# Galaxy Cluster science with XRISM

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# Outline

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Introduction

Thermal processes

Gas motions

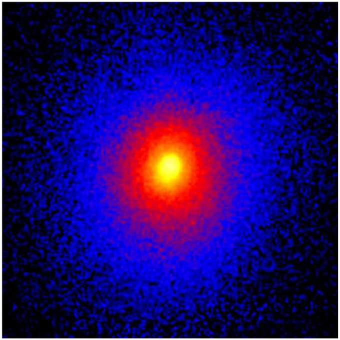
Metal enrichment

Abell 2744, JWST

# The intracluster medium (ICM)

Abell 1835 ($z = 0.25$)

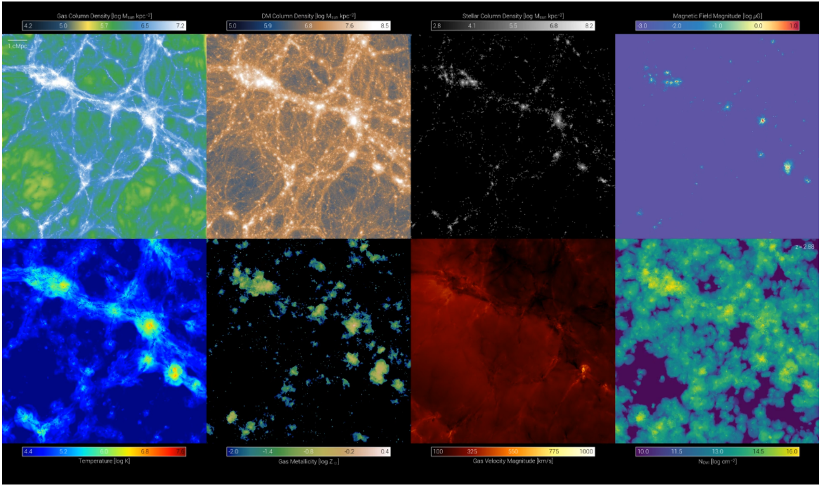
X-ray



Optical

Galaxy clusters are filled with a hot ($10^7 - 10^8$ [K]), low density gas ($n_e \sim 10^{-4} - 10^{-2}$ [cm$^{-3}$]) which traces the dark matter halo

# Hot gas in large-scale structures




Illustris TNG Simulation

Most of the baryons in the Universe are so hot that they will probably never form stars

# Hydrostatic equilibrium

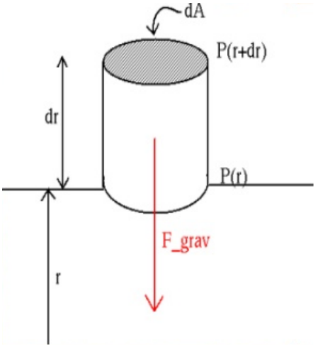
The dynamics of an inviscid, collisional fluid is described by the Euler equation

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{1}{\rho}\nabla P = -\nabla \Phi$$

In case the gas is at rest in a spherically symmetric potential well, it reduces to the hydrostatic equilibrium equation,

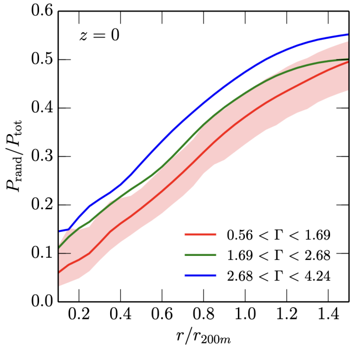
$$\frac{dP}{dr} = -\rho \frac{d\Phi}{dr}$$

The pressure gradient induces a repulsive force which balances gravity

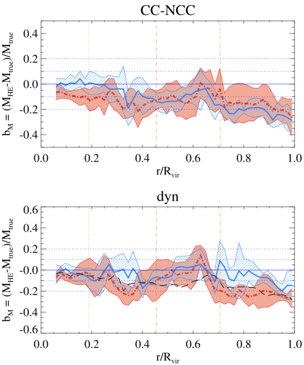


# Hydrostatic bias

If the energy is not completely thermalized, hydrostatic equilibrium masses are biased low




Nelson et al. 2014




Biffi et al. 2016

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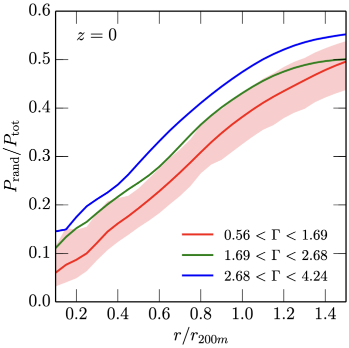
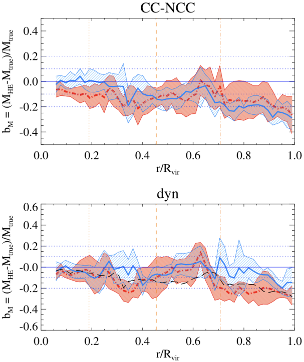



