Blaizot et al. 2023, soon on arXiv !

Simulating the many shapes of the Lya line

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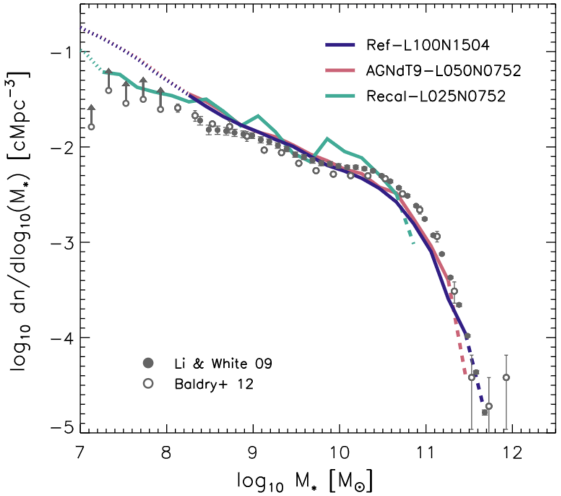
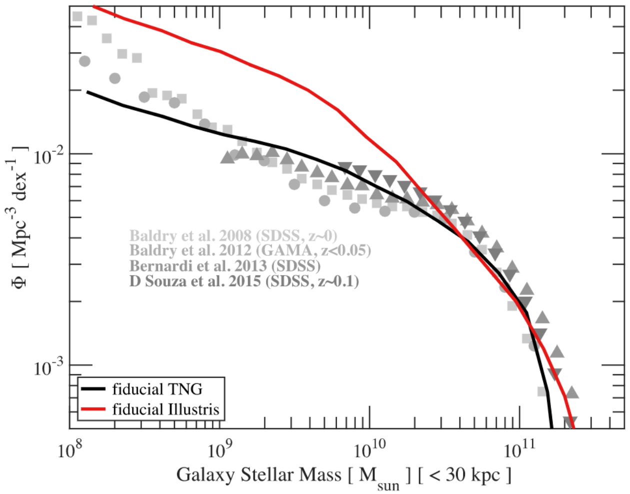
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

Galaxy formation and feedback from massive stars

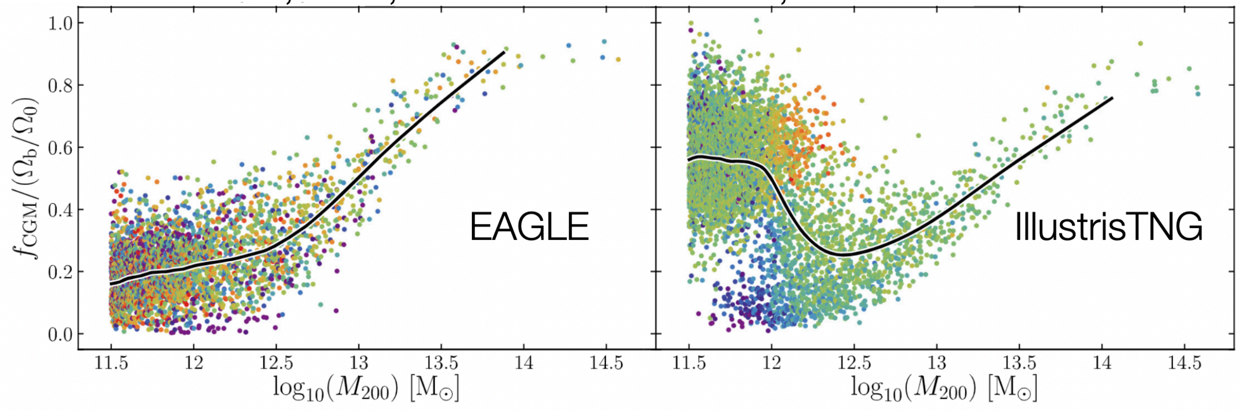
EAGLE (Schaye et al., 2015)



IllustrisTNG (Pillepich et al., 2018)



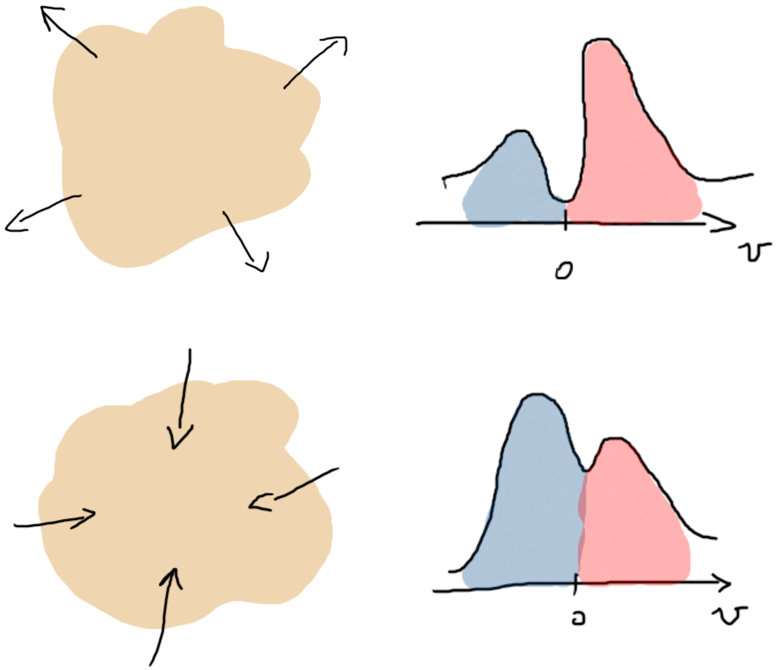
Davies et al., 2020, see also Mitchell et al., 2020.



Models for galaxy formation can now reproduce very accurately the stellar mass function of galaxies, thanks to **very strong feedback from massive stars (and AGNs)**.

How feedback works is however unknown, and **the CGM may be an important constraint** to lift modelling degeneracies.

The puzzle of the Lyman-alpha line shape …



Red means outflow
Blue means inflow

Scattering on HI atoms in the ISM, CGM and IGM determine the **shape of the Lya line**.

