# Untangling the complexity of cosmic flows (in galaxy clusters): accretion, mergers, shock waves and turbulence

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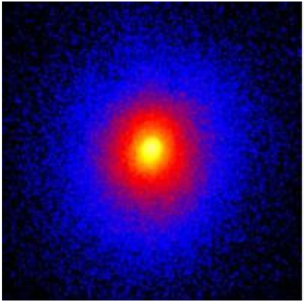
# Outlines

1. Galaxy clusters: the crossroad of Cosmology and Astrophysics
2. Cosmological simulations with `MASCLET`
3. The complexity of cosmic flows around galaxy clusters
4. The complexity of cosmic flows around cosmic voids

# Galaxy clusters

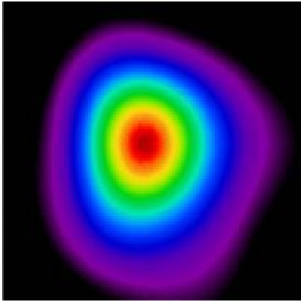
- The largest and most massive gravitationally bound objects

(Voit, 2005)



X-ray
ICM at $\sim 10^7\mathrm{K}$
Thermal bremsstrahlung
$\sim 10\,\mathrm{keV}$
$L_X \sim 10^{43} - 10^{45}\,\mathrm{erg/s}$

Optical
$\sim 100 - 1000$ of member galaxies
Lensing of background galaxies

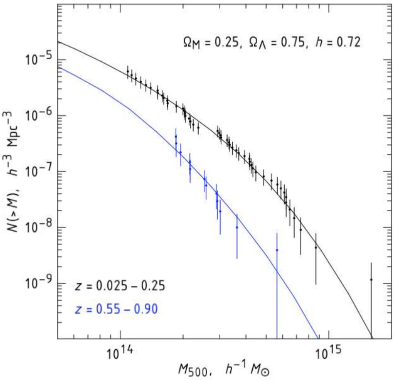


Microwaves
(Sunyaev-Zel'dovich)
ICS of CMB photons by high-energy electrons
Independent of distance

# Galaxy clusters as cosmological probes

- Almost a century of history... (Zwicky, 1933)

- Cluster counts: extremely sensitive to cosmological parameters

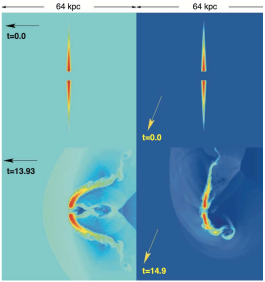



- And much more...
  - Constraining baryon (gas) fraction
  - Determination of $H_0$ and distance measurement using X-ray + tSZ
  - tSZ power spectrum ($C_\ell$)
  - Determination of the LSS 'peculiar' velocity field (measuring velocities)
  - Constraining Dark Energy EoS and its evolution, neutrinos, etc.

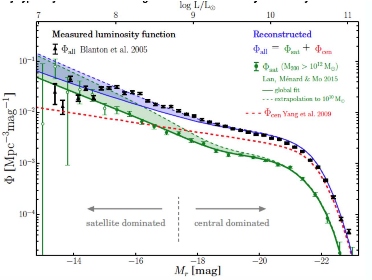
(Allen et al., 2011)

# Galaxy clusters as astrophysical laboratories

- The nearly closed-box nature of deep cluster gravitational potentials act as veritable astrophysical laboratories
  - Galaxy formation (Naab & Ostriker, 2017)
  - Effects on the surrounding IGM (e.g., AGN feedback, metal enrichment)
- Just a few examples (*not exhaustive at all!*)




Ram-pressure stripping (Quilis+00, Quilis+17)




Location matters (Lan+11)


Galactic outflows: SN, AGN, ... (e.g., Zhang18)

# Understanding galaxy clusters: the Kaiser (1986) self-similar model

## Why self-similarity?

- Primordial density fluctuations can be described by a power-law spectrum $\Longrightarrow$ scale-free initial conditions
- Gravity does not have a preferred scale

As long as gravity is the driving mechanism for GC formation, their properties ought to be described by scale-free relations (power laws)

- X-ray scaling relations (*in their simplest form*; c.f. Giodini, 2013):

$$M_{\Delta_z} \propto R_{\Delta_z}^3$$

$$M_{\Delta_z} \propto T_{\rm gas}^{3/2}$$

$$L_X \propto T_{\rm gas}^2$$

$f_{\rm gas}$ independent of $M_{\Delta_z}$

$$S \propto T_{\rm gas} \propto M_{\Delta_z}^{2/3}$$

...