Nelson et al. 2014



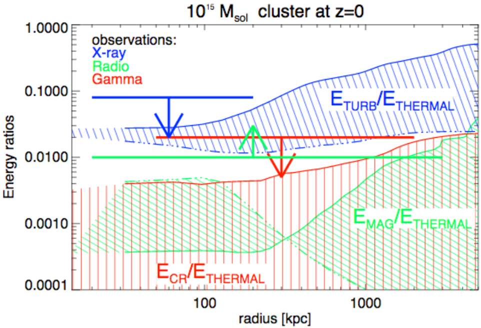

Biffi et al. 2016

In the presence of random motions the total pressure becomes

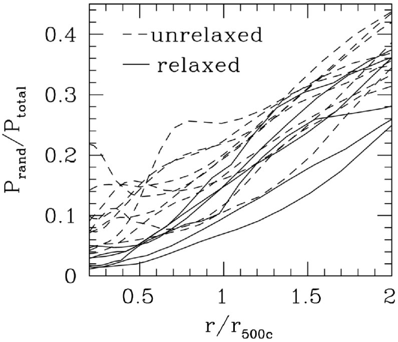
$$P_{tot} \approx P_{th} + \frac{1}{3}\rho\sigma_v^2$$

# Non-thermal processes in galaxy clusters

A fraction of the energy in clusters is not thermalized



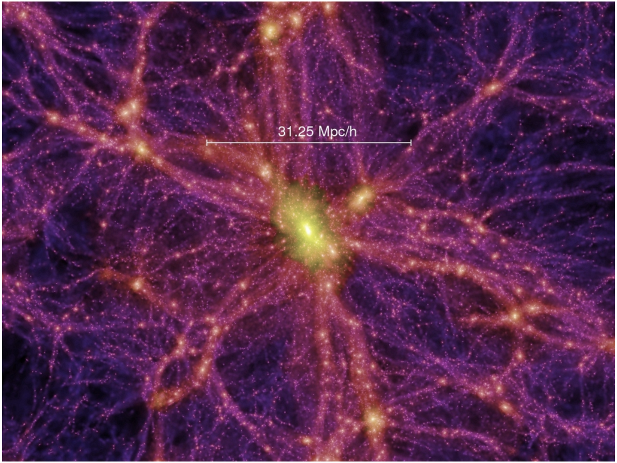

Vazza et al. 2015




Lau et al. 2009

Non-thermal energy can be in the form of bulk motions, turbulence, magnetic fields, cosmic rays...

# Turbulence in the ICM




Vazza et al. 2011

Turbulence is expected to be the dominant non-thermal component in the ICM (e.g. Rasia et al. 2006; Lau et al. 2009; Nelson et al. 2014)

# Particle acceleration

- Radio halos are diffuse Mpc-scale radio sources coincident with X-ray emission
- Implies the existence of volume-filling $\sim$GeV electrons and $\sim \mu$G magnetic fields

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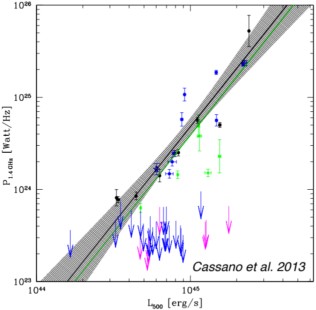
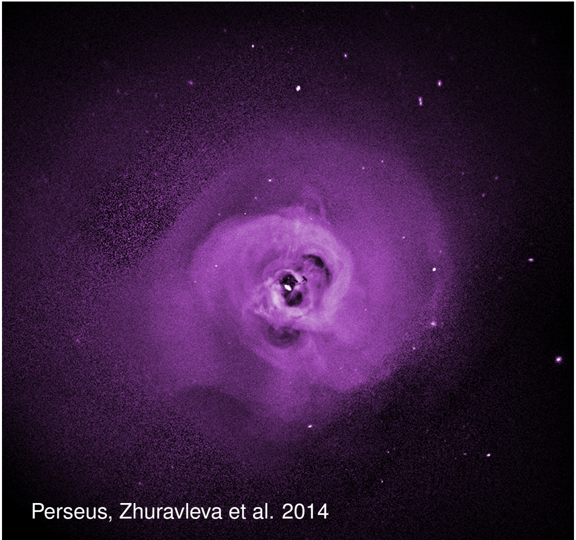
- Radio halos are diffuse Mpc-scale radio sources coincident with X-ray emission
- Implies the existence of volume-filling ∼GeV electrons and $\sim \mu$G magnetic fields
- The cluster population is split between radio-quiet and radio-halo systems (Cassano et al. 2010,2013; Cuciti et al. 2015)

# AGN feedback

AGN outflows interact with the ICM and generate gas motions (bubbles, shocks, turbulence...) preventing cooling



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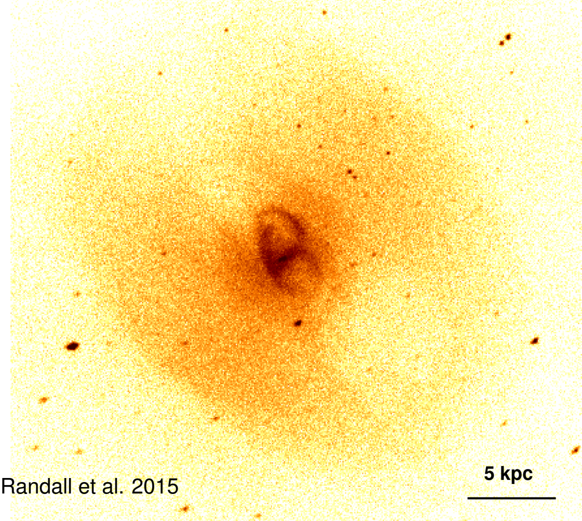


NGC 5813, Randall et al. 2015

# XRISM galaxy cluster science in a nutshell

How does the ICM *become* so hot ?

