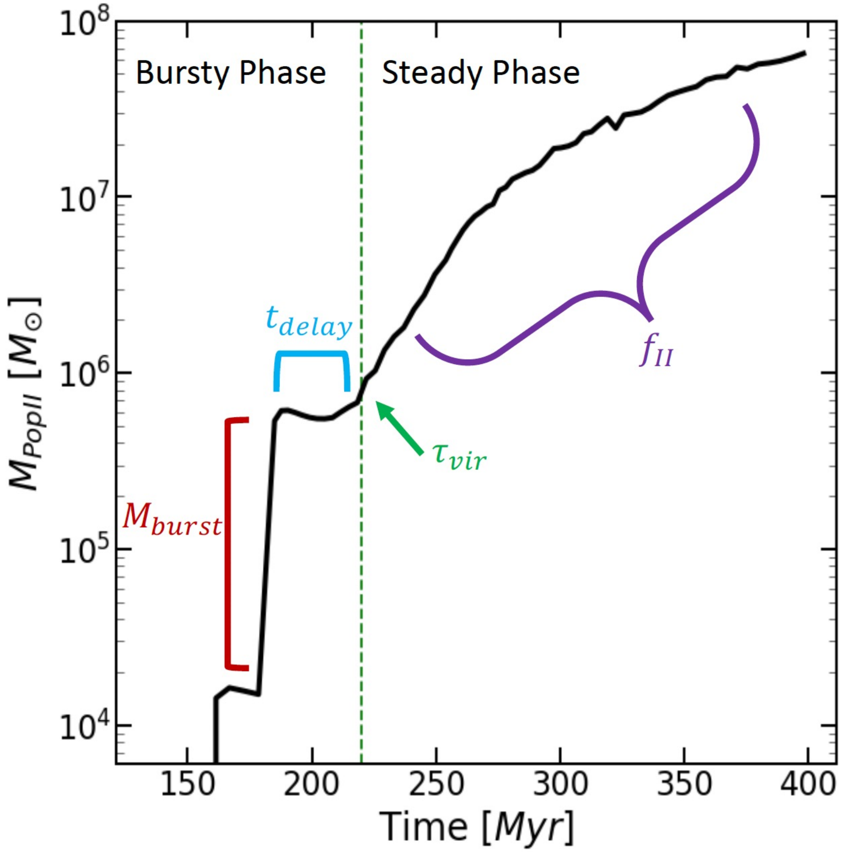


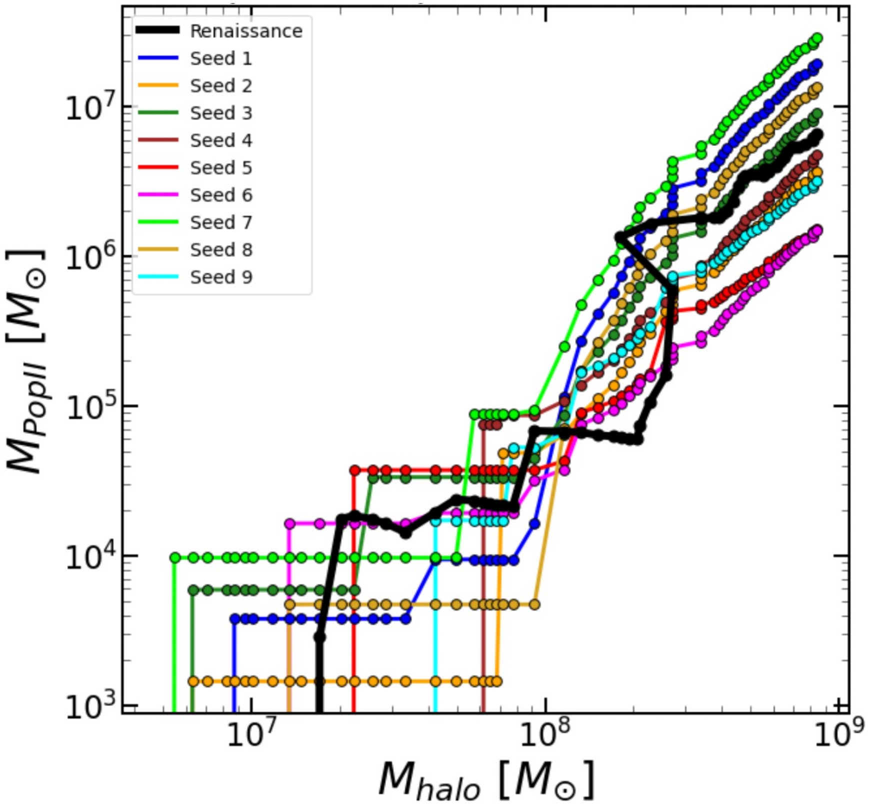
Metal-enriched intergalactic medium



Calibration of Semi-analytic Model to Renaissance Simulations

Ryan Hazlett



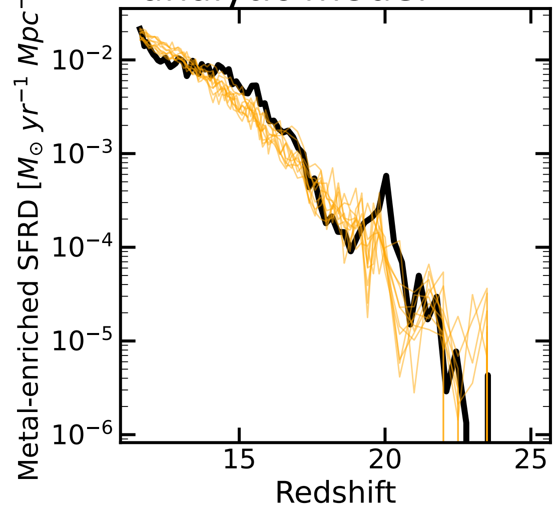


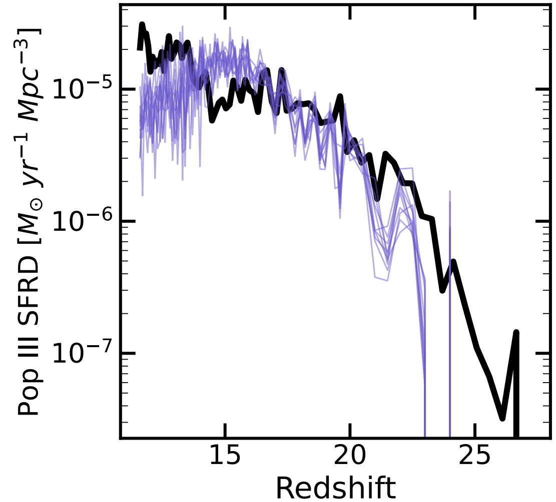
Hazlett, EV+, in prep.

