High Energy Astrophysics in Cosmic Structures (2)

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Outline

- Part 1: Historical remarks
- Part 2: Basics of high-E Astrophysics
  - Emission Mechanisms
  - Origin of particles: Leptons vs. hadrons
  - Condition in cosmic structures
- Part 3: High-E sources : Properties & Science
  - SNR, Pulsars, PWN
  - Galactic Center
  - AGNs
  - Galaxy clusters
  - DM annihilation and/or decay
  - Cosmology & Fundamental Physics
  - The highest-E particles
- Part 4: AstroParticle Physics in cosmic structure
  - An overall picture
- Part 5:Strategies: Observations, Theory, Data-analysis

GRBs

Dark Matter

Cosmology

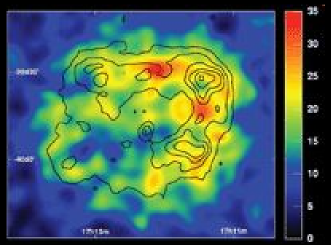
Space-Time

Part 3

Sources of High-E radiation

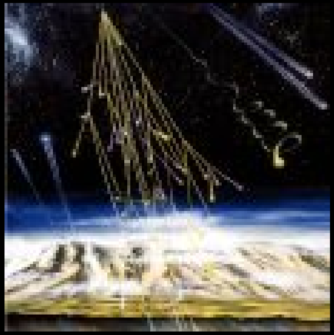
Properties

Science



SNR

Pulsars
PWN



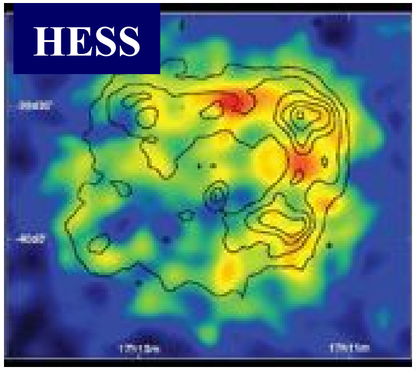
Origin of
Cosmic Rays

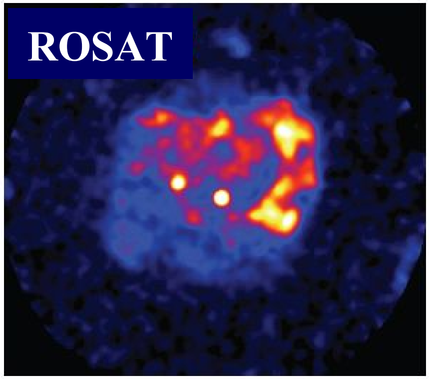
AGNs

SNR SEDs

RX J1713.7 -3946

Non-thermal X-ray source
First TeV γ-ray resolved SNR
Correlated keV-TeV morphology
Old (1000 yrs)
D=1kpc
Dense environment

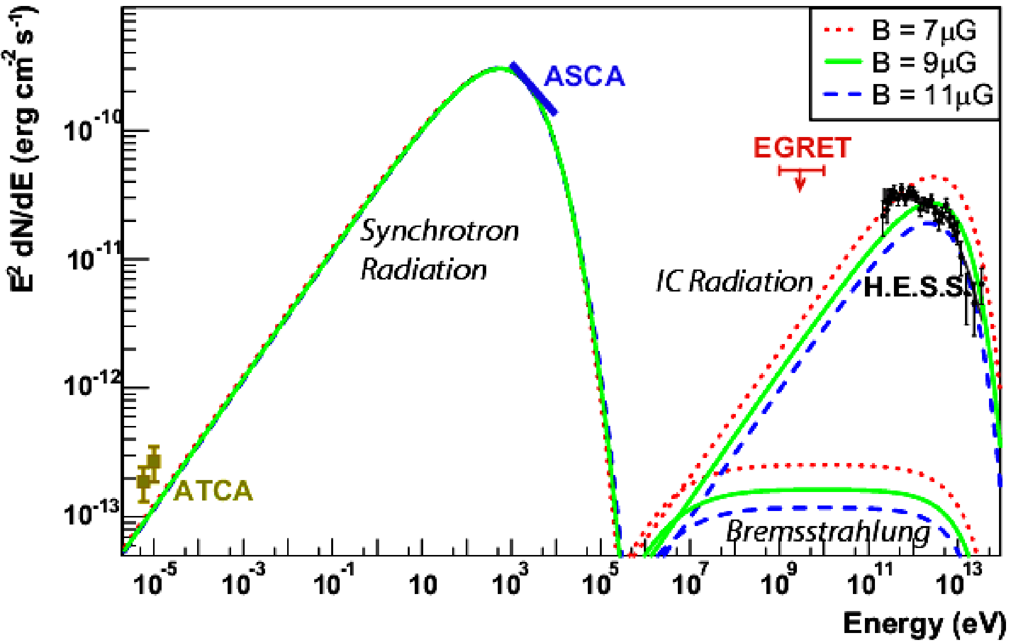


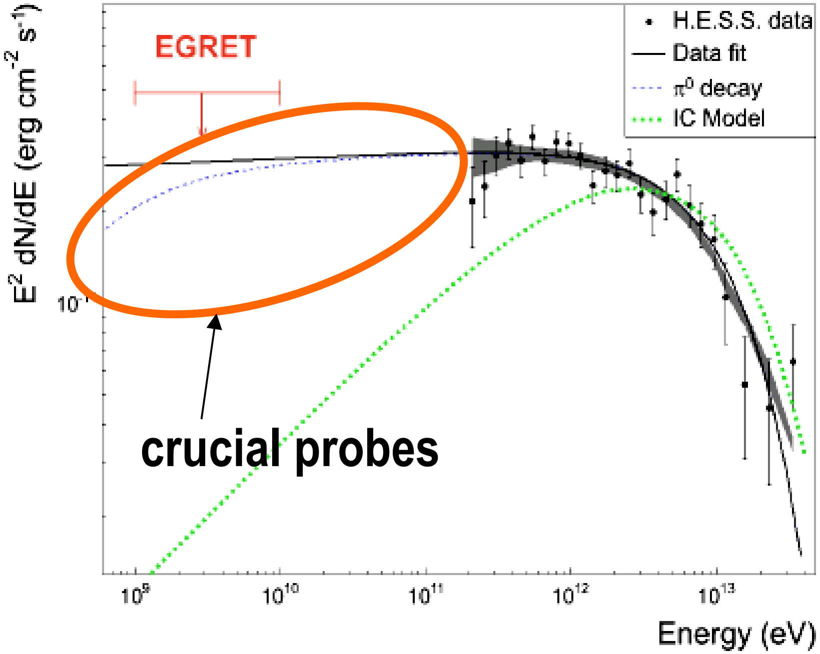


Hadronic origin?

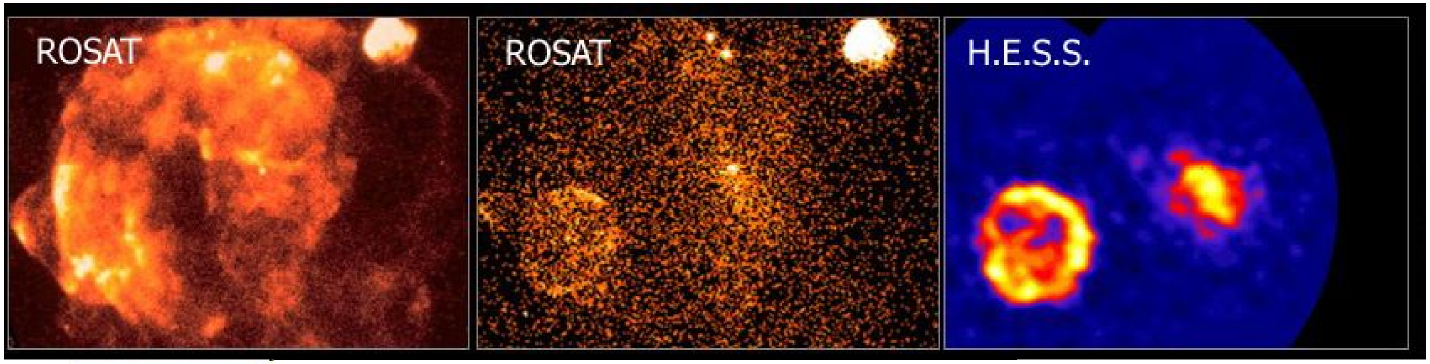
pros.:
- spectral shape
- X-ray - TeV morphology

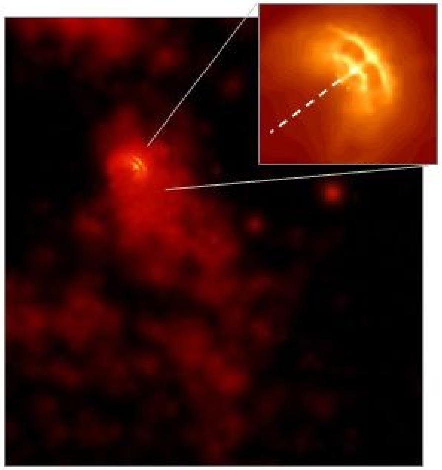
cons.:
- ICS interpretation implies very low B
- no correlation with molecular material



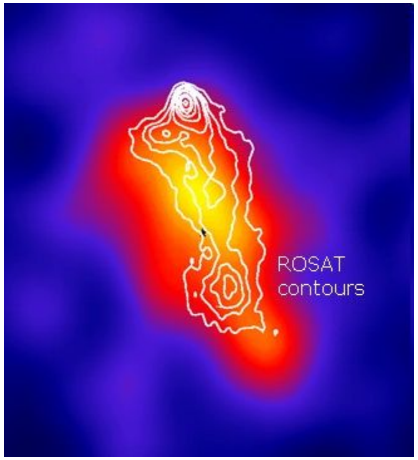


Vela X: A Cosmic Accelerator 900 l.y. from Earth

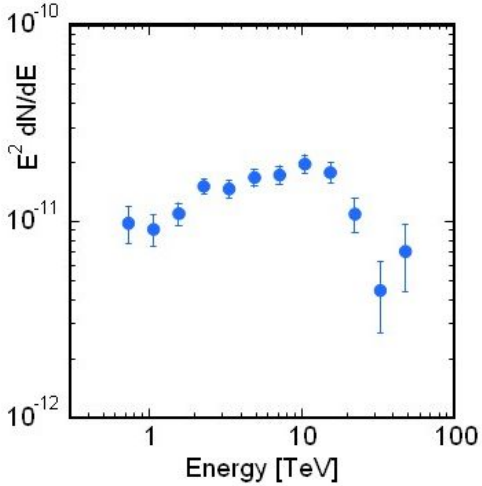




Chandra view of the Vela pulsar (small inset) and of the Vela X nebula south of the pulsar. The Chandra image shows that, contrary to earlier assumptions, the X-ray nebula does not line up with the pulsar axis, which is indicated by the dashed line.

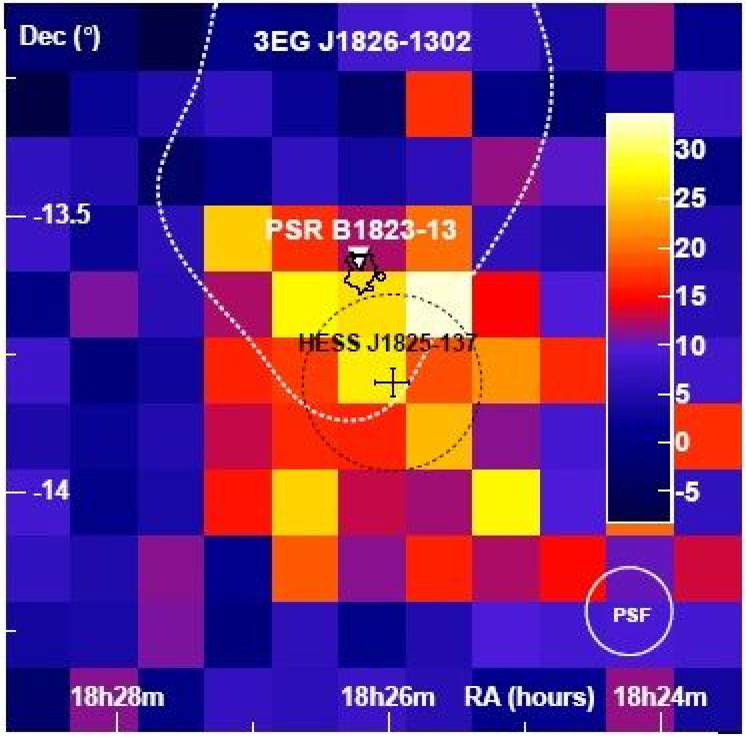


Intensity of very high energy gamma rays (color scale), with superimposed ROSAT X-ray contours. The gamma ray emission extends over roughly 1 degree. While the Vela pulsar is clearly visible in X-rays, no excess is seen in gamma rays.

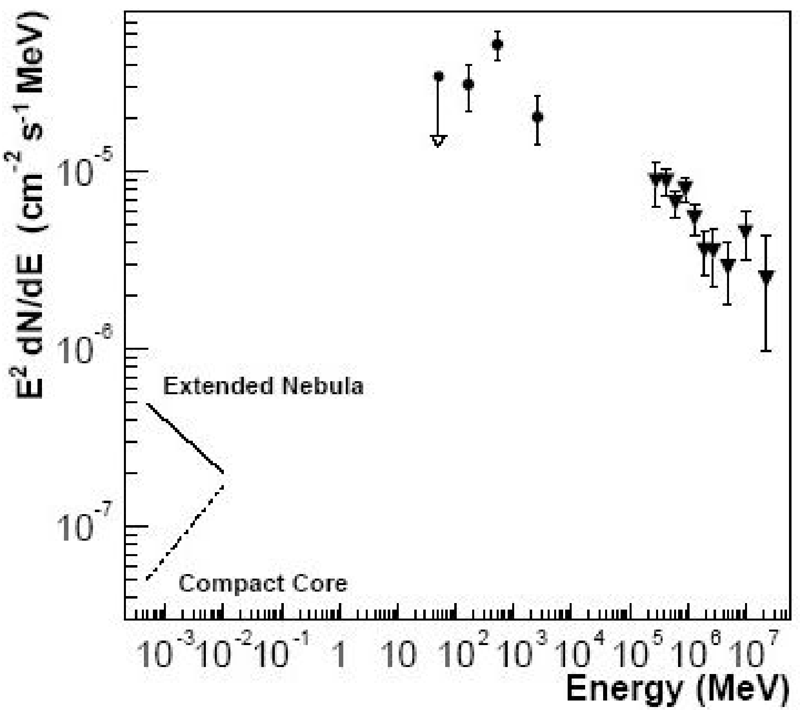


Spectral energy distribution of the VHE gamma rays from Vela X. Most of the energy is emitted in the interval around 10 TeV. Vela X is the first source where the spectral energy distribution peaks at TeV energies.

Pulsar Wind Nebulae SEDs

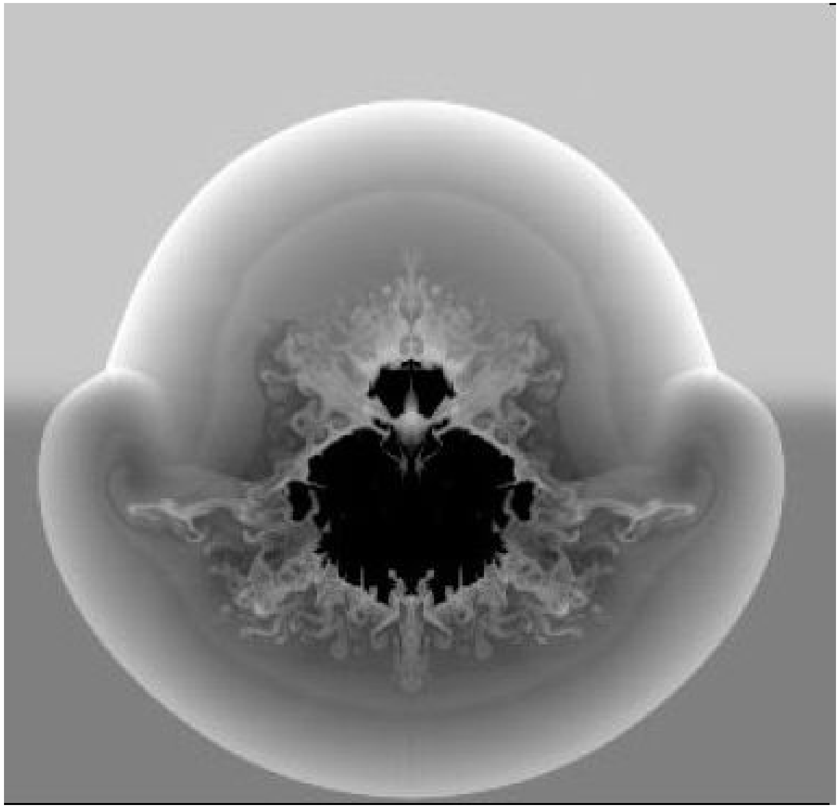


Sky map of TeV gamma ray emission from the vicinity of the pulsar **PSR B1823-13** (white triangle). The small black contour downwards (South) from the pulsar indicates an asymmetric X-ray pulsar wind nebula (Gaensler et al. 2003). The centeroid of the TeV source HESS J1825-137 is indicated by a cross; it is shifted by about 11' from the pulsar position.



The X-ray emission is relatively faint; the reason could be that the X-rays are generated by higher-energy electrons (~100 TeV) than the gamma rays; since these high-energy electrons lose their energy much more quickly, they have more of less "died out".

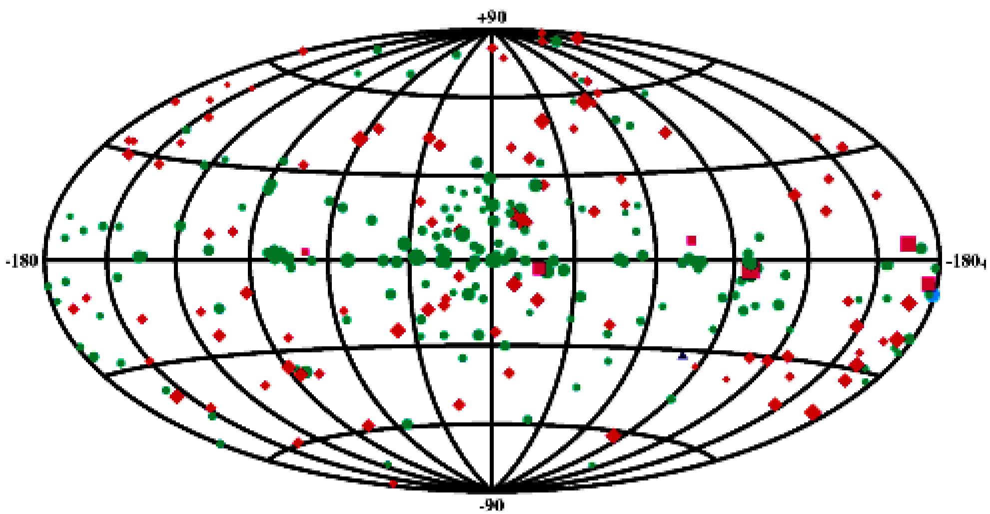
PWN nebulae: origin

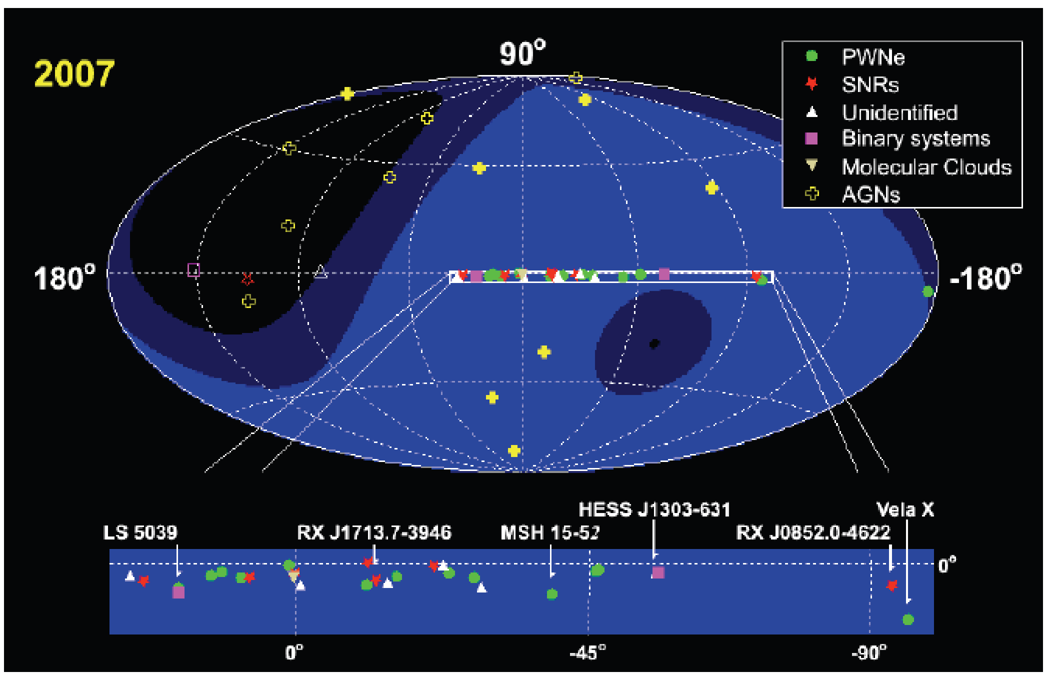


Simulation of a supernova exploding into an inhomogeneous interstellar medium (Blondin et al, 2001). In the less dense regions (bottom), the shock wave (outer contour) propagates faster. At the center is a pulsar left over from the explosion; it generates a relativistic pulsar wind of electrons and positrons, which blows a bubble (black) into the supernova ejecta. At the edge of the bubble, in the pulsar wind termination shock, particles are accelerated, creating a pulsar wind nebula (like the Crab Nebula or MSH 15-52). The size of the pulsar wind bubble is regulated by the "reverse shock": when the outgoing supernova shock wave hits the interstellar material, a second shock wave is created, moving backward into the ejecta, and a some point running into the pulsar wind nebula and crushing it.

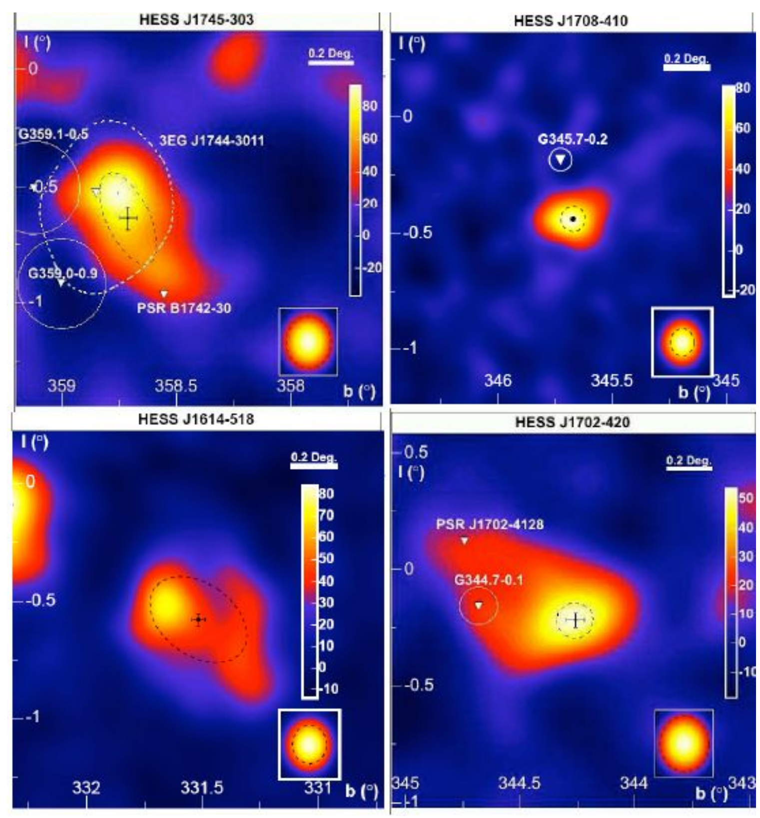
In the simulation shown on the left, the stronger reverse shock from the denser (top) side has already reached and crushed the top half of the pulsar wind nebula, whereas the bottom half of the nebula is still expanding. The net effect is that the pulsar wind nebula appears shifted with respect to the pulsar.

Unidentified High-E sources





Examples of unidentified TeV sources HESS observation

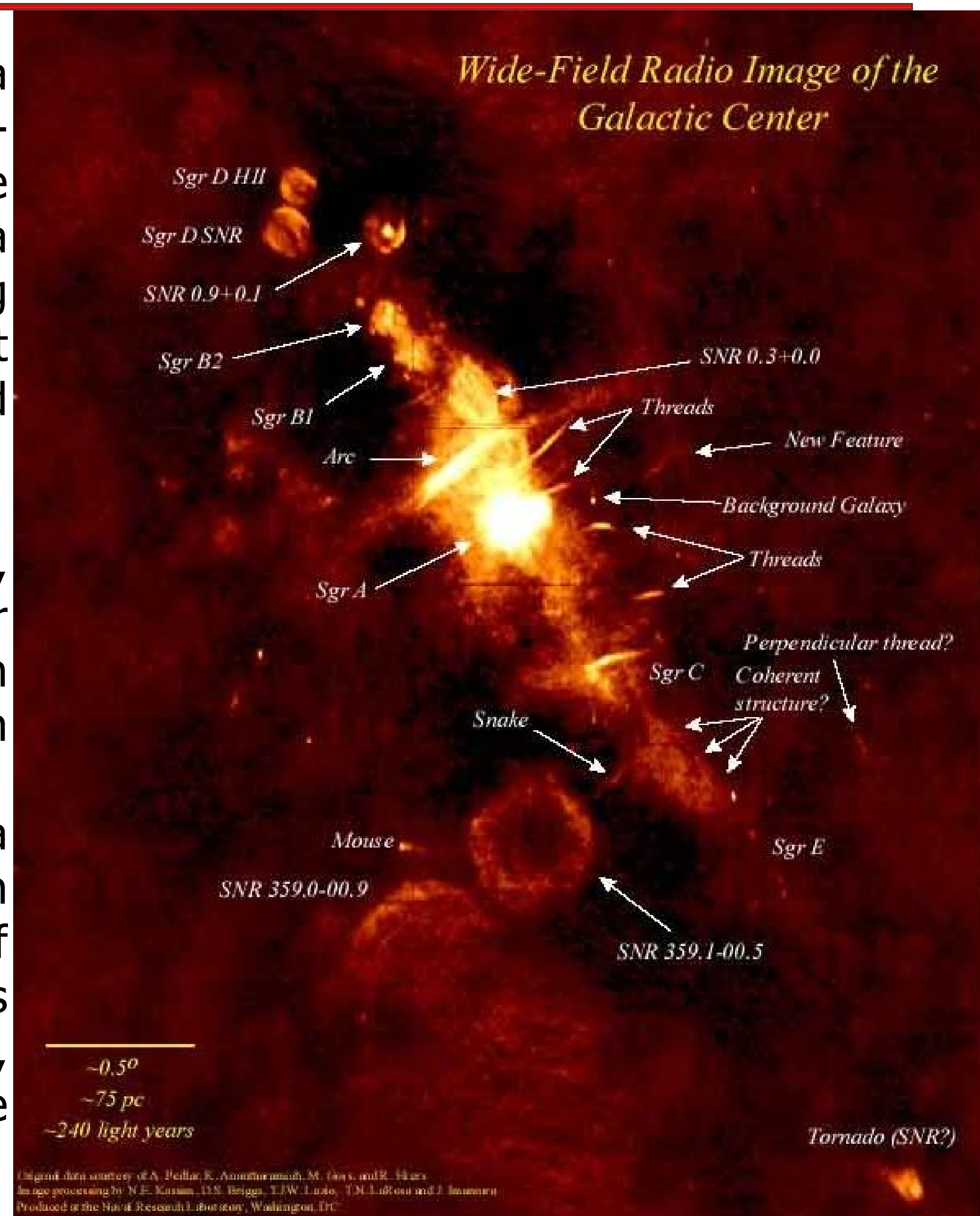


The centre of our Galaxy

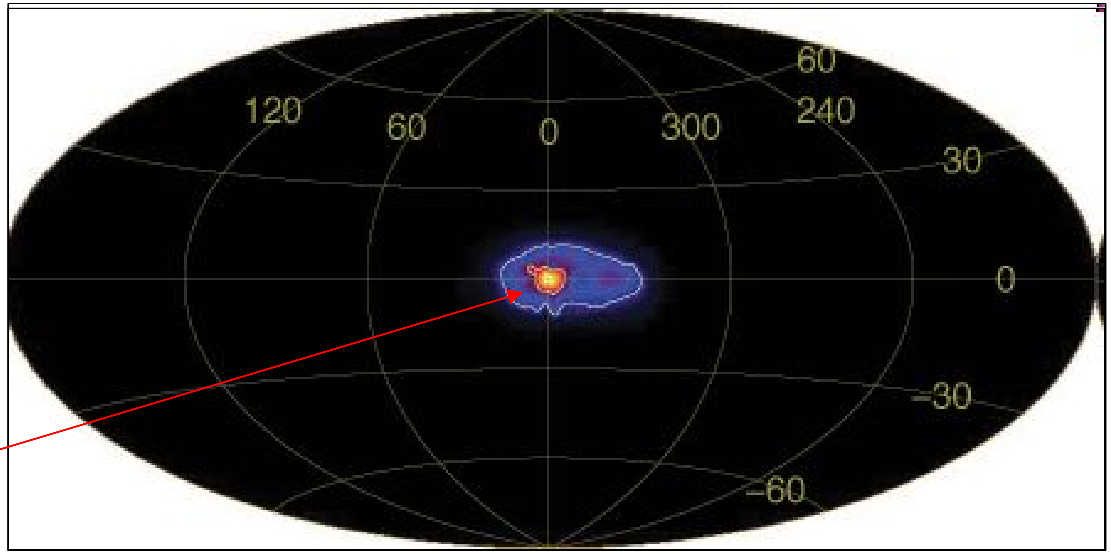
The Galactic Center region harbors a variety of potential sources of high-energy radiation, such as the supermassive black hole Sgr A* and a number of supernova remnants, among them the Sgr A East remnant of a giant supernova explosion which happened about 10,000 years ago.

Particles of the mysterious Dark Matter, which accumulate at the Galactic Center and which undergo pair annihilation provide another speculative mechanism for gamma ray production.

The Galactic Center was therefore a prime target for observations with Cherenkov telescopes, and detection of high-energy (TeV) gamma rays was reported by the CANGAROO instrument, by the VERITAS group and by the H.E.S.S. collaboration.

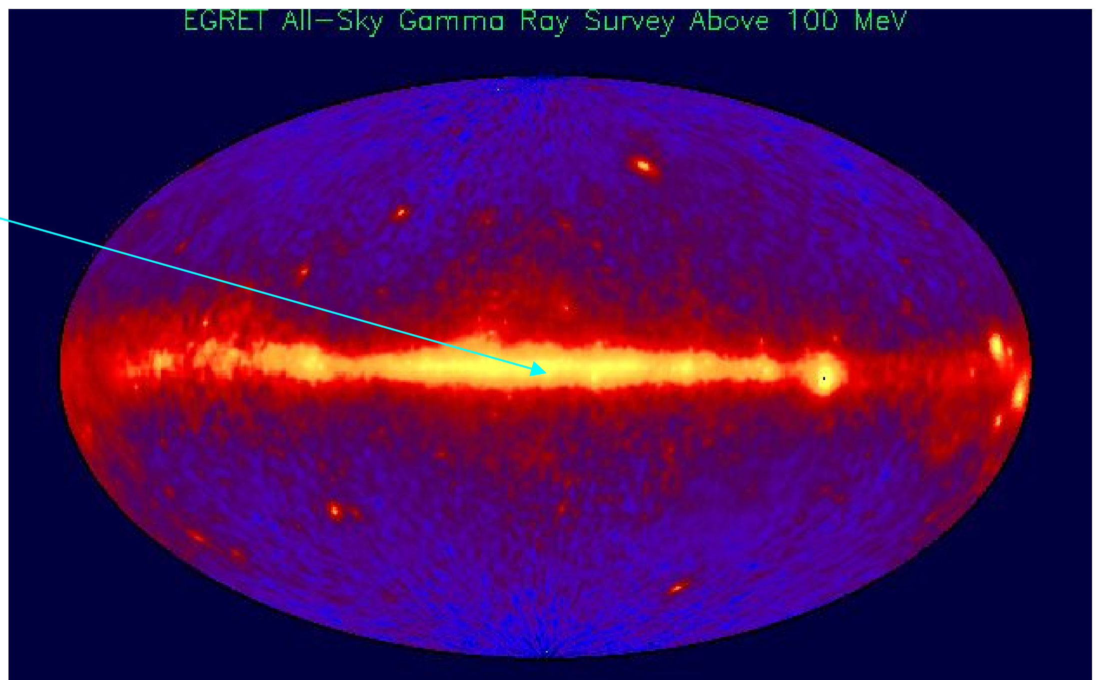


MeV to GeV maps of the GC



INTEGRAL
511 keV line

Dark Matter

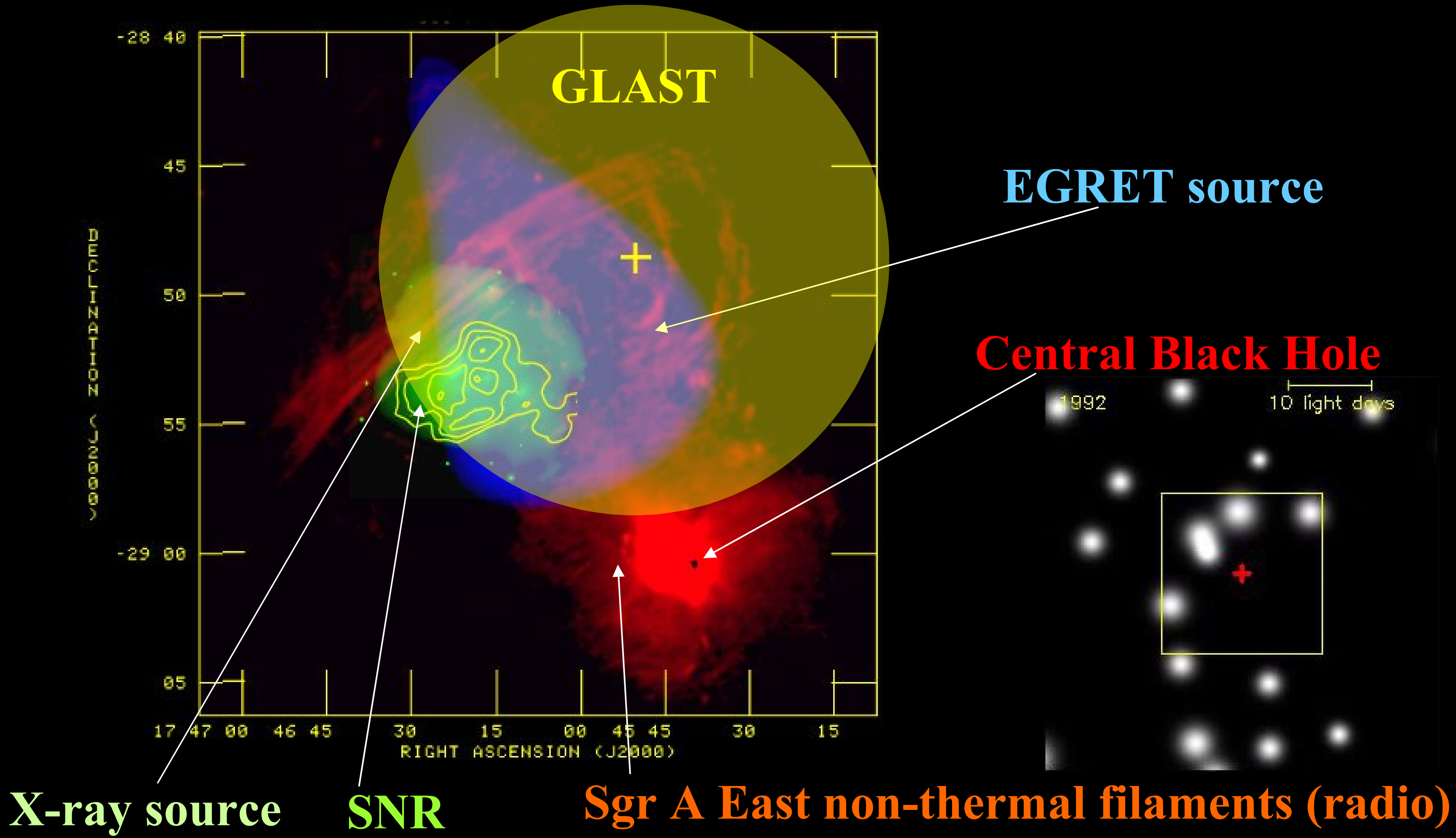


EGRET
E>100 MeV

See also
Suggestion of a
microwave haze
in WMAP maps

Galactic Center demography

Crowded, active environment

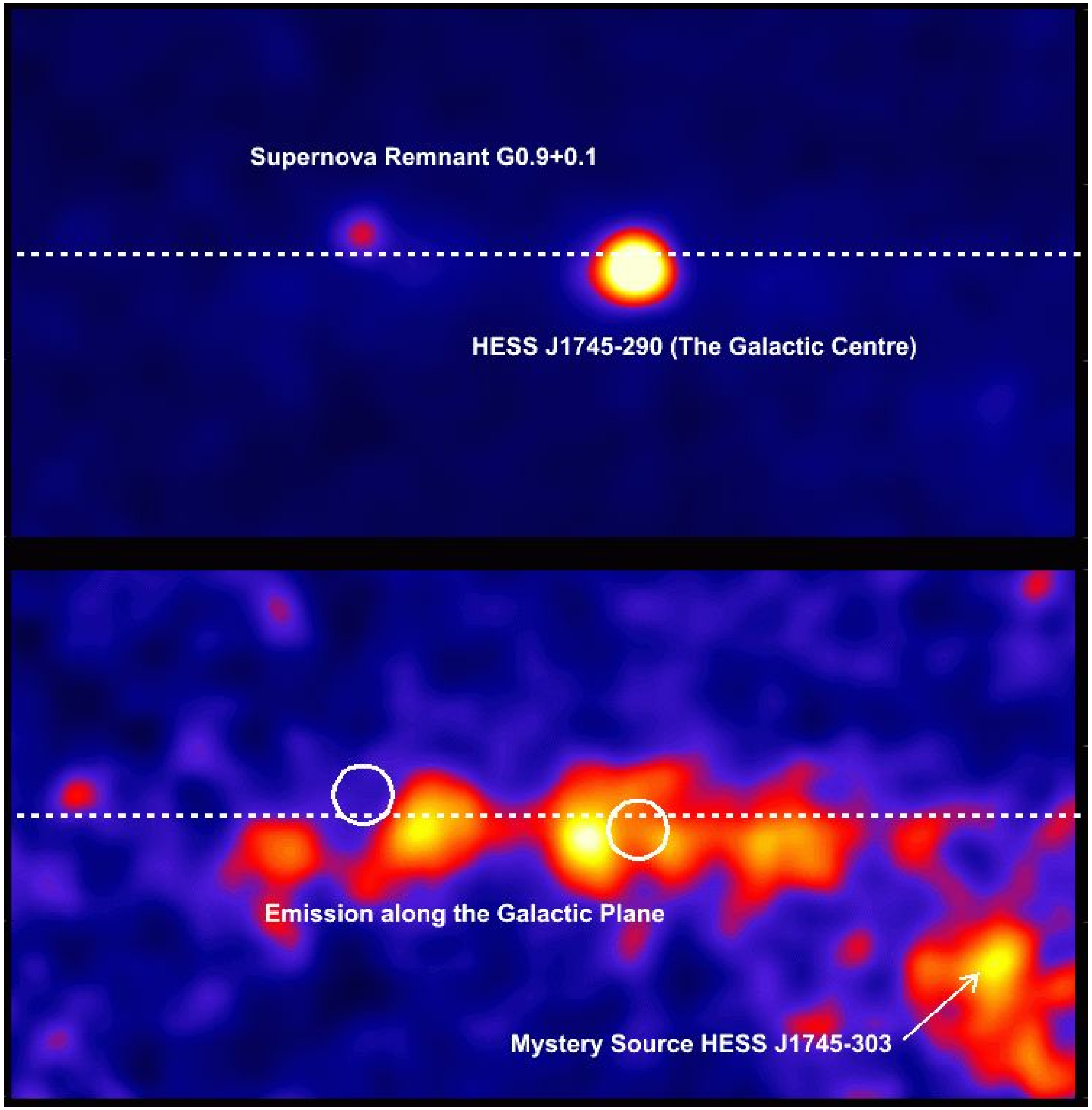


Galactic Center: very high-E view

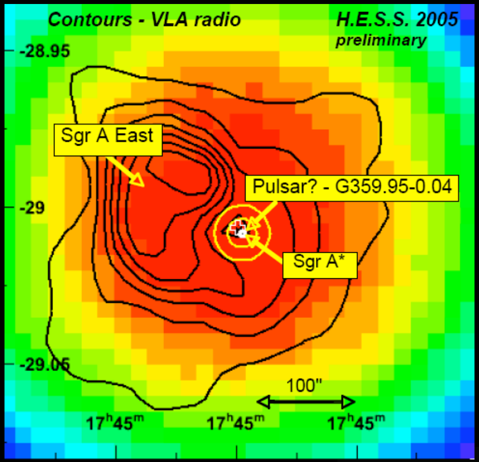
The H.E.S.S. view

The top panel shows the gamma-ray image of the Galactic Centre region taken by H.E.S.S. Two bright sources dominate the view: HESS J1745-290, a mysterious source right at the centre of the Galaxy; and, about 1 degree away, the gamma-ray supernova remnant G 0.9+0.1.

