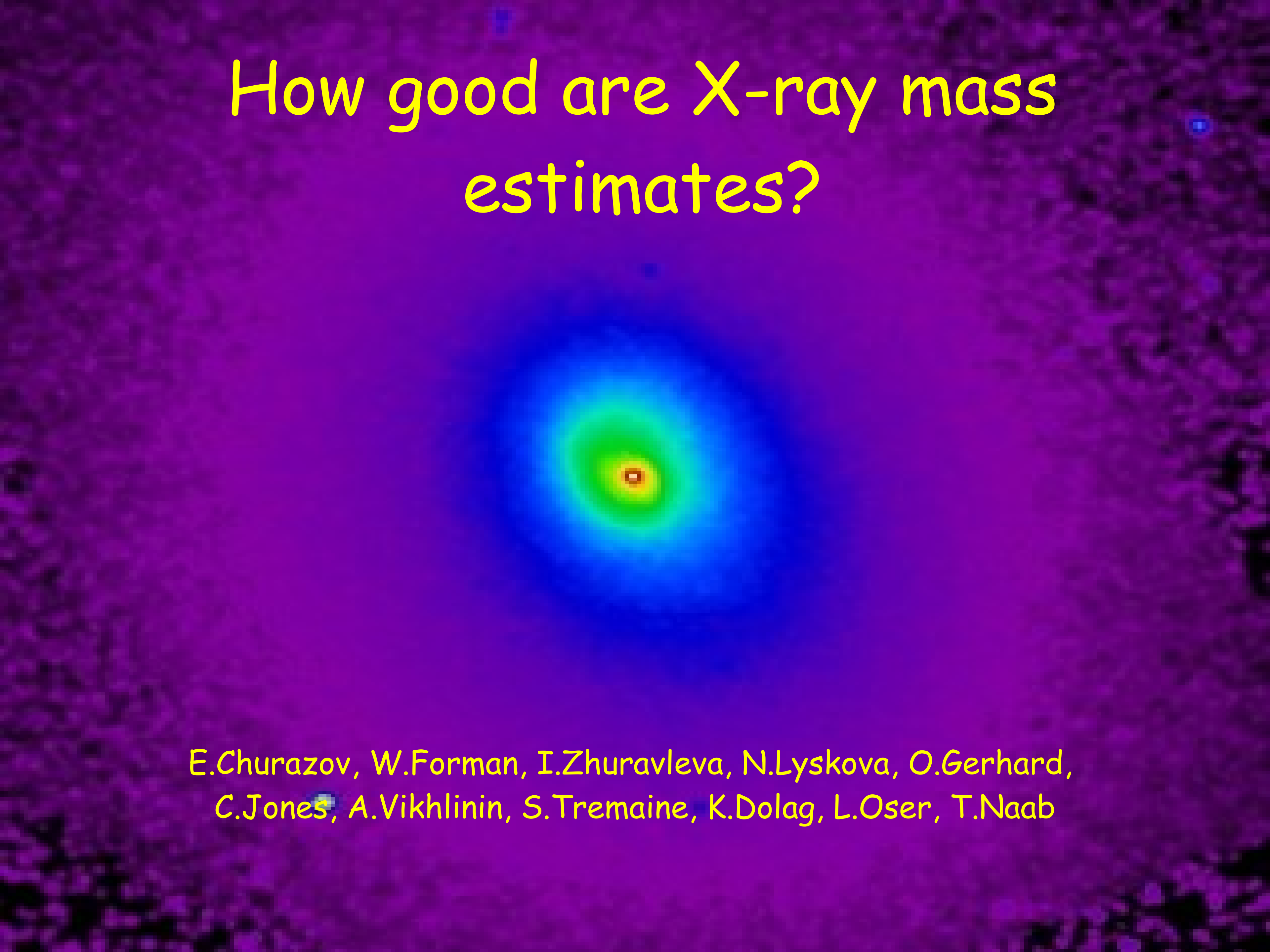
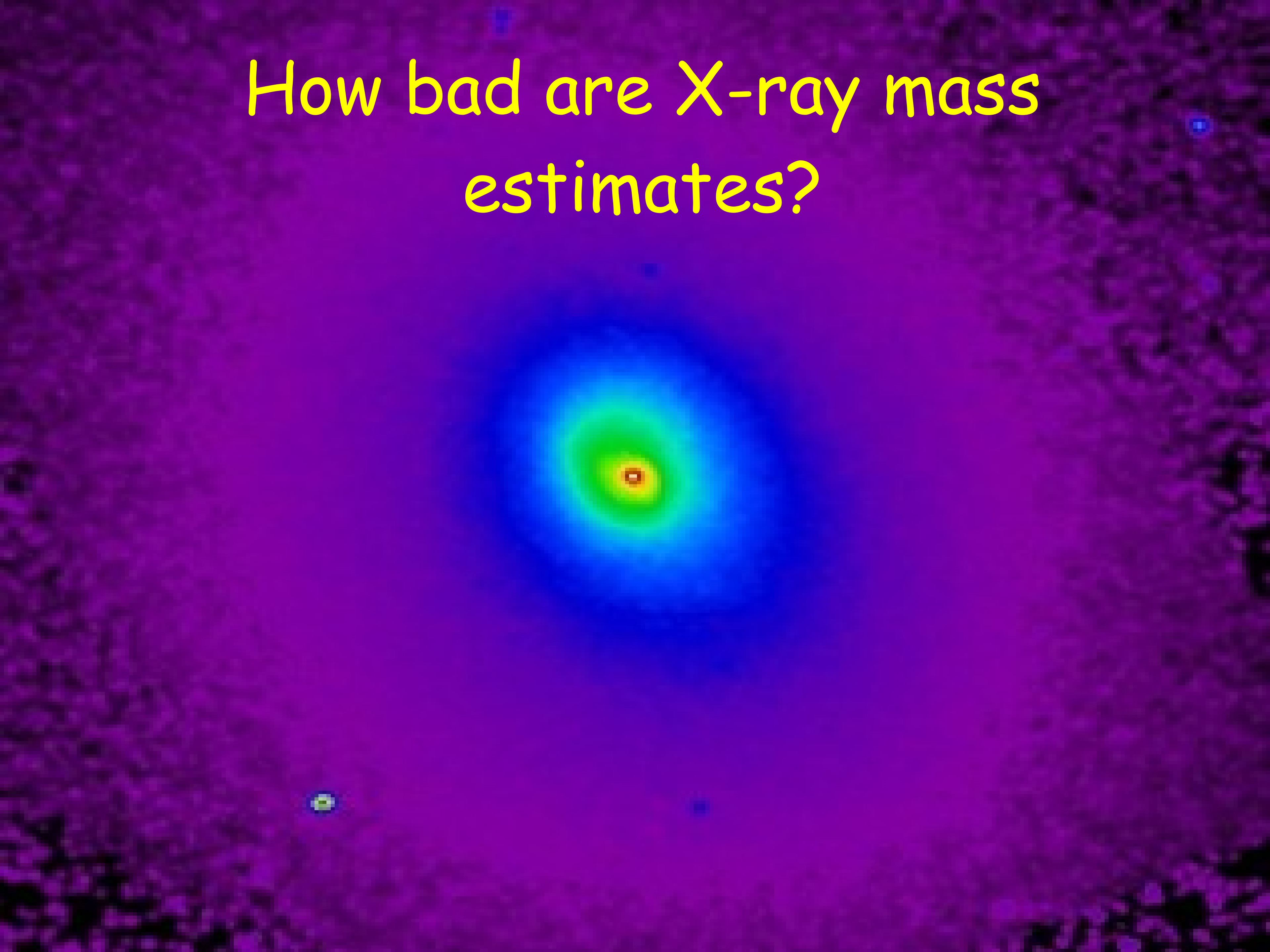
How good are X-ray mass estimates?



E.Churazov, W.Forman, I.Zhuravleva, N.Lyskova, O.Gerhard, C.Jones, A.Vikhlinin, S.Tremaine, K.Dolag, L.Oser, T.Naab

How bad are X-ray mass estimates?



What we see in X-rays?

Are the objects we see in X-rays special?

What we need for mass determination?

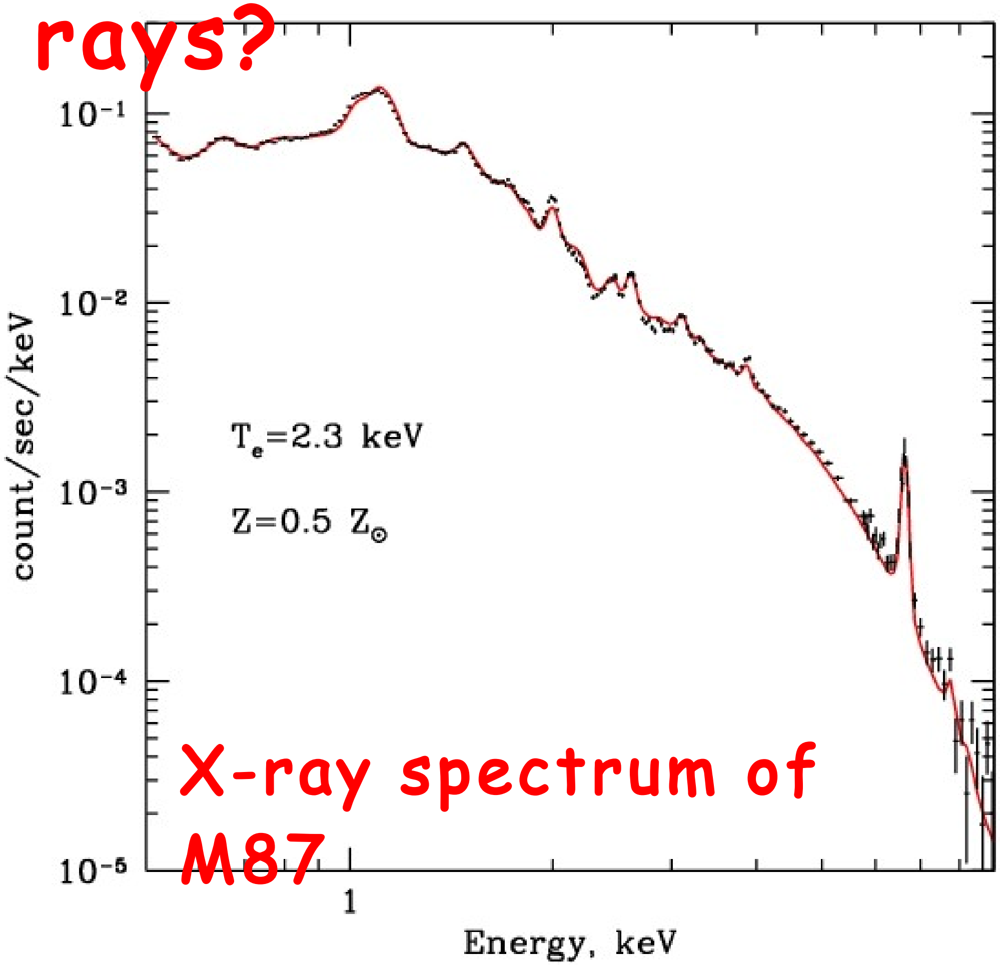
What to compare with?

What can go wrong?

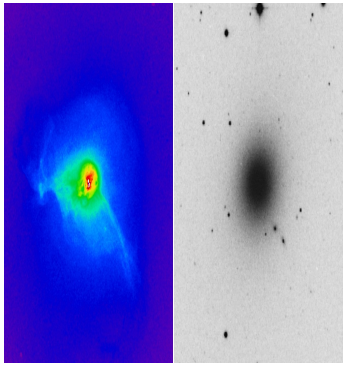
This is environmentally friendly talk:

50% of objects, data and slides are recycled from talks by Andy Fabian,
Bill Forman, Ortwin Gerhard and Thorsten Naab

What we see in X-rays?

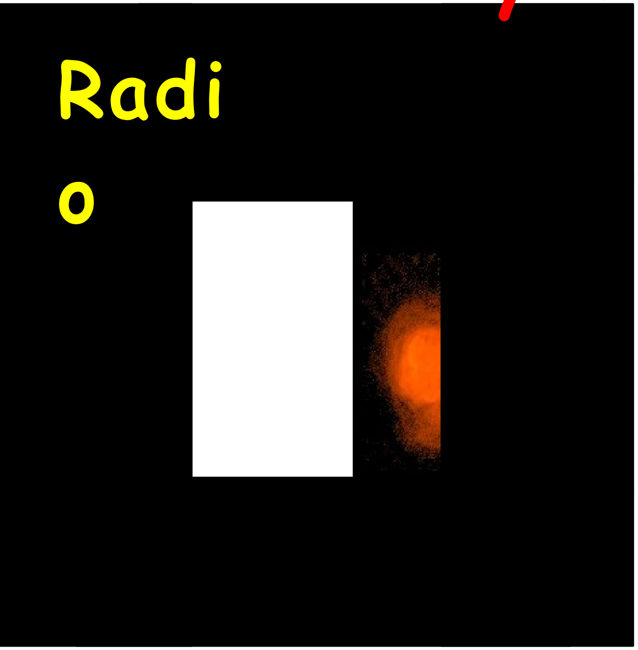


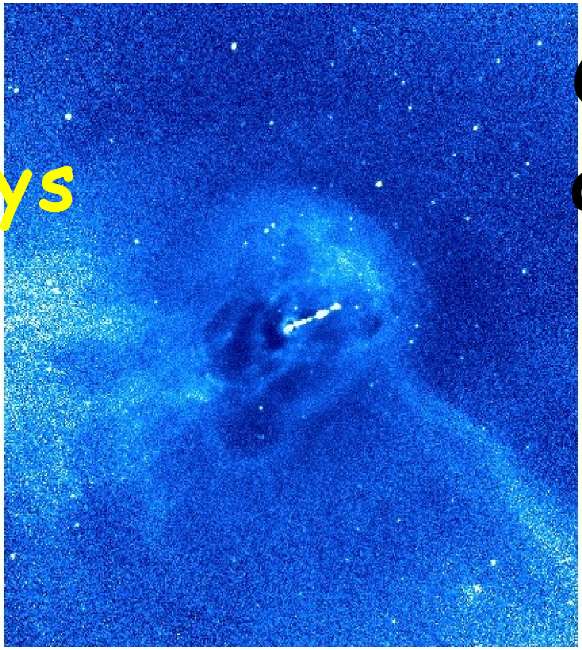
X-ray spectrum of M87

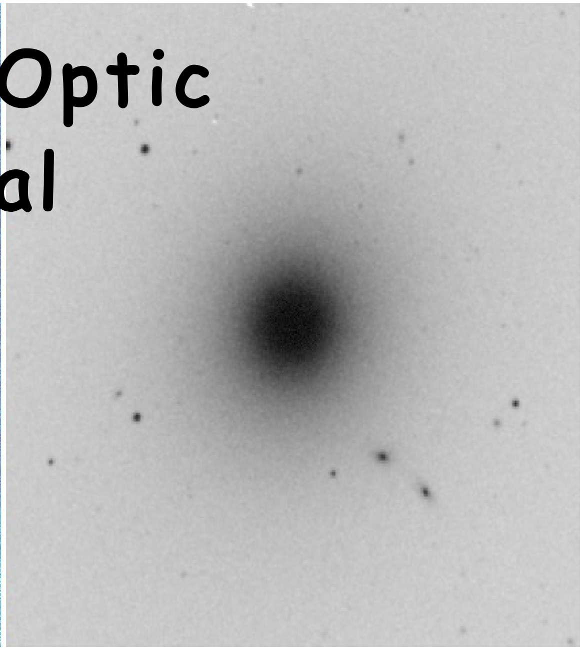


Optically thin thermal bremsstrahlung + lines $I(E) \propto g\, n^2\, T^{1/2} / E\, e^{-E/kT}$ phot/s/cm^3/keV

What we see in X-rays?



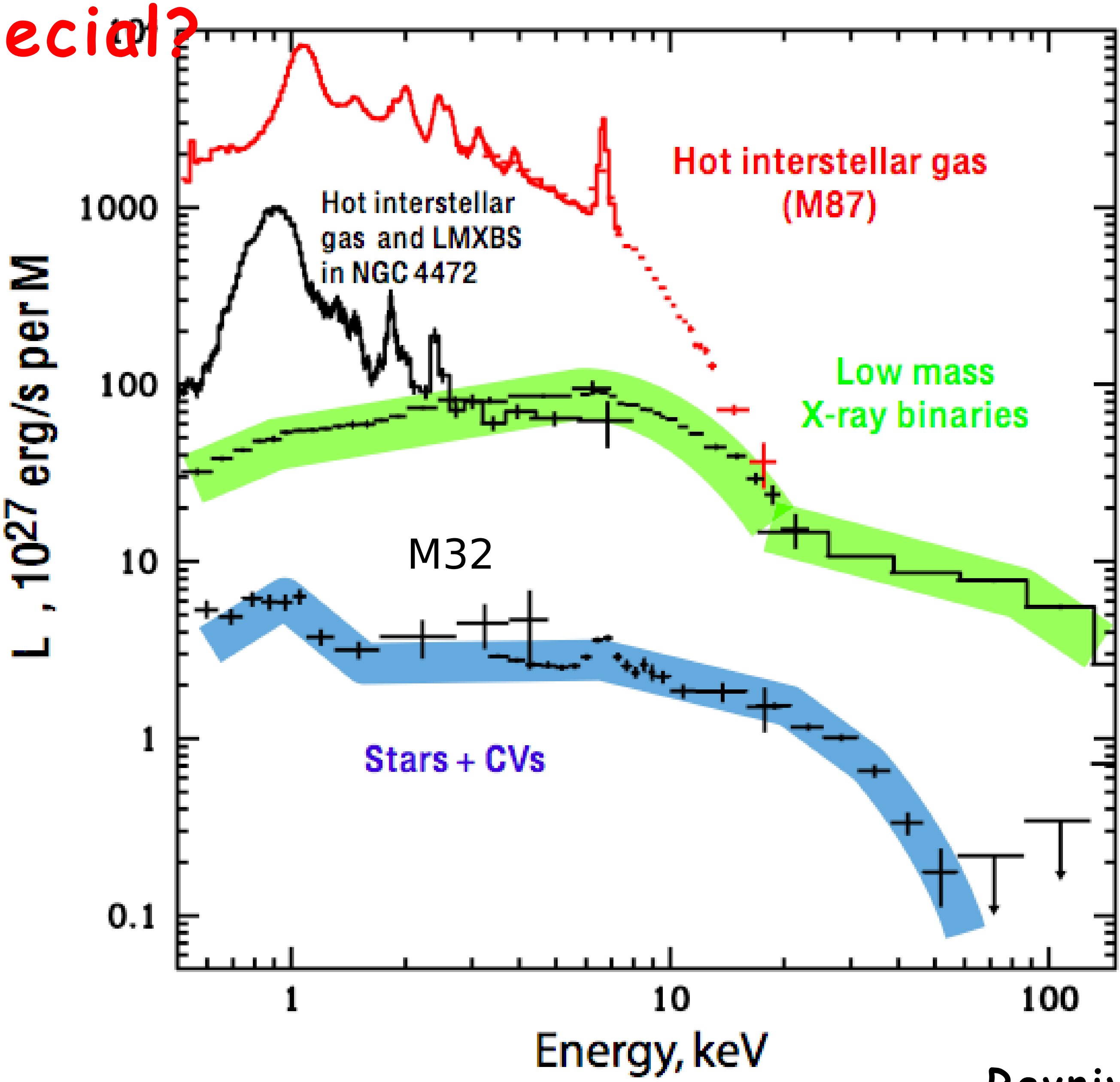




1. X-ray emitting material is pushed away by relativistic plasma
2. X-ray spectrum = thermal emission of optically thin plasma

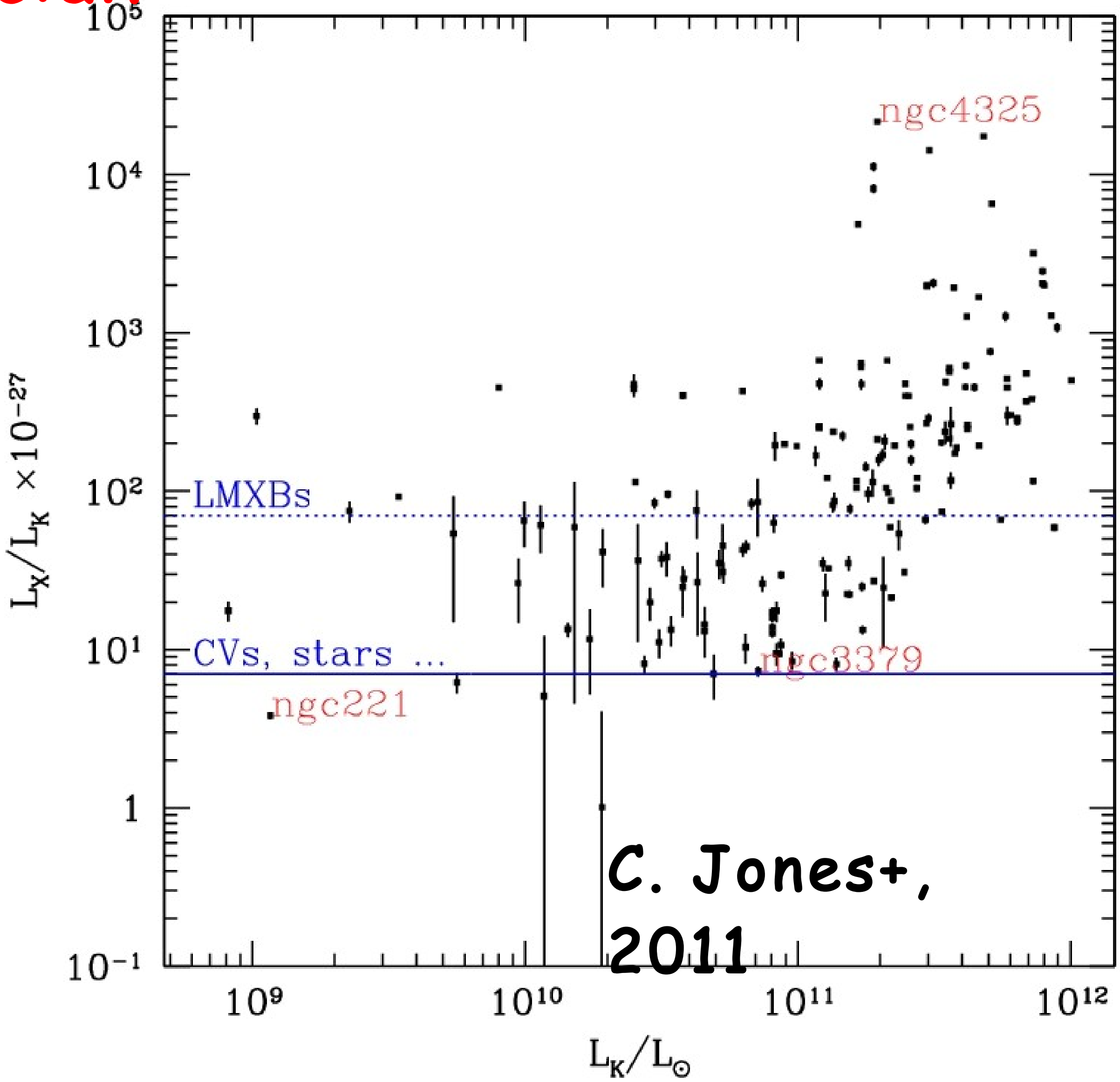
Diffuse thermal gas, filling the gravitational potential well.
In a static potential the gas settles down in few sound crossing times. Solving hydrostatic equilibrium equation gives you mass.

Are the objects we see in X-rays special?



Revnivtsev+,200

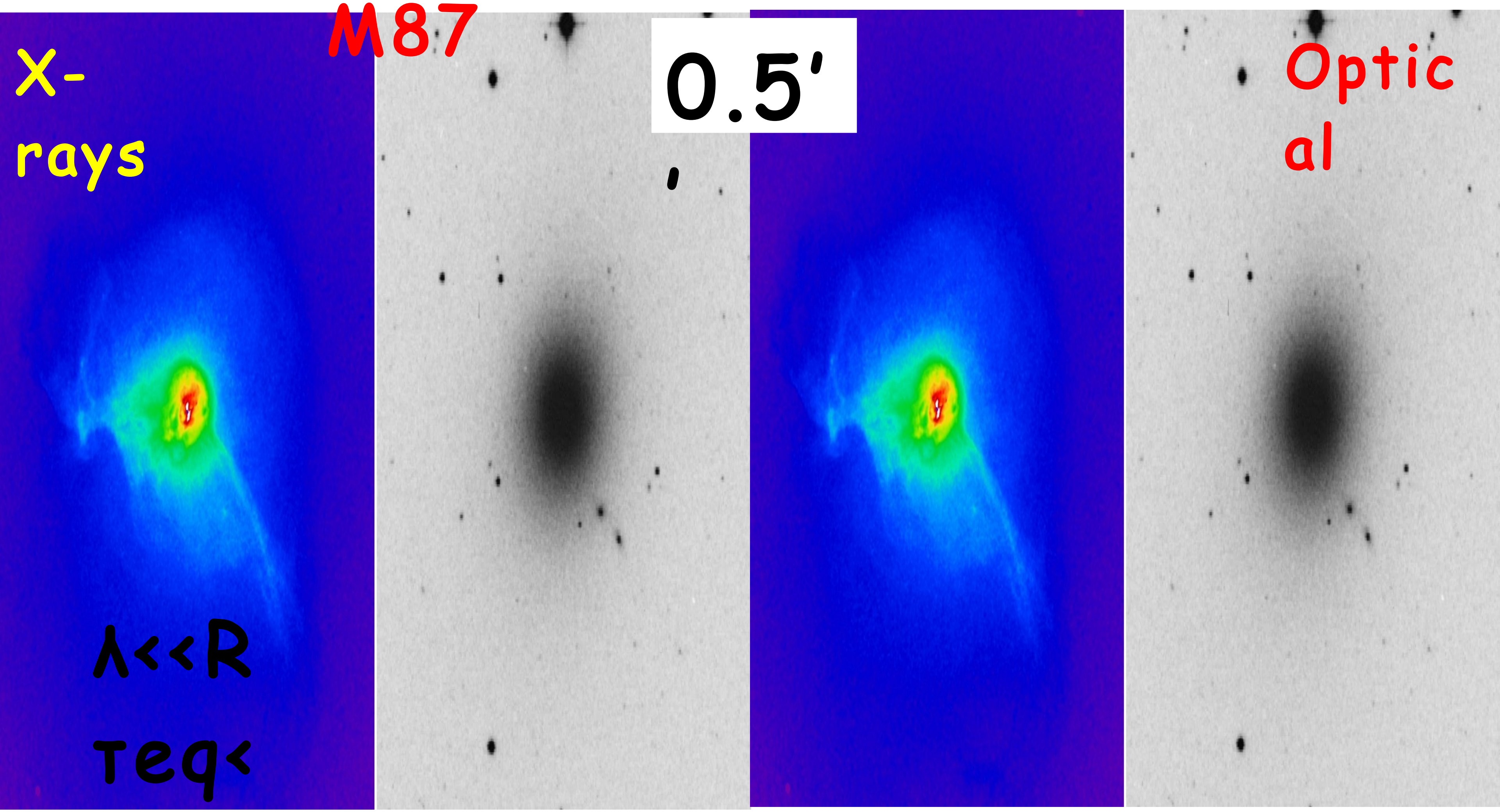
Are the objects we see in X-rays special?



C. Jones+, 2011

Most massive ellipticals (often in

Massive objects like M87



$\lambda \ll R$

$T_{eq} \ll t$

Gas: density, temperature, collisional; local;

Stars: density, dispersion, collisionless; non-local;

Hydrostatic Equilibrium

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

Mathews, 1978
Forman+, 1985

$$P = nkT$$

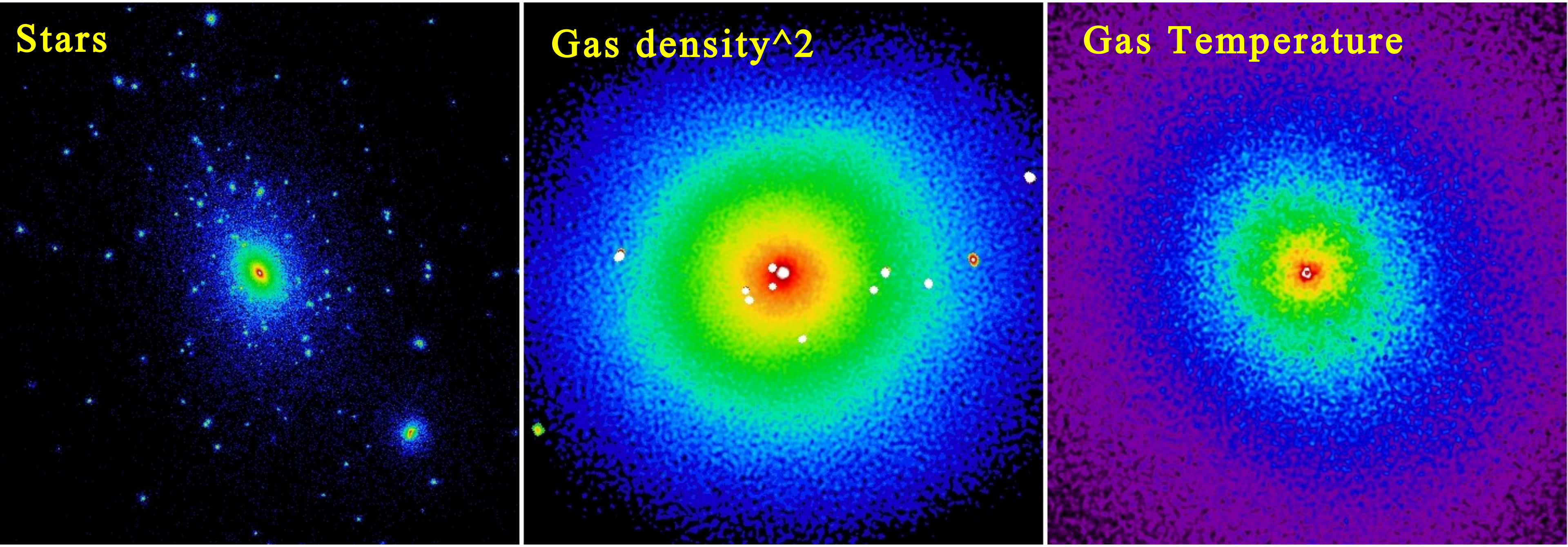
$$\rho = \mu\, m_p n$$

n from X-ray data

T form X-ray data

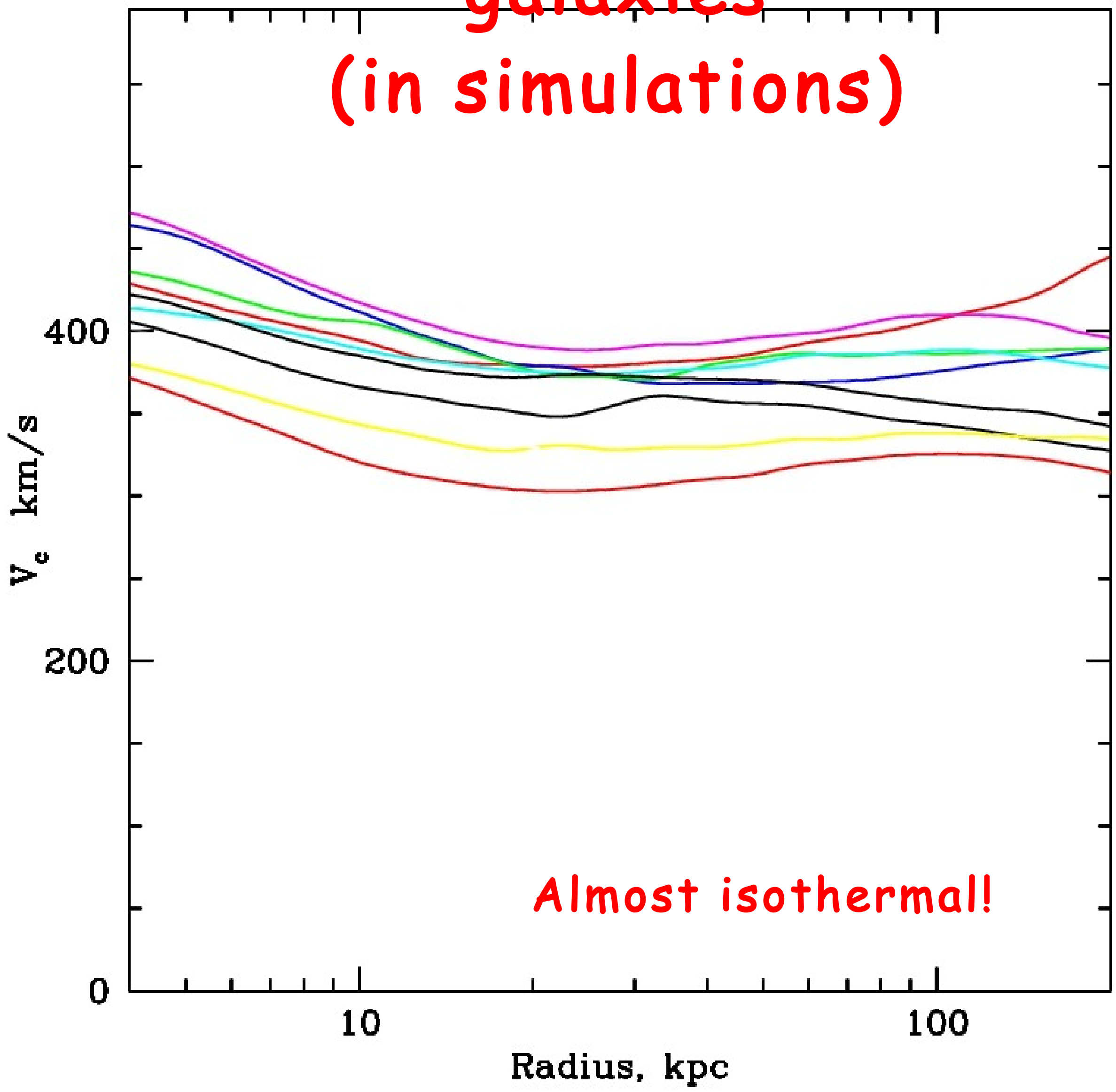
$\mu = 0.61$ ionized plasma (He)

How good is X-ray mass (compared to what)?
Simulations?



Oser et al,
2010

Mass profiles of most massive galaxies (in simulations)



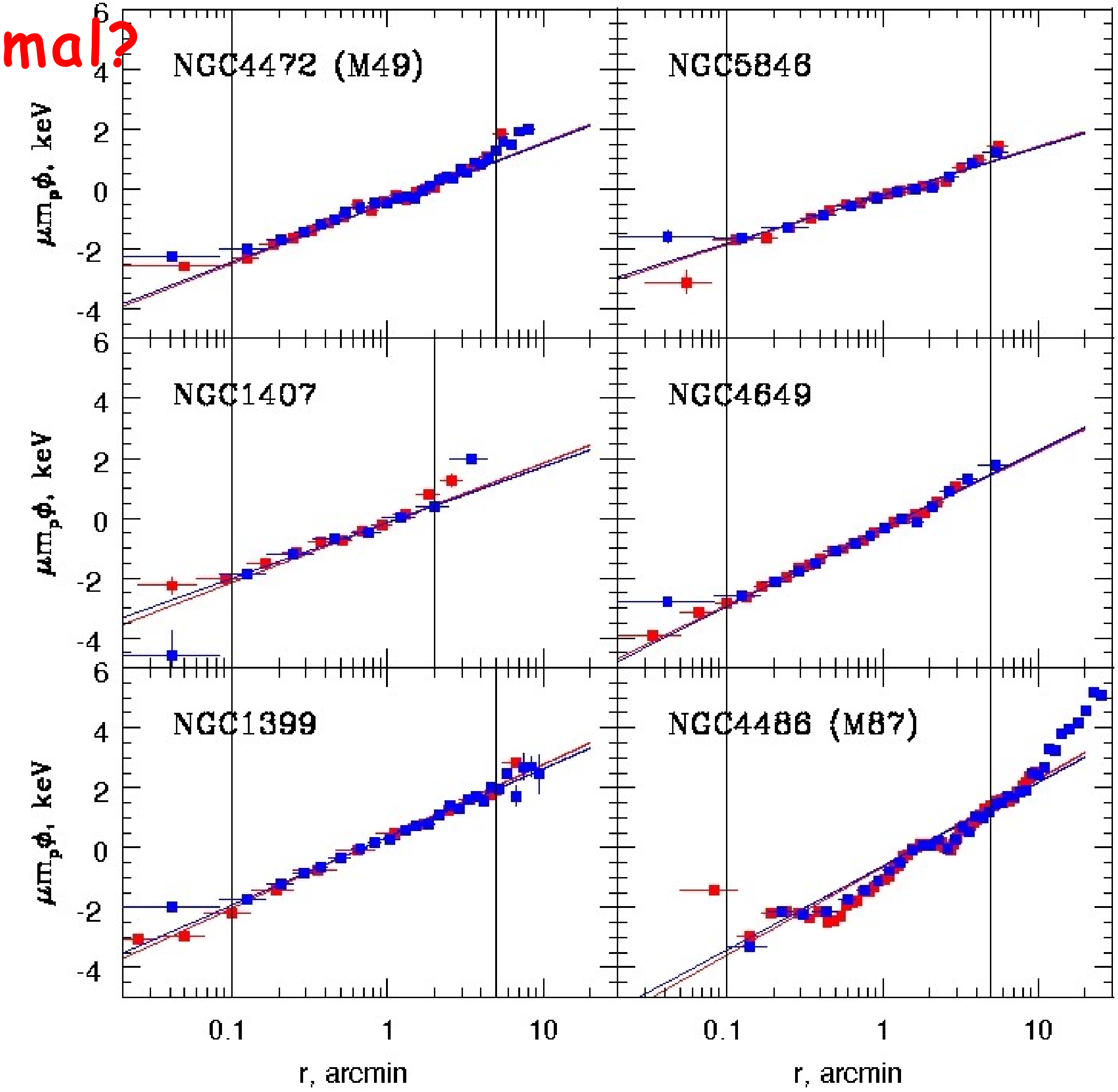
Almost isothermal!

Are real massive galaxies isothermal?

$$\varphi = \mathrm{v}_c^2 \ln r + C$$

Chandra

XMM-Newton

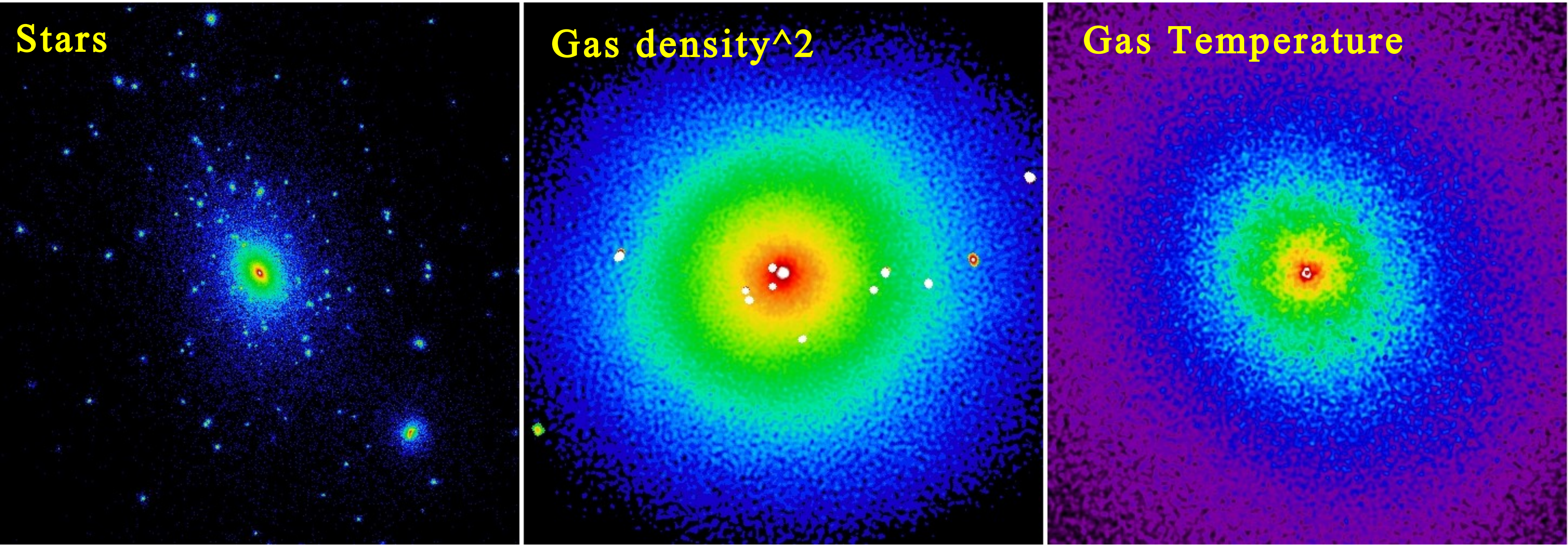


~Linear in log/lin

EC+,2010

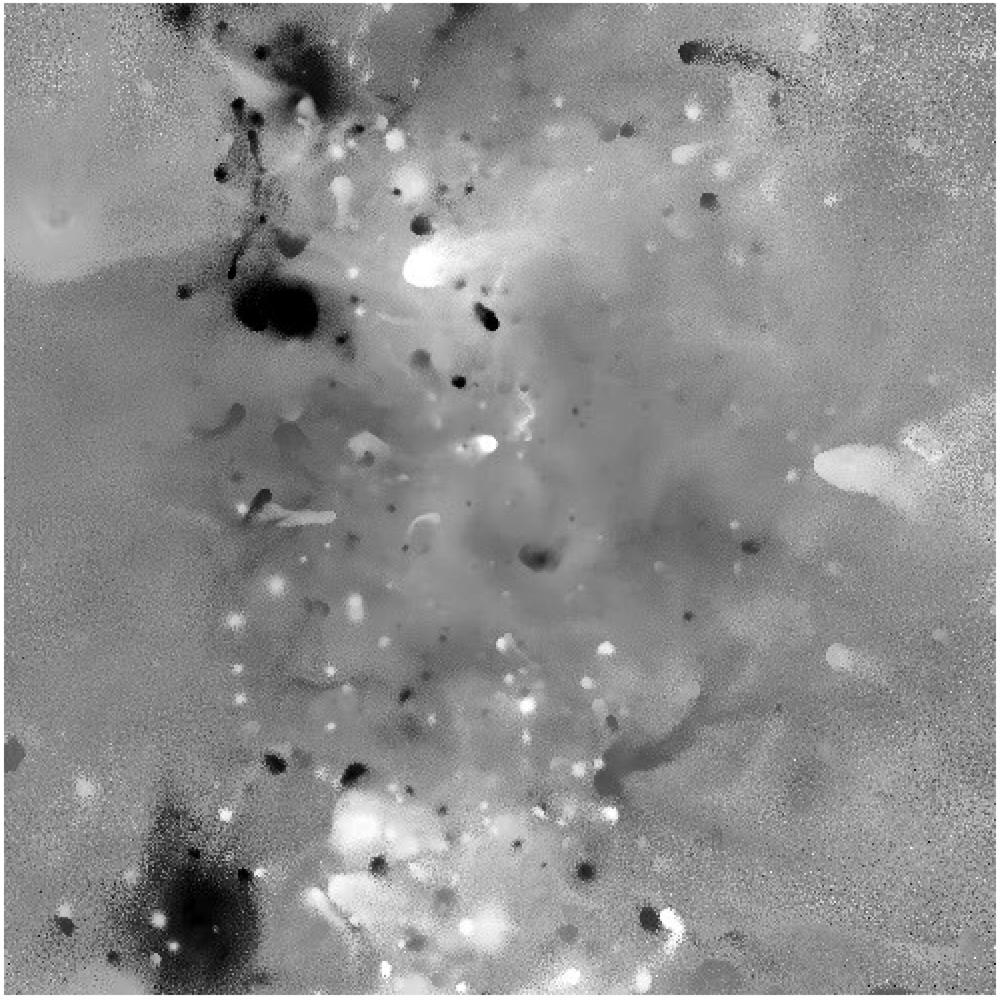
How good is X-ray mass (compared to what)?

Simulations?

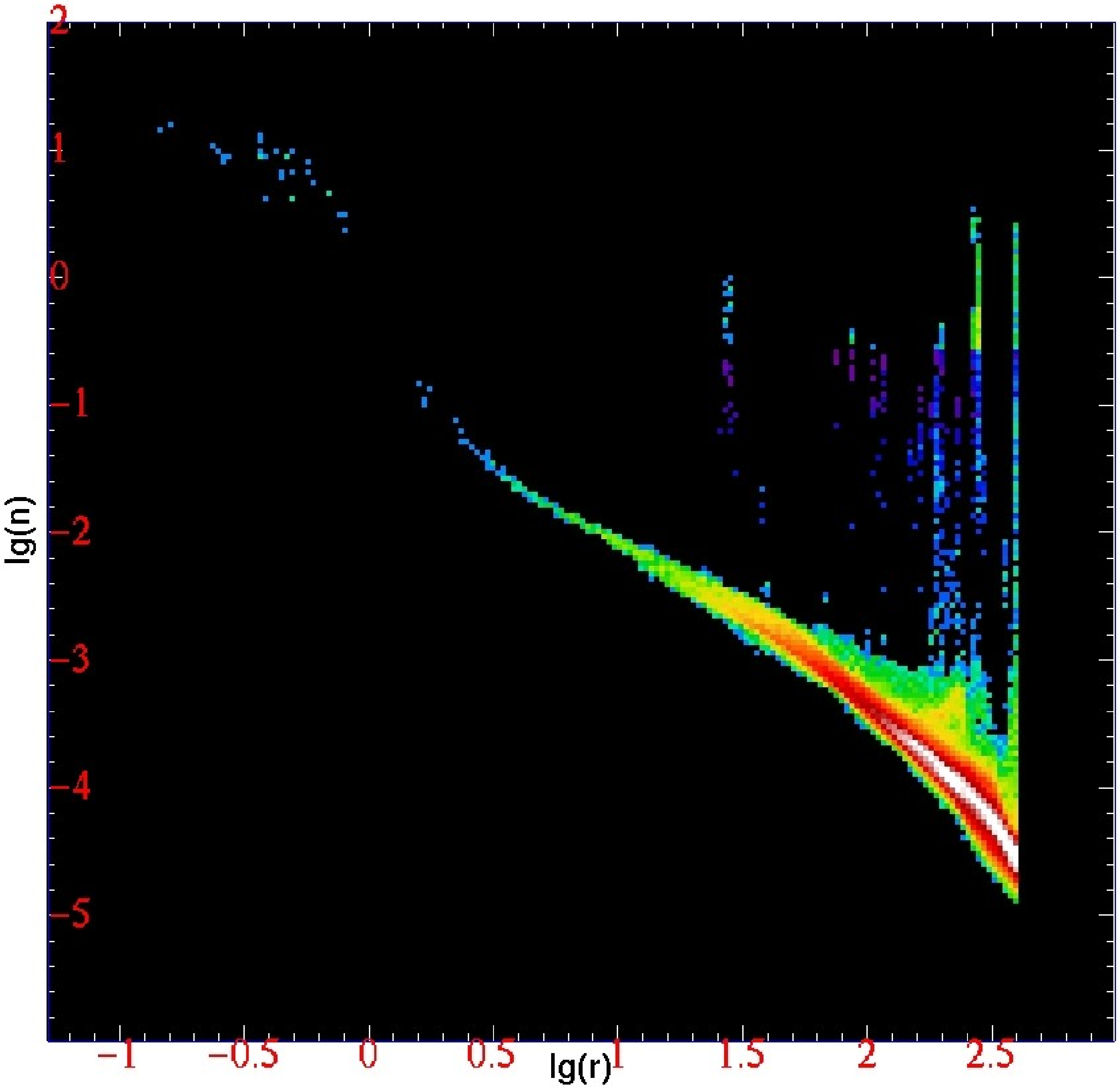


Mass profiles are approximately isothermal (s,o)

Let us now extract n,T (P) from simulations

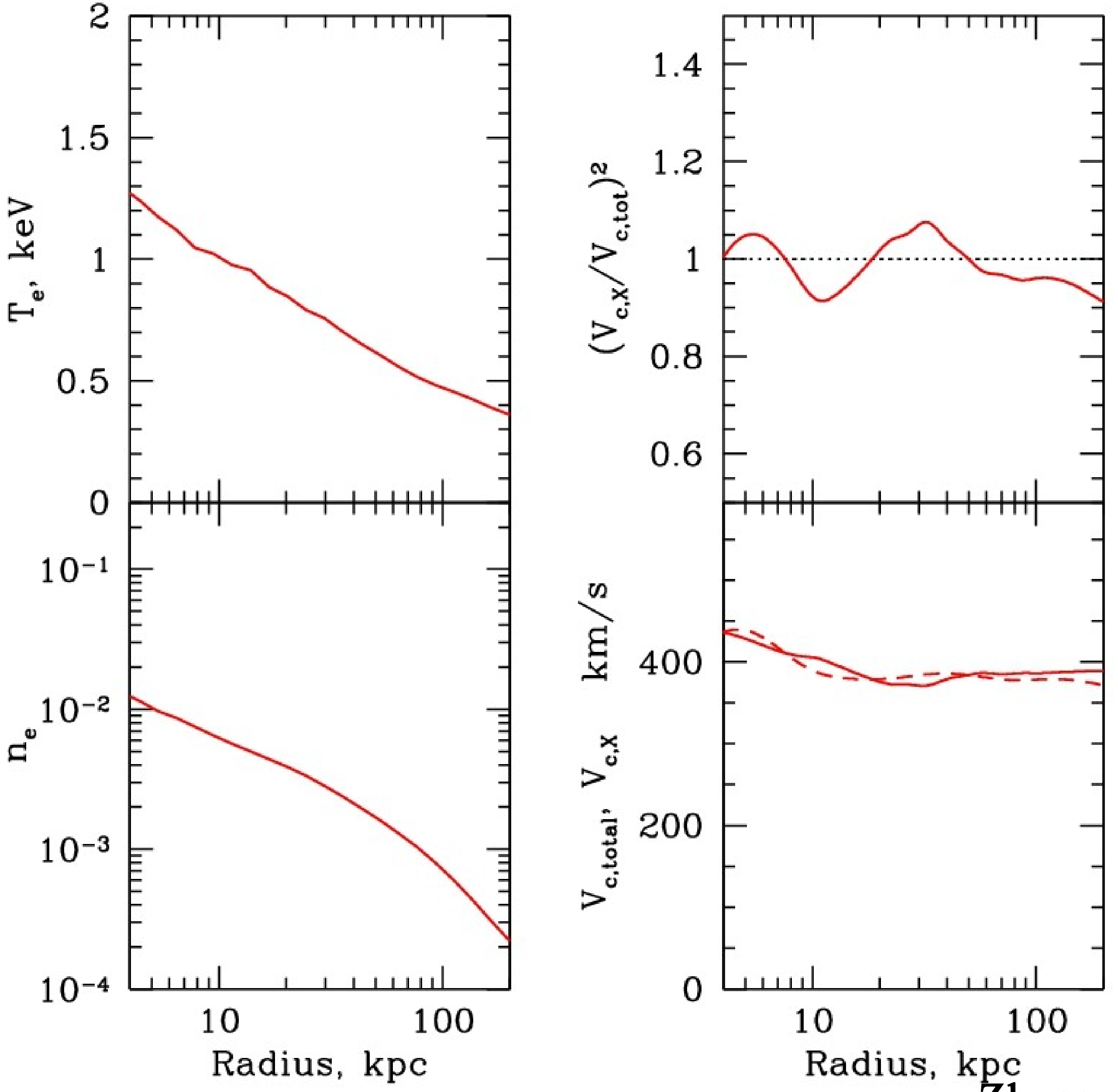


Density distribution in radial shells (in simulations)



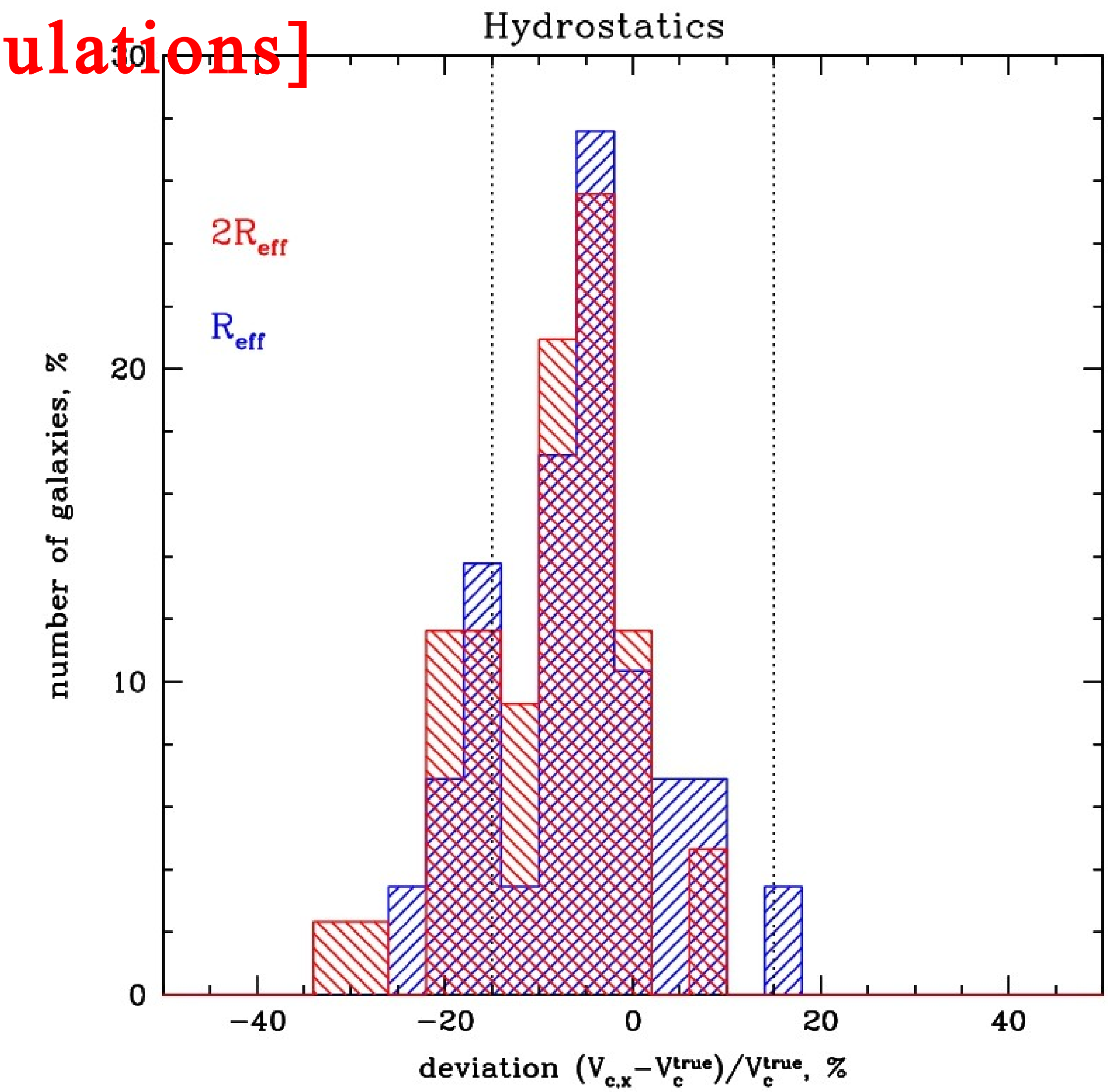
Zhuravleva+, 2011

Median n,T in radial shells (in simulations)



Zhuravleva+, 2011

Deviations of VC from true value [simulations]



RMS~8%, Bias ~5-8% (traceable to residual gas motions)

How good are X-ray masses? What to compare with (for real objects)?

Stellar kinematics?

X-rays:

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

Optical: I(R), σ(R)

Lyskova+,2011
Poster #30

Isothermal potential + Power law I(R) + β=const

$$\varphi(r) = \mathrm{v}_c^2 \ln r$$

$$I(R) \propto R^{-\alpha}$$

$$\frac{\sigma_p}{\mathrm{V}_c}$$

independent on R

$$\sigma_{iso}^2(R) = \mathrm{v}_c^2 \frac{1}{1+\alpha}$$

$$\sigma_{circ}^2(R) = \frac{1}{2}\mathrm{v}_c^2 \frac{\alpha}{1+\alpha}$$

$$\sigma_{rad}^2(R) = \frac{1}{2}\mathrm{v}_c^2 \frac{1}{\alpha^2-1}$$

For α=2 no dependence on β!

(Gerhard, 1993)

Relax the assumption I(R)=R-α

Local σ/vc relation

$$\sigma^2_{iso}(R) = \mathrm{v}_c^2 \frac{1}{1+\alpha+\gamma}$$

[isotropic]

$$\sigma^2_{circ}(R) = \frac{1}{2}\mathrm{v}_c^2 \frac{\alpha}{1+\alpha+\gamma}$$

[circular]

$$\sigma^2_{rad}(R) = \frac{1}{2}\mathrm{v}_c^2 \frac{1}{(\alpha+\gamma)^2 + \frac{d^2 \ln[\sigma^2 I(R)]}{d(\ln R)^2} - 1}$$

[radial]

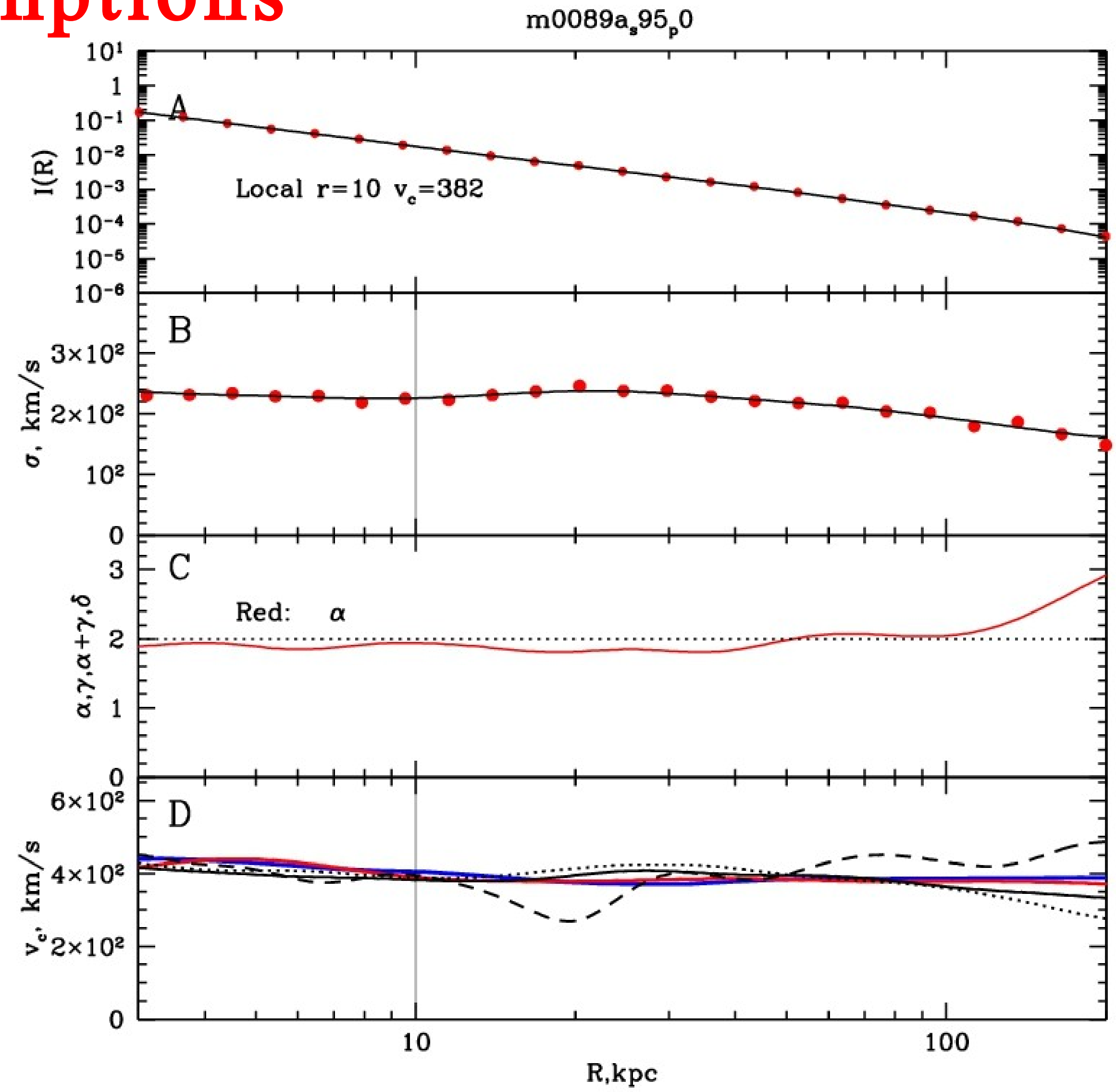
$$\alpha = -\frac{d\ln I(R)}{d\ln R}; \qquad \gamma = -\frac{d\ln \sigma_p^2}{d\ln R}$$

$$\boxed{I(R) \propto R^{-2}}$$

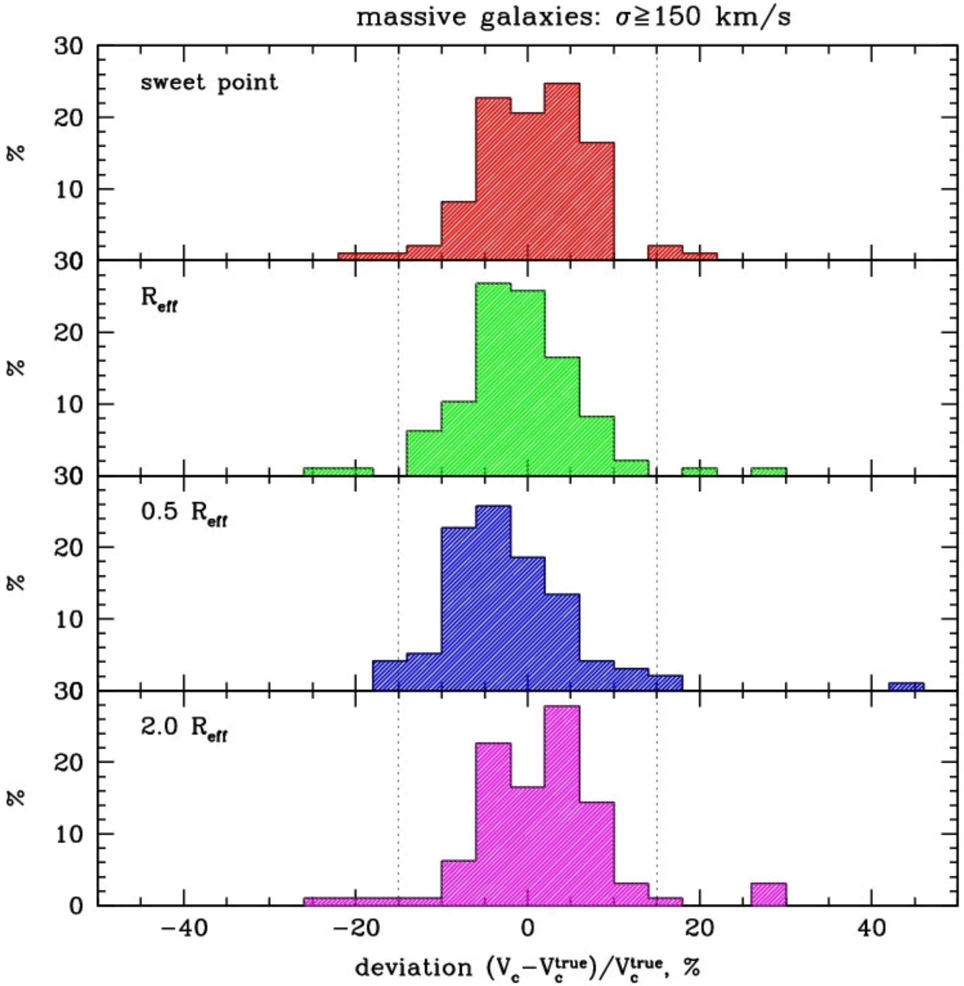
EC+,

Relax all assumptions

$$I(R) \propto R^{-2}$$



Lyskova+, 2011



Trivial analysis of optical data gives RMS~6%

[in simulations]

We can use optical + X-rays analysis

Lyskova+, 2011

What can go wrong with X-rays?

$$P,\rho,\mu$$

Annoying:

- Deviations from spherical symmetry
- Multi-temperature plasma => n,T
- Abundance determination => n
- LMXBs contribution => T

Interesting:

- Turbulent gas motions
- Magnetic fields
- Cosmic Rays
- μ – He abundance

Annoying problems (error budget)

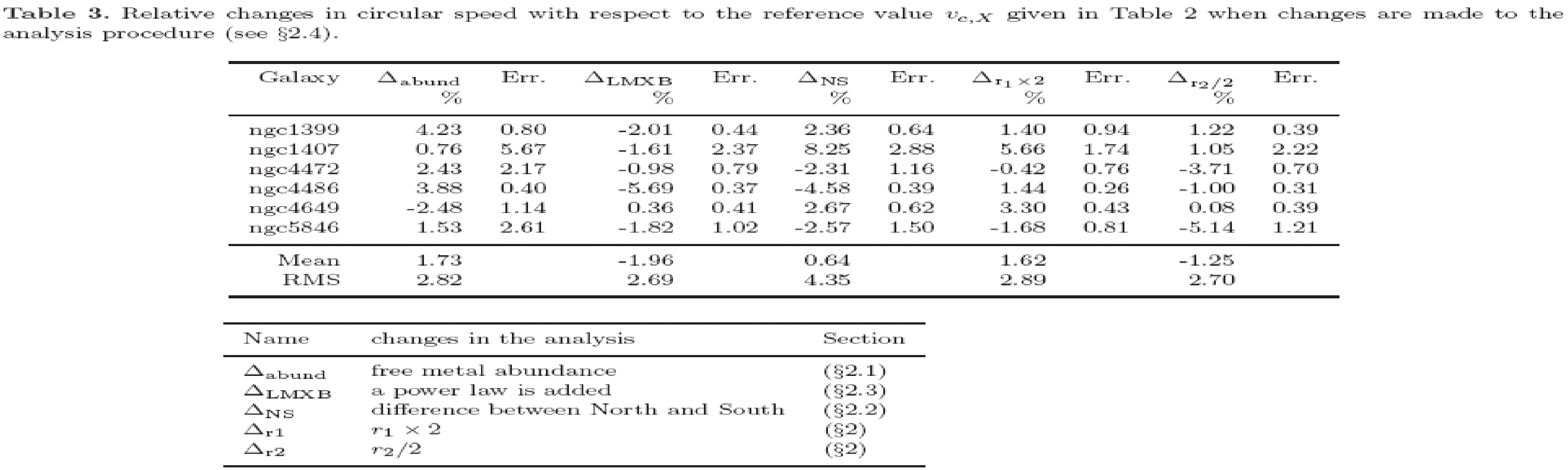


Table 3. Relative changes in circular speed with respect to the reference value $v_{c,X}$ given in Table 2 when changes are made to the analysis procedure (see §2.4).

Galaxy	$\Delta_{\rm abund}$ %	Err.	$\Delta_{\rm LMXB}$ %	Err.	$\Delta_{\rm NS}$ %	Err.	$\Delta_{r_1\times 2}$ %	Err.	$\Delta_{r_2/2}$ %	Err.
ngc1399	4.23	0.80	-2.01	0.44	2.36	0.64	1.40	0.94	1.22	0.39
ngc1407	0.76	5.67	-1.61	2.37	8.25	2.88	5.66	1.74	1.05	2.22
ngc4472	2.43	2.17	-0.98	0.79	-2.31	1.16	-0.42	0.76	-3.71	0.70
ngc4486	3.88	0.40	-5.69	0.37	-4.58	0.39	1.44	0.26	-1.00	0.31
ngc4649	-2.48	1.14	0.36	0.41	2.67	0.62	3.30	0.43	0.08	0.39
ngc5846	1.53	2.61	-1.82	1.02	-2.57	1.50	-1.68	0.81	-5.14	1.21
Mean	1.73		-1.96		0.64		1.62		-1.25	
RMS	2.82		2.69		4.35		2.89		2.70	

Name	changes in the analysis	Section
$\Delta_{\rm abund}$	free metal abundance	(§2.1)
$\Delta_{\rm LMXB}$	a power law is added	(§2.3)
$\Delta_{\rm NS}$	difference between North and South	(§2.2)
$\Delta_{\rm r1}$	$r_1 \times 2$	(§2)
$\Delta_{\rm r2}$	$r_2/2$	(§2)

RMS~7% [good objects]

EC+,

More Interesting Part : Non-thermal pressure

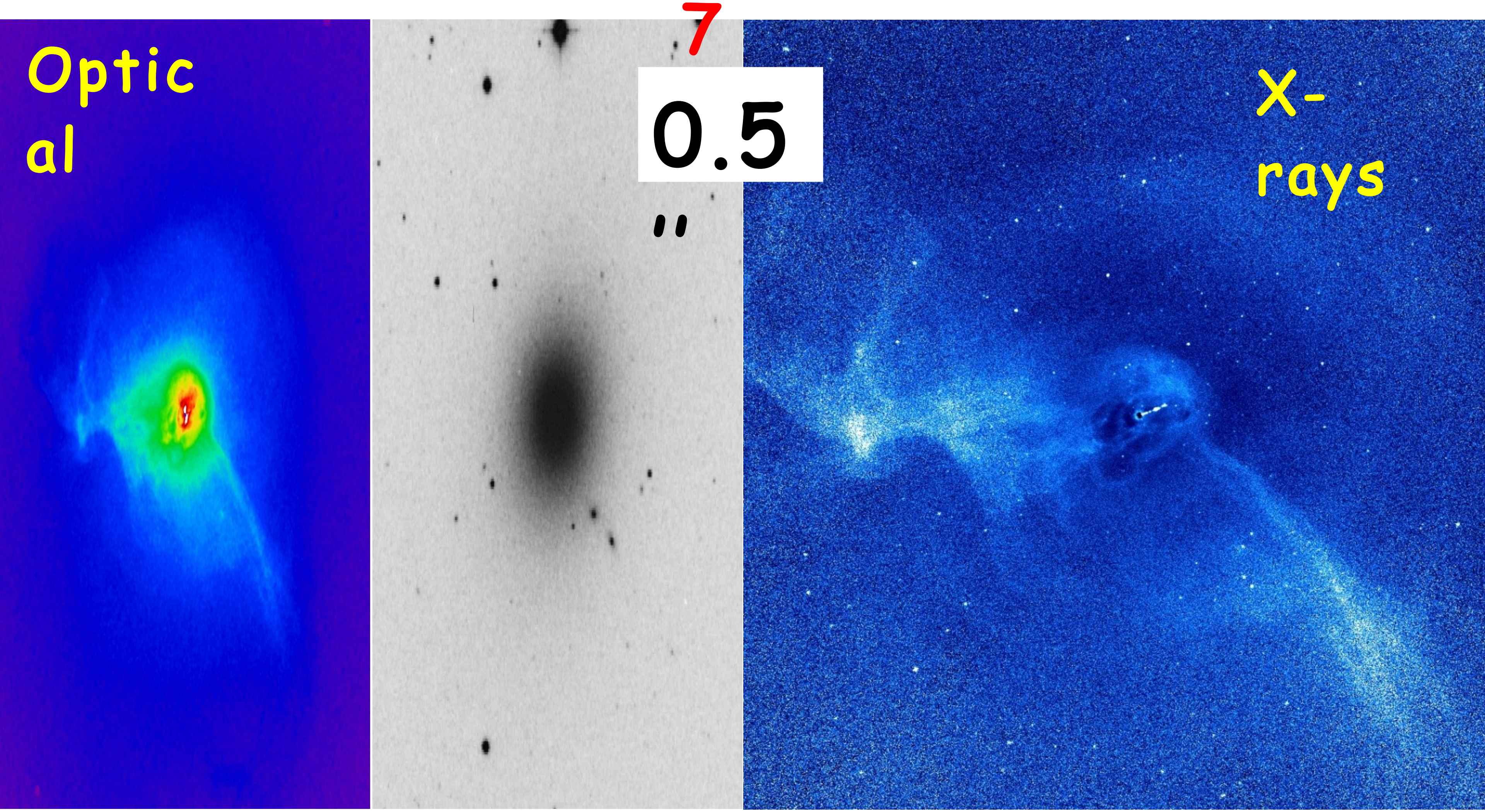
$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2}$$

$$P = \overset{\uparrow}{nkT} + \underbrace{P_{CR} + \frac{B^2}{8\pi} + P_{turb}}$$

Thermal pressure (easy to measure)

Non-thermal pressure (invisible)

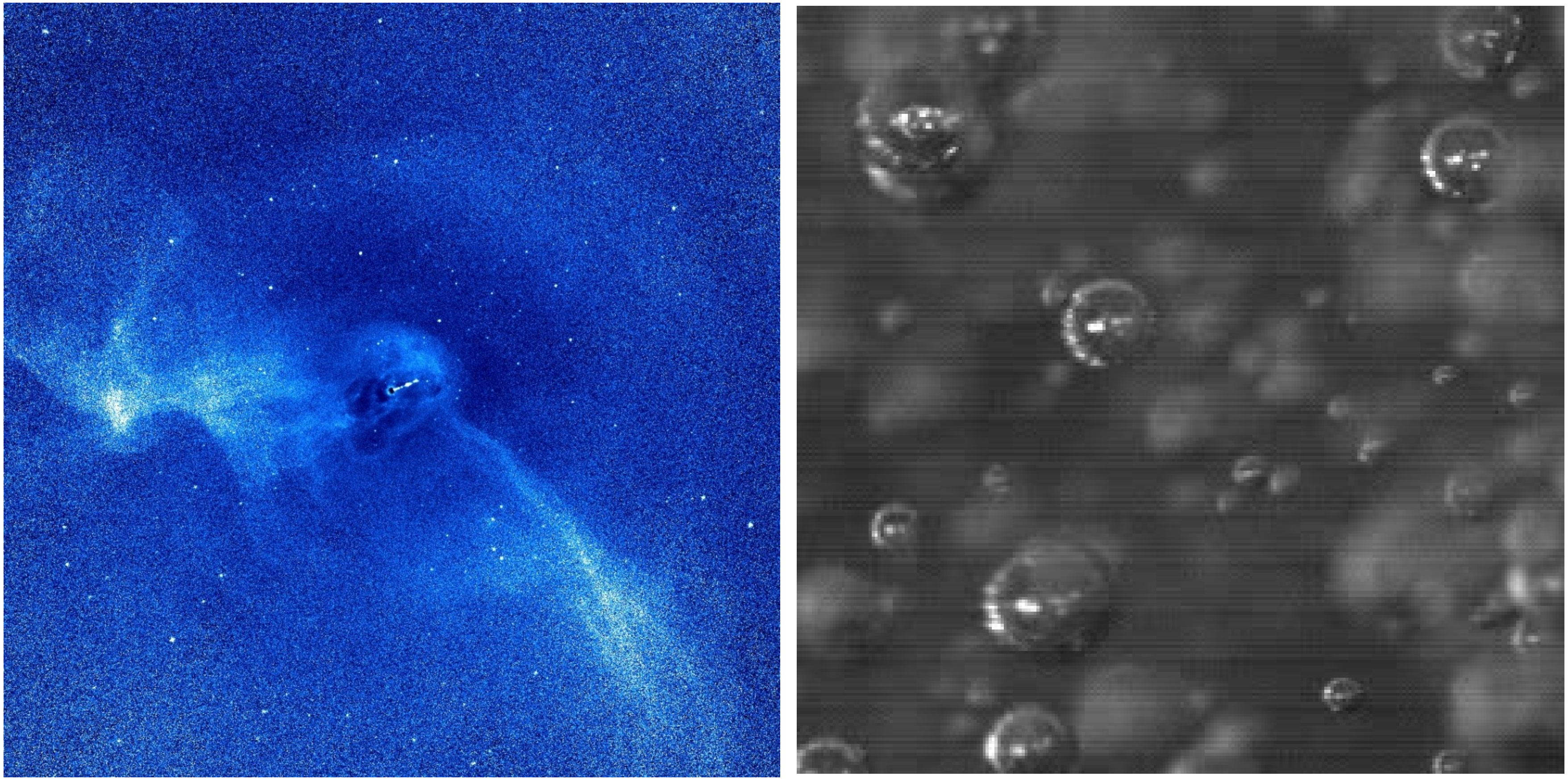
M87



Stars: gravity only

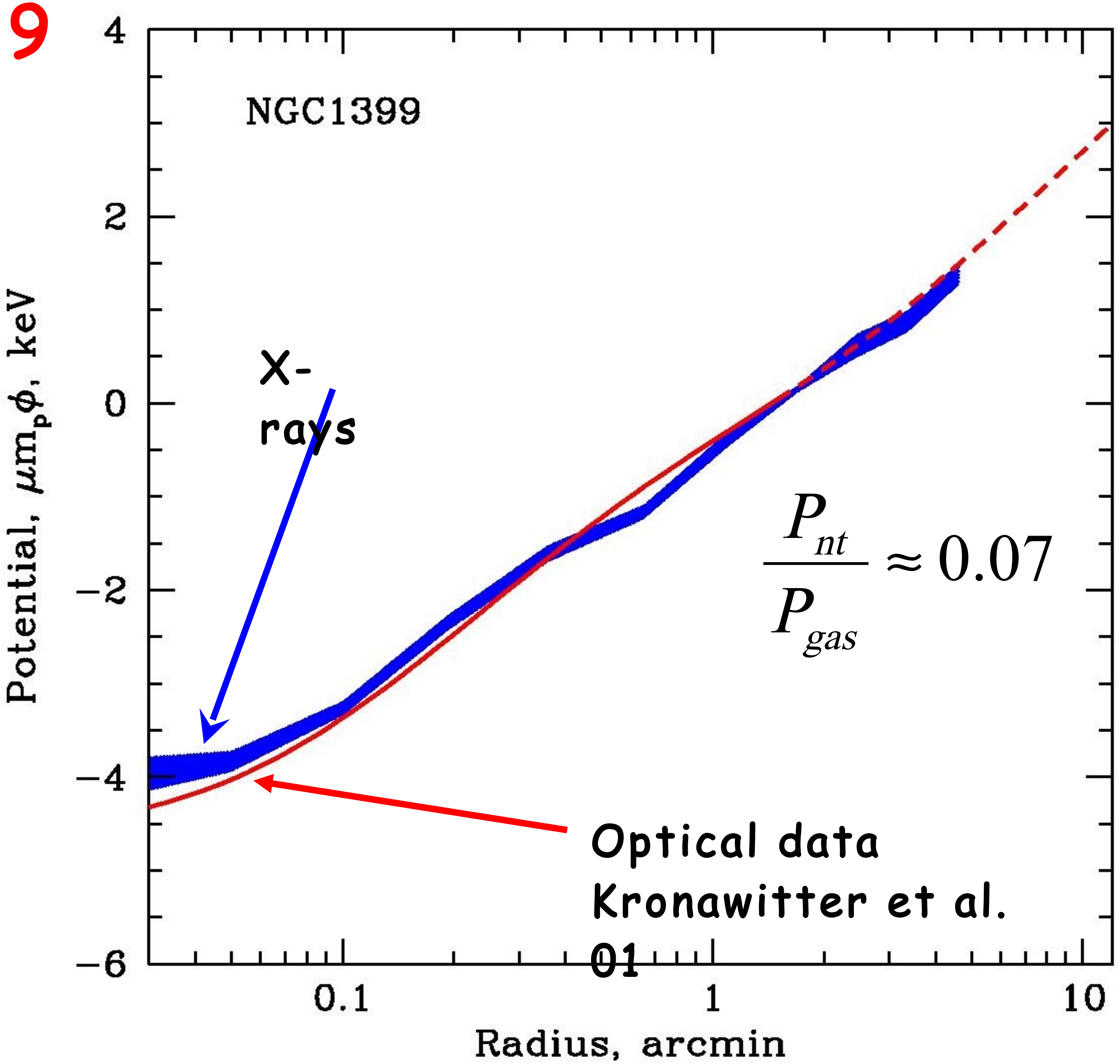
Gas: gravity, magnetic fields, cosmic rays, turbulent motions

Cosmic rays + magnetic fields + turbulent motions



Extra (non-thermal) energy makes the gas distribution broader!
Comparison of optical and X-ray mass is a proxy for non-thermal

NGC1399



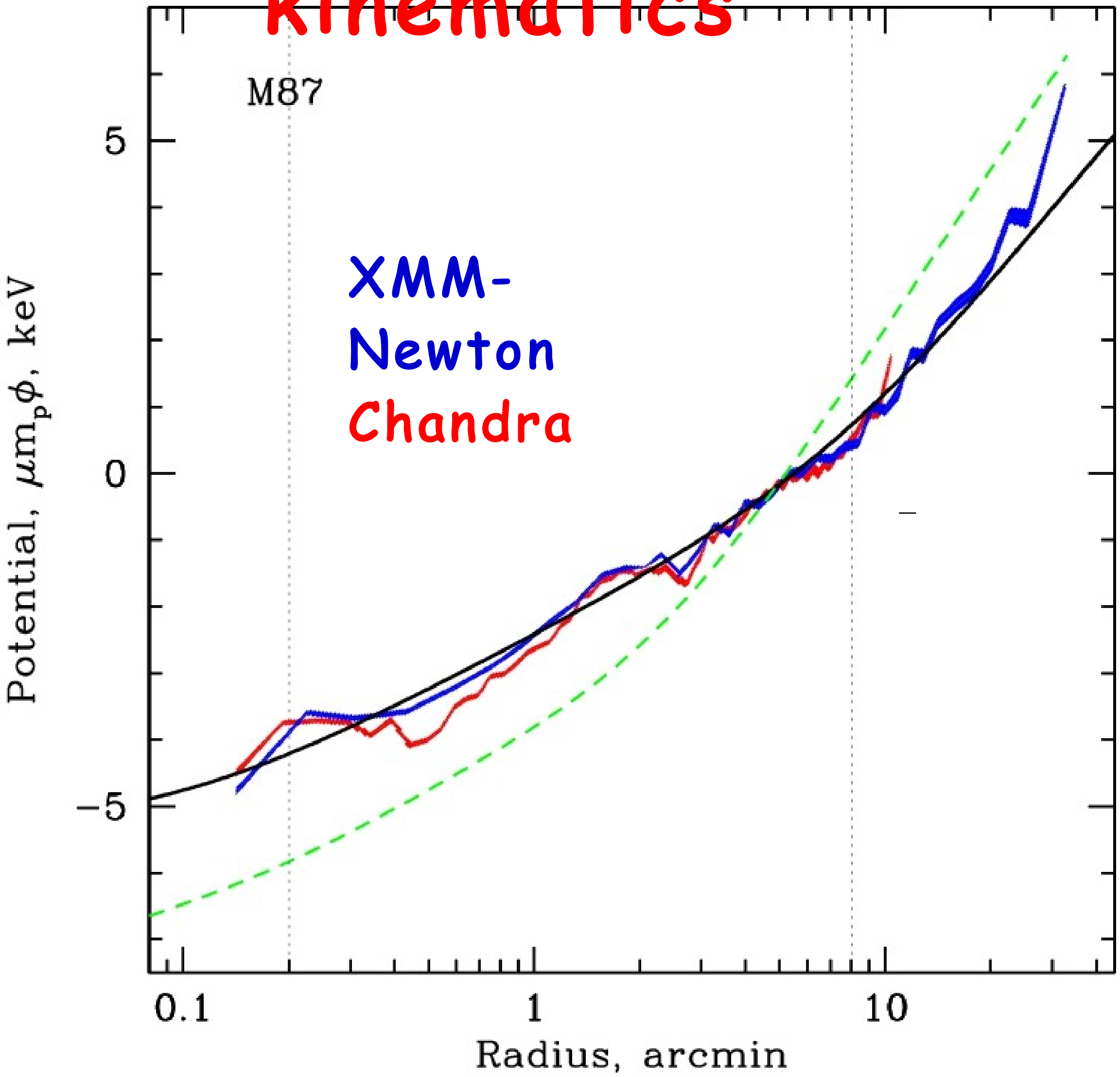
X-rays

$$\frac{P_{nt}}{P_{gas}} \approx 0.07$$

Optical data Kronawitter et al. 01

EC+,

M87: X-rays + stellar kinematics



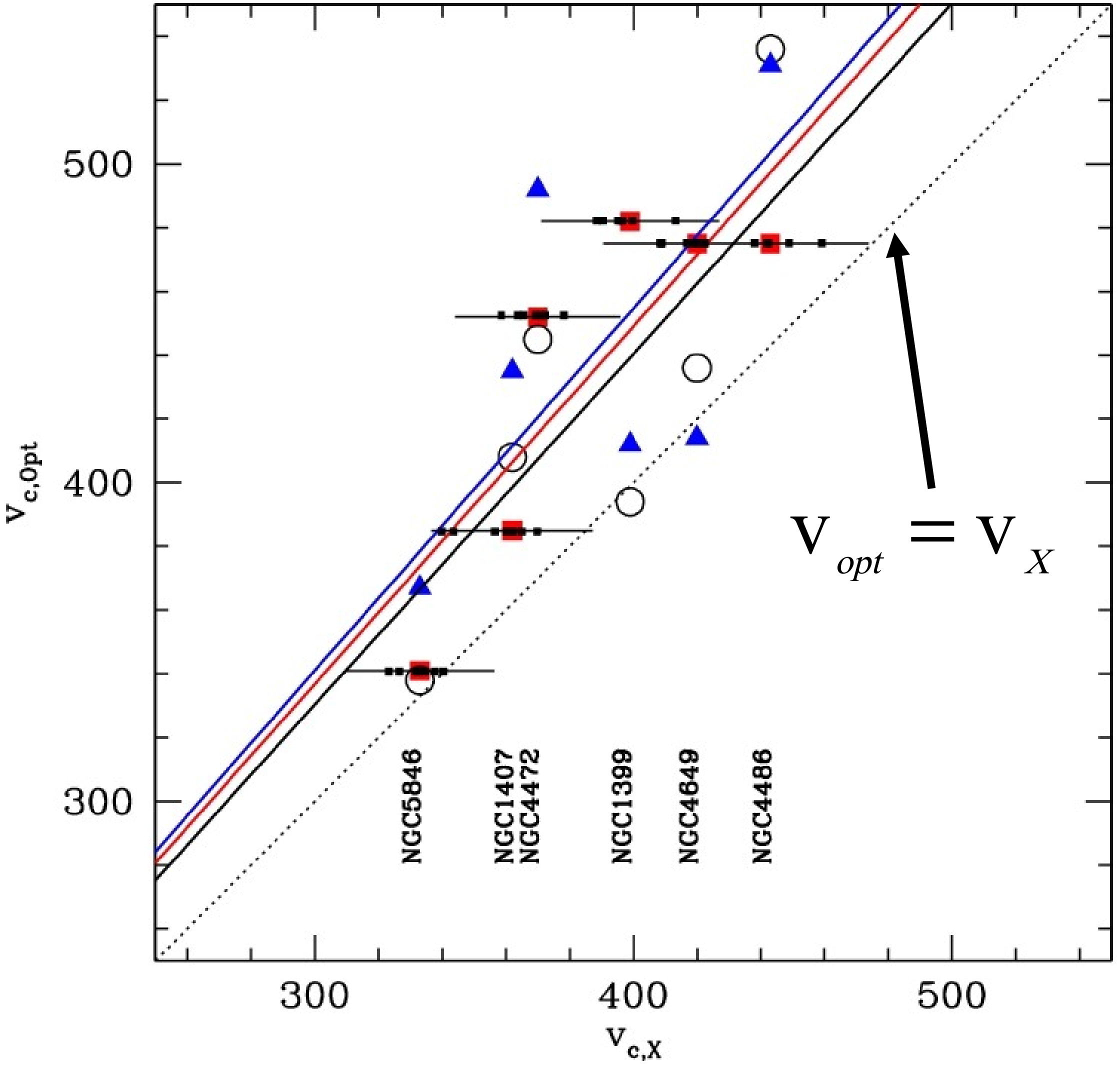
XMM-Newton

Chandra

Romanowsky & Kochanek, 2001

Gebhardt & Thomas, 2010

Comparison of optical and X-ray effective Vc



Red - central vel.disp.

