Galaxy Clusters

Alexander Knebe (*Universidad Autonoma de Madrid*)

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“Galaxy clusters are the largest gravitationally bound objects in the Universe.”

- introduction
- properties
- scaling relations
- application

- **introduction**
- properties
- scaling relations
- application

Galaxy Clusters

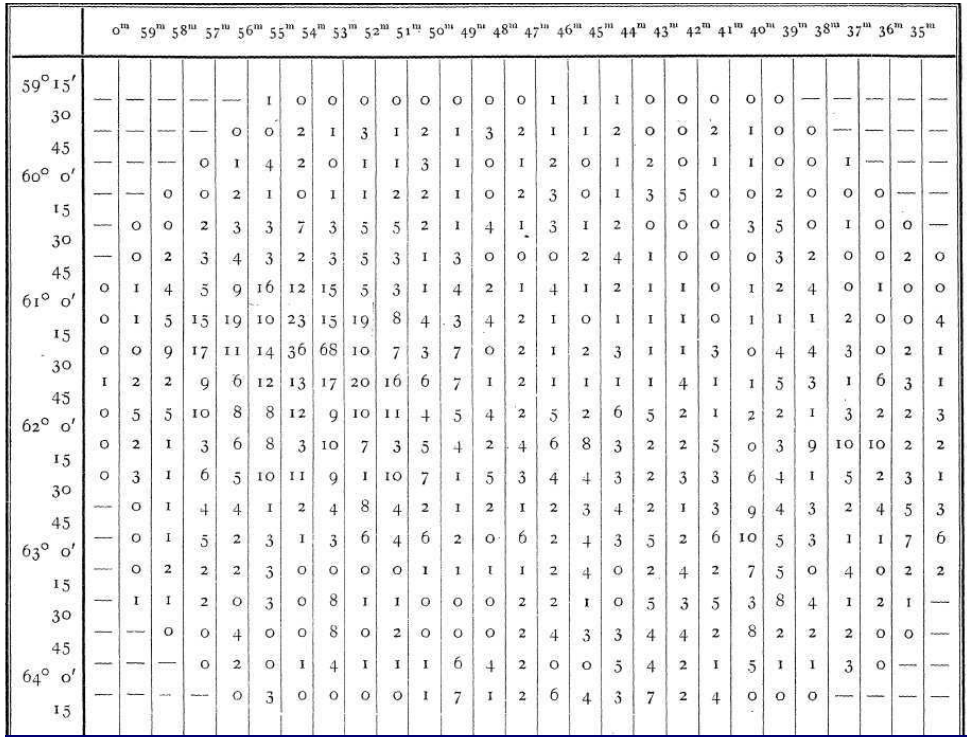
first mentioning?

Galaxy Clusters

introduction

first mentioning* by Max Wolf in 1901/02:

- “strange accumulation of nebulae”



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59° 15′	—	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—
30	—	—	—	—	0	0	2	1	3	1	2	1	3	2	1	1	2	0	0	2	1	0	0	—	—	—	—
45	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	1	0	0	1	—	—	—
60° 0′	—	—	0	0	2	1	0	1	1	2	2	1	0	2	3	0	1	3	5	0	0	2	0	0	0	—	—
15	—	0	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0	0	—
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61° 0′	0	1	5	15	19	10	23	15	19	8	4	3	4	2	1	0	1	1	1	0	1	1	1	2	0	0	4
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45	—	0	1	5	2	3	1	3	6	4	6	2	0	6	2	4	3	5	2	6	10	5	3	1	1	7	6
63° 0′	—	0	2	2	2	3	0	0	0	0	1	1	1	1	2	4	0	2	4	2	7	5	0	4	0	2	2
15	—	1	1	2	0	3	0	8	1	1	0	0	0	2	2	1	0	5	3	5	3	8	4	1	2	1	—
30	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	3	4	4	2	8	2	2	2	0	0	—
45	—	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	4	2	1	5	1	1	3	0	—	—
64° 0′	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—
15																											

(https://ui.adsabs.harvard.edu/abs/1902PAIKH...1..125W/abstract)
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*actually William Herschel already found in 1783 some 23 nebuluous things in that direction...

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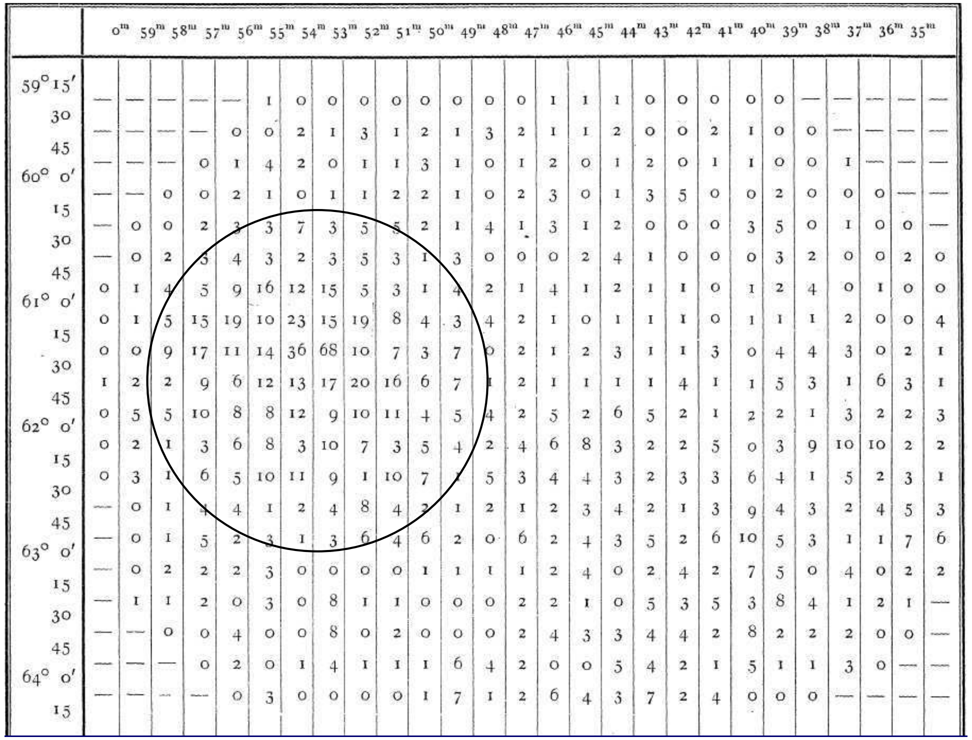

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59° 15′	—	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—
30	—	—	—	—	0	0	2	1	3	1	2	1	3	2	1	1	2	0	0	2	1	0	0	—	—	—	—
45	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	1	0	0	1	—	—	—
60° 0′	—	—	0	0	2	1	0	1	1	2	2	1	0	2	3	0	1	3	5	0	0	2	0	0	0	—	—
15	—	0	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0	0	—
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15	—	1	1	2	0	3	0	8	1	1	0	0	0	2	2	1	0	5	3	5	3	8	4	1	2	1	—
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64° 0′	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—
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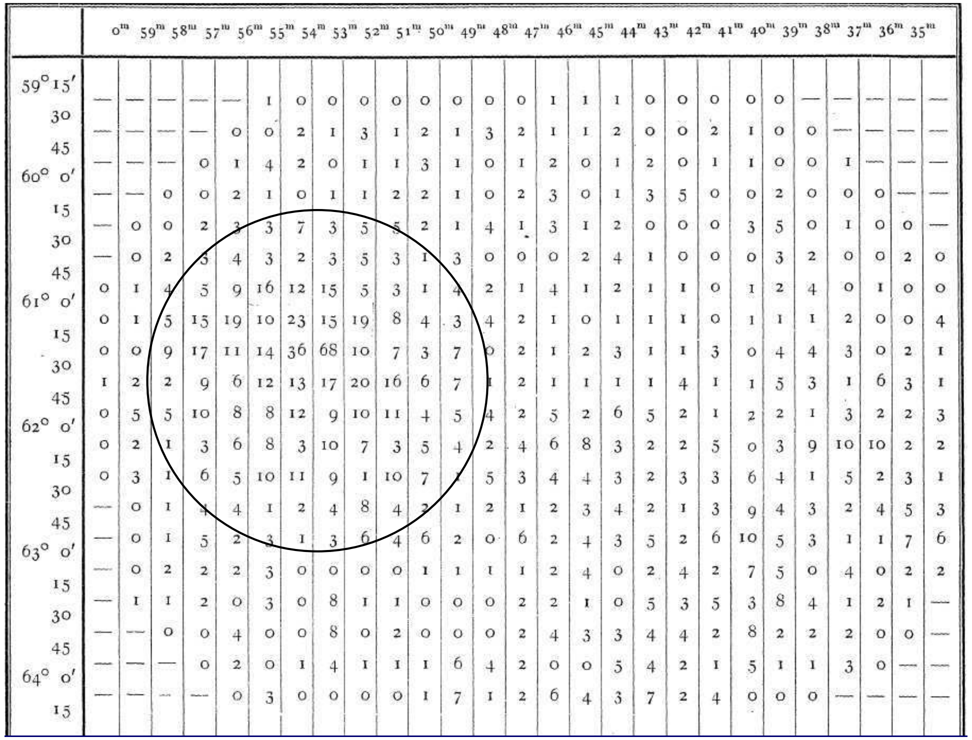

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$59^\circ 15'$	—	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—
30	—	—	—	—	0	0	2	1	3	1	2	1	3	2	1	1	2	0	0	2	1	0	0	—	—	—	—
45	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	1	0	0	1	—	—	—
$60^\circ 0'$	—	—	0	0	2	1	0	1	1	2	2	1	0	2	3	0	1	3	5	0	0	2	0	0	0	—	—
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45	0	1	4	5	9	16	12	15	5	3	1	4	2	1	4	1	2	1	1	0	1	2	4	0	1	0	0
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$64^\circ 0'$	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—
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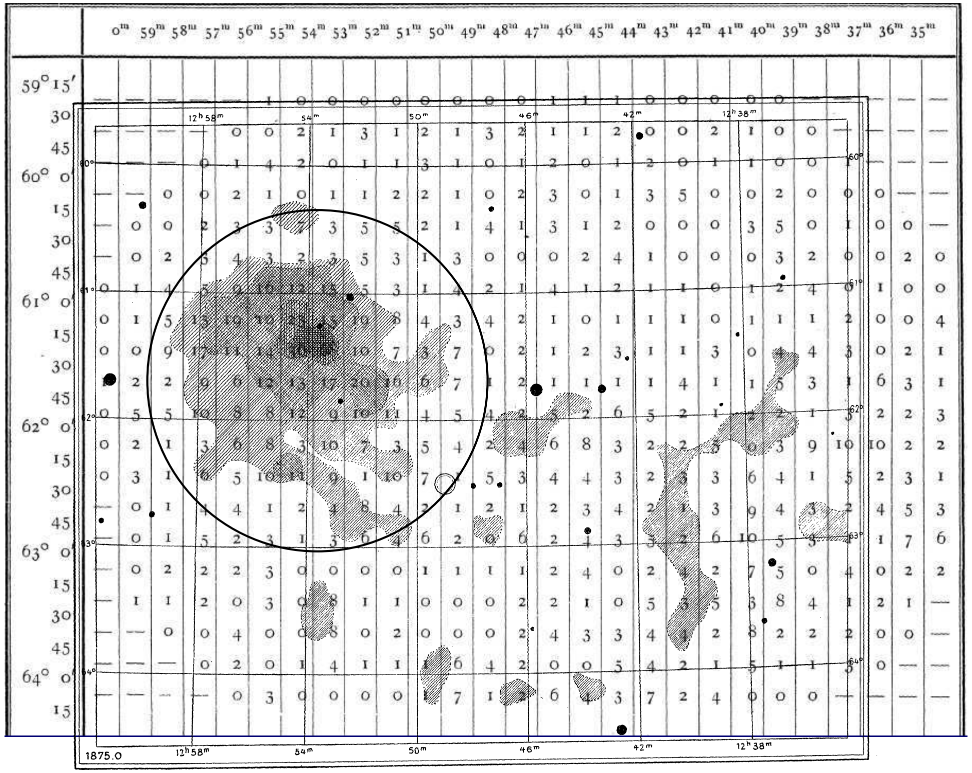

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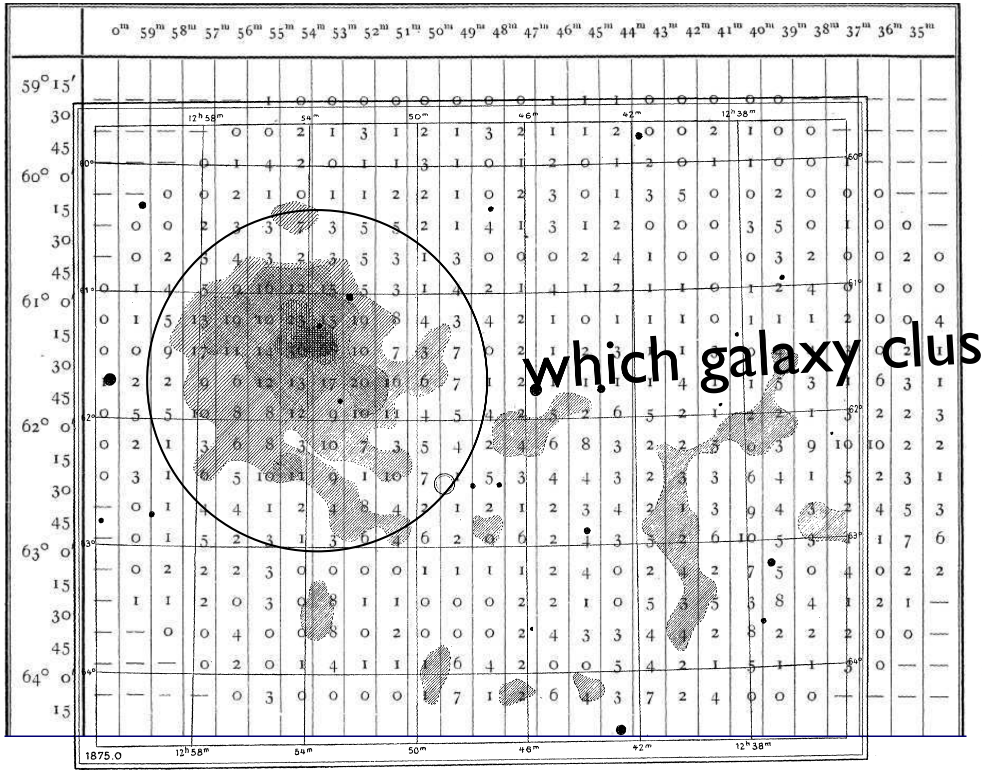

which galaxy cluster is this?

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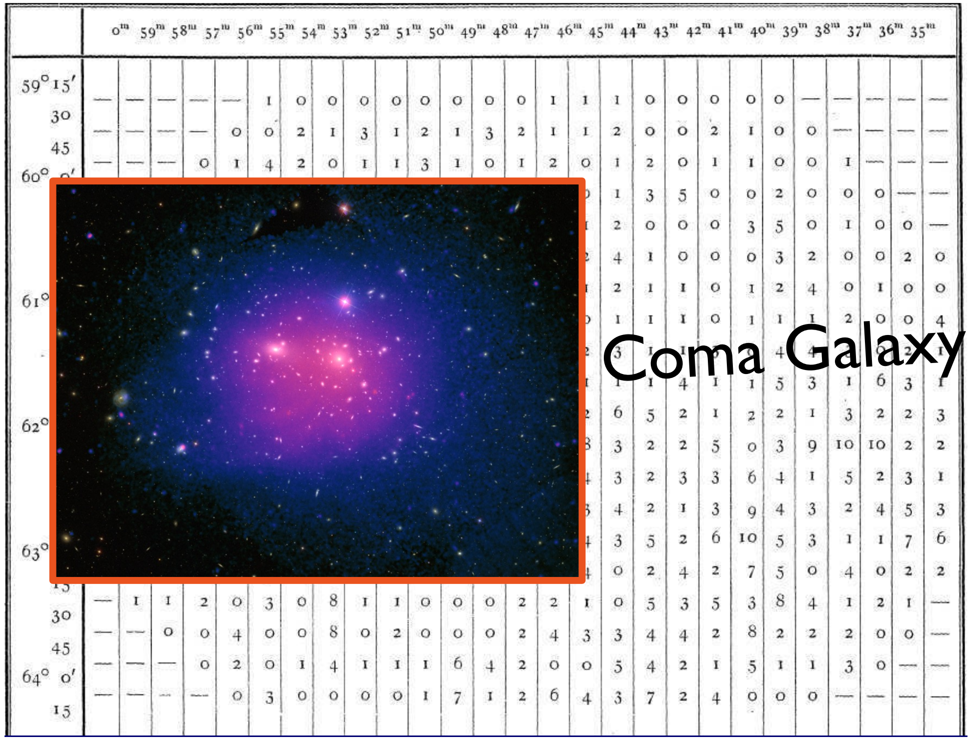

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59° 15′	—	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—
30	—	—	—	—	0	0	2	1	3	1	2	1	3	2	1	1	2	0	0	2	1	0	0	—	—	—	—
45	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	1	0	0	1	—	—	—
15	—	1	1	2	0	3	0	8	1	1	0	0	0	2	2	1	0	5	3	5	3	8	4	1	2	1	—
30	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	3	4	4	2	8	2	2	2	0	0	—
45	—	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	4	2	1	5	1	1	3	0	—	—
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Coma Galaxy Cluster!

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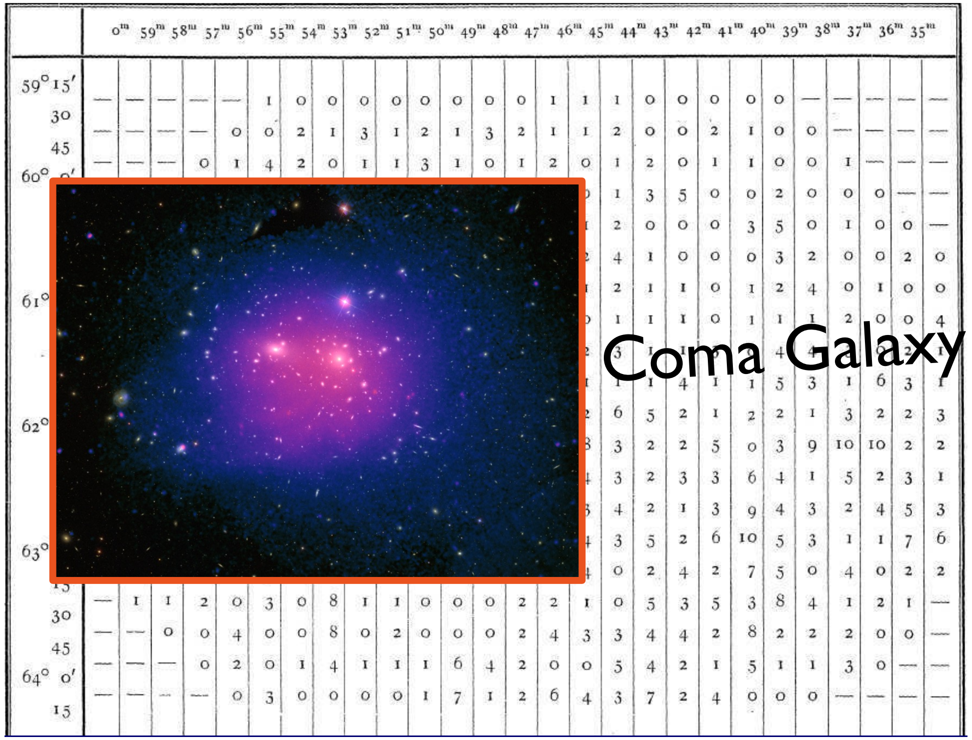

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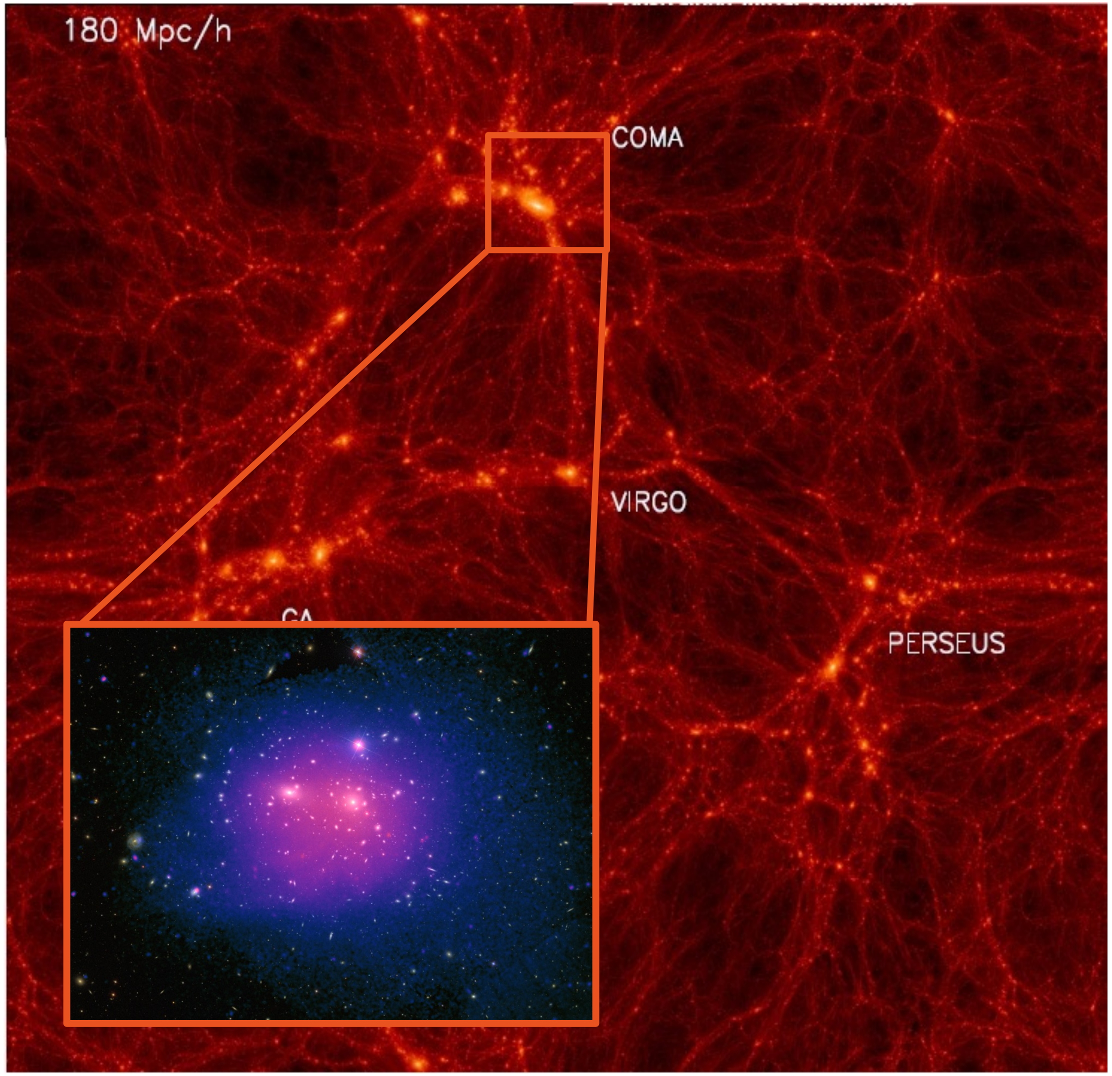

constrained simulation of the local universe
(www.clues-project.org)

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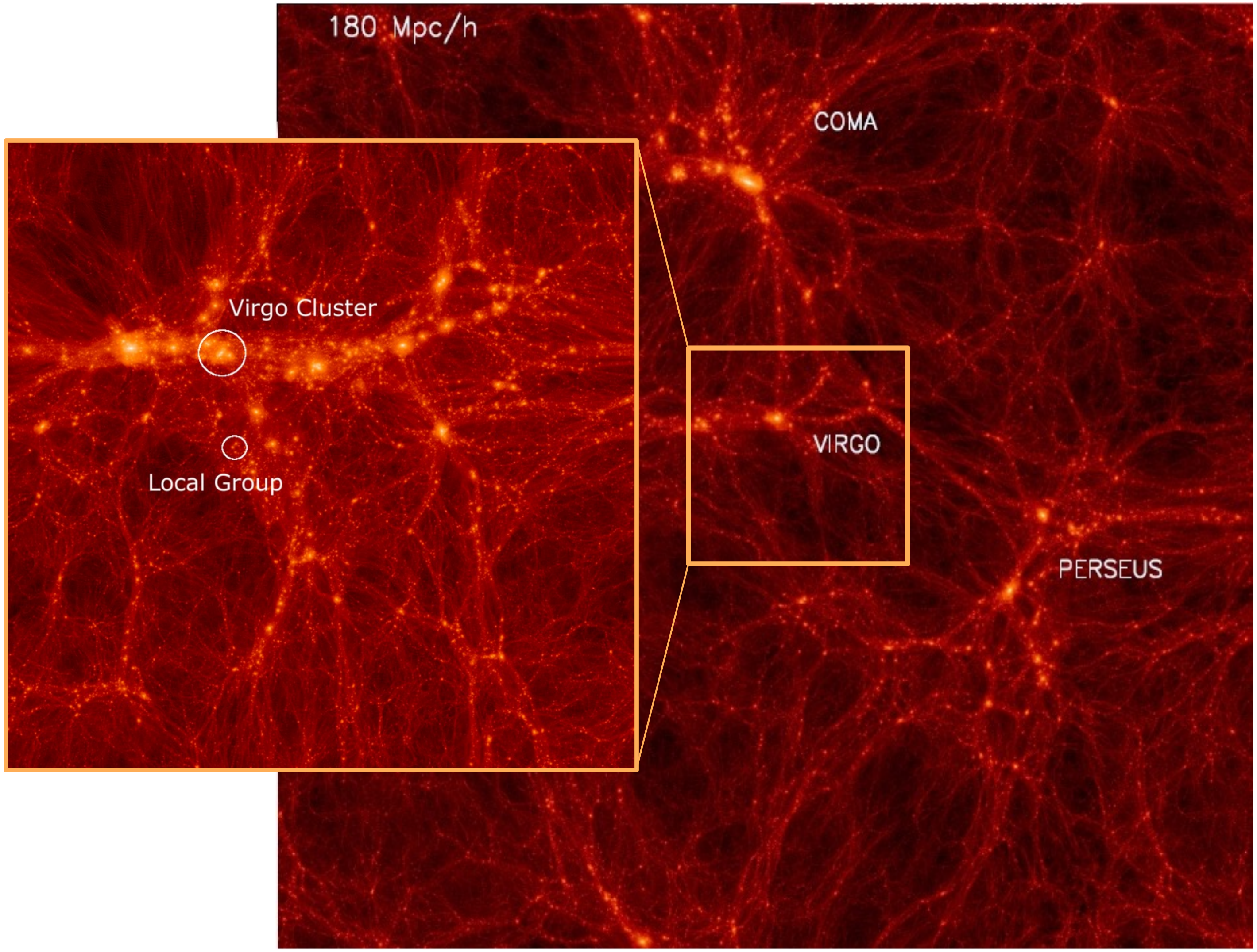

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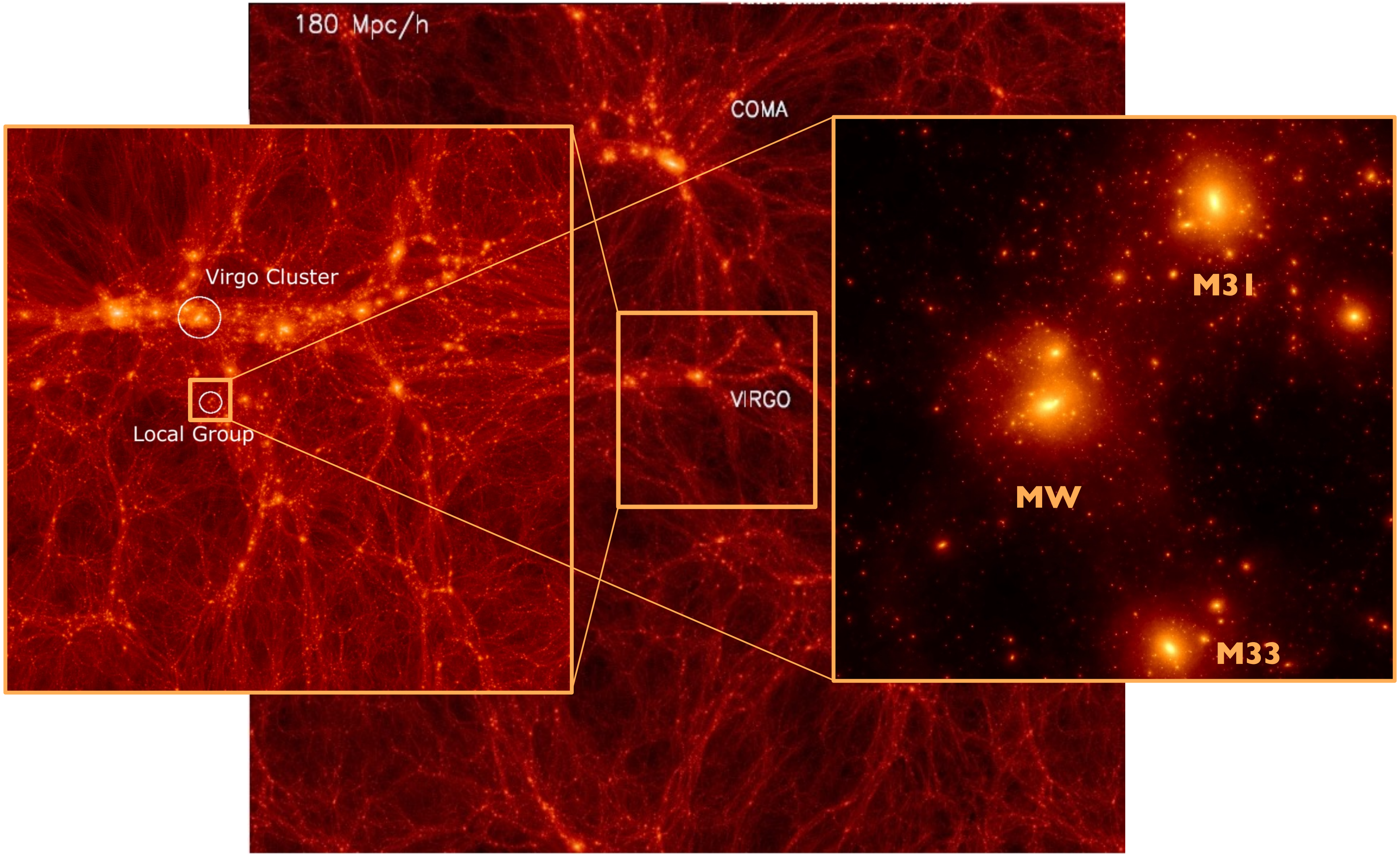

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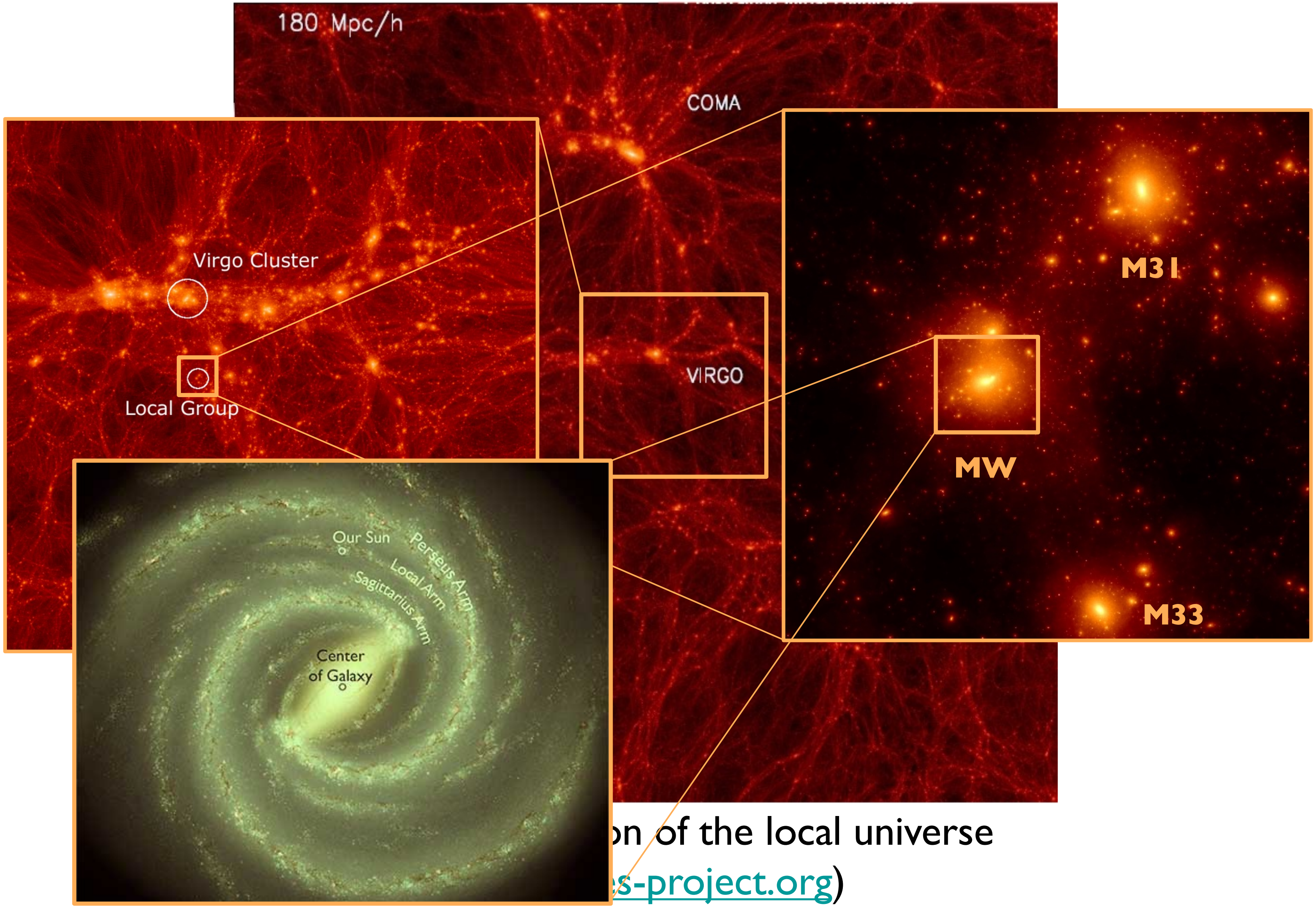

on of the local universe

s-project.org)

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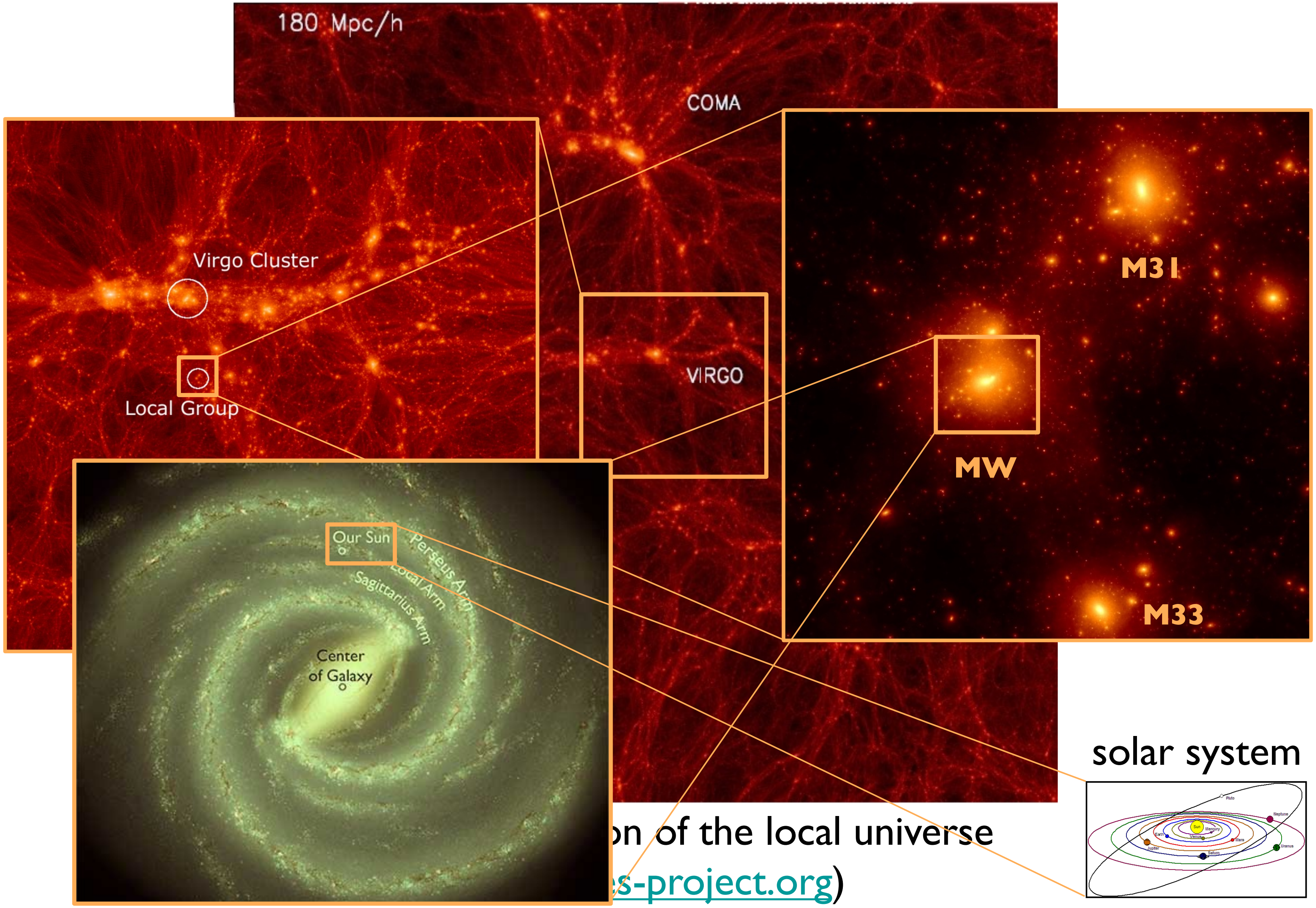

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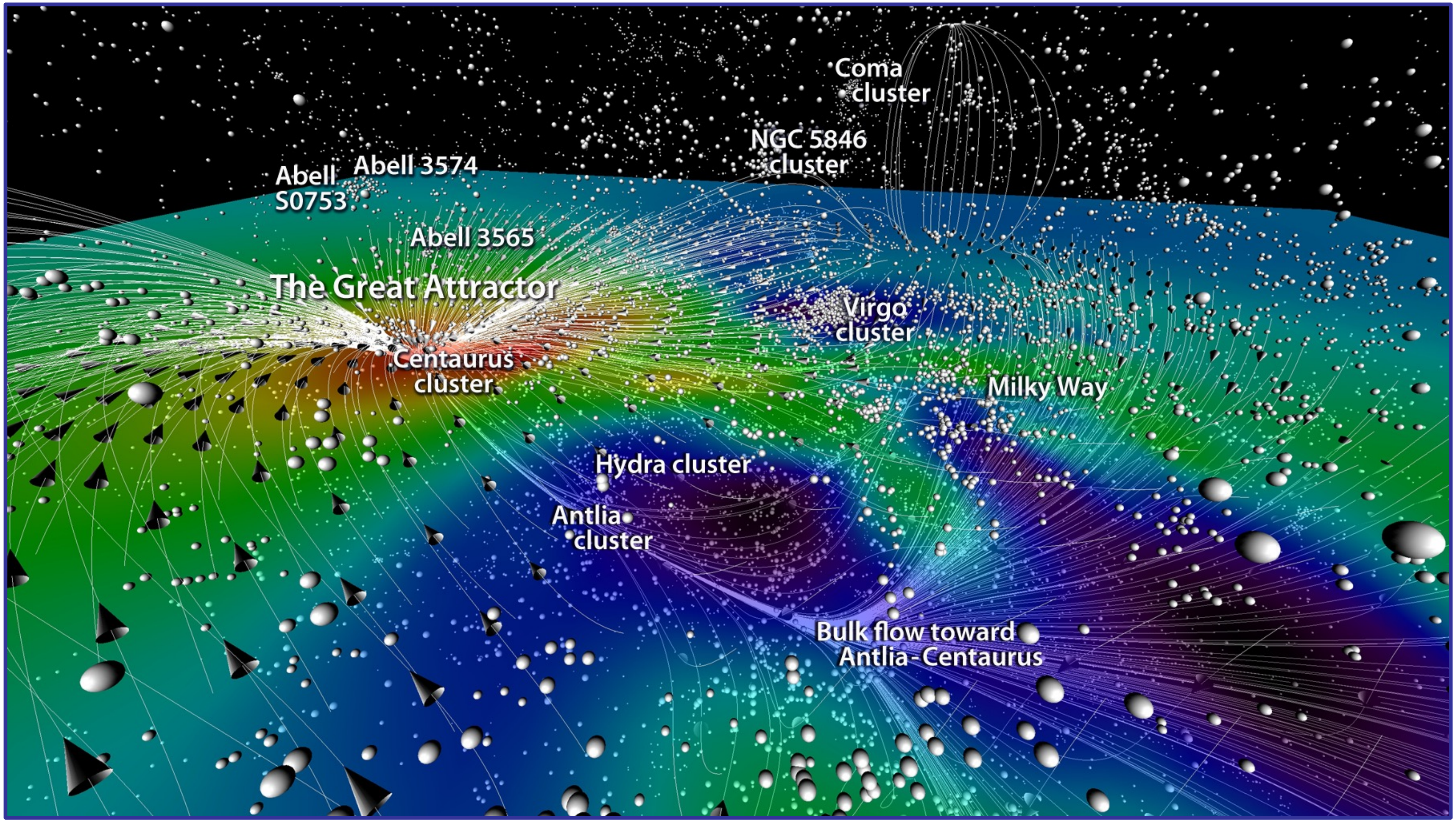
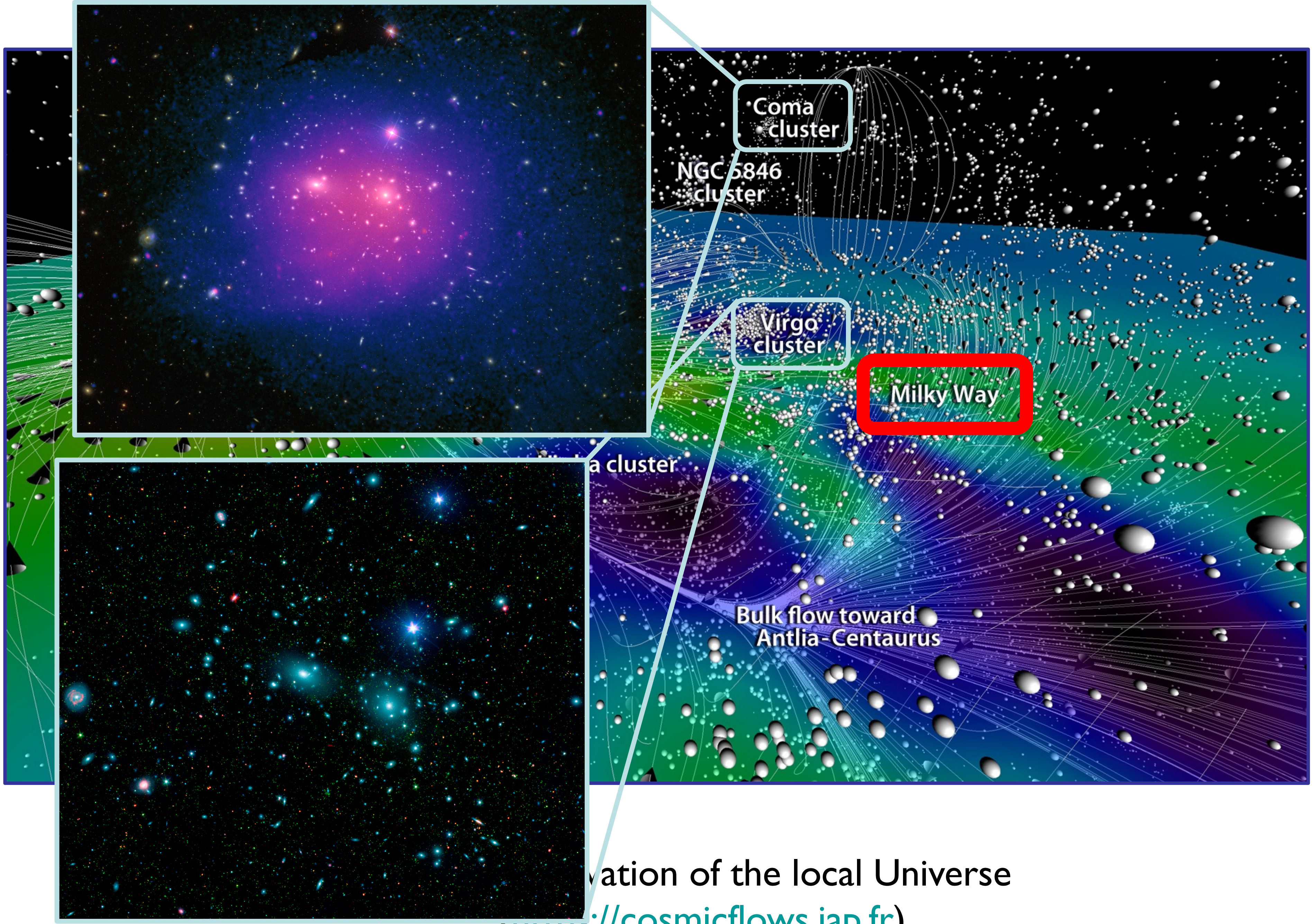


actual observation of the local Universe
(https://cosmicflows.iap.fr)