Calibration of Semi-analytic Model

- Fast models (~10 CPU-hours vs 10 million CPU-hours), consistent with the simulations
- Will soon apply to observational predictions
  - Low-mass galaxies from JWST
  - Supermassive black hole seeding
  - 21cm observations

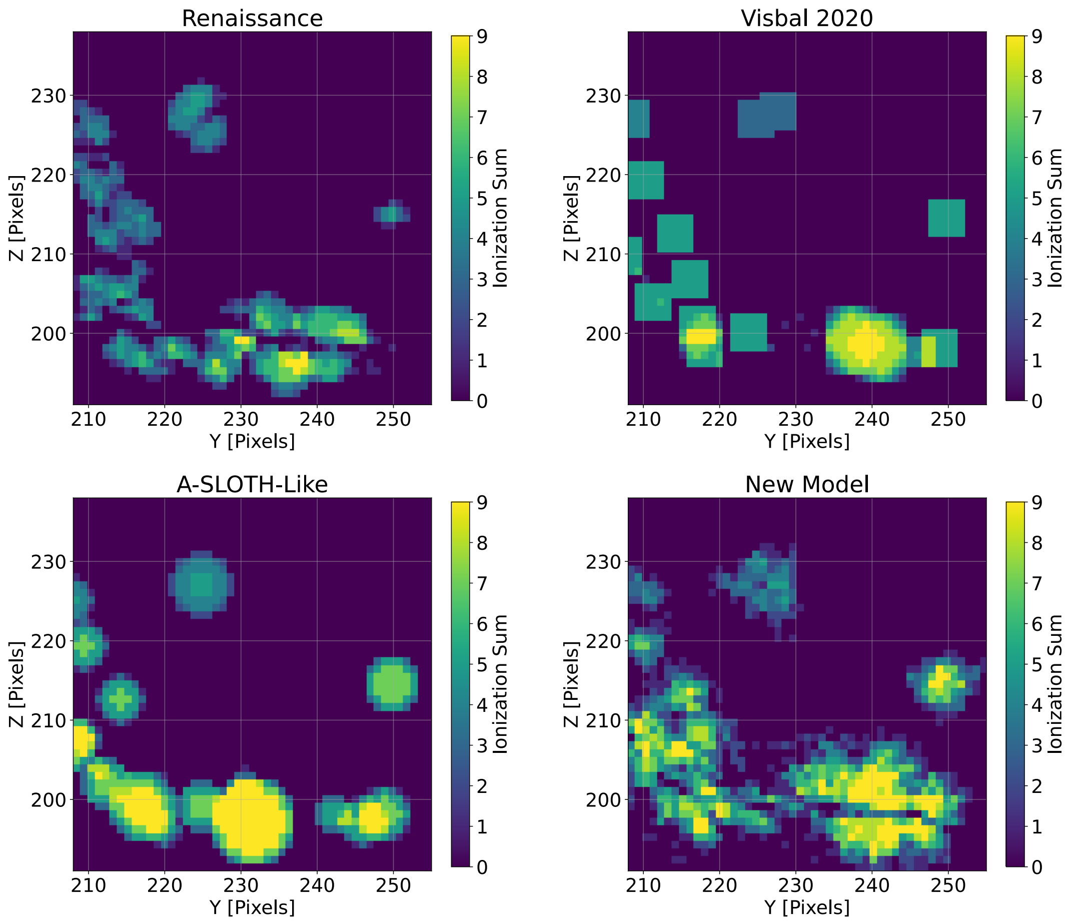
Global Star formation history in simulations vs semi-analytic model





Hazlett, EV+,. in prep.

Calibration of Early Reionization in Semi-analytic Model



Thomas Behling

First Stars – Summary/Conclusions

- Determined minimum mass of halos to form Pop III stars with Lyman-Werner + streaming velocity
  - Fitting forms available for observational predictions
  - Lower mass found due to H2 self shielding
  - Order of magnitude increase in abundance of first stars/galaxies compared to previous calculations, implications for 21cm observations, first galaxies
- New semi-analytic model of the first stars/galaxies
  - Efficient method to compute Pop III and high-z galaxy abundance including
  - Performed detailed calibration with hydro sims
  - Can be utilized for variety of observational predictions

Outline

- First stars (Population III)
  - Hydrodynamical cosmological simulations
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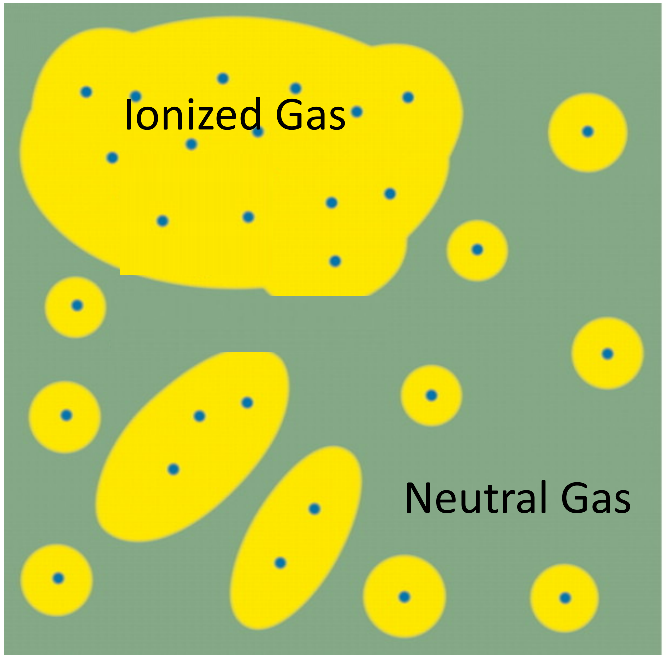
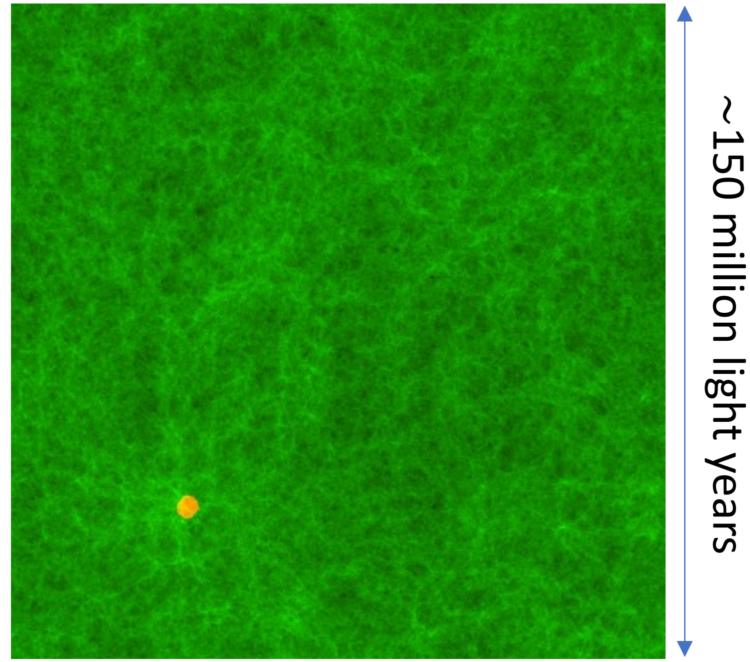
  - Lyman-α intensity mapping observations
  - Cross correlating JWST galaxies and line-intensity maps