# Understanding galaxy clusters beyond the self-similar model: numerical simulations

## Gas (collisional component): hydrodynamics in an expanding frame

$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\nabla \cdot [(1+\delta)\mathbf{v}] = 0$$
$$\frac{\partial \mathbf{v}}{\partial t} + \frac{1}{a}(\mathbf{v}\cdot\nabla)\mathbf{v} + H\mathbf{v} = -\frac{1}{a}\nabla\phi - \frac{1}{\rho a}\nabla p$$
$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla \cdot [(E+p)\mathbf{v}] = -3H(E+p) - H\rho v^2 - \frac{\rho \mathbf{v}}{a}\nabla\phi$$

EoS: $p = (\gamma - 1)\rho\varepsilon$

$\Longrightarrow$ Can be written as a *hyperbolic system of conservation laws*

## DM (collisionless): *N*-Body

$$\mathbf{v} = a(t)\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t}$$
$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{1}{a(t)}\nabla\phi - H(t)\mathbf{v}$$

$\Longrightarrow$ $6N$ ODEs

## Poisson equation

$$\nabla^2\phi = 4\pi G a^2 \rho_B \delta_T, \quad \delta_T = \delta + \delta_{\mathrm{DM}} + \delta_* + 2$$

## Additional physics (§3.1.3)

Cooling & heating, stars, feedback, etc.

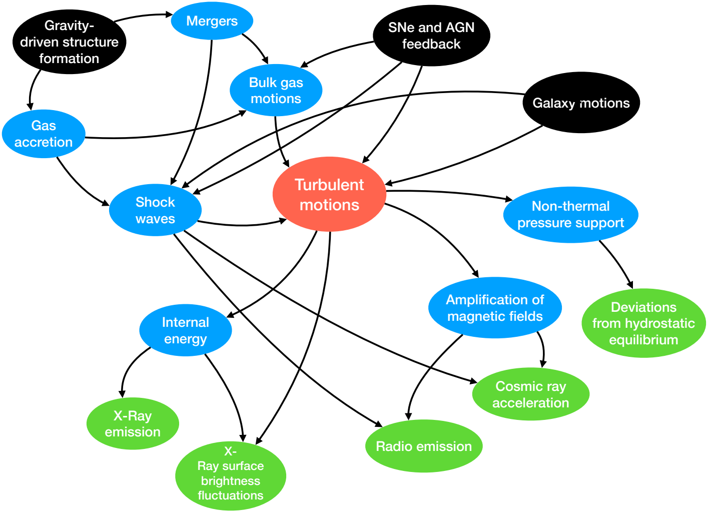
Dolag, 2008; Borgani & Kravtsov, 2011; Kravtsov & Borgani, 2012; Planelles et al., 2015

$\delta \equiv \frac{\rho - \rho_B}{\rho_B}$: density contrast, $\mathbf{v}$: peculiar velocity, $\varepsilon$: specific internal energy, $p$: pressure, $\gamma$: adiabatic index

$E \equiv \rho\varepsilon + \frac{1}{2}\rho v^2$: *total* energy density, $\phi$: peculiar gravitational potential, $H(z) \equiv \frac{\dot{a}}{a}$: Hubble parameter

# Understanding galaxy clusters outskirts

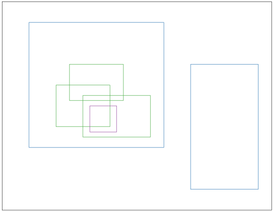
- The exciting new frontier of cluster astrophysics... (Walker, 2019)



# Cosmological simulations with MASCLET

(Quilis, 2004; Quilis+2020)