Blue - sweet point

Black - local

$$v_c = 1.12 \times v_X$$

$$v_s = 1.14 \times v_X$$

$$v_l = 1.10 \times v_X$$

Non-thermal pressure 20-28%

This is what we need to keep the gas hot!

Conclusions

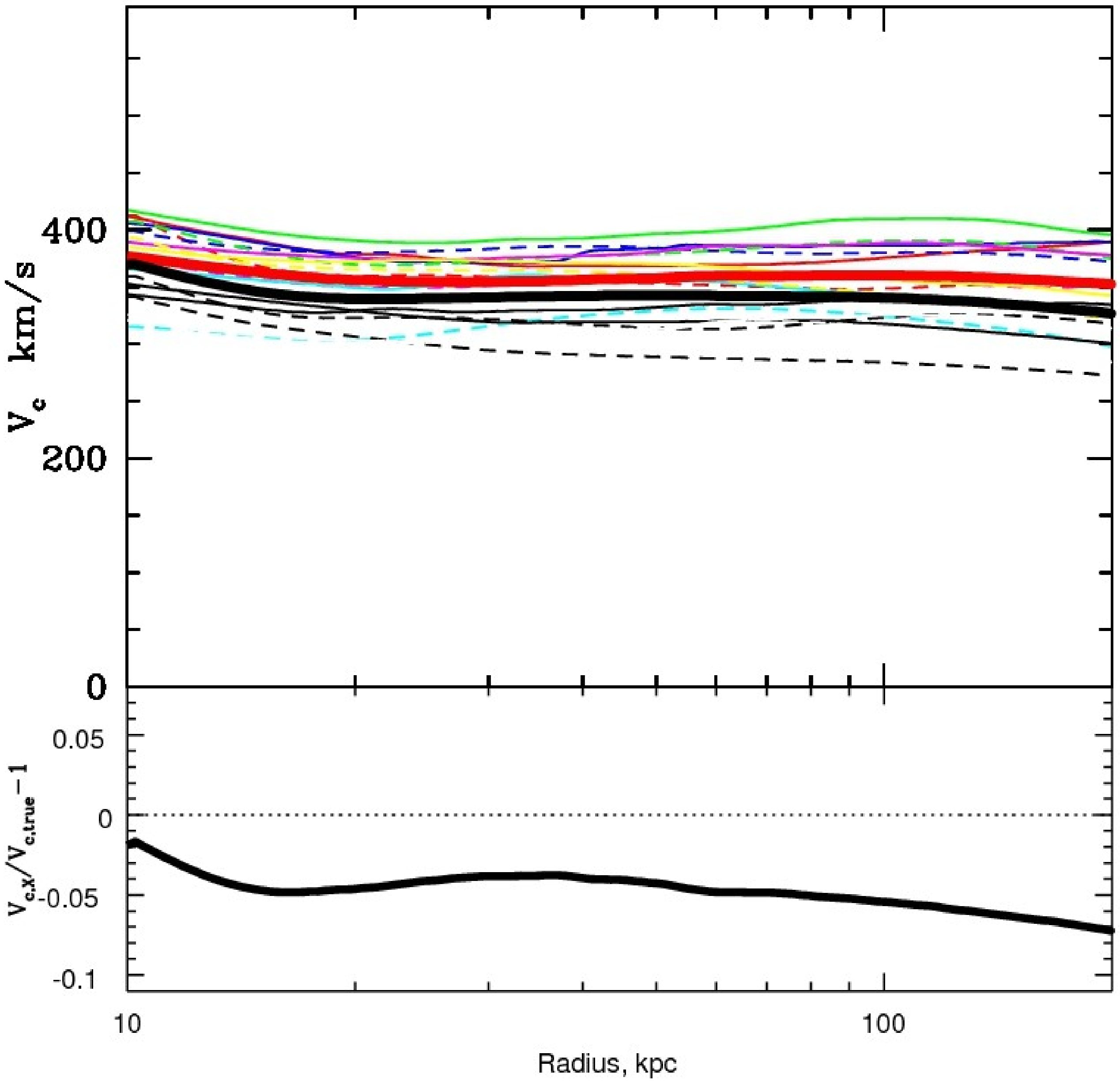
In X-rays we see gas in very massive ellipticals (groups, clusters)
Collisional nature => local, isotropic pressure => H.E.

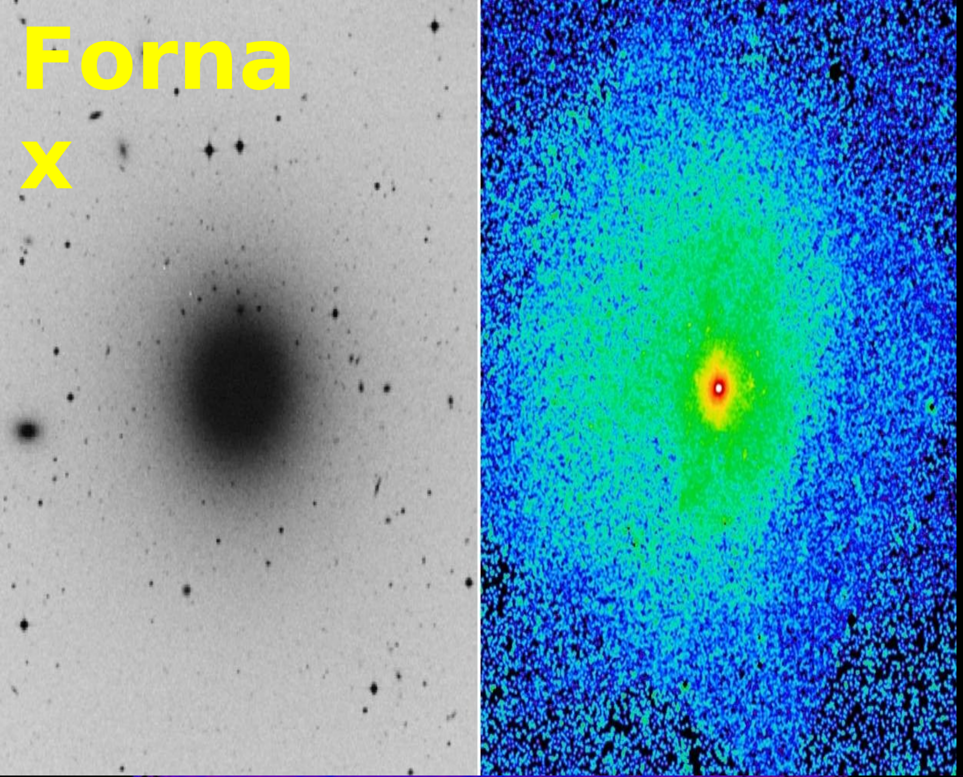
Massive ellipticals have approximately isothermal potential
Scatter and bias in measuring Vc from H.E. ~ 5-8% [sim]
Bias is traceable to gas motions [sim]

Typical uncertainty in X-ray derived Vc is ~7%
Bias in Vc is ~10 % [non-thermal pressure]
Bias in Vc is partly correctable [with extra measurements]

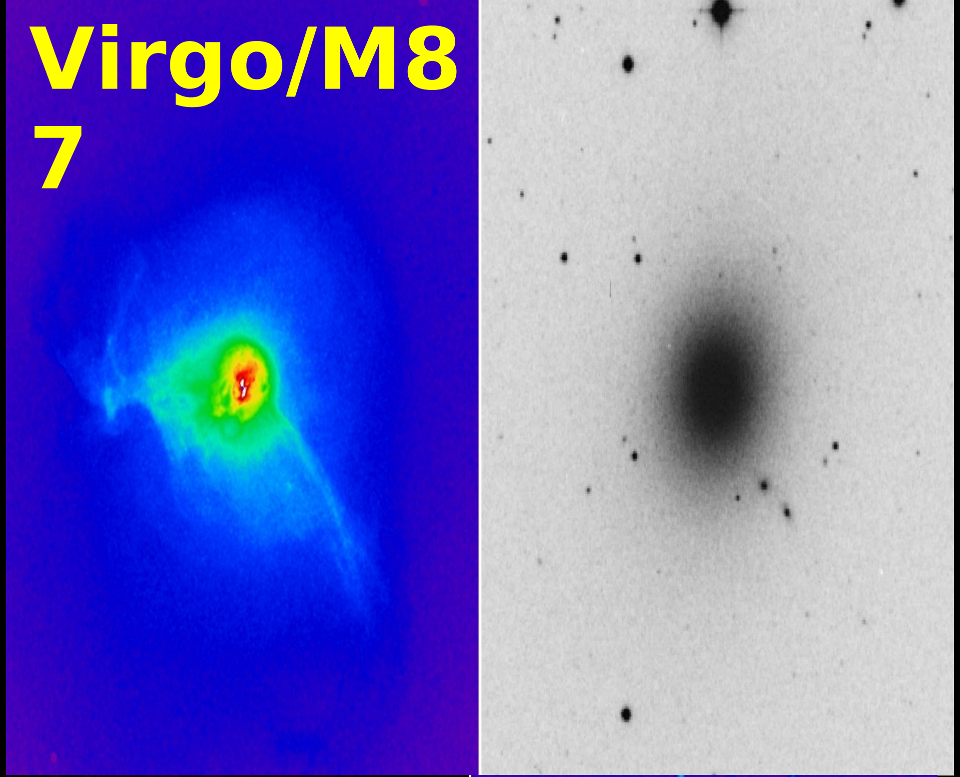
10% [smaller for a

Mean Vc,x vs Vc,true (in simulations)

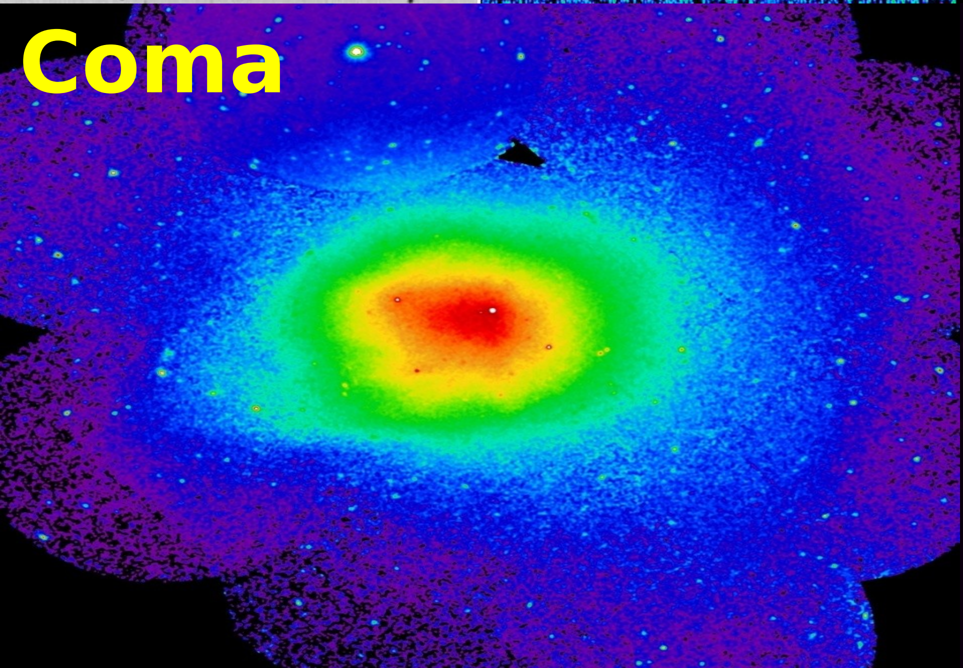




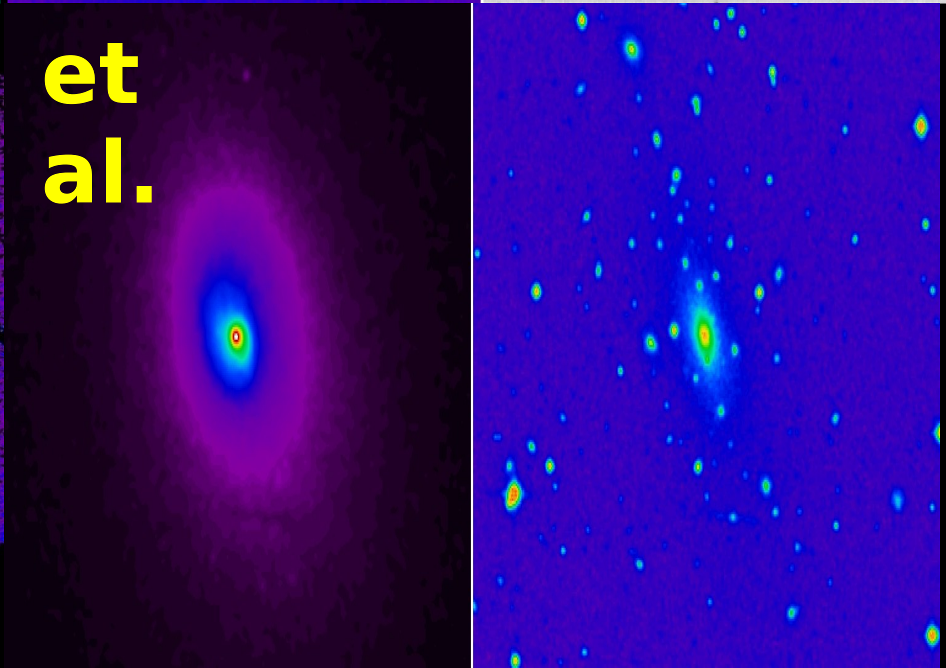
Fornax



Virgo/M87

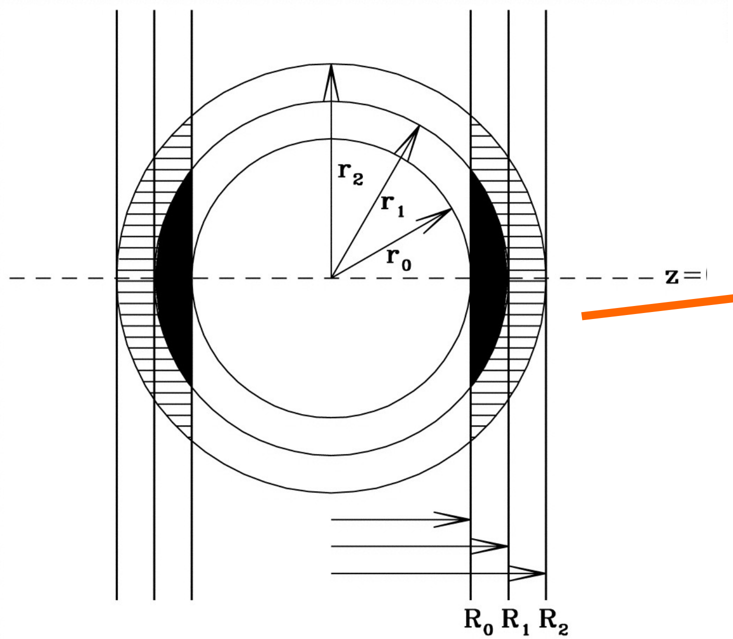


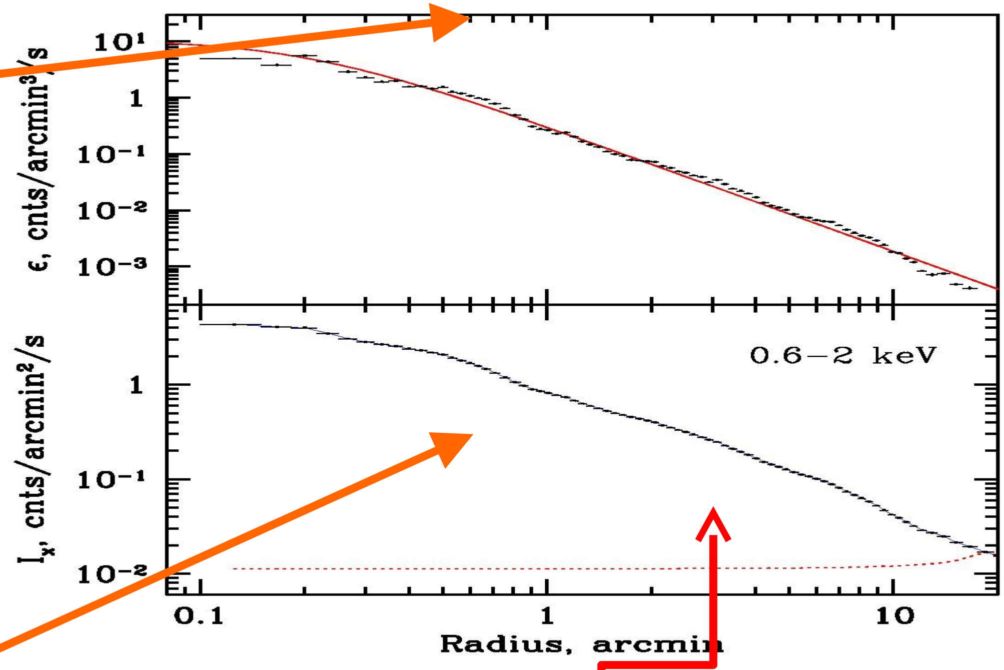
Coma

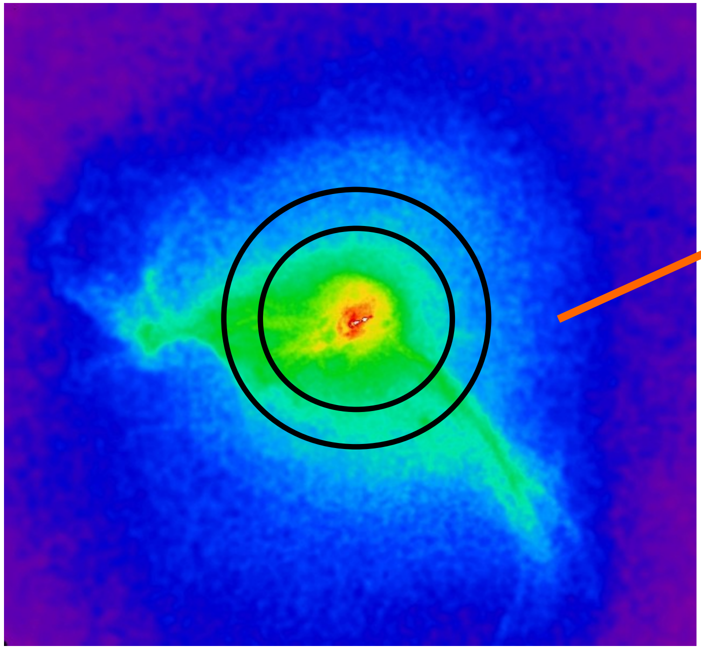


et al.

Surface brightness deprojection

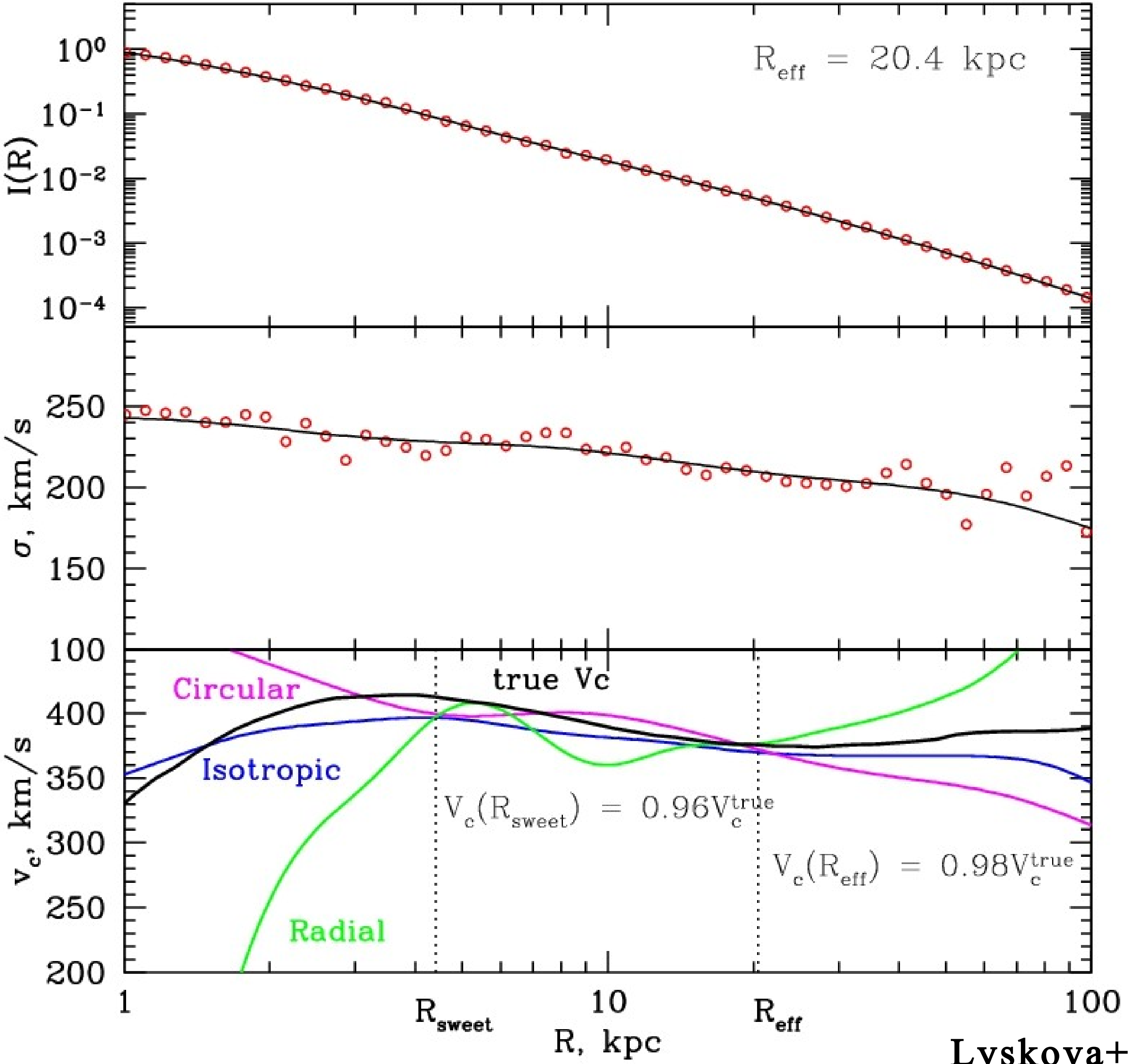




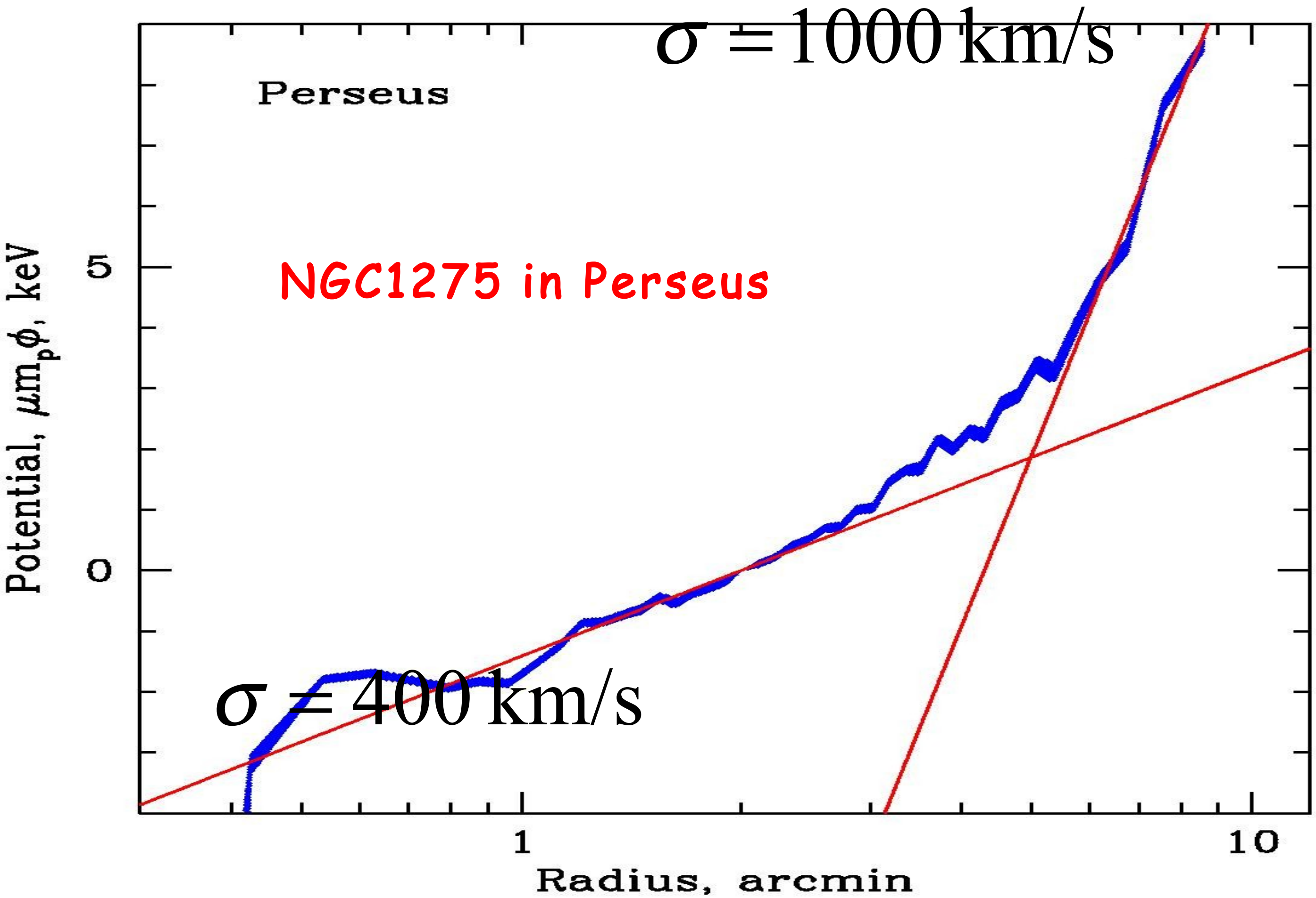


$$\begin{pmatrix} I_1 \\ I_2 \\ \dots \\ I_n \end{pmatrix} = \begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{1n} \\ 0 & p & p & p \\ 0 & \dots & \dots & p \\ 0 & 0 & 0 & p_{nn} \end{pmatrix} \begin{pmatrix} e_1 \\ e_2 \\ \dots \\ e_n \end{pmatrix} + e_{out} \begin{pmatrix} q_1 \\ q_2 \\ \dots \\ q_n \end{pmatrix}$$

M0125



Lyskova+, 2011

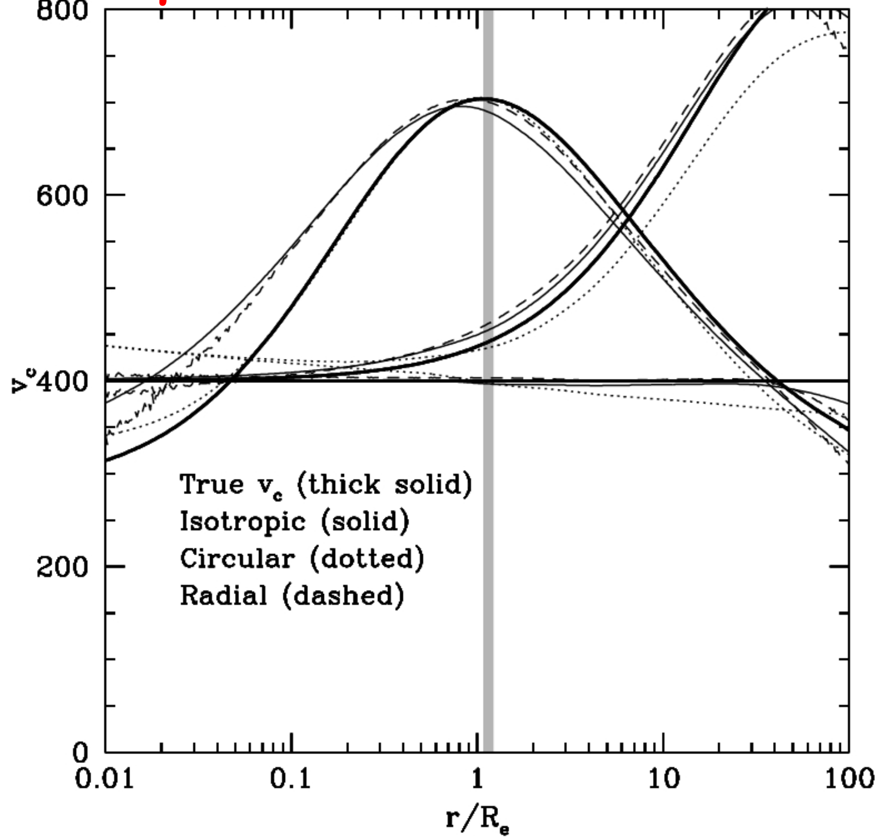


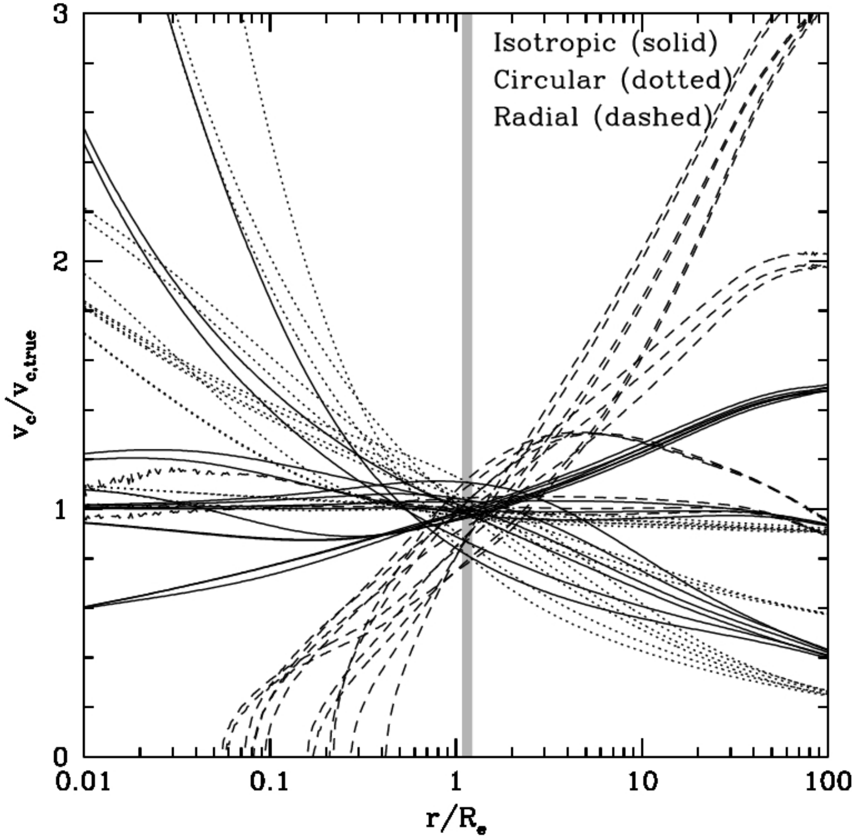
$\sigma = 1000$ km/s

NGC1275 in Perseus

$\sigma = 400$ km/s

Relaxing assumption of isothermal potential and β=const

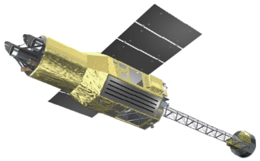




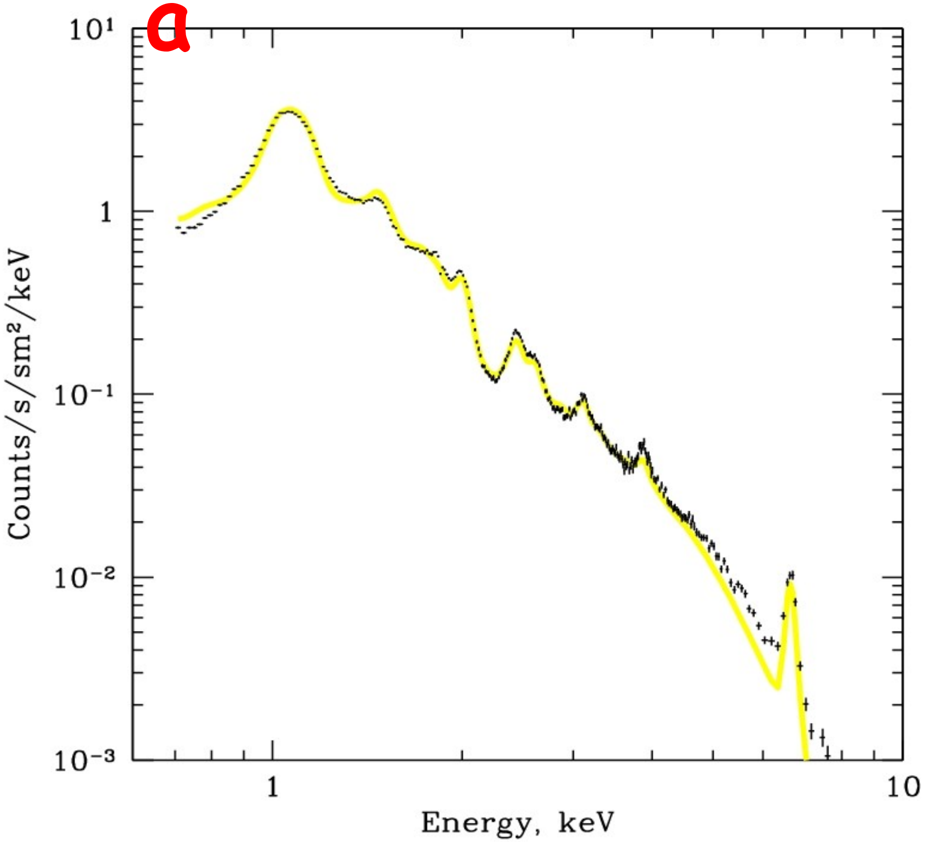
If anisotropy is know => local estimate works at all radii

If anisotropy is not know => use R where I~R-2

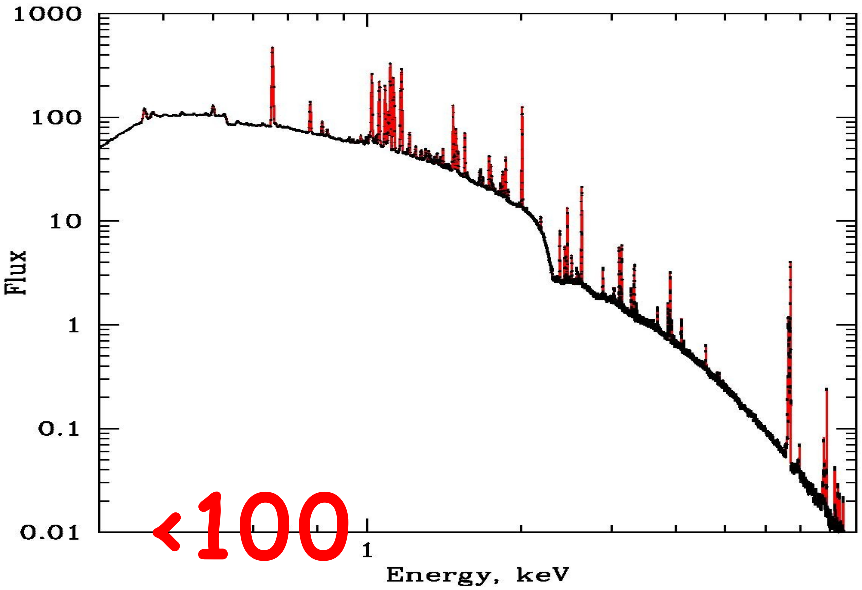
Direct velocity measurements



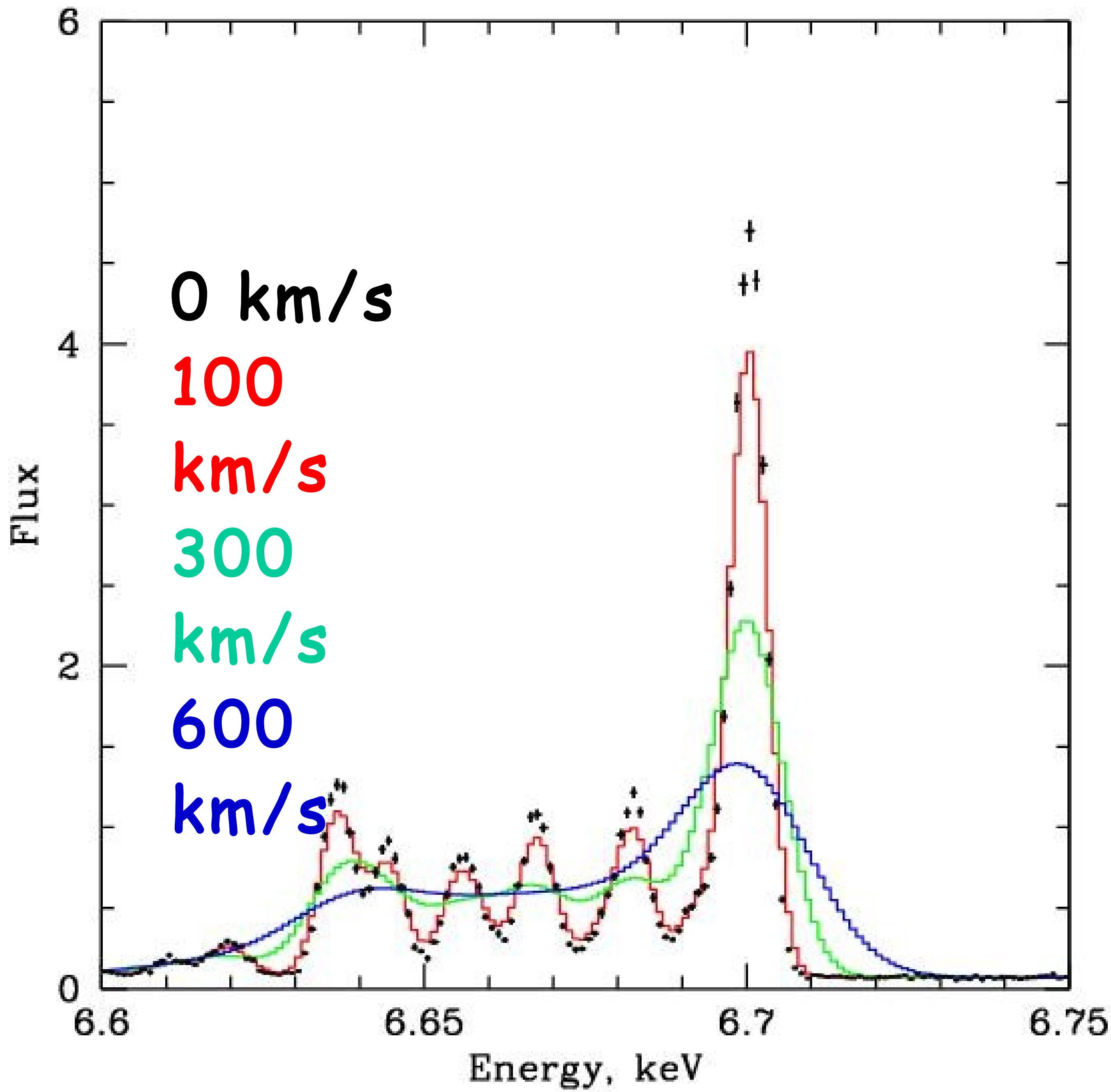
Chandra



Astro-H, 2013



<100 km/s

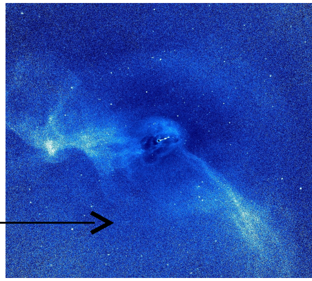

0 km/s
100 km/s
300 km/s
600 km/s
Flux
0
2
4
6
6.6
6.65
6.7
6.75
Energy, keV

Measuring cosmic rays, magnetic fields and turbulence **separately**

Cosmic rays: limits on the gamma-ray flux

$$p + p \rightarrow \pi^{0} \rightarrow 2\gamma$$

$$p + p \rightarrow \pi^{+,-} \rightarrow e^{+,-} \Rightarrow \mathrm{IC}$$



FERMI

$$\frac{E_{CR}}{E_{therml}} \leq 0.02 - 0.1$$

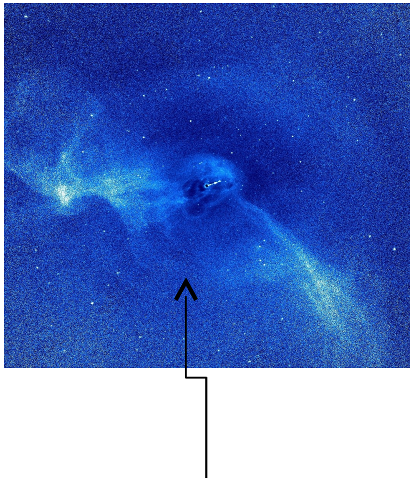
Ackermann+, 2010

(provided cosmic ray protons are mixed with

Measuring cosmic rays, magnetic fields and turbulence separately

Magnetic fields: Faraday rotation

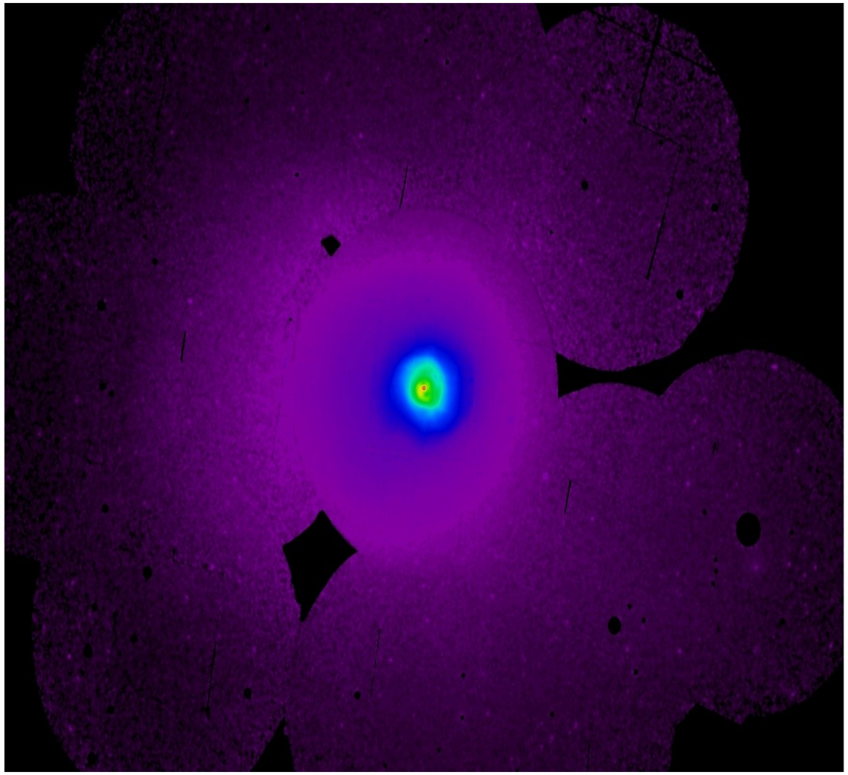
$$\propto \int n_e B_{\parallel} dl$$



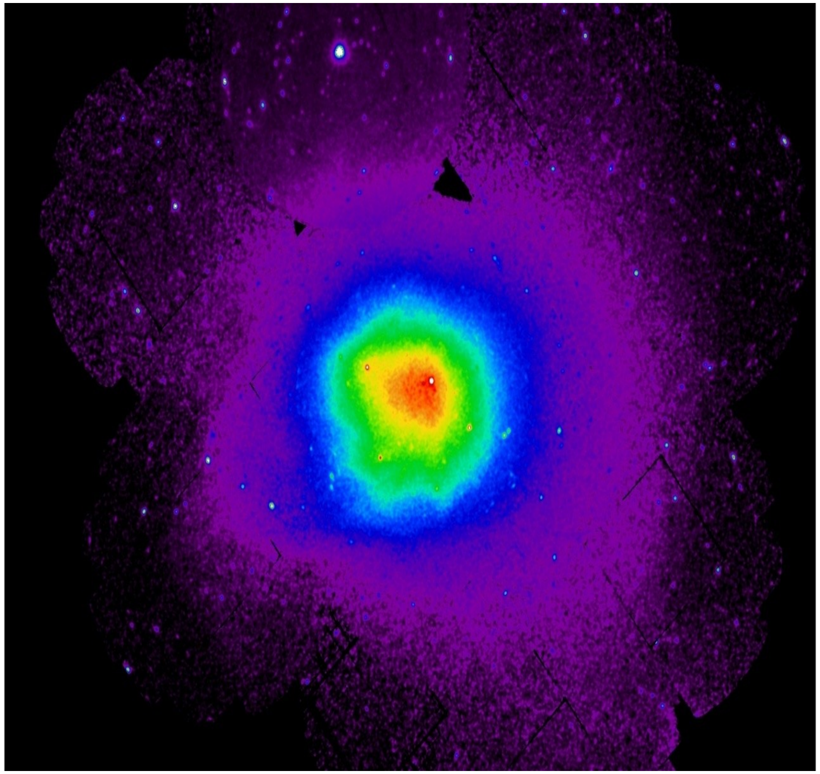
(provided magnetic field and thermal plasma are mixed;
correlation length)

Are CC and NCC Clusters different?

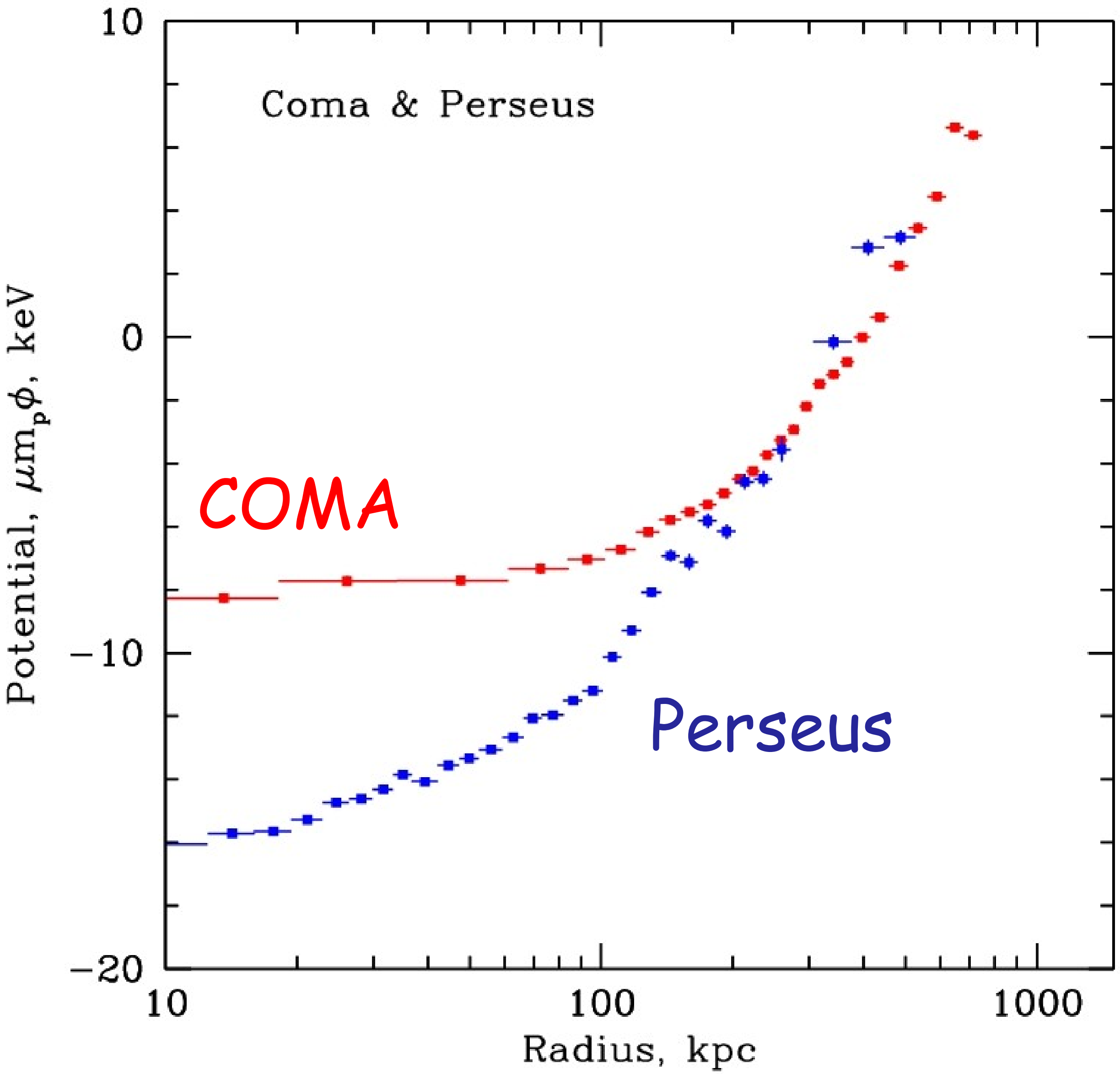
Perseus cluster (cool core)



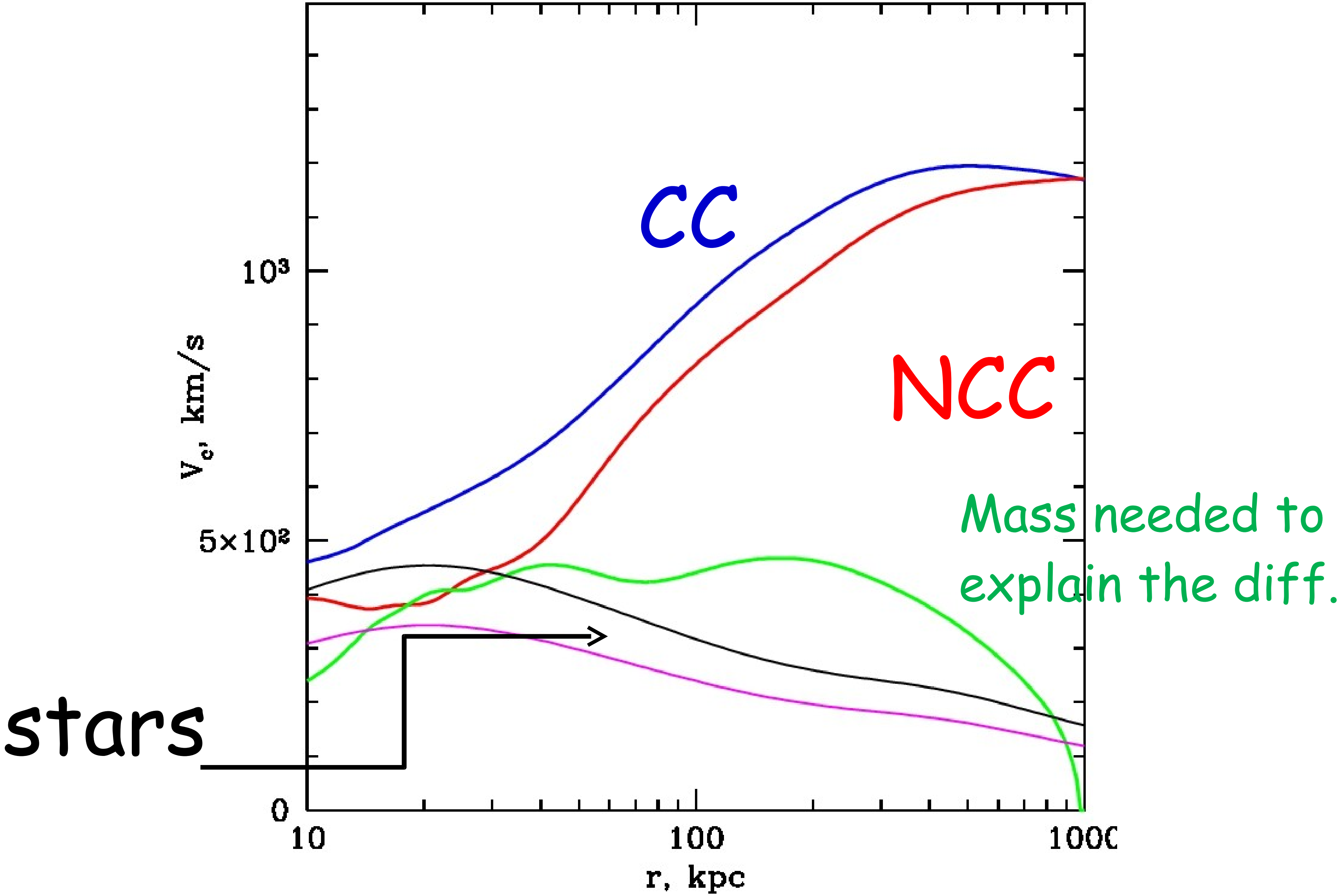
Coma cluster (no cool core)



Gravitating potentials for Coma and Perseus



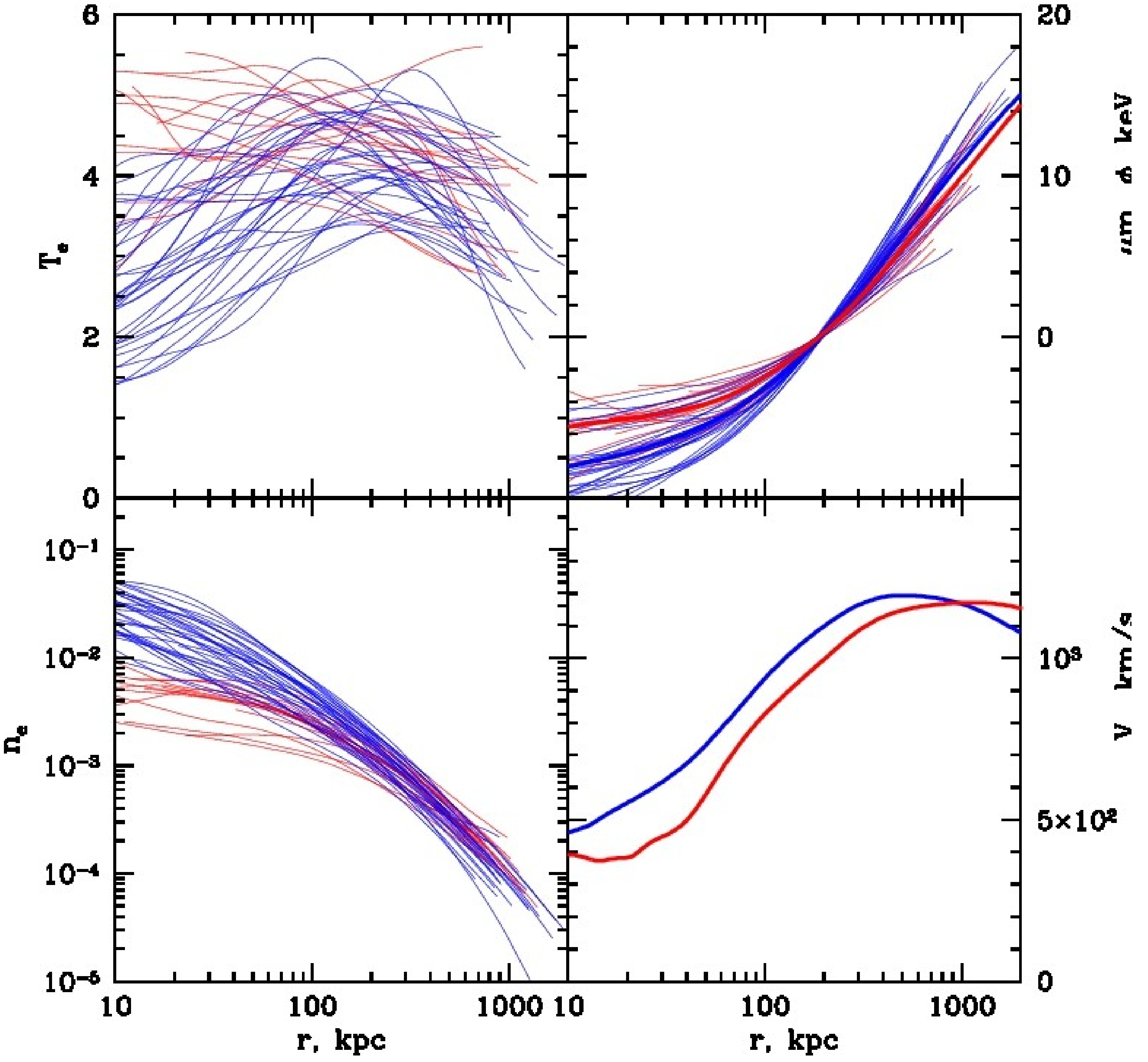
Cool Core vs Non Cool Core Clusters



More mass in CC? CC=NCC+400 km/s SIS

More turbulence in NCC?

35 CC + 15 NCC, z->0, R500 -> 1000 kpc



S.Tsygankov, I.Zhuravleva +

What we see

What can be wrong?

Physical

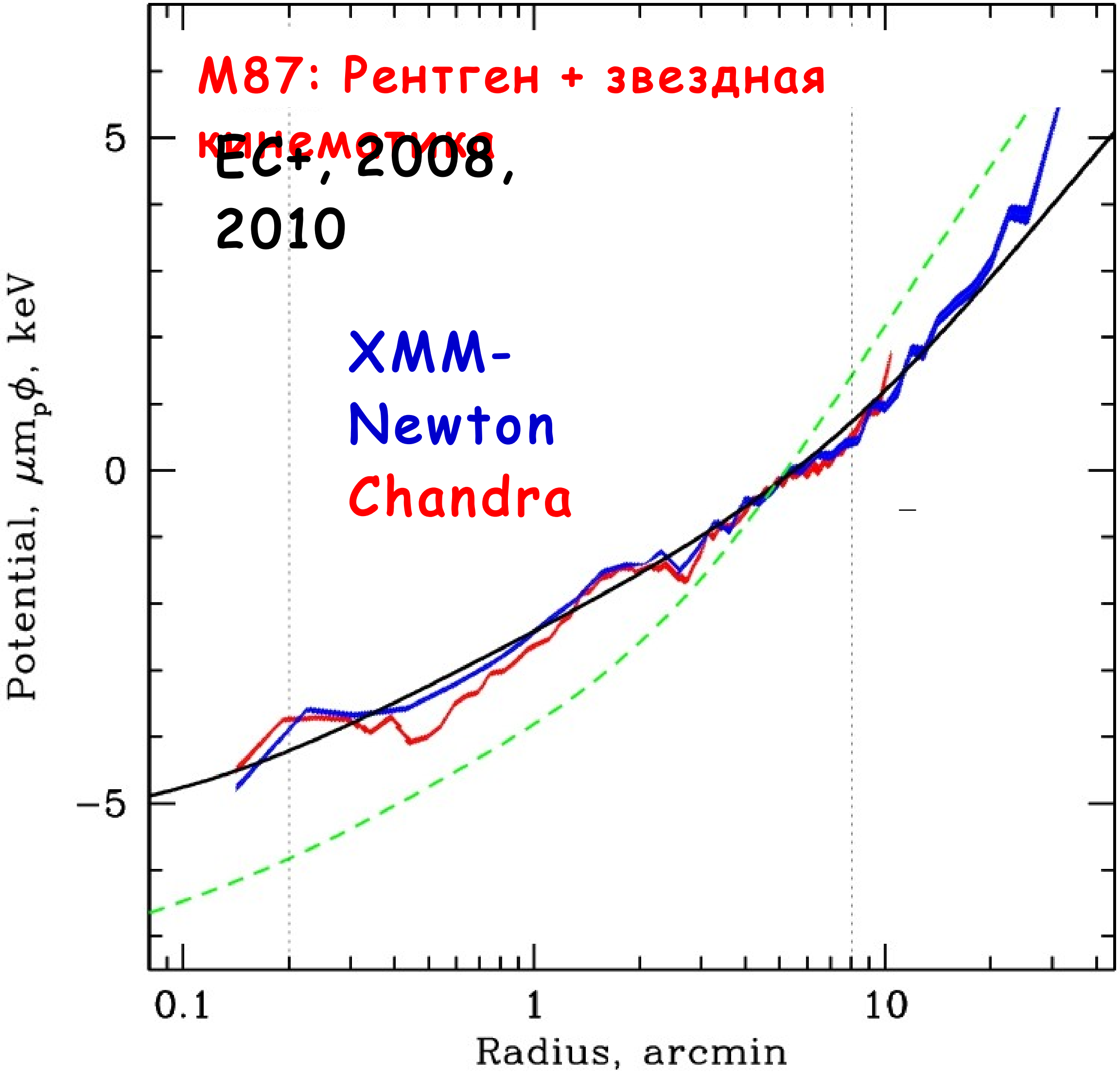
- Turbulent gas motion
- Relativistic particles
- Non-stationary

Analysis:

- Bias in n_e, T_e, P

What to compare with?