Cosmic Reionization

Illiev et al. (2007)

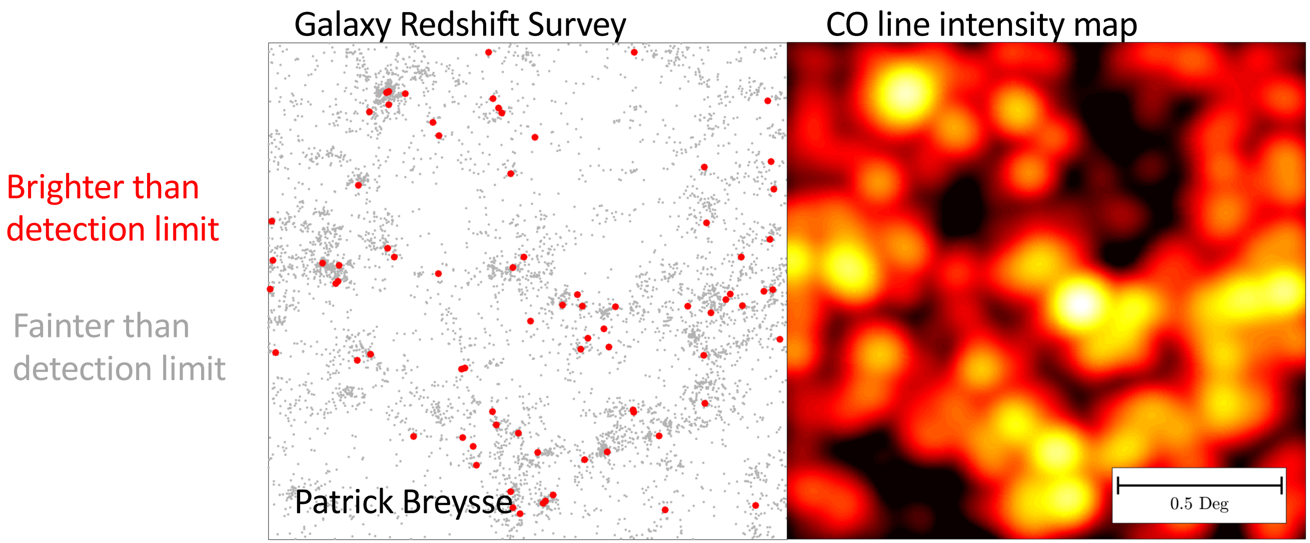




- Universe neutral at t=380,000 years → Intergalactic gas ionized by $t\sim10^9$ years (z=6)
- **How did reionization occur**?
  - Radiation from early galaxies → ionized bubbles
  - Bubbles grow and eventually overlap
- Detailed reionization history/geometry → lead to better understanding of high-redshift galaxies and characterize cosmic milestone

Measuring Large Scale Structure: Galaxy Line Intensity Mapping

EV & Loeb (2010); Chang et al. (2010); EV, Trac, & Loeb (2012); Gong+(2011/2012); Lidz+(2011); Silva+(2013); Croft et al. (2015); Kovetz et al. (2017)

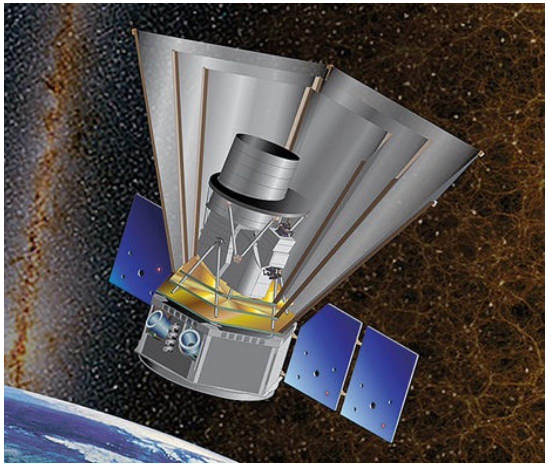


- Large-scale 3D maps of galaxy line emission
- Measures cumulative emission from ***ALL*** sources
- Proposed lines include 21cm (HERA), CO (COMAP), CII (TIME), Lyman-α (SPHEREx)
- Probe of cosmology & galaxy evolution

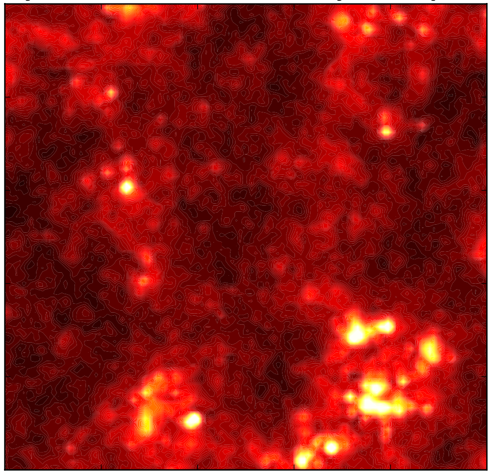
Lyman-α Intensity Mapping

Silva et al. (2012), Pullen et al. (2014), **Visbal** & McQuinn (2018)

