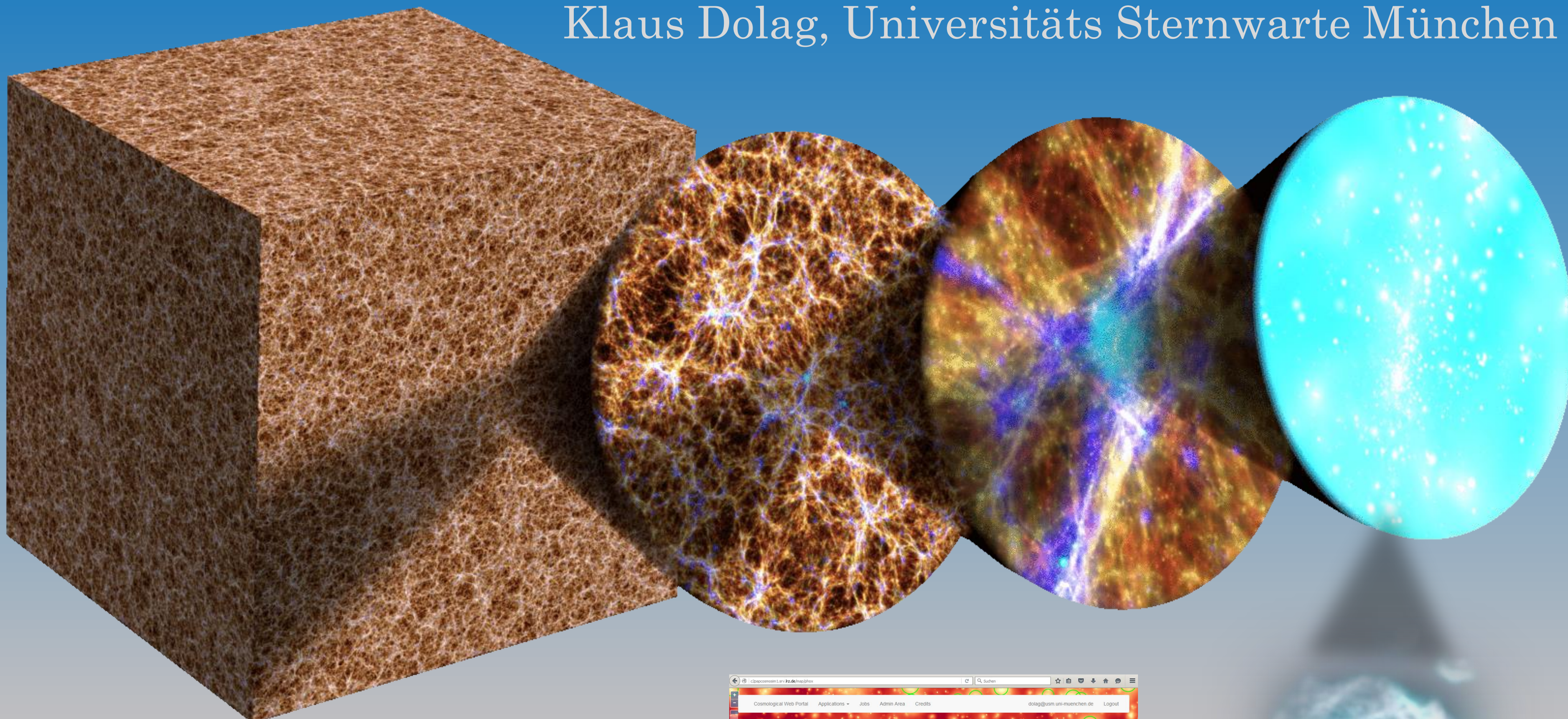
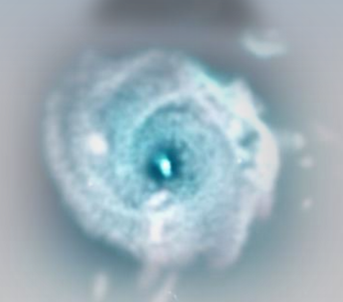
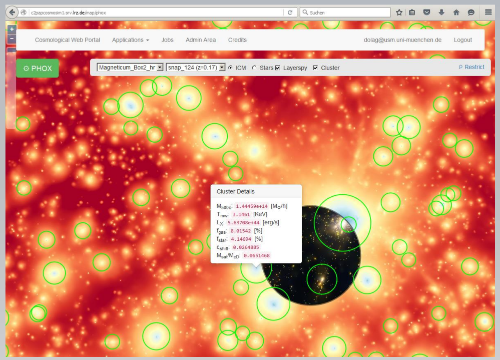
The Magneticum Simulations

Klaus Dolag, Universitäts Sternwarte München





www.magneticum.org

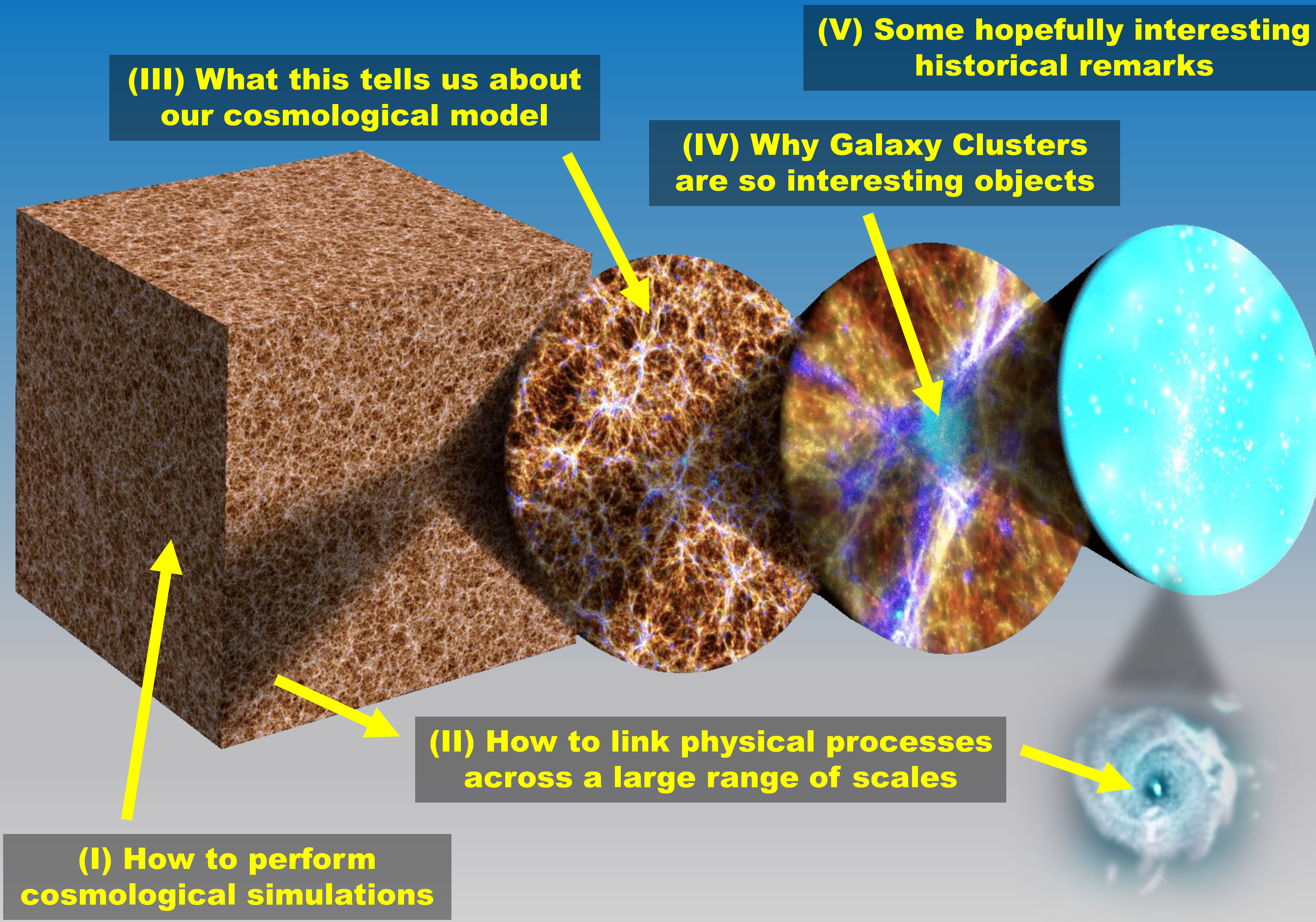


www.c2papcosmosim.svr.lrz.de

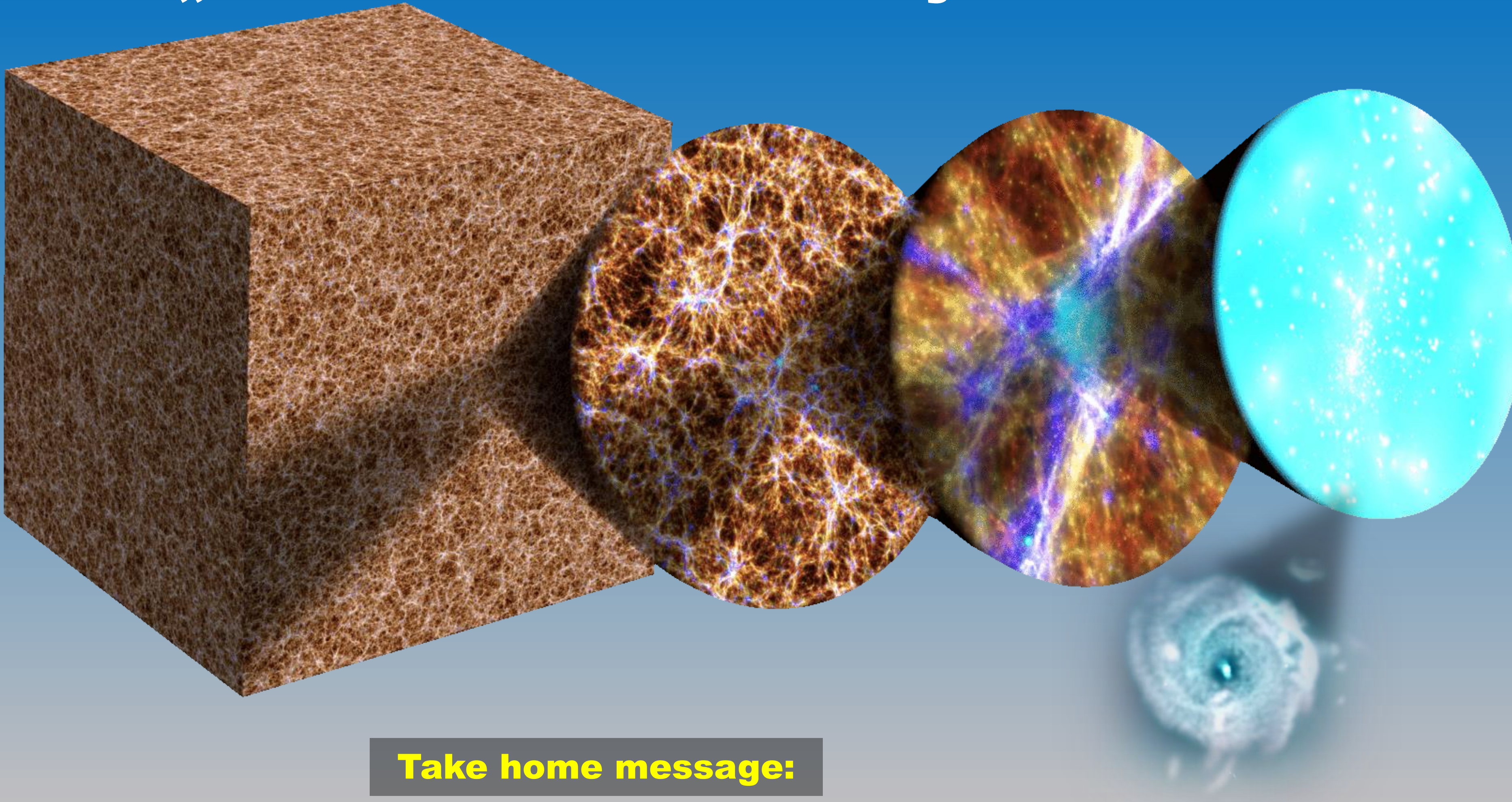
MAGNETICUM

Biffi (OATS), Petkova (C2PAP), Ragagnin (LRZ),
Remus, Steinborn, Teklu, Lotz (USM)

„Simulations and Galaxy Cluster“

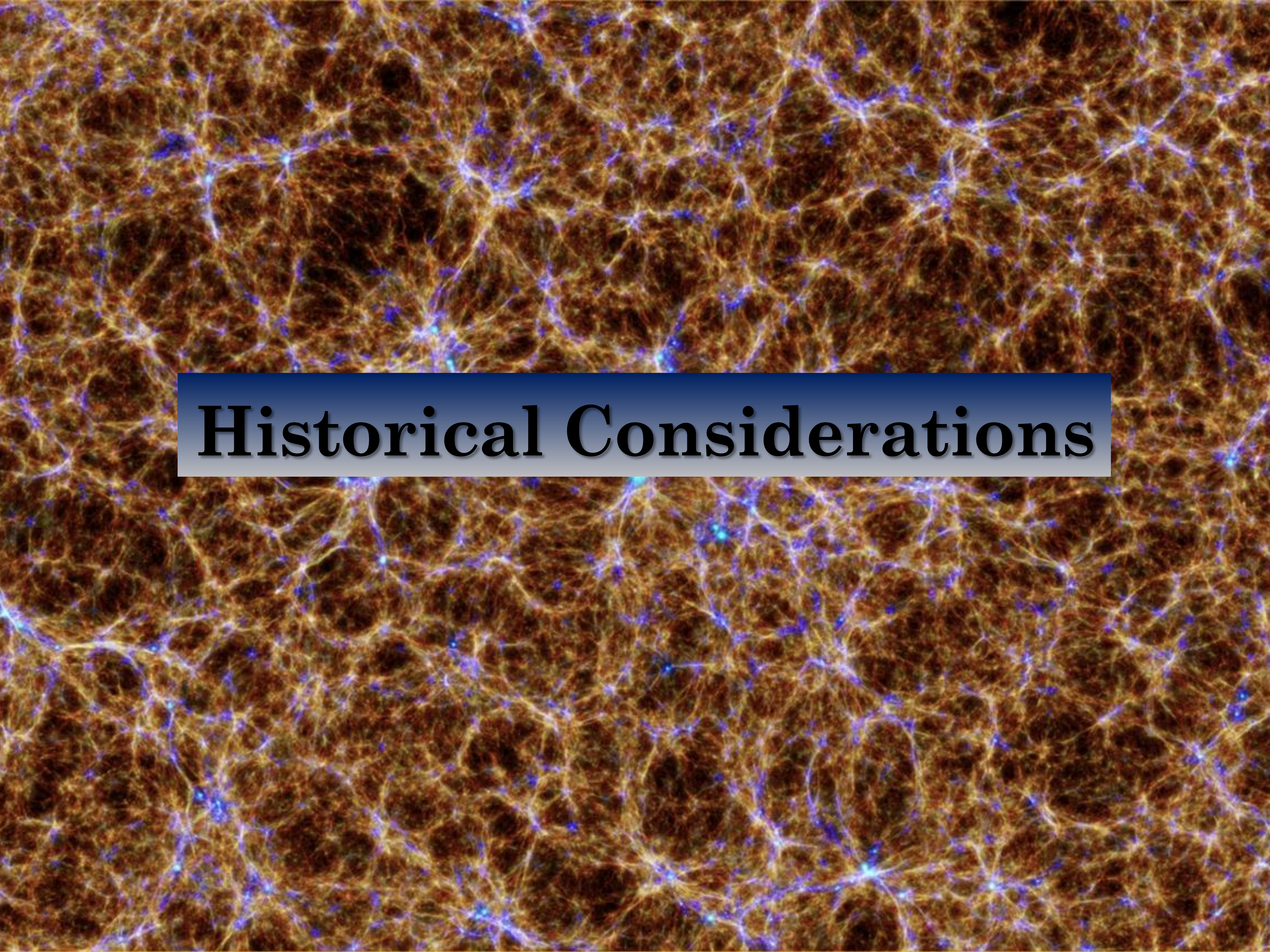


„Simulations and Galaxy Cluster“



Take home message:

Increased, available computational power together with improvement in the underlying numerical shemes and the improved treatment of physical processes made cosmological, hydrodynamical simulations to a robust tool to study and understand the complex interplay in the formation of large scale structure, galaxy clusters and galaxies and allow to improve our understanding of the internal dynamica of these objects.



Historical Considerations

Importance of Galaxy Clusters

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.

	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																											

uch close
sight of the
f nebulae.

4 or 5 with large extend and
densities, as well as several
s. However most of them are
pared to other observations).

Max Wolf (1863 – 1932)

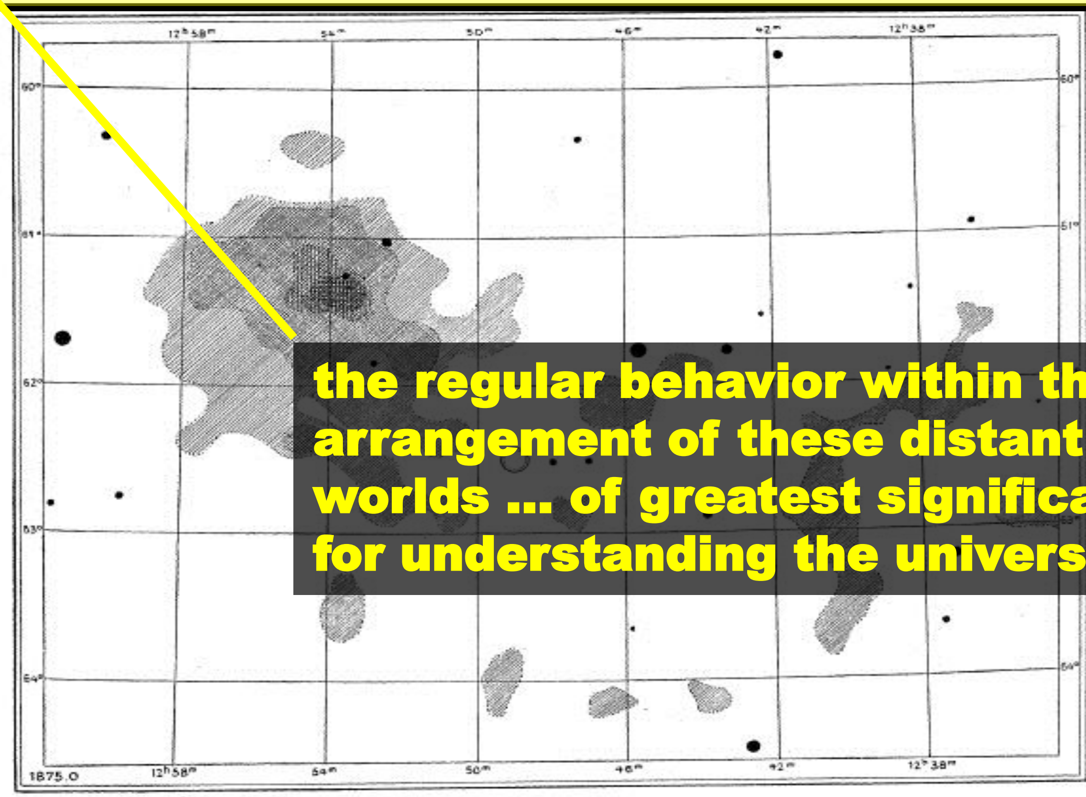
Quelle: Wikipedia

Importance of Galaxy Clusters

Ein merkwürdiger Haufen von Nebelflecken.

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.*)



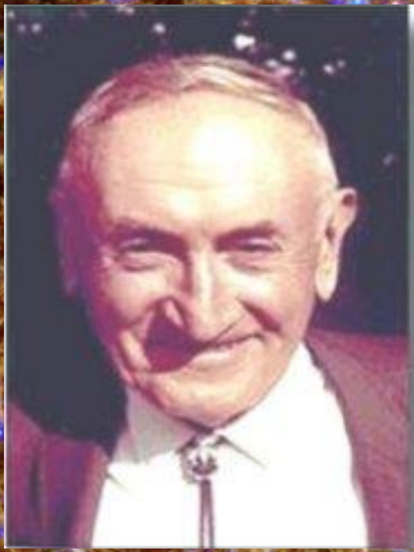
Nebelvertheilung um den Pol der Milchstrasse

the regular behavior within the arrangement of these distant worlds … of greatest significance for understanding the universe !

Max Wolf (1863 – 1932)

Quelle: Wikipedia

Importance of Galaxy Clusters



Fritz Zicky
(1863 – 1932)
Quelle: Wikipedia

- **1933: Clusters of galaxies: Dark Matter (Dynamics of the galaxies)**
- **1937: Clusters of galaxies: Gravitational Lensing („Einstein“ Effect)**
- **1938: Supernovae and Neutronstars, Standard Candles (with W. Baade)**

Matter in Galaxy Clusters

Mon. Not. R. astr. Soc. (1970) **151**, 1–44.

RADIO OBSERVATIONS OF THE CLUSTER OF GALAXIES IN COMA BERENICES—THE 5C4 SURVEY

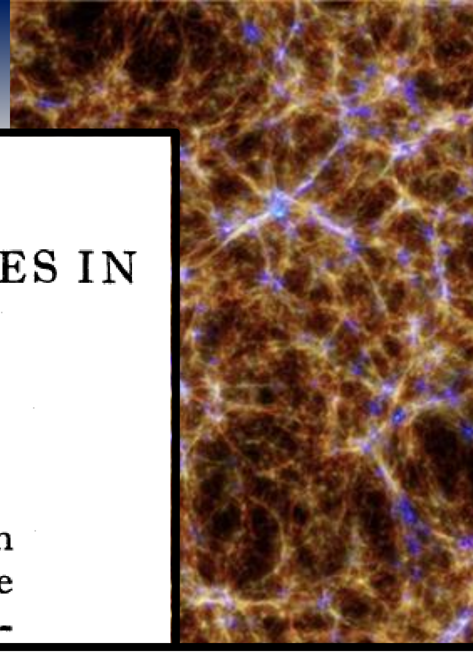
M. A. G. Willson

SUMMARY

High-resolution observations of the Coma cluster have enabled the detection of 189 radio sources with $S_{408} > 16 \times 10^{-29}$ W m^{-2} Hz^{-1}. Twenty-four were also detected at 1407 MHz. Most of them are believed to be field objects unconnected with the cluster. Optical identifications are suggested for many and the counts and spectra are compared with the results of earlier 5C surveys.

Two components of the complex of radio sources Coma C coincide with the bright galaxies NGC 4874 and NGC 4869, and about nine other cluster galaxies have radio luminosities $P_{408} \gtrsim 10^{21}$ W Hz^{-1} sr^{-1}. It is shown that the other component of Coma C, a large diameter source observed at low frequencies, must be intergalactic emission rather than the integrated radiation from normal galaxies. Such extensive sources appear to be a common feature of rich clusters.

Matter in Galaxy Clusters



Mon. Not. R. astr. Soc. (1970) **151**, 1–44.

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THE ASTROPHYSICAL JOURNAL, 167:L81–L84, 1971 August 1

A STRONG X-RAY SOURCE IN THE COMA CLUSTER OBSERVED BY *UHURU*

H. GURSKY, E. KELLOGG, S. MURRAY, C. LEONG, H. TANANBAUM, AND R. GIACCONI

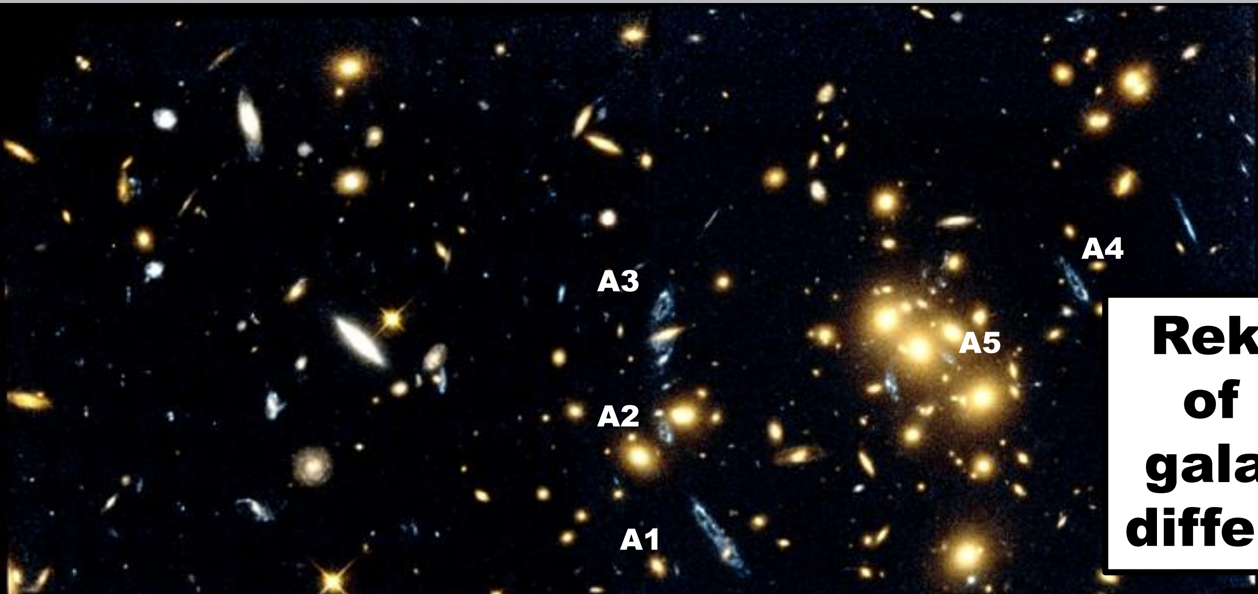
American Science and Engineering, Inc., Cambridge, Massachusetts 02142

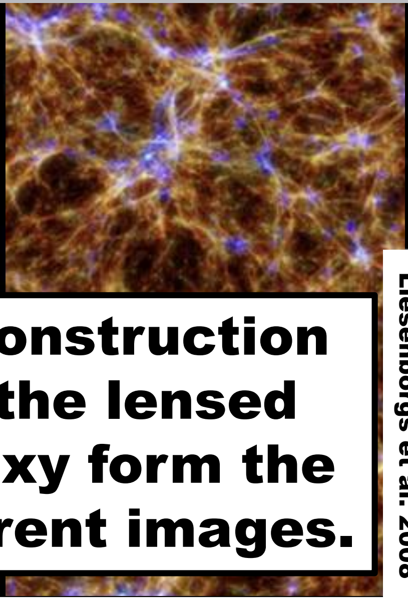
Received 1971 May 17; revised 1971 June 1

ABSTRACT

X-rays have been observed from a source in the Coma cluster of galaxies. The source is extended, with a size of about 45′. Its X-ray luminosity is 2.6×10^{44} ergs s^{-1}, and its spectrum is consistent with thermal bremsstrahlung at 7.3×10^7 ° K or a power law. If the source is hot gas, its mass is $3 \times 10^{13}\ M_\odot$, which is about 1 percent of the mass required to stabilize the cluster.

