Mock Streams: Modeling the CircumGalactic Medium

SIP AST-02
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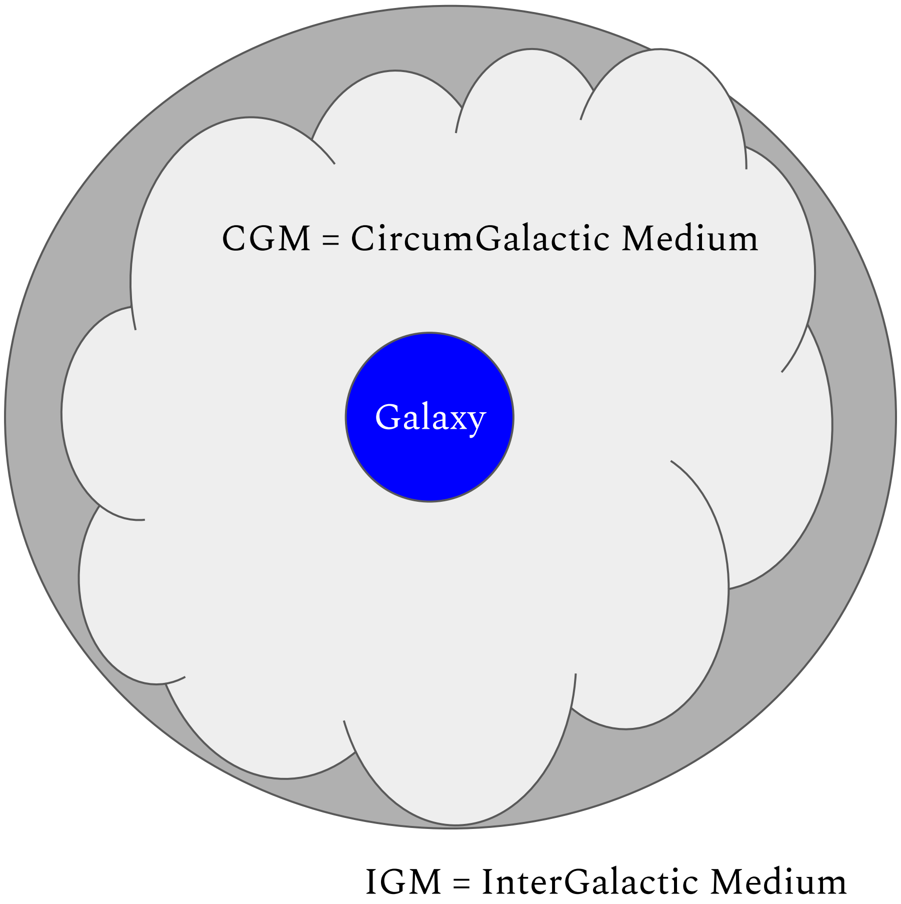
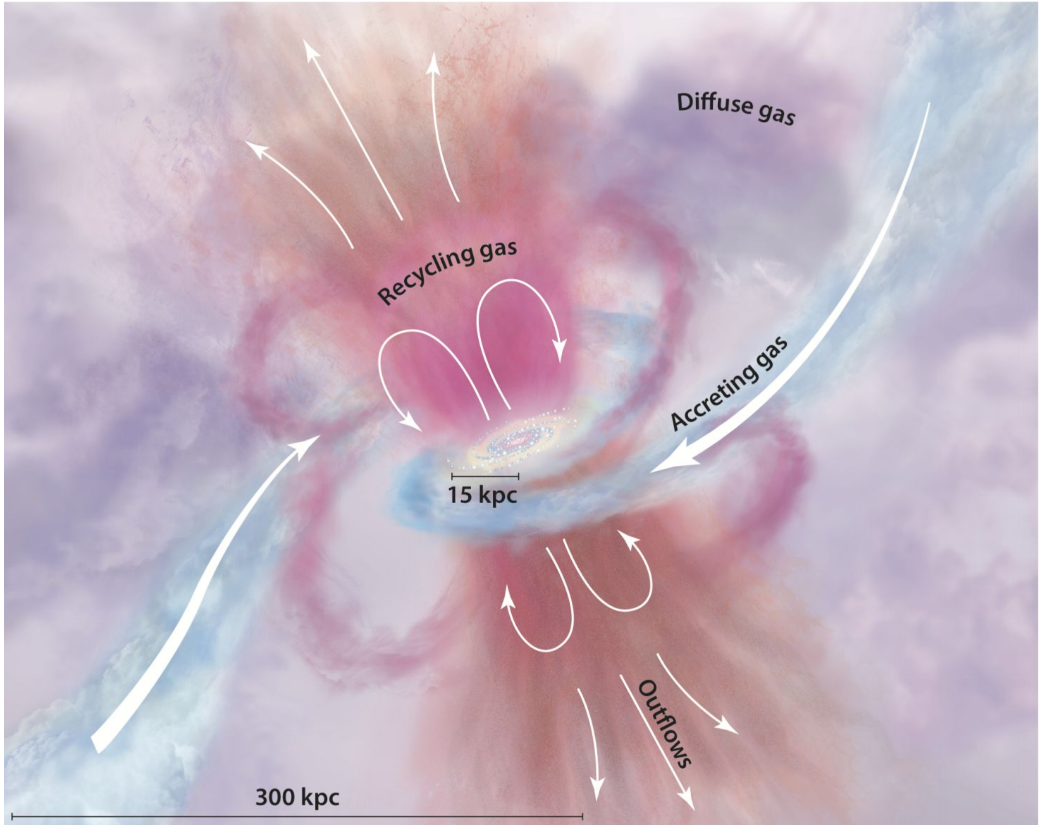
Our Area of Focus

- The Circumgalactic Medium, or CGM, is the reservoir of gas outside of galaxies
- CGMs lies within a galaxy's specific virial radius (~10x as large as galaxy itself)
- Most of the material that will flow into or out of galaxies passes through the CGM



Properties of the CGM

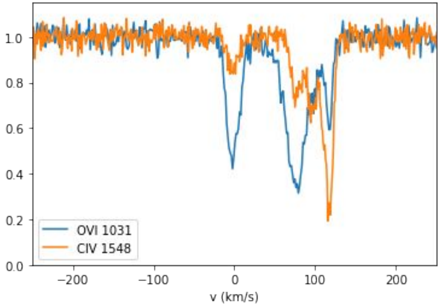
- Gas flows in from the "cosmic web" outside galaxies in the IGM
- Inflowing gas is cold and has low metallicity
- Within galaxies, supernovae heat up gas which then leaves through outflows