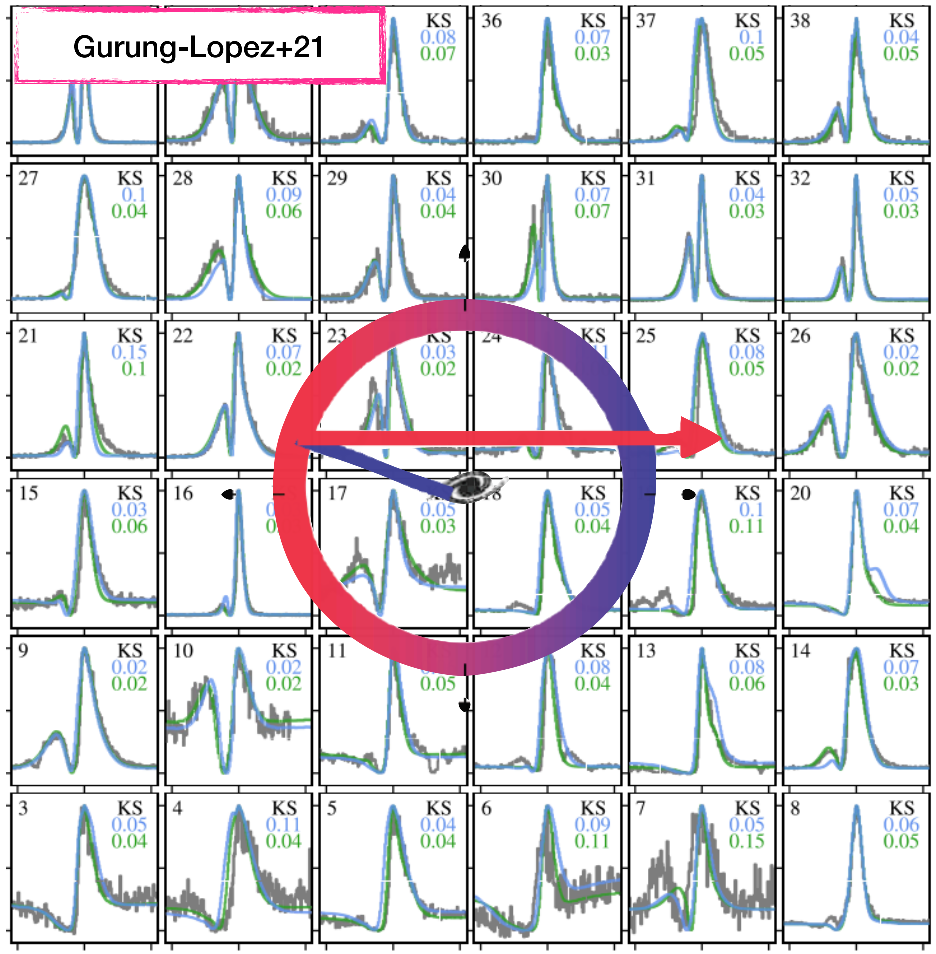
Can the Lya line shape inform us on what's going on in the ISM/CGM ?

Theoretical frameworks for the interpretation of the Lya line shape

Our **quantitative interpretations** of the Lya line shapes **rely on idealised models** (shell model, clumps, mist, fog, …) which are ***very successful***.

(See Li's talk this morning.)

It is not clear how these models relate to real complex, multiphase, flows of gas …
We need high-resolution simulations to go further.



In this talk :

- Update from simulations: Lya spectra that reproduce observations.
- What processes are responsible for the Lya line shape (scattering vs. absorption) ?
- Where do these processes occur and which gas do they trace (ISM, CGM, IGM) ?
- What can we learn from the shape of the Lya line in terms of gas flows ?

The simulation and mock Lya spectra

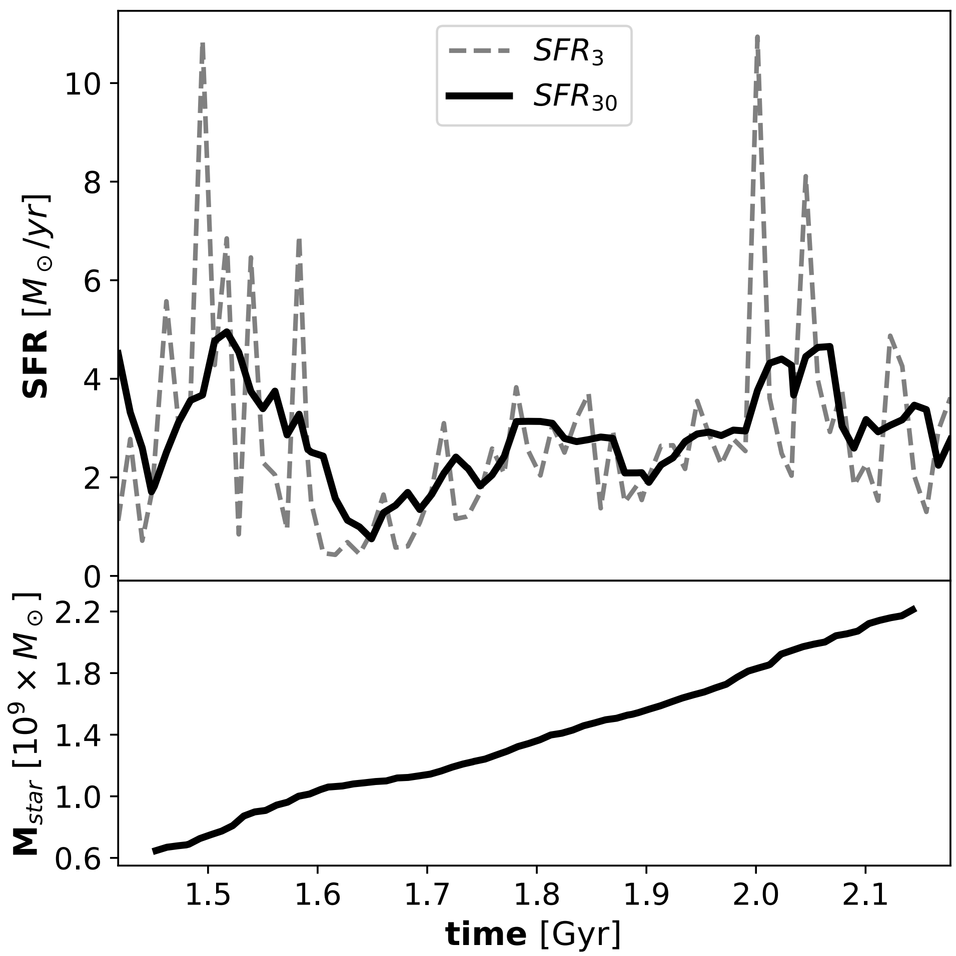
RHD simulation of a Lyman-alpha emitter (LAE)

RAMSES-RT cosmological zoom-in RHD simulation (same as in Mauerhofer+21)

M_{halo} = 5.5 10^{10} M_{sun} at z = 3, DM particles ~10^4 M_{sun}, star particles ~10^3 M_{sun}, **spatial resolution ~15pc**.

