Beyond the Standard Lore of the SZ effect

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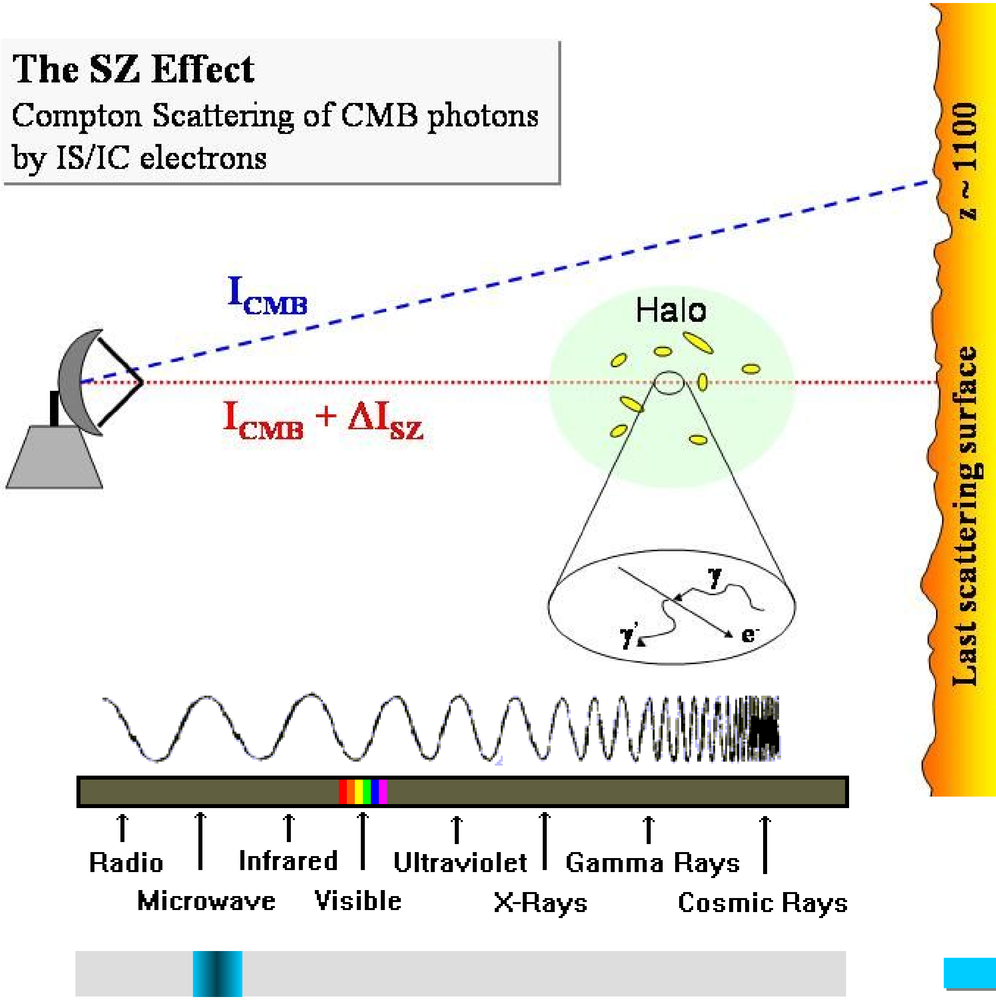
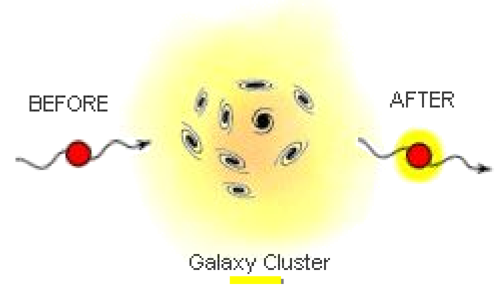
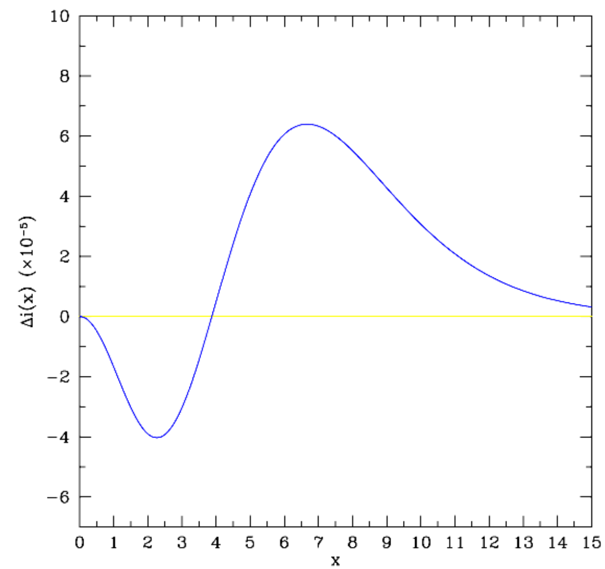
SZ effect: the Standard Lore

The SZ Effect
Compton Scattering of CMB photons by IS/IC electrons





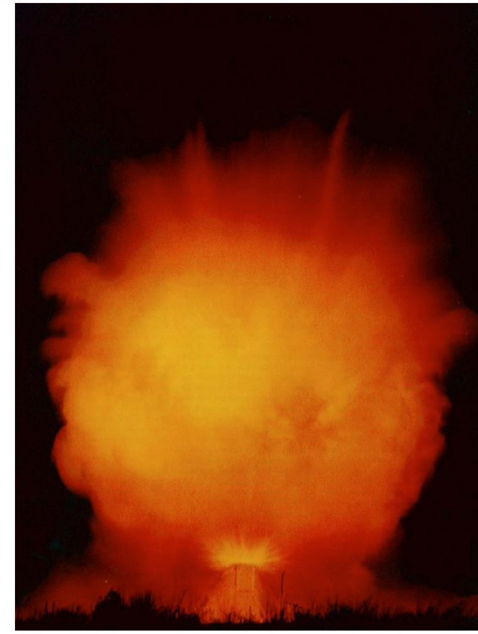


thermal NR e⁻ $\frac{\Delta \nu}{\nu} \approx 4 \frac{kT_e}{m_e c^2}$

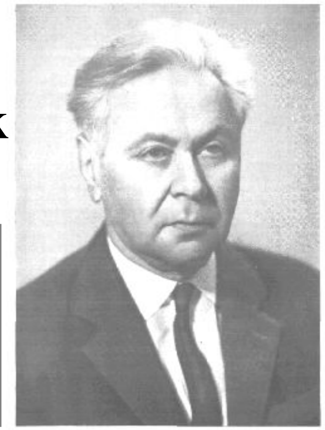
The origin of the SZ effect

Non-coherent Compton Scattering

Fall-out effect of the Cold War



1957 A.S. Kompaneets publishes his Compton scattering Fokker-Planck equation



$$\frac{\partial n}{\partial y} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(\frac{\partial n}{\partial x} + n + n^2\right)$$

(derived by A.S. Kompaneets in Soviet Union ~ 1950 but was classified due to nuclear bomb research until 1956)

1 Ya. B. Zel'dovich & R. Sunyaev derive the thermal SZ effect (i.e., applied the Kompaneets eq.)

SZ effect: observational timeline

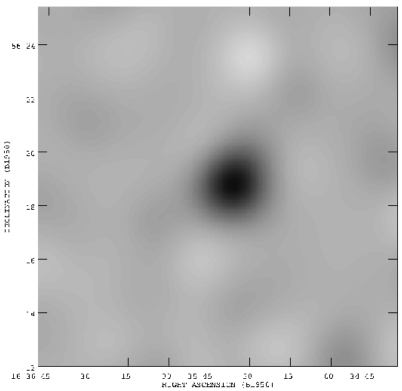
1993 - Ryle tel. first detect the SZE from A2218 (Jones et al. 1993)

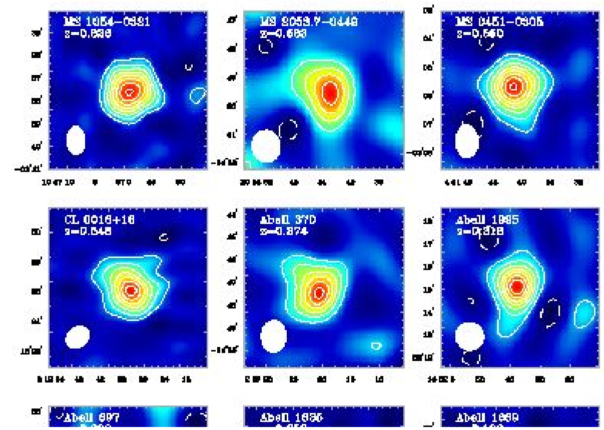
1999 - Interferometric SZE maps out to z ~ 1 (OVRO) (Carlstrom et al. 1999)

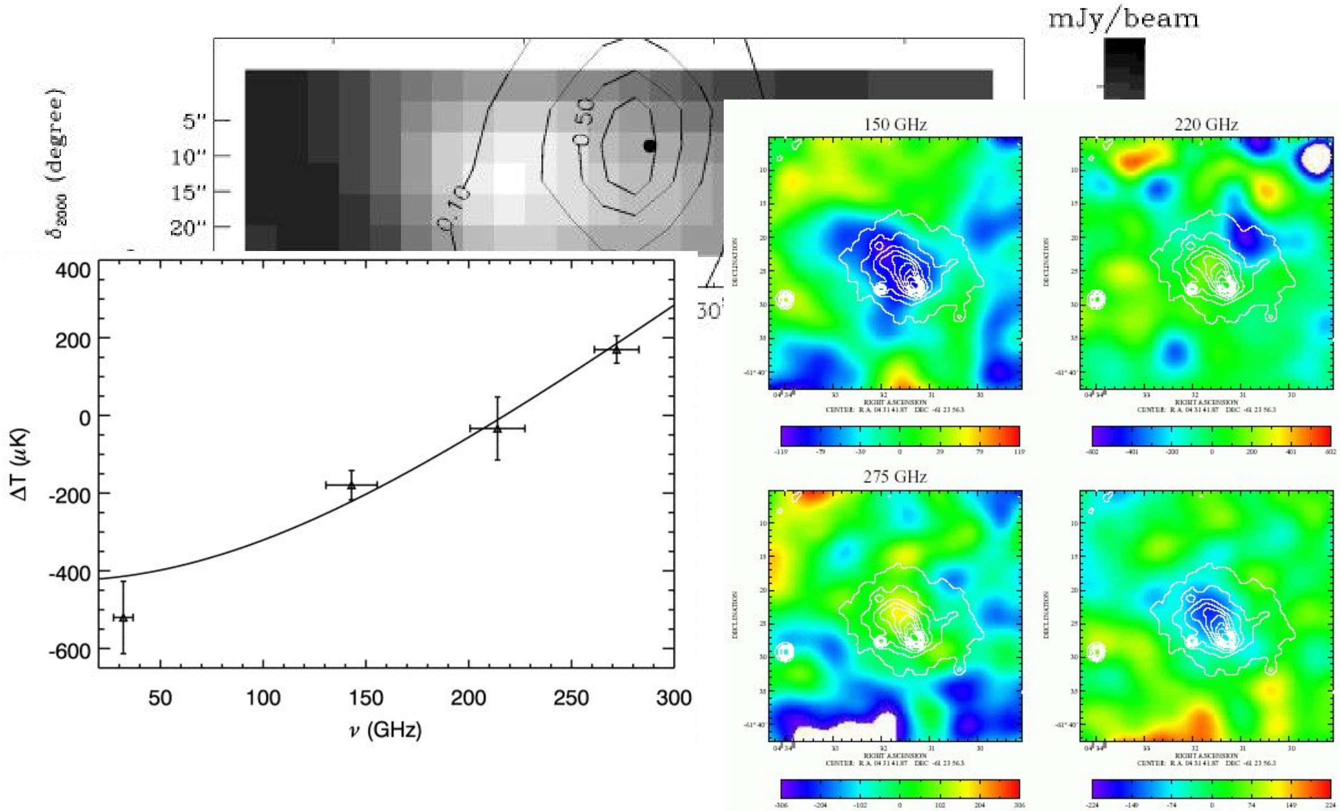
1998 – First sub-mm SZE detection of RXJ1347 (Diabolo) (Pointecouteau et al. 1998)

2002 – First SZE spectrum Coma cluster (DePetris et al. 2002)

2003 – Bolometric observations (5'' FWHM) A3266 (VIPER + ACBAR) (Gomez et al. 2003)







SZ effect: theoretical timeline

1980
Sunyaev & Zel'dovich
ARA&A, 18, 37
Review


CMB distortions by hot IC gas:
- first principles
- non-relativistic approach

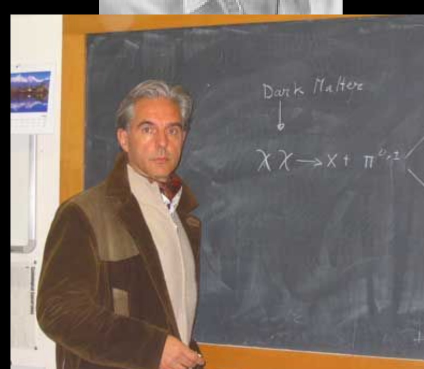
1995
Y.Rephaeli
ARA&A, 33, 541
Review

SZE:
-Various physical mechanisms
  (thermal, kin., pol., …)
- Relativistic treatment

1999
M. Birkinshaw
Phys.Rep., 310, 97
Review

SZE:
- Various astrophysical sources
- Observational techniques
- Theoretical backgrounds

2007
S. Colafrancesco
NewA.Rev., 51, 304
Review



SZE:
- Generalized description
- Thermal, non-thermal, DM, B-field, …
- Unique tool for µwave tomography of LSS

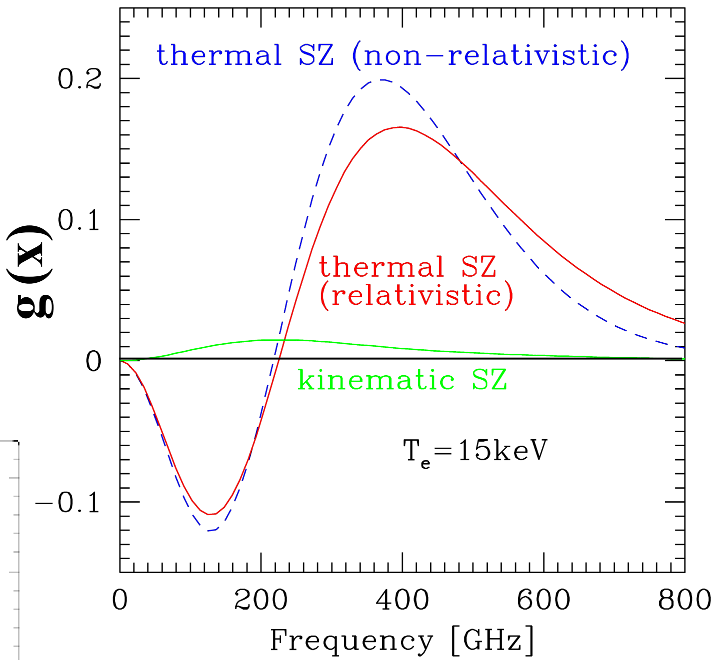
SZ_{th}: working approximations

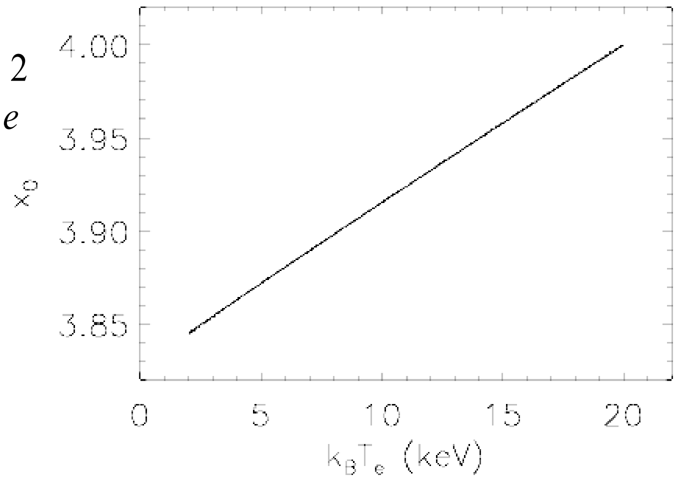
$$\Delta I_{th} = 2\frac{(kT_0)^3}{(hc)^2} y_{th} g(x)$$

$$y_{th} = \sigma_T \int d\ell n_e \frac{kT_e}{m_e c^2}$$

$$X_{0,th} \approx a + b\theta_e + c\theta_e^2$$

$$\theta_e \equiv \left(\frac{k_B T_e}{m_e c^2}\right)$$

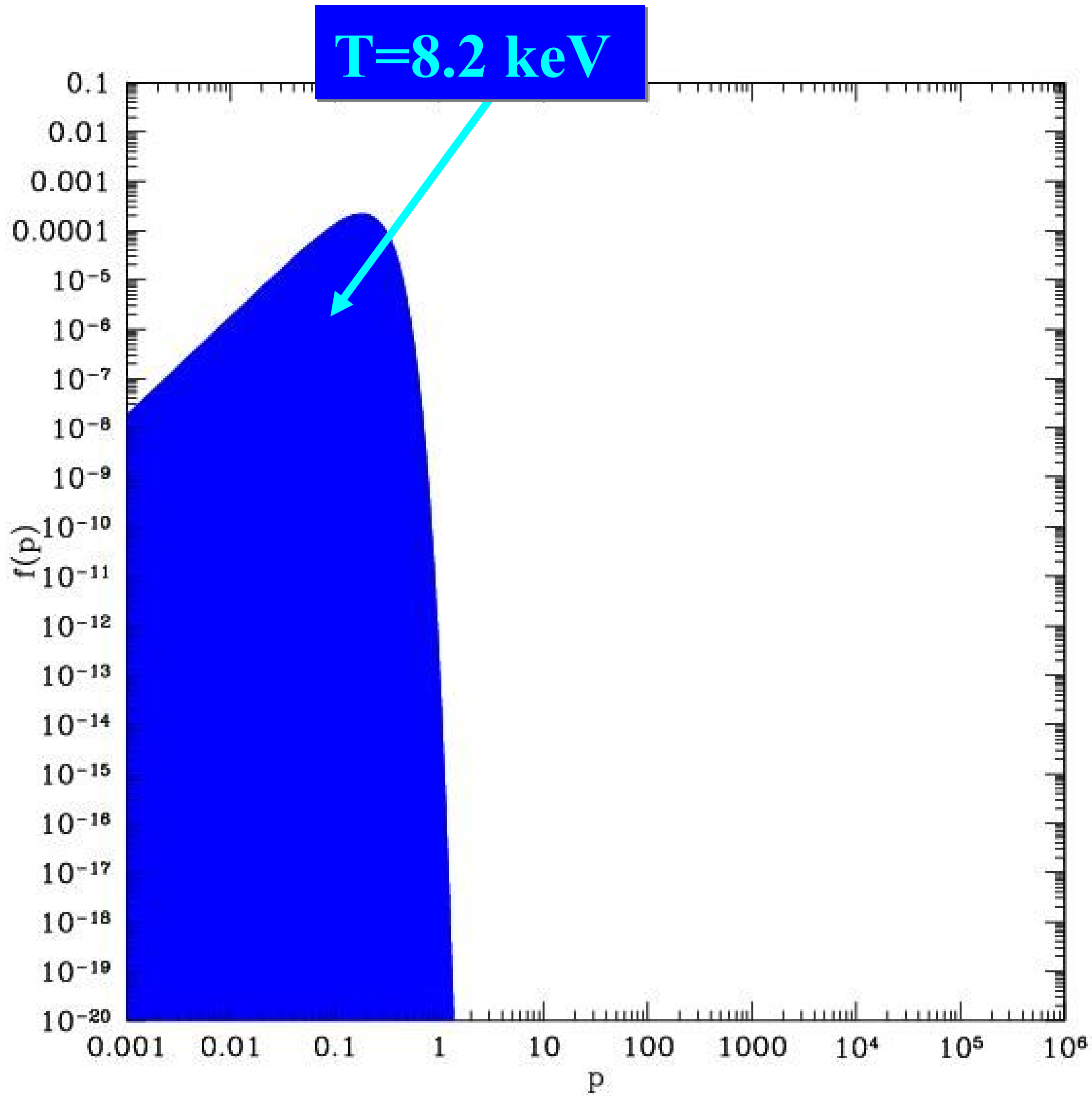




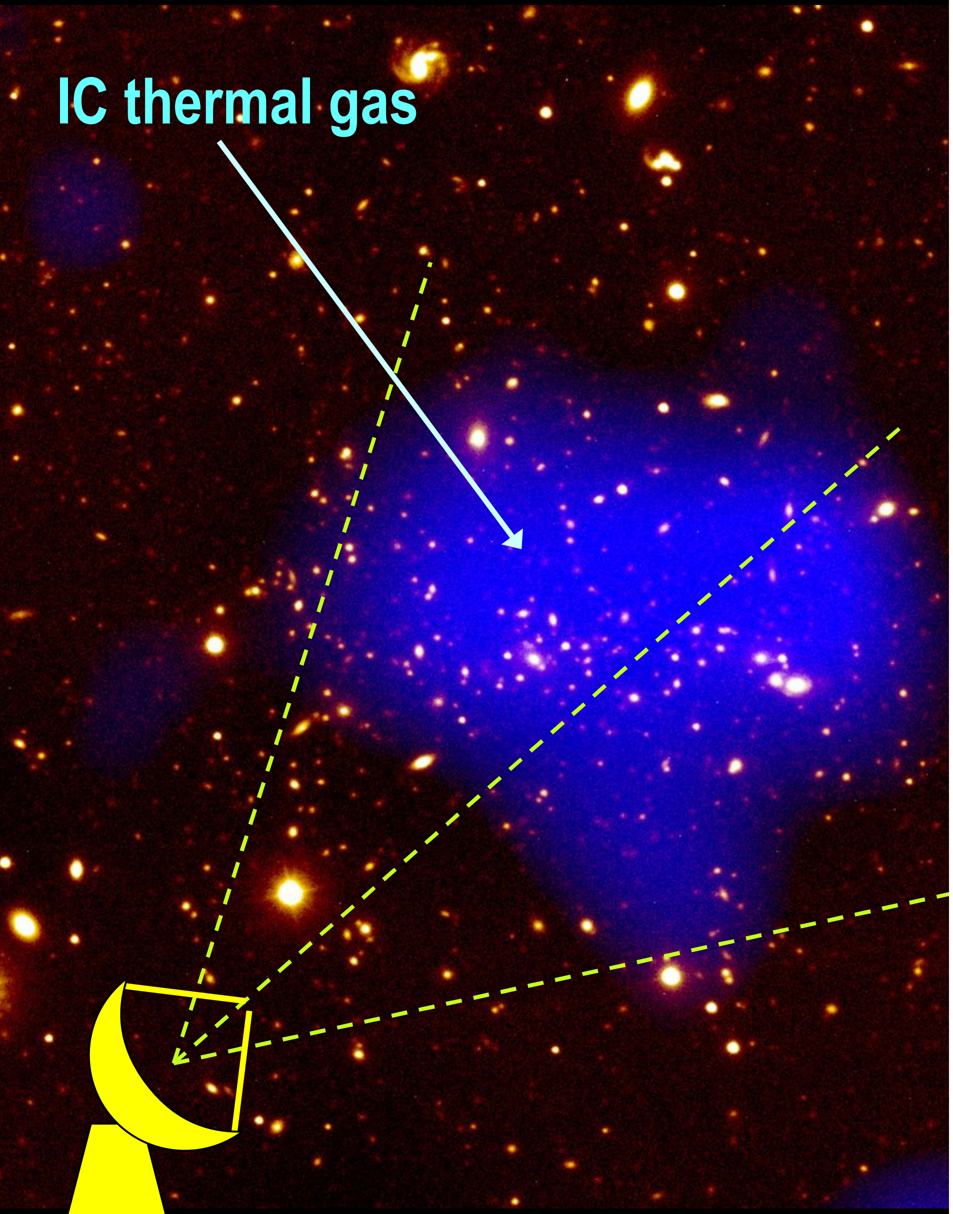
Diffusion limit → Single scattering (τ « 1)

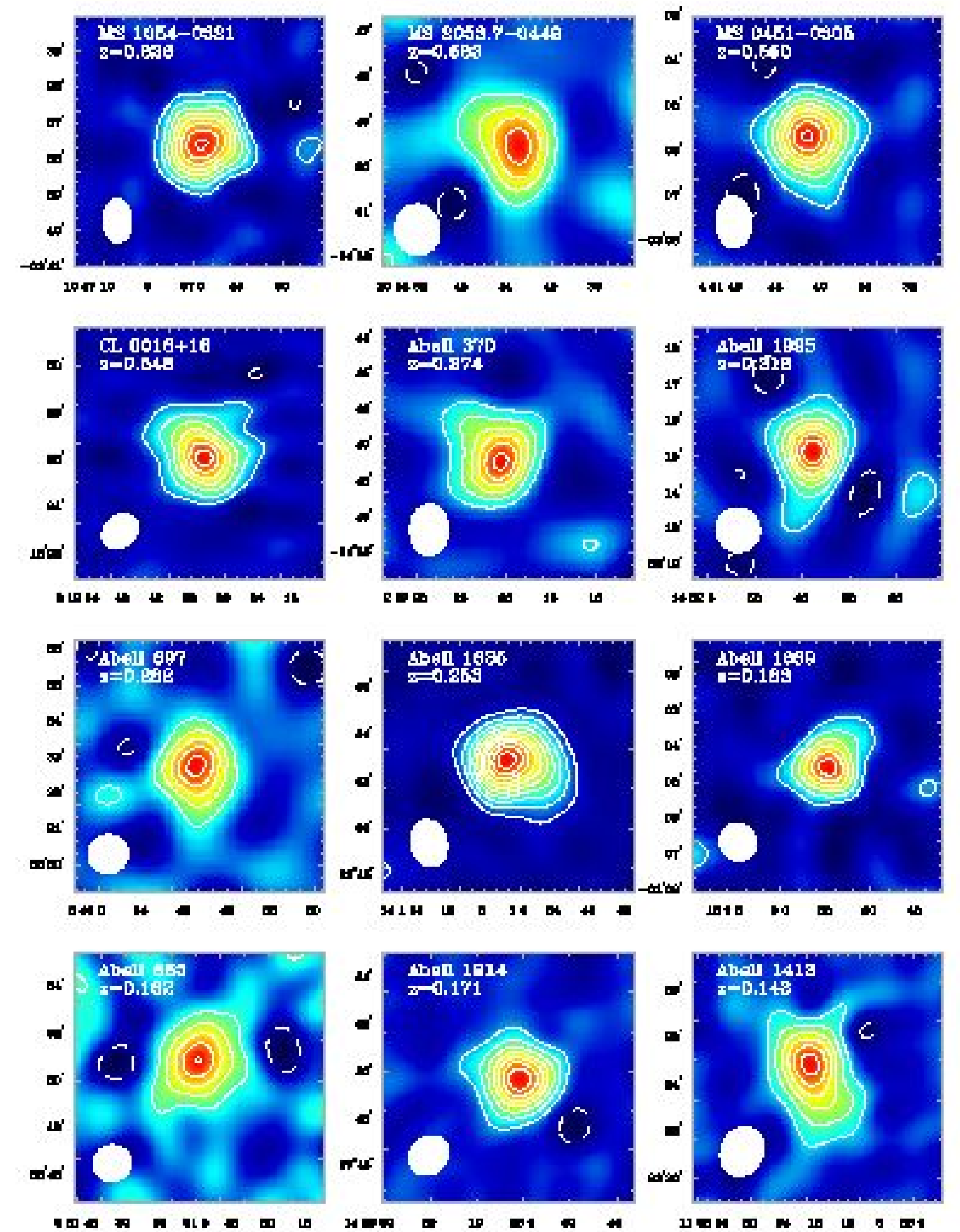
Single thermal population → Thermal electrons (X-ray)

The e- distribution in Coma



Blob-ology


IC thermal gas


MS 1054-0321
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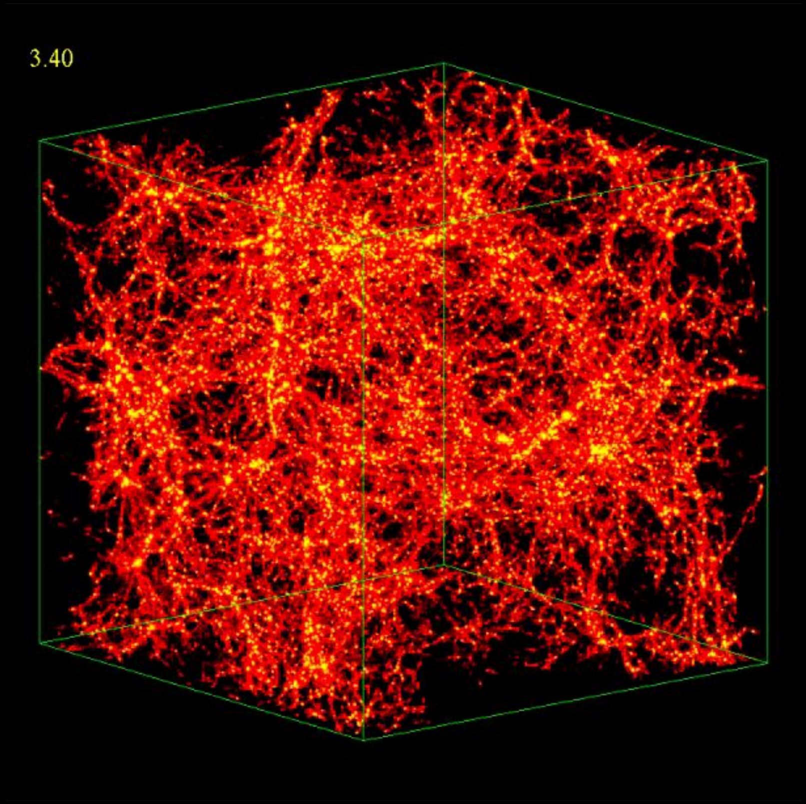
MS 2053.7-0449
z=0.583
MS 0451-0305
z=0.550
CL 0016+16
z=0.546
Abell 370
z=0.374
Abell 1995
z=0.318
Abell 697
z=0.282
Abell 1835
z=0.253
Abell 1689
z=0.183
Abell 665
z=0.182
Abell 1914
z=0.171
Abell 1413
z=0.143

