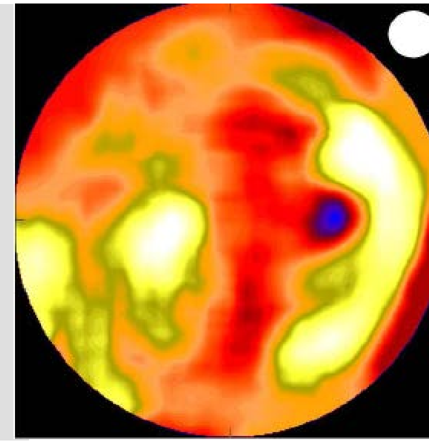
Interaction of the CMB with Astrophysical Plasma: high-E



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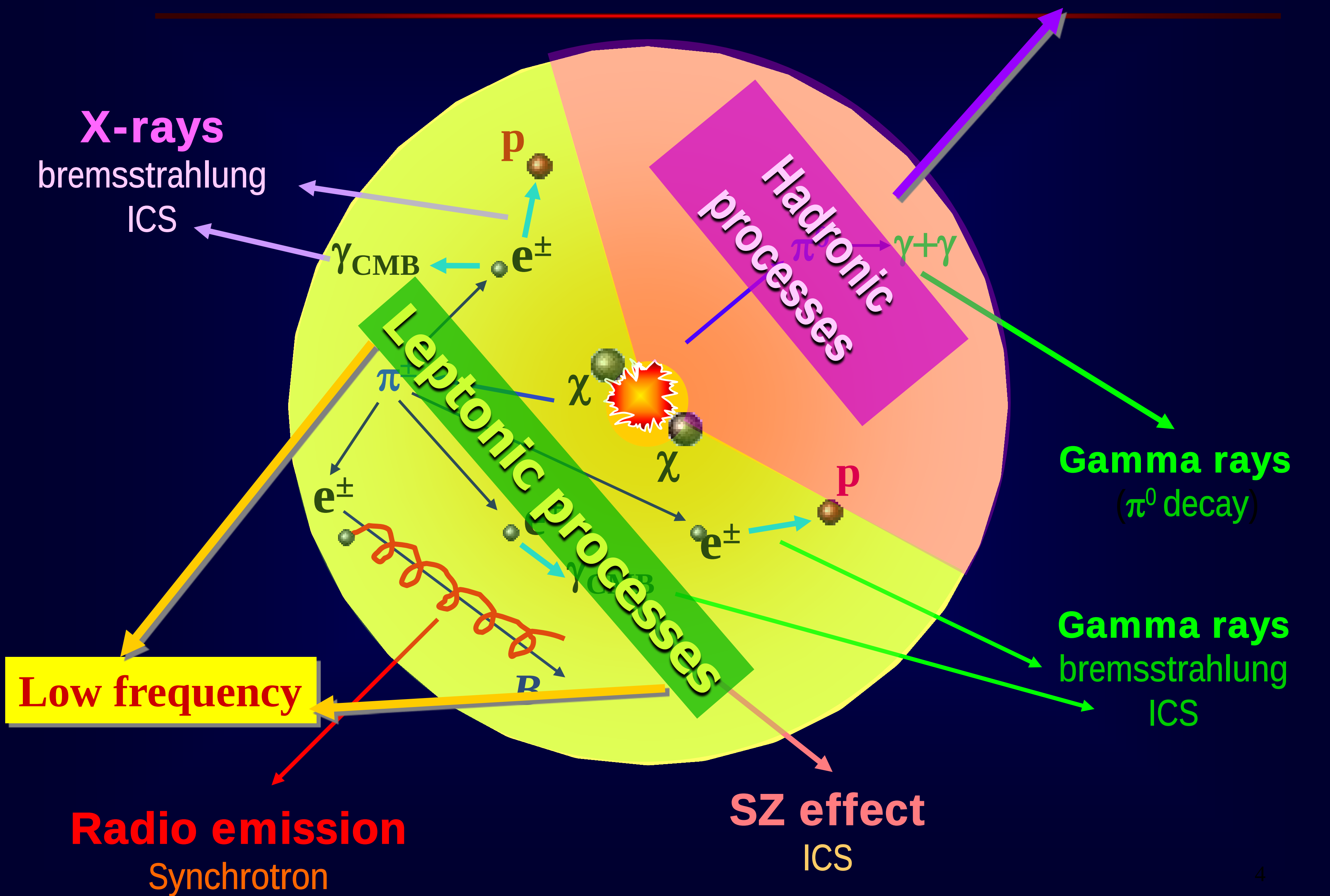
Outline

- Lecture 1
  - CMB photon interaction
  - LSS: plasma content
  - Spectral and spatial properties
  - Plasma – CMB photon interaction: basic mechanisms
  - ICS, Pair production, Primakov effect
- Lecture 2
  - The SZ effect: thermal, non-th, kinetic, polarization
  - General description
  - Galaxy clusters
  - RGs and other cases
  - Experimental outline
- Lecture 3
  - IC-CMB and high energy phenomena
  - X-rays
  - Gamma-rays
  - Multi-frequency studies
  - An experimental outline

Inverse Compton Scattering

- Interaction of secondary electrons from DM annihilation with the CMB
  - Hard X-Rays
  - Gamma-rays
- Interaction of Cosmic Rays in cluster (with Radio Halos) with the CMB
  - Hard X-Rays
  - Gamma-rays
  - The WR model
- Interaction of Cosmic Rays in cavities with the CMB
  - HXR
  - Gamma-rays
- Interaction of Cosmic Rays in radiogalaxy lobes with the CMB
  - X-rays
  - Gamma-rays

Dark Matter annihilation

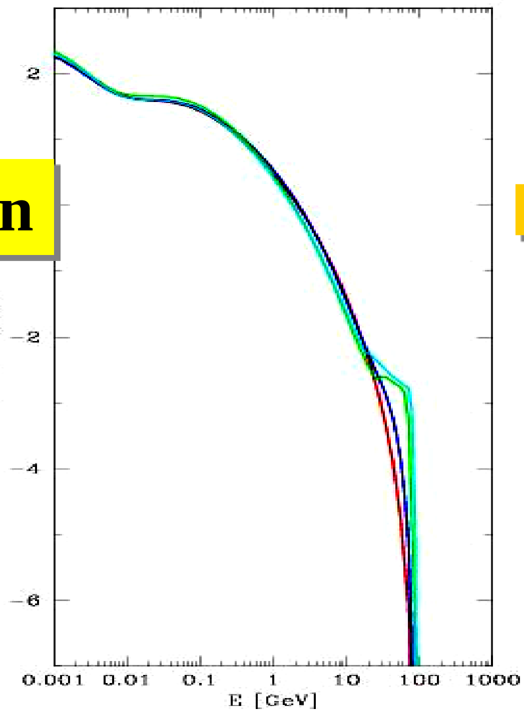


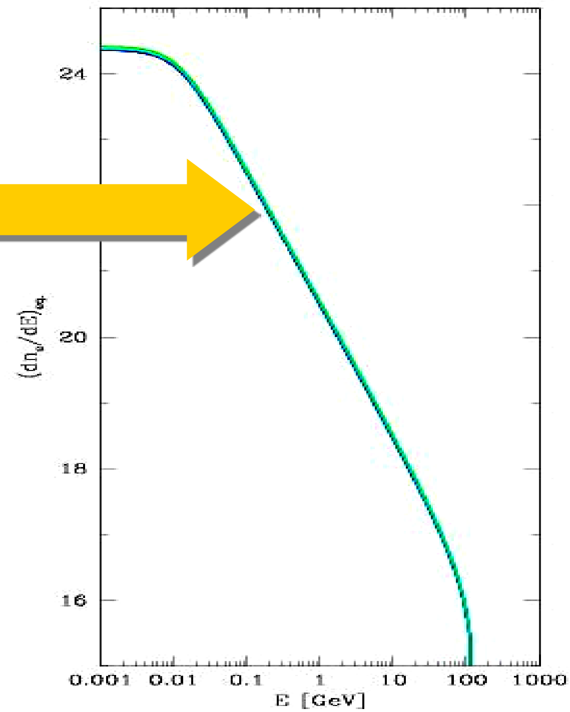
Leptons: $e^{\pm}$ equilibrium spectrum

$$\frac{\partial n_e(E,r)}{\partial t} - \nabla\left[D(E)\nabla n_e(E,r)\right] - \frac{\partial}{\partial E}\left[b_e(E)n_e(E,r)\right] = Q_e(E,r)$$

Production

$Q_e(E,r)$





Equilibrium

$n_e(E,r)$

Diffusion

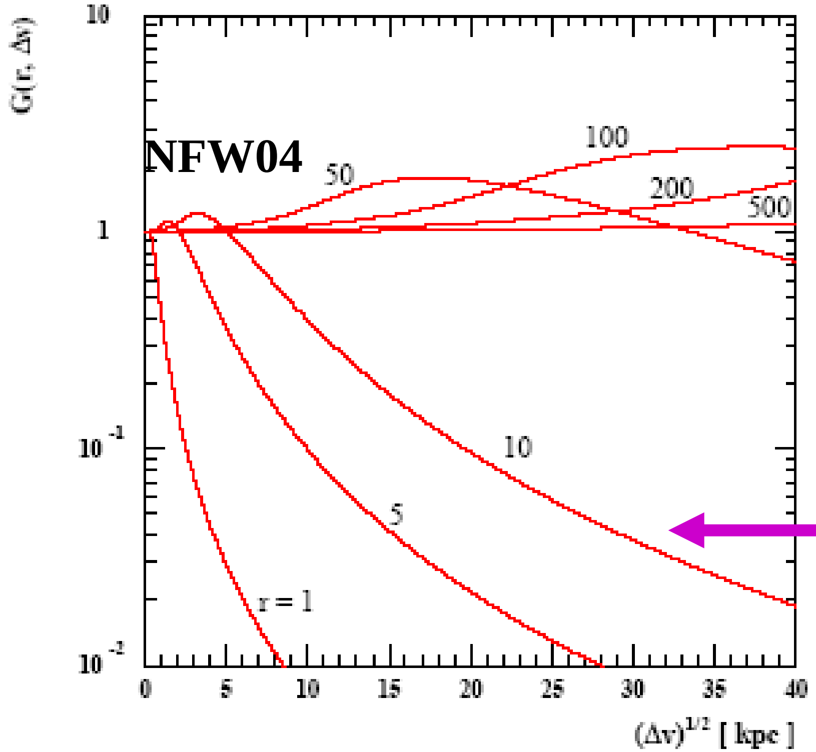
$$D(E) = D_0 E^{\gamma} B^{-\gamma}$$

E losses

$$b_e(E) = b_{IC} + b_{sync} + b_{Coul} + b_{brem}$$

Solution: complete

$$n_e(E,r) = \frac{1}{b(E)} \int_E^{M_\chi} dE' \hat{G}(r, \lambda - \lambda') Q_e(E,r)$$



Galaxy clusters

Galaxies

$$\hat{G} = \frac{1}{[4\pi\Delta\lambda]^{1/2}} \sum_{n=-\infty}^{+\infty} (-1)^n \int_0^{R_h} dr' \frac{(r')^2}{r_n' r} \left[\exp\left(-\frac{(r' - r_n)^2}{4\Delta\lambda} \right) - \exp\left(-\frac{(r_n' + r)^2}{4\Delta\lambda} \right) \right] \frac{n_\chi^2(r')}{n_\chi^2(r)}$$

[Colafrancesco, Profumo & Ullio 2006-2007]

Energy losses vs. Diffusion

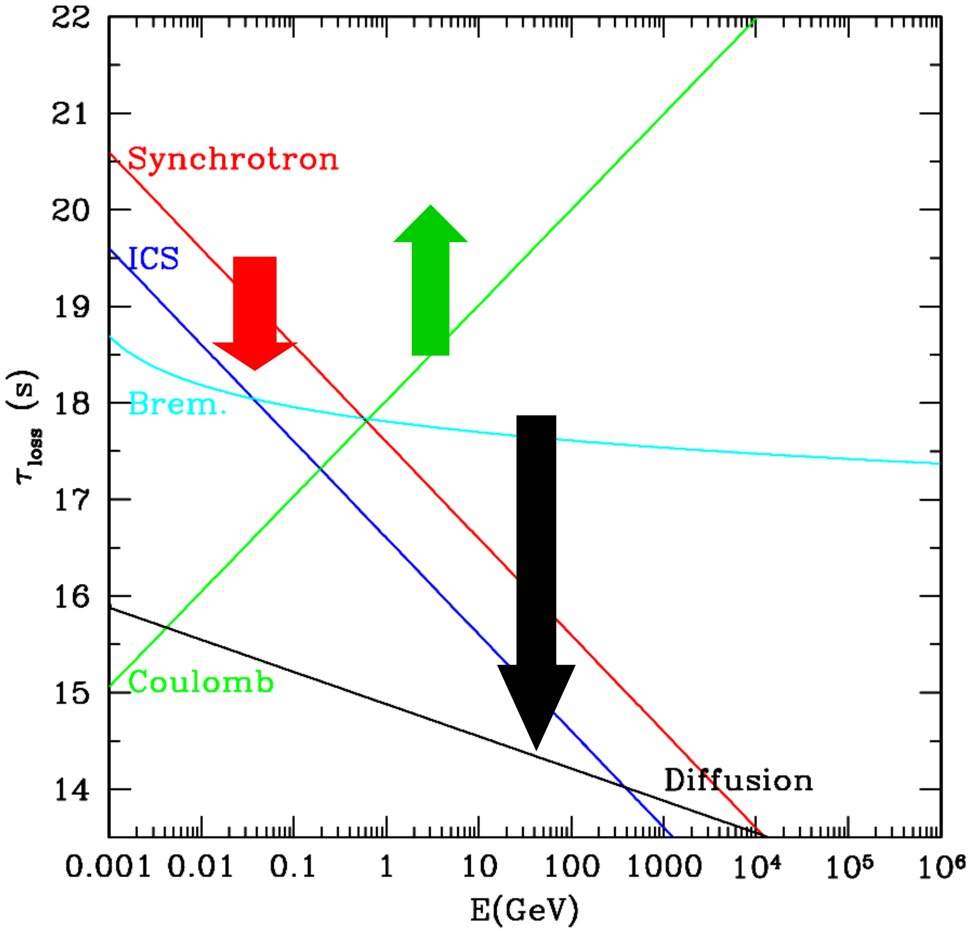
$$\tau_{loss} = \frac{E}{b(E, B, n_{th})}$$

$$\tau_D = \frac{R_h^2}{D(E)}$$

B increase

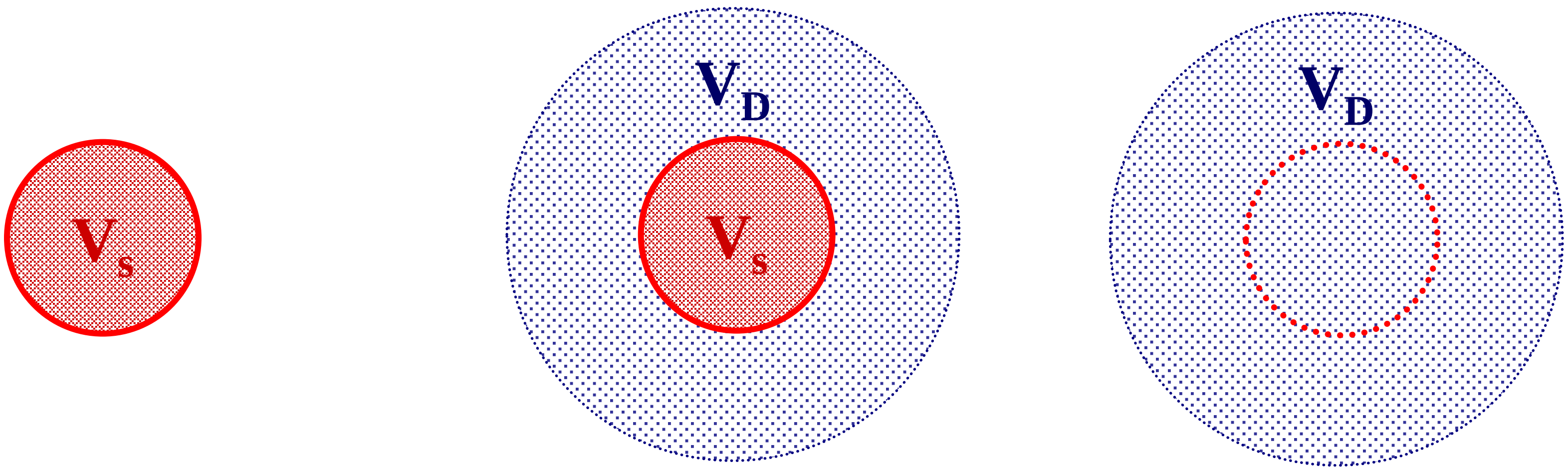
n_{th} decrease

R_h decrease



Solution: qualitative

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



$\tau_{loss} \ll \tau_D$

$\tau_{loss} \gg \tau_D$

$$n_e(E,r) = \left[Q_e(E,r)\tau_{loss}\right]$$

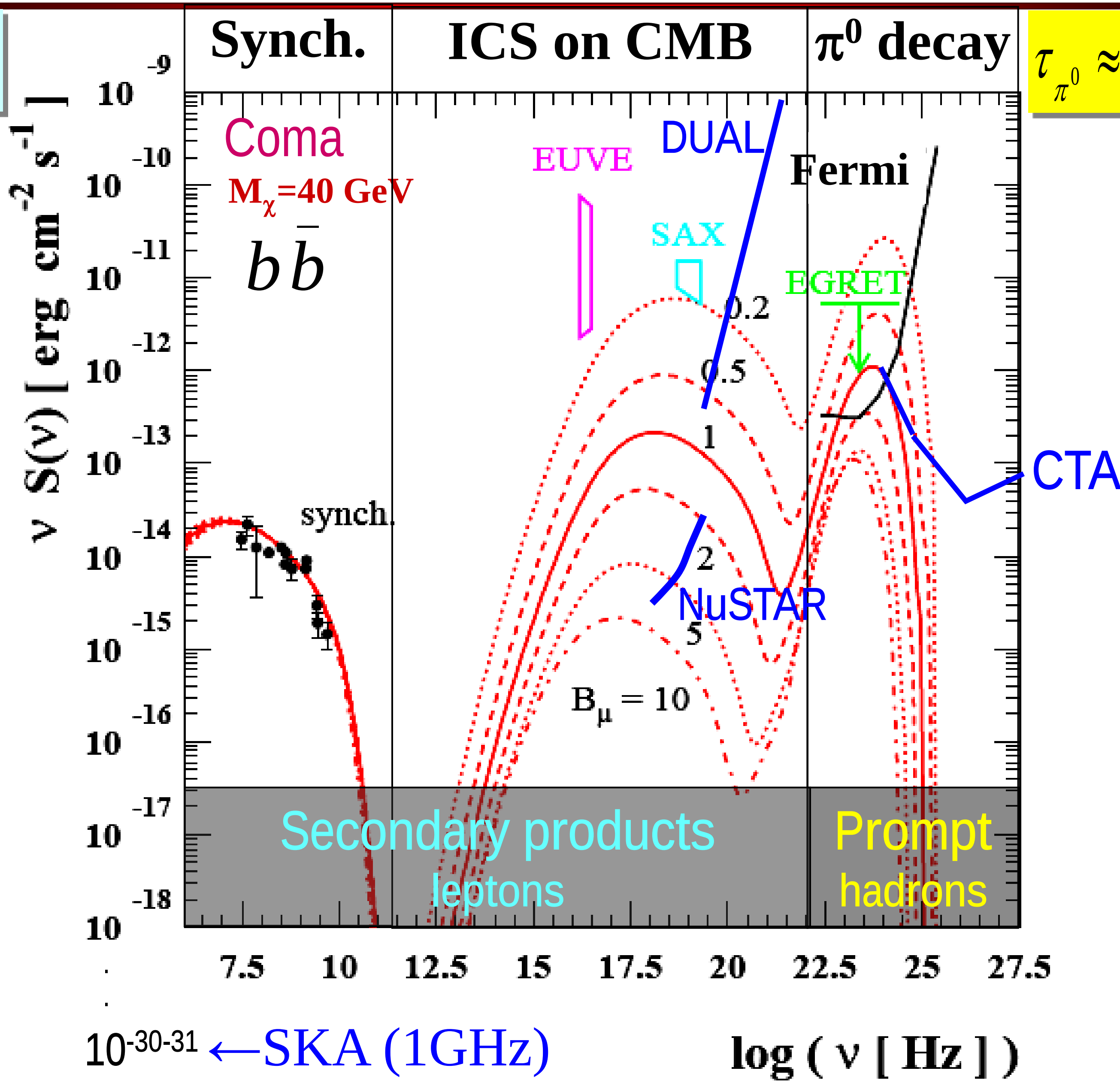
Galaxy clusters

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

Galaxies

Neutralino DM: SED

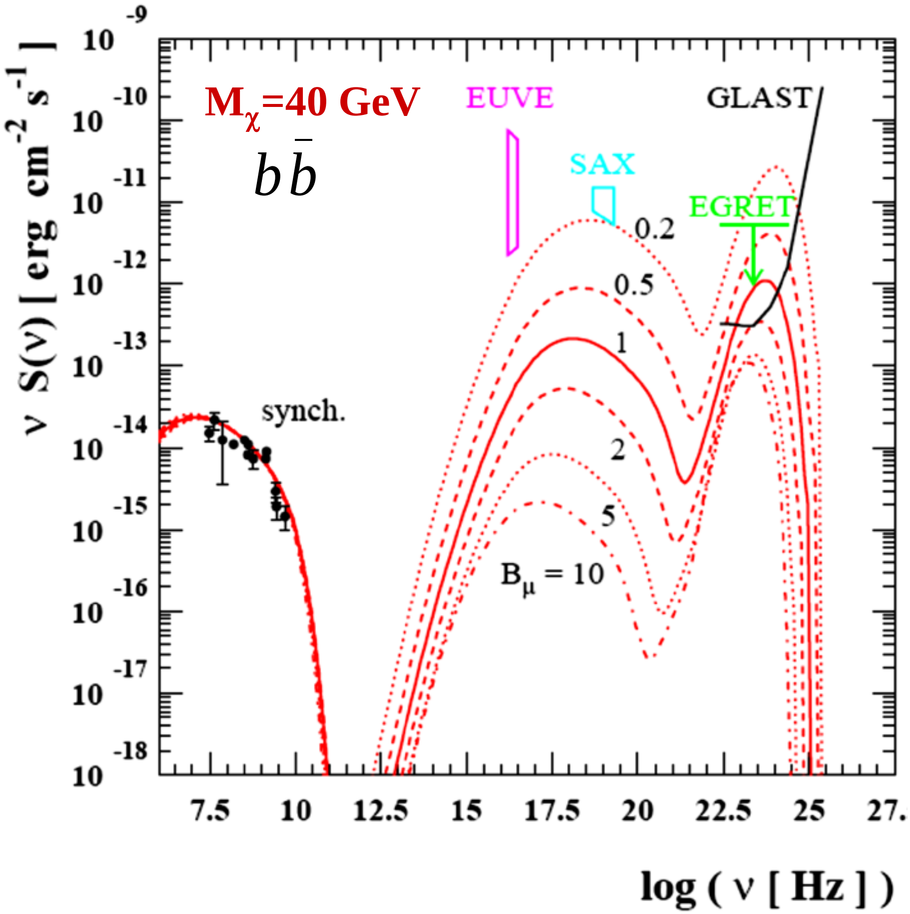
$\tau_{\pi^{\pm}} \approx 2.6 \cdot 10^{-8} s$



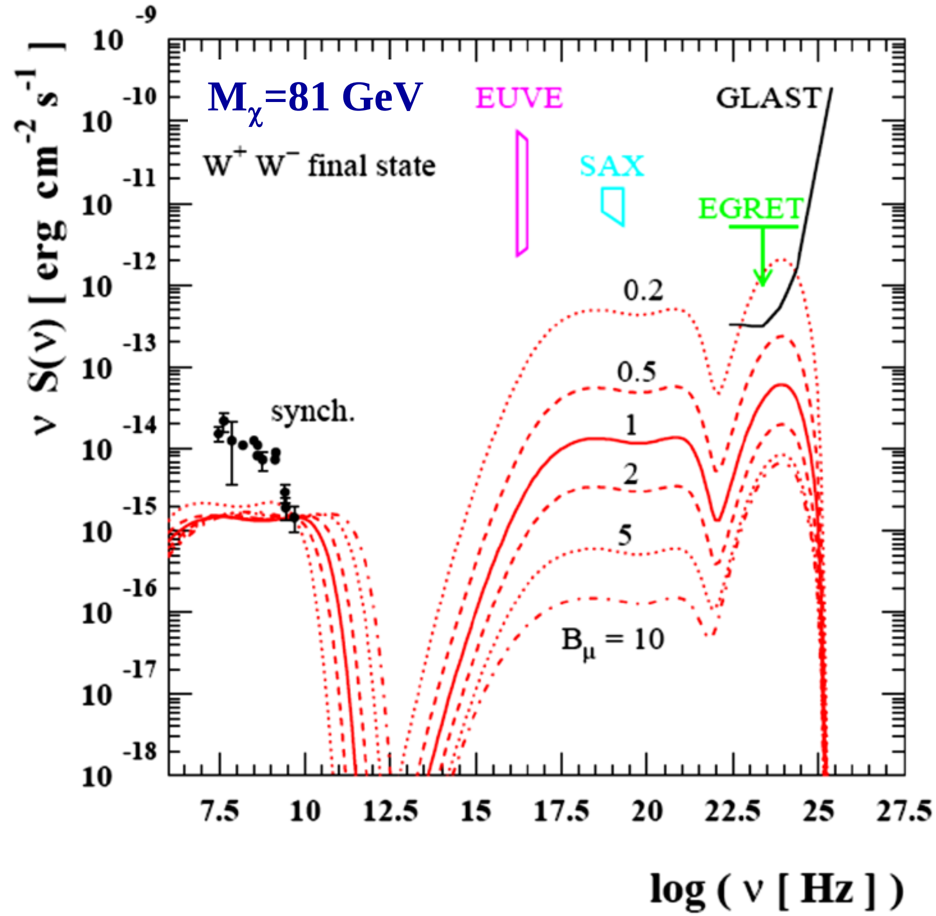
$\tau_{\pi^{0}} \approx 8.4 \cdot 10^{-17} s$

WIMP (neutralino) composition

Soft WIMP model



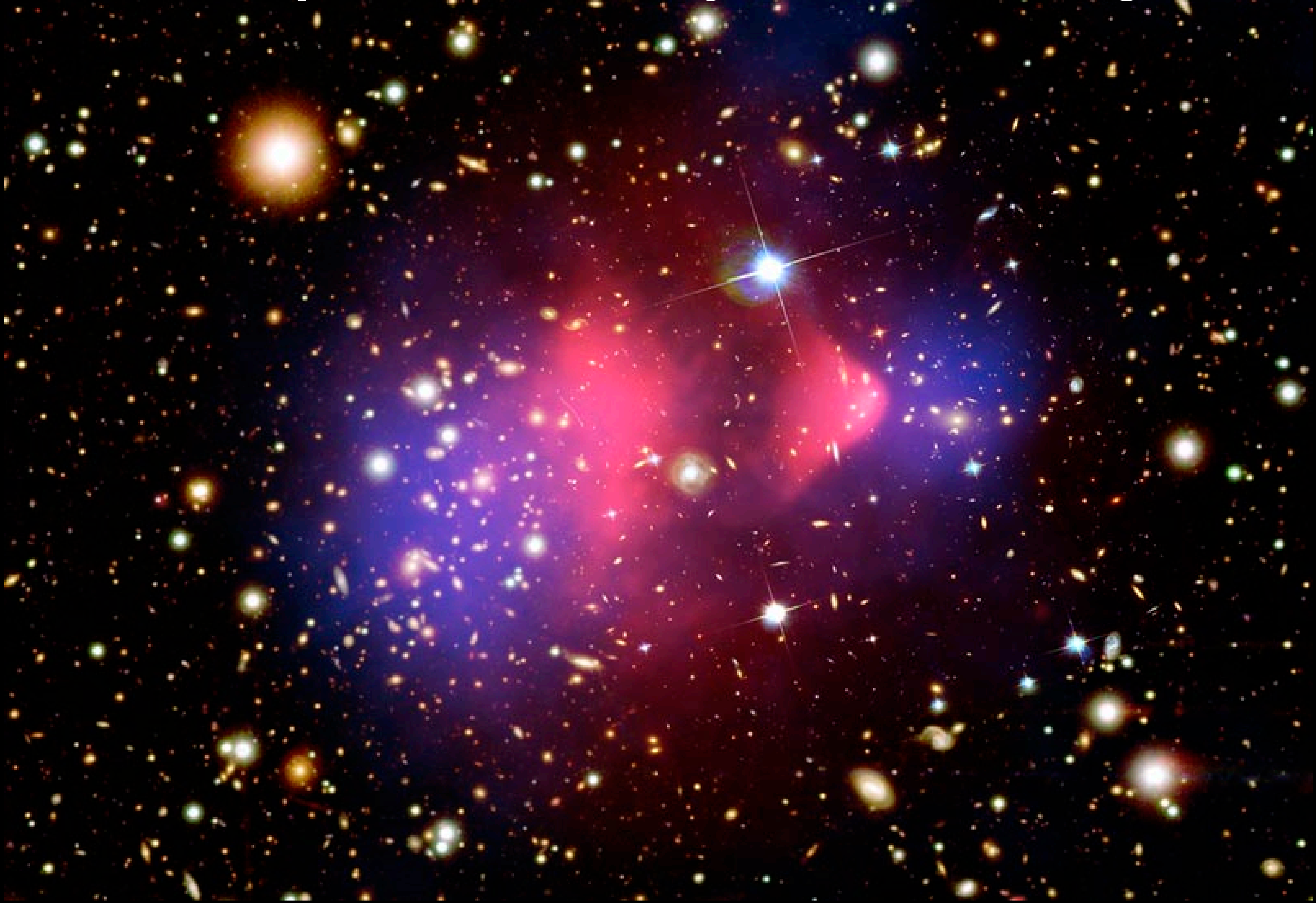
Hard WIMP model



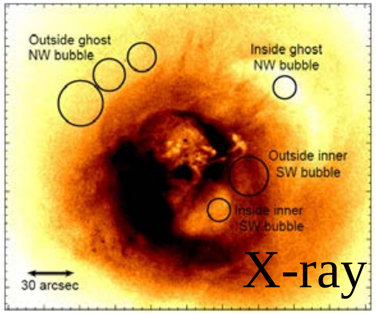
[Colafrancesco, Profumo, Ullio 2006]

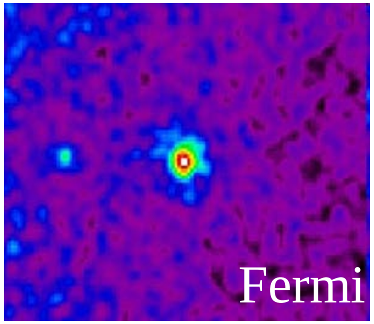
Galaxy Clusters DM Challenge

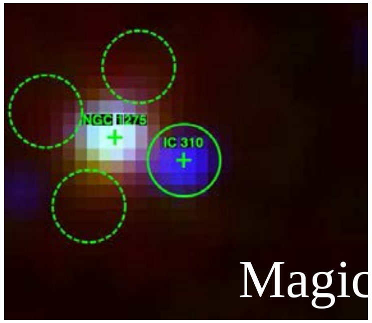
Large-size, co-spatial DM & baryons… but few good cases !



