Astrophysical Spectroscopy

Eugene Churazov

Outline

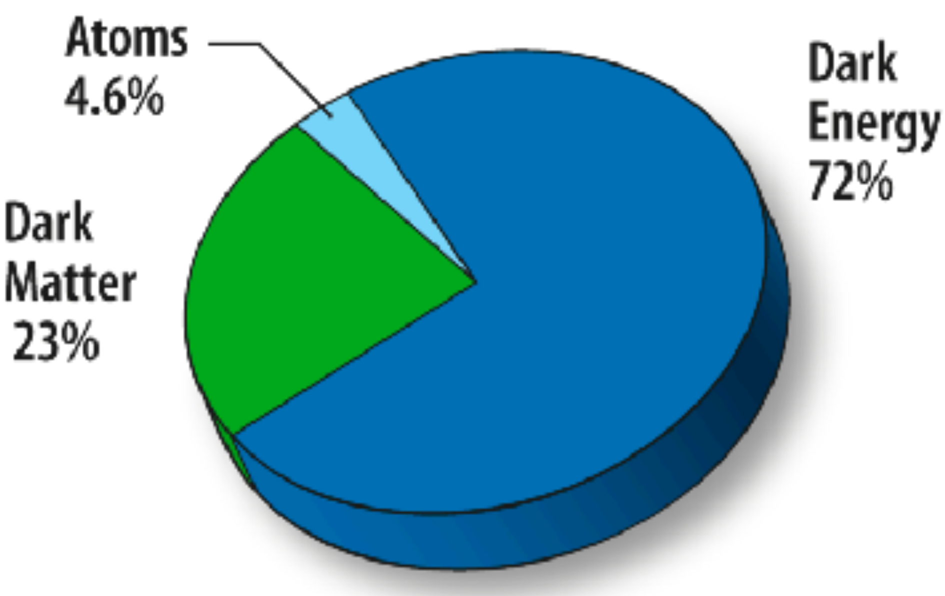
Astrophysically abundant elements

Two examples of "Hydrogen" spectroscopy

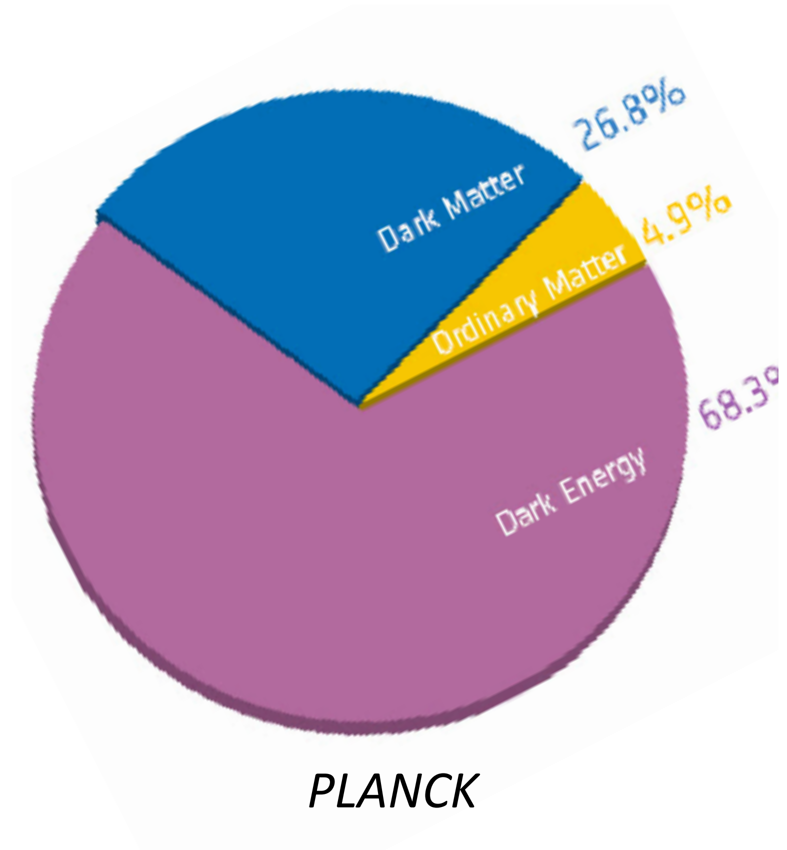
X-ray Astronomy

Galaxy clusters and hot plasma

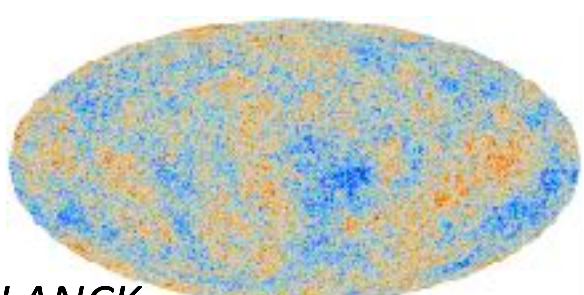
LCDM Universe (Today)



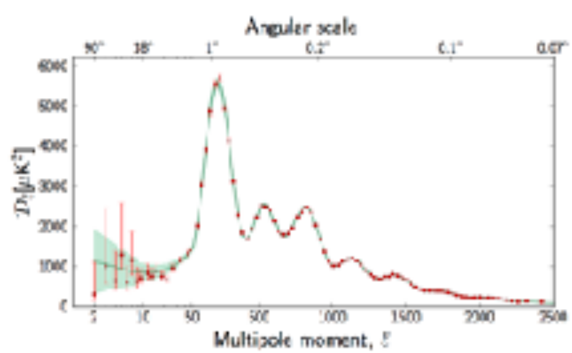
WMAP



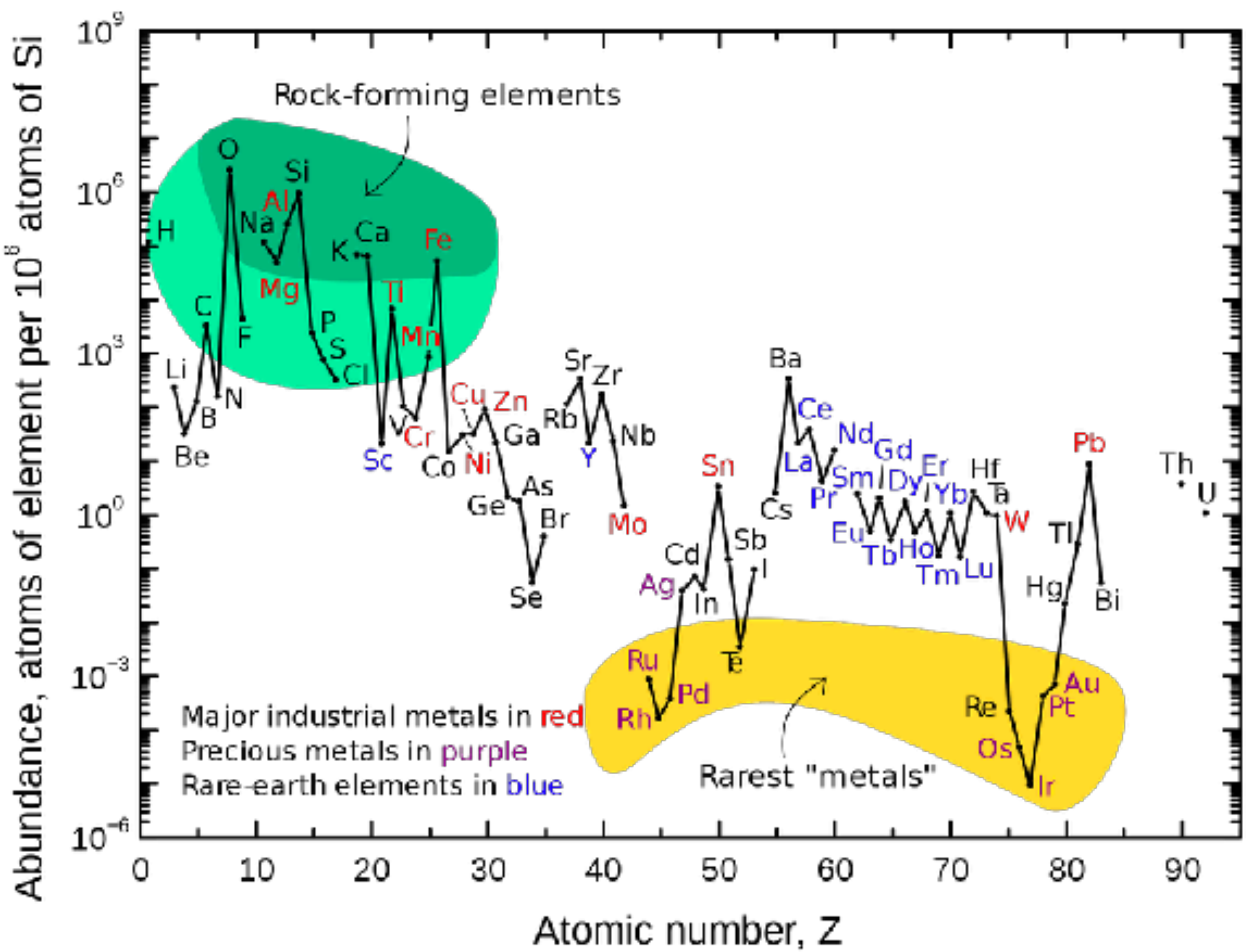
PLANCK



PLANCK

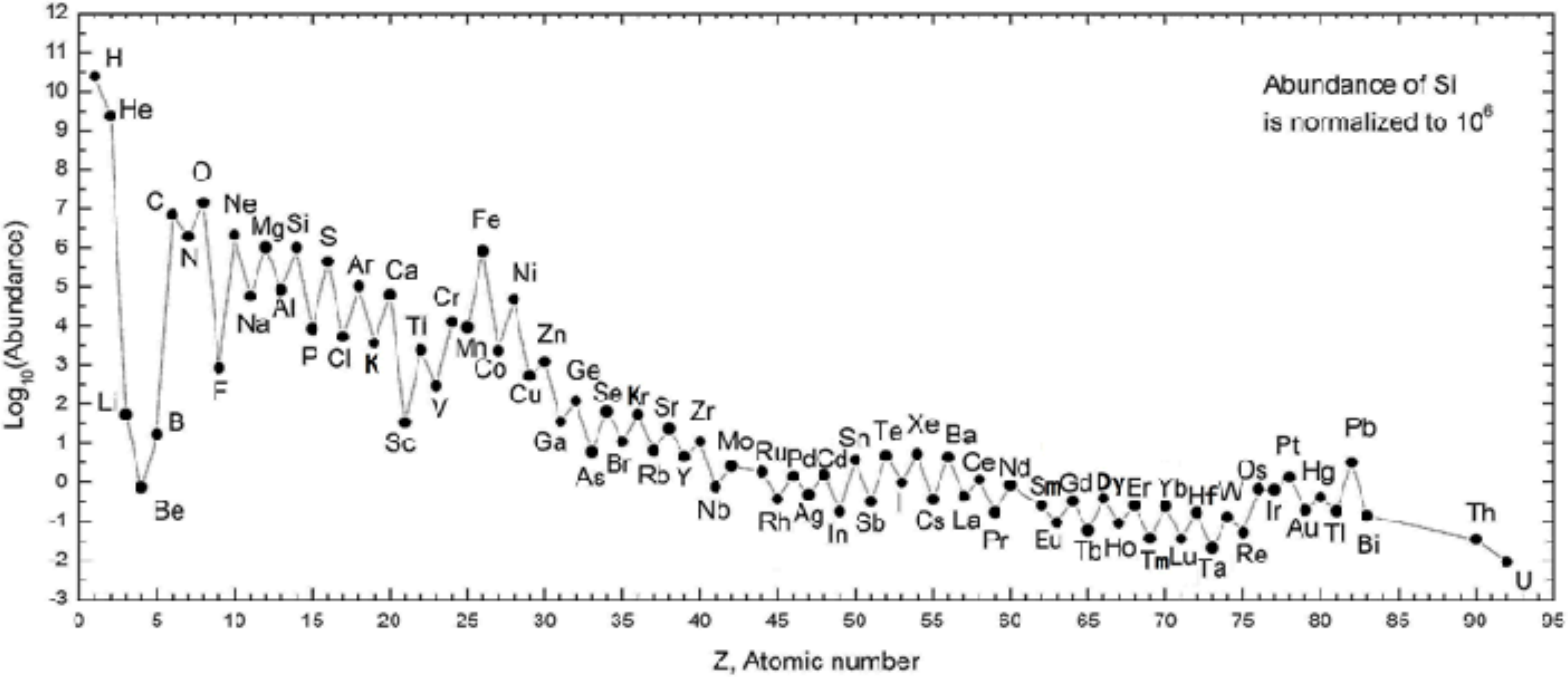


Abundance of elements in the Earth (crust)



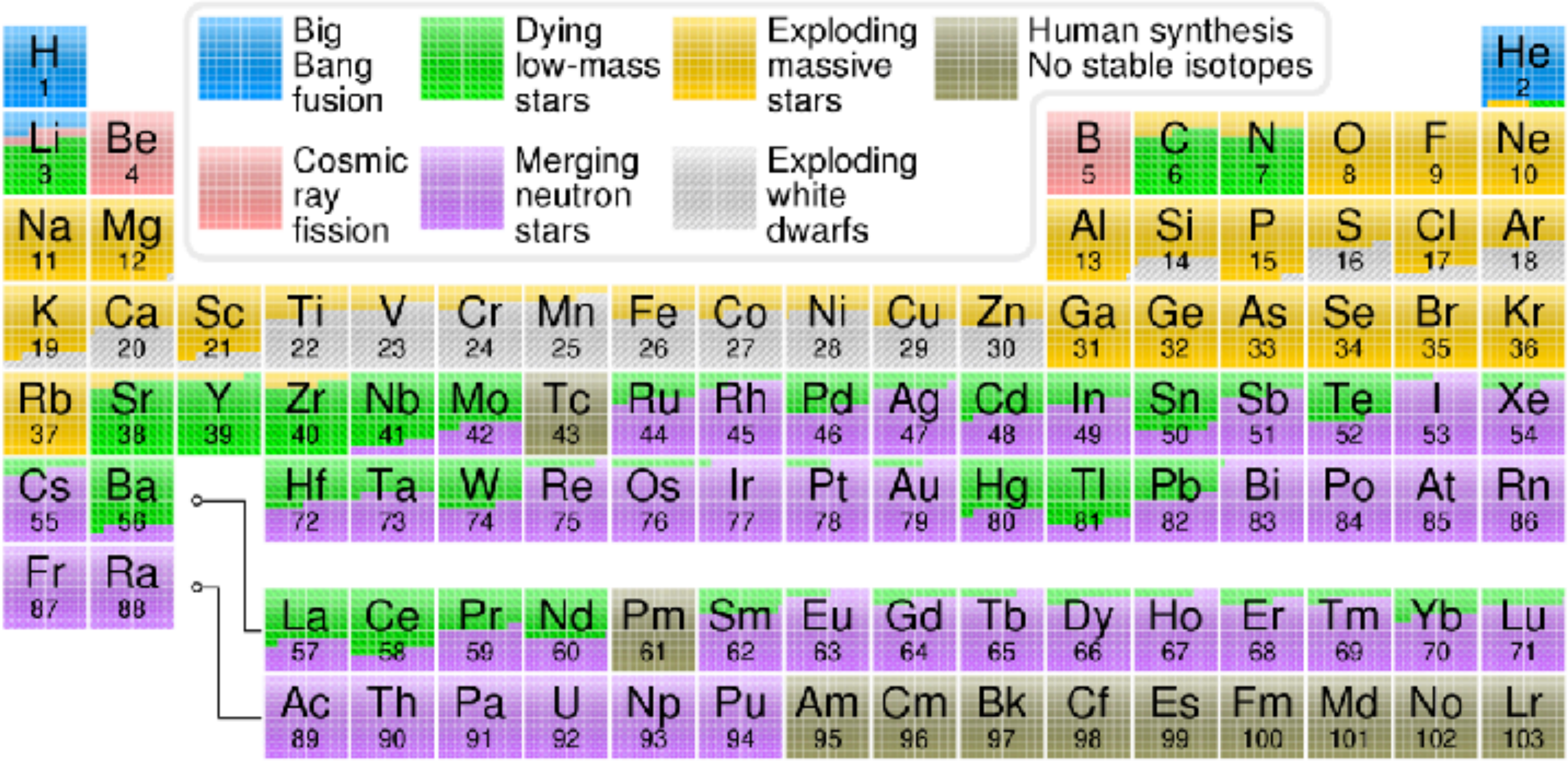
https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth%27s_crust

Abundance of elements in the Universe (today)



https://en.wikipedia.org/wiki/Nucleosynthesis

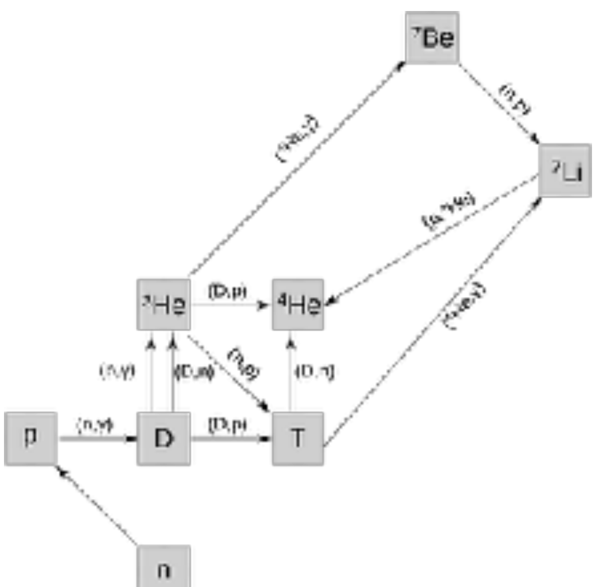
Origin of elements

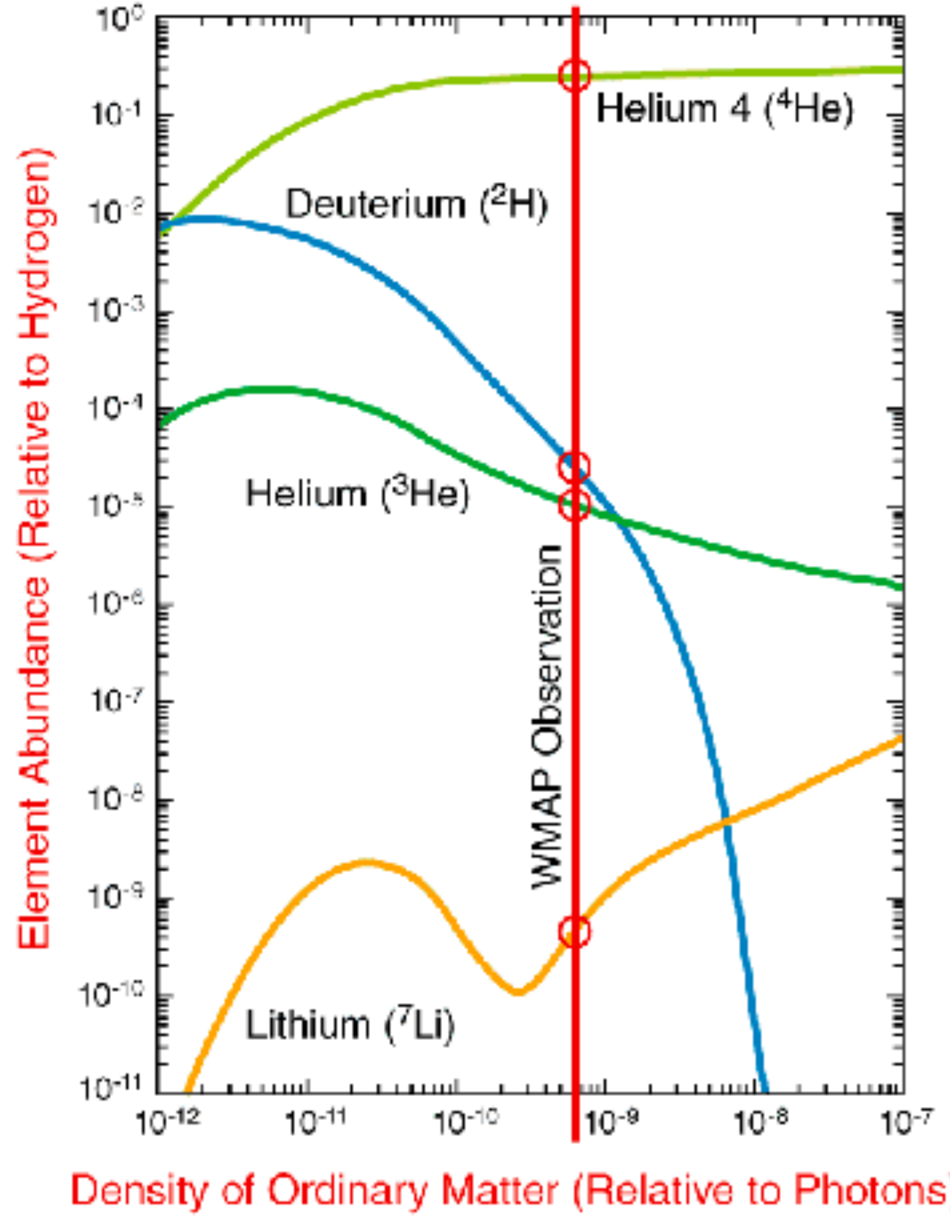


https://en.wikipedia.org/wiki/Nucleosynthesis#/media/File:Nucleosynthesis_periodic_table.svg

Big Bang Nucleosynthesis

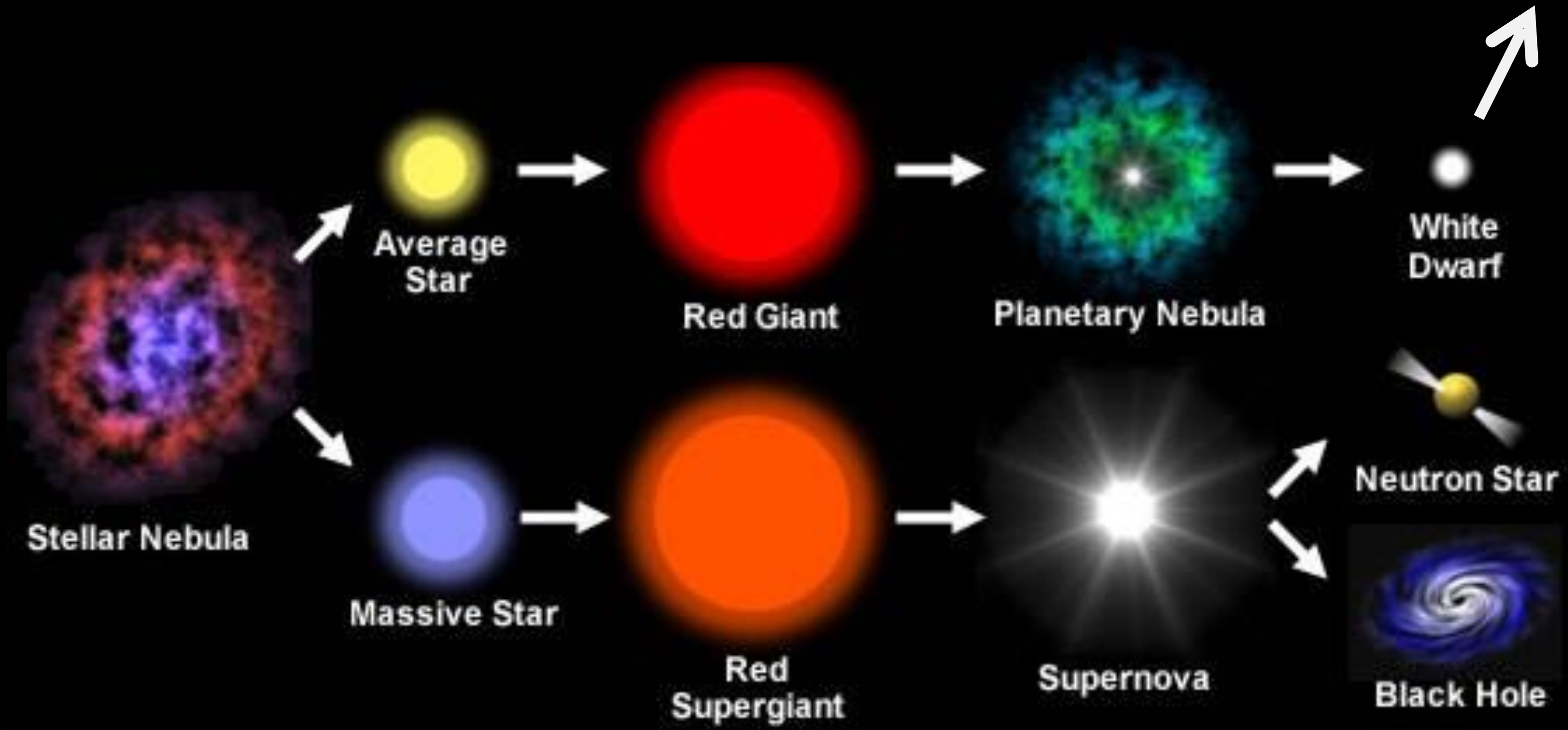
$$\mathrm{p} + \mathrm{n} \longrightarrow {}^2\mathrm{H} + \gamma$$
$$\mathrm{p} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{He} + \gamma$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{He} + \mathrm{n}$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{H} + \mathrm{p}$$
$${}^3\mathrm{He} + {}^2\mathrm{H} \longrightarrow {}^4\mathrm{He} + \mathrm{p}$$
$${}^3\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^4\mathrm{He} + \mathrm{n}$$





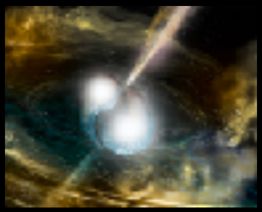
Stellar evolution

Type Ia
SN2014J



Type II
SN1987A

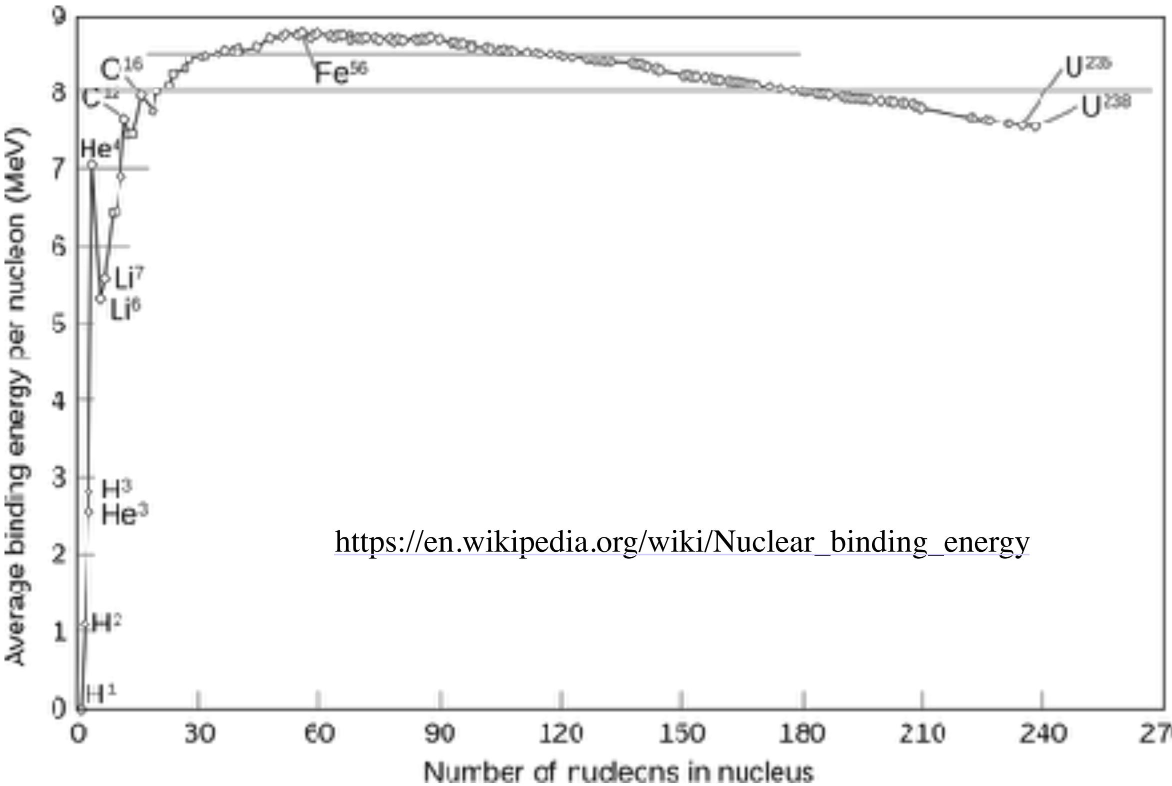
GW170817



https://scioly.org/wiki/index.php/Astronomy/Stellar_Evolution

Typical abundances today (Sun photosphere)

Element	Abundance (by number)
H	1.00e+0
He	9.77e-2
C	3.63e-4
N	1.12e-4
O	8.51e-4
Ne	1.23e-4
Na	2.14e-6
Mg	3.80e-5
Al	2.95e-6
Si	3.55e-5
S	1.62e-5
Cl	1.88e-7
Ar	3.63e-6
Ca	2.29e-6
Cr	4.84e-7
Fe	4.68e-5
Ni	1.78e-6
Co	8.60e-8



https://en.wikipedia.org/wiki/Nuclear_binding_energy

Our Universe is dominated by hydrogen +10% of He + small amount of other el.

