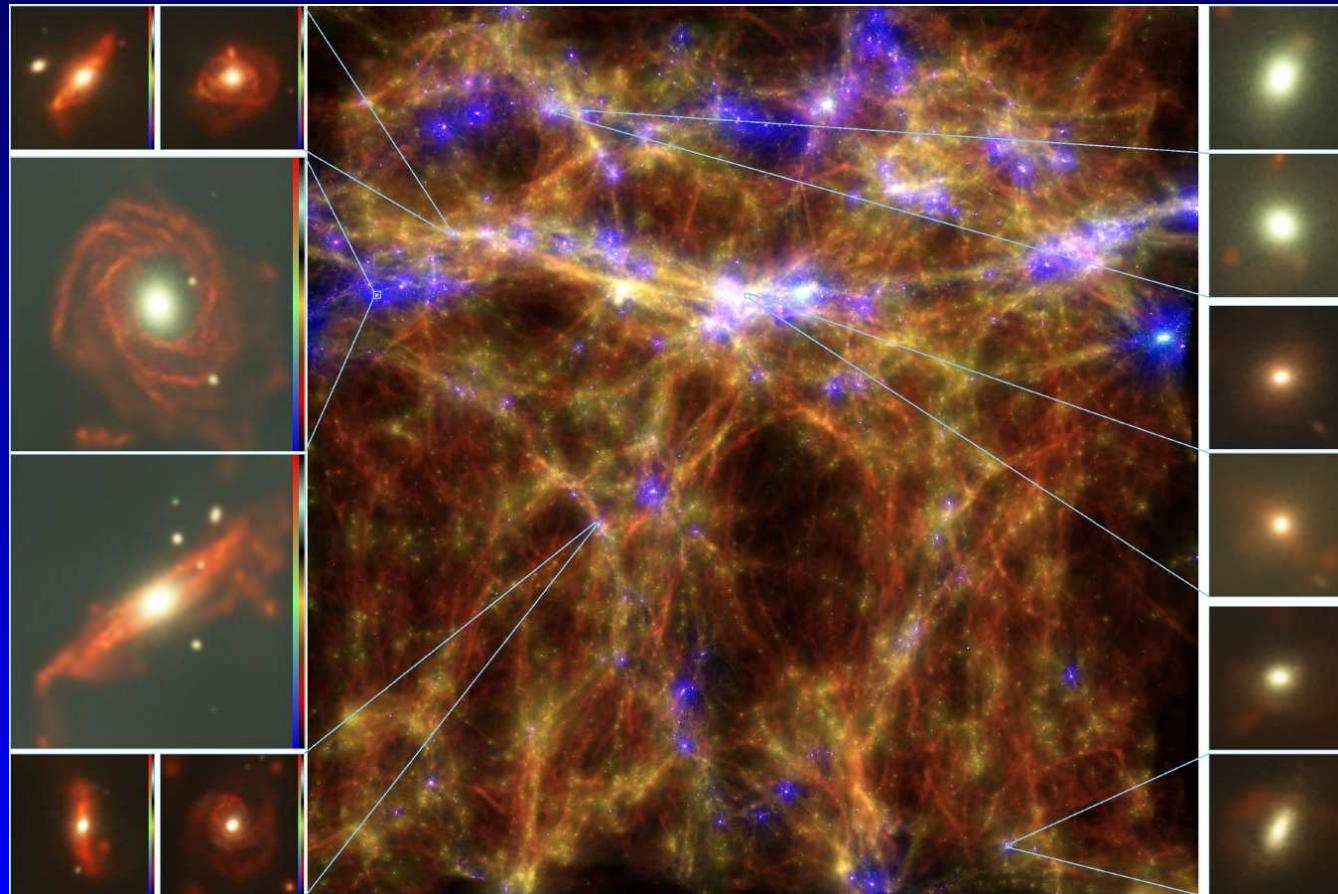


# The Magneticum Pathfinder Simulation

Klaus Dolag

Universitäts-Sternwarte München

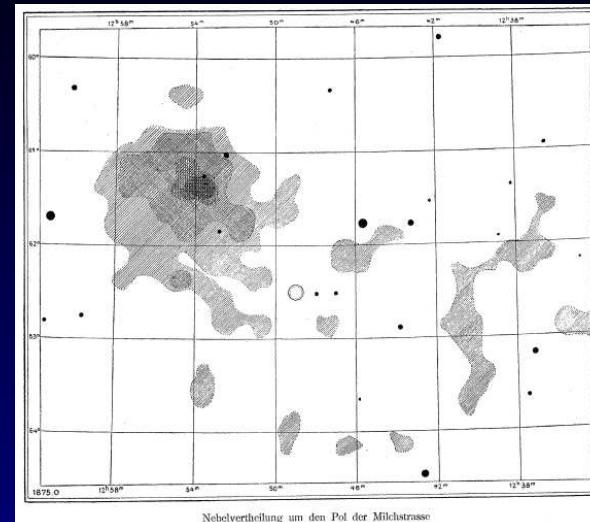


# Outline

- Introduction
  - Historic note
  - Cosmological Simulations
  - Physical processes to capture
- The Numerical Challenge
  - Method, Implementation, Performance
- The Magneticum Project
  - Aim, Setup, Design
- Preliminary Results
  - Clusters, Halos, AGNs, Galaxies
- Conclusions

# A Historic Example (Coma)

	0 <sup>m</sup>	59 <sup>m</sup>	58 <sup>m</sup>	57 <sup>m</sup>	56 <sup>m</sup>	55 <sup>m</sup>	54 <sup>m</sup>	53 <sup>m</sup>	52 <sup>m</sup>	51 <sup>m</sup>	50 <sup>m</sup>	49 <sup>m</sup>	48 <sup>m</sup>	47 <sup>m</sup>	46 <sup>m</sup>	45 <sup>m</sup>	44 <sup>m</sup>	43 <sup>m</sup>	42 <sup>m</sup>	41 <sup>m</sup>	40 <sup>m</sup>	39 <sup>m</sup>	38 <sup>m</sup>	37 <sup>m</sup>	36 <sup>m</sup>	35 <sup>m</sup>			
59° 15'	—	—	—	—	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—				
30	—	—	0	2	1	3	1	2	1	3	2	1	2	0	2	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			
30	—	—	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0				
45	—	—	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0				
61° 0'	—	—	0	1	4	5	9	16	12	15	5	3	1	4	2	1	4	1	2	1	0	1	2	4	0	1	0		
15	—	—	0	1	5	15	19	10	23	15	19	8	4	3	4	2	1	0	1	1	0	1	1	1	2	0	0	4	
30	—	—	0	0	9	17	11	14	36	68	10	7	3	7	0	2	1	2	3	1	1	3	0	4	4	3	0	2	1
45	—	—	1	2	2	9	6	12	13	17	20	16	6	7	1	2	1	1	1	1	4	1	1	5	3	1	6	3	1
62° 0'	—	—	0	5	5	10	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3	
15	—	—	0	2	1	3	6	8	3	10	7	3	5	4	2	4	6	8	3	2	5	0	3	9	10	10	2	2	
30	—	—	0	3	1	6	5	10	11	9	1	10	7	1	5	3	4	4	3	2	3	3	6	4	1	5	2	3	1
45	—	—	0	1	4	4	1	2	4	8	4	2	1	2	1	2	3	4	2	1	3	9	4	3	2	4	5	3	
63° 0'	—	—	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	
15	—	—	0	2	2	2	3	0	0	0	0	1	1	1	2	4	0	2	4	2	7	5	0	4	0	2	2		
30	—	—	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	—	
45	—	—	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	4	4	2	8	2	2	2	0	0	—	
64° 0'	—	—	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	4	2	1	5	1	1	3	0	—	—	
15	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—		



Max Wolf, 1901/1902

## Ein merkwürdiger Haufen von Nebelflecken.

Auf zwei mit dem Bruce-Teleskop genommenen Aufnahmen vom 24. März dieses Jahres, welche die Umgebung von 31 Comae Berenices darstellen, findet sich eine sehr interessante Gegend des Himmels. Um die Stelle

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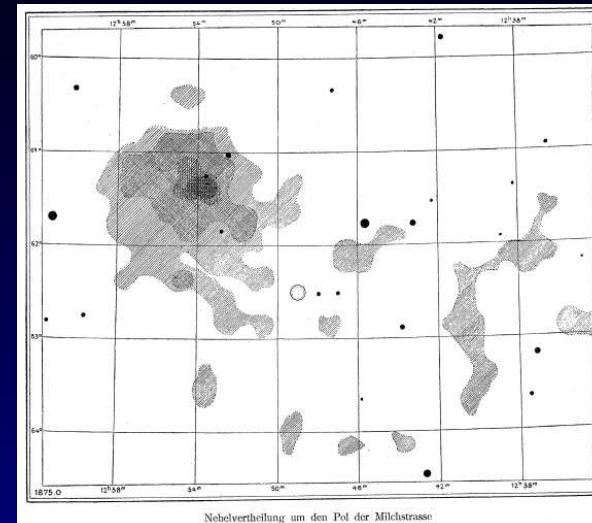
Heidelberg, 1901 März 27.

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Max Wolf.

# A Historic Example (Coma)

	0° <sup>m</sup>	59° <sup>m</sup>	58° <sup>m</sup>	57° <sup>m</sup>	56° <sup>m</sup>	55° <sup>m</sup>	54° <sup>m</sup>	53° <sup>m</sup>	52° <sup>m</sup>	51° <sup>m</sup>	50° <sup>m</sup>	49° <sup>m</sup>	48° <sup>m</sup>	47° <sup>m</sup>	46° <sup>m</sup>	45° <sup>m</sup>	44° <sup>m</sup>	43° <sup>m</sup>	42° <sup>m</sup>	41° <sup>m</sup>	40° <sup>m</sup>	39° <sup>m</sup>	38° <sup>m</sup>	37° <sup>m</sup>	36° <sup>m</sup>	35° <sup>m</sup>	
59° 15'	—	—	—	—	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	—	—	—	—	
30	—	—	0	2	1	3	1	2	1	3	2	1	1	2	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	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	1	0	1	1	2	2	1	0	2	3	0	1	3	5	0	0	2	0	0	0	—	
30	—	—	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0	0	
45	—	—	0	2	3	3	5	3	1	3	0	0	2	4	1	0	0	3	5	0	1	0	0	—	—	—	
61° 0'	—	—	0	1	4	5	9	16	12	15	5	3	1	4	2	1	4	1	2	1	0	1	2	4	0	1	0
15	—	—	0	1	5	15	19	10	23	15	19	8	4	3	4	2	1	0	1	1	0	1	1	1	2	0	0
30	—	—	0	0	9	17	11	14	36	68	10	7	3	7	0	2	1	2	3	1	1	3	0	4	4	3	0
45	—	—	1	2	2	9	6	12	13	17	20	16	6	7	1	2	1	1	1	4	1	1	5	3	1	6	3
62° 0'	—	—	0	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2
15	—	—	0	2	1	3	6	8	3	10	7	3	5	4	2	4	6	8	3	2	2	5	0	3	9	10	2
30	—	—	0	3	1	6	5	10	11	9	1	10	7	1	5	3	4	4	3	2	3	3	6	4	1	5	2
45	—	—	0	1	4	4	1	2	4	8	4	2	1	2	1	2	3	4	2	1	3	9	4	3	2	4	
63° 0'	—	—	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
15	—	—	0	2	2	2	3	0	0	0	0	1	1	1	2	4	0	2	4	2	7	5	0	4	0	2	2
30	—	—	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
45	—	—	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	4	4	2	8	2	2	2	0	0
64° 0'	—	—	—	—	0	2	0	1	4	1	1	1	6	3	2	0	0	5	4	2	1	5	1	1	3	0	—
15	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—



Max Wolf, 1901/1902

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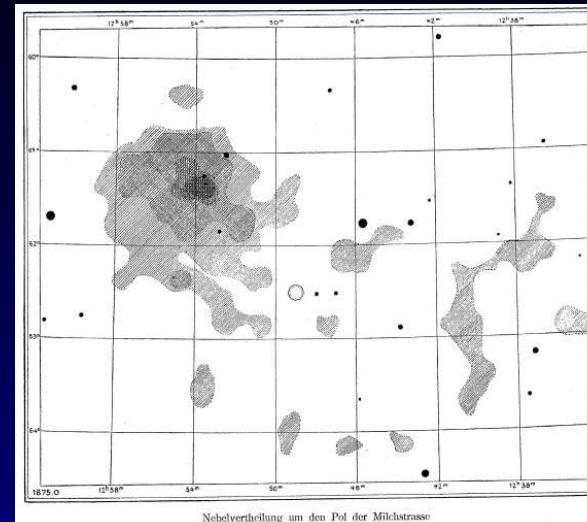
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Max Wolf.

numerous small nebulæ are standing such close together, that once literally frightens in sight of the remarkable appearance of this cluster of nebulæ.

# A Historic Example (Coma)

	0 <sup>m</sup>	59 <sup>m</sup>	58 <sup>m</sup>	57 <sup>m</sup>	56 <sup>m</sup>	55 <sup>m</sup>	54 <sup>m</sup>	53 <sup>m</sup>	52 <sup>m</sup>	51 <sup>m</sup>	50 <sup>m</sup>	49 <sup>m</sup>	48 <sup>m</sup>	47 <sup>m</sup>	46 <sup>m</sup>	45 <sup>m</sup>	44 <sup>m</sup>	43 <sup>m</sup>	42 <sup>m</sup>	41 <sup>m</sup>	40 <sup>m</sup>	39 <sup>m</sup>	38 <sup>m</sup>	37 <sup>m</sup>	36 <sup>m</sup>	35 <sup>m</sup>	
59° 15'	—	—	—	—	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—		
30	—	—	0	2	1	3	1	2	1	3	2	1	1	2	0	2	1	0	0	—	—	—	—	—			
45	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	1	0	0	1	—	—	—	—	—		
60° 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	
30	—	—	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0		
45	—	—	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0		
61° 0'	—	—	0	1	4	5	9	16	12	15	5	3	1	4	2	1	4	1	2	1	0	1	2	4	0	1	0
15	—	—	0	1	5	15	19	10	23	15	19	8	4	3	4	2	1	0	1	1	0	1	1	1	2	0	0
30	—	—	0	0	9	17	11	14	36	68	10	7	3	7	0	2	1	2	3	1	1	3	0	4	4	3	0
45	—	—	1	2	2	9	6	12	13	17	20	16	6	7	1	2	1	1	1	4	1	1	5	3	1	6	3
62° 0'	—	—	0	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2
15	—	—	0	2	1	3	6	8	3	10	7	3	5	4	2	4	6	8	3	2	2	5	0	3	9	10	2
30	—	—	0	3	1	6	5	10	11	9	1	10	7	1	5	3	4	4	3	2	3	6	4	1	5	2	
45	—	—	0	1	4	4	1	2	4	8	4	2	1	2	3	4	2	1	3	9	4	3	2	4	5	3	
63° 0'	—	—	0	1	5	2	3	1	3	6	4	6	2	0	6	2	4	3	5	2	6	10	5	3	1	1	
15	—	—	0	2	2	2	3	0	0	0	1	1	1	2	4	0	2	4	2	7	5	0	4	0	2	2	
30	—	—	1	1	2	0	3	0	8	1	1	0	0	0	2	2	1	0	5	3	5	3	8	4	1	2	
45	—	—	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	4	4	2	8	2	2	2	0	
64° 0'	—	—	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	4	2	1	5	1	1	3	0	
15	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	



Max Wolf, 1901/1902

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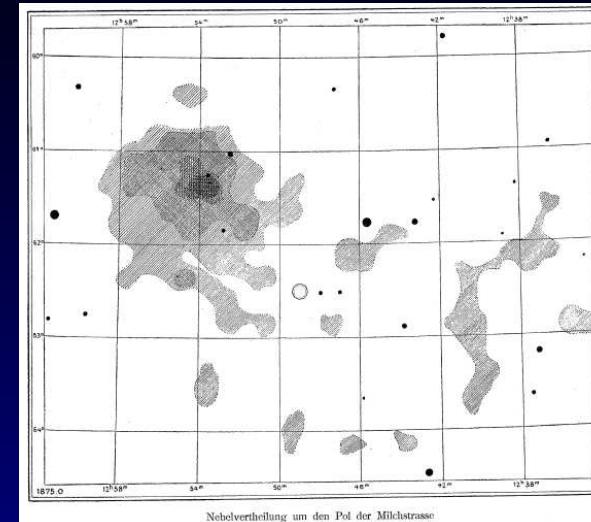
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Among them there are 4 or 5 with large extend and with central enhanced densities, as well as several strongly stretched ones. However most of them are round and smaller (compared to other observations).

# A Historic Example (Coma)

	0°	59°	58°	57°	56°	55°	54°	53°	52°	51°	50°	49°	48°	47°	46°	45°	44°	43°	42°	41°	40°	39°	38°	37°	36°	35°				
59° 15'	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—					
30	—	—	—	0	2	1	3	1	2	1	3	2	1	1	2	0	2	1	0	0	—	—	—	—	—					
45	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	0	0	1	—	—					
60° 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	1	0	1	1	2	2	1	0	2	3	0	1	3	5	0	0	2	0	0					
30	—	—	—	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1					
45	—	—	—	0	2	3	3	5	3	1	3	0	0	2	4	1	0	0	3	5	0	1	0	0	—					
61° 0'	—	—	—	0	1	4	5	9	16	12	15	5	3	1	4	2	1	4	1	2	1	0	1	2	4	0	1	0		
15	—	—	—	0	1	5	15	19	10	23	15	19	8	4	3	4	2	1	0	1	1	0	1	1	1	2	0	0	4	
30	—	—	—	0	0	9	17	11	14	36	68	10	7	3	7	0	2	1	2	3	1	1	3	0	4	4	3	0	2	1
45	—	—	—	1	2	2	9	6	12	13	17	20	16	6	7	1	2	1	1	1	4	1	1	5	3	1	1	6	3	1
62° 0'	—	—	—	0	5	10	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3	1	
15	—	—	—	0	2	1	3	6	8	3	10	7	3	5	4	2	4	6	8	3	2	2	5	0	3	9	10	10	2	2
30	—	—	—	0	3	1	6	5	10	11	9	1	10	7	1	5	3	4	4	3	2	3	3	6	4	1	5	2	3	1
45	—	—	—	0	1	4	4	1	2	4	8	4	2	1	2	3	4	2	1	3	9	4	3	2	4	5	3	—	—	
63° 0'	—	—	—	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	—
15	—	—	—	0	2	2	2	3	0	0	0	0	1	1	1	2	4	0	2	4	2	7	5	0	4	0	2	2	—	
30	—	—	—	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	—	
45	—	—	—	—	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	4	4	2	8	2	2	2	0	0	—
64° 0'	—	—	—	—	—	—	0	2	0	1	4	1	1	1	6	3	2	0	0	5	4	2	1	5	1	1	3	0	—	—
15	—	—	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—	—



Max Wolf, 1902

the regular behavior within the arrangement of these distant worlds

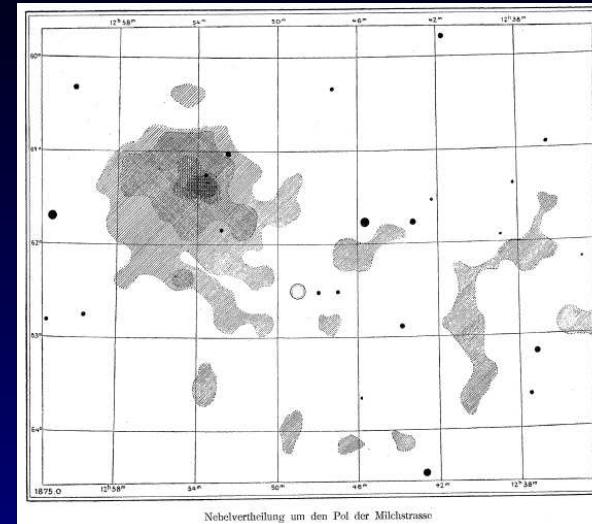
Es ist sofort zu sehen, wenn man die Tabelle oder die Tafel betrachtet, dass das Zusammendrängen der Nebel immer stärker wird, je weiter man in's Innere der Hauptinsel eindringt. Je näher man dem Puncte grösster Dichtigkeit kommt, umso dichter treten auch die Nebel an einander, so dass auf dem innersten Quadratgrad mehr als 320 einzelne Nebelflecken beisammen stehen. An der dichtesten Stelle dieses »Weltpoles« finden sich mehr als 70 Nebel auf der Fläche von  $\frac{1}{16}$  Quadratgrad.

Wir finden also hier ein völlig gesetzmässiges Verhalten in der Anordnung dieser fernen Welten; und dieser ungeheure Reichthum führt uns so eine Ordnung im Weltsystem vor Augen, die sicher für die Erkenntniss des Universums von allergrösster Bedeutung ist, von der wir uns aber auch zugestehen müssen, dass wir noch lange keine erschöpfende Erklärung für sie werden finden können.\*)

of greatest significance for understanding the universe

# A Historic Example (Coma)

	0°	59°	58°	57°	56°	55°	54°	53°	52°	51°	50°	49°	48°	47°	46°	45°	44°	43°	42°	41°	40°	39°	38°	37°	36°	35°
59° 15'	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	
30	—	—	0	2	1	3	1	2	3	2	1	1	2	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	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	
30	—	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0		
45	—	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0		
61° 0'	0	1	4	5	9	16	12	15	5	3	1	4	2	1	4	1	2	1	0	1	2	4	0	1	0	
15	0	1	5	15	19	10	23	15	19	8	4	3	4	2	1	0	1	1	0	1	1	1	2	0	0	
30	0	0	9	17	11	14	36	68	10	7	3	7	0	2	1	2	3	1	1	3	0	4	4	3	0	
45	1	2	2	9	6	12	13	17	20	16	6	7	1	2	1	1	1	1	4	1	1	5	3	1	6	
62° 0'	0	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	
15	0	2	1	3	6	8	3	10	7	3	5	4	2	4	6	8	3	2	2	5	0	3	9	10	10	
30	0	3	1	6	5	10	11	9	1	10	7	1	5	3	4	4	3	2	3	3	6	4	1	5	2	
45	—	0	1	4	4	1	2	4	8	4	2	1	2	1	2	3	4	2	1	3	9	4	3	2	4	
63° 0'	—	0	1	5	2	3	1	3	6	4	6	2	0	6	2	4	3	5	2	6	10	5	3	1	1	
15	—	0	2	2	2	3	0	0	0	0	1	1	1	2	4	0	2	4	2	7	5	0	4	0	2	
30	—	1	2	0	3	0	8	1	1	0	0	0	2	2	1	0	5	3	5	3	8	4	1	2	1	
45	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	3	4	4	2	8	2	2	2	0	
64° 0'	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—	
15	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	



Max Wolf, 1902

The directions of elongated nebulae align on the same angle on the sky.

Daraus ersehen wir, dass sich meine Vermuthung thatsächlich bestätigt. Die Richtungen aller länglichen Nebel gruppieren sich um den Positionswinkel  $60^\circ$ .

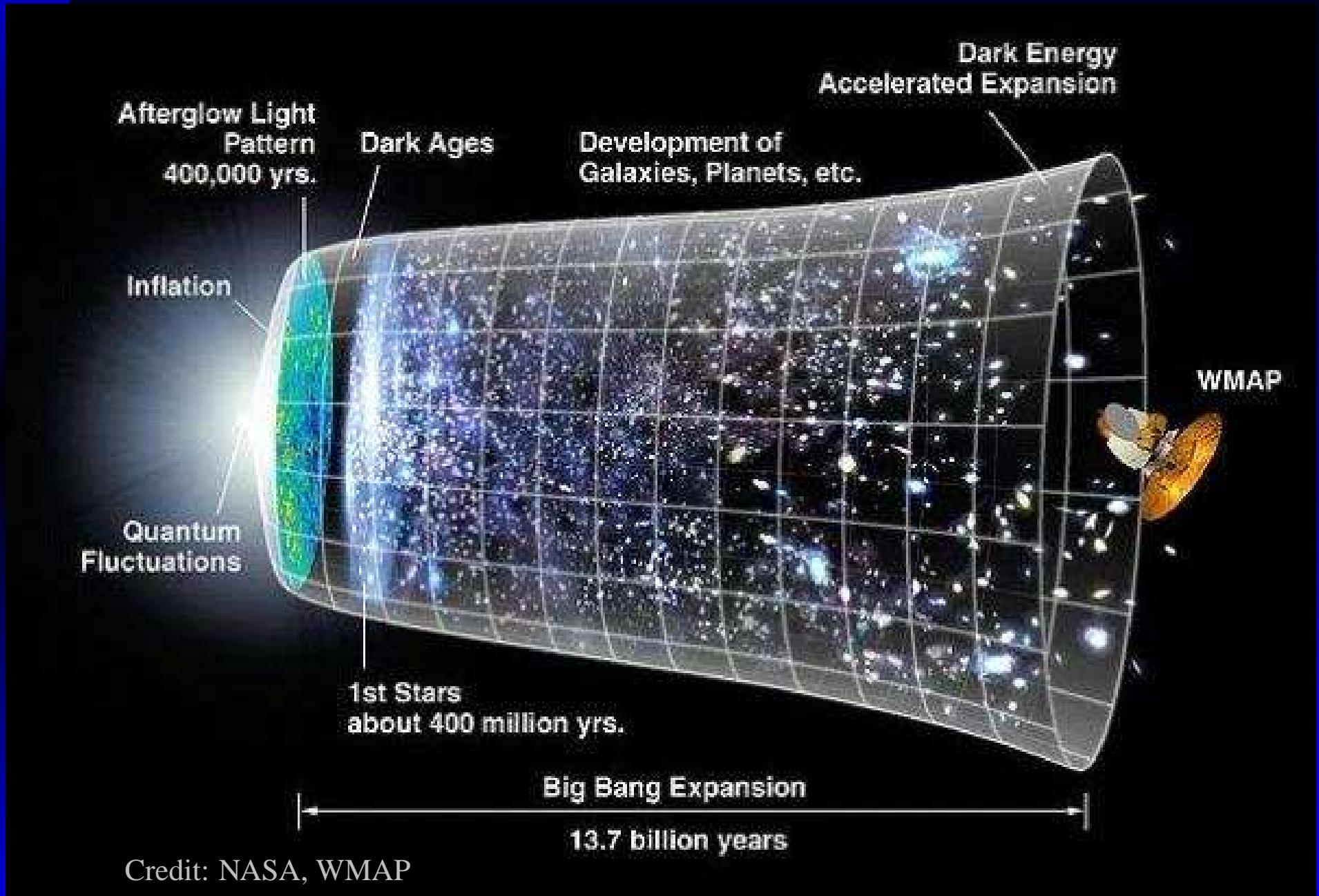
Das hatte ich so aus dem allgemeinen Eindruck, den ich beim Messen nach und nach erhalten hatte, erwartet. Nur hatte ich damals  $50^\circ$  dafür annehmen zu müssen geglaubt.

Aus der Tabelle ist ersichtlich, dass die Erscheinung am ausgesprochensten in jener Gegend ist, wo die Zusammendrängung der Nebelflecken auf den engsten Raum stattfindet. Je weiter wir uns von diesem Pol entfernen, desto mehr nimmt sie ab.

Es wäre verfrüht, irgend welche Speculationen an dieses merkwürdige Resultat zu knüpfen. Immerhin möchte ich nicht versäumen, es der allgemeinen Aufmerksamkeit zu empfehlen.

I can not even speculate on the implications but but want to bring it to the general attention.