SZ effect and simple physics

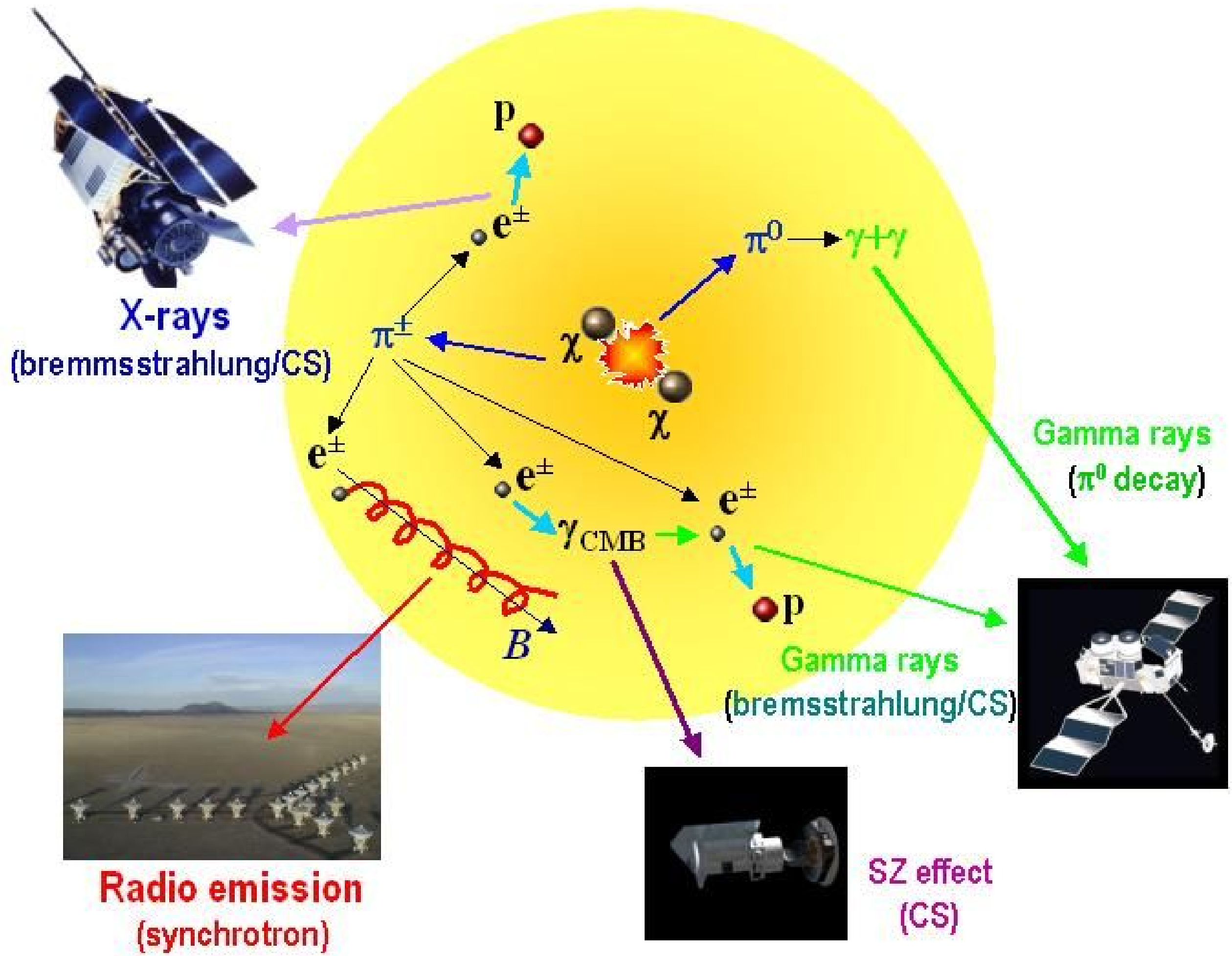
Science	Technique	Quantity
Simple science results - cluster physics	**Integrated SZ effects**	
	total thermal energy content	E_e
	total hot electron content	N_e
	SZ structures	
	not as sensitive as X-ray data	
	need for gas temperature	
	Mass structures vs. lensing	M_{gas}, M_{tot}
	Radial peculiar velocity via SZ kinematic	V_r
	Transverse velocity via Rees-Sciama effect (Nottale, 1984)	V_t
Simple science results - cosmology	**Cosmological parameters**	
	cluster-based Hubble diagram	H_0
	cluster counts as function of redshift	$\Omega_m \Omega_\Lambda \Omega_0$
	Cluster evolution physics	
	evolution of cluster atmospheres	$T_e(z)$, $n_e(z)$
	evolution of radial velocity distribution	$V_r(z)$
	evolution of baryon fraction	Ω_b
	$T_{CMB}(z)$ elsewhere in the Universe	$T_{CMB}(z)$

Astro-Particle Physics view of Large-Scale Structures

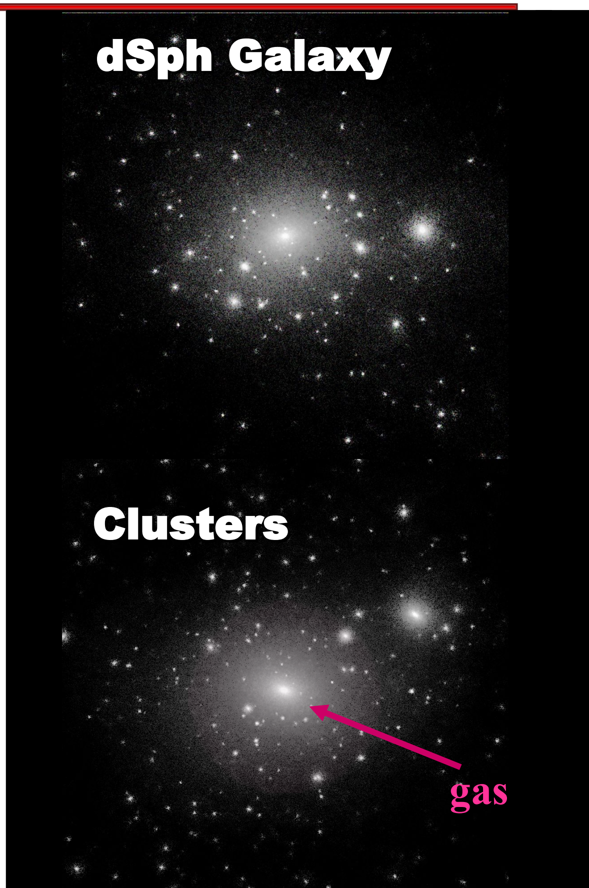
LSS and Dark Matter

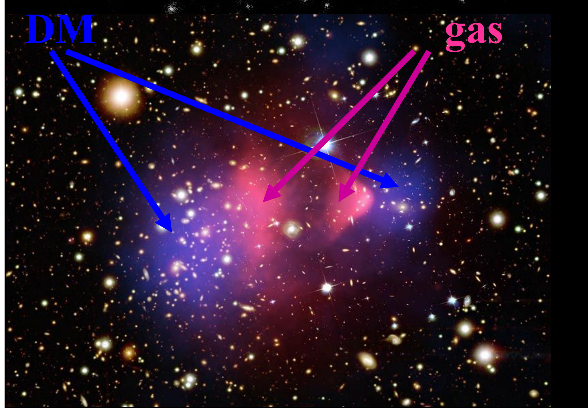


DM signals Best Labs.



[Colafrancesco 2006, 2007]

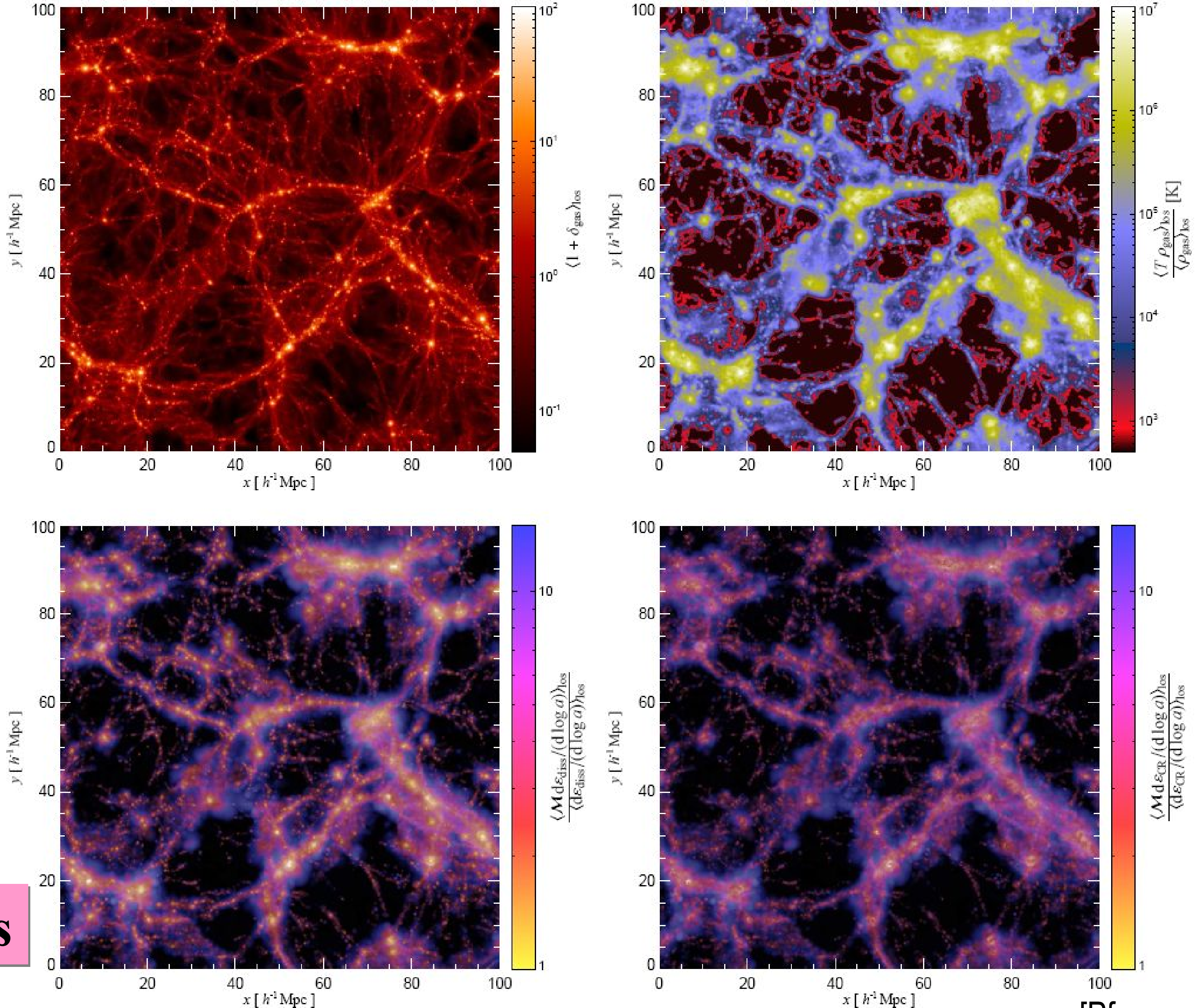




LSS shock waves

ρ_{gas}

T_{gas}



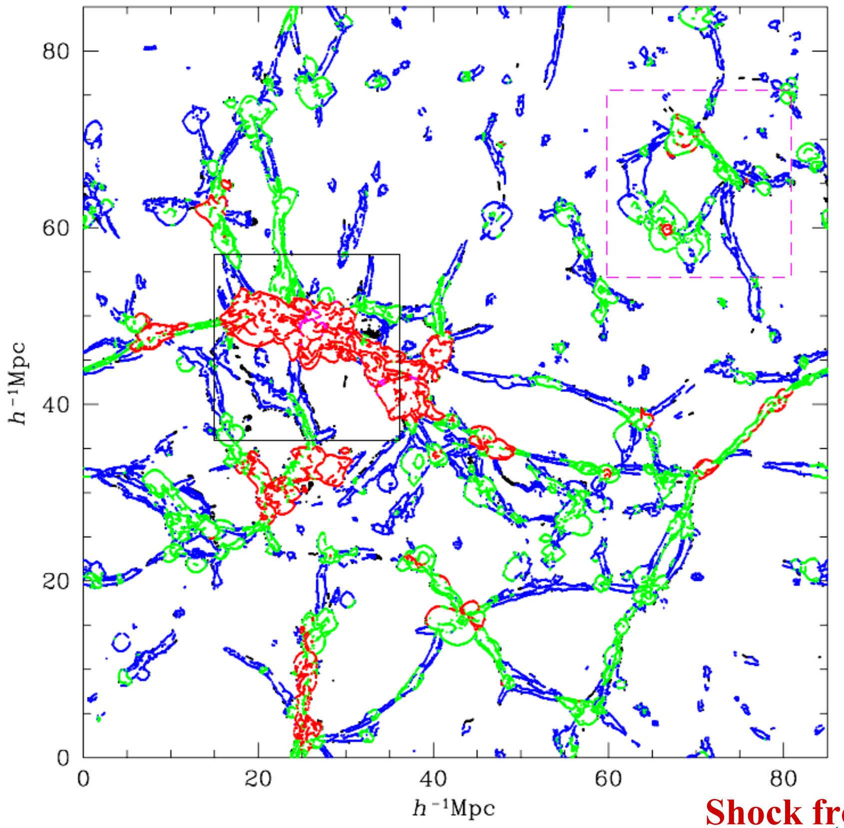
Shocks

$\mathcal{M}$

[Pfrommer et al. 2006]

Shock wave acceleration ⇒ CRs

[Kang et al. 1996-2006]



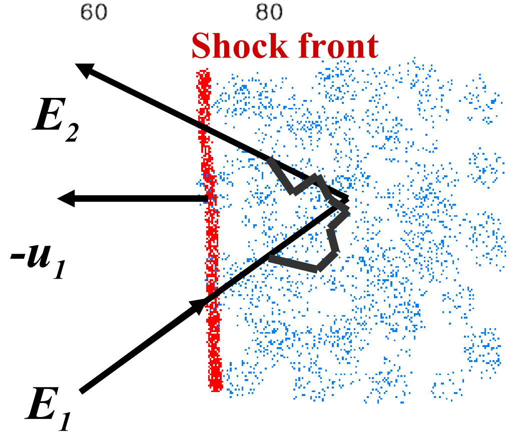
Black: V_s(km/s)< 15

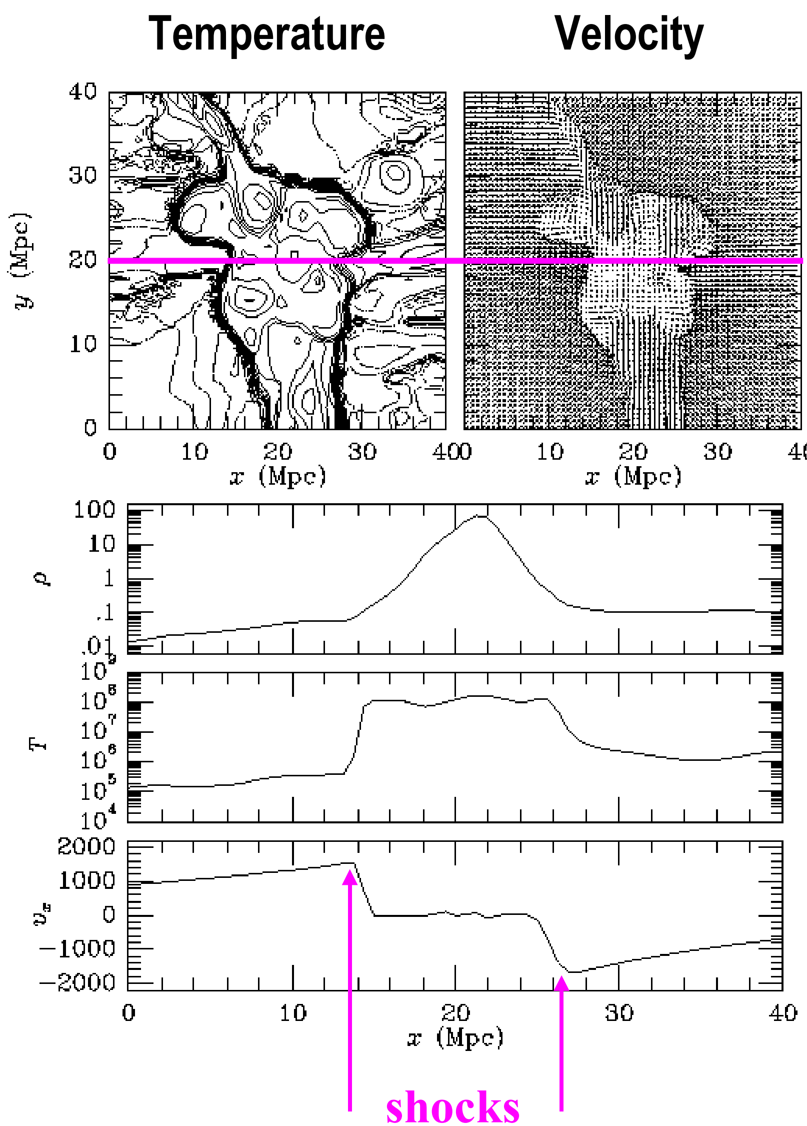
Blue: 15 <V_s(km/s)< 65

Green: 65 <V_s(km/s)< 250

Red: 250 <V_s(km/s)< 1000

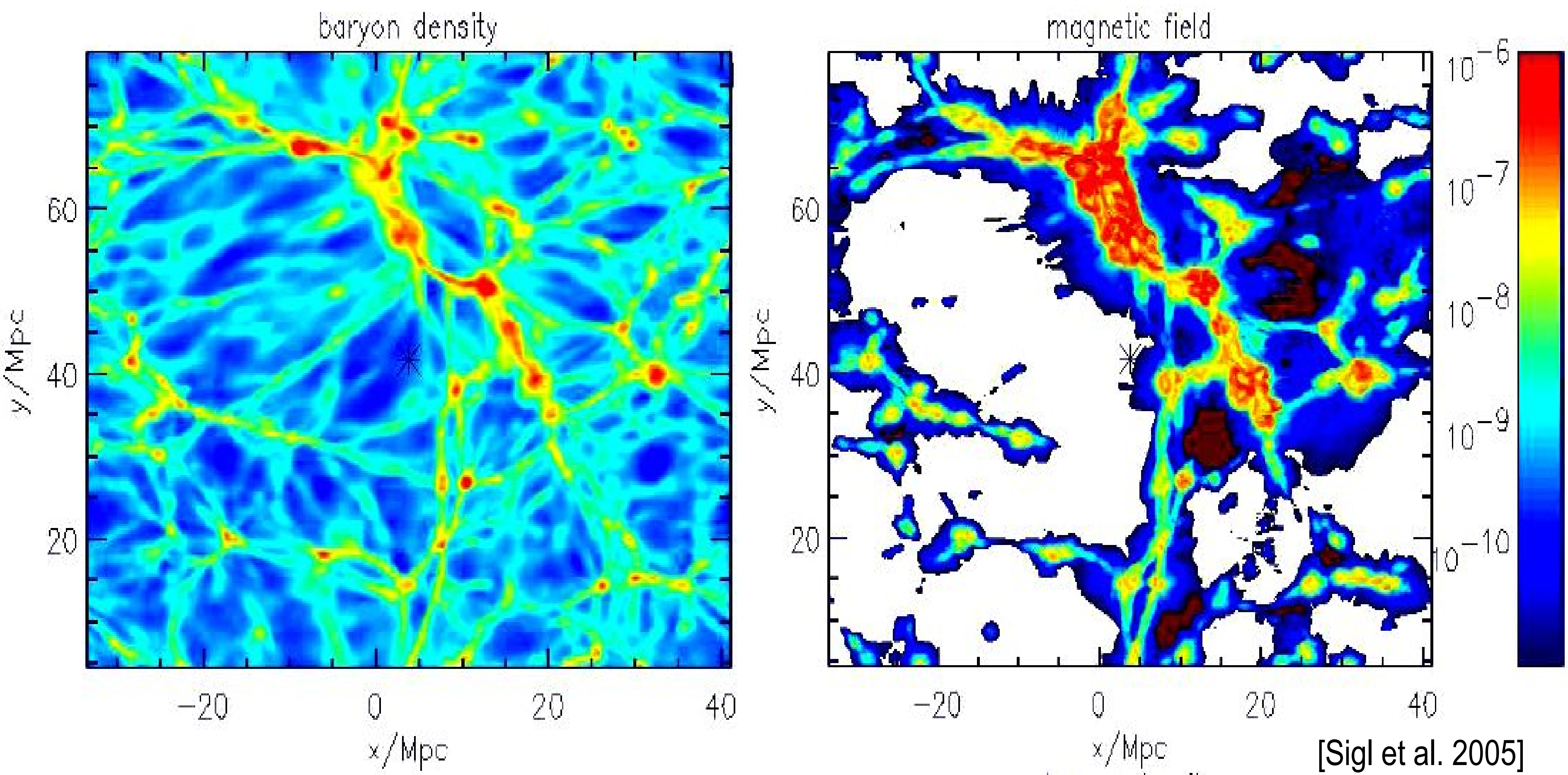
Magenta: V_s(km/s)> 1000





Magnetic fields in LSS

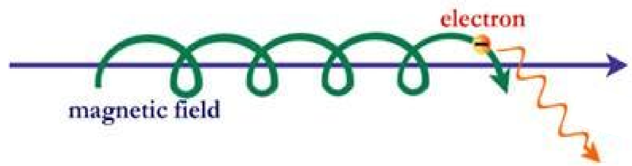
Origin → **Primordial** / **Post-recombination** → **G + MHD** → **B**($\delta\rho$, z; P_k)



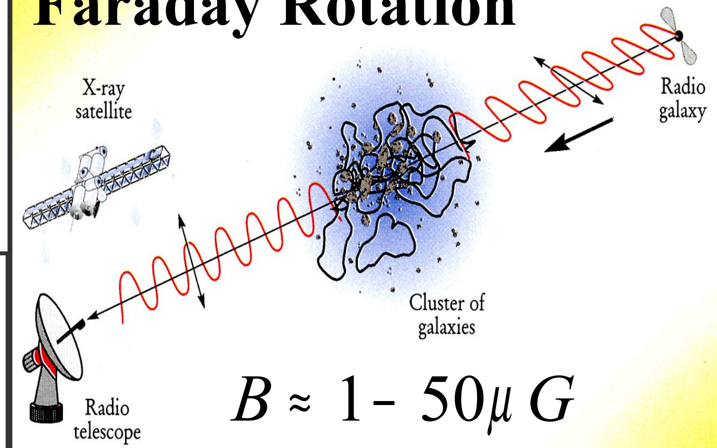
[Sigl et al. 2005]