The lower panel shows the same image with the bright sources subtracted. In this image gamma-ray emission extending along the plane is visible as well as another mysterious source: HESS J1745-303. The dashed lines show the position of the Galactic Plane. The white circles show the positions from which the two sources were removed.

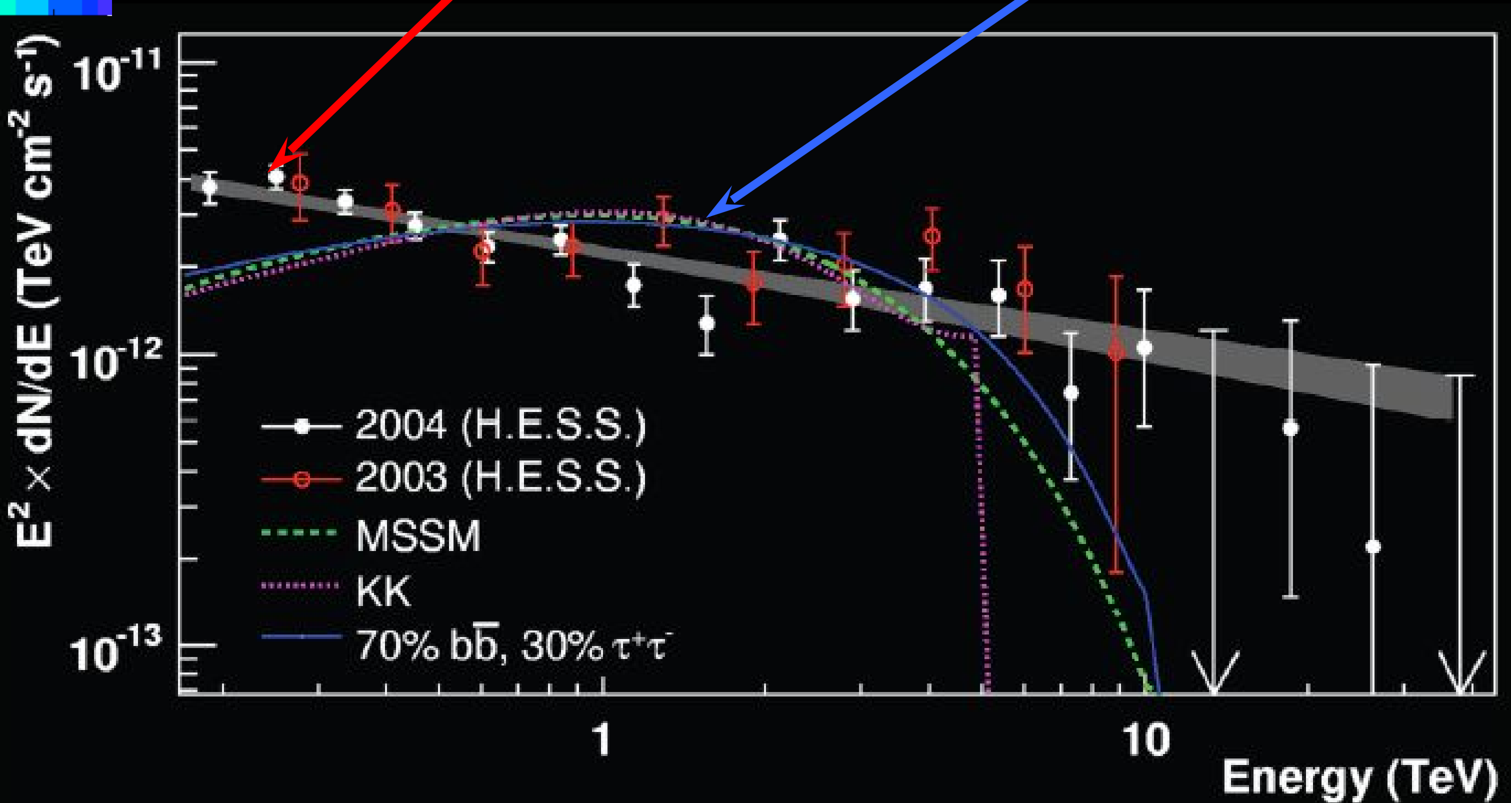


The spectrum of Sgr A



Power-law spectrum

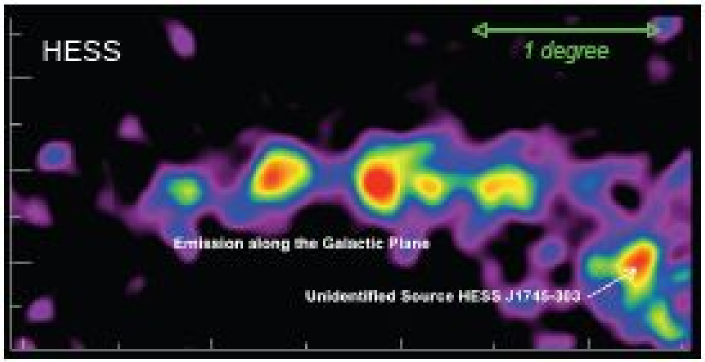
DM annihilation spectra

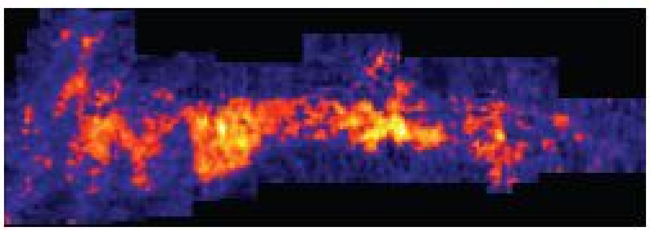


ASDC ASI Science Data Center

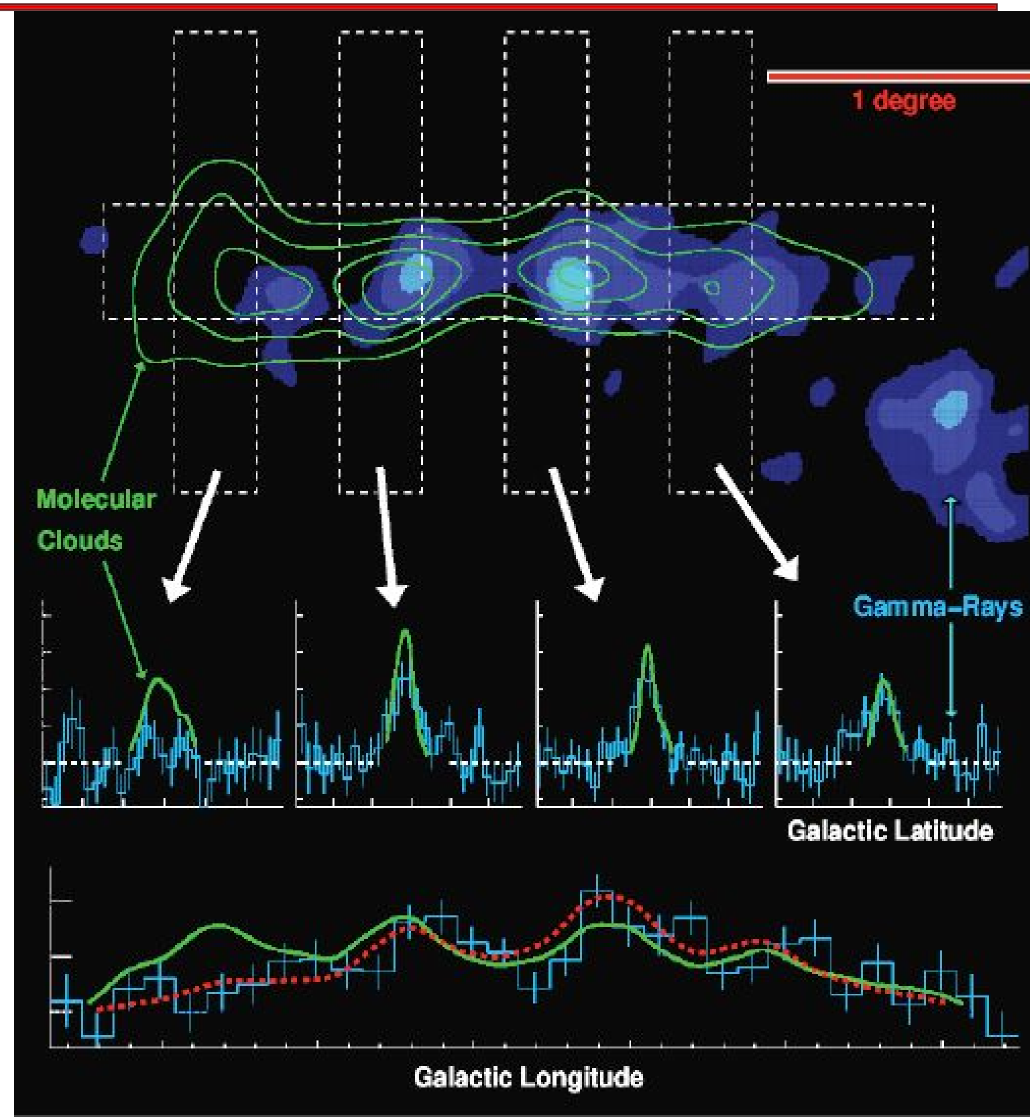
Diffuse emission at the GC

TeV image
after subtraction of point-like sources



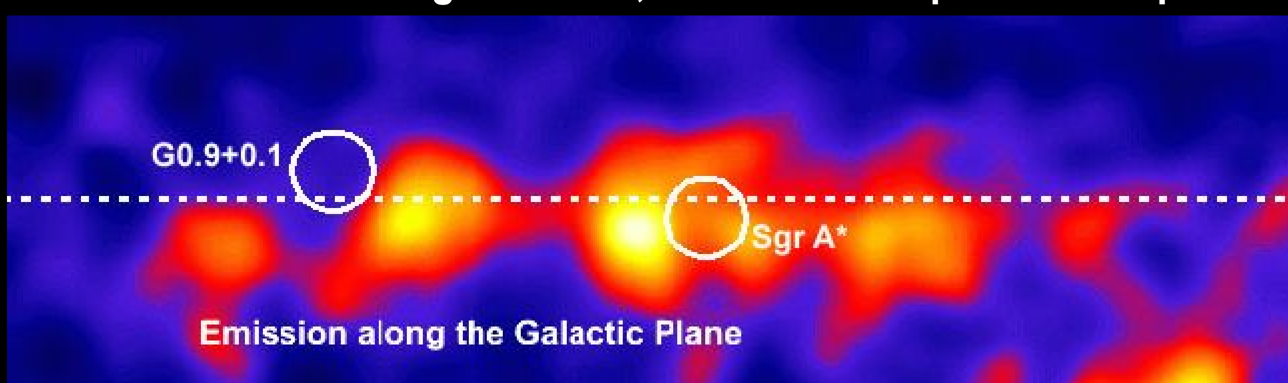


CS line emission (dense cloud) image
smoothed to match HESS PSF

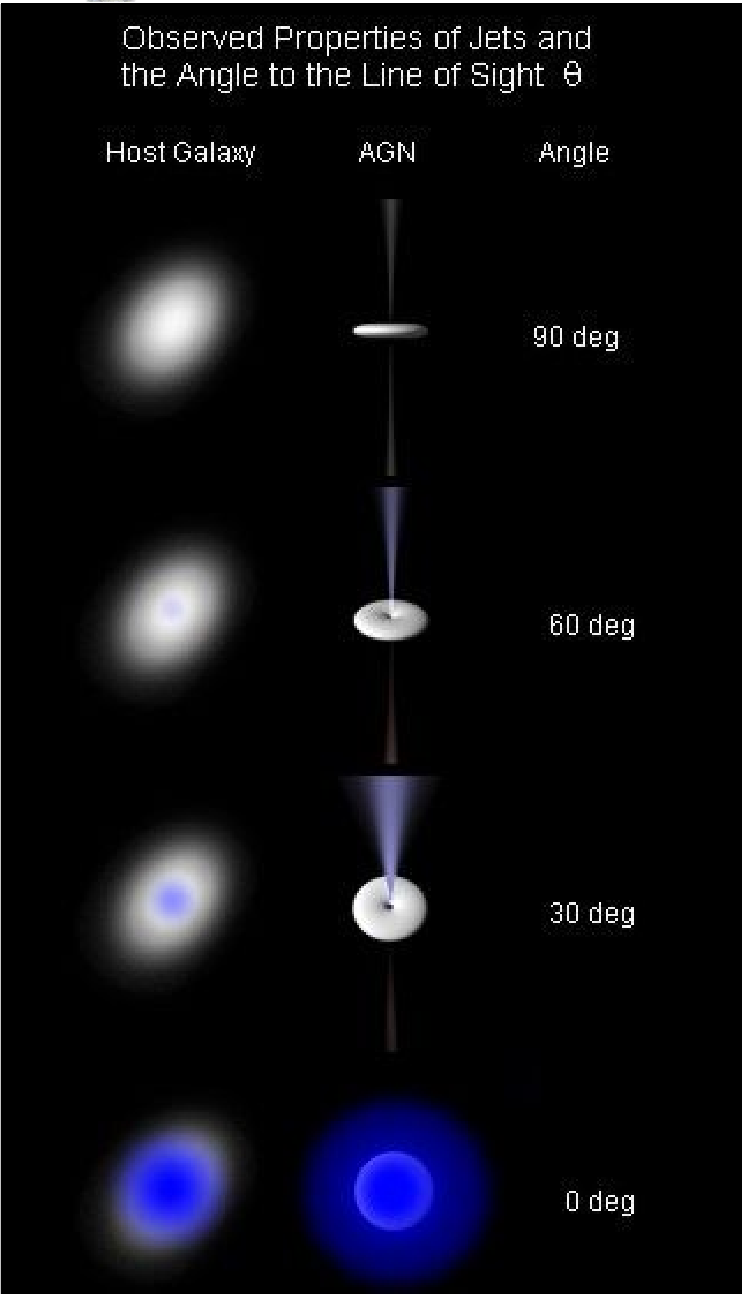


Who is the Smooth Accelerator?

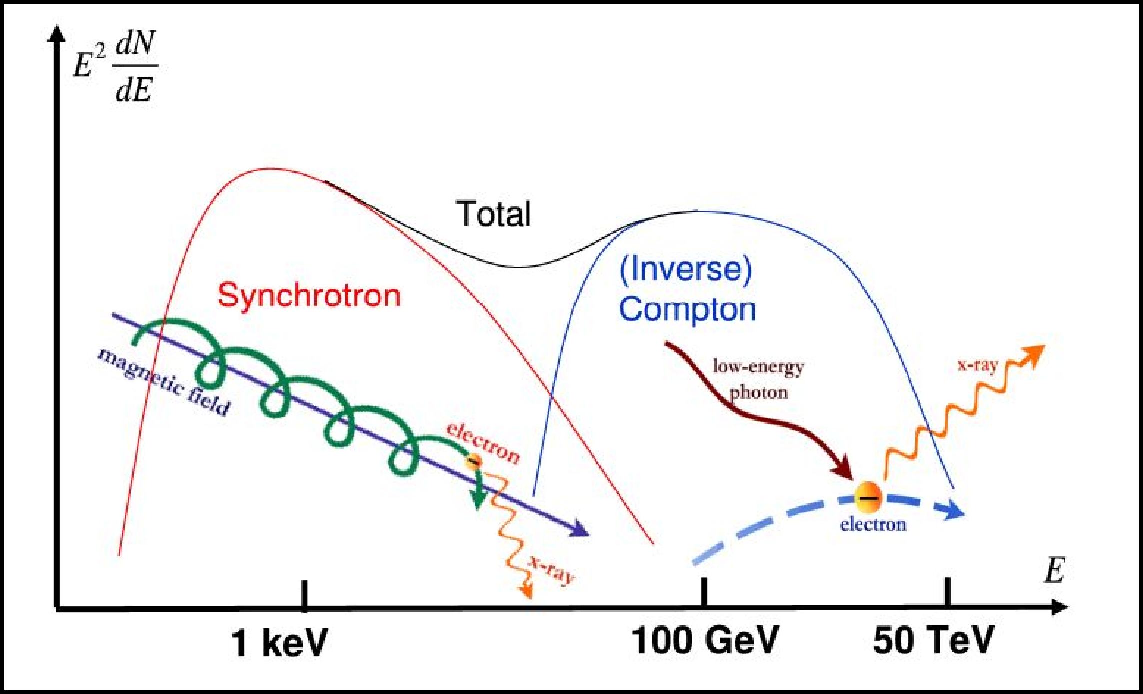
γ-ray afterglow from Galactic Centre gas clouds, indicative a of pre-historic particle acceleration



AGN SEDs



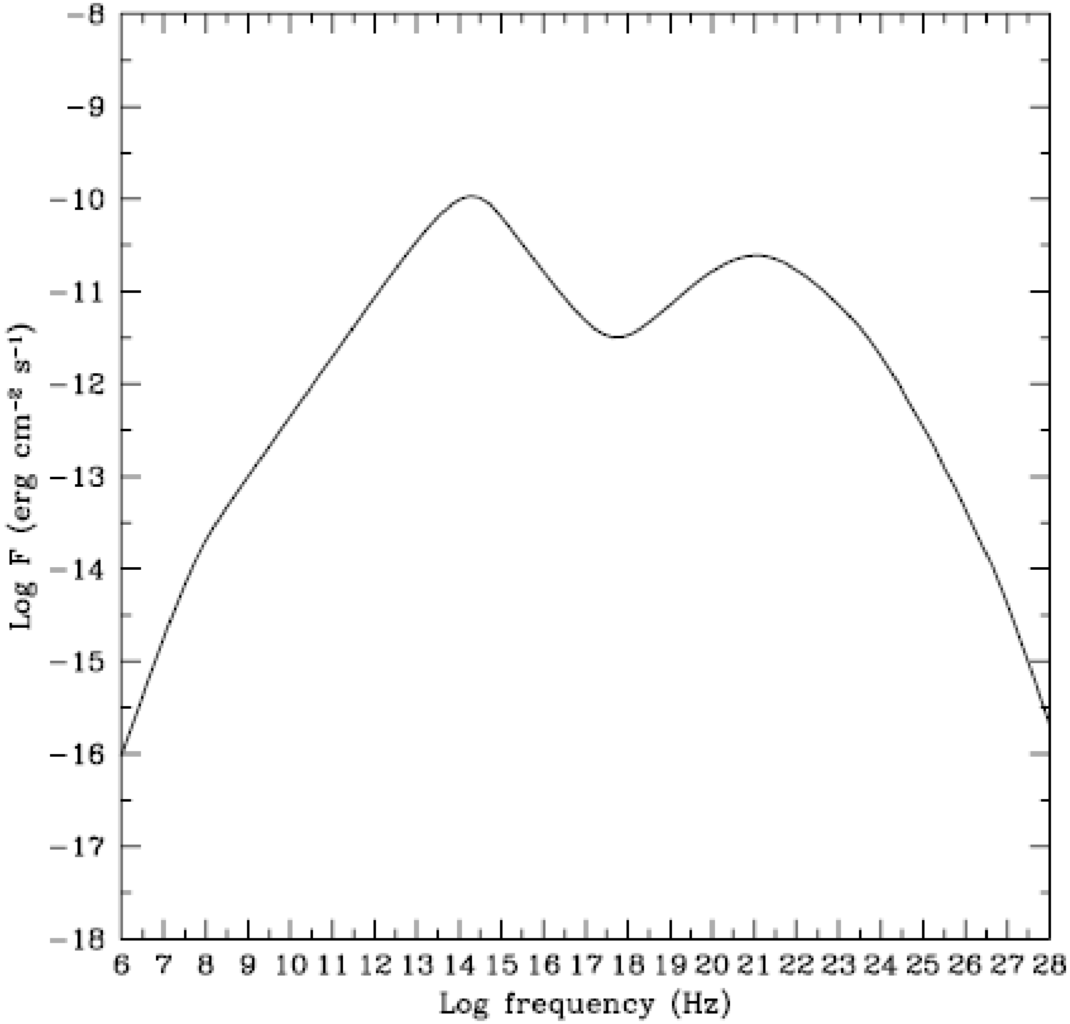
Observed Properties of Jets and the Angle to the Line of Sight θ
Host Galaxy
AGN
Angle
90 deg
60 deg
30 deg
0 deg



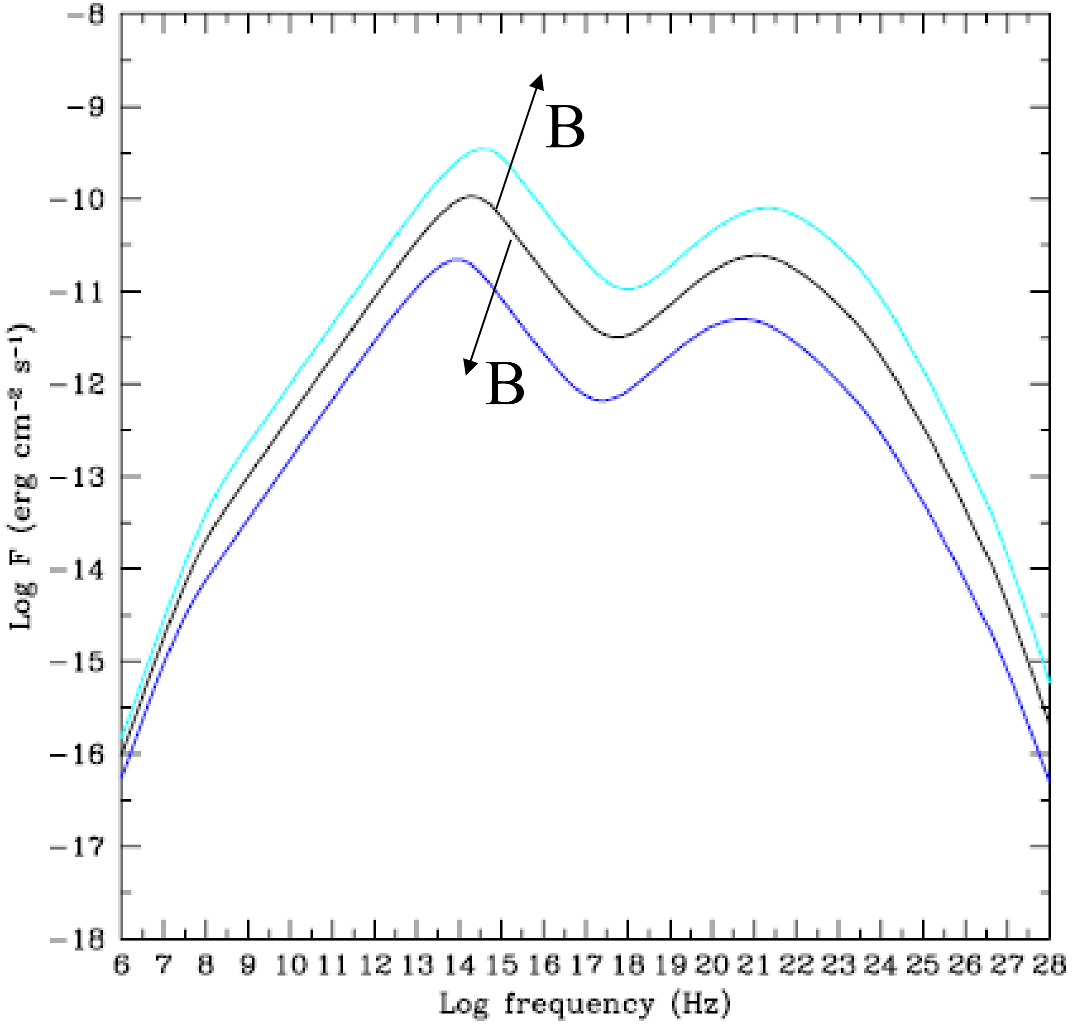
$E^2 \frac{dN}{dE}$
Total
Synchrotron
(Inverse) Compton
magnetic field
electron
x-ray
low-energy photon
x-ray
electron
E
1 keV
100 GeV
50 TeV

AGN SEDs: parameter dependence

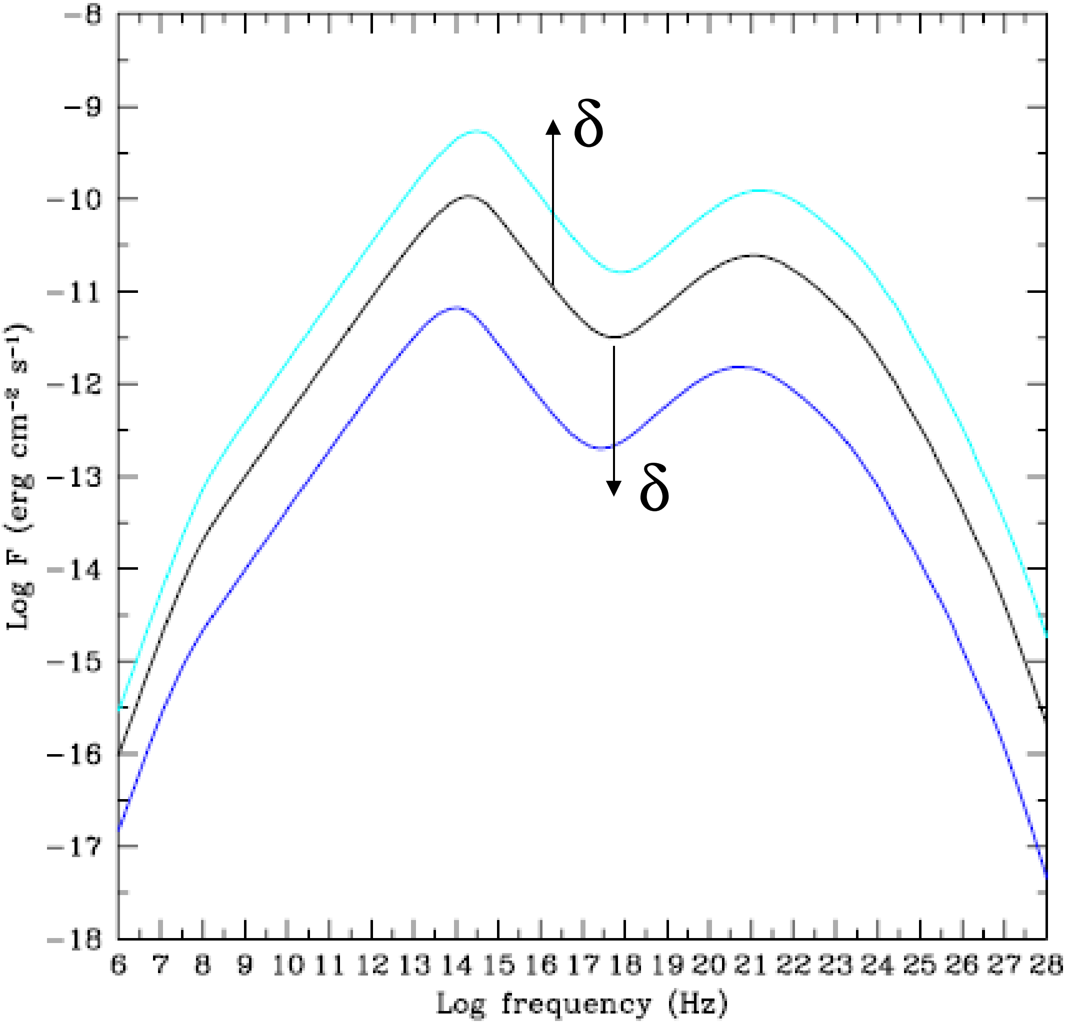
$N_0=10^{2.8}$ cm^{-3}
$p_1=1.7$
$p_2=4.2$
B=1.1 μG
$\gamma_b=10^{3.25}$
$\delta=20$
$r_0=0.01$ pc
z=0.4