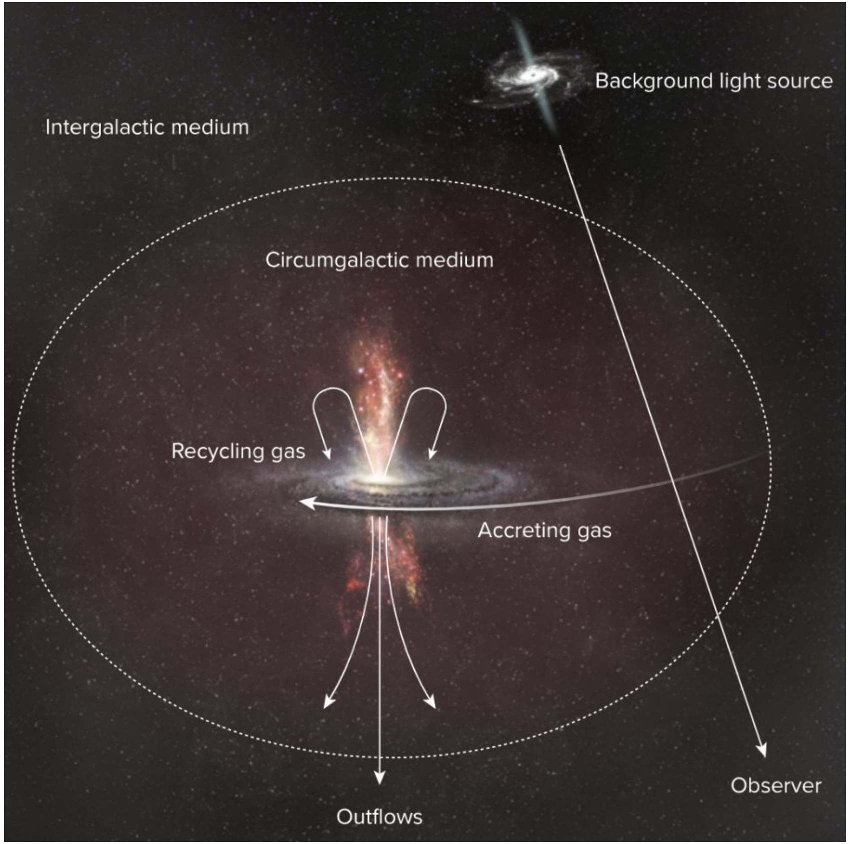


Tumlinson, Peeples, and Werk 2017

Observing the CGM

- The CGM is filled with low density gas which is hard to study
- Rather than using emission, we use absorption spectra
- As light passes through specific gasses in the CGM, specific colors are subtracted from the spectra →

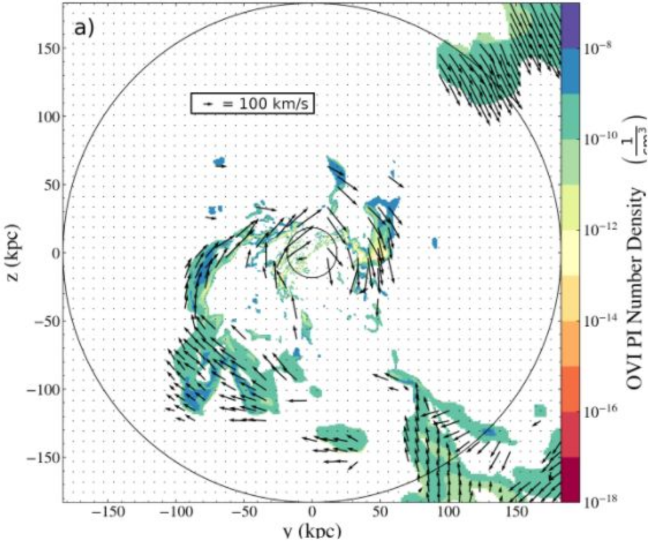




https://astrobites.org/2021/05/06/cool-metal-gas-search-thanks-it-was-automated/

Importance of Current Simulations: Strawn et al. 2021

Strawn et al. 2021

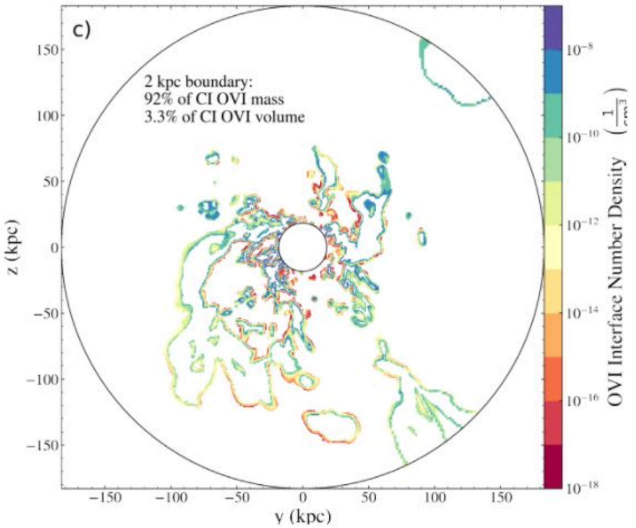


Codified distinction between photoionized and collisionally ionized O VI

Strawn et al. 2021 analyzed the CGM of the VELA simulations, focusing on the ion O VI

Results showed us that it would be useful to build an analytic model of the phenomena seen in VELA

Strawn et al. 2021



Identified interface layers which preserve the cool streams and allow them to have a significant cool O VI component

Our Project's Goal

Simulation: current method

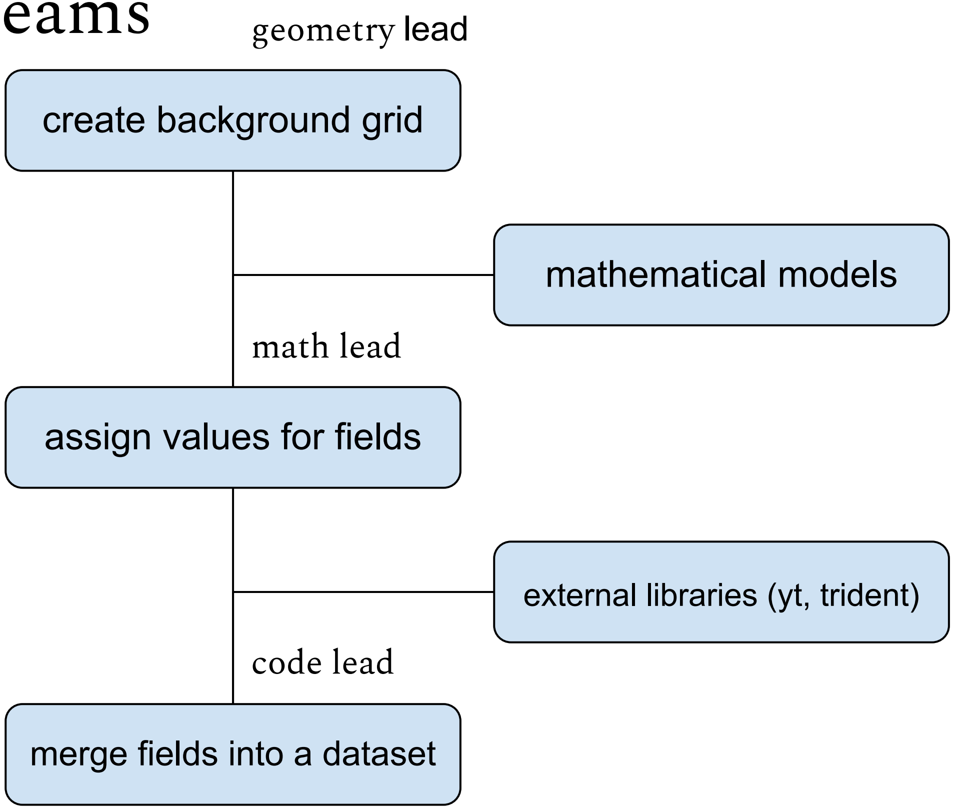
- Starts with physics rules and initial conditions, lets the galaxies evolve on their own towards an (unknown) final state
- Check at end if galaxy looks similar to the observations
- Very expensive with long computational time
- Existing CGM simulations are in disagreement

