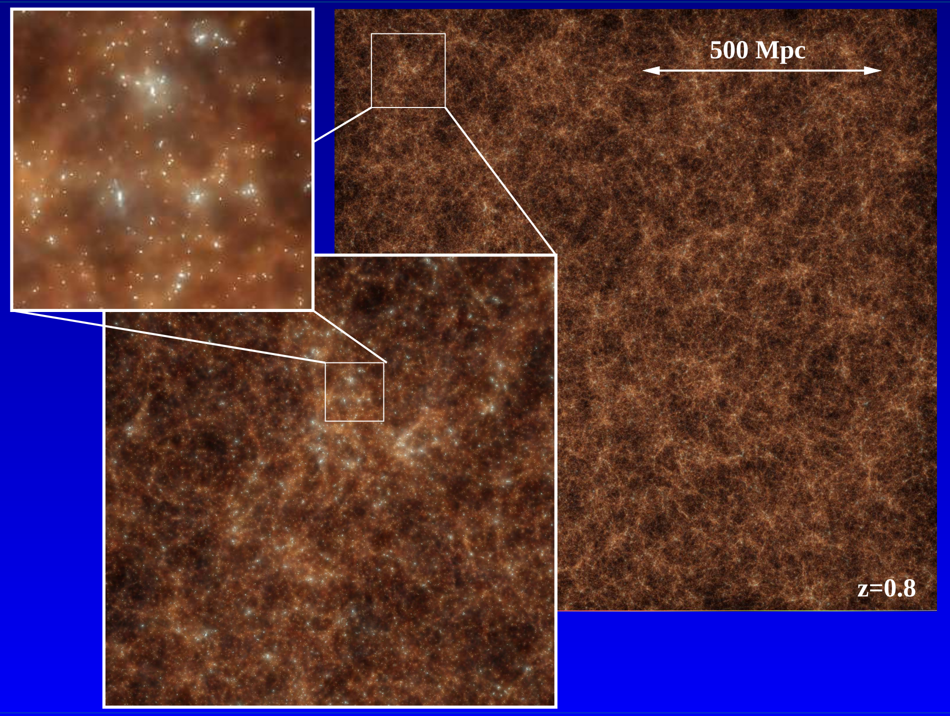
Lecture I:
(*) Structure Formation
(*) Simulations
(*) Galaxy Clusters

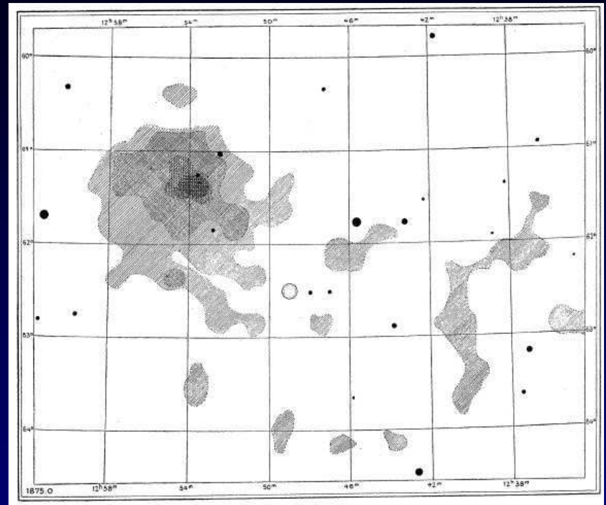
Klaus Dolag

Universitäts-Sternwarte München, LMU



A Historic Example (Coma)

	0m	59m	58m	57m	56m	55m	54m	53m	52m	51m	50m	49m	48m	47m	46m	45m	44m	43m	42m	41m	40m	39m	38m	37m	36m	35m	
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	—
30	—	0	2	3	4	3	2	3	5	3	1	3	0	0	0	2	4	1	0	0	0	3	2	0	0	2	0
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
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
15	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
30	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
45	0	5	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3
62° 0′	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
15	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
30	—	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
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																											



Nebelvertheilung um den Pol der Milchstrasse

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

$$\alpha = 12^h\,52^m.6 \quad \delta = +28°\,42' \ (1855.0)$$

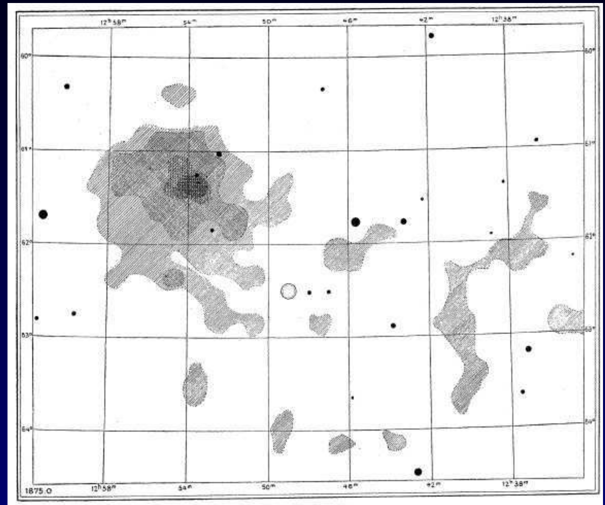
stehen nämlich zahlreiche kleine Nebelflecken so dicht beisammen, dass man beim Anblick der Gegend förmlich über das merkwürdige Aussehen dieses »Nebelhaufens« erschrickt. Ich habe die Anzahl der Nebel in einem Kreis von 30′ Durchmesser um die angegebene Stelle bestimmt und finde, dass mindestens 108 Nebelflecken auf dieser Fläche beisammen stehen, also auf einer Fläche etwa von der Grösse des Vollmondes. Darunter sind vier oder fünf grössere ausgedehnte und centralverdichtete Nebel, sowie mehrere langgestreckte. Die weitaus meisten haben aber rundliche Form und sind kleiner. *)

Heidelberg, 1901 März 27.

Max Wolf.

A Historic Example (Coma)

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



Nebelvertheilung um den Pol der Milchstrasse

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

$$\alpha = 12^h\,52^m{,}6 \quad \delta = +28°\,42' \quad (1855.0)$$

stehen nämlich zahlreiche kleine Nebelflecken so dicht beisammen, dass man beim Anblick der Gegend förmlich über das merkwürdige Aussehen dieses »Nebelhaufens« erschrickt.

Ich habe die Anzahl der Nebel in einem Kreis von 30' Durchmesser um die angegebene Stelle bestimmt und finde, dass mindestens 108 Nebelflecken auf dieser Fläche beisammen stehen, also auf einer Fläche etwa von der Grösse des Vollmondes. Darunter sind vier oder fünf grössere ausgedehnte und centralverdichtete Nebel, sowie mehrere langgestreckte. Die weitaus meisten haben aber rundliche Form und sind kleiner. *)

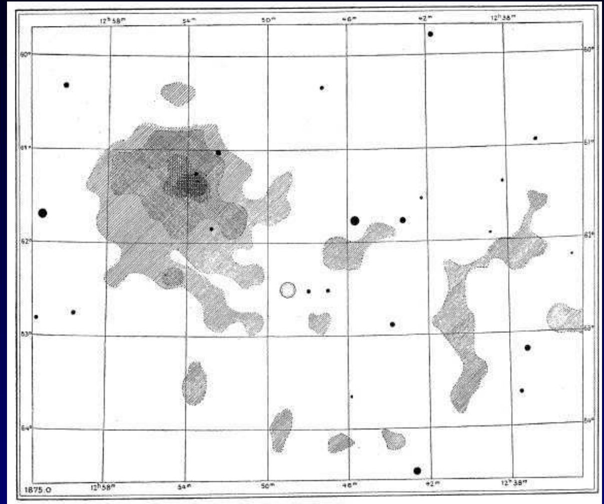
Heidelberg, 1901 März 27.

Max Wolf.

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

A Historic Example (Coma)

	0m	59m	58m	57m	56m	55m	54m	53m	52m	51m	50m	49m	48m	47m	46m	45m	44m	43m	42m	41m	40m	39m	38m	37m	36m	35m	
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	—
30	—	0	2	3	4	3	2	3	5	3	1	3	0	0	0	2	4	1	0	0	0	3	2	0	0	2	0
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
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
15	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
30	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
45	0	5	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3
62° 0′	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
15	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
30	—	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
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																											



Nebelvertheilung um den Pol der Milchstrasse

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

$$\alpha = 12^h\,52^m\!.6 \quad \delta = +28°\,42' \;(1855.0)$$

stehen nämlich zahlreiche kleine Nebelflecken so dicht beisammen, dass man beim Anblick der Gegend förmlich über das merkwürdige Aussehen dieses »Nebelhaufens« erschrickt.

Heidelberg, 1901 März 27.

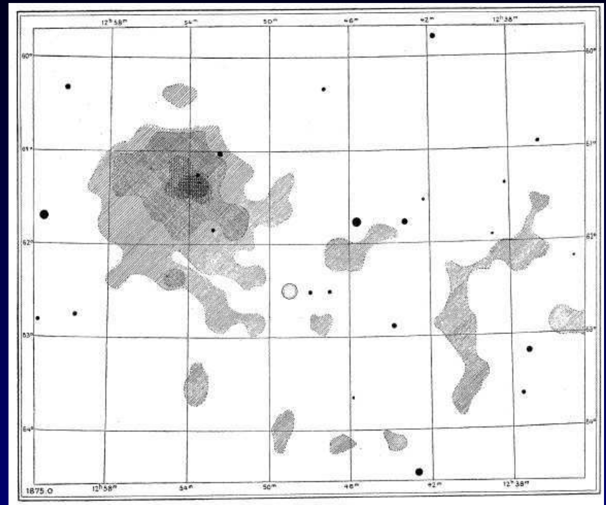
Ich habe die Anzahl der Nebel in einem Kreis von 30′ Durchmesser um die angegebene Stelle bestimmt und finde, dass mindestens 108 Nebelflecken auf dieser Fläche beisammen stehen, also auf einer Fläche etwa von der Grösse des Vollmondes. Darunter sind vier oder fünf grössere ausgedehnte und centralverdichtete Nebel, sowie mehrere langgestreckte. Die weitaus meisten haben aber rundliche Form und sind kleiner. *)

Max Wolf.

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)

	0m	59m	58m	57m	56m	55m	54m	53m	52m	51m	50m	49m	48m	47m	46m	45m	44m	43m	42m	41m	40m	39m	38m	37m	36m	35m	
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	—
30	—	0	2	3	4	3	2	3	5	3	1	3	0	0	0	2	4	1	0	0	0	3	2	0	0	2	0
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
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
15	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
30	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
45	0	5	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3
62° 0′	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
15	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
30	—	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
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																											



Nebelvertheilung um den Pol der Milchstrasse

Max Wolf, 1902

the regular behavior within the arrangement of these distant worlds

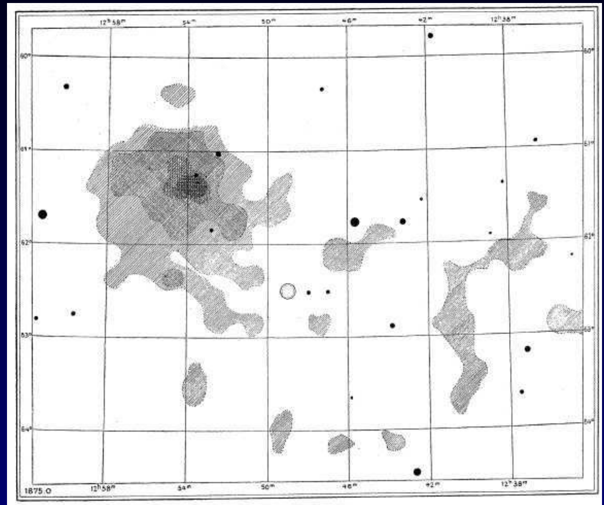
Es ist sofort zu sehen, wenn man die Tabelle oder die Tafel betrachtet, dass das Zusammendrängen der Nebel immer stärker wird, je weiter man in's Innere der Hauptinsel eindringt. Je näher man dem Puncte grösster Dichtigkeit kommt, umso dichter treten auch die Nebel an einander, so dass auf dem innersten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

	0m	59m	58m	57m	56m	55m	54m	53m	52m	51m	50m	49m	48m	47m	46m	45m	44m	43m	42m	41m	40m	39m	38m	37m	36m	35m	
59° 15′ – 30	—	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—
30 – 45	—	—	—	—	0	0	2	1	3	1	2	1	3	2	1	1	2	0	0	2	1	0	0	—	—	—	—
45 – 60° 0′	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	1	0	0	1	—	—	—
60° 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	—	—
15 – 30	—	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	—
30 – 45	—	0	2	3	4	3	2	3	5	3	1	3	0	0	0	2	4	1	0	0	0	3	2	0	0	2	0
45 – 61° 0′	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
61° 0′ – 15	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
15 – 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
30 – 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
45 – 62° 0′	0	5	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3
62° 0′ – 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
15 – 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
30 – 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
45 – 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
63° 0′ – 15	—	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 – 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	—
30 – 45	—	—	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 – 64° 0′	—	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	4	2	1	5	1	1	3	0	—	—
64° 0′ – 15	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—


Nebelvertheilung um den Pol der Milchstrasse

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 gruppiren sich um den Positionswinkel 60°.

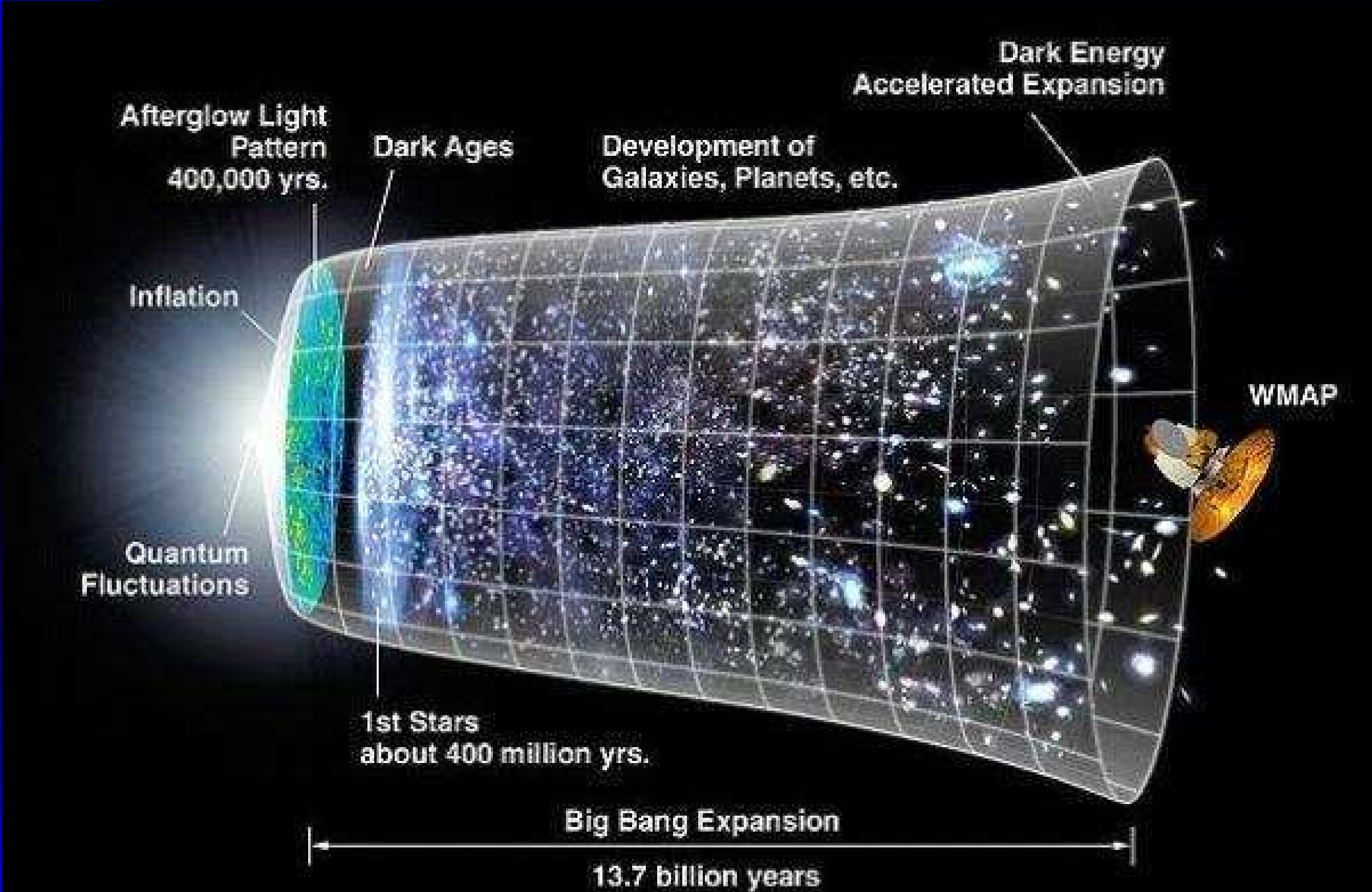
Das hatte ich so aus dem allgemeinen Eindruck, den ich beim Messen nach und nach erhalten hatte, erwartet. Nur hatte ich damals 50° dafür annehmen zu müssen geglaubt.

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.

Measuring Cosmology

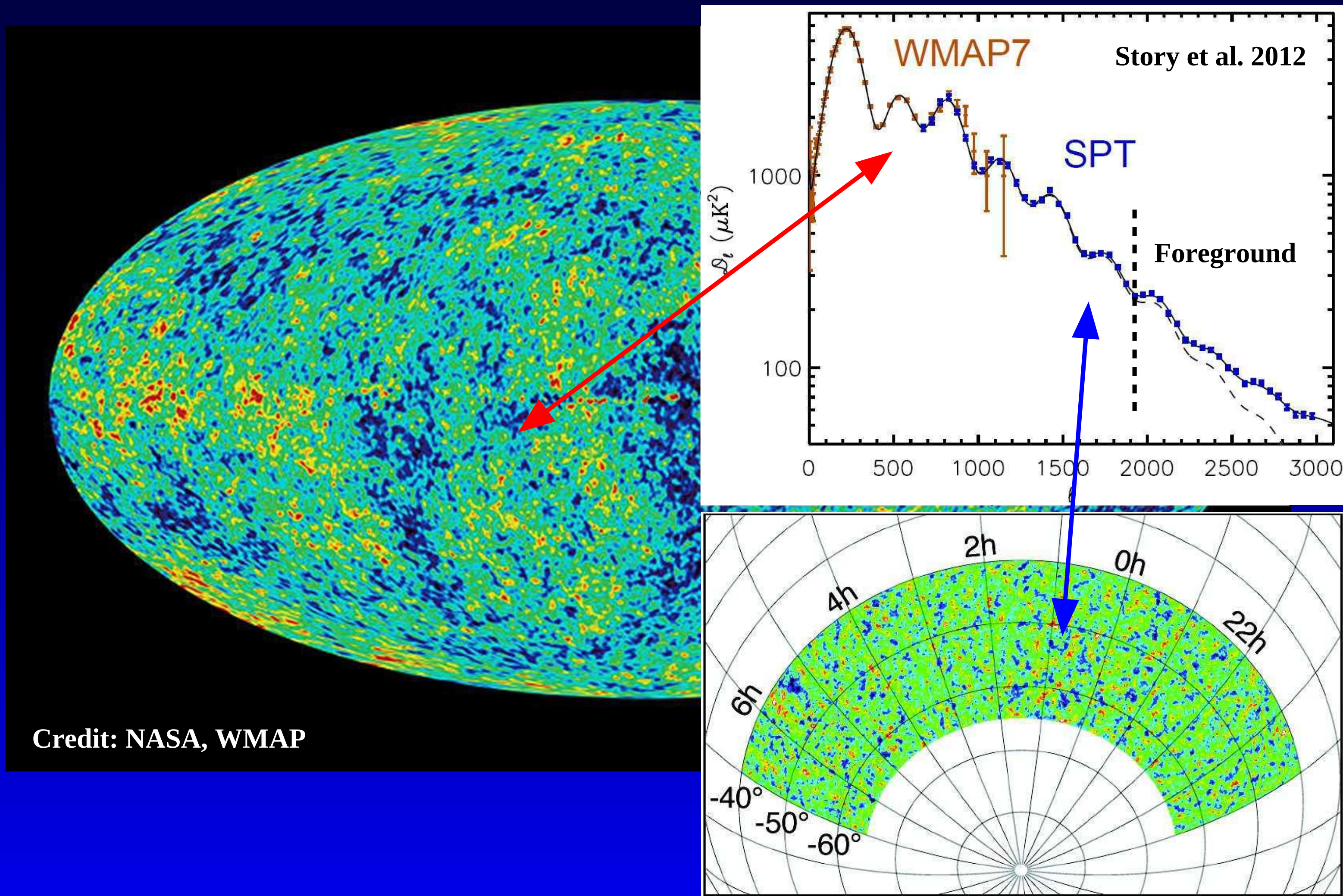


Credit: NASA, WMAP

Interplay between background cosmology and structure formation.

Measuring Cosmology

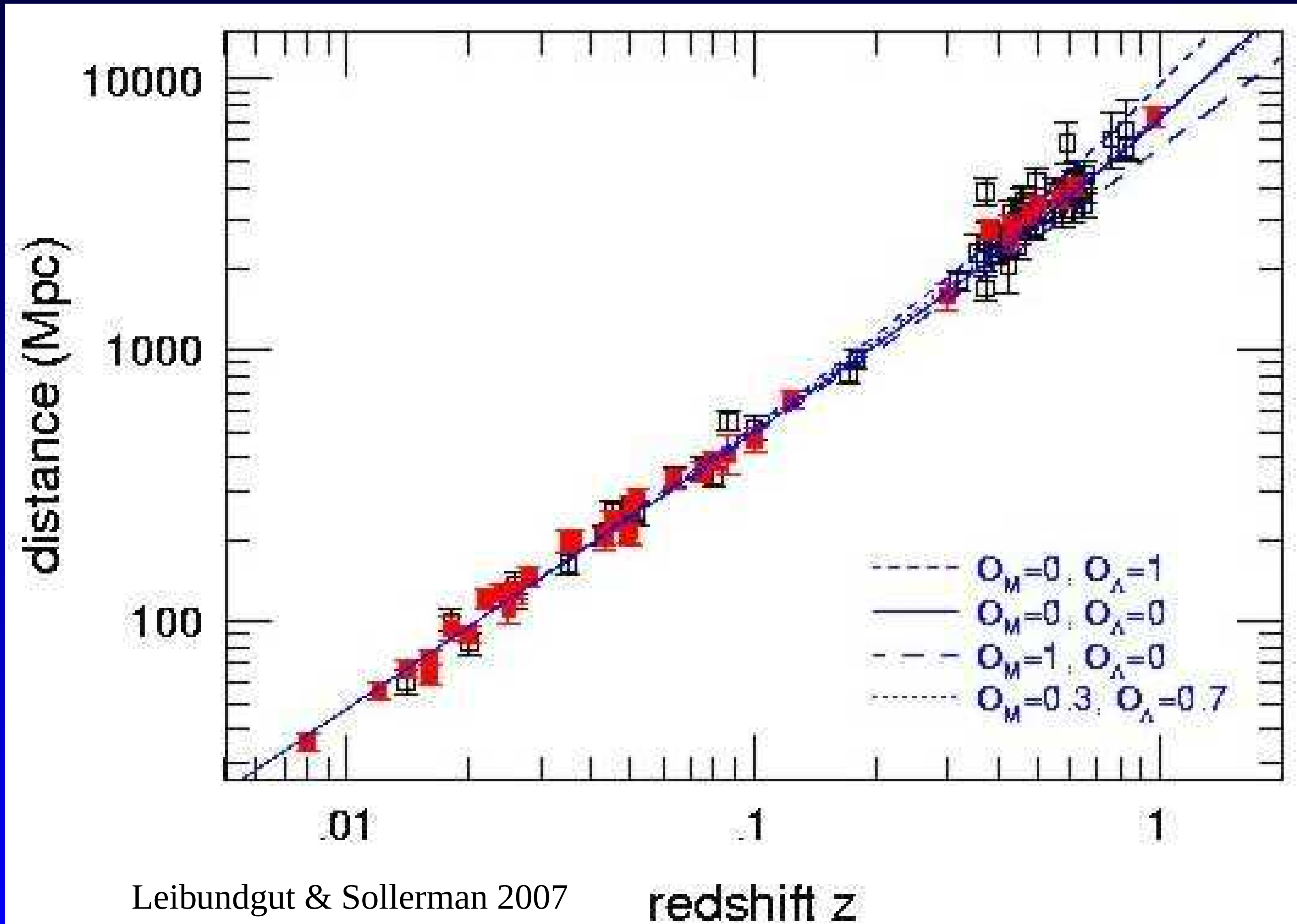
Measuring the angular size corresponding to the first acoustic peak in the CMB power spectrum, one can establish the measured angular diameter distance.



$\Omega_\Lambda = 0.750 \pm 0.02$ (e.g. $\Omega_K = 0$), $\sigma_8 = 0.750$.

Measuring Cosmology

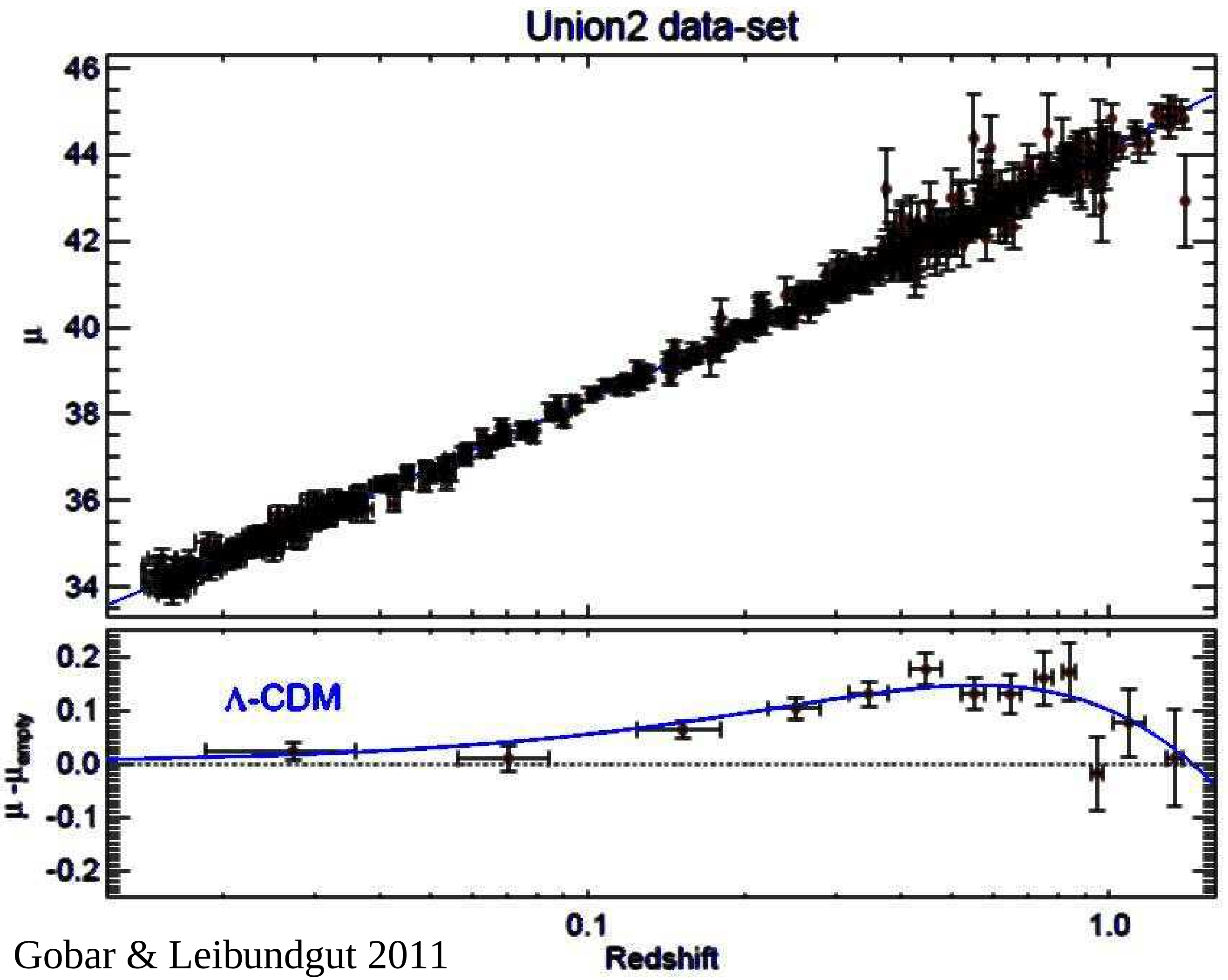
Using observed luminosities of a special, well calibrated subclass of supernova (type 1a) as standard candles, one can establish the measured luminosity distance.



Leibundgut & Sollerman 2007

Measuring Cosmology

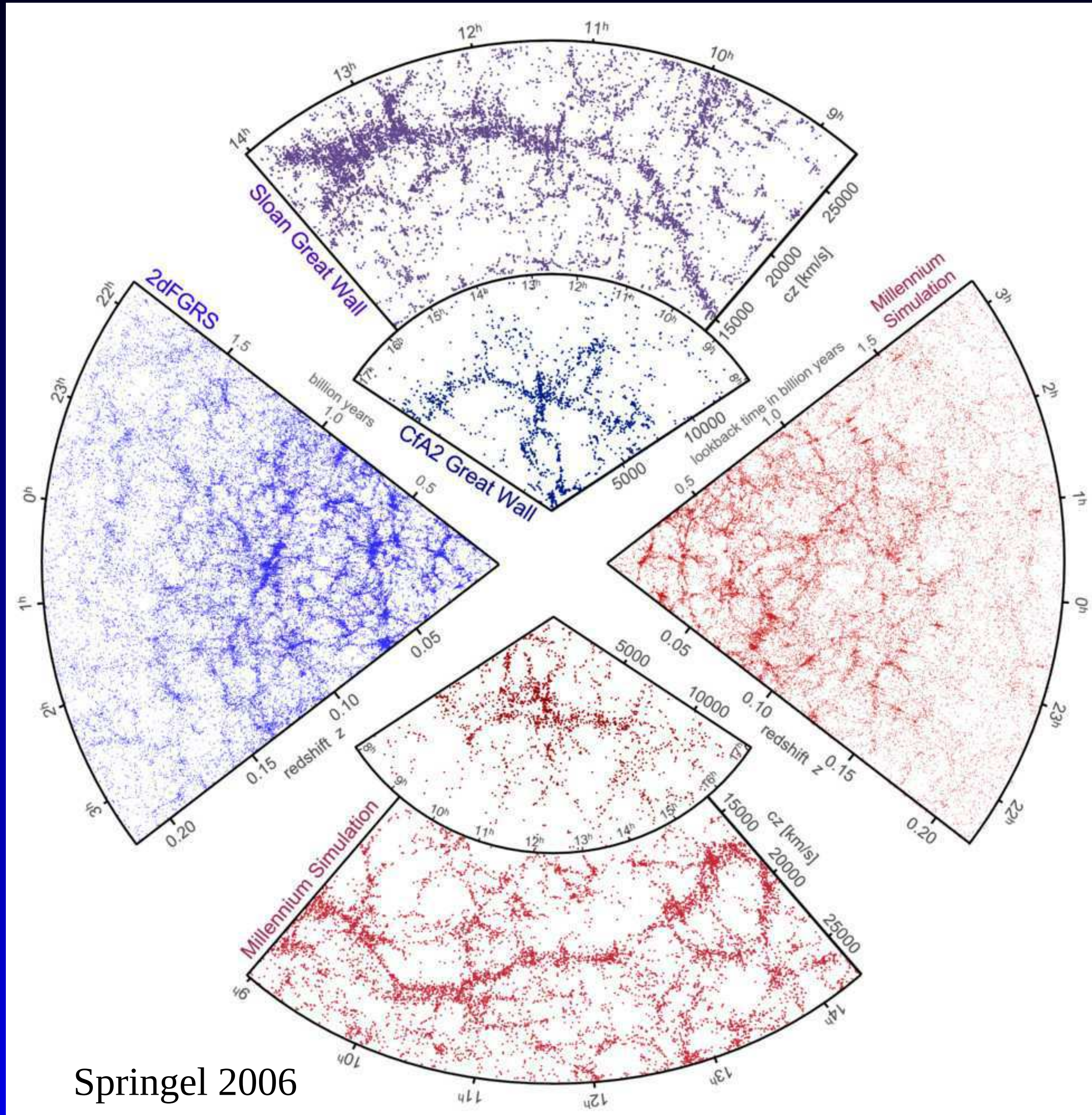
Using observed luminosities of a special, well calibrated subclass of supernova (type 1a) as standard candles, one can establish the measured luminosity distance.



Gobar & Leibundgut 2011

$\Omega_M = 0.279 \pm 0.017$ ($w = -0.997 \pm 0.13$), (Amanullah et al. 2010).

