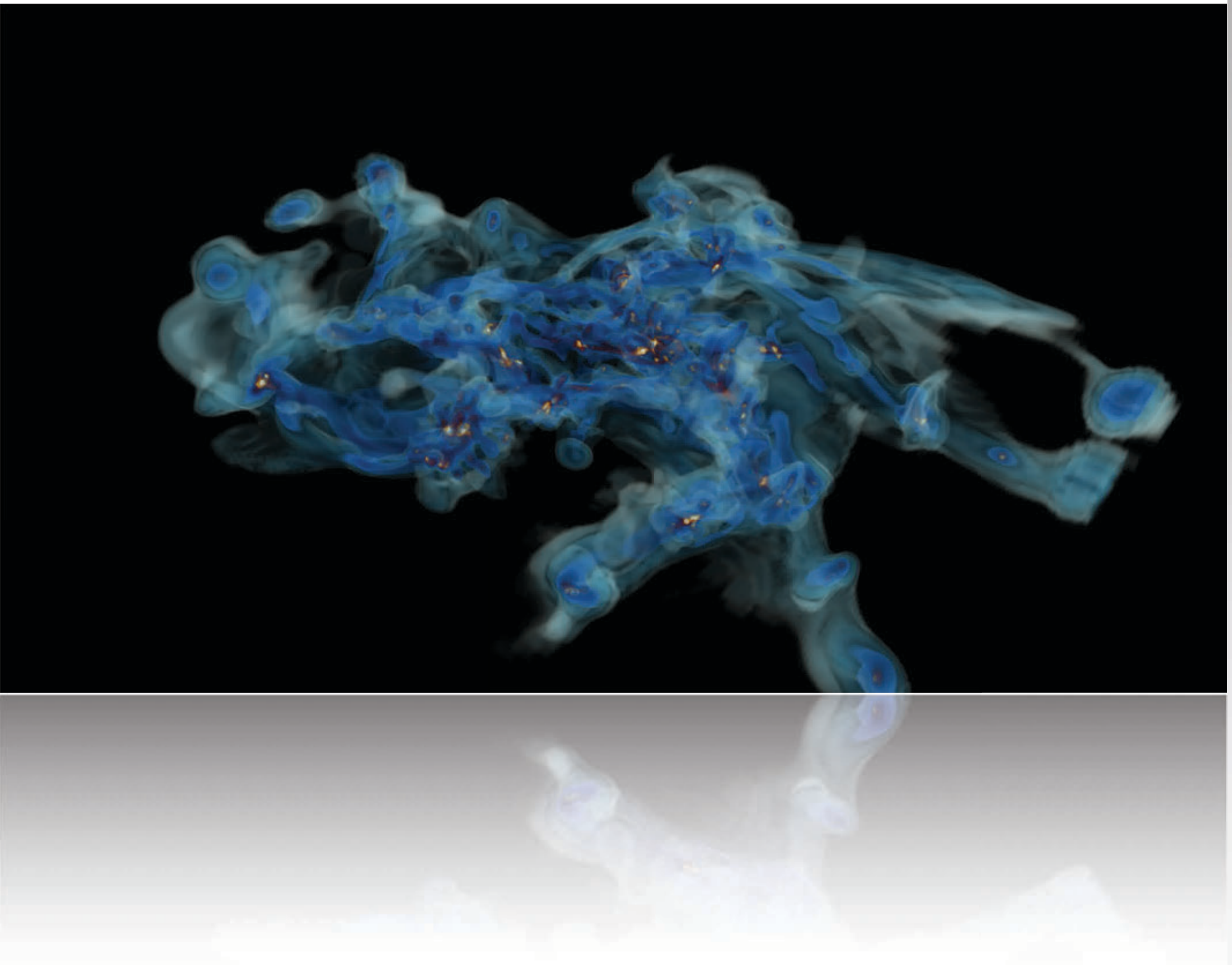
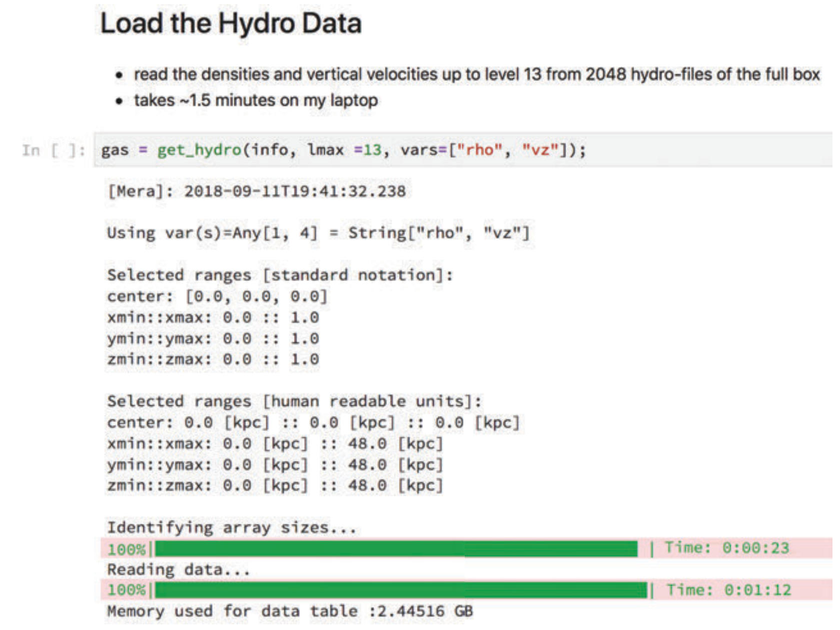
Clumpy Galaxies at High-Redshift



Postprocessing in Julia

MERA



Load the Hydro Data

- read the densities and vertical velocities up to level 13 from 2048 hydro-files of the full box
- takes ~1.5 minutes on my laptop

```
In [ ]: gas = get_hydro(info, lmax =13, vars=["rho", "vz"]);
```

```
[Mera]: 2018-09-11T19:41:32.238

Using var(s)=Any[1, 4] = String["rho", "vz"]

Selected ranges [standard notation]:
center: [0.0, 0.0, 0.0]
xmin::xmax: 0.0 :: 1.0
ymin::ymax: 0.0 :: 1.0
zmin::zmax: 0.0 :: 1.0

Selected ranges [human readable units]:
center: 0.0 [kpc] :: 0.0 [kpc] :: 0.0 [kpc]
xmin::xmax: 0.0 [kpc] :: 48.0 [kpc]
ymin::ymax: 0.0 [kpc] :: 48.0 [kpc]
zmin::zmax: 0.0 [kpc] :: 48.0 [kpc]

Identifying array sizes...
100%|██████████████████████████████████████| Time: 0:00:23
Reading data...
100%|██████████████████████████████████████| Time: 0:01:12
Memory used for data table :2.44516 GB
```

