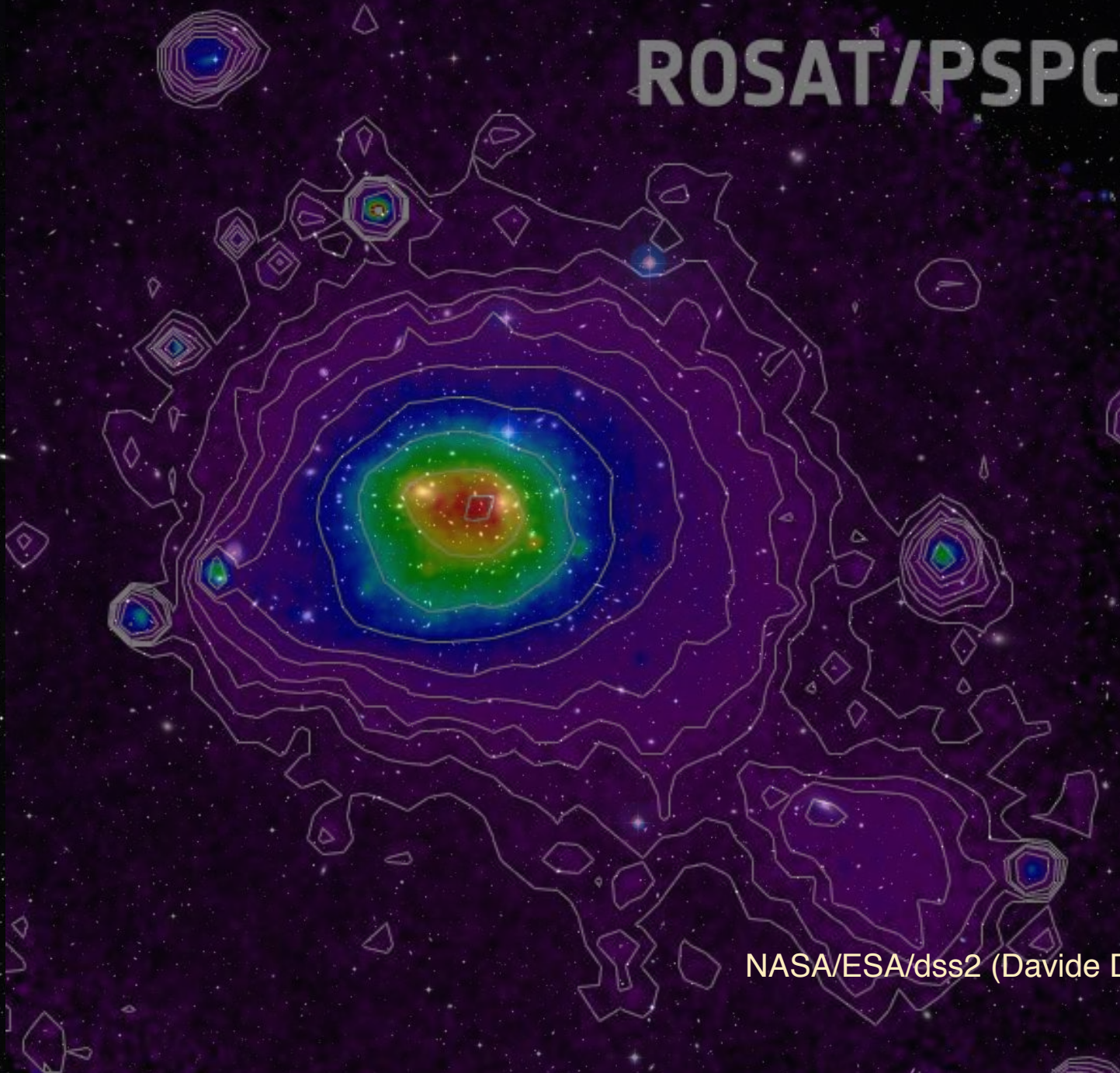


Les amas de galaxies vus en rayon X

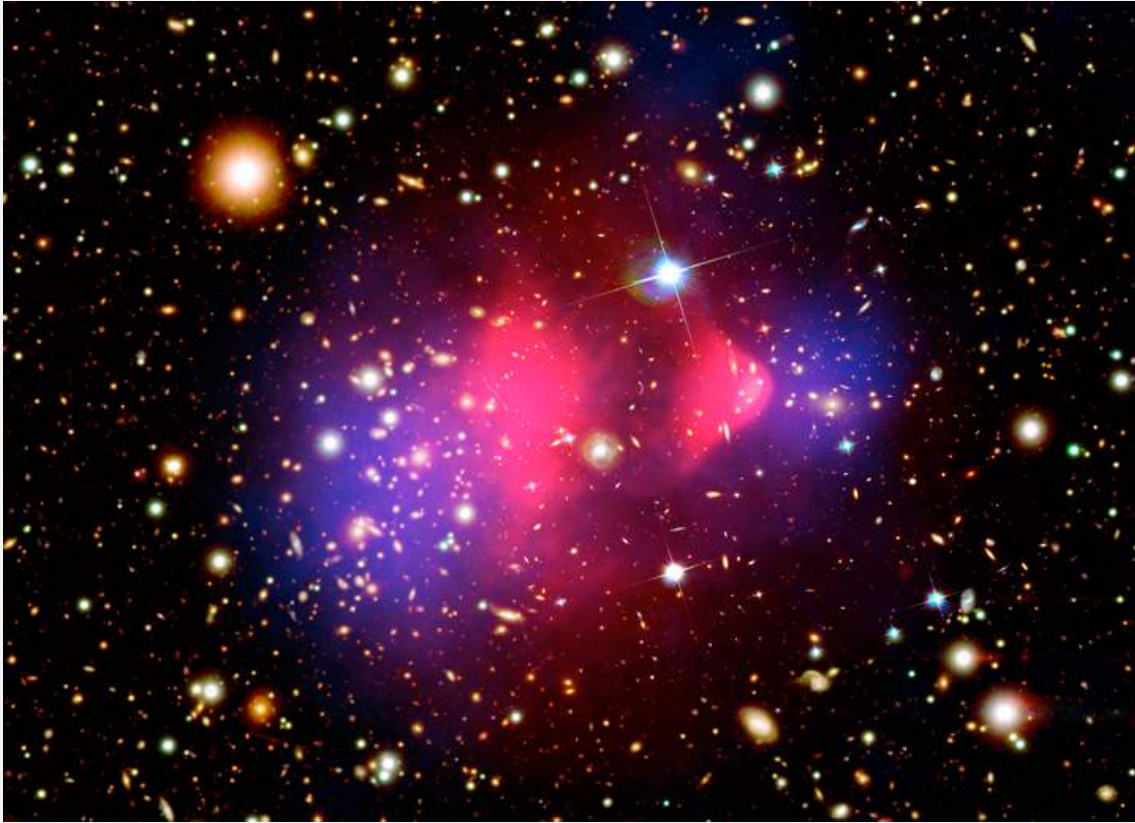
M. Arnaud
(Département d'Astrophysique - CEA Saclay)

ROSAT/PSPC



NASA/ESA/dss2 (Davide De Martin)
ROSAT
PSPC

Un amas de galaxies



*Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.*

- Galaxies 2%
(Herschel 1785)
- Matière noire 85%
(Zwicky 1933)
- Gaz dans le MIA 13%
(X-rays 1960s-1970s; SZ 1970s)

Masse $\sim 1-15 \cdot 10^{14} M_{\odot} \sim 10^{47} \text{g}$

Taille $\sim 1-2 \text{ Mpc} \sim 10^{24} \text{ cm}$

Le gas chaud intra-amas



$$\frac{GM_\delta}{R_\delta} \propto kT$$

Gas chaud

$$\Rightarrow T \sim 10^6 - 10^8 \text{ K}$$

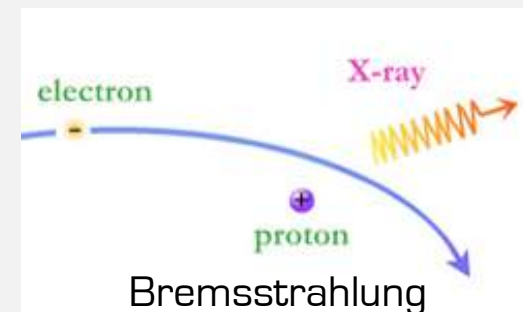
(1- 15 keV)

très peu dense

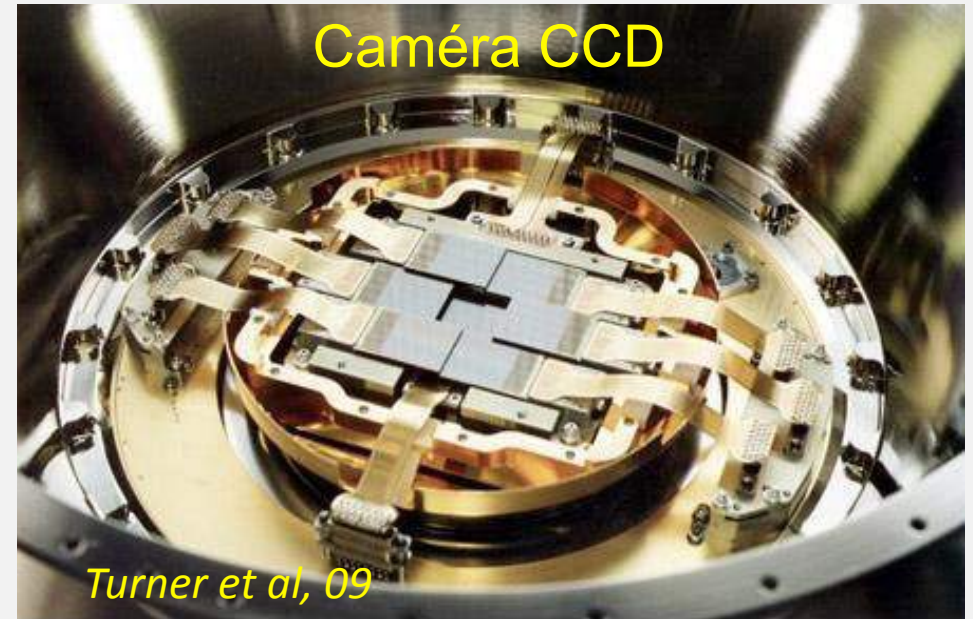
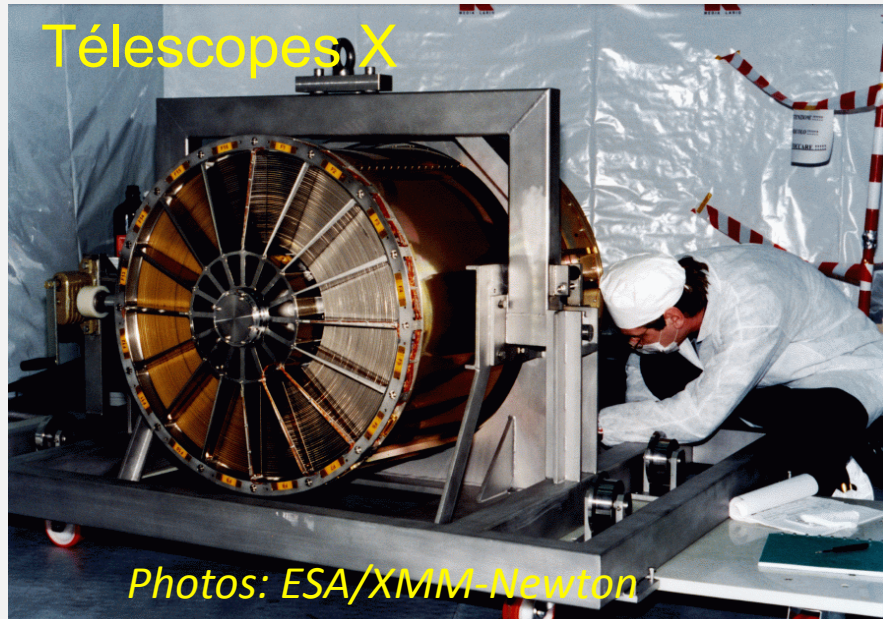
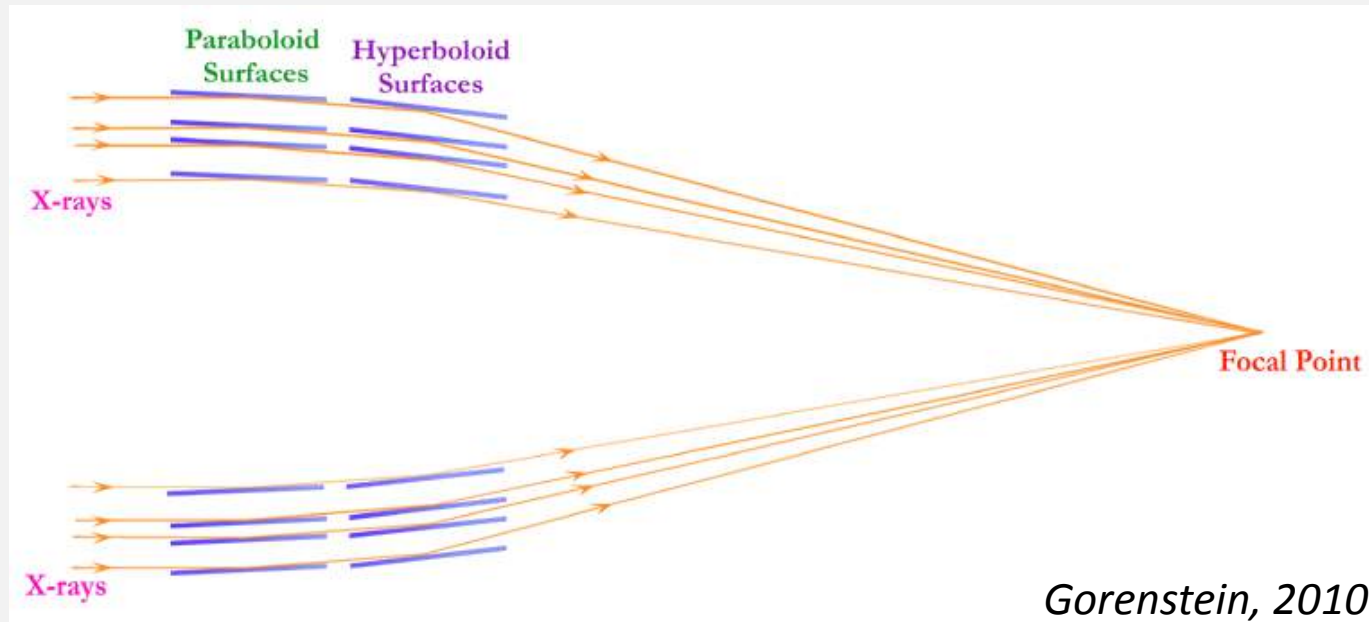
$$\Rightarrow n_e \sim 10^{-2} - 10^{-4} \text{ cm}^{-3}$$

Plasma ionisé émetteur de photons X

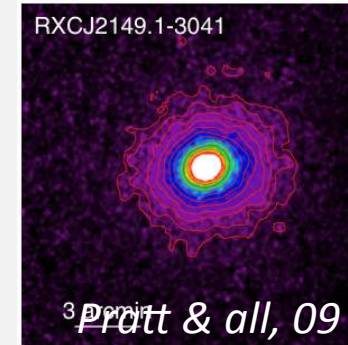
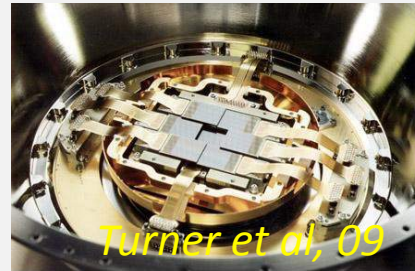
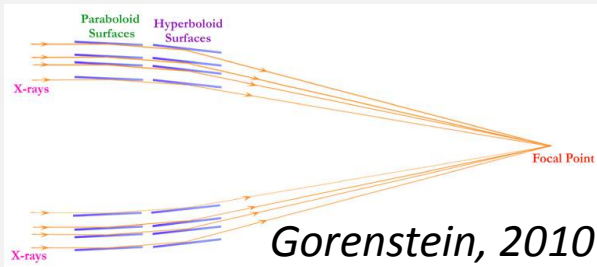
$$S_X \propto \int_{los} n_e^2 \Lambda(T) dl$$