Galaxy Clusters



vation of the local Universe

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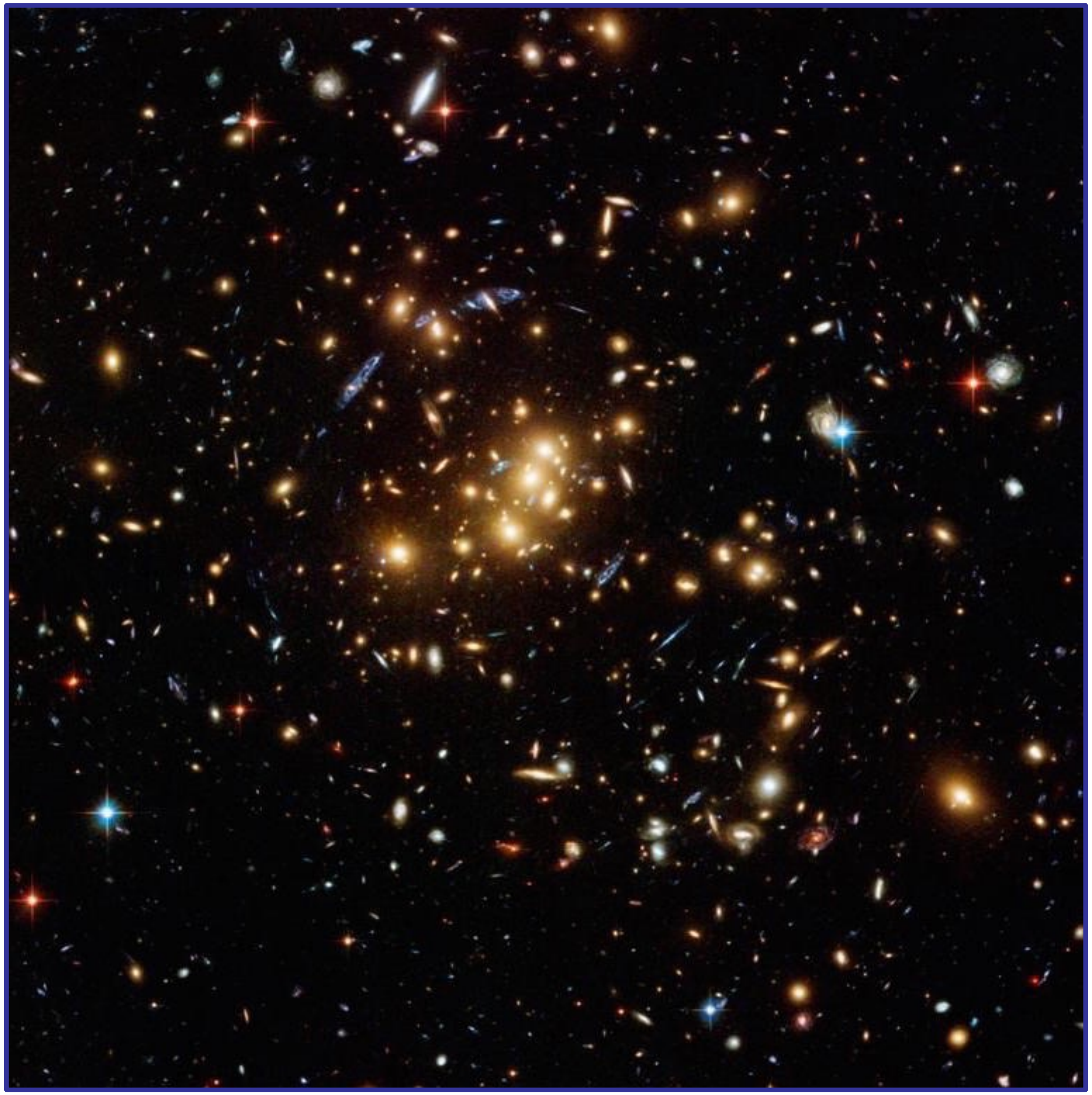
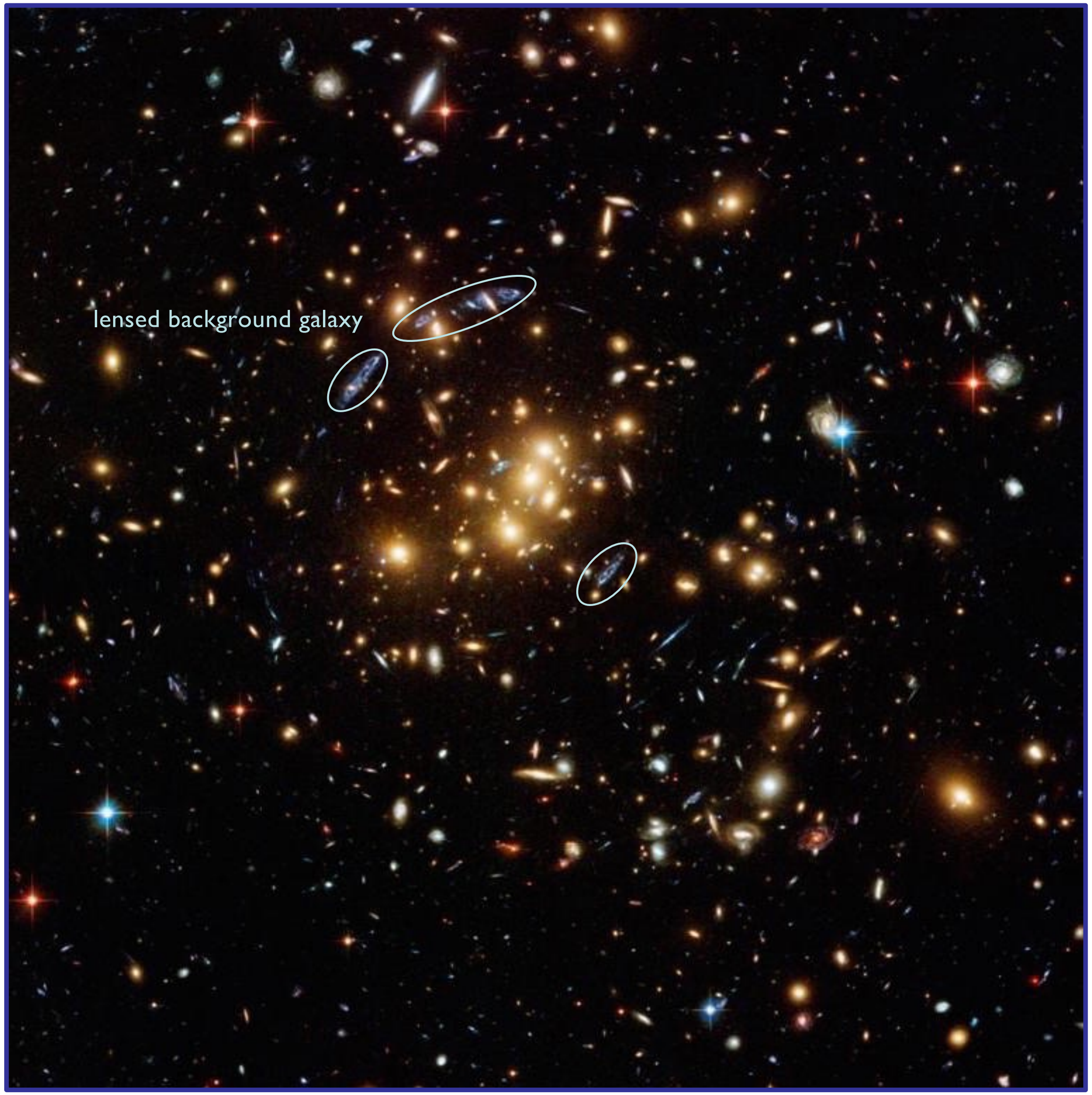


CL0024+17

gravitational lensing effects used to reconstruct matter distribution



CL0024+17

dark matter ring

(Lee et al., 2007, ApJ, 661, 728)

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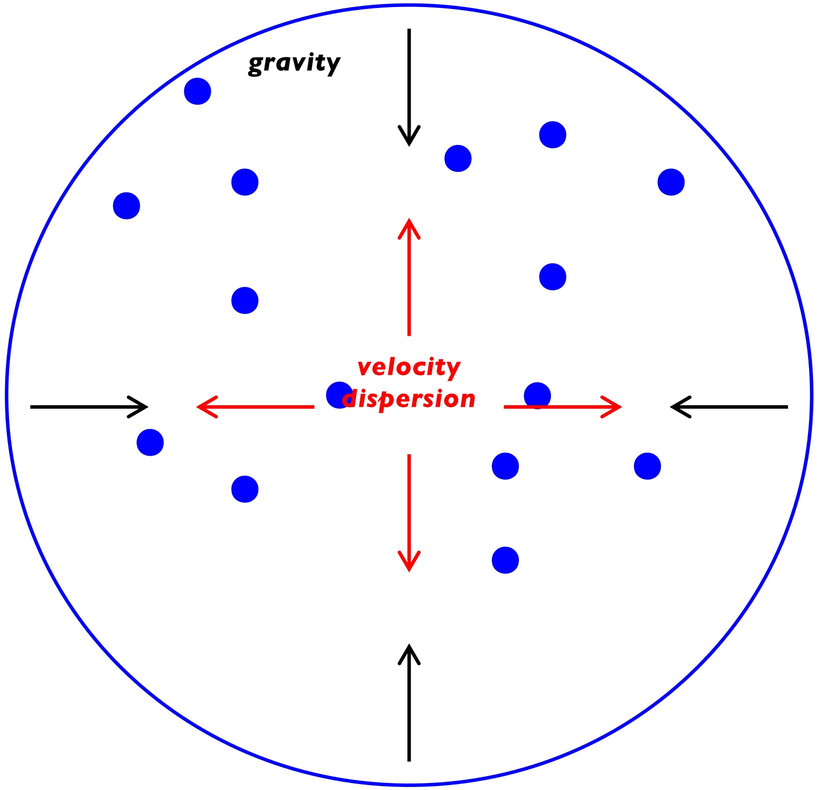
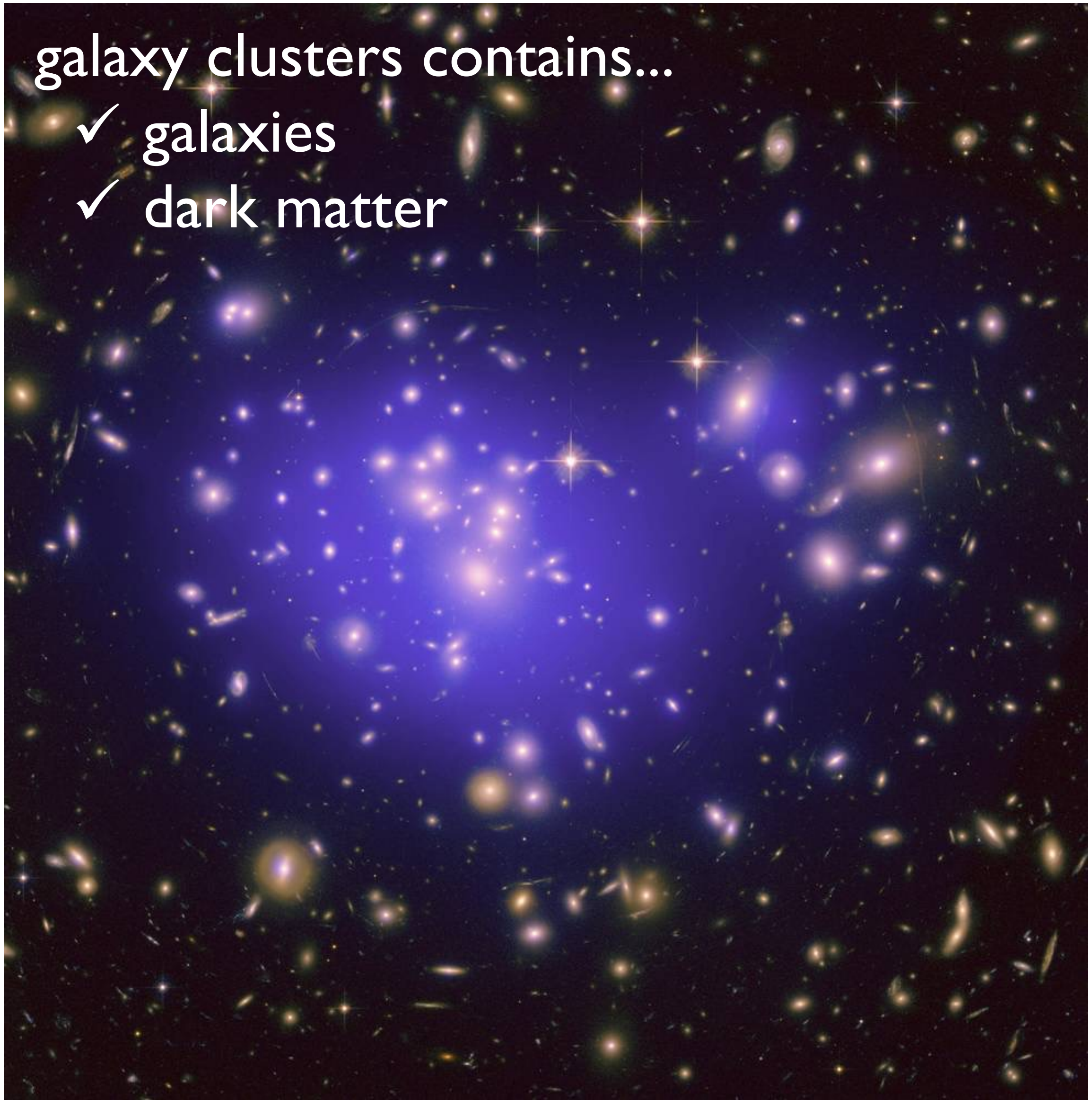
CL0024+17

dark matter in galaxy clusters...

...already proposed by Fritz Zwicky in 1933:

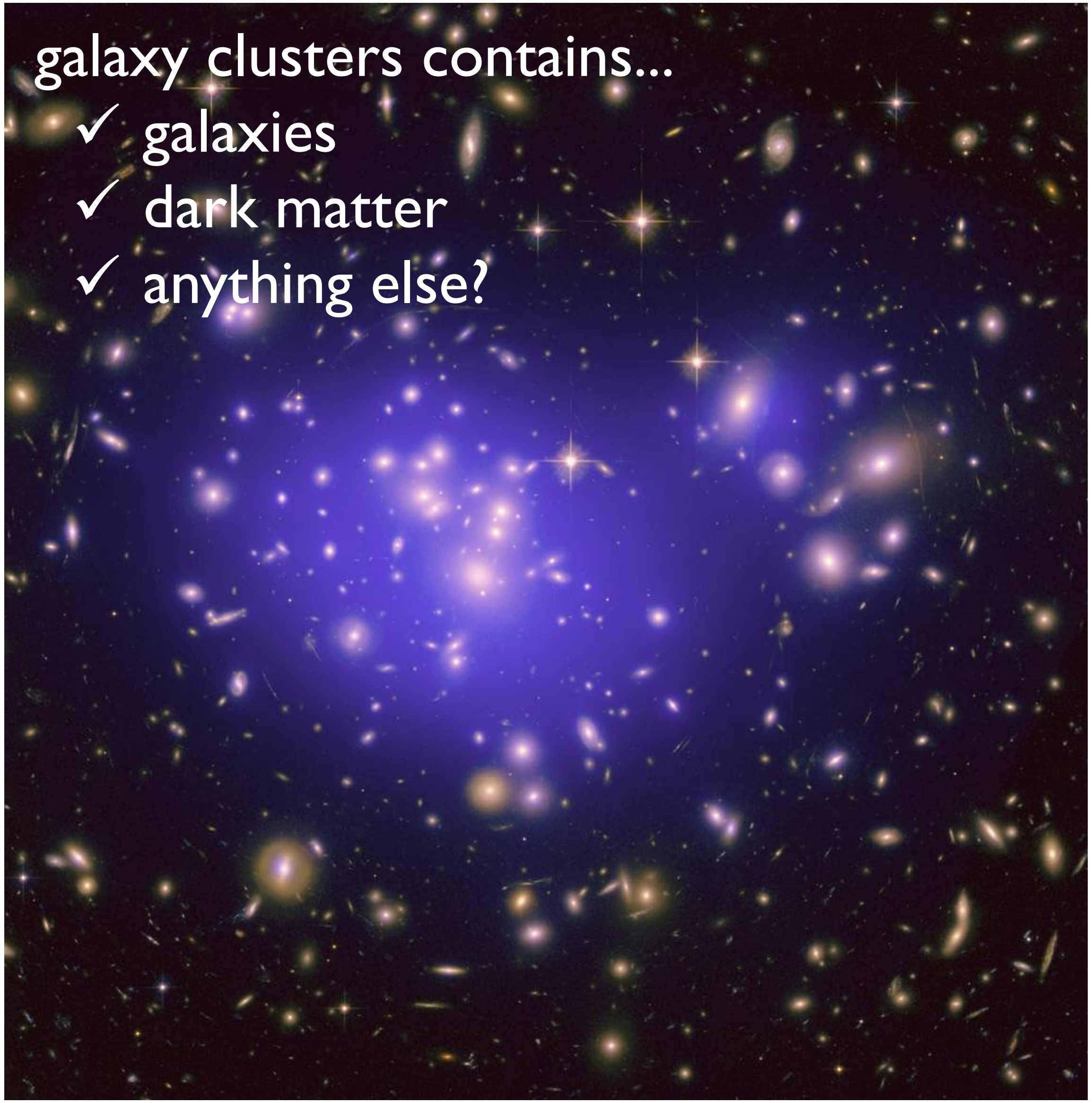


equilibrium requires more matter than is seen



galaxy clusters contains...

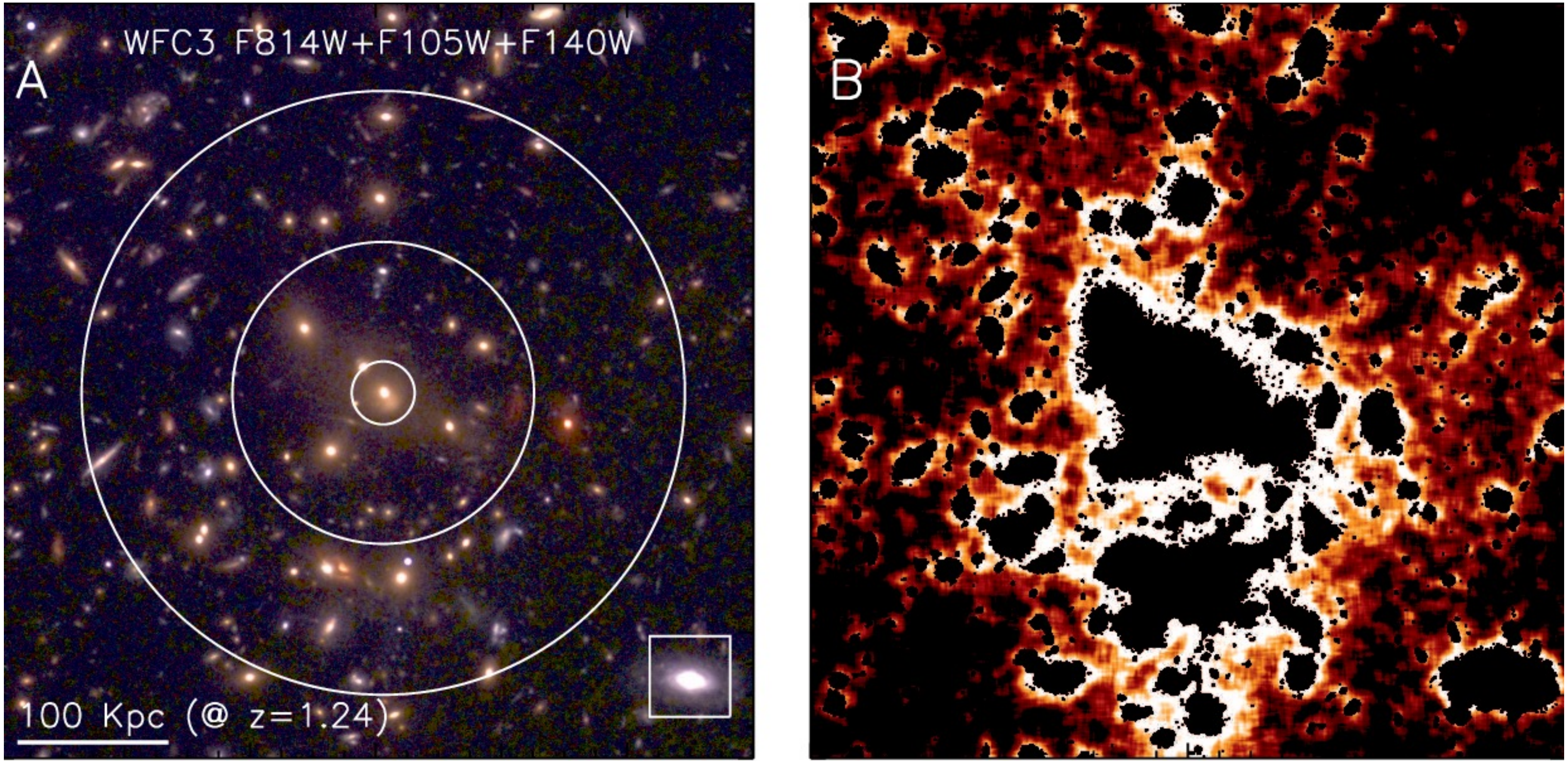
- ✓ galaxies
- ✓ dark matter



galaxy clusters contains...

- ✓ galaxies
- ✓ dark matter
- ✓ anything else?

intra-cluster stars/light



Ko & Jee (2018)

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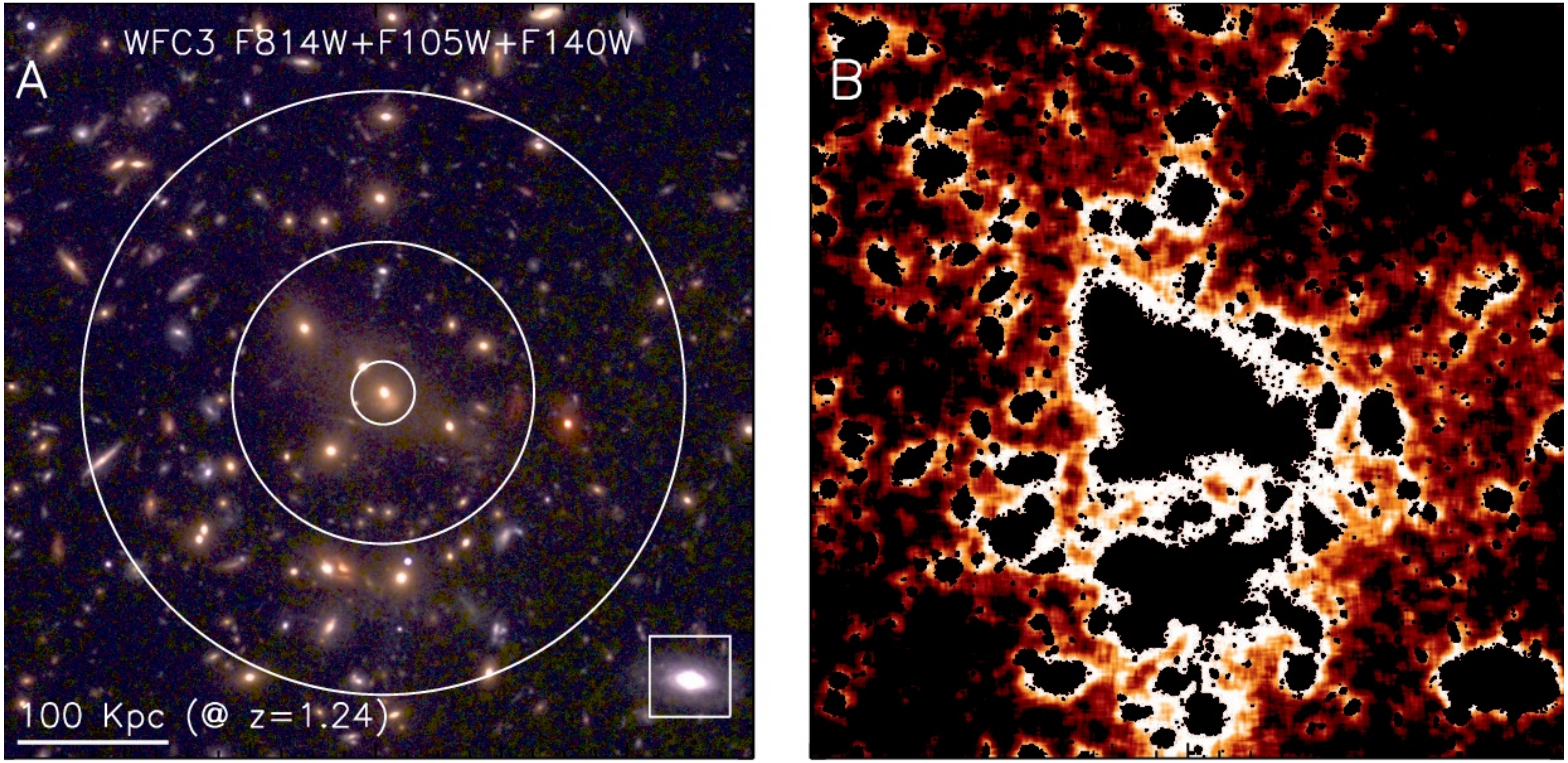
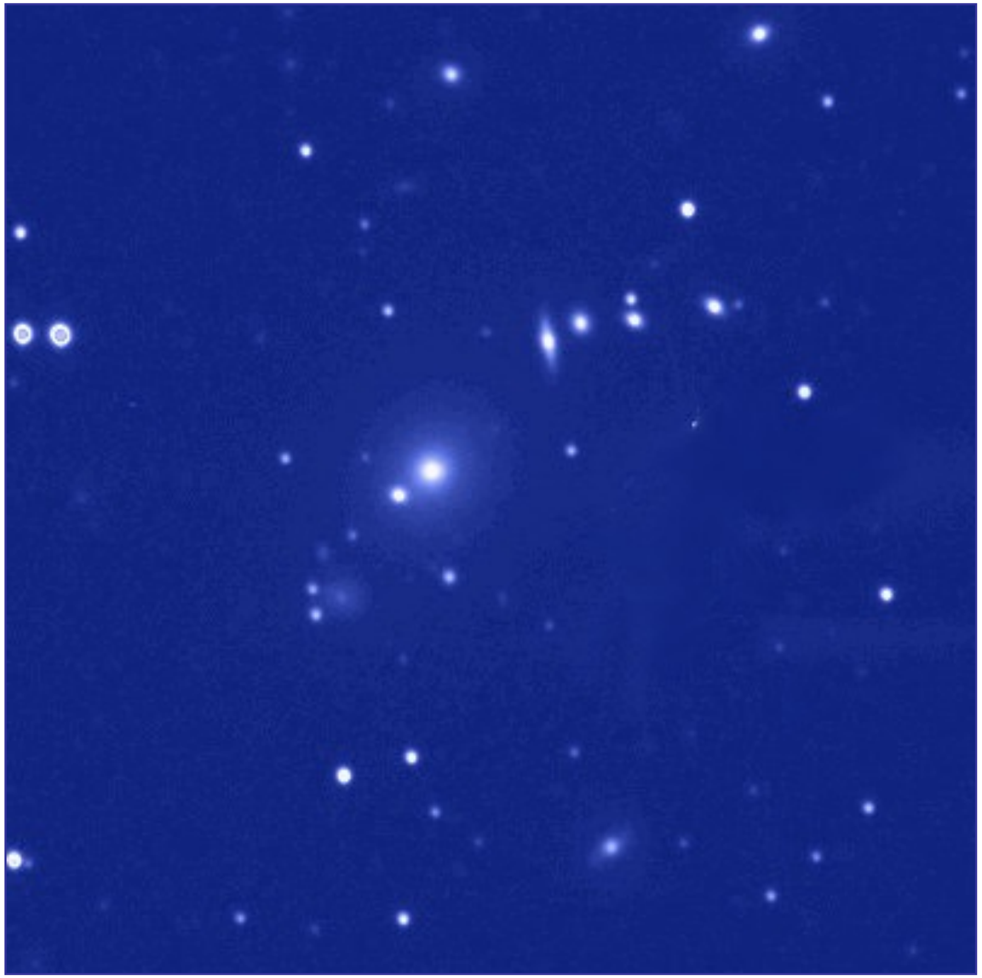


Ko & Jee (2018)

...but what about non-optical wavebands?!

observations in different wave-bands



Hydra A - optical

http://chandra.harvard.edu/photo/0087/index.html

observations in different wave-bands

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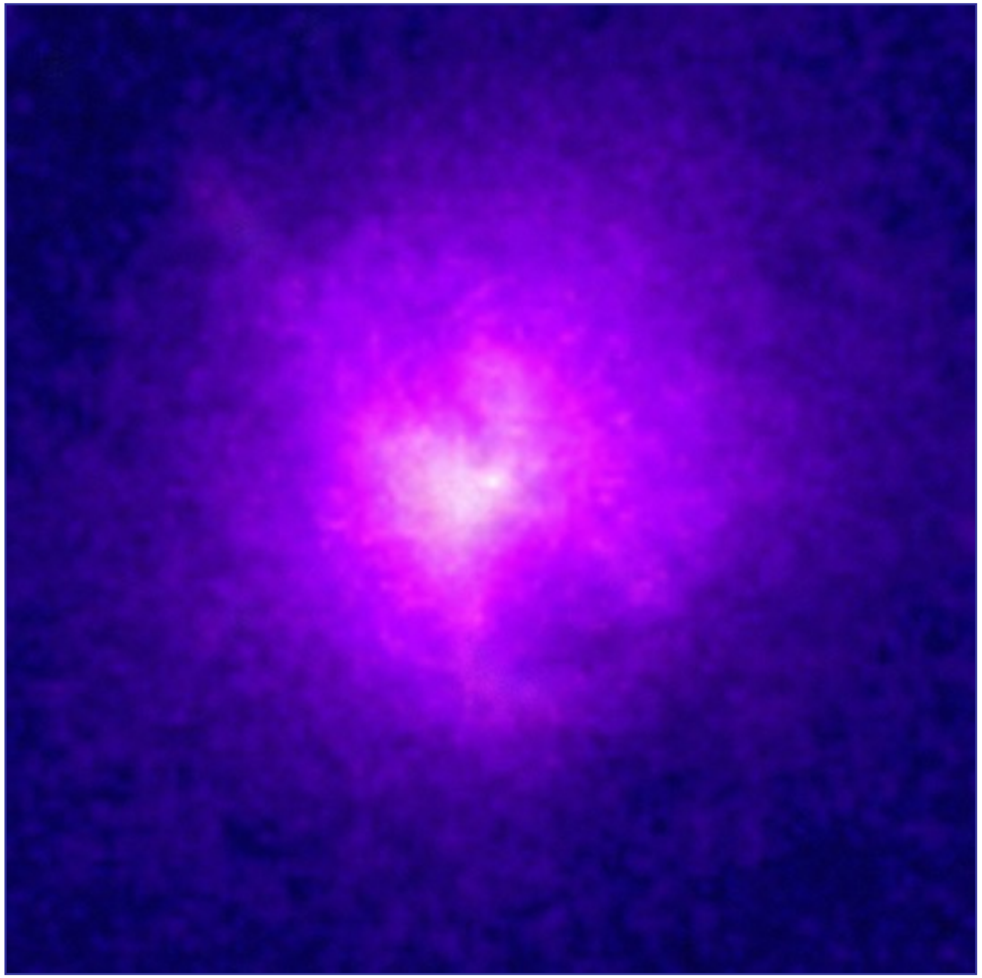
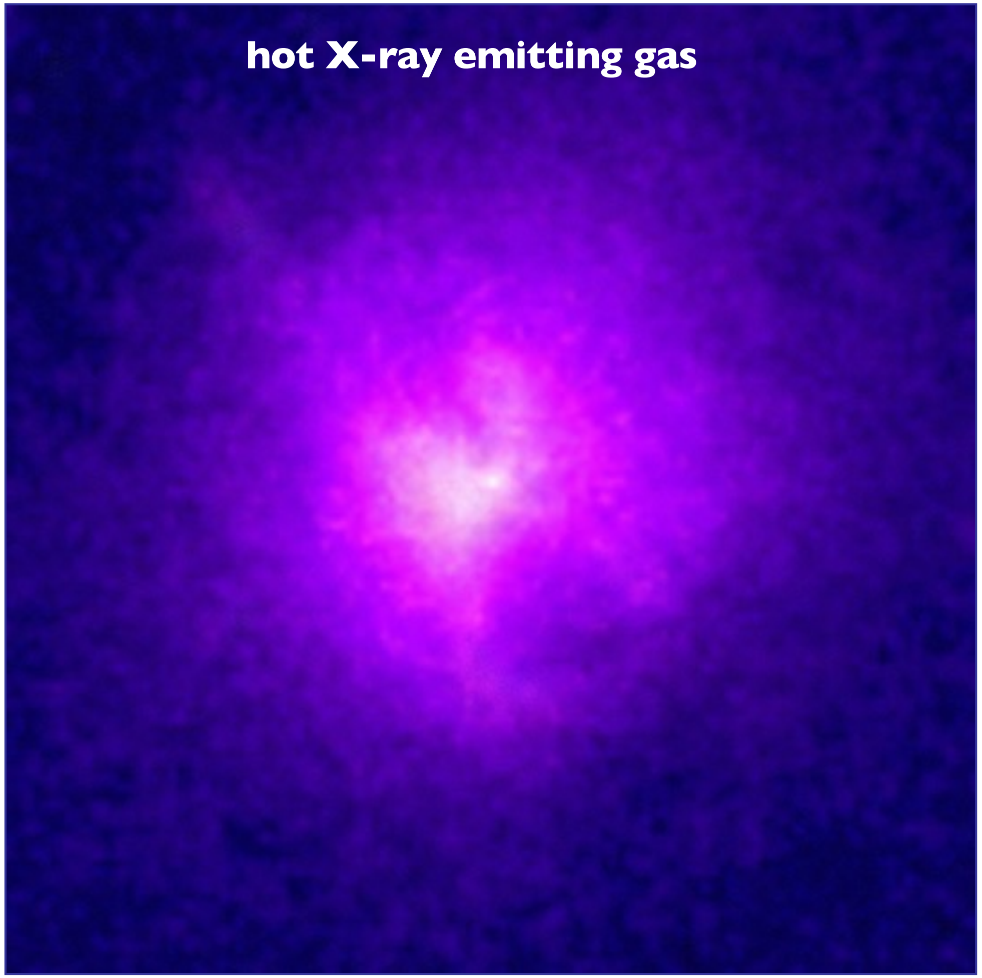


Hydra A – X-rays

http://chandra.harvard.edu/photo/0087/index.html

observations in different wave-bands



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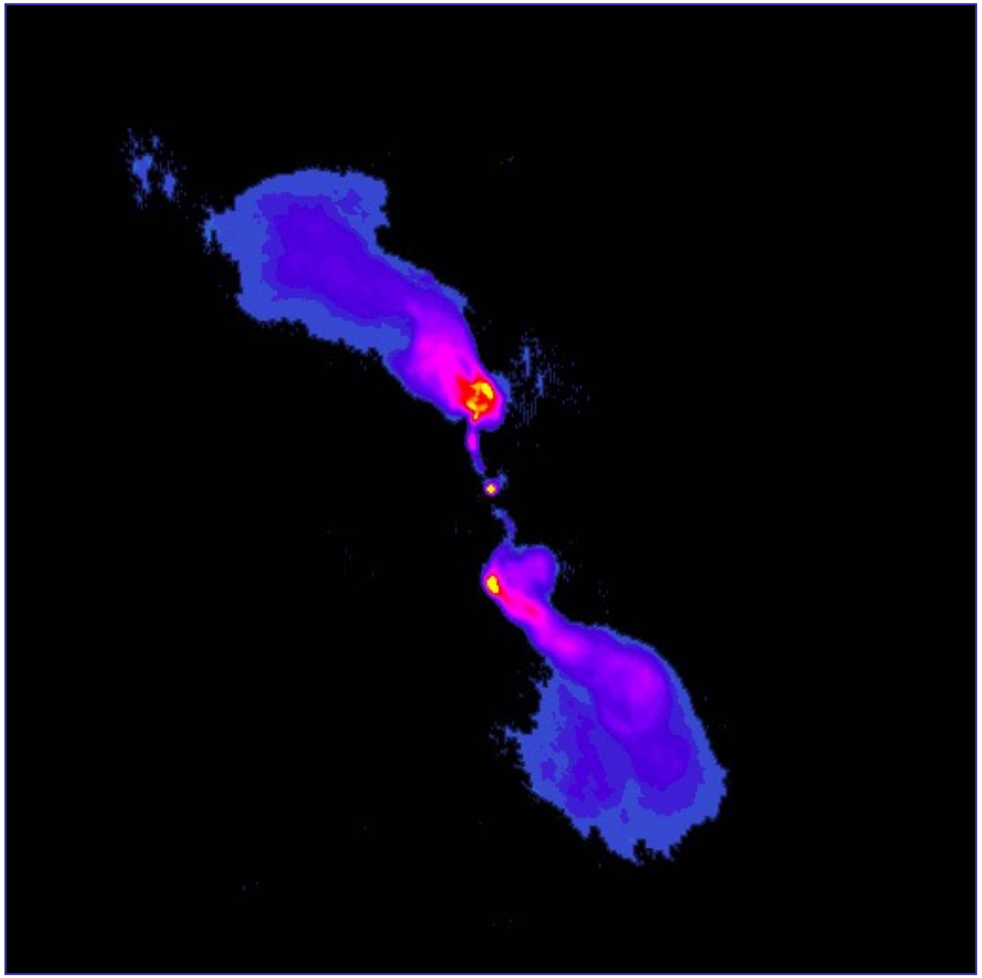
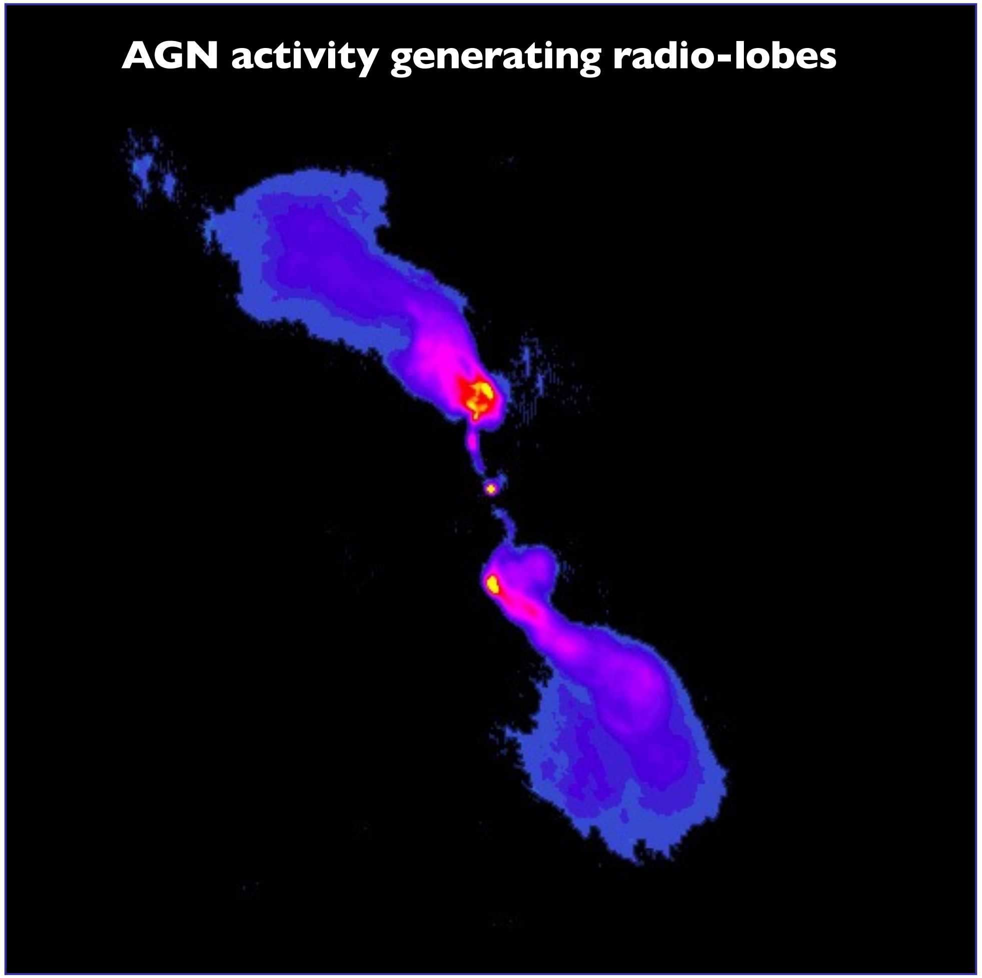


Hydra A – radio

http://chandra.harvard.edu/photo/0087/index.html

observations in different wave-bands



Hydra A – radio

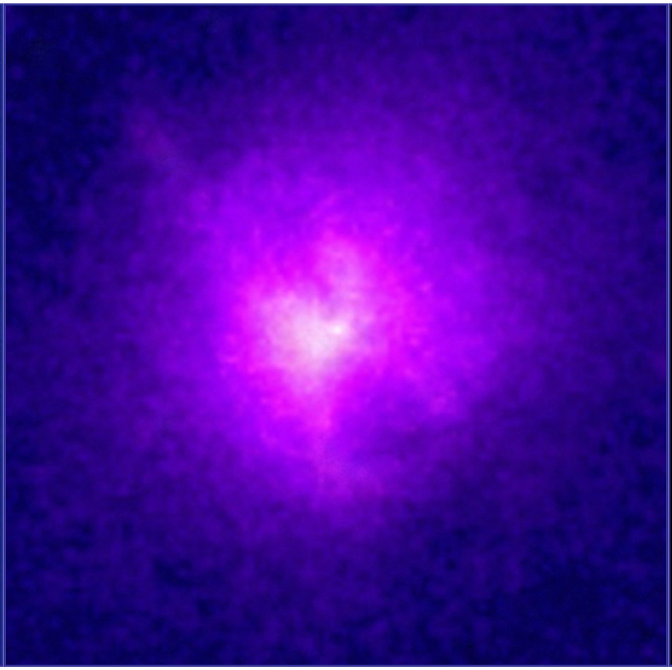
http://chandra.harvard.edu/photo/0087/index.html

observations in different wave-bands

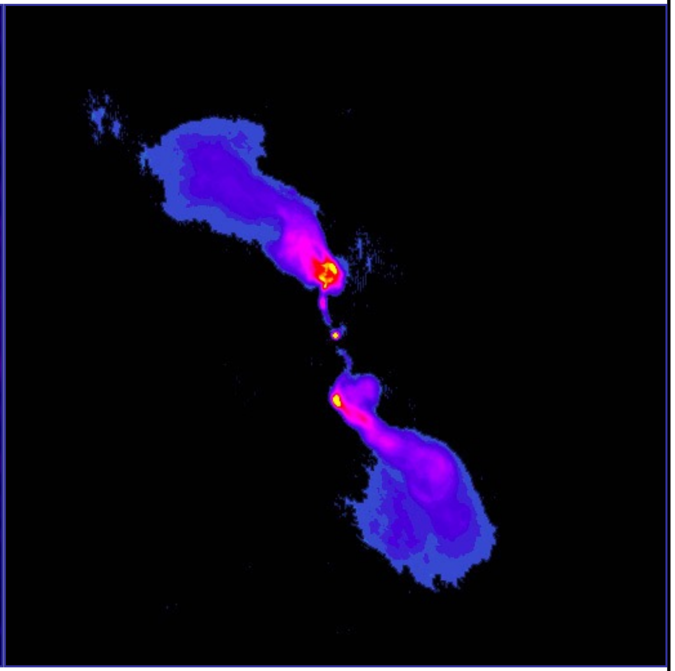
galaxy clusters contains...

- ✓ galaxies
- ✓ dark matter
- ✓ intra-cluster stars
- ✓ hot gas
- ✓ AGN

Hydra A - optical



Hydra A – X-rays



Hydra A – radio

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observations in different wave-bands

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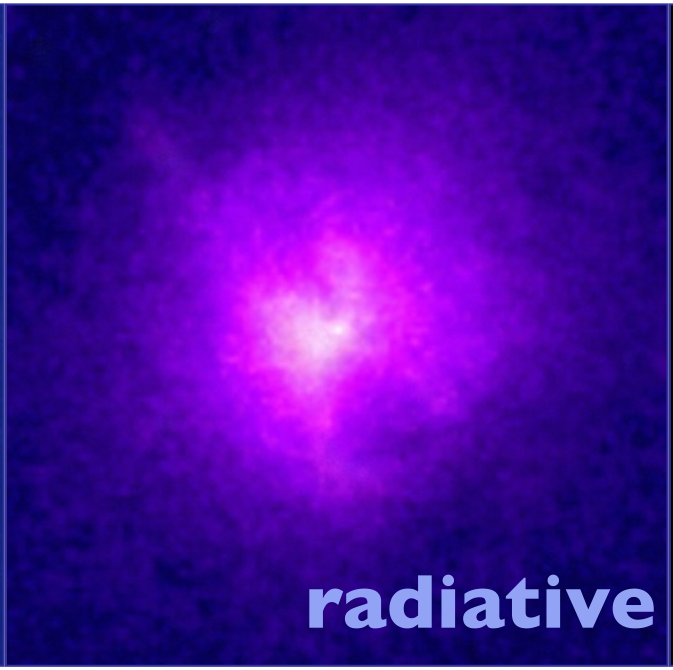
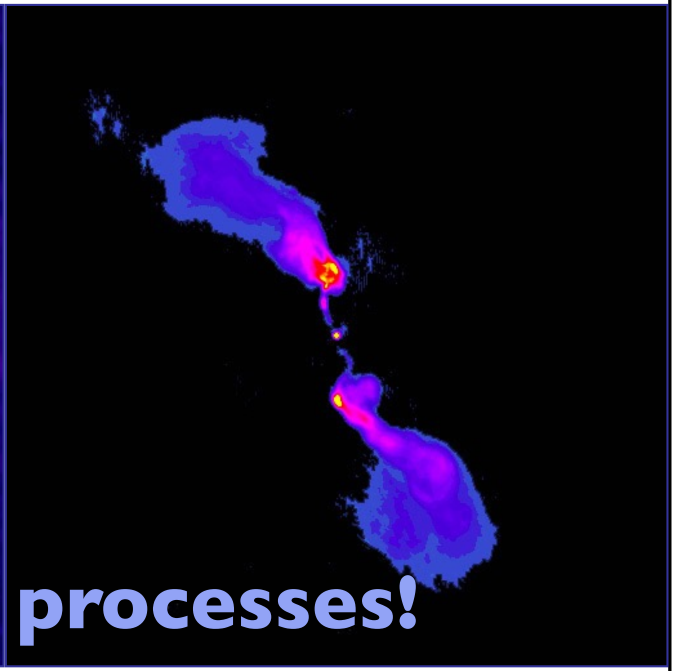


Hydra A – X-rays



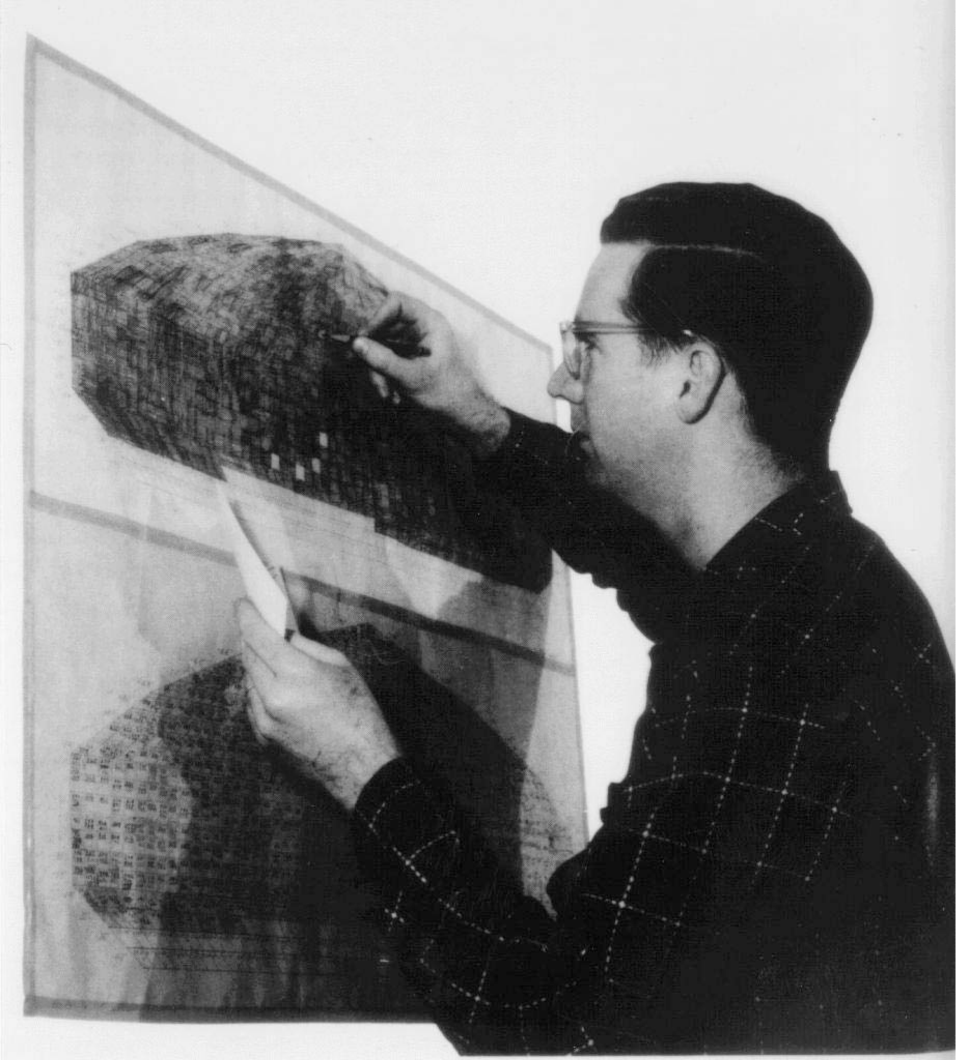
Hydra A – radio

radiative processes!

