N-body Simulations in Cosmology

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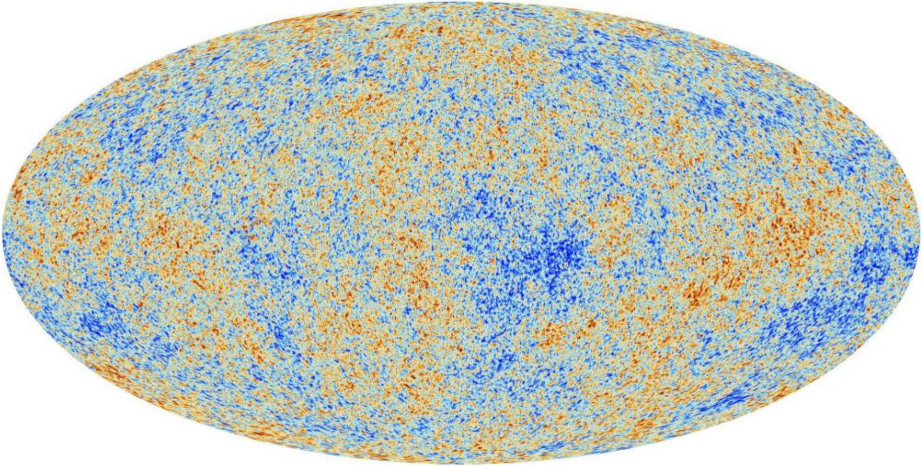
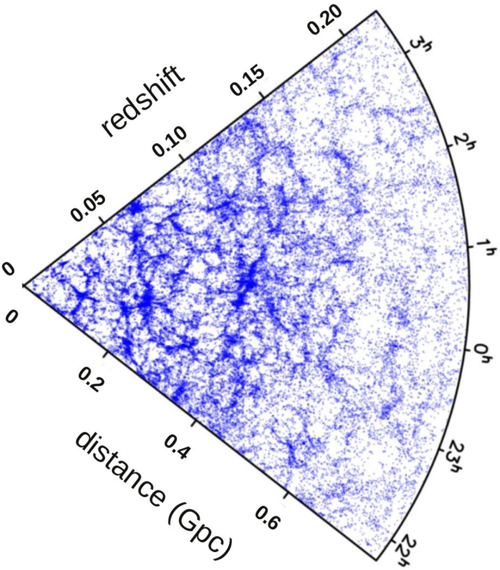
Seminário ao Grupo de Cosmologia, Departamento de Física da UFES – Vitória, 27/09/2013

Cosmic Microwave Background



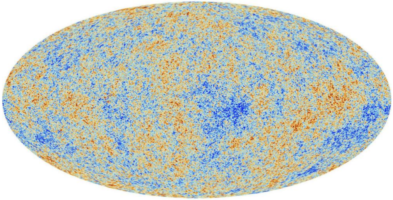
Planck (2013)

Galaxy surveys

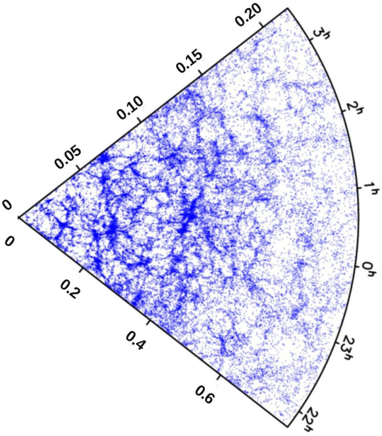


2dF

Early universe:
highly homogeneous

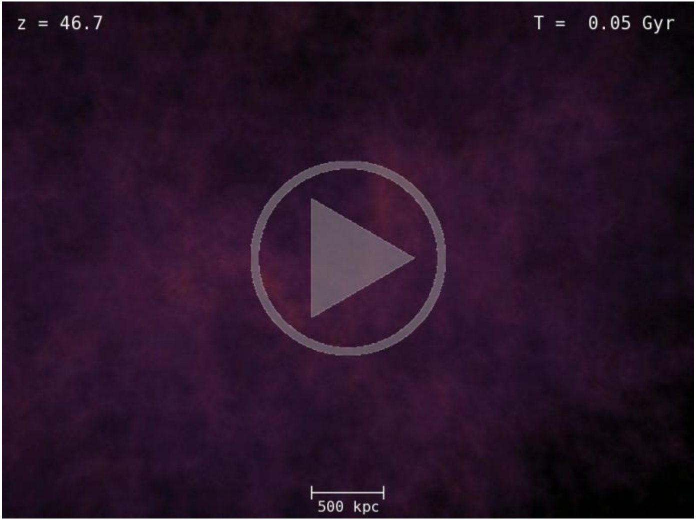


Present universe:
a lot of structure



numerical simulations

Aquarius simulation



http://www.youtube.com/watch?v=HbFhB5T6hiE

Springel et al. (2008)

The gravitational N-body problem

- Dark matter amounts to $\sim 80\%$ of total mass
- Assume no baryons: collisionless dynamics

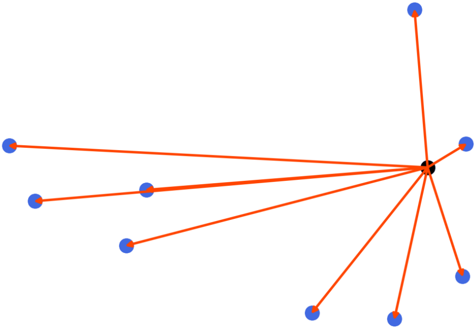
- Newtonian gravity:

$$\Phi(\mathbf{r}_i) = -G \sum_{j=1}^{N} \frac{m_j}{|\mathbf{r}_i - \mathbf{r}_j|^2 + \epsilon^2} \qquad , \qquad \ddot{\mathbf{r}}_i = -\boldsymbol{\nabla}\Phi(\mathbf{r}_i)$$

- Set of $3N$ coupled non-linear second-order differential equations

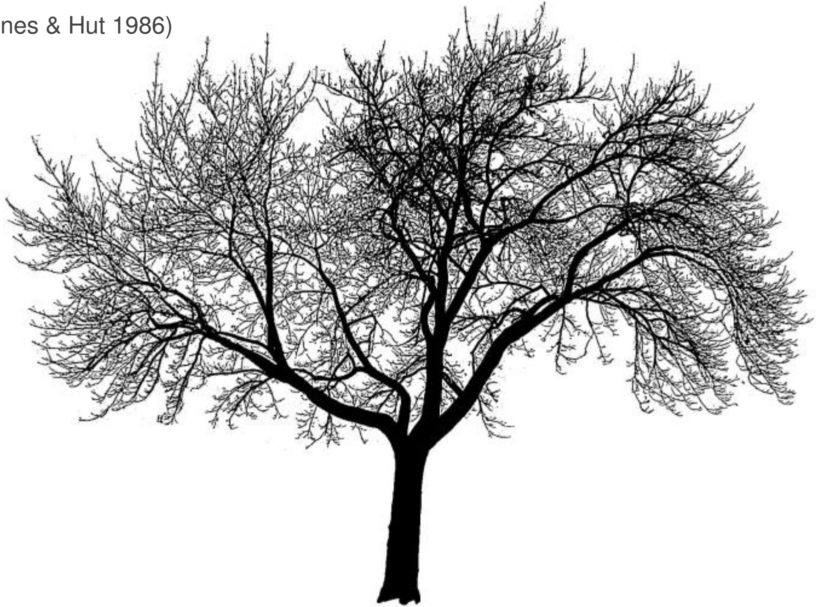
The gravitational N-body problem

- **Direct summation** is not feasible in practice ($\propto N^2$)
- other algorithms: e.g. **tree code** ($\propto N \log N$)