SPHEREx, NASA



Lyman-α Intensity Map

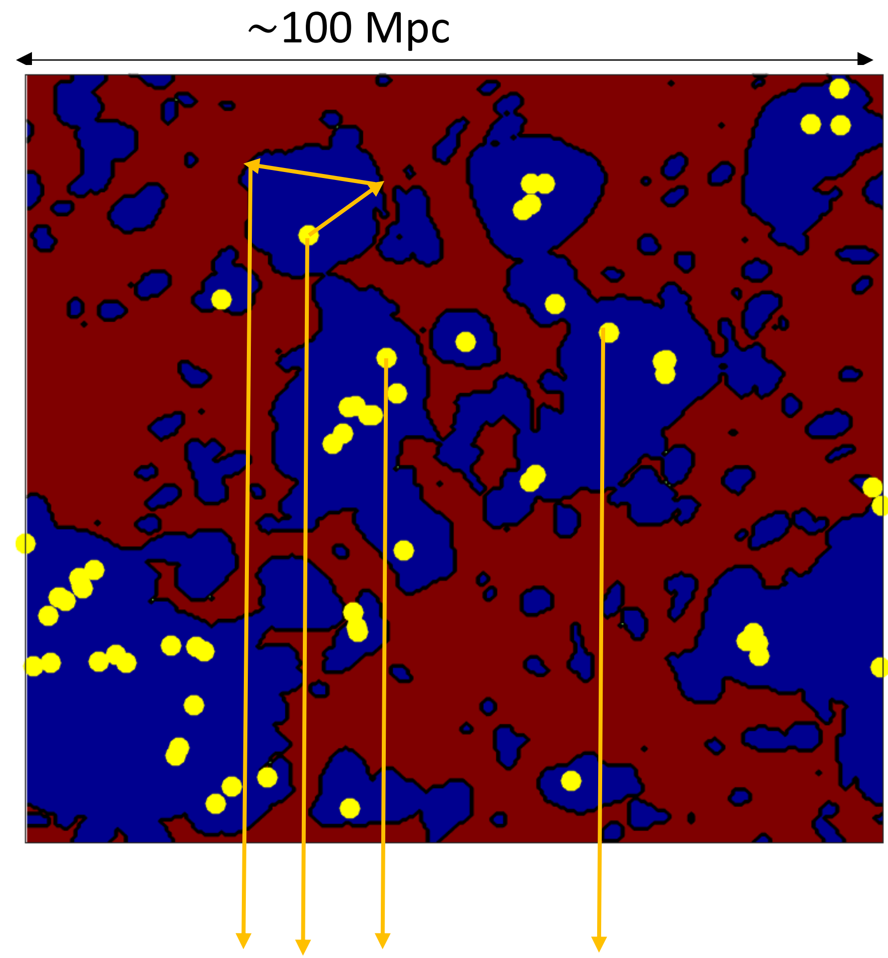


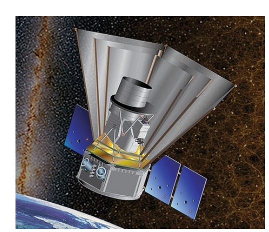
Visbal & McQuinn 2018

- Large-scale Lyman-α maps can probe reionization (**Visbal** & McQuinn 2018, Abrose, EV+ in prep)
- *SPHEREx (*Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer)
  - **Scheduled for 2025 launch!**

Lyman-α Radiative Transfer

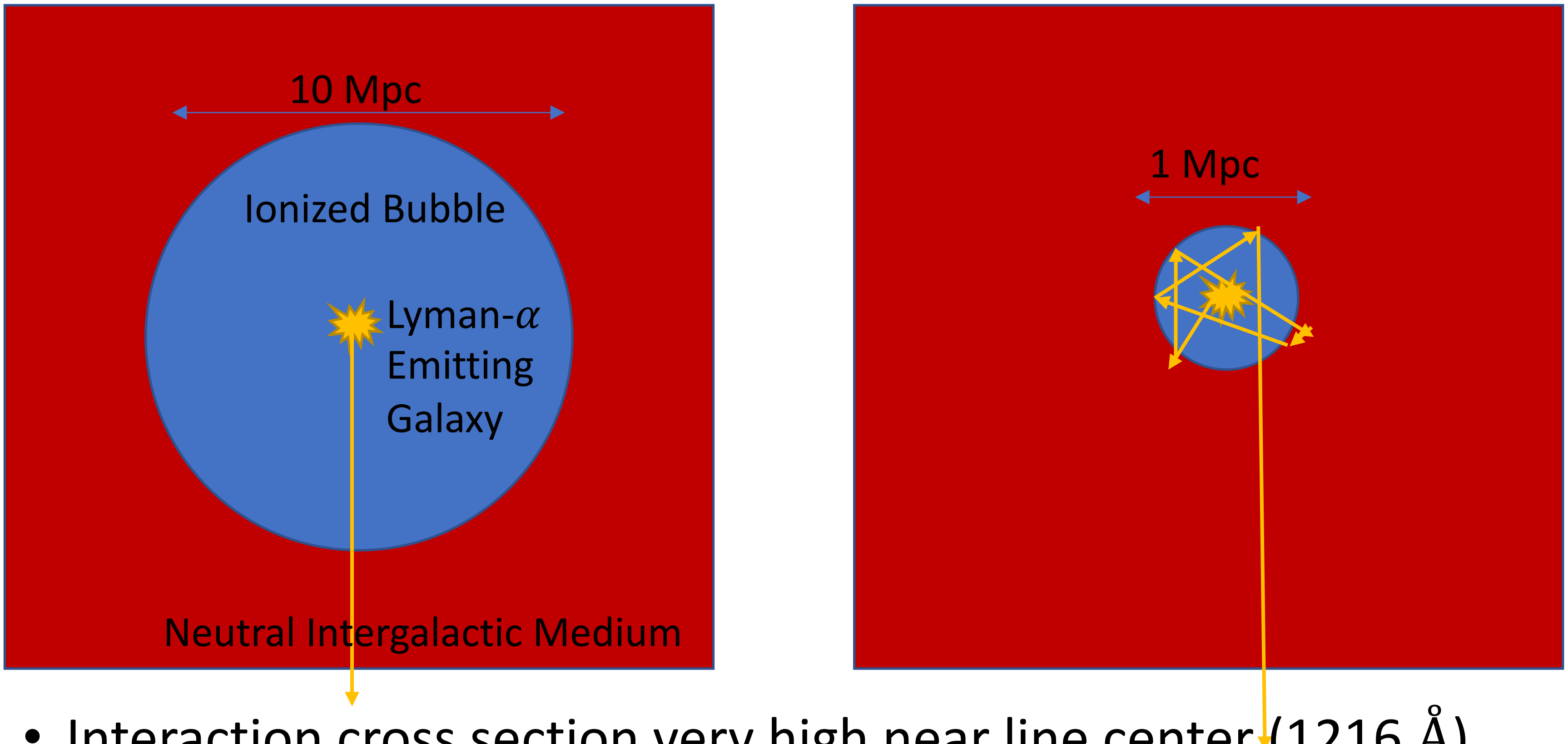
- Scattering in intergalactic gas previously ignored, but important!
- Developed Monte Carlo RT code (**Visbal** & McQuinn 2018)