Measuring Cosmology



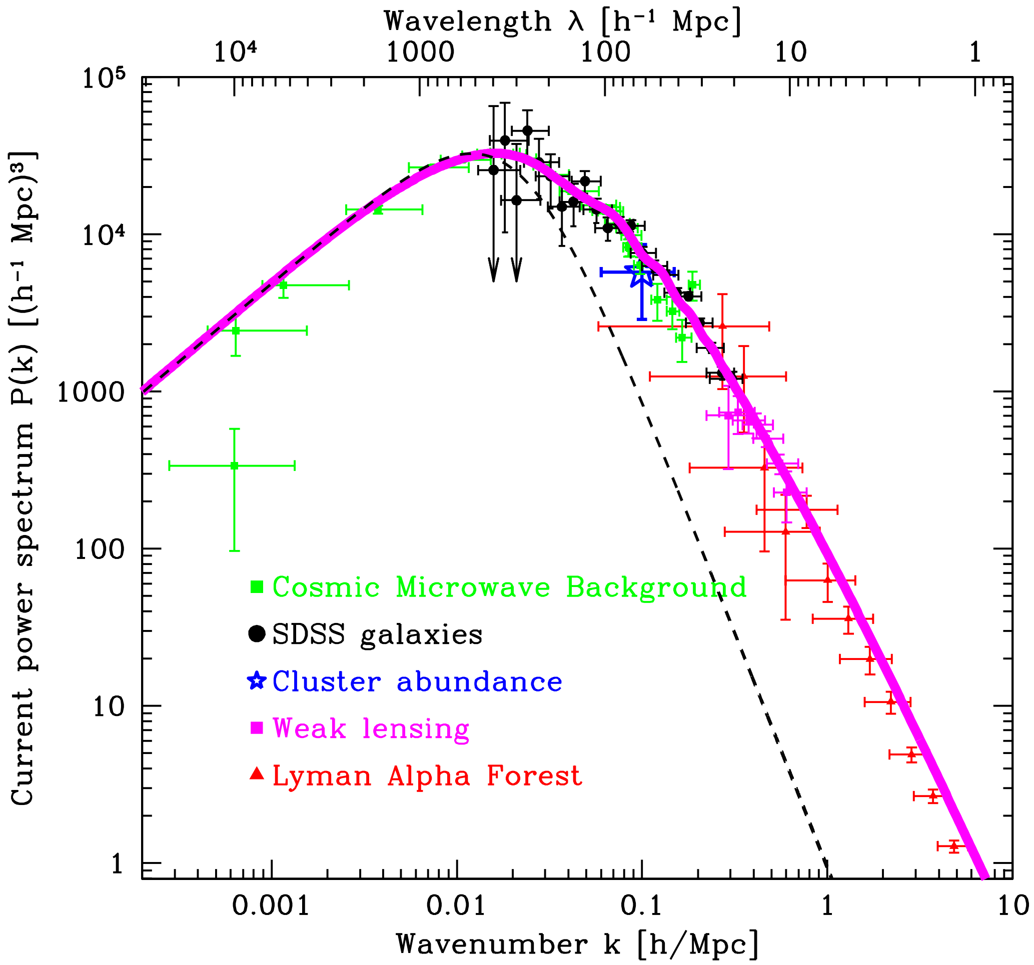
Springel 2006

Large scale structures traced by galaxies

Dark Matter simulations (gravity only) ⇒ halos ⇒ Galaxies

Measuring Cosmology

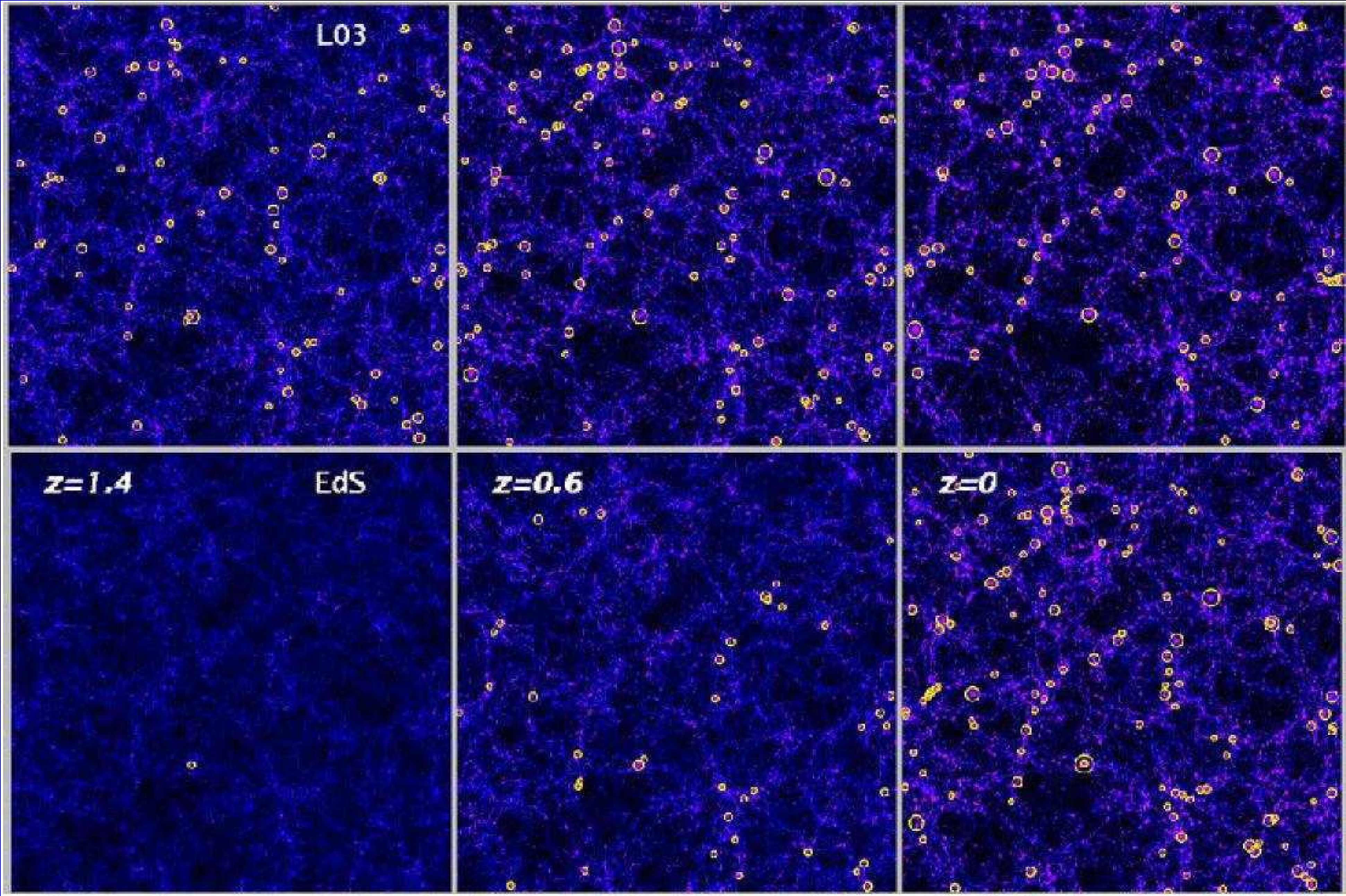
Comparison of density perturbations measured at different scales with linear growth (dashed line) and non linear growth measured from n-body simulations (solid line).



Tegmark et al. 2004

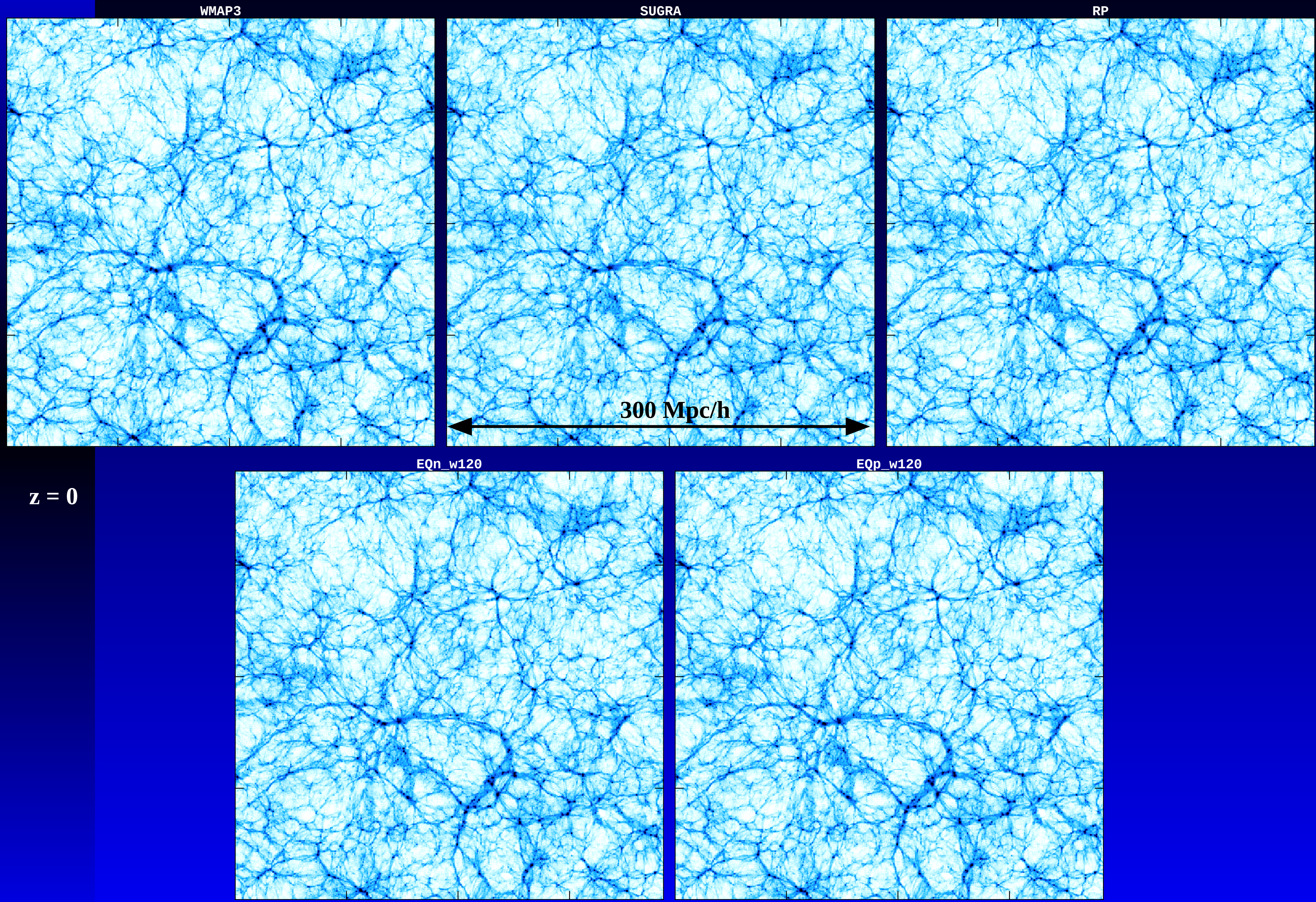
⇒ Bias from comparing pure dark matter with luminous matter !

Measuring Cosmology



Number of Massive galaxy clusters (Borgani & Guzzo 2001)

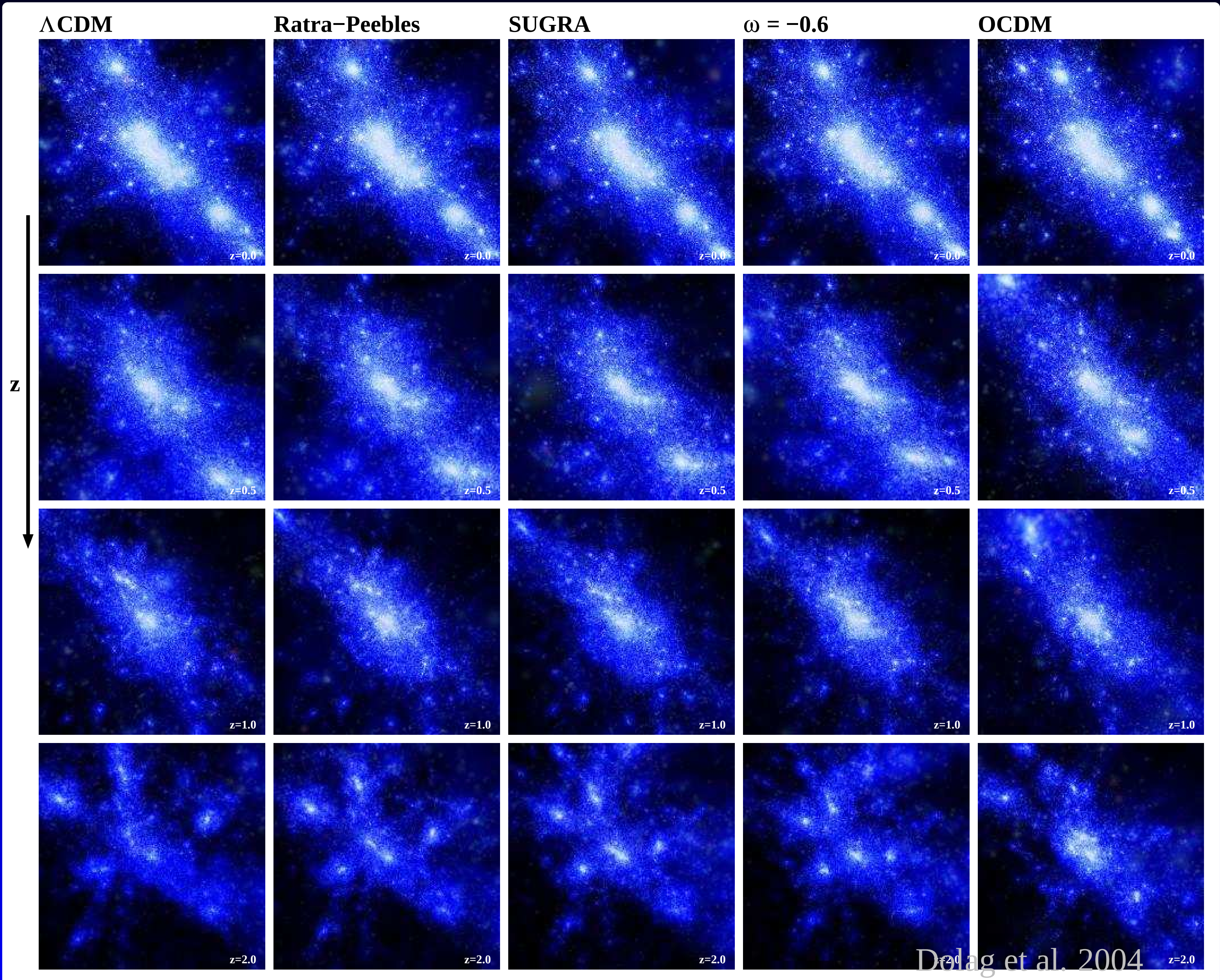
Measuring Cosmology



$z = 0$

Details between different DE models difficult to catch !

Measuring Cosmology

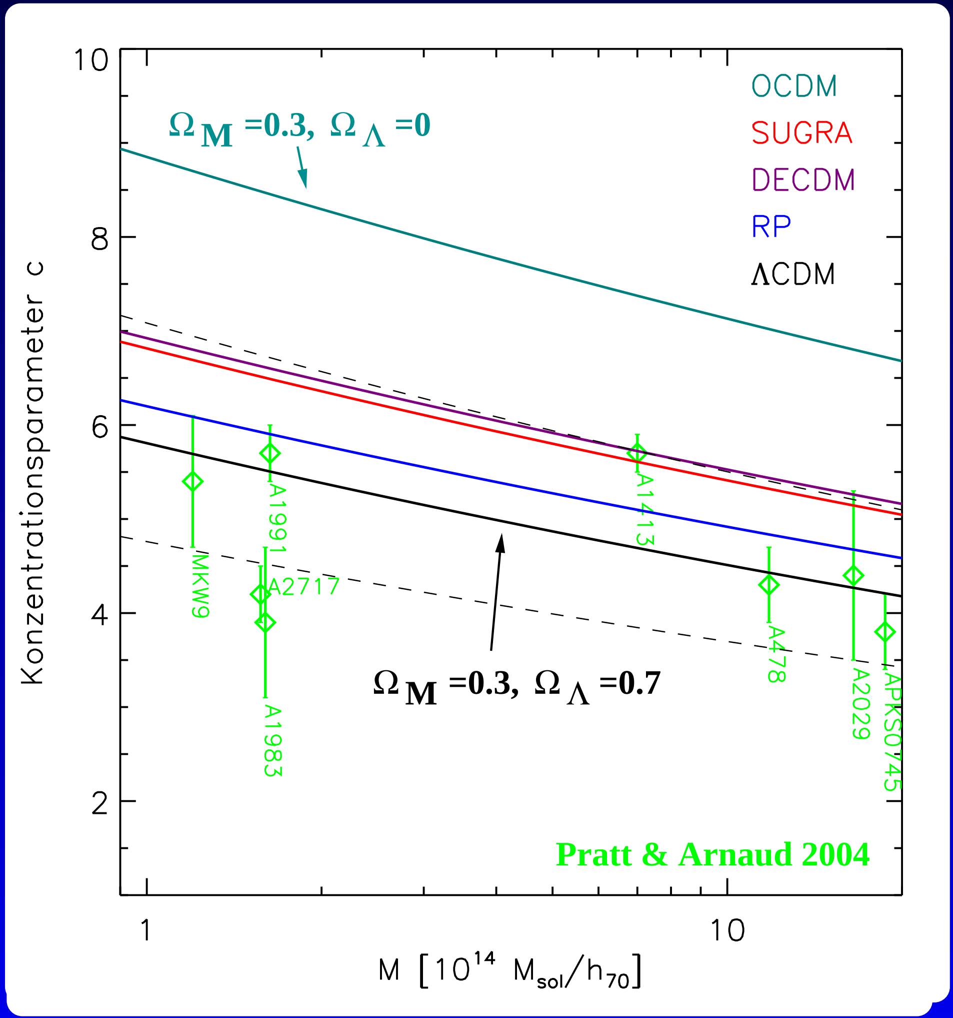


Evolutionary sequence of cluster in various DE scenarios.

Measuring Cosmology

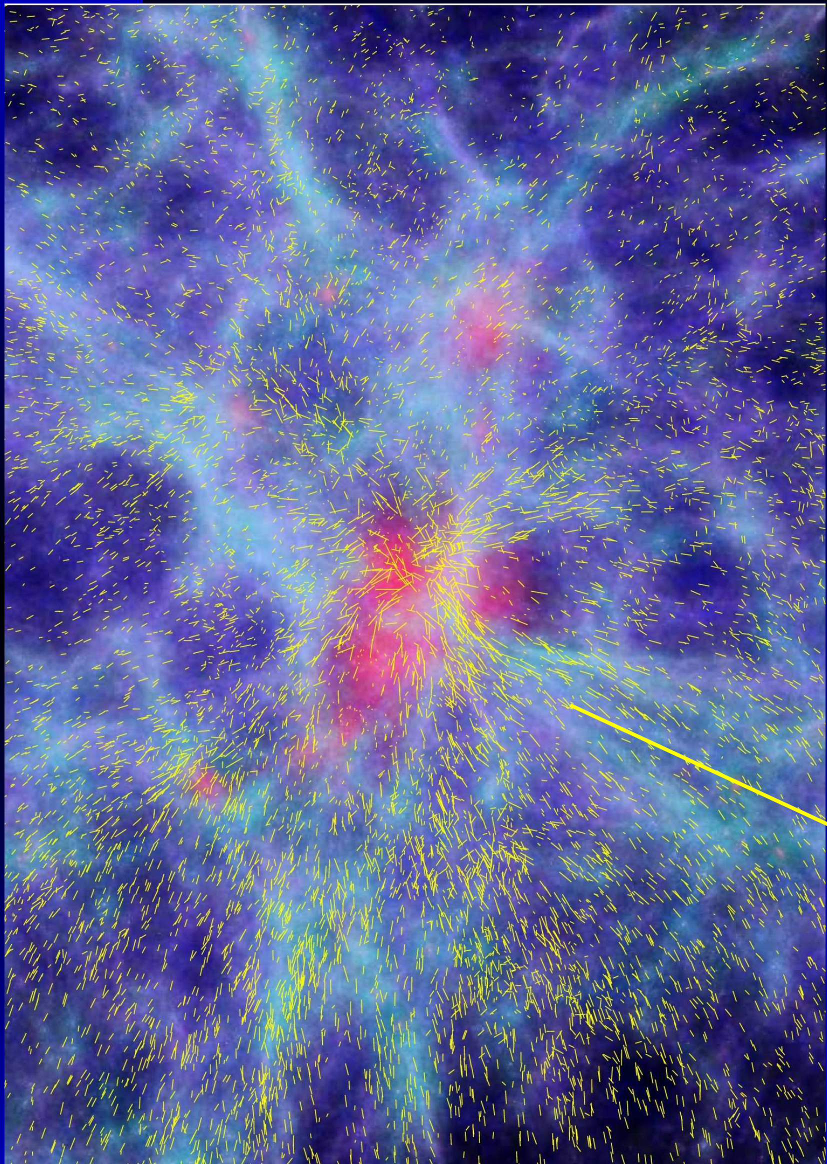
Universal density profile (NFW, 1997):

$$\rho(r) = \frac{\rho_0}{(r/r_\mathrm{s})(1+r/r_\mathrm{s})^2}, c = r_{200}/r_\mathrm{s}$$



Inner structure remembers formation history !

Measuring Cosmology



Vol 451|31 January 2008|doi:10.1038/nature06555 nature

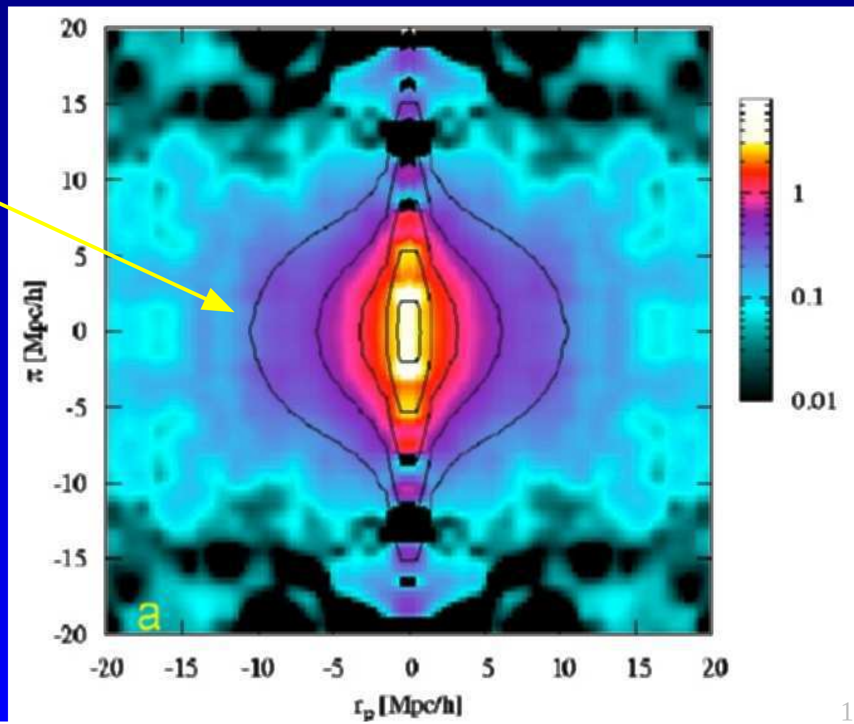
Nature 2008 LETTERS

A test of the nature of cosmic acceleration using galaxy redshift distortions

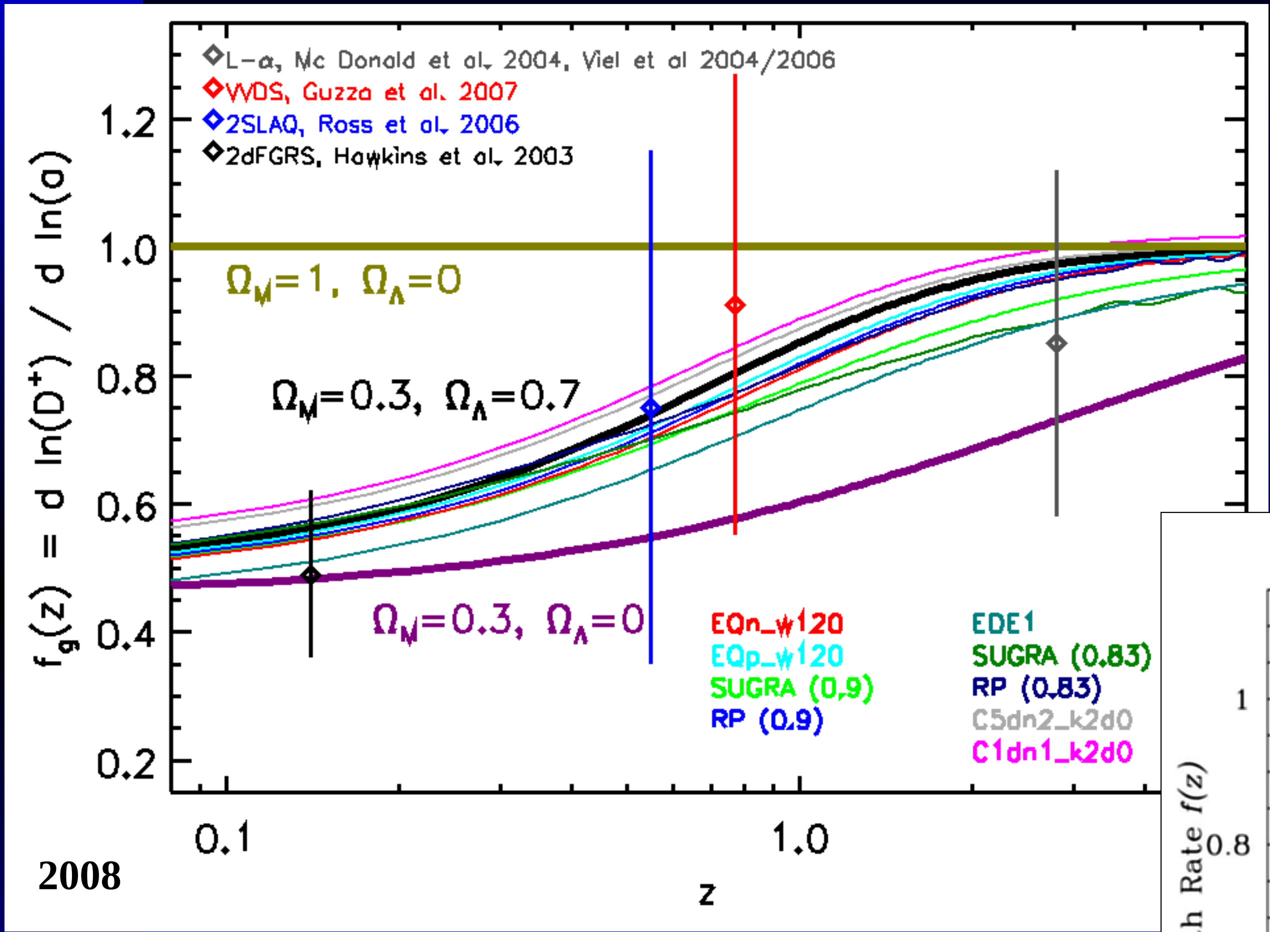
L. Guzzo[1,2,3,4], M. Pierleoni[3], B. Meneux[5], E. Branchini[6], O. Le Fèvre[7], C. Marinoni[8], B. Garilli[5], J. Blaizot[3], G. De Lucia[3], A. Pollo[7,9], H. J. McCracken[10,11], D. Bottini[5], V. Le Brun[7], D. Maccagni[5], J. P. Picat[12], R. Scaramella[13,14], M. Scodeggio[5], L. Tresse[7], G. Vettolani[13], A. Zanichelli[13], C. Adami[7], S. Arnouts[7], S. Bardelli[15], M. Bolzonella[15], A. Bongiorno[16], A. Cappi[15], S. Charlot[10], P. Ciliegi[15], T. Contini[12], O. Cucciati[1,17], S. de la Torre[7], K. Dolag[3], S. Foucaud[18], P. Franzetti[5], I. Gavignaud[19], O. Ilbert[20], A. Iovino[1], F. Lamareille[15], B. Marano[16], A. Mazure[7], P. Memeo[5], R. Merighi[15], L. Moscardini[16,21], S. Paltani[22,23], R. Pellò[12], E. Perez-Montero[12], L. Pozzetti[15], M. Radovich[24], D. Vergani[5], G. Zamorani[15] & E. Zucca[15]

Observations of distant supernovae indicate that the Universe is now in a phase of accelerated expansion[1,2] the physical cause of which is a mystery[3]. Formally, this requires the inclusion of a term acting as a negative pressure in the equations of cosmic expansion, accounting for about 75 per cent of the total energy density in the Universe. The simplest option for this 'dark energy' corresponds

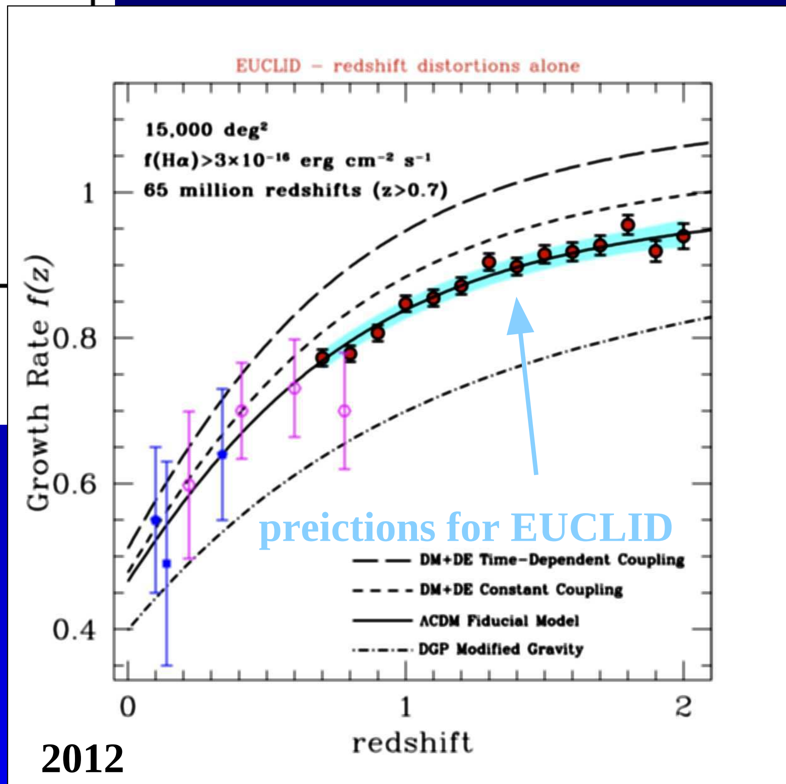
linear growth rate f that measures how rapidly structure is being assembled in the Universe as a function of cosmic time, or, equivalently, of the redshift. The redshift $z = \lambda_{meas}/\lambda_{emis} - 1$ of the radiation emitted by a distant object is a measure of the time of emission through its dependence on the cosmic scale factor $a(t)$, which is $1 + z = 1/a(t_{emis})$. $f(z)$ essentially depends on the value of the mass



Measuring Cosmology



provided by G. Guzzo



Measuring the growth of structure from large galaxy surveys.

$\Rightarrow$ It confirms $\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$

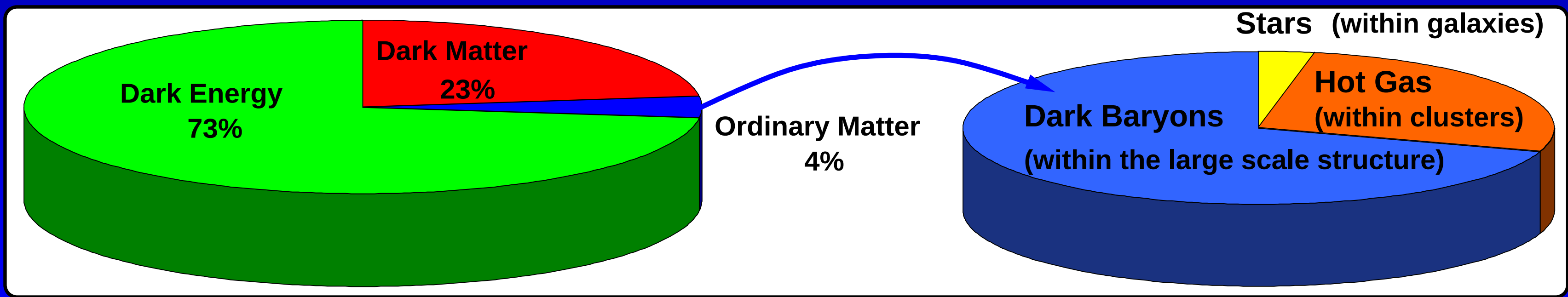
Galaxy Clusters in Numbers

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

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

Observed to be virialized:

$$3\sigma^2_{\rm galaxies} \approx \frac{GM_{\rm tot}}{R_{\rm cluster}} \approx \frac{3kT_{\rm ICM}}{2\mu m_p}$$



Galaxy Clusters in Numbers

-70 Years:

Unvisible matter needed to explain cluster dynamics

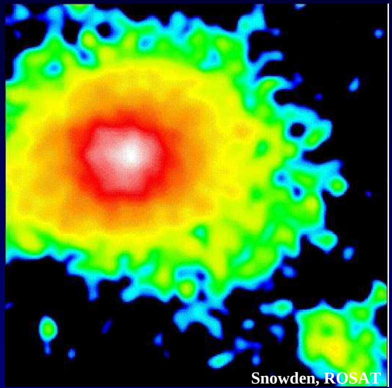
Zwicky 1936

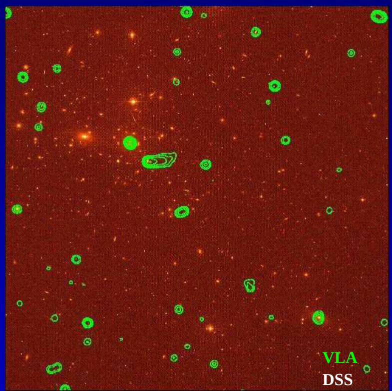
-50 Years:

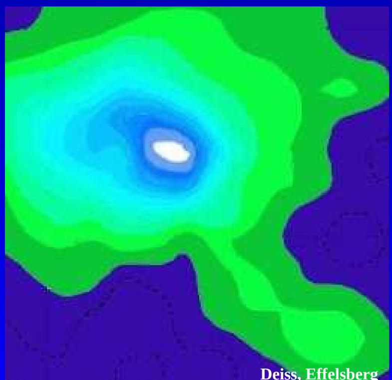
- Abell's Catalog of Rich Clusters
  Abell 1958
- Coma C detected as extended radio source
  Large, Masthewson & Haslam 1959
- Confirmed to be diffuse radio emission
  Willson 1970 ⇒ problem of large extend Jaffe 1977
- No similar emission found in 72 rich clusters
  Hanisch 1982
- Diffuse X-ray emission detected
  Meekins, Fritz, Chubb & Friedman 1971
- Faraday Rotation (RM) of ICM detected
  Dennison 1979

Galaxy Clusters in Numbers

Observations ($\Rightarrow$), Processes ($\Leftarrow$) and the role of $\vec{B}$:







ICM (X-ray, $T \approx 10^8$K, Bremsstrahlung):

- $\Rightarrow$ Dynamical state of ICM
- $\Leftarrow$ Non thermal **pressure** support
- $\Leftarrow$ **Turbulence**, **Viscosity**, Shocks

Galaxies (optical, radio, $N_{\rm gal} > 1000$):

- $\Rightarrow$ Interaction with the ICM
- $\Leftarrow$ Galaxies in dense environment (**stripping**, distribution of metals)
- $\Leftarrow$ Magnetic field **seeding** (outflows)

ICM (radio, synchrotron radiation, RM):

- $\Rightarrow$ Distribution of $\vec{B}$, CRs (diffuse + RM)
- $\Leftarrow$ **Evolution** and **buildup** of $\vec{B}$
- $\Leftarrow$ **Acceleration** and **propagation** of CRs

Galaxy Clusters in Numbers

Characteristic Time Scales:

- Crossing time: $t_{\rm cross} \approx \frac{R}{\sigma} \approx 10^9 {\rm yrs} \frac{R[{\rm Mpc}]}{\sigma[1000{\rm km/s}]}$
- Relaxation time (two body relaxation): $t_{\rm relax} \approx \frac{0.1 N t_{\rm cross}}{f^2 \ln(\Lambda)}$,

  $f = \frac{Nm}{M_{\rm tot}} \approx 0.1$ (90% dark matter), $\ln(\Lambda) \approx 3$, see: Binney/Tremain

  - Relaxation of Galaxies:

    $N \approx 300 \ldots 3000 \Rightarrow t_{\rm relax} \approx 10^{12} \ldots 10^{13} {\rm yrs}$
  - Relaxation of sub-clumps:

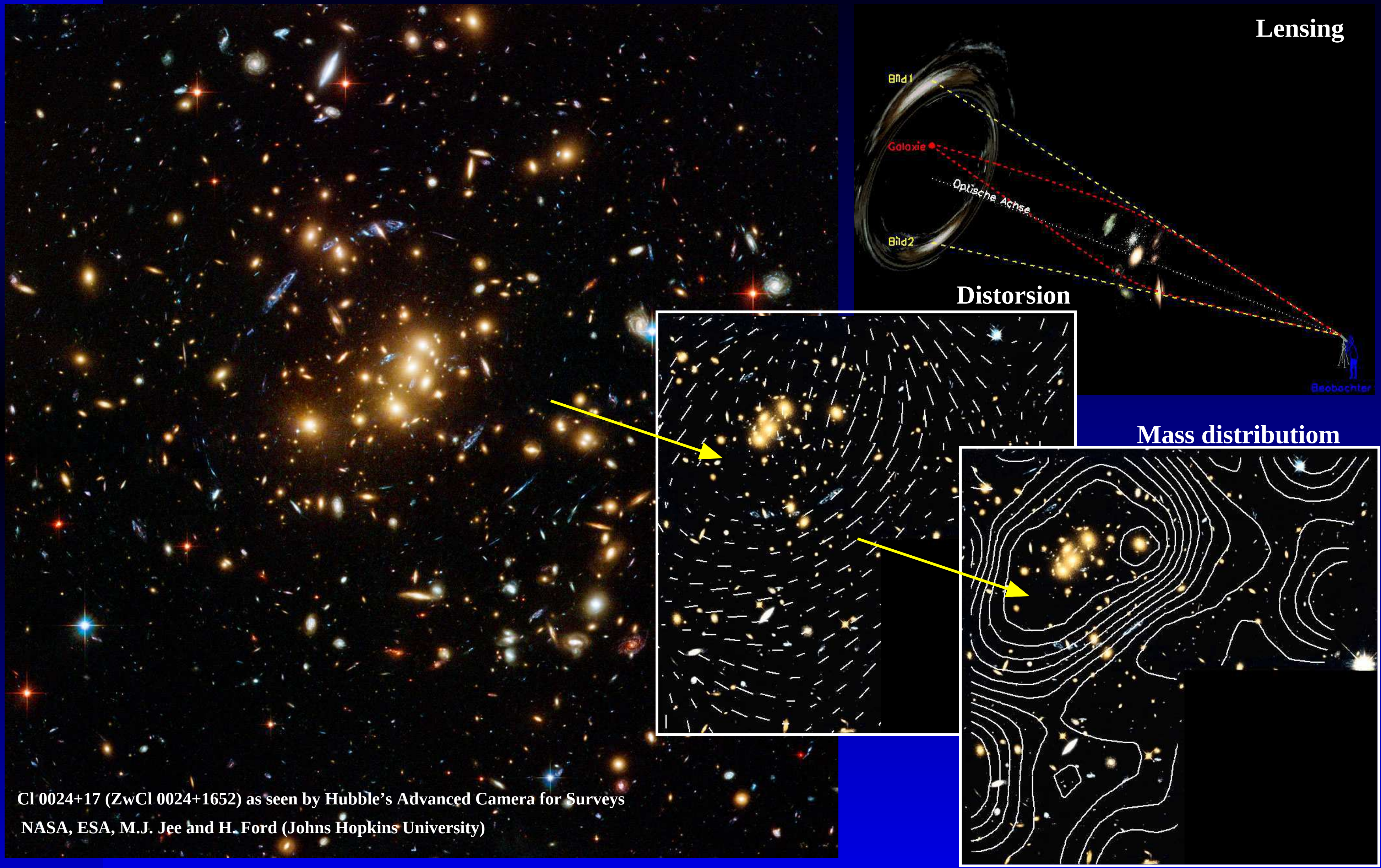
    $N \approx 3 \ldots 30 \Rightarrow t_{\rm relax} \approx 10^{10} \ldots 10^{11} {\rm yrs}$
  - Violent Relaxation (major merger):

    $t_{\rm violent} \approx 5 t_{\rm cross} \approx 5 \times 10^9 {\rm yrs} \frac{R[{\rm Mpc}]}{\sigma[1000{\rm km/s}]}$
- Dynamical friction: $\frac{{\rm d}v}{{\rm d}l} \approx 2 \frac{GM}{r^2}$

  $t_{\rm friction} \approx 5 \times 10^{13} {\rm yrs} \frac{v[{\rm km/s}](R[{\rm Mpc}])^2}{M[10^{10} {\rm M}_\odot]}$

  (Massive object moving between numerous less massive bodies)

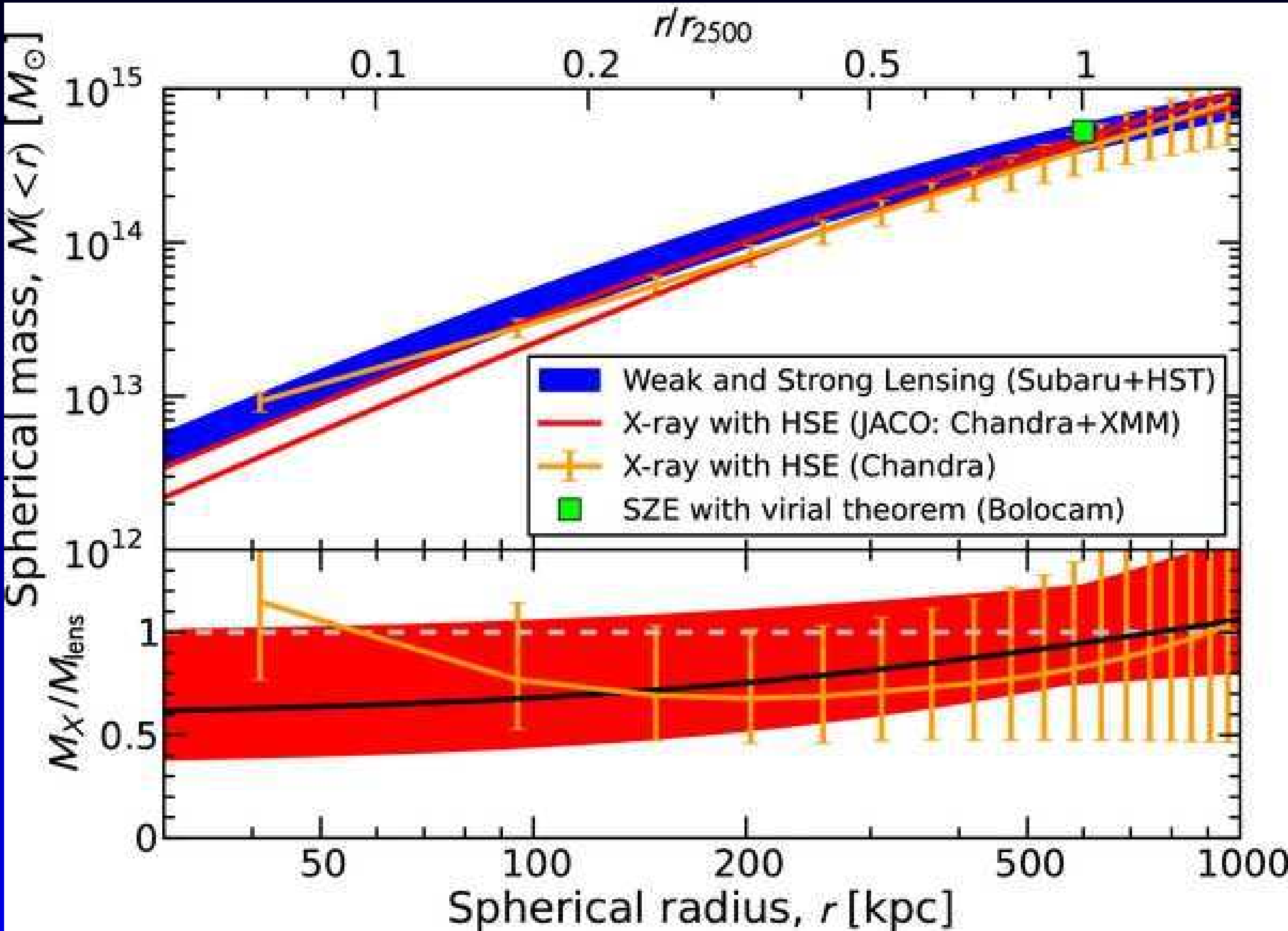
Galaxy Clusters in Numbers



Cl 0024+17 (ZwCl 0024+1652) as seen by Hubble's Advanced Camera for Surveys
NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)

Gravitational Lensing of background galaxies allows to infer the total mass of a galaxy cluster !

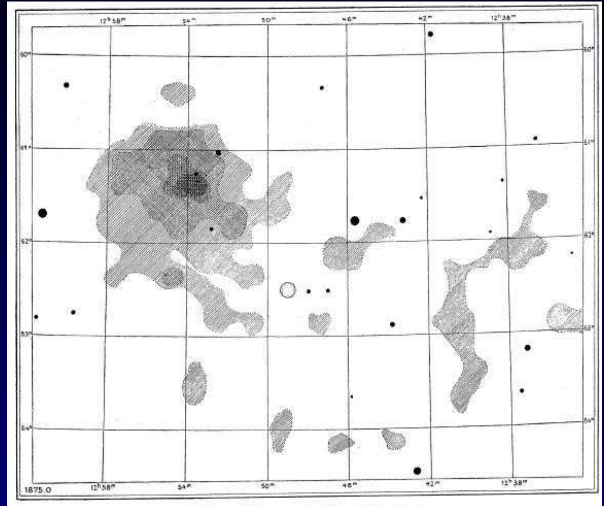
Galaxy Clusters in Numbers



MACS J1206.2-0847 Keiichi Umetsu et al. 2012

Galaxy Bimodality

	0^m	59^m	58^m	57^m	56^m	55^m	54^m	53^m	52^m	51^m	50^m	49^m	48^m	47^m	46^m	45^m	44^m	43^m	42^m	41^m	40^m	39^m	38^m	37^m	36^m	35^m	
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	—
30	—	0	2	3	4	3	2	3	5	3	1	3	0	0	0	2	4	1	0	0	0	3	2	0	0	2	0
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
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
15	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
30	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
45	0	5	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3
62° 0′	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
15	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
30	—	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
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																											



Nebelvertheilung um den Pol der Milchstrasse

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

$$\alpha = 12^h\,52^m\!.6 \quad \delta = +28^\circ\,42' \ (1855.0)$$

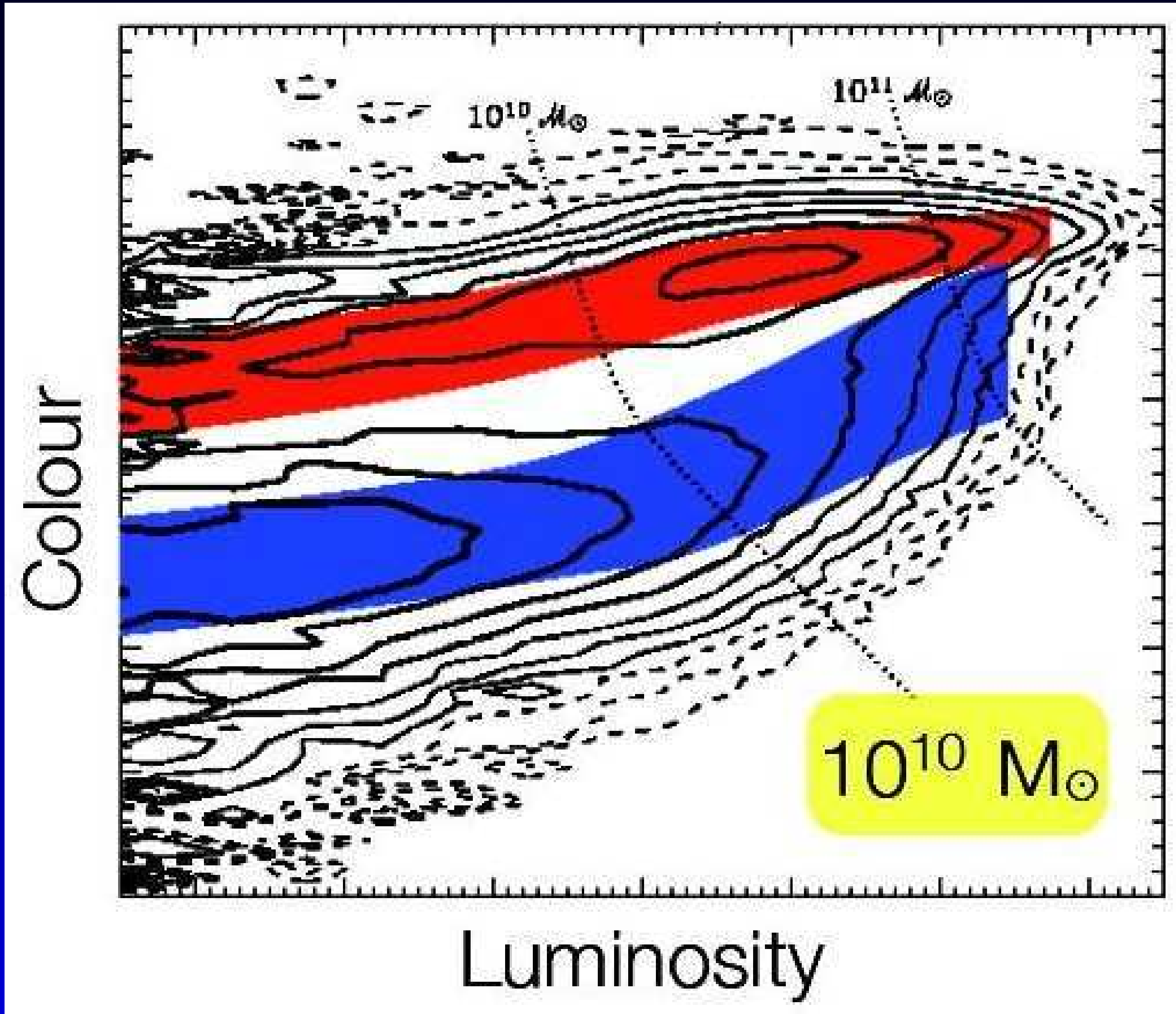
stehen nämlich zahlreiche kleine Nebelflecken so dicht beisammen, dass man beim Anblick der Gegend förmlich über das merkwürdige Aussehen dieses »Nebelhaufens« erschrickt. Ich habe die Anzahl der Nebel in einem Kreis von 30′ Durchmesser um die angegebene Stelle bestimmt und finde, dass mindestens 108 Nebelflecken auf dieser Fläche beisammen stehen, also auf einer Fläche etwa von der Grösse des Vollmondes. Darunter sind vier oder fünf grössere ausgedehnte und centralverdichtete Nebel, sowie mehrere langgestreckte. Die weitaus meisten haben aber rundliche Form und sind kleiner. *)

Heidelberg, 1901 März 27.

Max Wolf.

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).

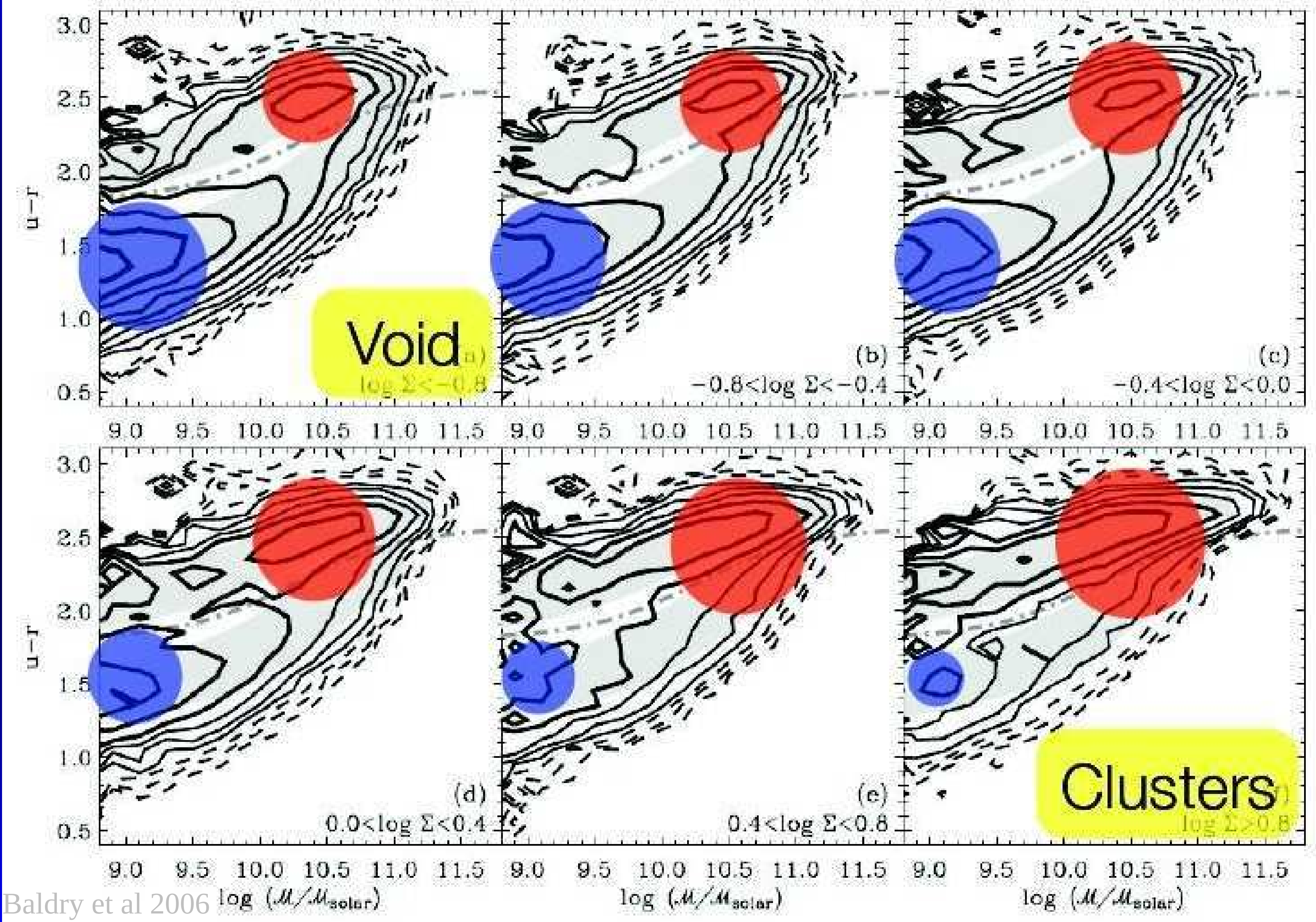
Galaxy Bimodality



Baldry et al 2006

Galaxies occupy two distinct regions, the red sequence and the blue cloud. Also mass seems to be important.