- MASCLET: Mesh Adaptive Scheme for CosmologicaL structurE evoluTion
  - Eulerian hydrodynamics based on HRSC techniques for the gas
  - $N$-Body (Particle-Mesh) for evolving DM
- Coupled by gravity solver (Poisson eqn)
- On top of that,
  - Cooling & UV heating
  - Star formation
  - SN and AGN feedback
- Recently $\Longrightarrow$ MHD version (Quilis+20)
- All these elements are built into an AMR scheme:
  - Can be varied upon application
  - Hierarchy of refinement levels with $\Delta x_{\ell+1}/\Delta x_\ell = 1/2$



# Cosmological simulations with MASCLET: analysis tools

- ASOHF: adaptive SO (DM) halo finder (Planelles+10, Knebe +11)
- HALMA: adaptive FoF (stellar) halo finder (Navarro-González+13)
- Shock Finder (Planelles+13)
- SPEV: radiative transfer code (Mimica+09, Cuesta-Martínez+15, Mimica+16, Planelles+18)
- vortex: Helmholtz-Hodge decomposition in AMR data (+ extensions; Vallés-Pérez+21a,b)
- Void finder (Ricciardelli+13,14, Vallés-Pérez+21c)

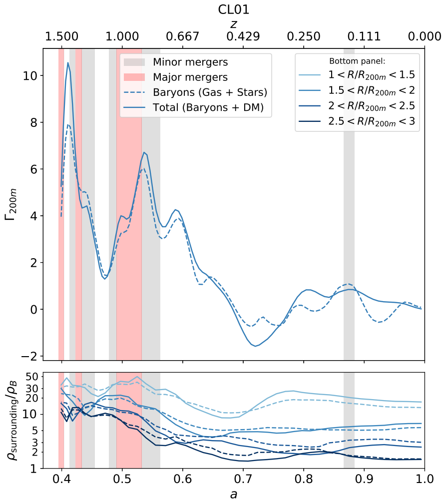
# Galaxy cluster mergers and accretion of matter

- How do galaxy clusters grow?
  - Which are the main channels for clusters mass growth?
  - Do DM and baryons behave differently?

$$\Gamma_\Delta = \frac{\mathrm{d}\log M_\Delta}{\mathrm{d}\log a}$$

(Diemer & Kravtsov, 2014)

- Most of the mass growth occurs during mergers
- However, a large amount of gas is '*left behind*' and slowly reaccreted
- Larger differences between DM and gas for less massive systems



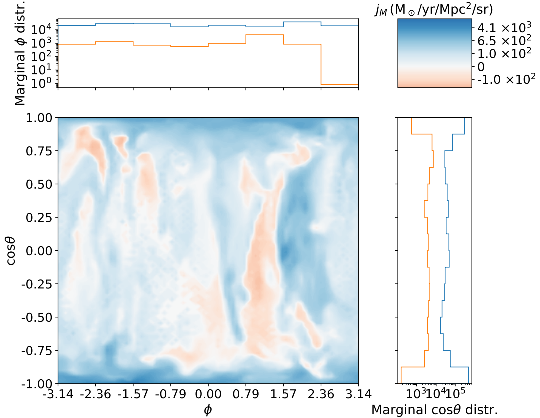

*Vallés-Pérez, Planelles & Quilis* (2020, MNRAS 499, 2303)

# Accretion of gas onto galaxy clusters

- Does gas fall isotropically into the cluster, or does it fall through some preferential directions?

$$j_M = \frac{\Delta M}{R_{\rm vir}^2 \Delta\Omega \Delta t}$$

  - How does this evolve with cosmic time?
  - Does the gas from all directions present the same properties (e.g., entropy, temperature, baryon fraction, etc.)




*Vallés-Pérez, Planelles & Quilis* (2020, MNRAS 499, 2303)

# Turbulence in galaxy clusters (I: numerical tools)

## Helmholtz-Hodge decomposition (Vallés-Pérez, Planelles & Quilis, 2021, CPC 263, 107892)

$$\mathbf{v} = \mathbf{v}_\mathrm{c} + \mathbf{v}_\mathrm{s}$$
$$\nabla \times \mathbf{v}_\mathrm{c} = \mathbf{0} \implies \mathbf{v}_\mathrm{c} = -\nabla\phi$$
$$\nabla \cdot \mathbf{v}_\mathrm{s} = 0 \implies \mathbf{v}_\mathrm{s} = \nabla \times \mathbf{A}$$