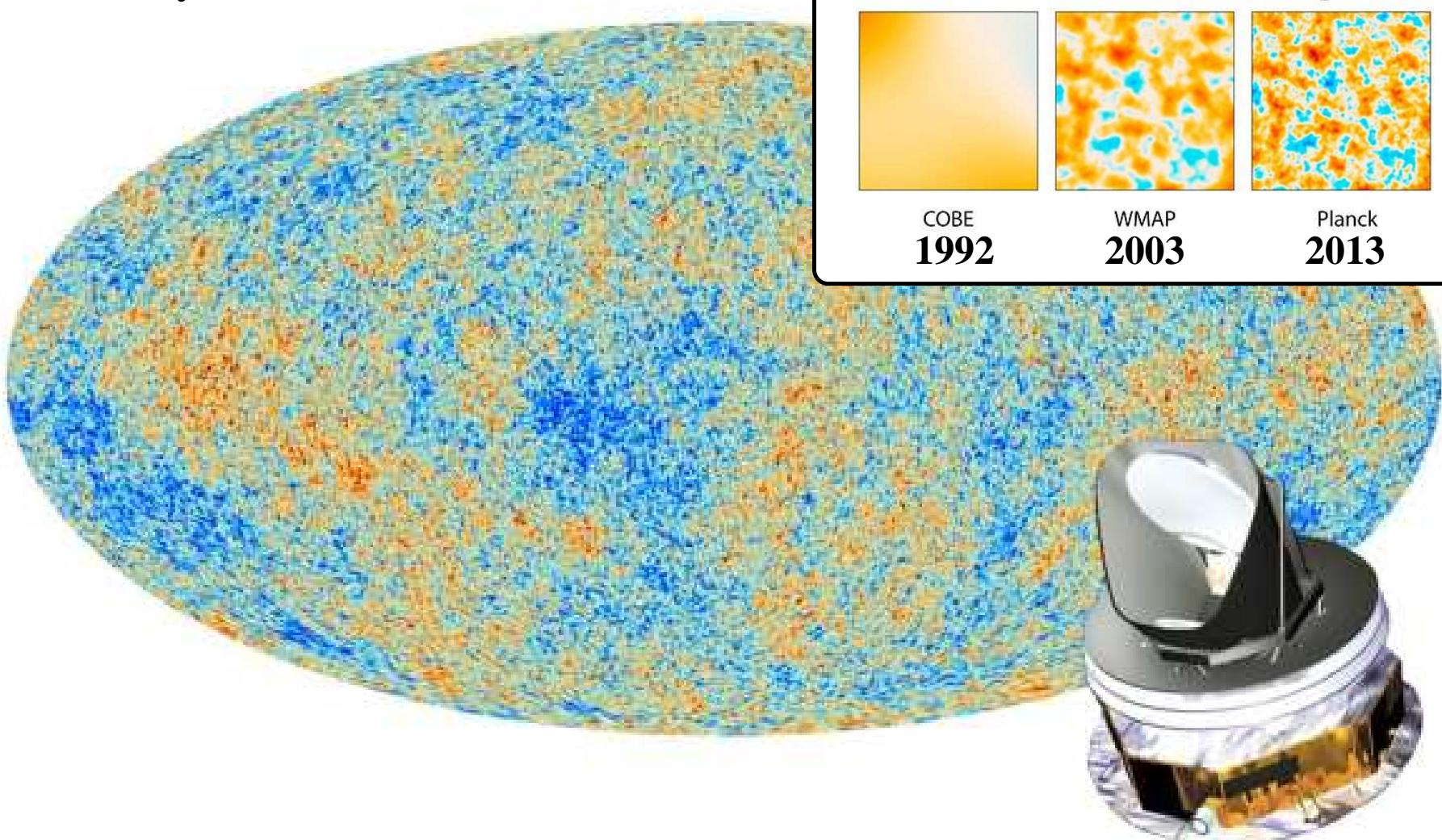
# Structure Formation



Interplay between background cosmology and structure formation.

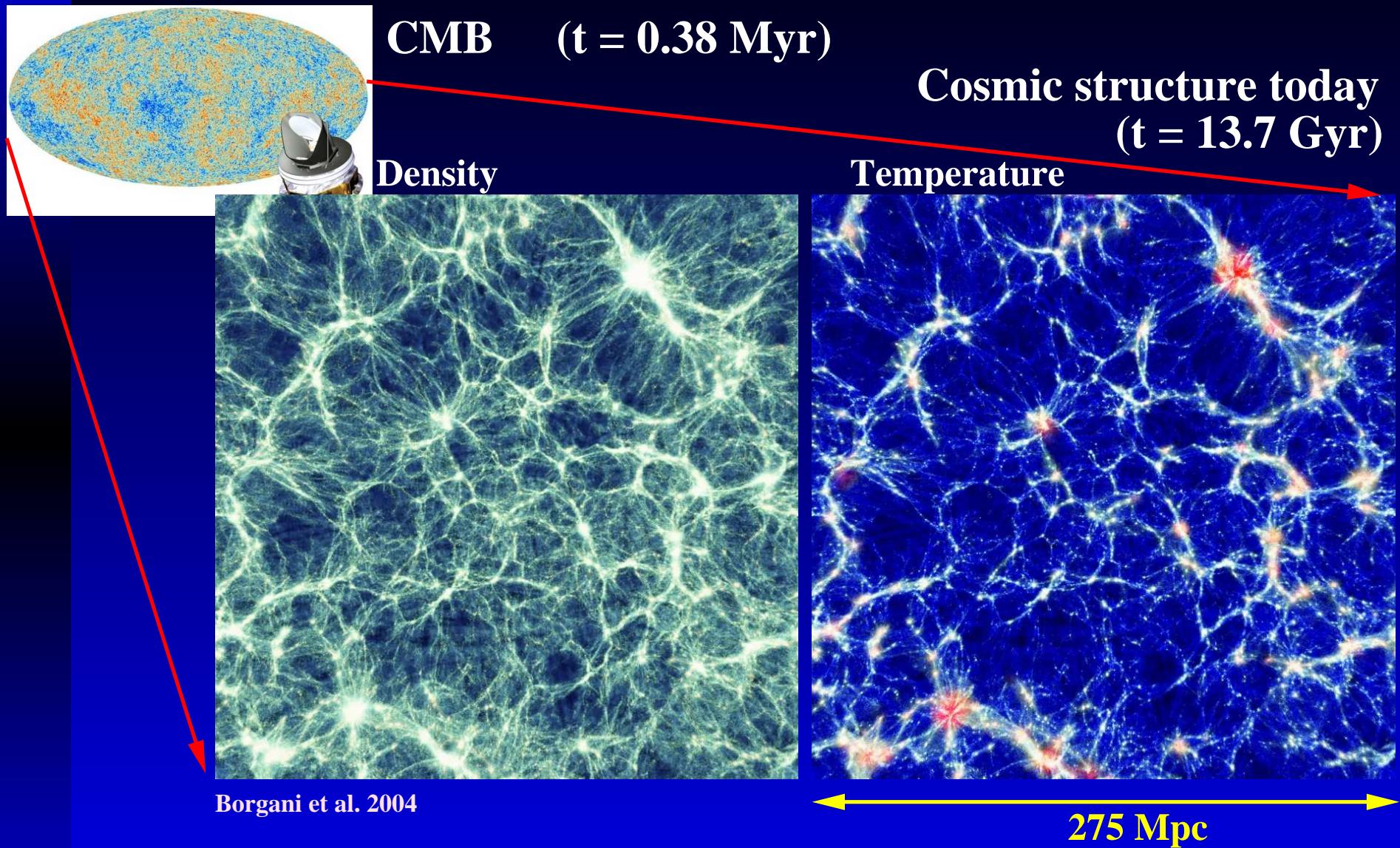
# Structure Formation

$t = 0.38 \text{ Myr}$



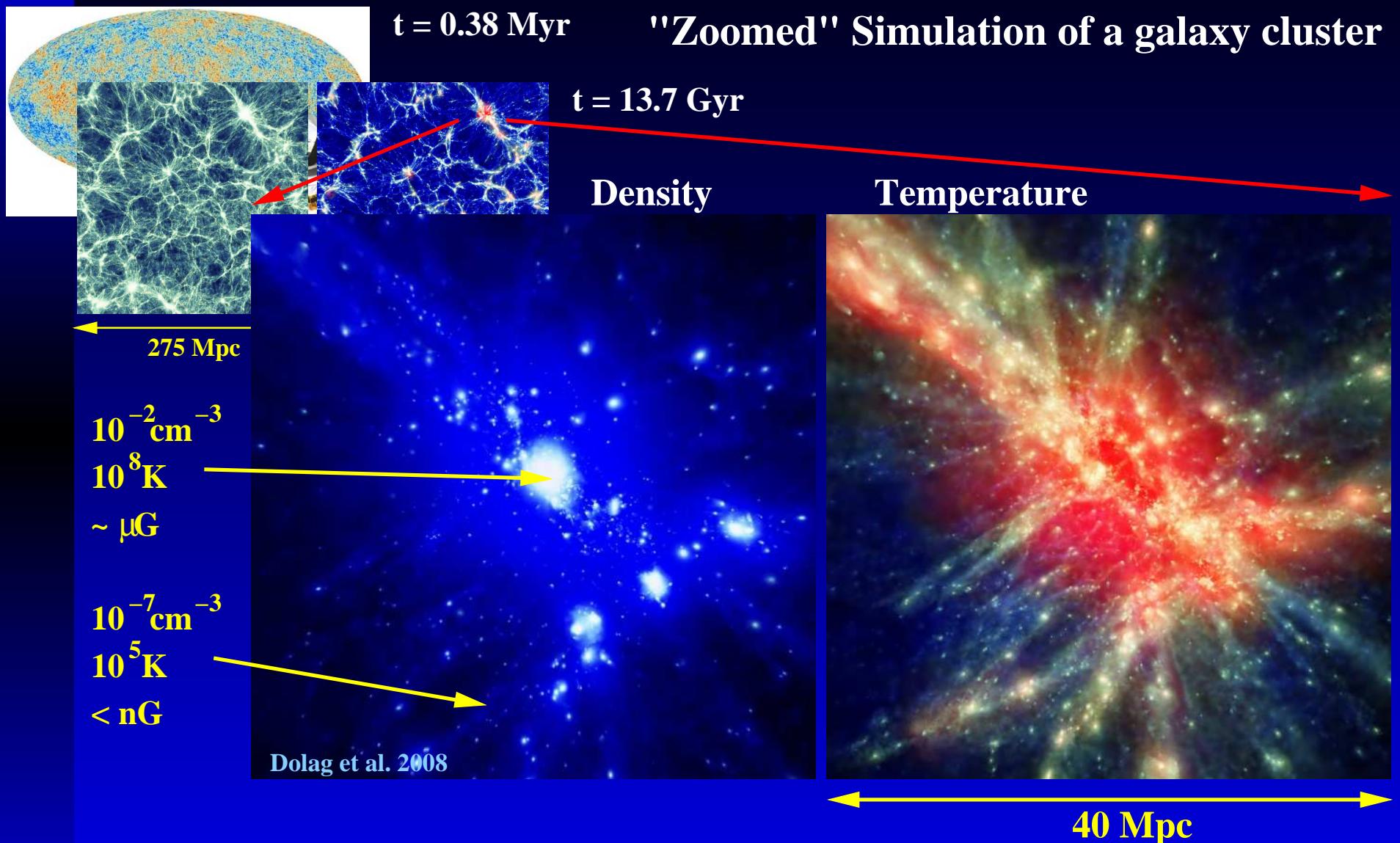
Cosmic Microwave Background, early picture of the structure in the Universe.

# Structure Formation



The cosmic web today ( $z = 0$ ) is mainly accessible through simulations (warm, thin). Simulations important to predict the non linear formation of cosmological structures.

# Structure Formation



Clusters form at the nodes of the cosmic web and trace the high density environments. The gas falls into the potential, cools and form stars.

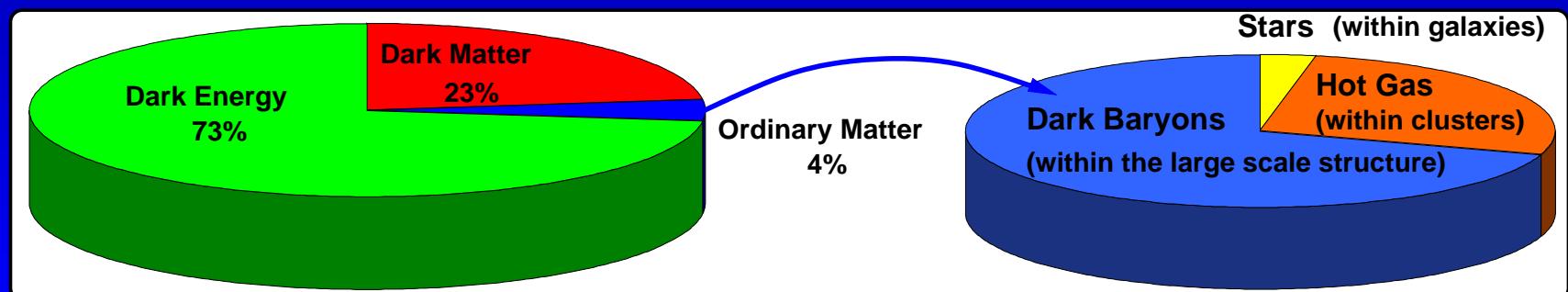
# Structure Formation

Galaxy clusters are the largest, gravitationally bound objects in the Universe and represent an almost fair sample of the cosmological composition.

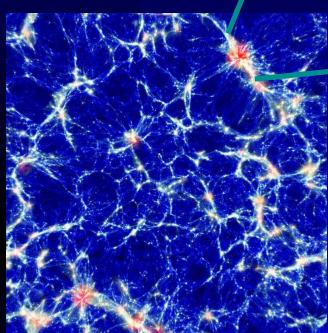
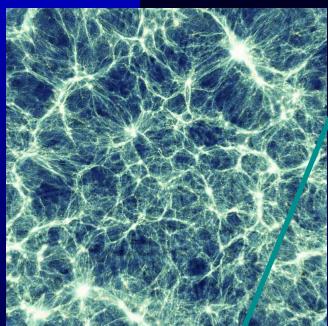
- Up to thousands of galaxies with  $\sigma_{\text{gal}}$  up to 1000 km/s
- Size ( $R_{\text{cluster}}$ ) of several Mpc
- Large Reynolds numbers ( $\Rightarrow$  turbulence)
- Total mass ( $M_{\text{tot}}$ ) up to several  $10^{15} M_{\odot}$  ( $\Rightarrow$  dark matter)
- Nearly cosmic baryon fraction ( $\approx 95\%$ )
- ICM temperatures ( $T_{\text{ICM}}$ ) higher than 10<sup>8</sup>K

Observed to be virialized:

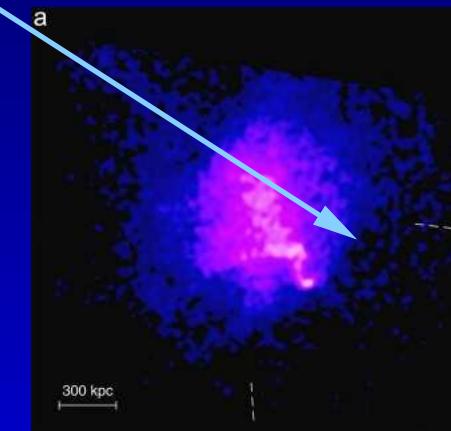
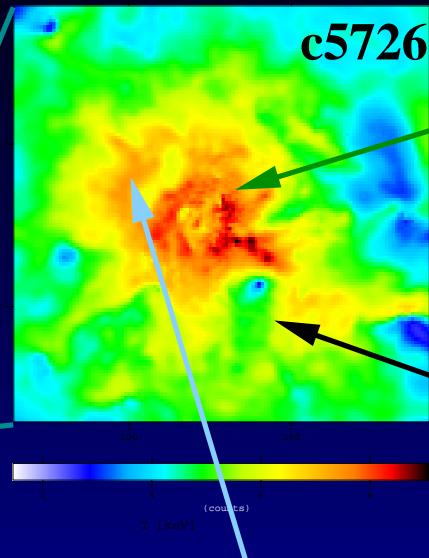
$$3\sigma_{\text{galaxies}}^2 \approx \frac{GM_{\text{tot}}}{R_{\text{cluster}}} \approx \frac{3kT_{\text{ICM}}}{2\mu m_p}$$



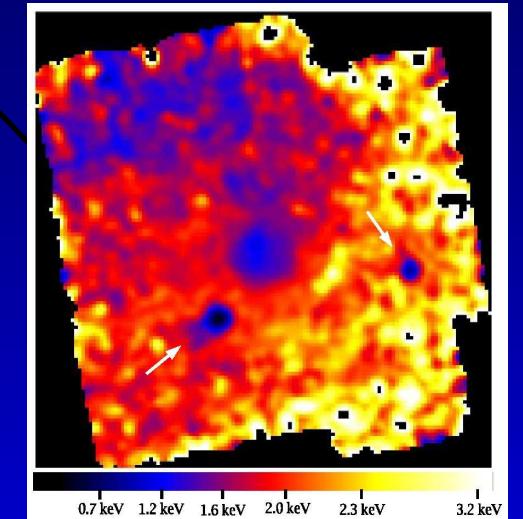
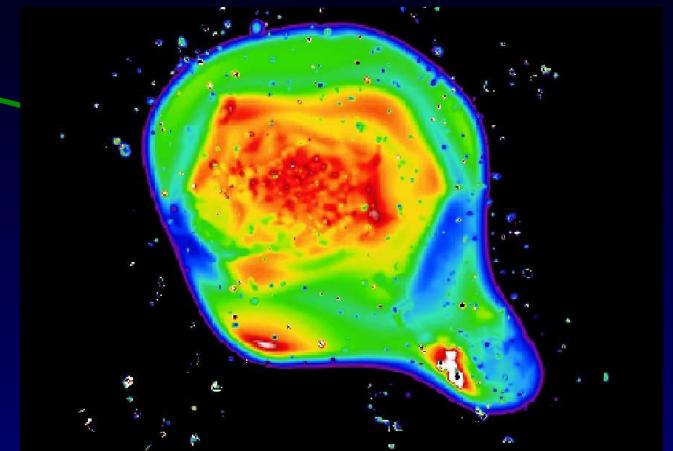
# Structure Formation



Simulation (Borgani et al. 2004)



A520 (Markevitch et al. 2005)

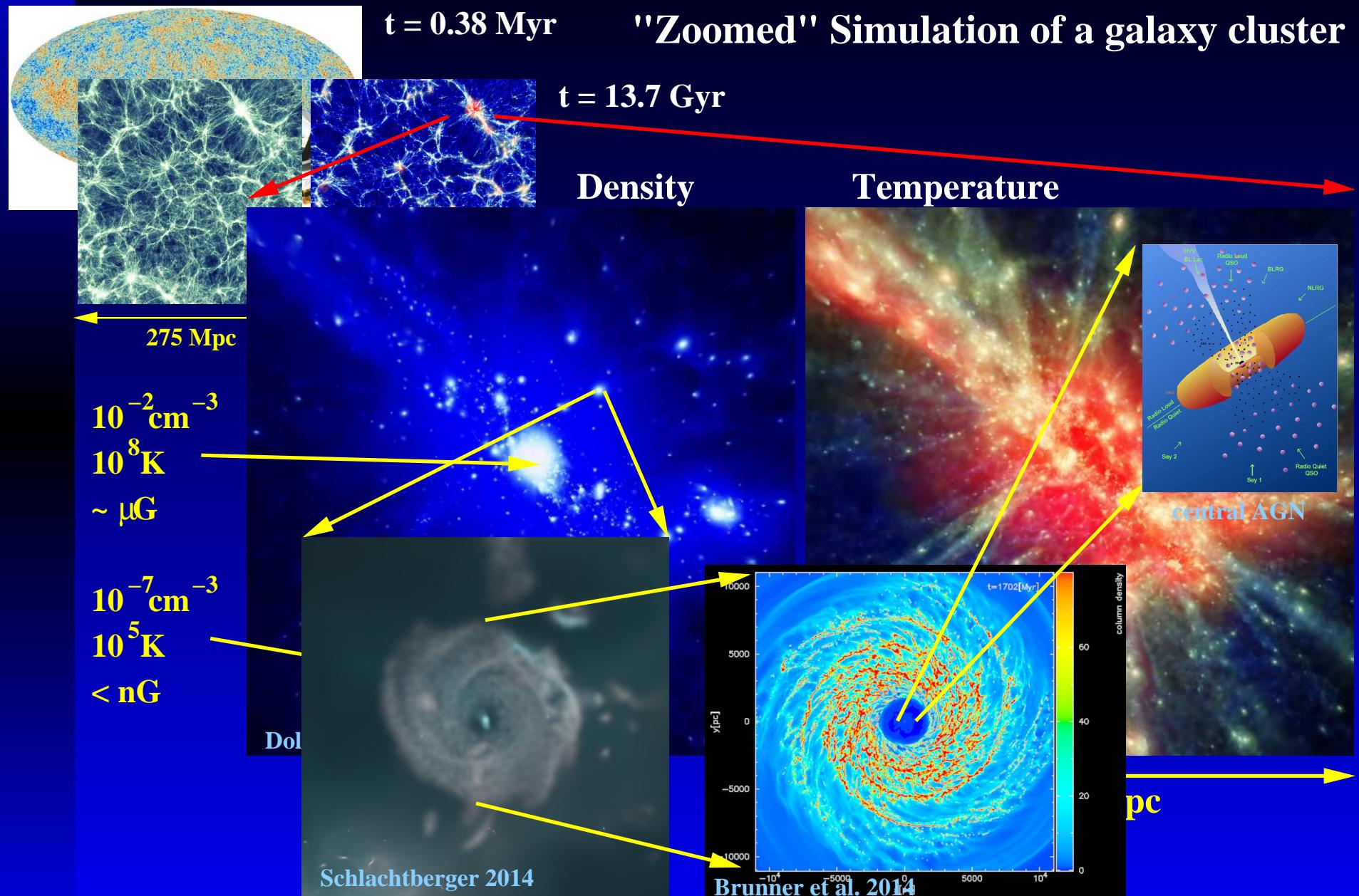


Fornax (Scharf et al. 2004)

Interplay between dynamics, environment and evolution.  
⇒ Effects of environment directly observable.

# Simulating the Universe

# Simulating the Universe

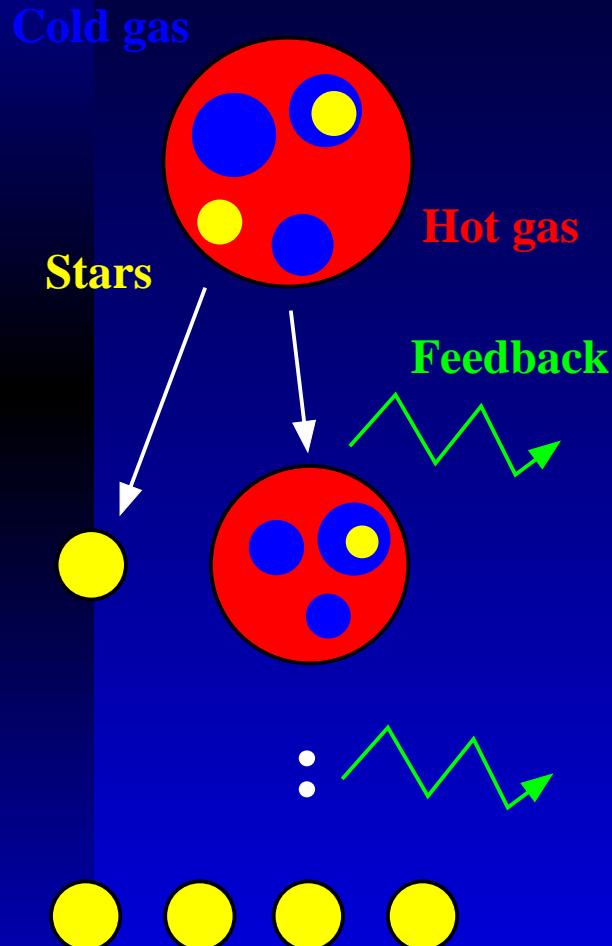


Need to capture processes happening far below the resolution !

# Simulating the Universe

## Multi phase model (sub-scale)

Springel & Hernquist 2002



Star formation

$$\frac{d\rho_*}{dt} = (1 - \beta) \frac{\rho_c}{t_*}$$

supernova mass fraction

star formation timescale

Cloud evaporation

$$\left. \frac{d\rho_h}{dt} \right|_{\text{evap}} = A \beta \frac{\rho_c}{t_*}$$

cloud evaporation parameter

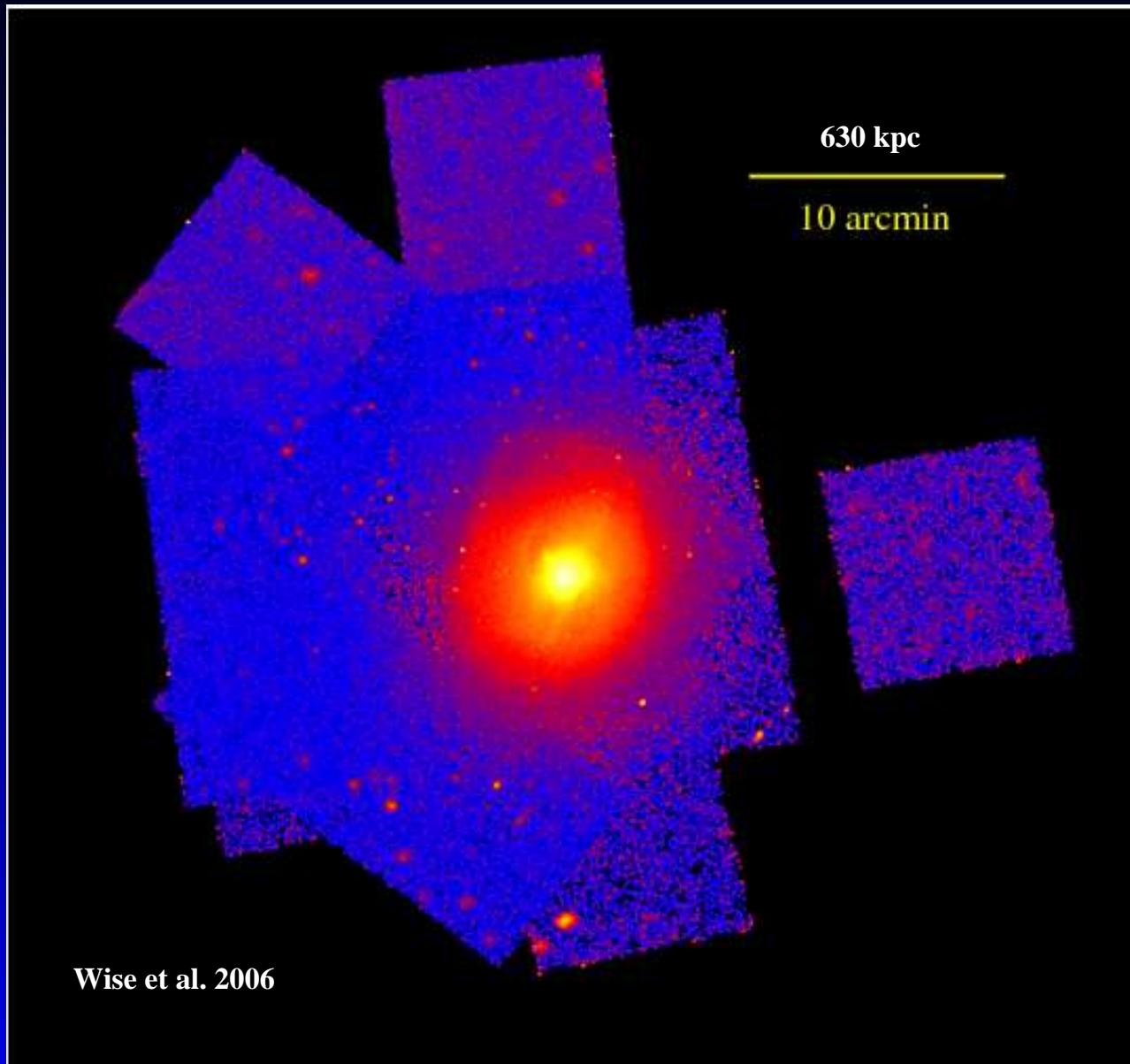
Growth of clouds

$$\left. \frac{d\rho_c}{dt} \right|_{\text{TI}} = - \left. \frac{d\rho_h}{dt} \right|_{\text{TI}} = \frac{\Lambda_{\text{net}}(\rho_h, u_h)}{u_h - u_c}$$

cooling function

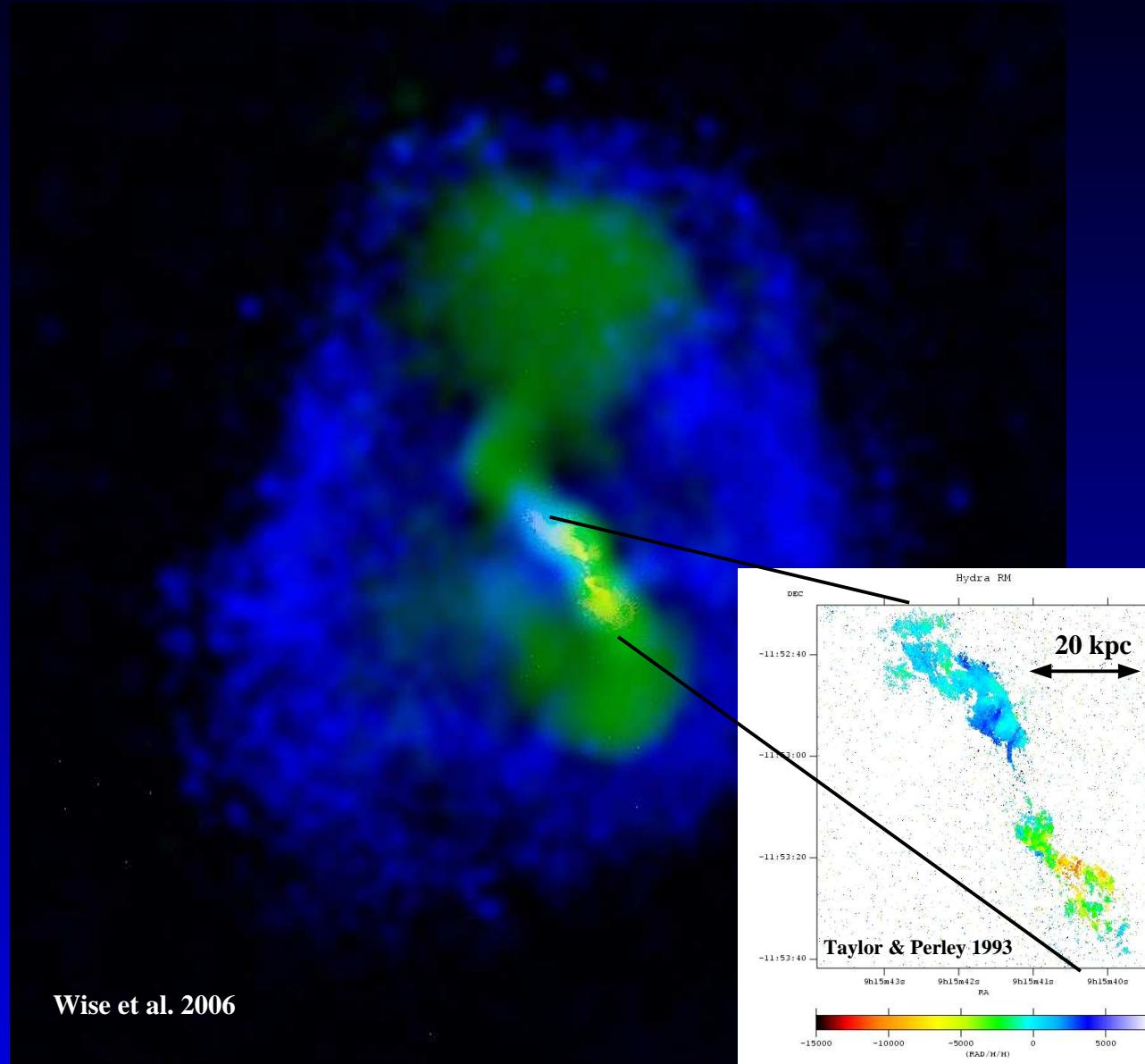
Sub-scale model for star-formation:  
gas particle ( $m = 10^9 M_\odot$ ) = star formation region  
start particle ( $m = 10^8 M_\odot$ ) = star cluster