Galaxy Bimodality



Baldry et al 2006

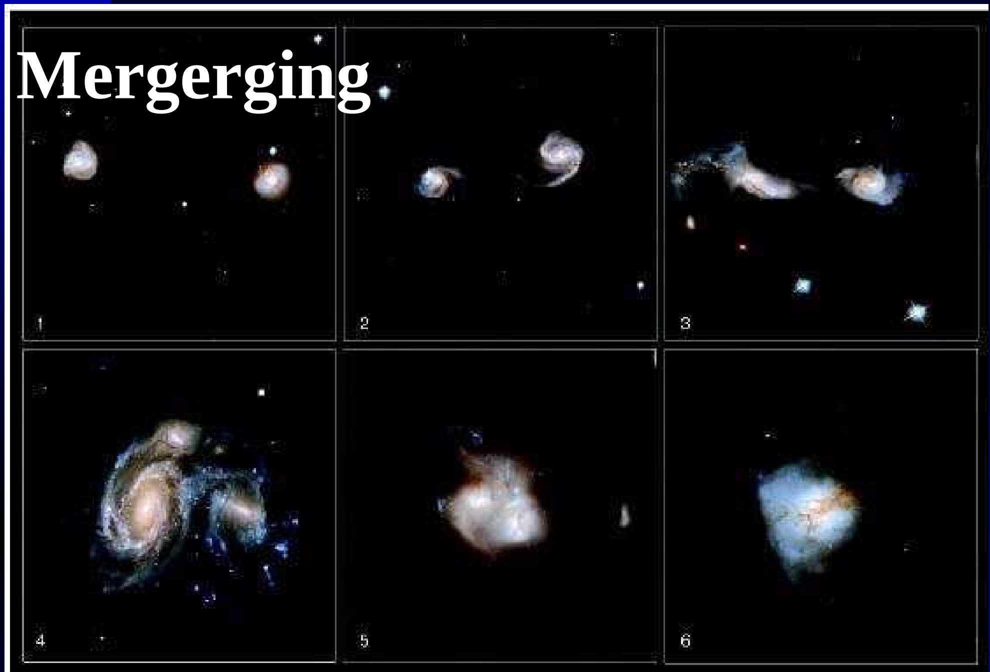
Galaxy Bimodality

Four classes of tranformation processes

Galaxy Bimodality

Four classes of tranformation processes

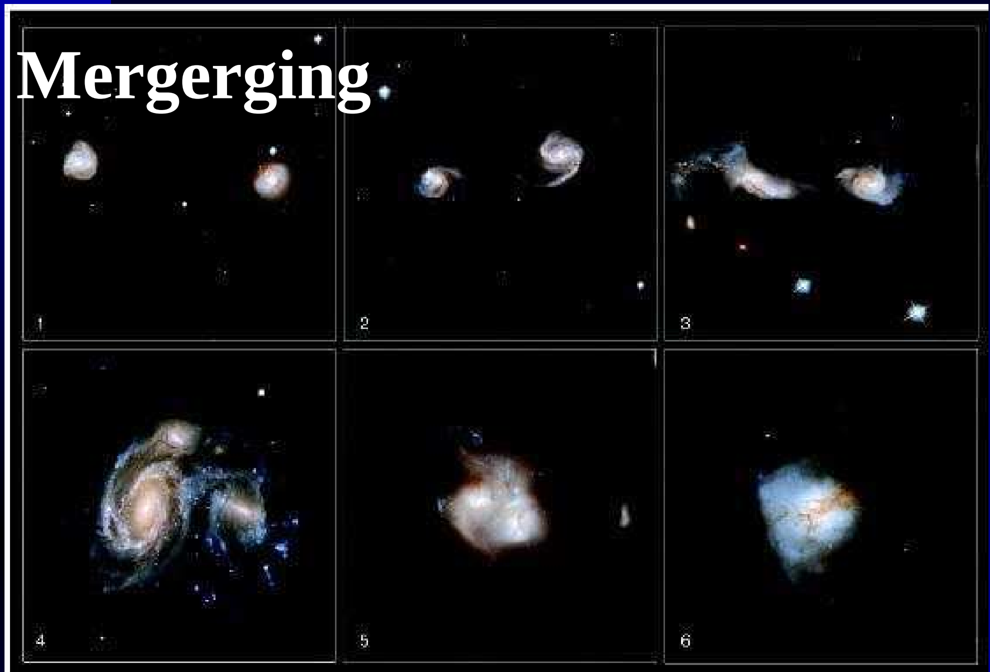
Mergerging



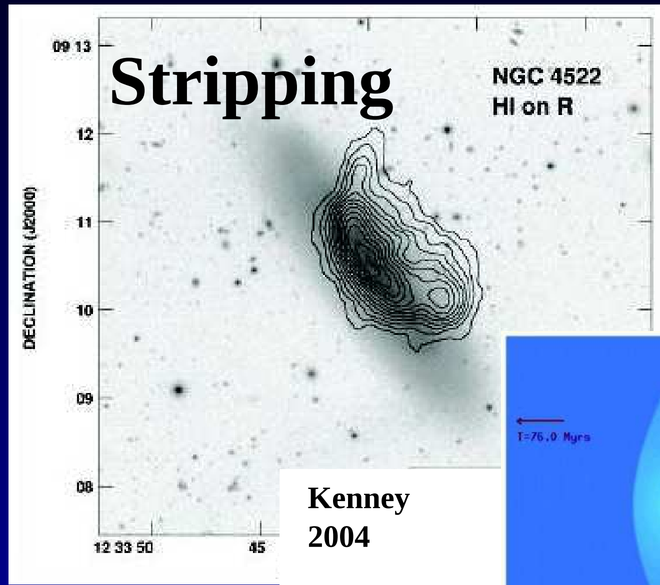
Galaxy Bimodality

Four classes of tranformation processes

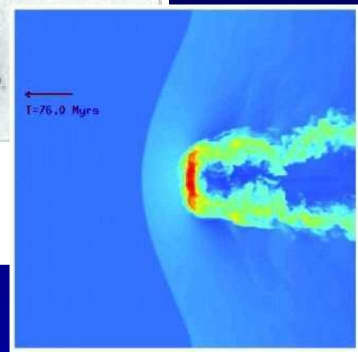
Mergerging



Stripping

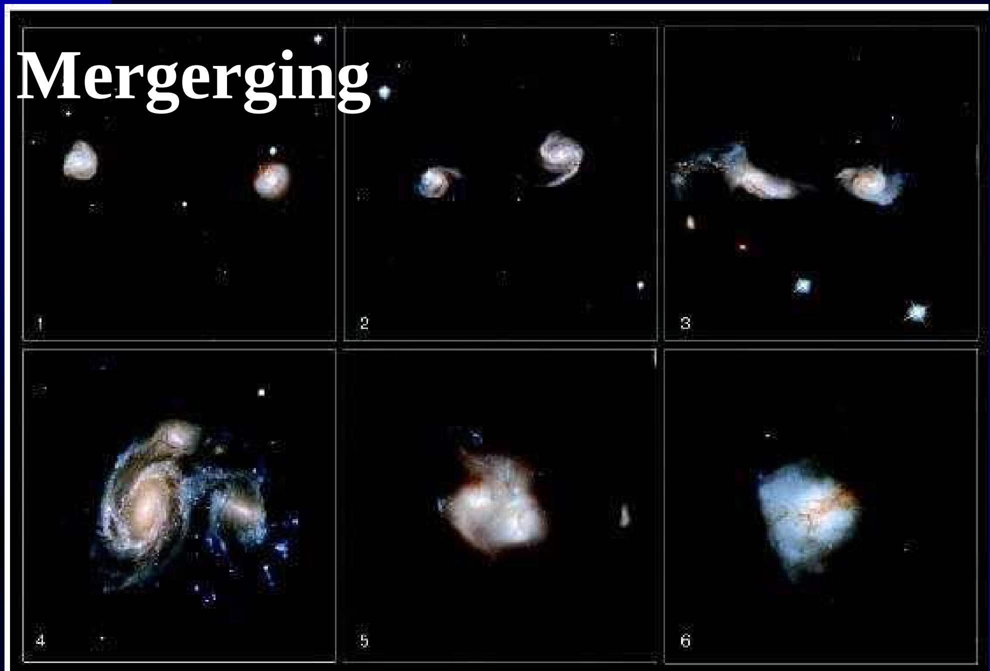


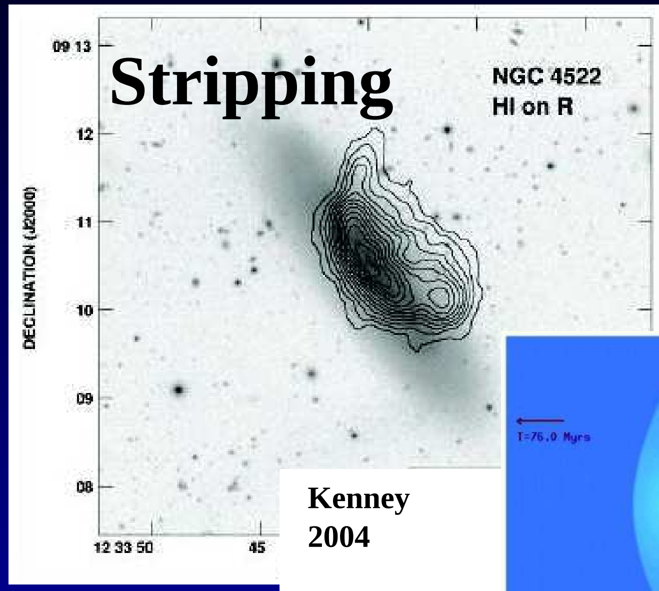
Kenney
2004

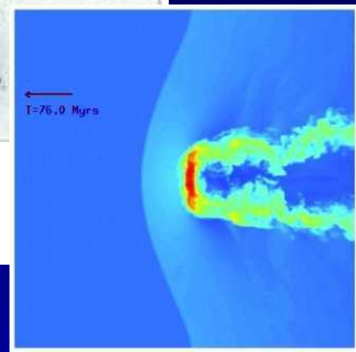


Galaxy Bimodality

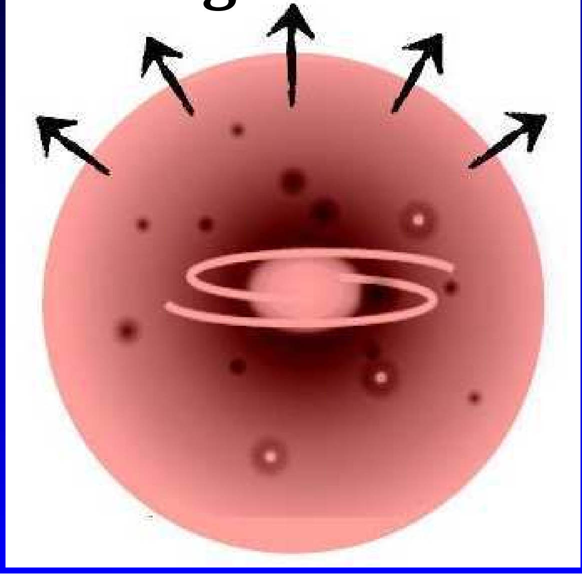
Four classes of tranformation processes





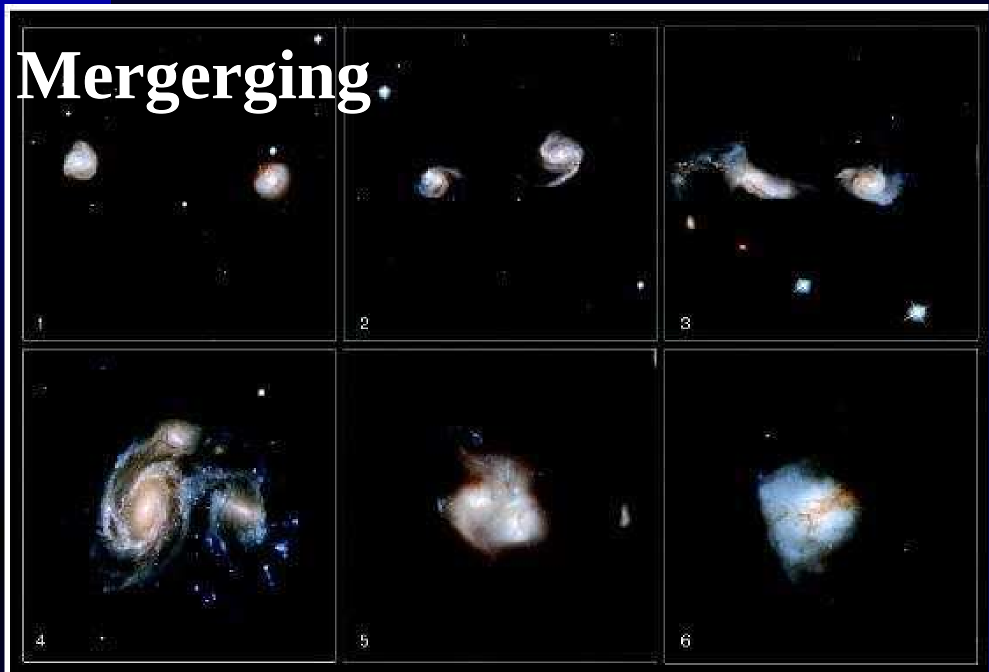


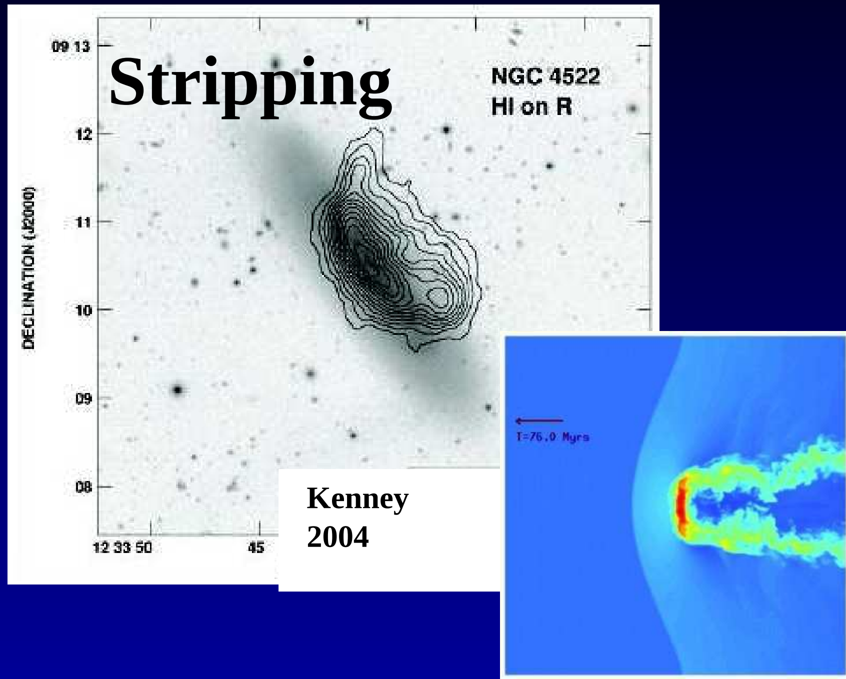
Strangulation

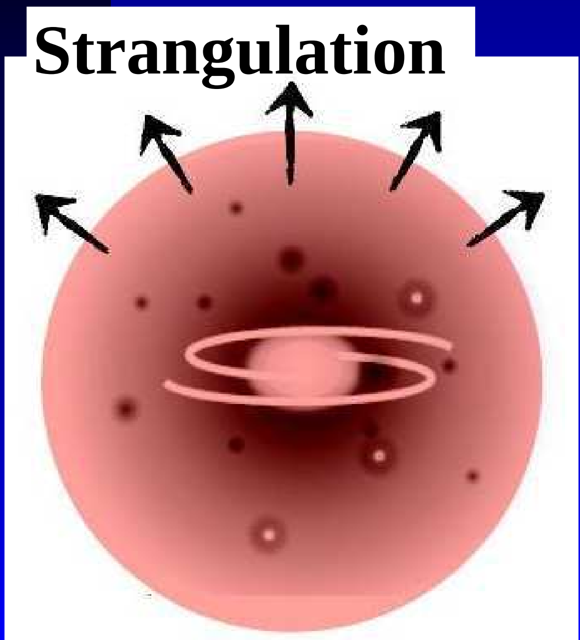


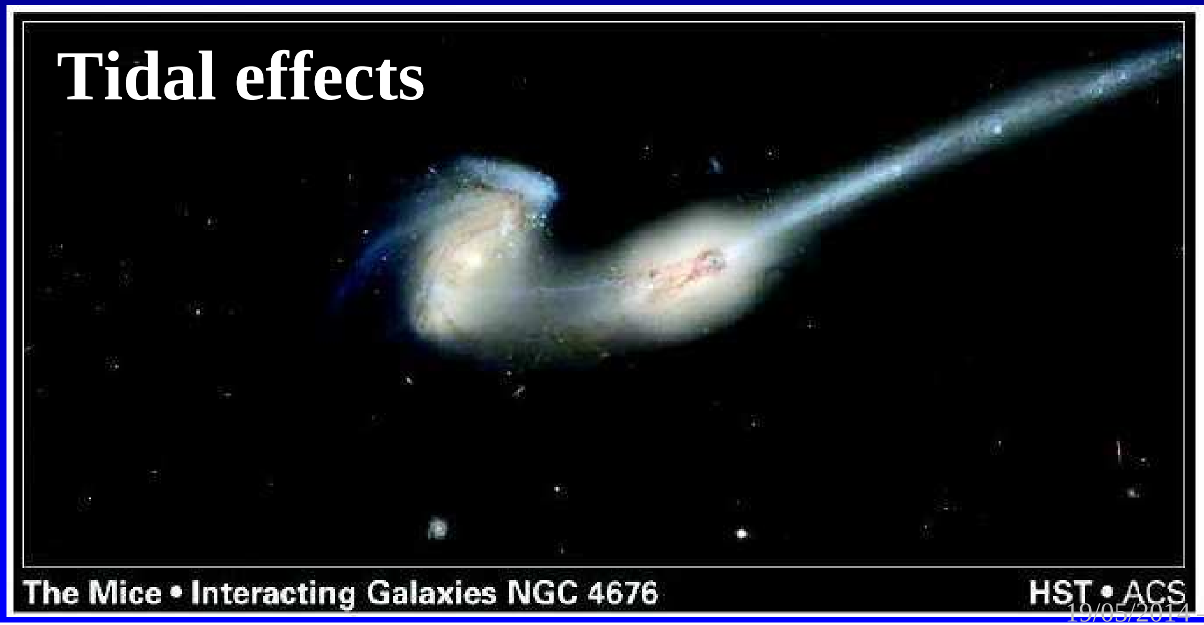
Galaxy Bimodality

Four classes of tranformation processes

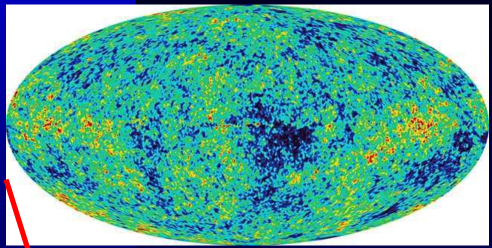








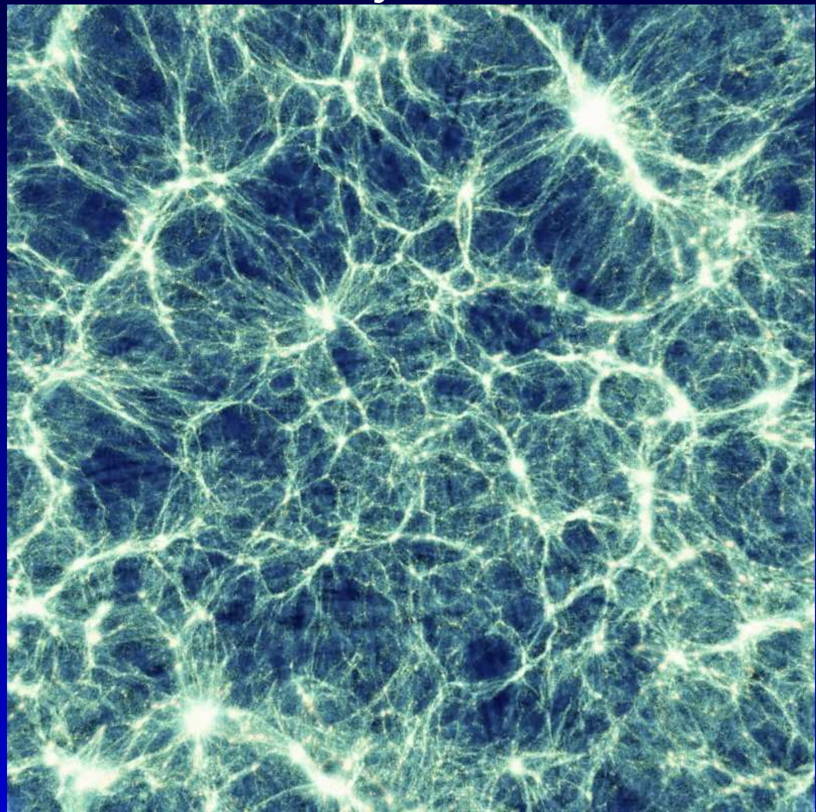
Structure Formation



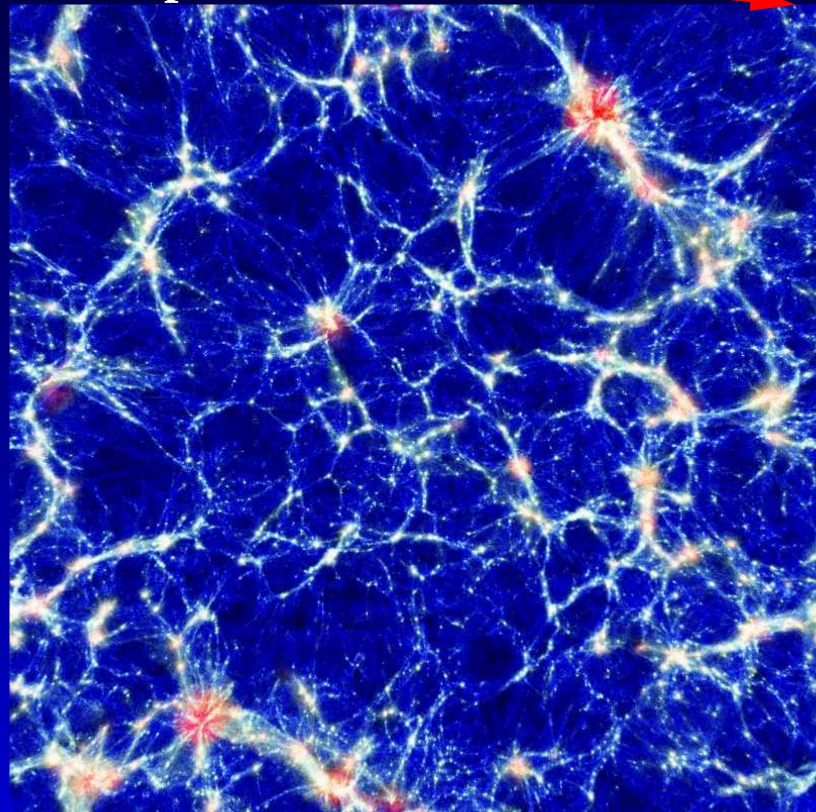
CMB (t = 0.38 Myr)

Cosmic structure today
(t = 13.7 Gyr)

Density



Temperature

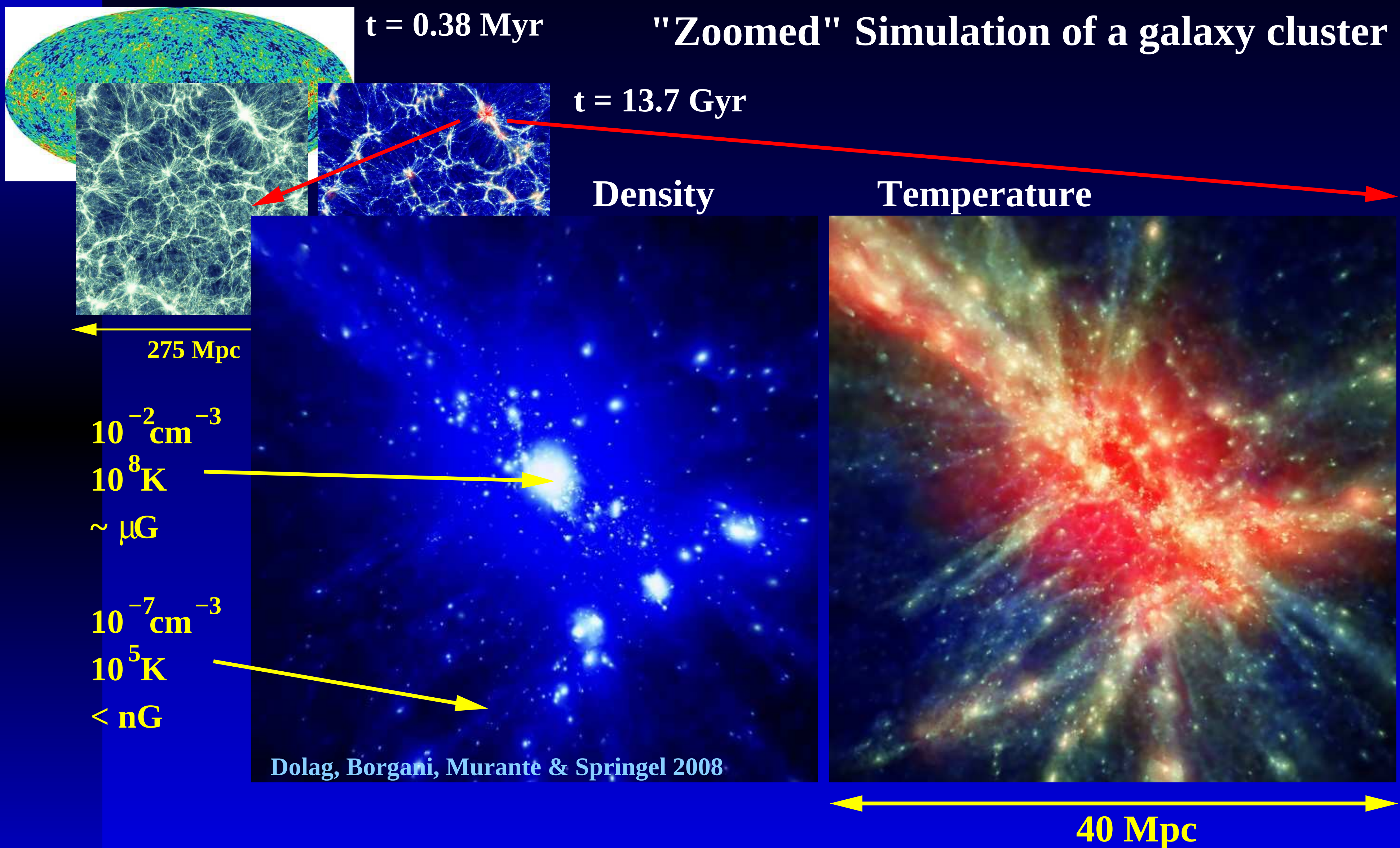


Borgani, Murante, Springel, Diaferio, Dolag et al. 2004

275 Mpc

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

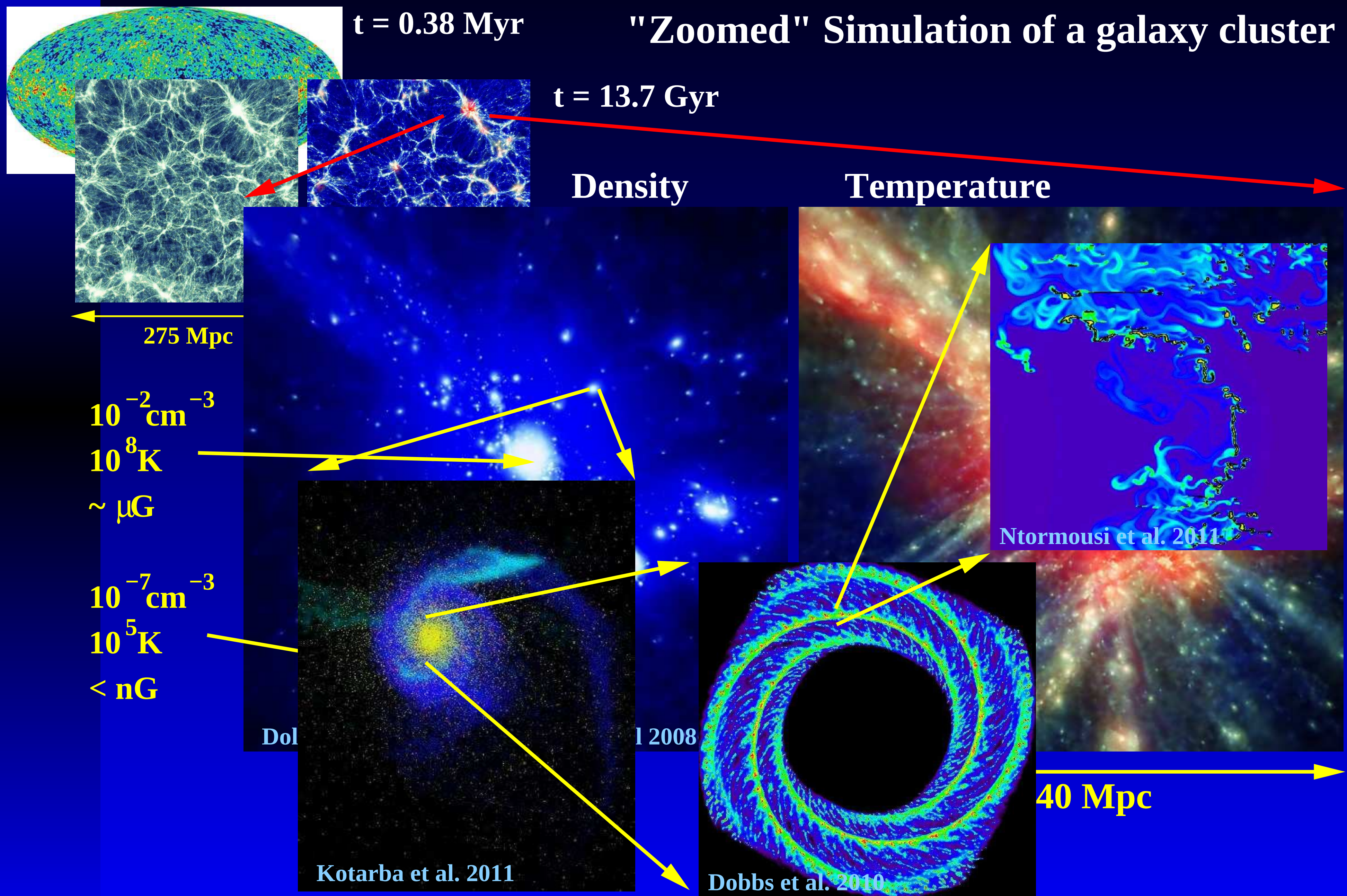
Structure Formation



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.

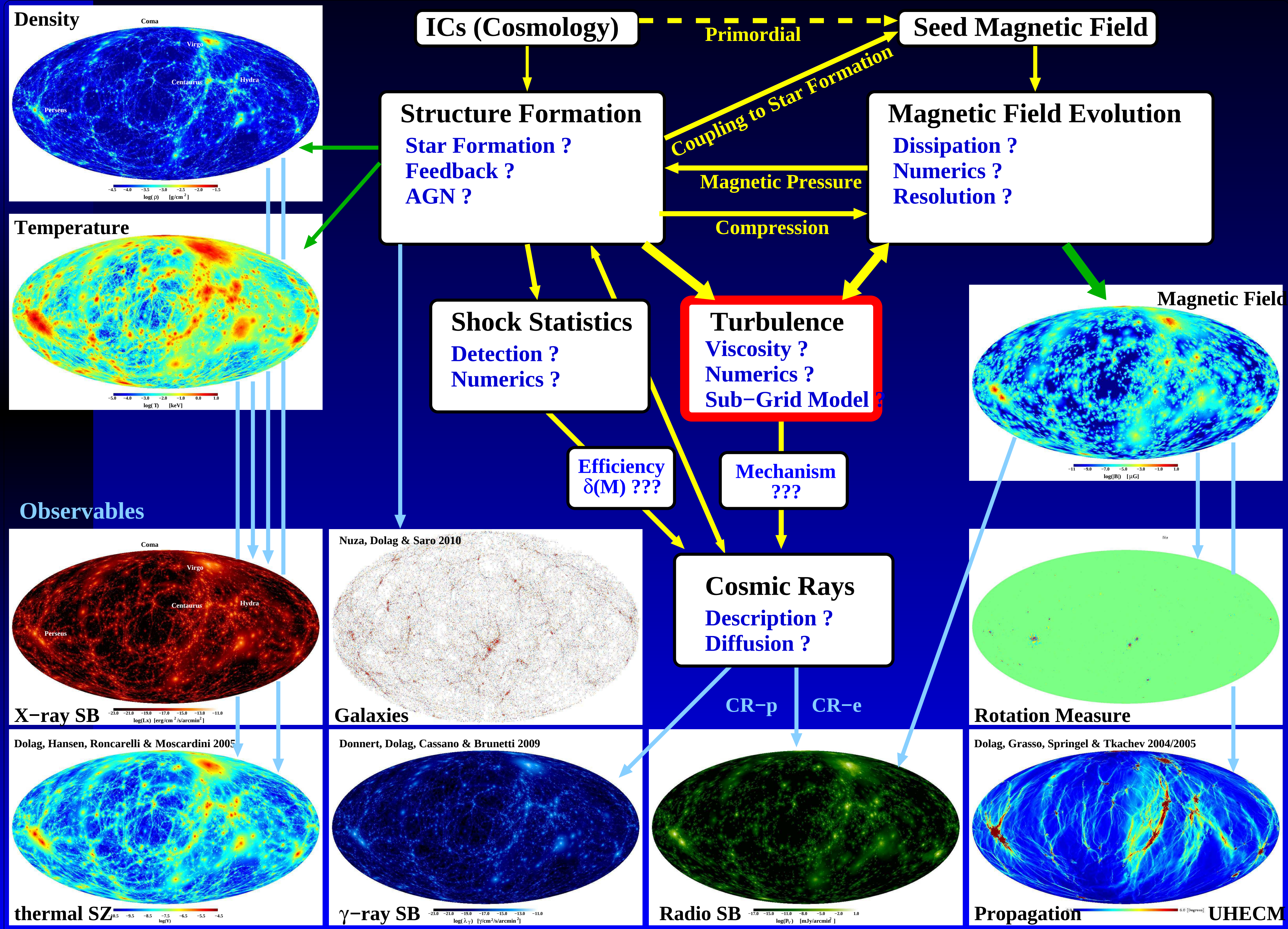
Structure Formation

"Zoomed" Simulation of a galaxy cluster

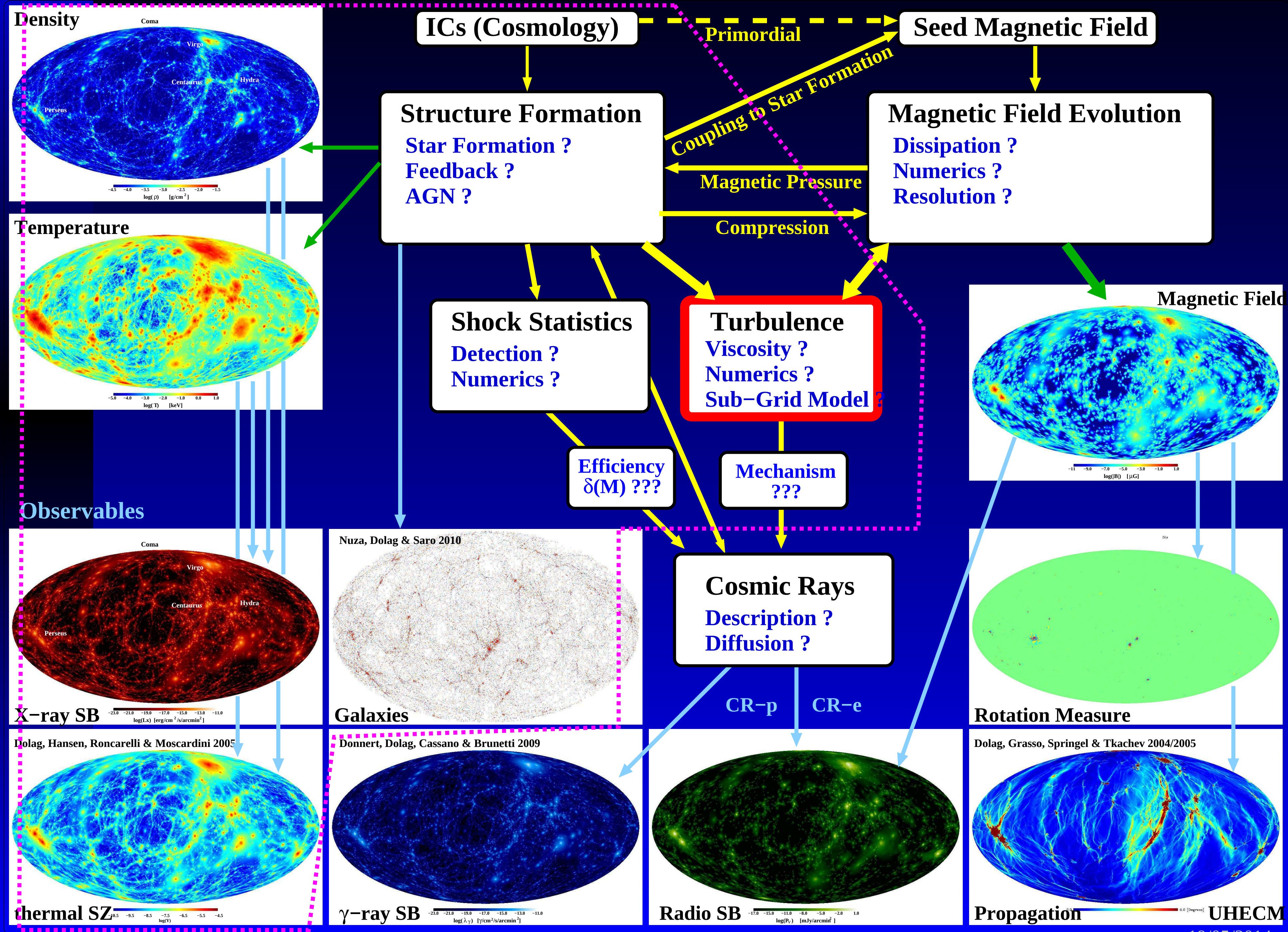


Need to capture processes happening far below the resolution !

Process Network

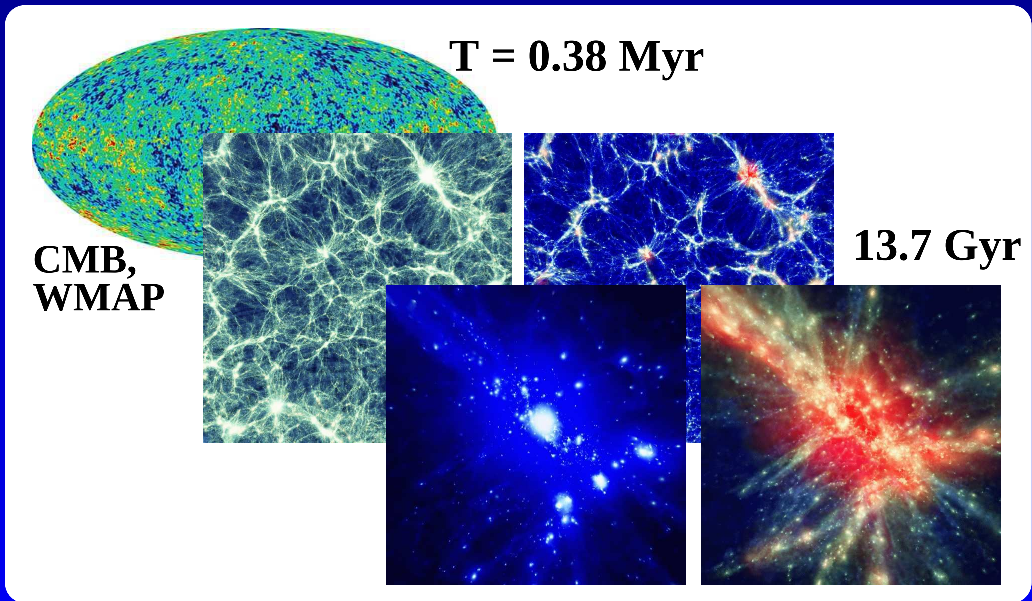


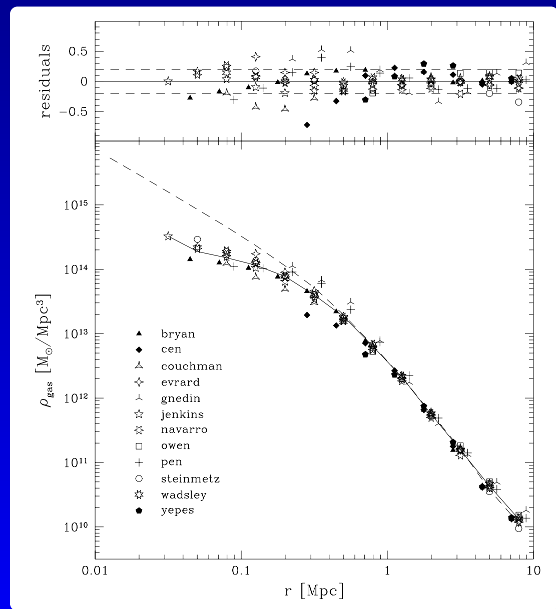
Process Network



Cosmological Simulations

- Gravity (N-Body system)
  Direct sum, Tree, Particle-Mesh, ...
- Hydrodynamics (including shocks)
  Mesh, Adaptive-Mesh, Shock capturing schemes, SPH, ...
- Cooling (radiative losses)
  primordial mixture, metals, ...





Frenk et al. 1999

Cosmological Simulations

- Star-formation (not resolved)
  simplified description, sub-grid models, ...
- Feedback (poorly understood)
  energetics, kinetics, ...
- AGN, Radiolopes, Bubbles
- Cosmic Rays
  from shocks, Feedback (SN), AGN, ...
- **Magnetic Fields**
- Thermal Conduction
- ...

Movie: stars,gas

Simulating the universe

Assuming that the matter filling the universe is collision-less and non-relativistic (e.g. cold dark matter, CDM), the evolution of its phase-space distribution function $f(\vec{x}, \vec{p}, t)$ can be described by the collision-less *Boltzmann* (e.g. *Vlasov*) equation.

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{ma(t)^2}\vec{\nabla} f - m\vec{\nabla}\Phi\frac{\partial f}{\partial \vec{p}} = 0$$

coupled with the *Poisson* equation

$$\vec{\nabla}^2\Phi(\vec{x}, t) = 4\pi G a(t)^2\left[\rho(\vec{x}, t) - \bar{\rho}(t)\right]$$

Φ: gravitational potential; $\bar{\rho}(t)$: background density.

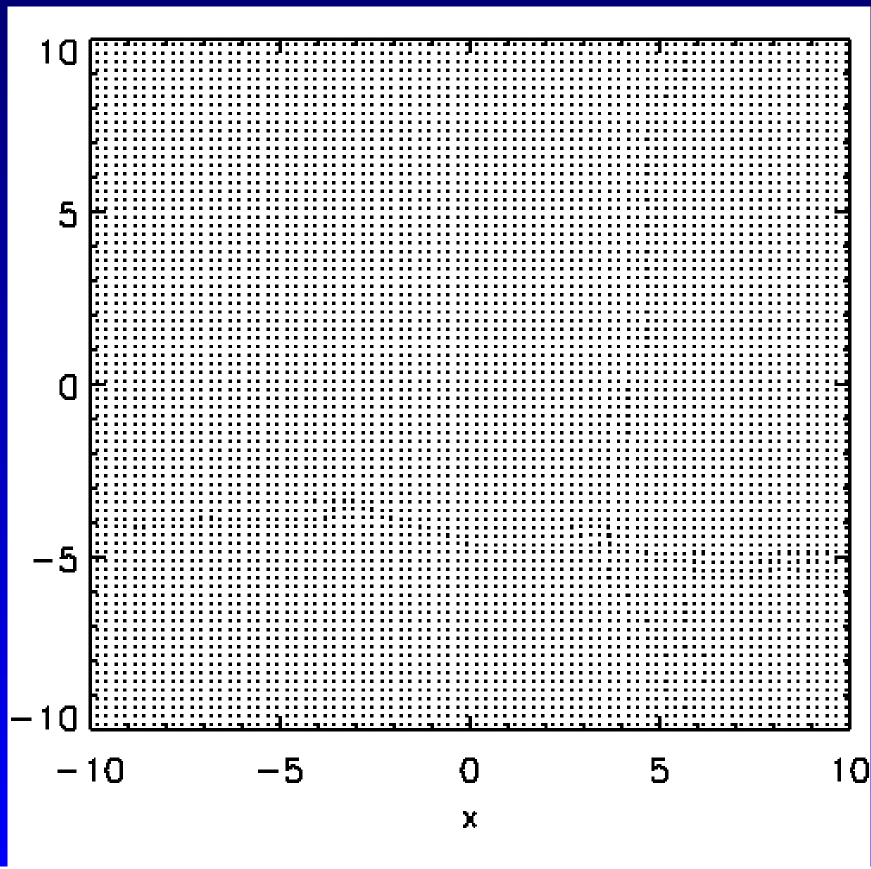
$$\rho(\vec{x}, t) = \int f(\vec{x}, \vec{p}, t)\mathrm{d}^3 p$$

$\Rightarrow$ high-dimensional problem !

Simulating the universe

One method to solve these equations is to sample the phase space density using tracing particles and to solve their equation of motion (e.g. n-body simulation).

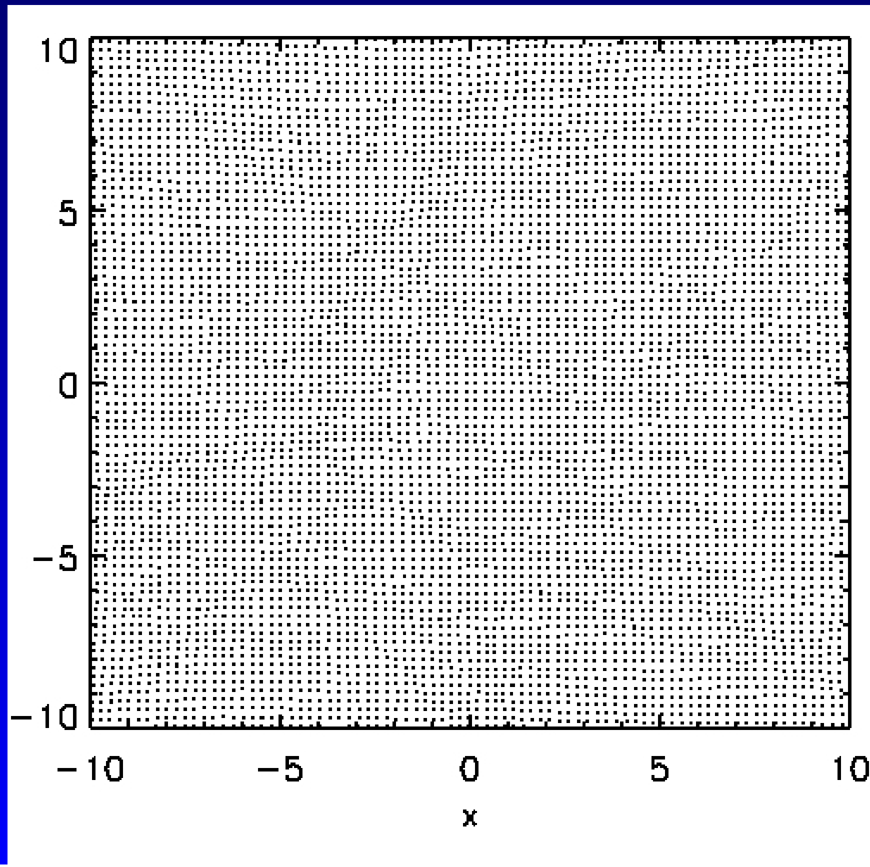
$$\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} + \vec{v}H(a) = -\frac{\vec{\nabla}\Phi}{a(t)}.$$



Simulating the universe

Assuming initial Gaussian density perturbation corresponding to a given density power spectrum, $P(|\vec{k}|)$, one can compute the potential $\Phi(\vec{q})$ on the grid $\vec{q}$. Using *Zel'dovich* approximation), one obtains the perturbed particle positions as initial conditions.

$$\vec{x}(a_{ini}) = \vec{q} - D_+(a_{ini})\Phi(\vec{q}), \quad \vec{v}(a_{ini}) = \dot{D}_+(a_{ini})\vec{\nabla}\Phi(\vec{q})$$



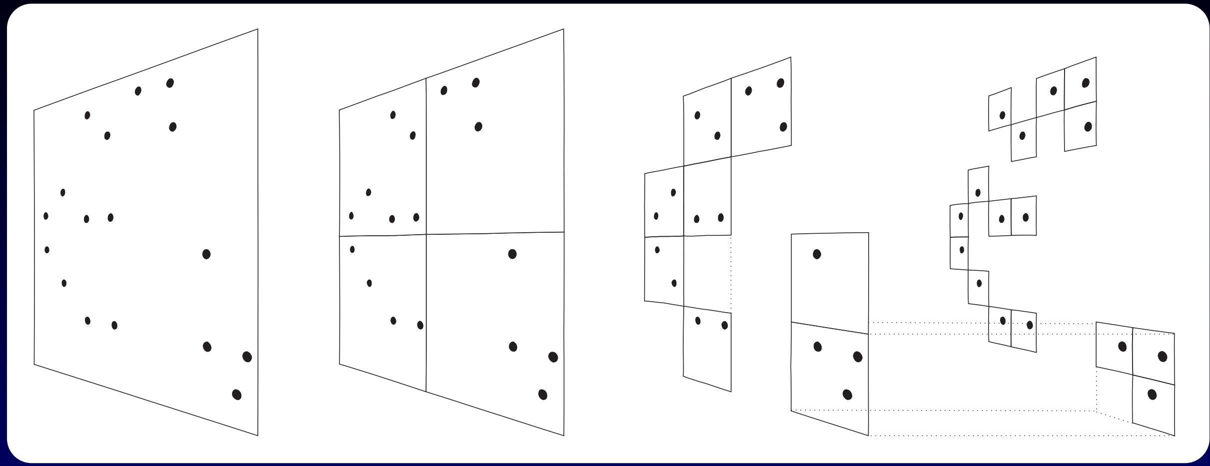
Simulating the universe

Integrate the equation of motion, within the framework of the expanding universe.