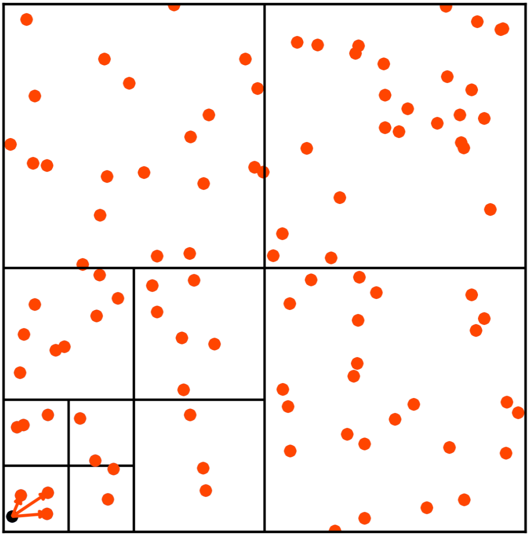


Tree code

(Barnes & Hut 1986)



Number of operations is drastically reduced



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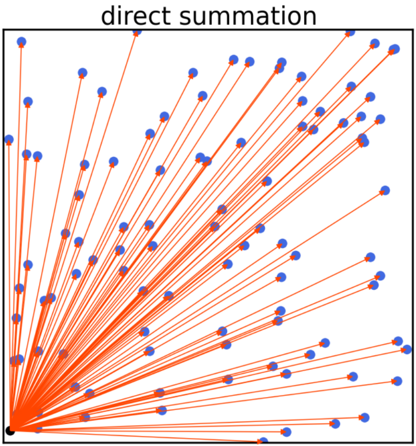
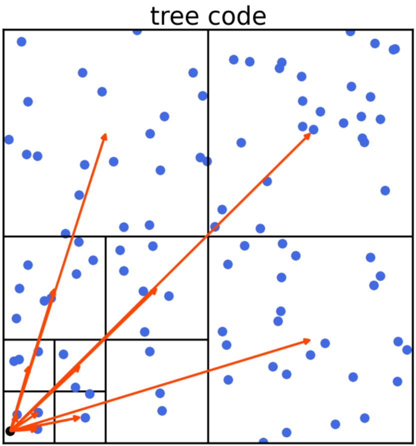
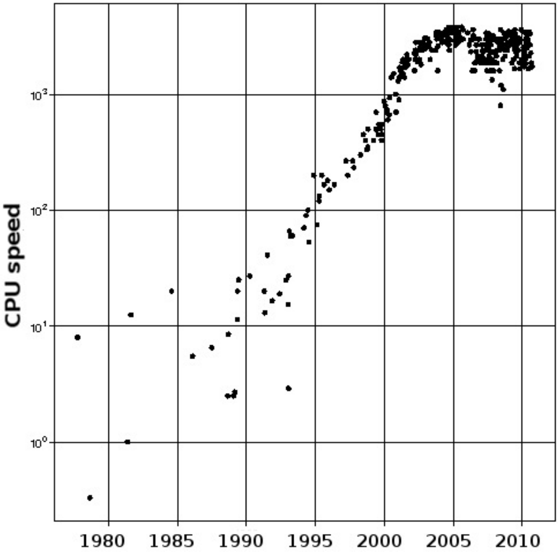


$\propto N^2$

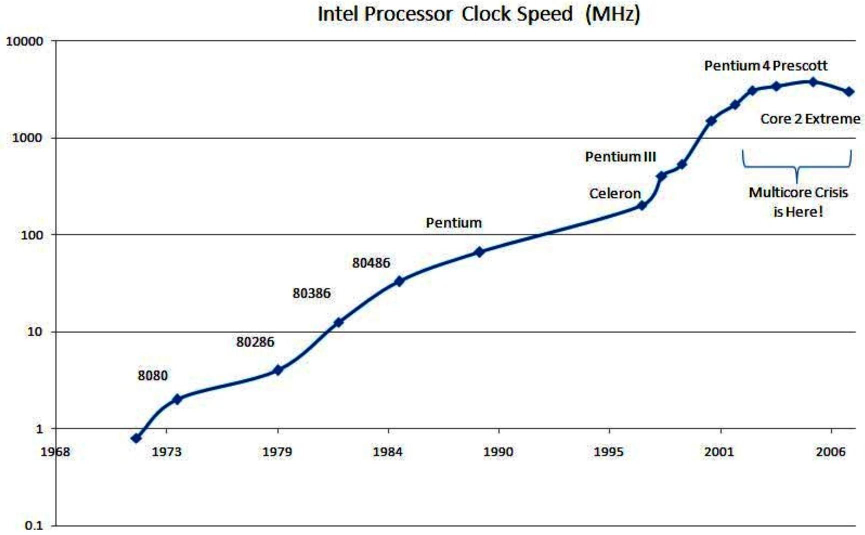


$\propto N \log N$

Breakdown of Moore's law for individual CPU speed



Breakdown of Moore's law for individual CPU speed



Parallel Computing

Simulation	Supercomputer	Type	Center	Country	core-hours [10^6]	N_{cores}	memory [TB]	disk space [TB]
DEUS FUR	*Curie Thin Nodes*	Bullx B510	Très Grand Centre de Calcul (TGCC)	France	10	38016	230	3000
Horizon Run 3	*Tachyon II*	Sun Blades B6275	KISTI Supercomputing Center	Korea	4	8240	21	400
Millennium-XXL	*JuRoPa*	Bull / Sun Blades	Forschungzentrum Jülich	Germany	2.86	12288	28.5	100
Horizon-4Π	*Platine*	Bull Novascale 3045	Commissariat a l'Energie Atomique	France	8	6144	14.7	300
Millennium-II	*VIP*	IBM Power 6	Rechenzentrum Garching	Germany	1.4	2048	8	35
MultiDark Run1	*Pleiades*	SGI Altix ICE	NASA Ames Research Center	USA	0.4	4000	8	20
Bolshoi	*Pleiades*	SGI Altix ICE	NASA Ames Research Center	USA	6	13900	12	100
Phoenix A-1	*DeepComp 7000*	HS21/x3950 Cluster	Chinese Academy of Science	China	1.9	1024	3	15
Aquarius A-1	*HLRB-II*	SGI Altix 4700	Leibniz Rechenzentrum Garching	Germany	3.5	1024	3	45
GHalo	*Marenostrum*	IBM JS21 Blades	Barcelona Supercomputing Center	Spain	2	1000	1	60
Via Lactea II	*Jaguar*	Cray XT4	Oak Ridge National Lab	USA	1.5	3000	0.3	20

Kuhlen et al. (2012)

DM-only simulations

Name	Code	L_{box} $[h^{-1}Mpc]$	N_p $[10^9]$	m_p $[h^{-1}\,M_\odot]$	ϵ_{soft} $[h^{-1}kpc]$
COSMIC					
DEUS FUR	RAMSES-DEUS	21000	550	1.2×10^{12}	$40.0^\dagger$
Horizon Run 3	GOTPM	10815	370	2.5×10^{11}	150.0
Millennium-XXL	GADGET-3	3000	300	6.2×10^{9}	10.0
Horizon-4Π	RAMSES	2000	69	7.8×10^{9}	$7.6^\dagger$
Millennium-II	GADGET-3	100	10	6.9×10^{6}	1.0
MultiDark Run1	ART	1000	8.6	8.7×10^{9}	$7.6^\dagger$
Bolshoi	ART	250	8.6	1.4×10^{8}	$1.0^\dagger$

†For AMR simulations (RAMSES, ART) ϵ_{soft} refers to the highest resolution cell width.