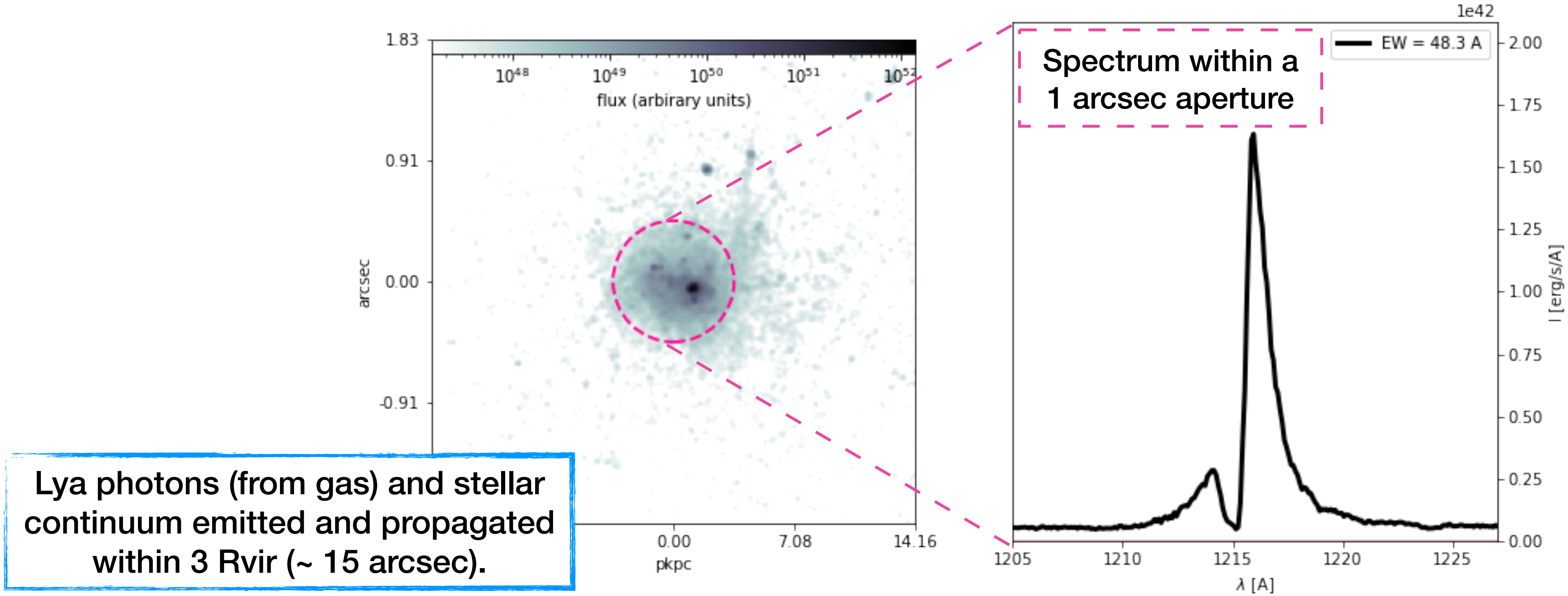
Physical models are **similar to SPHINX simulations** (*Rosdahl+18, Garel+21*).

The simulated galaxy is a typical LAE seen in MUSE deep fields.