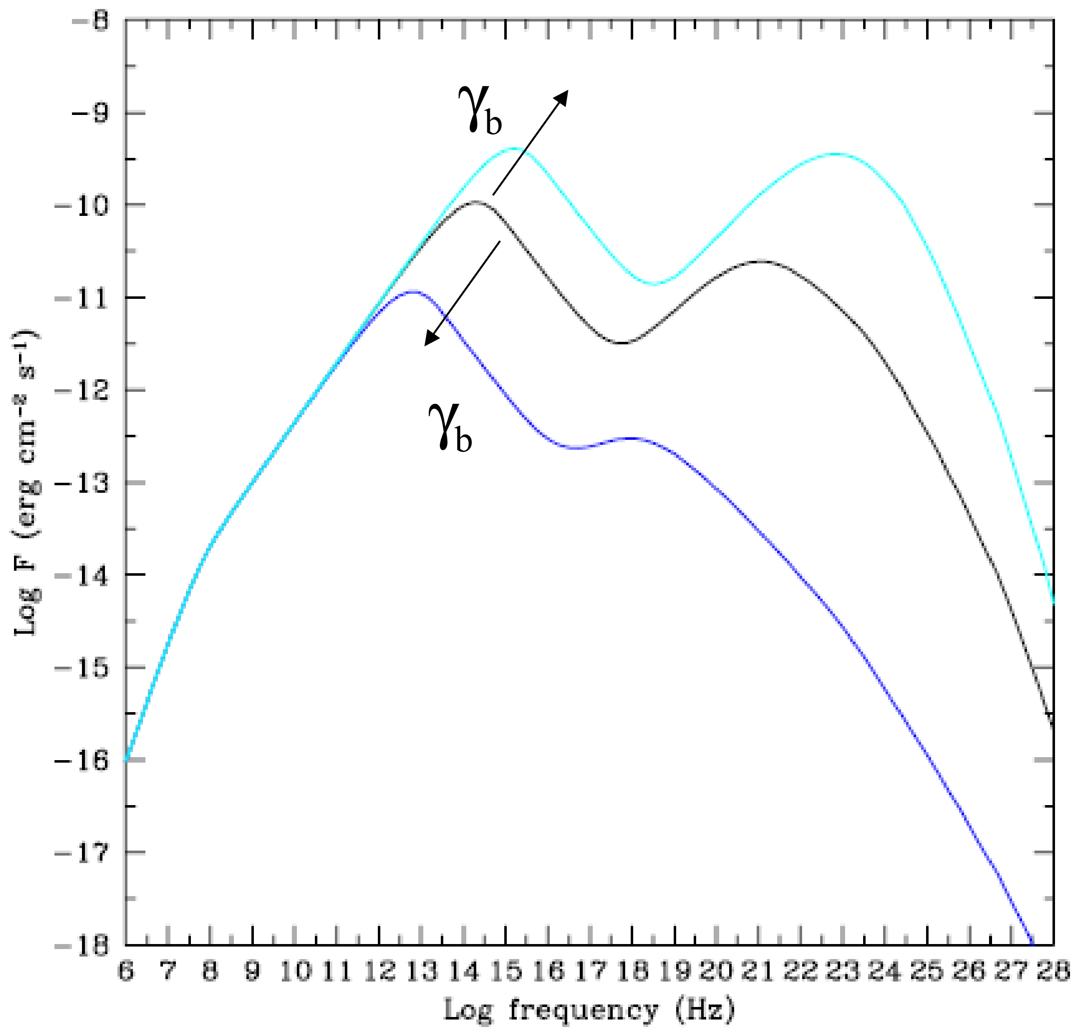
AGN SEDs: parameter dependence



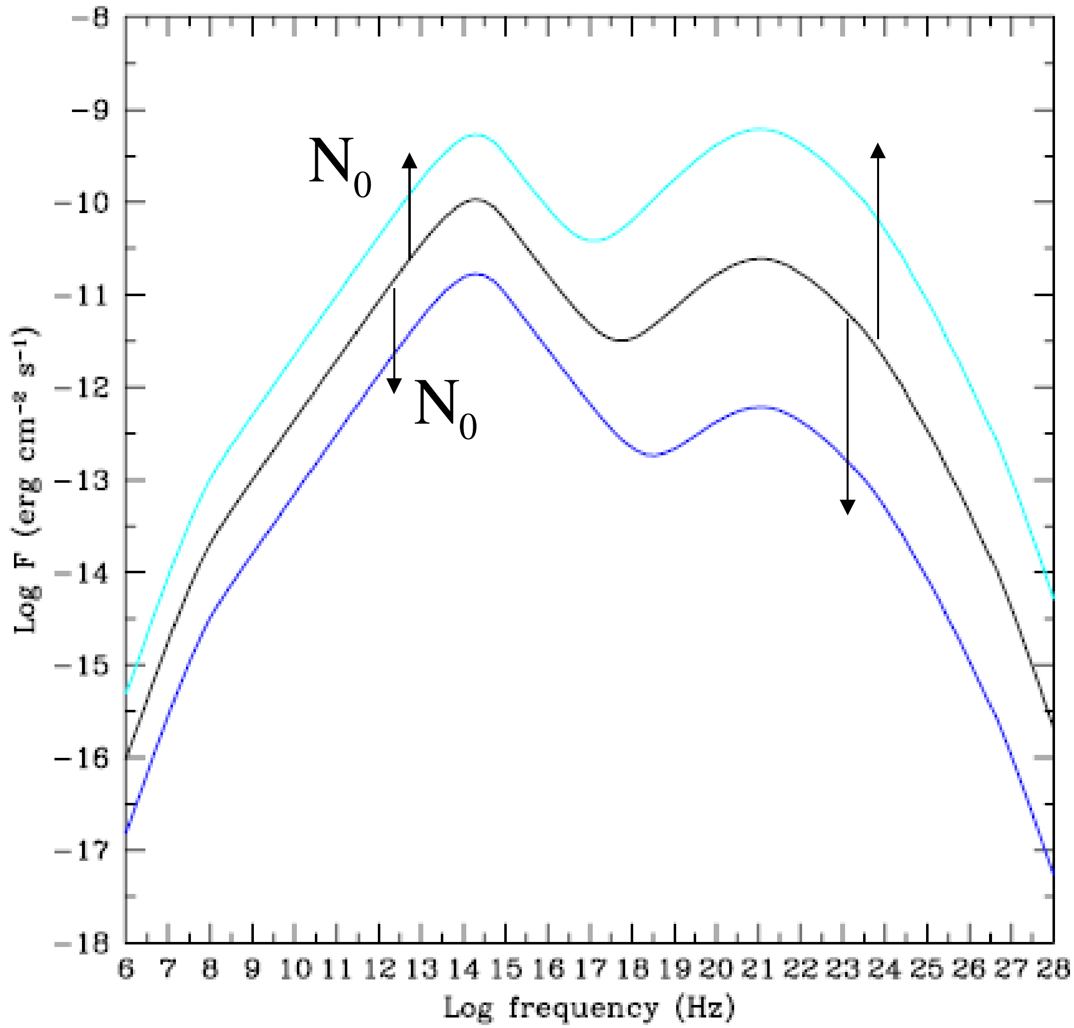
AGN SEDs: parameter dependence



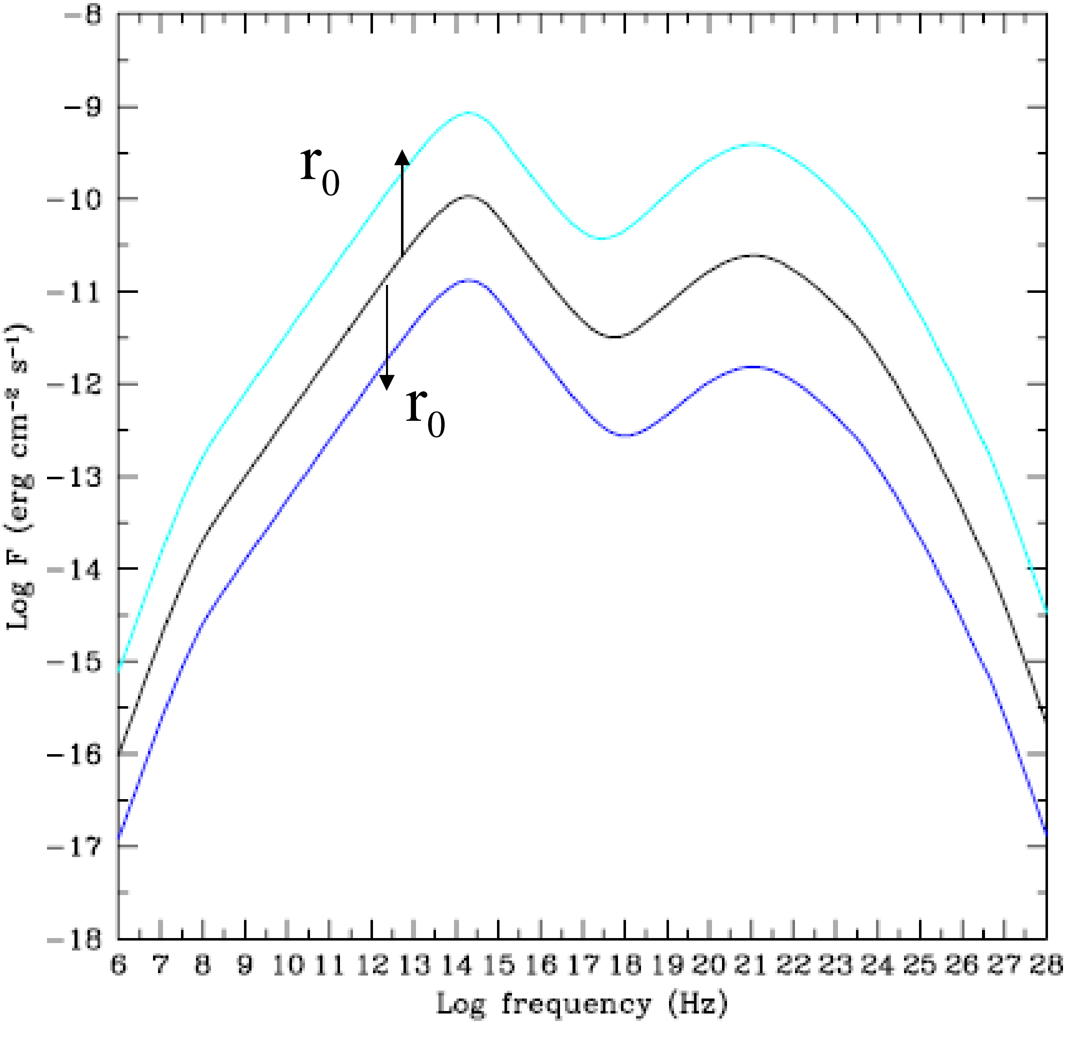
AGN SEDs: parameter dependence



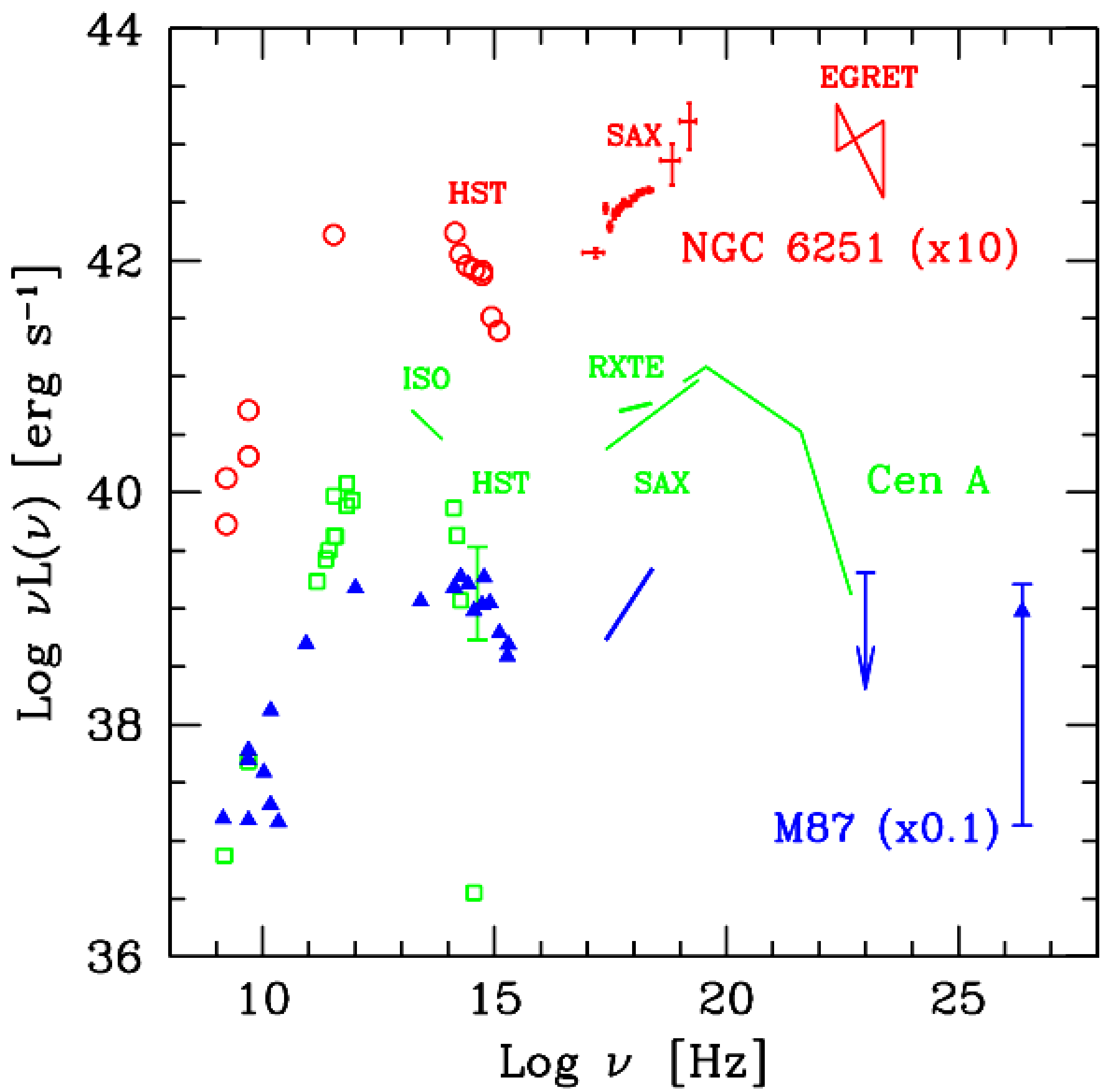
AGN SEDs: parameter dependence

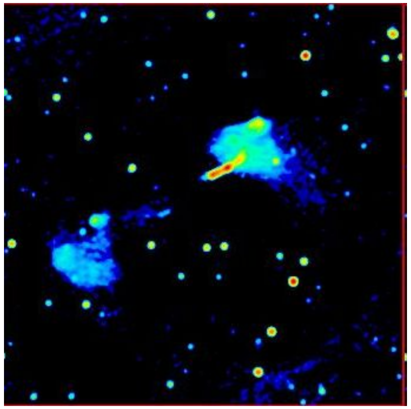


AGN SEDs: parameter dependence

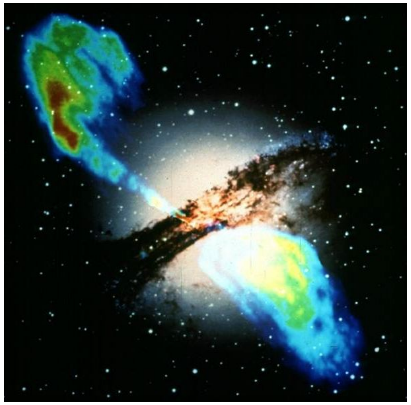


Radio Galaxy SEDs

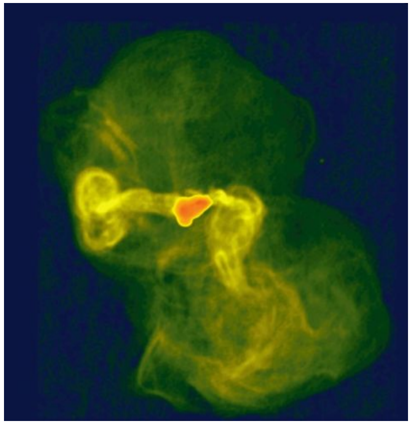




NGC6251
327 MHz

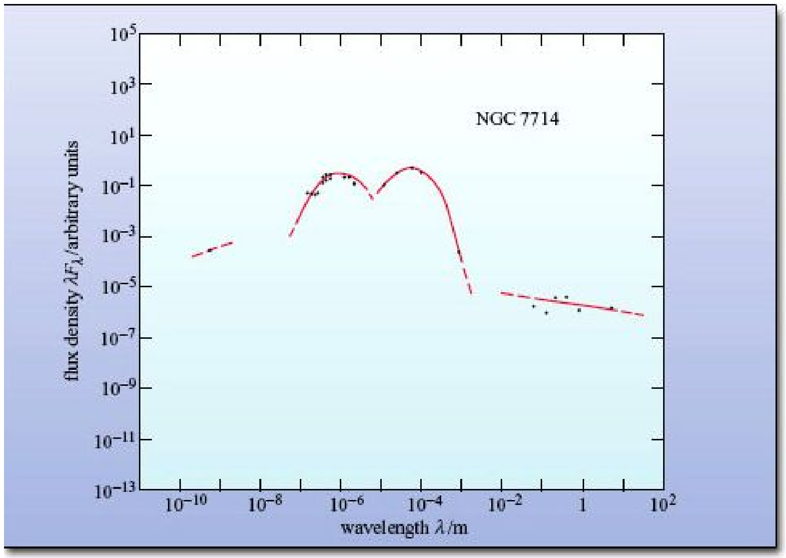


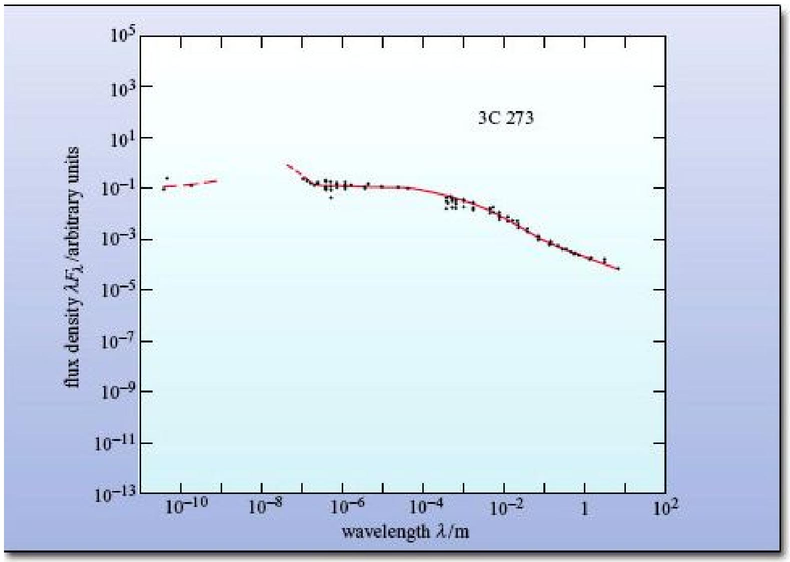
Cen A
1400 MHz



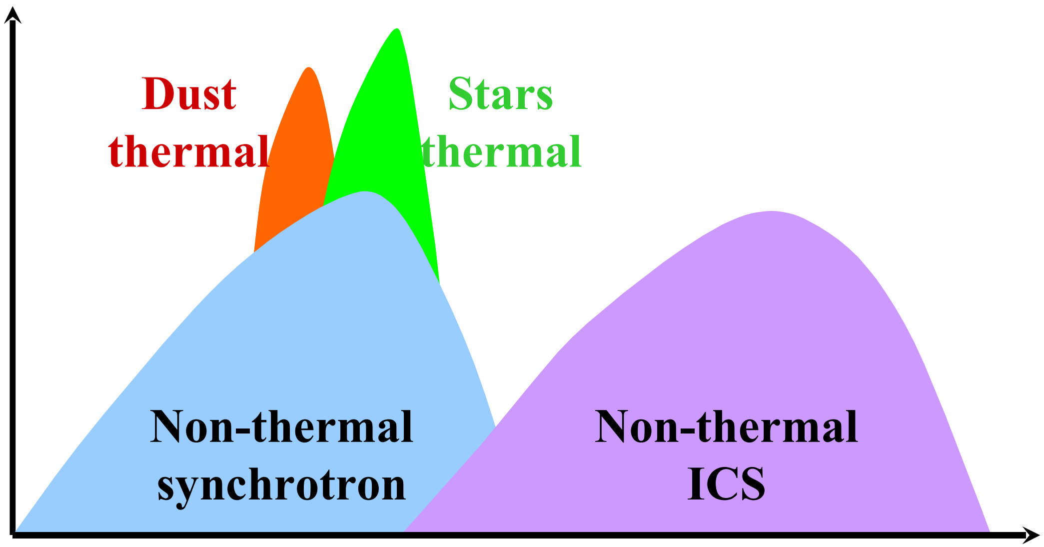
M 87
1400 MHz

From thermal to Non-Thermal AGNs

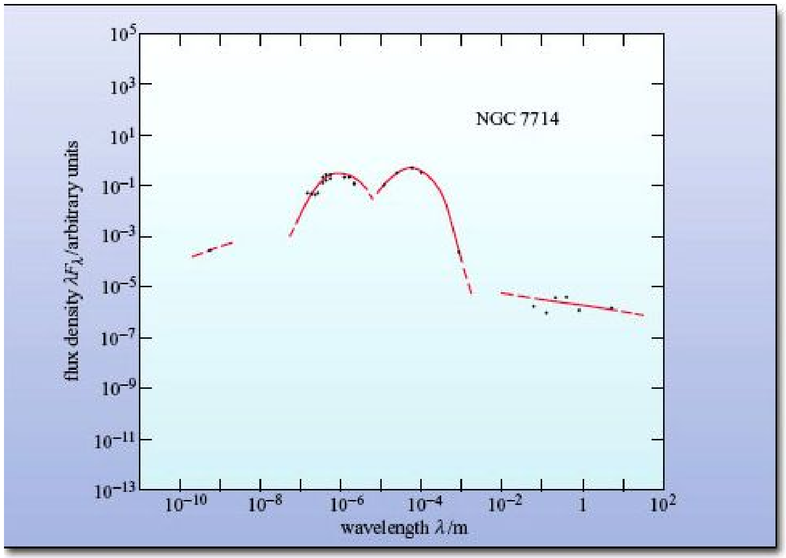


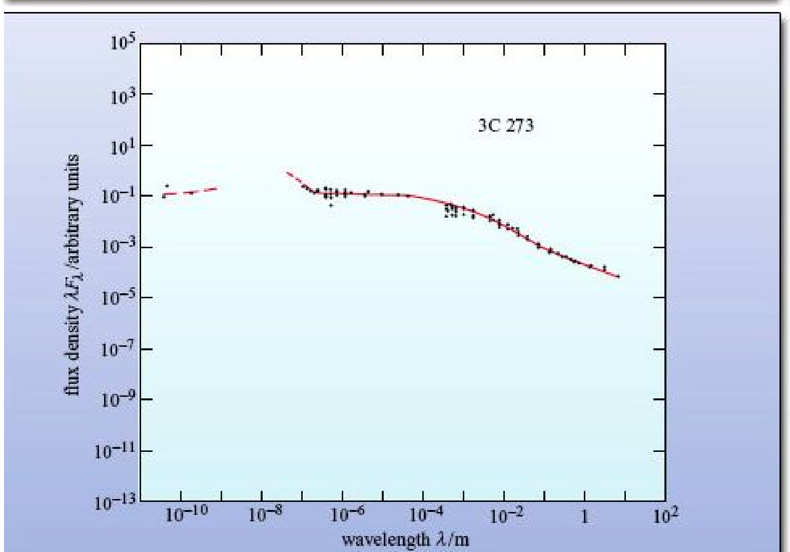


Thermal dominated AGN
(Starburst-like)

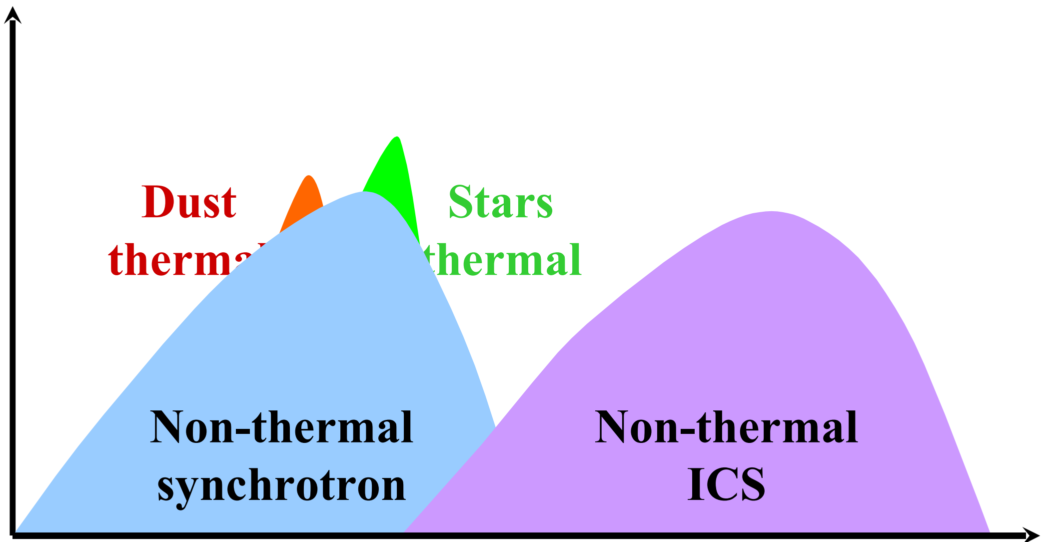


From thermal to Non-Thermal AGNs

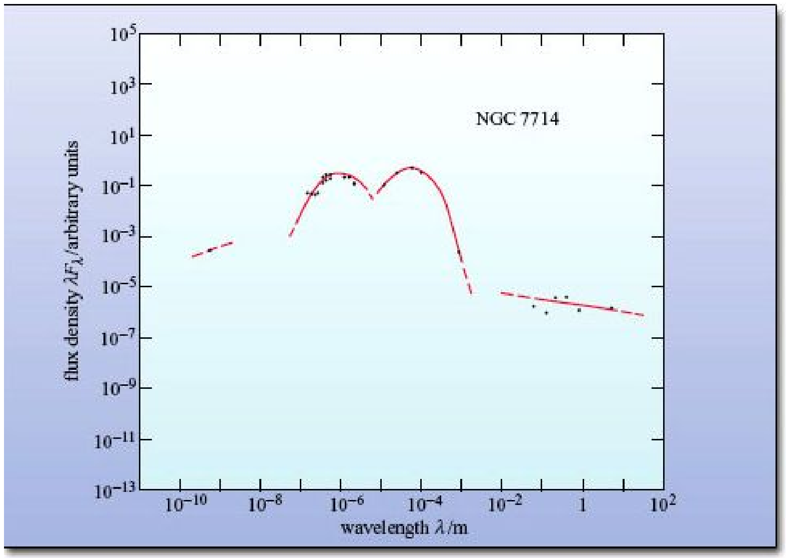


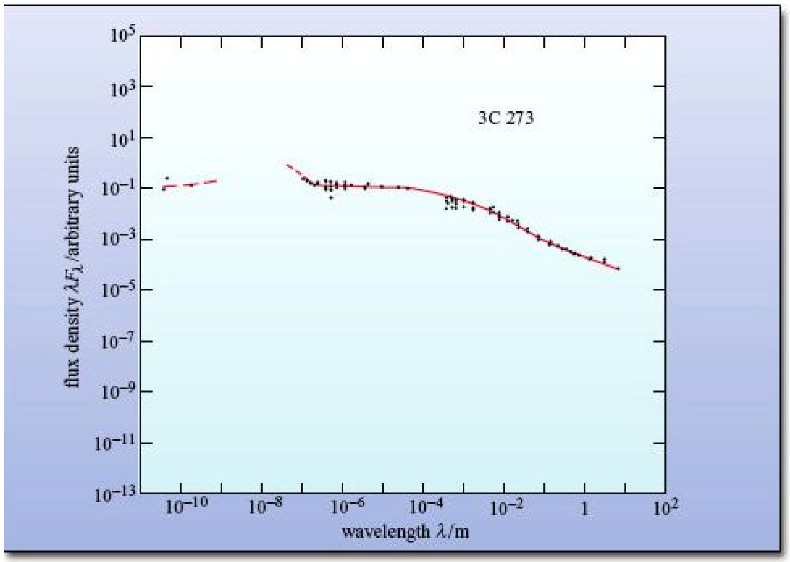


Transition type AGN
(Seyfert-like, QSO-like)

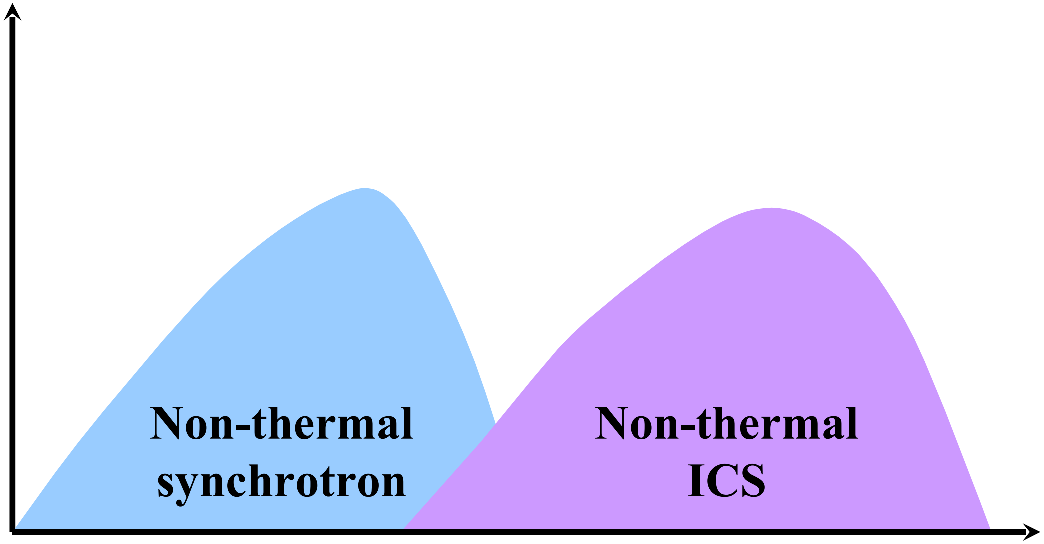


From thermal to Non-Thermal AGNs

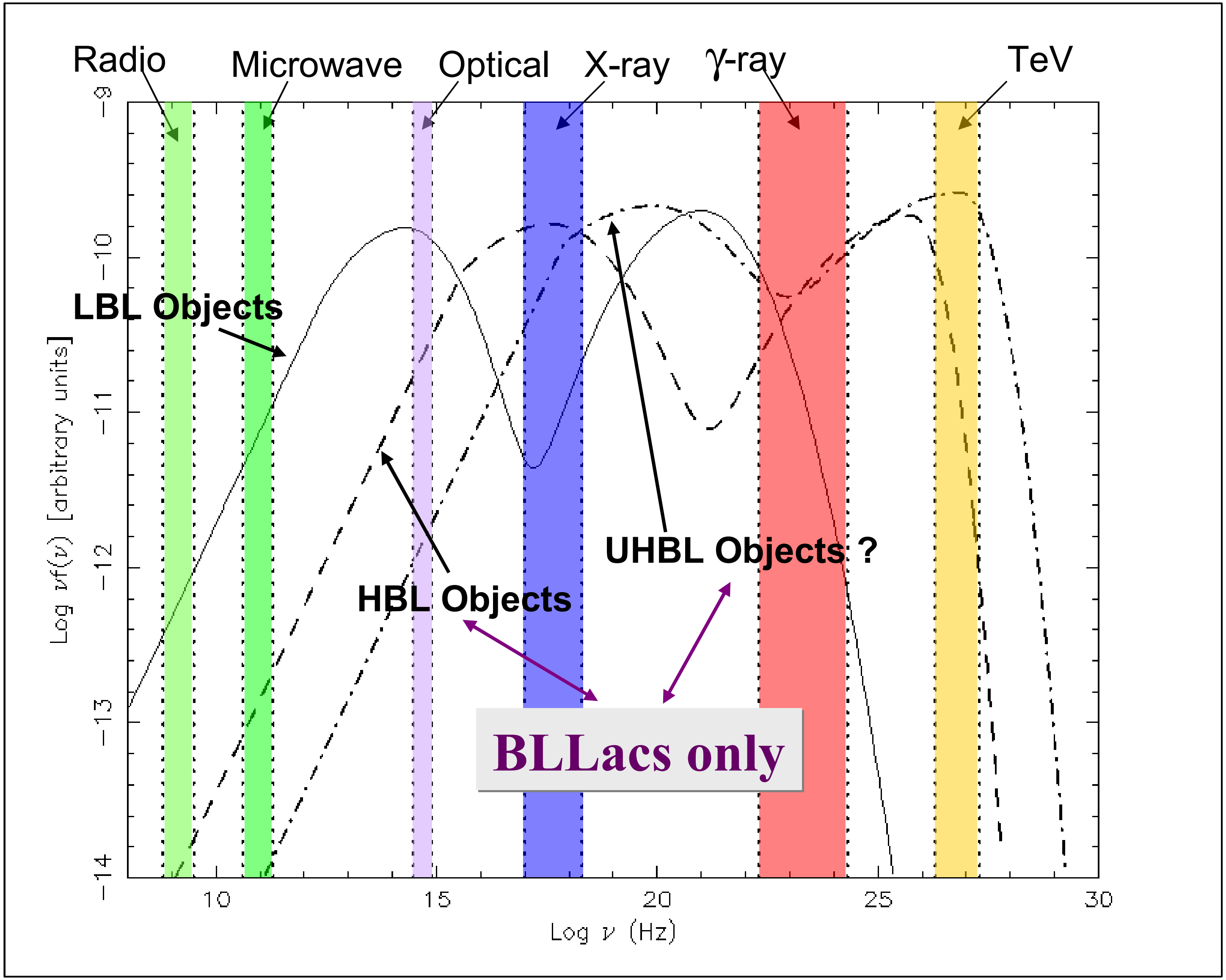




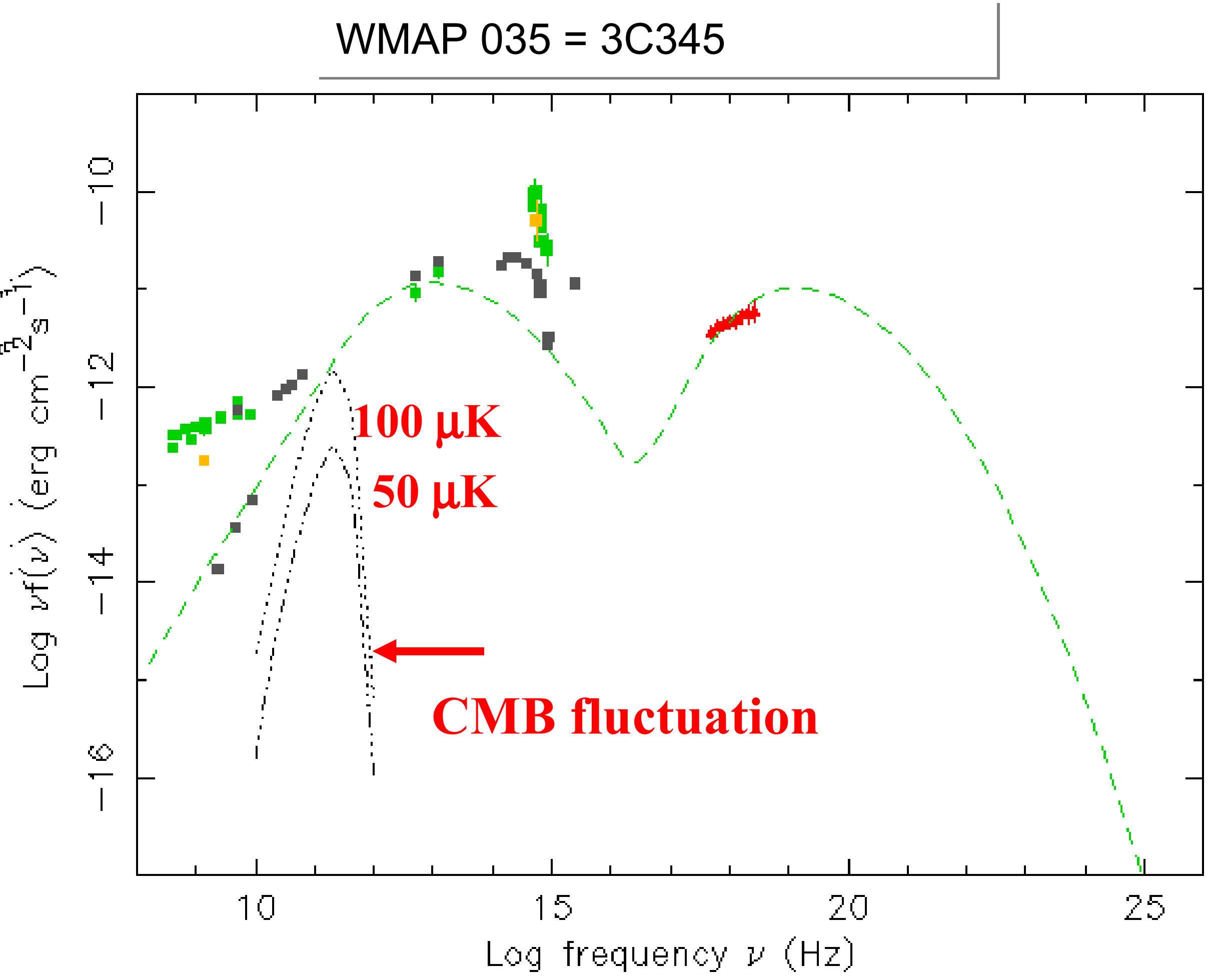
Non-Thermal dominated AGN
(Blazar, BL Lac, Radio Galaxy)



The Blazar zoo: BLLacs + FSRQs



WMAP Blazar SEDs

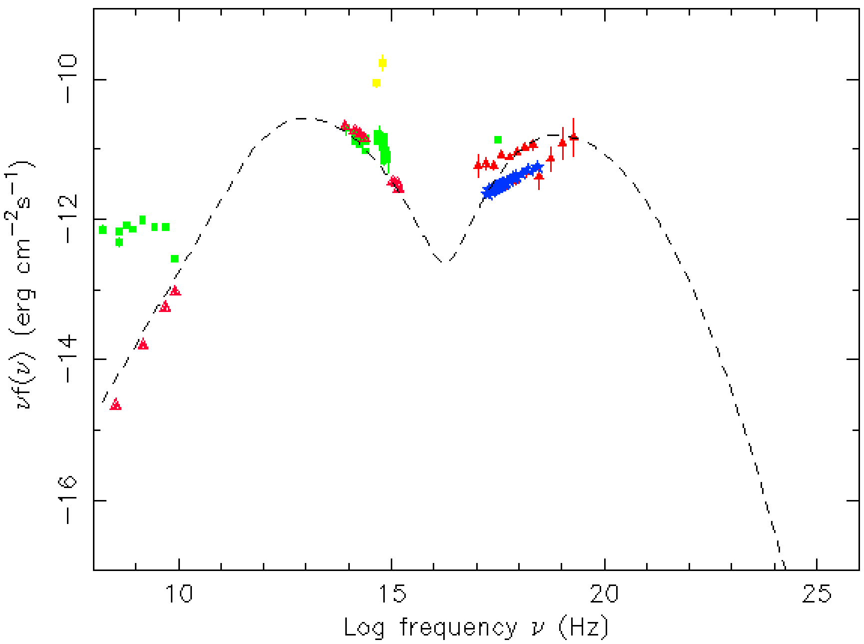


Radio galaxy nuclear component

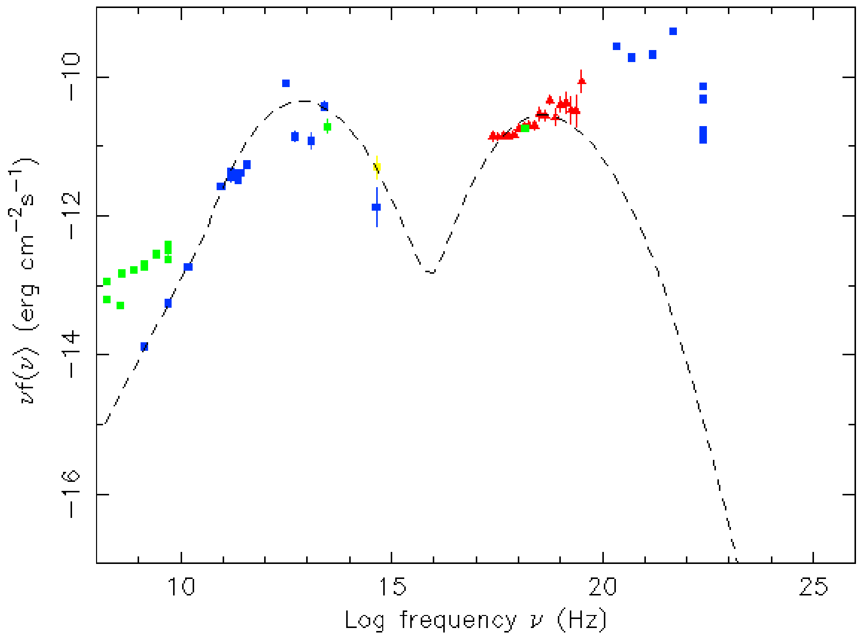
Radio galaxies with steep-spectrum at low-ν which flatten at high-ν

Emergency of nuclear non-thermal component

Radio Galaxy PKS 0518-45



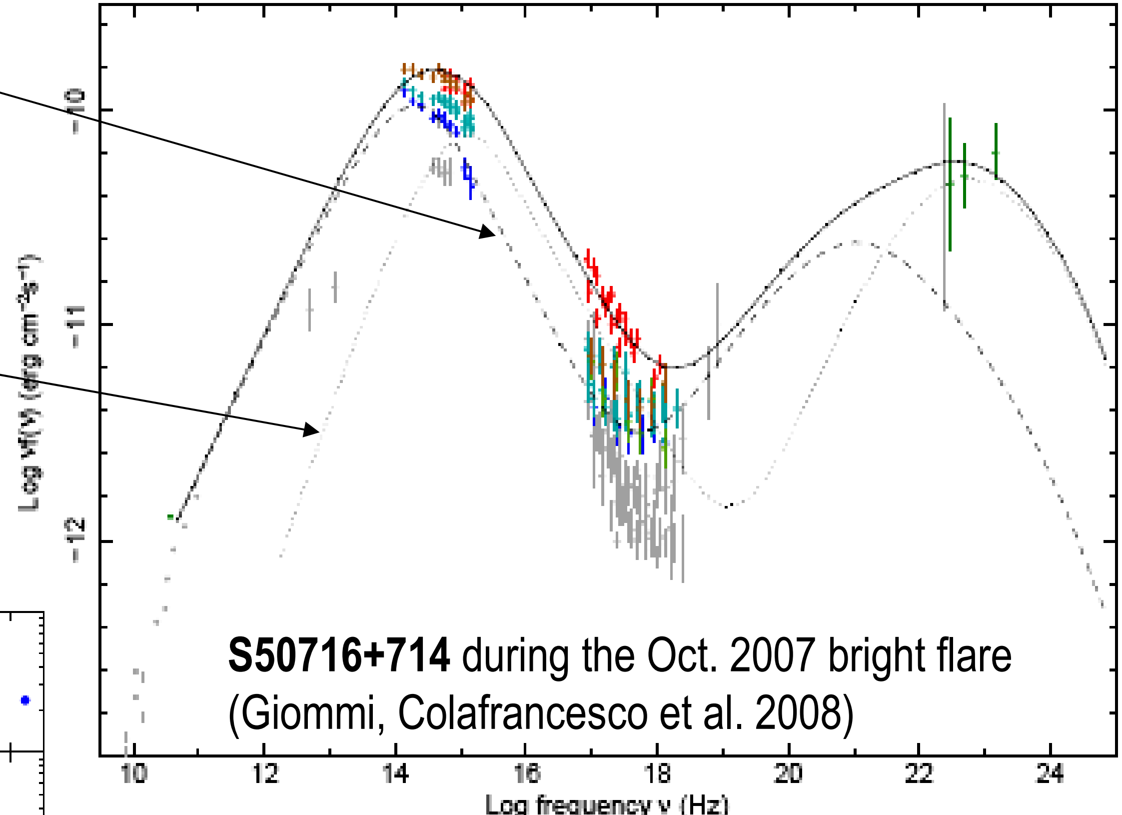
Radio Galaxy 3C 111

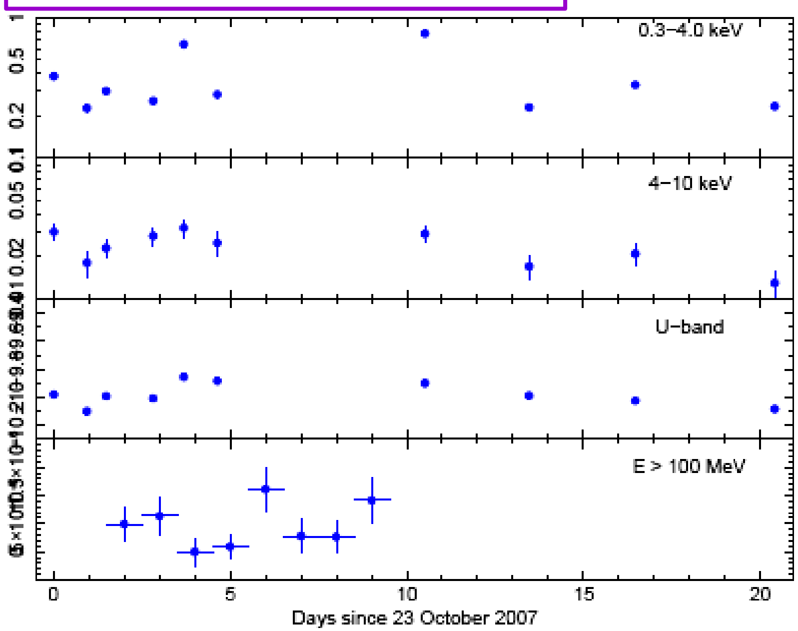


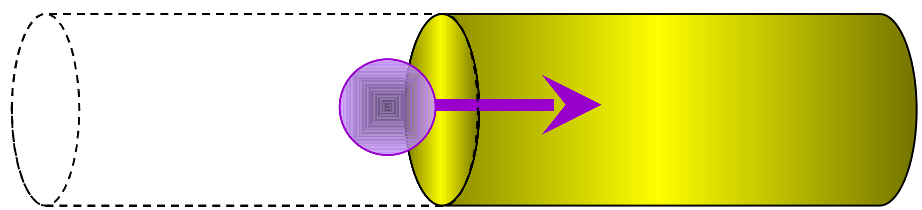
Blazar: multiple components

Stationary component:
p1=1.7; p2=4.2
γ_b=1.8 103
N=631 cm^{-3}
R=0.01 pc

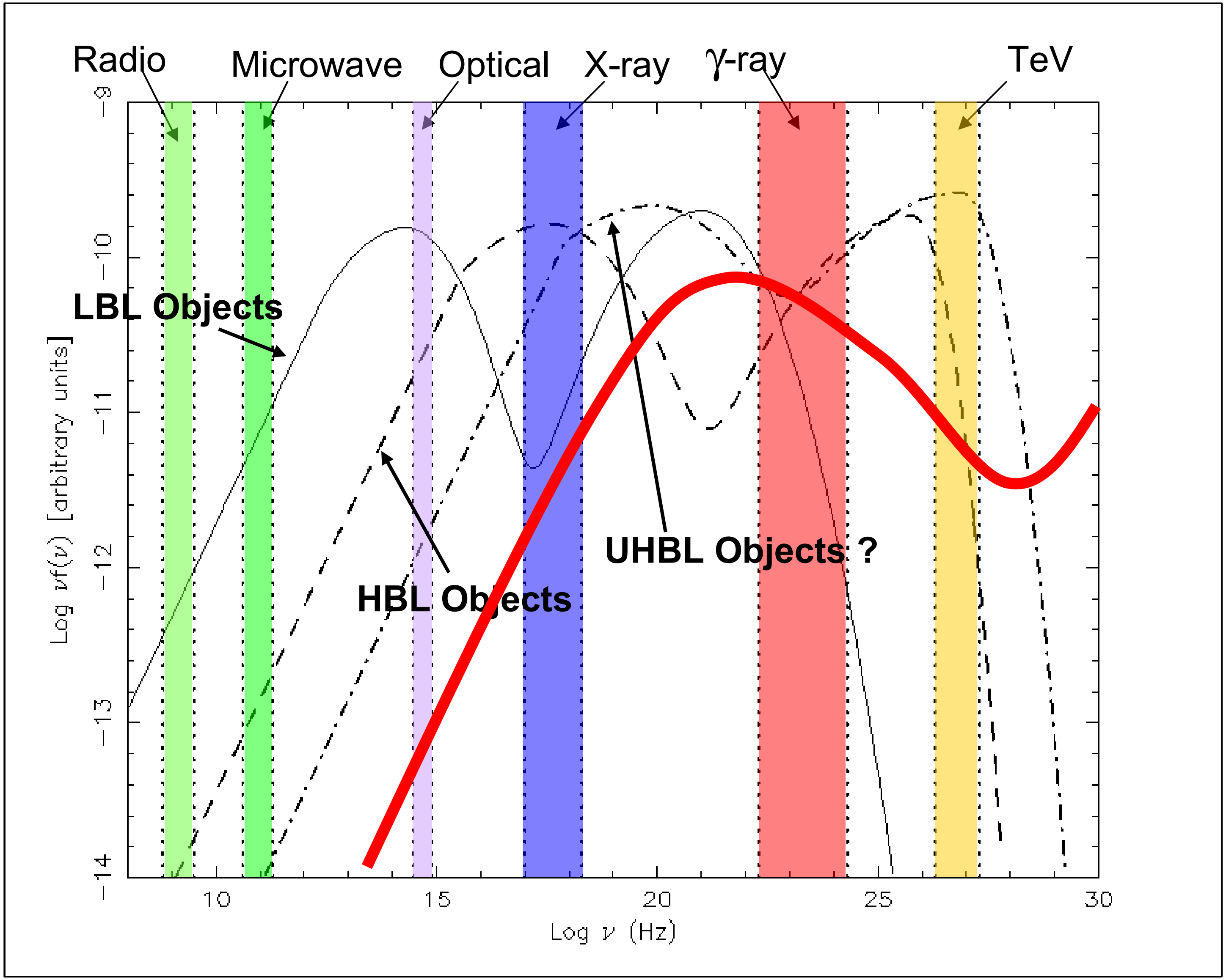
Additional component:
p1=1.1; p2=4.05
γ_b=3.9 103
N=8.91cm^{-3}
R=0.005 pc





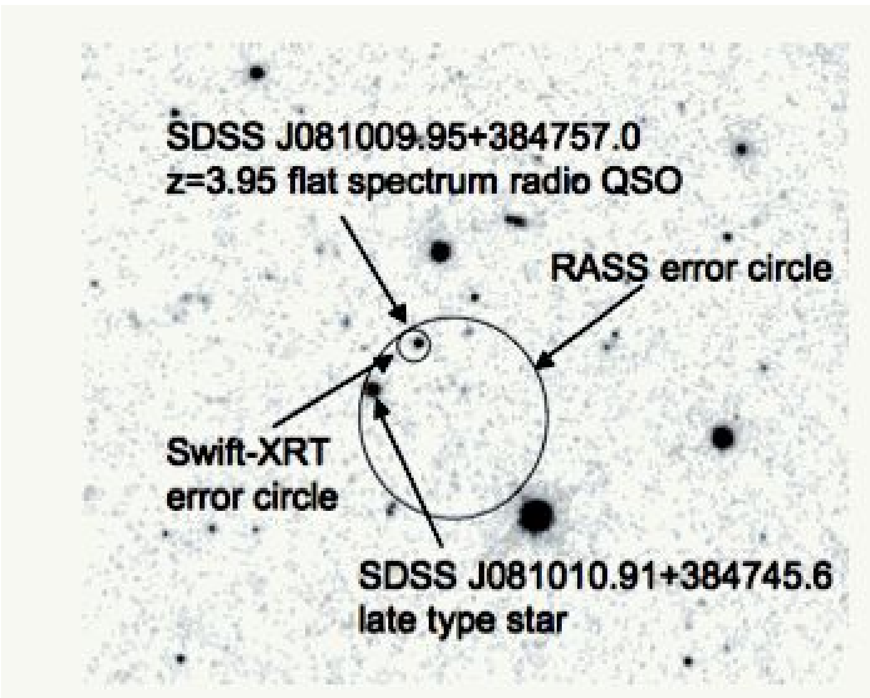


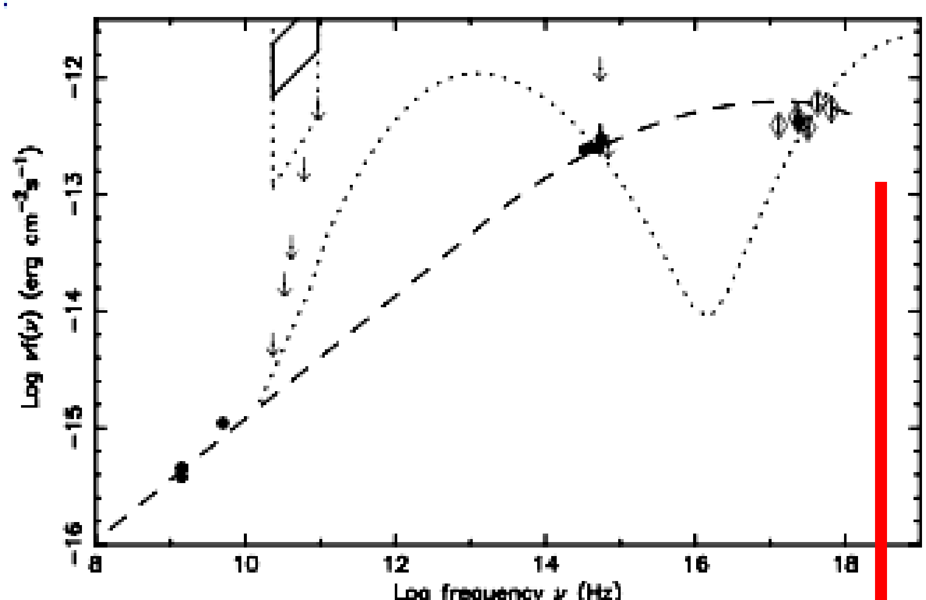
Extreme Blazars ?



BHs and (UHE) CRs

ROXA J081009.9+384757.0: a 10^{47} erg s^{-1} blazar with hard X-ray synchrotron peak or a new type of radio loud AGN?

