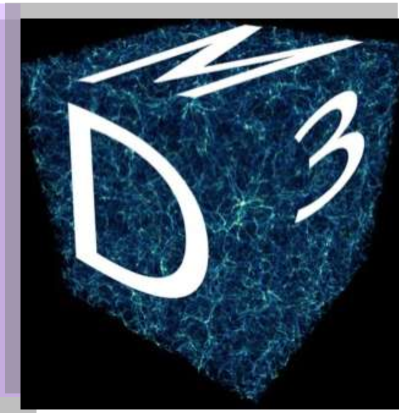
Multi³ approach to DM from the GC to LSS



Sergio Colafrancesco
ASI - ASDC
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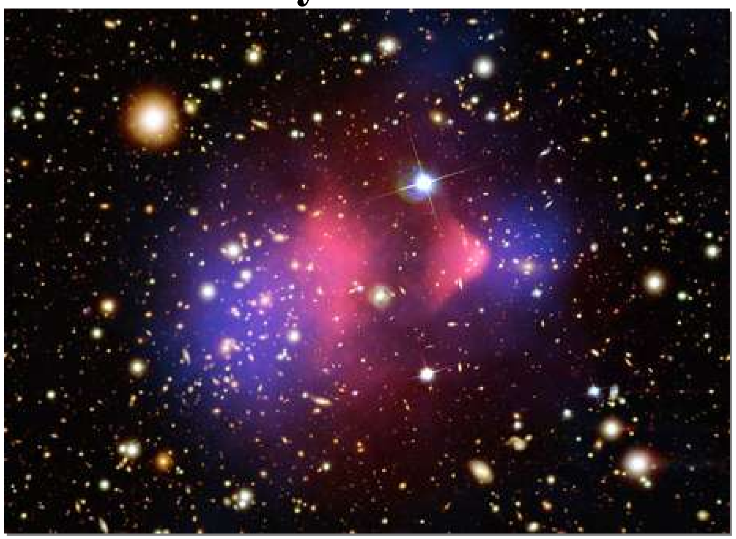
Colafrancesco@asdc.asi.it

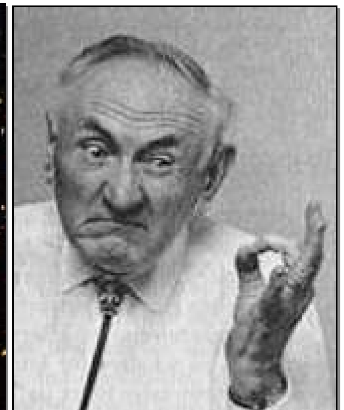
Dark Matter exists !

NATIONAL GEOGRAPHIC NEWS

REPORTING YOUR WORLD DAILY

Dark Matter Proof Found, Scientists Say





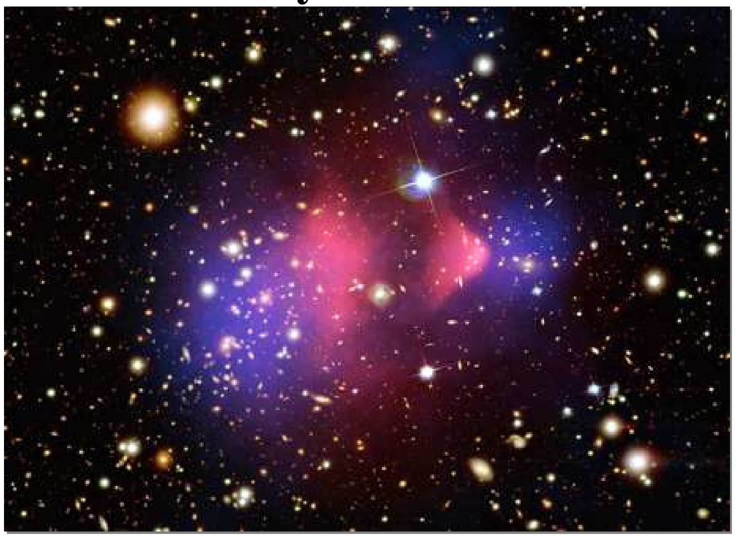
[F. Zwicky 1933]

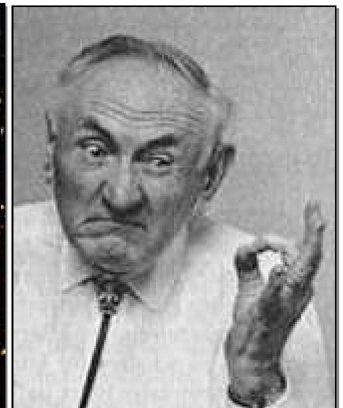
A team of researchers has found the first direct proof for the existence of dark matter, the mysterious and almost invisible substance thought to make up almost a quarter of the universe. In this composite image, two clusters of galaxies are seen after a collision. Hot gas, seen in red, was dragged away from the galaxies during the collision. That gas makes up more than 90 percent of the mass of normal, or visible, matter. But most of the mass—and thus matter—is located in the galaxy portions of the clusters, shown in blue, scientists say. In other words, the bulk of visible matter in the clusters has been separated from the majority of mass—which therefore must be dark matter.

Dark Matter exists ! … or not !?

NATIONAL GEOGRAPHIC NEWS
REPORTING YOUR WORLD DAILY

Dark Matter Proof Found, Scientists Say





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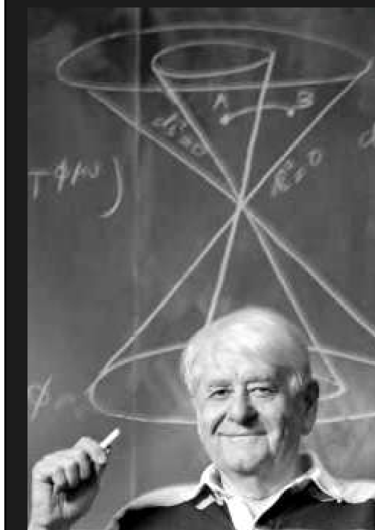
A team of researchers has found the first direct proof for the existence of dark matter, the mysterious and almost invisible substance thought to make up almost a quarter of the universe. In this composite image, two clusters of galaxies are seen after a collision. Hot gas, seen in red, was dragged away from the galaxies during the collision. That gas makes up more than 90 percent of the mass of normal, or visible, matter. But most of the mass—and thus matter—is located in the galaxy portions of the clusters, shown in blue, scientists say. In other words, the bulk of visible matter in the clusters has been separated from the majority of mass—which therefore must be dark matter.

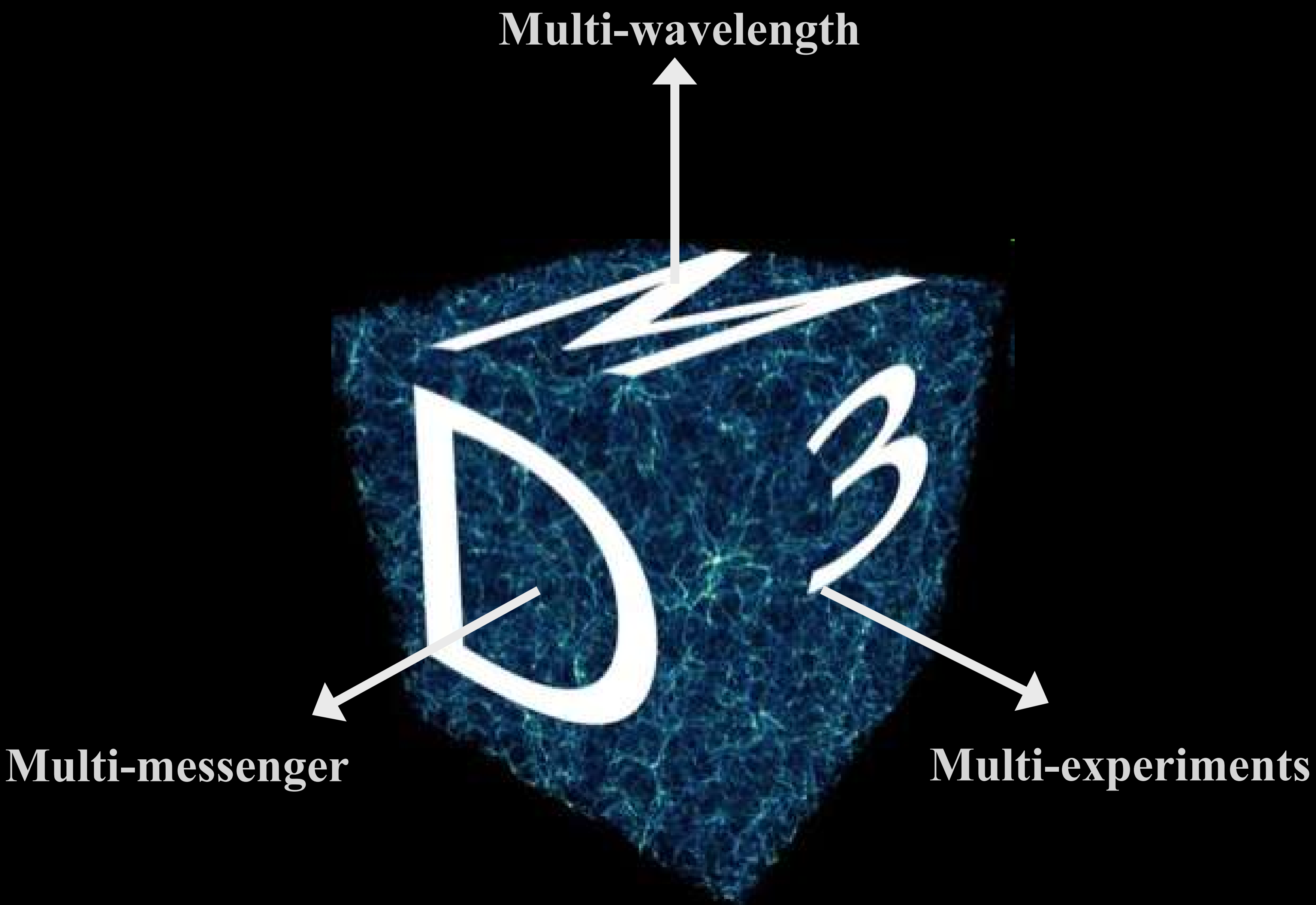
Nanogallery.info:

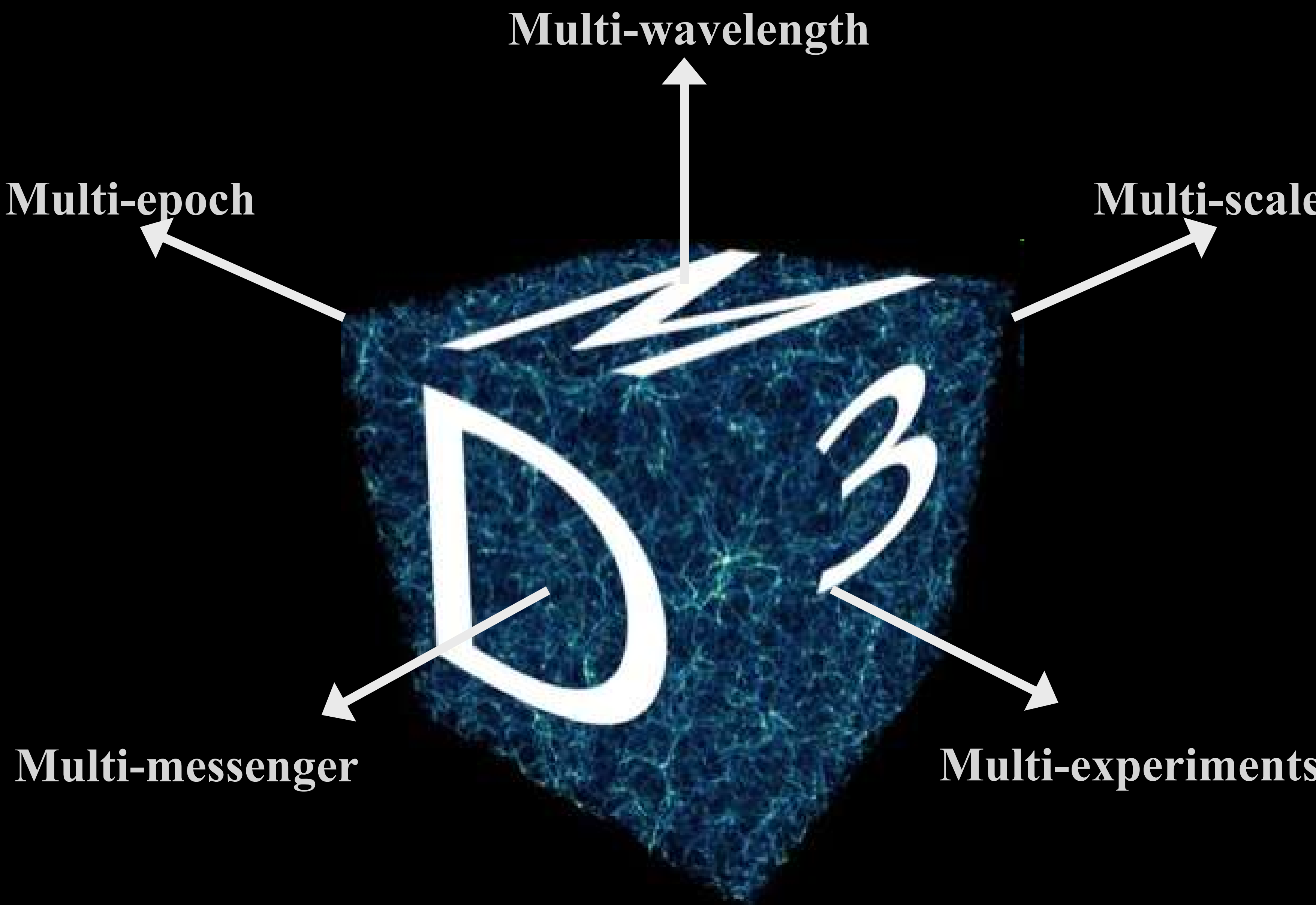
Dark matter does not exist ! Einstein wins again!



J. Moffat and colleagues suggest that there is a good reason dark matter why has never been directly detected:
It doesn't exist .

J. Moffat suggests that his Modified Gravity (MOG) theory can explain the Bullet Cluster observation. MOG predicts that the force of gravity changes with distance.
Moffat thinks that the present day expectation by many that dark matter must exist is similar to the expectation by many leading scientists in the beginning of the 20th century that a "luminiferous ether" should exist. This was a hypothetical substance, in which the waves of light were supposed to propagate


Multi-wavelength
M
D
3
Multi-messenger
Multi-experiments


Multi-wavelength
Multi-epoch
Multi-scale
M
D
3
Multi-messenger
Multi-experiments

Outline

- Multi-epoch
  - The Dark Matter Timeline
  - The present
- Multi-Scale + M^3
  - Galactic center
  - Galactic structures
  - Galaxy Clusters
- The Future
  - The DM search challenge

Outline

- Multi-epoch
  - The Dark Matter Timeline
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- Multi-Scale + M^3
  - DM search at various astronomical scales
    - Galactic center
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- The Future
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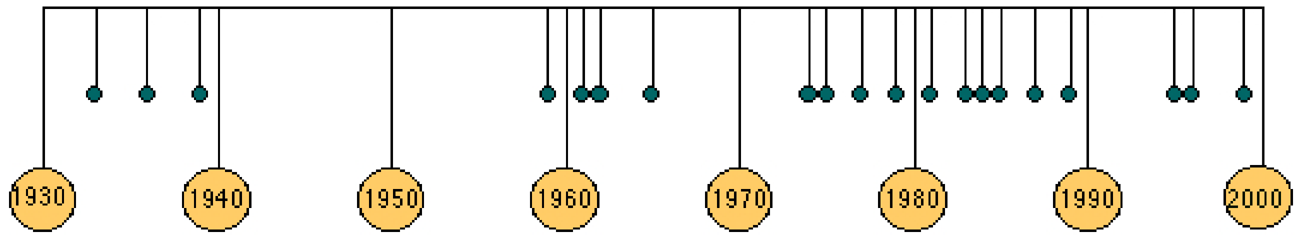
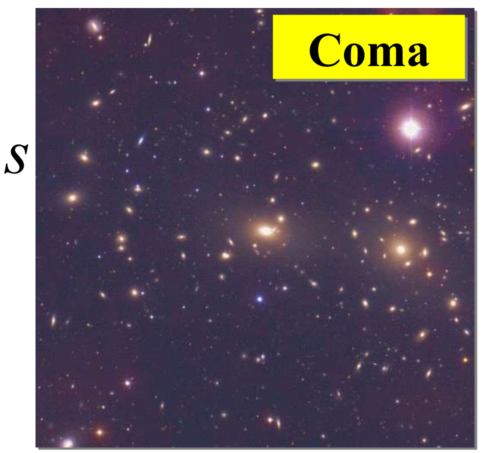
Dark Matter timeline

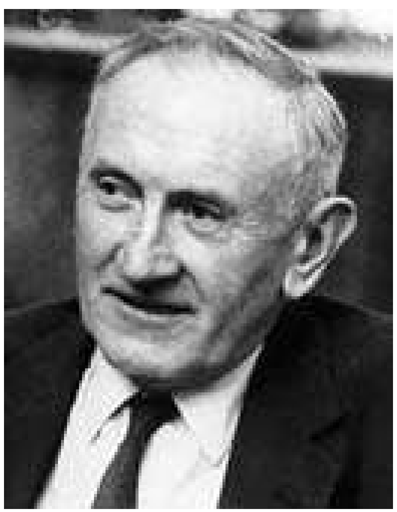


$$2T + U = 0$$

$$\sigma_V \approx (1019 \pm 360)\, km/s$$

$$\frac{M}{L} \approx 400$$

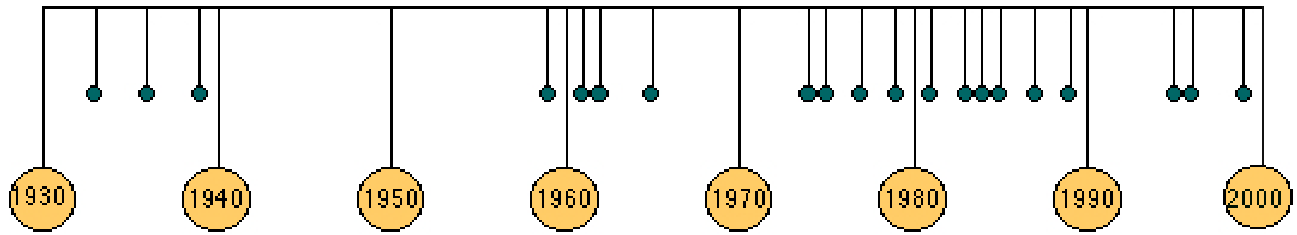


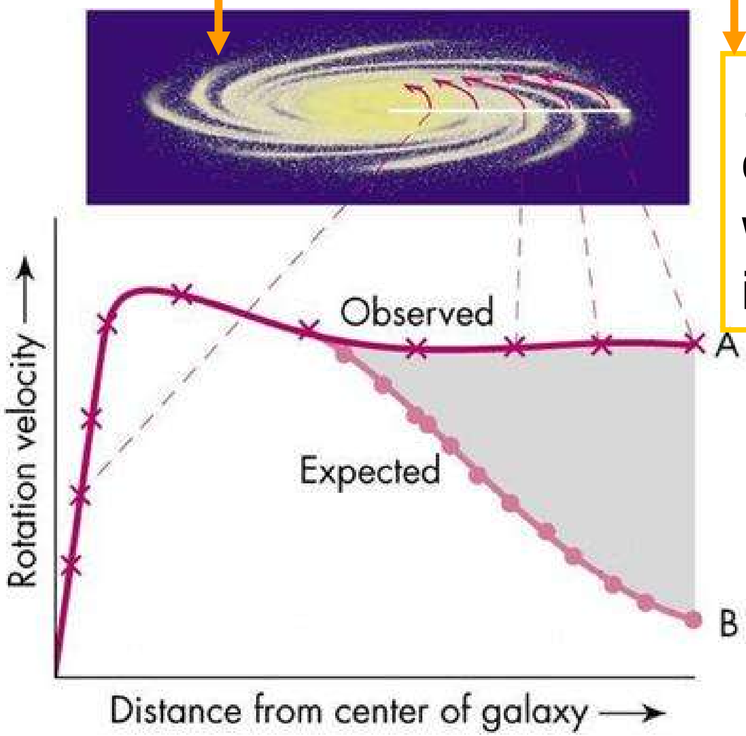


Fritz Zwicky
[Varna (Bulgaria), 1898 – Pasadena (USA), 1974]

Zwicky used the words "dunkle (kalte) Materie"
dark (cold) Matter
which might be regarded as the first reference to Cold Dark Matter
… even though not in the modern sense (!?)

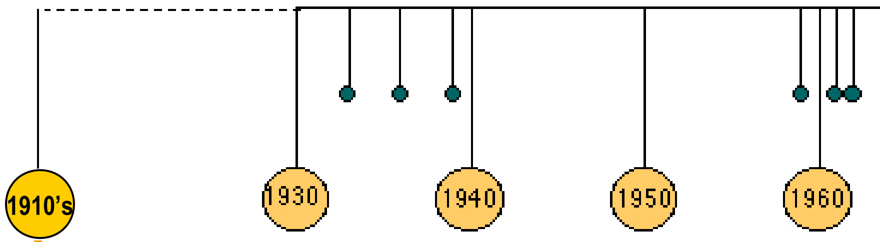
Dark Matter timeline

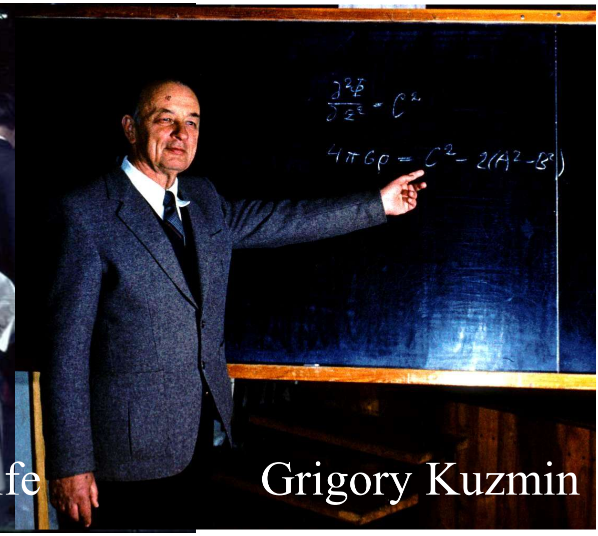




1939 - **Babcock** noticed that the outer regions of M31 were rotating with an unexpectedly high velocity indicating a missing mass.

Dark Matter tim





Local Dark Matter

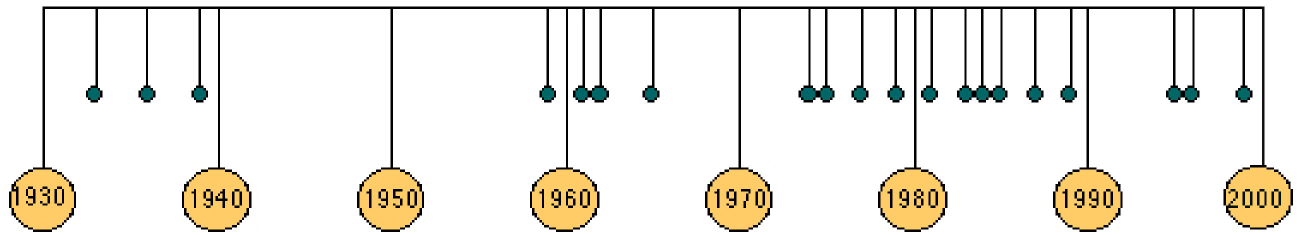
- Öpik (1915)
- Oort (1932, 1960)
- Kuzmin (1952, 1955)
- Eelsalu (1959)
- Jõeveer (1972, 1974)
- Bahcall (1985)
- Gilmore et al (1989)

Global Dark Matter

Zwicky (1933)

Zwicky discovered what so many scientists find when probing the depths of the current and accepted knowledge of the times.
What Zwicky uncovered was considered an **anomaly**.
Zwicky, who did not particularly belong to the astronomical community, was making a claim that could overthrow present knowledge of the universe.
It was not the right time for the astronomical community to accept such a revolutionary idea.

Dark Matter timeline



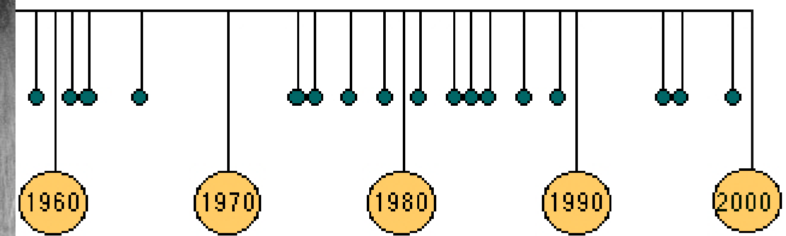
1959 - **Kahn & Woltjer** published their discovery of a missing mass in the Local Group (□ hot gas with T ~ $5 \cdot 10^5$ K)
Interestingly enough, they did not cite Zwicky's (1933) paper.

1961 - The renaissance of Dark Matter truly began with the Santa Barbara Conference on the Instability of Galaxies.
By this time, enough research was done for the community to see that the **missing mass anomaly** was not going to go away.
"When... an anomaly comes to seem more than just another puzzle of normal science, the transition to crisis and to extraordinary science has begun" (Kuhn).

Vera Rubin working at the Ford spectrograph (1955)

Dark Matter timeline

Jim Peebles explains the secrets of galaxy formation to Scott Tremaine (Tallinn 1977)



1980 - Experimental results on the neutrino rest mass were announced.

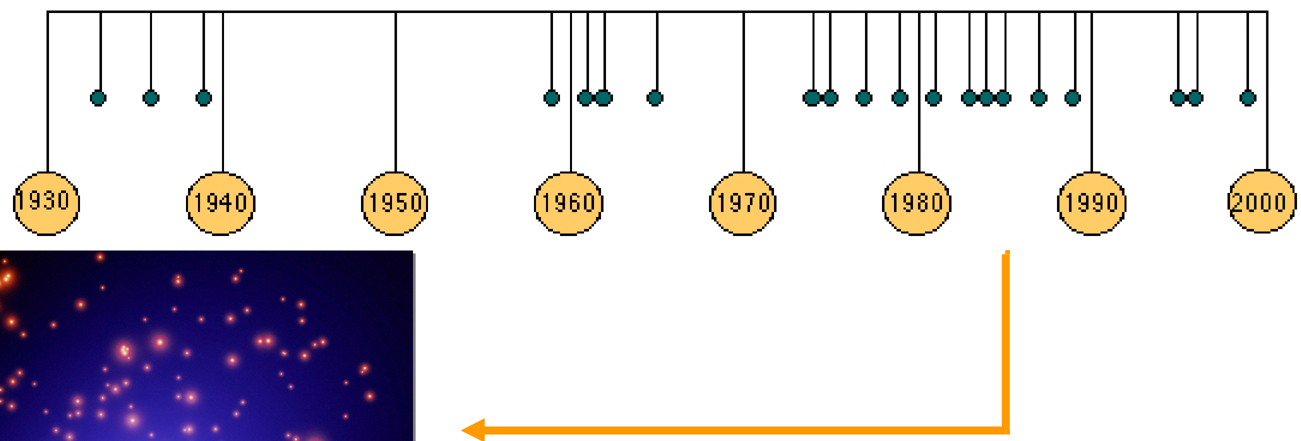
1975 – By this time the majority of astronomers had become convinced that missing mass existed in cosmologically significant amounts.
Uncertainty on the Dark Matter nature remained !!!