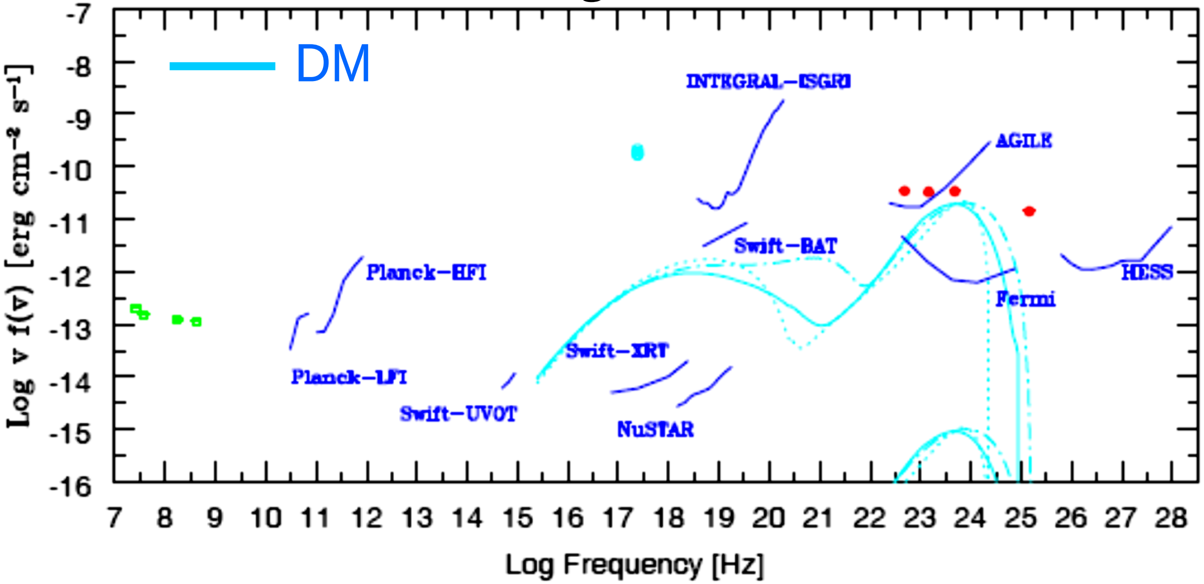
DM signals: the case of Perseus

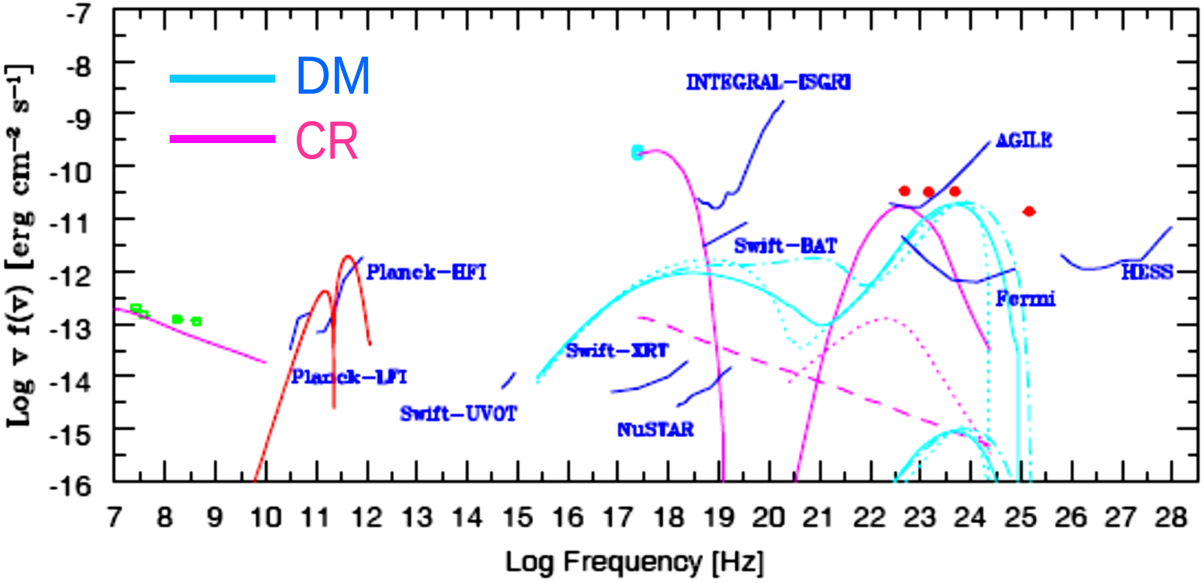




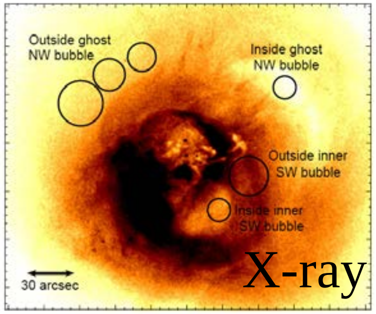


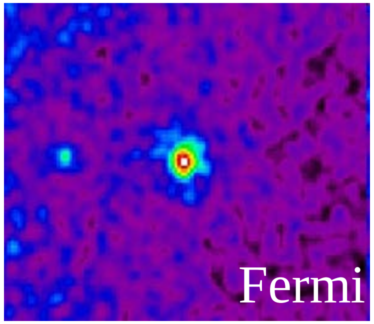
[S.C., Marchegiani & Giommi 2010]

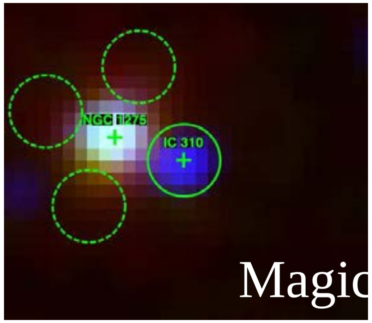


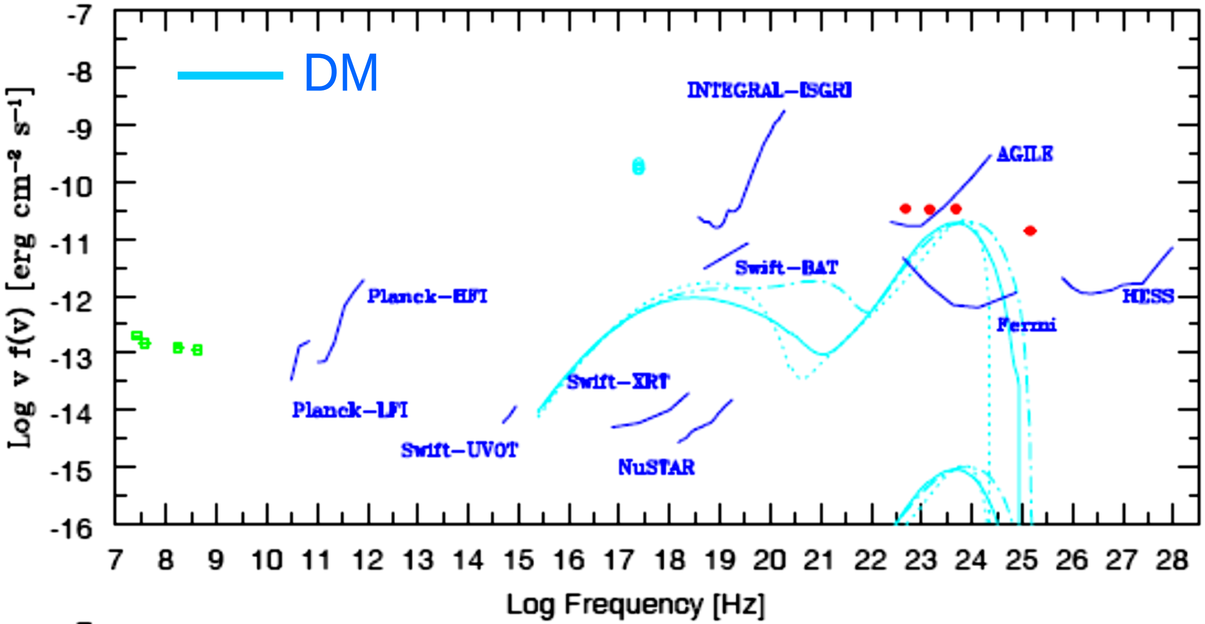


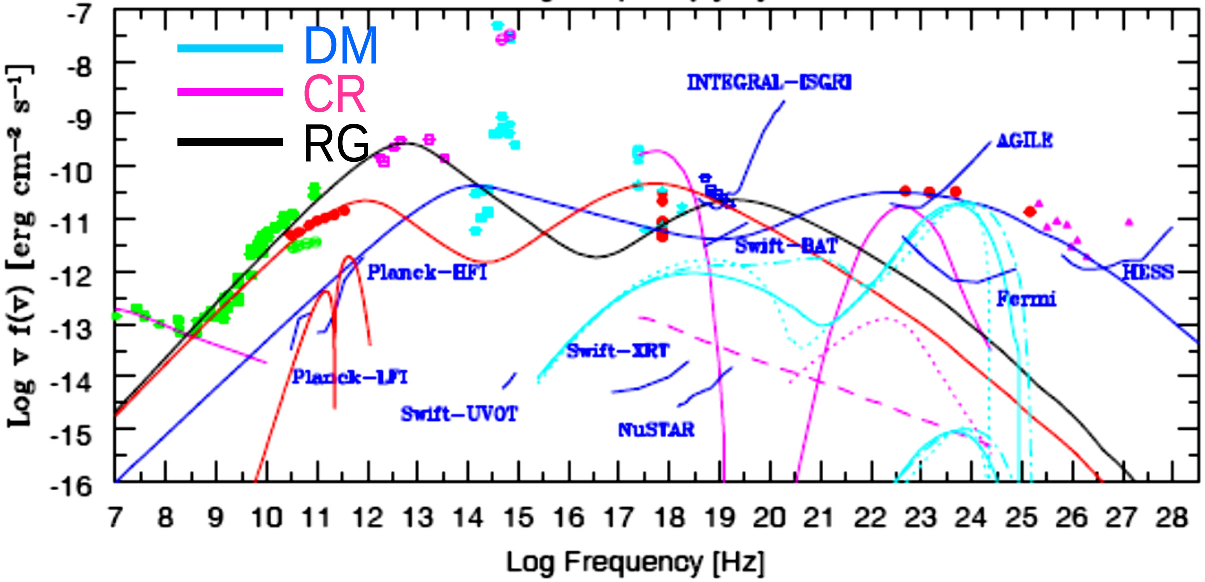
DM signals: the case of Perseus





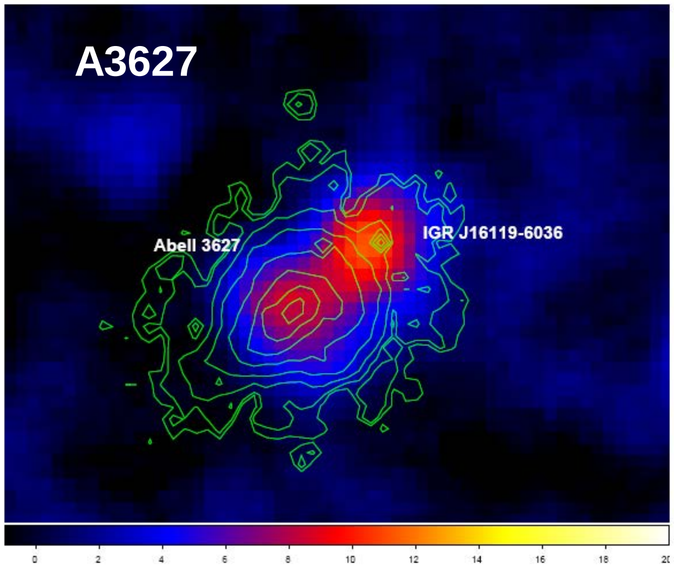






A Dark Temptation

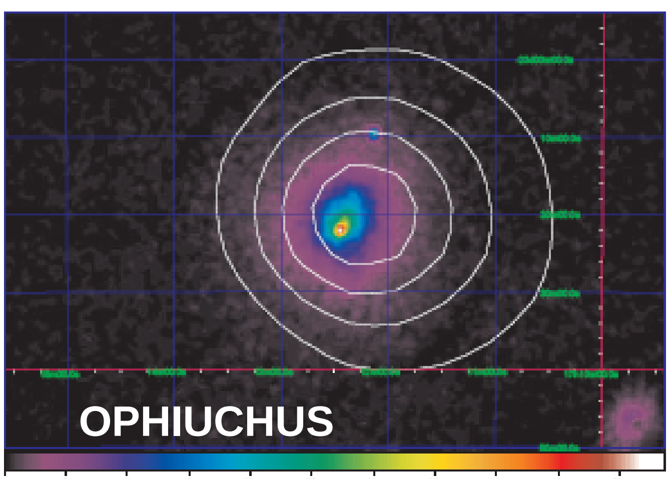
Explain HXR in cluster as DM annihilation signals

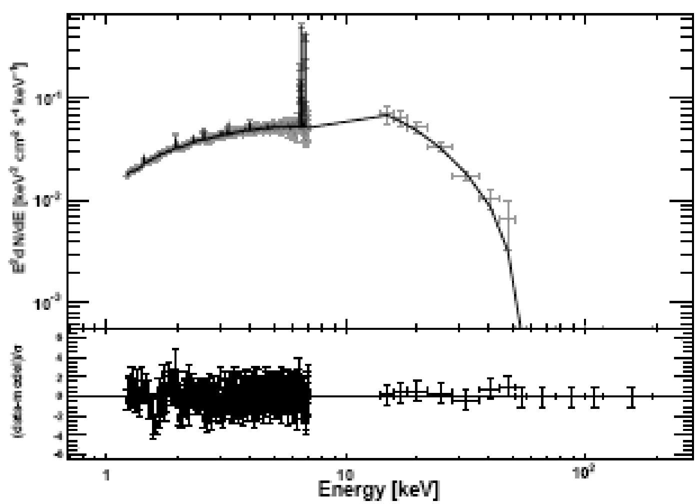


More than 20 clusters with Hard X-ray excess at E> 20 keV (Swift-BAT data, BeppoSAX data)

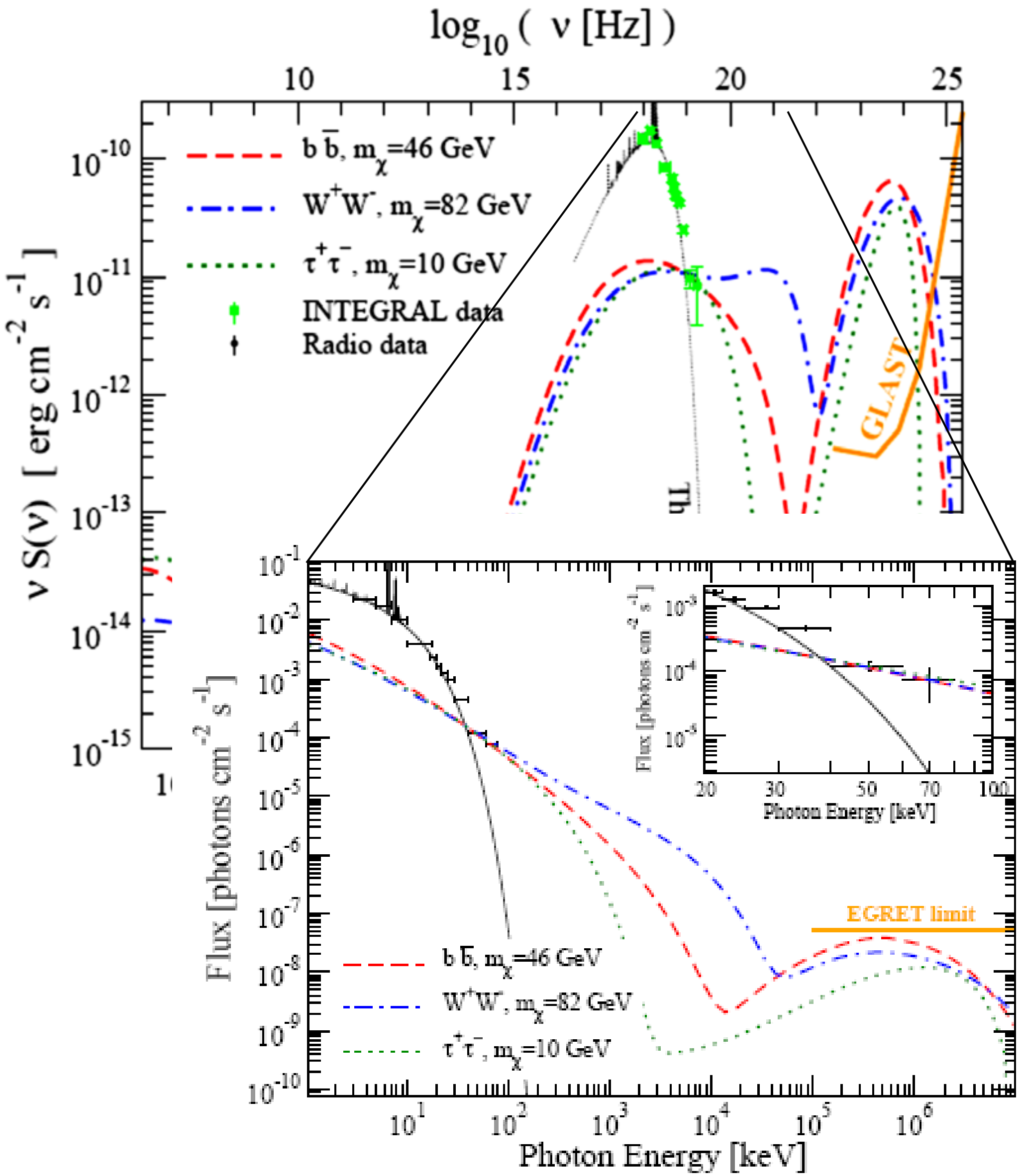
Equally fit with:
- Two temperature (thermal) plasma
- Thermal plasma + non-thermal power-law

AGN emission or ICS from DM / CR interaction

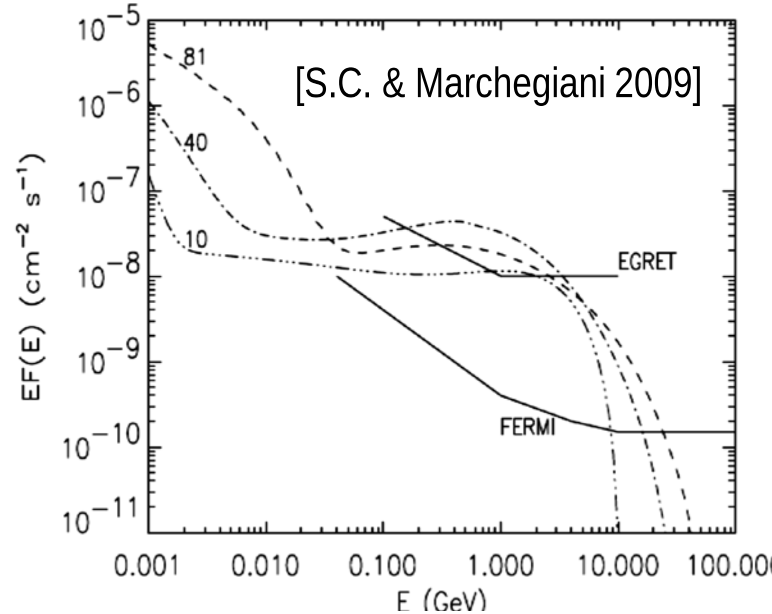


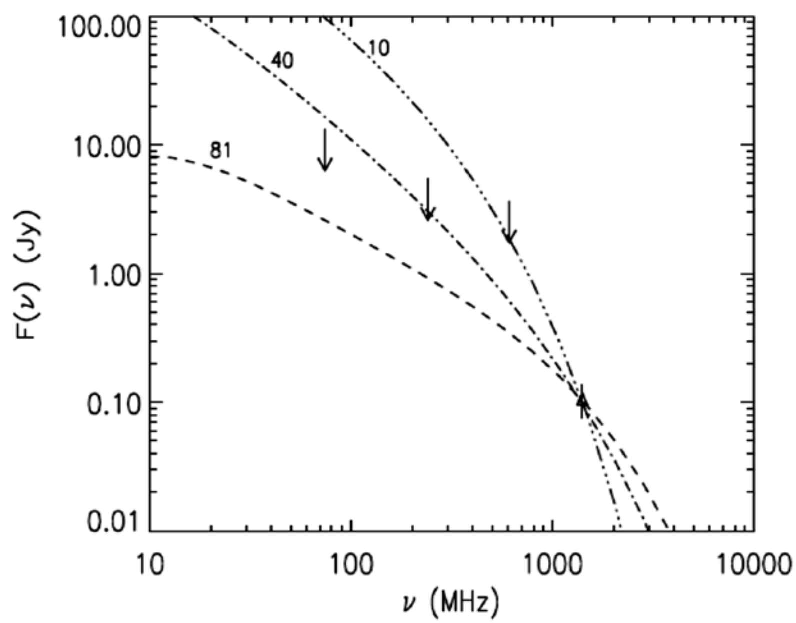


Hard X-ray excess   Consequences

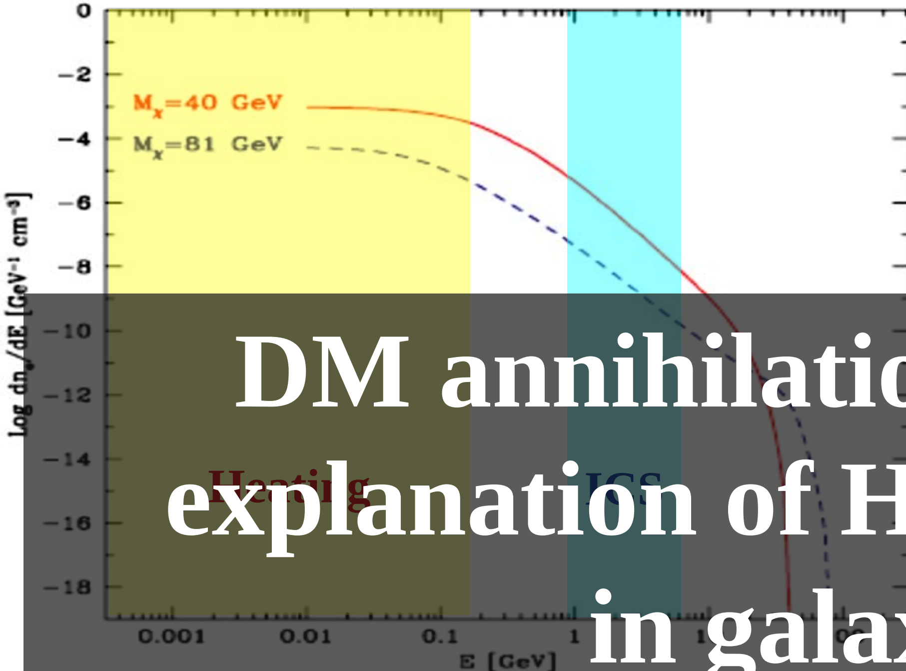


[Profumo 2008, Peres-Torres et al. 2008]

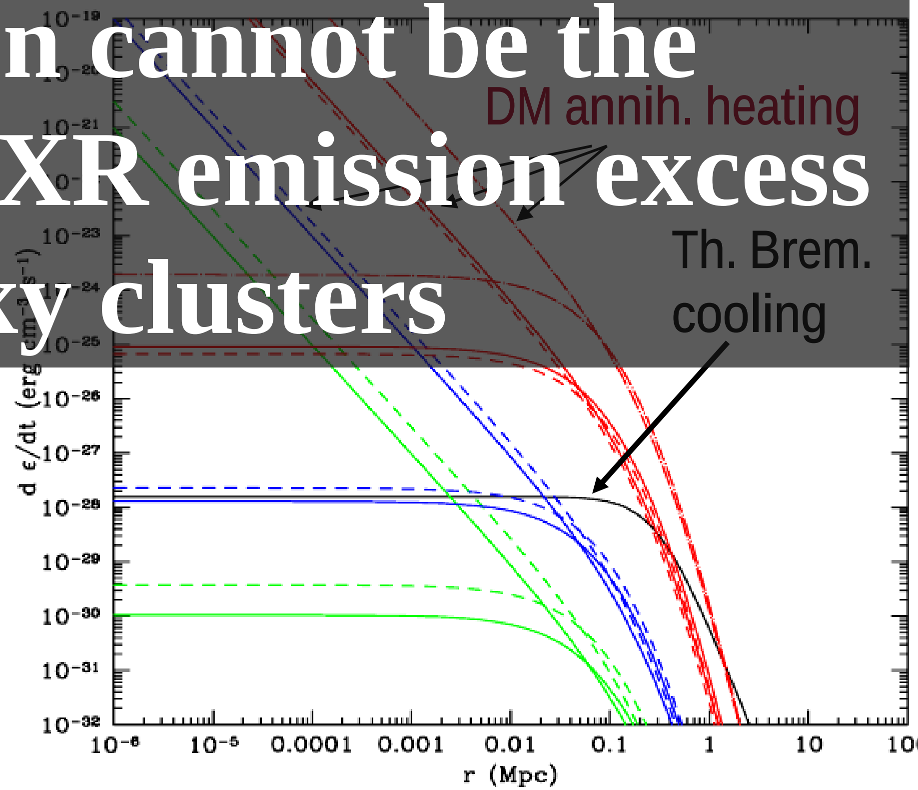




Consequences: DM & gas heating



DM models that fit the HXR flux of galaxy clusters produce also an excess heating of the gas.

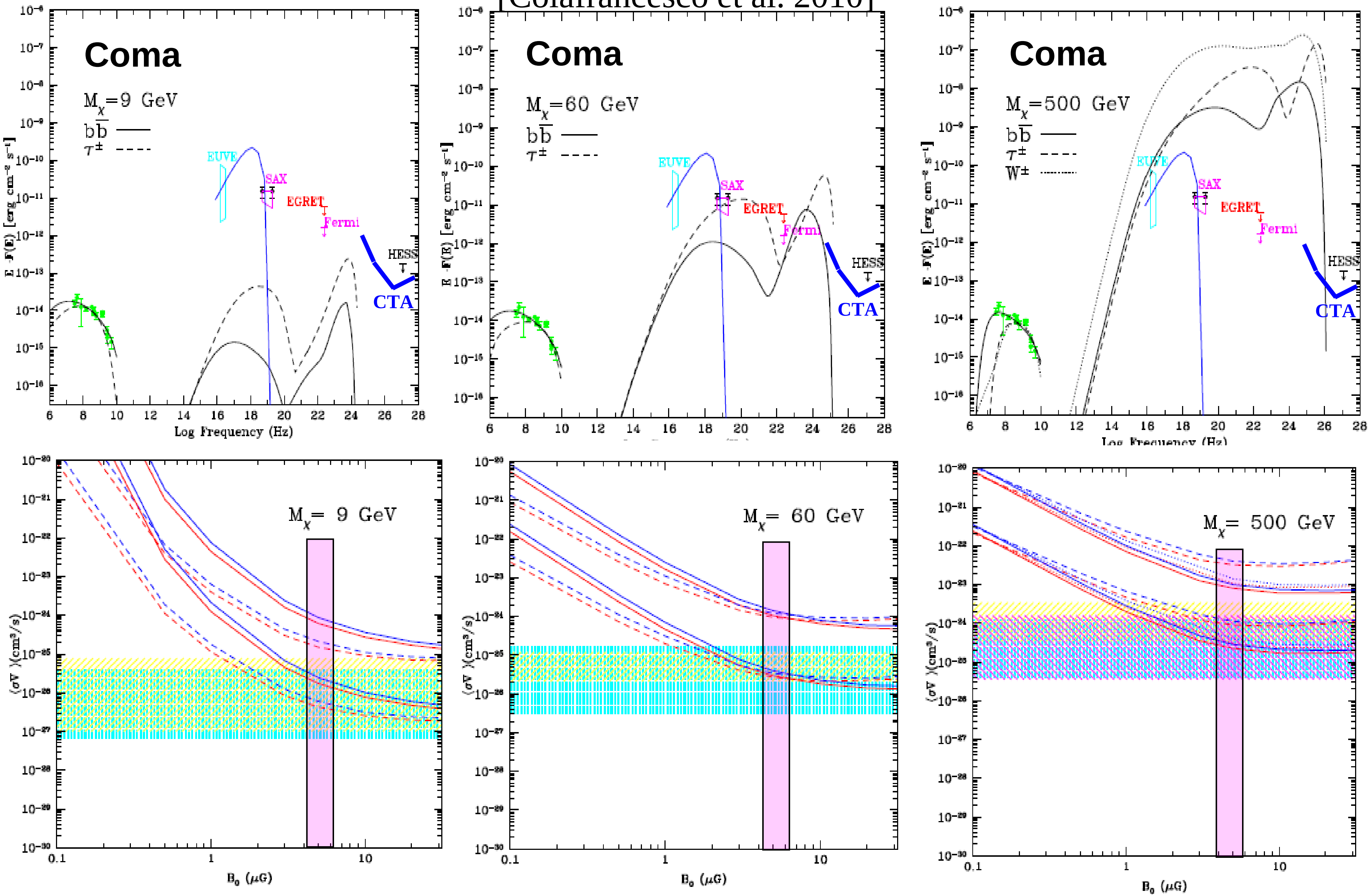


DM annihilation cannot be the explanation of HXR emission excess in galaxy clusters

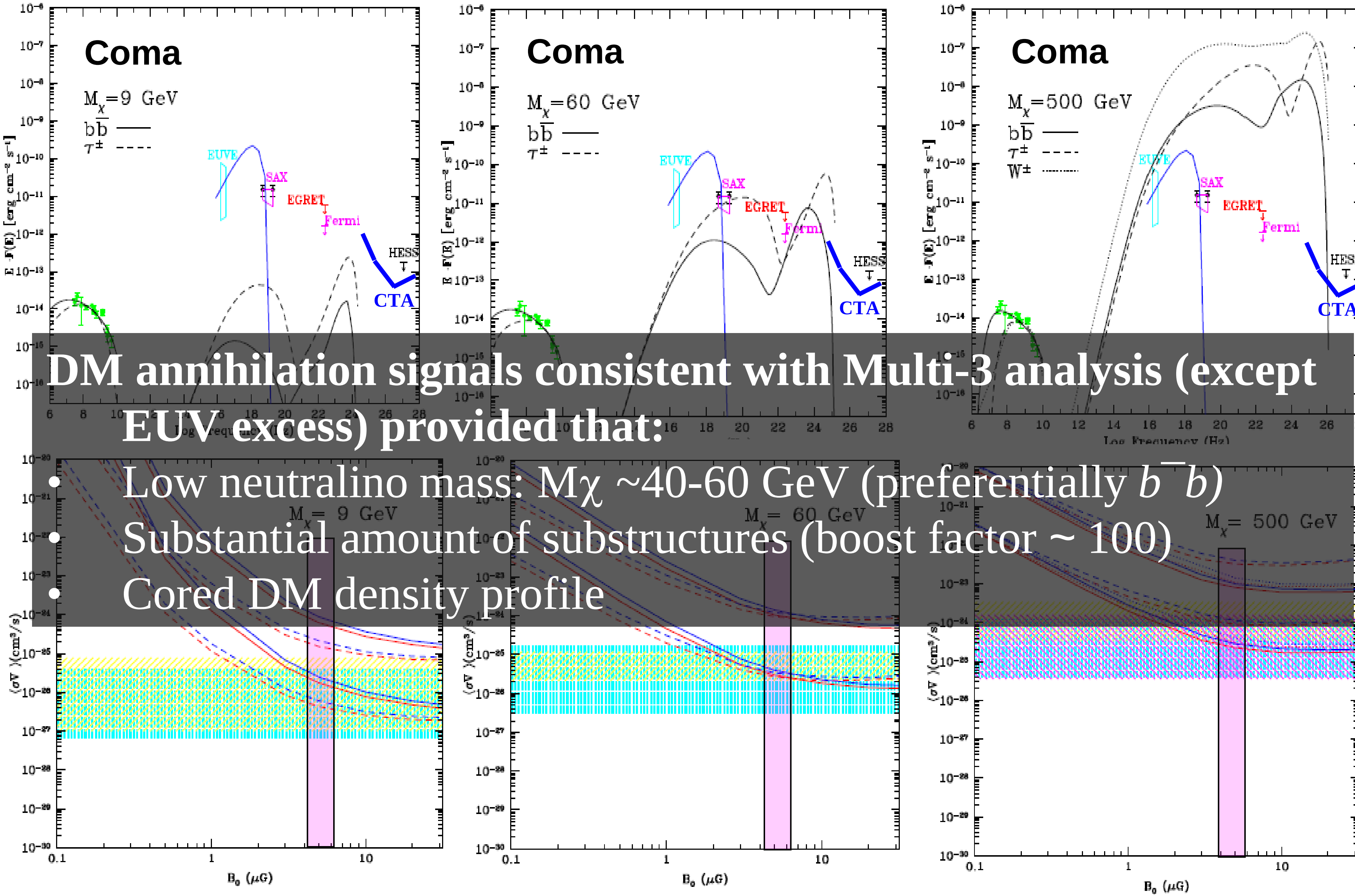
[Colafrancesco & Marchegiani 2009]