B-field in clusters: evidence

Synchrotron radiation



Faraday Rotation



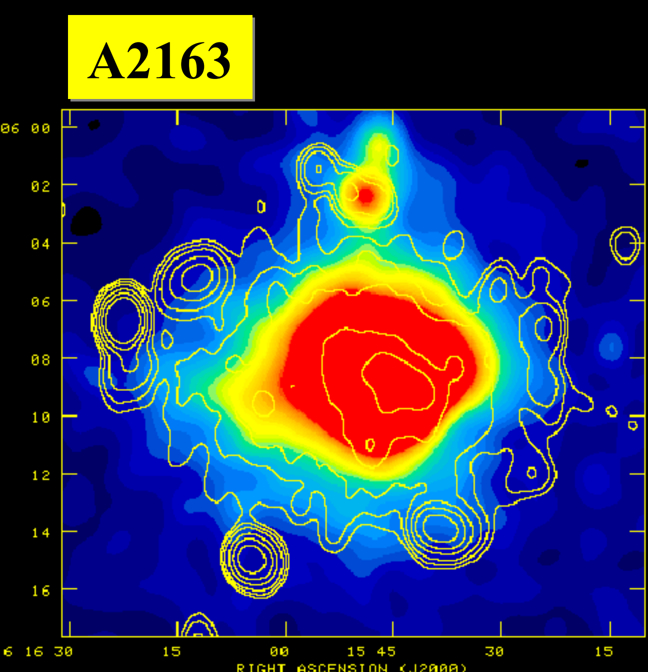
$B \approx 1 - 50 \mu G$

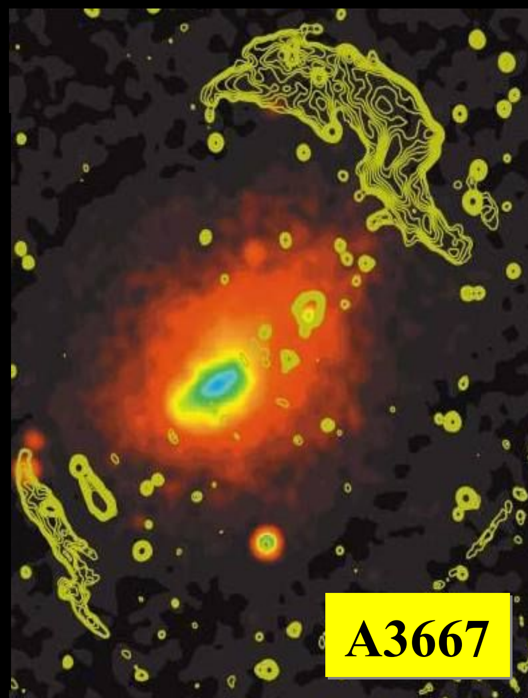
Radio Halos

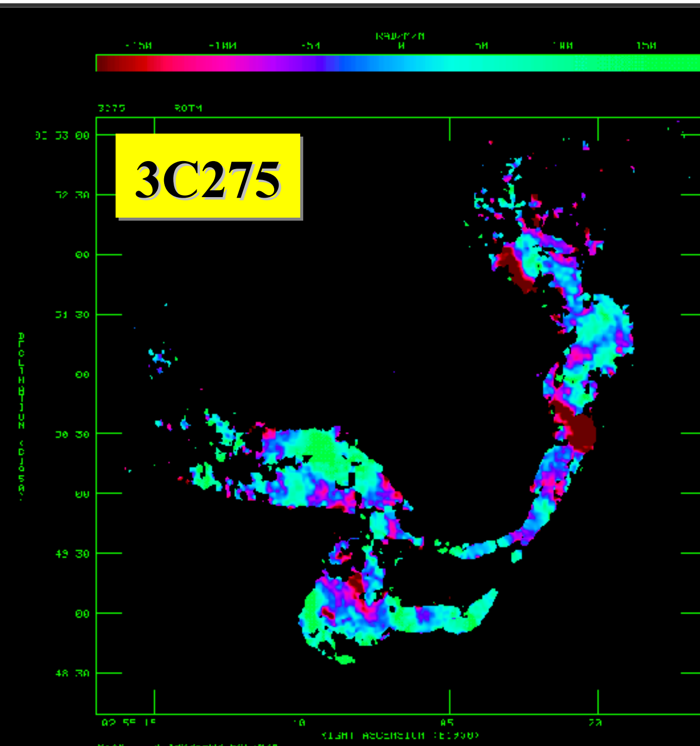
$B \approx 0.1 - 5 \mu G$

Radio Relics

$B \approx 0.2 - 8 \mu G$

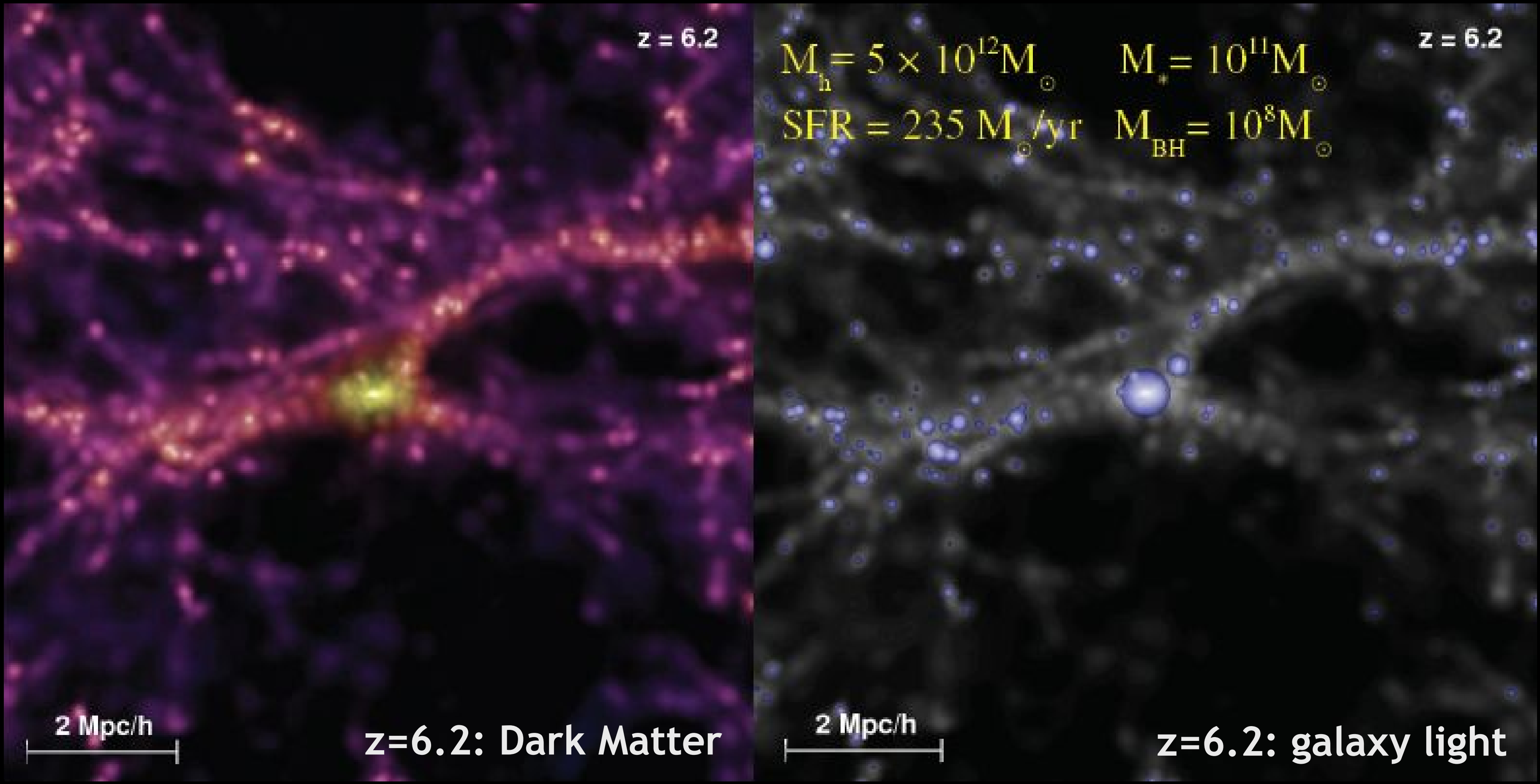






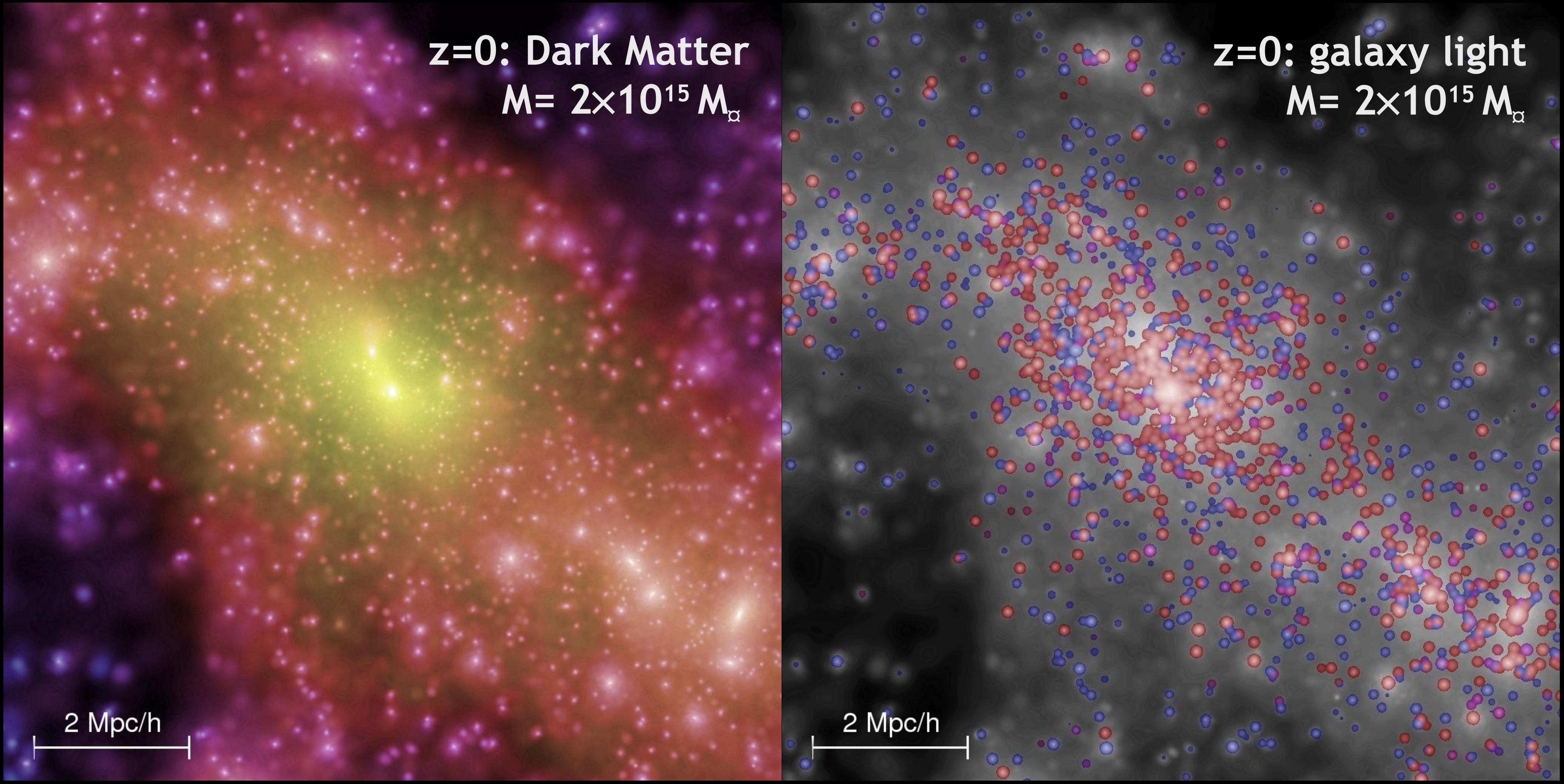
LSS and Black Holes

One of the most massive DM clumps at t = 1 Gyr
containing one of the most massive galaxies and most massive BH

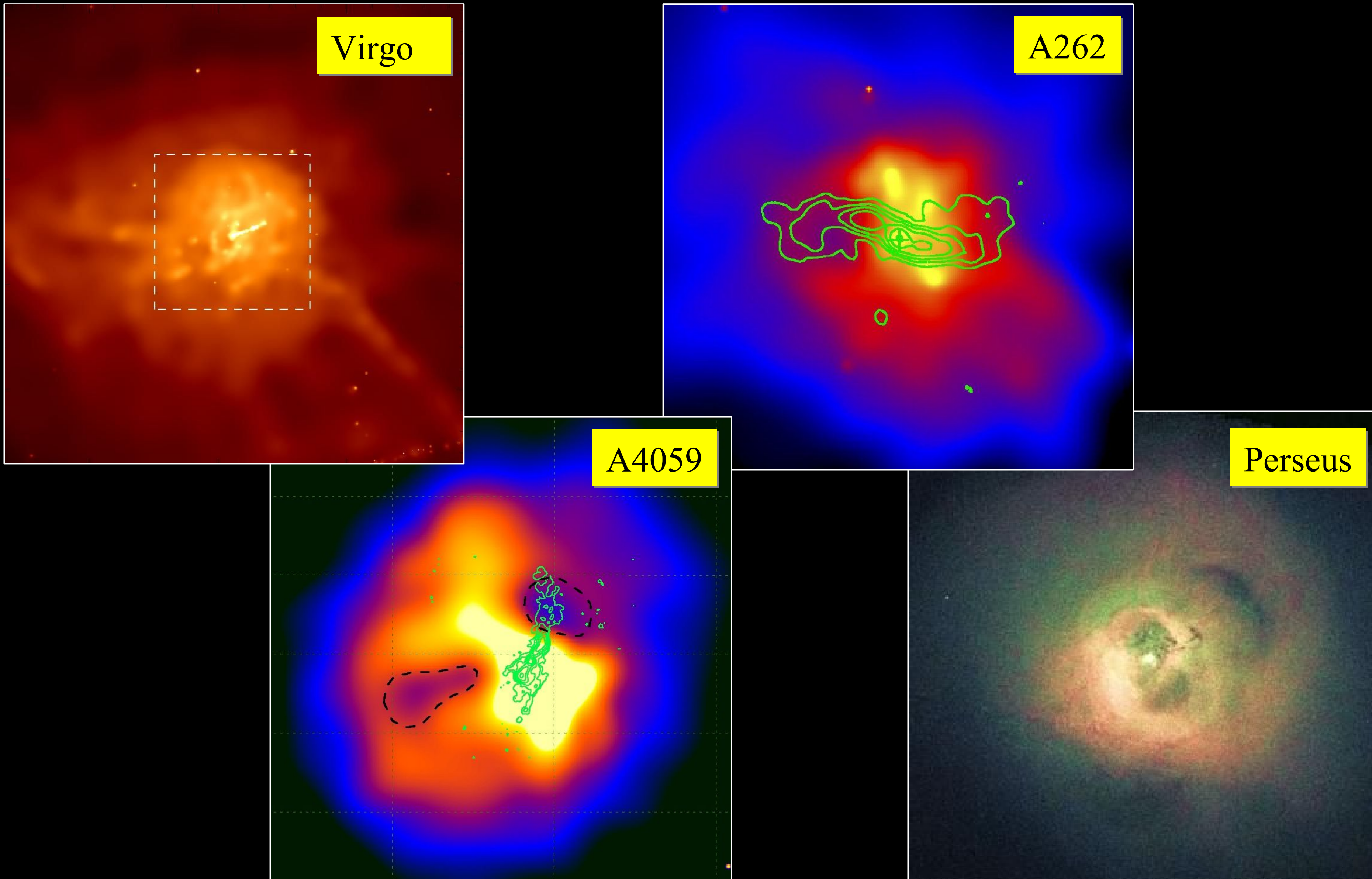


The first object descendants today

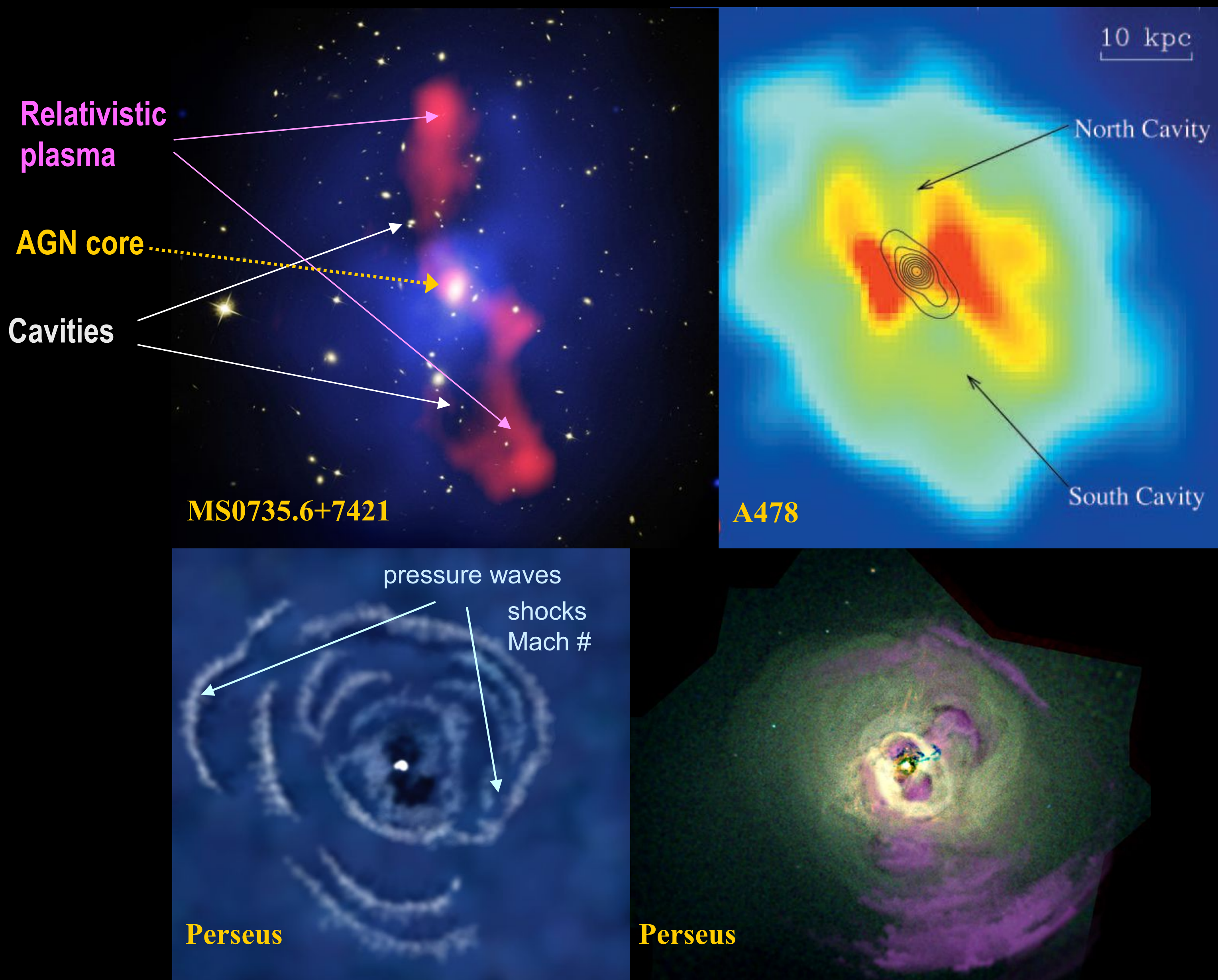
One of the most massive galaxy clusters at t = 13.7 Gyrs
The AGN descendant is part of the central massive galaxy



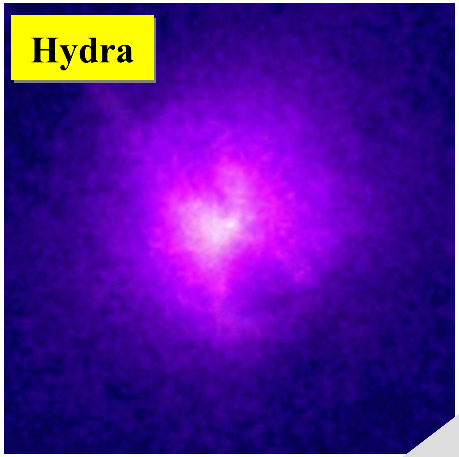
BHs in galaxy clusters: evidence

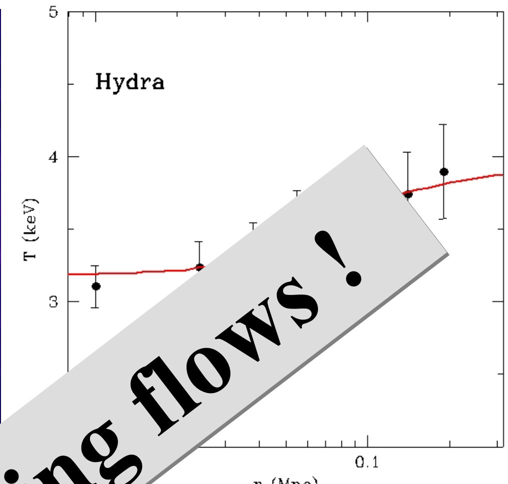


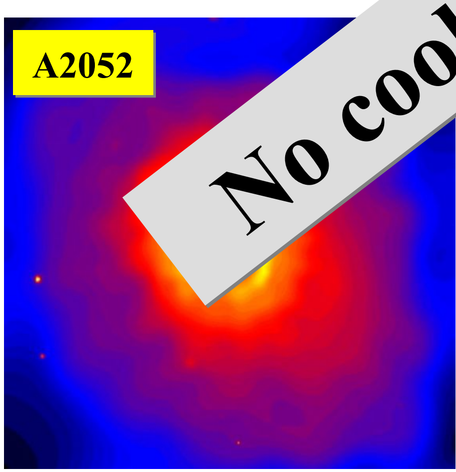
BHs: ejecta and pressure waves

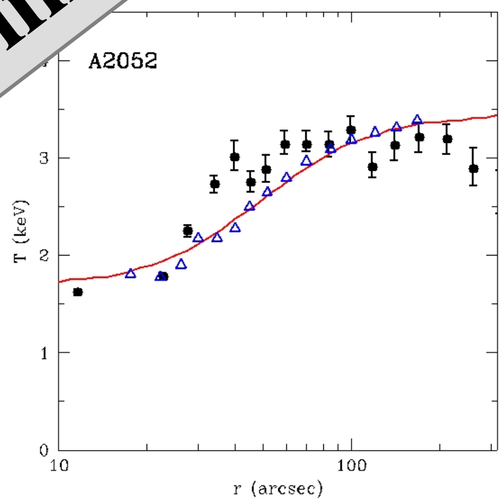


Cluster cool cores

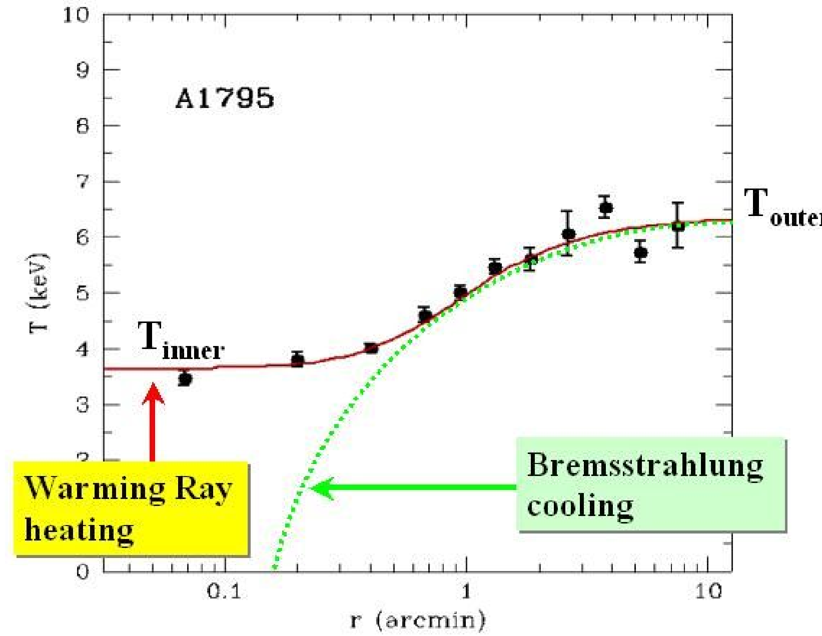


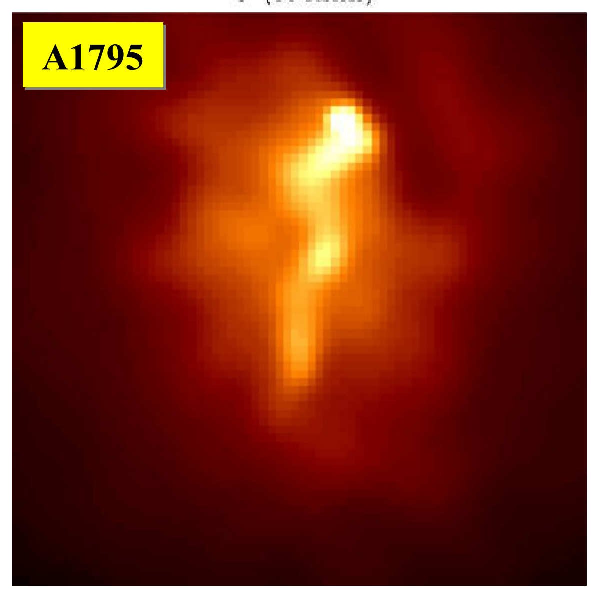






No cooling flows !



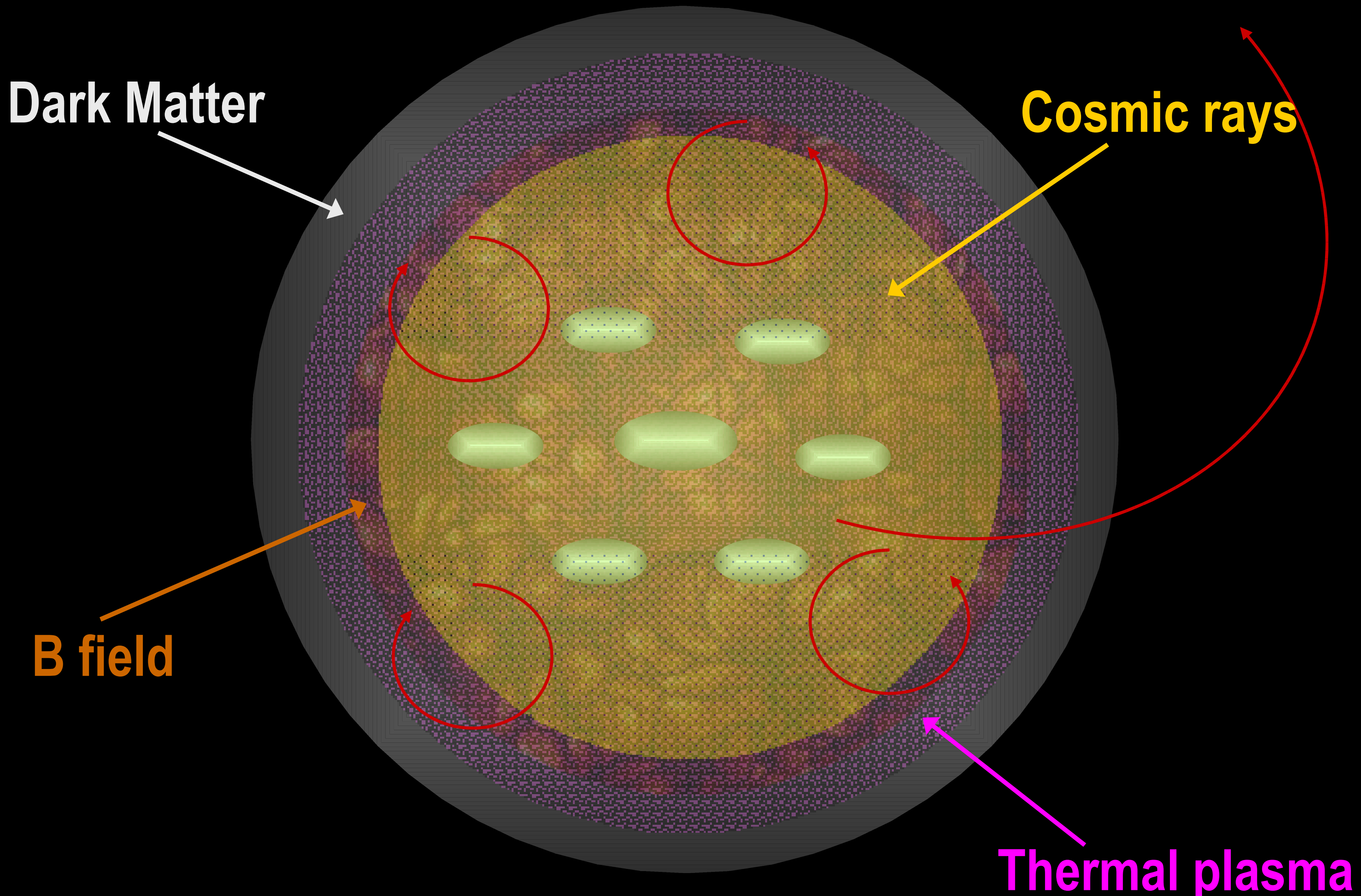


[**S.C.** Dar & DeRujula (2004)]

[**S.C.** (2005)]

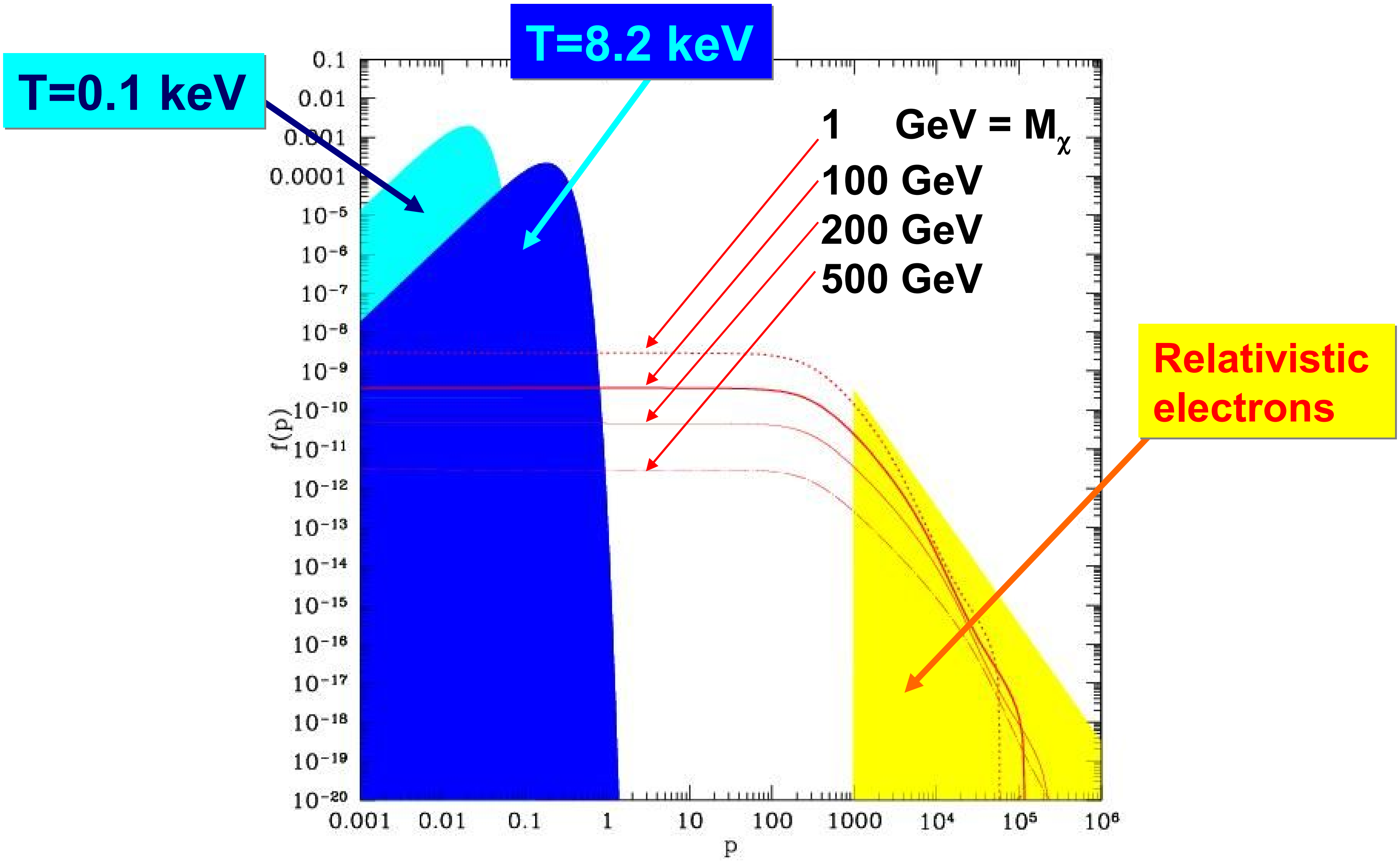
[**S.C.** & Marchegiani (2007)]

Storage rooms for cosmic material

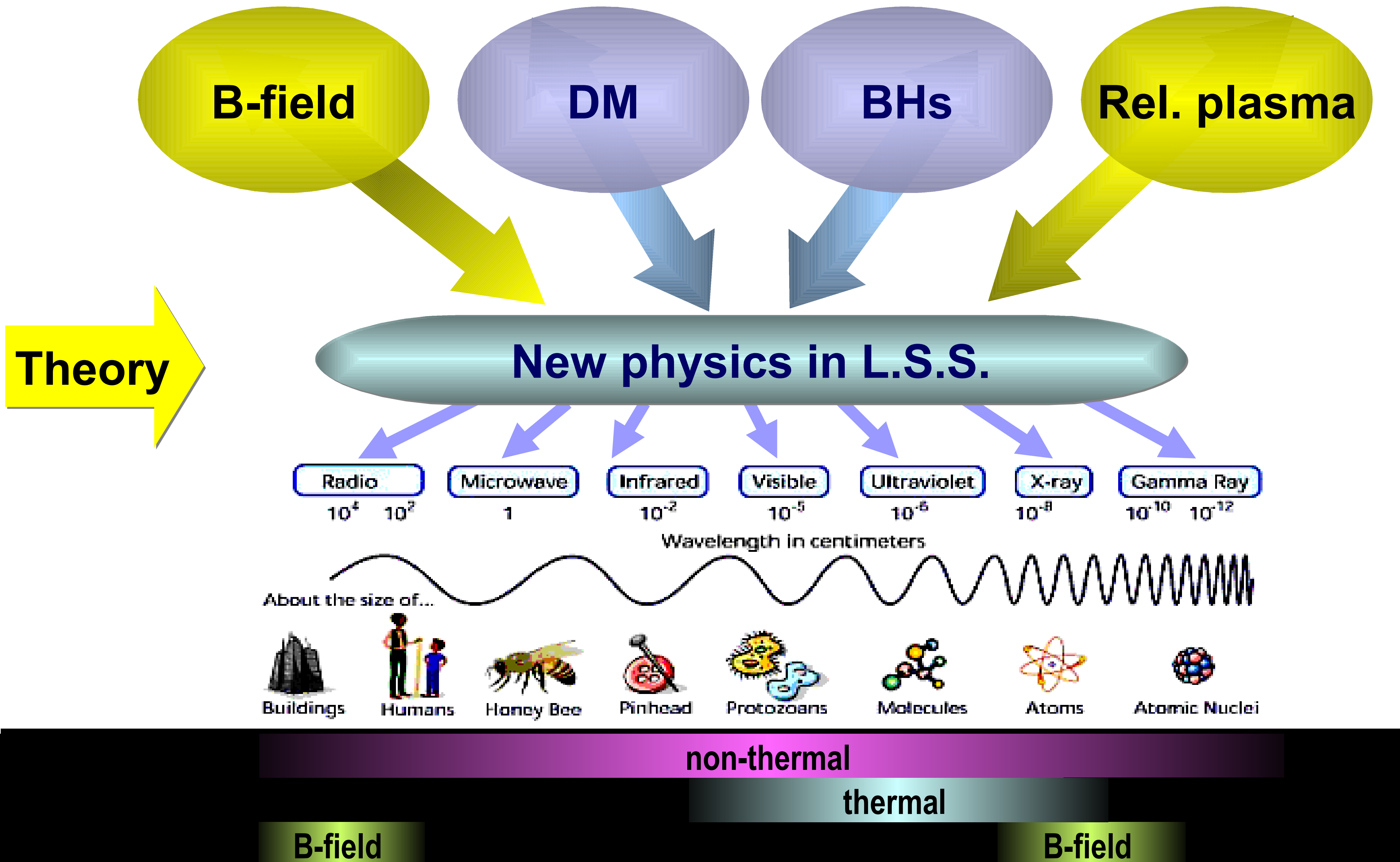


The e⁻ distributions in clusters

[S.C. (2005 - 2007)]



Cosmo-Astro-Particle Physics in L.S.S.