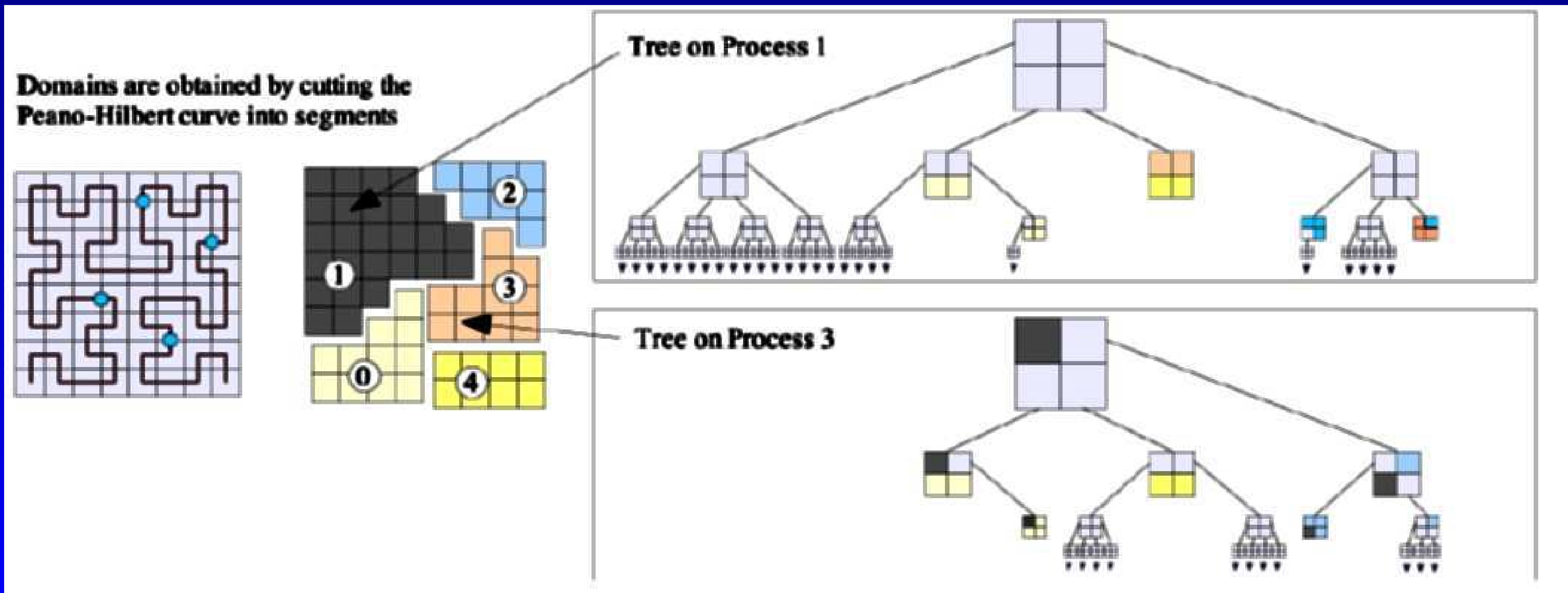
$\Rightarrow$ formation of typical, cosmic structures like voids, filaments and collapsed objects (e.g. galaxies and galaxy clusters)

Gravity

Tree-PM



$$\Phi(\vec{r}) = -G \sum_j \frac{m_j}{(|\vec{r} - \vec{r}_j|^2 + \epsilon^2)^{\frac{1}{2}}}.$$



Gravity

Tree-PM

- density on the grid

$$\rho_m = \frac{1}{h^3} \sum_i m_i W(\vec{x}_i - \vec{x}_m).$$

- solve for Φ using FFT methods FFTW

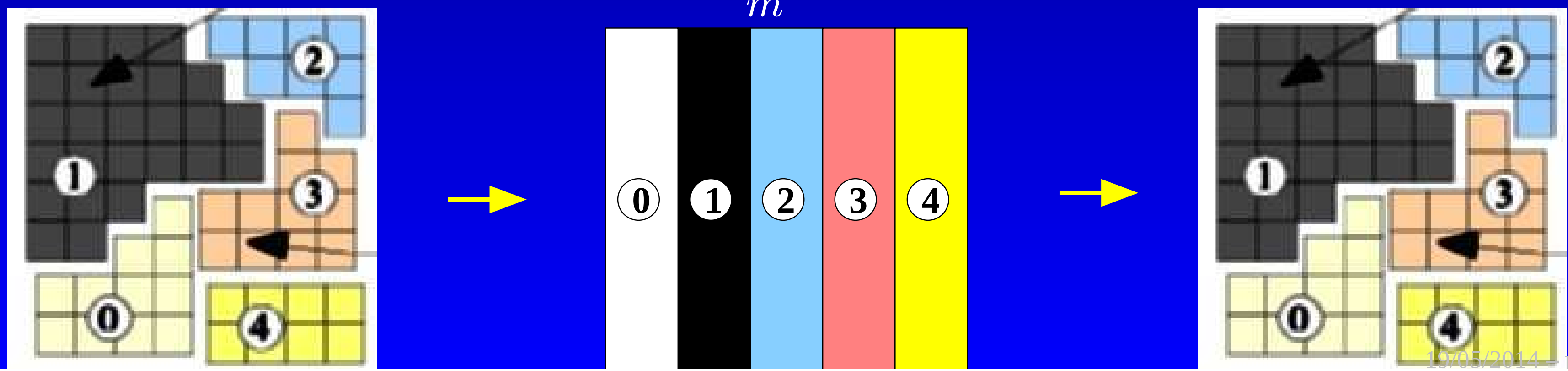
$$\Phi(\vec{x}) = \int g(\vec{x} - \vec{x}')\rho(\vec{x}')\mathrm{d}\vec{x}'$$

- calculate force using finite differences

$$f^{(x)}_{i,j,k} = -\frac{\Phi_{i+1,j,k} - \Phi_{i-1,j,k}}{2h}.$$

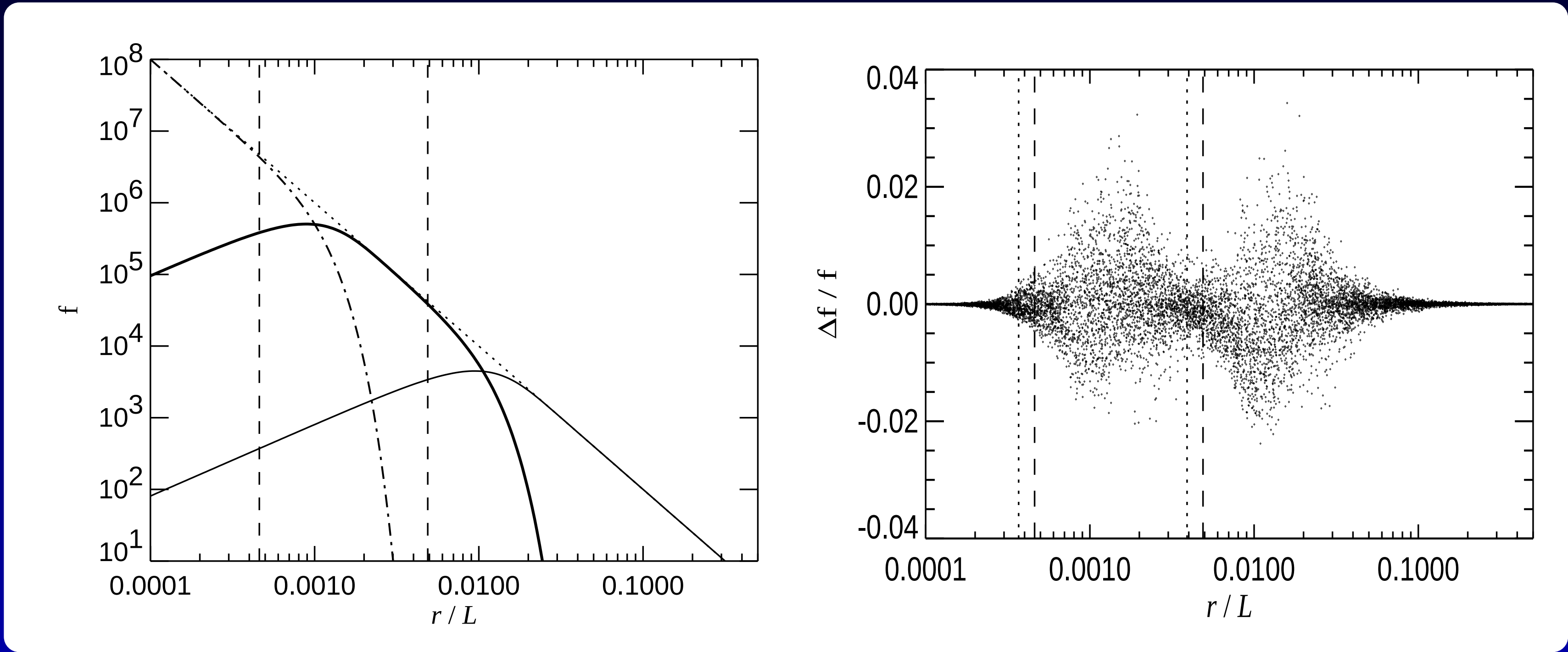
- interpolate force back to particles

$$\vec{f}(\vec{x}_i) = \sum_m W(\vec{x}_i - \vec{x}_m)\vec{f}_m,$$



Gravity

Tree-PM: $\Phi_{\vec{k}} = \Phi_{\vec{k}}^{\rm long} + \Phi_{\vec{k}}^{\rm short}$

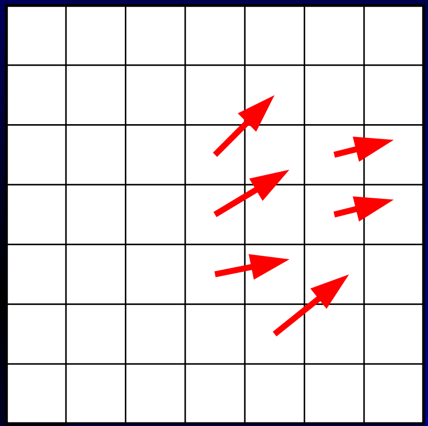


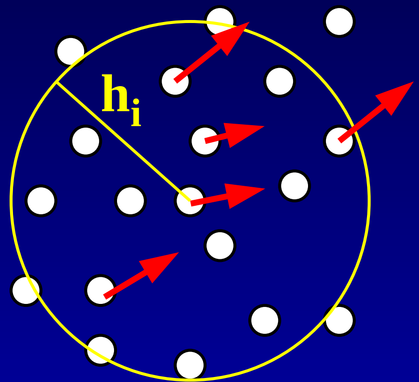
$$\Phi_{\vec{k}}^{\rm long} = \Phi_{\vec{k}} \exp(-\vec{k}^2 r_s^2)$$

$$\Phi^{\rm short}(\vec{x}) = -G \sum_i \frac{m_i}{\vec{r}_i} \mathrm{erfc}\left(\frac{\vec{r}_i}{2r_s}\right)$$

From dark to light (SPH)

Eulerian	Lagrangian	SPH
discretized space	**discretized mass**	**kernel estimate**

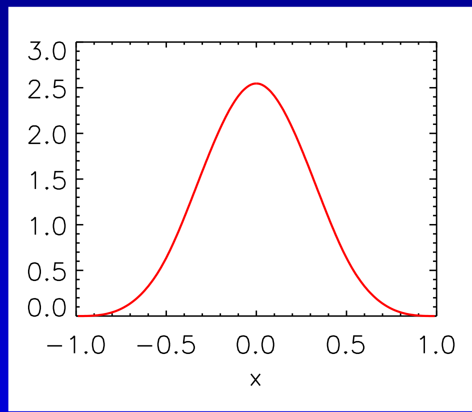




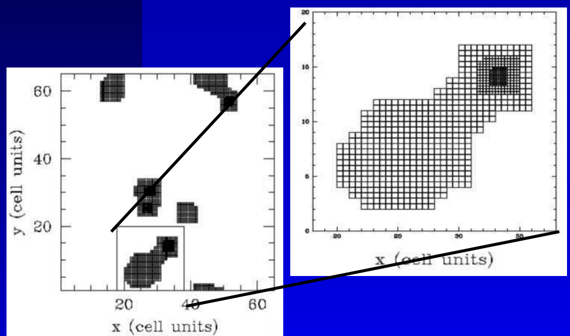
$$\langle A(\mathbf{r})\rangle = \int W(\mathbf{r}-\mathbf{r}', h)\, A(\mathbf{r}')\, \mathrm{d}^3 r'$$

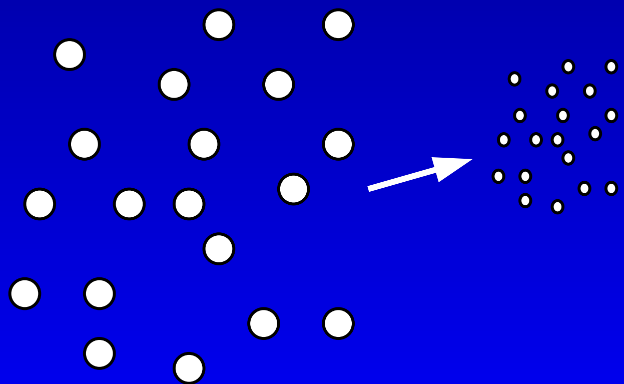
$$\mathrm{d}^3 r' \mapsto \frac{m_j}{\rho_j}$$

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



Collapse:





From dark to light (SPH)

Add a baryonic component into n-body simulations (e.g. additional tracing particles) which has also hydrodynamic interactions (e.g. fluid equations) where continuous fluid quantities are based on kernel estimates

$$\langle A(\vec{x})\rangle = \int W(\vec{x}-\vec{x}', h)A(\vec{x}')\mathrm{d}\vec{x}' = \sum_j \frac{m_j}{\rho_j} A_j W(\vec{x}_i - \vec{x}_j, h)$$

Lagrangian for the fluid (represented by the tracer particles)

$$L(\vec{q},\dot{\vec{q}}) = \frac{1}{2}\sum_i m_i \dot{\vec{x}}_i^2 - \sum_i m_i u_i, \qquad \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{\vec{q}}_i} - \frac{\partial L}{\partial \vec{q}_i} = 0$$

$\Rightarrow$ equation of motion (e.g. *Euler* equation)

$$\frac{\mathrm{d}\vec{v}_i}{\mathrm{d}t} = -\sum_j m_j \left(\frac{P_j}{\rho_j^2}\vec{\nabla}_i W(\vec{x}_i - \vec{x}_j, h_j) + \frac{P_i}{\rho_i^2}\vec{\nabla}_i W(\vec{x}_i - \vec{x}_j, h_i) \right)$$

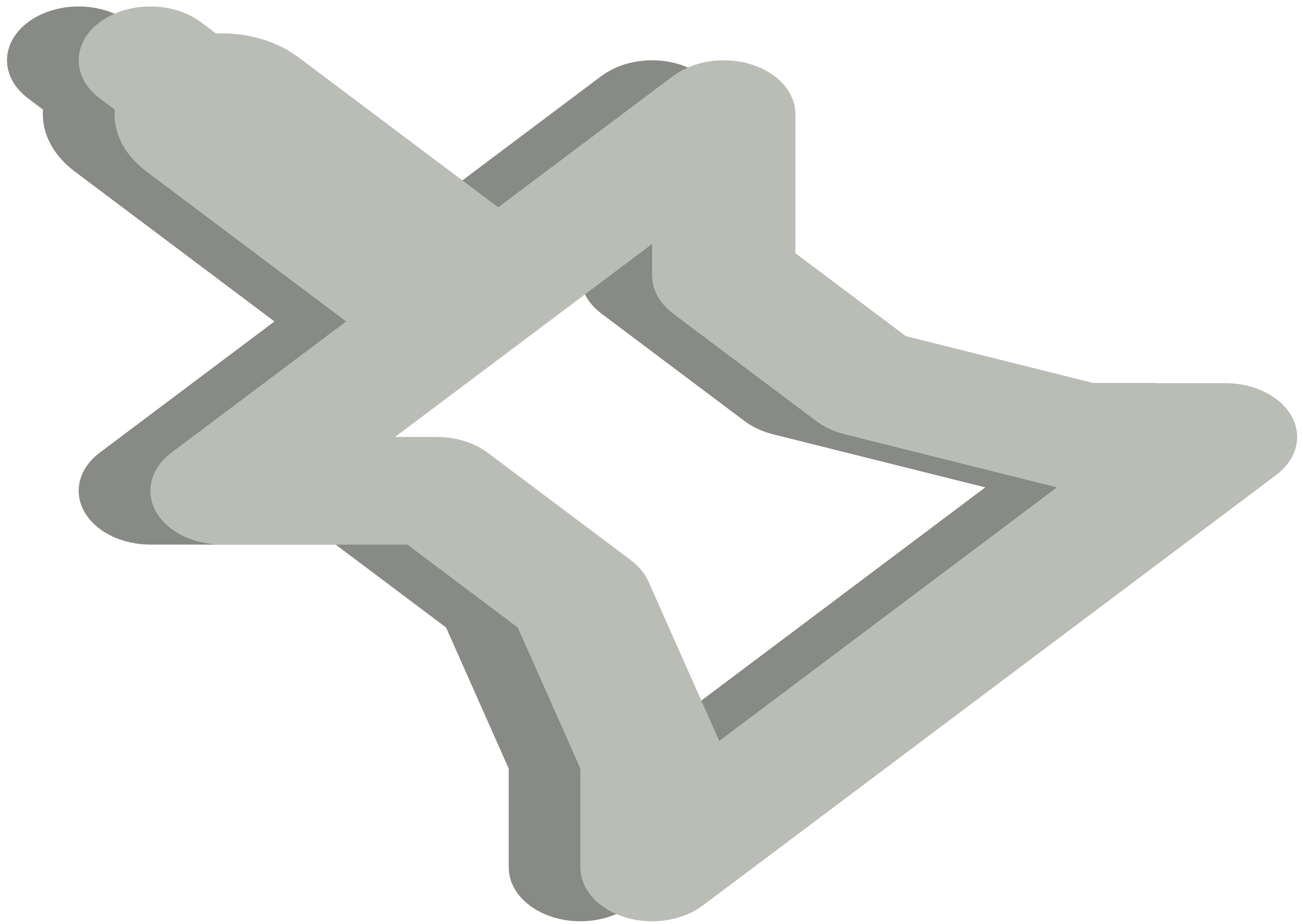
with $P_i = (\gamma - 1)\rho u_i$ (EoS) and artificial viscosity (shocks).

From dark to light (SPH)

Now we can follow the equation of motion of two species of particle, but for the gas additional terms appear.

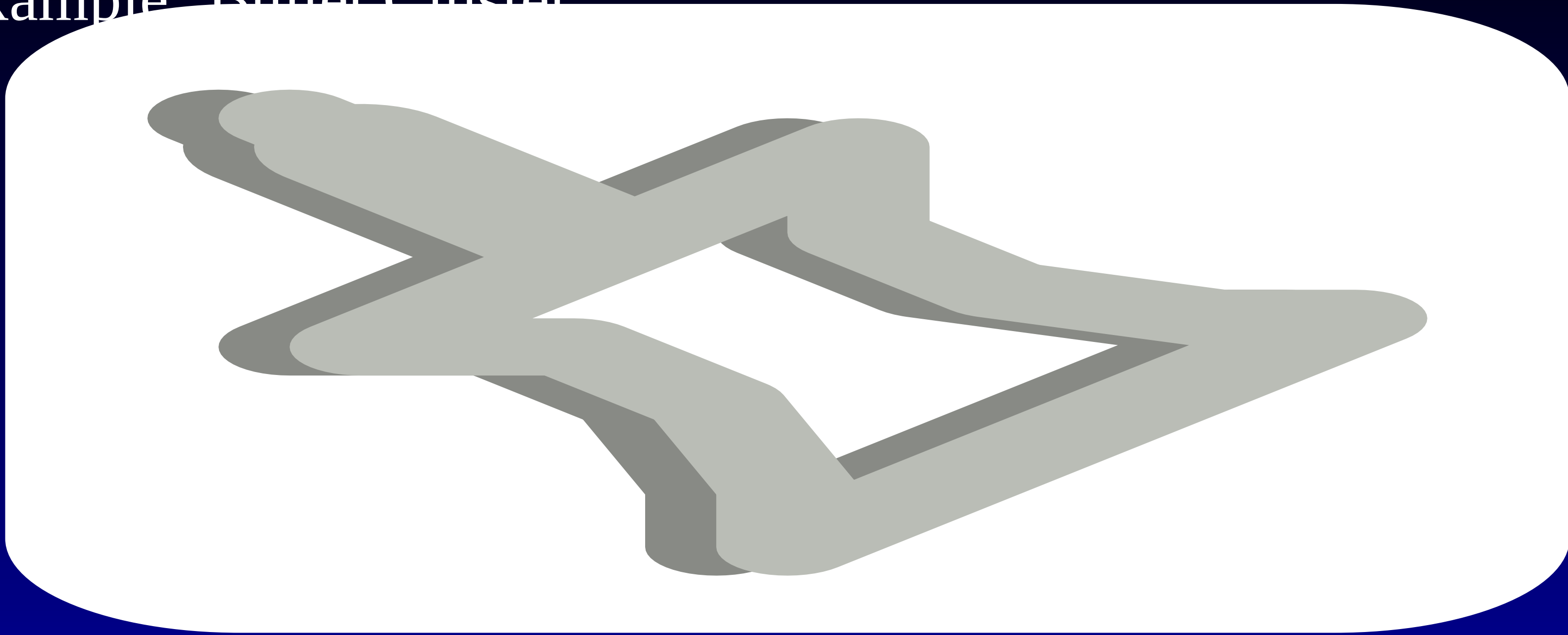
$$\left(\frac{\mathrm{d}\vec{v}}{\mathrm{d}t}\right)_{\mathrm{D}M} = -\vec{\nabla}\Phi, \quad \left(\frac{\mathrm{d}\vec{v}}{\mathrm{d}t}\right)_{gas} = -\frac{\vec{\nabla}P}{\rho} - \rho\vec{\nabla}\Pi_{ij} - \vec{\nabla}\Phi$$

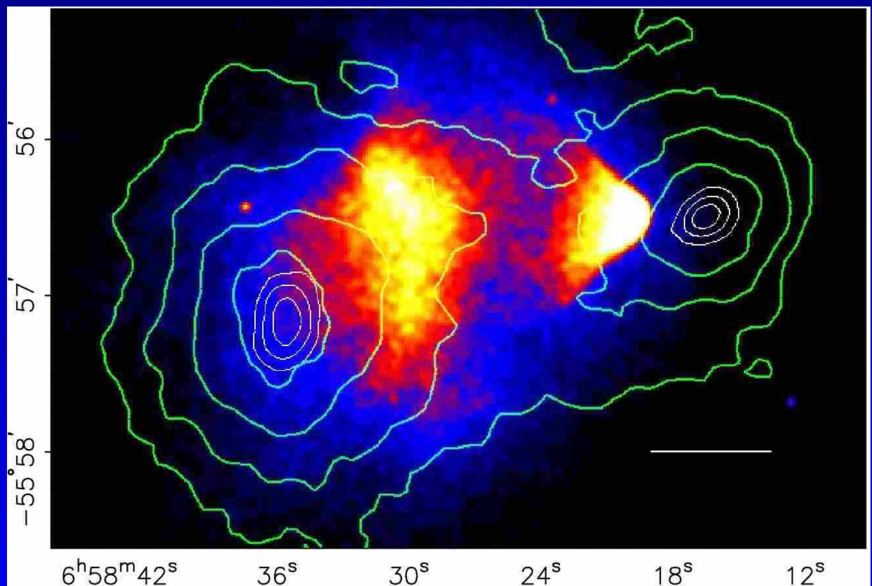
From dark to light (SPH)