# Simulating the Universe



Chandra X-ray image of the Hydra cluster (cool core)  
Simulations: Only cool-core clusters, to massive galaxies.

# Simulating the Universe



Composite image to illustrate the connection between the X-ray cavity (blue) and 330Mhz radio emission (green).

# Simulating the Universe

## BH model (sub-scale)

Springel & Di Matteo 2006

### Seeding

Constant seeding  
Seeding on m-sigma

### Accretion on BH

$\alpha$ -Bondi (Springel & Di Matteo 06)  
 $\beta$ -Bondi (Booth & Schaye 09)

....

### Feedback

Thermal (Springel & Di Matteo 06)  
Bubbles (Sijacki et al. 07)

....

### Merging

Instant merging  
Based on velocity

....

### Growth of BH

$$\dot{M}_B = \alpha \times 4\pi R_B^2 \rho c_s \simeq \frac{4\pi \alpha G^2 M_\bullet^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

$$\dot{M}_\bullet = \min(\dot{M}_B, \dot{M}_{\text{Edd}})$$

gas density

sound speed

### Feedback by BH

$$L_{\text{bol}} = 0.1 \times \dot{M}_\bullet c^2$$

$$\dot{E}_{\text{feedback}} = f \times L_{\text{bol}}$$

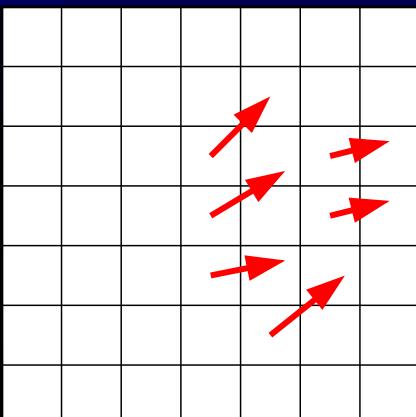
efficiency

Sub-scale model for BH growth:  
Resolution dependence ?  
Various subtle extensions ...

# The Numerical Challenge

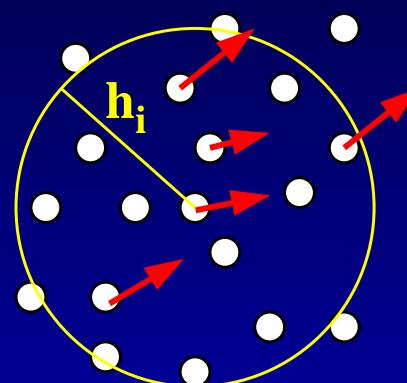
Eulerian

discretized space



Lagrangian

discretized mass



SPH

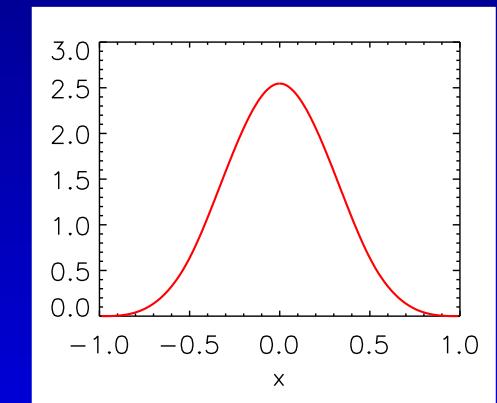
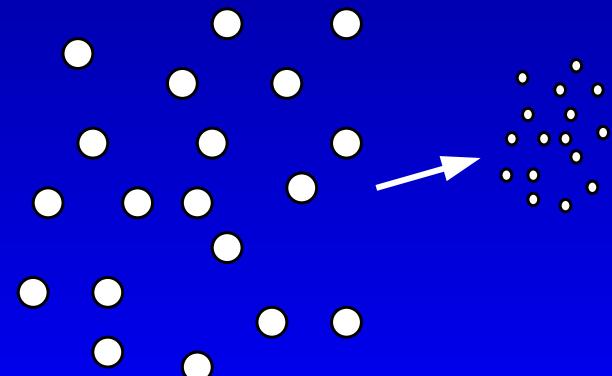
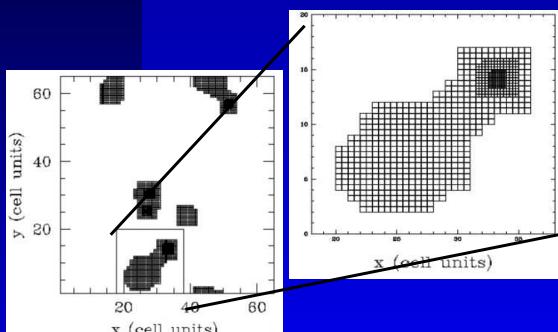
kernel estimate

$$\langle A(\mathbf{r}) \rangle = \int W(\mathbf{r} - \mathbf{r}', h) A(\mathbf{r}') d^3 r'$$

$$d^3 r' \mapsto \frac{m_j}{\rho_j}$$

$$\langle A_i \rangle = \sum_{j=1}^N \frac{m_j}{\rho_j} A_j W(\mathbf{r}_{ij}; h_i)$$

Collapse:



# The Numerical Challenge

$$\frac{d\vec{v}_a}{dt} = - \sum_b m_b \left( f_b^{\text{co}} \frac{P_b}{\rho_b^2} + f_a^{\text{co}} \frac{P_a}{\rho_a^2} + \Pi_{ab} \right) \nabla_a W(\vec{r}_a - \vec{r}_b, h)$$

$$+ \sum_b m_b \left[ \left( \frac{\mathcal{M}_{ij}}{\rho_{ab}^2} \right)_a + \left( \frac{\mathcal{M}_{ij}}{\rho^2} \right)_b \right] \nabla_{a,j} W(\vec{r}_a - \vec{r}_b, h)$$

$$- \sum_b \frac{m_b}{(|\vec{r}_a - \vec{r}_b|^2 + \epsilon_a^2)^{1.5}} (\vec{r}_a - \vec{r}_i)$$

$$\frac{dA_a}{dt} = \frac{1}{2} \frac{\gamma - 1}{\rho_a^{\gamma-1}} \sum_b m_b \Pi_{ab} \vec{v}_{ab} \cdot \nabla_a \bar{W}_{ab}$$

$$+ \frac{2\mu}{k_B} \frac{\gamma - 1}{\rho_a^{\gamma-1}} \sum_b \frac{m_b}{\rho_a \rho_b} \frac{4\kappa_a \kappa_b}{\kappa_a + \kappa_b} \left( \frac{A_b}{\rho_b^{\gamma-1}} - \frac{A_a}{\rho_a^{\gamma-1}} \right) \frac{\nabla_a W(\vec{r}_a - \vec{r}_b, h)}{(x_a - x_b)^2}$$

$$- \frac{\eta_m(\gamma - 1)}{2\mu_0 \rho_a^{\gamma-1}} \sum_b \frac{m_b}{\rho_{ab}^2} (\vec{B}_a - \vec{B}_b)^2 \nabla_a W(\vec{r}_a - \vec{r}_b, h)$$

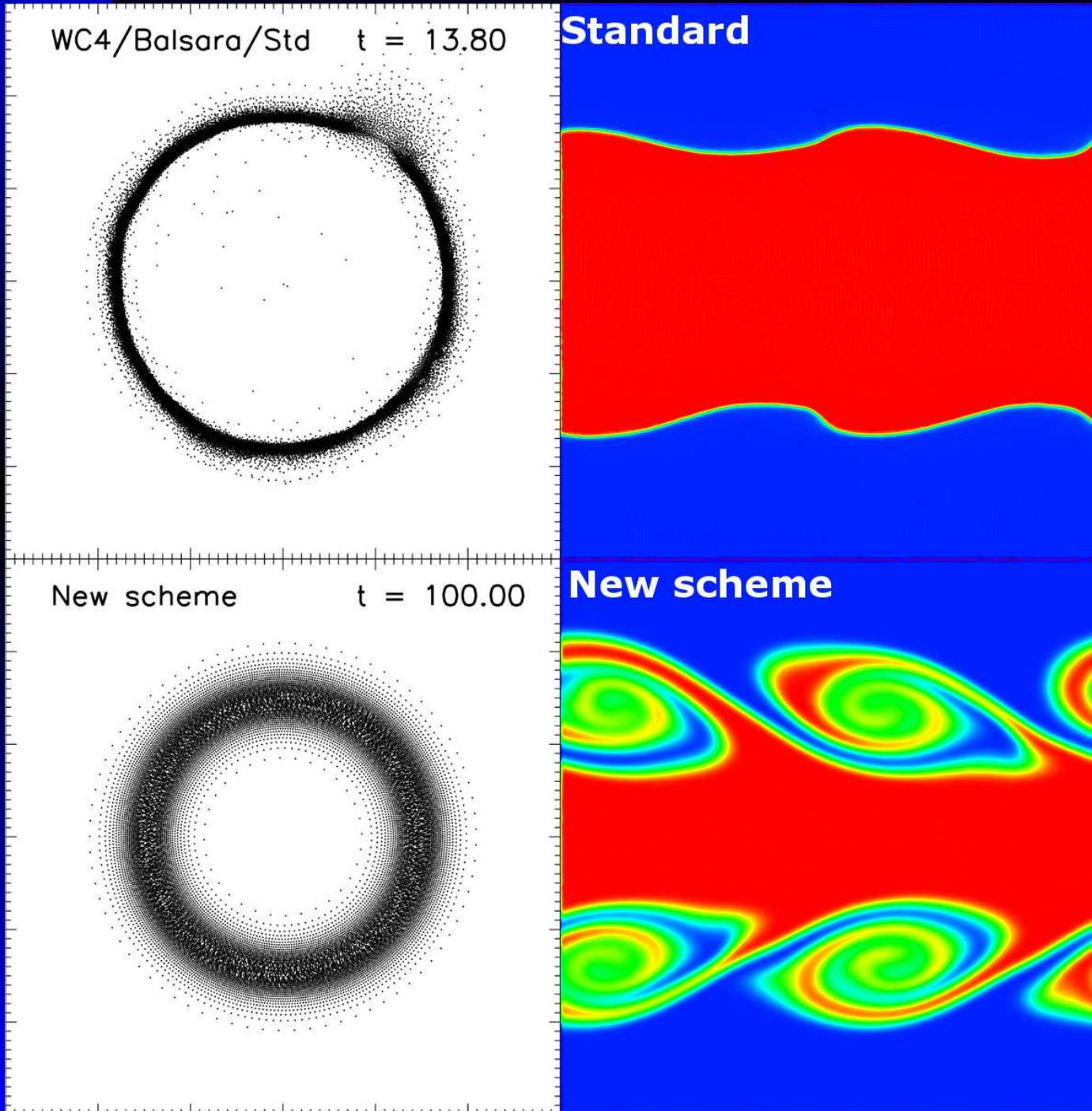
$$- \Lambda(T, \vec{z}) + \epsilon_{\text{SN}} + \epsilon_{\text{AGN}}$$

$$\frac{d\vec{B}_{a,j}}{dt} = \frac{f_i^{\text{co}}}{\rho_a} \sum_b m_b (\vec{B}_{a,j} \vec{v}_{ab} - \vec{v}_{ab,j} \vec{B}_a) \nabla_a W(\vec{r}_a - \vec{r}_b, h)$$

$$+ \eta_m \rho_a \sum_b \frac{m_b}{\rho_{ab}^2} (\vec{B}_a - \vec{B}_b) \nabla_a W(\vec{r}_a - \vec{r}_b, h)$$

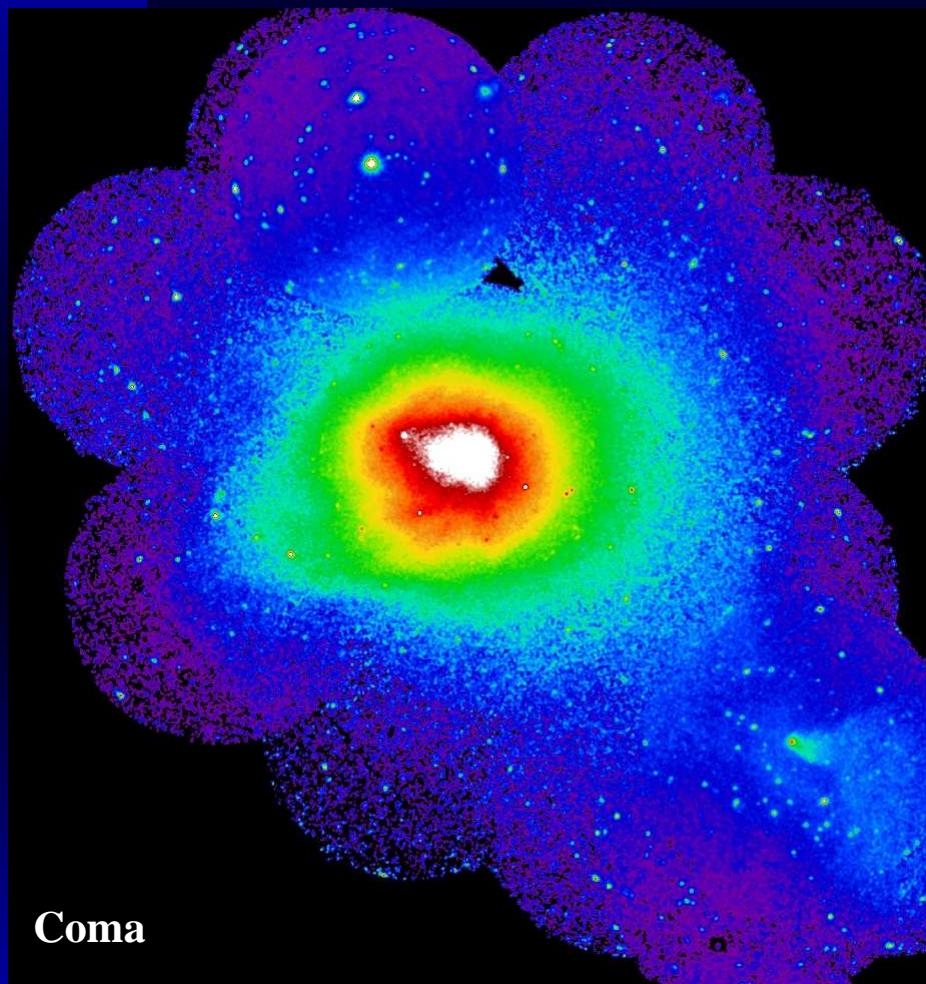
$$+ \frac{\sqrt{N_{\text{SN}} \Delta t}}{\Delta t} B_{SN} \left( \frac{r_{\text{SN}}}{r_{\text{SB}}} \right)^2 \left( \frac{r_{\text{SB}}}{r_{\text{inj}}} \right)^3 e_B$$

# The Numerical Challenge

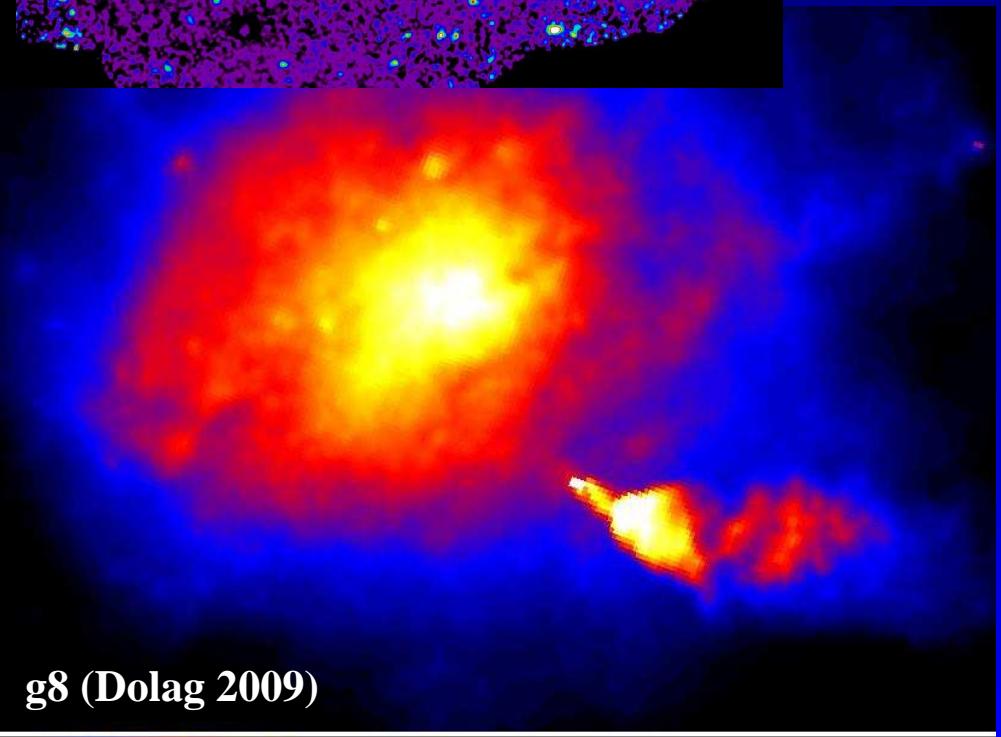
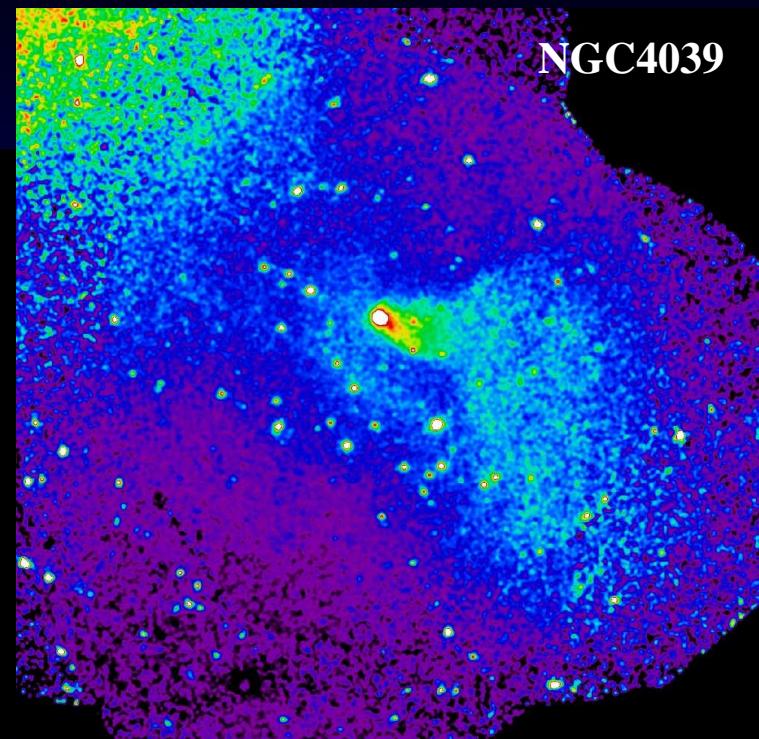


Wendland WC6 Kernel  
Viscosity treatment  
Thermal Mixing  
Beck et al., in prep