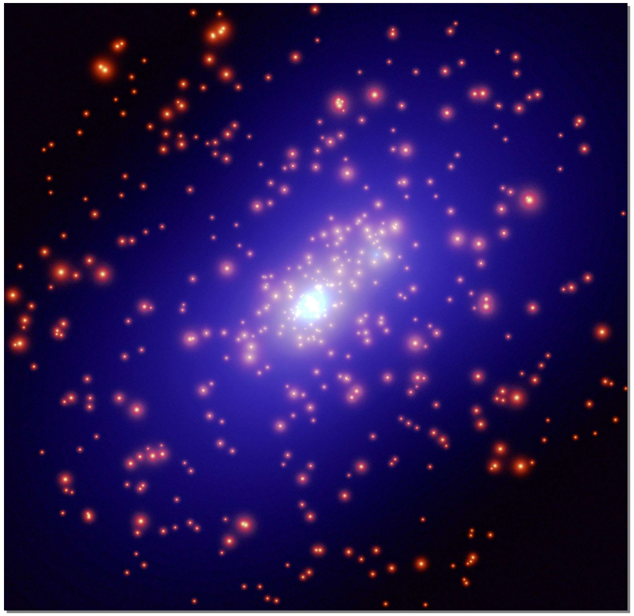
1977 – **Rees** speculated that *"there are other possibilities of more exotic character – for instance the idea of neutrinos with small (~few eV) rest mass"*

Zel'dovich & Longair

(Tallinn 1977)

Dark Matter timeline



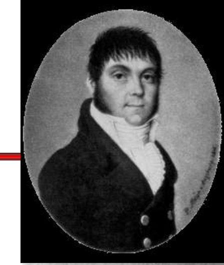


A high-resolution CDM simulation with small-scale structure

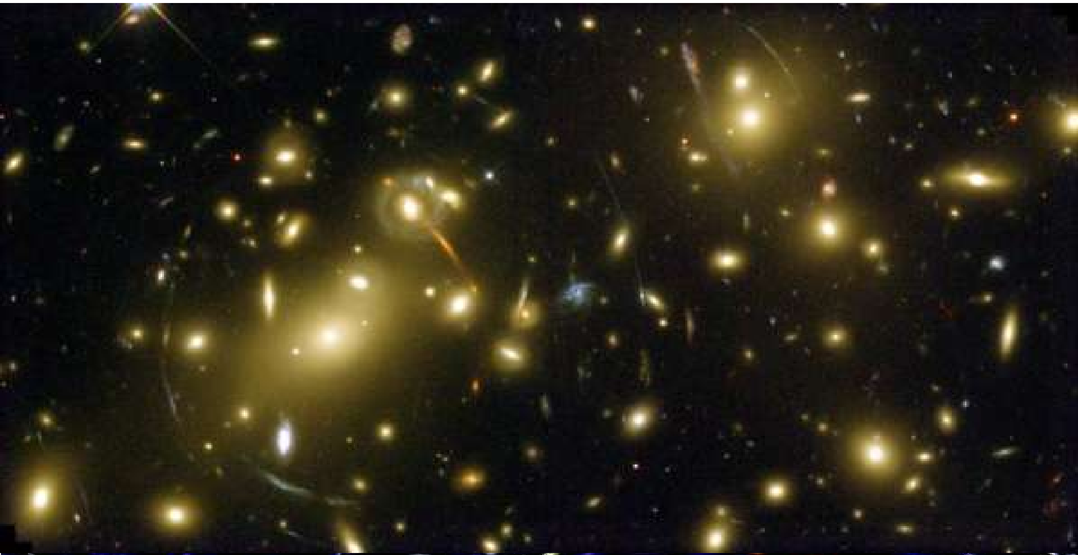
1980's – The **Cold Dark Matter** model with **axions** or other weakly interactive particles **WIMP** was as an alternative to neutrino models (providing the Hot Dark Matter).

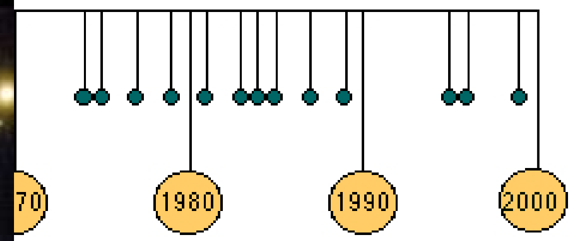
Dark Matter timeline

J. Soldner 1804

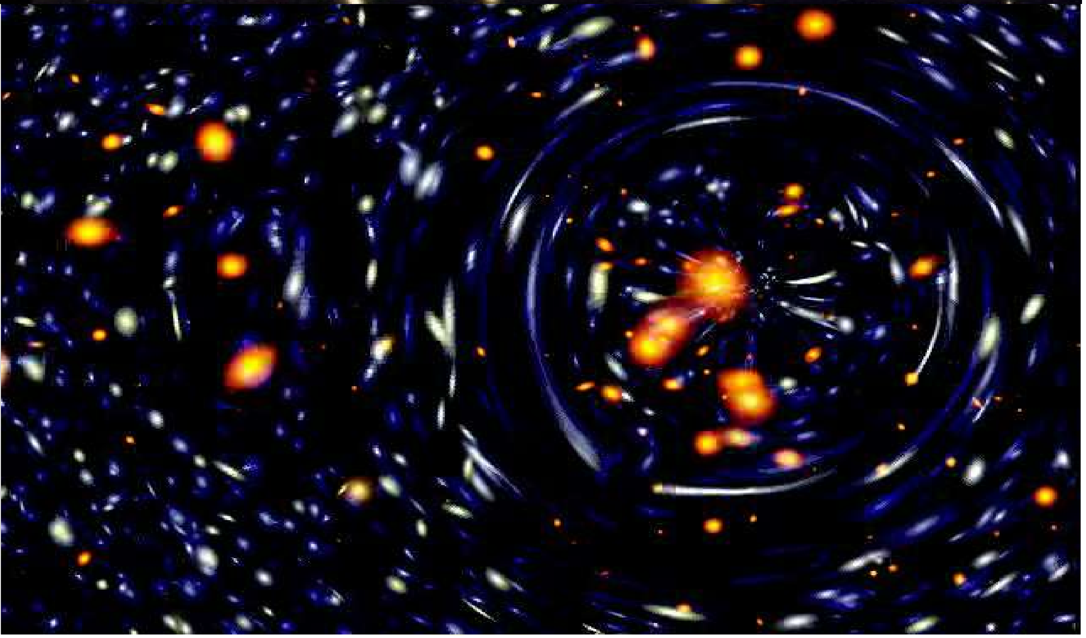


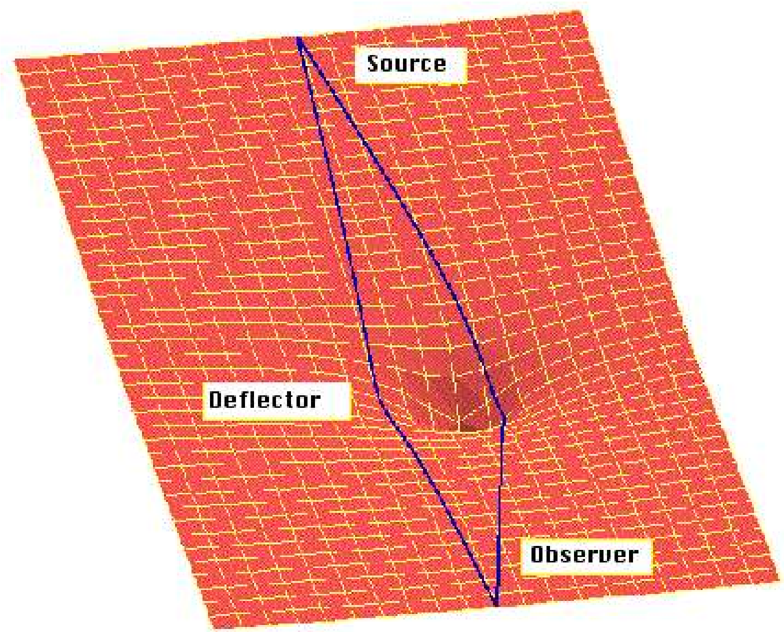
A. Einstein 1911



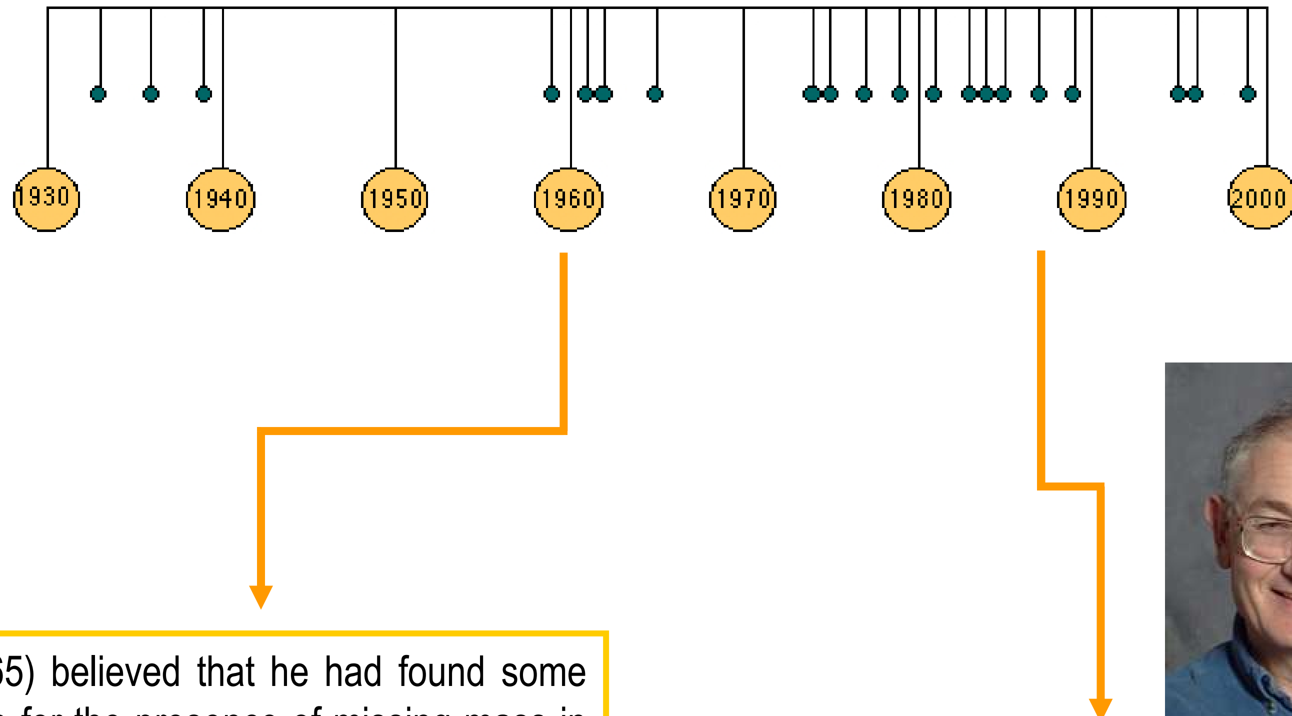


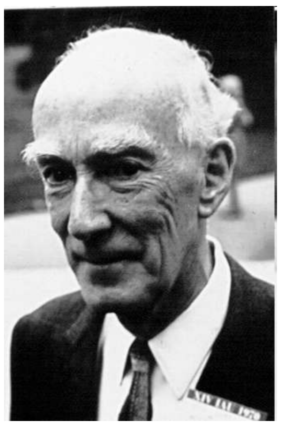
1990's – **Dark Matter** distribution in clusters can explain the **gravitational lensing** of background galaxies.





False Alarms & Diversionary Manouvres

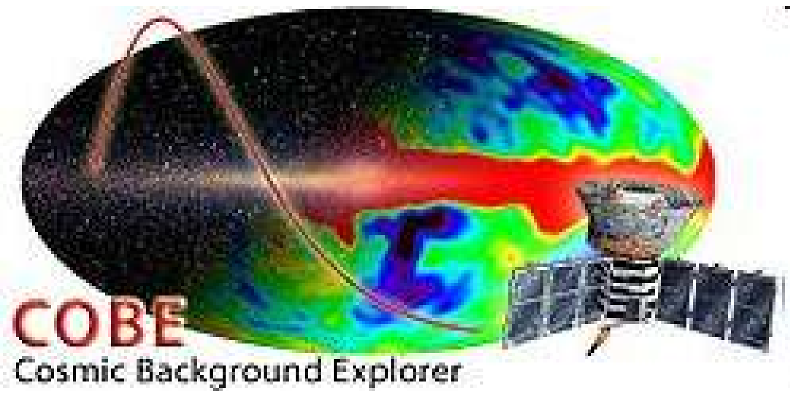


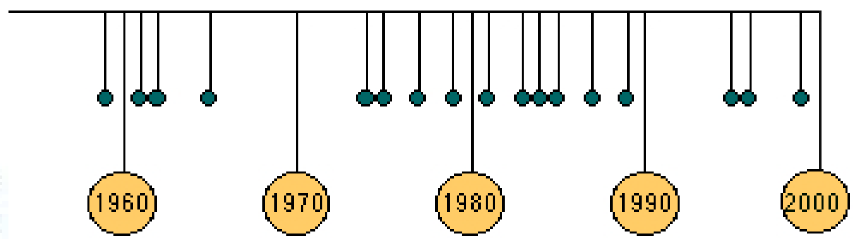


J. Oort (1960, 1965) believed that he had found some dynamical evidence for the presence of missing mass in the disk of the Galaxy. If true, this would have indicated that some of the DM was dissipative in nature. However, late in his life, Oort confessed that the existence of missing mass in the Galactic plane was never one of his most firmly held scientific beliefs. Detailed observations, (reviewed by Tinney 1999), show that brown dwarfs cannot make a significant contribution to the density of the Galactic disk near the Sun.

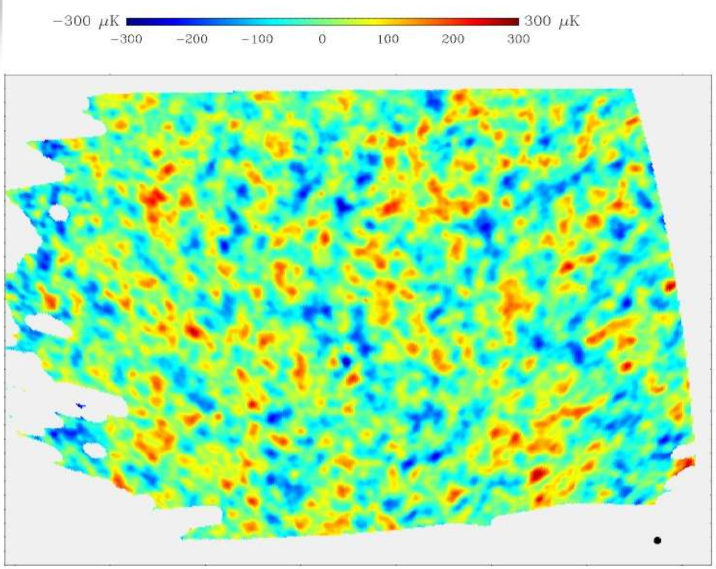
1987 – One particularly interesting dissenter: **M.Milgrom**. He believed that the existence of the DM implied that Newton's law of gravity must be amended for gravitational accelerations that are very small, such as the gravitational accelerations seen in a galaxy's outer fringes.
Bekenstein followed up Milgrom's idea in TeVeS model

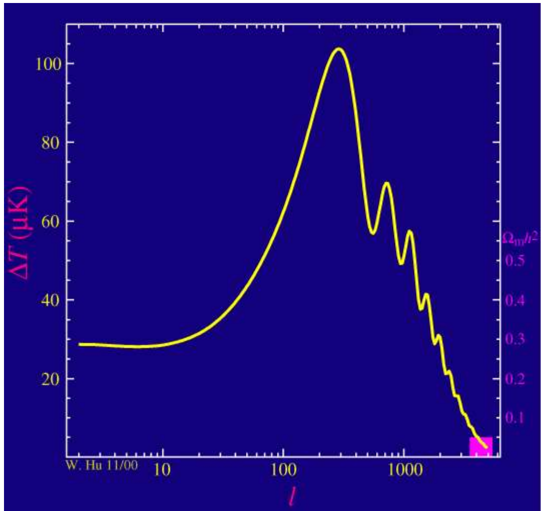
Dark Matter timeline



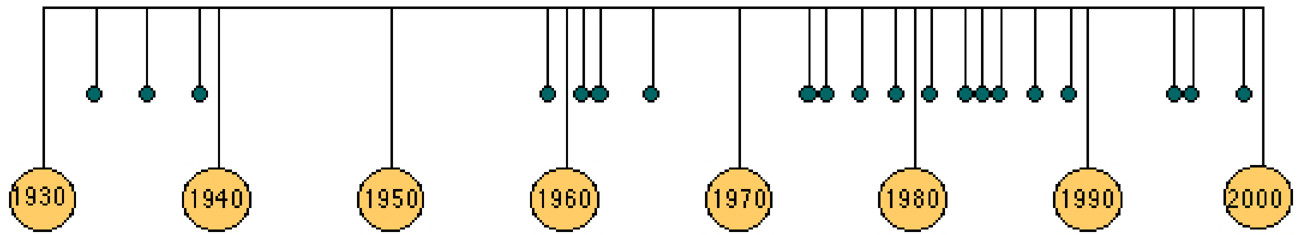


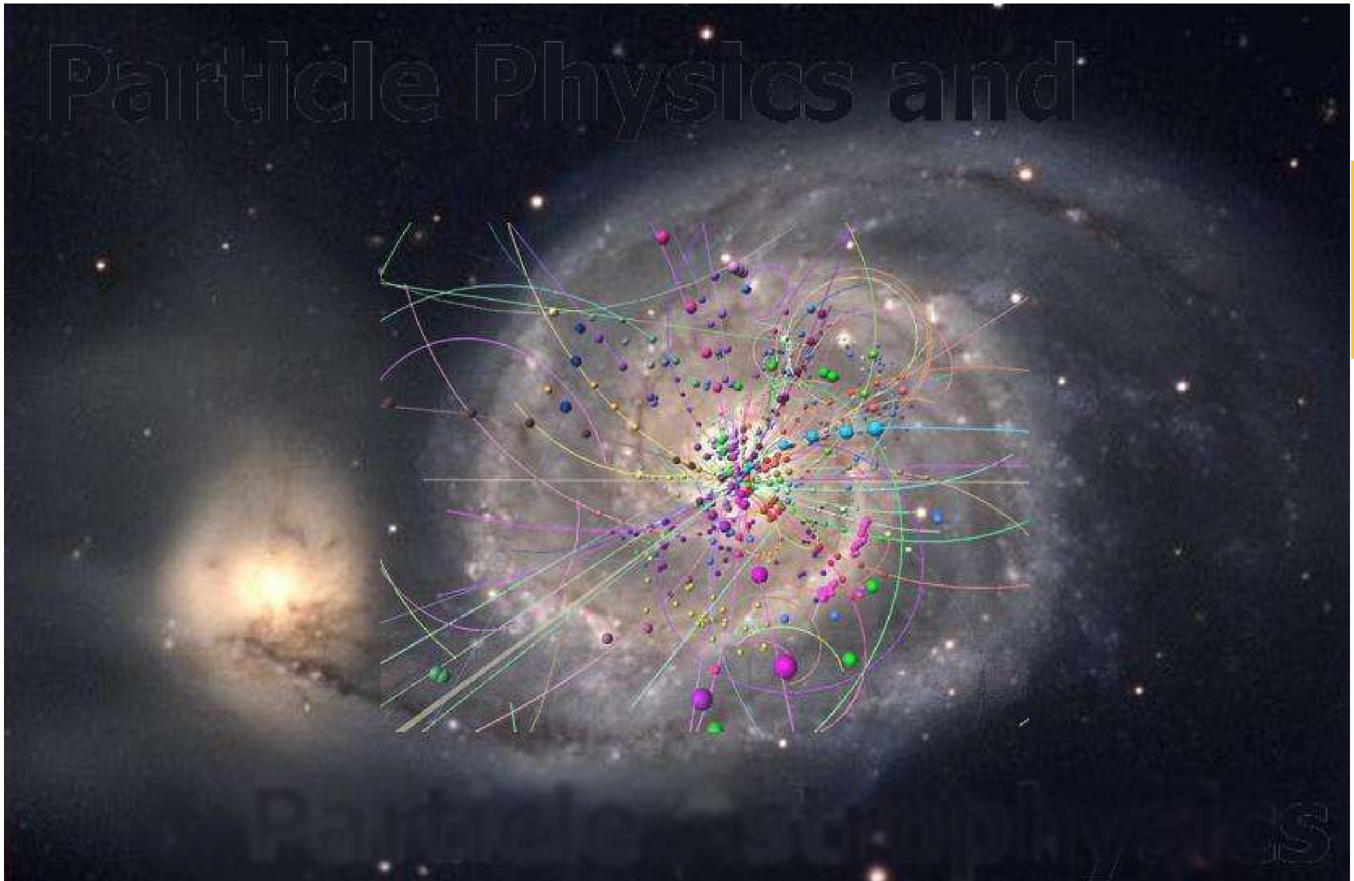
1992-99 – **Dark Matter** is a main ingredient of the cosmic fluid and its effect is present in the **CMB anisotropy spectrum** .





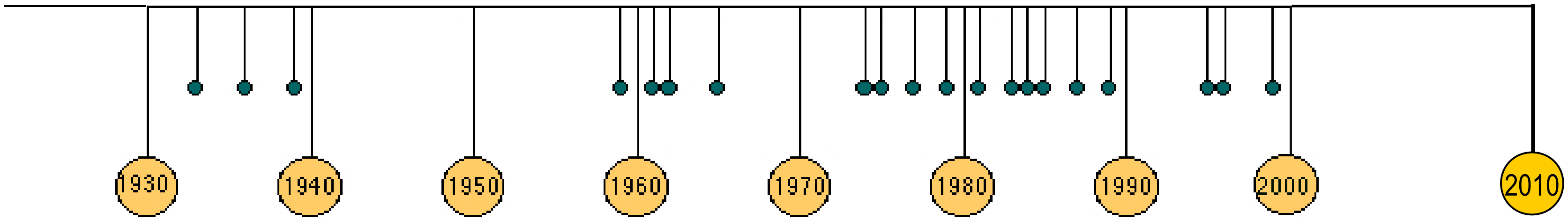
Dark Matter timeline





1990-2000 – Naissance of **Astroparticle – Dark Matter** physical connection.

The Dark Matter Scenario: timeline



Astronomy

Cosmology

Astro Particle Physics

Particle Physics

Missing mass Dynamics

Rotation curves

N-body simulations

Lensing

CMB

1977
Thermal relics
(Lee & Weinberg)

1984
Indirect DM search idea
(Silk & Srednicki)

1985
Direct DM experiments
(Goodman & Witten)

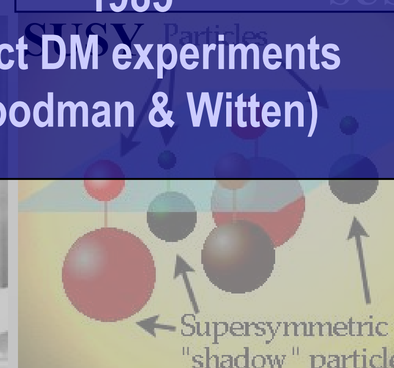
Today

!?

ν - mass theo. & exp.