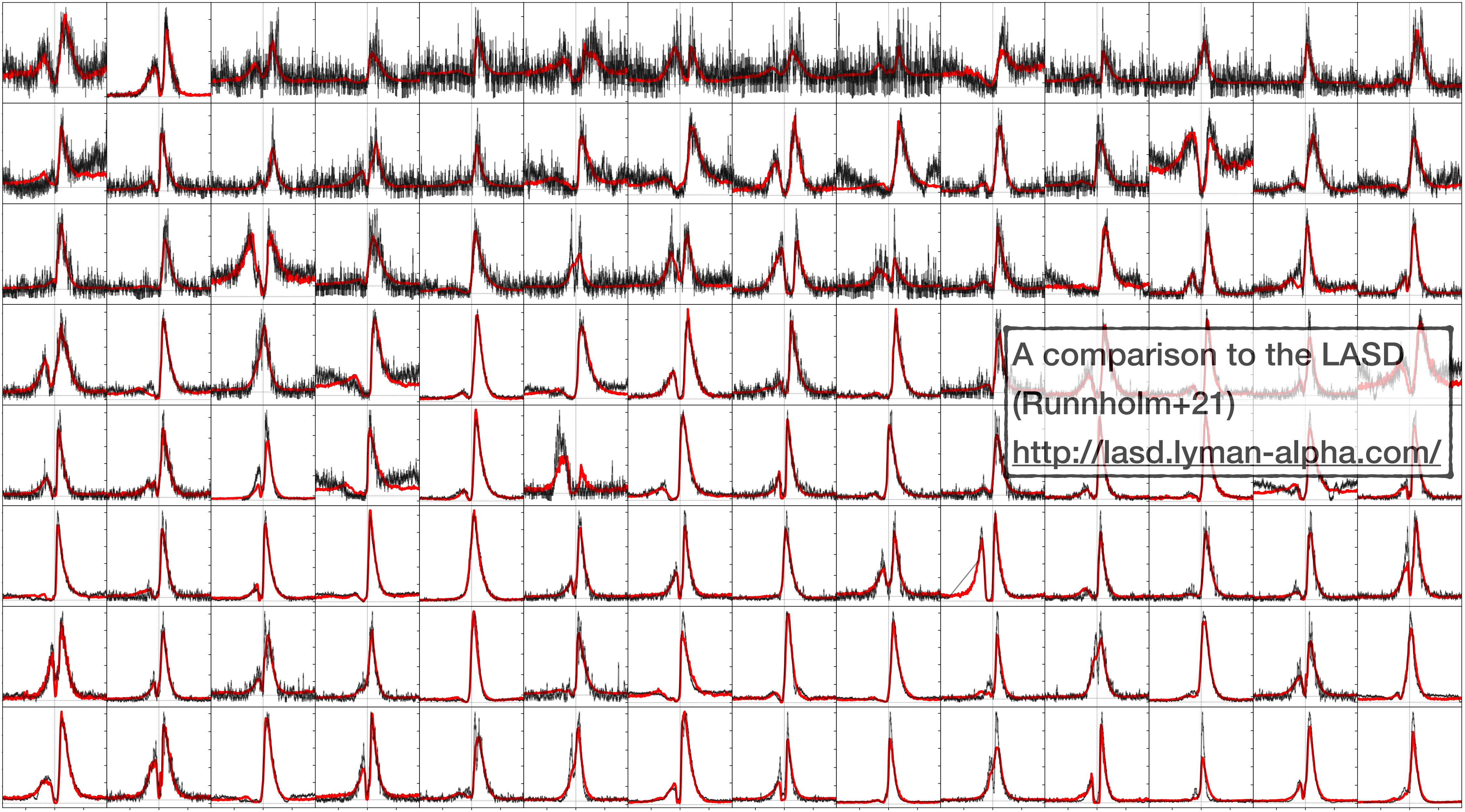


Mock observations of the Lya line

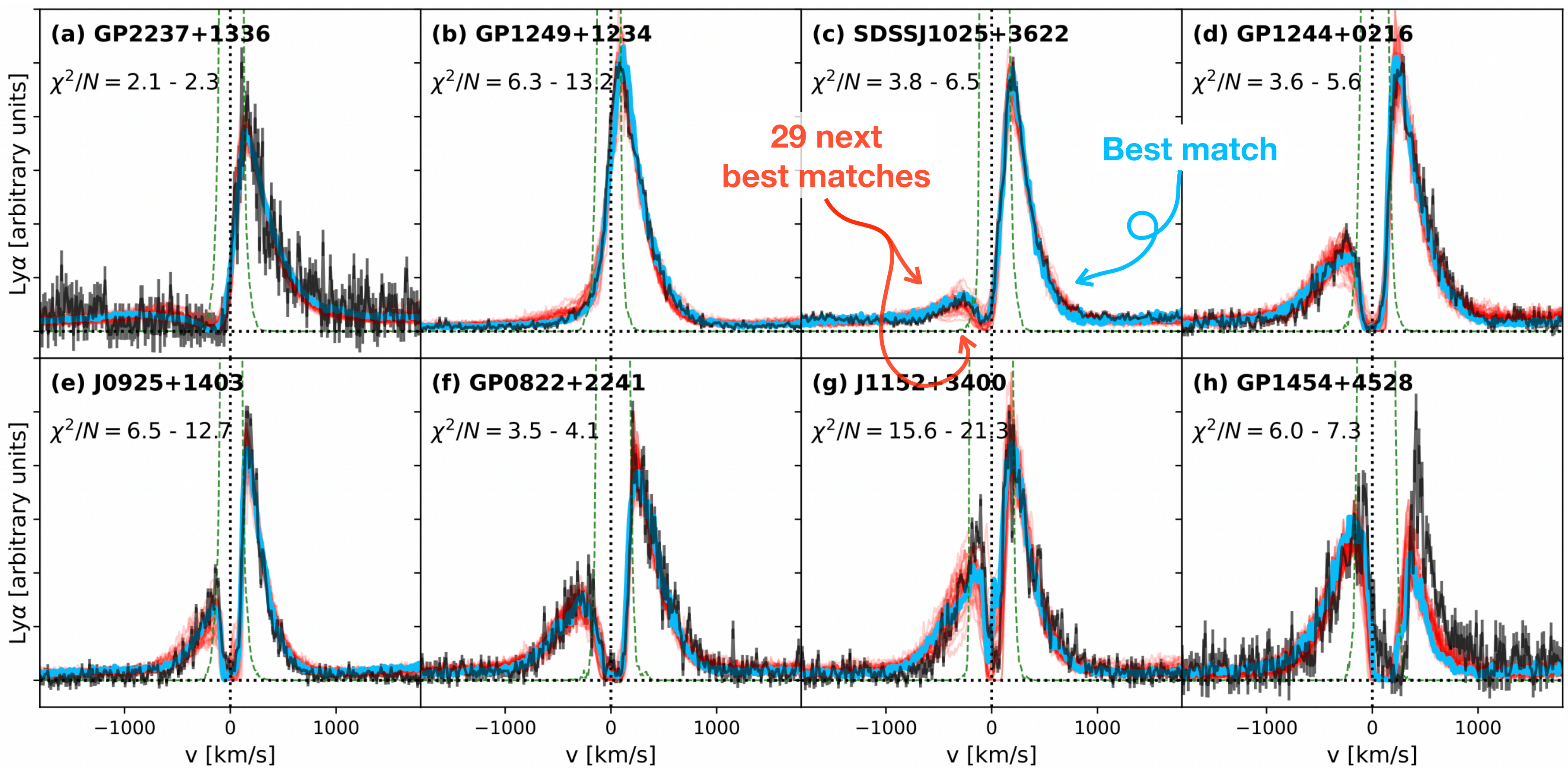
Mock observations in 300 directions of 75 outputs between z = 4 and z = 3.
22,500 mock spectra.



Lya RT includes Laursen's dust model etc. The mocks are now constructed with peeling off.

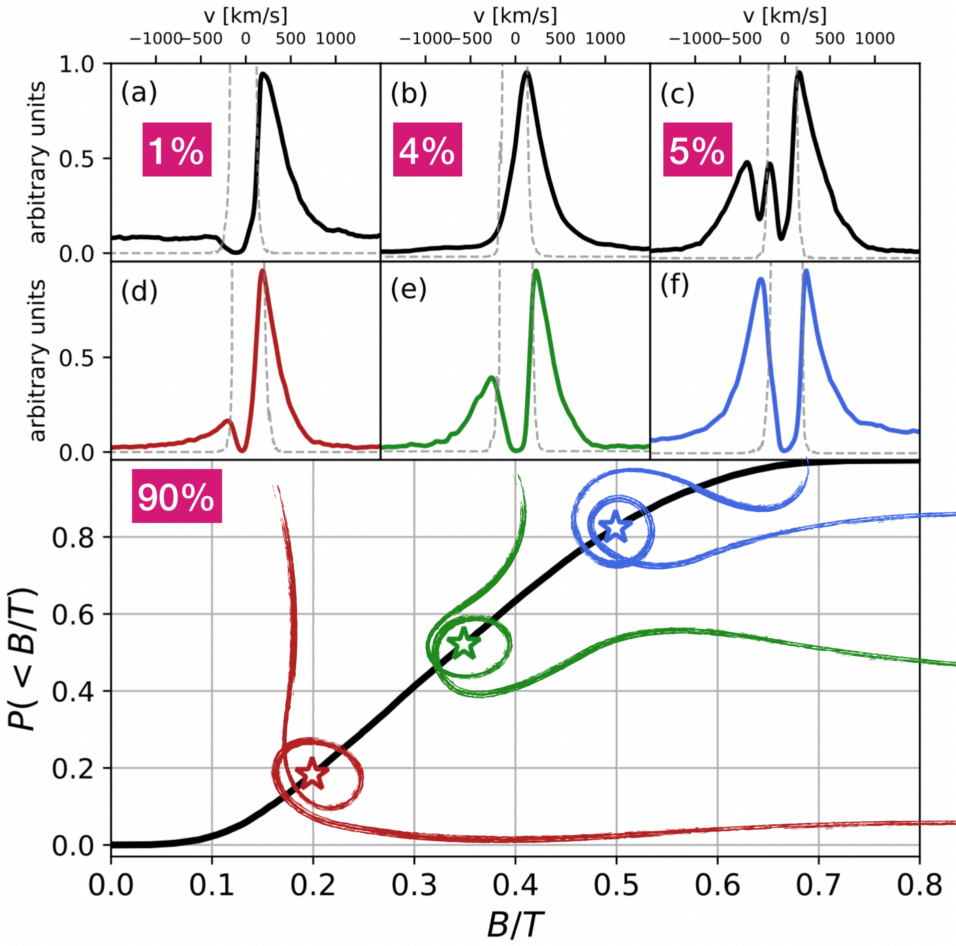

A comparison to the LASD
(Runnholm+21)
http://lasd.lyman-alpha.com/

A comparison to the **L**yman **A**lpha **S**pectral **D**atabase



Generally, tens of mocks produce an acceptable match to any observation.

Distribution of typical line shapes in the mocks (of one galaxy)



Blue-peak to total flux ratio

Mocks are generally consistent with observations, with a majority of red, asymmetric lines.

Less than 20% double peaks have a (moderately) dominant blue peak

Half double peaks have ~25-45% flux in the blue peak

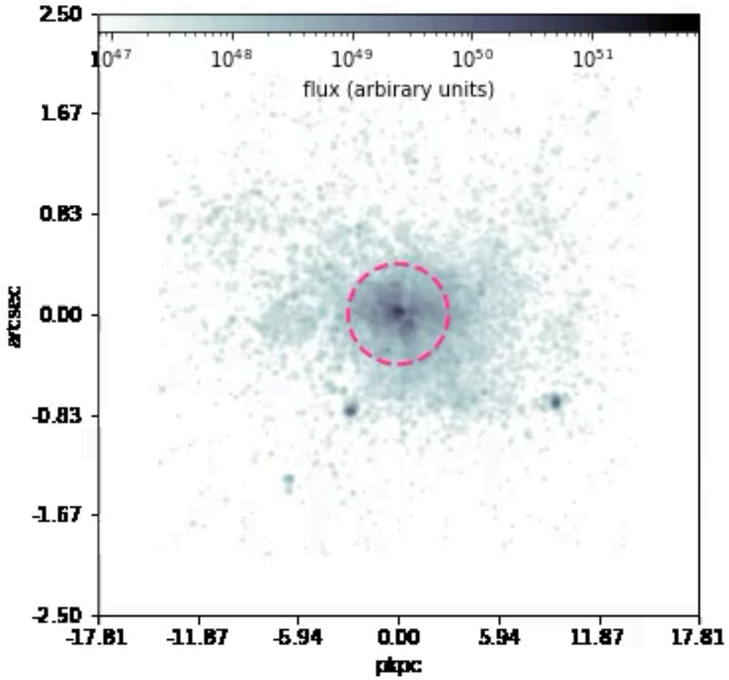
About 20% double peaks have a marginally detectable blue peak.