Our method:

- Instantiates a model, looks like a simulation but isn't
- Create a final end state, no simulation evolution necessary
- Make sure physical parameters are within "reasonable" bounds, and the end state in question seems physically plausible
- Create instantaneously, no need for much computational time

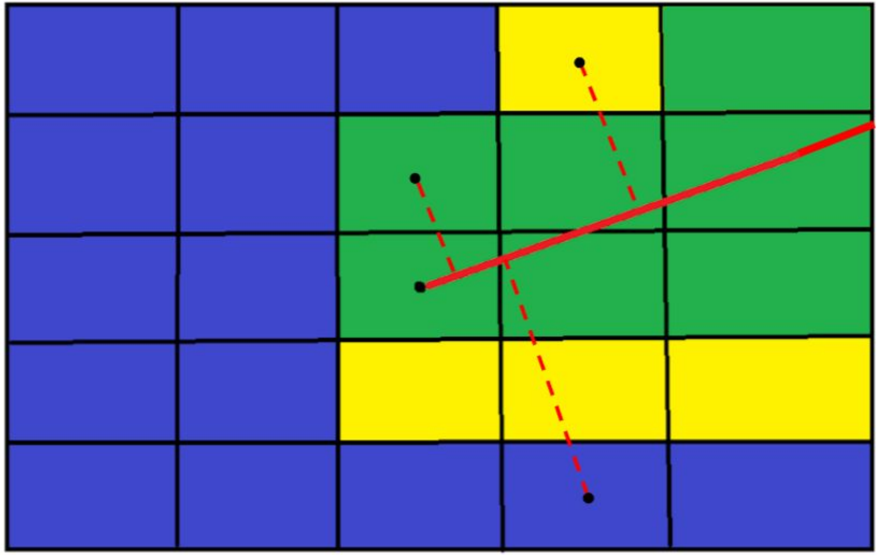
Coding the Model: mock_streams

- Code can be divided up into 3 stages
- Each of us chose a role and worked on its respective code
- mock_streams: python github repository



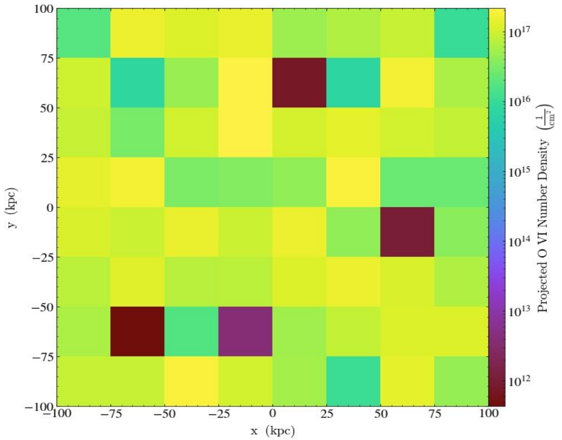
Geometry Lead

- Fill in the background grid with a field with three possible elements: bulk, stream, and interface
- Streams contain cold, inflowing gasses
- The bulk is the largest component by volume and contains warmer, recycled gas
- The interface is a thin layer surrounding the stream that acts as a buffer for incoming gasses.

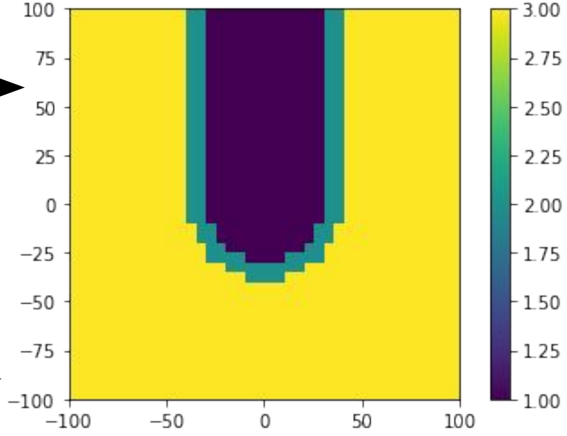


- Designate each of the cells in a grid as part of the stream, interface, or bulk, based on its distance from a given line

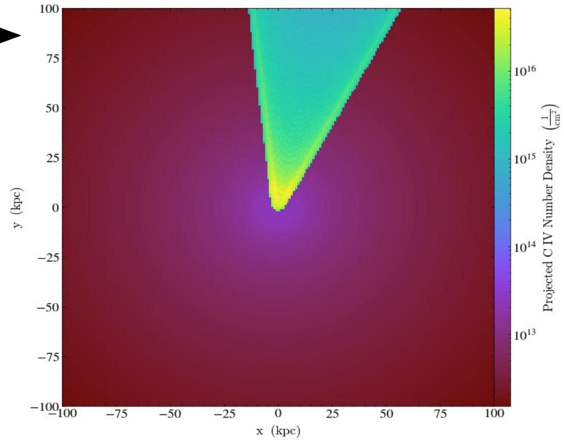
Progression of the Mock's Geometric Complexity



Working with randomized noise

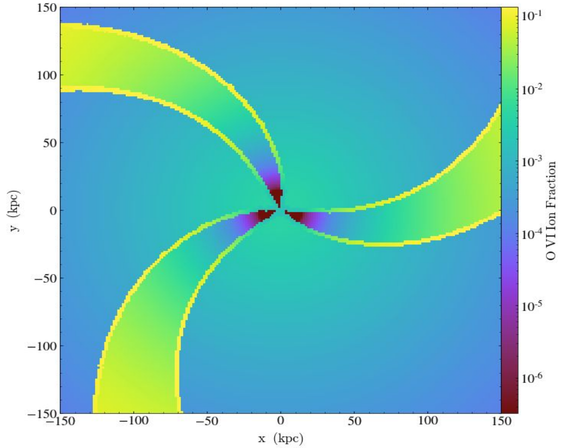


Progressed to a cylindrical stream



Developed a formula to widen the stream as it goes away from the center

Highly complex model with stream rotation, multiple streams, and other variables to make a realistic simulation (final product)