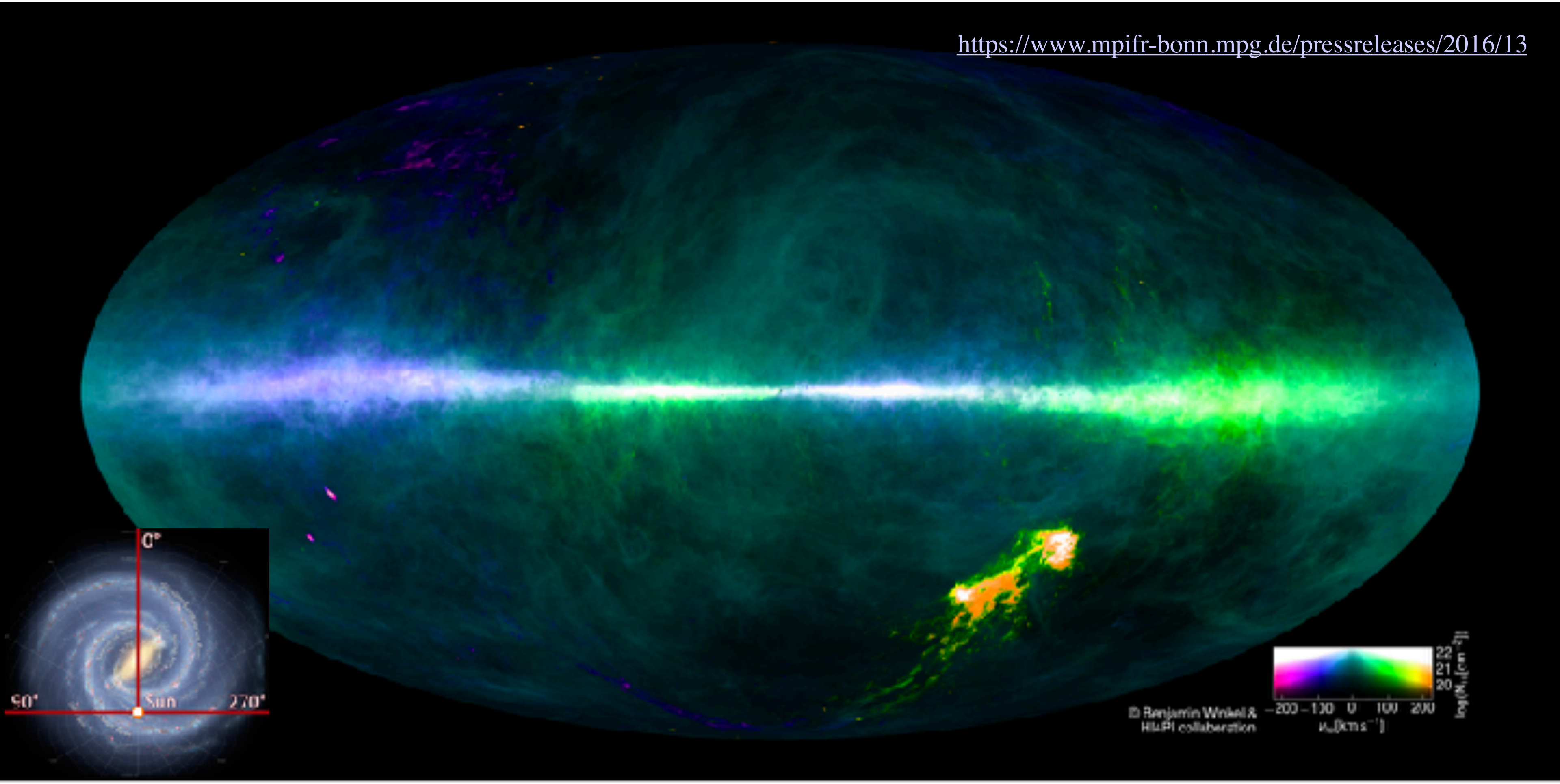
Hydrogen 21 cm line

Hyperfine splitting of the ground state

$$A \sim 10^{-15}\ \mathrm{s}^{-1} \qquad \text{Lifetime} \sim 10\ \text{Myr}$$

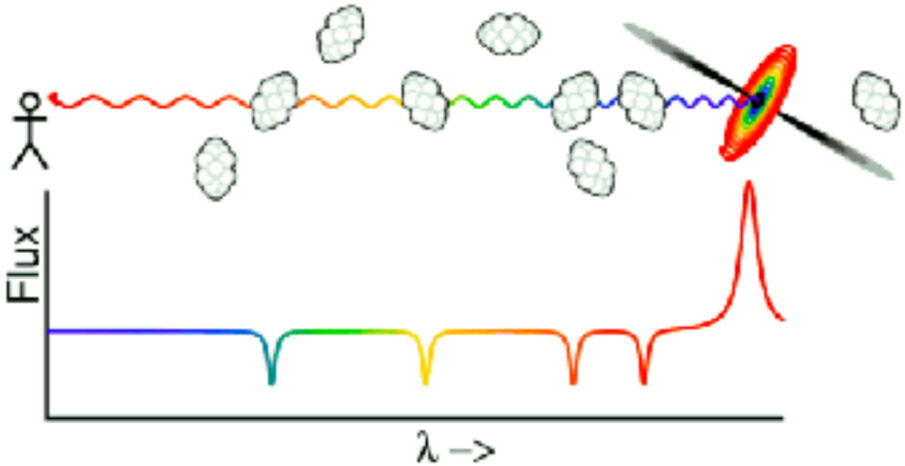
$$kT_s \gg h\nu \qquad I = C \times n_H$$

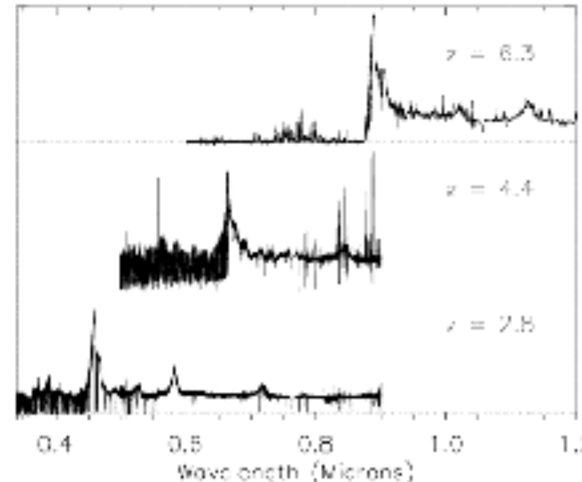
https://www.mpifr-bonn.mpg.de/pressreleases/2016/13

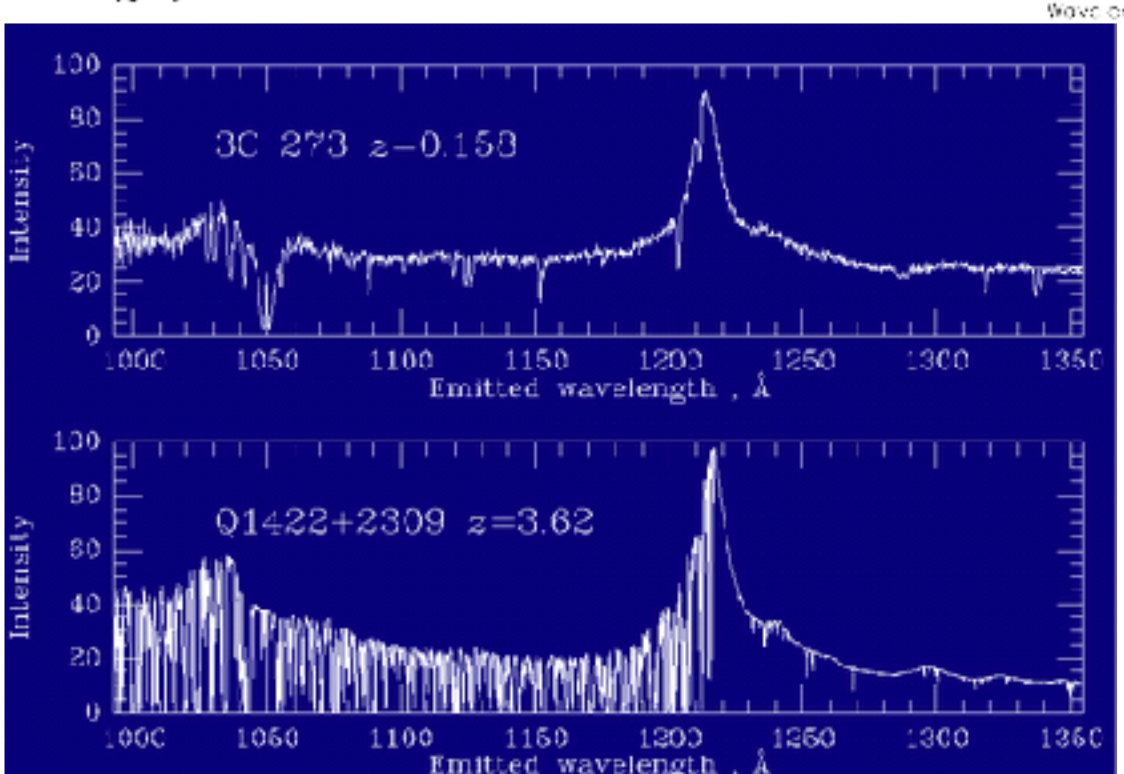


Other elements? $^{14}N_7$ and $^{57}Fe_{26}$; For instance, [H]-like N, or [Li]-like Fe?

Hydrogen Ly$_{\alpha}$ (1215 Å) Forest

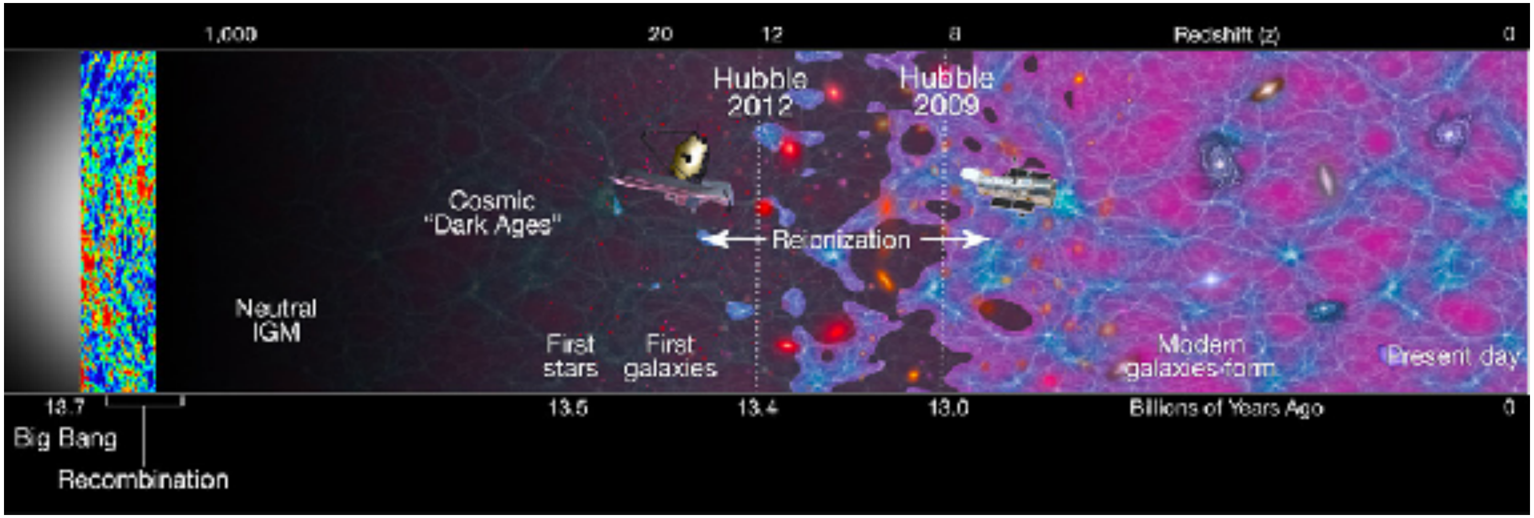






http://www.astro.ucla.edu/~wright/Lyman-alpha-forest.html

Gunn-Peterson Trough



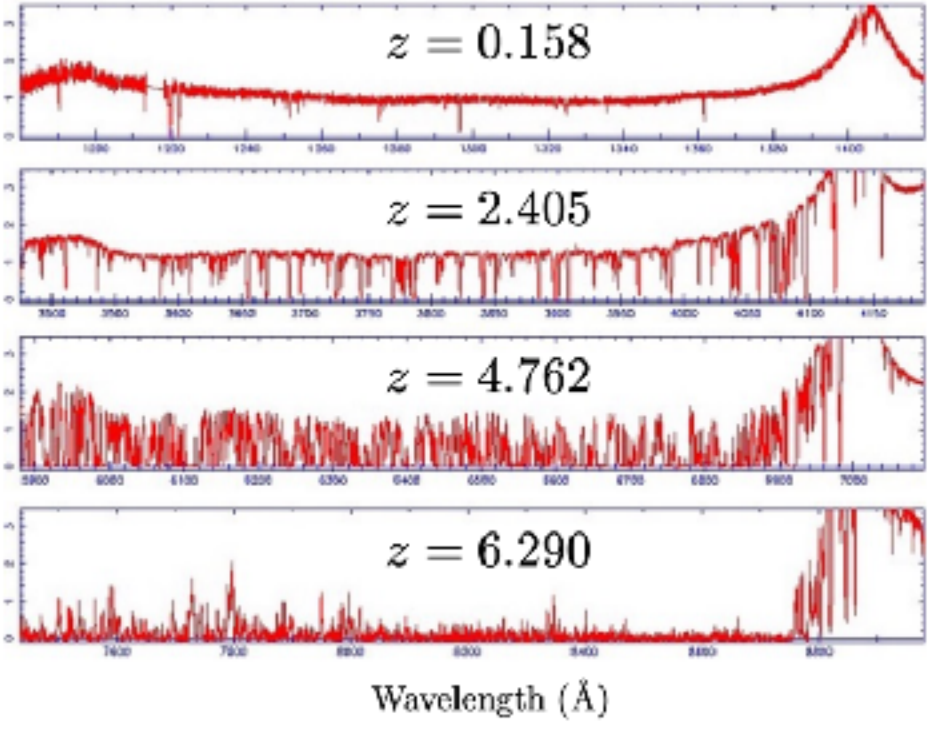
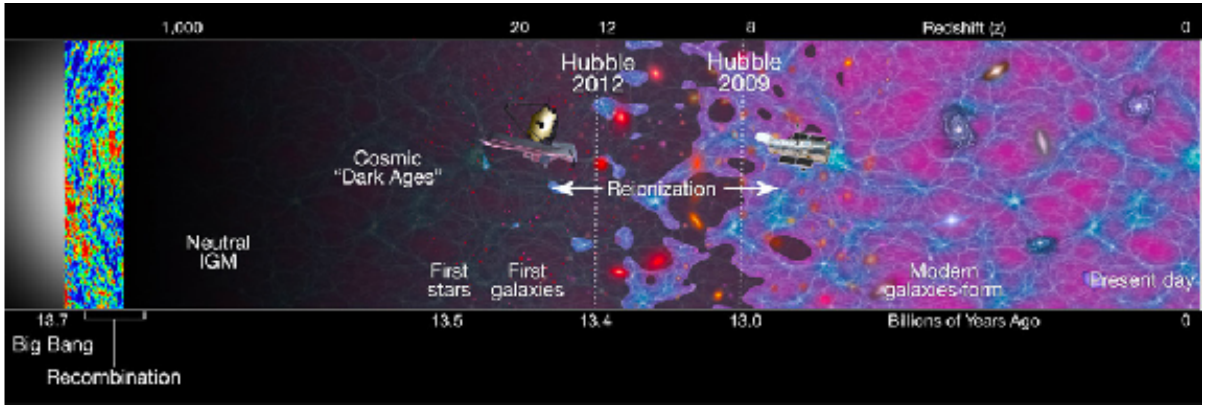


Image: Bob Carswell

21 cm again



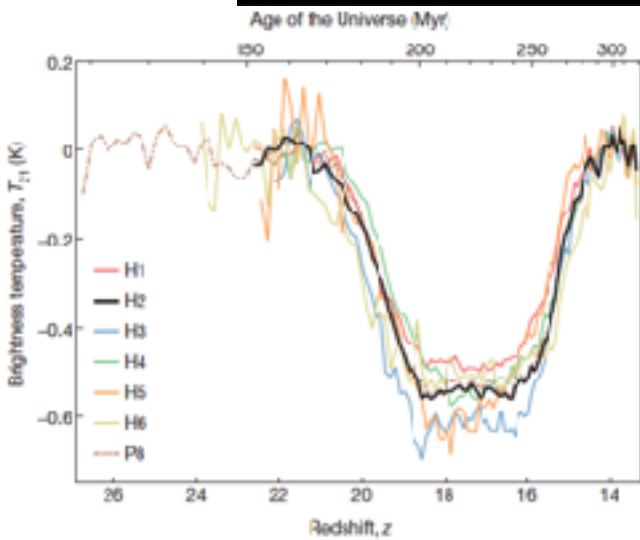
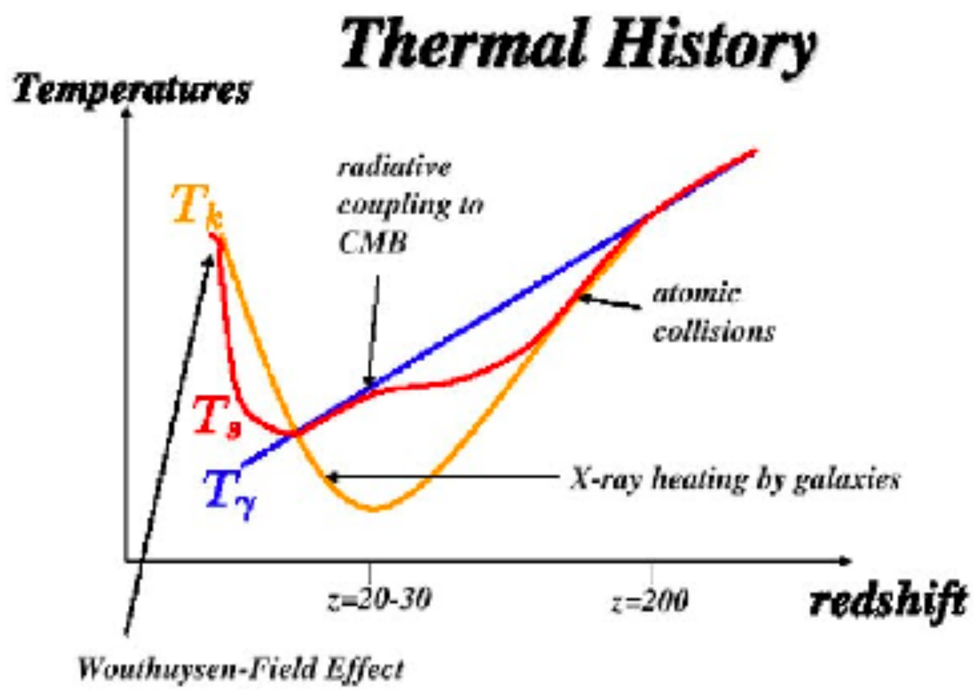


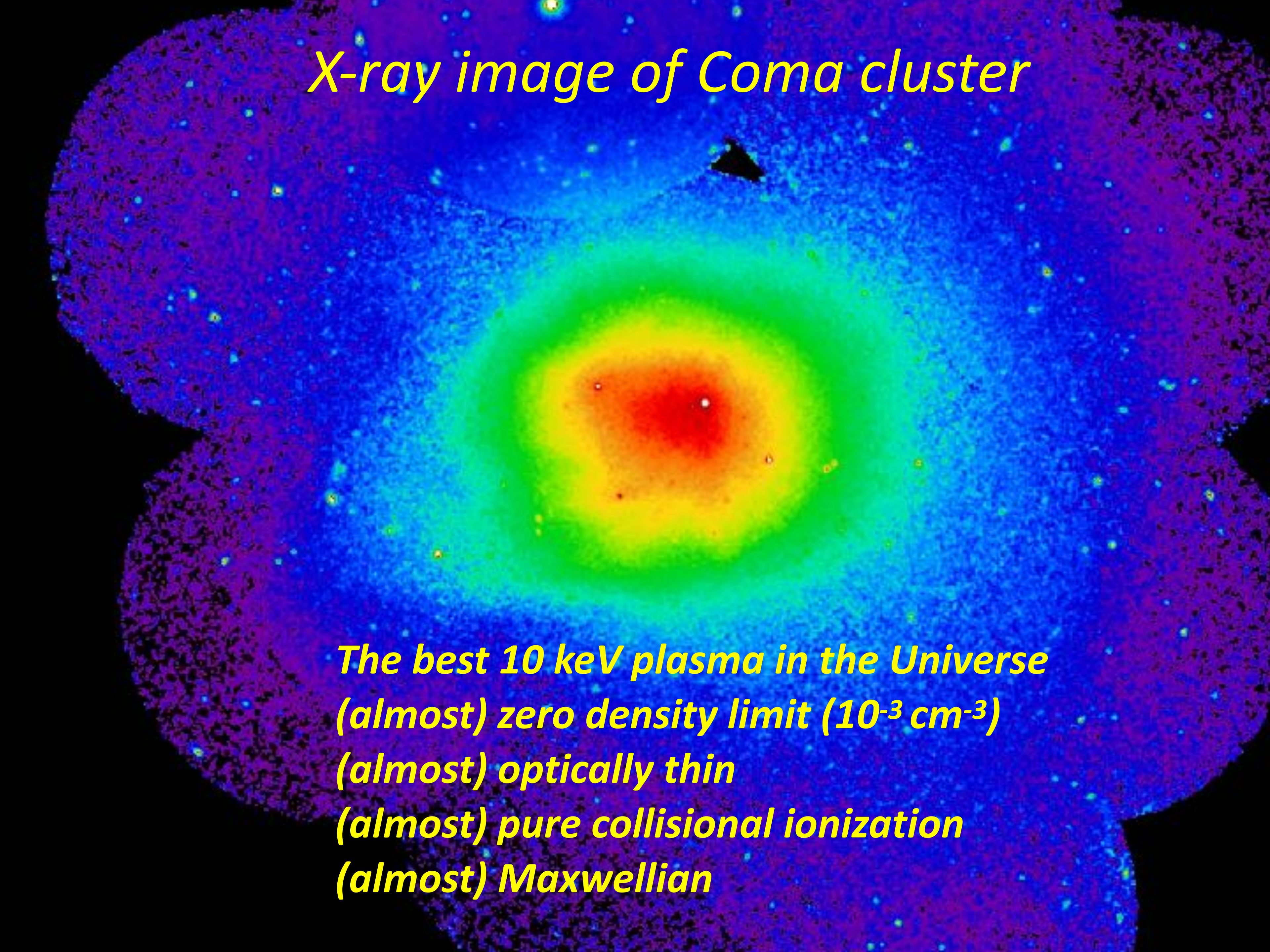
Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case. Each profile for the brightness temperature T_{21} is added to its residuals and plotted against the redshift z and the corresponding age of the Universe. The thick black line is the model fit for the hardware and analysis configuration with the highest signal-to-noise ratio (equal to 52; H2; see Methods), processed using 60–99 MHz and a four-term polynomial (see equation (2) in Methods) for the foreground model. The thin solid lines are the best fits from each of the other hardware configurations (H1, H3–H6). The dash-dotted line (P8), which extends to $z > 26$, is reproduced from Fig. 1c and uses the same data as for the thick black line (H2), but a different foreground model and the full frequency band.



Bowman+18

X-ray astronomy & spectroscopy

X-ray image of Coma cluster



The best 10 keV plasma in the Universe
(almost) zero density limit (10^{-3} cm^{-3})
(almost) optically thin
(almost) pure collisional ionization
(almost) Maxwellian

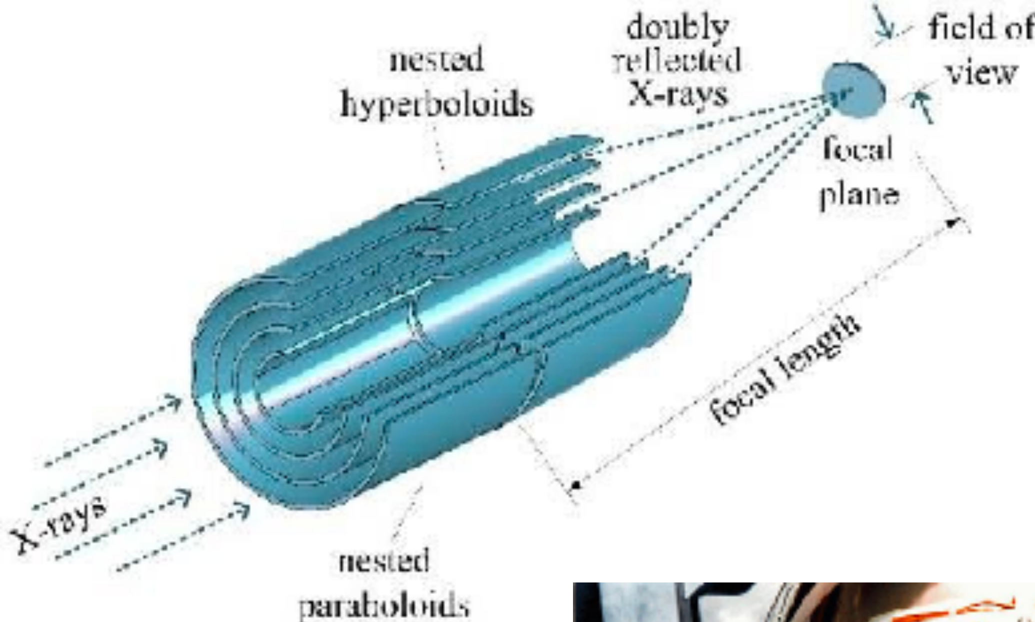
X-ray astronomy

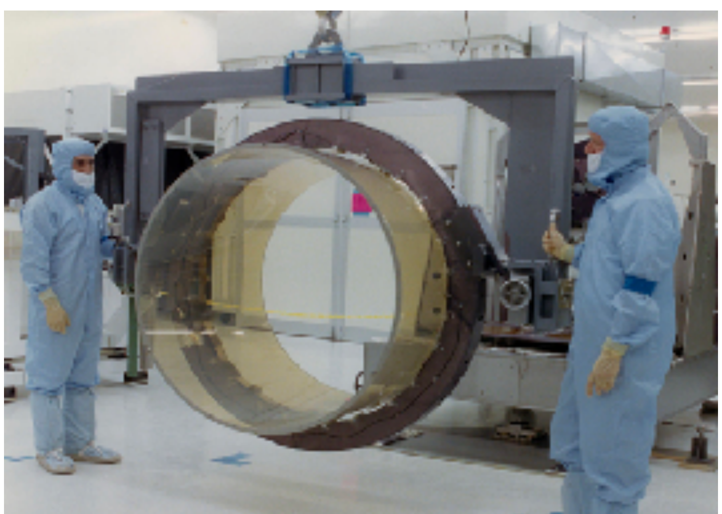
Atmosphere is transparent in optical band
Atmosphere is opaque to X-rays

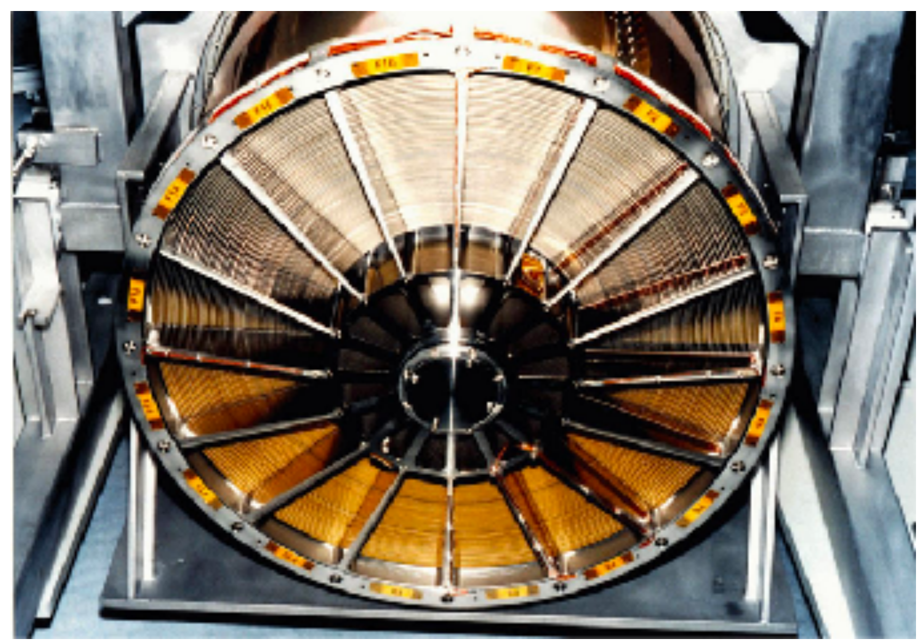
We are opaque in optical band
We are ~transparent for X-rays

X-ray astronomy is only possible from space

It is difficult to reflect X-rays



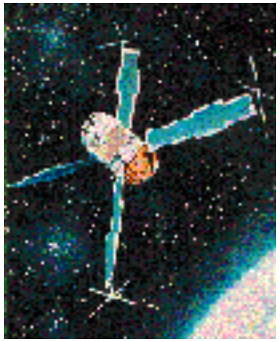




https://imagine.gsfc.nasa.gov/observatories/technology/xray_telescopes1.html

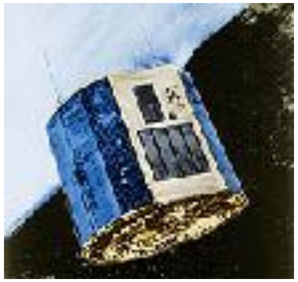
X-ray history (of clusters)

First extragalactic X-ray source detected – M87/ Virgo (Byram et al., 1966, Bradt et al., 1967) – Aerobee rocket flight



UHURU satellite (1970-1973)
(Kellog et al., 1972, Forman et al., 1972)
Many clusters, very powerful L_x~$10^{43\text{-}45}$ erg/s

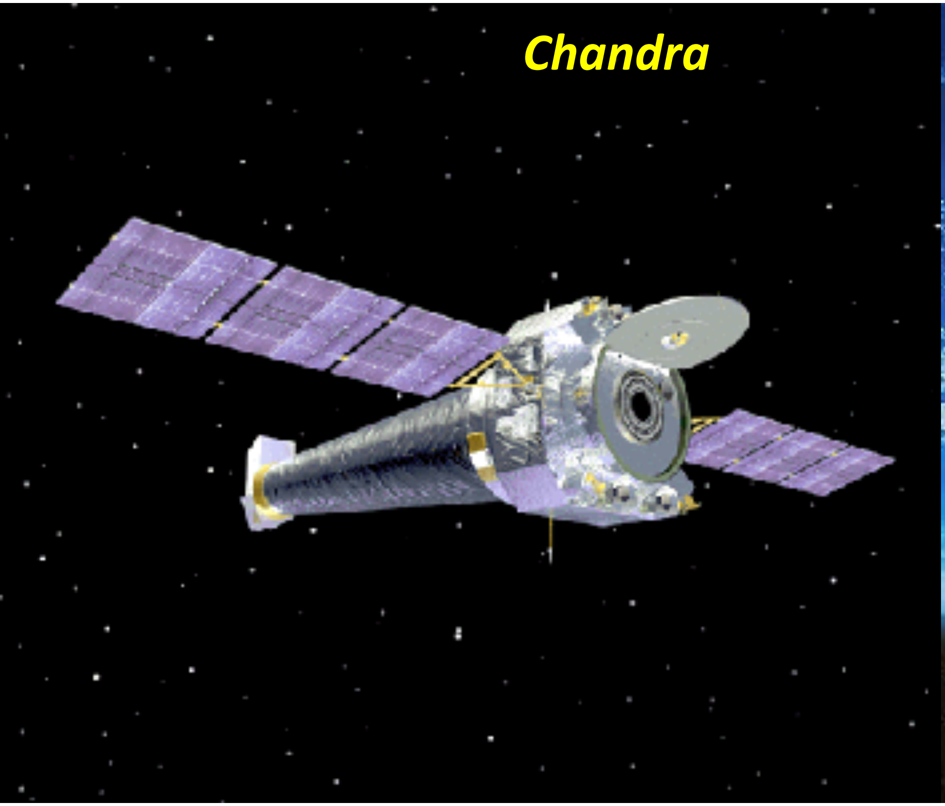
Extended!