Observer en rayon X



La mesure en rayon X



Sources de faible intensité

$\sim 1 - 10^{-3}$ photons/s

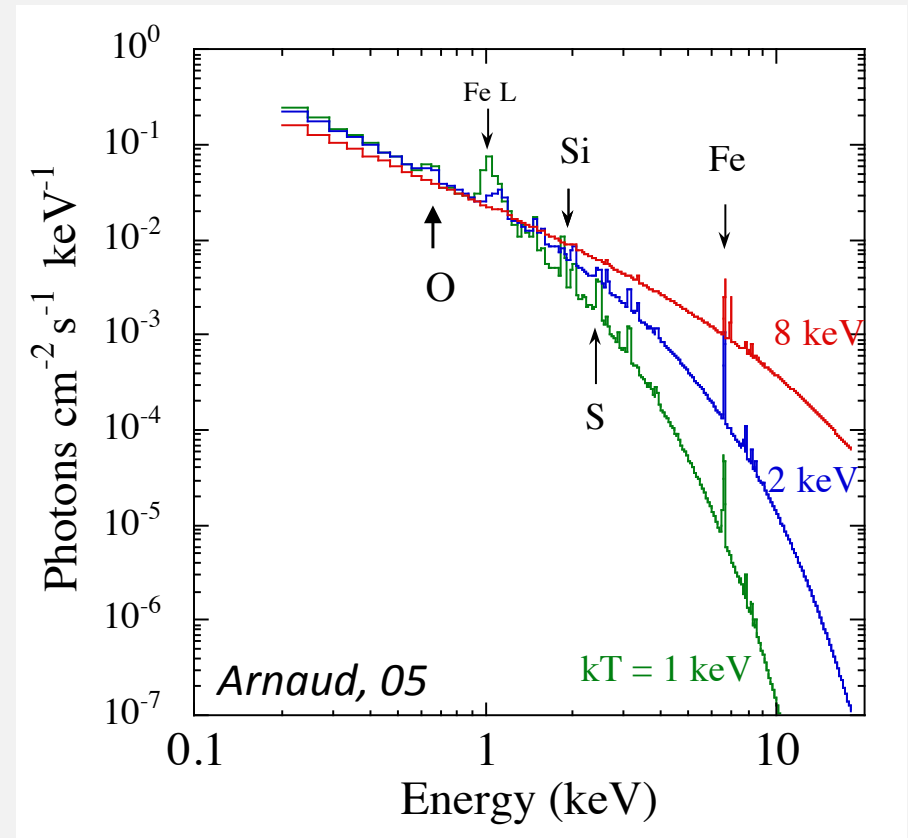
Détection de chaque photon

⇒ Position, Energie

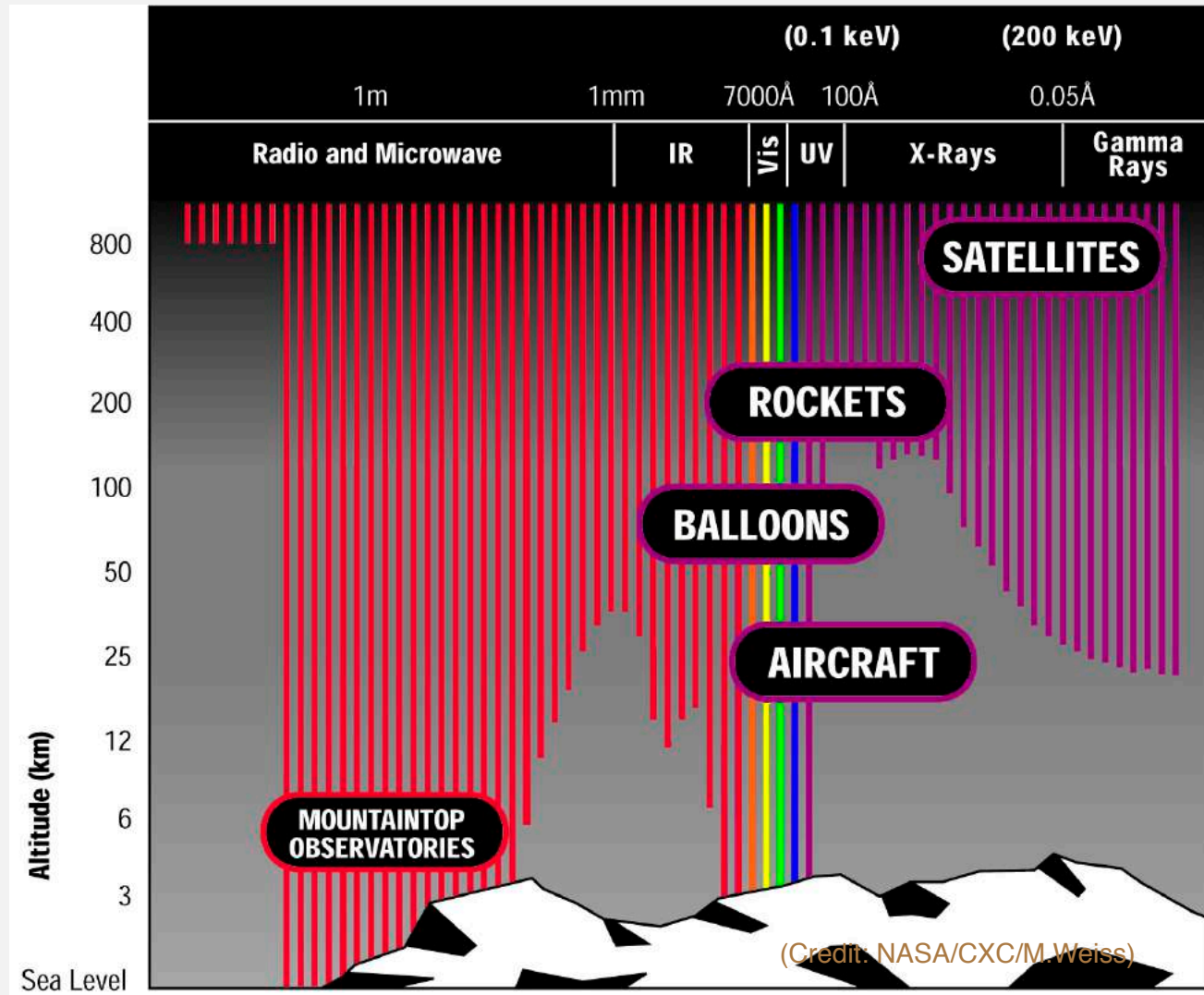
⇒ Images ; spectres

$$dN(E)/dE \sim n_e^2 V [g(E,T) T^{-1/2} \exp(-E/kT)]$$

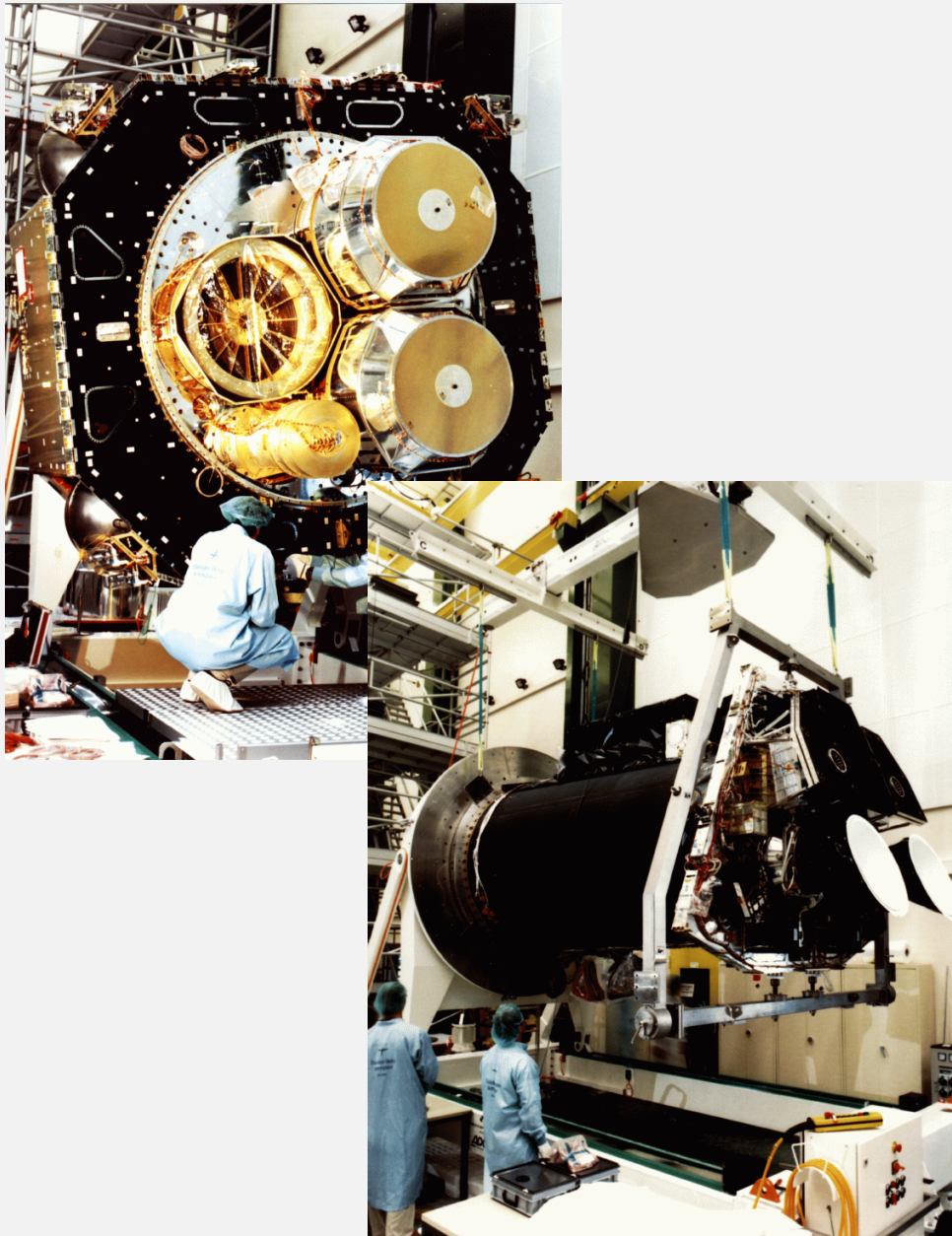
⇒ densité et température du gaz



Une observation depuis l'espace



Le montage du satellite XMM-Newton

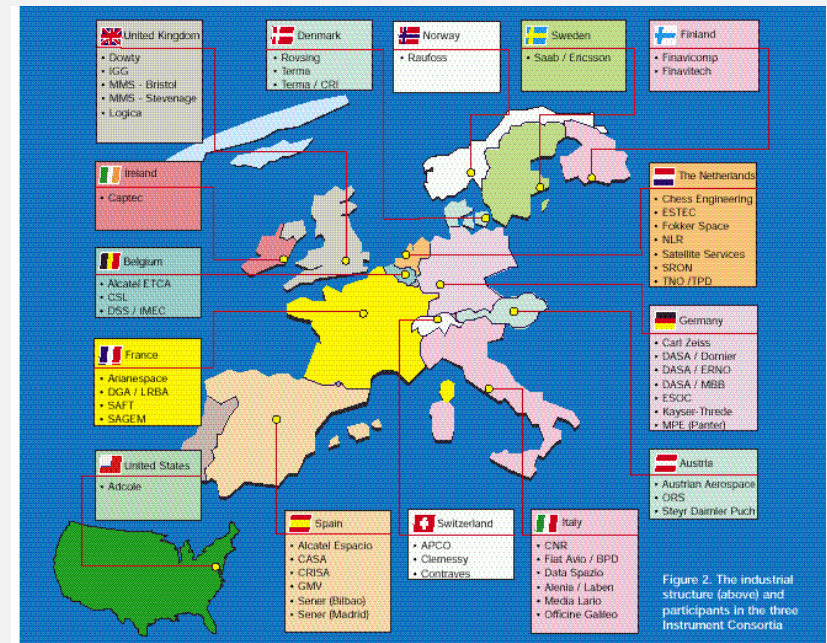


Photos: ESA/XMM-Newton

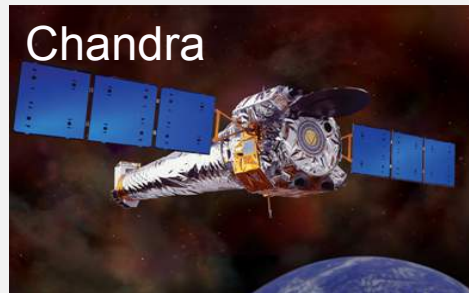
Les observatoires X



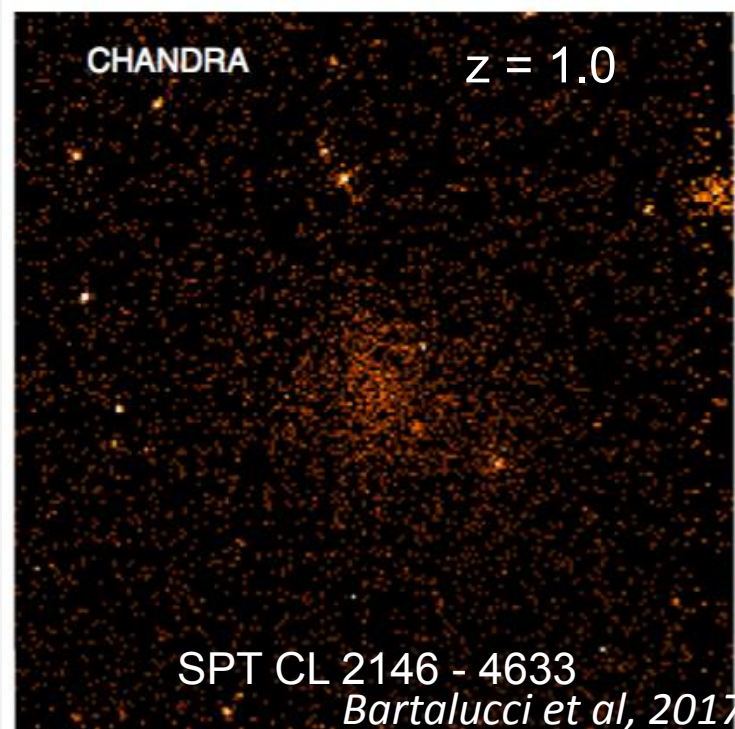
Une grande collaboration internationale



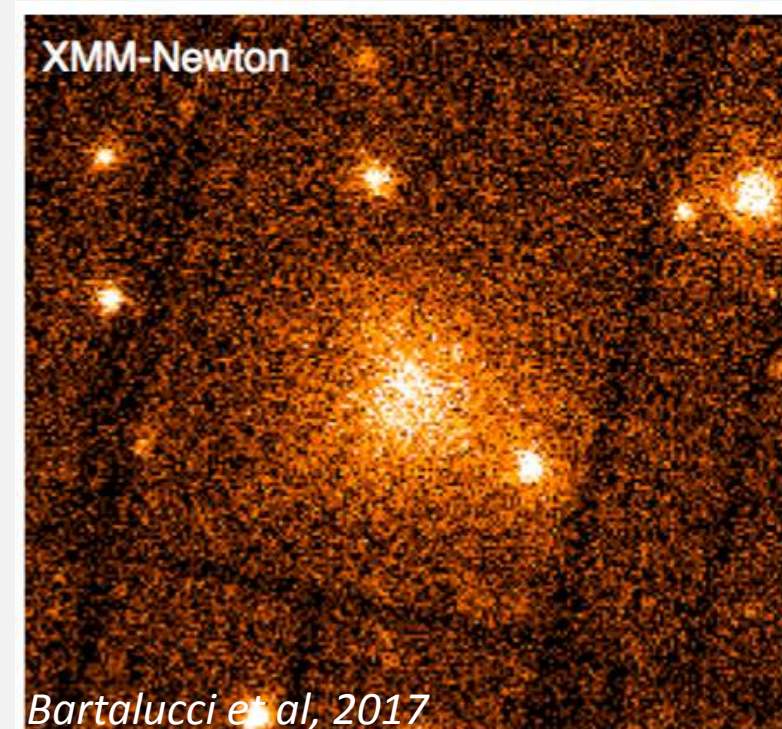
des performances complémentaires



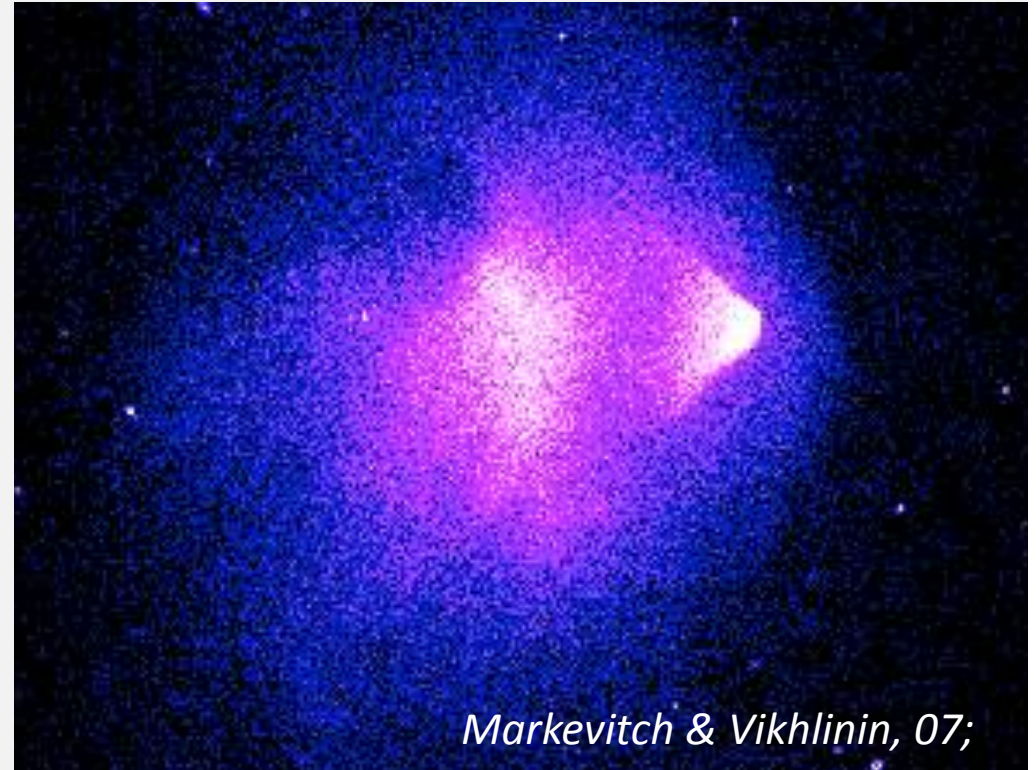
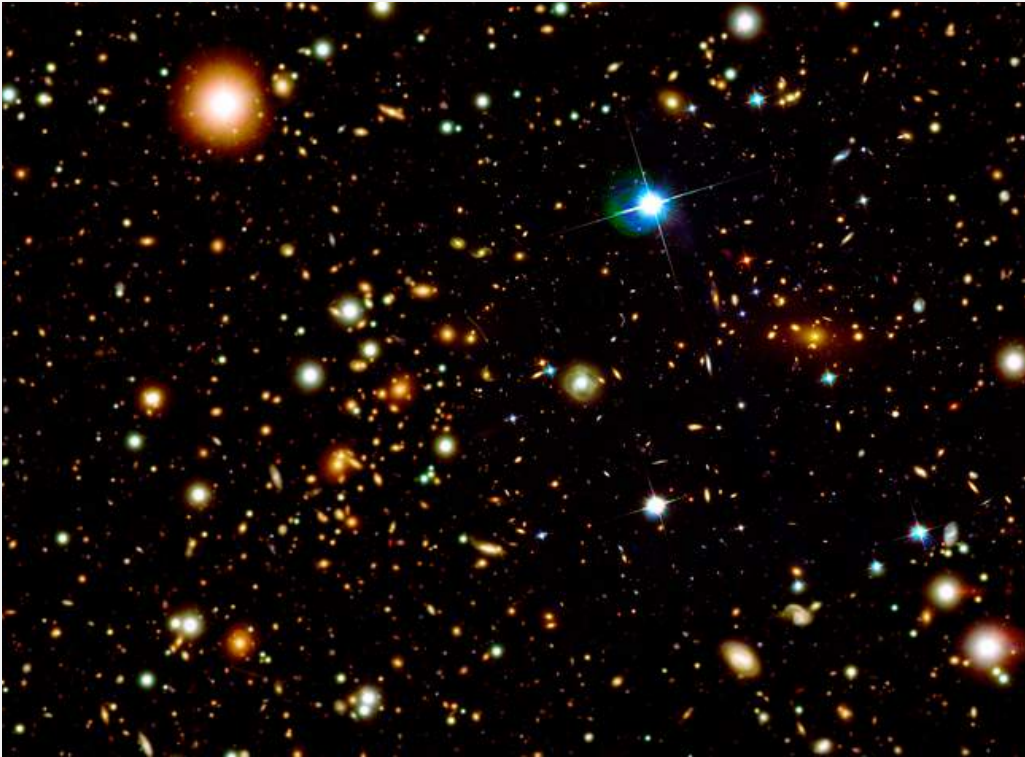
1 télescope 340 cm²
champ 17' résolution < 0.5''



3 télescopes 2000 cm²
champ 30' résolution 10''



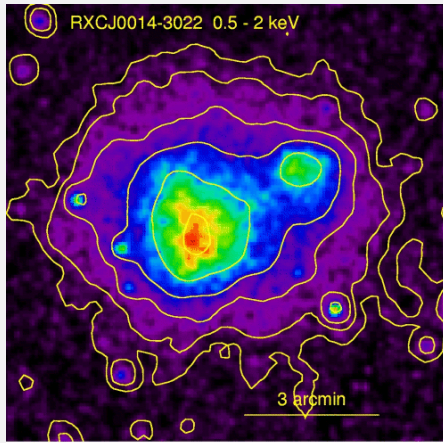
Voir les amas en rayon X



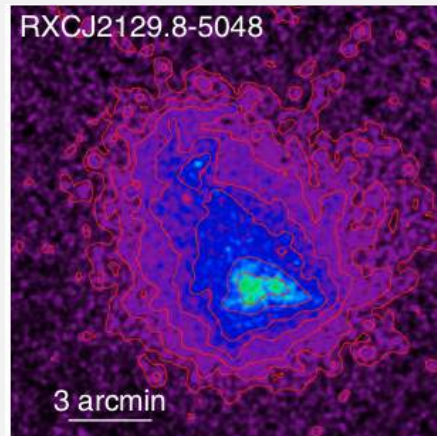
Credit: Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al. 2006;

Plus facile d'identifier et de caractériser l'état dynamique
⇒ formation et évolution