Beyond the SM

SUSY

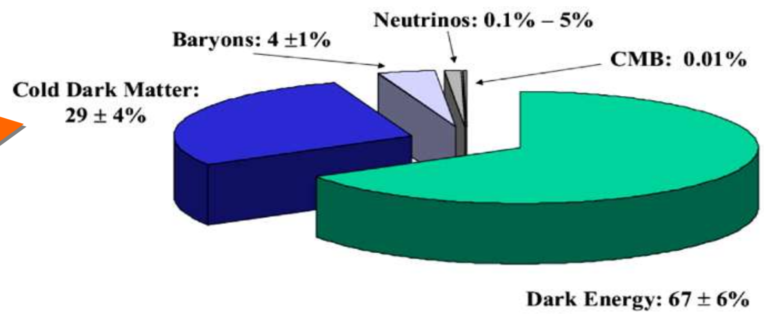


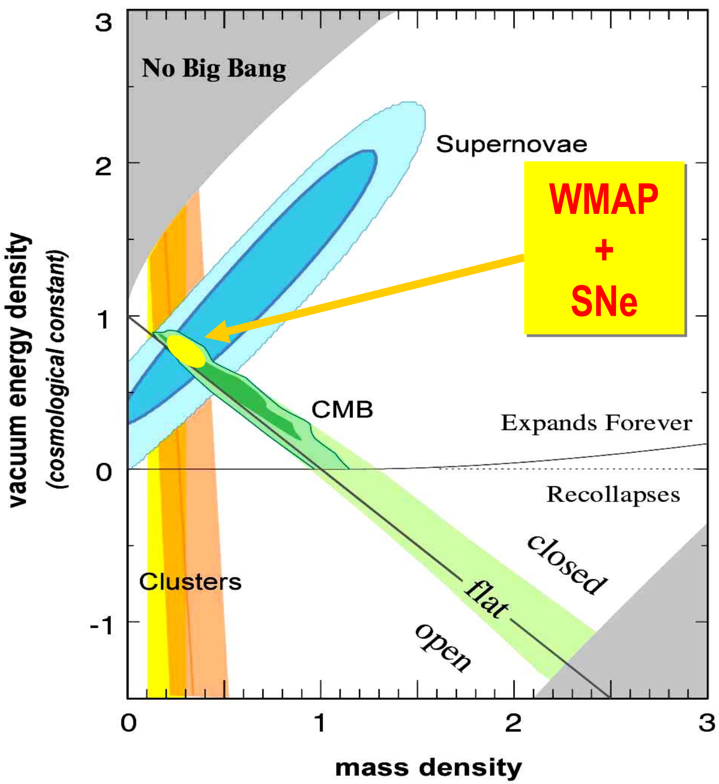
The Present

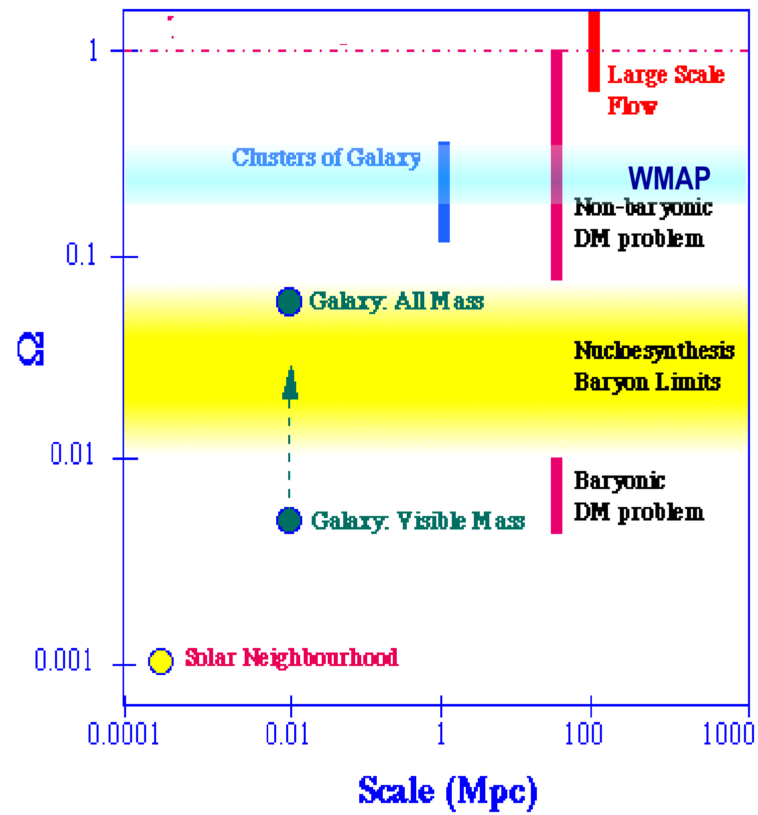
"Il presente e le bolle del tempo" -Olio e acrilico su cartoncino telato (B. D'Aleppo)

Dark Matter Scenario: motivations

Matter and Energy in the Universe: A Strange Recipe

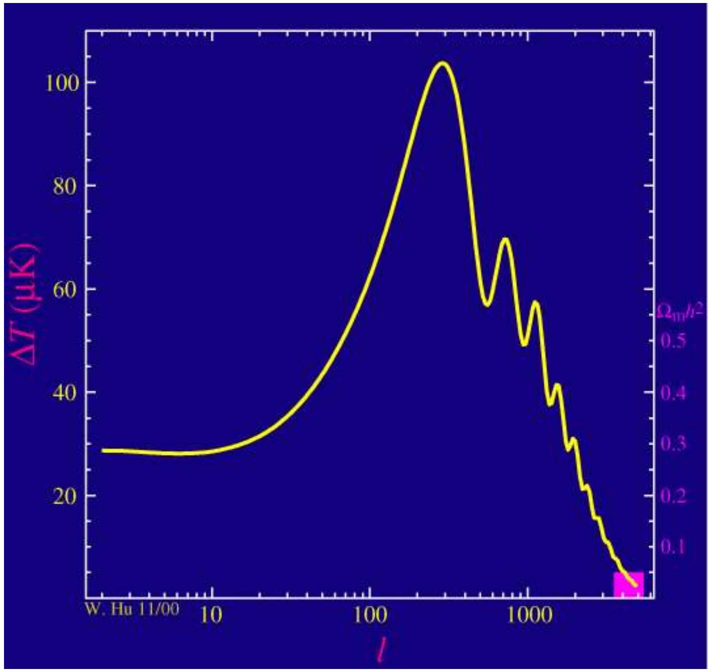




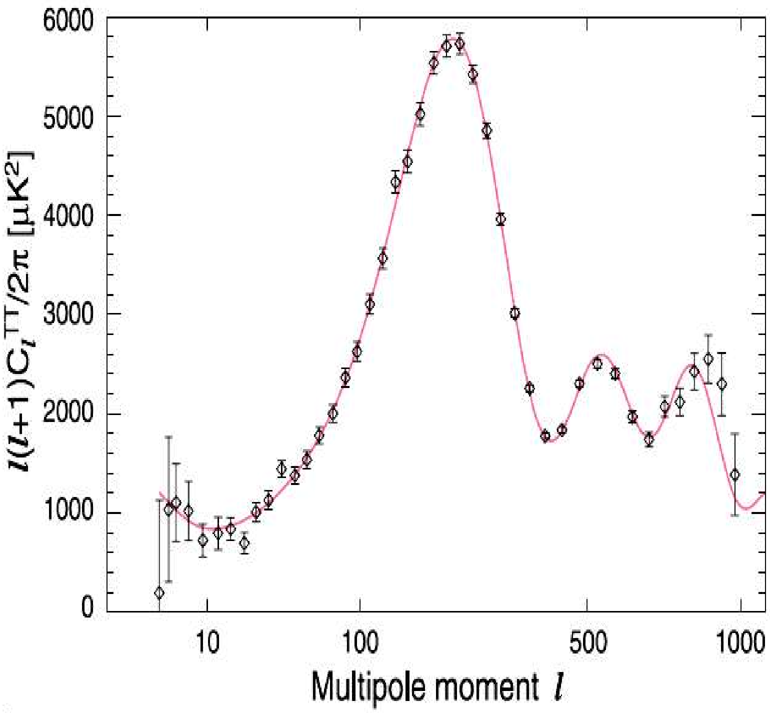


DM & CMB

Generic ΛCDM



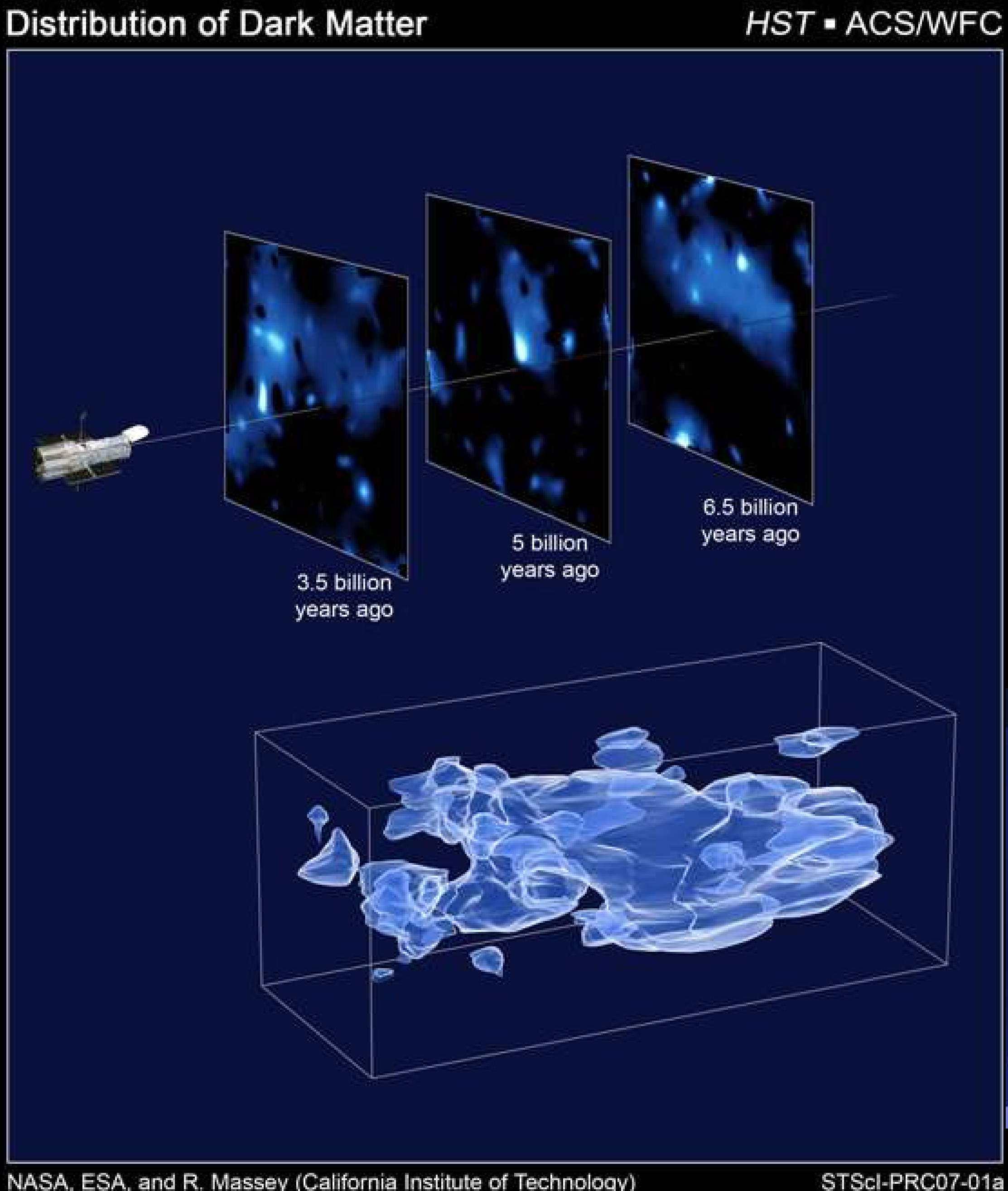
WMAP 5yr



$$0.1332 \leq \Omega_{DM} h^2 \leq 0.1406$$

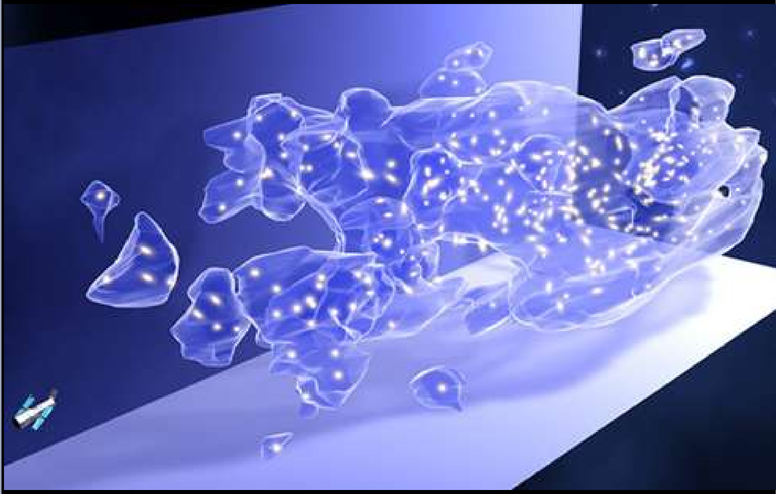
$$0.27 \leq \Omega_{DM} \leq 0.29$$

DM distribution in cosmic time

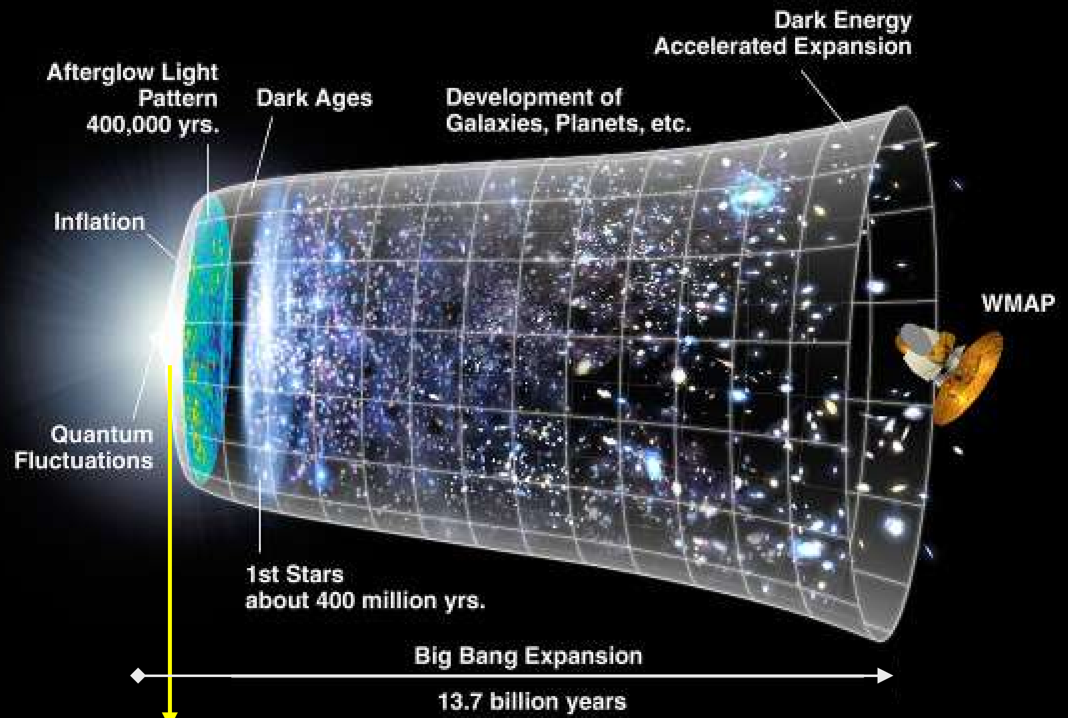


Dark Matter grows increasingly 'clumpy' as it collapses under gravity.

The map stretches halfway back to the beginning of the universe



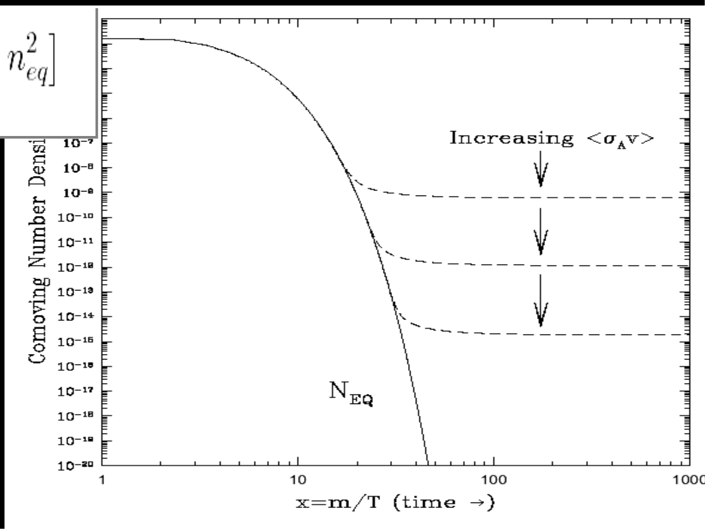
DM relic density



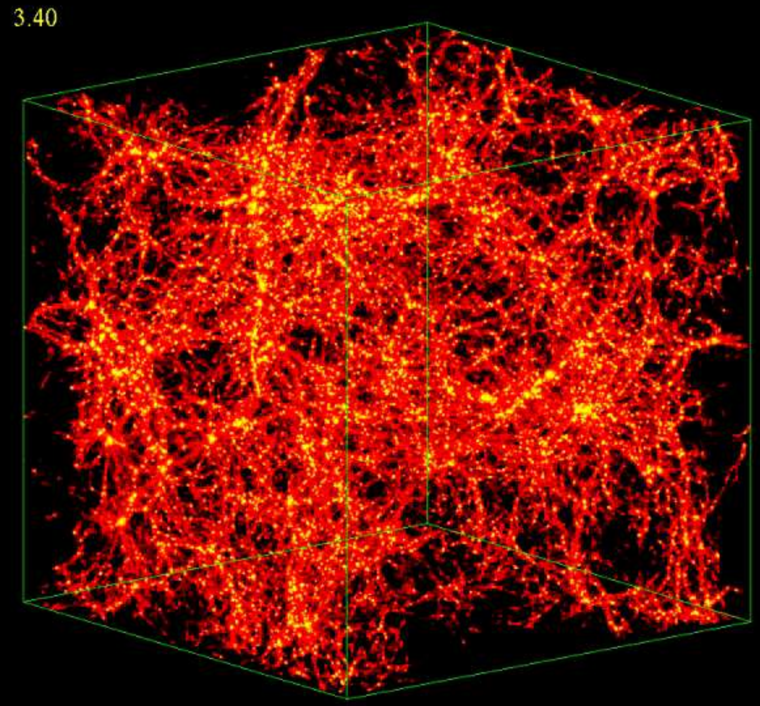
WIMPs
in thermal equilibrium

Freeze-out

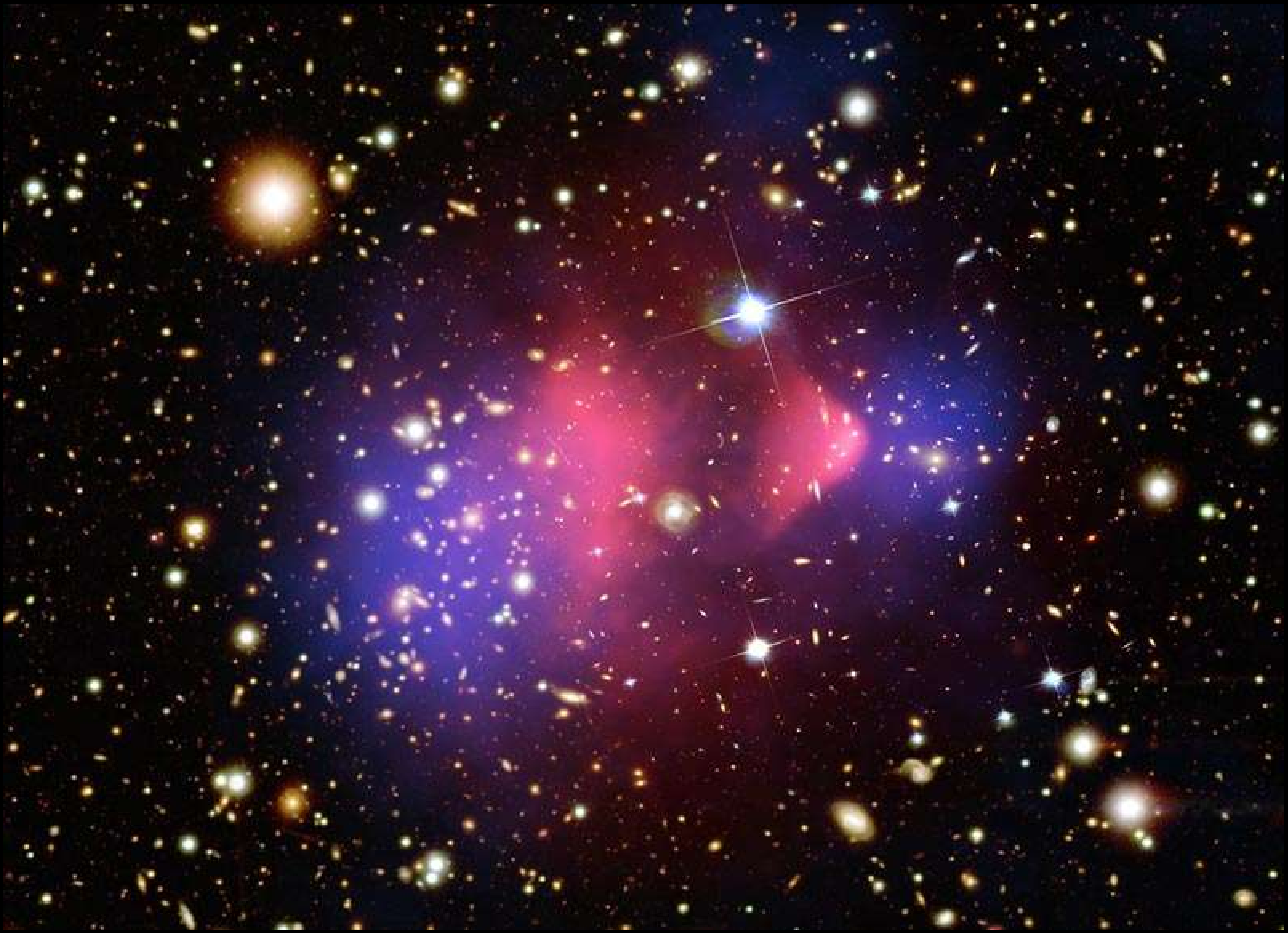
$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$



Formation of DM halos



DM: the most palpable proof



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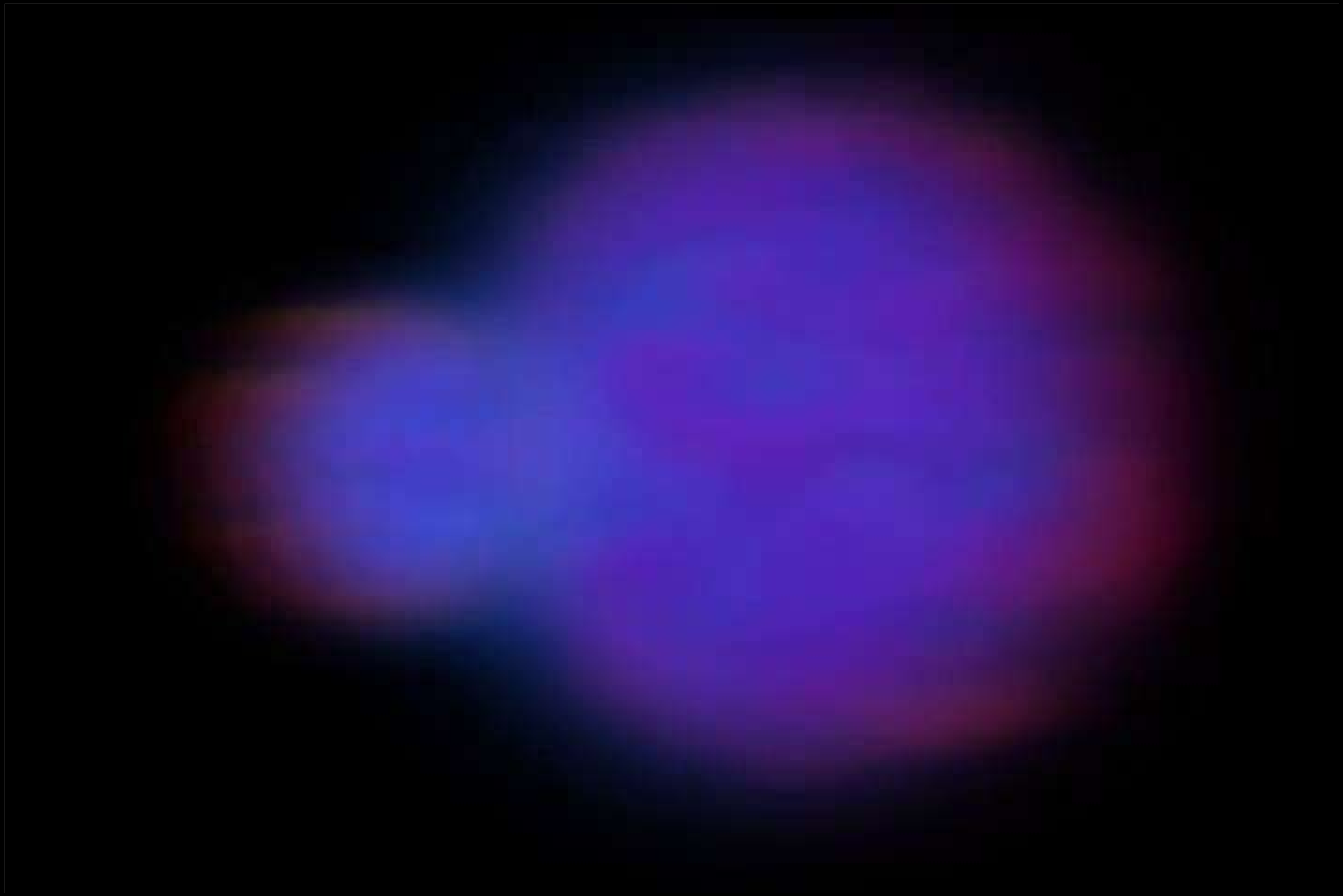


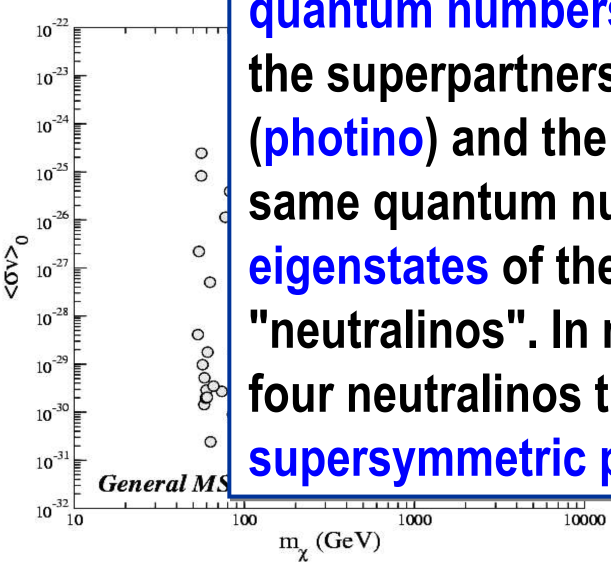
Viable DM candidates

Neutralinos

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

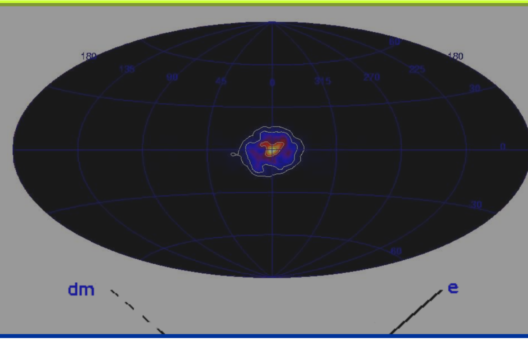
$$\Omega_\chi h^2 \approx \frac{3\cdot 10^{-27}\, cm^{-3} s^{-1}}{\langle \sigma V \rangle_A}$$

$0.09 \leq$



In supersymmetry models, all Standard Model particles have partner particles with the same quantum numbers but spin differing by 1/2. Since the superpartners of the Z boson (zino), the photon (photino) and the neutral higgs (higgsino) have the same quantum numbers, they can mix to form four eigenstates of the mass operator called "neutralinos". In many models the lightest of the four neutralinos turns out to be the lightest supersymmetric particle (LSP).

Light (MeV) DM

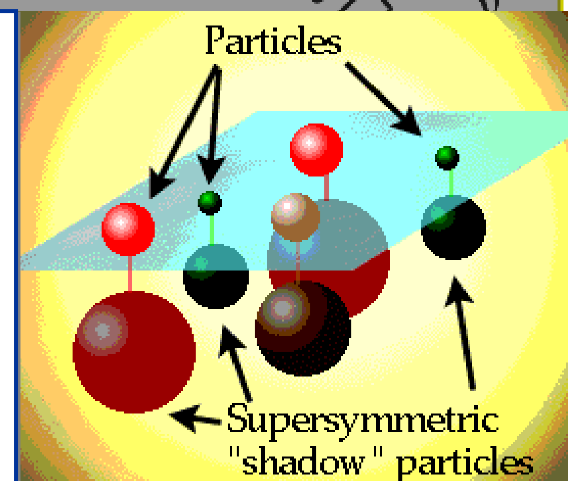


Sterile ν's

Unstable

$$\tau \simeq 5\times 10^{23}\,\text{sec}\left(\frac{10\text{keV}}{M_I}\right)^5 \left(\frac{10^{-10}}{|\Theta|^2}\right)$$

Radiative decay: line



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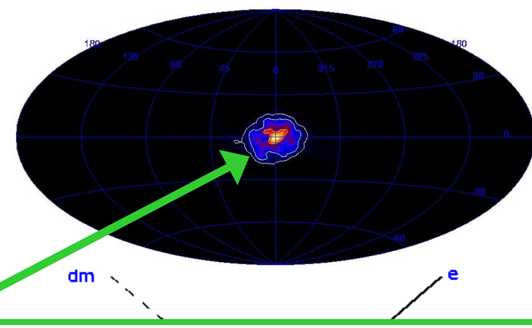
Light (MeV) DM



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Radiative decay: line

e ν γ

Scalar (**spin=0**) particles may be DM candidates, provided they annihilate sufficiently strongly through new interactions, such as those induced by a new light neutral spin-1 boson U. The corresponding interaction is stronger than weak interactions at lower energies, but weaker at higher energies. Annihilation cross sections of (axially coupled) spin-1/2 DM particles, induced by a U vectorially coupled to matter, are the same as for spin-0 particles. In both cases, the cross sections ($\sigma_{ann}V_{rel}/c$) into e+e− automatically include a v^2_{dm} suppression factor, needed to avoid an excessive production of γ-rays from residual DM annihilations. **Spin-0 DM particles** annihilating into e+e− have been claimed to be responsible for the bright **511 keV γ-ray line** observed by **INTEGRAL** from the **galactic bulge**.