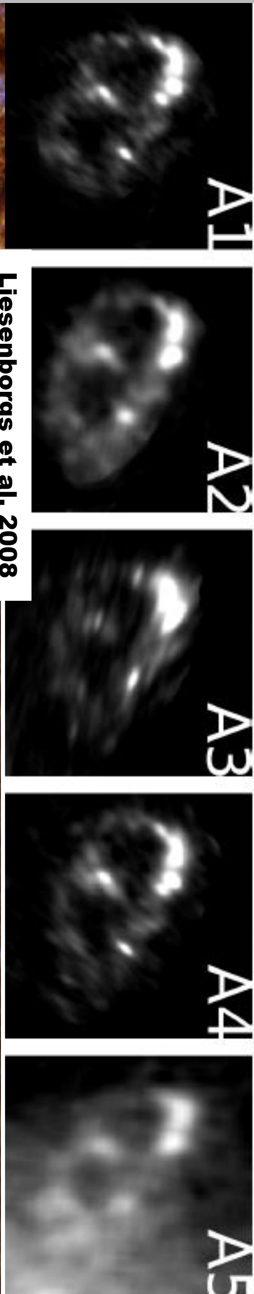
Gravitational lensing („Einstein“ effect)

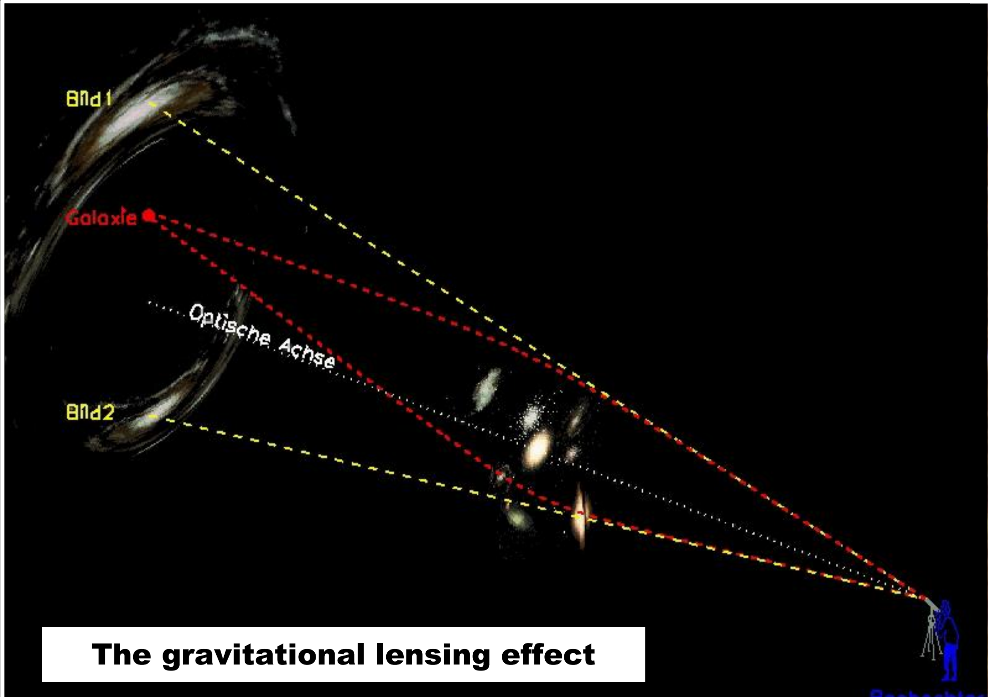




Rekonstruction of the lensed galaxy form the different images.

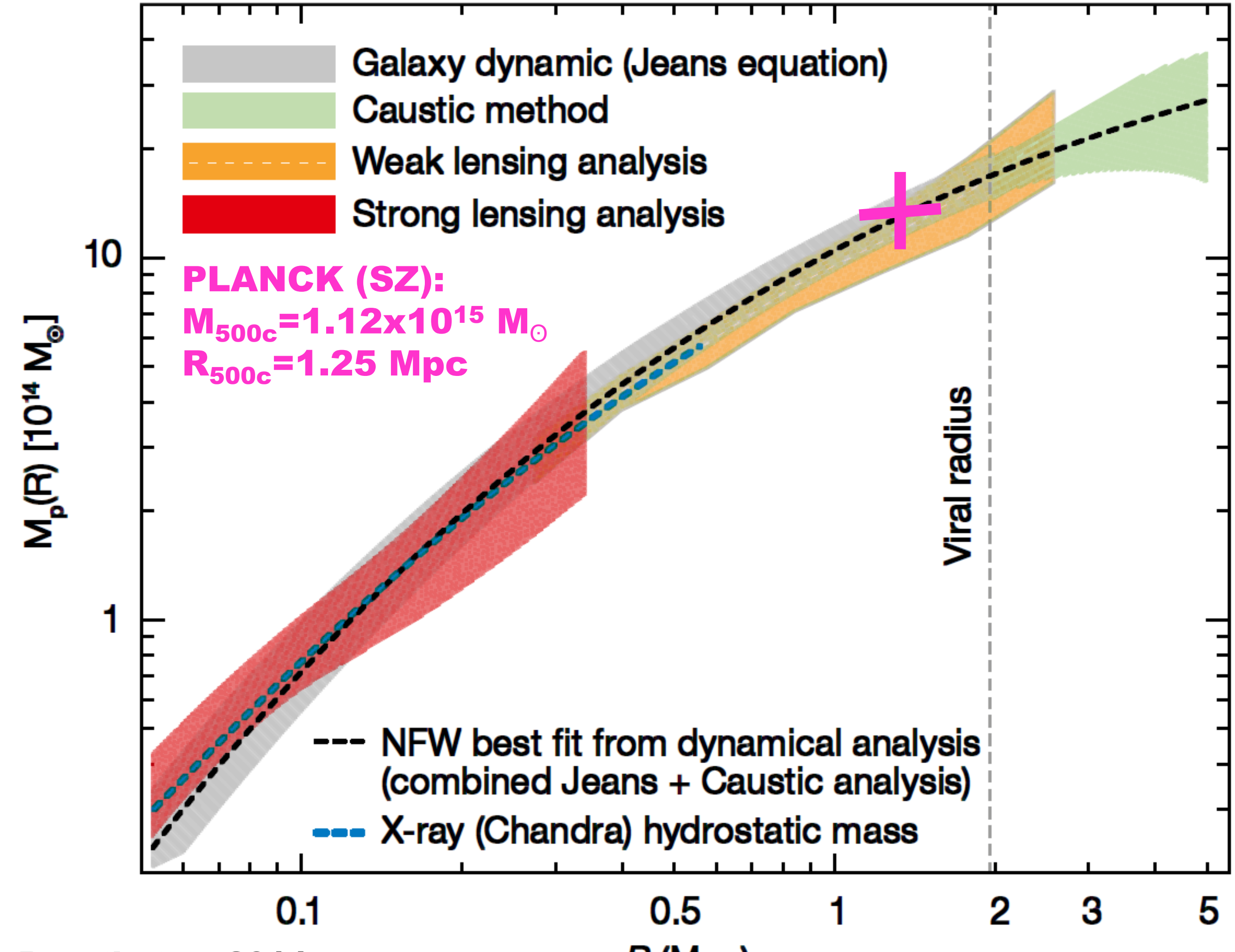
Liesenborgs et al. 2008



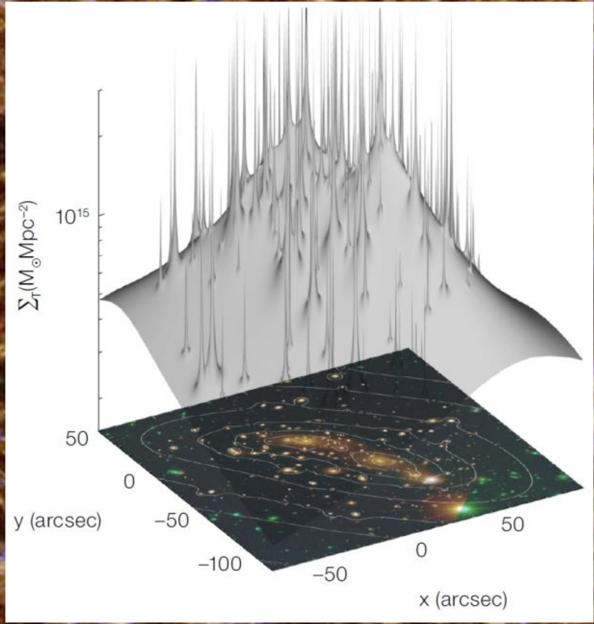


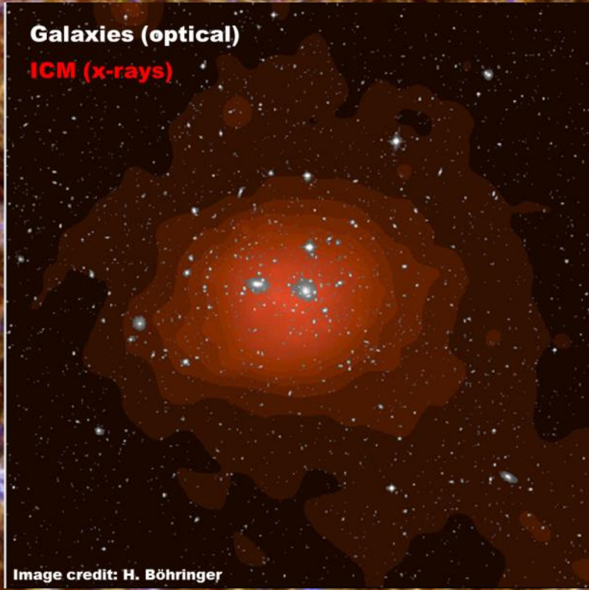
The gravitational lensing effect

Dark Matter in Galaxy Clusters

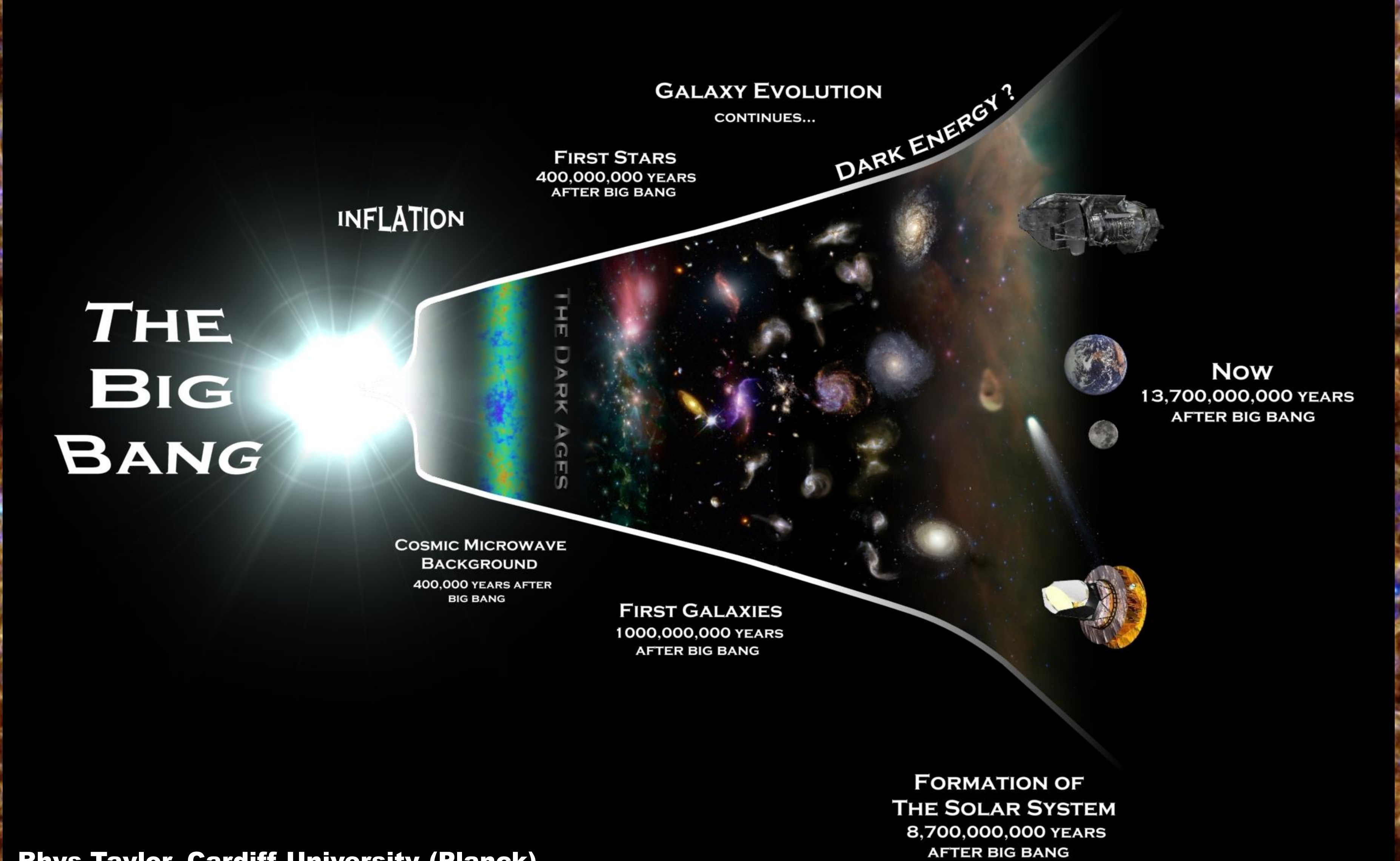


Rosati et al. 2014





Setting the framework: Evolving Universe



Rhys Taylor, Cardiff University (Planck)

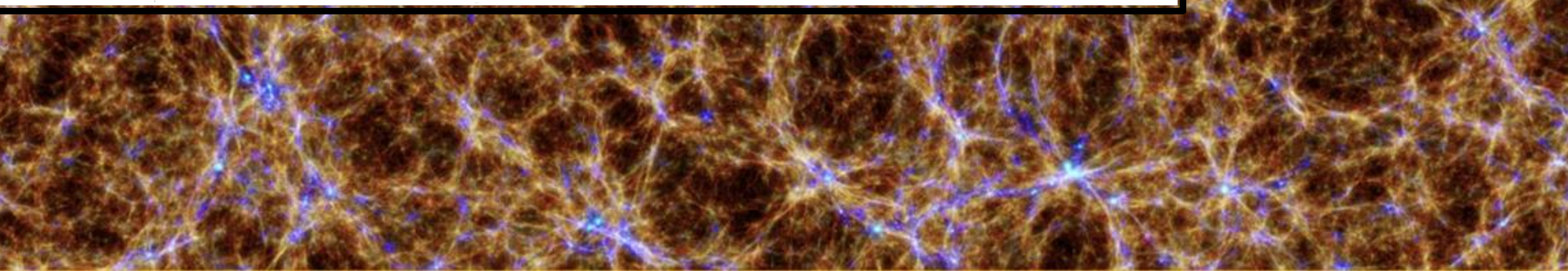
Galaxy Clusters and Cosmology

Mon. Not. R. astr. Soc. (1982) **201**, 365–383

Galactic and intergalactic Faraday rotation

R. C. Thomson and A. H. Nelson *Department of Applied Mathematics and Astronomy, University College, PO Box 78, Cardiff CF1 1XL*

Summary. A model of the systematic component of the magnetic field of the Galaxy is fitted to a sample of 459 extragalactic rotation measures (*RM*), and the results are found to be consistent with a previous analysis of pulsar *RM*s by Thomson & Nelson. The model is then used to reduce the effect of galactic Faraday rotation on the *RM*s of 134 QSOs, and the results used to investigate the existence of a Faraday-active intergalactic medium. Three models are considered in order to explain the redshift dependence of the *RM* variance. Although none of these models can be excluded, a significant fraction of the observed Faraday rotation may take place in extended cluster/supercluster haloes with dimensions ~ 9 Mpc, electron densities $\sim 10^{-4}\ \mathrm{cm}^{-3}$ and magnetic fields ~ 0.1–$1\ \mu\mathrm{G}$. The inferred filling-factor $\sim 2 \times 10^{-3}$, implies $\Omega \sim 0.1$.



Galaxy Clusters and Cosmology

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Summary. A model of the systematic component of the magnetic field of
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The Astrophysical Journal, 504:1–6, 1998 September 1

THE MOST MASSIVE DISTANT CLUSTERS: DETERMINING Ω AND σ_8

Neta A. Bahcall and Xiaohui Fan
Princeton University Observatory, Princeton, NJ 08544; neta@astro.princeton.edu, fan@astro.princeton.edu
Received 1997 November 12; accepted 1998 April 6

ABSTRACT

The existence of the three most massive clusters of galaxies observed so far at $z > 0.5$ is used to constrain the mass density parameter of the universe, Ω, and the amplitude of mass fluctuations, σ_8. We find $\Omega = 0.2^{+0.3}_{-0.1}$ and $\sigma_8 = 1.2^{+0.5}_{-0.4}$ (95%). We show that the existence of even the *single* most distant cluster at $z = 0.83$, MS 1054−03, with its large gravitational lensing mass, high temperature, and large velocity dispersion, is sufficient to establish powerful constraints. High-density, $\Omega = 1$ ($\sigma_8 \simeq 0.5$–0.6) Gaussian models are ruled out by these data ($\lesssim 10^{-6}$ probability); the $\Omega = 1$ models predict only $\sim 10^{-5}$ massive clusters at $z > 0.65$ ($\sim 10^{-3}$ at $z > 0.5$) instead of the one (three) clusters observed.

Galaxy Clusters and Cosmology

Mon. Not. R. astr. Soc. (1982) **201**, 365–383

Galactic and intergalactic Faraday rotation

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Summary. A model of the systematic component of the magnetic field of
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Number of cluster

THE ASTROPHYSICAL JOURNAL, 504:1–6, 1998 September 1

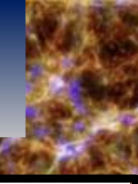
THE MOST MASSIVE DISTANT CLUSTERS: DETERMINING Ω AND σ_8

NETA A. BAHCALL AND XIAOHUI FAN
Princeton University Observatory, Princeton, NJ 08544; neta@astro.princeton.edu, fan@astro.princeton.edu
Received 1997 November 12; accepted 1998 April 6

ABSTRACT

The existence of the three most massive clusters of galaxies observed so far at $z > 0.5$ is used to constrain the mass density parameter of the universe, Ω, and the amplitude of mass fluctuations, σ_8. We find $\Omega = 0.2^{+0.3}_{-0.1}$ and $\sigma_8 = 1.2^{+0.5}_{-0.4}$ (95%). We show that the existence of even the *single* most distant cluster at $z = 0.83$, MS 1054–03, with its large gravitational lensing mass, high temperature, and large velocity dispersion, is sufficient to establish powerful constraints. High-density, $\Omega = 1$ ($\sigma_8 \simeq 0.5$–0.6) Gaussian models are ruled out by these data ($\lesssim 10^{-6}$ probability); the $\Omega = 1$ models predict only $\sim 10^{-5}$ massive clusters at $z > 0.65$ ($\sim 10^{-3}$ at $z > 0.5$) instead of the one (three) clusters observed.

Galaxy Clusters and Cosmology



Mon. Not. R. astr. Soc. (1982) 201, 365–383

Galactic and intergal

R. C. Thomson and

Mathematics and Astronomy, Uni

Summary. A model of the

THE ASTROPHYSICAL JOURNAL, 504

© 1998. The American Astronomical Society.

THE MOST

Princeton University

The existence of the thr strain the mass density par $\Omega = 0.2^{+0.3}_{-0.1}$ and $\sigma_8 = 1.2$ $z = 0.83$, MS 1054−03, w dispersion, is sufficient to models are ruled out by th clusters at $z > 0.65$ (~10

Astron. Astrophys. 330, 1–9 (1998)

Arc statistics with realistic cluster potentials

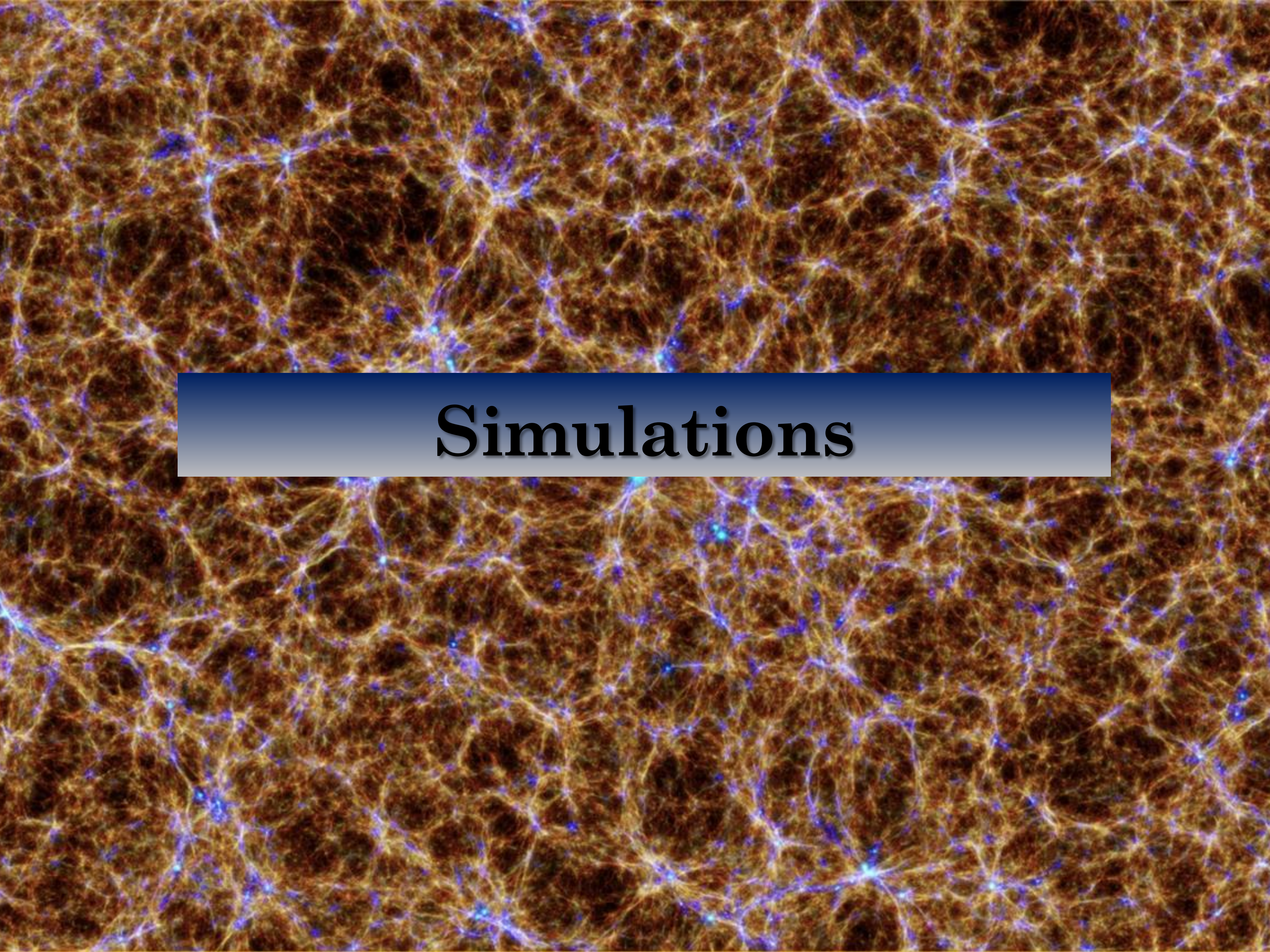
IV. Clusters in different cosmologies

Matthias Bartelmann[1], Andreas Huss[1], Jörg M. Colberg[1], Adrian Jenkins[2], and Frazer R. Pearce[2]

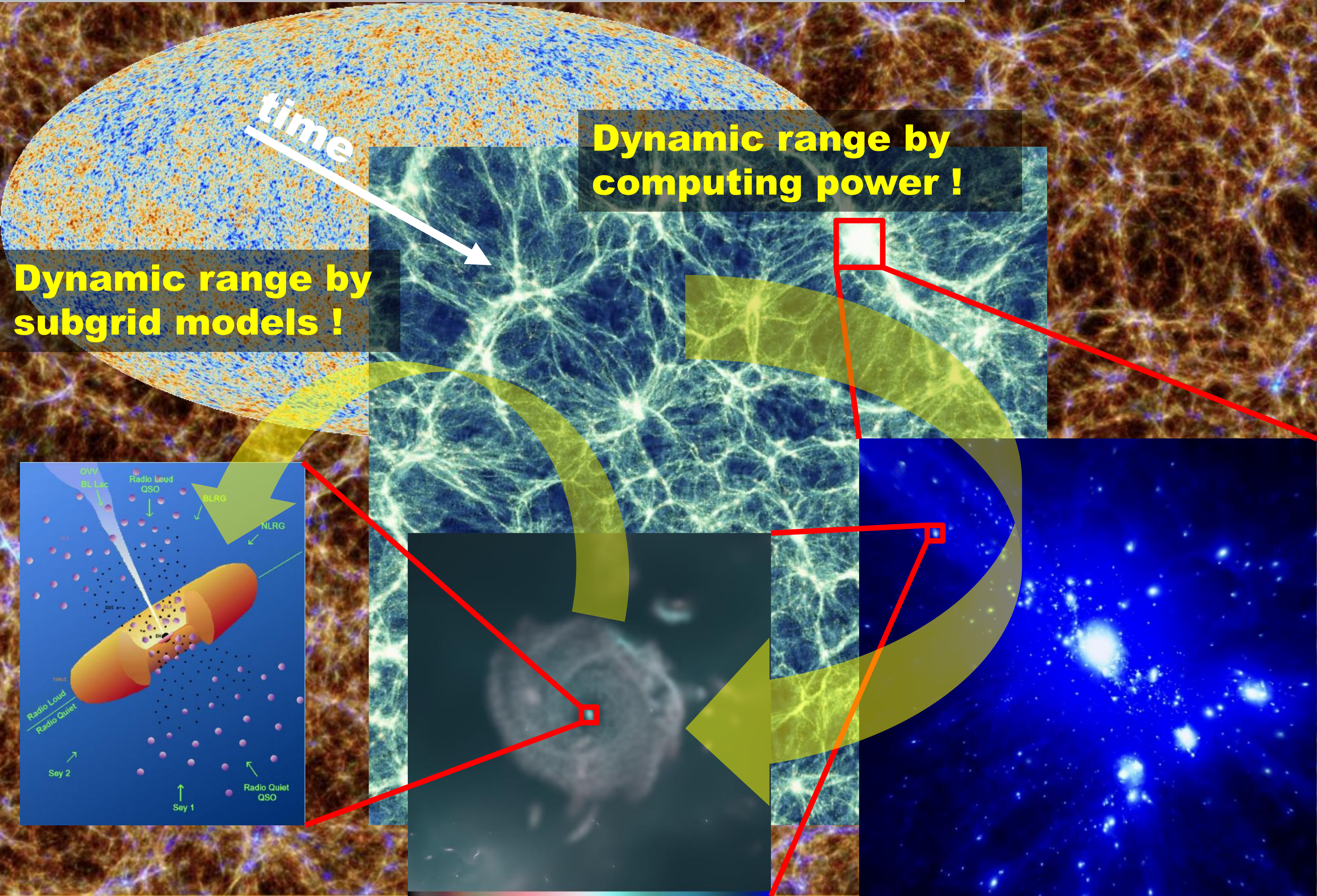
Abstract. We use numerical simulations of galaxy clusters in different cosmologies to study their ability to form large arcs. The cosmological models are: Standard CDM (SCDM; $\Omega_0 = 1$, $\Omega_\Lambda = 0$); τCDM with reduced small-scale power (parameters as SCDM, but with a smaller shape parameter of the power spectrum); open CDM (OCDM; $\Omega_0 = 0.3$, $\Omega_\Lambda = 0$); and spatially flat, low-density CDM (ΛCDM; $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$). All models are normalised to the local number density of rich clusters. Simulating gravitational lensing by these clusters, we compute optical depths for the formation of large arcs. For large arcs with length-to-width ratio ≥ 10, the optical depth is largest for OCDM. Relative to OCDM, the optical depth is lower by about an order of magnitude for ΛCDM, and by about two orders of magnitude for S/τCDM. These differences originate from the different epochs of cluster formation across the cosmological models, and from the non-linearity of the strong lensing effect. We conclude that only the OCDM model can reproduce the observed arc abundance well, while the other models fail to do so by orders of magnitude.