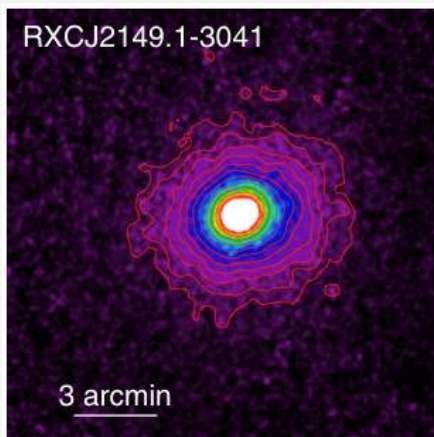
Croissance des amas



fusion



post-fusion



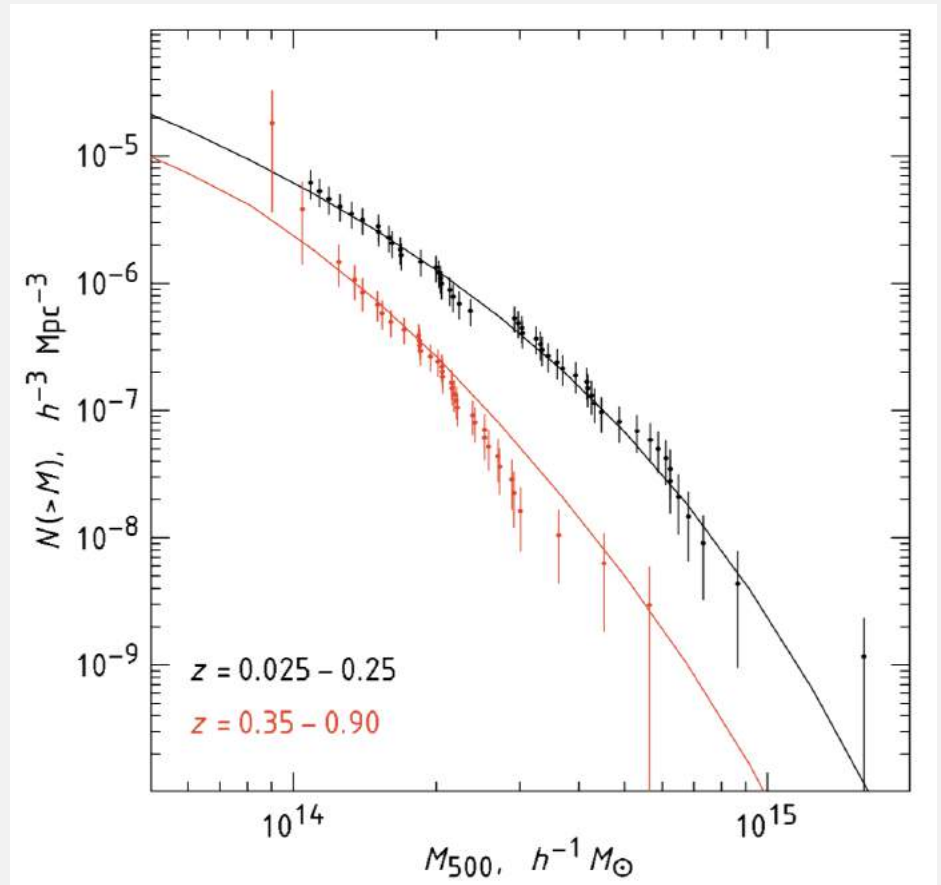
amas relaxés

Images from Pratt et 09



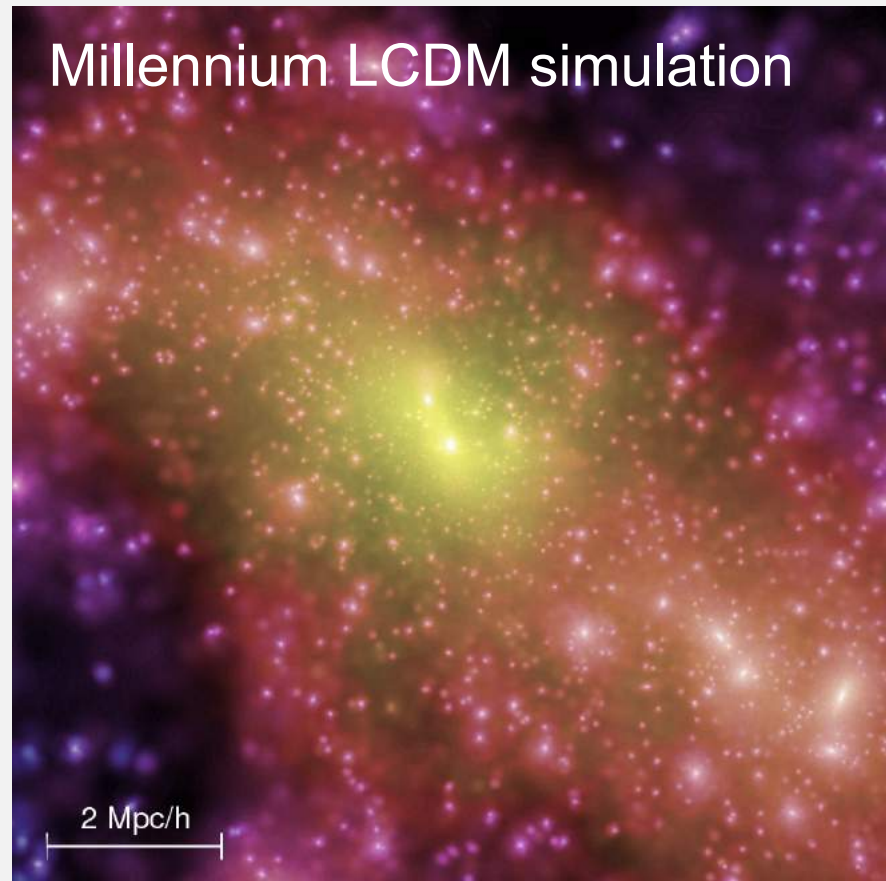
Gobat et al, 11

l'amas le +distant

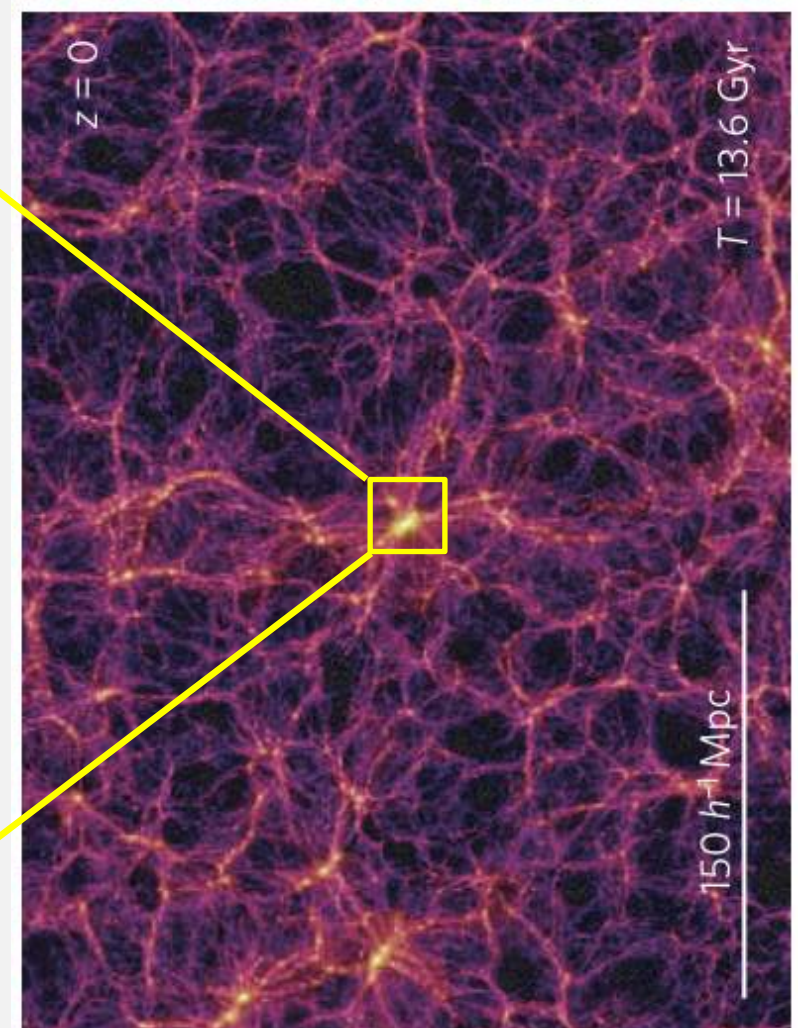


CCCP Vikhlinin et al, 09

Amas et formation des structures

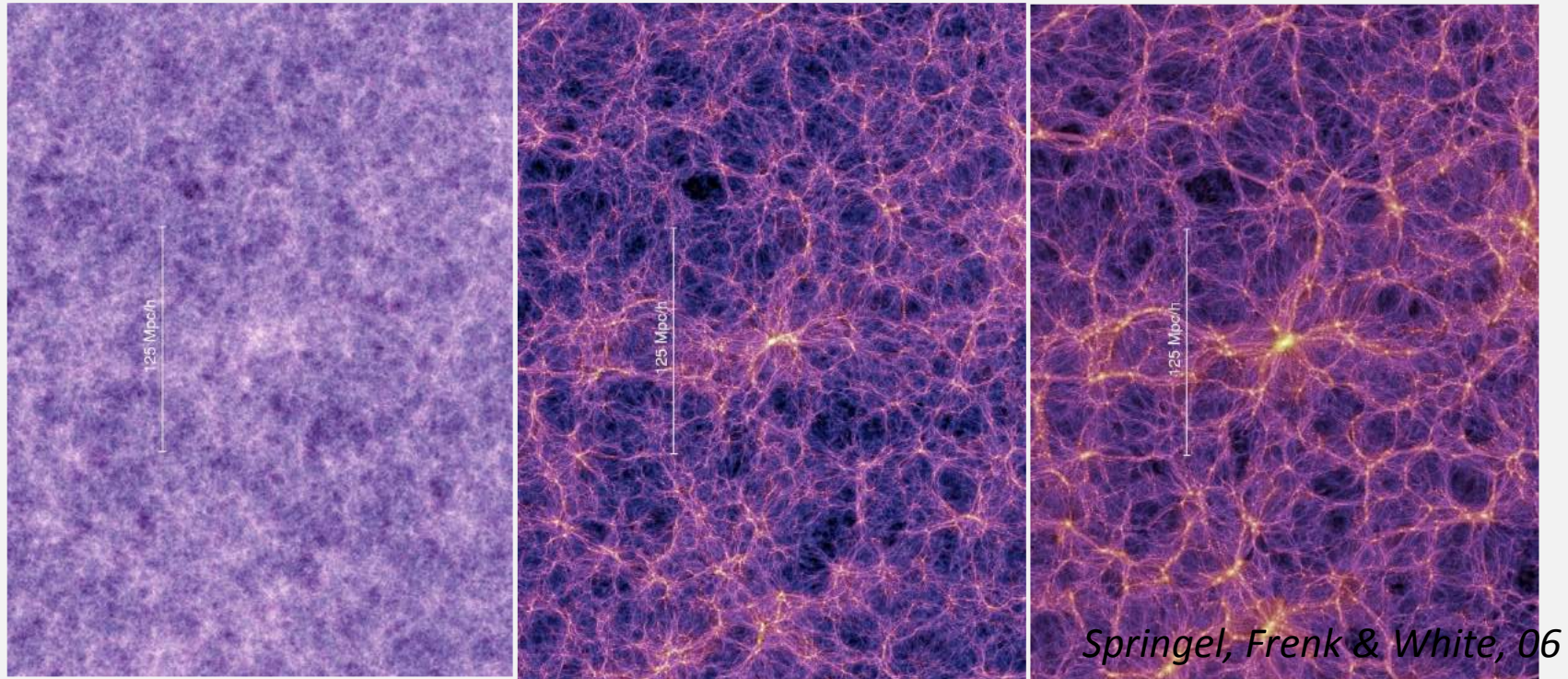


Springel, Frenk & White, 06



Les noeuds de la toile cosmique

Structuration de la matière noire



13.2 GYr; $z=8.5$

3.6 GYr; $z=1.4$

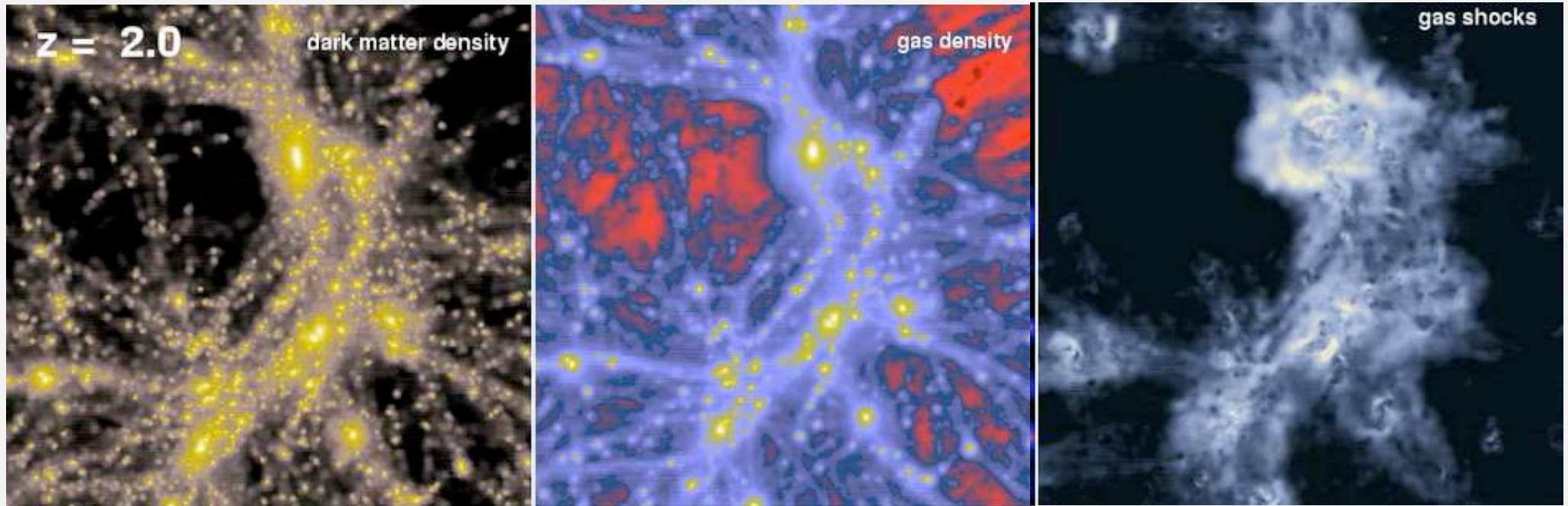
aujourd'hui ; $z=0.0$



temps

régie par la gravité

Evolution, gravité et matière noire



Credit: V. Springel

Formation et évolution par fusion/accrétion le long des filaments

Dominée par la matière noire

Physique complexe: effondrement grav. ; chauffage du gaz

Etude des amas

⇒ Tester le modèle cosmologique

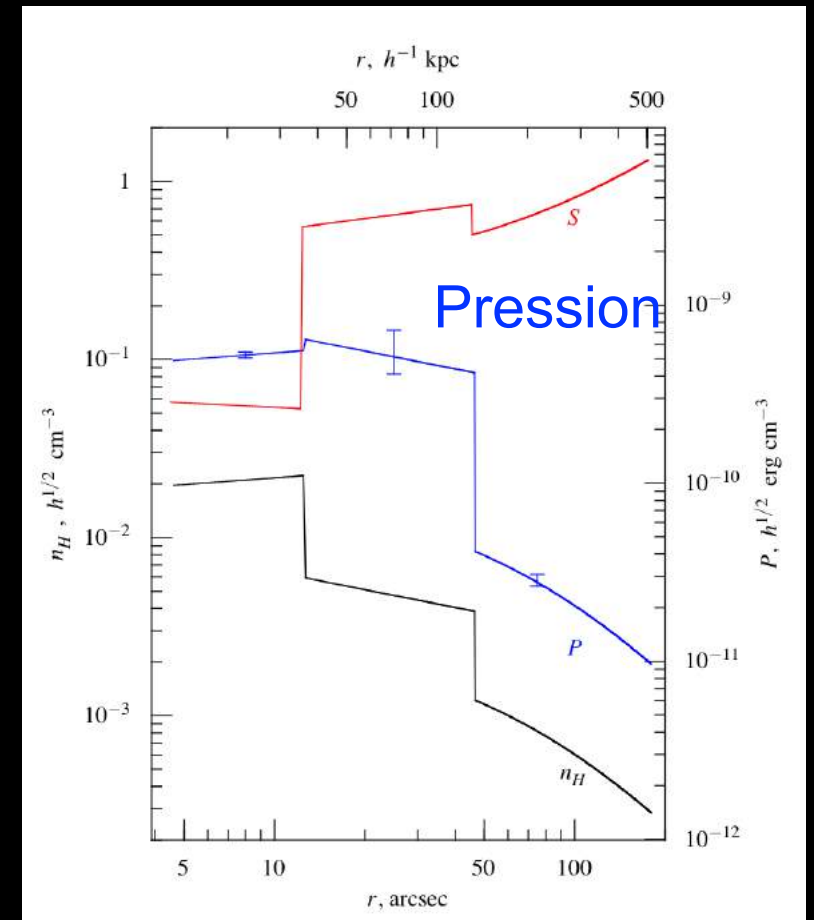
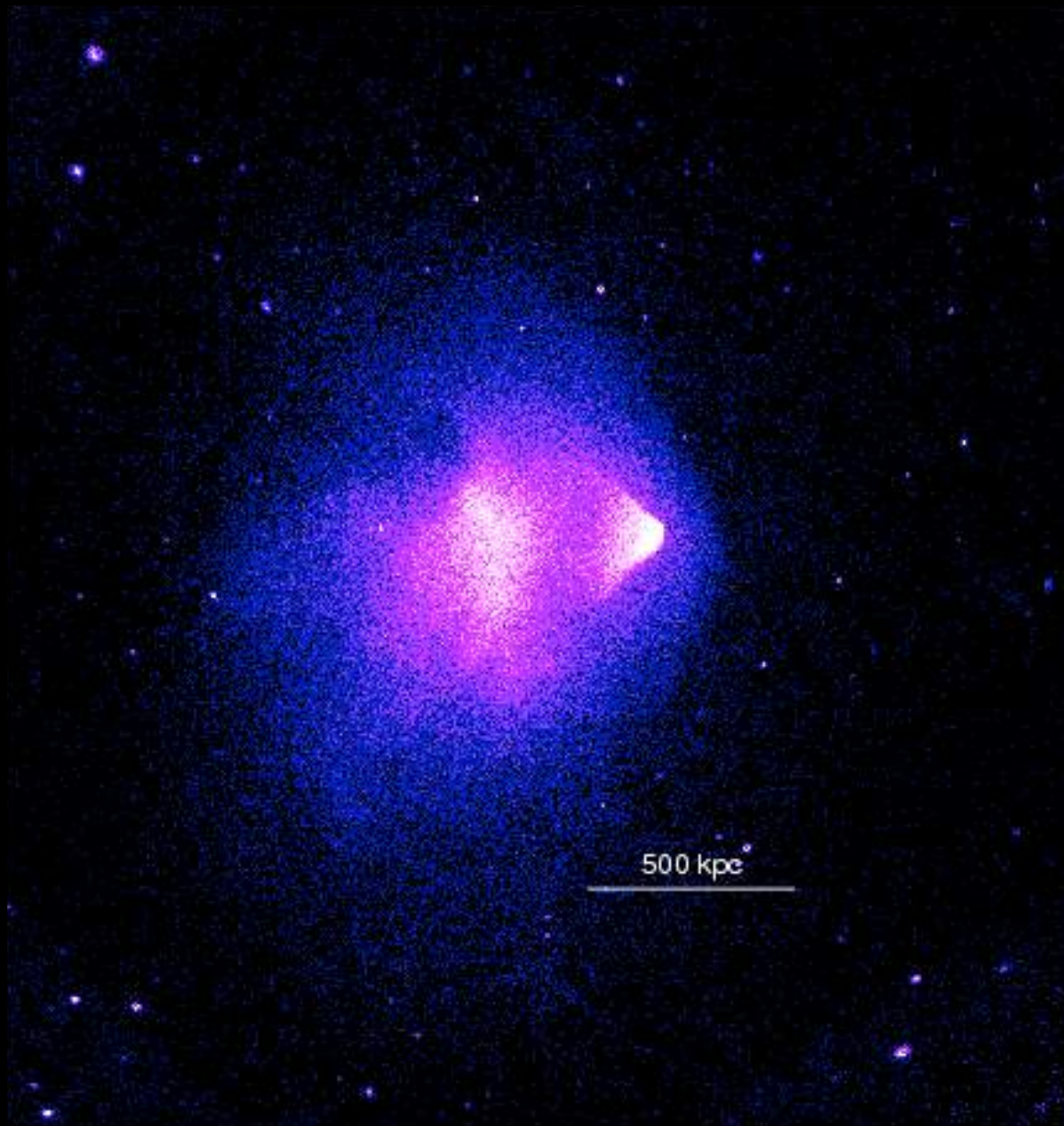
⇒ Comprendre la physique de formation des structures (MN, gas, *)

⇒ Etude détaillée d'amas "bien choisis "