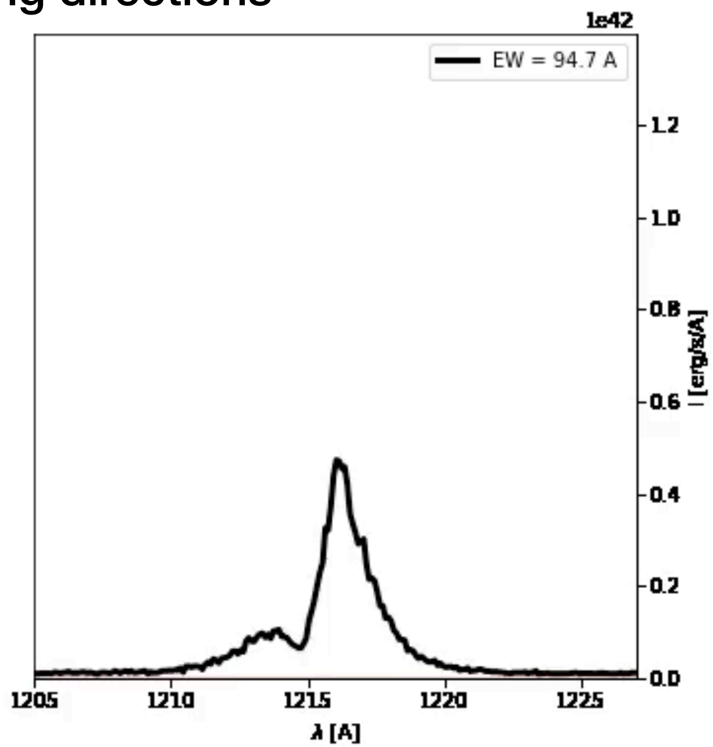
How can one single simulated galaxy fit so many observations ?

1. Line-of-sight / orientation effects.
2. Time evolution : star-formation / feedback cycle.

The distribution of line shapes varies with inclination

Fixed time, varying directions

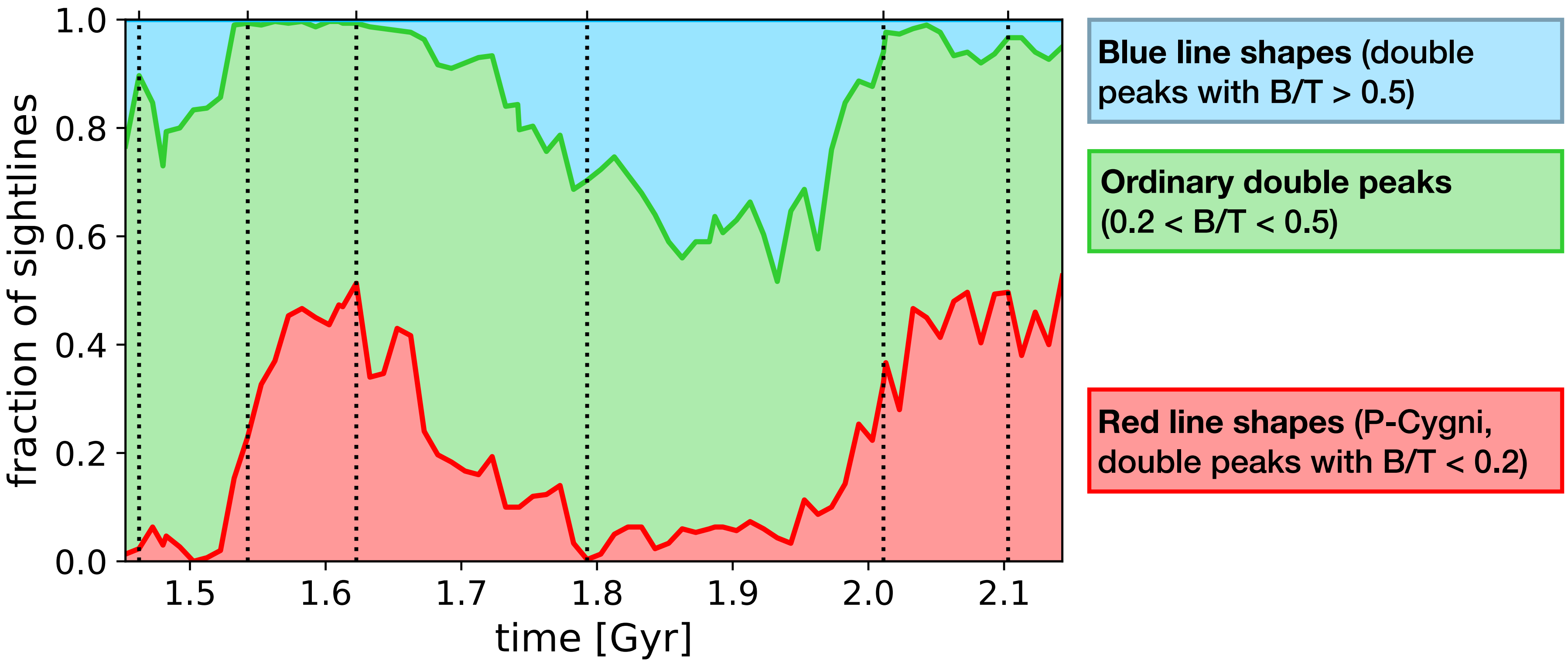




Very red (blue) lines are preferentially seen face-on (edge-on).

The majority of ordinary double peaks are seen in no preferred direction.