Math Lead

- Assign values for fields according to the passed on phase types
  - e.g. density, temperature, metallicity
- Fields follow models with dependence on physical arguments, phase types, position in the CGM, and other parameters

$$\rho(r) = \rho_0 \times \left(\frac{r}{Rvir}\right)^{-\beta}$$

The density field follows a power law model with different beta values and initial densities.

r = radius from center

Rvir = virial radius

β = growth slope

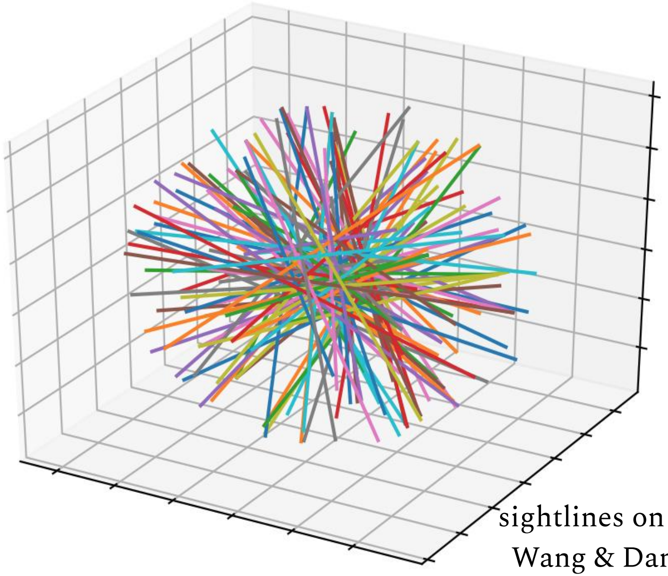
Code Lead

- Create the framework to convert raw data into a yt dataset object
    - Convert multiple fields into a singular dataset
- Each dataset has the ability to be
    - plotted
    - analyzed further with other libraries (trident, quasarscan)
- mock_streams on github

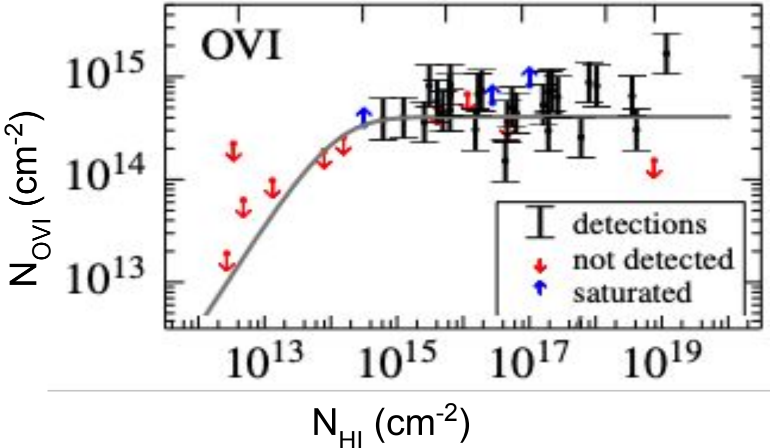
yt is an open-source, permissively-licensed python package for analyzing and visualizing volumetric data.

Analysis Software: Quasarscan

- Quasarscan reads in the yt dataset object created with our code
- Creates randomized absorption sightlines that run throughout the mock
- Sightlines track all the properties of the mock
  - density, metallicity, ion fractions...



sightlines on a 3d grid
Wang & Dange 2018

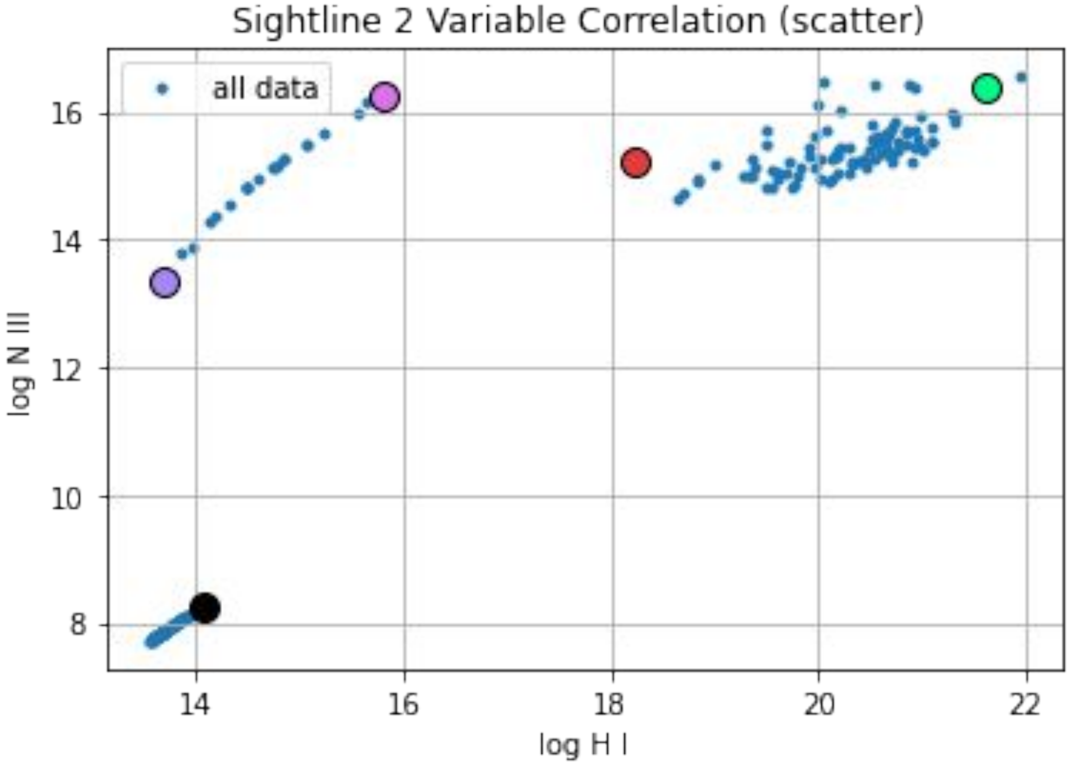


Stern et al. 2016

Results of our Mocks

Sightlines and Off-Axis Slices

- Scatter plot of NIII vs HI
- Contains three distinct clusters which we hypothesized to be the bulk, stream, and interface
- 200 sightlines generated
- 5 sightlines chosen from this graph to analyze further