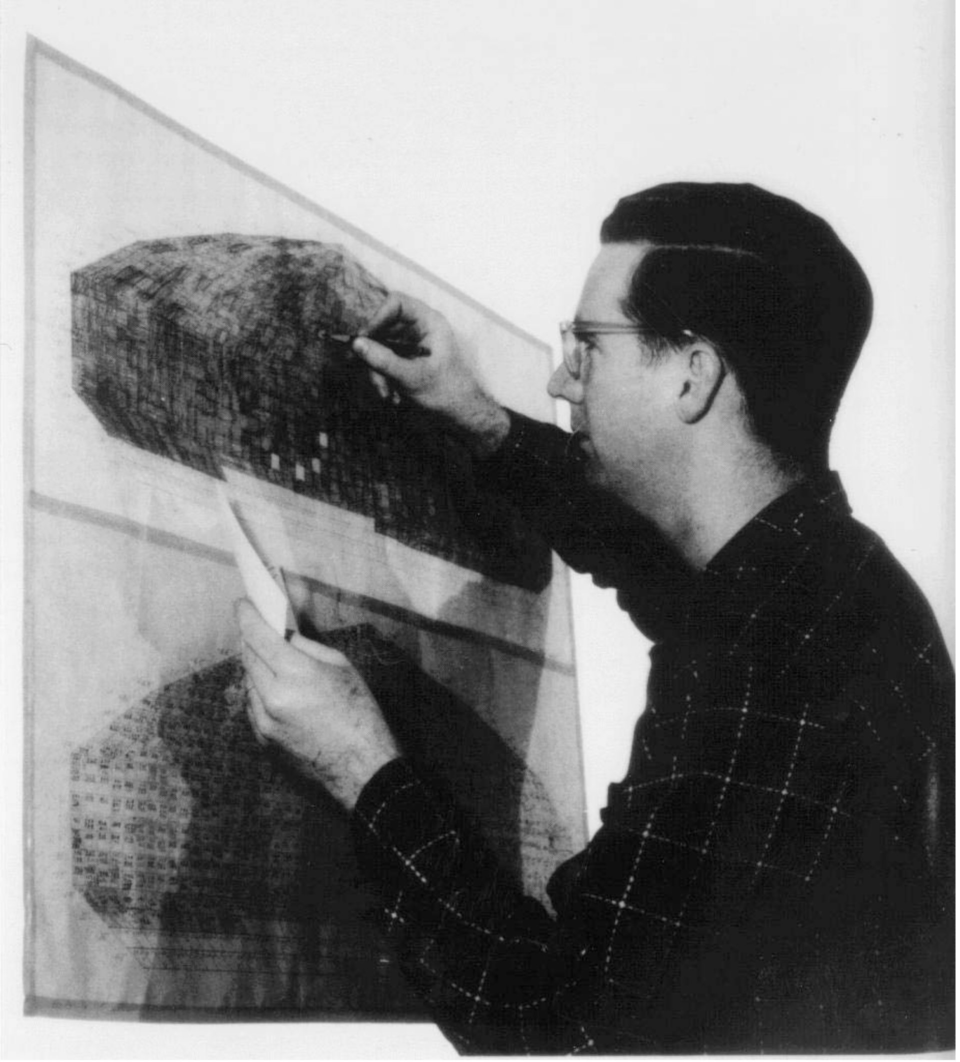
http://chandra.harvard.edu/photo/0087/index.html

- introduction
- **properties**
- scaling relations
- application

- George Abell



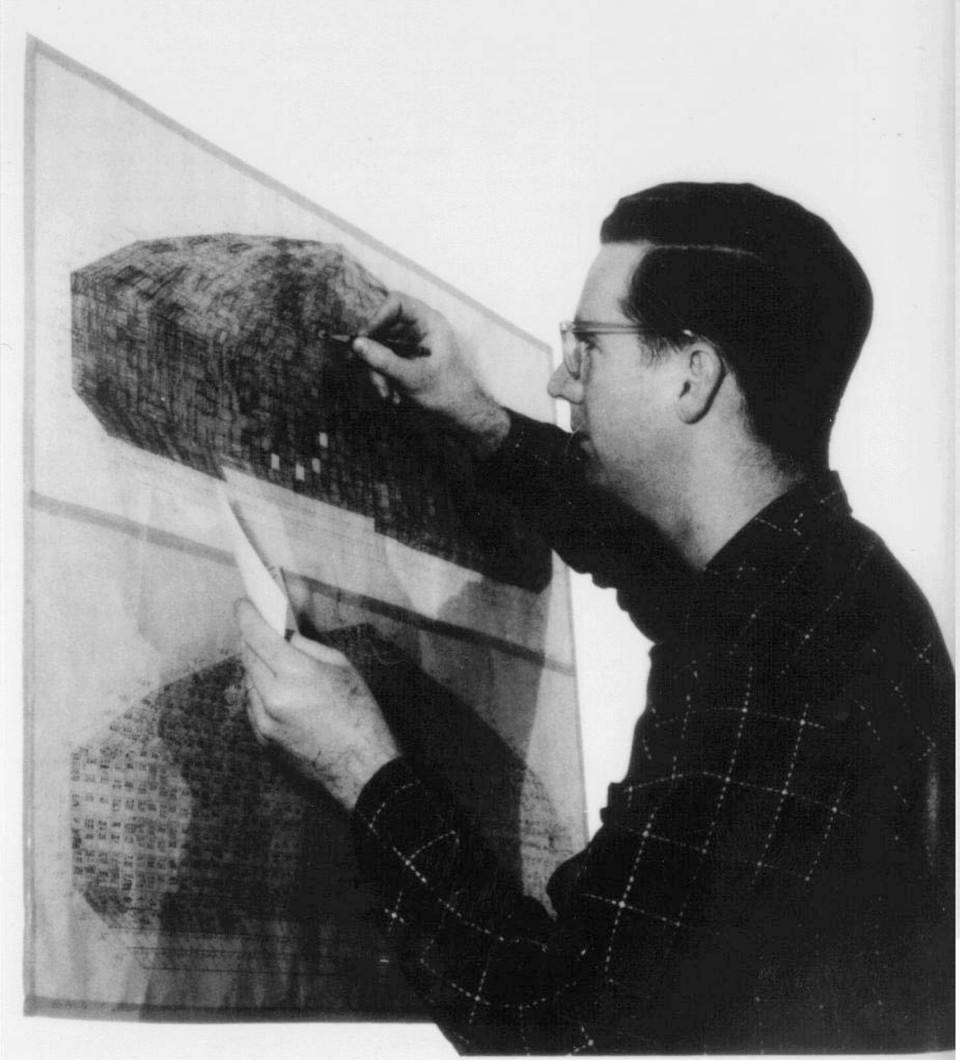
- George Abell

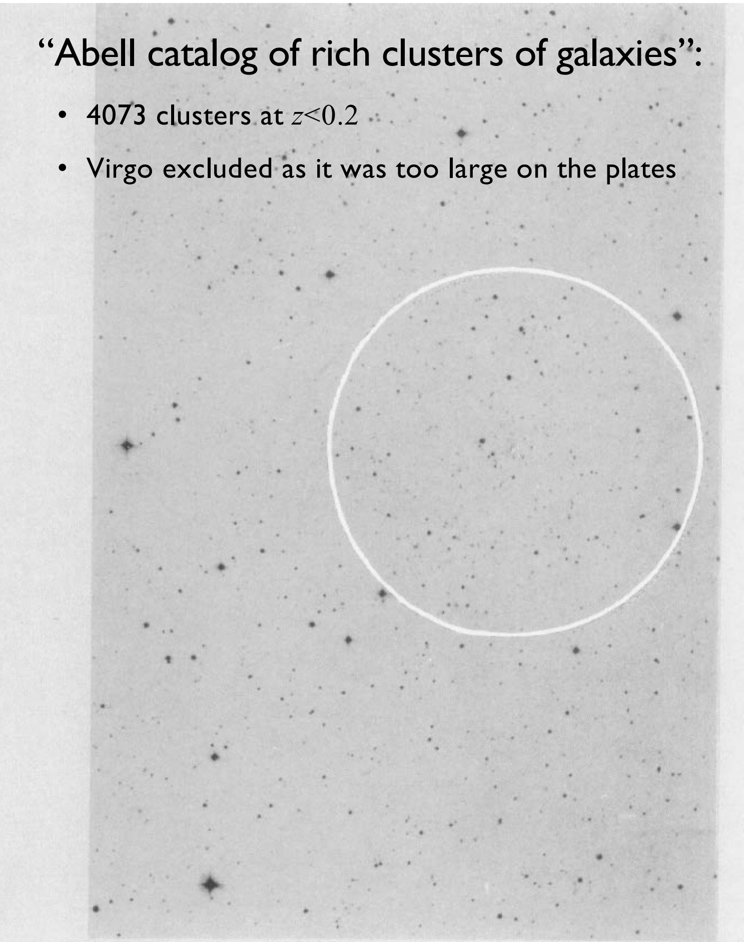


"Abell catalog of rich clusters of galaxies":

- 4073 clusters at $z<0.2$
- Virgo excluded as it was too large on the plates

- George Abell





"Abell catalog of rich clusters of galaxies":

- 4073 clusters at $z<0.2$
- Virgo excluded as it was too large on the plates

- galaxy cluster classification

  - Abell 'Richness': - number of galaxies
    - a) in cylinder of radius 1.5 Mpc, and
    - b) must lie in magnitude intervall [m_{3rd}, m_{3rd}-2]

galaxy cluster classification

Abell 'Richness':	- number of galaxies a) in cylinder of radius 1.5 Mpc, and b) must lie in magnitude intervall [m_{3rd}, m_{3rd}-2]
regular clusters:	- well defined geometrical centre - dominated by central, elliptical galaxy (BCG*)

*Brightest Cluster Galaxy

▪ galaxy cluster classification

• Abell 'Richness':	- number of galaxies a) in cylinder of radius 1.5 Mpc, and b) must lie in magnitude intervall [m_{3rd}, m_{3rd}-2]
• regular clusters:	- well defined geometrical centre - dominated by central, elliptical galaxy (BCG)
• irregular clusters:	- no well-defined centre - signs of substructure

Galaxy Clusters

properties

- general properties

$N_{galaxies}$ ~ $10-10^3$

Mass ~ $10^{14}-10^{15}\ M_{\odot}$

Radius ~ 1-5 Mpc

- general properties

$N_{galaxies}$	~	$10\text{-}10^3$
Mass	~	$10^{14}\text{-}10^{15}$ $M_\odot$
Radius	~	1-5 Mpc

- abundance

$n_{clusters}$	~	10^{-5} / Mpc^3

- general properties

$N_{galaxies}$	~	$10\text{-}10^3$
Mass	~	$10^{14}\text{-}10^{15}\ M_\odot$
Radius	~	1-5 Mpc

- abundance

$n_{clusters}$	~	10^{-5} / Mpc^3
$n_{galaxies}$	~	10^{-2} / Mpc^3

Galaxy Clusters *properties*

- general properties

$N_{galaxies} \sim 10\text{-}10^3$

$\mathrm{Mass} \sim 10^{14}\text{-}10^{15}\ M_\odot$

$\mathrm{Radius} \sim 1\text{-}5\ \mathrm{Mpc}$

- abundance

$n_{clusters} \sim 10^{-5}\ /\ \mathrm{Mpc}^3$

$(n_{galaxies} \sim 10^{-2}\ /\ \mathrm{Mpc}^3)$

- baryonic properties

$L_x \sim 10^{43}\text{-}10^{45}\ \mathrm{erg/s}$

$T_{ICM} > 10^8\ \mathrm{K}$

$M_g \sim 10^{13}\text{-}10^{14}\ M_\odot$

$f_b \sim 0.95\ f_{b,cosmic}$

Galaxy Clusters *properties*

- general properties

$N_{galaxies}$ ~ $10\text{-}10^3$

Mass ~ $10^{14}\text{-}10^{15}\ M_\odot$

Radius ~ 1-5 Mpc

- abundance

$n_{clusters}$ ~ 10^{-5} / Mpc^3

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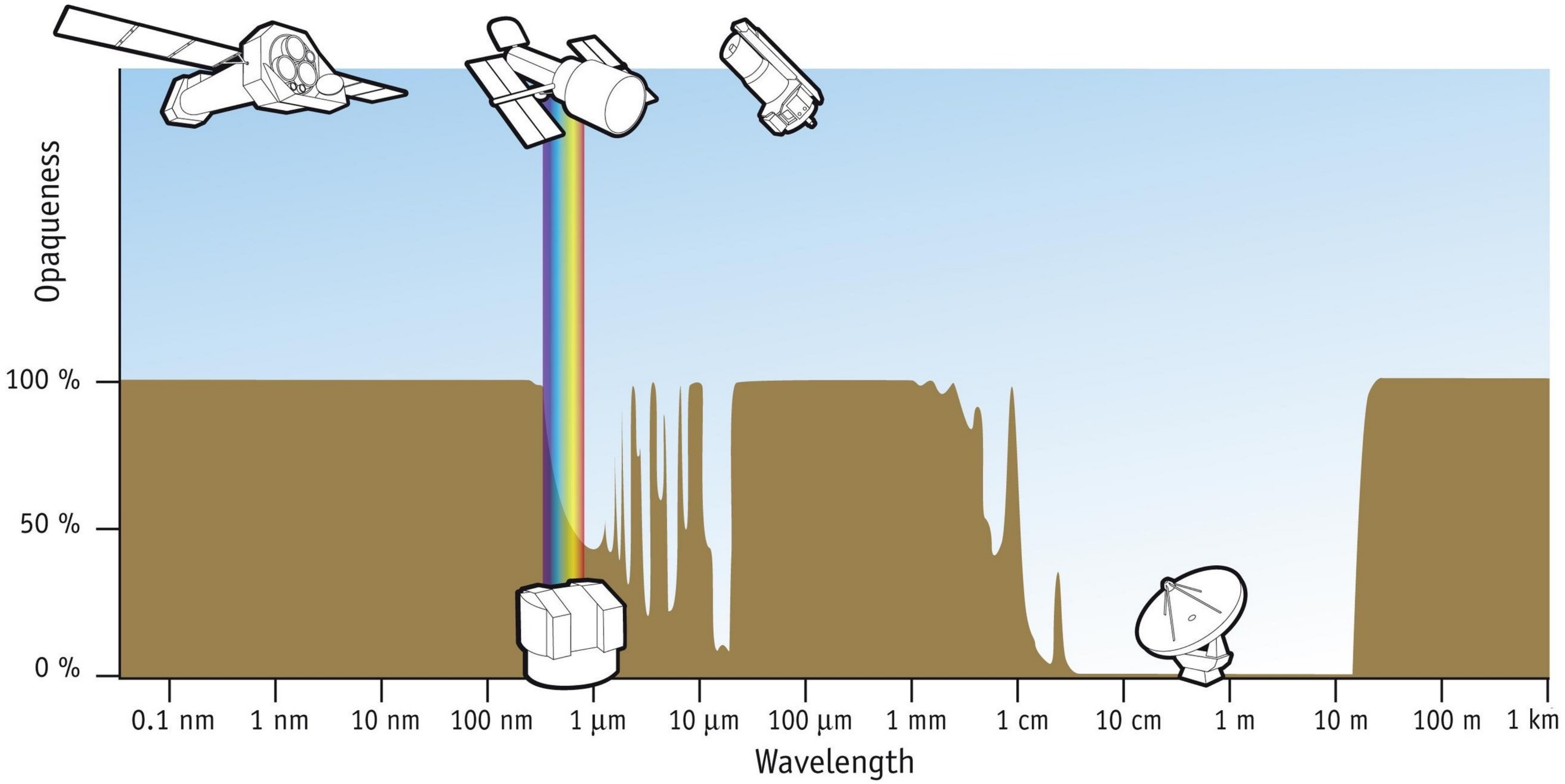
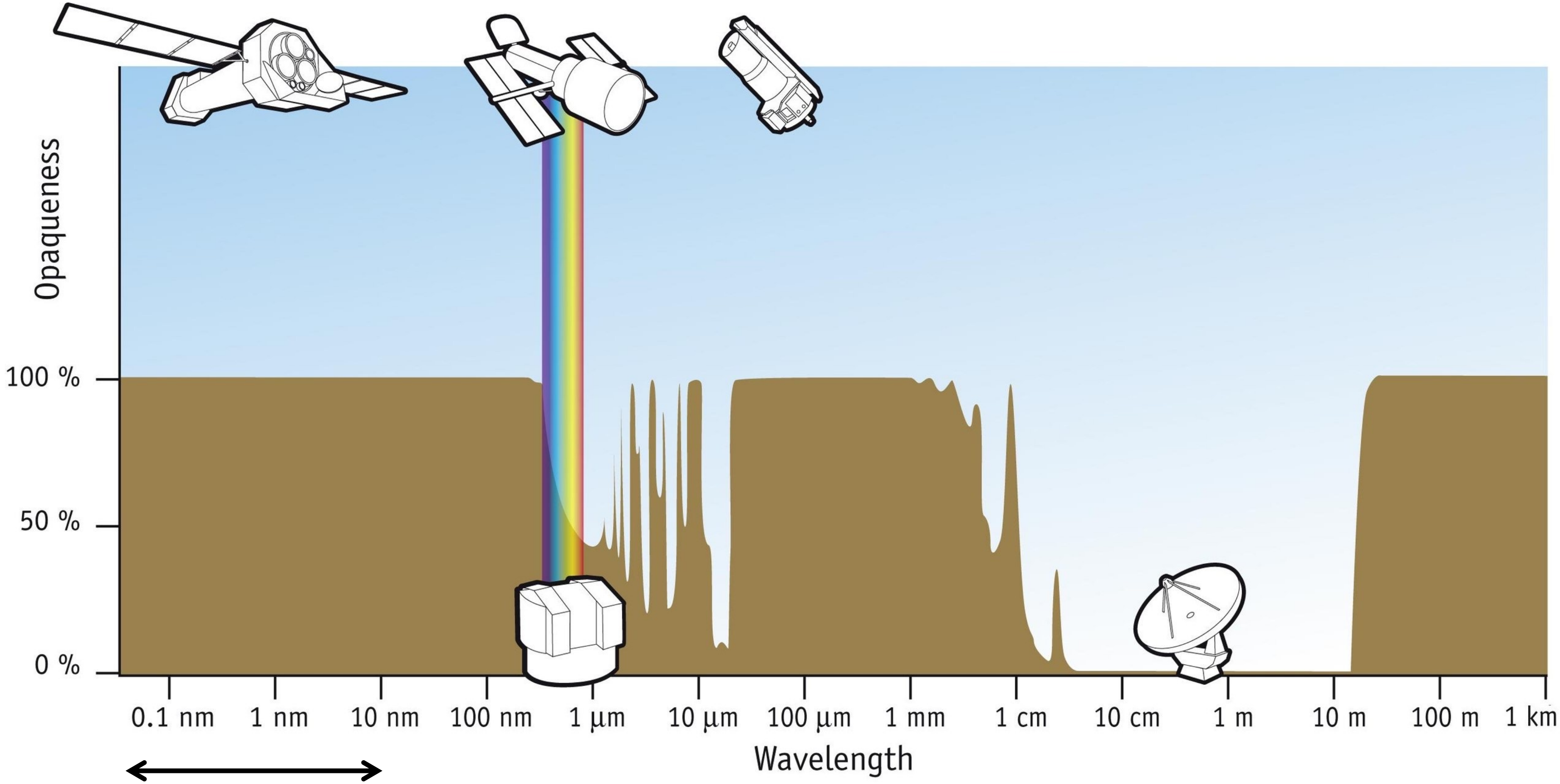
- hot X-ray gas


Opaqueness
100 %
50 %
0 %
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

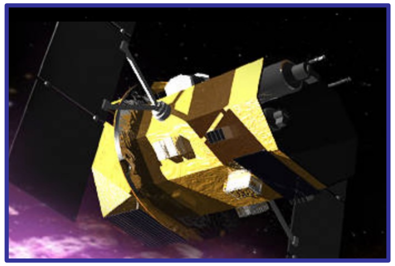
- hot X-ray gas



X-ray astronomy requires satellites!

- hot X-ray gas

XMM-Newton

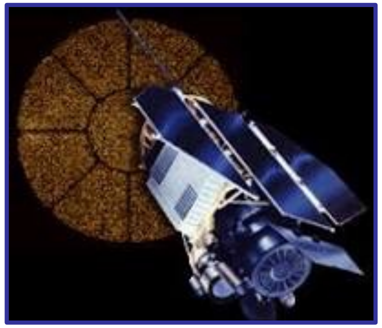


Swift

Exosat

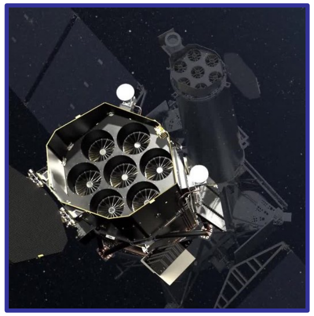
Hitomi

Chandra



Rosat

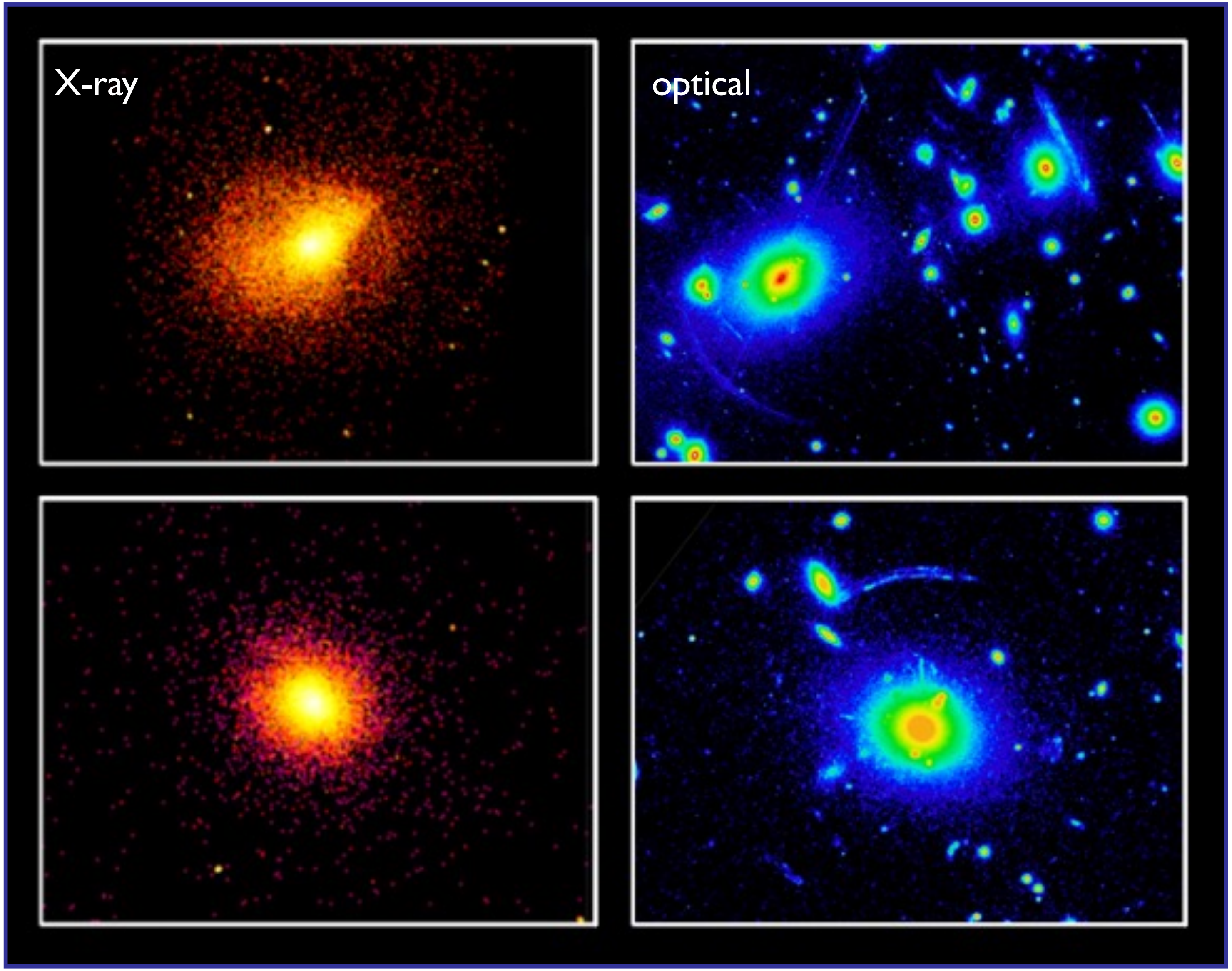
Rossi



eRosita

Athena

- hot X-ray gas

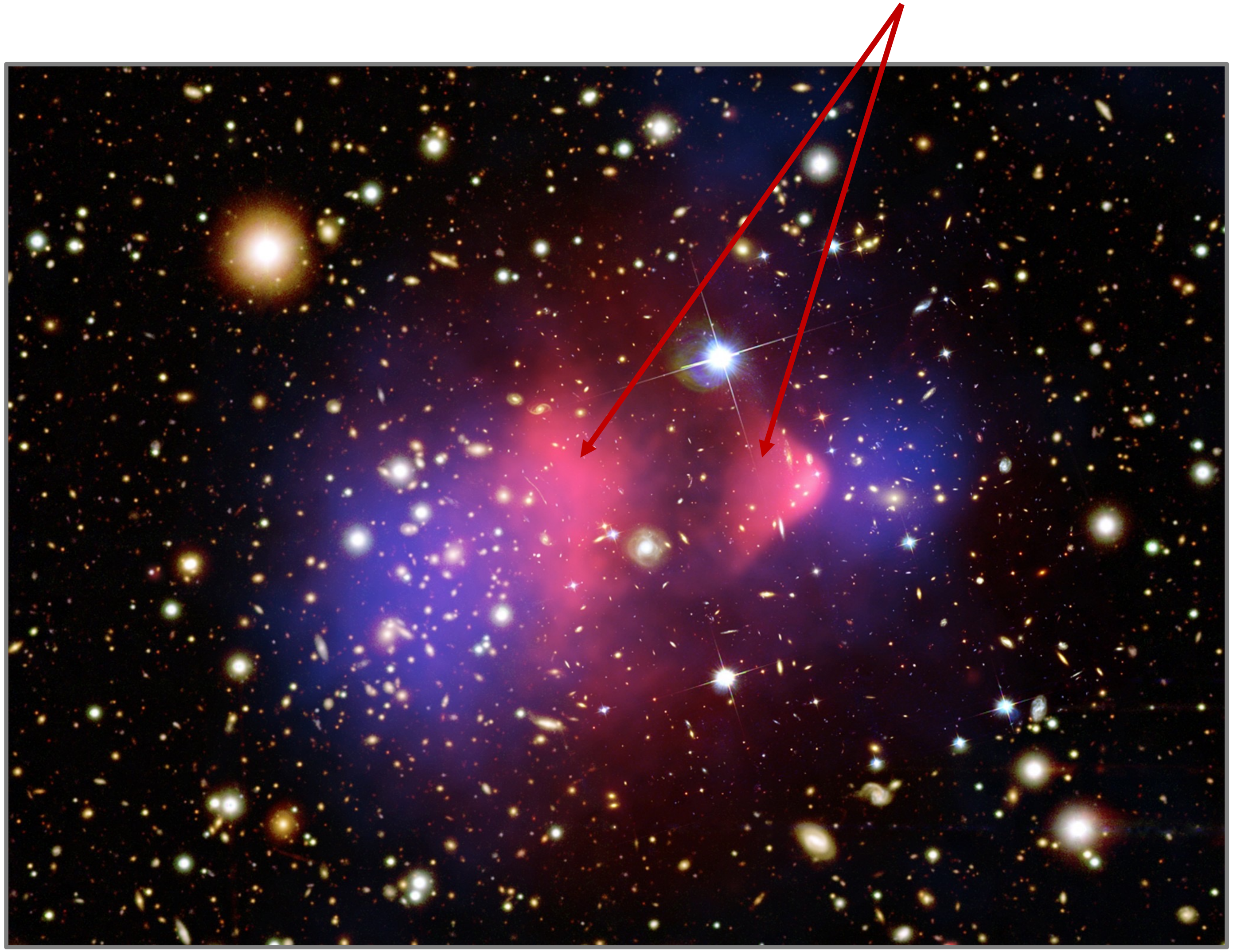


http://antwrp.gsfc.nasa.gov/apod/astropix.html

- hot X-ray gas

Bullet cluster (1E 0657-558)

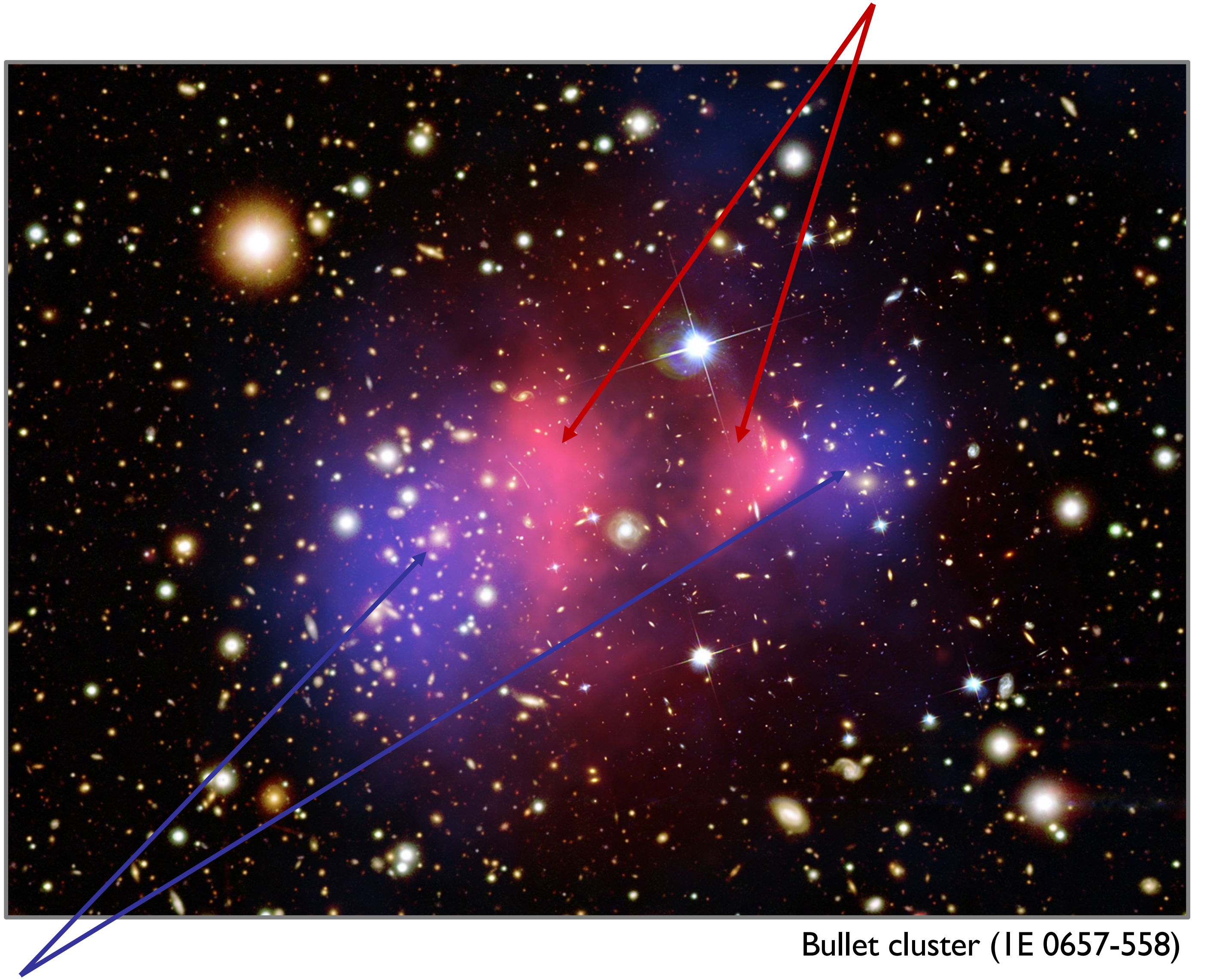
- hot X-ray gas



X-ray observation (Chandra satellite)

Bullet cluster (1E 0657-558)

- hot X-ray gas



X-ray observation (Chandra satellite)

Bullet cluster (1E 0657-558)

dominant (dark matter) mass distribution (reconstructed via grav. lensing)

- hot X-ray gas
  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

- hot X-ray gas
  - X-ray luminosity

$$\boxed{L_x \sim 10^{43}\text{-}10^{45} \text{ erg/s}}$$

measured with X-ray satellites...

not measured, but inferred!

- hot X-ray gas

  - X-ray luminosity

$\boxed{L_x \sim 10^{43}\text{-}10^{45}\ \text{erg/s}}$

measured with X-ray satellites...

not measured, but inferred!

- $\boxed{\text{hot}}$ X-ray gas
  - X-ray luminosity $\boxed{L_x \sim 10^{43}\text{-}10^{45} \text{ erg/s}}$

measured with X-ray satellites...

but what is causing this emission?

- hot X-ray gas
  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

  emission processes:

  - Bremsstrahlung (free-free radiation)
  - collisionally excited emission lines

- hot X-ray gas
  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

emission processes:

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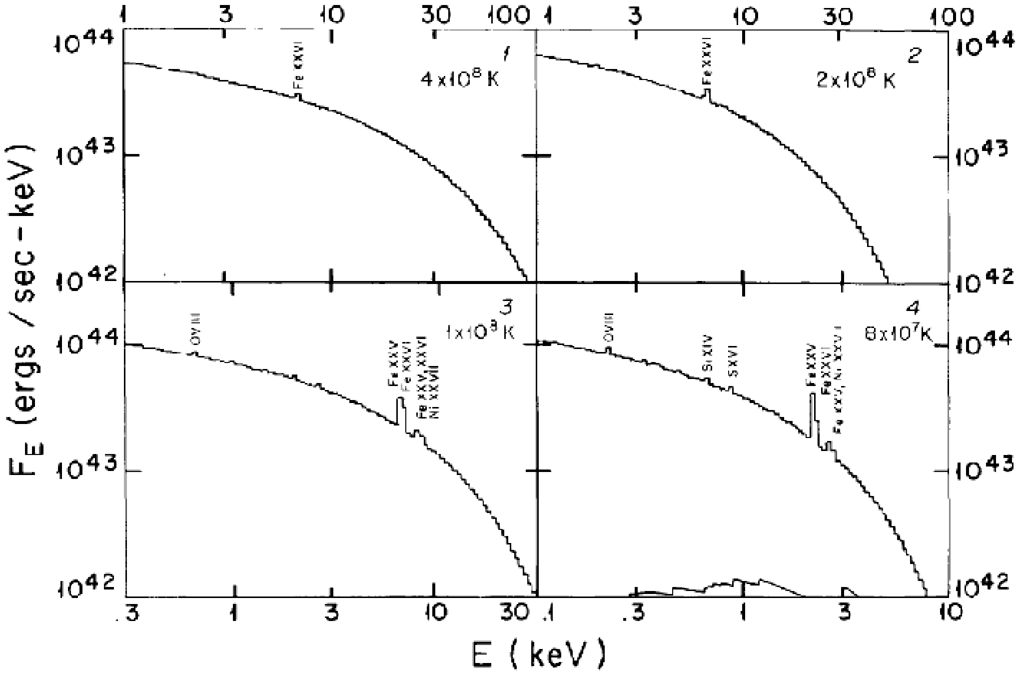
which is the dominant component?

- hot X-ray gas
  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

emission processes:

- Bremsstrahlung (free-free radiation)
- collisionally excited emission lines

T>5x10⁷ K (=2.5keV)



- hot X-ray gas

  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

  emission processes:

  - Bremsstrahlung (free-free radiation, T>2.5keV):
    - X-ray gas is highly ionized
    - free electrons are accelerated in the E-field
    - free-free emissivity:

$$\epsilon_\nu^{ff} = \frac{2^5 \pi e^6}{3 m_e c^3} \left(\frac{2\pi}{3 m_e k} \right)^{1/2} n_e T^{-1/2} e^{-h\nu/kT} Z^2 n_i g(Z, T, \nu).$$

    - total emissivity*:

$$\epsilon_{tot} = \int \epsilon d\nu \propto n_e n_i T^{1/2}$$

*emissivity: $\epsilon = \frac{dL}{dV}$

- hot X-ray gas

  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

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Galaxy Clusters

properties

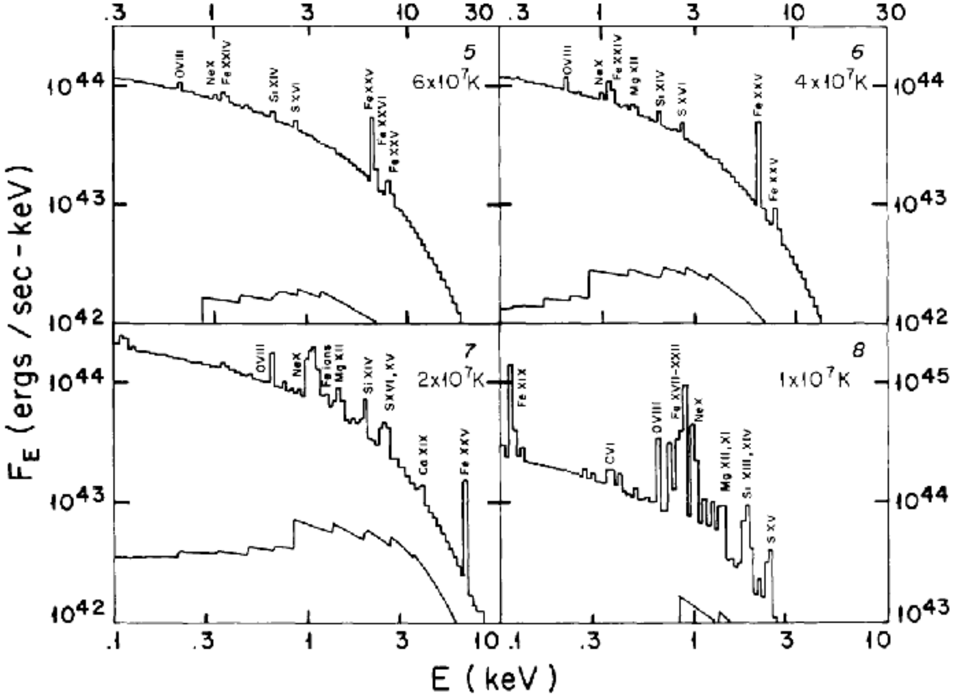
- hot X-ray gas

  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

  emission processes:

  - Bremsstrahlung (free-free radiation)
  - collisionally excited emission lines

T<5x10^7 K (=2.5keV)



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  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

<u>emission processes:</u>

- Bremsstrahlung (free-free radiation)
- collisionally excited emission lines (T<2.5keV):
  - rate of collisional excitations:

$$R = n_e n_i^m C_{mn}(T),$$

$$C_{mn}(T) = \int_{v_0}^{\infty} v f(v,T) \sigma_{mn}(v) dv \propto T^{-1/2}$$

$$f(v,T) = 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} v^2 e^{-mv^2/2kT}.$$

  - line emissivity:

$$\epsilon_{tot} = \int \epsilon^{line} d\nu \propto R \propto n_e n_i T^{-1/2}$$

- hot X-ray gas

  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s

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Galaxy Clusters

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- hot X-ray gas
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Galaxy Clusters

properties

- hot X-ray gas

  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s $= \iiint \epsilon dV$

  emission processes:

  - Bremsstrahlung (free-free radiation) $\epsilon = \int \epsilon_\nu d\nu \propto n_e n_i T^{1/2} \quad \rightarrow \; T\nearrow \; \Rightarrow \varepsilon\nearrow \; \Rightarrow L_x\nearrow$
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- hot X-ray gas

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emission processes:

dominant component

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Galaxy Clusters

properties

- hot X-ray gas

  - X-ray luminosity $L_x \sim 10^{43}\text{-}10^{45}\ \text{erg/s} = \iiint \epsilon dV$

<u>emission processes:</u>

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can this be used to learn something about the gas?

- hot X-ray gas

  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s = $\iiint \epsilon dV$

emission processes:

dominant component

- Bremsstrahlung (free-free radiation) $\epsilon = \int \epsilon_\nu d\nu \propto n_e n_i T^{1/2} \rightarrow T\nearrow \Rightarrow \varepsilon\nearrow \Rightarrow L_x\nearrow$
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$$L_X = \iiint \epsilon dV \propto n_e^2 T^{1/2} R^3$$

(assuming n_e=const. T=const.)

can this be used to learn something about the gas?

Galaxy Clusters

properties

- hot X-ray gas

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emission processes:

dominant component

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$$\boxed{L_X} = \iiint \epsilon dV \propto n_e^2 T^{1/2} \boxed{R^3}$$

(assuming n_e=const. T=const.)

observed

observed

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<u>emission processes:</u>

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$$\underbrace{\boxed{L_X}}_{\text{observed}} = \iiint \epsilon dV \propto \underbrace{\boxed{n_e^2 T^{1/2}}}_{\textbf{modelled}} \underbrace{\boxed{R^3}}_{\text{observed}}$$

(assuming n_e=const. T=const.)

can this be used to learn something about the gas?

- hot X-ray gas

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<u>emission processes:</u>

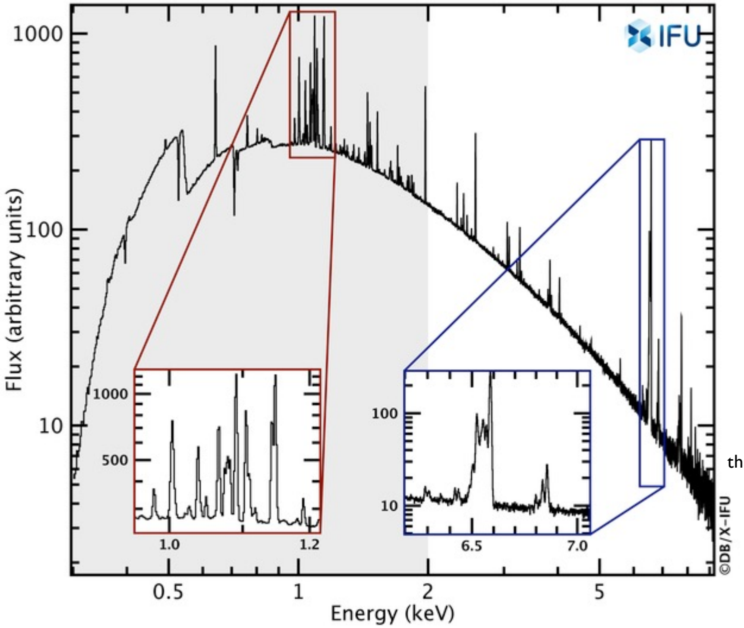
- Bremsstrahlung (free-free radiation)
- collisionally excited emission lines

}

- **shape of spectrum, and**
- **strength of emission lines**

⇩

$T\, ,\, n_e$



simulated spectrum demonstrating the detail
that will be captured by ESA's Athena X-ray observatory

- hot X-ray gas
  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s
  - very low density n_e ~ 10^{-1}-10^{-4} cm^{-3}
  - extremely hot T ~ 10^7-10^8 K

Galaxy Clusters

properties

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but why?

Galaxy Clusters

properties

- hot X-ray gas

• X-ray luminosity	L_x ~ 10^{43}-10^{45} erg/s
• very low density	n_e ~ 10^{-1}-10^{-4} cm^{-3}
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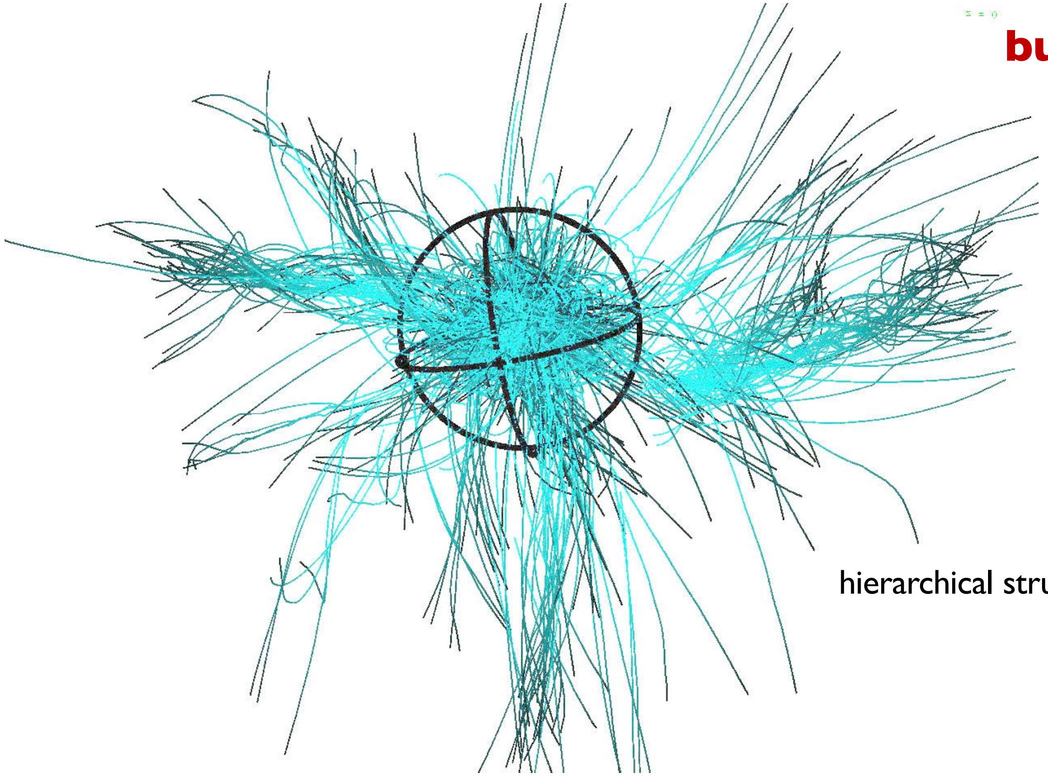
but why?



hierarchical structure formation

- hot X-ray gas
  - X-ray luminosity $L_x \sim 10^{43}$-10^{45} erg/s
  - very low density $n_e \sim 10^{-1}$-10^{-4} cm^{-3}
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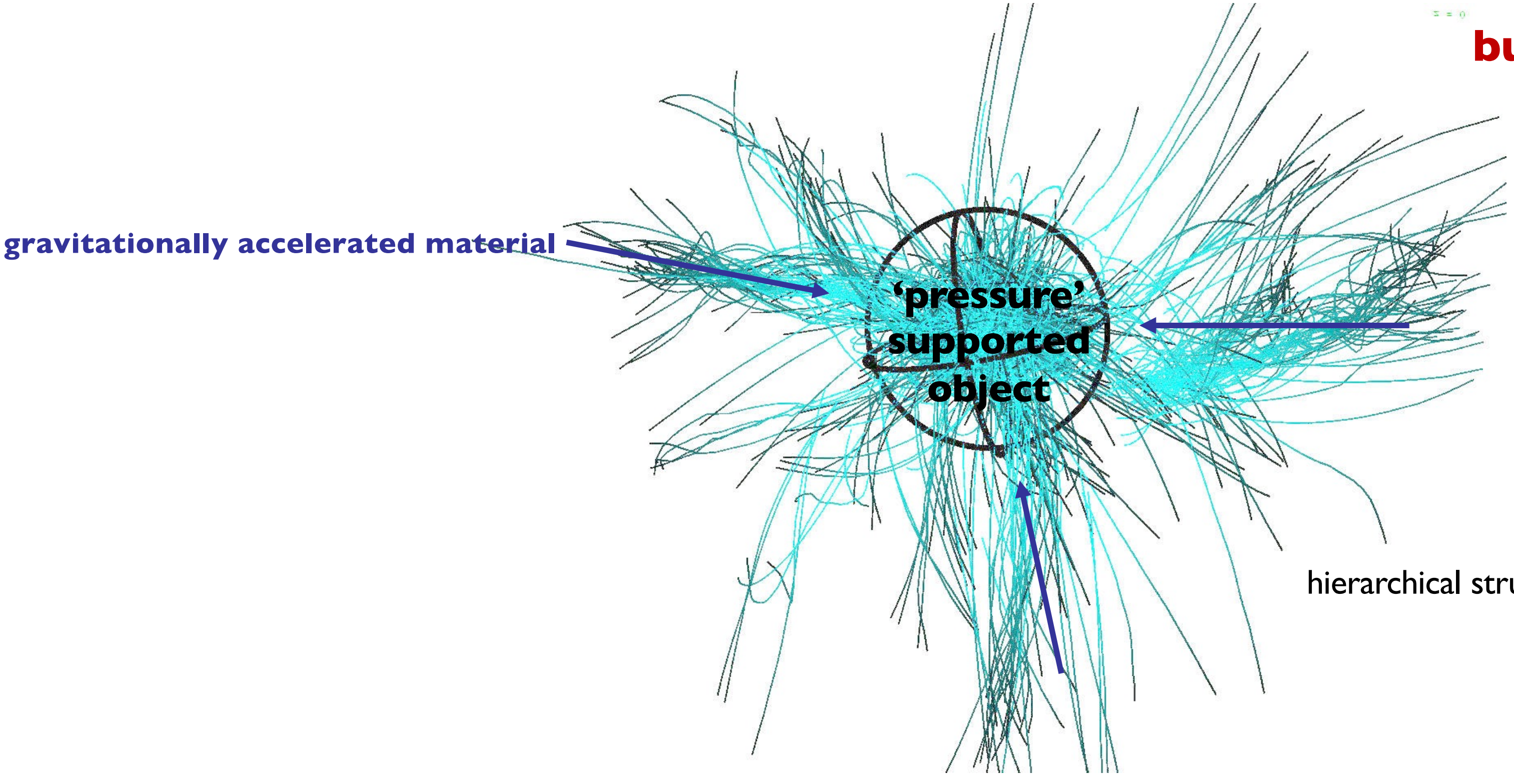


hierarchical structure formation

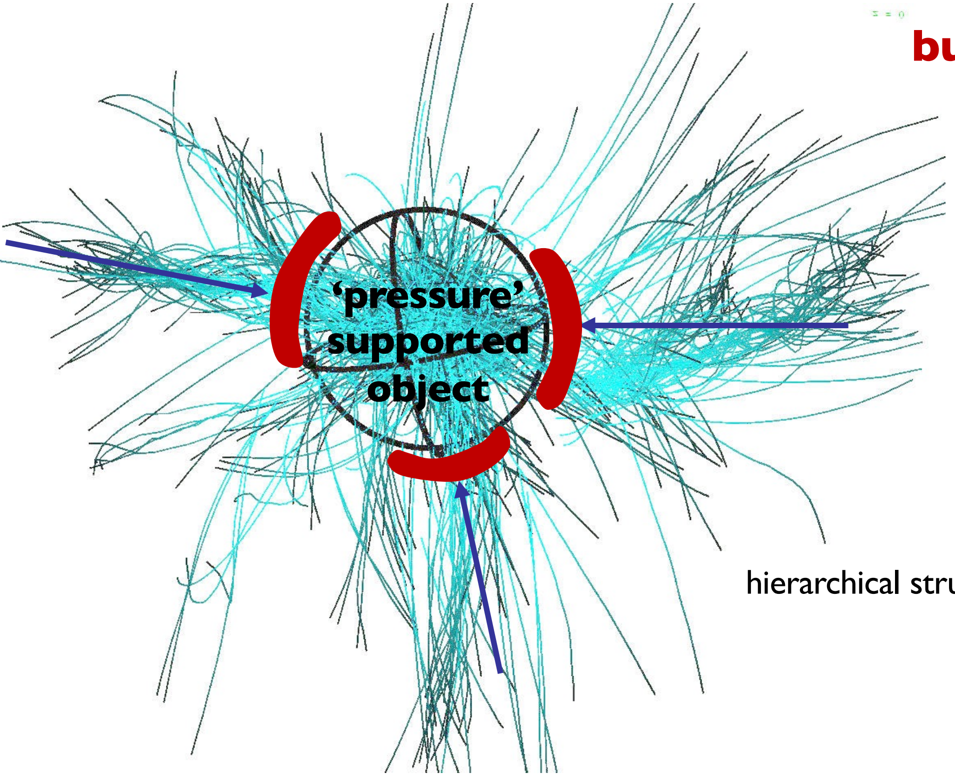
Galaxy Clusters *properties*

- hot X-ray gas
  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s
  - very low density n_e ~ 10^{-1}-10^{-4} cm^{-3}
  - extremely hot T ~ 10^7-10^8 K

but why?

accretion shocks:

gravitationally accelerated material



kinetic energy is converted into thermal energy

hierarchical structure formation

- hot X-ray gas

  - X-ray luminosity $L_x \sim 10^{43}$-10^{45} erg/s
  - very low density $n_e \sim 10^{-1}$-10^{-4} cm^{-3}
  - extremely hot $T \sim 10^{7}$-10^{8} K

but why?