DM models & non-thermal phenomena

[Colafrancesco et al. 2010]



DM models & non-thermal phenomena

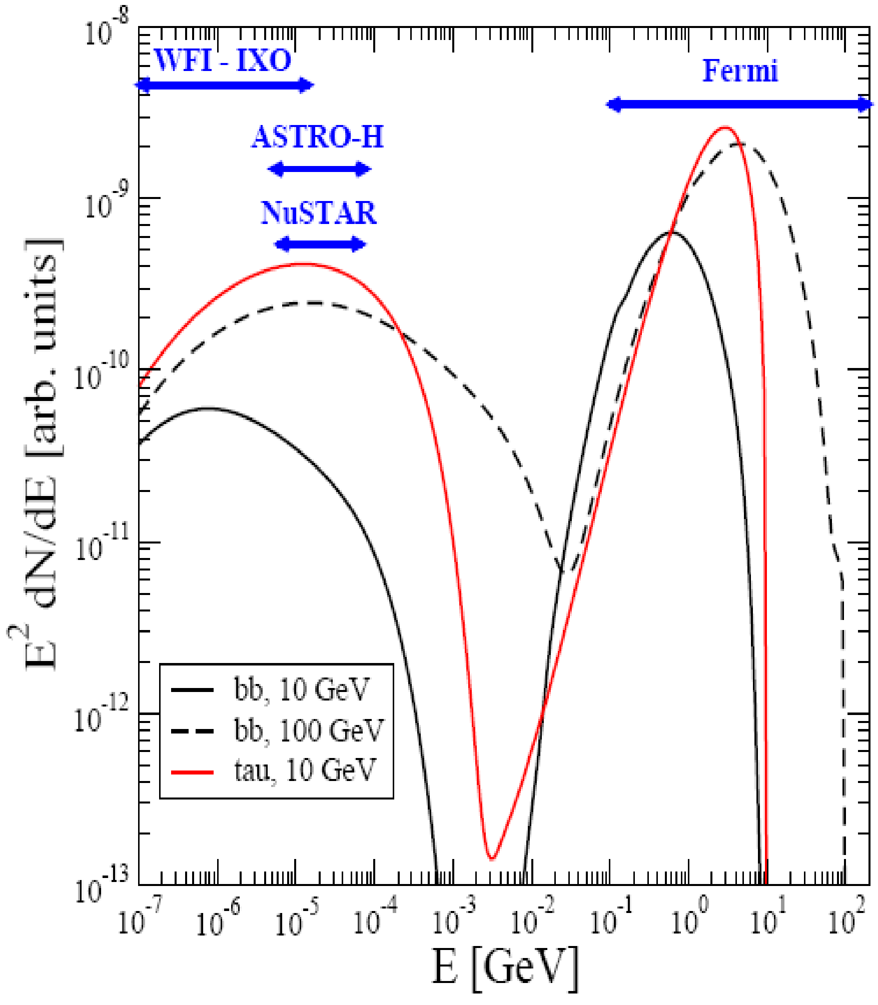


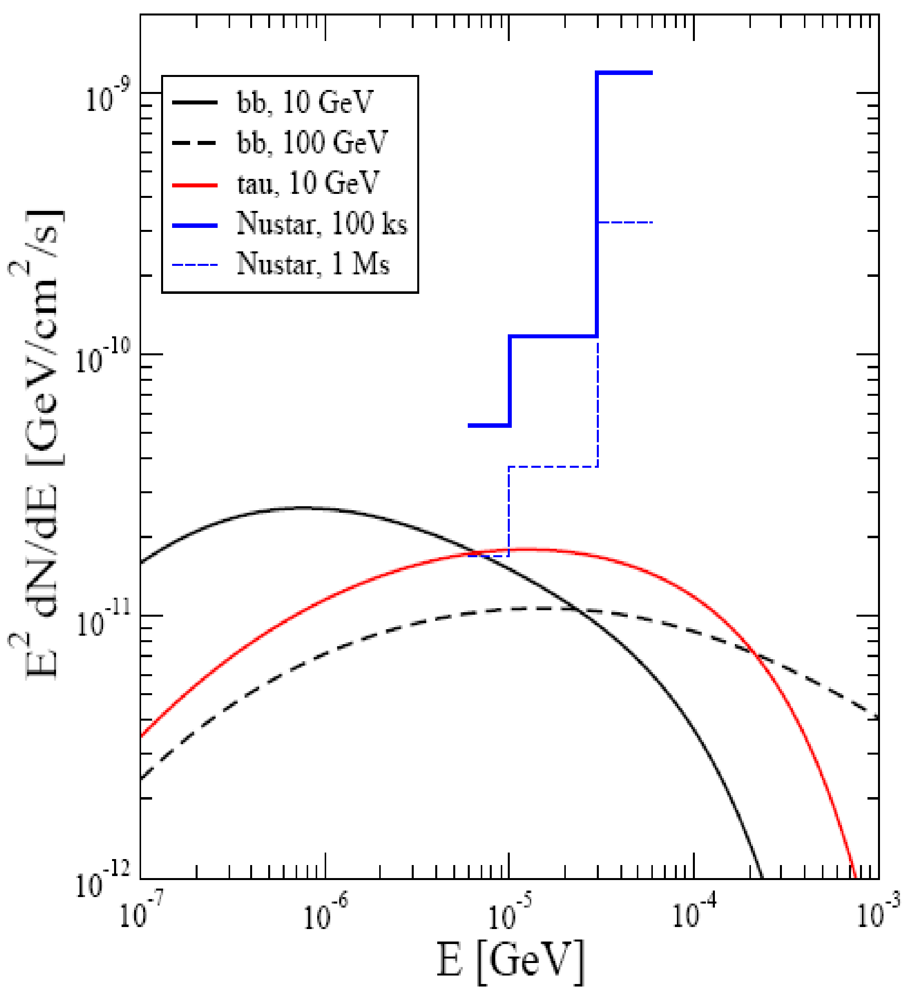
DM annihilation signals consistent with Multi-3 analysis (except EUV excess) provided that:

- Low neutralino mass: Mχ ~40-60 GeV (preferentially $b\bar{b}$)
- Substantial amount of substructures (boost factor ~ 100)
- Cored DM density profile

Dark Temptations never go away ...

Normalized to F(E> 0.1 GeV) ⇒ Possible detection for t_{exp}> 4Msec



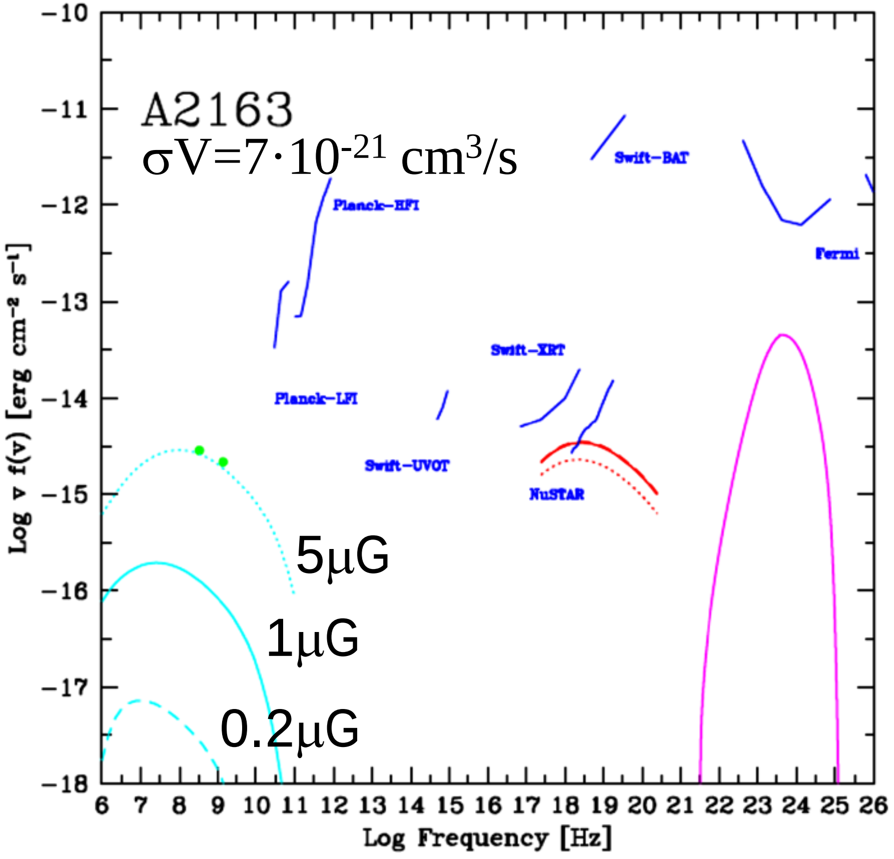


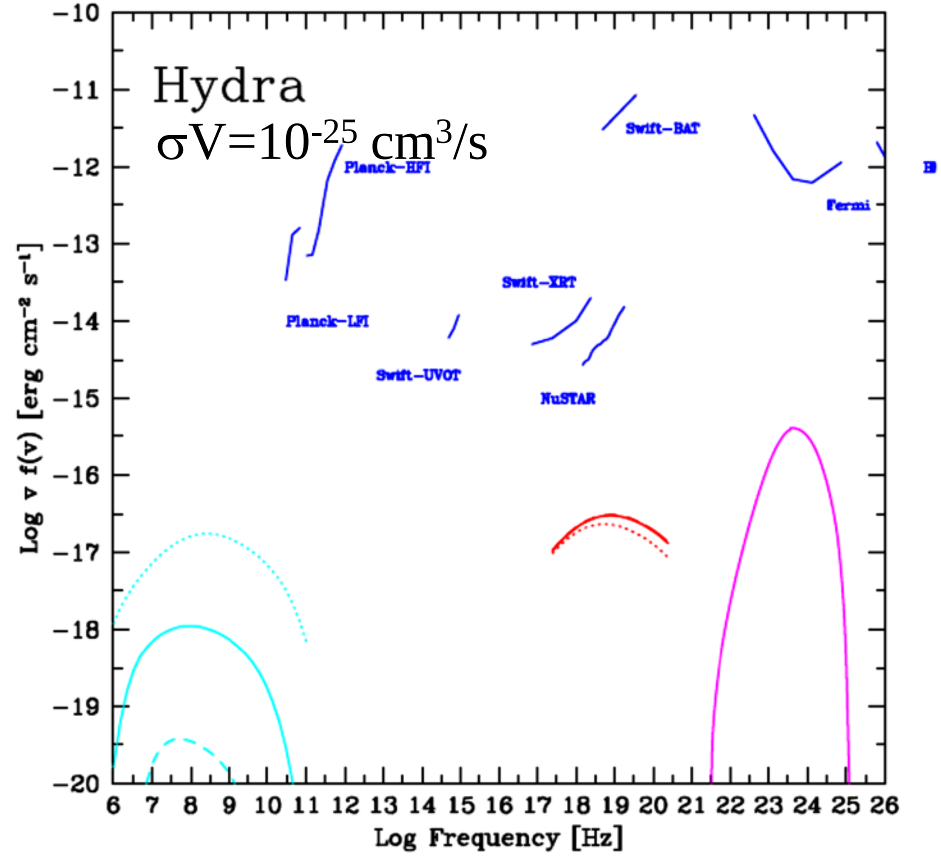
[Jeltema & Profumo arXiv:1108.1407]

HXR – gamma vs. HXR - Radio

Normalized to F(ν=1.4GHz)
With known B=5μG

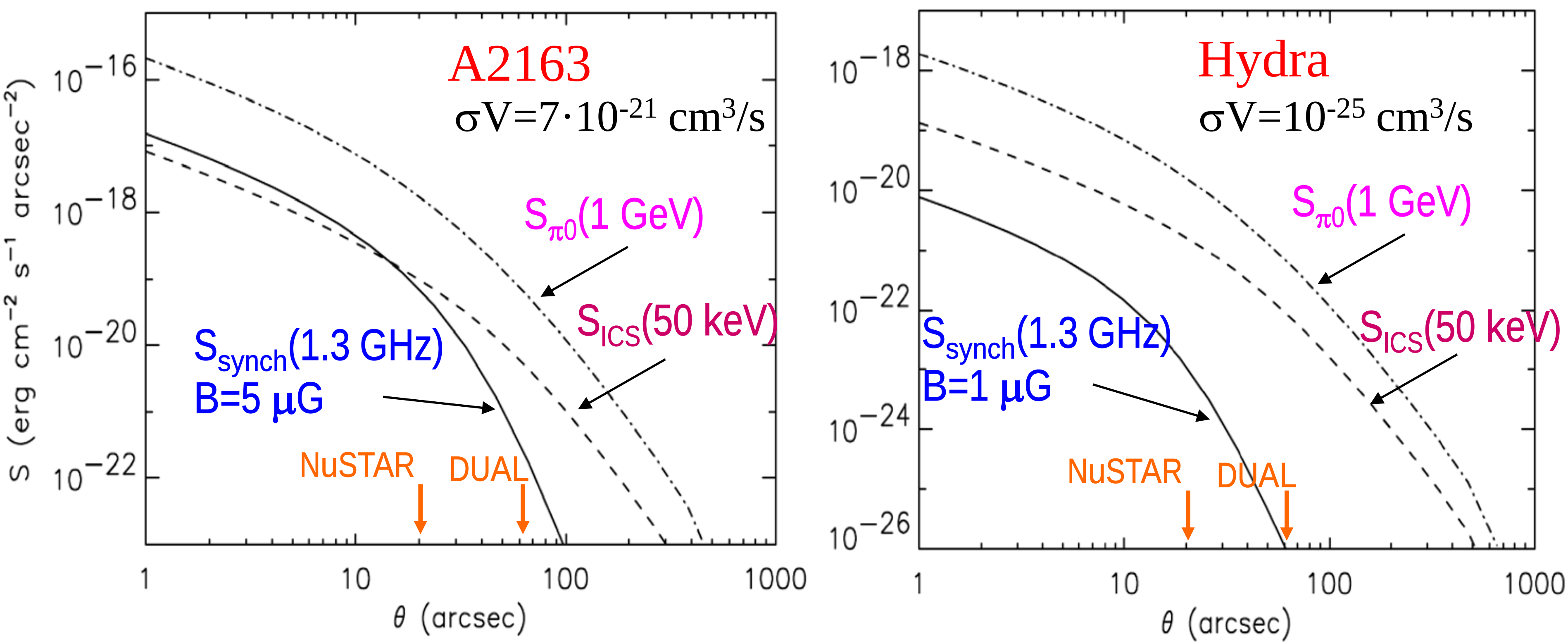
GeV experiments are far from
DM signal detections





HXR – Radio correlation provides stronger constraints on DM
(MeerKAT/SKA vs. NuSTAR/DUAL combined observations)

DM signal profiles HXR-Radio-gamma

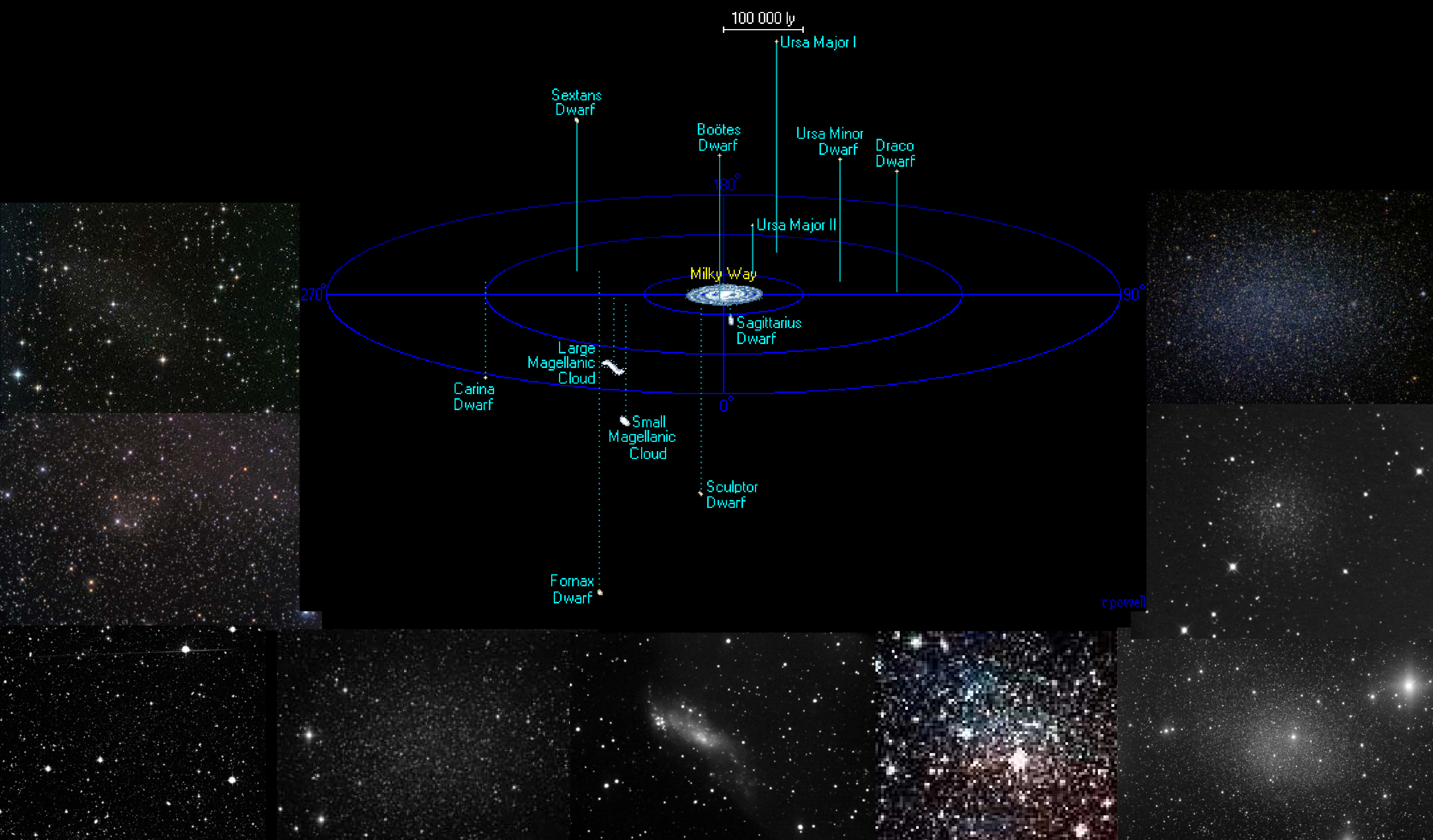


There is a clear spatial signature of DM signals visible in the HXRs

- Clear HXR-radio correlations at large angular scales (> 1 arcmin)
- No clear HXR-gamma correlation at all angular scales

Dwarf Spheroidals DM challenge

Small-size, dynamically un-relaxed… but few good cases !



The darkest galaxies in the universe

Segue 1 dwarf galaxy → $M/L_V \sim 3400 \ M_\odot/L_\odot$

The Dwarf Galaxies DM challenge

Sub-galactic size systems

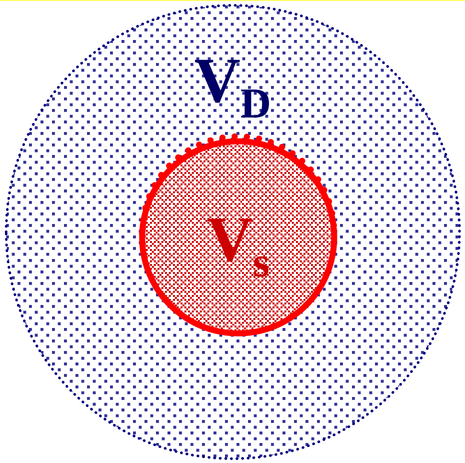
- R ~ kpc
- No gas
- Little dust
- No Crs
- 1 (or 2) stellar populations
- M/L ~ 500 - 3500

+ Ideal systems to probe DM
+ Clean multi-ν features

but…

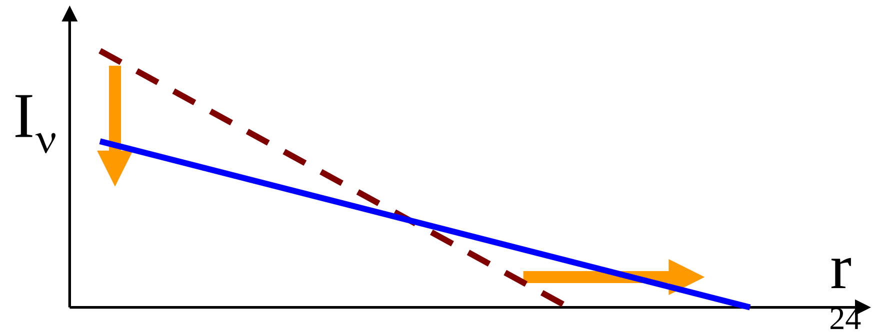
- Strong diffusion effects
- Low signals

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



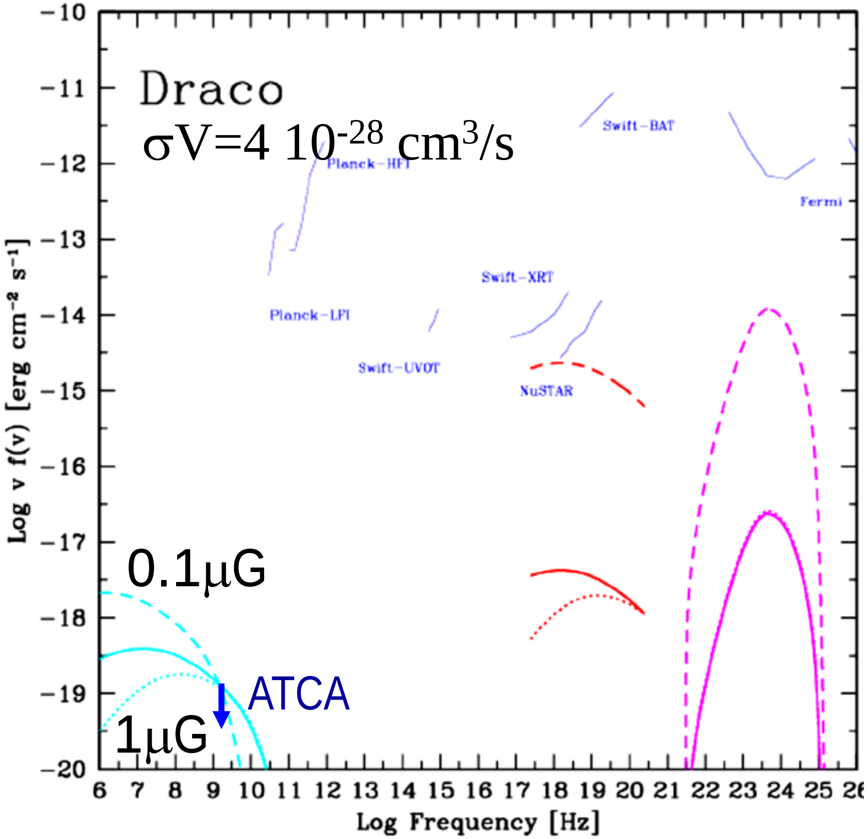
$\tau_{loss} \gg \tau_D$

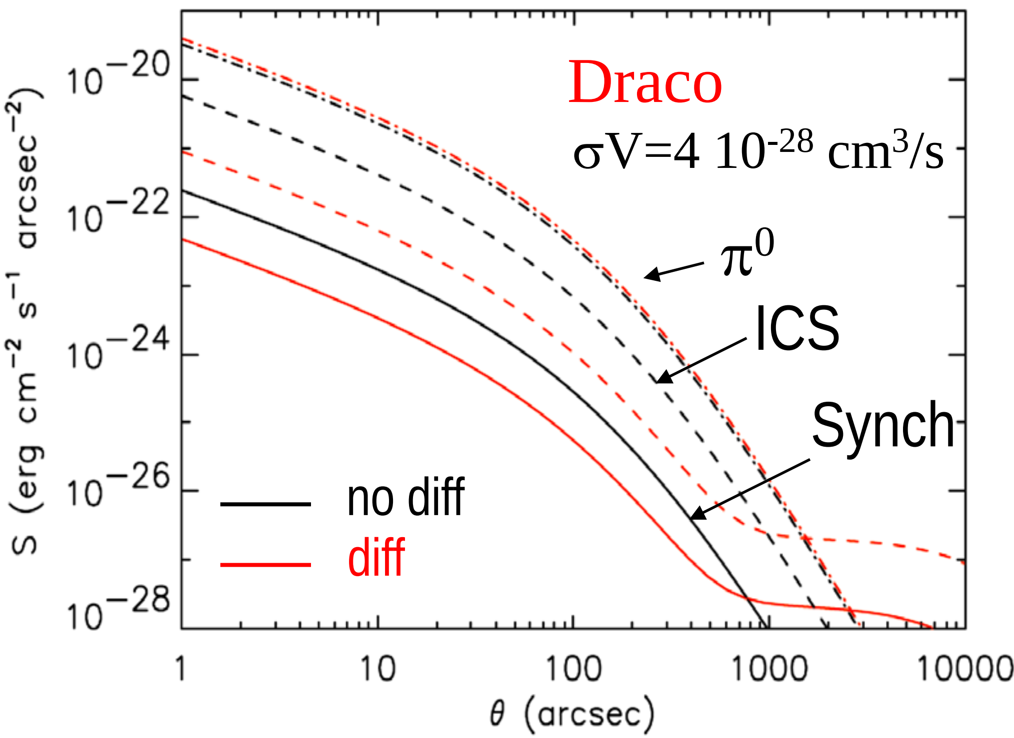
$$n_e(E,r) = \left[Q_e(E,r)\tau_{loss}\right] \cdot \frac{V_{source}}{V_{diffusion}} \cdot \frac{\tau_D}{\tau_{loss}}$$



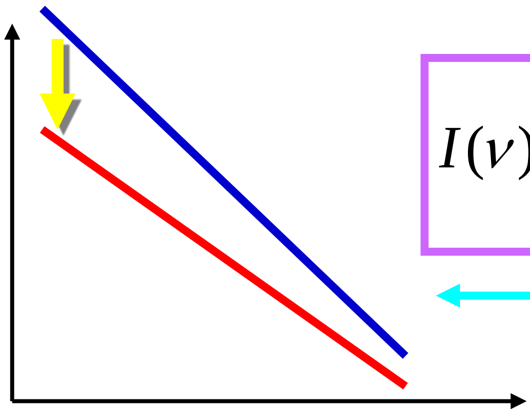
Expectations: the HXR range

Normalization fixed by lack of detection by ATCA ($F_{1.3GHz} < 10\mu Jy$)