SPHEREx, NASA

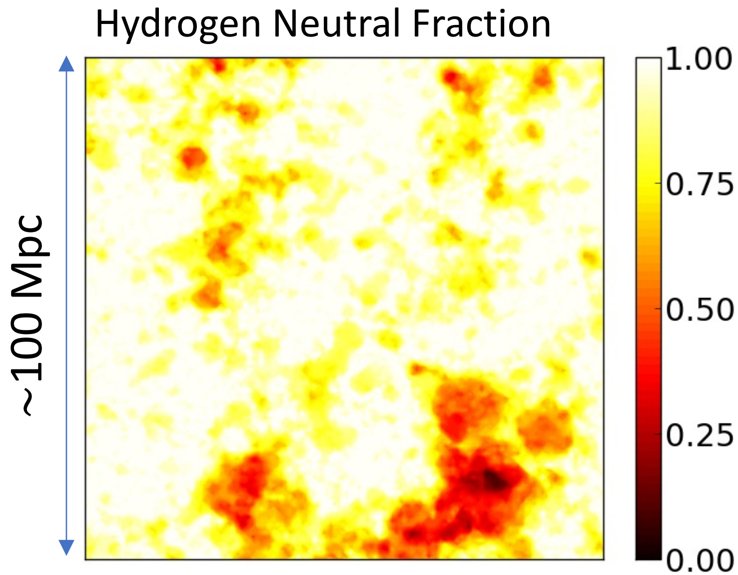
Lyman-α Radiative Transfer During Reionization

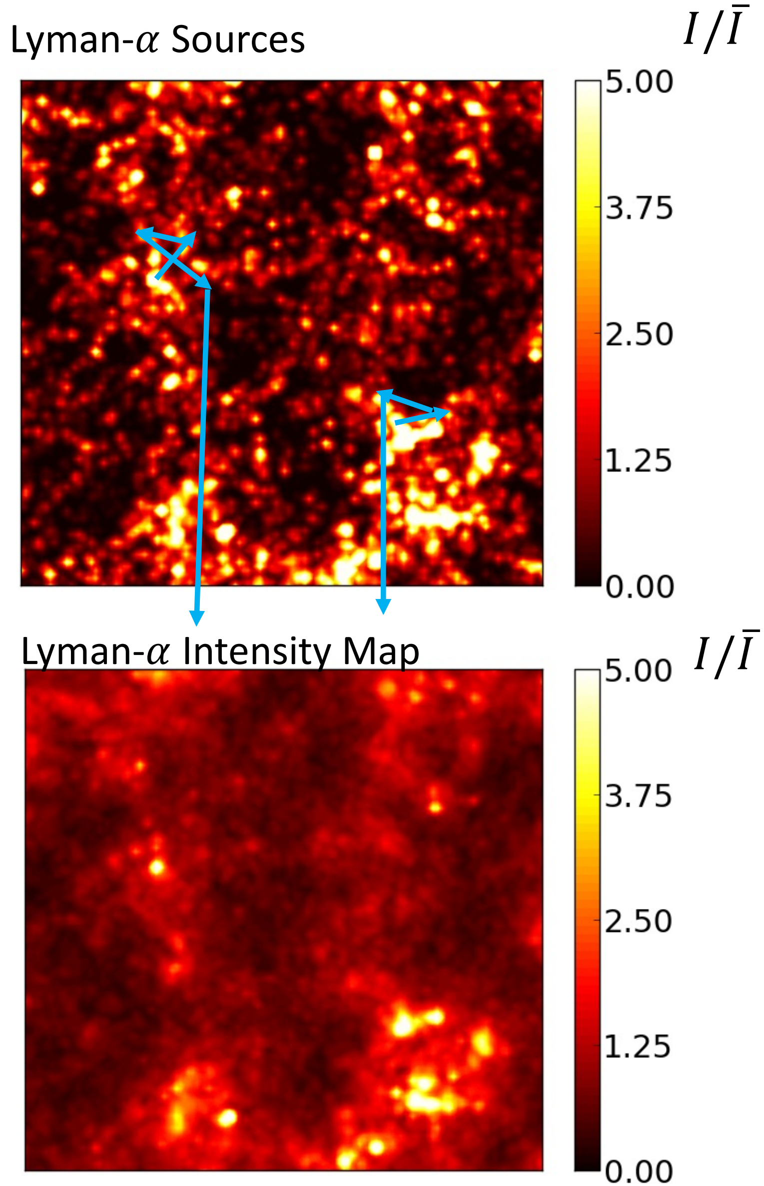


- Interaction cross section very high near line center (1216 Å)
- Expansion of the Universe → Doppler shift
- Large bubbles → high velocity at bubble edge → Lyman-α photons escape