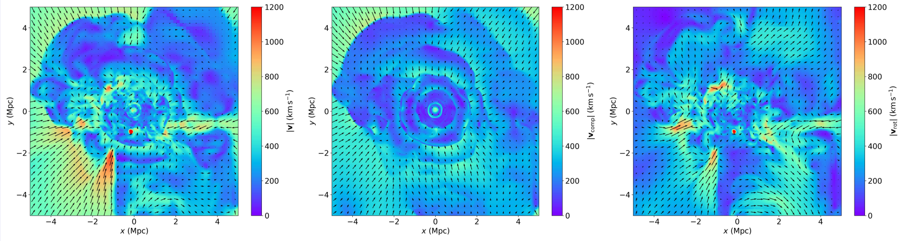
Had been done for fixed grids (e.g., Vazza+17), but never for AMR data.

It is easy to show that $\phi$, $\mathbf{A}$ are the solution to:

$$\nabla^2\phi = -\nabla\cdot\mathbf{v} \qquad \nabla^2\mathbf{A} = -\nabla\times\mathbf{v}$$

Elliptic PDEs, formally equivalent to Poisson equations!

- FFT (Green's Method) for the base grid (if periodic boundaries)
- Iterative methods (SOR) for the AMR grids




The implementation is publicly avilable!: https://github.com/dvallesp/vortex

# Turbulence in galaxy clusters (I: numerical tools)

## Reynolds decomposition (Vallés-Pérez, Planelles & Quilis, 2021, MNRAS 504, 510)

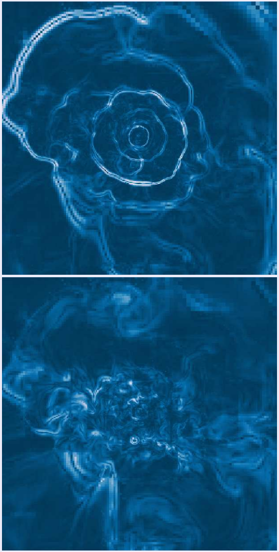
$$\mathbf{v}(\mathbf{x}) \equiv \langle \mathbf{v} \rangle(\mathbf{x}) + \delta \mathbf{v}(\mathbf{x})$$

$$\langle \mathbf{v} \rangle(\mathbf{x}) = \iiint_V \mathrm{d}\mathbf{y}\, \mathbf{v}(\mathbf{x}+\mathbf{y}) G_L(\mathbf{y};\mathbf{x})$$

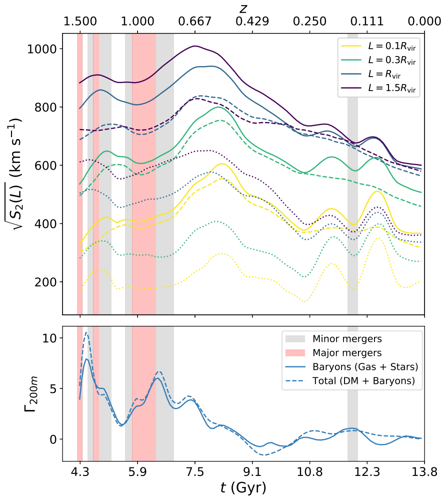
ICM turbulence is extremely *multi-scale*: $L = L(\mathbf{x})$.

Again, there were algorithms for fixed grids (Vazza+17) and SPH (Valdarnini19): at each position, increase $L(\mathbf{x})$ until $\delta\mathbf{v}(\mathbf{x})$ converges.

Extended for AMR, and included in `vortex`.



# Turbulence in galaxy clusters (II: some results)




(Vallés-Pérez, Planelles & Quilis, 2021, MNRAS 504, 510)

Global statistic of turbulence: Velocity structure functions:

$$S_p(L) = \langle|\mathbf{v}(\mathbf{x} + L\hat{\mathbf{n}}) - \mathbf{v}(\mathbf{x})|^p\rangle_{\hat{\mathbf{n}},\mathbf{x}}$$

We study $[S_p(L)](z)$ at some fixed $L$.