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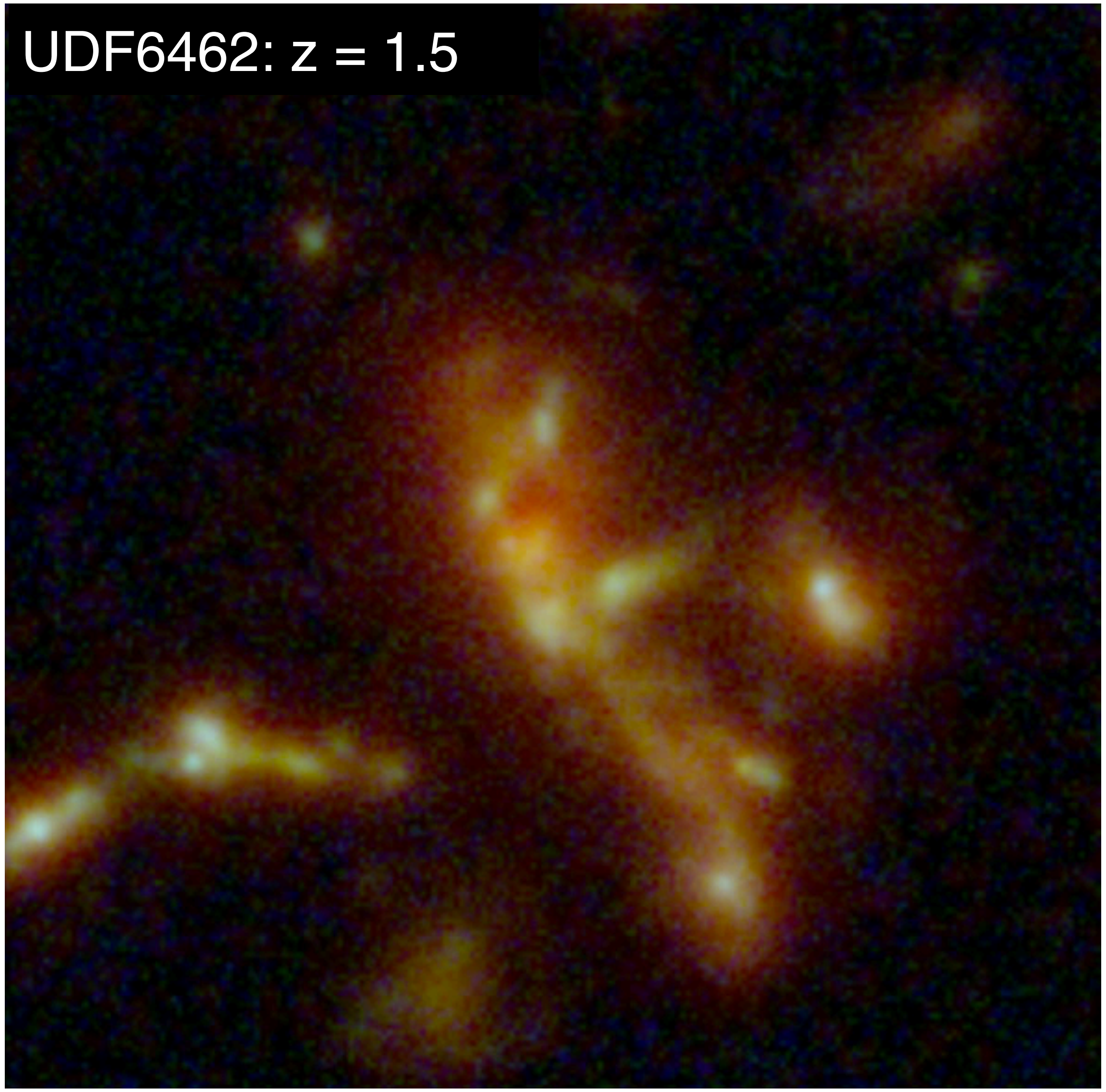
RAMSES user meeting 2018, Lyon

Different Star Forming Galaxies at High-z

Bournaud+15



Local galaxy: f_{gas}~5-10%

- spirals
- gmc masses/sizes 10^4-10^6 M_{sol} on ~100 pc
- low SFR~1 M_{sol}/yr
- low σ ~10 km/s (ISM)

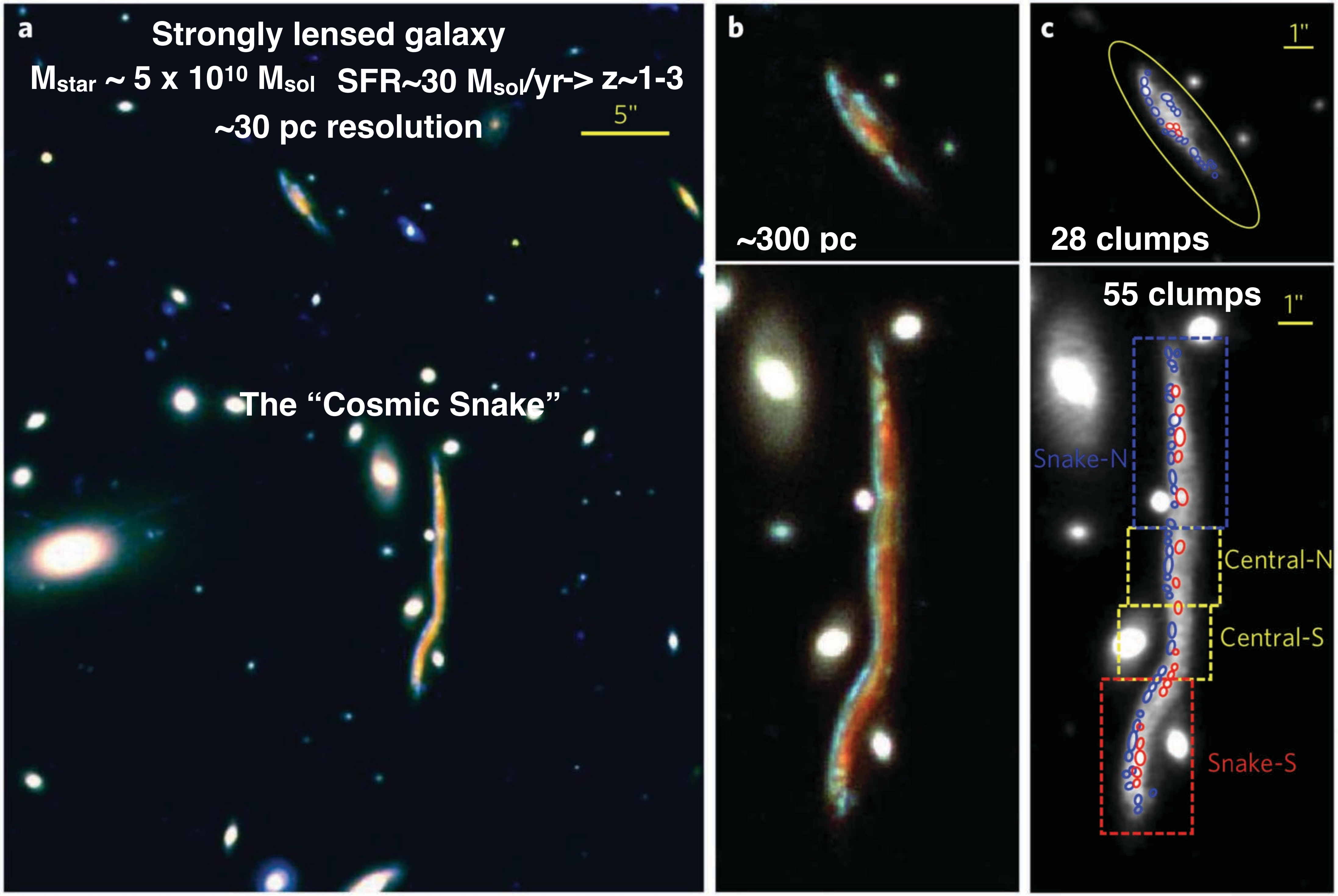
High-z galaxy: f_{gas}~50%

- clumpiness/irregularity is ubiquitous
- clump masses/sizes 10^8-10^9 M_{sol} on ~1 kpc
- high SFR~10-100 M_{sol}/yr
- high σ ~20-100 km/s (ionized/molecular)
- underling rotating disks
- Observational resolution 1-2 kpc

Review: Bournaud et al. (2016)