Name	Code	L_{hires} $[h^{-1}Mpc]$	$N_{p,hires}$ $[10^9]$	$m_{p,hires}$ $[h^{-1}\,M_\odot]$	ϵ_{soft} $[h^{-1}kpc]$
CLUSTER					
Phoenix A-1	GADGET-3	41.2	4.1	6.4×10^{5}	0.15

Name	Code	L_{hires} [Mpc]	$N_{p,hires}$ $[10^9]$	$m_{p,hires}$ $[M_\odot]$	ϵ_{soft} [pc]
GALACTIC					
Aquarius A-1	GADGET-3	5.9	4.3×10^{9}	1.7×10^{3}	20.5
GHalo	PKDGRAV2	3.89	2.1×10^{9}	1.0×10^{3}	61.0
Via Lactea II	PKDGRAV2	4.86	1.0×10^{9}	4.1×10^{3}	40.0

Kuhlen et al. (2012)

Parallel Computing

Rank	Site	Name	Cores	Rpeak *(Petaflops)*
1	National University of Defense Technology (China)	Tianhe 2	3,120,000	55
2	DOE/SC/Oak Ridge National Lab (United States)	Titan	560,640	27
3	DOE/NNSA/LLNL (UnitedStaes)	Sequoia	1,572,864	20
4	RIKEN/AICS (Japan)	K computer	705,024	11
5	DOE/SC/Argonne National Lab (United States)	Mira	786,432	10
...	...	...	...	...
7	Forschungszentrum Juelich (Germany)	JUQUEEN	458,752	5,8
...	...	...	...	...
12	CINECA (Italy)	Fermi	163,840	2,1
...	...	...	...	...
15	CEA/TGCC-GENCI (France)	Curie	77,184	1,7

Luminet (2013)

Hydrodynamics

- **Collisionless simulations** (only DM):
  - gravitational *N*-body problem is well understood
  - robust numerical solutions
  - little doubt about how to achieve high accuracy
- **Hydrodynamical simulations** (also gas):
  - fundamentally different numerical methods in use
  - Eulerian (mesh) *vs.* Lagrangian (particles)
- **Sub-grid physics**:
  - cooling, star formation, supernova feedback, AGN, etc

Hydrodynamics

Euler equation:

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\boldsymbol{\nabla} P}{\rho} - \nabla\Phi$$

Continuity equation:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\boldsymbol{\nabla}\cdot\mathbf{v} = 0$$

Energy conservation:

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\boldsymbol{\nabla}\cdot\mathbf{v} - \frac{\Lambda}{\rho}$$

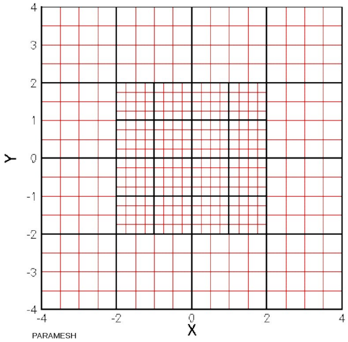
Equation of state:

$$P = (\gamma - 1)\,\rho\,u$$

Numerical methods to discretize a fluid

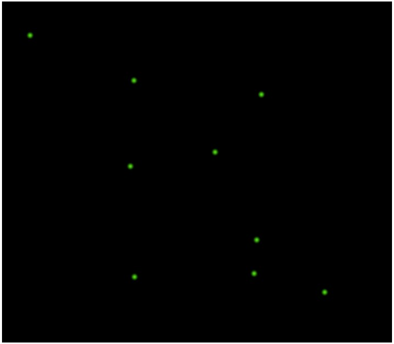
Eulerian:

- discretization of *space*
- AMR
  (Adaptive Mesh Refinement)



Lagrangian:

- discretization of *mass*
- SPH
  (Smoothed Particle Hydrodynamics)



Numerical methods to discretize a fluid

Eulerian:

- discretization of *space*
- AMR
  (Adaptive Mesh Refinement)

Lagrangian:

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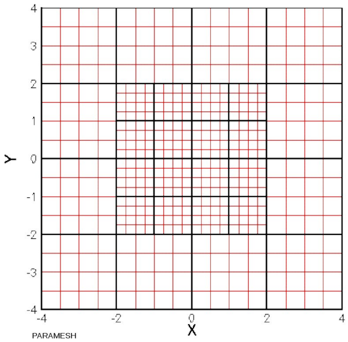
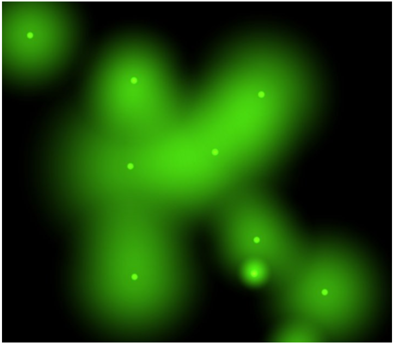
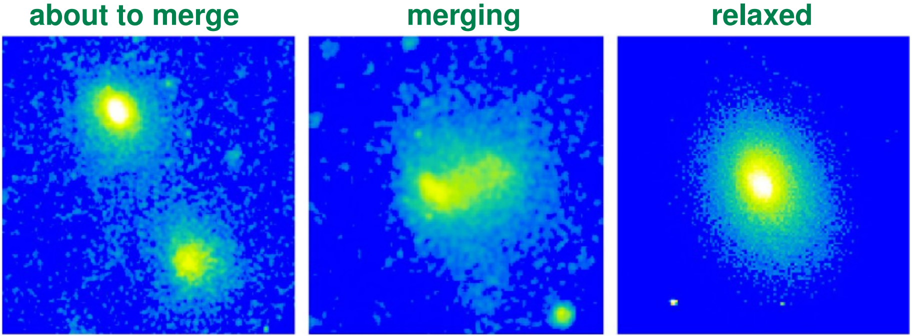




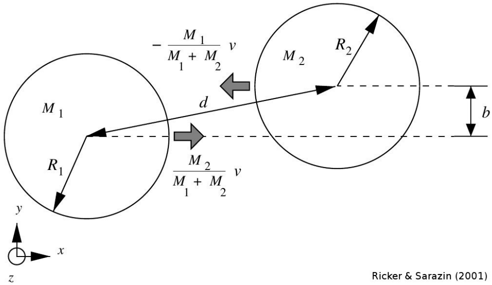
Cluster mergers

Cluster mergers



Markevitch & Vikhlinin (2007)

Cluster mergers are the mechanisms by which clusters assemble



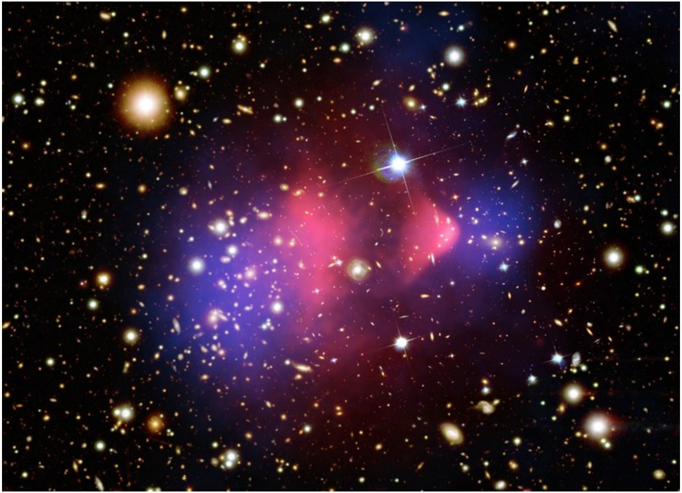
Ricker & Sarazin (2001)