# The Numerical Challenge

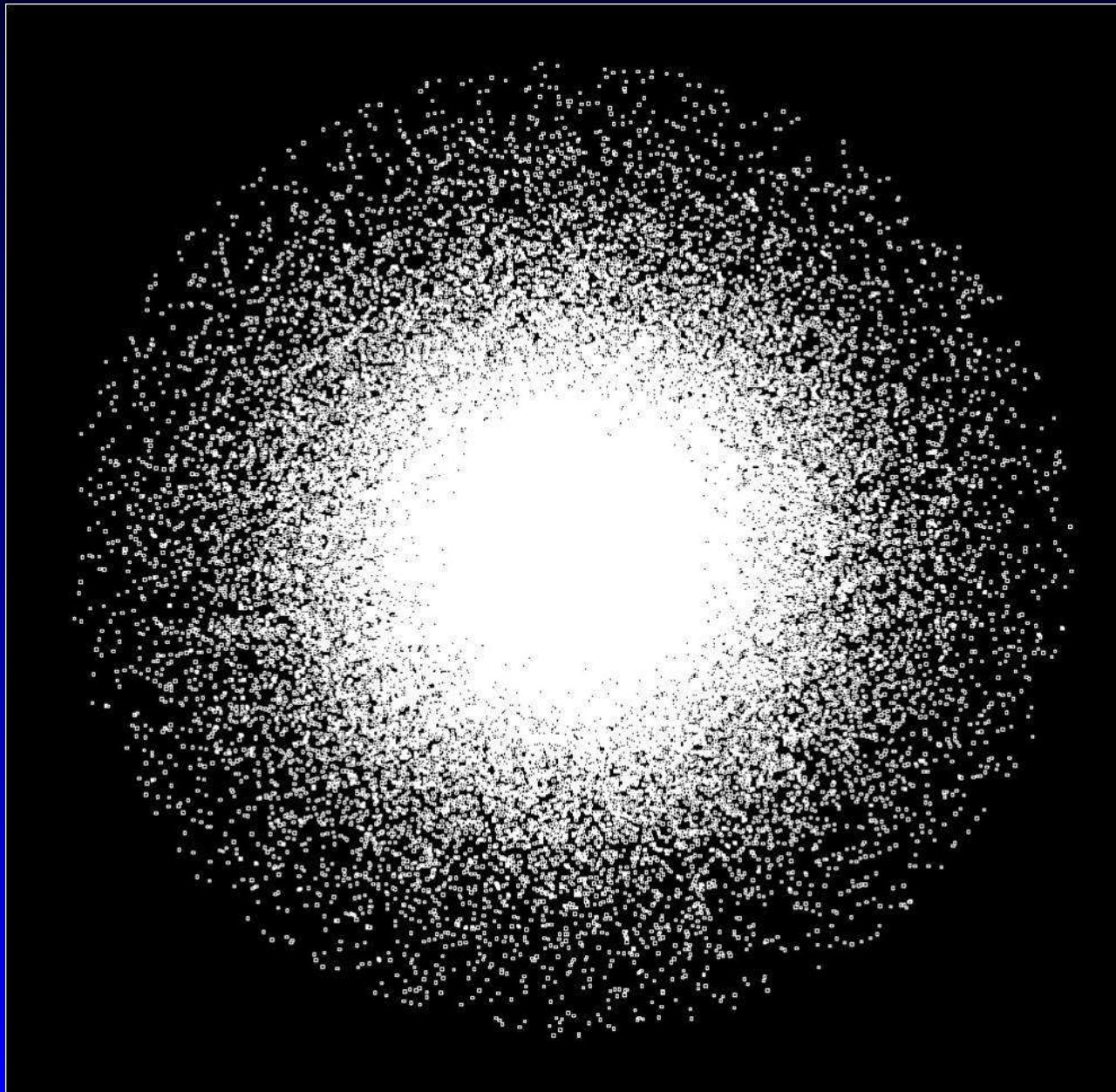


Provided by N. Lyskova & E. Churazov



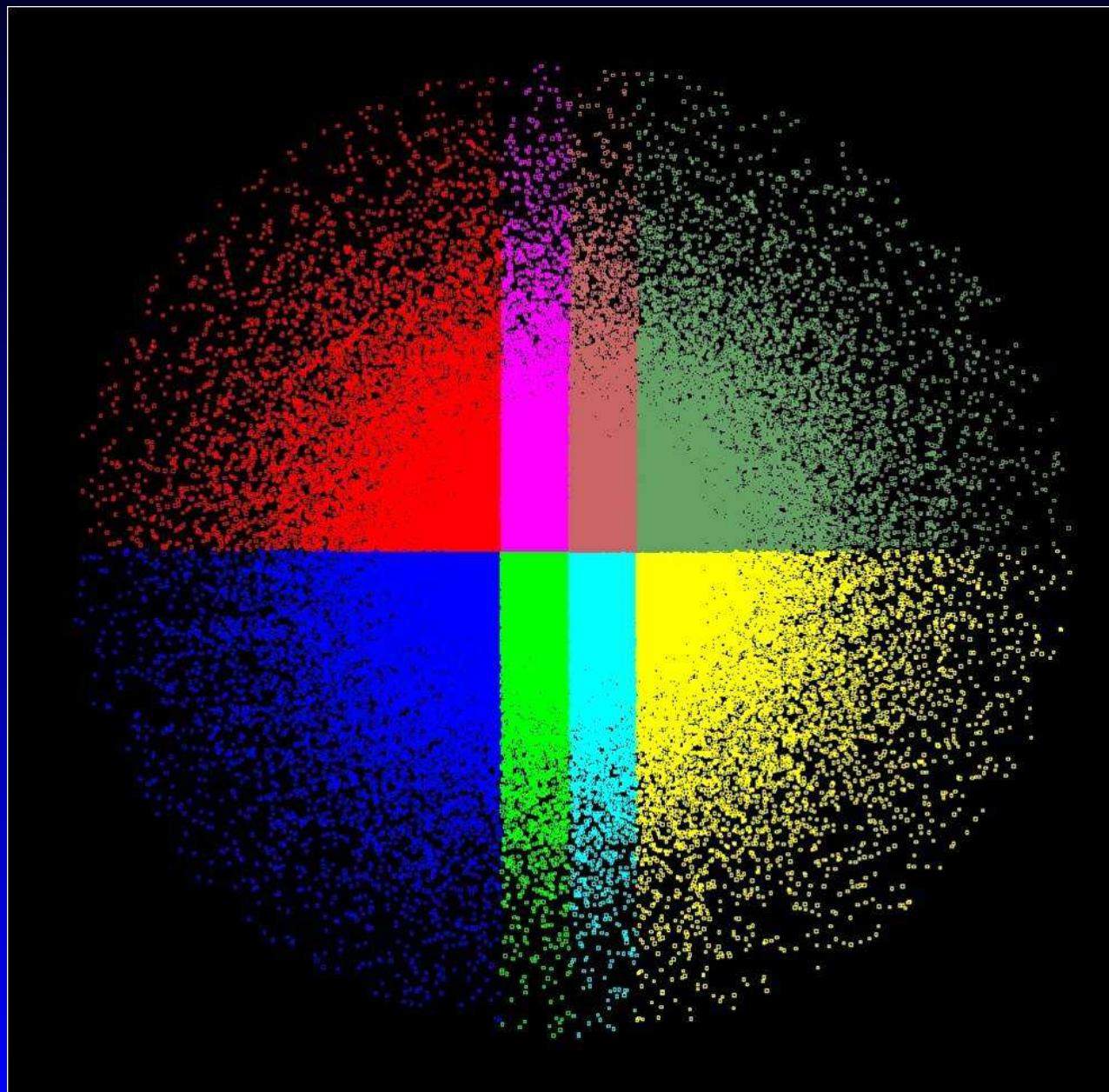
# The Numerical Challenge

## Distributing Work



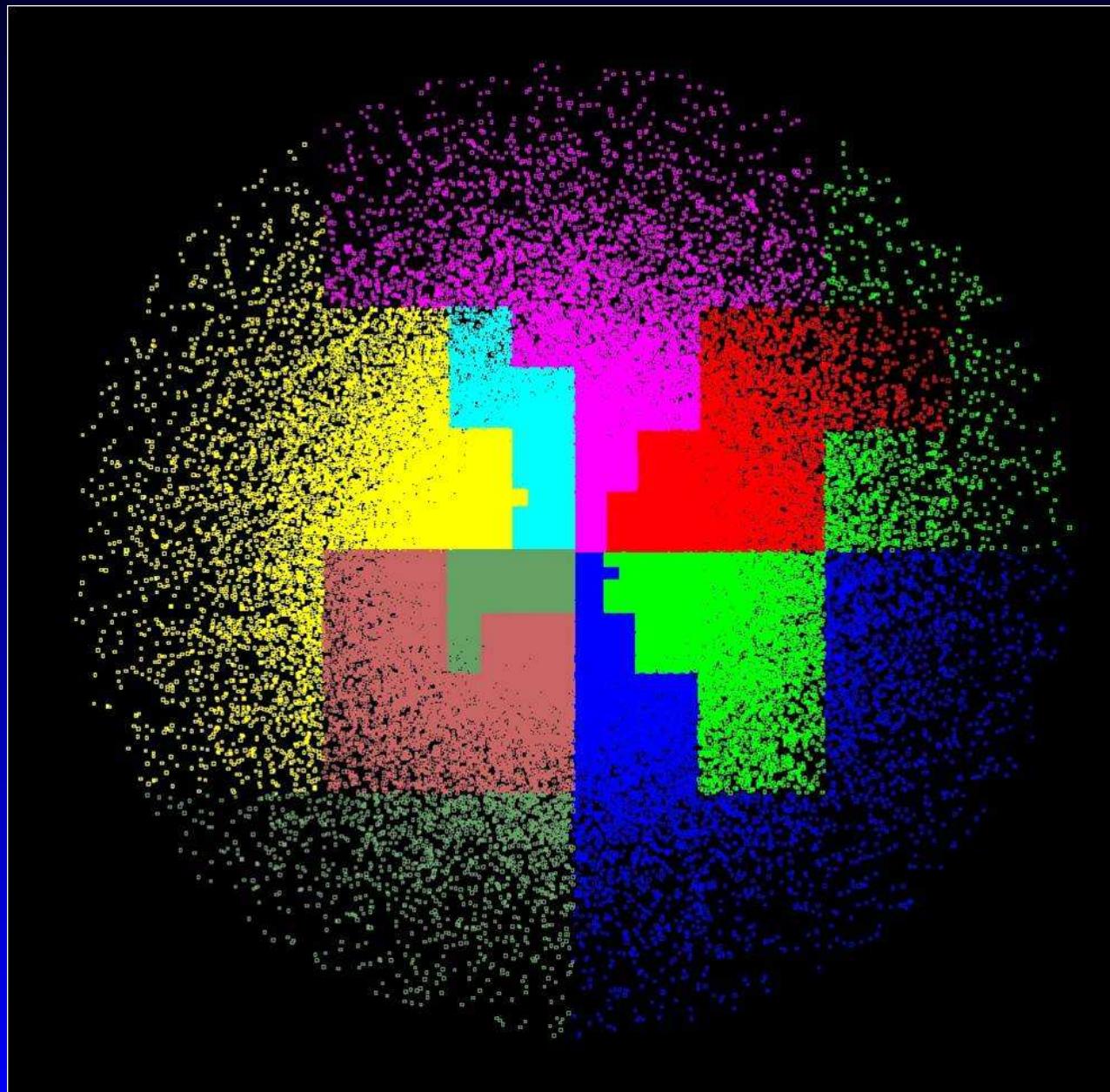
# The Numerical Challenge

Gadget1



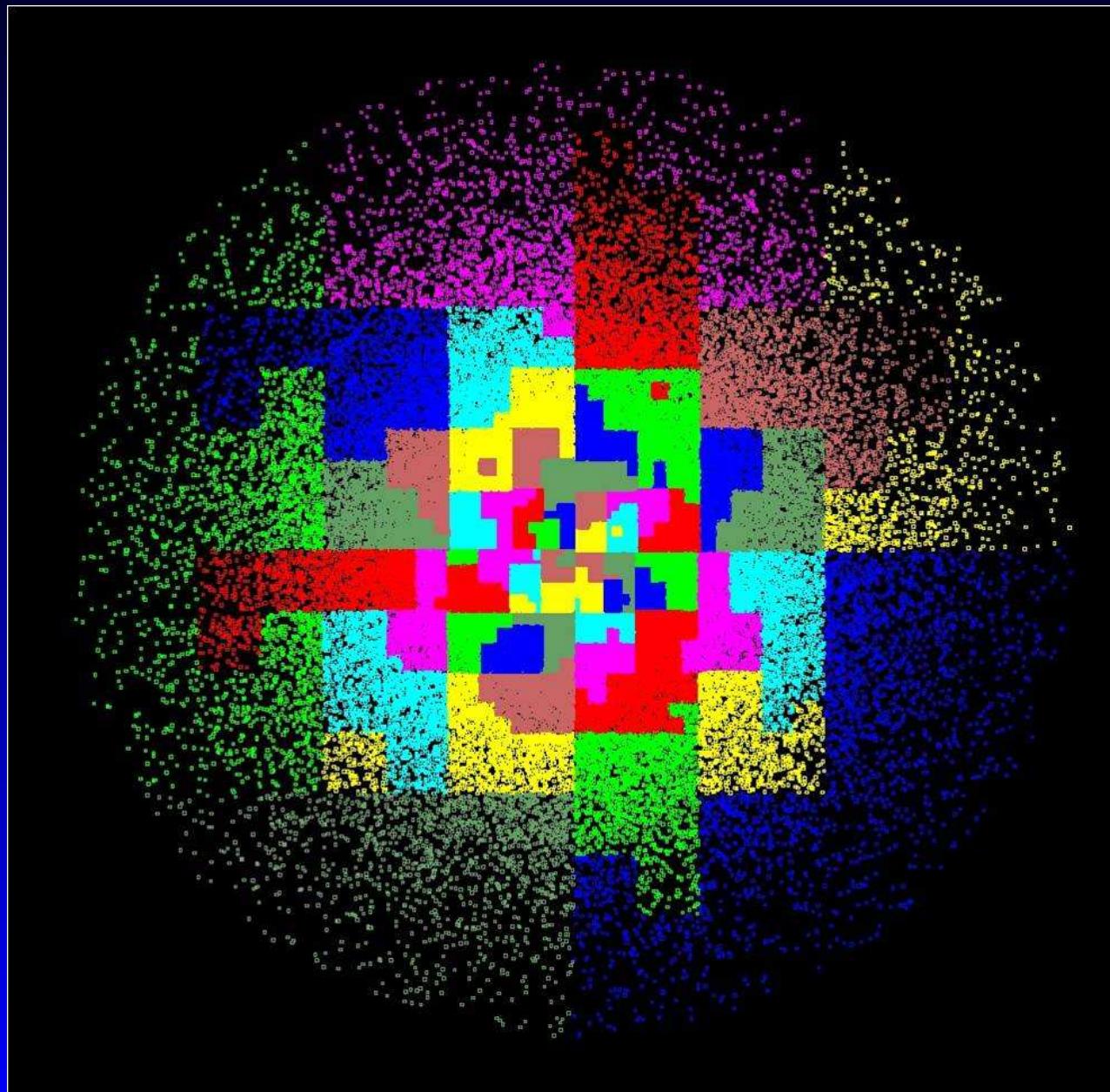
# The Numerical Challenge

Gadget2



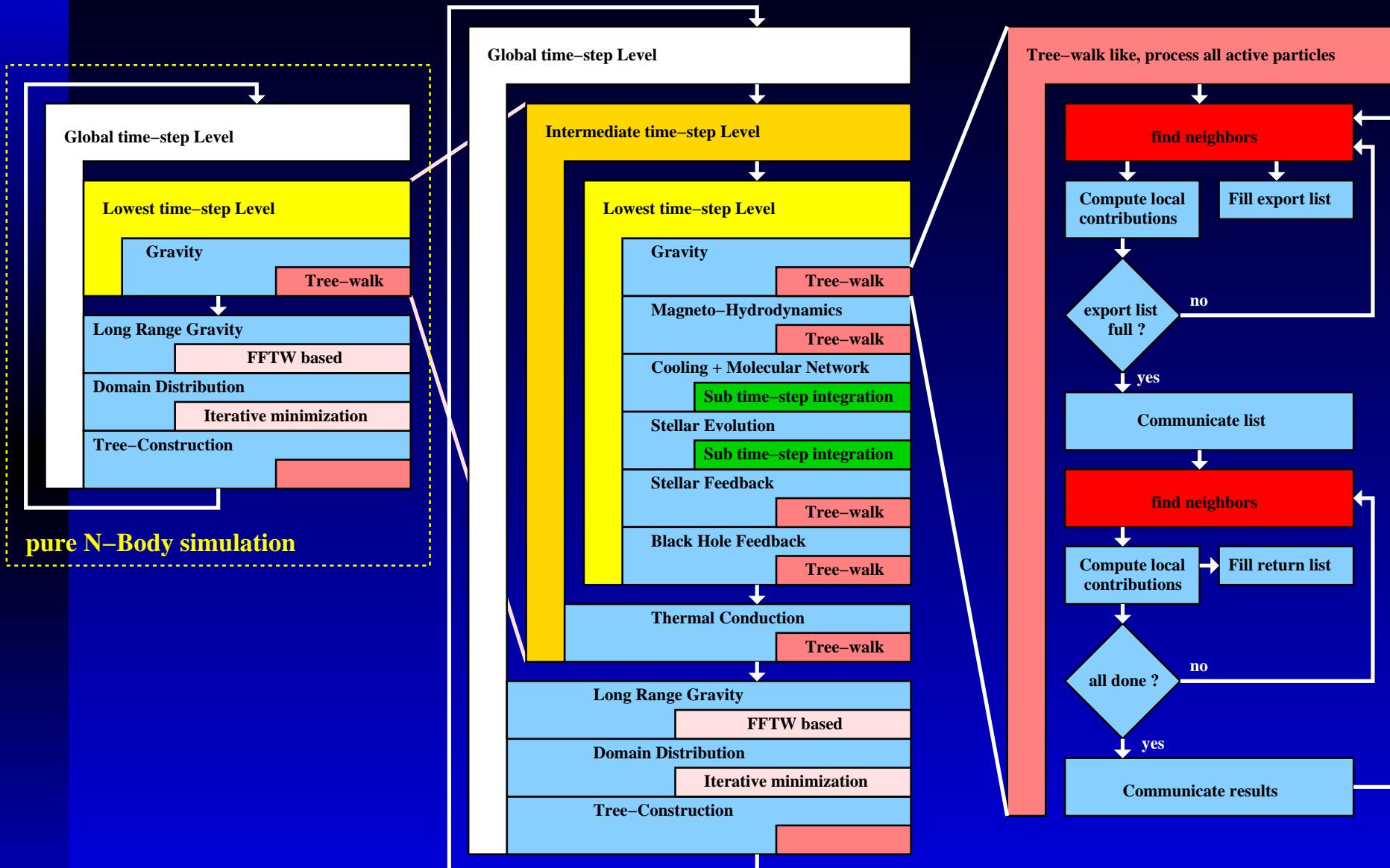
# The Numerical Challenge

Gadget3



# The Numerical Challenge

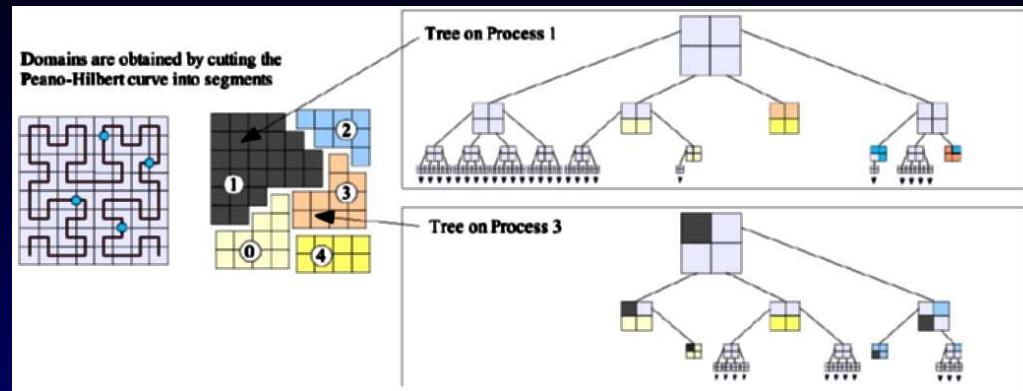
Interplay of different physics modules in Gadget3



- Hydrodynamical simulations have to handle larger and more complex data
- Many more different physical processes using different numerical methods
- Much more challenging to optimize on modern HPC platforms

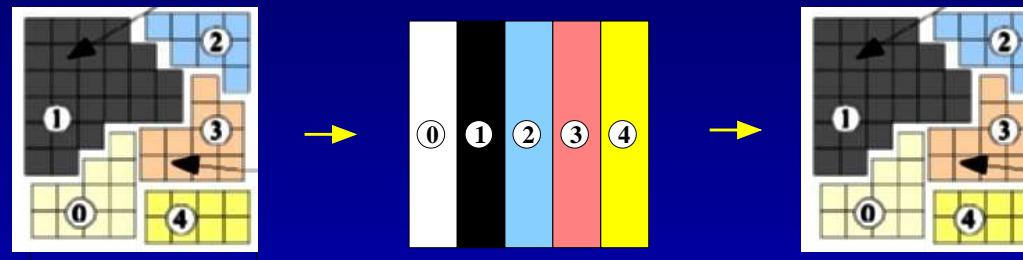
# The Numerical Challenge

- Tree like



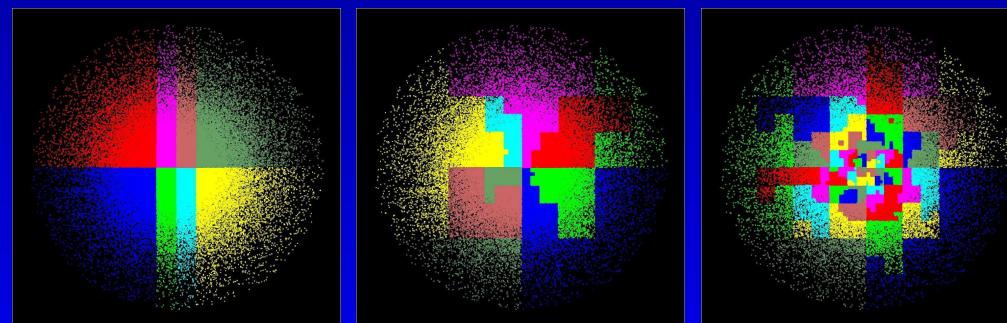
Short range gravity, Hydrodynamics, Transport,  
Star-formation/AGN feedback

- Grid like



Long range gravity (including FFTW)

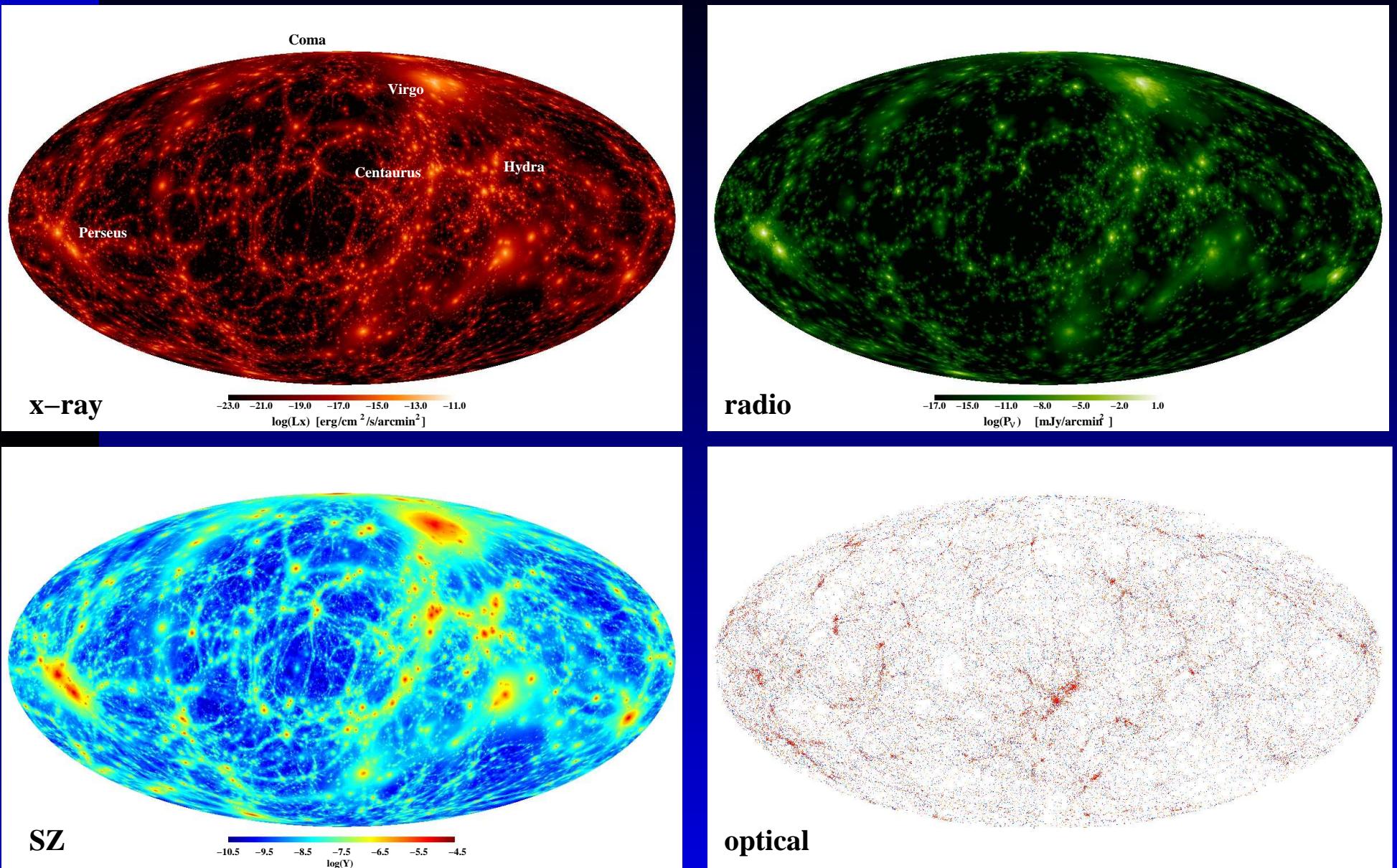
- Work load



- Post processing

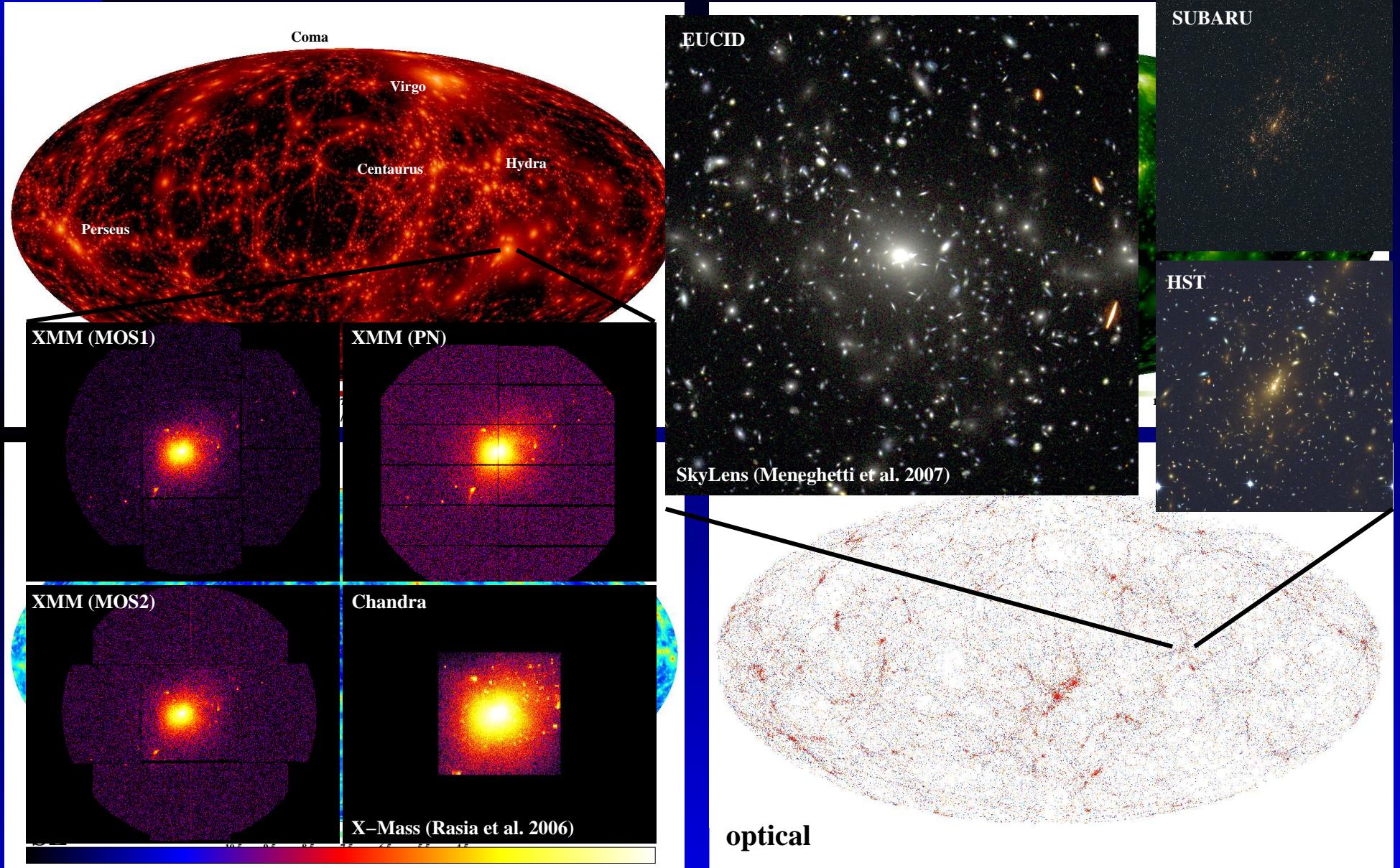
Various different algorithms, all distributed, more complex.

# The Aim



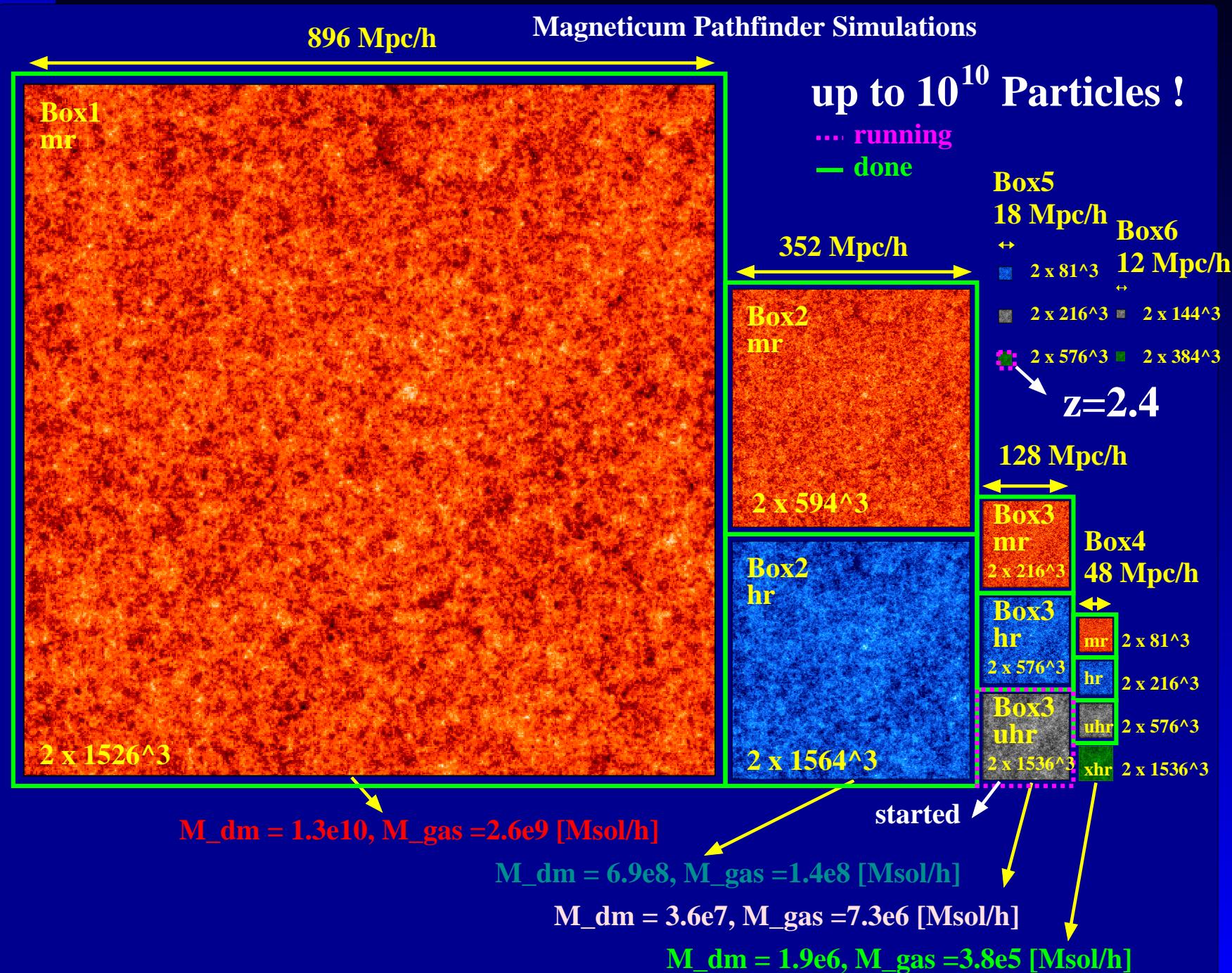
Cosmological, hydrodynamical simulations which at the same time allows predictions for ICM and stellar component for ongoing/future missions (Planck, SPT, LOFAR, eROSITA .,.)