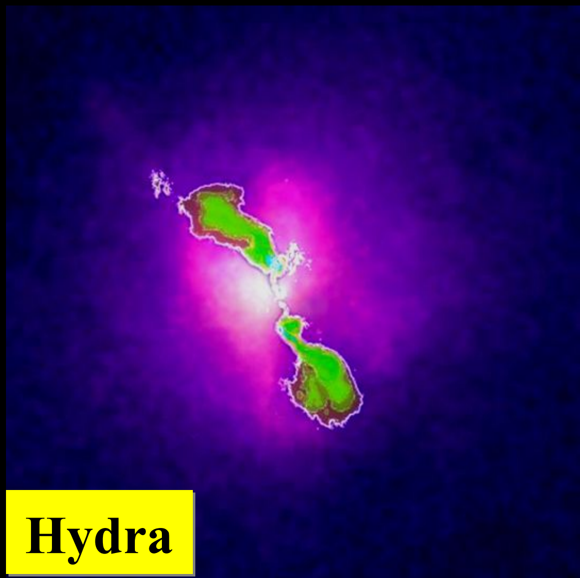


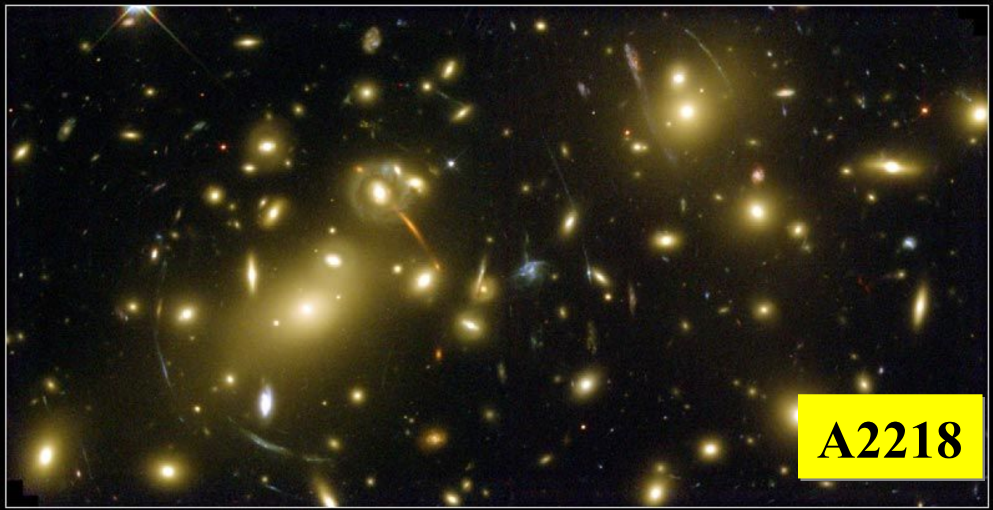


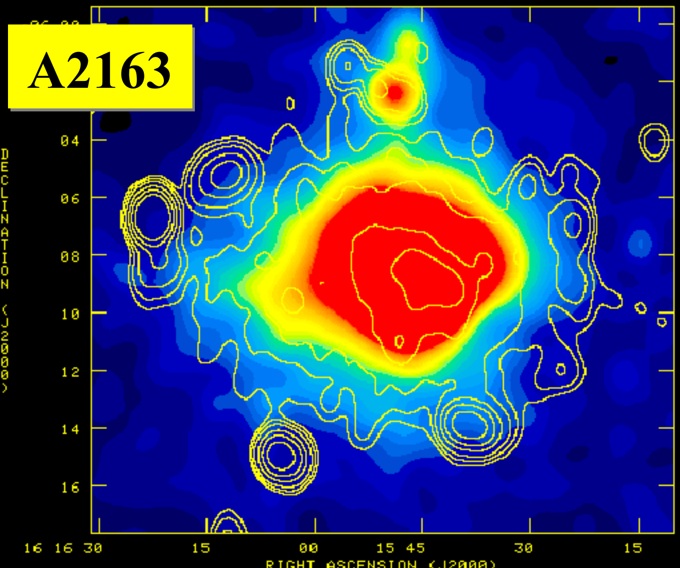
[Giommi, S.C. et al. 2006]

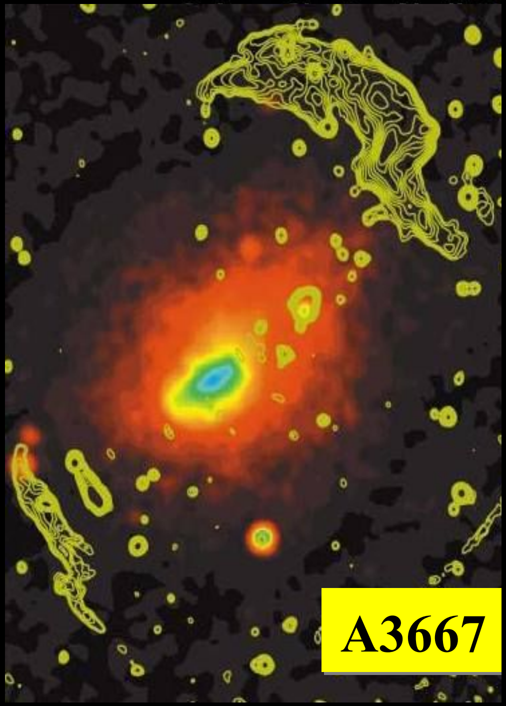
TeV → PeV → EeV γ & particles ?

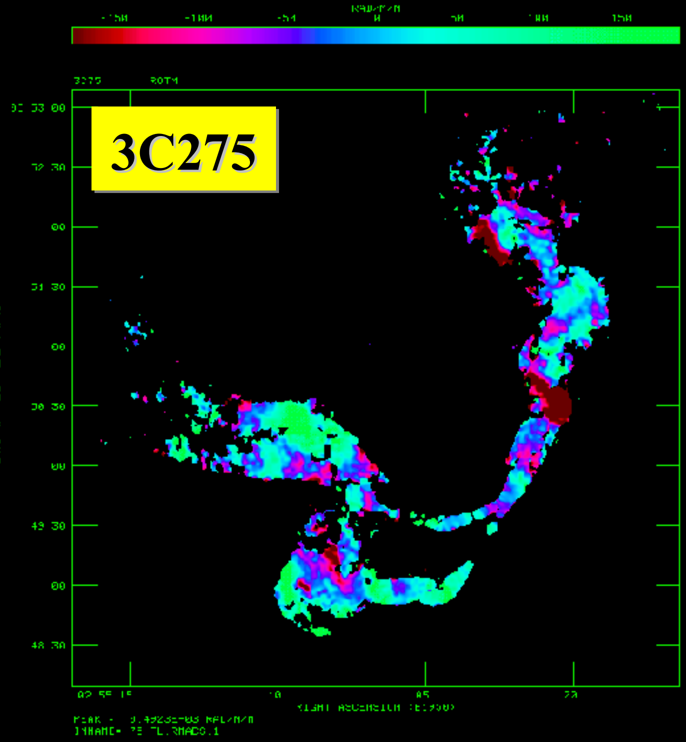
Galaxy Clusters at High-E



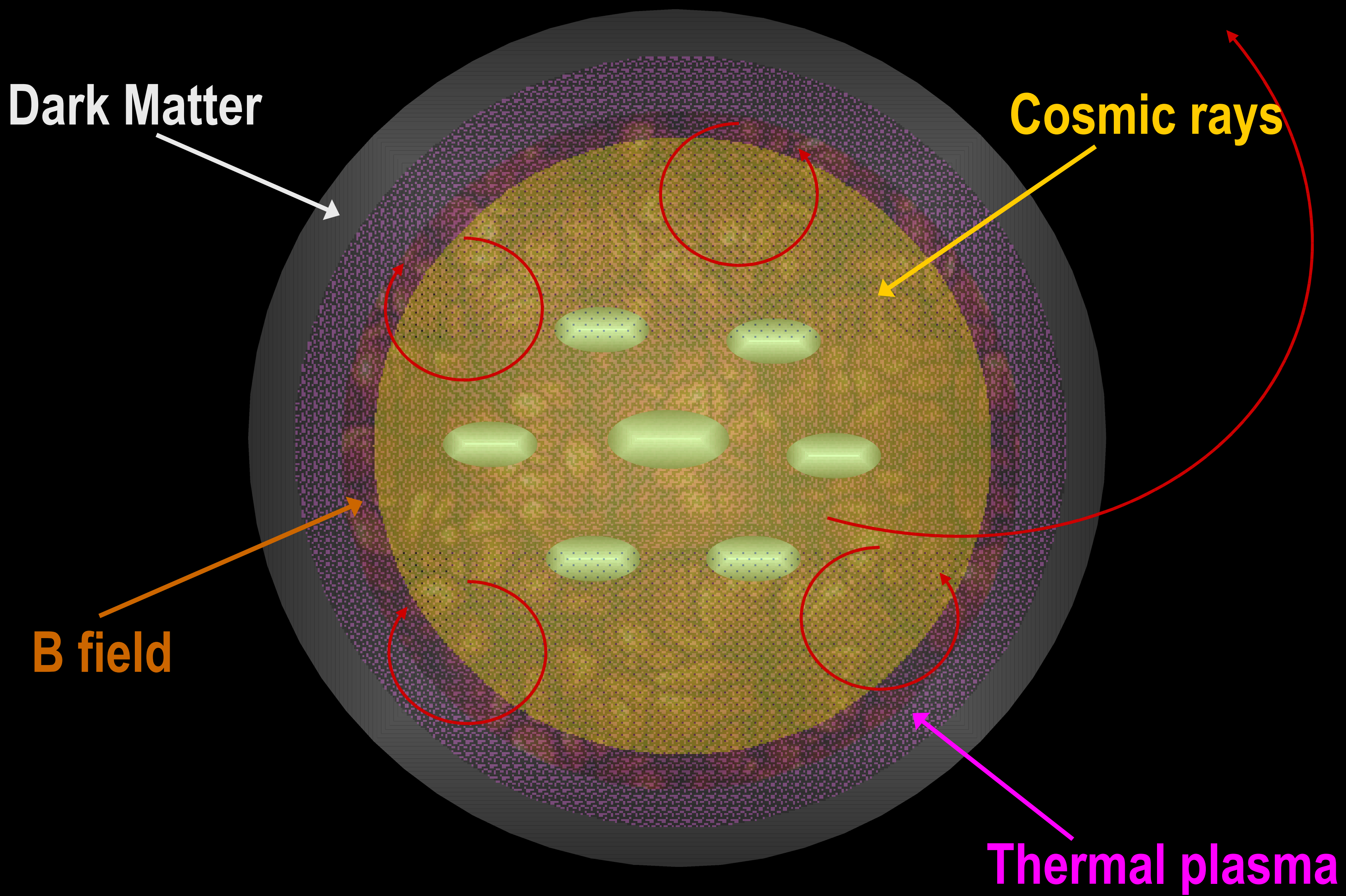




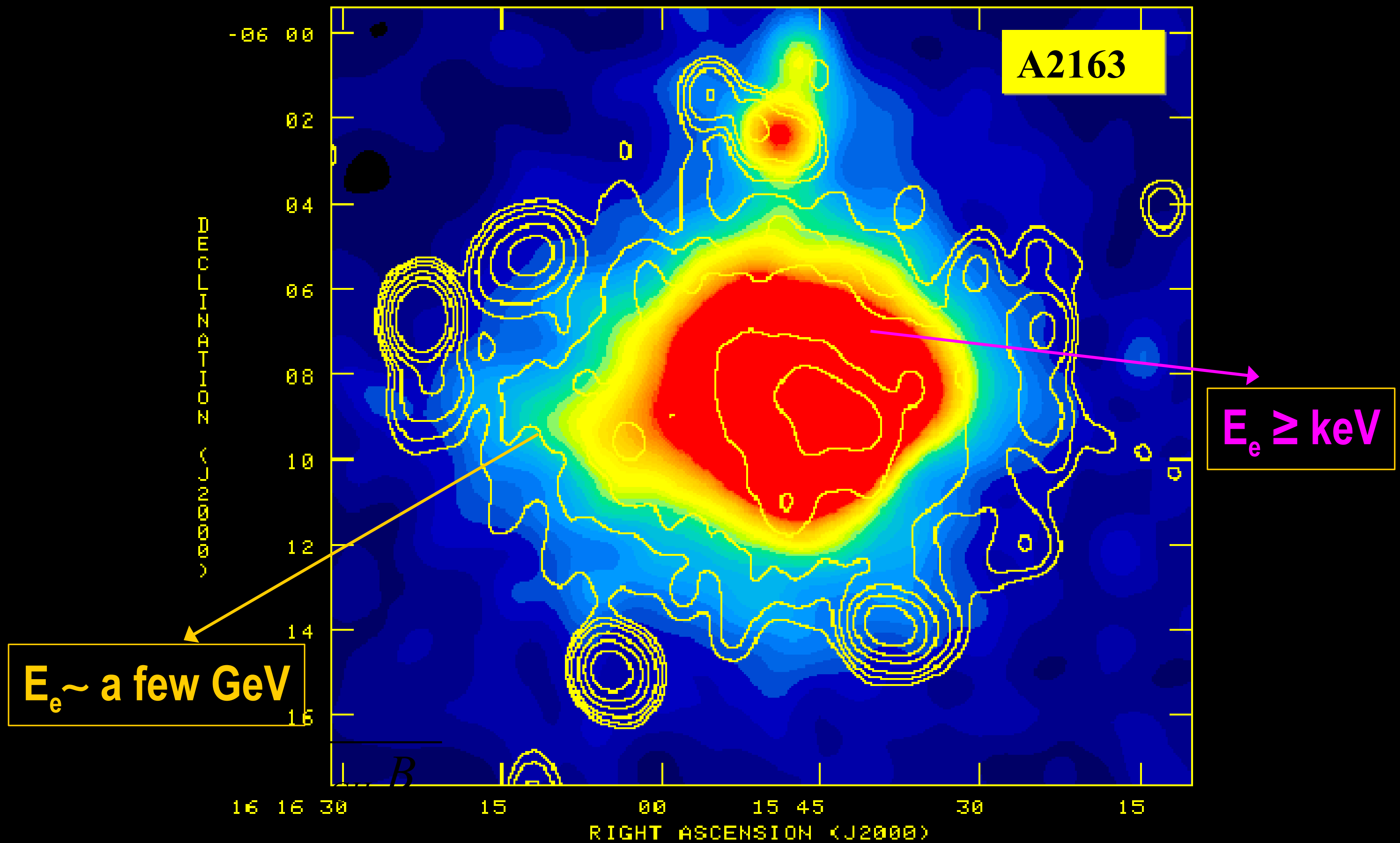




Storage rooms for cosmic material

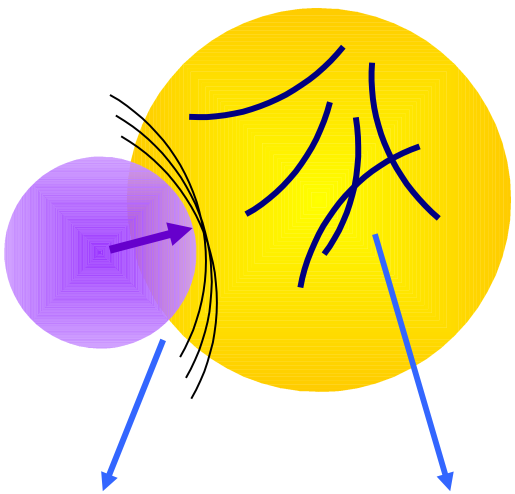
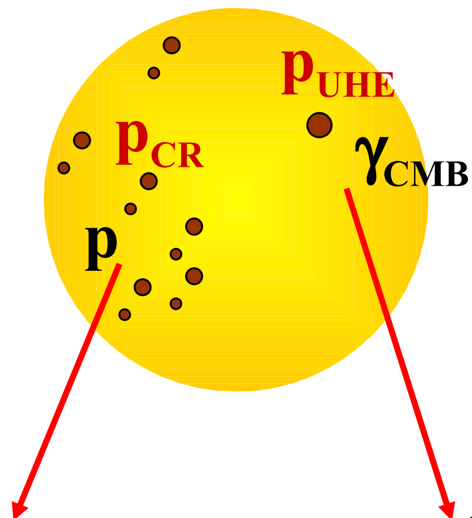


CRs in clusters do exist



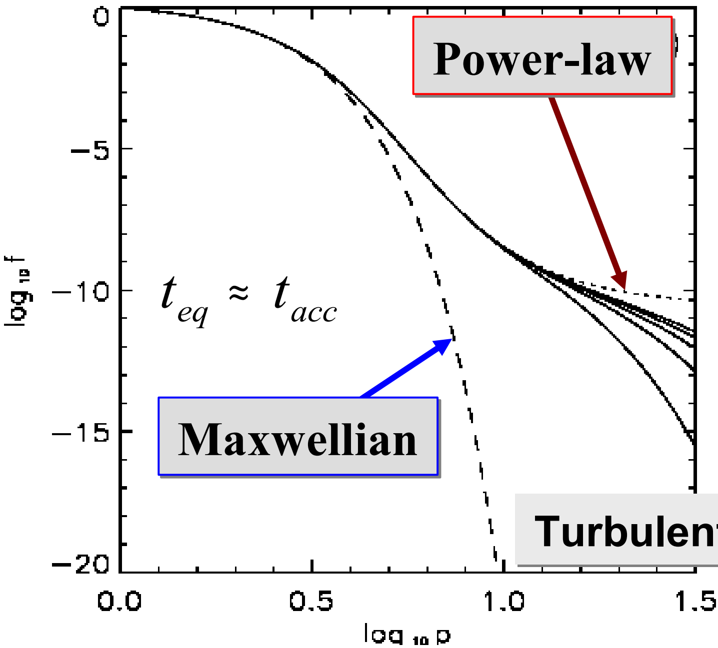
[Feretti et al. 2001]

Cosmic rays in clusters: models

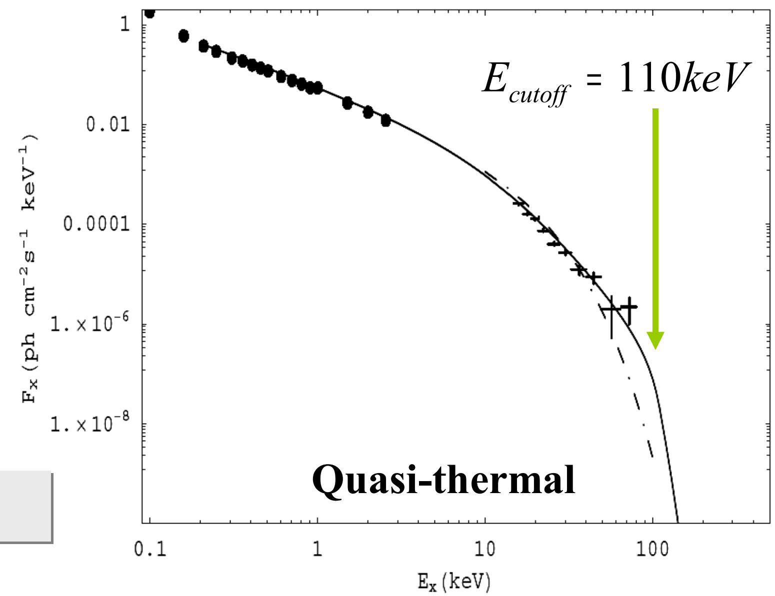
	Acceleration $t_{acc} << t_{loss}, t_{eq}$		**In-situ** $\partial n_e / \partial t \approx 0$	
				
	Direct	**Stochastic**	$\mathbf{p_{CR}}$ **- p**	$\mathbf{p_{UHE}}$ **-** $\boldsymbol{\gamma_{CMB}}$
	e^-, p	e^-, p	$p_{CR} + p \rightarrow X + \pi^{\pm}$ $\pi^{\pm} \rightarrow X + e^{\pm}$	$p_{UHE} + \gamma \rightarrow p + e^{\pm}$
$E_e \approx 10^{-5,-6} GeV$	**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 acceleration efficiency

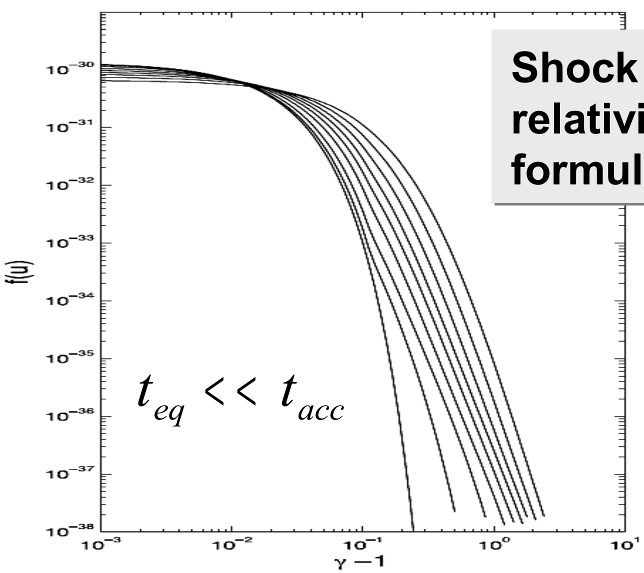
[Dogiel, Colafrancesco et al. 2007]



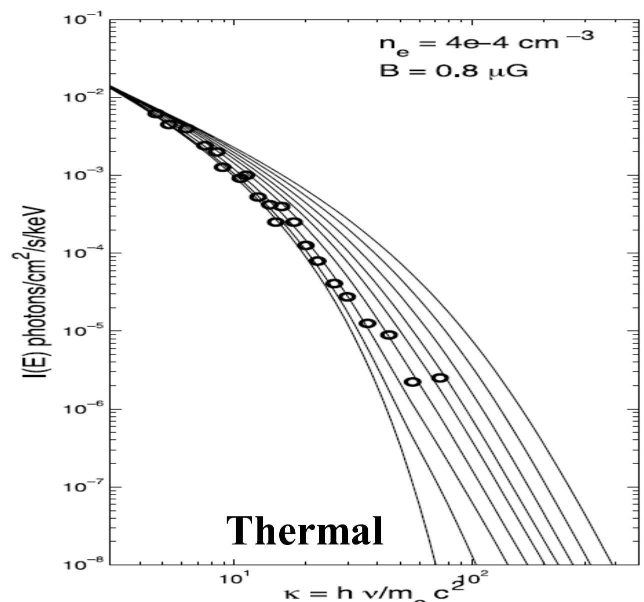
Turbulent acceleration



Shock acceleration: relativistic covariant formulation

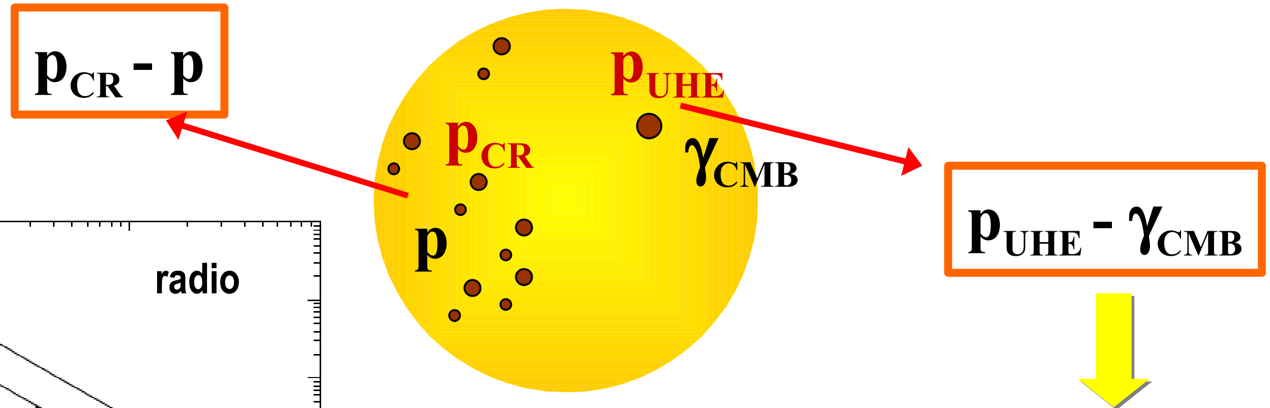


[Wolfe & Melia 2006]

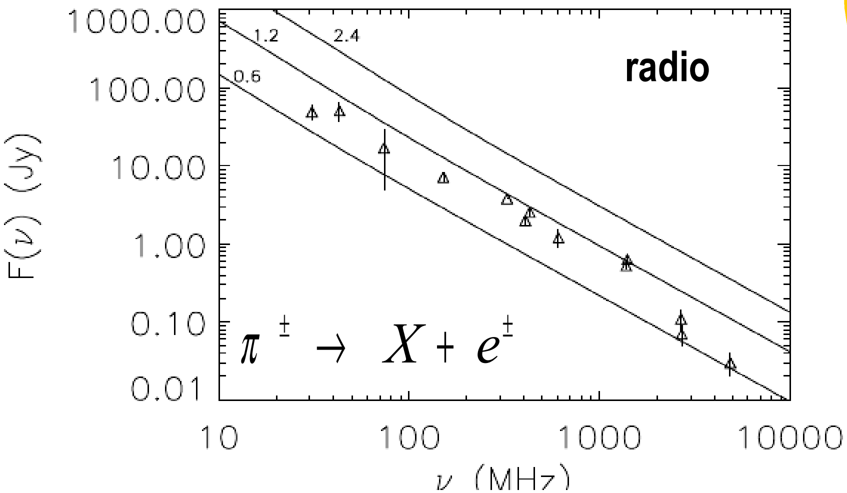


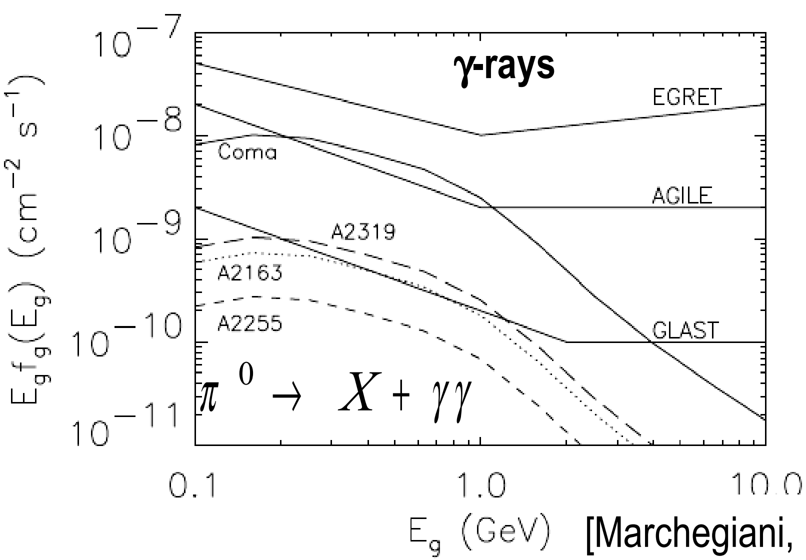
CRs → *in-situ* production

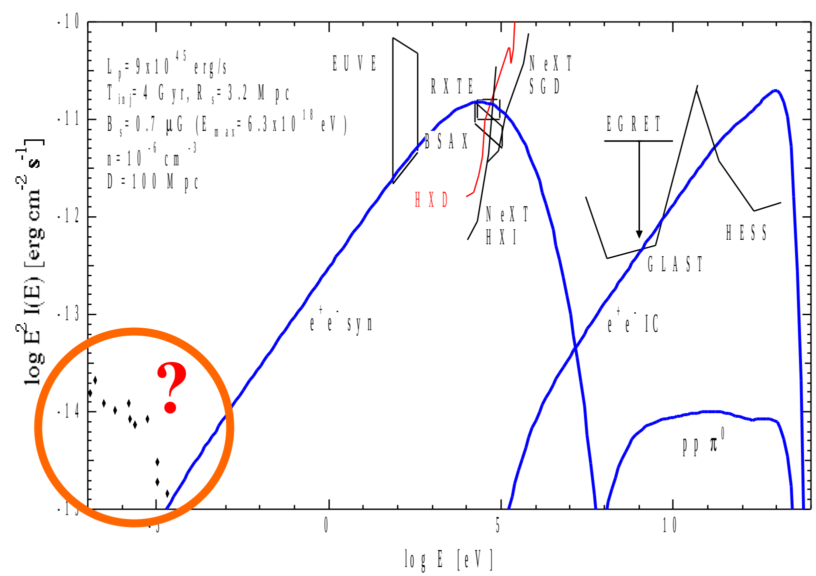
$p_{CR} + p \to X + \pi^{0,\pm}$



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



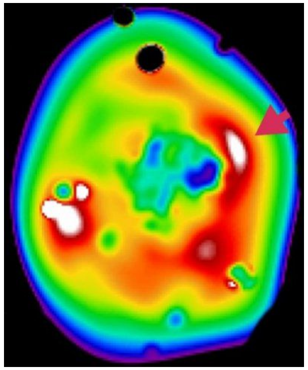




[Marchegiani, Perola & S.C. 2007]

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

CRs → production



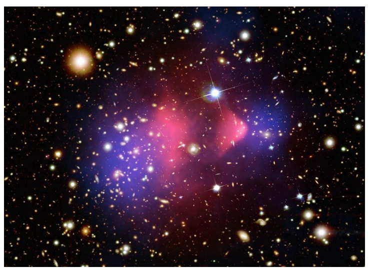
Merging

• Shock-acceleration

• Re-acceleration

Inefficient

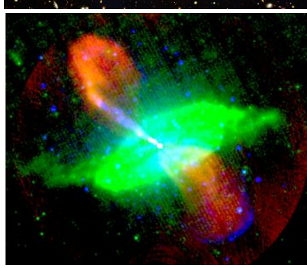
Fine-tuned



Dark Matter annihilation

Stationary CR production

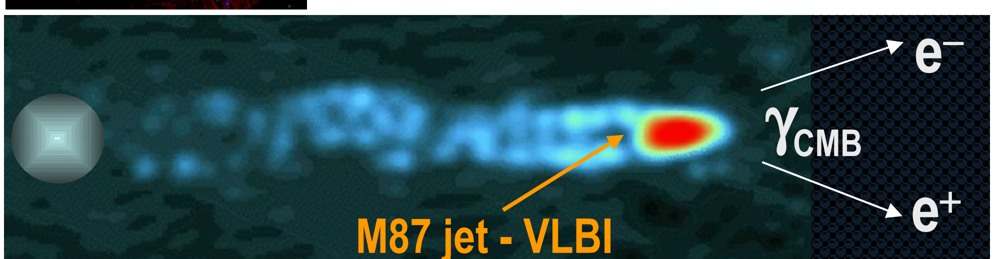
Stationary Seed-population



Jets

CR injection

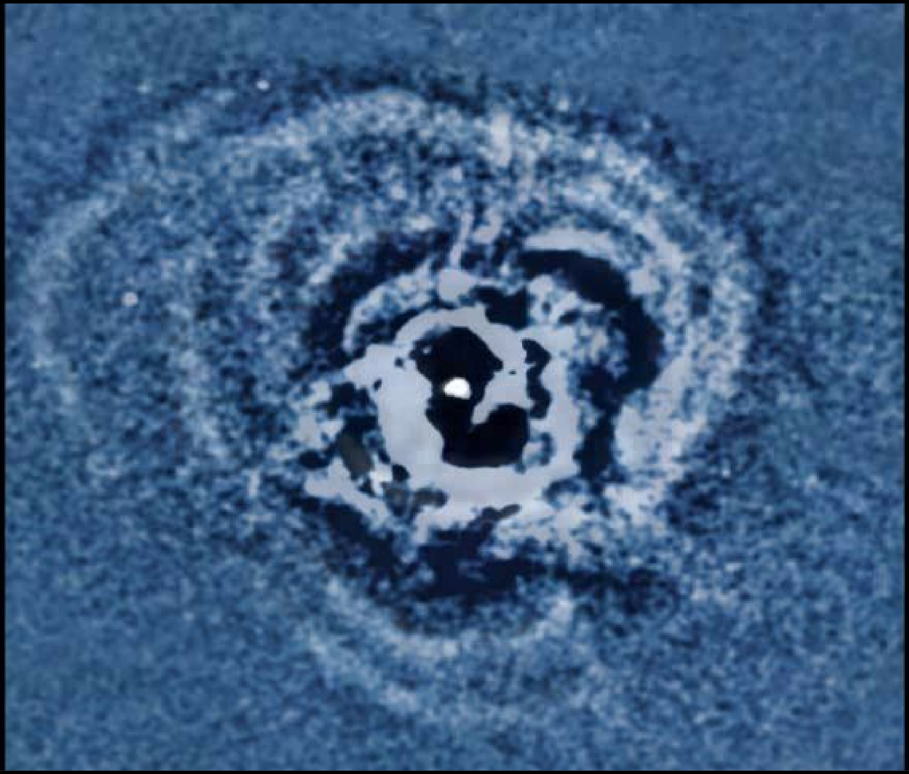
Continuous accumulation of p_{CR}



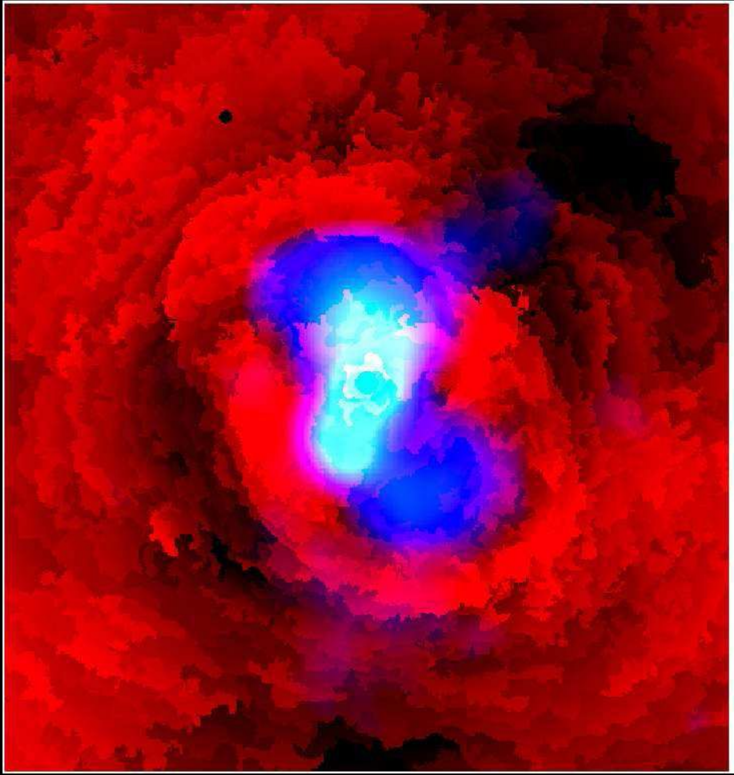
Very High-E jet source

BHs in clusters

Cavities - Pressure waves



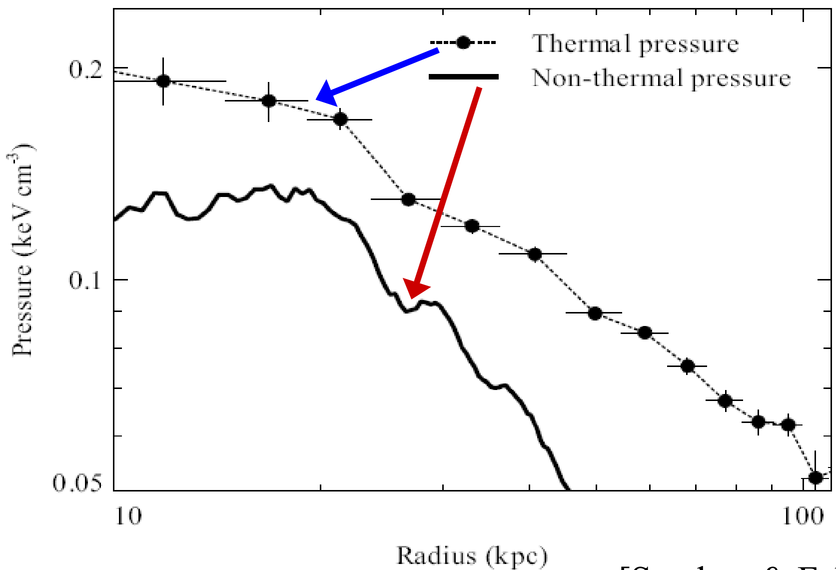
Relativistic plasmas



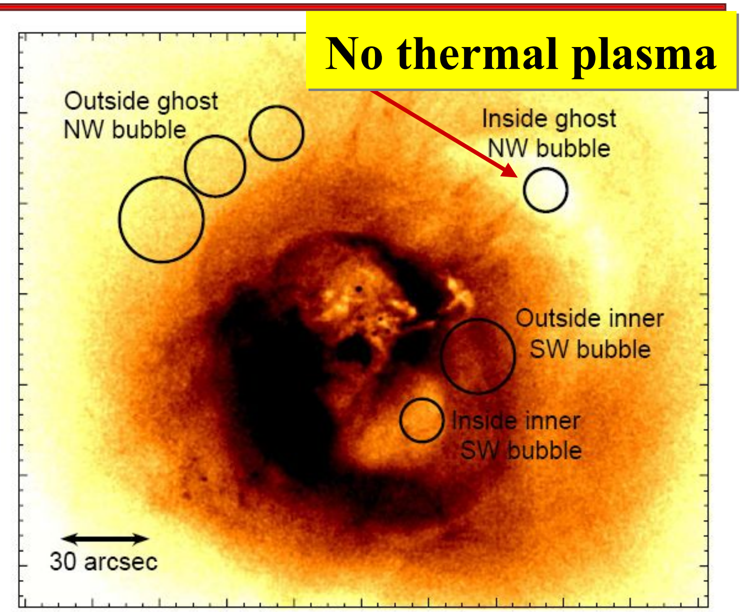
Perseus cluster

[Fabian et al. 2005]

BHs, CRs & Cooling Flows



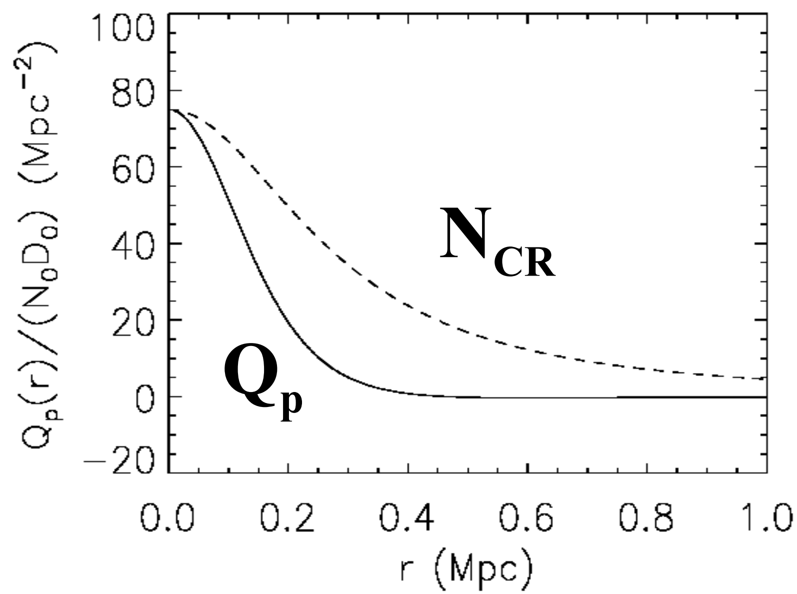
[Sanders & Fabian 2007]



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

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

[Colafrancesco & Marchegiani 2007]

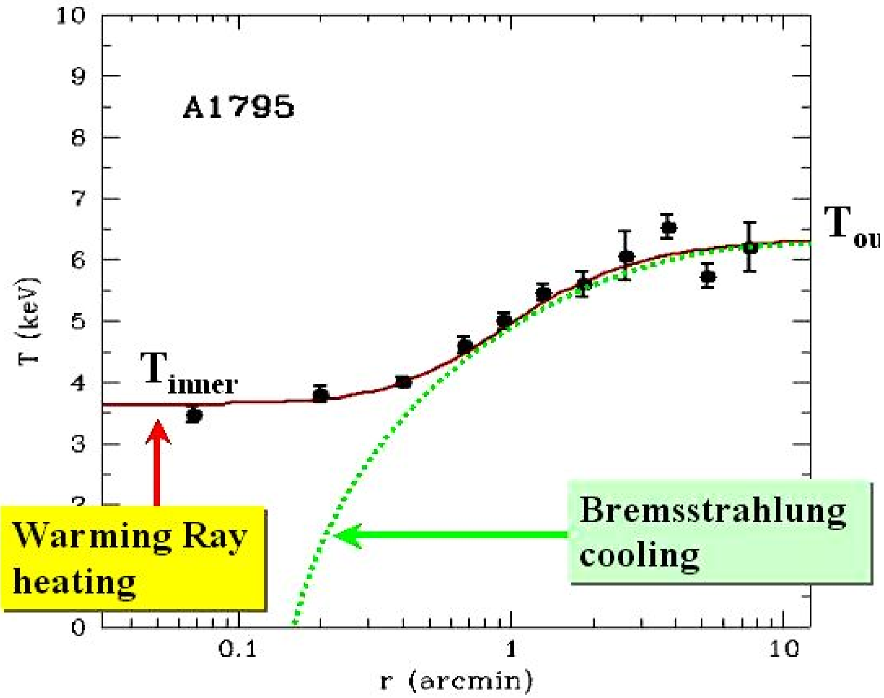


Warming Rays in cool cores

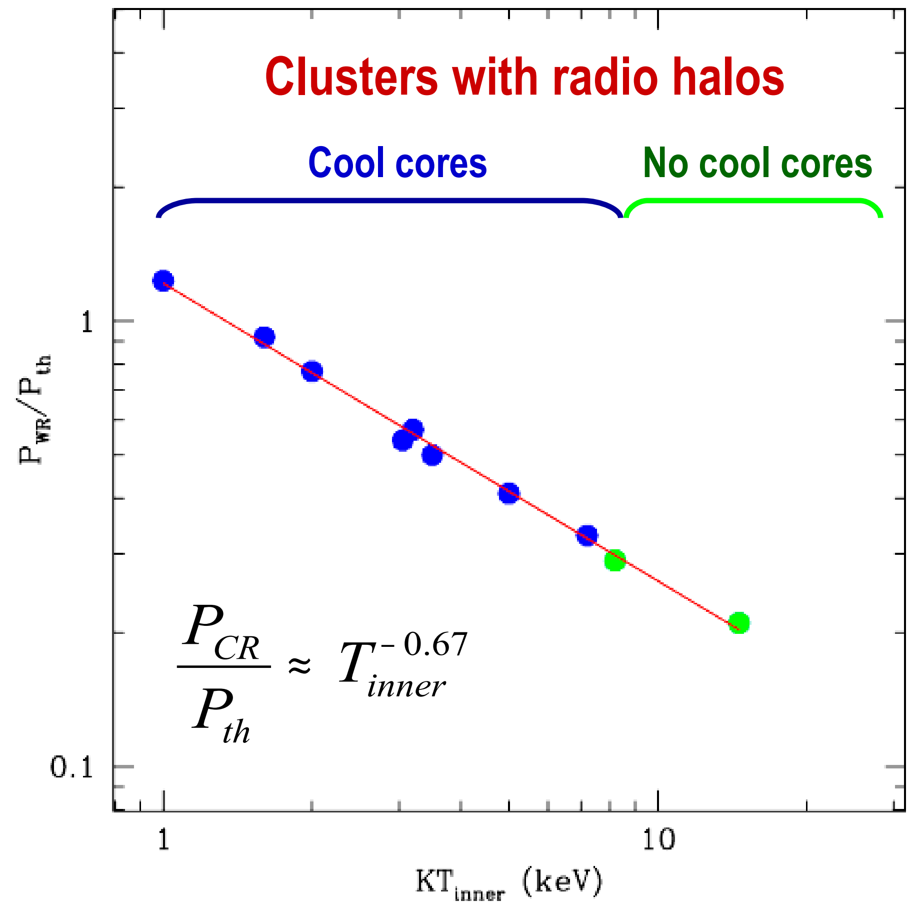
$$3kn(r)\frac{dT(r,t)}{dt} = \left(\frac{dE}{dt}\right)_{WR} - \left(\frac{dE}{dt}\right)_{X}$$