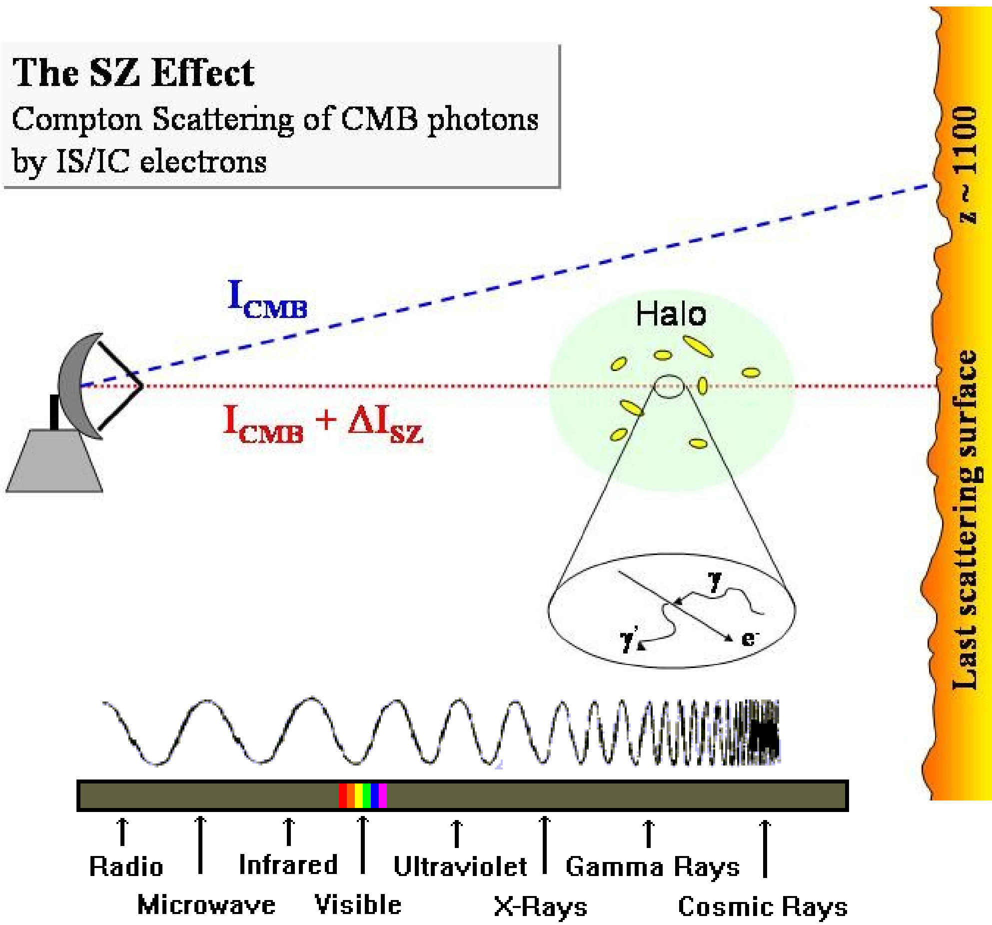


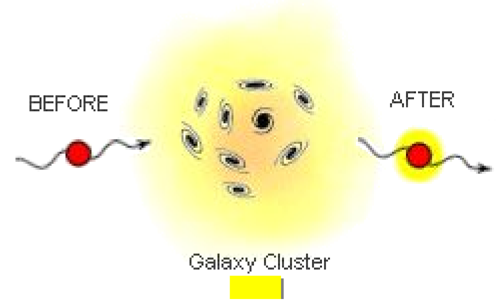
Probing the origin of every particle family using a single technique

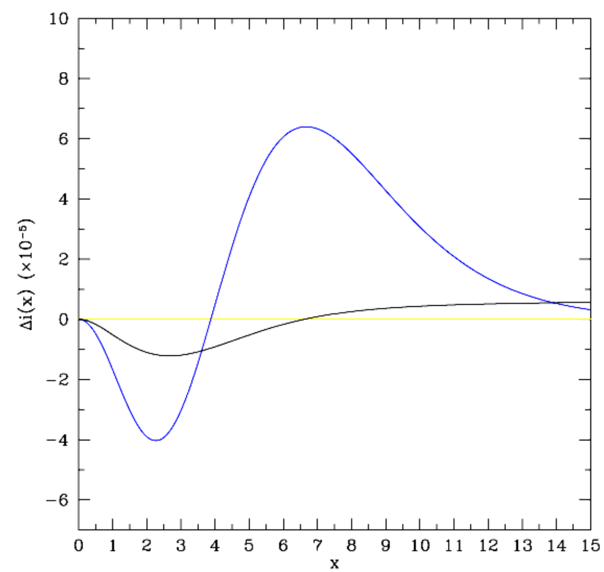
$$y = \frac{\sigma_T}{m_e c^2} \int d\ell \cdot \left[P_{e,th} + P_{e,rel} + P_{e,DM} + \ldots \right]$$

The SZ effect

SZ effect: ...more than basics







(x)

thermal NR e⁻ $\frac{\Delta \nu}{\nu} \approx 4 \frac{kT_e}{m_e c^2}$

relativistic e⁻ $\frac{\Delta \nu}{\nu} \approx \frac{4}{3} \gamma^2$

SZE: general derivation

[Colafrancesco et al. 2003, A&A, 397, 27]

Intensity change

$$\Delta I(x) = 2\frac{(k_B T_0)^3}{(hc)^2} y \tilde{g}(x)$$

$$y = \frac{\sigma_T}{m_e c^2} \int P d\ell.$$

Pressure → Thermal / Relativistic

Thermal:

$$P_{th} = n_e k_B T_e$$

Relativistic:

$$P_{rel} = n_e \int_0^\infty dp f_e(p) \frac{1}{3} p v(p) m_e c$$

Spectral shape

$$\tilde{g}(x) = \frac{m_e c^2}{\langle k_B T_e \rangle} \left\{ \frac{1}{\tau} \left[\int_{-\infty}^{+\infty} i_0(x e^{-s}) P(s) ds - i_0(x) \right] \right\}.$$

$$\langle k_B T_e \rangle = \frac{\sigma_T}{\tau} \int P d\ell = \frac{\int P d\ell}{\int n_e d\ell}.$$

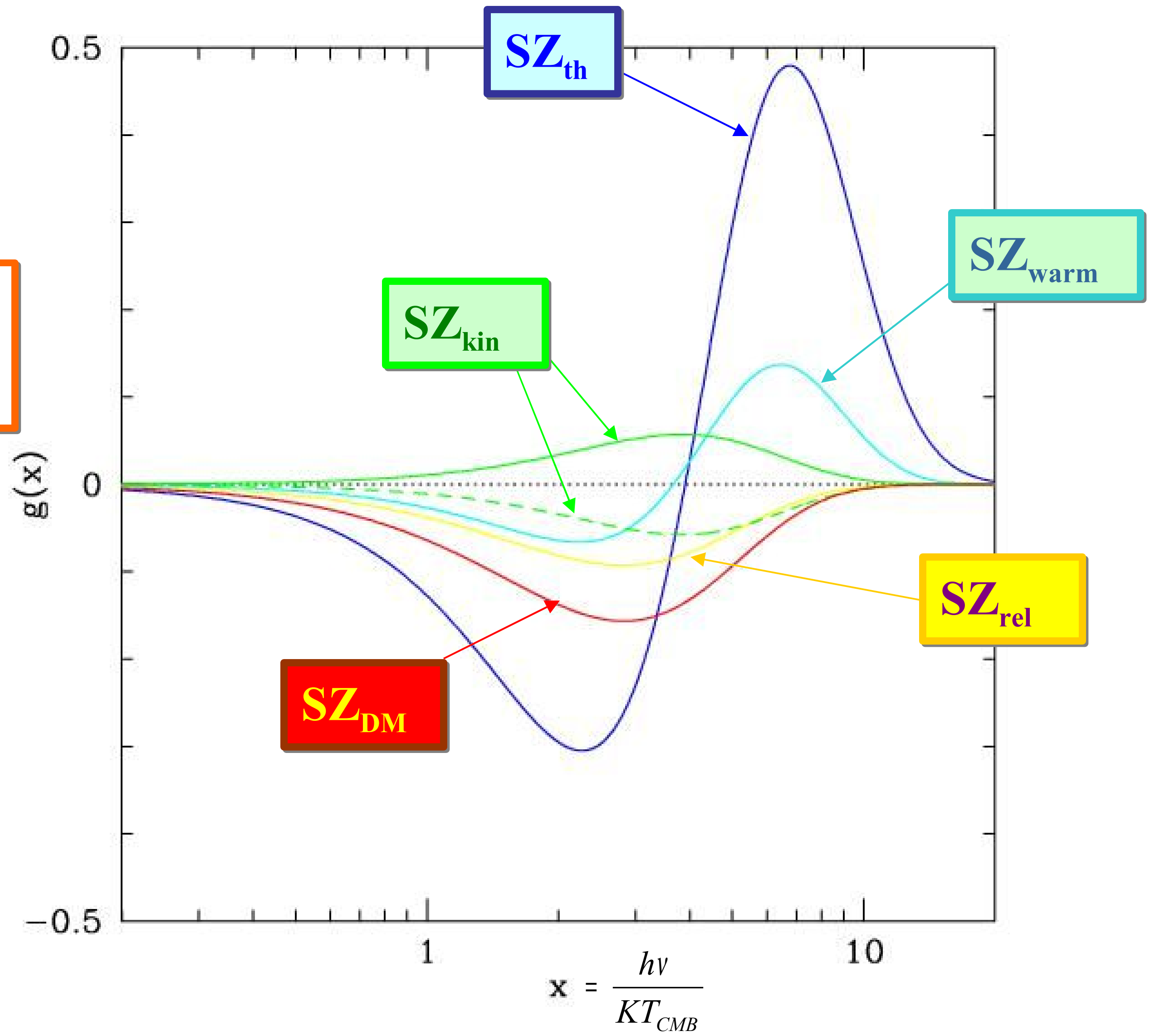
Redistribution function

$$P(s) = \int_0^\infty dp f_e(p) P_s(s; p)$$

SZE from various e^- populations

$$\Delta I(x) = 2\frac{(k_B T_0)^3}{(hc)^2} y \tilde{g}(x)$$

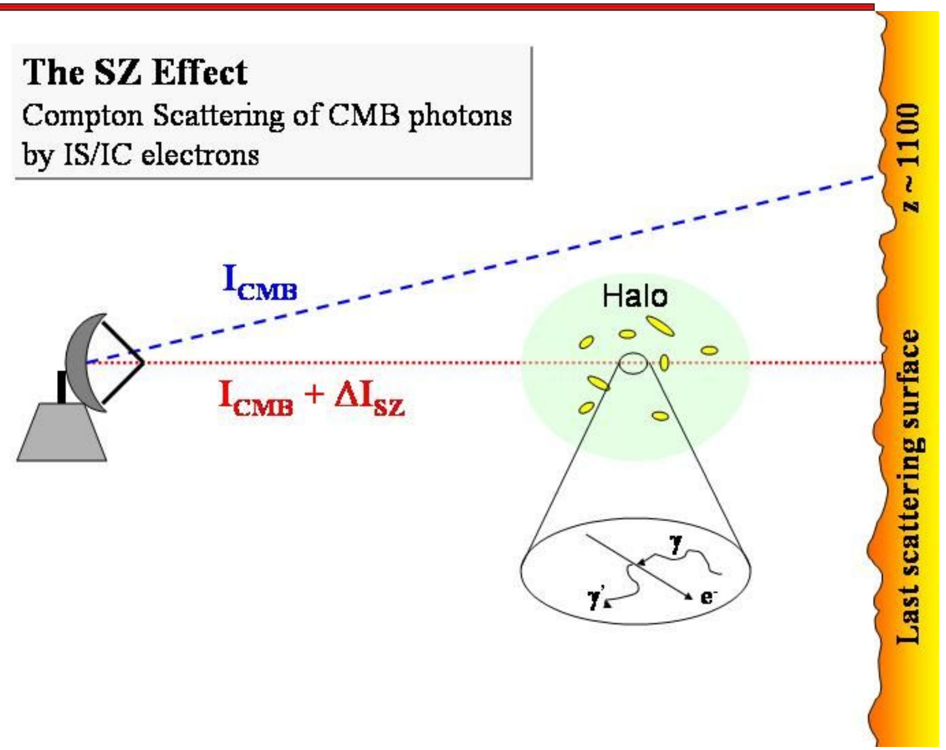
$$y = \frac{\sigma_T}{m_e c^2} \int P d\ell.$$



ASDC
ASI Science Data Center

The SZ effect:

unique tool to probe Astro-Particle Physics in cosmic structures



Relativistic particles

AGN jets cavities

DM nature

Dwarf galaxies

Magnetic field

...

SZ effect
&
cosmic rays

Relativistic particles in the ICM

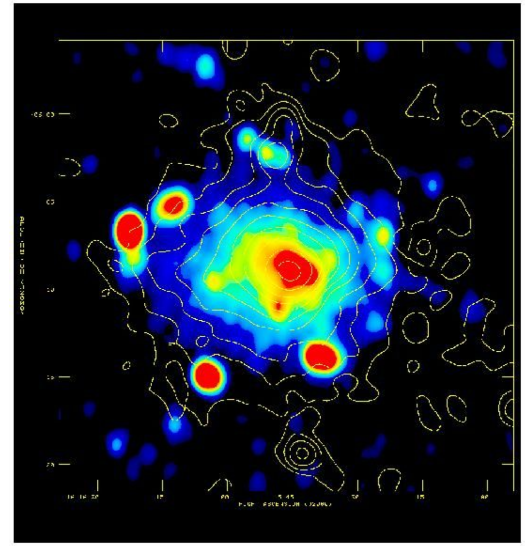
- **Relativistic electrons (re-) accelerated**:

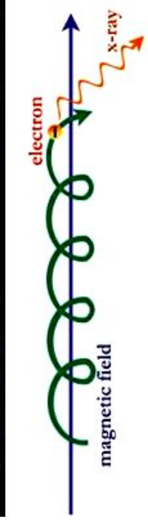
Merging shock acceleration $\tau_{loss} \sim 10^8\ yrs$

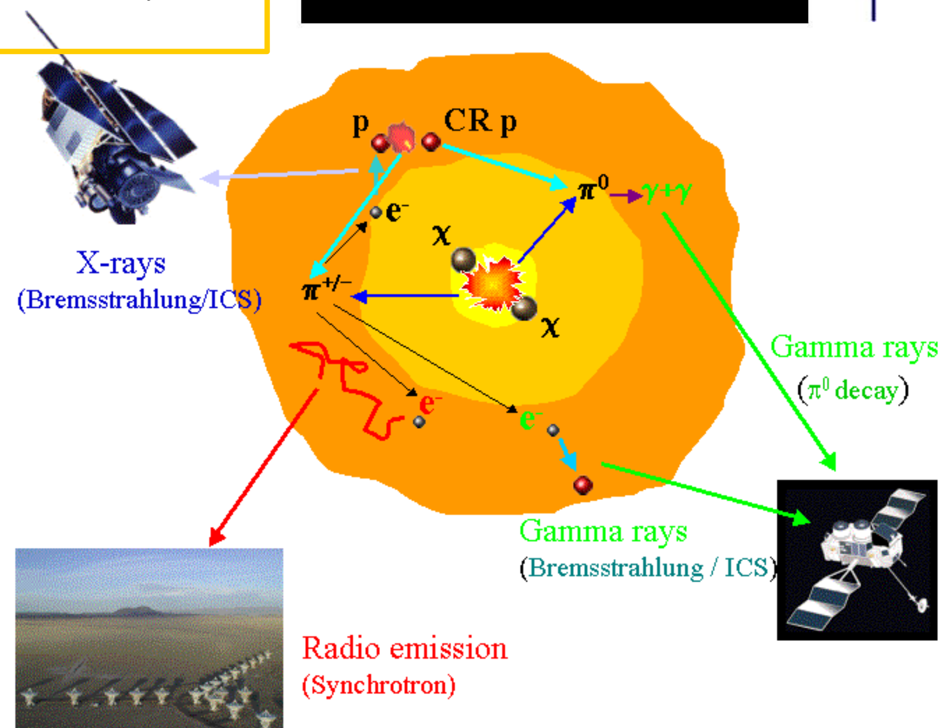
$$D_{travel} \sim 3 \cdot 10^{-1}\ kpc$$

Shock turbulence re-acceleration

$$\tau_{acc} \leq \tau_{equil} \approx 2 \cdot 10^7\ yrs$$







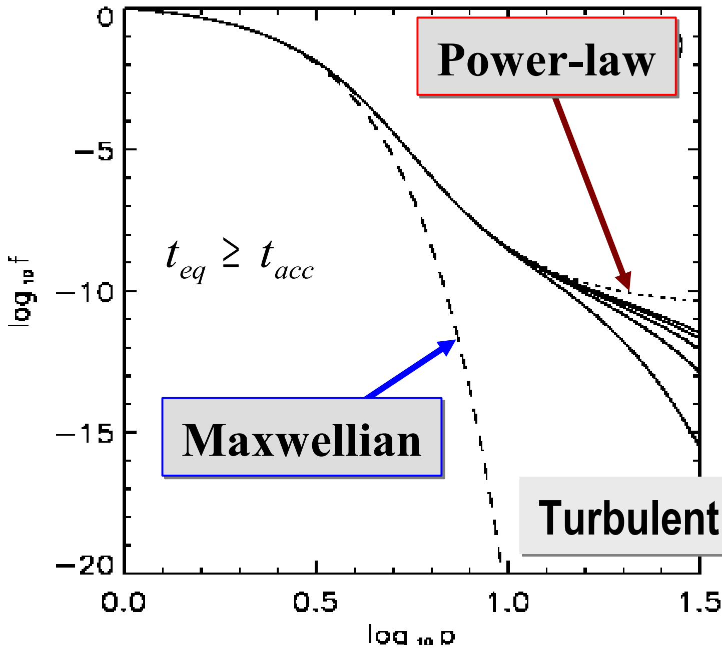
- **Relativistic protons accelerated**:

$$pp \rightarrow \pi^0 \rightarrow \gamma + \gamma$$

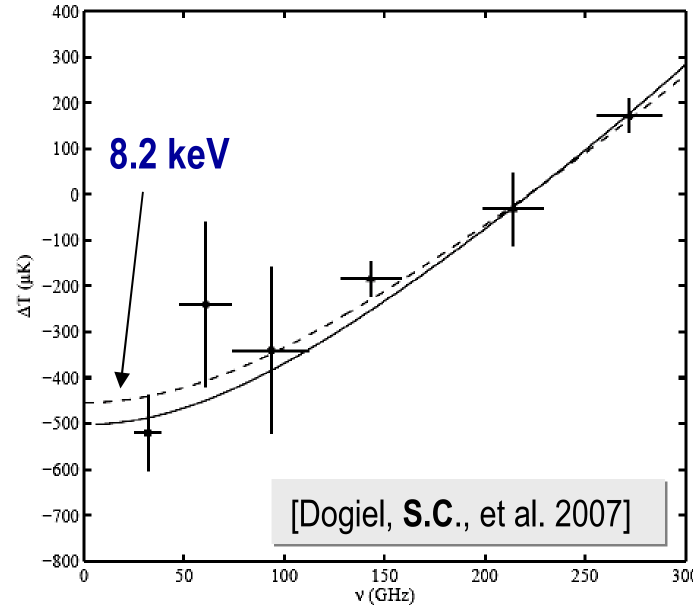
$$\rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \overline{\nu_\mu}(\nu_\mu)$$

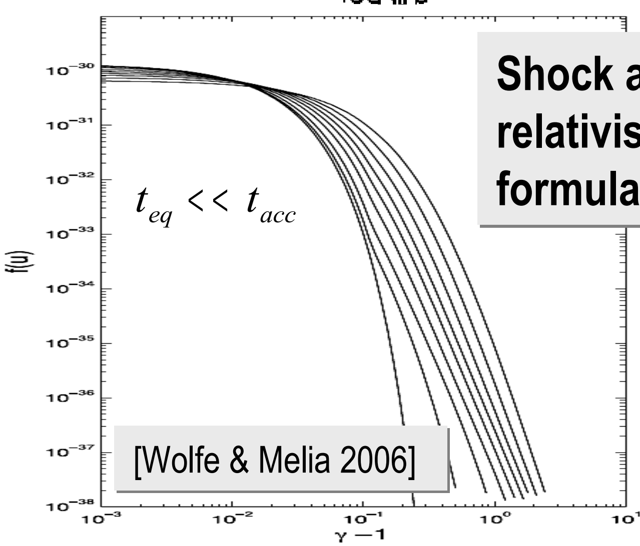
$$\mu^{\pm} \rightarrow e^{\pm} + \overline{\nu_\mu}(\nu_\mu) + \nu_e(\overline{\nu_e})$$

SZ effect and CR acceleration

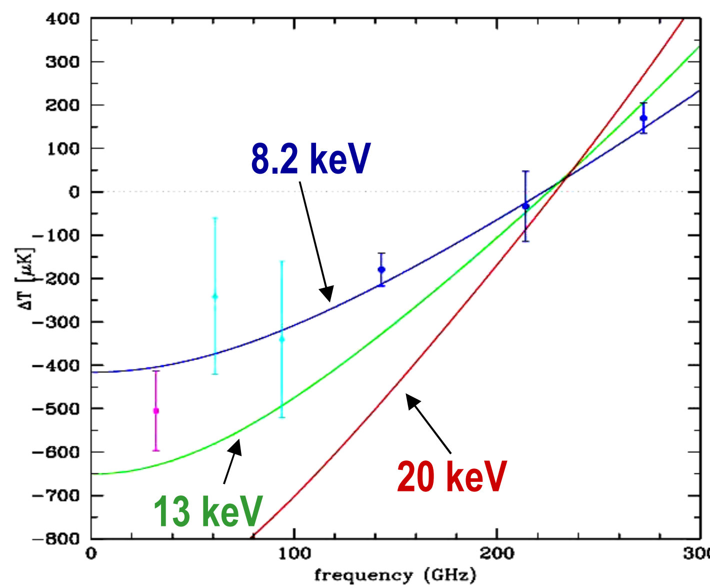


Turbulent acceleration

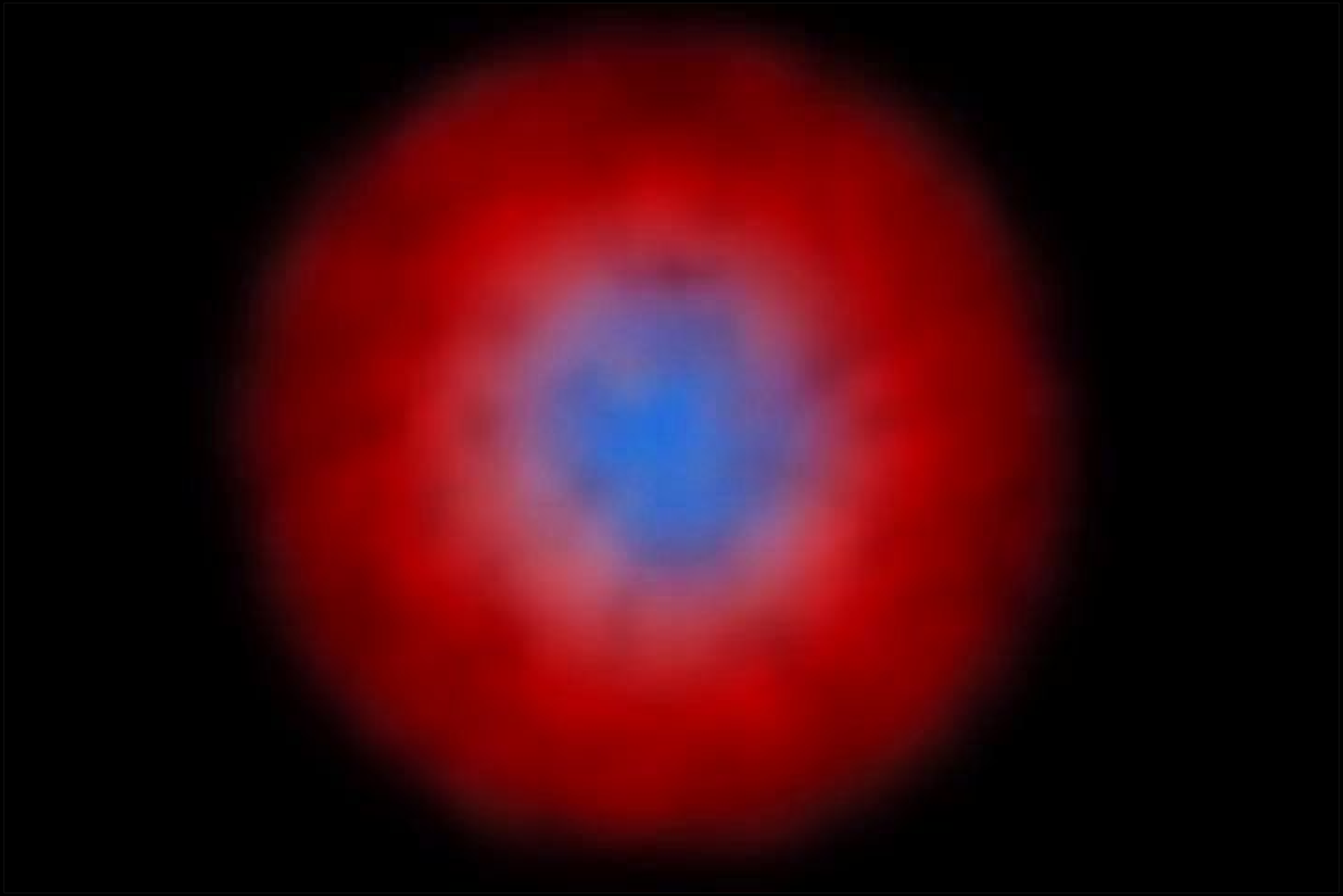




Shock acceleration: relativistic covariant formulation



SZE, CRs & cooling flows

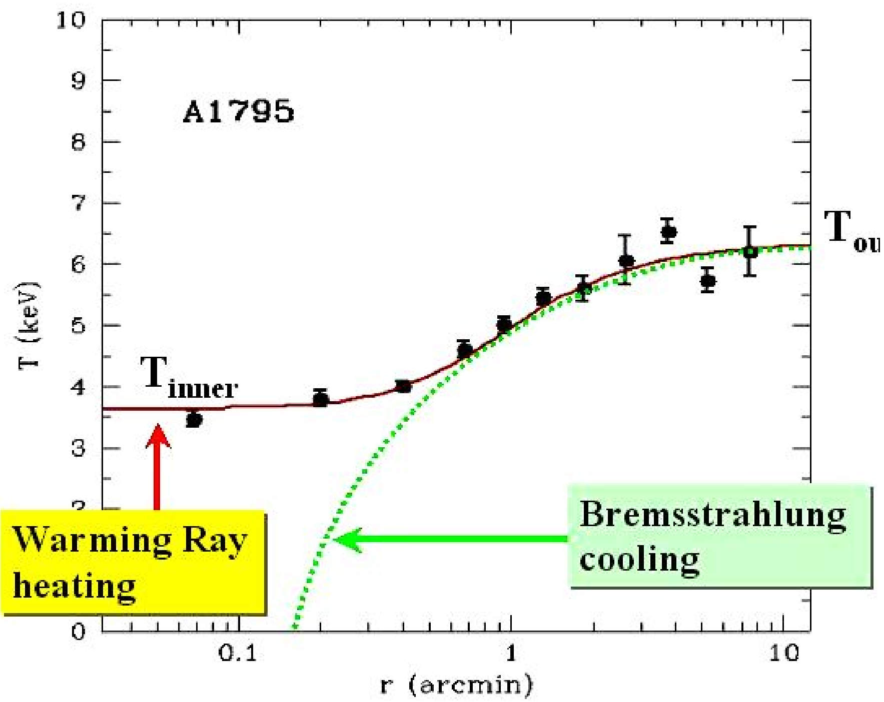


Warming Rays in cool cores

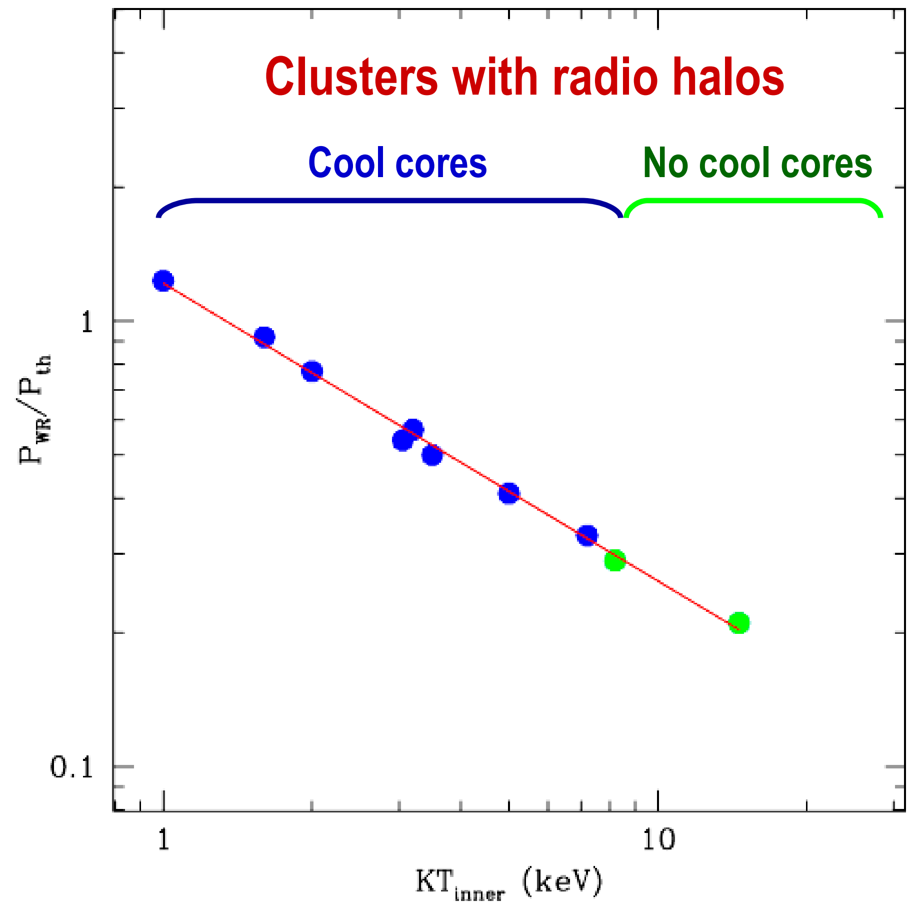
$$3kn(r)\frac{dT(r,t)}{dt} = \left(\frac{dE}{dt}\right)_{WR} - \left(\frac{dE}{dt}\right)_{X}$$

$$\left(\frac{dE}{dt}\right)_{WR} = bn^2(r)$$ Heating

$$\left(\frac{dE}{dt}\right)_{X} = an^2(r)T^{1/2}$$ Cooling



[Colafrancesco, Dar & deRujula 2004]