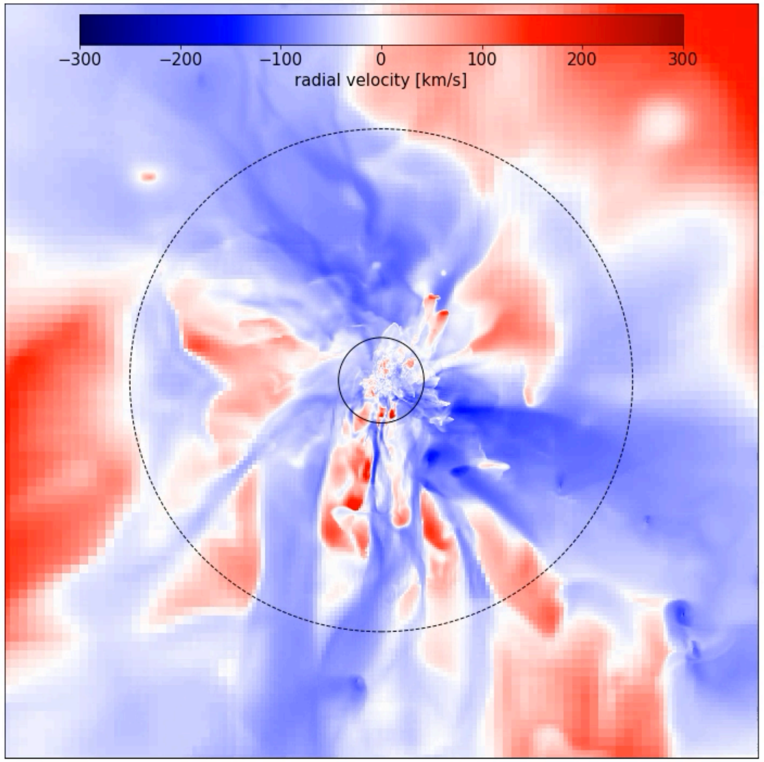
The distribution of line shapes varies with time

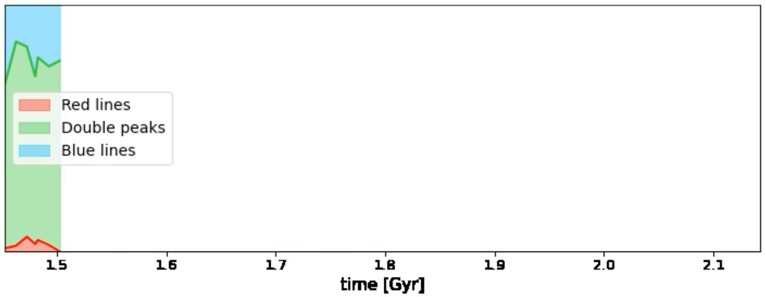


There is always ~ 50% of ordinary double peaks.

Very red or very blue profiles appear at different times.

The line shape is related to an inflow and outflow cycle





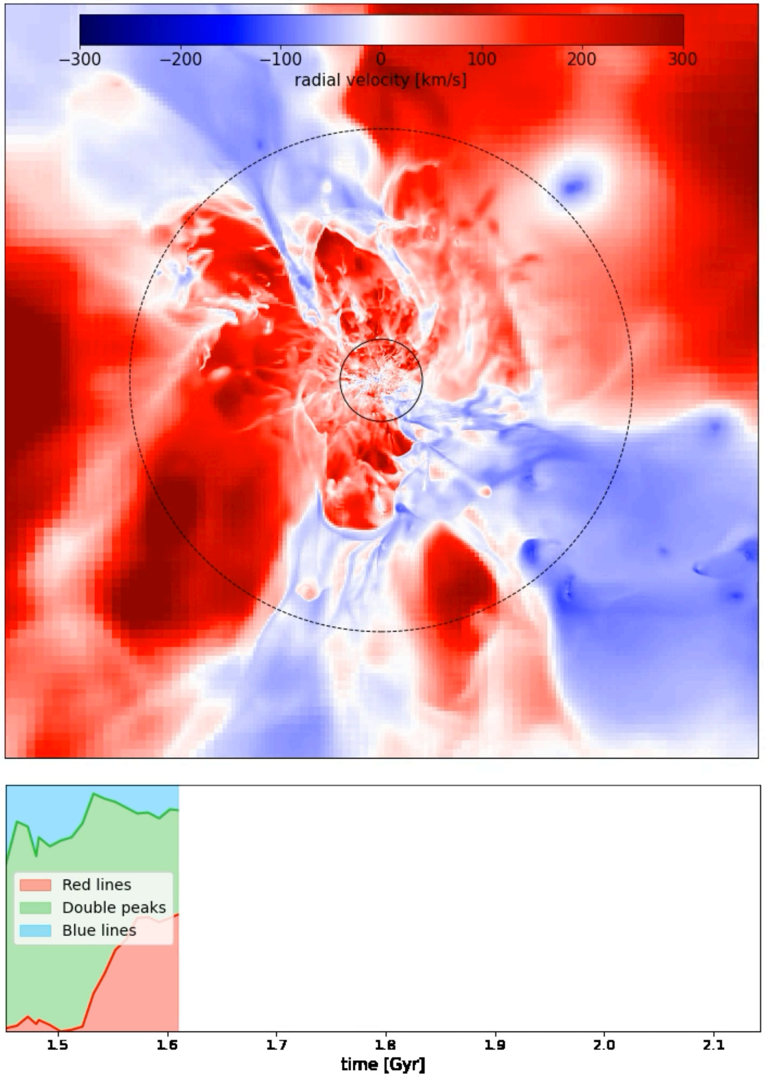
Outflowing gas
Inflowing gas

Accretion phases produce bluer profiles.

Accretion leads to star formation and outflows, which produce redder lines.

When outflows stop, cold streams reform …

The line shape is related to an inflow and outflow cycle



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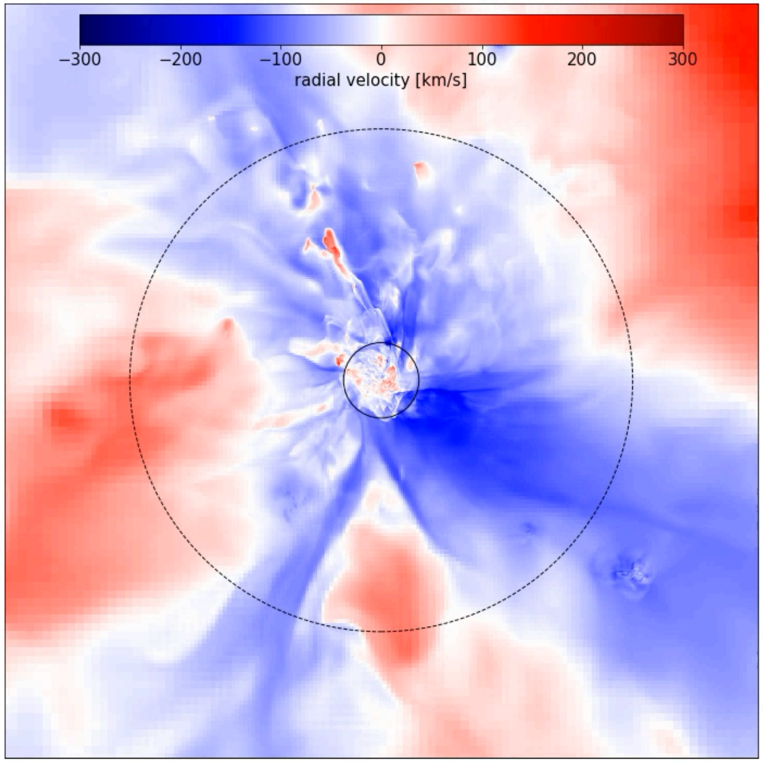