Ariel-5 satellite (1974-1980)
Lines in the spectra – thermal plasma!
(Mitchell et al 1976)

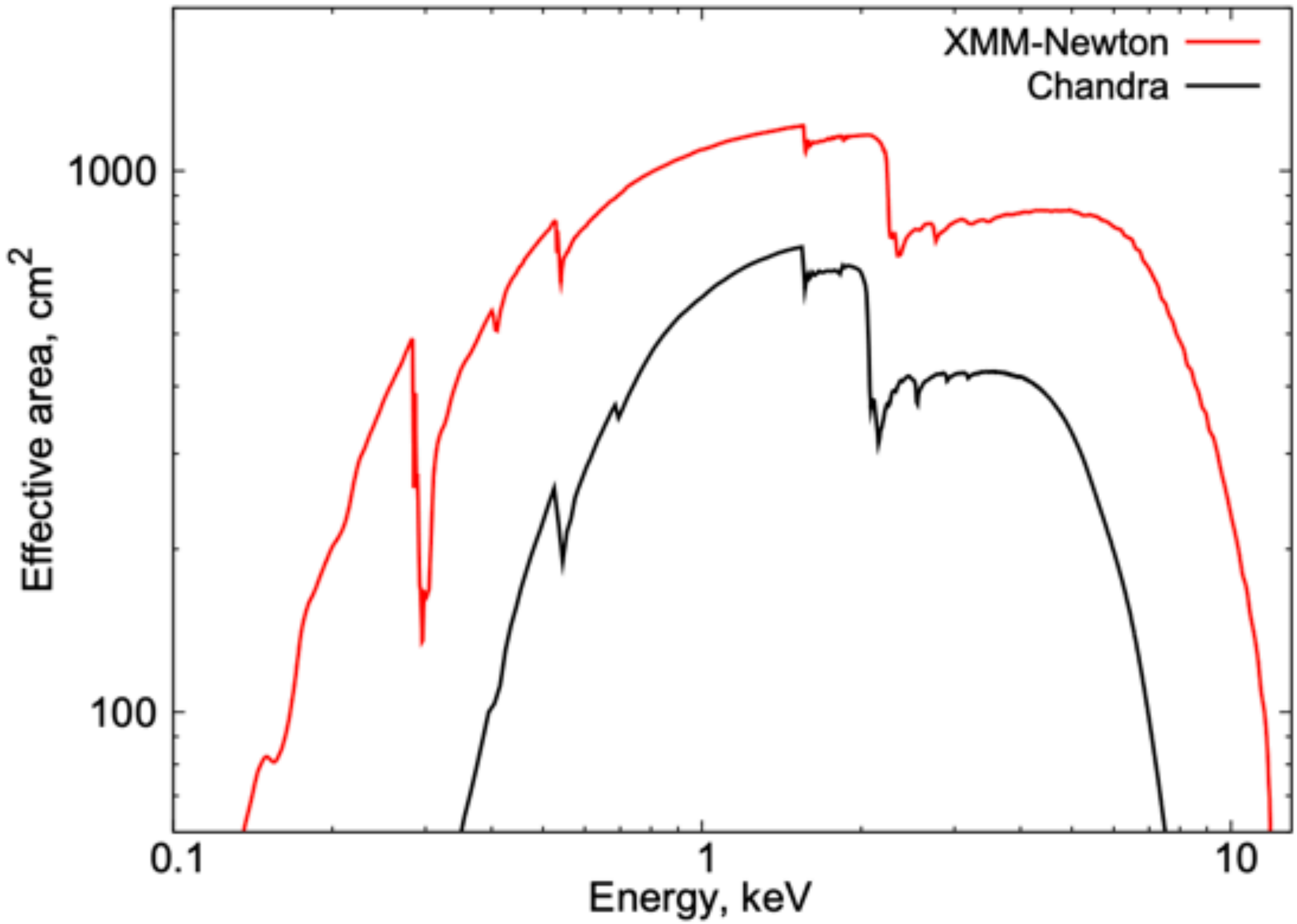
…Einstein observatory, Rosat, ASCA, Chandra, XMM-Newton

Major X-ray observatories (for clusters) today



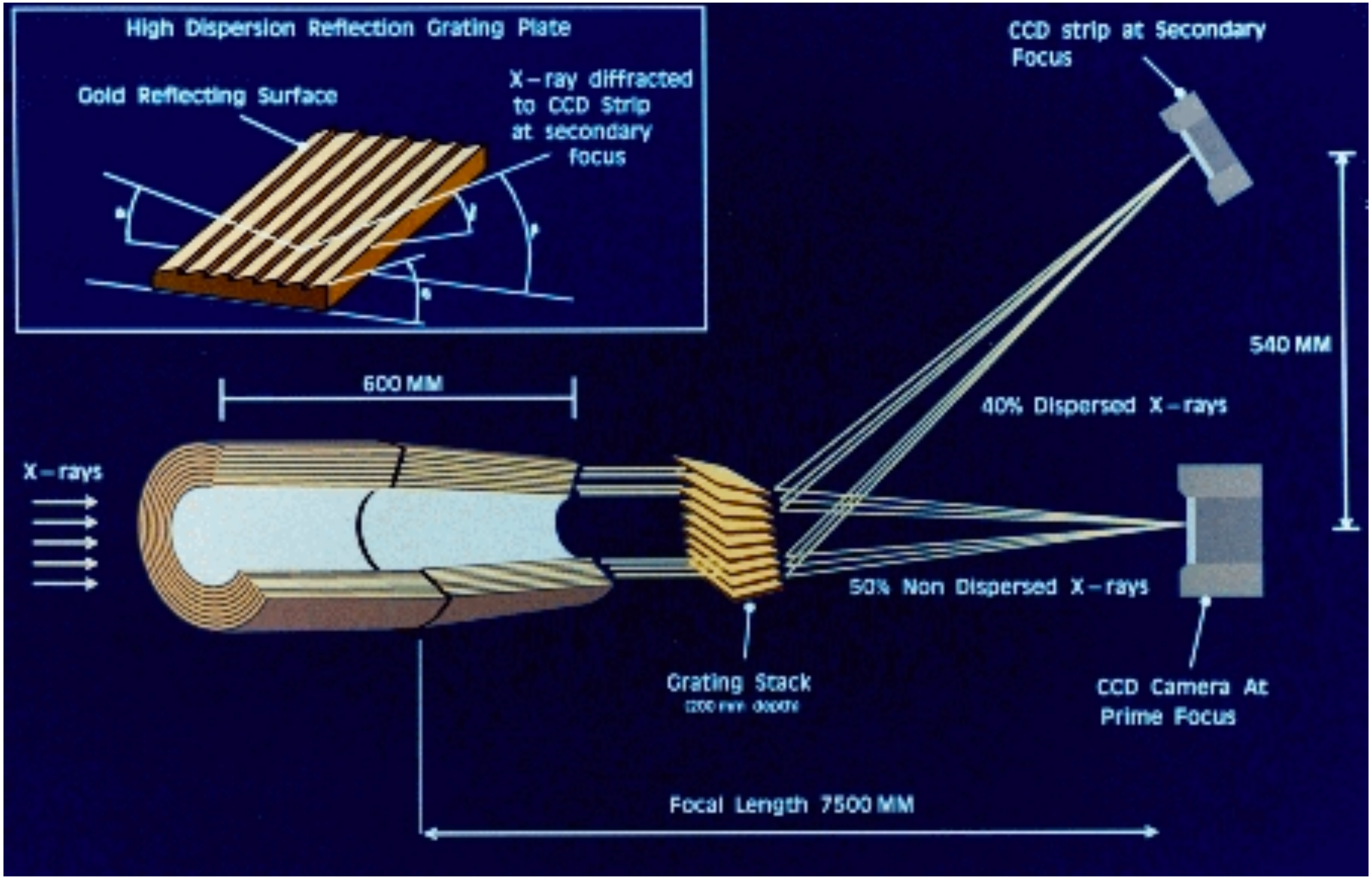
Angular resolution <1"

Effective area ~2500 cm^2



$$\Delta E \sim 150 \text{ eV}$$

Gratings on XMM and Chandra

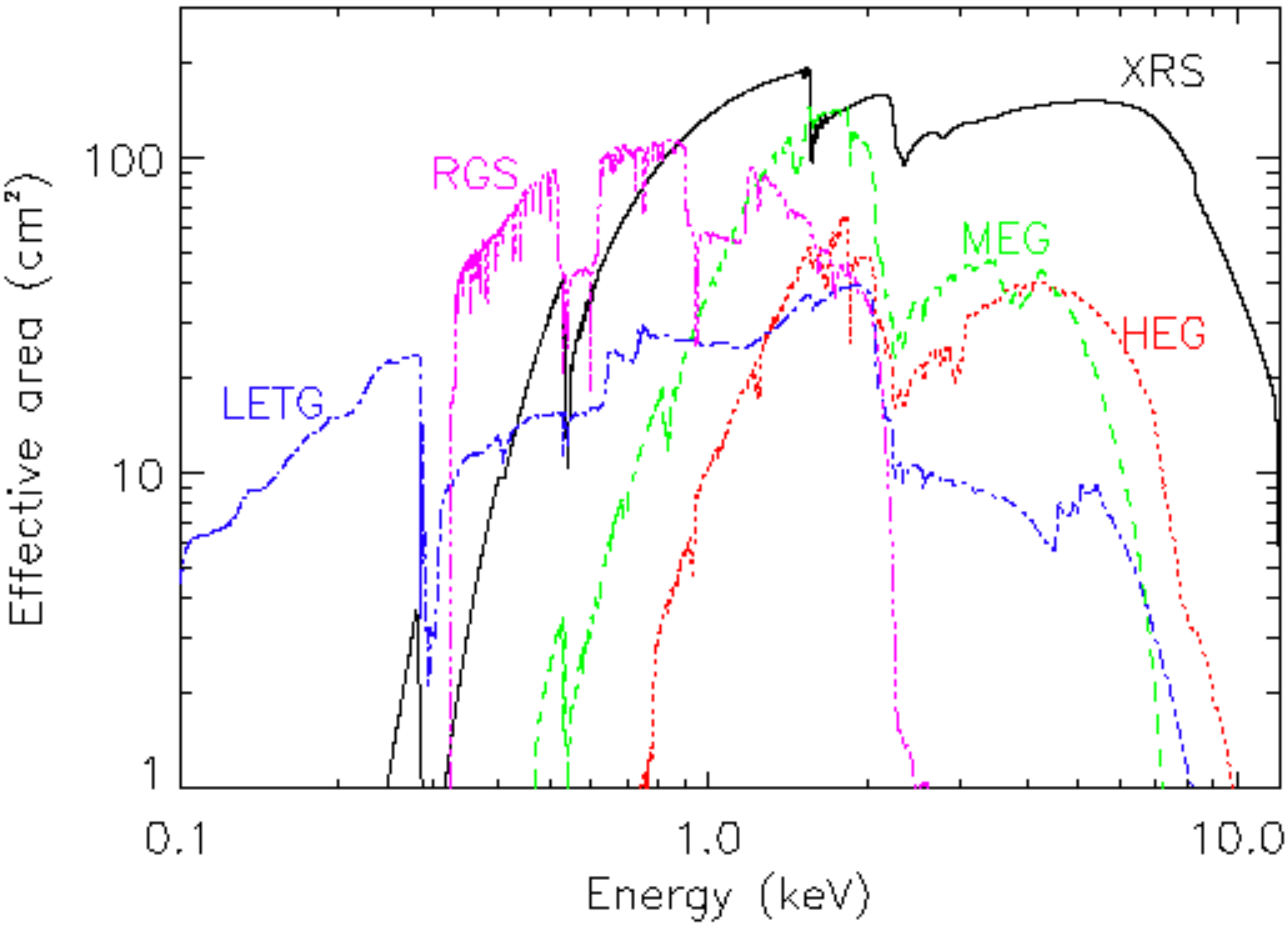


http://www.mssl.ucl.ac.uk/www_xmm/ukos/onlines/uhb/XMM_UHB/node14.html

$$\Delta E \sim 4 \text{ eV}$$

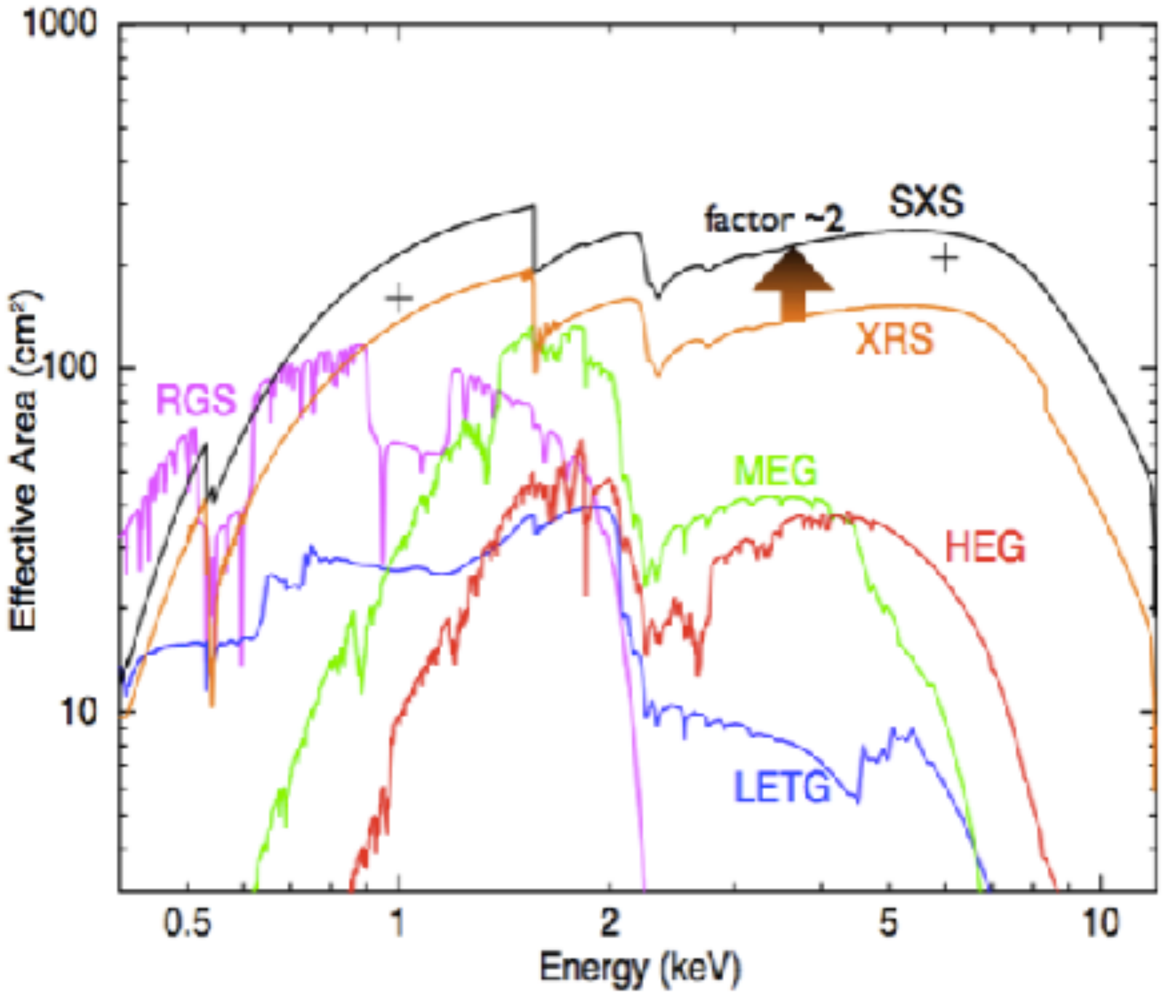
(But only for compact sources and with small efficiency)

~100 cm²



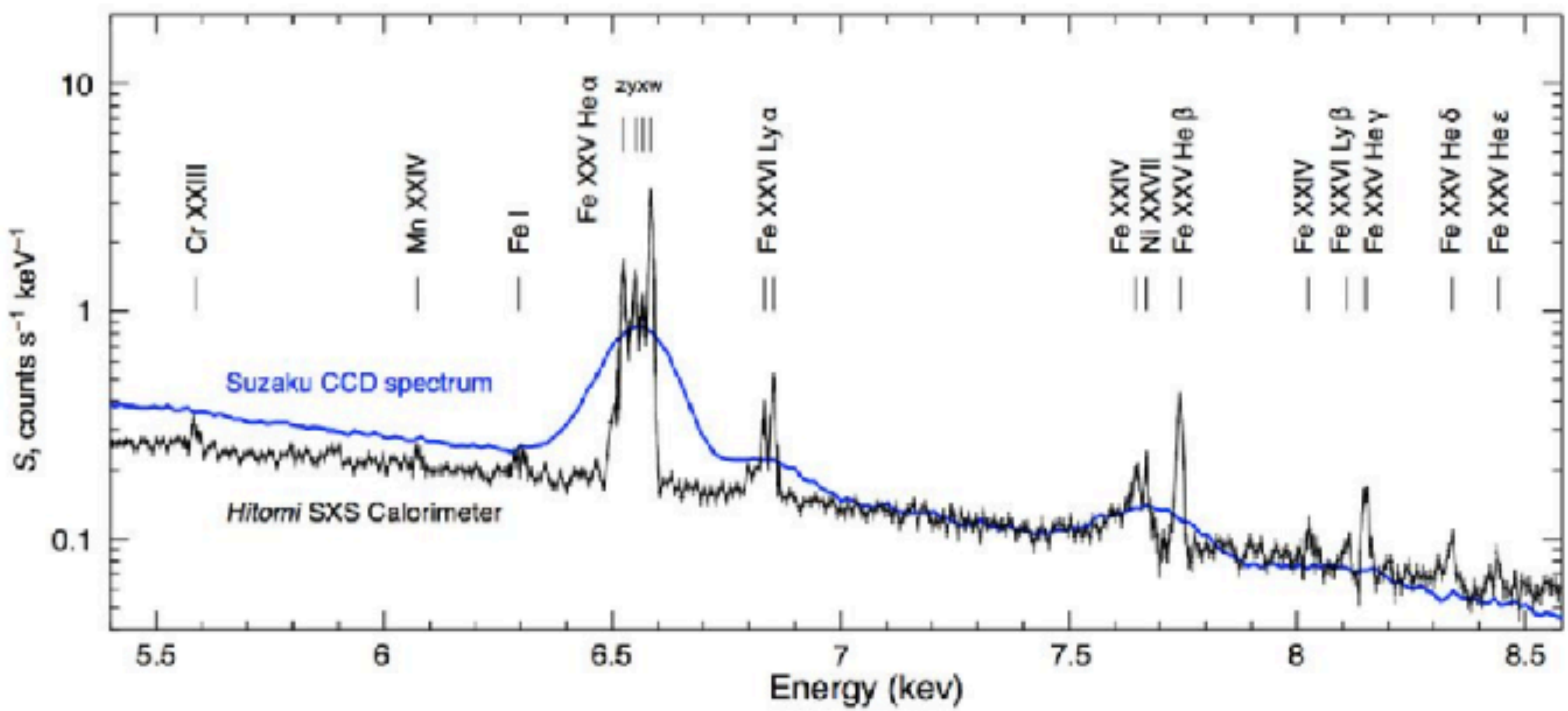
XRS
RGS
MEG
HEG
LETG
100
10
1
0.1
1.0
10.0
Effective area (cm²)
Energy (keV)

For clusters - one needs non-dispersive spectrometer



Solution: cryogenic bolometers with <5 eV resolution

Hitomi



BLACK: Hitomi SXS (FWHM 4.9 eV)

BLUE: Best previous spectrum (Suzaku CCD; FWHM 140 eV)

Hitomi Collaboration

Galaxy clusters

Clusters usually refer as

Clusters are the most massive gravitationally bound structures in the Universe….

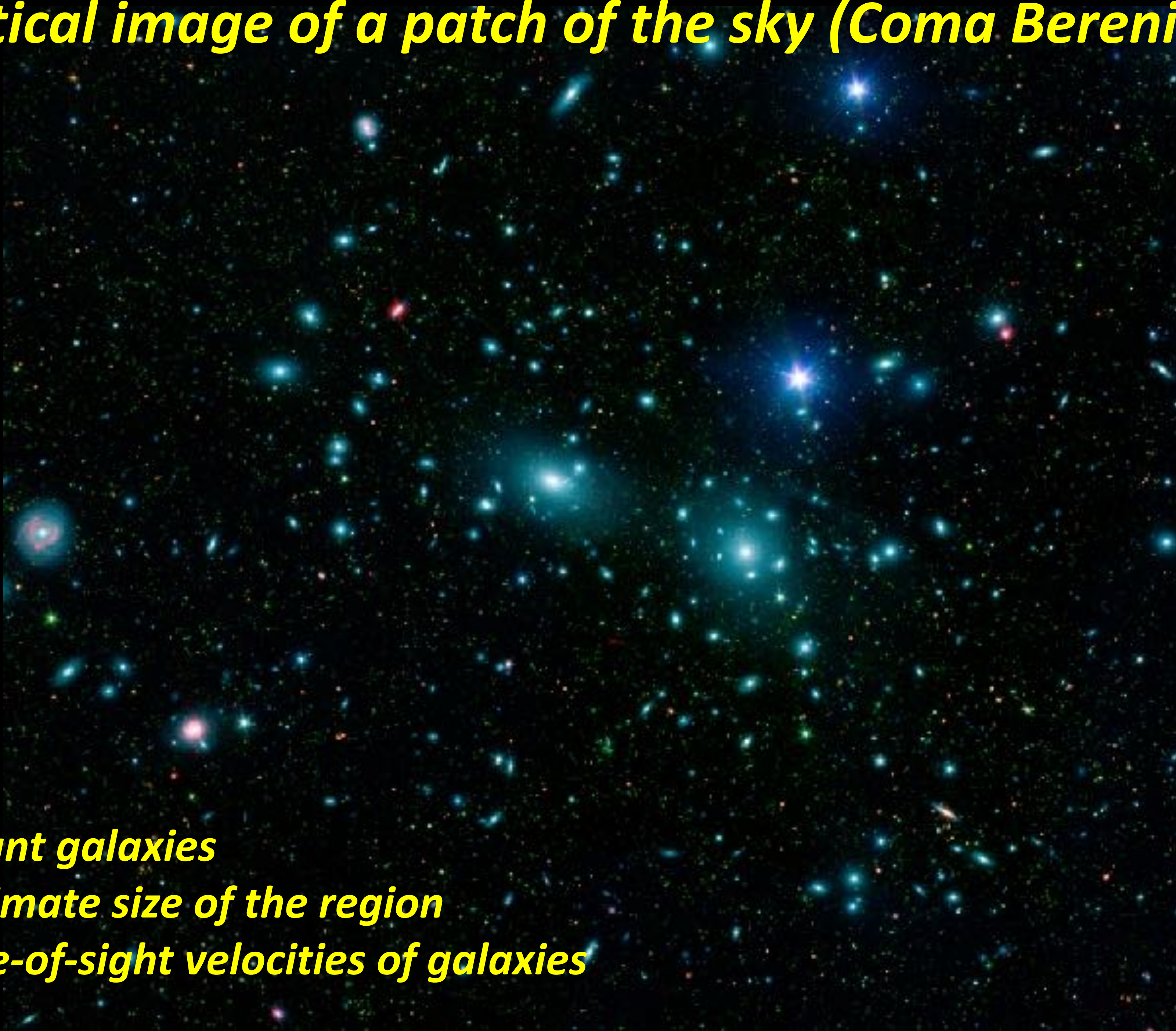
Clusters are formed recently...

Clusters are powerful X-ray sources….

Clusters represent a fair sample of matter (which is able to cluster) in the Universe….

Clusters are great astrophysical plasma laboratories

Optical image of a patch of the sky (Coma Berenices)

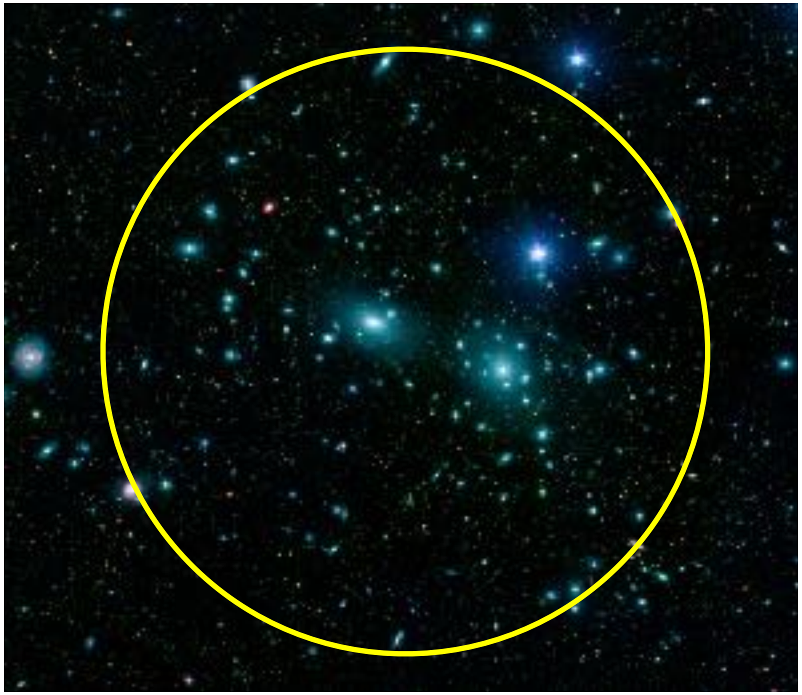


Count galaxies

Estimate size of the region

Line-of-sight velocities of galaxies

Clusters and Dark Matter



$$R \sim \text{Mpc}, \quad \sigma \sim 1000\ \text{km/s}$$

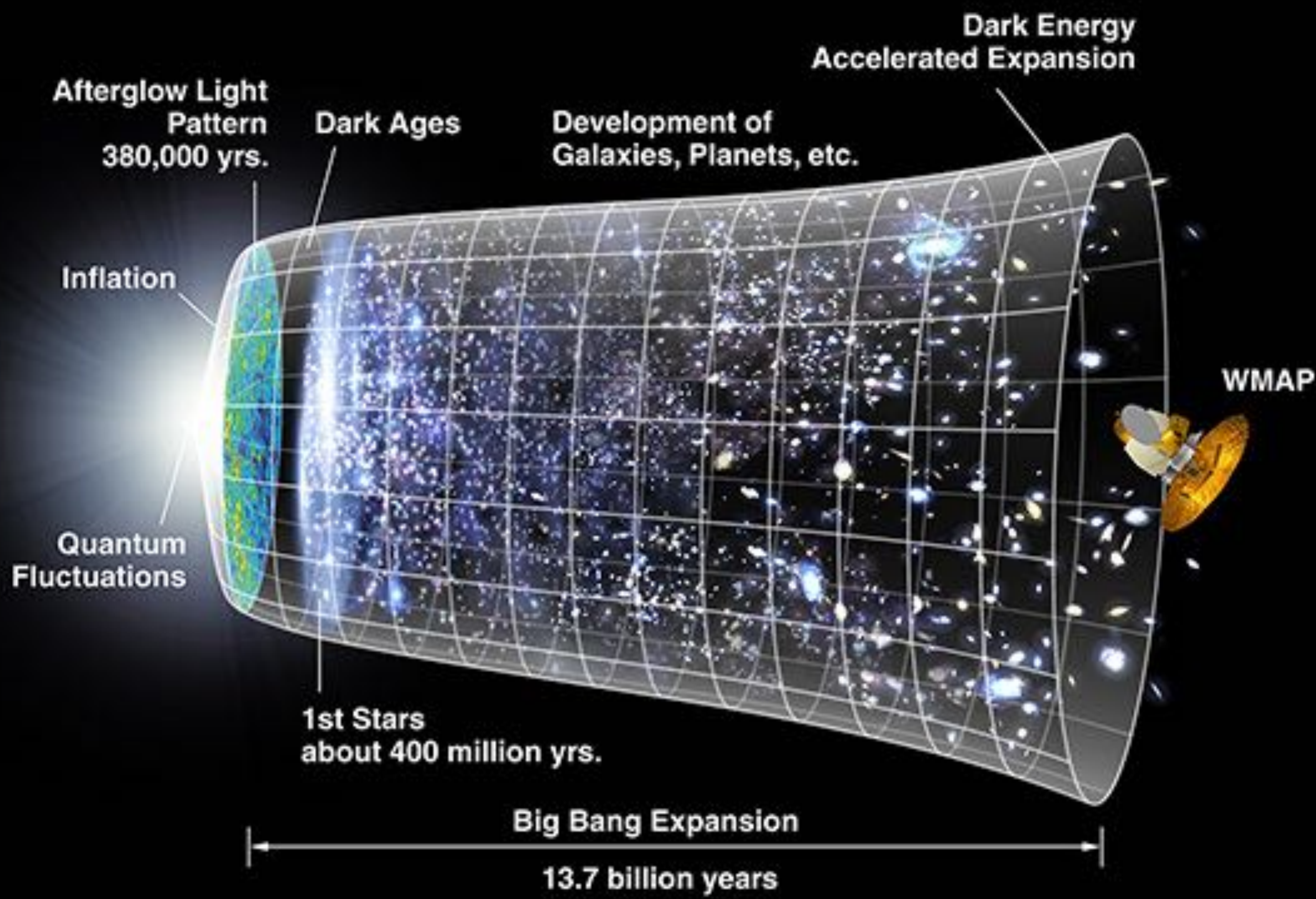
$$-U = 2K$$

$$\frac{GM}{R} \approx \langle v^2 \rangle = 3\sigma^2$$

$$M \sim 10^{15}\, M_{\odot}$$

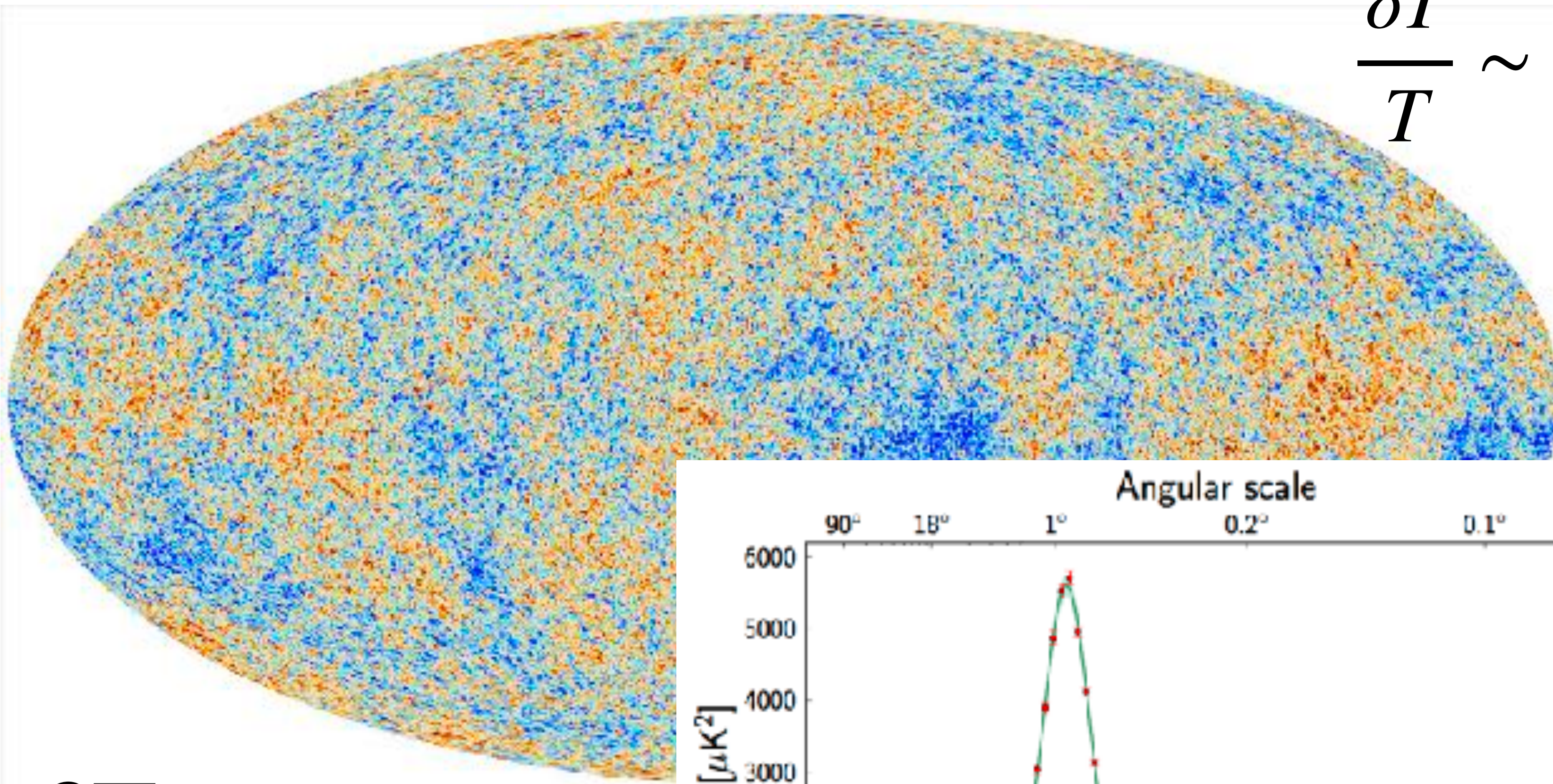
While examining the Coma galaxy cluster in 1933, Zwicky was the first to use the virial theorem to infer the existence of unseen matter, what is now called dark matter. He obtained a cluster mass about 160 times greater than expected from galaxies luminosity, and proposed that most of the matter was dark.