- $M_{vir} \sim 10^{14}\ M_\odot$
- $R_{vir} \sim 1$ Mpc

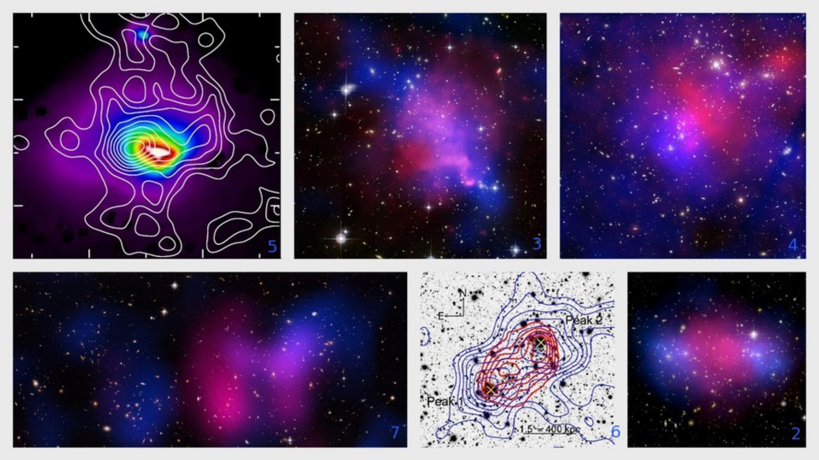
- $b \sim 100$ kpc
- $v \sim 1000$ km/s
- $\Delta t \sim 1$ Gyr

- Mach $\sim 1 - 3$
- $E_{grav} \sim 10^{63}$ erg

Dark matter is collisionless
Gas has pressure

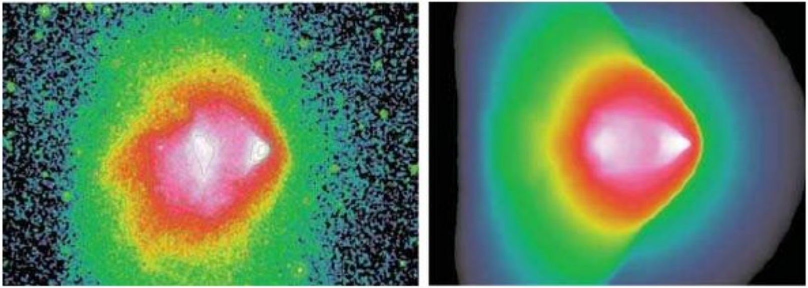


Clusters in which gas has become dissociated from dark matter



1) 1E 0657-56 (Clowe et al. 2006), *"Bullet Cluster"*
2) MACS J0025.4-1222 (Bradac et al. 2008)
3) Abell 520 (Mahdavi et al. 2007), *"Train Wreck"*
4) Abell 2744 (Merten et al. 2011), *"Pandora's Cluster"*
5) Abell 2163 (Okabe et al. 2011)
6) Abell 1758 (Ragozzine et al. 2011)
7) DLSCL J0916.2+2951 (Dawson 2012), *"Musket Ball Cluster"*

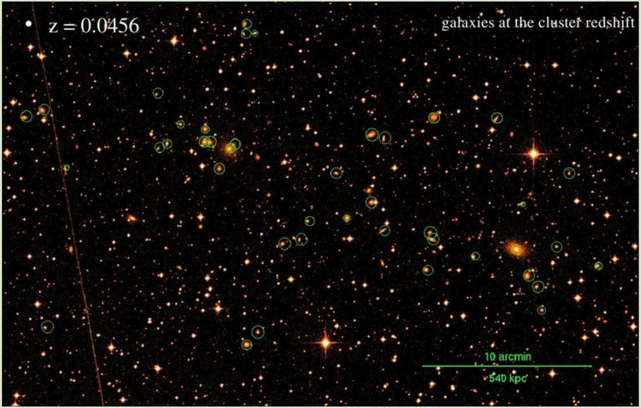
Simulations of the Bullet Cluster



Springel & Farrar (2007)

Abell 3376

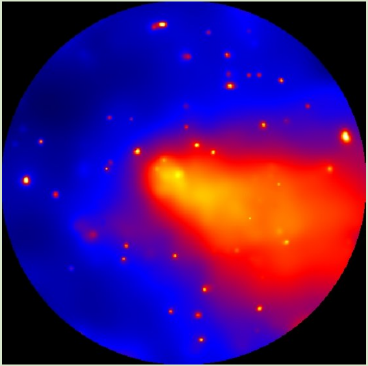
Abell 3376



- $M_{vir} = 5.2 \times 10^{14}\ M_\odot$
- $z = 0.0456$

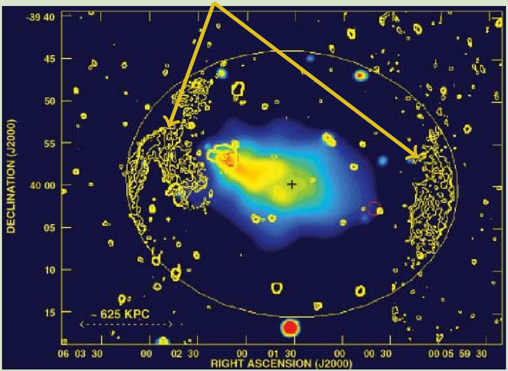
Abell 3376: a nearby merging cluster

X-ray emission



XMM-Newton

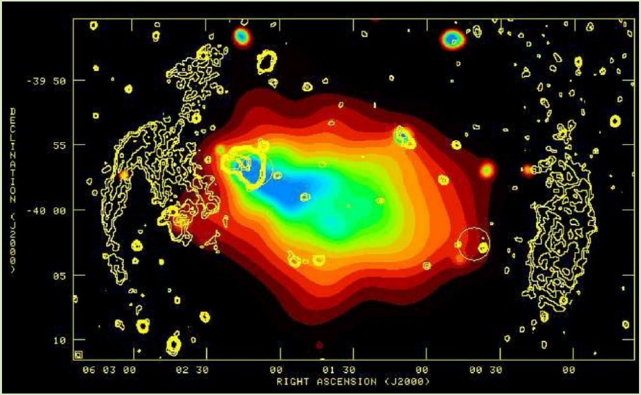
radio relics



ROSAT (X-ray) + VLA (radio)

Bagchi, Durret, Lima Neto & Paul (2006)

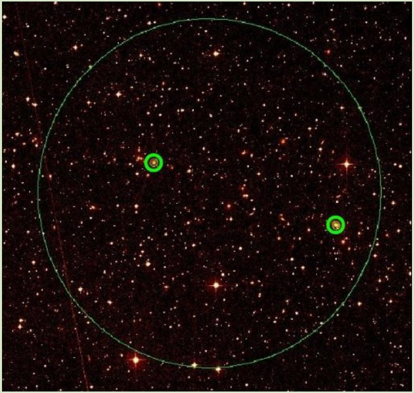
Abell 3376: radio



- giant (2 Mpc) radio lobes around cluster
- no associated jets
- magnetic field $\sim 1\mu$G

Abell 3376: brightest cluster galaxies

optical (galaxies)



Abell 3376: brightest cluster galaxies

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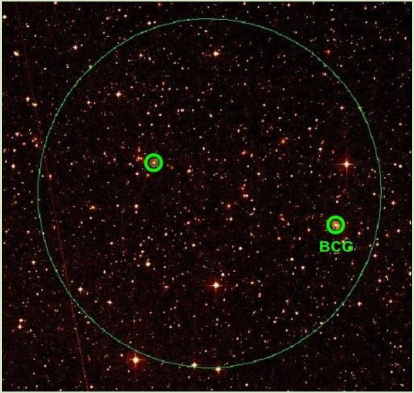
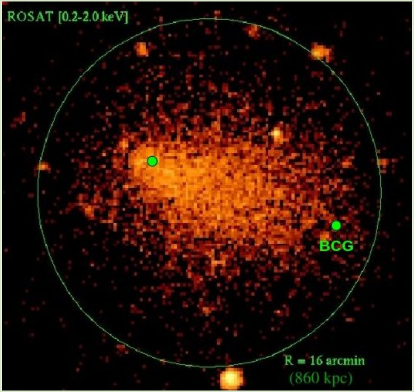