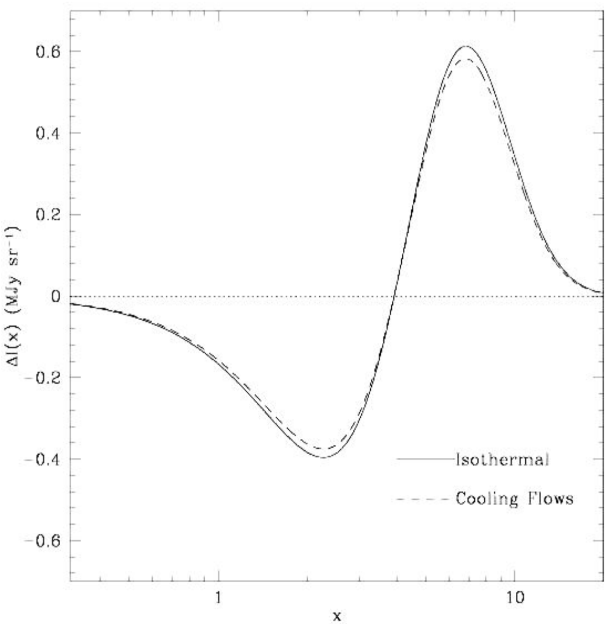
[Colafrancesco & Marchegiani 2007]

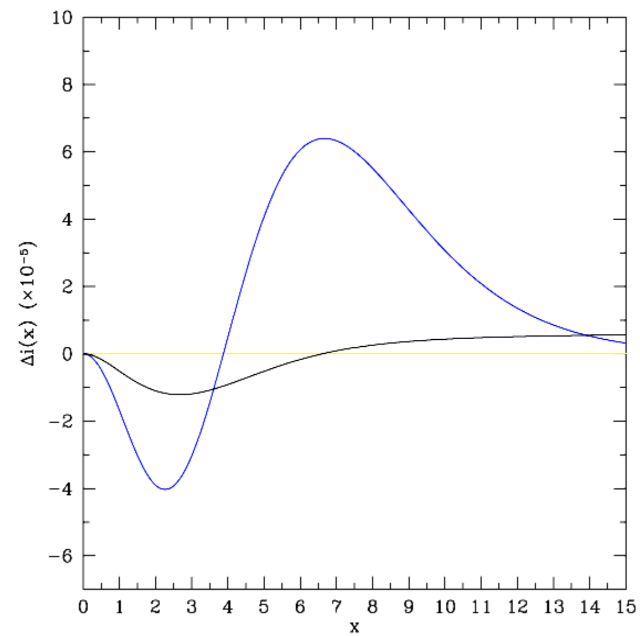
SZE in clusters' cool cores

SZ_{total}

SZ_{th}

$SZ_{non\text{-}th}$

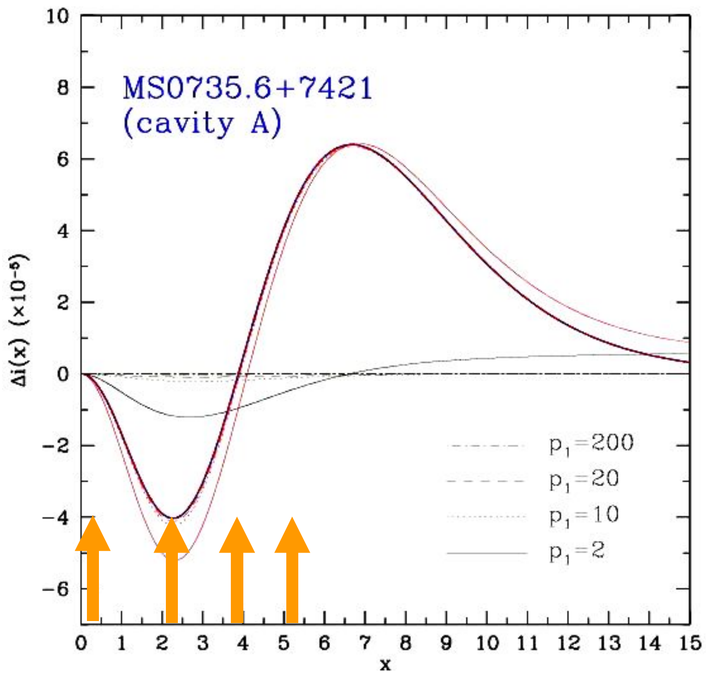


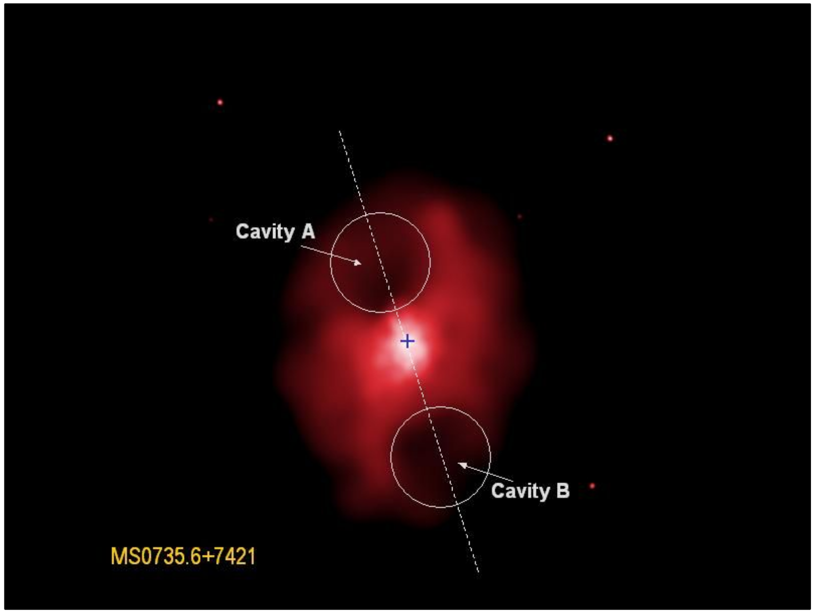


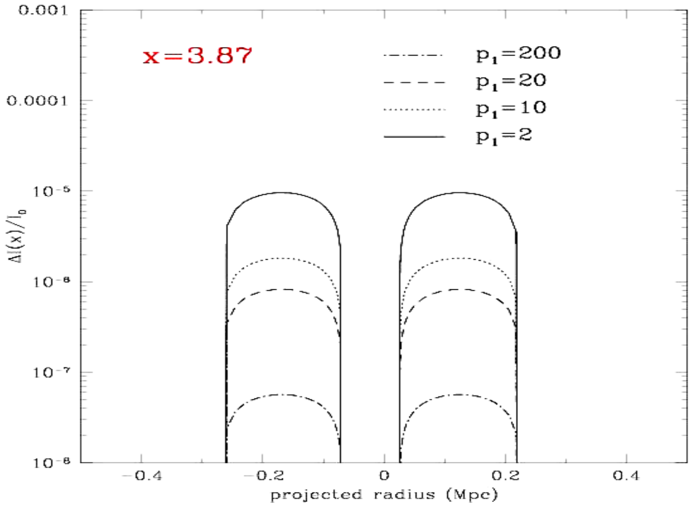
CRs from AGNs

SZE & cavities in Clusters

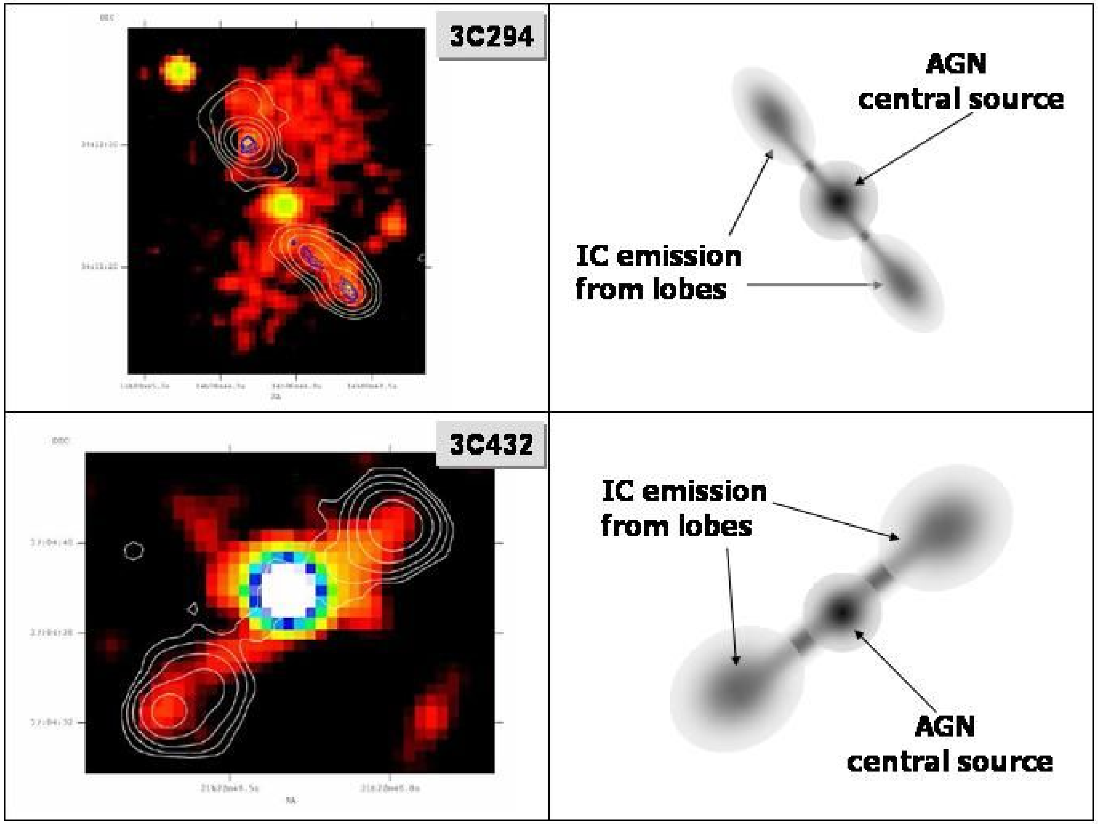
[S.C. 2005, A&A, 435, L9]

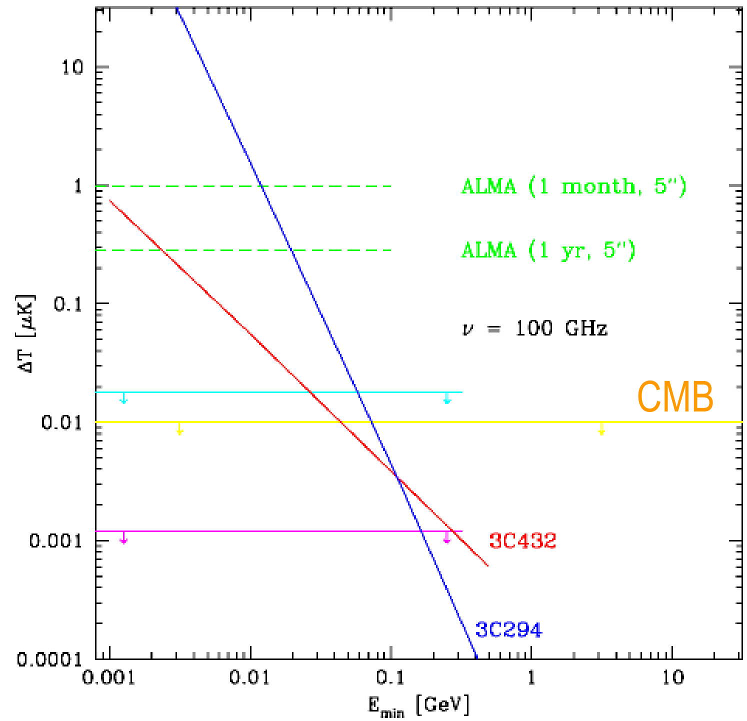


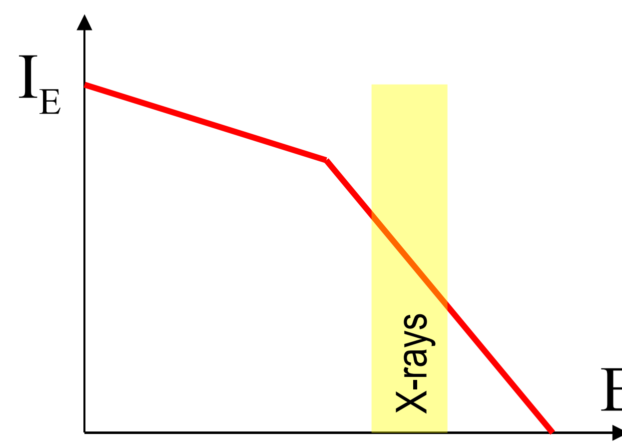




SZE from radio-galaxy lobes







$$\frac{\Delta T_{SZ}}{F_{IC}} \propto (kT_{CMB})^{-3} \times \gamma_{\min}^{-(\alpha-1)} \cdot E_{X\min}^{-(\alpha-1)/2}$$

measure → $T_{CMB}(z)$

[**S.C.** 2007, MNRAS]

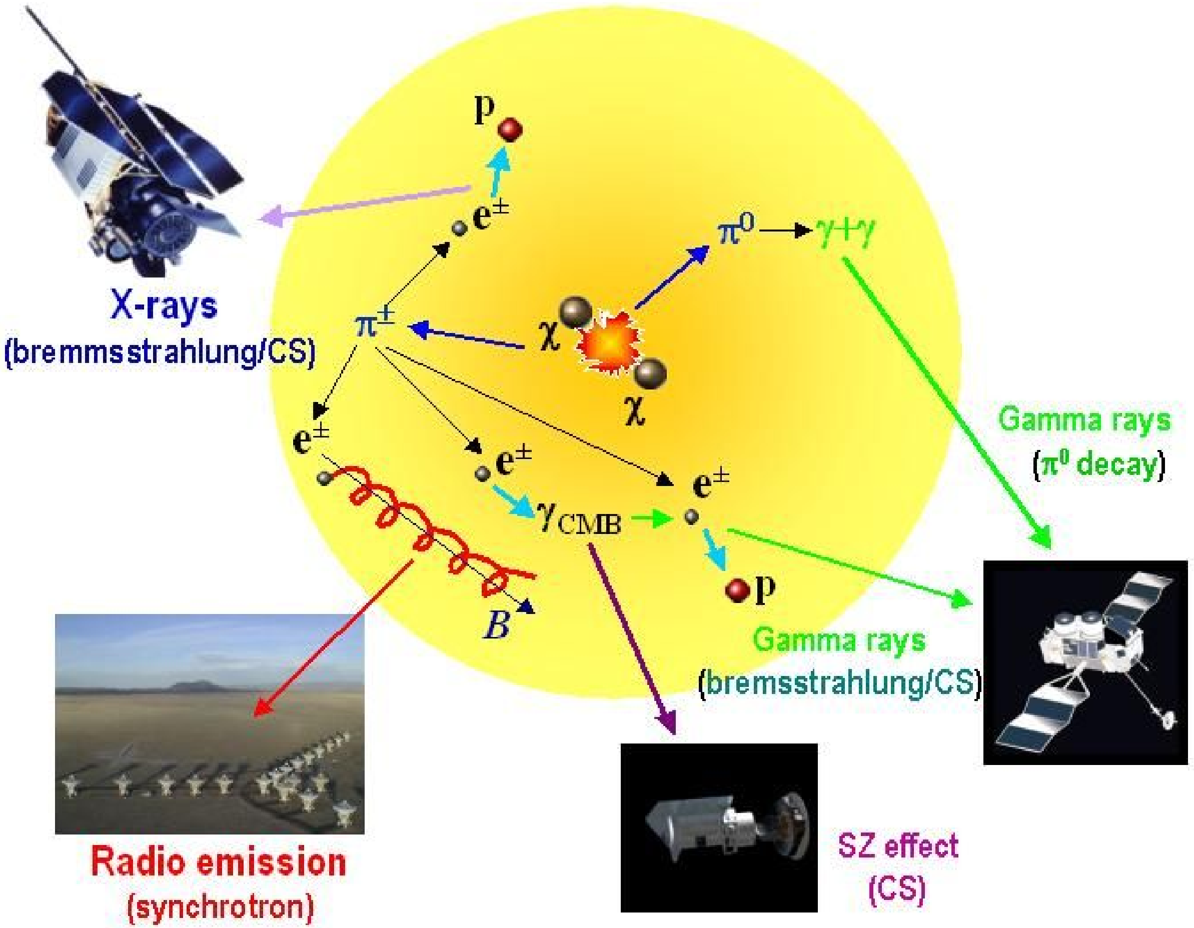
SZ effect
&
Dark Matter

SZE & DM nature

Illuminating halos with DM

Constraints on
DM physics
from
multi-ν observations
of DM Halos

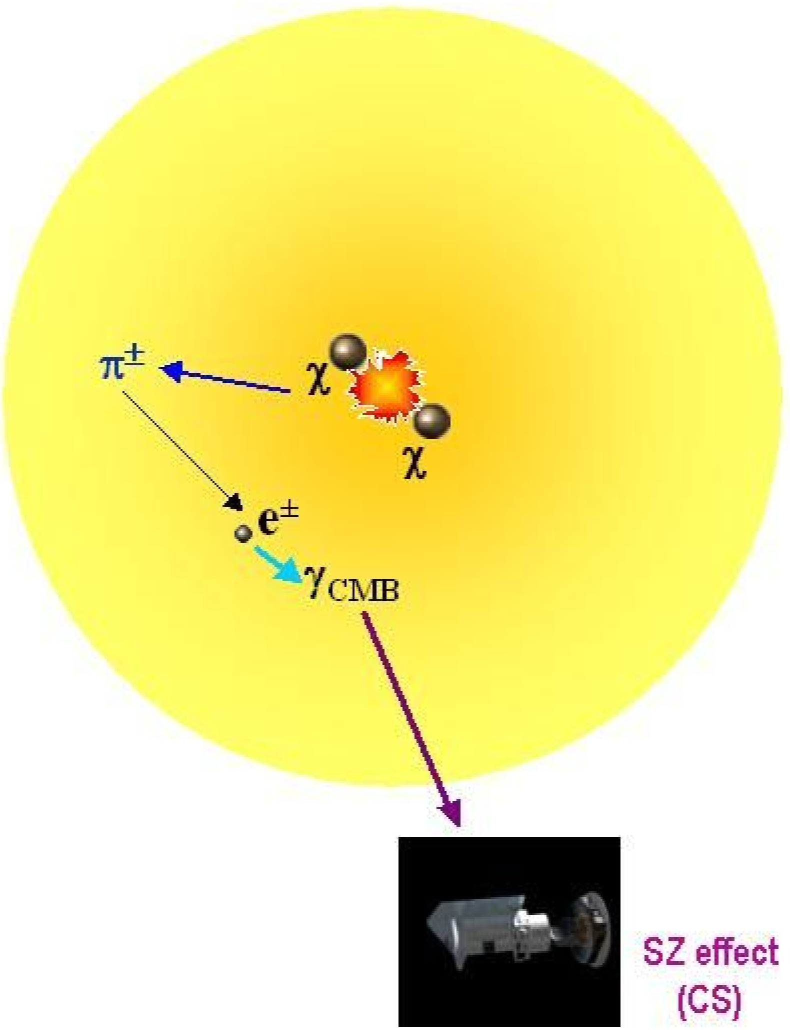
- Radio
- X-rays
- γ-rays
- SZ effect
- Heating



Signal

$$F_\nu \propto \langle \sigma V \rangle_{ann} \cdot n_\chi^2 \cdot \frac{dn_e}{dE_e} \cdot \left(\frac{dE_e}{dE_\nu} \right)$$

SZE from χχ annihilation



The case of Coma cluster

SZ_{th} in Coma

$$k_B T_e = 8.2 keV$$

$$\tau_e = 4.9 \cdot 10^{-3}$$

SZ_{kin} in Coma

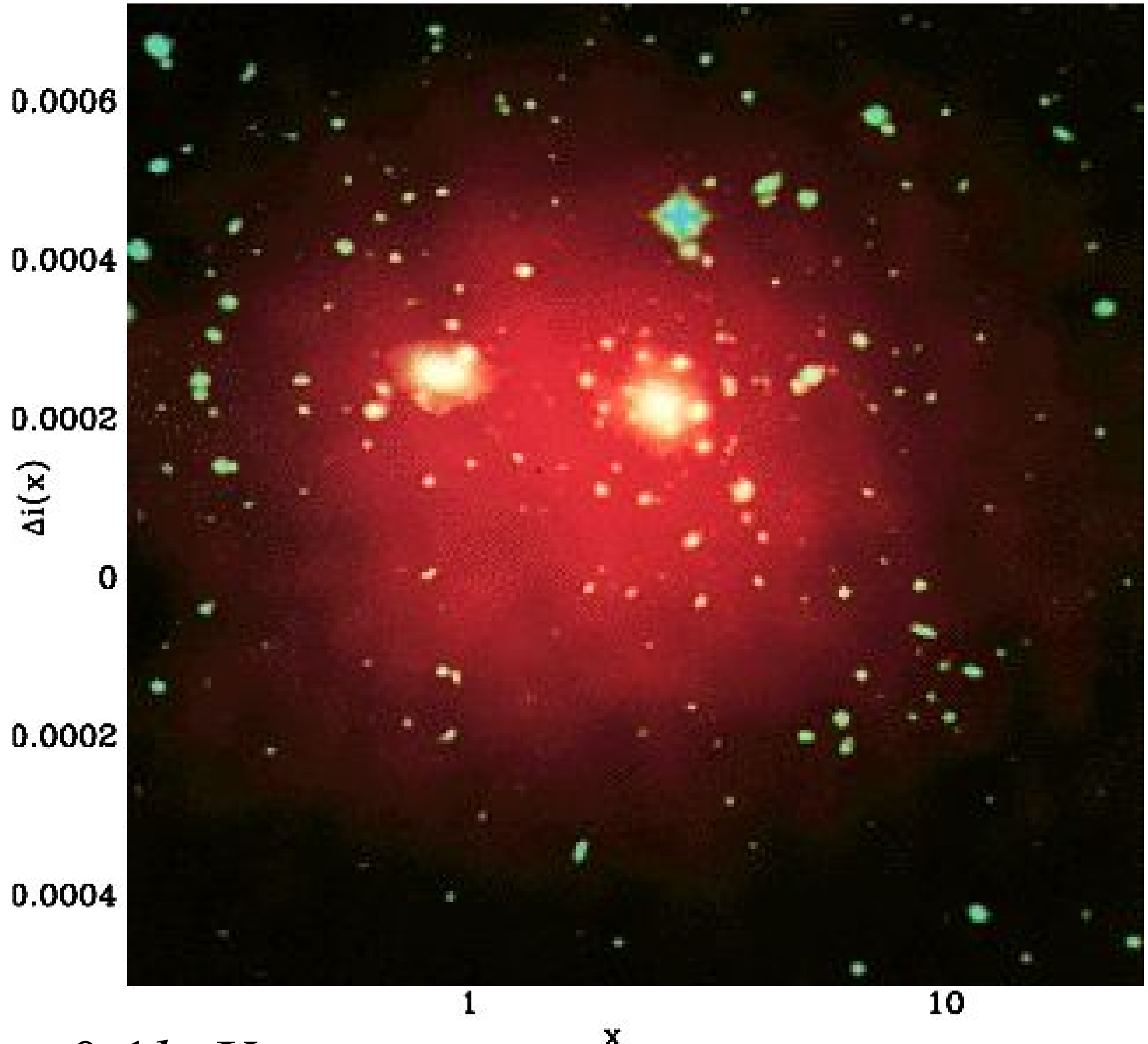
$$V_r = 0 km/s$$

SZ_{rel} in Coma

$$n_{rel} = 10^{-6} cm^{-3}$$

SZ_{warn} in Coma

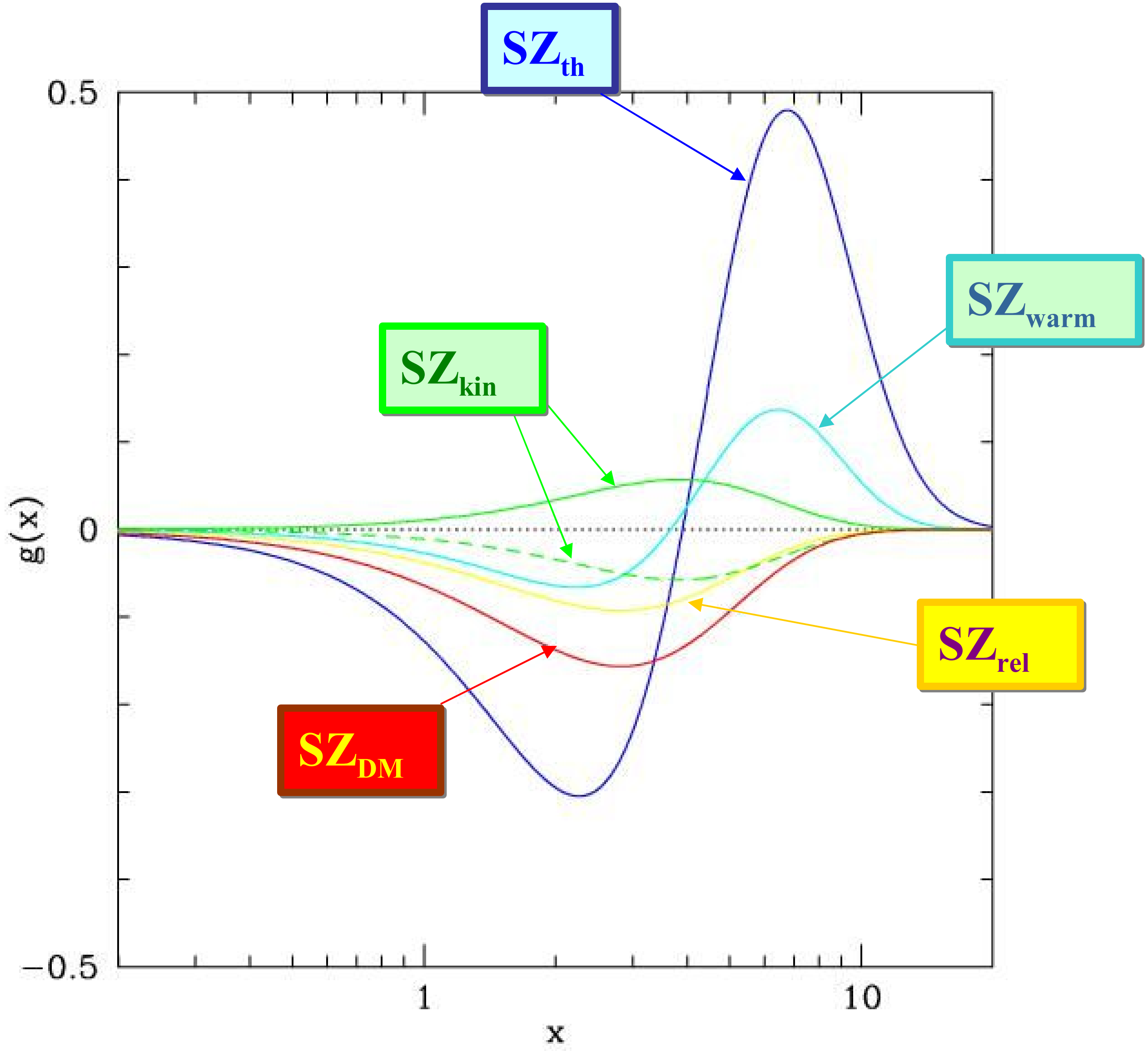
$$n_{warm} = 10^{-3} cm^{-3} \quad T_{warm} = 0.1 keV$$



SZE in DM halos

A structure with:

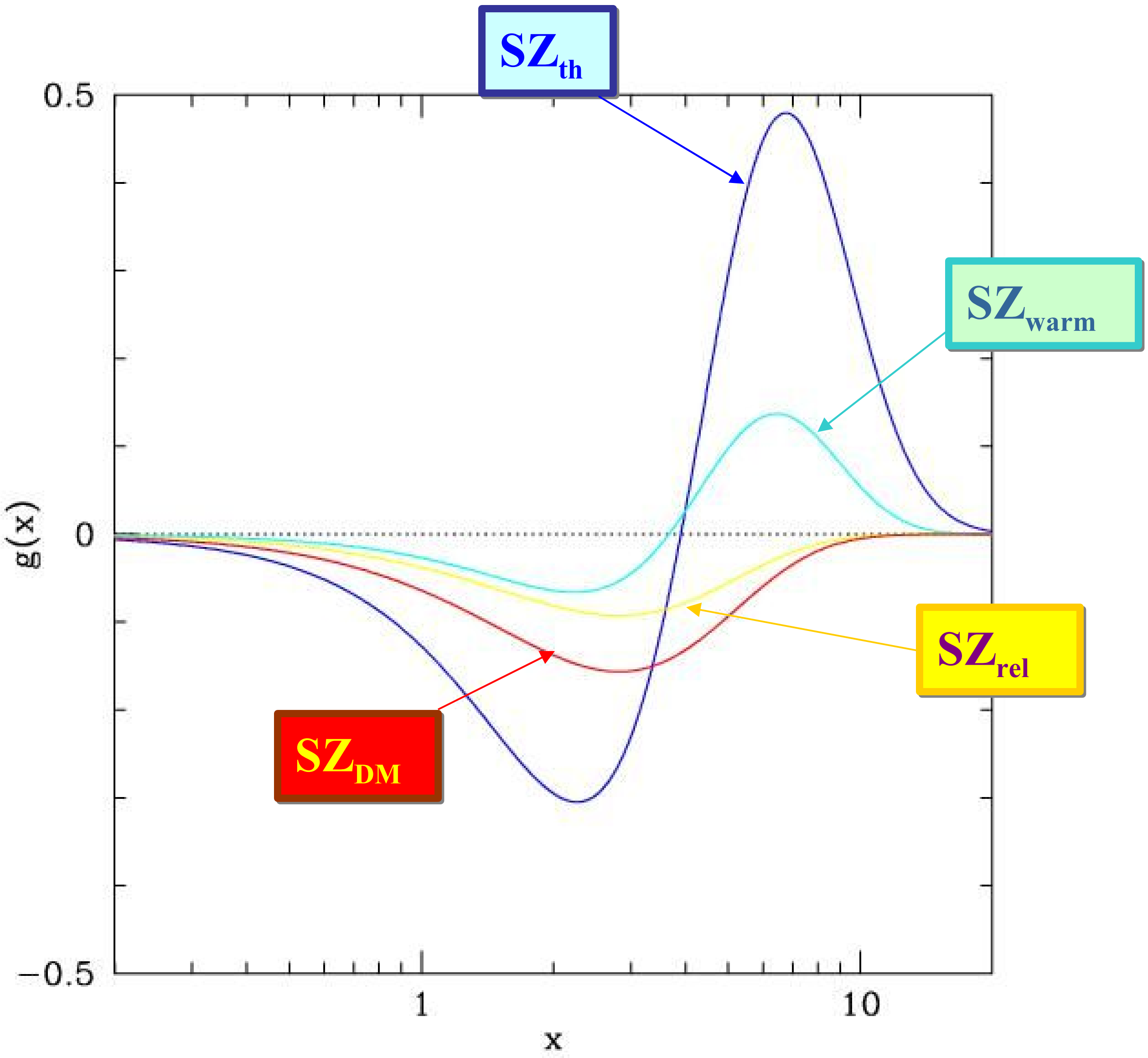
- Hot gas
- Warm gas
- Rel. Plasma
- DM
- $V_r > 0$



SZE in DM halos

A structure with:

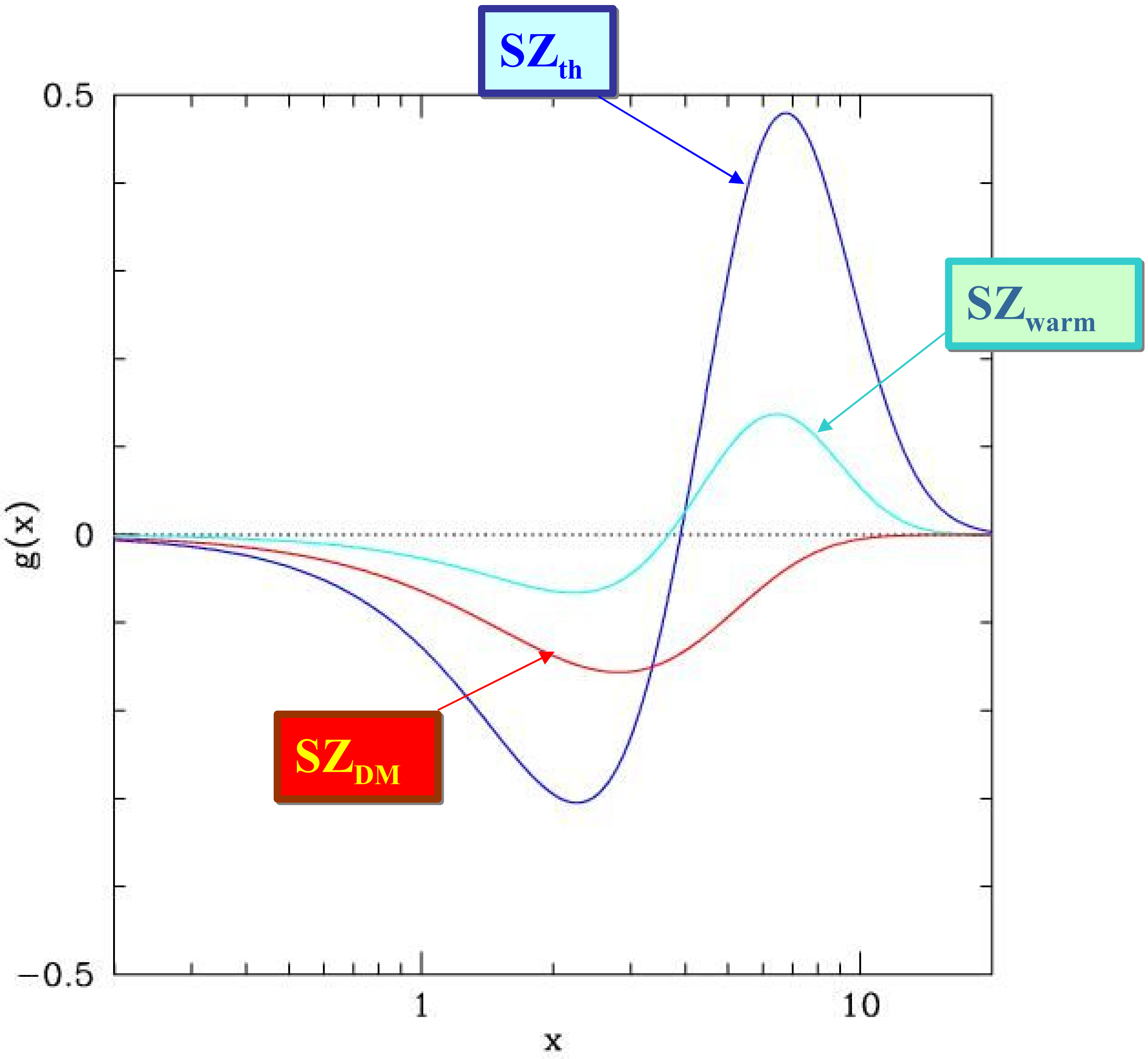
- **Hot gas**
- **Warm gas**
- **Rel. Plasma**
- **DM**
- **($V_r \approx 0$)**



SZE in DM halos

A structure with:

- **Hot gas**
- **Warm gas**
-
- **DM**
- **($V_r \approx 0$)**



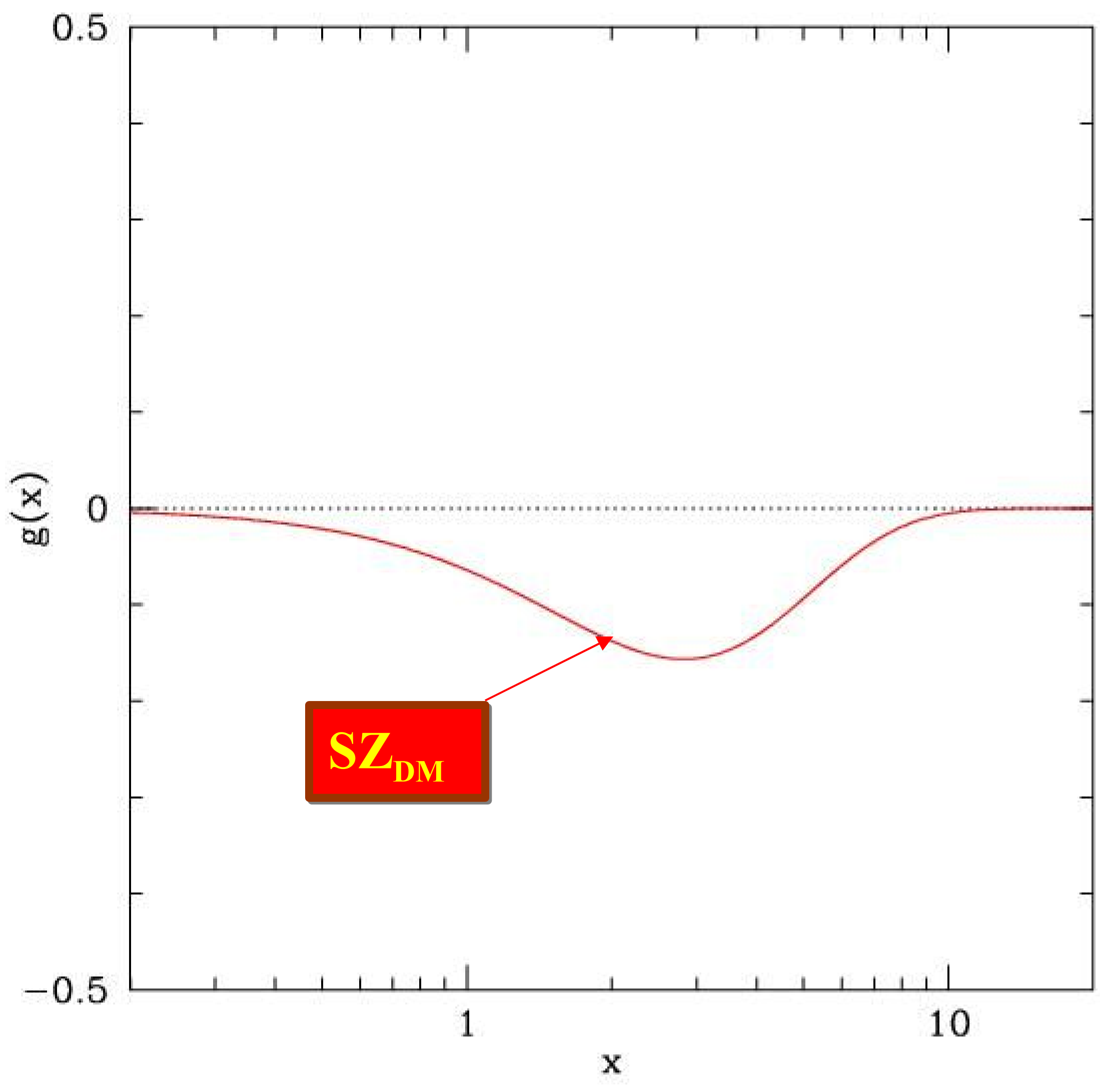
SZE in DM halos

[S.C. 2004, A&A, 422, L23]

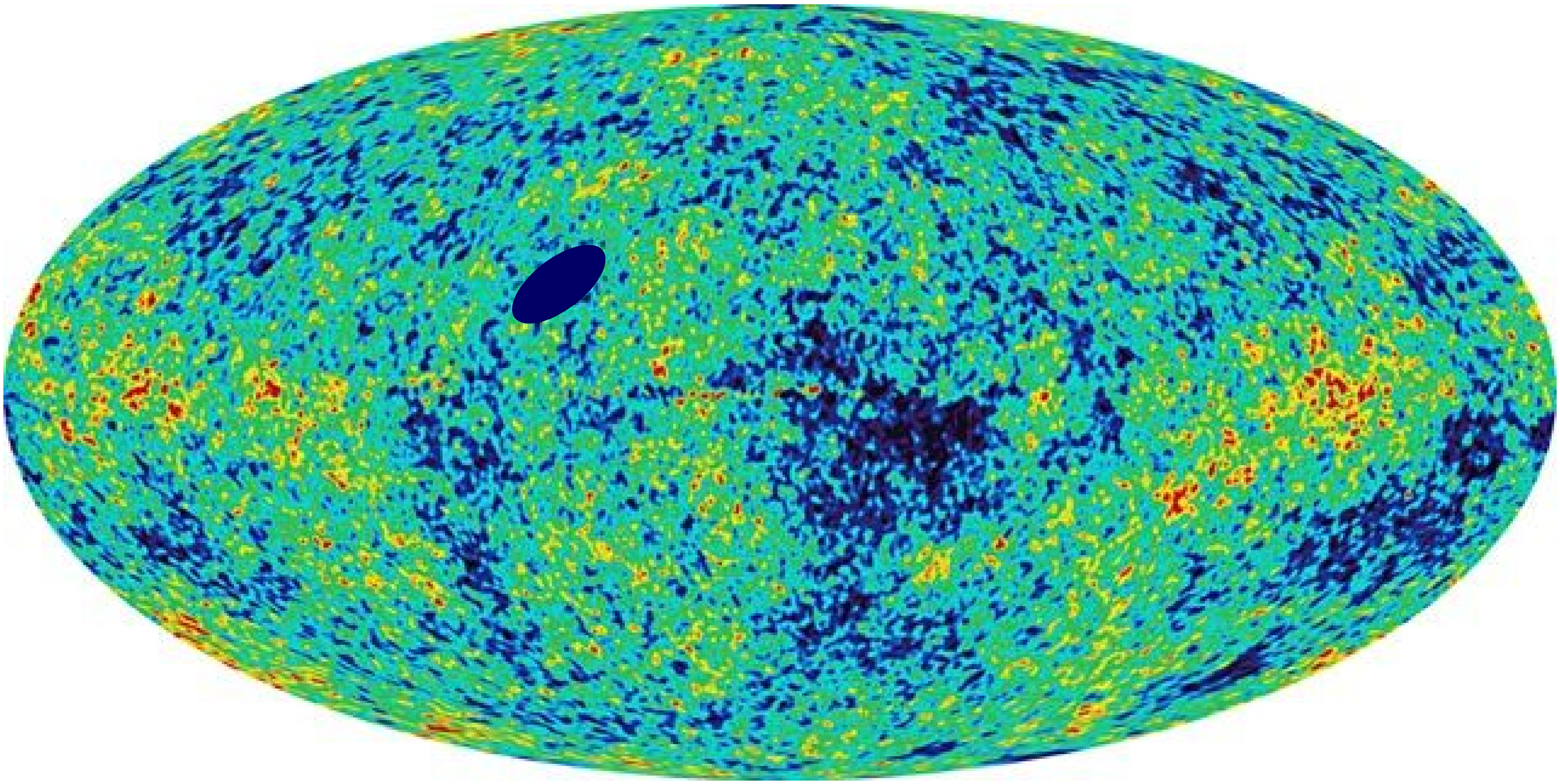
A structure with:

-
-
-
- **DM**
- **($V_r \approx 0$)**

Pure DM halo

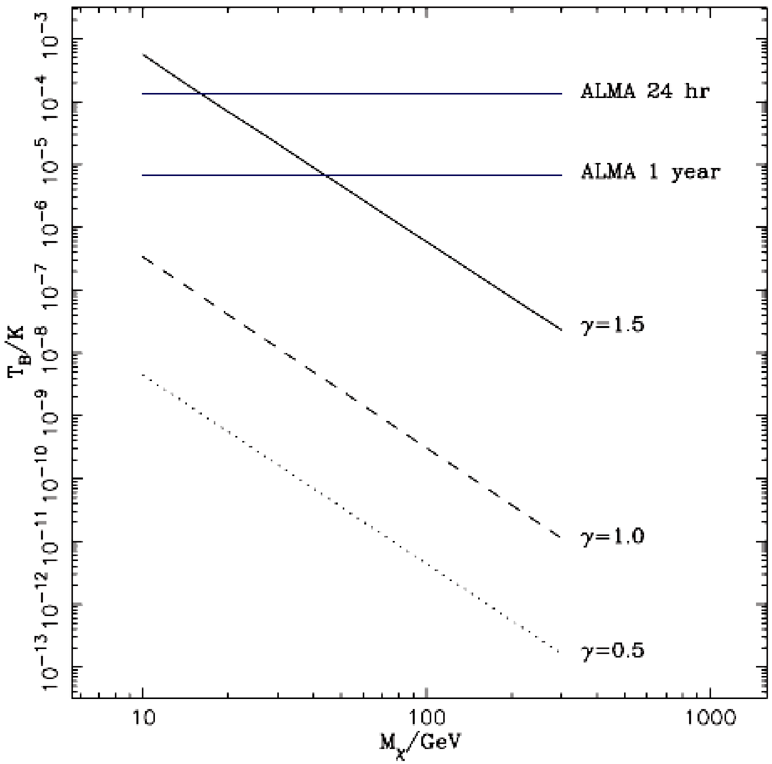


CMB maps & dSph galaxies (Draco)



SZ_{DM} in Draco

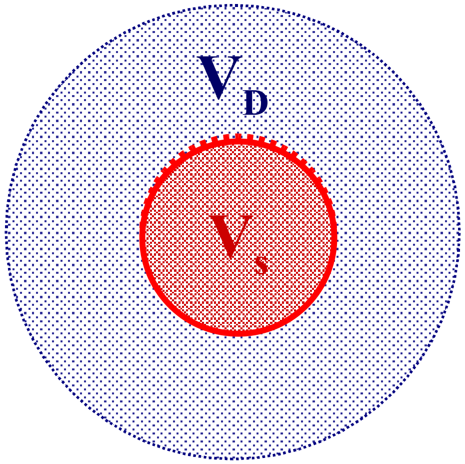
Diffusion effects



[Culverhouse, Ewans & Colafrancesco 2006]

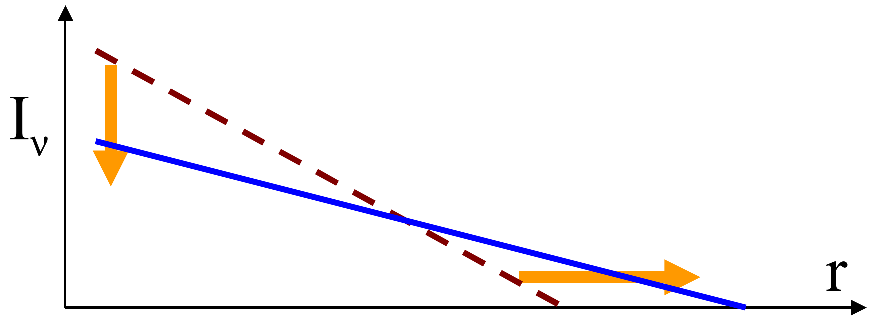
[Colafrancesco, Profumo & Ullio 2007]

$$n_e(E,r) = [Q_e(E,r)\tau_{loss}] \cdot \frac{V_{source}}{V_{source} + V_{diffusion}} \cdot \frac{\tau_D}{\tau_D + \tau_{loss}}$$



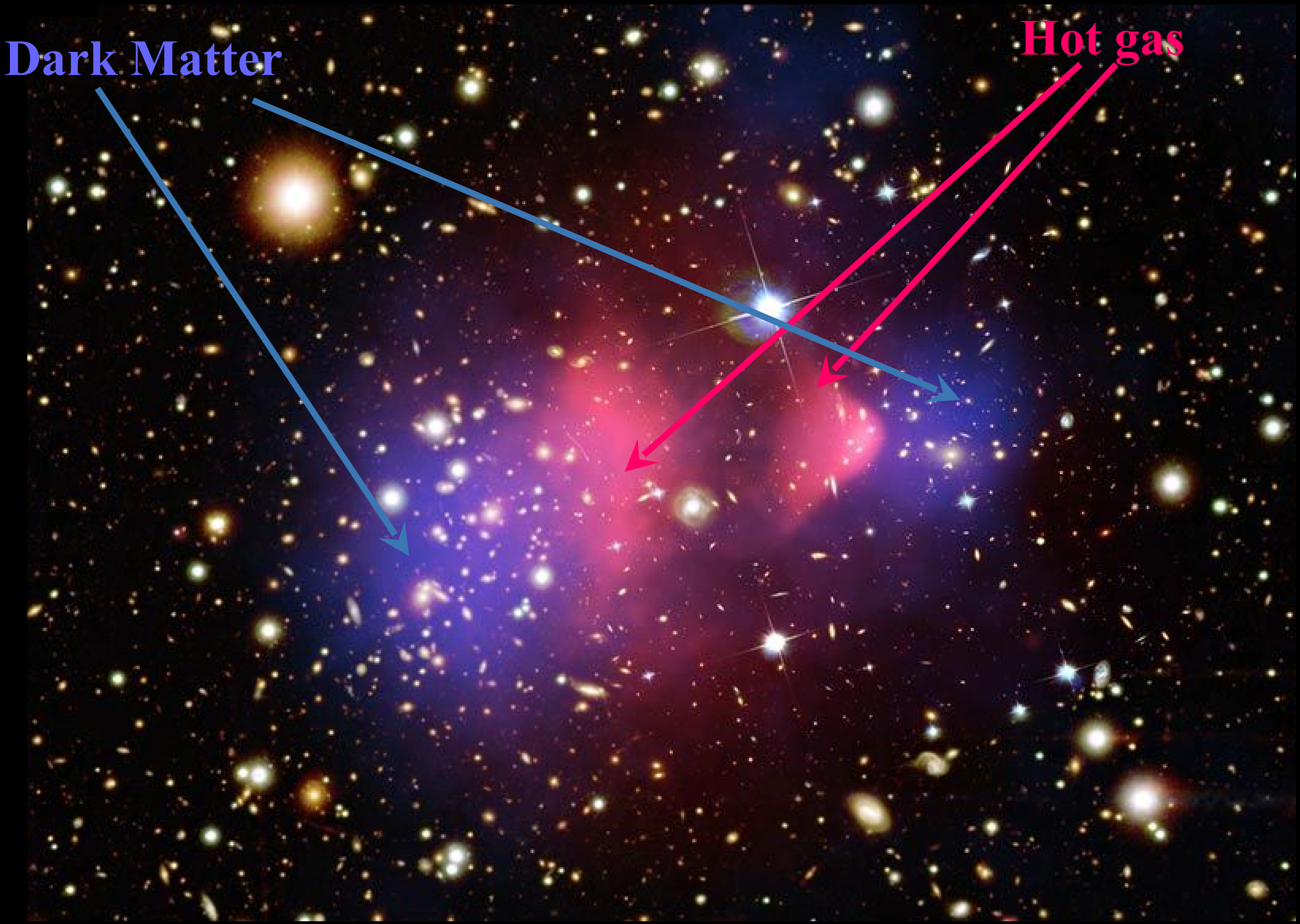
$\tau_{loss} \gg \tau_D$

$$n_e(E,r) = [Q_e(E,r)\tau_{loss}] \cdot \frac{V_{source}}{V_{diffusion}} \cdot \frac{\tau_D}{\tau_{loss}}$$