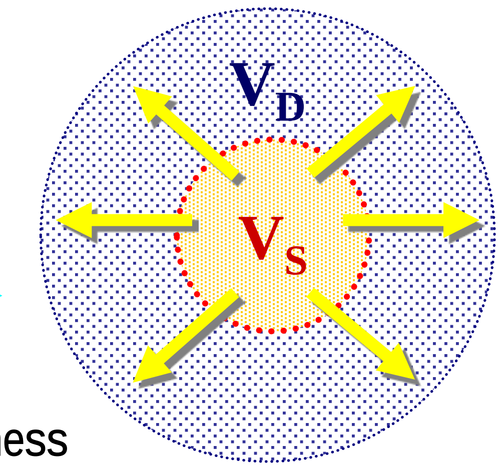
Dwarf Sph. Galaxies & DM



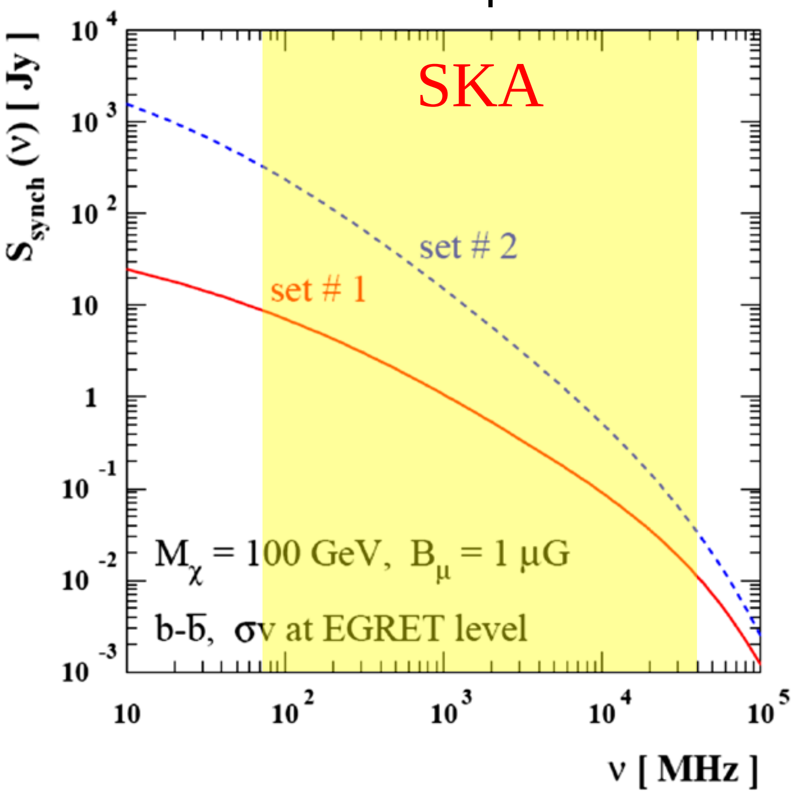
Spectrum

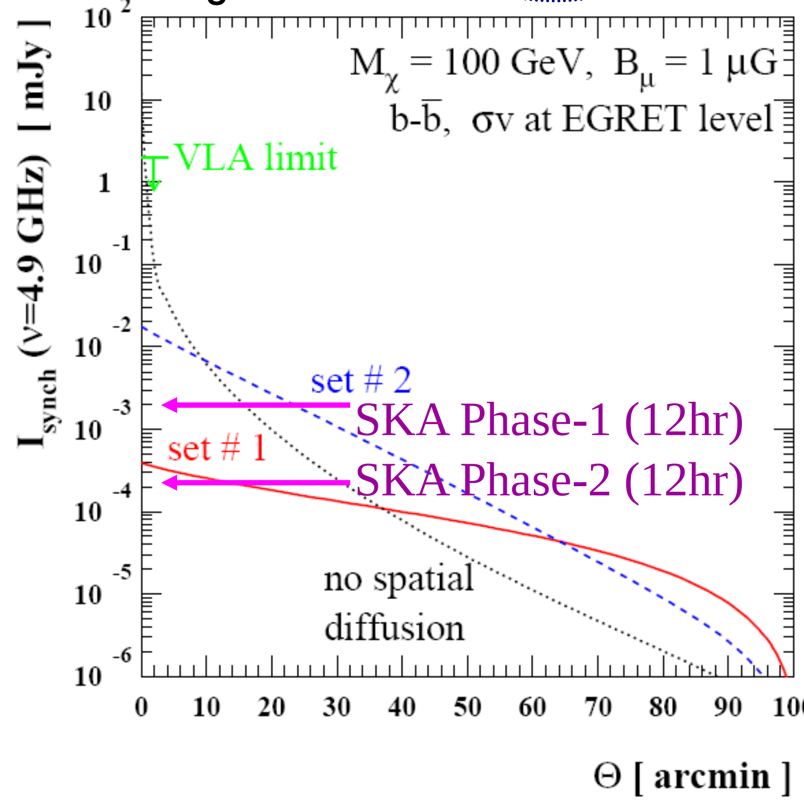
$$I(\nu) \propto B \otimes D_e \otimes n_e(E_e, \nu, r) \frac{\langle \sigma v \rangle}{M_\chi^2}$$

$$D_e = D_0 (E_e / B)^\gamma$$

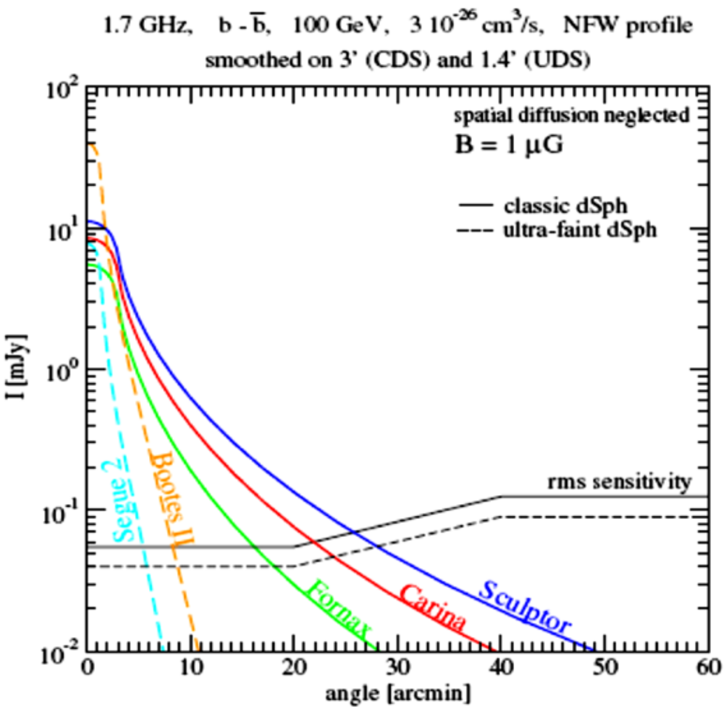


Brightness





ATCA → MeerKAT → SKA

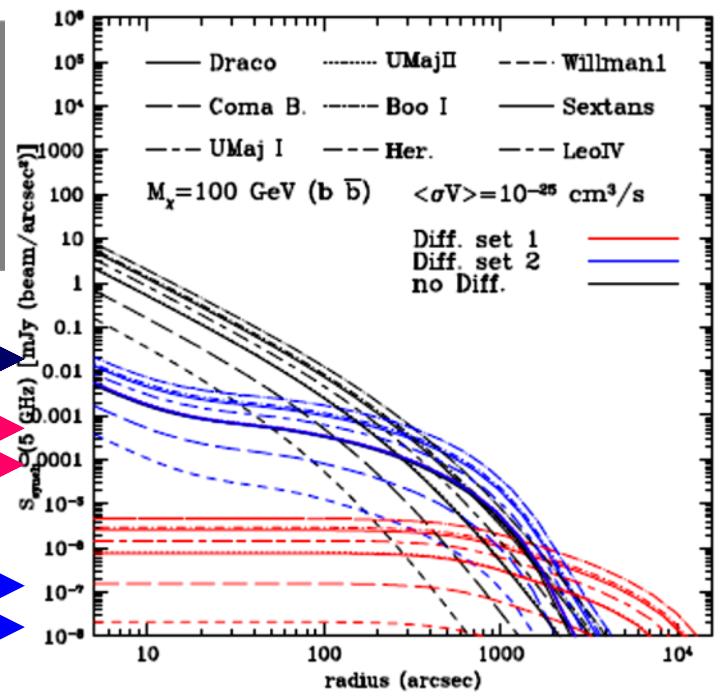


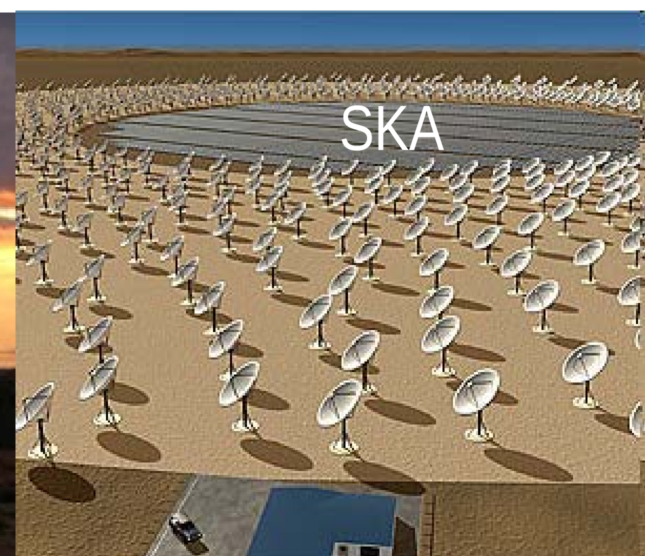
121.5 hours ATCA observations

ATCA →

MeerKAT →

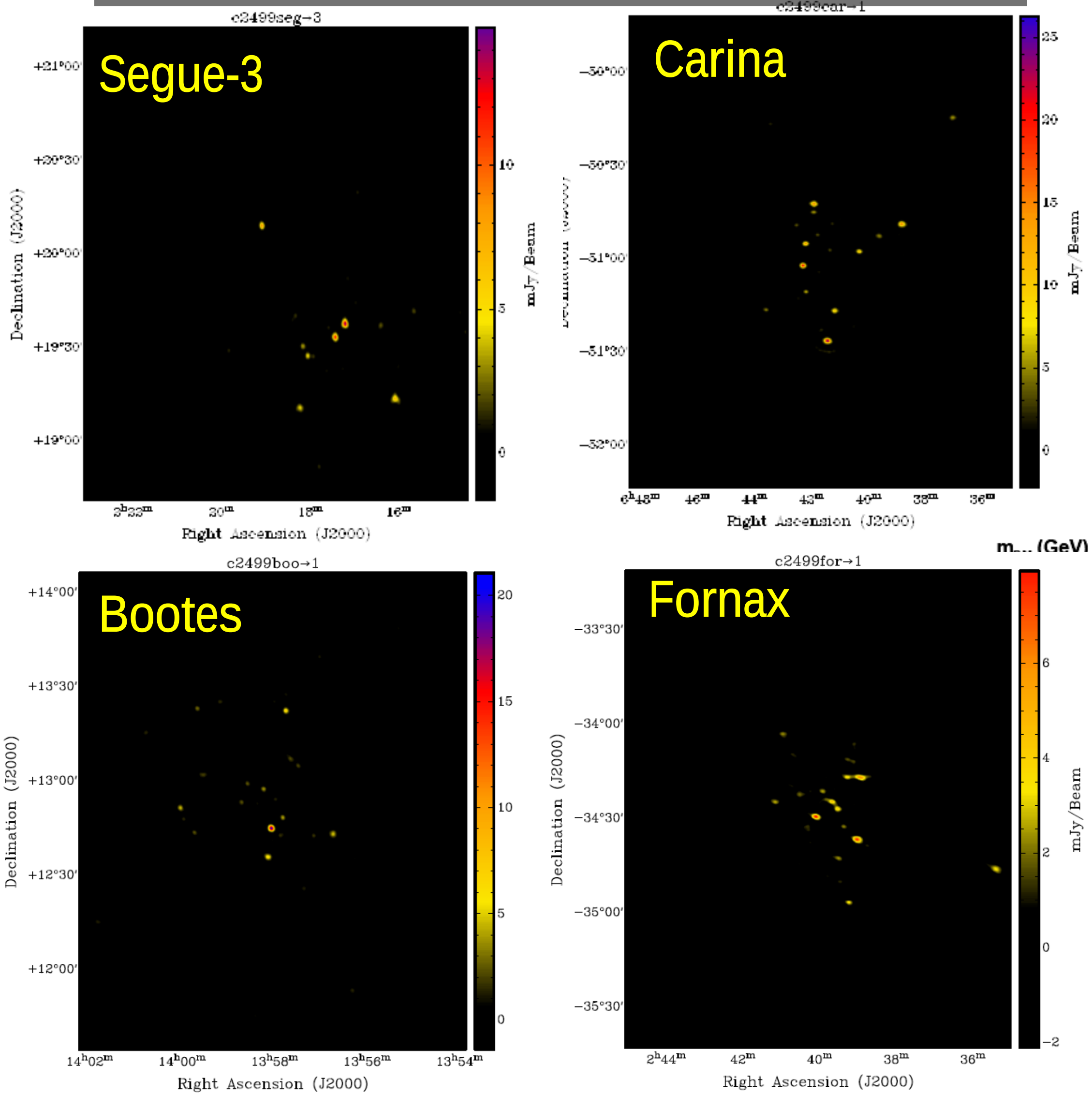
SKA →

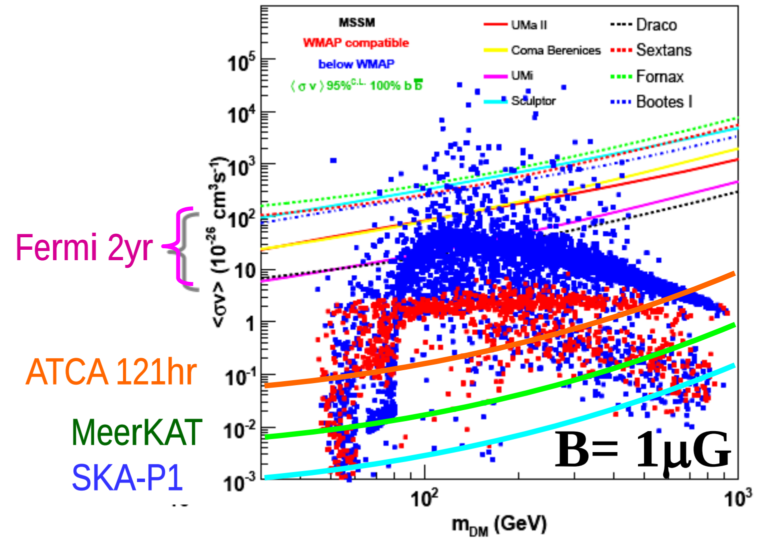




Dark Matter search @ radio

121.5 hr ATCA [S.C. et al. 2011]





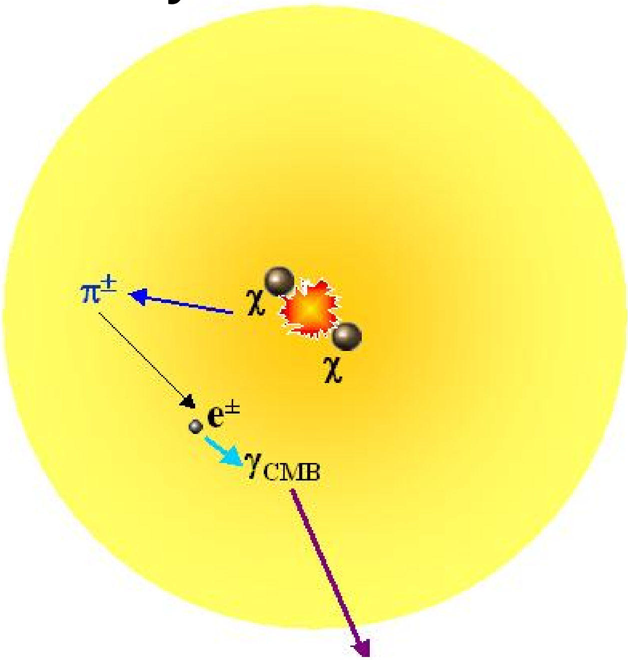
Improve current DM limits by a factor:

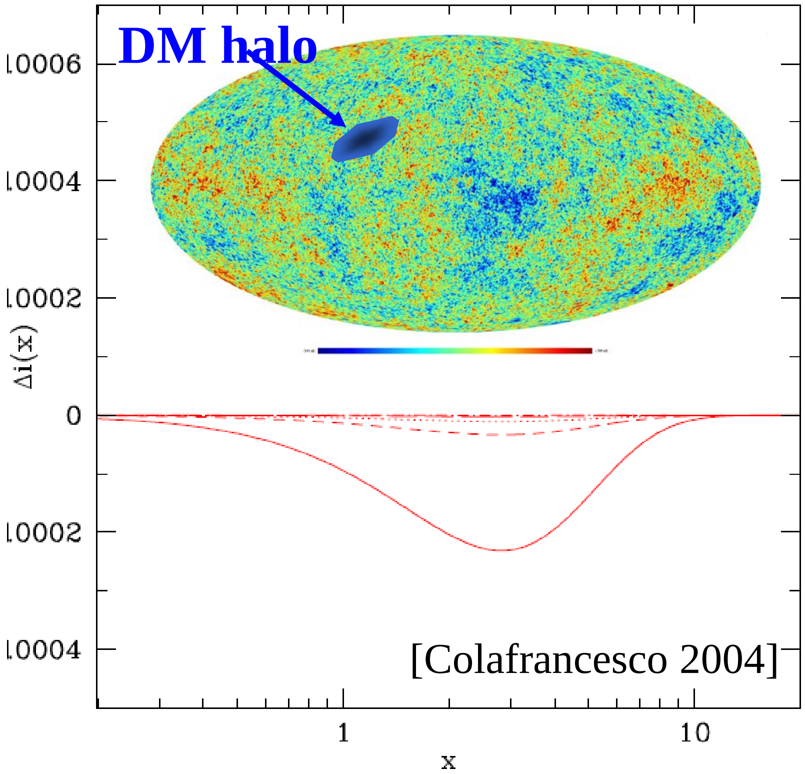
~100 ATCA (20 μJy)
~1000 MeerKAT (1 μJy)
~10000 SKA-P1 (0.1μJy)

DM search @ radio: Synch+SZE$_{DM}$

Inverse Compton Scattering
of CMB photons
by secondary DM electrons

$$\frac{\Delta T_{CMB}}{T_{CMB}} \approx g(x; M_\chi) \cdot \int d\ell \cdot P_e$$



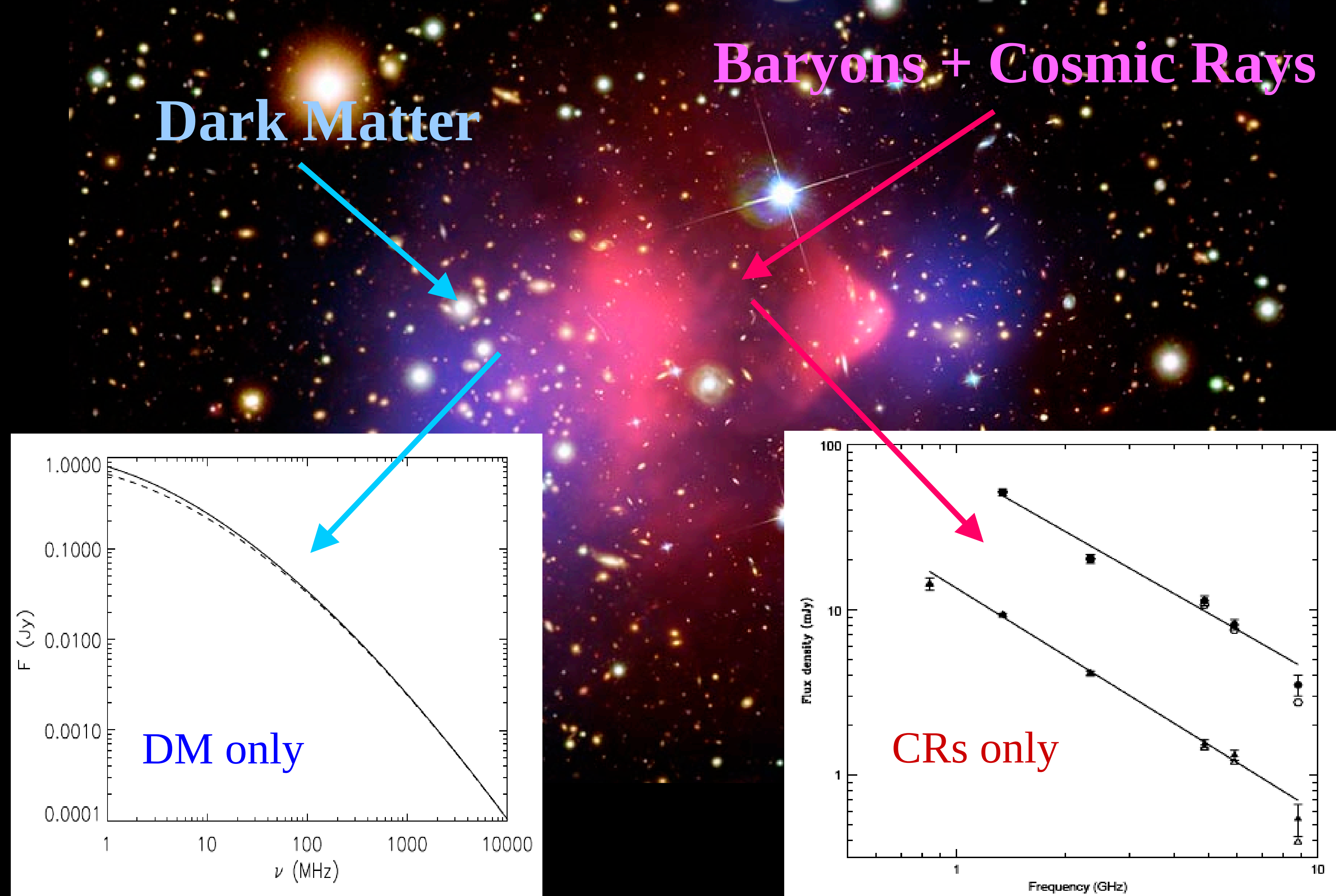


SKA-P2 (0.1-45 GHz)

MeerKAT (0.7-20 GHz)

- Measure radio (low ν) & ICS emission (high ν)
- Disentangle electron population and B-field → **$F_{radio}/F_{ICS} = U_B/U_{CMB}$**
- DM halo Cosmology: "purified" DM halo

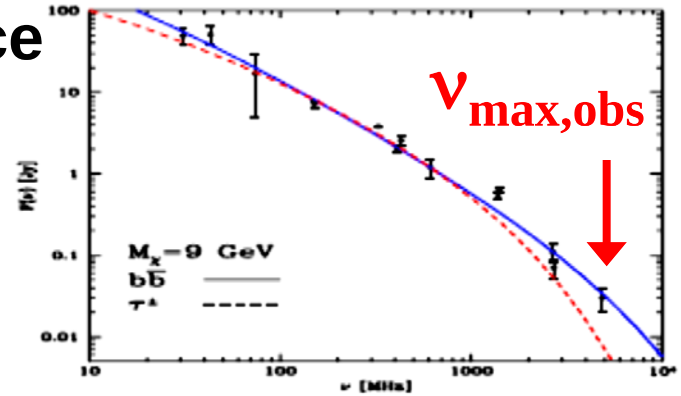
DM search @ radio: galaxy clusters



Dark Matter & Radio Halos

Dark Matter annihilation can reproduce the spectral and spatial features of galaxy clusters Radio Halos

[S.C. et al. 2001, 2006, 2008, 2010, 2011]

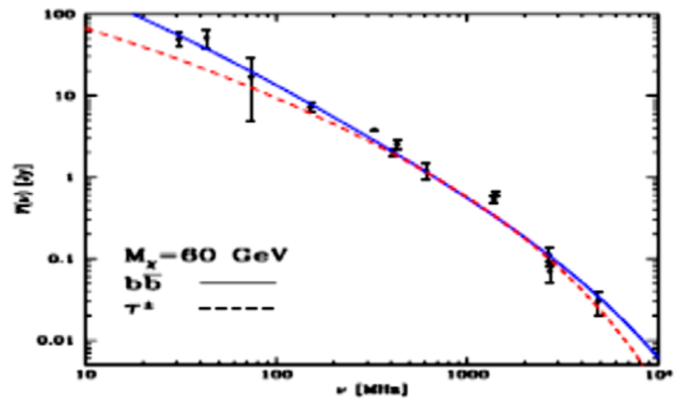


Sensitivity to DM composition

b-$\bar{b}$ model preferred by RH spectra

with neutralino mass M_χ~40-60 GeV

(□CRESST-II results)



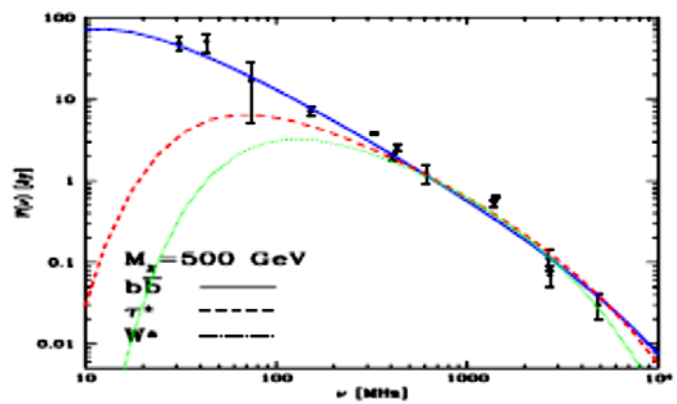
Sensitivity to DM particle mass

Lower l.

$$M_\chi \geq \frac{16.44}{k} \text{ GeV} \left(\frac{\nu_{max,obs}}{\text{GHz}}\right)^{1/2} B_\mu^{-1/2}$$

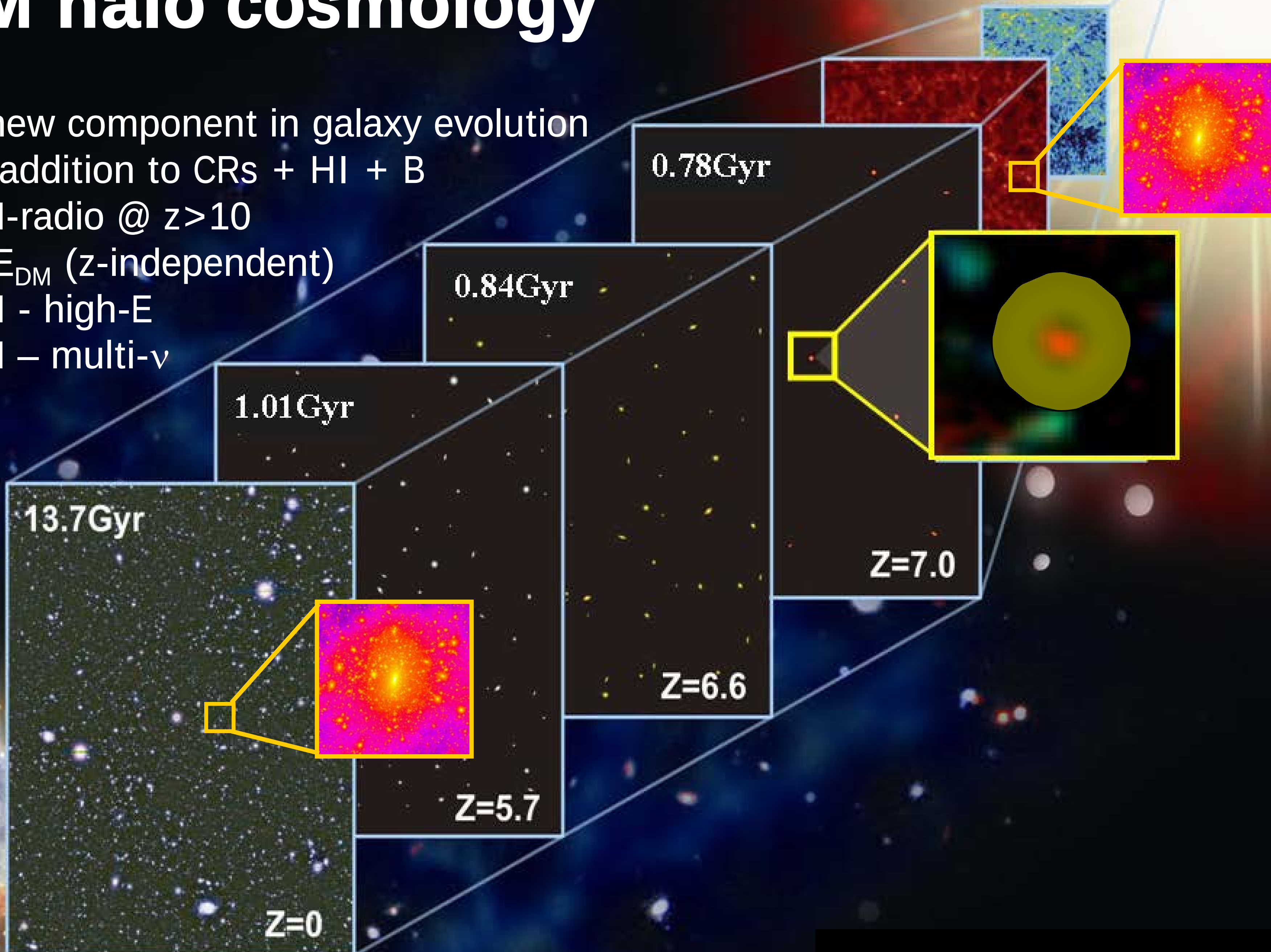
Upper l.

$$M_\chi \leq 74.3 \text{ GeV} \left(\frac{\nu_{max}}{10 \text{ GHz}}\right)^{1/2} B_\mu^{-1/2}$$



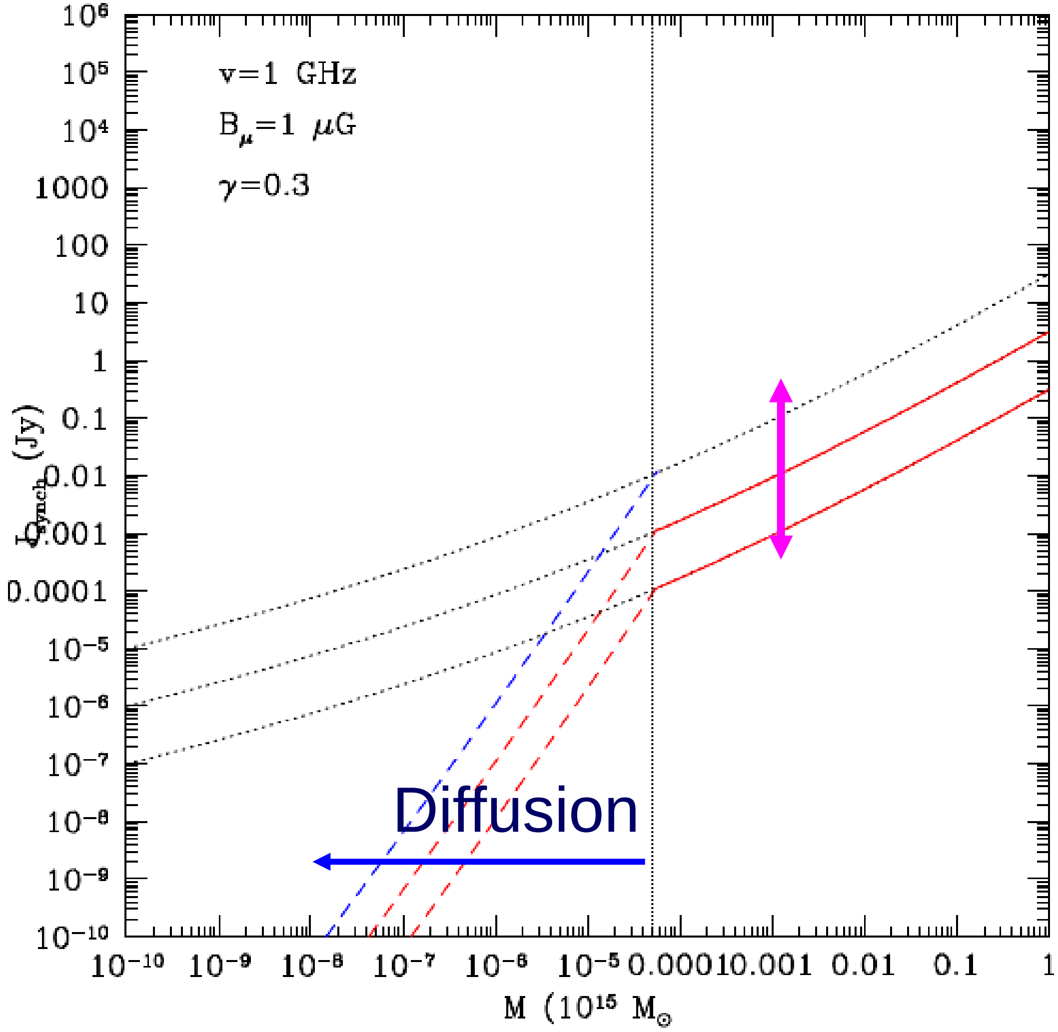
DM halo cosmology

- A new component in galaxy evolution in addition to CRs + HI + B
- DM-radio @ z>10
- SZE_{DM} (z-independent)
- DM - high-E
- DM – multi-ν