⇒ Etude de population

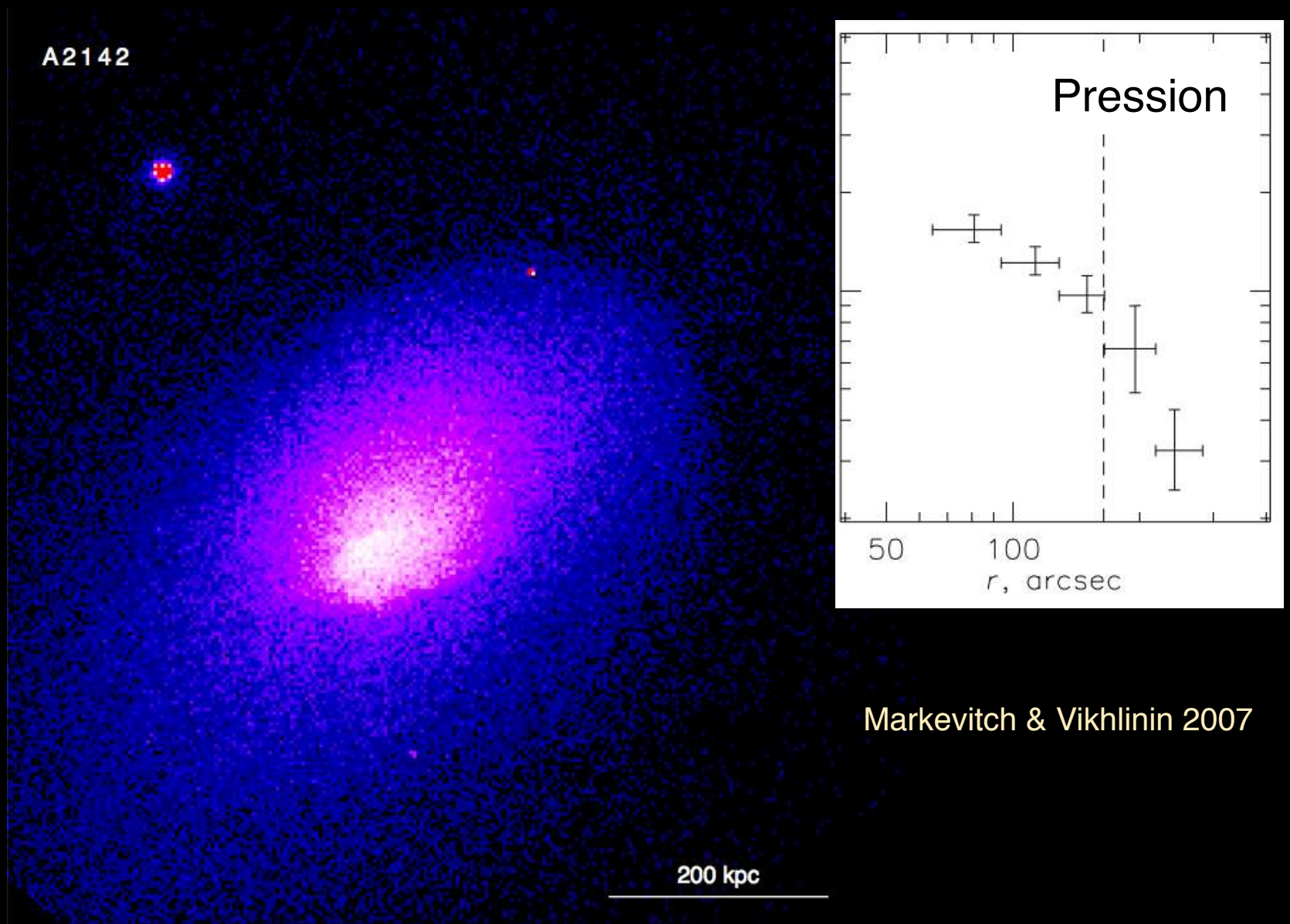
*Etude de cas
la dynamique du gaz*

Chocs



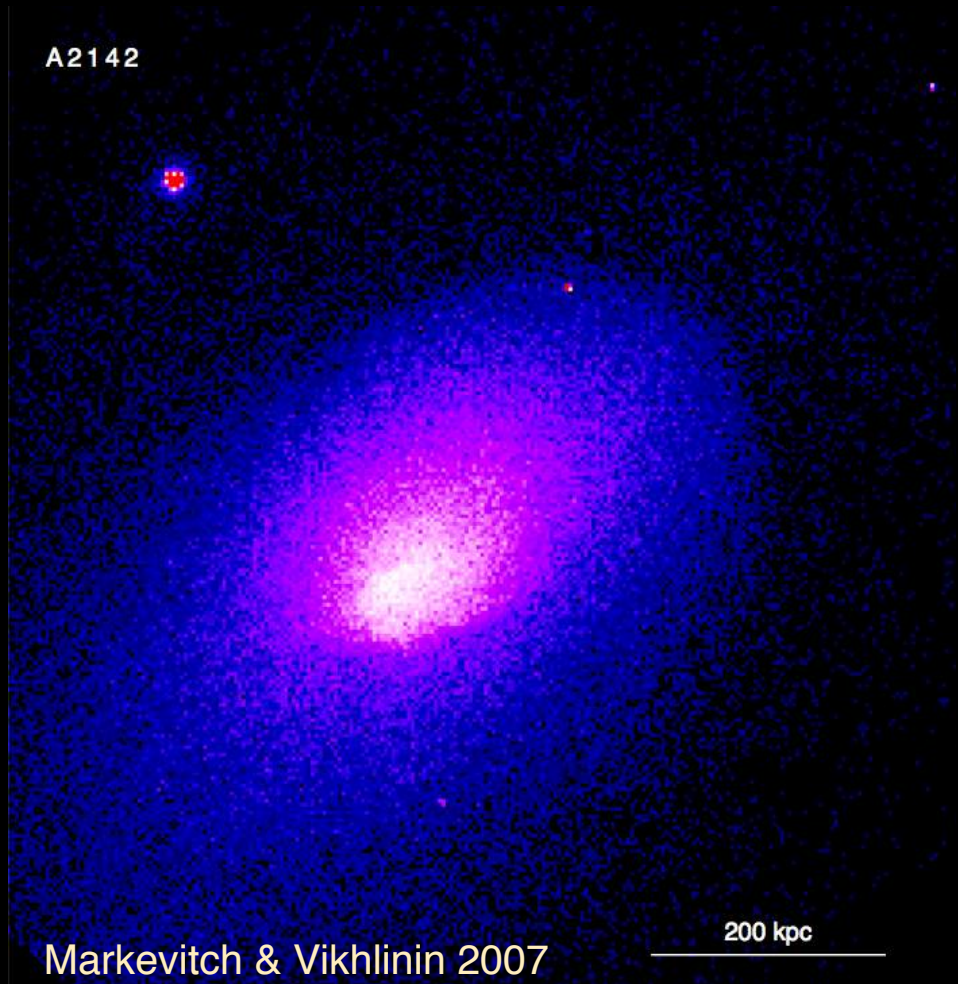
Markevitch et al 2002, 2004

Fronts froids



Markevitch & Vikhlinin 2007

Fronts froids

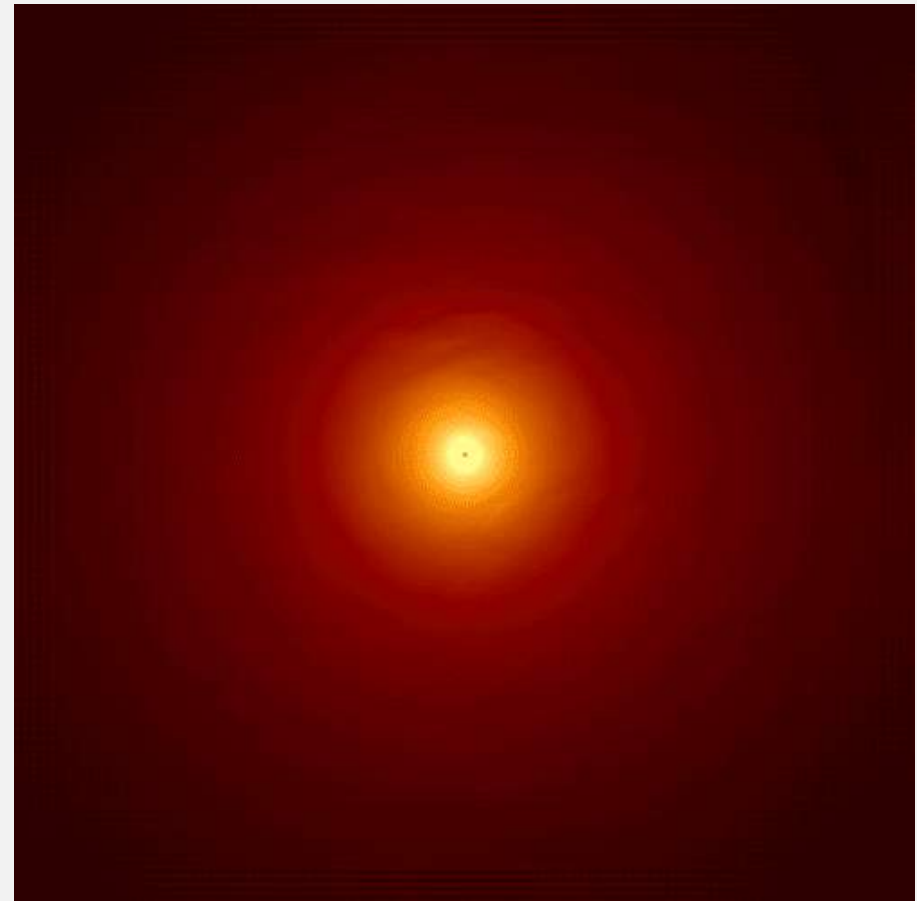


promotech software demonstr

Propagation d'onde



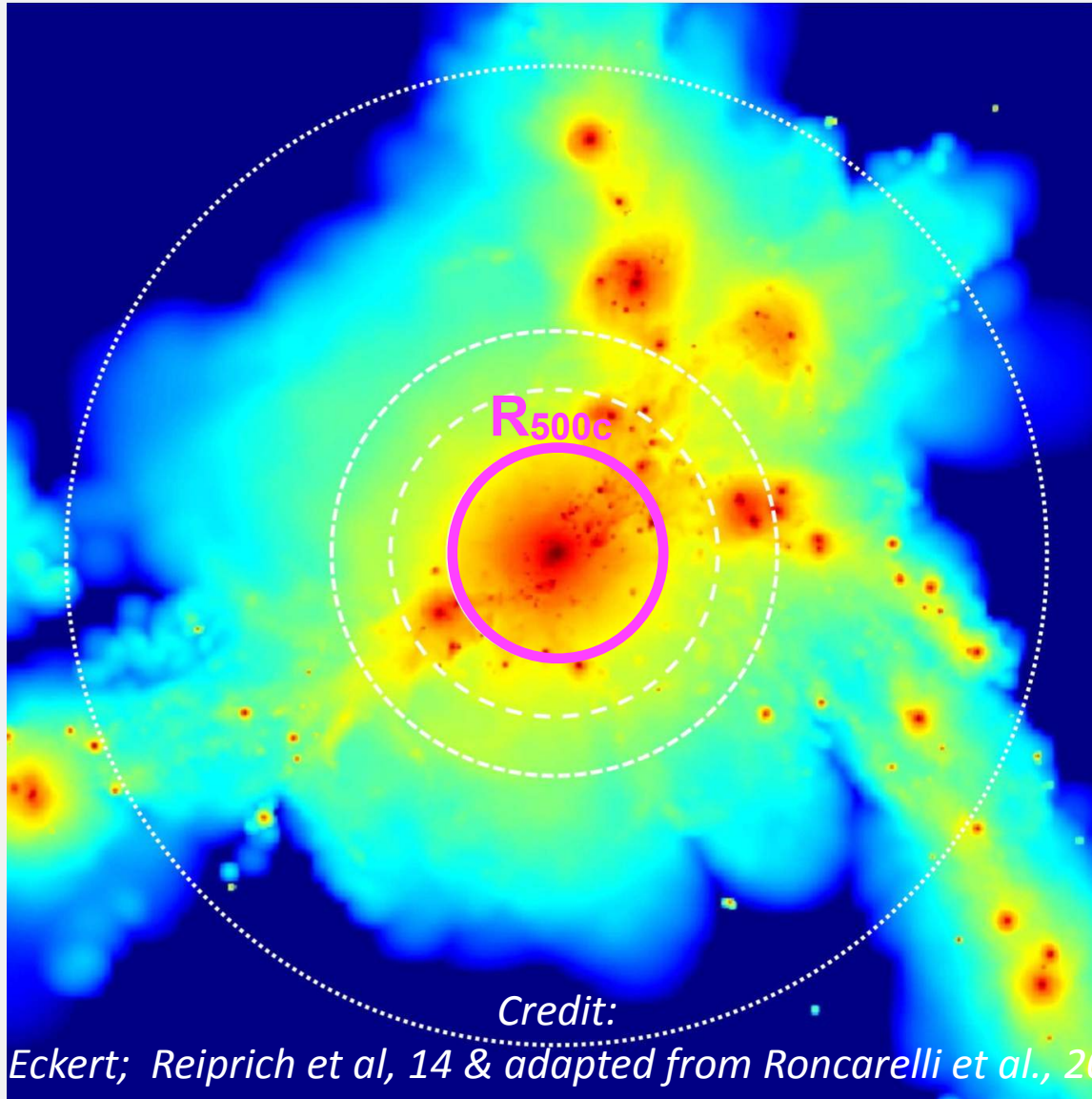
Sanders et al 2016; Walker et al, 2017



Credit: NASA's Goddard Space Flight Center

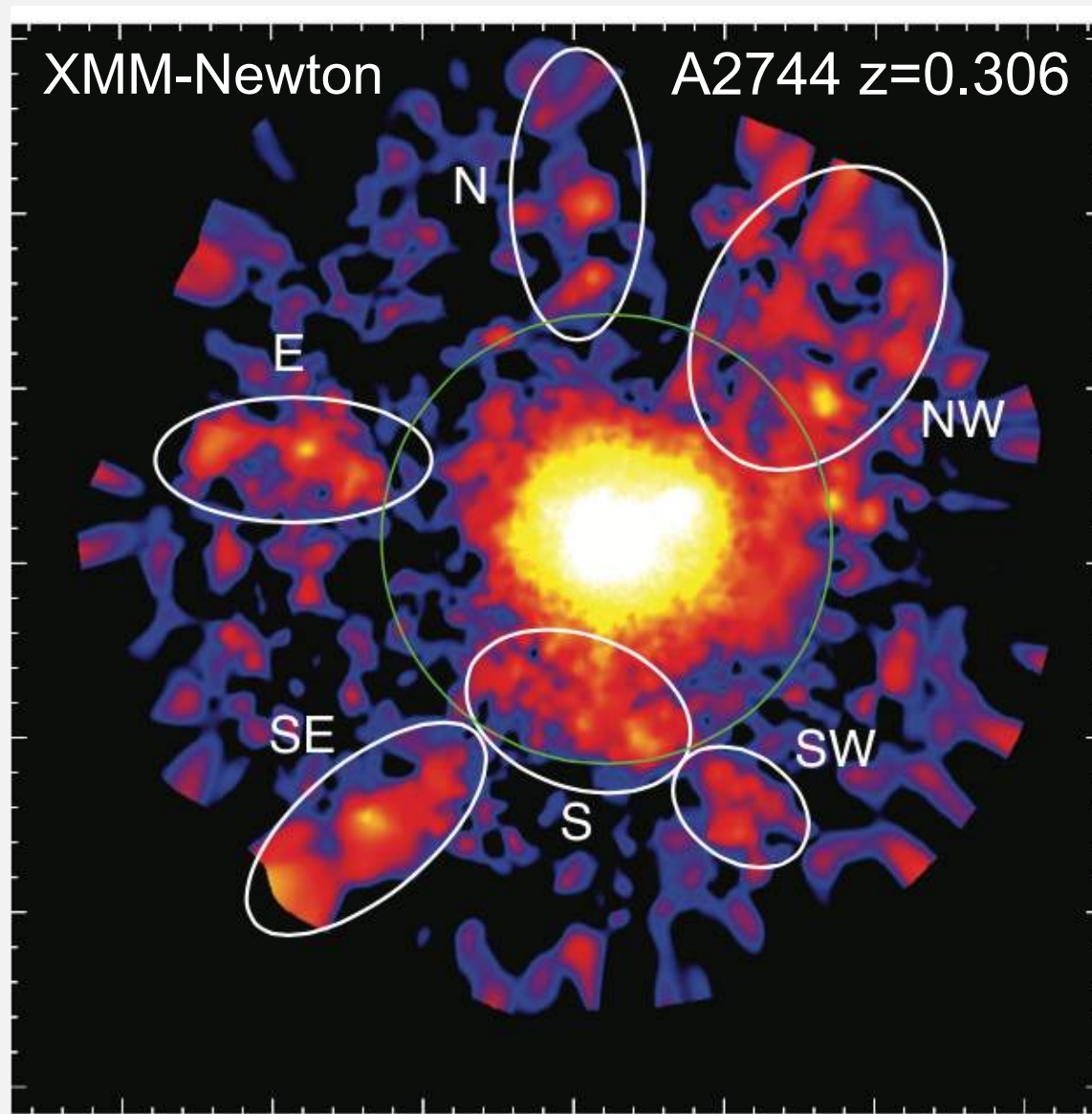
après le passage/fusion d'un petit groupe

Les régions extérieures



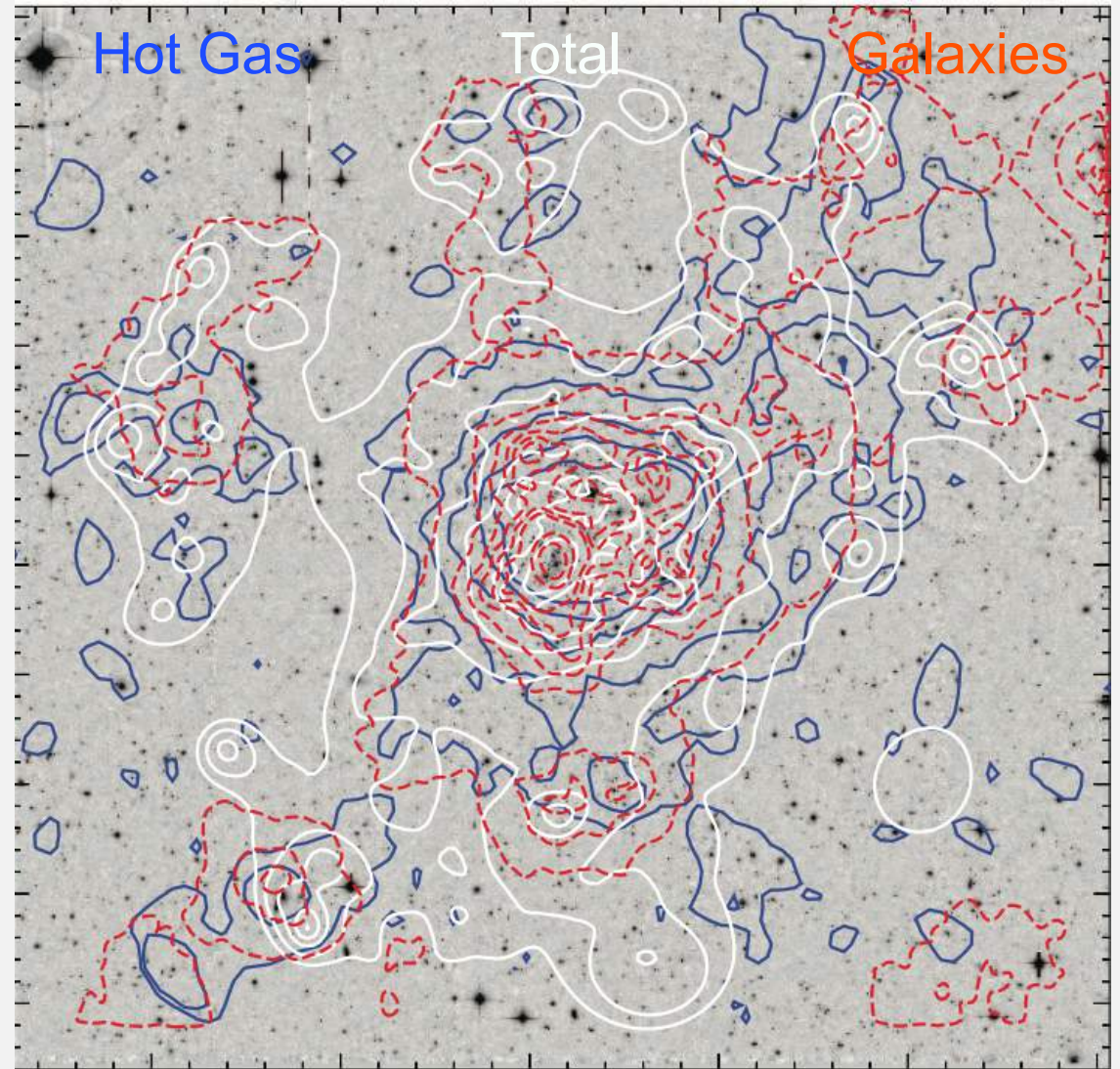
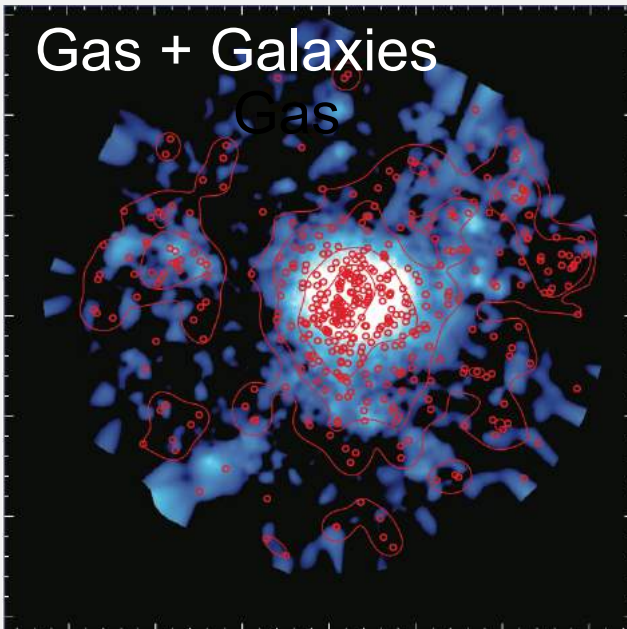
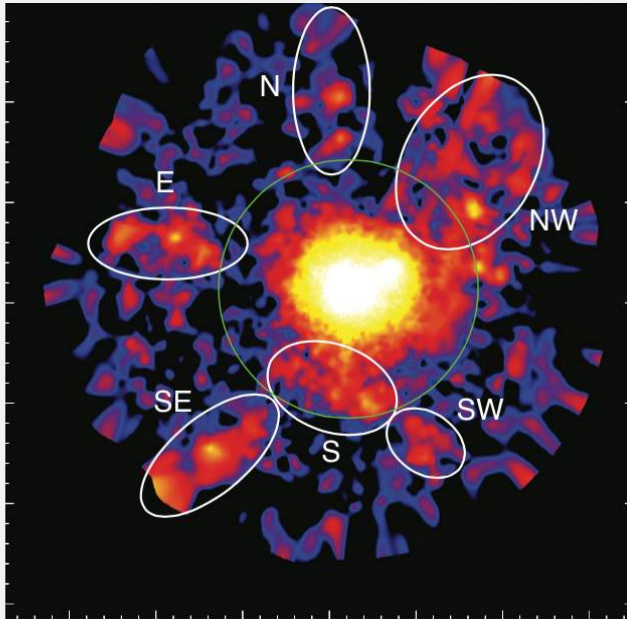
Credit:
D. Eckert; Reiprich et al, 14 & adapted from Roncarelli et al., 2006