How does the ICM *remain* so hot ?

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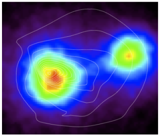
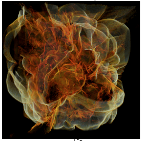
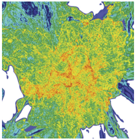
Structure Formation



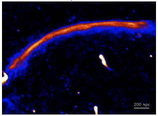
Shocks

Turbulence





Dissipation


Heating

Particle acceleration

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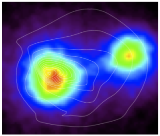
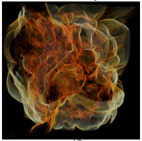


Shocks



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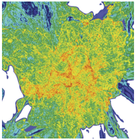
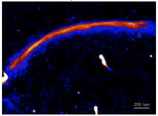


Dissipation

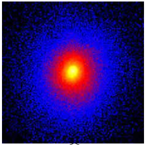

Heating



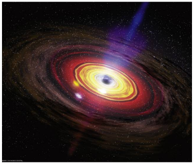

Particle acceleration

How does the ICM *remain* so hot ?

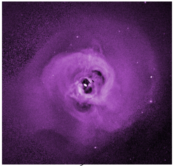
Radiative Cooling



AGN outflows



Feedback



Bubbles, Shocks, Turbulence...


Heating

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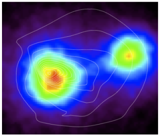

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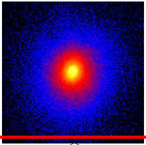
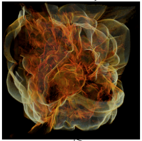


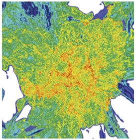
Shocks

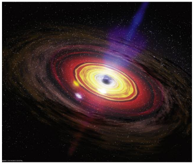
Turbulence

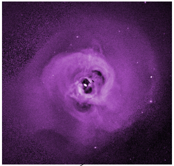
AGN outflows

Feedback





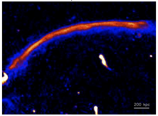




Dissipation

Bubbles, Shocks, Turbulence...


Heating




Particle acceleration


Heating

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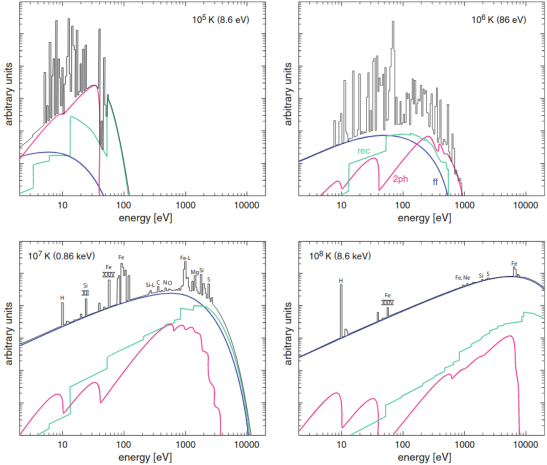
# Collisional ionization equilibrium (CIE) spectra

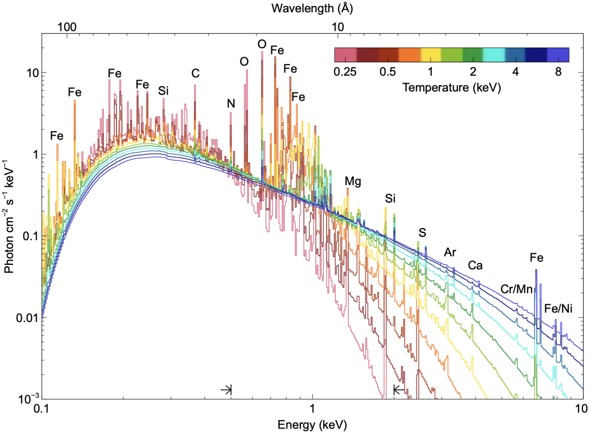
Below $\sim 10^7$ [K] line cooling dominates; continuum dominates at high temperatures




See talk by Jelle Kaastra

# Model spectra

Example CIE spectra from the Advanced Plasma Emission Code (APEC) ; alternative is SPEXACT




Sanders 2023

The spectral shape of the continuum depends on electron temperature

# Model spectra

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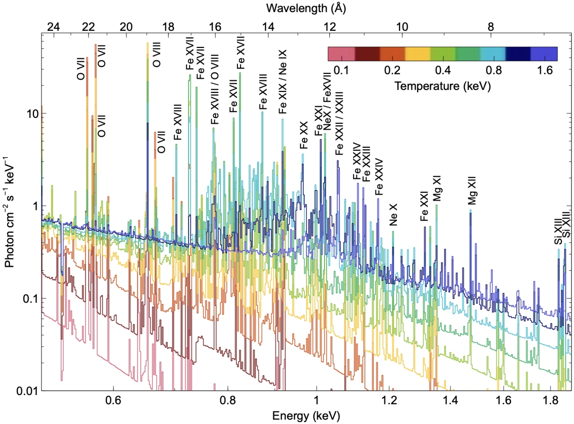
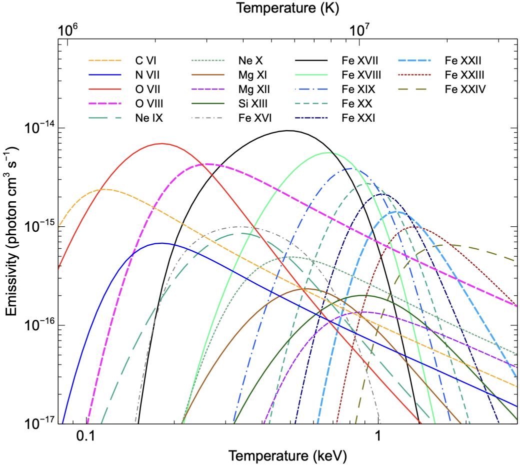