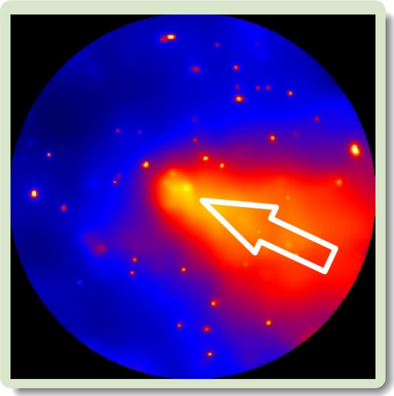
Abell 3376: brightest cluster galaxies

X-ray (intracluster gas)



- second BCG coincides with X-ray peak; *BCG does not*
- separation: 970 kpc

Numerical simulations: initial conditions



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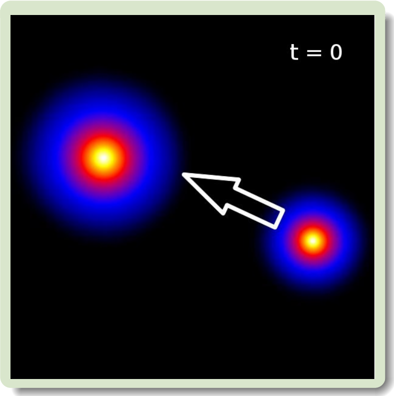

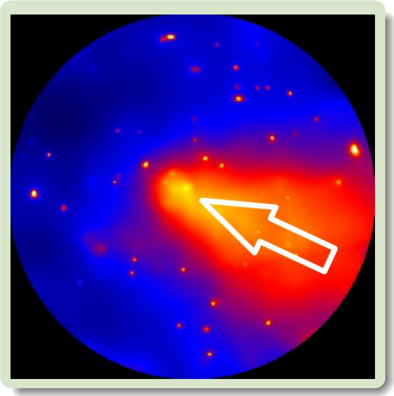

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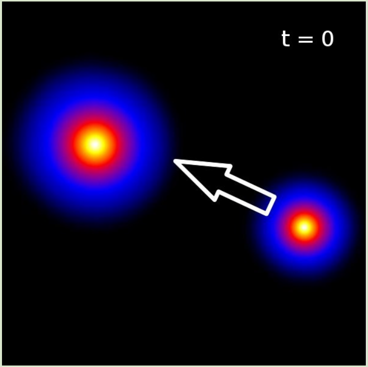
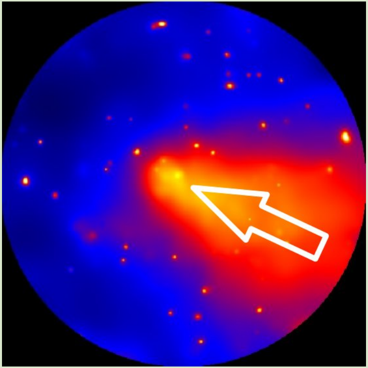
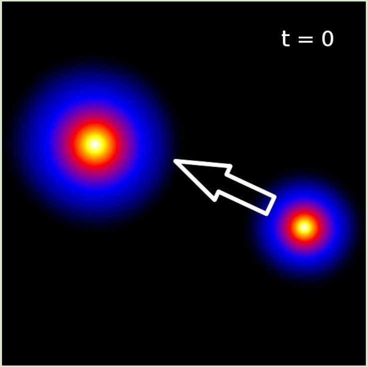


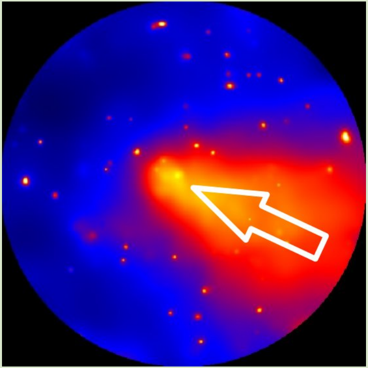


initial parameters:

- DM density profile
- gas density profile
- initial relative velocity
- mass ratio
- gas fraction
- impact parameter

Numerical simulations: initial conditions





initial parameters:

- DM density profile
- gas density profile
- initial relative velocity
- mass ratio
- gas fraction
- impact parameter

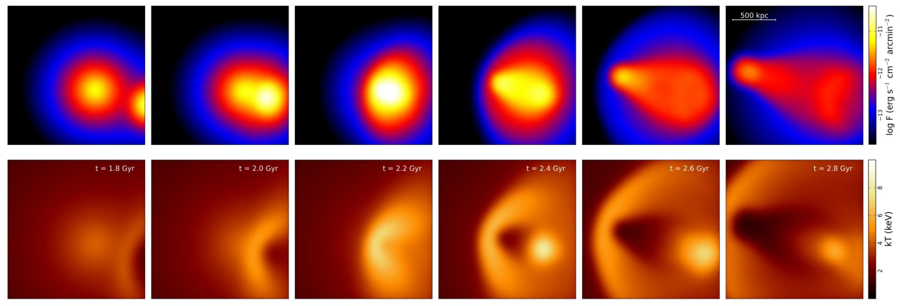
***a posteriori*:**

- time after central passage
- projection angles

Numerical simulations

Numerical simulations

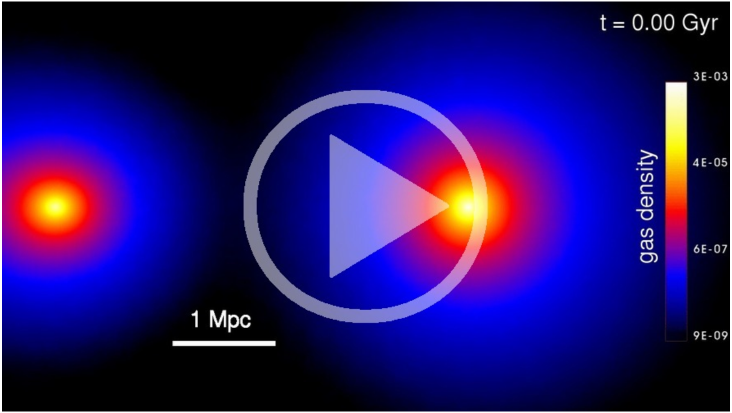
X-ray surface brightness



emission-weighted temperature

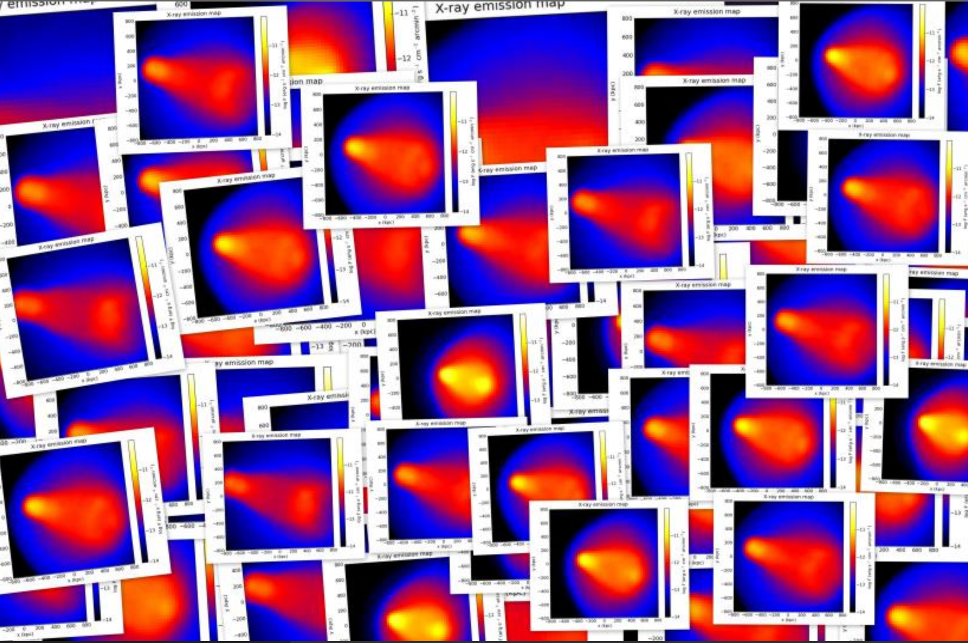
time

Numerical simulations: evolution



http://www.youtube.com/watch?v=XYyYIOwdVcw

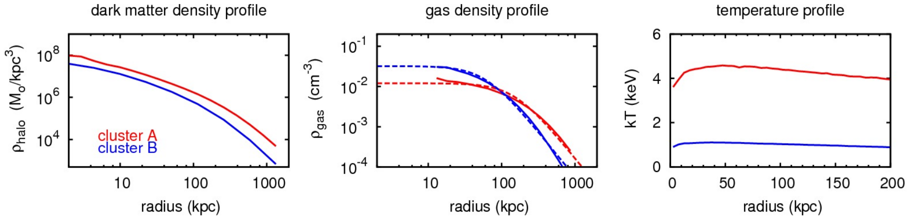
Numerical simulations: parameter space sample