- Accretion rates tightly correlated (although delayed) with velocity fluctuations
- Solenoidal motions are dominant at all scales

# Turbulence in galaxy clusters (II: some results)

- Enstrophy:

$$\epsilon \equiv \frac{1}{2}\omega^2, \qquad \boldsymbol{\omega} \equiv \nabla \times \mathbf{v}$$

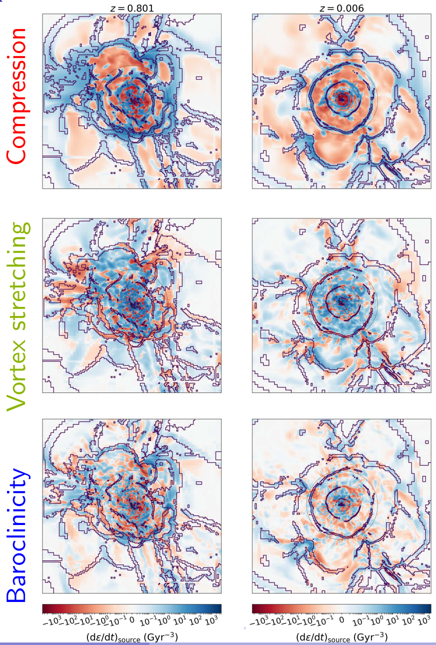
  - Easy evolution equation

$$\frac{\partial \epsilon}{\partial t} + \frac{1}{a}\nabla \cdot (\epsilon \mathbf{v}) = -2H\epsilon$$

$$-\frac{1}{a}\epsilon(\nabla \cdot \mathbf{v}) + \frac{1}{a}\omega(\omega \cdot \nabla)\mathbf{v}$$

$$+\frac{\boldsymbol{\omega}}{\rho^2 a}(\nabla\rho \times \nabla P)$$

(Vallés-Pérez, Planelles & Quilis, 2021, MNRAS 504, 510)



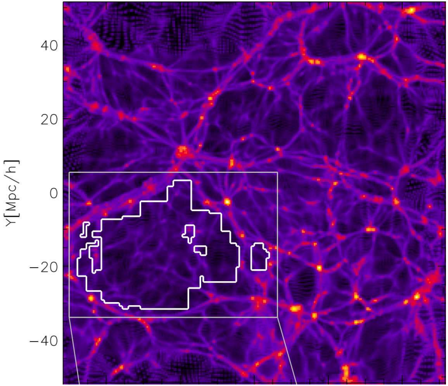
# What does the future hold?

- Systematic observation of clusters outskirts
  - In radio (e.g., SKA)
    - Accretion shocks of clusters
    - Particle acceleration
    - Magnetic fields
  - In X-ray (e.g., Athena)
    - Explore the thermodynamic conditions in the outskirts
    - How does gas fall into the cluster?
- Large SZ surveys $\implies$ Discovery of high-redshift systems
  - kSZ $\implies$ Directly measure gas proper motions!

- Still a lot of work to do to understand the physical processes acting on galaxy and GC formation!

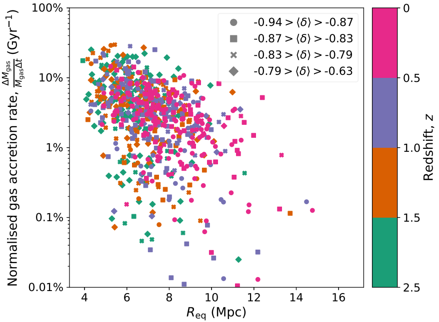
# The complexity of cosmic flows around cosmic voids

- Huge ($R_{\mathrm{eq}} \gtrsim 10\,\mathrm{Mpc}$), underdense ($\langle\rho\rangle/\rho_B \sim 0.1$) regions filling up most of the Universe
- Notable applications to:
  - Cosmology
  - Galaxy evolution
- Dominated by outflows




(Ricciardelli+13)

# Void Replenishment: How Voids *Accrete* Matter Over Cosmic History




(Vallés-Pérez, Quilis & Planelles, 2021, ApJ Letters 920, L2)

- We defined a sample of $\sim 200$ ellipsoidal voids, from a $100\, h^{-1}\, \mathrm{Mpc}$ simulation
- Using a pseudo-Lagrangian algorithm, we compute mass fluxes through their boundaries
  - 10% of the mass in voids accreted from overdense regions
  - Reaching 35% for a significant fraction
  - Part of the gas in voids could have been partially pre-processed outside

Thanks! Time for questions & comments?

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