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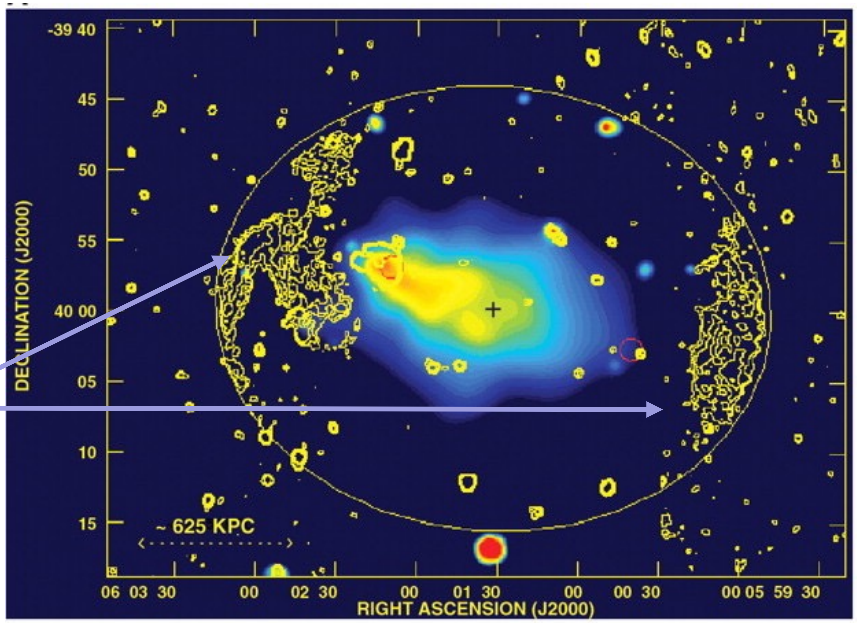

radio emission
caused by
accretion shocks

(Bagchi et al. 2006)

- hot X-ray gas
  - X-ray luminosity L_x ~ 10^{43}-10^{45} erg/s
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but why?

accretion shocks:

possible sites for
cosmic ray creation!

radio emission
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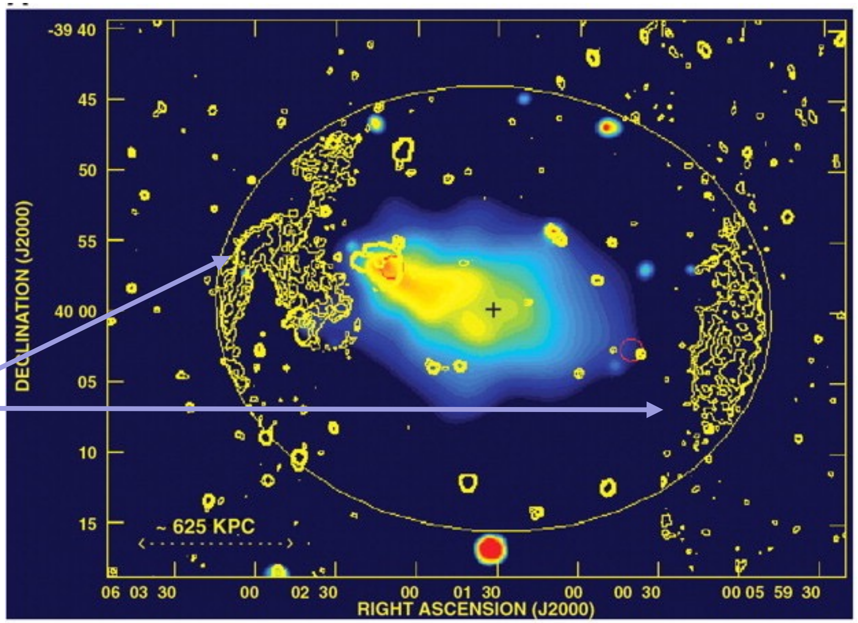

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Galaxy Clusters

properties

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another estimate of T:

$$\frac{1}{2} m_p \sigma_{v,gal}^2 \approx \frac{3}{2} kT$$

galaxies & gas
live in the same potential

$$\Rightarrow T \approx \frac{m_p \sigma_{v,gal}^2}{3k} \approx 4 \cdot 10^7 K$$

- hot X-ray gas – radiative cooling

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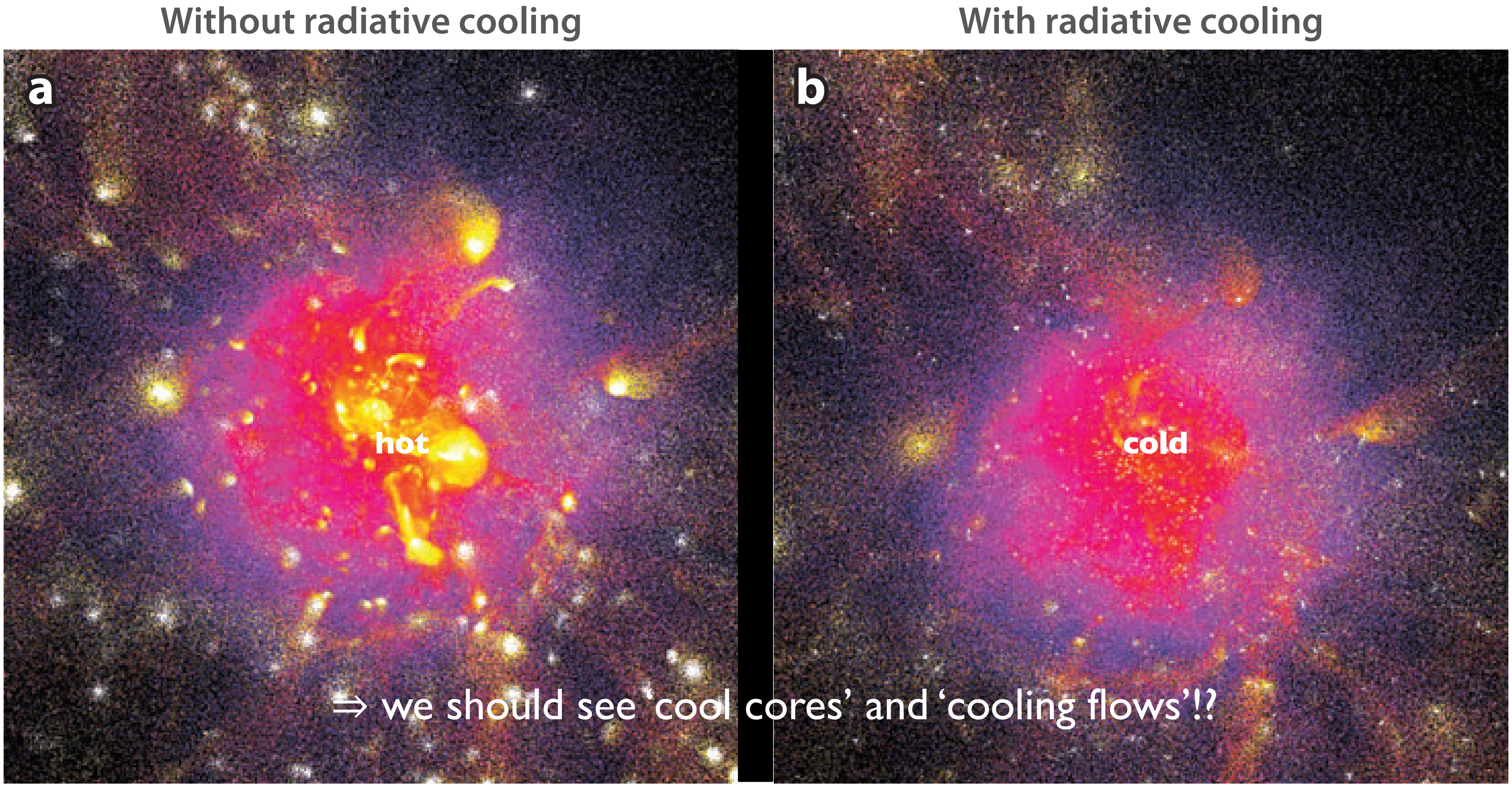
⇒ we should see 'cool cores' and 'cooling flows'!?

- hot X-ray gas – radiative cooling



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(Kravtsov & Borgani 2012)

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<u>“cooling flow problem”:</u>

only a few clusters (if any) show signs of cooling flows and/or cool cores...

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$$t_{\text{[illegible]}} = \frac{\frac{5}{2} n_e k T}{\text{[illegible]}} \ldots \left(\frac{T}{\text{[illegible]}}\right) \ldots \left(\frac{\text{[illegible]}}{10^{-2}\ \mathrm{cm}^{-3}}\right)$$

Hubble time

<<1 in the cluster centre

galaxy clusters (also) require some heating mechanism!

⇒ we should see 'cool cores' and 'cooling flows'!?

<u>"cooling flow problem":</u>

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- hot X-ray gas – radiative cooling vs. AGN heating

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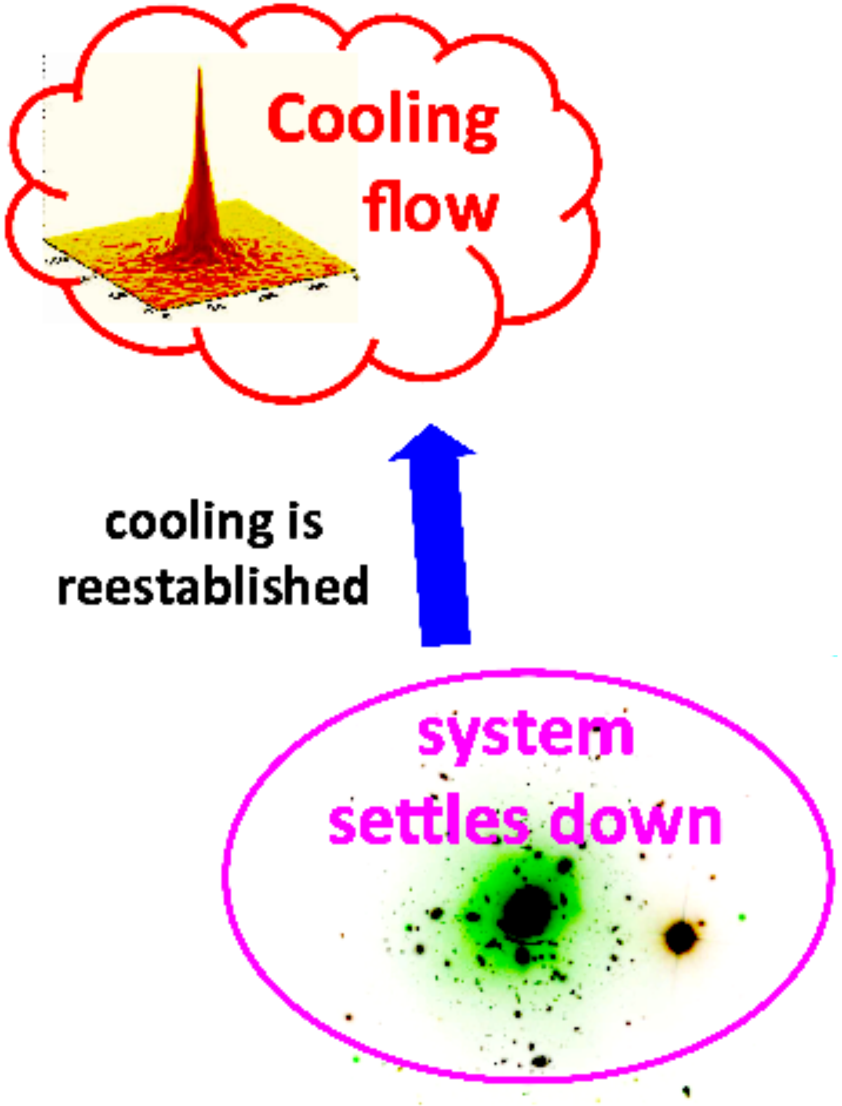
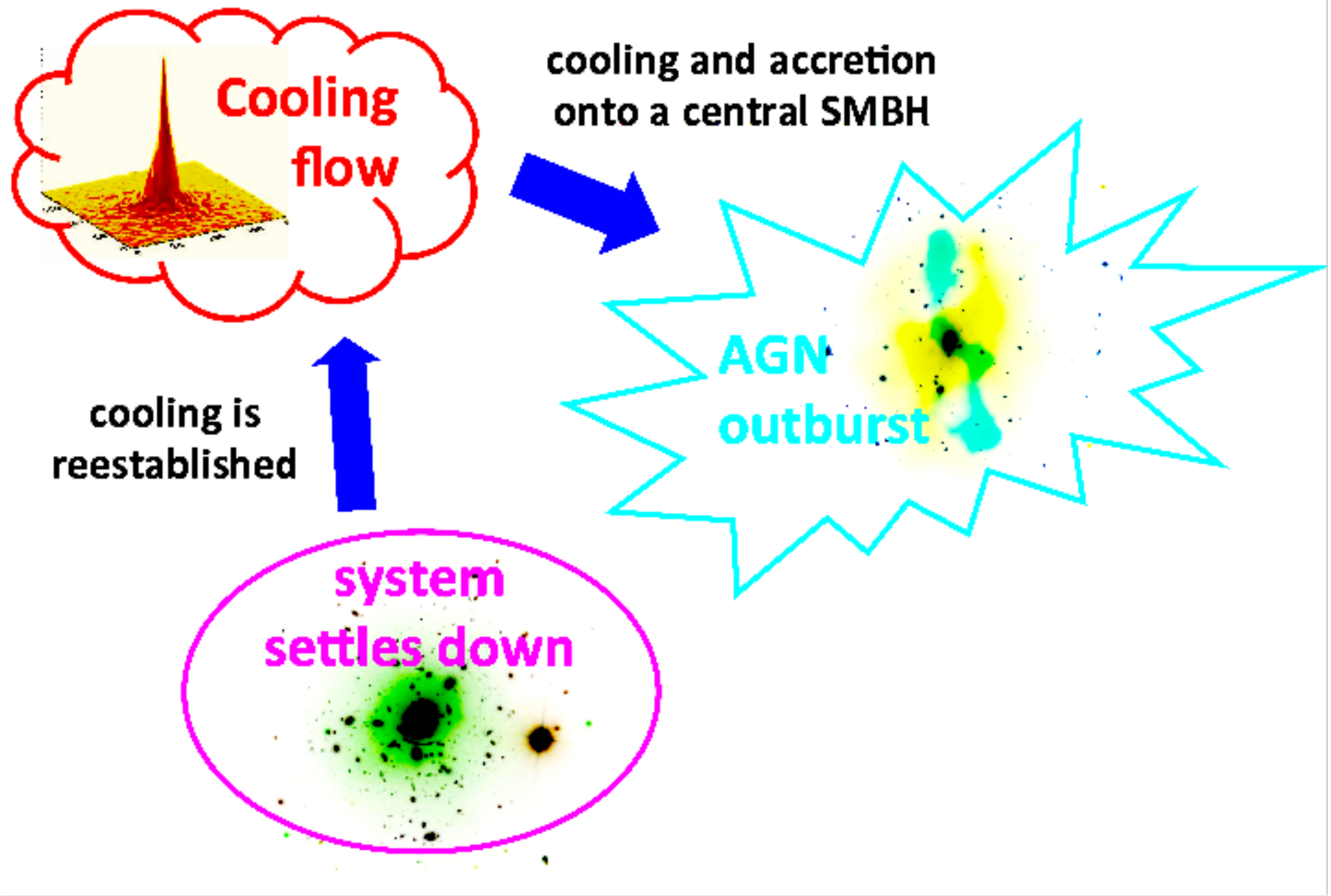


Cooling flow

cooling is reestablished

system settles down

- hot X-ray gas – radiative cooling vs. AGN heating



Cooling flow

cooling and accretion onto a central SMBH

AGN outburst

system settles down

cooling is reestablished

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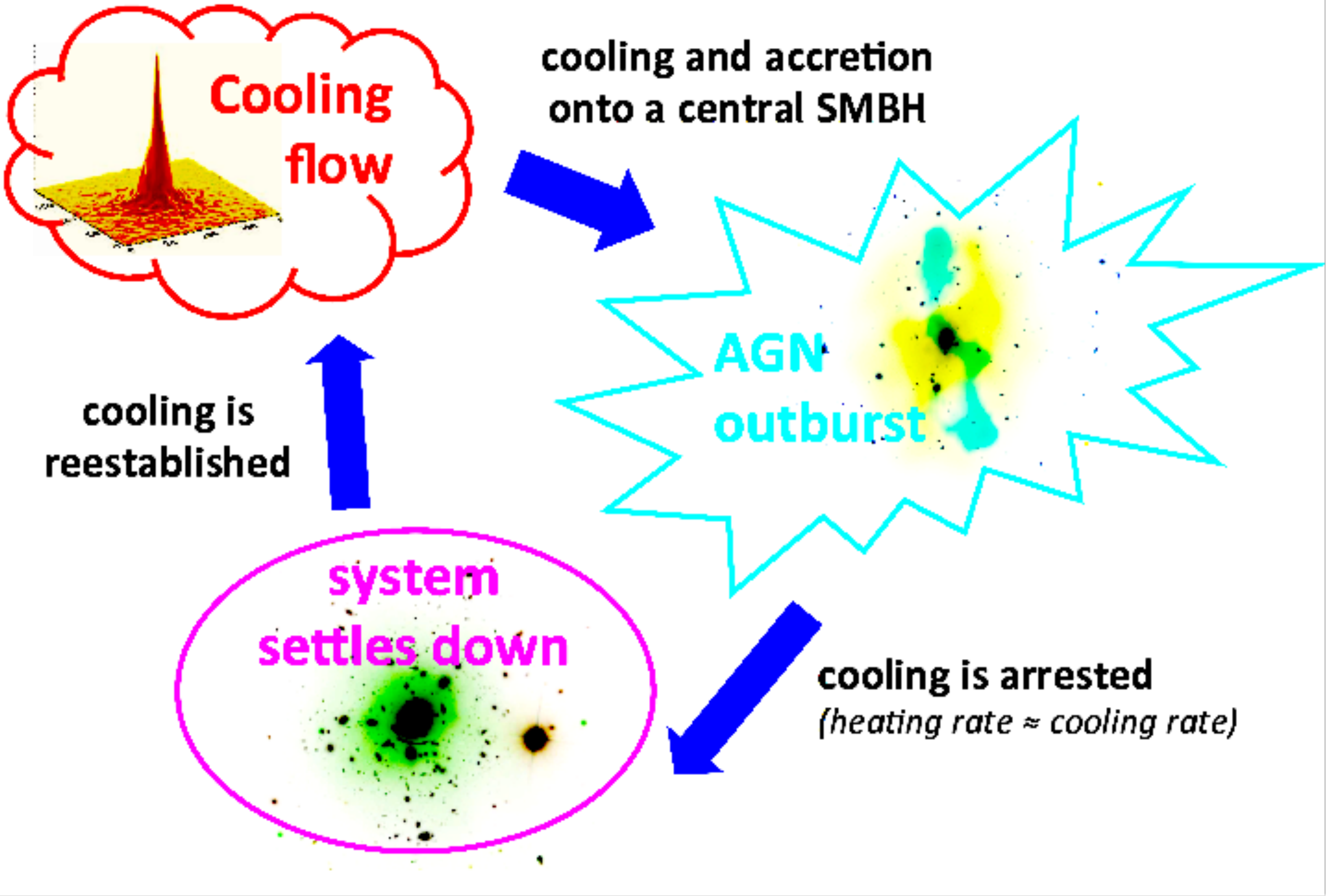


Cooling flow

cooling and accretion onto a central SMBH

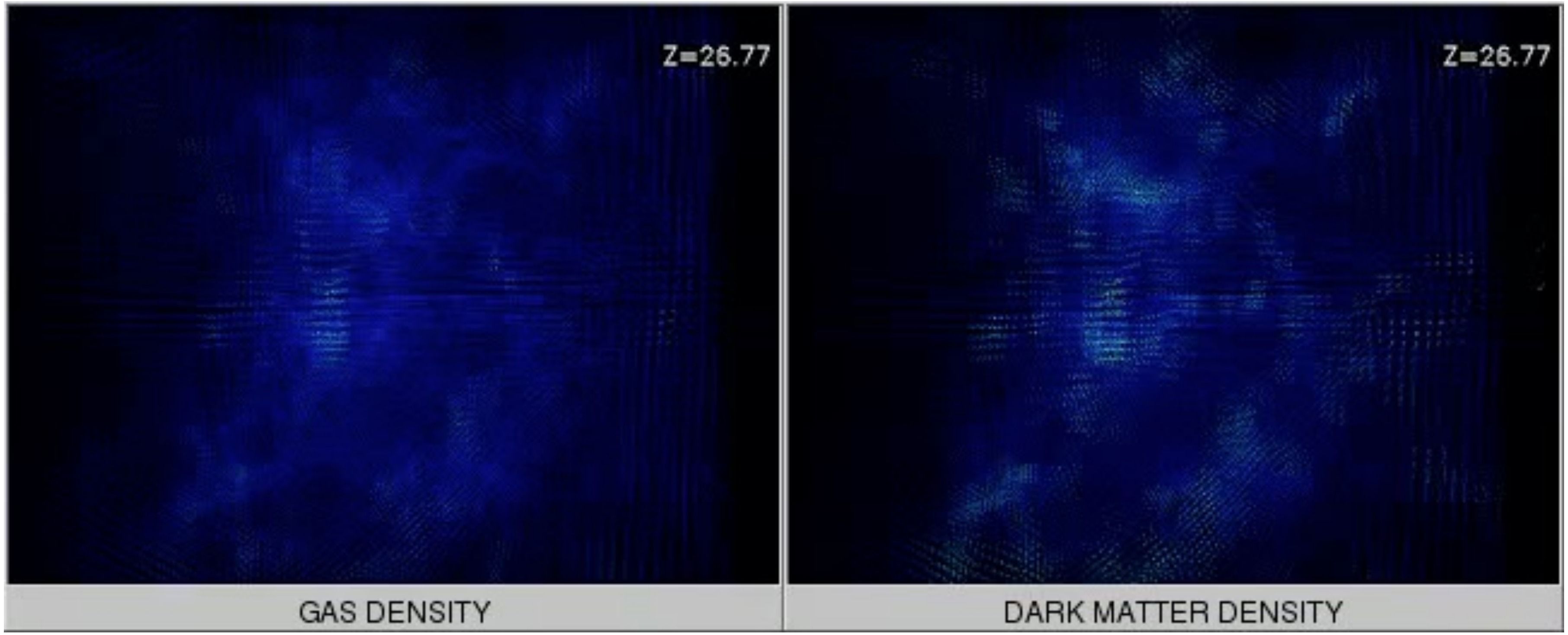
AGN outburst

cooling is arrested
(heating rate ≈ cooling rate)

system settles down

cooling is reestablished

- hot X-ray gas – numerical modelling



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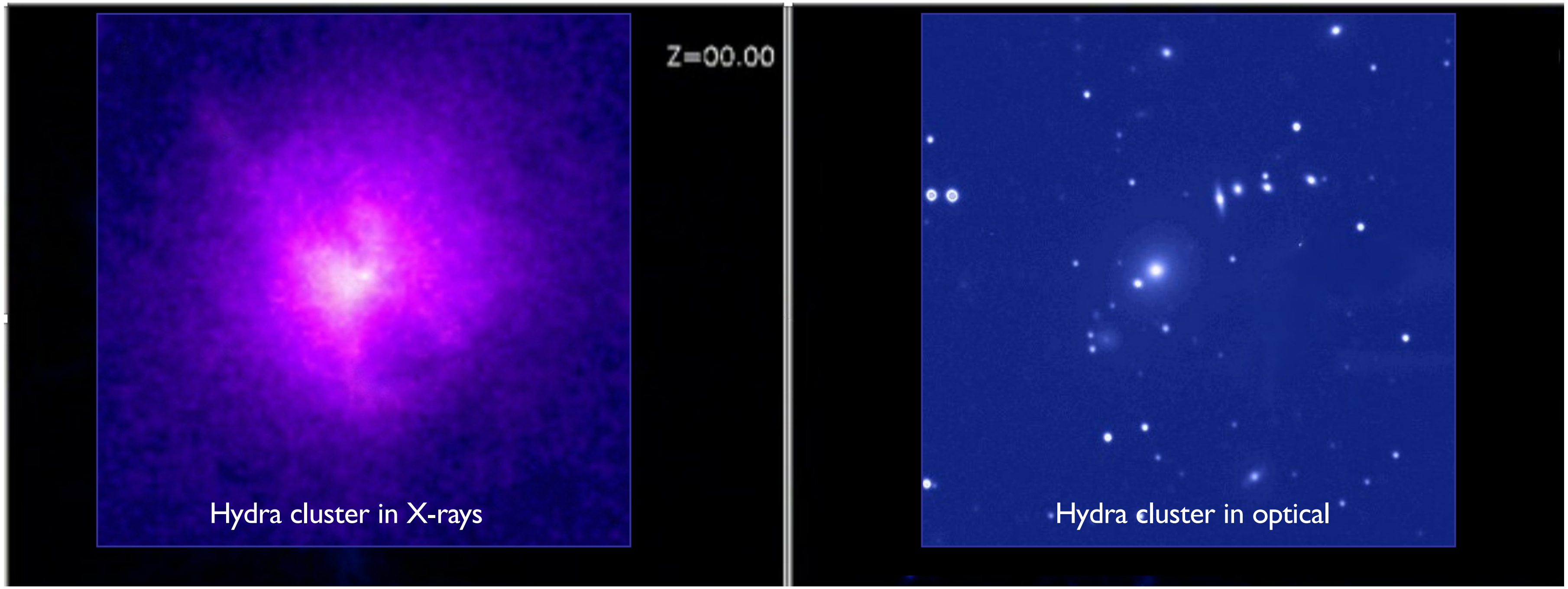
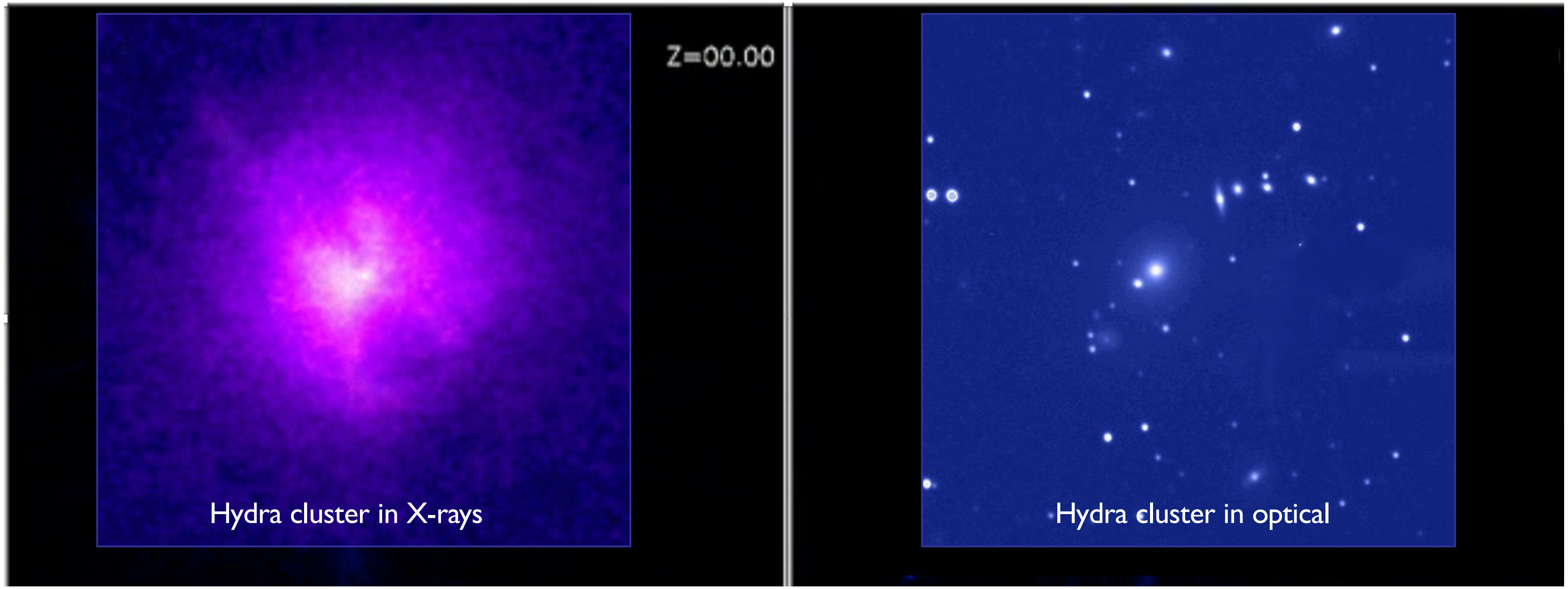


Hydra cluster in X-rays

Hydra cluster in optical

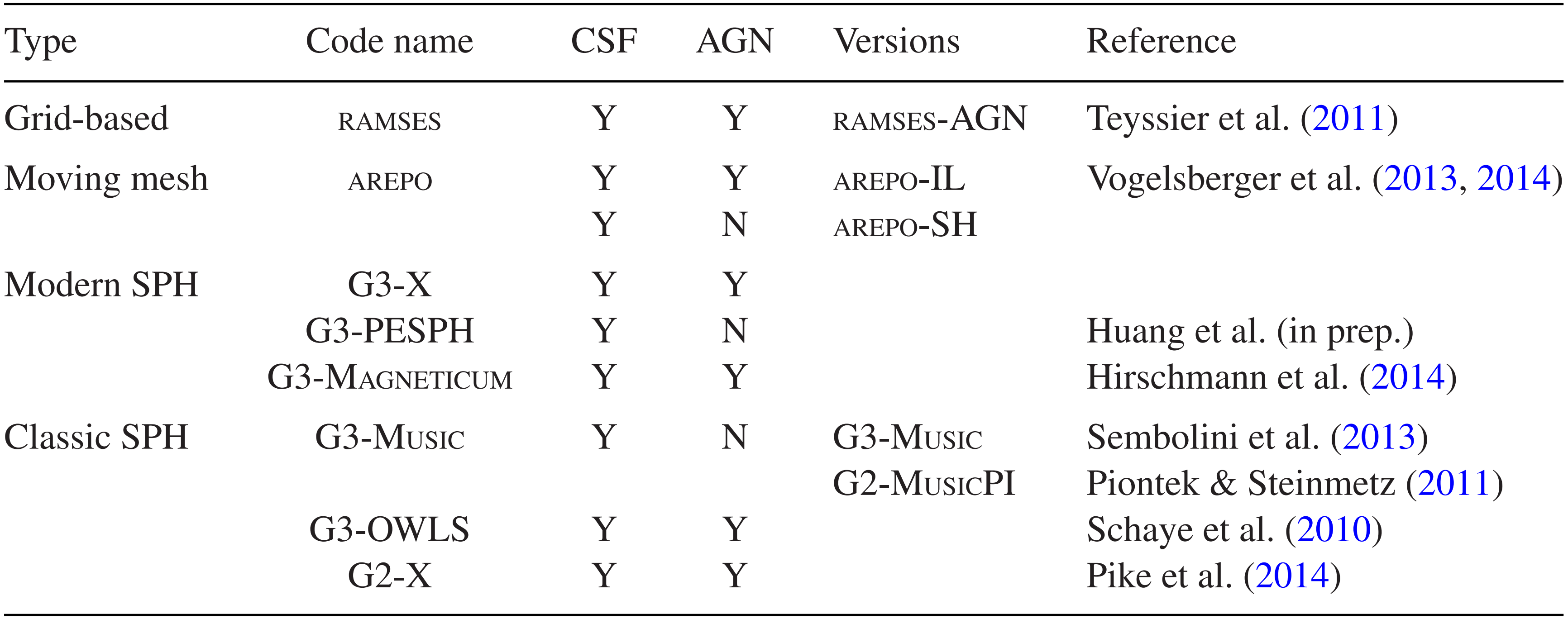
- hot X-ray gas – ***numerical*** modelling

can we be sure that this is done correctly?



- hot X-ray gas – numerical modelling

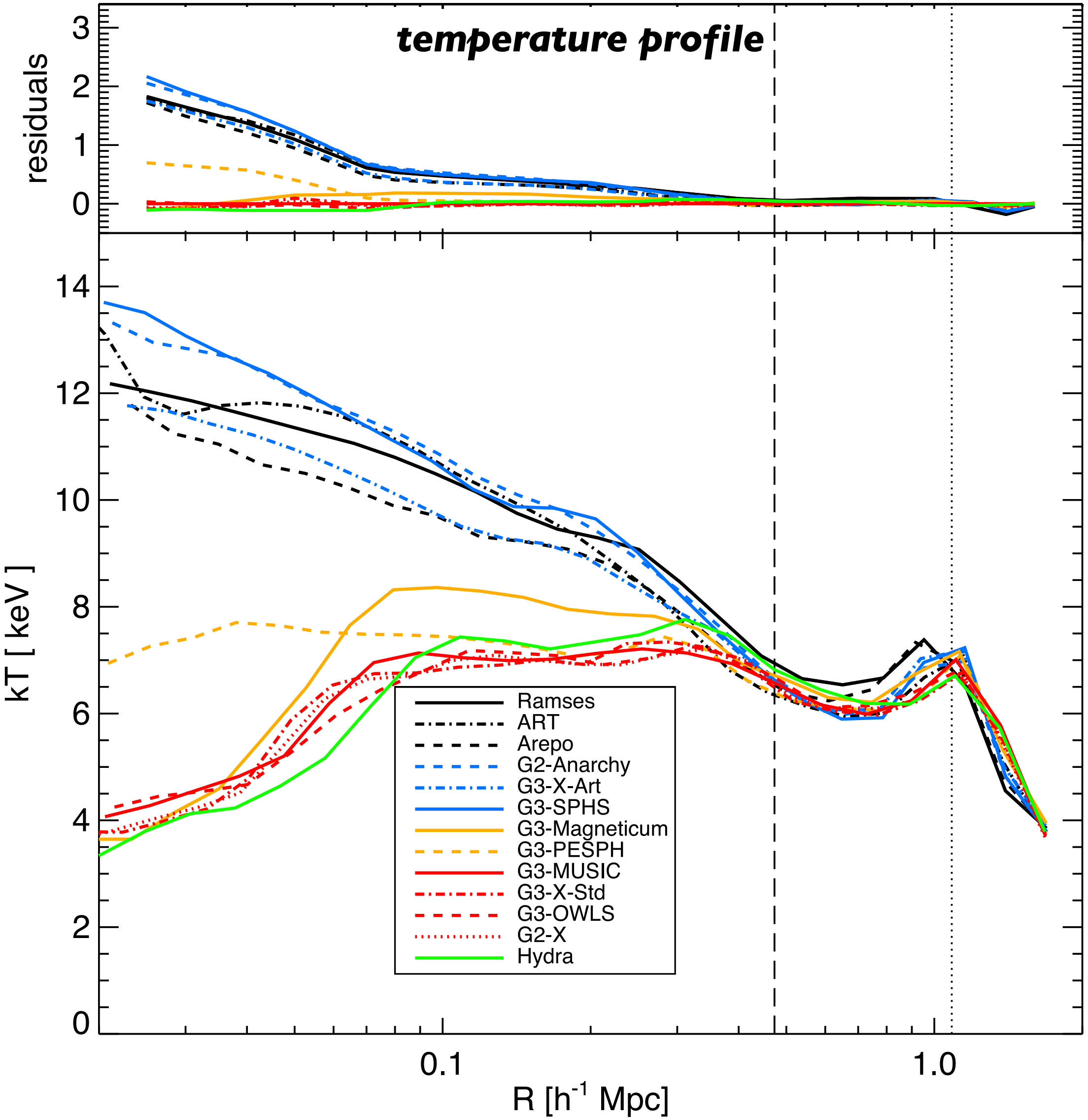
comparison of different codes



Type	Code name	CSF	AGN	Versions	Reference
Grid-based	RAMSES	Y	Y	RAMSES-AGN	Teyssier et al. (2011)
Moving mesh	AREPO	Y	Y	AREPO-IL	Vogelsberger et al. (2013, 2014)
		Y	N	AREPO-SH	
Modern SPH	G3-X	Y	Y		
	G3-PESPH	Y	N		Huang et al. (in prep.)
	G3-MAGNETICUM	Y	Y		Hirschmann et al. (2014)
Classic SPH	G3-MUSIC	Y	N	G3-MUSIC	Sembolini et al. (2013)
				G2-MUSICPI	Piontek & Steinmetz (2011)
	G3-OWLS	Y	Y		Schaye et al. (2010)
	G2-X	Y	Y		Pike et al. (2014)

(Sembolini et al. 2016)

- hot X-ray gas – numerical modelling: no feedback



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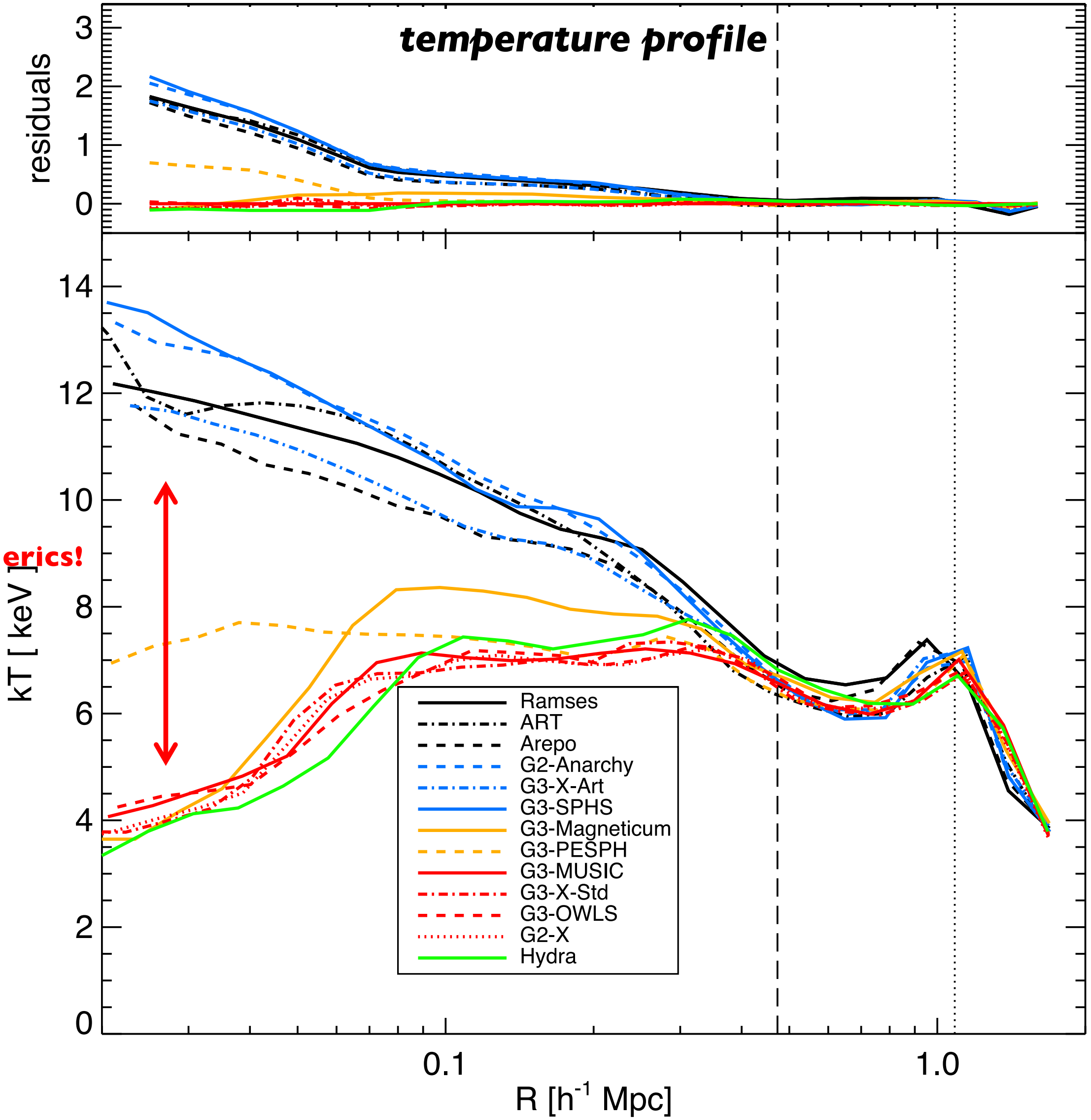


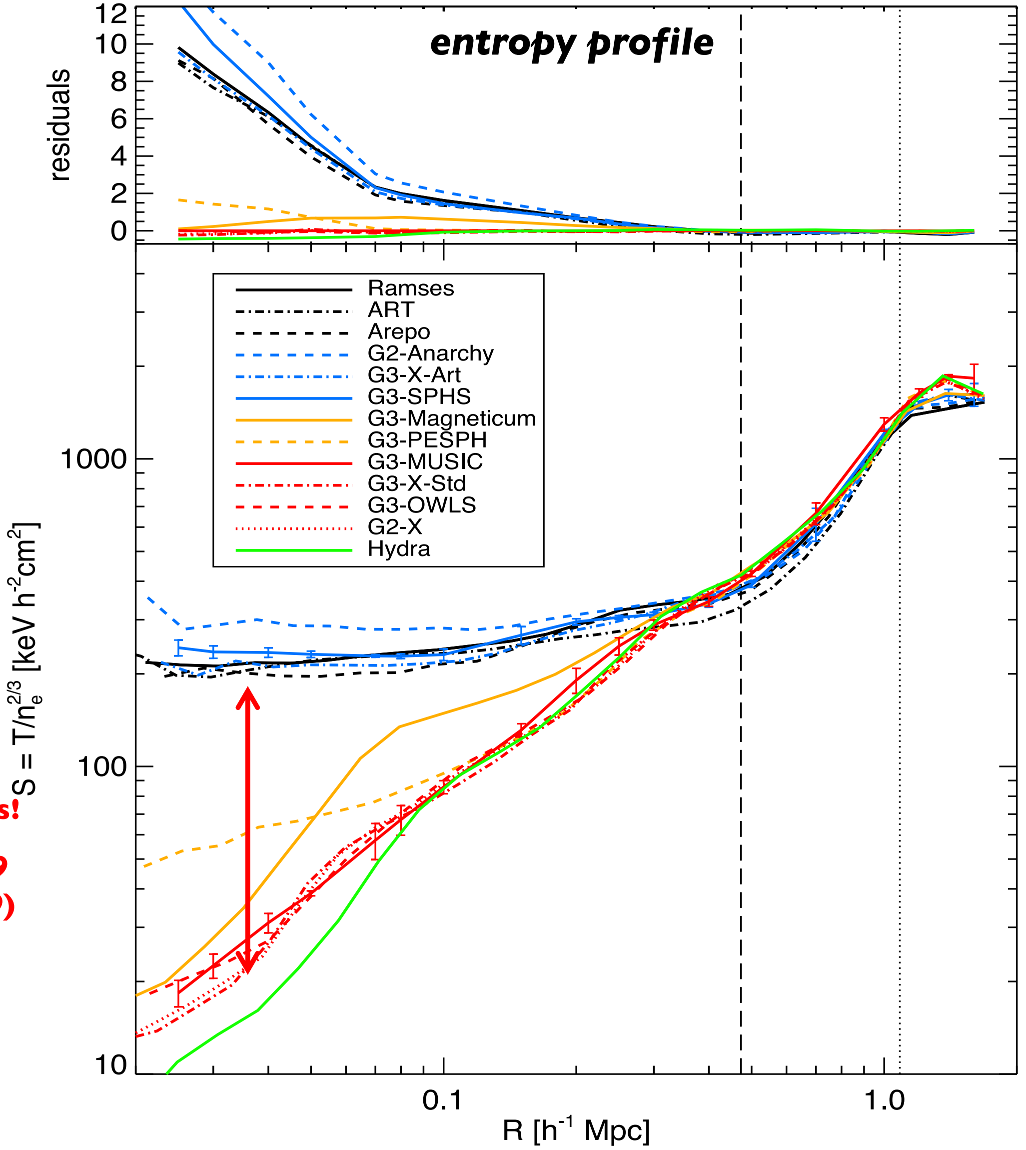
discrepancy due to numerics!