Simulated Lyman-α Intensity Maps

Visbal & McQuinn 2018

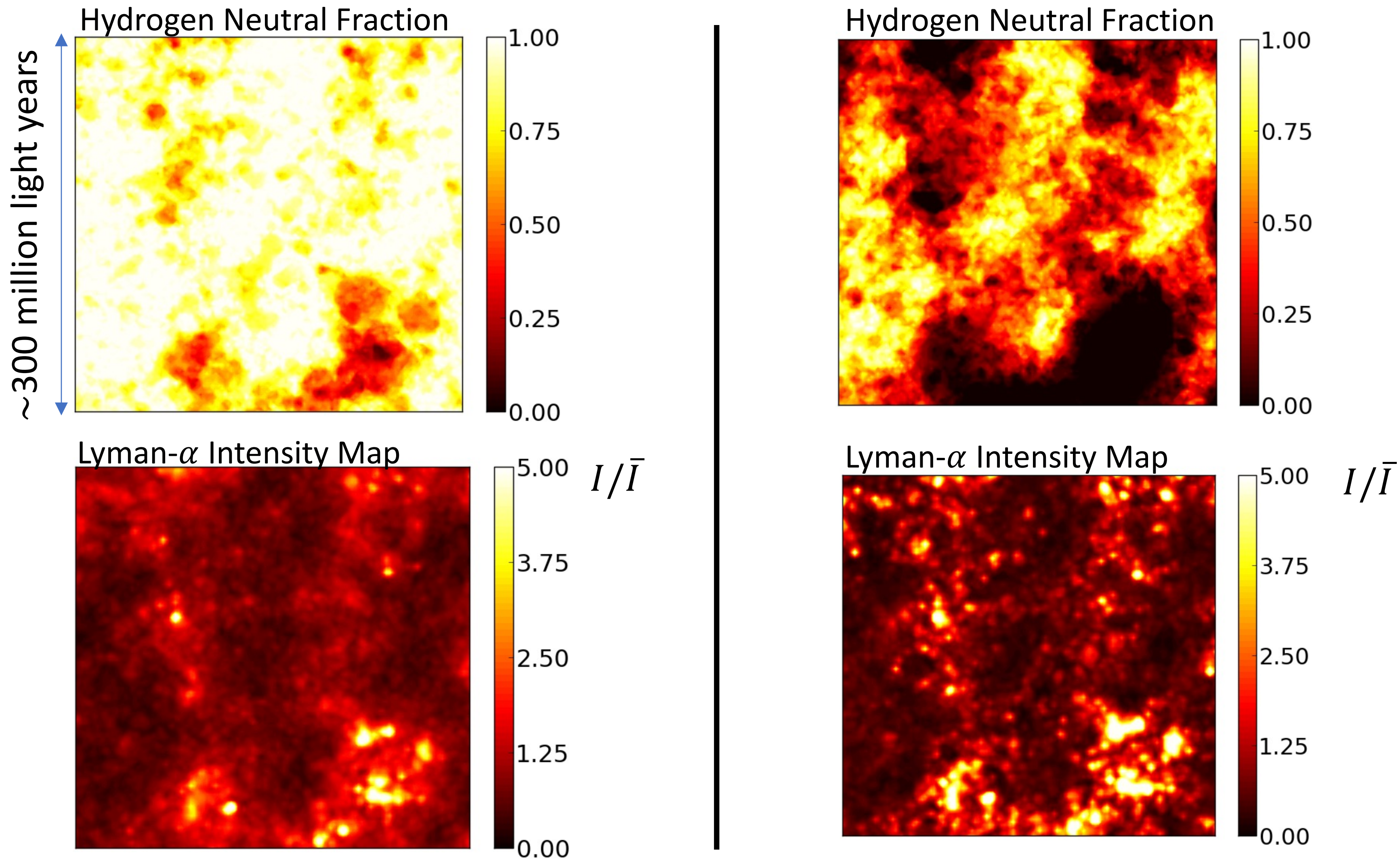




- Simulated reionization with 21cmFAST (Mesinger et al. 2011)
- Utilize Monte Carlo Lyman-α RT code
- Maps smoothed by photon scattering