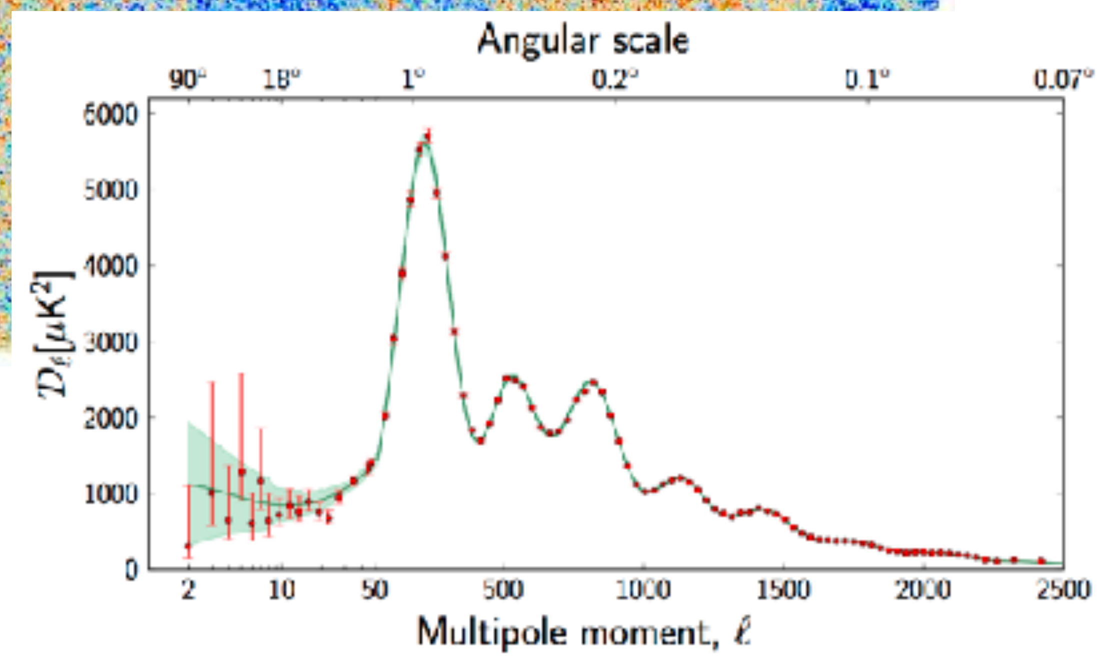
Radiation dominated *(Dark) Matter dominated* *(Dark) Energy dominated*



Planck: Map of the CMB temperature fluctuations

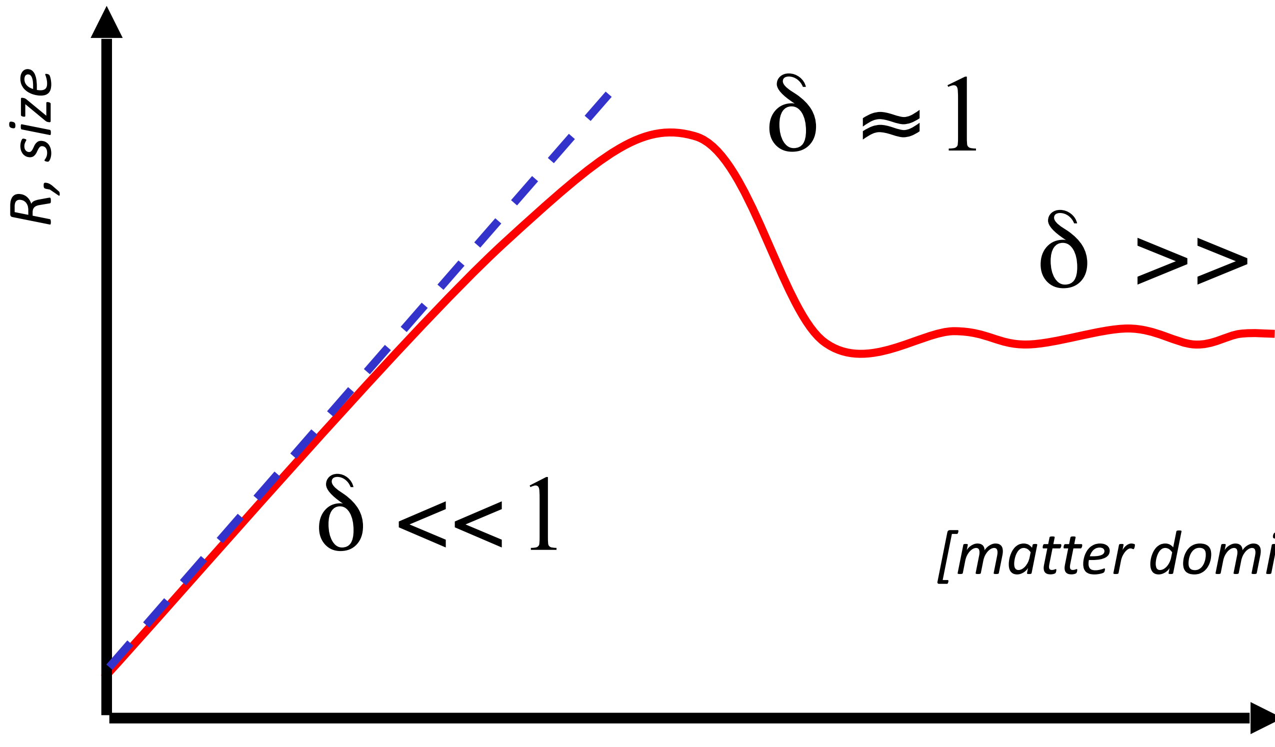
$$\frac{\delta T}{T} \sim \frac{1}{3}\frac{\phi}{c^2}$$





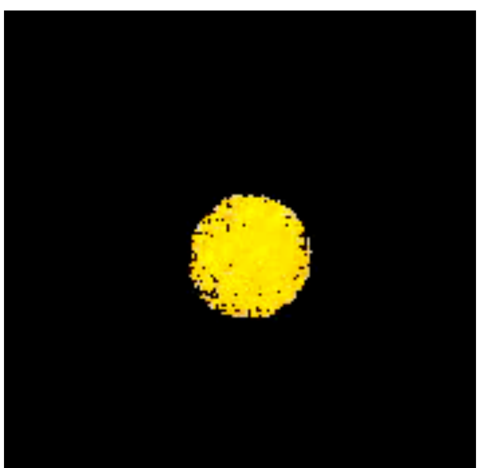
$$\frac{\delta T}{T} \sim 10^{-5}$$

$$\delta = \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle}$$



[matter dominated Universe]

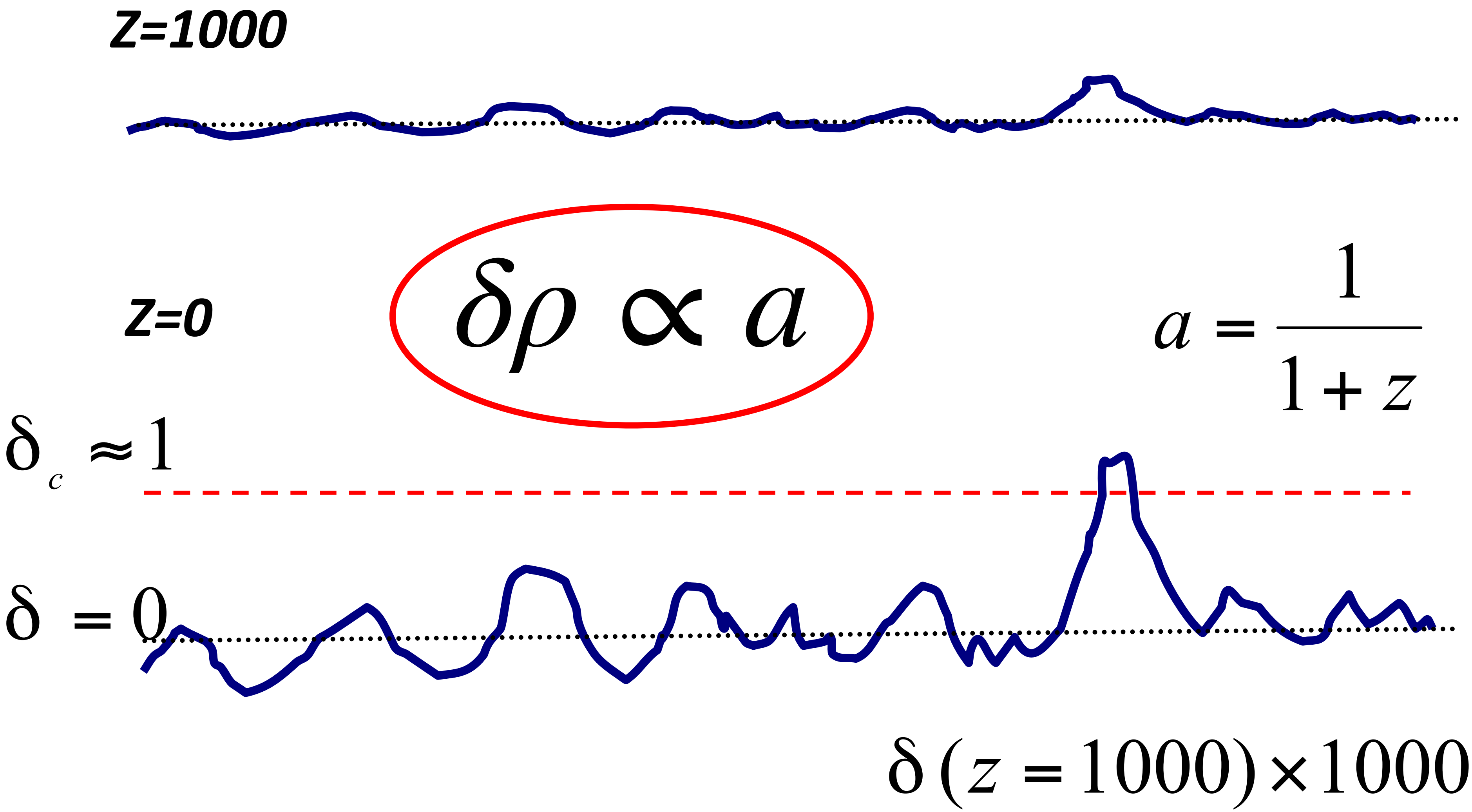
a, scale factor



$$\delta \approx 1 \quad \left(\rho \approx 2\langle \rho \rangle\right)$$

Spherical collapse model

Growth of perturbations in EdS Universe [z=1-1000]



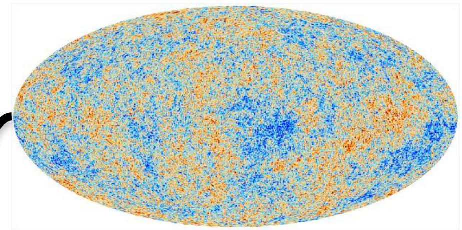
$$\delta\rho \propto a$$

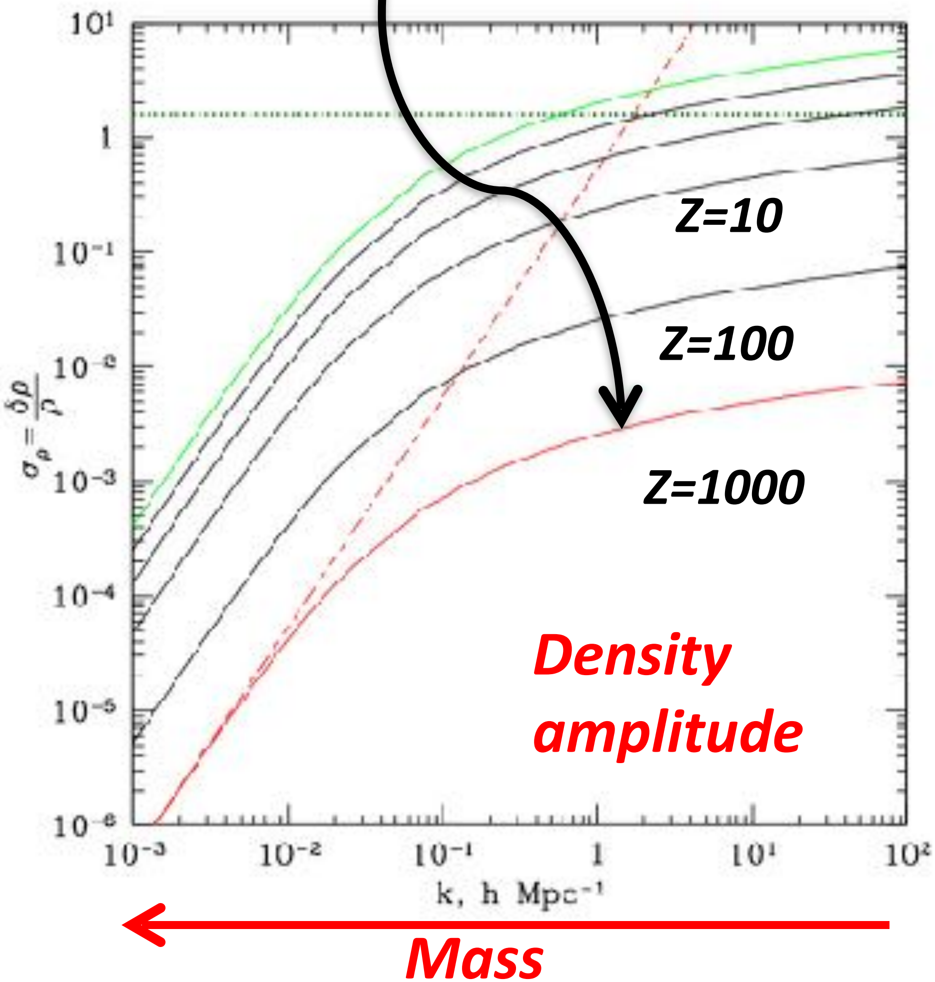
$$a = \frac{1}{1+z}$$

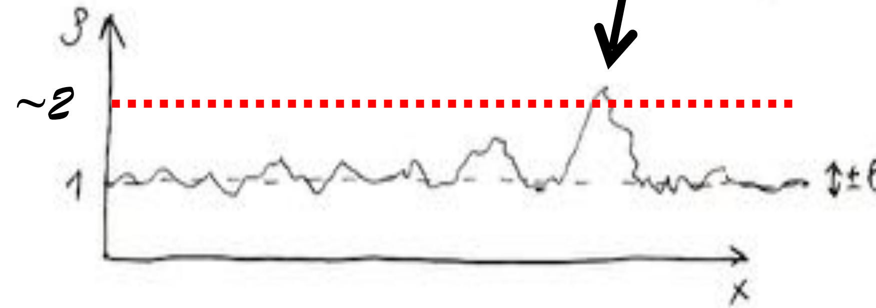
Density/potential fluctuations

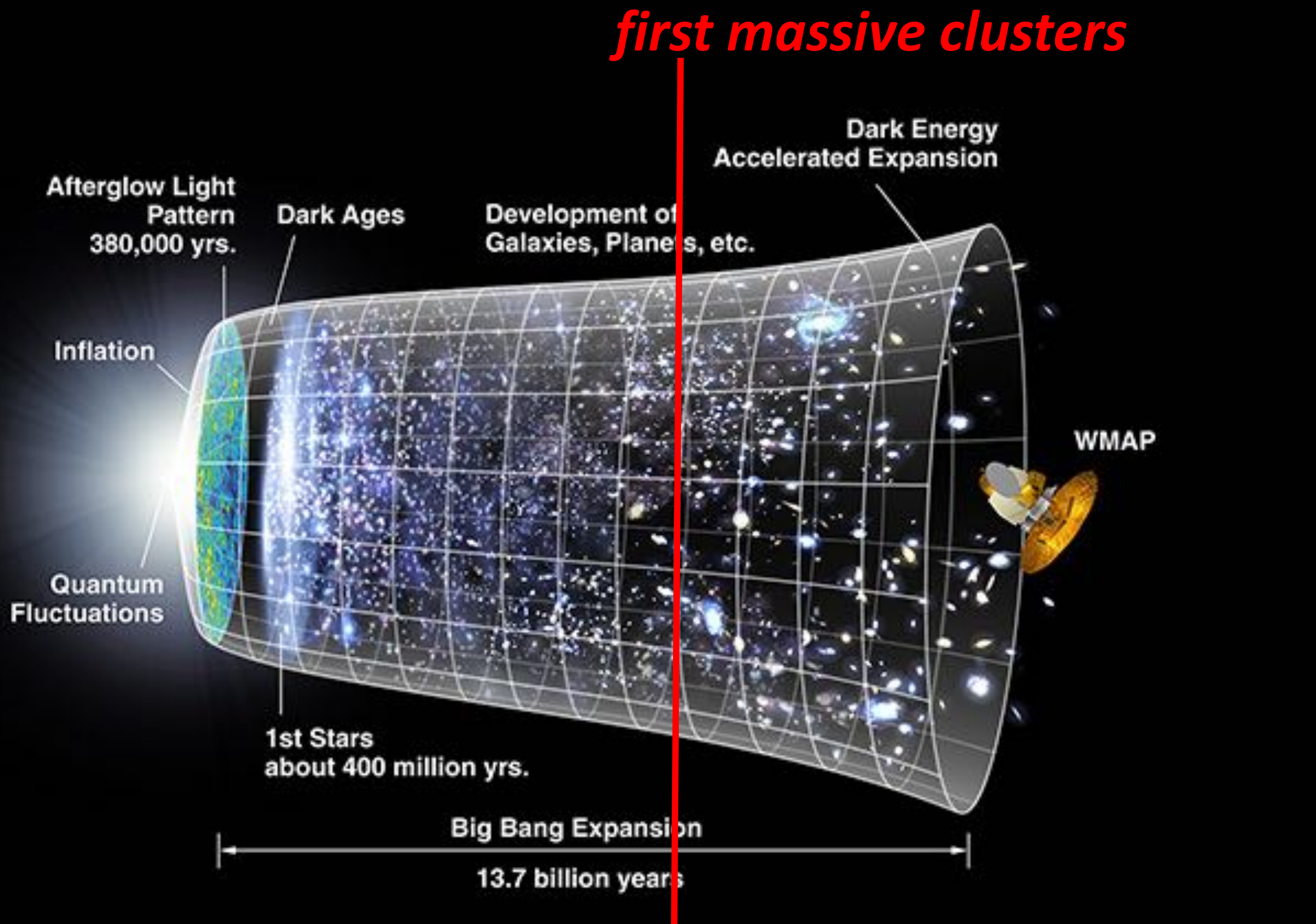
$$N \propto \exp\left\{-\frac{\delta_c^{\,2}}{\sigma^{\,2}}\right\}$$

$$\delta \propto a$$







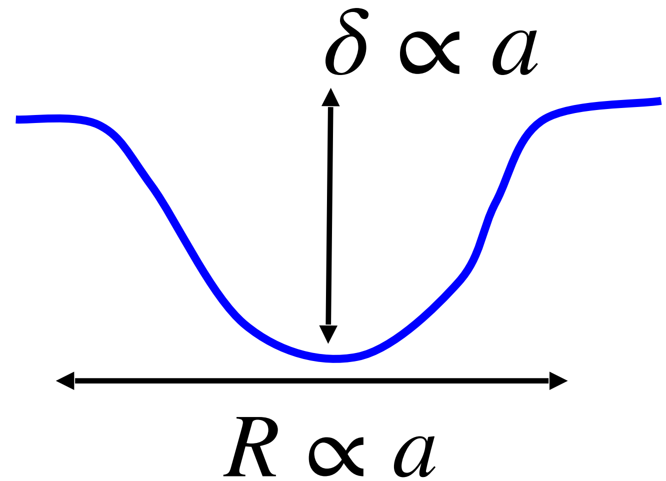


This is why clusters are the most massive systems in the Universe (there are ~50 clusters in observable Universe with mass > 10^{15} M_{Sun})

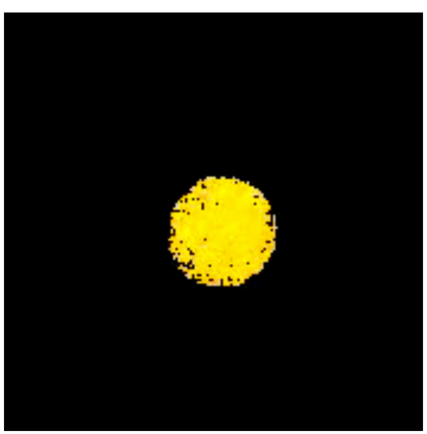
Linear evolution of gravitational potential

$$\phi \propto G\frac{\delta M}{R} \propto \frac{\delta}{a} \sim \text{const}$$

No DE



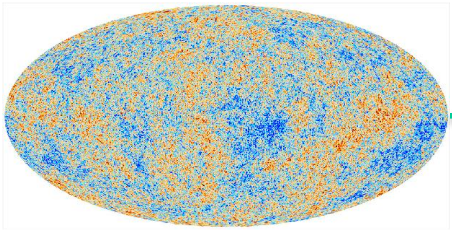
Nonlinear evolution of the potential



$$-G\frac{M^2}{R_i} = -G\frac{M^2}{R_f} + \frac{1}{2}G\frac{M^2}{R_f}$$

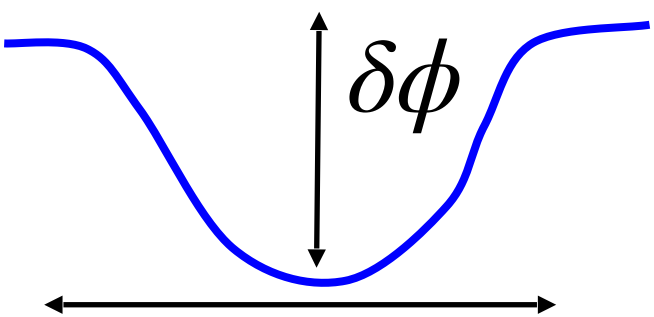
$$R_f \sim \frac{1}{2}R_i \implies \phi_f \sim 2\phi_i$$

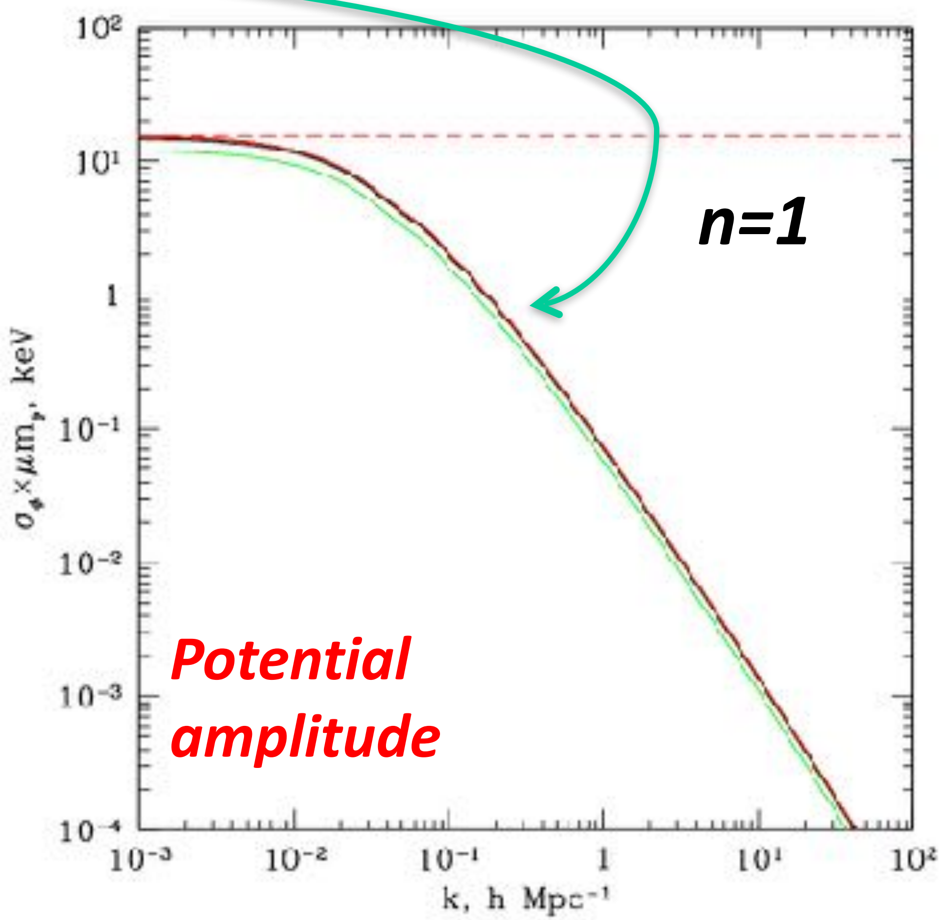
Big and deep potential well => Hot plasma => X-rays



$$\frac{\delta T}{T} \sim \frac{\delta\phi}{c^2} \sim 10^{-5}$$

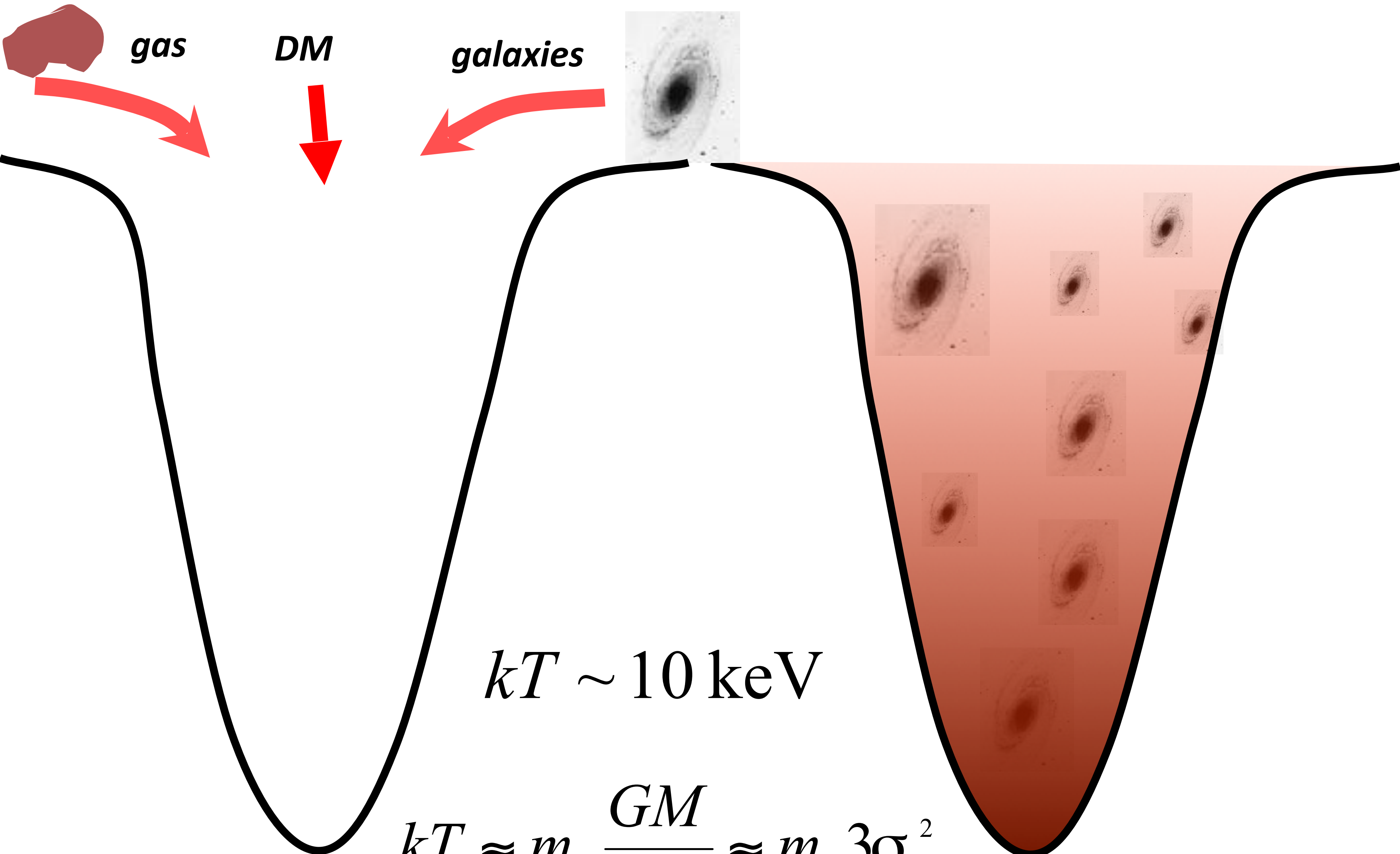
$$\delta\phi m_p \sim 15\ \mathrm{keV}$$