Radio emission from DM halos

$$\frac{R_{halo}}{L_{Diff}} << 1 \qquad \frac{R_{halo}}{L_{Diff}} >> 1$$



$$\langle \sigma V \rangle \rho_{DM}^2$$

$$\propto \langle \sigma V \rangle M_{\chi}^{-2}$$

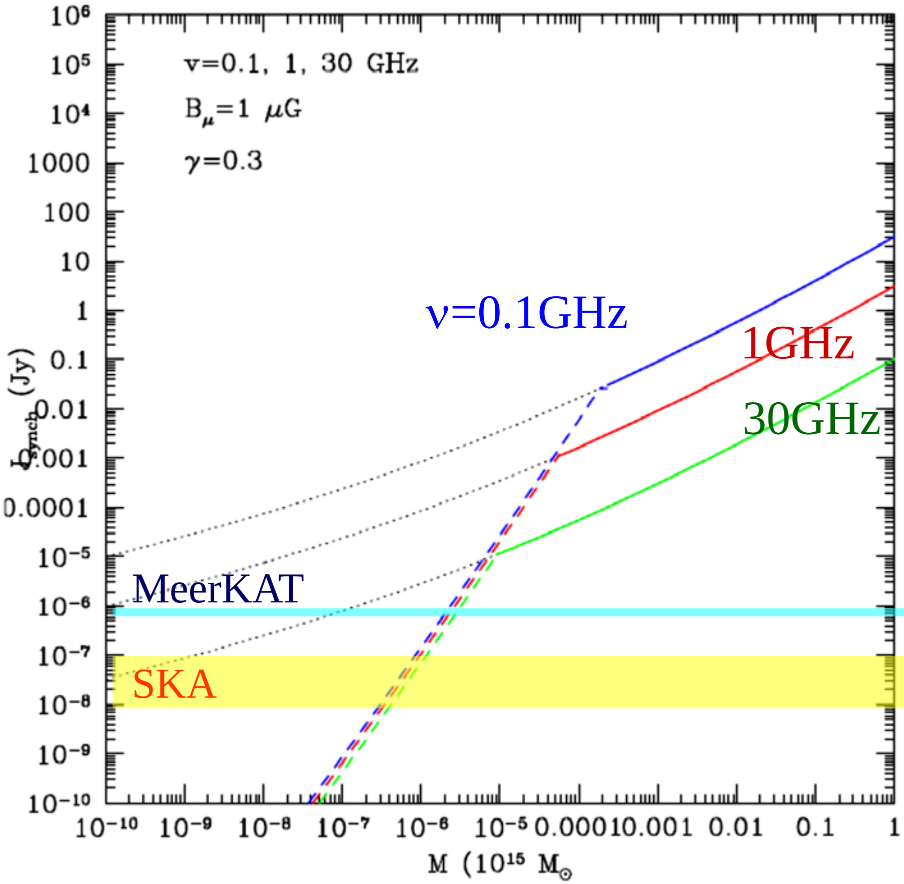
$$L_{Diff} = \left[D(E,B) \cdot \tau_{loss} \right]^{1/2}$$

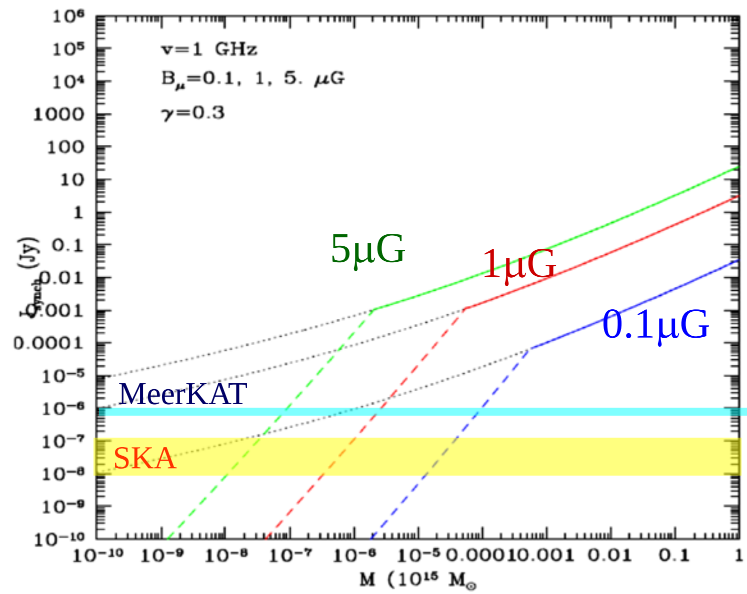
[Colafrancesco & Marchegiani 2011]

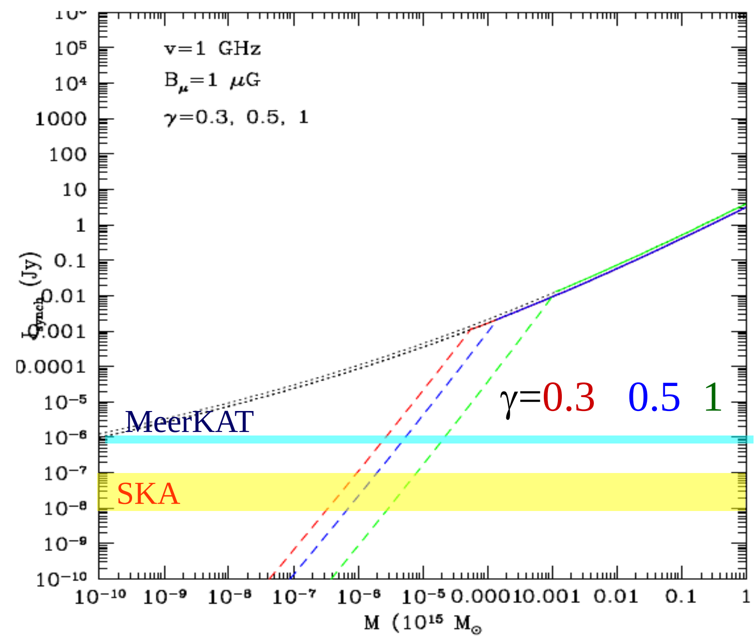
Radio emission from DM halos

SKA can probe ~10^7 -10^8 $M_\odot$ DM halos with standard <σV> and Mχ

- Dwarf galaxies (→ DM halos)
- Proto-galaxies (→ DM halos)

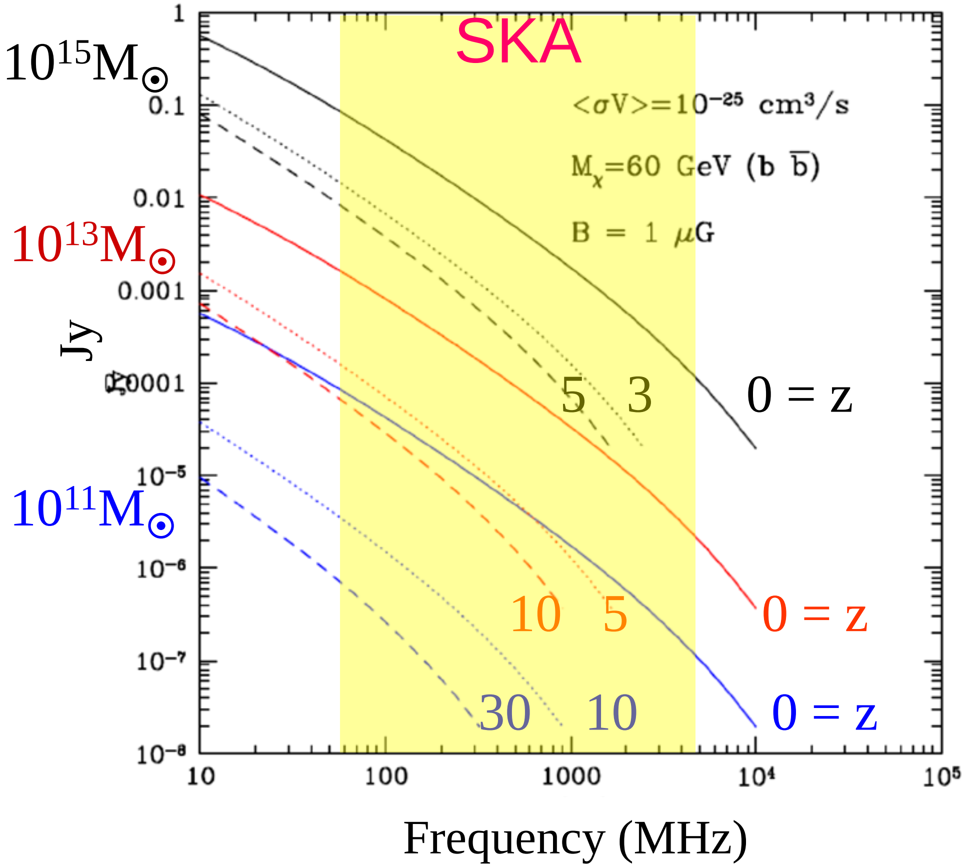




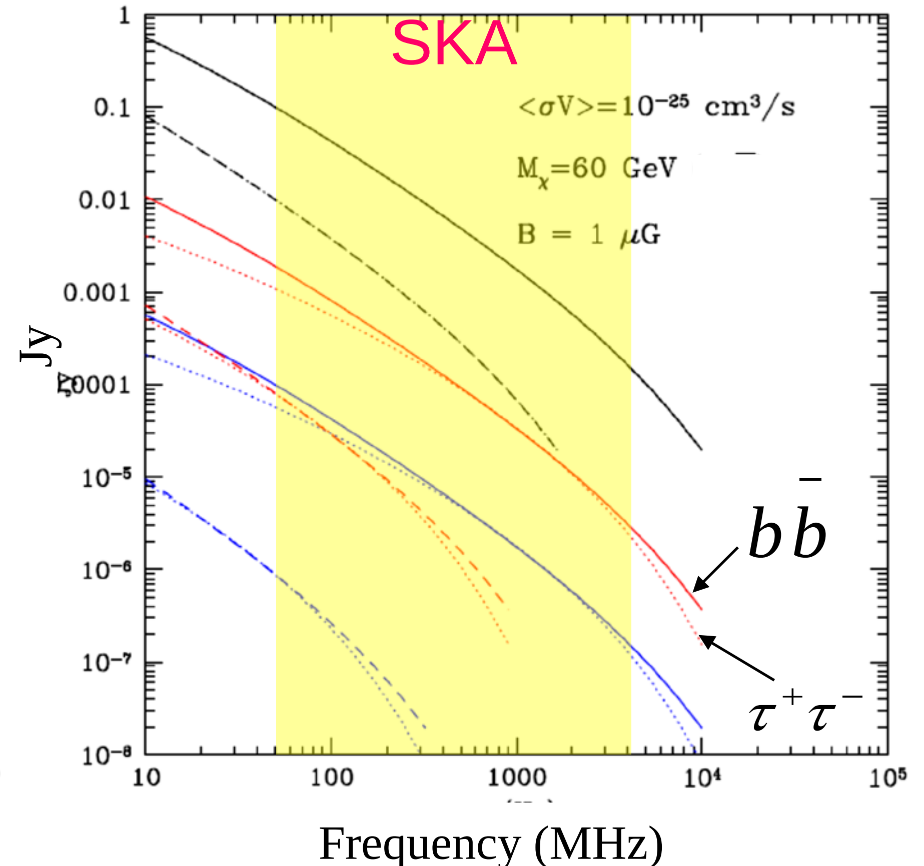


Probing early DM halos @ radio

High-z DM halos
Early proto galaxies



High-z DM halos
χ mass & composition



M_χ from radio spectrum cutoff

$$\nu \approx (3.7\ \mathrm{MHz}) B_\mu \left(\frac{E}{\mathrm{GeV}}\right)^2$$

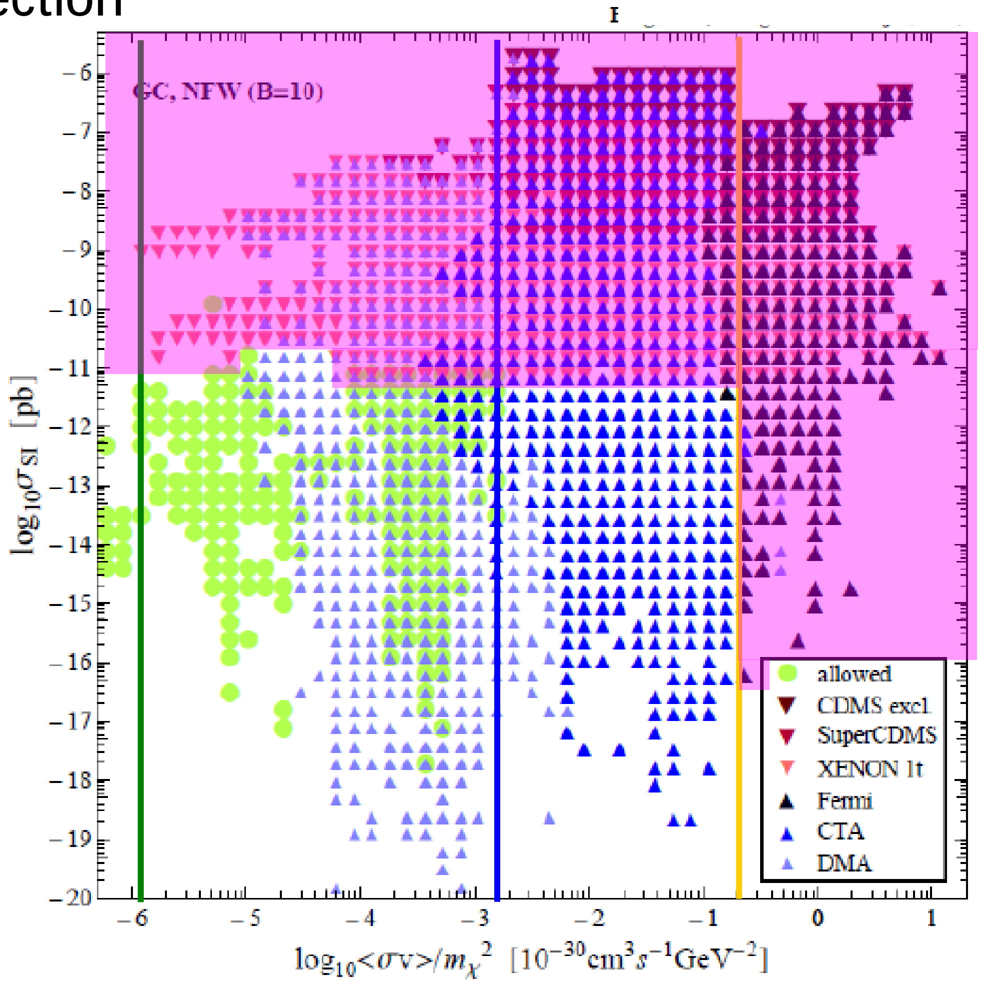
$$\nu_{\max} \sim (3.7\ \mathrm{MHz}) B_\mu \left(\frac{k M_\chi}{\mathrm{GeV}}\right)^2$$

$$M_\chi \geq \frac{16.44}{k}\ \mathrm{GeV} \left(\frac{\nu_{\max,\mathrm{obs}}}{\mathrm{GHz}}\right)^{1/2} B_\mu^{-1/2}$$

Exploring DM universes

Direct Detection

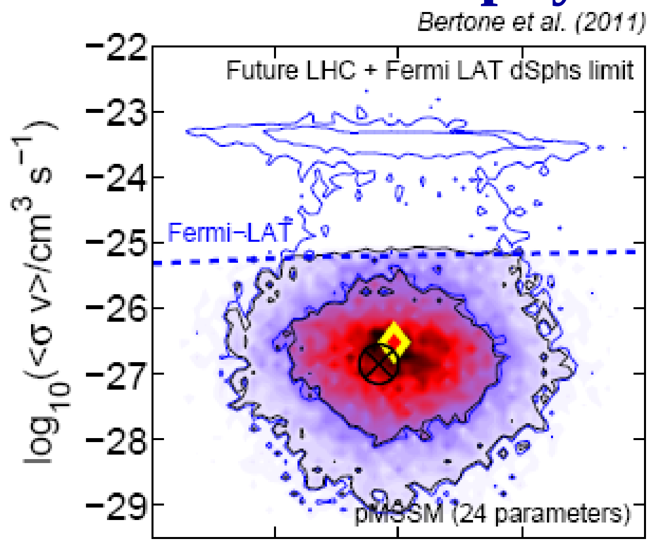
DM detectors + Astrophysics

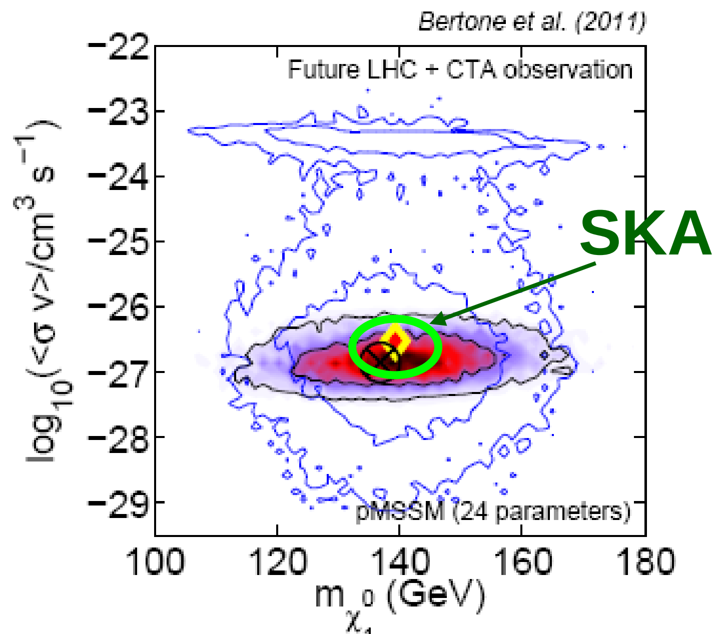


SKA ← CTA ← Fermi

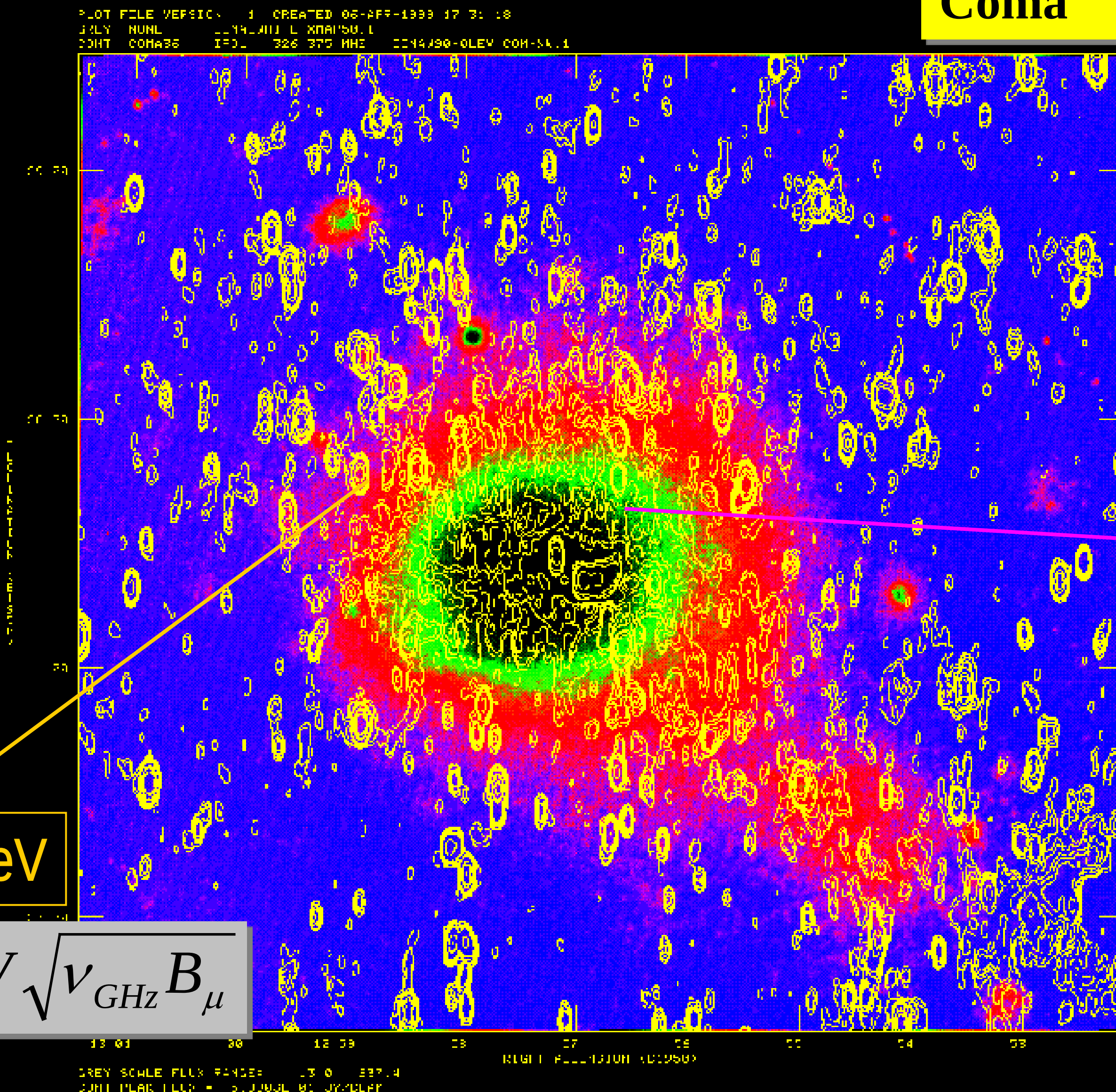
← Indirect Detection

LHC + Astrophysics





CRs in clusters: radio emission



$E_e \geq$ keV

$E_e \sim$ a few GeV

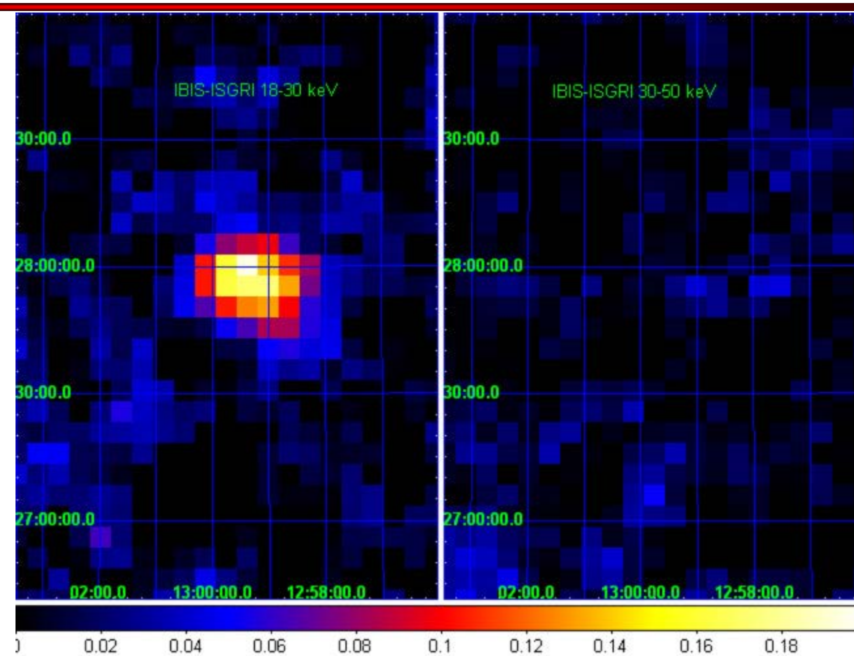
$$E \approx 16.6 GeV \sqrt{\nu_{GHz} B_{\mu}}$$

[Feretti et al. 2001]

CRs in clusters: Hard X-Rays

Beppo-SAX
INTEGRAL

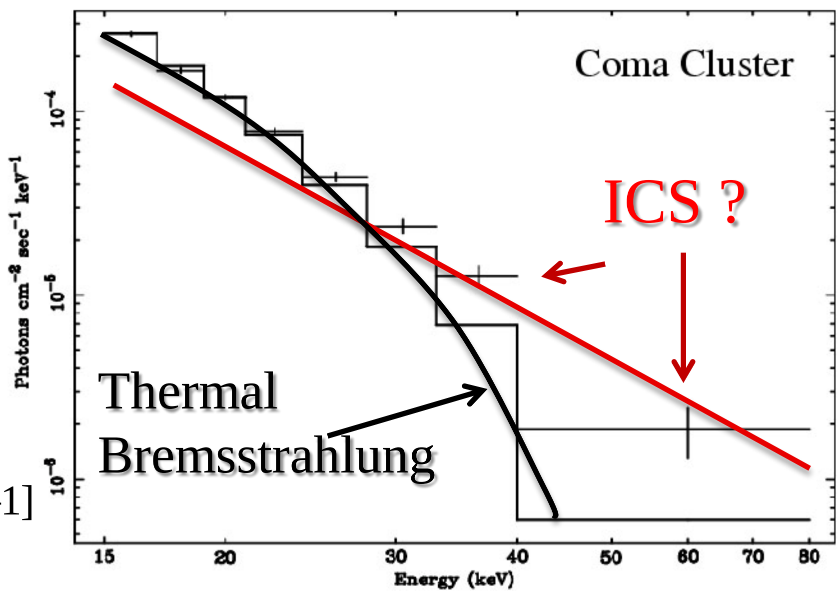
First detection of hard X-rays in Coma at E > 20keV



HXR spectrum has a slope consistent with the synchrotron radio spectrum

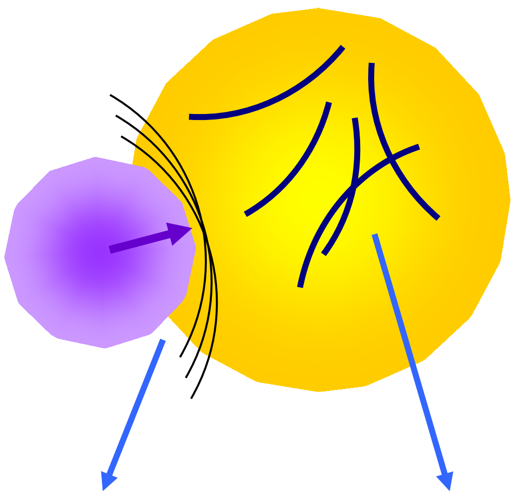
$$I_{ICS}(\nu) \propto E^{-(p-1)/2}$$

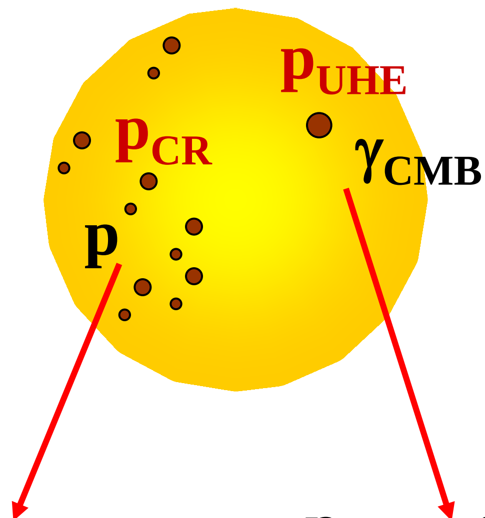
$$I_{Sync}(\nu) \propto E^{-(p-1)/2} \cdot B^{[(p-1)/2+1]}$$



Cosmic rays in clusters

Acceleration $t_{acc} << t_{loss}, t_{eq}$		**In-situ** $\partial n_e / \partial t \approx 0$	

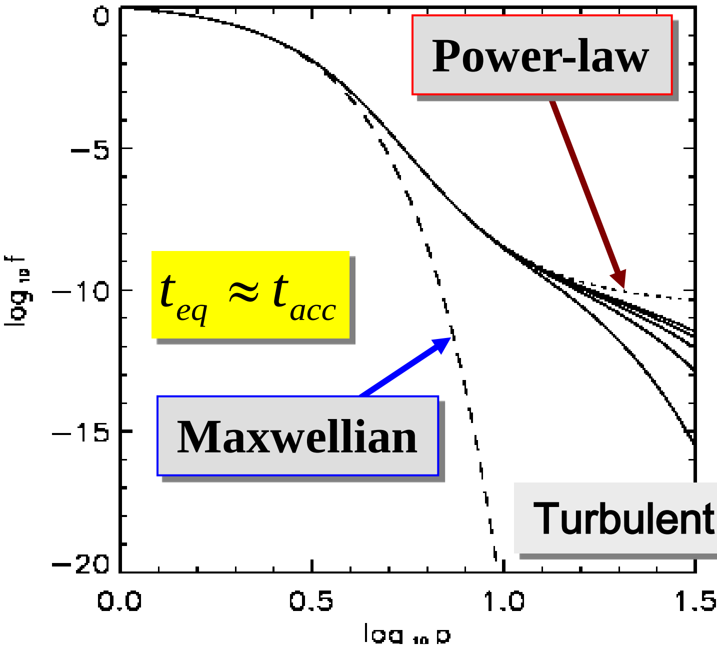




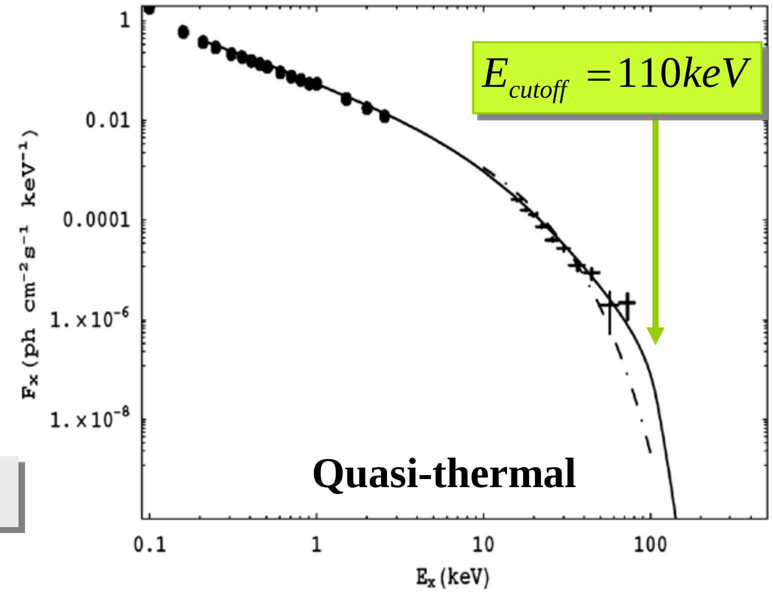
	Direct	**Stochastic**	p_{CR} - p	p_{UHE} - γ_{CMB}
	e^-, p	e^-, p	$p_{CR} + p \rightarrow X + \pi^\pm$ $\pi^\pm \rightarrow X + e^\pm$	$p_{UHE} + \gamma \rightarrow p + e^\pm$
$E_e \approx 10^{-5,-6} GeV$	**Bremsstrahlung**	**Bremsstrahlung**	**Bremsstrahlung**	
$E_e \approx GeV$	**ICS on CMB**	**ICS on CMB**	**ICS on CMB**	
$E_e \approx 10^{5-6} GeV$				**Synchrotron**

CR direct acceleration efficiency

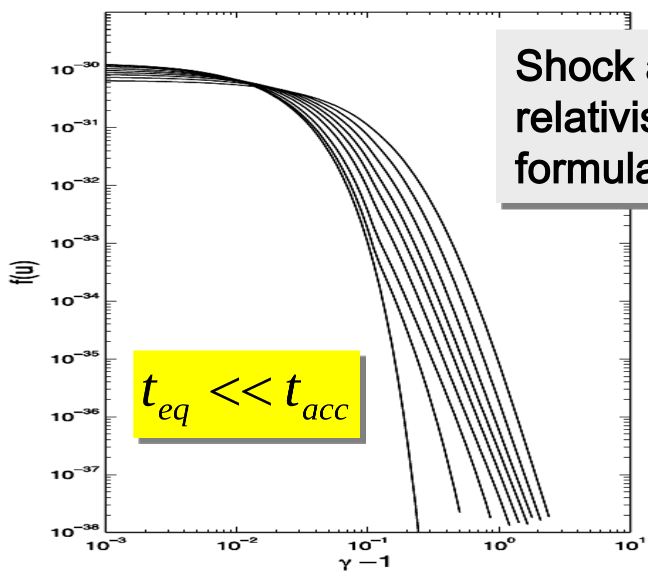
[Dogiel, Colafrancesco et al. 2007]