Сравнение оценок массы из рентгеновских и оптических данных



M87: Рентген + звездная кинематика

ЕС+, 2008, 2010

XMM-Newton

Chandra

Romanowsky & Kochanek, 2001

$$\frac{\rho v^2}{3nkT} < 0.1$$

Gebhardt & Thomas, 2010

$$\frac{\rho v^2}{3nkT} \approx 0.35$$

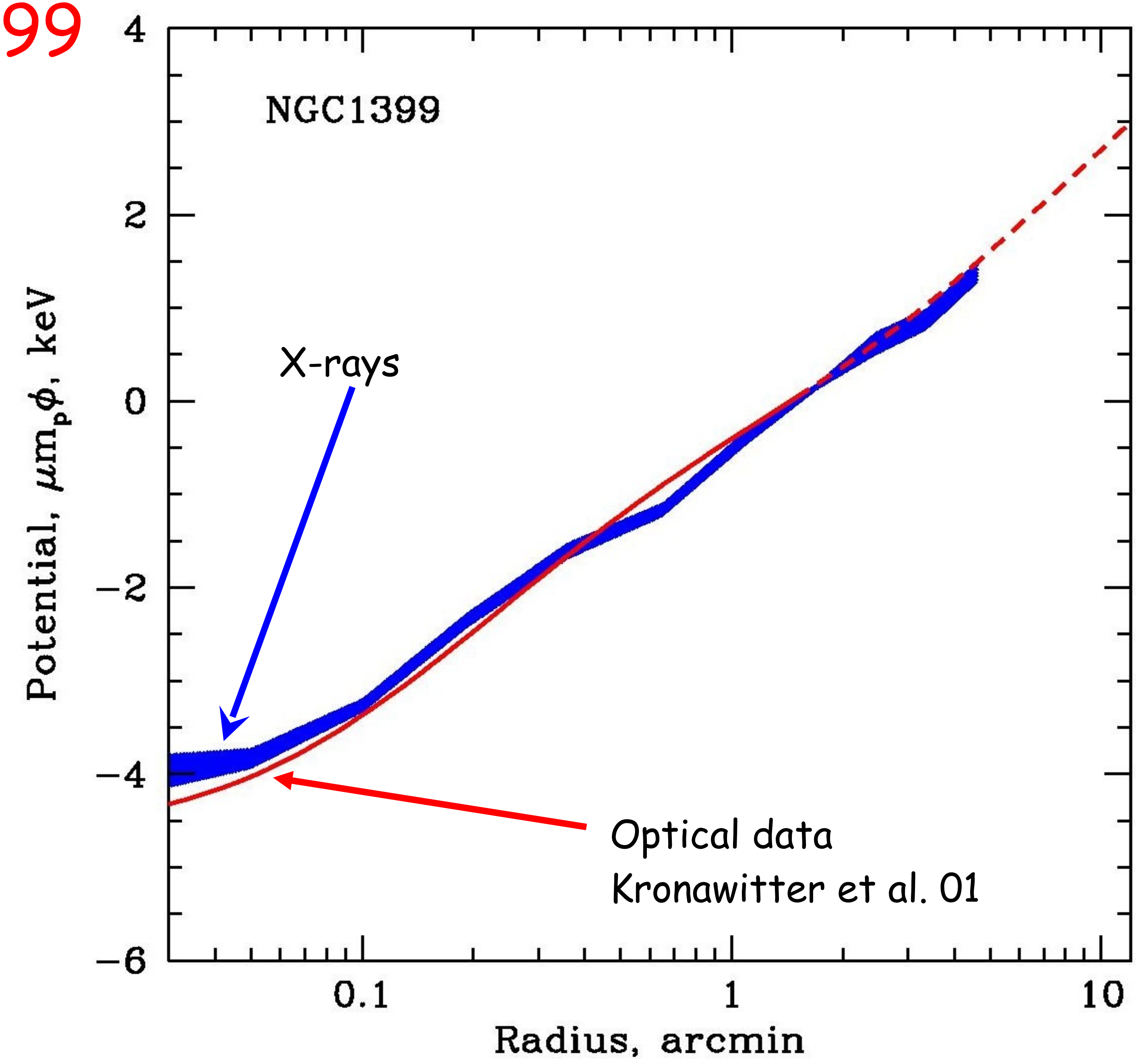
Сильченко, Моисеев

Mopt=

M

MX=a

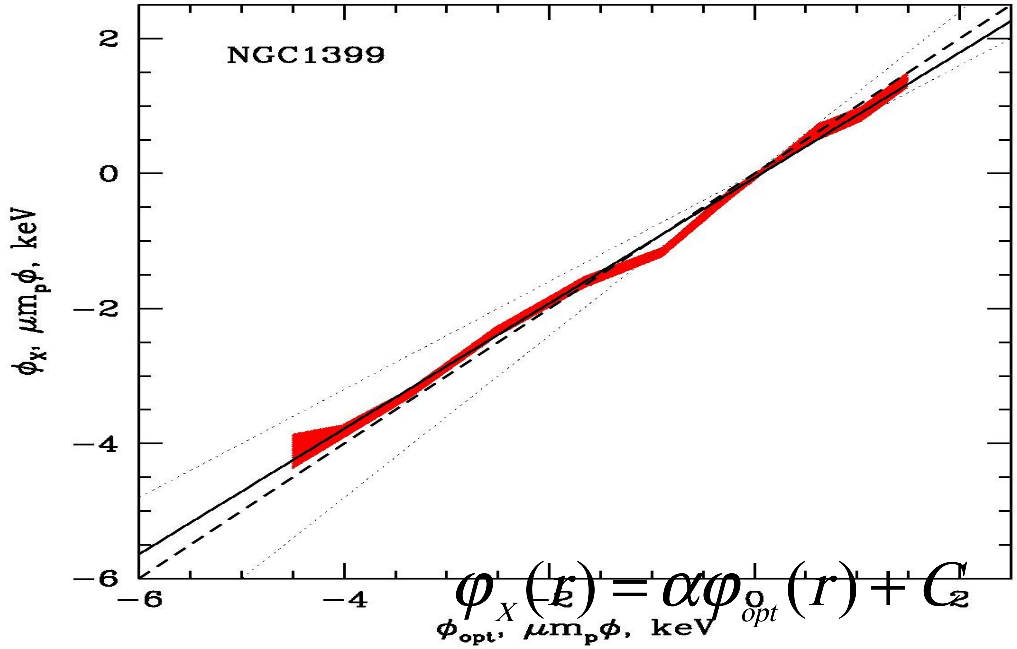
NGC1399



X-rays

Optical data
Kronawitter et al. 01

NGC1399



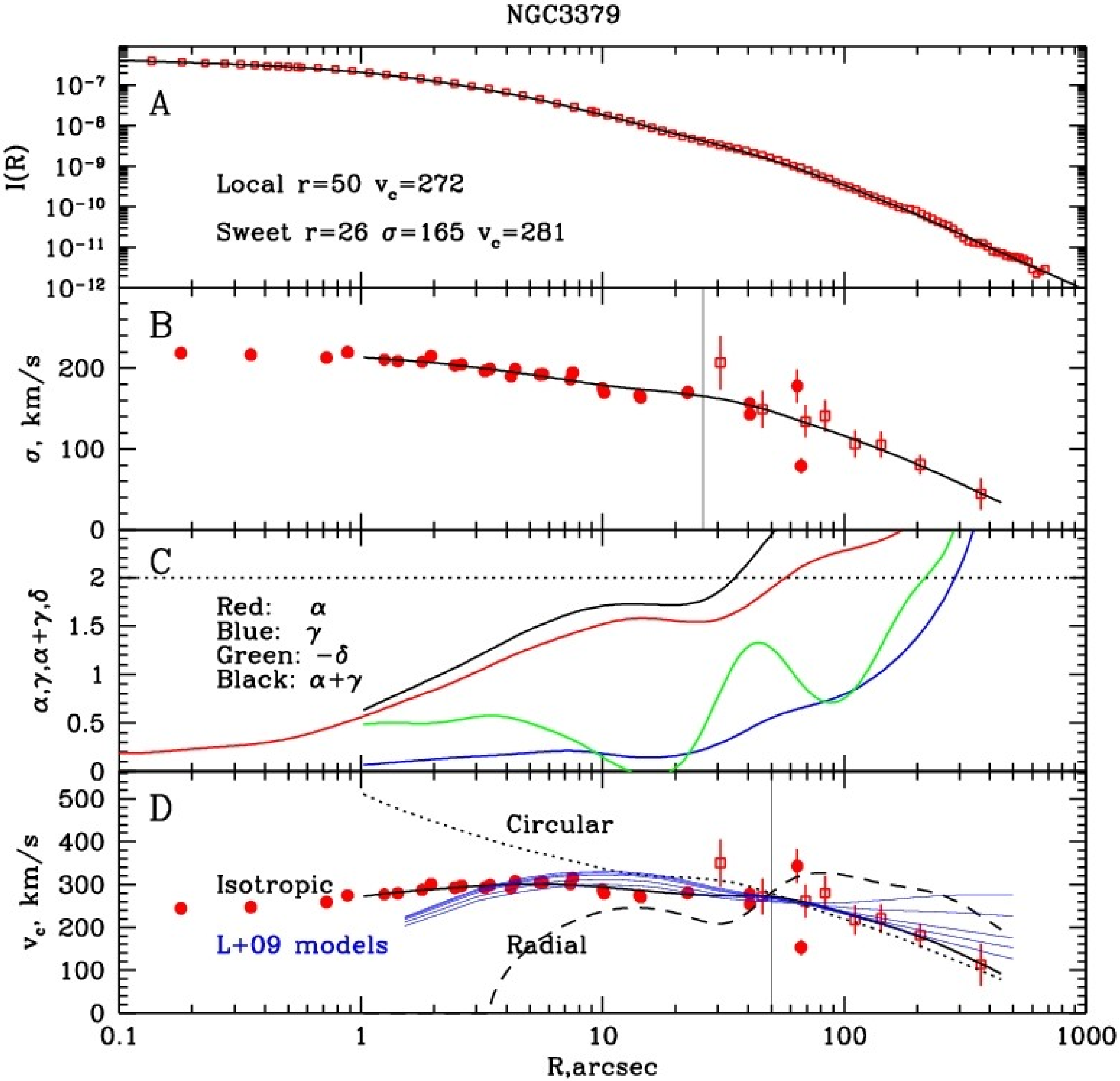
$$\varphi_X(r) = \alpha\varphi_{opt}(r) + C$$

$$\varphi_X(r) \approx 0.93\varphi_{opt}(r) + C$$

$$U_{CR} + \frac{B^2}{8\pi} + U_{turb} = 0.07\,U_{thermal}$$

Previous slide: state-of-the art optical model

This slide: “Street art” optical model (10-3 s of CPU time)



$$I(R)$$

$$\sigma_p(R)$$

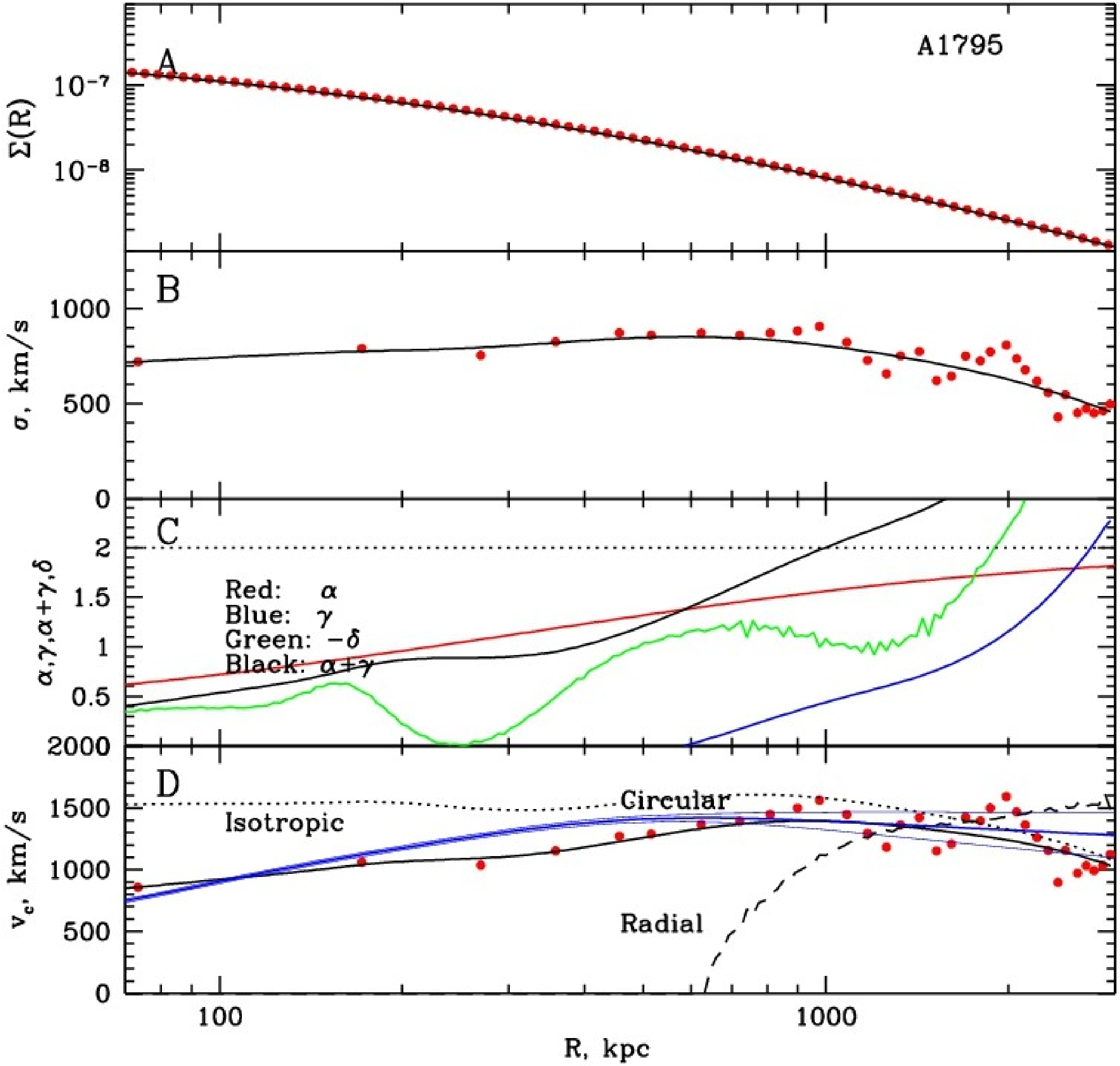
$$\alpha = -\frac{d\ln I(R)}{d\ln R}$$

$$\gamma = -\frac{d\ln\sigma_p^2}{d\ln R}$$

$$\mathrm{v}_c = (1+\alpha+\gamma)^{1/2}\sigma_p$$

EC+, 2010

Using galaxies instead of stars

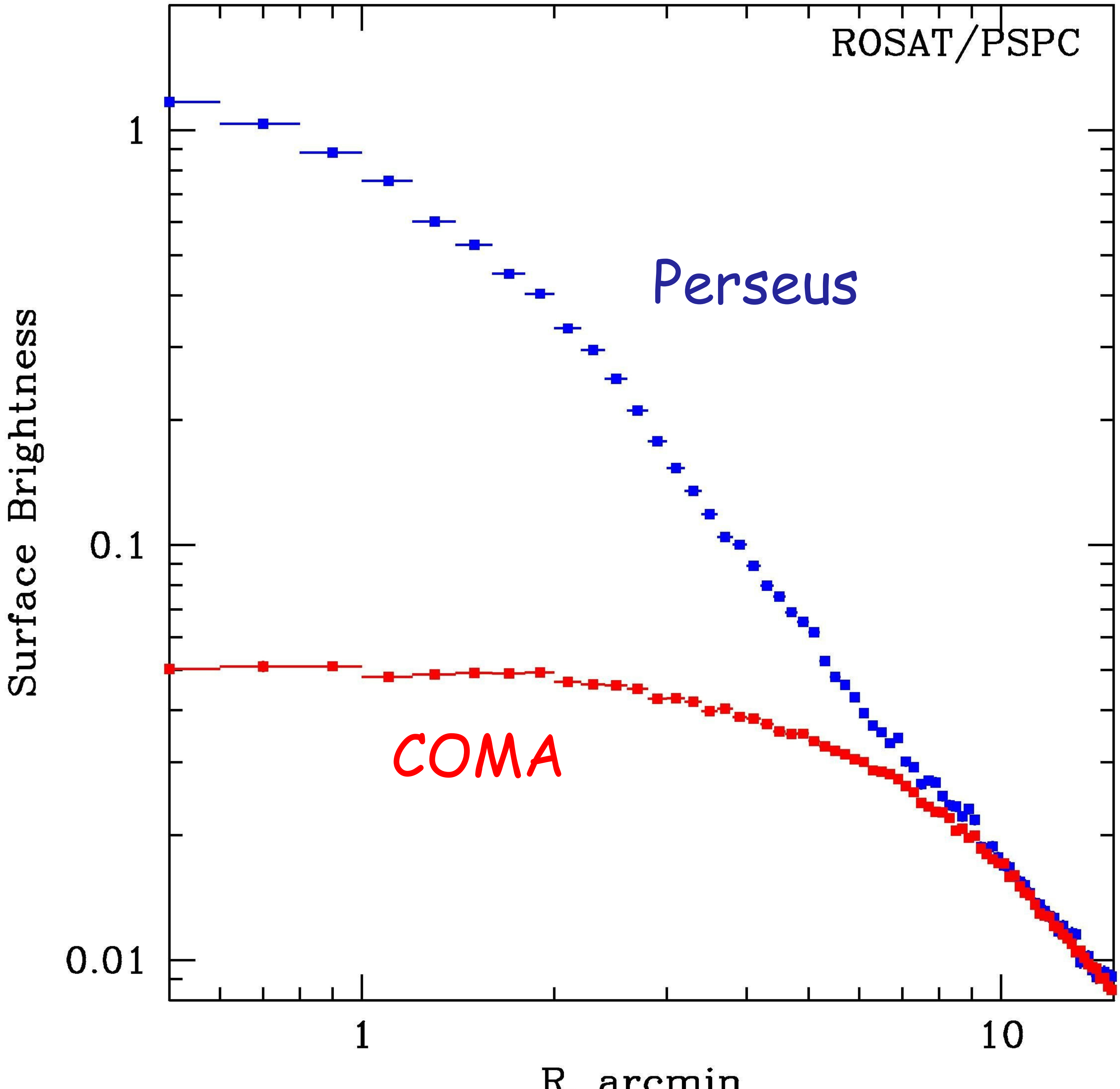


Arithmetic with Energy and Power

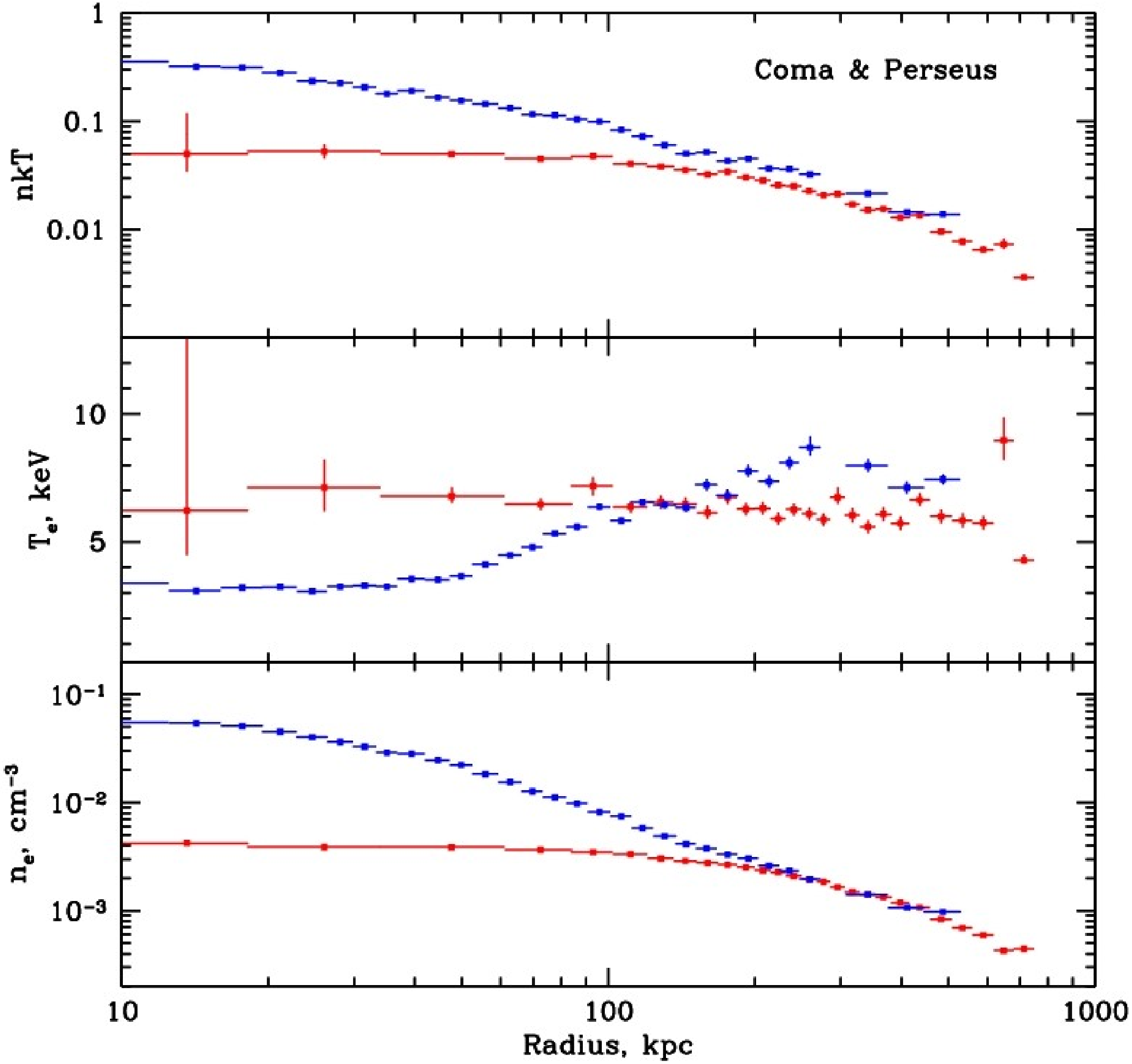
$$\frac{E_{AGN}}{t_{dis}} \approx \frac{E_{thermal}}{t_{cool}} \Rightarrow t_{dis} = t_{cool}\frac{E_{AGN}}{E_{thermal}} \approx 0.1-0.3\, t_{cool}$$

[Turbulence only]

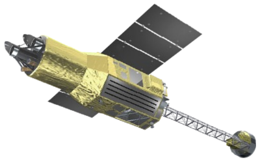
Easy with ASTRO-H; Mitsuda
RGS – J.Sanders, #75
Res.Scat. – I.Zhuravleva, #35


ROSAT/PSPC
Perseus
COMA
Surface Brightness
1
0.1
0.01
1
10
R, arcmin

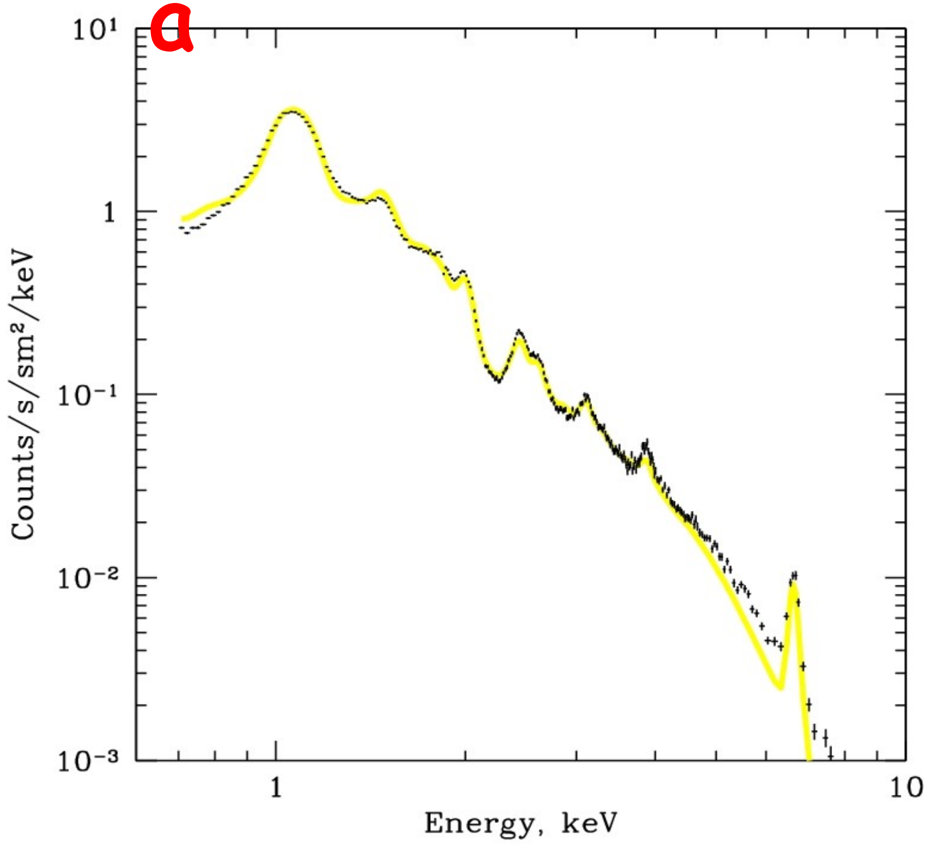
Deprojected n,T for Coma and Perseus



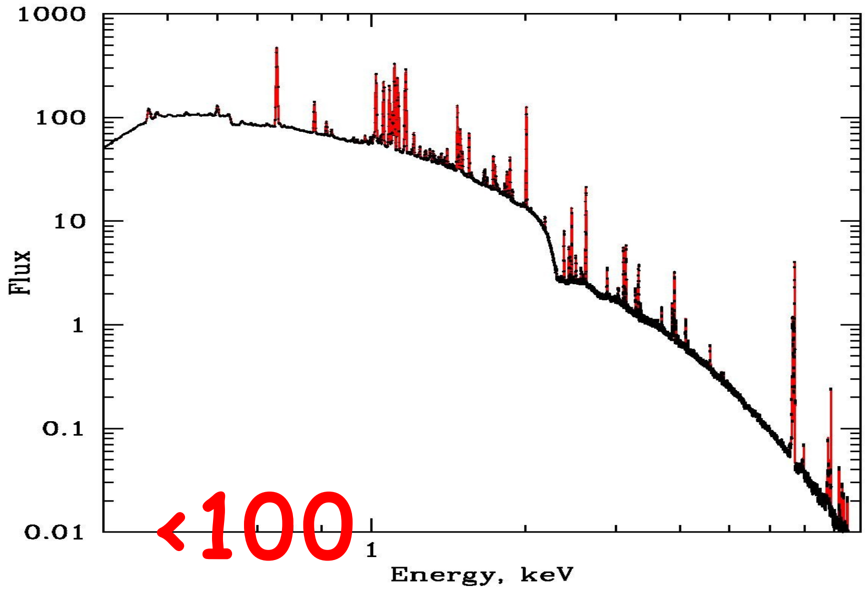
Direct velocity measurements



Chandra

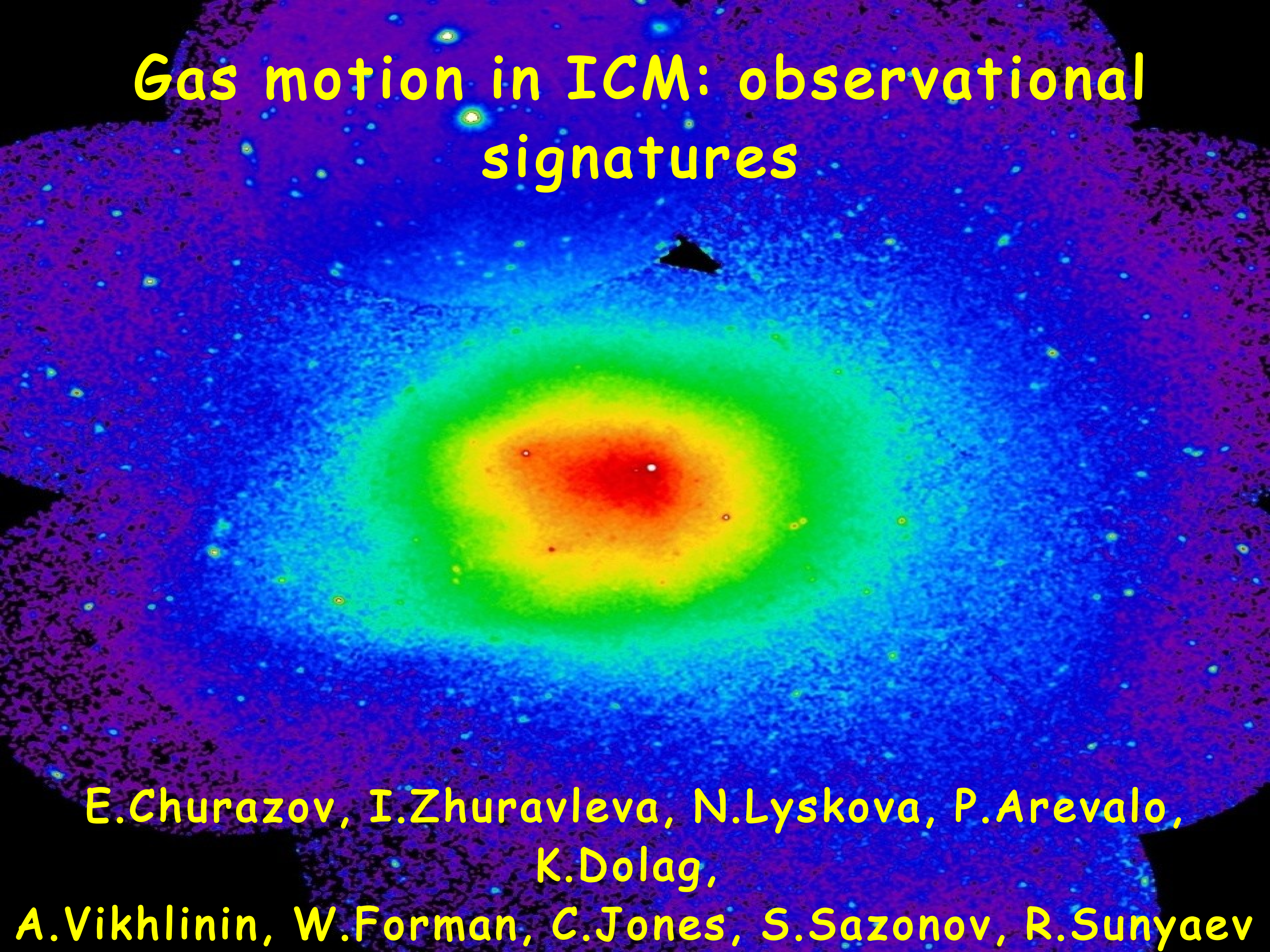


Astro-H, 2013



<100 km/s

XMM/RGS, broadening < 200 km/s [1D]

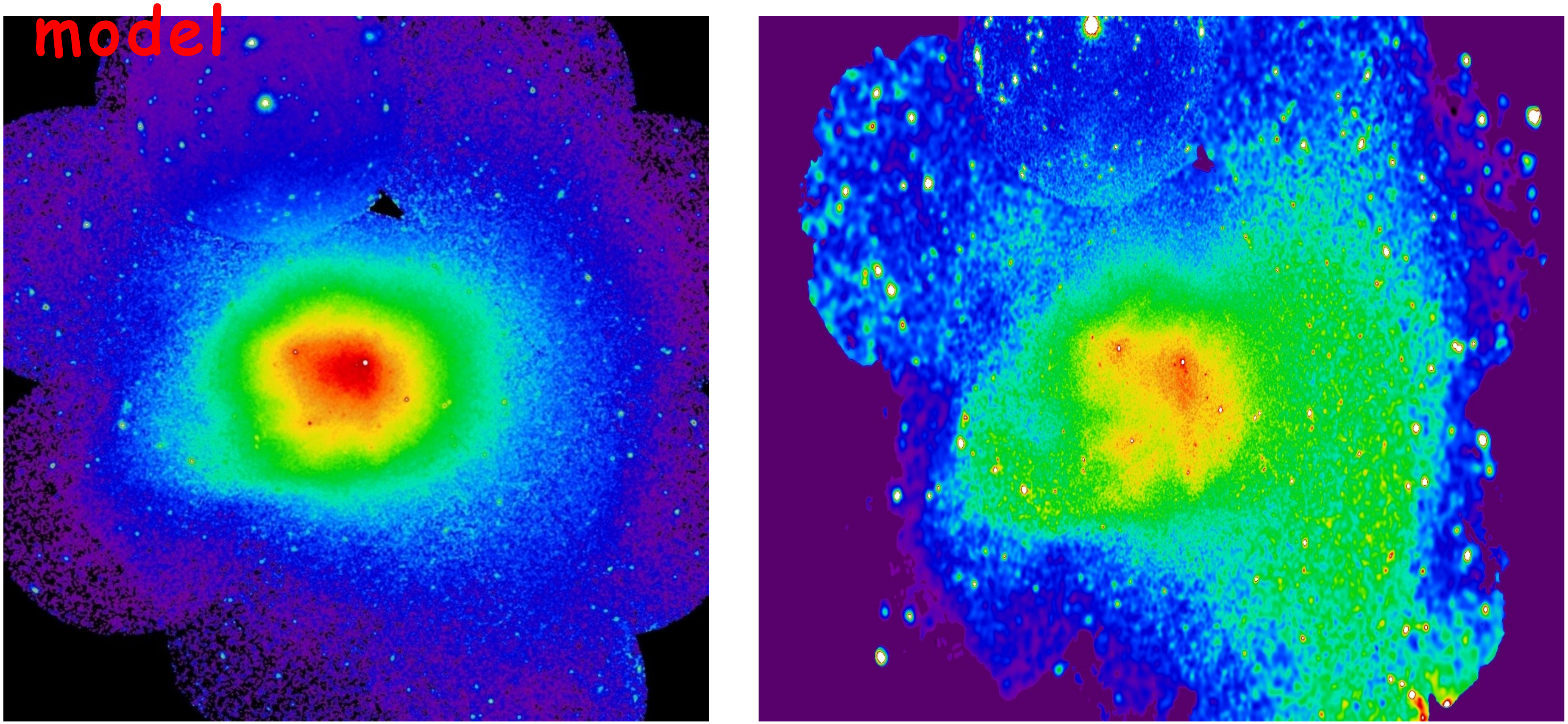


Gas motion in ICM: observational signatures

E.Churazov, I.Zhuravleva, N.Lyskova, P.Arevalo,
K.Dolag,
A.Vikhlinin, W.Forman, C.Jones, S.Sazonov, R.Sunyaev

Coma

X-ray image and residuals from symmetric model



Gas is not at rest!

We want to "measure" hot ICM velocity field

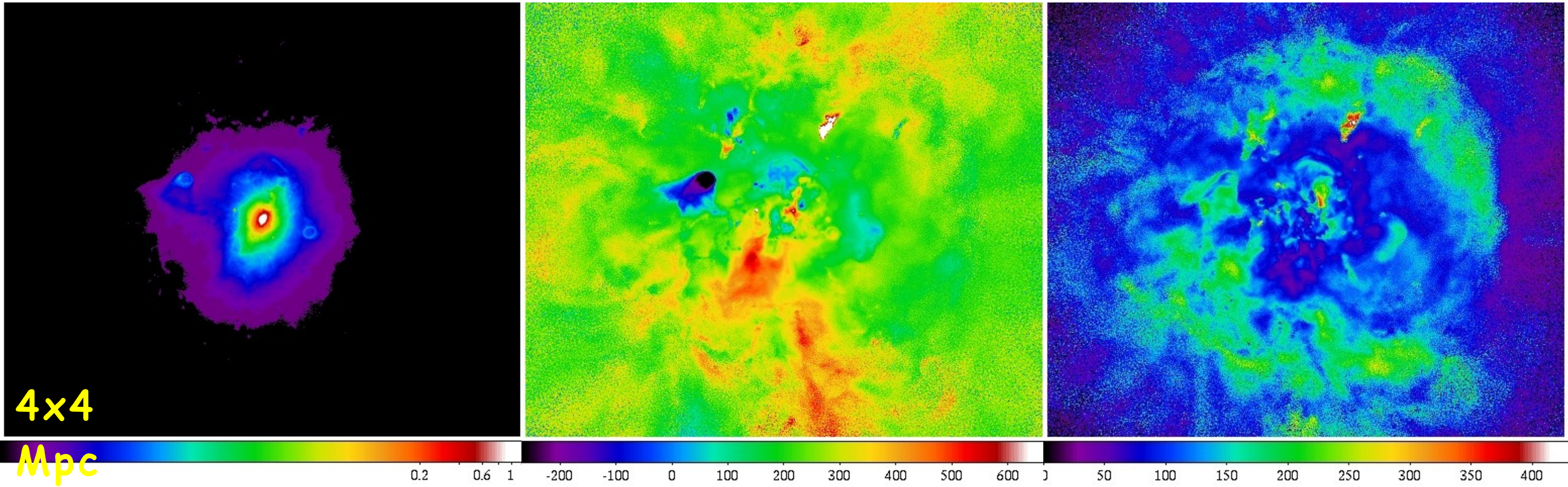
How to measure?

How we characterize the velocity field and observables?

Using simulations to calibrate observables

Any differential gas motions
Gaussian isotropic

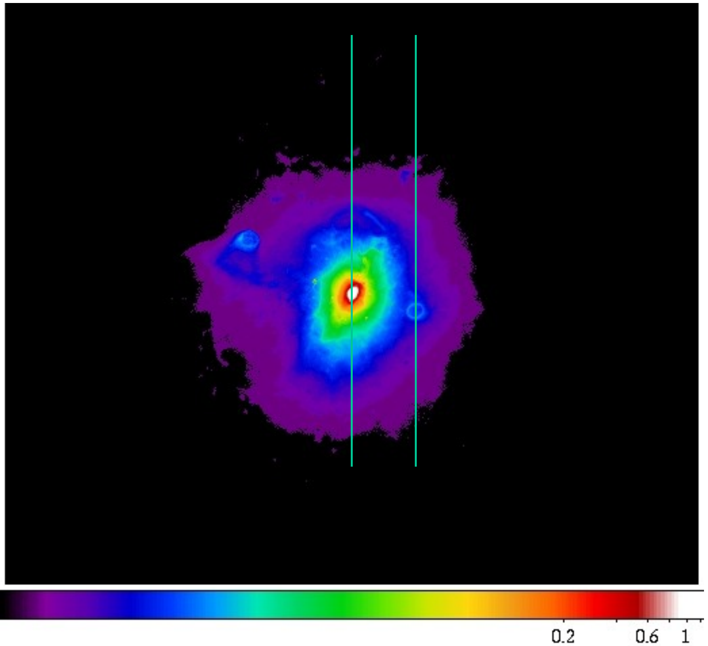
$$\int n_e^2 dl \qquad \langle v_z \rangle_1 \qquad \sqrt{\langle v_z^2 \rangle_1 - \langle v_z \rangle_1^2}$$

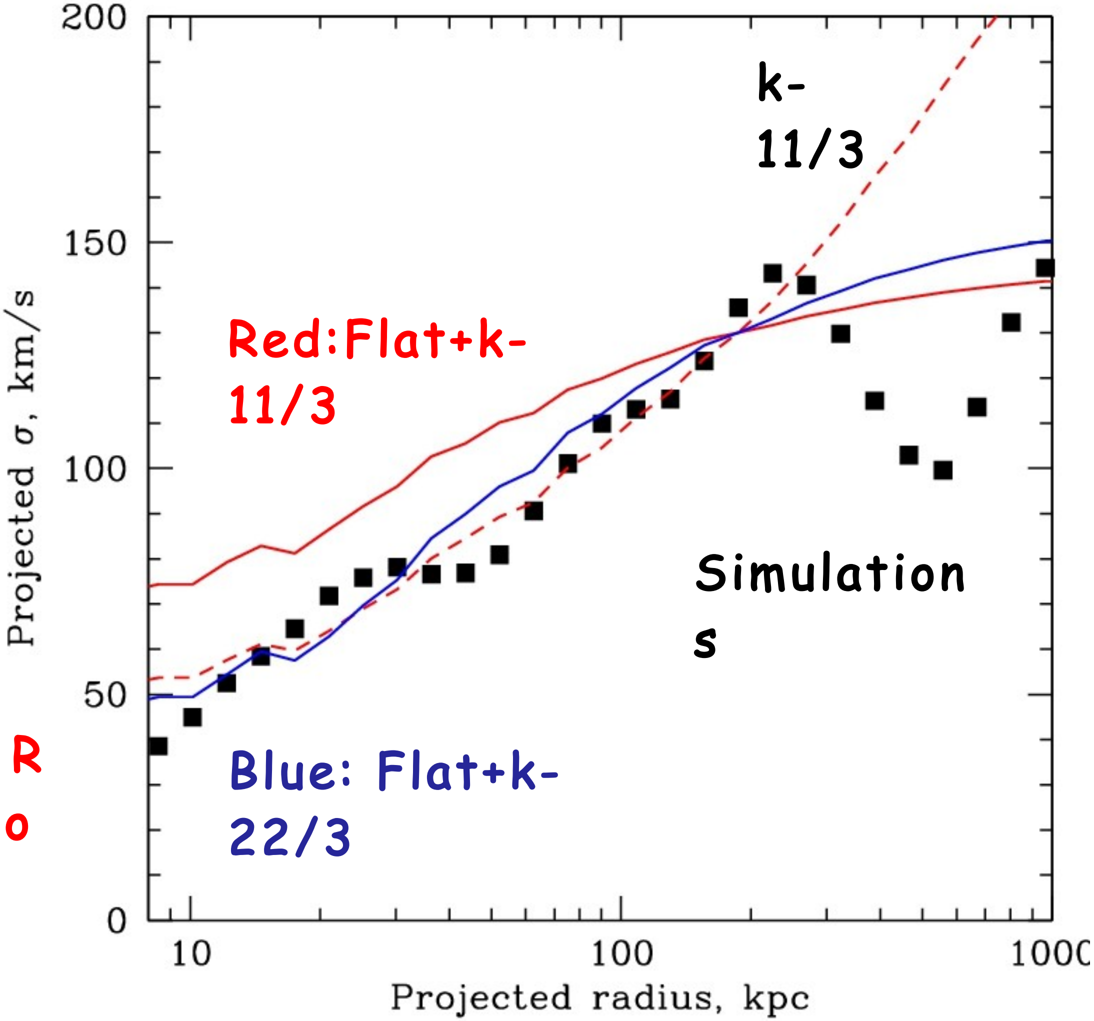


Observables: ne, emission measure weighted vz, σ

Projected velocity dispersion ≈ Structure Function

$$S(\Delta x) = \left\langle \left(\mathrm{v}(x+\Delta x) - \mathrm{v}(x) \right)^2 \right\rangle$$





k-11/3

Red:Flat+k-11/3

Blue: Flat+k-22/3

Simulations

At a given projected radius R an interval ~R contributes to σ

σ2 ≈ structure function

$$\sigma^2 = \int P_{3D}\left[1 - W^2(k_z)\right] dk_z dk_x dk_y$$

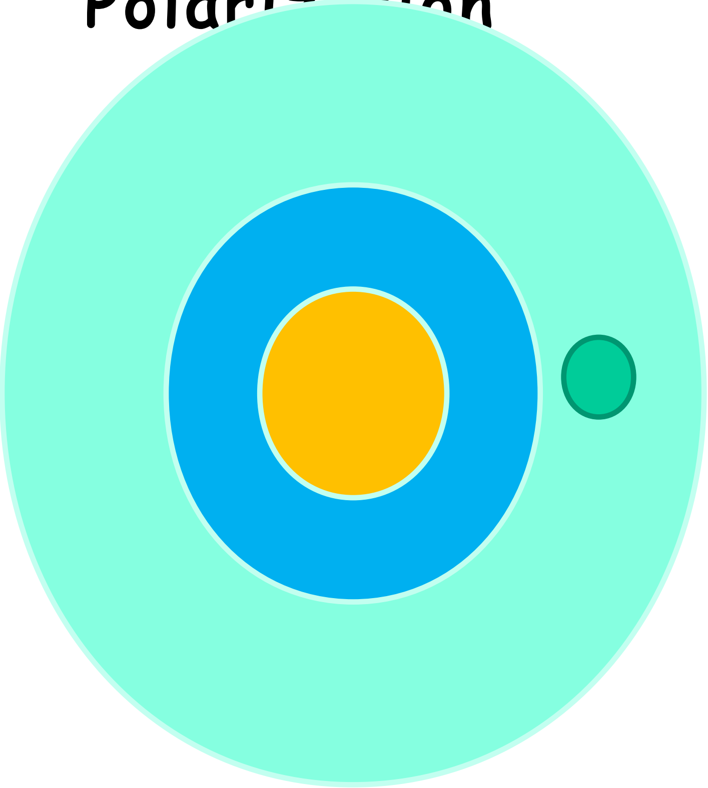
Zhuravleva,

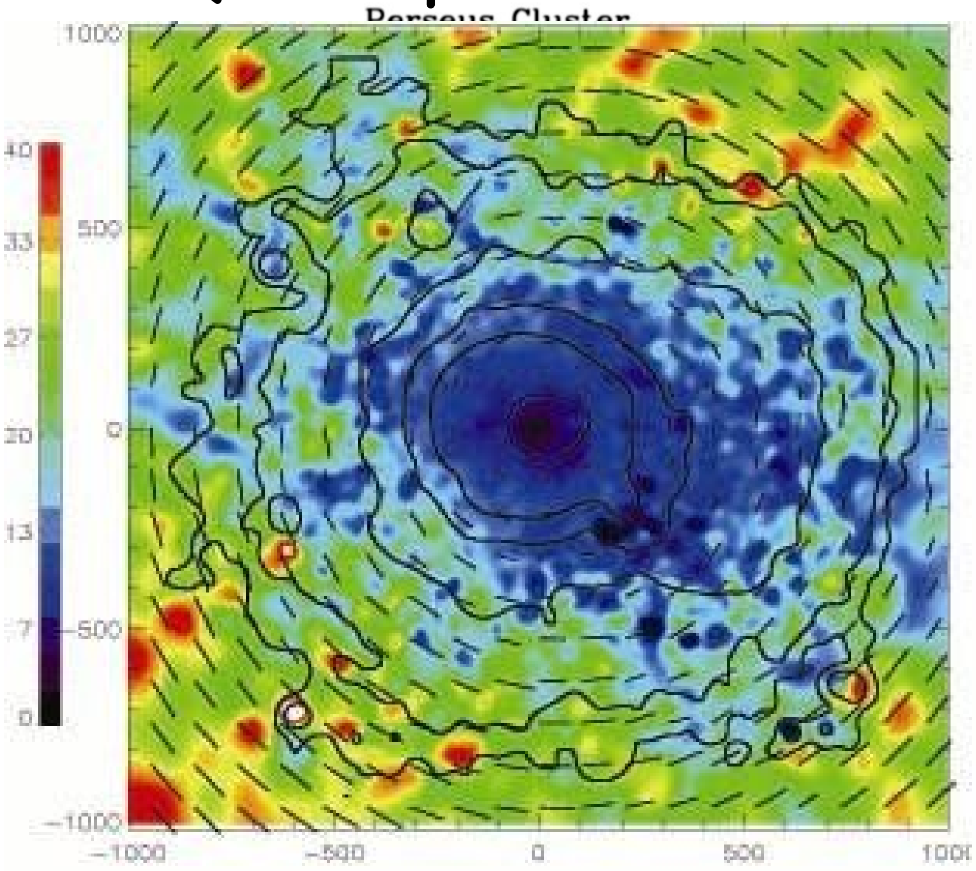
Less direct ways of measuring ICM velocities

Kinetic SZ effect	<V>, ΔV	Benson+03 Osborne+11
Resonant scattering	ΔV, PS(V)	Werner+09, Hayshi+09, Zhuravleva+11
Polarization due to resonant scattering	V, ΔV	Zhuravleva+10
Faraday Rotation	PS(B)->V	Vogt+03, Bonafede+10
Ha filaments	V	Fabian+03
Pressure fluctuations	PS(P)->V	Schuecker+04
SB fluctuations	PS(ne)	

Polarization of 6.7 keV Iron line

Rayleigh phase function + Quadrupole = Polarization





100% polarized

Center: 0%
Outskirts: 10%

Sazonov+ 2002: Zhuravleva+

Transverse ICM velocities and polarization

Quadrupole component can be induced by gas motions!

Motion along l.o.s.

Motion transverse l.o.s.

Click to edit Master subtitle style

Doppler shift	No Doppler shift
No polarization	Polarization

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

Very indirect ways of measuring ICM velocities.

Turbulent Diffusion of metals	D~VL	Rebusco+05
Cool Cores: Heating=Cooling	Heating~V3/L	
Correction to mass from hydrostatic equilibrium	V2	EC+08,10
Many more..		

Combinations provide both V L

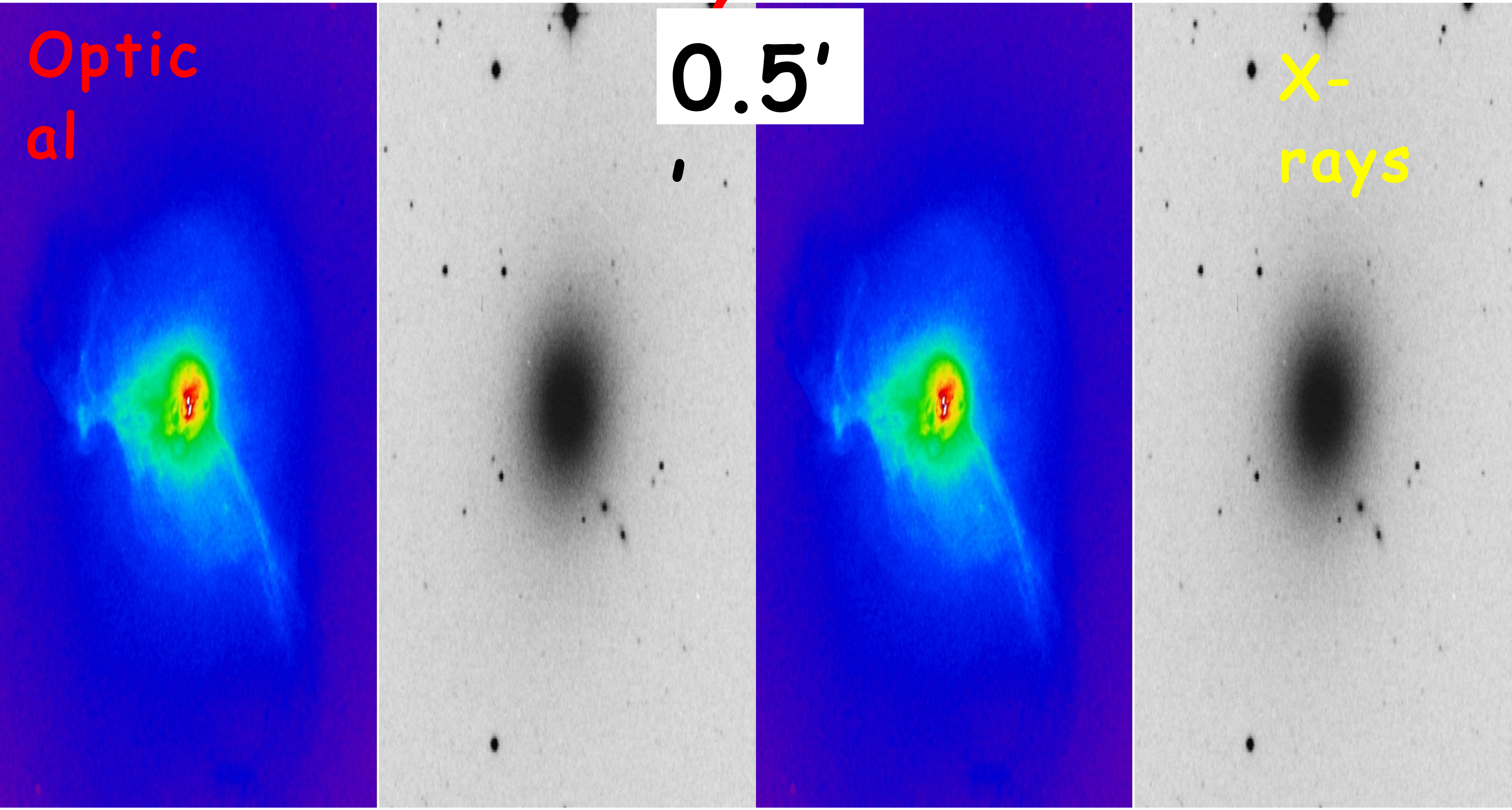
$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2}$$

$$P = nkT + \underbrace{P_{CR} + \frac{B^2}{8\pi} + P_{turb}}$$

Thermal
pressure
(easy to
measure)

Non-thermal pressure
(invisible)

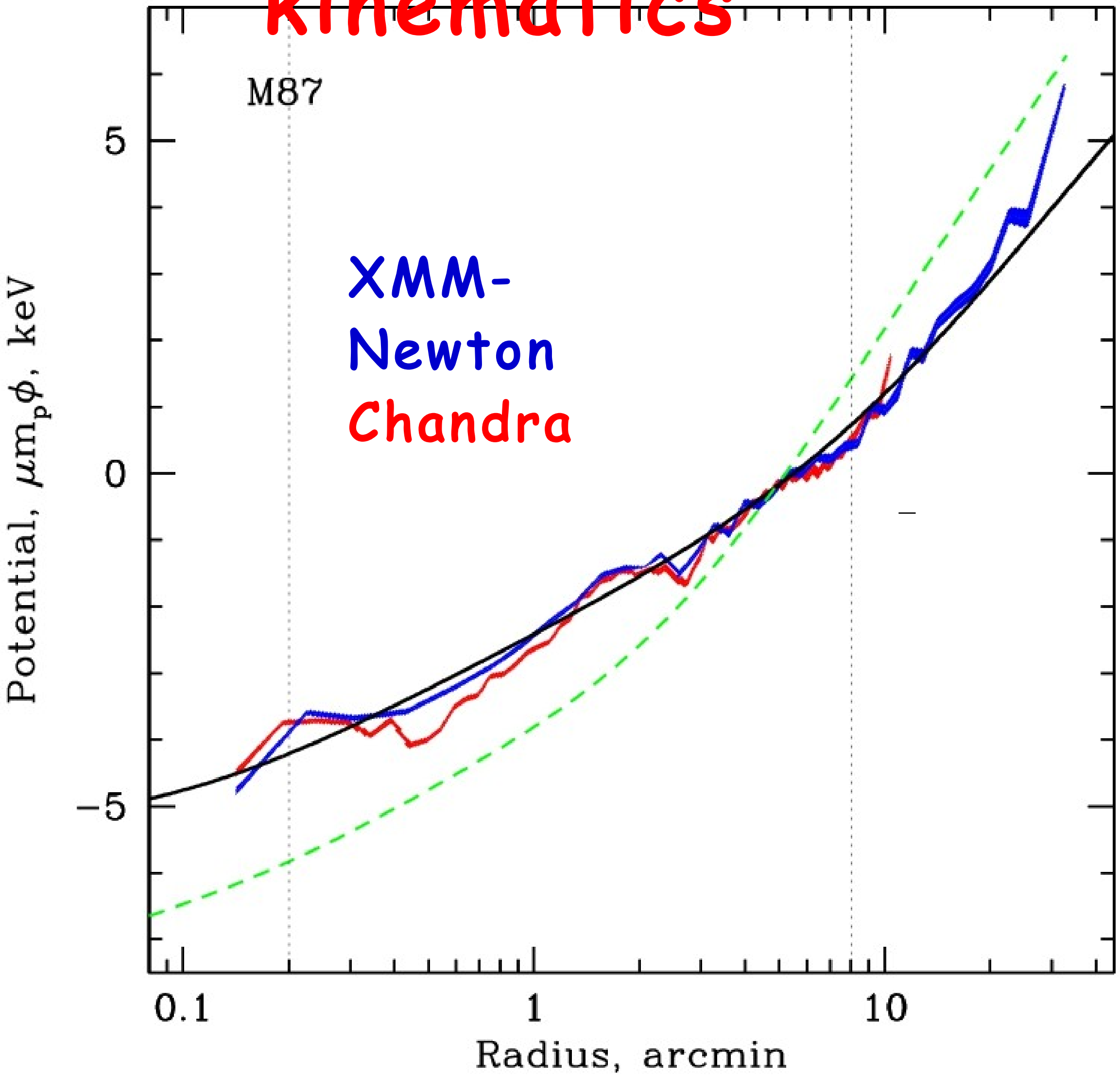
M87



Stars: gravity only

Gas: gravity, magnetic fields, cosmic rays, turbulent motions,

M87: X-rays + stellar kinematics



Romanowsky & Kochanek, 2001

Gebhardt & Thomas, 2010

V~few 100 km/s -> Power Spectra

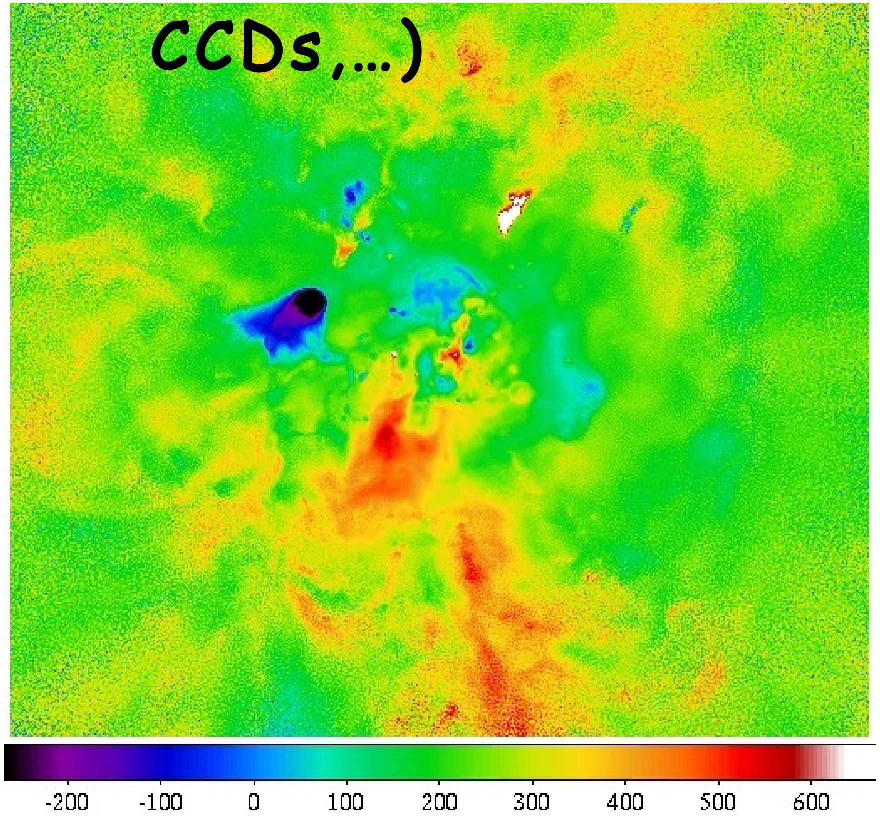
Characterizing ICM velocity field
(3D simulations, RM maps, etc)

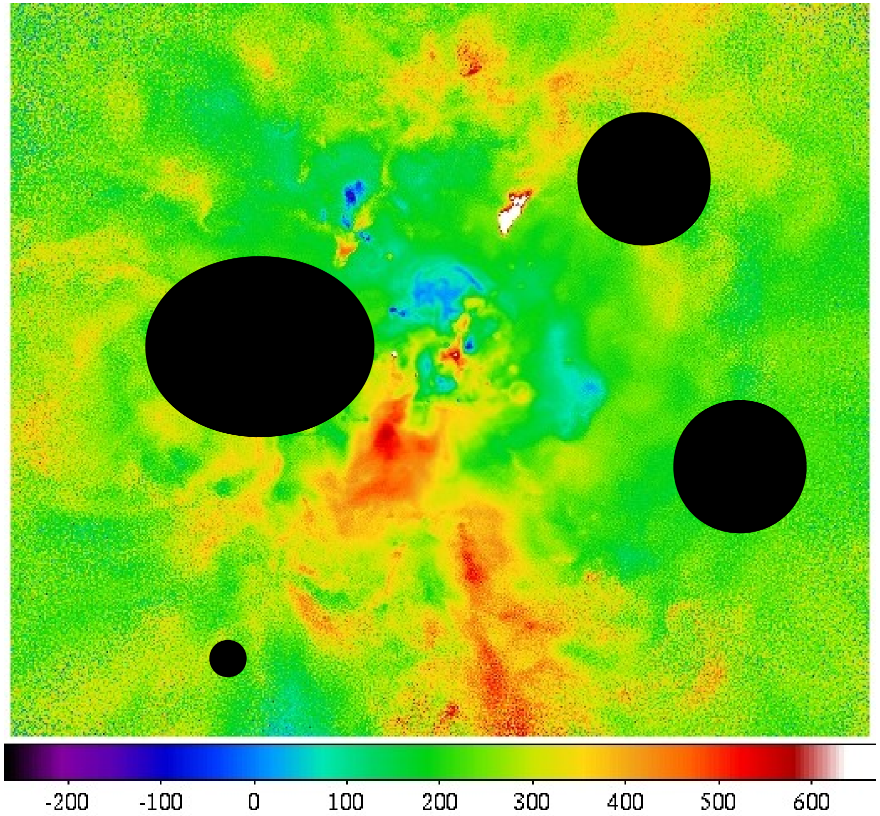
Calculating Power Density Spectra
for featureless continuum

Calculating characteristic

Calculating Power Density Spectrum for the data with holes (making Fourier transform of the velocity map)

1. Non-periodic
2. Missing data (points sources, gaps between CCDs,…)

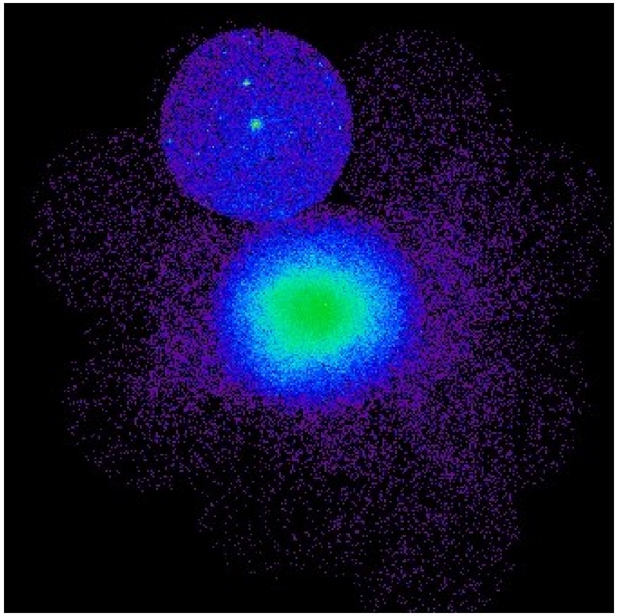




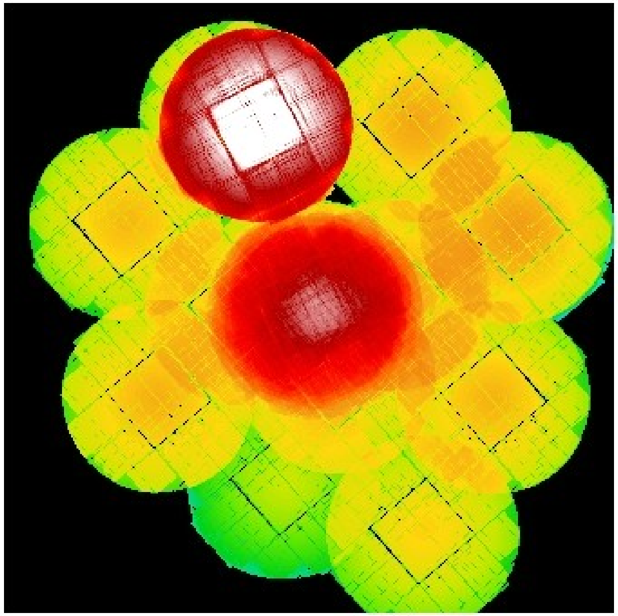
Fourier is tuned for periodic arrays without gaps

Smoothing of X-ray images

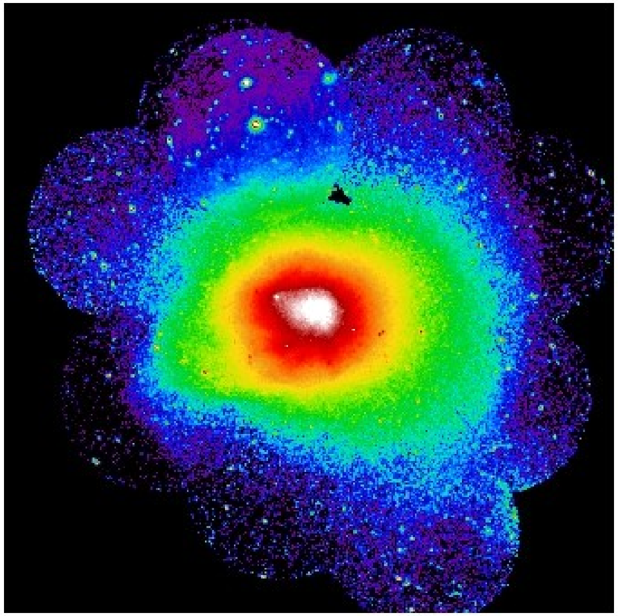
Raw image



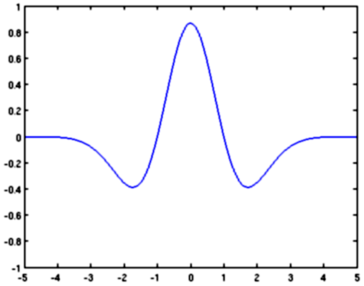
Exposure map



S(Images)/S(E_map)



$$G_{\sigma_1} \circ I = \frac{G_{\sigma_1} \circ I}{G_{\sigma_1} \circ M}$$

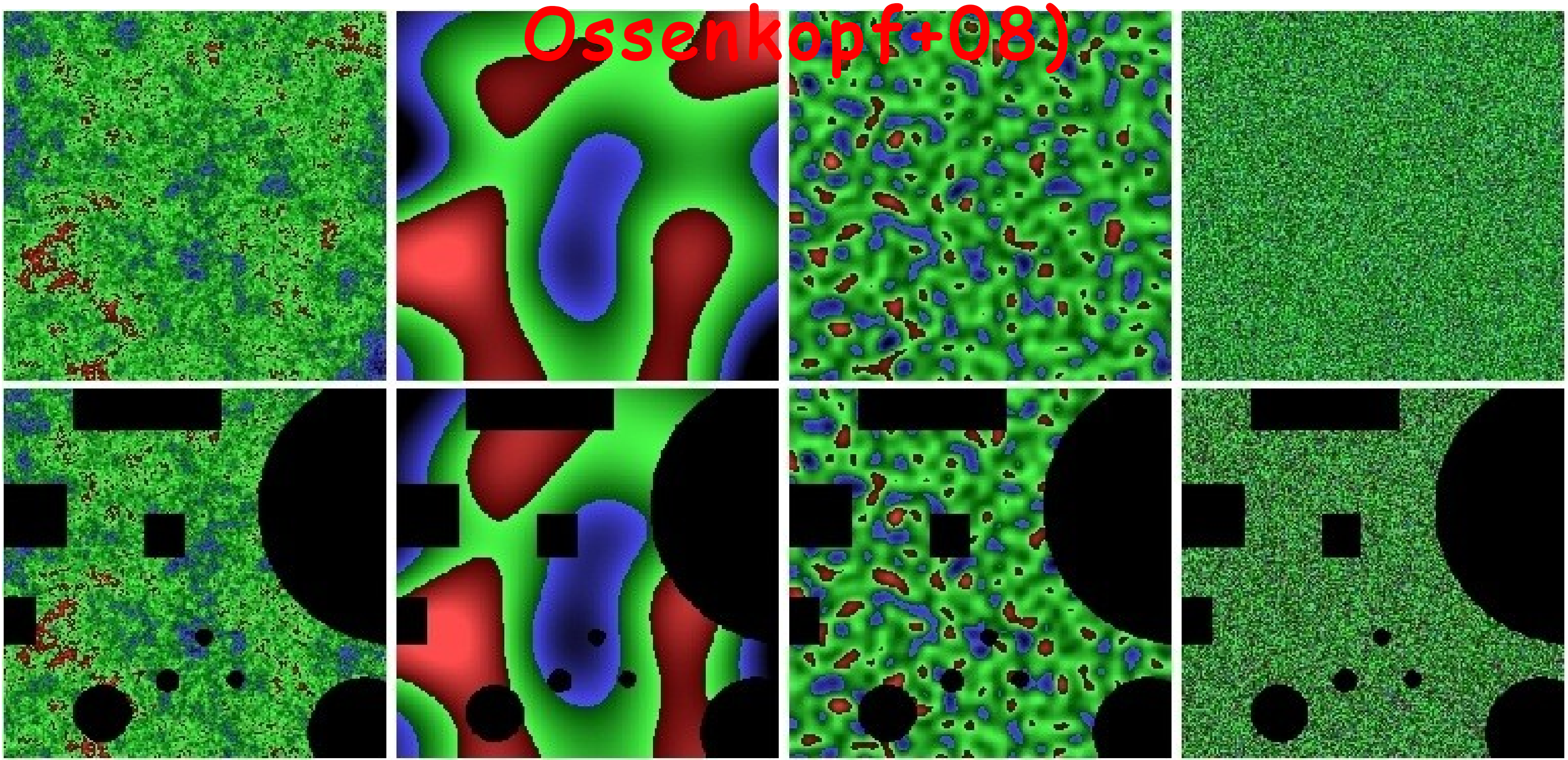


$$G_{\sigma_1} \circ I - G_{\sigma_2} \circ I$$ = Mexican Hat

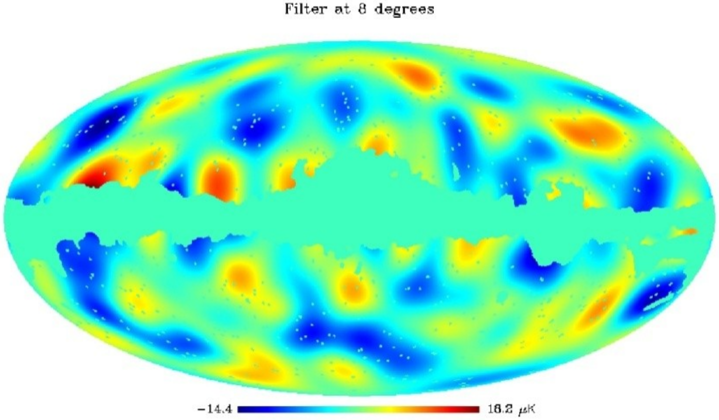
Modified Mexican Hat Filter for data with gaps

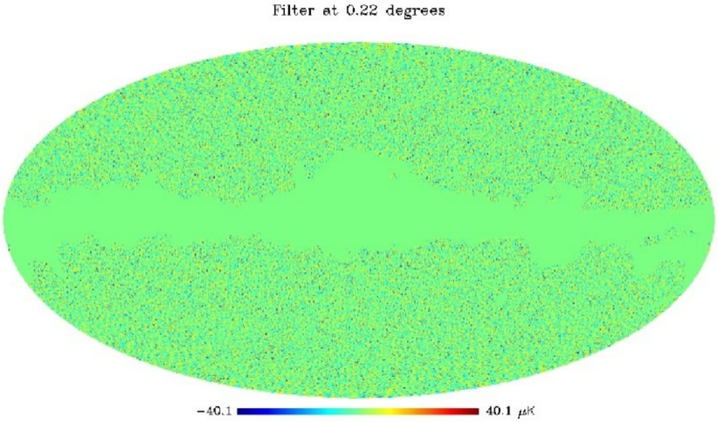
$$\tilde{F} \circ I = \frac{G_{\sigma_1} \circ I}{G_{\sigma_1} \circ M} - \frac{G_{\sigma_2} \circ I}{G_{\sigma_2} \circ M}$$

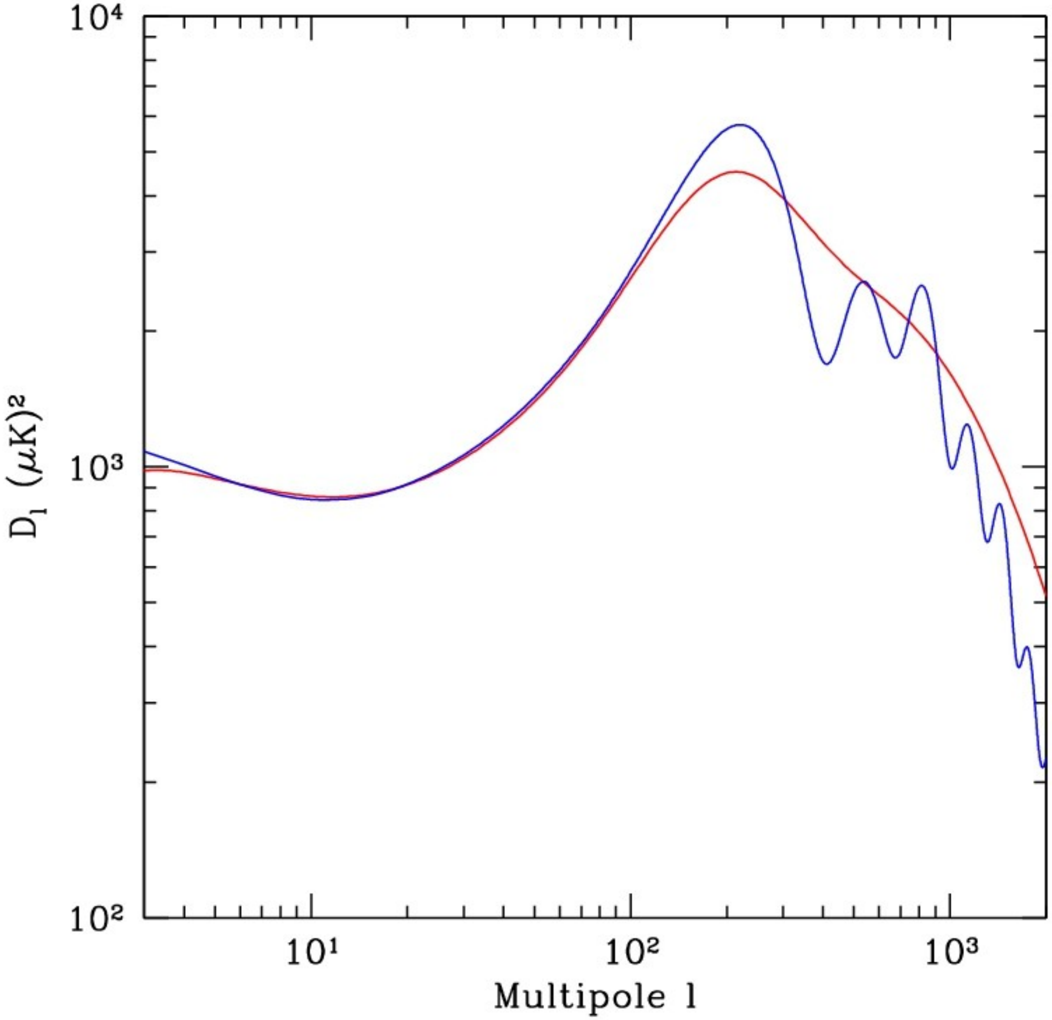
(Arevalo et al, submitted, see also Ossenkopf+08)