Hotter ⟷ *Colder*

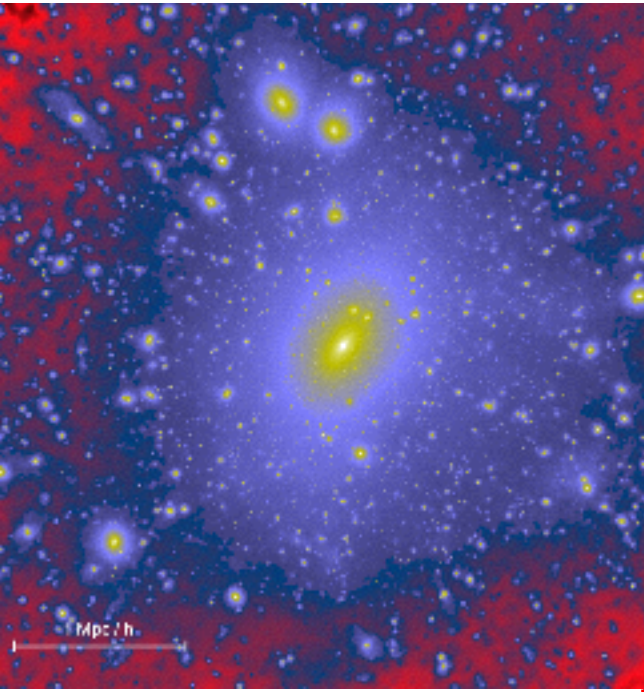
(DM+Baryons) Potential Well

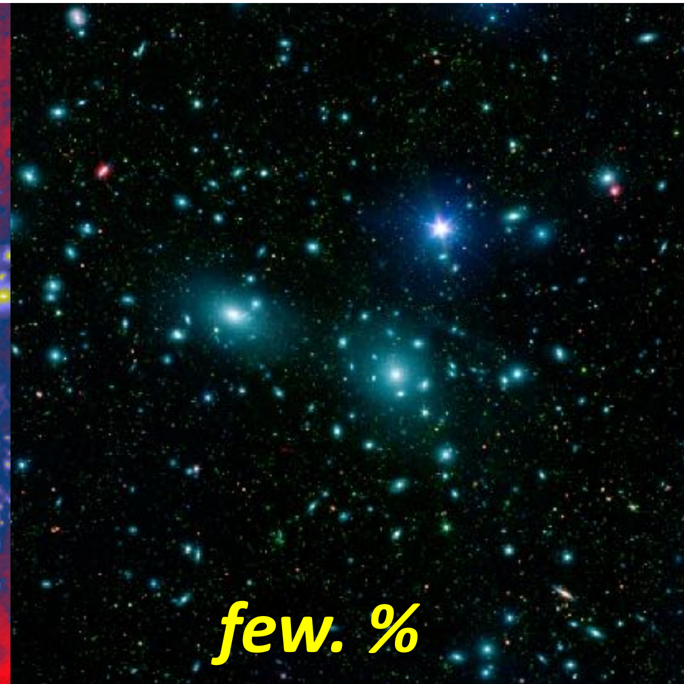


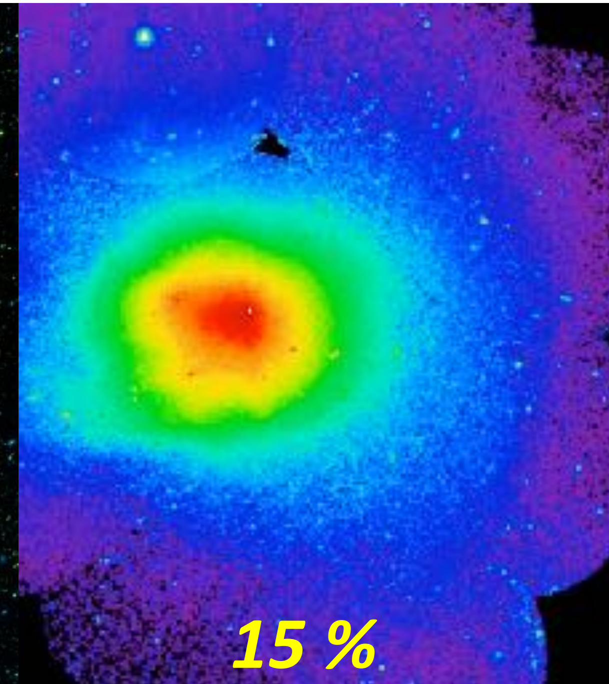
$$kT \sim 10\,\mathrm{keV}$$

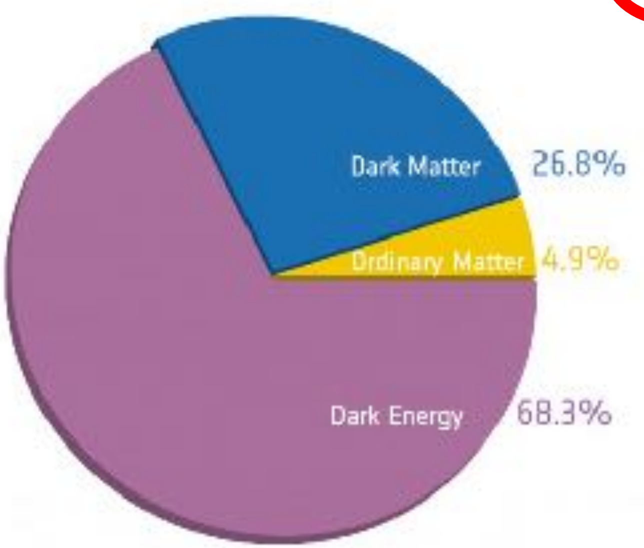
$$kT \approx m_p \frac{GM}{R} \approx m_p 3\sigma^2$$

Dark matter *Stars* *Hot gas*









baryons

$$\frac{\text{baryons}}{\text{DM}} = \frac{\text{gas} + \text{stars}}{\text{DM}} \approx 0.2$$

Universe *Clusters*

Clusters usually refer as

Clusters are the most massive gravitationally bound structures in the Universe….

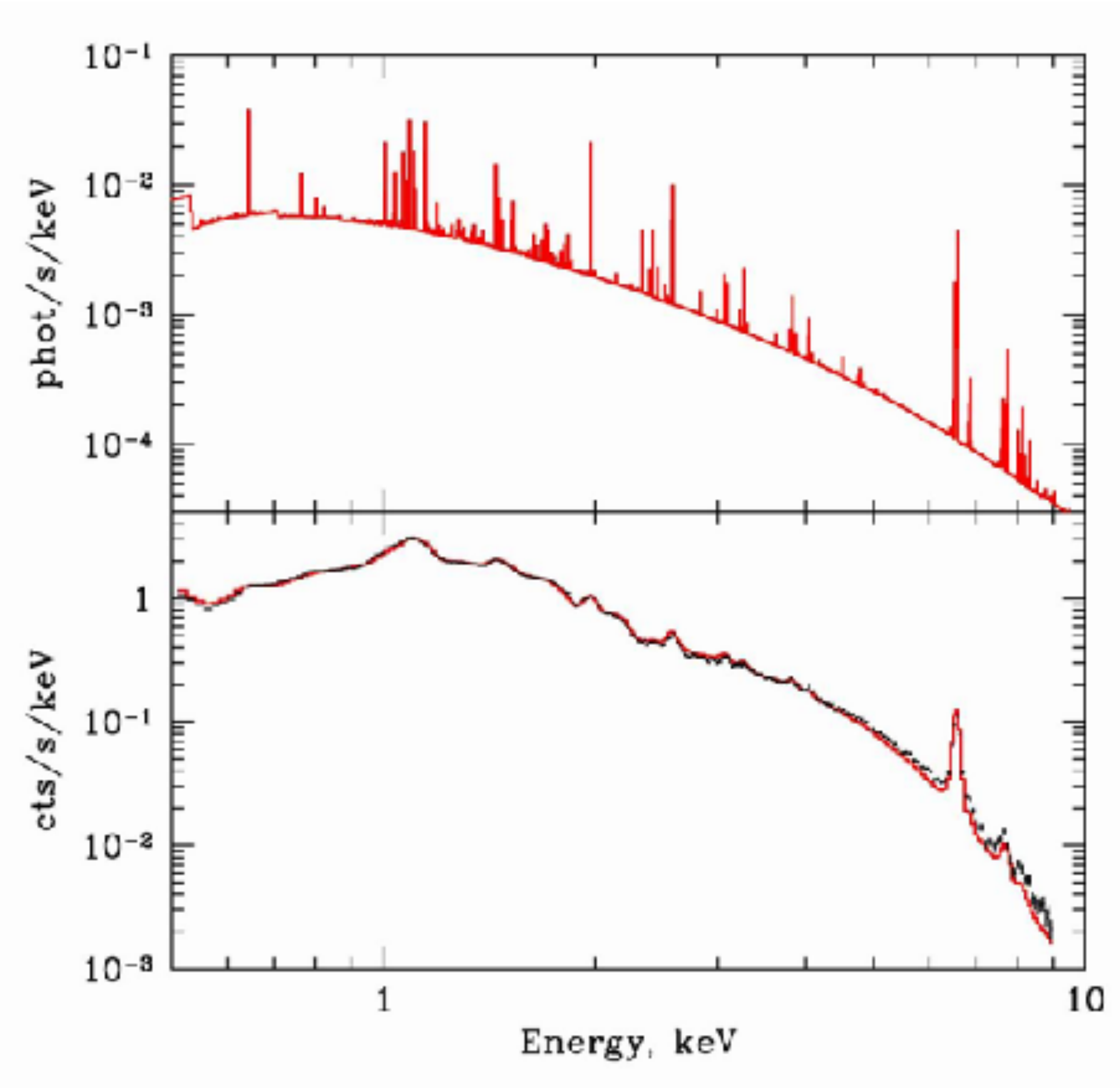
Clusters are formed recently…

Clusters are powerful X-ray sources….

Clusters are representing a fair sample of matter (which is able to cluster) in the Universe….

Clusters are great astrophysical plasma laboratories

What we can learn from X-ray spectra



Bremsstrahlung + lines + recombination + 2-photon

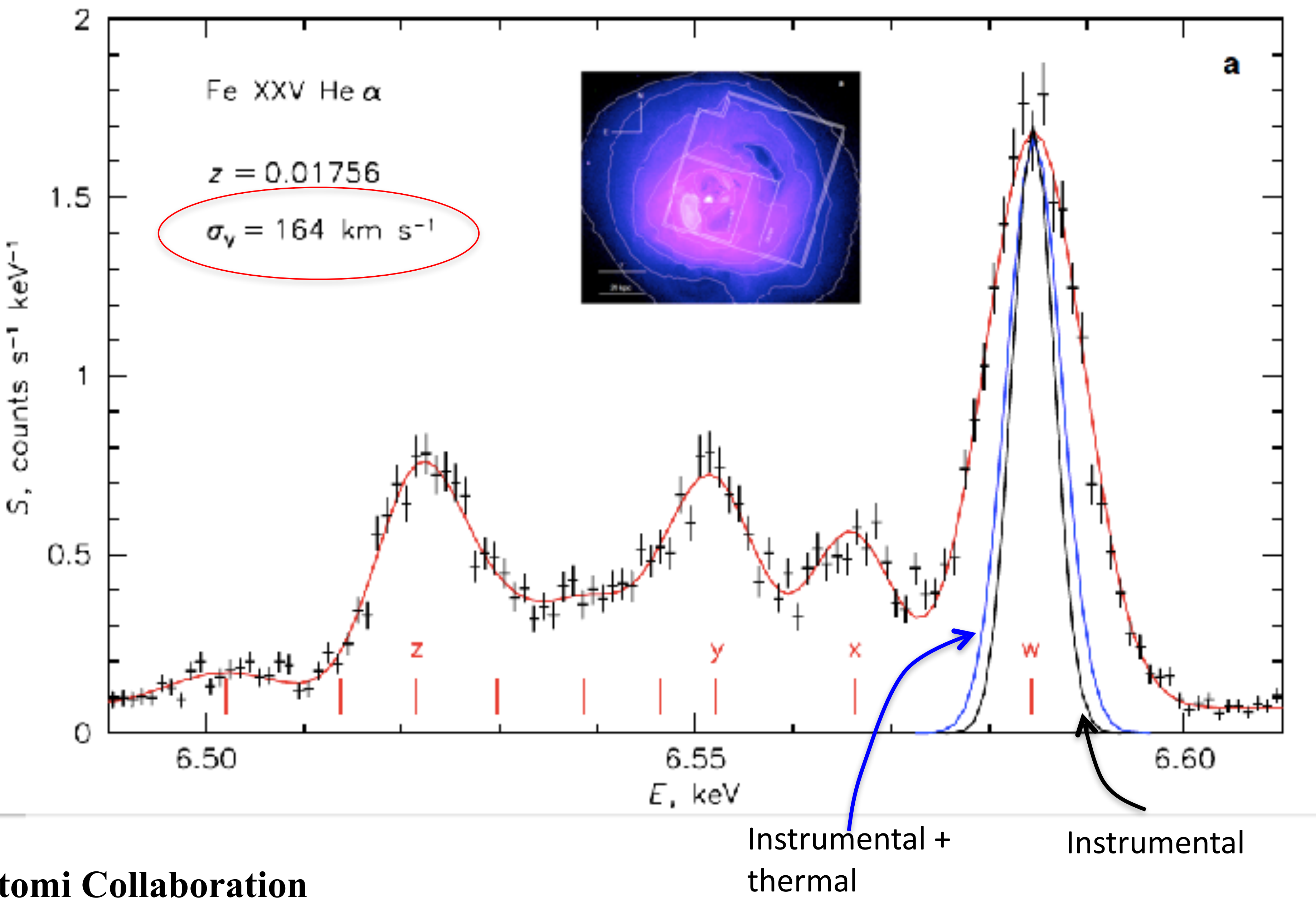
Flux → density

Curvature → temperature

Line Energy → redshift

Line Strength → abundance

The only existing resolved He-like triplet of Iron from a cluster



Hitomi Collaboration

Plasma in galaxy clusters

$n_e \sim 10^{-3}\,\mathrm{cm}^{-3}$ $kT_e \sim 10\,\mathrm{keV}$ $\boxed{u \sim 500\,\mathrm{km\,c}^{-1}}$ $L \sim 1\,\mathrm{Mpc}$

Spectroscopy

CEI, t_i~10 Myr; Age~Gyr

t_{ee}~3 10^5 yr; t_{ei}~few 10^8 yr

~Maxwellian

Optically thin (free-free)

Material properties

$$\lambda \sim 10\,\mathrm{kpc}$$

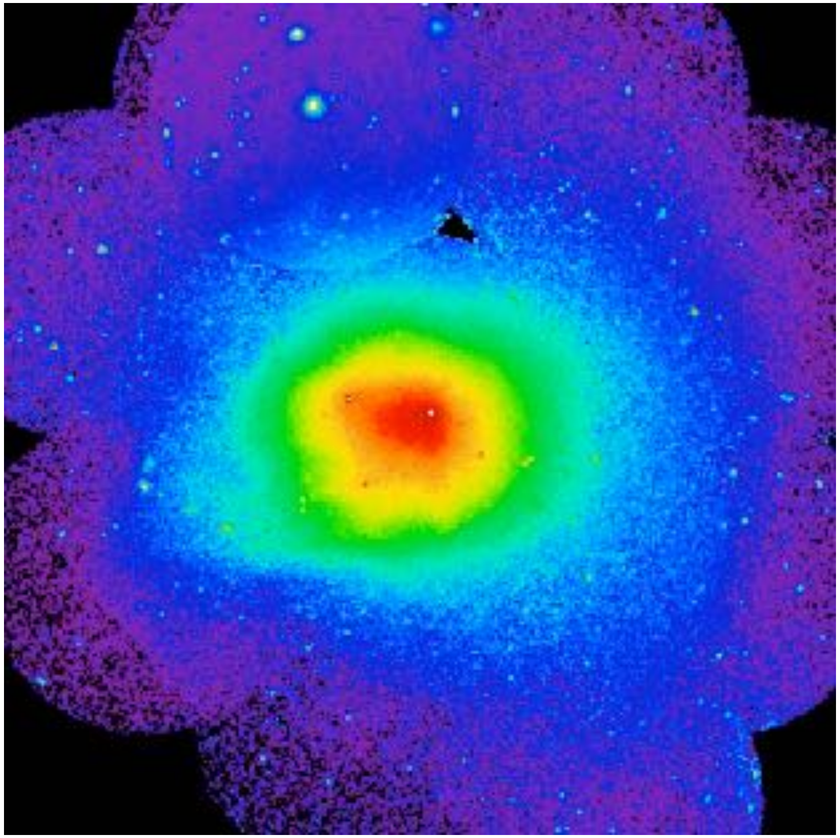
$$\mathrm{Re} \sim 10$$

$$\mathrm{Pr} \sim 0.02$$

$$\beta = 8\pi \frac{nkT}{B^2} \sim 100$$

$$\rho_e \sim 10^3\ \mathrm{km} \lll \lambda$$

Are clusters optically thin?



Optical depth for free-free

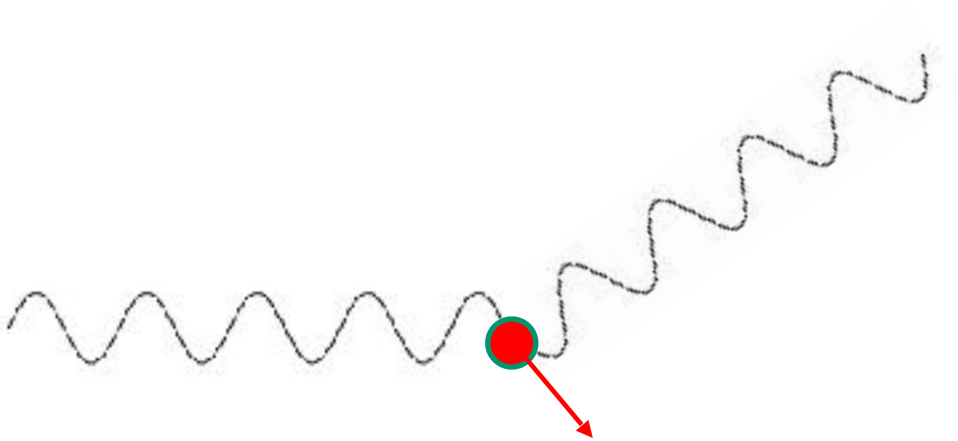
$$\frac{L_X}{4\pi R^2 \sigma T^4} \approx \frac{10^{45}\ \text{erg/s}}{10^{77}\ \text{erg/s}} \approx 10^{-32}$$

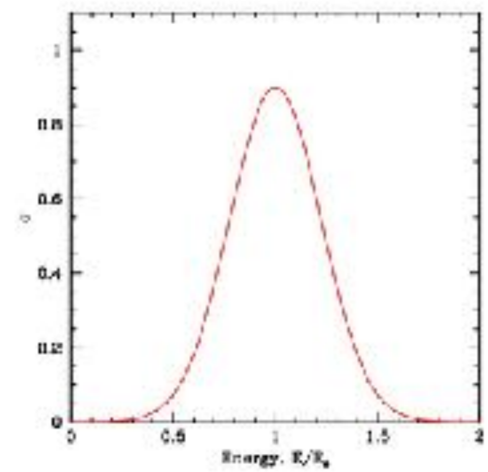
Thomson optical depth

$$\tau_T = \sigma_T n_e R \approx 10^{-3} - 10^{-2}$$

Clusters are optically thin in X-rays (in continuum)

Resonant scattering (absorption+emission)

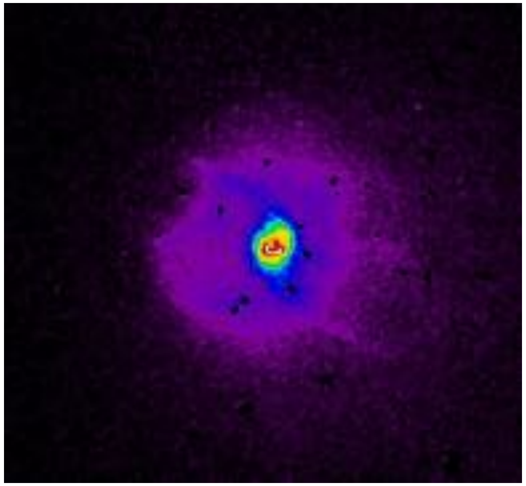




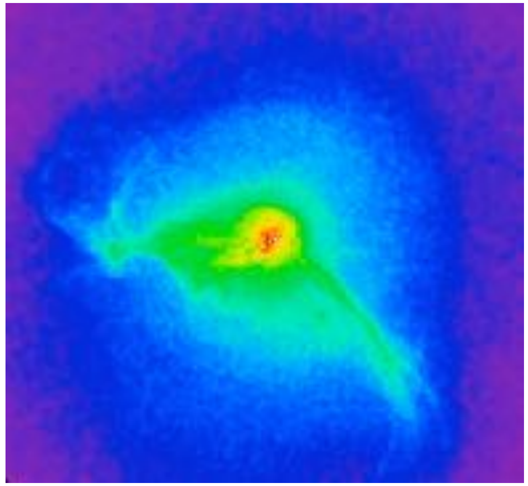
$$\sigma_0 = \frac{\sqrt{\pi}\, h r_e c f_{ik}}{\Delta E_D}; \quad \Delta E_D = E_0 \frac{v}{c} = E_0 \left[\frac{2kT}{A m_p c^2} \right]^{1/2}; \quad \tau_0 = n_i l \sigma_0$$

1) ***Abundant elements; He-like ions; maximal oscillator strength***
2) ***Heavy elements have narrow lines (if no turbulent motions)***
3) ***Product of density and size***

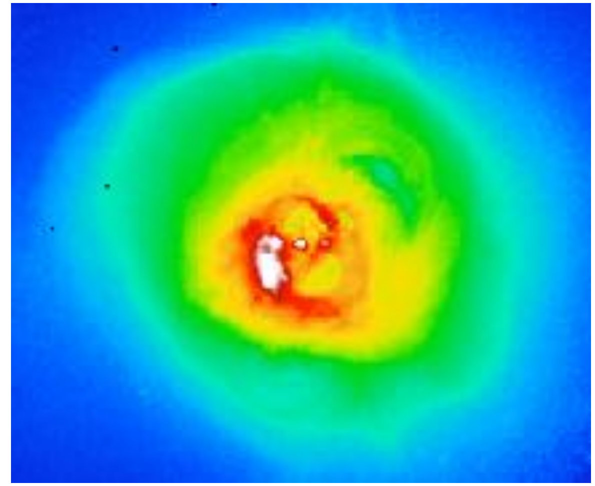
Optical depth in lines



NGC4636; 0.6 keV



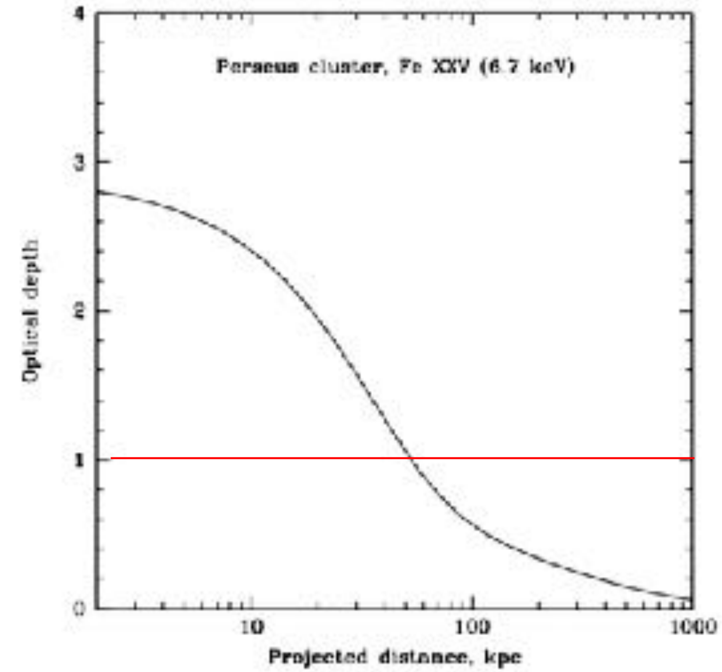
M87; 1-3 keV

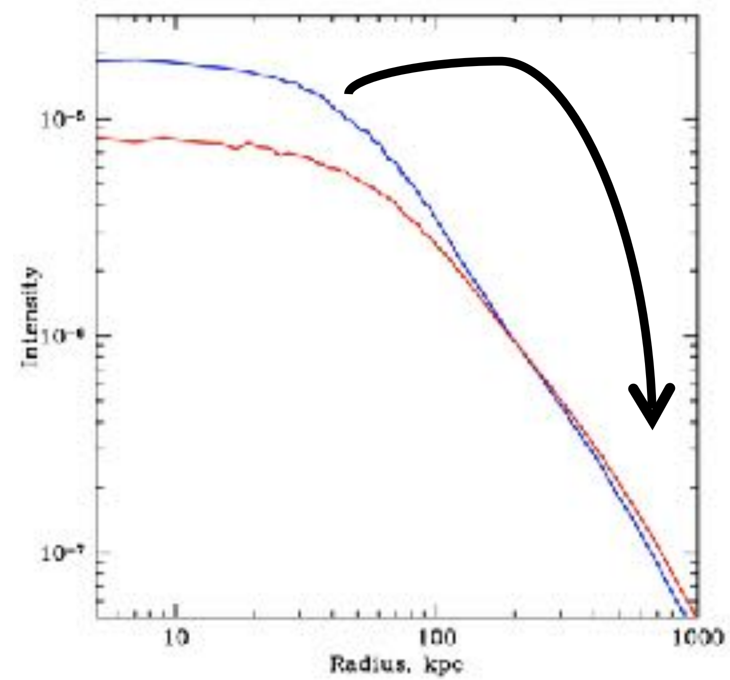


Perseus; 3-7 keV

Ion	E, keV	f	w_2	τ, NGC 4636	τ, Virgo/M87	τ, Perseus
O VIII	0.65	0.28	0.5	1.2	0.34	0.19
Fe XVIII	0.87	0.57	0.32	1.3	0.0007	$1.5 \cdot 10^{-7}$
Fe XVII	0.83	2.73	1	8.8	0.0005	$2.8 \cdot 10^{-8}$
Fe XXIII	1.129	0.43	1	0.016	1.03	0.16
Fe XXIV	1.168	0.245	0.5	0.002	1.12	0.73
Fe XXV	6.7	0.78	1	0.0002	1.44	2.77

Impact on the surface brightness

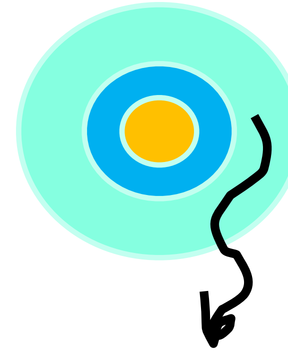


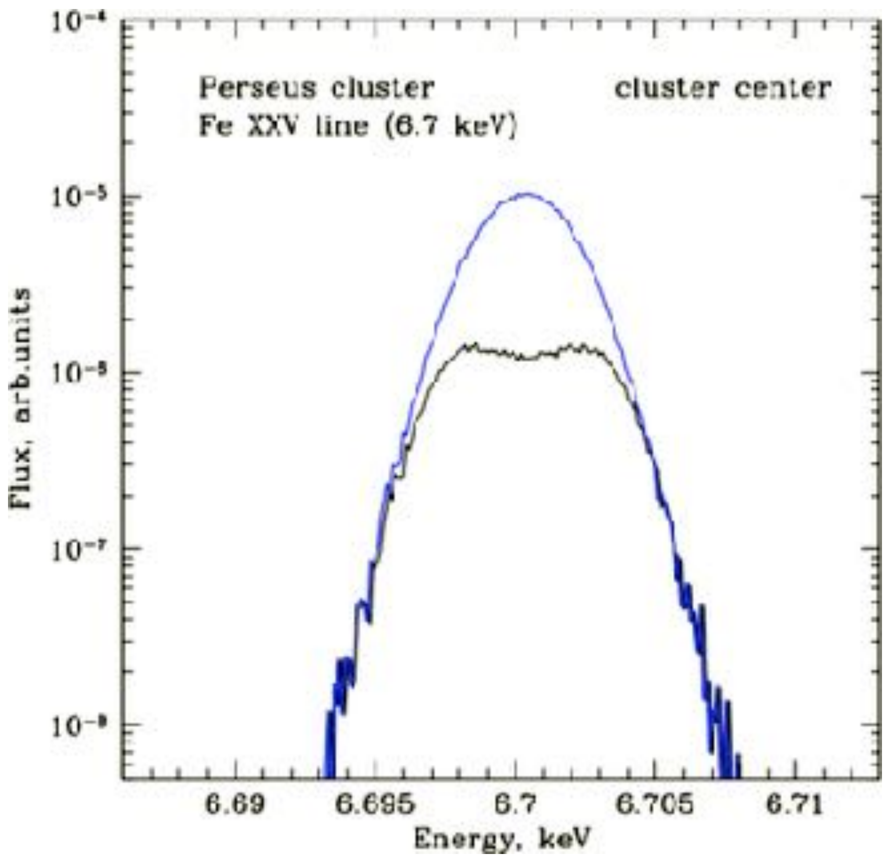


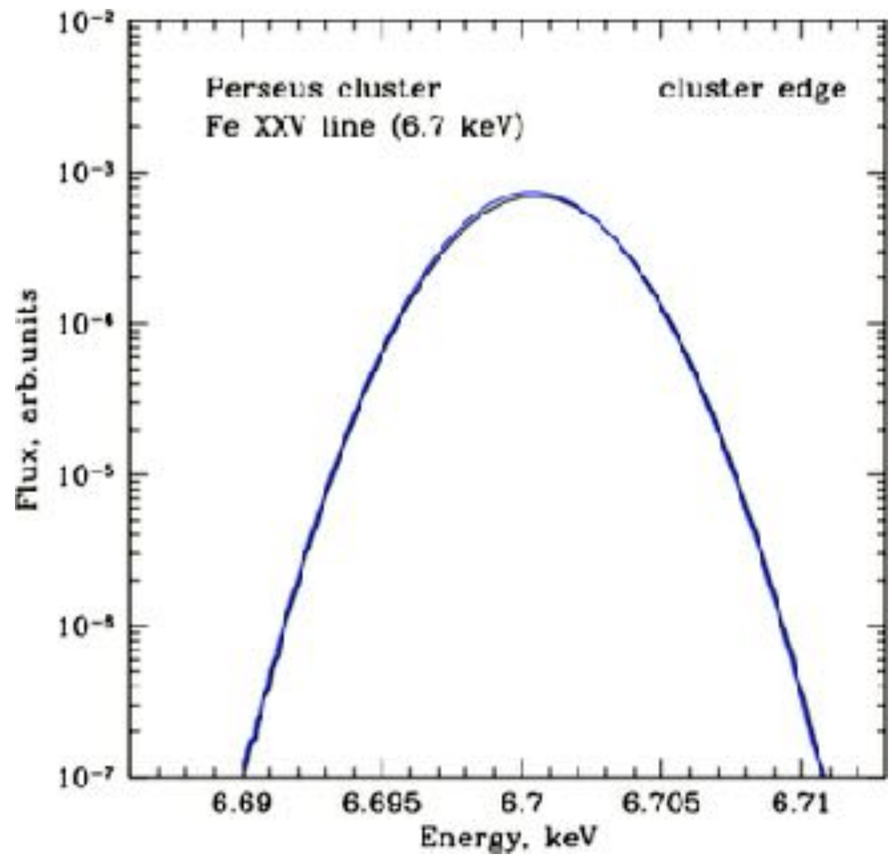
Line is suppressed in the core

Photons are re-emitted at the outskirts

Spectral shape of the line







Core of the line is suppressed

Gas Velocities I

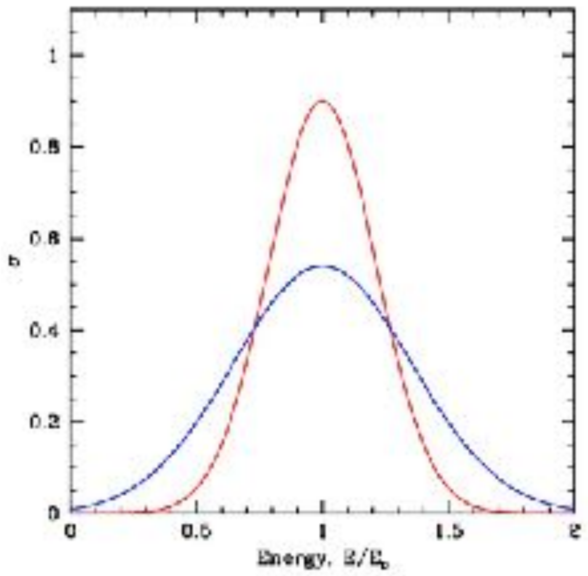
$$\sigma_0 = \frac{\sqrt{\pi}\, h r_e c f_{ik}}{\Delta E_D}; \quad \Delta E_D = E_0 \left[\frac{2kT}{A m_p c^2} + \frac{V_{turb}^2}{c^2} \right]^{1/2}$$