Sanders 2023

Line ratios probe ionization balance

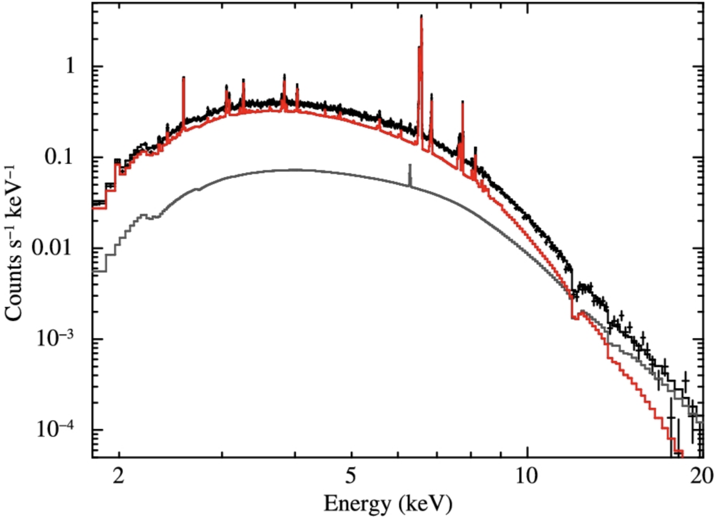
# Line ratio temperatures

The emissivity of individual ion species depends on the ionization state, i.e. on temperature



# Hitomi/SXS Perseus observation

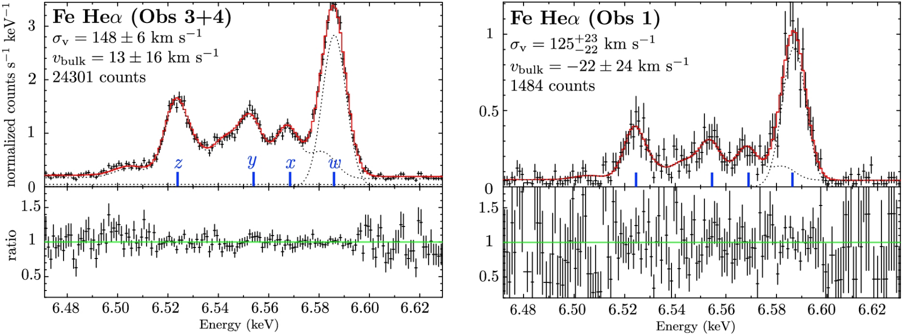
Hitomi obtained ∼5 eV resolution spectra of the Perseus cluster




Hitomi Collaboration 2018a

# Hitomi/SXS Perseus observation

Zoom on the Fe XXV (He-$\alpha$) complex

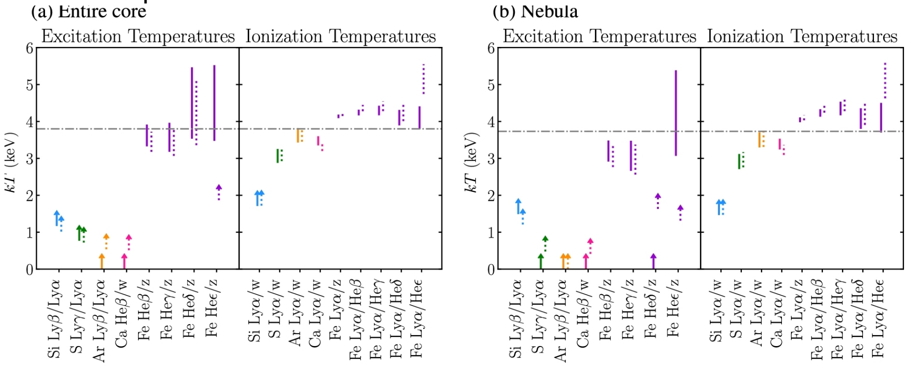



Hitomi Collaboration 2018a

Resonant (*w*), intercombination (*x*, *y*) and forbidden line (*z*) spectrally resolved

# Line ratio temperatures /2

With high-resolution X-ray spectra it is possible to determine the temperature of *individual ions*



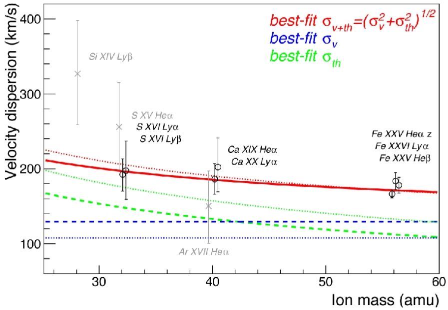

Hitomi Collaboration 2018a

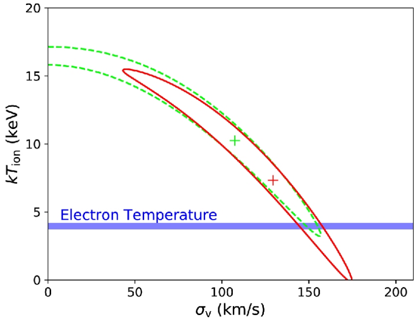
Line ratios consistent with collisional equilibrium with electrons