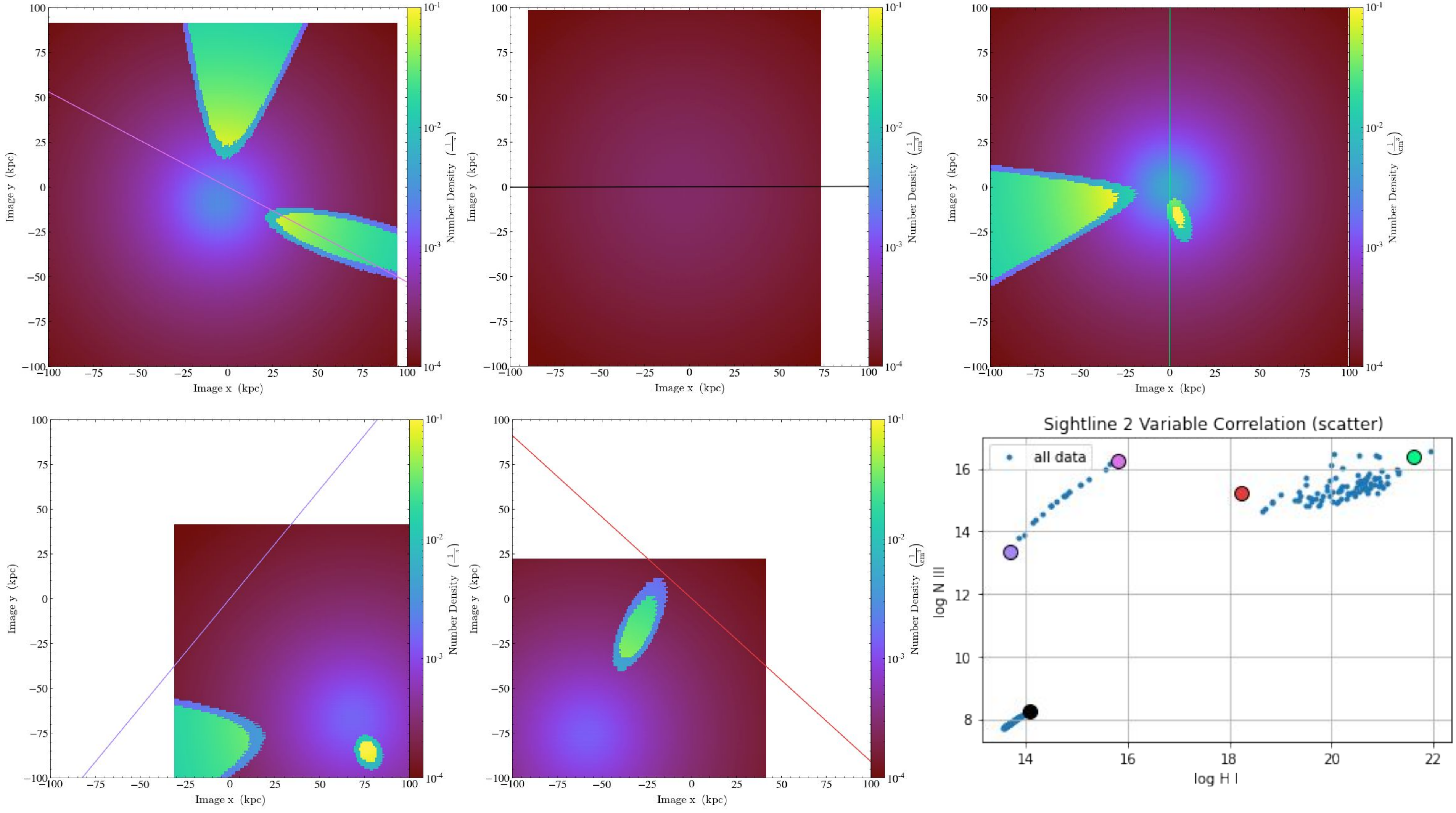


Image x (kpc)
Image y (kpc)
Number Density $\left(\frac{1}{\mathrm{cm}^3}\right)$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Sightline 2 Variable Correlation (scatter)
all data
log H I
log N III

Usage and Application: Variables in our M20 Model

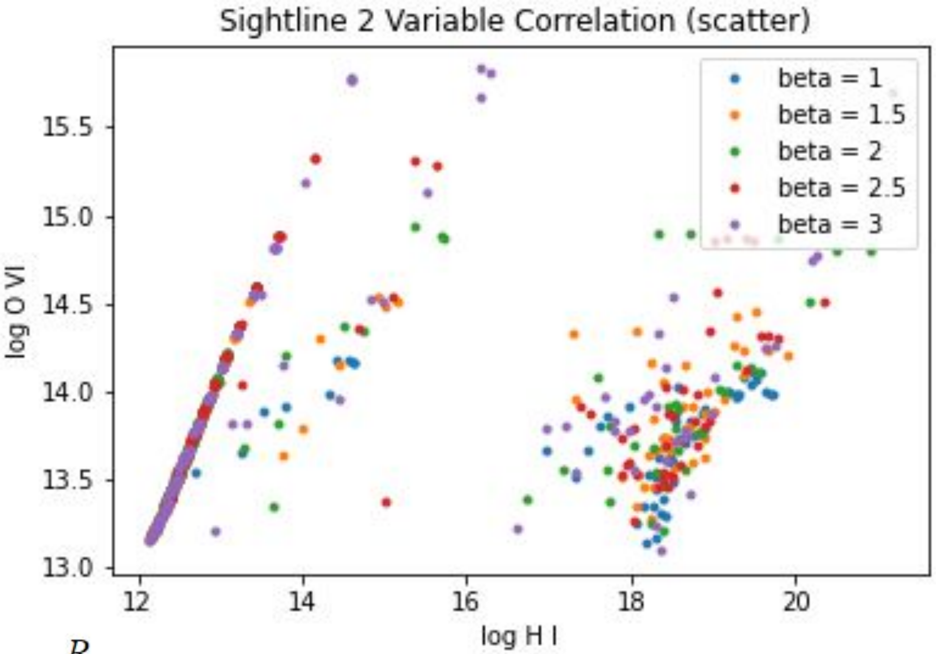
Model from a recent paper by collaborator Nir Mandelker