Les régions extérieures



Eckert et al., 2015

Les régions extérieures

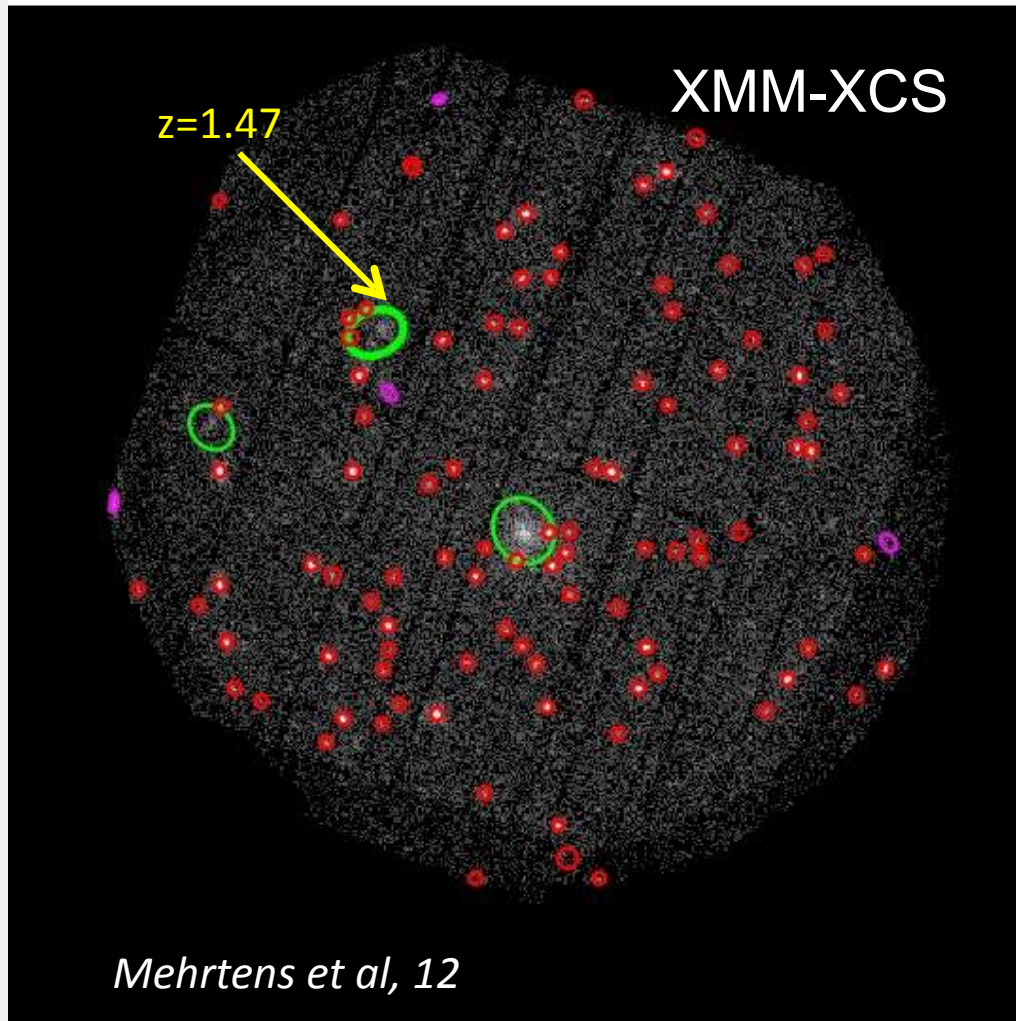


Eckert et al., 2015

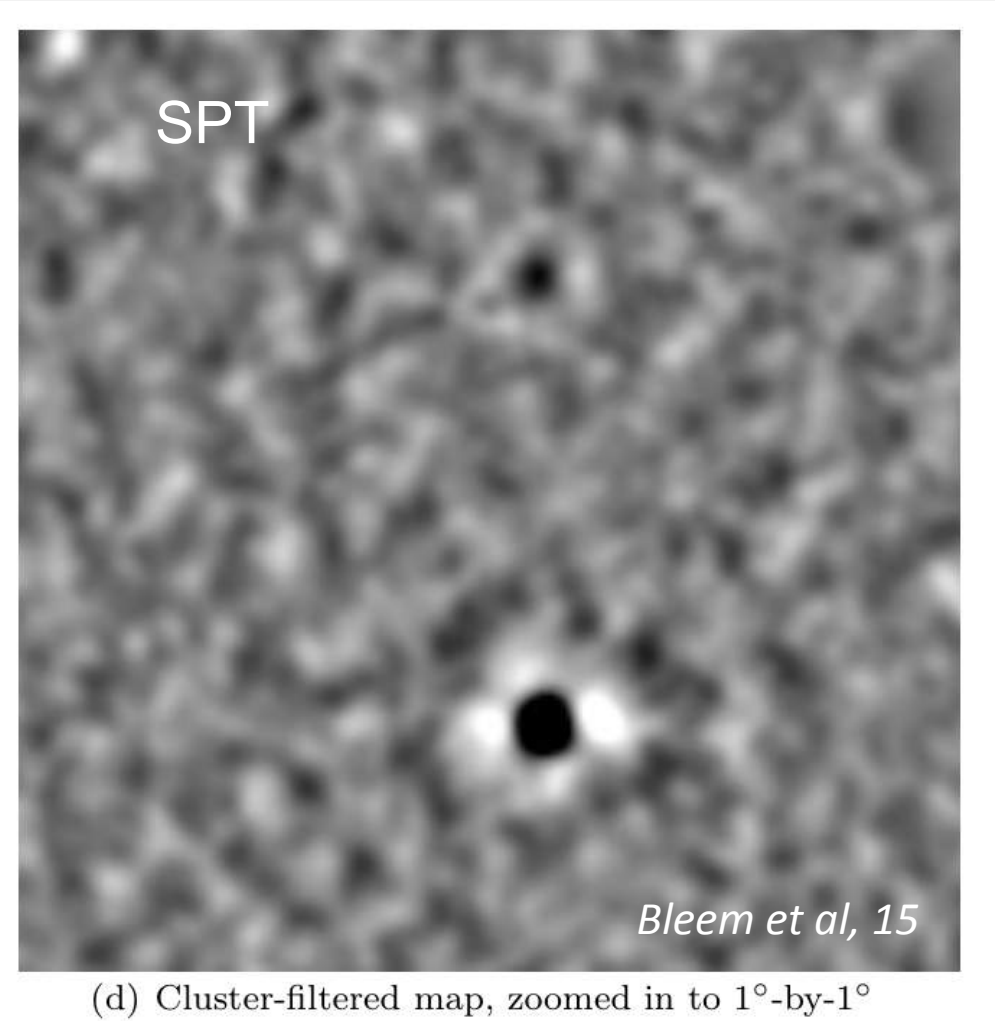
ESO+CFHT+HST

Etude de population

Détection d'amas en X/SZ

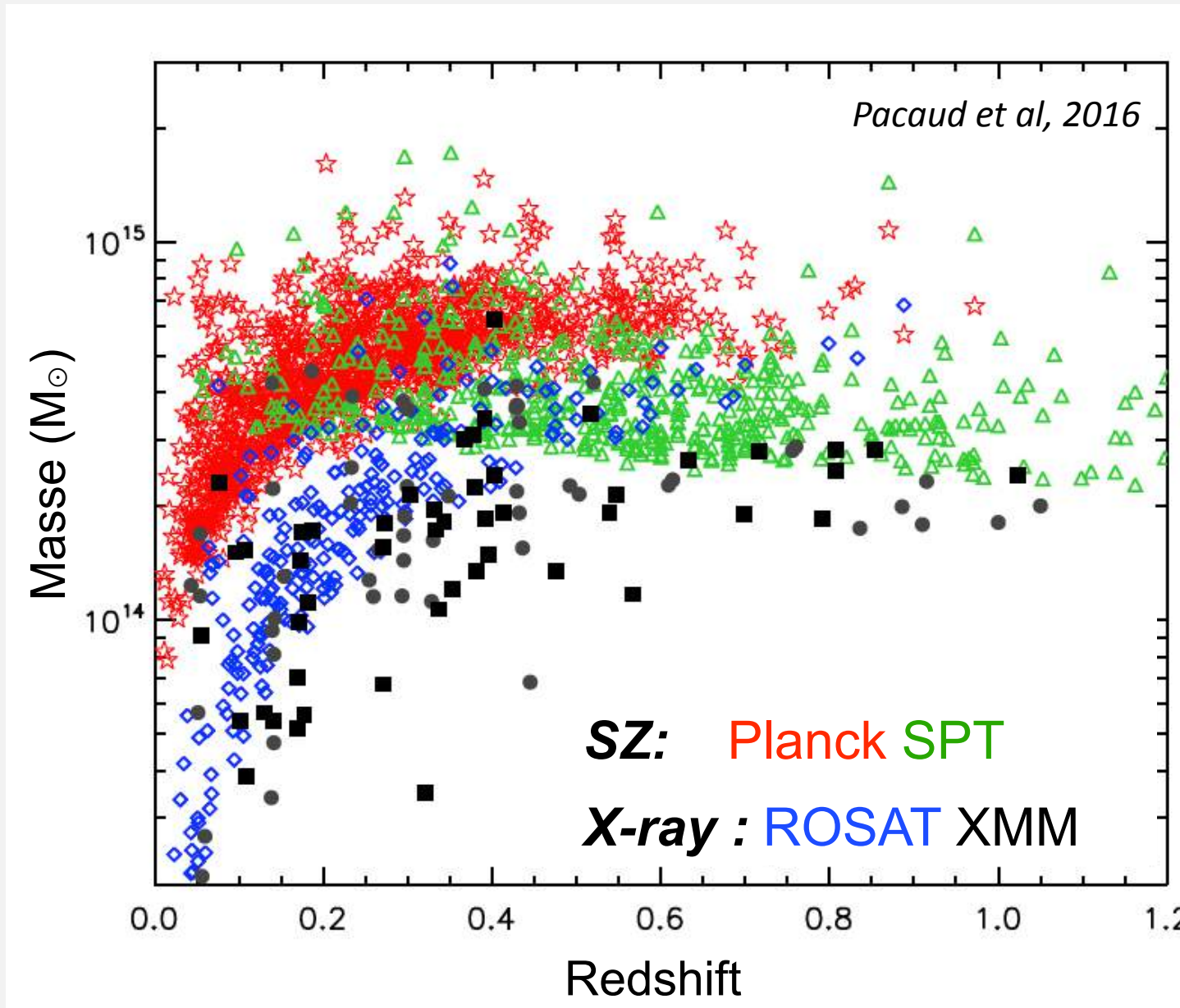


Emission X étendue



Effet SZ : "trou" dans le FDC

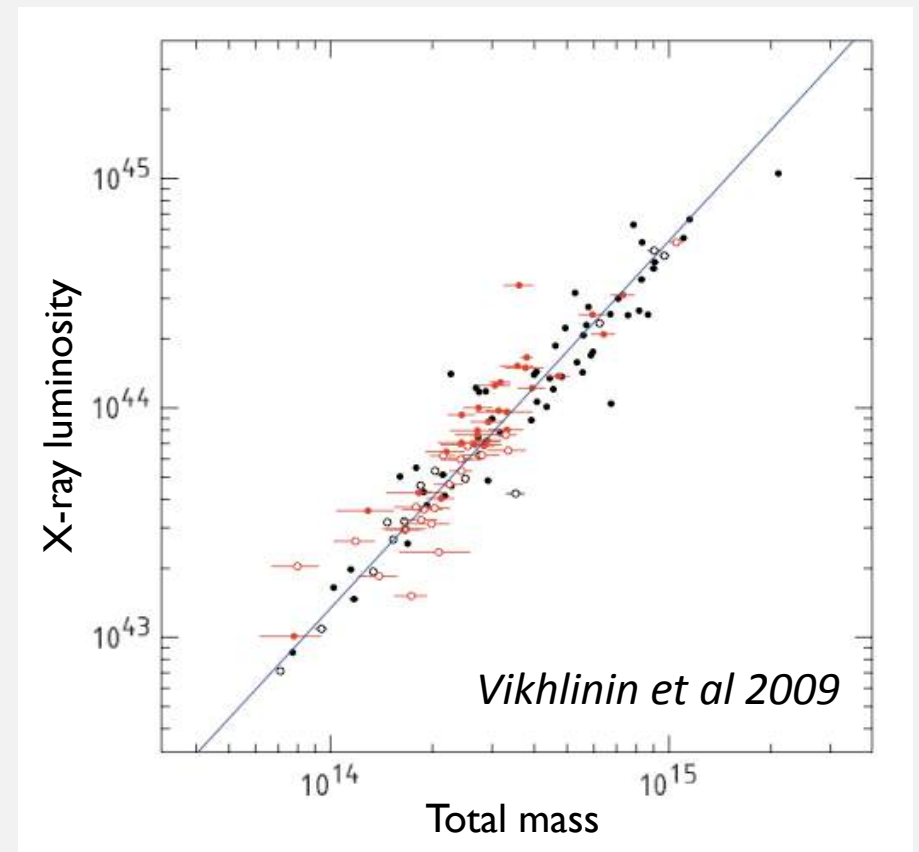
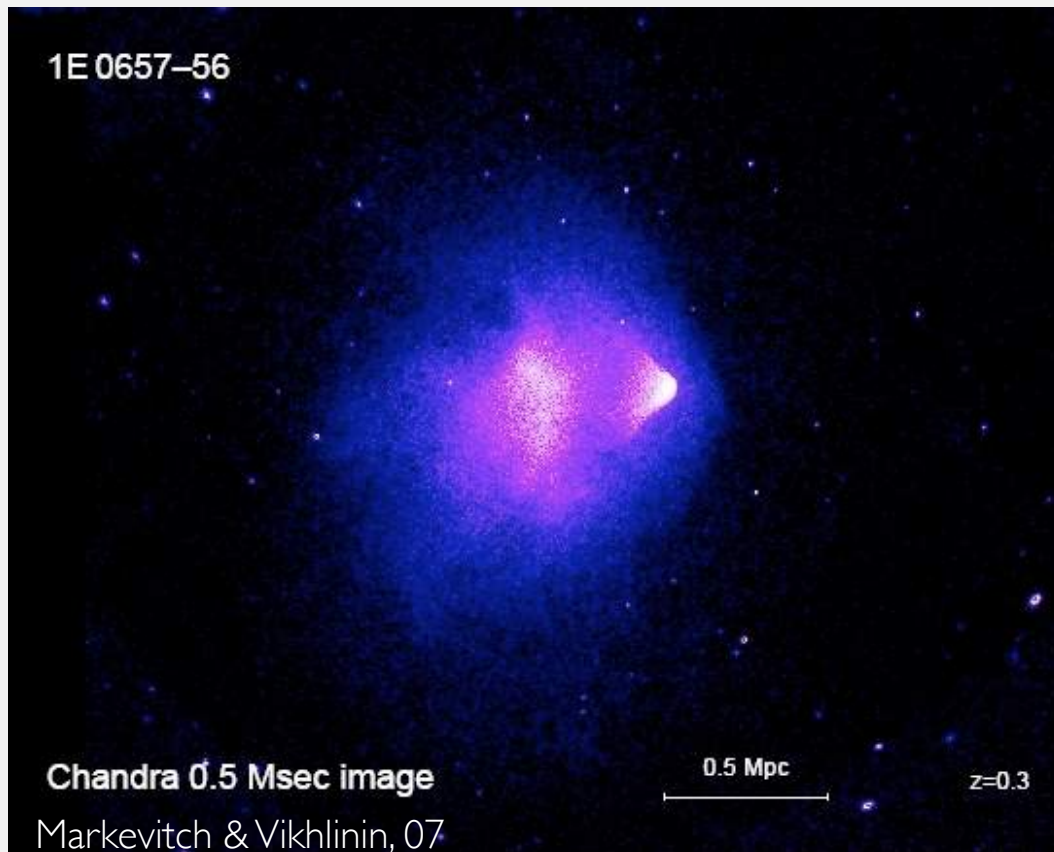
Catalogues d'amas de galaxies



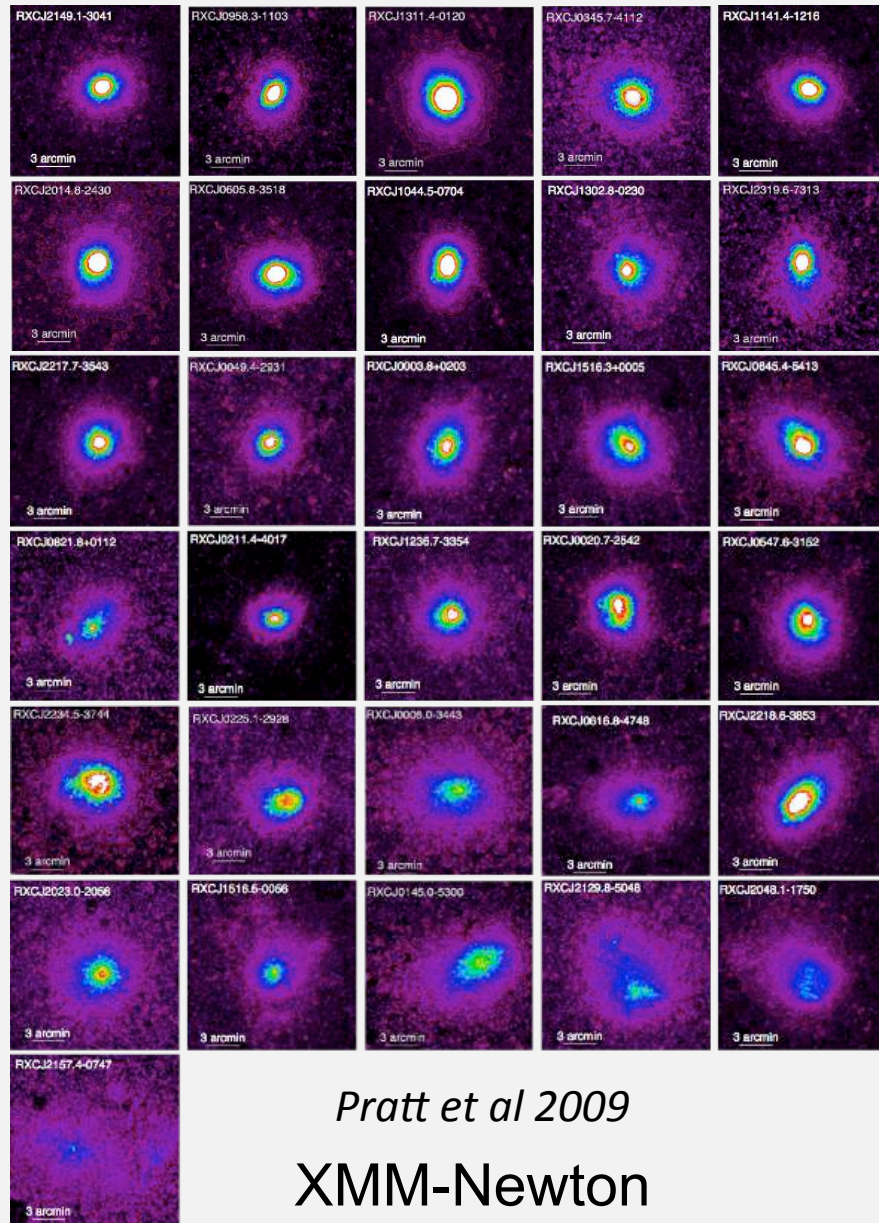
La population d'amas

individuellement complexes

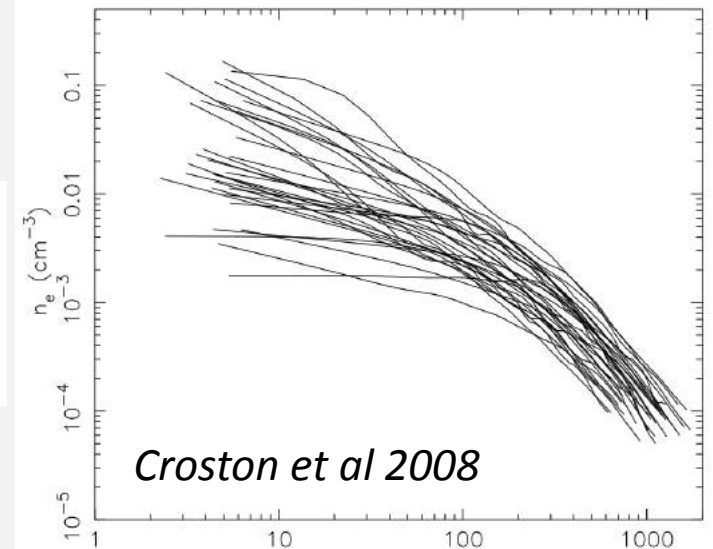
..mais globalement simples



Une certaine similarité

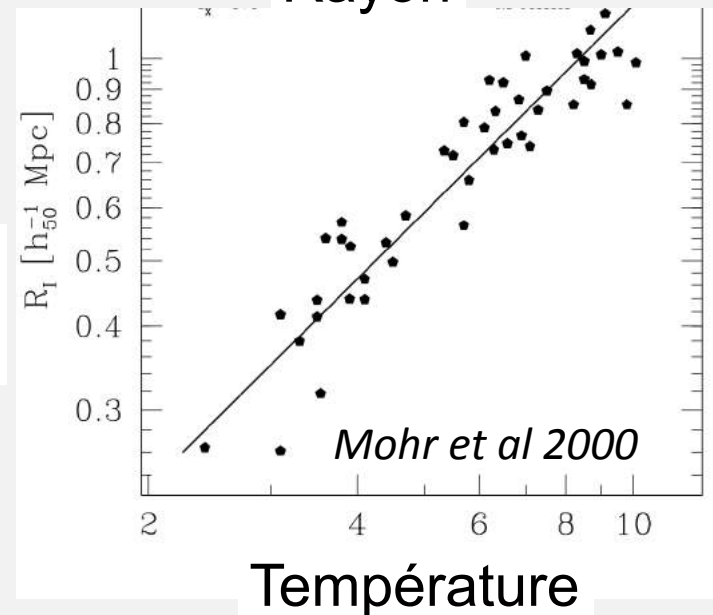


Densité



Rayon

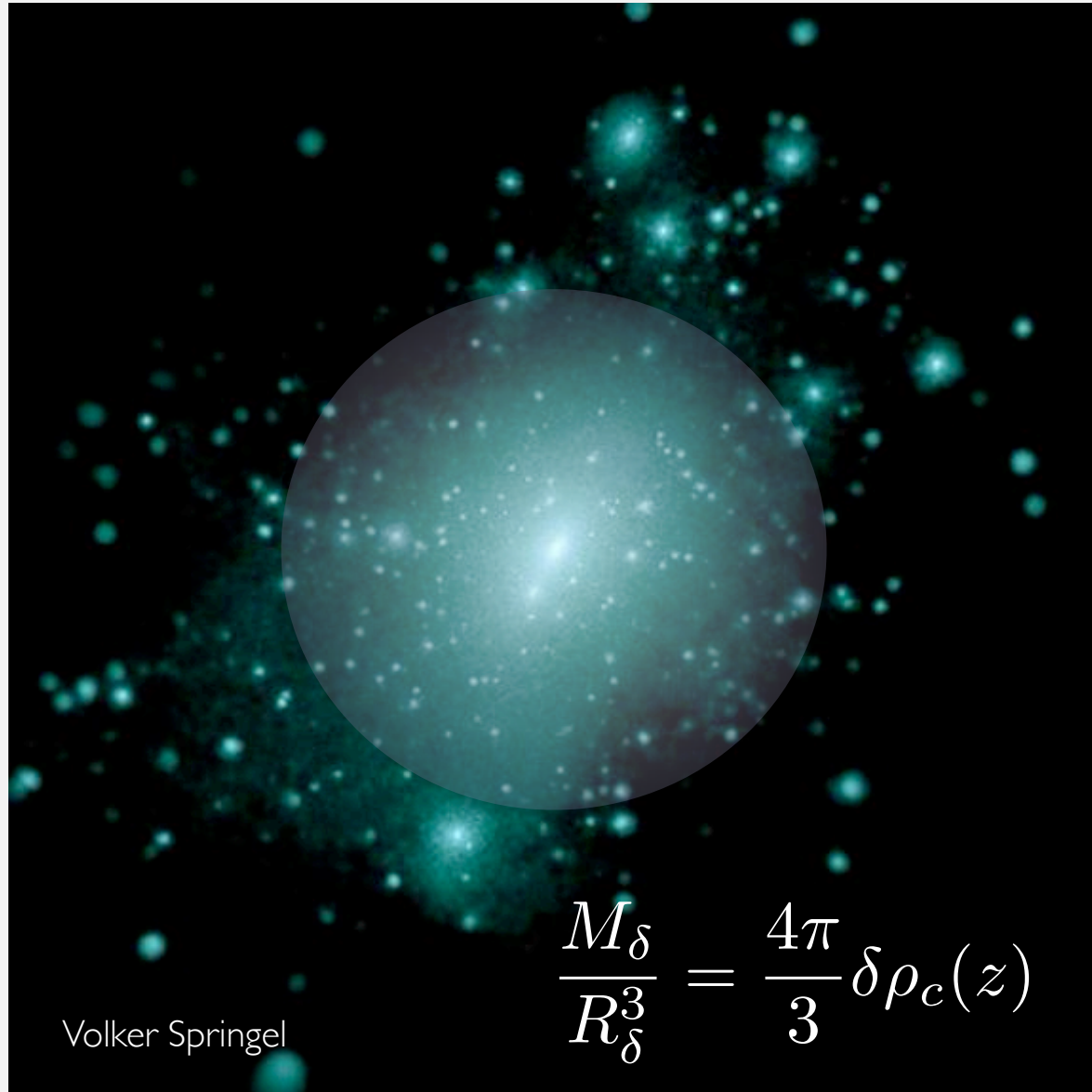
Taille



Température



Le modèle auto-similaire



Le modèle auto-similaire

Gaz évolue dans le potentiel de la matière noire

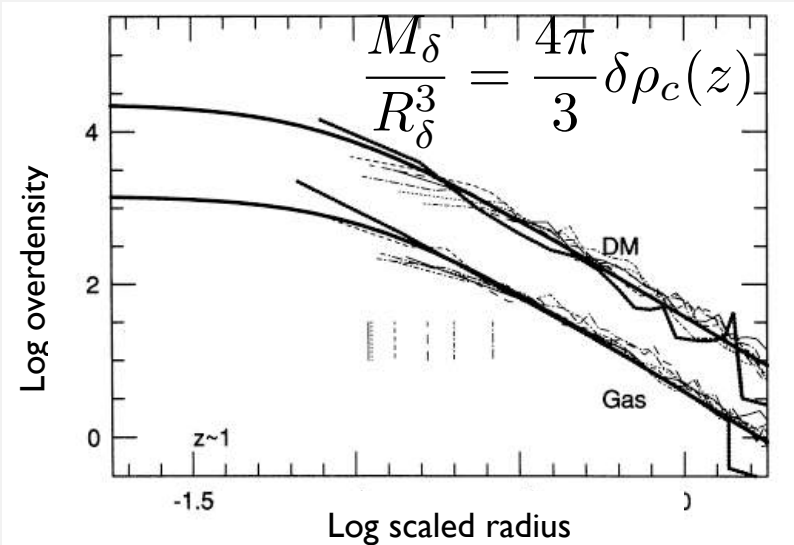
⇒ Equilibre dans le potentiel de la MN

$$kT \propto \frac{GM_\delta}{r_\delta}$$

⇒ Composition 'universelle' $f_{\text{gaz}} = \text{const.}$

$$M_{\text{gaz}} \propto M_\delta$$

Lois d'échelles



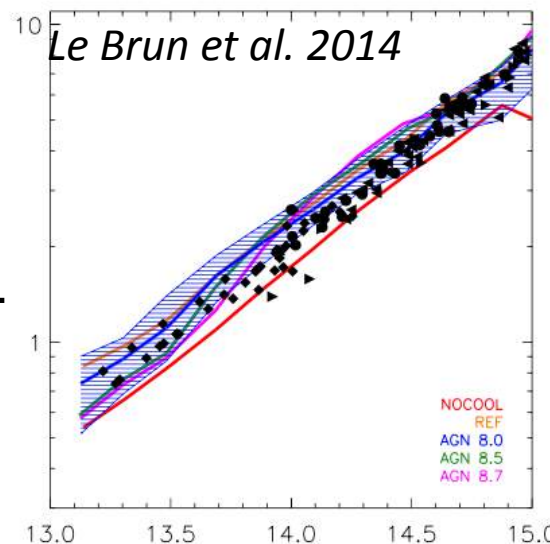
Navarro et al. 1997

Pas d'échelle particulière

Structure interne universelle

(MN et donc gaz)