CMB: Works fine for low resolution PS


Filter at 8 degrees

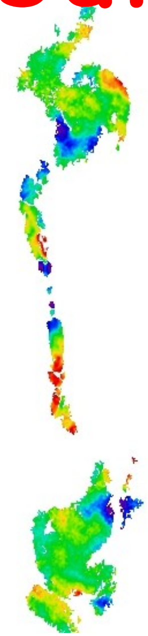

Filter at 0.22 degrees

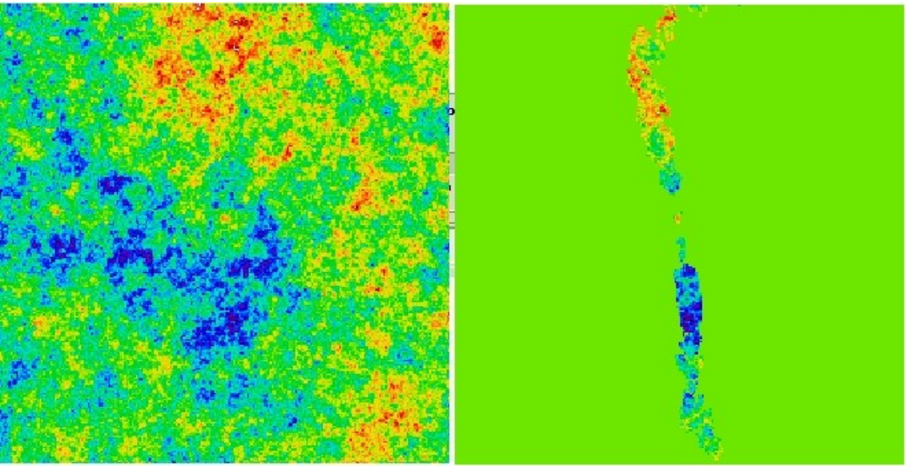


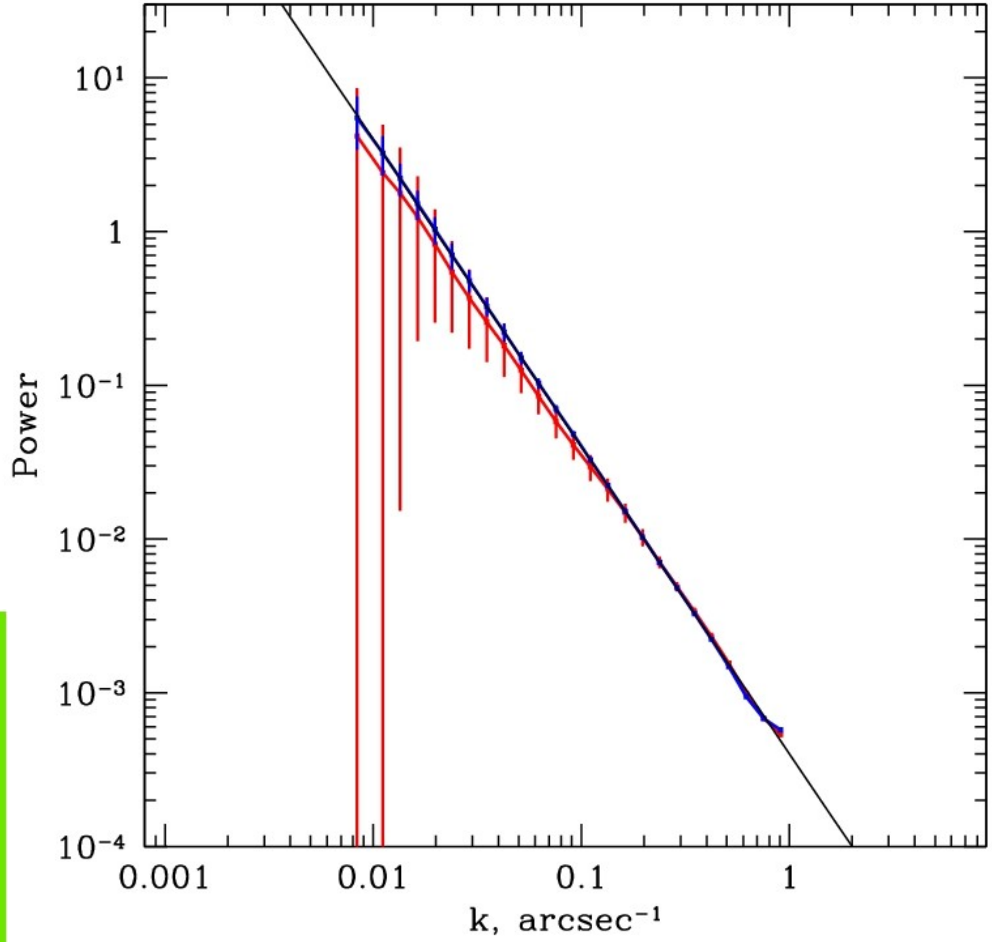
Arevalo+,

Faraday Rotation Measure

$$\int n_e B_{\|} dl$$

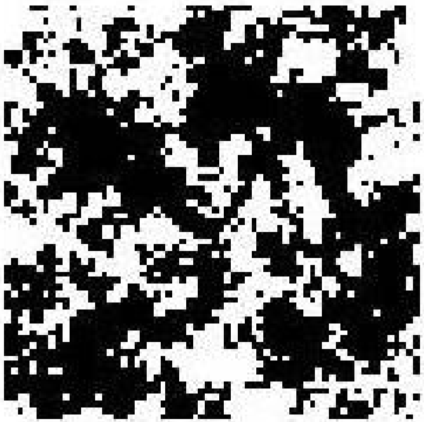




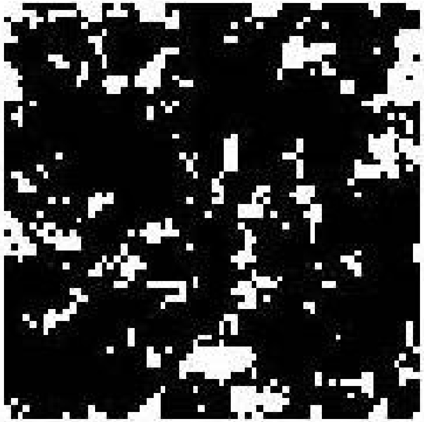


Lyskova

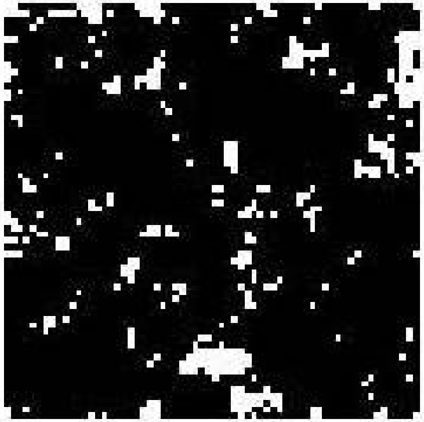
Simulated 3D velocity cube



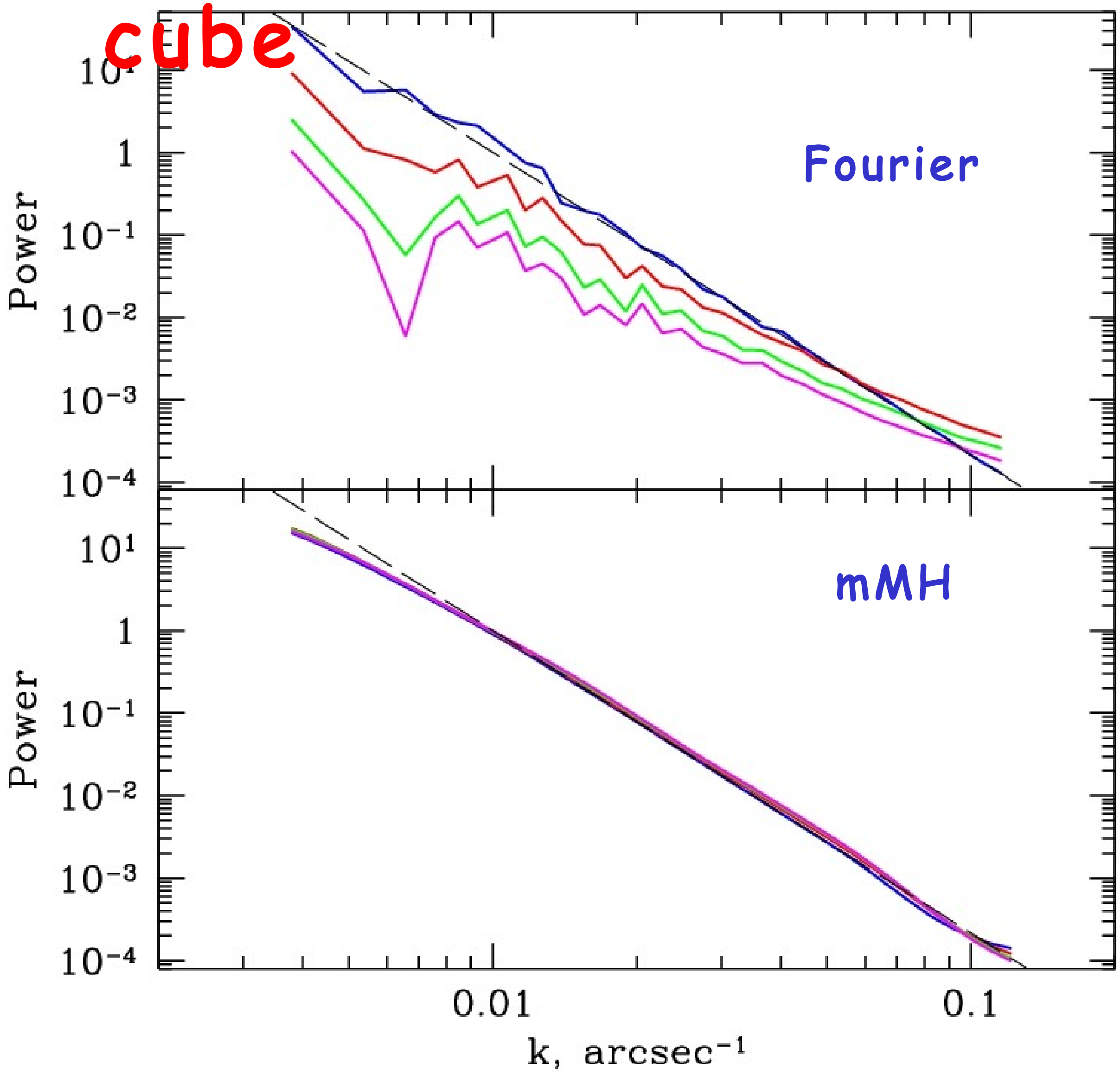
50%



75%

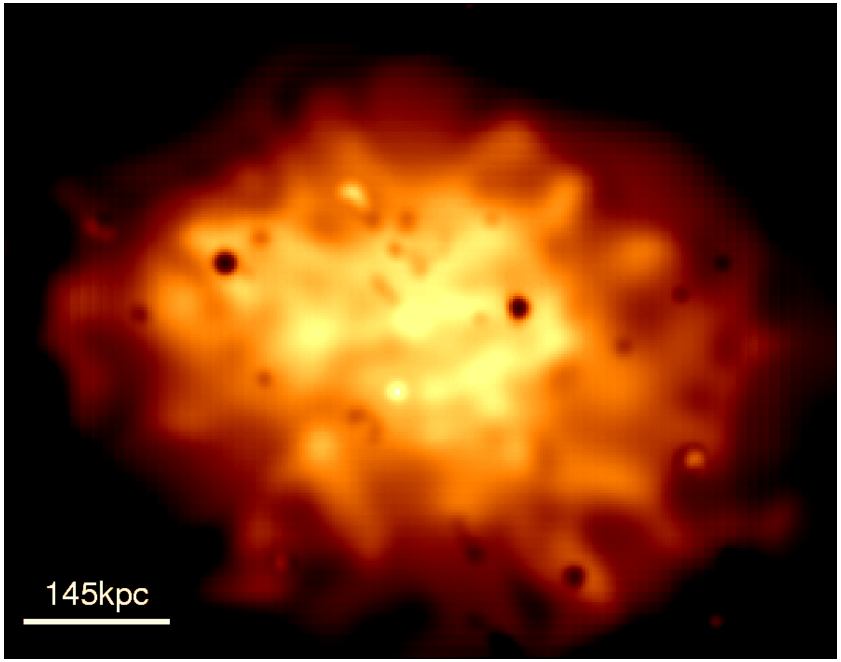


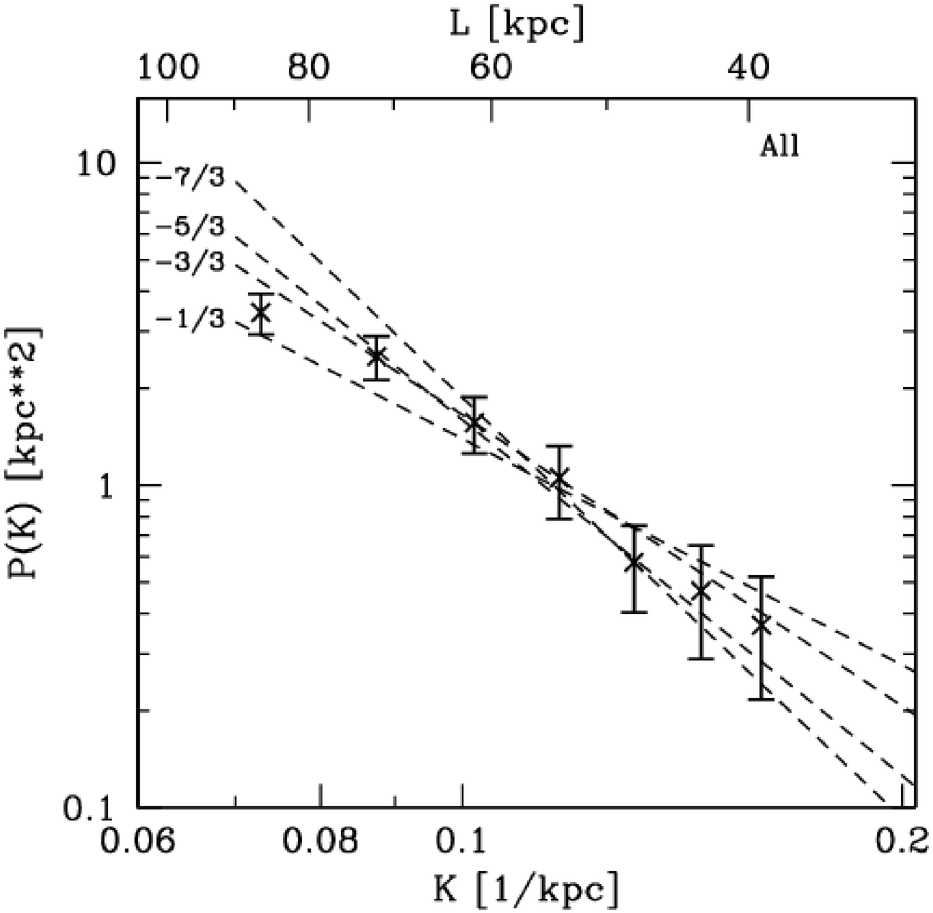
85%



Zhuravlev

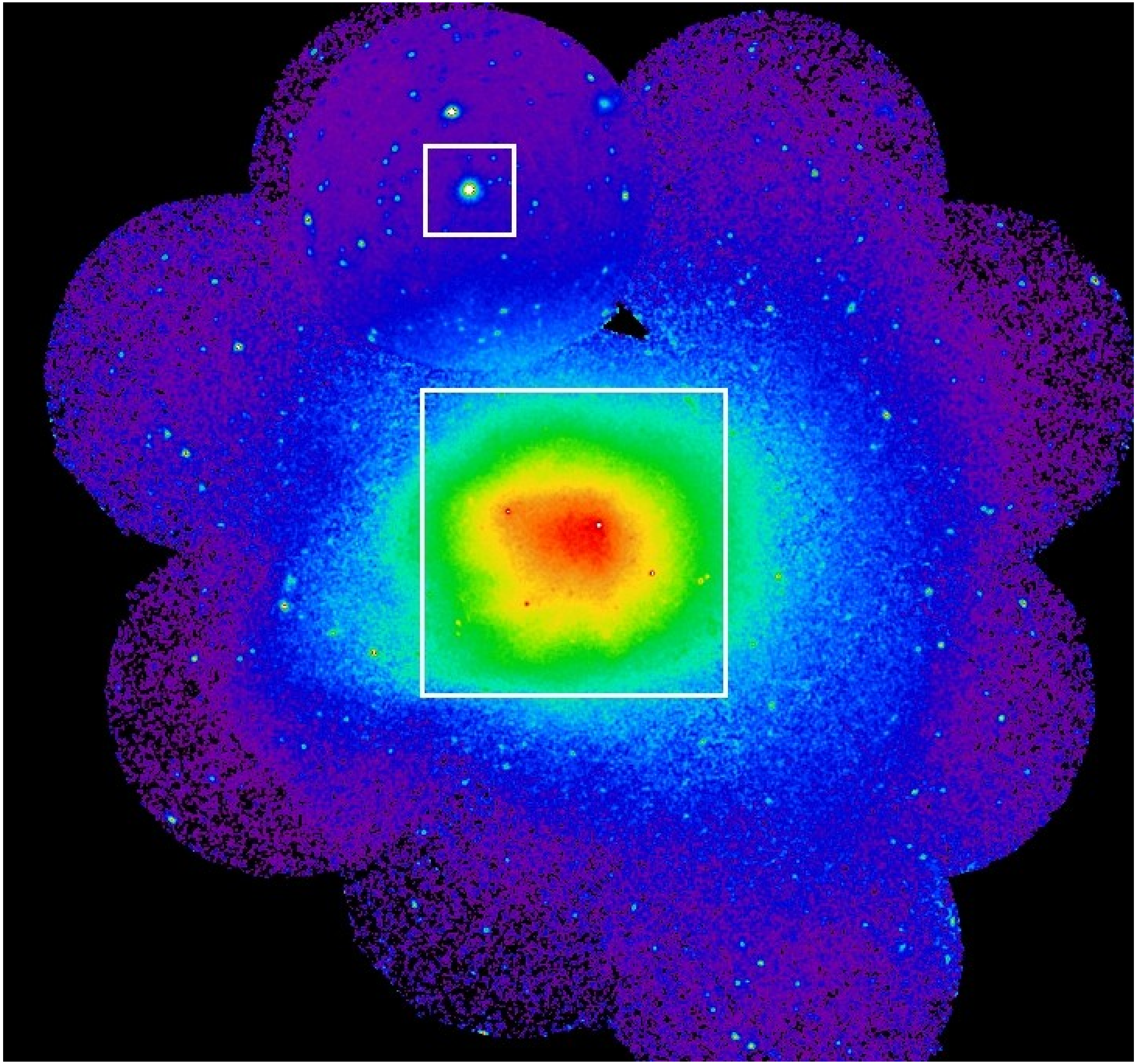
Pressure fluctuations in Coma



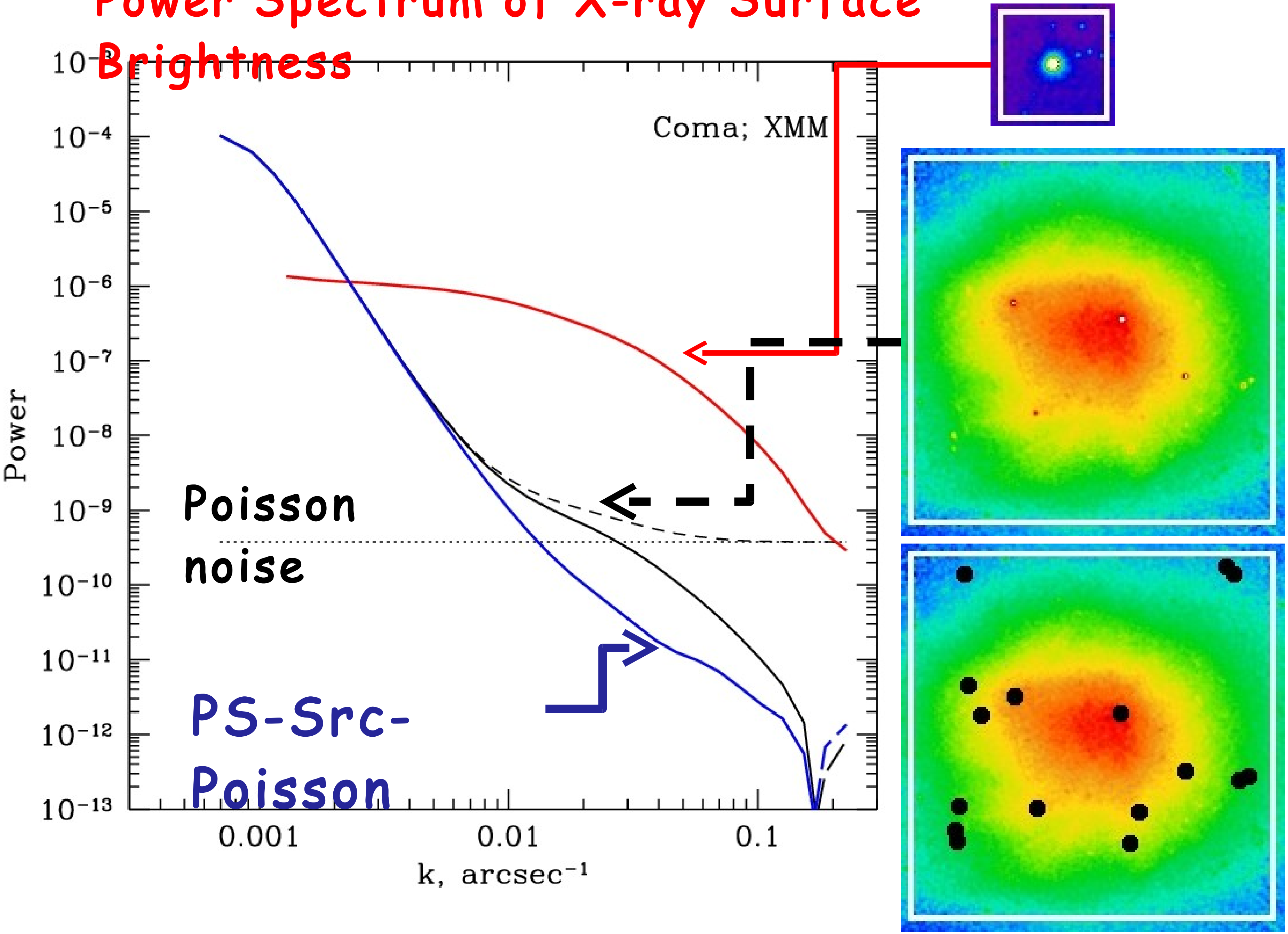


Schuecker et al. (2004)

Let us do SB



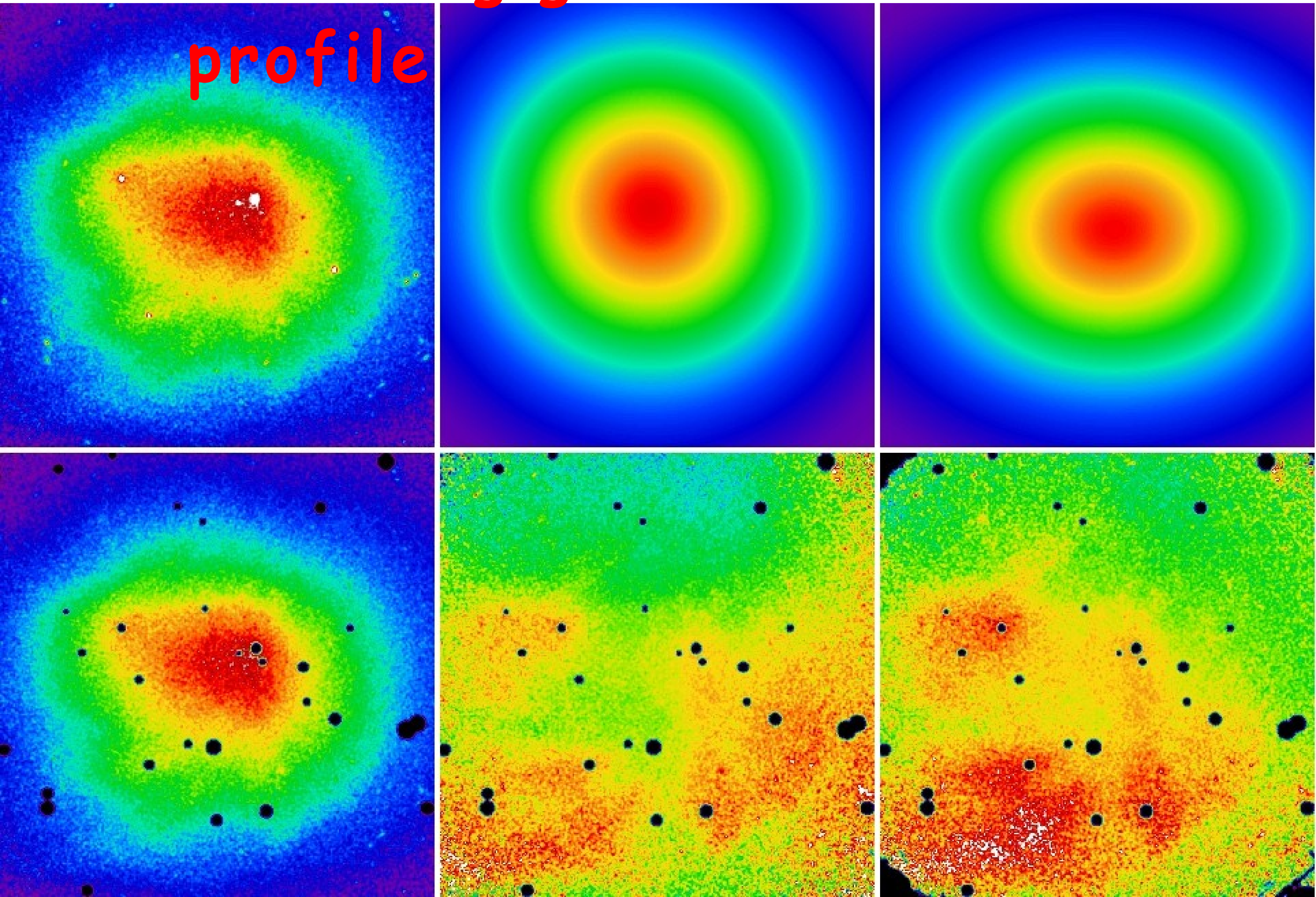
Power Spectrum of X-ray Surface Brightness



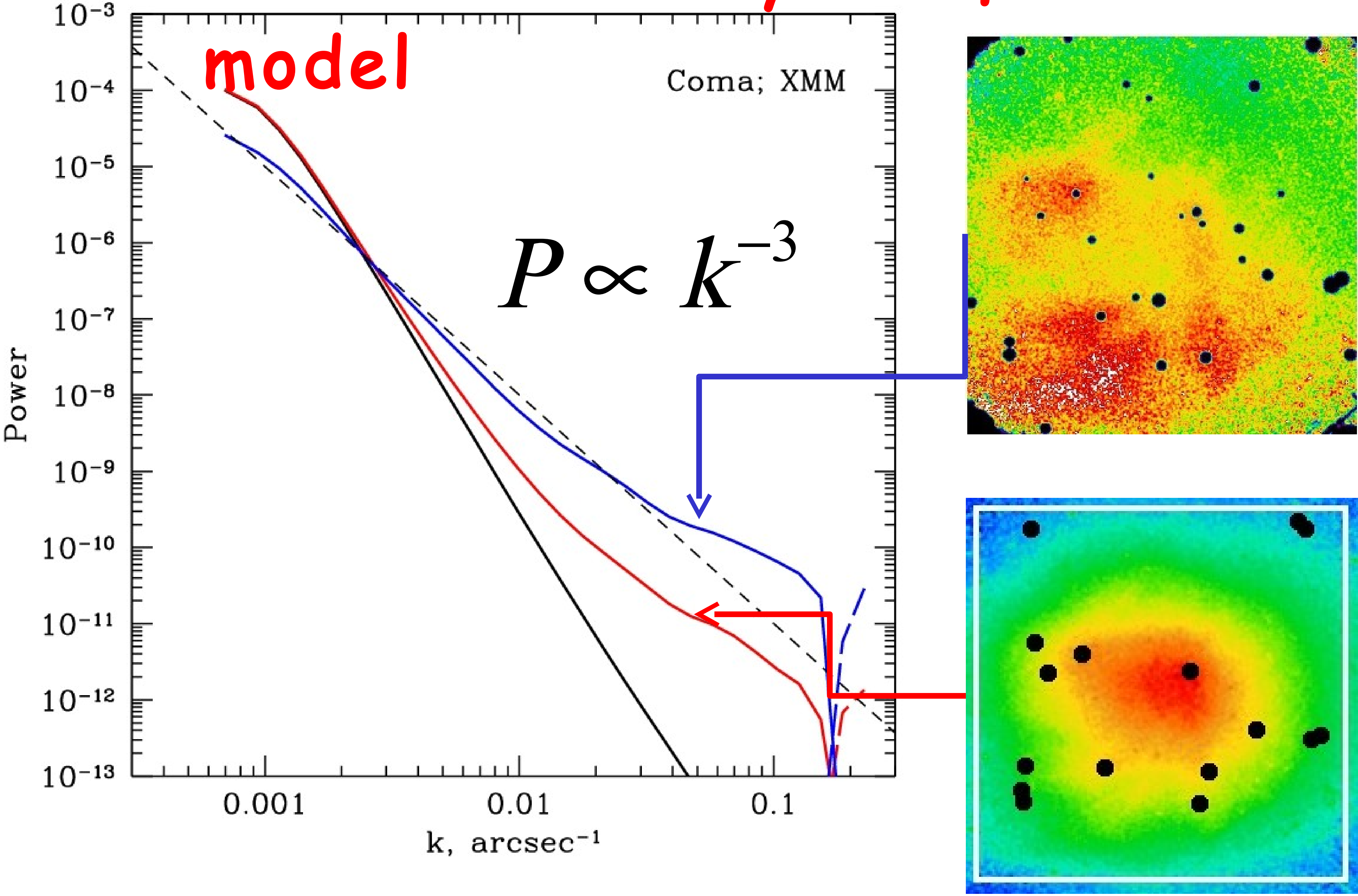
Poisson noise

PS-Src-Poisson

Removing global Coma profile

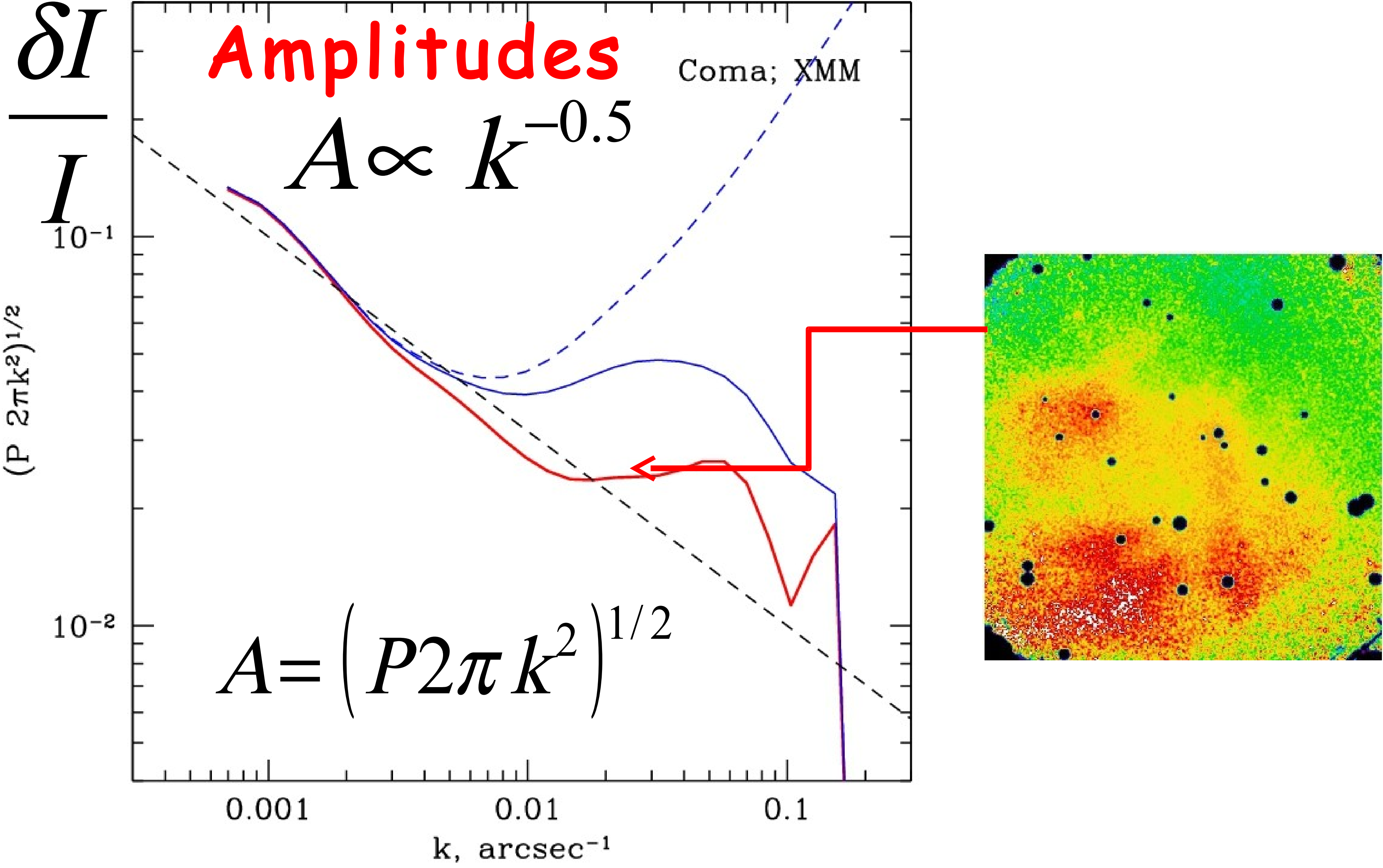


Coma divided by the β model



$$P \propto k^{-3}$$

Converting to Amplitudes



$$\frac{\delta I}{I}$$

$$A \propto k^{-0.5}$$

$$A = \left(P 2\pi k^2\right)^{1/2}$$

Relating 3D and 2D power spectra

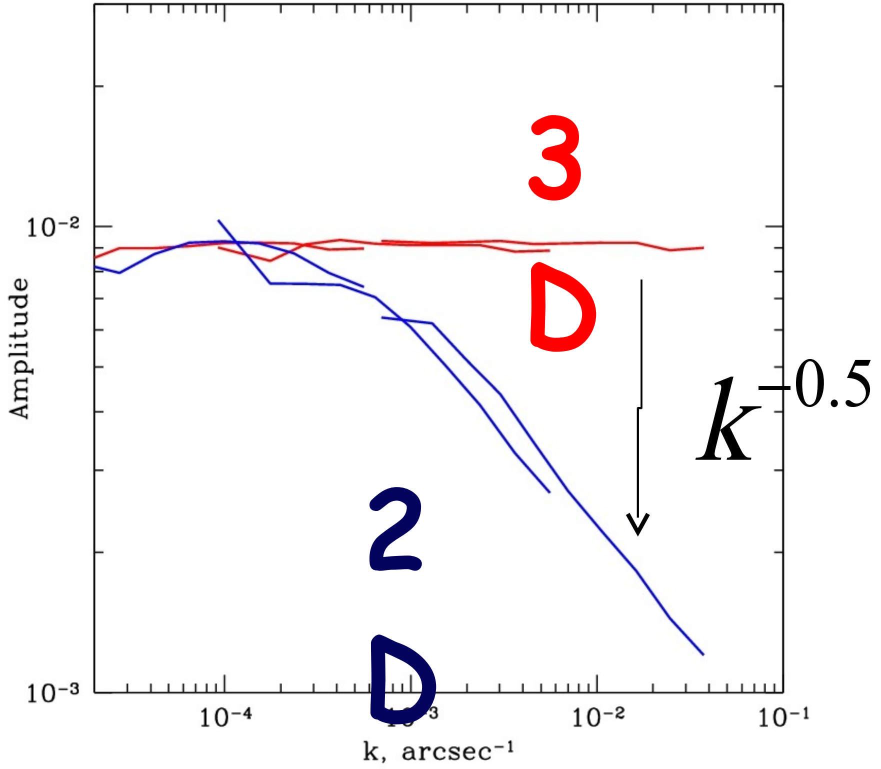
$$I(x,y)=\int \delta(x,y,z)\,n_e^2(x,y,z)\,dz$$

$$P_{2D}(k)=\int P_{3D}\left(\sqrt{k^2+k_z^2}\right)W(k_z)\,dk_z$$

$$W=P_1[n_e^2(z)]$$

$$k \gg \frac{1}{l_z} \Rightarrow P_{2D}=aP_{3D}$$

$$k \ll \frac{1}{l_z} \Rightarrow P_{2D}=aP_{3D}\times k$$

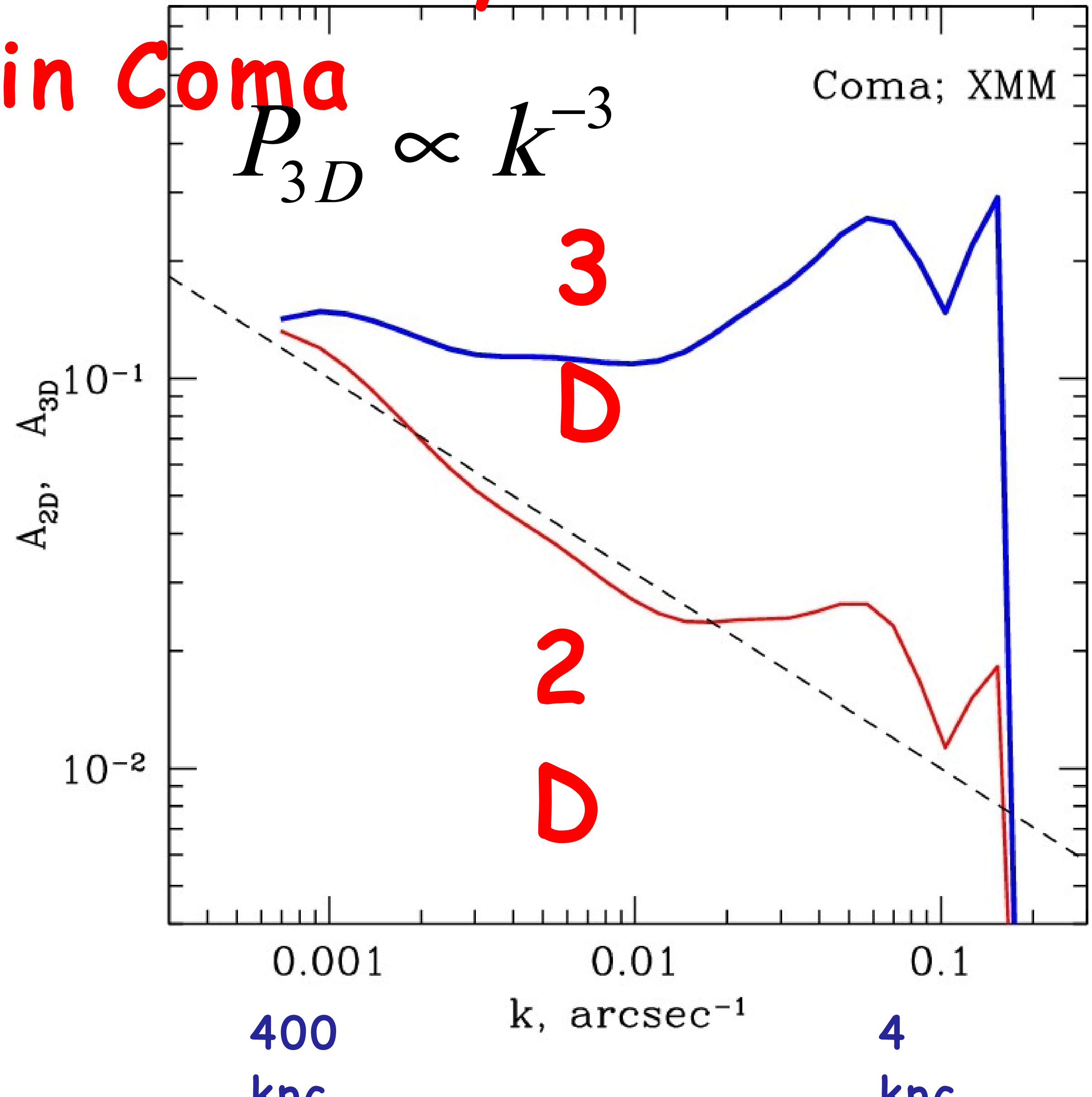


3D Density fluctuations in Coma

$$2\frac{\delta n_e}{n_e}$$

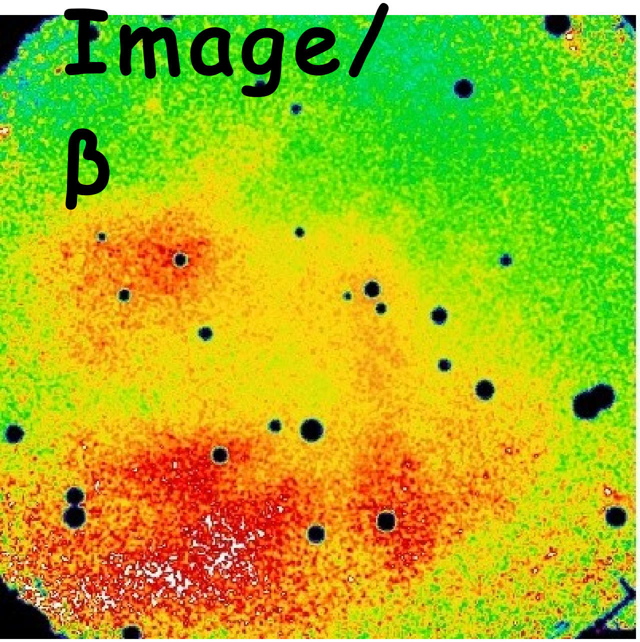
$$\frac{\delta I}{I}$$

$$P_{3D} \propto k^{-3}$$

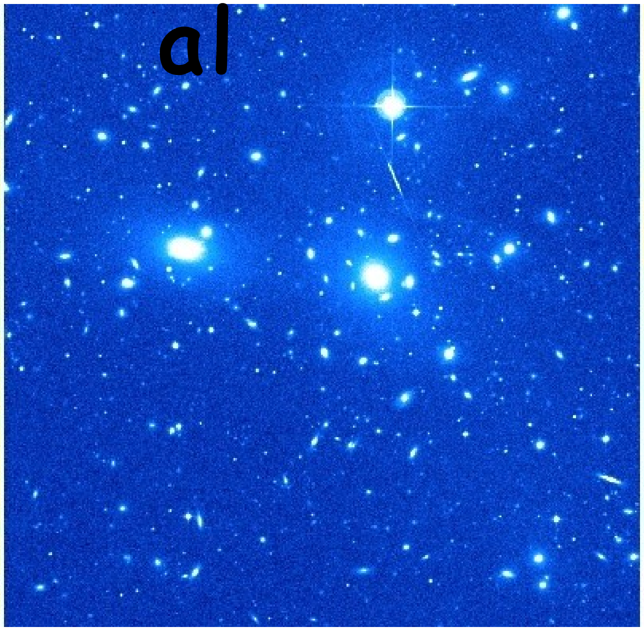


Density fluctuations ~5-10% on

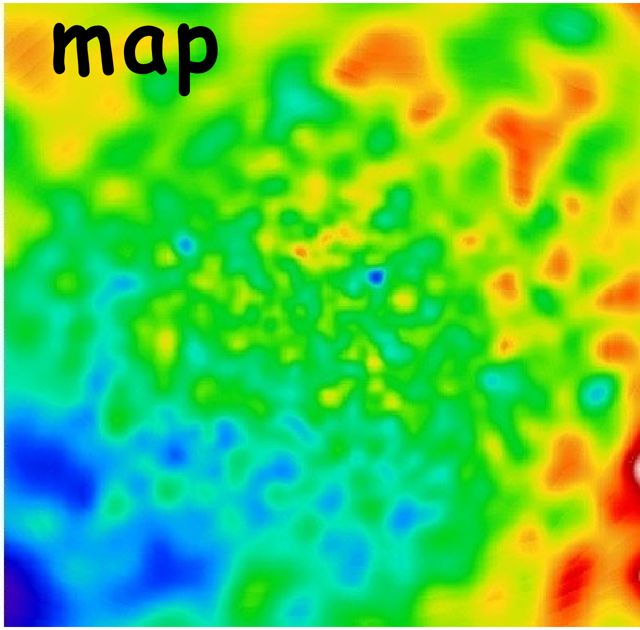
X-Image/β



Optical



Gas T-map



~5-10% density fluctuations include (4-400 kpc):

potential perturbation (big galaxies)

$$P_{3D} \propto k^{-3}$$

Conclusions

ICM velocities ~ few 100 km/s
[except for mergers]

Direct V measurements ->
structure function

Modified MH method provides robust
measure of V(k)

Relating 3D and 2D power spectra

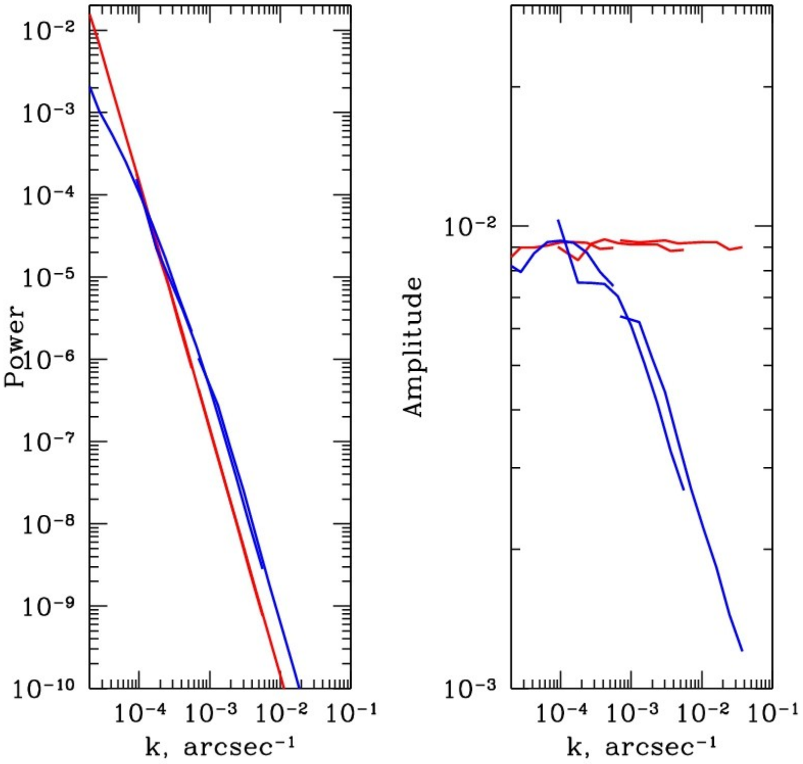
$$I(x,y)=\int \delta(x,y,z)\,n_e^2(x,y,z)\,dz$$

$$P_{2D}(k)=\int P_{3D}\left(\sqrt{k^2+k_z^2}\right)W(k_z)\,dk_z$$

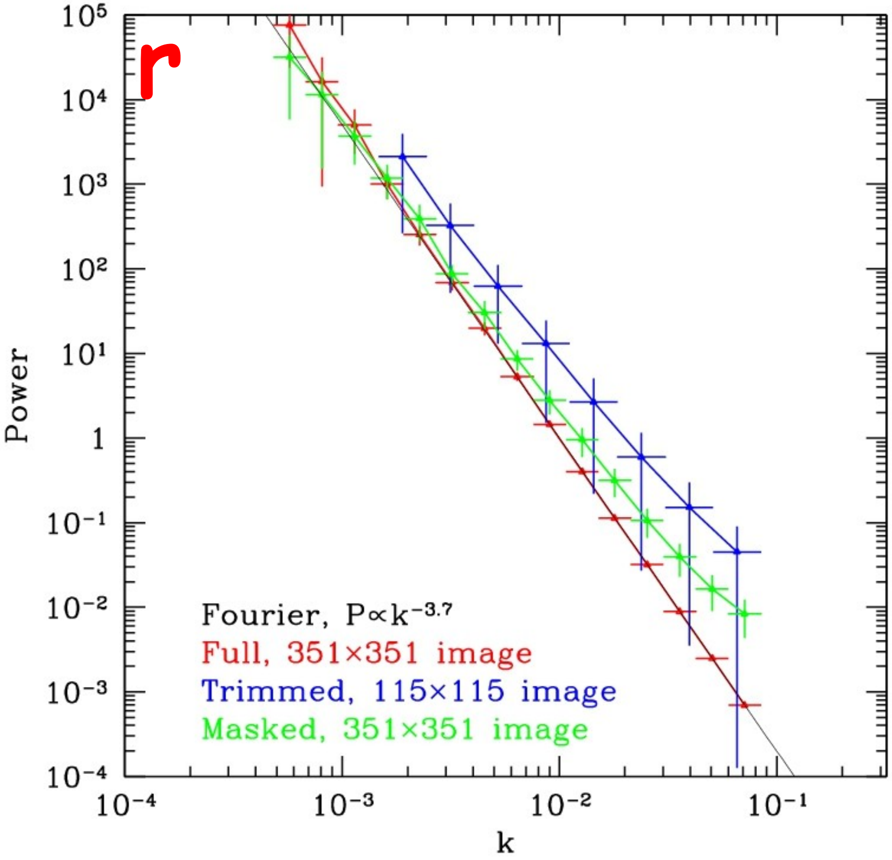
$$W=P_1[n_e^2(z)]$$

$$k>>\frac{1}{l_z}\Rightarrow P_{2D}=aP_{3D}$$

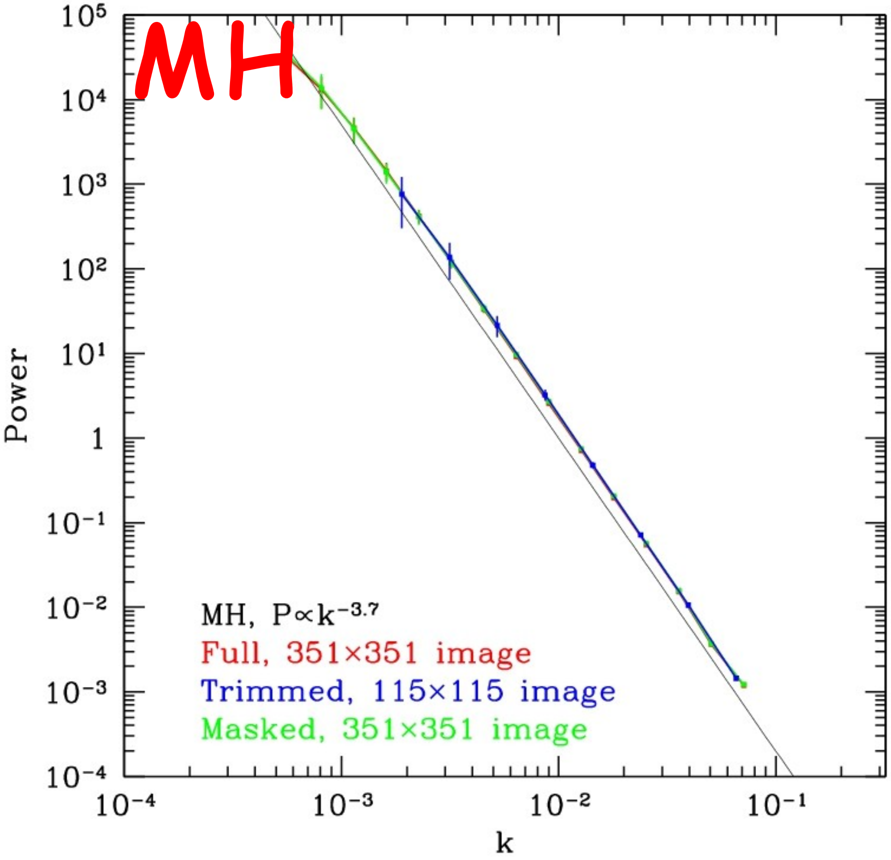
$$k<<\frac{1}{l_z}\Rightarrow P_{2D}=aP_{3D}\times k$$



Fourier

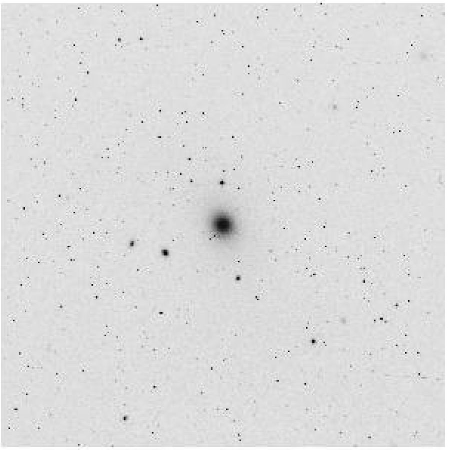


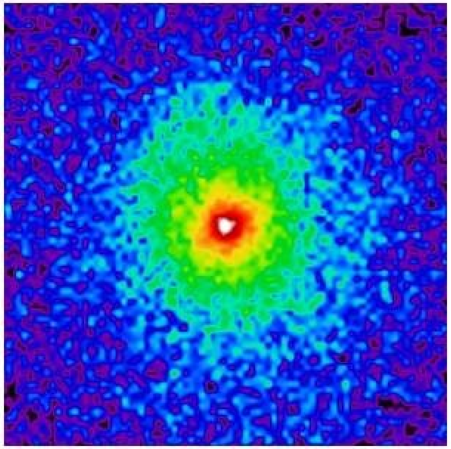
Modified MH

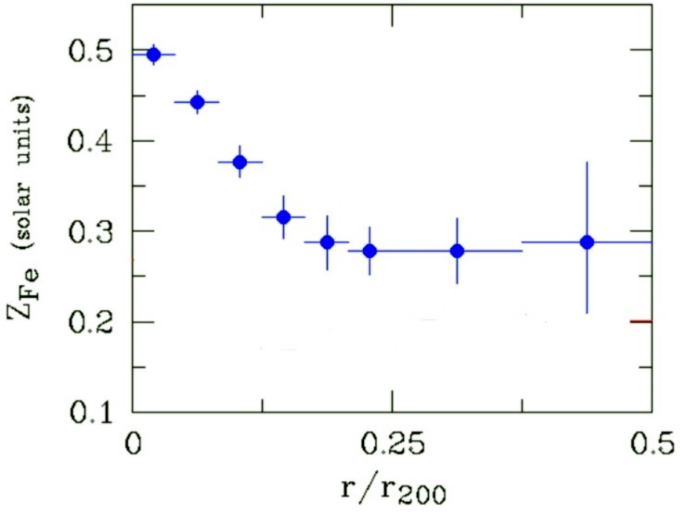


Arevalo et al

Heavy metal turbulent diffusion

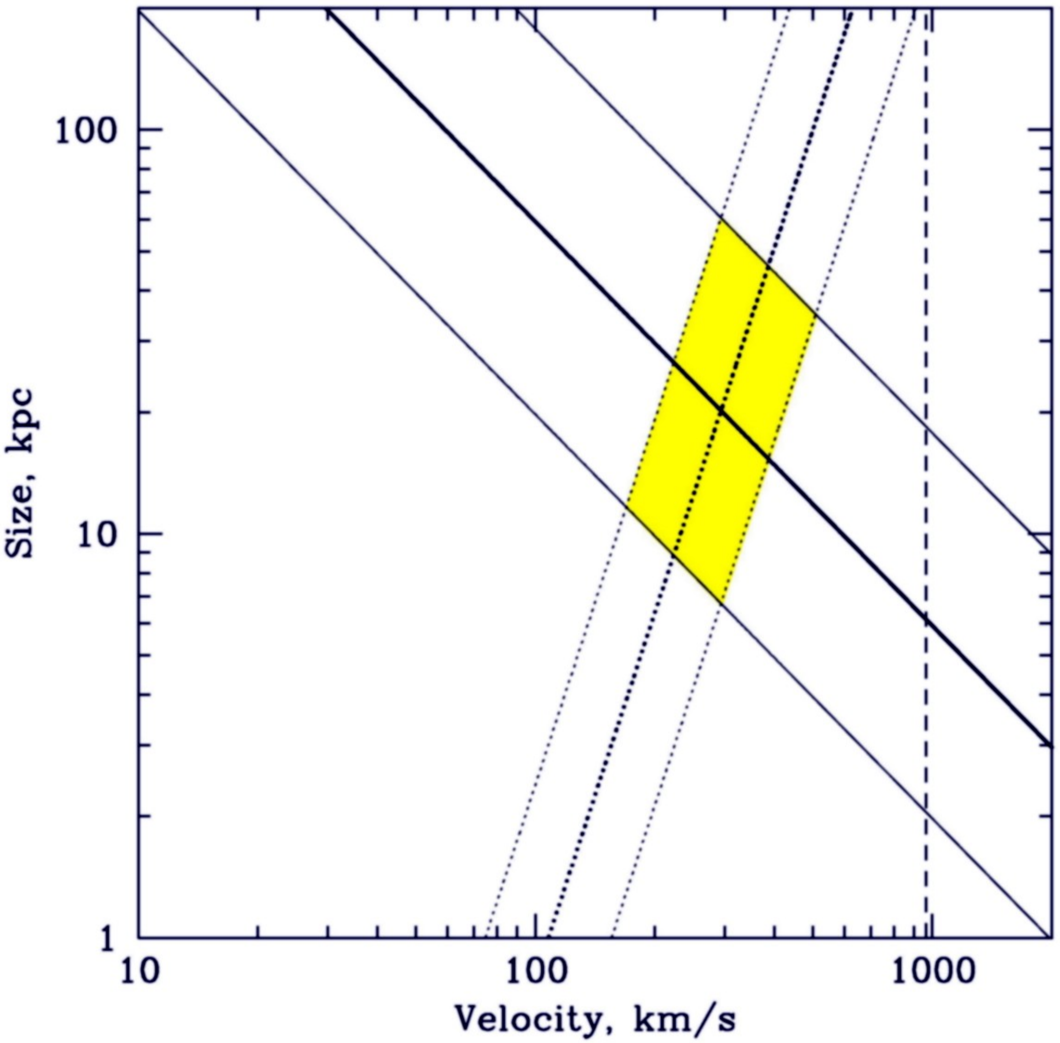






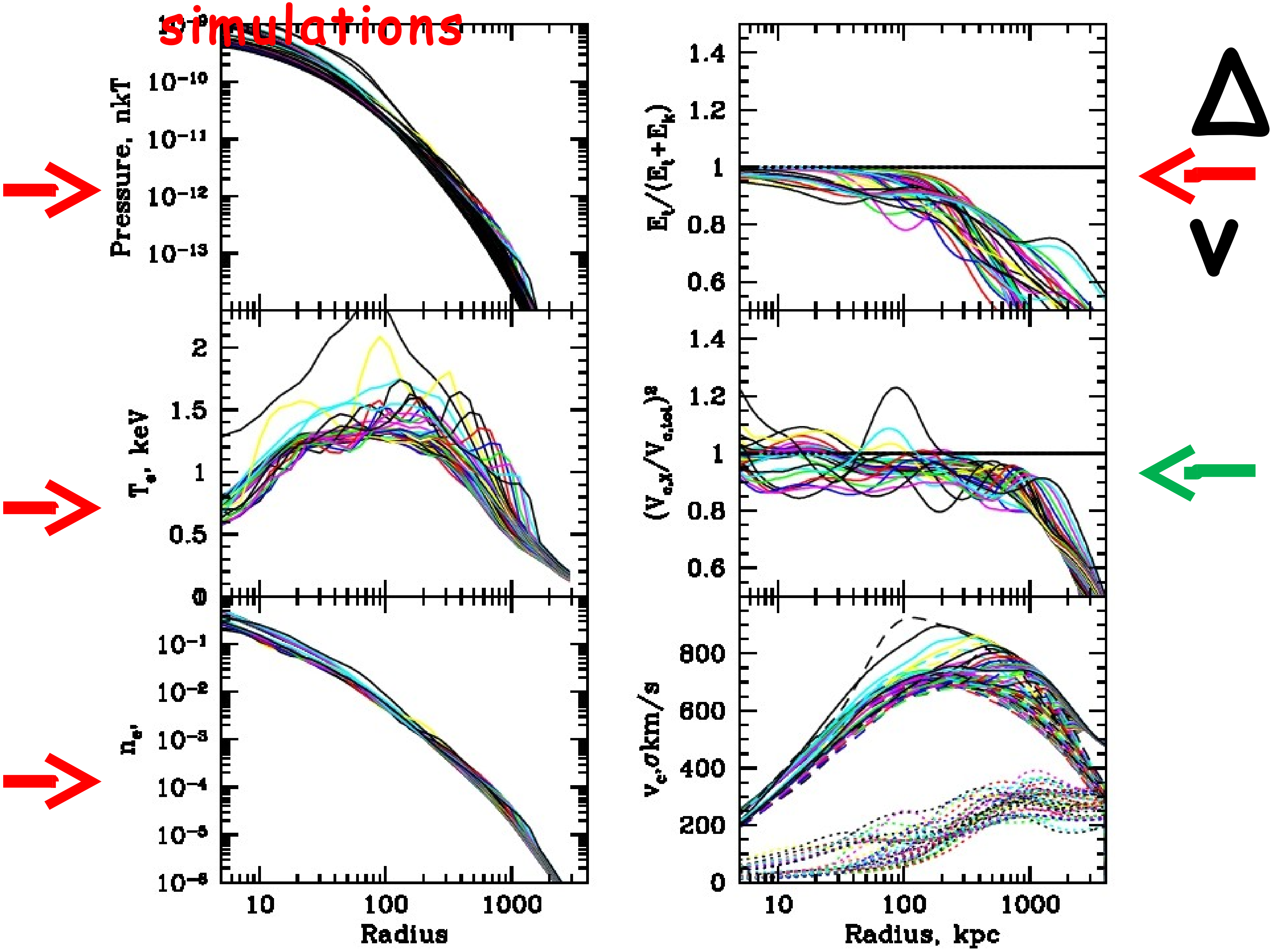
If turbulent motions mix the gas and spread metals

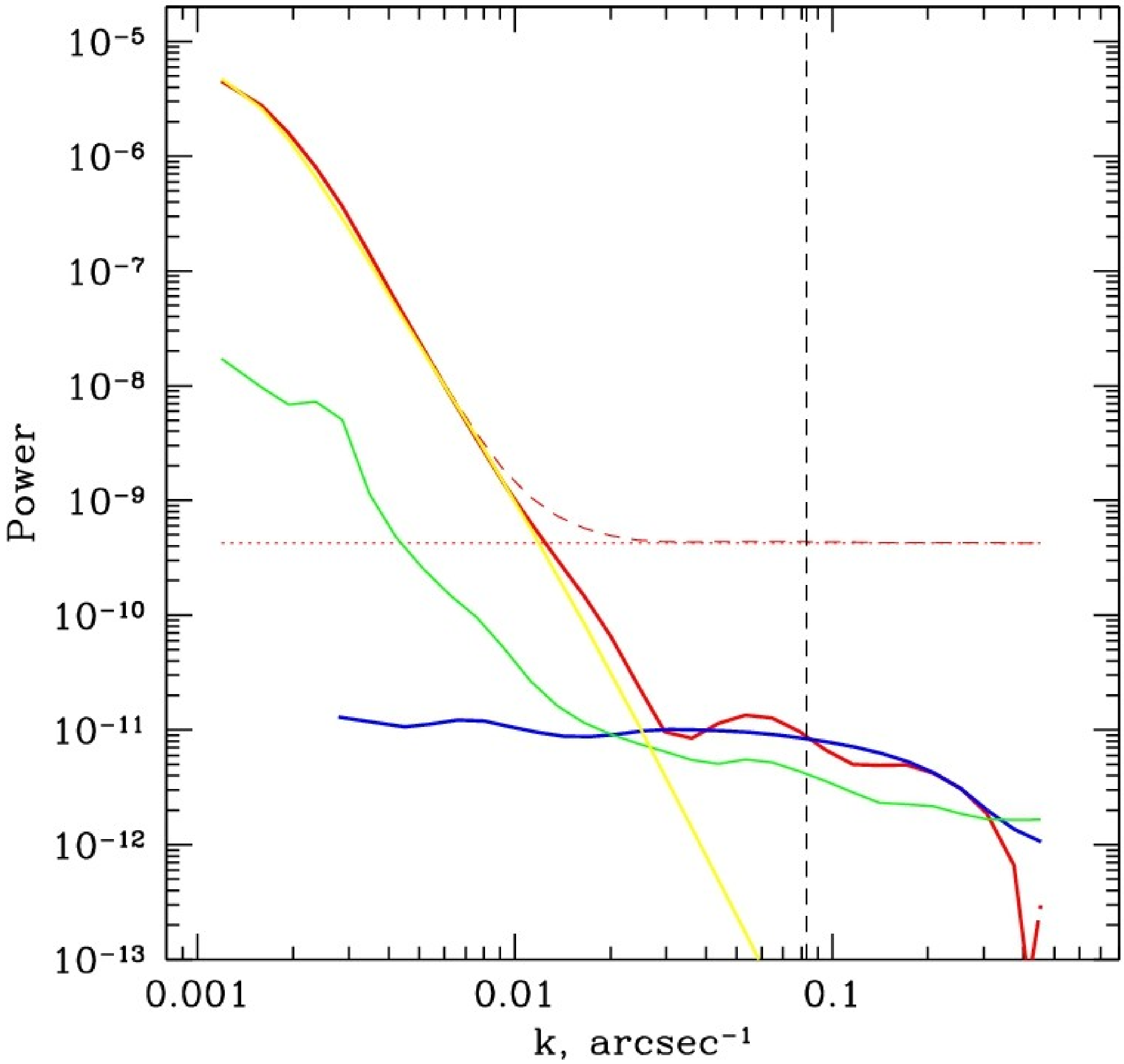
$$D \sim \frac{1}{3} vl$$



Rebusco et al (2005,2006)

HE masses vs total masses in simulations

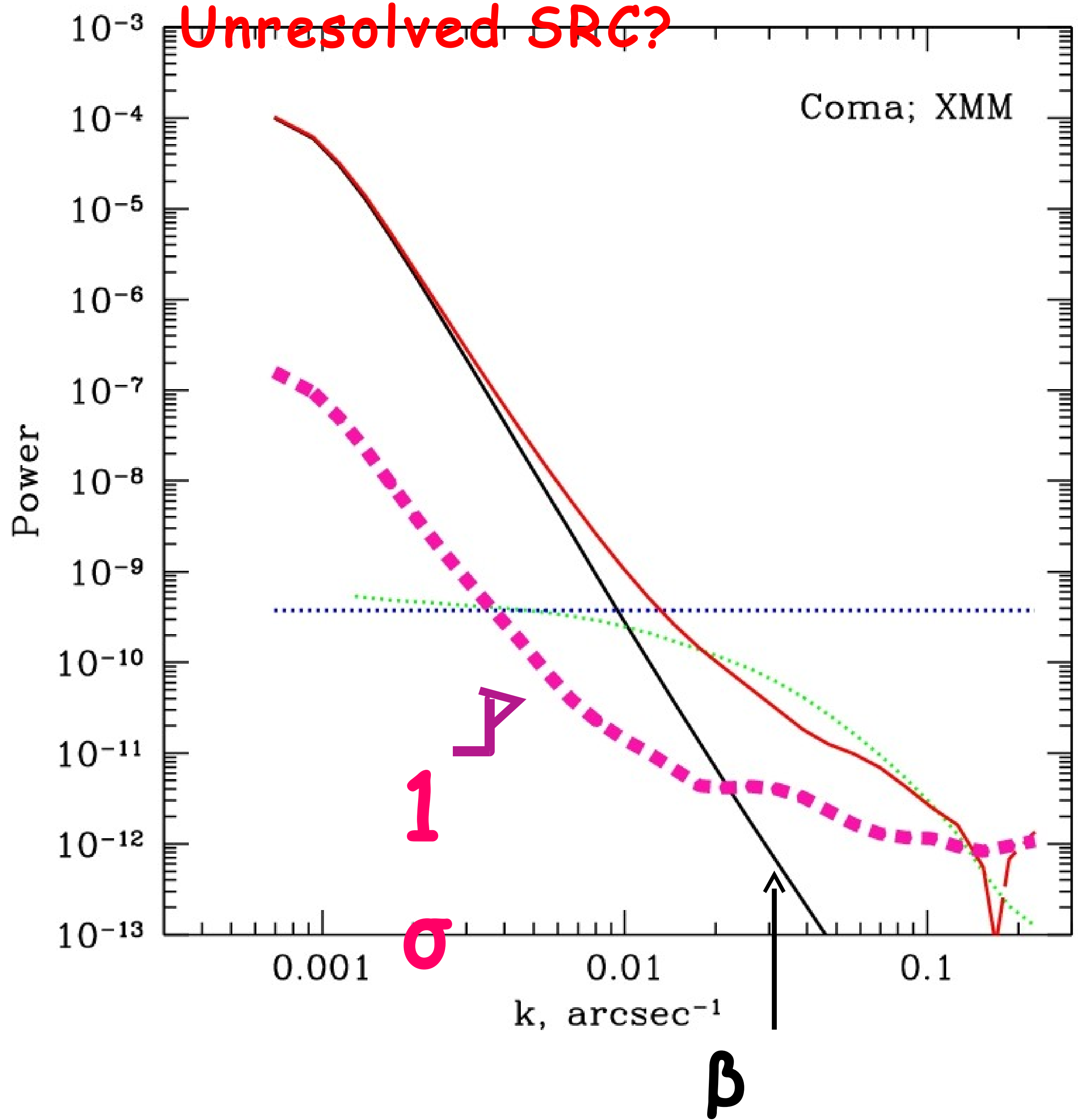


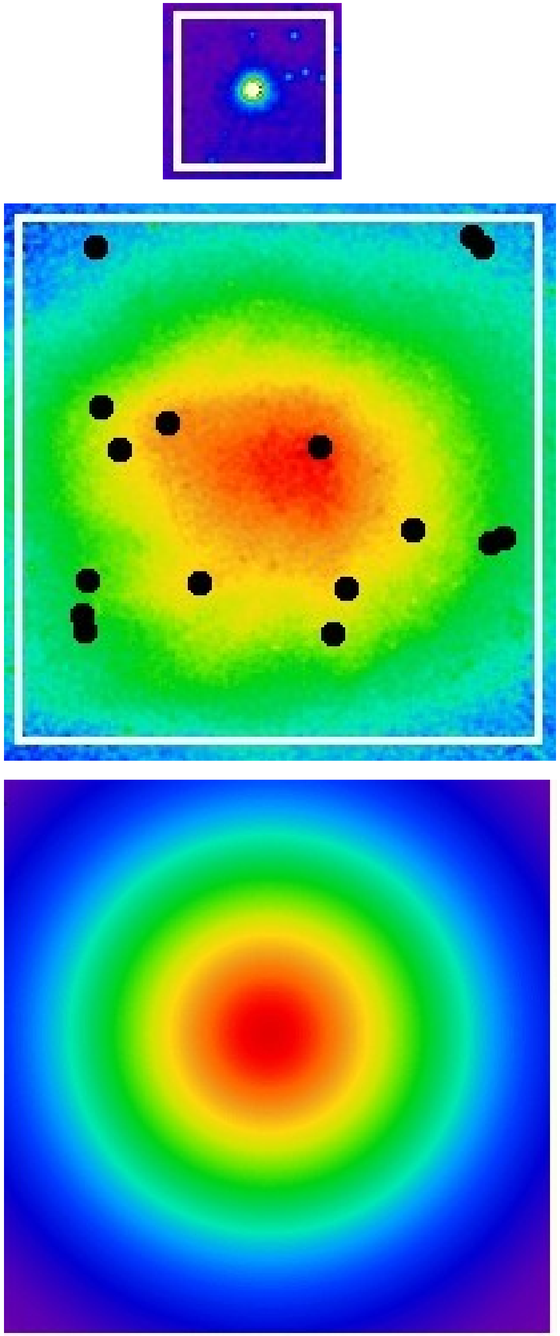


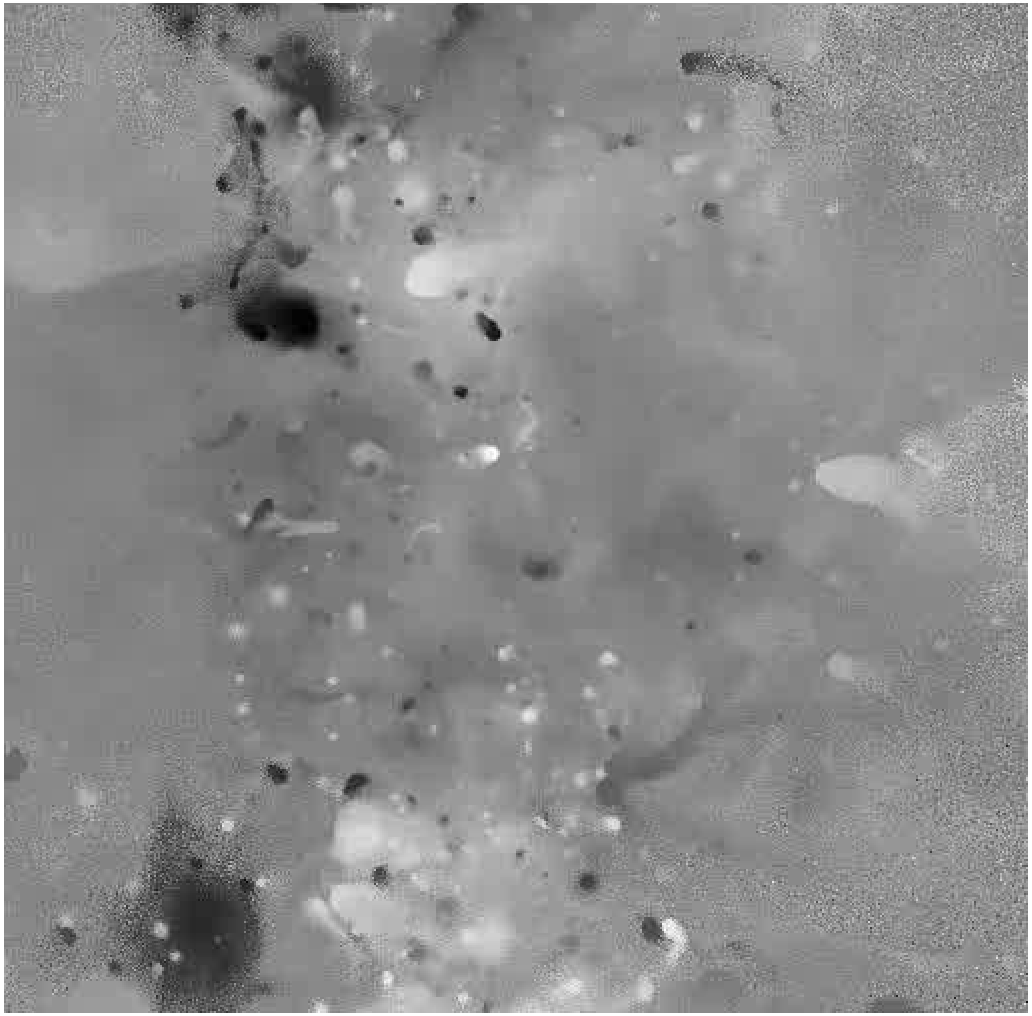
Power
k, arcsec^{-1}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0.001
0.01
0.1

Coma;

Coma=Beta Model + Unresolved SRC?