(Sembolini et al. 2016)

Galaxy Clusters

properties

- hot X-ray gas – numerical modelling: no feedback



discrepancy to to numerics!

...and actually known since 1999
(Frenk et al. 1999)

(Sembolini et al. 2016)

Galaxy Clusters *properties*

- hot X-ray gas – numerical modelling: with feedback

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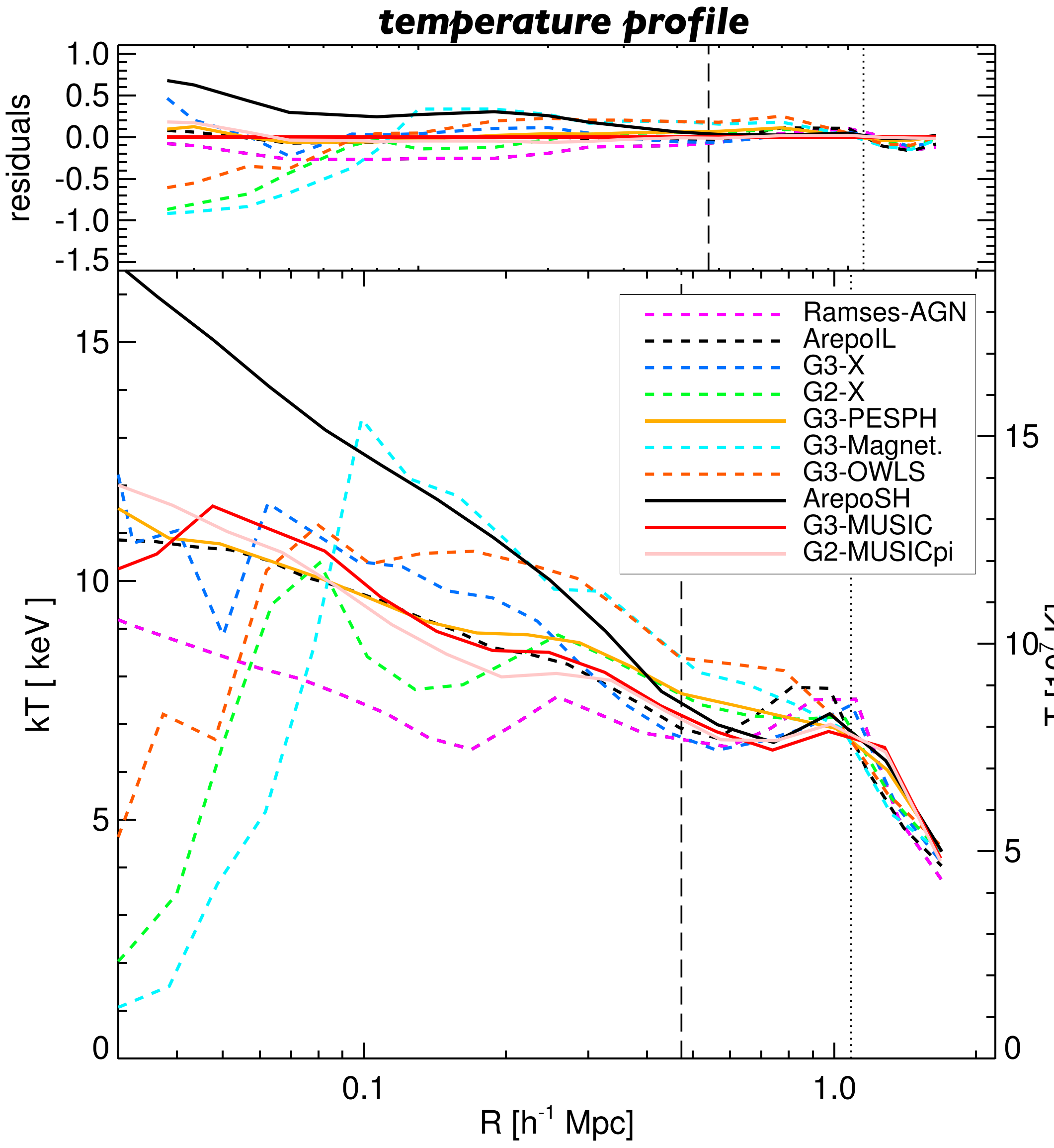
temperature profile



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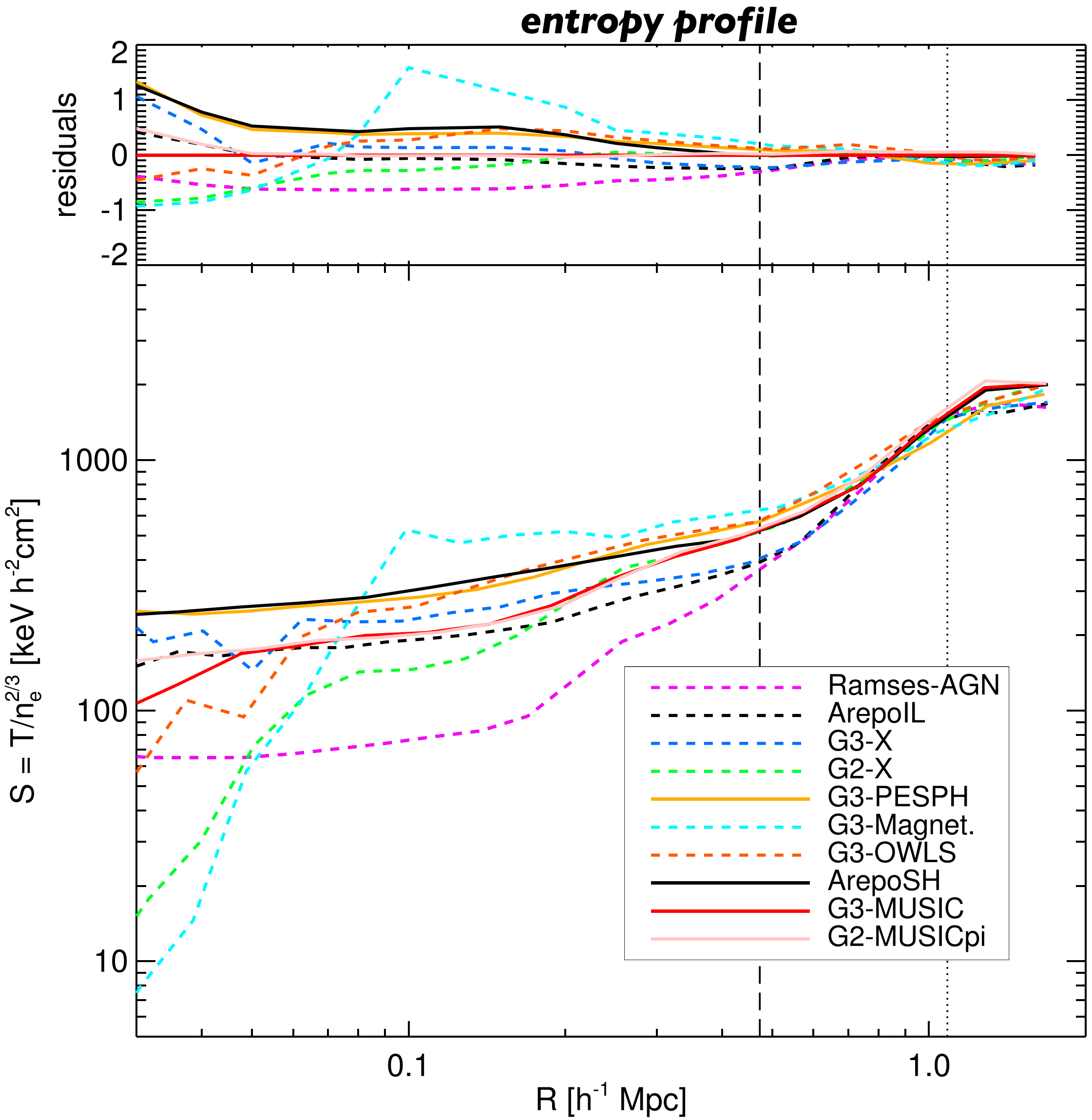

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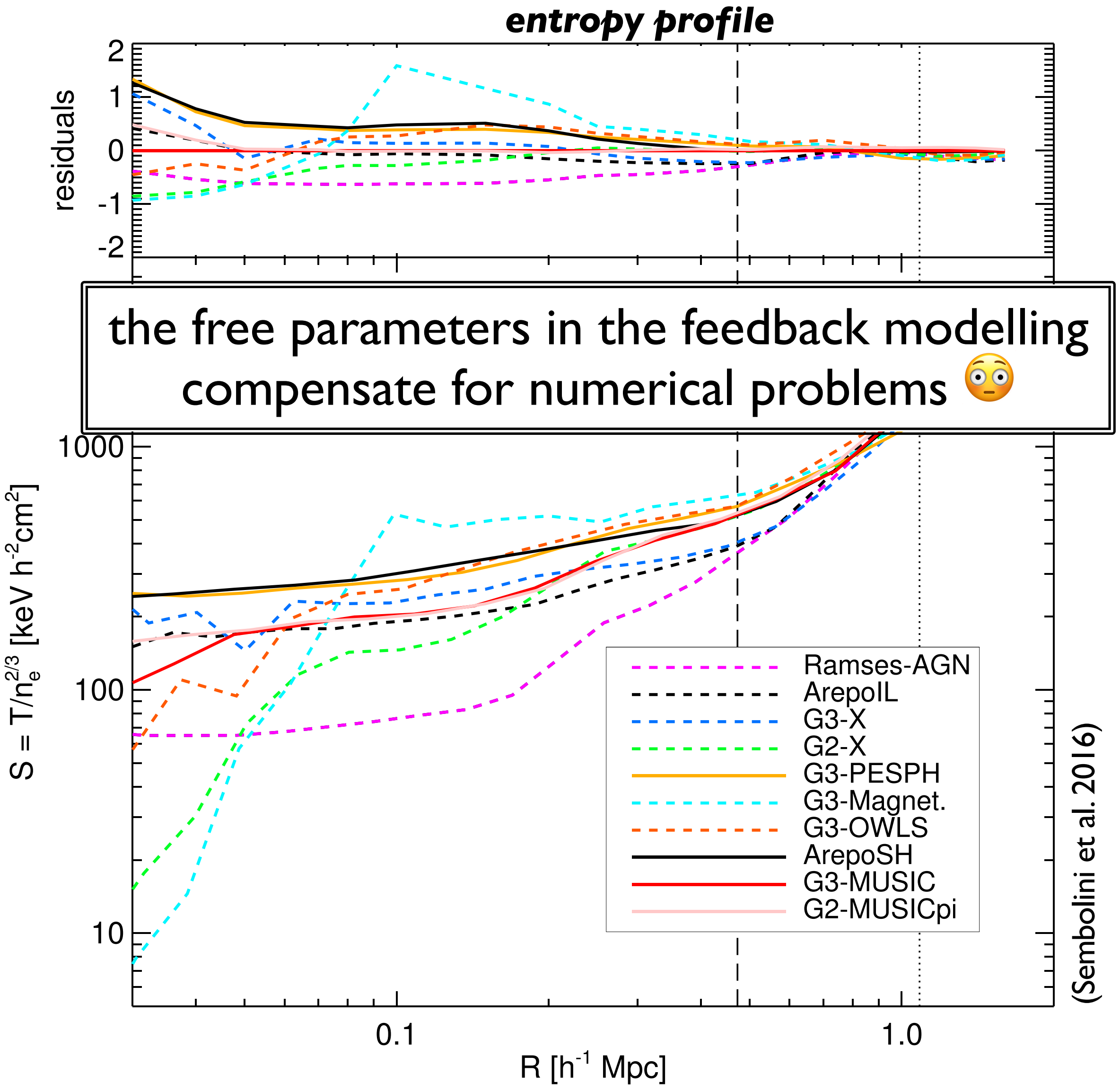

the free parameters in the feedback modelling compensate for numerical problems 😳

(Sembolini et al. 2016)

Galaxy Clusters

- hot X-ray gas
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Galaxy Clusters *properties*

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X-ray luminosity profile

$$L_X(R_-, R_+) = 4\pi \int_0^\infty dz \int_{R_-}^{R_+} dR \;\; R \; \underset{M_g}{\boxed{n_e(r) n_H(r)}} \; \Lambda(T)$$

with: $r^2 = R^2 + z^2$

n_e	electron number density
n_H	proton number density
Λ	radiative cooling coefficient

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turns out to be $f_b \sim 0.95\, f_{b,\mathrm{cosmic}}$
(see total mass estimation on following slides...)

Galaxy Clusters

properties

- general properties

$N_{galaxies}$ ~ $10\text{-}10^3$

Mass ~ $10^{14}\text{-}10^{15}\ M_\odot$

Radius ~ 1-5 Mpc

- abundance

$n_{clusters}$ ~ 10^{-5} / Mpc^3

($n_{galaxies}$ ~ 10^{-2} / Mpc^3)

- **baryonic properties**

L_x ~ $10^{43}\text{-}10^{45}$ erg/s

T_{ICM} > 10^8 K

M_g ~ $10^{13}\text{-}10^{14}\ M_\odot$

f_b ~ 0.95 $f_{b,cosmic}$

Galaxy Clusters

properties

- general properties

$N_{galaxies}$ ~ 10-10^3

total cluster Mass ~ 10^{14}-10^{15} $M_\odot$

Radius ~ 1-5 Mpc

- abundance

$n_{clusters}$ ~ 10^{-5} / Mpc^3

($n_{galaxies}$ ~ 10^{-2} / Mpc^3)

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  - galaxy motion inside cluster
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  - gravitational lensing

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  - galaxy motion inside cluster
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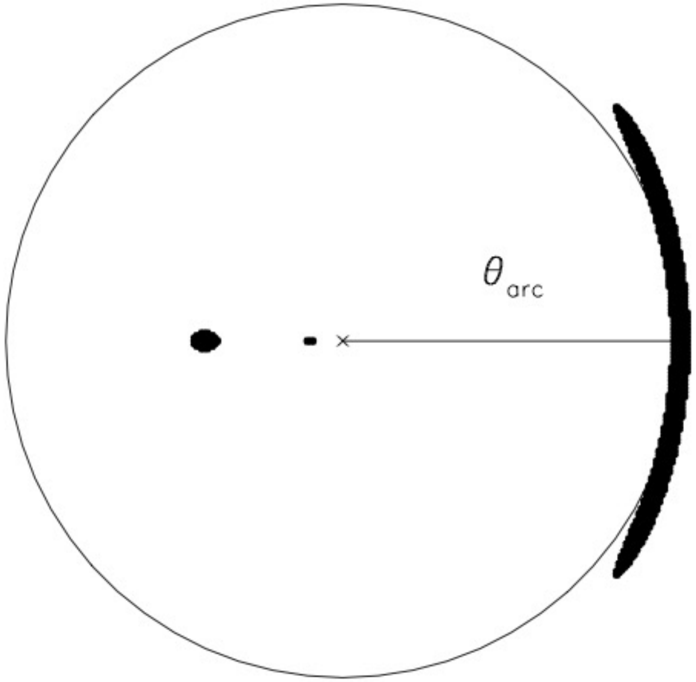
  - **gravitational lensing**

Galaxy Clusters *properties*

- cluster mass estimates
  - gravitational lensing*:



$$\boxed{M(<\theta_{arc}) = 1.1 \text{ x } 10^{14} \text{ M}_{\odot} \ (\theta_{arc}/30'')^2 \ (D/\text{Gpc})}$$

with $D = D_L \, D_{LS} \, / \, D_S$

*more details in Advanced Cosmology lecture...

- cluster mass estimates
  - galaxy motion inside cluster
  - **hot X-ray gas**
  - gravitational lensing

- cluster mass profile
  - hot X-ray gas - in hydrostatic equilibrium:

$$\boxed{M(<r) = -\frac{kTr}{G\mu m_p}\left(\frac{dln\rho_g}{dlnr} + \frac{dlnT}{dlnr}\right)}$$

(***exercise***)

- cluster mass estimates
  - **galaxy motion inside cluster***
  - hot X-ray gas
  - gravitational lensing

*remember Zwicky back in 1933...

- cluster mass estimates
  - galaxy motion inside cluster:

$$\boxed{\text{virial theorem:}\quad 2\,E_{\mathrm{kin}} + E_{\mathrm{pot}} = 0}$$

- cluster mass estimates
    - galaxy motion inside cluster:

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$$2\,E_{\mathrm{kin}} = \sum m_{\mathrm{i}}\, v_{\mathrm{i}}^2 = \sum m_{\mathrm{i}}\,(\, v_{\mathrm{x,i}}^2 + v_{\mathrm{y,i}}^2 + v_{\mathrm{z,i}}^2\,)$$

$$E_{\mathrm{pot}} = -\,(3/5)\;G\,M^2/R$$

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    - galaxy motion inside cluster:

virial theorem: $2\,E_{\mathrm{kin}} + E_{\mathrm{pot}} = 0$

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$$E_{\mathrm{pot}} = -\,(3/5)\,G\,M^2/R$$

$$\downarrow$$

$$\boxed{M = 5\,R\,\sigma_{\mathrm{los}}^2 / G}$$

Galaxy Clusters *properties*

- cluster mass estimates
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$$E_{\rm pot} = -\,(3/5)\,G\,M^2/R$$

$$\downarrow$$

$$\boxed{M = 5\,R\,\sigma_{\rm los}^2\,/\,G}$$

we can do even better and get the mass *profile*...

- cluster mass profile
  - galaxy motion inside cluster:

$$\boxed{\text{Jeans equation*: } \frac{1}{\rho}\frac{d}{dr}\left(\rho\sigma_r^2\right) + 2\beta\,\frac{\sigma_r^2}{r} = -\frac{GM(<r)}{r}} \quad ; \quad \beta = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$$

---

*analog to hydrostatic equilibrium, but now velocity dispersion balances gravity...

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<u>anisotropy parameter</u>:
difference between radial and tangential velocities...

*analog to hydrostatic equilibrium, but now velocity dispersion balances gravity...

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$$\downarrow$$

$$\boxed{M(<r) = -\frac{\sigma_r^2 r}{G}\left(\frac{dln\rho}{dlnr} + \frac{dln\sigma_r^2}{dlnr} + 2\beta\right)}$$

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  - galaxy motion inside cluster:

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Galaxy Clusters

properties

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circular problem as $\rho = \frac{dM}{dr}$

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circular problem as $\rho = \frac{dM}{dr}$ → iterative solution...

- cluster mass profile

hydrostatic equilibrium:

$$M(<r) = -\frac{kTr}{\mu m_p G}\left(\frac{dln\rho_g}{dlnr} + \frac{dlnT}{dlnr}\right)$$

Jeans equation:

$$M(<r) = -\frac{\sigma_r^2 r}{G}\left(\frac{dln\rho}{dlnr} + \frac{dln\sigma_r^2}{dlnr} + 2\beta\right)$$

- cluster mass profile
  - the β – model*:

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*has nothing to do with the anisotropy parameter!

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hydrostatic equilibrium:

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Jeans equation:

$$M(< r) = -\frac{\sigma_r^2 r}{G}\left(\frac{dln\rho}{dlnr} + \frac{dln\sigma_r^2}{dlnr} + 2\beta\right)$$

$0 \; = \beta = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$ (isotropic velocity dispersion)

σ_r^2=const.

T =const.

---

*has nothing to do with the anisotropy parameter!

- cluster mass profile
  - the $\beta-$ model:

hydrostatic equilibrium:

$$M(< r) = -\frac{kTr}{\mu m_p G}\left(\frac{dln\rho_g}{dlnr}\right)$$

Jeans equation:

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$$\Rightarrow \quad \frac{d\ln\rho_g}{d\ln r}\frac{kT\,r}{\mu m_p} = \sigma_r^2\frac{d\ln\rho}{d\ln r}$$

$$\frac{d\ln\rho_g}{d\ln\rho} = \frac{\sigma_r^2\mu m_p}{kT} \equiv \beta$$

$$\Rightarrow \quad \frac{\rho_g}{\rho_{g0}} = \left(\frac{\rho}{\rho_0}\right)^{\beta}$$

- cluster mass profile
  - the $\beta-$ model:

hydrostatic equilibrium:
$$M(< r) = -\frac{kTr}{\mu m_p G}\left(\frac{dln\rho_g}{dlnr}\right)$$

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$$\frac{d\ln\rho_g}{d\ln\rho} = \frac{\sigma_r^2\mu m_p}{kT} \equiv \beta$$

careful: β here is not the anisotropy-β!

$$\Rightarrow \quad \frac{\rho_g}{\rho_{g0}} = \left(\frac{\rho}{\rho_0}\right)^\beta$$

- cluster mass profile
  - the β – model:

$$\frac{\rho_g}{\rho_{g,0}} = \left(\frac{\rho}{\rho_0}\right)^{\beta} \qquad \beta = \frac{\sigma_r^2 \mu m_p}{kT}$$

under the assumptions:

$0 \ = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$ (isotropic velocity dispersion)

σ_r^2=const.

T =const.

- general properties

$N_{galaxies}$	~	10-10^3
Mass	~	10^{14}-10^{15} $M_\odot$
Radius	~	1-5 Mpc

- abundance

$n_{clusters}$	~	10^{-5} / Mpc^3
($n_{galaxies}$	~	10^{-2} / Mpc^3)

- baryonic properties

L_x	~	10^{43}-10^{45} erg/s
T_{ICM}	>	10^8 K
M_g	~	10^{13}-10^{14} $M_\odot$
f_b	~	0.95 $f_{b,cosmic}$

- general properties

$N_{galaxies}$	~	**$10\text{-}10^3$**	just count...
Mass	~	$10^{14}\text{-}10^{15}\ M_\odot$	
Radius	~	1-5 Mpc	

- abundance

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Galaxy Clusters

properties

- general properties

the cluster galaxy *population*!?	$\mathbf{N_{galaxies}}$	**~**	$\mathbf{10\text{-}10^3}$
	Mass	~	$10^{14}\text{-}10^{15}\ M_\odot$
	Radius	~	1-5 Mpc

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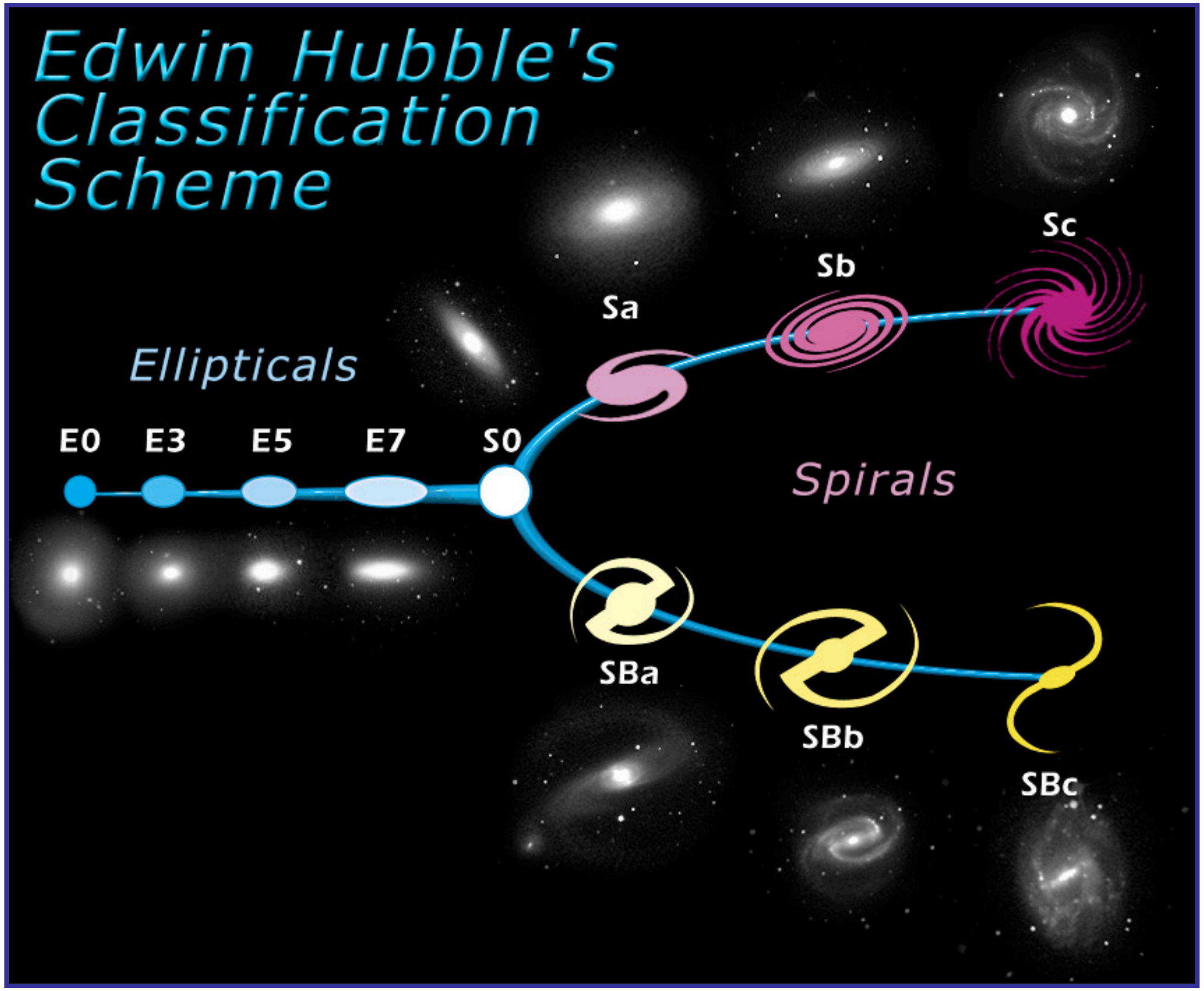
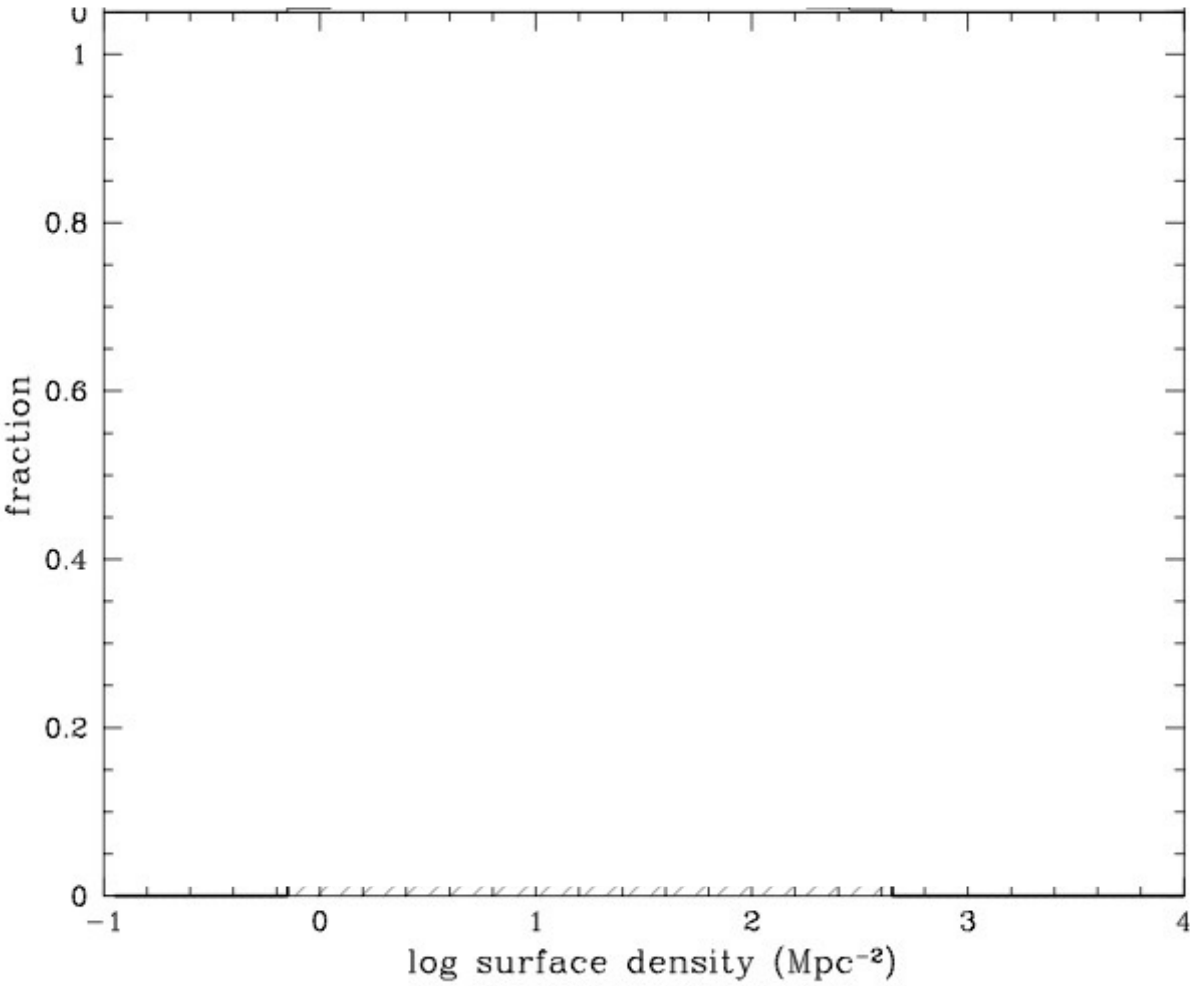
- galaxy population

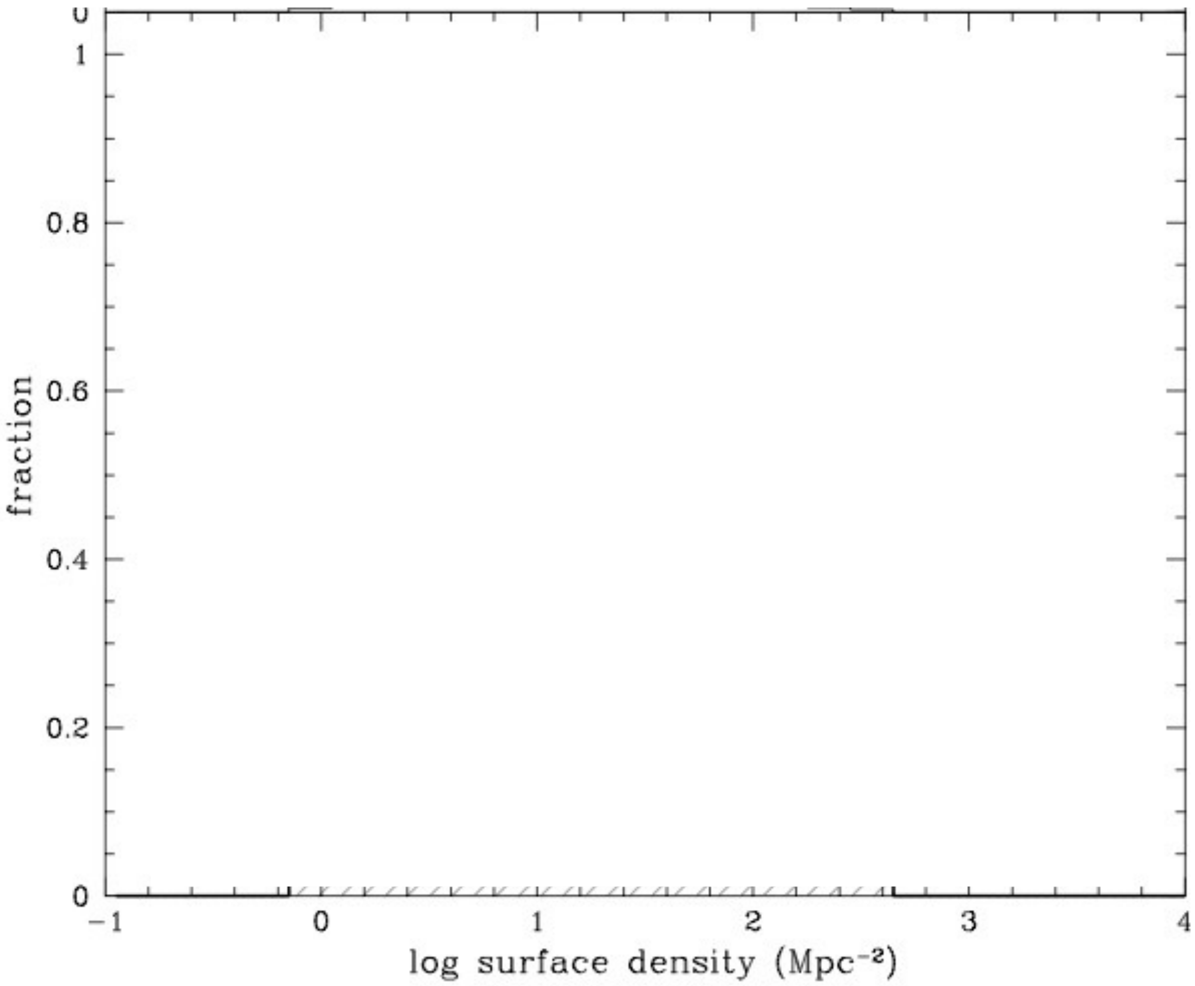


- galaxy population: morphology-density relation



(Dressler et al. 1997)

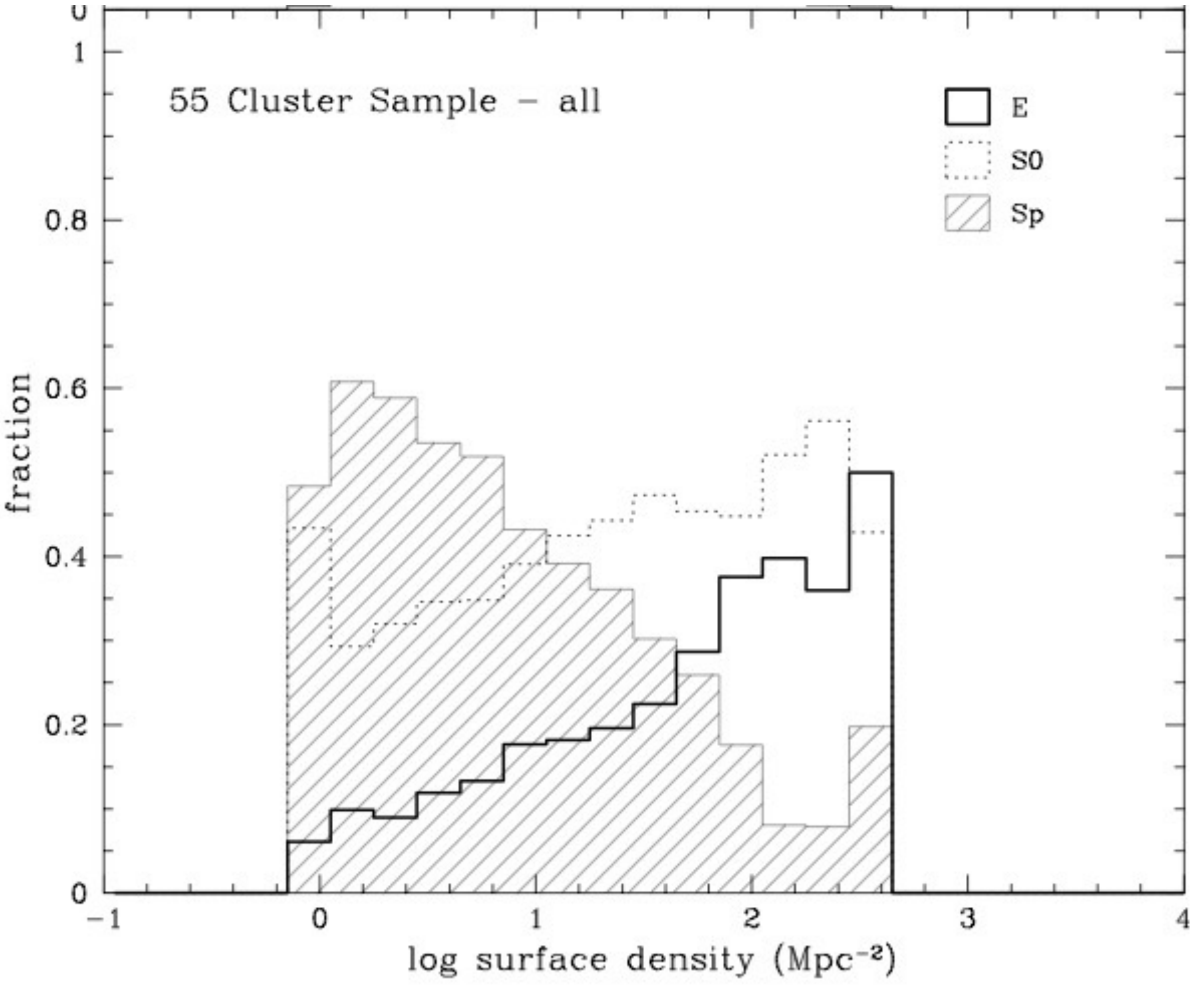
- galaxy population: morphology-density relation



(Dressler et al. 1997)

increasing density = closer to cluster centre

- galaxy population: morphology-density relation



(Dressler et al. 1997)

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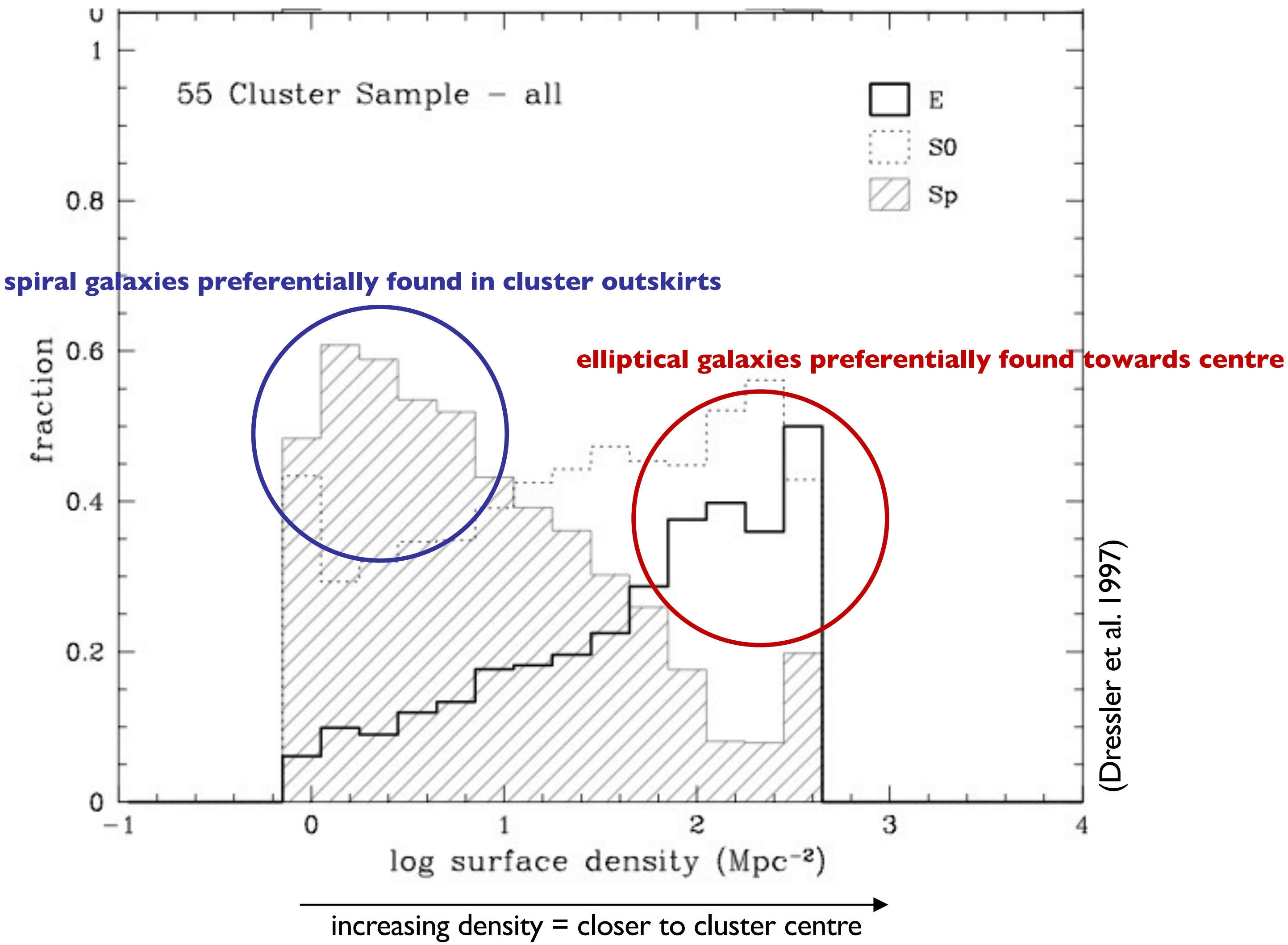


spiral galaxies preferentially found in cluster outskirts

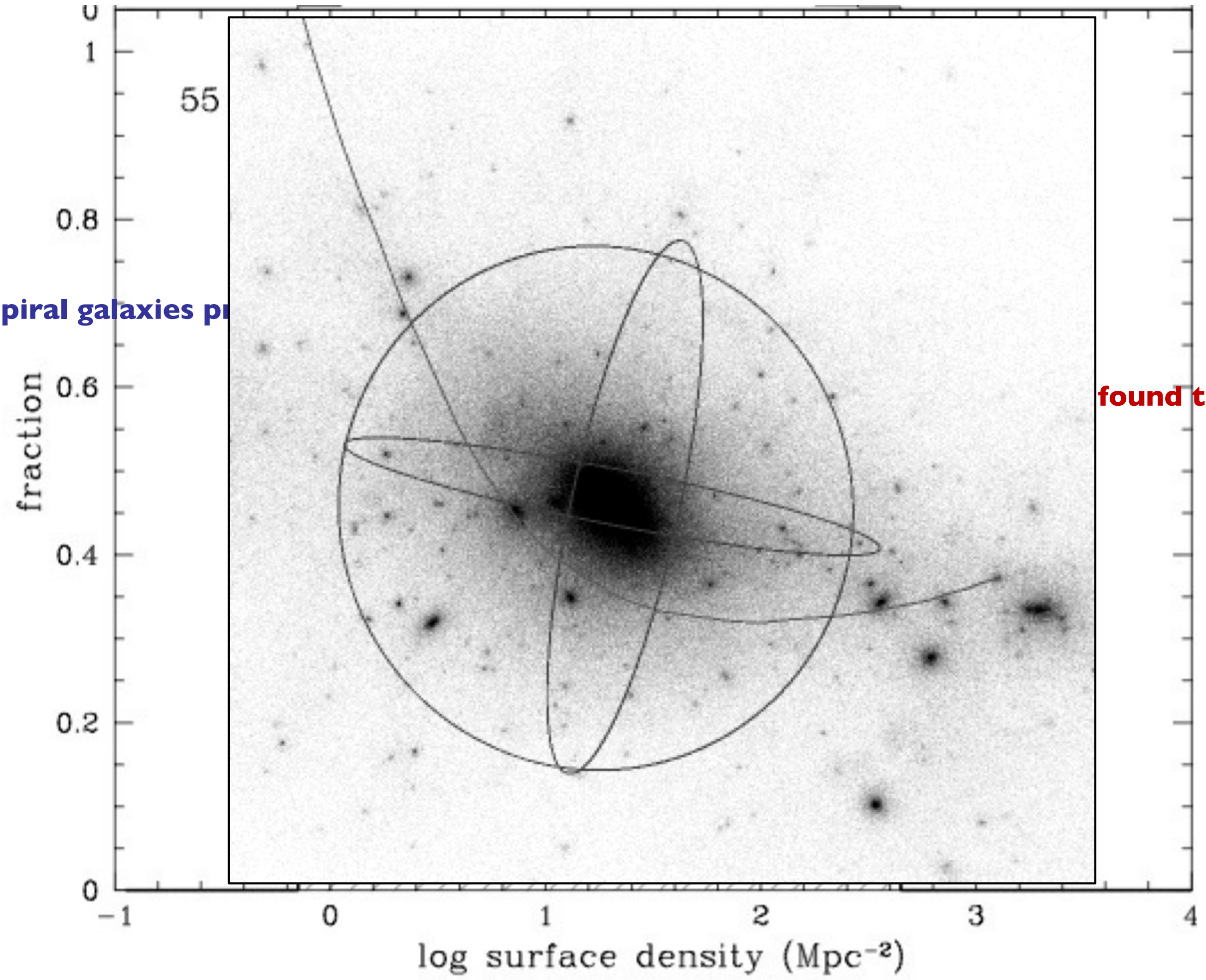
elliptical galaxies preferentially found towards centre

(Dressler et al. 1997)

increasing density = closer to cluster centre

- galaxy population: morphology-density relation

carful though...