FeXXV; 6.7 keV line; T=5 keV

Radiative width: ***0.3 eV***

Thermal width: ***3 eV***

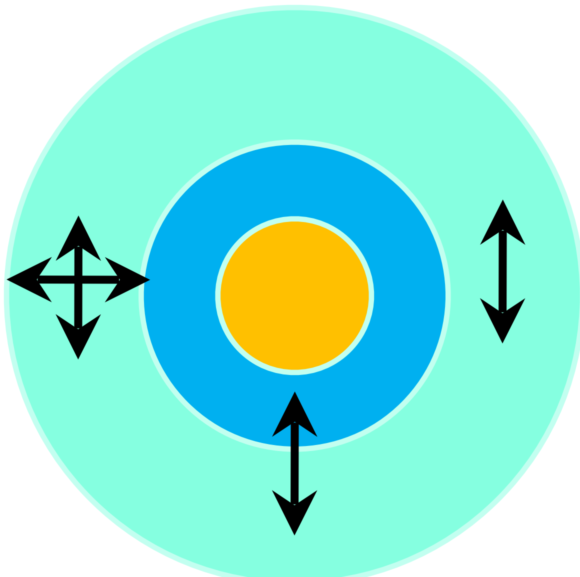
Turbulence (300 km/s): ***7 eV***

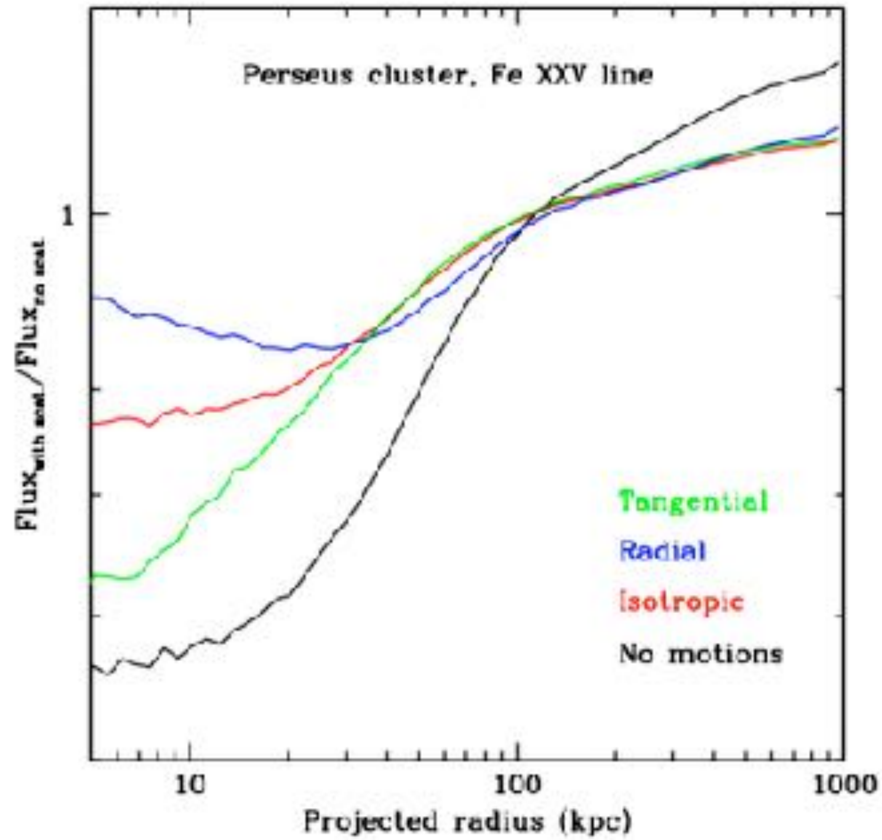


Gas Velocities

$$F_{6.7} / F_{thin}$$

Isotropic, radial, tangential





$$\tau \Leftrightarrow E_{kin}$$

Optical depth strongly depends on the character of motions (and on the correlation length)

Direct evidence for resonant scatterings from HITOMI

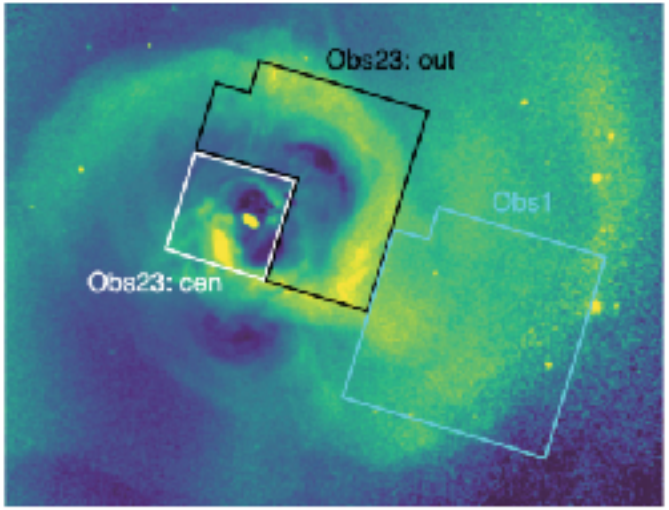


Fig. 1. Hitomi SXS observation regions overlaid on the Chandra X-ray image of the Perseus Cluster in the 1.8–9.0 keV band divided by the spherically symmetric model for the surface brightness. In this paper we will c
includes the central
obs1_whole (cyan). I

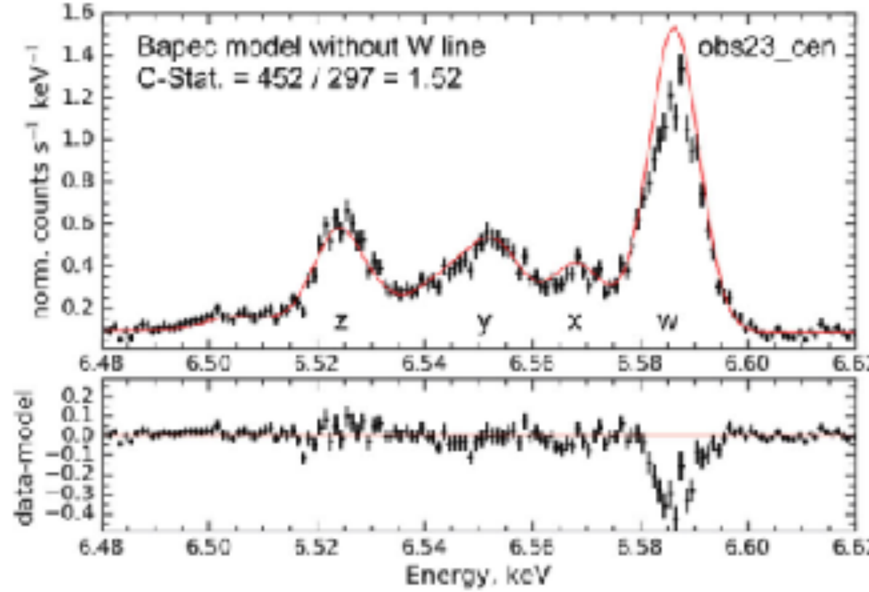


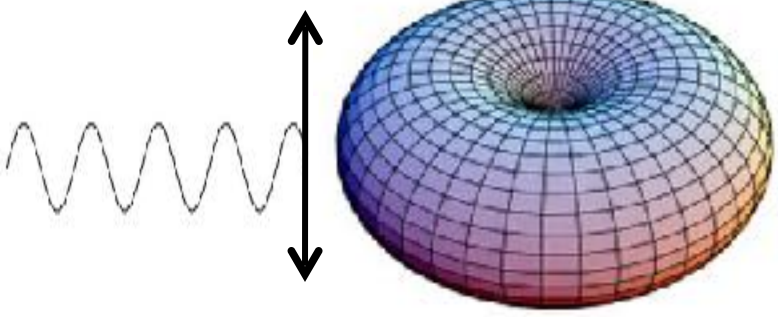
Table 3. Rest-frame Fe line properties in the 6–8 keV band that have optical depth $\gtrsim$0.01.

Ion	Energy (eV)	Lower level*	Upper level*	Oscillator strength	Optical depth τ $\sigma_v = 0$ km s^{-1}	Comments*
Fe XXIV	6616.73	$1s^2 2s_{1/2}\,^2S_{1/2}$	$1s_{1/2}2s_{1/2}2p_{1/2}\,^4P_{3/2}$	3.26×10^{-2}	2.22×10^{-2}	u
Fe XXV	6636.58	$1s^2\,^1S_0$	$1s2s\,^3S_1$	3.03×10^{-7}	6.75×10^{-3}	Heα, z
Fe XXIV	6653.30	$1s^2 2s_{1/2}\,^2S_{1/2}$	$1s_{1/2}2s_{1/2}2p_{1/2}\,^2P_{1/2}$	3.13×10^{-1}	1.54×10^{-2}	r
Fe XXIV	6661.88	$1s^2 2s_{1/2}\,^2S_{1/2}$	$1s_{1/2}2s_{1/2}2p_{3/2}\,^2P_{3/2}$	9.78×10^{-1}	4.69×10^{-1}	q
Fe XXV	6667.55	$1s^2\,^1S_0$	$1s_{1/2}2p_{1/2}\,^3P_1$	5.79×10^{-2}	1.92×10^{-1}	Heα, y
Fe XXIV	6676.59	$1s^2 2s_{1/2}\,^2S_{1/2}$	$1s_{1/2}2s_{1/2}2p_{3/2}\,^2P_{1/2}$	1.92×10^{-1}	9.67×10^{-2}	t
Fe XXV	6682.30	$1s^2\,^1S_0$	$1s_{1/2}2p_{3/2}\,^3P_2$	1.70×10^{-5}	7.26×10^{-3}	Heα, x
Fe XXV	6700.40	$1s^2\,^1S_0$	$1s_{1/2}2p_{3/2}\,^1P_1$	7.19×10^{-1}	2.27	Heα, w
Fe XXVI	6951.86	$1s$	$2p_{1/2}$	1.36×10^{-1}	8.81×10^{-2}	Lyα_2
Fe XXVI	6973.07	$1s$	$2p_{3/2}$	2.73×10^{-1}	1.69×10^{-1}	Lyα_1
Fe XXV	7872.01	$1s^2\,^1S_0$	$1s3p\,^3P_1$	1.18×10^{-2}	3.87×10^{-2}	Heβ_2, intercomb.
Fe XXV	7881.52	$1s^2\,^1S_0$	$1s3p\,^1P_1$	1.37×10^{-1}	3.73×10^{-1}	Heβ_1, resonance

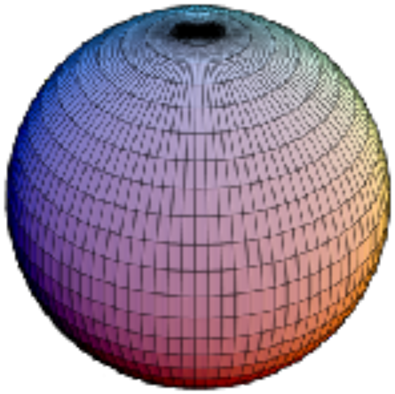
*Optical depths are integrated over an $r = 0'$–$40'$ region with $\sigma_v = 0$ km s^{-1}. Energies and oscillator strengths are from AtomDB version 3.0.8.
†Letter designations for the transitions as per Gabriel (1972).

Polarization I

Scattering phase function =
W_2 x Rayleight + W_1 x Isotropic



+



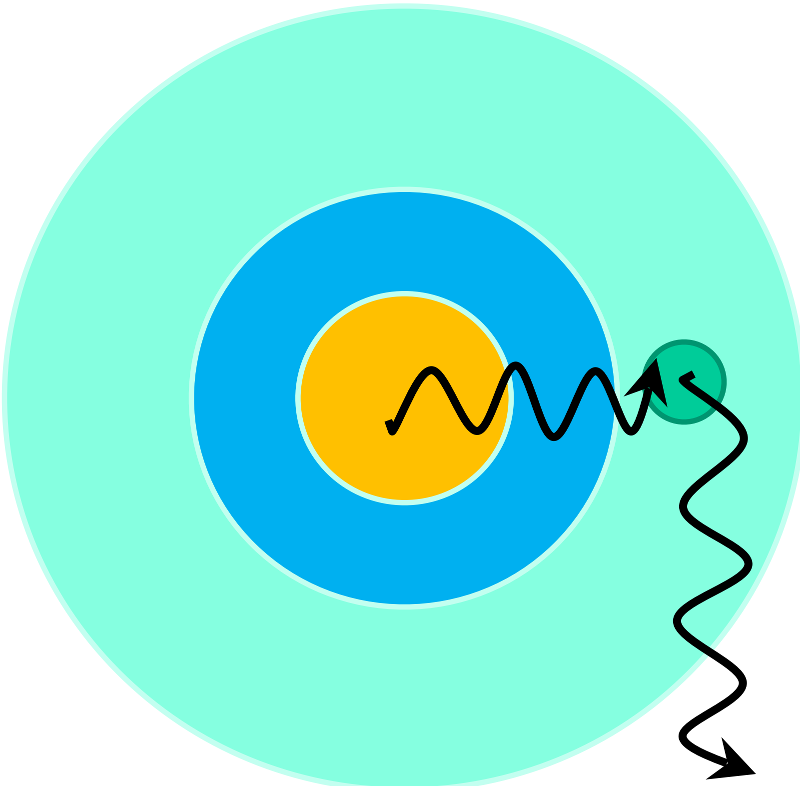
Polarization ***No Polarization***

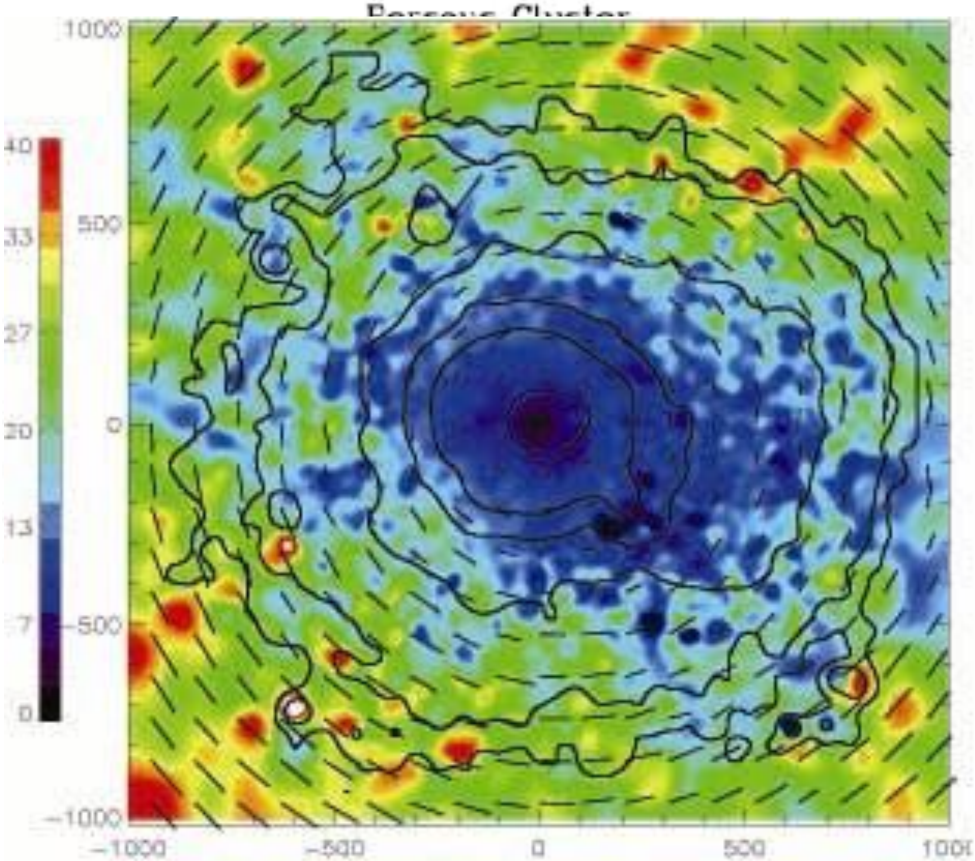
$$W_2(J_1, J_2)$$ ***Hamilton, 1947; [Chandrasekhar 1950]***

He-like ions; $1s^2$ ($^1S_0$) – 1s2p ($^1P_1$) => W_2=1

Polarization II

Rayleigh phase function + Quadrupole = Polarization





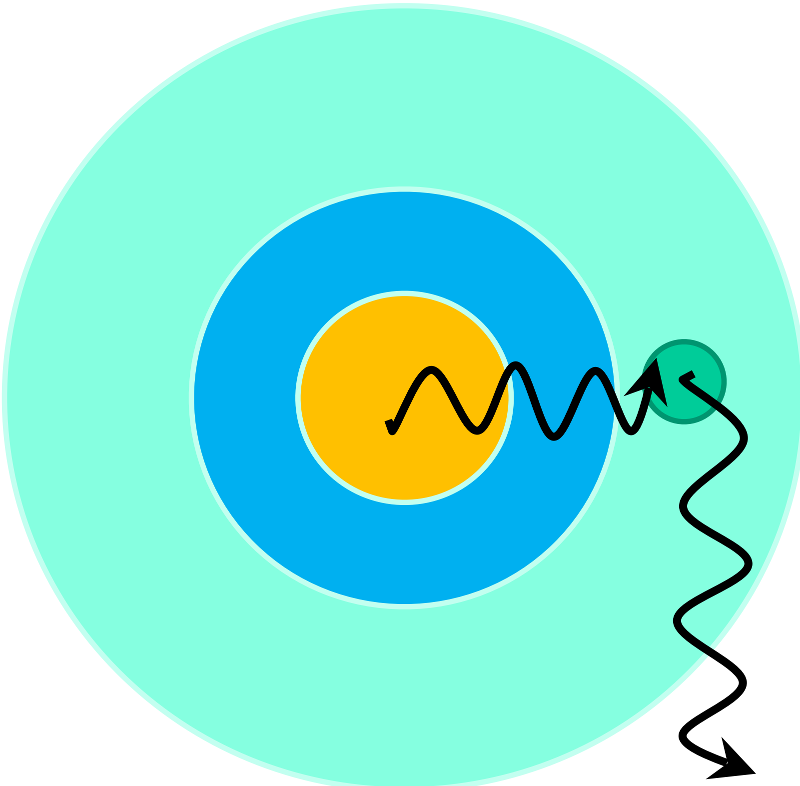
100% polarized

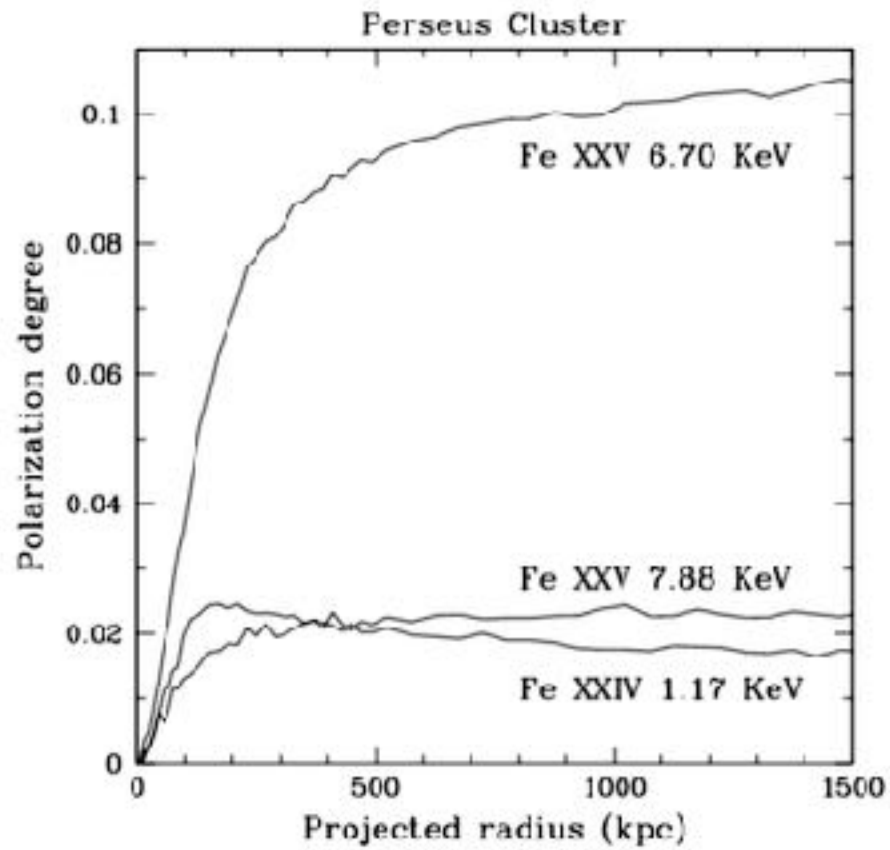
Center: 0%

Outskirts: 10%

Polarization II

Rayleigh phase function + Quadrupole = Polarization





100% polarized

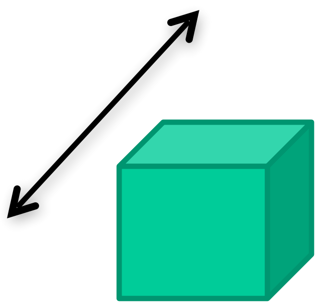
Center: 0%

Outskirts: 10%

Transverse ICM velocities and polarization

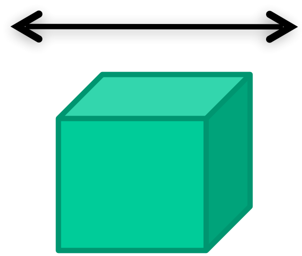
Quadrupole component can be induced by gas motions!

Motion along l.o.s.

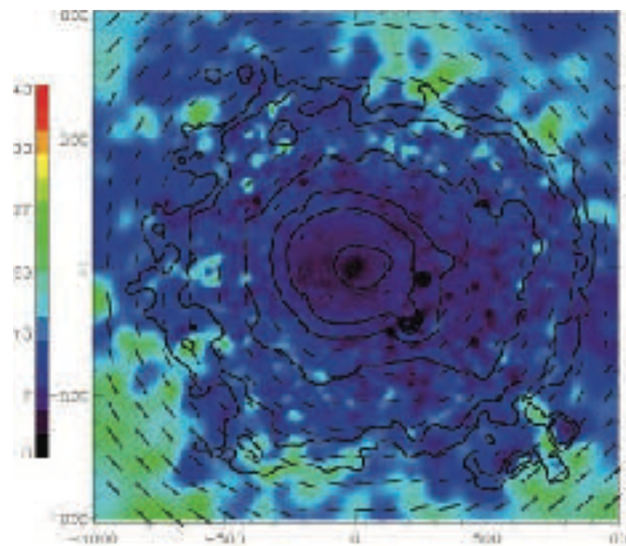


Doppler shift
No polarization

Motion transverse l.o.s.



No Doppler shift
Polarization



1) *On average gas motions reduce optical depth*
2) *But can cause polarization in the cluster core*

What we want from X-ray spectroscopy?

Density

Temperature

Abundances

Velocities

Why?

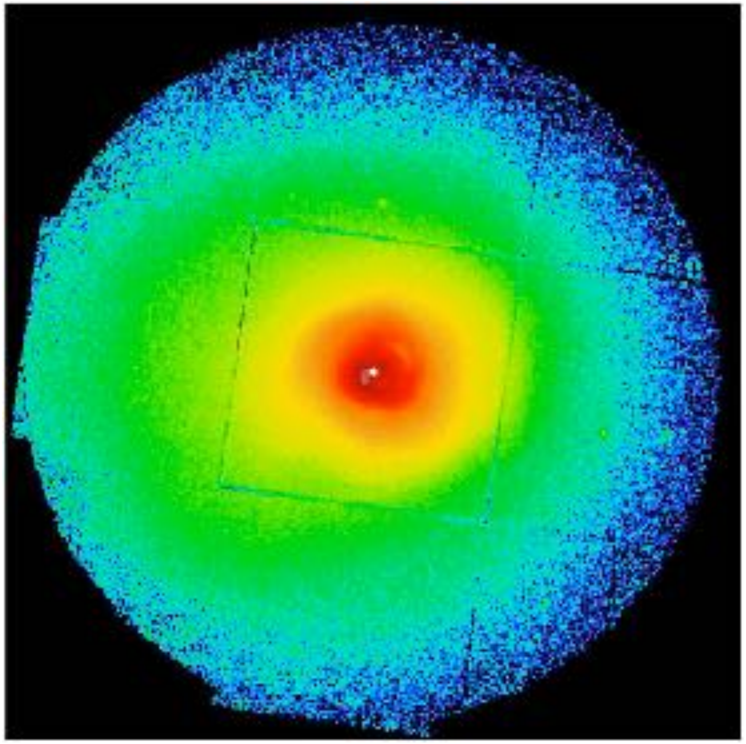
To accurately measure cluster masses

To understand gas heating processes

Cooling flows

Cooling time

$$t_{cool} = \frac{\frac{3}{2} nkT}{n^2 \Lambda(T)} \approx 5\,10^8 \text{ years}$$



Fastest cooling near the center

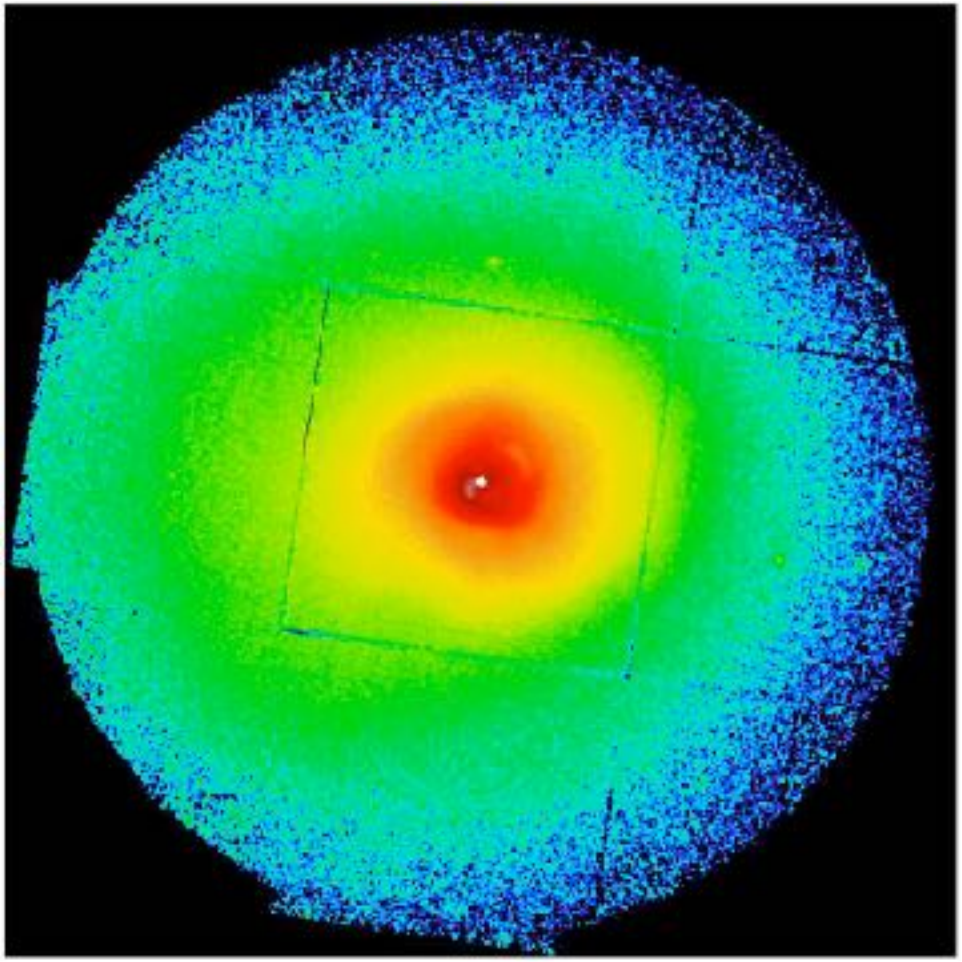
Cooling rate

$$\dot{M} = \frac{L_X}{\frac{3}{2} kT} \times \mu m_p \approx 1000\, M_\Theta \text{ yr}^{-1} \qquad (L_X = 10^{45} \text{ erg/s})$$

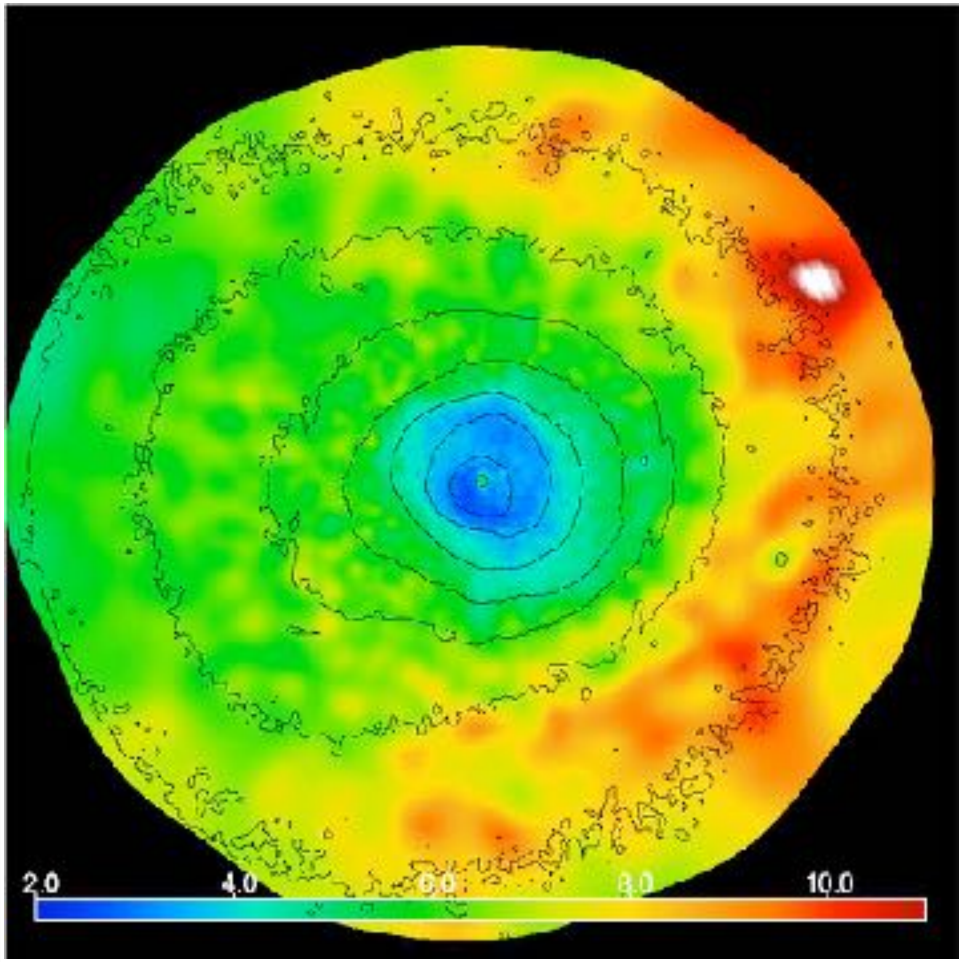
Gas density

Gas temperature

Surface brightness



Temperature



The highest density is at the center => cools first!
When densest gas cools it is compressed and becomes even denser!