⟨σv⟩ 10 10 100 1000 10000 m_χ (GeV)

Viable DM candidates

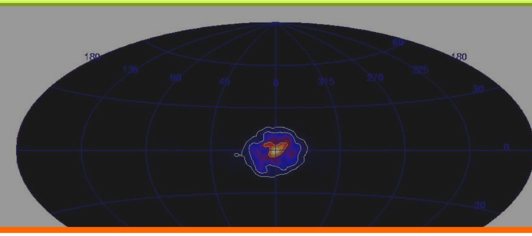
Neutralinos

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

$3 \cdot 10^{-27}\, cm^{-3} s^{-1}$

m_χ (GeV)

Light (MeV) DM

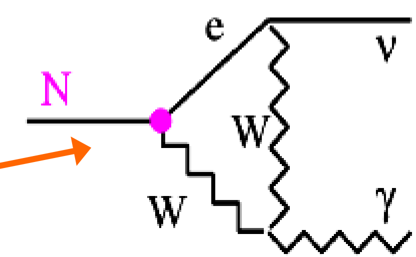


Sterile ν's

Unstable

$$\tau \simeq 5 \times 10^{23}\,\text{sec}\left(\frac{10\text{keV}}{M_I}\right)^5 \left(\frac{10^{-10}}{|\Theta|^2}\right)$$

Decay



Radiative decay: line

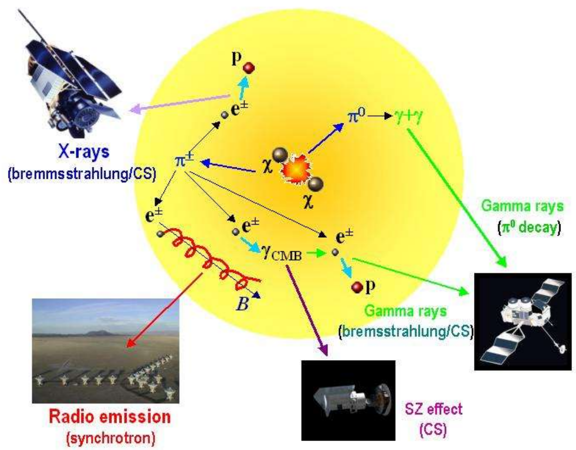
$$\nu_s \rightarrow \nu_\alpha + \gamma$$

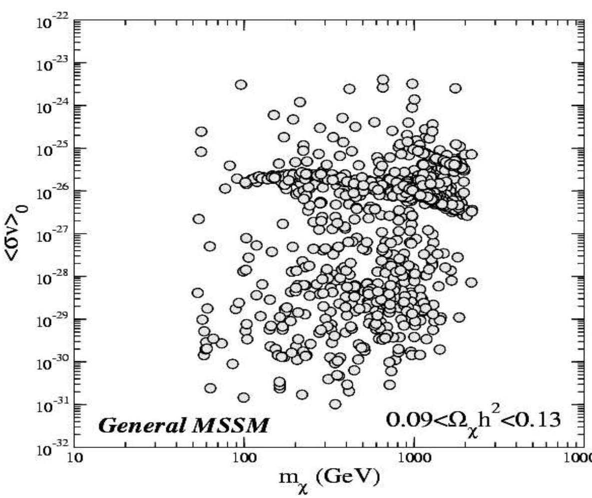
The term **sterile neutrino** was coined by **Bruno Pontecorvo** who hypothesized the existence of the right-handed neutrinos in a seminal paper (1967), in which he also considered vacuum neutrino oscillations in the laboratory and in astrophysics, the lepton number violation, the neutrinoless double beta decay, some rare processes, such as μ → e γ, and several other questions that have dominated the neutrino physics for the next four decades. Most models of the neutrino masses introduce **sterile (or right-handed) neutrinos** to generate the masses of the ordinary neutrinos via the seesaw mechanism.

Viable DM candidates

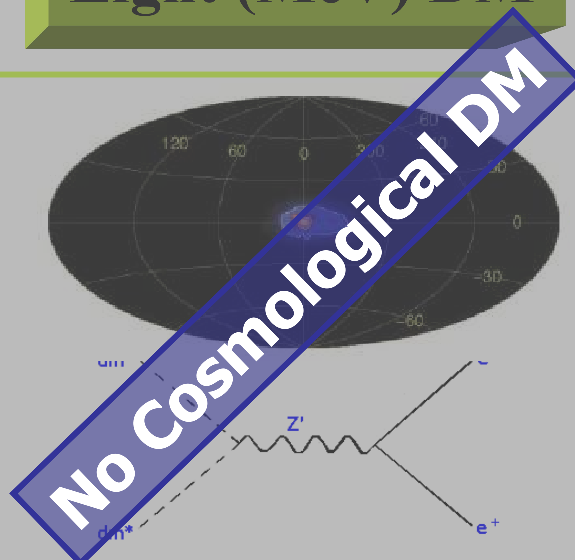
Neutralinos

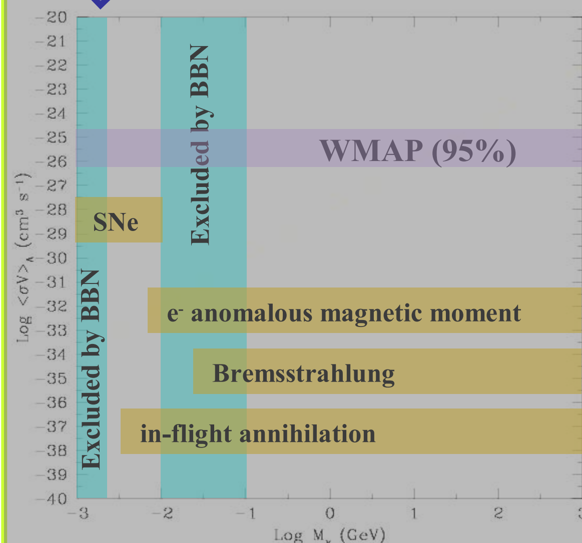
$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$





Light (MeV) DM



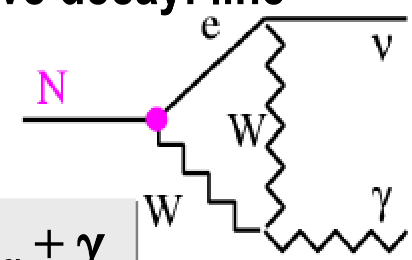


Sterile ν's

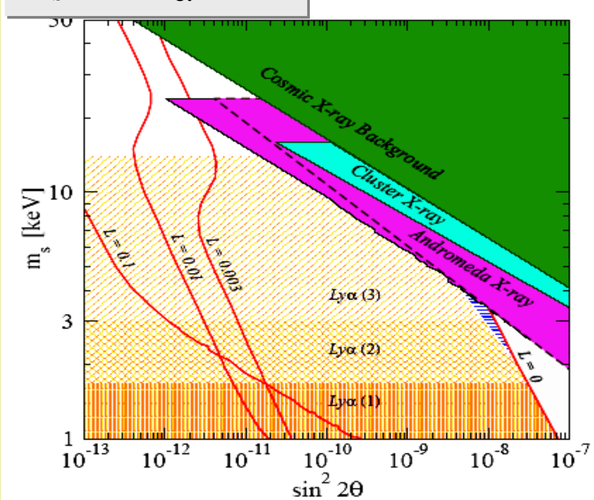
Unstable

$$\tau \simeq 5\times10^{23}\,\text{sec}\left(\frac{10\text{keV}}{M_I}\right)^5\left(\frac{10^{-10}}{|\Theta|^2}\right)$$

Radiative decay: line



$$\nu_s \rightarrow \nu_\alpha + \gamma$$



Outline

- Multi-epoch
  - The Dark Matter Timeline
  - The present
- Multi-Scale + M^3
  - Galactic center
  - Galactic structures
  - Galaxy Clusters
- The Future
  - The DM search challenge

Hunt for the DM particle

DM exists:
we feel its (gravitational) presence

DM is mostly non-baryonic:
we must think of a specific search strategy

DM is very elusive:
we must consider un-ambiguous evidence

➡ **Crucial Probes are required !**

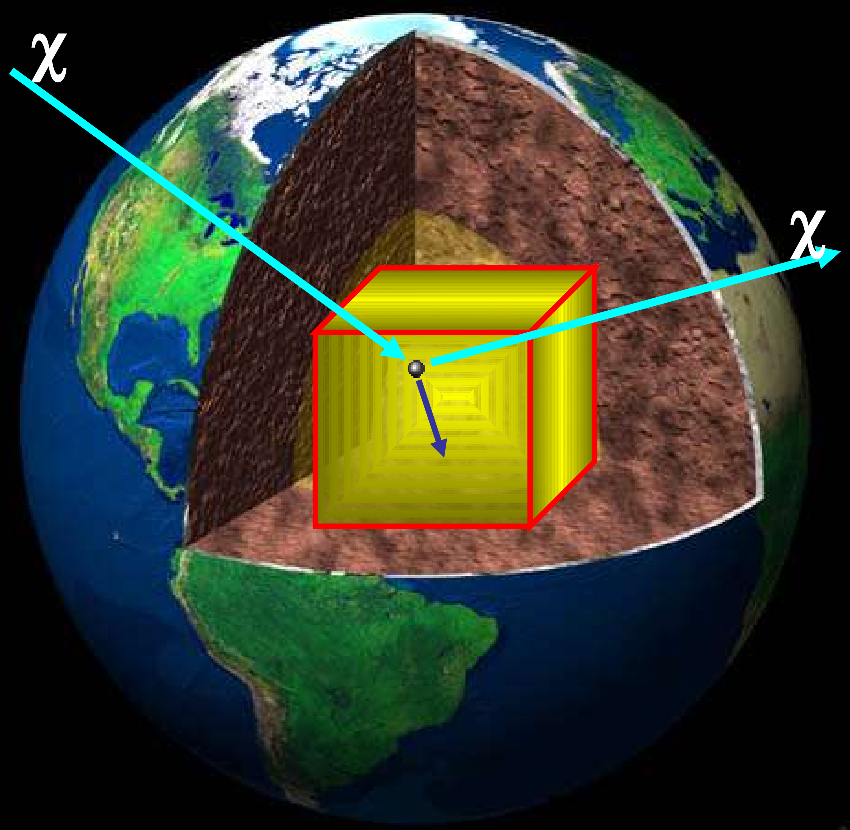
Dark Matter probes

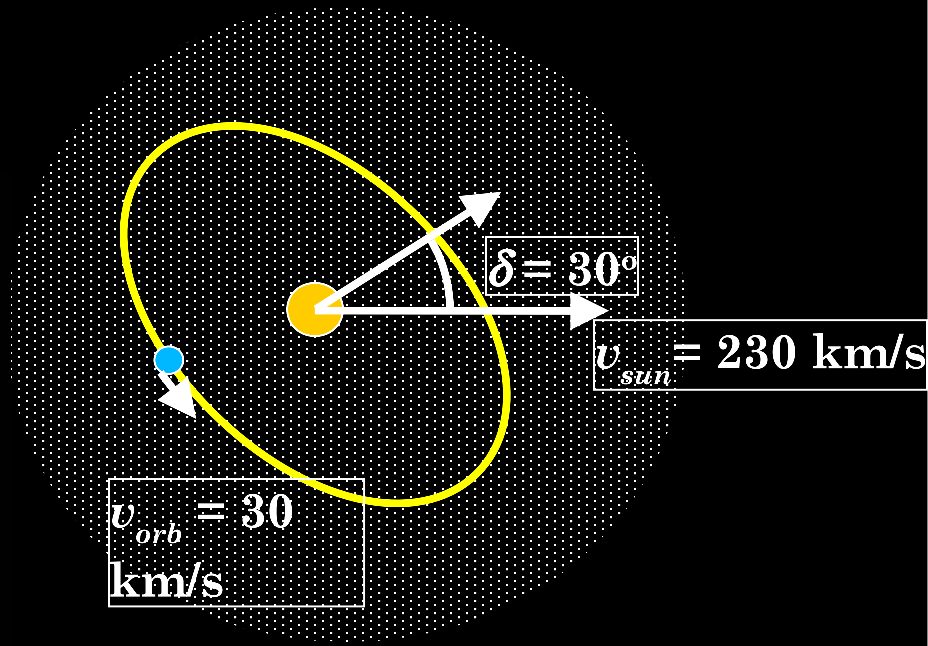
Under-ground

On-the-ground

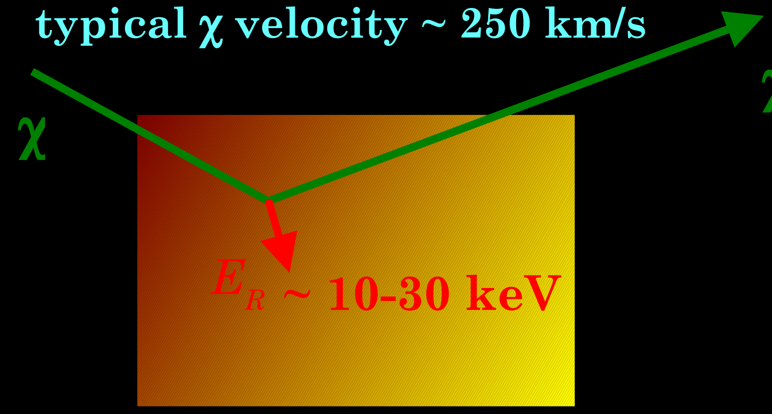
Above-the-ground

DM direct search



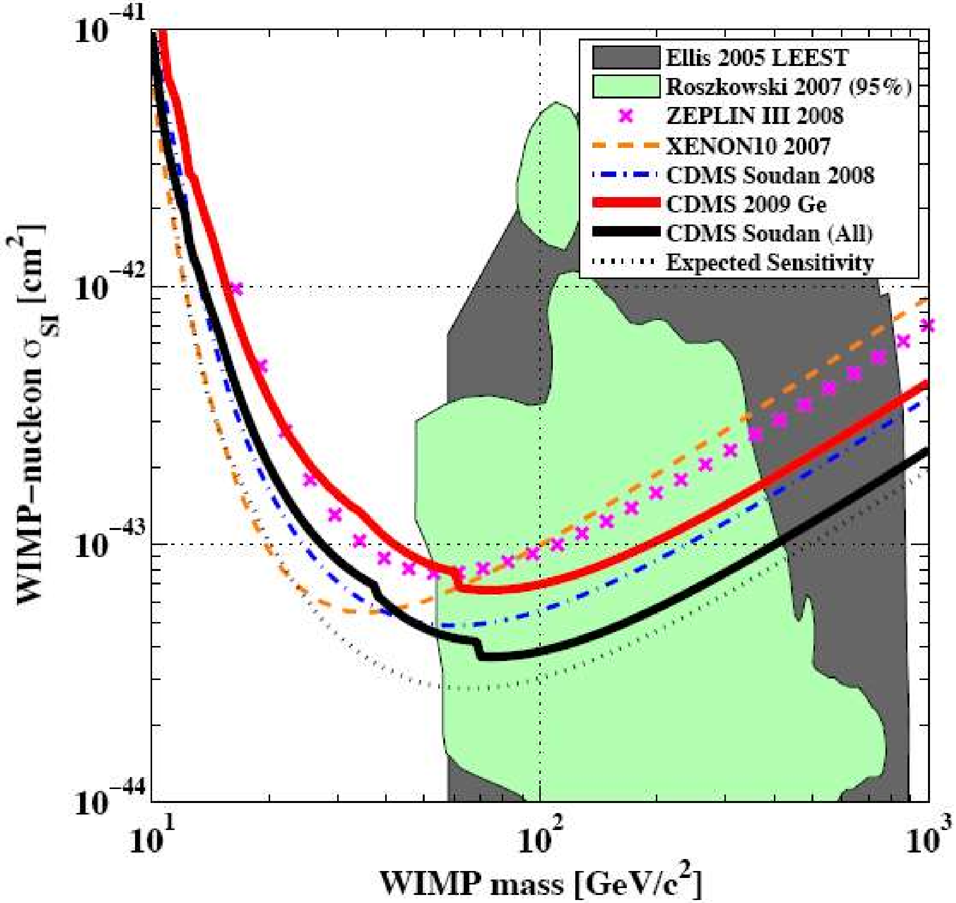


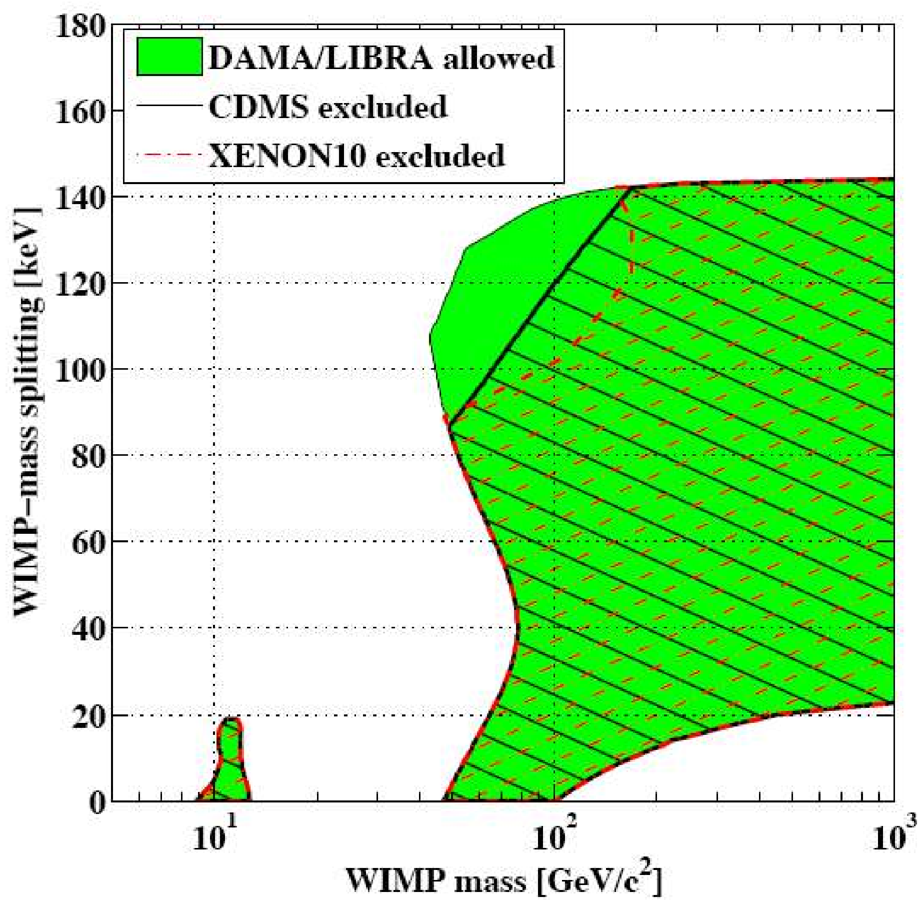
Elastic interaction on nucleus, typical χ velocity ~ 250 km/s



The latest results: CDMS II

2 events in the observed signal region.
Based on background estimate, the probability of observing two or more background events is ~23%.



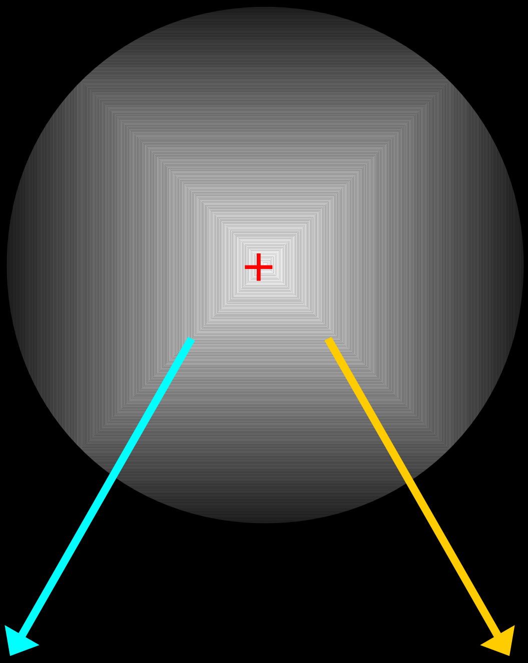


Ahmed et al. arXiv:0912.3592v1

DM - Astrophysical probes

INFERENCE

PHYSICAL



Virial Theorem

Hydro Equilibrium

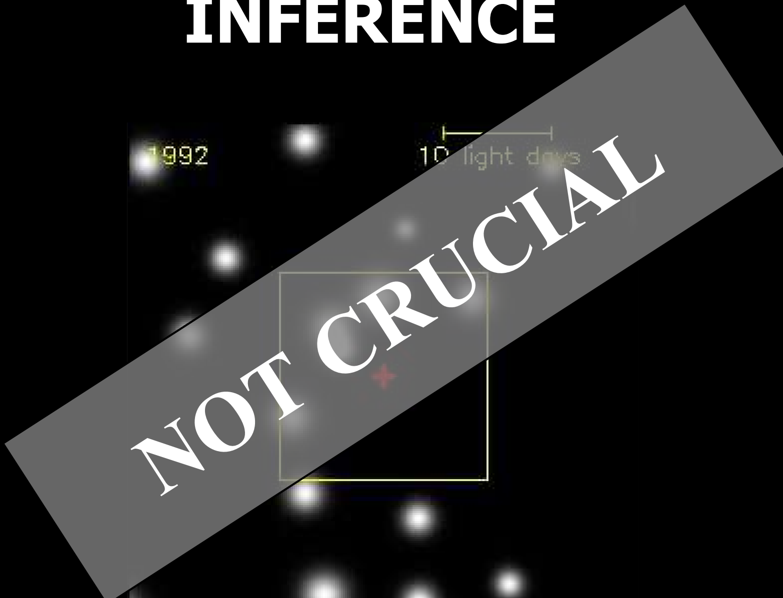
Gravitational lensing

Annihilation

Decay

DM - Astrophysical search

INFERENCE



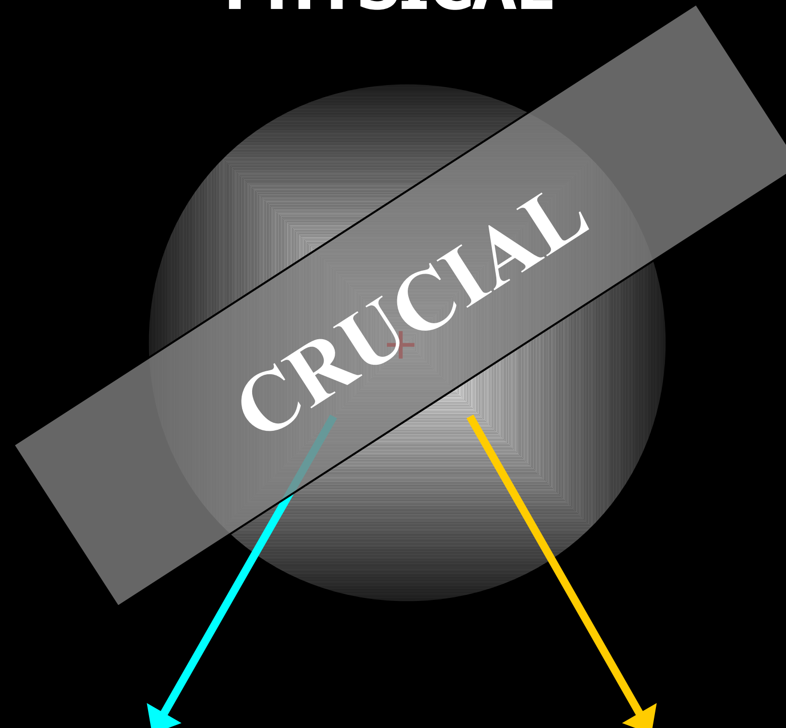
Vulnerable against:

MOND: **Modified Newtonian Dynamics**
TeVeS : **Tensor-Vector-Scalar**

Ordinary matter feels a transformed metric

$$\tilde{g}_{\mu\nu} = e^{-2\phi} g_{\mu\nu} + 2\sinh(2\phi) U_\mu U_\nu$$

PHYSICAL



Testable against:

Electromagnetic signals

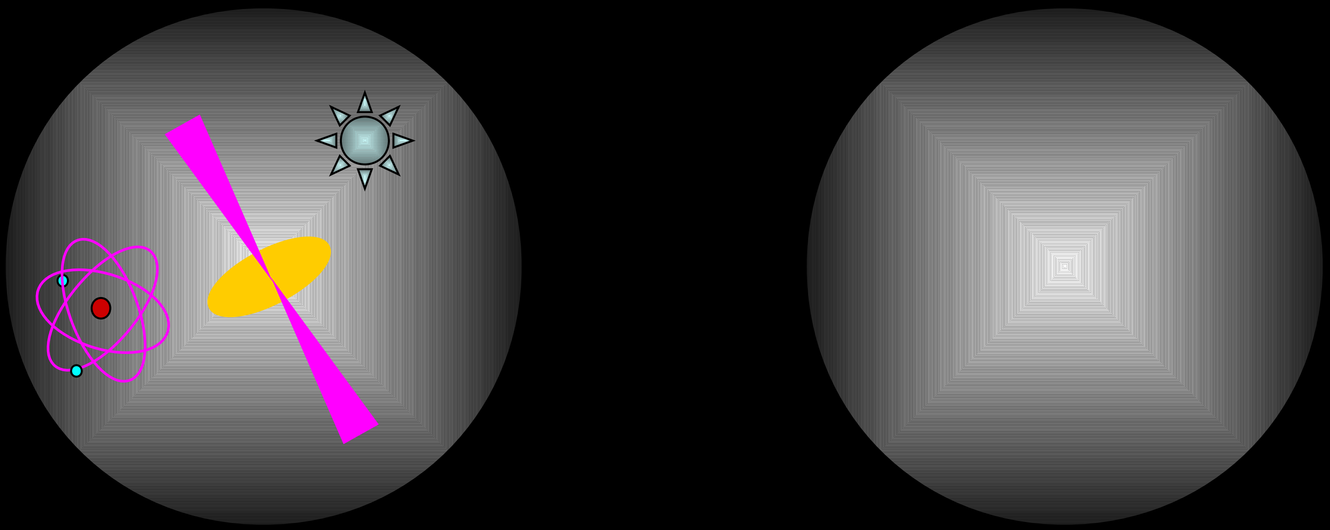
DM illuminates thru its interaction

DM - Astrophysical search

Clean and unbiased location in the sky

⇒ Best Astrophysical Laboratories

NO



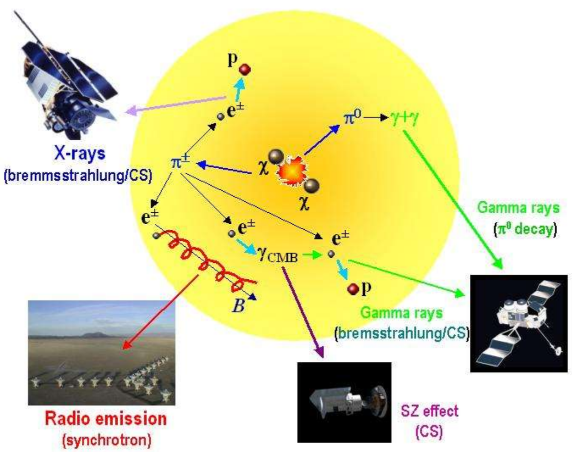
YES

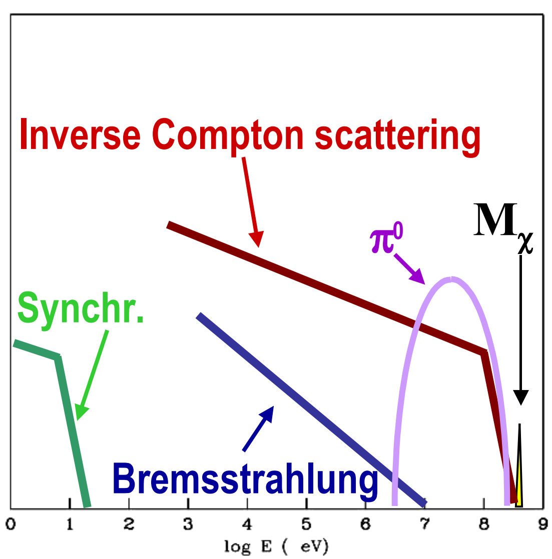
Clear and specific SED in the e.m. spectrum