# The Aim

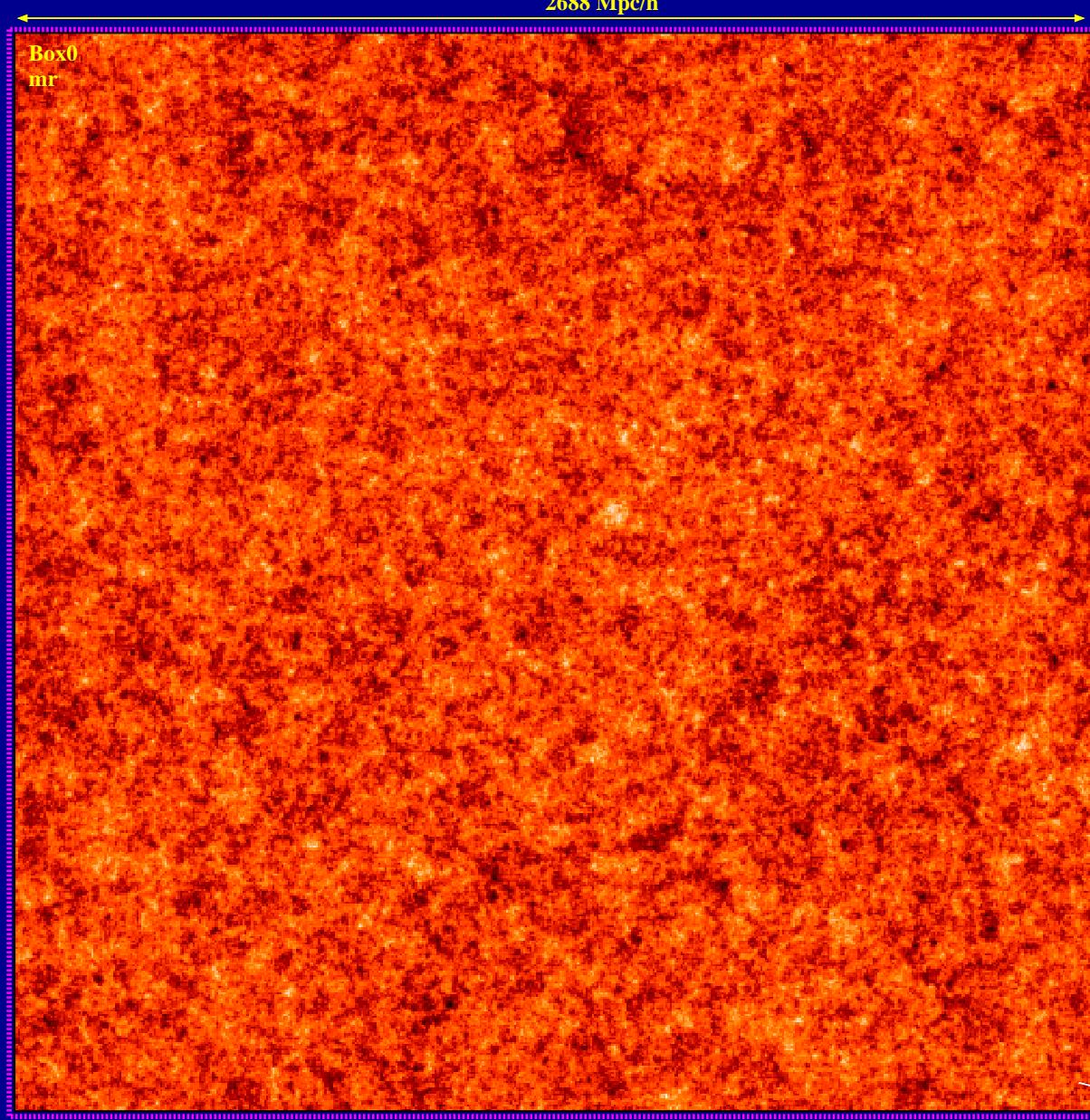


Mock optical/x-ray observations using SkyLens (Meneghetti 2010), X-Mass (Rasia 2007) and Phox (Biffi 2011).

# Magneticum Pathfinder

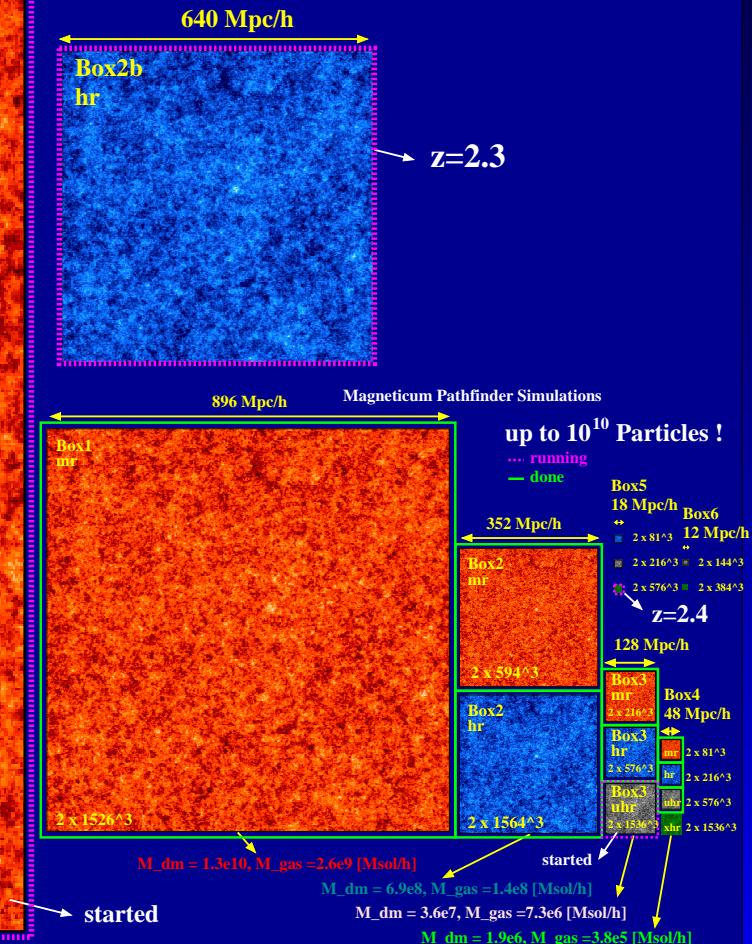


# Magneticum Pathfinder



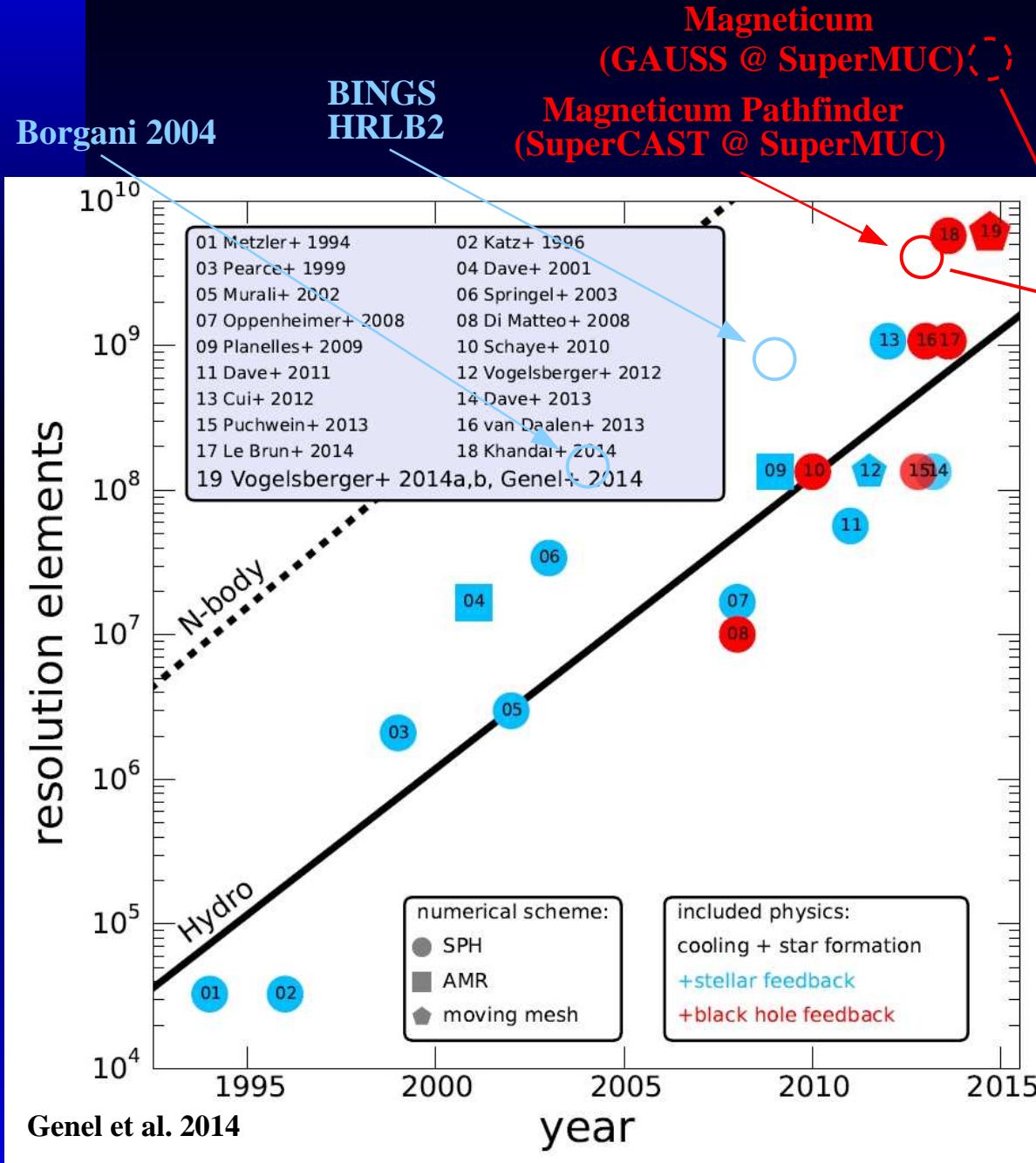
# Magneticum Simulations

up to  $10^{11}$  Particles

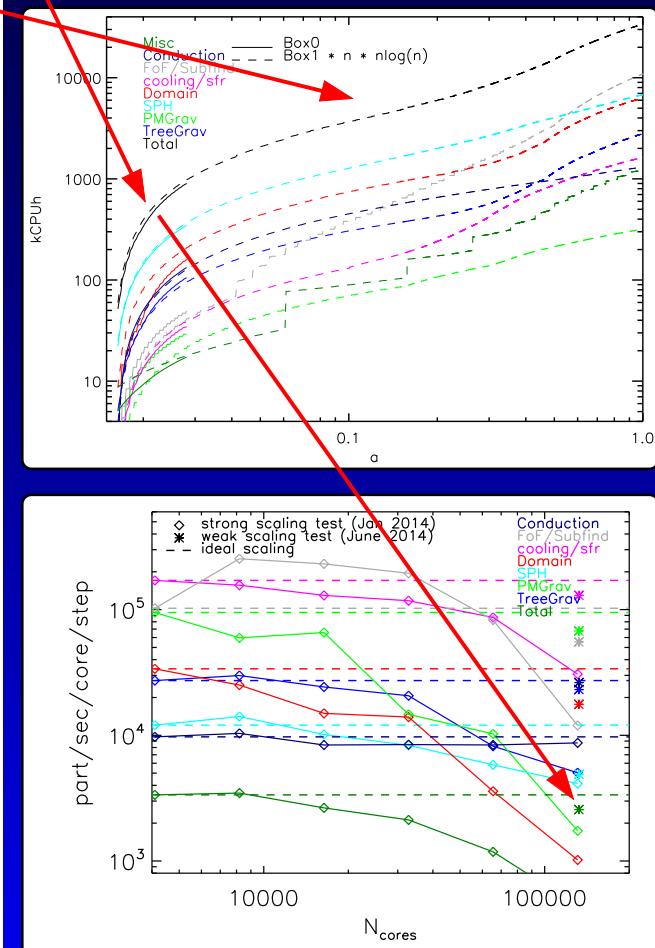


Next generation of Simulations are under way !

# Magneticum Pathfinder



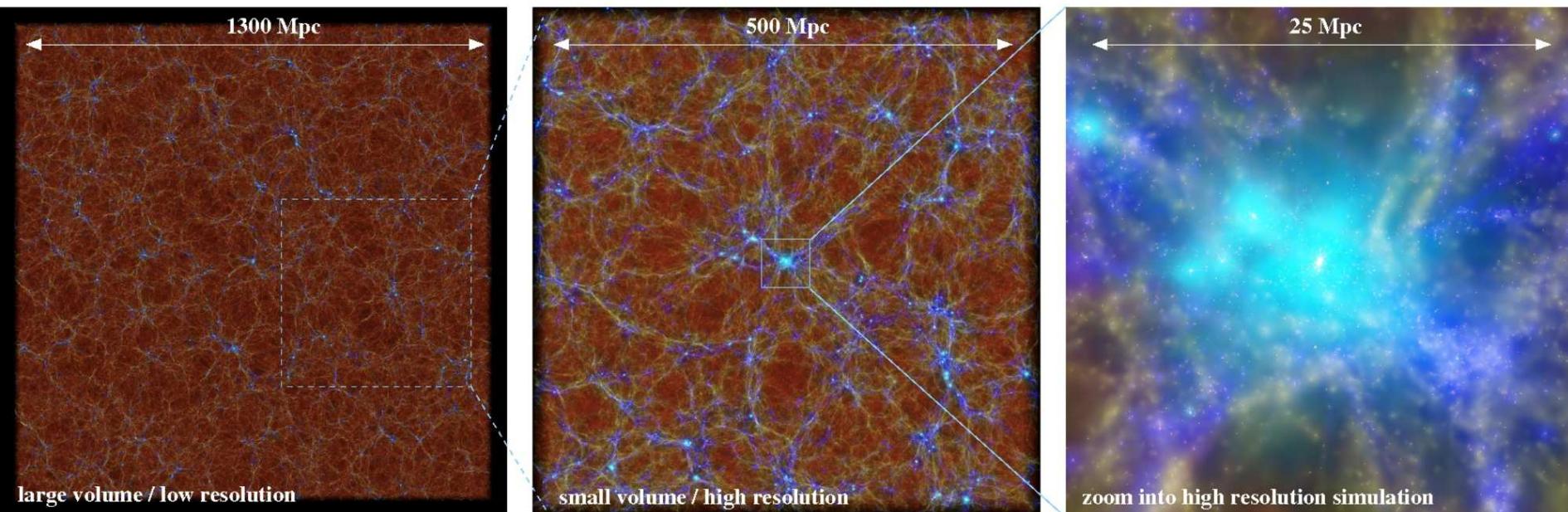
- $2 \times 10^{11}$  Particles !
- running on full SuperMUC
- 16 Islands, 132768 Cores
- 256 TB of Main Memory
- perfect strong scaling !
- using  $8192^3$  grid for FFTW !



Supported by KONWIHR and C<sup>2</sup>PAP

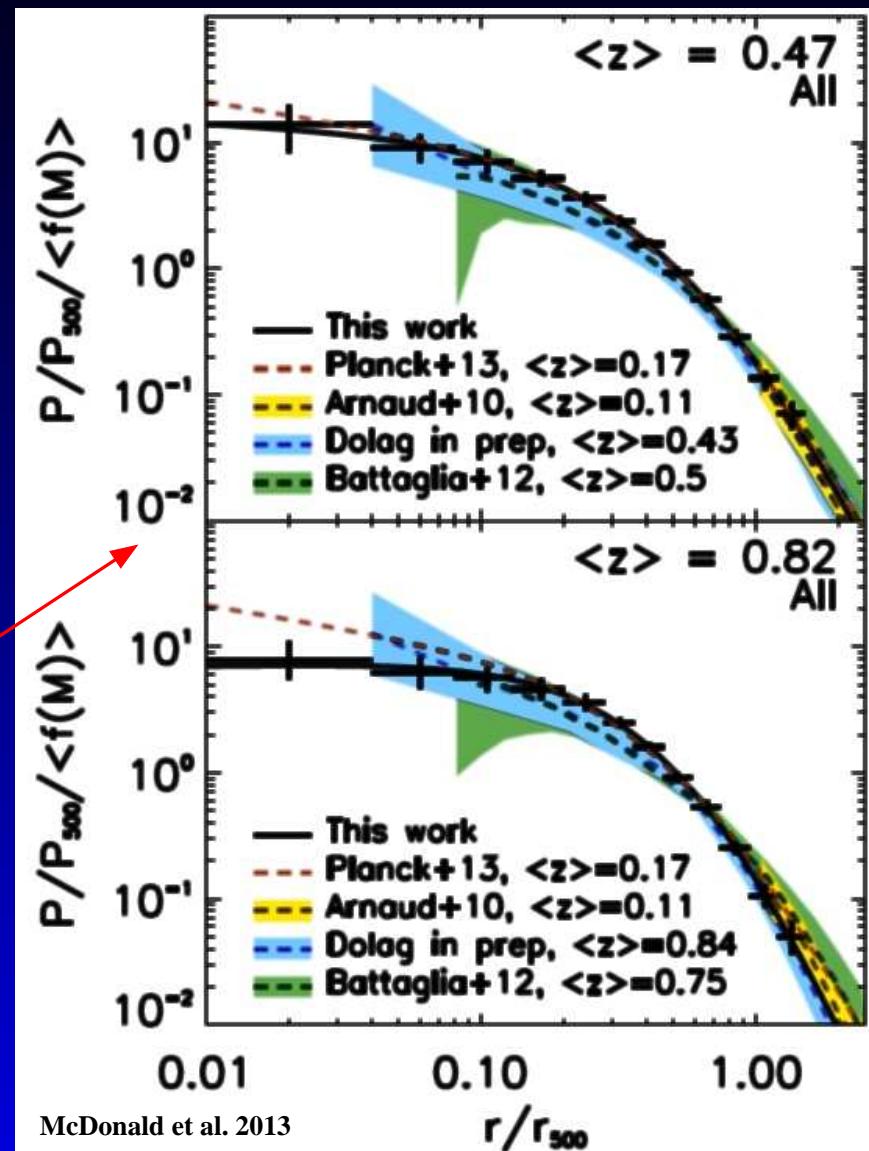
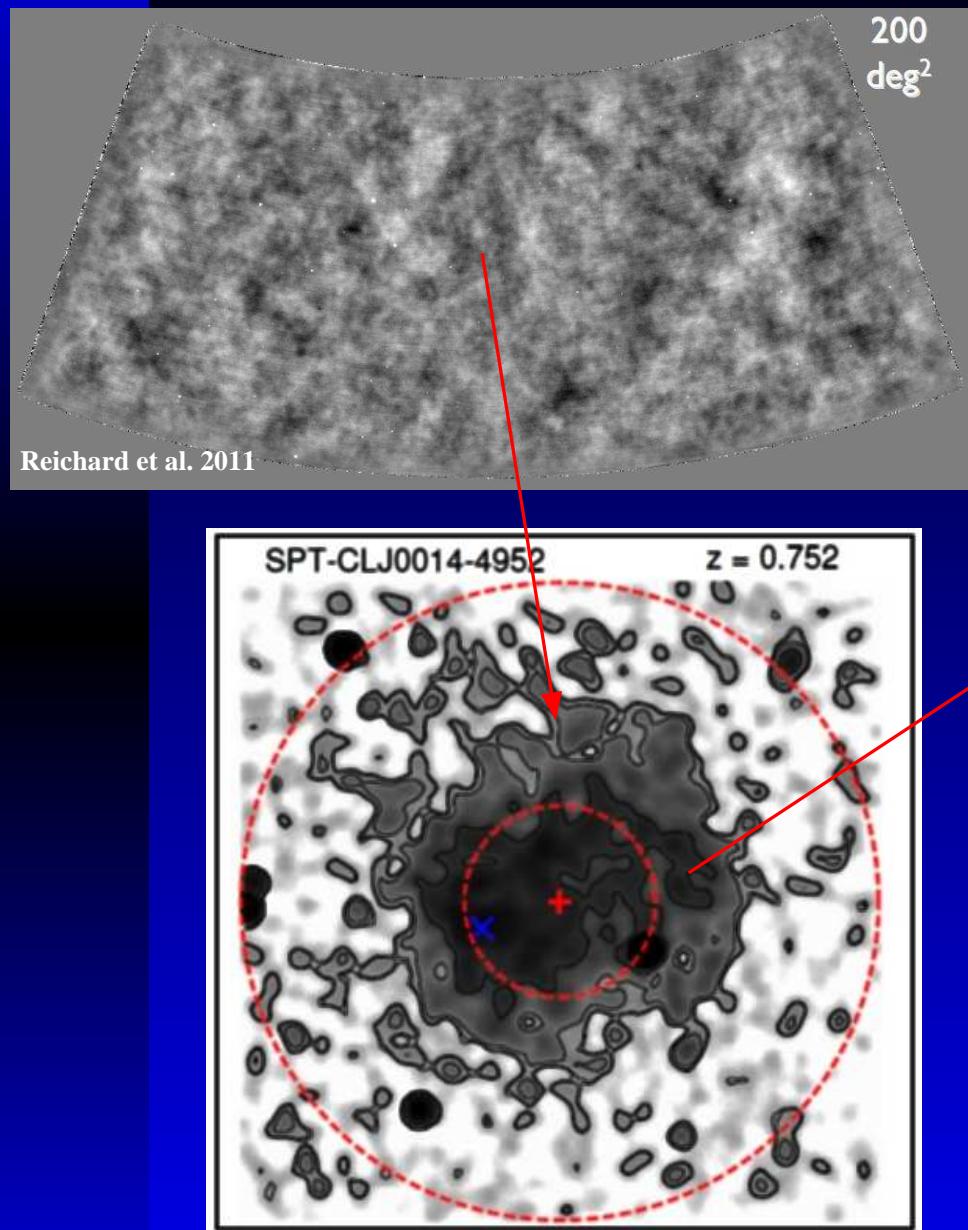
# Magneticum Pathfinder

## Magneticum Pathfinder Simulations



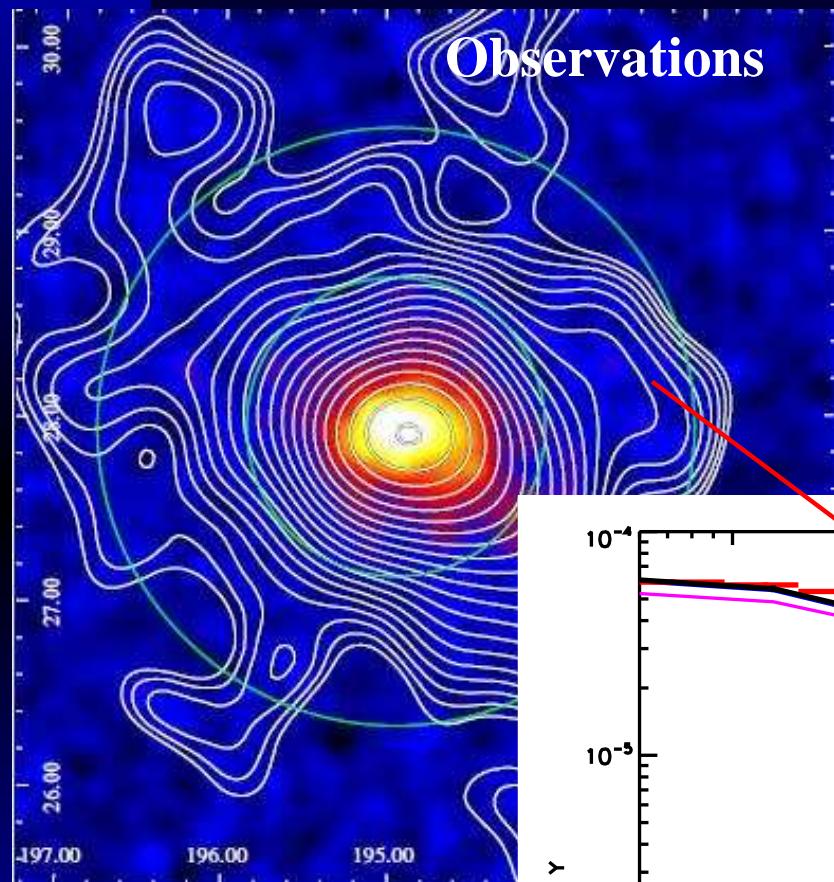
- cooling + star formation + winds Springel & Hernquist 2002/2003
- Metals, Stellar population and chemical enrichment, SN-Ia, SN-II, AGB Tornatore et al. 2003/2006 + new cooling tables Wiersma et al. 2009
- BH and AGN feedback Springel & Di Matteo 2006, Fabjan et al. 2010 + various modifications Hirschmann et al. 2013
- Low viscosity scheme to track turbulence Dolag et al. 2005
- Magnetic Fields (passive) Dolag & Stasyszyn 2009
- Thermal Conduction (1/20th Spitzer) Dolag et al. 2004
- High order SPH Kernels Dehnen et al. 2012
- Galaxy properties (Opt/NIR: u,V,G,r,i,z,Y,J,H,K,L,M; sfr)

# ICM Properties



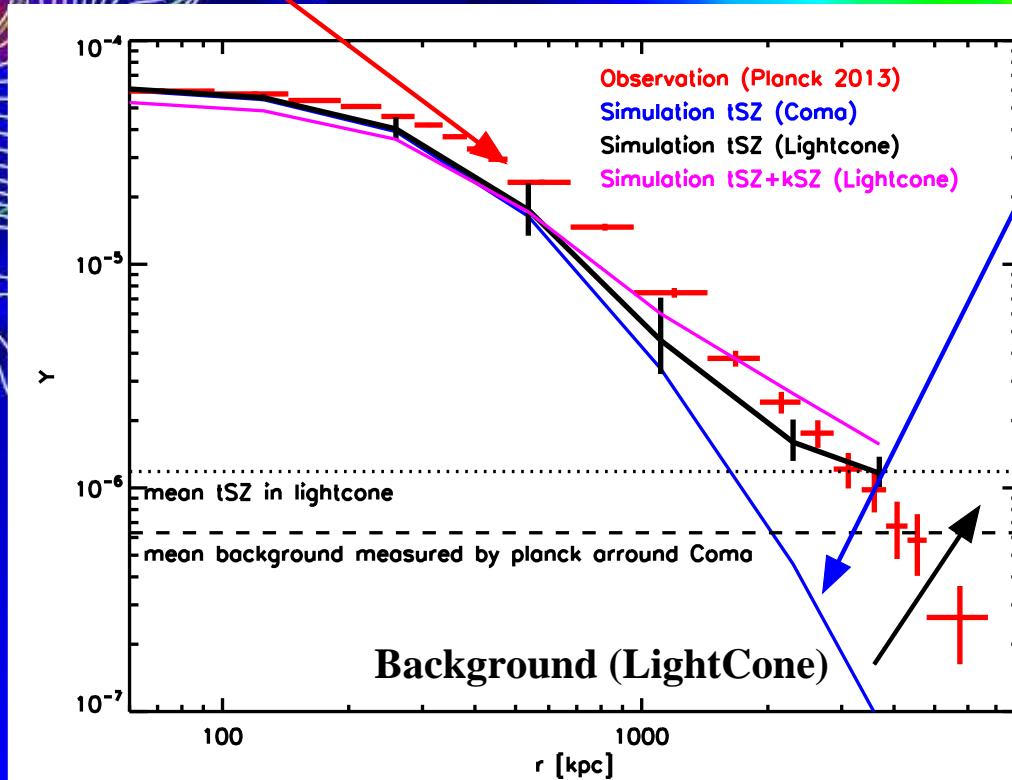
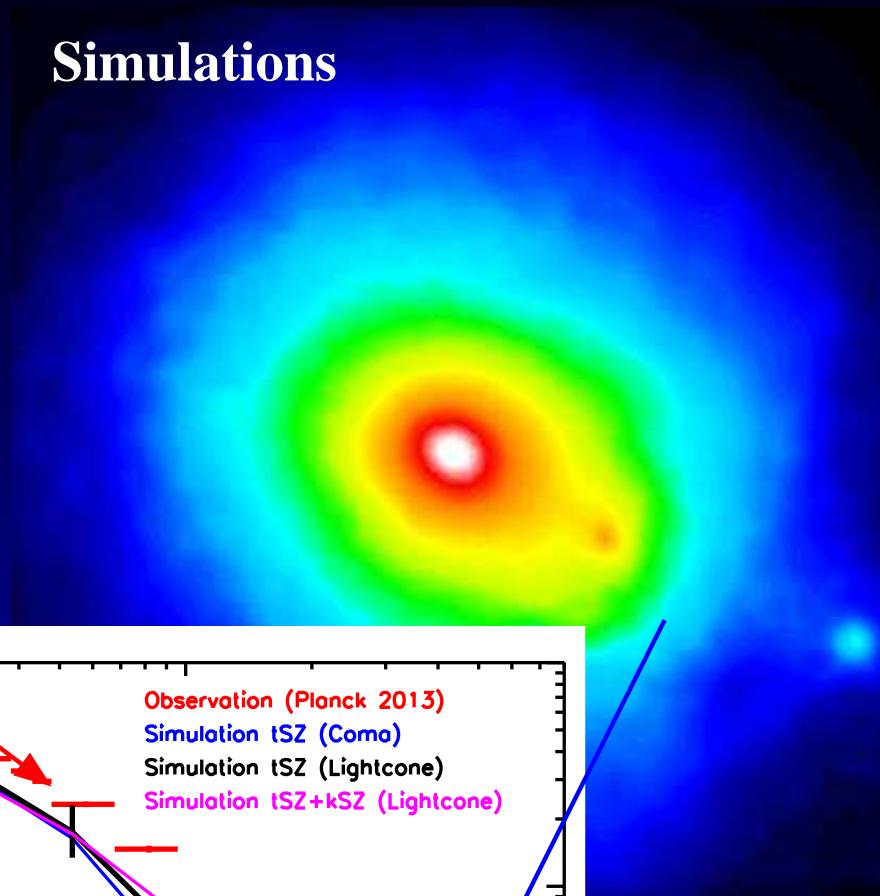
Mean ICM pressure profiles from CMB foreground (SPT).