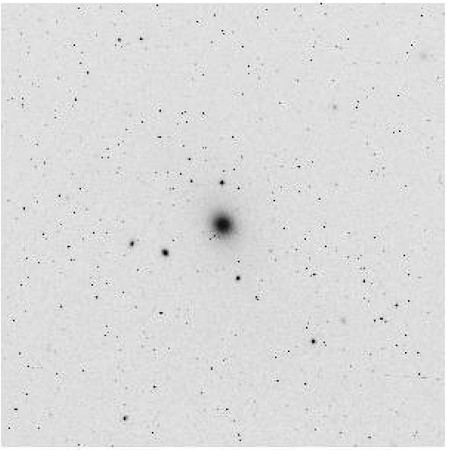




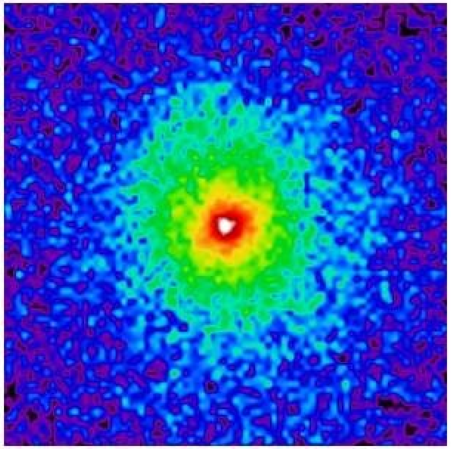
	Т	Э	
Численное моделирование	+/-	+/-	все
Прямые измерения скоростей и уширение линий	+	2013+	v, Δv
Резонансное рассеяние	+	+	Δv
Поляризация	+	202X	v, Δv
Кинетический SZ эффект	+	Скоро	v
Влияние на массу	+	+	v2
Потоки охлаждения	+	+	v3/l
Турбулентная диффузия тяжелых элементов	+	+	vl
Флуктуации поверхностной яркости	+/-	+/-	v2

Турбулентная диффузия тяжелых элементов

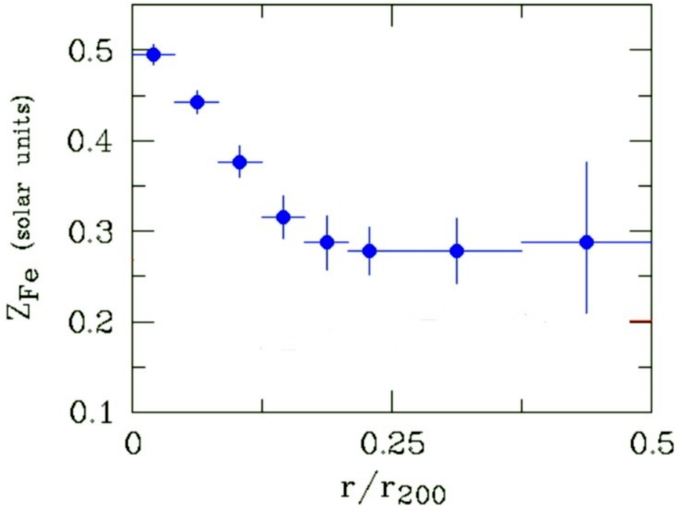
Оптика



Рентген



Обилие железа



Железо производится звездами центральной галактики

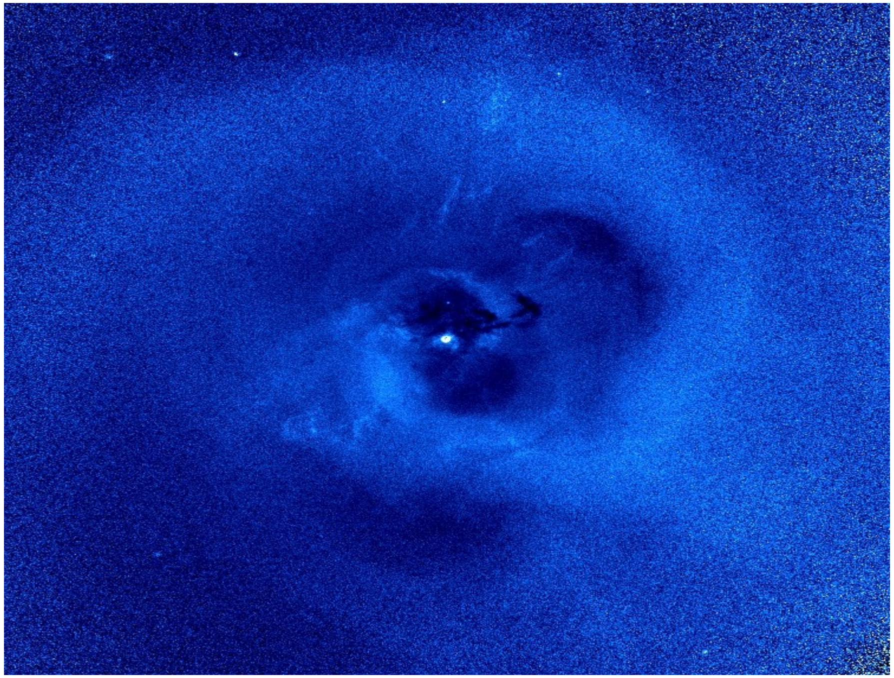
«Пик» железа в газе шире оптической галактики

Если железо «размывается» турбулентной диффузией: $D \sim \frac{1}{3} v l$

Rebusco et al. 2005,2006

Потоки охлаждения в центрах скоплений

Время радиационного охлаждения газа << возраста скоплений
Потери газа компенсируются потоком механической энергии Ч.Д.



$$n^2\Lambda(T) = \frac{\rho v^2}{2}\frac{v}{l} = C\rho\frac{v^3}{l}$$

ЕЧ и др. 2000,2002

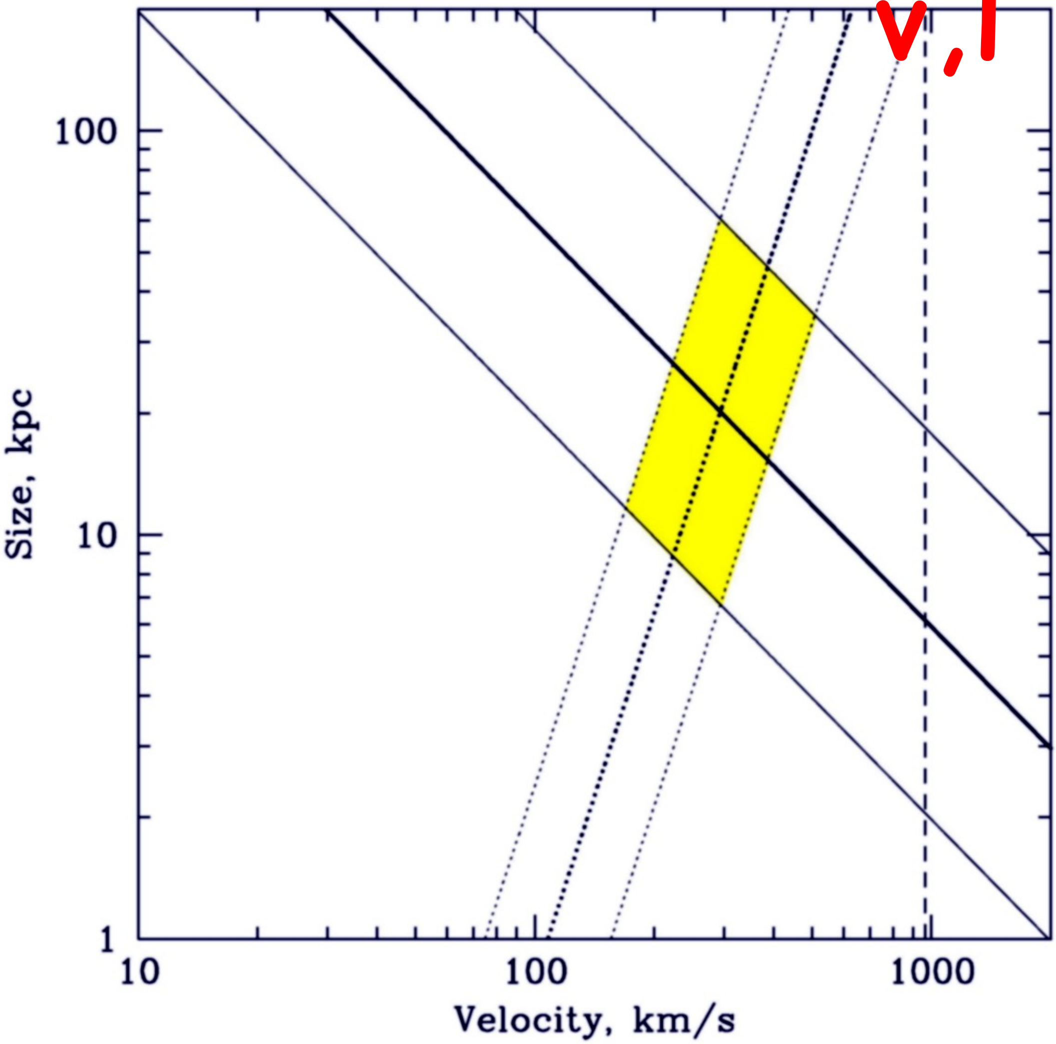
Поправка к гравитирующей массе из гидростатики

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

Тепловое давление

Нетепловое давление (включая микро-турбулентность)

Три уравнения для v,l



$$n^2\Lambda(T) \approx C_1\,\rho\,\frac{\mathrm{v}^3}{l}$$

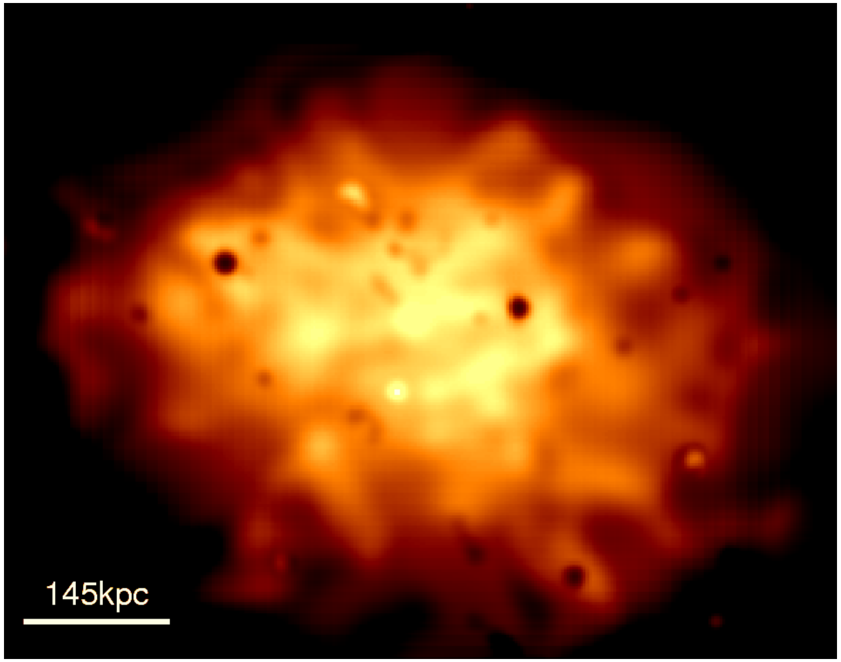
$$D \approx C_2\,\mathrm{v}l$$

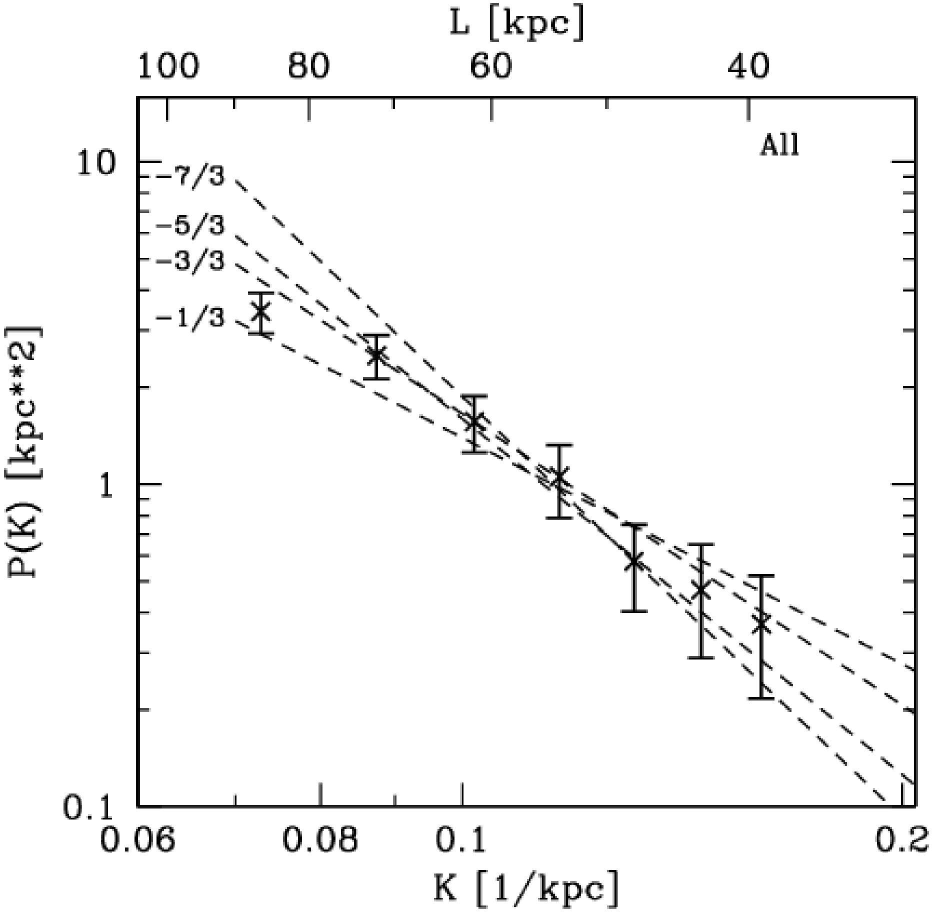
$$\rho\mathrm{v}^2 \approx C_3 nkT$$

$$\Rightarrow\ \ \mathrm{v}, l$$

v~ неск. 100 км/с

Флуктуации давления или поверхностной яркости

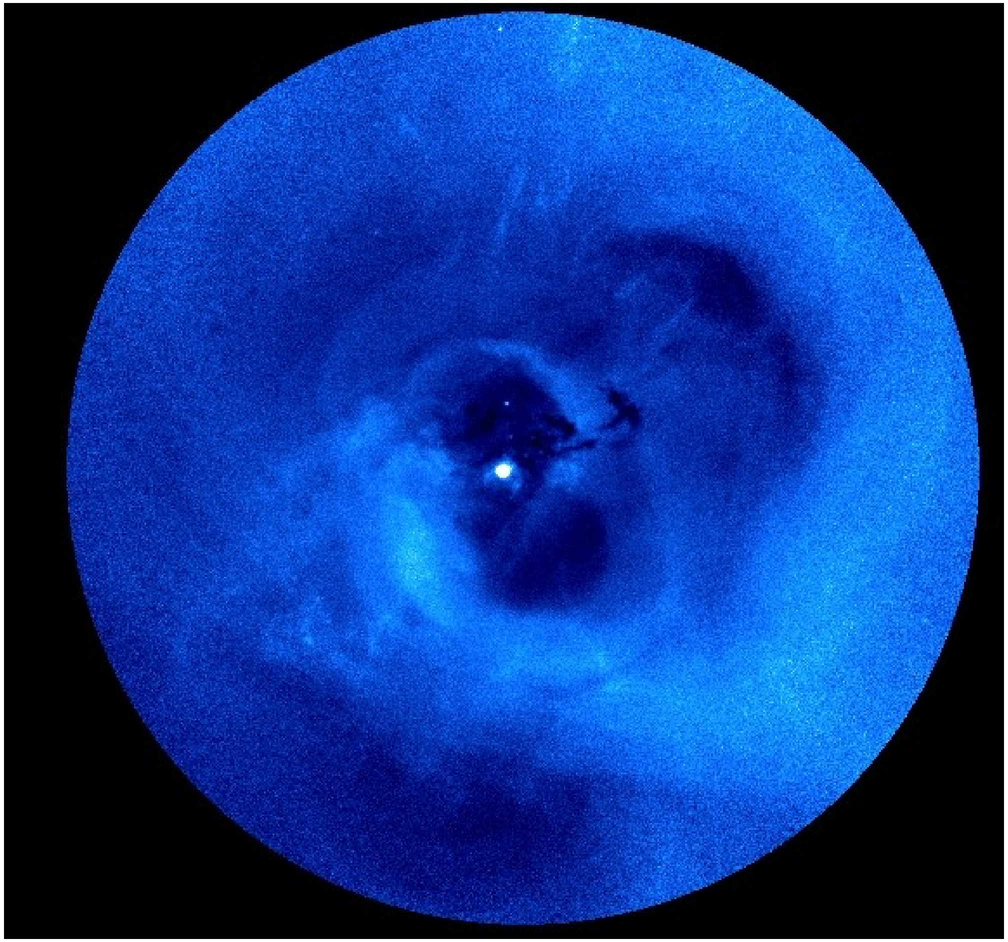


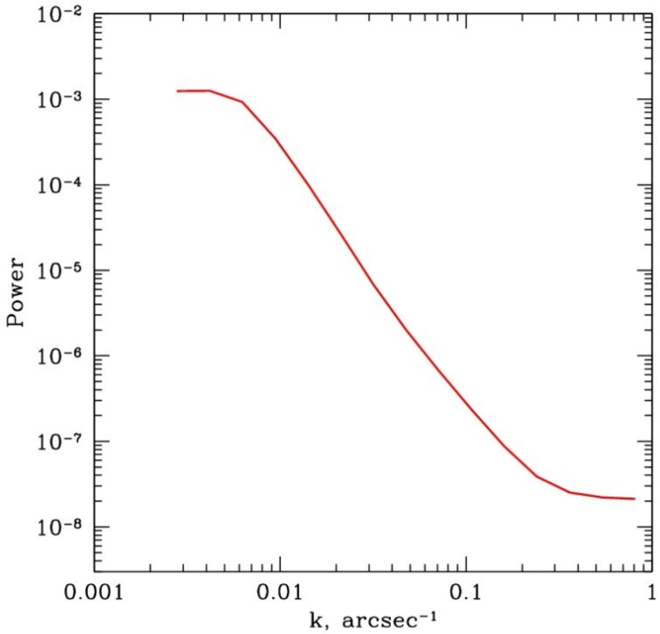


Schuecker et al. (2004)

Центральная часть скопления в созвездии Персея

(70 миллионов фотонов)



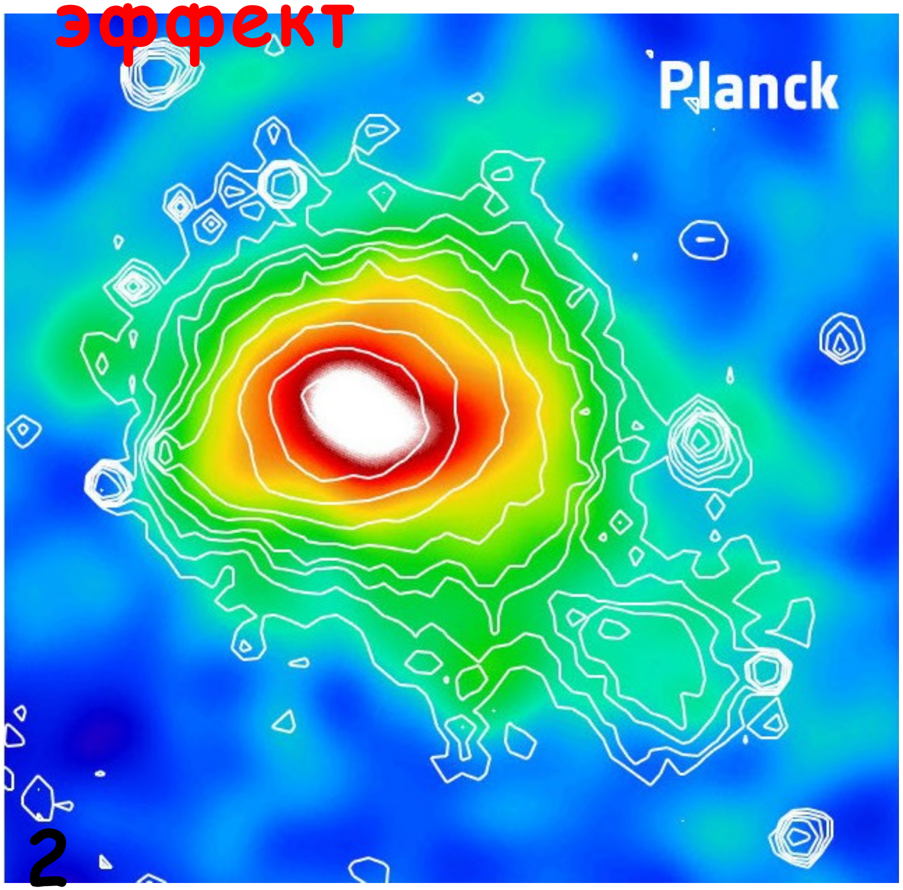


2D->3D

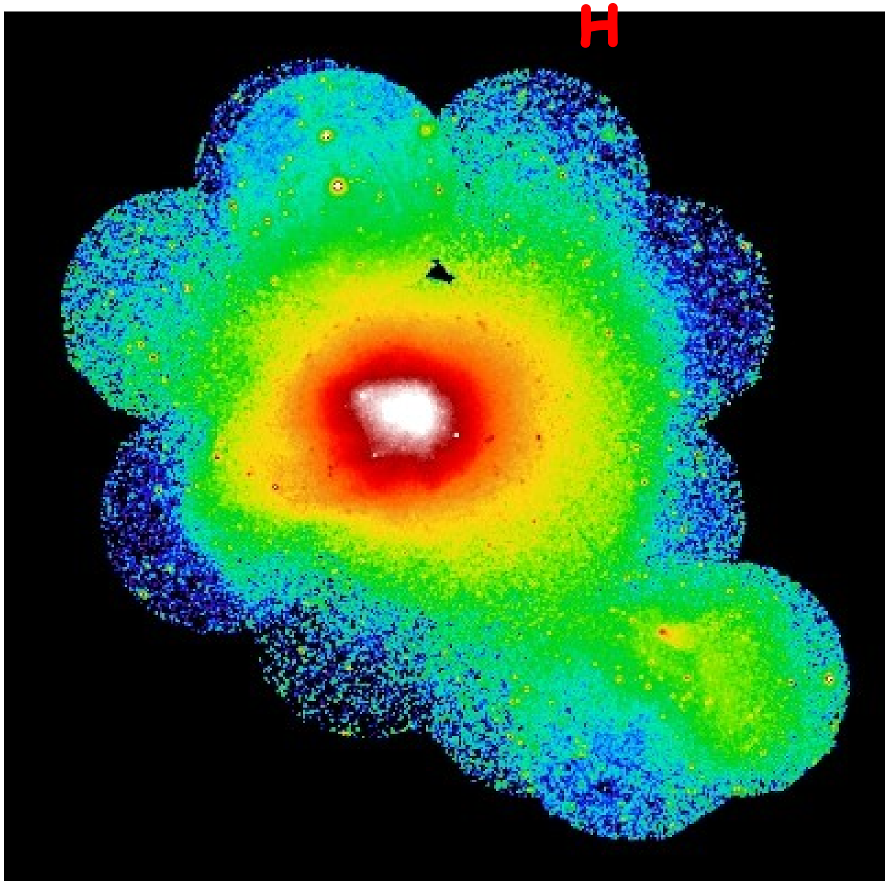
Края, дыры?

Тепловой SZ эффект

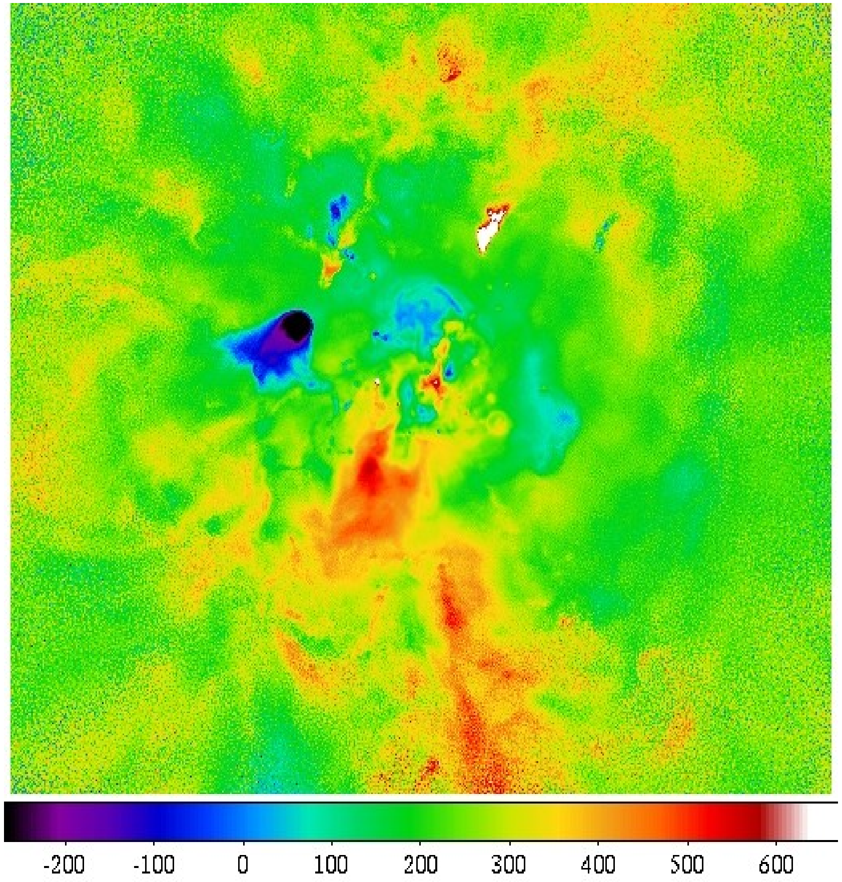
Рентген



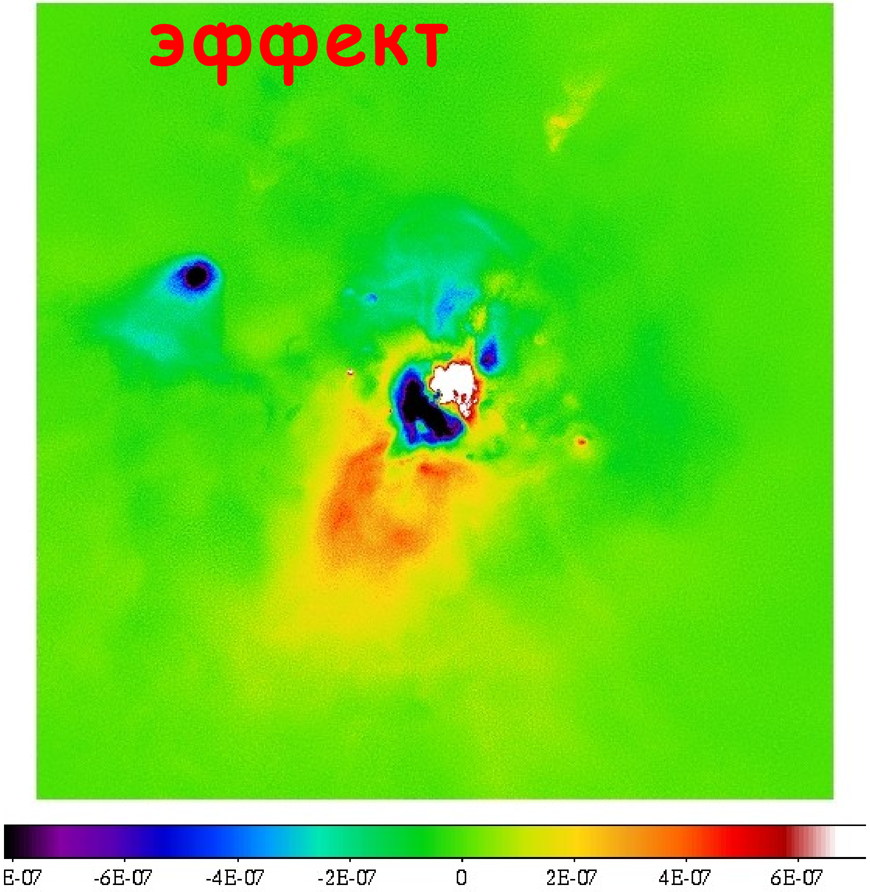
2 deg



Сдвиг



Кин. SZ эффект



$$\Delta E \propto E\int \frac{V}{c}\, n_e^2(z)\,dz$$

$$\mathrm{kSZ} \propto \sigma_T \int \frac{V}{c}\, n_e(z)\,dz$$

Что «хочется» обнаружить

MHD TURBULENCE IN THE SOLAR WIND 285

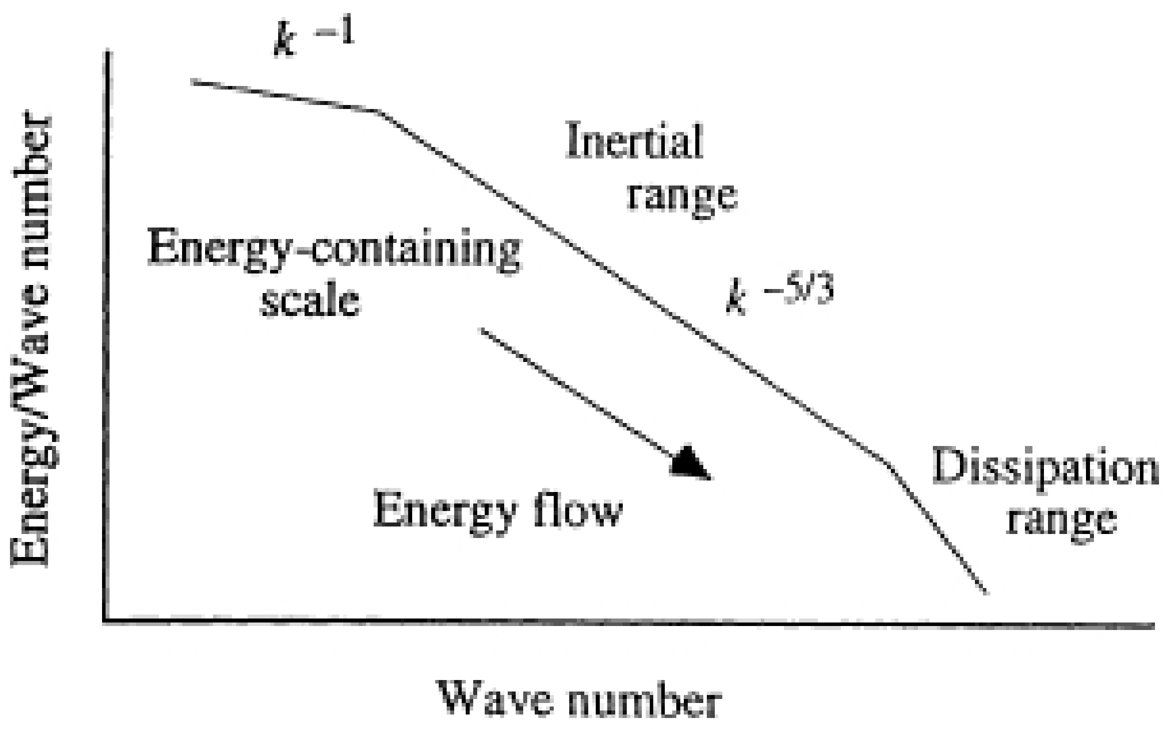
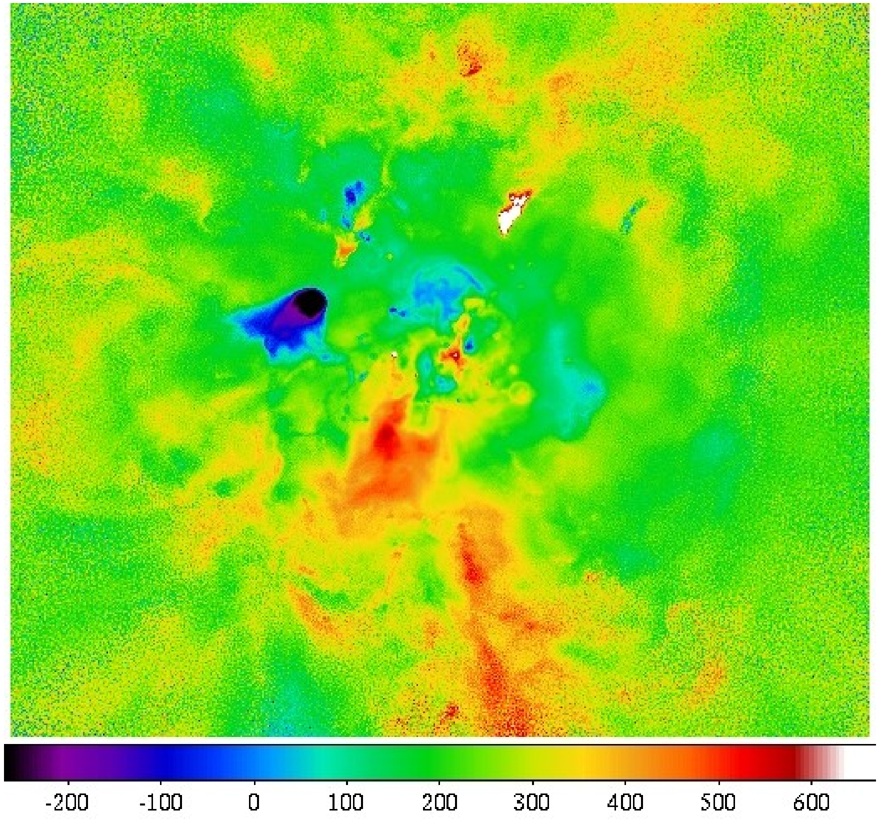


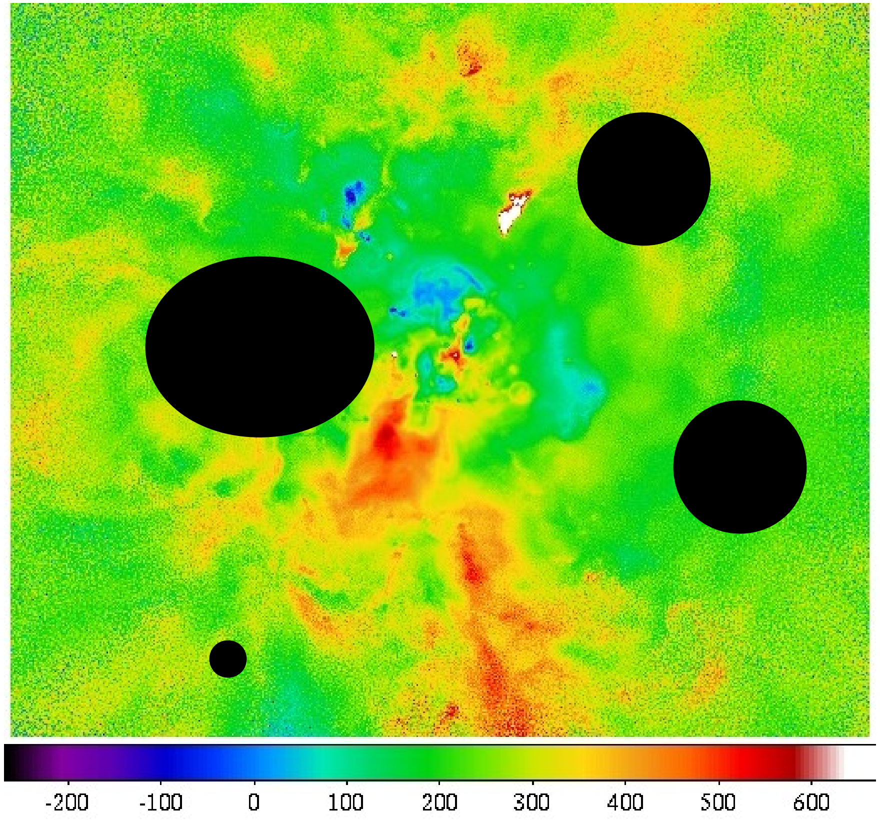
Figure 1 A schematic representation of a power spectrum of either magnetic fluctuations or fluctuations of the total energy of solar wind fields.

Плавный континнуум (без особых деталей)

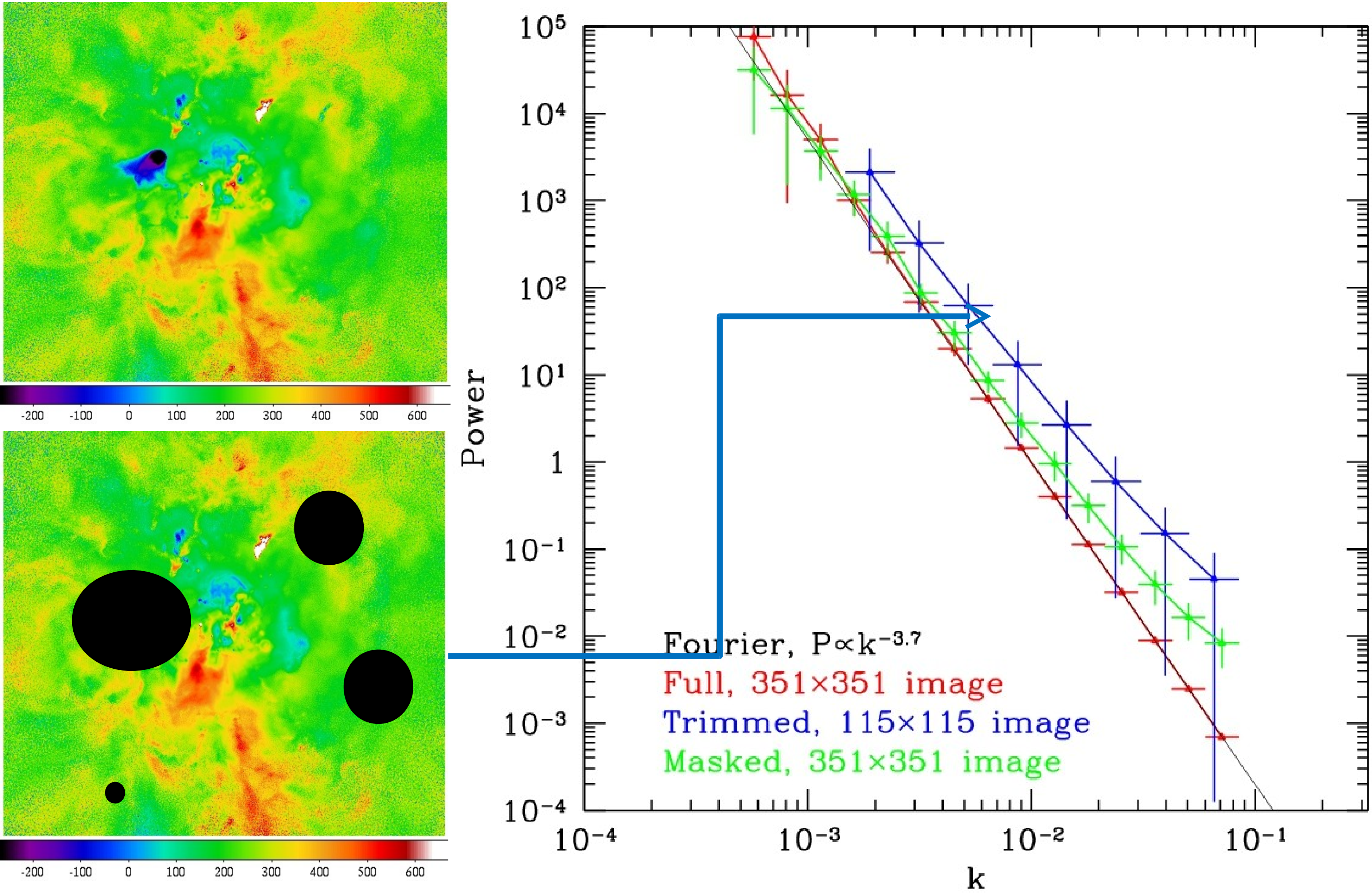
Вычисление спектра мощности для данных с дырками (например, спектр мощности поля скоростей)

1. Непериодическая функция
2. Дырки в данных (точечные источники и т.п.)



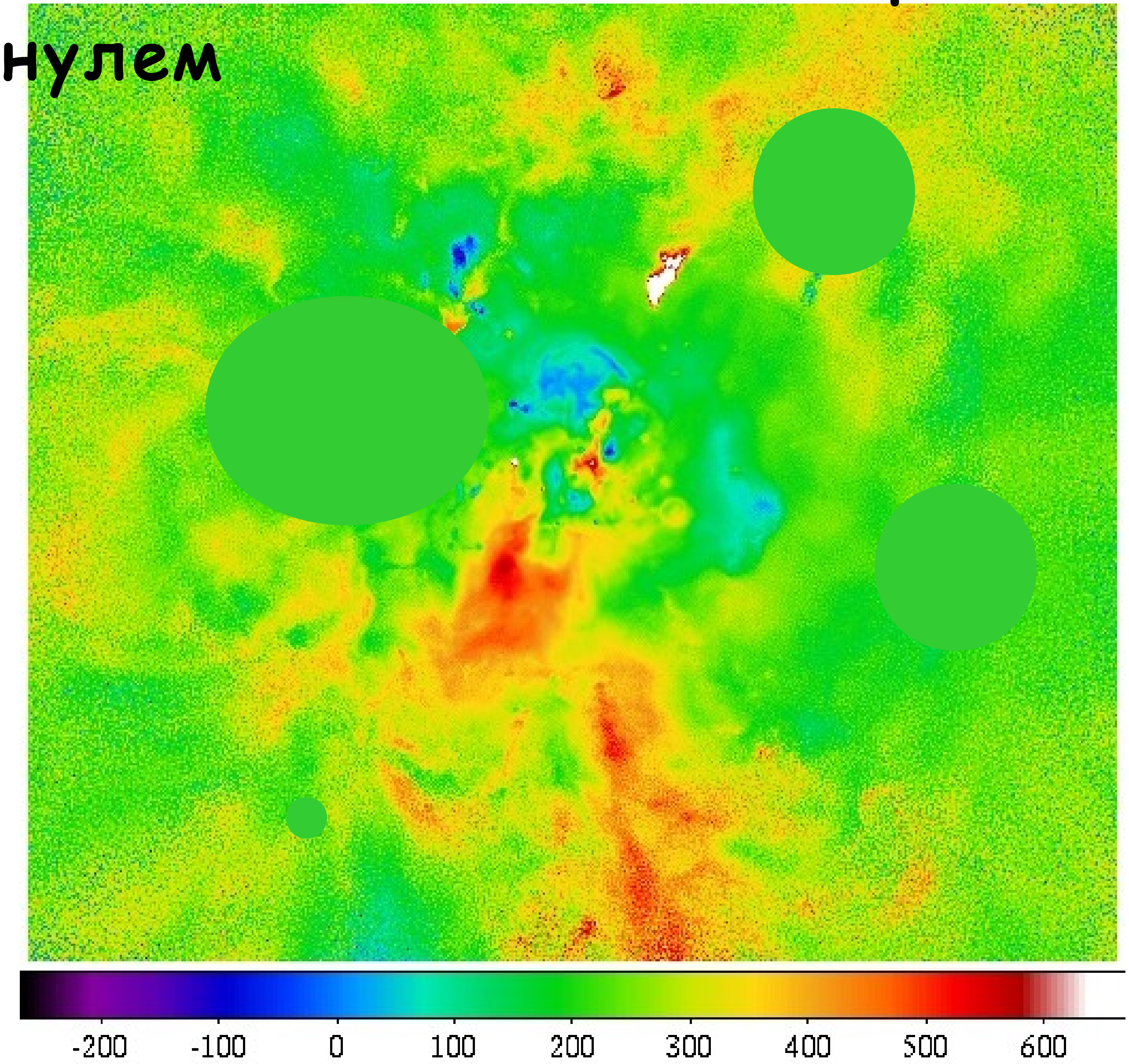


Стандартное преобразование Фурье «настроено» на периодический сигнал без дыр.

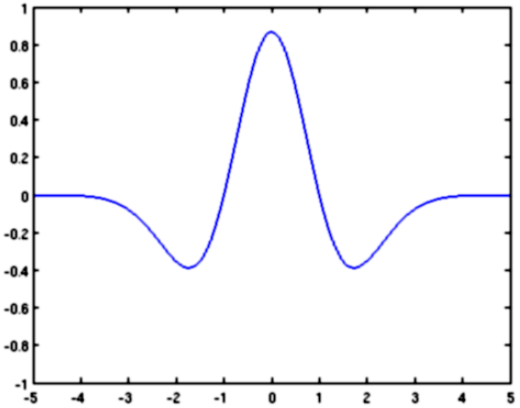


Неправильный наклон и нормировка

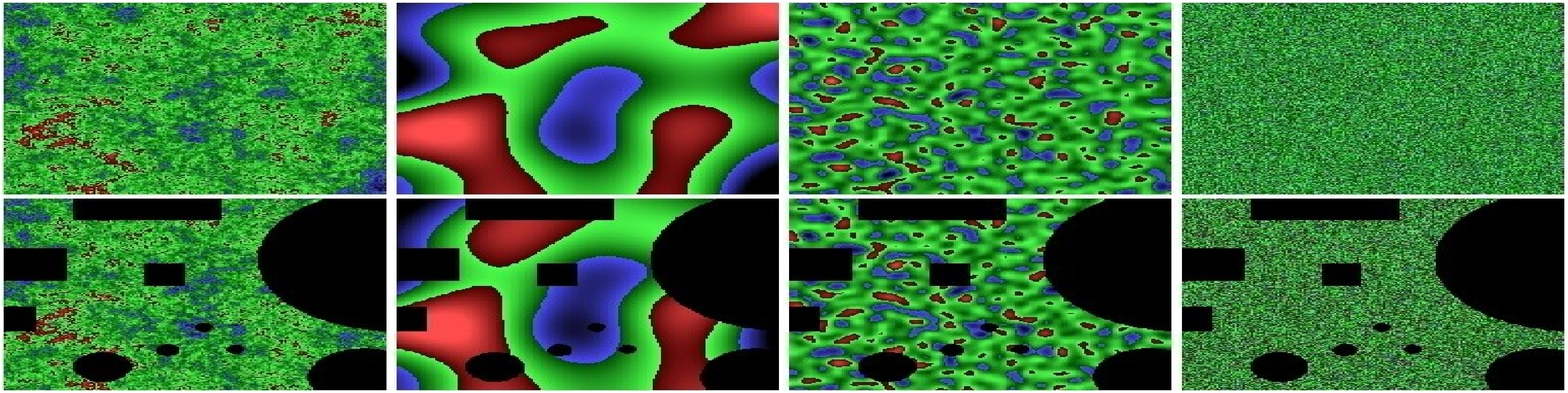
Окно Ханна + замена дыр нулем



Построение спектра низкого разрешения с помощью Вайвлетов (Arevalo et al, submitted, see also Stutzki et al)



$$\left[1-\frac{x^2}{\sigma^2}\right]e^{-\frac{x^2}{2\sigma^2}}$$

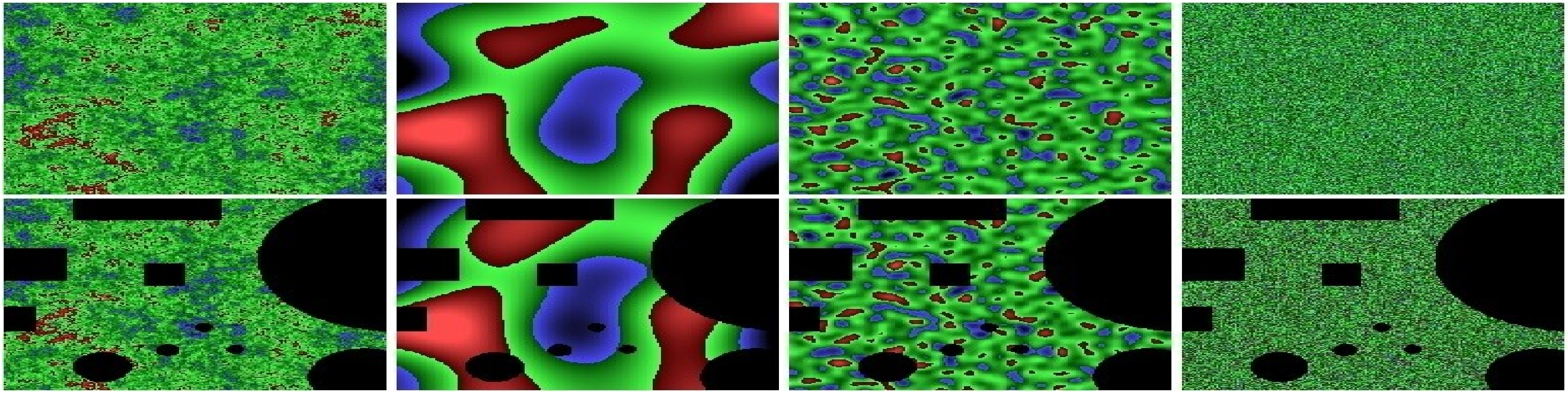


Большая σ

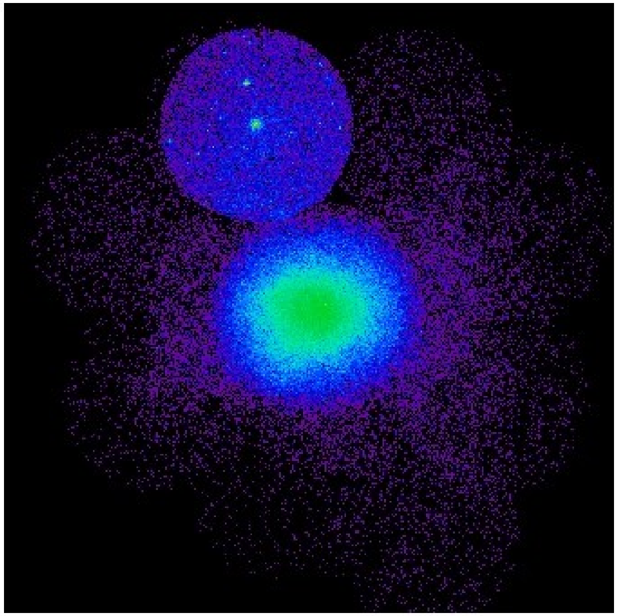
Маленькая σ

1. Свертка с МН фильтром разной ширины
2. Подсчет RMS = мощность на данном масштабе

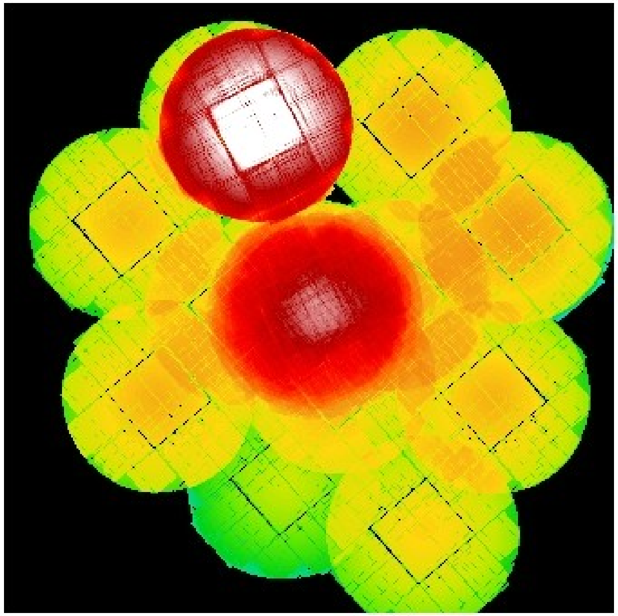
Построение спектра низкого разрешения с помощью Вайвлетов (Arevalo et al, submitted, see also Stutzki et al)



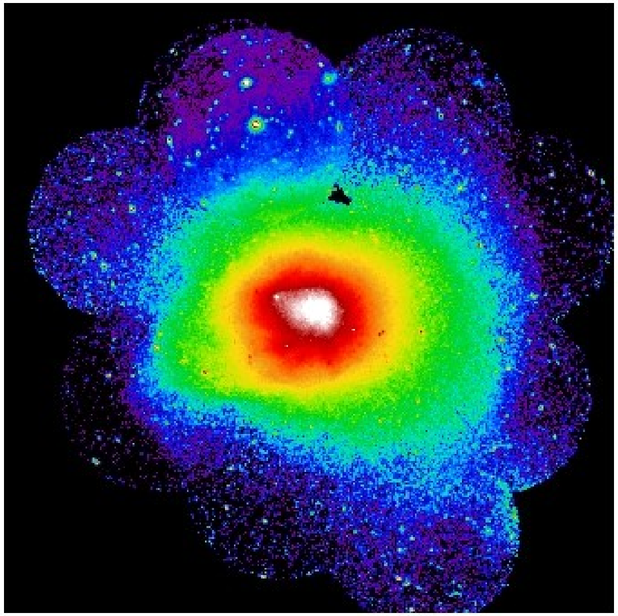
Сглаживание изображений



Сырое изображение



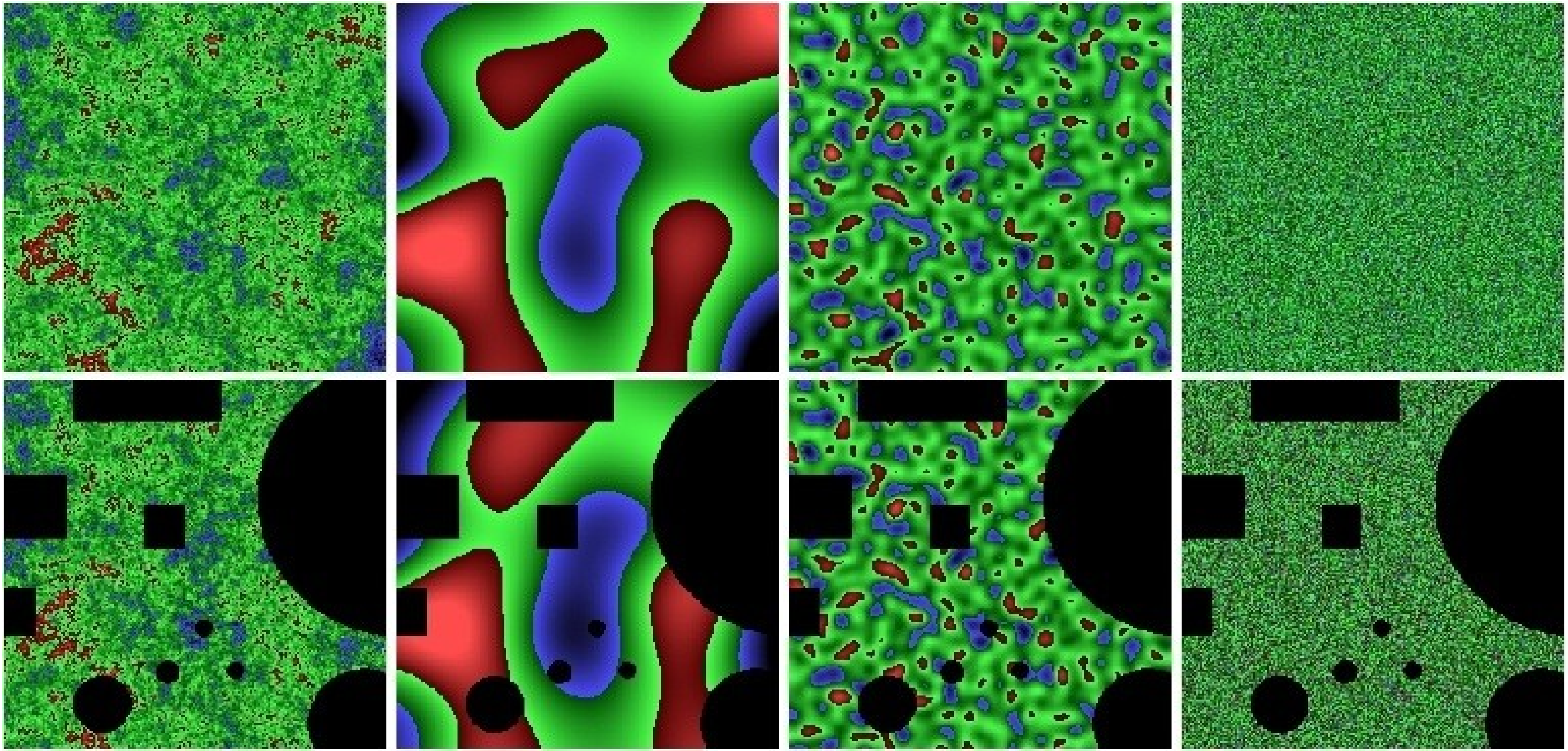
Карта экспозиции



Сглаженное изобр.

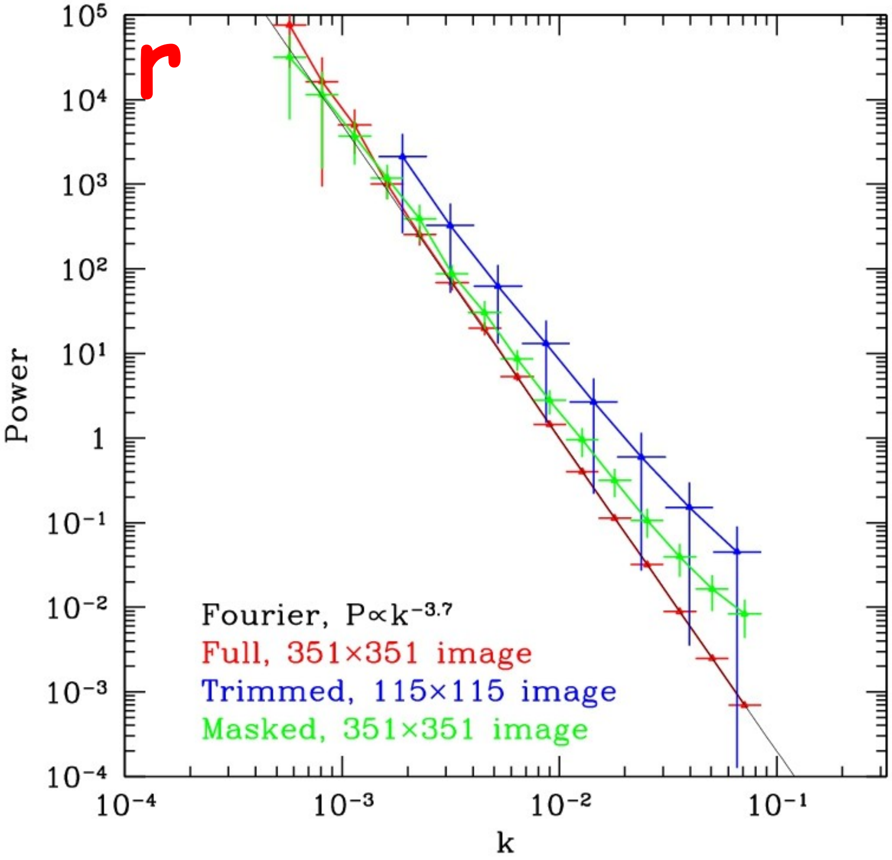
$$G_{\sigma_1} \circ I = \frac{G_{\sigma_1} \circ I}{G_{\sigma_1} \circ M}$$

Что делать с краями и дырами?

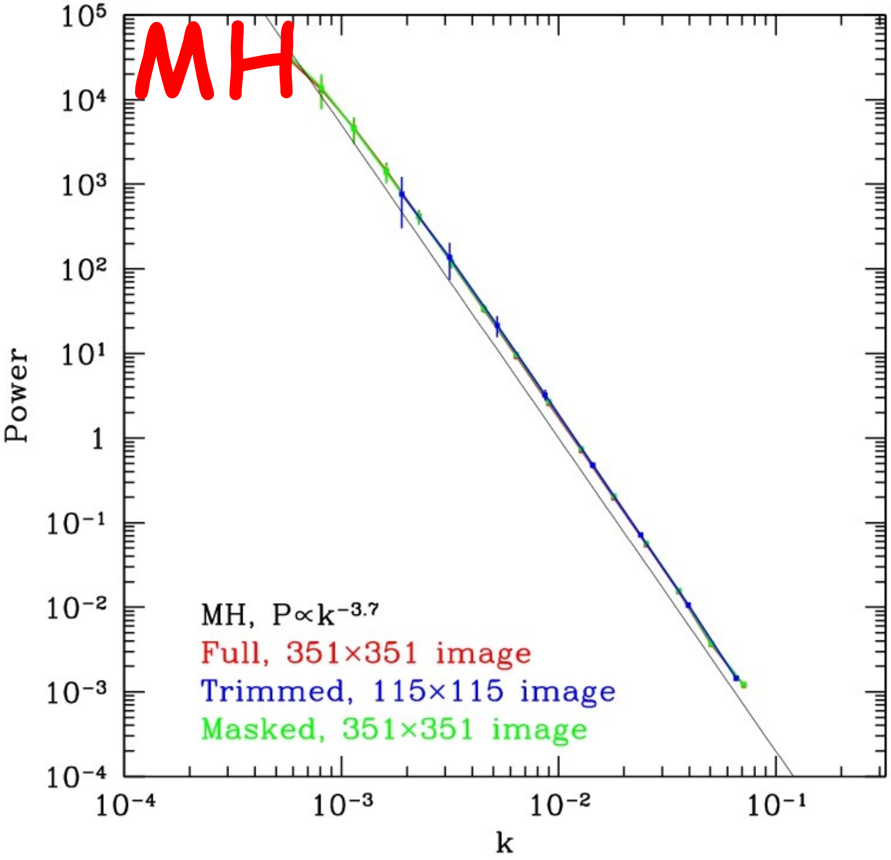


2D

Fourier

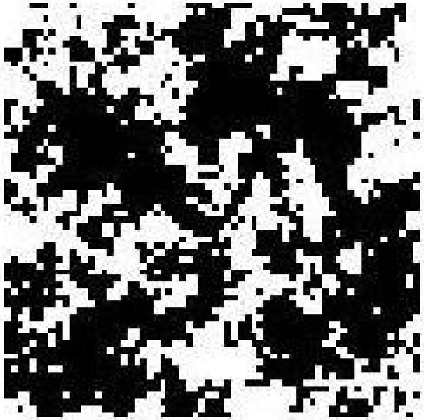


Modified MH

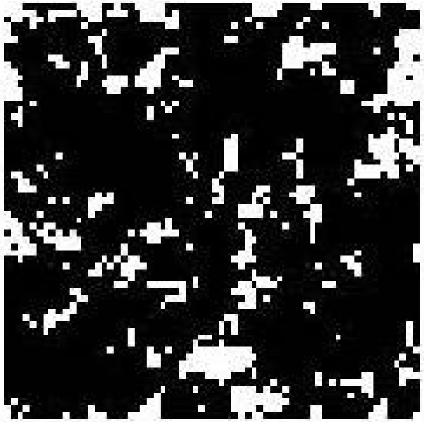


Arevalo, EC, Zhuravleva, Hernandez, Revnivtsev, 2011

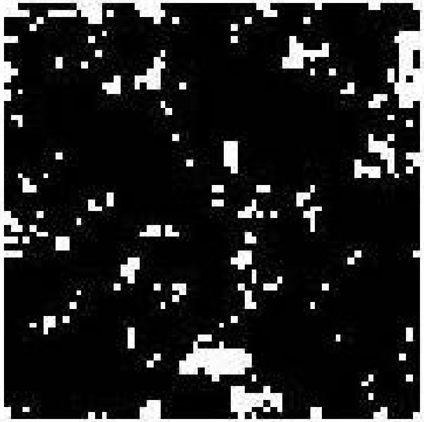
3D данные - v(x,y,z)



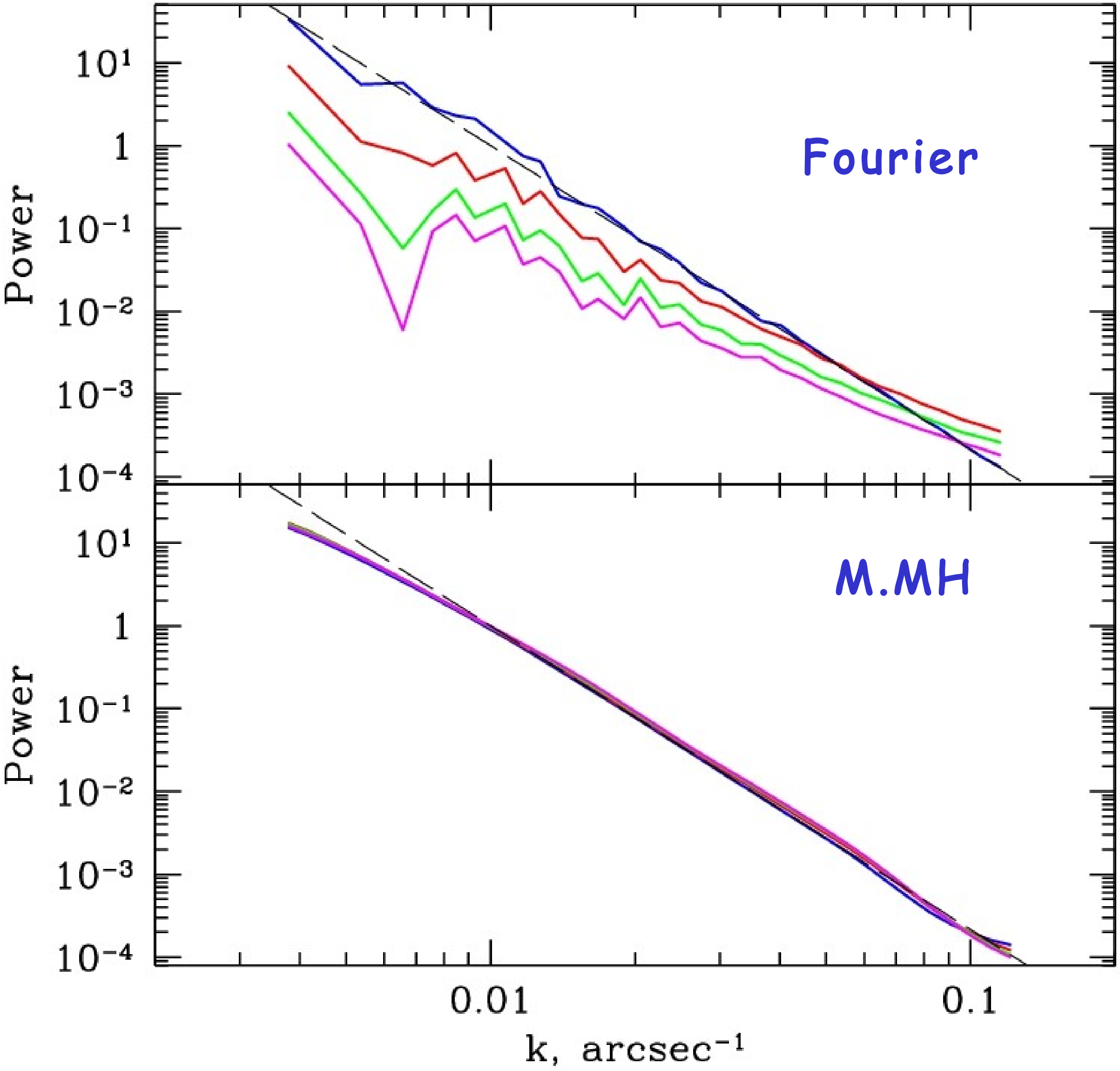
50%



75%



85%



Arevalo, EC, Zhuravleva, Hernandez, Revnivtsev,

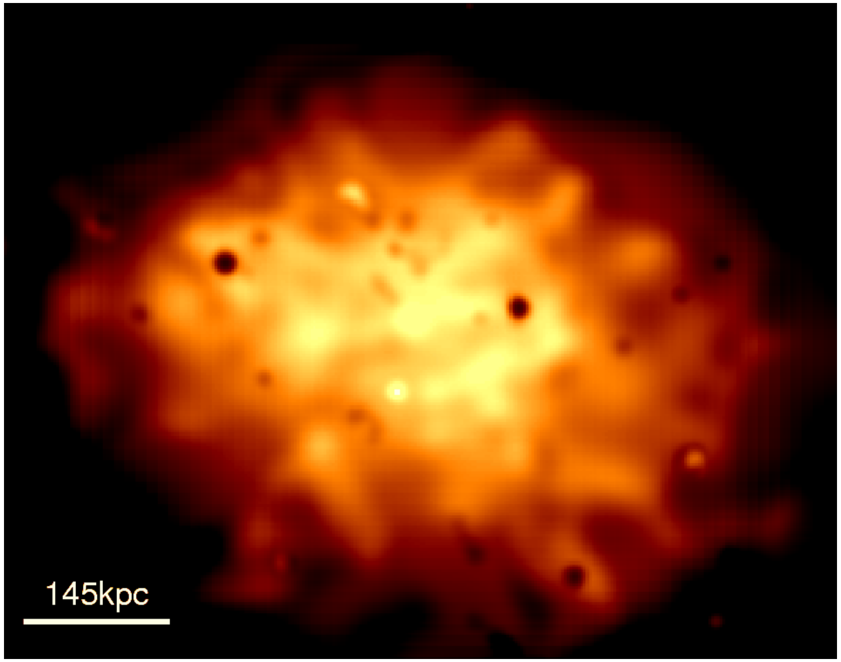
Выводы

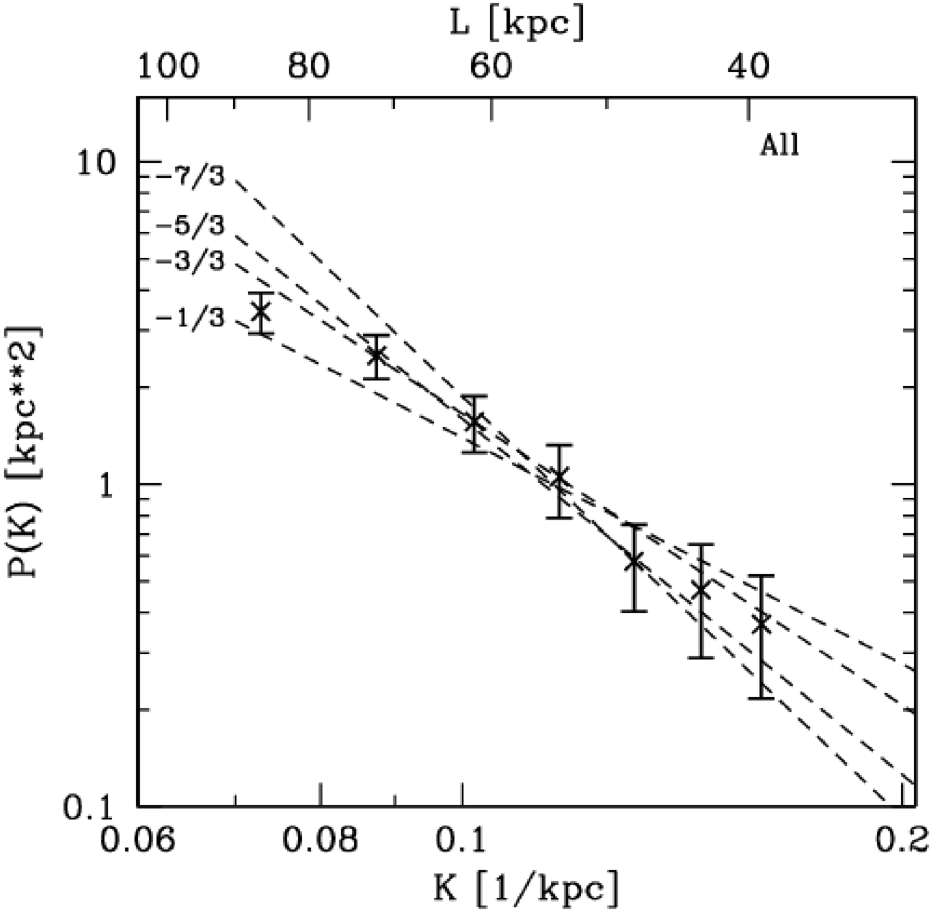
Есть еще 3 года для построения спекулятивных теорий (до ASTRO-H)

Несколько независимых методов измерения скоростей + численные расчеты

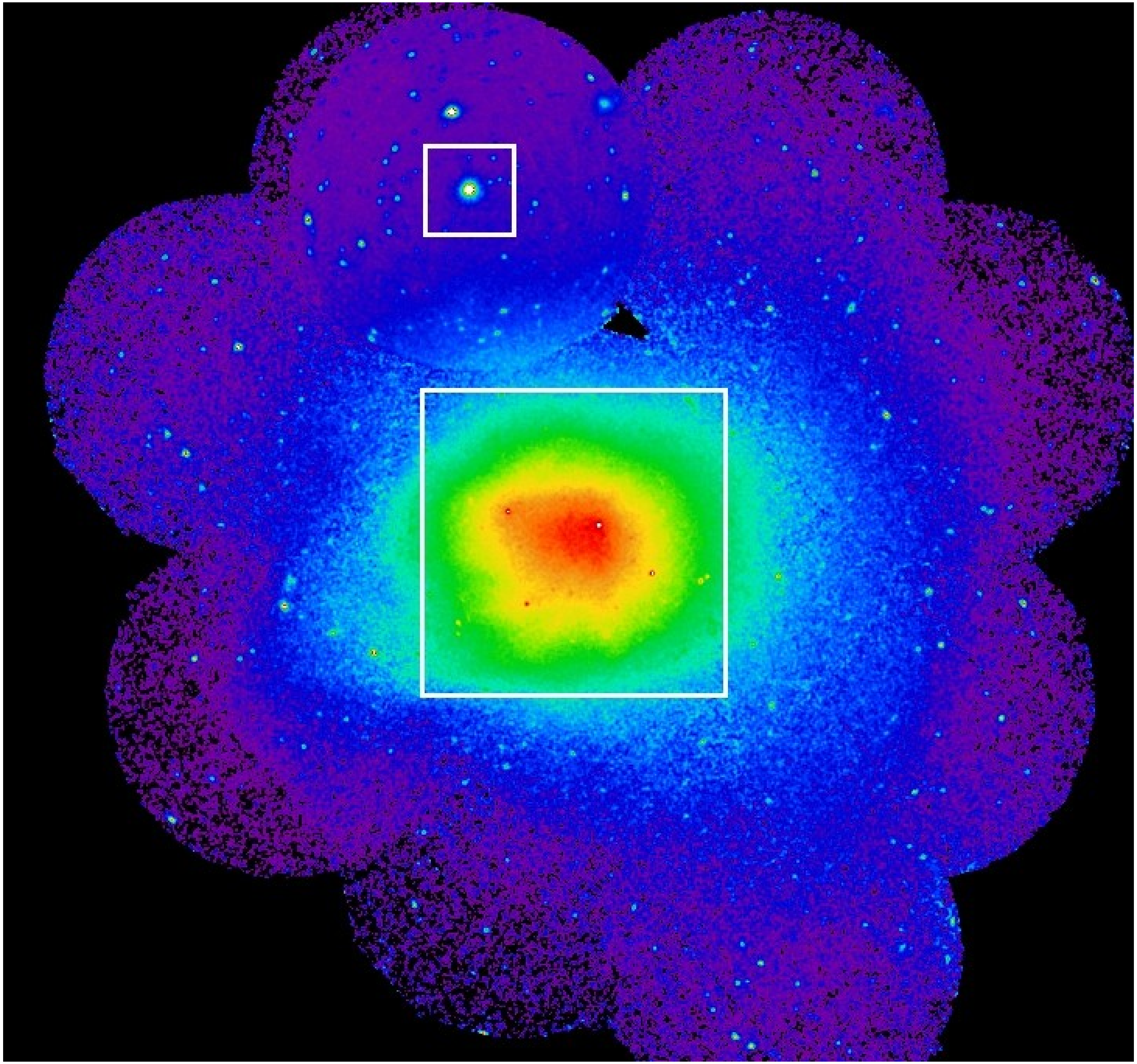
Простое решение технических проблем построения спектров мощности низкого разрешения

Pressure fluctuations in Coma

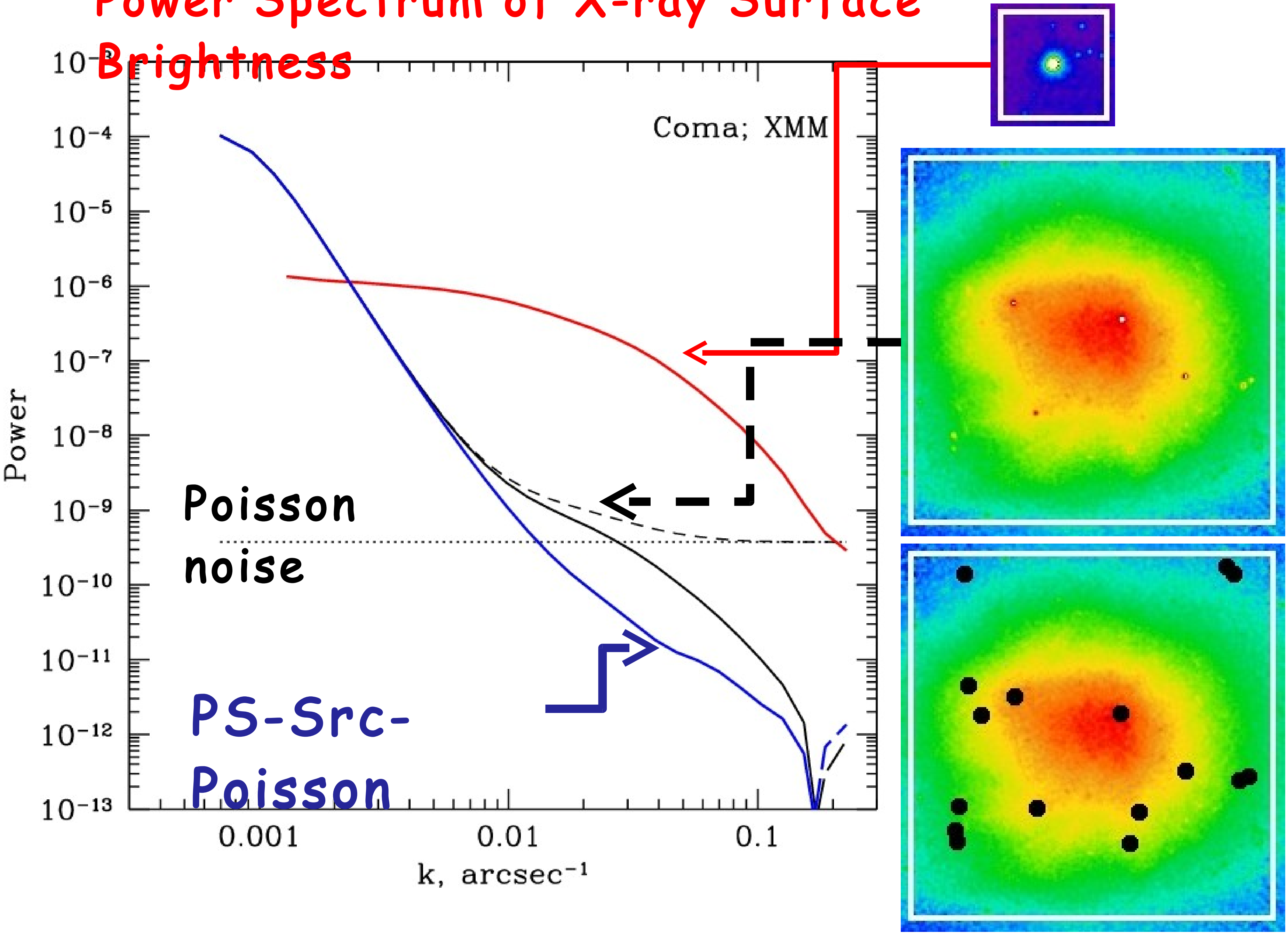




Schuecker et al. (2004)



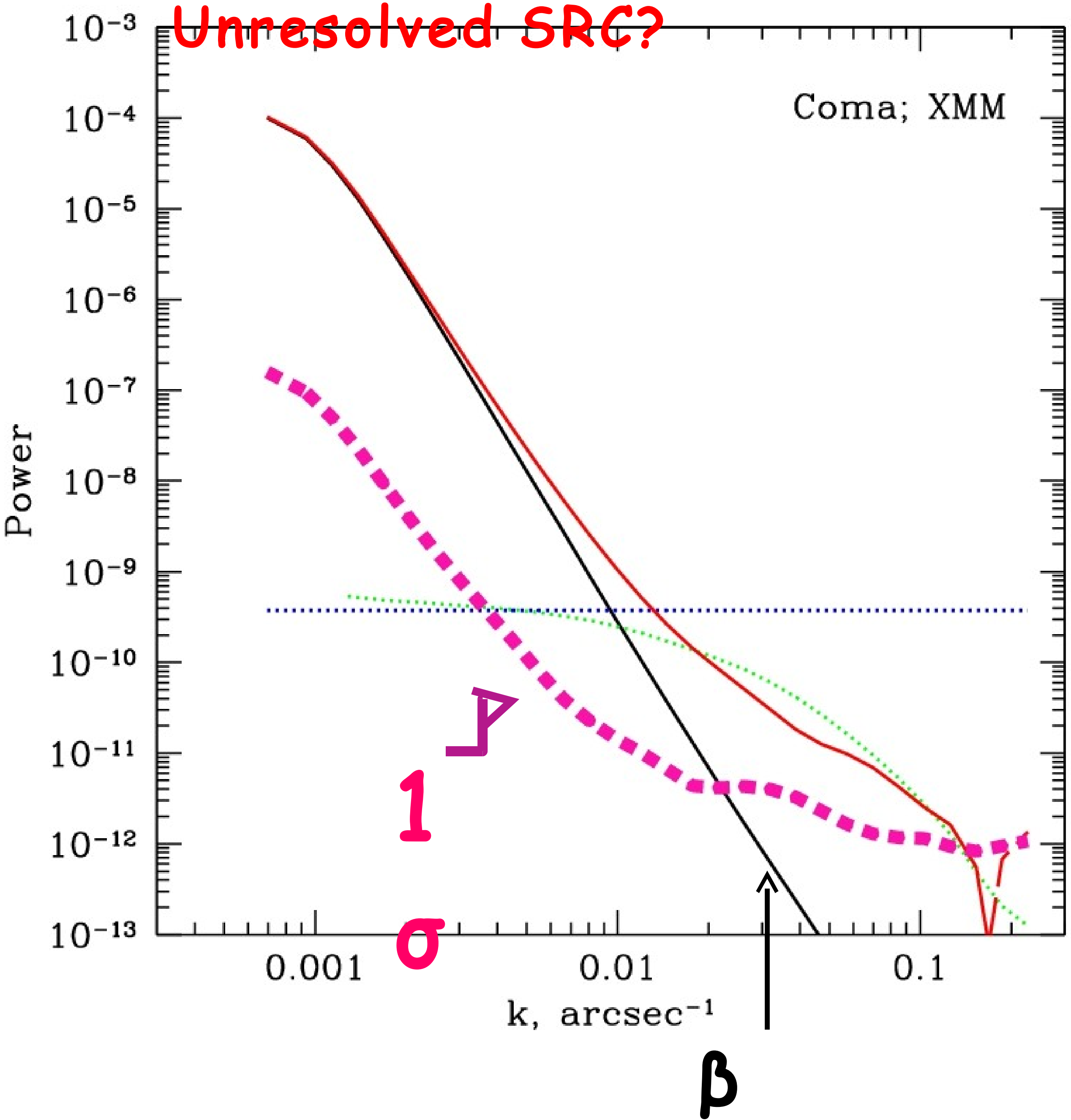
Power Spectrum of X-ray Surface Brightness

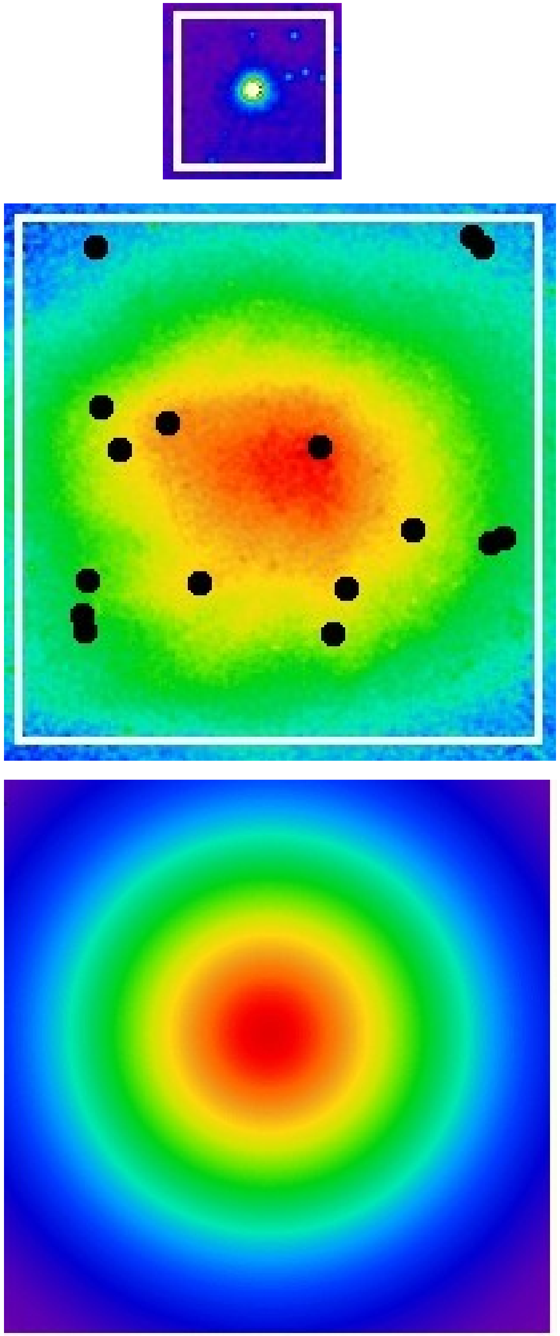


Poisson noise

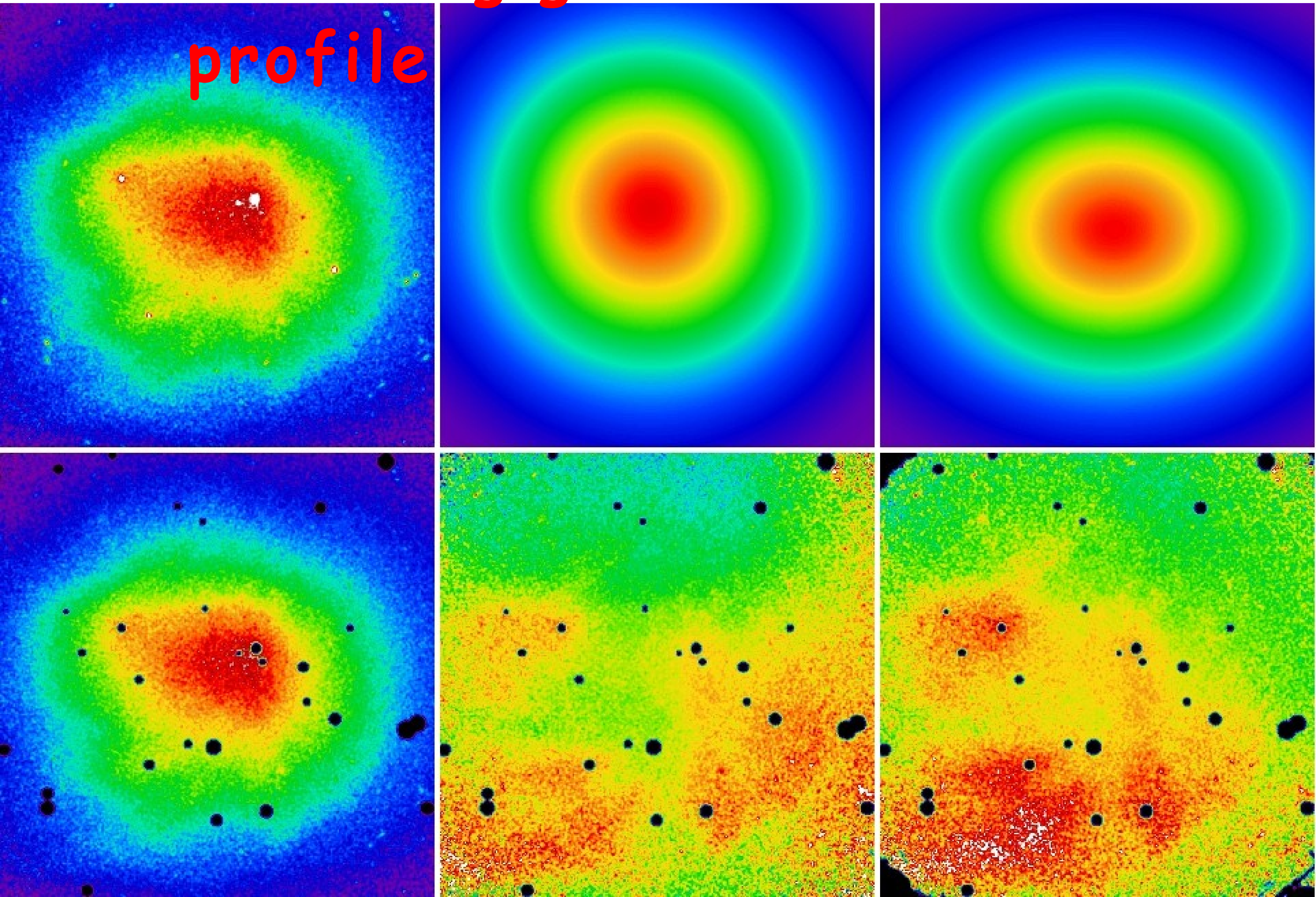
PS-Src-Poisson

Coma=Beta Model + Unresolved SRC?