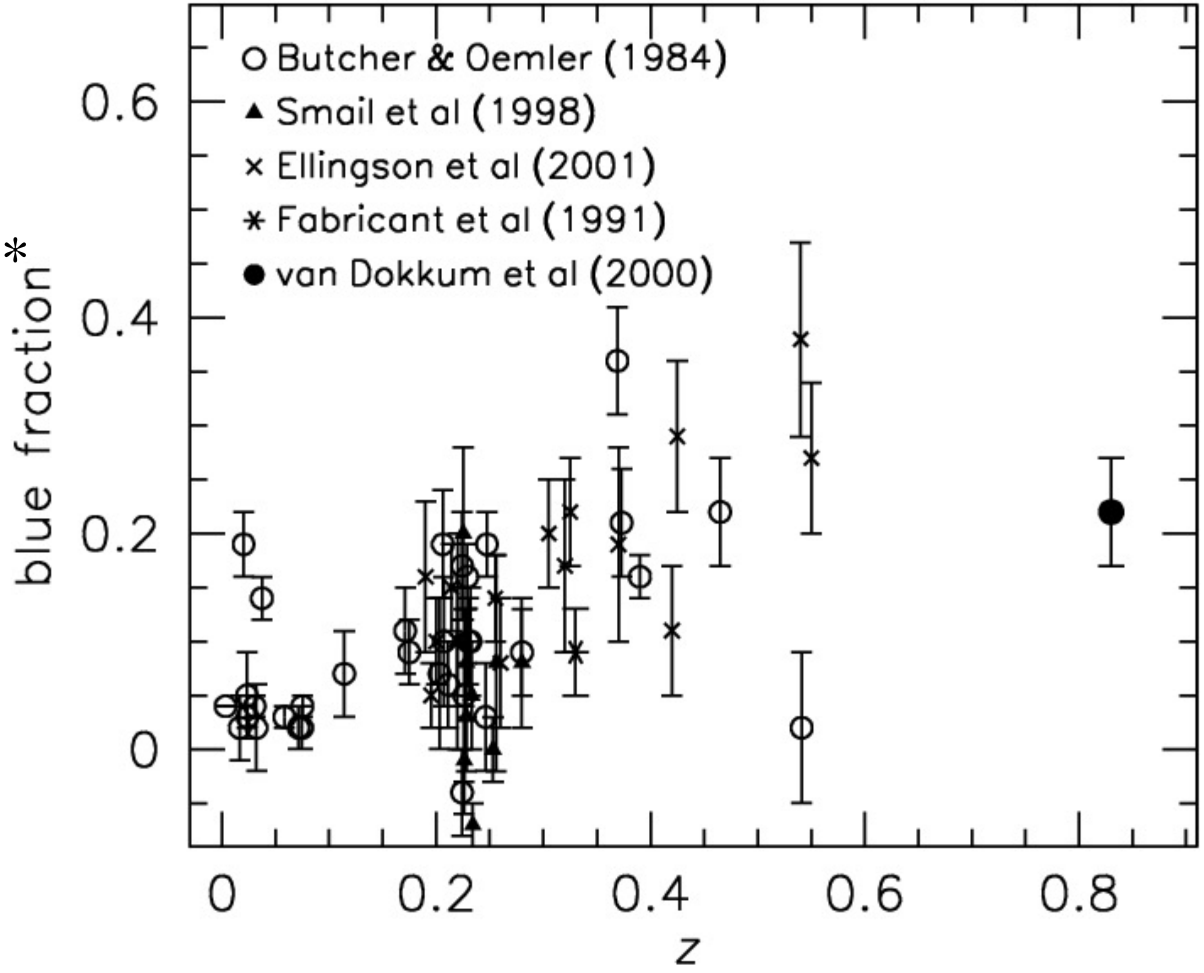
spiral galaxies pr

found towards centre

(Dressler et al. 1997)

increasing density = closer to cluster centre

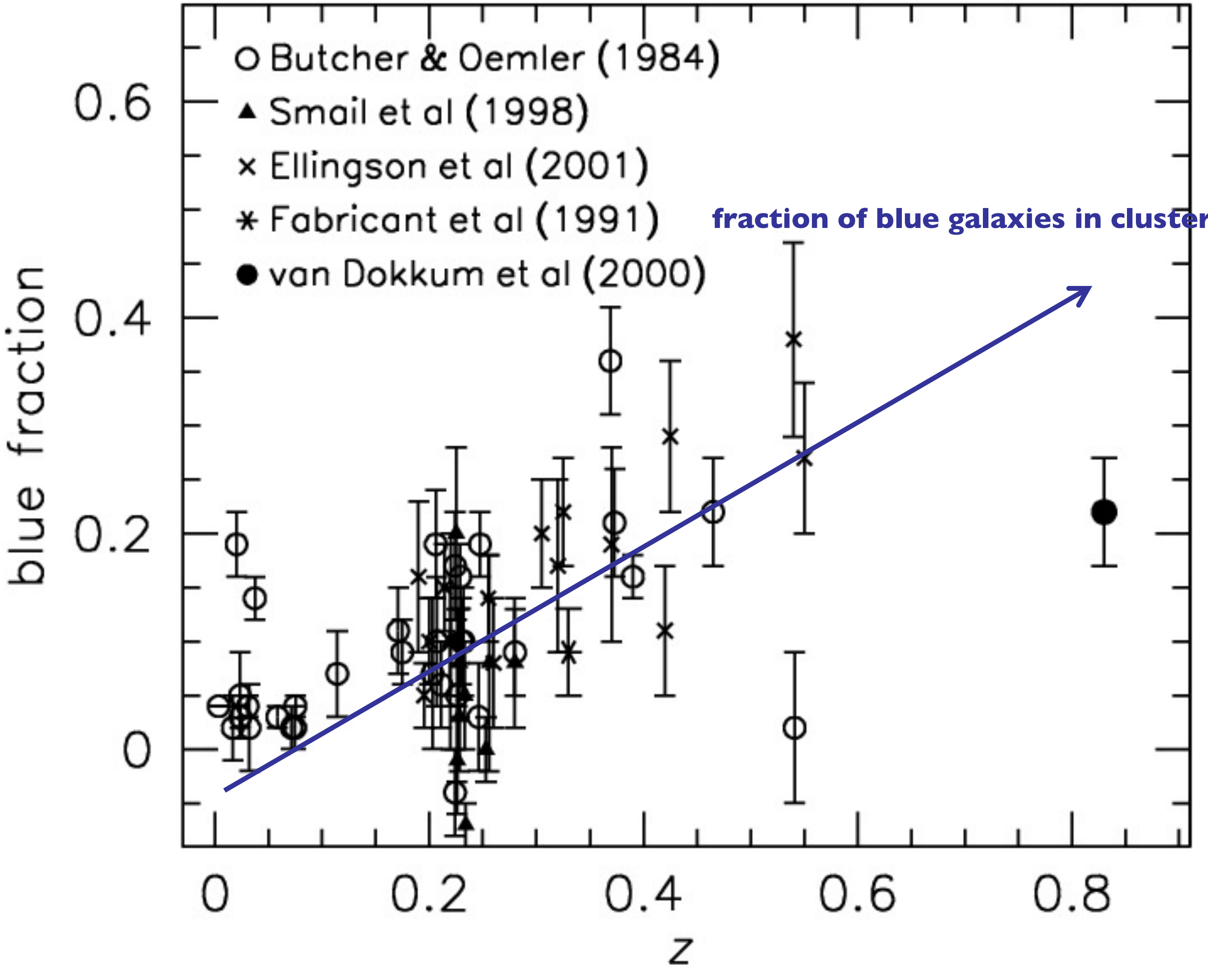
- galaxy population: Butcher-Oemler effect



(van Dokkum 2002)

*spiral galaxies are preferentially blue

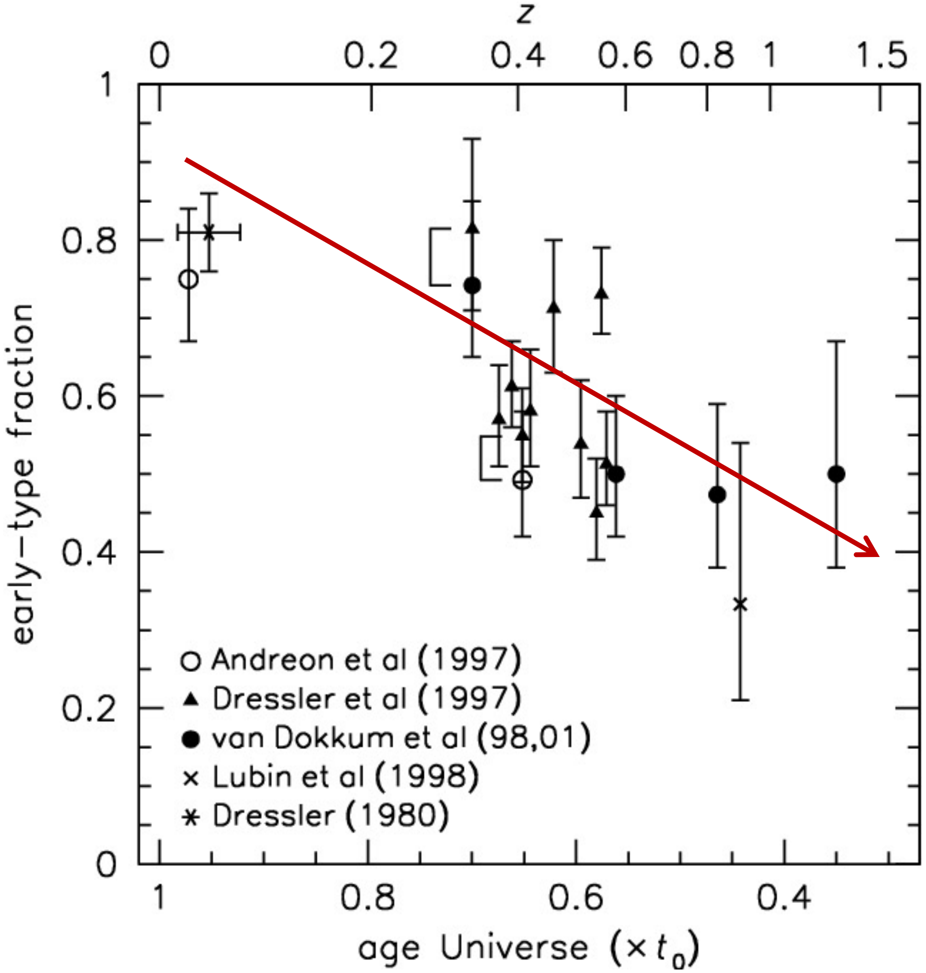
- galaxy population: Butcher-Oemler effect



fraction of blue galaxies in clusters increases with redshift

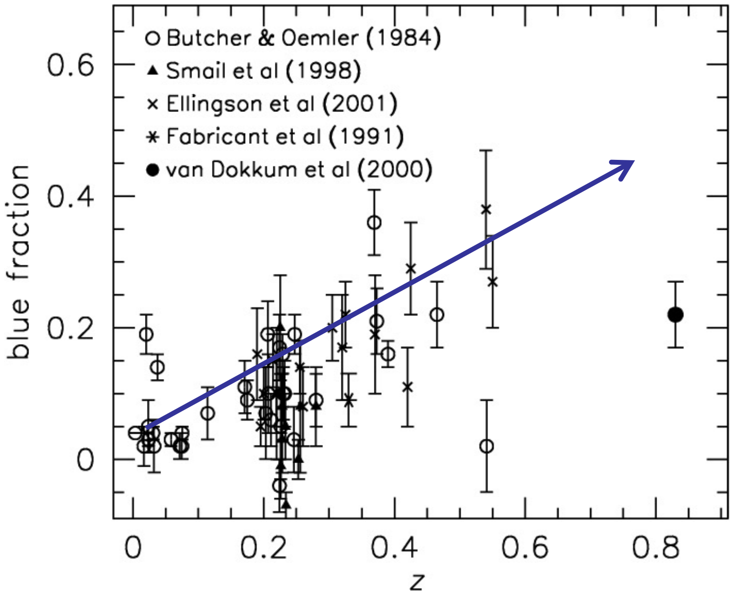
(van Dokkum 2002)

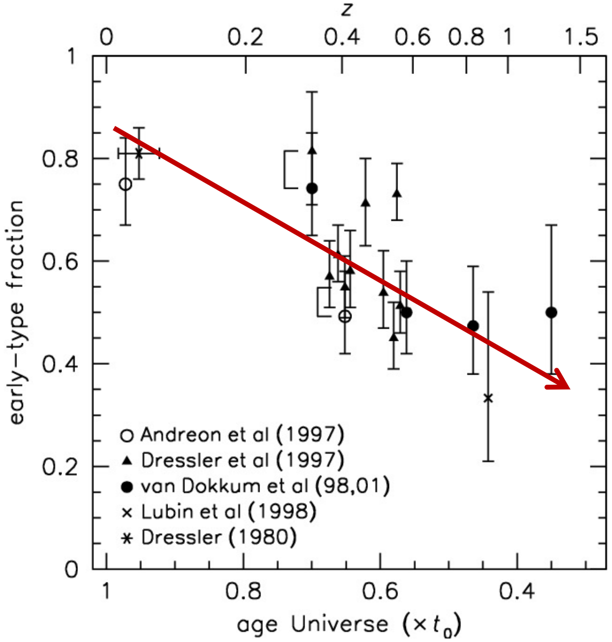
- galaxy population: decline of elliptical galaxies with redshift



(van Dokkum 2002)

- galaxy population: clear signs of temporal evolution





- galaxy population vs. intra-cluster stars

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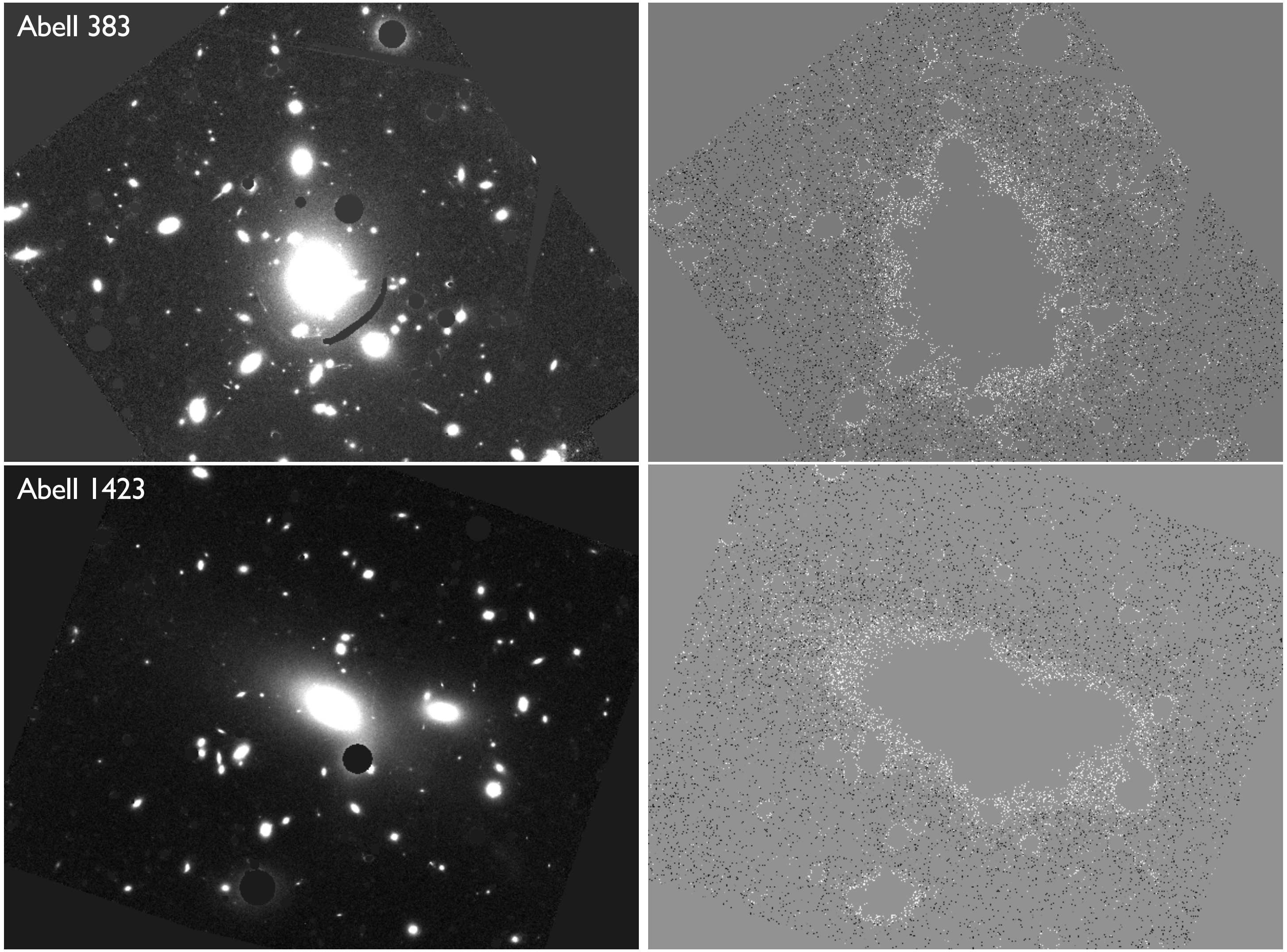
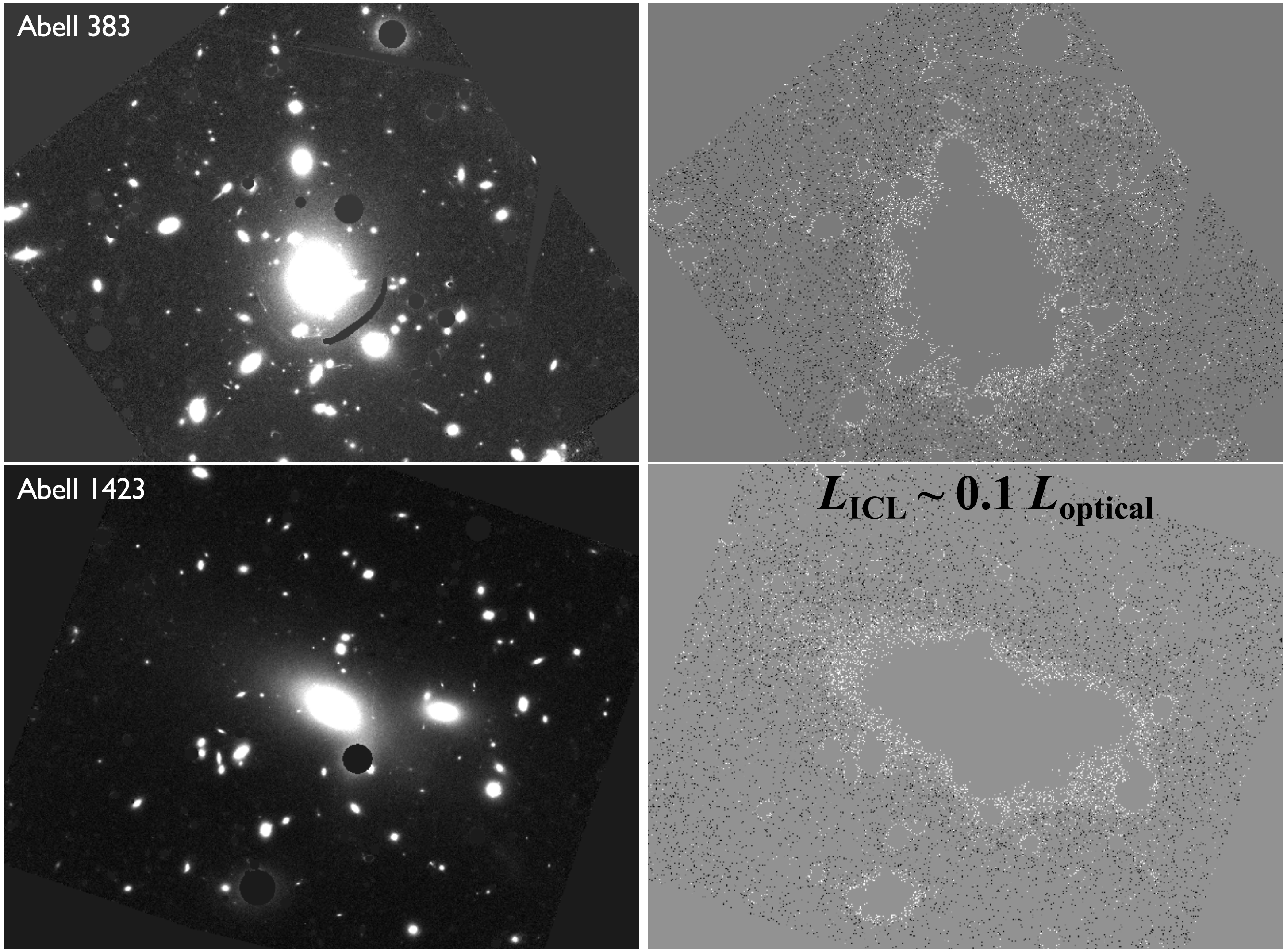


(Burke et al. 2015)

- galaxy population vs. intra-cluster stars



(Burke et al. 2015)

- introduction
- properties
- **scaling relations**
- application

- properties

• total mass	M_{vir}	$\sim 10^{14}$-10^{15} $M_\odot$
• extremely hot	T	$\sim 10^{7}$-10^{8} K
• gas mass	M_g	$\sim 10^{13}$-10^{14} $M_\odot$
• X-ray luminosity	L_x	$\sim 10^{43}$-10^{45} erg/s

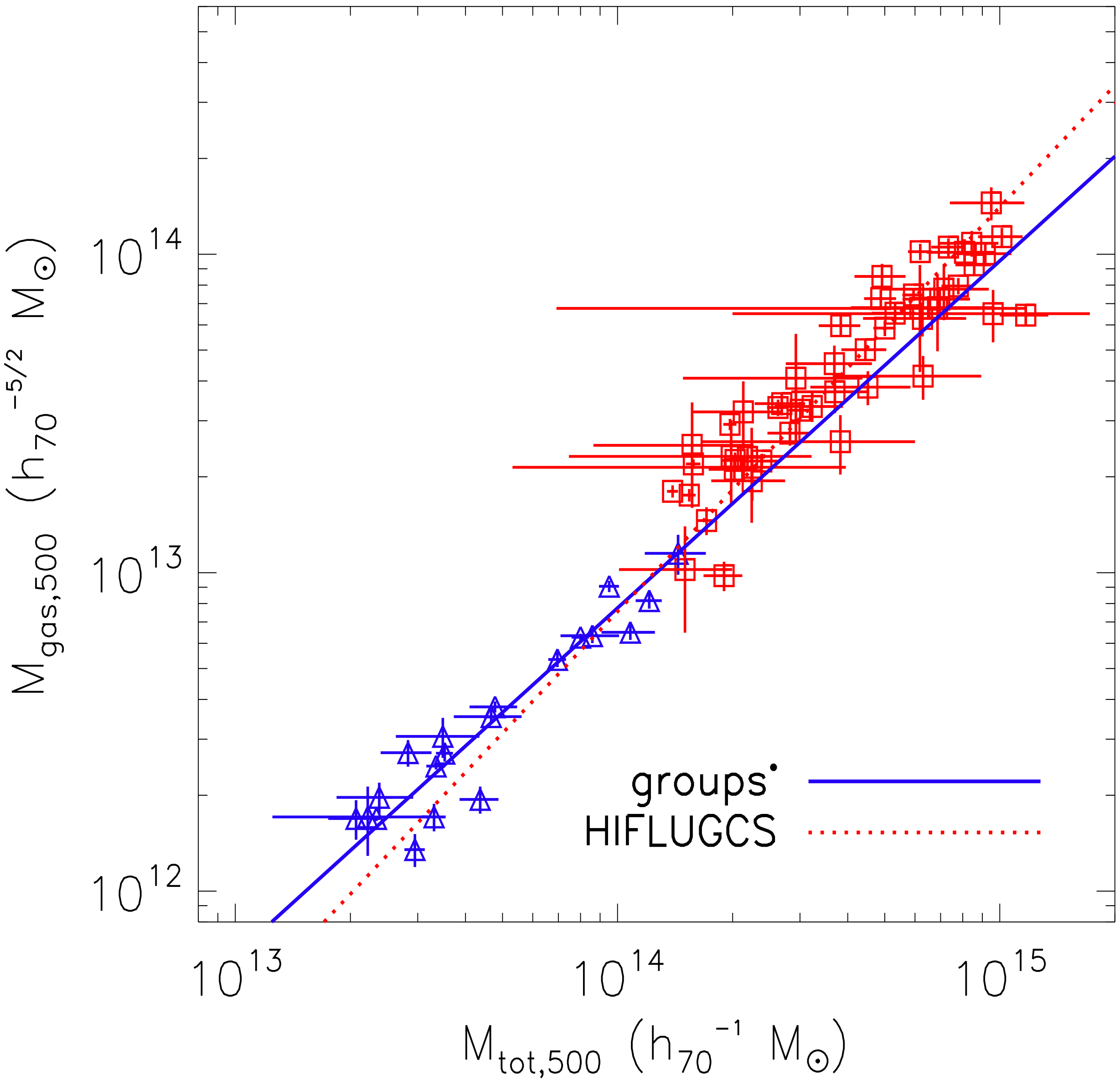
- properties

related!

• total mass	M_{vir}	~ 10^{14}-10^{15} $M_\odot$
• extremely hot	T	~ 10^7-10^8 K
• gas mass	M_g	~ 10^{13}-10^{14} $M_\odot$
• X-ray luminosity	L_x	~ 10^{43}-10^{45} erg/s

- $M_{vir} - M_g$ **relation**

$$M_g \propto f_{b,cosmic} \, M_{vir}$$



(Lovisari et al. 2015)

- $M_{vir} - T$ relation

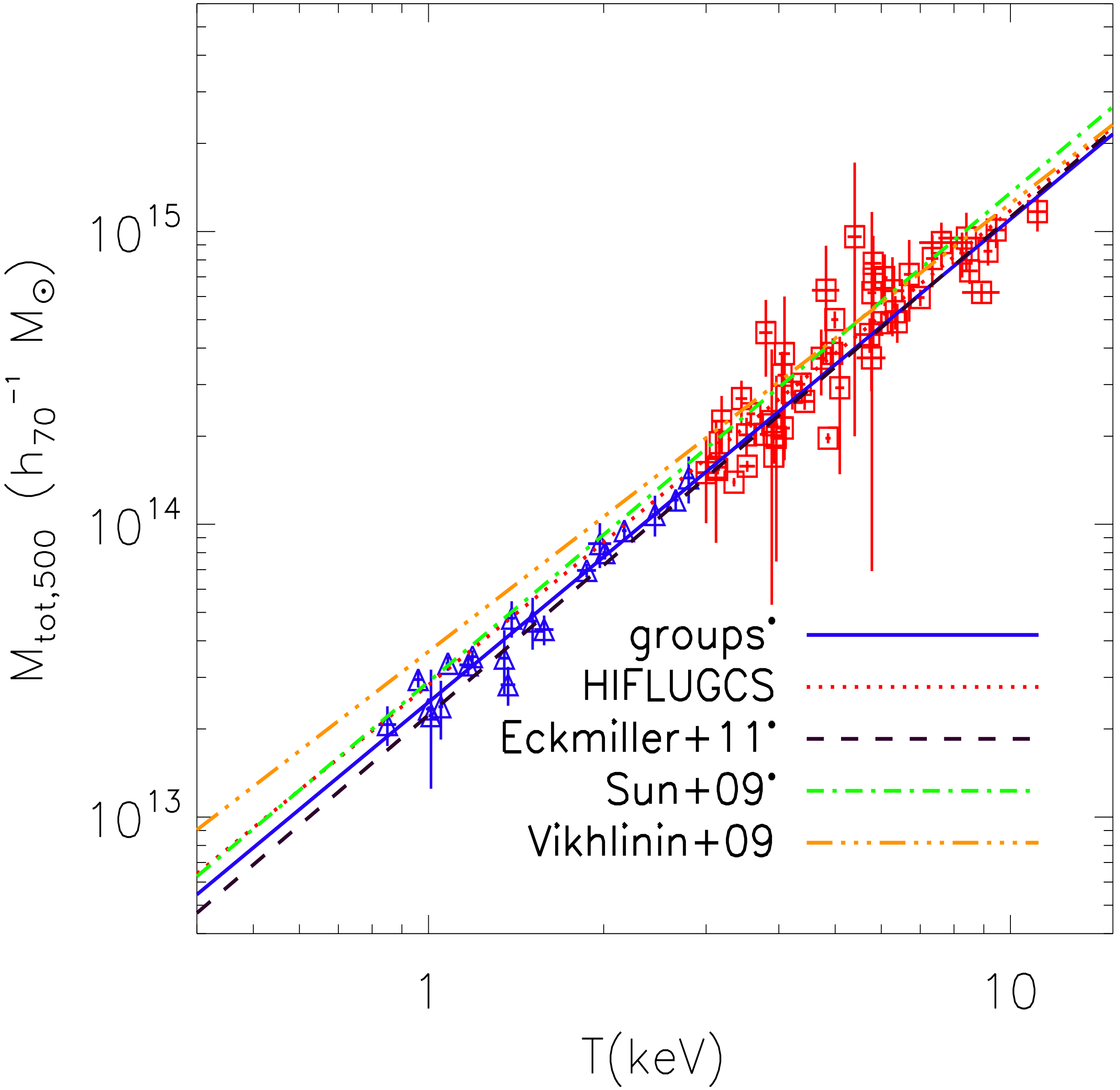
?

$$\left.\begin{array}{c} \\ \\ \\ \end{array}\right\} \quad M_{vir} \propto T^{3/2}$$

(**exercise**)

- $M_{vir} - T$ relation

$$M_{vir} \propto T^{3/2}$$



(Lovisari et al. 2015)

- $M_{vir} - L_x$ relation

Bremsstrahlung: $L_X \propto \epsilon(T, \rho_g) r^3 \propto T^{1/2} \rho_g^2 r^3,$

$$M_{vir} = \frac{4\pi}{3} \Delta_c \rho_c r_{vir}^3.$$

$$\rho_c(z) = E^2(z) \frac{3H_0^2}{8\pi G}$$

$$\rho_g \propto \frac{f_g M_{vir}}{r_{vir}^3}$$

$$M_{vir} \propto T^{3/2}$$

- $M_{vir} - L_x$ relation

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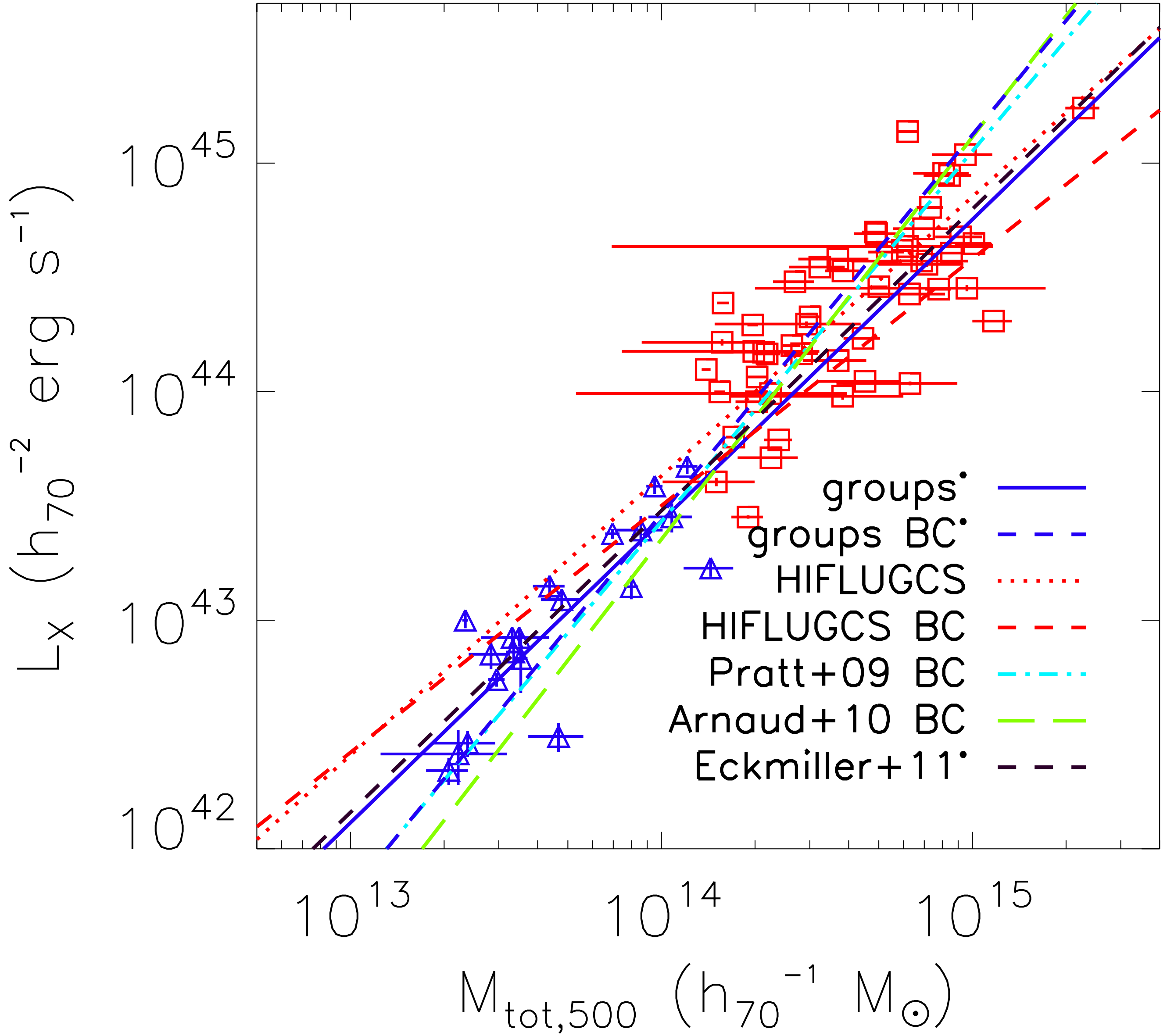
$$\left.\right\} \quad M_{vir} \propto L_X^{3/4}$$

- $M_{vir} - L_x$ relation

$M_{vir} \propto L_X^{3/4}$



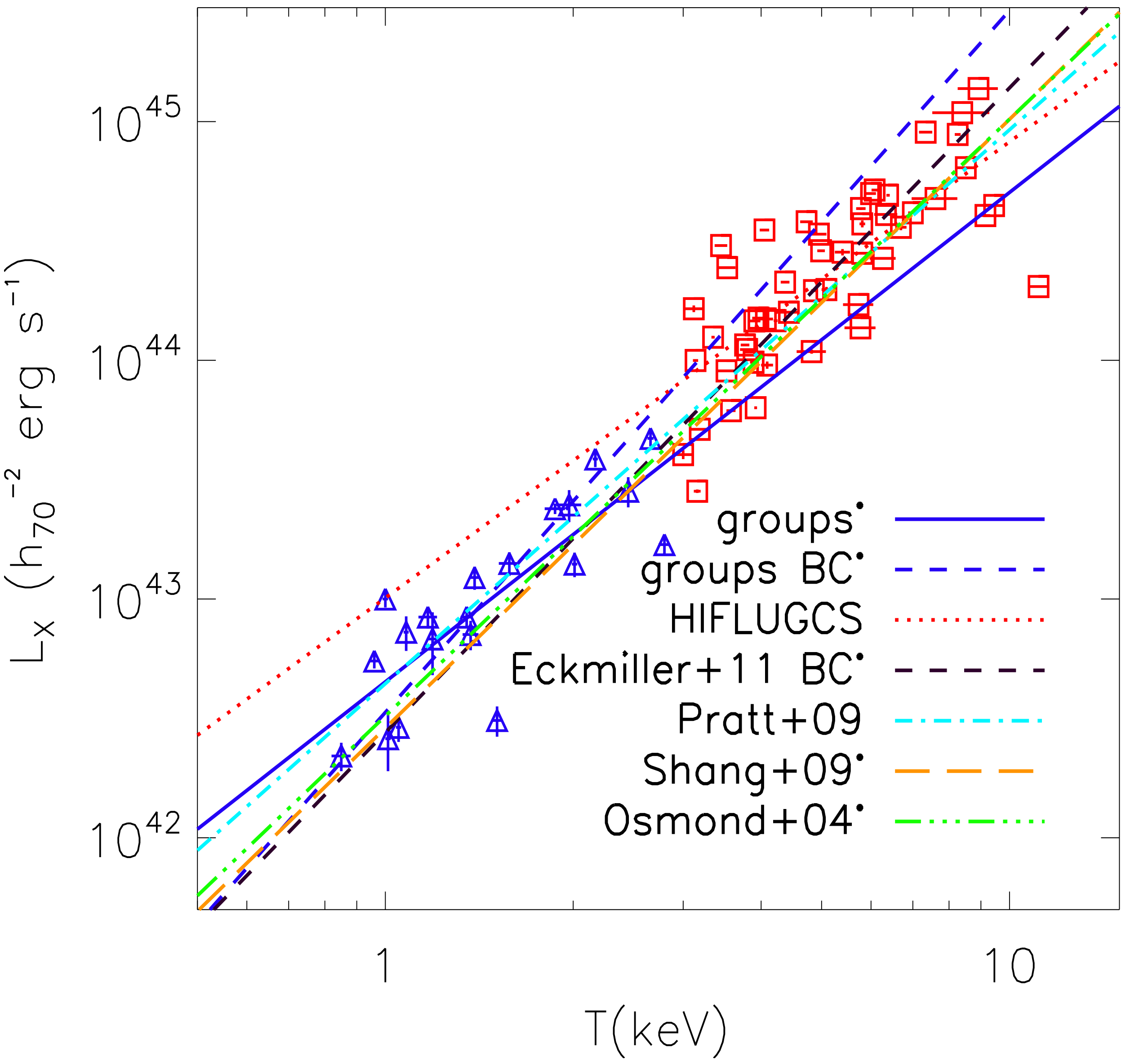
(Lovisari et al. 2015)

- $T - L_x$ relation

$$\left.\begin{array}{l} M_{vir} \propto T^{3/2} \\ \\ M_{vir} \propto L_X^{3/4} \end{array}\right\} \qquad L_X \propto T^2$$

- $T - L_x$ relation

$L_X \propto T^2$

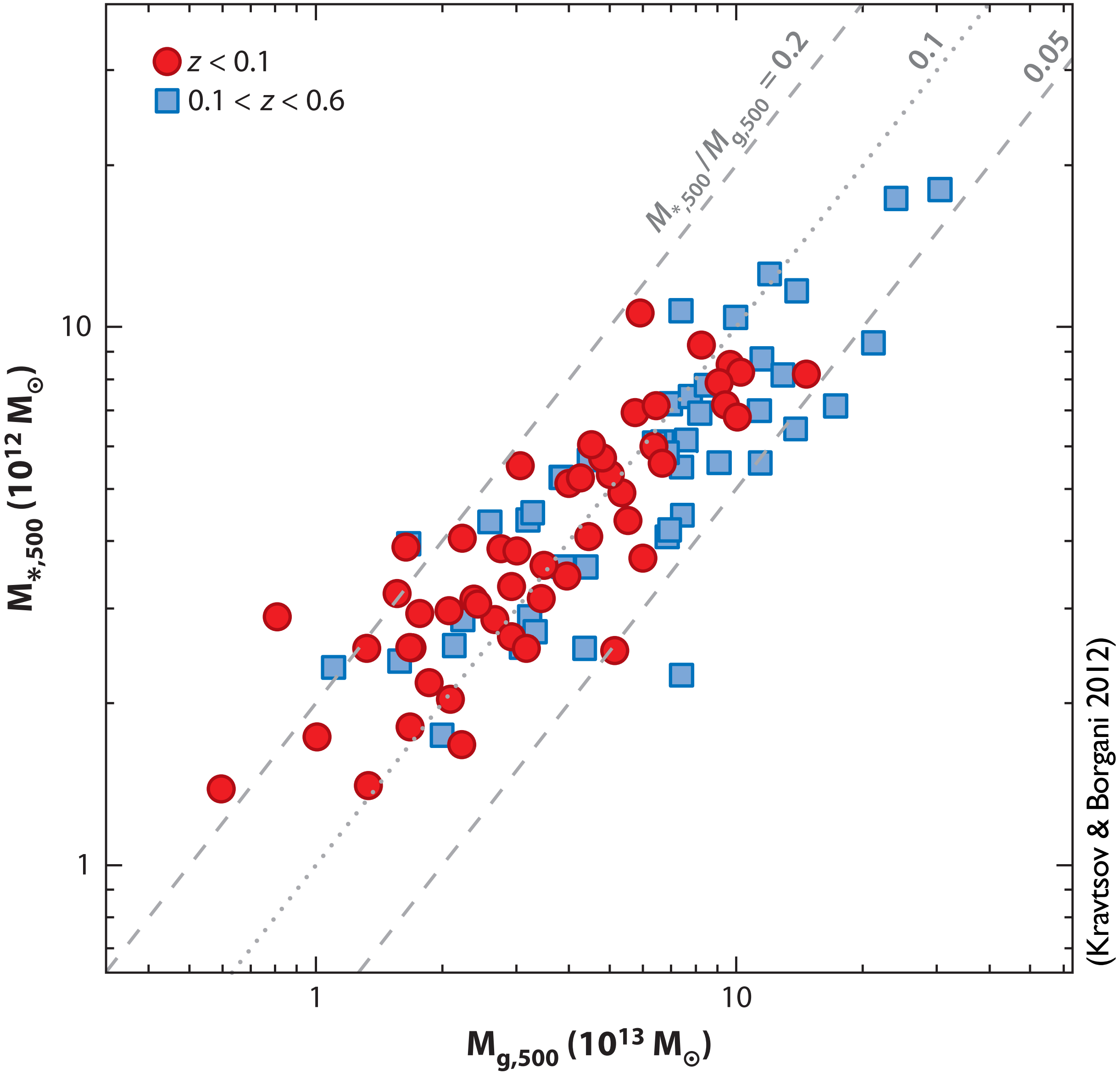


(Lovisari et al. 2015)

- $M_* - M_g$ relation?

- $M_* - M_g$ relation!

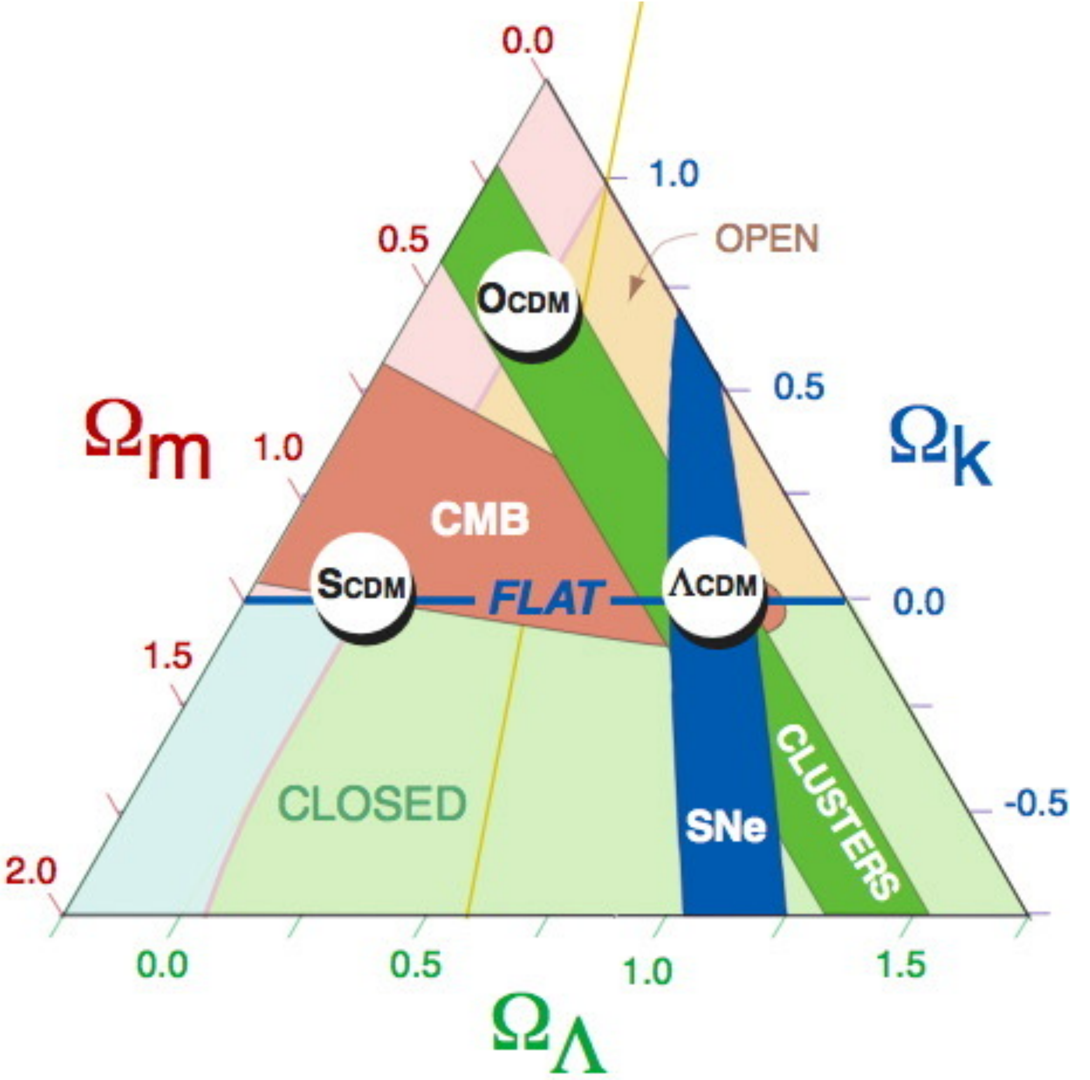
$M_* \propto M_g$



(Kravtsov & Borgani 2012)

- introduction
- properties
- scaling relations
- **application**

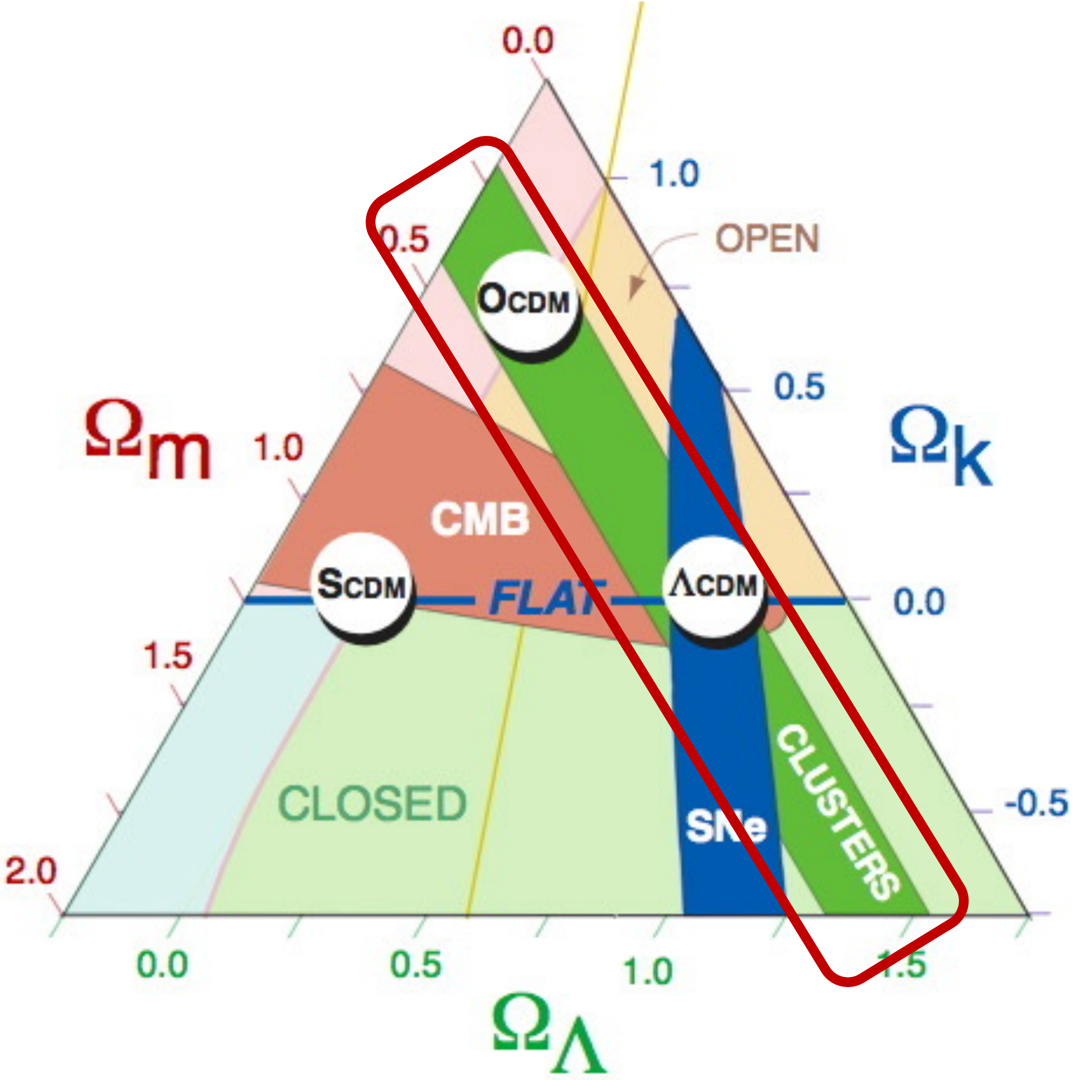
Galaxy Clusters



(Bahcall et al. 1999)

Galaxy Clusters

galaxy clusters have been one of the pilars in the determination of cosmological parameters