# Broadening of various ion species

For a given non-thermal velocity dispersion $\sigma_v$, the total line width will be given by

$$\sigma_{tot} = \sqrt{\sigma_v^2 + \sigma_{th}^2} \quad , \quad \sigma_{th} \propto m^{-1/2}$$



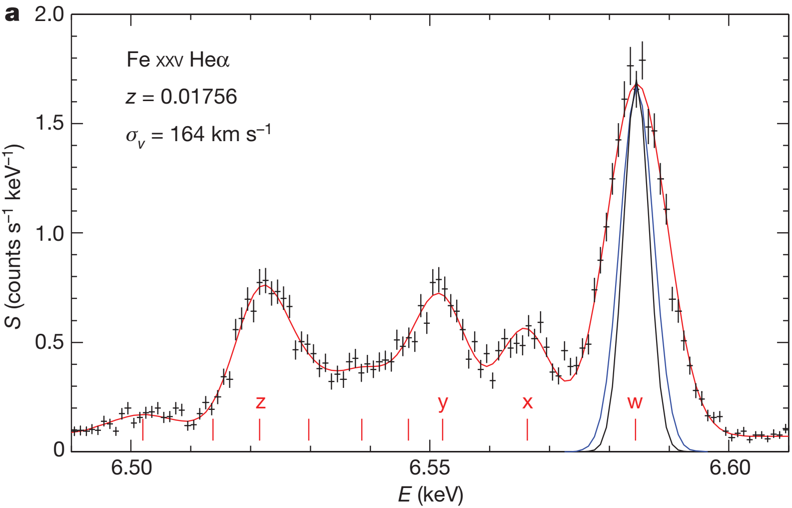




Hitomi Collaboration 2017b

Thermal broadening consistent with electron (i.e. continuum) temperatures

# Outline

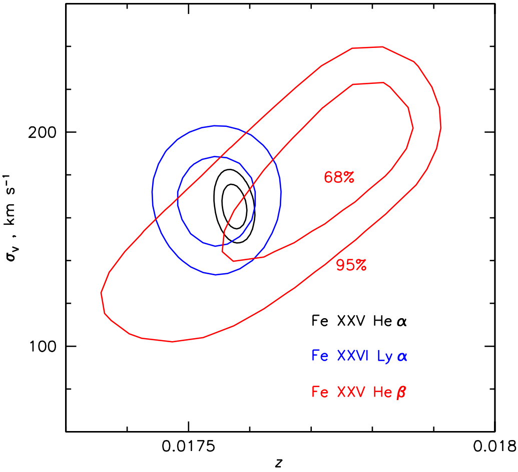
# Line broadening




Hitomi Collaboration 2016

A line broadening of $\sigma_v = 164 \pm 10$ km/s is detected

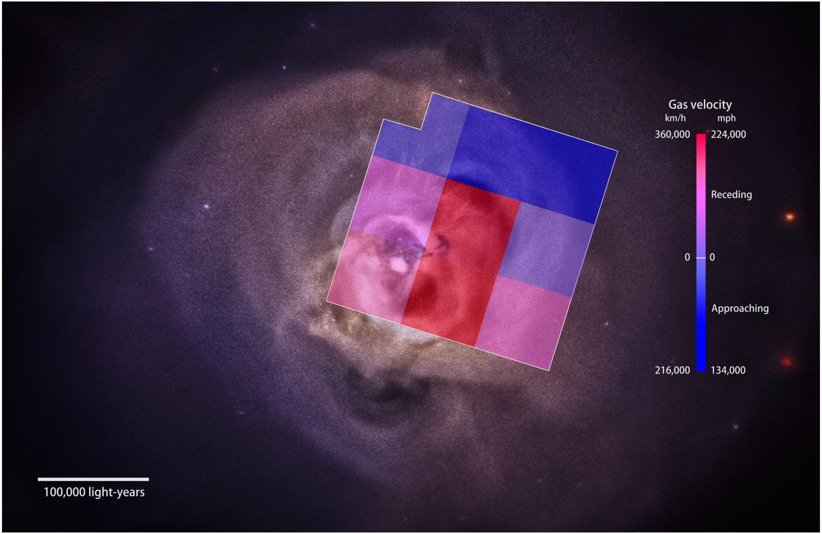
# Line broadening




Hitomi Collaboration 2016

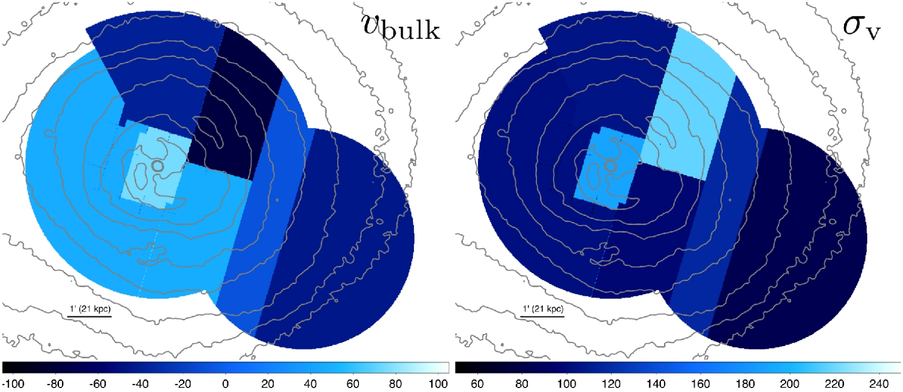
Consistent information in 3 different transitions