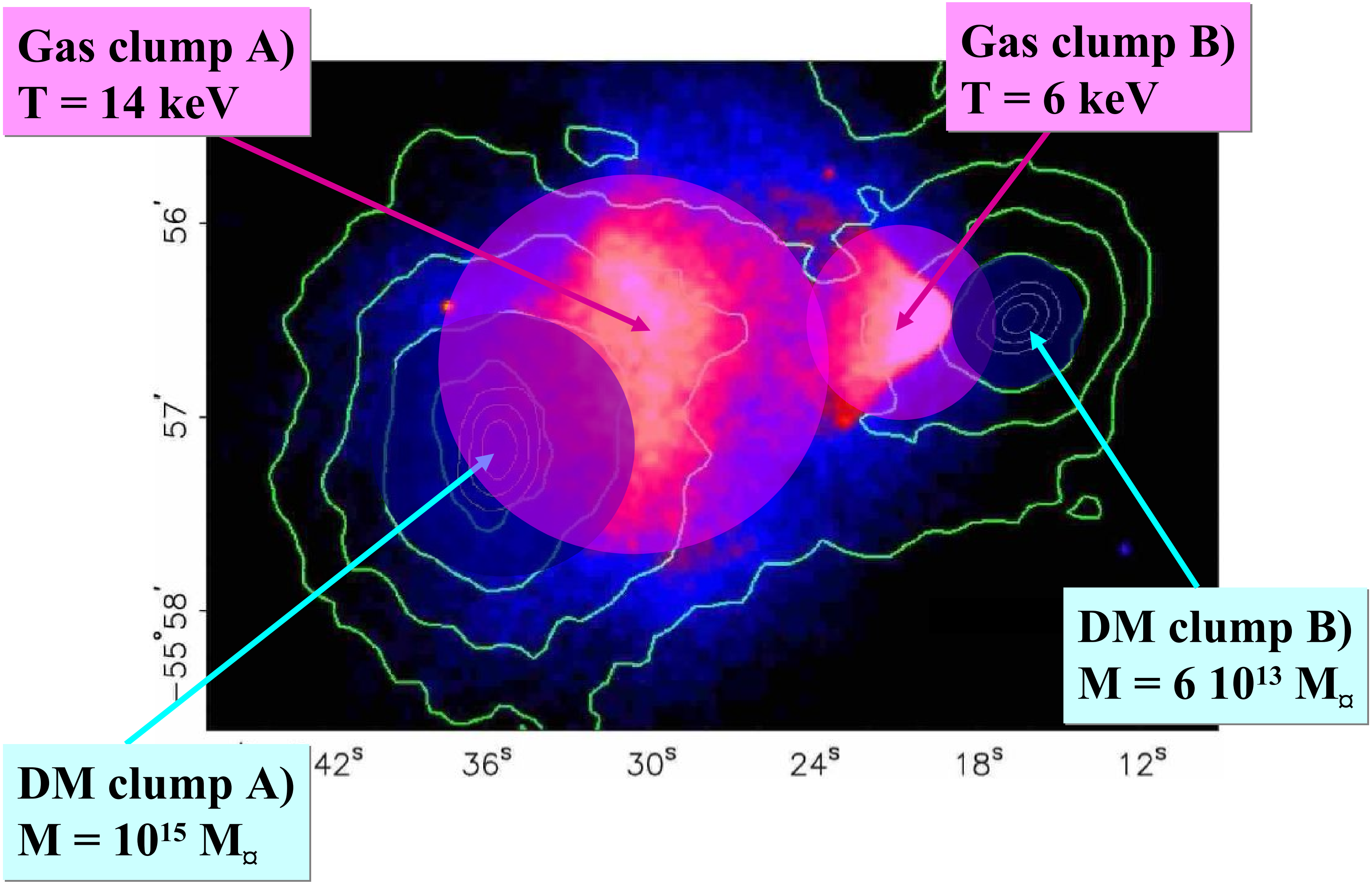


1ES0657-556

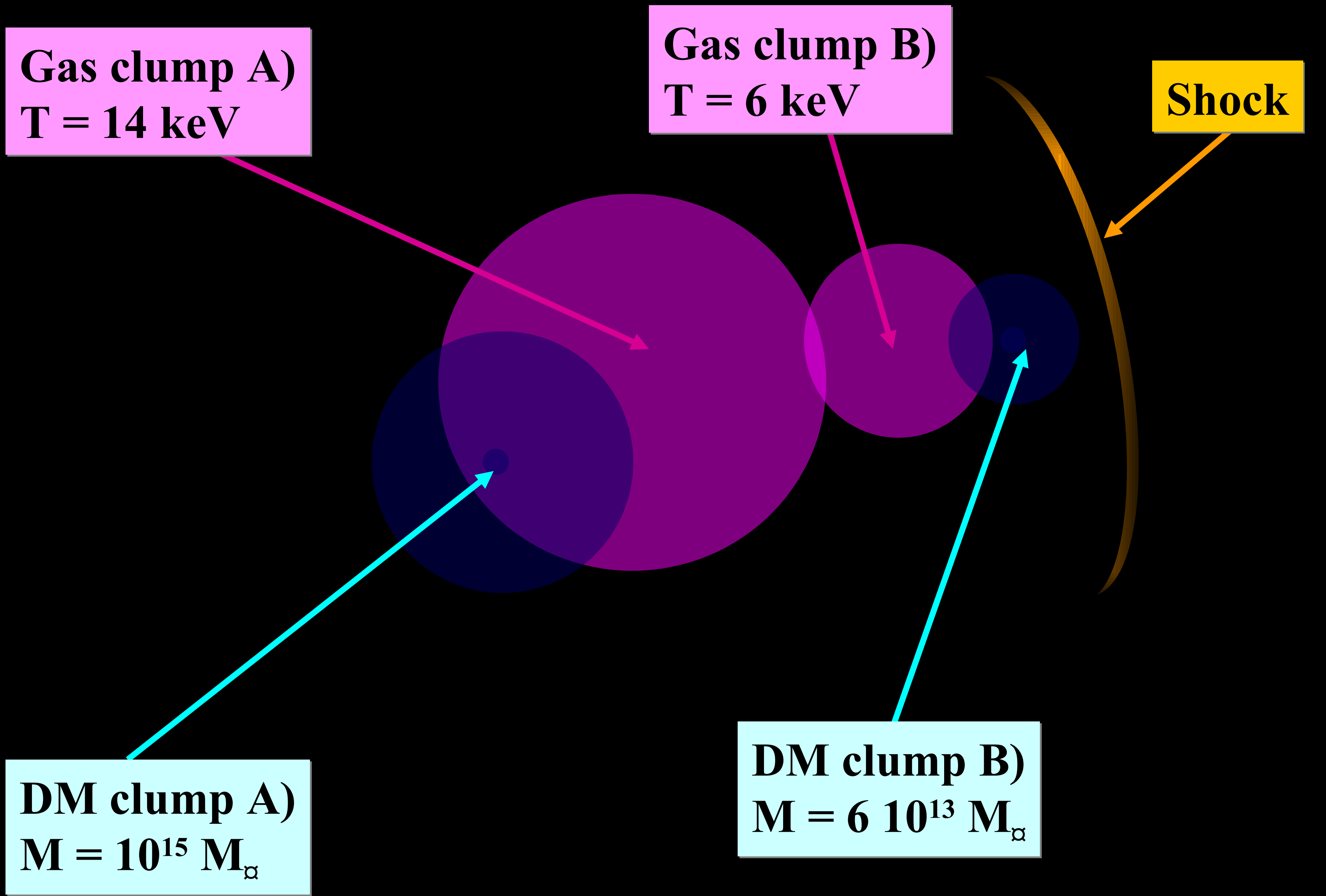
1ES0657-556



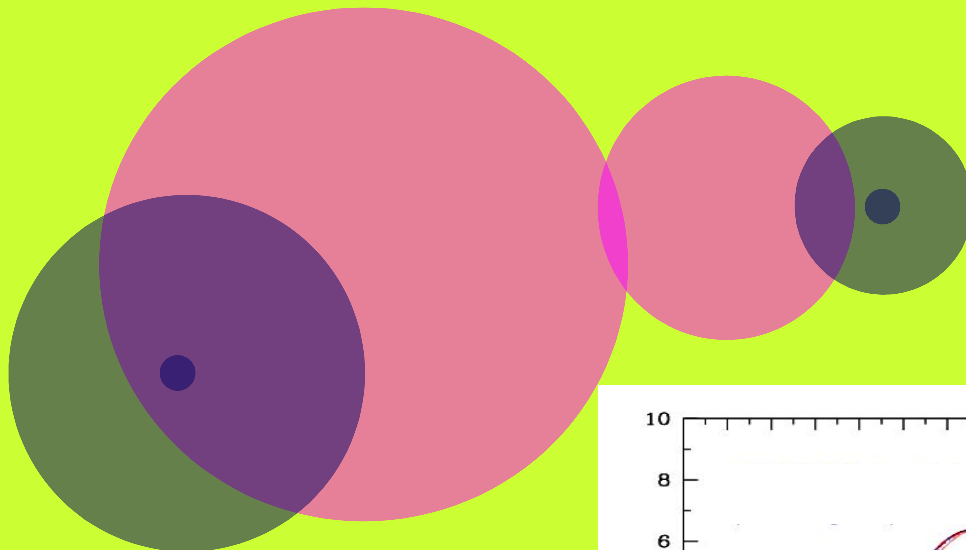
The cluster 1ES0657-556

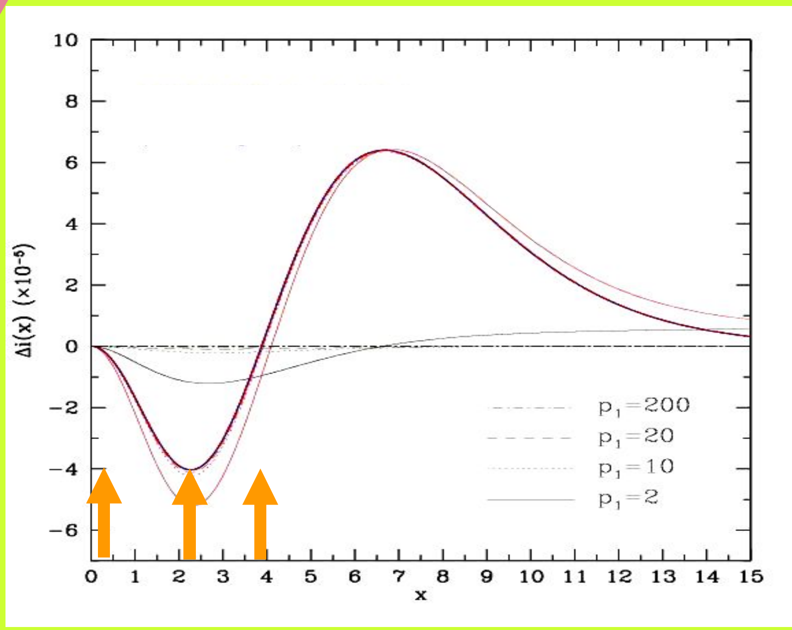


1ES0657-556: simple model



SZ_{DM} from 1ES0657-556

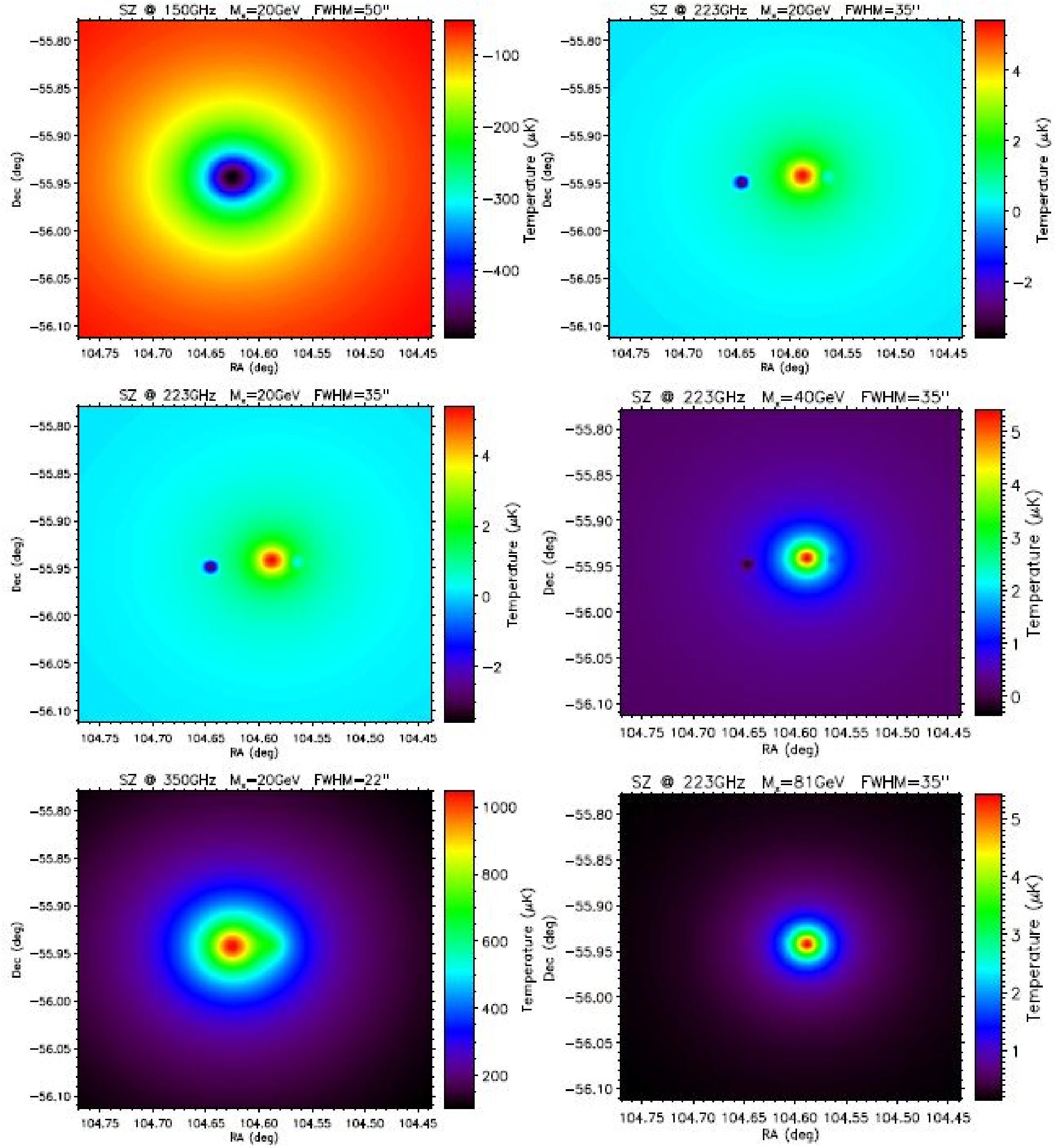




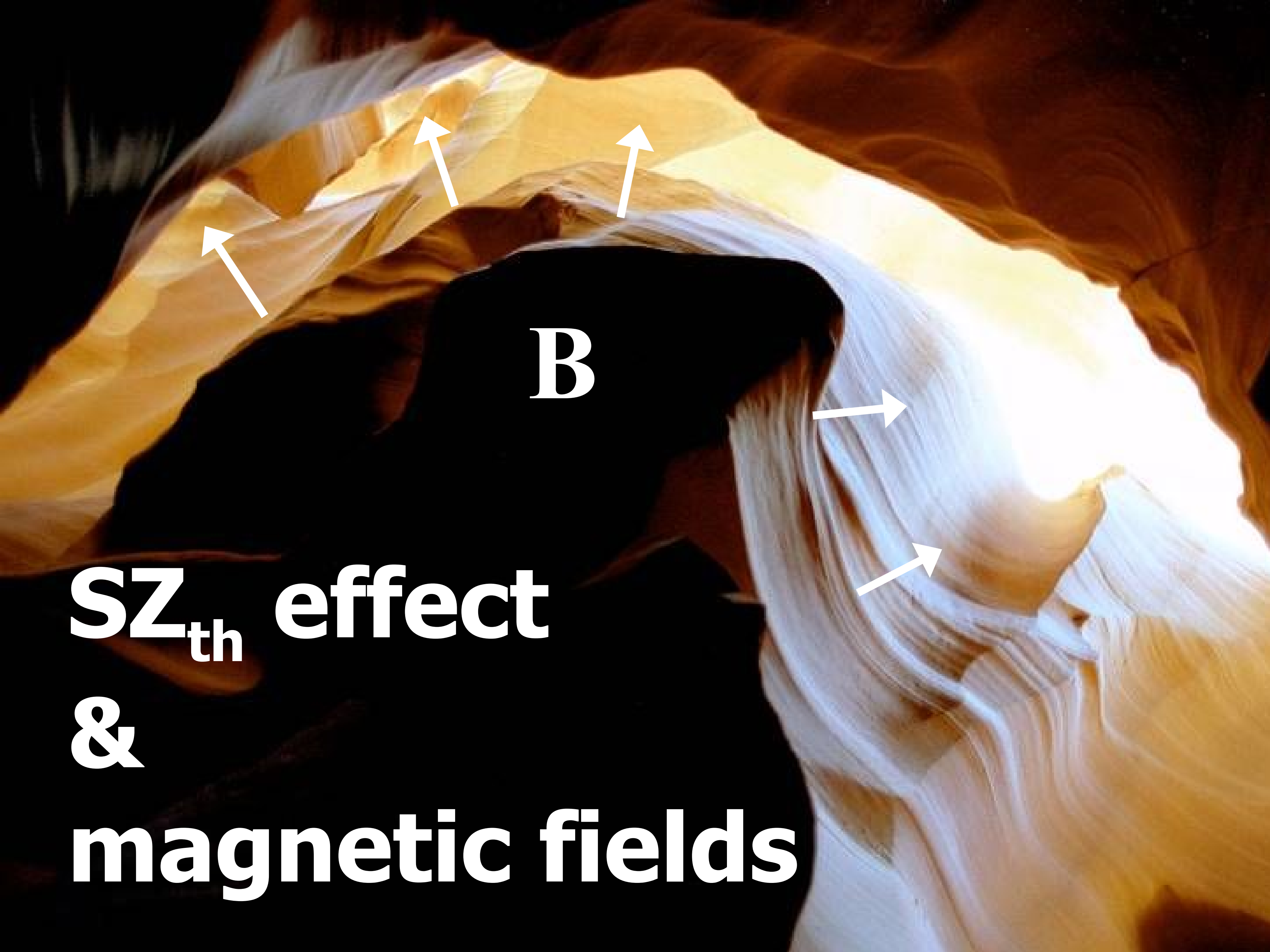
Isolating SZ_{DM} at ~223 GHz

[**S.C.** et al. 2007]

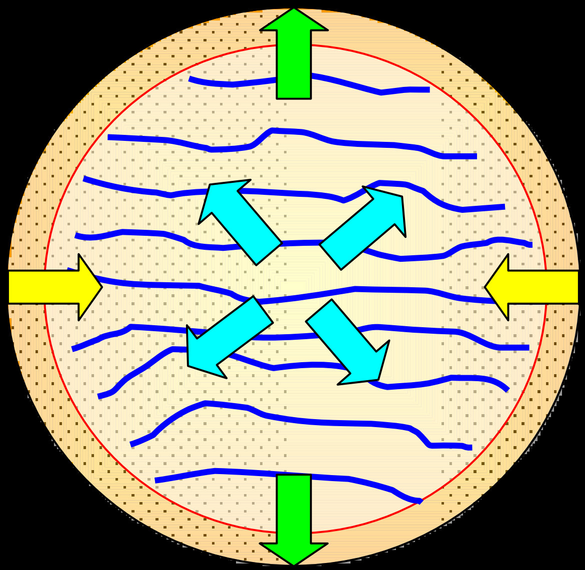
Frequency (Mχ= 20 GeV)



Neutralino mass (ν=223 GHz)


B
SZ$_{th}$ effect
&
magnetic fields

B-field in clusters



B - field

Magnetic Virial Theorem

Temperature structure

$$\frac{1}{2}\frac{d^2 I_{ik}}{dt^2} = 2K_{ik} + \frac{2}{3}U\delta_{ik} + \int_V F_{ik} d^3x + W_{ik}$$

$$2K + 2U + U_B + W = 0$$

Hydrostatic Equilibrium

Density structure

$$\frac{\partial p_g(r,B)}{\partial r} + \frac{\partial p_B(r,B)}{\partial r} = -\frac{GM(\leq r)}{r^2}\rho_g(r,B),$$

Density structure

[Colafrancesco & Giordano 2007]

$$\frac{\partial p_g(r,B)}{\partial r} + \frac{\partial p_B(r,B)}{\partial r} = -\frac{GM(\le r)}{r^2}\rho_g(r,B)$$

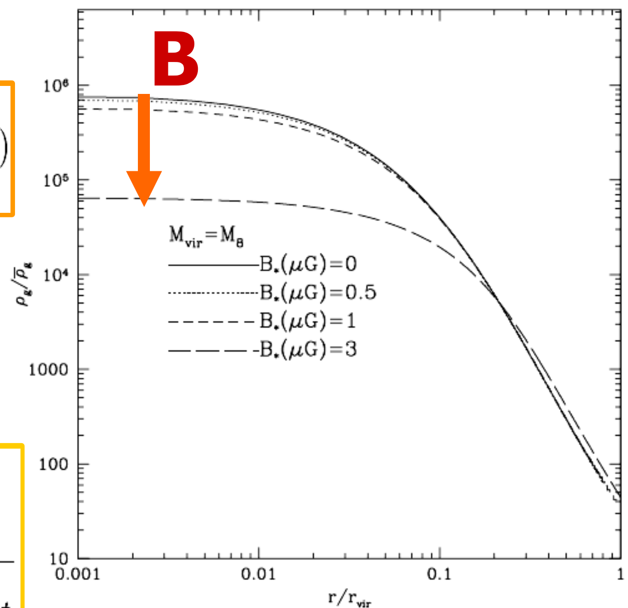
$$\ln y_g(r,B) \;+\; \eta'(y_g(r,B)^{2\alpha-1}-1) = \;= \frac{\ln y_g(r,0)}{1-\frac{M_\phi(B)^2}{M_{vir}^2}+\frac{4\pi}{G}\frac{r_{vir}^4}{M_{vir}^2}P_{ext}}$$

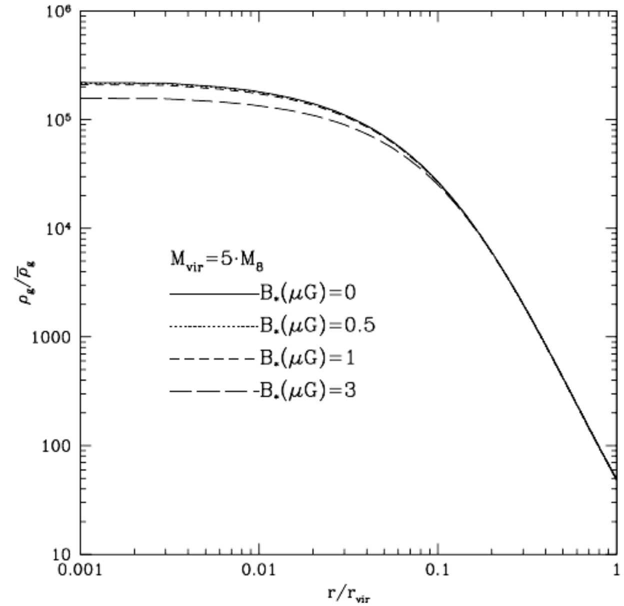
$$\rho_g(r) = \rho_g(0)e^{-3\frac{c}{m(c)}\int_0^x \frac{m(u)}{u^2}du}$$

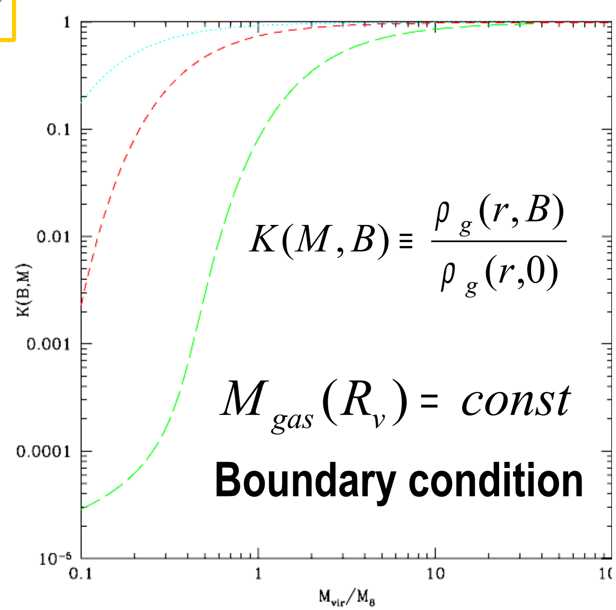
$$\eta' = \frac{C_2^2}{8\pi}\left(\frac{2\alpha}{2\alpha-1}\right)\rho_g(0,B)^{2\alpha-1}\frac{\mu m_p}{k_B T_g(B}$$

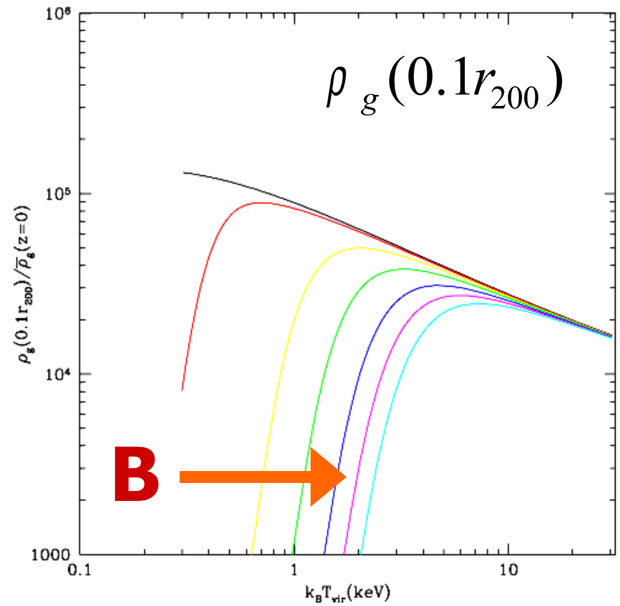
$$B(r) \propto B_* \cdot \rho_g^{\alpha}$$

[Dolag et al. 2001]









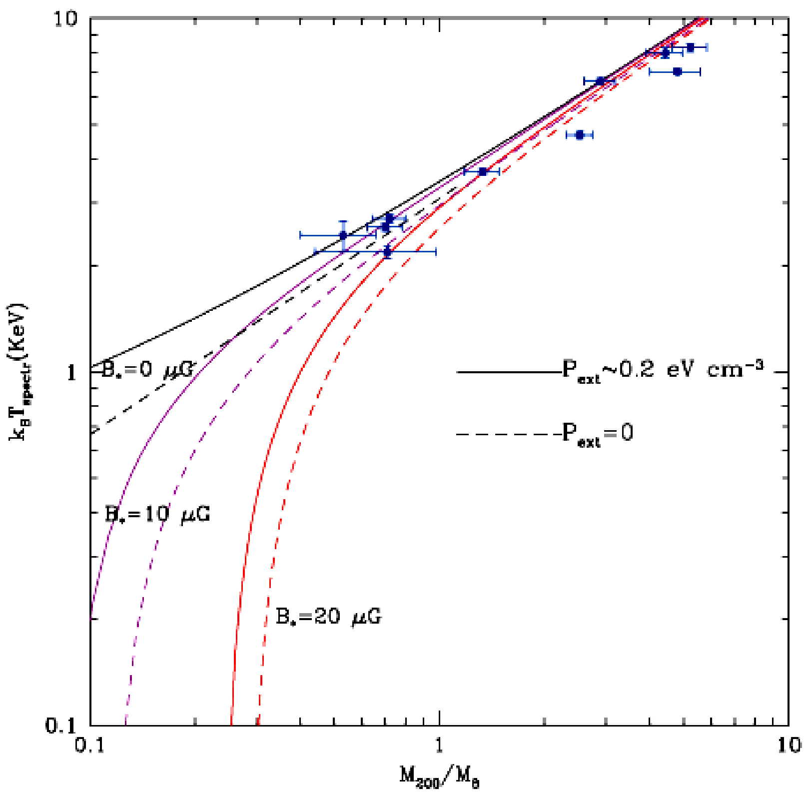
The T-M relation

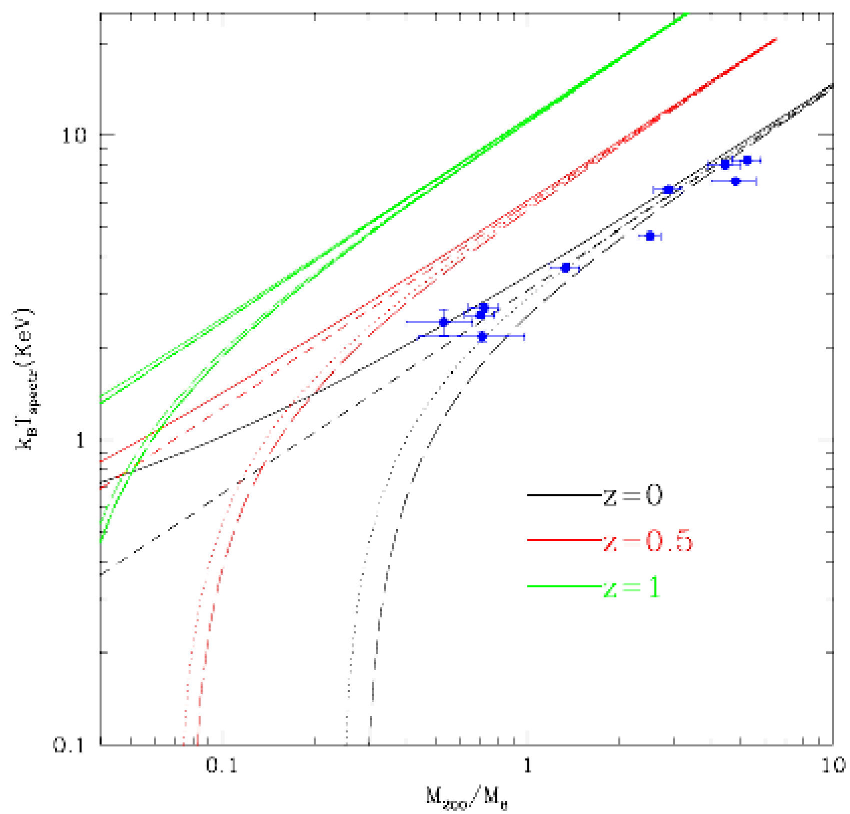
[Colafrancesco & Giordano 2006]

$$kT_g = kT_g(B=0)\left(1 - \frac{M_\phi^2}{M_{vir}^2} + \frac{P_{ext}}{P_{vir}}\right)$$

$$k_B T_g(B=0) = -\frac{\xi \mu m_p W}{3 M_{vir}}$$

$$M_\phi \simeq 1.32 \times 10^{13} M_\odot \left[\frac{I(c)}{c^3}\right]^{1/2} \left(\frac{B_*}{\mu G}\right)\left(\frac{r_{vir}}{Mpc}\right)^2$$

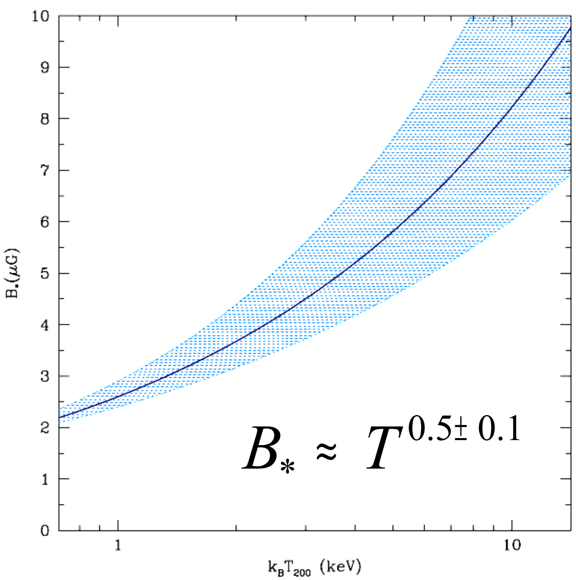


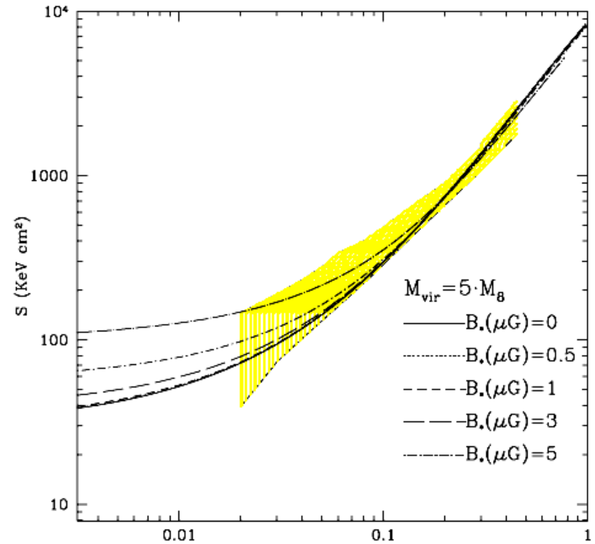


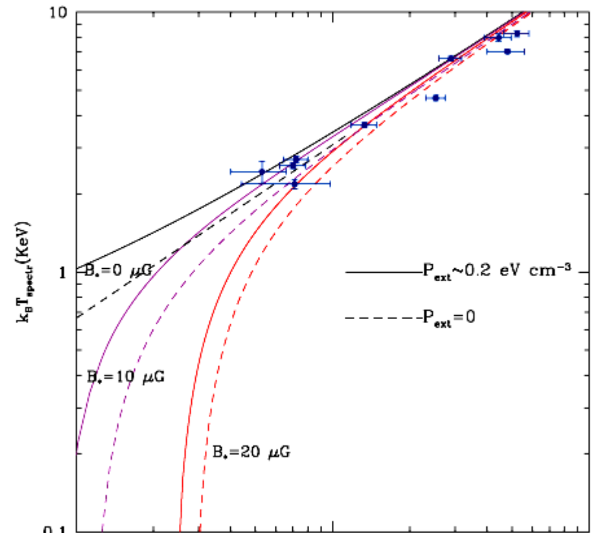
[Data taken from Arnaud 2005]

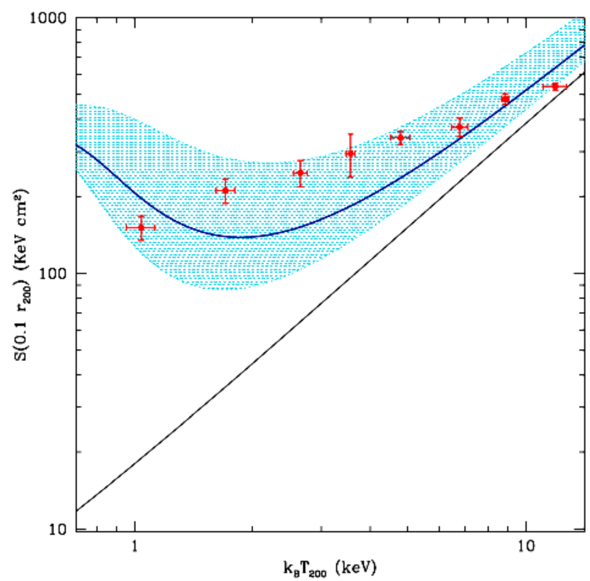
B-field & cluster structure: *panacea*

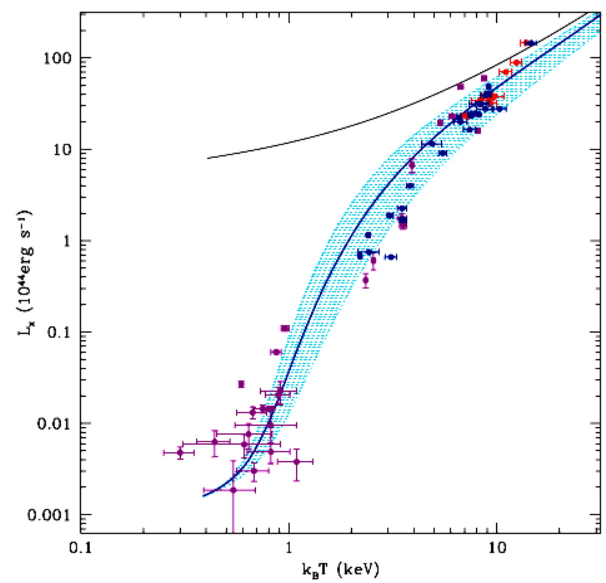
"**B**-field solves many (or all) of the still problematic aspects of cluster evolution"