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

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



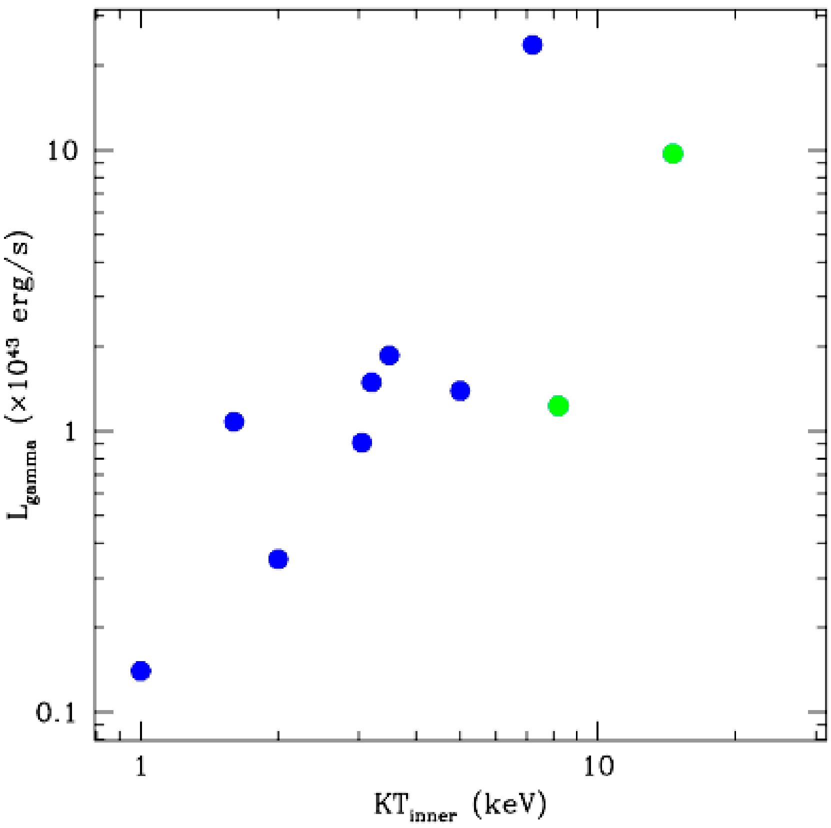
[Colafrancesco, Dar & deRujula 2004]

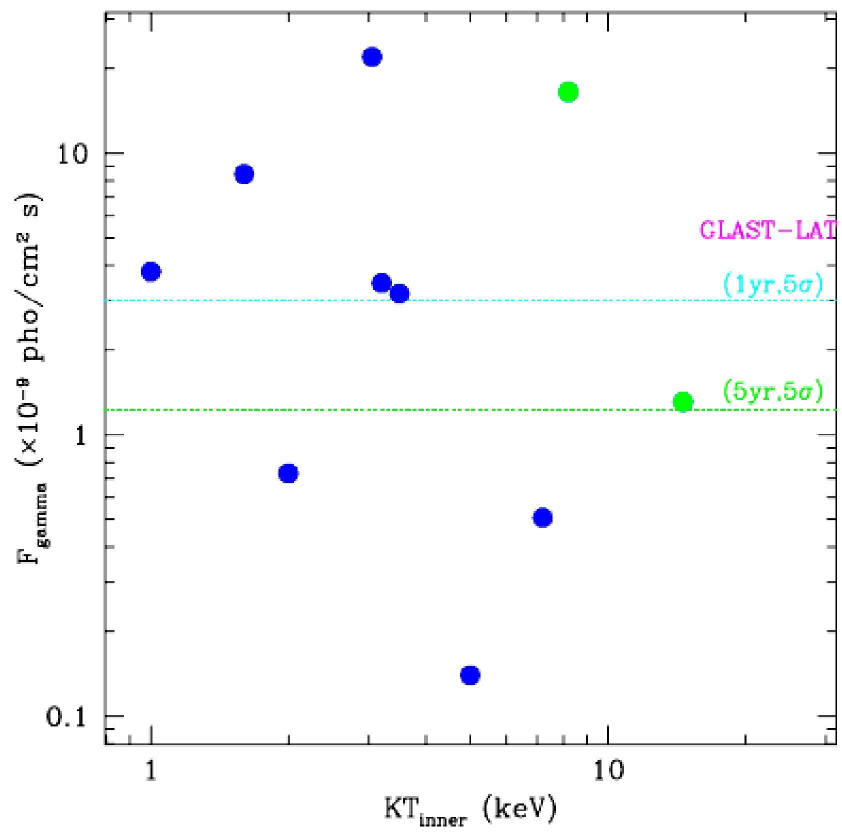


[Colafrancesco & Marchegiani 2007]

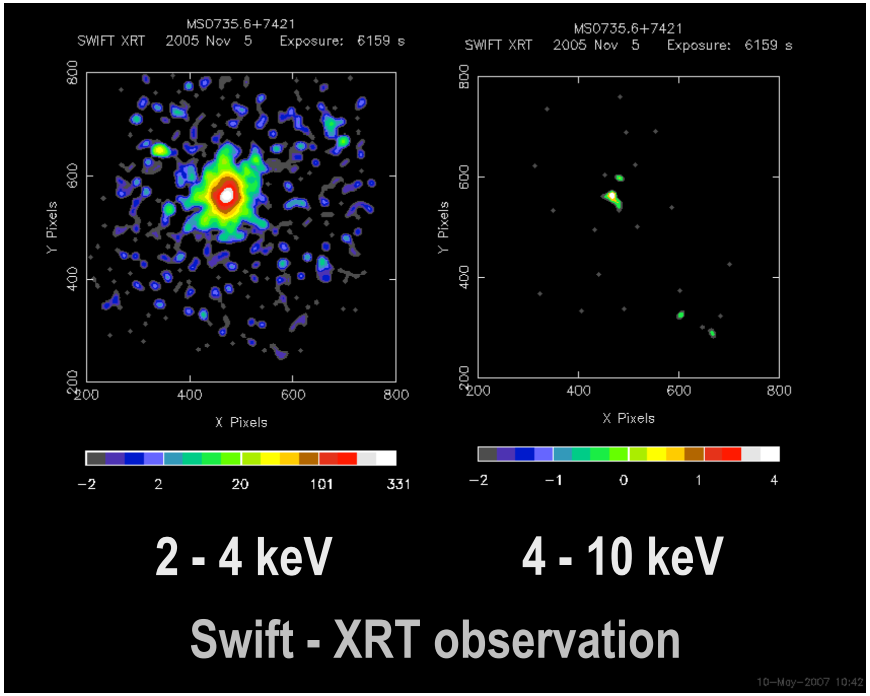
BHs,CRs, CFs, HXR and γ-rays

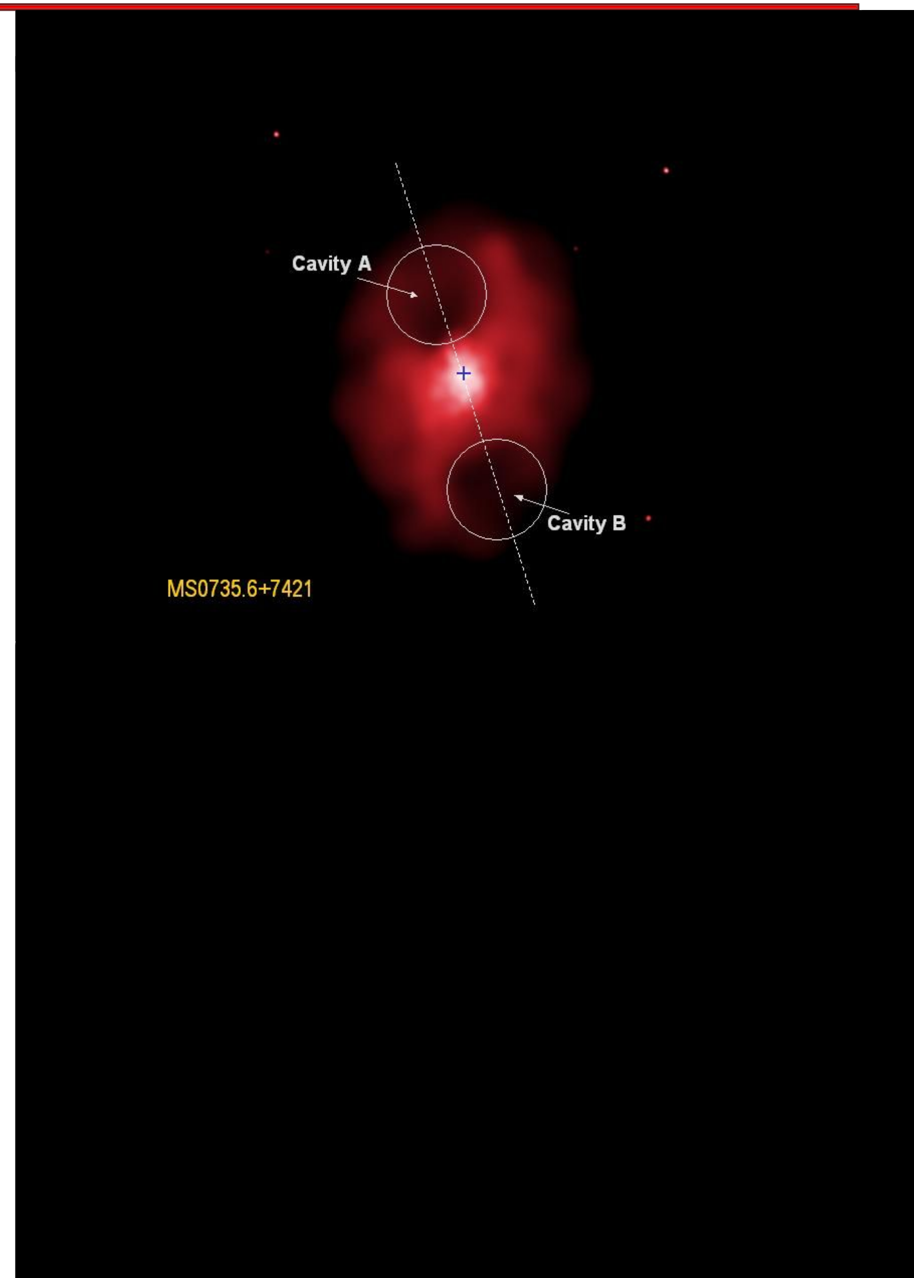
Cluster	α	$n_{WR,0}$ cm^{-3}	P_{WR}/P_{th}	F_γ cm^{-2} s^{-1}	L_γ erg s^{-1}	F_{HXR} erg cm^{-2} s^{-1}
A262	0.83	2.20×10^{-3}	1.23	3.89×10^{-9}	1.43×10^{42}	3.87×10^{-14}
A2199	0.83	2.31×10^{-3}	0.92	8.43×10^{-9}	1.08×10^{43}	3.06×10^{-13}
A133	0.84	4.56×10^{-4}	0.77	7.30×10^{-10}	3.53×10^{42}	6.10×10^{-15}
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}

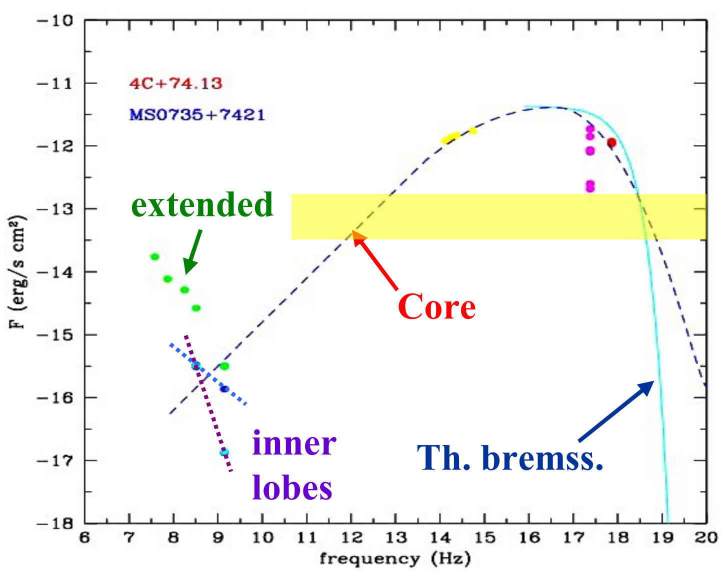




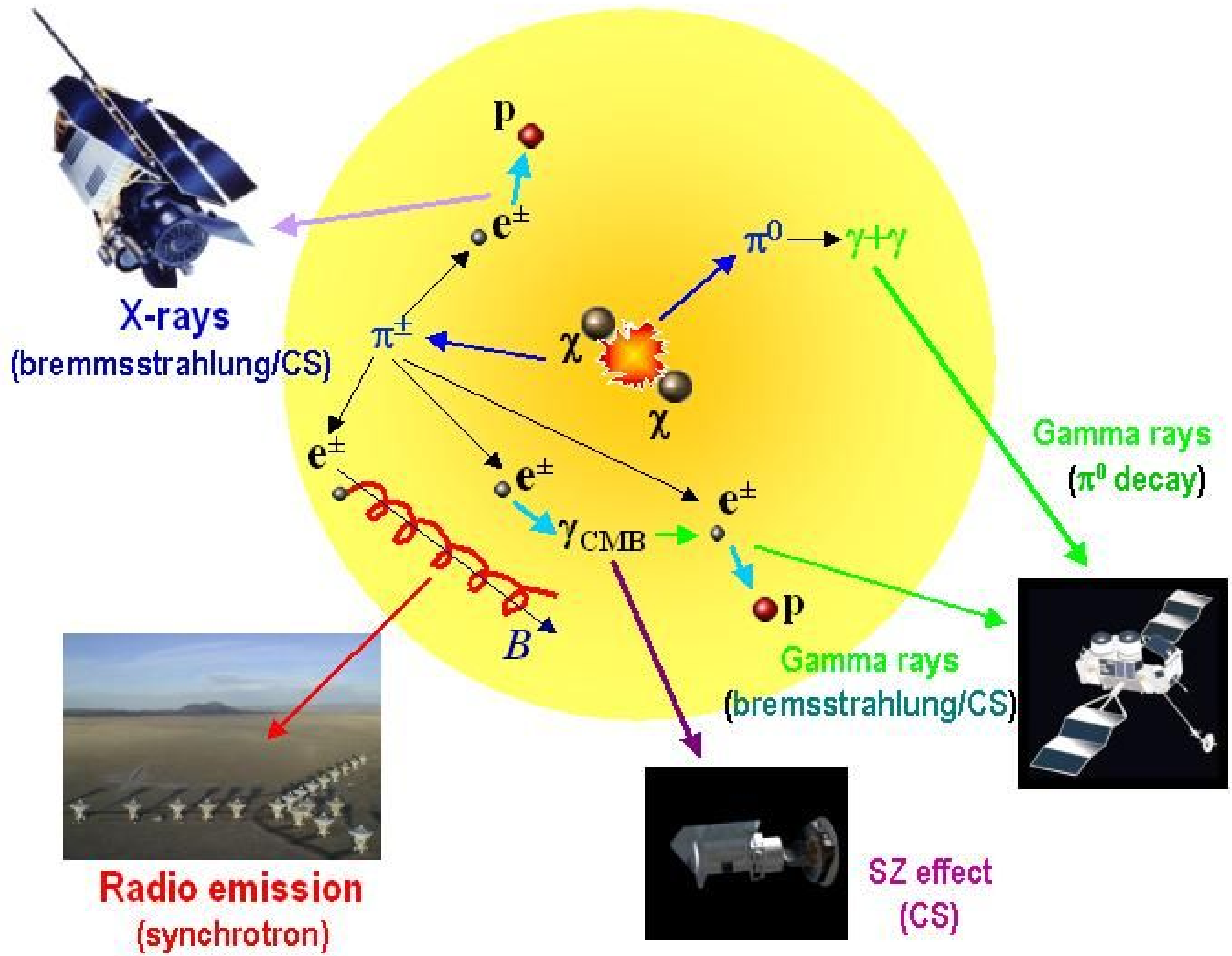
Xrays from BHs & cavities in clusters



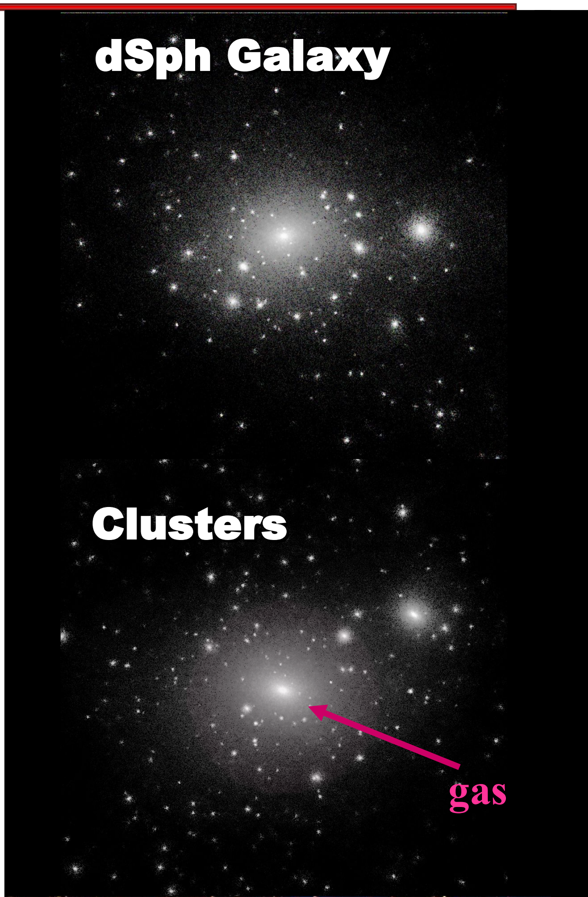




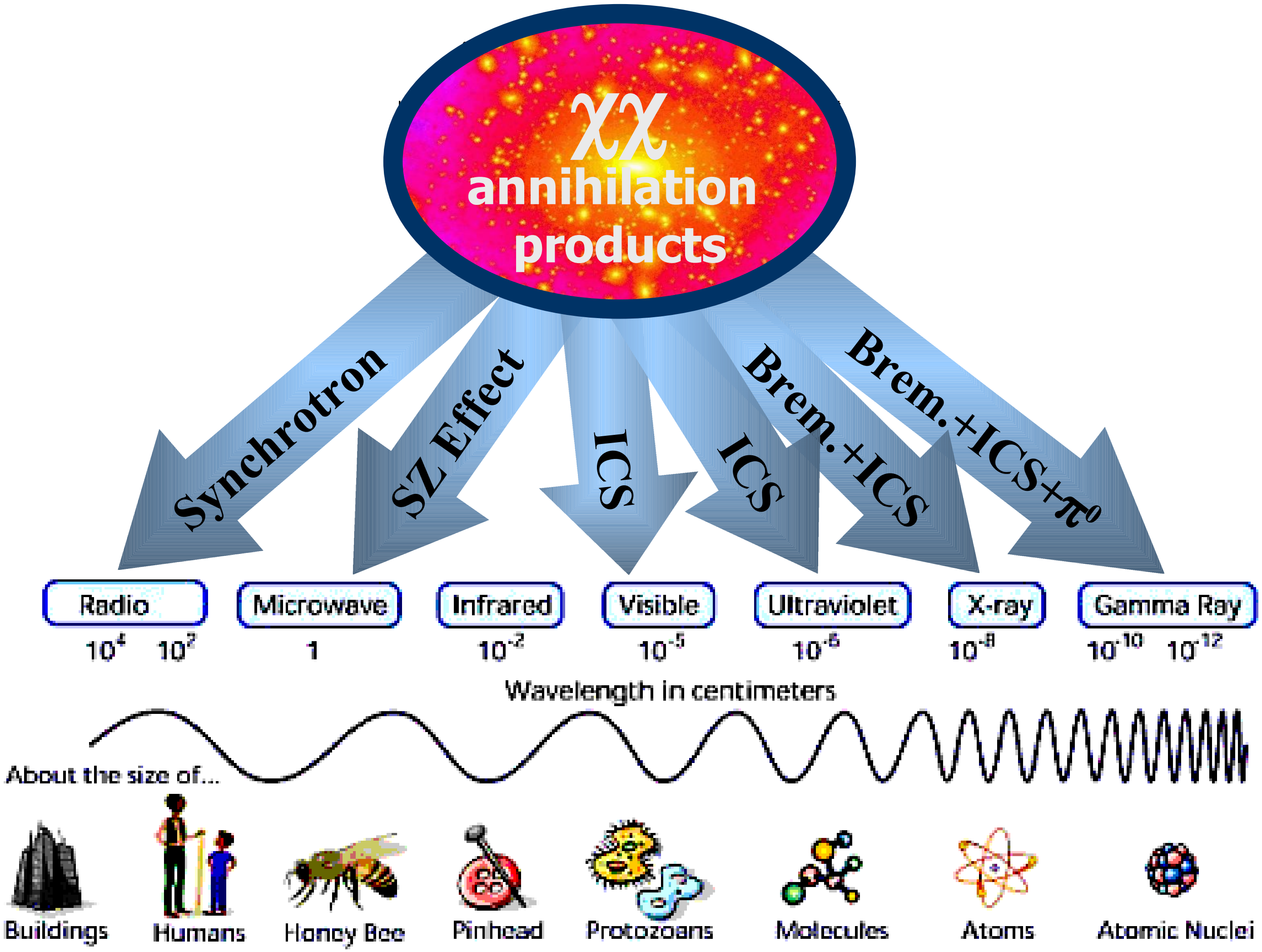
DM signals Best Labs.



[Colafrancesco 2006, 2007]

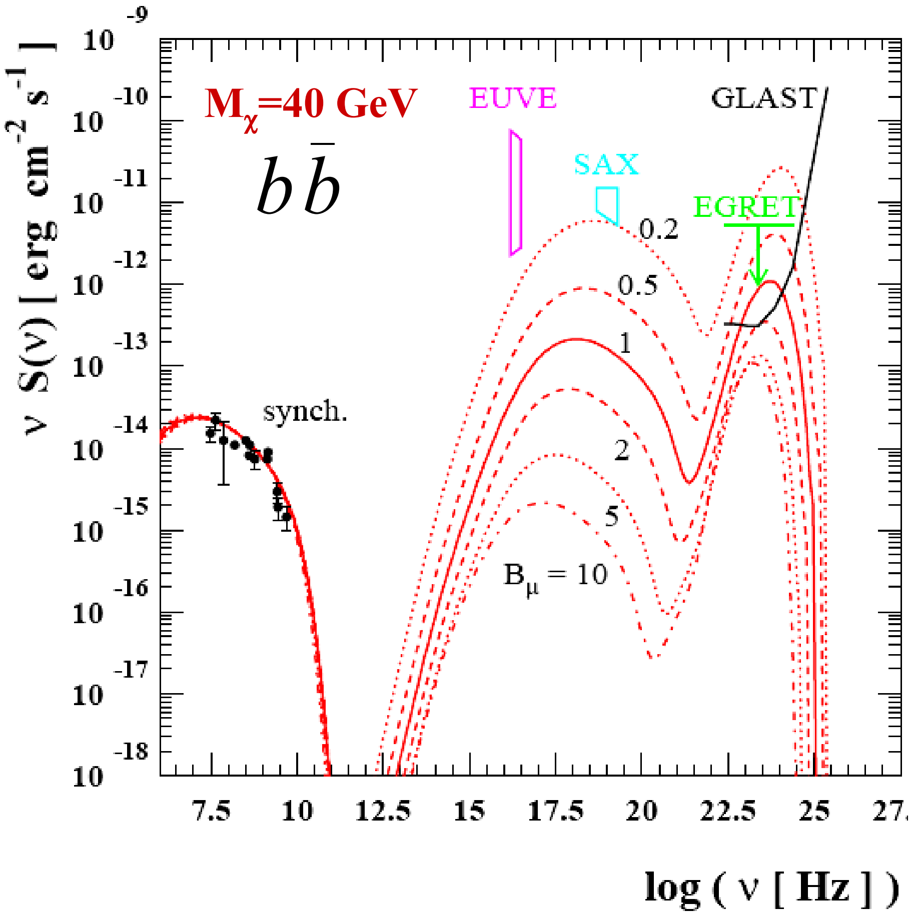


Covering the whole e.m. spectrum

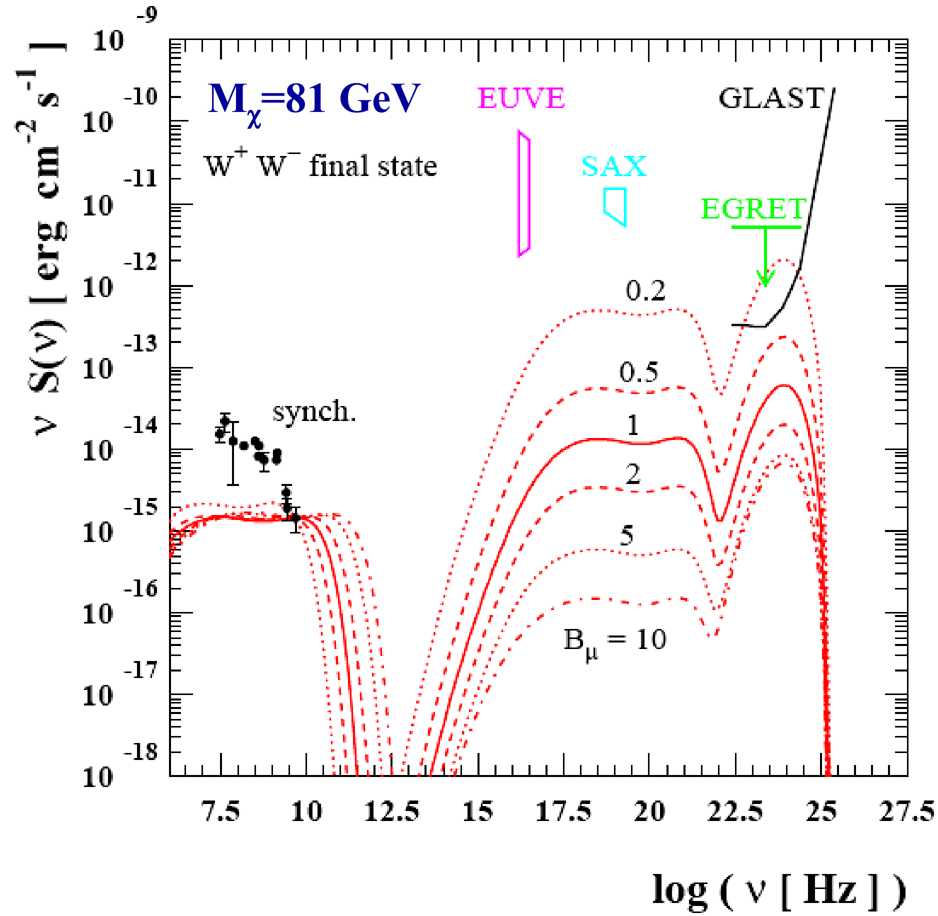


Neutralino DM annihilation

Soft χ model

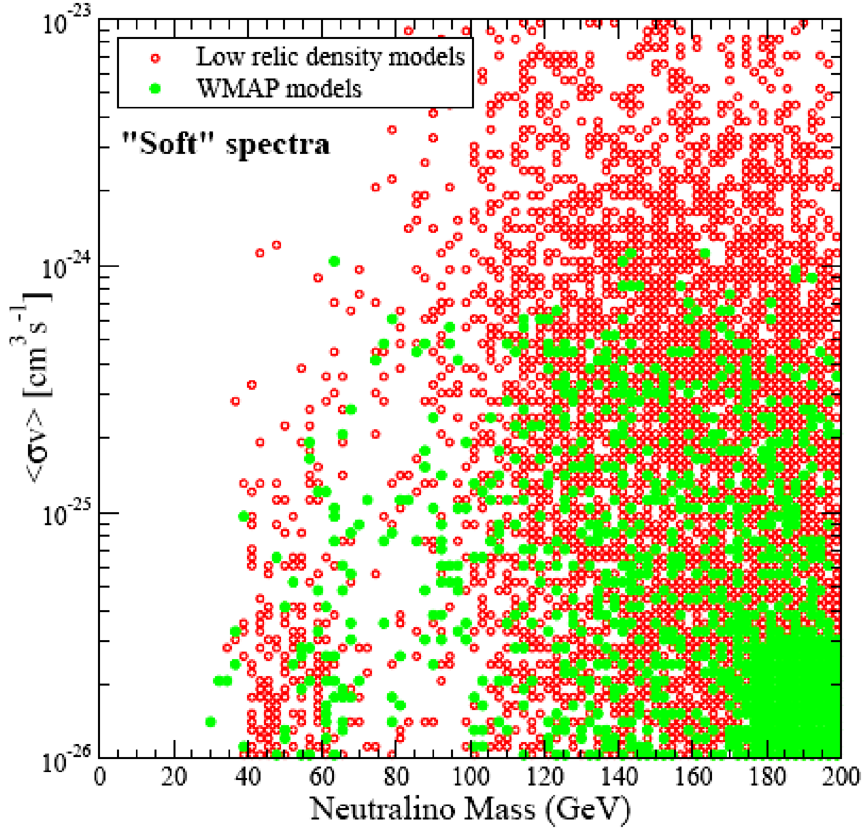


Hard χ model

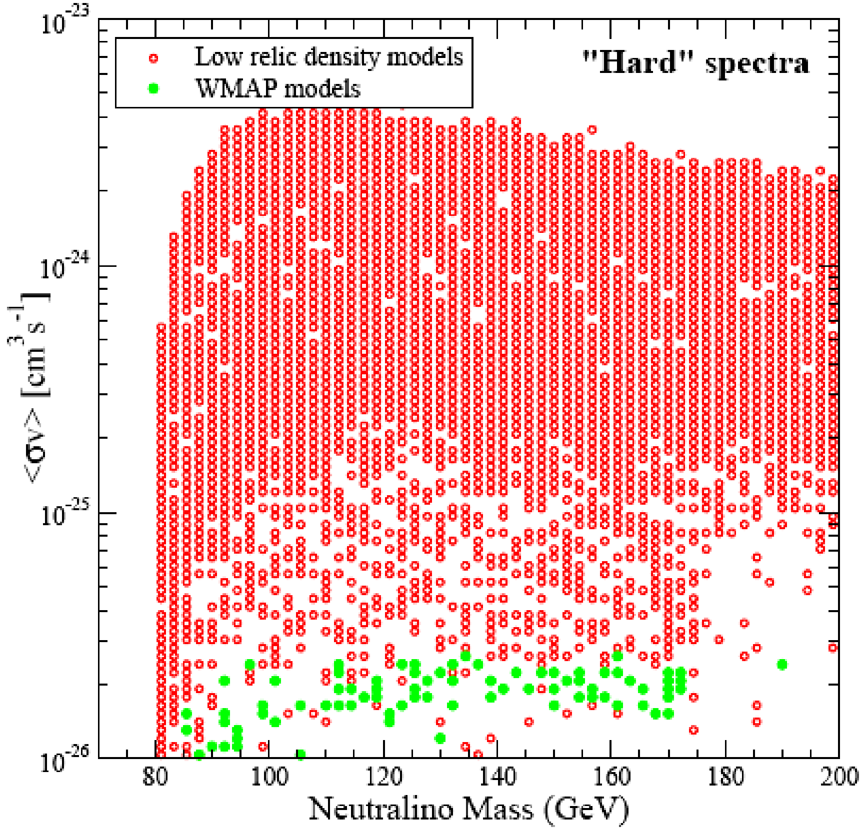


Exclusion plots

Soft χ model



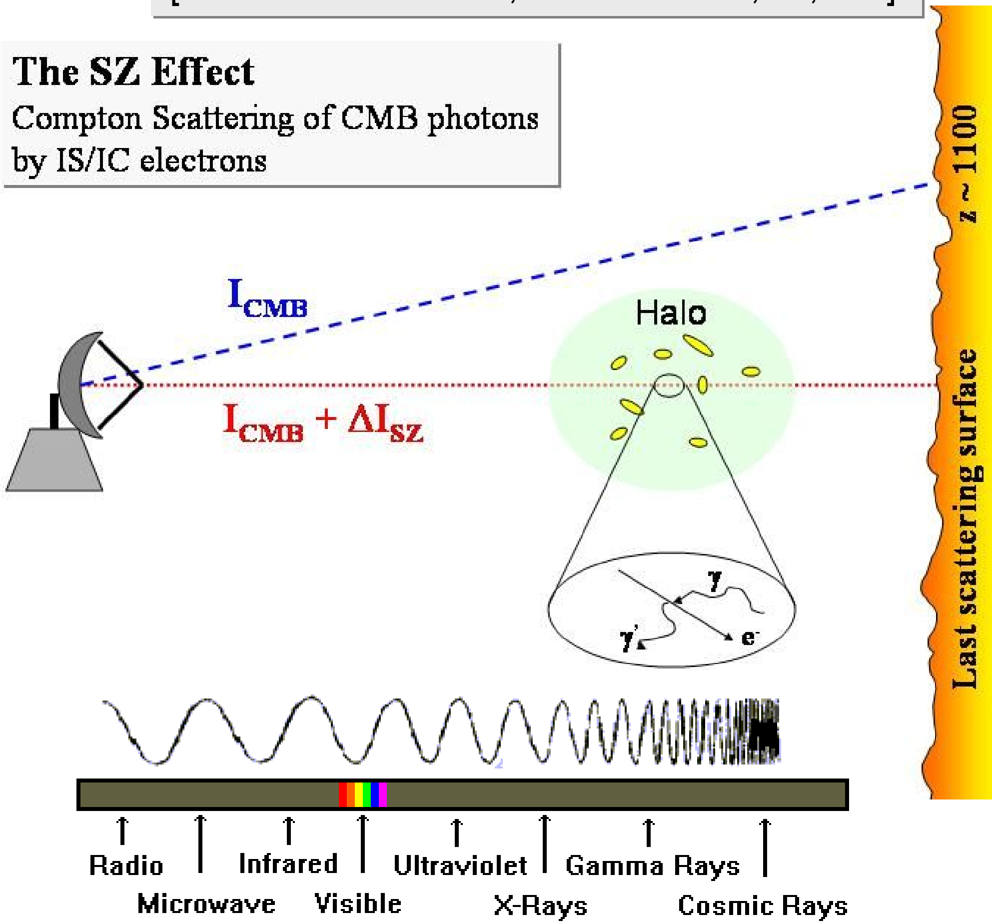
Hard χ model

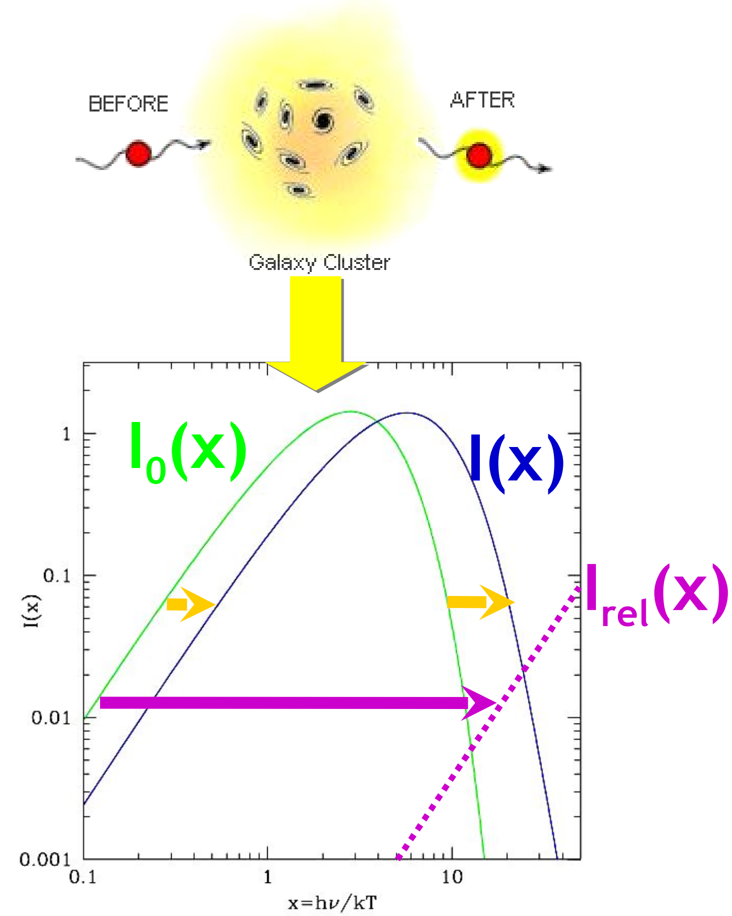


SZE: probe of cluster atmospheres

[**Colafrancesco** 2007, New Astr.Rev., 51, 394]

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





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

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

SZE: general derivation

[Colafrancesco & 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

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

Relativistic

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

Spectral shape

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

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

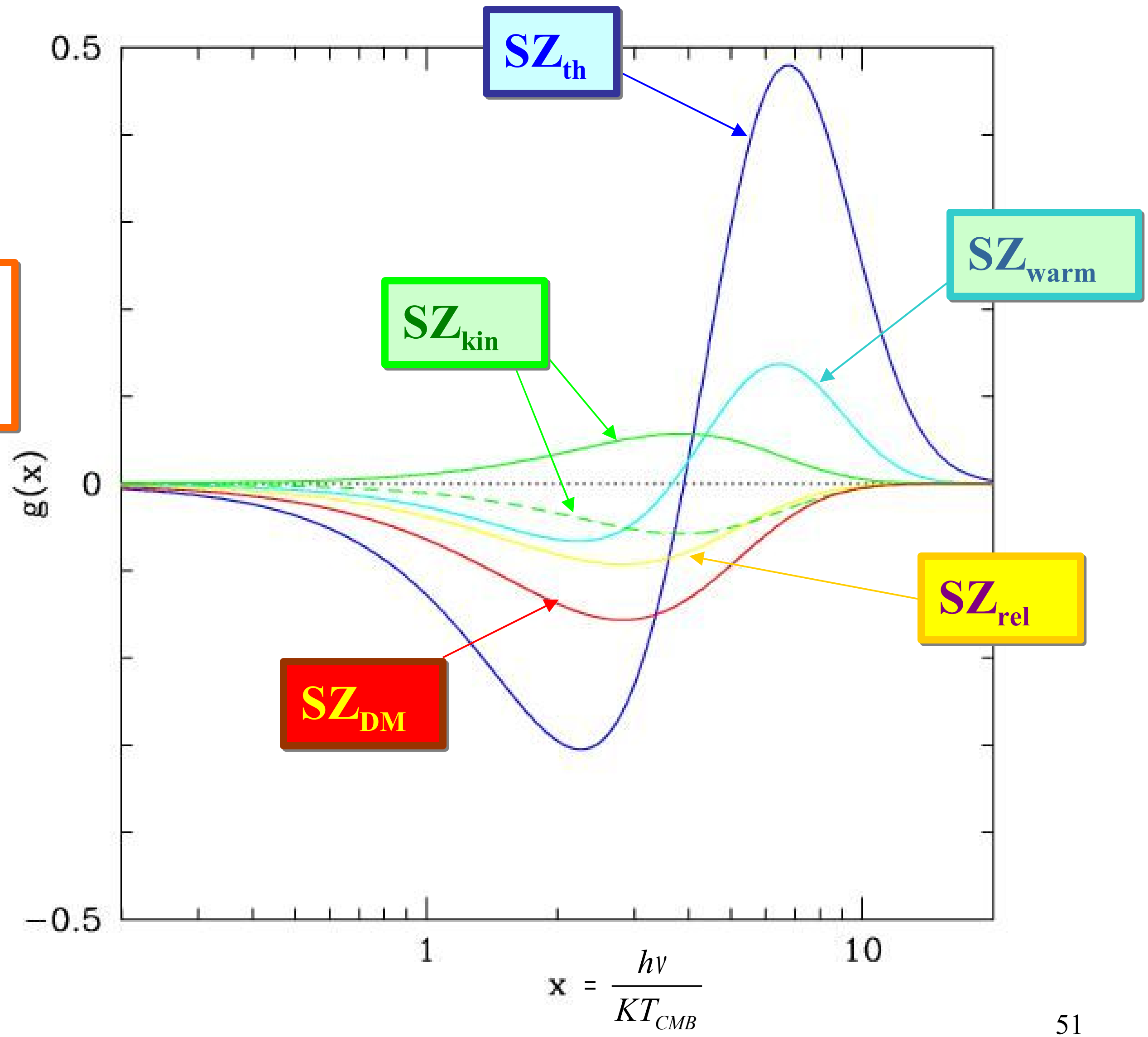
Redistribution function

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

The SZE from various e± populations

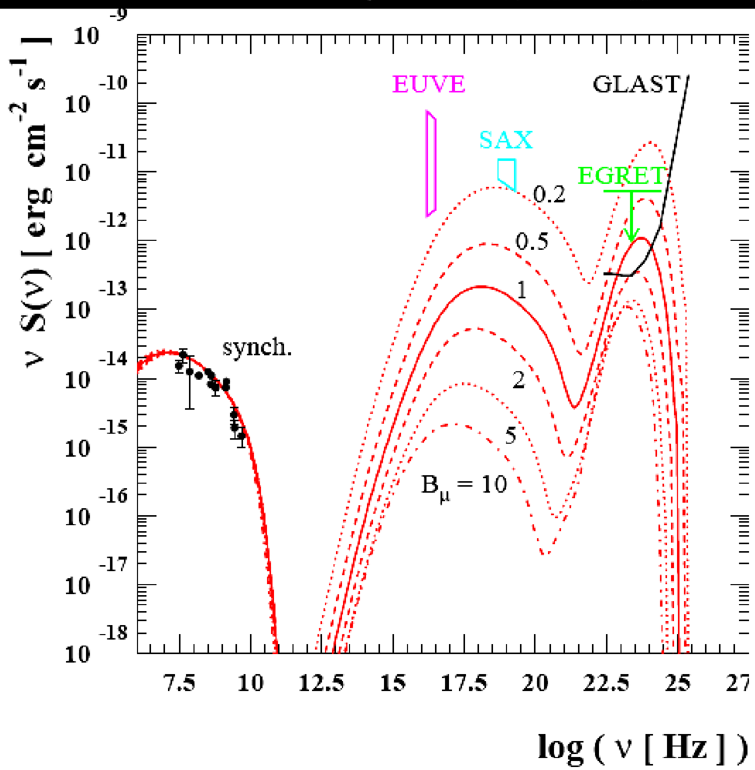
$$\Delta I(x) = 2\frac{(k_B T_0)^3}{(hc)^2} y \tilde{g}(x)$$

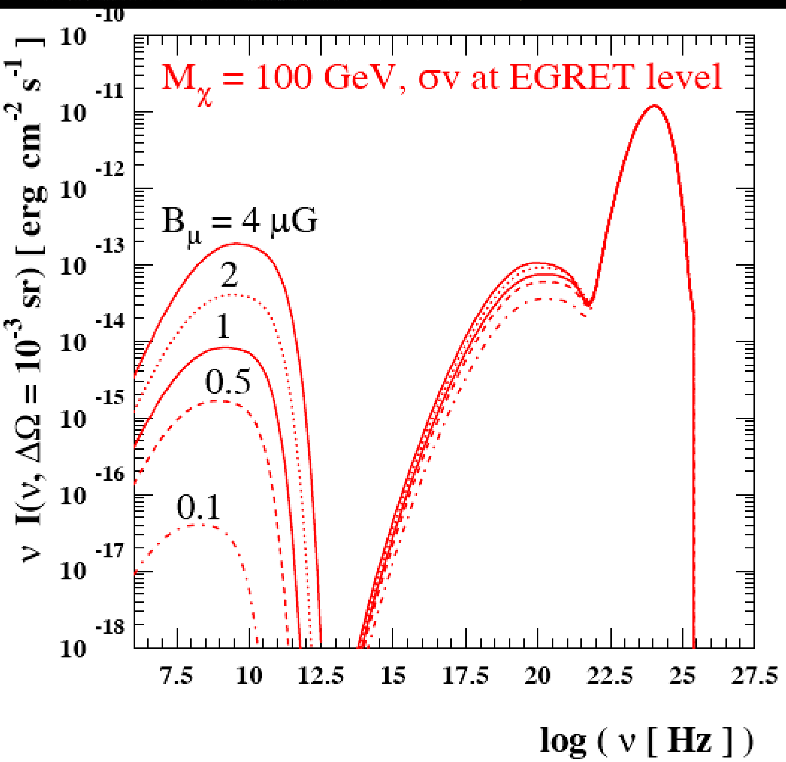
$$y = \frac{\sigma_T}{m_e c^2} \int P d\ell.$$



[Colafrancesco et al. 2007]

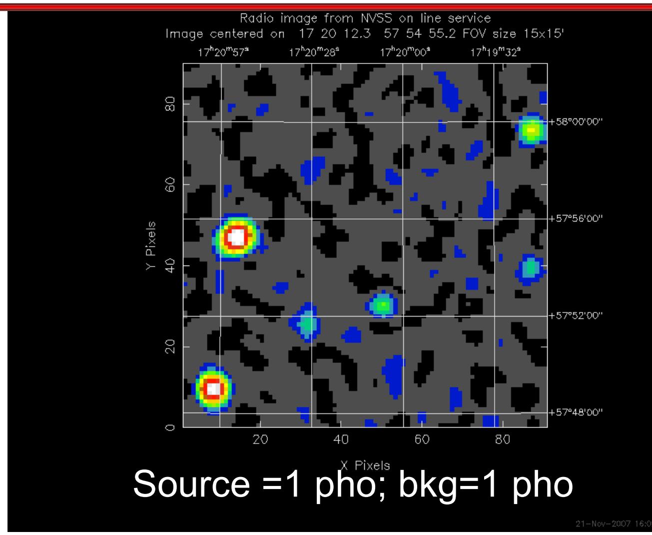
Dark Matter clumps at high-E





The strange case of the Draco dSph.