# ICM Properties

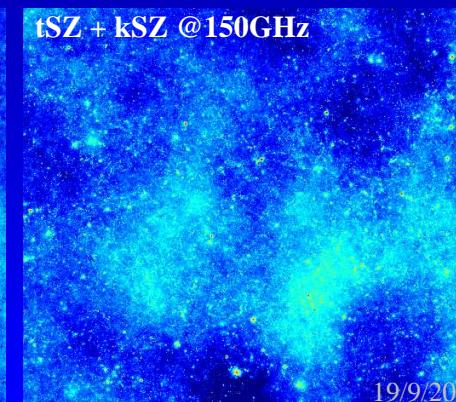
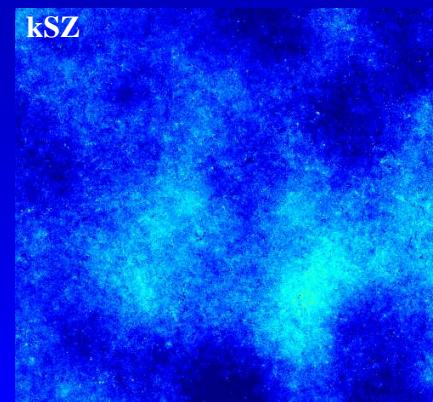
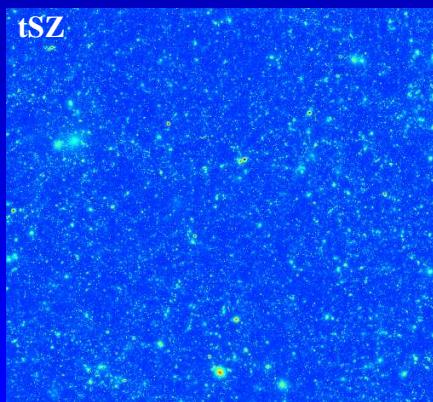
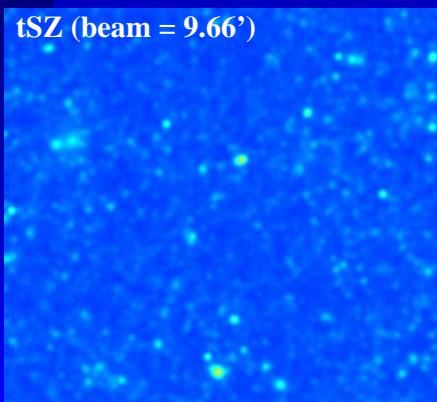
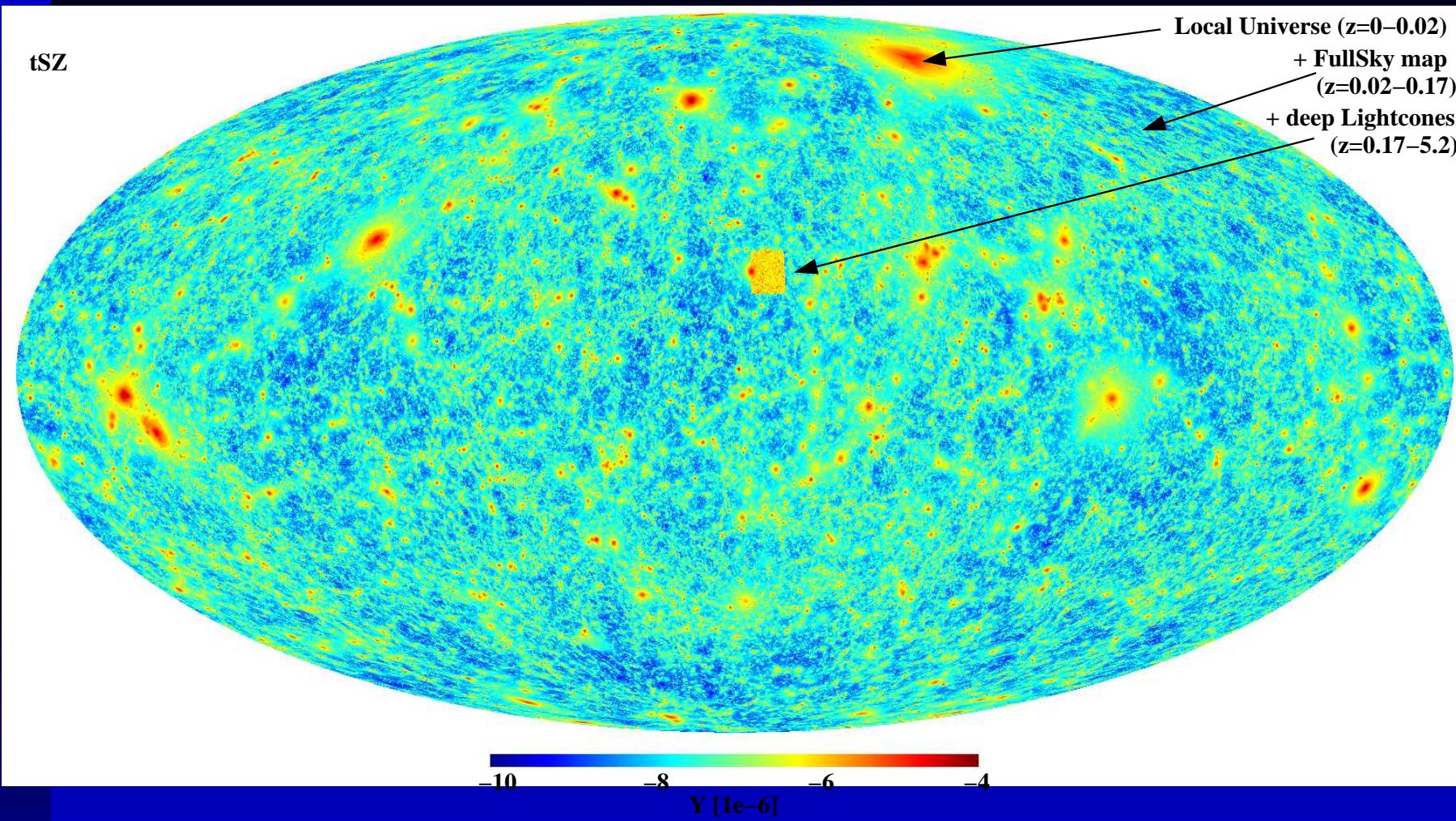


PLANCK 2013

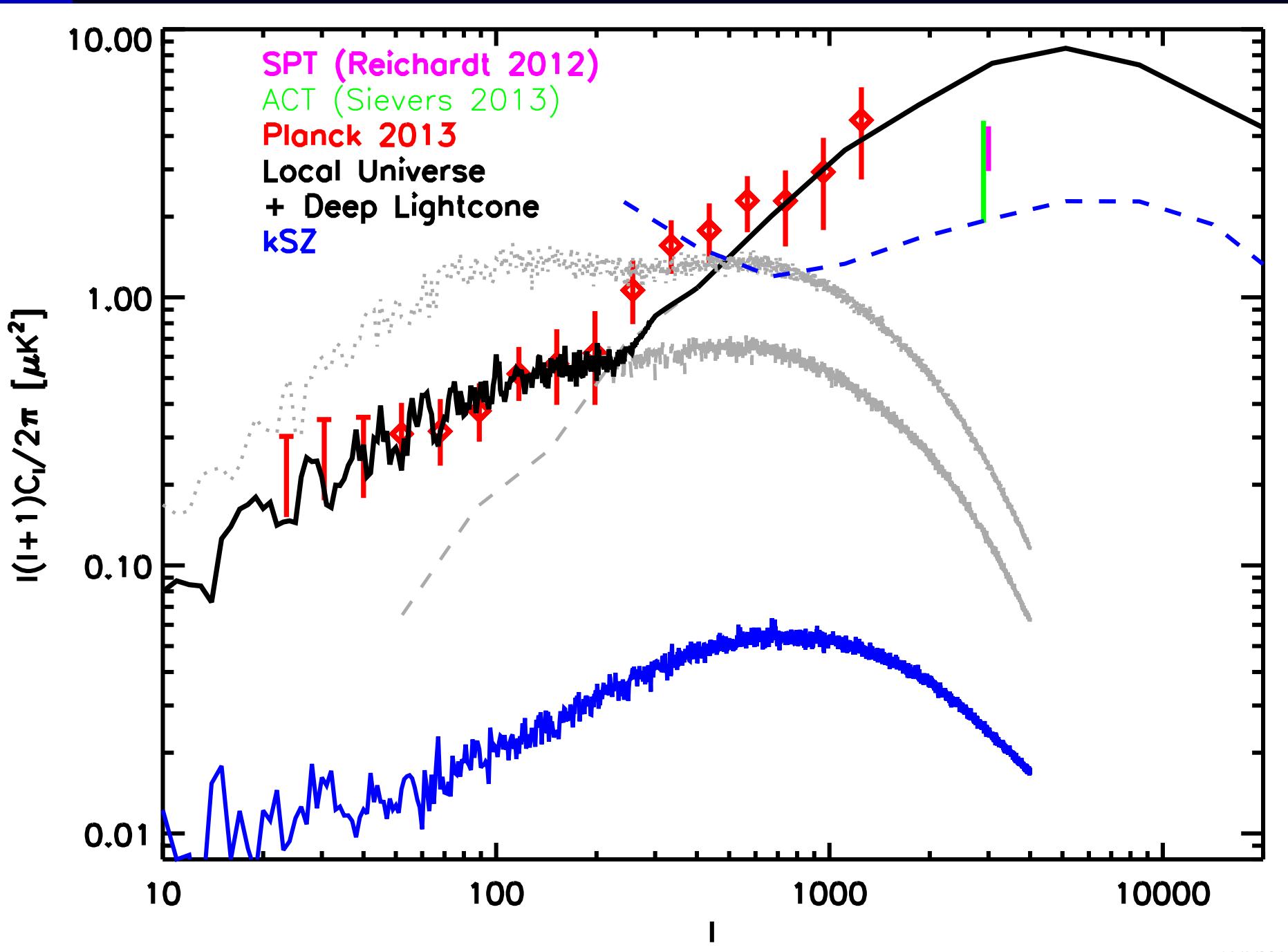
## Simulations



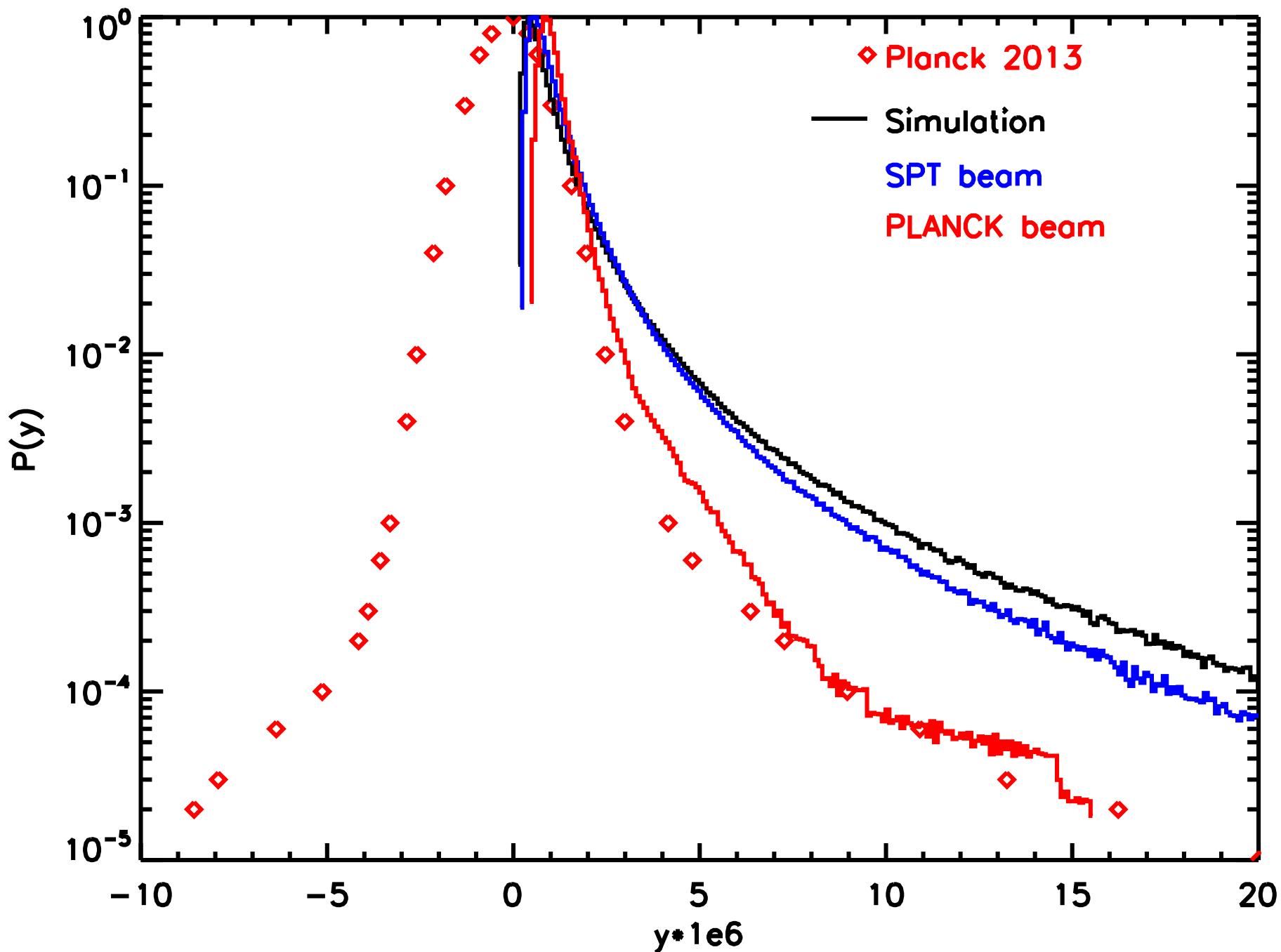
# ICM Properties



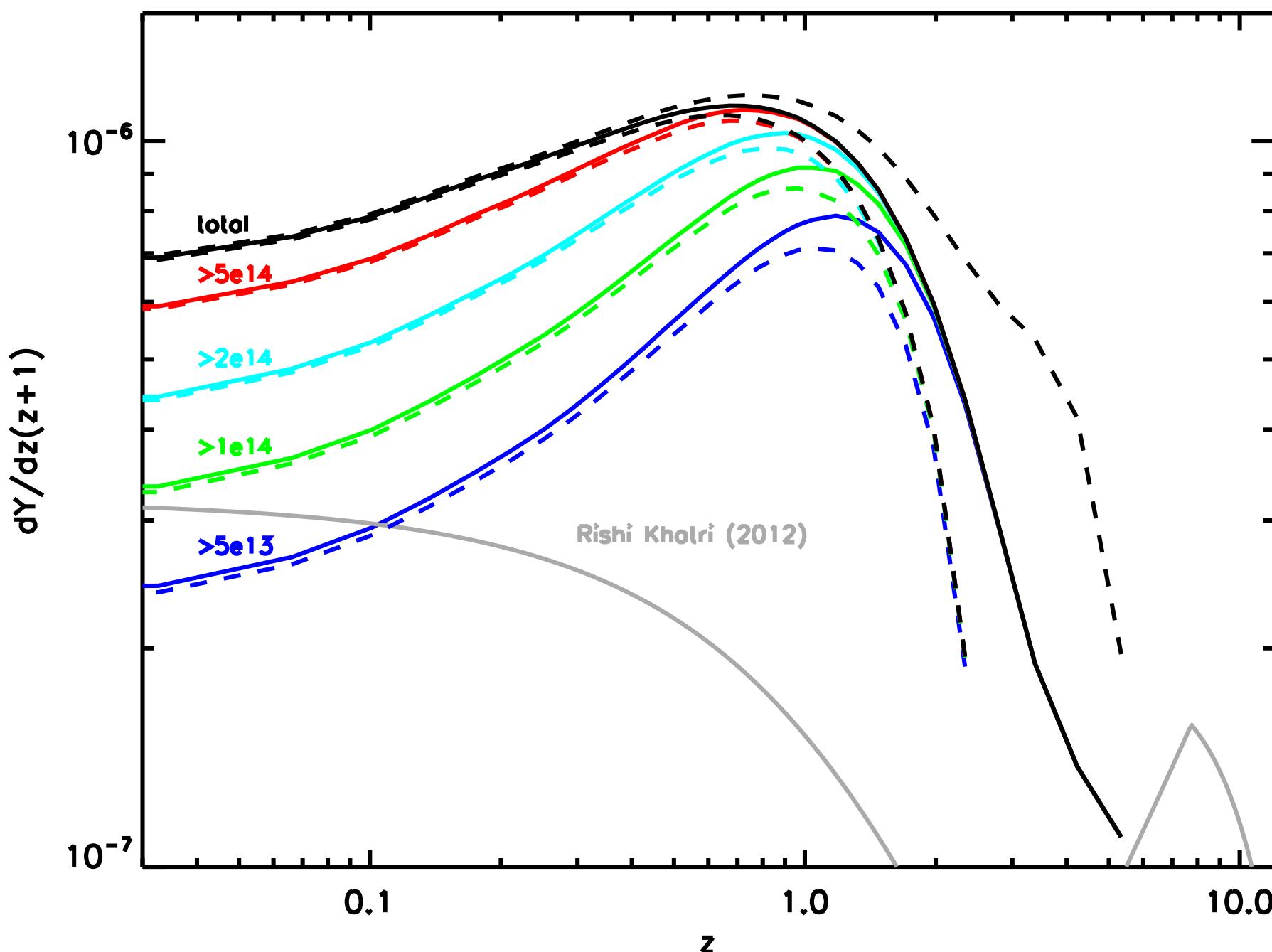
# ICM Properties



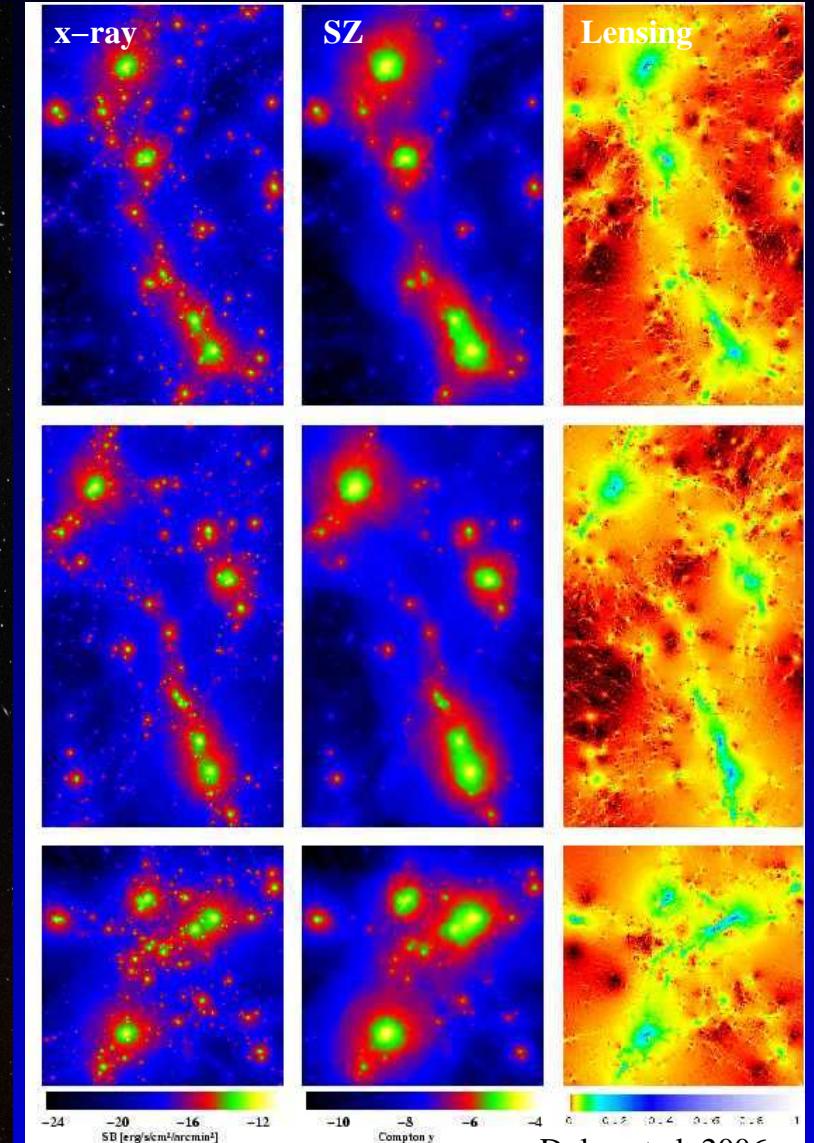
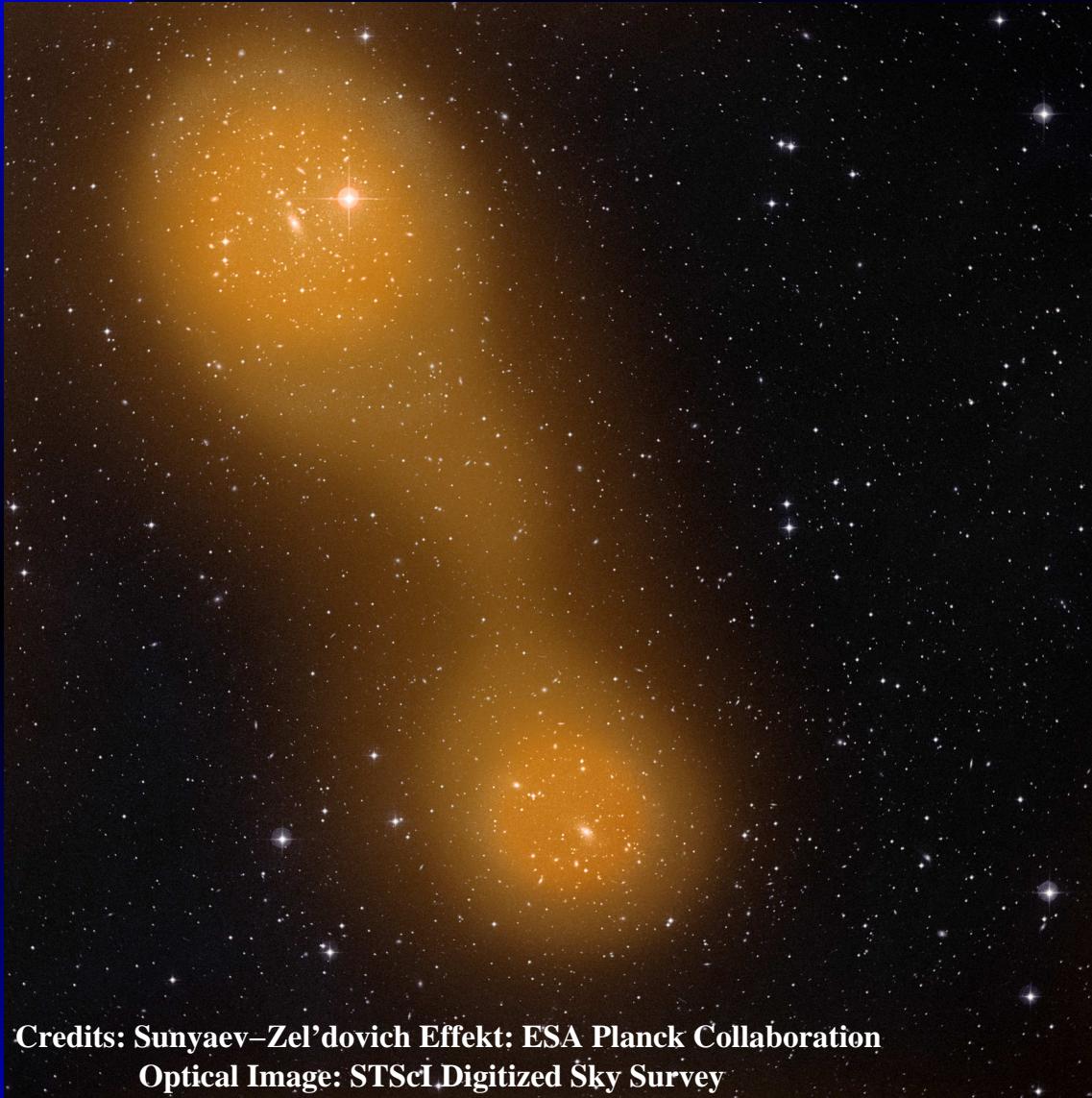
# ICM Properties



# ICM Properties



# Cosmological Filaments

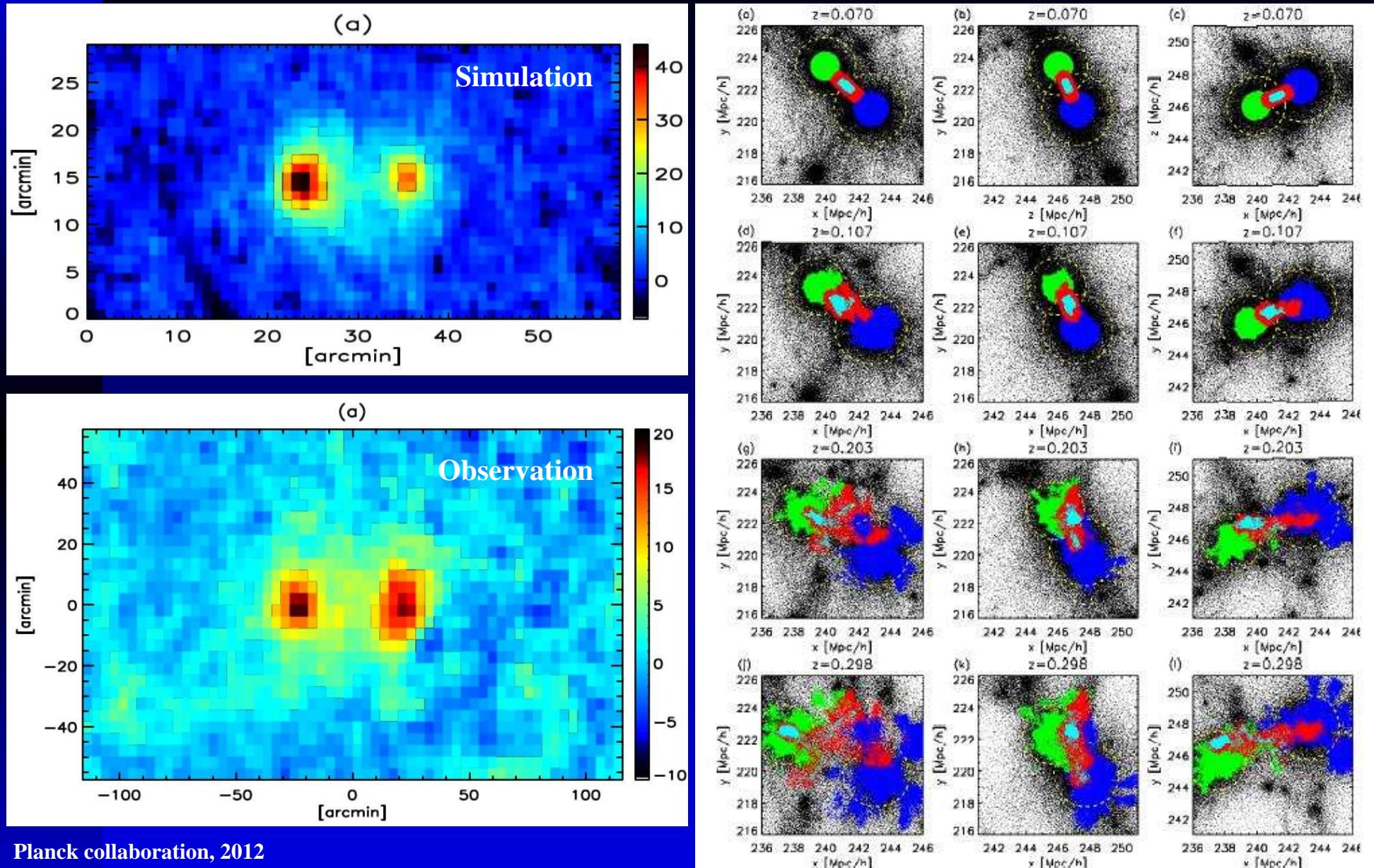


Credits: Sunyaev–Zel'dovich Effekt: ESA Planck Collaboration  
Optical Image: STScI Digitized Sky Survey

Dolag et al. 2006

Planck detected bridge between two galaxy clusters !  
Real filament or “only” merger ?  
⇒ compare to hydrodynamical simulations !