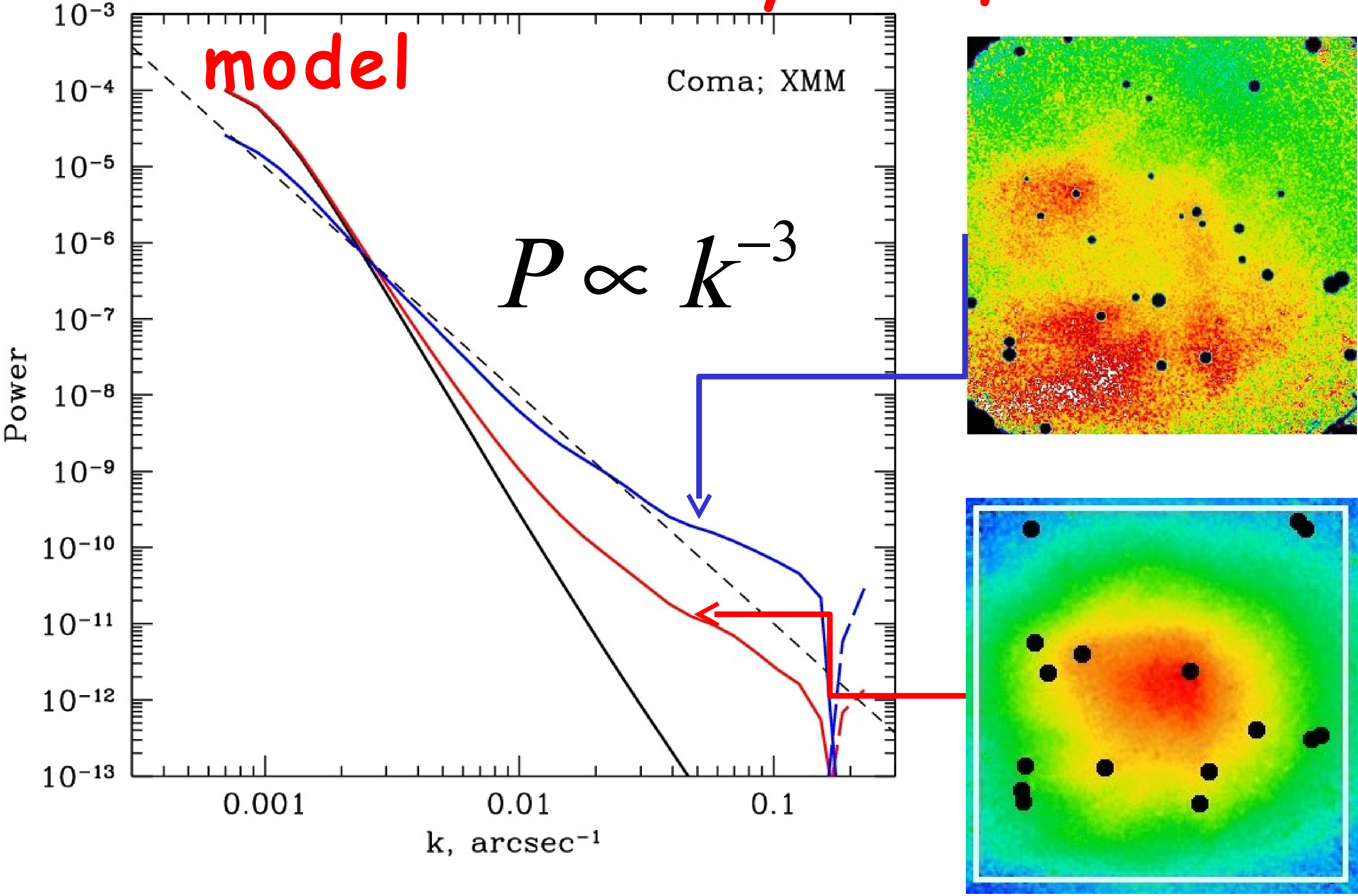




Removing global Coma profile



Coma divided by the β model

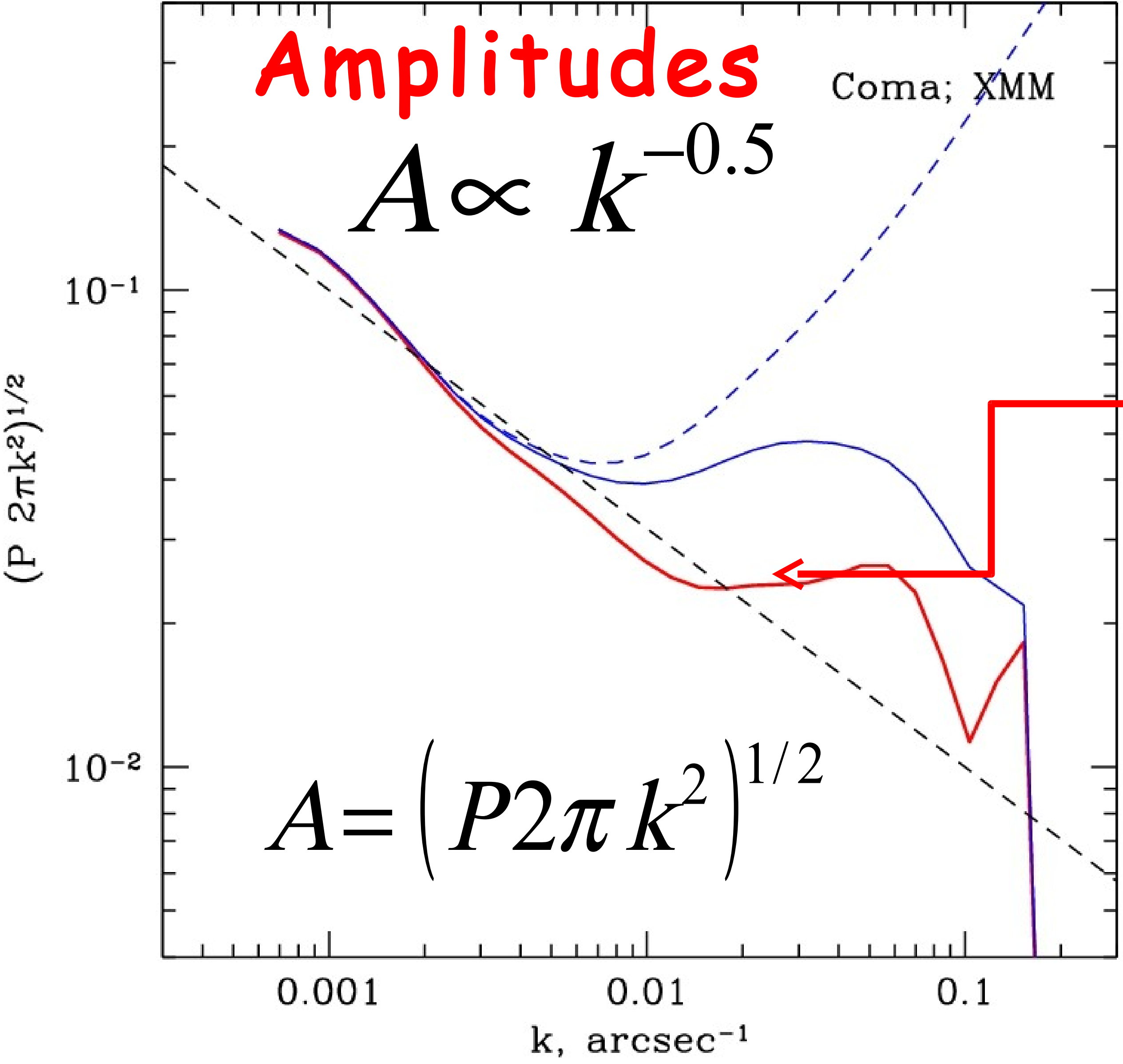


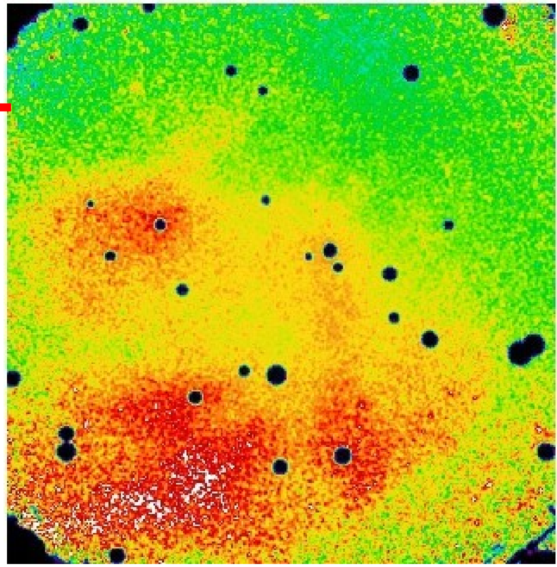
$$P \propto k^{-3}$$

Converting to Amplitudes

$$A \propto k^{-0.5}$$

$$A = \left(P 2\pi k^{2}\right)^{1/2}$$





Relating 3D and 2D power spectra

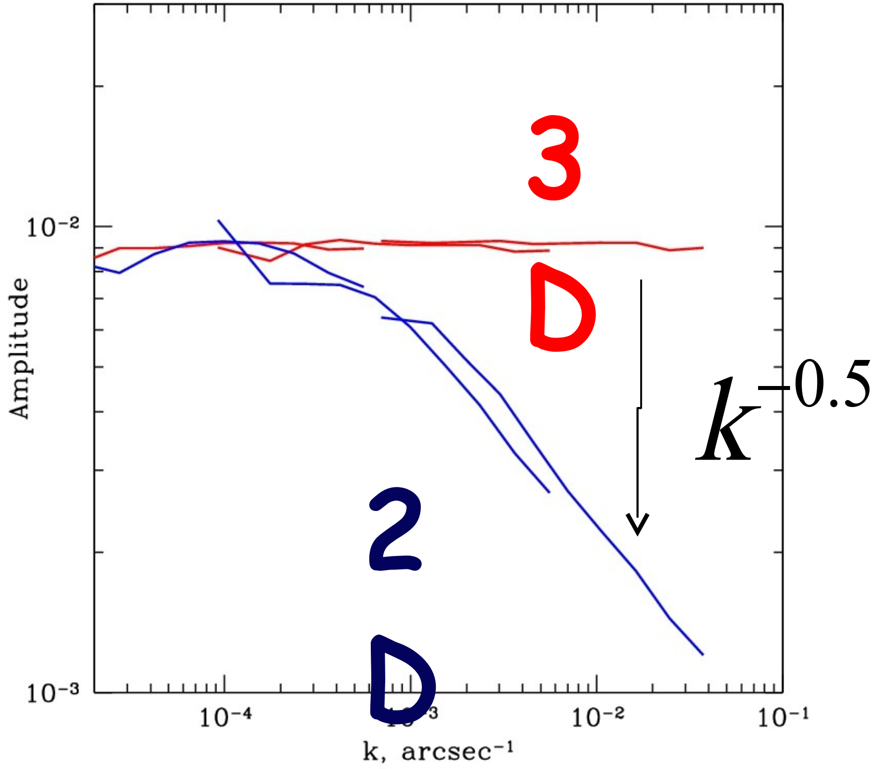
$$I(x,y)=\int\delta(x,y,z)\,n_e^2(x,y,z)\,dz$$

$$P_{2D}(k)=\int P_{3D}\left(\sqrt{k^2+k_z^2}\right)W(k_z)\,dk_z$$

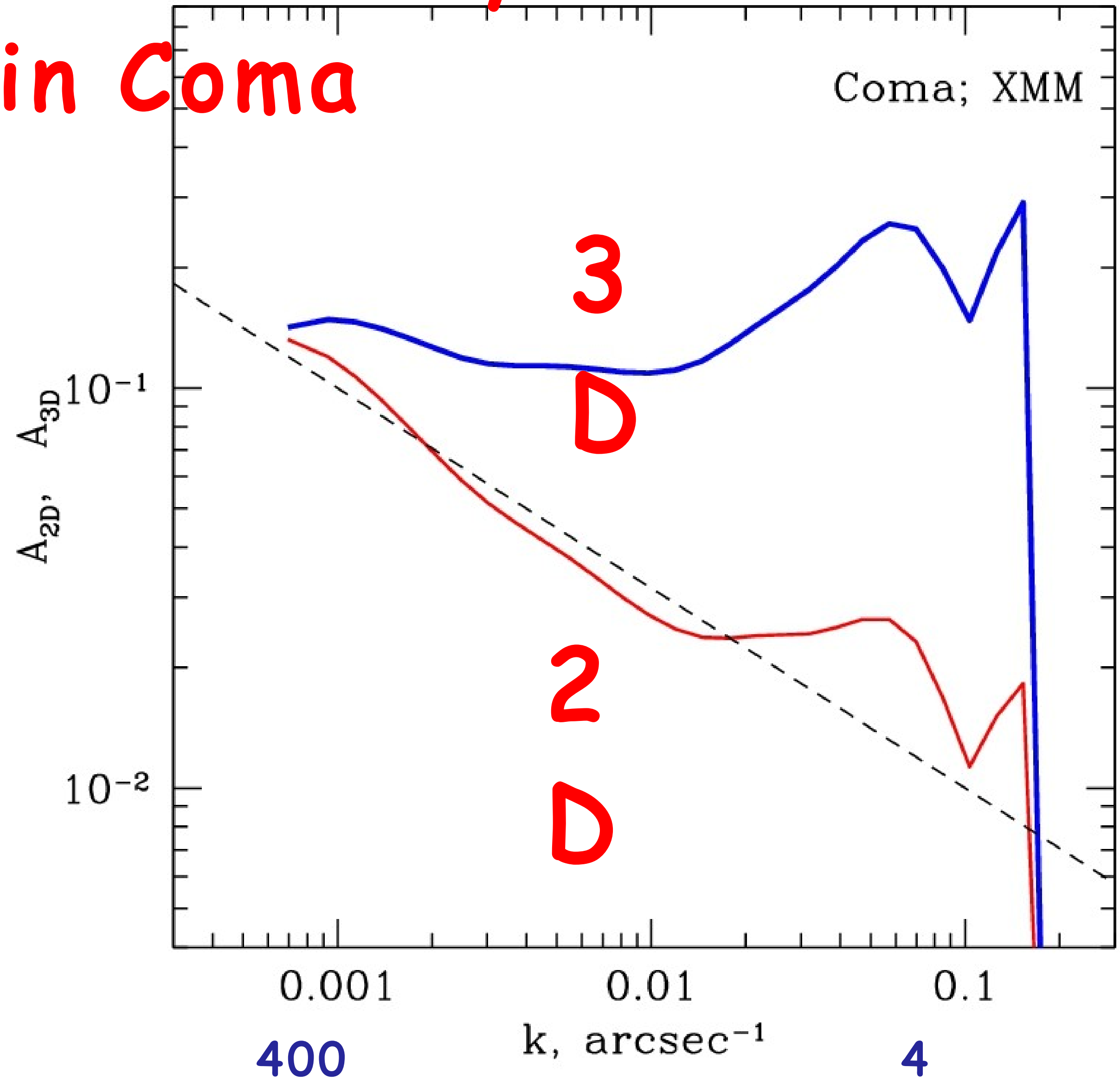
$$W=P_1[n_e^2(z)]$$

$$k\gg\frac{1}{l_z}\Rightarrow P_{2D}=aP_{3D}$$

$$k\ll\frac{1}{l_z}\Rightarrow P_{2D}=aP_{3D}\times k$$

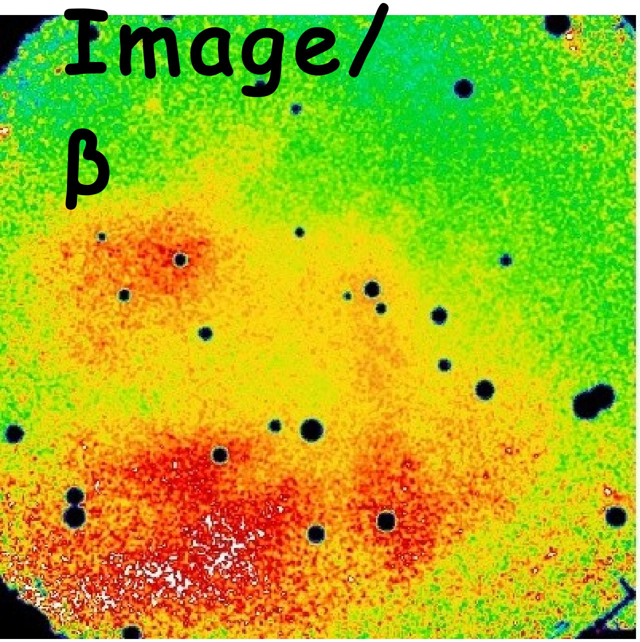


3D Density fluctuations in Coma

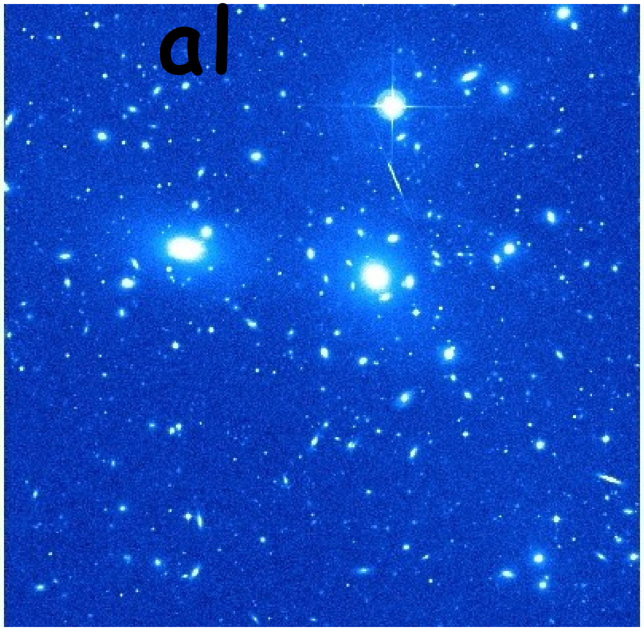


Density fluctuations ~5-10% on

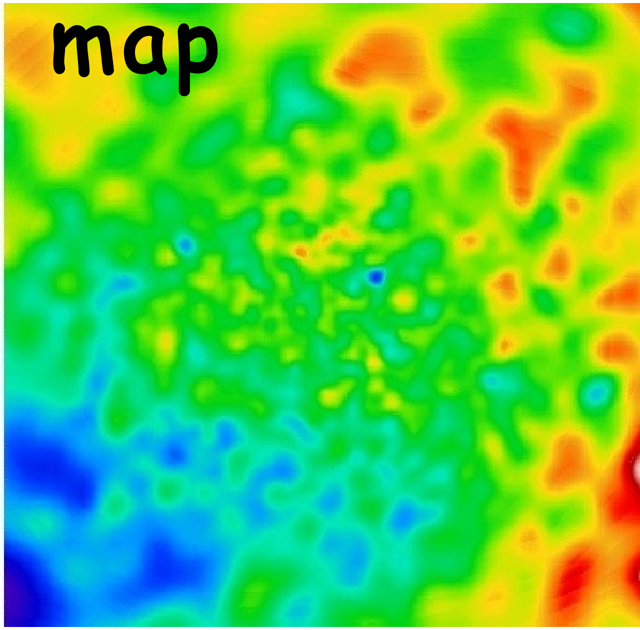
X-Image/β



Optical



Gas T-map



~5-10% density fluctuations include (4-400 kpc):

potential perturbation (big galaxies)

Stars: Jeans equation [stationary, spherical system]

$$\frac{1}{n_*}\frac{dn_*\sigma_r^2}{dr}+2\frac{\beta}{r}\sigma_r^2=-\nabla\varphi$$

or Schwarzschild's method

Gas: hydrostatic equilibrium [stationary, spherical system]

$$\frac{1}{\rho_{gas}}\frac{dP_X}{dr}=-\nabla\varphi_X$$

$$P_X=nkT$$

$$\varphi_X(r)\approx\alpha\,\varphi_{true}(r),\qquad \alpha\leq 1$$

Спектры мощности движений газа в скоплениях галактик

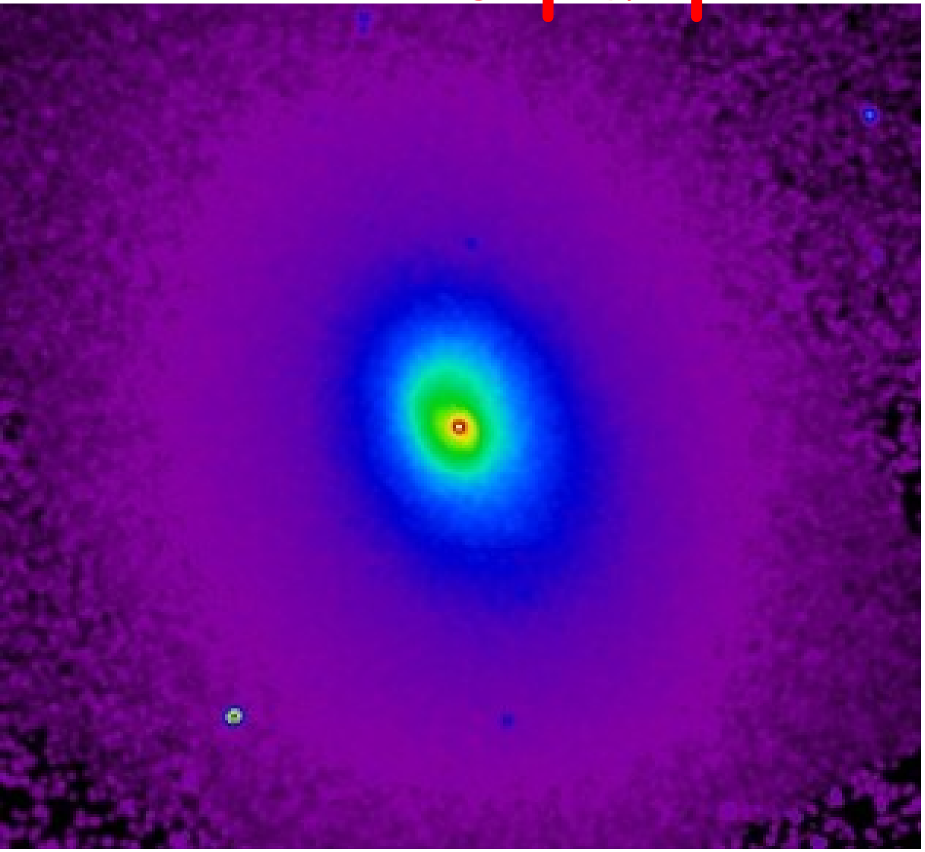
Е.Чуразов, И.Журавлева, Р.Сюняев, К.Долаг,
С.Цыганков,К.Постнов, П.Аревало,
Н.Лыскова,
С.Комаров, Л.Иапичино

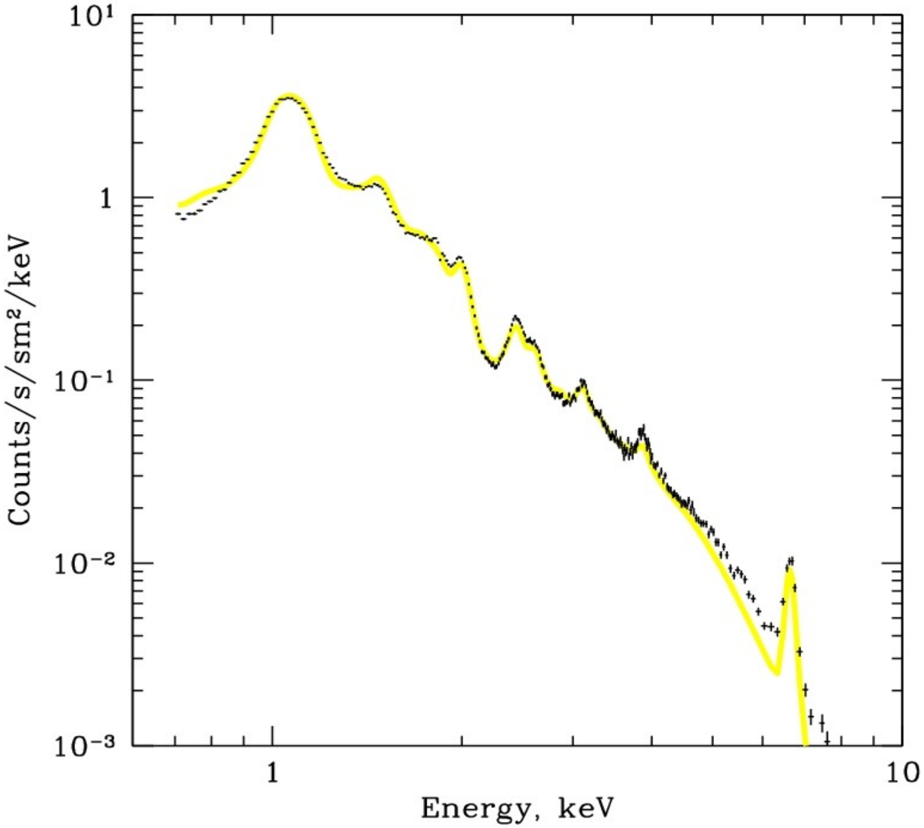
Как измерять скорости газа?

Как считать спектр мощности?

Иногамов, Вихлинин, Кравцов, Маркевич, Финогенов,
Крицук, Sarazin, Norman, Bryan, Vazza, Nagai, Lau,
Chandran, Brueggen, Scannapieco, Ruszkowski, Roediger, Heinz…..

Изображения и энергетические спектры с разрешением 150 эВ





Горячий межгалактический газ

мы знаем:

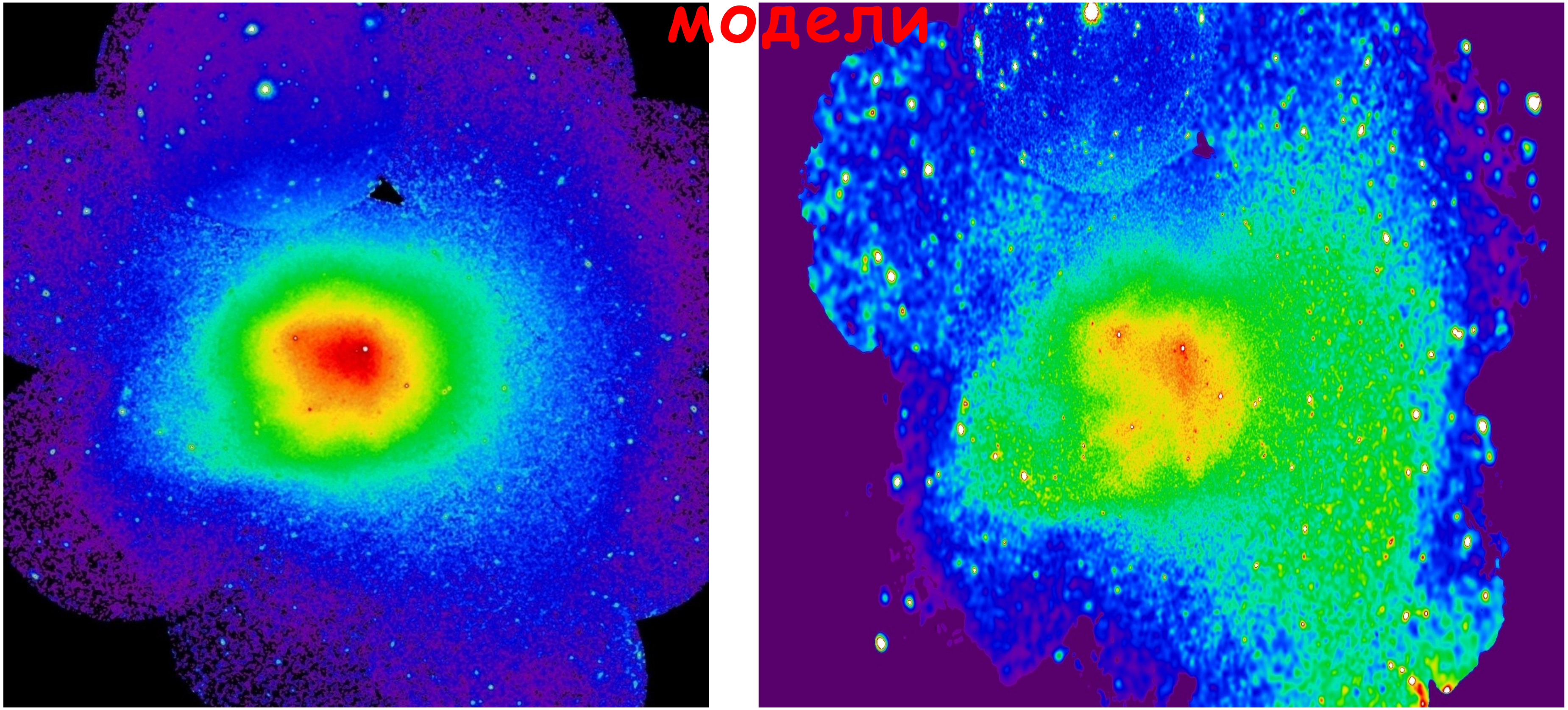
Плотность
Температуру
Обилие

мы не знаем:

Поле скоростей
Теплопроводность
Вязкость
Магнитные поля
Космические лучи

Движения газа - измерение массы, ускорение частиц, генерация магн. полей

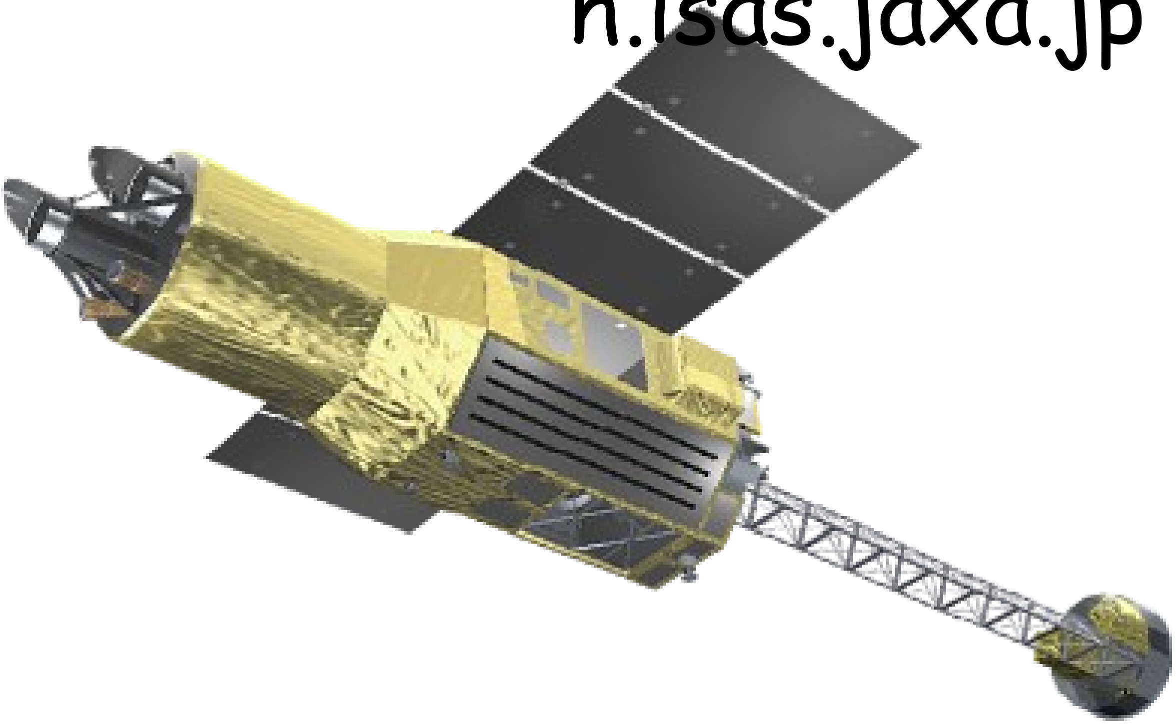
Изображение скопления и отклонения от симметричной модели



Газ обязан двигаться

ASTRO-H

http://astro-h.isas.jaxa.jp



2013

6 м

2.8´x2.8´

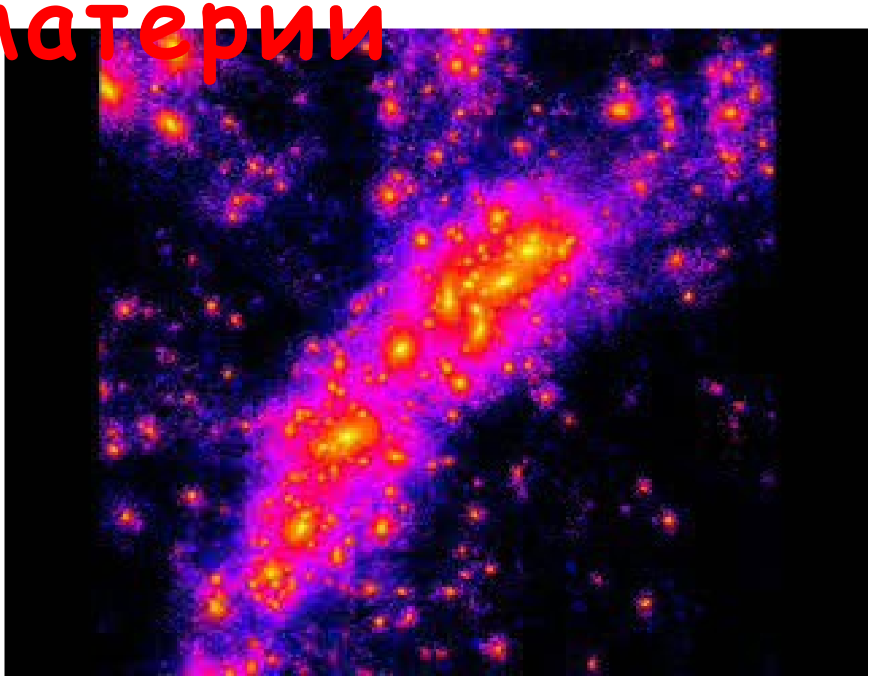
0.48´

5 эВ

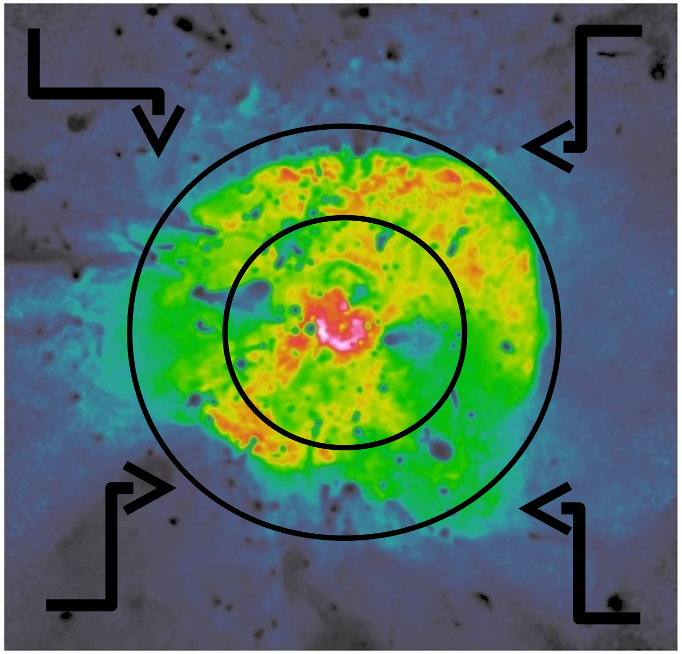
200-300 см2

0.3-12 кэВ

Эволюция темной материи

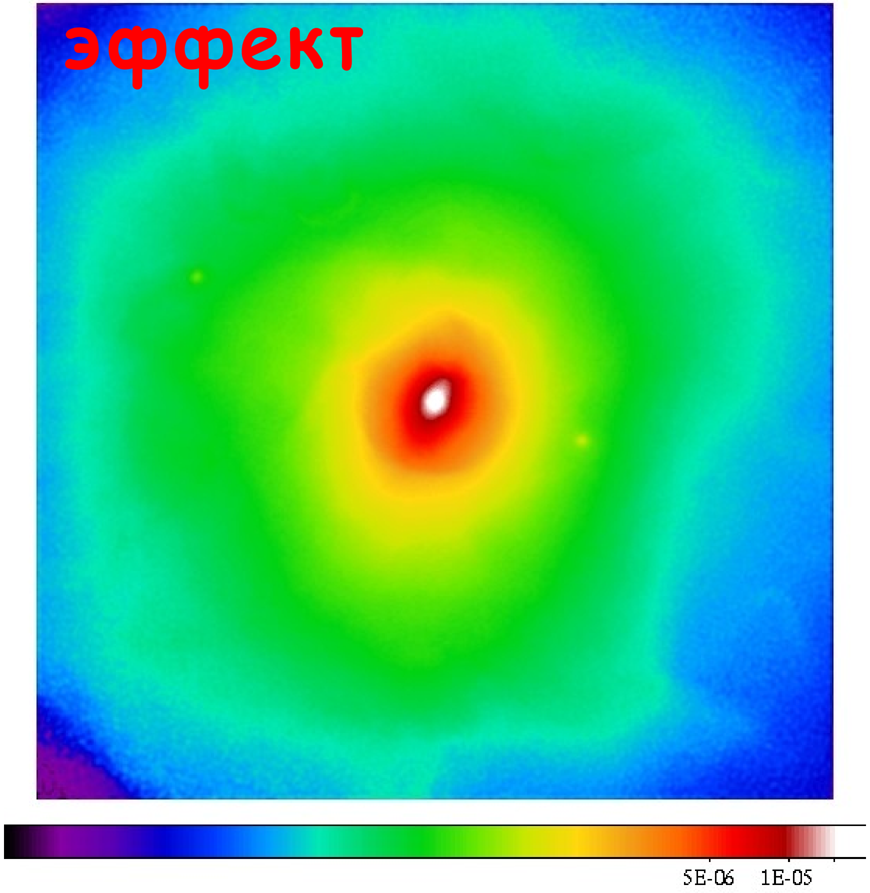


Moore et al.



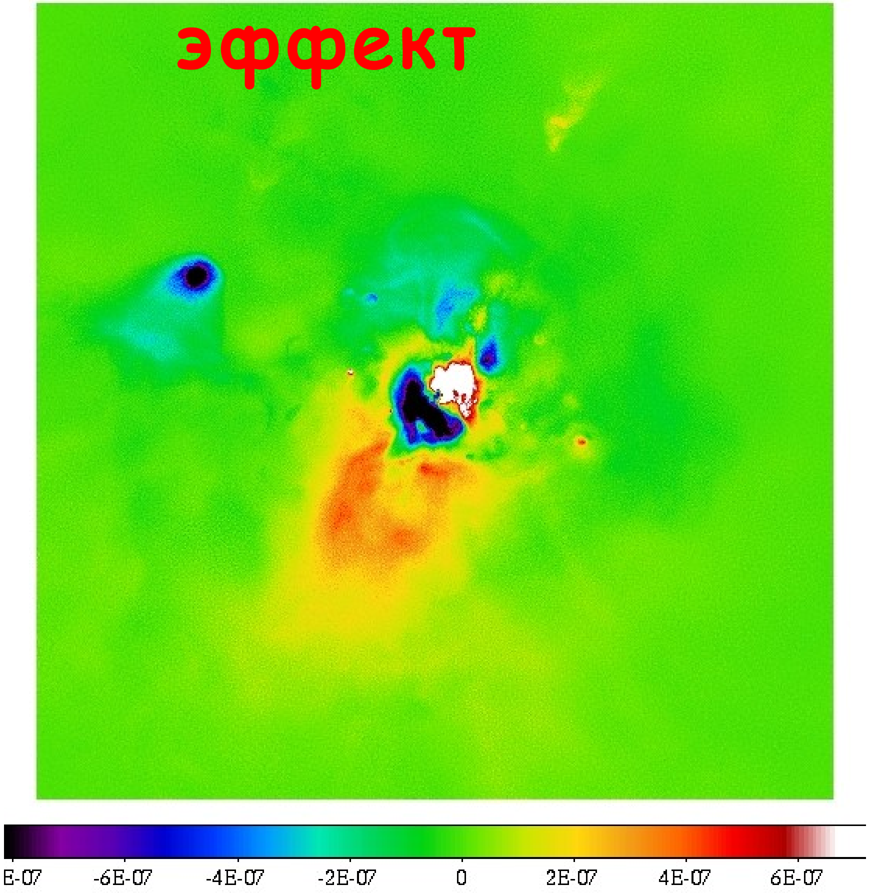
Карта температуры газа

Тепловой SZ эффект



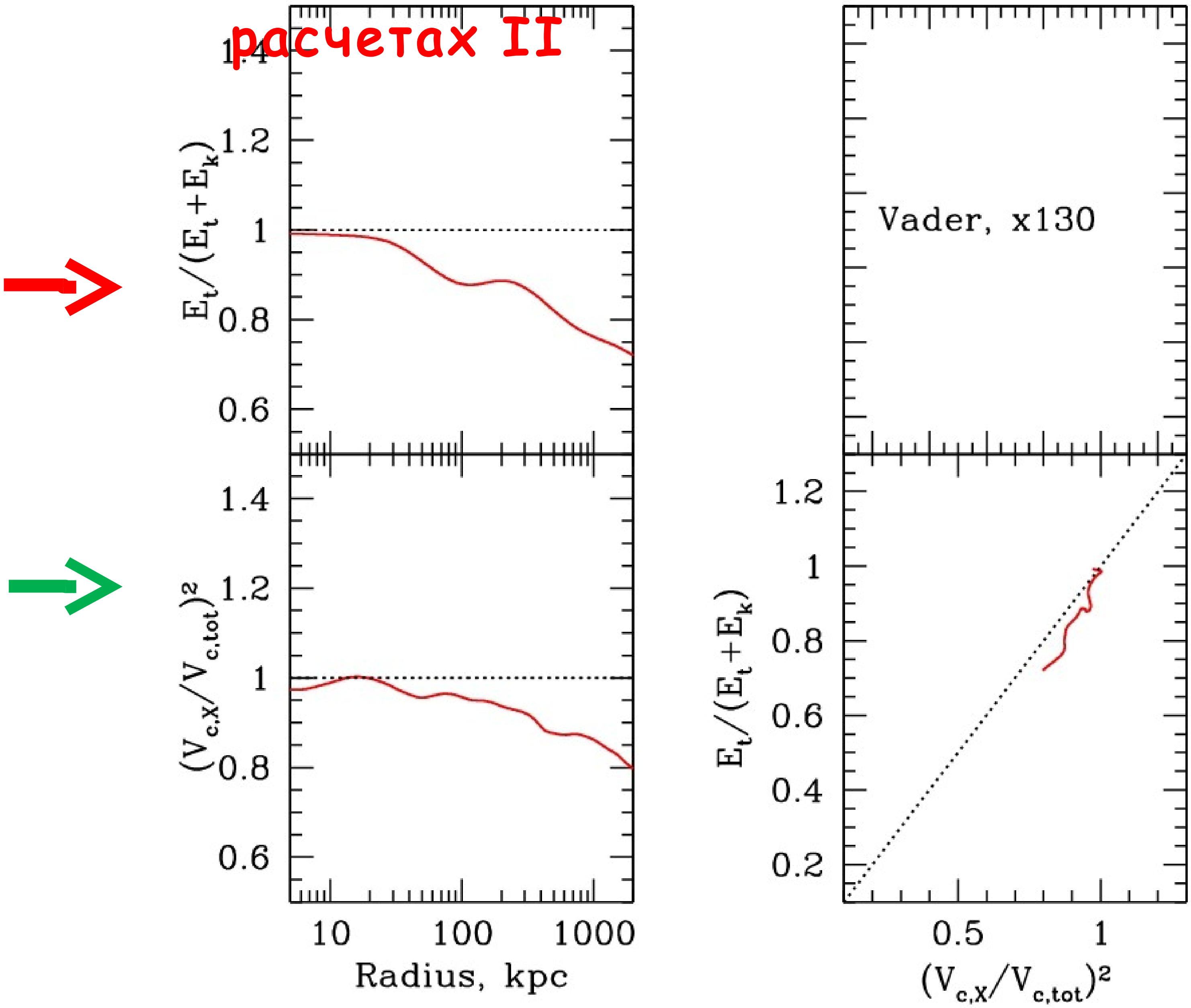
$$\frac{\Delta T_r}{T_r} = 2y = 2\tau_T \frac{kT_e}{m_e c^2}$$

Кин. SZ эффект

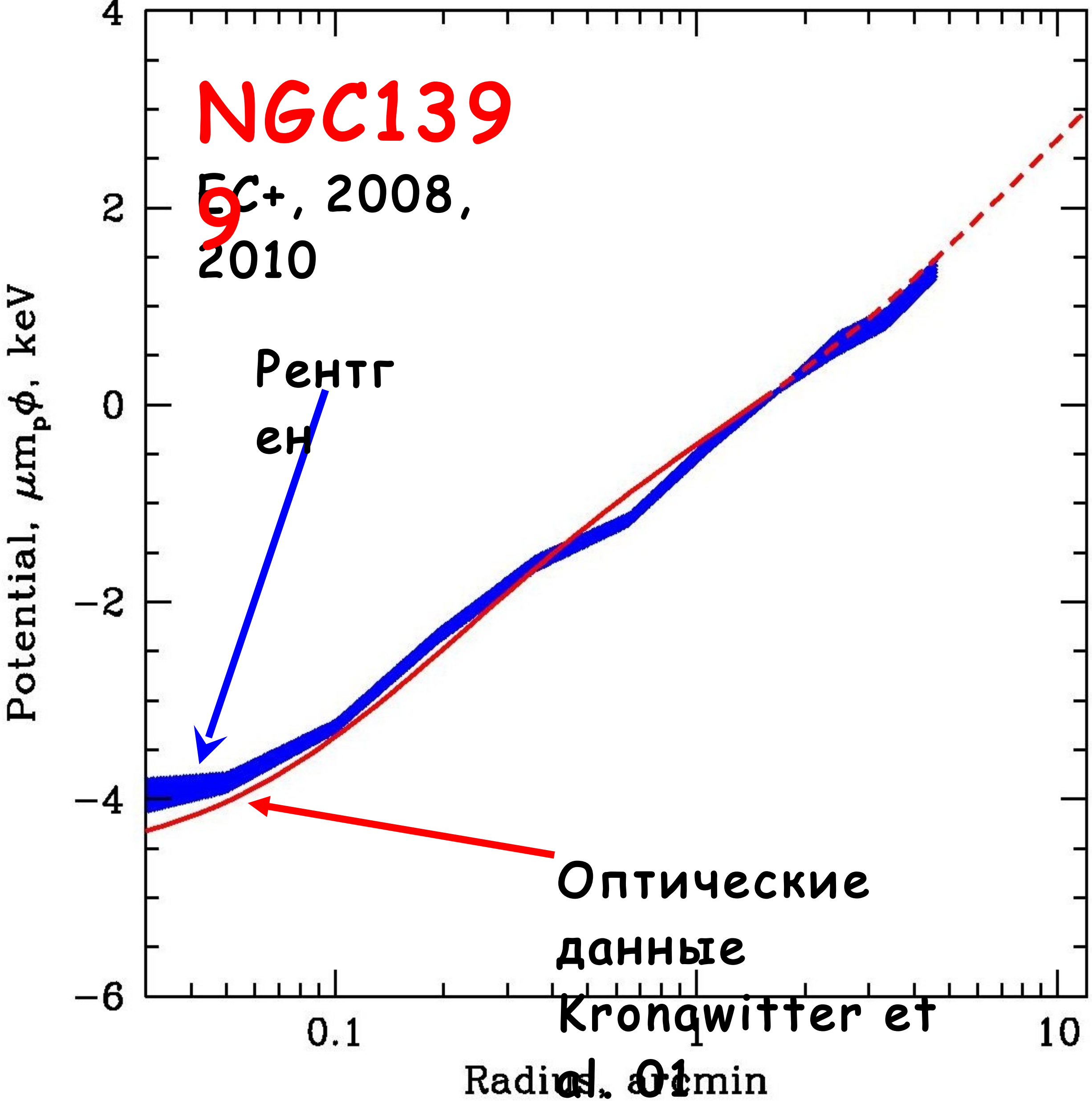


$$\frac{\Delta T}{T_{CMB}} = -\tau_T \left(\frac{v_{pec}}{c} \right)$$

Измерение масс в численных расчетах II



Сравнение оценок массы из рентгеновских и оптических данных



NGC1399

БС+, 2008, 2010

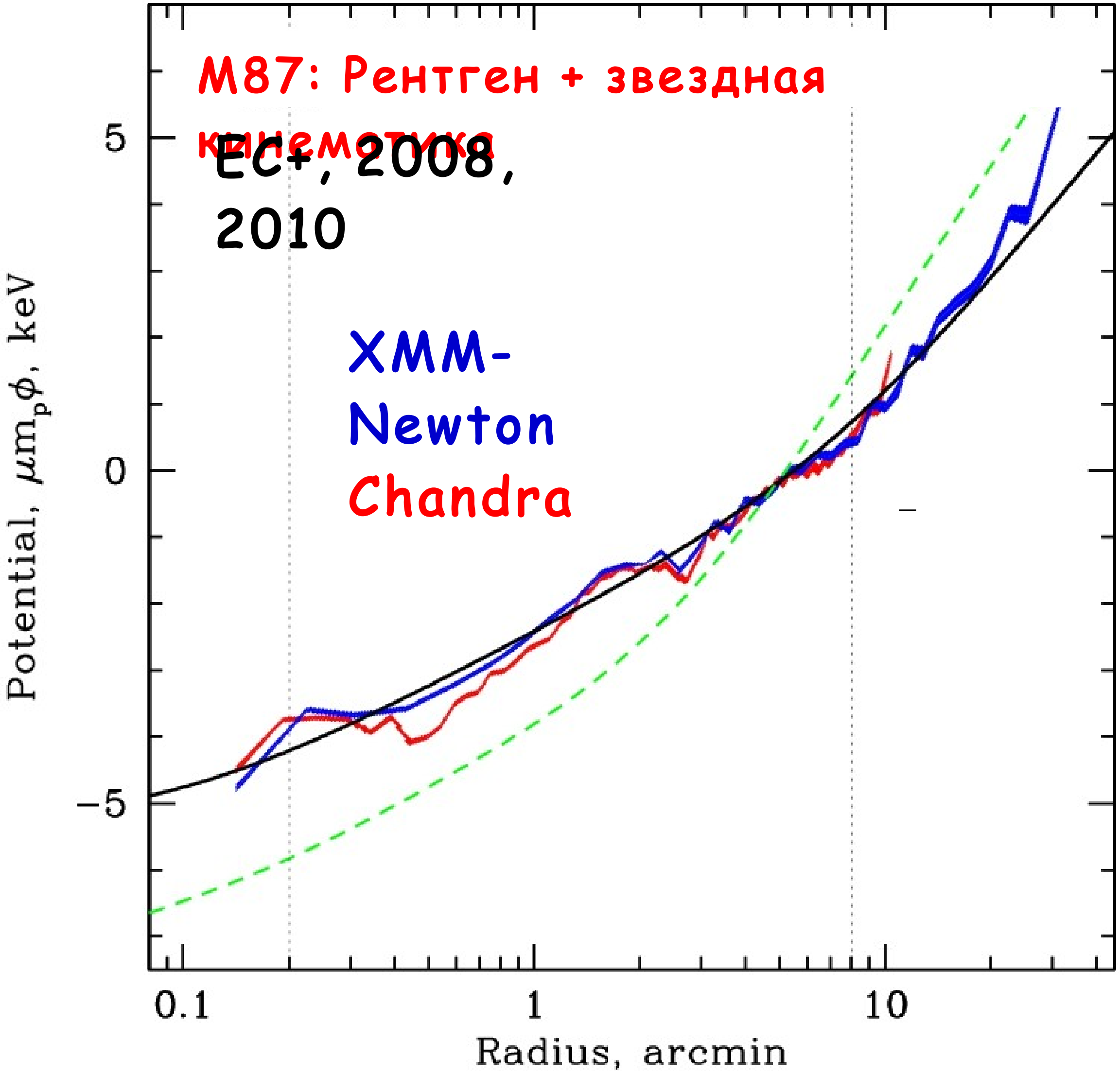
Рентген

Оптические данные Kronawitter et al. 01

$$\frac{\rho v^2}{3nkT} \approx 0.05 - 0.3$$

Сильченко, Моисеев, Журавлева, Цыганков, Лыскова, Буренин

Сравнение оценок массы из рентгеновских и оптических данных



M87: Рентген + звездная кинематика

EC+, 2008, 2010

XMM-Newton

Chandra

Romanowsky & Kochanek, 2001

$$\frac{\rho v^2}{3nkT} < 0.1$$

Gebhardt & Thomas, 2010

$$\frac{\rho v^2}{3nkT} \approx 0.35$$

Сильченко, Моисеев

Проблемы численных симуляций:

1) Разрешение
    а) газ
    б) бесстолкновительная темная материя

2) Искусственная вязкость (SPH)

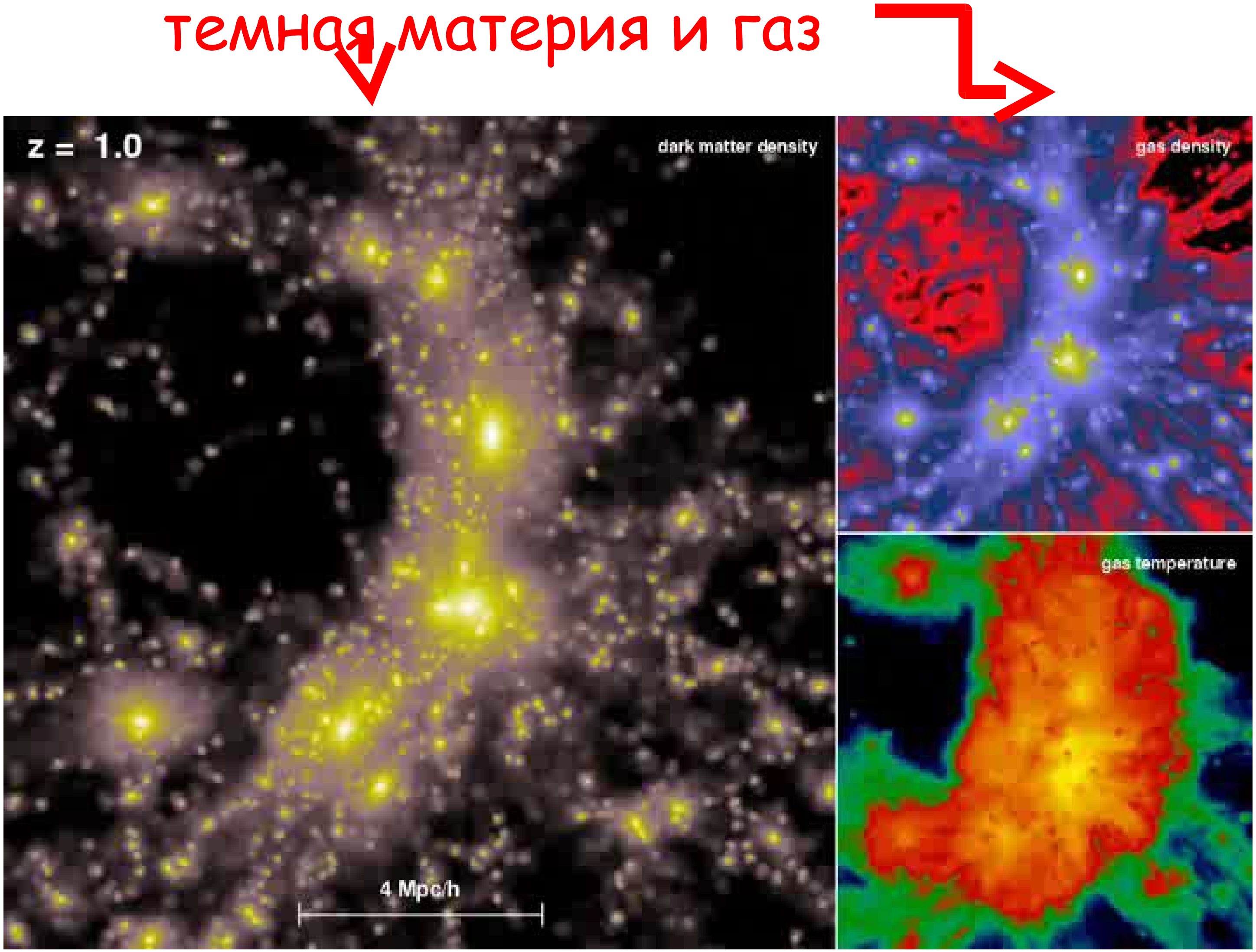
2) Стратификация атмосферы (много высот)

2) Физическая вязкость и теплопроводность

2) Магнитные поля

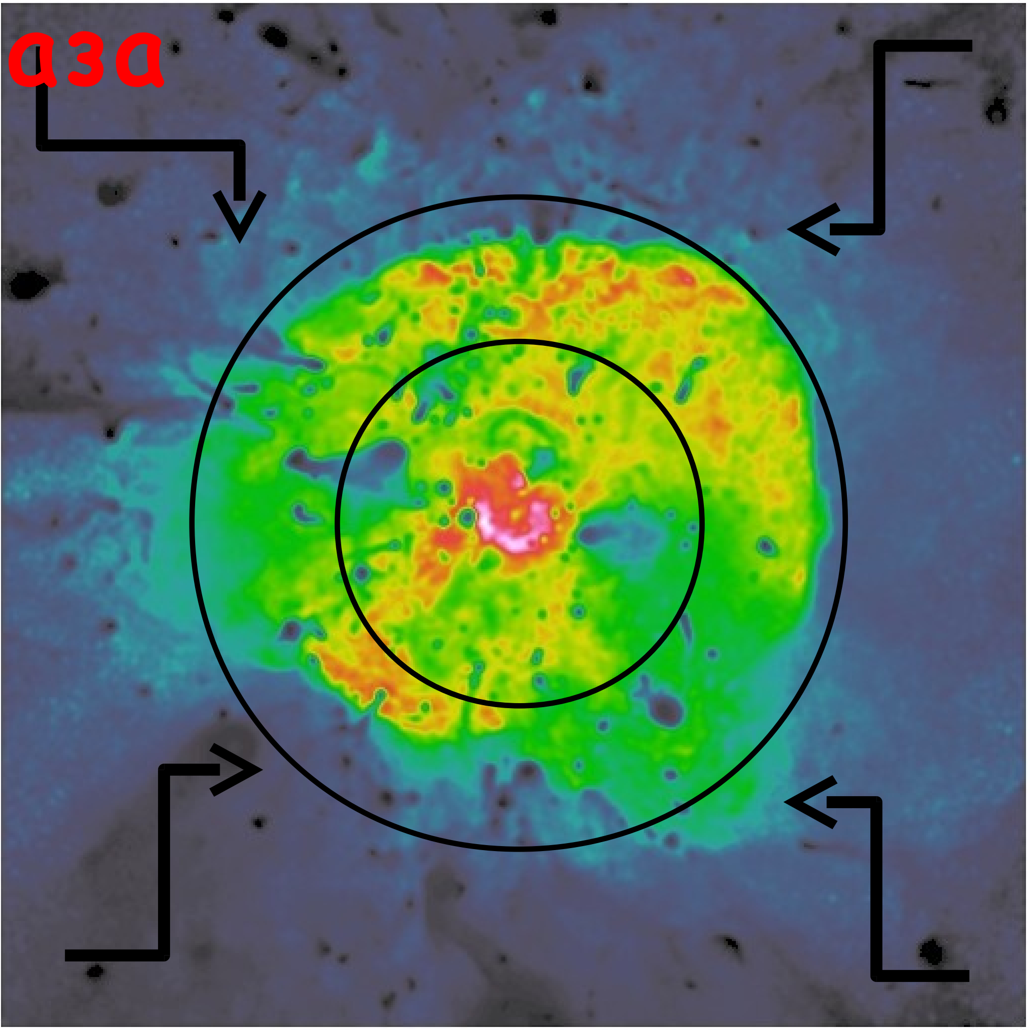
Текущая цель: невязкая жидкость без магнитного

Формирование скопления:
темная материя и газ



Темная материя и газ собираются из большого объема
и остаются в скоплении (это не так для маломассивных систем)

Карта температуры газа



Main directions

- Hydro simulations

  Numerical issues + Cosmology + ICM physics

- Physical processes leading to observational signatures

  Line shift and broadening, resonant scattering, polarization, kinetic SZ effect, surface brightness fluctuations, metal distribution, impact on mass

- Tools to link observations/simulations/theory

  Power density spectra?

- Real observations

Gas motions: simulations

- SPH vs AMR codes (to agree on the velocity field)
- What resolution is needed to model velocity field across the cluster
- Impact of Cosmology/initial power spectrum
- ICM physics (viscosity, thermal conduction, magnetic fields)

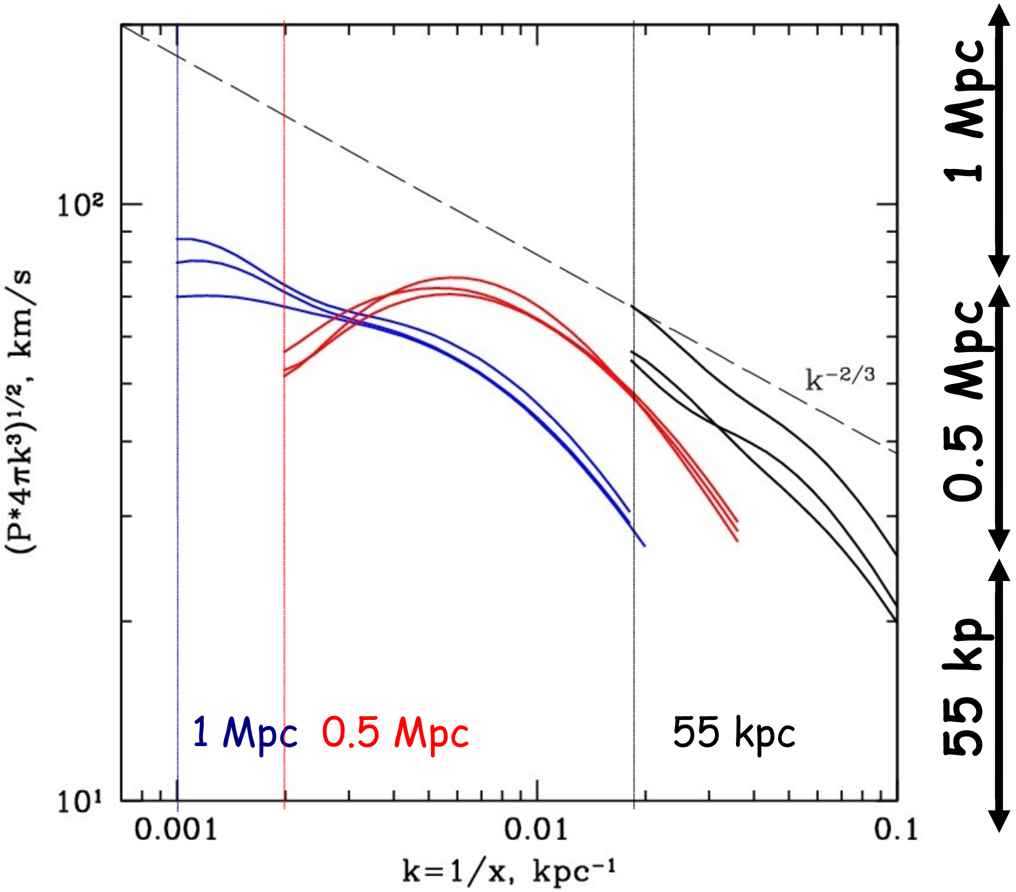
- Test the relation between observables and true physical characteristics (3D velocity field, ICM microphys.)

3D velocity power spectrum

SPH (Dolag et al. 2005), ~ 70·106 particles;

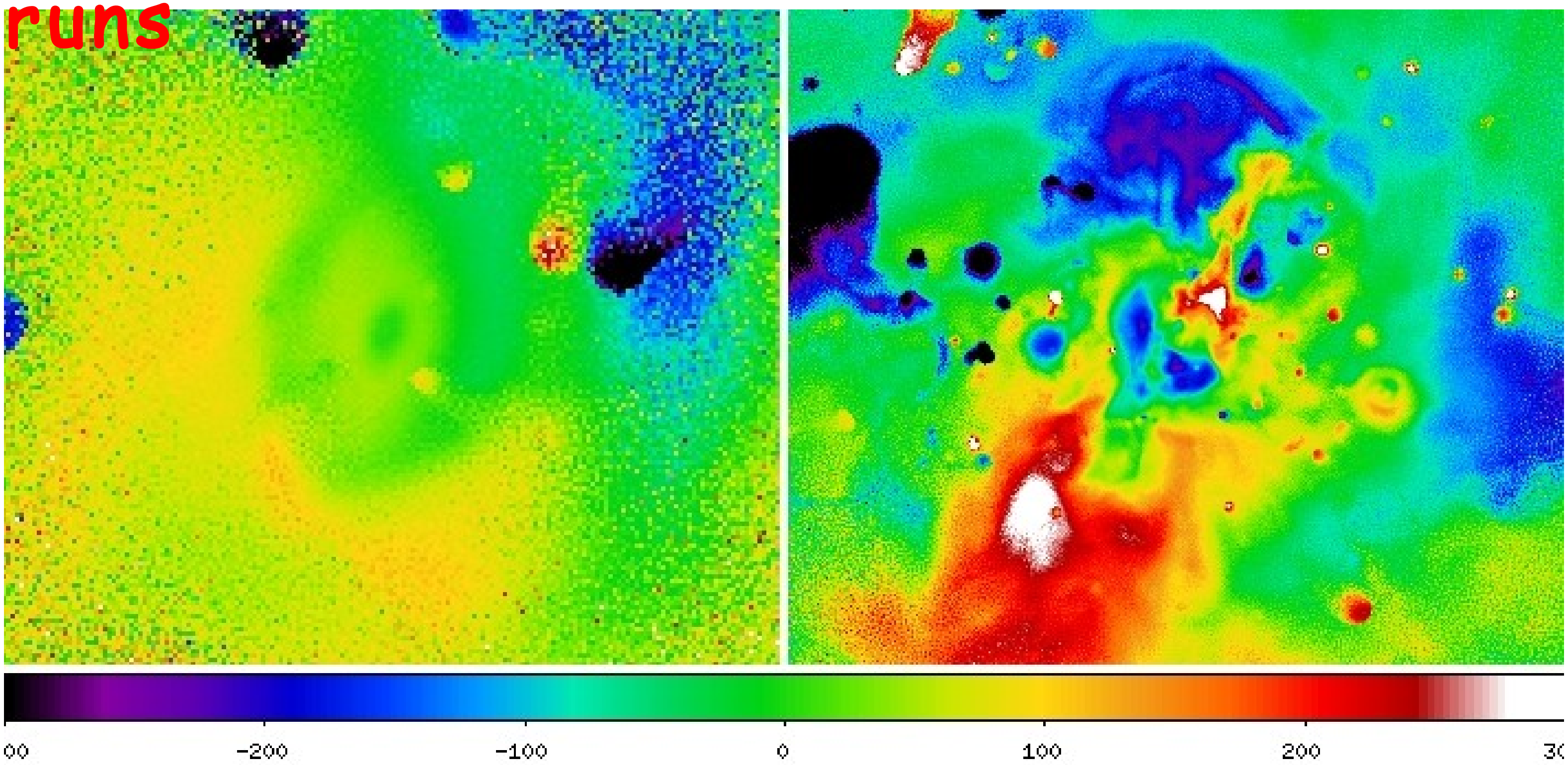
Mvir=1.6·1014 Msun, Rvir=1.43 Mpc

z=0.02 z=0.01 z=0

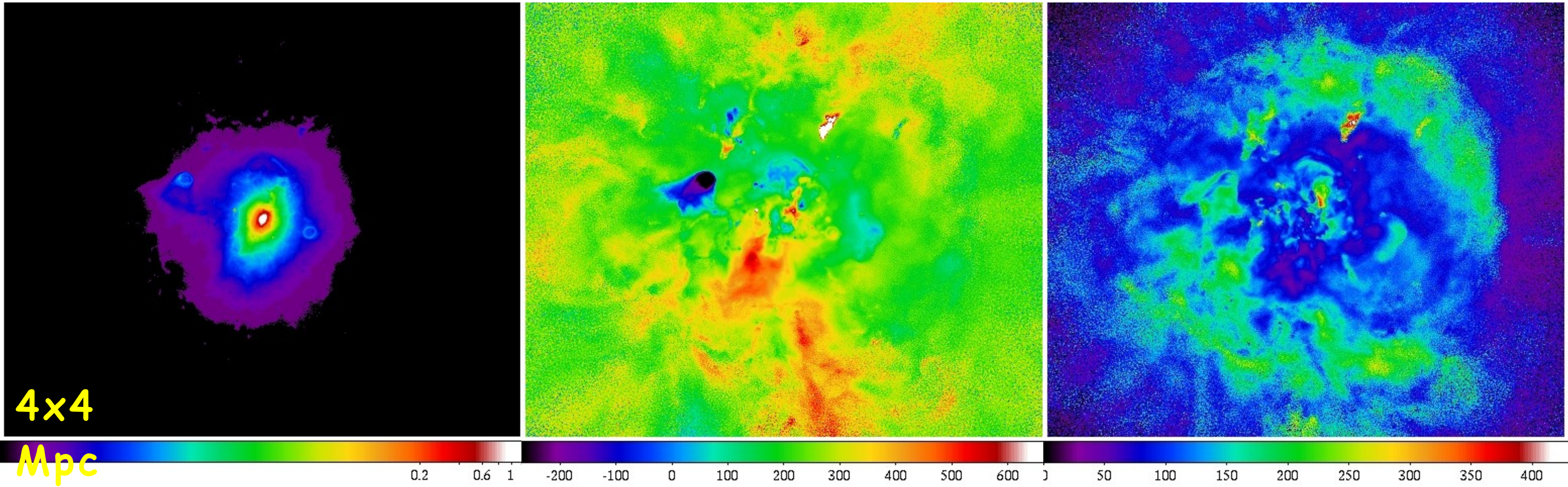


Does PS depend on considered volume of

Projected line-of-sight velocity in two runs

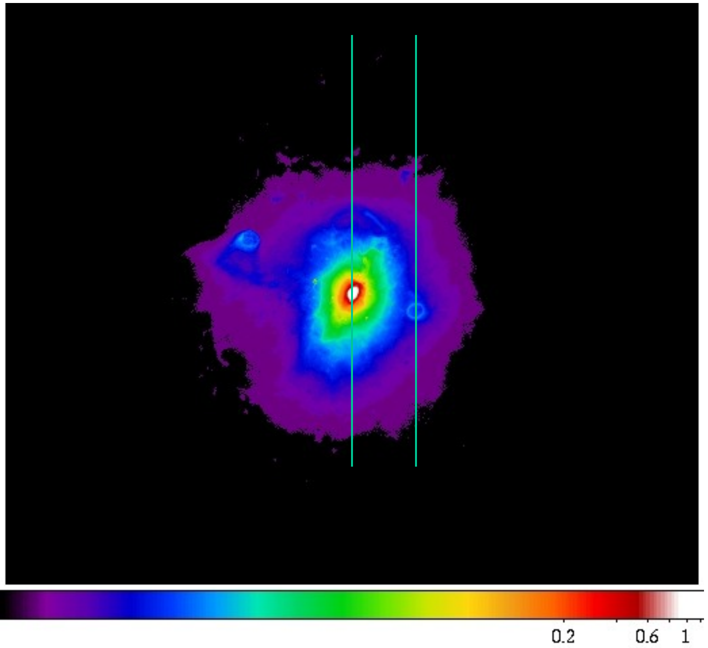


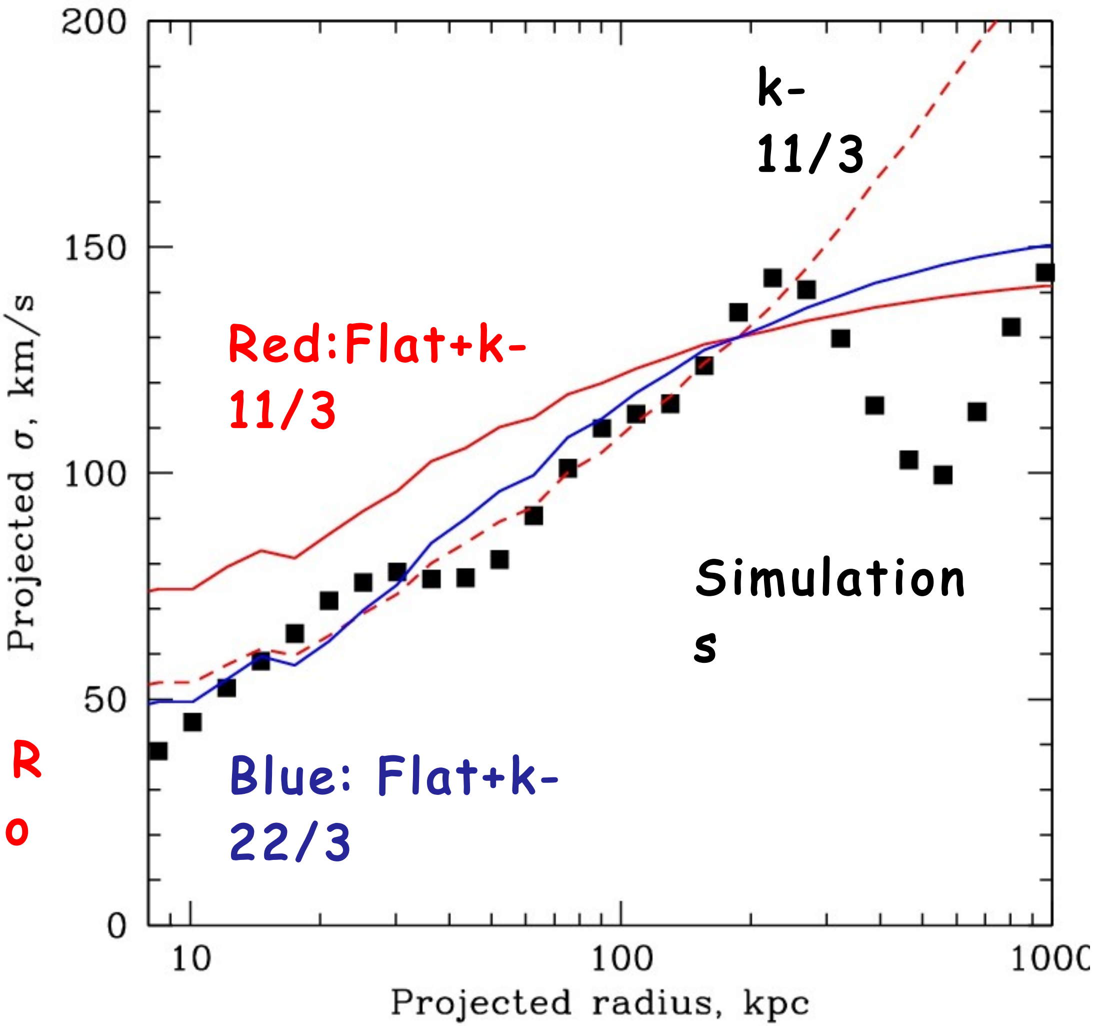
$\int n_e^2 dl$ $\langle v_z \rangle_1$ $\sqrt{\langle v_z^2 \rangle_1 - \langle v_z \rangle_1^2}$



Observables: **ne**, emission measure weighted **vz, σ**

Projected velocity dispersion ≈ Structure Function





k-11/3

Red:Flat+k-11/3

Simulations

Blue: Flat+k-22/3

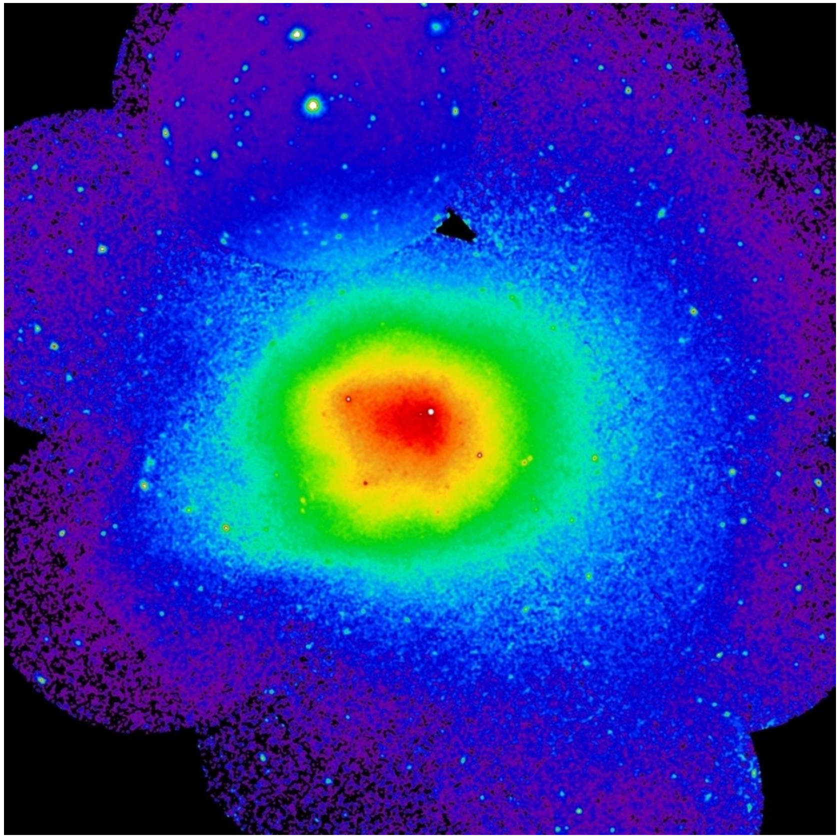
At a given projected radius R an interval ~R contributes to σ