EGRET
E>100 MeV



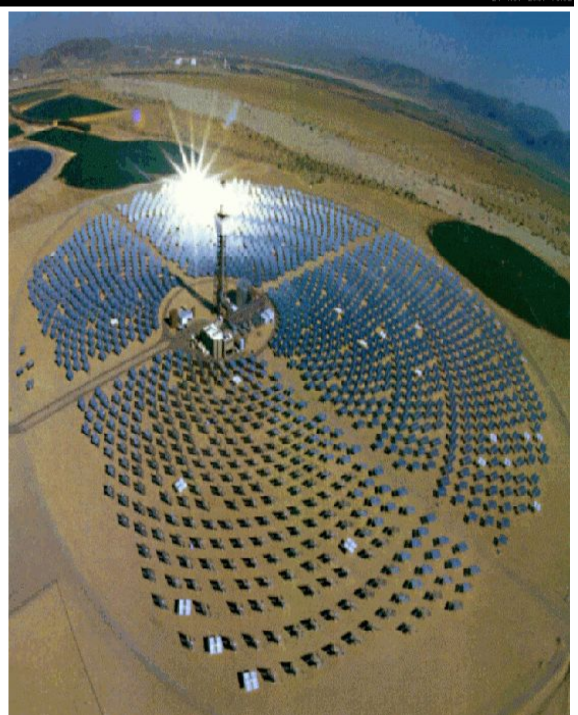
EGRET: < 1. 10^{-11} pho cm^{-2} s^{-1} (E >100 MeV)

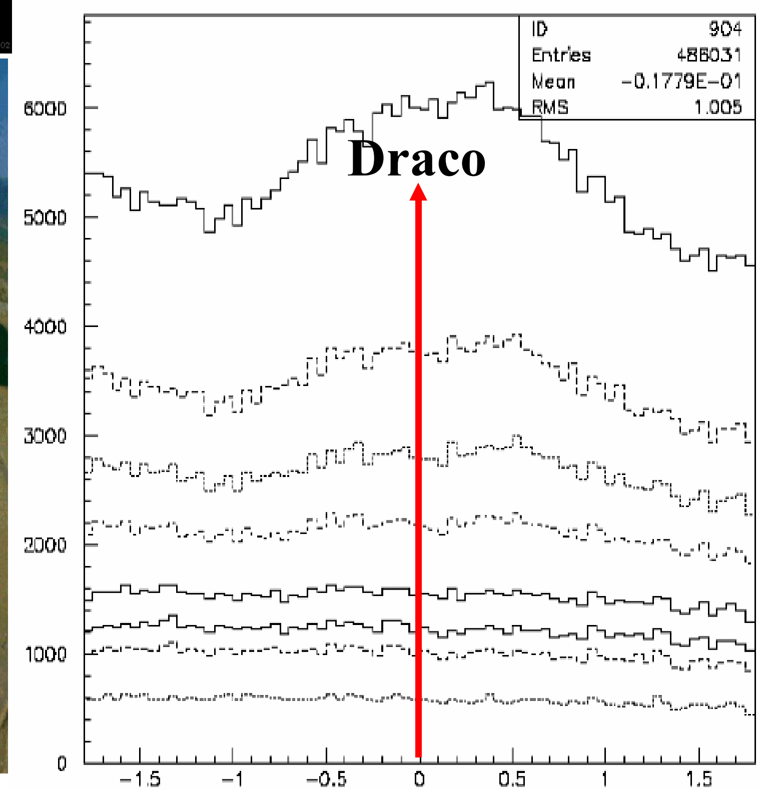
Whipple: < 5.1 10^{-12} erg cm^{-2} s^{-1} (E=400 GeV)

MAGIC: < 1.1 10^{-11} pho cm^{-2} s^{-1} (E >140 GeV)

STACEE: < 4 10^{-8} pho cm^{-2} s^{-1} GeV^{-1} (E= 220 GeV)

Cactus
E>100 MeV





All Data

P.H.>100

P.H.>125

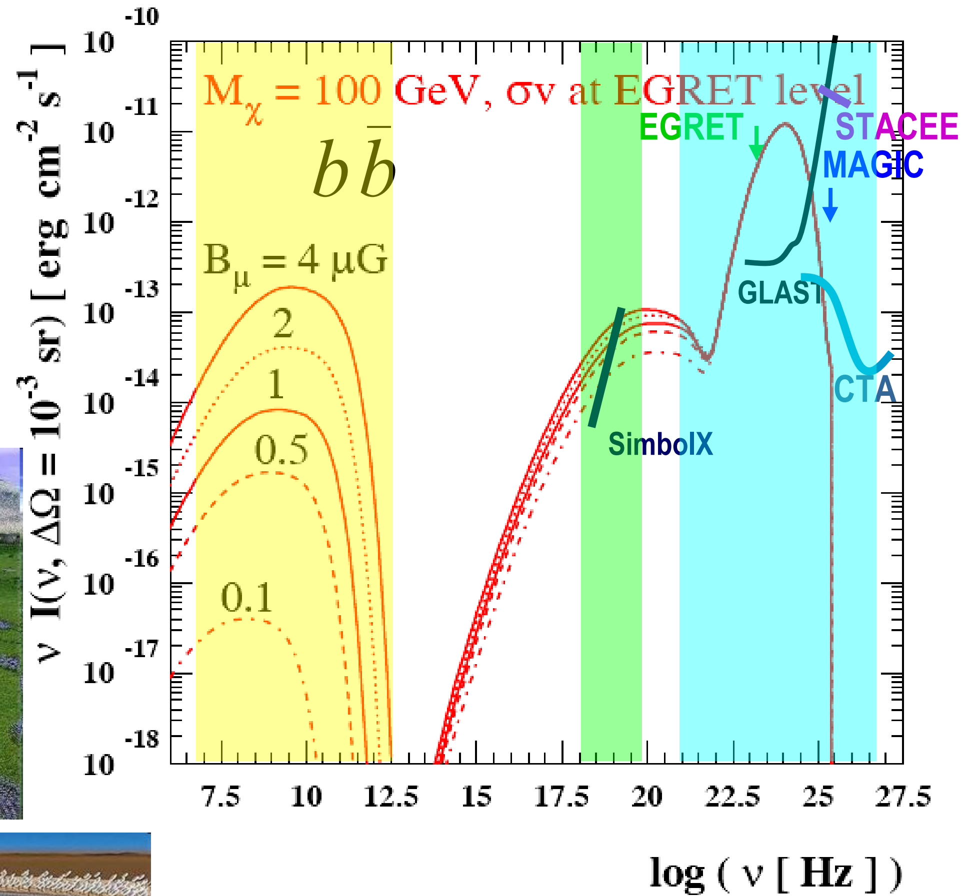
P.H.>150

Only positive result

- never published
- 3 papers on WEB
- no one published

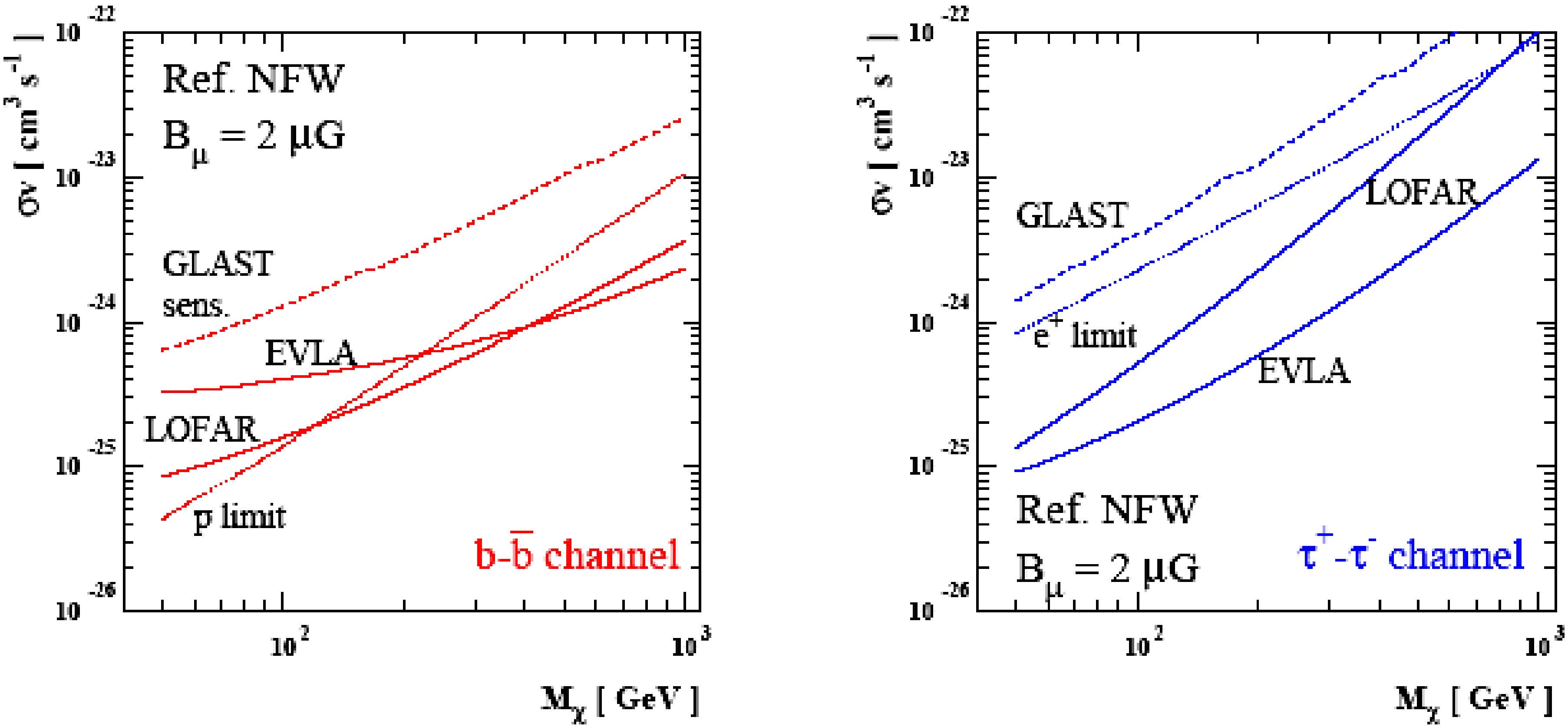
?

Draco: a multifrequency perspective



Draco: constraints on χ physics

Radio + γ-rays



[Colafrancesco, Profumo & Ullio 2007 (astro-ph/0607073)]

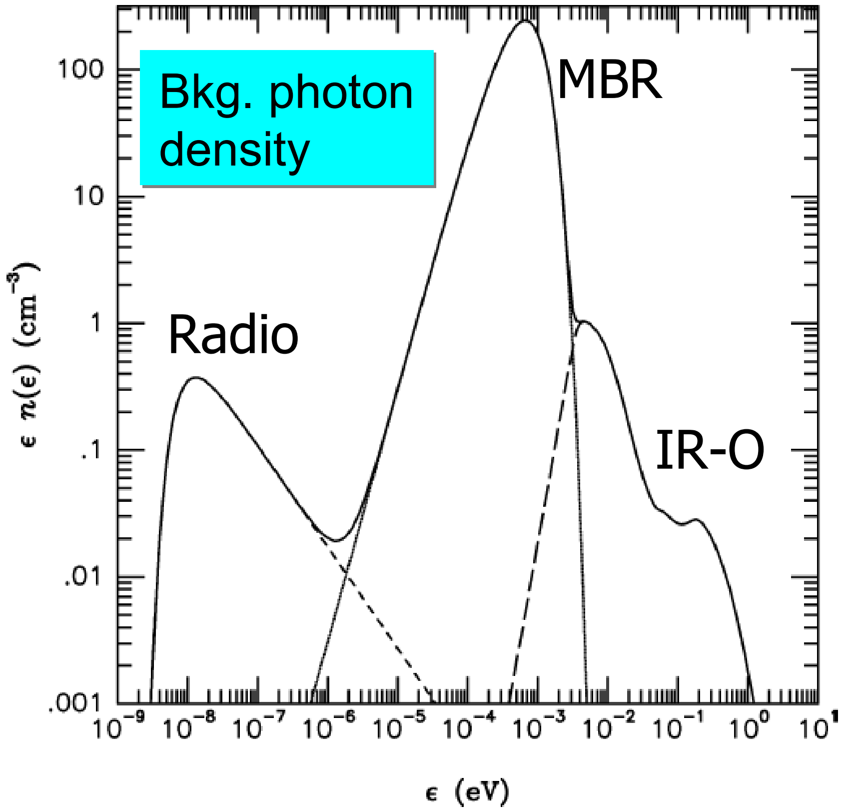
Cosmology & Fundamental Physics

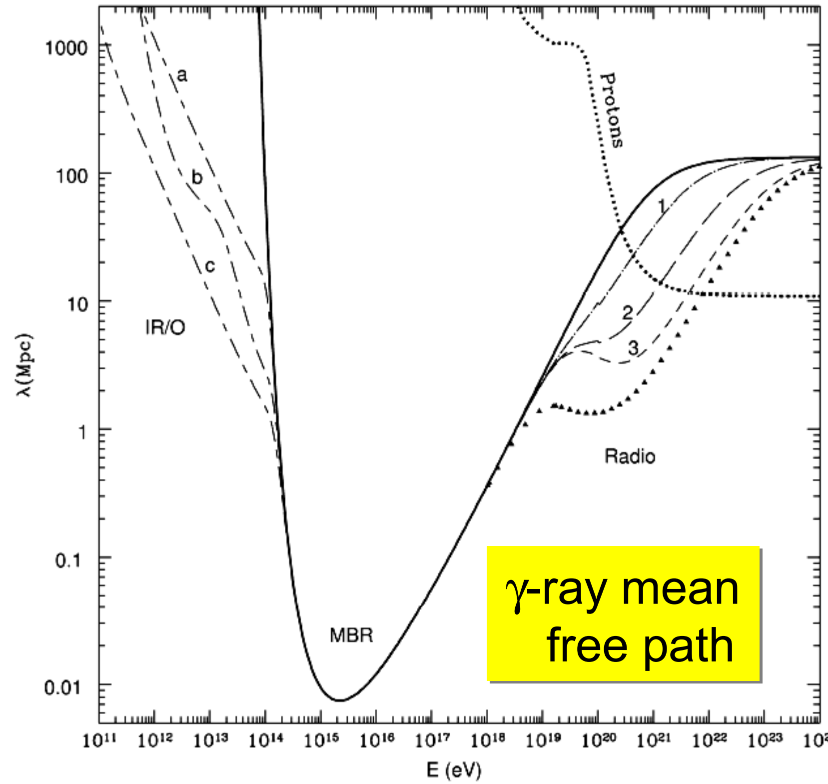
Propagation of gamma-rays

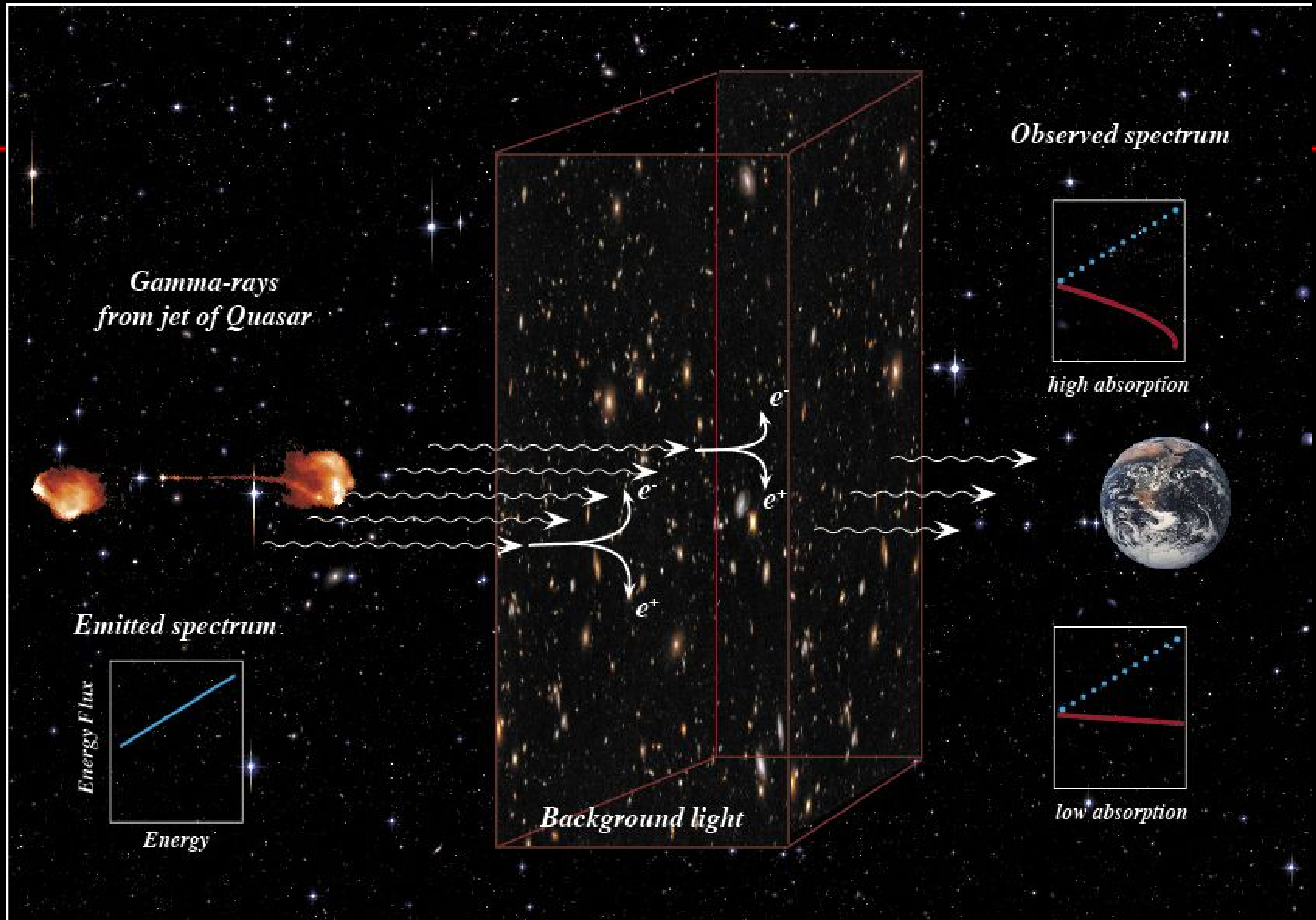
$\gamma + \gamma_{bkg} \rightarrow e^{+} + e^{-}$ production in the interaction of emitted photons off extragalactic background photons is a source of opacity of the Universe to γ-rays whenever the emitted photon mean free path is smaller than the source distance.

$$\sigma(E,\epsilon) \simeq 1.25 \cdot 10^{-25}(1-\beta^2) \cdot \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \mathrm{cm}^2 \qquad \beta = \sqrt{1 - \frac{(m_e c^2)^2}{E\,\epsilon}},$$

The Bethe-Heitler cross-section is maximized when $\varepsilon = 500 GeV / E$







Gamma-rays, which are produced in the most active structures in the Universe, are absorbed in their journey from distant objects to Earth if they happen to hit a photon of the background light. This fog of light in which the Universe is bathed is a fossil record of all the light emitted in the Universe over its lifetime, from the glare of the first stars and galaxies up to the present time.

So, one can use high-E AGNs as a probe of the EBL and study the effect of the fossil light on the energy distribution of the original gamma-rays emitted to derive a limit on the maximum amount of the 'extragalactic background light.

Extragalactic Background Light (EBL)

E=1 TeV → ε=0.5 eV (IR/O)
E=1 PeV → ε=5 10^{-4} eV (MBR)
E=10^9 GeV → ε=5 10^{-7} eV (Radio)

EBL proven today

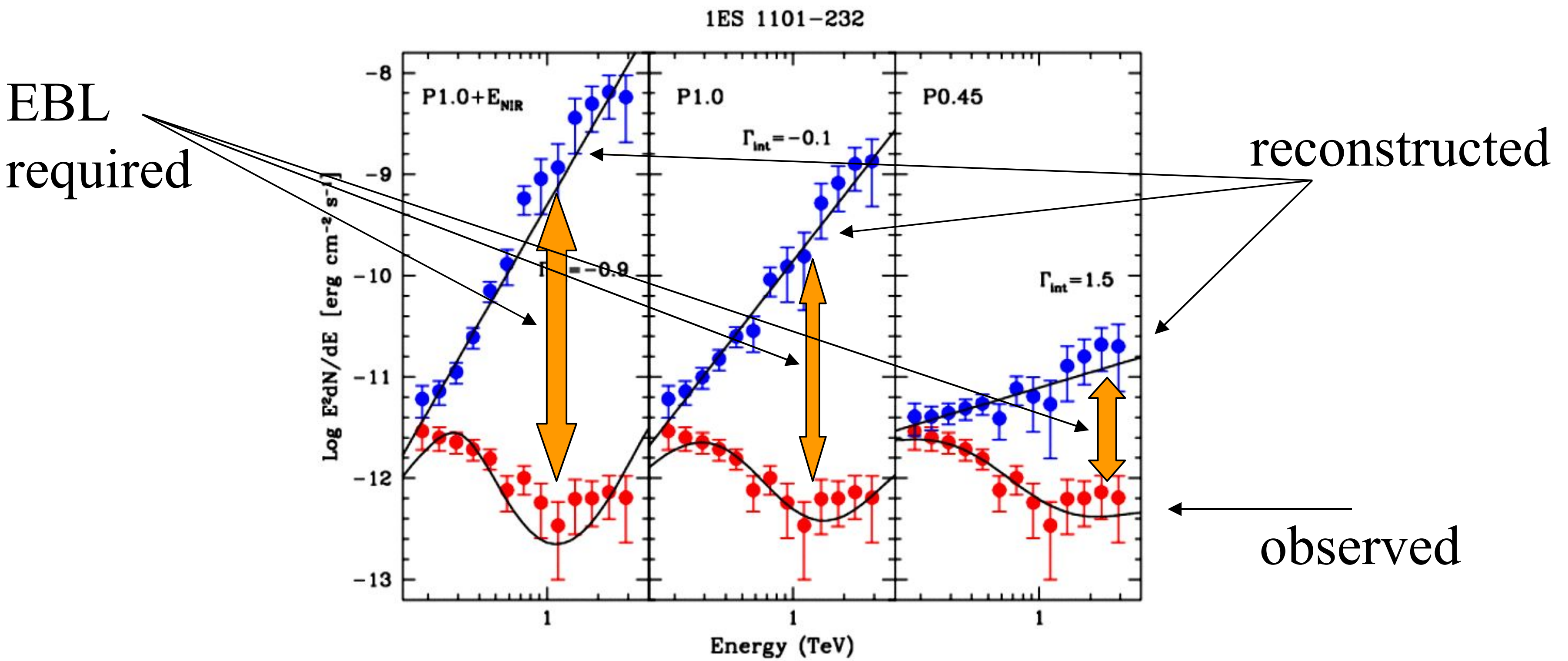
The EBL consists of the sum of starlight emitted by galaxies throughout their whole cosmic history, plus possible additional contributions, like, e.g., light from hypothetical first stars that formed before galaxies were assembled.
Therefore, in principle the EBL contains important information both the evolution of baryonic components of galaxies and the structure of the Universe in the pre-galactic era.
The attenuation suffered by observed VHE spectra can thus be used to derive constraints on the EBL density

$$e^{-\tau(E,z)} .$$

$$\tau(E,z) = \int_0^z dl(z) \int_{-1}^{1} d\cos\theta \frac{1-\cos\theta}{2} \int_{\frac{2(m_e c^2)^2}{E(1-\cos\theta)}}^{\infty} d\epsilon(z)\, n_\epsilon\big(\epsilon(z), z\big)\, \sigma(E(z), \epsilon(z), \theta)$$

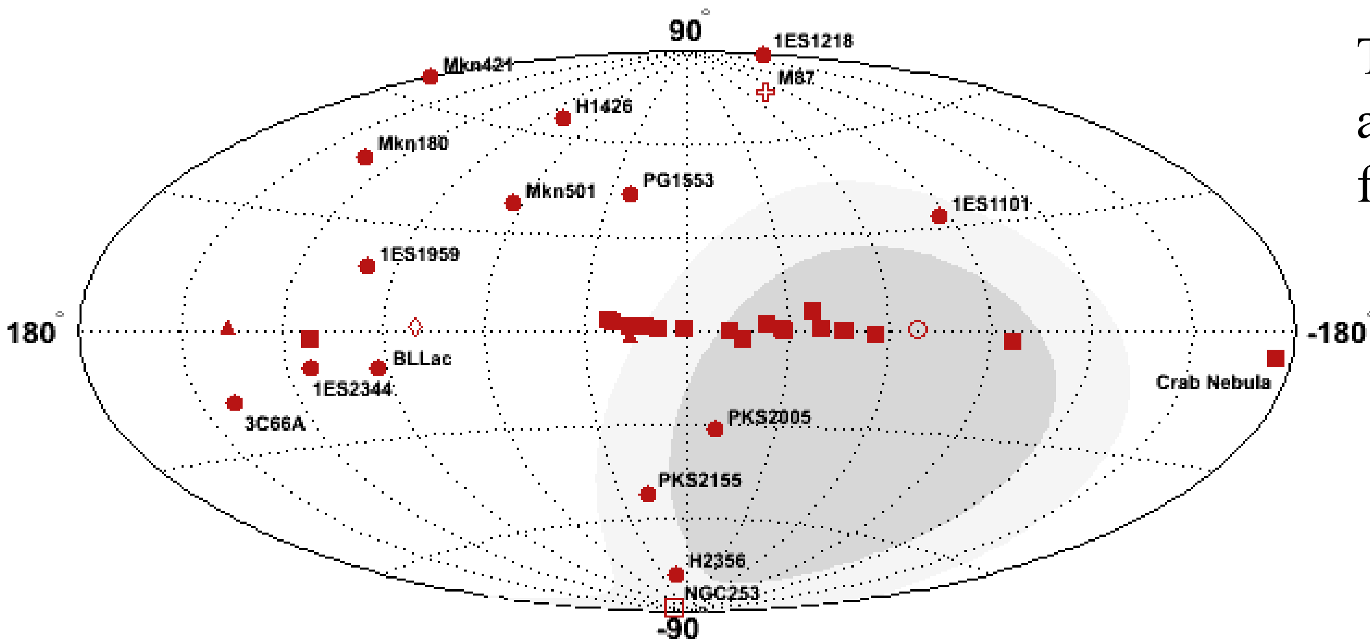
Probability for a photon of observed energy E to survive absorption along its path from its source at redshift z to the observer plays the role of an attenuation factor for the radiation flux:

Some indications on EBL



The H.E.S.S. spectrum of the blazar 1ES 1101-232. *The observed distribution of energies (spectrum) of the detected gamma-rays is plotted in red. In blue is shown the deduced original distribution as emitted at the source, reconstructed supposing different levels of the diffuse background light. If the level is high (left and centre panel), the original spectrum is dramatically different from the typical distribution expected from such objects, and cannot be easily explained as an intrinsic feature. With a low background light level (right panel), the original spectrum becomes compatible with the normal characteristics of this type of AGN.*

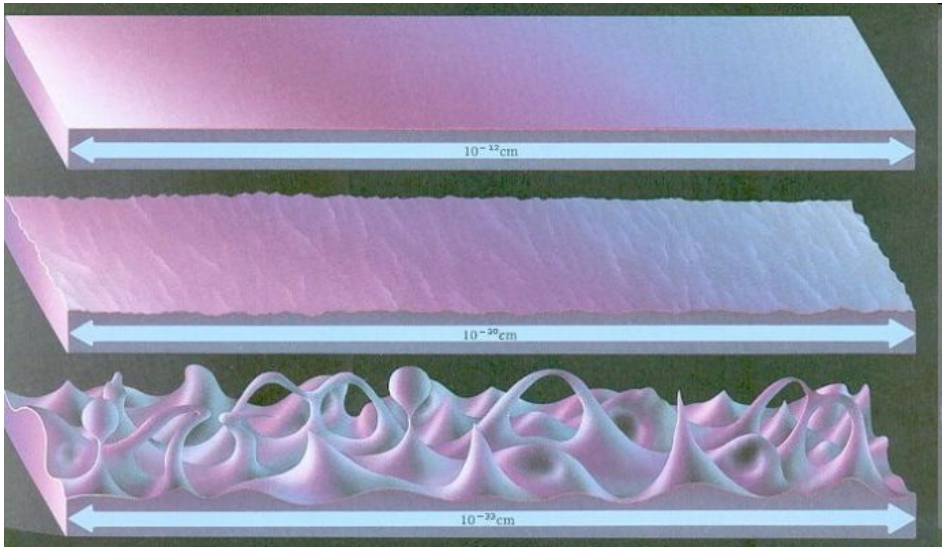
The TeV Sky



There are 12 blazars at E> 100 GeV firmly established

- Assume SSC (or more complex) SED model from low-E data (need also redshift… sometimes unknown !)
- Simple leptonic models usually work but there are exceptions (see, e.g. 1ES1959+650)
- De-absorbed spectra are the harder the further away the sources are.
- Observational bias or complex astrophysics?

Quantum Gravity, LI, & …



In QG scenarios, the space-time appears completely smooth at the scale of 10^{-12} cm.; a certain roughness starts to show up at scale of 10^{-30} cm.; and at the scale of the Planck length space becomes a froth of probabilistic quantum foam and the notion of a simple, continuous space-time becomes inconsistent.

Test needed!

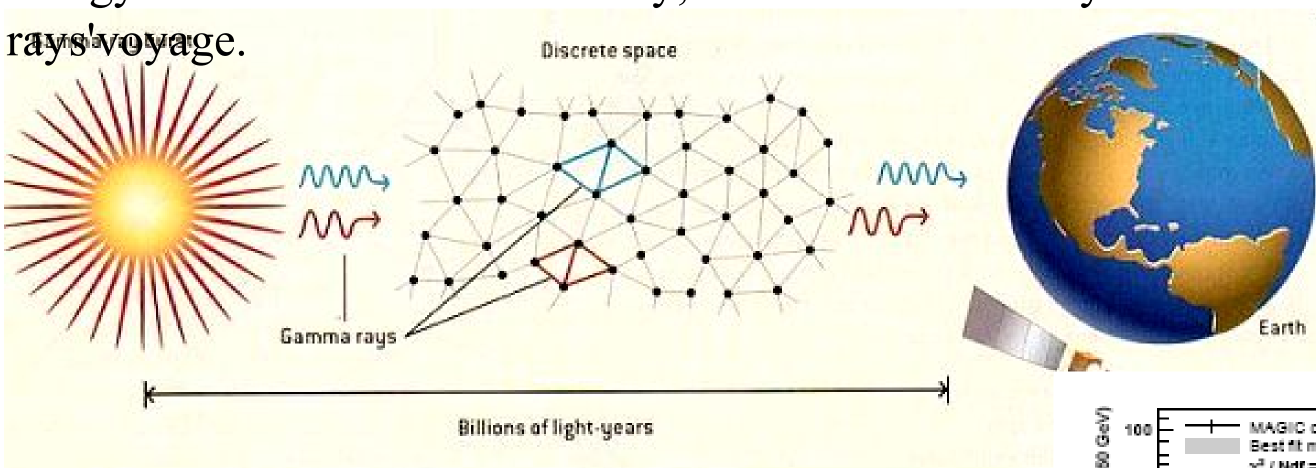
The QG effects might reflect in modifications of the propagation of high-E particles, namely dispersive effects due to a non-trivial refractive index induced by the QG fluctuations in the space-time foam.

Sub-luminal refraction only for photons in string-inspired models

$$\frac{\Delta c}{c} = -\frac{E}{M_{\rm QG1}}, \quad \text{or} \quad \frac{\Delta c}{c} = -\frac{E^2}{M_{\rm QG2}^2}.$$

One might guess that the scale $M_{\rm QG1}$ or $M_{\rm QG2}$ would be related to $\tilde{M}_{\rm P}$, where $\tilde{M}_{\rm P} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass, but smaller values might be possible in some string theories [2, 3], or models with large extra dimensions [11]. Superluminal modes and birefringence effects are also allowed in some other models [4–8].

Pulses of radiation from distant high-E sources might provide a way to test whether QG effects are real. GRBs, AGNs are the preferred sources.
The discrete nature of space causes higher-E gamma rays to travel slightly faster than lower-energy ones. The difference is tiny, but its effect steadily accumulating during the rays'voyage.



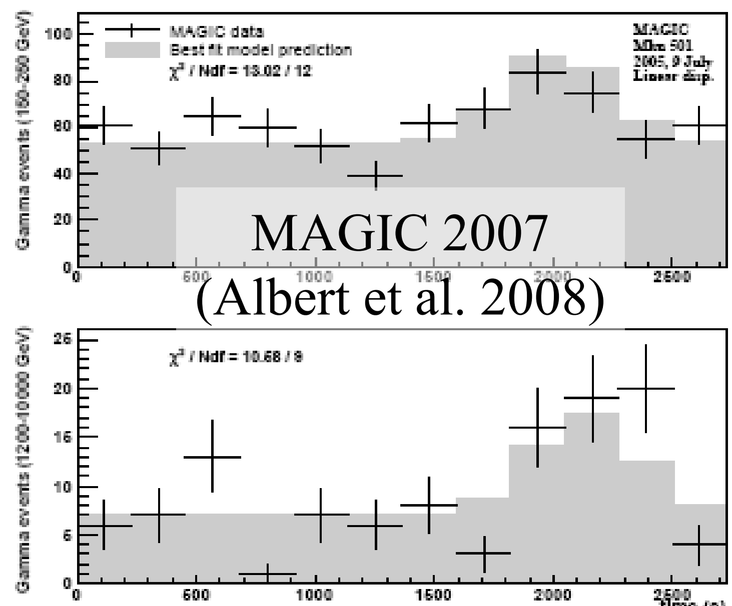
Larger sensitivity for short pulses at high z or photons observed on large E range.