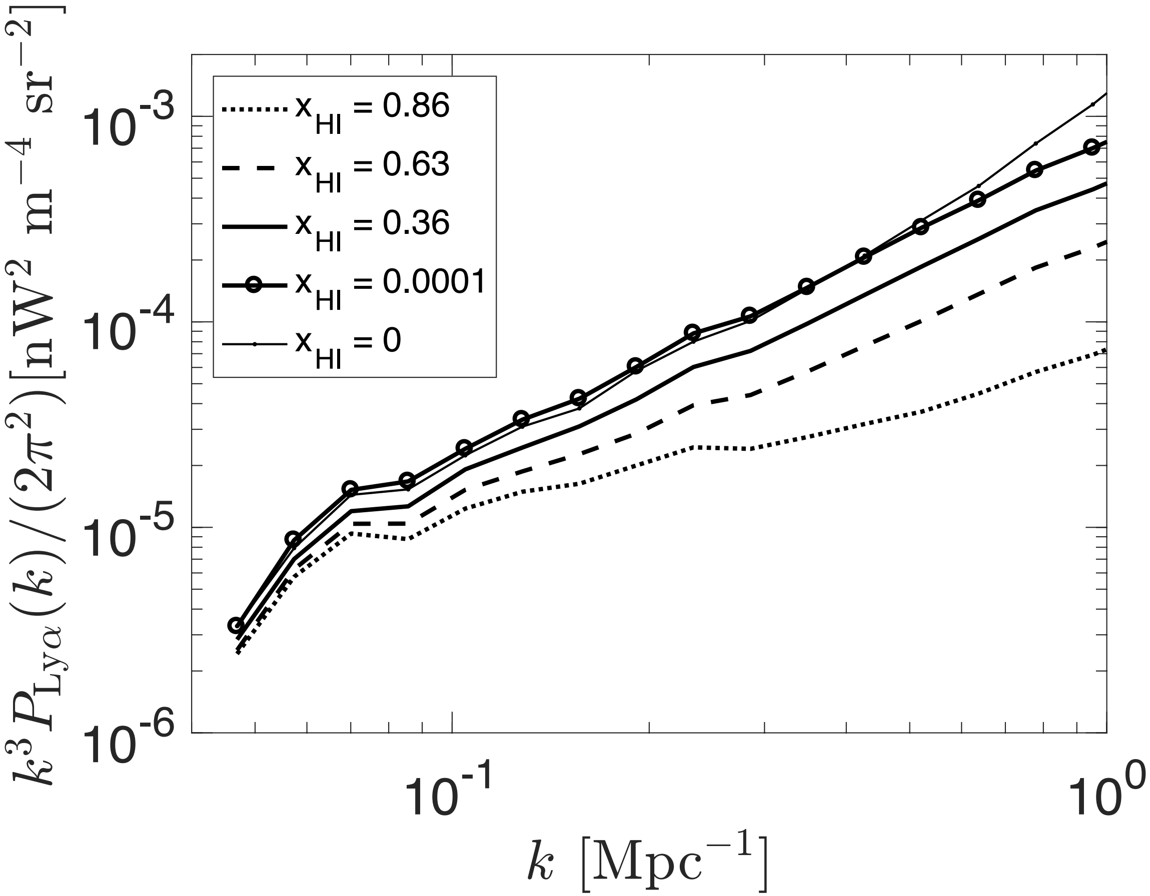
New Probe of Reionization

Visbal & McQuinn 2018



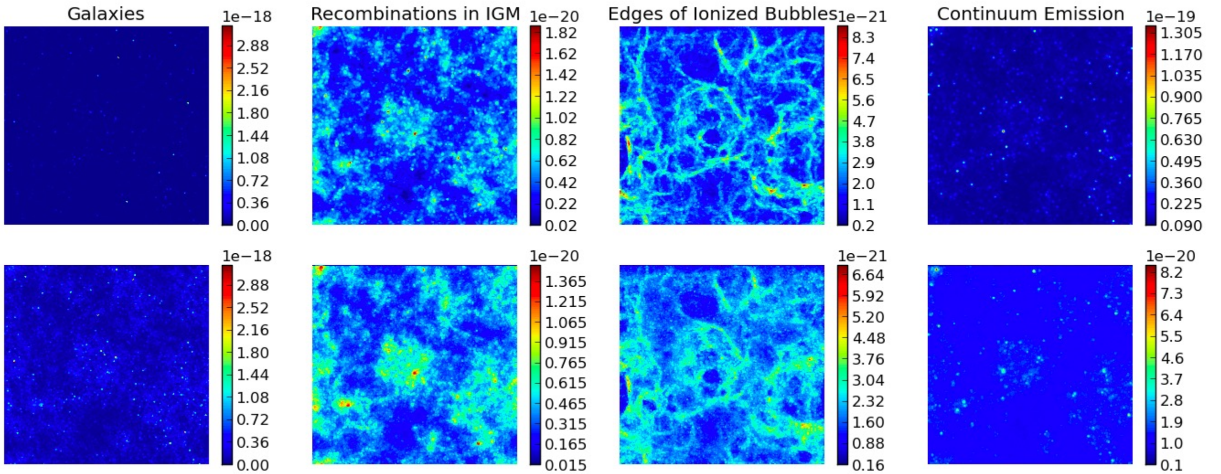
- Higher neutral fraction → additional smoothing
- **Powerful probe of reionization, detectable with *SPHEREx***

High Neutral Fraction → Suppresses Power on Small Scales



Can be used to constrain ionization history!

Additional Lya Sources



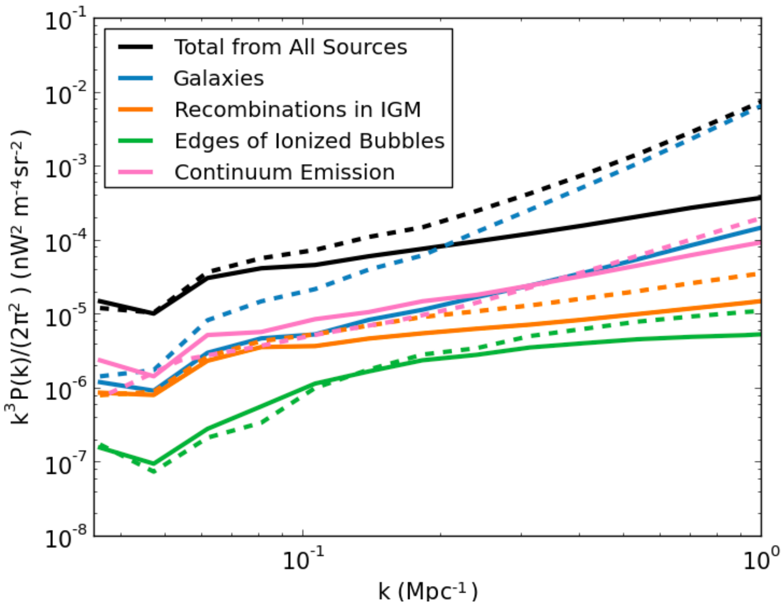
Abigail Ambrose

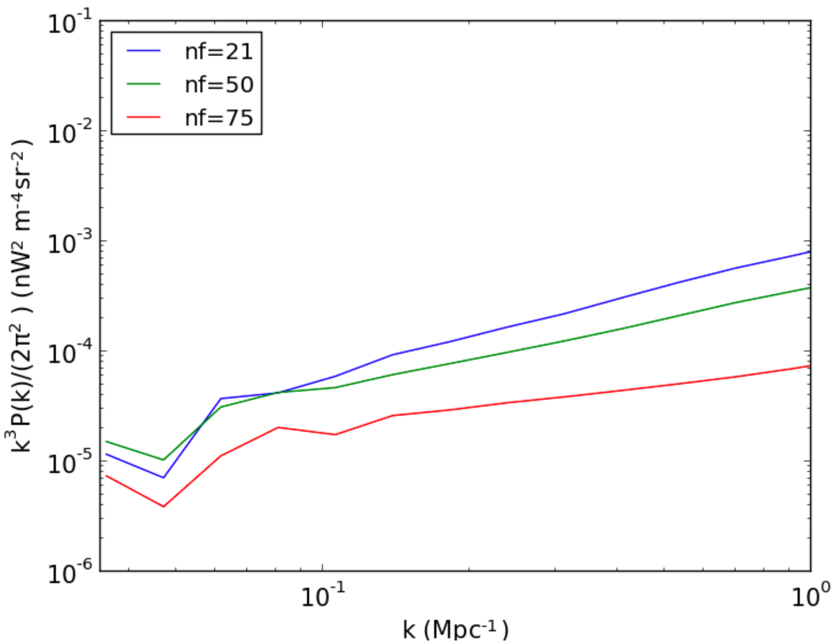
- EV & McQuinn (2018) only included Lyman-alpha from galaxies
- Completing sims with all sources (Ambrose, EV+ in prep)
  - Collisional cooling at bubble edges
  - Recombinations
  - Galaxy continuum photons absorbed in Lyman series lines and reprocessed into Lya