σ2 ≈ structure function

$$\sigma^2 = \int P_{3D}\left[1 - W^2(k_z)\right] dk_z dk_x dk_y$$

Resonant
Scattering

X-ray resonant scattering in ICM



Optical depth for free-free

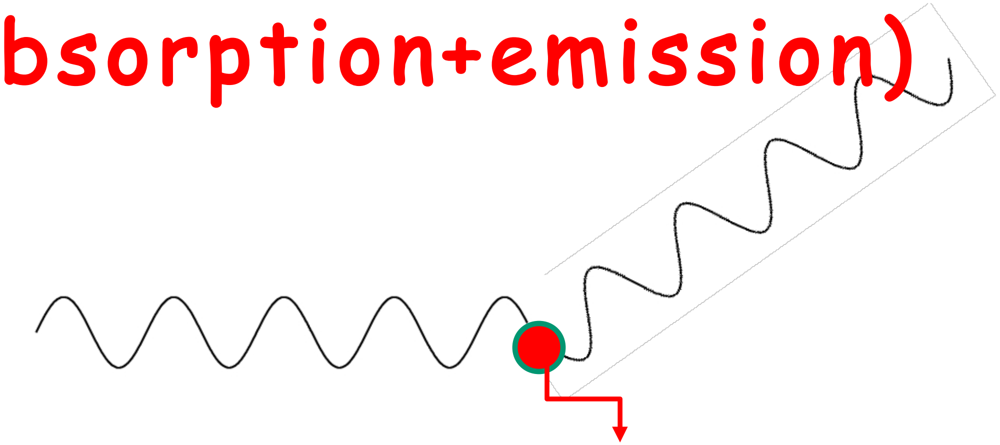
$$\frac{L_X}{4\pi R^2 \sigma T^4} \approx \frac{10^{45}\ \mathrm{erg/s}}{10^{77}\ \mathrm{erg/s}} \approx 10^{-32}$$

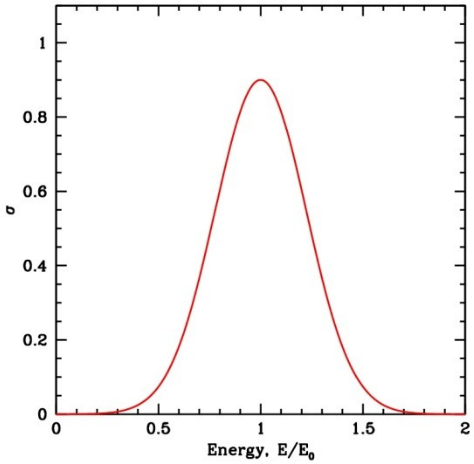
Thomson optical depth

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

Clusters are optically thin in X-rays (in

Resonant scattering (absorption+emission)

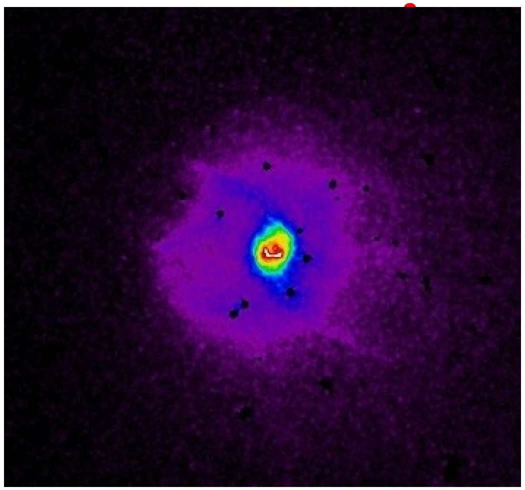




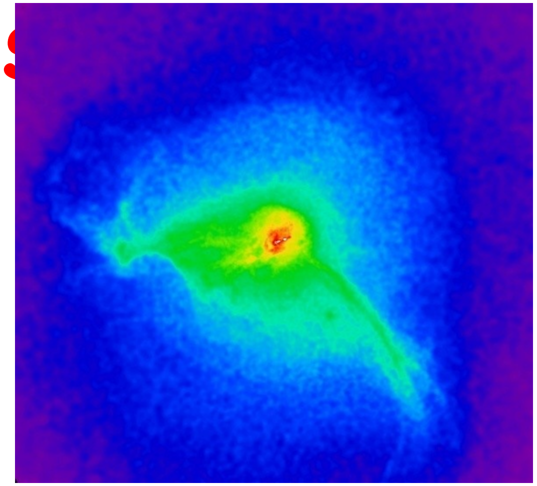
$$\sigma_0 = \frac{\sqrt{\pi}\, h r_e c f_{ik}}{\Delta E_D}; \quad \Delta E_D = E_0 \frac{\mathrm{v}}{c} = E_0 \left[\frac{2kT}{A m_p c^2} \right]^{1/2}; \quad \tau_0 = n_i l \sigma_0$$

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

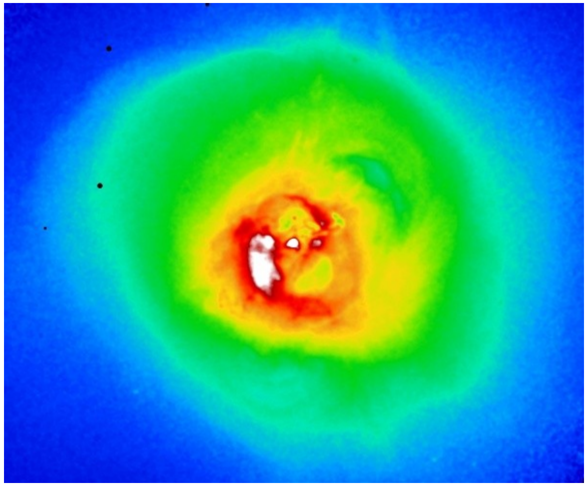
Optical depth in



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

For Solar corona:
Elwert 1956, Acton 1978, Rugge & McKenzie

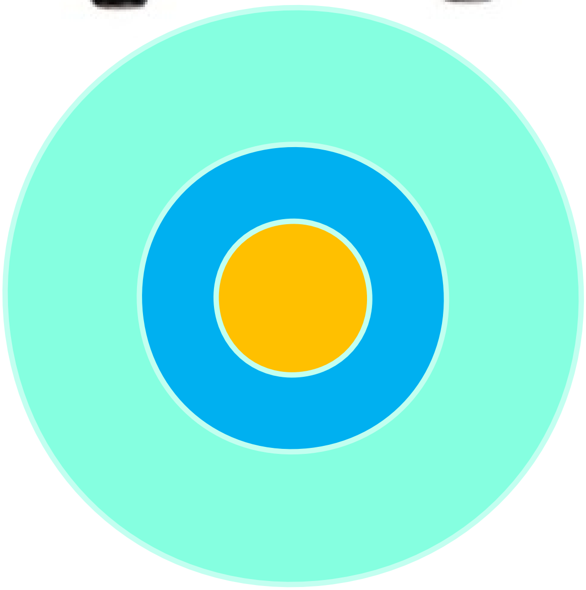
Gilfanov+,

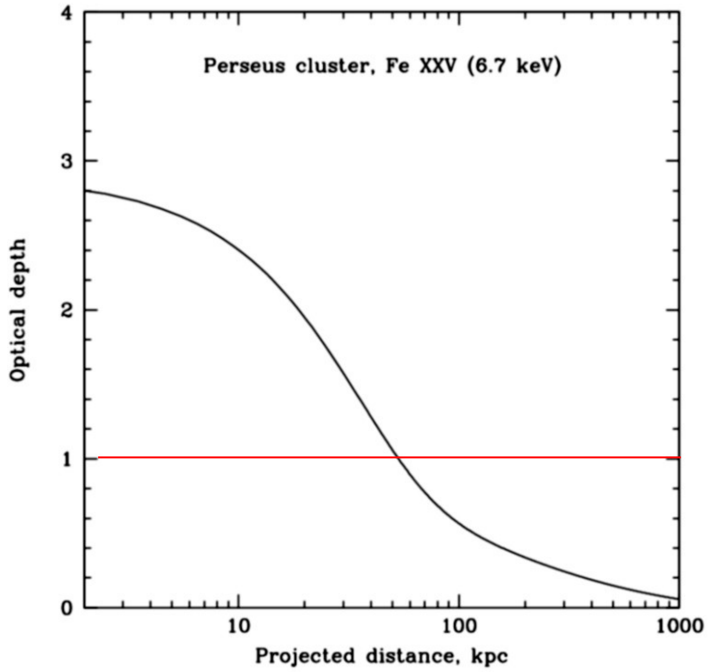
Resonant scattering in clusters (incomplete list)

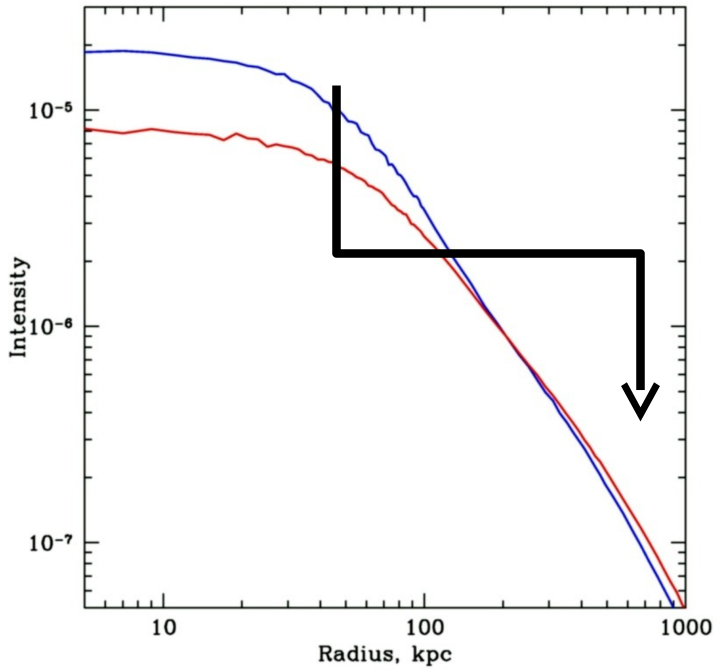
Gilfanov+, 1987; Krolik & Raymond, 1988; Molendi+, 1998;
Shigeyama 1998; Akimoto+, 1999; Kaastra+, 1999;
Churazov+, 2001; Mathews+, 2001; Bohringer+, 2001;
Sakelliou+ 2002; Xu+, 2002; Sazonov+,2002a;
Sazonov+, 2002b; Kahn+, 2003; Churazov+, 2004;
Gastaldello & Molendi, 2004; Sanders+, 2004;
Sanders & Fabian, 2006; Molnar+, 2006;
Werner+, 2009; Hayashi+, 2009; Zhuravleva+, 2010a,b;

See our recent review on RS:
EC+, 2010

Impact on the surface brightness

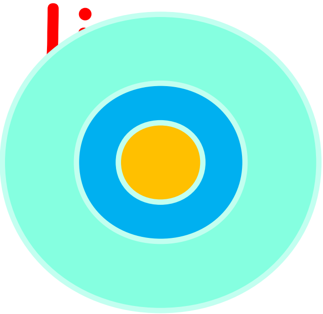


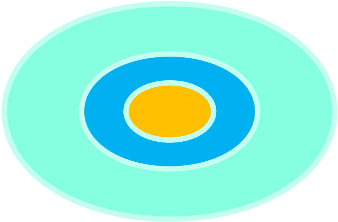


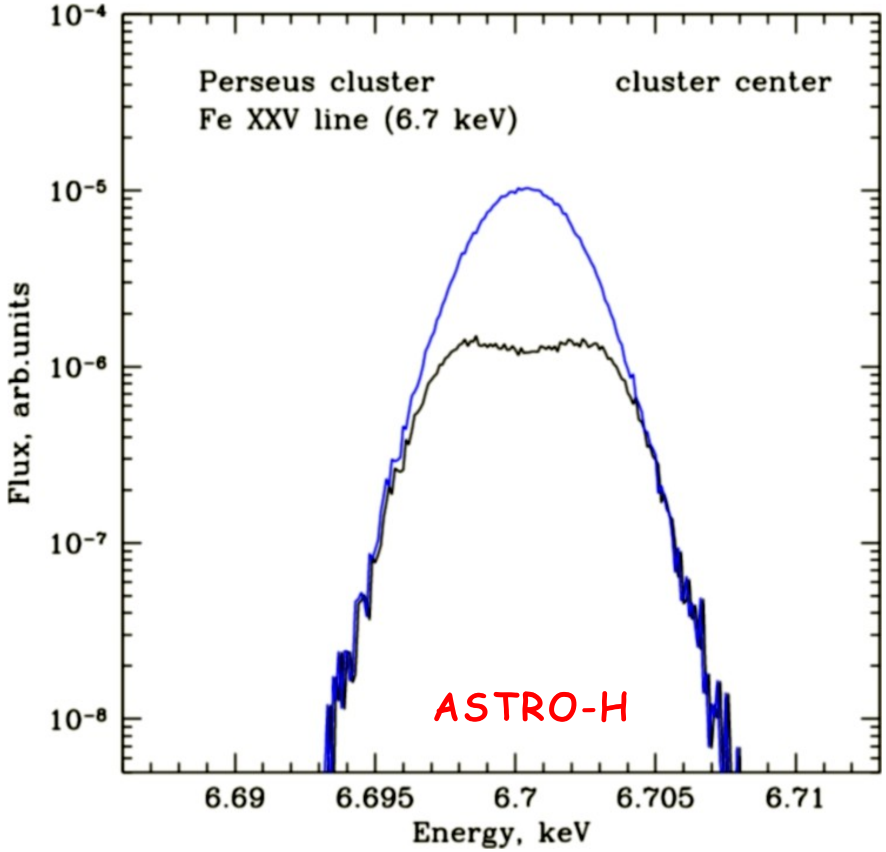


Line is suppressed in the core
Photons are re-emitted at the

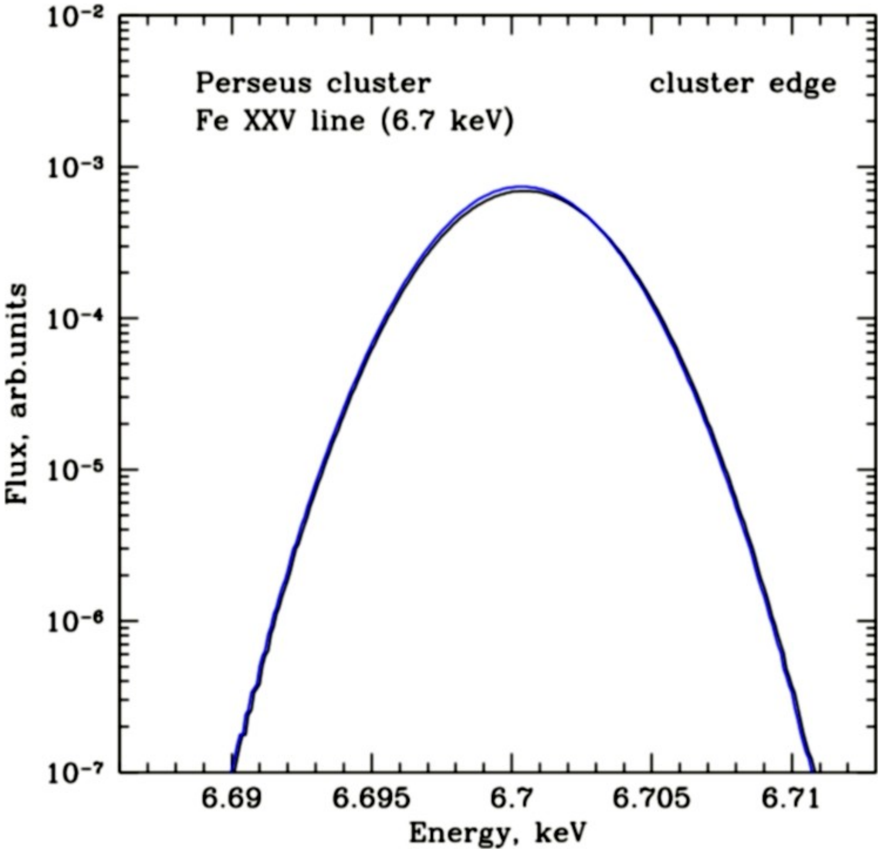
Spectral shape of the Li







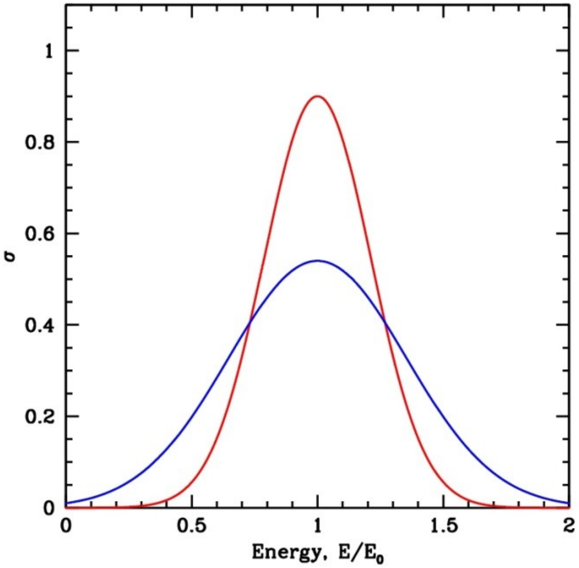
ASTRO-H



Core of the line is

Gas Velocities I

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



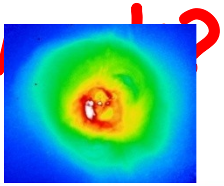
FeXXV; 6.7 keV line; T=5 keV

Radiative width: 0.3 eV

Thermal width: 3 eV

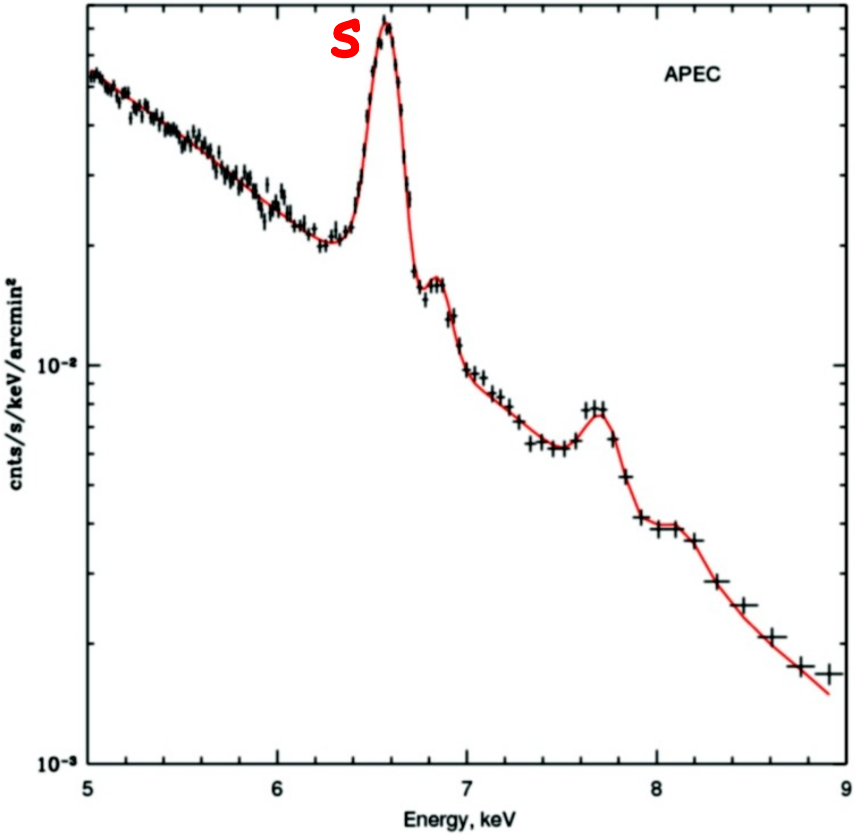
Turbulence (300 km/s): 7

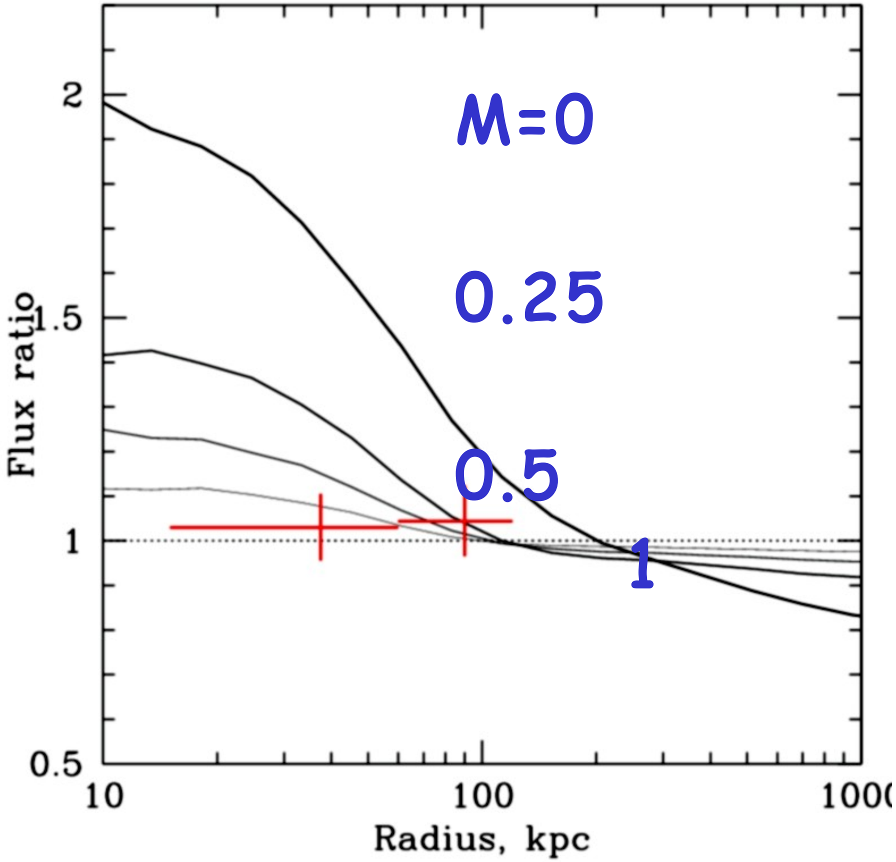
Do we see resonant scattering at w ?



Perseus

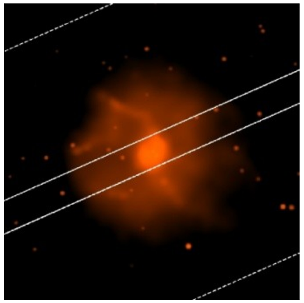
$$F_{thin} \big/ F_{6.7}$$





6.7 keV line is not suppressed => velocity > 400 km/s

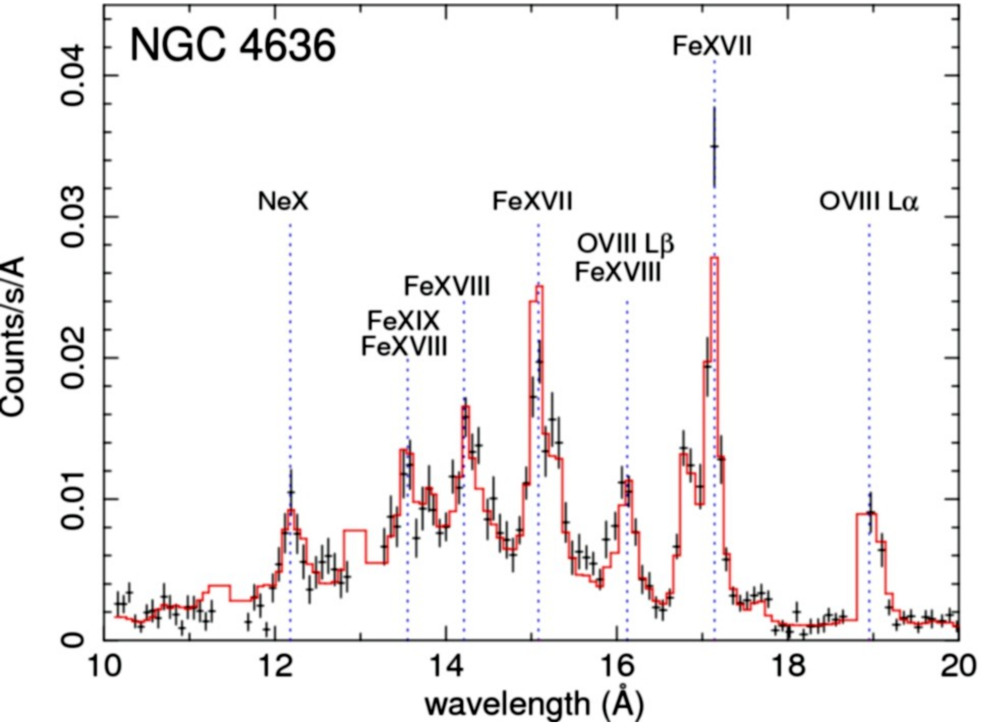
EC+, 2004; Gastaldello & Molendi,

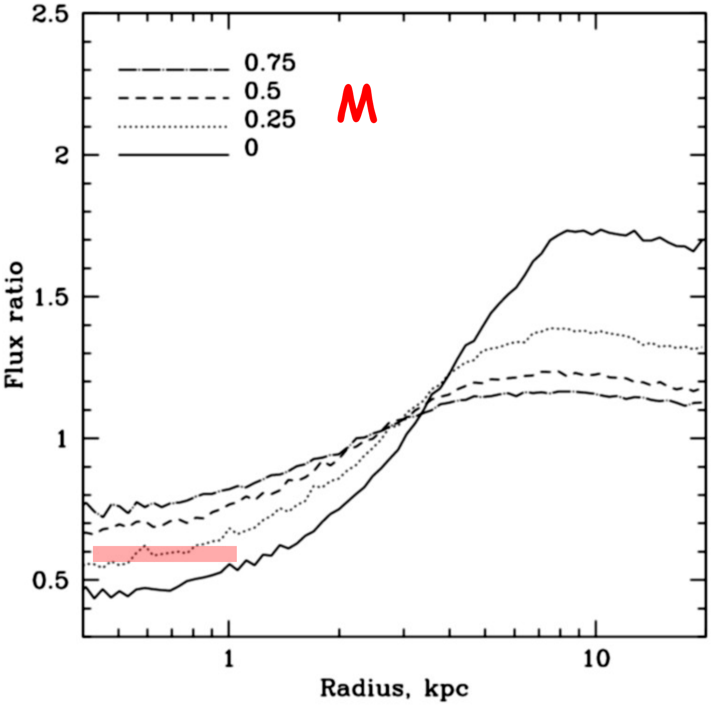


NGC4636 - bright, cool system
Fe XVII lines; compact core suitable for RGS

[NGC1404, 5813, 4472]

F_{15A} / F_{17A}



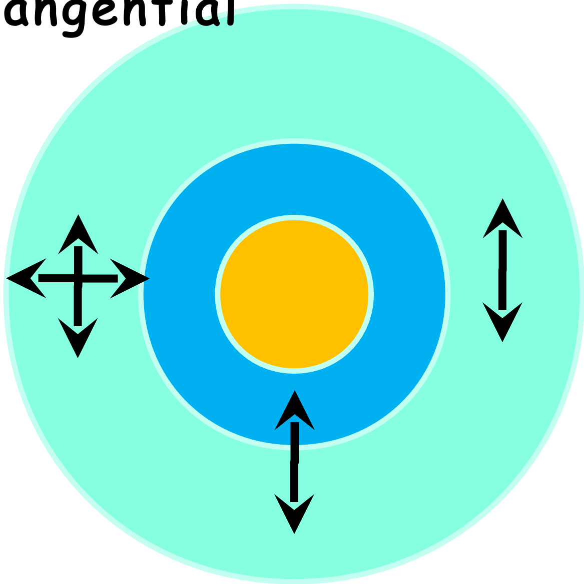


15 Å line is suppressed => velocity < 100 km/s

Xu+, Werner+, Hayashi+

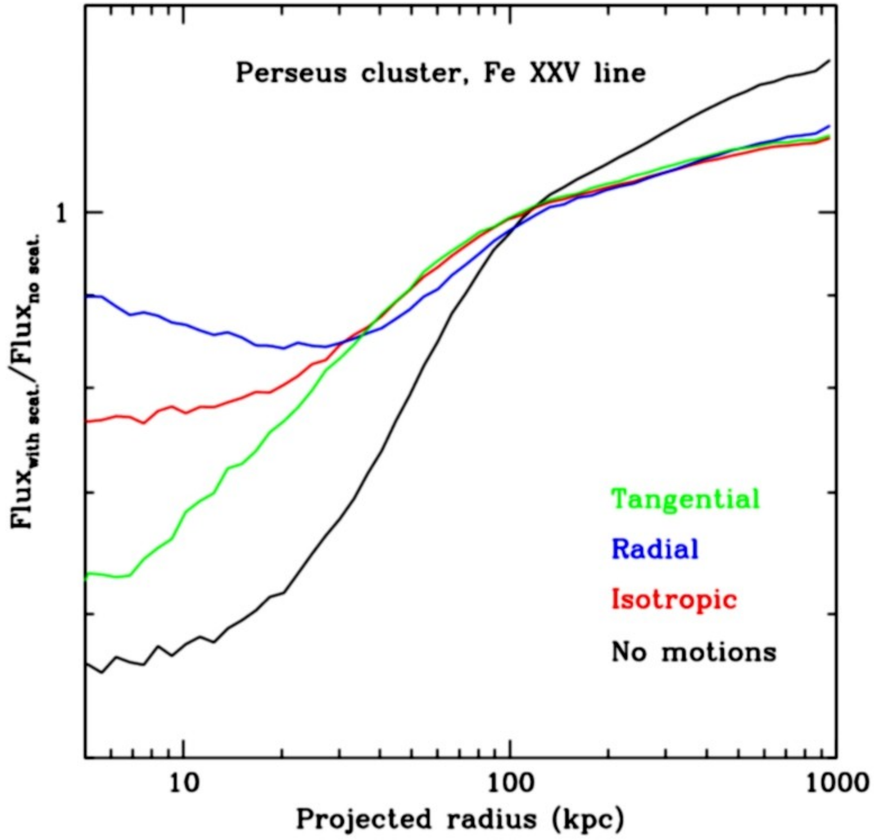
Gas Velocities II

Isotropic, radial, tangential



$$\tau \leftrightarrow E_{kin}$$

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

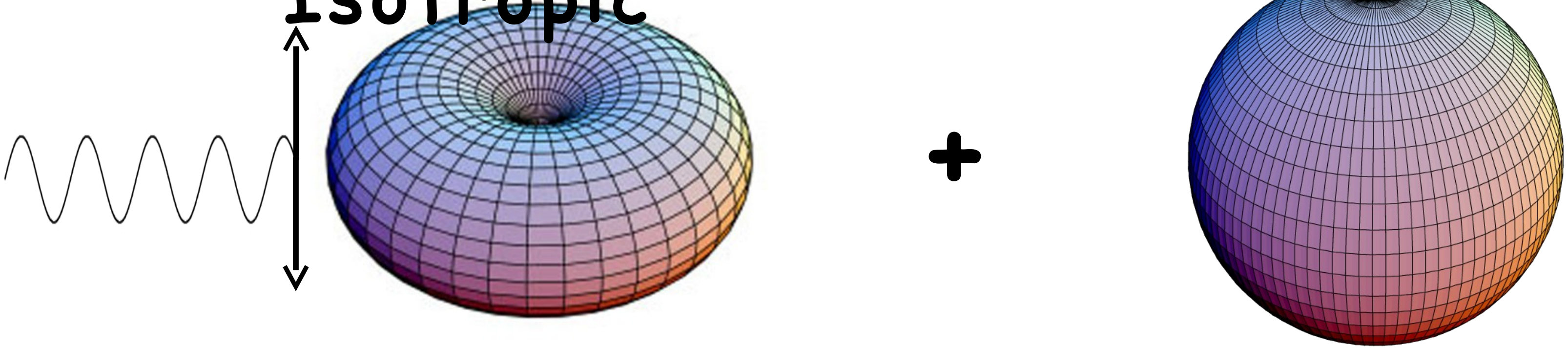


Optical depth strongly depends on the character of motions

Zhuravleva et al, 2010b

Polarization I

Scattering phase function = W2 x Rayleight + W1 x Isotropic



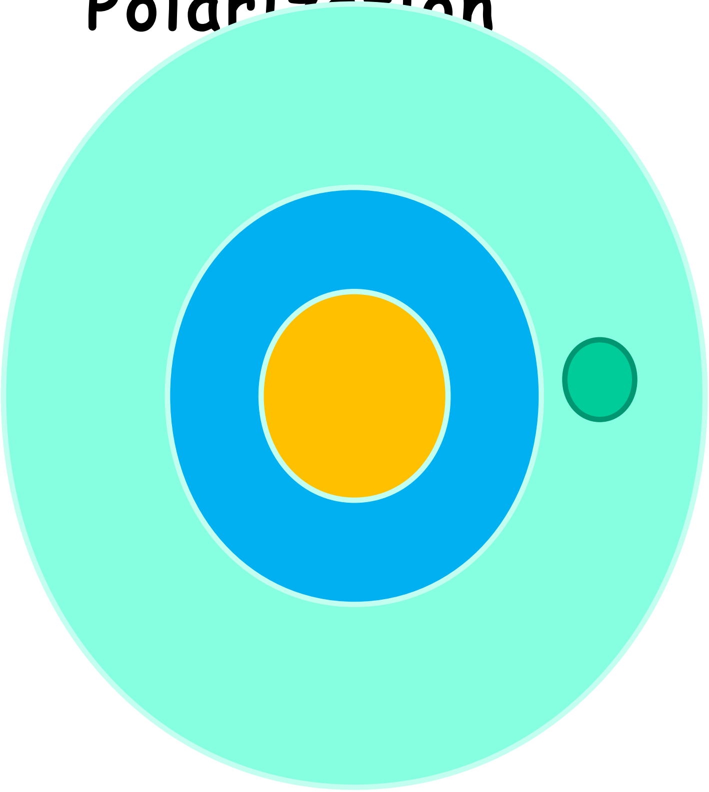
Polarization No Polarization

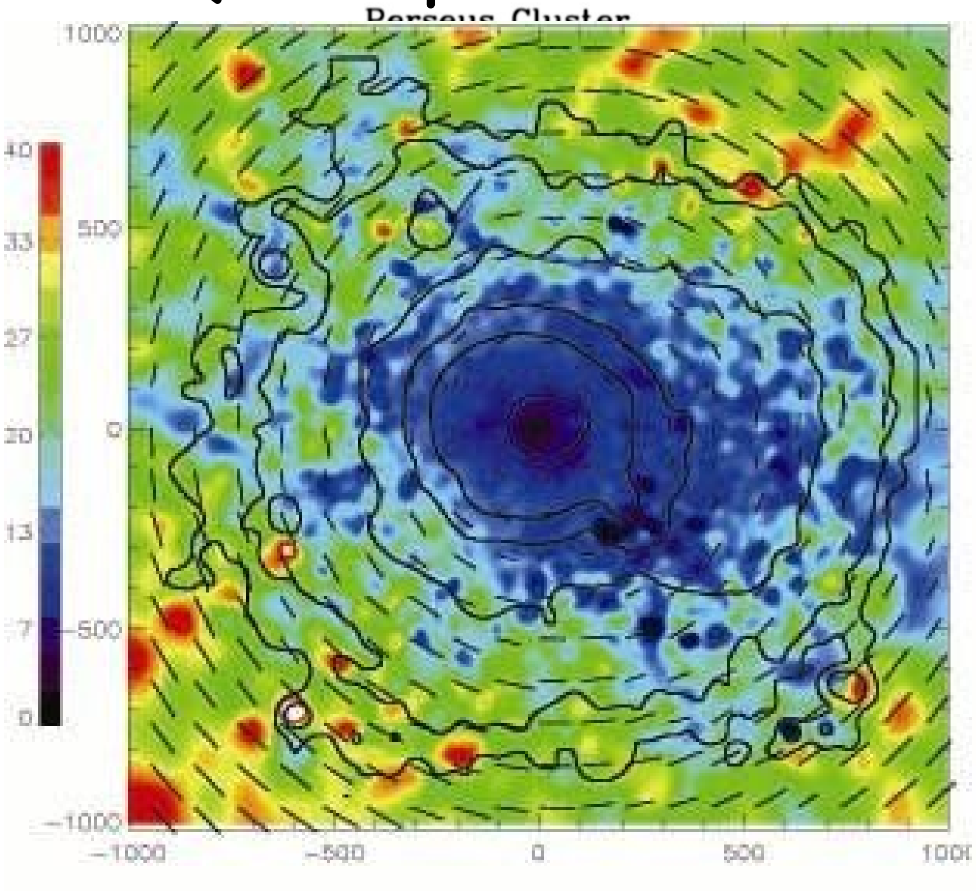
Hamilton, 1947; [Chandrasekhar 1950]

He-like ions; 1s2 (1S0) - 1s2p

Polarization II

Rayleigh phase function + Quadrupole = Polarization





100% polarized

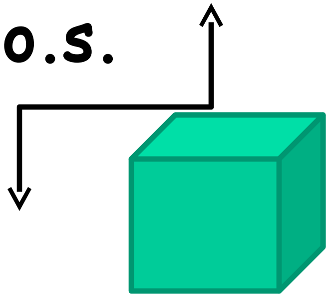
Center: 0%
Outskirts: 10%

Sazonov+ 2002; Zhuravleva+

Transverse ICM velocities and polarization

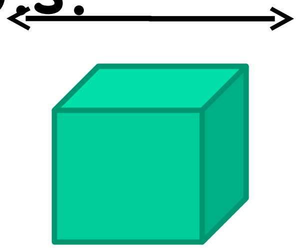
Quadrupole component can be induced by gas motions!

Motion along l.o.s.



Doppler shift
No polarization

Motion transverse l.o.s.

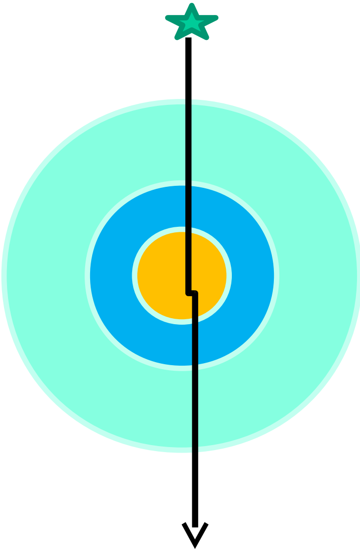


No Doppler shift
Polarization

Click to edit Master subtitle style

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

Angular diameter-redshift relation



[SZ+X-rays (e.g. Silk & White, 78)]

1) Background QSO
2) Polarization, Line shape

Single observation in X-rays!

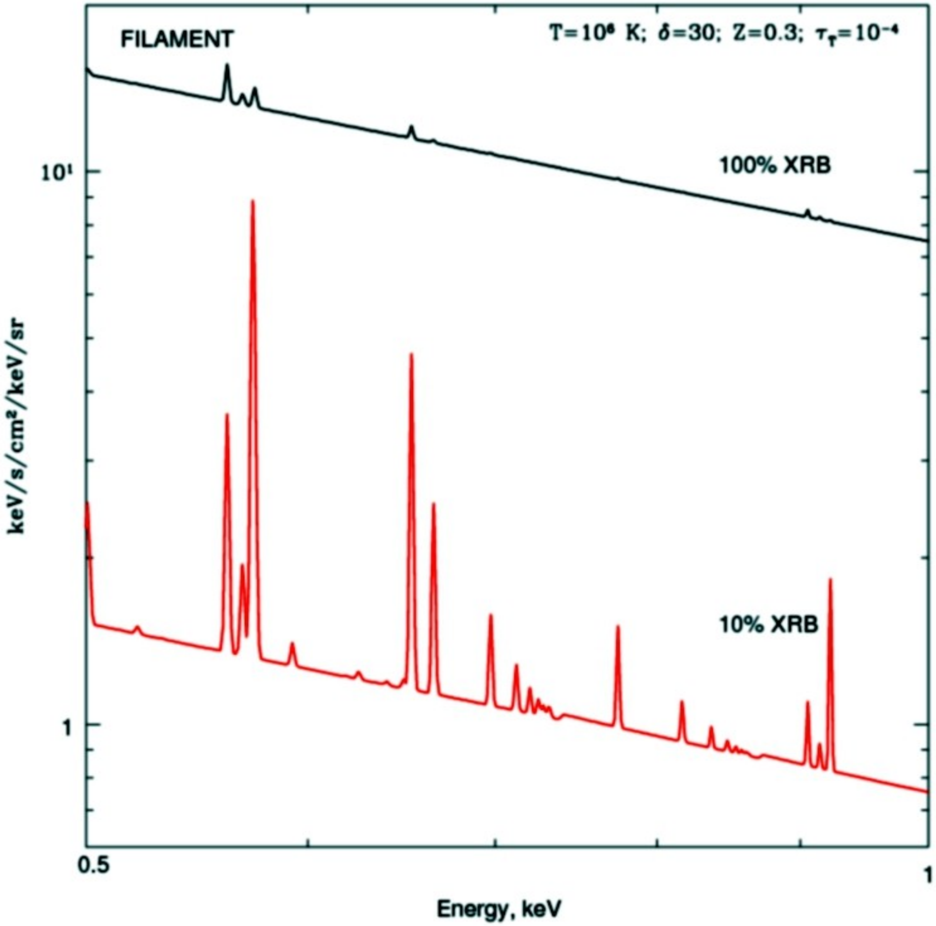
Krolik & Raymond 88; Sazonov et al. 02; Molnar et al.

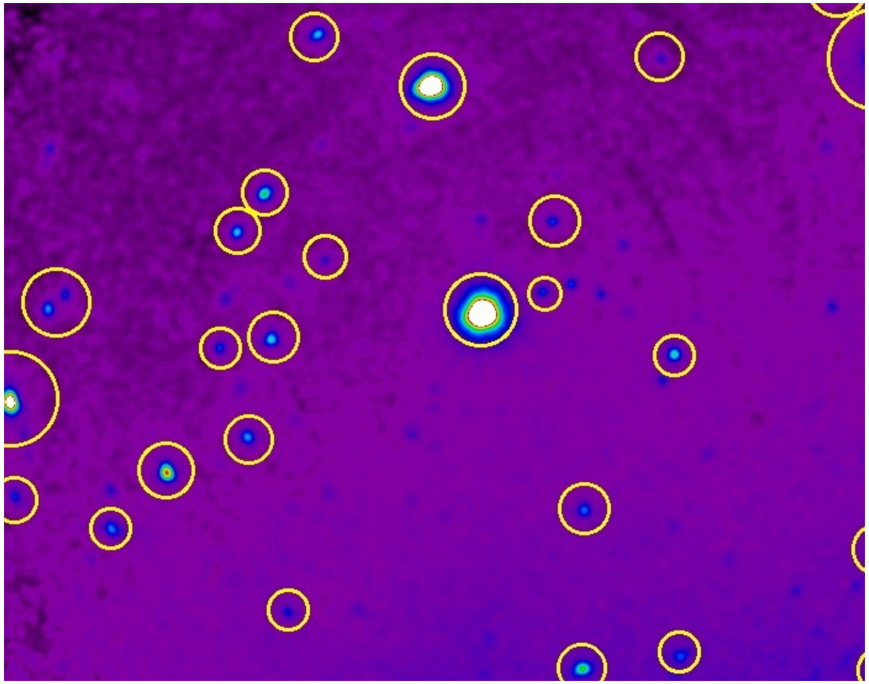
Scattering in Warm-Hot IGM

$$n < 10^{-5}\ \mathrm{cm}^{-3}$$

$$EW \approx 90 \frac{Z}{Z_{Sun}}\ \mathrm{keV}$$

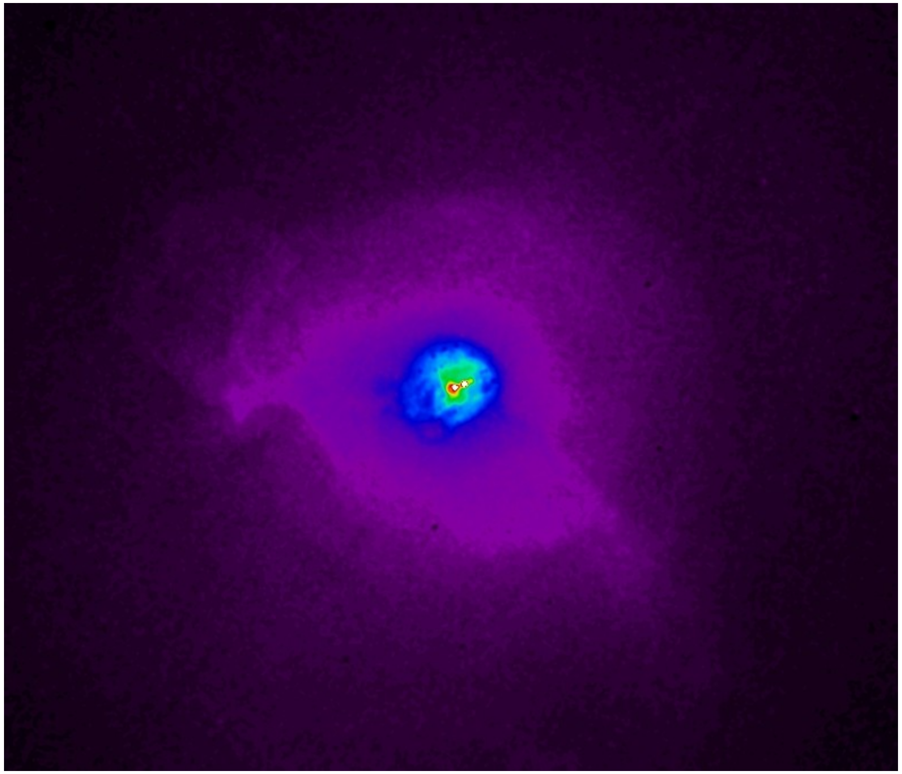
$$T \approx 10^{6}\ \mathrm{K}$$

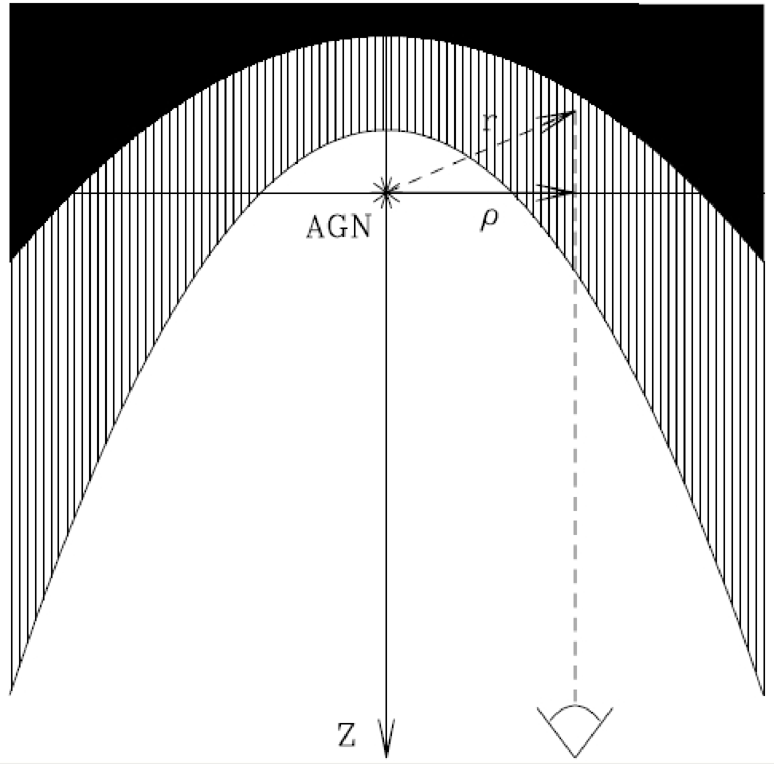




EC+,

AGN echo in X-ray





$$L \approx \tau \times L_{AGN} \frac{\Delta t}{t_{cross}}$$

Scattered flux in line (few 105 years after the outburst)

Equivalent width of resonant lines relative to

Sazonov+,

Conclusions

- Surface brightness decrement (line ratios) - now
- Line profile - near future
- Polarization - future

- Velocity diagnostics (including transverse component)
- Distances
- WHIM

What is next?

+High energy resolution: line profiles: ASTRO-H

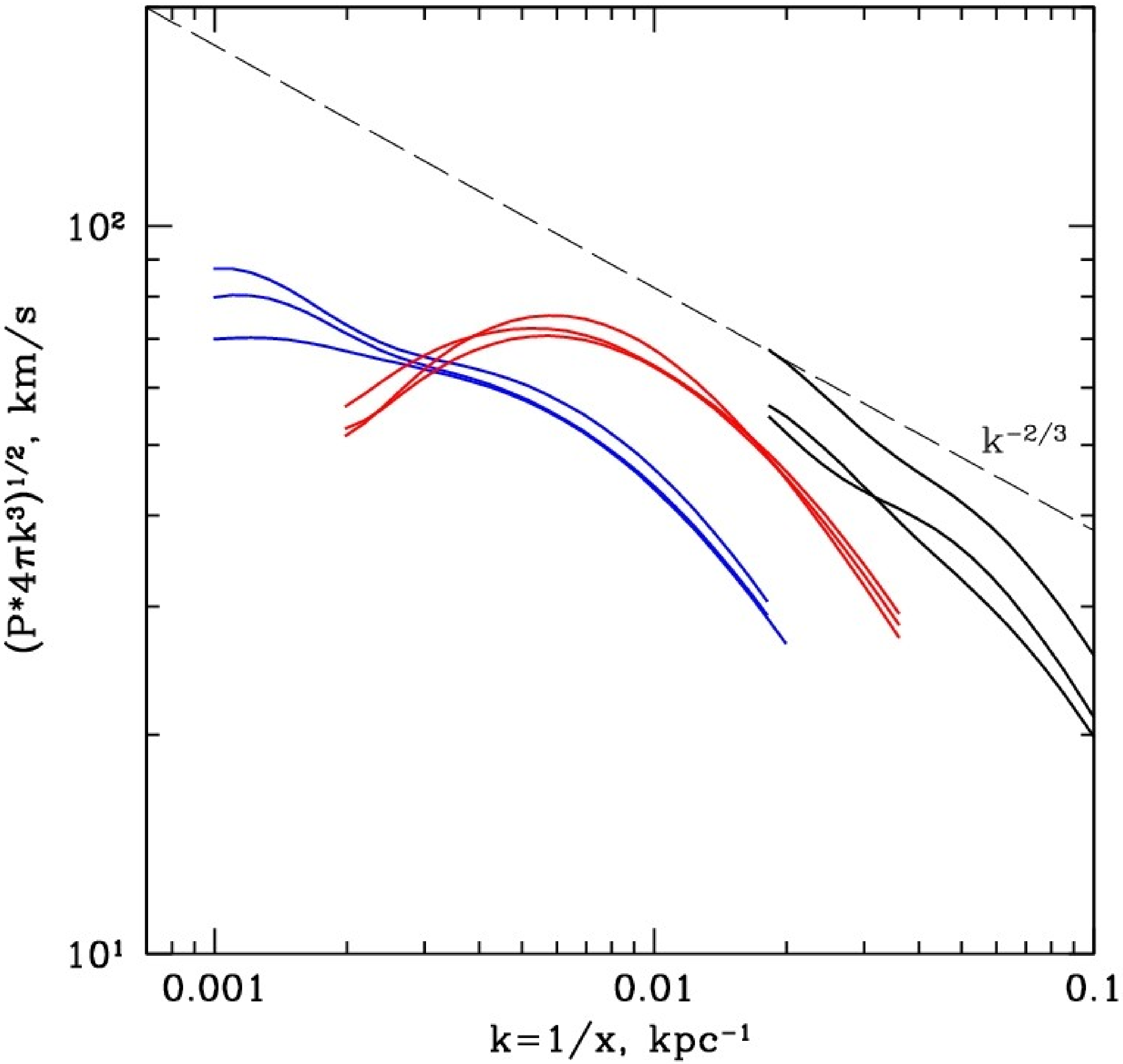
$V_\perp$

+Polarimetry: only due to scattering;

IXO po r

continu

Parameter	Value
Mirrors*QE	1000 cm2
FOV	20'x20'
Energy resolution	100 eV
Modulation	0.5


$(P*4\pi k^3)^{1/2}$, km/s
10^2
10^1
0.001
0.01
0.1
k=1/x, kpc^{-1}
$k^{-2/3}$

NON-THERMAL PRESSURE SUPPORT

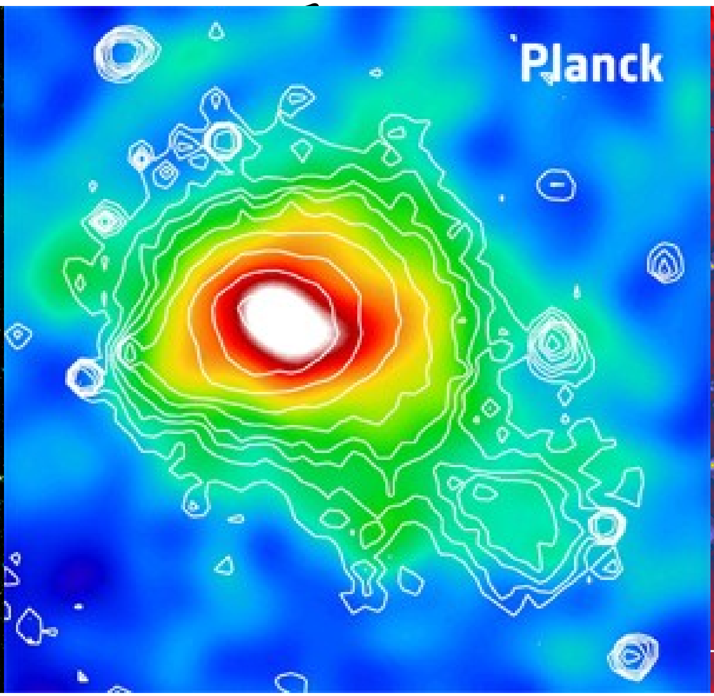
Major components of a galaxy cluster

Star

few %

Optical

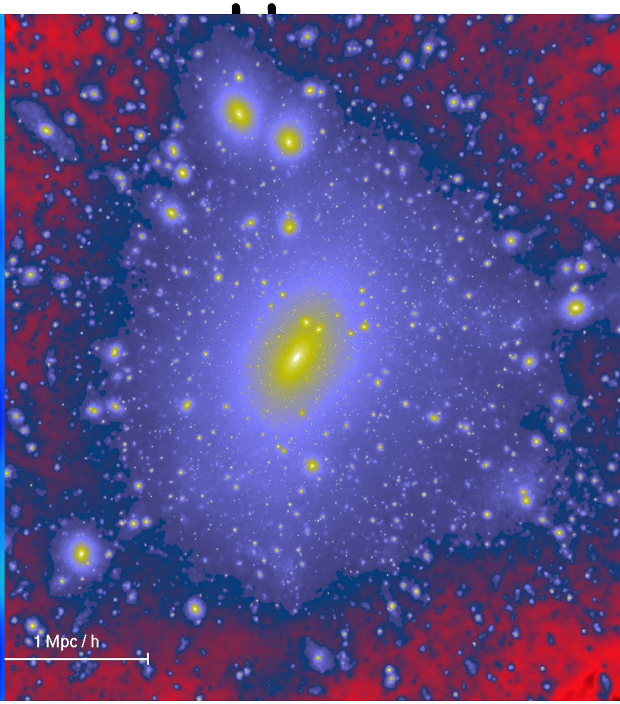
Hot



15 %

X-rays, CMB (SZ)

Dark

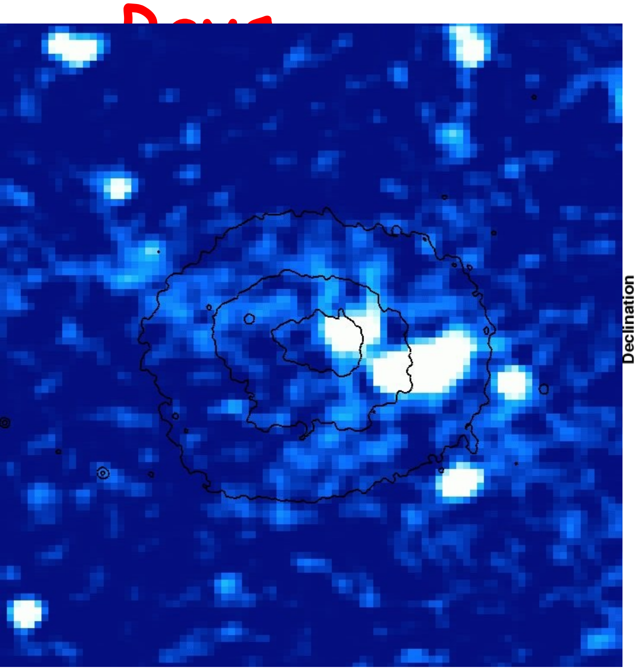


80 %

Indirect

More components

Cosmic Rays

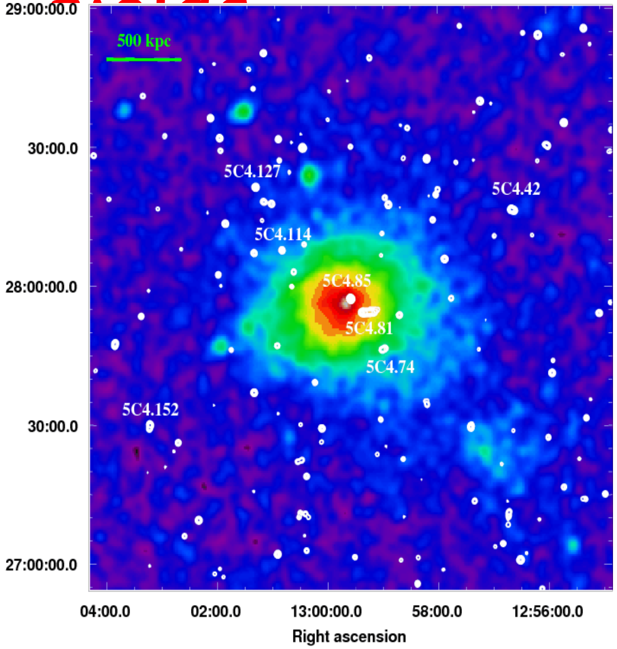


0%

Radio (electrons)
Hard X-rays (electrons)

….

Magnetic fields



0%

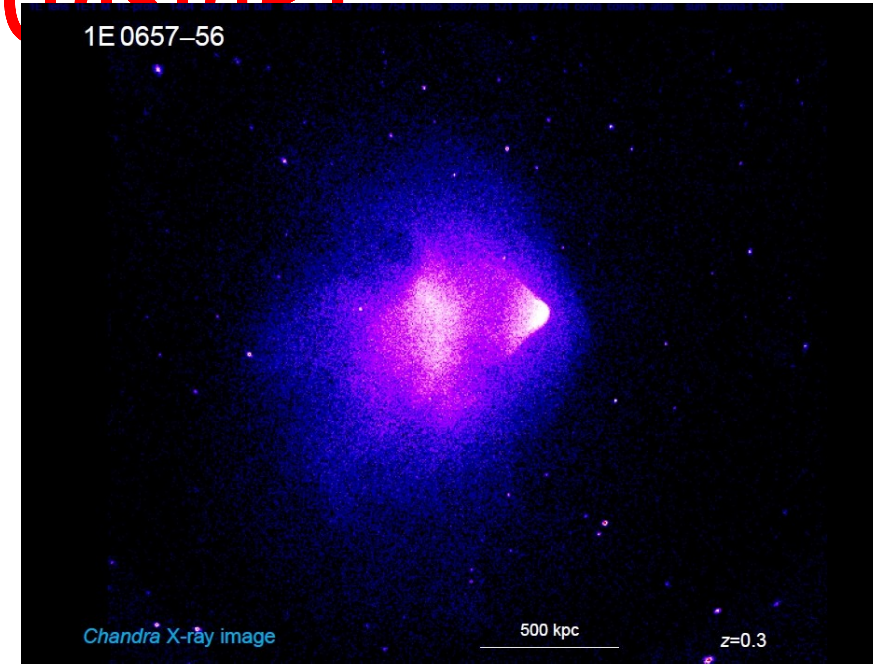
Faraday rotation

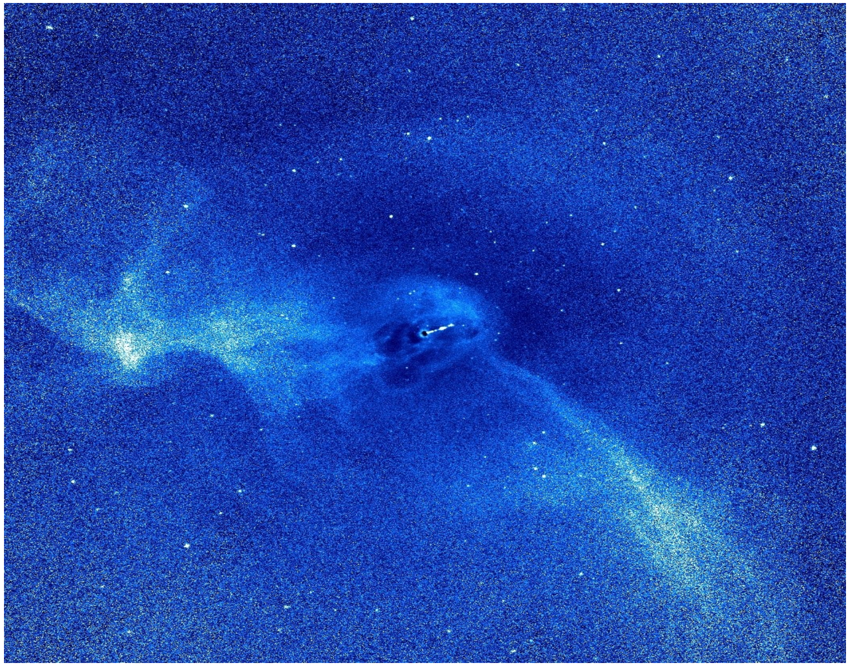
Turbulence

0%

Lines (2014)

Mergers (outside) and AGN outflows (inside)

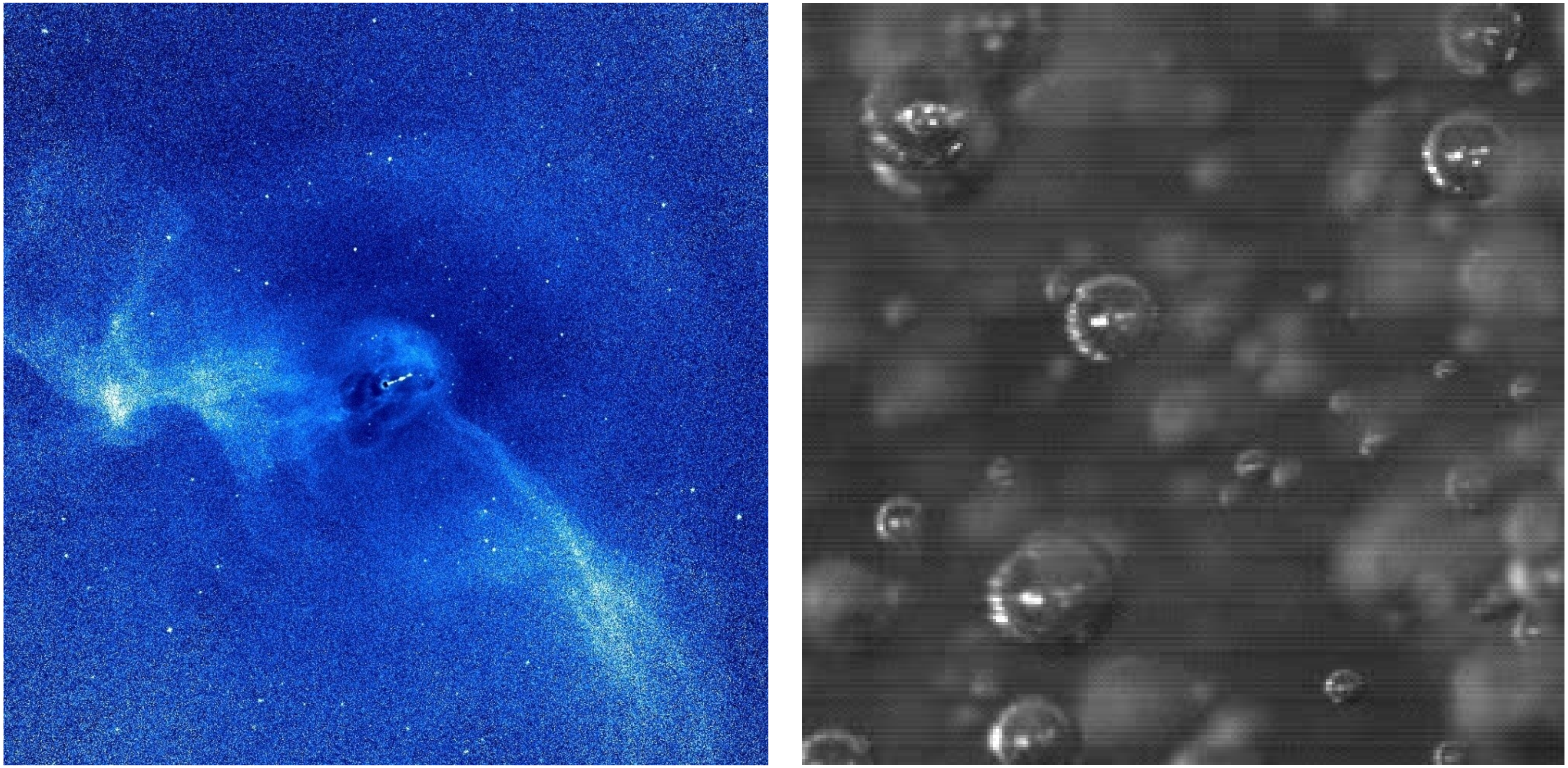




Bullet Cluster:
Turbulence
Shocks -> CR, magnetic fields

M87/Virgo:
Bubbles of CR, magnetic fields
Drive turbulence in ICM

Cosmic rays + magnetic fields + turbulent motions



Extra (non-thermal) energy per thermal

Measuring masses (clusters and early-type galaxies)

1) Hot ICM + Hydrostatic Equilibrium

1) Kinematics of stars, GC, PNe and galaxies

1) Weak lensing

If bias in M => wrong cosmological parameters

If M is known => measure non-thermal

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

$$P = \underbrace{nkT}_{\text{Thermal pressure (easy to measure)}} + \underbrace{P_{CR} + \frac{B^2}{8\pi} + P_{turb}}_{\text{Non-thermal pressure (invisible)}}$$

Stars: Jeans equation [stationary, spherical system]

$$\frac{1}{n_*}\frac{dn_*\sigma_r^2}{dr}+2\frac{\beta}{r}\sigma_r^2=-\nabla\varphi$$

or Schwarzschild's method

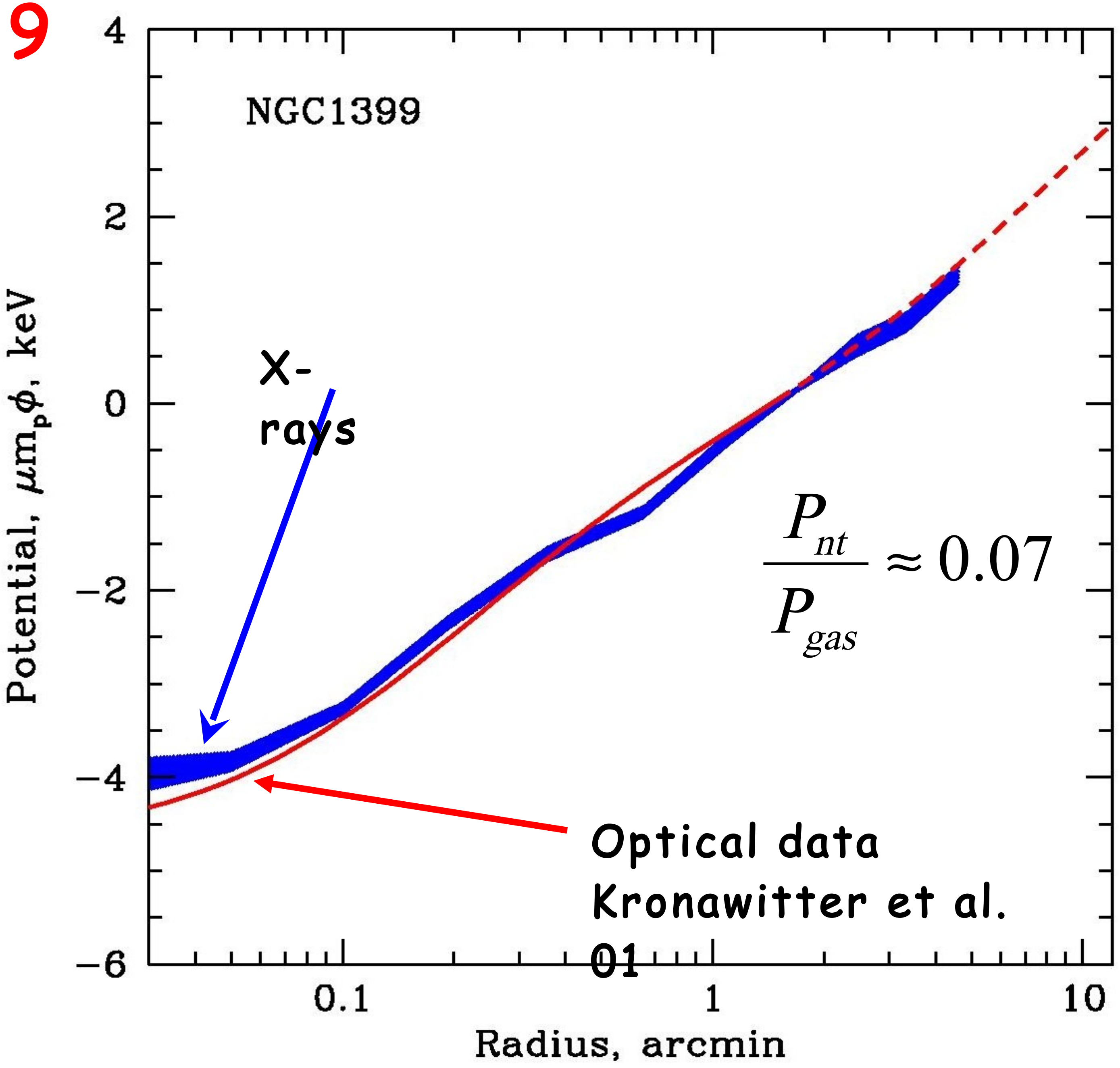
Gas: hydrostatic equilibrium [stationary, spherical system]

$$\frac{1}{\rho_{gas}}\frac{dP_X}{dr}=-\nabla\varphi_X$$

$$P_X=nkT$$

$$\varphi_X(r)\approx\alpha\,\varphi_{true}(r),\qquad \alpha\leq 1$$

NGC1399



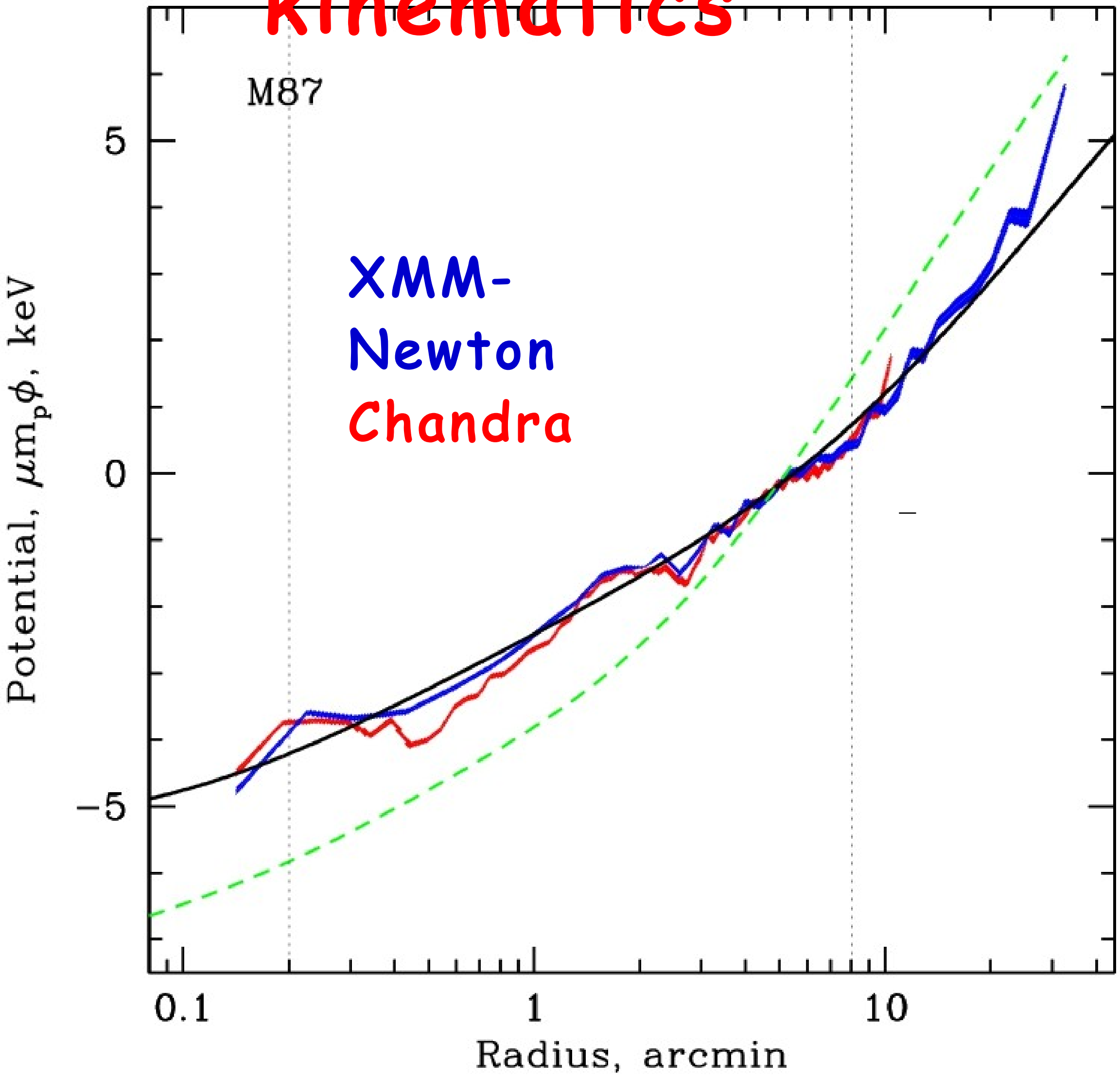
X-rays

$$\frac{P_{nt}}{P_{gas}} \approx 0.07$$

Optical data
Kronawitter et al. 01

EC+,

M87: X-rays + stellar kinematics



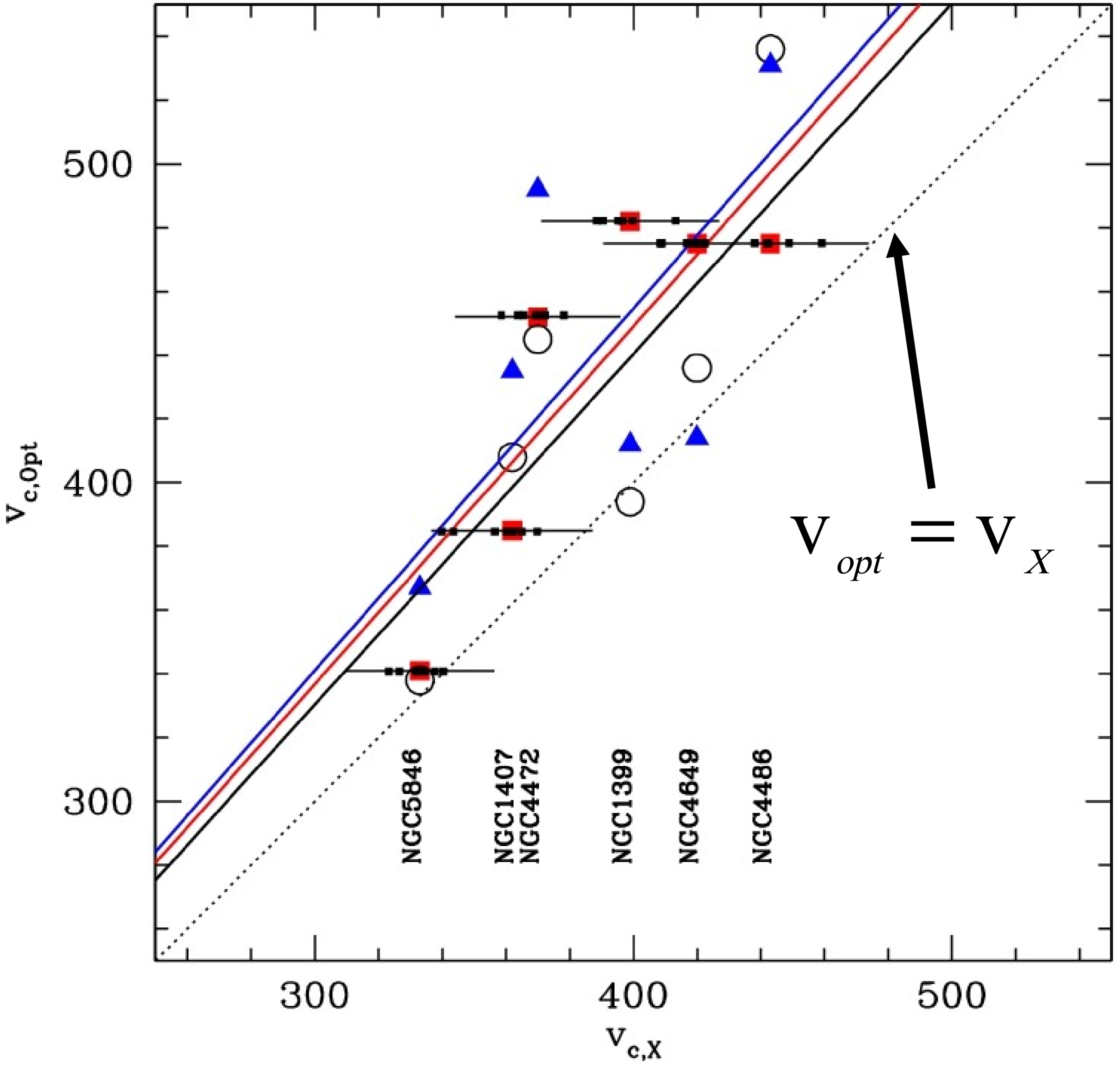
XMM-Newton

Chandra

Romanowsky & Kochanek, 2001

Gebhardt & Thomas, 2010

Comparison of optical and X-ray effective Vc



$$v_{opt} = v_X$$

Red - central vel.disp.