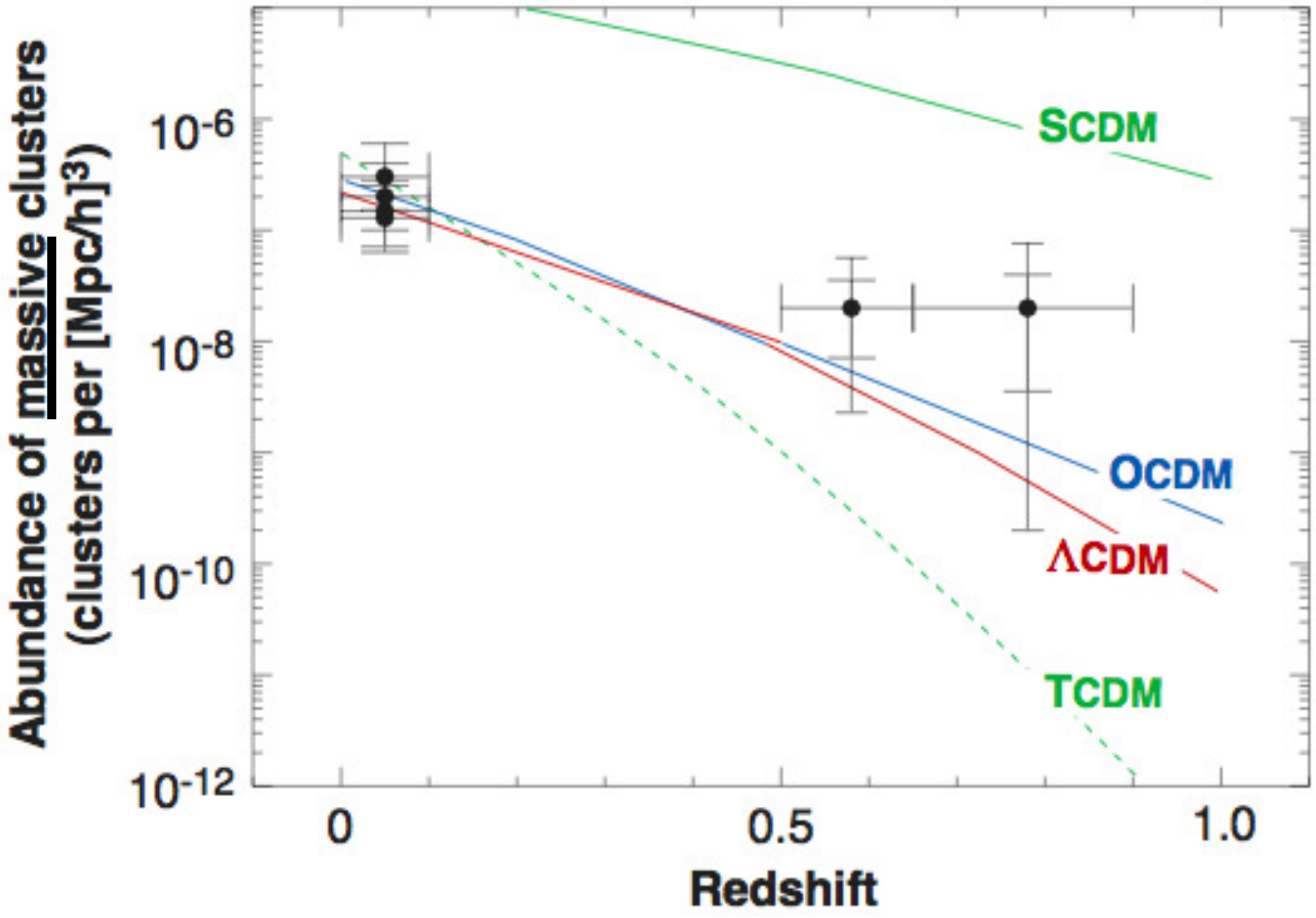
(Bahcall et al. 1999)

Galaxy Clusters

- number density evolution
- high-mass end of massfunction
- Sunyaev-Zeldovich effect

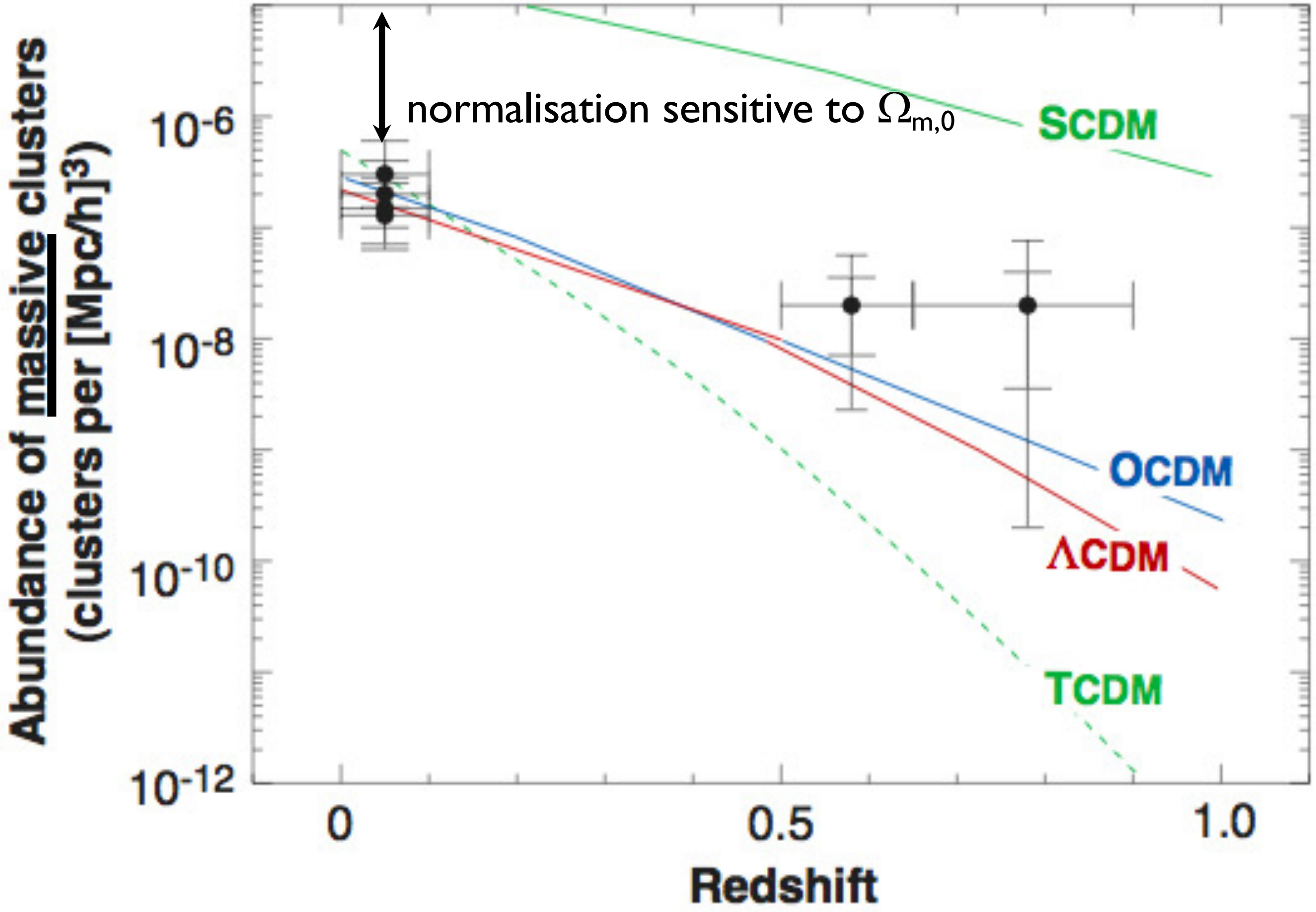
- **number density evolution**
- high-mass end of massfunction
- Sunyaev-Zeldovich effect

- number density evolution



(Bahcall et al. 1999)

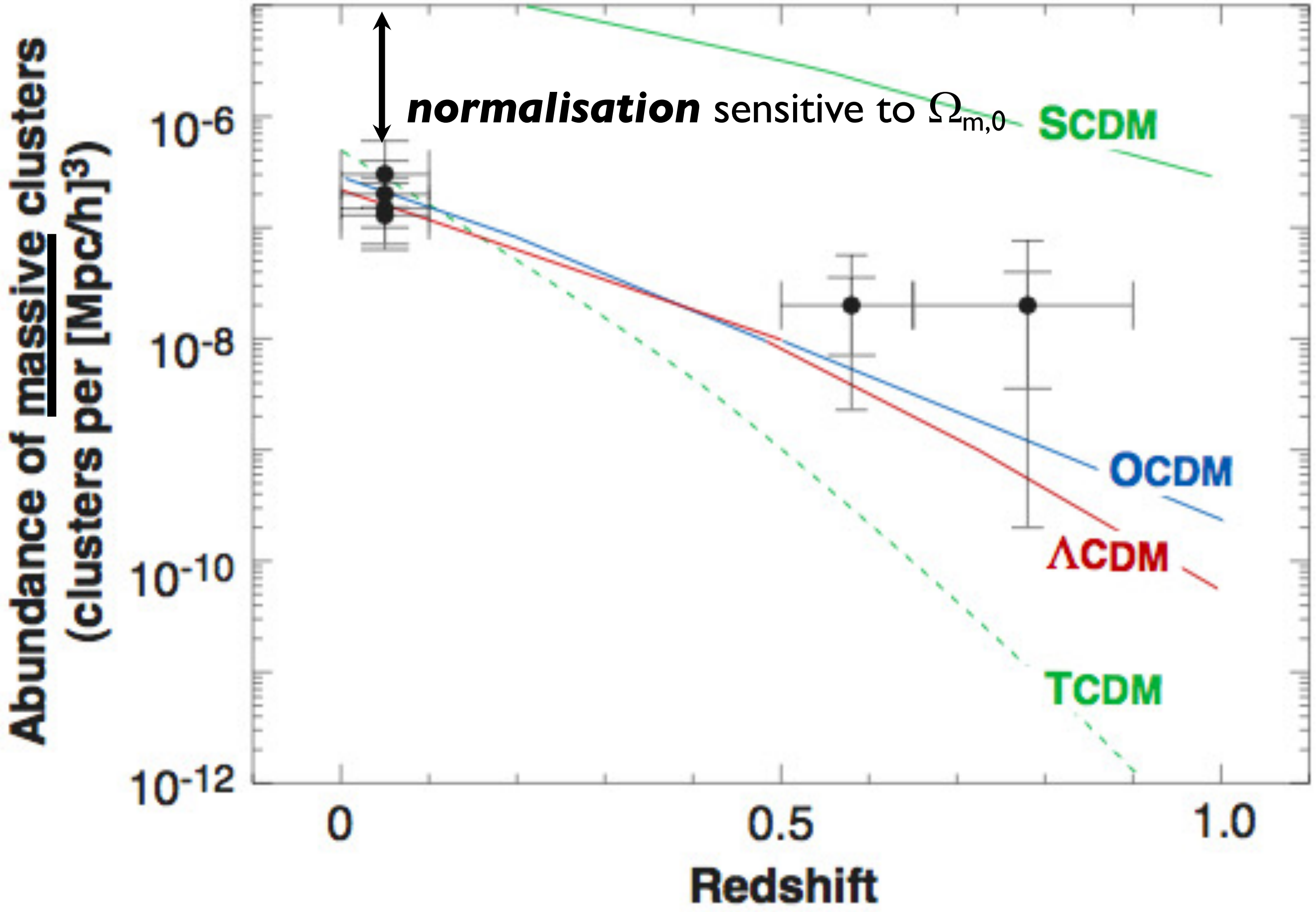
- number density evolution



(Bahcall et al. 1999)

Galaxy Clusters

- number density evolution



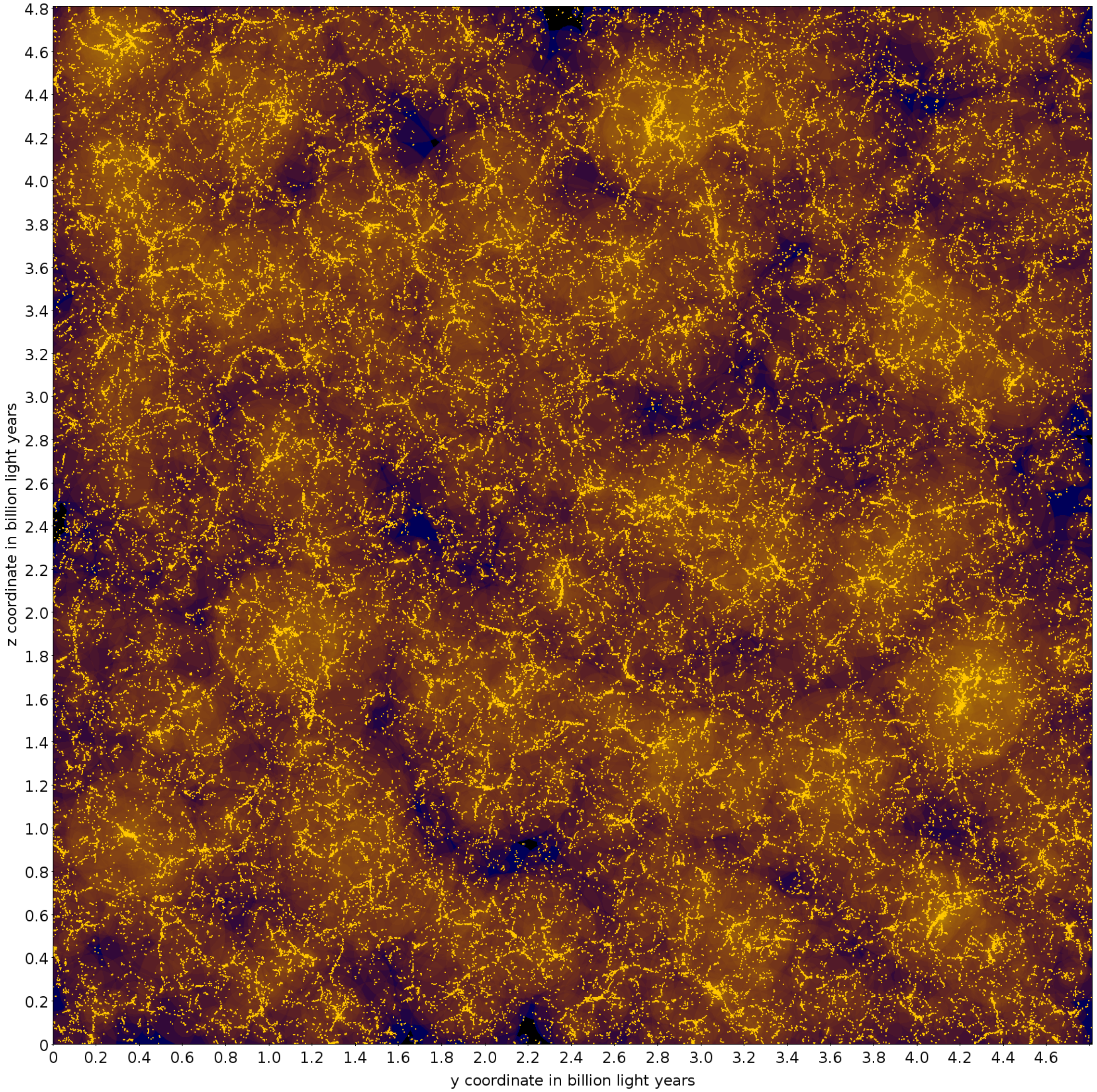
normalisation sensitive to $\Omega_{m,0}$

(Bahcall et al. 1999)

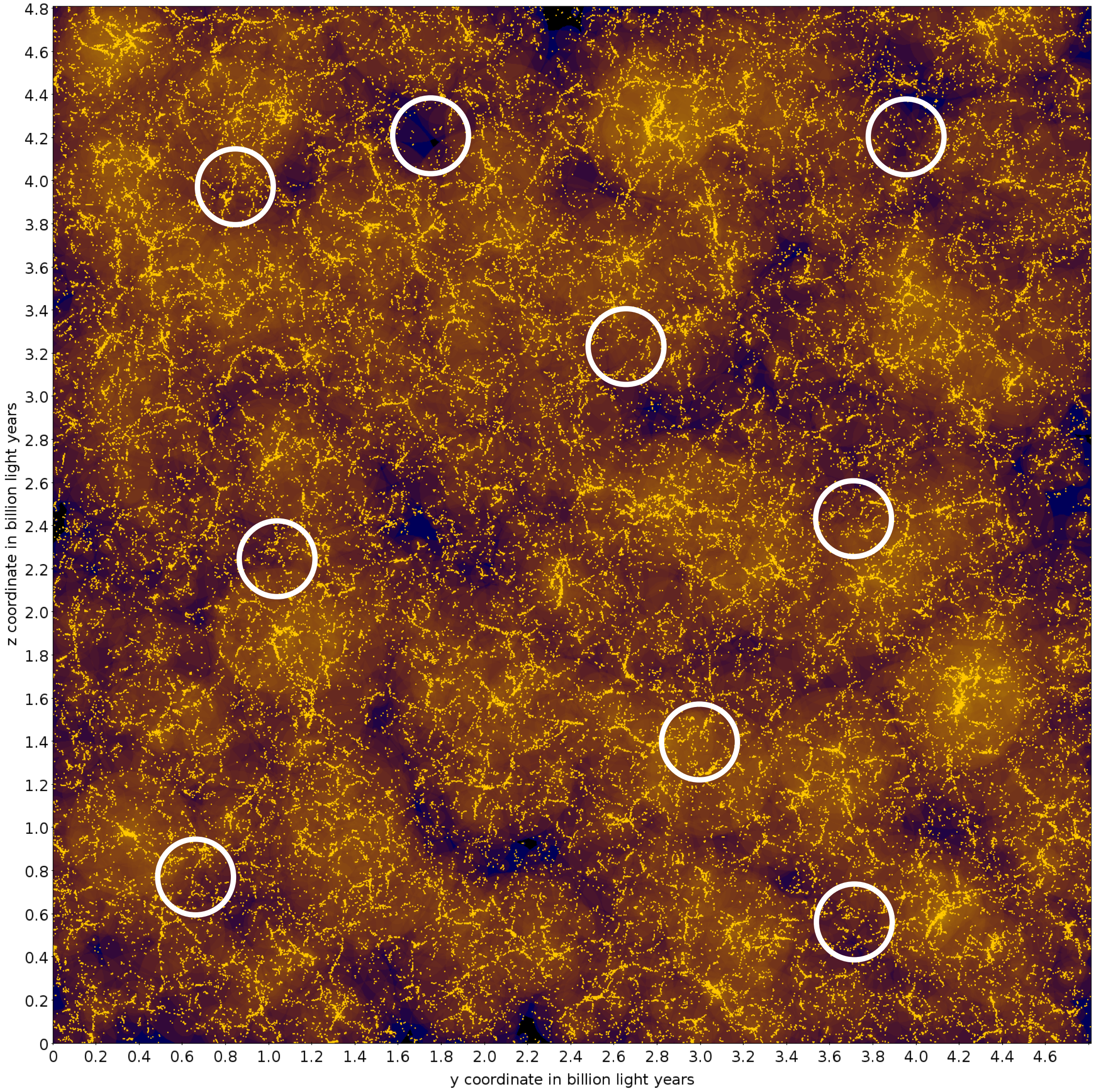
Galaxy Clusters

application

- number density - σ_8 = variance of mass on scale of 8 Mpc

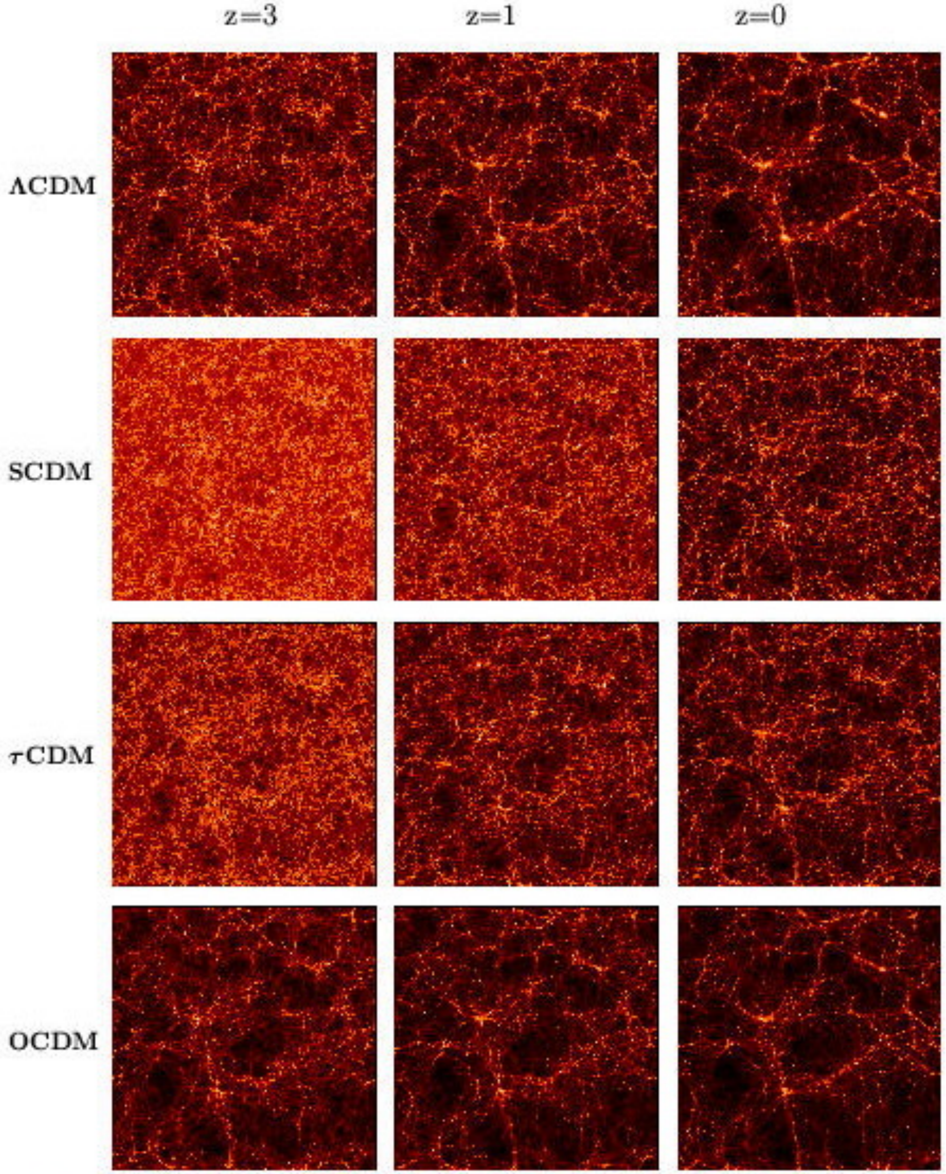


- number density - σ_8 = variance of mass on scale of 8 Mpc



Galaxy Clusters

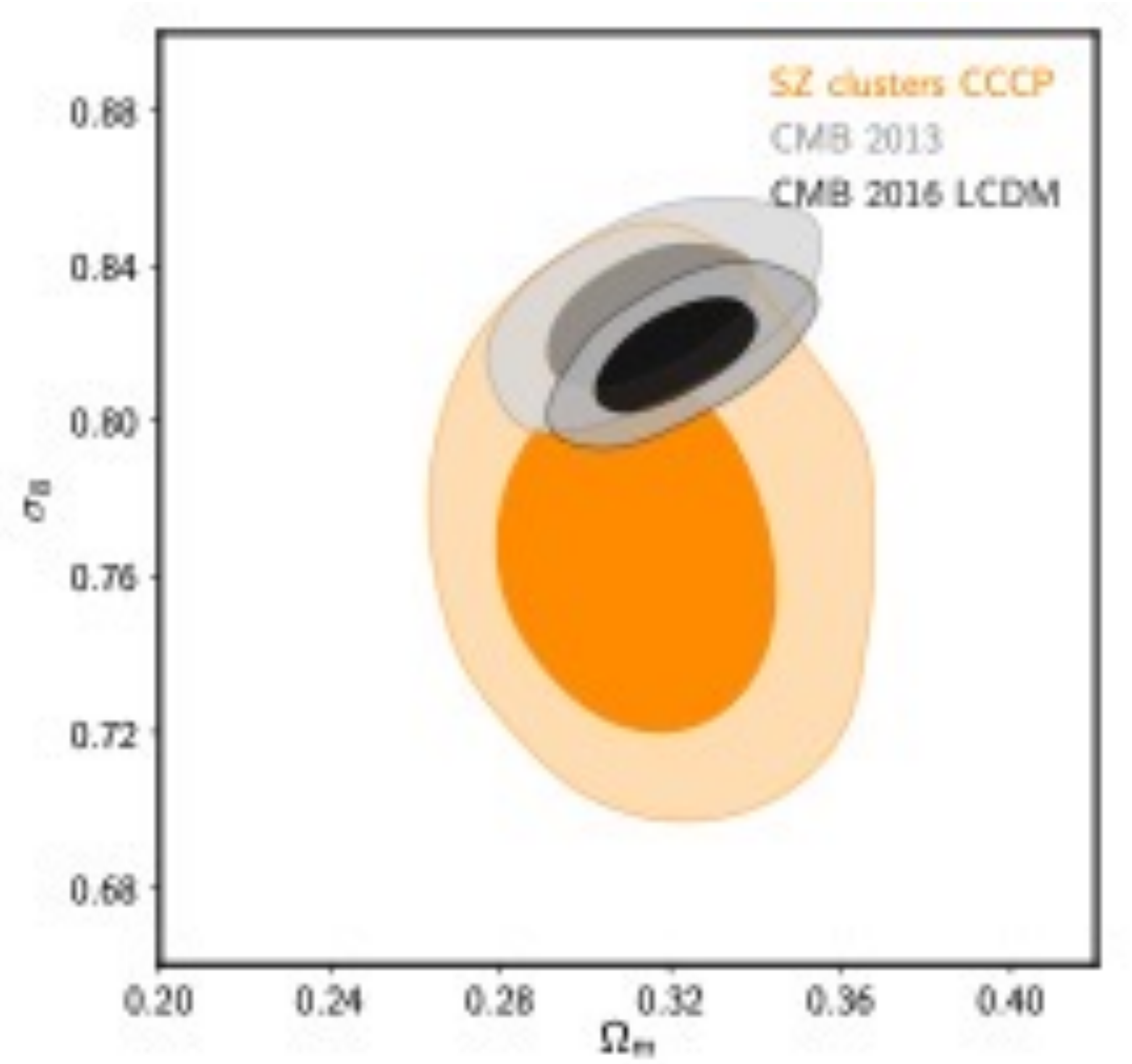
- number density - σ_8 = variance of mass on scale of 8 Mpc



$$\sigma_8 = 0.52\ \Omega_0^n$$

$$n = -0.52+0.13\Omega_0$$

- number density - $\sigma_8 - \Omega_m$ tension



Galaxy Clusters

- number density evolution
- **high-mass end of massfunction**
- Sunyaev-Zeldovich effect

- the mass function:

mass spectrum of objects
(dark matter haloes)

Galaxy Clusters

properties

- the mass function:*

$$\frac{dn}{dM}dM = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M}\,\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right|\exp\left(\frac{-\delta_c^2}{2\sigma_M^2}\right)\frac{dM}{M}$$

$$\sigma_M^2 = \frac{1}{2\pi^2}\int_0^{+\infty} P(k)\hat{W}^2(kR)k^2\,dk \qquad P(k) = \left(\frac{D(a)}{D(a_0)}\right)^2 P_0(k)$$

$$\hat{W}(x) = \frac{3}{x^3}\big(\sin(x) - x\cos(x)\big)$$

mass spectrum of objects
(dark matter haloes)

---

*Press-Schechter (1974) mass function (cf. LSS lecture of Cosmology)

- the mass function:

$$\frac{dn}{dM}dM = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M}\,\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right|\exp\left(\frac{-\delta_c^2}{2\sigma_M^2}\right)\frac{dM}{M}$$

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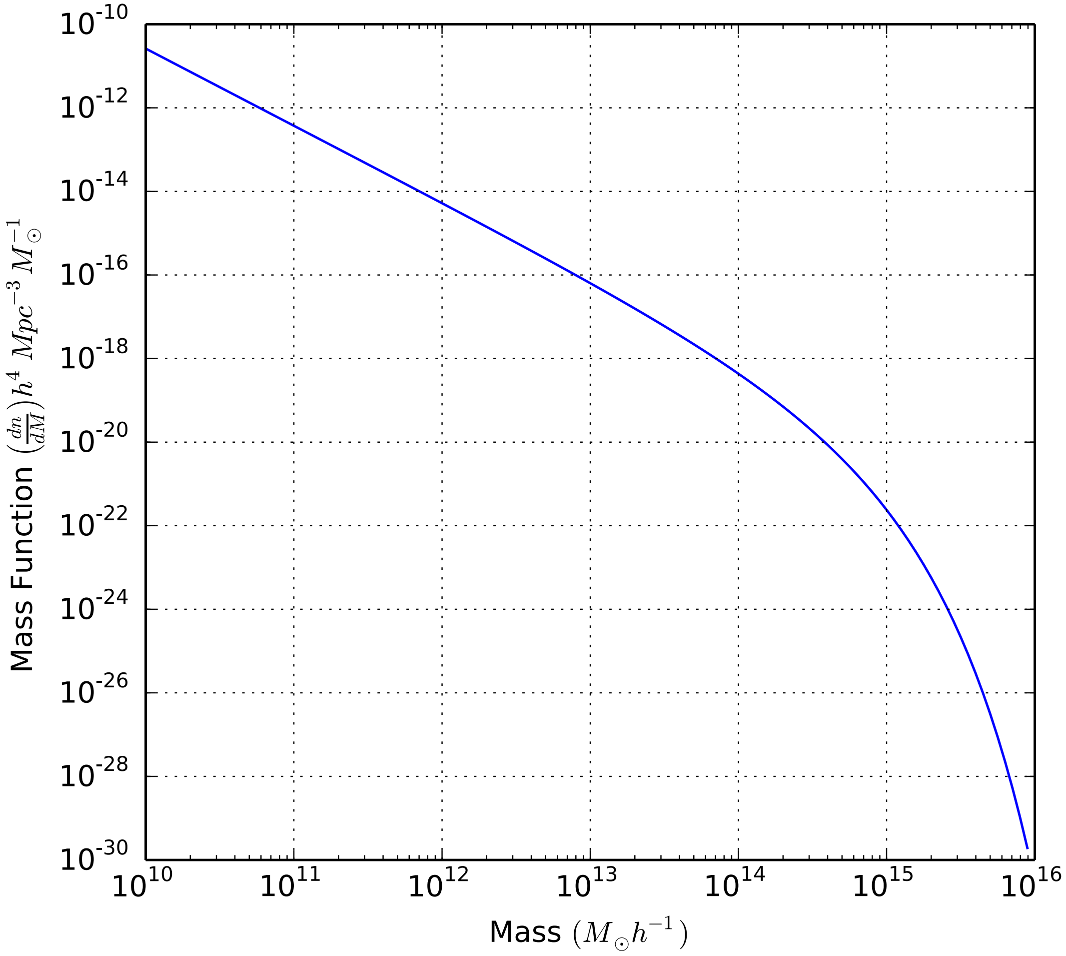

(http://hmf.icrar.org)

- the mass function: high-mass end

$$\frac{dn}{dM}dM = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M}\,\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right|\exp\left(\frac{-\delta_c^2}{2\sigma_M^2}\right)\frac{dM}{M}$$

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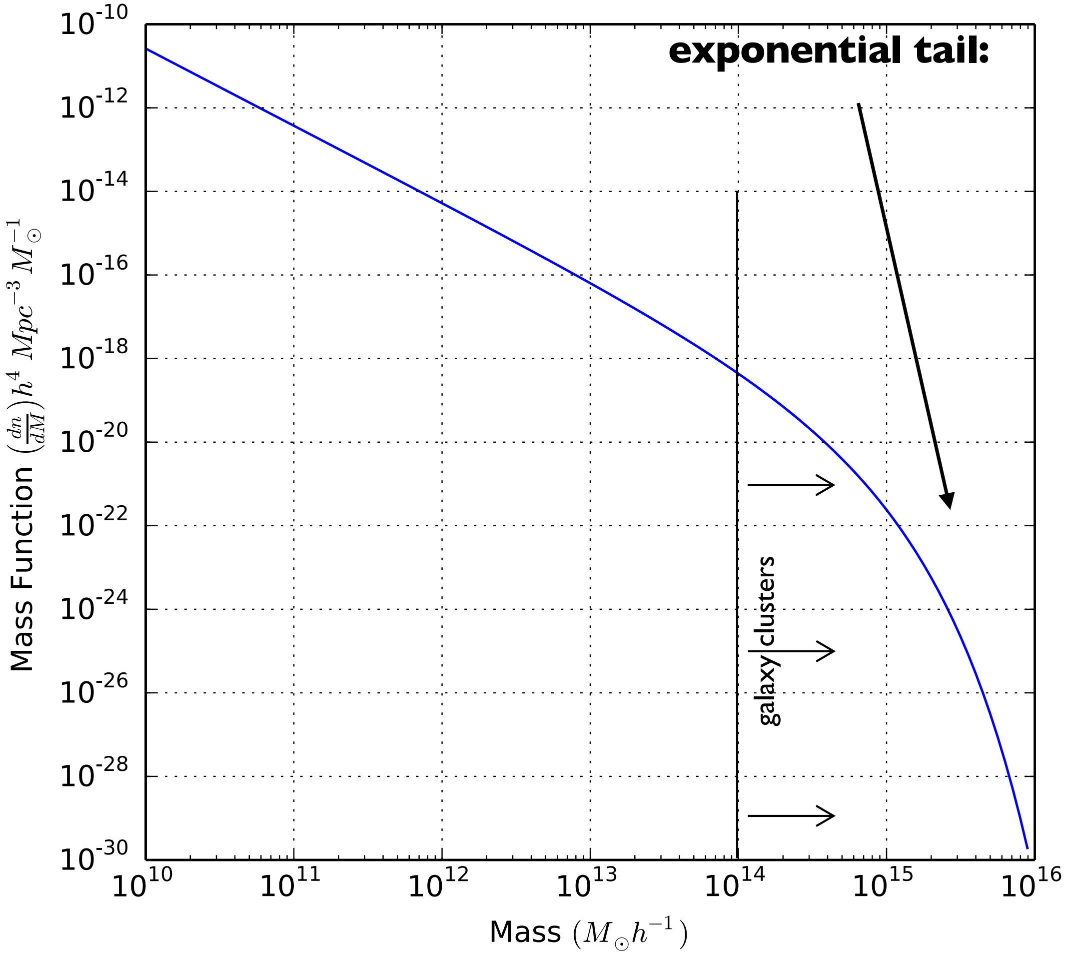

exponential tail:

there should be very few objects with high mass!

(http://hmf.icrar.org)

- the mass function: high-mass end

$$\frac{dn}{dM}dM = \sqrt{\frac{2}{\pi}}\frac{\bar{\rho}}{M}\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right|\exp\left(\frac{-\delta_c^2}{2\sigma_M^2}\right)\frac{dM}{M}$$

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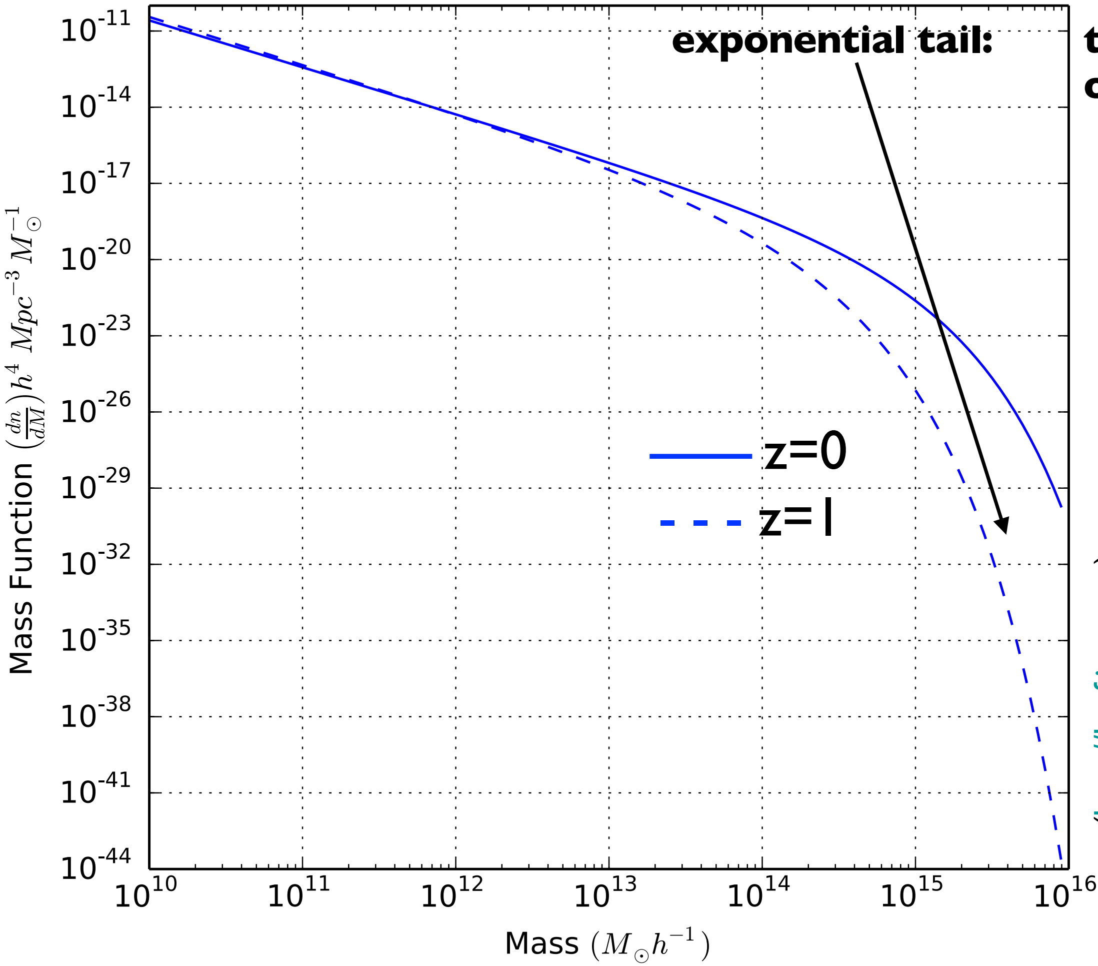
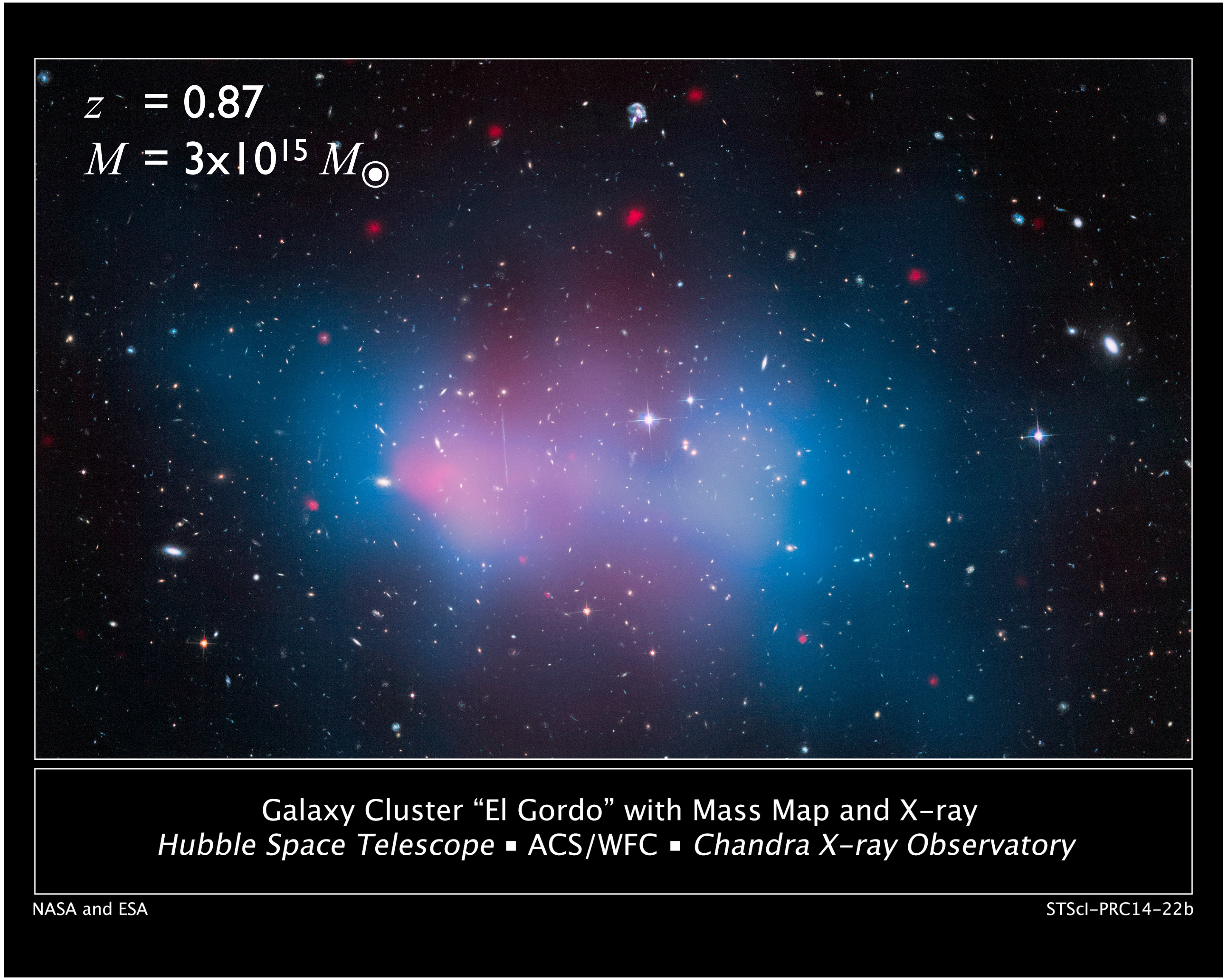


(http://hmf.icrar.org)

there should be very few objects with high mass! (especially at high-z)

- the mass function: high-mass end

“El Gordo”



$z = 0.87$

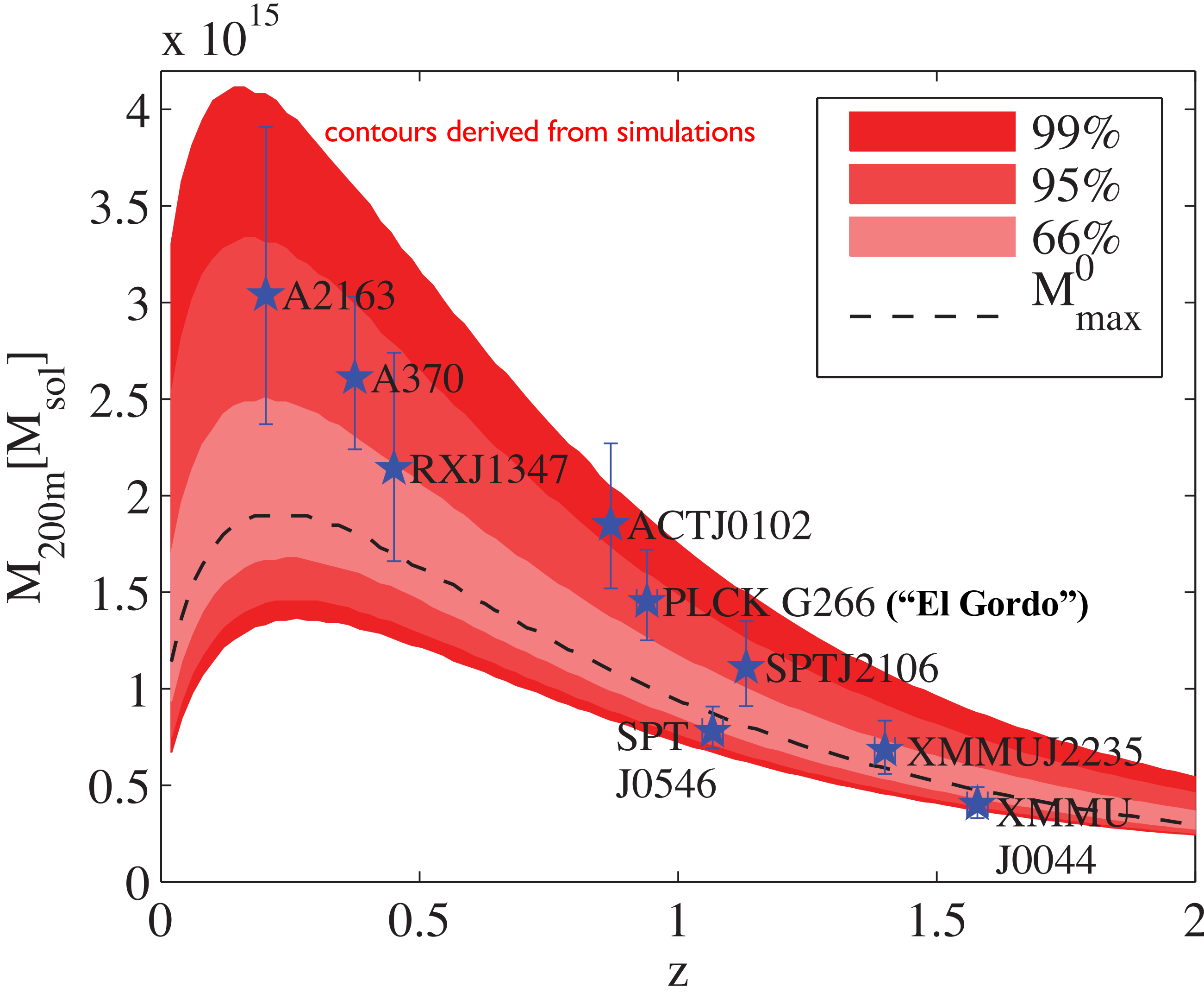
$M = 3\text{x}10^{15}\ M_\odot$

Galaxy Cluster “El Gordo” with Mass Map and X-ray
Hubble Space Telescope ▪ ACS/WFC ▪ *Chandra X-ray Observatory*

NASA and ESA

STScI-PRC14-22b

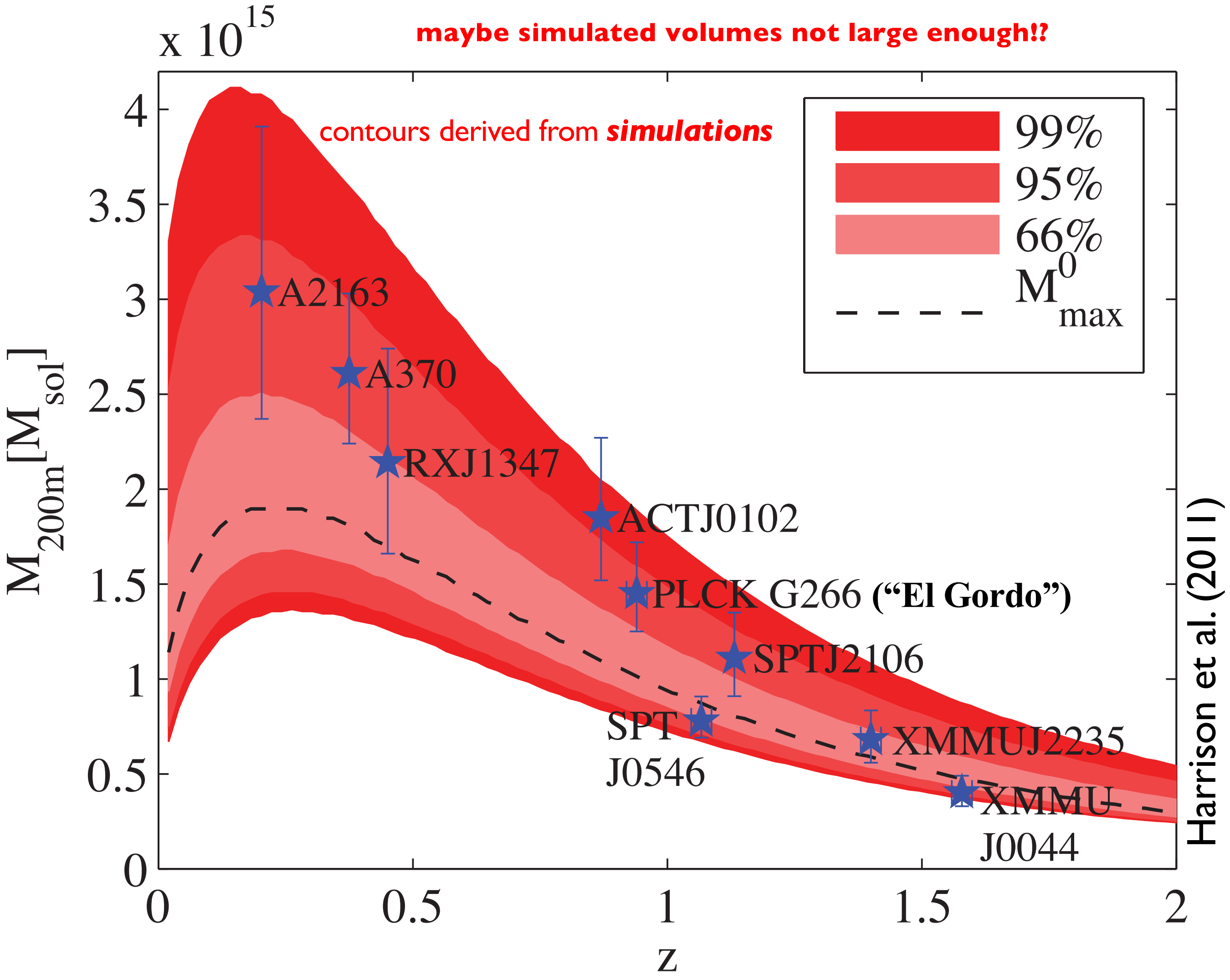
- the mass function: high-mass end "El Gordo"
  - galaxy clusters found at any given redshift too massive for ΛCDM?