6 key variables: β (beta), η (eta), s, Θ_{h}, Θ_{s}, f_h

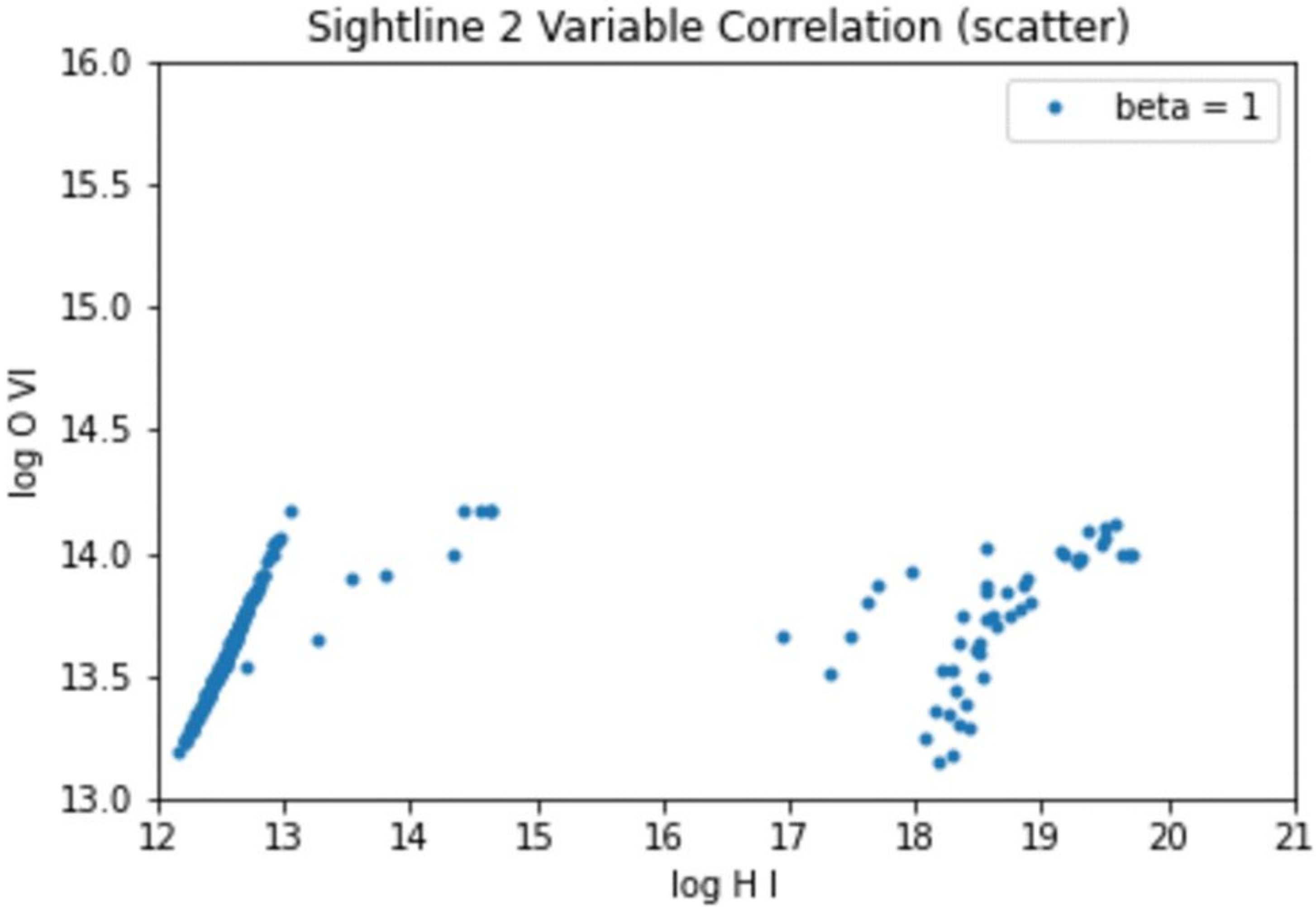
$$\delta = \rho_s/\rho_b \qquad \mu = \frac{\Lambda}{\Lambda_{max}}$$

$$M_b = \frac{v}{c_b} \qquad \beta = \frac{P_{therm}}{P_{mag}}$$

$$\frac{R_s}{R_v} \sim \frac{t_{sc}}{t_v} \qquad \tau_2 = \frac{t_{max}}{t_{shear}} \quad \tau = \frac{t_{shear}}{t_{cool,mix}} = \frac{R_s}{R_{s,crit}}$$

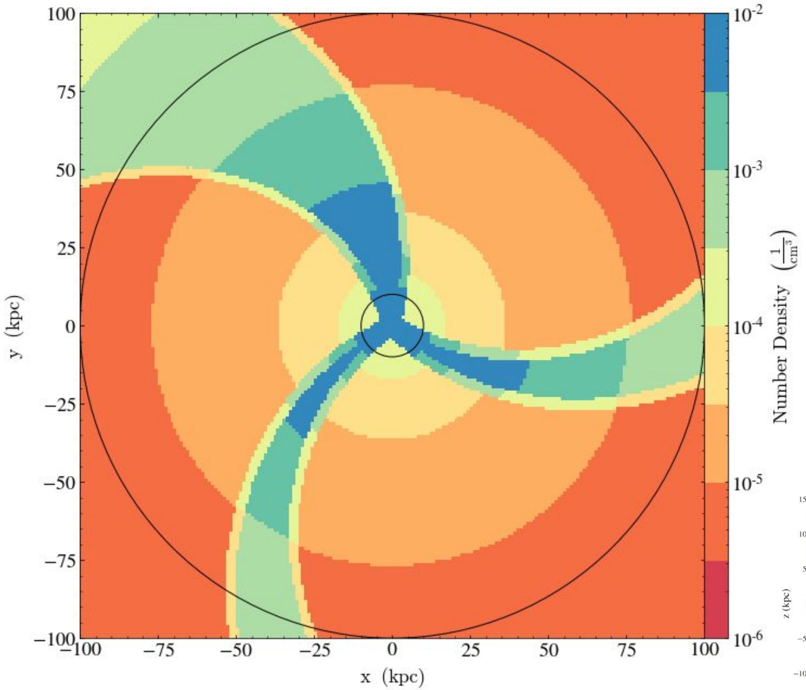


Superimposed sightlines for β (1 - 3)

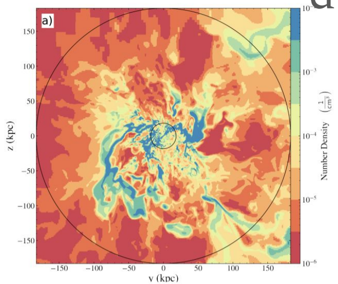


Sightline 2 Variable Correlation (scatter)
beta = 1
log O VI
16.0
15.5
15.0
14.5
14.0
13.5
13.0
12
13
14
15
16
17
18
19
20
21
log H I