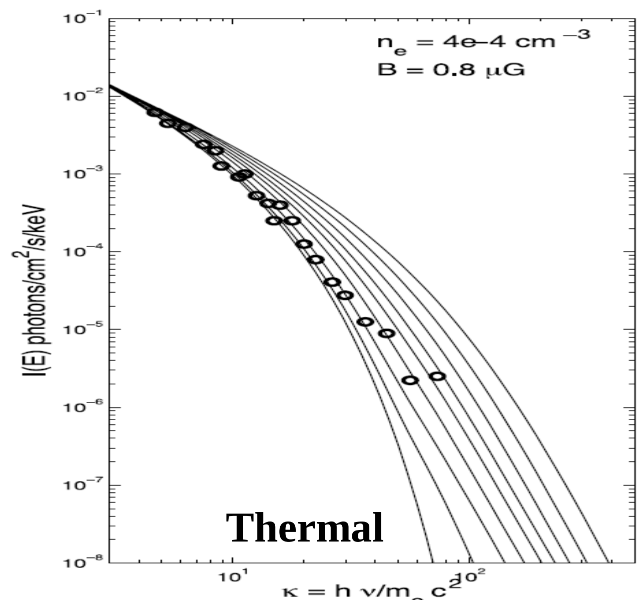
Turbulent acceleration



Shock acceleration: relativistic covariant formulation



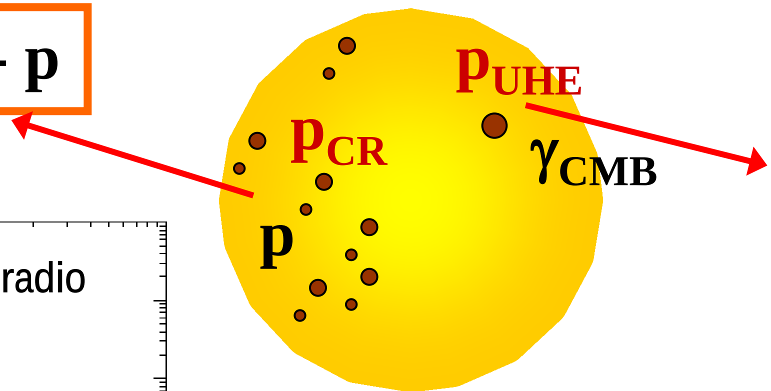
[Wolfe & Melia 2006]



CRs of high-E → *in-situ* production

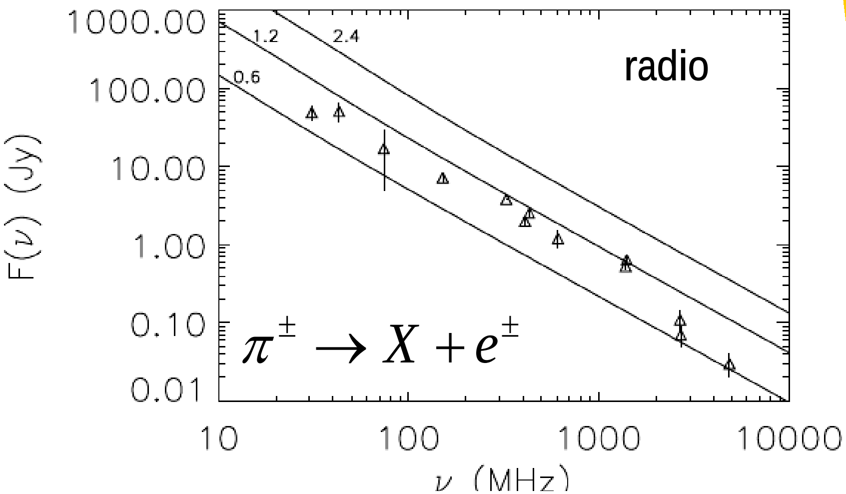
$$p_{CR} + p \rightarrow X + \pi^{0,\pm}$$

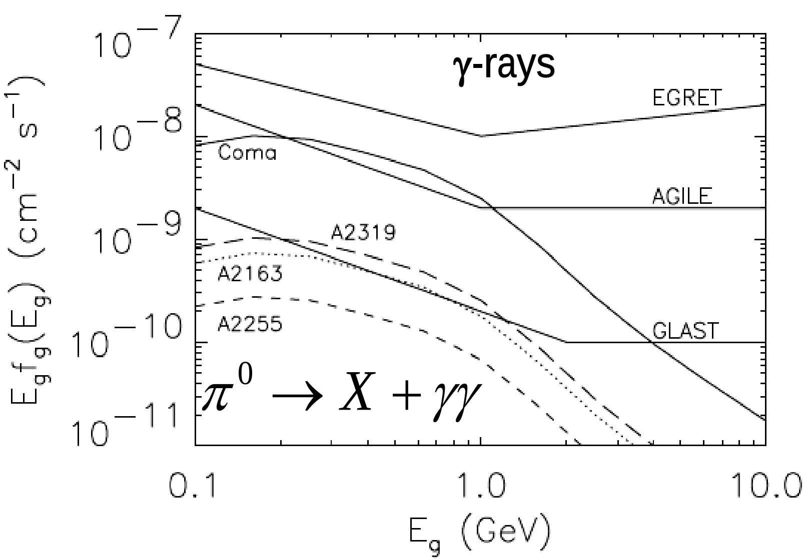
p_{CR} - p



p_{UHE} - γ_{CMB}

$$p_{UHE} + \gamma \rightarrow X + e^{\pm}$$





If we interpret the HXR emission in clusters as due to ICS of CRs, we have three consequences:

1. The number density of CRs is high
2. The cluster B field must be very low B ~ 0.15 μG
3. The ICS and π0 →γγ gamma-ray emission exceeds the observed upper limits

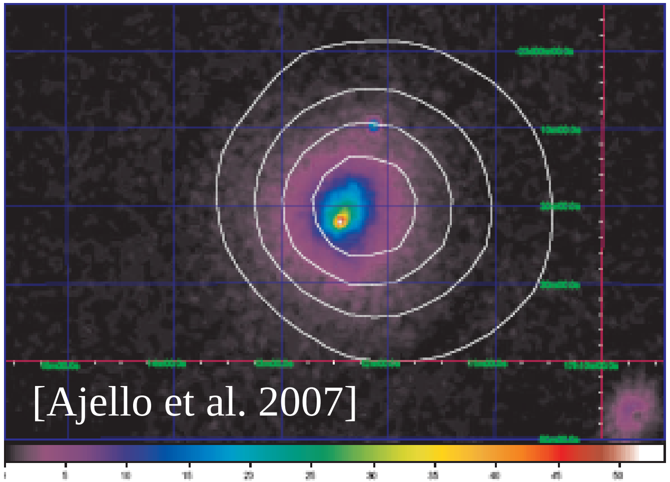
[Marchegiani & S.C. 2007]

Examples: Ophiuchus and Perseus

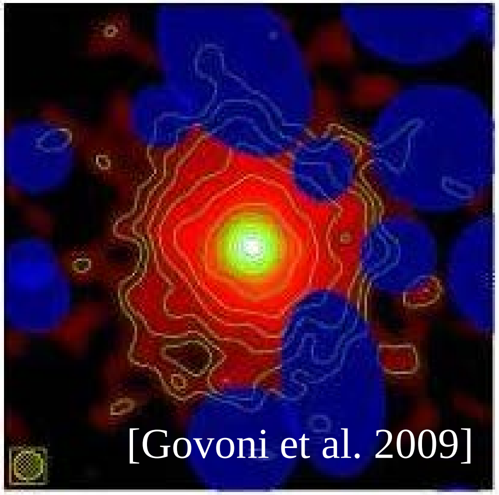
Ophiuchus cluster

- Single-T ~ 9.5 keV
- no-Cool Core
- no AGN in the core
- Radio halo @1.4GHz

(DM, CRs, WRs,...)



[Ajello et al. 2007]

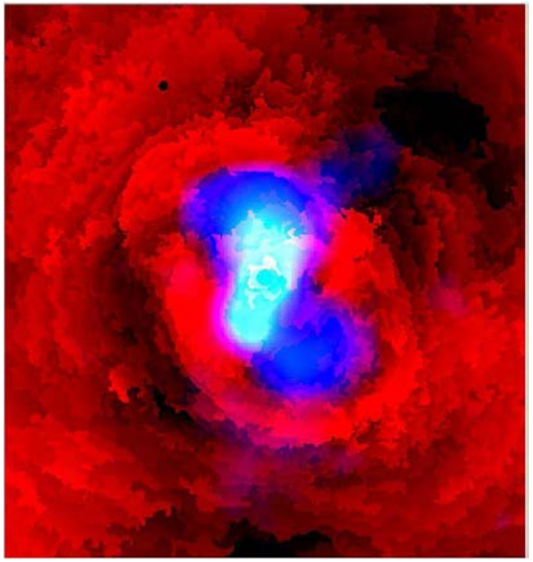


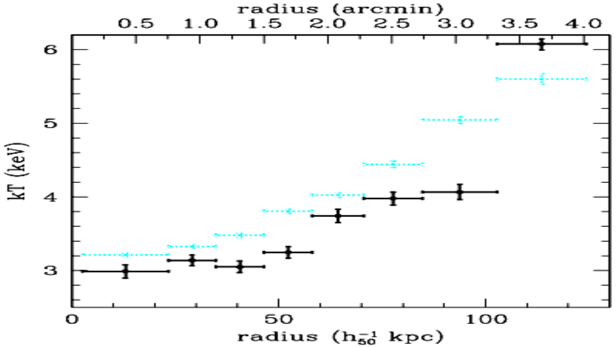
[Govoni et al. 2009]

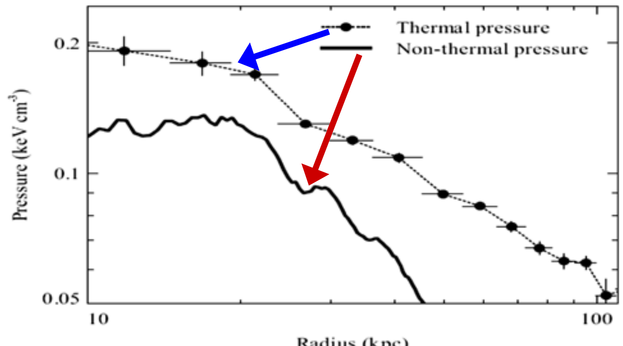
Perseus cluster

- Multi-T
- Cool Core
- AGN-dominated core
- Mini Radio halo
- Non-thermal plasma

(DM, CRs, WRs, BH,..)



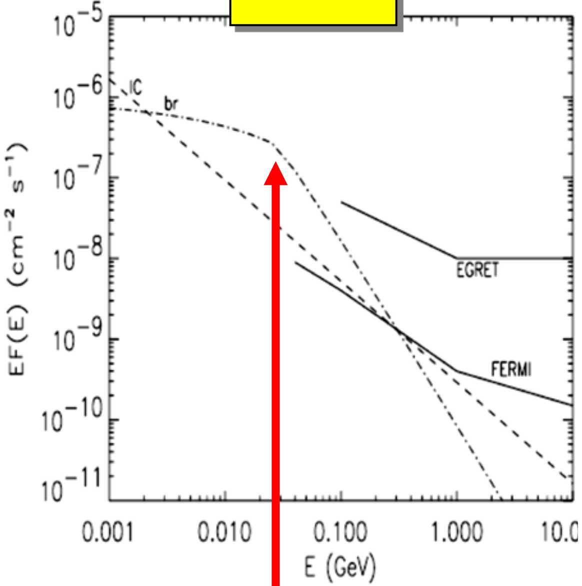




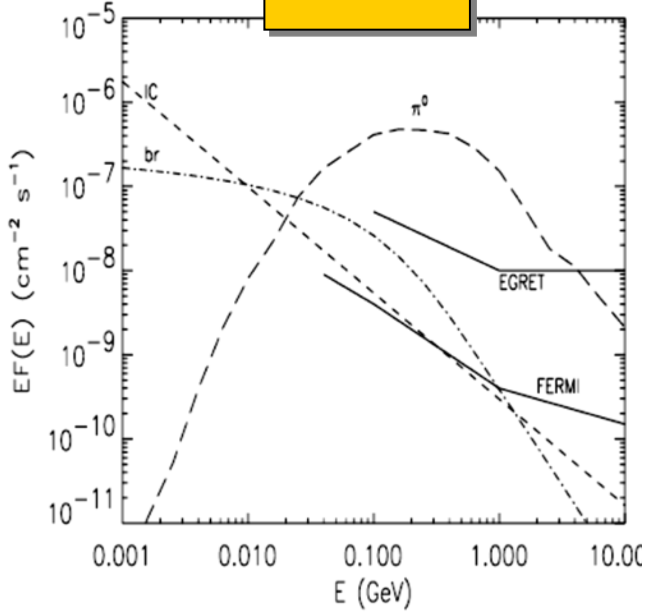
Constraints

[Colafrancesco & Marchegiani 2009]

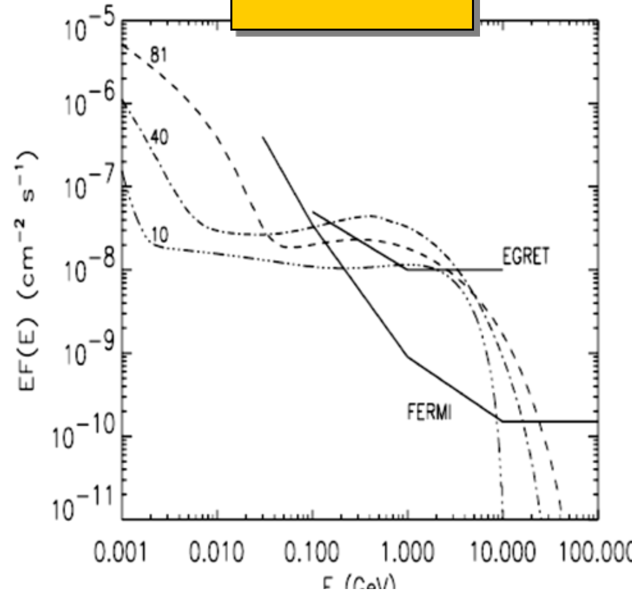
PEM



SEM-pp

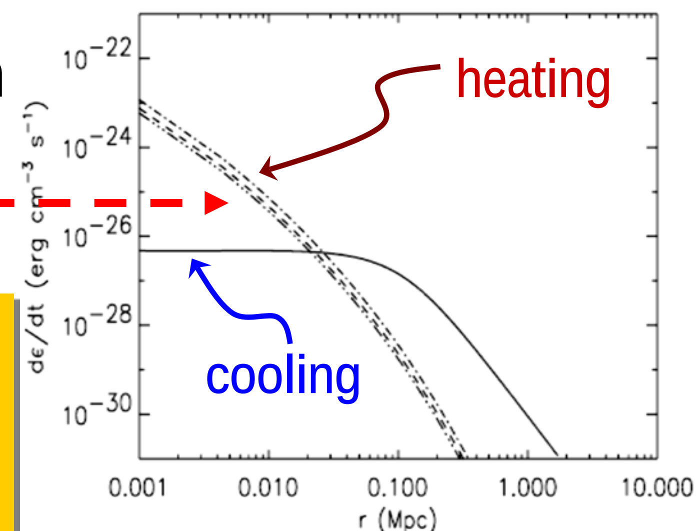


SEM-DM



γ-ray emission normalized to the HXR emission

Excessive Heating



Need cut-off E_e spetrum at low $E_e \sim 30$ MeV

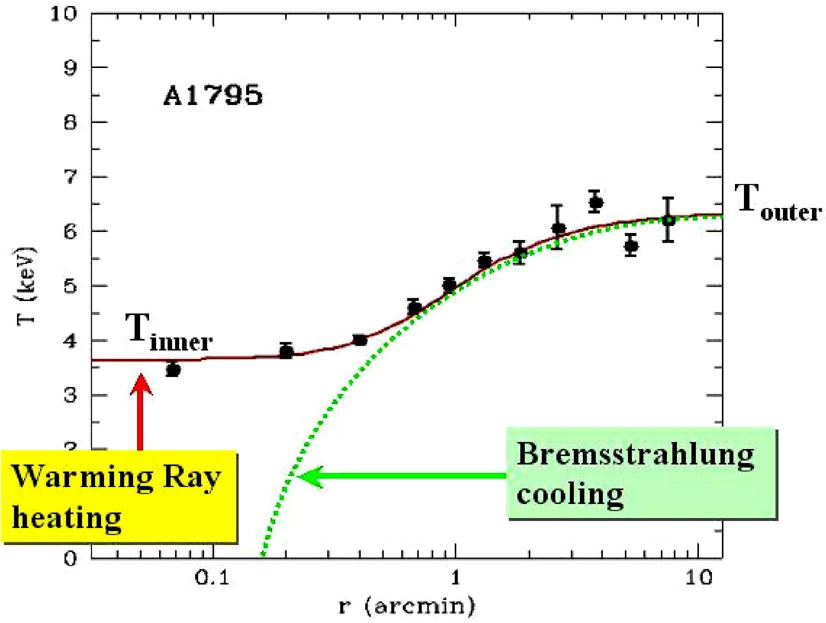
Untenable SEM models

A consistent model: Warming Rays

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

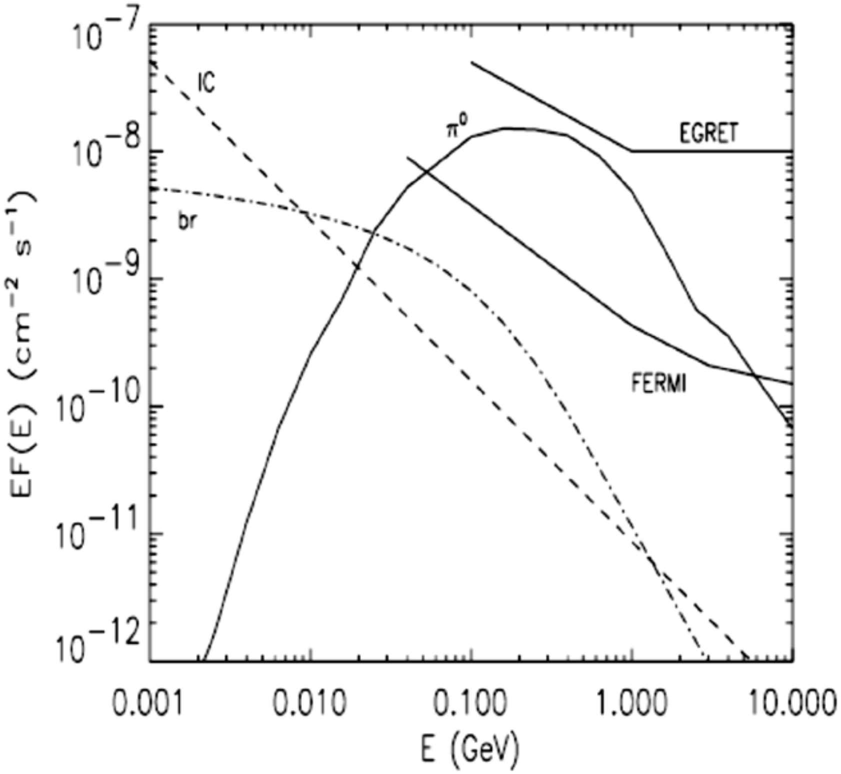
$$\left(\frac{dE}{dt}\right)_{WR} = bn^2(r)$$ Heating

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



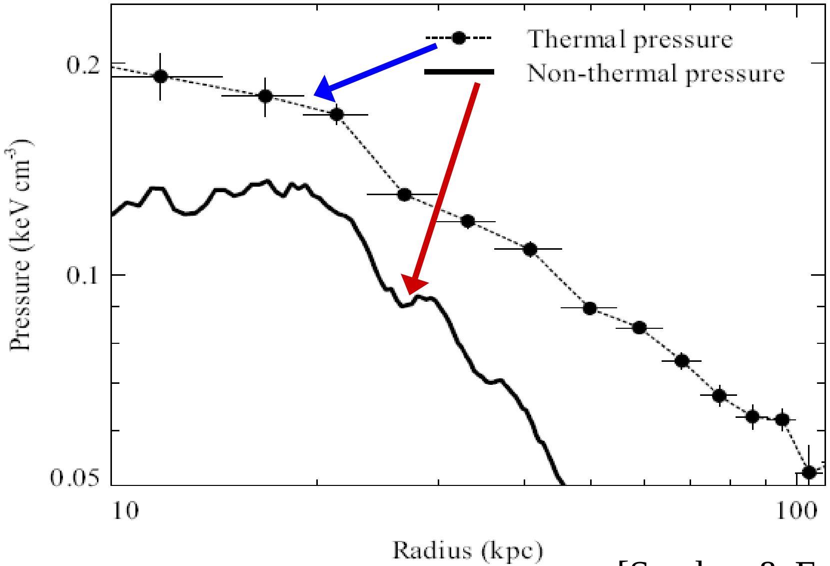
Warming Ray Model

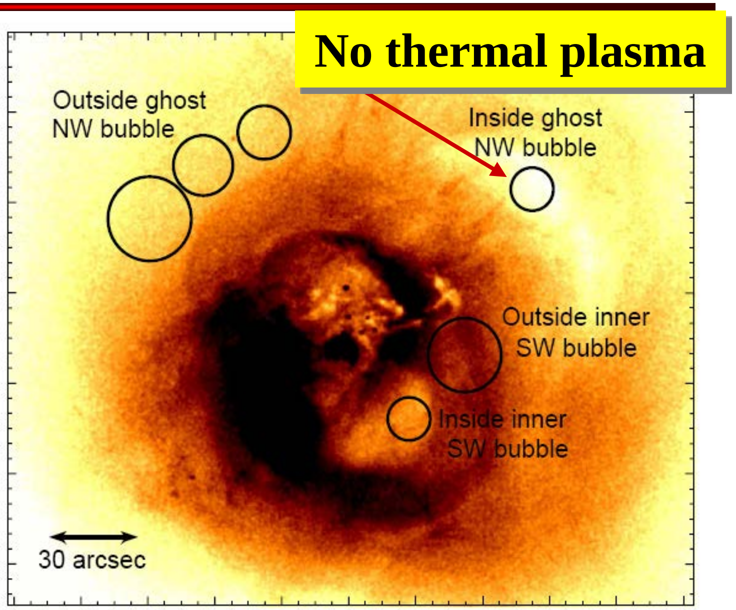
[Colafrancesco, Dar & deRujula 2004]
[Colafrancesco & Marchegiani 2008]



A self-consistent description of non-thermal phenomena in clusters based on the ability to recover the thermal structure of clusters.

BHs, WRs & Cooling Flows



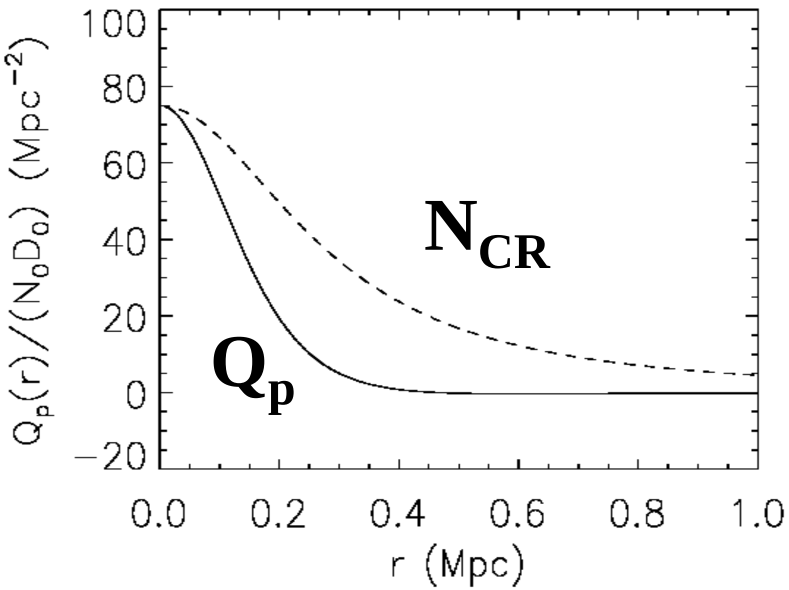


[Sanders & Fabian 2007]

$$\frac{\partial N}{\partial t} - \nabla(D\nabla N) - \frac{\partial(b_p N)}{\partial E} = Q_p$$

$$N_{CR}(r) \sim [n_{th}(r)]^{\alpha}$$

[Colafrancesco & Marchegiani 2008]

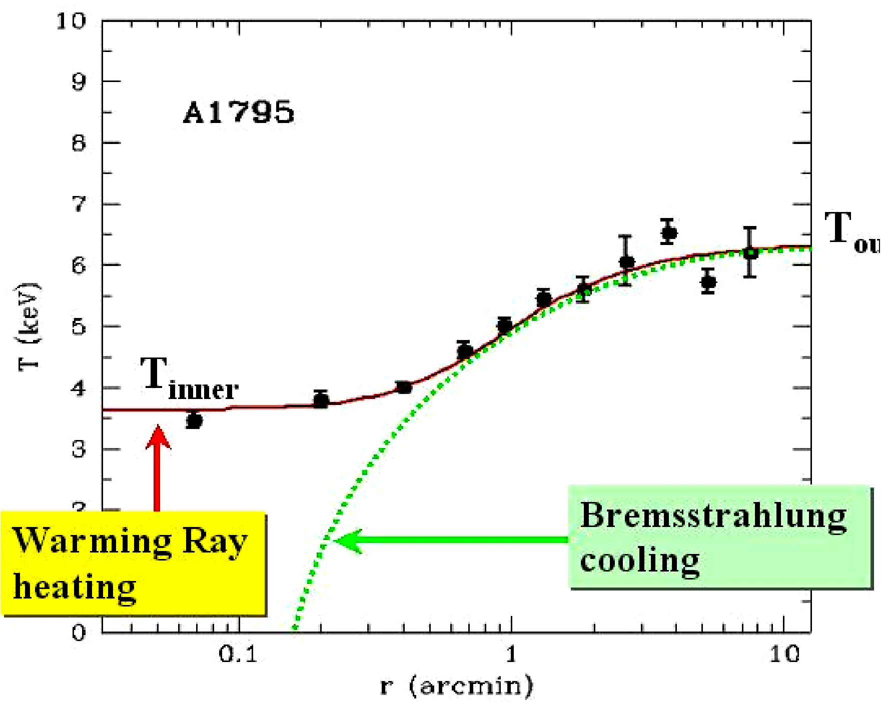


Warming Rays in cool cores

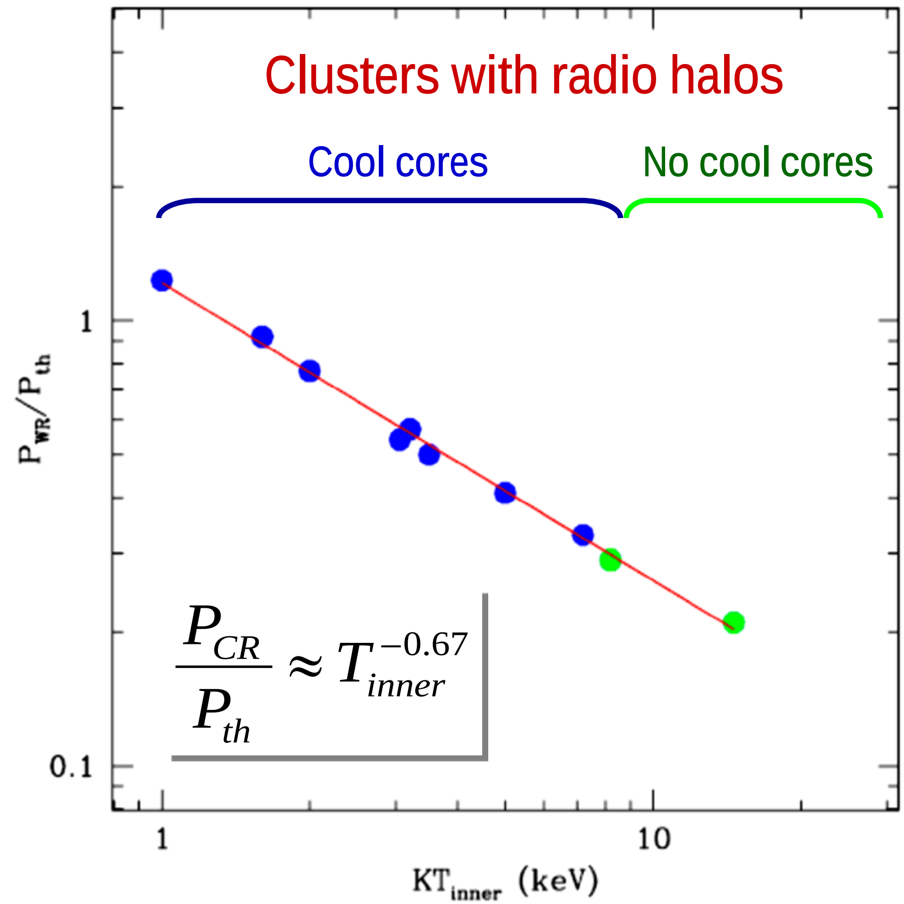
$$3kn(r)\frac{dT(r,t)}{dt} = \left(\frac{dE}{dt}\right)_{WR} - \left(\frac{dE}{dt}\right)_{X}$$

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

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



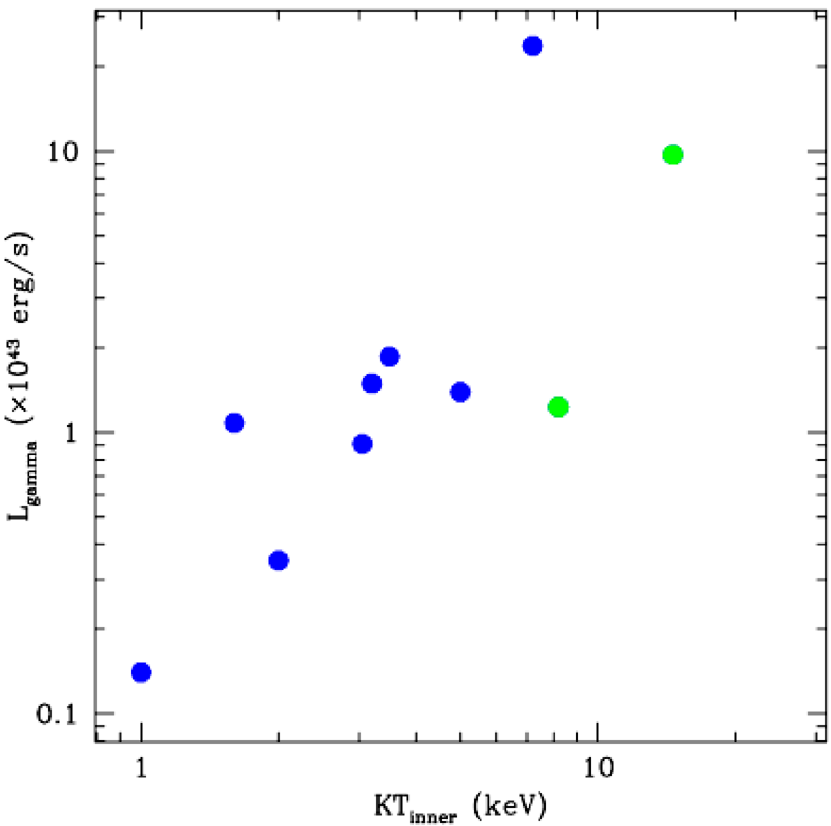
[Colafrancesco, Dar & deRujula 2004]