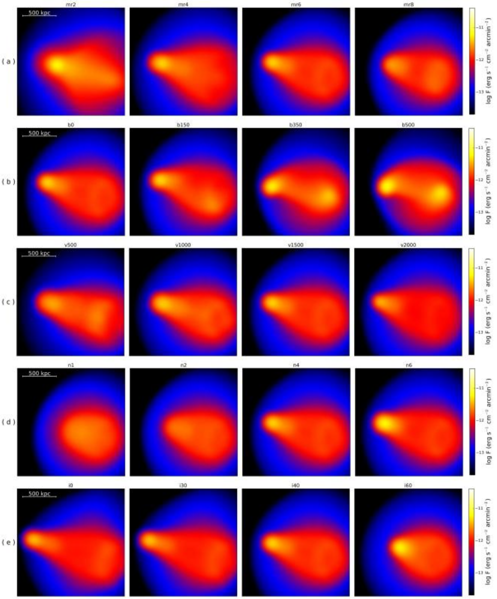
Numerical simulations: initial conditions

initial parameters:

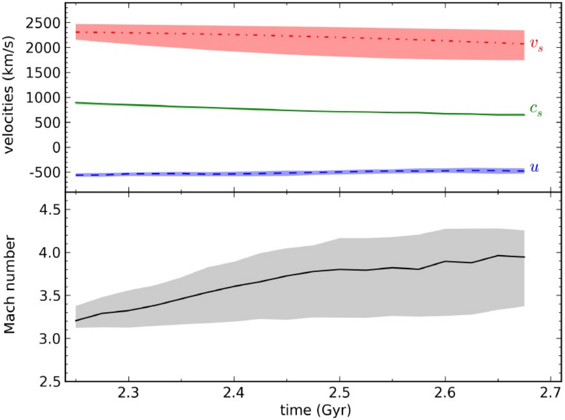
- DM density profile : Hernquist (similar to NFW)
- gas density profile : Dehnen γ=0 (similar to β-model)
- initial relative velocity
- mass ratio
- gas fraction : $f_{gas} = 0.18$
- impact parameter
- temperature profile : from hydrostatic equilibrium



Numerical simulations: parameter space



Mach number



shock velocity (c.o.m.)

sound speed

velocity of upstream gas (c.o.m.)

$$\mathcal{M} = \frac{v_s - u}{c_s}$$

Mach number: Rankine-Hugoniot jump conditions

emission
map

temperature
map

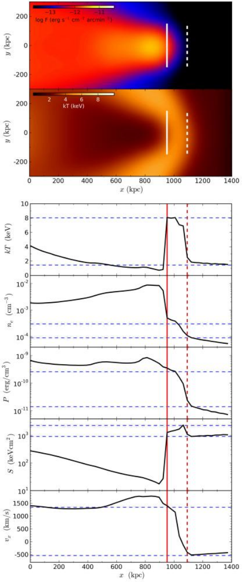
temperature

density

pressure

entropy

streaming
gas velocity



$$\frac{T_2}{T_1} = \frac{5\mathcal{M}^4 + 14\mathcal{M}^2 - 3}{16\mathcal{M}^2}$$

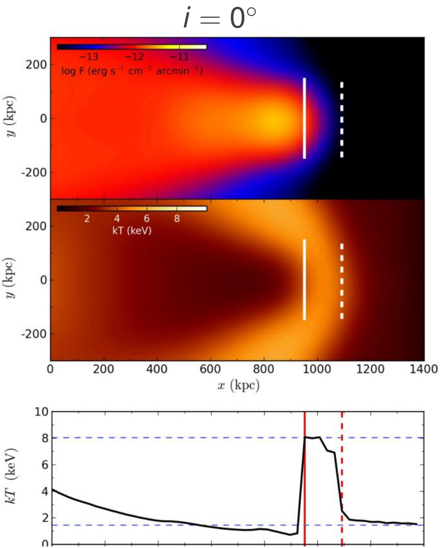
$$\frac{n_2}{n_1} = \frac{4\mathcal{M}^2}{\mathcal{M}^2 + 3}$$

$$\frac{P_2}{P_1} = \frac{5\mathcal{M}^2 - 1}{4}$$

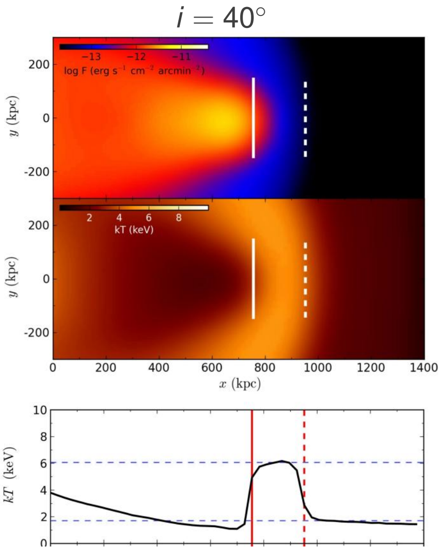
$$\frac{S_2}{S_1} = \left(\frac{5\mathcal{M}^2 - 1}{4}\right)\left(\frac{4\mathcal{M}^2}{\mathcal{M}^2 + 3}\right)^{-5/3}$$

$$(v_{x,2} - v_{x,1}) = (v_s - u)\left(\frac{3\mathcal{M}^2 - 3}{4\mathcal{M}^2}\right)$$

Mach number: inclination



$\mathcal{M}$ = 3.9

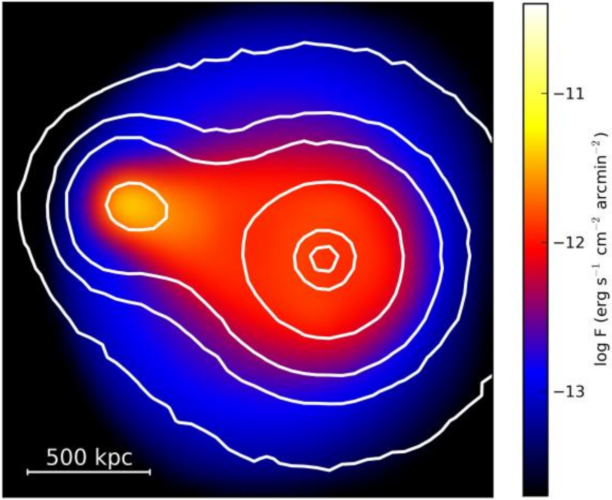


$\mathcal{M}$ = 2.9

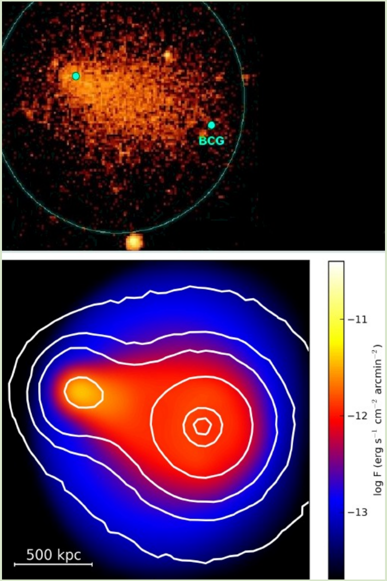
Where is the dark matter?