Example fields for the Vela Model



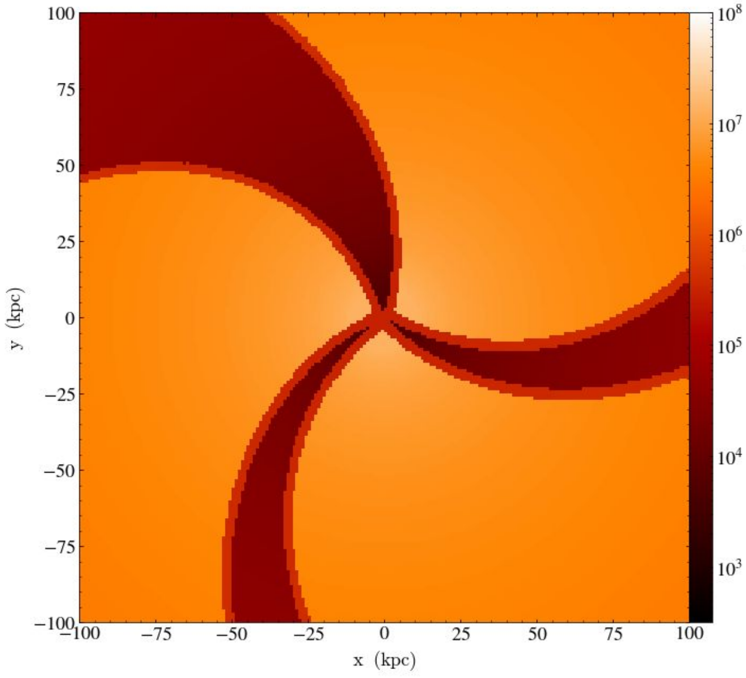
Number density field through mock streams



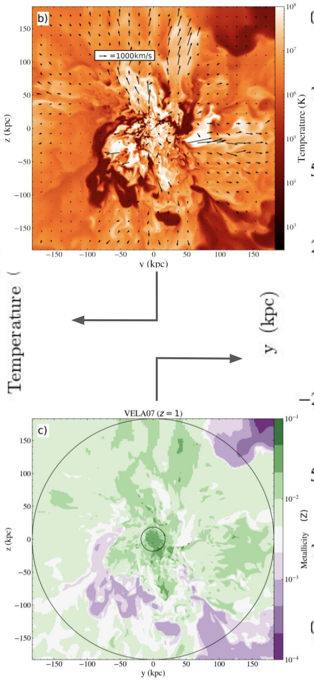
Number density field through simulation
(Strawn et al. 2021)

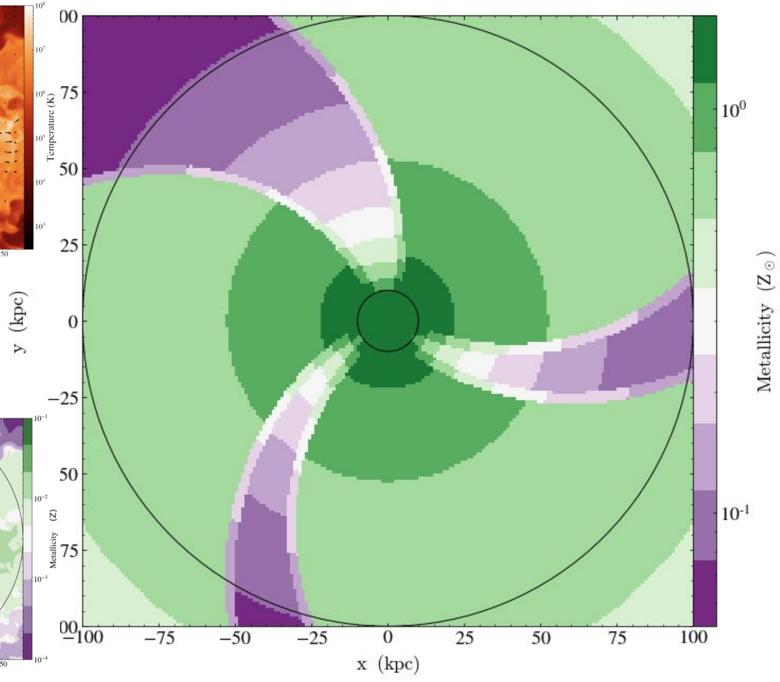
- 2D slice plots of the number density, temperature, and metallicity fields
- Used default values from the VELA07 simulation
- All phases have different radial dependence
  - Separate beta parameters

Example fields for Vela Model (cont.)



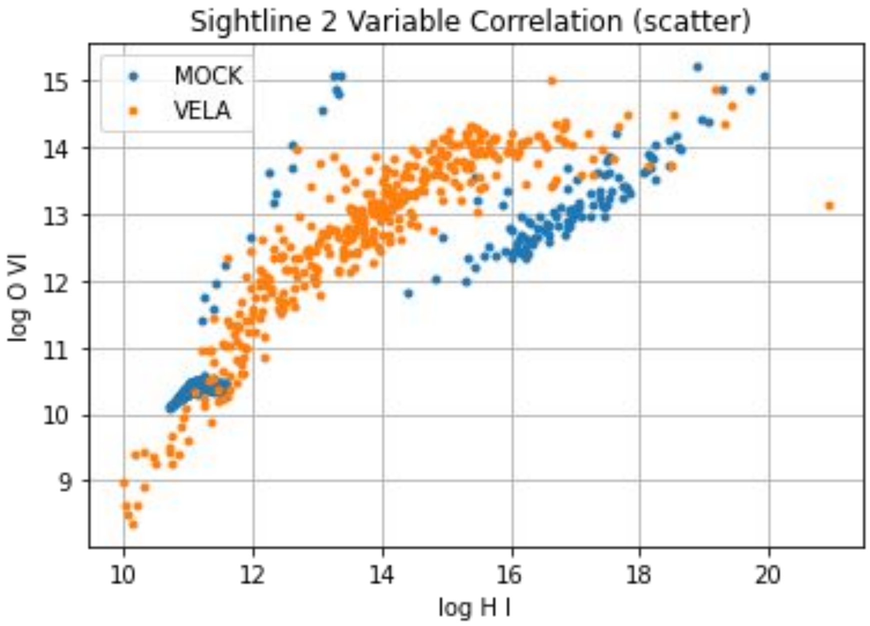
Temperature field through mock streams





Metallicity field through mock streams

Sightlines for the Vela Model



Superimposed sightlines for mock model (MOCK) and simulation (VELA)

Conclusion

Results

- Accurate mock following results of previous simulations
- First mock software that is yt compatible

Future work

- Further experimentation with various functions and models
- Include more structures
- Documentation for public use