- GRB $M_{QG1} > 0.9 \times 10^{16} \quad GeV$

- AGN $M_{QG1} > 4 \times 10^{16} \quad GeV$ (MKN 421)

$M_{QG1} > 2.1 \times 10^{17} \quad GeV$

$M_{QG2} > 2.6 \times 10^{10} \quad GeV$ (MKN 501)



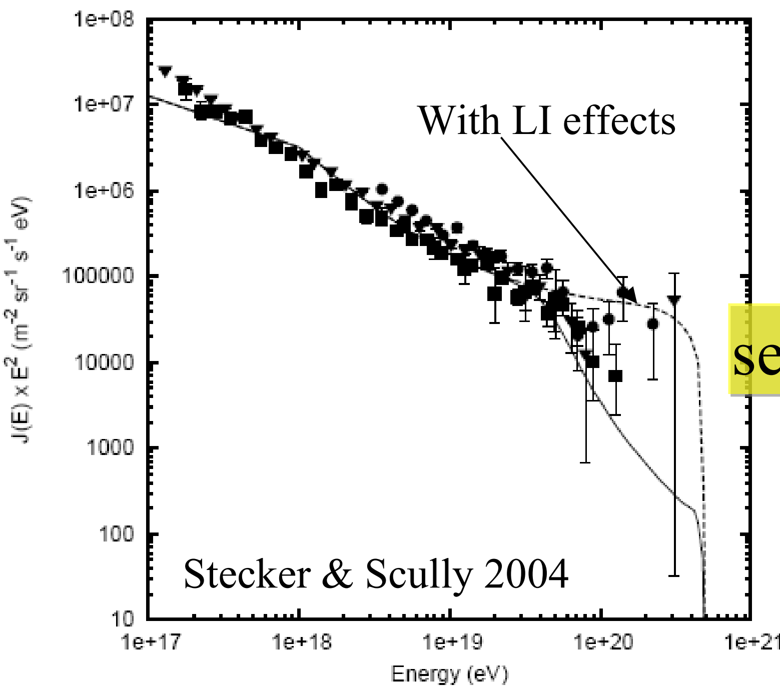
MAGIC 2007
(Albert et al. 2008)

LI and UHECRs

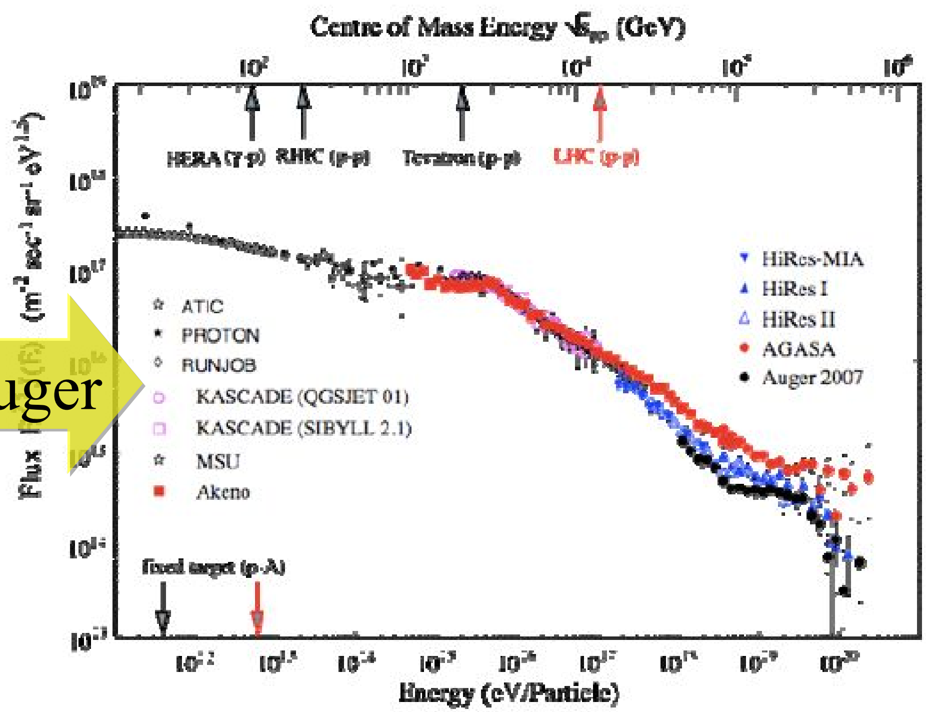
Coleman & Glashow (1999) have shown that for interactions of protons with CBR photons of energy ε and temperature T_{CBR} = 2.73K, pion production is kinematically forbidden and thus photomeson interactions are turned off if

$$\delta_{p\pi} > 5 \times 10^{-24} (\epsilon / T_{CBR})^2 . \qquad \delta_{p\pi} = c_p - c_\pi$$

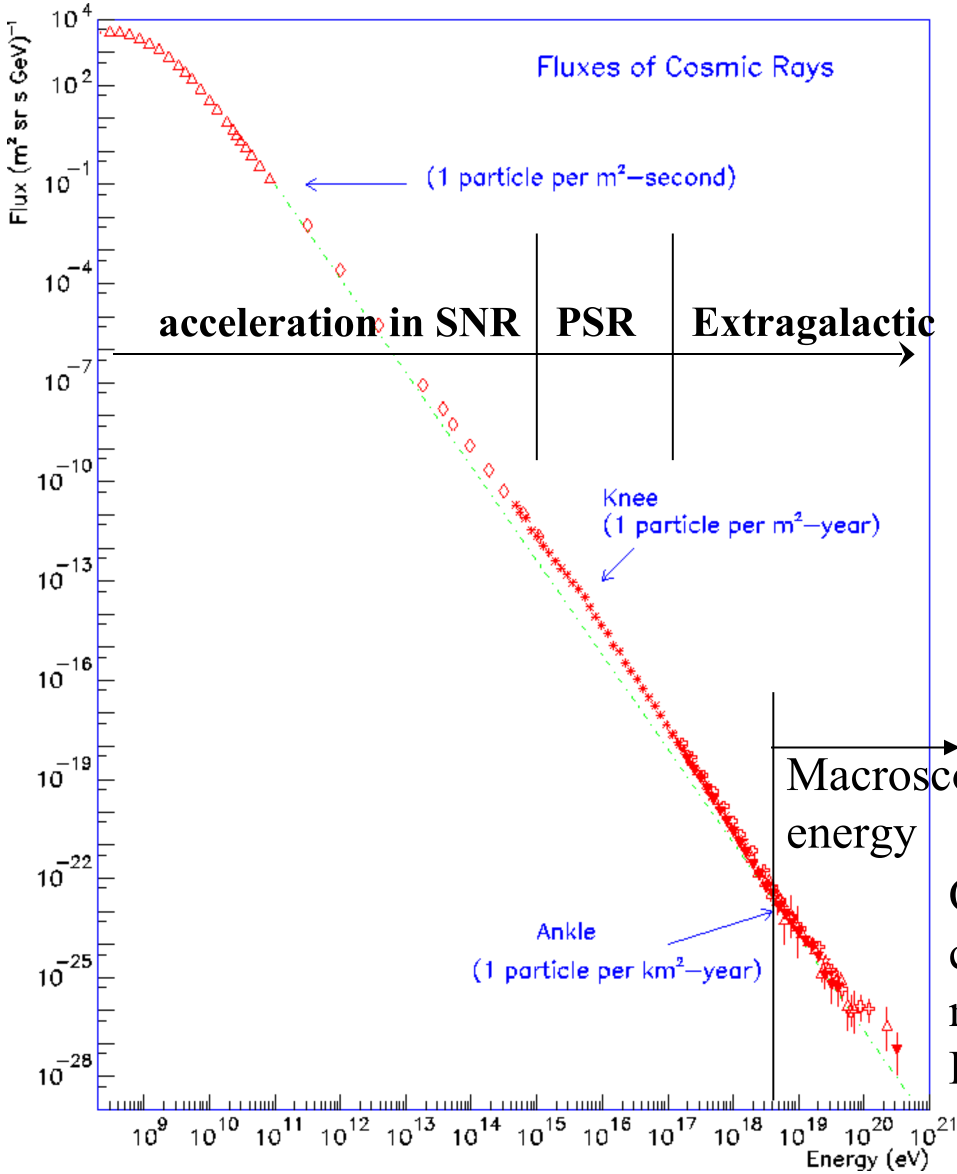
Thus, given even a very small amount of LI, photomeson and pair-production interactions of UHECR with the CBR can be turned off.



see Auger



Cosmic Ray origin



P. Auger Obs. results

- UHECRs must be hadrons
- Cutoff at $E > 4\ 10^{19}$ eV
- Horizon at 50-100 Mpc

Of order of the energy carried by a tennis ball moving at 100 km/h
R. Federer's ace

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Propagation of cosmic-rays

Typical length scale of propagation

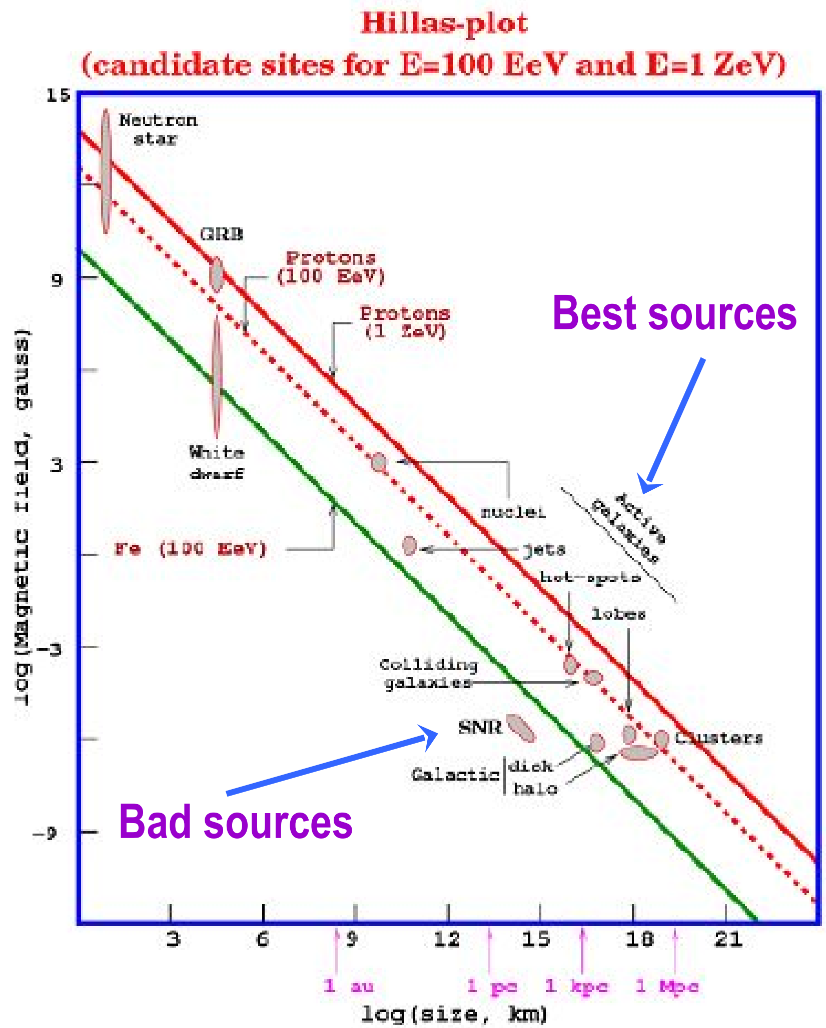
Gyroradius $r_g = E/(ZeB)$

If the CR E is accelerated, an estimate of the Emax can be obtained by requiring rg < R R being the linear size of the accelerator.

$$r_g \sim 10^2 E/(ZB) < R$$

More general estimate $E_{max} \sim \alpha 10^{18} Z R B \quad eV$

$$\alpha = \mathcal{E}/B$$



This argument can be used as a criterion to identify possible sources of UHECR by looking at the largest values of RB.

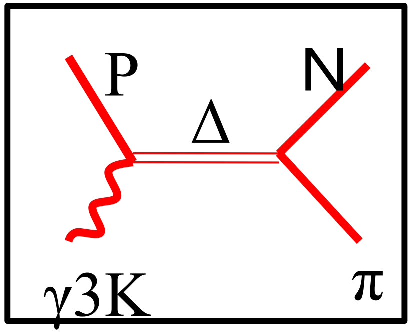
At a given E the gyroradius is larger for smaller charge of the particle.

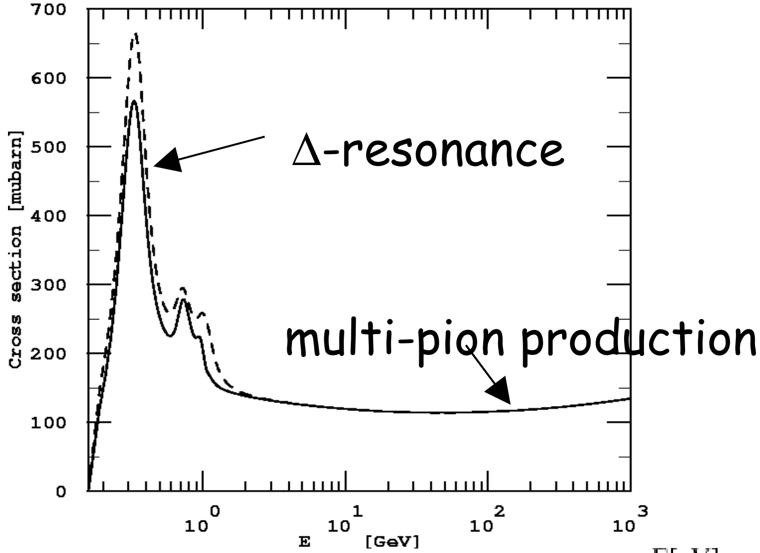
Therefore, if UHECRs are mostly protons, they are not deviated significantly by B-fields, so they should point back to their sources within an angle that depends on the intensity of the intergalactic B-field. For heavy nuclei, the effect of the B-field becomes more important

The end of the CR spectrum

$$p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n+\pi^{+}$$

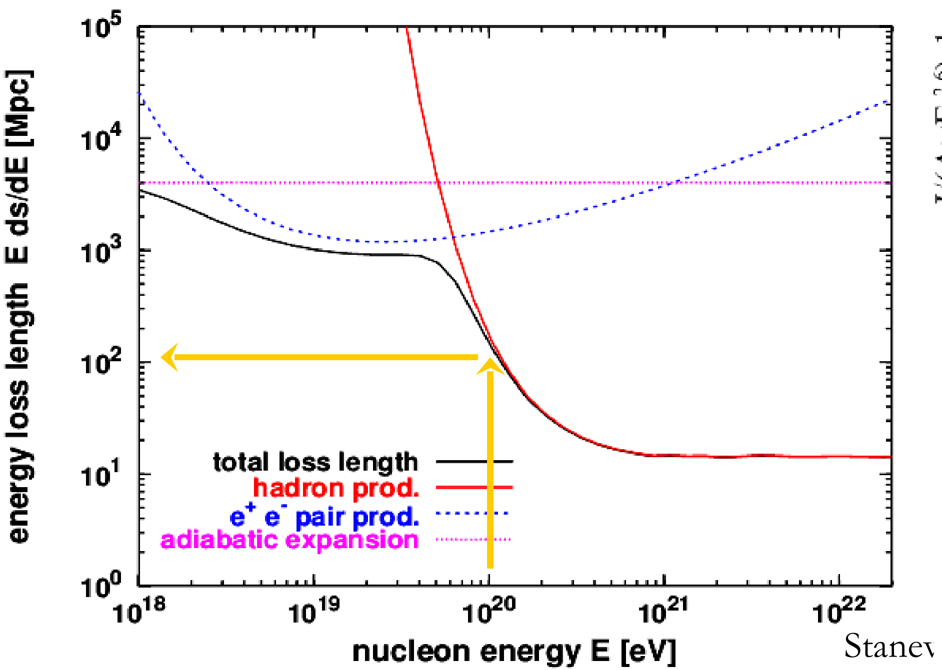
$$p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p+\pi^{0}$$

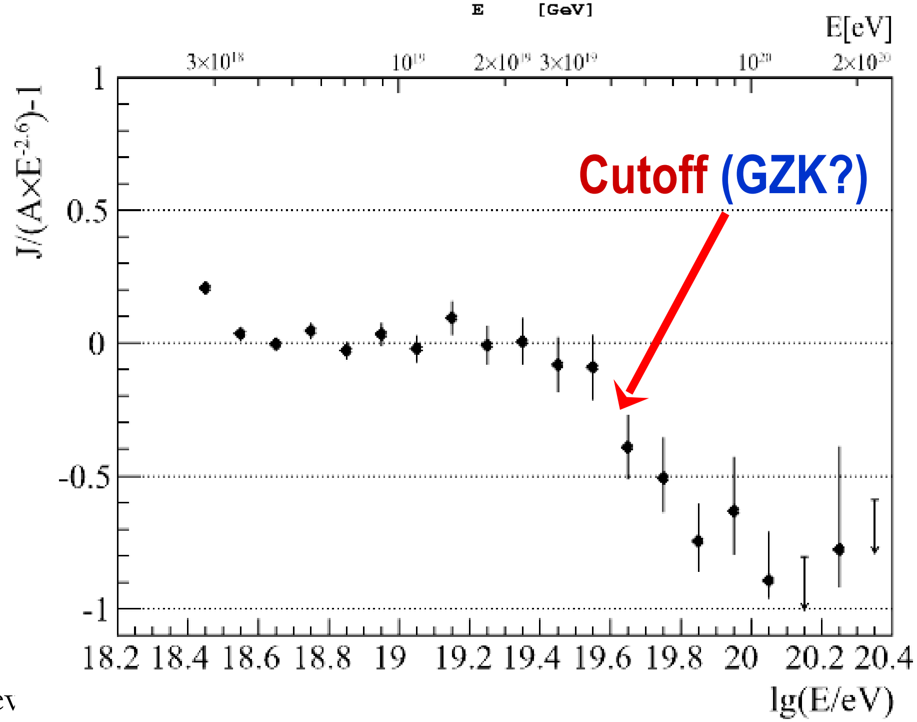




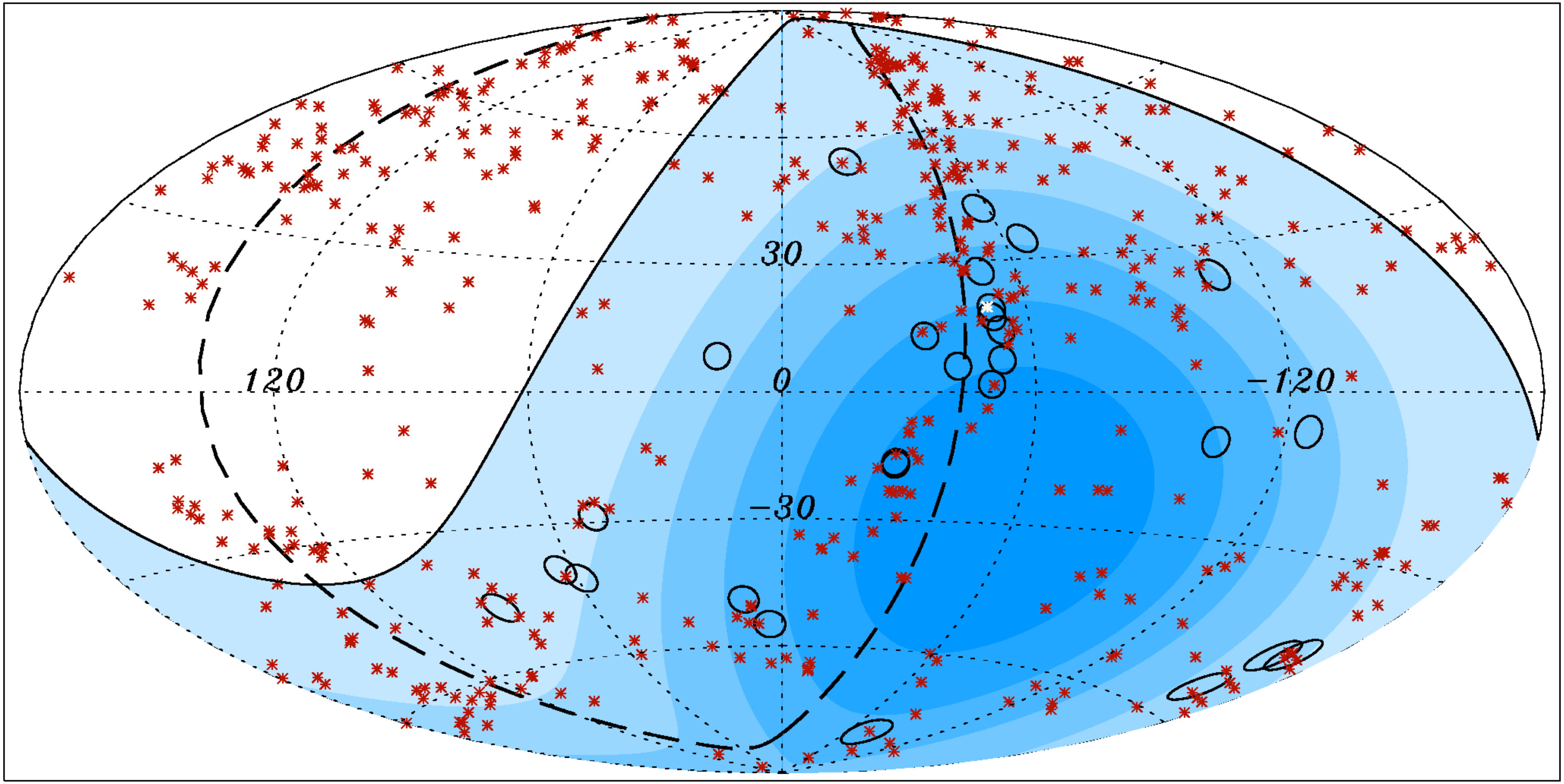
GZK effect

K. Greisen, Phys. Rev. Lett. 16, 748 - 750 (1966) ;
G. T. Zatepin & V. A. Kuz'min, Sov. Phys. JETP. Lett. 4 (1966) 78.





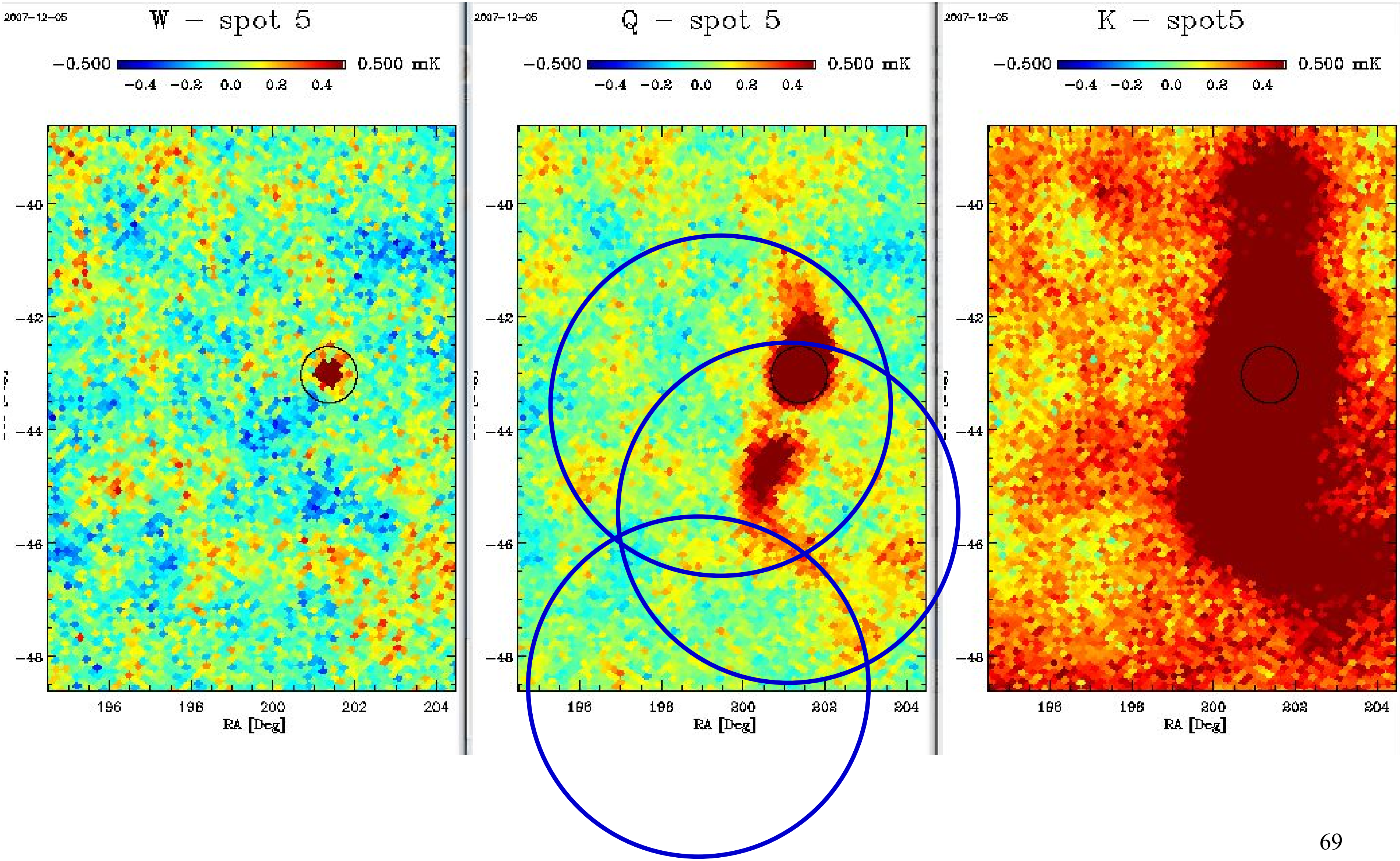
UHECR Astronomy



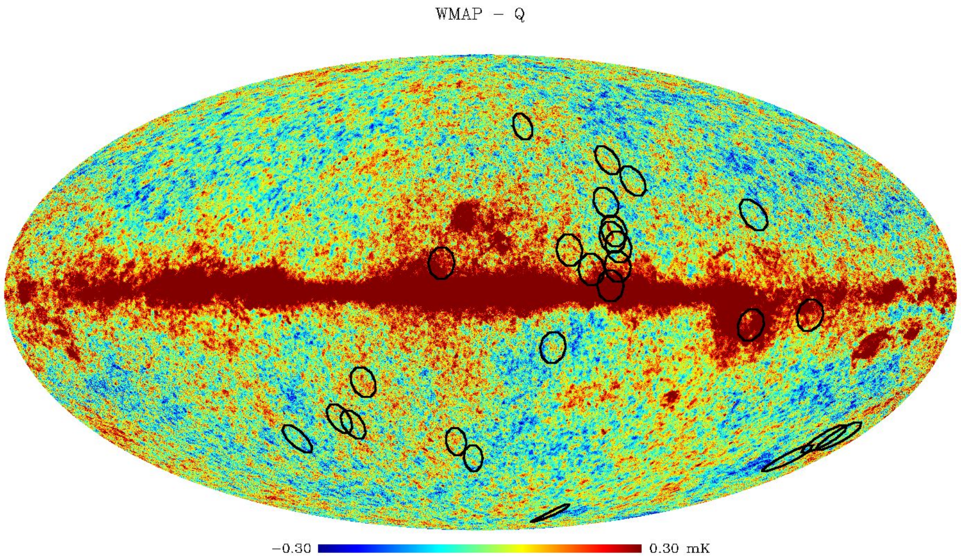
Science AAAS

Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects
The Pierre Auger Collaboration, *et al.*
Science **318**, 938 (2007);
DOI: 10.1126/science.1151124

Event 5,6,7

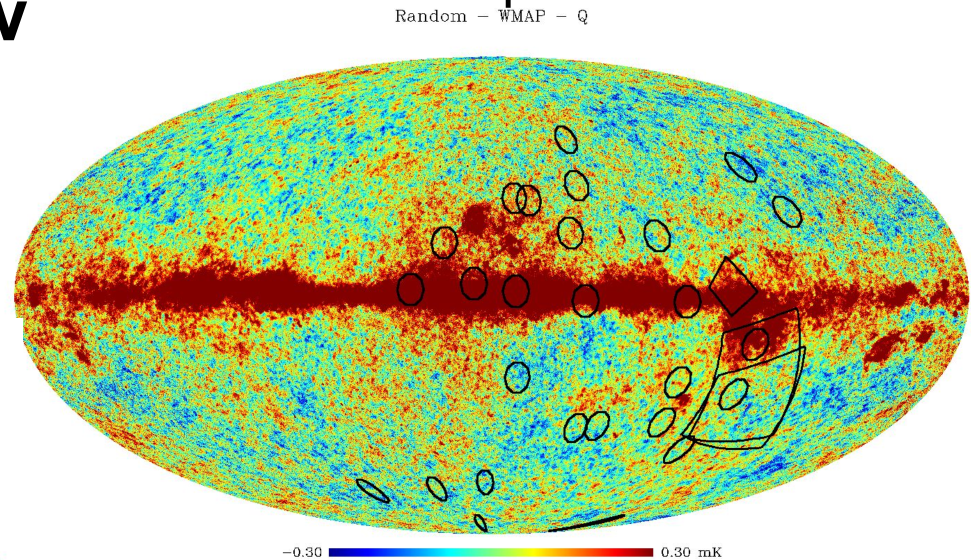

2007-12-05
W – spot 5
–0.500
0.500 mK
–0.4 –0.2 0.0 0.2 0.4
2007-12-05
Q – spot 5
–0.500
0.500 mK
–0.4 –0.2 0.0 0.2 0.4
2007-12-05
K – spot5
–0.500
0.500 mK
–0.4 –0.2 0.0 0.2 0.4
–40
–42
–44
–46
–48
196 198 200 202 204
RA [Deg]

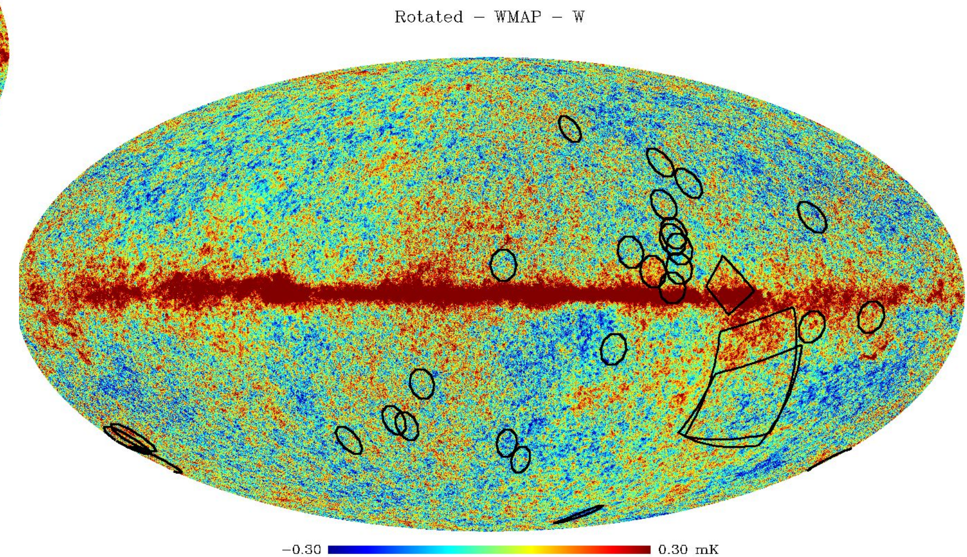
Every Auger event with E > 57 EeV can be associated to a cosmic accelerator with appropriate properties for UHECR production
(Colafrancesco et al. 2008)



Observed distribution

Random pattern





Random rotated pattern

The Neutrino and γ-ray connections

Accelerated protons interact:

$$p + \begin{matrix} N \\ \gamma \end{matrix} \rightarrow X + \left. \begin{matrix} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{o} \rightarrow \gamma\text{ - rays} \end{matrix} \right\}$$

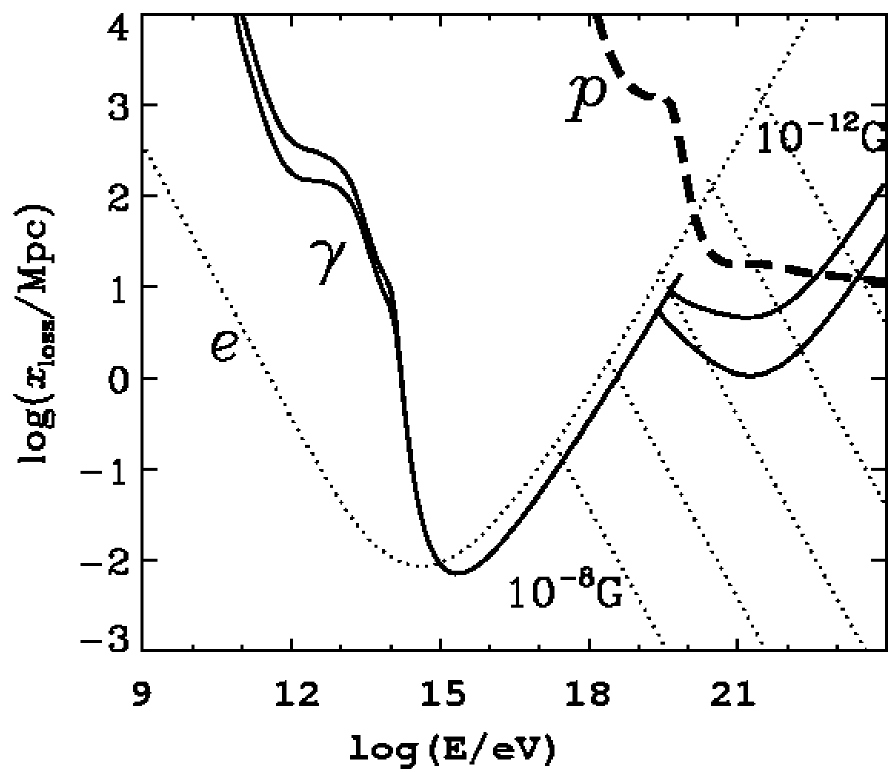
The neutrino spectrum is unmodified, whereas γ-rays pile up below the pair production threshold on the CMB at a few 10^{14} eV.

The Universe acts as a calorimeter for the total injected electromagnetic energy above the pair threshold. This constrains the neutrino fluxes.

Results from PAO give a limit to the fraction of photons in the integral CRs flux of 16% at E>10^{19} eV (29 high quality hybrid events).

Neutrinos component will also be estimated by PAO and specific experiments for neutrinos detection (IceCube, Antares, km3Net . . .).

$x_{loss} = x_{int}$ /mean inelasticity



Included processes:

Electrons: inverse Compton; synchrotron rad (for fields from pG to 10 nG)

Gammas: pair-production through IR, CMB, and radio backgrounds

Protons: Bethe-Heitler pair production, pion photoproduction

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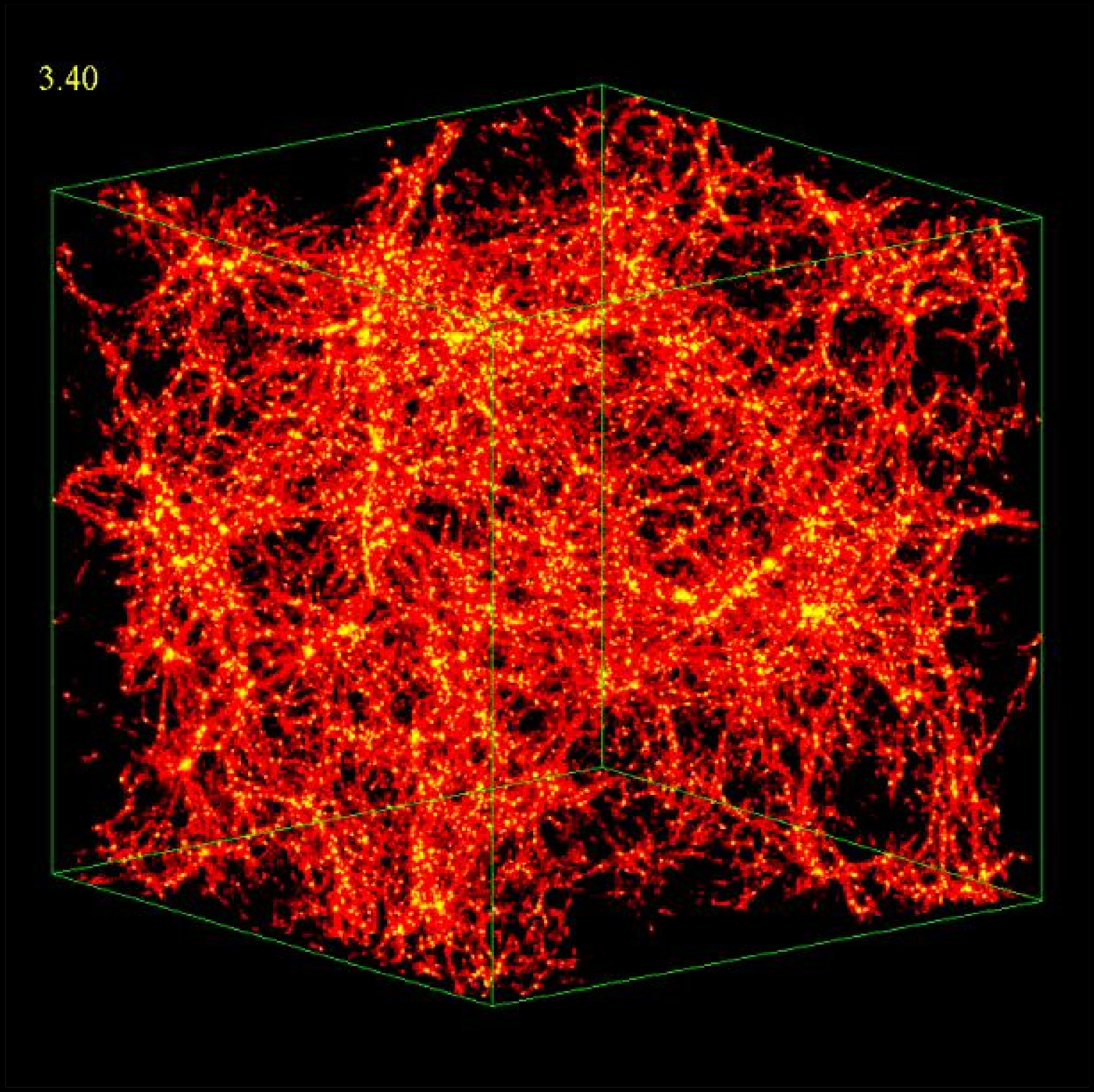
Part 4
Astro-Particle Physics in Cosmic Sources
(an overall picture)

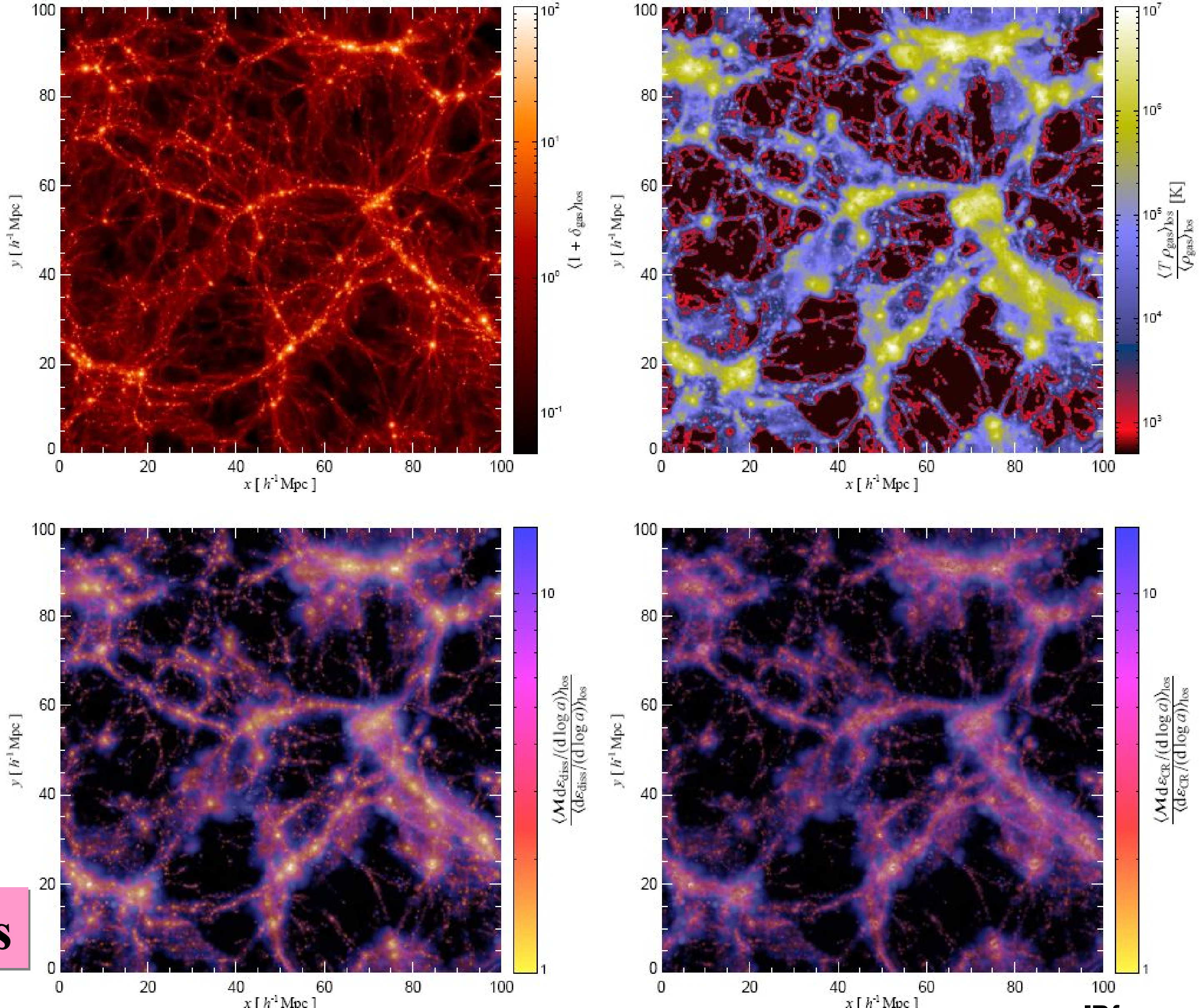
LSS and Dark Matter



LSS shock waves

ρ_{gas}

T_{gas}

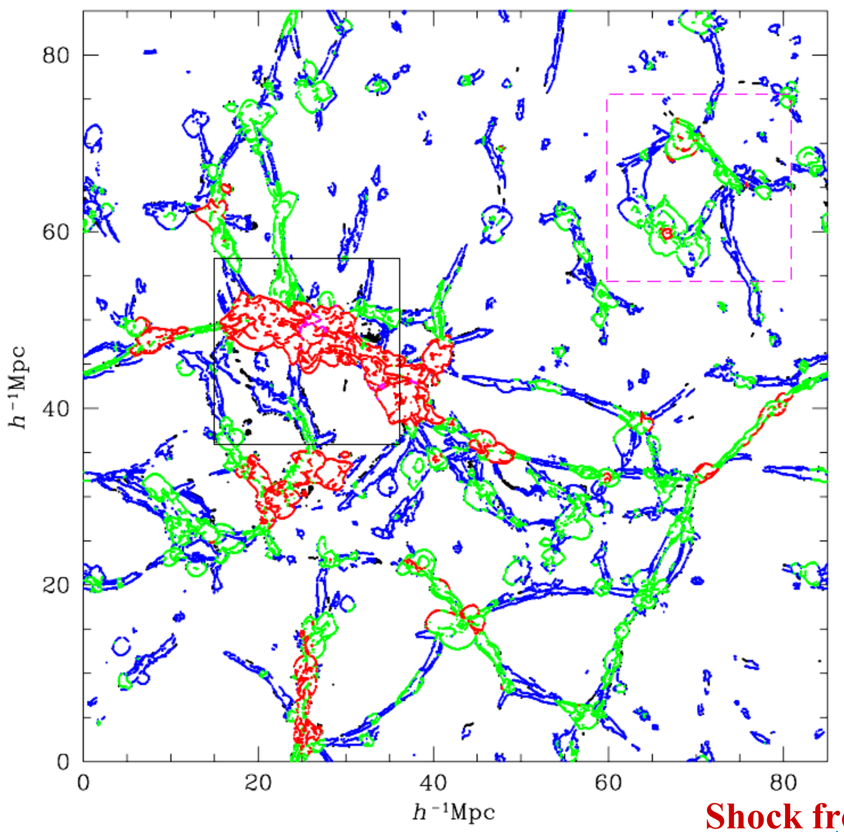


Shocks

$\mathcal{M}$

[Pfrommer et al. 2006]