# Bulk gas motions




We observe a gradient of 150 km/s in mean gas velocity

# Gas motion distribution




Hitomi Collaboration 2016

Higher velocity dispersion ($\sim$ 200 km/s) around the AGN-inflated cavities; low $\sigma_v \approx$ 100 km/s beyond them

# Non-thermal energy in Perseus

- Given the thermal pressure $P_{th} = \frac{k}{\mu m_p} \rho T$ and the total pressure $P_{tot} \approx P_{th} + \frac{1}{3} \rho \sigma_v^2$ we can write

$$\frac{P_{NT}}{P_{tot}} \approx \frac{\sigma_v^2}{\sigma_v^2 + 3kT/\mu m_p}$$

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- The speed of sound in the medium is

$$c_s = \left(\frac{\gamma kT}{\mu m_p}\right)^{1/2} \approx 1,000 \text{ [km/s]}, \quad \mathcal{M} = \frac{\sigma_v}{c_s} \approx 0.16$$

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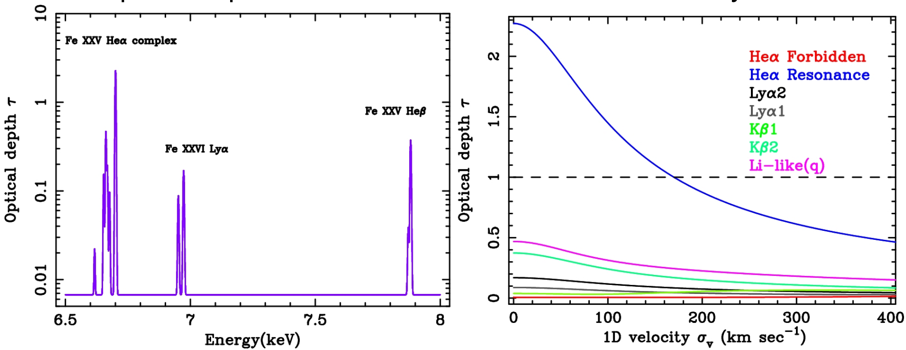
- Therefore

$$\frac{P_{NT}}{P_{tot}} = \frac{\mathcal{M}^2}{\mathcal{M}^2 + 3/\gamma} < 0.04$$

- Non-thermal energy in the core of Perseus is dynamically unimportant

# Resonant scattering

The optical depth of some lines can be of order ∼unity



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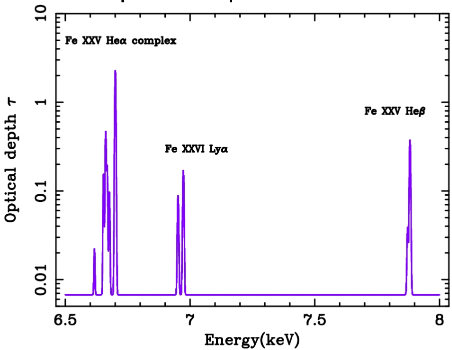
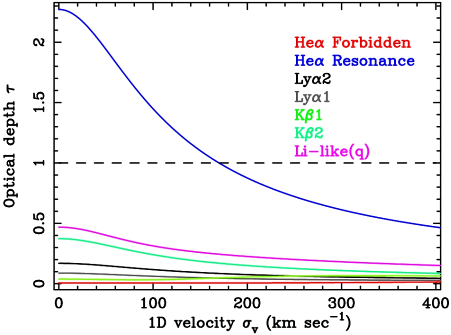
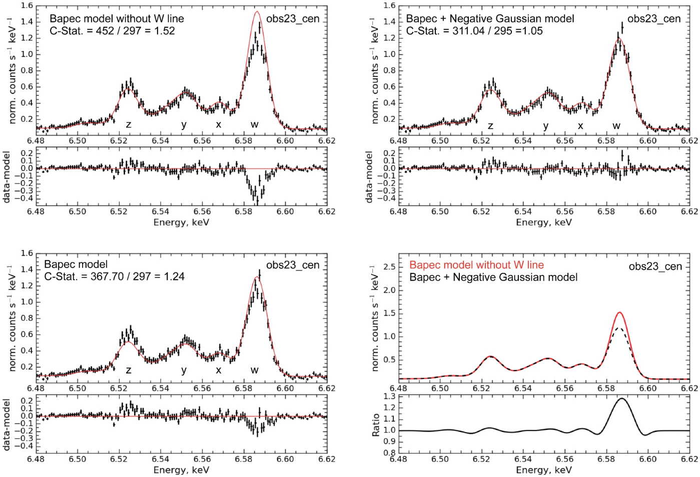



Photons at the precise line energy can be absorbed and immediately re-emitted in another direction
⇒ Reduction in line flux