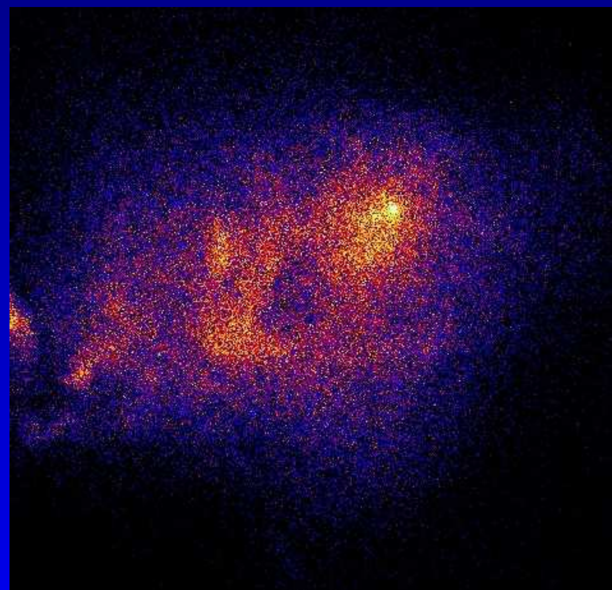


The Bullet Cluster

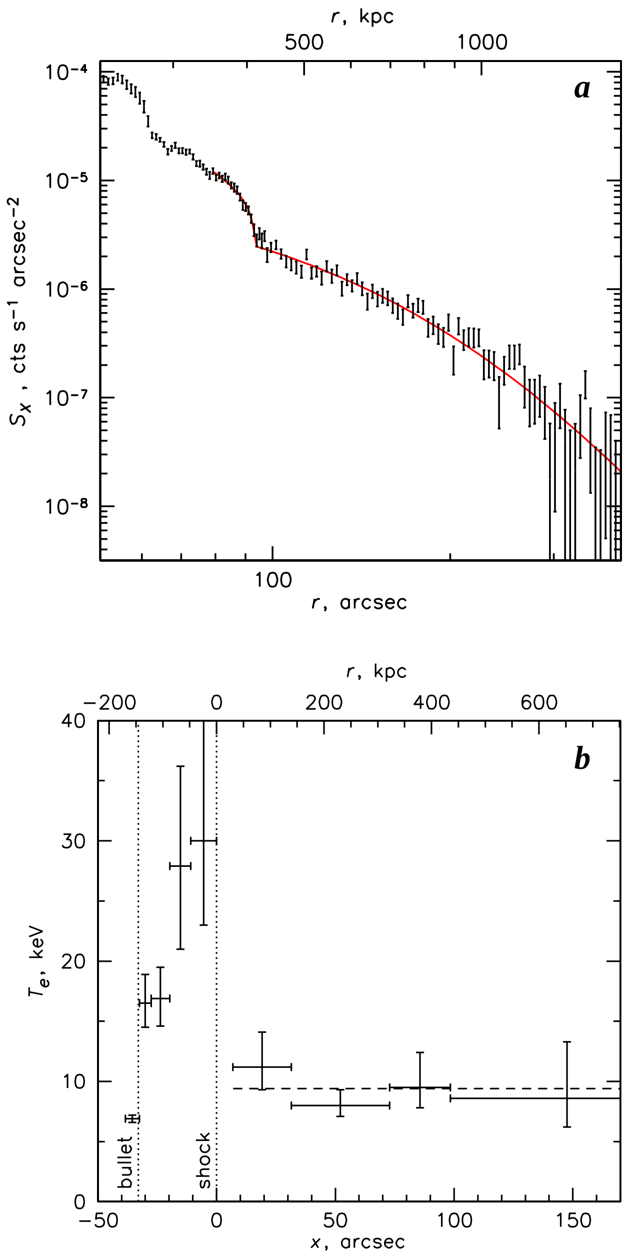
Example: Bullet Cluster

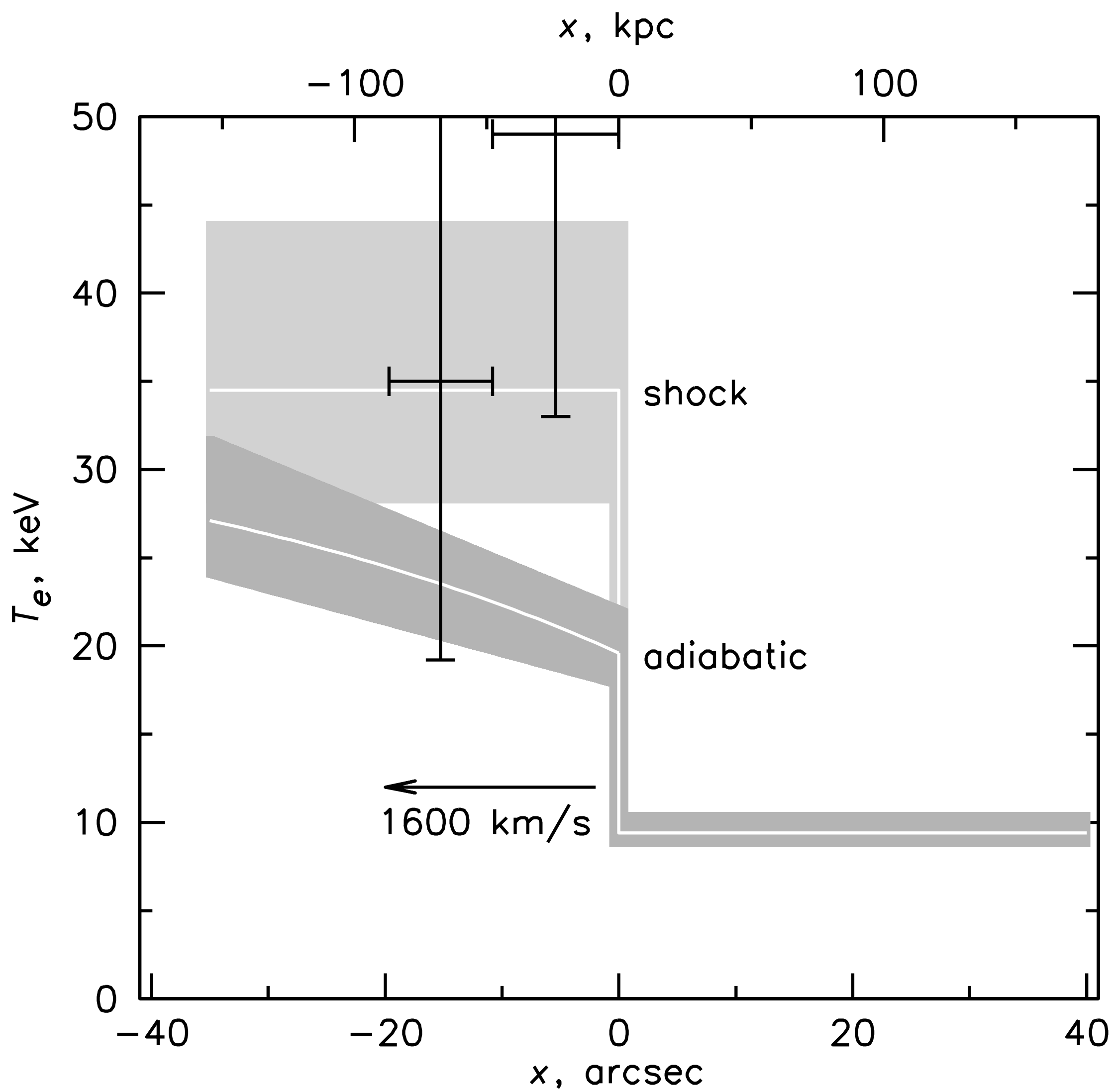






The Bullet Cluster



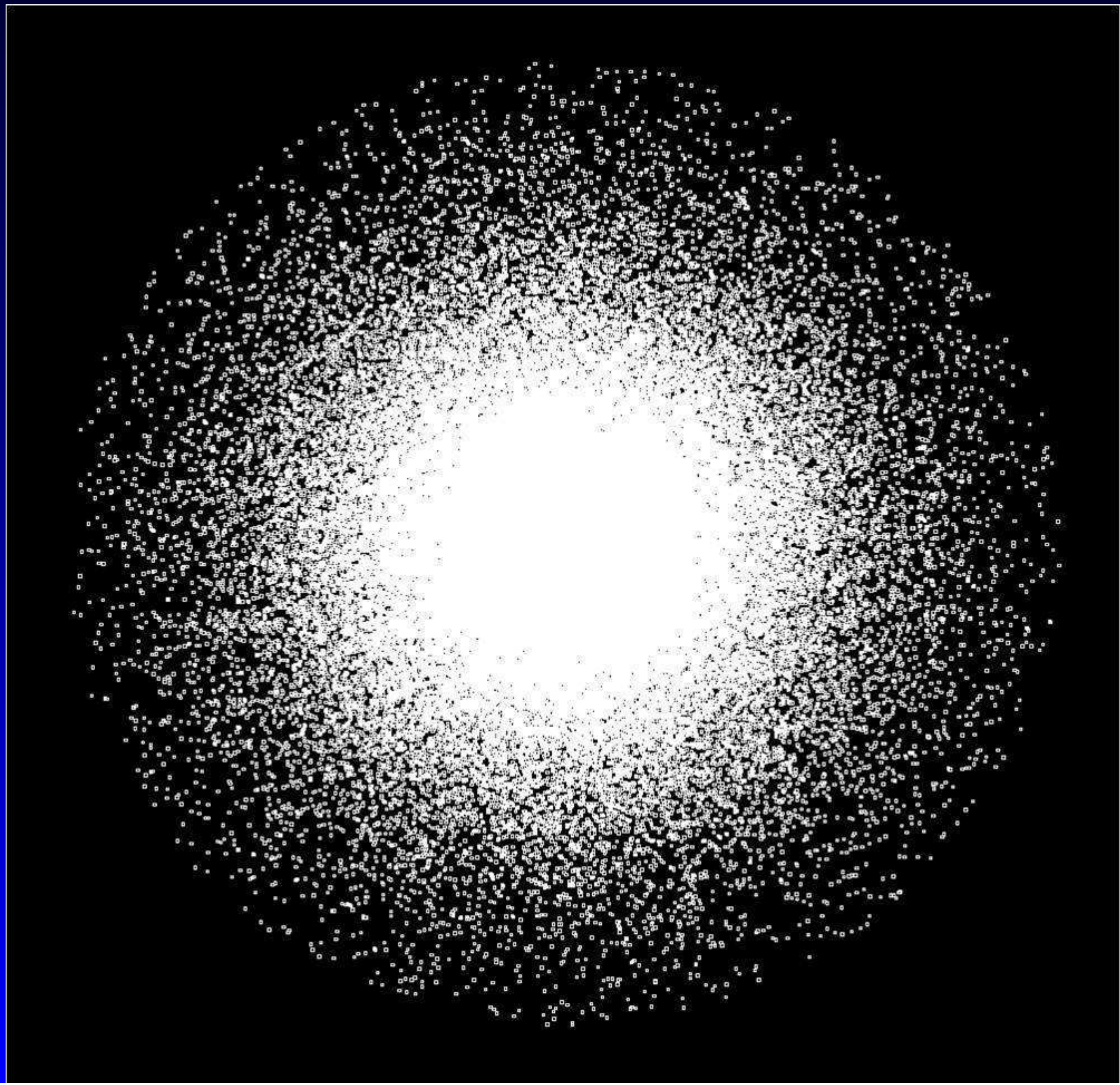


Markevich 2005

Electron-Ion equiblibration much faster than Spitzer timescale
⇒ Hydro/MHD

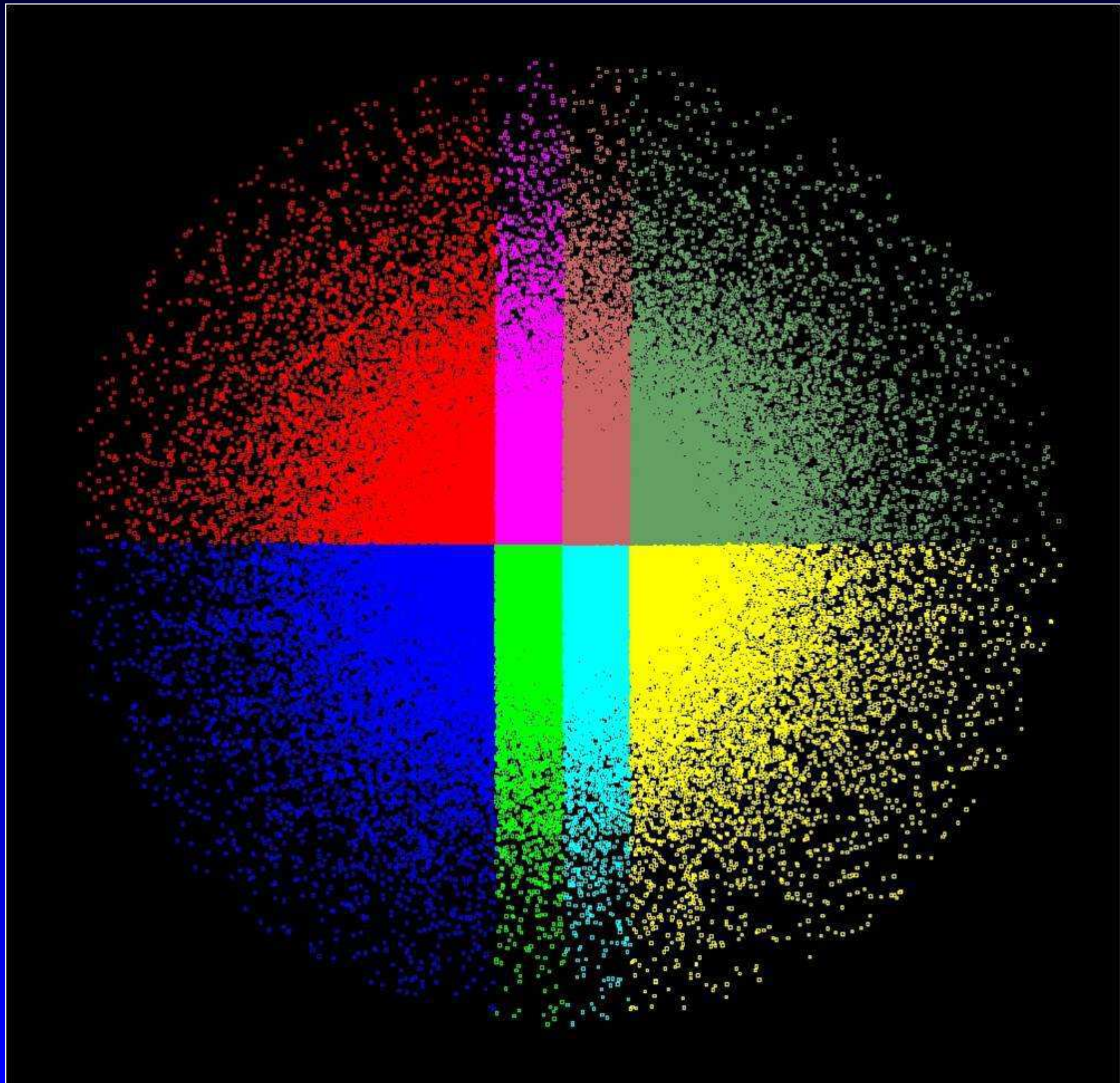
Distributing the Work

Example



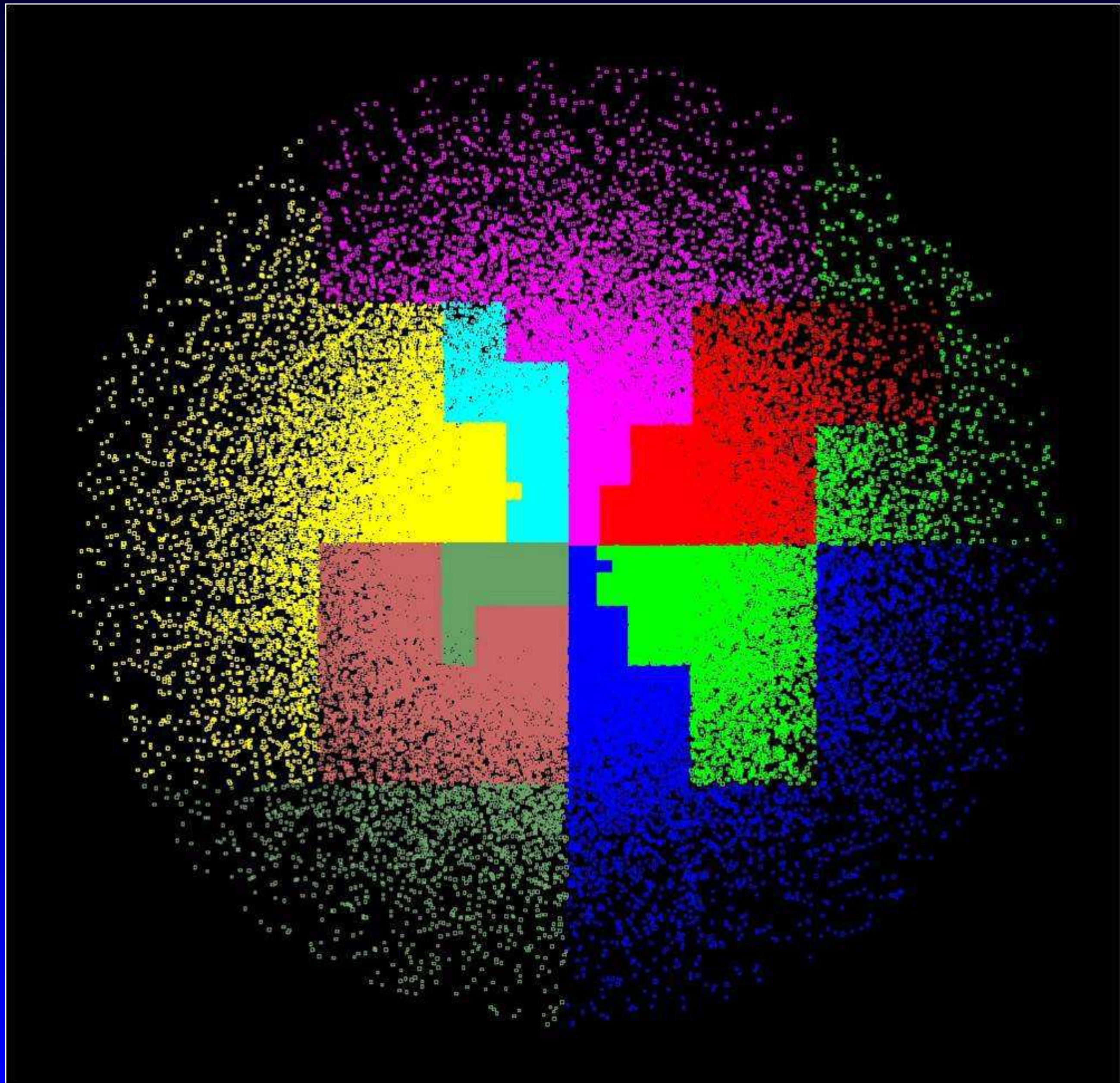
Distributing the Work

Simple



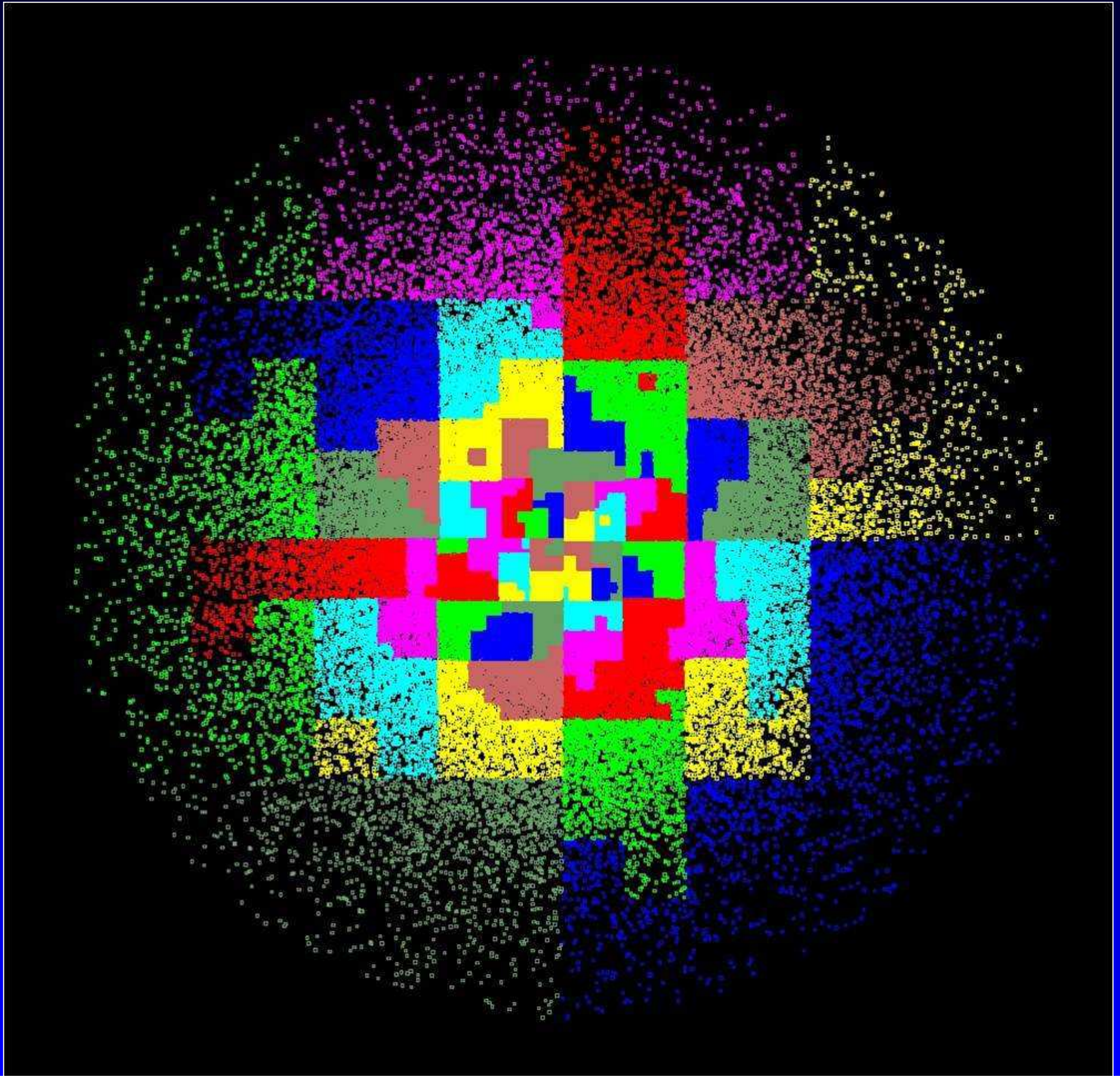
Distributing the Work

Space-filling curve (Peano Hilbert)

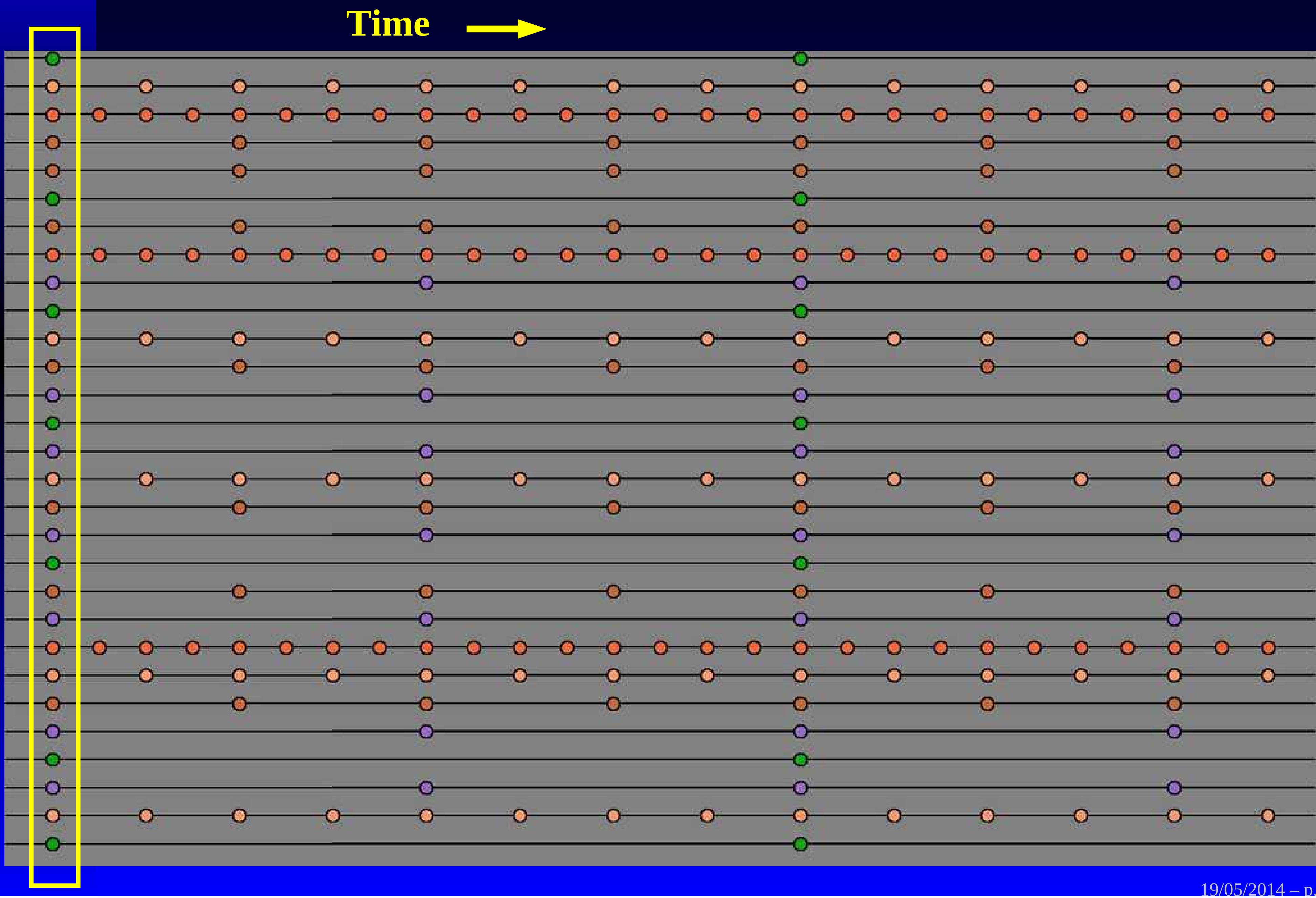


Distributing the Work

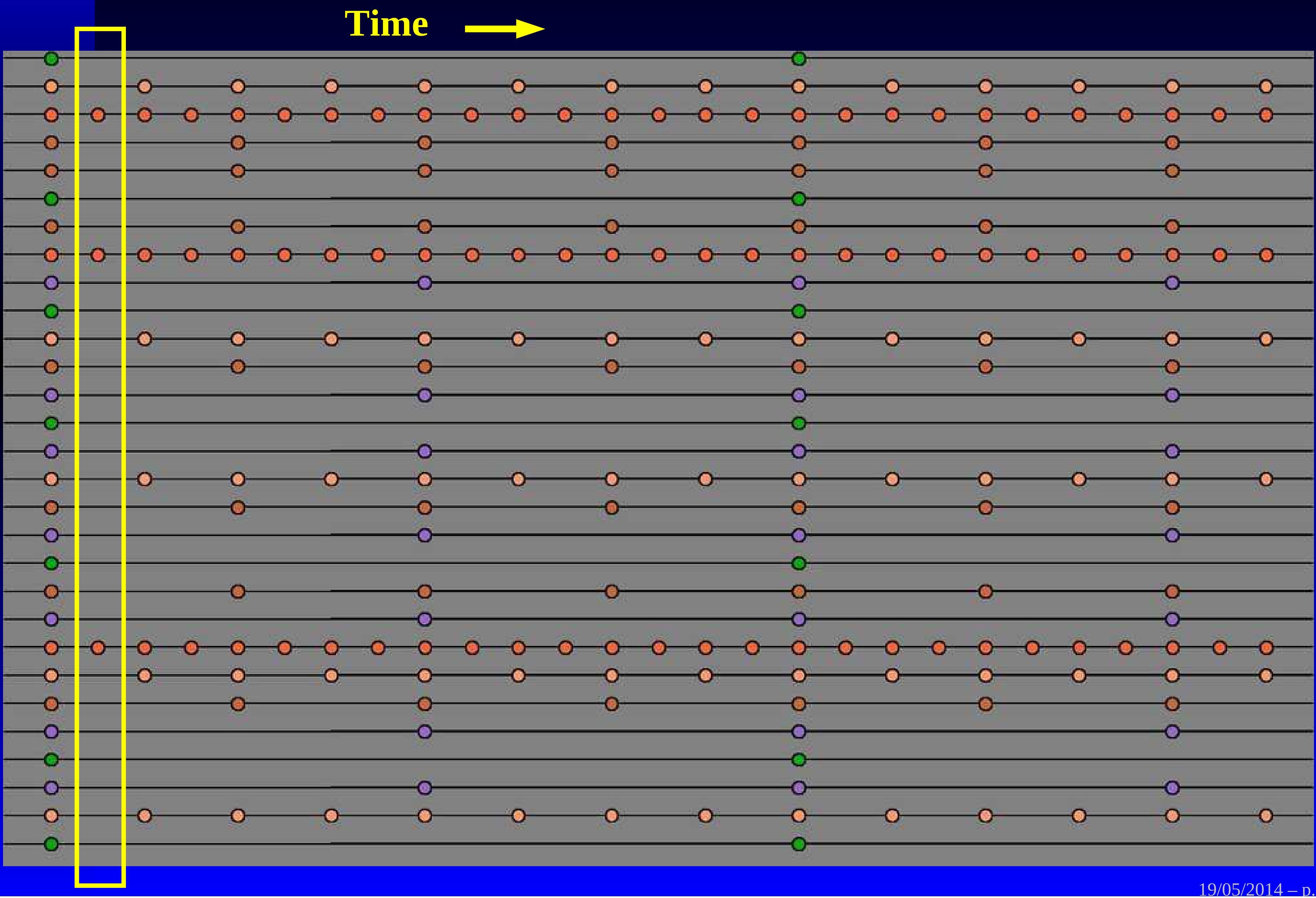
Multiple space-filling curve



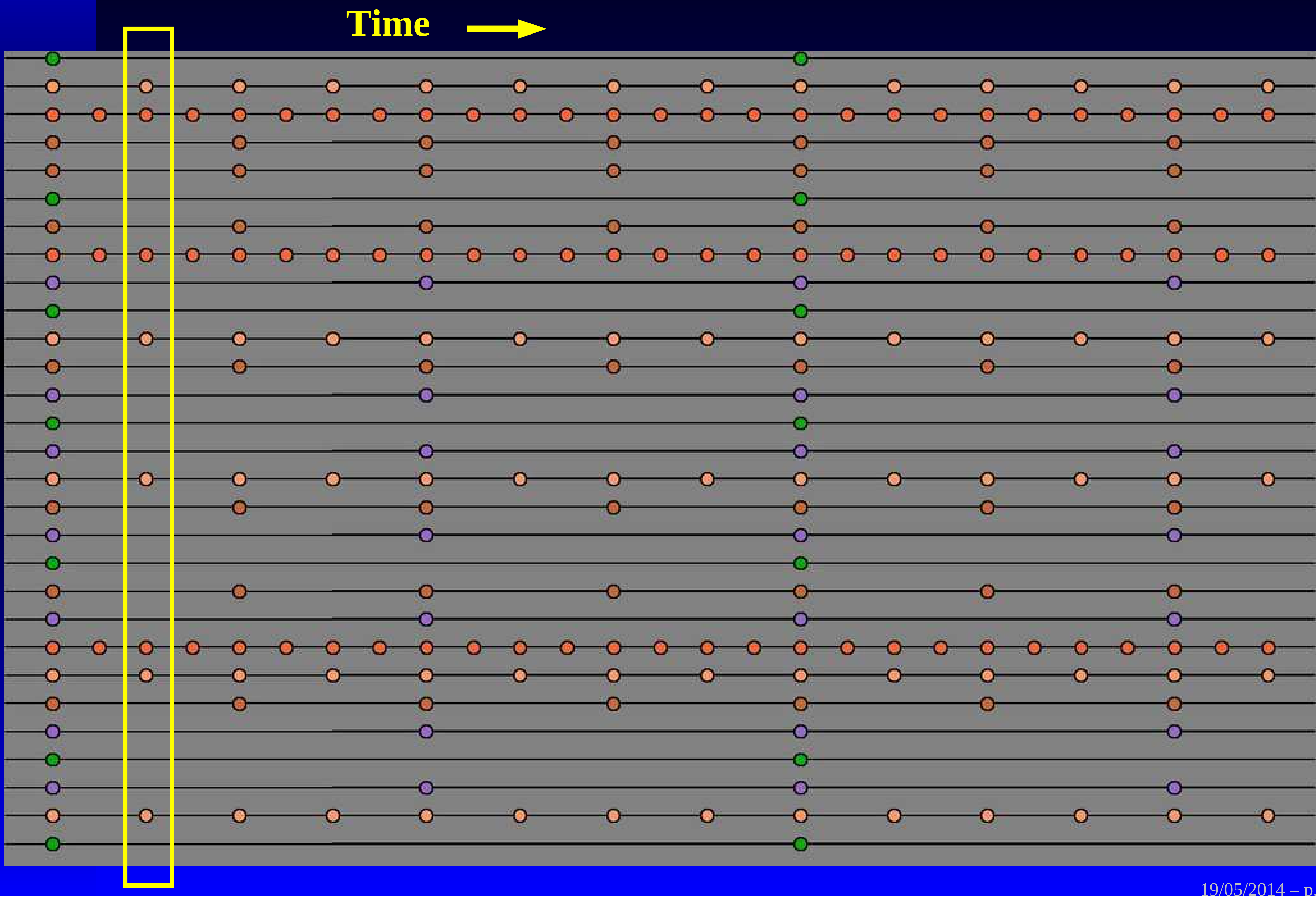
Time Integration



Time Integration

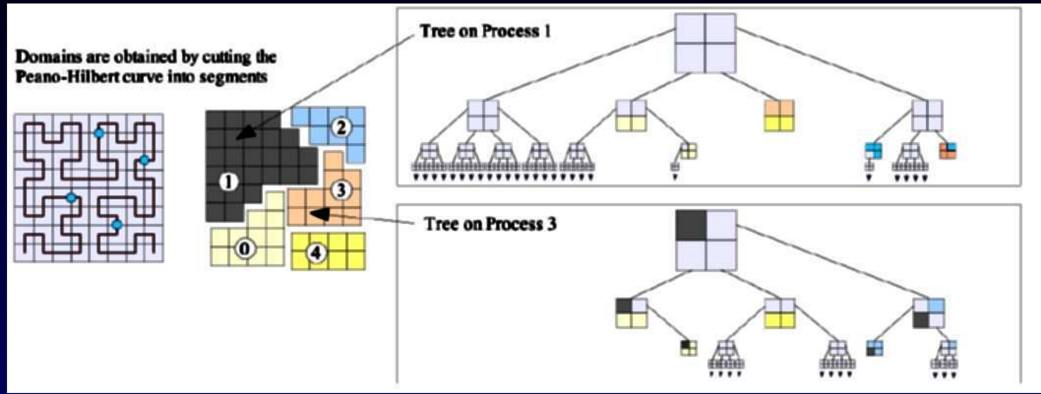


Time Integration



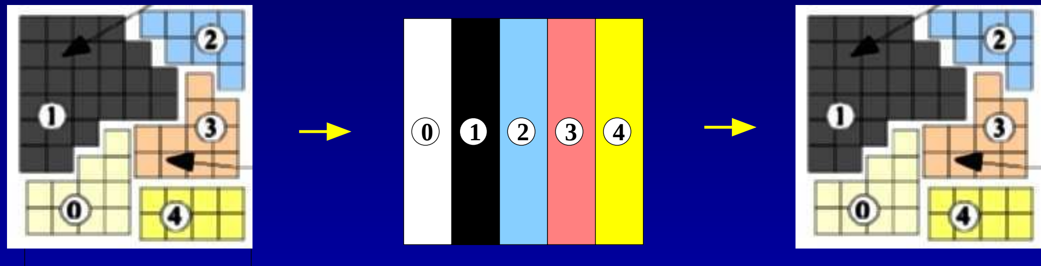
Summary

- **Tree like**



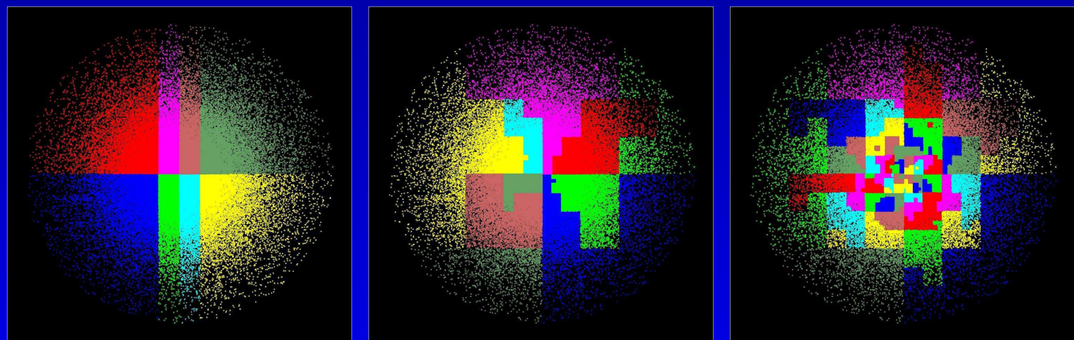
Short range gravity, Hydrodynamics, Transport, Star-formation/AGN feedback

- **Grid like**



Long range gravity (including FFTW)

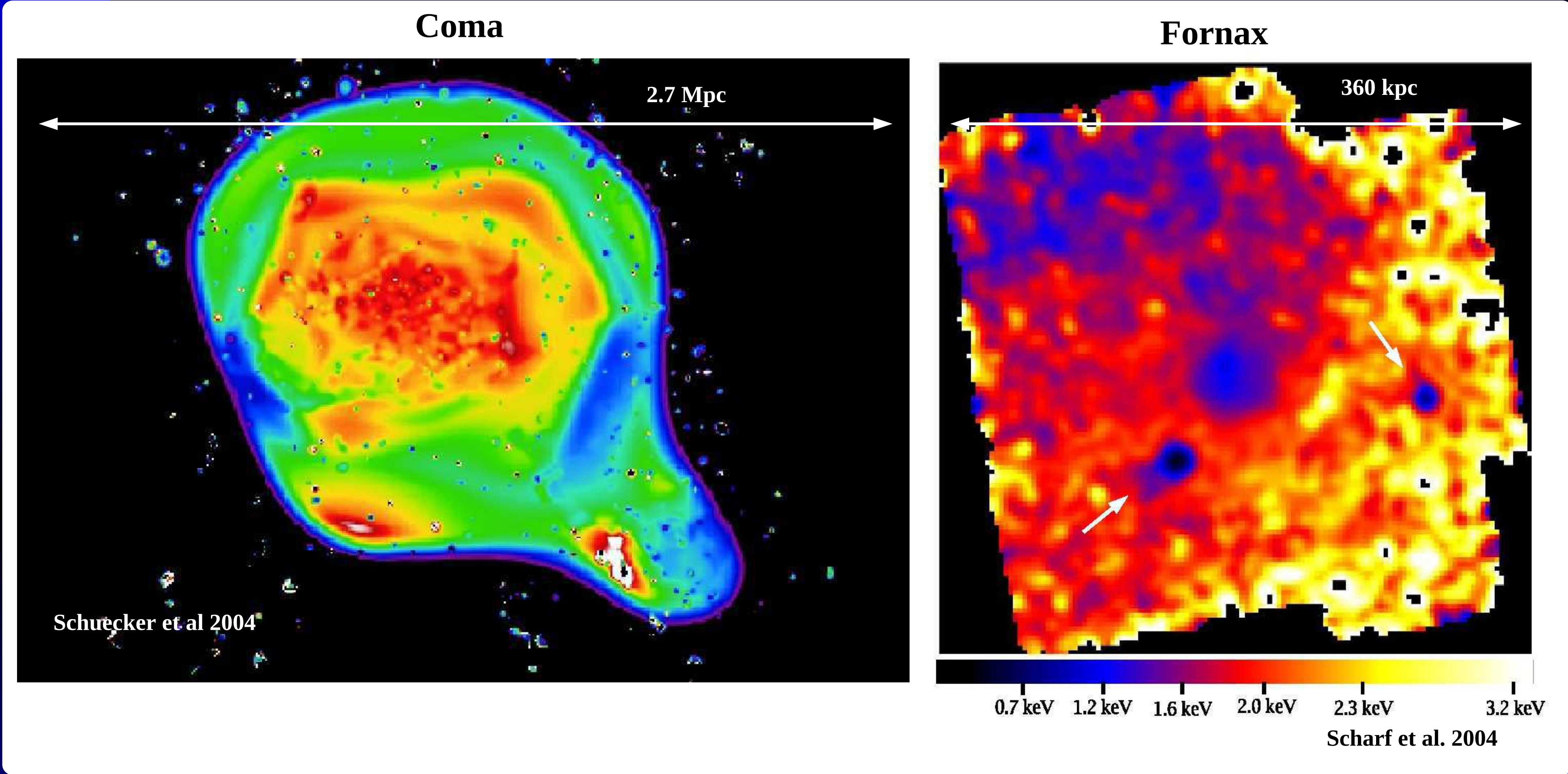
- **Work load**



- **Post processing**

Various different algorithms, all distributed.

Summary

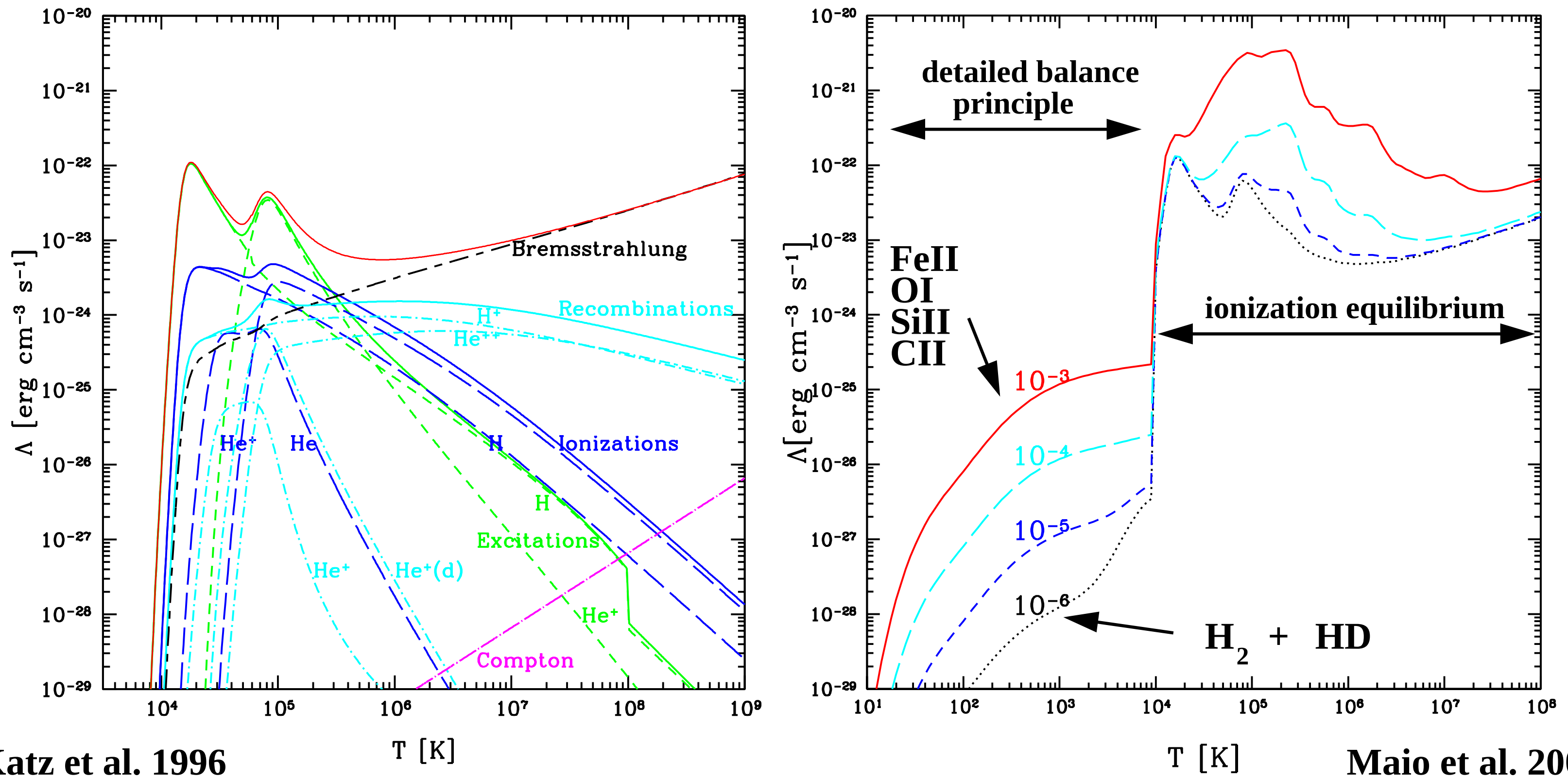


X-ray temperature map of Coma (left) and Fornax cluster (right).

- How much turbulence is present in galaxy clusters ?
- How effective does gas stripping work ?
- Details still unexplored, again viscosity and instabilities depend on **magnetic field**

Cooling & Star-formation

This diffuse, optically thin gas with primordial composition (e.g. H,He) can cool because of various physical processes (e.g assuming ionization equilibrium). But pollution from metals (e.g. Fe,O,Si,C) will increase the cooling function.



Katz et al. 1996

Maio et al. 2007

But cooling $\propto n^2$ therefore cooling catastrophe in collapsed objects !

Cooling & Star-formation

In nature cooled gas will form stars (on scales much below resolution). Therefore “*suitable*” recipes have to be build in. Simplest form (Katz et al 1996):

- convergent flow, e.g. $\vec{\nabla}\vec{v} < 0$.
- high density region, e.g. $\rho > 0.1$ Atoms/cm^3.
- Jeans instability $\frac{h}{c} > t_{\rm dyn}$ with $t_{\rm dyn} = (4\pi G\rho)^{-0.5}$.

$\Rightarrow$ Conversion of cold gas into stars: $\frac{\mathrm{d}\rho_*}{\mathrm{d}t} = -\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{c_*\rho}{t_*}$.
c_*: Star-formation efficiency (e.g. $\approx 10\%$).
t_*: Star-formation time (e.g. max of $t_{\rm dyn}$ and $t_{cool} = u/\dot{u}$).

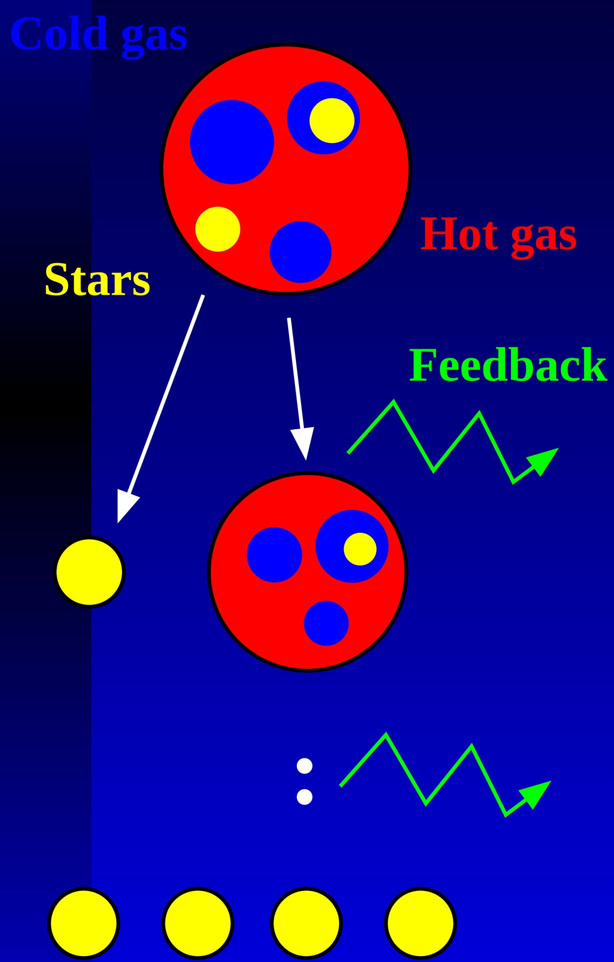
$\Rightarrow$ Heating of the gas by type-II supernovae (e.g. 10^{51} erg/SN).
Livetime of $m_* > 8M_\odot$ typically < than $\Delta t_{\rm sim}$ (e.g. IRA).
Number of SNII from initial mass function (e.g. *Salpeter*).

$\Rightarrow$ When significant fraction of gas is converted to stars, spawn new star particles (e.g. 2-3).
Such star particles further interact in a collisionless way.