Acknowledgements

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DEEP-Theory Group

SIP Team

Our parents and peers

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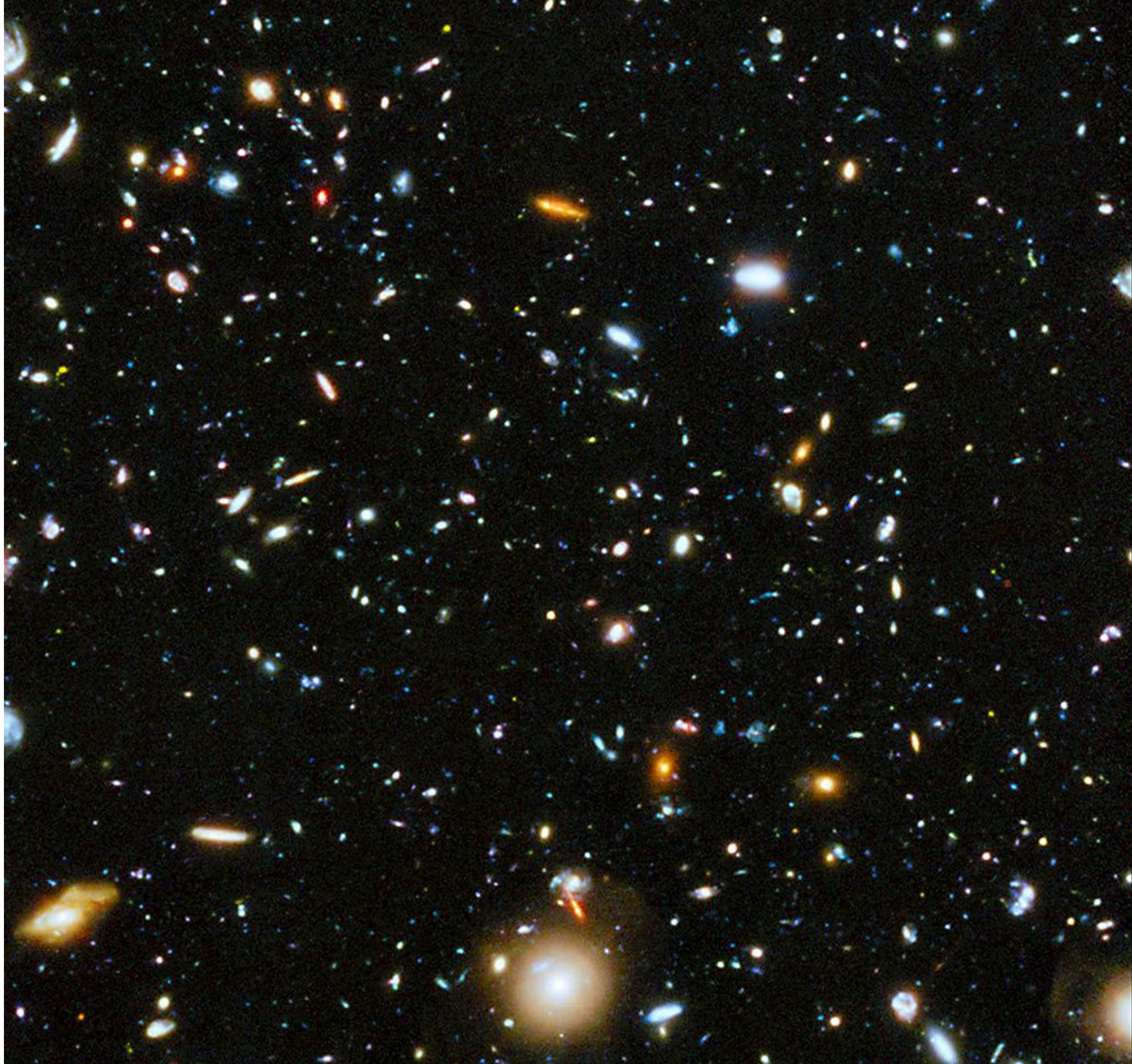
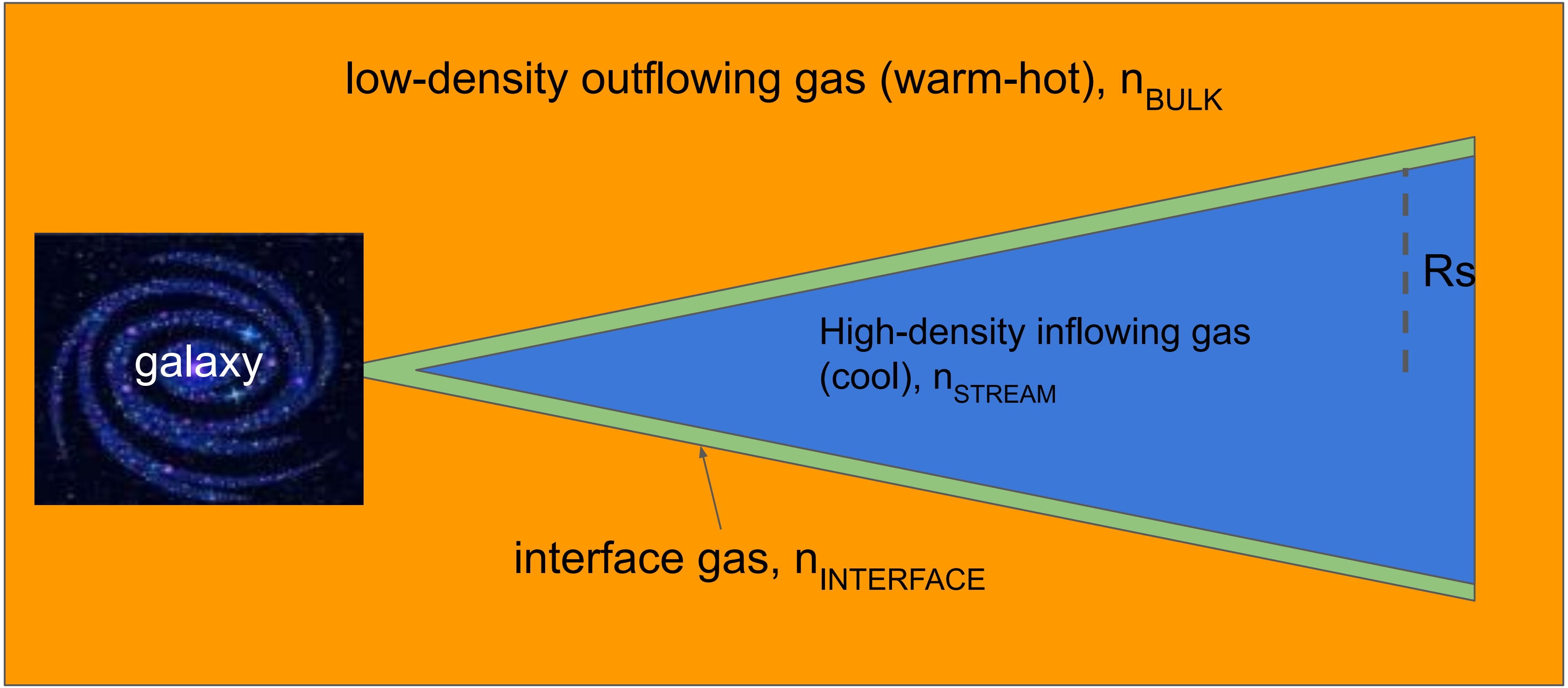


Our Model



low-density outflowing gas (warm-hot), n_BULK
Rs
galaxy
High-density inflowing gas
(cool), n_STREAM
interface gas, n_INTERFACE

Superimposed and Separated Sightlines for Θ_h

Θ_h is how hot the bulk is compared to a constant virial temperature (10^6 K)