This is the case of the resonant (*w*) line of the Fe XXV He-$\alpha$ complex

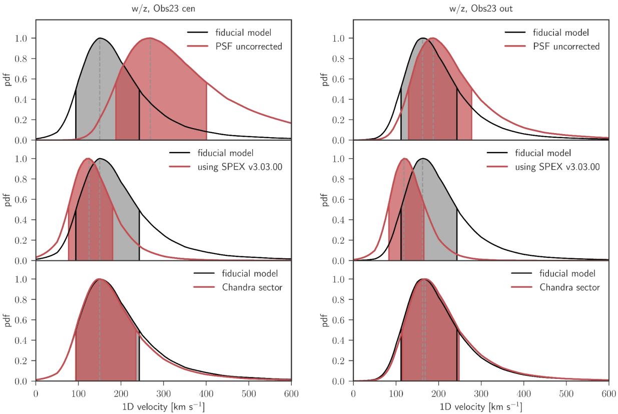
# Resonant scattering in Hitomi data




Hitomi Collaboration 2017b

Suppression of the resonant line clearly detected with respect to optically thin case

# Resonant scattering in Hitomi data



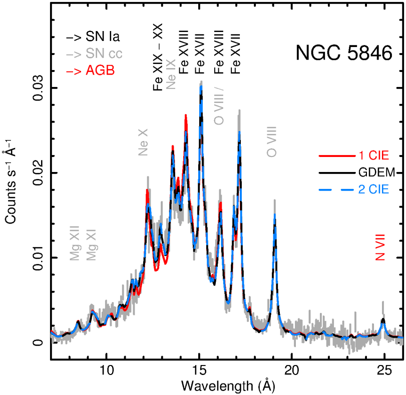

Hitomi Collaboration 2017b

Evidence for low turbulent velocities : line shifts would change the energy of photons and *decrease* resonant scattering

# Outline

# Metallicity of the ICM

The ICM is enriched in heavy elements




XMM-Newton/RGS, De Plaa et al. 2017

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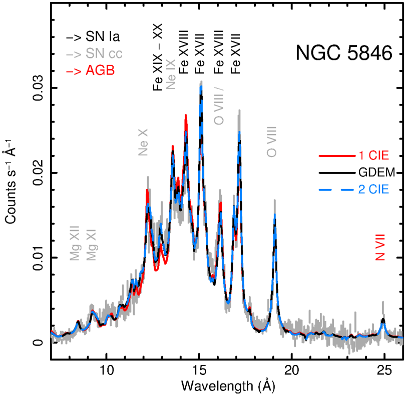
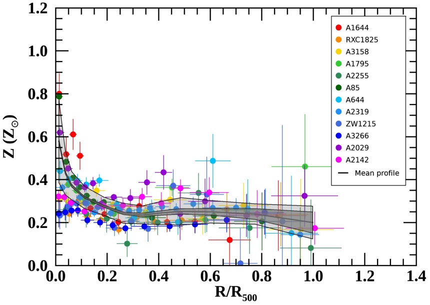


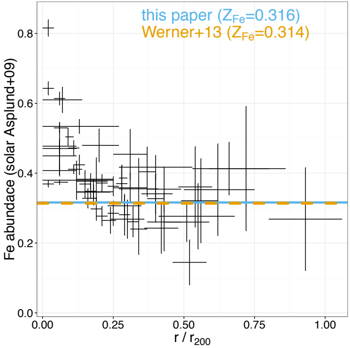

XMM-Newton/RGS, De Plaa et al. 2017

Abundance patterns tell us about the chemical enrichment history

# Metal abundance profiles

The ICM acts as a fossil record of all metals injected by SNe since the formation epoch