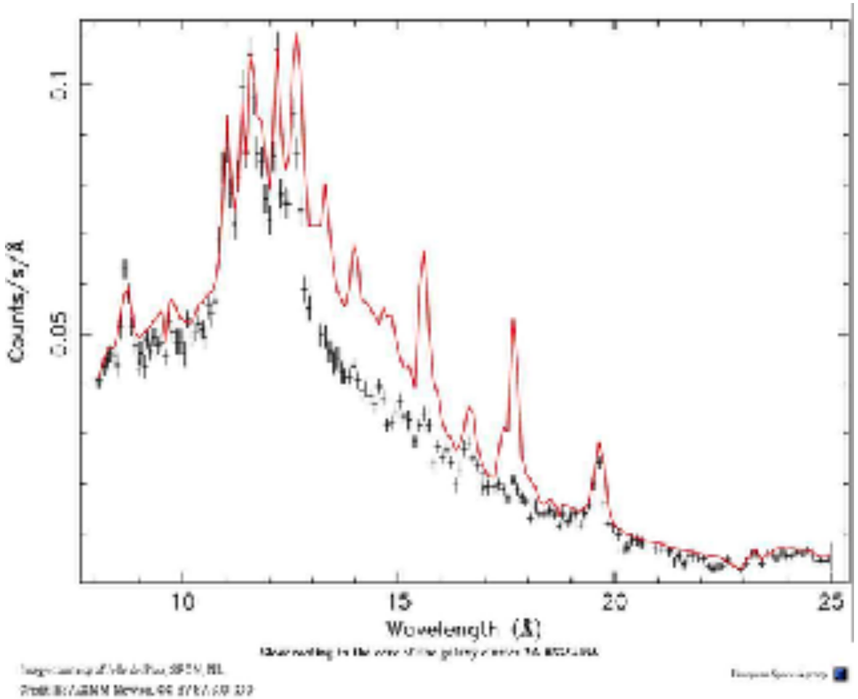
But

What is the fate of cooled gas? Stars?

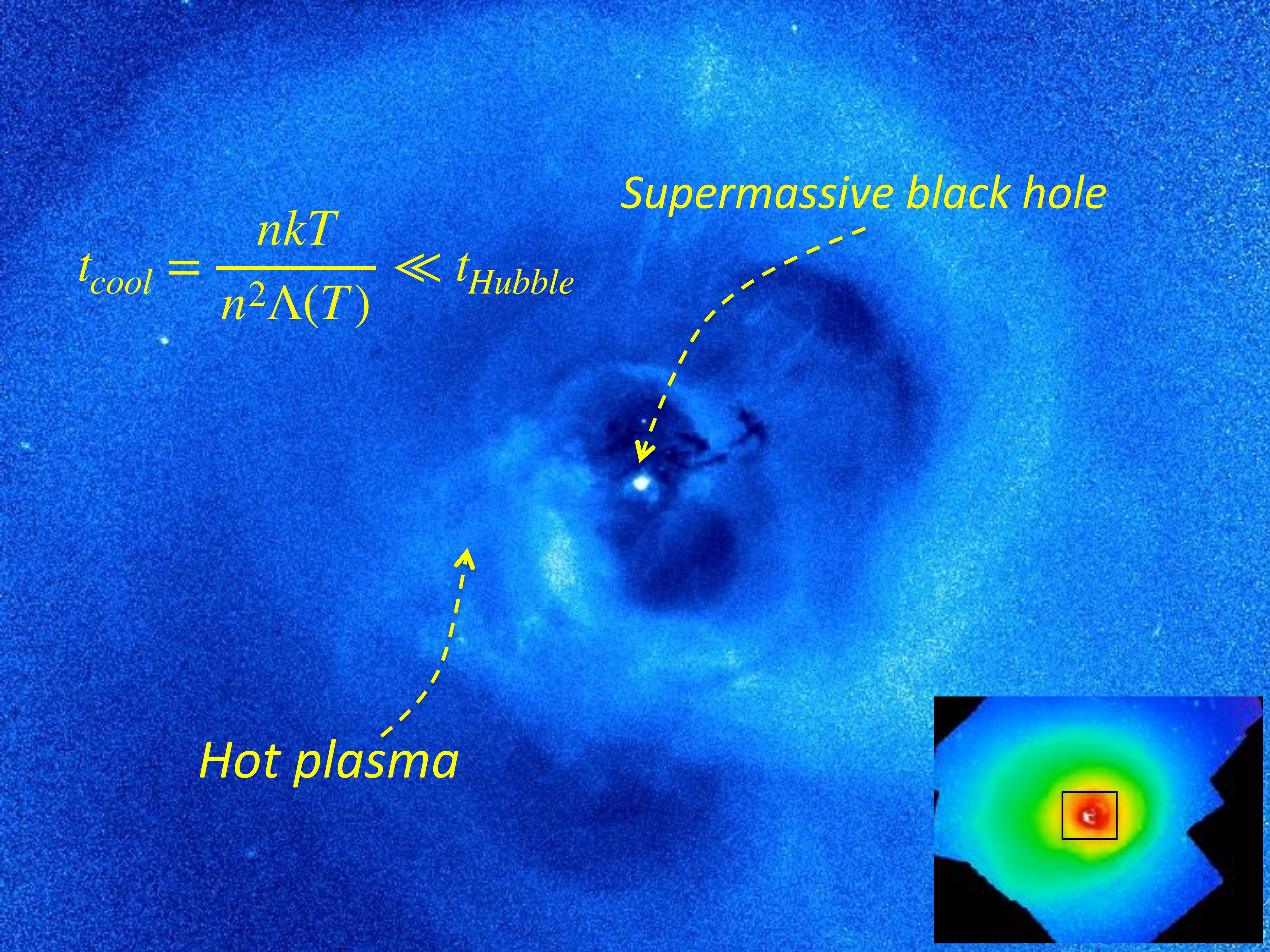
$$10^3 M_\odot \, \mathrm{yr}^{-1}$$

$$10^3 \times 10^{10} \, \mathrm{yr} \sim 10^{13} \, M_\odot$$

Where are emission lines, characteristic for cool gas?

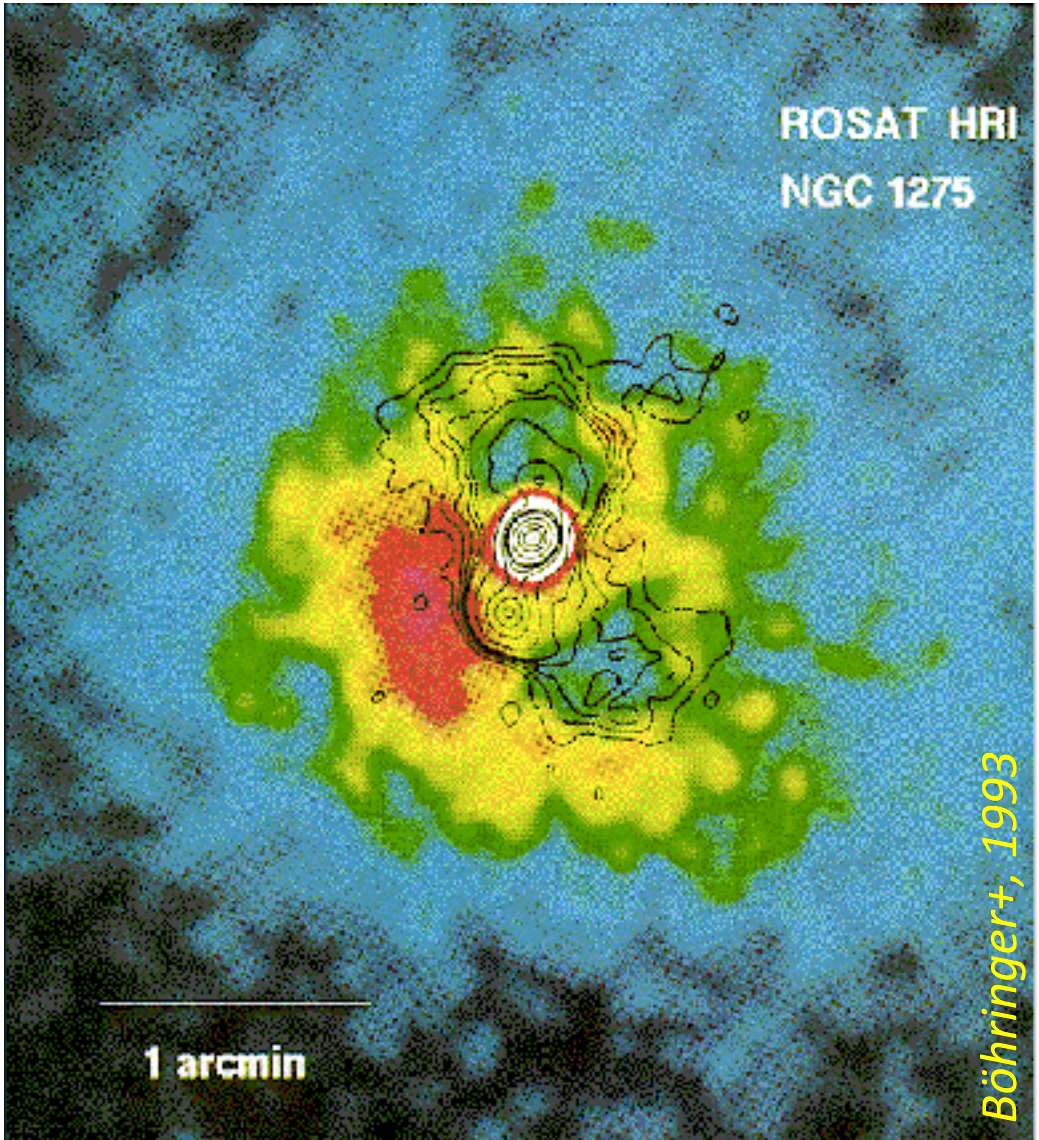


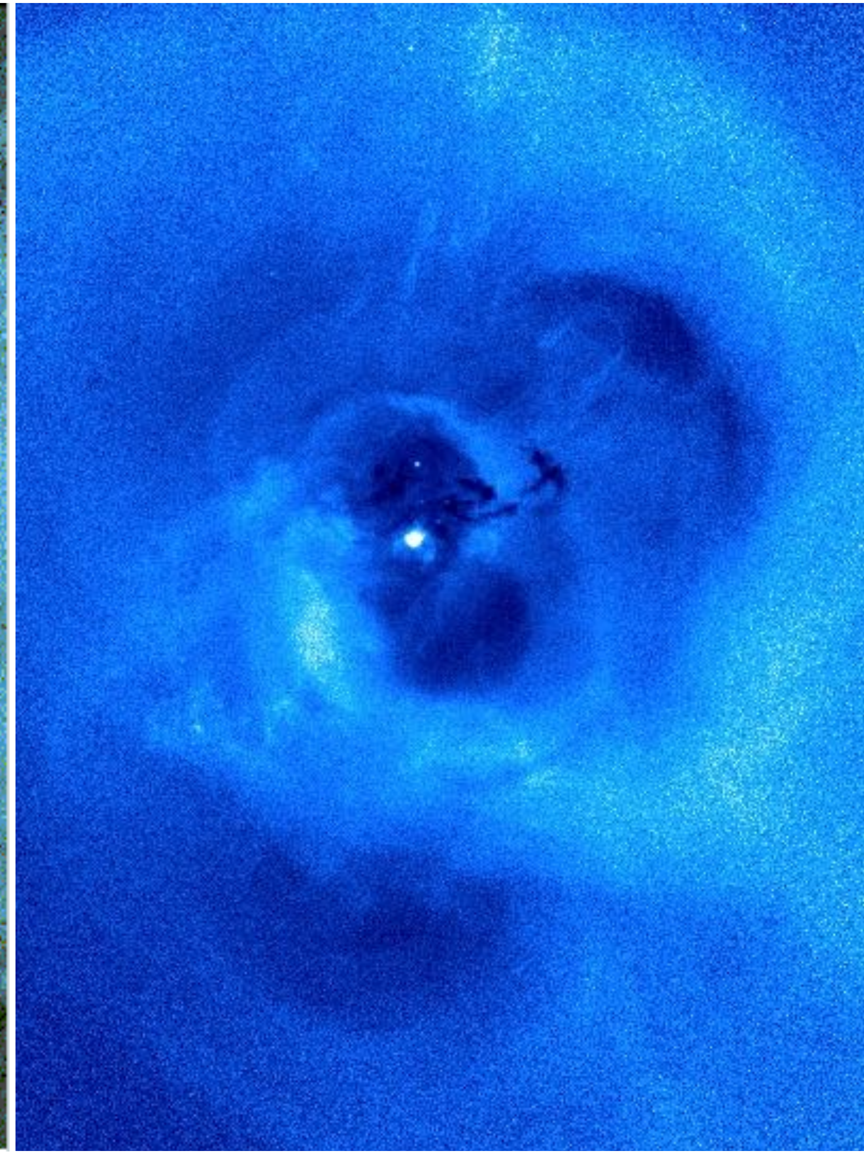
Or there is a source of energy that keeps the gas hot?



$t_{cool} = \frac{nkT}{n^2\Lambda(T)} \ll t_{Hubble}$
Supermassive black hole
Hot plasma

Clear evidence for the impact of relativistic plasma on thermal gas

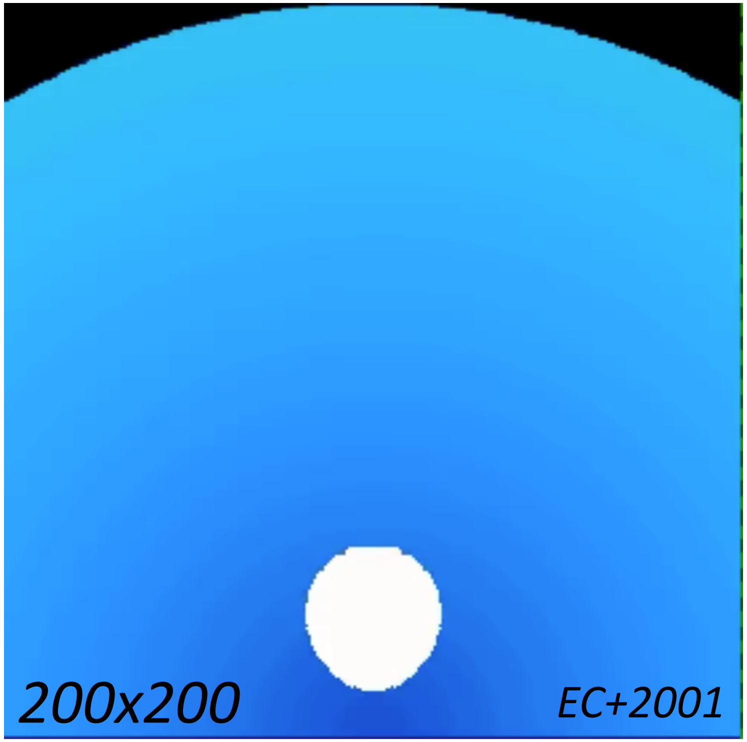


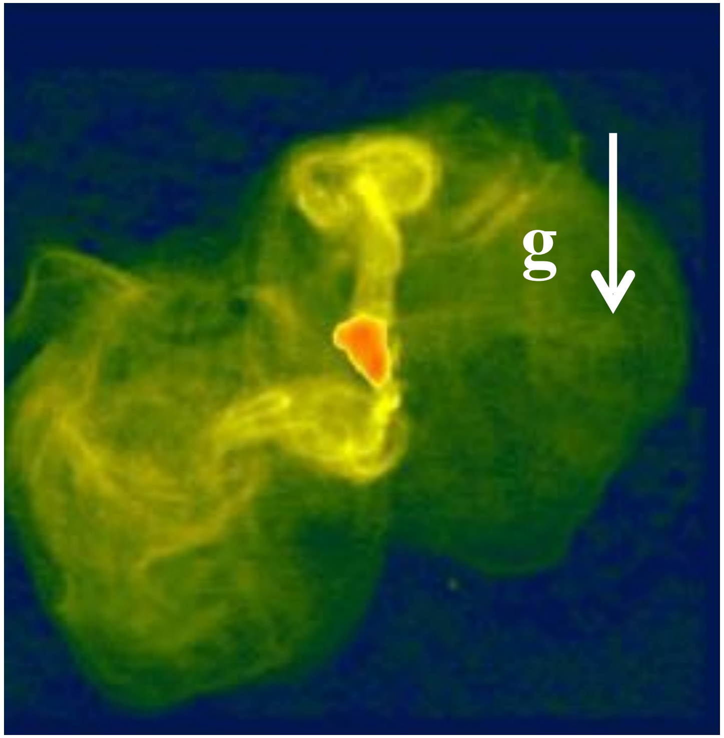


Bubbles of relativistic plasma inflated by SMBH

How to measure the energy release rate?

Simple numerical simulations





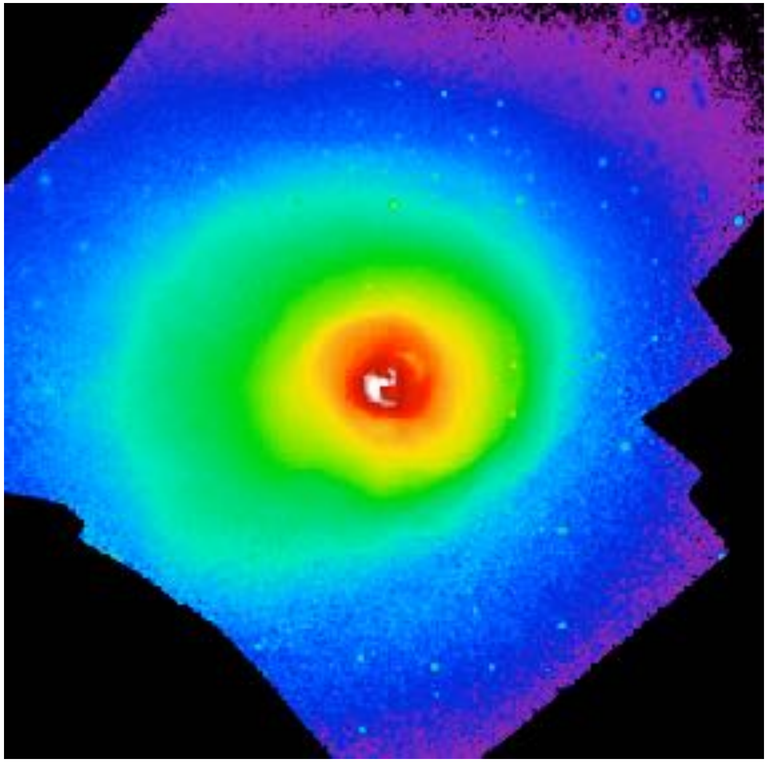
$$L_{AGN} \sim L_{cooling}$$

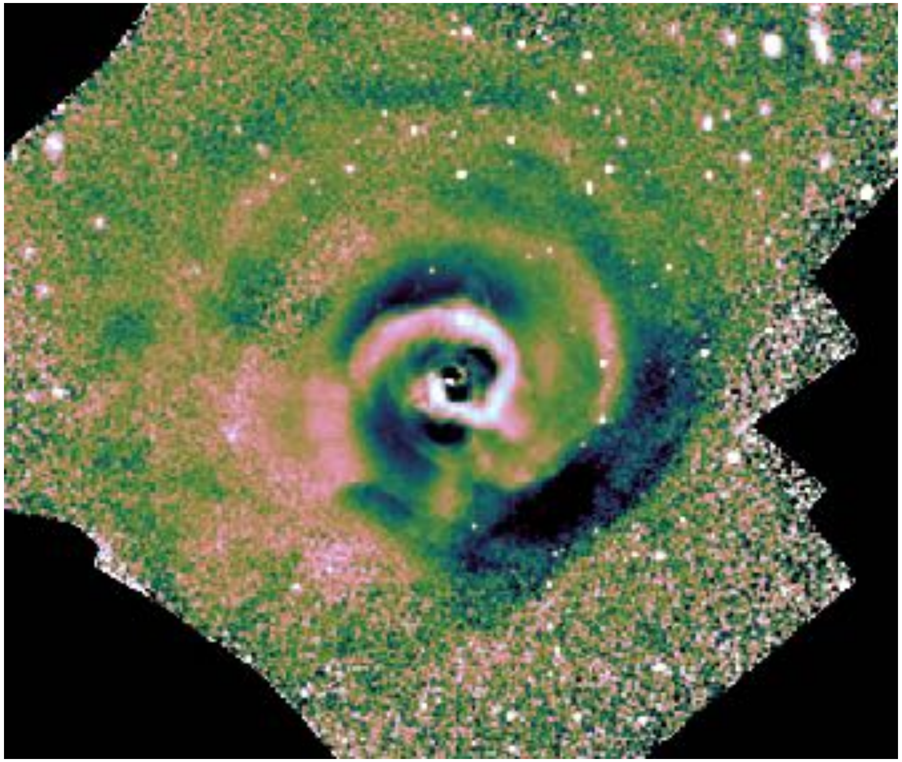
How the gas is heated?

Bubbles induce gas motions - motions dissipate into heat

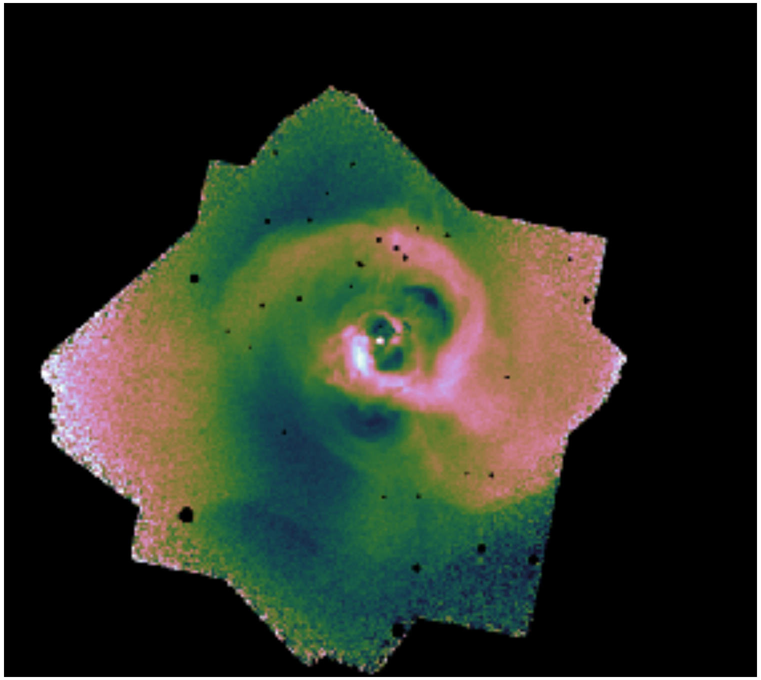
Identify perturbations in images

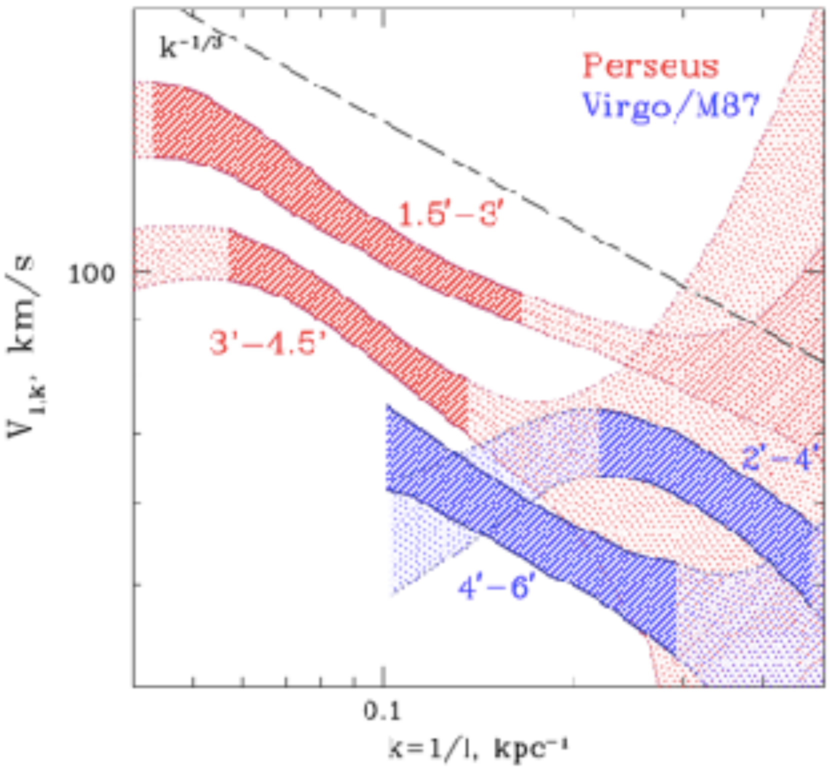
Relate the amplitude of perturbations to velocities





Getting gas velocity power spectrum from images



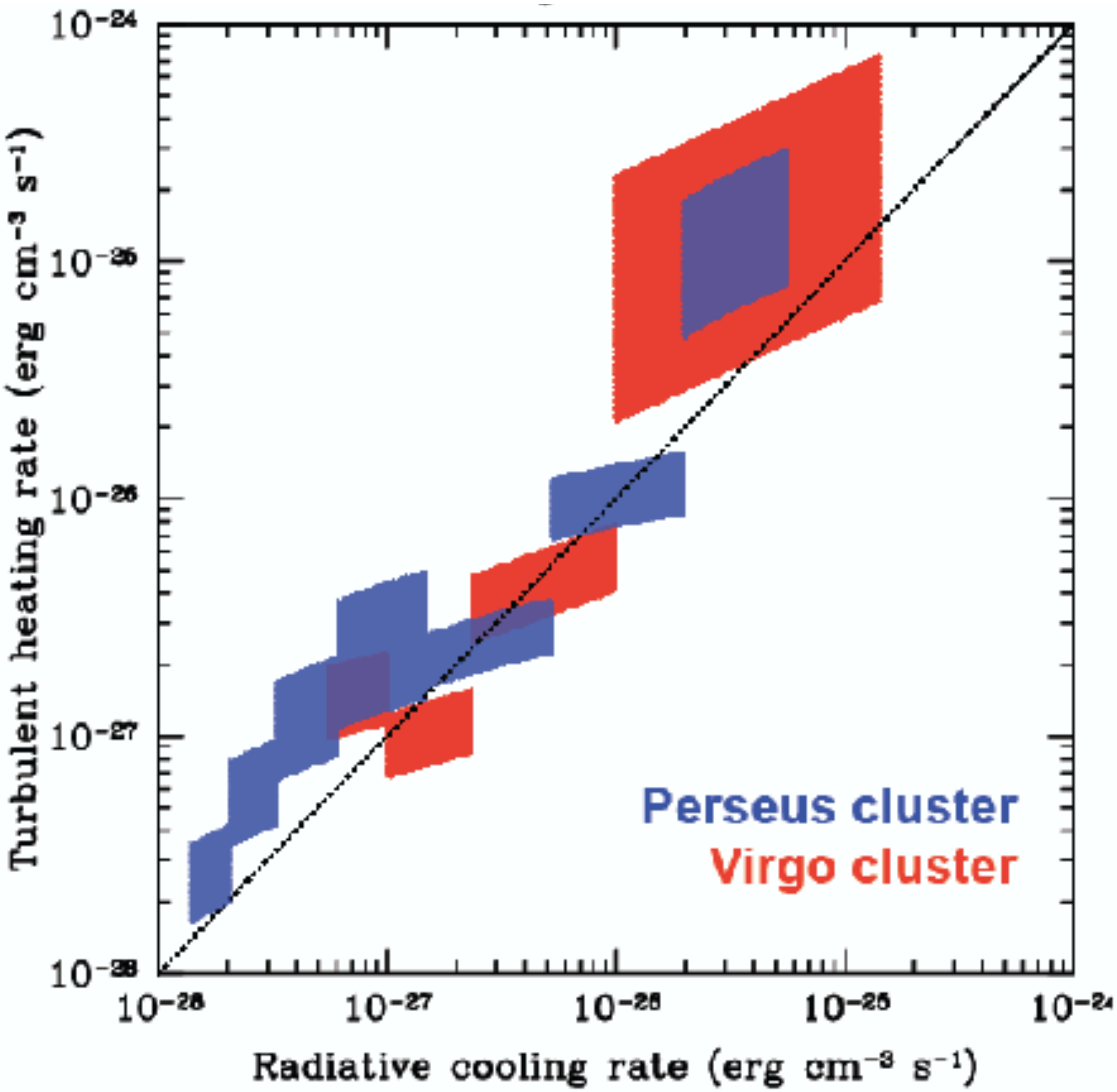


Zhuravleva et al., 2014

$$\frac{\delta I}{I} \Rightarrow P_{2D}(k) = C \times P_{3D}(k) \Rightarrow \frac{\delta\rho}{\rho} \Rightarrow \frac{\mathrm{v}}{c_s}$$