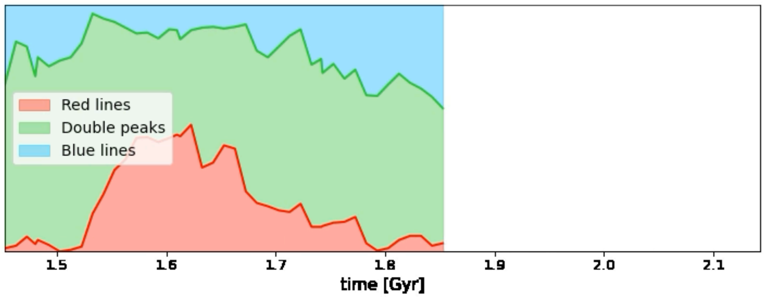

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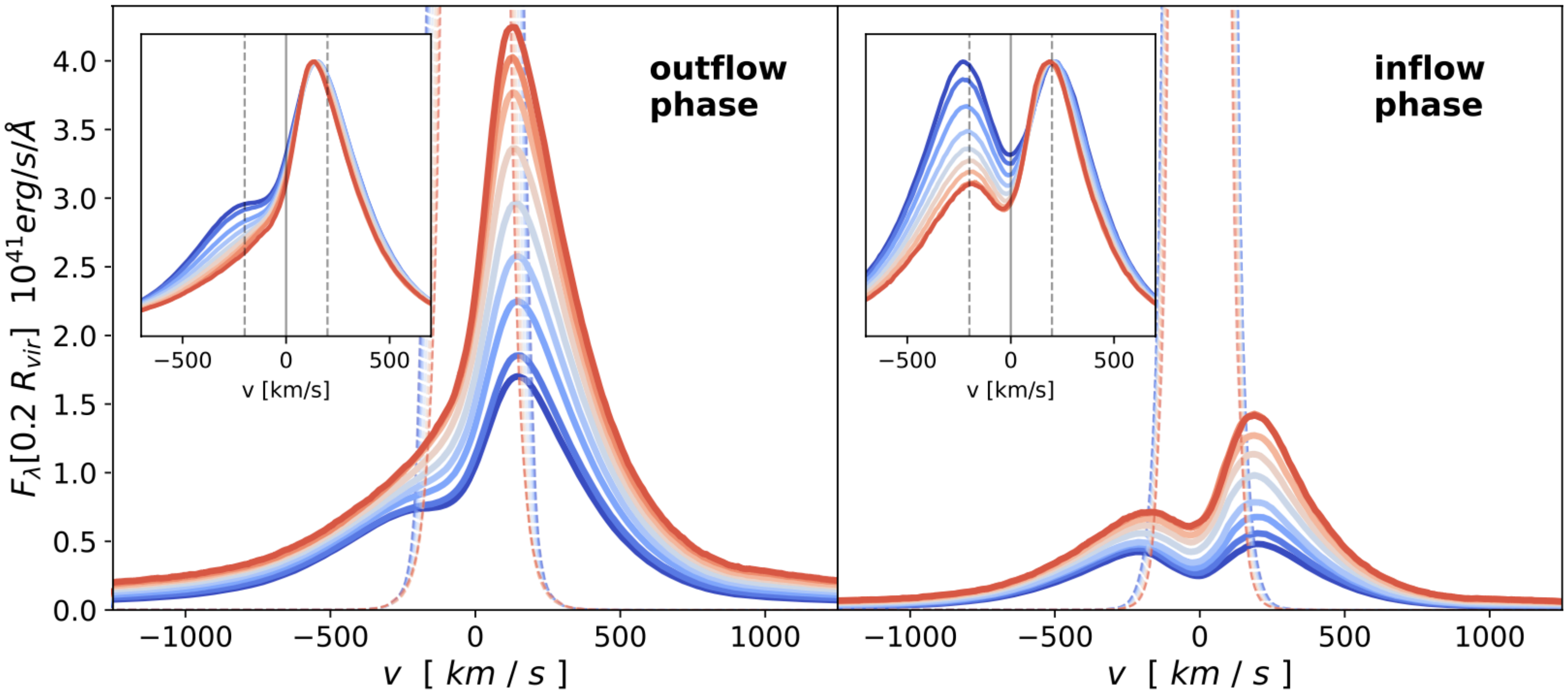
What processes drive the line shape ?

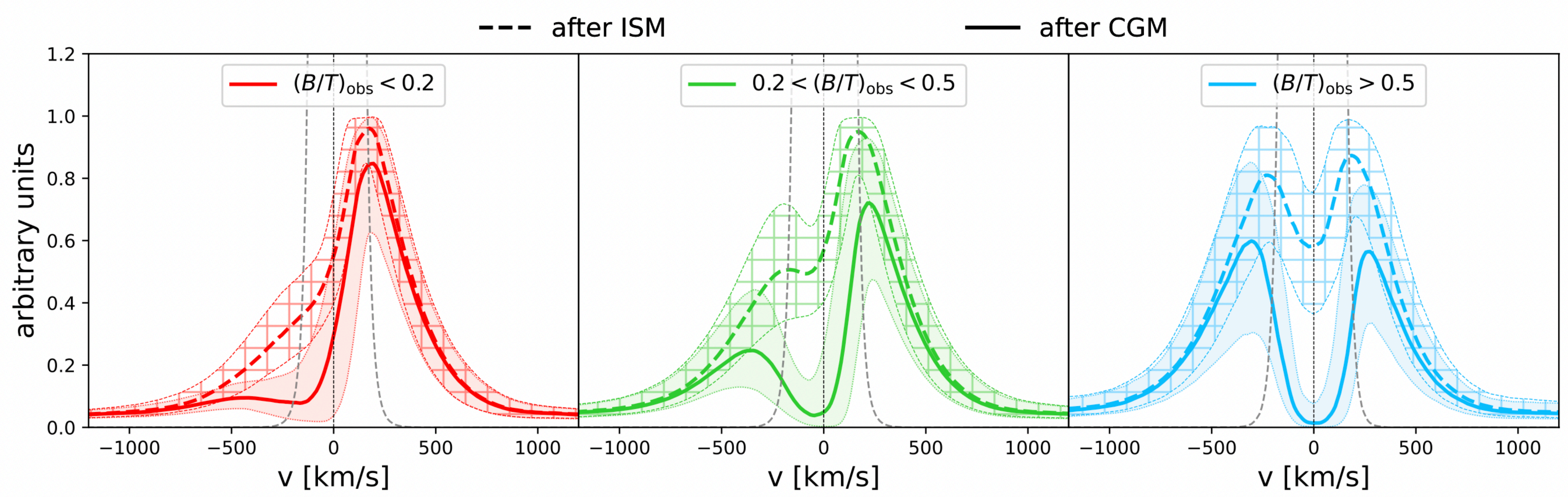
1. Resonant scattering in the ISM and inner CGM.
2. Screening by the outer CGM.

Resonant transfert out to 0.2 x R_{vir} : the ISM and inner CGM



The lines emerging from the ISM and inner CGM (<0.2 Rvir) are broadened and redshifted by resonant scattering effects. The line shape depends on time and orientation in connection with outflows / inflows at 0.2 Rvir. The luminosity is mostly driven by the very recent star formation history (not escape frac).