Evidence For a Giant Clump Substructure

Cava et al. 2018



Strongly lensed galaxy

M_{star} ~ 5 x 10^{10} M_{sol} SFR~30 M_{sol}/yr-> z~1-3

~30 pc resolution

The “Cosmic Snake”

~300 pc

28 clumps

55 clumps

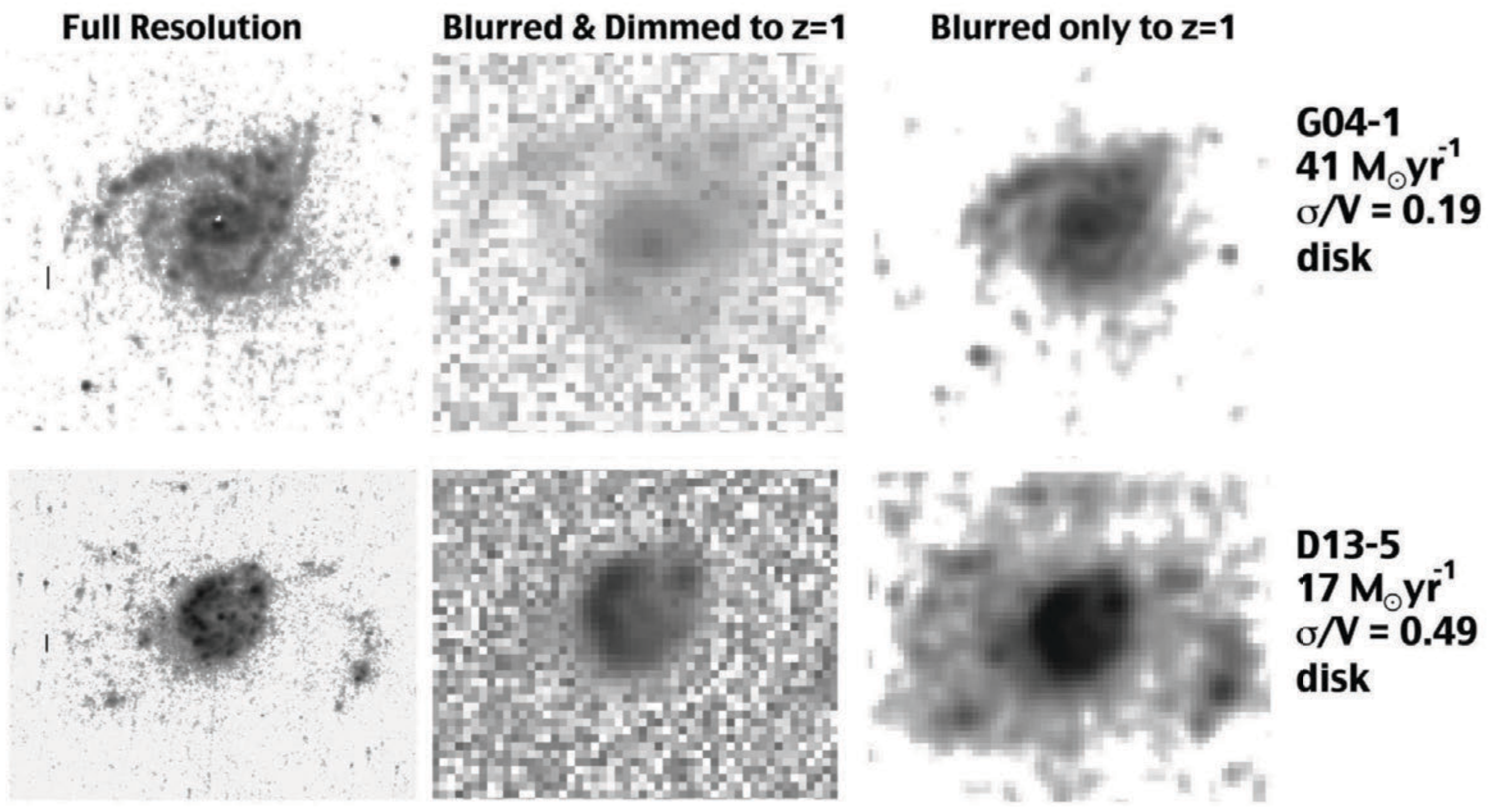
Clump masses 10^7 - 10^9 M_{sol} strongly related to the magnification

Resolution: 30pc - 300pc

Evidence For a Giant Clump Substructure

Local - High-redshift clumpy disk analogues

(Extremely rare)



(Fisher et al. 2017)

A few kpc sized clumps

decreased sensitivity:

- surface brightness dimming $(1+z)^4$
- AO sensitivity of H_{alpha}

DYNAMO sub-sample

10 Local galaxies

H_{alpha} (HST observations)

M_{star} ~ 1-6 x 10^{10} M_{sol}

SFR~10-30 M_{sol}/yr

Correspond to z~1-2.5

~100 pc resolution

Massive star forming clumps

D_{HWHM}~several 100 pc

Origin of The Observed Giant Clumps

$$Q=\frac{\kappa\ \sigma_R}{\pi G\Sigma}, \quad \kappa \propto \frac{V_{Rot}}{R}$$

stabilizing

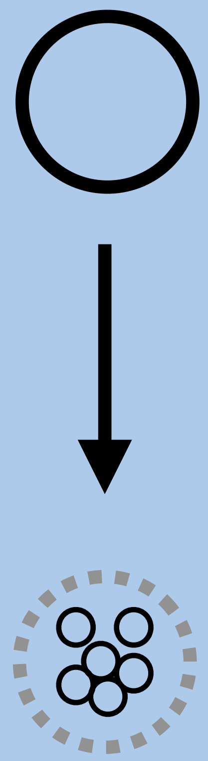
destabilizing

- Well explained within the framework of **gravitational disc instability**:
$Q_{Toomre} < Q_{crit}$ ->a range of perturbations can **grow**; but **Toomre length the fastest**

- Observed galaxy conditions point to **kpc-sized perturbations (Toomre length)**:
high gas densities and high random motions

Two possible scenarios for building sub-structure

Top-down



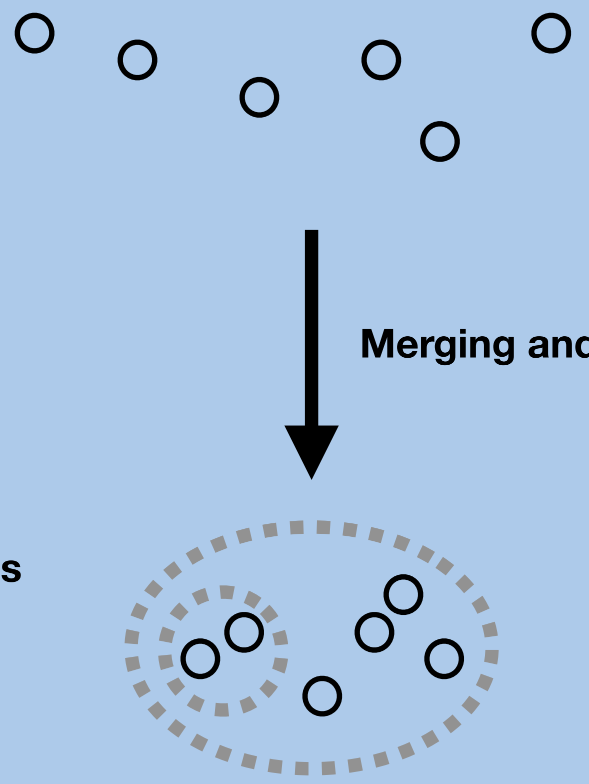
Direct formation
typically found in
cosmological
simulations

Sub-fragmentation
- Giant-Clump with dense substructure, gravitationally bound

- Allowed by higher-resolution

Common hypothesis

Bottom-up



Many clumps
Form on smaller scales
~100 pc

Merging and grouping

“Sub-Structure” appears
as giant object through glases
of limited resolution etc.