Two peaks of dark matter

Projected mass (total)



BCG separation and dark matter



Summary (A3376)

reproduced features

- virial mass
- integrated X-ray flux
- approximate X-ray morphology
- temperature range
- (proxy of) BCG separation

approximate constraints

- collision axis inclined by i=40° wrt plane of the sky
- observed $\sim$0.5 Gyr after central passage
- mass ratio 1/6 – 1/8
- Mach $\sim$3–4
- small impact parameter (b<150 kpc), if any

Summary (A3376)

We have proposed a specific scenario of a dynamical history for the merging event of Abell 3376.

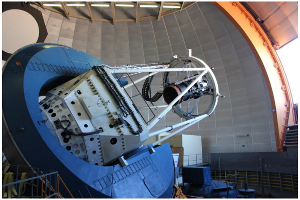
We have offered a possible combination of parameters that accounts for several of its features.

Machado & Lima Neto (2013)

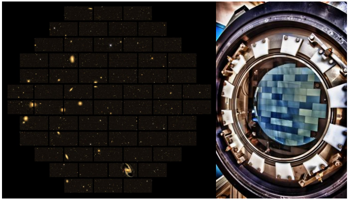
Perspectives: distribution of dark matter

Mass maps from gravitational weak lensing will either corroborate this scenario or necessitate its improvement.

Cerro Tololo



Blanco Telescope



Dark Energy Camera

Abell 2052

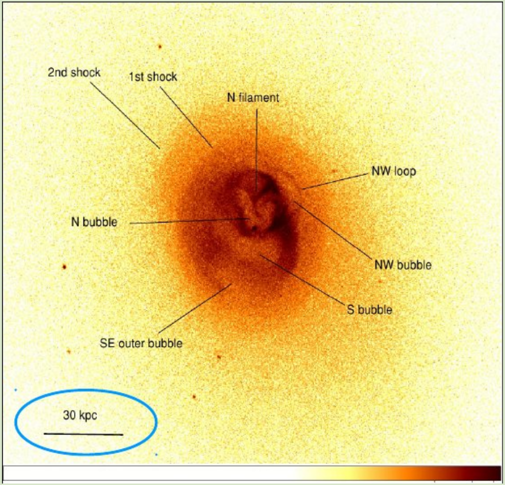
Abell 2052

moderately rich cluster at **z=0.035**

Blanton et al. (2011)

- *small scales:* bubbles (cavities) evacuated by AGN radio lobes
- *large scales:* spiral feature

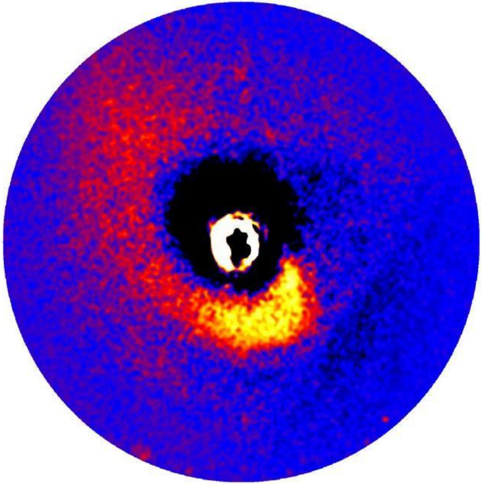
Abell 2052



Blanton et al. (2011)

- *small scales:* AGN $\sim$ 10 kpc

Abell 2052



Blanton et al. (2011)

- *large scales:* spiral $\sim$ 200 kpc

1. X-ray excess
2. low temperature
3. low entropy
4. high metallicity

Abell 2052

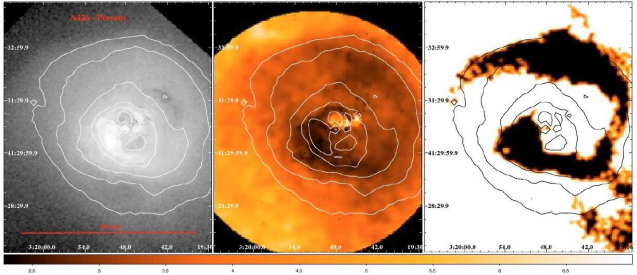
The sum of evidence:

- **surface brightness**
- **temperature**
- **entropy**
- **abundance**

points to the spiral being a

cold front (sloshing) feature resulting from an off-axis merger earlier in the cluster history

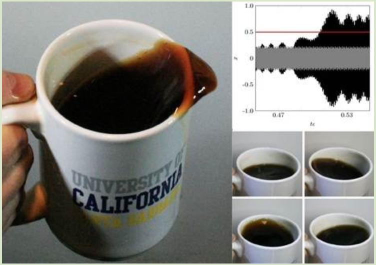
X-ray temperature substructure

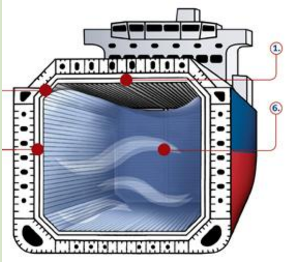


Laganá, Andrade-Santos & Lima Neto (2010)

- cold gas in spiral structures

Sloshing

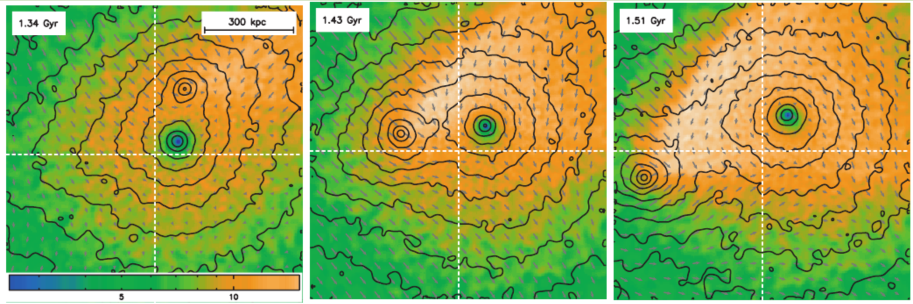




sloshing: the motion of a fluid (subjected to gravity) inside a container (which is also undergoing motion)

Sloshing: numerical simulations

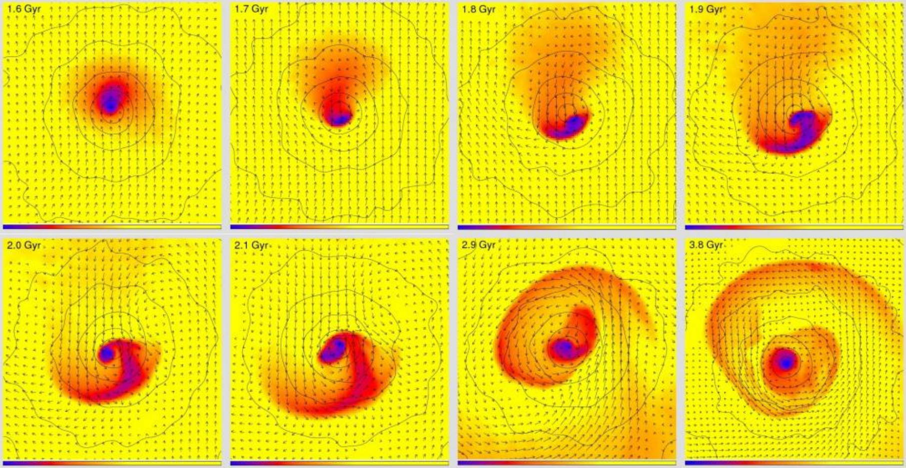
temperature



Ascasibar & Markevitch (2006)