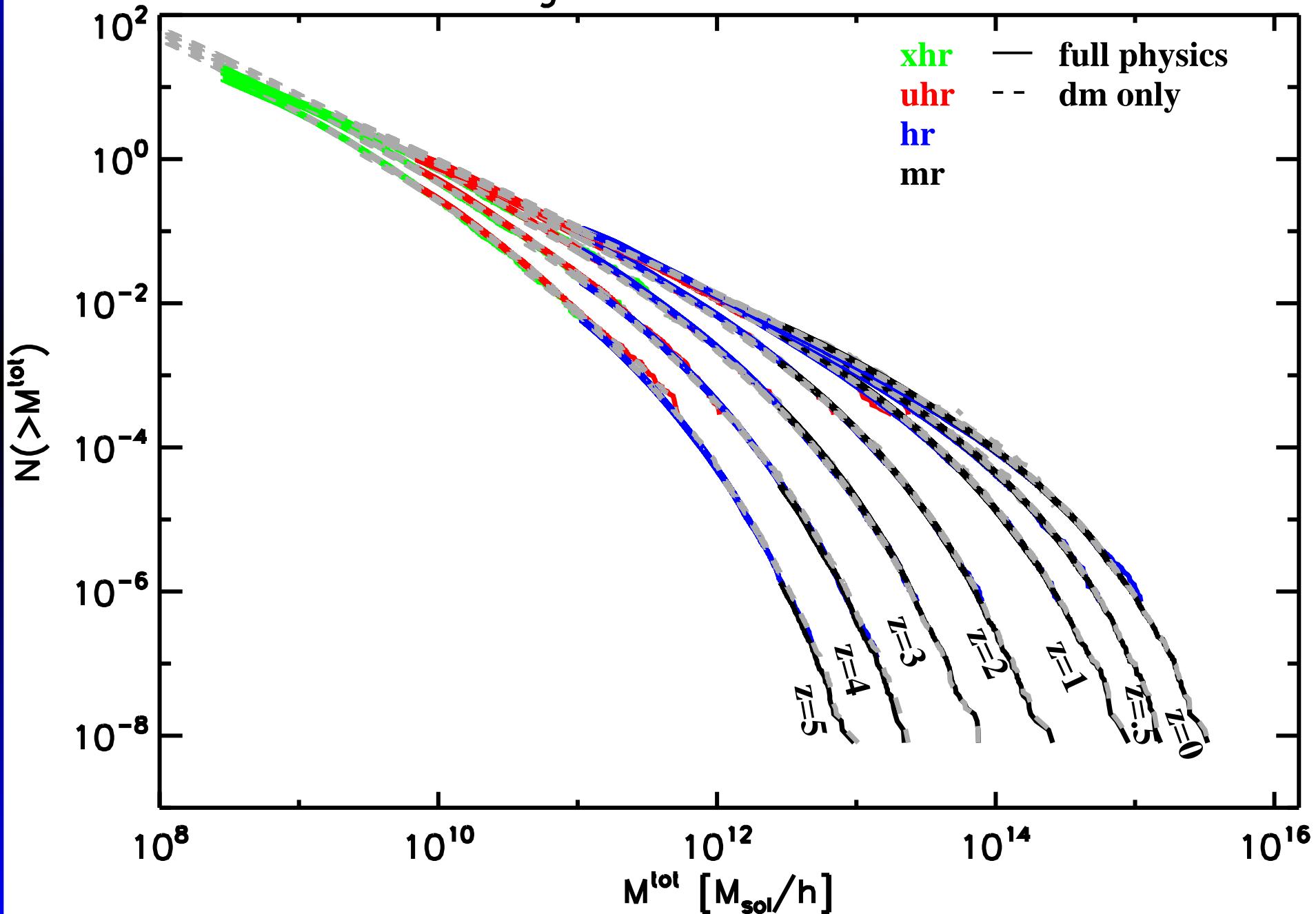
# Cosmological Filaments



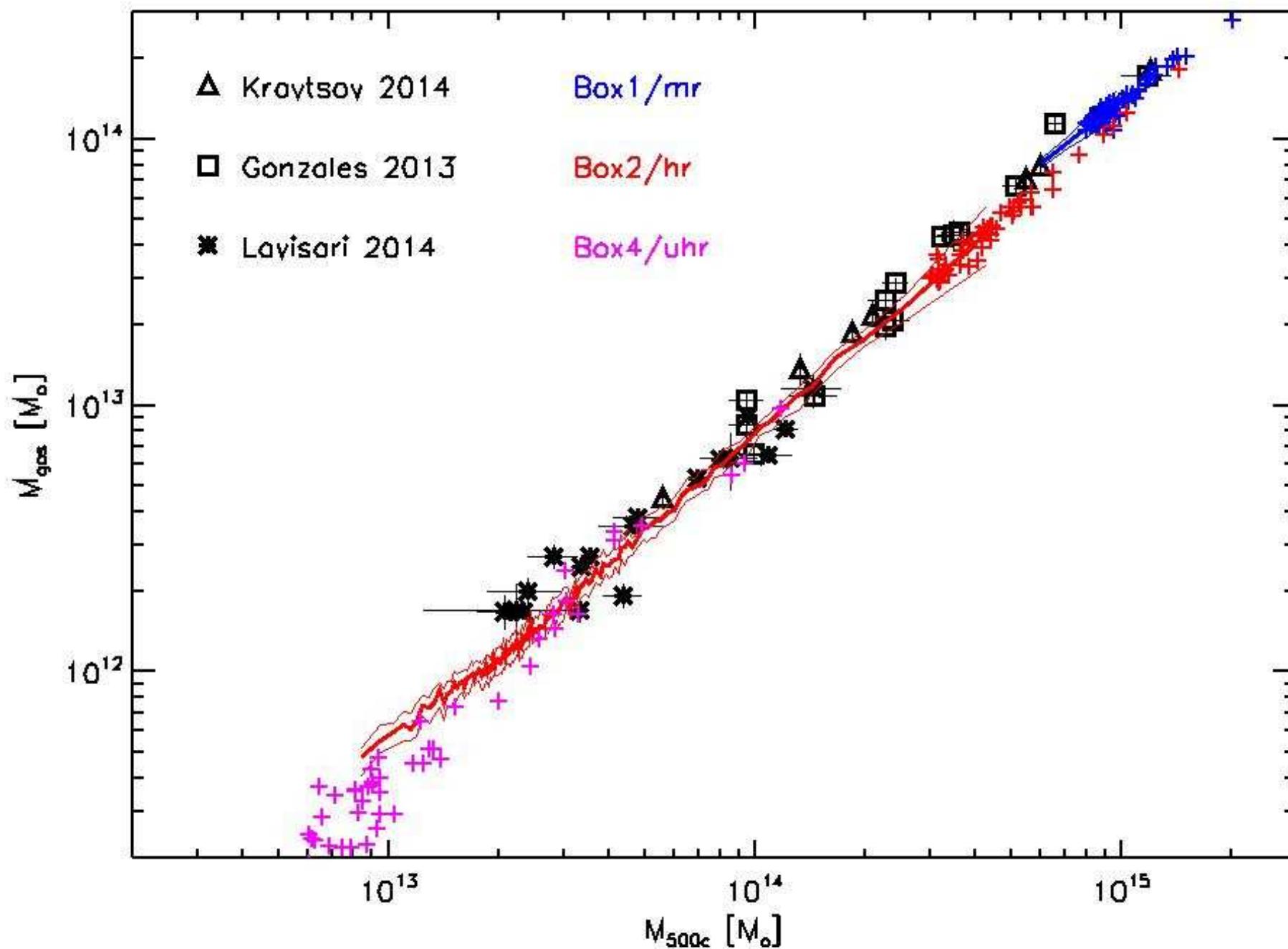
Tracing the particles in simulations suggest that significant fraction of the material comes from outside the clusters !

# Halo Properties

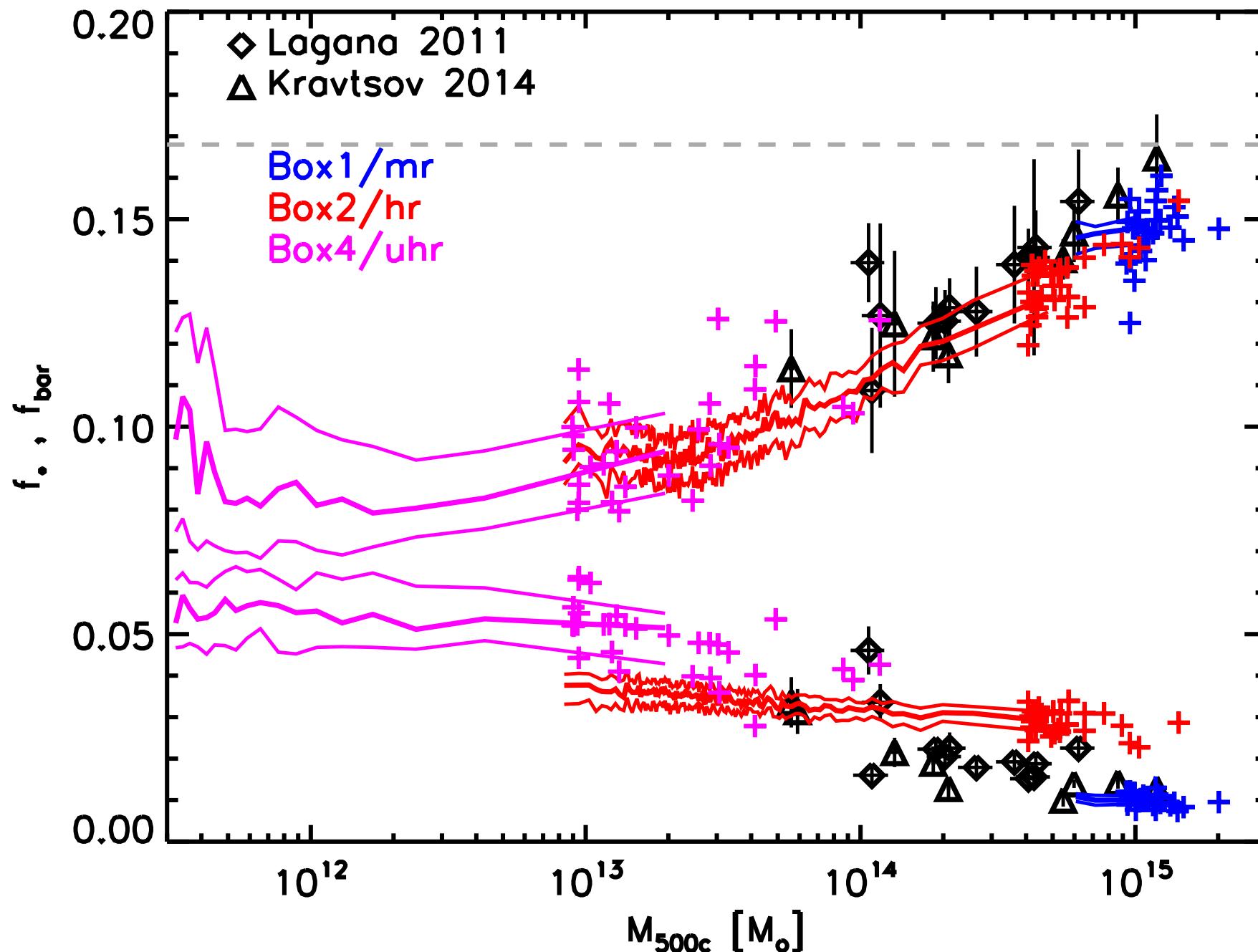
Magneticum Pathfinder



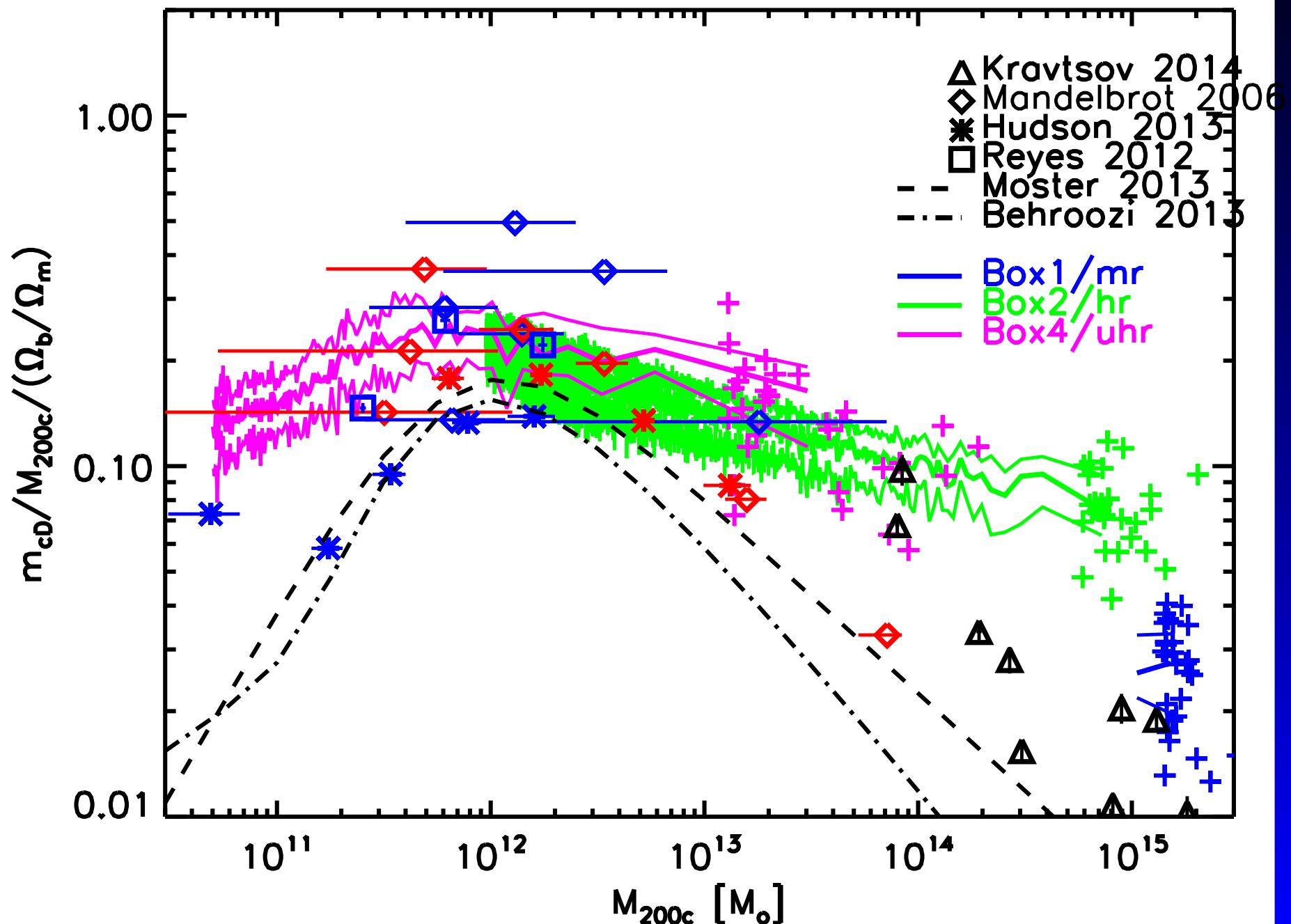
# Halo Properties



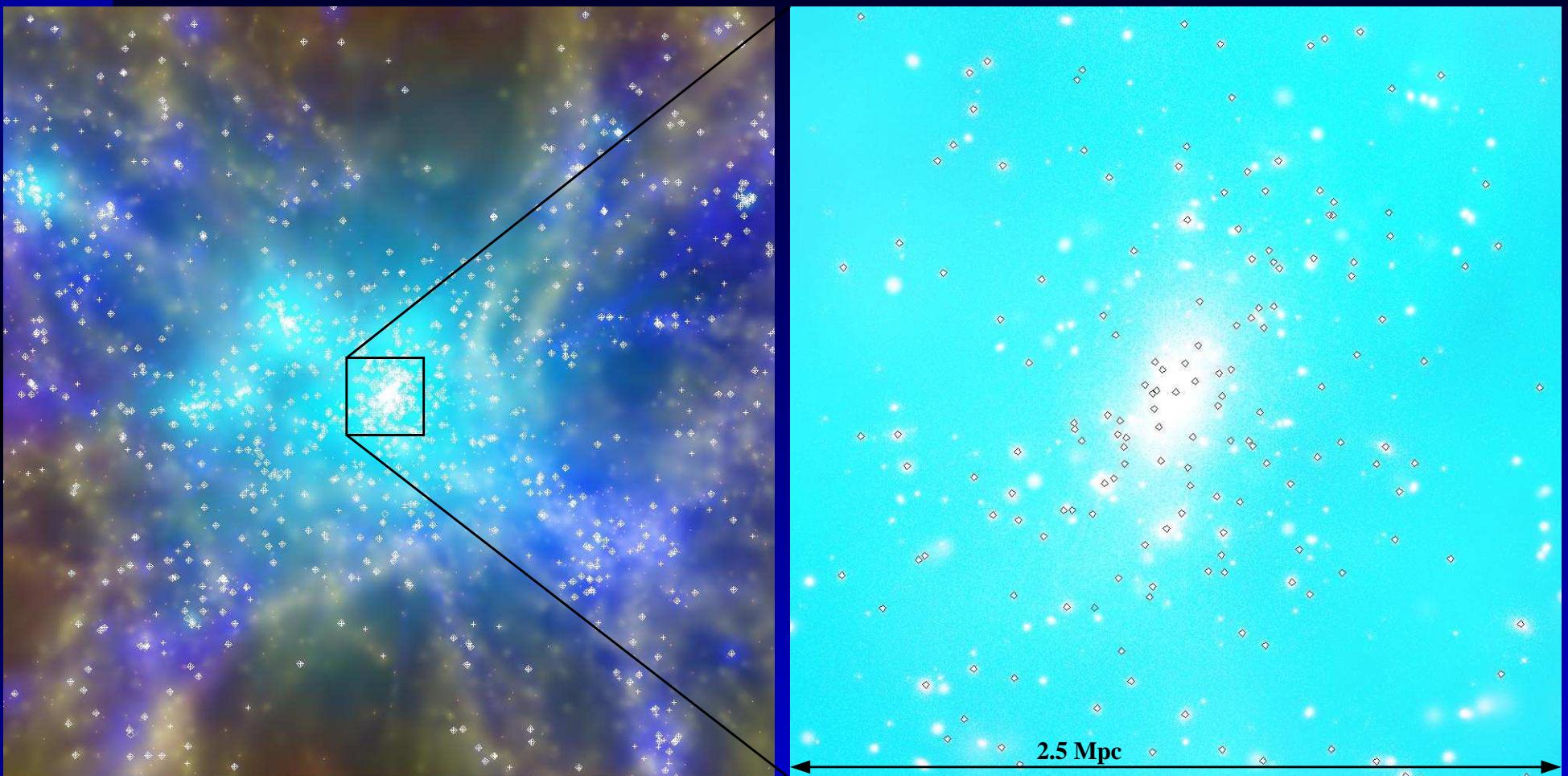
# Halo Properties



# Halo Properties



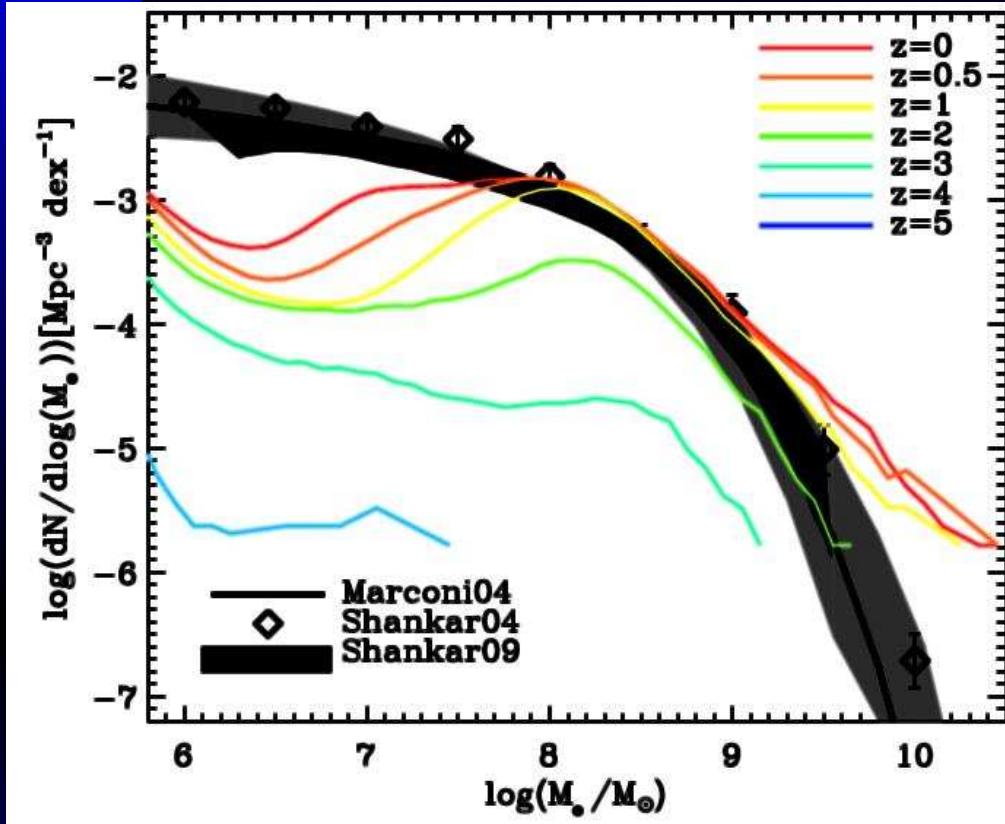
# AGN feedback model



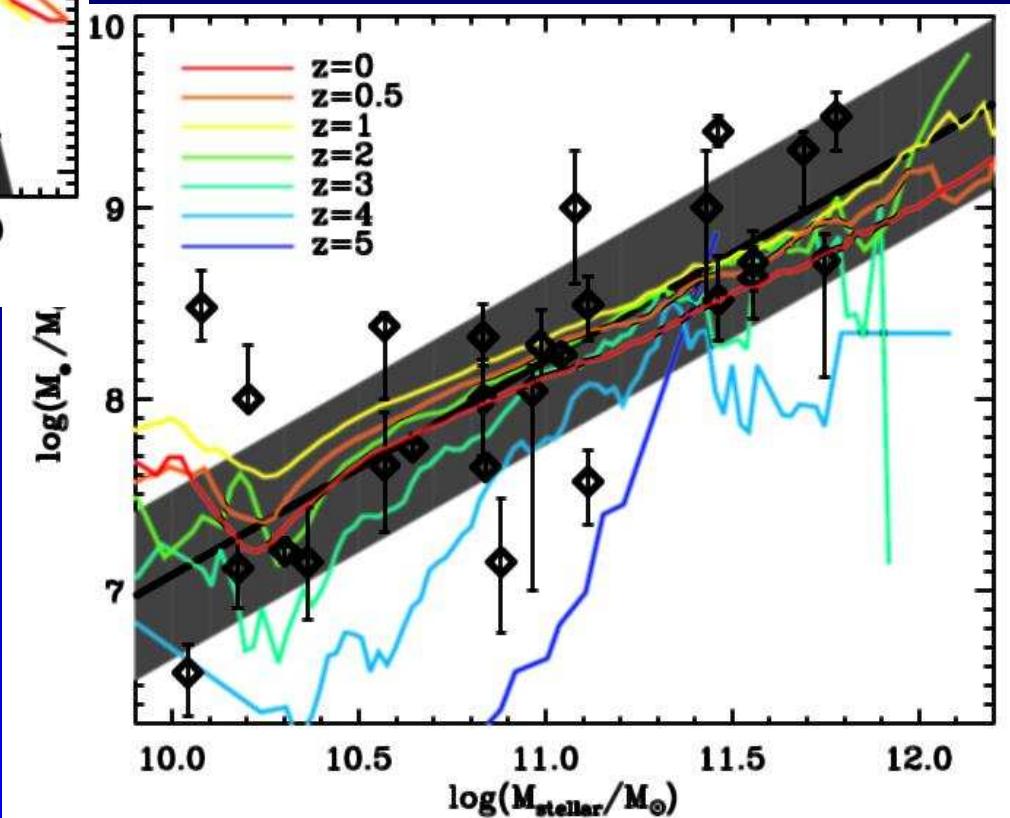
Zoom onto most massive cluster in Box2/hr. Transformation of galaxies inside the denser environment.