Not necessarily gravitationally
bound groups

Behrendt et al. 2015, 2016

Unstable Gas Disk - Resolution Study

Within radius of 16 kpc

M_{disc} ~ 3 x 10^{10} M_{sol}

M_{dm} ~ 10^{11} M_{sol} (external potential)

V_{rot} ~190 km/s

Exponential disc

Toomre unstable = Ring instability
-> several hundred pc to kpc
scales perturbations aregrowing

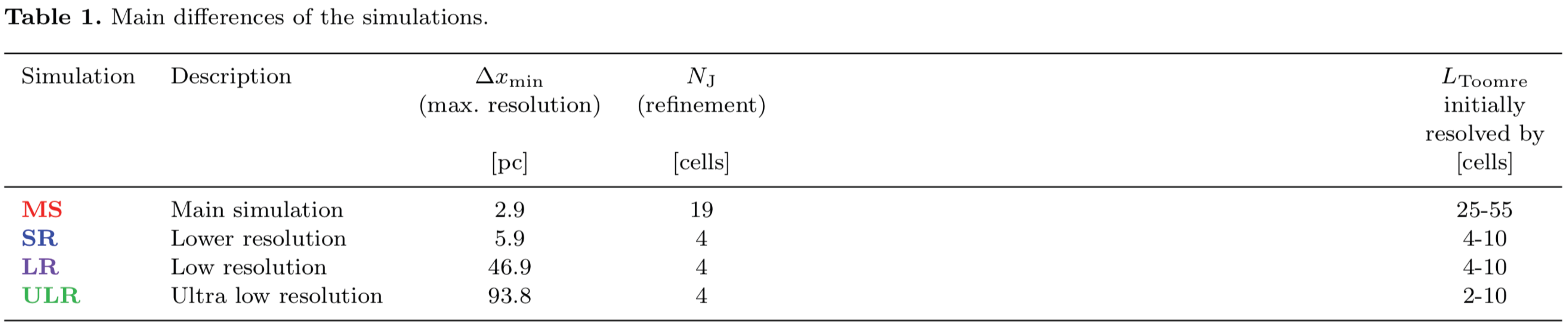
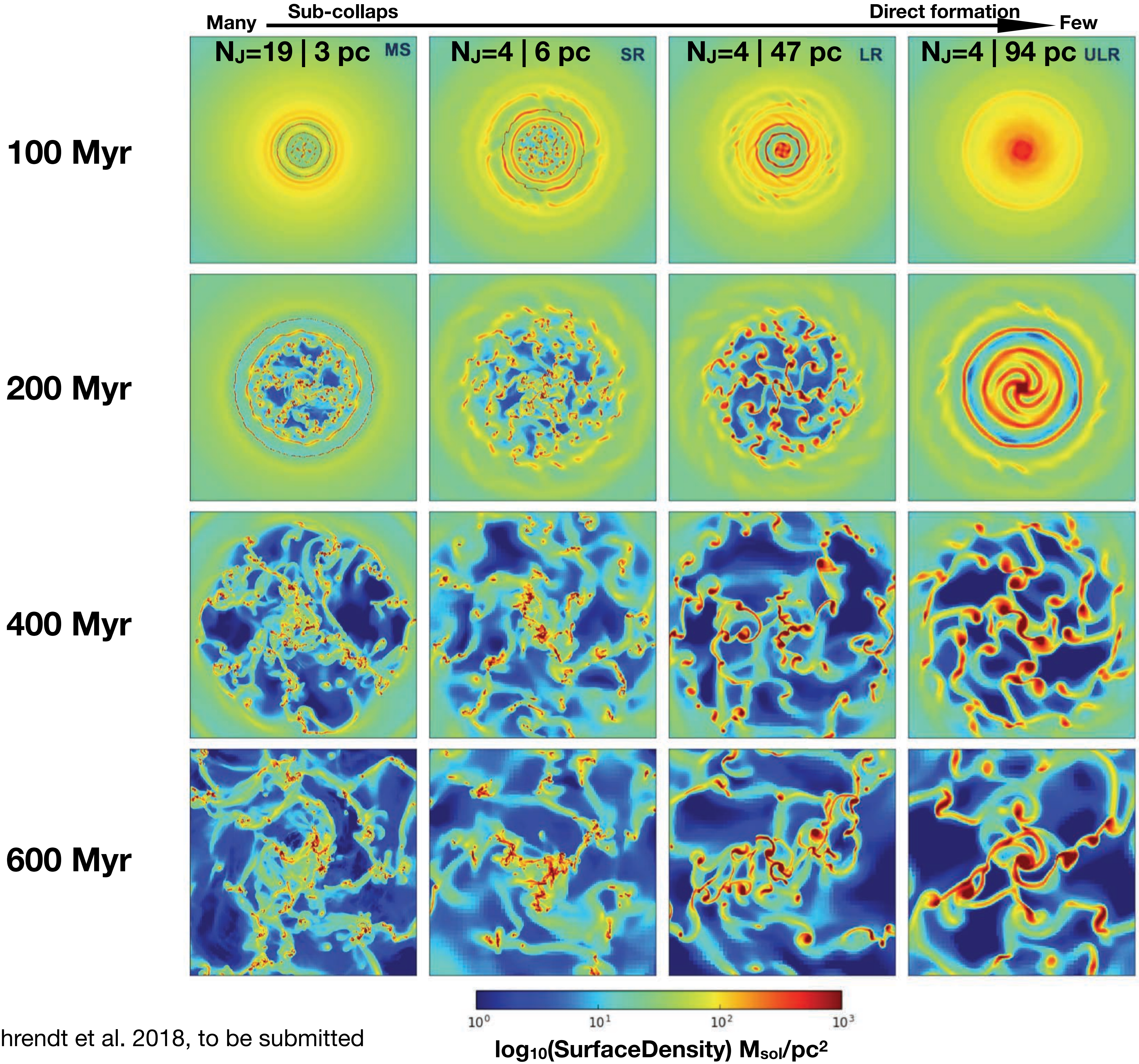


Table 1. Main differences of the simulations.

Simulation	Description	$\Delta x_{\rm min}$ (max. resolution) [pc]	$N_{\rm J}$ (refinement) [cells]	$L_{\rm Toomre}$ initially resolved by [cells]
MS	Main simulation	2.9	19	25-55
SR	Lower resolution	5.9	4	4-10
LR	Low resolution	46.9	4	4-10
ULR	Ultra low resolution	93.8	4	2-10