Internal structure of cluster

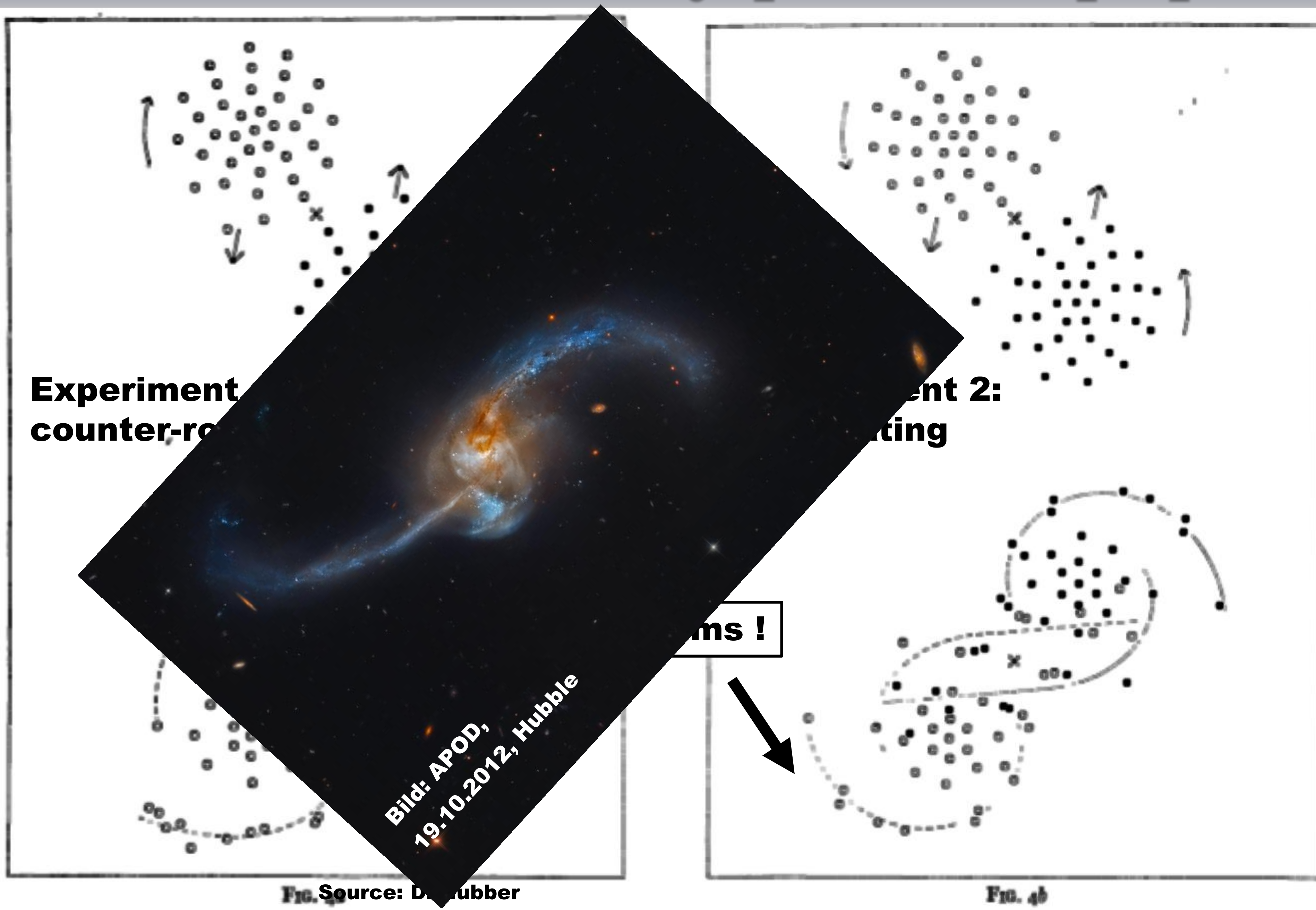
Simulations



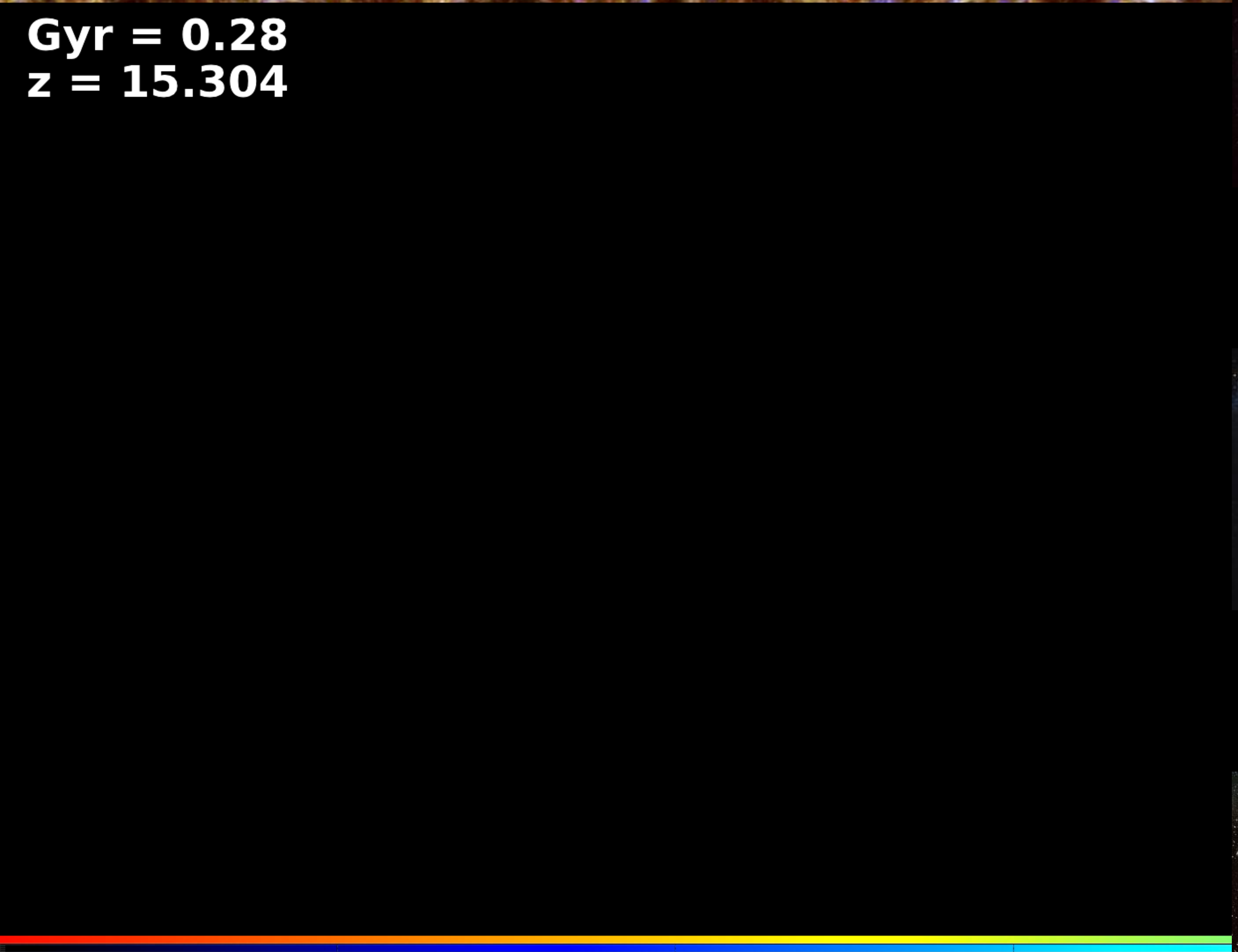
Performing Simulations

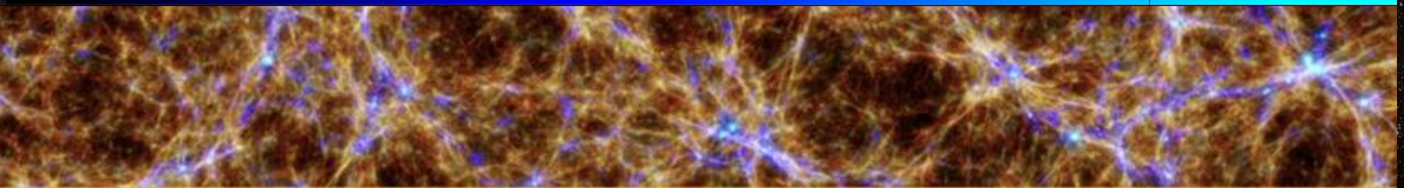


First simulation by pen and paper



The many lives of galaxies

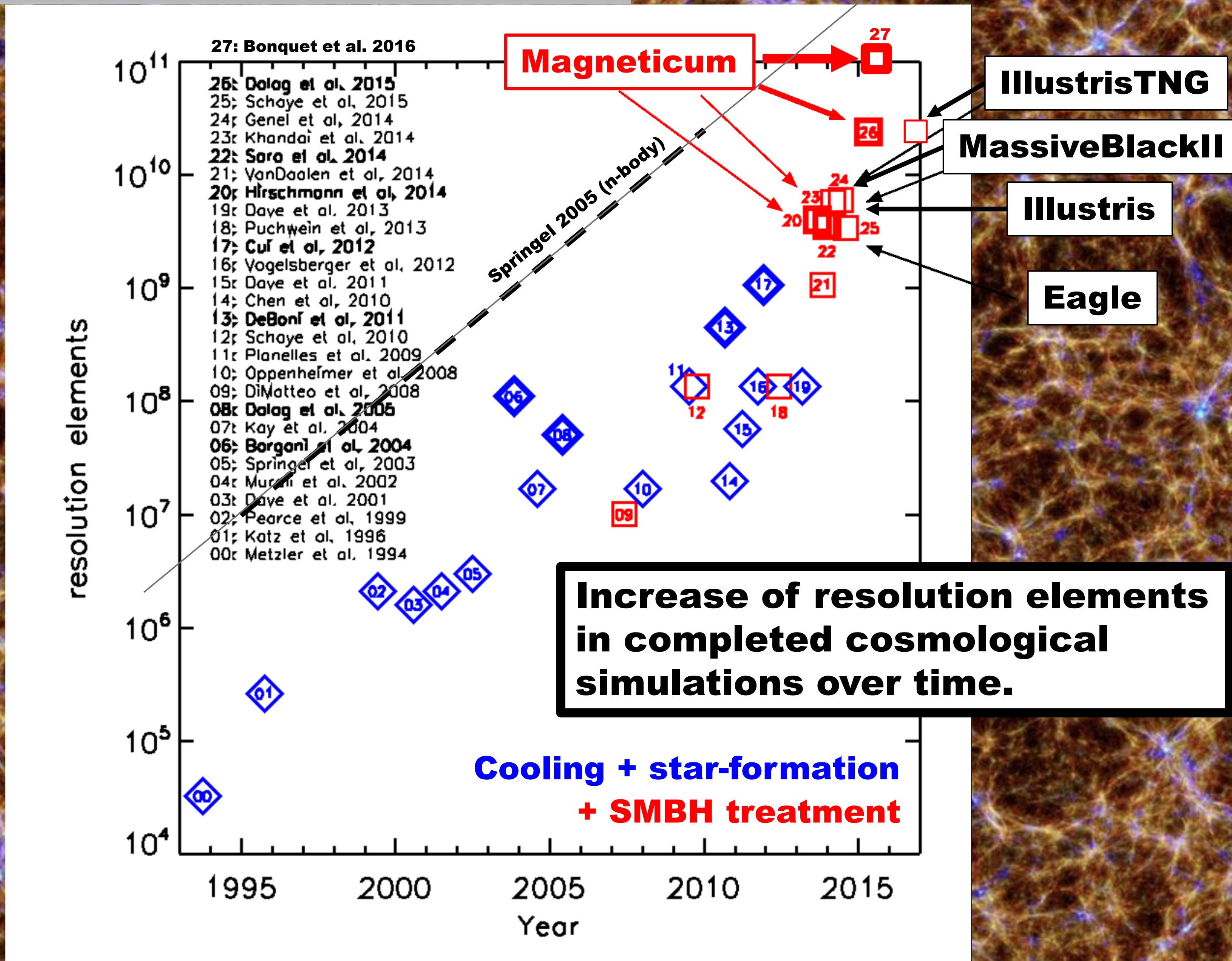


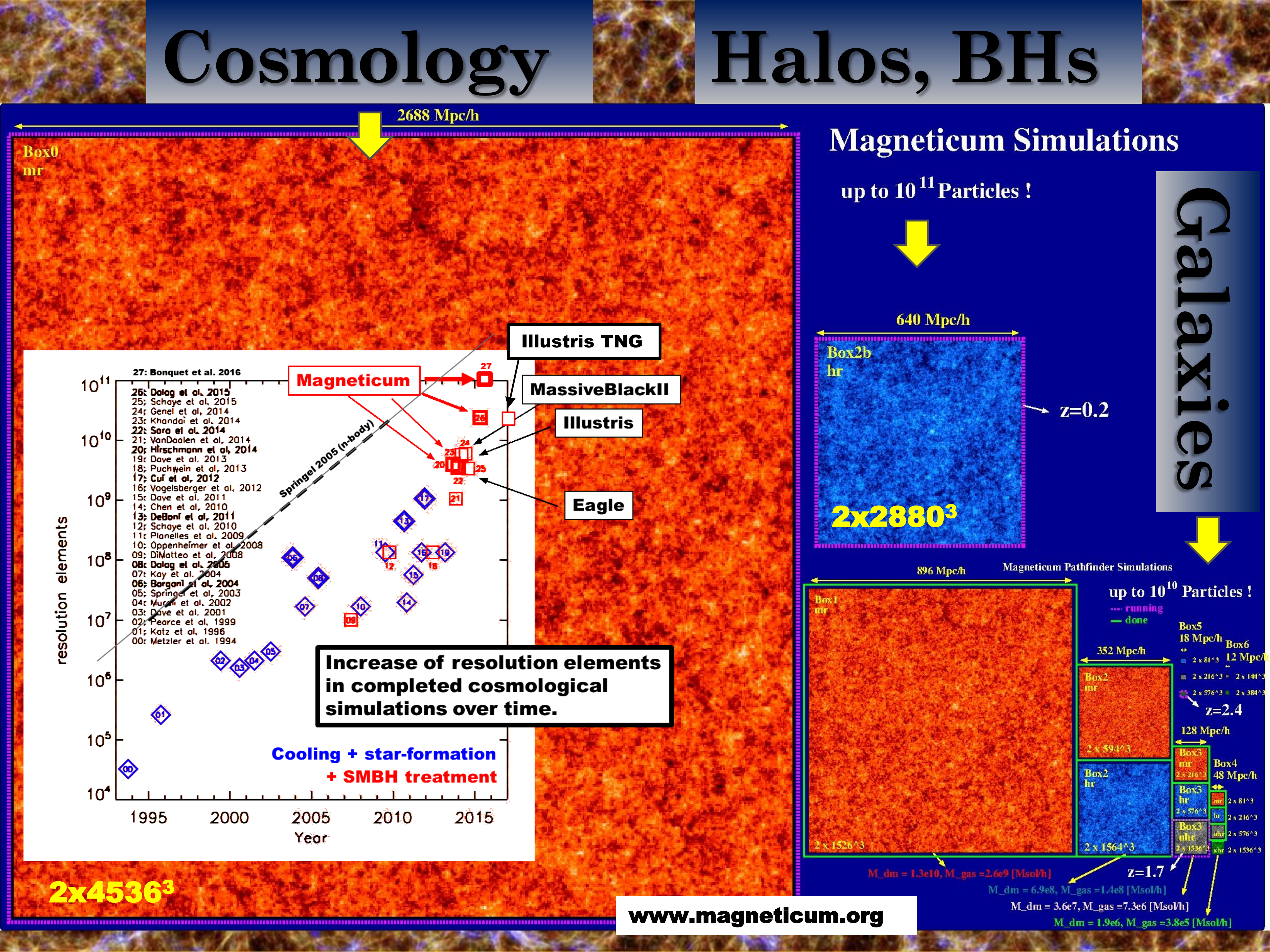


NGC1300

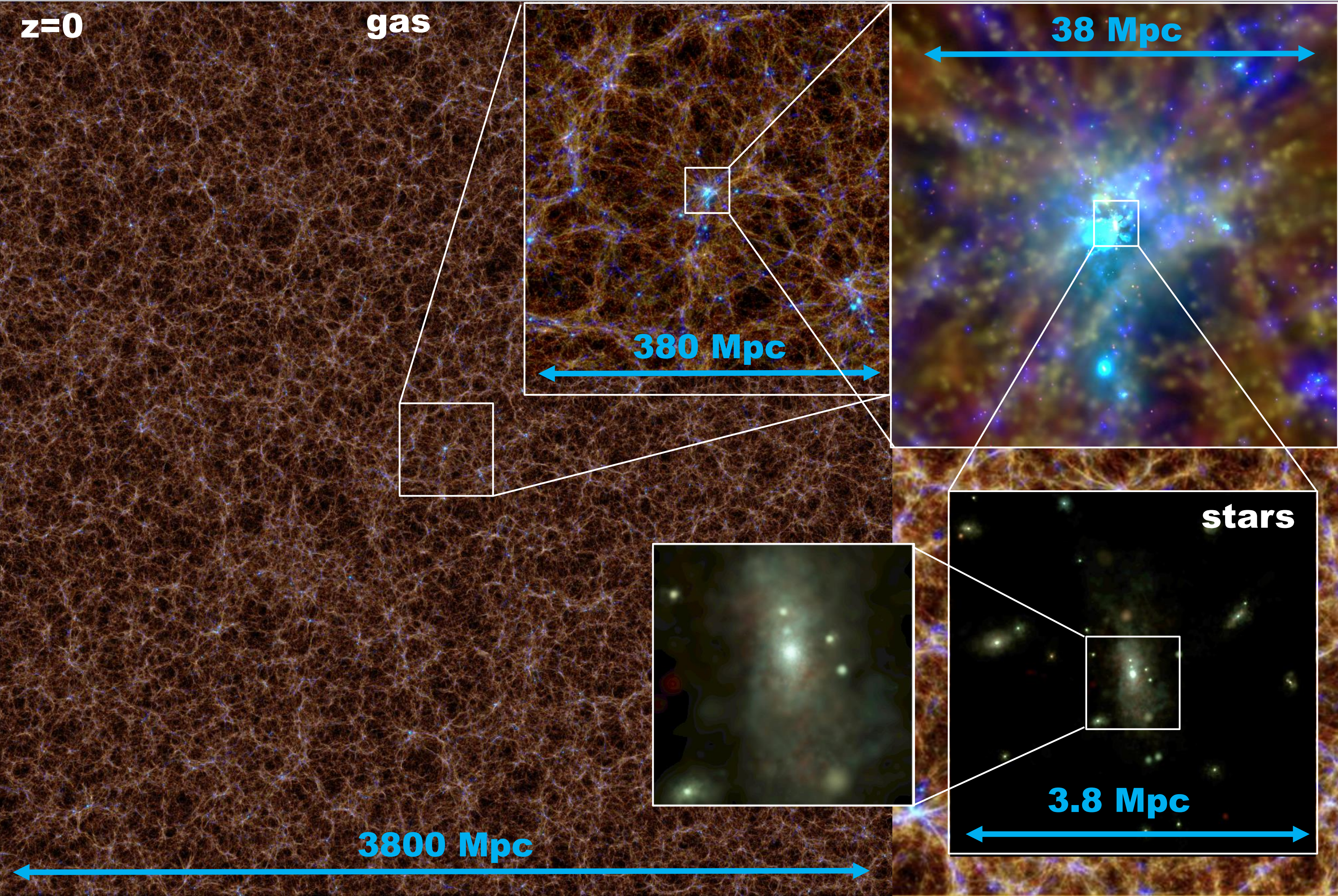
Hydro Simulations

Box2b/hr, Box0/mr

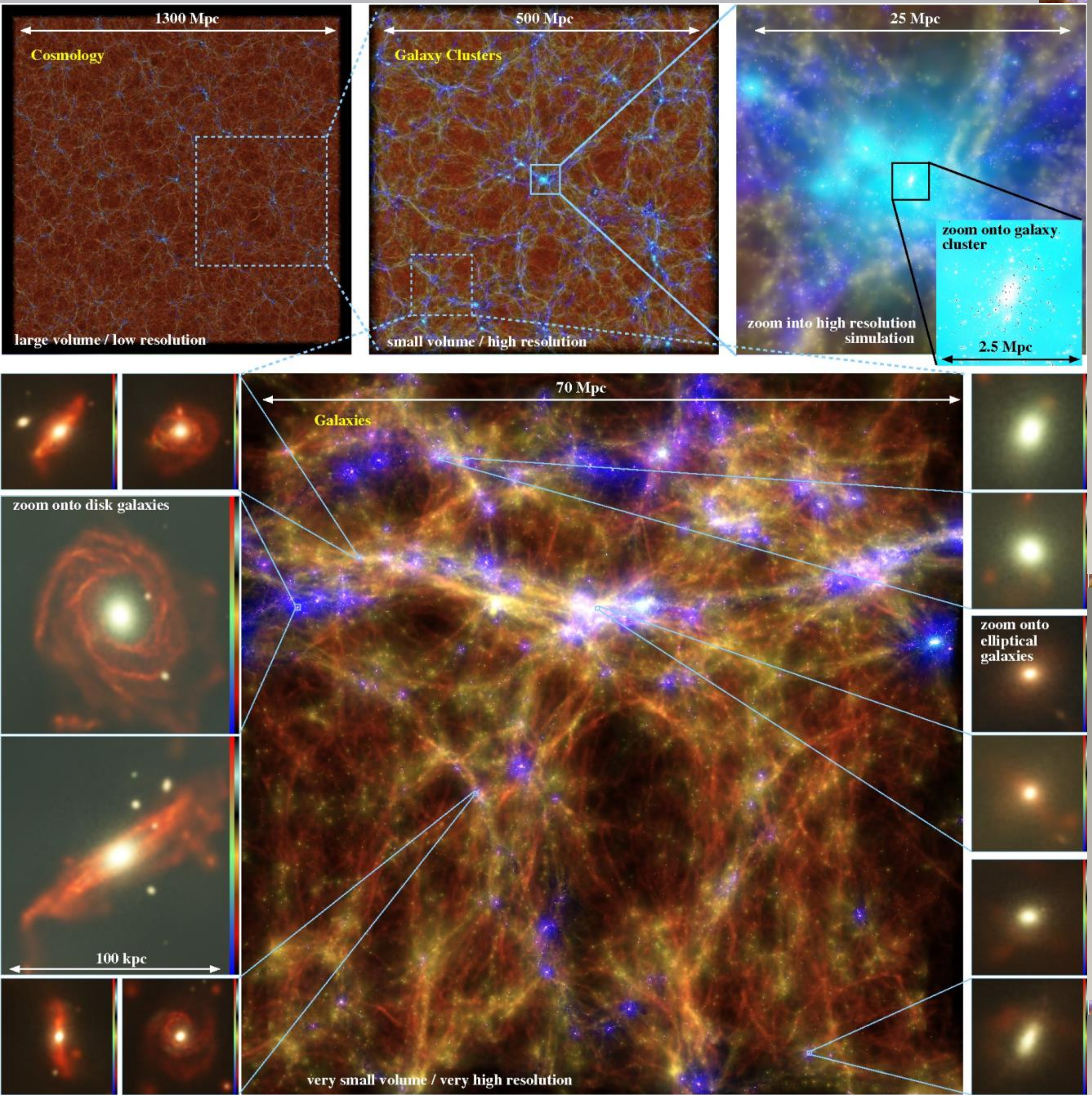



Cosmology
Halos, BHs
Galaxies
2688 Mpc/h
Box0
mr
2x4536³
Magneticum Simulations
up to 10^11 Particles !
640 Mpc/h
Box2b
hr
z=0.2
2x2880³
27: Bonquet et al. 2016
26: Dolag et al. 2015
25: Schaye et al. 2015
24: Genel et al. 2014
23: Khandai et al. 2014
22: Saro et al. 2014
21: VanDaalen et al. 2014
20: Hirschmann et al. 2014
19: Dave et al. 2013
18: Puchwein et al. 2013
17: Cui et al. 2012
16: Vogelsberger et al. 2012
15: Dave et al. 2011
14: Chen et al. 2010
13: DeBoni et al. 2011
12: Schaye et al. 2010
11: Planelles et al. 2009
10: Oppenheimer et al. 2008
09: DiMatteo et al. 2008
08: Dolag et al. 2005
07: Kay et al. 2004
06: Borgani et al. 2004
05: Springel et al. 2003
04: Murali et al. 2002
03: Dave et al. 2001
02: Pearce et al. 1999
01: Katz et al. 1996
00: Metzler et al. 1994
Springel 2005 (n-body)
Magneticum
Illustris TNG
MassiveBlackII
Illustris
Eagle
resolution elements
Year
Increase of resolution elements in completed cosmological simulations over time.
Cooling + star-formation
+ SMBH treatment
896 Mpc/h
Magneticum Pathfinder Simulations
up to 10^10 Particles !
running
done
Box1
mr
2 x 1526^3
352 Mpc/h
Box2
mr
2 x 594^3
Box2
hr
2 x 1564^3
Box5
18 Mpc/h
Box6
12 Mpc/h
2 x 81^3
2 x 216^3
2 x 144^3
2 x 576^3
2 x 384^3
z=2.4
128 Mpc/h
Box3
mr
2 x 216^3
Box3
hr
2 x 576^3
Box3
uhr
2 x 1536^3
Box4
48 Mpc/h
mr 2 x 81^3
hr 2 x 216^3
uhr 2 x 576^3
xhr 2 x 1536^3
z=1.7
M_dm = 1.3e10, M_gas =2.6e9 [Msol/h]
M_dm = 6.9e8, M_gas =1.4e8 [Msol/h]
M_dm = 3.6e7, M_gas =7.3e6 [Msol/h]
M_dm = 1.9e6, M_gas =3.8e5 [Msol/h]
www.magneticum.org

Largest Simulation (Box0/mr)



... and Physics Included



cooling+sfr+winds
Springel & Hernquist 2002/2003

Metals cooling
Wiersma et al. 2009

SNIa,SNII,AGB
Tornatore et al. 2003/2006

BH+AGN feedback
Springel & Di Matteo 2006
Fabjan et al. 2010
Hirschmann et al. 2014 (std)
Steinborn et al. 2015 (new)

Thermal conduction
1/20th Spitzer
Dolag et al. 2004

Numerics:

New Kernels: WC6
Dehnen et al. 2012

Low visc. scheme
mr/hr (time dep. alpha)
Dolag et al. 2005
uhr (high order grad.)
Beck et al. 2015

+ zoomed clusters

MAGNETICUM

	Box0	Box1	Box2b	Box2	Box3	Box4
[Mpc/h]	2688	896	640	352	128	48
mr	2×4536^3	2×1526^3	–	2×594^3	2×216^3	2×81^3
hr	–	–	2×2880^3	2×1584^3	2×576^3	2×216^3
uhr	–	–	–	–	$2 \times 1536^3 (z = 2)$	2×576^3

Setup:

$2x4536^3$ = 186.659.085.312 particle

Almost 20 times size of ILLUSTRIS or EAGLE

Full Physics + improved SPH:

200 bytes per DM particle, 456 bytes per GAS particle

Complete SuperMUC Phase II:

6 x 512 x 2 x 28 = 172032 tasks

1 MPI task per socket, 28 OpenMP per MPI

68.5 TB for single checkpointing

reaching 170 Gbyte/sec

20 TB for single snapshot

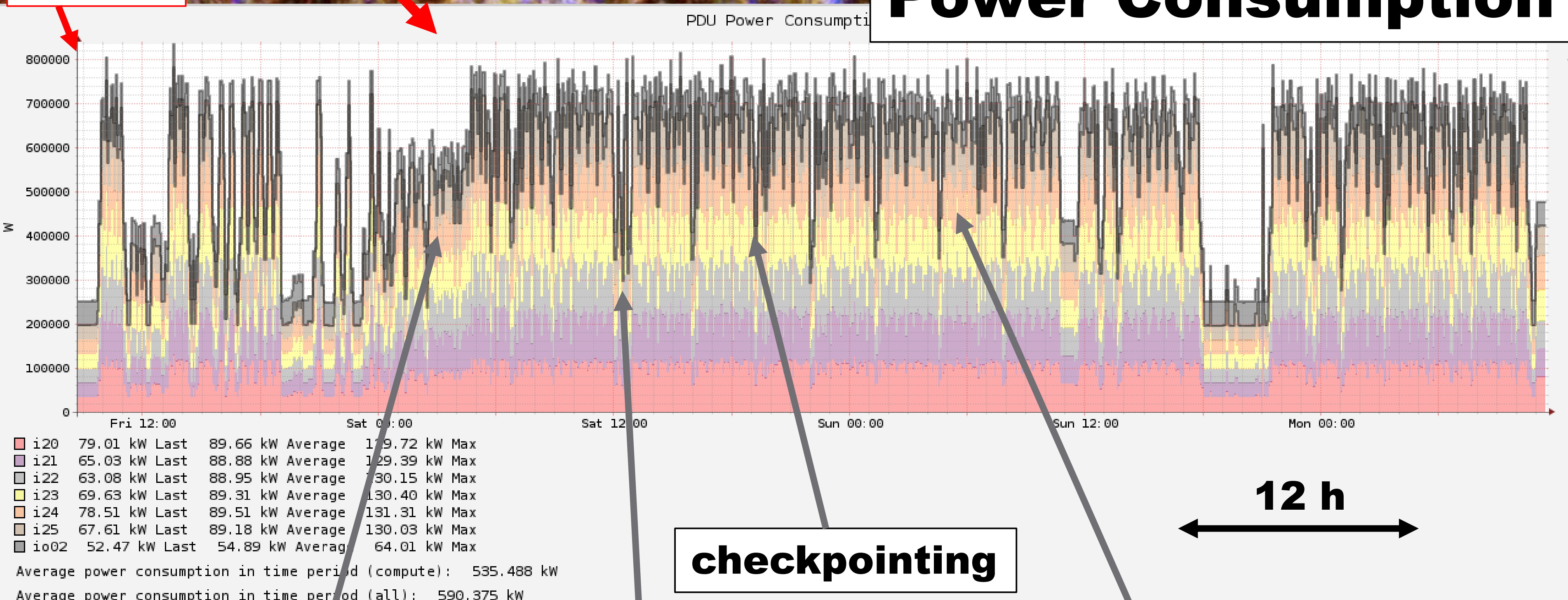
Including indexing scheme

MAGNETICUM

	Box0	Box1	Box2b	Box2	Box3	Box4
[Mpc/h]	2688	896	640	352	128	48
mr	2×4536^3	2×1526^3	–	2×594^3	2×216^3	2×81^3
hr	–	–	2×2880^3	2×1584^3	2×576^3	2×216^3
uhr	–	–	–	–	$2 \times 1536^3 (z = 2)$	2×576^3