We also resolve black holes in satellite systems !

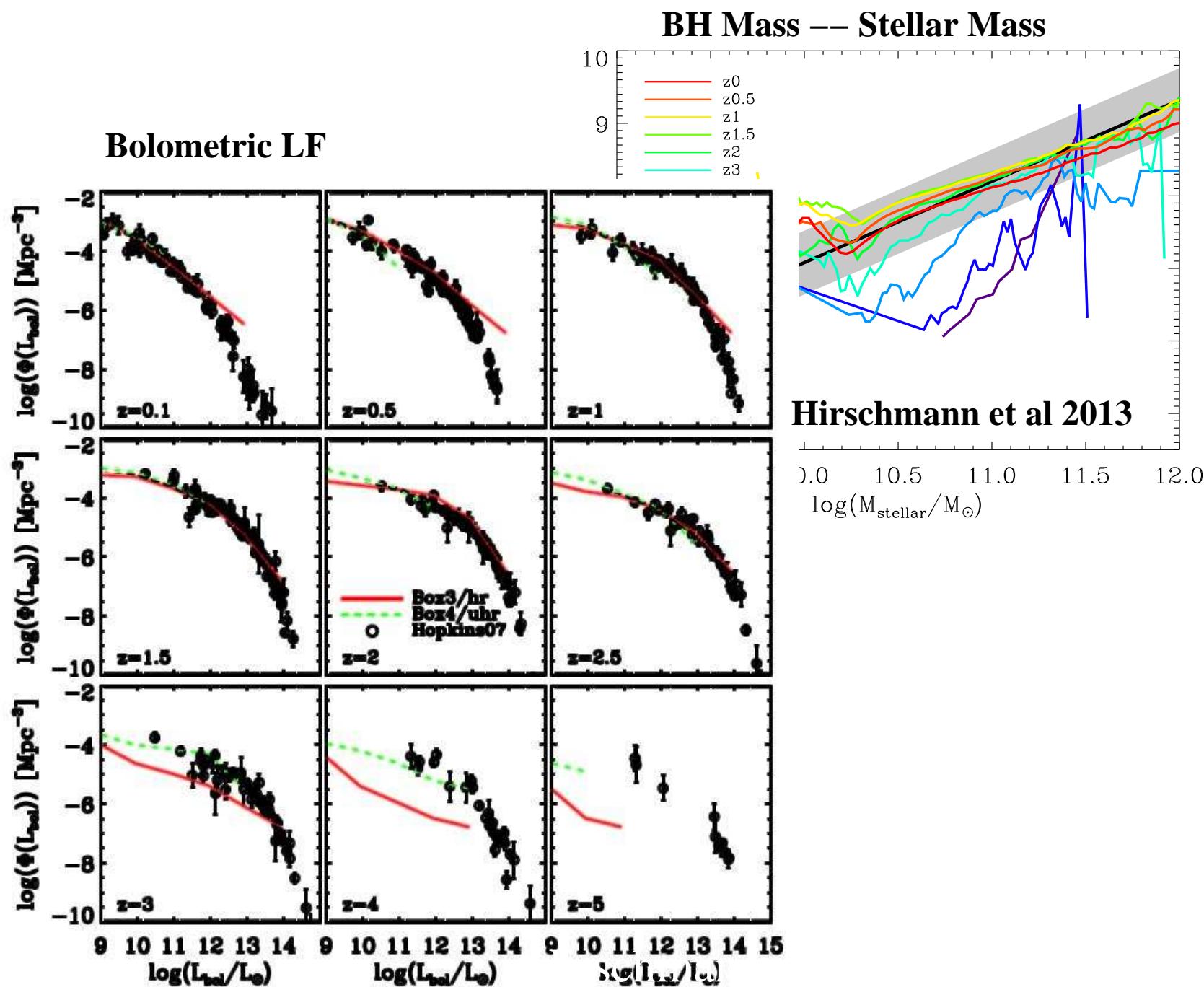
# AGN feedback model



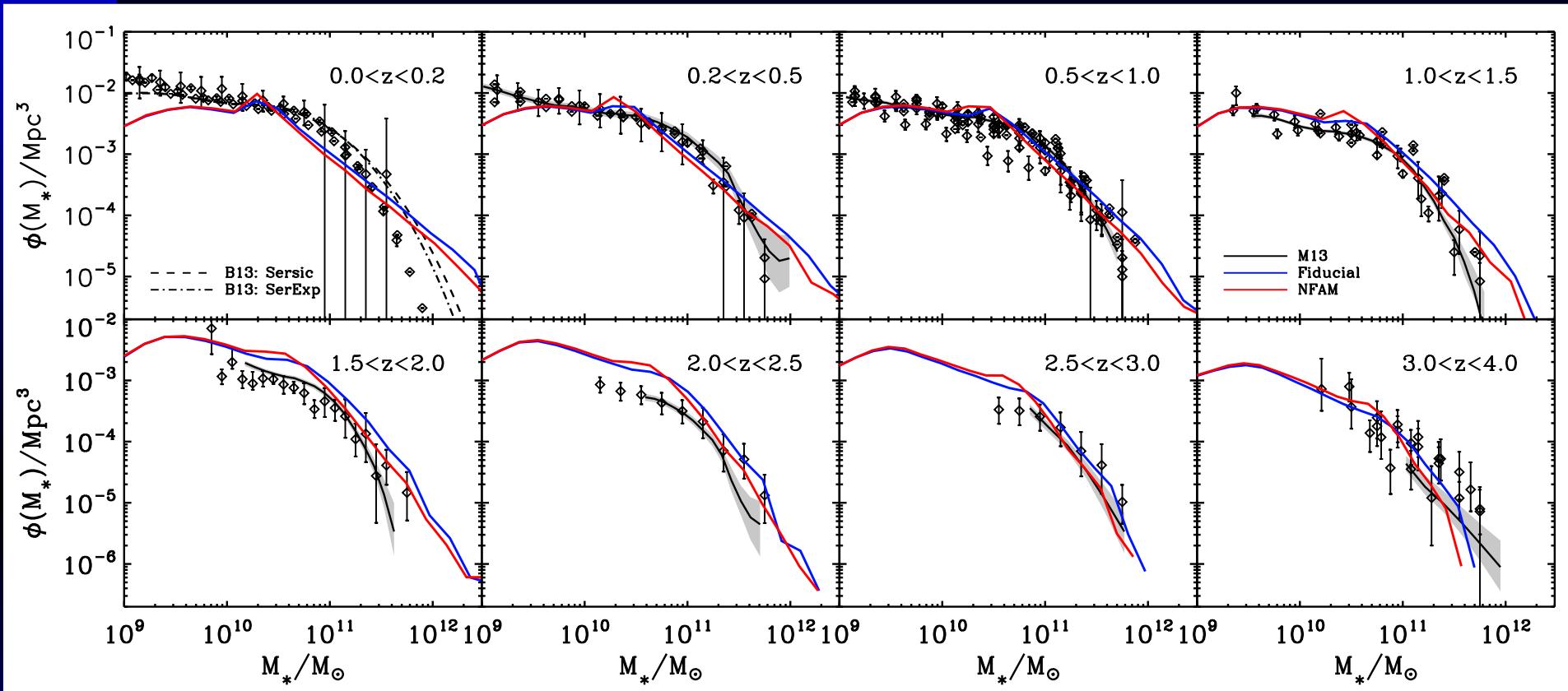
Hirschmann et al. 2013



# AGN feedback model



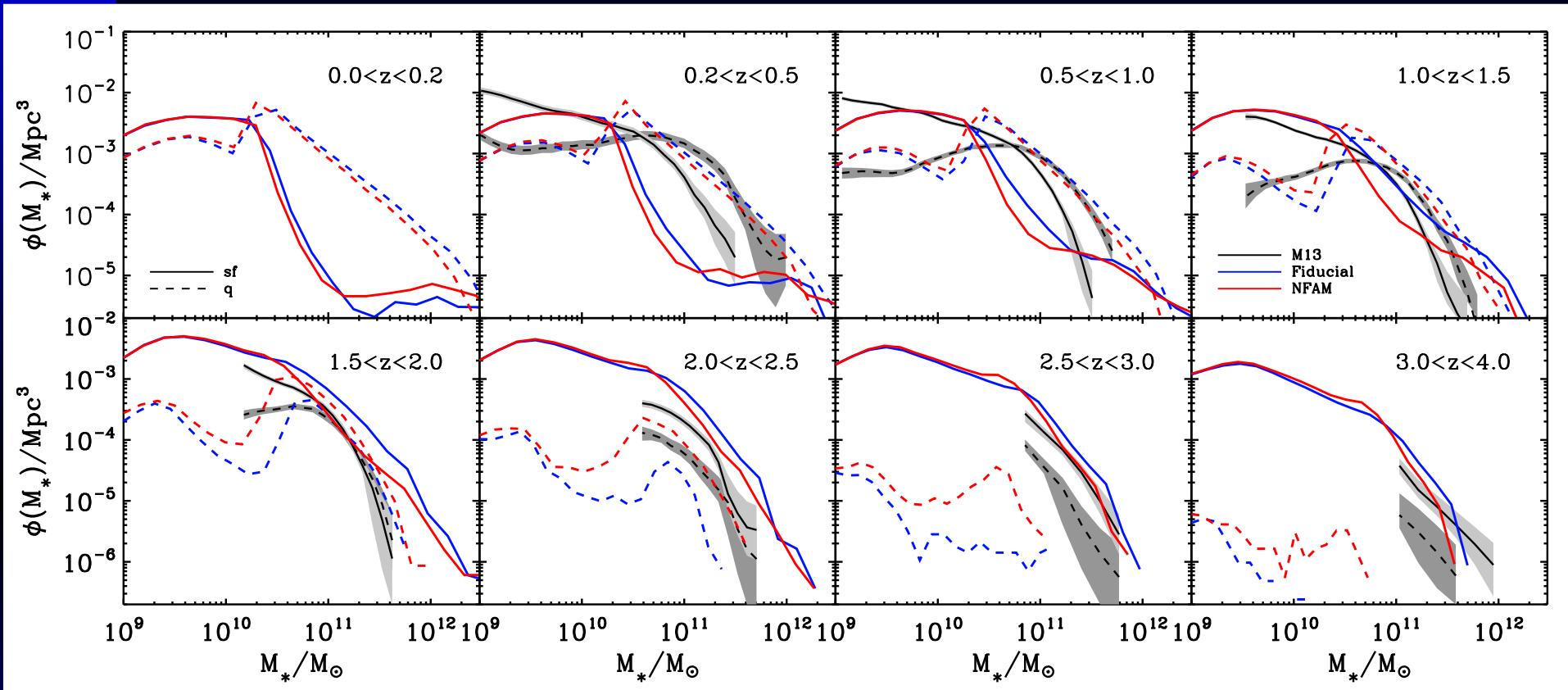
# Galaxy Properties



Stellar mass functions in different redshift ranges  
compated to a collection of different observations.  
High mass end at  $z = 0$  still slightly high.  
Colored lines are two different AGN models.

Bachmann et al. 2014

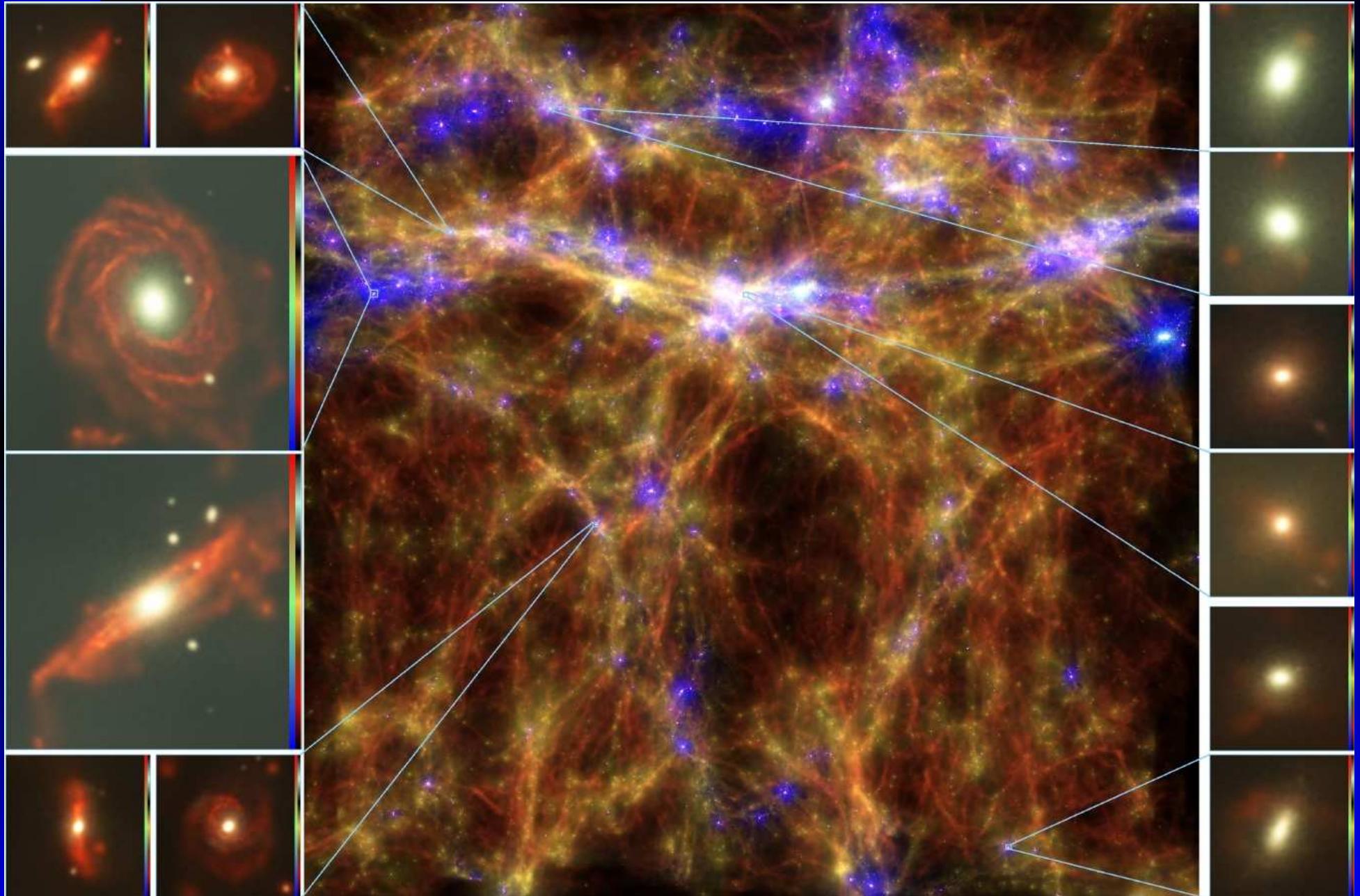
# Galaxy Properties



Stellar mass functions deviding galaxies in quiescent (dashed lines) and star-forming (solid lines) using a specific star formation rate of  $0.3/t_{\text{Hubble}}$  as threshold.

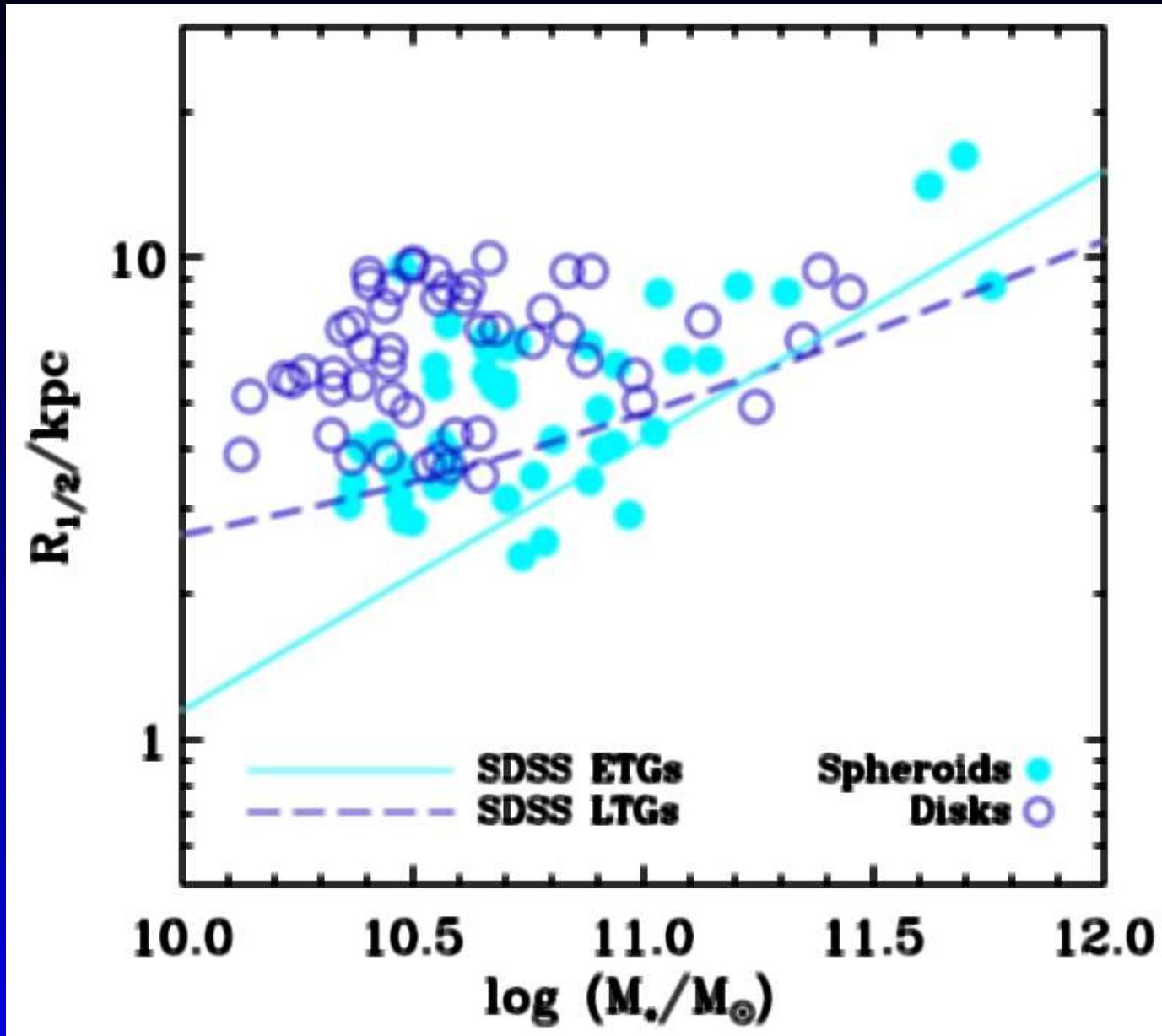
Bachmann et al. 2014

# Galaxy Properties



At highest resolution, a morphological classification can be applied !

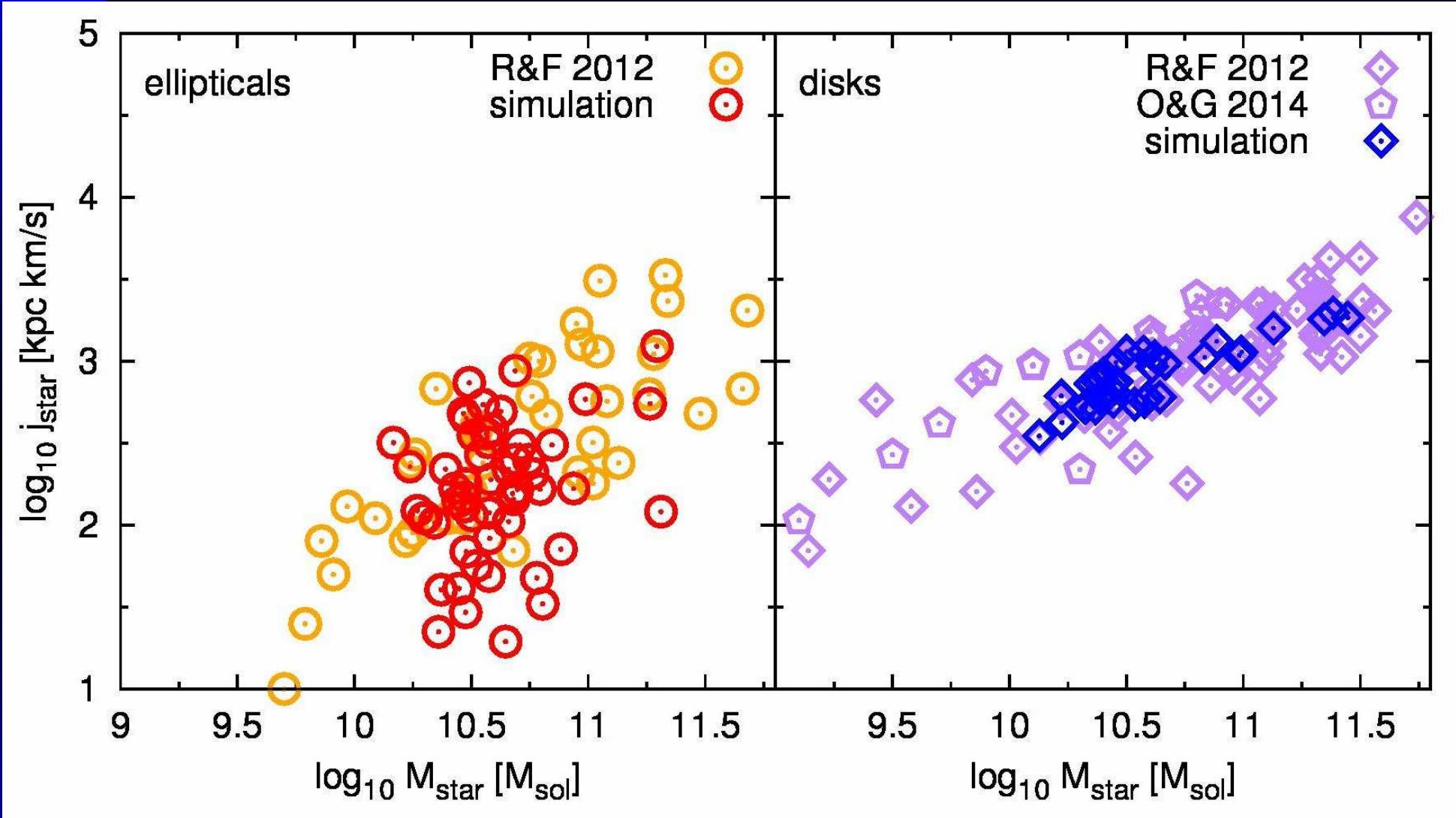
# Galaxy Properties



Comparison of the mass-size relation with SDSS data of Shen et al. 2003

Remus et al., in prep

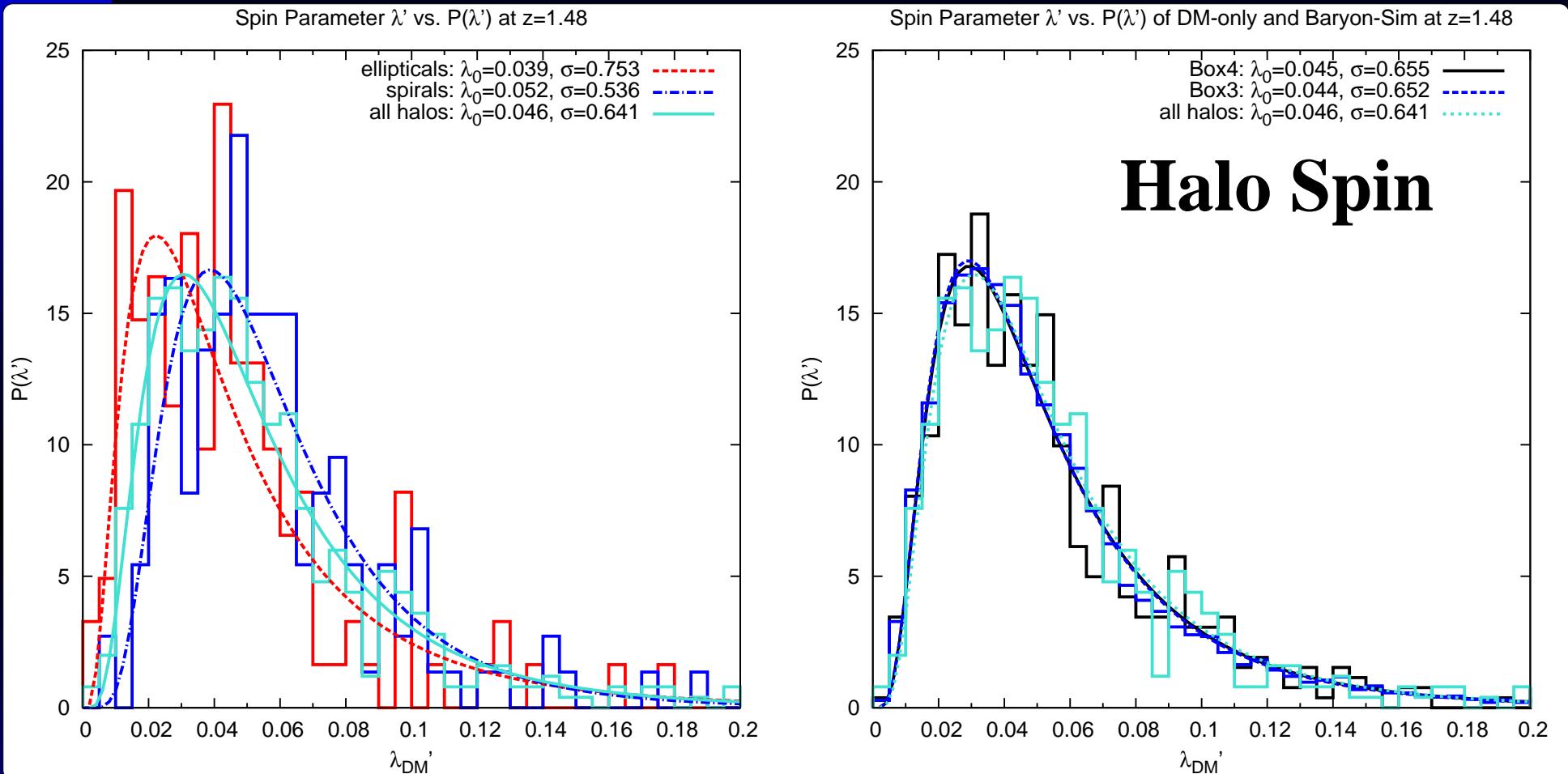
# Galaxy Properties



Comparison of the angular momentum of disk and elliptical galaxies as found in the simulations with observations.

Teklu et al., in prep

# Galaxy Properties



The dichotomy in the total angular momentum of  
haloes hosting disc and elliptical galaxies.

Teklu et al., in prep

# Conclusions

Cosmological, hydrodynamical simulations which at the same time allows predictions for ICM and stellar and AGN component for ongoing/future missions.

- ICM properties (very good)  
pressure profiles, x-ray scaling relations
- Halo properties (very good)  
baryon content, starformation efficiencies
- AGN properties (very good)  
accretion histories, luminosity functions
- Simulated stellar properties (reasonable)  
luminosity function, colors, specific star-formation rates
- Dynamics of galaxies (first time testable !)  
Spirals vs. Ellipticals, Spin, Warps, Bars, ...