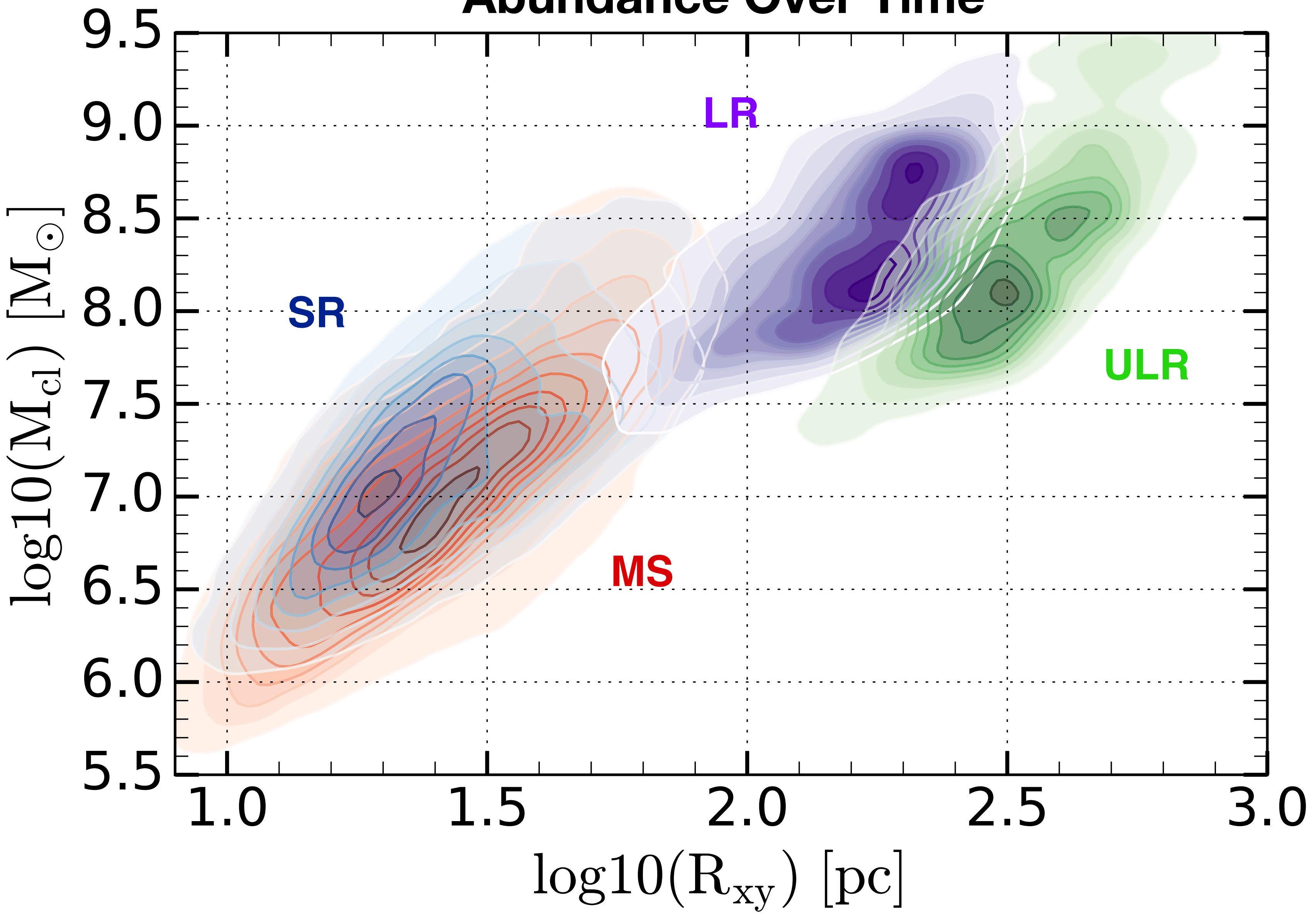
Behrendt et al. 2018, to be submitted

Shift in Clump Properties

RAMSES clump finder
MS/SR: nH > 100 $\mathrm{cm^{-3}}$
LR: nH > 10 $\mathrm{cm^{-3}}$
ULR: nH > 1 $\mathrm{cm^{-3}}$

- 50% of mass in high density clumpss
- Clumps surrounded by 30% more mass
- initial clumps ~ 10^7 $\mathrm{M_{sol}}$
- Most mass in 10^8 $\mathrm{M_{sol}}$ mergers
- Low resolution clumps show different/shifted properties (lower density, higher mass, larger scales)

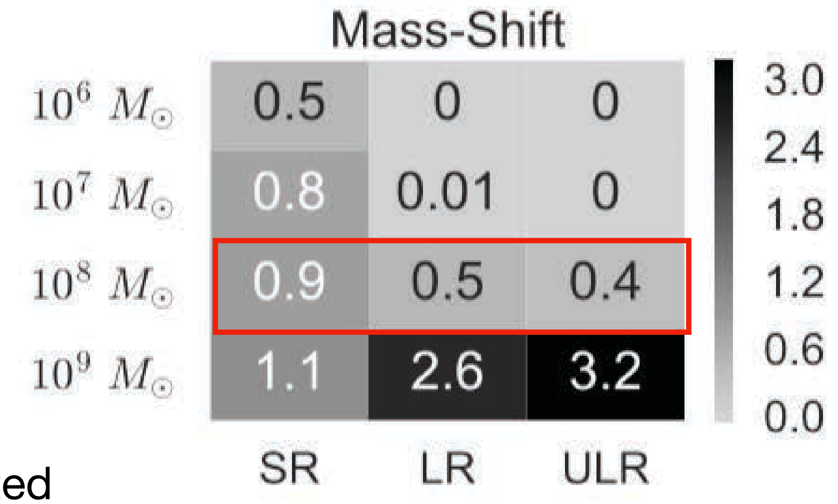
Abundance Over Time



Compared to MS:

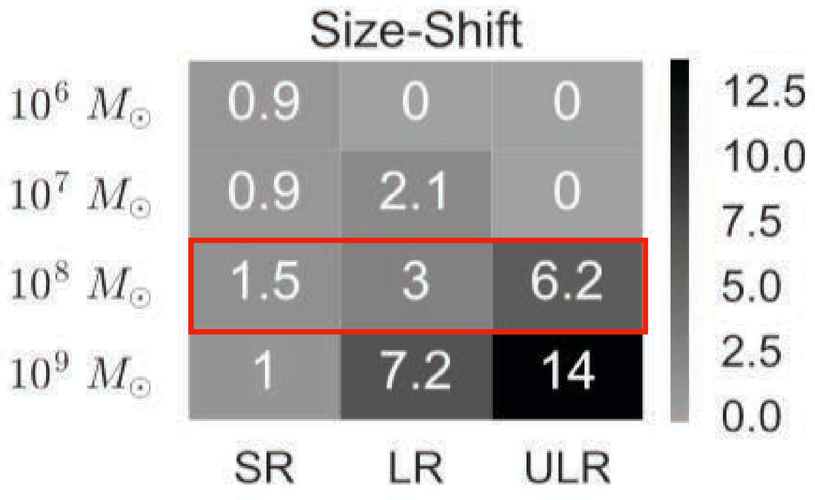
Clumps are not the same

Mass-Shift



	SR	LR	ULR
$10^6\ M_\odot$	0.5	0	0
$10^7\ M_\odot$	0.8	0.01	0
$10^8\ M_\odot$	0.9	0.5	0.4
$10^9\ M_\odot$	1.1	2.6	3.2

Size-Shift



	SR	LR	ULR
$10^6\ M_\odot$	0.9	0	0
$10^7\ M_\odot$	0.9	2.1	0
$10^8\ M_\odot$	1.5	3	6.2
$10^9\ M_\odot$	1	7.2	14