Blue - sweet point

Black - local

$$v_c = 1.12 \times v_X$$

$$v_s = 1.14 \times v_X$$

$$v_l = 1.10 \times v_X$$

Non-thermal pressure

10-20-30%

$$\varphi_X(r) \approx \alpha\varphi_{true}(r) + C$$

Non-thermal pressure and AGN/ICM interaction?

Observations:

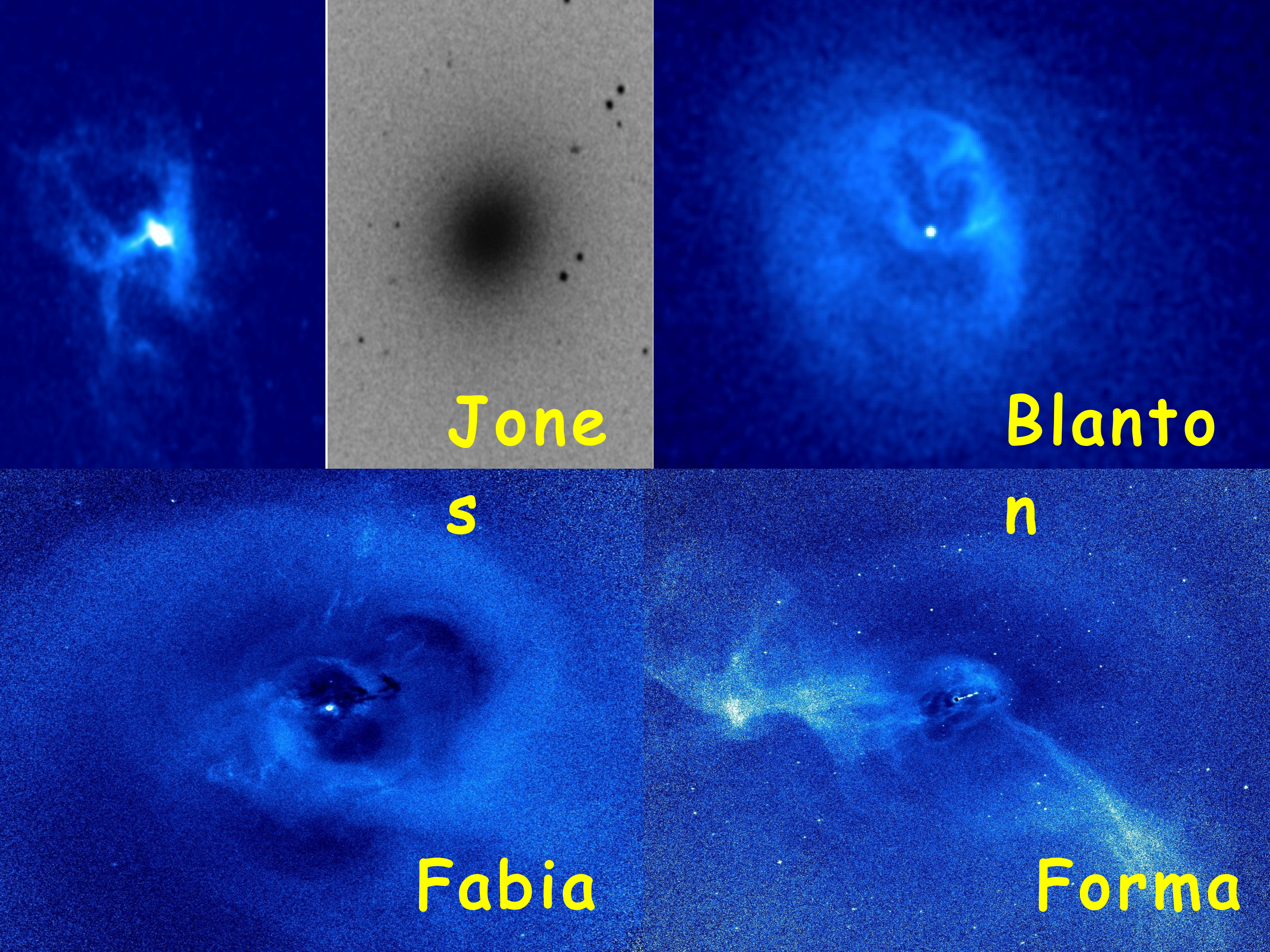
In nearby clusters and groups central SMBH provides enough mechanical energy to offset ICM cooling losses

Simulations:

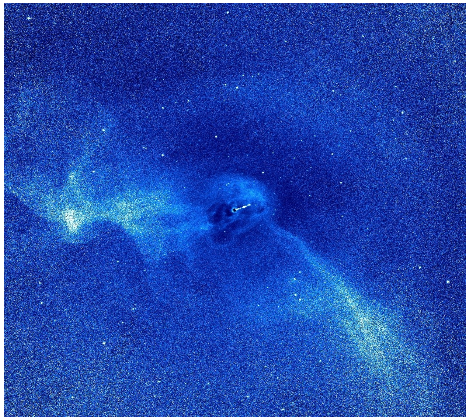
Fraction of the SMBH rest mass (if released at appropriate time) can stop star formation in galaxies

Minimal model: same physical mechanism

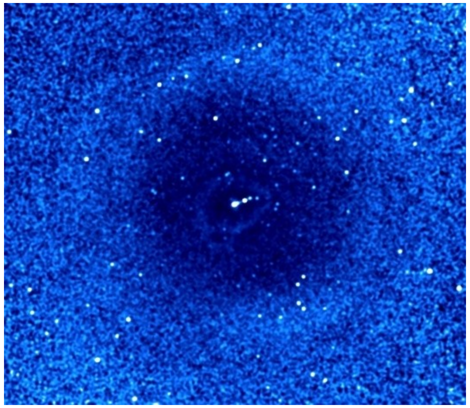
AGN supplies to ICM: cosmic rays, magnetic fields and generates turbulence


Jones
Blanton
Fabia
Forma

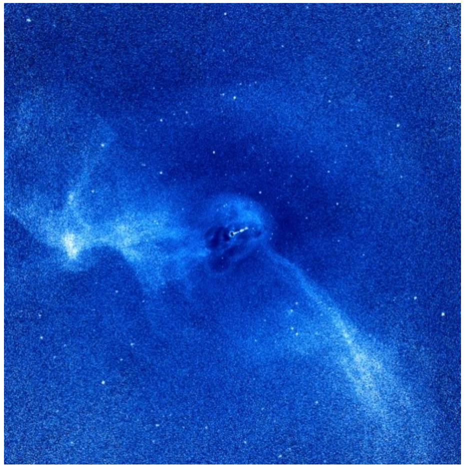
What AGN does to ICM? (outflow of rel. plasma)



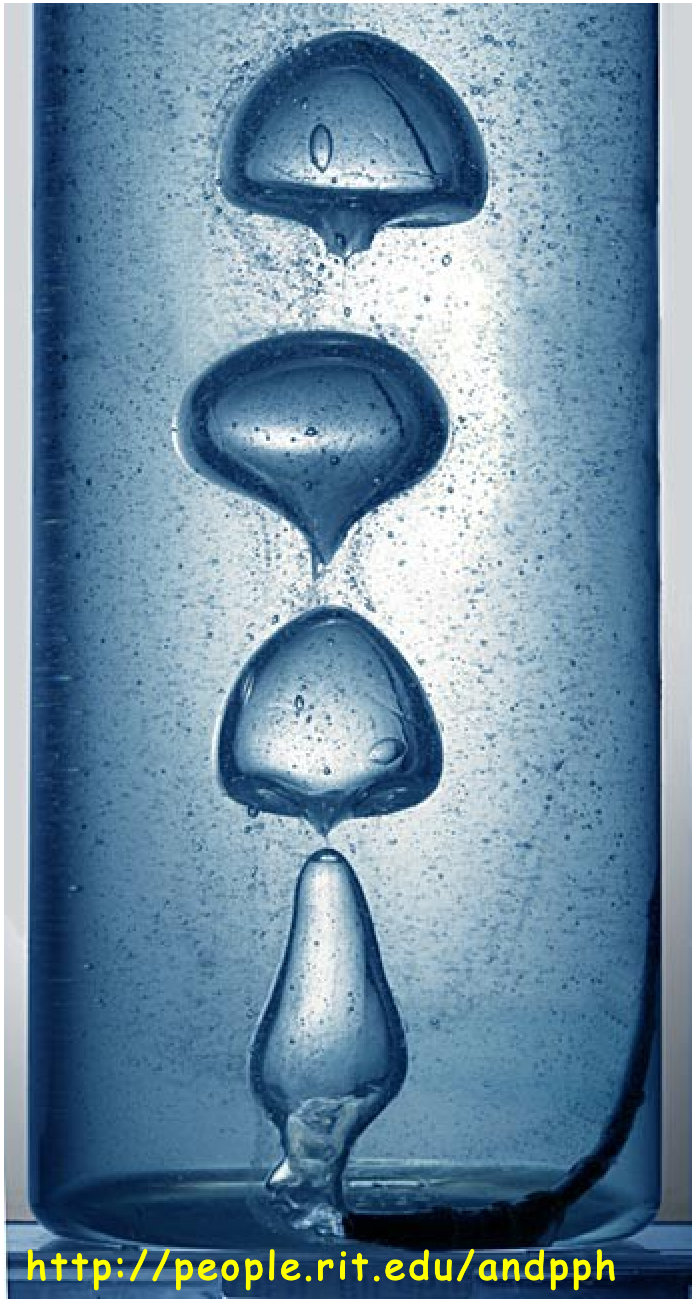
Inflation of bubbles



Shocks around bubbles



Entrainment of low entropy gas



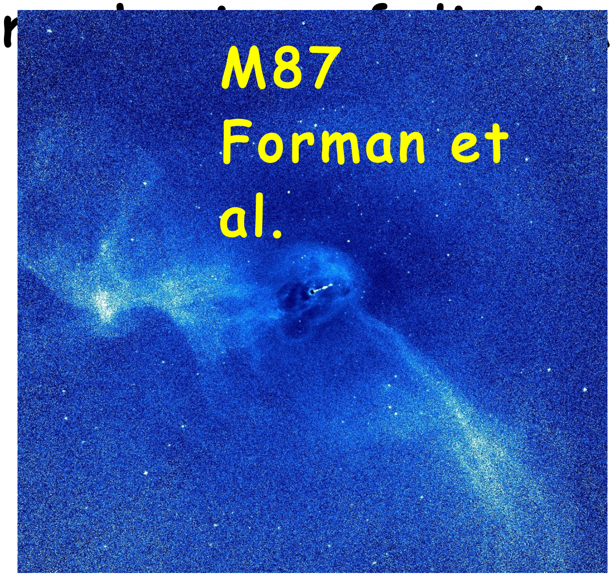
http://people.rit.edu/andpph

Most efficient way to capture mechanical energy flow from AGN

1) Put all energy into relativistic plasma
2) Subsonically inflate a bubble
3) Let it rise few scale-heights

100% efficient,

r tion is not



M87
Forman et al.

Efficiency $\alpha_M \sim 1$

AGN supplies energy to ICM which offsets cooling

If

Heating=Cooling

Measuring the turbulence

$$\frac{E_{nt}}{E_{thermal}} \approx 0.1-0.3; \quad t_{dis} = \frac{E_{nt}}{L_{cool}}$$

If turbulence dominates =>

$$t_{dis} \approx \frac{l}{\mathrm{v}}$$

$$\mathrm{v} \approx 300\ \mathrm{km/s}$$

$$l \approx 10\ \mathrm{kpc}$$

To be measured by

Conclusions

10-30% of total pressure in the ICM is non-thermal
(estimates to be improved soon)

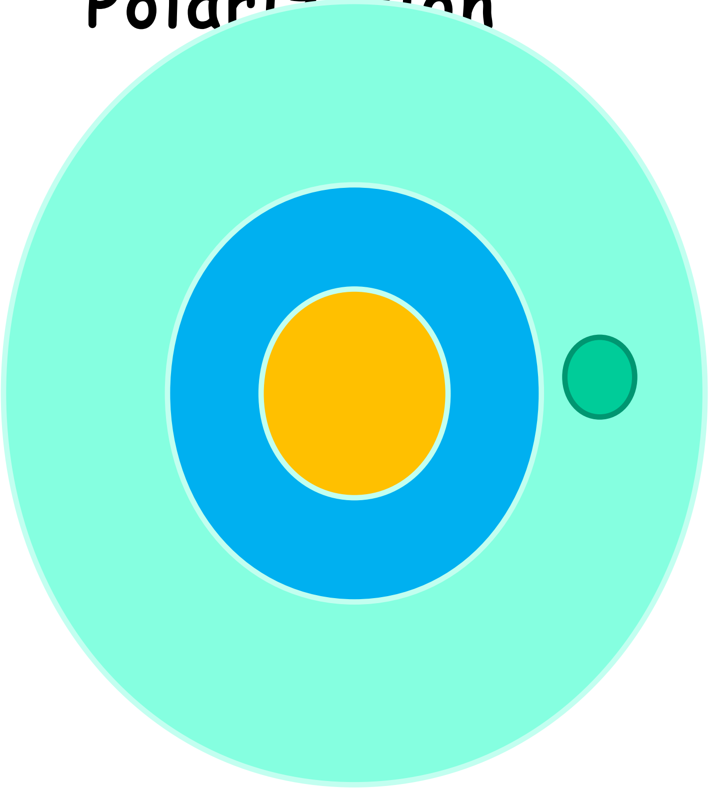
Simple recipe for potential comparison is available,
(although it does not replace full dynamic models)

Broadly consistent with AGN/ICM coupling scheme

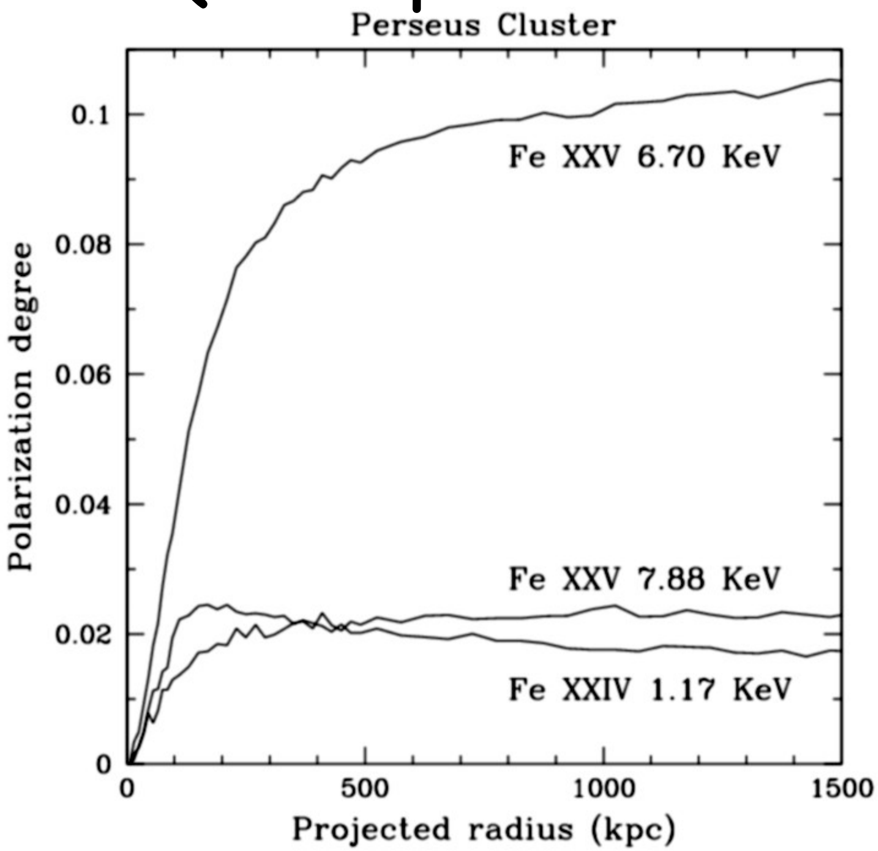
Backup slides….

Polarization II

Rayleigh phase function + Quadrupole = Polarization



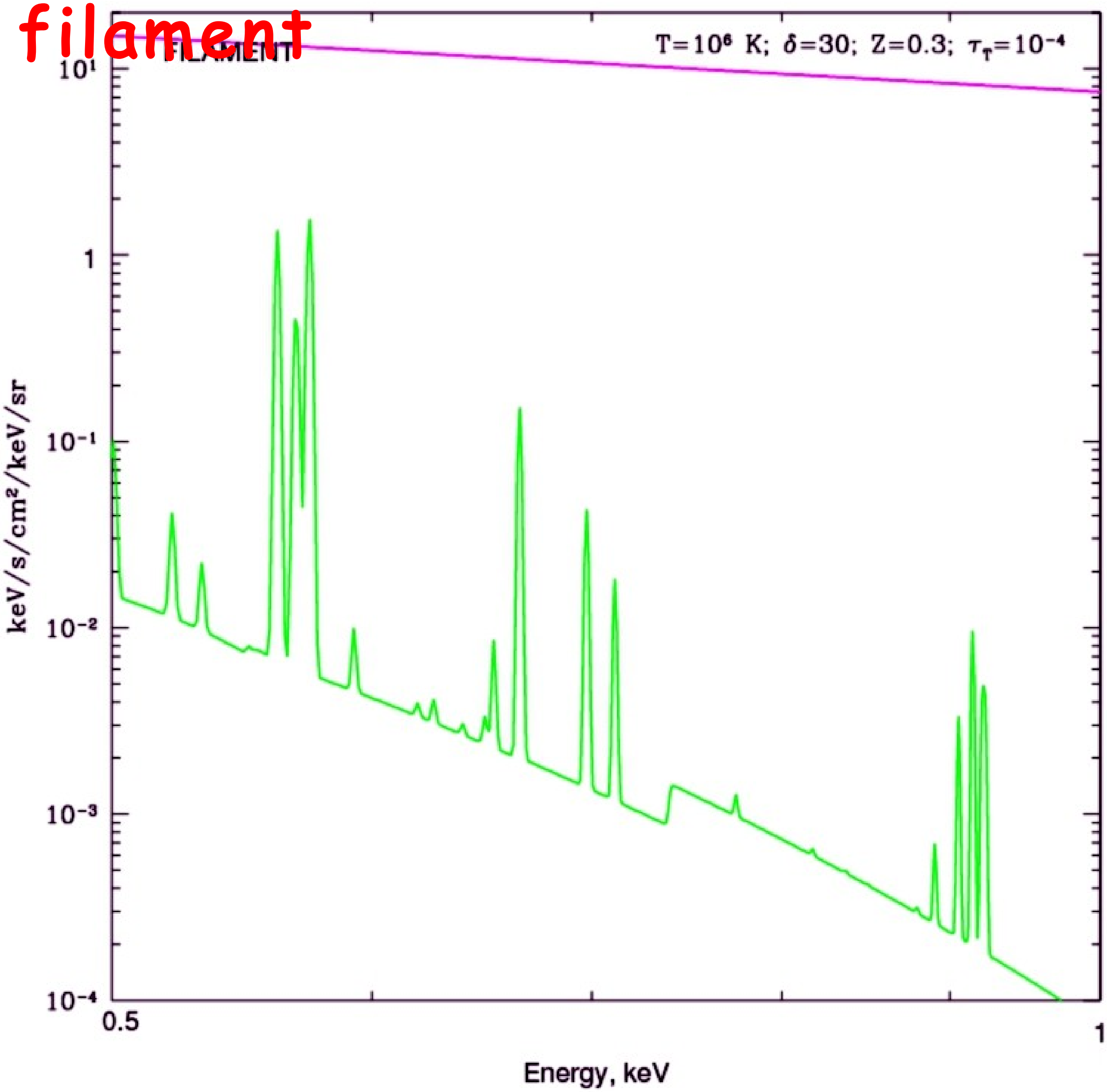
100% polarized



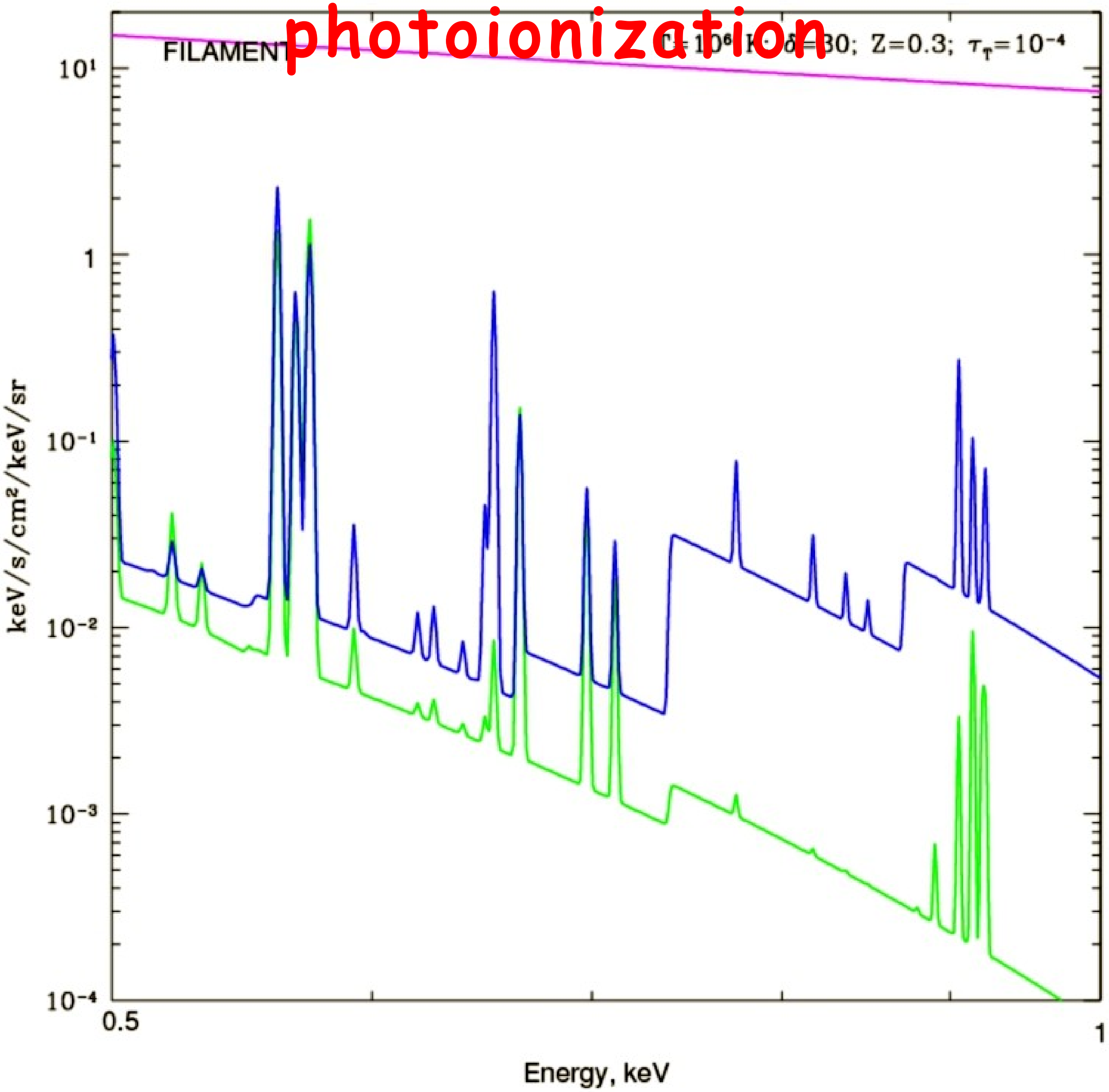
Center: 0%
Outskirts: 10%

Sazonov+ 2002a; Zhuravleva+

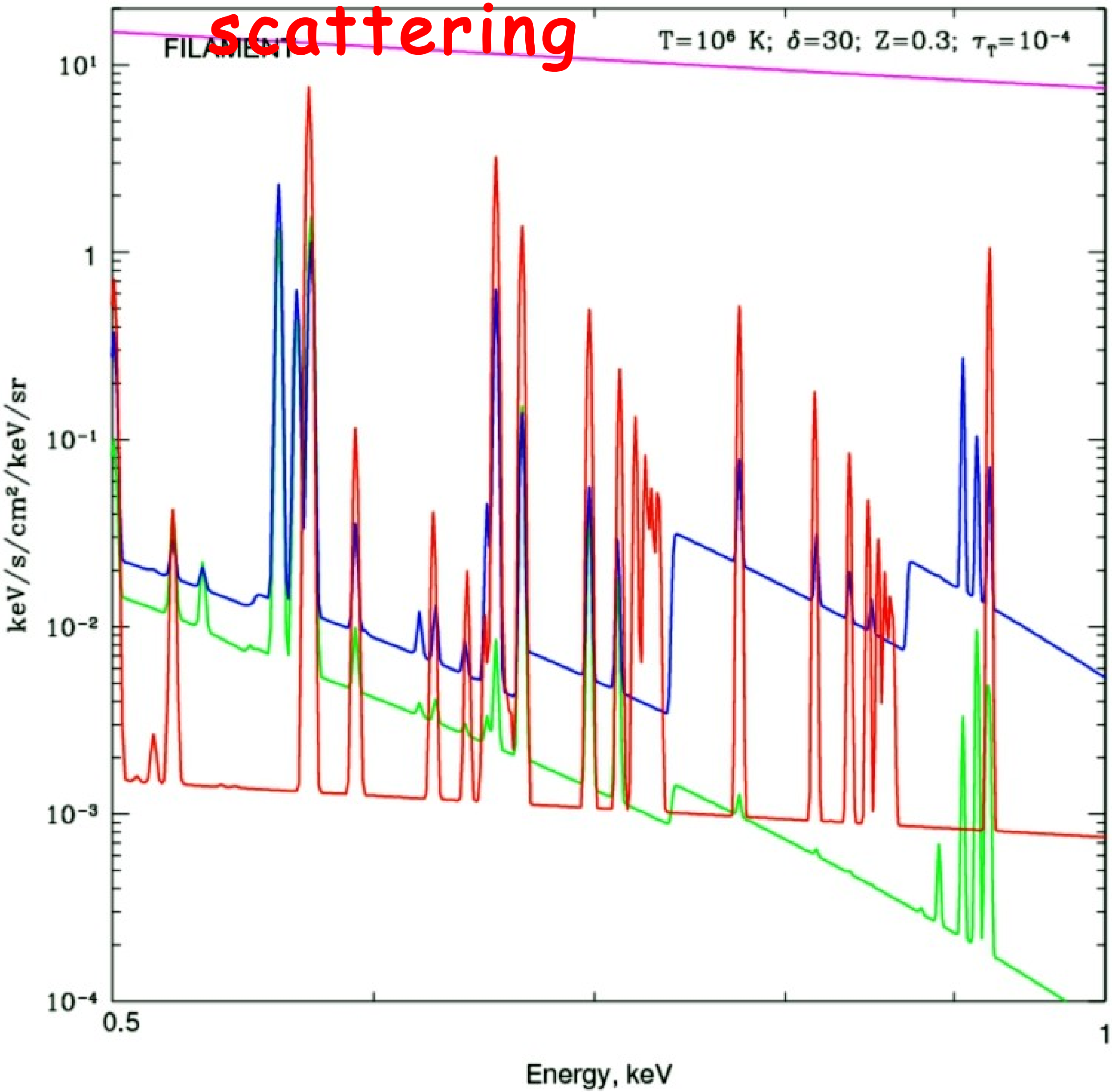
Thermal emission of the filament



\+ photoionization



+ resonant scattering

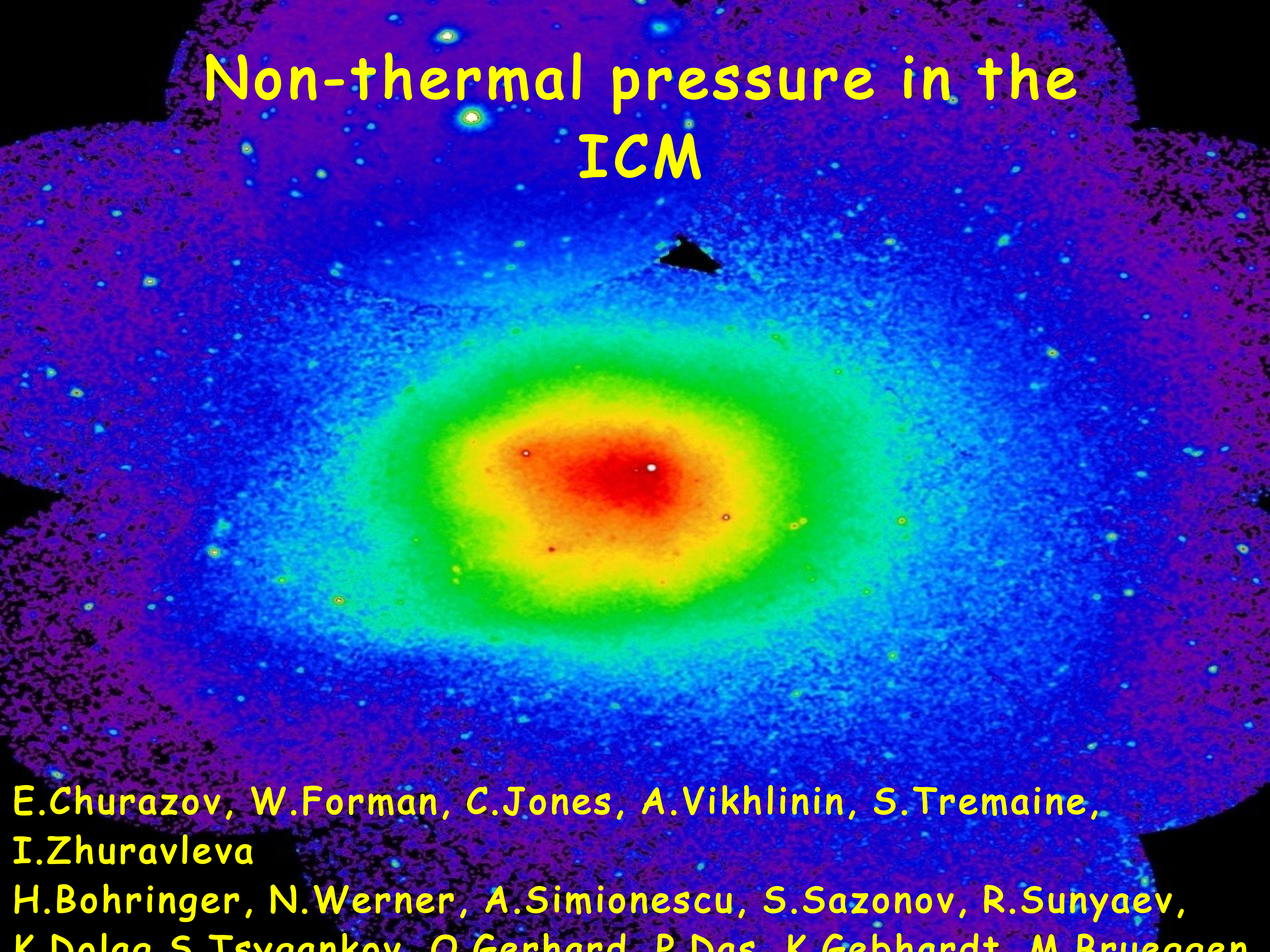


EW~90

Table 2. The best fit parameters for a single-temperature, optically thin plasma model fitted to the *XMM-Newton* RGS spectra extracted from 0.5′ wide regions centred on the cores of the galaxies. For NGC 4636 we also show the results from fits to spectra extracted from two 2.25′ wide regions surrounding the core (see Fig. 2). The 13.8–15.5 Å part of the spectrum, where the strongest Fe xvii and Fe xviii resonance lines are present was initially excluded from the fits. Fluxes are given in the 0.3–2.0 keV band. The emission measure is defined as $Y = \int n_e n_H dV$. The scale factor s is the ratio of the observed LSF width to the expected LSF for a flat abundance distribution. Abundances are quoted with respect to the proto-solar values of Lodders (2003). The last three rows list the best fit line ratios in the full spectral band (after the Fe xvii ion was set to zero in the model and replaced by gaussian lines), the theoretical line ratios predicted for an optically thin plasma, and the derived level of suppression of the 15.01 Å line, $(I/I_0)_{15.01\text{Å}}$.

galaxy	NGC 4636 core	NGC 4636 outer reg.	NGC 5813	NGC 1404	NGC 4649	NGC 4472
flux (10^{-12} erg cm^{-2})	1.75 ± 0.08	2.57 ± 0.17	1.47 ± 0.12	1.08 ± 0.11	1.63 ± 0.10	1.44 ± 0.08
Y (10^{64} cm^{-3})	0.47 ± 0.02	0.46 ± 0.03	1.01 ± 0.10	0.50 ± 0.05	0.31 ± 0.03	0.34 ± 0.02
kT (keV)	0.606 ± 0.006	0.695 ± 0.004	0.645 ± 0.008	0.608 ± 0.009	0.774 ± 0.007	0.781 ± 0.006
s	0.40 ± 0.04	1.02 ± 0.04	0.87 ± 0.11	0.97 ± 0.22	0.69 ± 0.21	0.79 ± 0.12
N	1.3 ± 0.3	1.5 ± 0.4	2.0 ± 0.8	2.3 ± 0.8	1.3 ± 0.7	1.3 ± 0.5
O	0.44 ± 0.05	0.61 ± 0.06	0.53 ± 0.09	0.58 ± 0.10	0.61 ± 0.15	0.53 ± 0.07
Ne	0.31 ± 0.08	0.39 ± 0.18	0.33 ± 0.19	0.81 ± 0.22	1.31 ± 0.35	1.18 ± 0.22
Fe	0.52 ± 0.03	0.92 ± 0.06	0.75 ± 0.09	0.67 ± 0.08	0.87 ± 0.18	0.83 ± 0.08
$[(I_{\lambda 17.05} + I_{\lambda 17.10})/I_{\lambda 15.01}]_{\text{observed}}$	2.04 ± 0.21	1.28 ± 0.13	1.99 ± 0.34	1.98 ± 0.29	1.25 ± 0.28	2.24 ± 0.34
$[(I_{\lambda 17.05} + I_{\lambda 17.10})/I_{\lambda 15.01}]_{\text{predicted}}$	1.31	1.31	1.30	1.31	1.27	1.27
$I_{15.01}/I_{0\ 15.01}$	0.64 ± 0.07	1.02 ± 0.10	0.65 ± 0.11	0.66 ± 0.10	1.02 ± 0.23	0.57 ± 0.09

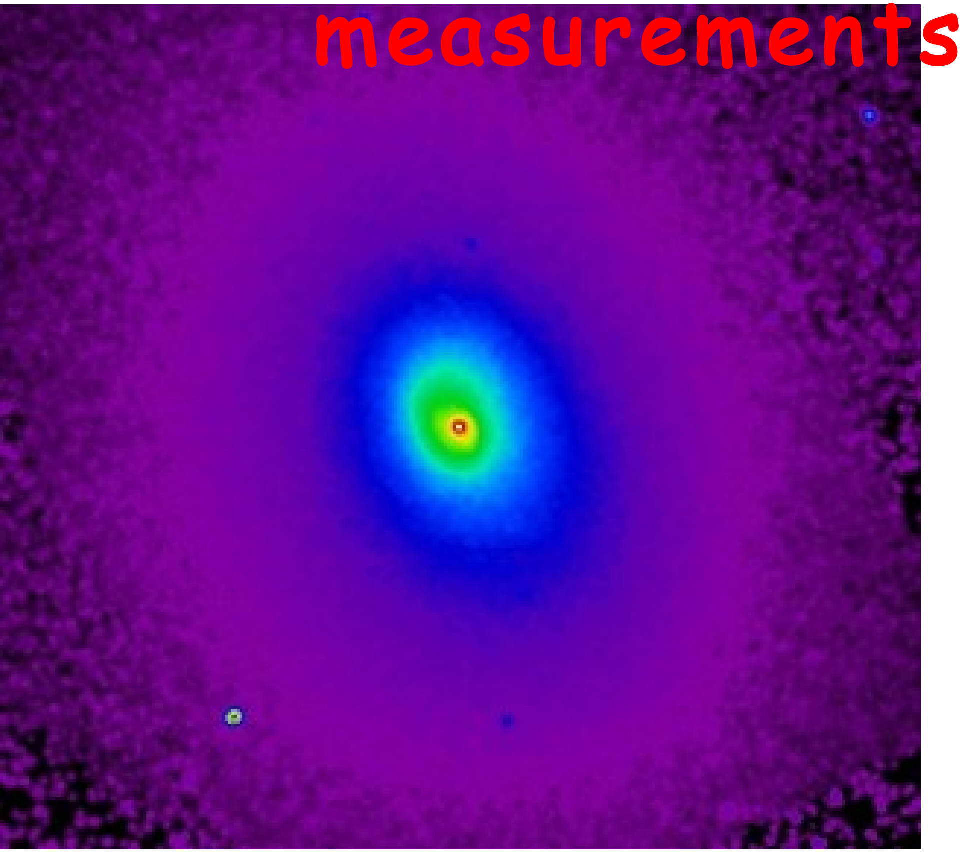
3D - 2D

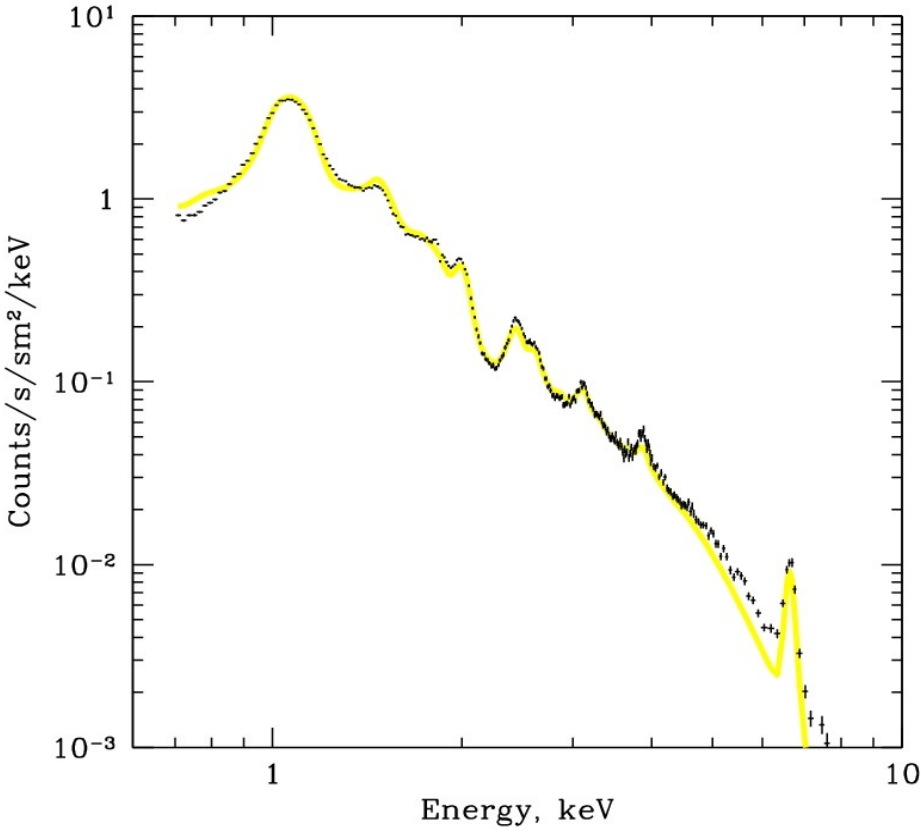


Non-thermal pressure in the ICM

E.Churazov, W.Forman, C.Jones, A.Vikhlinin, S.Tremaine, I.Zhuravleva
H.Bohringer, N.Werner, A.Simionescu, S.Sazonov, R.Sunyaev,
K.Dolag, S.Tsygankov, O.Gerhard, P.Das, K.Gebhardt, M.Brueggen

Mass from X-ray measurements





$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2} \quad \Rightarrow \quad M(< R)$$

Virial theorem in isothermal potential (spherical, stationary system)

$$\varphi = \mathrm{v}_c^2 \ln r$$

$$\ddot{\mathbf{r}} = -\nabla\varphi = \mathrm{v}_c^2 \frac{\mathbf{r}}{r^2} \qquad I = \frac{1}{2} r^2$$

$$\left\langle \ddot{I} \right\rangle = \left\langle \dot{\mathbf{r}}^2 + \mathbf{r}\cdot\ddot{\mathbf{r}} \right\rangle = \left\langle \mathbf{v}^2 \right\rangle - \mathrm{v}_c^2 = 0$$

$$\sigma_p^2 = \frac{1}{3}\left\langle \mathbf{v}^2 \right\rangle = \frac{1}{3}\mathrm{v}_c^2$$

$$\boxed{\mathrm{v}_c^2 = 3\sigma_p^2}$$

Anisotropy does not matter. But works
only for a distant galaxy, which is
entirely within the spectrograph

Next step beyond virial theorem: Isothermal potential + Isotropic orbits

$$\frac{1}{n_*}\frac{dn_*\sigma_r^2}{dr} + 2\frac{\beta}{r}\sigma_r^2 = -\frac{d\varphi}{dr}$$

$$\varphi = \mathrm{v}_c^2 \ln r, \quad \beta = 0 \Rightarrow \frac{1}{n_*}\frac{dn_*\sigma_r^2}{dr} = -\mathrm{v}_c^2 \frac{1}{r}$$

$$n_*(r)\sigma_r^2(r) = \mathrm{v}_c^2 \int_r^\infty \frac{dx}{x} n_*(x)$$

$$\sigma_p^2(R) = \frac{R\mathrm{v}_c^2}{I(R)} \int_R^\infty \frac{dx}{x^2} I(x)$$

Non-local and local σ/v relation

$$\sigma_{iso}^2(R) = \mathrm{v}_c^2 \frac{R}{I(R)} \int_R^\infty I(x) \frac{dx}{x^2}$$

Non-local

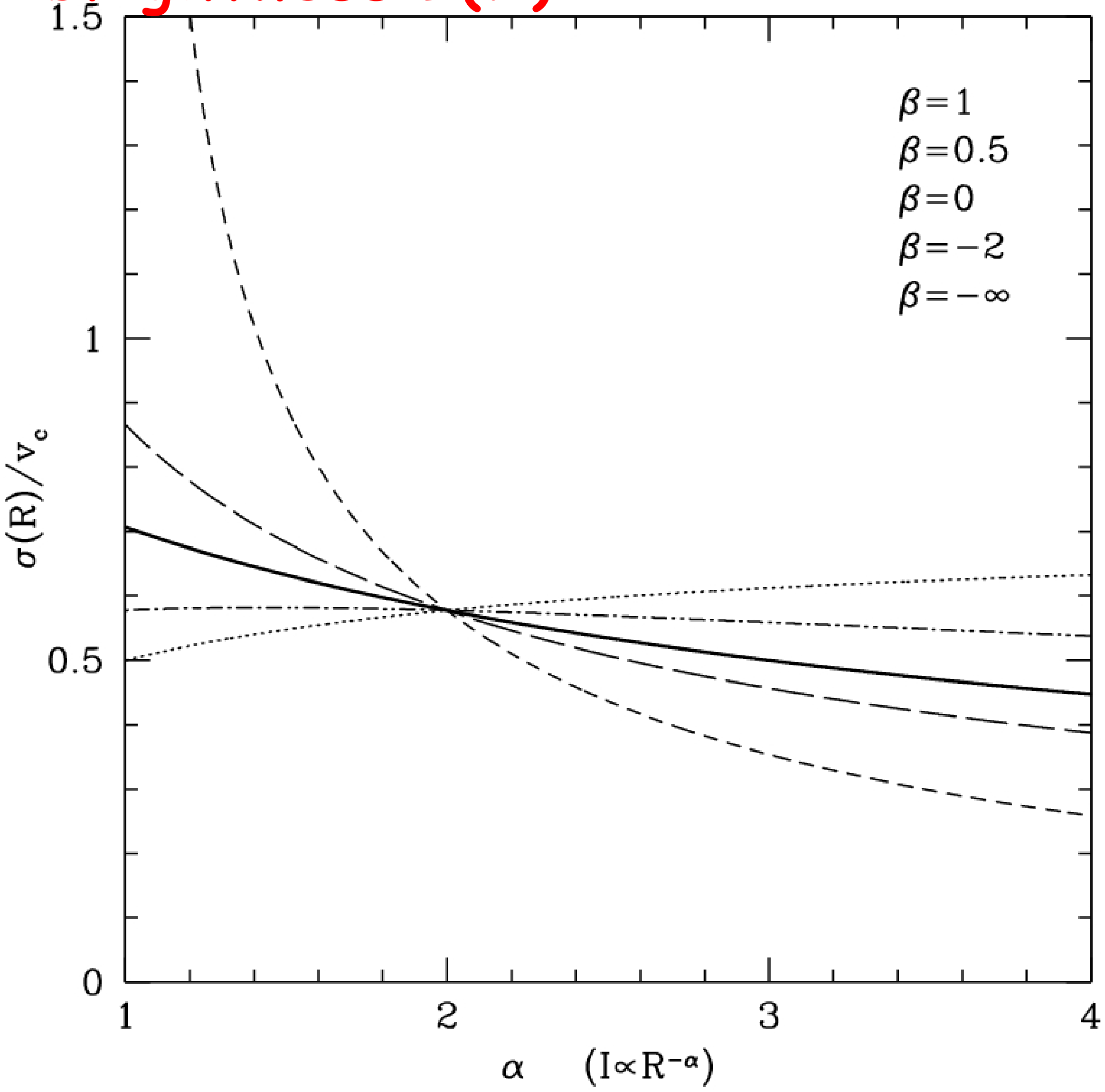
$$\frac{I(R)}{R} \sigma_{iso}^2(R) = \mathrm{v}_c^2 \int_R^\infty I(x) \frac{dx}{x^2}$$

$$\sigma_{iso}^2(R) = \mathrm{v}_c^2 \frac{1}{1+\alpha+\gamma}$$

Local

$$\alpha = -\frac{d \ln I(R)}{d \ln R}; \quad \gamma = -\frac{d \ln \sigma^2}{d \ln R}$$

Isothermal potential + Power law surface brightness I(R)



$$\varphi(r) = v_c^2 \ln r$$

$$I(R) \propto R^{-\alpha}$$

$$\frac{\sigma_p}{V_c}$$ independent on R

$$\sigma_{iso}^2(R) = v_c^2 \frac{1}{1+\alpha}$$

$$\sigma_{circ}^2(R) = \frac{1}{2} v_c^2 \frac{\alpha}{1+\alpha}$$

$$\sigma_{rad}^2(R) = \frac{1}{2} v_c^2 \frac{1}{\alpha^2-1}$$

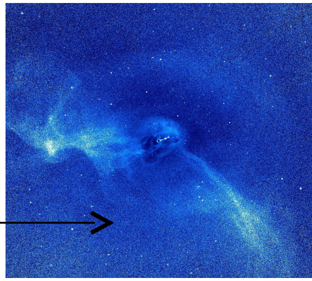
For α=2
no dependence on β!
(Gerhard, 1993)

Measuring cosmic rays, magnetic fields and turbulence separately

Cosmic rays: limits on the gamma-ray flux

$$p + p \rightarrow \pi^{0} \rightarrow 2\gamma$$

$$p + p \rightarrow \pi^{+,-} \rightarrow e^{+,-} \Rightarrow \mathrm{IC}$$



FERMI

$$\frac{E_{CR}}{E_{therml}} \leq 0.02 - 0.1$$

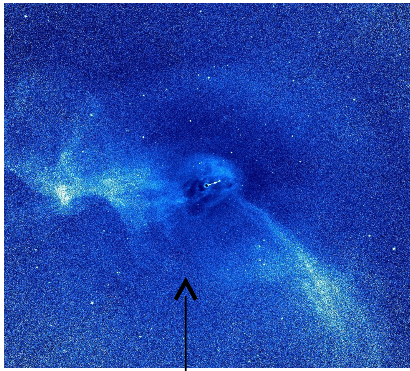
Ackermann+, 2010

(provided cosmic ray protons are mixed with plasma)

Measuring cosmic rays, magnetic fields and turbulence separately

Magnetic fields: Faraday rotation

$$\propto \int n_e B_{\parallel} dl$$



(provided magnetic field and thermal plasma are mixed;
correlation length)

Measuring cosmic rays, magnetic fields and turbulence separately

Micro-turbulence:

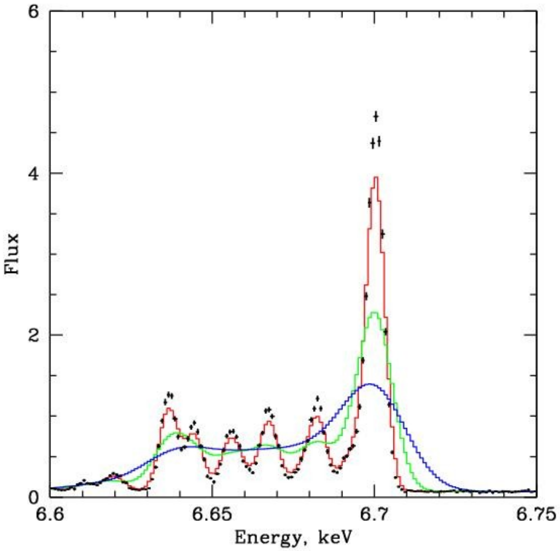
Resonant scattering: broader lines -> smaller optical depth (EC+,04; Xu+,02; Werner+,10: few % - 25% of thermal energy)

X-ray line broadening in RGS/XMM spect
(Sanders+,10; <13% of thermal energy)

Transport of heavy elements (Rebusco+,(

Impact on polarization (Zhuravleva+,10)

ASTRO-H – few %



Measuring cosmic rays, magnetic fields and turbulence together

Cosmic rays, magnetic fields, micro-turbulence increase energy per particle.

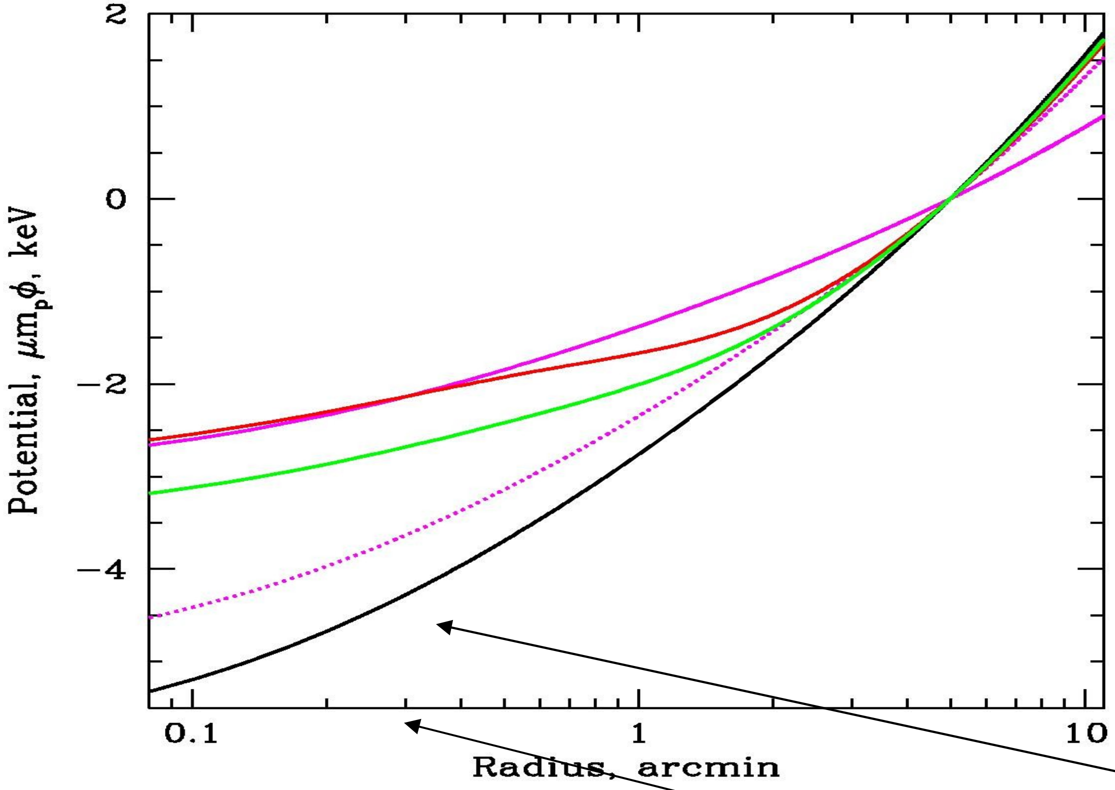
If the gas is in hydrostatic equilibrium => non-thermal component makes the gas distribution broader => wrong mass/potential

$$\varphi_X(r) = \alpha\,\varphi_{true}(r) + C$$

$$1-\alpha = \frac{P_{CR} + P_{mag} + P_{turb}}{nkT}$$

True potential comes from lensing or stellar kinematics

Impact of non-thermal pressure



$$\frac{d\varphi_{true}}{dr} = -\frac{1}{\rho_{true}}\frac{dP_{true}}{dr}$$

$$P_{thermal} = \alpha P_{true}$$

$$\frac{d\varphi_X}{dr} = -\frac{1}{\rho_{true}}\frac{d\alpha P_{true}}{dr}$$

$$\varphi_X(r) = \alpha\varphi_{true}(r)$$

"Observed" potential

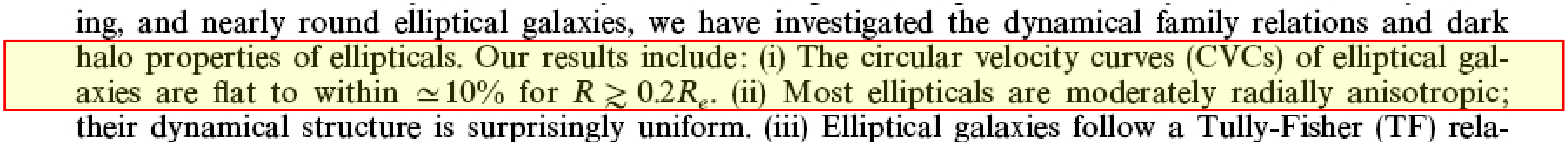
25% - cosmic rays

True potential

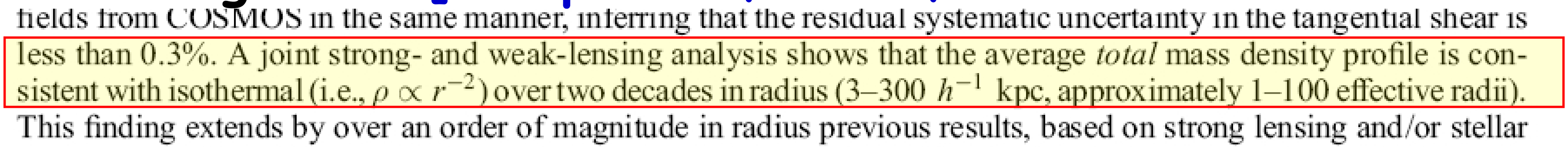
$$\varphi_X(r) \approx \alpha\,\varphi_{true}(r), \qquad \alpha \le 1$$

Are potentials of early-type galaxies isothermal?

Optical: Yes [e.g. Ortwin et al. 2001]


ing, and nearly round elliptical galaxies, we have investigated the dynamical family relations and dark halo properties of ellipticals. Our results include: (i) The circular velocity curves (CVCs) of elliptical galaxies are flat to within $\simeq 10\%$ for $R \gtrsim 0.2 R_e$. (ii) Most ellipticals are moderately radially anisotropic; their dynamical structure is surprisingly uniform. (iii) Elliptical galaxies follow a Tully-Fisher (TF) rela-

Lensing: Yes [Koopmans, Treu, Gavazzi et


fields from COSMOS in the same manner, inferring that the residual systematic uncertainty in the tangential shear is less than 0.3%. A joint strong- and weak-lensing analysis shows that the average *total* mass density profile is consistent with isothermal (i.e., $\rho \propto r^{-2}$) over two decades in radius (3–300 h^{-1} kpc, approximately 1–100 effective radii). This finding extends by over an order of magnitude in radius previous results, based on strong lensing and/or stellar

X-rays: Yes, within limited range of radii

(only very massive systems can be

Potential is approximately isothermal

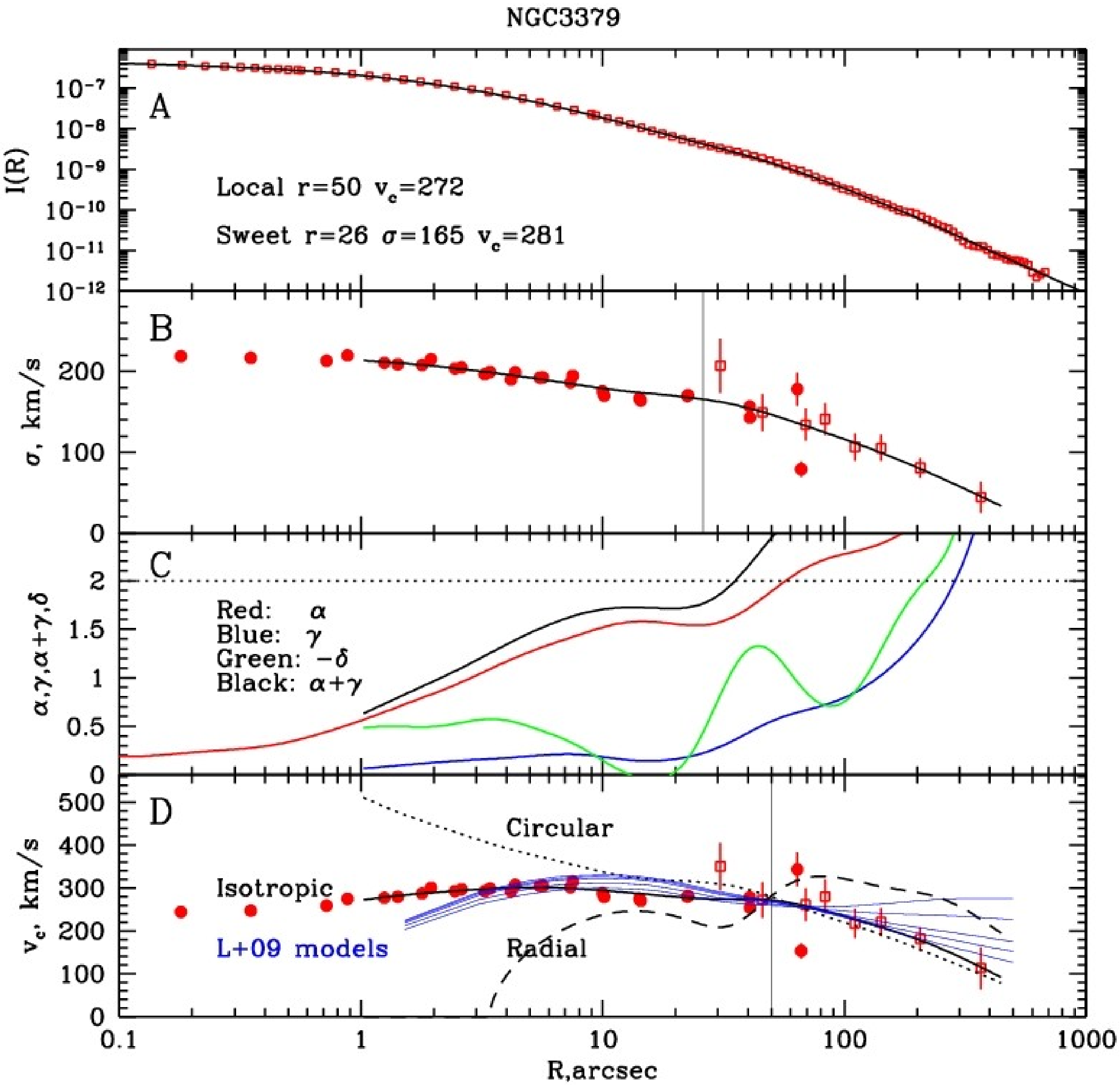
$$\varphi(r) = \mathrm{v}_c^2 \ln r$$

What is the simplest way to estimate circular velocity
from the optical data? Full dynamic models are expensive,
we want simpler method (may be less accurate).

$$I(R)$$

$$\sigma_p(R)$$

Goal: to be insensitive to (unknown) anisotropy of orbits.
Consider three limiting cases: isotropic, radial



$$I(R)$$

$$\sigma_p(R)$$

$$\alpha = -\frac{d\ln I(R)}{d\ln R}$$

$$\gamma = -\frac{d\ln \sigma_p^2}{d\ln R}$$

$$\mathrm{v}_c = (1+\alpha+\gamma)^{1/2}\,\sigma_p$$

EC+,

How quickly the energy deposited by the AGN is dissipated in the ICM?

$$t_{dis} \approx \xi \times t_{cross} \approx 0.1 - 0.2 \times t_{cool}$$

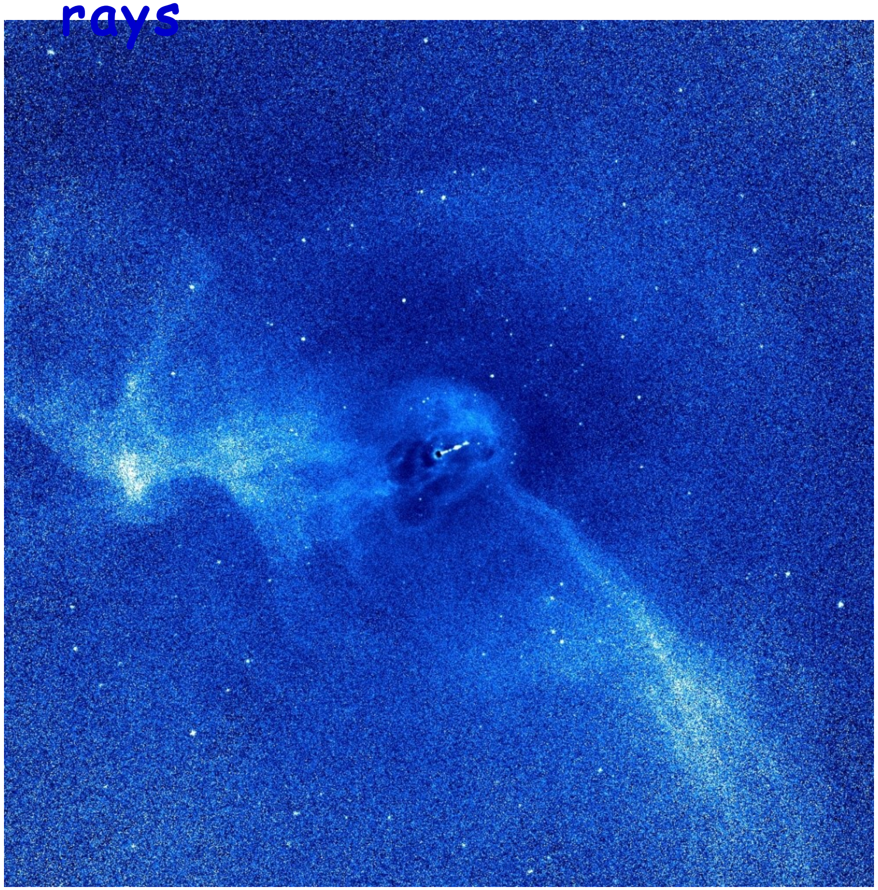
AGN supplies to ICM: cosmic rays, magnetic fields and generates turbulence

If

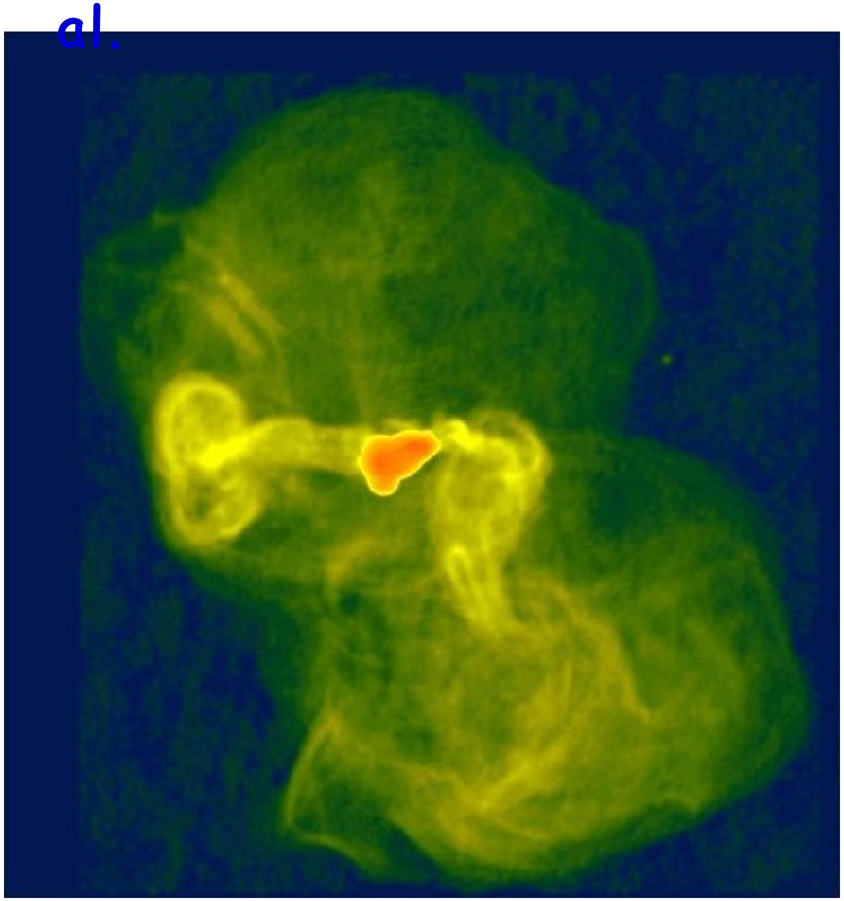
Heating=Cooling

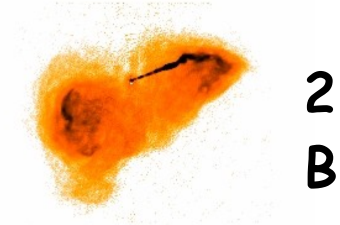
M87

X-rays



Radio, 90cm, Owen et al.

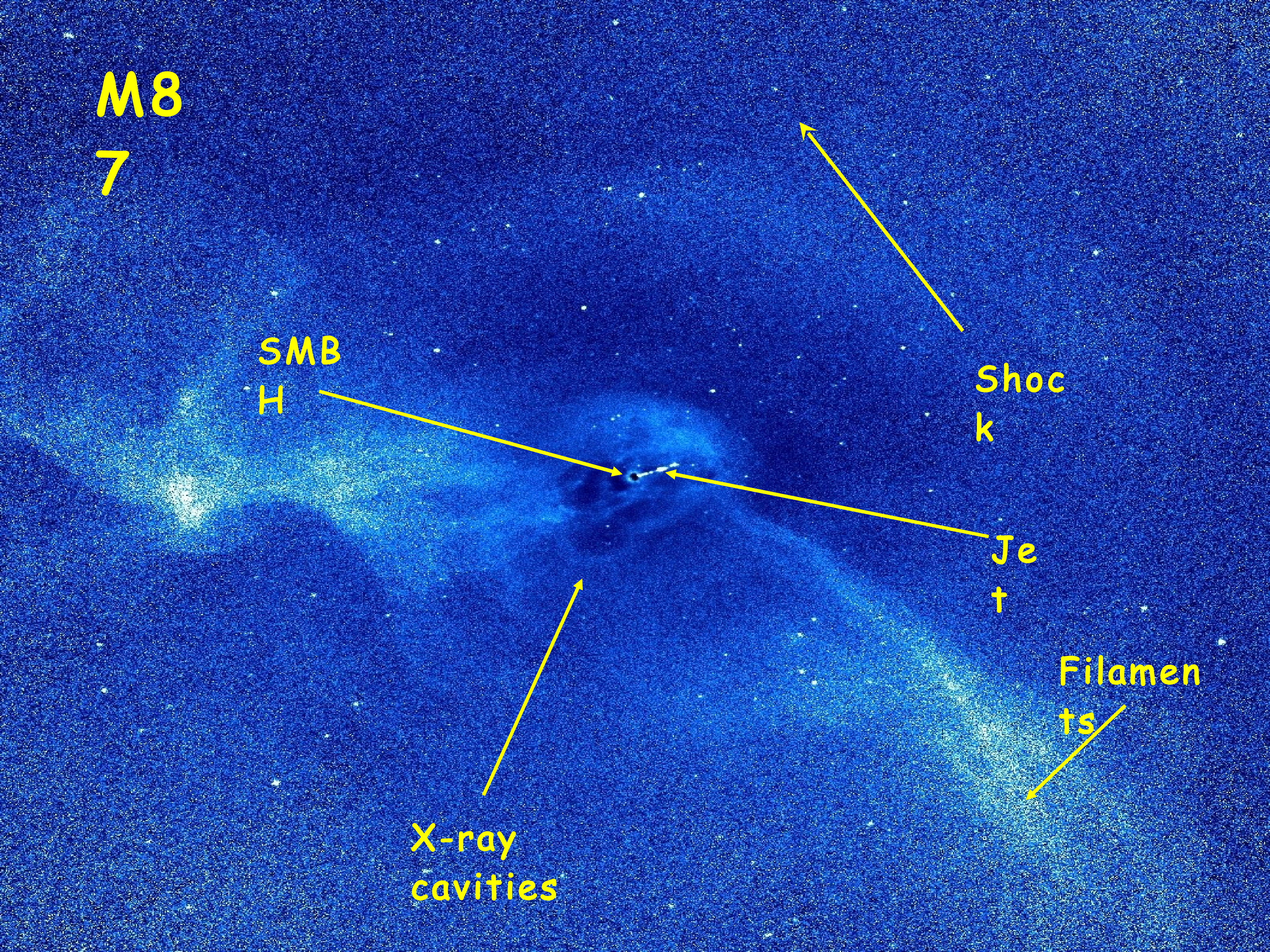




20 cm Biretta

AGN => shocks, bubbles, gas motions…

M87



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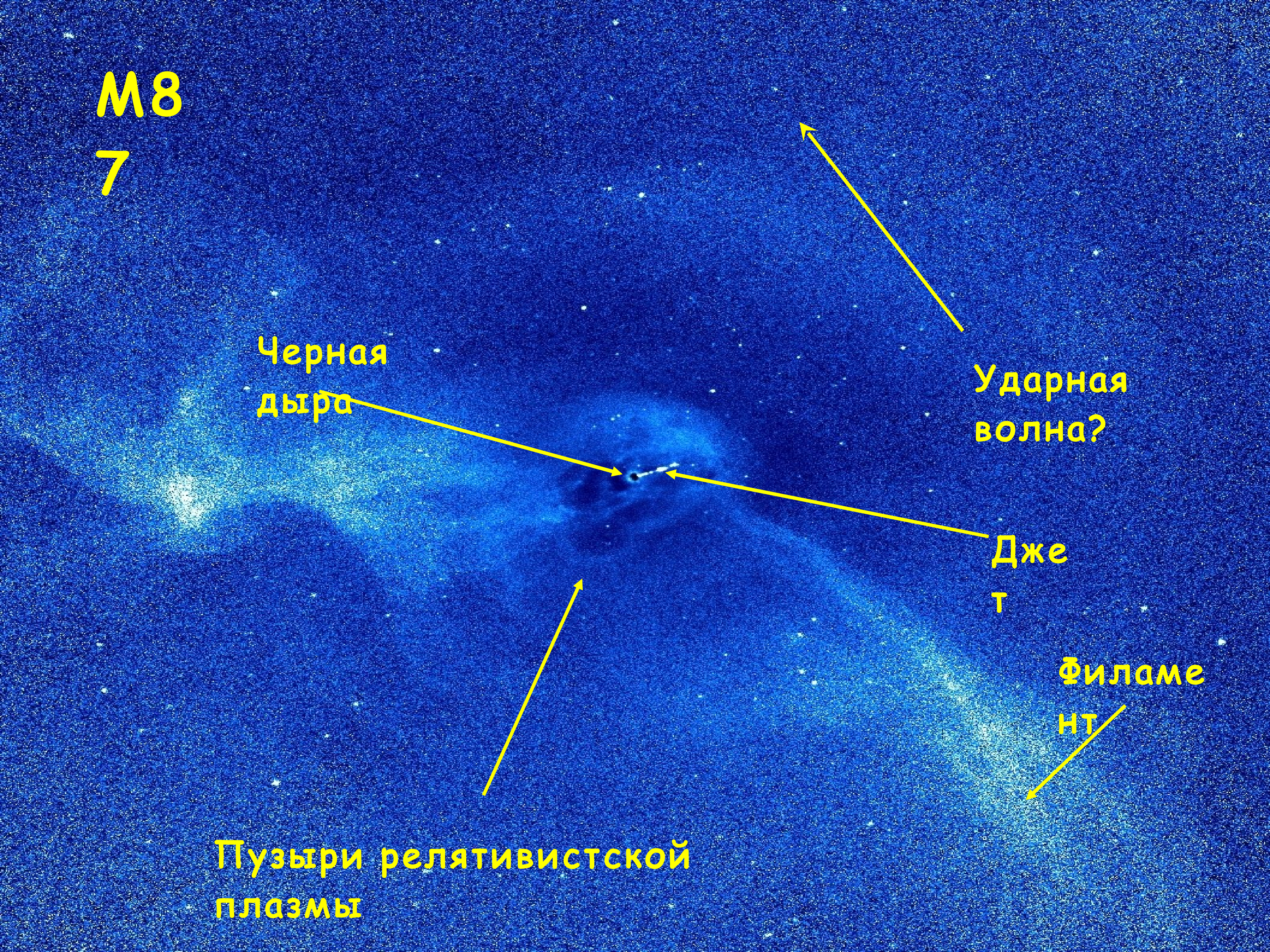


Черная дыра

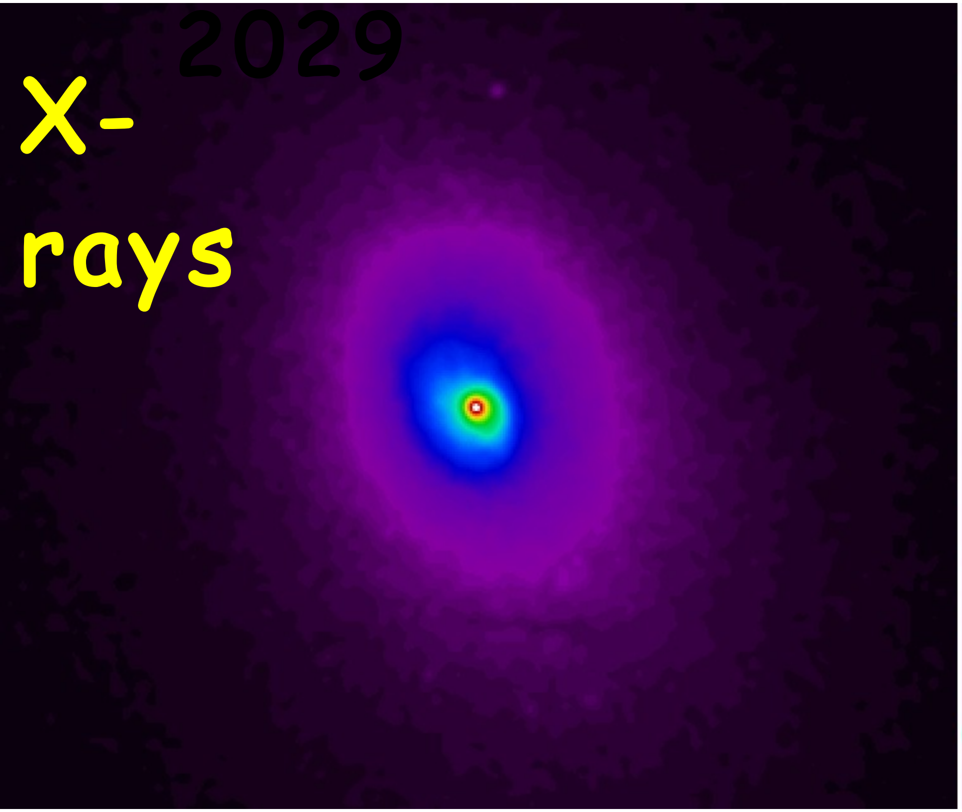
Ударная волна?

Джет

Филамент

Пузыри релятивистской плазмы

Abell 2029



UGC 9752 = IC 1101