Temperature

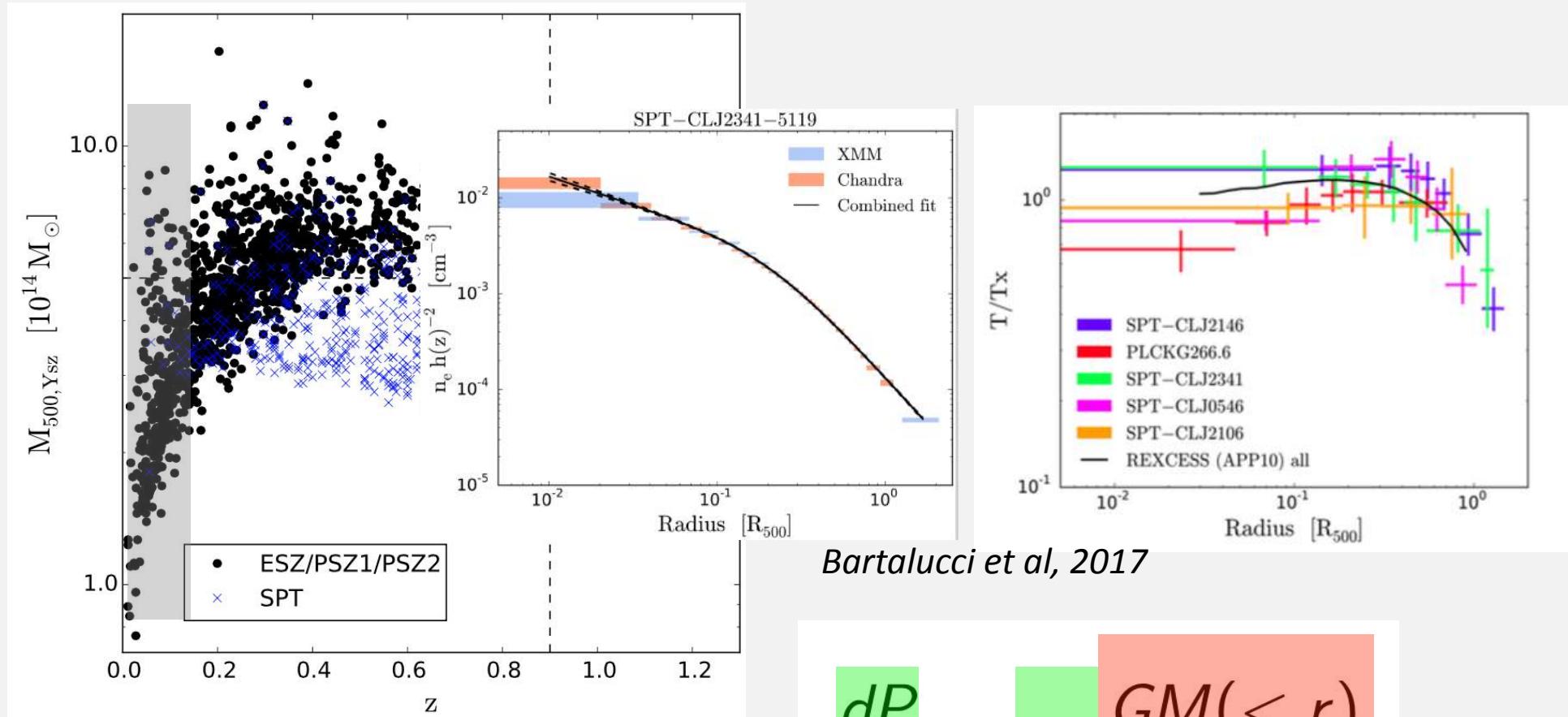


log(Masse [M_\odot])

$$T \propto \frac{M}{R} \propto R^2 \propto M^{2/3}$$



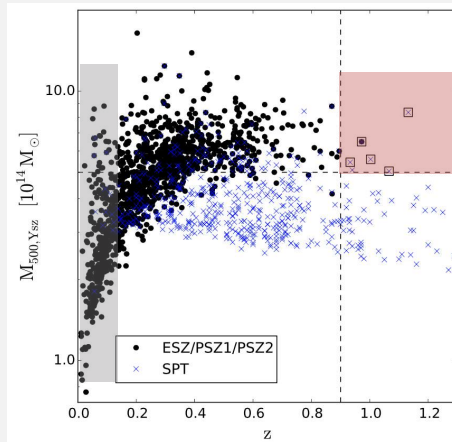
Tester le modèle auto-similaire



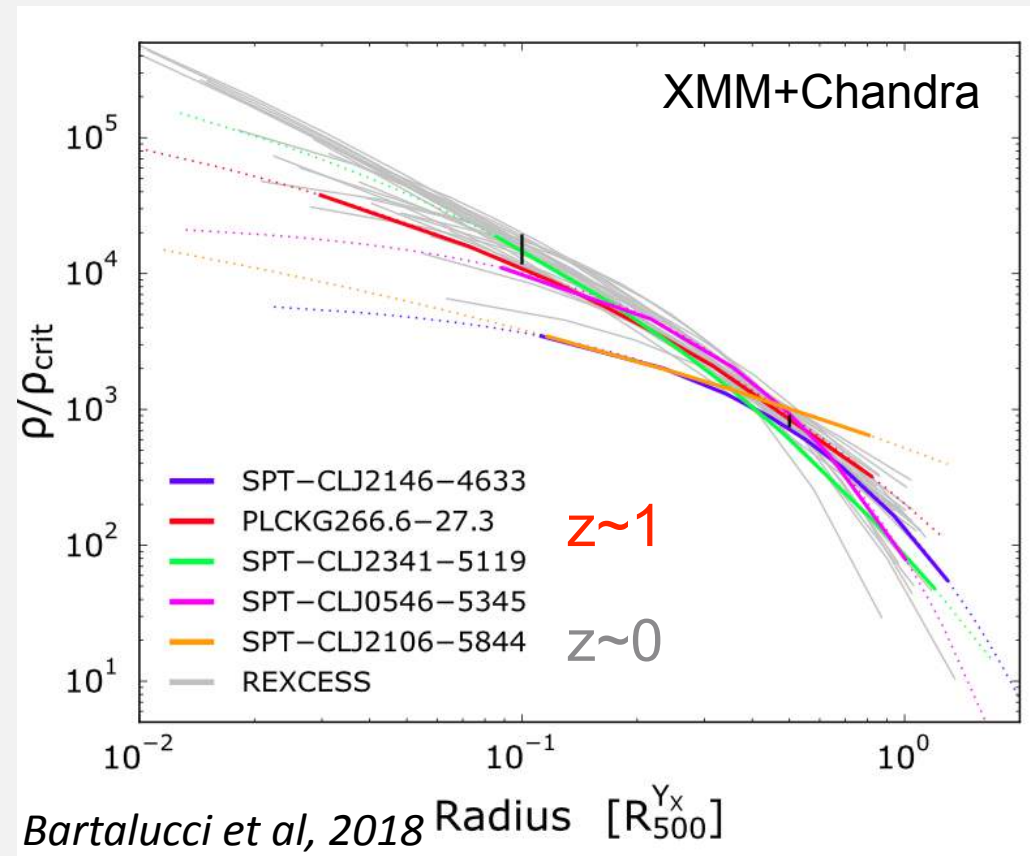
Bartalucci et al, 2017

$$\frac{dP}{dr} = -\rho \frac{GM(< r)}{r^2}$$

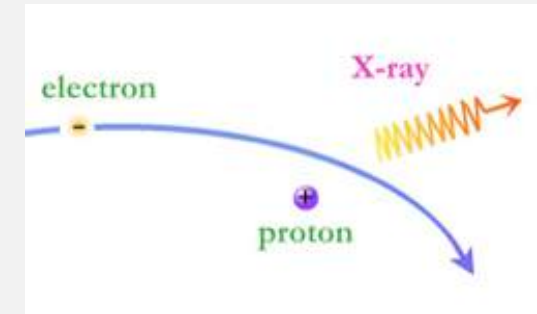
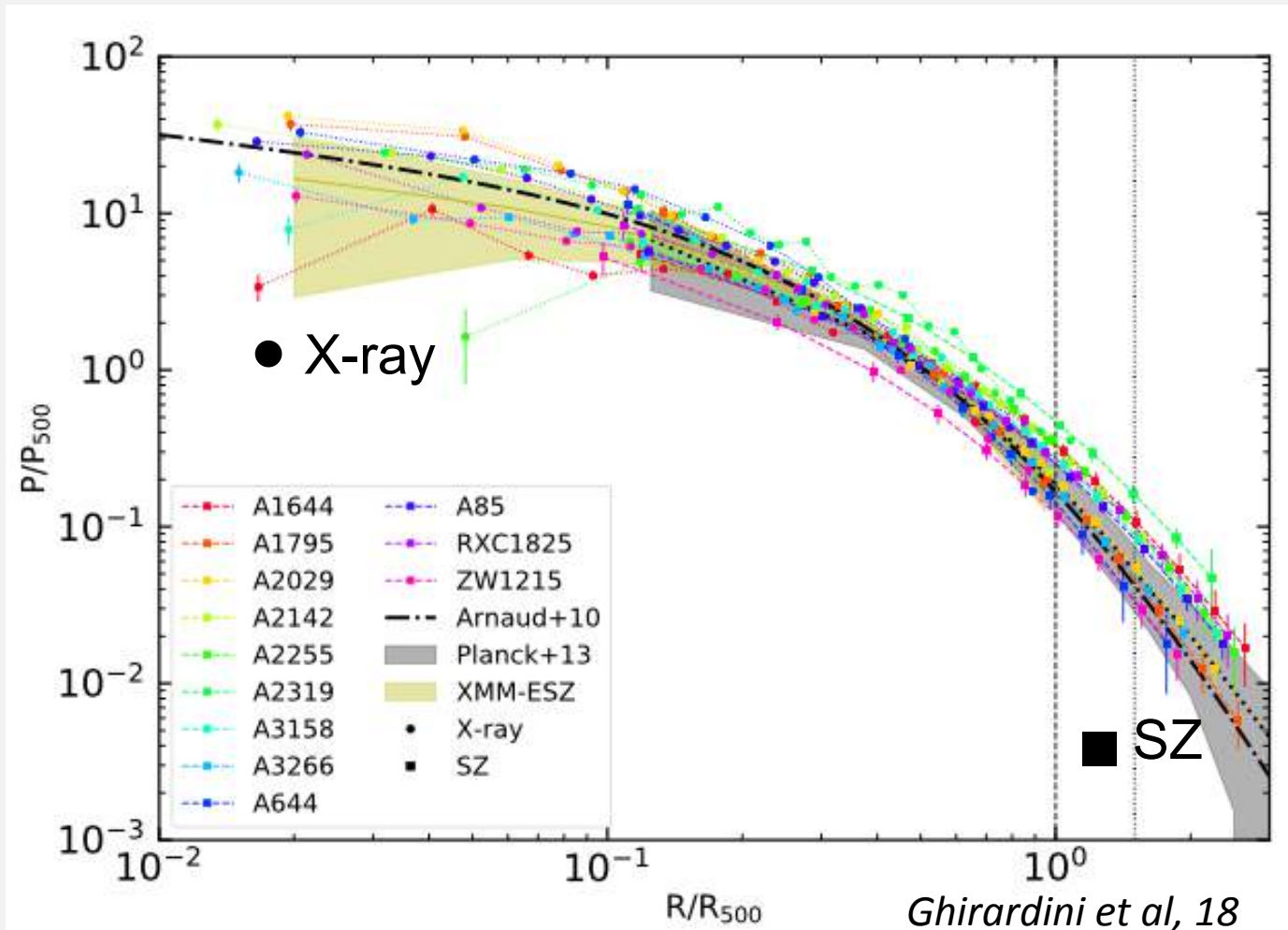
La distribution de masse (MN)



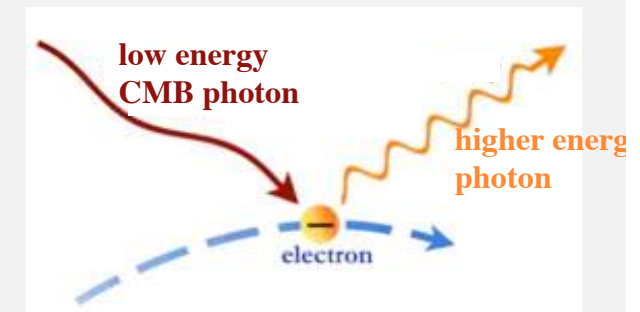
Universelle jusqu'à grand redshift



jusque dans les régions extérieures



$$S_X \propto \int_{los} n_e^2 \Lambda(T) dl$$



$$y_{SZ} \propto \int_{los} (P = n_e T) dl$$

Cohérence des mesures de masse

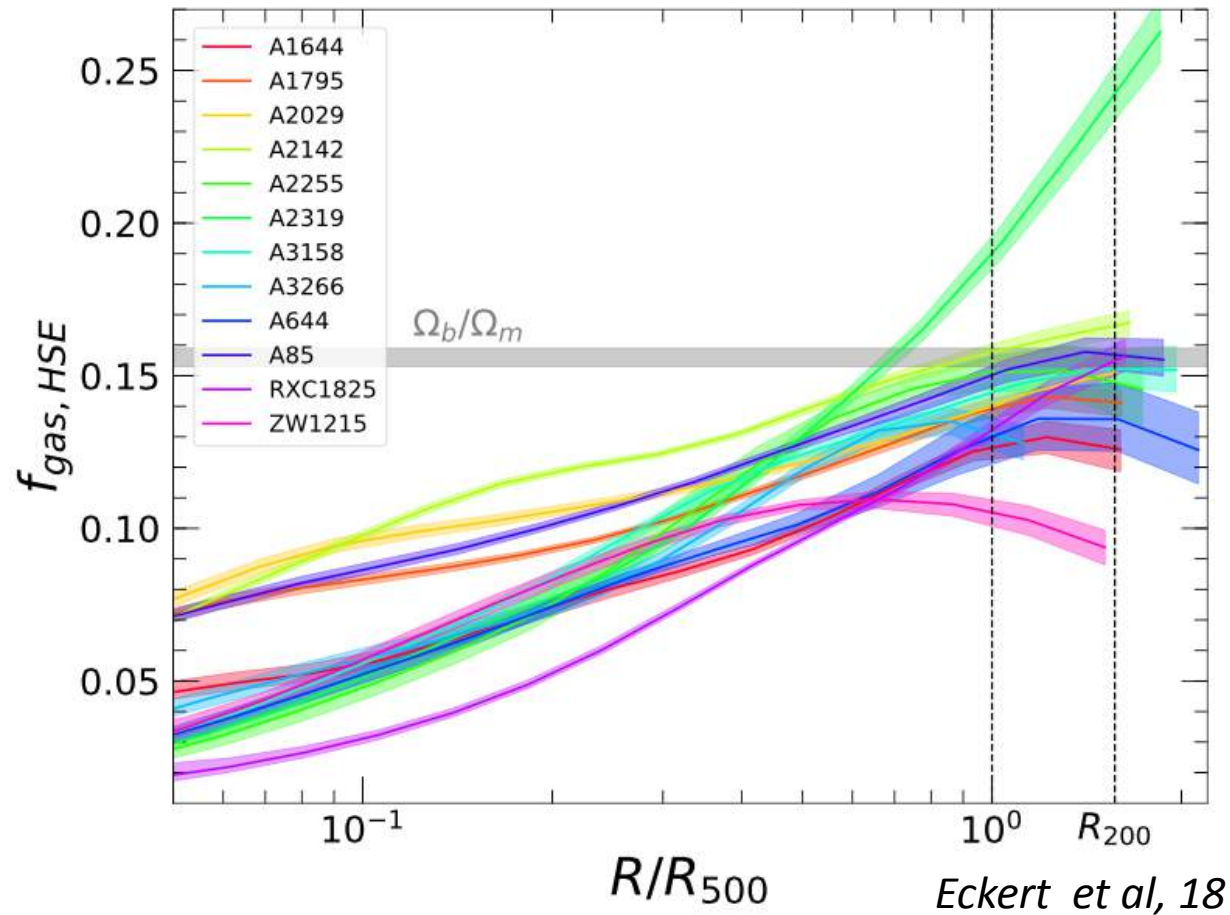


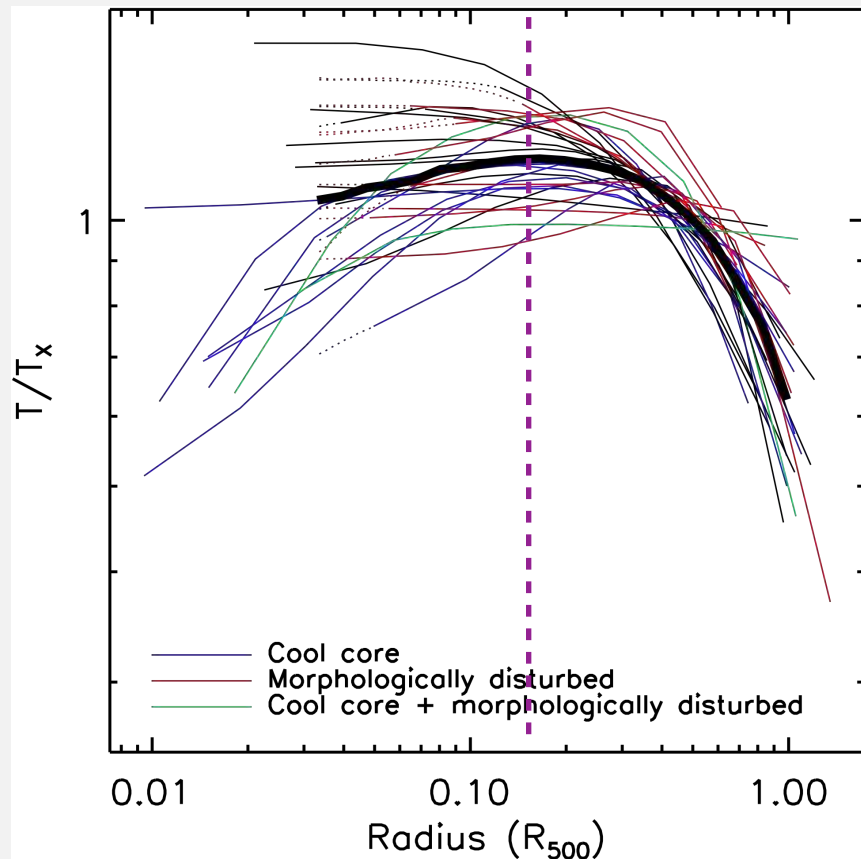
Fig. 1. Hydrostatic gas fraction profiles $f_{\text{gas, HSE}}(R) = M_{\text{gas}}(< R)/M_{\text{HSE}}(< R)$ as a function of scale radius R/R_{500} for the X-COP clusters. The gray shaded area shows the *Planck* universal baryon fraction Ω_b/Ω_m (Planck Collaboration XIII 2016).