Behrendt et al. 2018, to be submitted

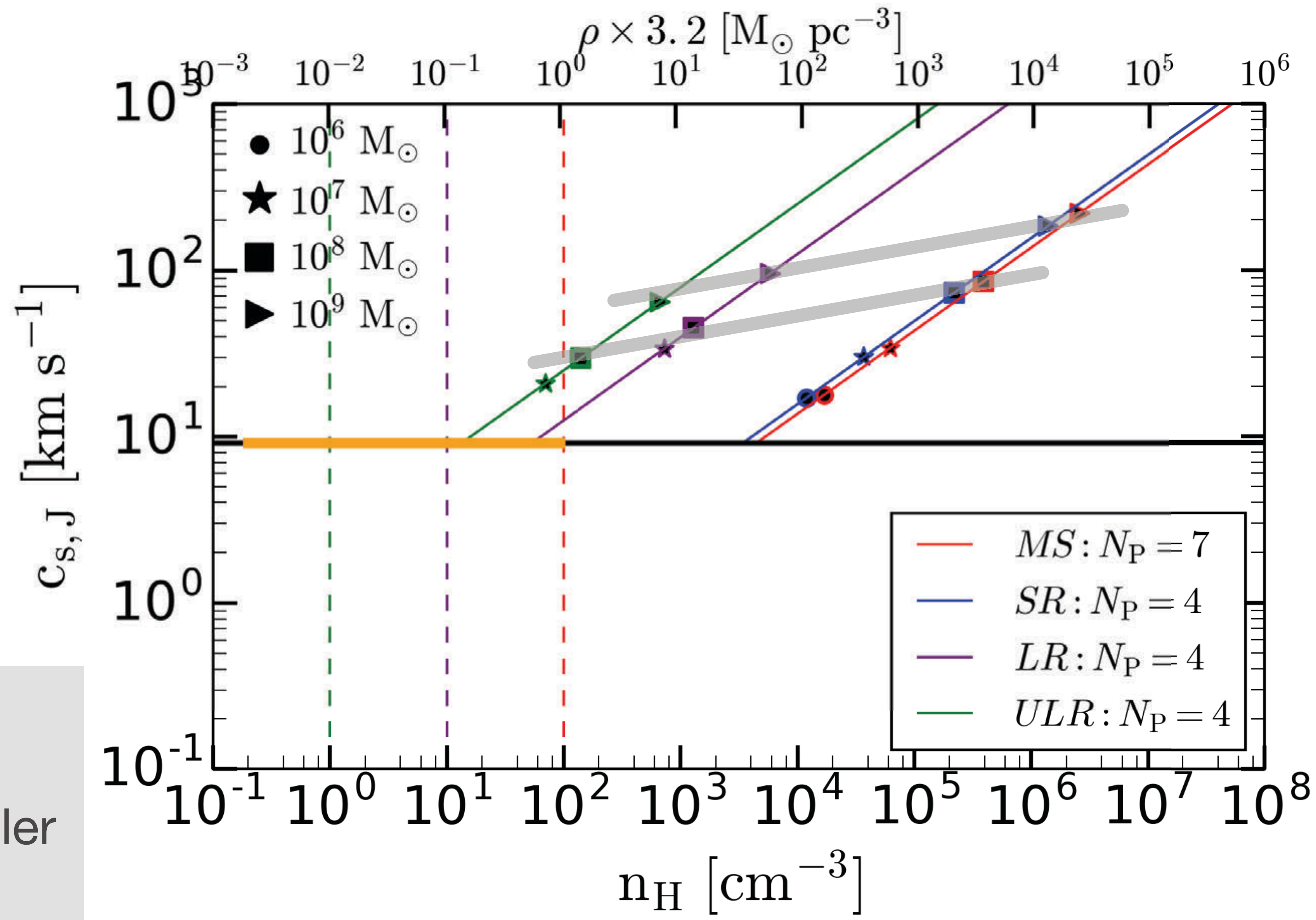
Effect of The Artificial Pressure Floor

At maximum resolution: Δx_{min}
Jeans length resolved by several elements

$$\lambda_{\mathrm{J}} = \sqrt{\frac{\pi c_{\mathrm{s}}^2}{G\rho}}$$

Sound speed:

$$c_{\mathrm{s,J}}^2 = \frac{G}{\pi} N_{\mathrm{P}}^2 \, \Delta x_{\mathrm{min}}^2 \, \rho,$$



High resolution simulations

- reach higher densities
- Structure can collapse to smaller scales for fragmentation

Low resolution simulations

- at lower densities already pressure floor acting
- Structure cannot really collapse to smaller scales
- Clumps are given by the APF Jeans Mass

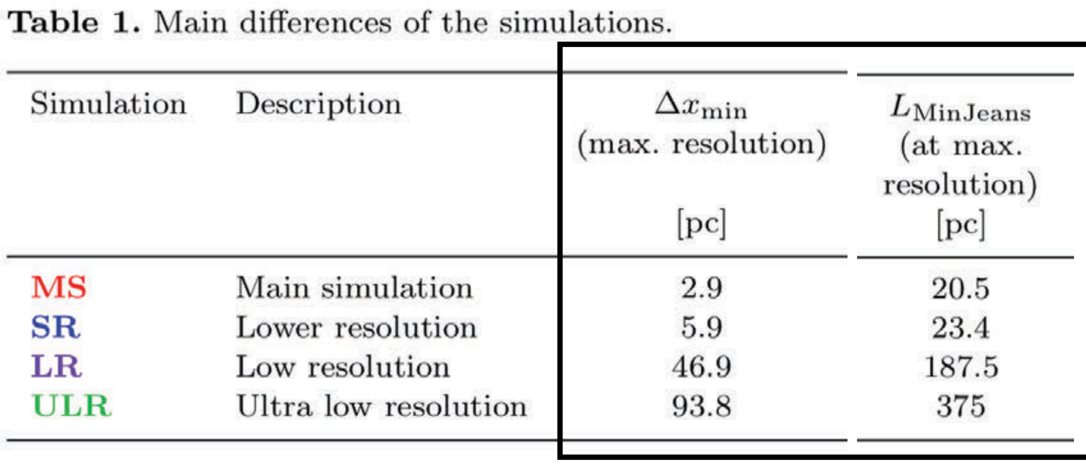


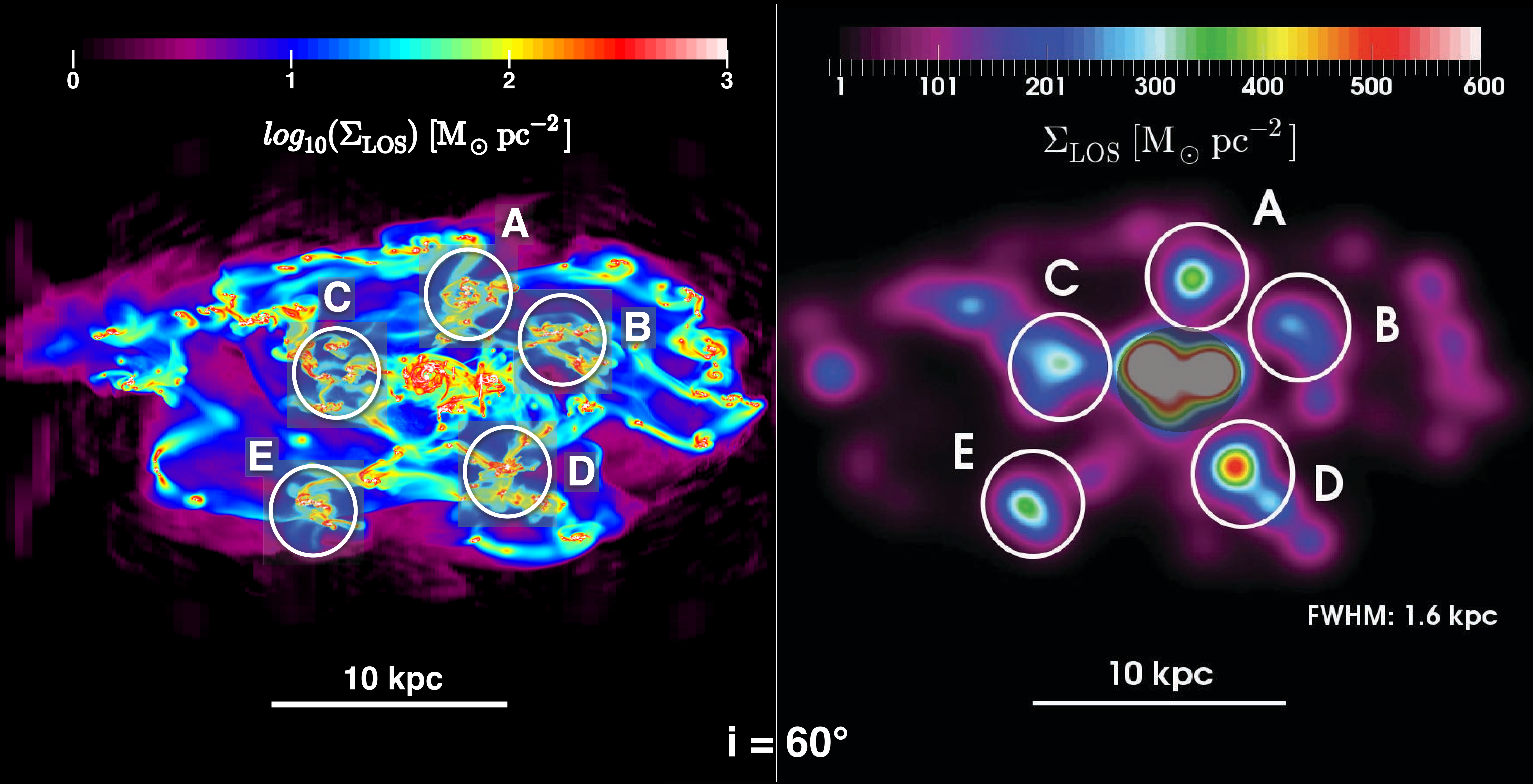
Table 1. Main differences of the simulations.