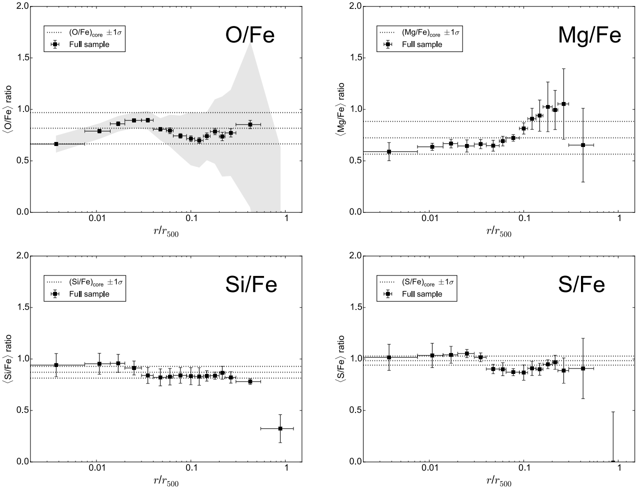




Ghizzardi et al. 2020

Urban et al. 2017

The ICM exhibits ∼constant metallicity of $0.2-0.3Z_\odot$ out to $R_{500}$

# Abundance ratios

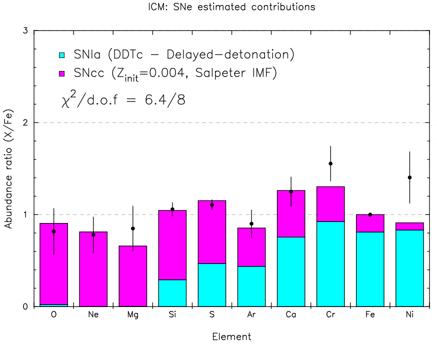



Mernier et al. 2017

Abundance ratios are consistent with Solar; no observed radial trend

# Constraining SN yields

Various SN types (Ia vs CC) produce different elemental yields




Mernier et al. 2017

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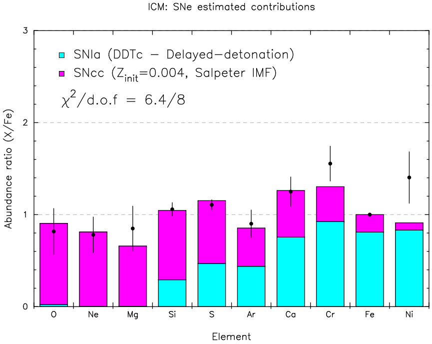
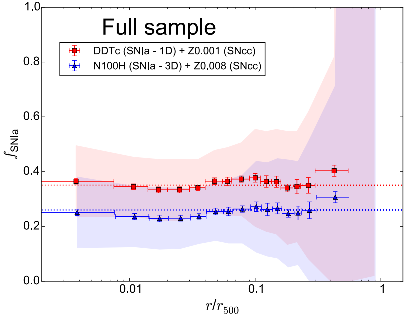


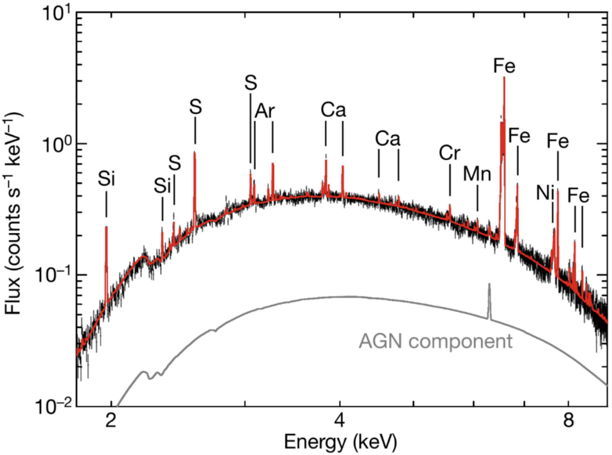




Mernier et al. 2017

Abundance pattern implies constant relative contribution SNIa and SNcc throughout the ICM

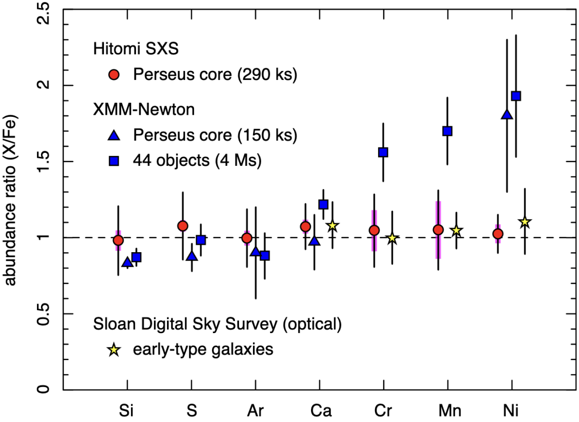
# The Hitomi view of chemical enrichment

In high-resolution Hitomi/SXS data we were able to detect for the first time rare elements (Cr, Mn)




Hitomi Collaboration 2018b

# A universal metal enrichment pattern?

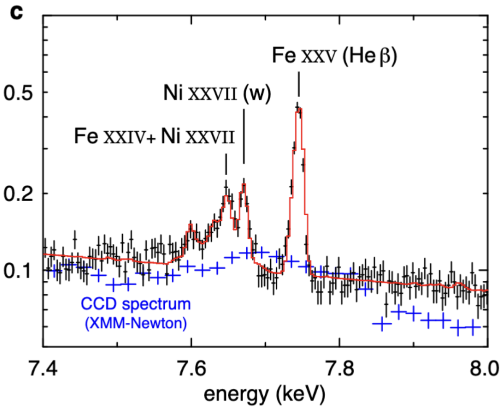



Hitomi Collaboration 2018b

Abundance ratios are surprisingly consistent with the Solar abundance pattern

# The power of high-resolution spectroscopy

The abundance of some elements (in particular Ni) were found to be substantially higher than Solar in CCD spectra

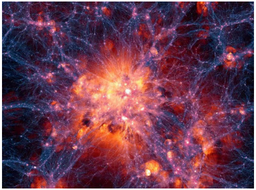



Hitomi Collaboration 2018b

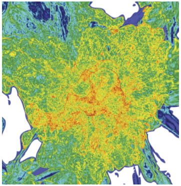
The line was a blend between the Fe XXV He-$\beta$ and the actual Ni XXVII line

# Take home message

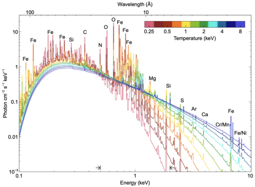
Most of the baryons in the Universe are hot ! How did they get so hot and why do they remain so hot ?



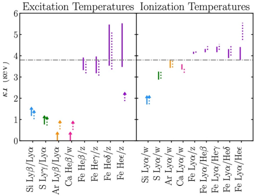
Understanding the virialization and reheating processes requires constraints on ICM dynamics



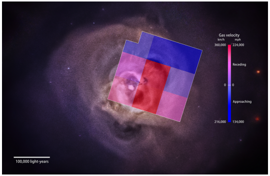
X-ray spectroscopy provides a wealth of information on the state of the gas




Collisional ionization and individual ion temperatures can be tested with X-ray line ratios




Line shifts and broadening tell us about non-thermal energy fraction and gas virialization




We can determine abundances of many individual species and constrain Supernova yields