⇒ Most specific e.m. signals

Viable DM candidates: signals

Neutralinos

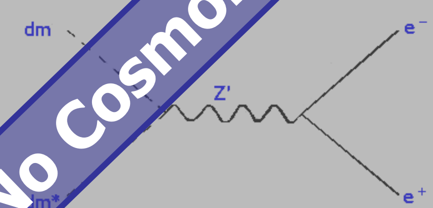


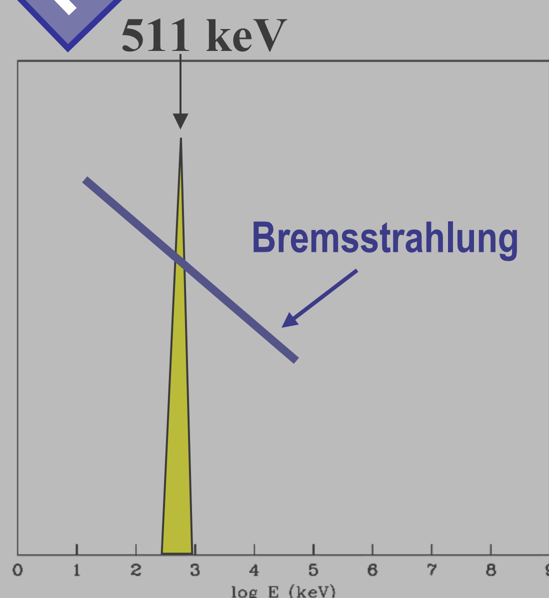


Light (MeV) DM

No Cosmological DM

Annihilating MeV DM
- Continuum: HXR/γ-rays
- Line: $e^\pm$ annihilation



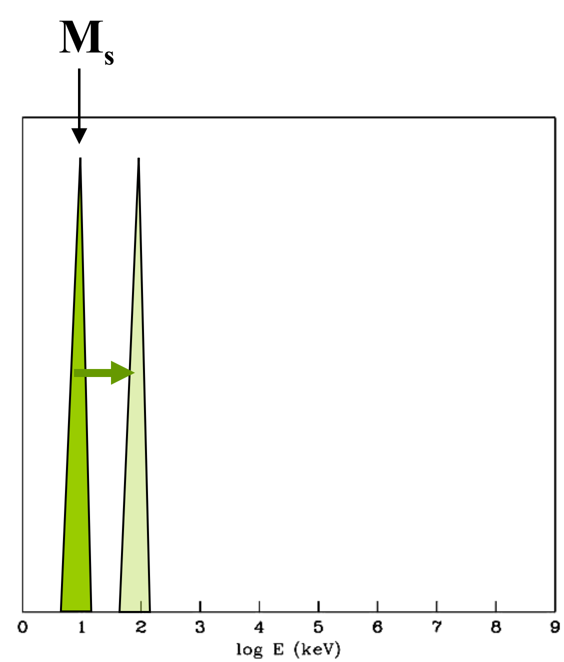


Sterile ν's

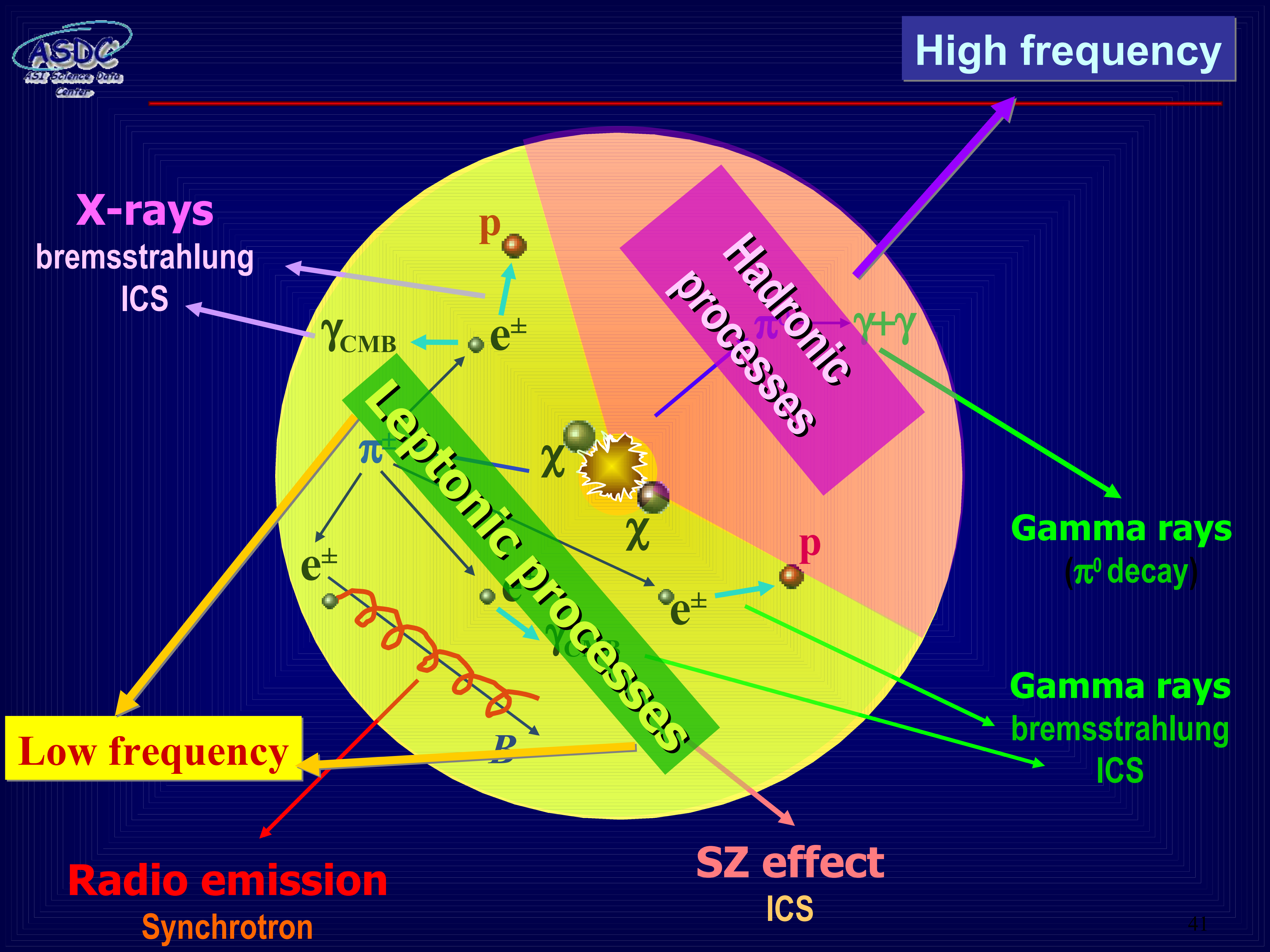
Radiative decay: line

$$\nu_s \rightarrow \nu_\alpha + \gamma$$

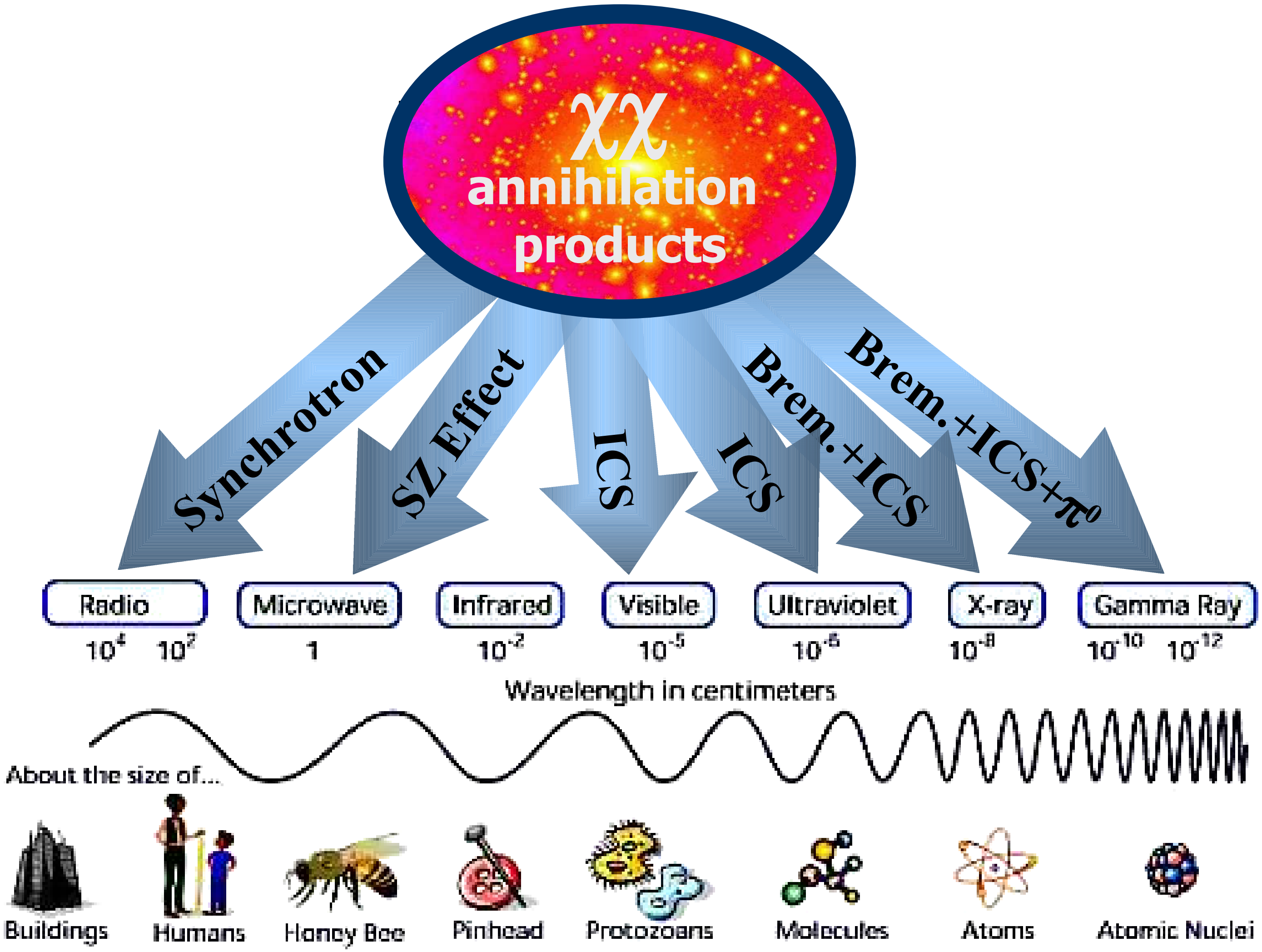
$$\Gamma_s \simeq 6.8 \times 10^{-33} \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^5$$



SUSY neutralino DM


High frequency
X-rays
bremsstrahlung
ICS
p
$e^{\pm}$
γ_{CMB}
Hadronic processes
$\pi^0 \rightarrow \gamma+\gamma$
Leptonic processes
$\pi^{\pm}$
χ
χ
$e^{\pm}$
$e^{\pm}$
$e^{\pm}$
p
γ_{CMB}
B
Gamma rays
(π^0 decay)
Gamma rays
bremsstrahlung
ICS
Low frequency
Radio emission
Synchrotron
SZ effect
ICS

Covering the whole e.m. spectrum

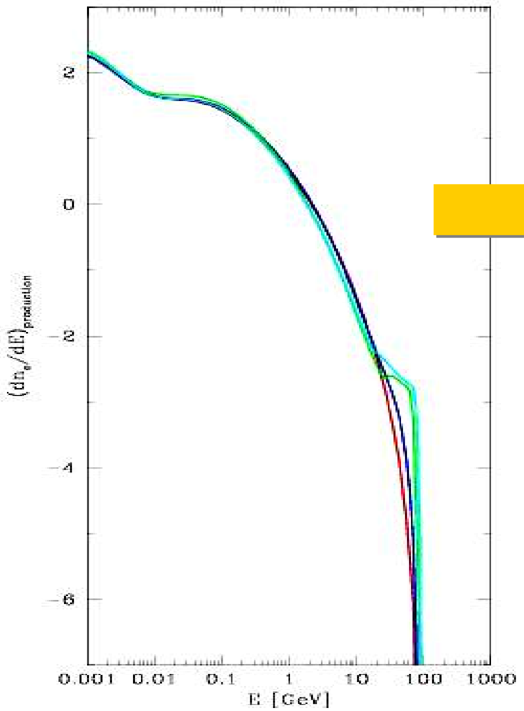


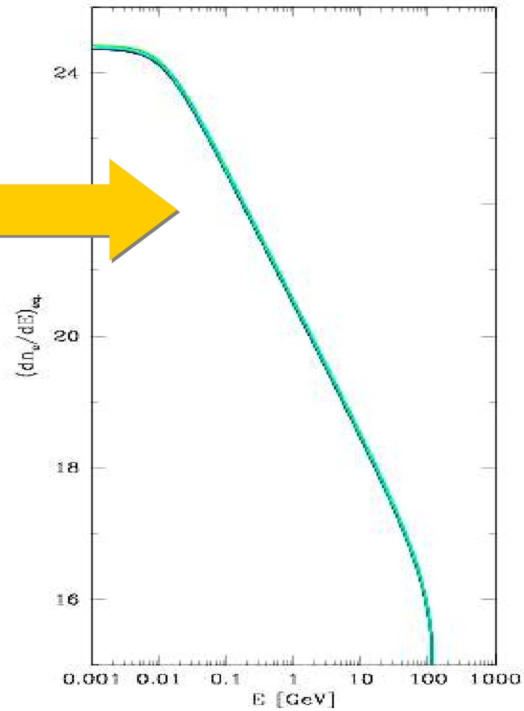
Leptons: e$^{\pm}$ equilibrium spectrum

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

Production

$Q_e(E,r)$





Equilibrium

$n_e(E,r)$

Diffusion

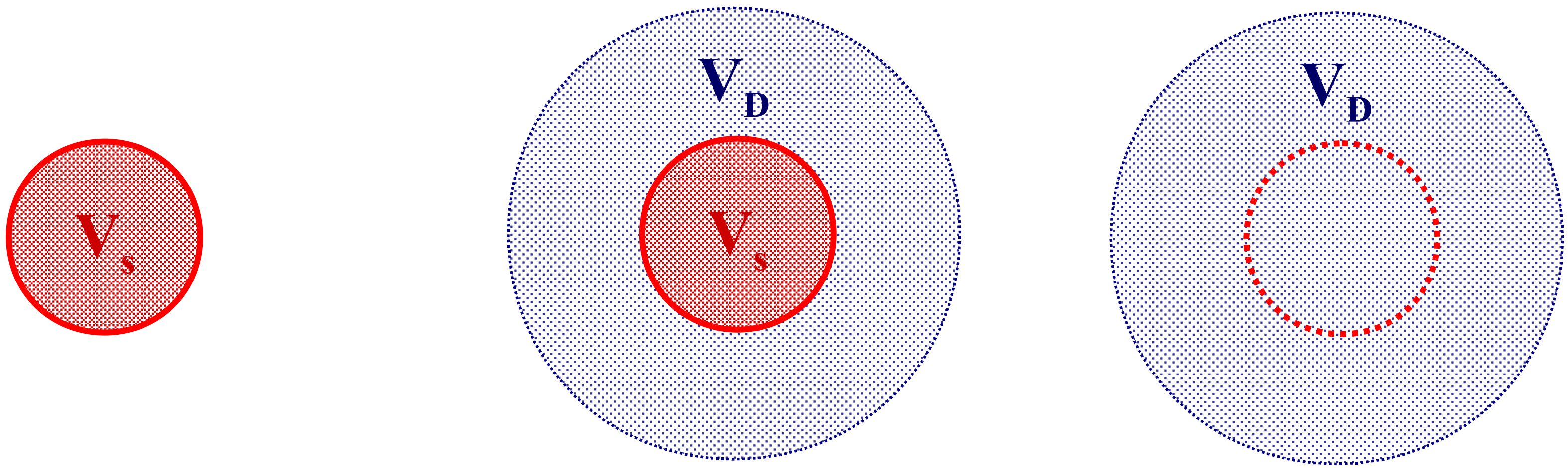
$$D(E) = D_0 E^{\gamma} B^{-\gamma}$$

E losses

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

Solution: qualitative

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



$\tau_{loss} \ll \tau_D$

$\tau_{loss} \gg \tau_D$

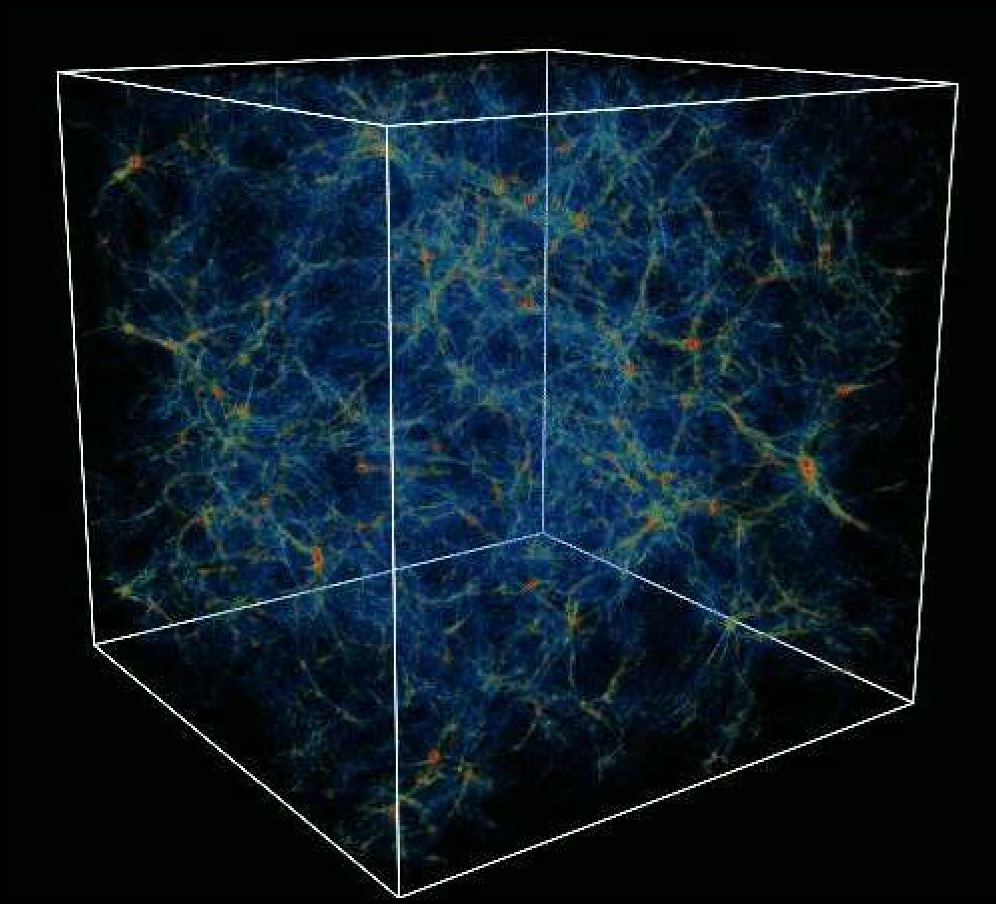
$$n_e(E,r) = \left[Q_e(E,r)\tau_{loss}\right]$$