Simulation	Description	Δx_{min} (max. resolution) [pc]	L_{MinJeans} (at max. resolution) [pc]
MS	Main simulation	2.9	20.5
SR	Lower resolution	5.9	23.4
LR	Low resolution	46.9	187.5
ULR	Ultra low resolution	93.8	375

Effective resolution ($L_{\mathrm{Min\ Jeans}}$) represents the minimum possible structure; the **maximum resolution** does not tell you everything.

Behrendt et al. 2018, to be submitted

Clump Clusters



Spatial and kinematic properties match those of observations!

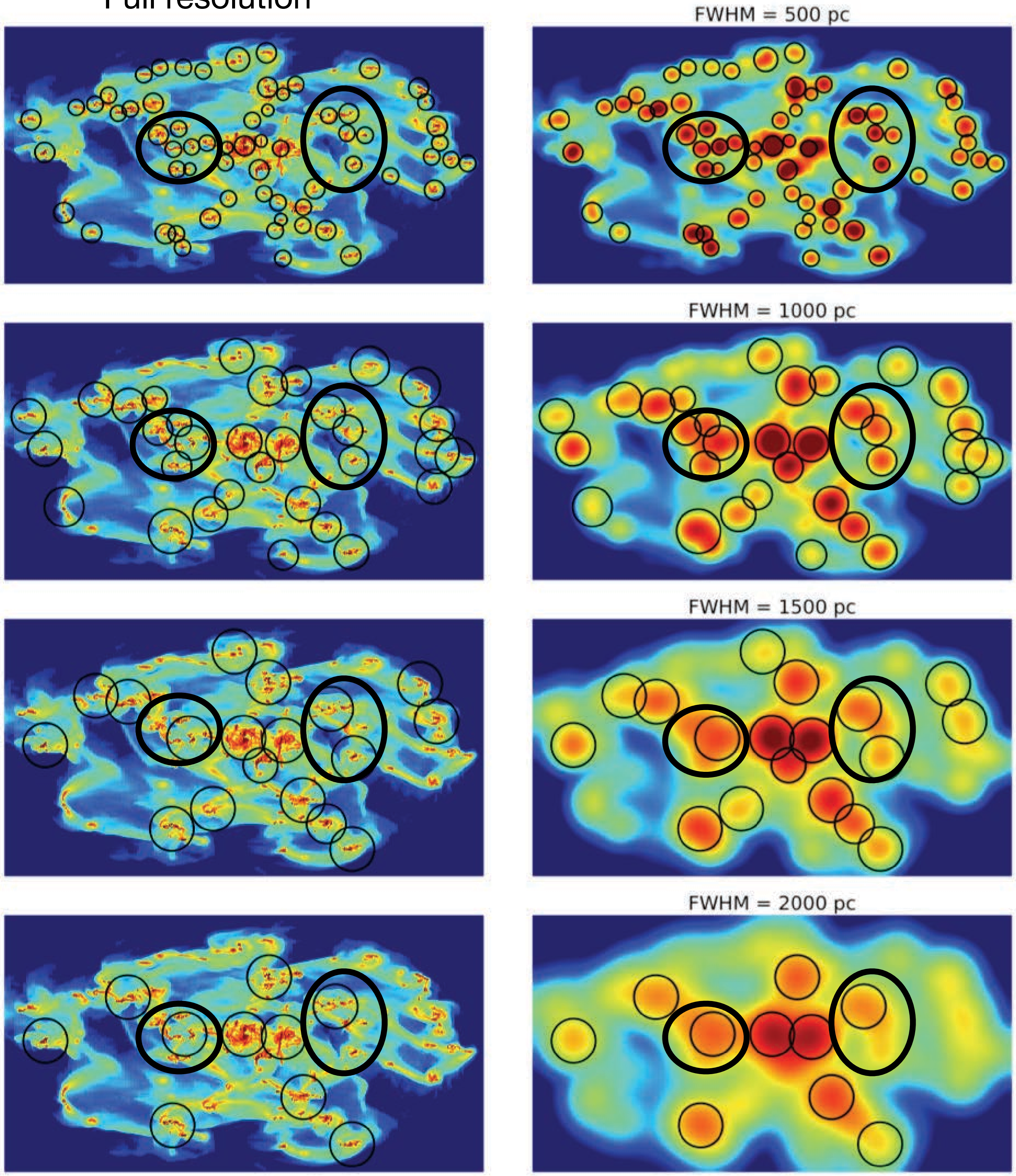
Behrendt et al. 2016

Hierarchical Scales of Clump Clusters

i = 60°

Gaussian bluring

Full resolution



$\sim 10^7\ M_{sol}$ **~ 120 pc**

mass/size increase

$\sim 10^9\ M_{sol}$ **> 2 kpc**

Behrendt et al. 2018, to be submitted

Hierarchical Scales of Clump Clusters

SFG z~2 main sequence

$M_{tot} \sim 4 \times 10^{10}$ M_{sol}

SFR ~ 30 M_{sol}/yr

t_{depl} ~ 750 Myr

f_{gas} ~ 75 %

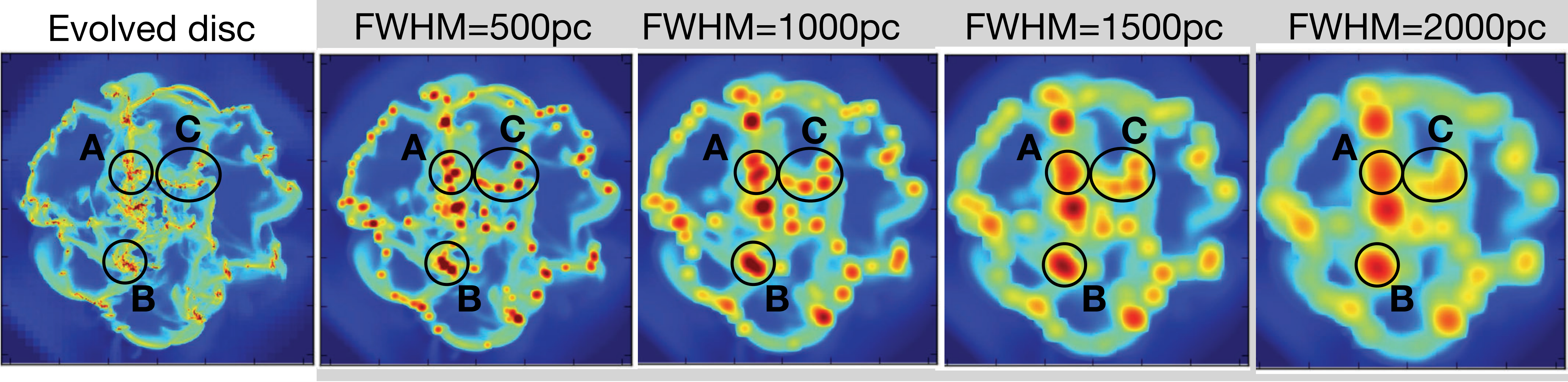
SN feedback

50% E_{kin}

50% E_{therm}

Cooling delay

Gaussian bluring


Evolved disc

FWHM=500pc

FWHM=1000pc

FWHM=1500pc

FWHM=2000pc

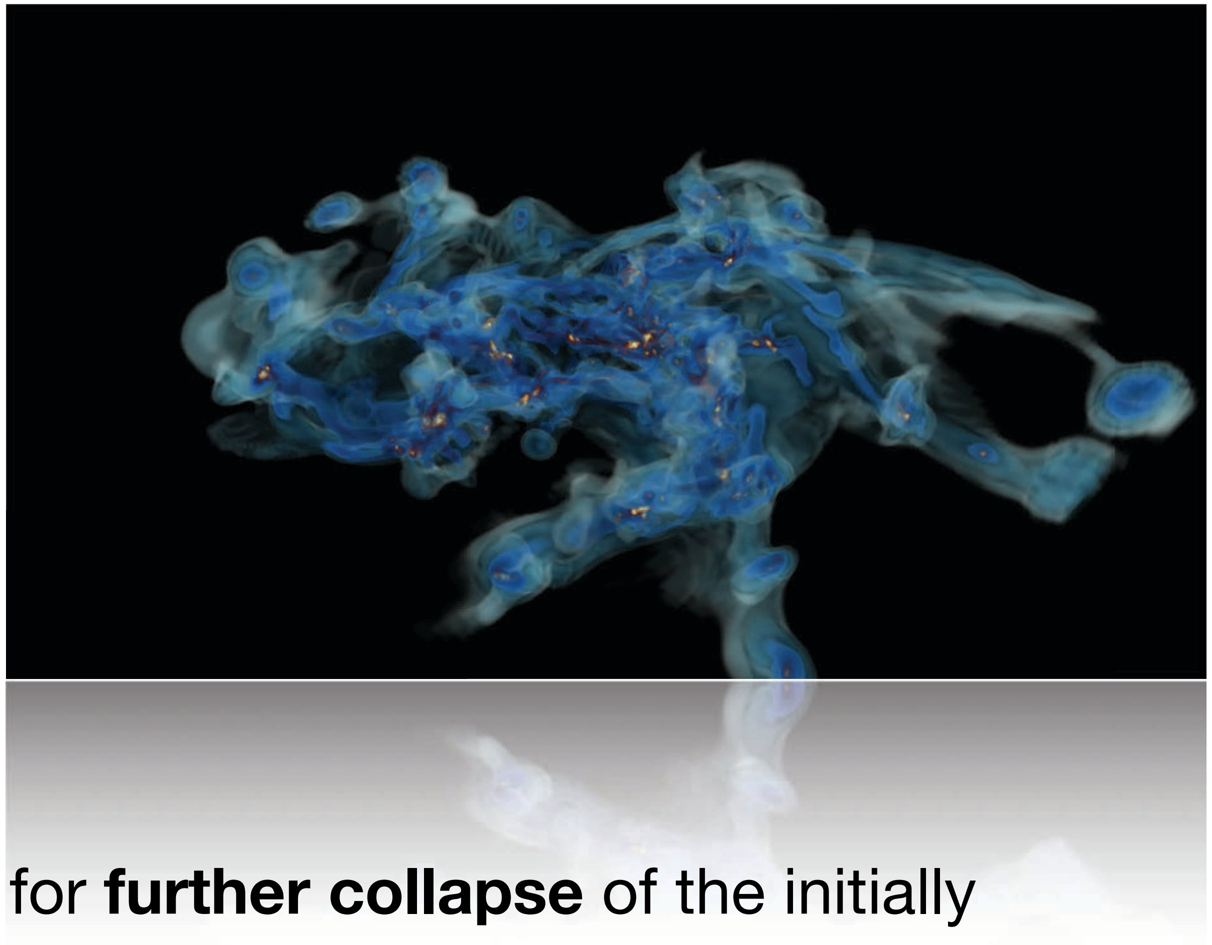
A: dense cluster - hierarchy on **several** scales

B: dense clusters - hierarchy on **less** scales

C: open clusters - hierarchy on **several** scales

Behrendt et al. 2018, PhD thesis

Summary



Clump Clusters from bottom-up

- **high resolution simulations** allow for **further collapse** of the initially growing perturbations on **kpc scales** which leads to a **fragmentation on much smaller scales**
- **rich sub-structure** of smaller clumps representing the giant clumps spatialy and the kinematic properties of observations

Hierarchy of Clump Clusters

- **prediction** for the next generation of large telescopes like the **ELT**: **several scales of clusters** depending on observational resolution.

Caution with artificial pressure floor

- **low resolution** simulation might produce **artificially given clumps**

More work has to be done by adding complexity to the system!