Cooling & Star-formation

Multi phase model (sub−scale)

Springel & Hernquist 2002



Star formation

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

supernova mass fraction

star formation timescale

Cloud evaporation

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

cloud evaporation parameter

Growth of clouds

cooling function

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

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

Cooling & Star-formation

Extending star-formation model for a more detailed description of the evolution of the stellar population.
(Tornatore, Borgani, Dolag & Matteucci 2007):

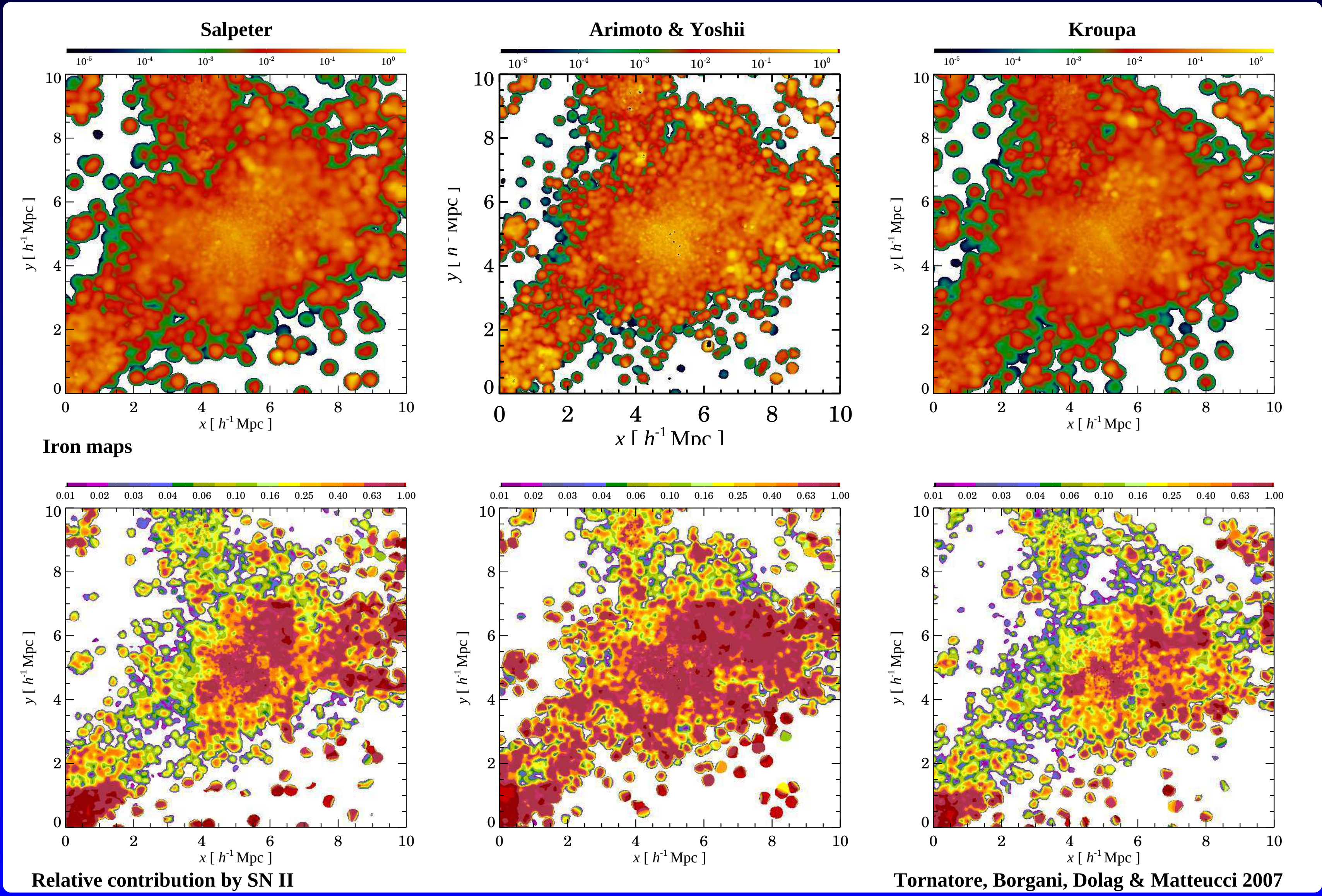
- Model rate of SN Ia (e.g. binary systems $0.8 - 8M_{\odot}$).
- Adopt lifetime function $\tau(m)$
  (Padovani & Matteucci 1993, Maeder & Maynet 1989, ...).
- Adopt yields $p_{Z_i}(m, Z)$
  (Hoek & Groenewegen 1997, Thielemann et al. 2003, Woosley & Weaver 1995, ...).
- The IMF fixes the number of stars at given mass
  (Salpeter 1955, Arimoto & Yoshii 1987, Kroupa 2001, ...).

$\Rightarrow$ Explicitly follow the evolution of rates for SN Ia, SN II and AGB stars along with their respective metal production.

$\Rightarrow$ "Stars" evolve and give back H, He, Fe, O, C, Mg, S to the surrounding medium.

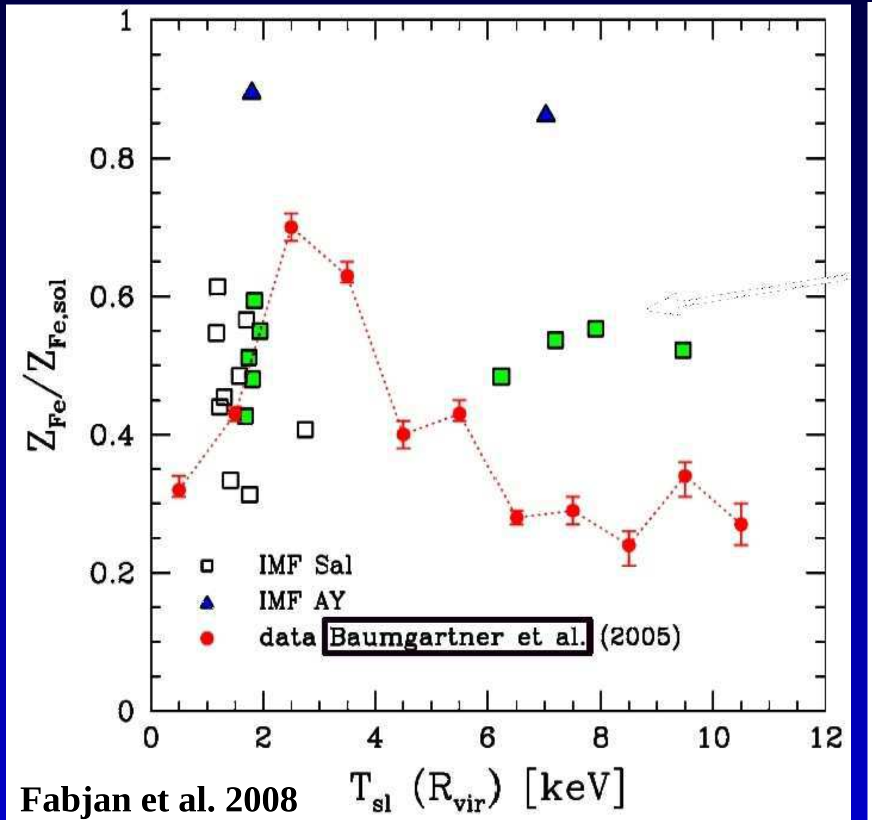
Cooling & Star-formation

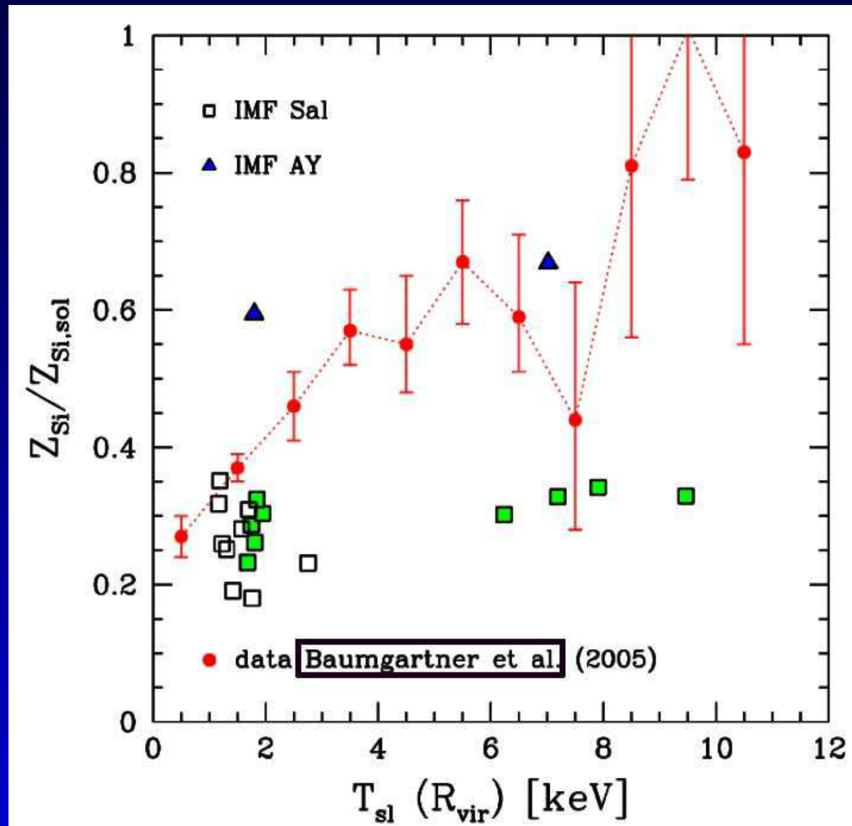
Example of the enrichment (e.g. Fe) of the ICM in a galaxy cluster simulation obtained using different IMFs.



Cooling & Star-formation

Example of the resulting Si and Fe content of the ICM in cluster simulations using different IMFs.





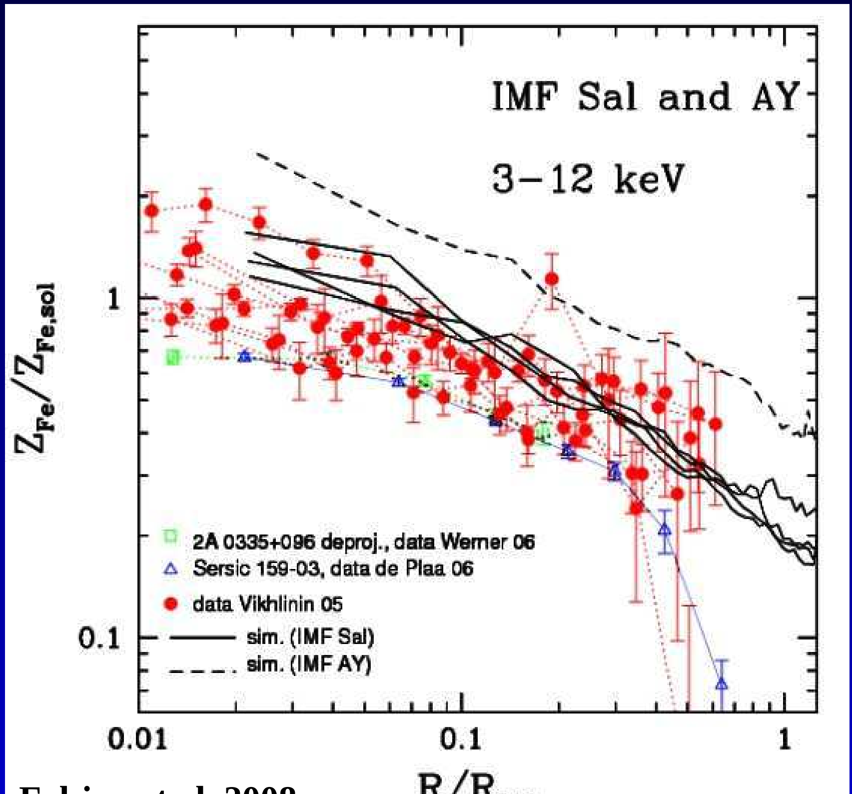
⇒ Salpeter IMF better for group data ?

⇒ Arimoto & Yoshii IMF better for Si in clusters ?

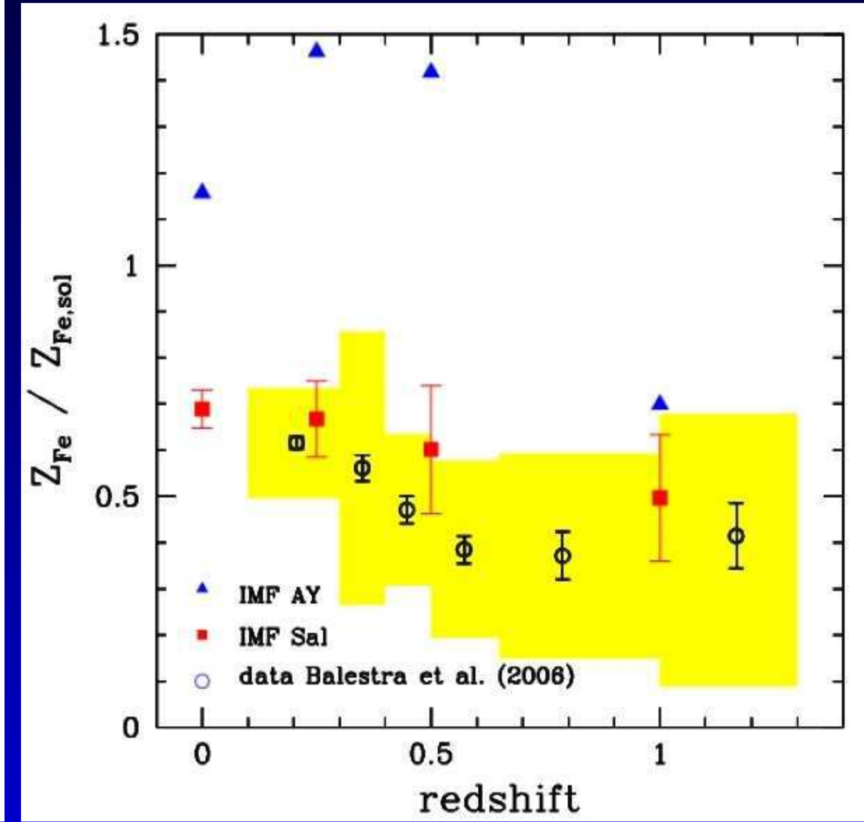
⇒ But uncertainties in observational data and biases in the observational process (see Rasia et al. 2007) !

Cooling & Star-formation

Example of the obtained Iron distribution and evolution in cluster simulations using different IMFs.



Fabjan et al. 2008

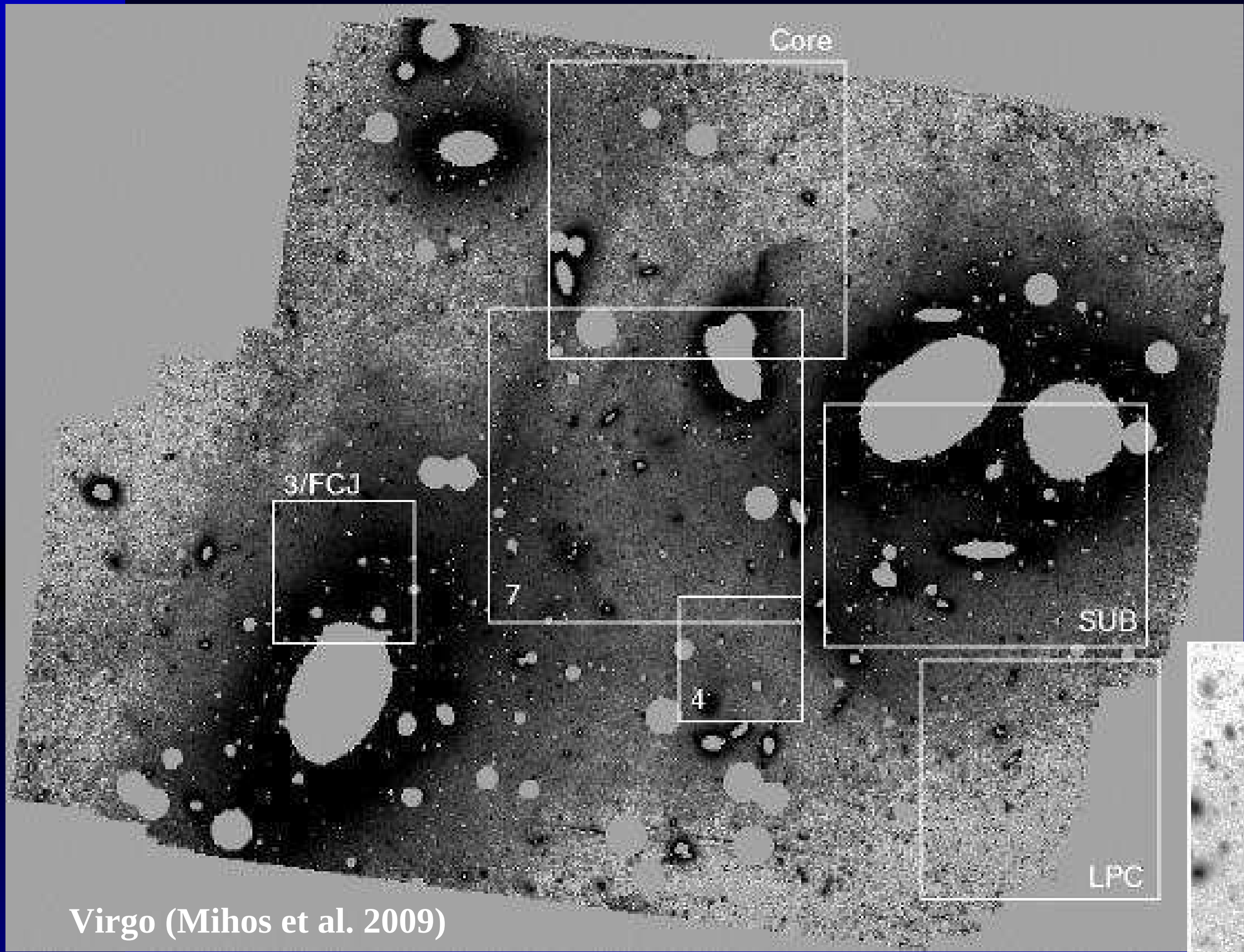


⇒ General trends reproduce observations.

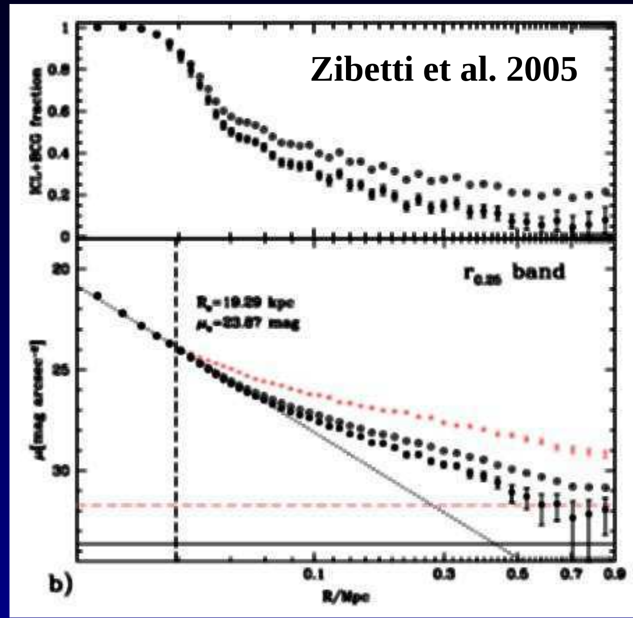
⇒ Simulated metal gradients too steep.

⇒ No needs for non-Salpeter IMF.

The ICL component

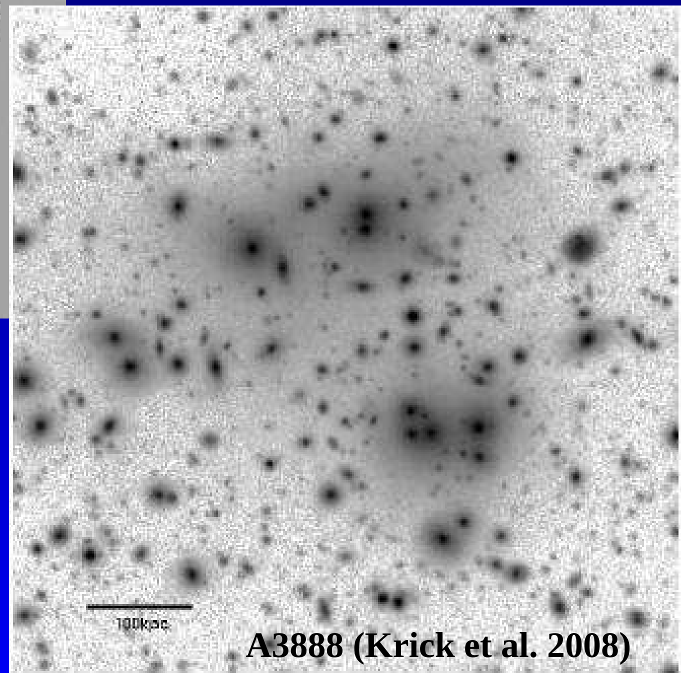


Virgo (Mihos et al. 2009)



Zibetti et al. 2005

Intra Cluster Ligth can make 10-40% of the stars in a cluster

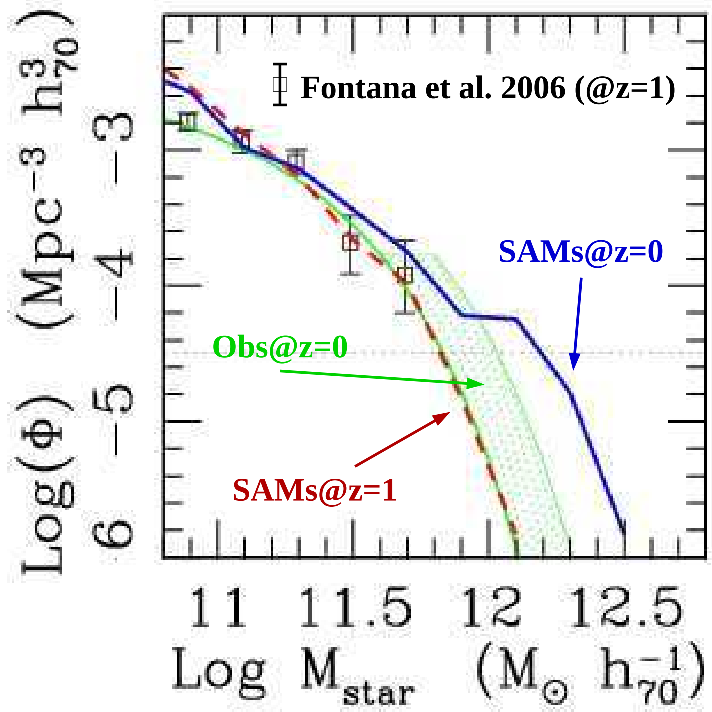


A3888 (Krick et al. 2008)

The ICL component

- Massive galaxies seem not to evolve significantly at $z < 1$.
  (e.g. Fontana et al. 2006)
- But all simulations predict many merger events at $z < 1$.

$\Rightarrow$ Stellar mass function will evolve !

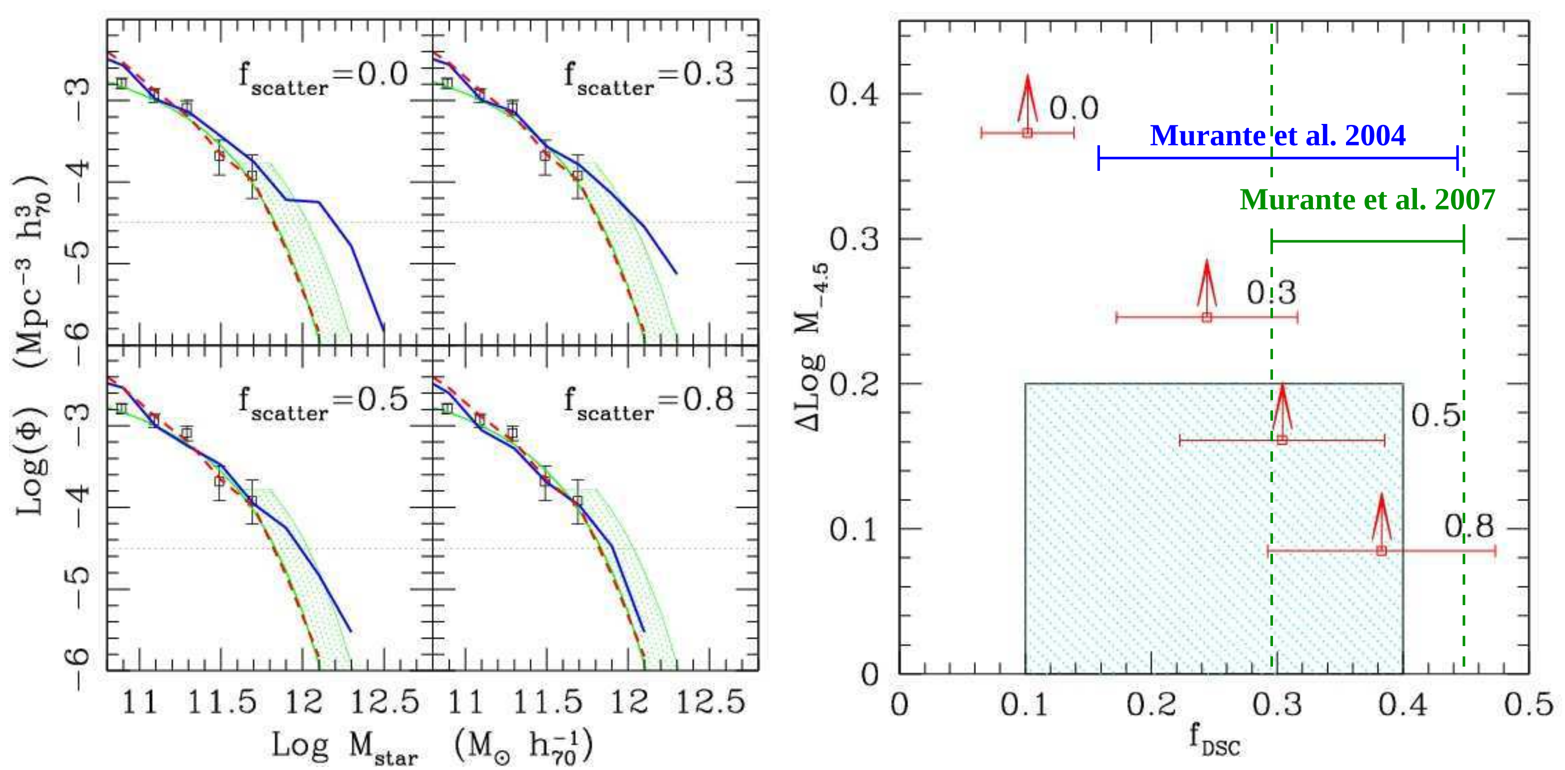


Monaco et al. 2006

The ICL component

Assuming that a given fraction f of stars gets scattered into ICL component when merging:

$\Rightarrow$ Less evolution of stellar mass function !

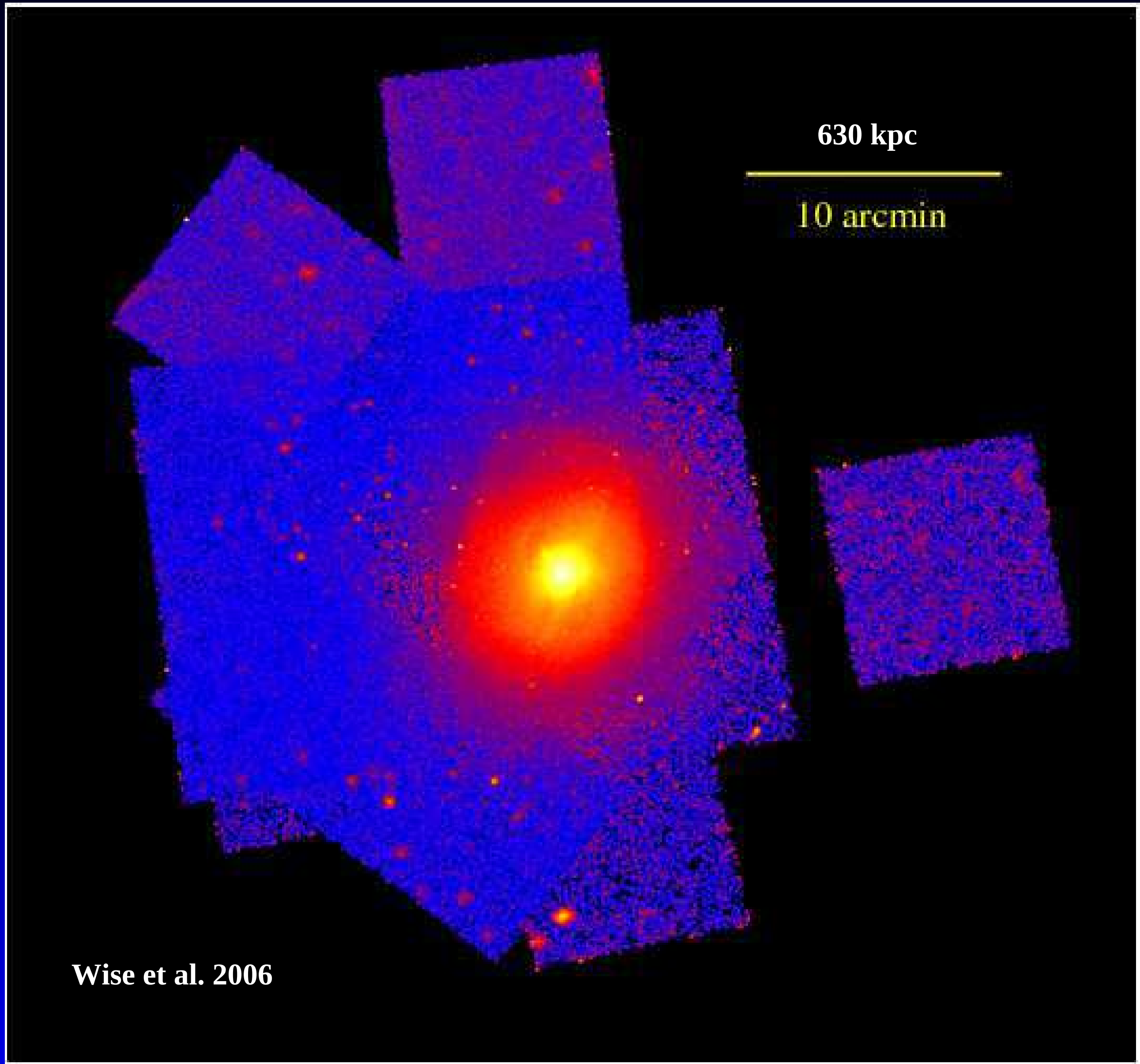


Monaco et al. 2006

$\Rightarrow$ ICL needed to avoid evolution !

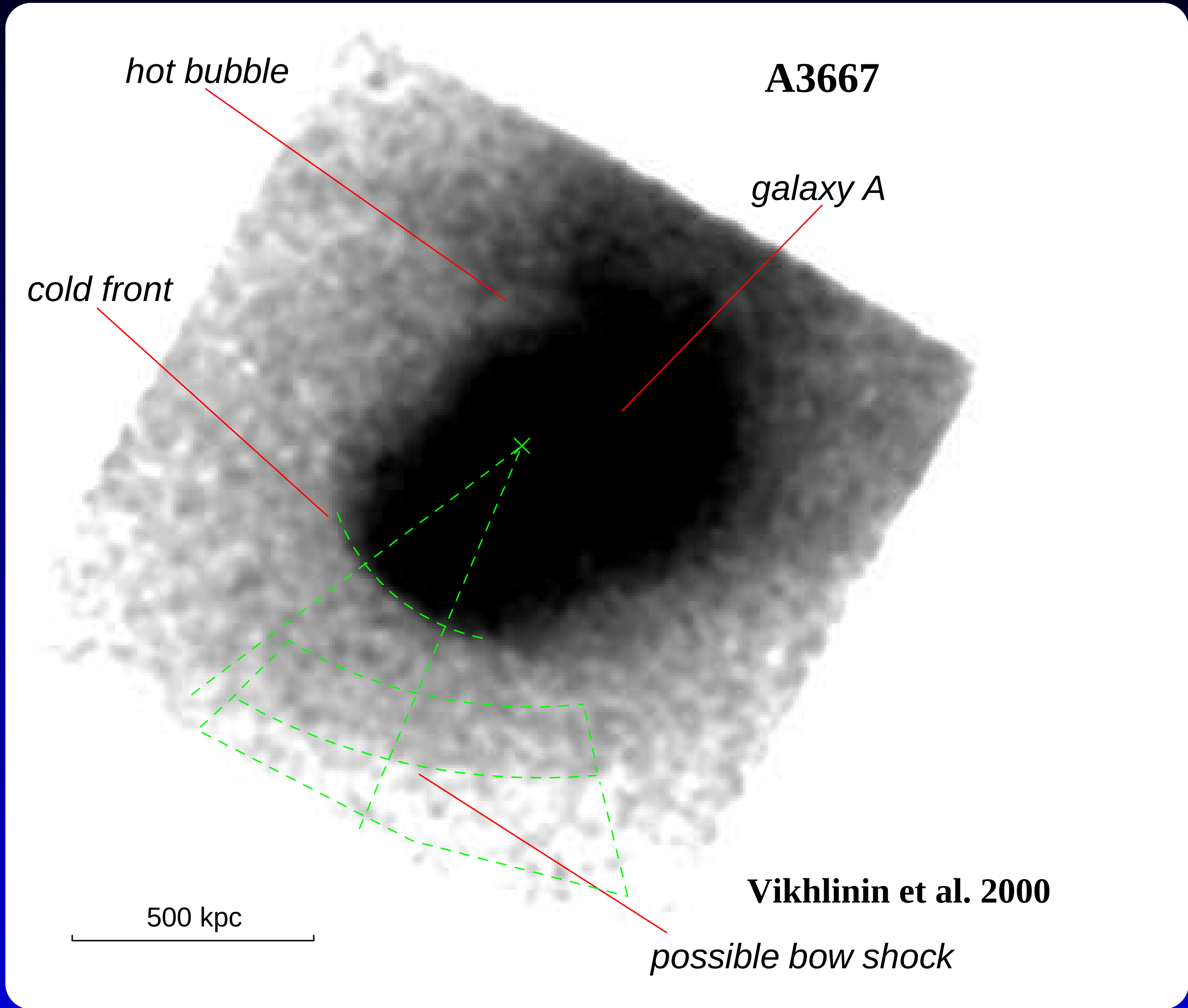
$\Rightarrow$ Similar to ICL predictions from simulations ?!