Heating rate

$$E(k) = K_0 \varepsilon^{2/3} k^{-5/3}$$

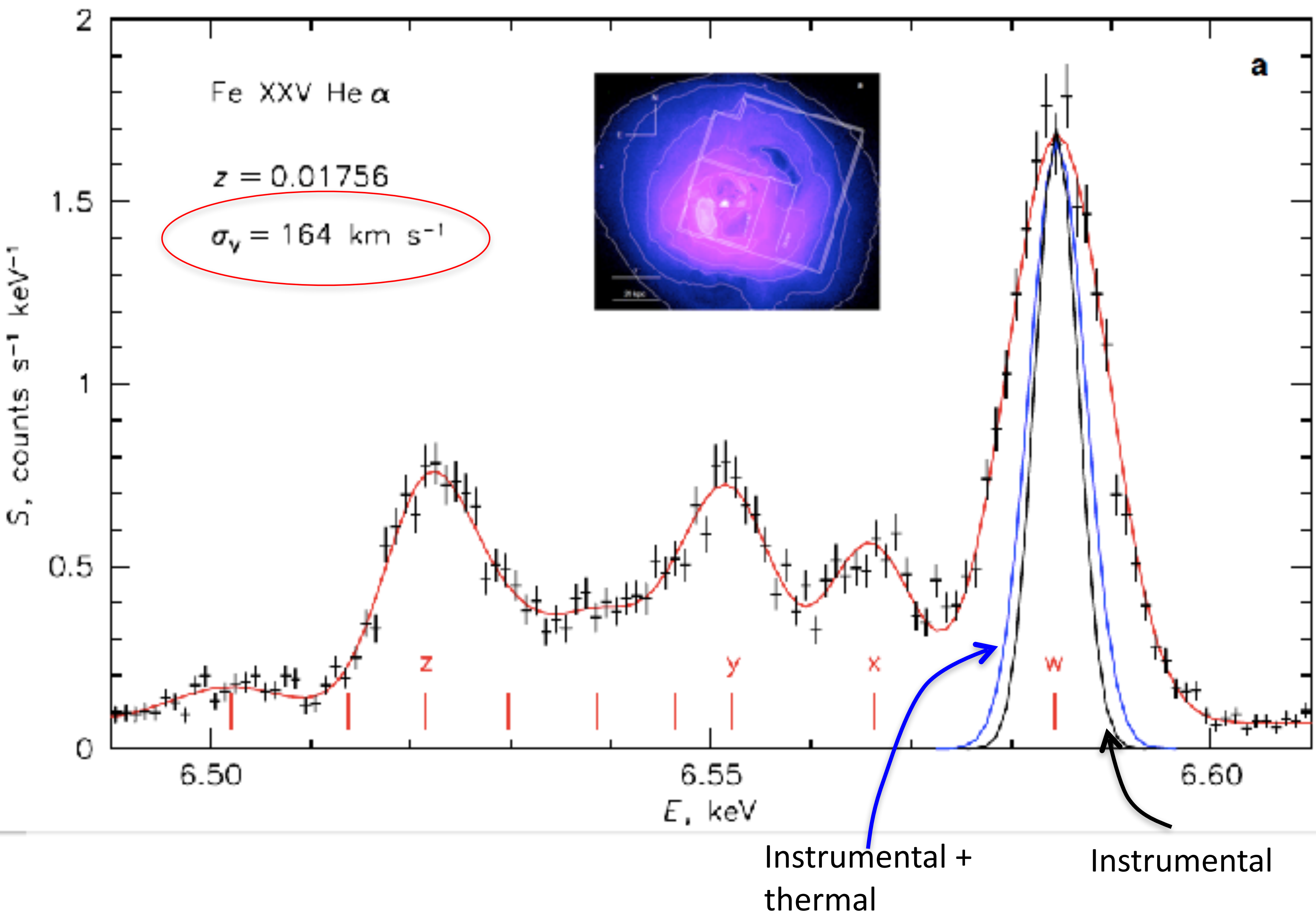


$$\text{Cooling} = n^2 \Lambda(T)$$

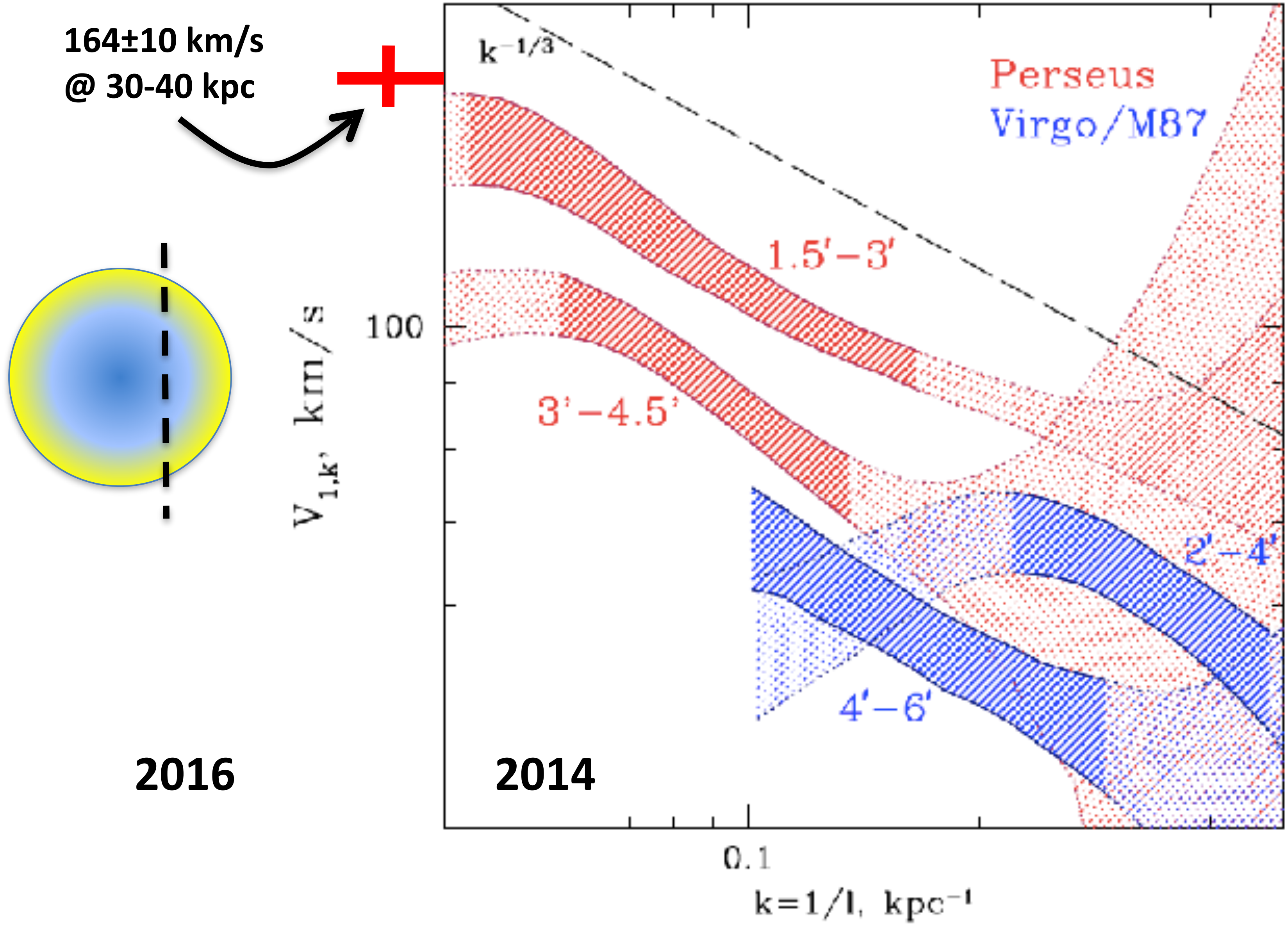
$$\text{Heating} = C \rho V_{1,k}^3 k$$

Zhuravleva et al., 2014

"Outer region" spectrum of the Perseus cluster (He-like triplet)



Predicted velocity power spectra in Perseus and M87



Zhuravleva et al., 2014

Cluster masses and X-ray spectroscopy

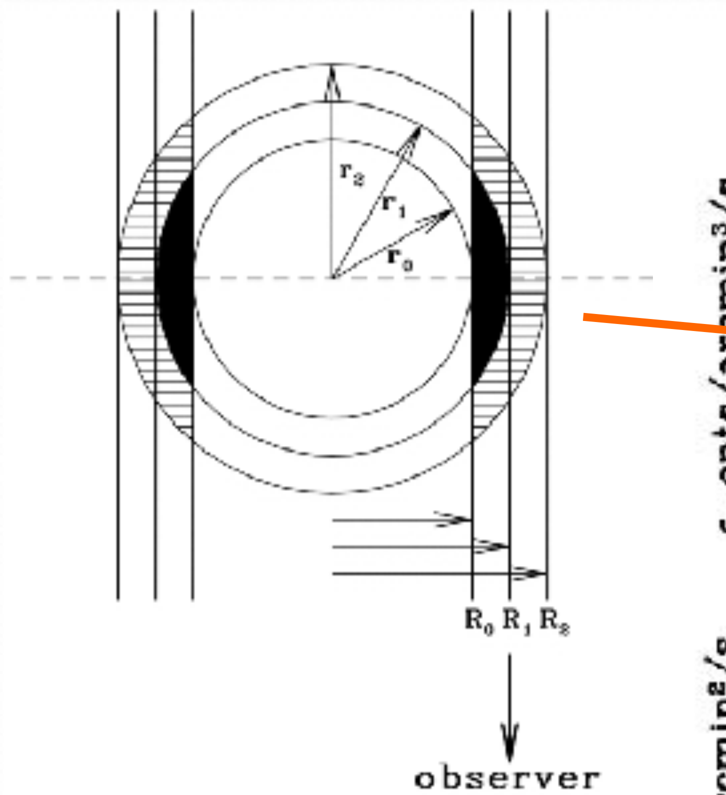
Mass profile of the cluster from X-ray data

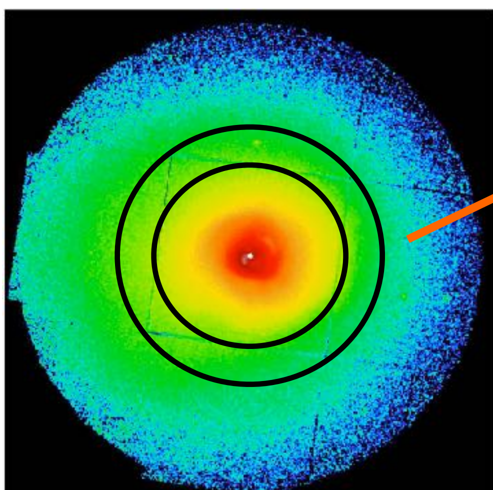
$$\frac{1}{\mu m_p n}\frac{dP}{dr} = -\frac{d\varphi}{dr} = -\frac{GM(<r)}{r^2} \quad [\text{stationary, sph.sym.}]$$

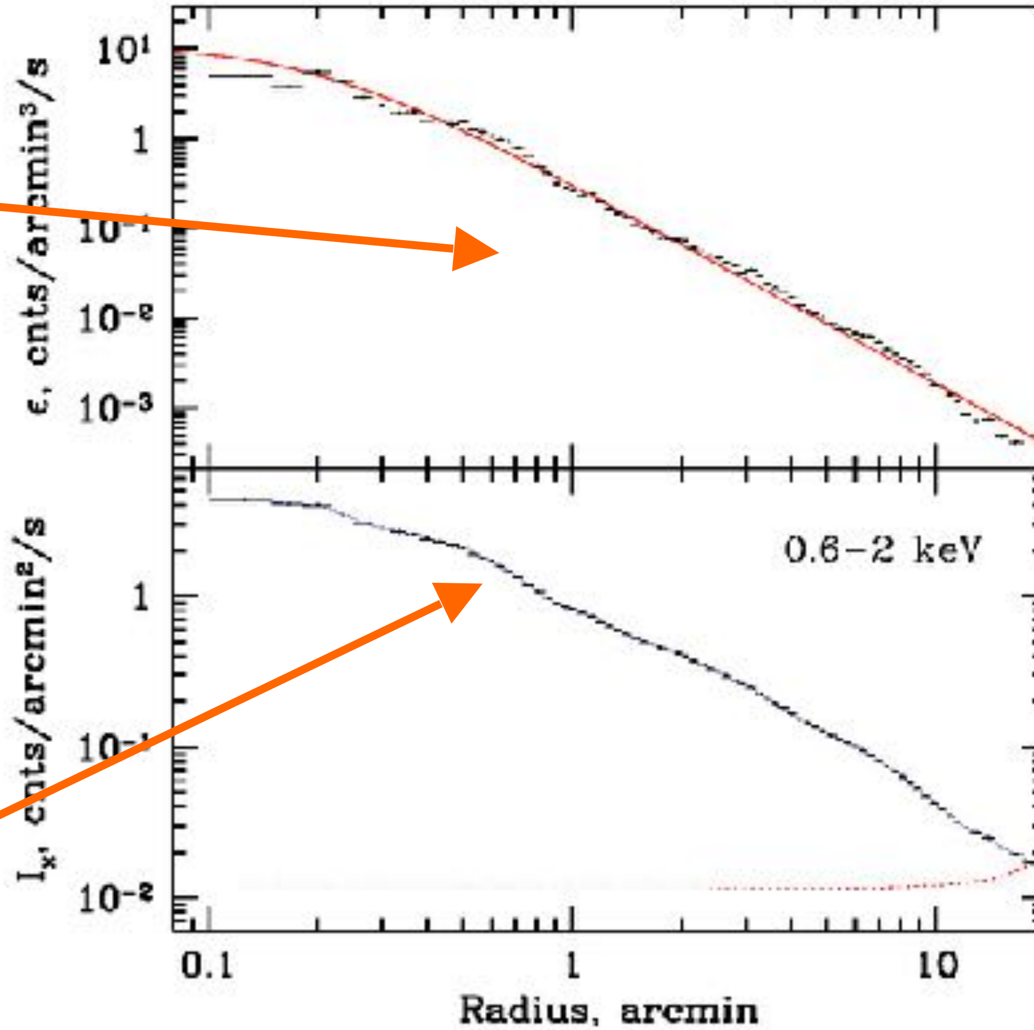
Hydrostatic equilibrium equation

$$P(r) = n(r)kT(r)$$

Deprojection of X-ray data



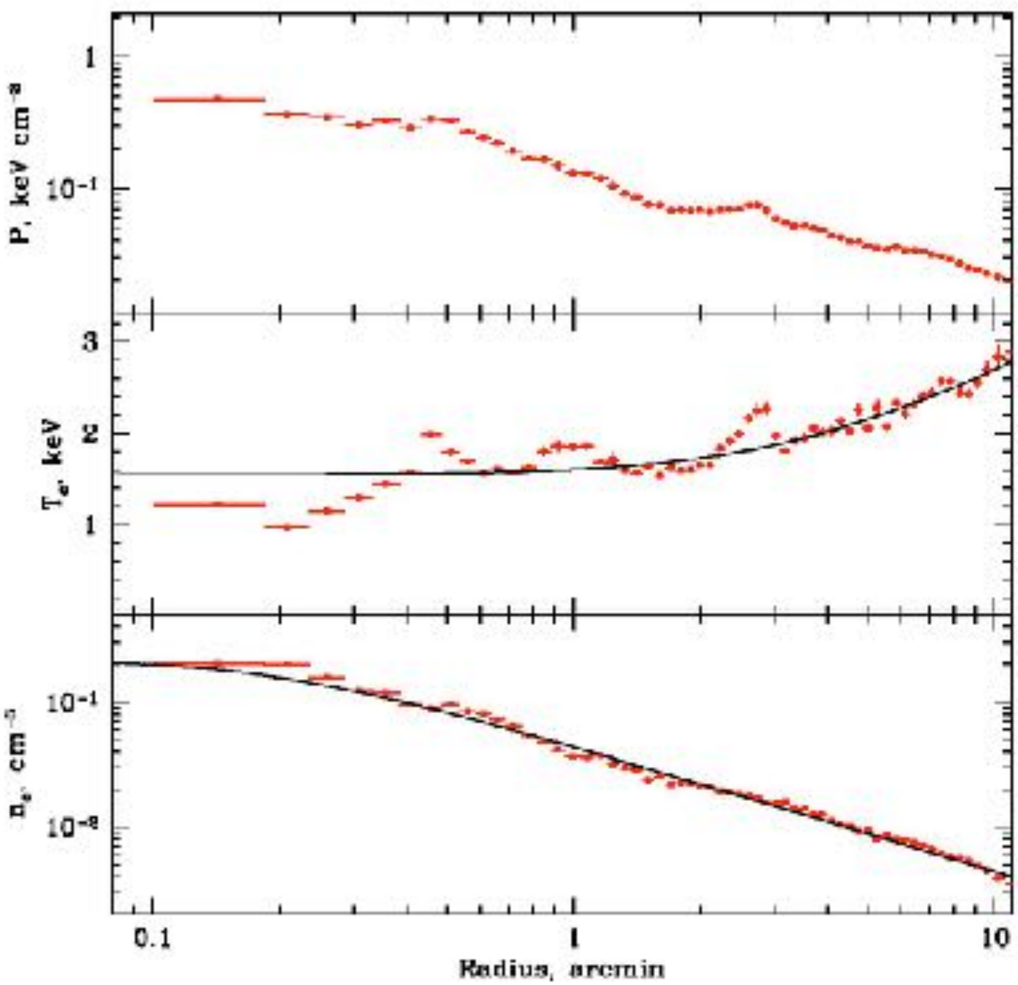




Repeat the same exercise at all energies

$\varepsilon(r,E)=n(r)^2S(E,T(r))$

Deprojected X-ray data: gas temperature and density

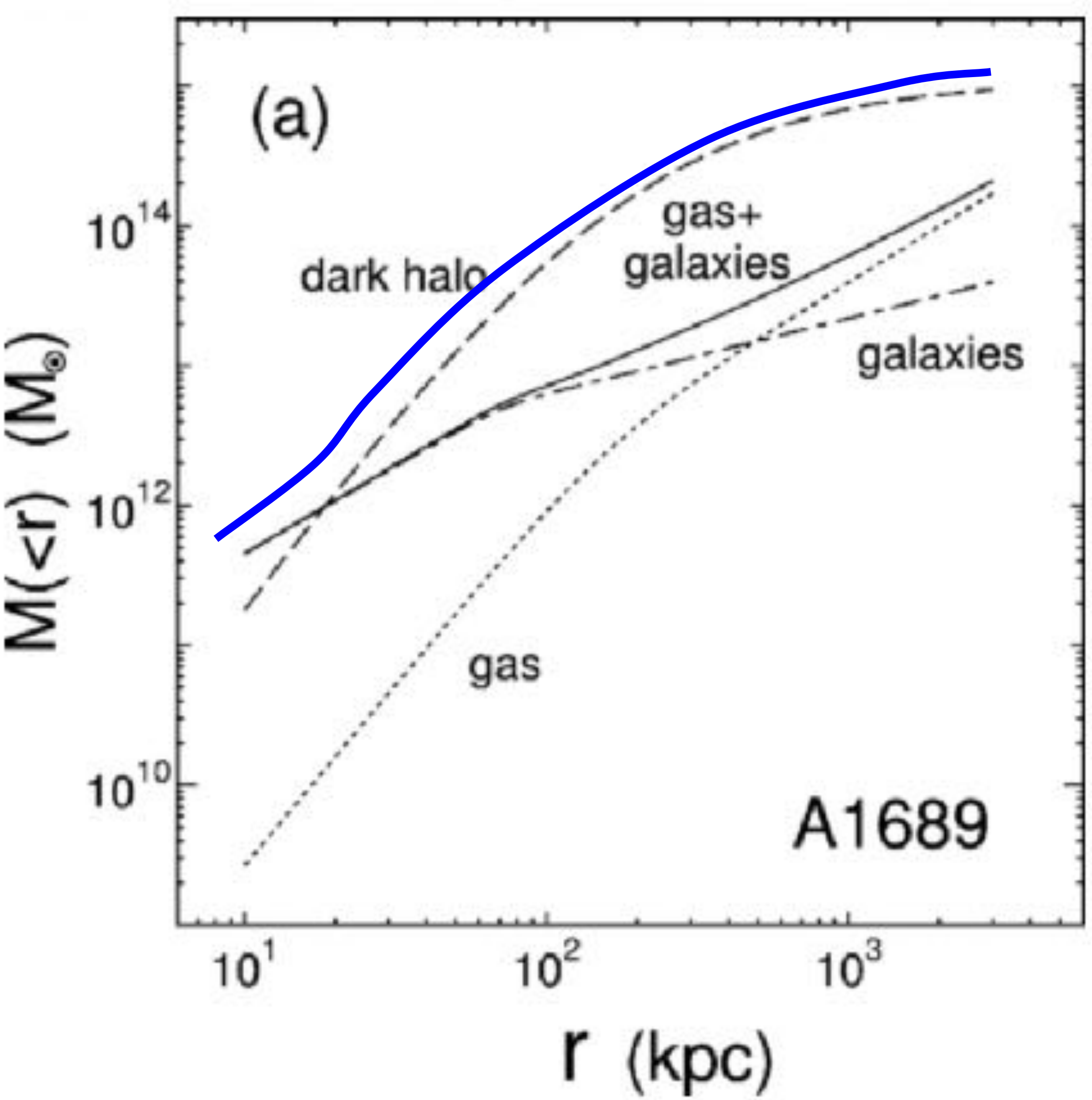


$$n_e(r), T_e(r) \quad P(r)$$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2}$$

$$M(<r) = \frac{r^2}{G}\frac{1}{\rho}\frac{dP}{dr}$$

Mass profile of a real cluster



DM : 80-85%

Gas : 12-15%

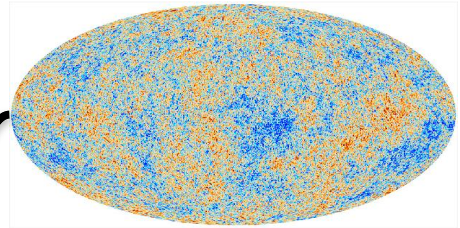
Stars : 2-5%

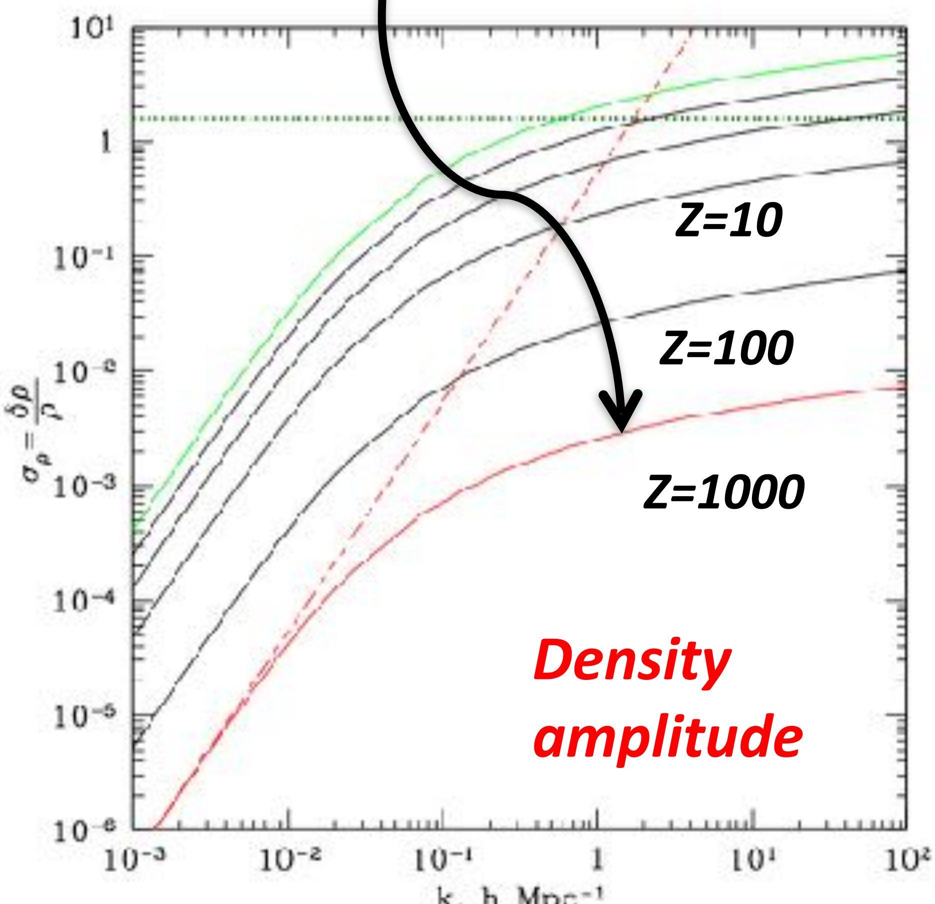
The results have to be corrected for gas velocities

Only possible with bolometers

Density/potential fluctuations

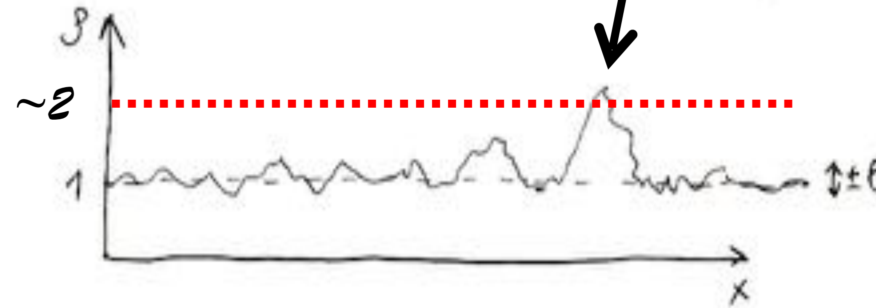
$$\delta \propto a$$



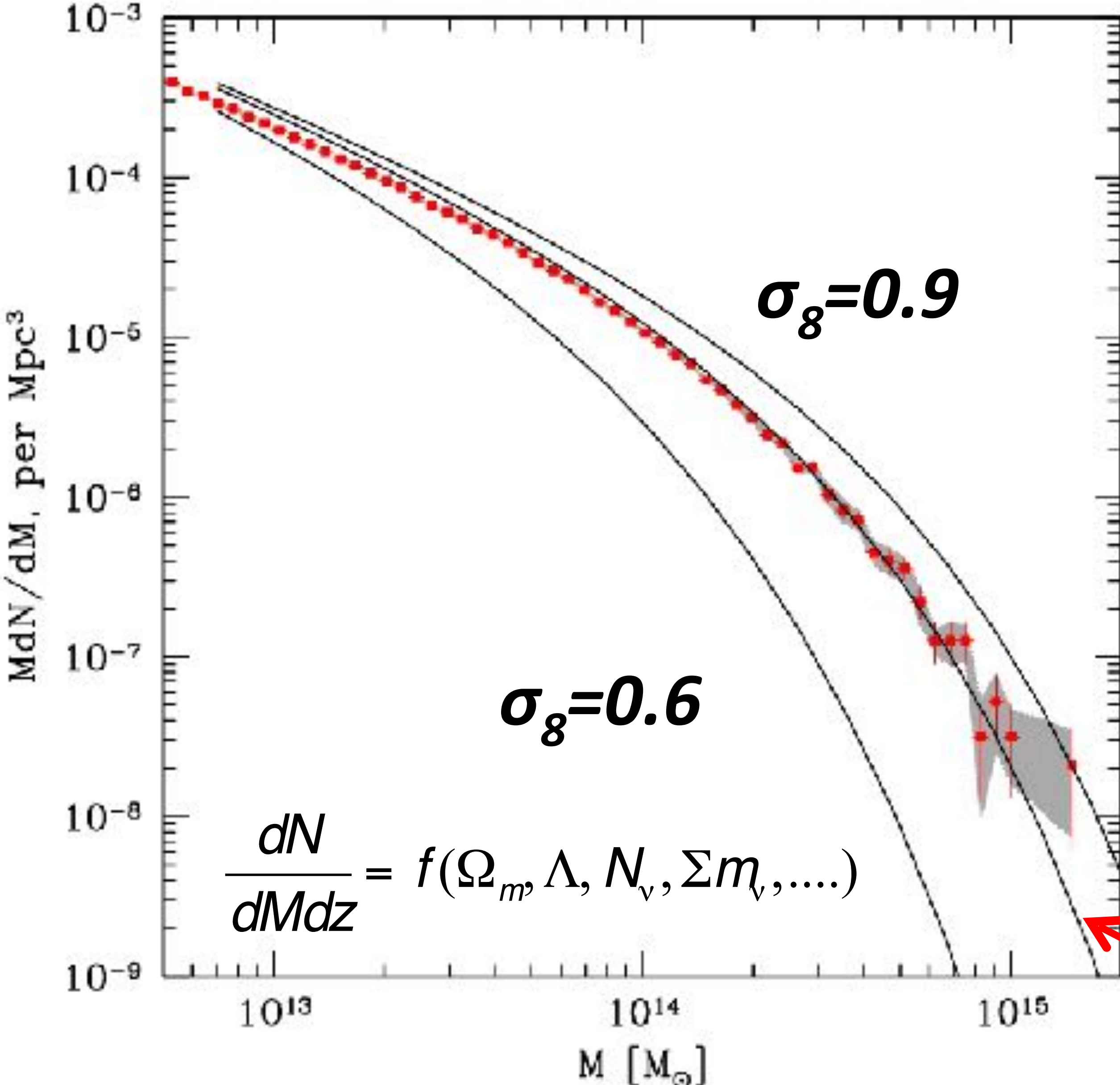


Mass

$$N \propto \exp\left\{-\frac{\delta_c^2}{\sigma^2}\right\}$$



Number of massive clusters as a function of amplitude



$$\frac{dN}{dMdz} = f(\Omega_m, \Lambda, N_\nu, \Sigma m_\nu, ...)$$

$$N \propto \exp\left\{-\frac{\delta_c^2}{\sigma^2}\right\}$$

$$\sigma_8 \propto \sqrt{\ln N}$$

σ_8=RMS($\Delta\rho/\rho$) @ 8 h^{-1} Mpc

High-resolution X-ray spectroscopy is coming to astronomy

(EBIT in space)

Spectroscopy can solve many astrophysical problems

Clusters offer an opportunity to test your models