MERA is a package for working with large 3D AMR and particle data sets from astrophysical simulations and is written in the language Julia!
Coming soon!

Description

With MERA, 3D hydrodynamic simulation data can be easily loaded into a database framework (currently supported: RAMSES). In our daily life we are dealing with steadily increasing amounts of data. MERA together with Julia, makes the processing of large data sets fast, clearly represented and the working memory lightweight.
Many functions with examples and tutorials are provided to create a simple and an efficient workflow of your analysis.
I created the package for my personal usage and it is constantly evolving. I am happy to share it with the community and hope it will be helpful in many ways.

Purpose

- **Easy to install and update**
- **Fast** and **memory lightweight** data processing
- **Simple coding** for the user
- **Many functionalities** for advanced analysis
- **Transparent** operations of the **functions**
- **Interactive** and **script** functionality
- Many **examples** and **tutorials**

Package Preview: Jupyter notebook

https://github.com/ManuelBehrendt/Notebooks

Subscribe: www.manuelbehrendt.com/mera.html

Why the language Julia?

In scientific computing we are dealing with a steadily increasing amount of produced data. This requires highest performance and therefore, most science related libraries are written in low-level languages like C or Fortran with relatively long development times. The reduced data is often processed in a high-level language like Python.
Julia is a relatively new and modern language and it combines high-level programing with high-performance numerical computing. The syntax is simple and great for math, the just-in-time compilation allows for interactive coding and to achieve an optimized machine code on the fly. Both enhance prototyping and code readability. Therefore, complex projects can be realized in relatively short development times.

Further features:
- Package manager
- Runs on multiple platform
- Multiple dispatch
- Build-in parallelism
- Metaprogramming
- Directly call C, Fortran and Python libraries (e.g. Matplotlib)

....