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

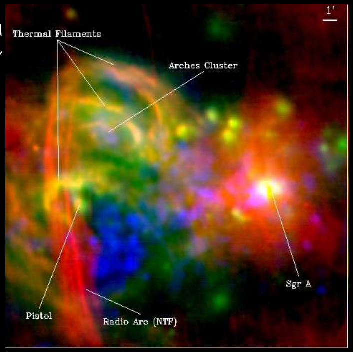
Galaxy clusters

Galaxies

DM - Astrophysical Laboratories



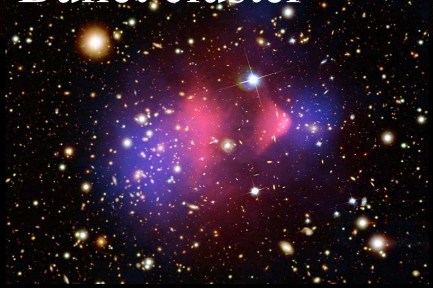
GC



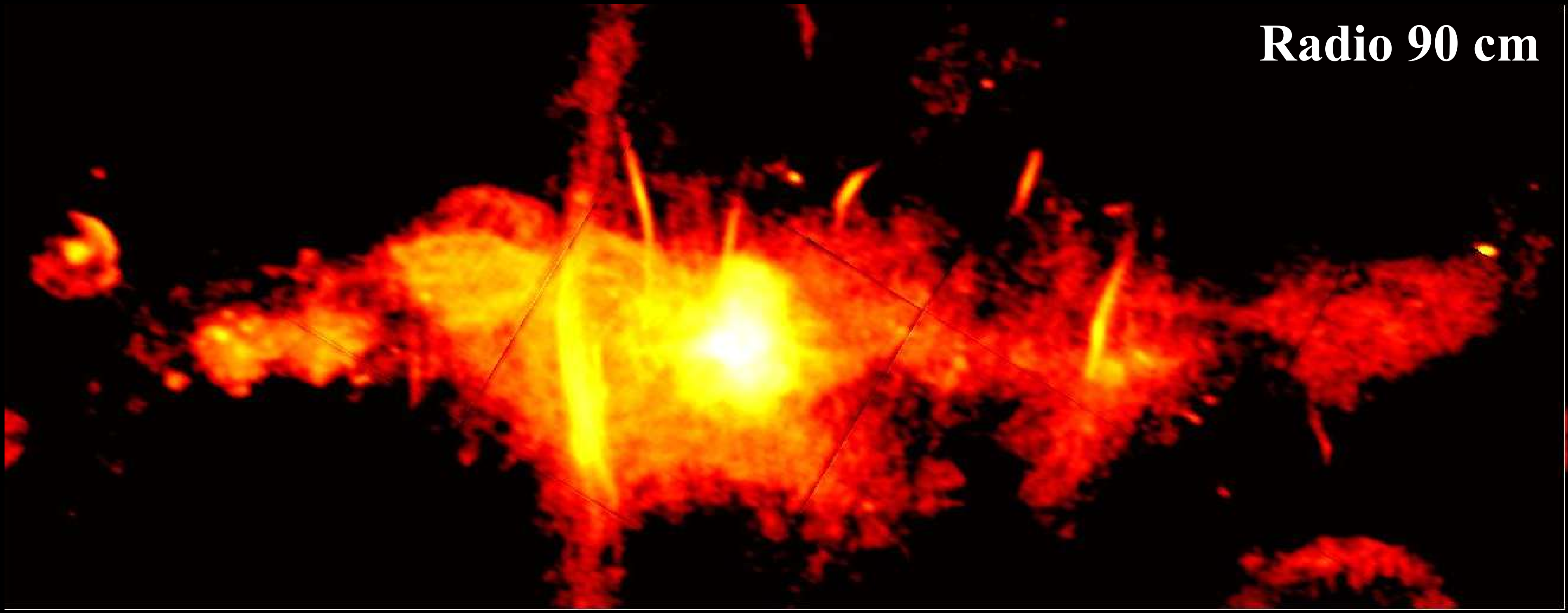
Leo I dSph

NGC3338

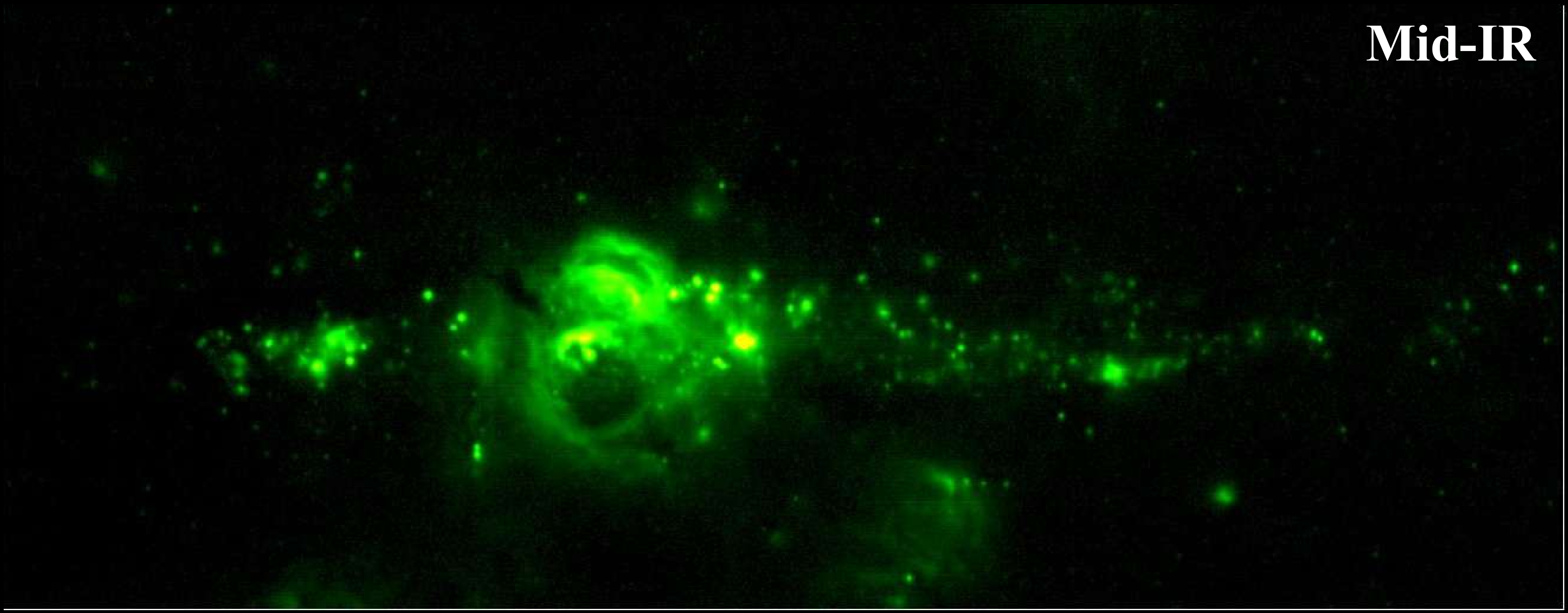
Bullet cluster



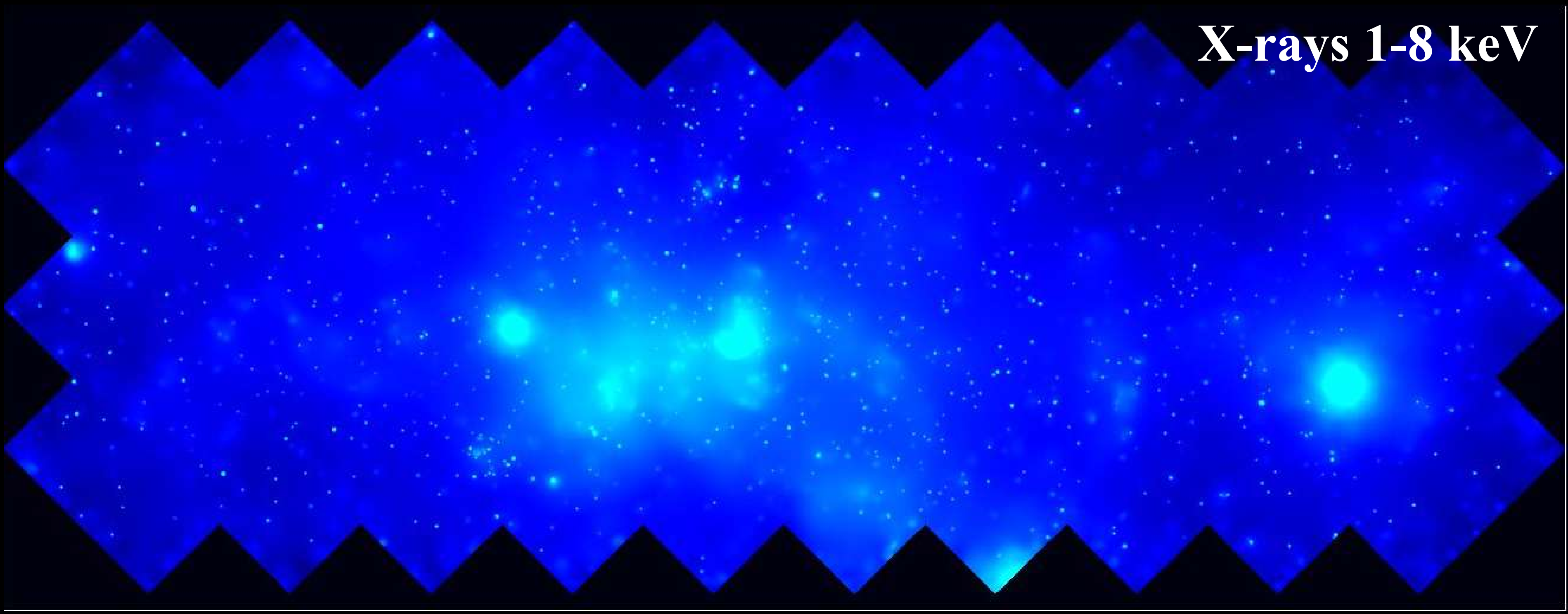
The Galactic Center



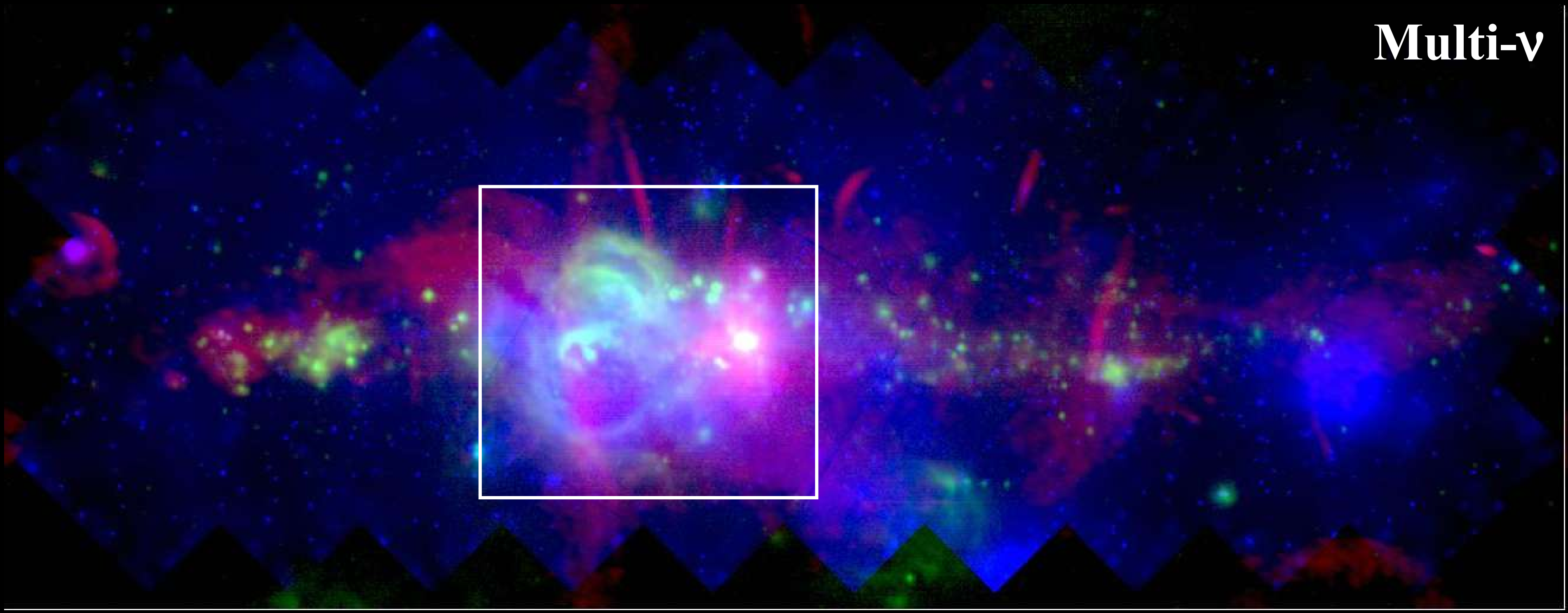
The Galactic Center



The Galactic Center



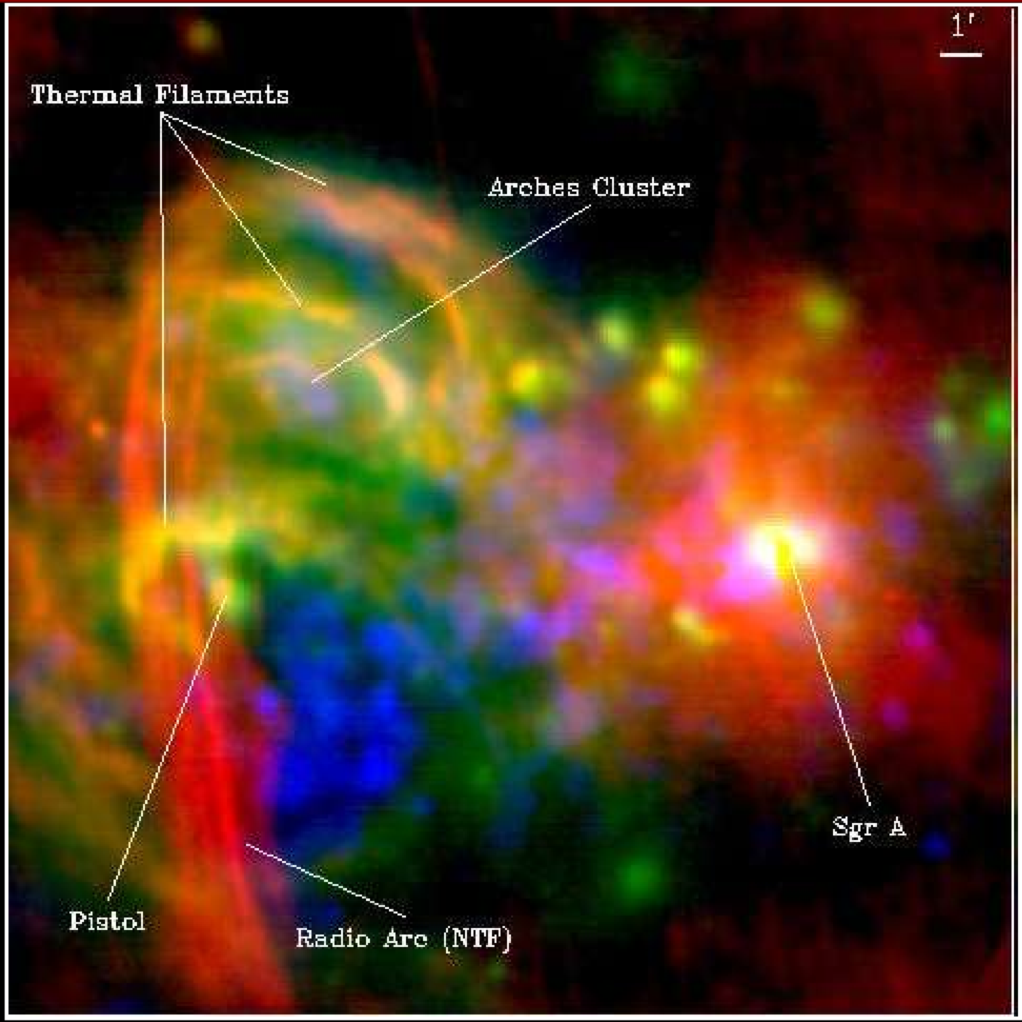
The Galactic Center



Galactic center region across the spectrum:

red: radio 90 cm (VLA); green: mid-infrared; blue: X-ray (1-8 keV; Chandra ACIS-I)

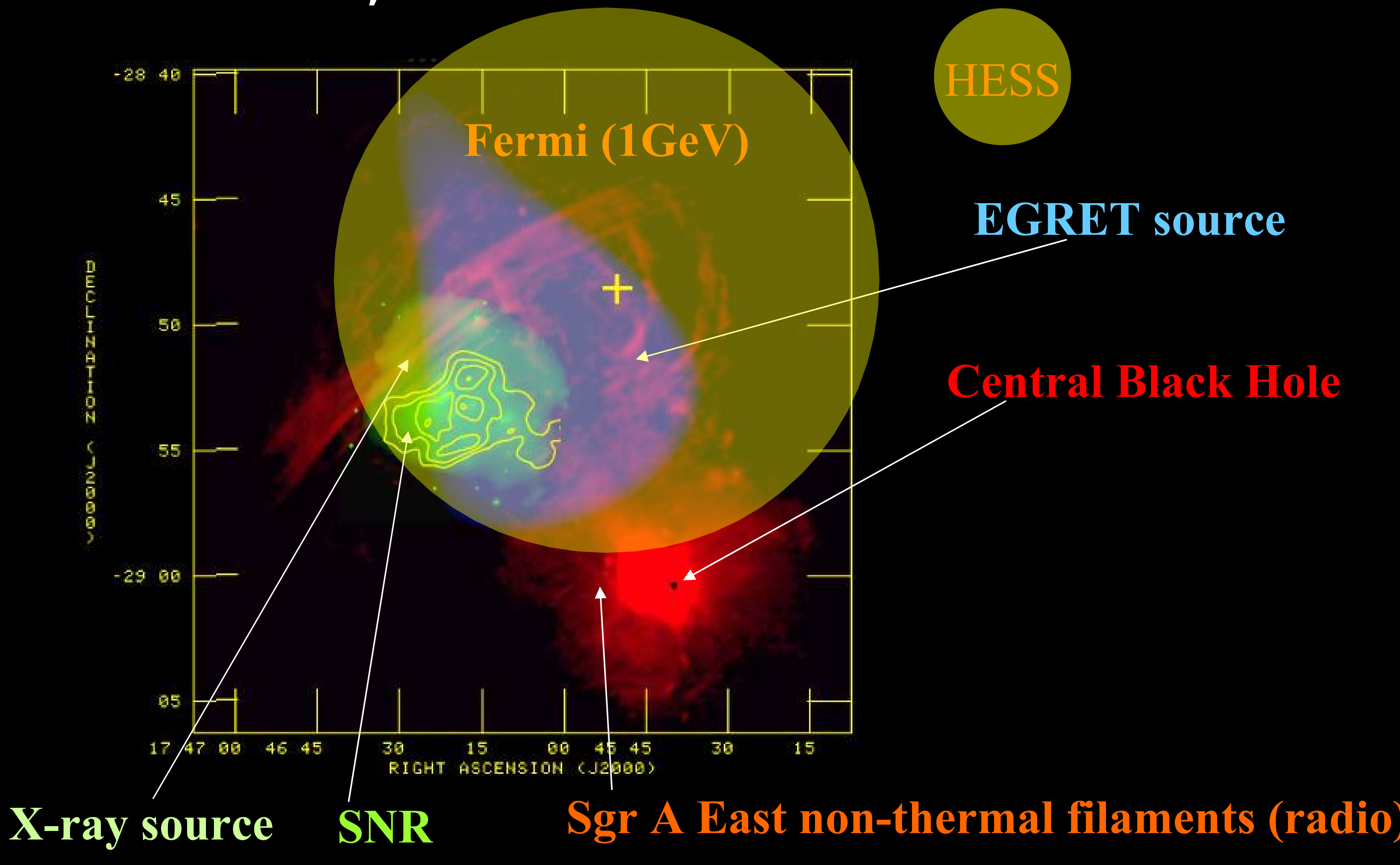
The Galactic Center: a close up



Galactic Center (Survey) Multiwavelength Close-Up
A multiwavelength close-up of the recent massive star-forming region near the Galactic center. The color image, plotted also in standard Galactic coordinates, is a composite of 20-cm radio continuum (red); 25-μm mid-infrared (green); and 6.4-keV line emission (blue).

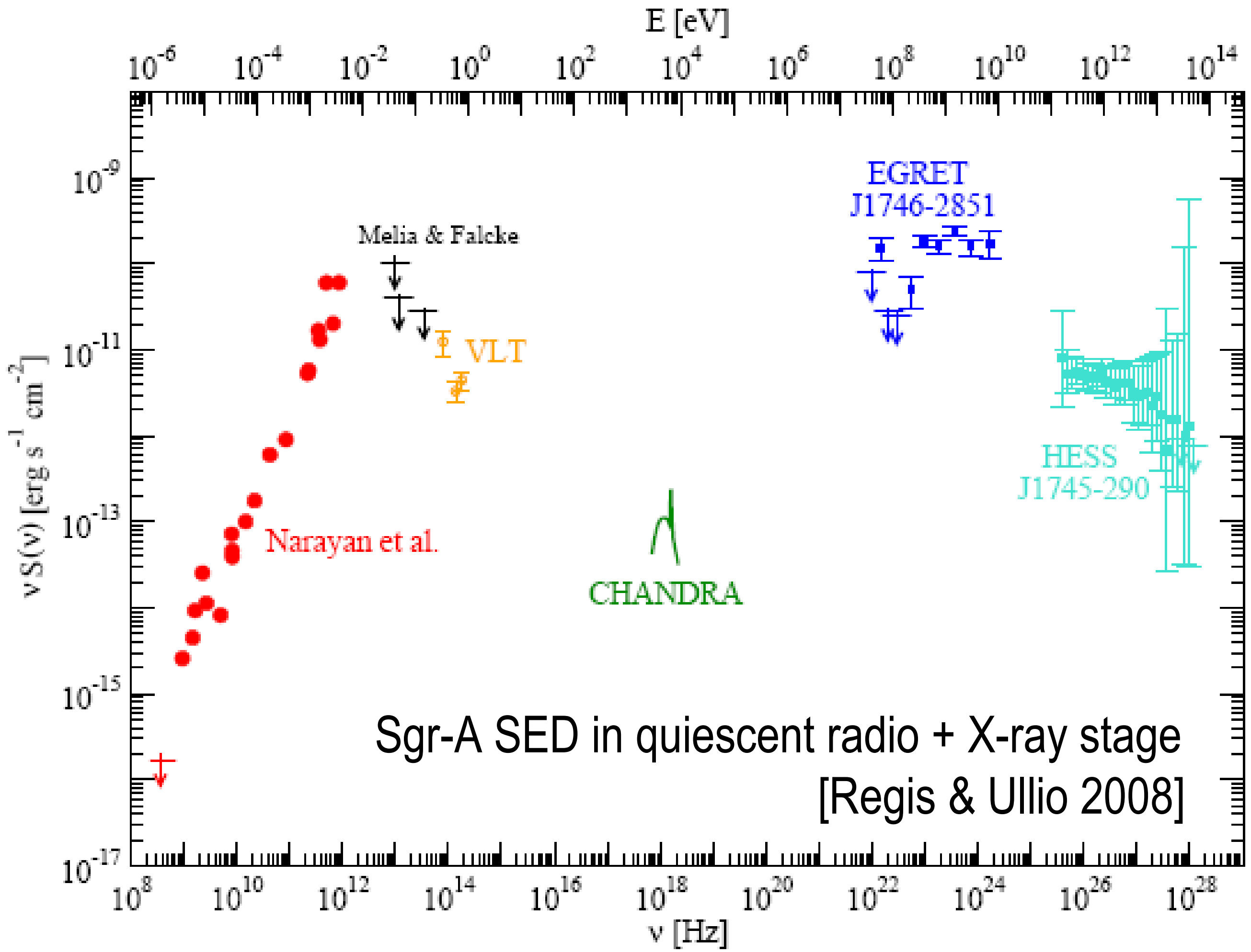
Galactic Center demography

Crowded, active environment



The GC region DM challenge

Gondolo	1998
Gondolo & Silk	1999
…	
Cesarini et al.	2003
…	
De Boer et al.	2005
…	
Hooper et al.	2008
…	
Borriello et al.	2008
Regis & Ullio	2008
Crocker et al.	2010

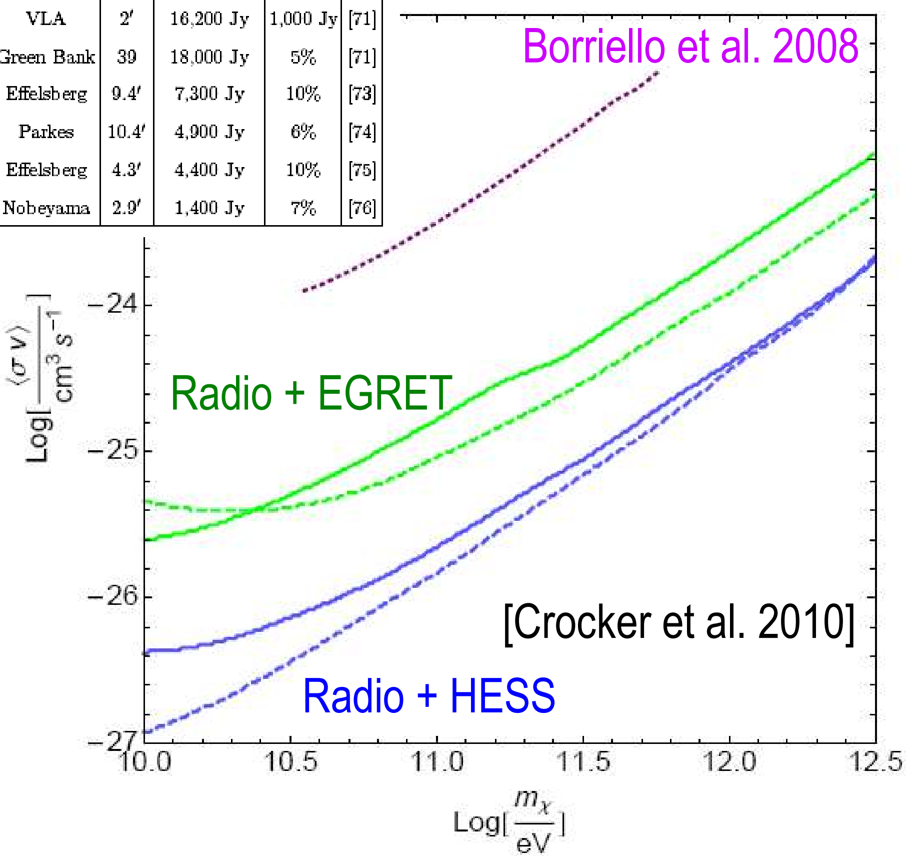


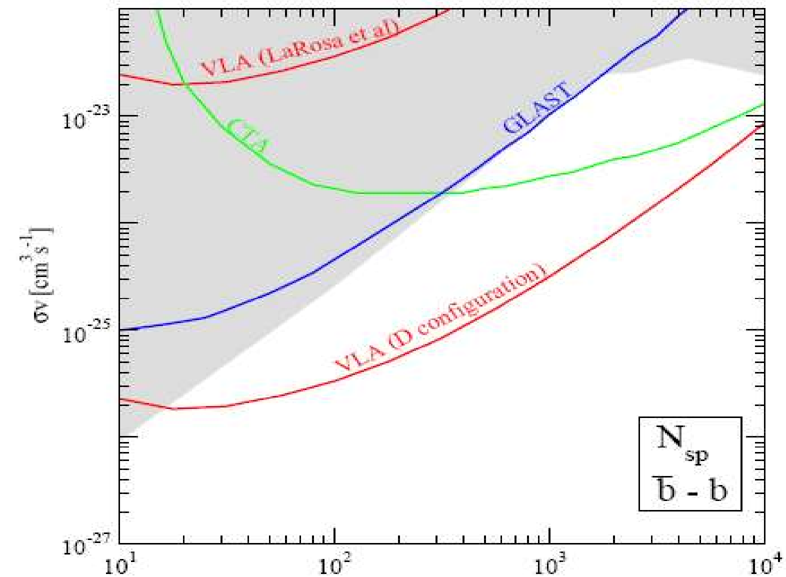
The GC region DM challenge: limits

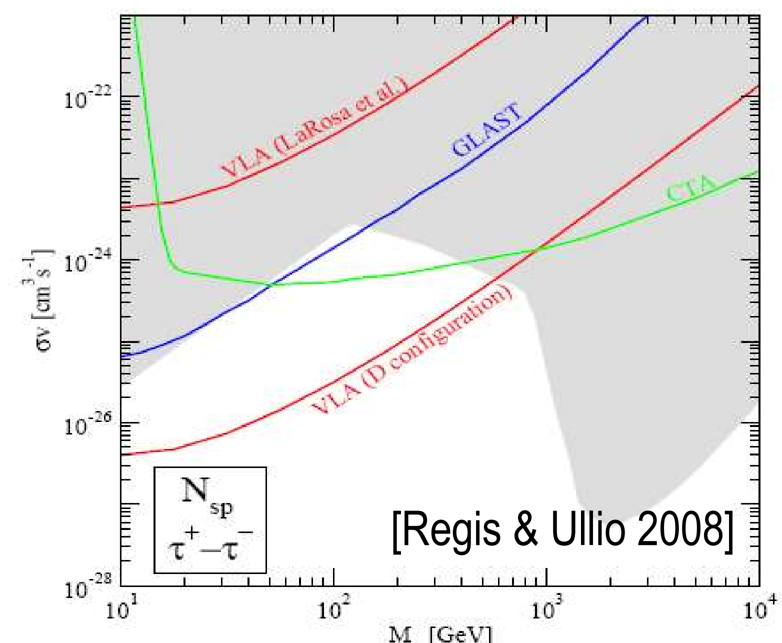
Stronger constraints from radio + γ-rays

- Radio: constrain to ~ GeV-TeV mass
- γ-rays: constrain to ≤ GeV mass
- ν's : constrain to > 10 TeV mass

ν (GHz)	Telescope	Beam	Flux density	Error	Ref.
.074*	VLA	2′	16,200 Jy	1,000 Jy	[71]
.330†	Green Bank	39	18,000 Jy	5%	[71]
1.408	Effelsberg	9.4′	7,300 Jy	10%	[73]
2.417	Parkes	10.4′	4,900 Jy	6%	[74]
2.695	Effelsberg	4.3′	4,400 Jy	10%	[75]
10.29	Nobeyama	2.9′	1,400 Jy	7%	[76]

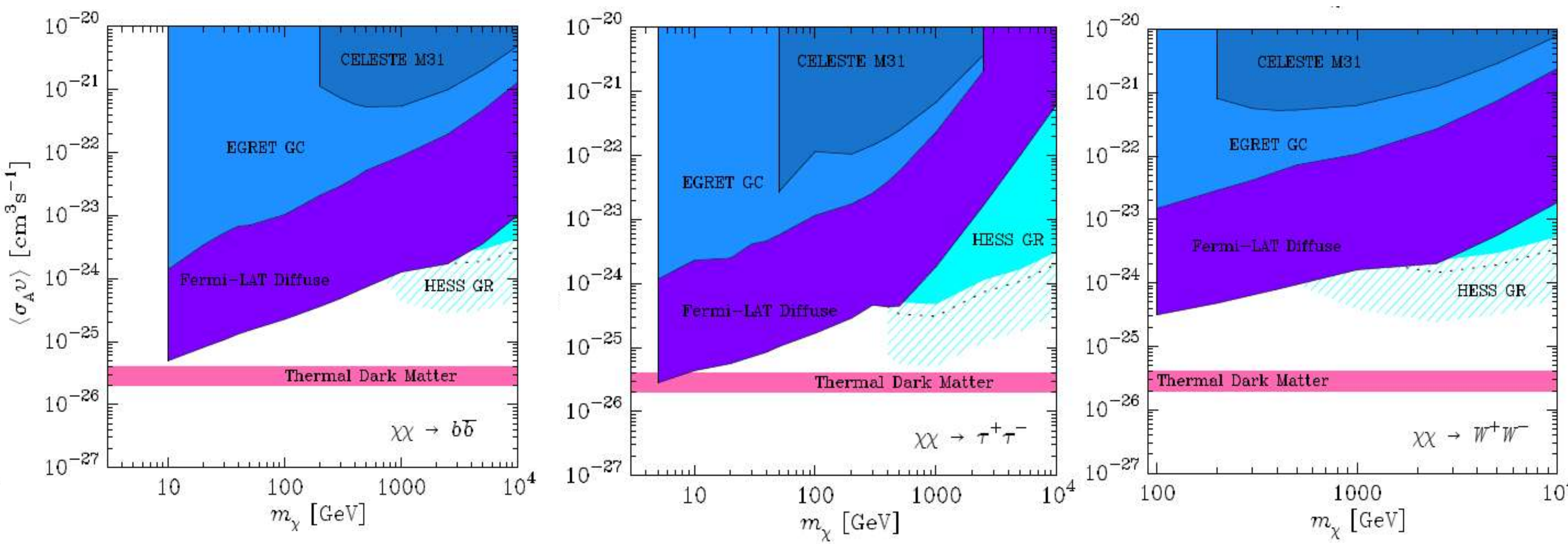






The GC region DM challenge: limits

Fermi-LAT results on the diffuse γ-ray emission improves DM limits
→ by a factor ~20-50



[Abazajian et al. 2010]