Additional Lya Sources

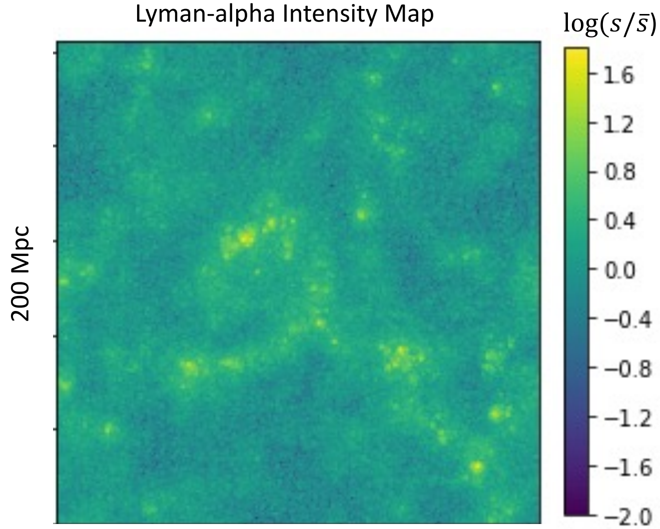
- Still find strong power dependance on neutral fraction (sensitive to reionization history)
- Continuum reprocessing provide strongest contribution (in addition to galaxies) for most realistic reionization models

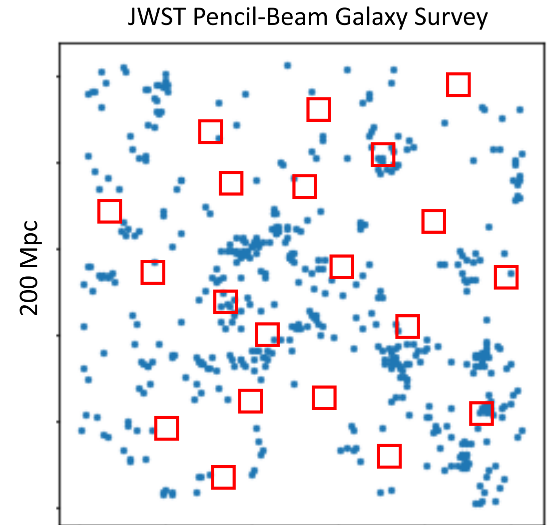
Abigail Ambrose





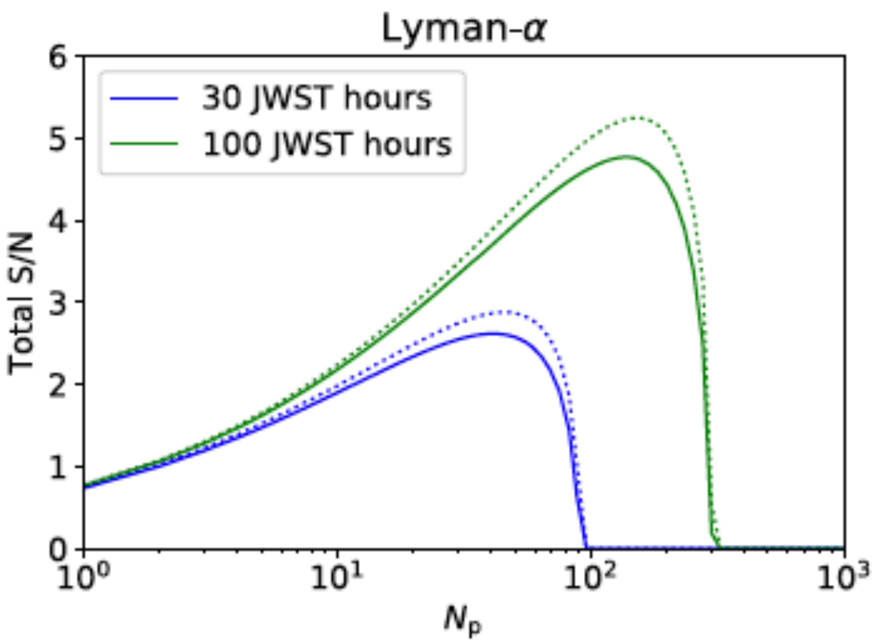
Role of James Webb Space Telescope (EV and McQuinn, 2023)

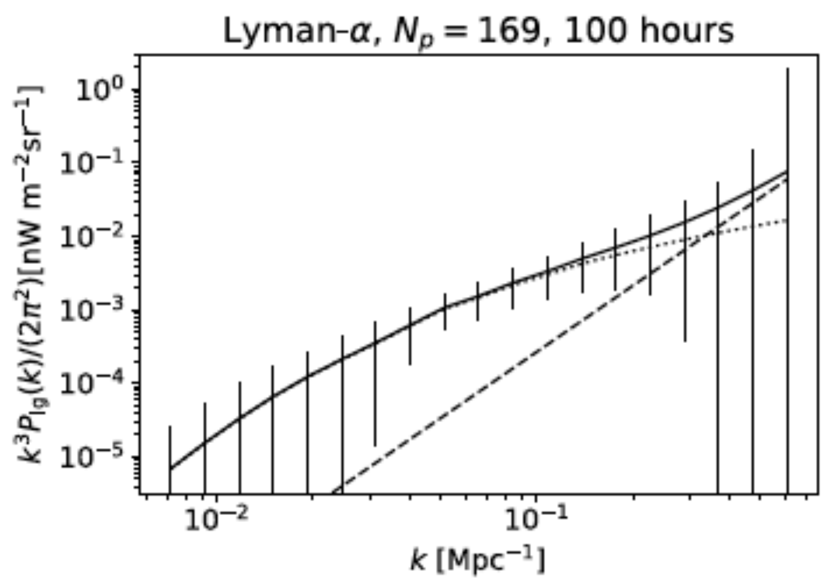




- Cross-correlating galaxies with intensity maps → promising way to remove contaminants in maps
- Our question: how well will JWST work for this?
- Small JWST field of view: 3’ versus degrees across for intensity mapping
- **Will it be possible to measure the cross power with sparse JWST pointings?**

Cross Correlation of JWST Galaxies and Lya IM with SPHEREx





Intensity Mapping Summary

- Lyman-α intensity mapping can potentially constrain the timing of reionization
  - Small bubbles → more scattering → reduced fluctuations on small scales
  - Detectable with SPHEREx
- JWST – Intensity Mapping Cross Correlation
  - Residual astrophysical foregrounds in IMs could be problematic
  - 3'x3' JWST FOV poorly matched to degree-scale IMs
  - Good signal-to-noise still achievable with pencil beams in reasonable JWST time