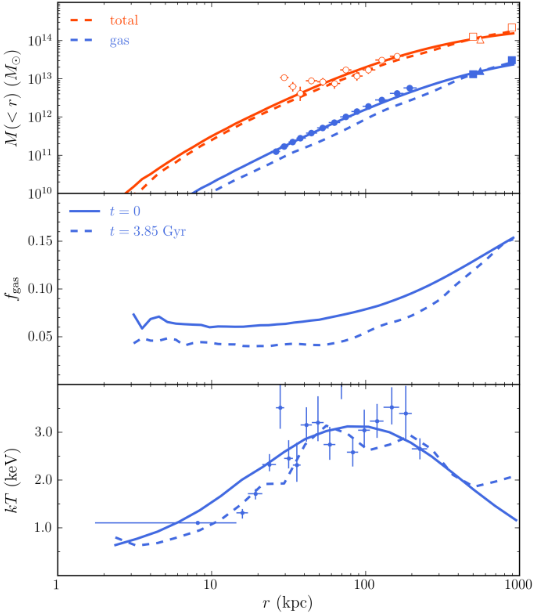
Sloshing: numerical simulations

temperature



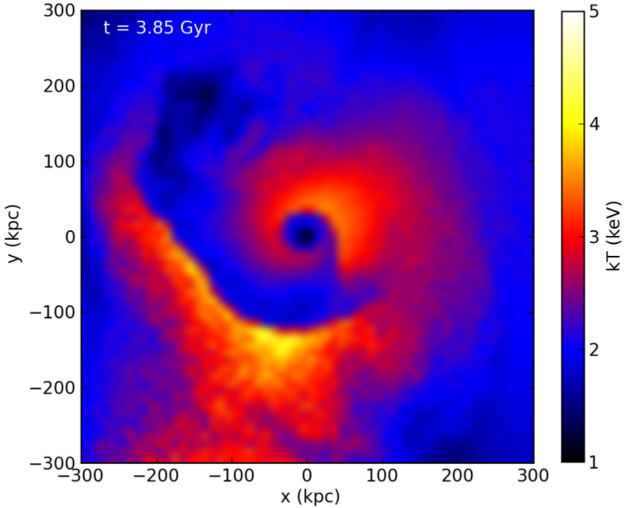
Ascasibar & Markevitch (2006)

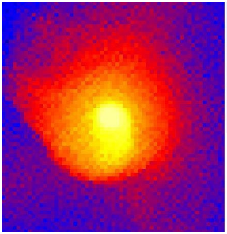
Abell 2052: preliminary results



Abell 2052: preliminary results

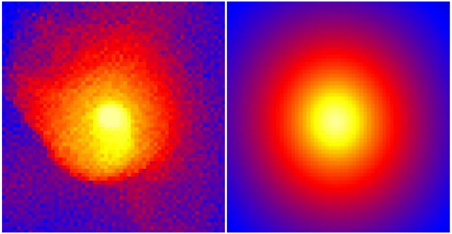
Abell 2052: temperature





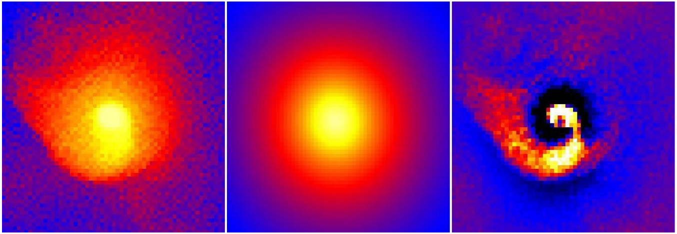
simulated X-ray

Abell 2052: X-ray excess



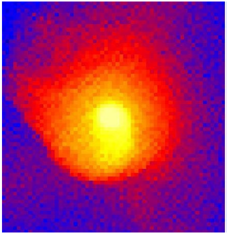
simulated X-ray fitted β-model

Abell 2052: X-ray excess

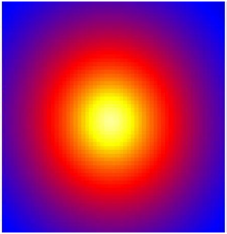


simulated X-ray fitted β-model residuals

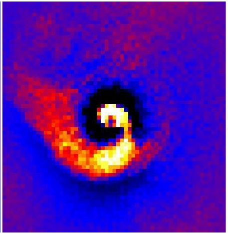
Abell 2052: X-ray excess



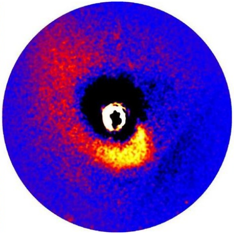
simulated X-ray



fitted β-model

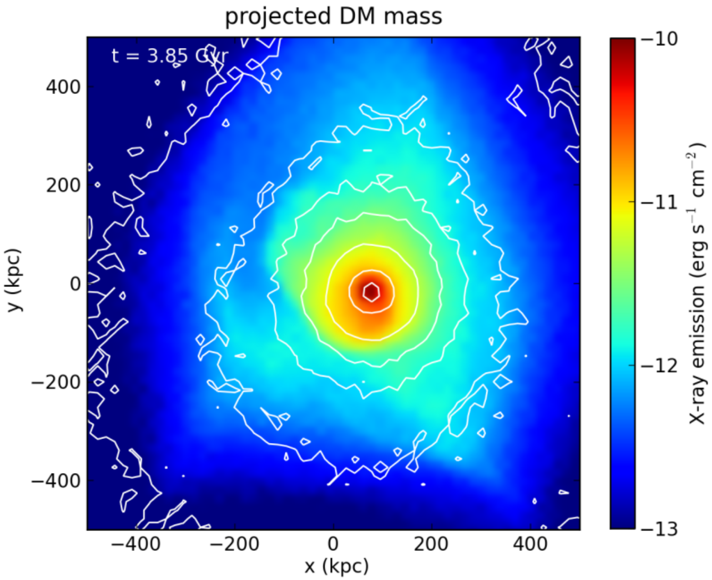


residuals

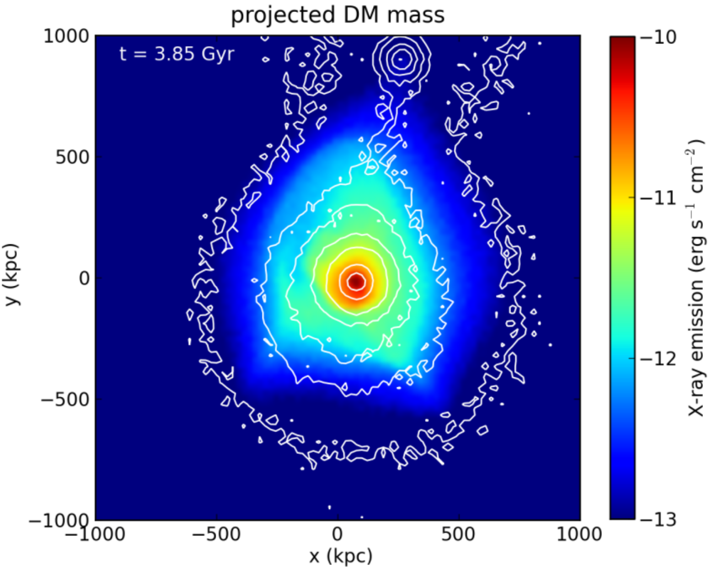


observation

Abell 2052: dark matter



Abell 2052: dark matter



Summary (A2052)

$$\begin{aligned}\frac{M_2}{M_1} &= 1/5 \\ b &= 100\ \mathrm{kpc} \\ v_0 &= 1000\ \mathrm{km/s} \\ i &= 0^\circ \\ \Delta t &\sim 0.9\ \mathrm{Gyr}\end{aligned}$$

Perspectives

Try to locate subcluster optical counterpart (low mass, gas-depleted, $\sim$Mpc away?)

☞ **“All models are wrong. Some models are useful.”**

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