800kW

Power Consumption

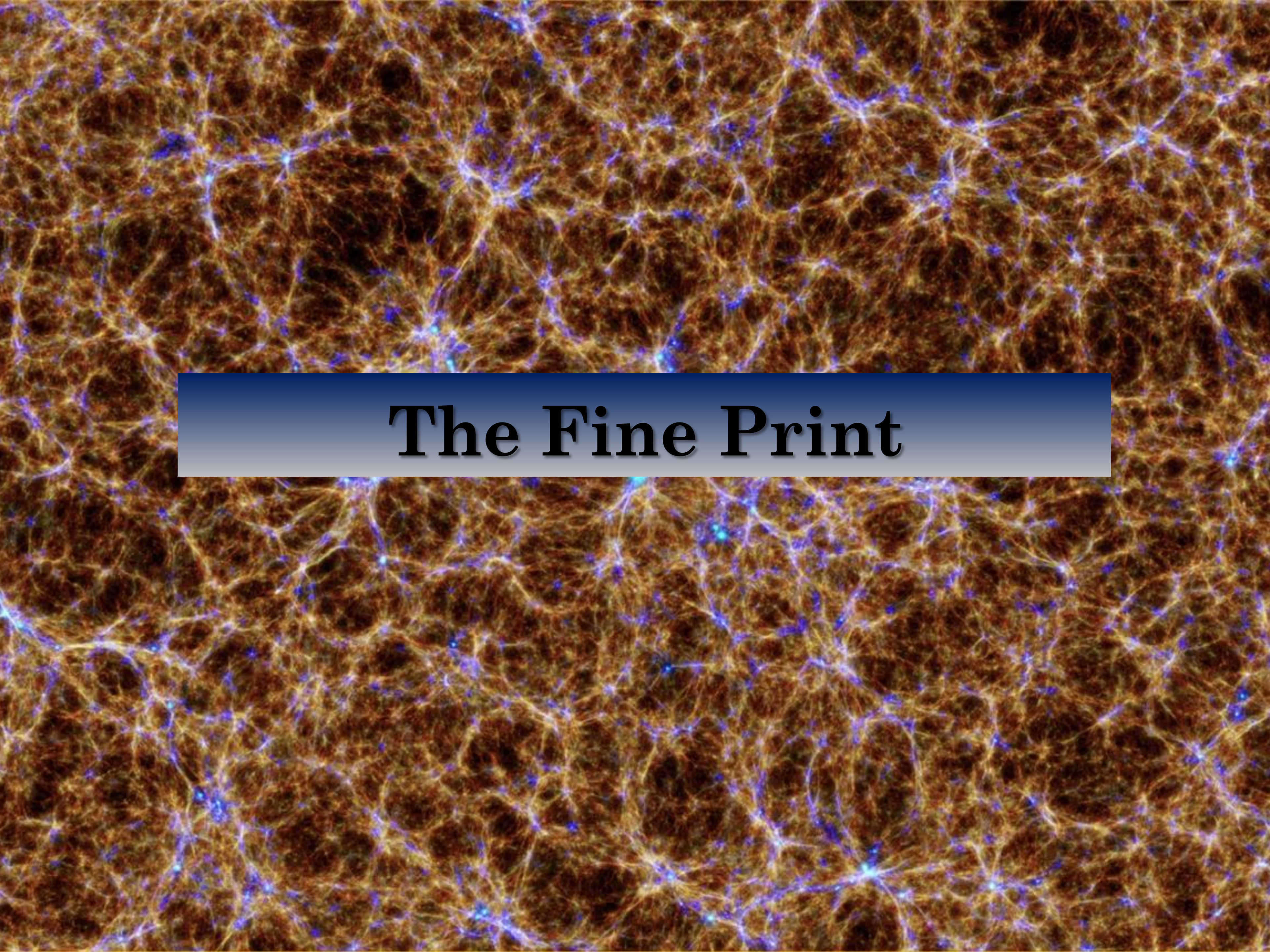


Single bad node

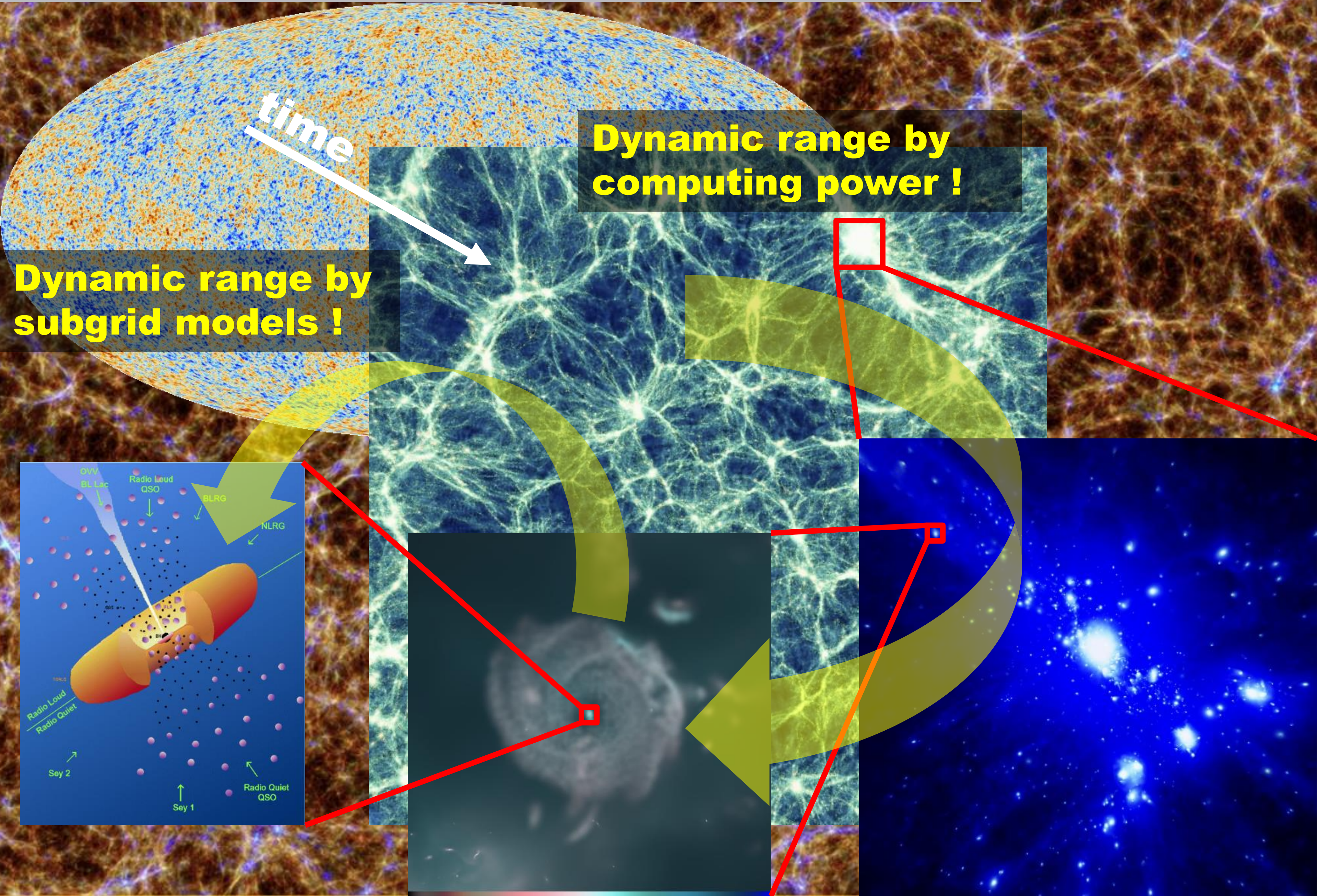
dying nodes

global timestep

The Fine Print



Performing Simulations



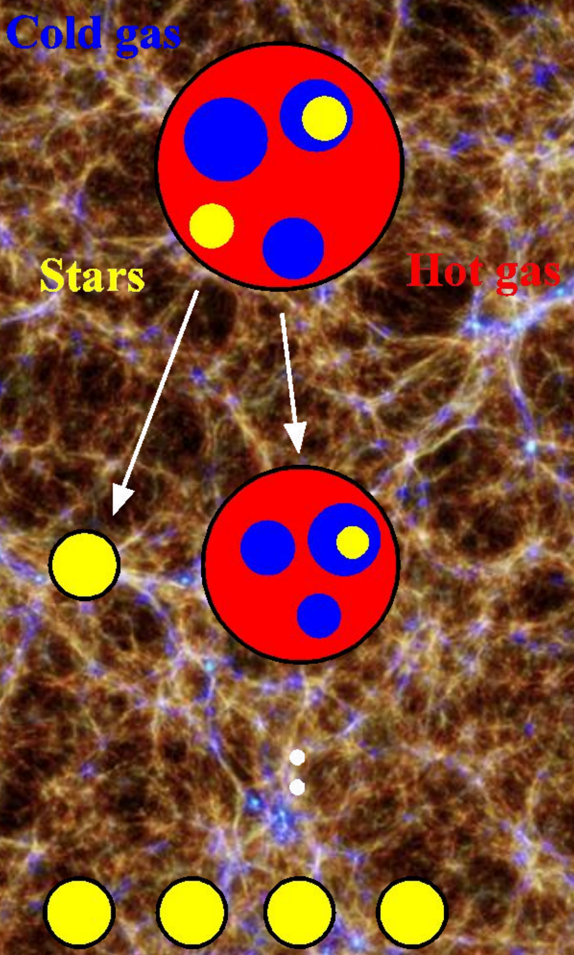
Dynamic range by subgrid models !

Dynamic range by computing power !

Sub-resolution star-formation:

Multi phase model (sub-scale)

Springel & Hernquist 2002



Star formation

supernova mass fraction

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

star formation timescale

Cloud evaporation

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

cloud evaporation parameter

Growth of clouds

cooling function

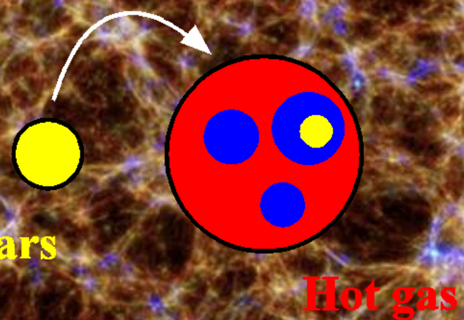
$$\left.\frac{d\rho_c}{dt}\right|_{\rm TI} = -\left.\frac{d\rho_h}{dt}\right|_{\rm TI} = \frac{\Lambda_{\rm net}(\rho_h, u_h)}{u_h - u_c}$$

Chemical enrichment:

Stellar evolution model (sub-scale)

Tornatore et al. 2003/2007

Energy: SNIa, SNII
Metals: SNIa, SNII, AGB winds
H,He,C,Ca,O,N,Ne,Mg
S,Si,Fe,Na,Al,Ar,Ni



IMF:
Salpeter, Kroupa, Chabrier, Arimoto & Yoshii

Life-time:
Maeder & Meynet 1989
Padovani & Matteucci 1993

Stellar yields:
AGB: Groenewegen, Karakas
SN1a: Thielemann
SNII: Woosly & Weaver
Romano, Kobayashi, ...

SNIa rate:

star-formation rate

fraction of stars in binary systems

$$R_{\mathrm{SN\,Ia}}(t) = A \int_{M_{\mathrm{B,inf}}}^{M_{\mathrm{B,sup}}} \phi(m_{\mathrm{B}}) \int_{\mu_{\mathrm{m}}}^{\mu_{\mathrm{M}}} f(\mu)\, \psi(t - \tau_{m_2})\, \mathrm{d}\mu\, \mathrm{d}m_{\mathrm{B}}$$

distribution of mass-ratios in binary systems

mass range of SN1a binary systems (0.8-8Msol)

SNII and AGB rate:

$$R_{\mathrm{SN\,II|ILMS}}(t) = \phi(m(t)) \times \left(-\frac{\mathrm{d}m(t)}{\mathrm{d}t}\right)$$

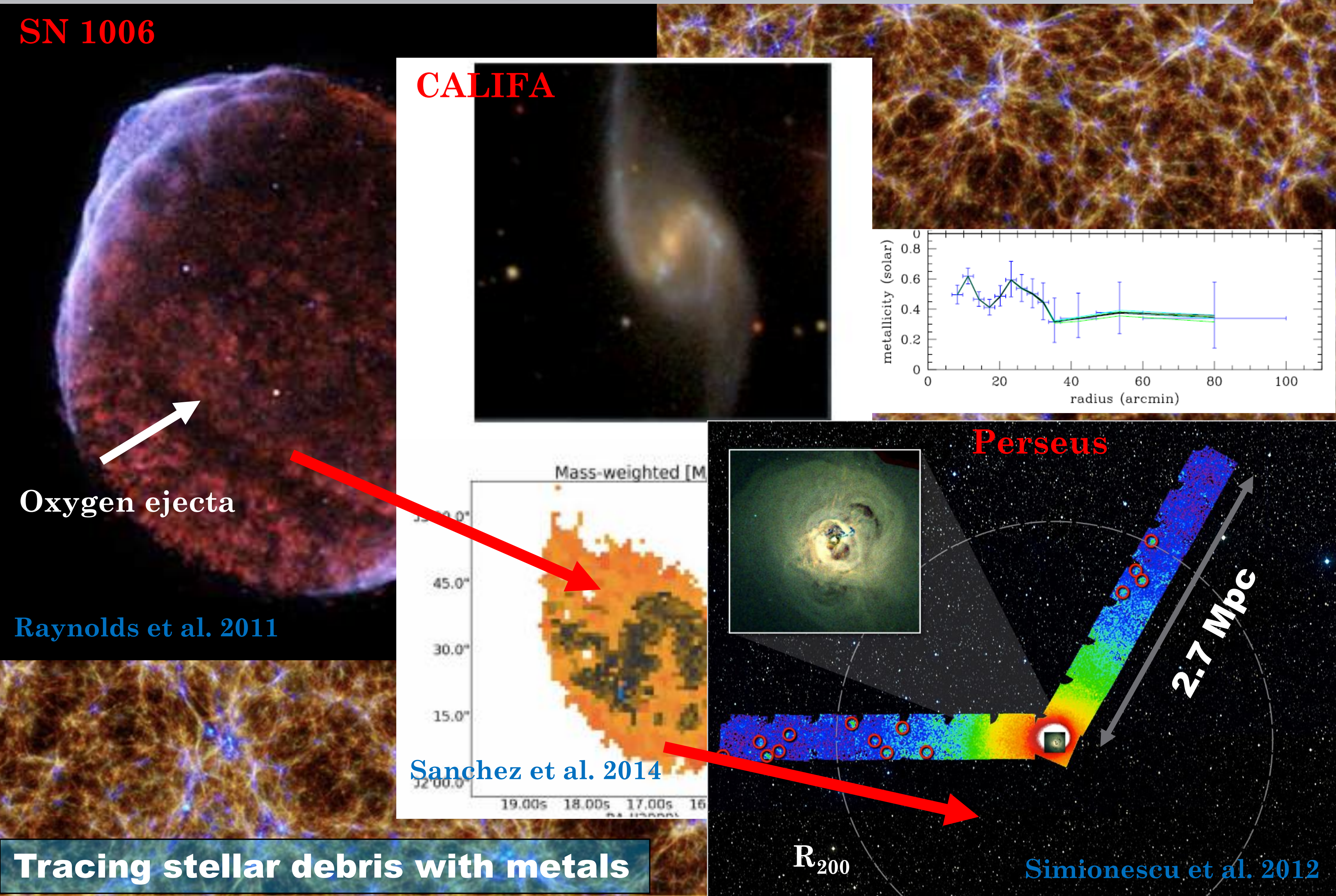
Initial mass function (IMF):

$$\phi(m) = dN/d\log m$$

Life-time of stars

$$\tau(m) = \begin{cases} 10^{[(1.34-\sqrt{1.79-0.22(7.76-\log(m))})/0.11]-9} & \text{for } m \leq 6.6\,\mathrm{M}_{\odot} \\ 1.2m^{-1.85} + 0.003 & \text{otherwise.} \end{cases}$$

Linking things across all scales



Sub-resolution SMBH-formation:

Black Hole 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)
cold/hot (Bachmann et al. 14)
....

Feedback

Thermal (Springel & Di Matteo 06)
Bubbles (Sijacki et al. 07)
Mass dependent (Steinborn 2015)
....

Merging

Instant merging
Based on velocity
....

Positioning:

Pinning to min. Potential
Free floating

Growth of Black Hole

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

gas density

sound speed

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

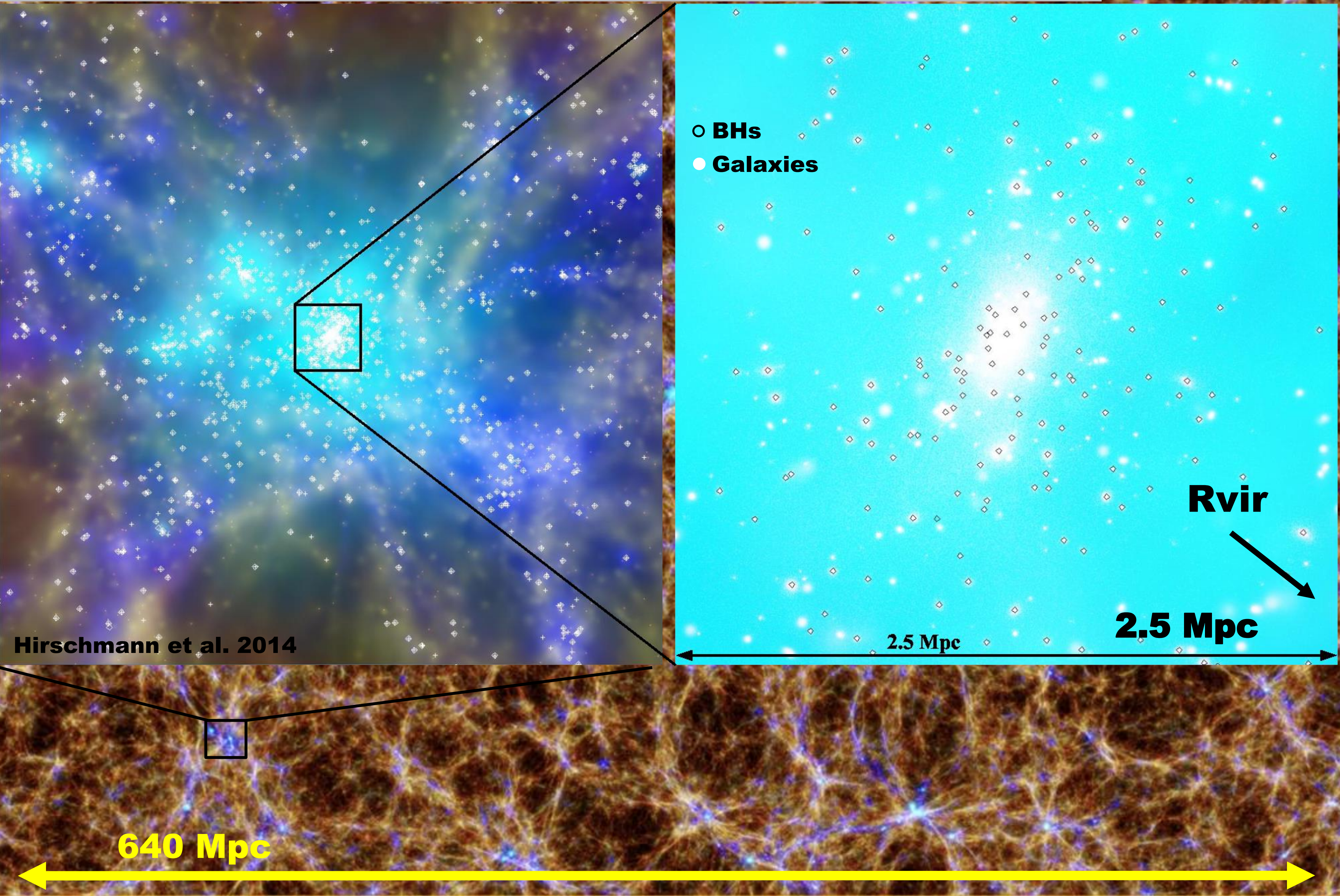
Feedback by Black Holes

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

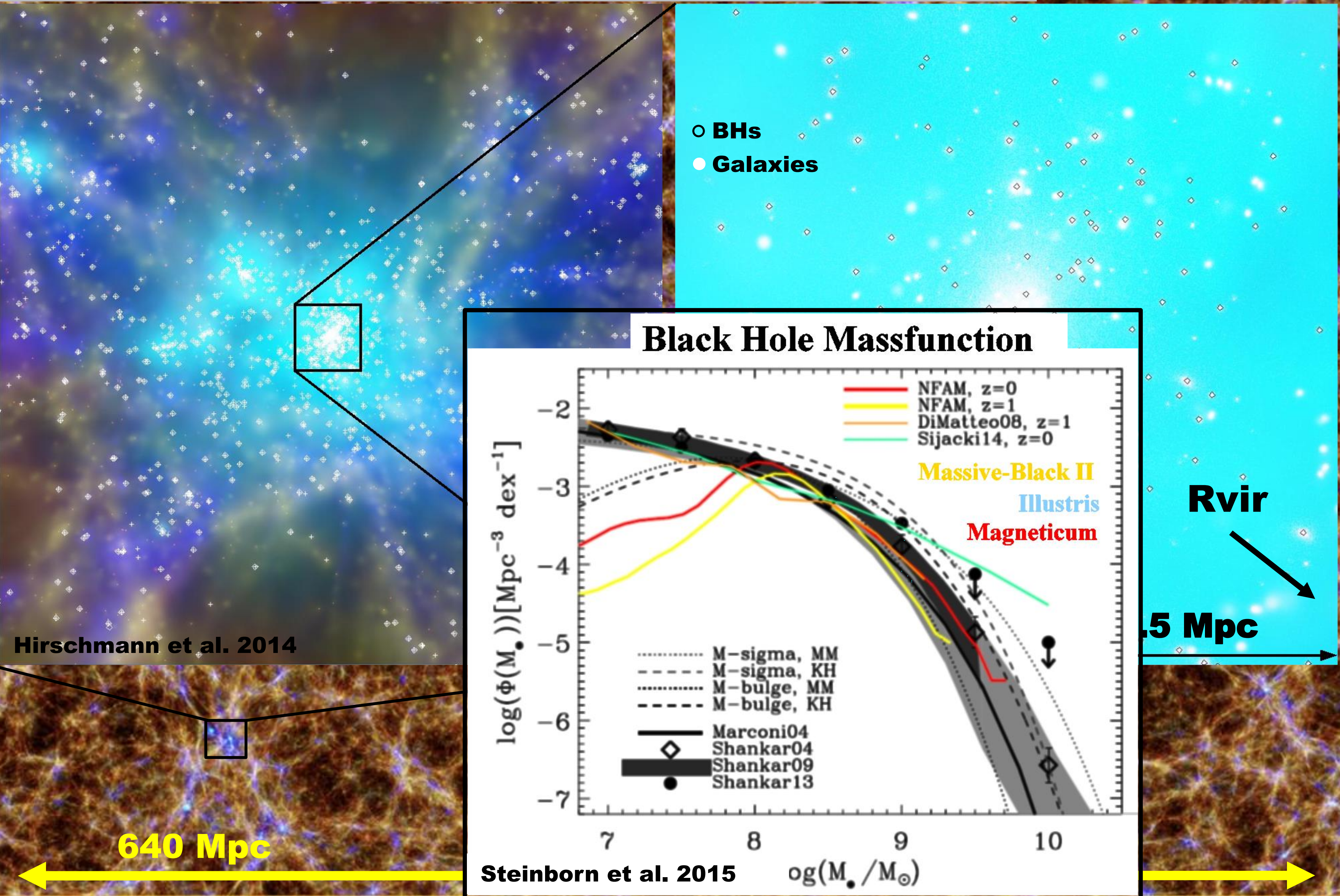
$$\dot{E}_{\rm feedback} = f \times L_{\rm bol}$$