Fraction de gaz
universelle

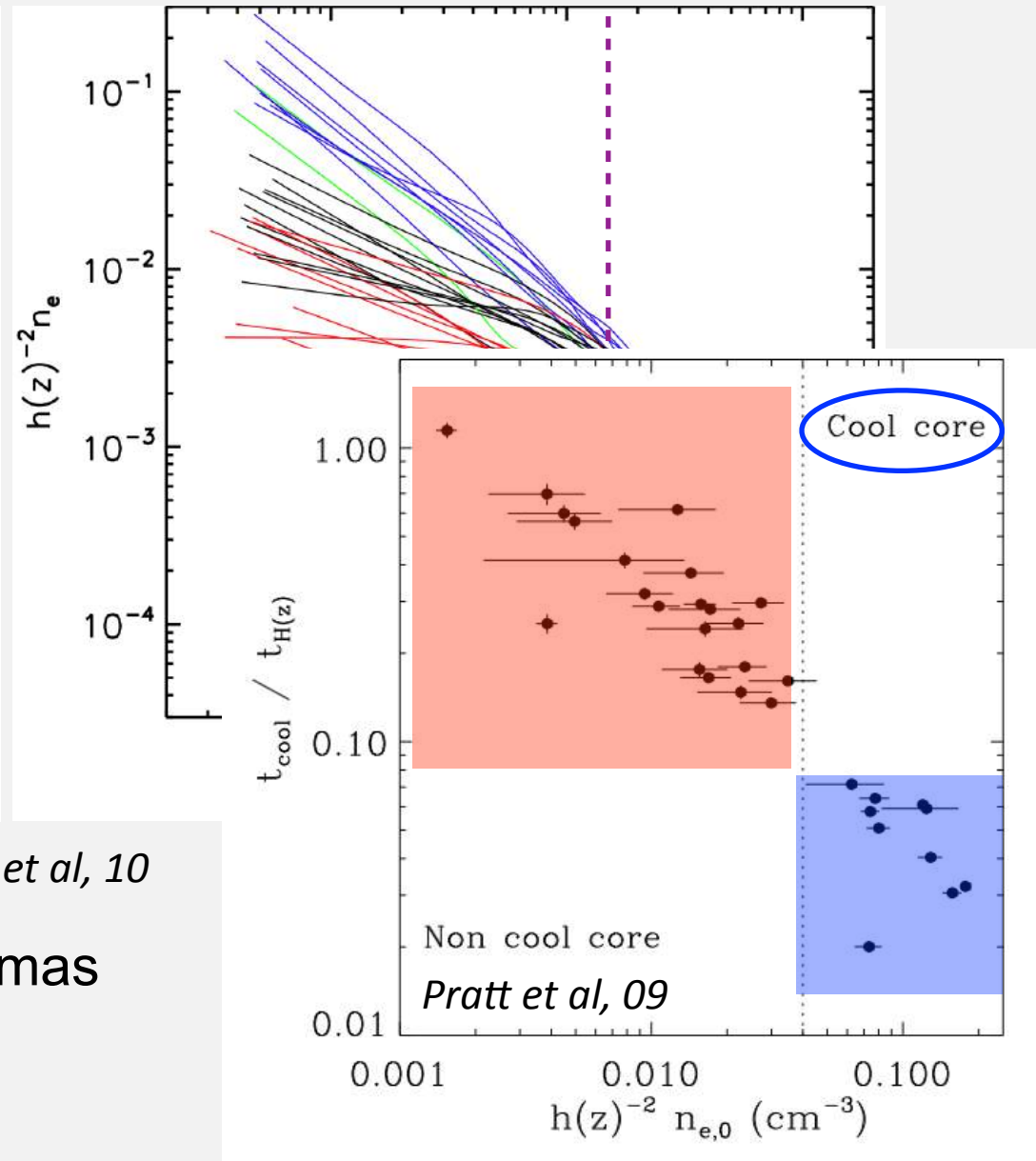
Peu d'écart à
l'équilibre
hydrostatique du
gaz

Estimation de
masse correcte

Ecart à l'auto-similarité

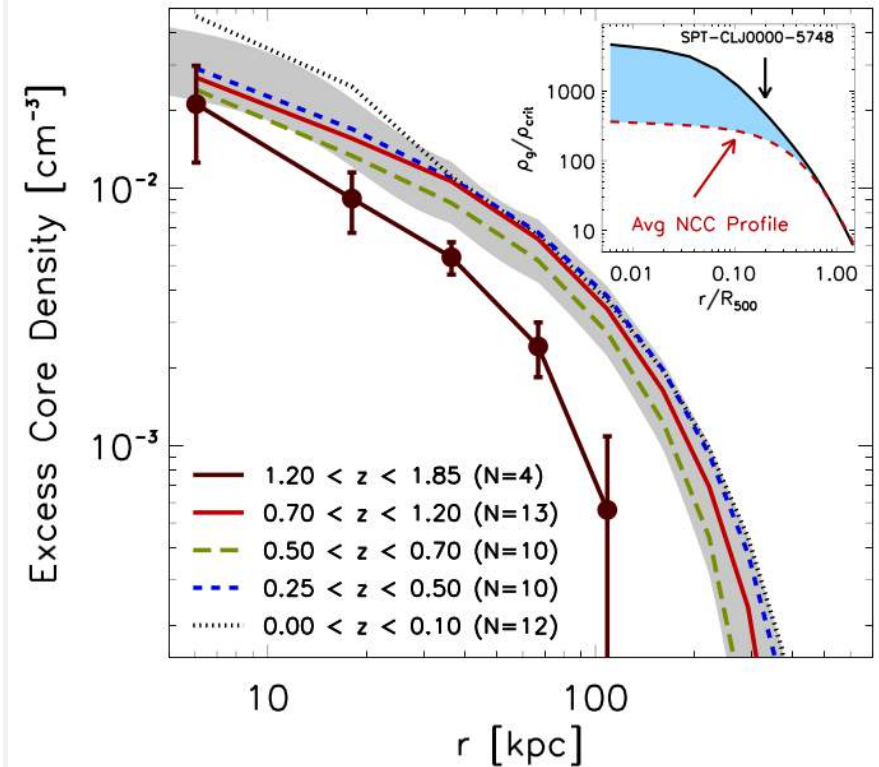
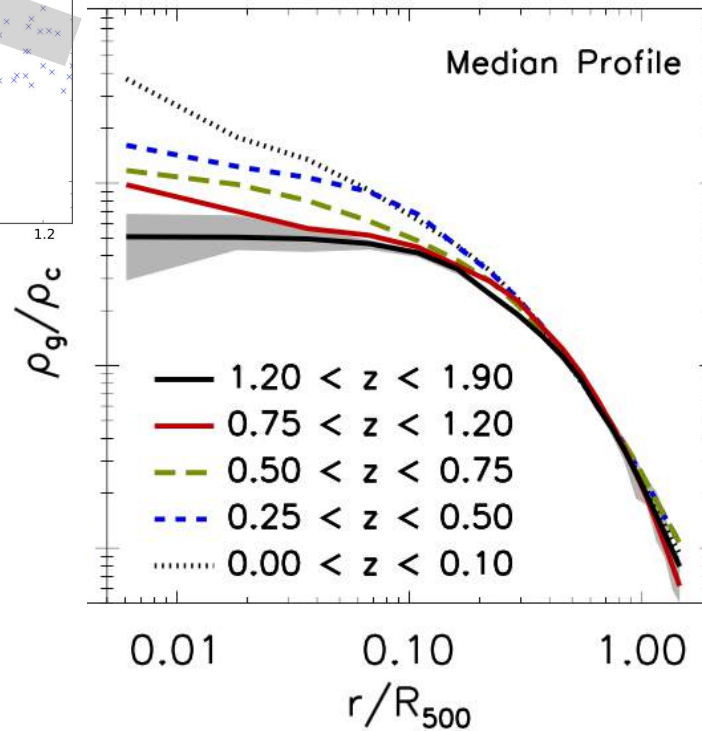
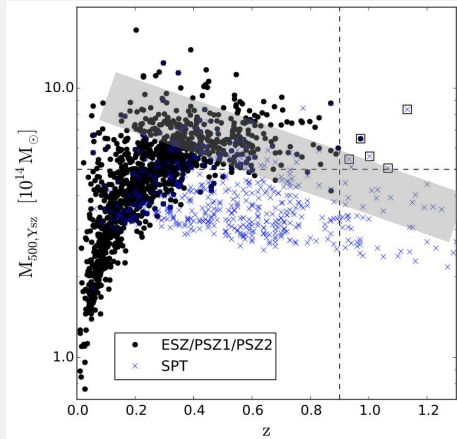


Arnaud et al, 10



Refroidissement au centre des amas

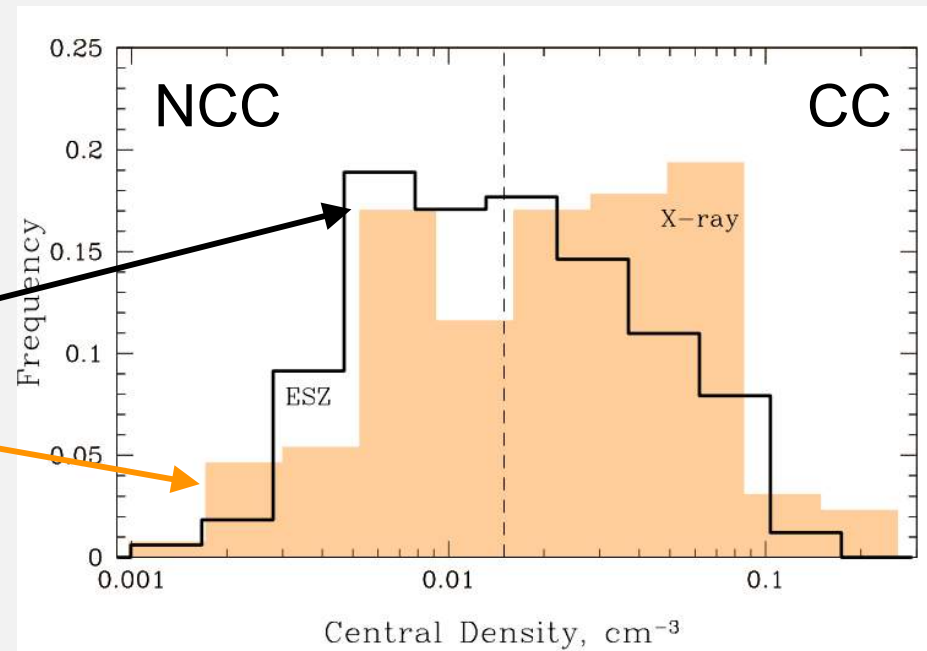
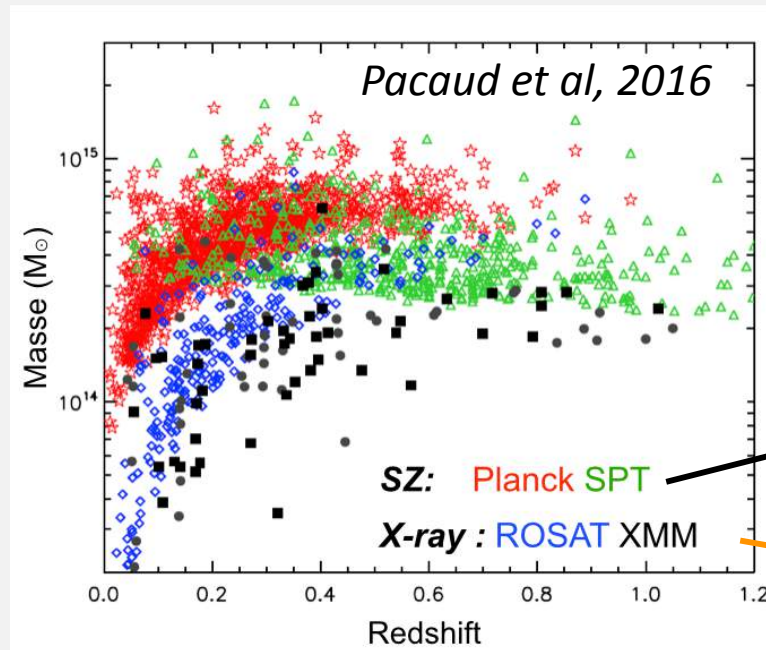
Evolution des coeurs froids



McDonald et al., 14, 17

Distribution auto-similaire + coeur froid constant
 équilibre refroidissement/chauffage établi très tôt

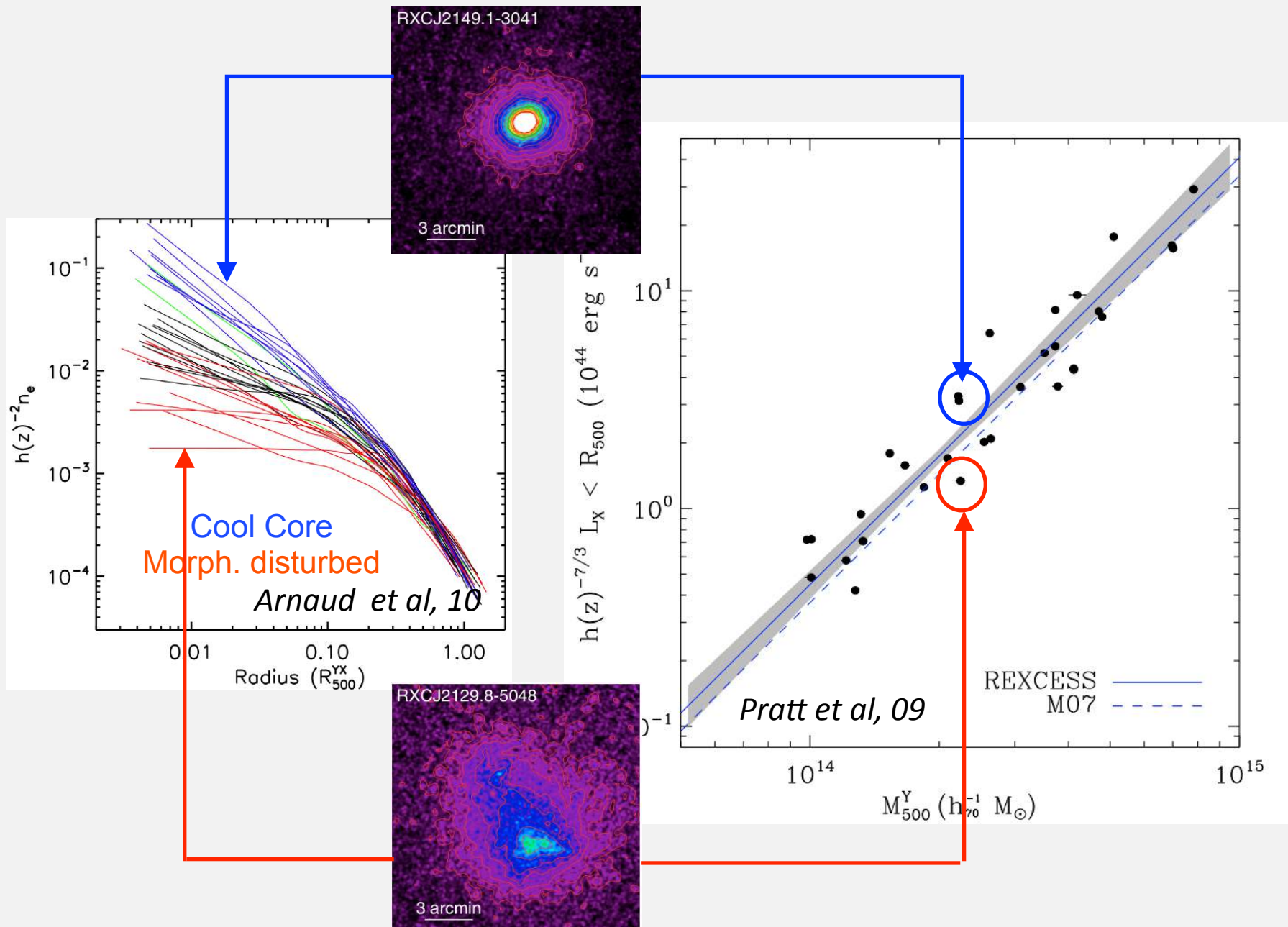
Effets de sélection



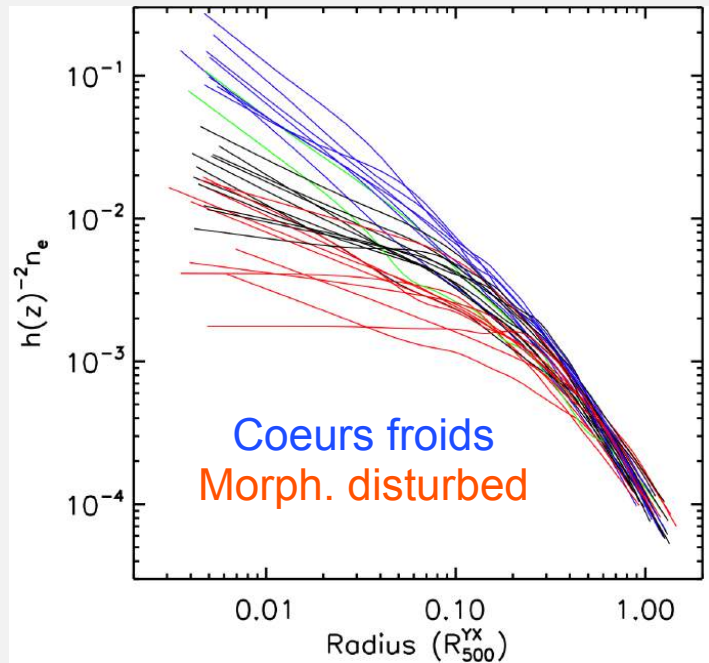
Andrade-Santos et al 17

Quelle est la vraie population d'amas ?

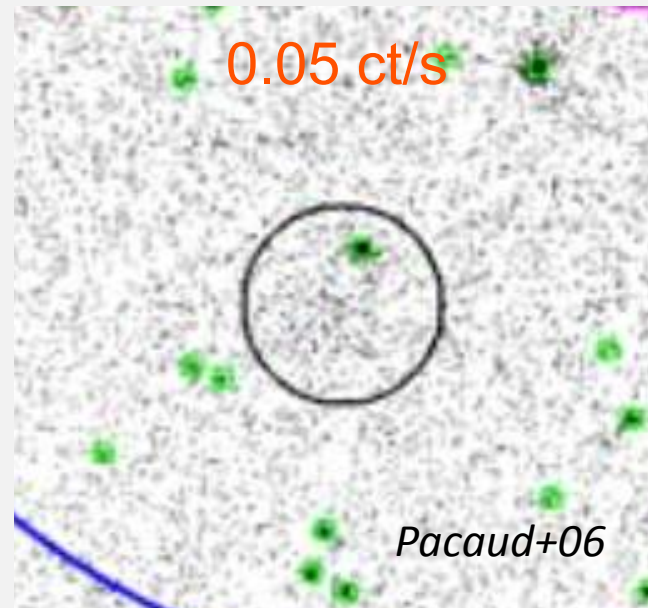
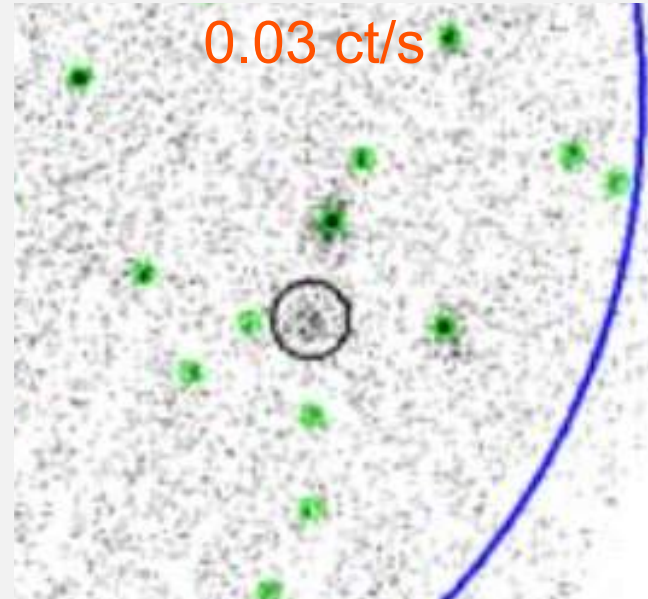
Luminosité & morphologie