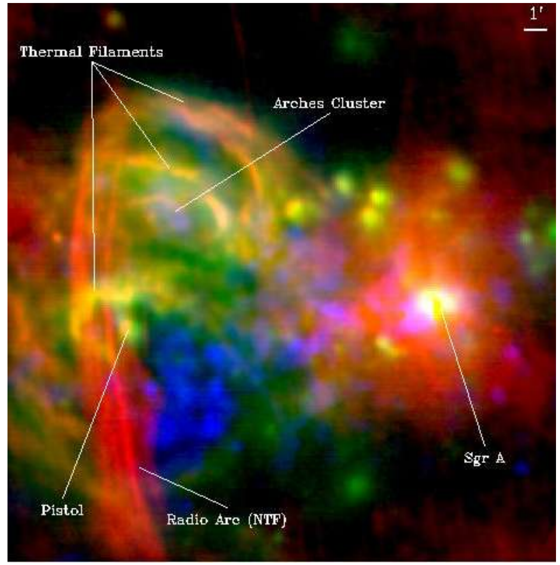
Caveats

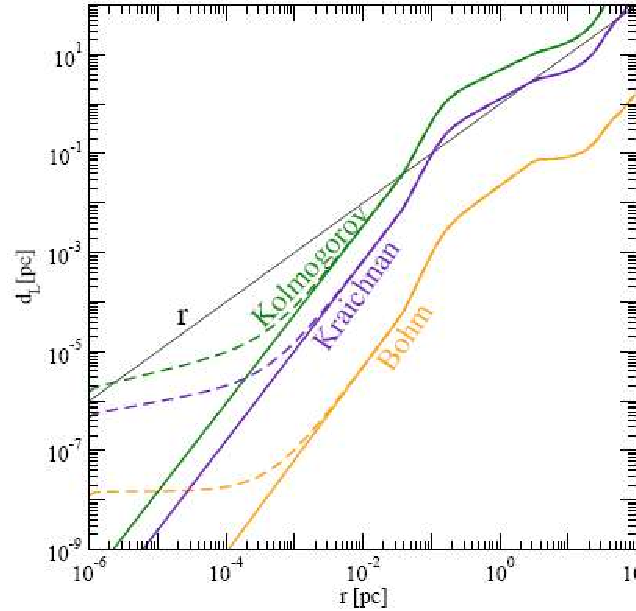
- modelling of diffuse foregrounds (Galactic, Extra-Galactic)
- unresolved point-like sources (PSR, MCs, AGNs, Starburst gal., Clusters, GRBs,..)
- data analysis techniques (Likelihood vs. photon counts)

The GC region DM challenge: uncert.s

B-field at GC
- from 4 to 1000 μG
- > 50μG (radio + γ-rays)

[Crocker et al. 2010]



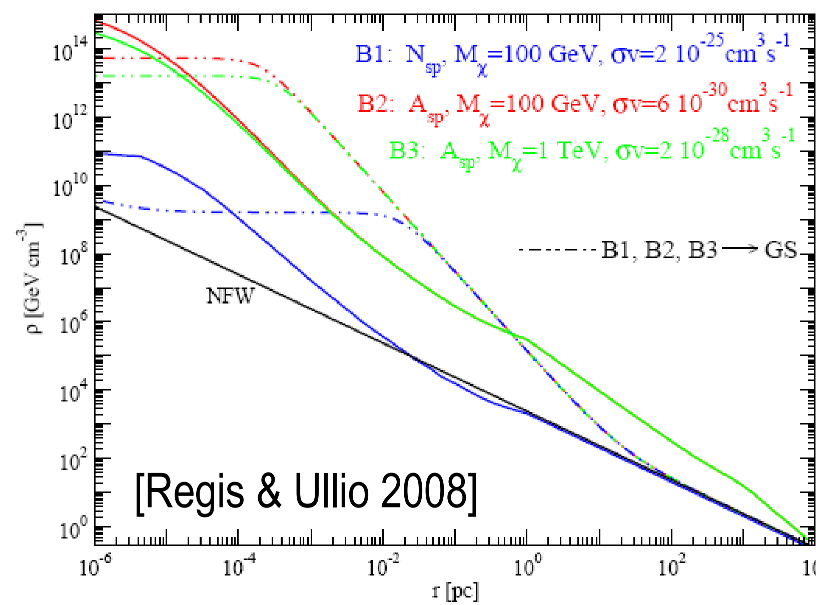


Diffusion

DM density profile

DM dynamics at GC
DM vs. BH

Astrophysical sources
Stationary & Transient



The GC Haze

Radio emission due to secondary $e^{\pm}$ is spatially extended (ν-dependent)

➔ Radio halo (haze)

RH size decreases with increasing ν

ICS emission due to secondary $e^{\pm}$ is spatially extended (ν-dependent)

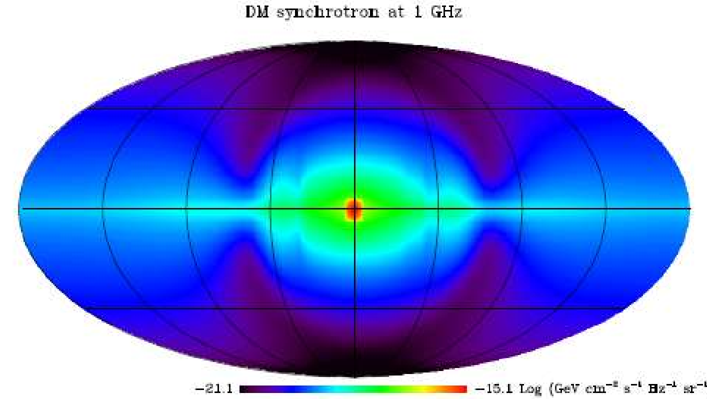
➔ IC halo (haze)

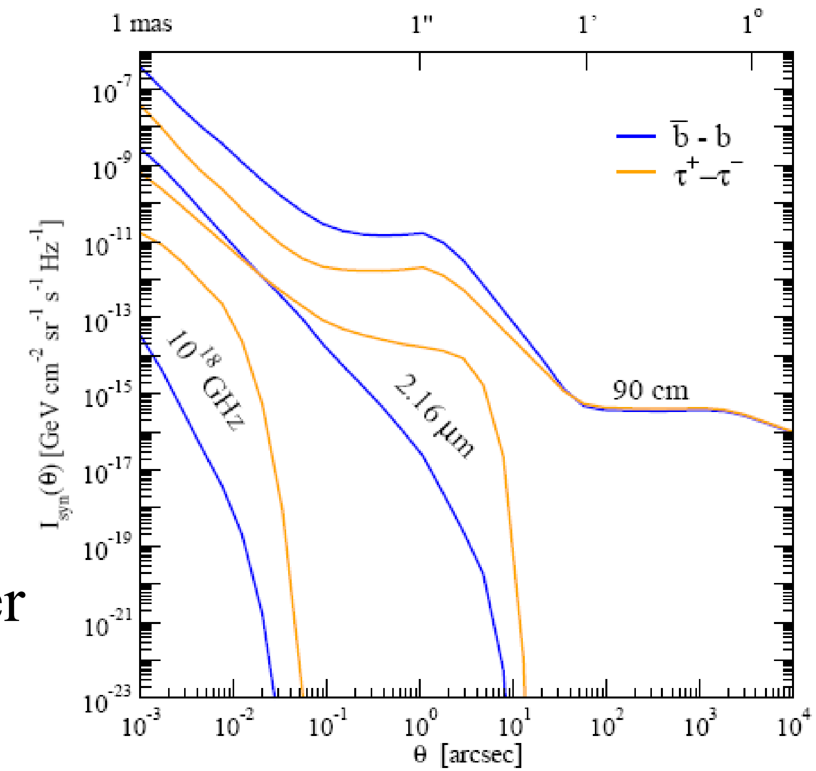
ICH size decreases with increasing ν

The angular size for the equilibrium no. density of high energy $e^{\pm}$ is much broader than the gamma-ray flux from π^0 decays

➔ π^0 halo (haze) = DM source

πH size smaller than RH / ICH size

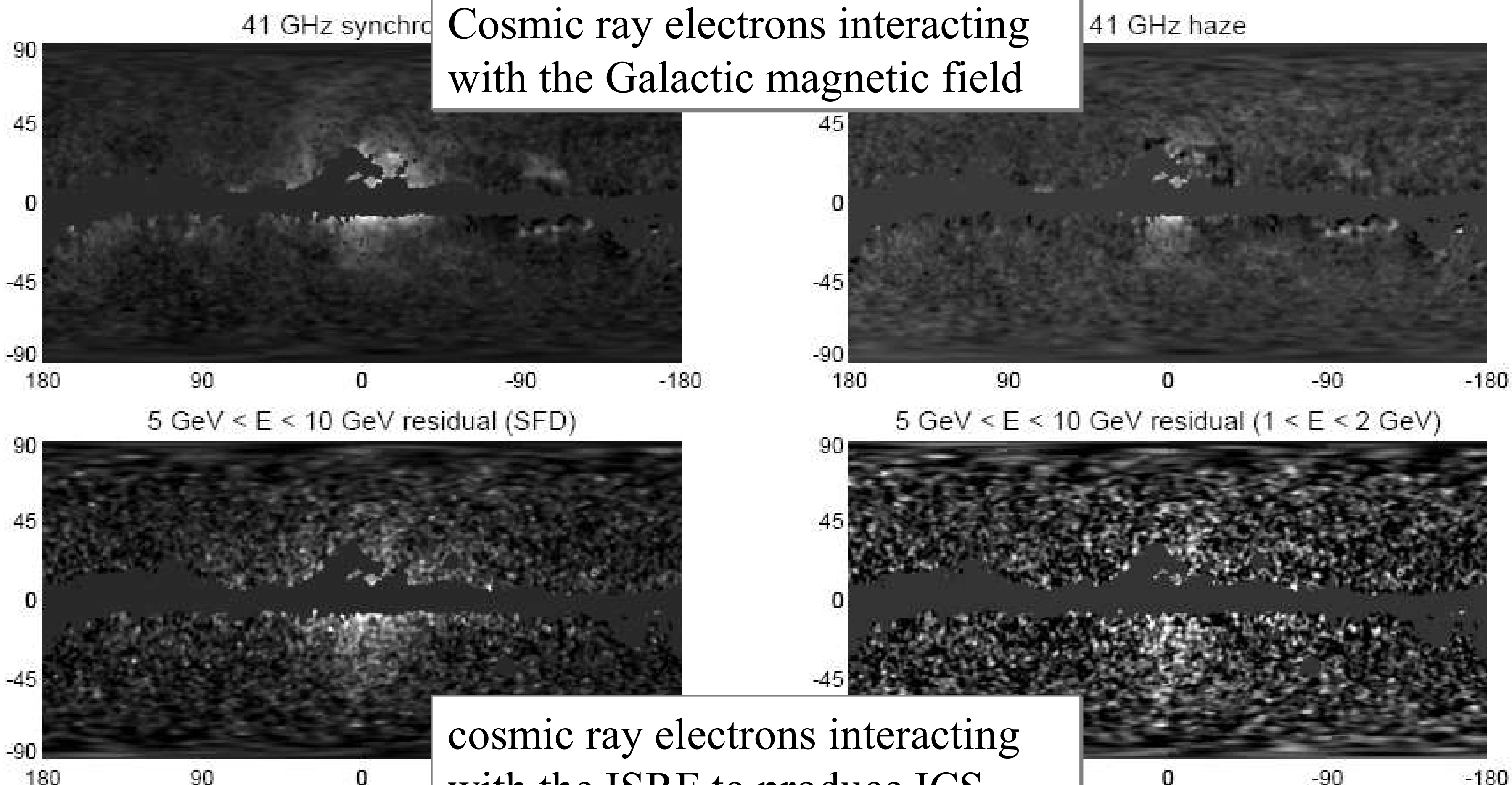




WMAP vs. Fermi haze

THE *FERMI* HAZE:
A GAMMA-RAY COUNTERPART TO THE MICROWAVE HAZE

GREGORY DOBLER,[1,2,5] DOUGLAS P. FINKBEINER,[1,3] ILIAS CHOLIS,[4]
TRACY SLATYER,[1,3] & NEAL WEINER[4]



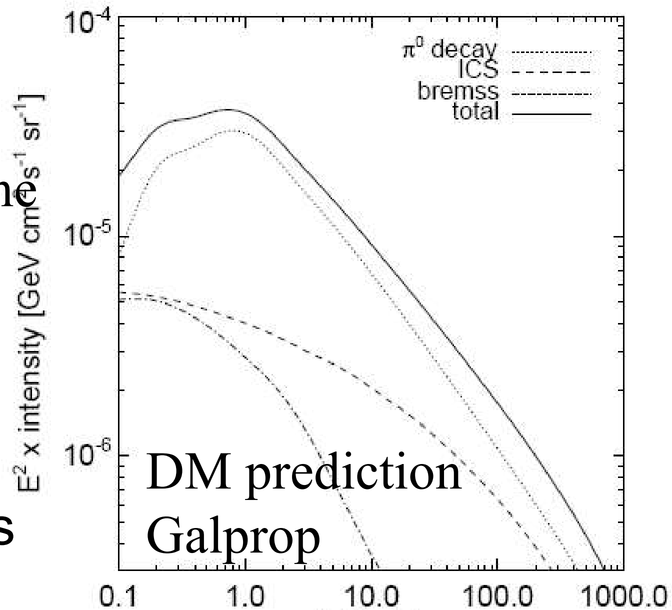
Cosmic ray electrons interacting with the Galactic magnetic field

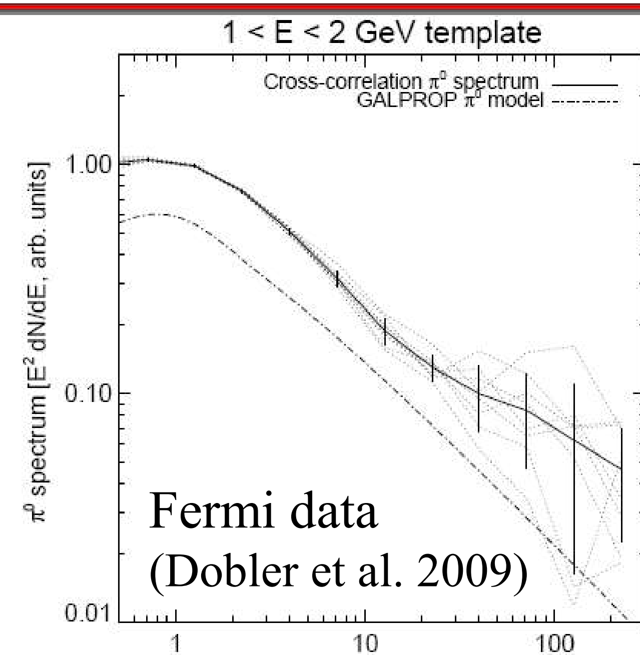
cosmic ray electrons interacting with the ISRF to produce ICS

GC hazes: puzzles or certainties

Dark Matter

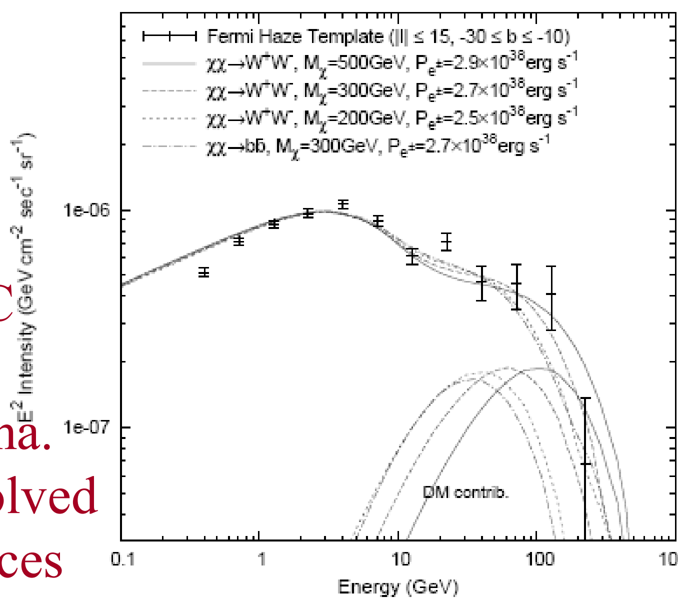
- DM ($W^{\pm}$,bb) is not the origin of Fermi haze
- DM ($e^{\pm}$) can fit the Fermi haze with a boost factor ~ 100
  → multi-ν problems

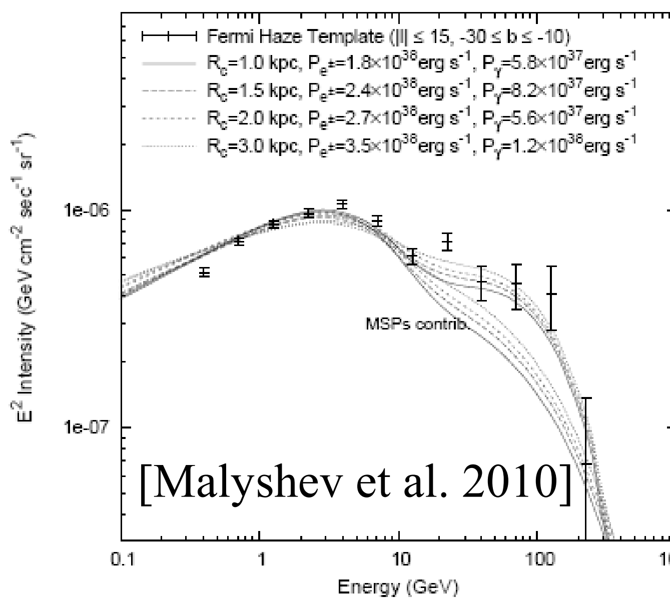




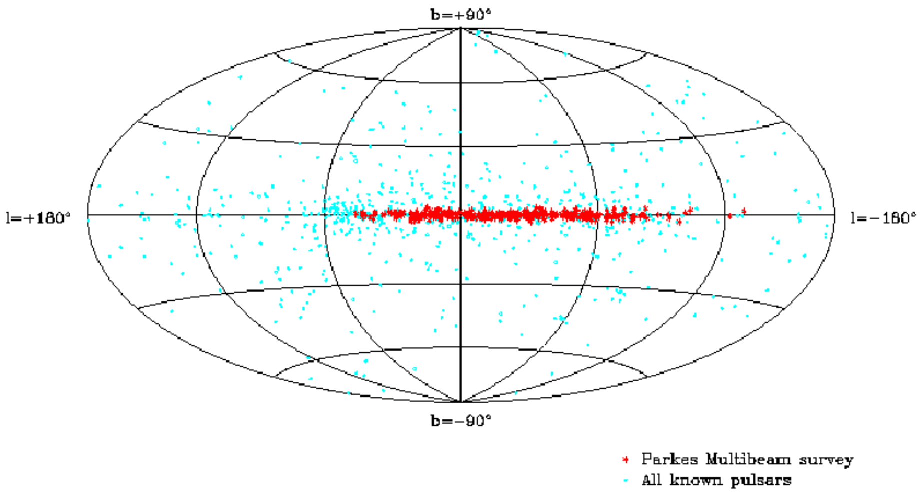
ms Pulsars

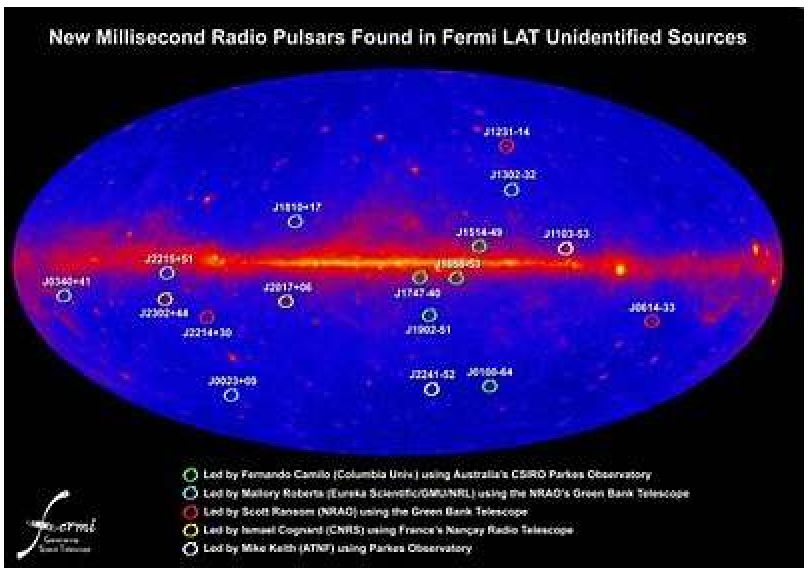
- 50 % energy conversion in $e^{\pm}$
- 30,000 msP in GC
- msP not resolved in radio and gamma.
  → Haze of unresolved point-like sources

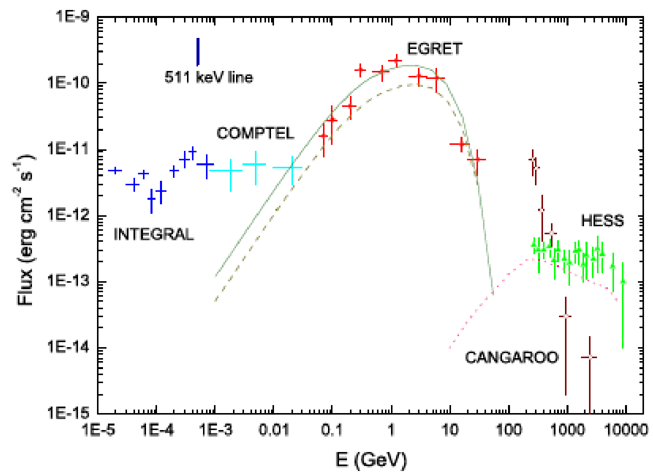




msP around the GC







[Wang 2005]

Fig. 2 The diffuse gamma-ray spectrum in the Galactic center region within 1.5° and the 511 keV line emission within 6°. The INTEGRAL and COMPTEL continuum spectra are from Strong (2005), the 511 keV line data point from Churazov et al. (2005), EGRET data points from Mayer-Hasselwander et al. (1998), HESS data points from Aharonian et al. (2004), CANGAROO data points from Tsuchiya et al. (2004). The solid and dashed lines are the simulated spectra of 6000 MSPs according to the different period and magnetic field distributions in globular clusters and the Galactic field respectively. The dotted line corresponds to the inverse Compton spectrum from MSPs.

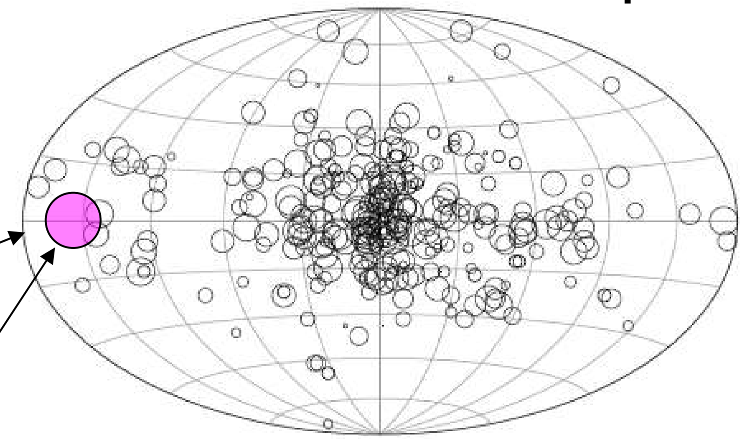
Galaxy sub-halos

Radio emission and ICS emission from sub-halos is a promising tool
[Baltz & Wai 2004, …Borriello et al. 2008, …]

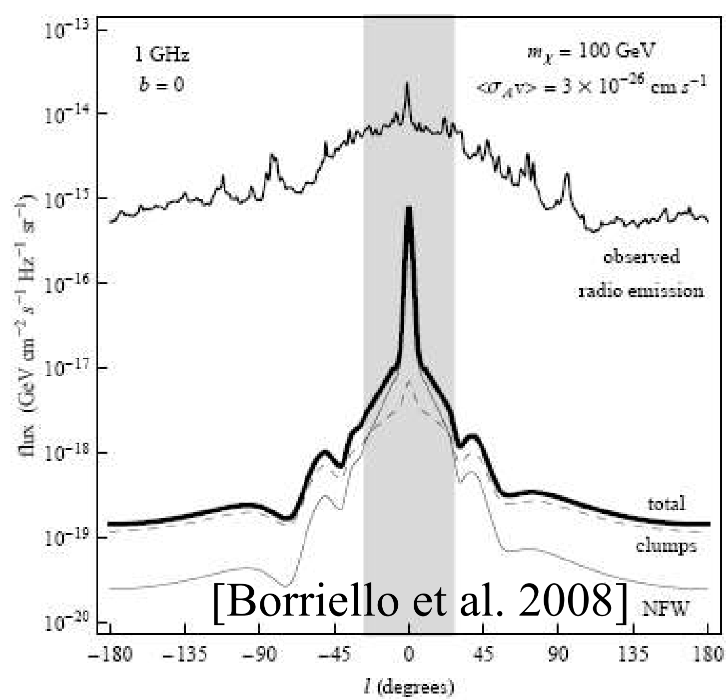
Radio synch. emission
- Strong diffusion effects
- Degeneracy of n_e and B-field
- B-field uncertainty: small & large radii

ICS emission
- Strong diffusion effects
- Degeneracy of n_e and radiation fields (IR, dust, O-UV, X-rays)
- Uncertainties in the description of radiation fields (except CMB)

Radio emission from clumps



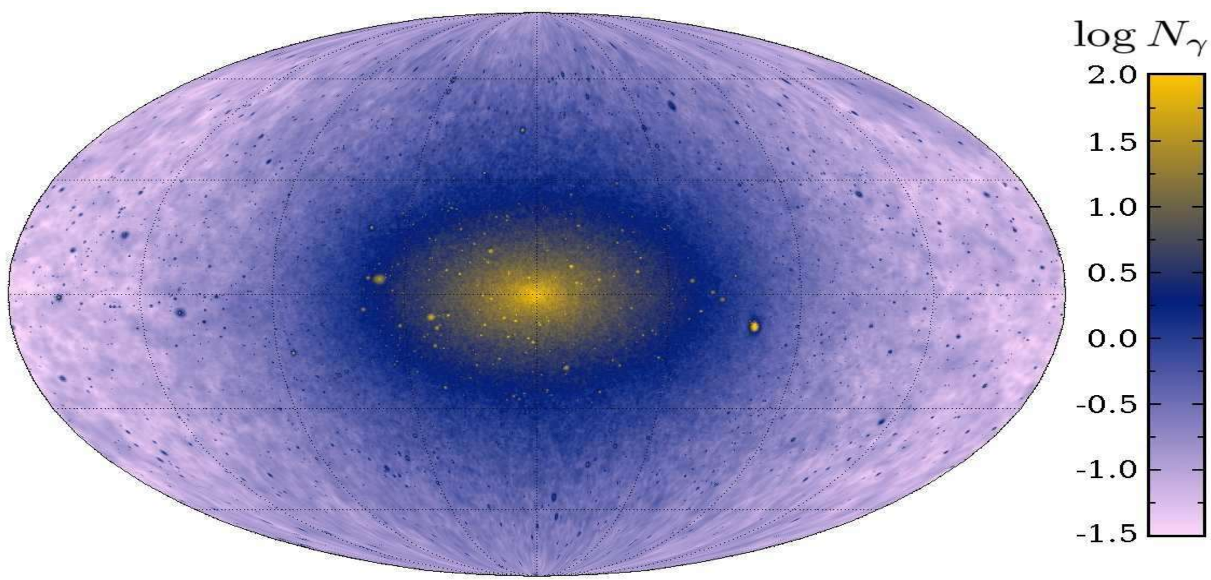
flux density (GeV cm^{-2} s^{-1} Hz^{-1})