efficiency

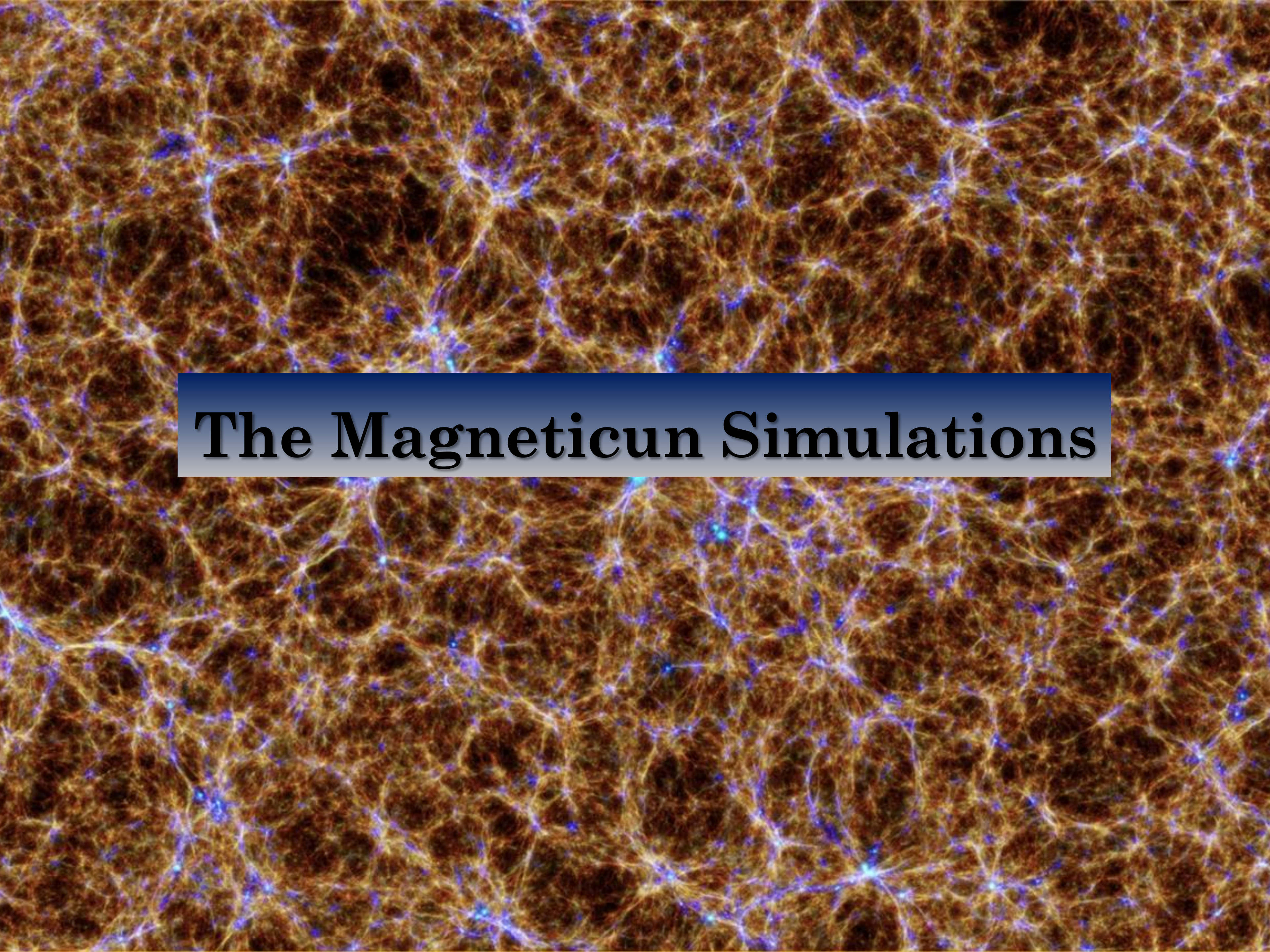
Halos: BH – Galaxy connection



Black Holes: mass-function

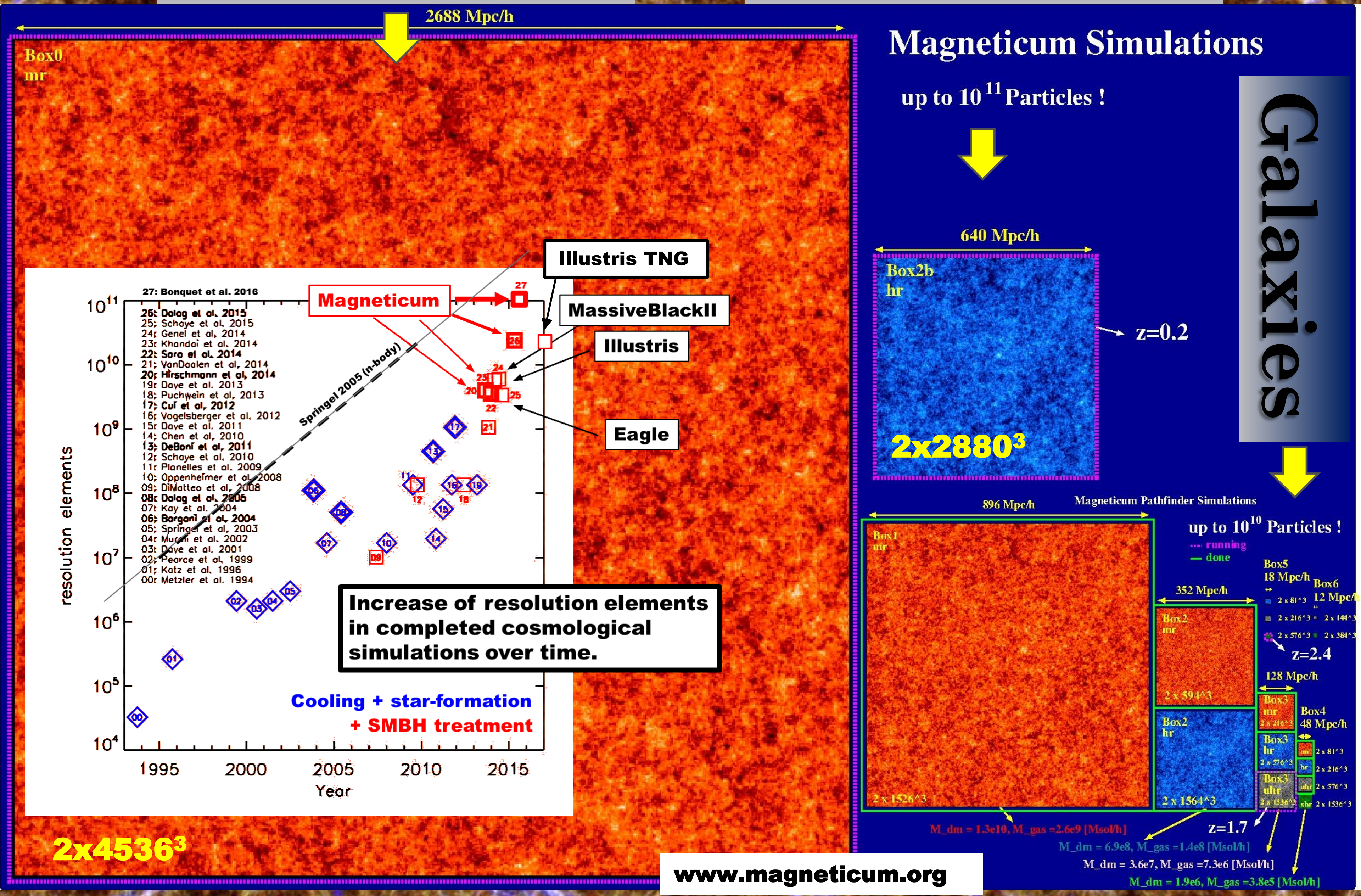


The Magneticun Simulations

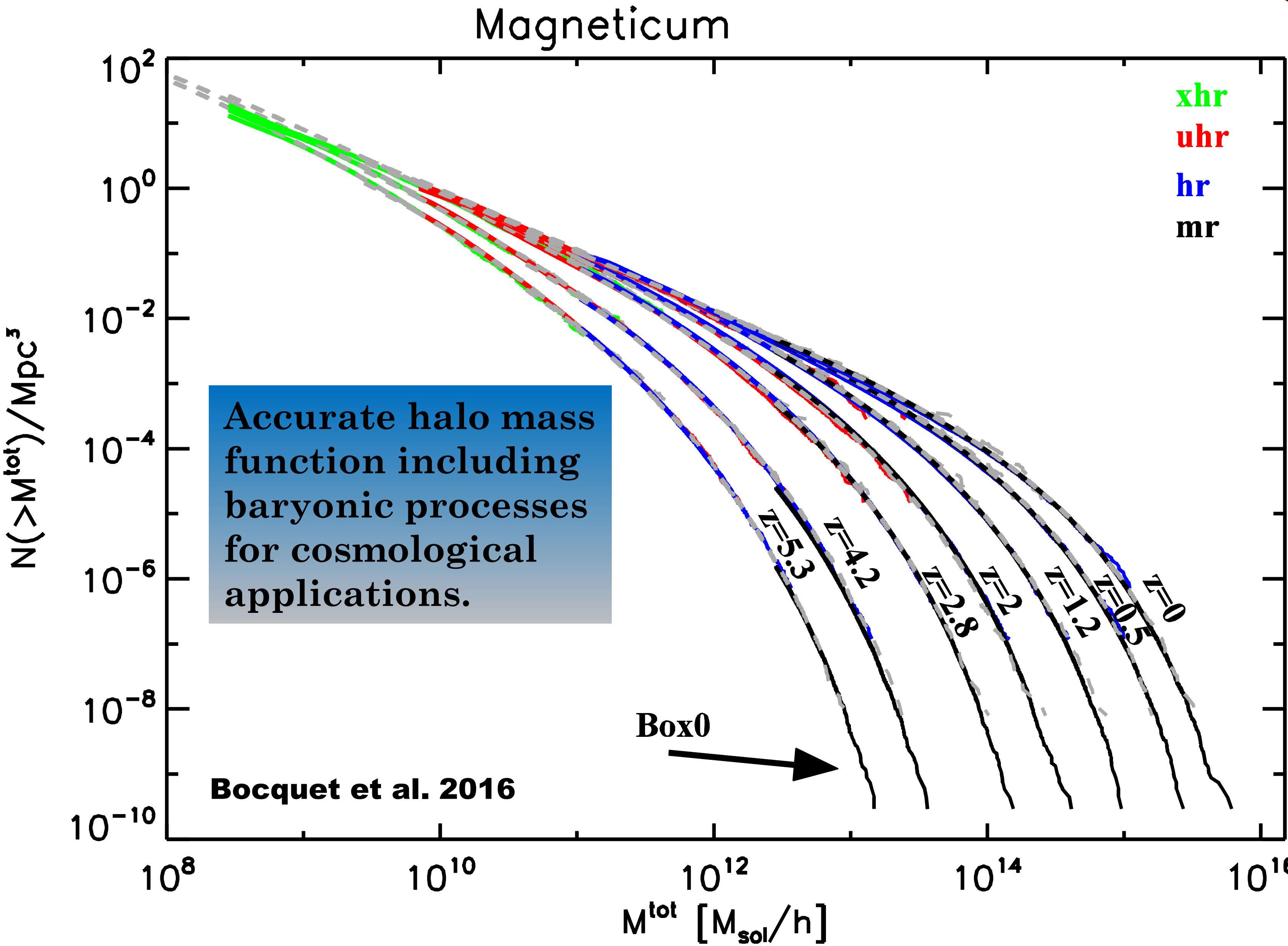


Cosmology

Halos, BHs

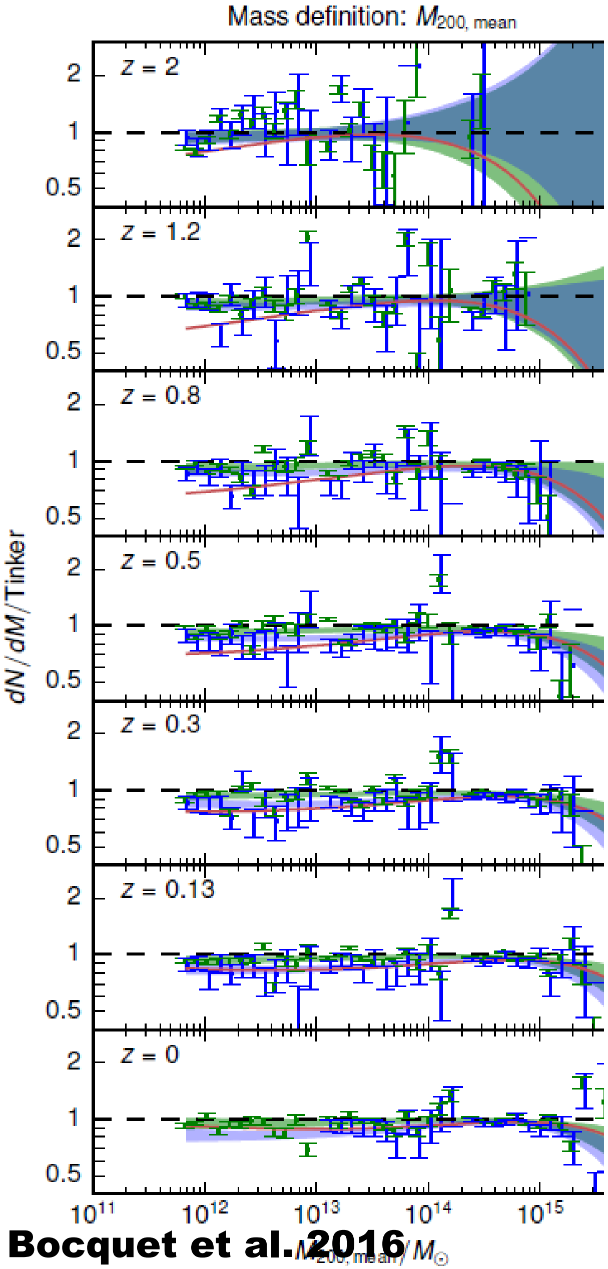


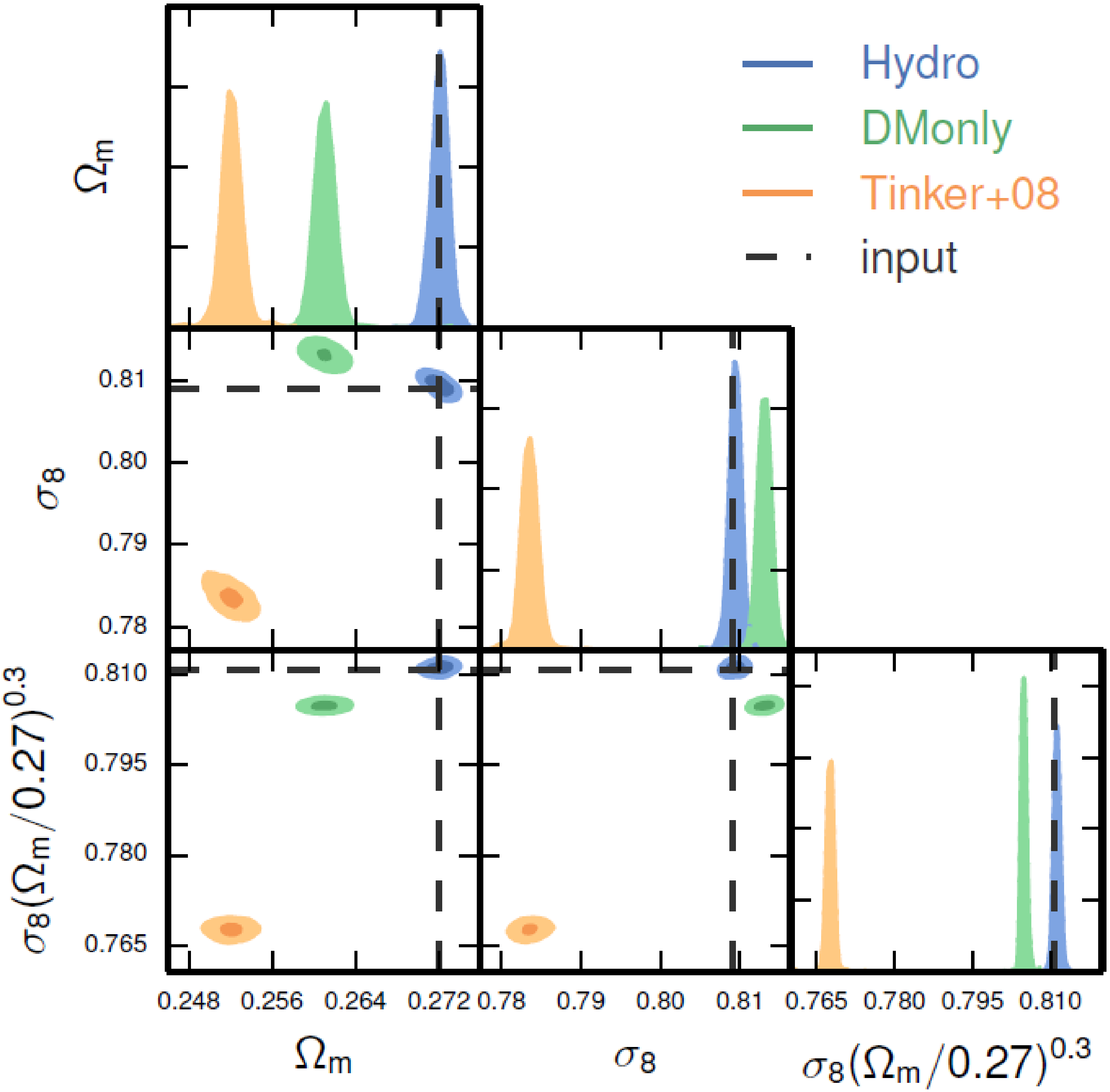
Big things: Clusters



Accurate halo mass function including baryonic processes for cosmological applications.