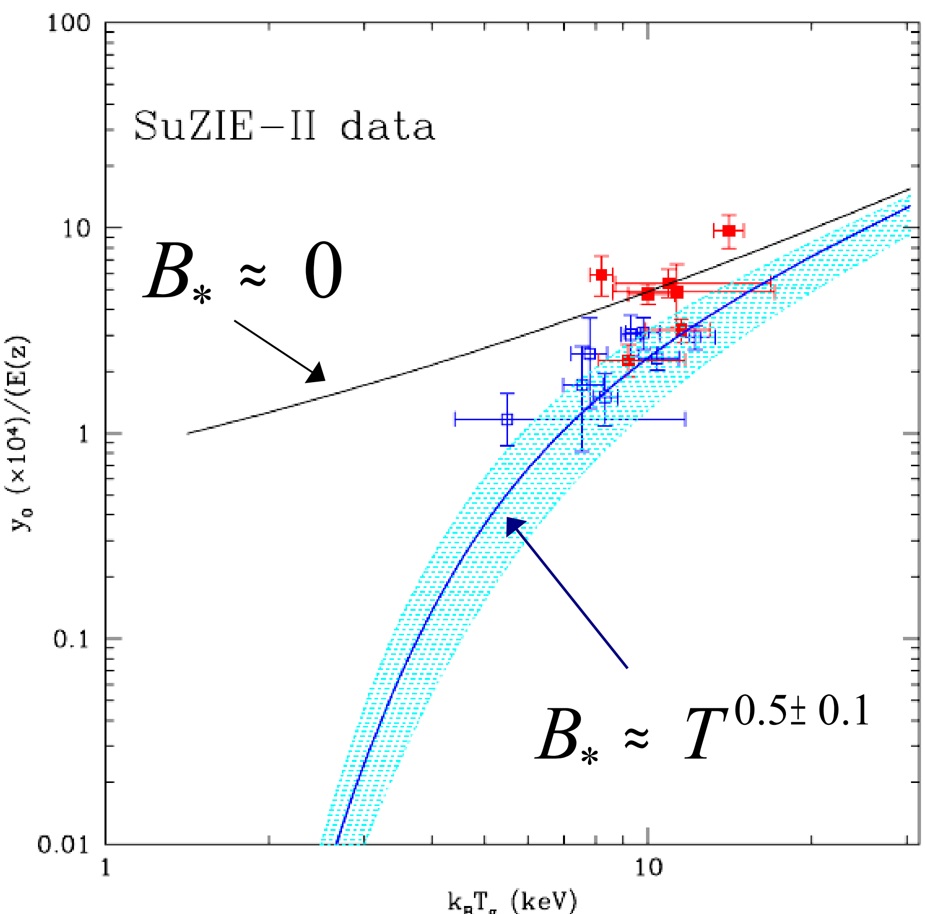


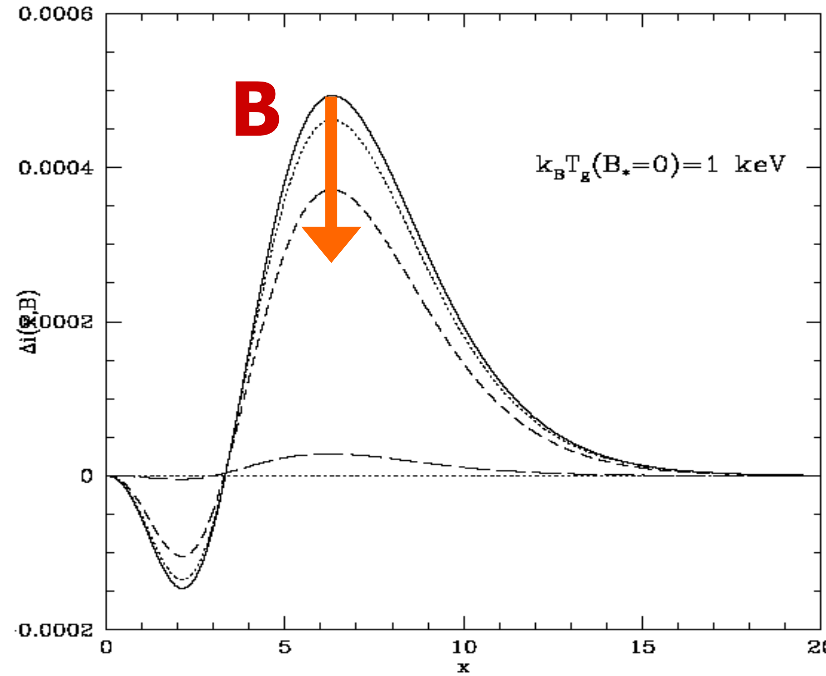
[Colafrancesco & Giordano 2006-2007]

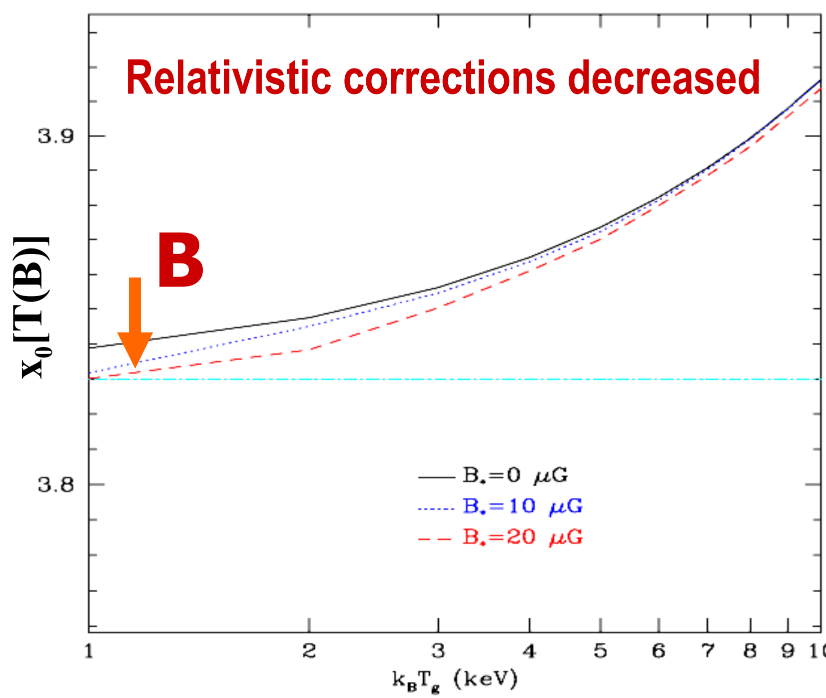
ASDC ASI Science Data Center

SZE and B-field

$$\Delta I_{SZE} \propto \int d\ell \rho_g T_g \cdot g(x)$$

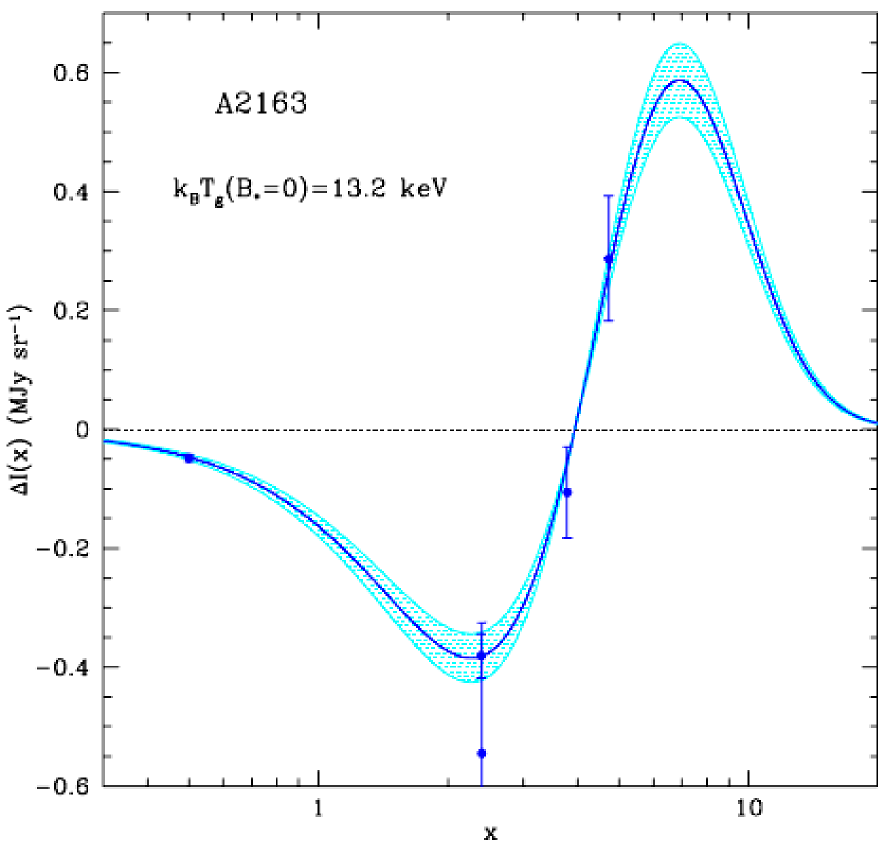


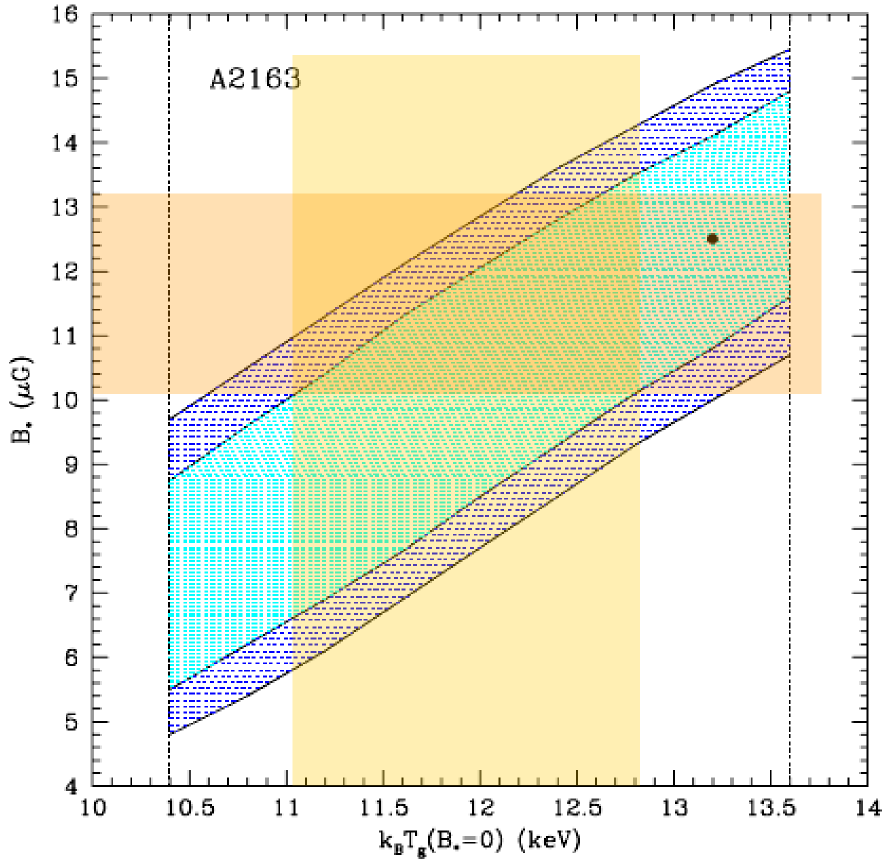




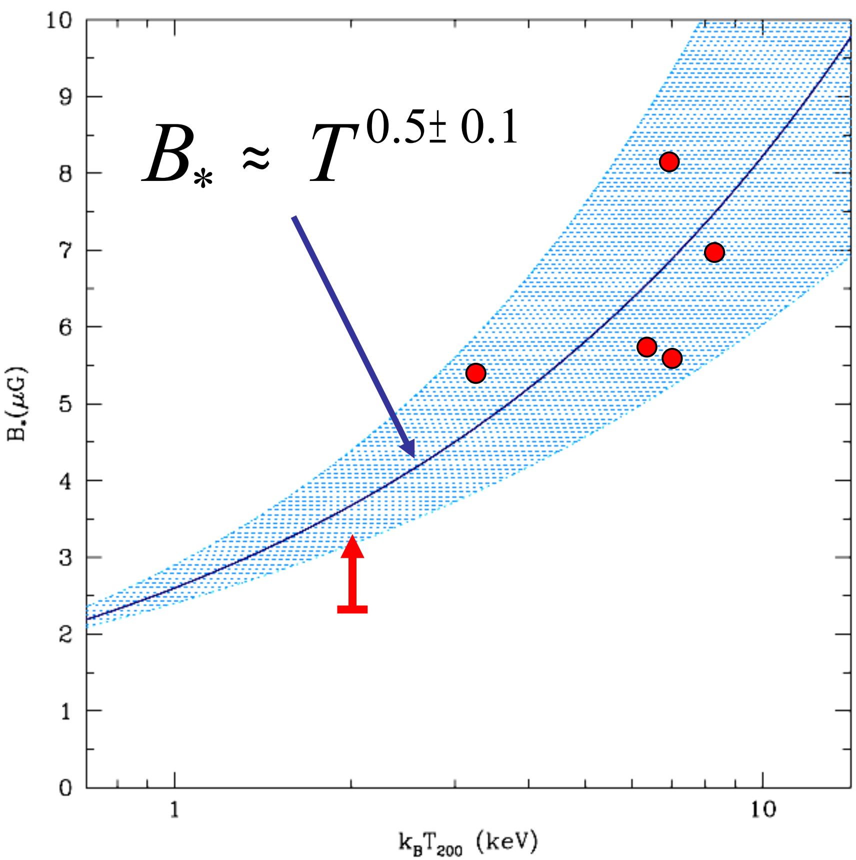
[Colafrancesco 2007]

B-field from SZE





B-field evolution



Cluster-bound <B-pressure>

Cluster-bound <B-tension>

CR confinement in LSS

Magnetic tomography of LSS

Cluster bound average B-field

$$\langle B \rangle = \int \frac{dV(z)}{dz} dz \int dM \cdot N(M,z) \cdot B(M,z)$$

$$\langle B \rangle \approx 200 - 500 \mu G$$

$$\langle B^2 \rangle^{1/2} \approx 40 - 100 \mu G$$

$$B = B_* \left[\frac{\rho_g(r)}{10^4 \overline{\rho_g(z=0)}} \right]^{\alpha}$$

ASDC ASI Science Data Center

SZE from LSS atmospheres

Strategy

SZE in LSS atmospheres

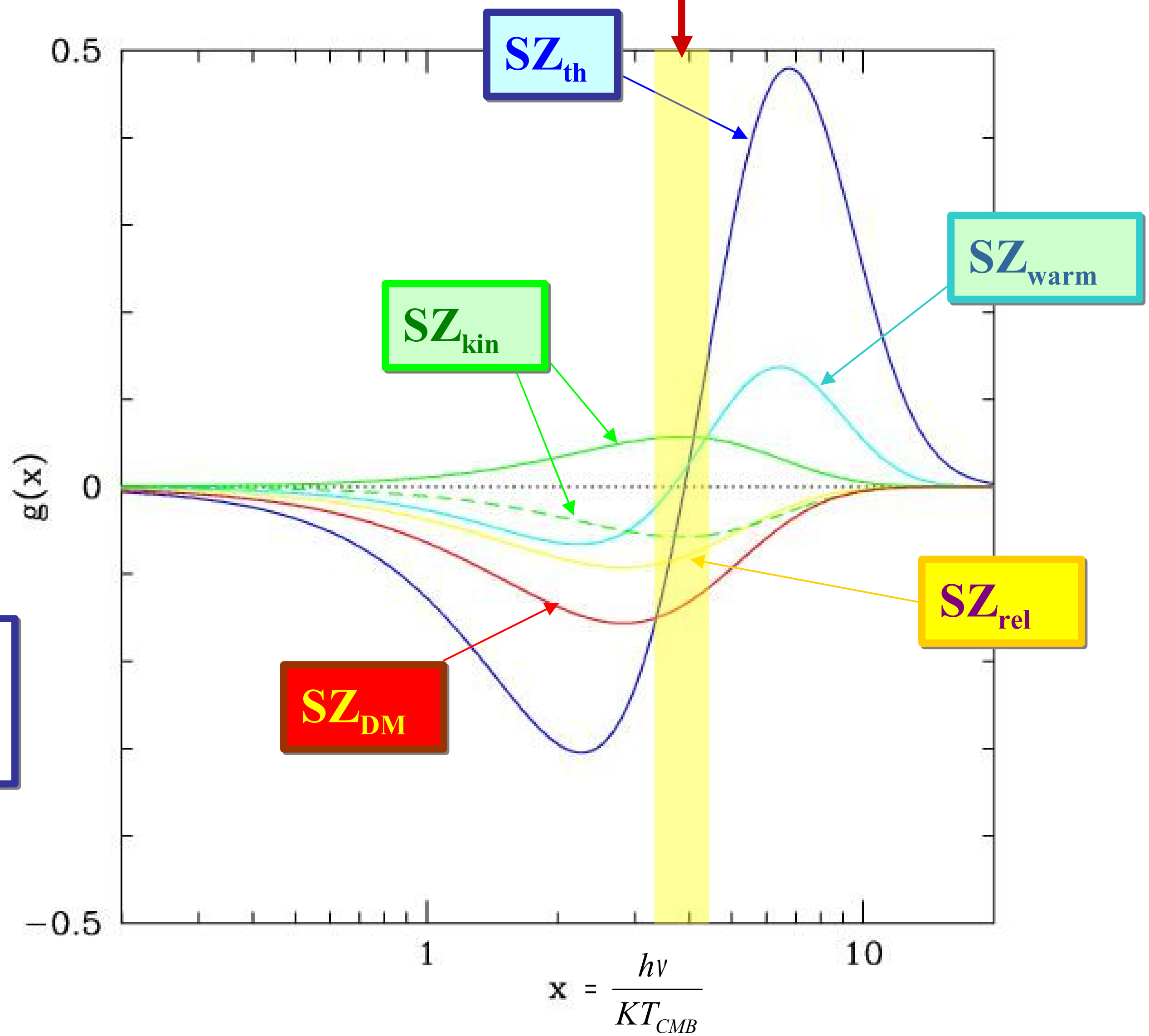
Continuous SZ spectroscopy around $x_0 = x_0(P_e)$

$$x_0 = x_0(P_e)$$

$$Slope = \frac{\Delta i(x)}{\Delta x}$$

$$\Delta I(x) = 2\frac{(k_B T_0)^3}{(hc)^2} y \tilde{g}(x)$$

$$y = \frac{\sigma_T}{m_e c^2}\int P d\ell.$$

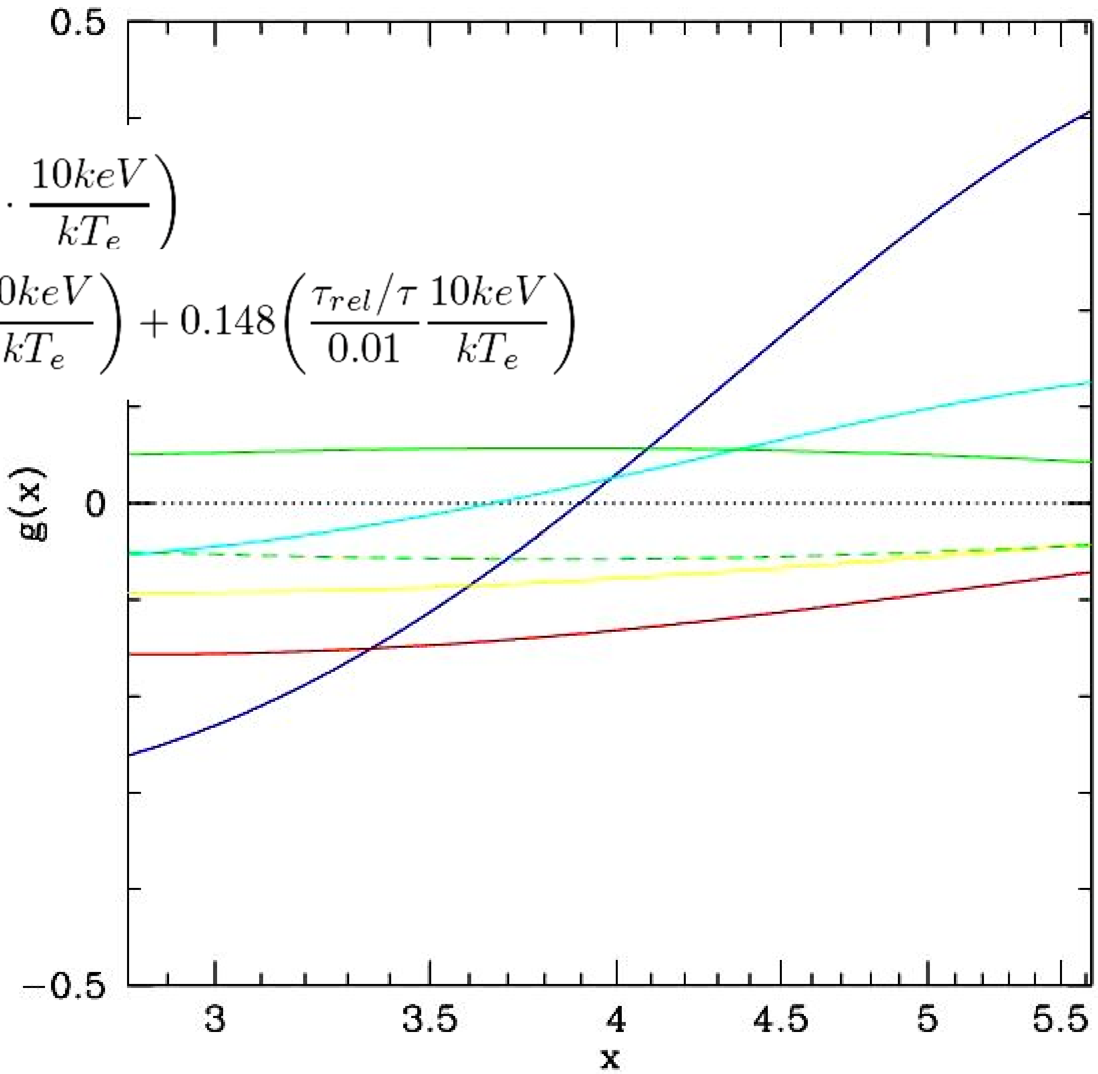


The zero of the SZE

$$i(x) = \frac{kT_e}{mc^2}\left[g(x) + \frac{V_r}{c}\frac{mc^2}{kT_e}h(x)\right]$$

$$X_{o,total,nr} = 3.83 - 0.193\left(\frac{V_r}{10^3 kms^{-1}} \cdot \frac{10keV}{kT_e}\right)$$

$$= 3.83 - 0.193\left(\frac{V_r}{10^3 km/s}\frac{10keV}{kT_e}\right) + 0.148\left(\frac{\tau_{rel}/\tau}{0.01}\frac{10keV}{kT_e}\right)$$



The amplitude of SZ_{kin} (and of other SZ effects) produce systematic bias in the value of the crossover frequency X_0

The position of X_0 cannot provide reliable information on the physics of the cluster atmosphere

[Colafrancesco, Prokhorov & Dogiel 2007]

The slope of the SZE around X_0

$$i_{th} = i_{th0} + Slope \cdot (x-4) + O(x-4)$$

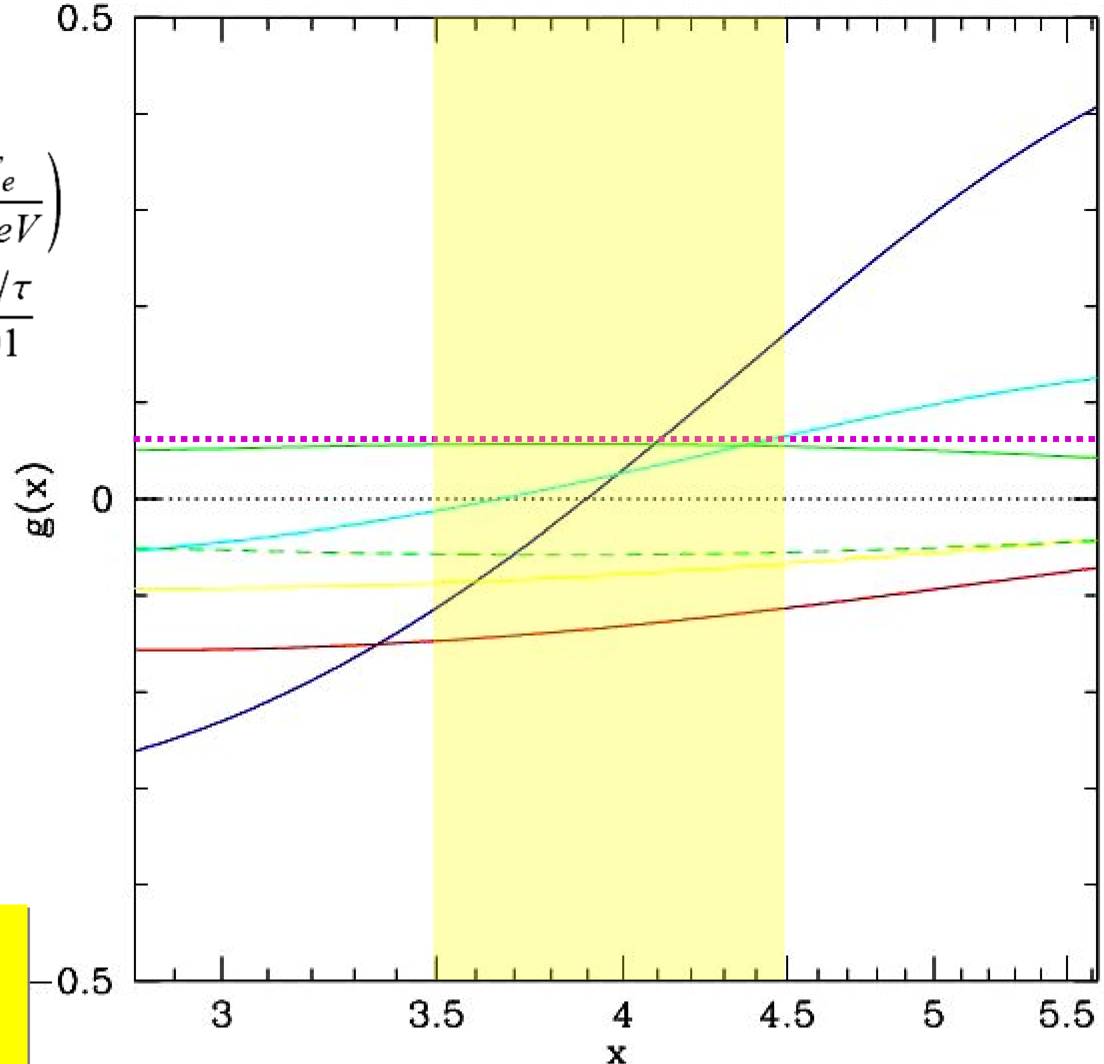
$$Slope_{th(rel)} = 0.08 \frac{kT_e}{10keV}\left(1 - 0.138\frac{kT_e}{10keV}\right)$$

$$Slope_{th(nr)+nth} = 0.08\frac{kT_e}{10keV} + 0.003\frac{\tau_{rel}/\tau}{0.01}$$

$$Slope_{acc} = 0.058 + 7.35\alpha + 5064\alpha^2$$

Slopes are independent of SZ_{kin} *around the position of X_0*

The Slope of the SZE around X_0 can provide reliable information on the physics of the cluster atmosphere



[Colafrancesco, Prokhorov & Dogiel 2007]

Conclusions

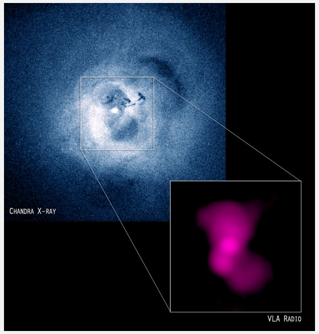
Simple SZ physics
not quite representative

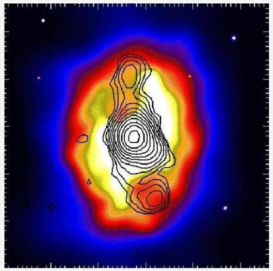
- no reliable cluster physics
- no cosmological use

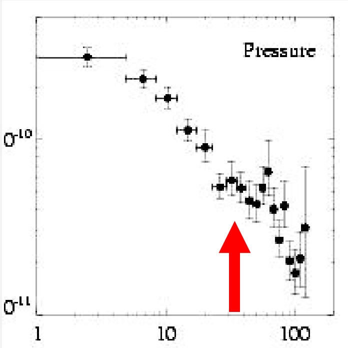
$$\Delta y \approx 10\% \Rightarrow \begin{cases} \dfrac{\Delta H_0}{H_0} \geq 20\% \\ \dfrac{\Delta \Omega_m}{\Omega_m} \geq 25\% \end{cases}$$

SZ as single technique to study the leptonic structure of cluster/galaxy atmospheres

- density, entropy, pressure, energy
- various electron populations
- equilibrium conditions, shocks, B-field
- Acceleration vs. Injection vs. *in-situ* prod.

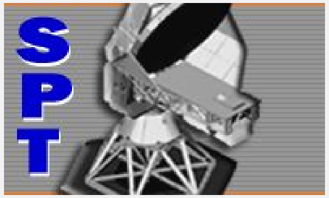






Technological challenge

- ~ μK sensitivity
- arcsec - arcmin resolution
- Continuous μ-wave spectroscopy



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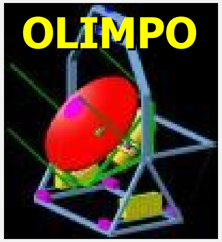
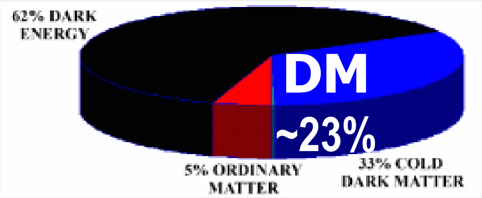
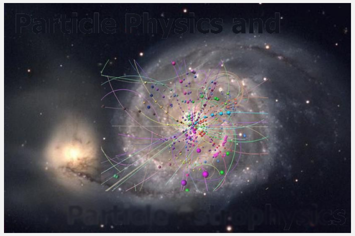


Astro-Particle Physics

- DM nature
- CR physics
- B-field relevance
- …





THANKS

for your attention !