Cool-cores and AGN feedback



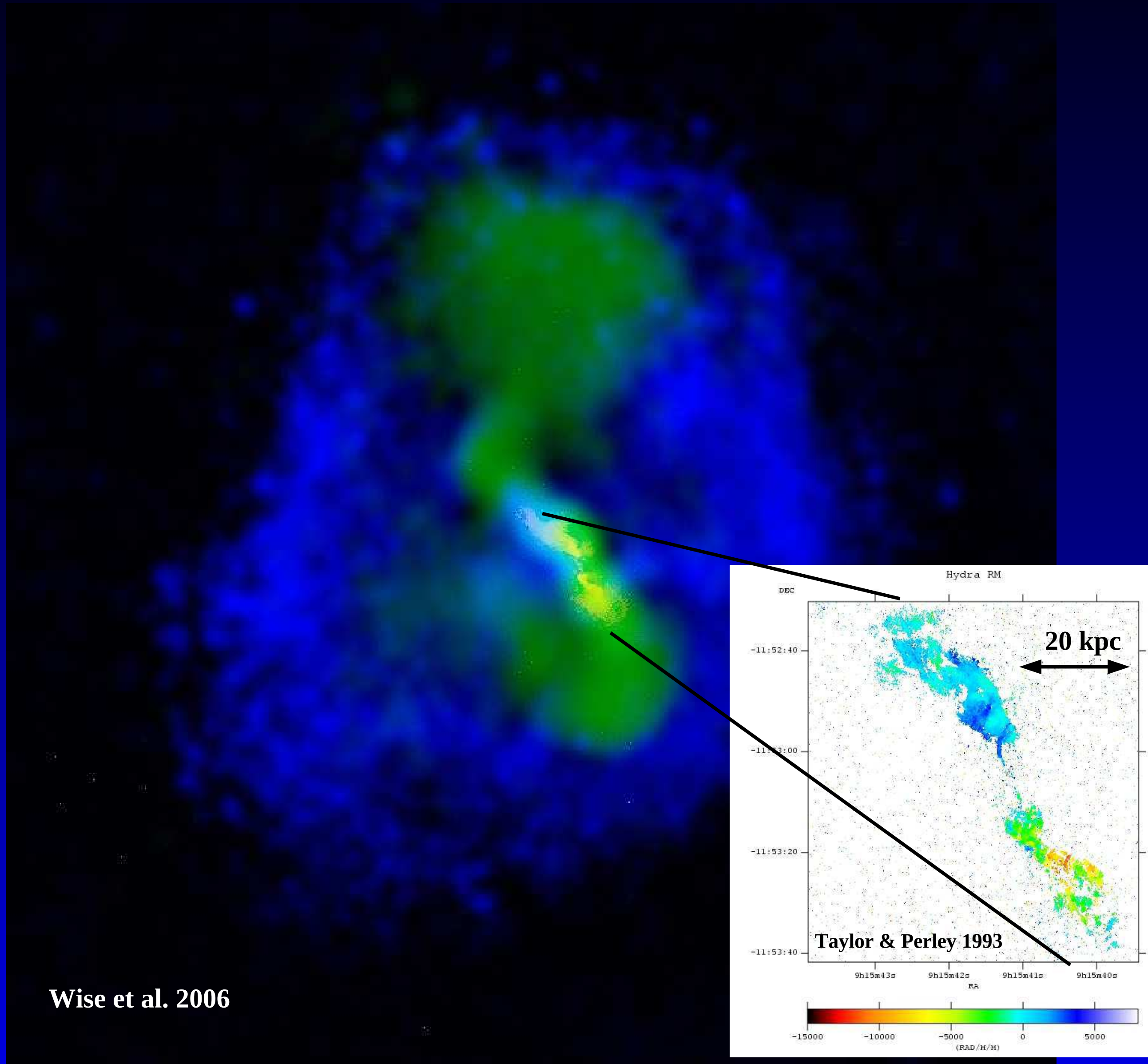
Chandra X-ray image of the Hydra cluster (cool core)
Simulations: Only cool-core clusters, to massive galaxies.

Cool-cores and AGN feedback



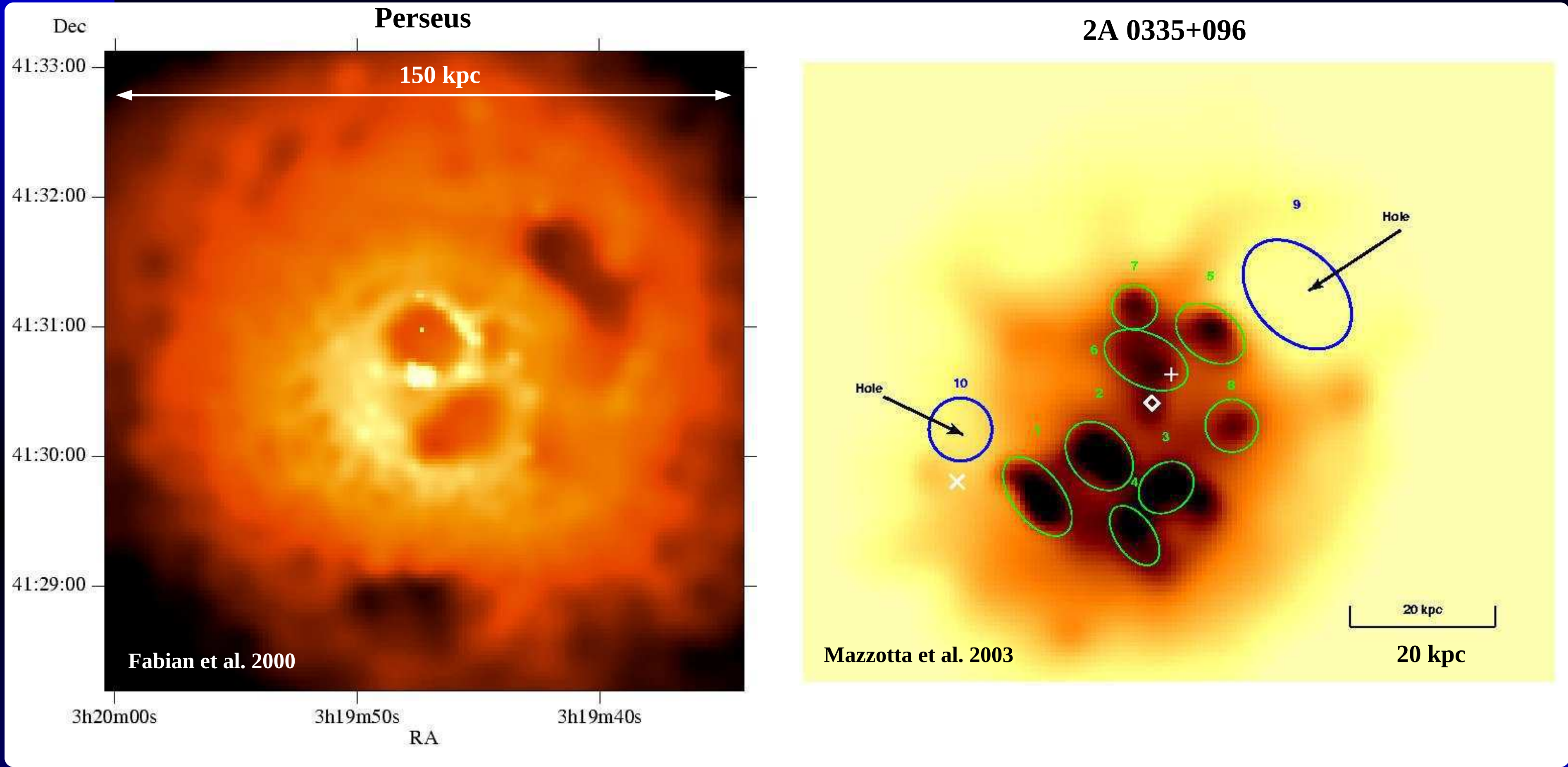
X-ray image of the A3667 cluster, illustrating the sloshing of gas on large scales. Sharp fronts indicate suppression of thermal conduction. ⇒ **magnetic field**

Cool-cores and AGN feedback



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

Cool-cores and AGN feedback

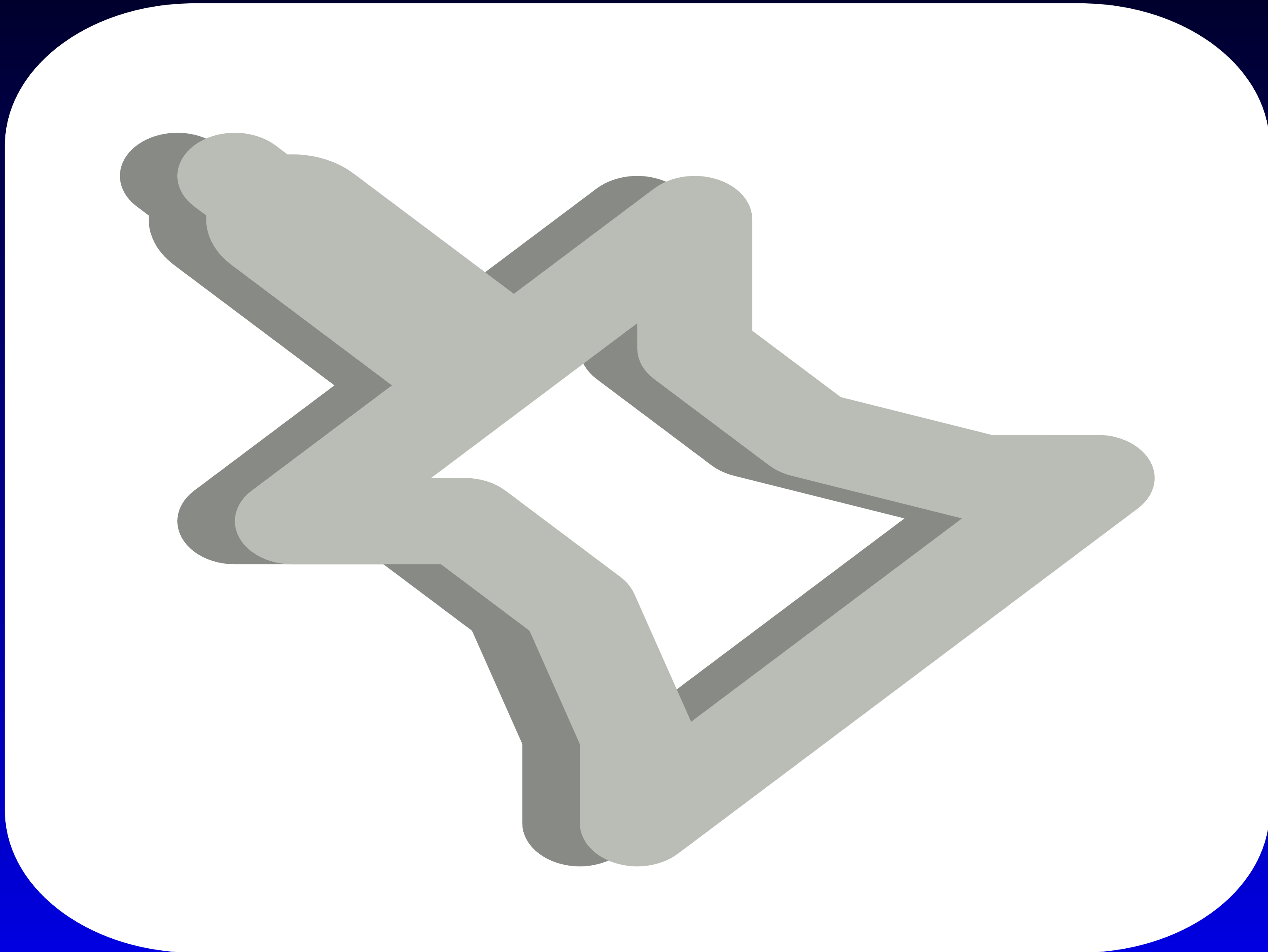


X-ray cavity in the cool core center of Perseus cluster (left) and 2A 0335+096 cluster (right). See work by E. Churazov.

- Does energy injected by the AGN heats the cool core ?
- Does the motion of cores induce mixing ?
- Details remain jet unclear (viscosity, turbulence, instabilities (RT,KH) ...) ⇒ **magnetic field**

Cool-cores and AGN feedback

Jets in realistic galaxy clusters environment



Mendygral, Jones & Dolag, ApJ, 2012

Cool-cores and AGN feedback

BH model (sub−scale)

Springel & Di Matteo 2006

Seeding

Constant seeding
Seeding on m−sigma

Accretion on BH

α −Bondi (Springl & Di Matteo 06)
β −Bondi (Booth & Schaye 09)
....

Feedback

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

Merging

Instant merging
Based on velocity
....

Growth of BH

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

gas density

sound speed

$$\dot{M}_\bullet = \min(\dot{M}_{\rm B}, \dot{M}_{\rm Edd})$$

Feedback by BH

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

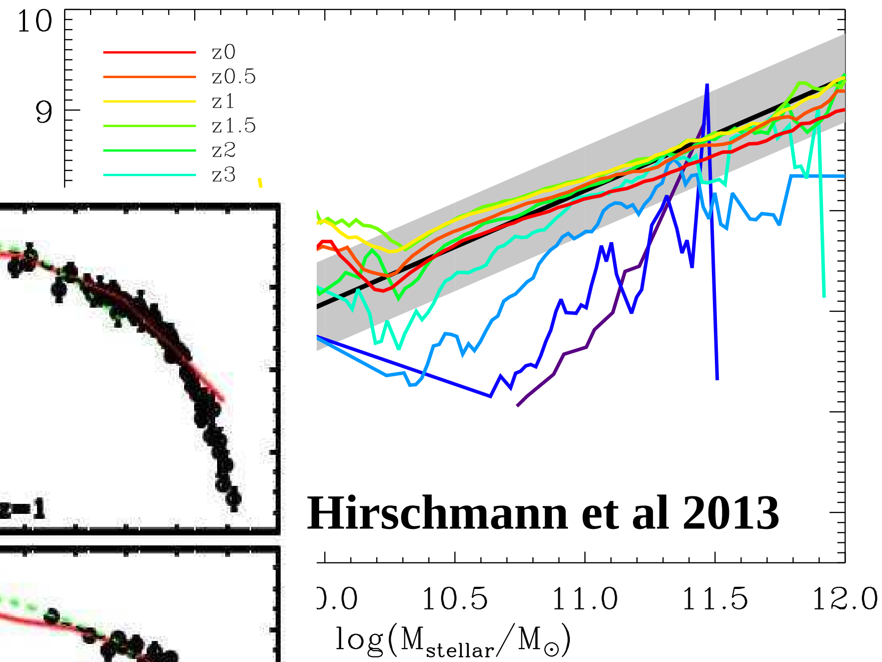
$$\dot{E}_{\rm feedback} = f \times L_{\rm bol}$$

efficiency

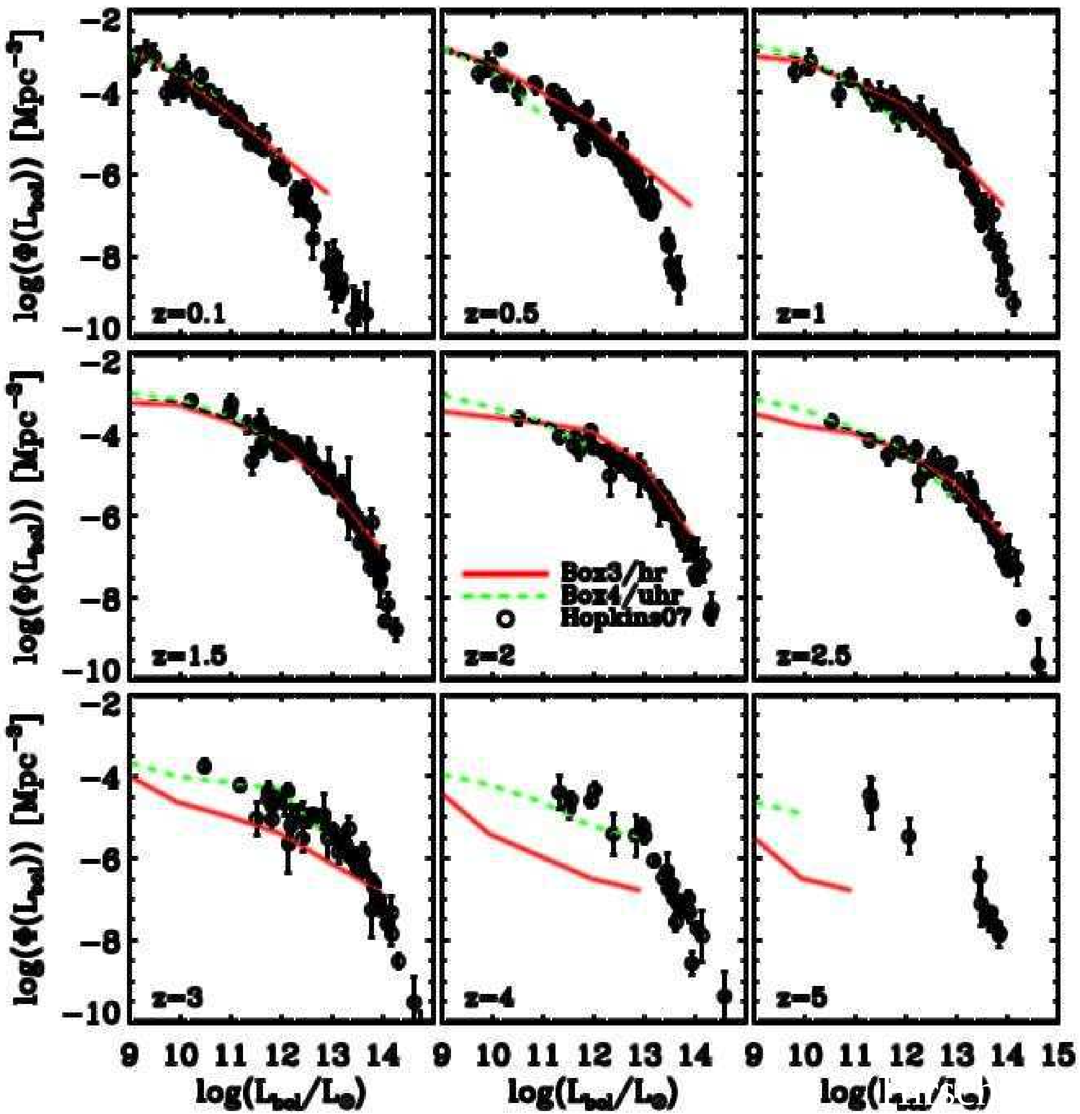
Sub-scale model for BH growth:
Resolution dependence ?
Various subtle extensions ...

Cool-cores and AGN feedback

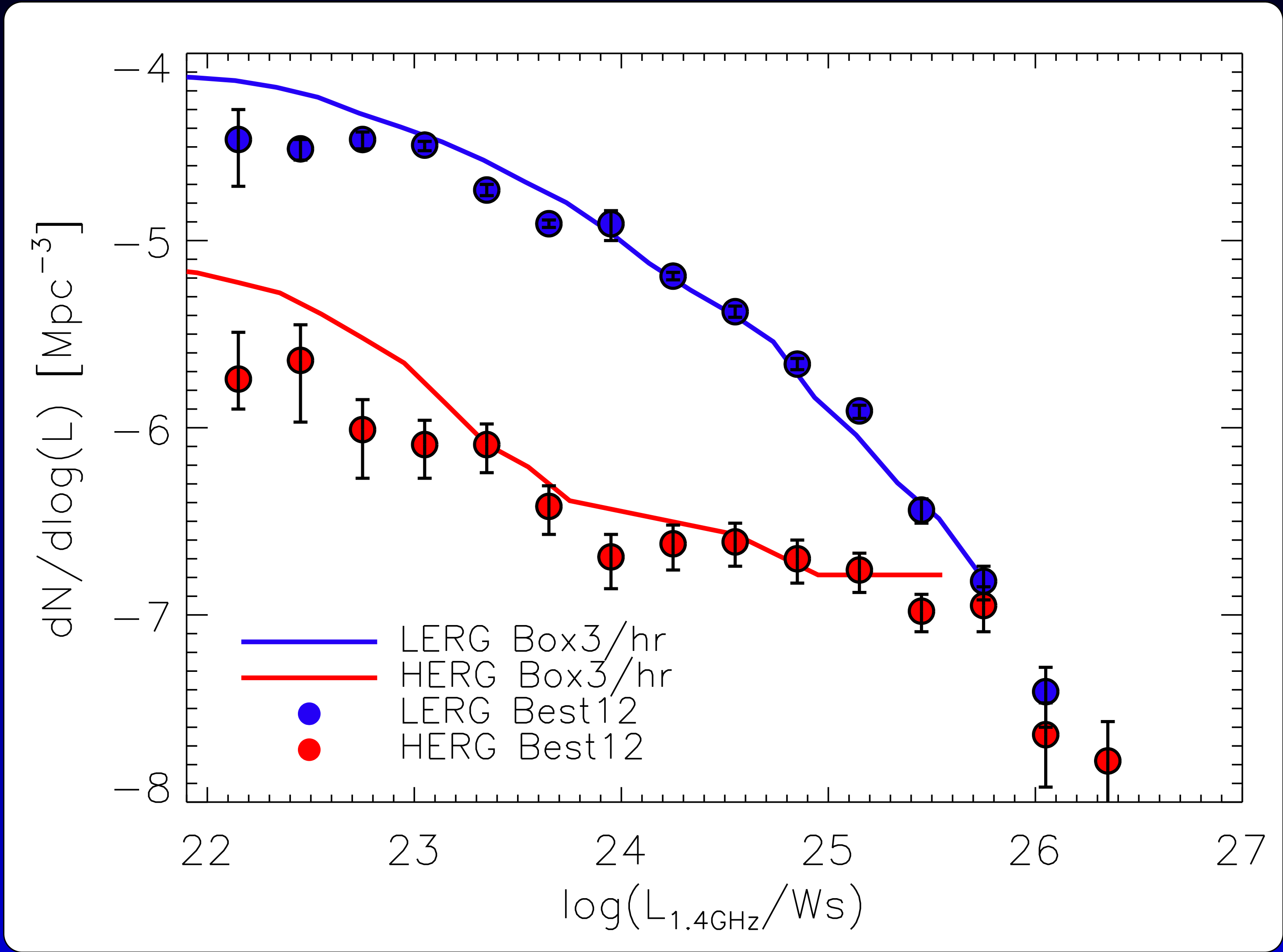
BH Mass −− Stellar Mass



Bolometric LF



Cool-cores and AGN feedback

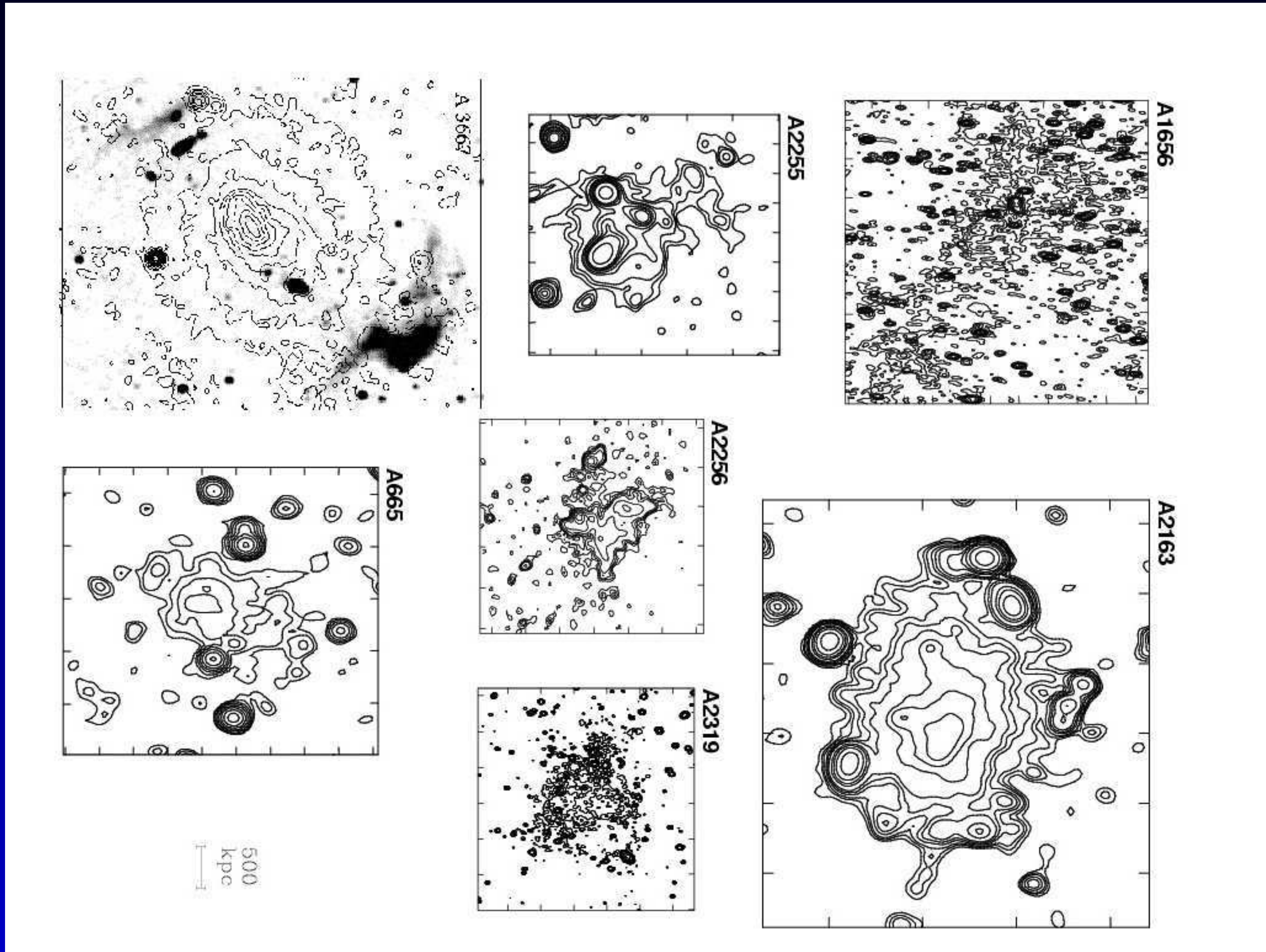


LERG: $f_{\rm edd} < 0.01$, HERG: $f_{\rm edd} > 0.01$

$(L_{\rm rad} + L_{\rm mech})/L_{\rm edd} =$ -1.6 , -3 (Best & Heckman 2012)

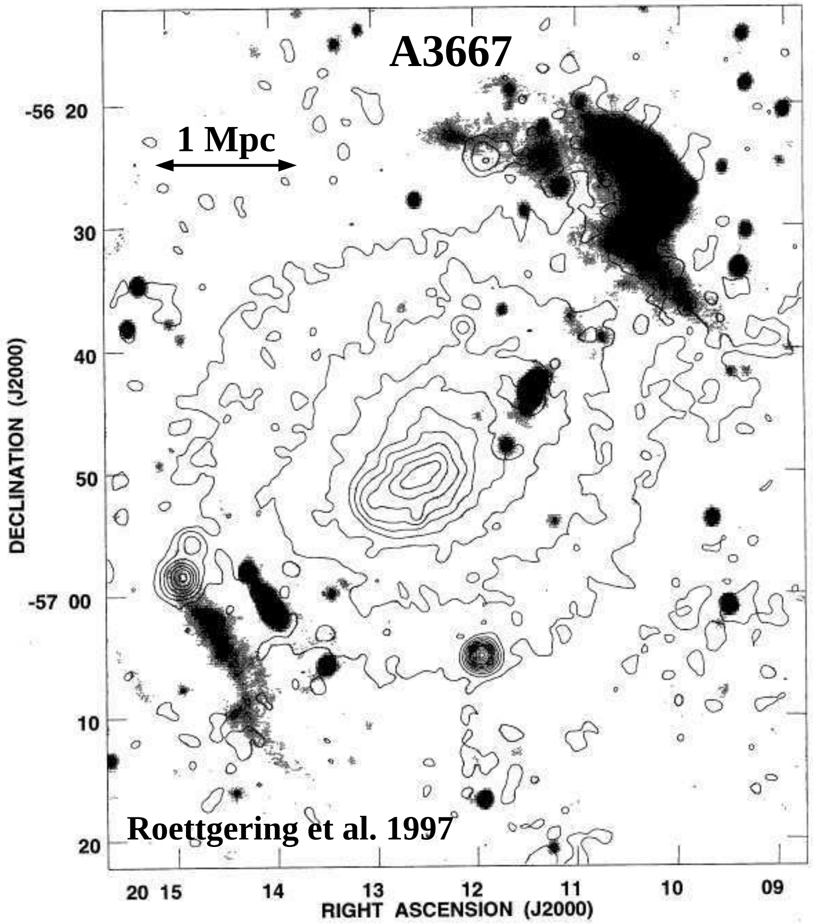
$L_{\rm mech} = 10^{36} \times (L_{1.4{\rm GHz}}/10^{24}{\rm WHz}^{-1})^{0.7}{\rm W}$ (Cavagnolo et al. 2010)

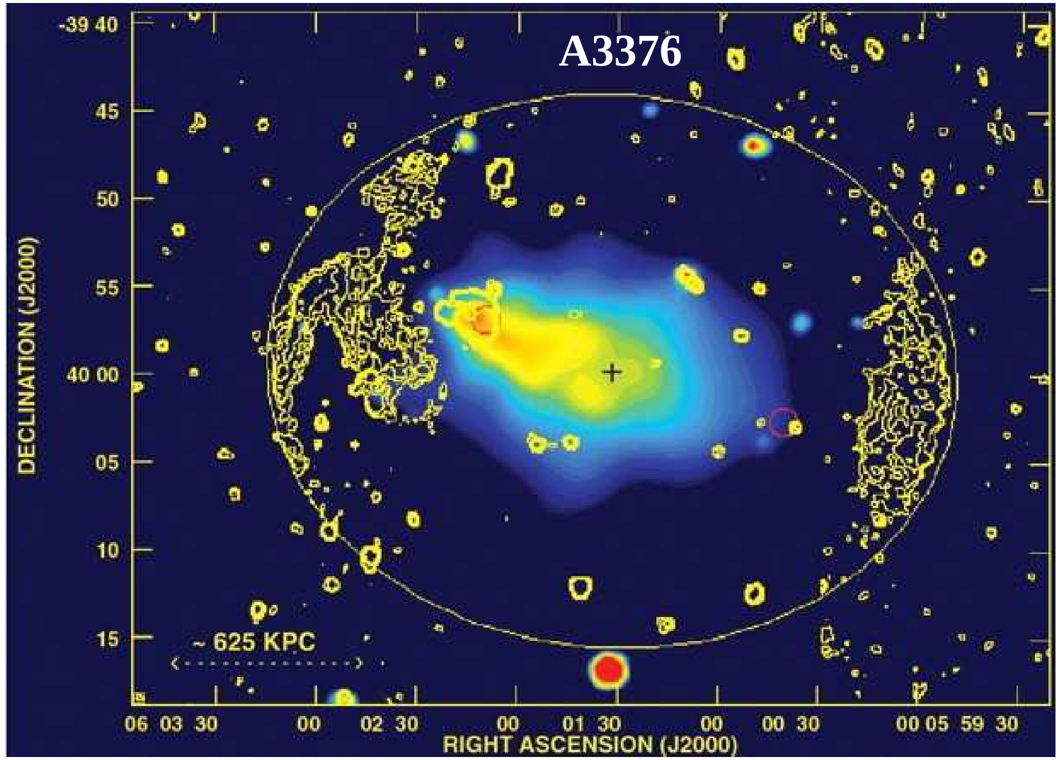
Radio Clusters



Cluster wide diffuse synchrotron emission (radio halos) of relativistic electrons in cluster magnetic fields. **Origin of relativistic electrons** (secondary, shocks, turbulence, ...) ?

Radio Clusters



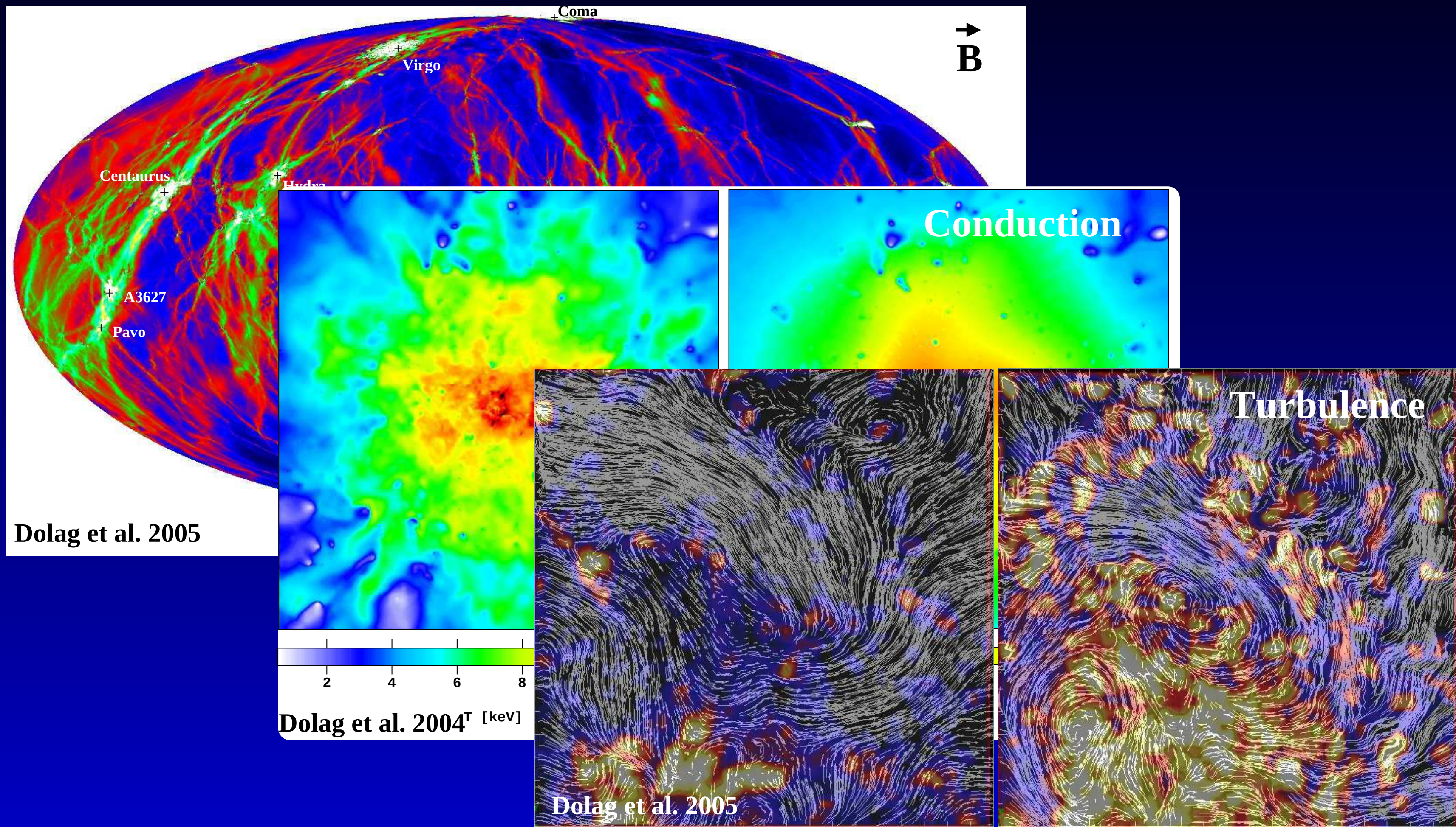


Bagchi et al. 2006

Peripheral synchrotron emission (radio relics) of A3667 (left) and A3376 (right).

- Related to **merger** or accretion **shock** ?
- Acceleration of electrons in shock ?
- Revival of (old) relativistic plasma ?

Further Complications



- Turbulence (e.g. distributing metals within ICM)
- Thermal conduction (e.g. thermal structure of ICM)
- $\vec{B}$ (e.g. non thermal pressure, turbulence, conduction)
- Cosmic Rays (e.g. non thermal pressure support, heating)

Process Network