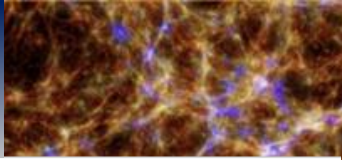
Improving the mass function

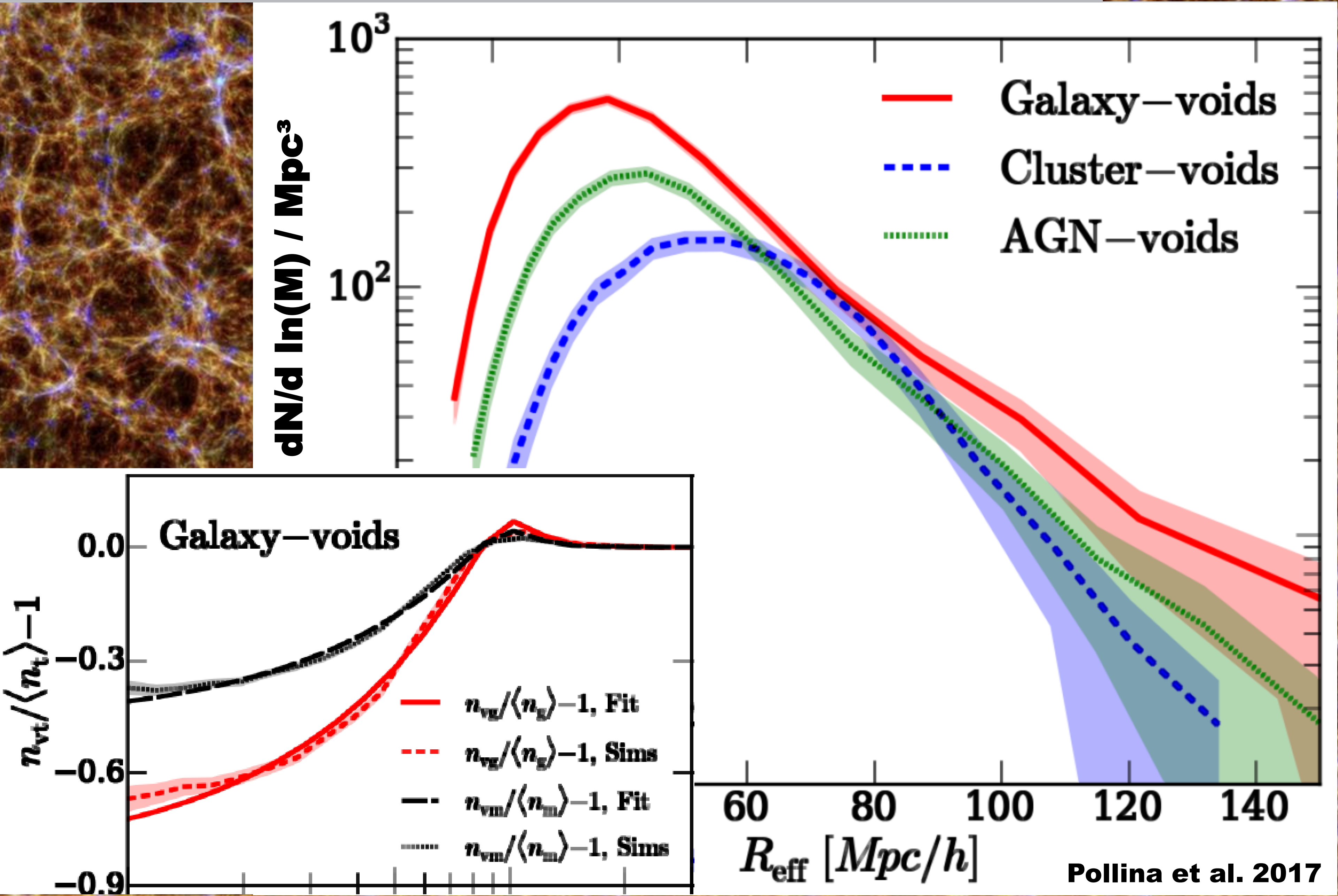




Bocquet et al. 2016

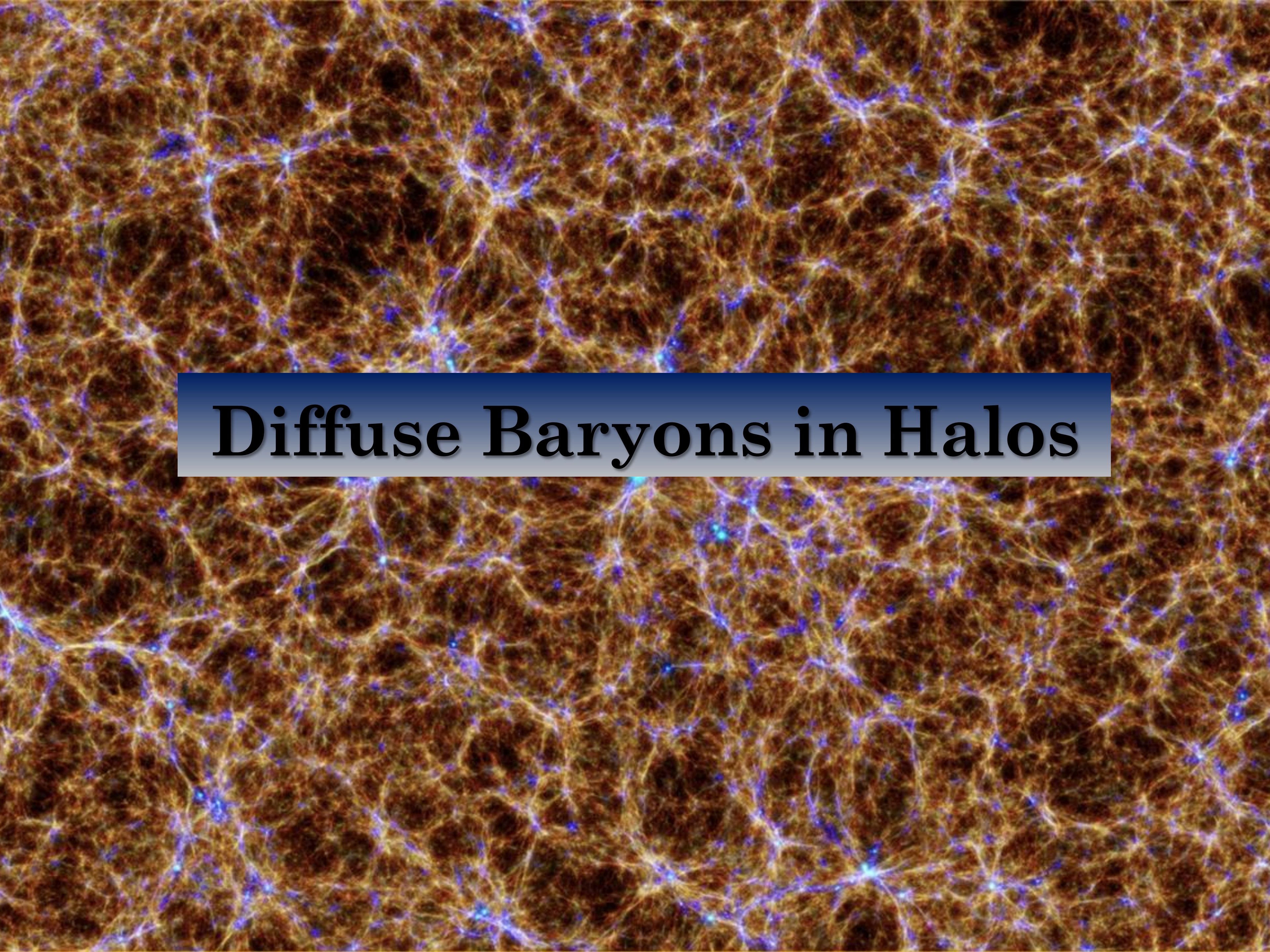
Voids from different tracers



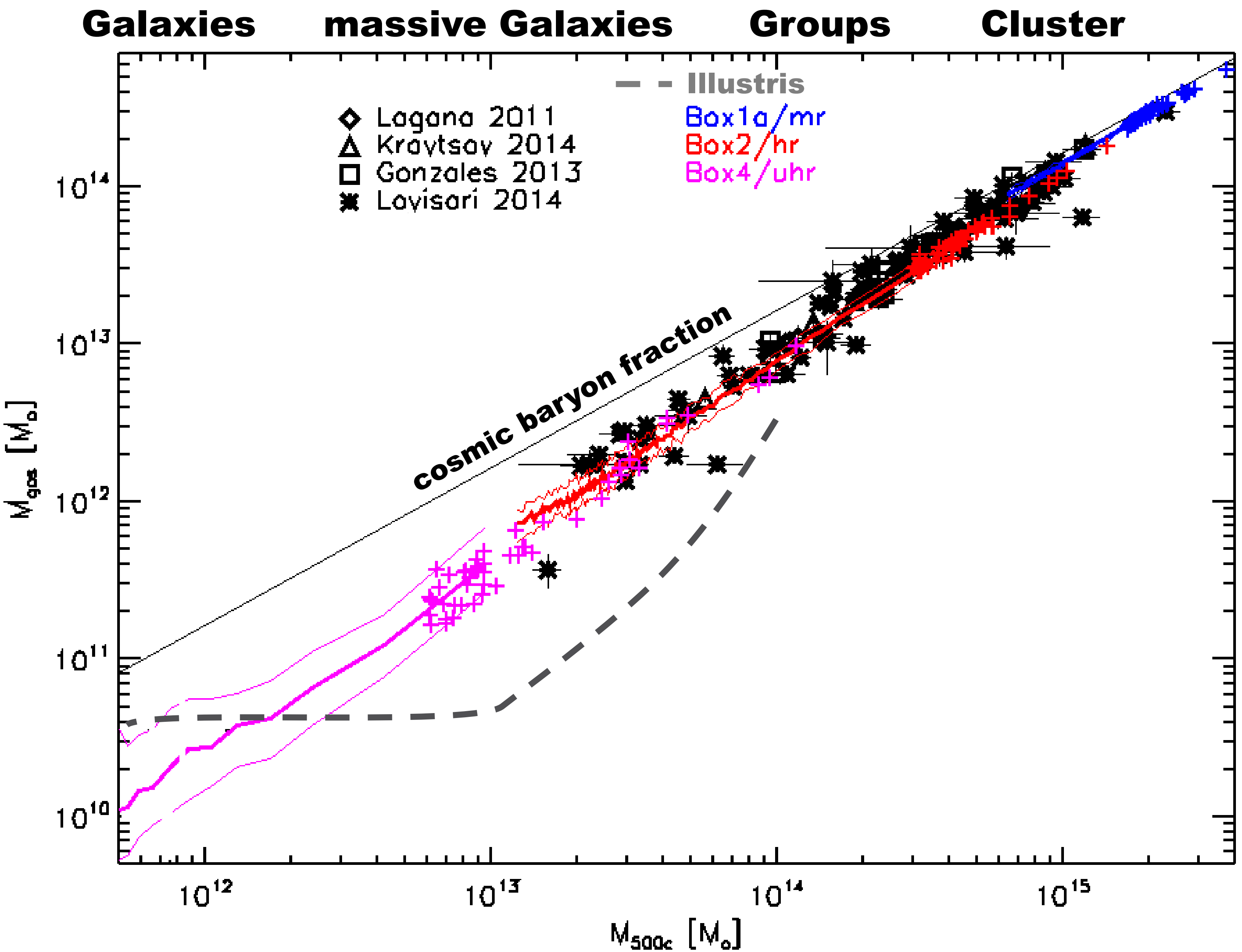


Pollina et al. 2017

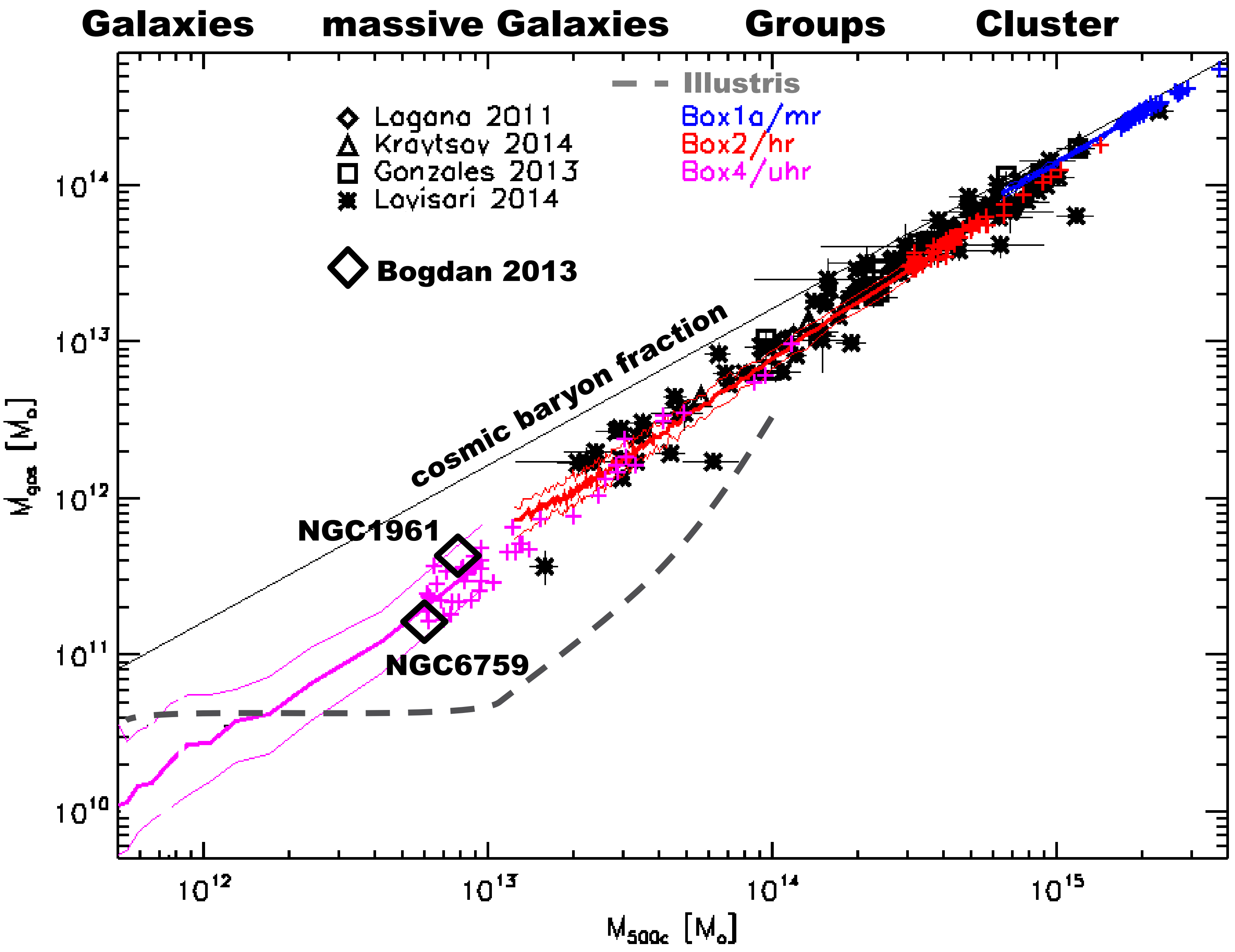
Diffuse Baryons in Halos



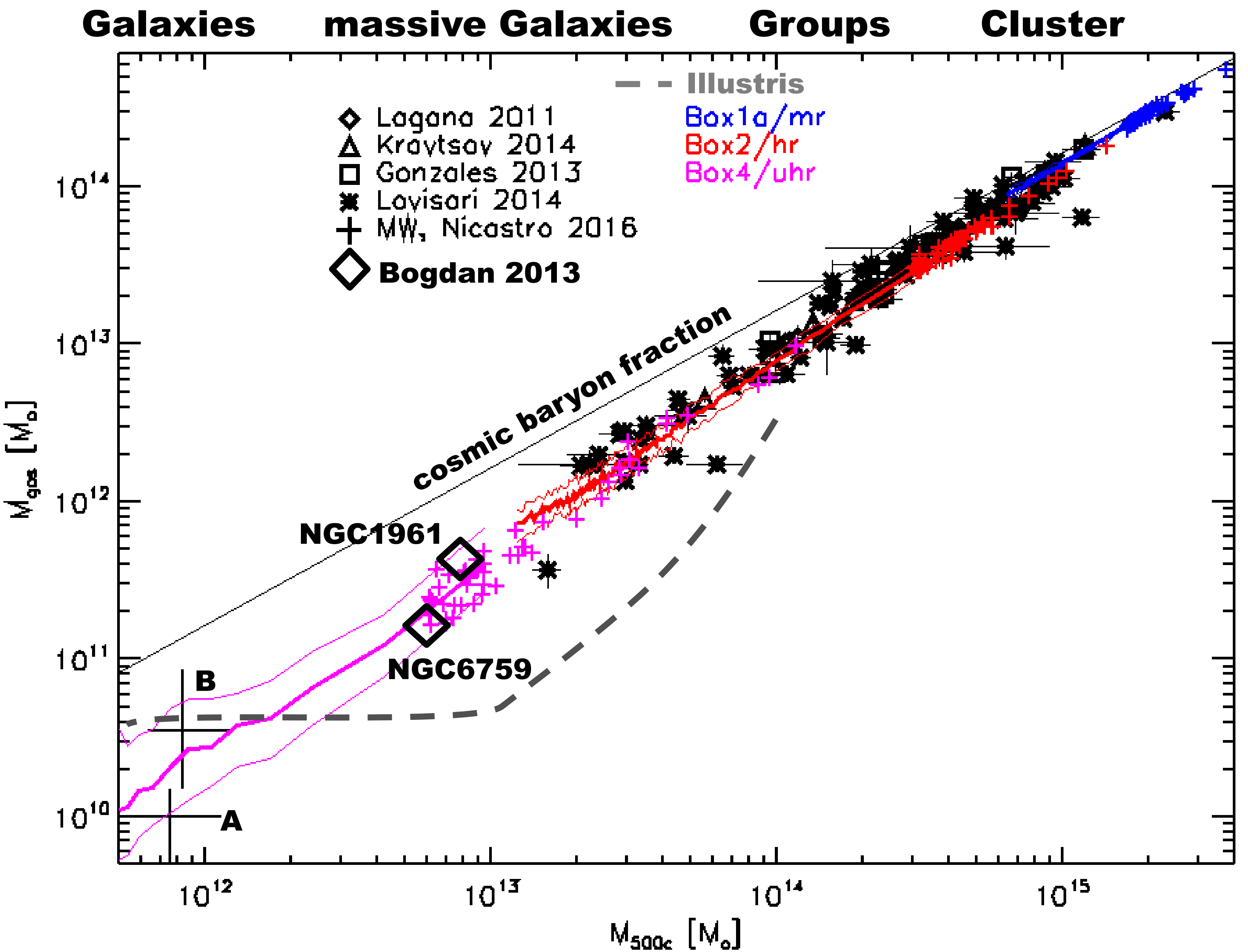
The Hot Gas reservoir of Halos …



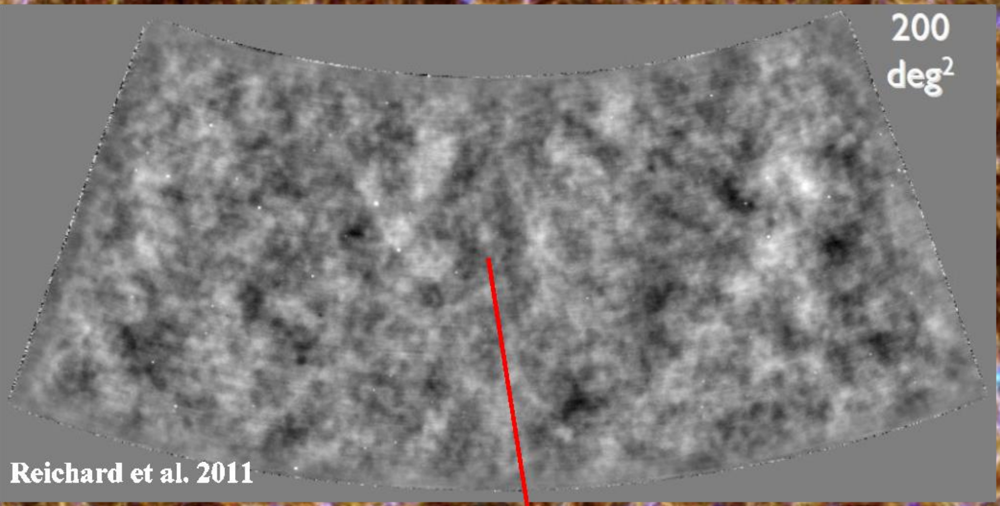
The Hot Gas reservoir of Halos …

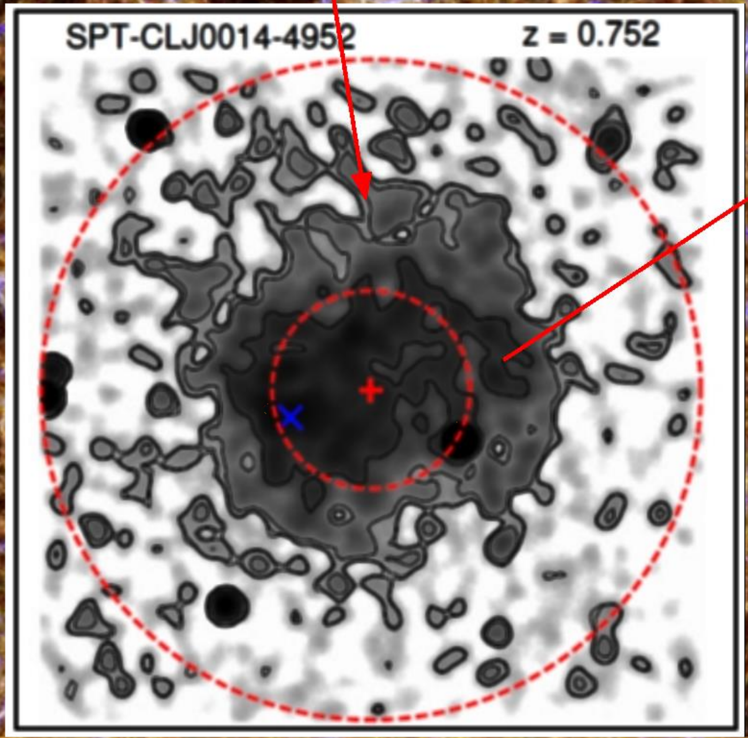


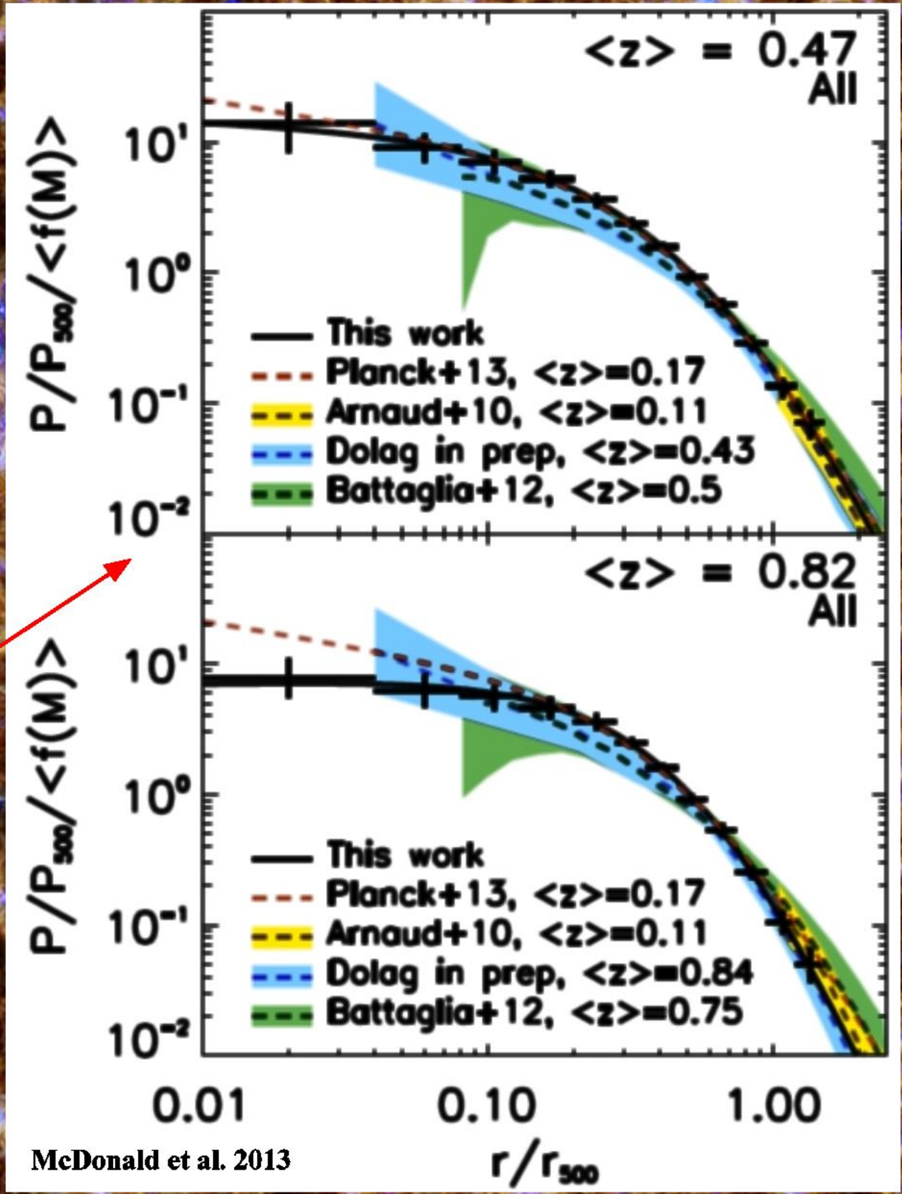
The Hot Gas reservoir of Halos …



Clusters: pressure profiles







Universal pressure profile

$$P_{\rm mod}(r,M,z) = P_{500}(M,z)\,\frac{c_{500}^{\gamma}(1+c_{500}^{\alpha})^{(\beta-\gamma)/\alpha}}{(c_{500}\ x)^{\gamma}[1+(c_{500}\ x)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

$$P_{500}(M,z) = 1.65\times10^{-3}P_0\,E(z)^{8/3+c_P}\left[\frac{M_{500c}}{3\times10^{14}{\rm M}_\odot}\right]^{2/3+\alpha_P}\ {\rm keV\ cm^{-3}}$$

Arnaud et al. 2010

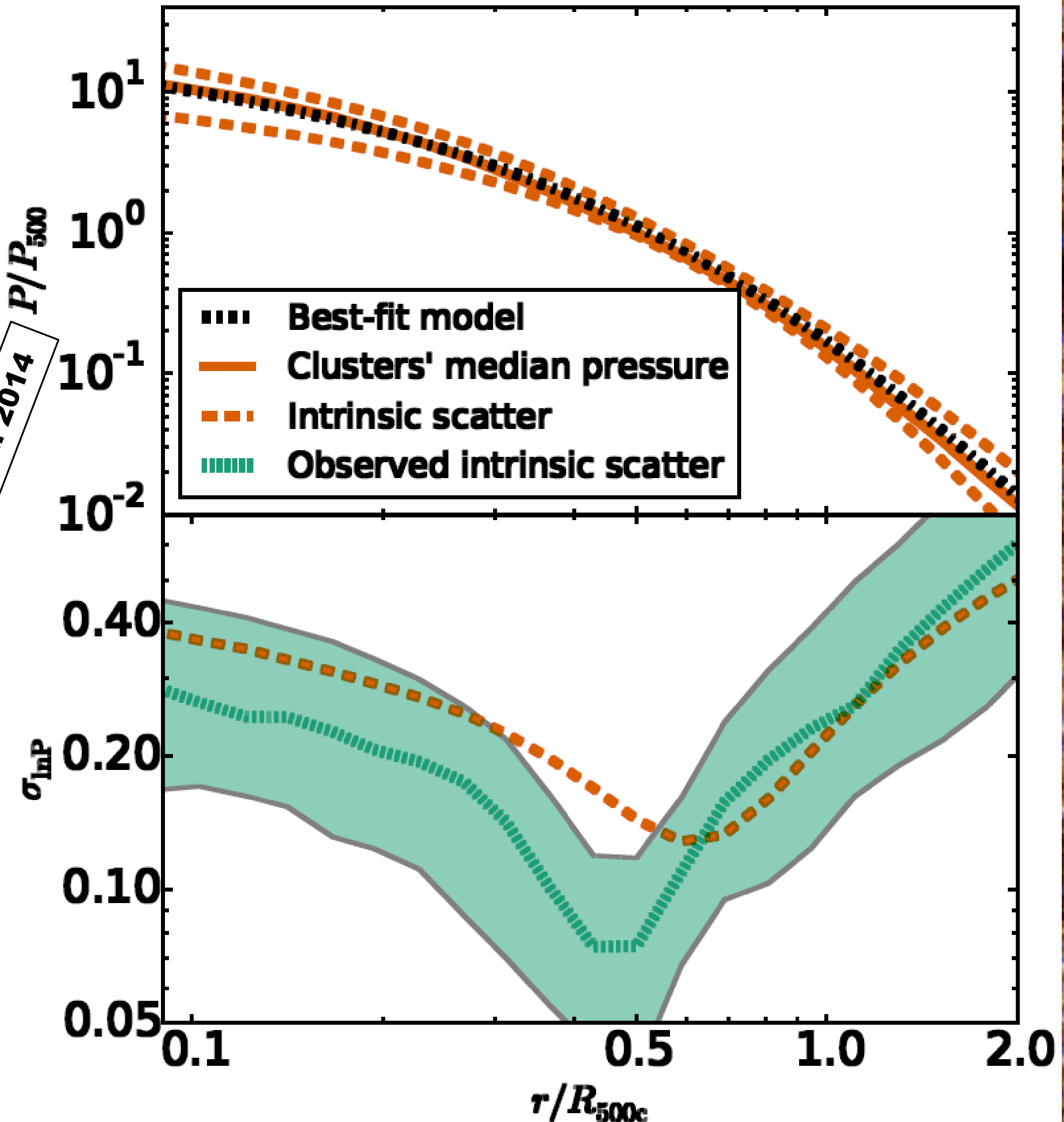
Kay et al. 2012

Planck et al. 2013

Arnaud et al. 2010

McDonald et al. 2014

	MPS	K12	PL13	A10	McD14
P_0	$0.1701^{+0.0001}_{-0.0001}$	0.33	0.19	0.21	$0.13^{+0.12}_{-0.05}$
c_{500}	$1.21^{+0.01}_{-0.01}$	1.97	1.81	1.18	$2.59^{+0.74}_{-0.79}$
γ	$0.37^{+0.01}_{-0.01}$	0.61	0.31	0.31	$0.26^{+0.26}_{-0.22}$
α	$1.23^{+0.01}_{-0.01}$	2.04	1.33	1.05	$1.63^{+1.01}_{-0.41}$
β	$5.06^{+0.03}_{-0.03}$	2.99	4.13	5.19	$3.30^{+0.86}_{-0.57}$
α_P	$0.0105^{+0.0006}_{-0.0006}$	0.12	0.12	0.12	0.12
c_P	$-0.121^{+0.002}_{-0.002}$	-	-	-	-



Grupta et al. 2017

Extended universal pressure profile

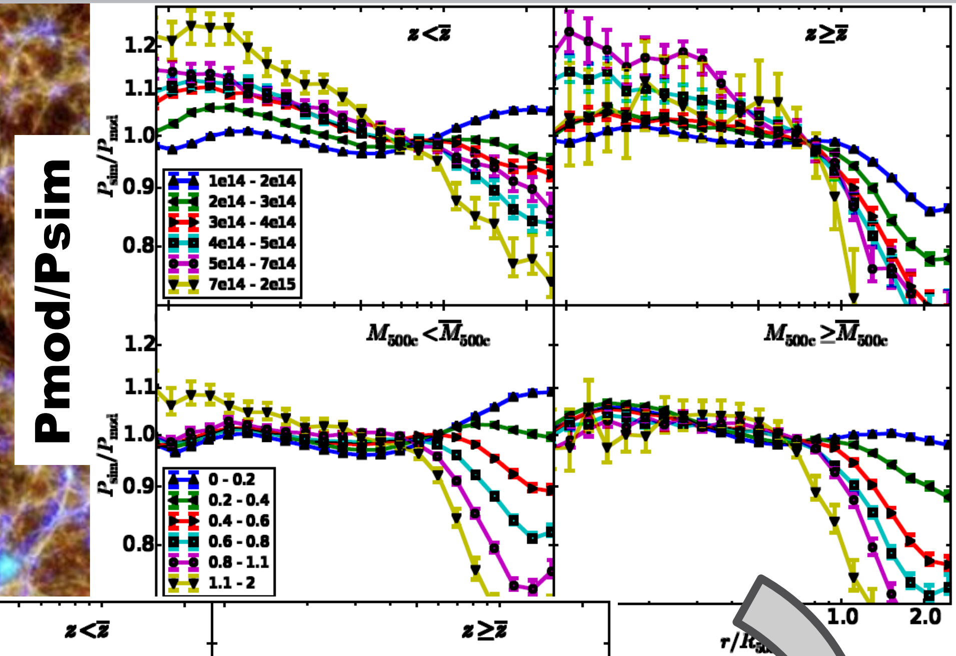
$$P_{\rm mod}(r, M, z) = P_{500}(M, z) \frac{c_{500}^{\gamma}(1 + c_{500}^{\alpha})^{(\beta-\gamma)/\alpha}}{(c_{500}\ x)^{\gamma}[1 + (c_{500}\ x)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

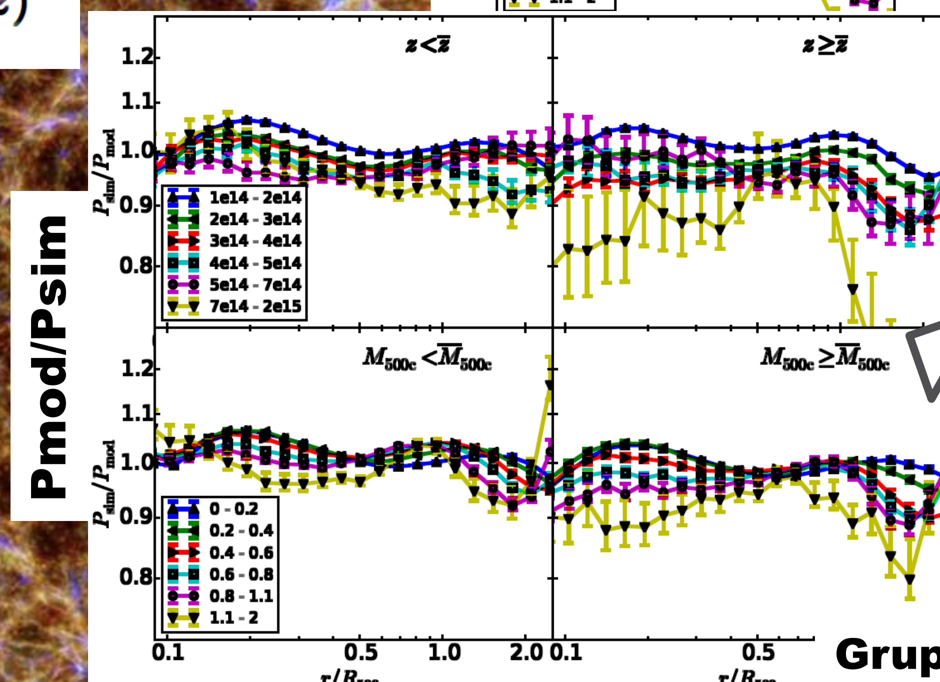
$$P_{500}(M, z) = 1.65 \times 10^{-3} P_0\, E(z)^{8/3+c_P} \left[\frac{M_{500c}}{3 \times 10^{14} M_{\odot}}\right]^{2/3+\alpha_P} \ \mathrm{keV\ cm^{-3}}$$

$$\gamma' = \gamma_0 \left[\frac{M_{500c}}{3 \times 10^{14} M_{\odot}}\right]^{\gamma_1} E(z)^{\gamma_2}$$

$$\beta' = \beta_0 \left[\frac{M_{500c}}{3 \times 10^{14} M_{\odot}}\right]^{\beta_1} E(z)^{\beta_2}$$

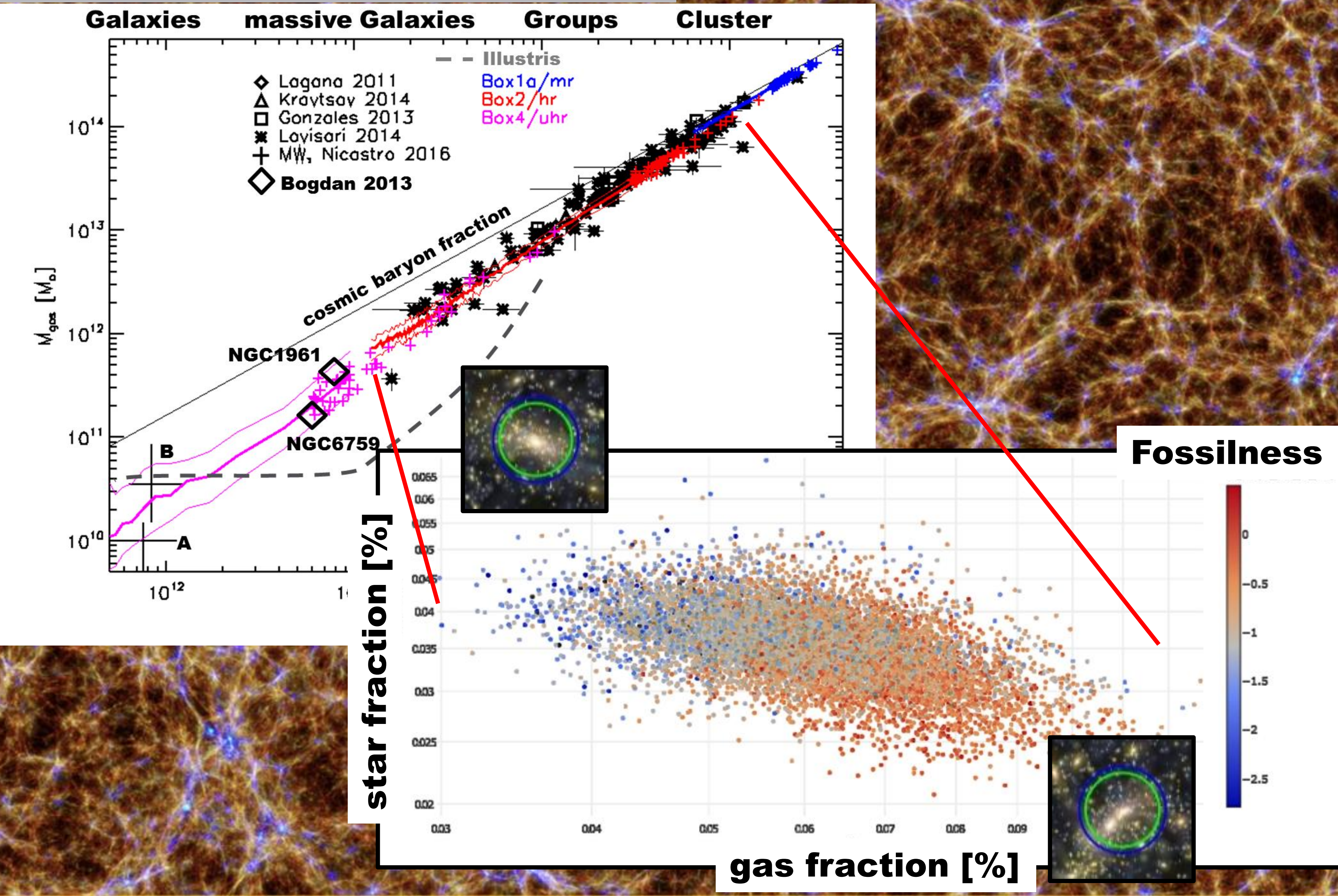
Parameter	values
P_0	0.1716 ± 0.0001
c_{500}	1.270 ± 0.006
γ_0	0.502 ± 0.008
γ_1	-0.050 ± 0.005
γ_2	-0.71 ± 0.02
α	1.33 ± 0.01
β_0	4.77 ± 0.02
β_1	0.056 ± 0.001
β_2	0.254 ± 0.002
α_P	-0.051 ± 0.001
c_P	-0.321 ± 0.002