Shock wave acceleration ⇒ CRs



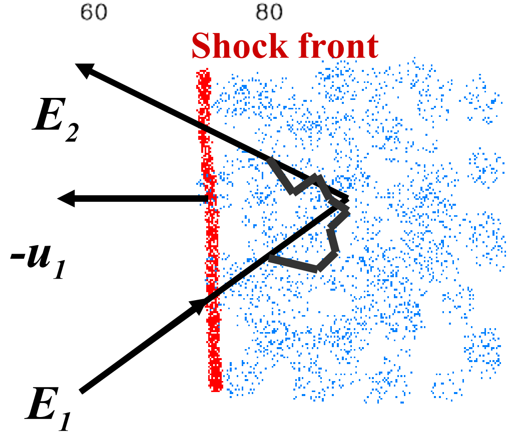
Black: V_s(km/s)< 15

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

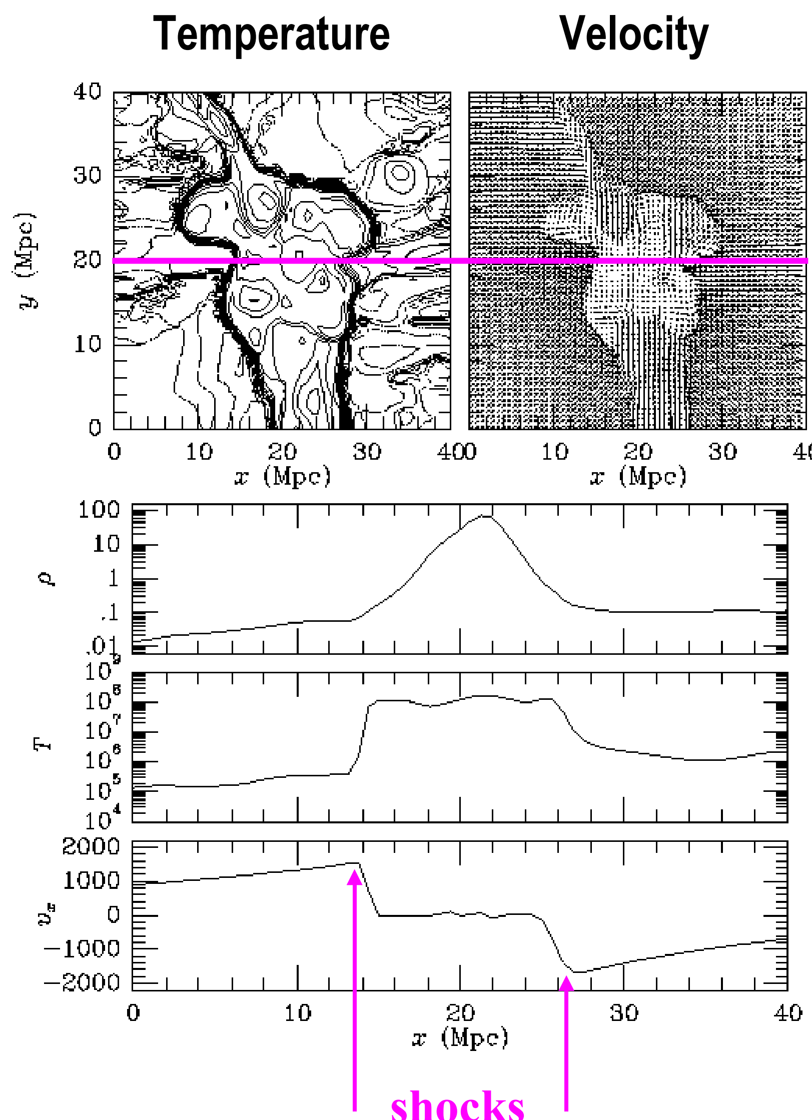
Green: 65 <V_s(km/s)< 250

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

Magenta: V_s(km/s)> 1000

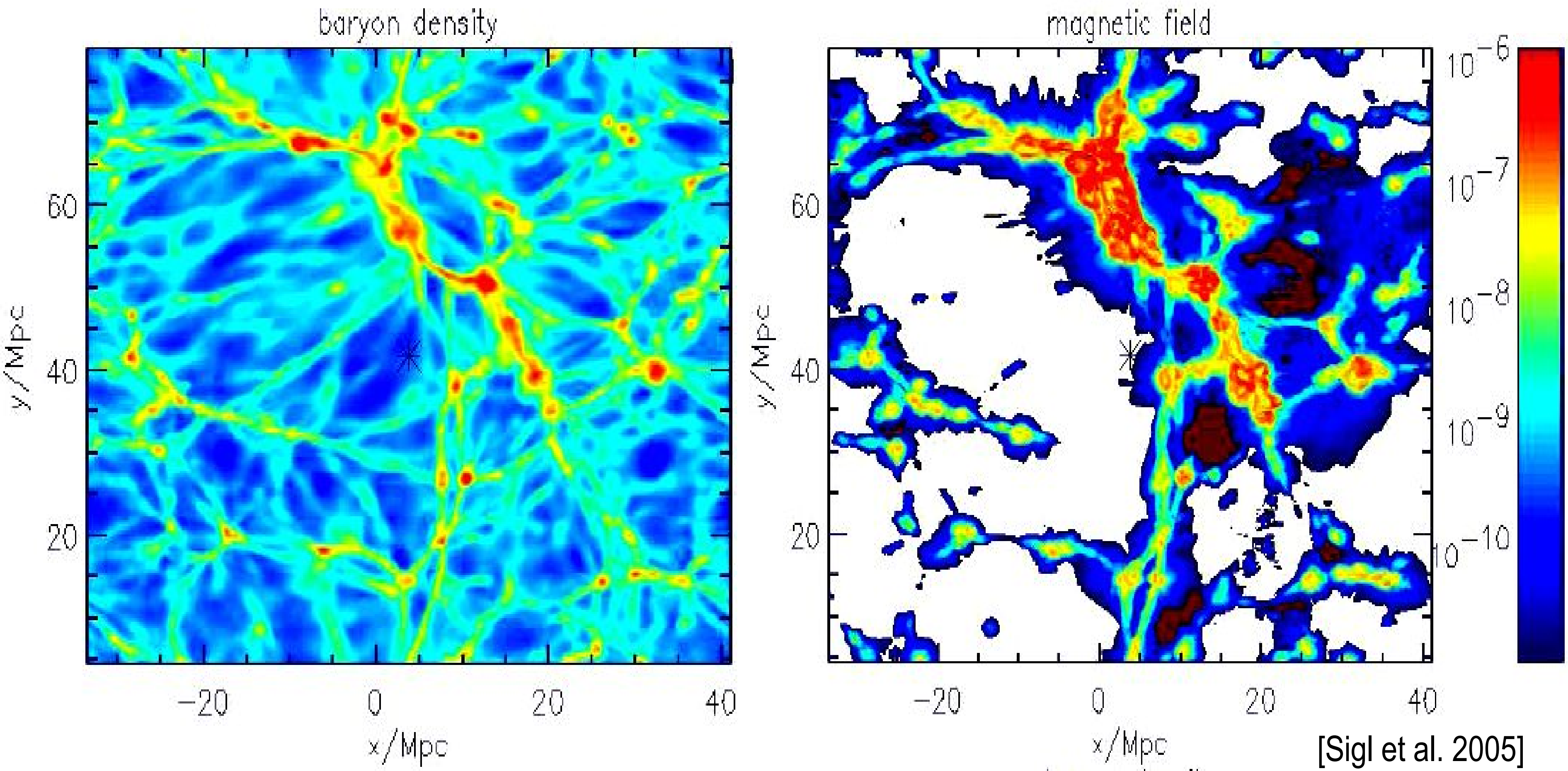


[Kang et al. 1996-2006]



Magnetic fields in LSS

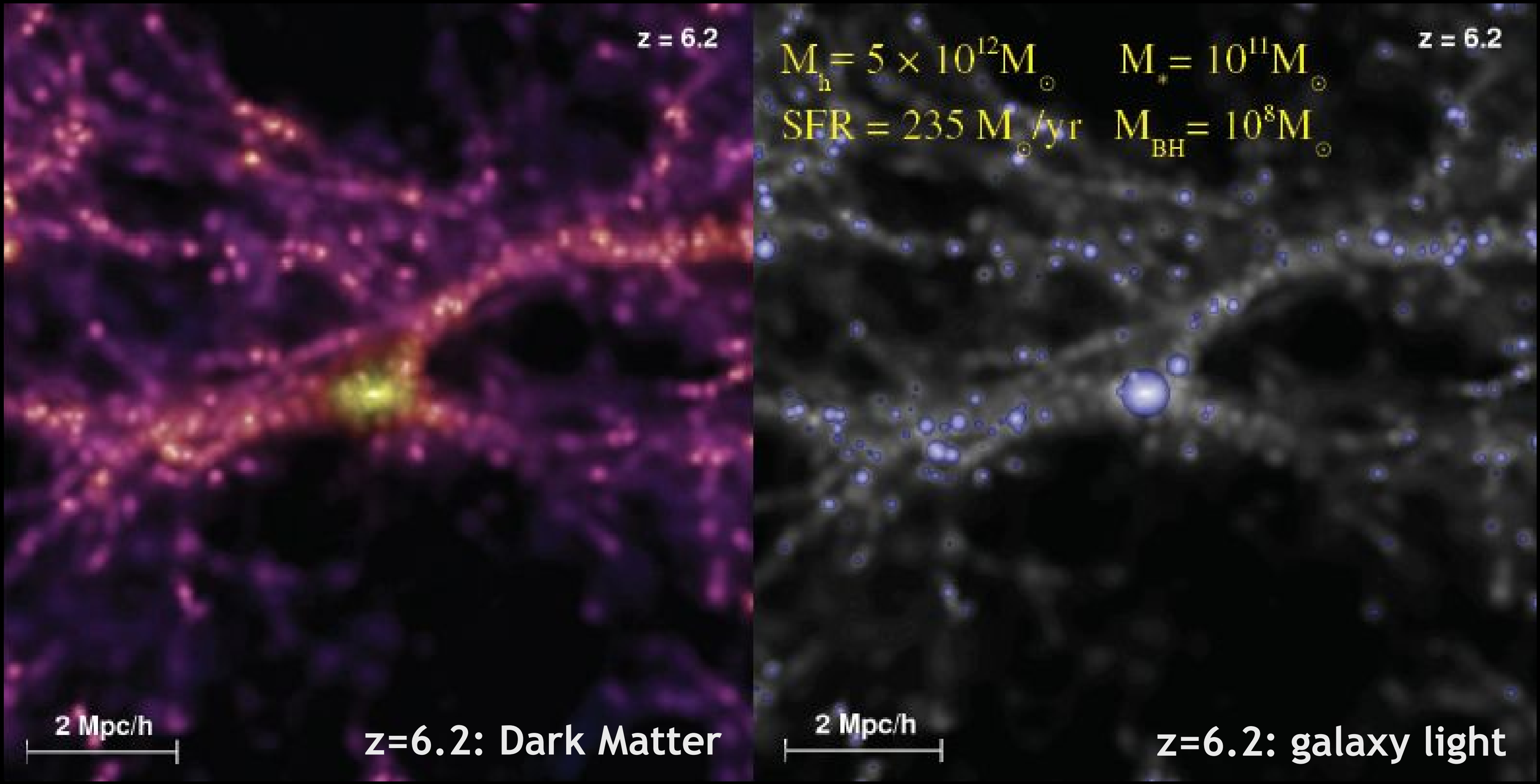
Origin → Primordial / Post-recombination → **G + MHD** → $\mathbf{B}(\delta\rho, z; P_k)$



[Sigl et al. 2005]

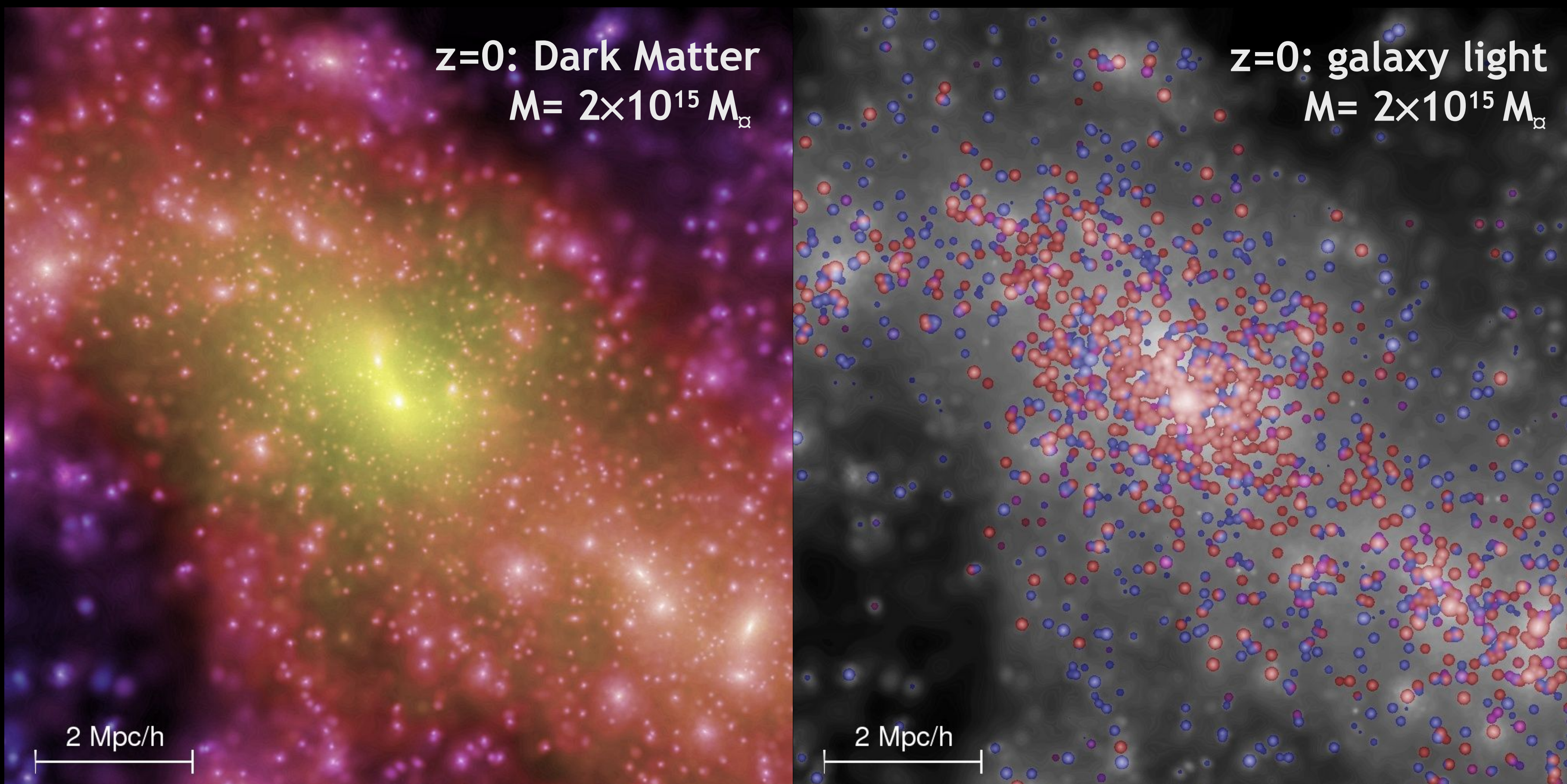
LSS and Black Holes

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

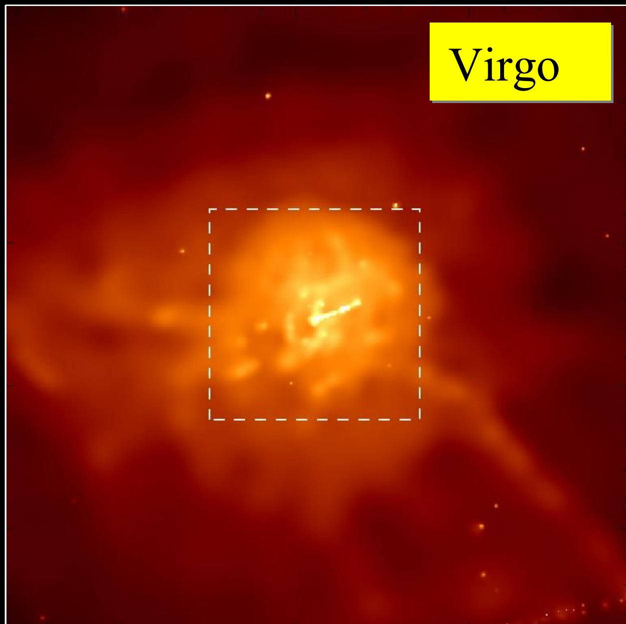


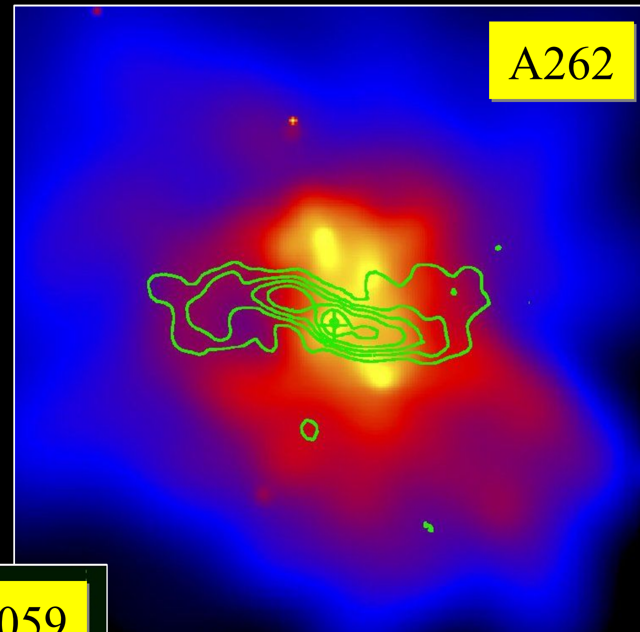
The first object descendants today

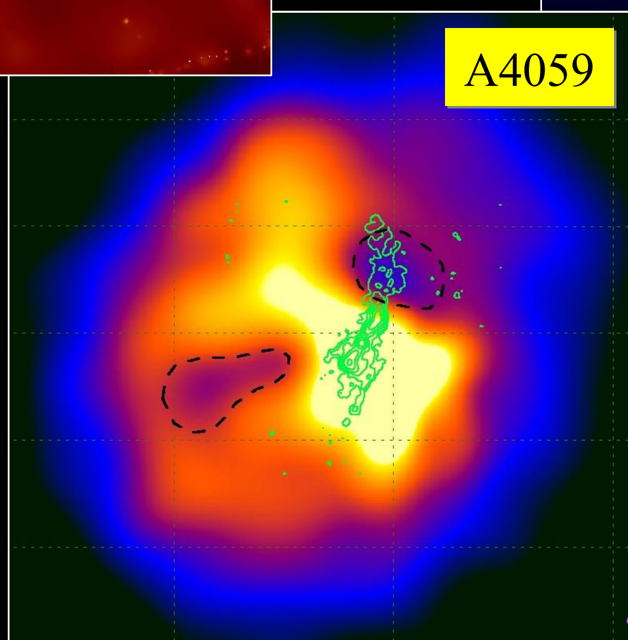
One of the most massive galaxy clusters at t = 13.7 Gyrs
The AGN descendant is part of the central massive galaxy

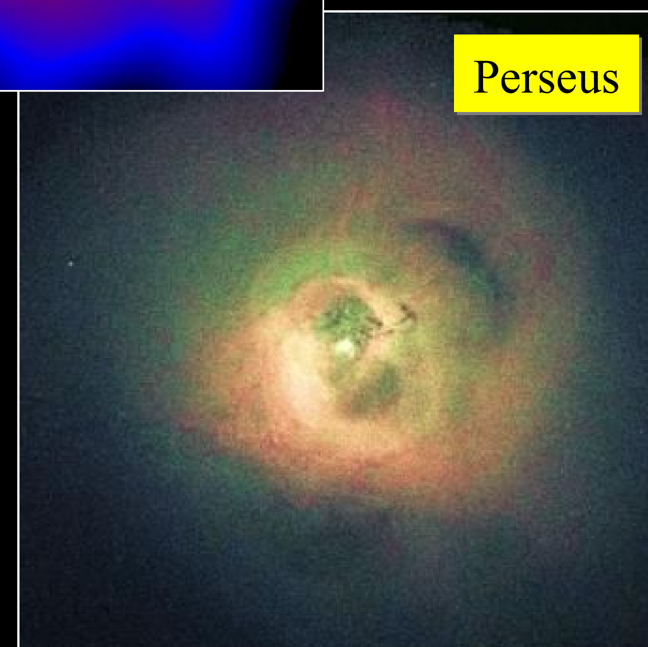


BHs in galaxy clusters: evidence

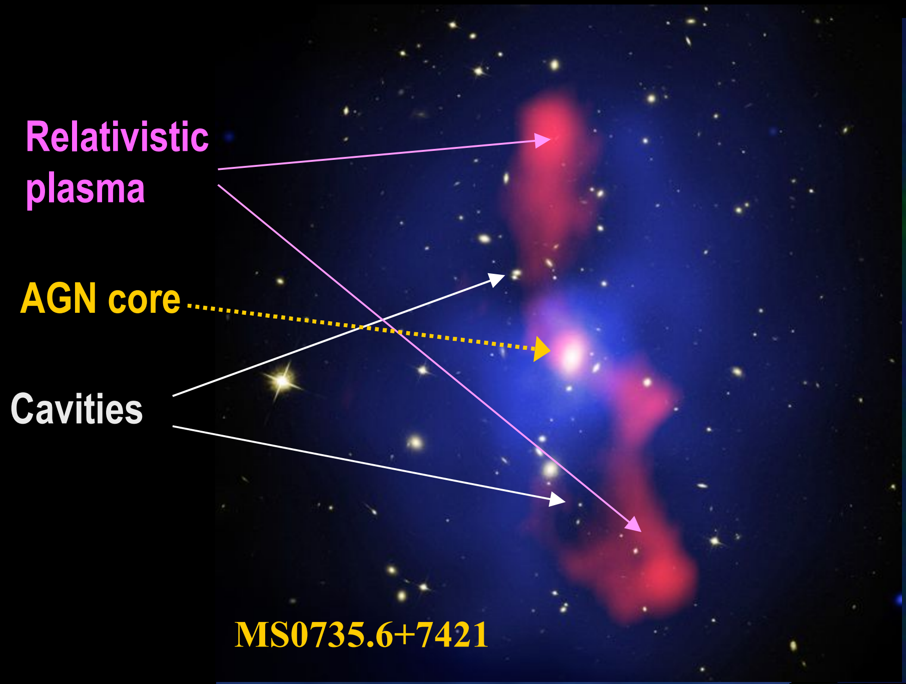


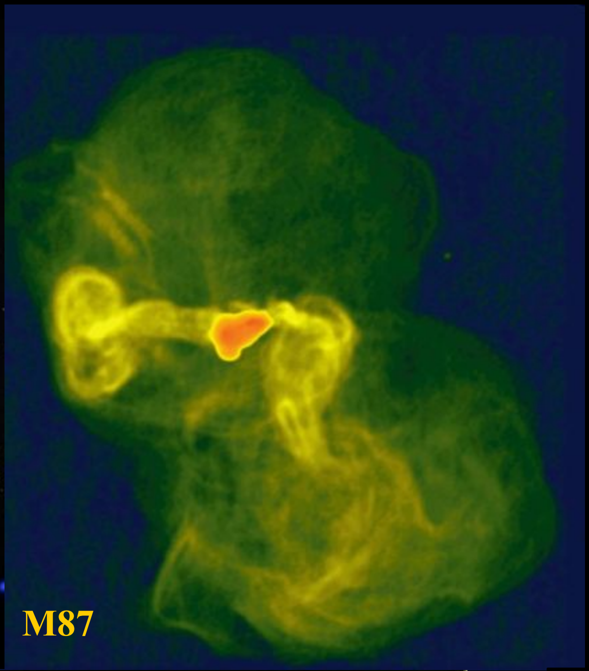


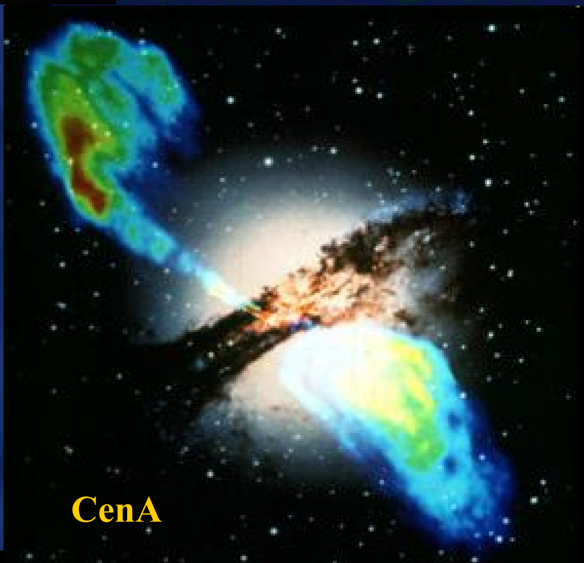




BH ejecta: photons,paricles, ...







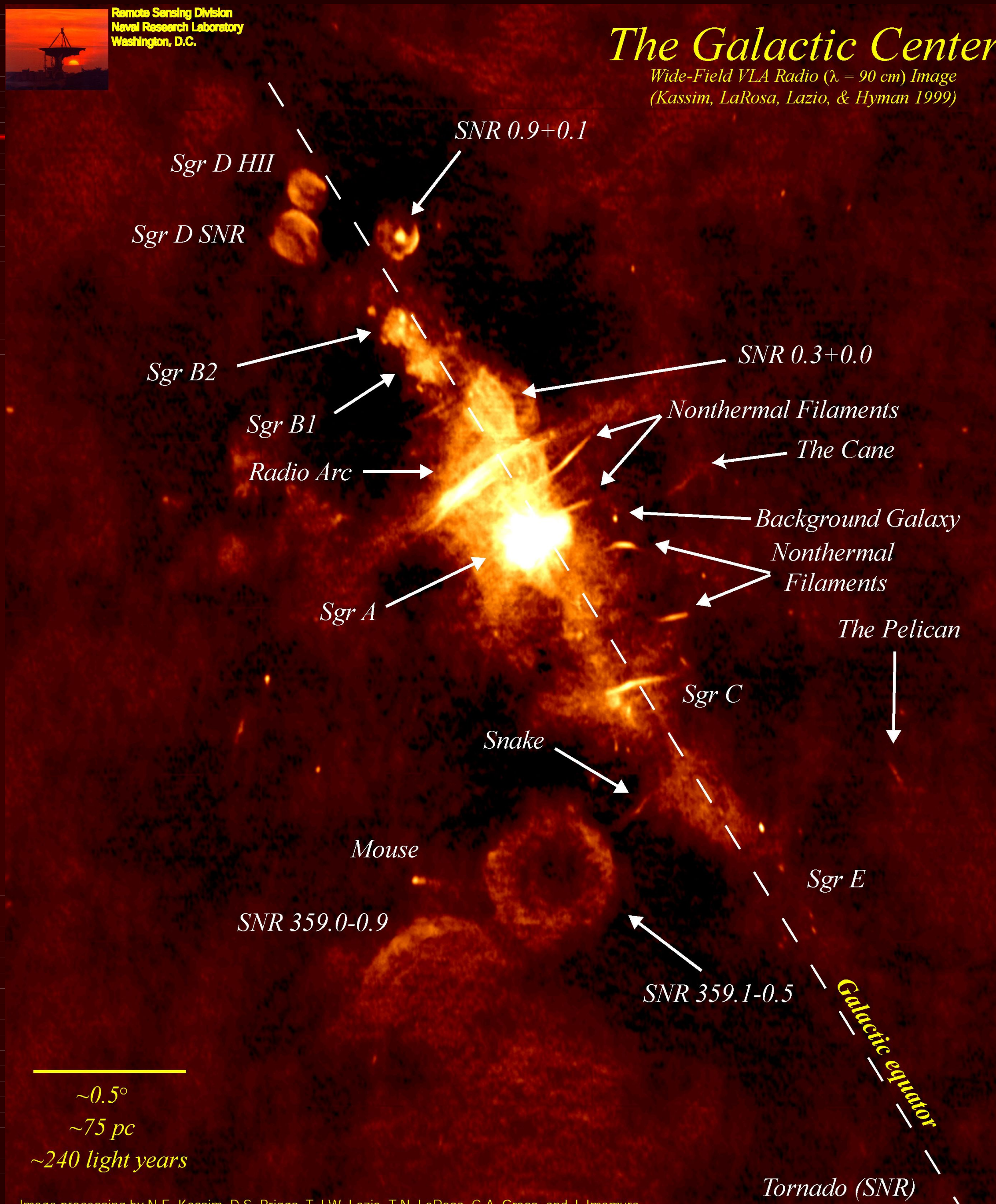


Image processing by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, C.A. Gross, and J. Imamura
Produced at the Naval Research Laboratory (Kassim et al. 1999, LaRosa et al. 2000)
Original data from the NRAO VLA courtesy of A. Pedlar, K. Anantharamaiah, M. Goss, and R. Ekers
URL: http://rsd-www.nrl.navy.mil/7213/lazio/GC

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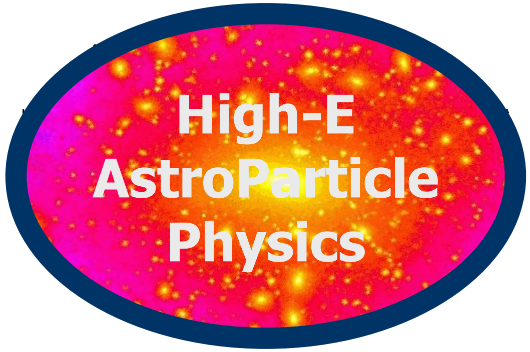
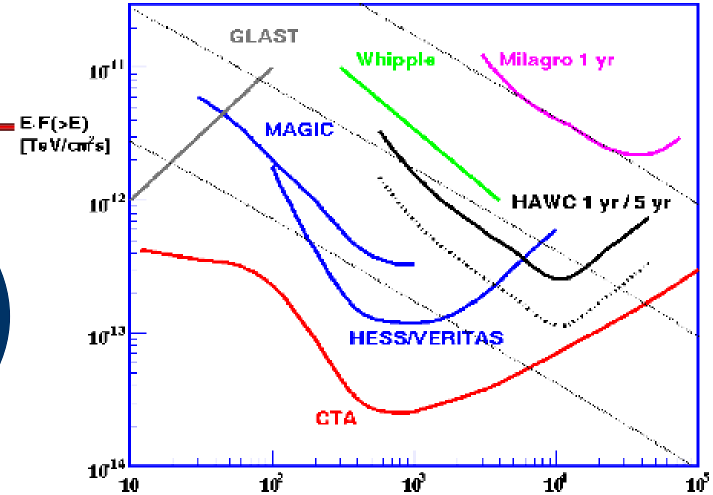
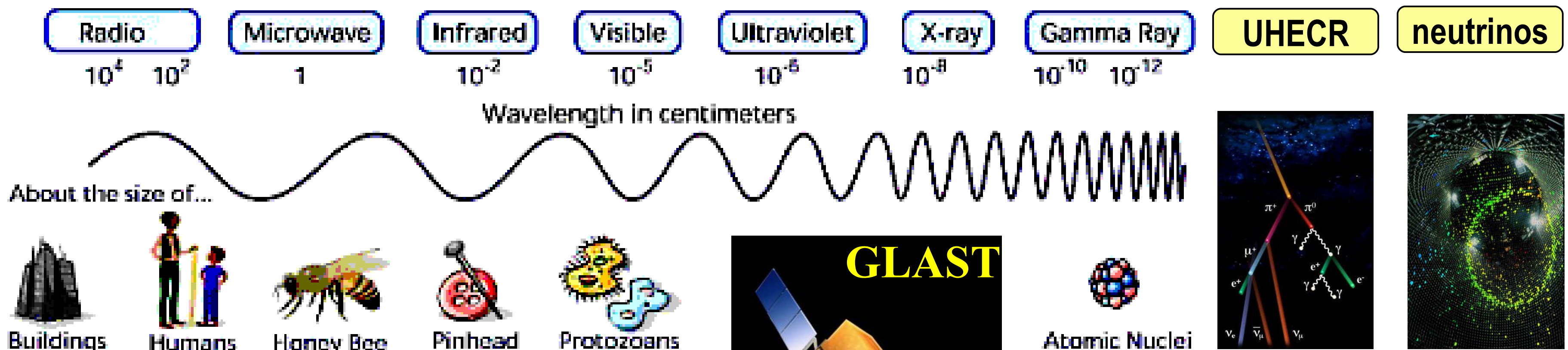
Part 5
Strategies
Observations, Theory, Data analysis

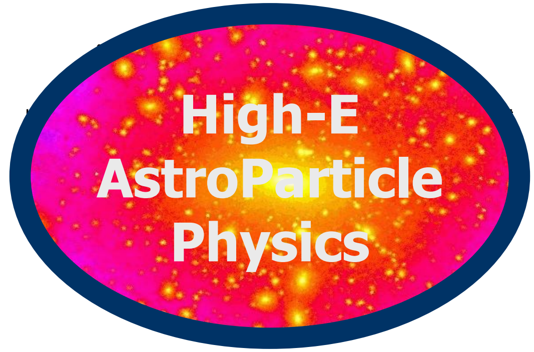
Observations

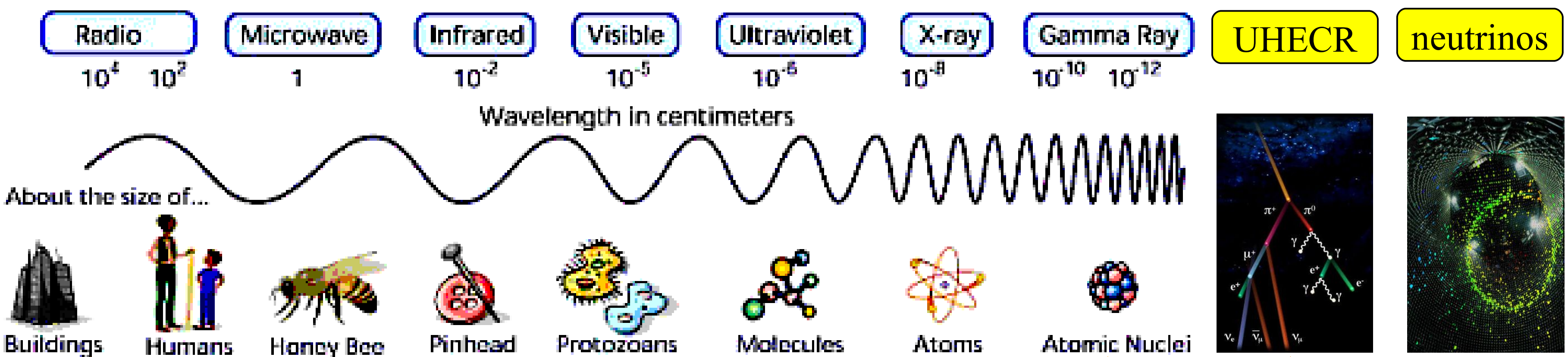






Theory



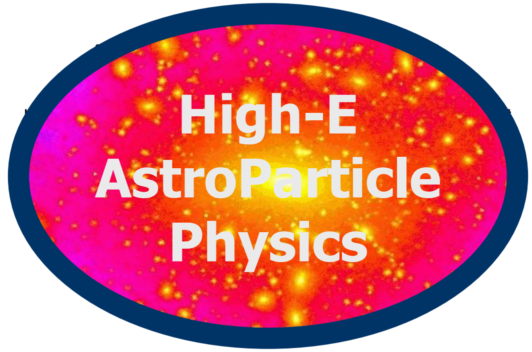


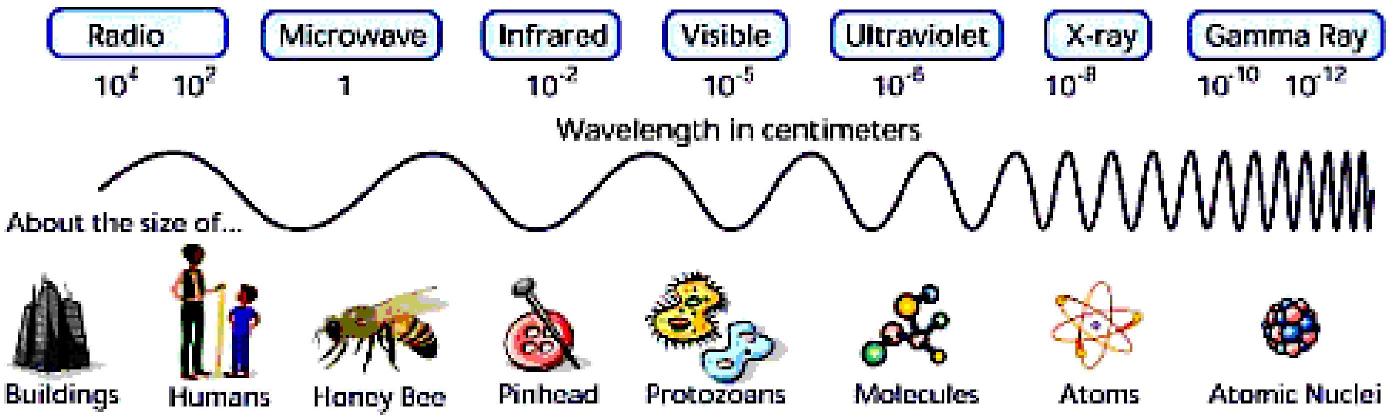
Origin of high-E particles

High-E phenomena in cosmic structures

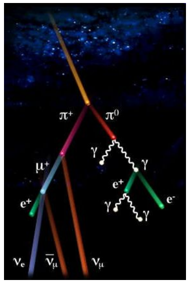
Identification of high-E cosmic structures

Data Analysis

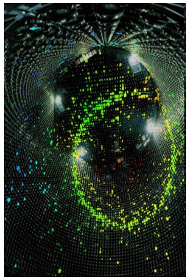




UHECR



neutrinos



Multi-frequency, multi-observatory analysis

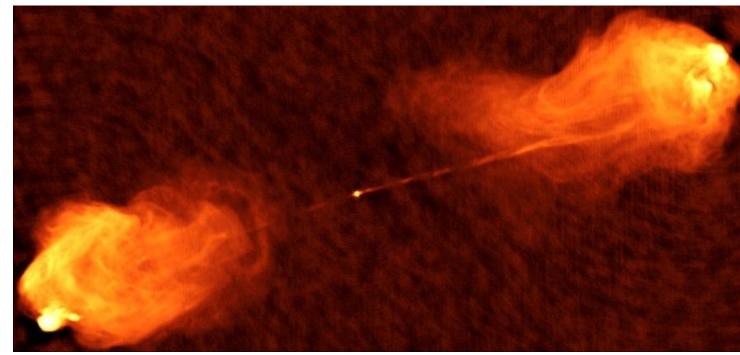
Non-astronomical data

Multi-disciplinary data analysis techniques and final products

… no conclusion… but still questions

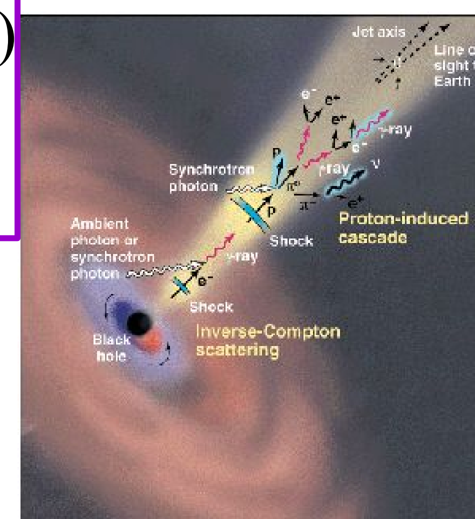
All issues here presented are far from being complete/exhaustive

… and many questions remain:



Jets
- continuous jets ? How? Stable?
- cannon-balls? How produced?

BHs
- From BHs (inside event horizon) to jets (our world)
- BHs or very compact objects?
- MECOs …



Many other questions
- …left to your research…

THANKS

for your attention !