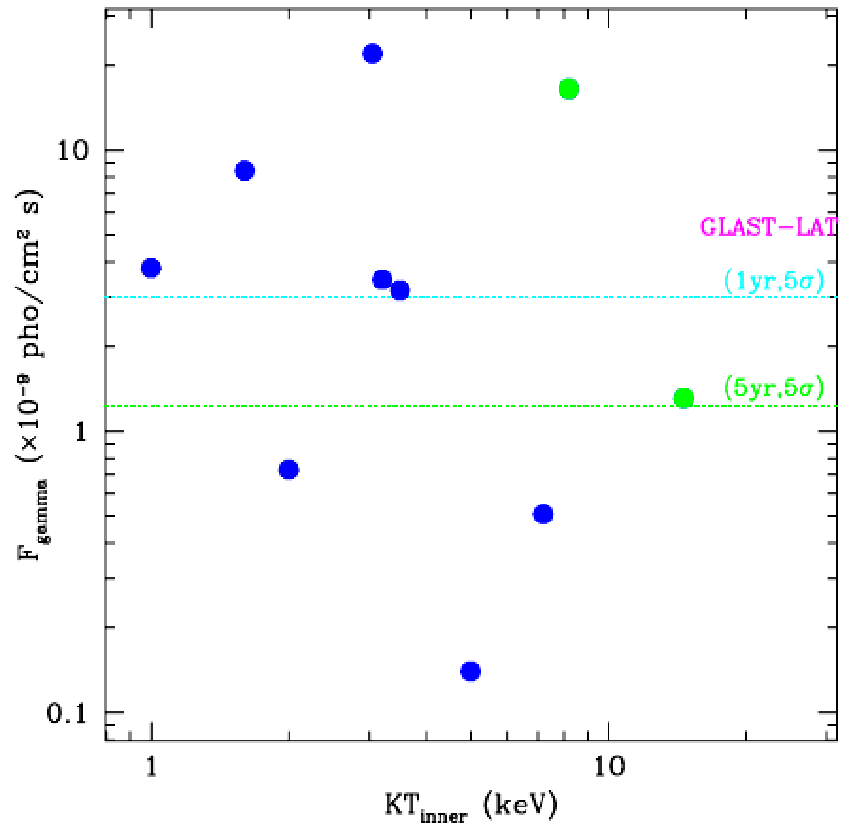


[Colafrancesco & Marchegiani 2007]

WRs, HXR and γ-rays

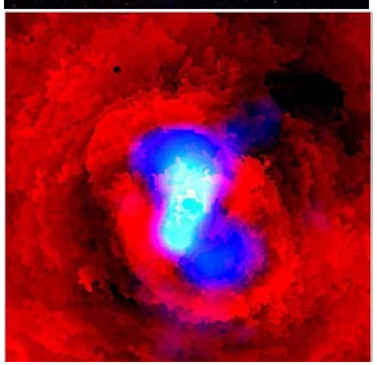
Cluster	α	$n_{WR,0}$ cm^{-3}	P_{WR}/P_{th}	F_γ cm^{-2} s^{-1}	L_γ erg s^{-1}	F_{HXR} erg cm^{-2} s^{-1}
A262	0.83	2.20×10^{-3}	1.23	3.89×10^{-9}	1.43×10^{42}	3.87×10^{-14}
A2199	0.83	2.31×10^{-3}	0.92	8.43×10^{-9}	1.08×10^{43}	3.06×10^{-13}
A133	0.84	4.56×10^{-4}	0.77	7.30×10^{-10}	3.53×10^{42}	6.10×10^{-15}
Perseus	0.91	4.98×10^{-4}	0.54	2.20×10^{-8}	9.91×10^{42}	1.59×10^{-13}
Hydra	0.97	6.24×10^{-4}	0.57	3.46×10^{-9}	1.49×10^{43}	2.57×10^{-14}
A1795	0.96	5.55×10^{-4}	0.50	3.17×10^{-9}	1.86×10^{43}	2.41×10^{-14}
A2390	0.94	2.21×10^{-4}	0.41	1.41×10^{-10}	1.39×10^{43}	6.17×10^{-16}

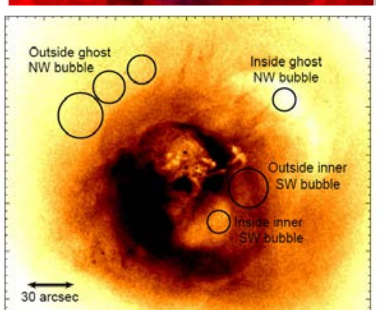


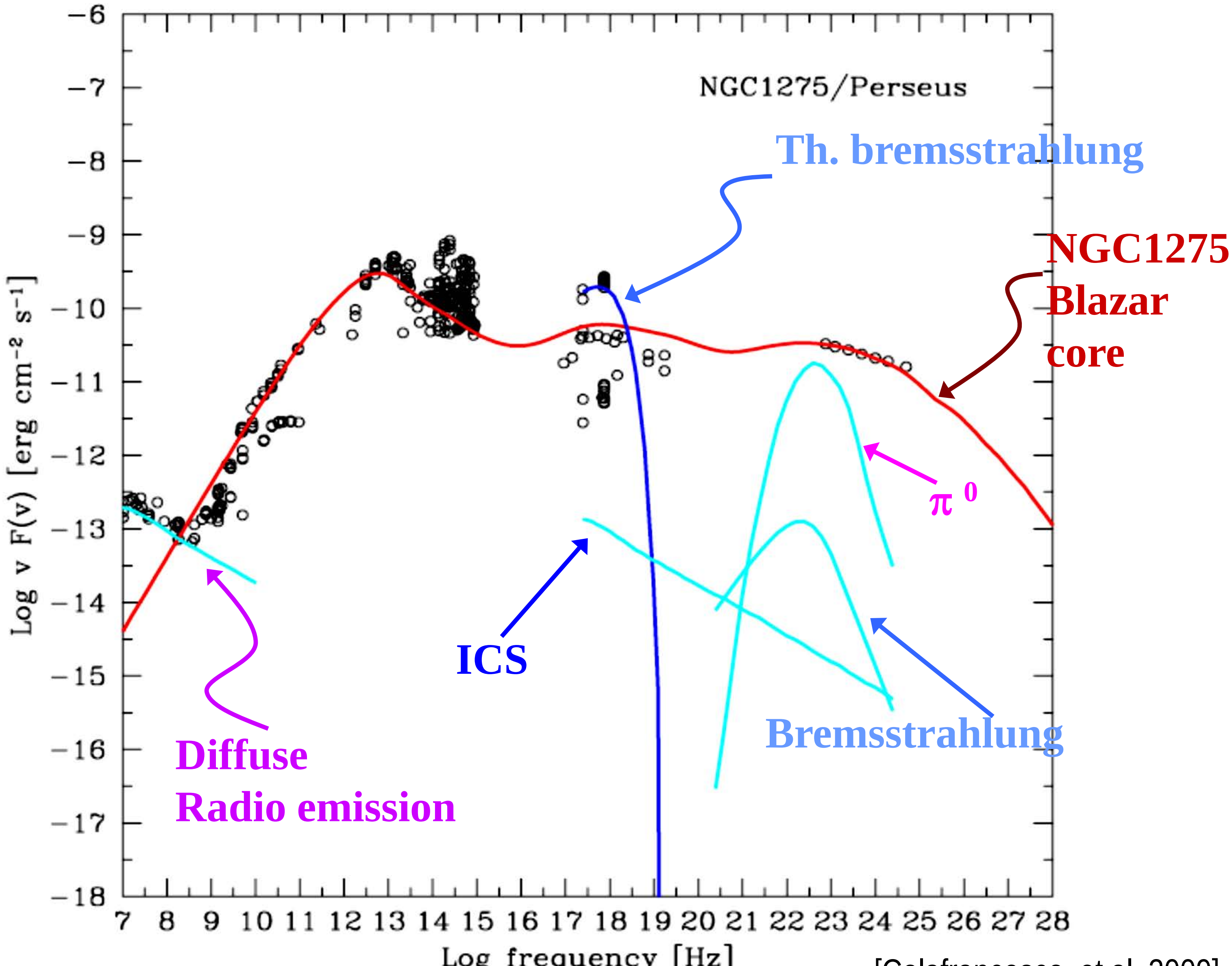


NGC 1275 / Perseus cluster

RG (3C84)
Mini RH
Sy 1.5
Blazar







[Colafrancesco et al. 2009]

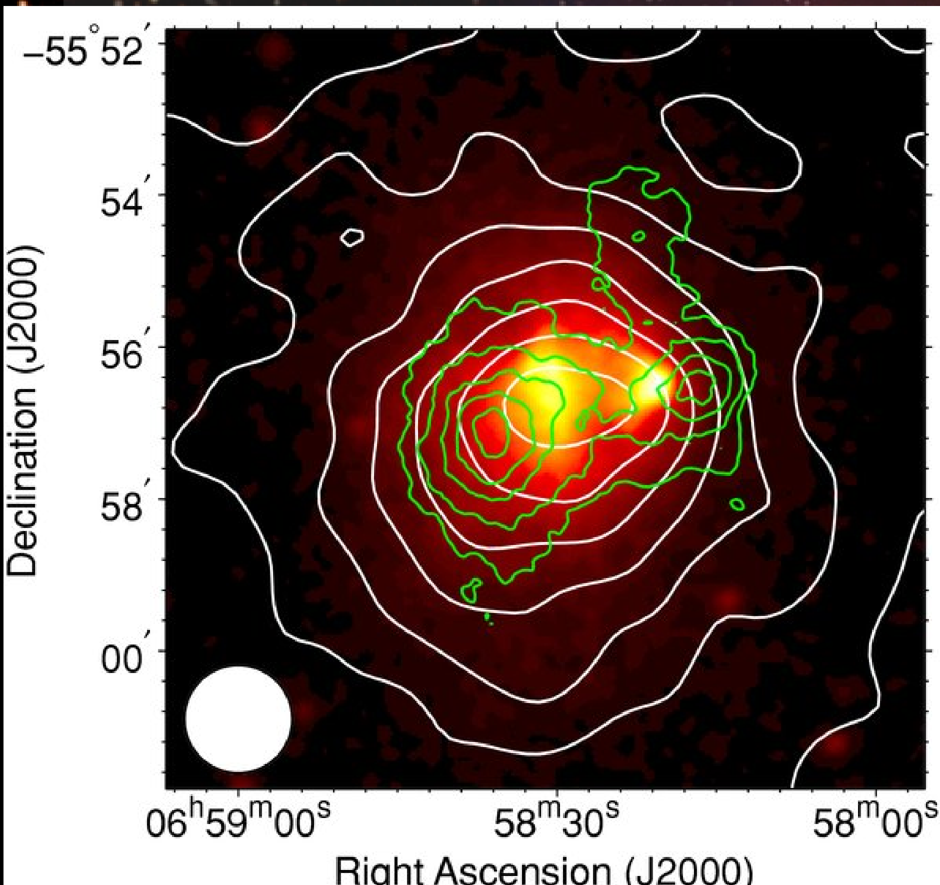
Radio Halos & Cosmic Rays

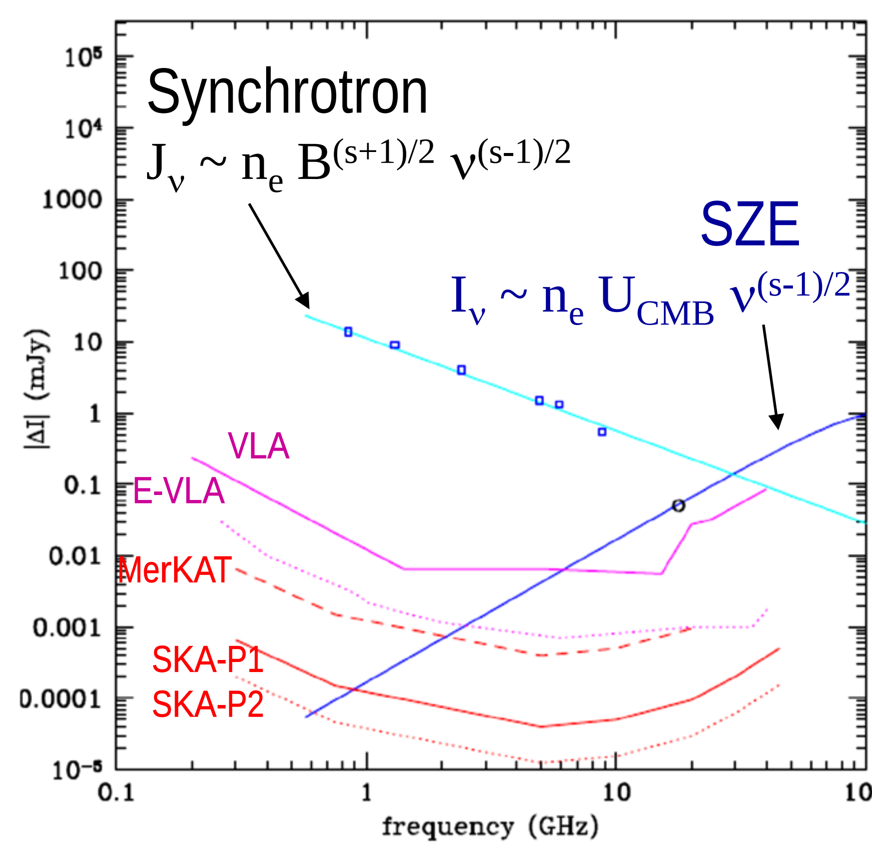
STRATEGY ⇨ SKA

Derive both n_e and B from single SKA observations

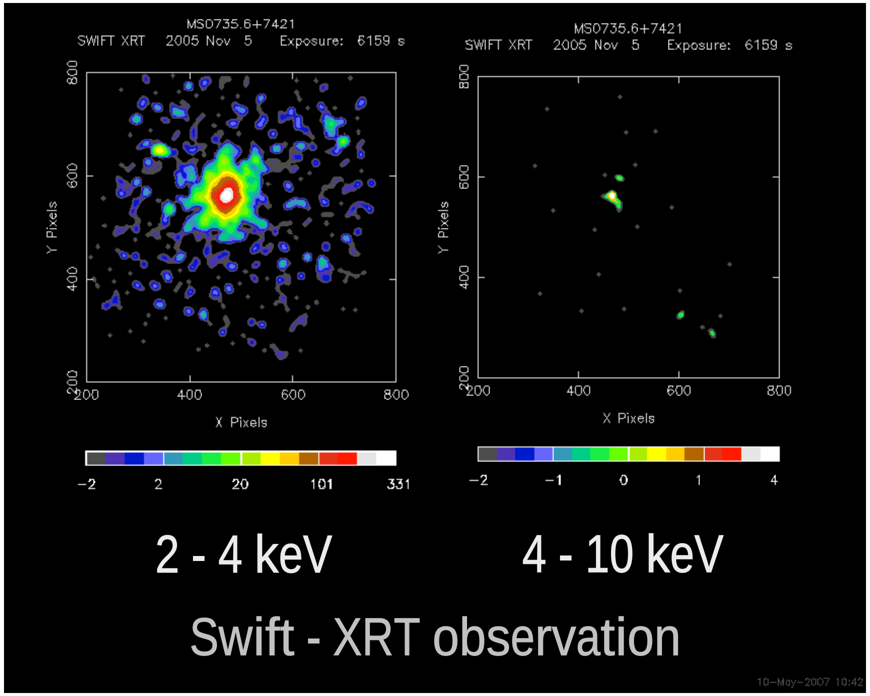
Combine: radio + ICS

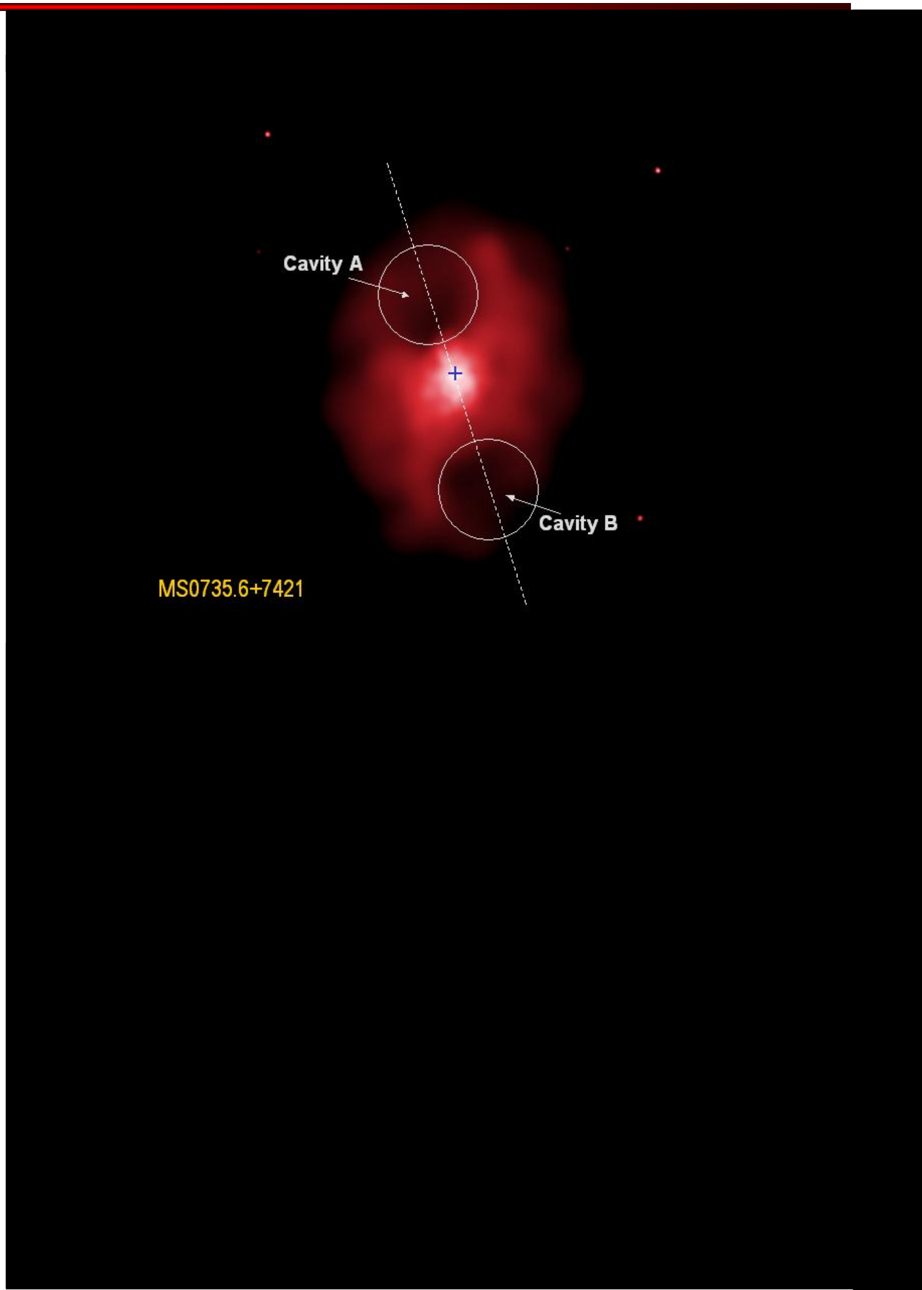
0.1-1 GHz + 30 GHz

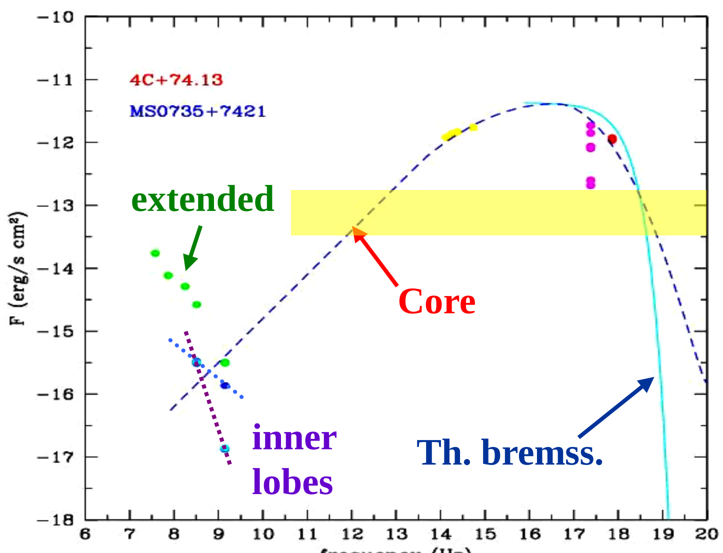




Xrays from BHs & cavities in clusters







Multi–ν emission from cavities

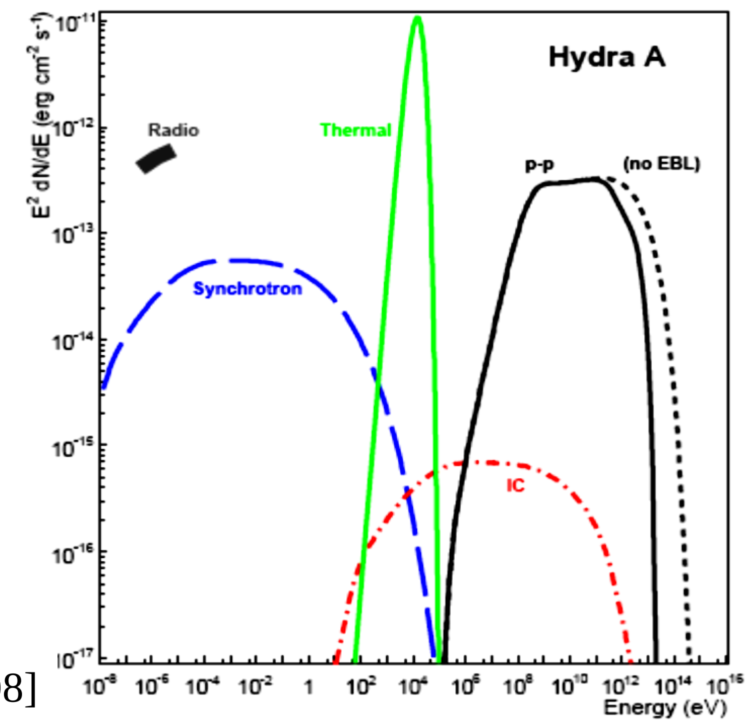
Cavity E ~ $10^{60\text{-}63}$ ergs

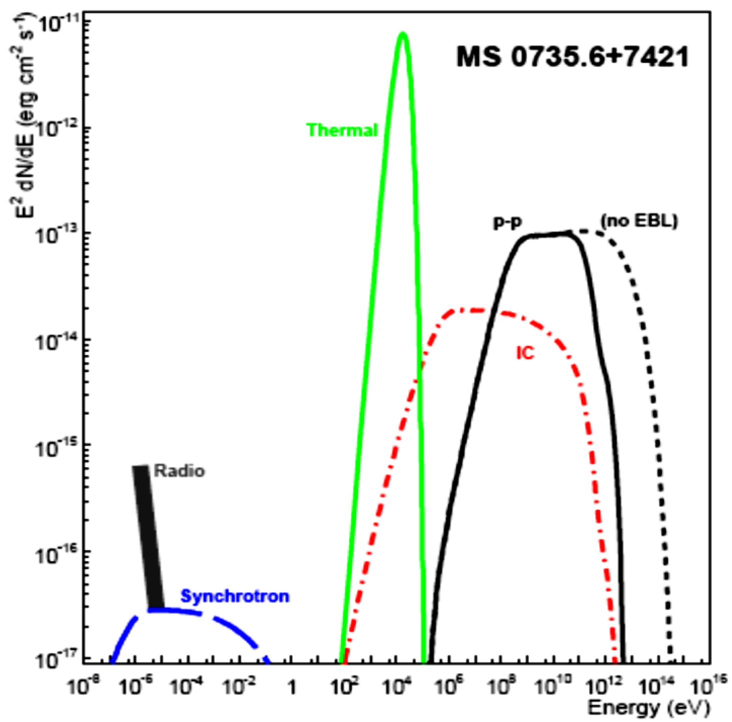
Cavity Age ≥ 10^{8} yrs

Diffusion D ≤10^{28} cm^{2}/s

[Brighenti & Matthews 2007]

Cavities likely supported by hadronic CRs

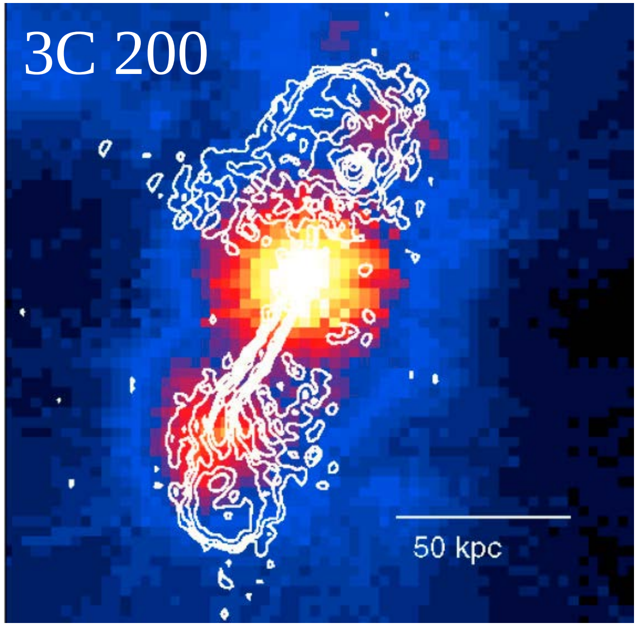




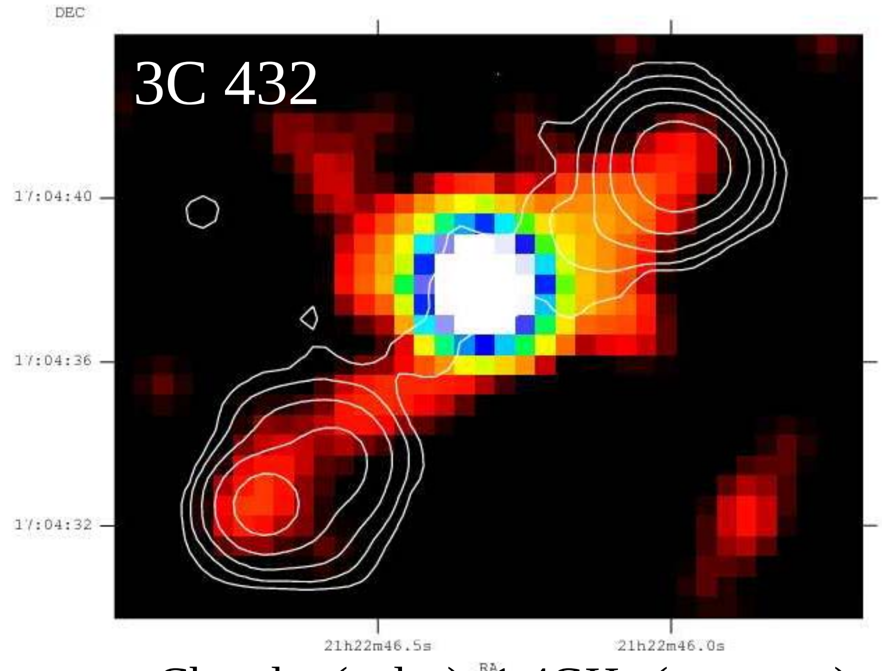
[Hinton et al. 2007]
[Domainko et al. 2008]

Radio galaxy jets

Radiogalaxy jets: emission



Chandra (color)+5GHz (contours)



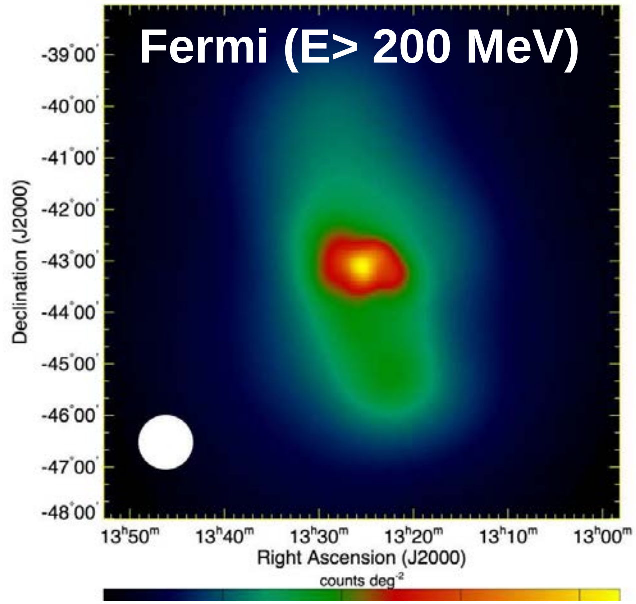
Chandra (color)+1.4GHz (contours)

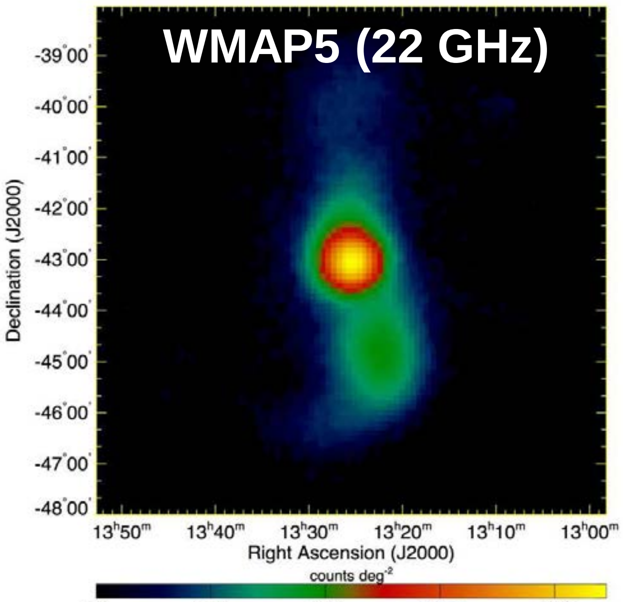
$$F_{radio} \approx \nu^{-\alpha} B^{2(\alpha+1)} \qquad F_{X-ray} \approx E^{-\alpha}$$