Morphologie & détectabilité



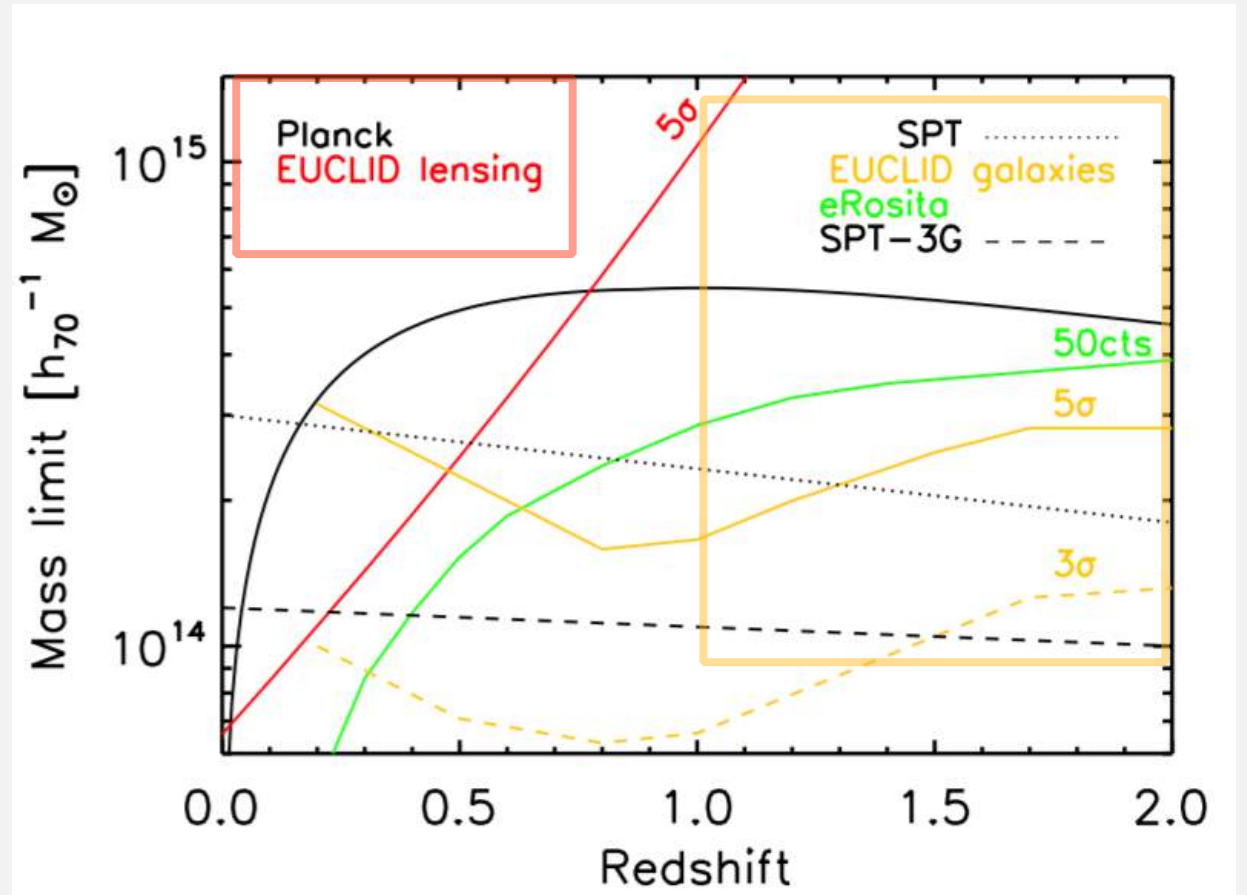
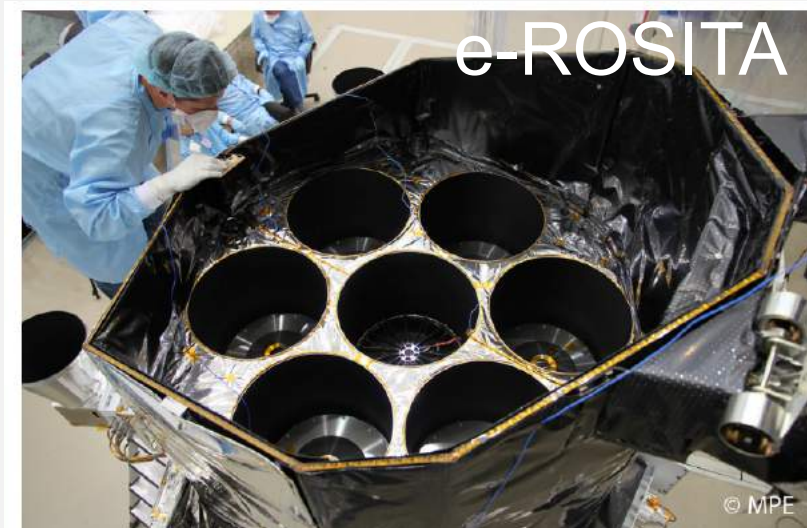
Arnaud et al, 10



Pacaud+06

Le futur

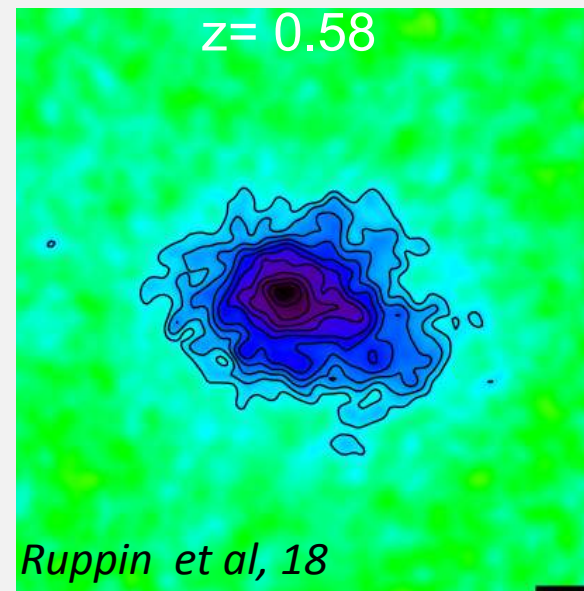
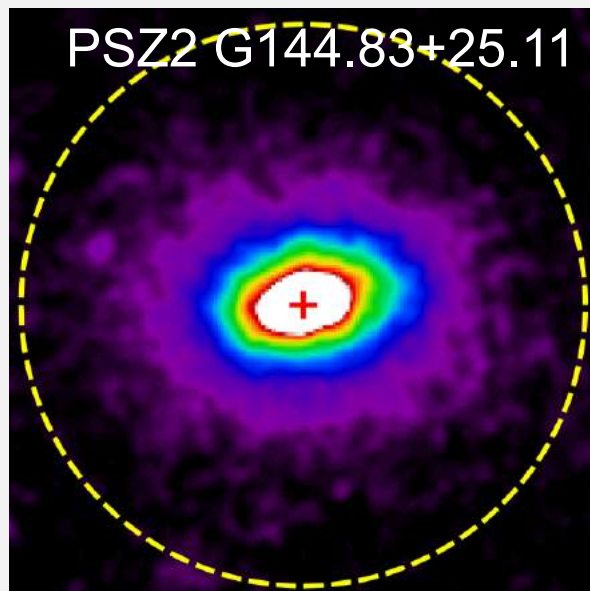
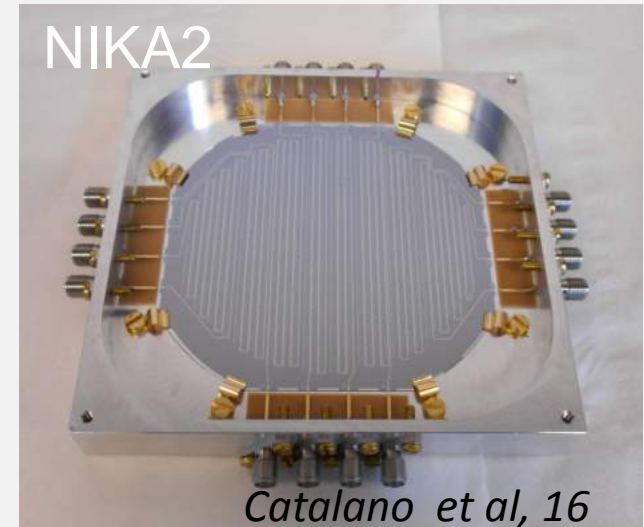
Les nouveaux relevés



From: Pillepich+12, Sartoris+16, Planck 2015 results XXVII, J Bartlett priv. comm., B.Benson invited talk

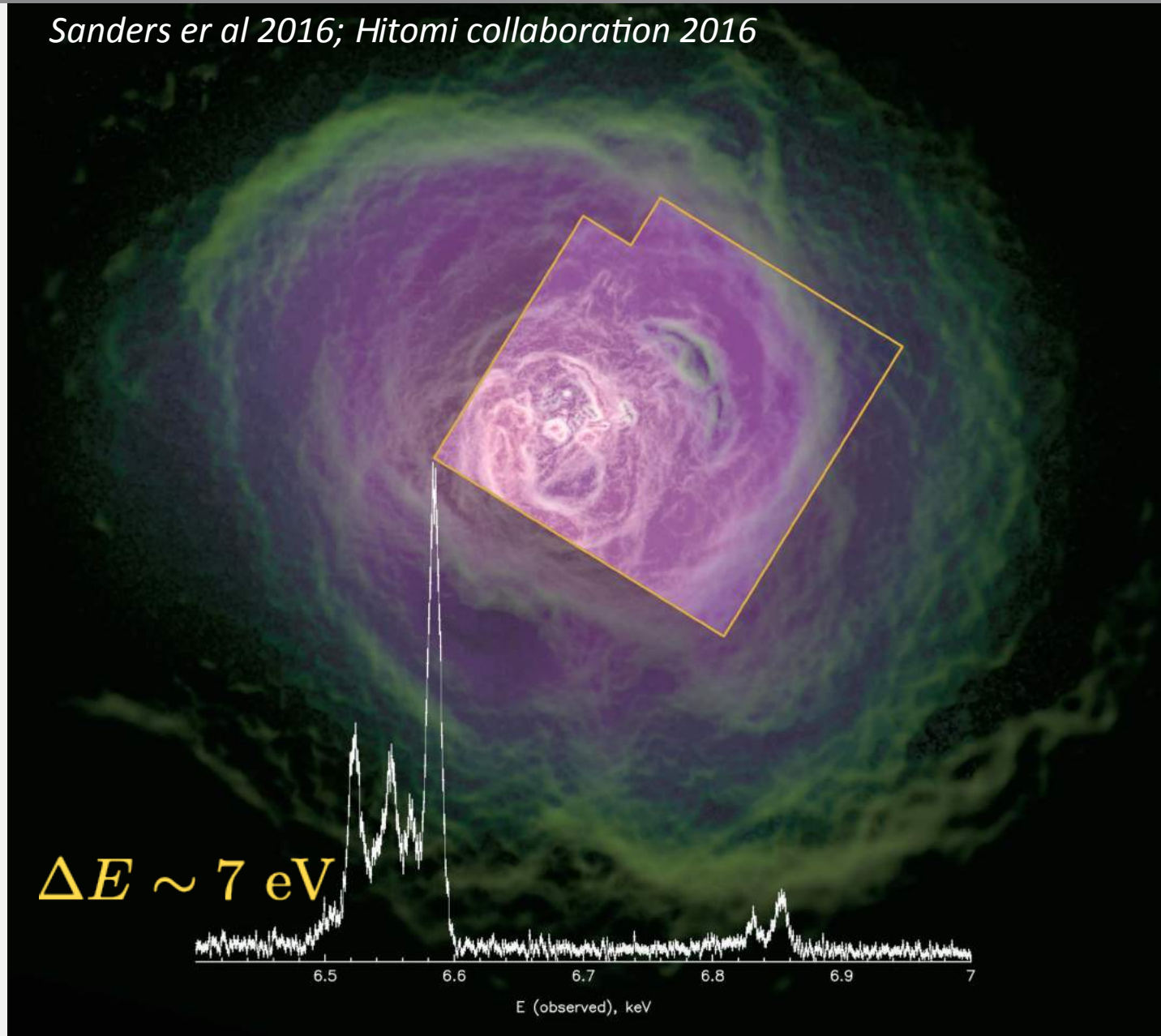
Effets de sélection et évolution

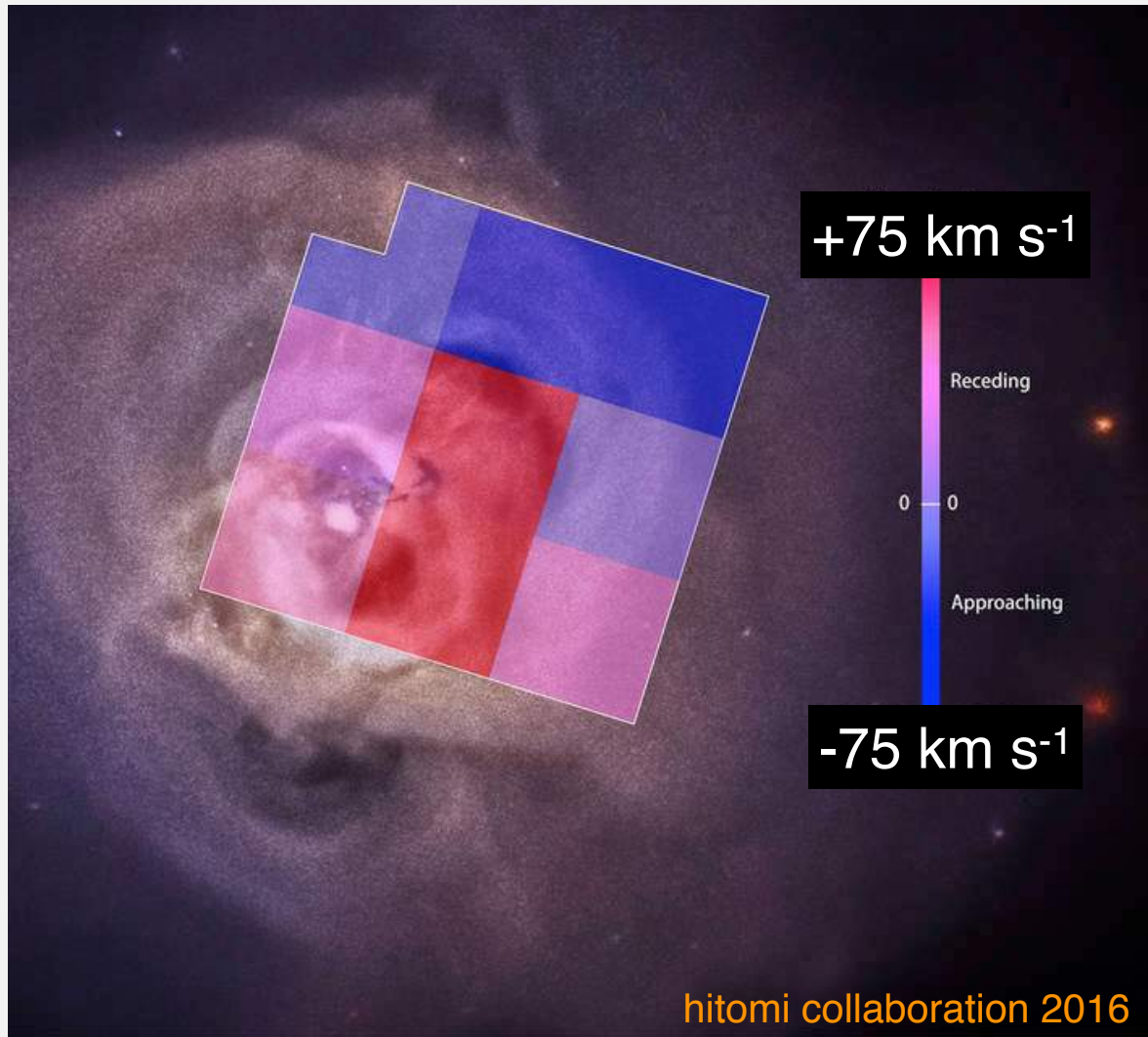
Combiner observations X et SZ



Spectroscopie à haute résolution

Sanders et al 2016; Hitomi collaboration 2016





The Advanced Telescope for High-ENergy Astrophysics

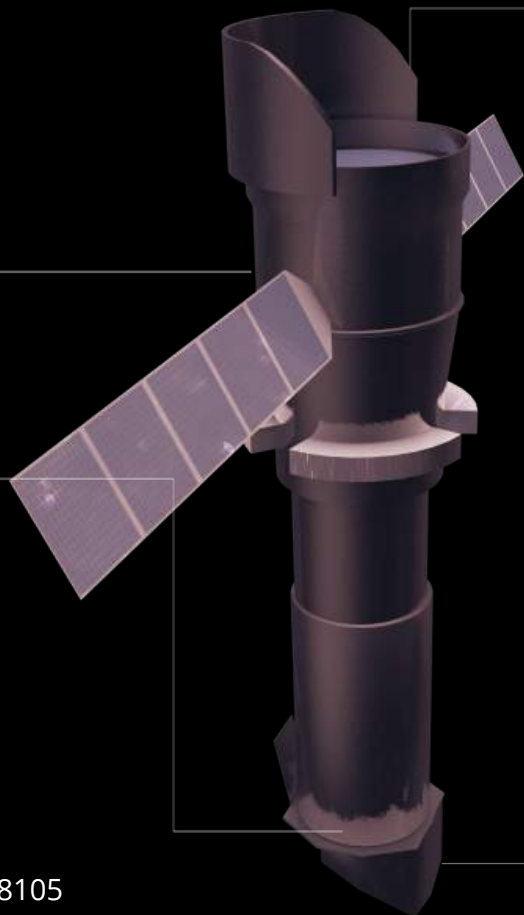
Athena

L2 orbit Ariane 6.4



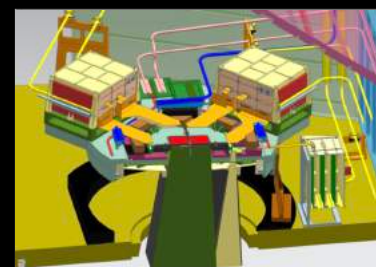
X-ray Integral Field Unit:
 ΔE : 2.5 eV
Field of View: 5 arcmin
Operating temp: 50 mk

Barret et al. 2016 arXiv:1608.08105



Silicon Pore Optics:
1.4 m²@1 keV; 0.17 m² @ 7 keV
5 arcsec HEW
Focal length: 12 m
Sensitivity: $3 \cdot 10^{-17}$ erg cm⁻² s⁻¹

12m

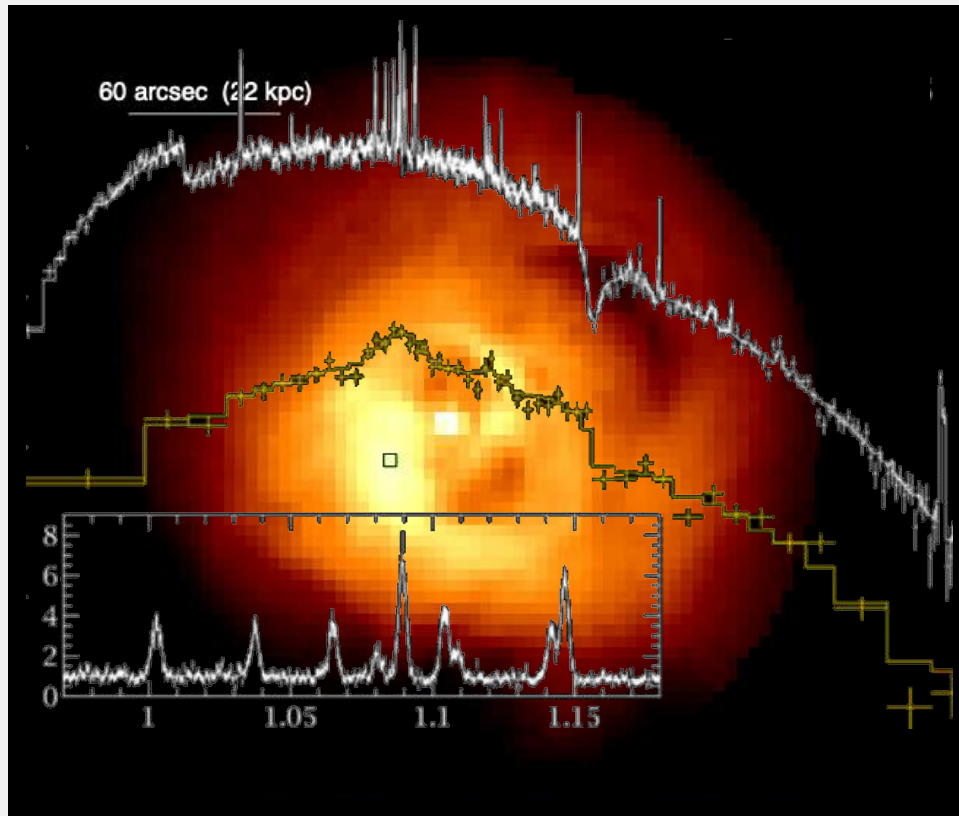


Wide Field Imager:
 ΔE : 125 eV
Field of View: 40 arcmin
High countrate capability

Rau et al. 2013 arXiv1307.1709

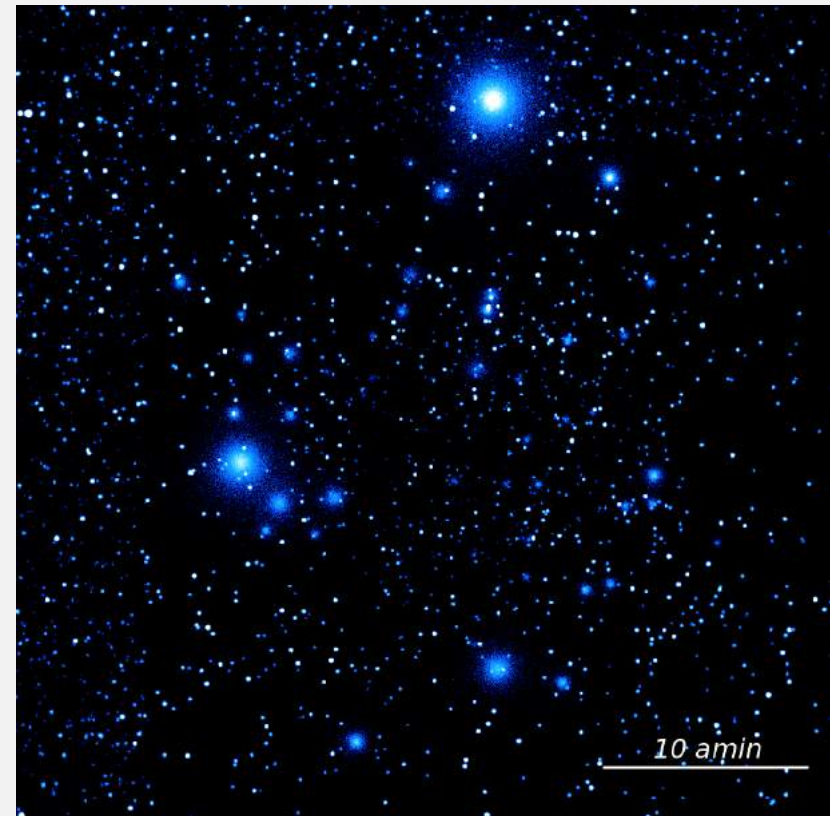
ATHENA

Spectro-imagerie à haute résolution



Croston, Sanders et al 2013

Imagerie grand champ



A. Rau / T. Dauser / J. Wilms / T. Brand

Conclusions

- Etude des amas en rayons X: observer le gaz chaud intra-amas
 - ⇒ Comprendre la physique de formation des structures (MN, gas, *)
 - ⇒ Comparaison observations/simulations et simulation/observations
- L'état et l'histoire d'un amas particulier est compliquée
 - ⇒ chauffage complexe du gaz dans le potentiel MN (choc, ondes etc..)
 - ⇒ processus physique additionnels (refroidissement etc..)
- Mais la population d'amas est relativement simple
 - ⇒ Formation et évolution régie d'abord par la gravitation (MN)
 - ⇒ Population ~ auto-similaire
 - ⇒ Attention aux effets de sélection !