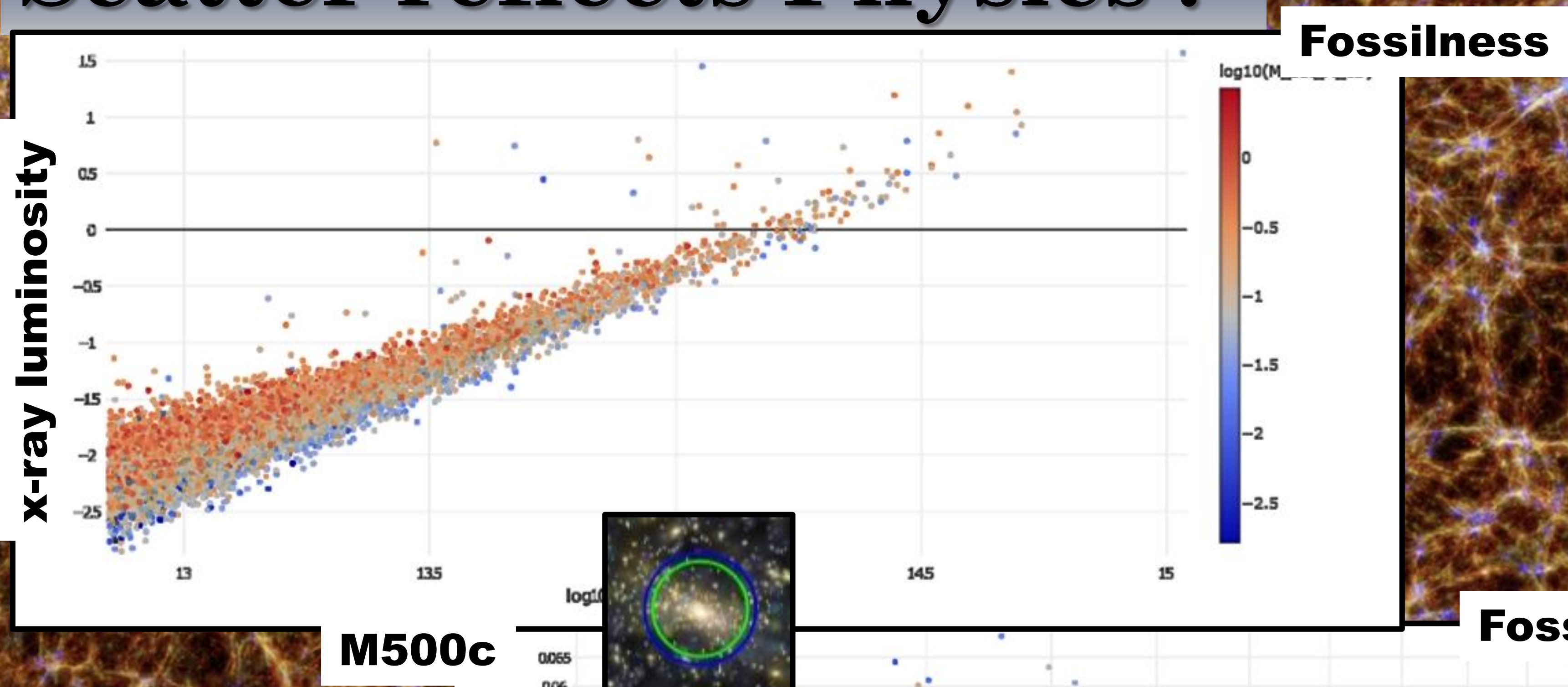


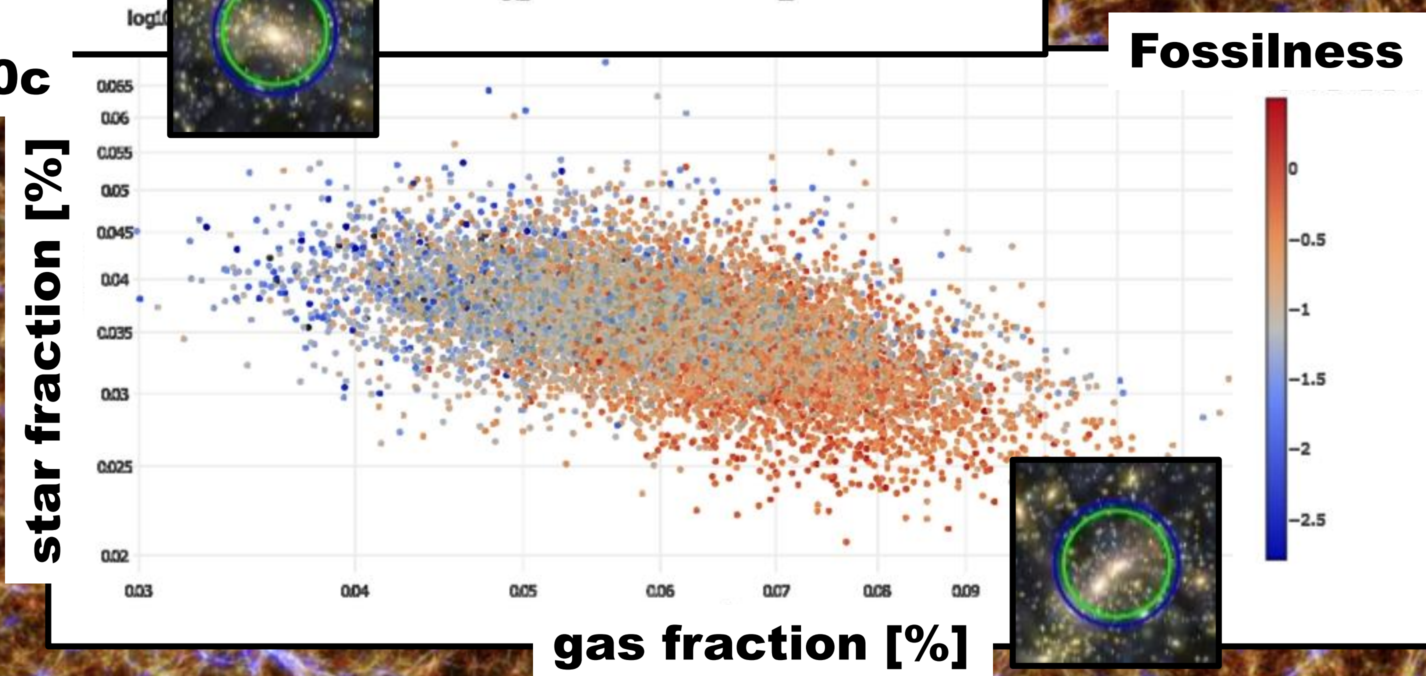
Grupta et al. 2017

... and it‘s Scatter



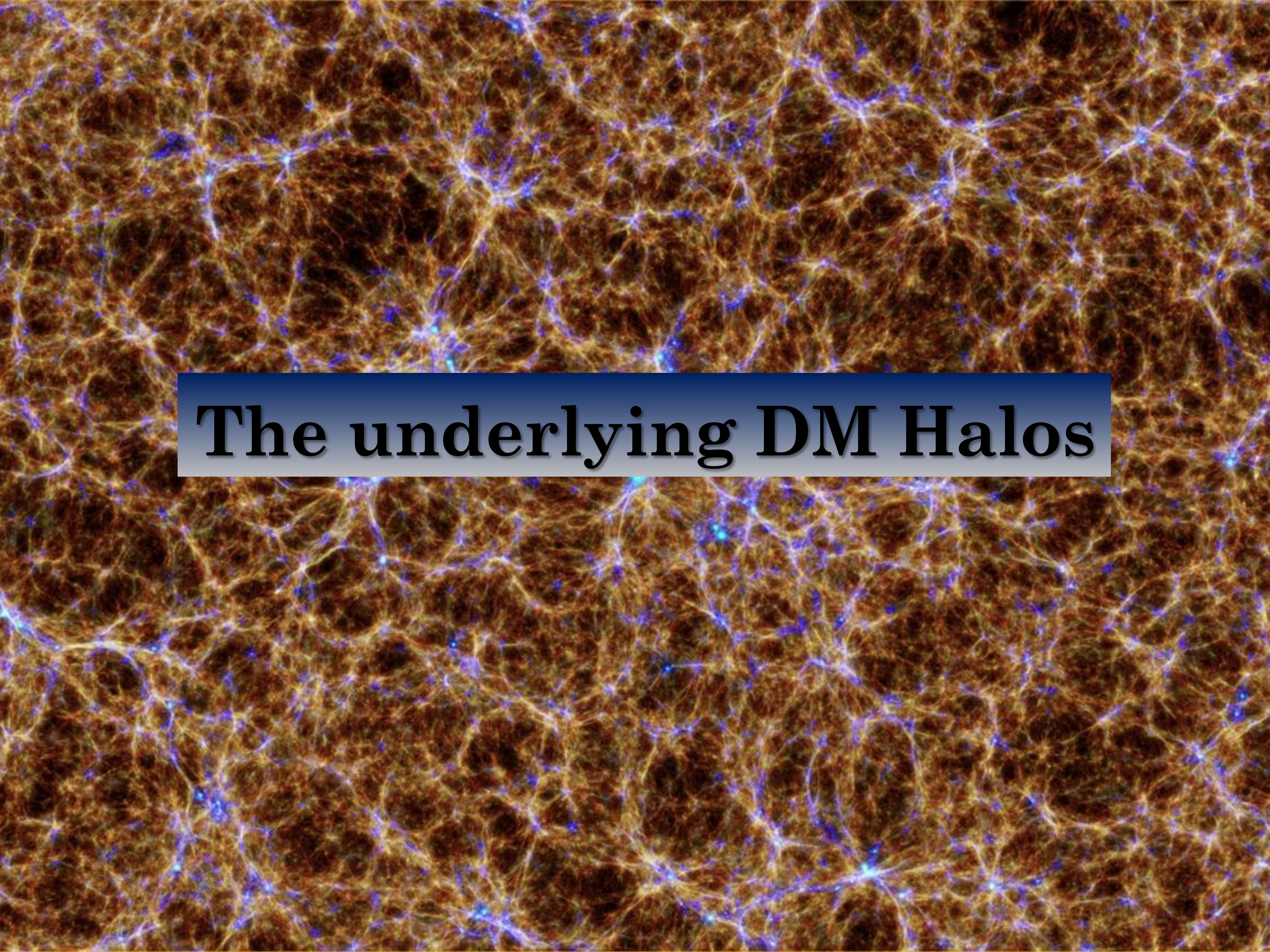
Scatter reflects Physics !



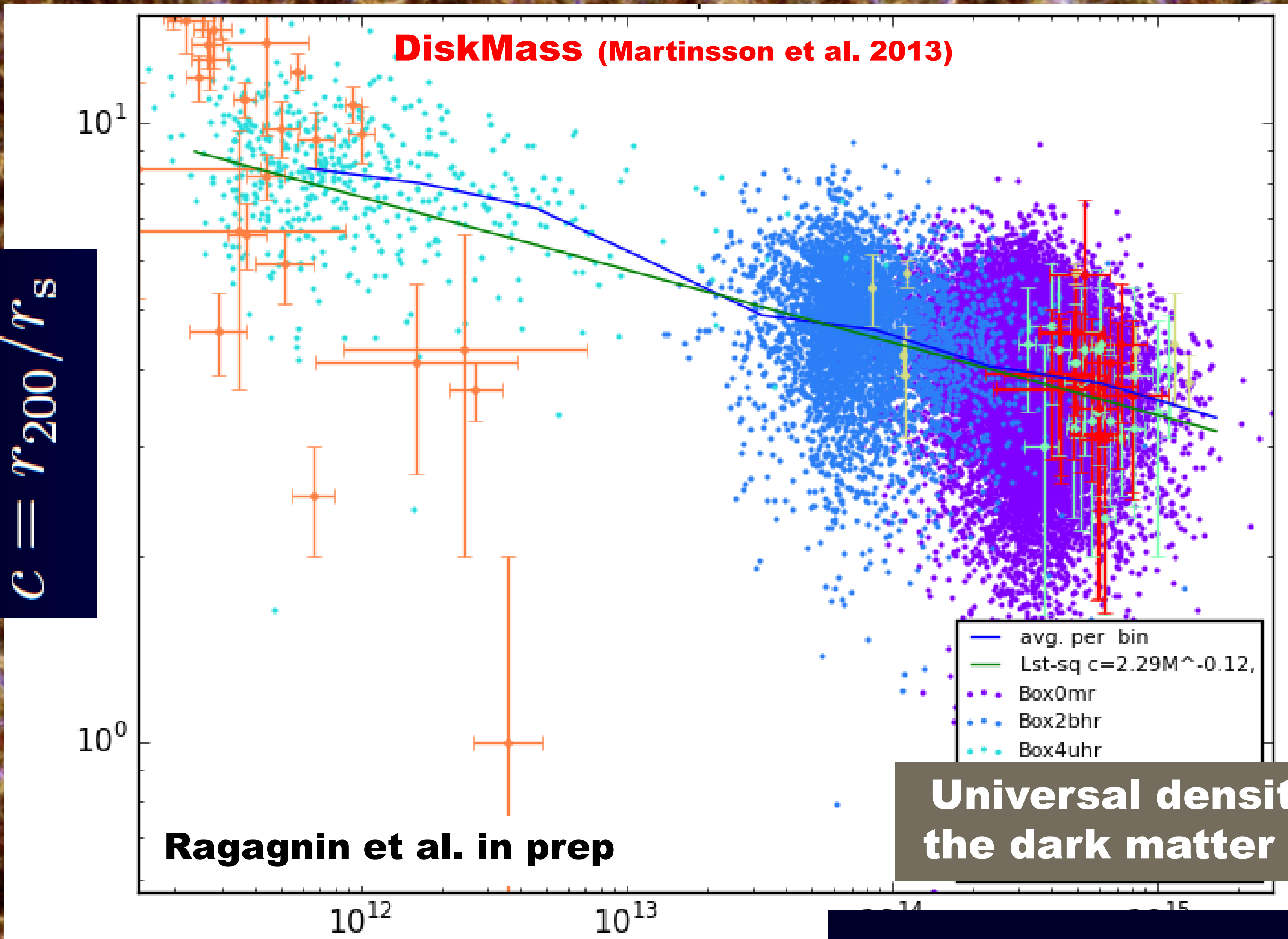


merging vs. phyiscal processes in the core

The underlying DM Halos



A deeper Link: M-c relation for Halos



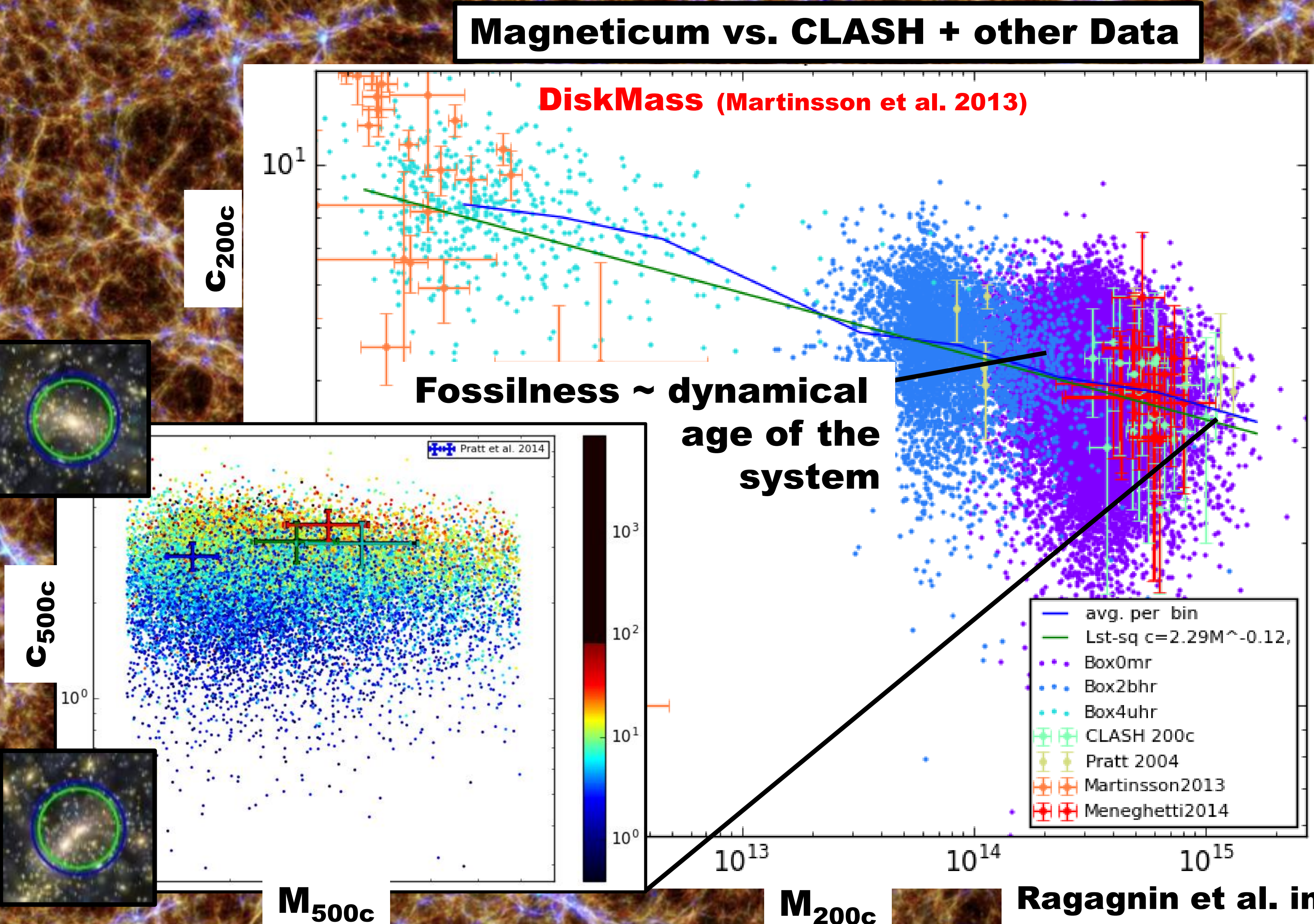
$c = r_{200}/r_s$

M_{200c}

Universal density profile of the dark matter (NFW,1997)

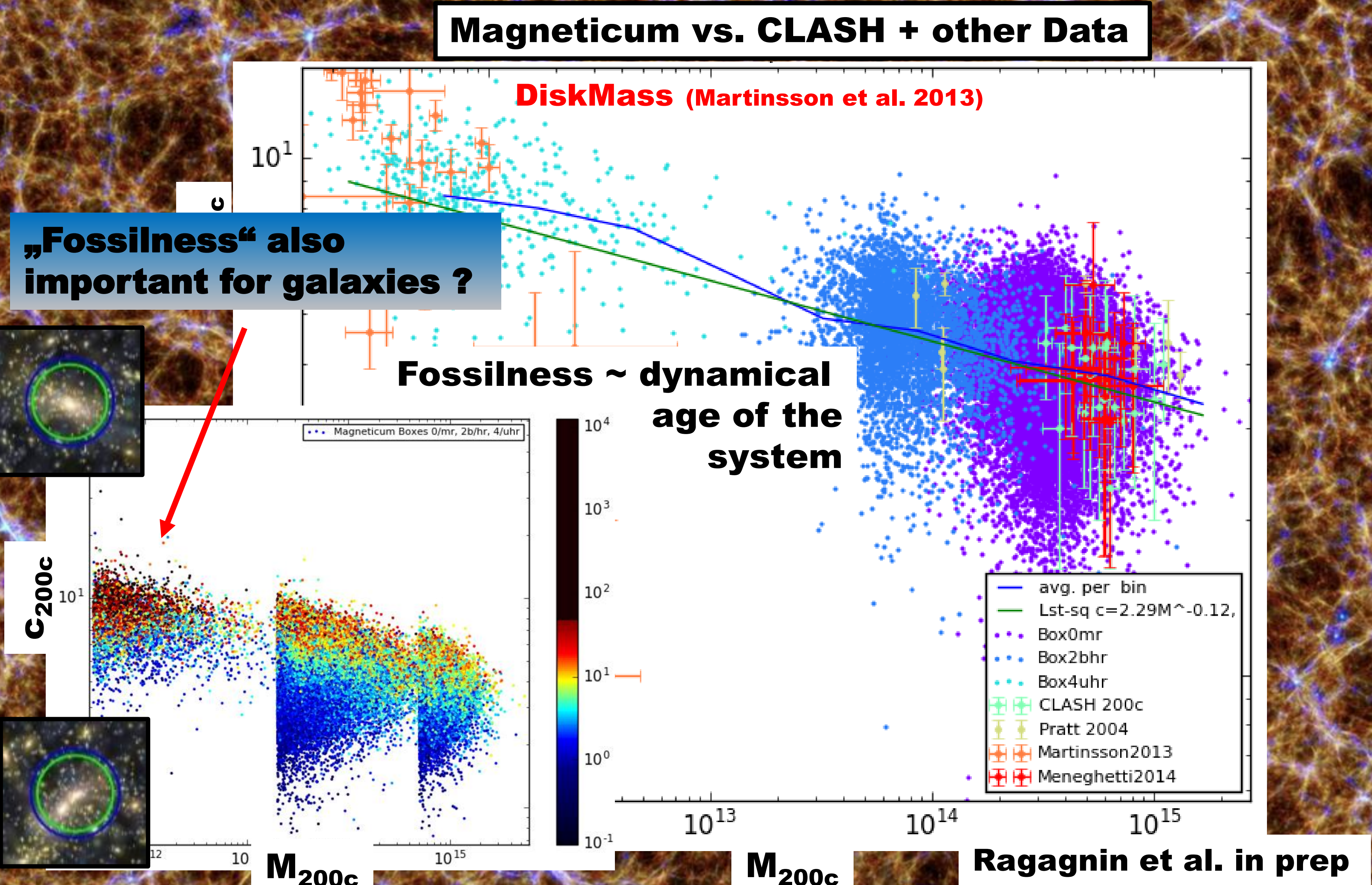
$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

A deeper Link: M-c relation for Halos



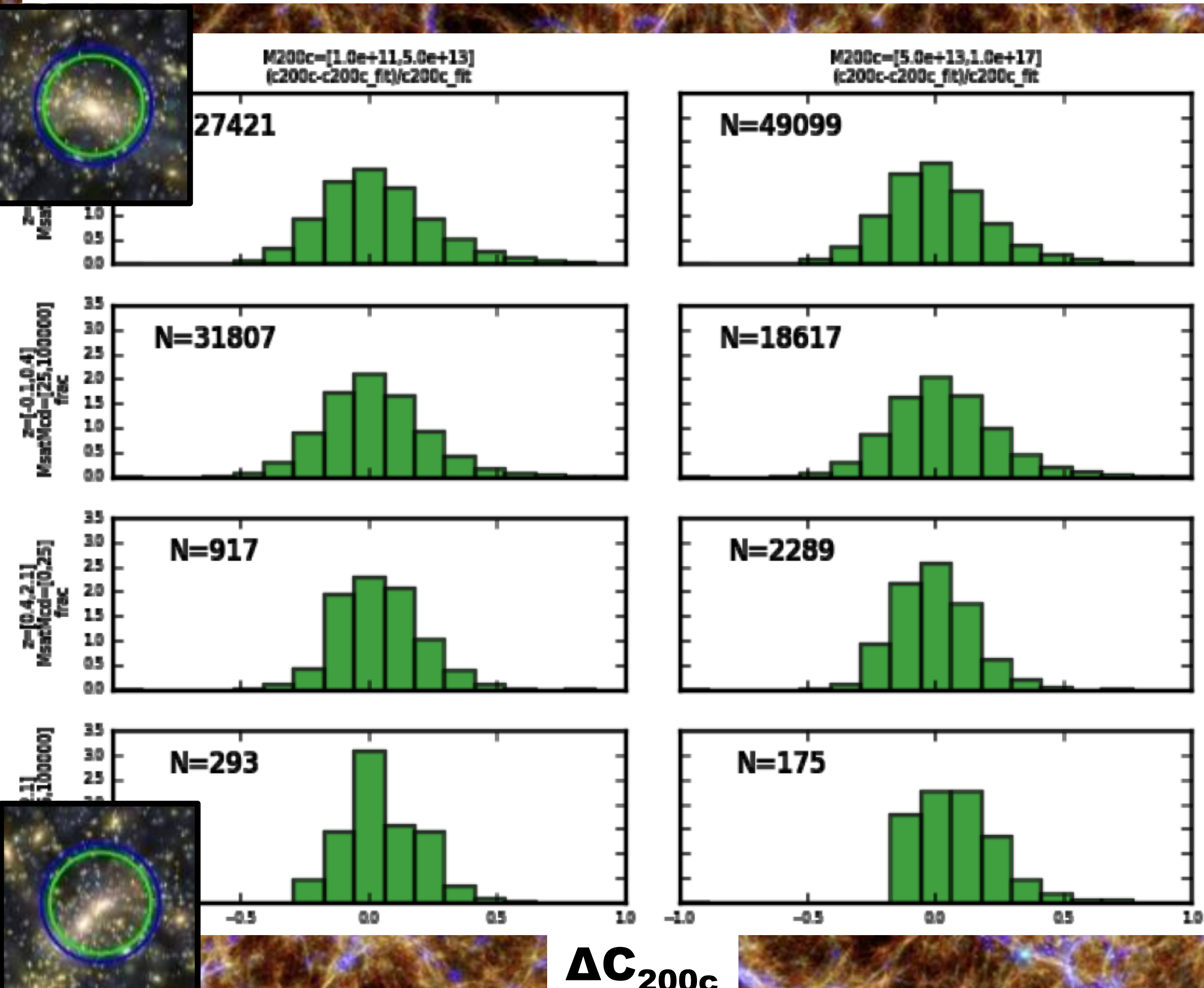
Ragagnin et al. in prep

A deeper Link: M-c relation for Halos



A deeper Link: M-c relation for Halos

$$c = A\left(\frac{M}{8\cdot 10^{14} M_\odot}\right)^{B}\left(\frac{1.34}{1+z}\right)^{C}\left(T_0\frac{M_{sat}}{M_{cD}}\right)^{T_1}\left(1+T_0\frac{M_{sat}}{M_{cD}}\right)^{T_2-T_1}$$



$A = 0.441$

$B = -0.083$

$C = 0.064$

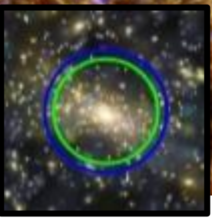
$T_0 = 10^{1.17} \approx 15.0$

$T_1 = 0.28$

$T_1 = -0.03$

Ragagnin et al. in prep

Related to virial equilibrium ?