Harrison et al. (2011)

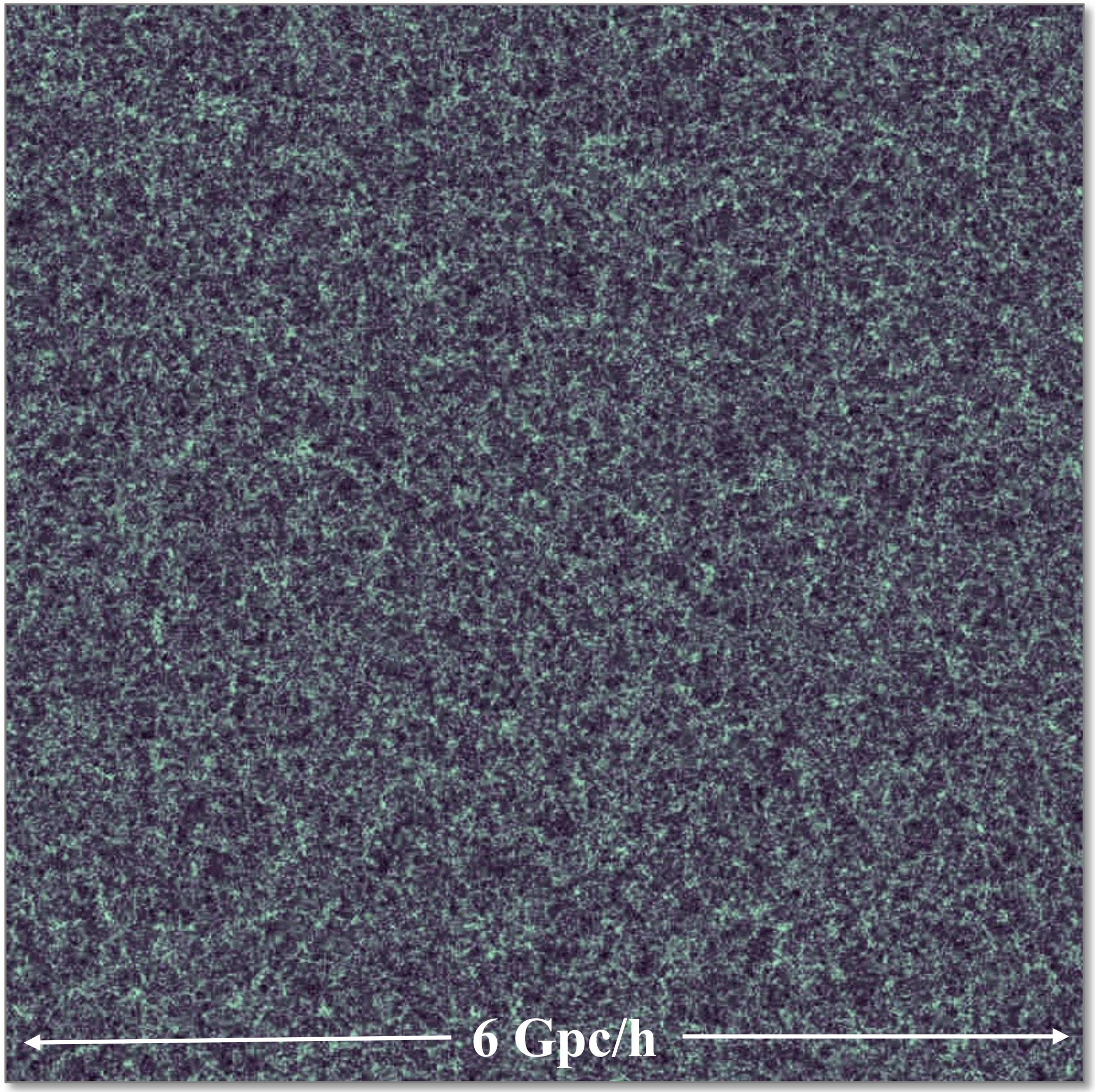
- the mass function: high-mass end "El Gordo"
  - galaxy clusters found at any given redshift too massive for ΛCDM?

maybe simulated volumes not large enough!?



Harrison et al. (2011)

- the mass function: high-mass end "El Gordo"
  - Jubilee simulation (http://jubilee.ft.uam.es)



- the mass function: high-mass end "El Gordo"
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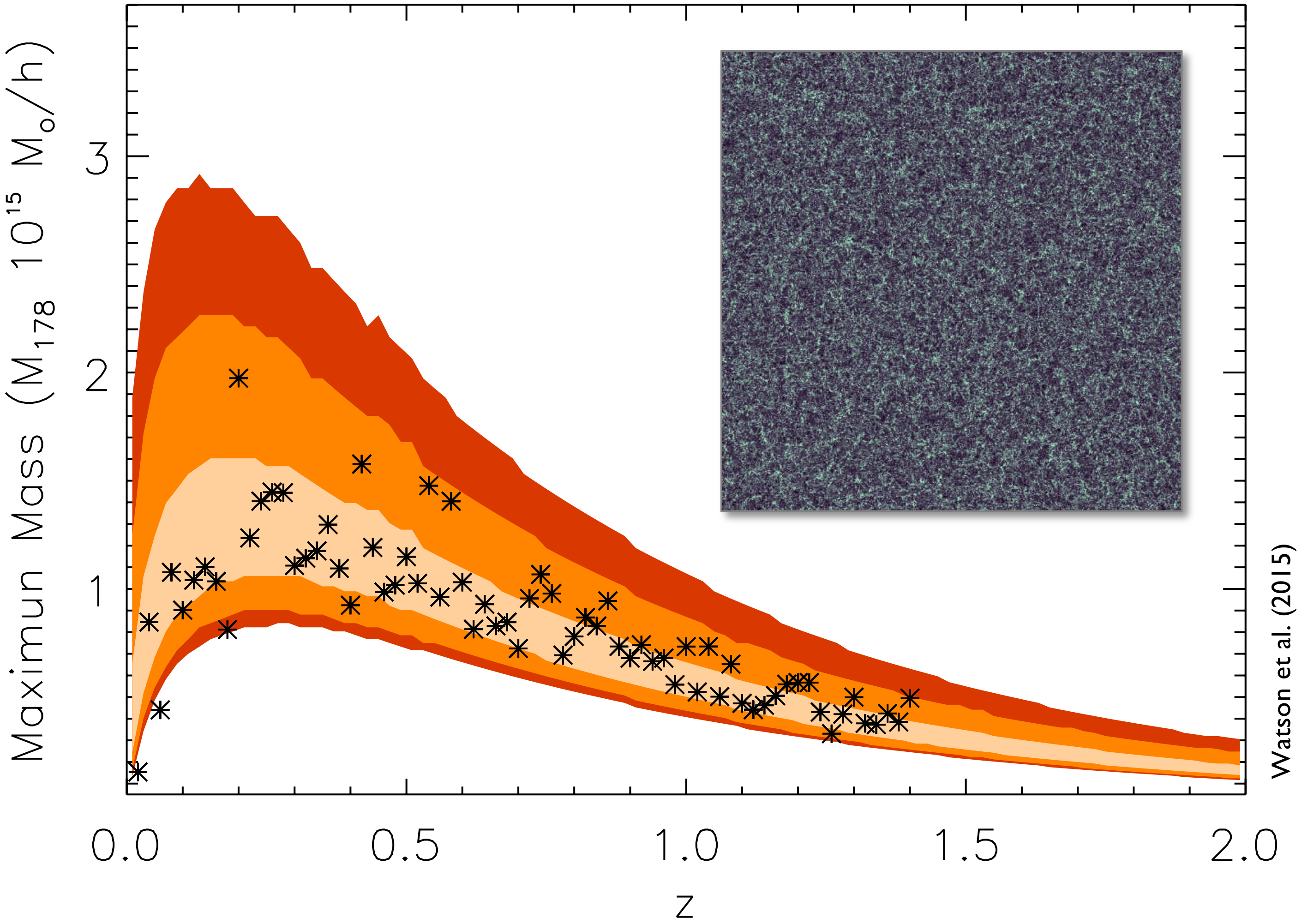
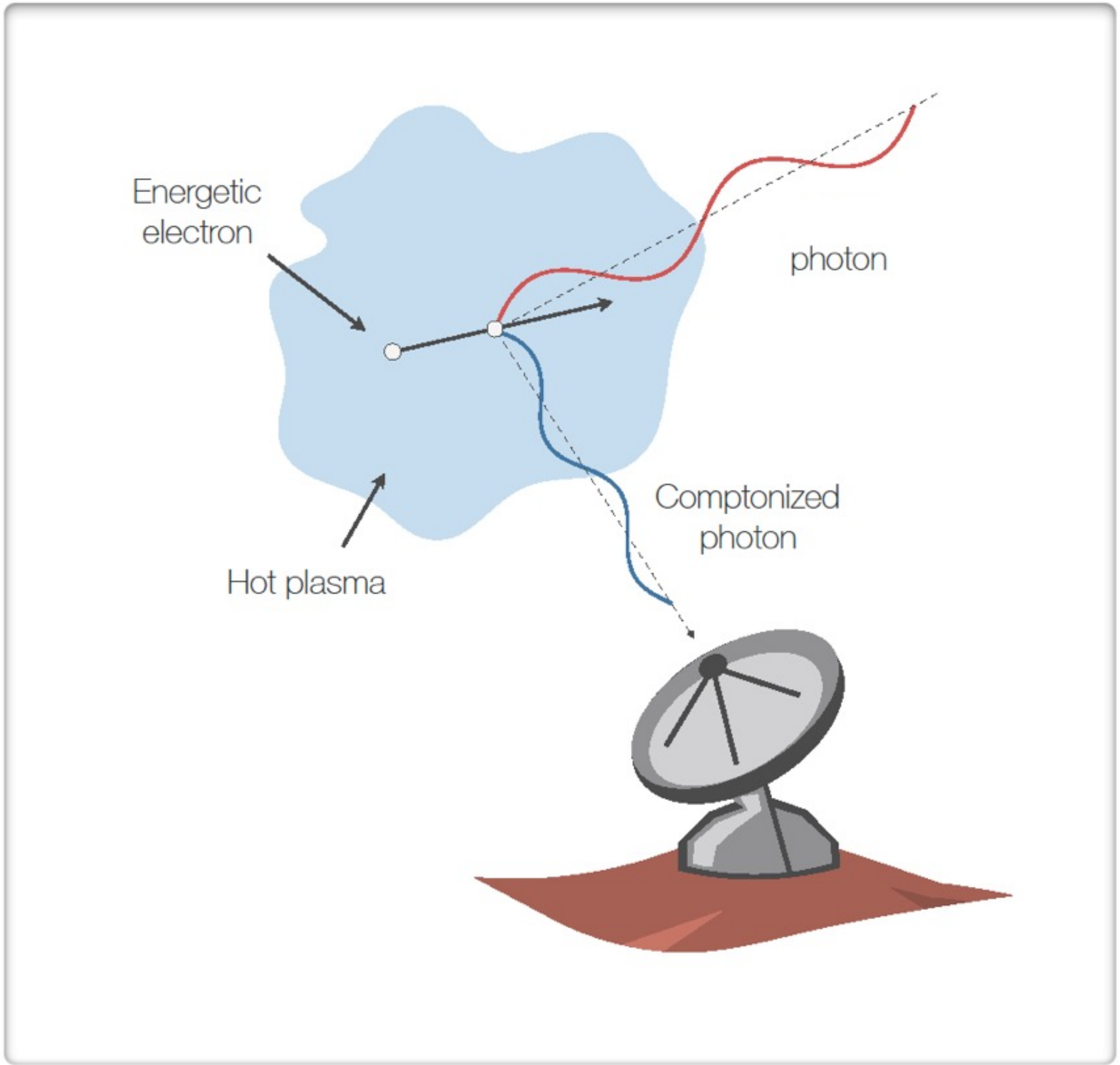


Watson et al. (2015)

- number density evolution
- high-mass end of massfunction
- **Sunyaev-Zeldovich effect**

Galaxy Clusters *application*

- Sunyaev-Zeldovich effect



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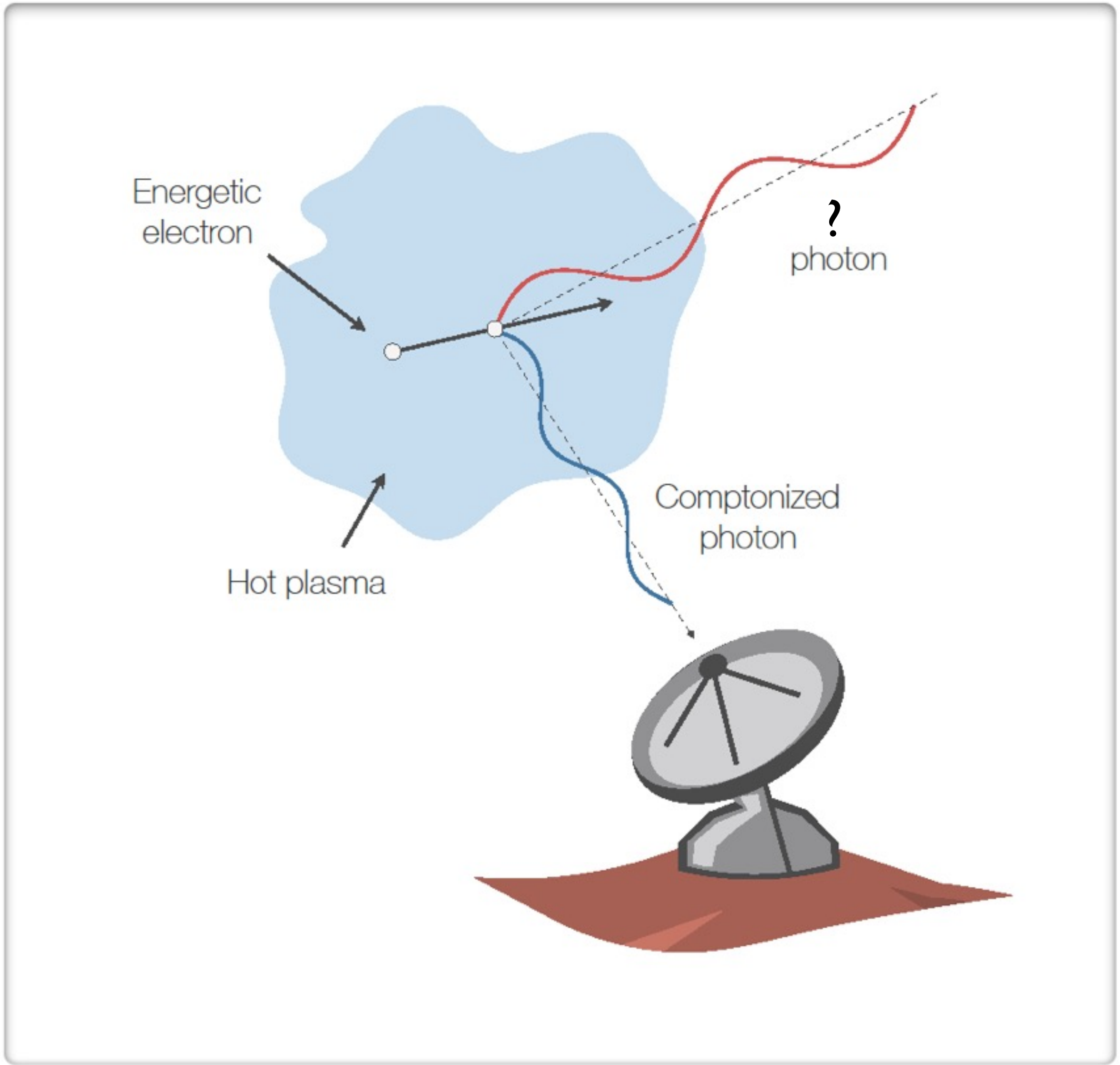

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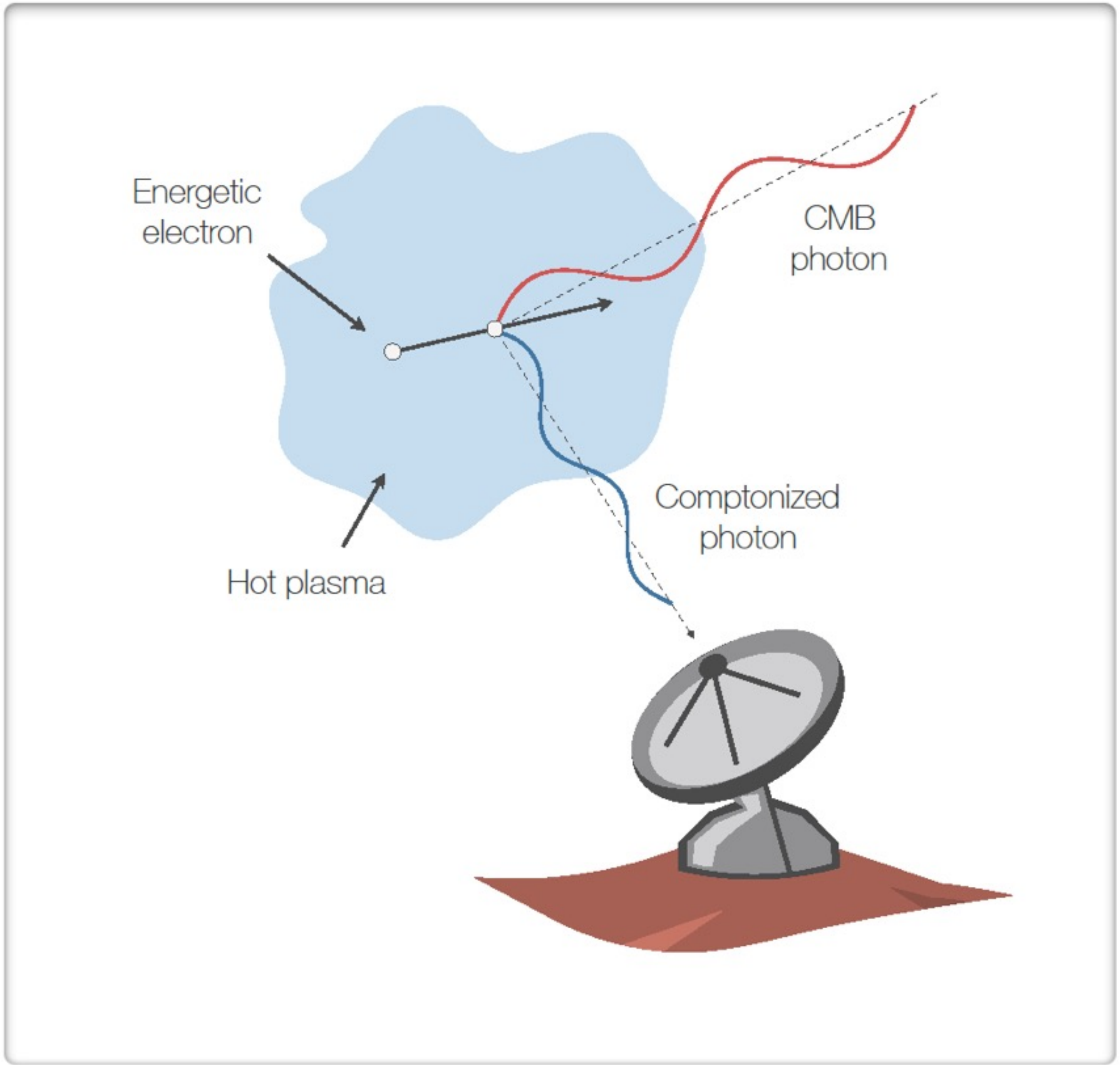

- Sunyaev-Zeldovich effect
  - thermal: CMB photons scatter off the hot intra-cluster gas
  - kinetic: the cluster gas has a bulk motion with respects to the CMB and hence induces a Doppler shift

Galaxy Clusters *application*

- Sunyaev-Zeldovich effect
  - thermal: CMB photons scatter off the hot intra-cluster gas

Galaxy Clusters

- Sunyaev-Zeldovich effect

  - thermal: CMB photons scatter off the hot intra-cluster gas

frequency shift:

$$\frac{\Delta\nu}{\nu} = \frac{\Delta E}{E} = \frac{kT - h\nu}{m_e c^2} \approx \frac{kT}{m_e c^2}$$

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  - thermal: CMB photons scatter off the hot intra-cluster gas

frequency shift:

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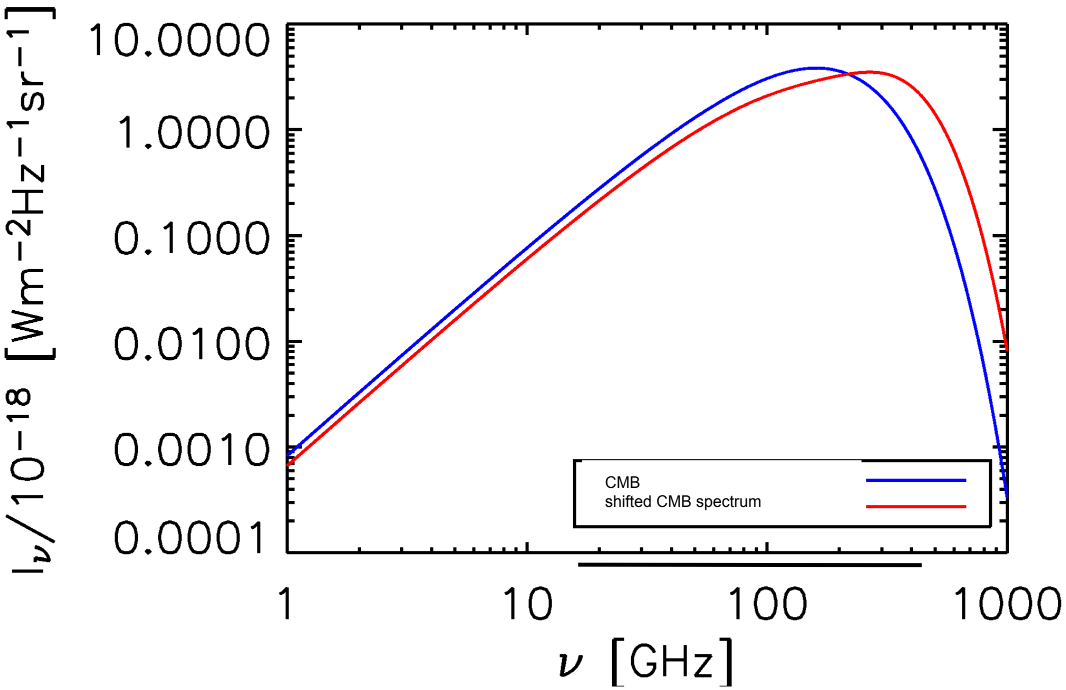
simple shift



Galaxy Clusters

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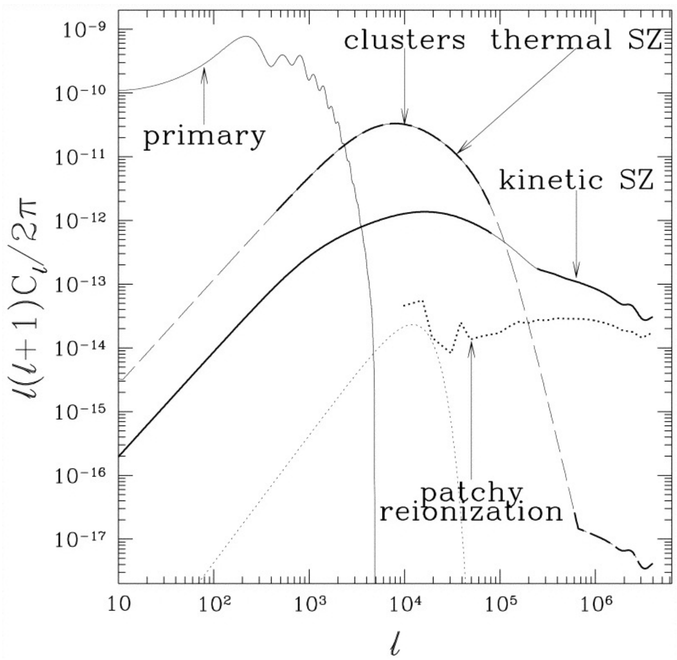
  - thermal: CMB photons scatter off the hot intra-cluster gas

...also affecting CMB anisotropies



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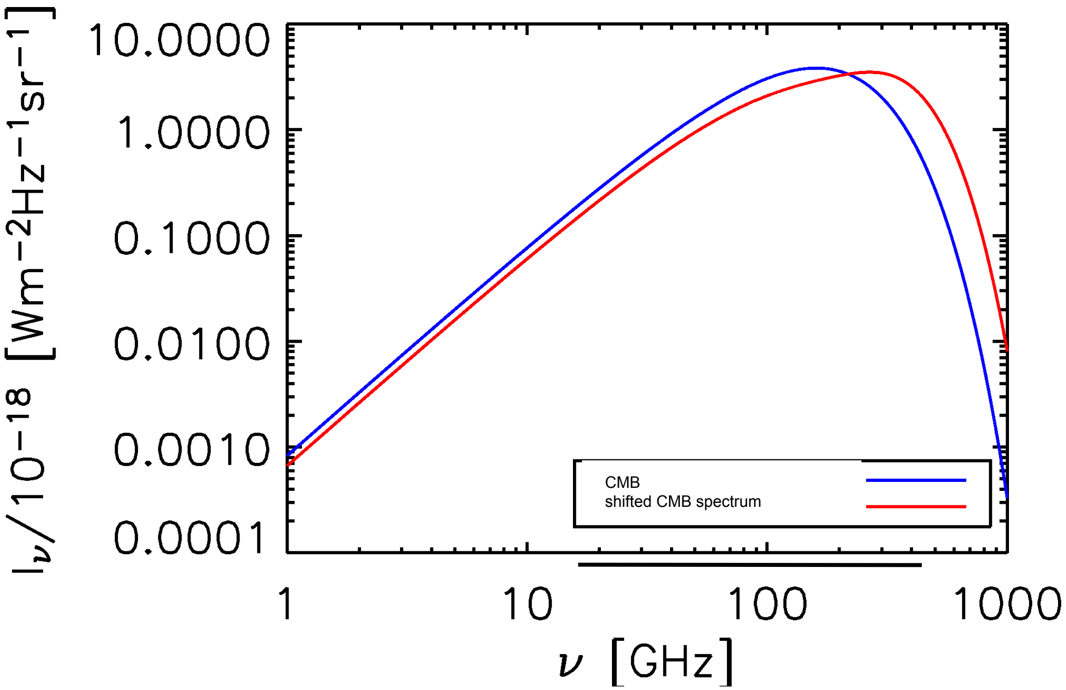

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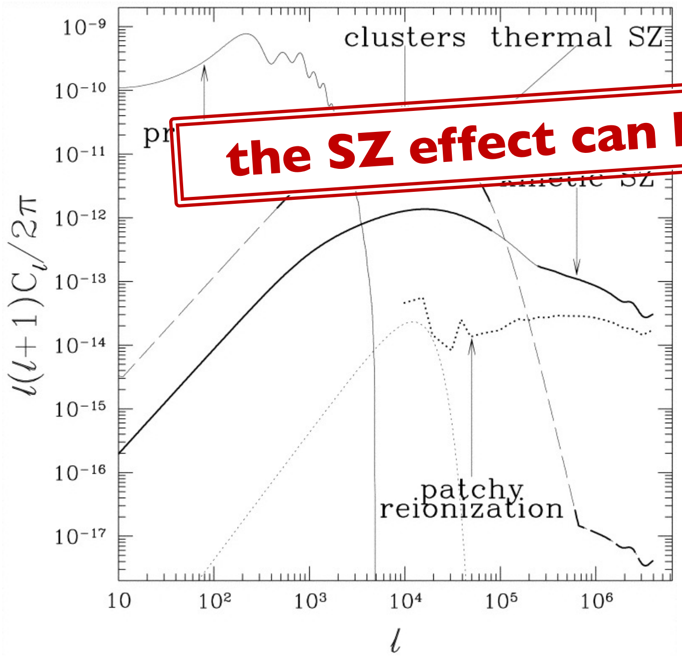
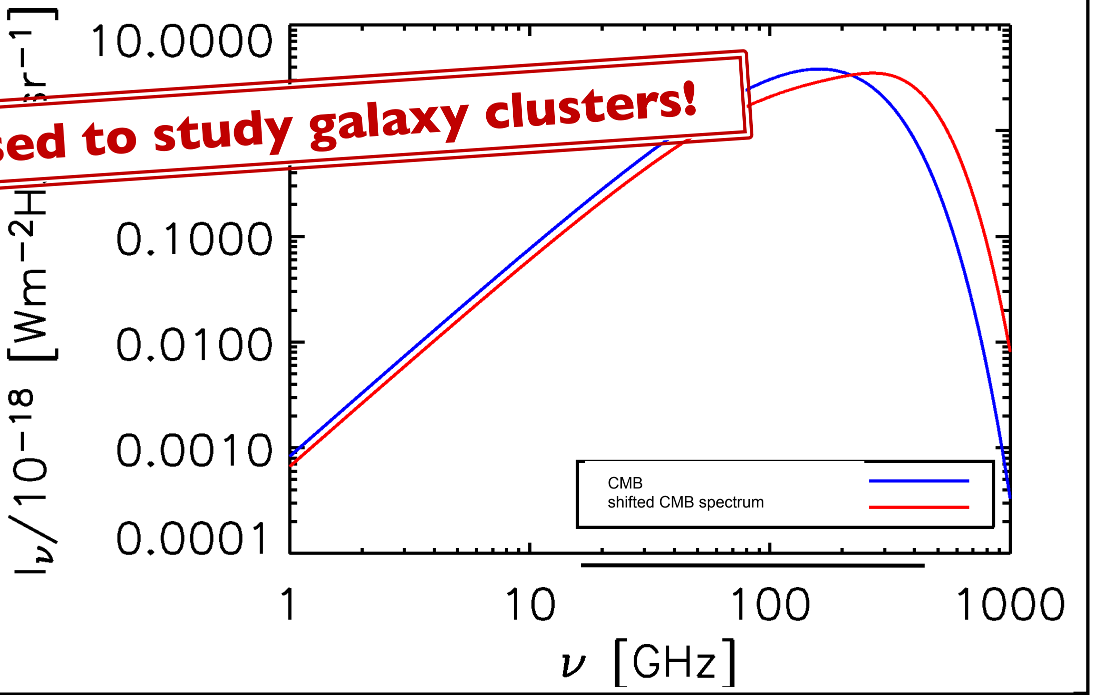
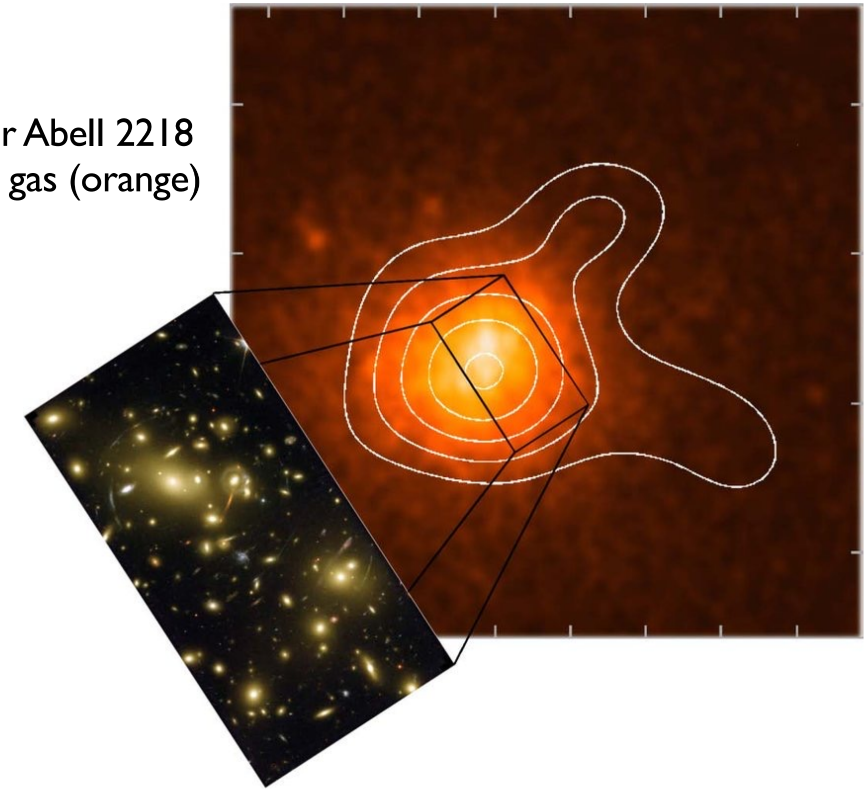




the SZ effect can be used to study galaxy clusters!

- Sunyaev-Zeldovich effect
    - thermal: CMB photons scatter off the hot intra-cluster gas



SZ effect (white contours) for Abell 2218 as modelled for the observed gas (orange)

(Bock et al., arxiv:0604101)

- Sunyaev-Zeldovich effect – applications

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  - scattering effect ⇒ magnitude is redshift independent!

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  - scattering effect ⇒ magnitude is redshift *independent*!

    ⇒ SZ effect allows for detection of high-z clusters

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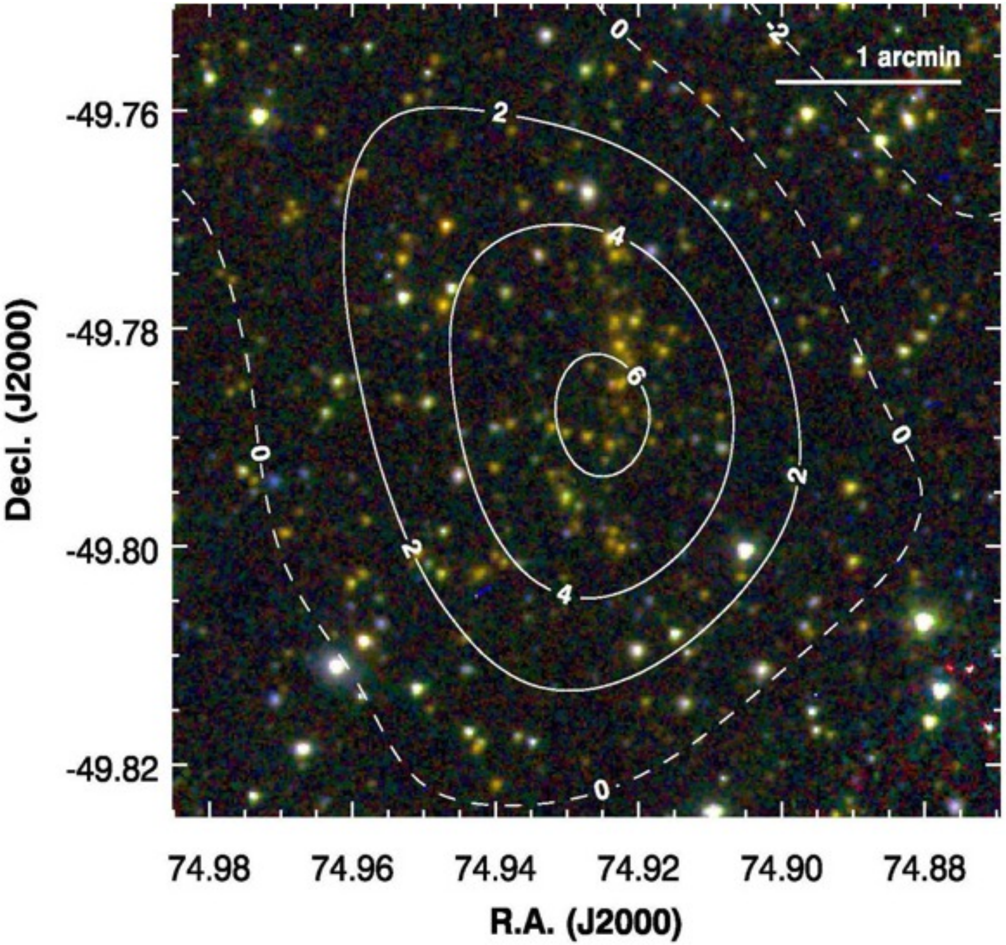


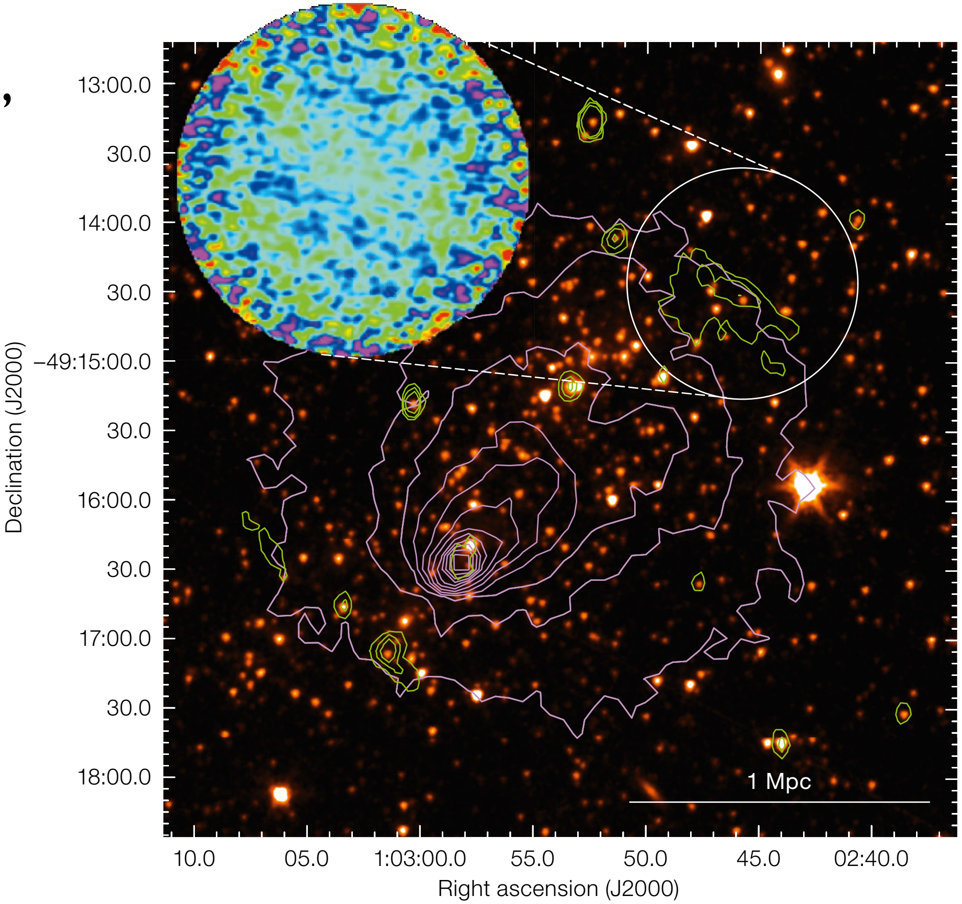
SPT-CL J0459−4947
- $z_{\rm est} > 1.5$
- $M \sim 10^{14}\,{\rm M}_\odot$

(Bleem et al. 2015)

- Sunyaev-Zeldovich effect – applications

  - detection of high-z clusters
  - detection of accretion shocks

'El Gordo'



(Basu et al. 2016)

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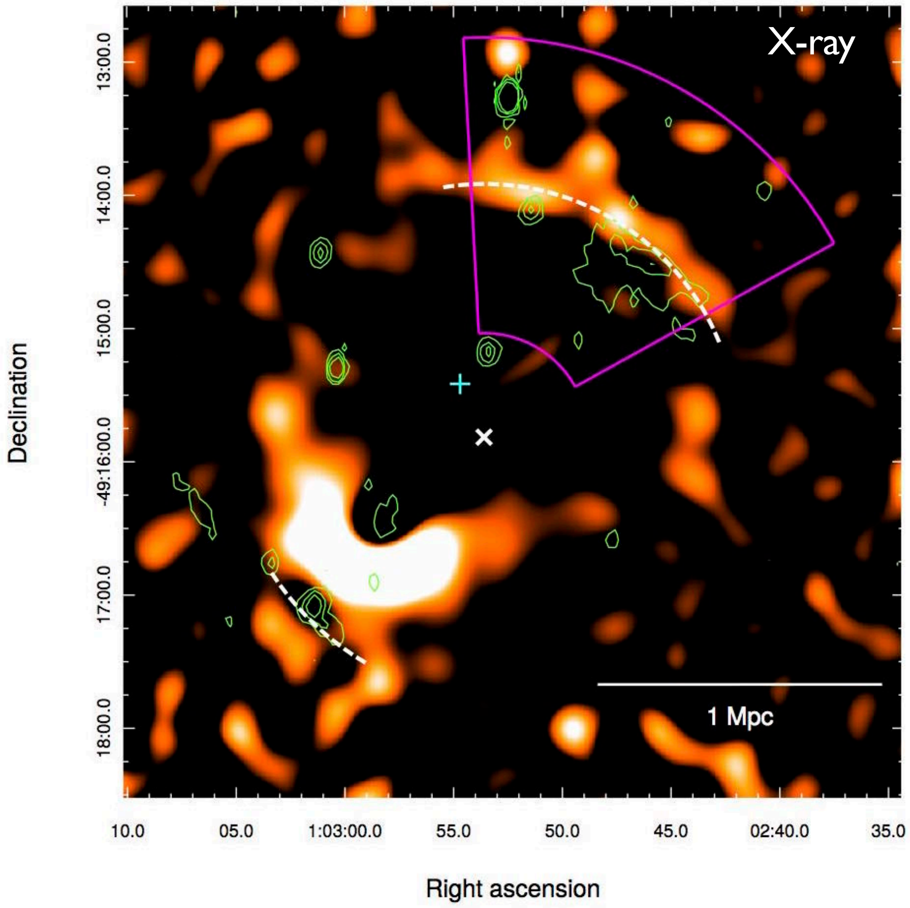

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$$L_X \propto 4\pi d_L^2 F_X$$

$$L_X \propto \left(\frac{\Delta T}{T}\right)^2 d_A$$

$\frac{\Delta T}{T}$: CMB temperature flucuations

(Cavaliere et al. 1979)

- Sunyaev-Zeldovich effect – applications
    - detection of high-z clusters
    - detection of accretion shocks
    - measuring H_0

$$L_X \propto 4\pi d_L^2 F_X$$

$$L_X \propto \left(\frac{\Delta T}{T}\right)^2 d_A$$

$$d_L = (1+z)^2 d_A$$

$$\left(\frac{\Delta T}{T}\right)^2 (1+z)^{-2} d_L \propto 4\pi d_L^2 F_X$$

- Sunyaev-Zeldovich effect – applications
  - detection of high-z clusters
  - detection of accretion shocks
  - measuring H_0 $d_L \propto \left(\frac{\Delta T}{T}\right)^2 (1+z)^{-2} F_X^{-1}$

- Sunyaev-Zeldovich effect – applications

  - detection of high-z clusters
  - detection of accretion shocks
  - measuring H_0

$$d_L \propto \left(\frac{\Delta T}{T}\right)^2 (1+z)^{-2} F_X^{-1}$$

X-ray observation

measured via SZ effect

- Sunyaev-Zeldovich effect – applications
  - detection of high-z clusters
  - detection of accretion shocks
  - measuring H_0: $$d_L \propto \left(\frac{\Delta T}{T}\right)^2 (1+z)^{-2} F_X^{-1} \overset{!}{\propto} \frac{c}{H_0}$$

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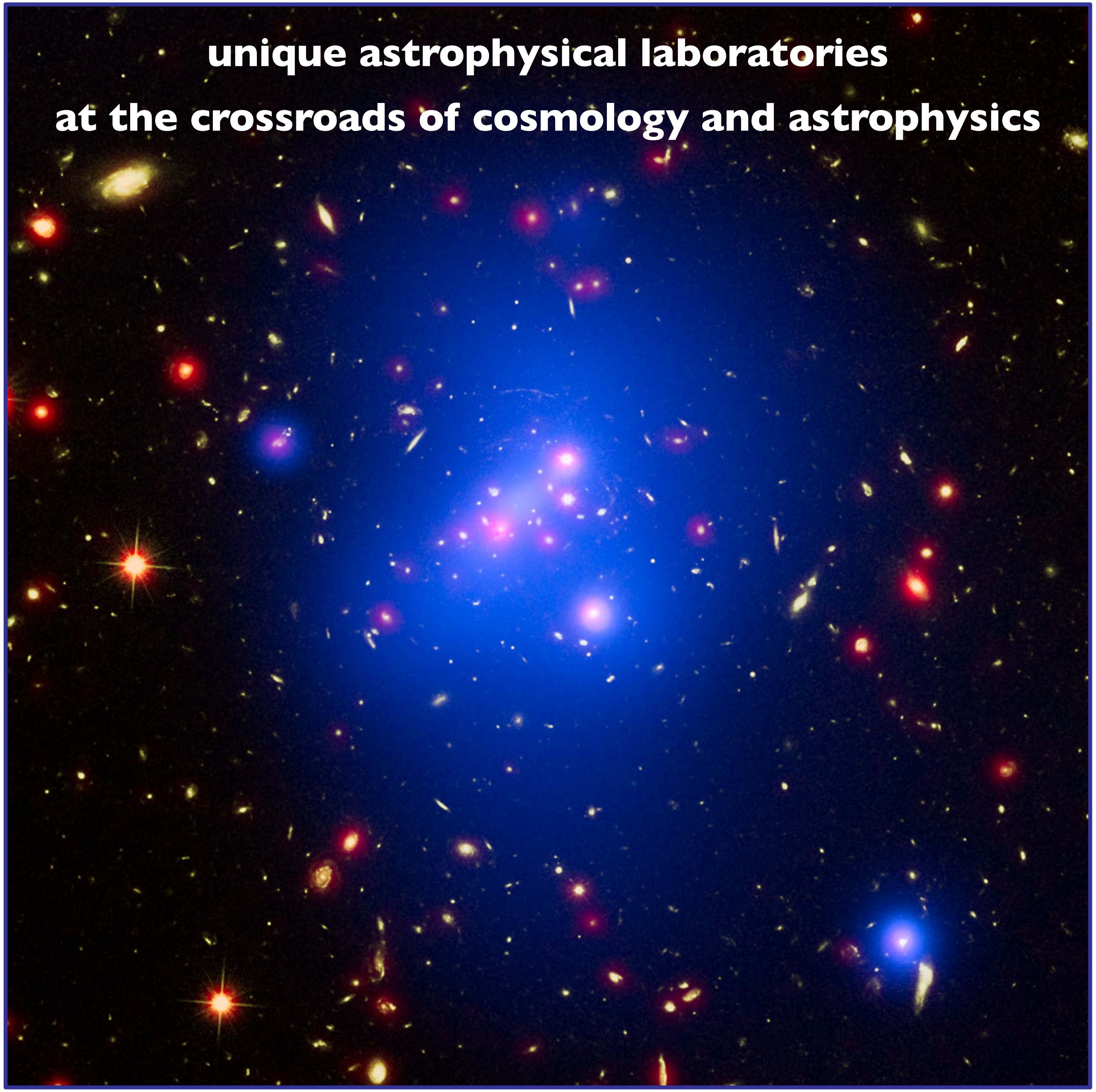
$$H_0 = \begin{cases} \text{66 km/s/Mpc (Mason et al. 2001)} \\ \ldots \\ \text{67 km/s/Mpc (Udomprasert et al. 2004)} \\ \ldots \\ \text{67 km/s/Mpc (Kozmanyan et al. 2019)} \end{cases}$$

Galaxy Clusters



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