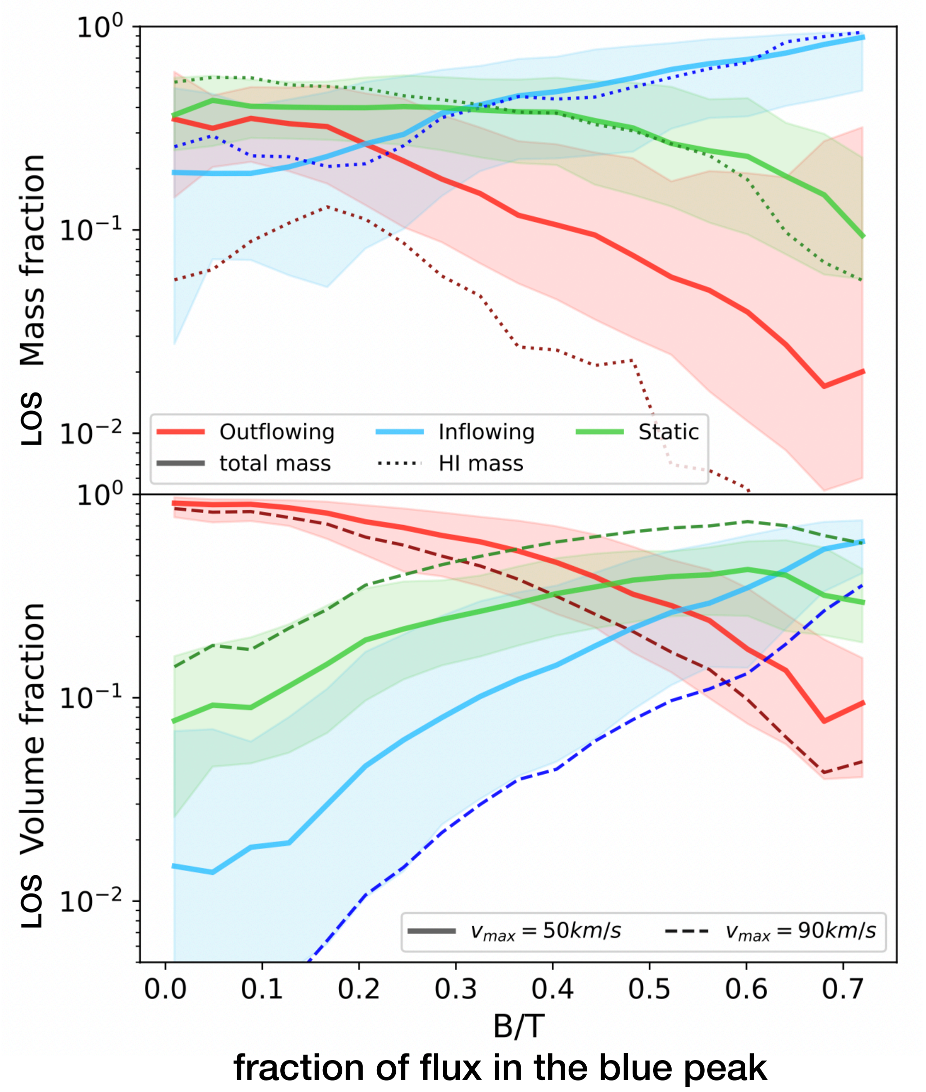
The role of the outer CGM : from 0.2 x R_{vir} to 3 x R_{vir}



The outer CGM finishes shaping the Lya line mostly by carving a deep absorption line. The velocity of this absorption line depends on the kinematic properties of the volume-filling component of the large-scale CGM.

Does the Lya line shape constrain flows of gas in the CGM ?

Can we constrain gas flows with Lya ?



Lines with a dominant blue peak have most of the line-of-sight gas inflowing, both in terms of mass and volume.

Very red profiles have most of the **line-of-sight volume** filled with outflowing gas, even though most of the **line-of-sight mass** is static or inflowing.

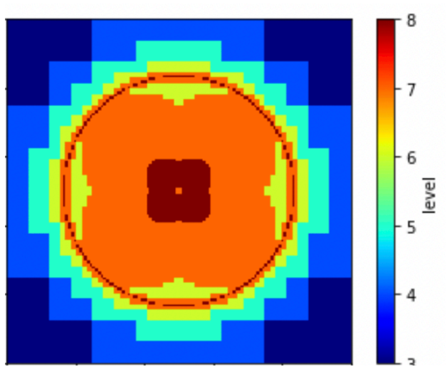
The rest is a fairly balanced mix…

One last thing before the end …

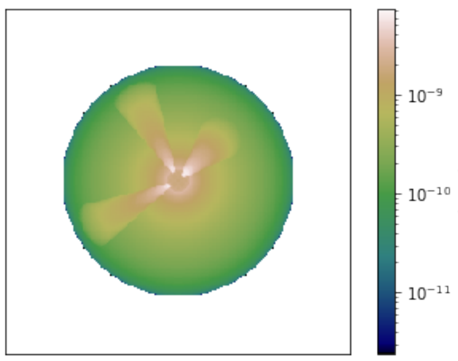
The numerical tools (RAMSES & RASCAS) used in this talk are **public**

RASCAS has a new set of **tutorials** which make it easy to compute scattering through ad-hoc geometries.

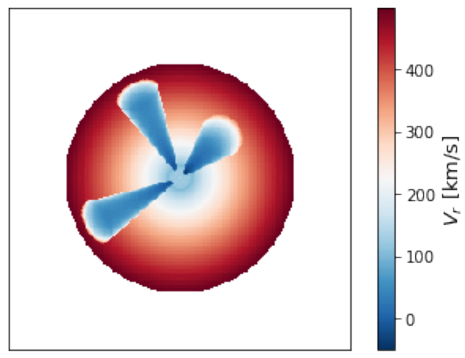
https://git-cral.univ-lyon1.fr/rascas/rascas/-/blob/SaasFee/doc/README.md



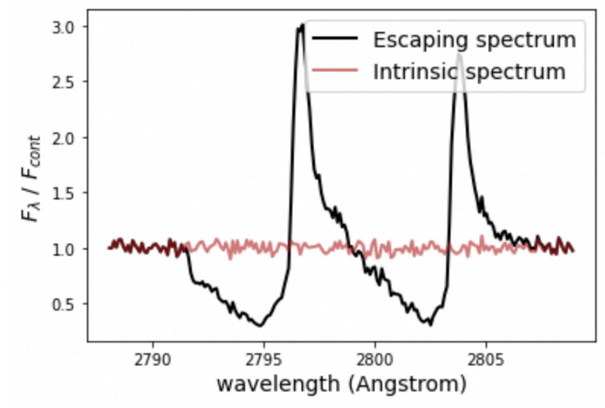
Adaptive grid (refined on density of velocity gradients)



Ad-hoc density profiles



Ad-hoc velocity profiles



Outputs can be 1D spectra, 2D images, 3D data cubes. Lines can be anything (Lya, MgII, …)

Summary

- Simulations can finally reproduce the diversity of observed Lya line shapes ! 🍾 🍾 🍾
- Very red lines (B/T < 0.2) are observed at times and in direction of outflows.
- Very blue lines (B/T > 0.5) are observed at times and in directions of inflows.
- Ordinary lines do not inform us on inclination or evolution.
- The shape and width of the line is already coarsely formed within the ISM and inner CGM.
- The outer CGM acts as a screen which produces more or less blue-shifted absorption.
- Redder lines are brighter, bluer lines are fainter, which may bias surveys.

The mock spectra from this talk are meant to be shared. Please ask.