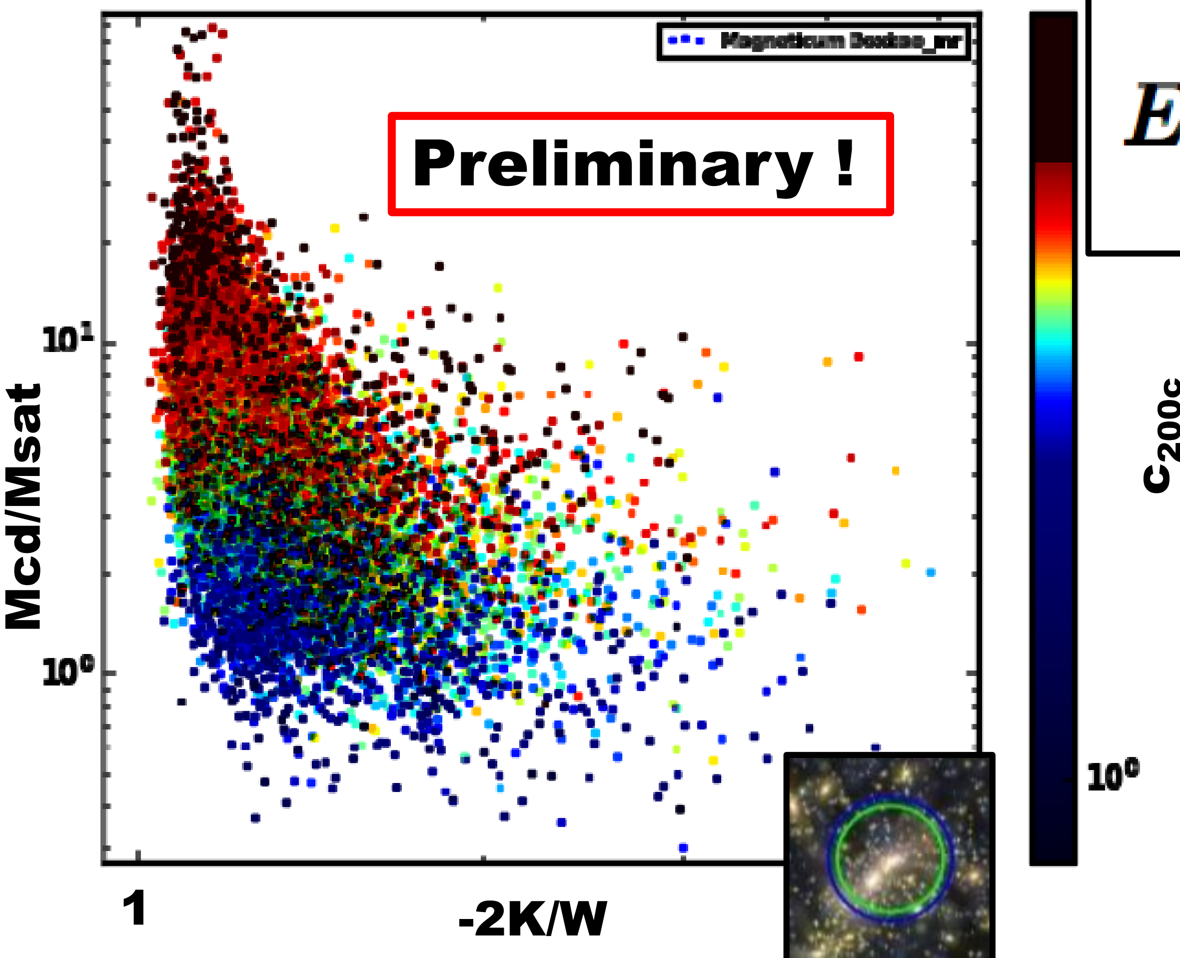


$$\frac{1}{2}\frac{d^2 I}{dt} = 2T + W + 3(\gamma - 1)U_{gas} - Es.$$

K

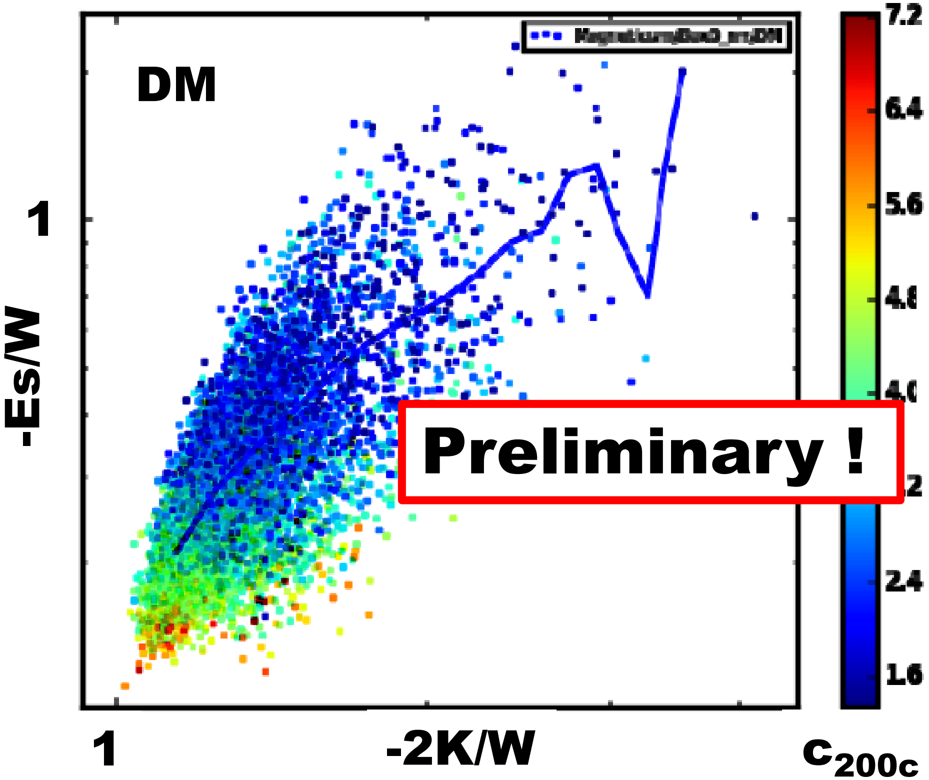
$$Es = \int_S p(\vec{r})r \cdot d\vec{S}$$

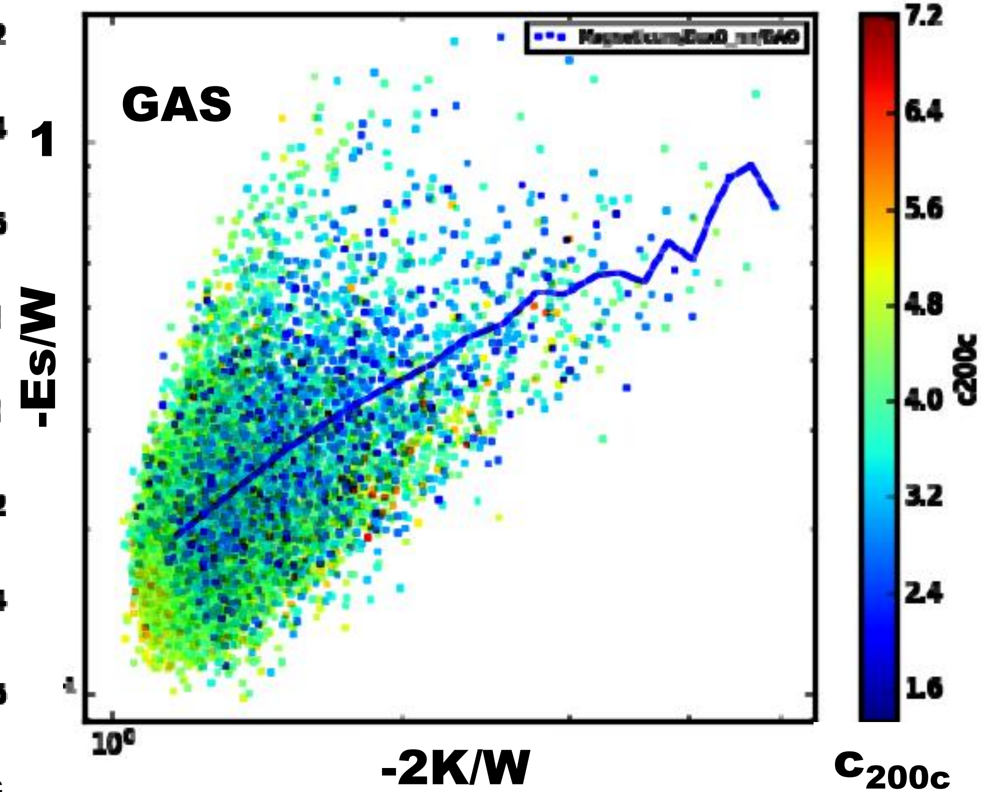
$$\frac{1}{3}\frac{\Sigma m_i v_i^2}{\Delta V}$$

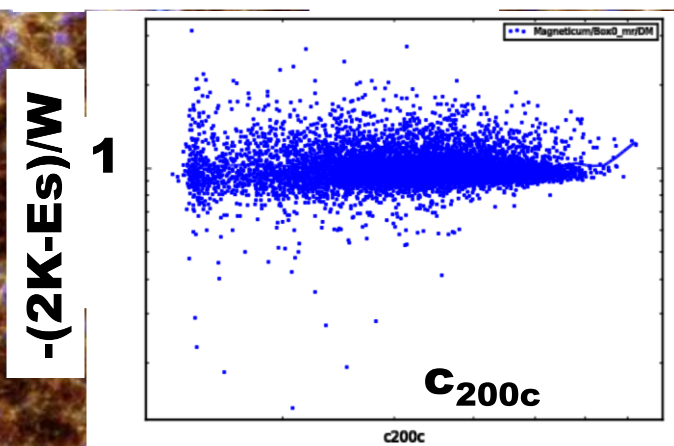


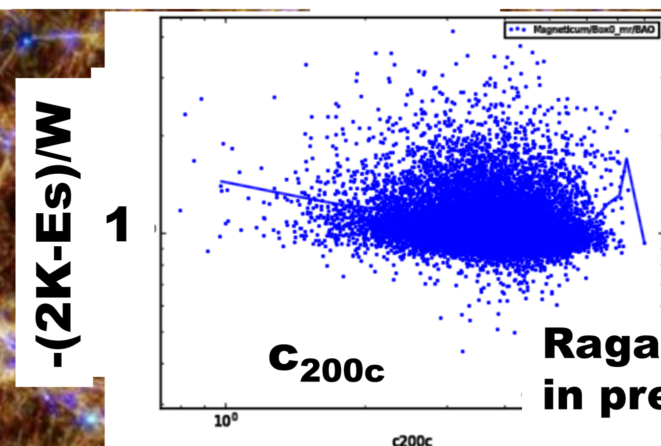
Ragagnin et al. in prep

The role of the baryons ...





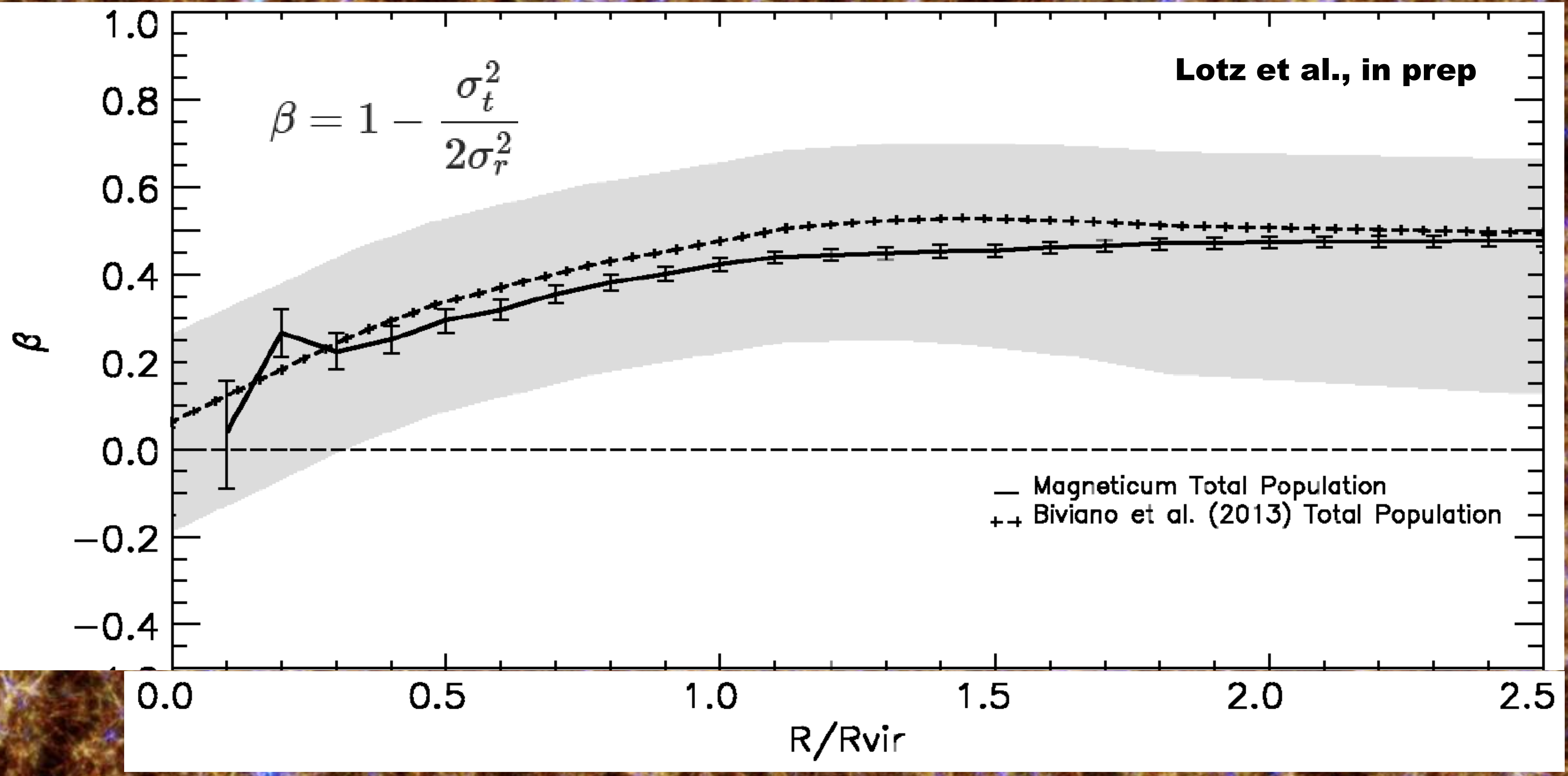




Ragagnin et al. in prep

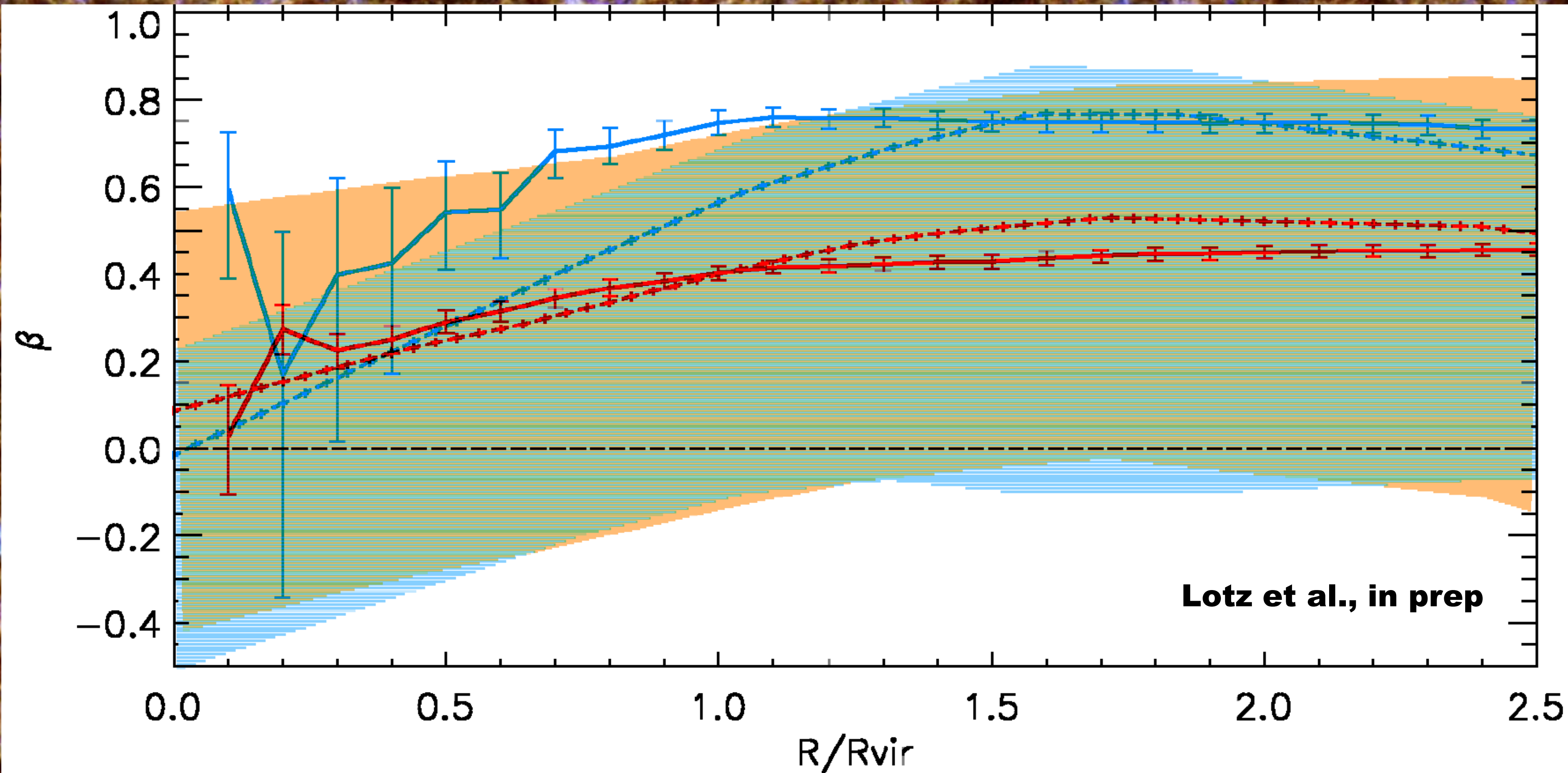
Cluster formation in 30 seconds

Orbits of Galaxies in Clusters



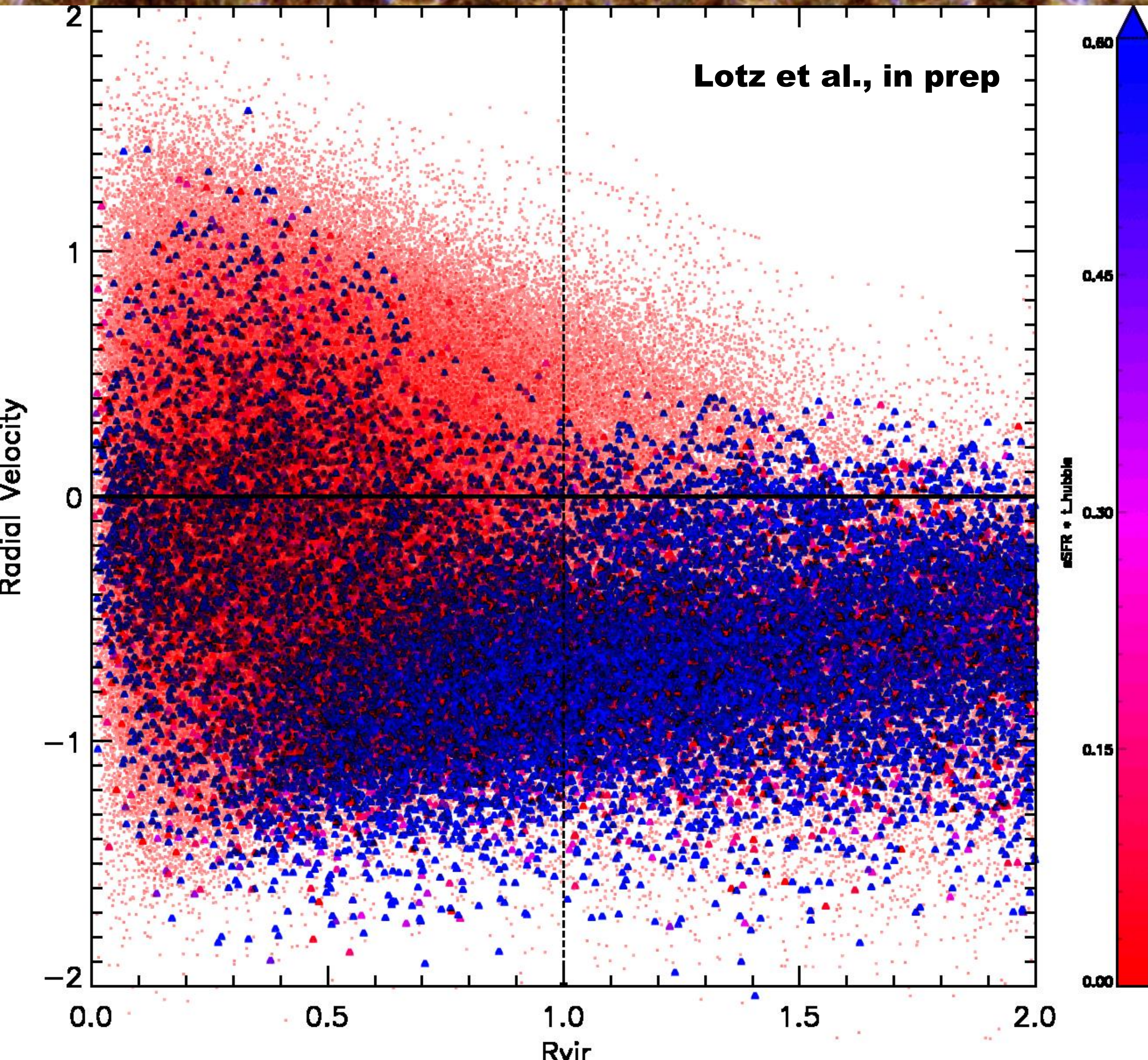
Profile of orbital anisotrpy β of member galaxies

Orbits of Galaxies in Clusters



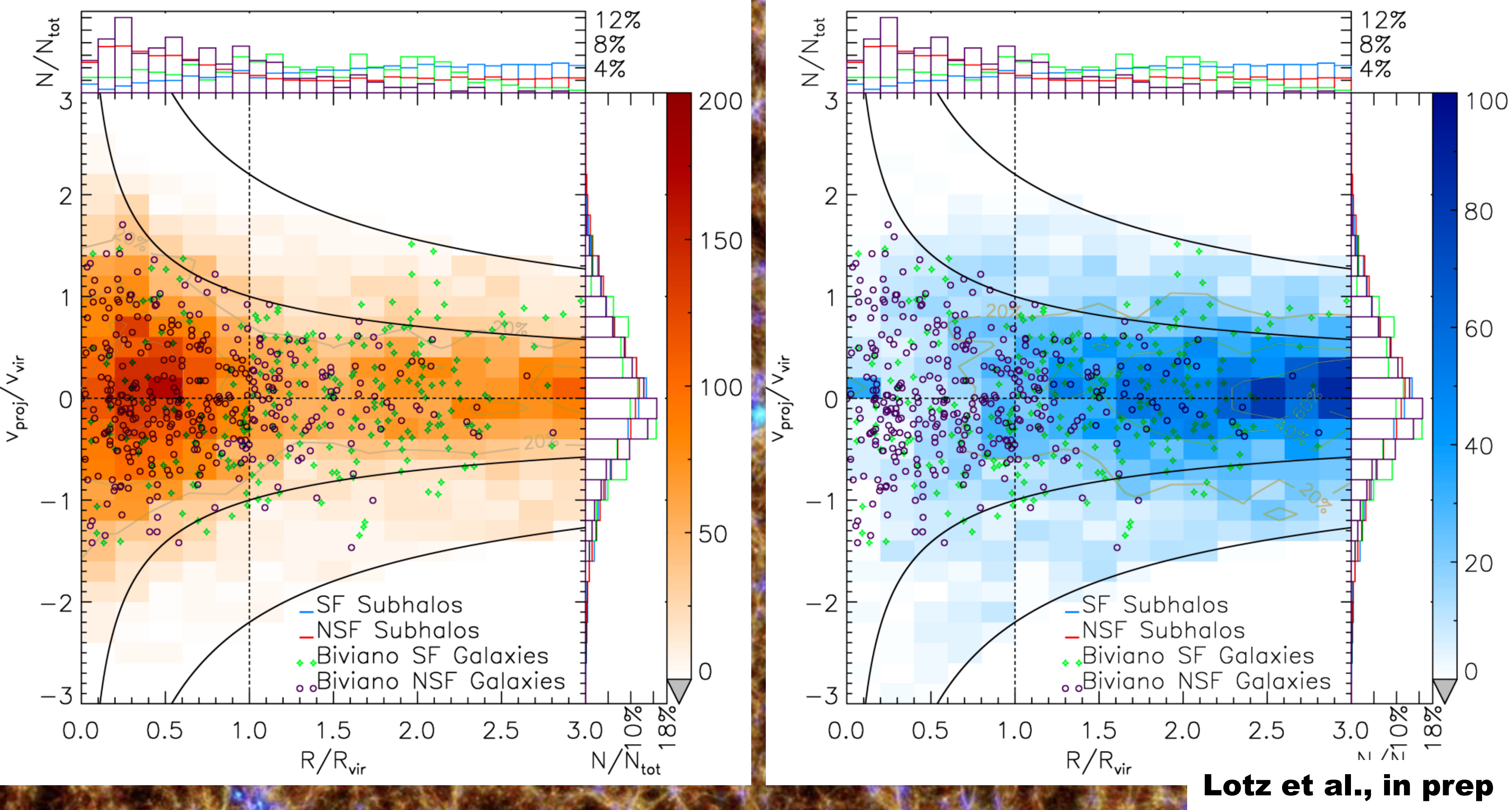
Profile of orbital anisotrpy β of member galaxies, devided into starformint/passive galaxies

Orbits of Galaxies in Clusters



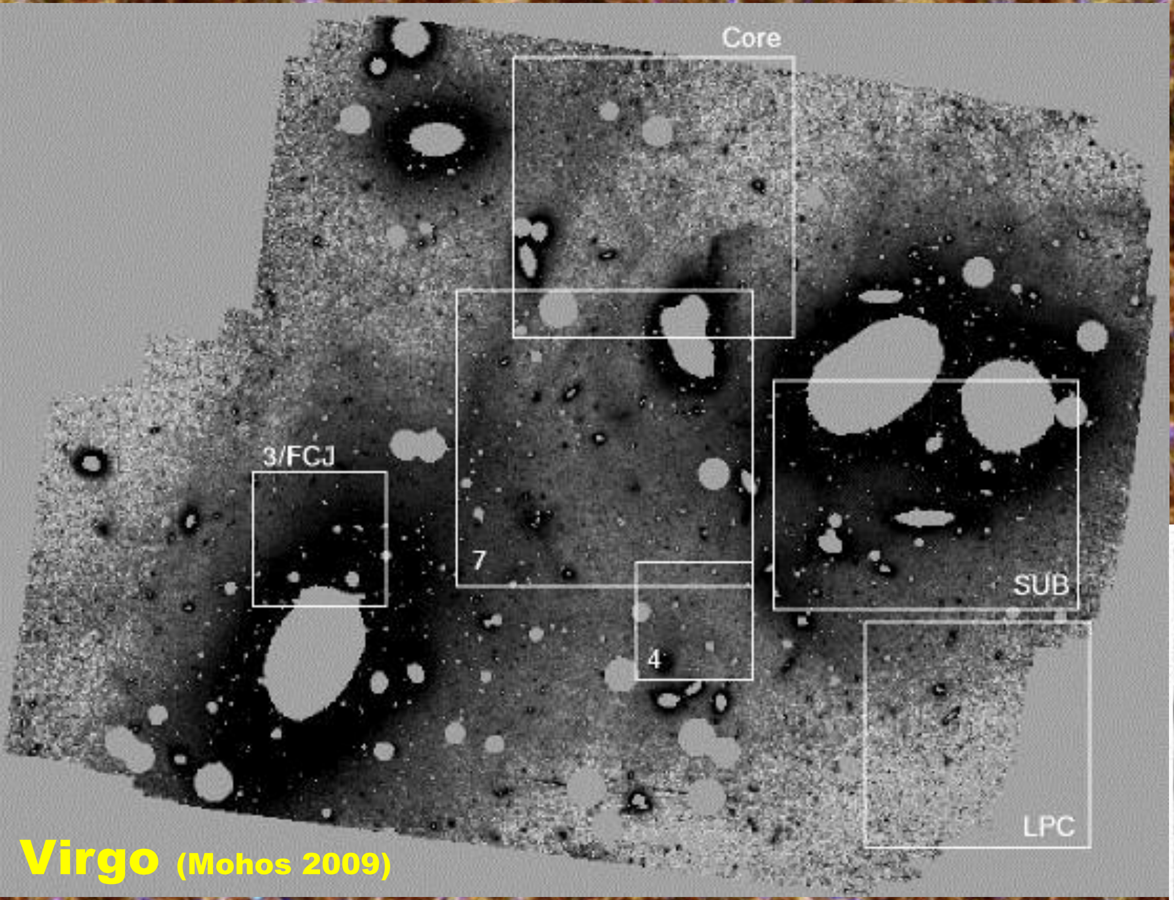
Phase-space of member galaxies and their star-formation

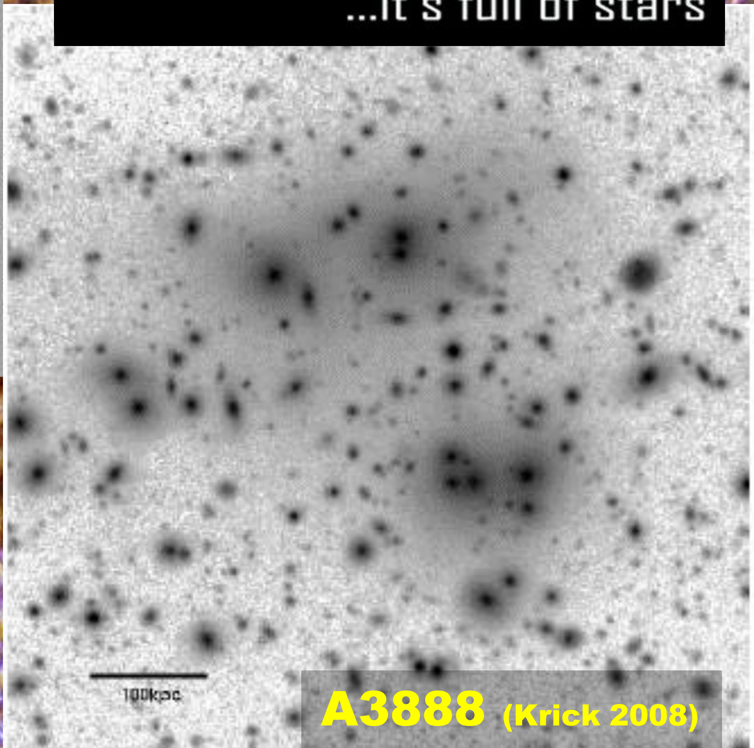
Orbits of Galaxies in Clusters



Distribution of starforming and non star forming galaxies in simulated / observed clusters.

A hidden component of stars …





The diffuse, stellar component build up out of the debris of destroyed galaxies marks another, very important component within galaxy clusters.

Conclusions:

- **Direct dynamical range of 10^6 almost reached**
  Combination of optimization and growing computing power
- **Further increased by „resonable“ sub-scale models**
  Need to be validated and still can be improved
- **Success across various scales**
  Global properties of LSS, galaxy clusters and galaxies
  AGN properties well reproduced in many respects
  Internal structure of galaxy clusters
  Morphology of Galaxies
  Internal dynamics of Galaxies
- **Data federalization for hydro sims is challenging**
  Need complex infrastructure