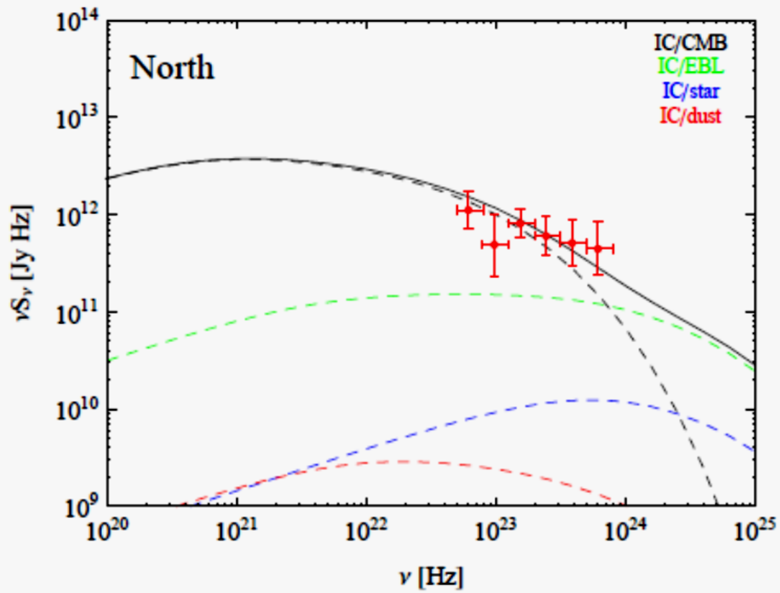
$$\alpha = (p-1)/2$$

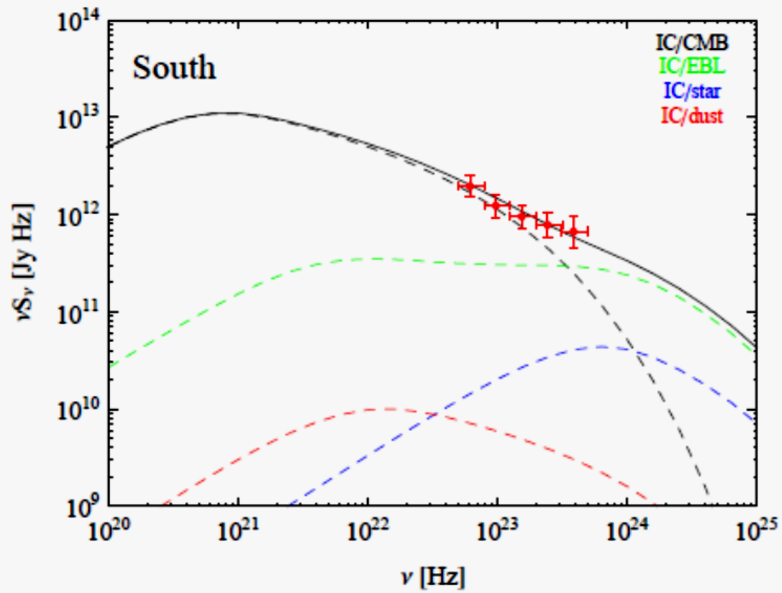
The co-spatial location and the similarity in the X-ray and radio spectra indicate a common parent population → $N_e \sim E^{-p}$ for the electrons responsible for the jet/lobe emission

RGs: jet / lobe diffuse emission







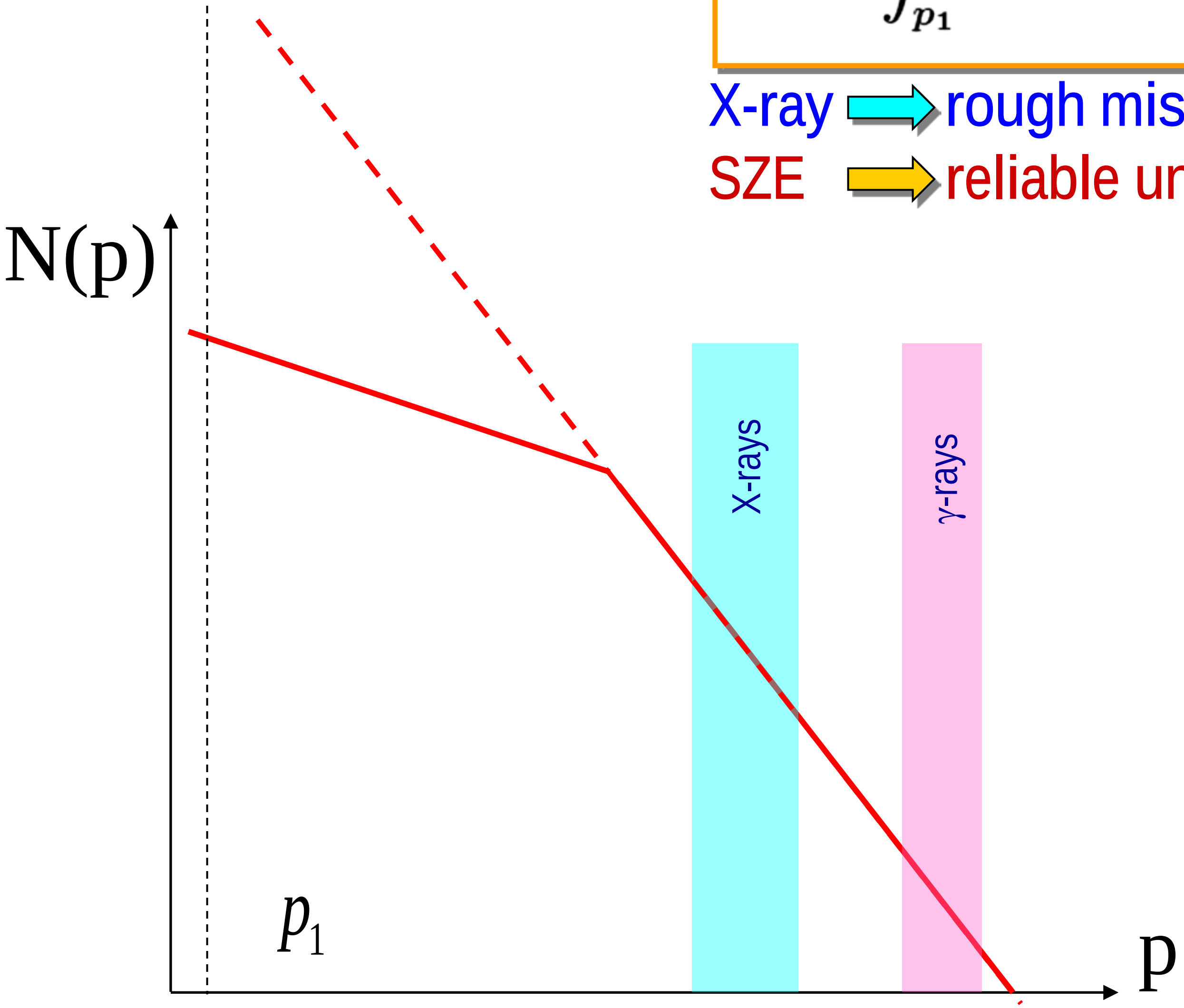


Radiogalaxy jet energetics

$$U_e = \int_{p_1}^{\infty} dp N(p)(\sqrt{1+p^2} - 1) m_e c^2$$

X-ray ⇒ rough misleading measure of Ue

SZE ⇒ reliable unbiased measure of Ue



$$h\nu \approx 0.35 keV \left(\frac{E_e}{GeV} \right)^2$$

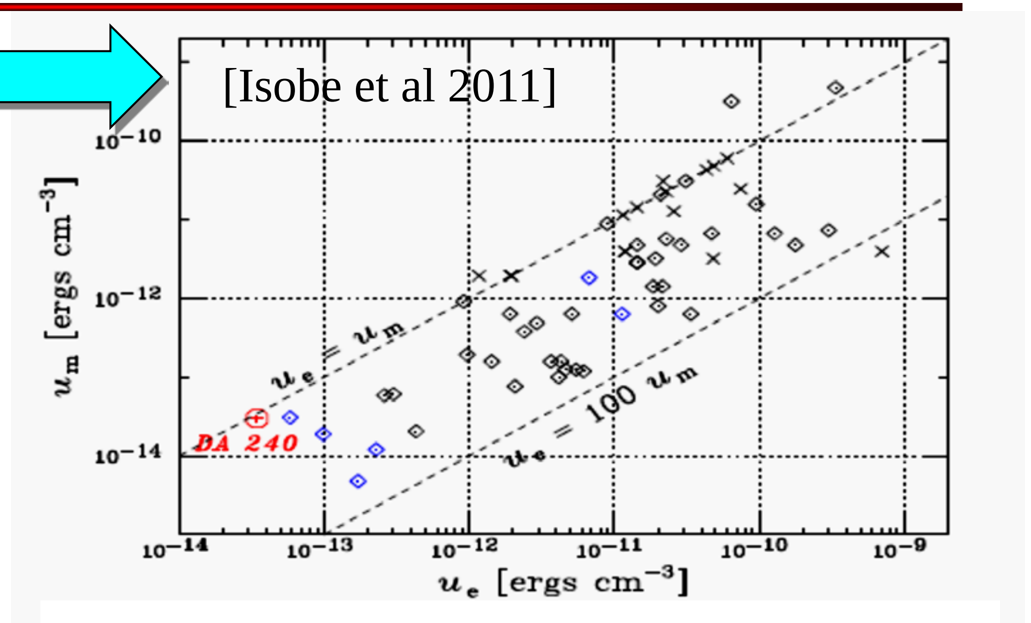
A tale of a giant radiogalaxy: DA 240

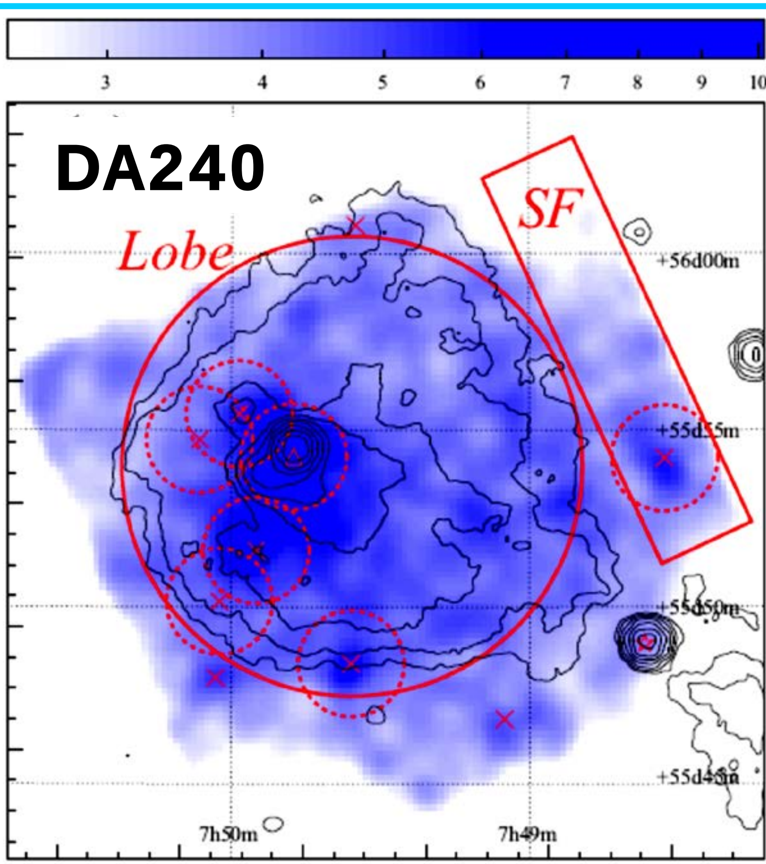
Suzaku obs. of U_e and U_B
[Isobe et al. 2011]

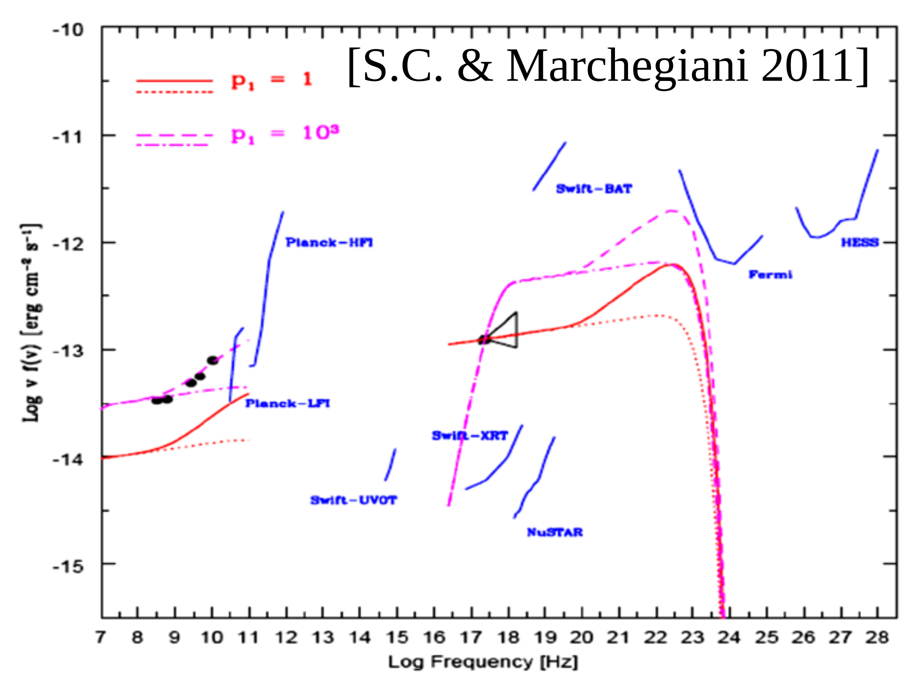
$\Delta\gamma = 10^3 - 10^5$

$\gamma_{min} = 10^3$ ⇨ $(p_1 = 10^3)$

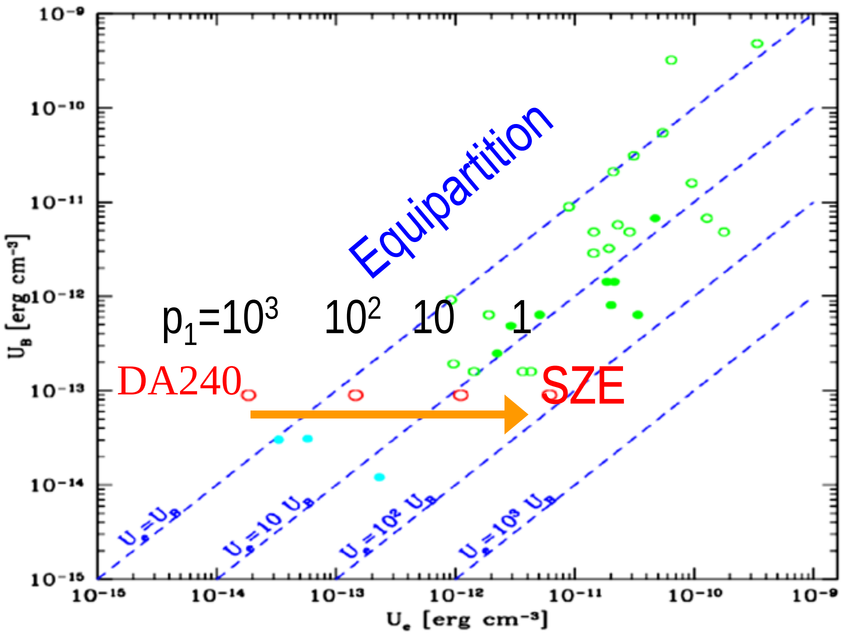
$U_e/U_B \sim 1.1$ (~ Equipartition)

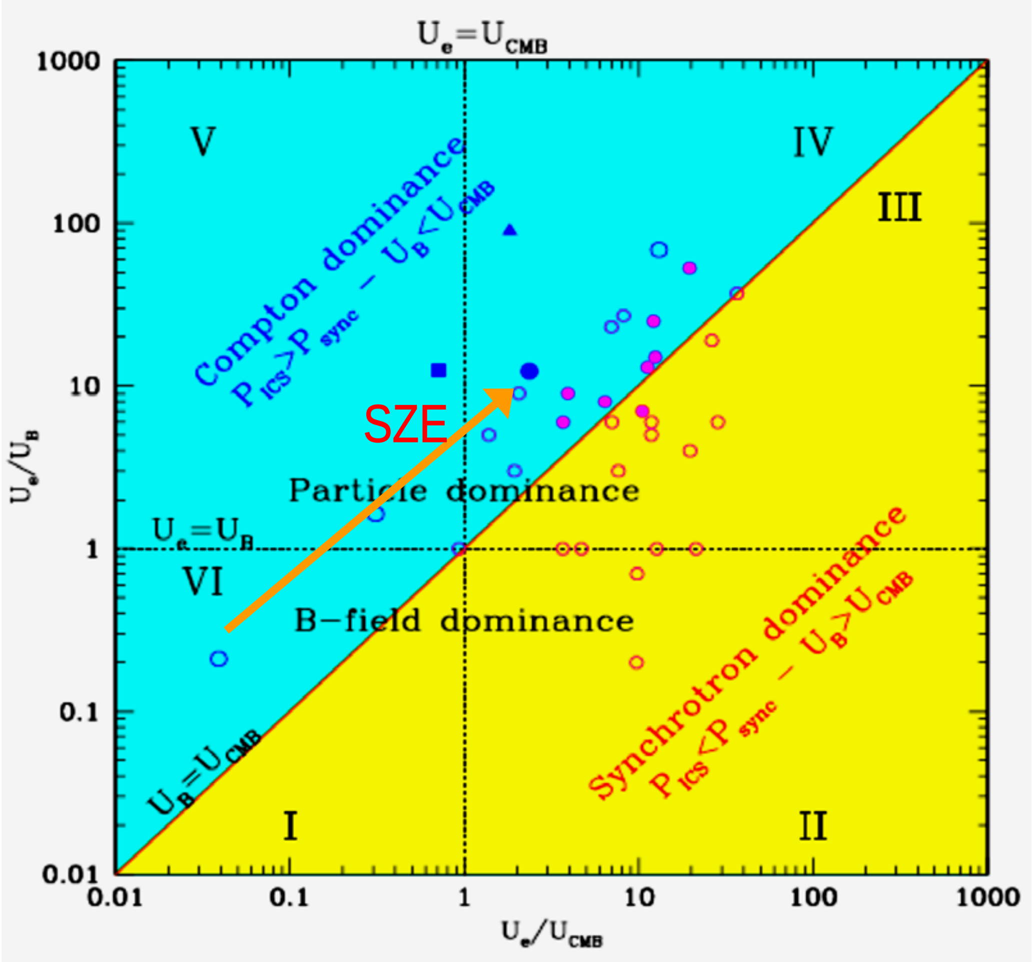




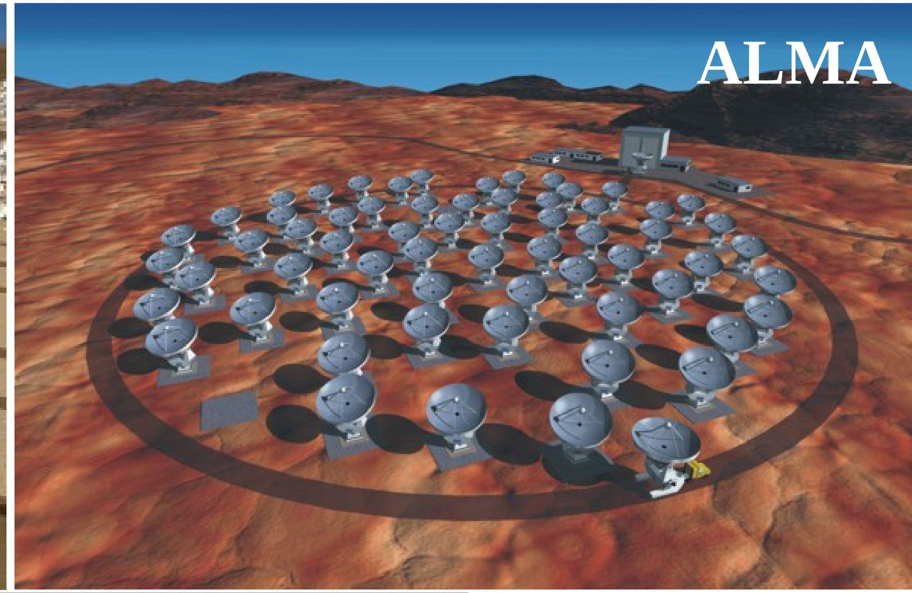


SZE: RG lobe energetics revisited

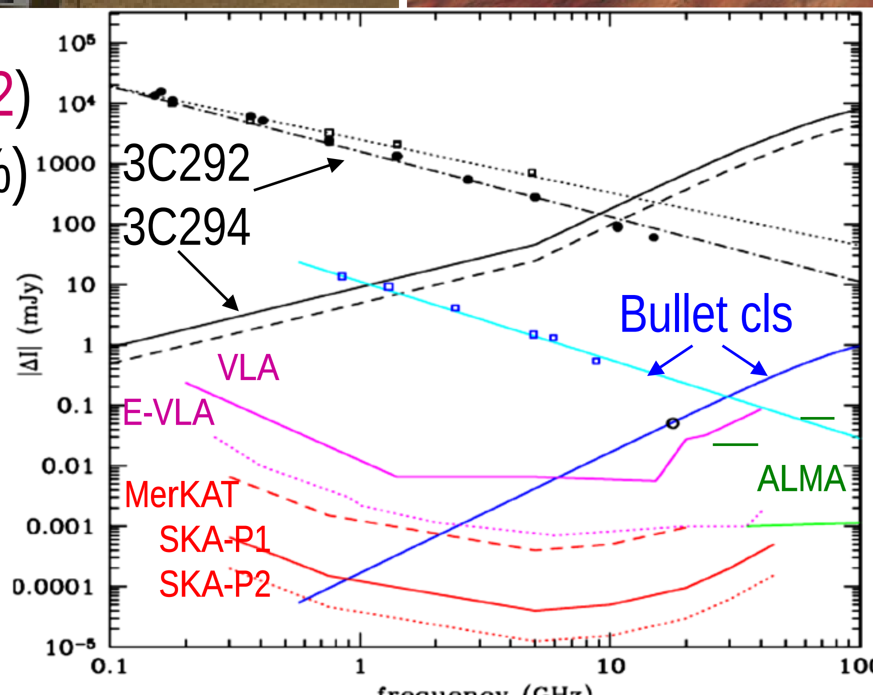




Synergy with ground-based exps.



- Approved (25/5/2012)
- SA (70%) & Au (30%)
  SA: 0.7-15 GHz
  Au: low-ν + high-ν
- Wide FOV
- Multi-beaming
- High survey speed
- Polarization

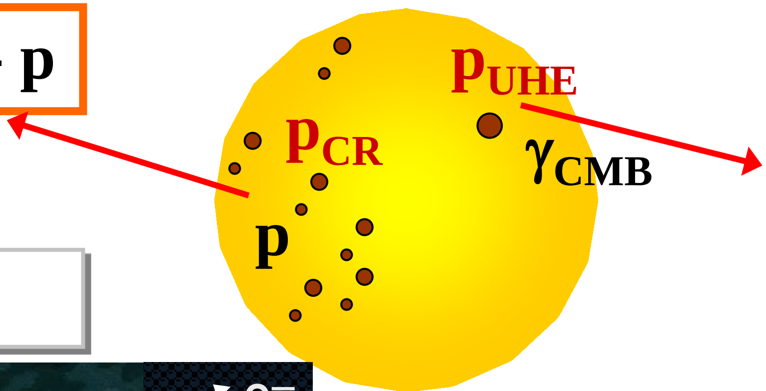


- Operating
- ESO
  84 - 950 GHz
  3.6" - 0.43"
- Small FOV
- Mosaicing mode
- Polarization

CRs of high-E → *in-situ* production

$$p_{CR} + p \rightarrow X + \pi^{0,\pm}$$

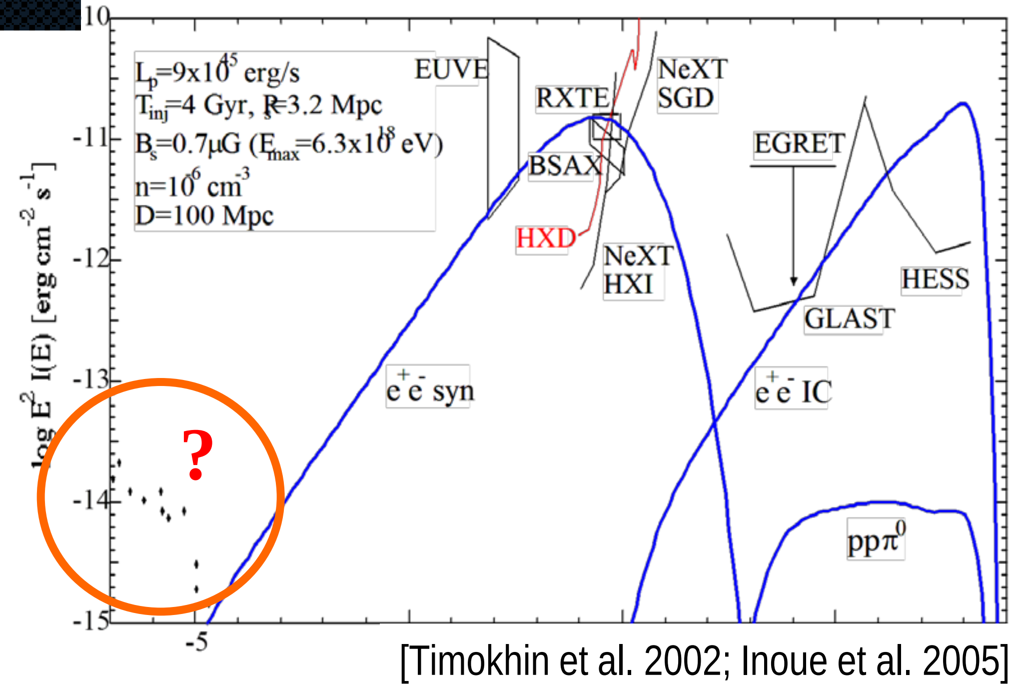
p_{CR} - p



p_{UHE} - γ_{CMB}

$$p_{UHE} + \gamma \rightarrow X + e^{\pm}$$

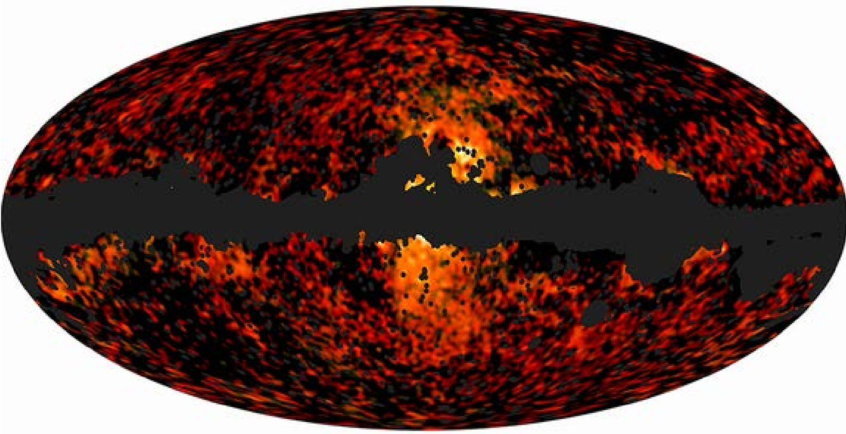
High-E jet source



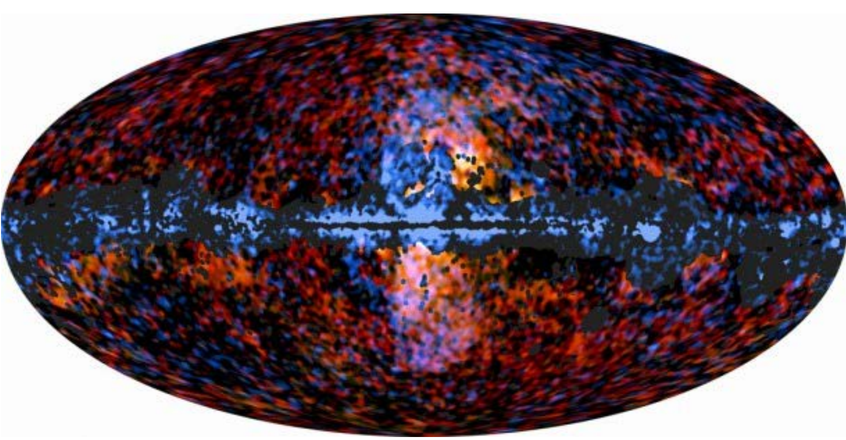
[Timokhin et al. 2002; Inoue et al. 2005]

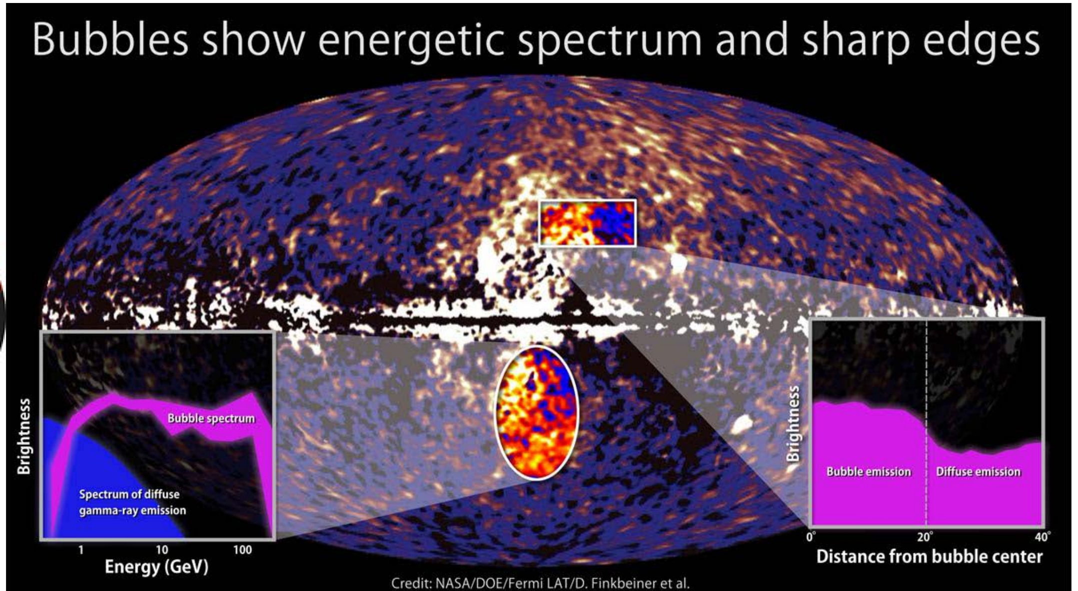
Galaxy cores

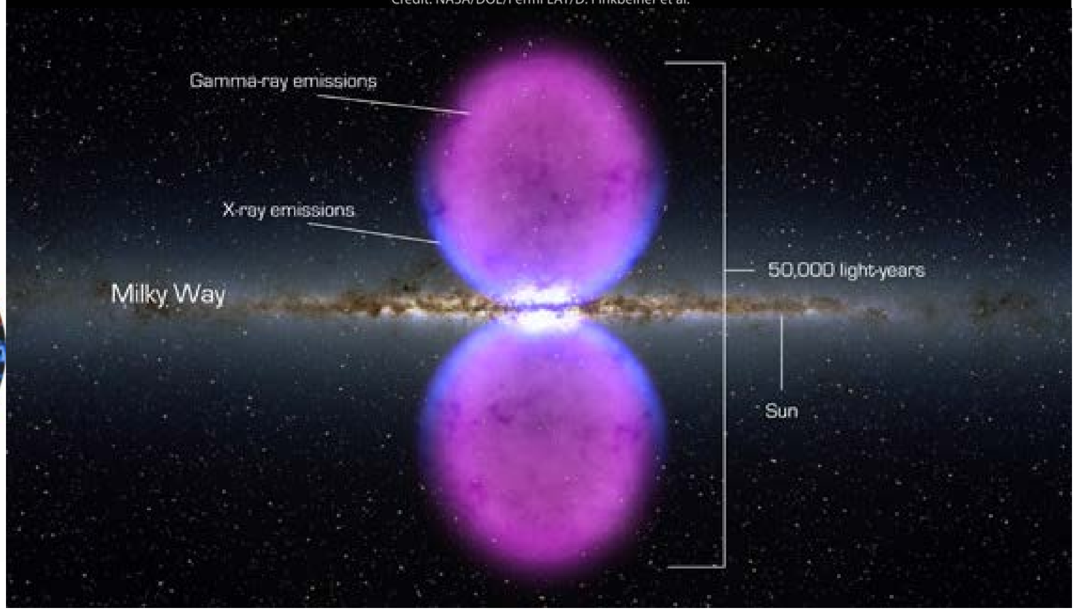
Galactic bubbles: Planck



Galactic bubbles:
Planck (red) + Fermi)violet)







Further readings

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