Galaxy sub-halos

Possibility to detect single or a population of DM clumps via their π^0 decay γ-ray emission.

$$M_\chi = 46\ \mathrm{GeV},\ \langle\sigma v\rangle = 5\times10^{-26}\ \mathrm{cm^3\ s^{-1}}$$



[DM simulation Kuhlen et al. arXiv:0704.0944]

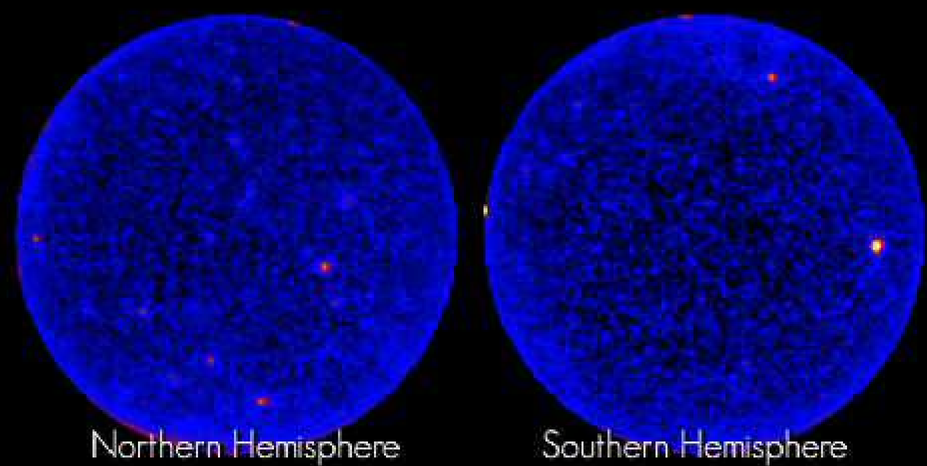
CAVEATS

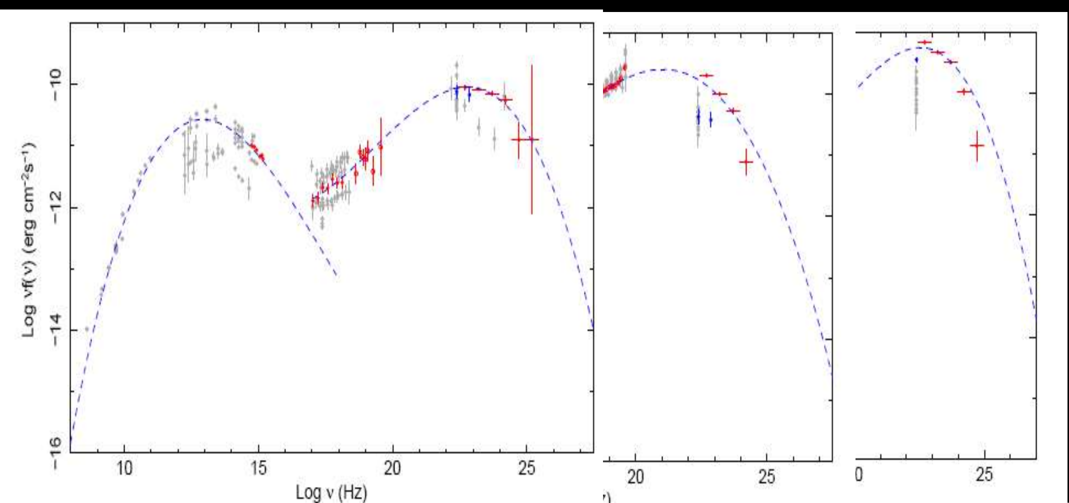
Galactic diffuse emission plus its fluctuations (spatial + spectral)
Foreground removal
- Galaxy
- Blazars
- Galaxies
- Starburst galaxies
- Galaxy clusters
- Pulsars
- SNRs
- MCs

Variability
Spectral separation
Clustering properties
…

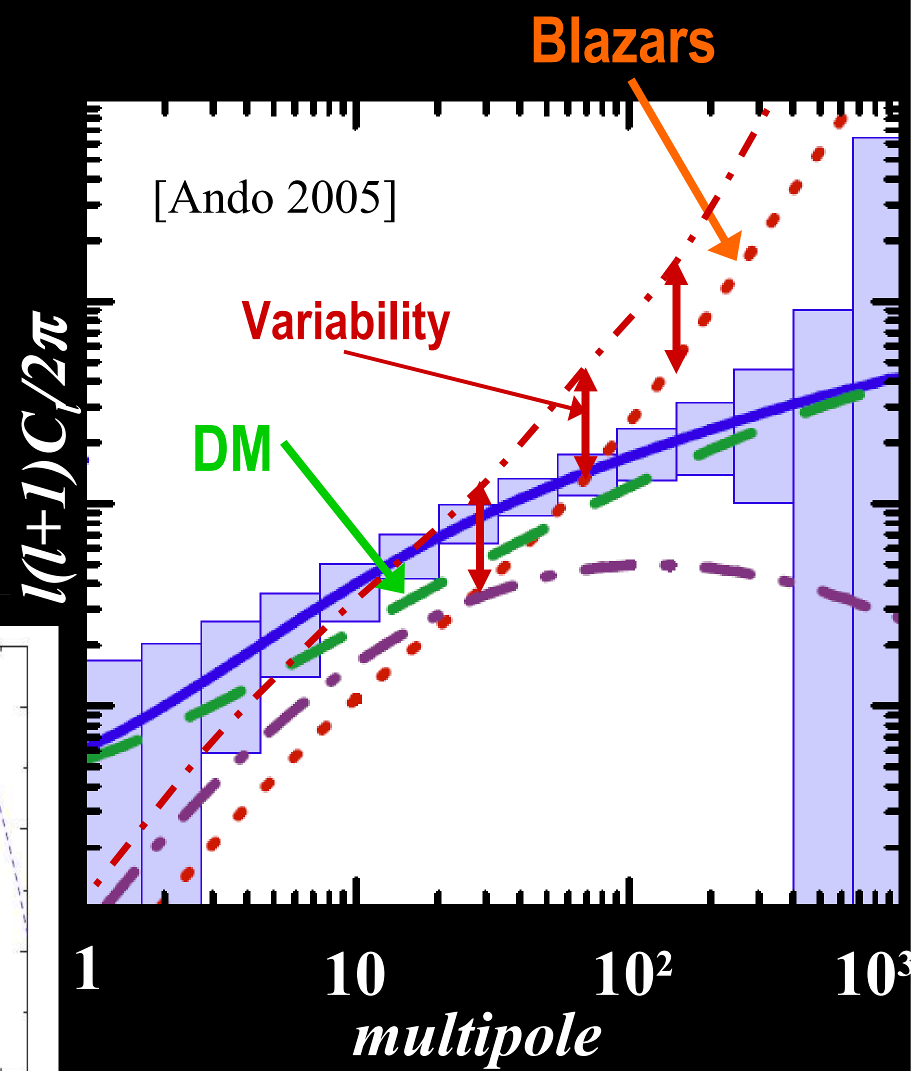
The Gamma-ray sky

Fermi all-sky survey





Angular power spectrum



γ-ray Anisotropy spectrum

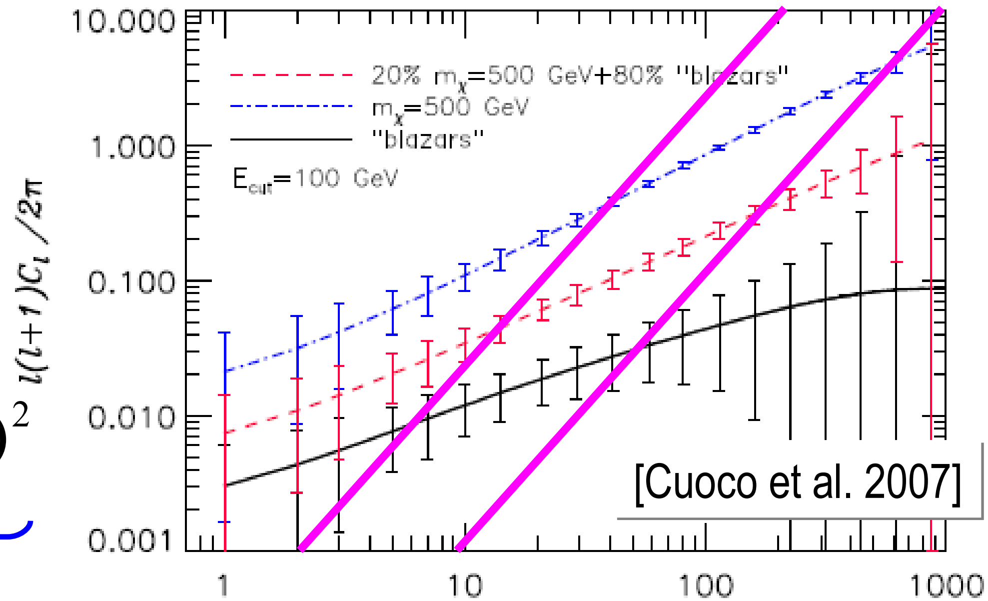
The Blazar power spectrum

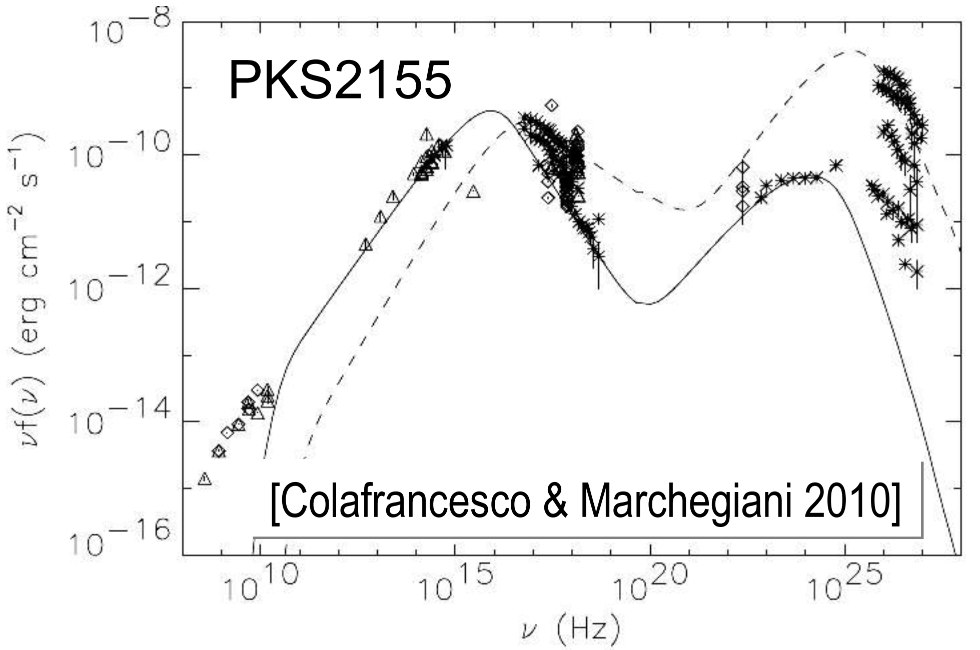
$$\left\langle \Delta S^2 \right\rangle = \frac{1}{2\pi} \cdot \ell(\ell+1) C_{\ell,Blazar}$$

$$C_{\ell,Blazar} = \underbrace{\int dS \cdot \frac{dN}{dS} \cdot S^2}_{\text{Poisson}} + \underbrace{\omega_{\ell,Blazar} (I)^2}_{\text{Clustering}}$$

Poisson → $\propto \frac{1}{2-\beta} \cdot \left[S_{max}^{2-\beta} - S_{min}^{2-\beta} \right]$

Clustering



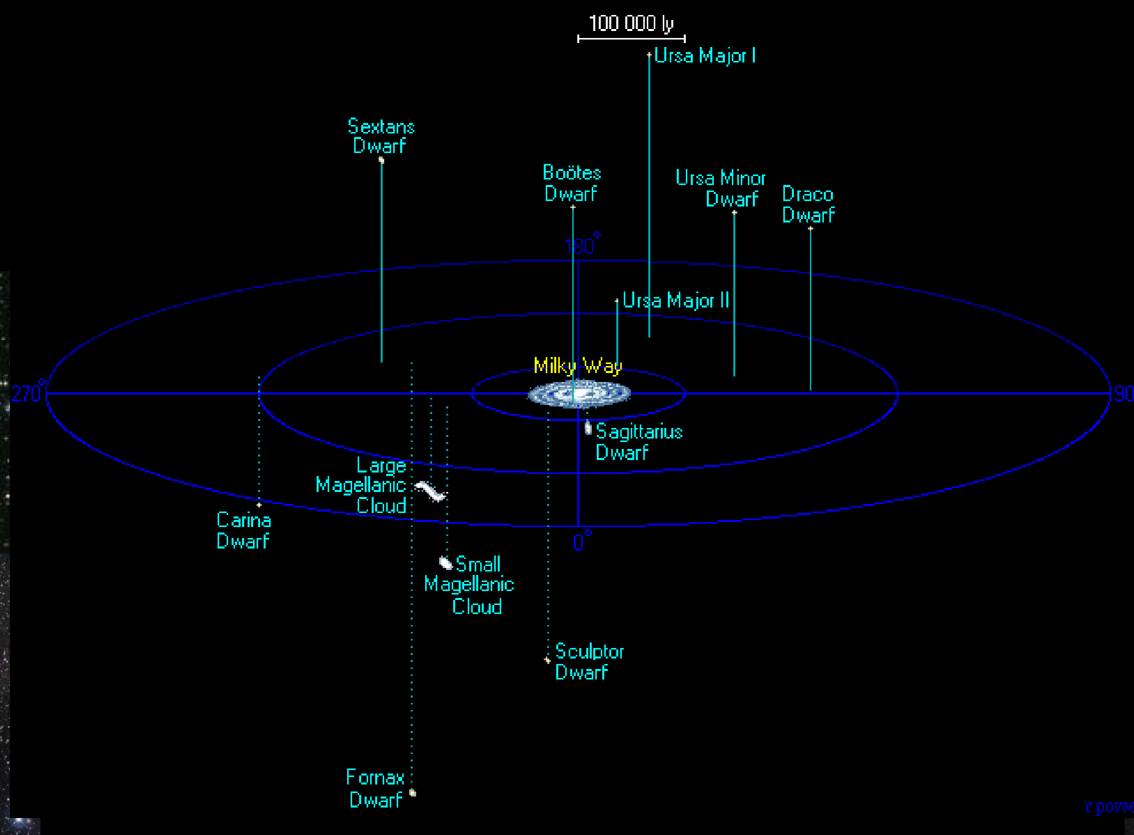


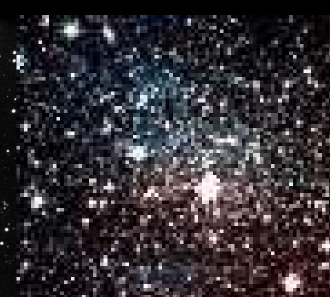
Blazars are flaring sources:

- Strong flux variability
- Strong spectral variability

Dwarf Spheroidal Galaxies: DM halos

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





The Dwarf Galaxies DM challenge

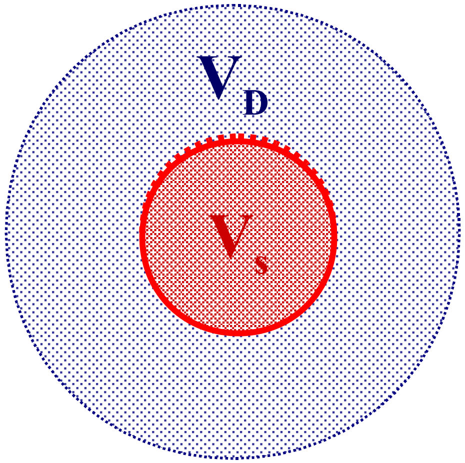
Sub-galactic size systems
- R ~ kpc
- No gas
- Little dust
- No Crs
- 1 (or 2) stellar populations
- M/L ~ 200 - 1500

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

but…

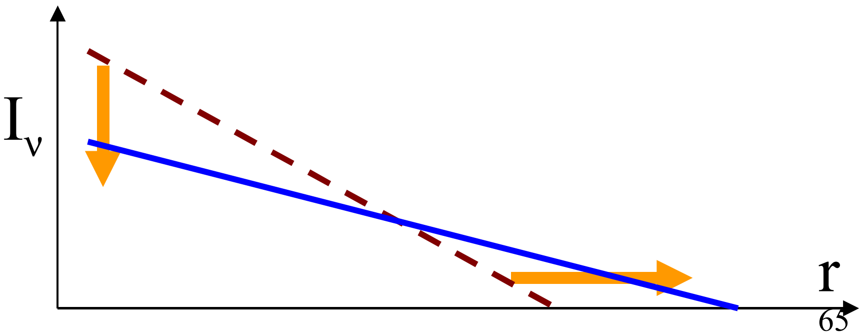
- Strong diffusion effects
- Low signals

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

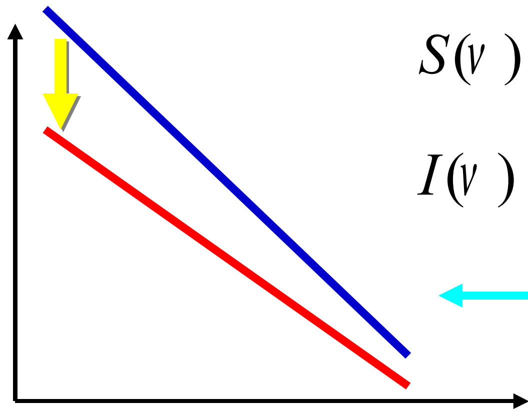


$\tau_{loss} \gg \tau_D$

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



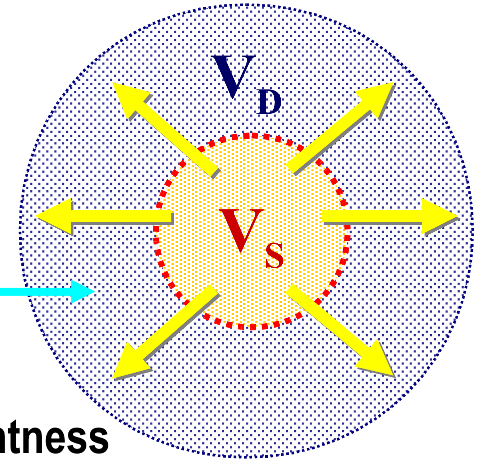
Dwarf galaxies & DM: synchrotron



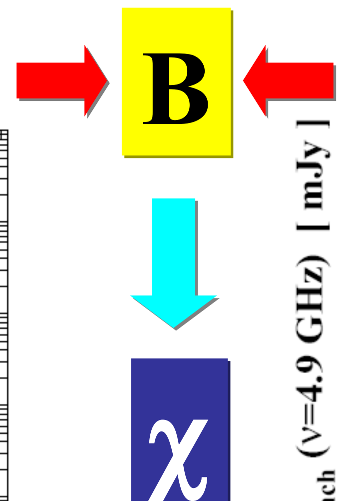
$$S(\nu) \propto B \otimes D_e \otimes n_e^2(E_e, \nu, r)\langle\sigma v\rangle$$

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

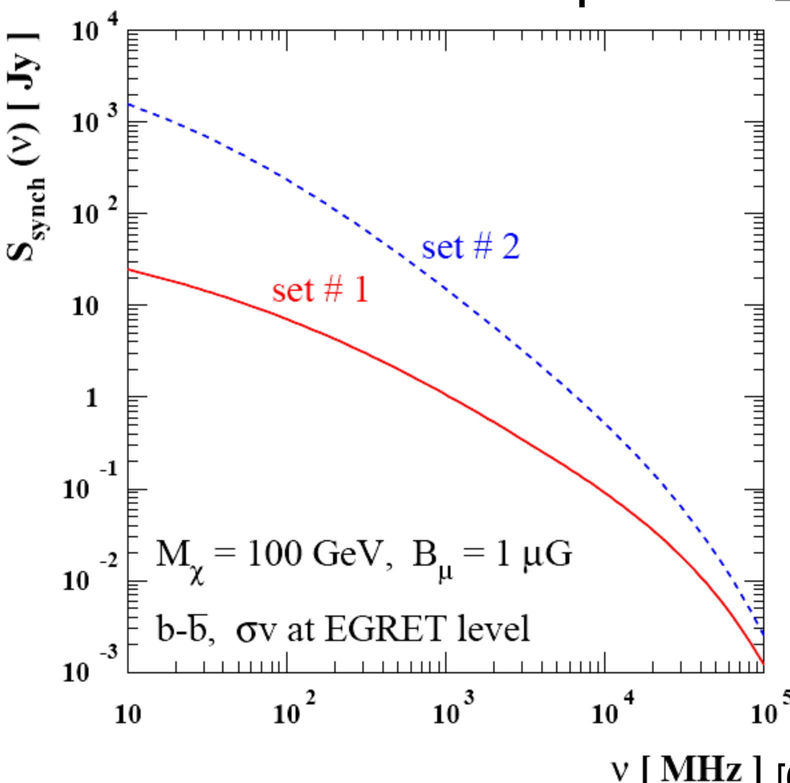
$$D_e = D_0 (E_e / B)^{\gamma}$$

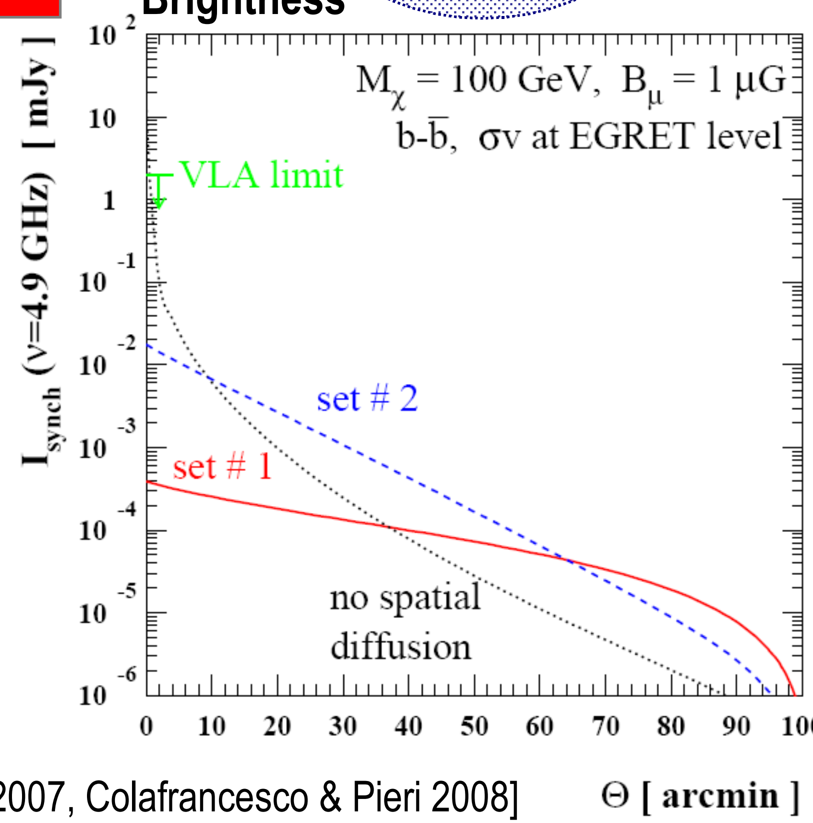


Spectrum



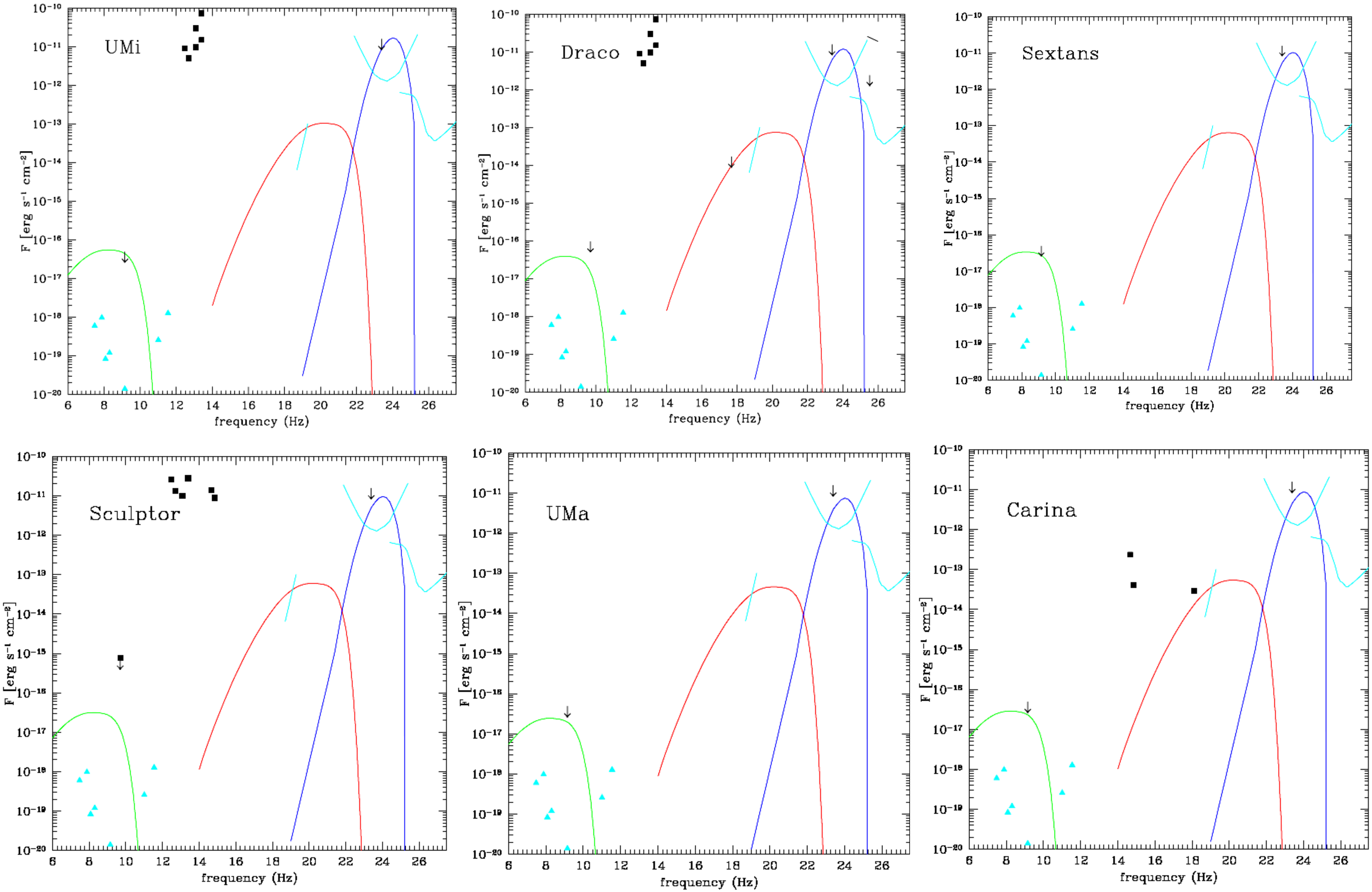
Brightness





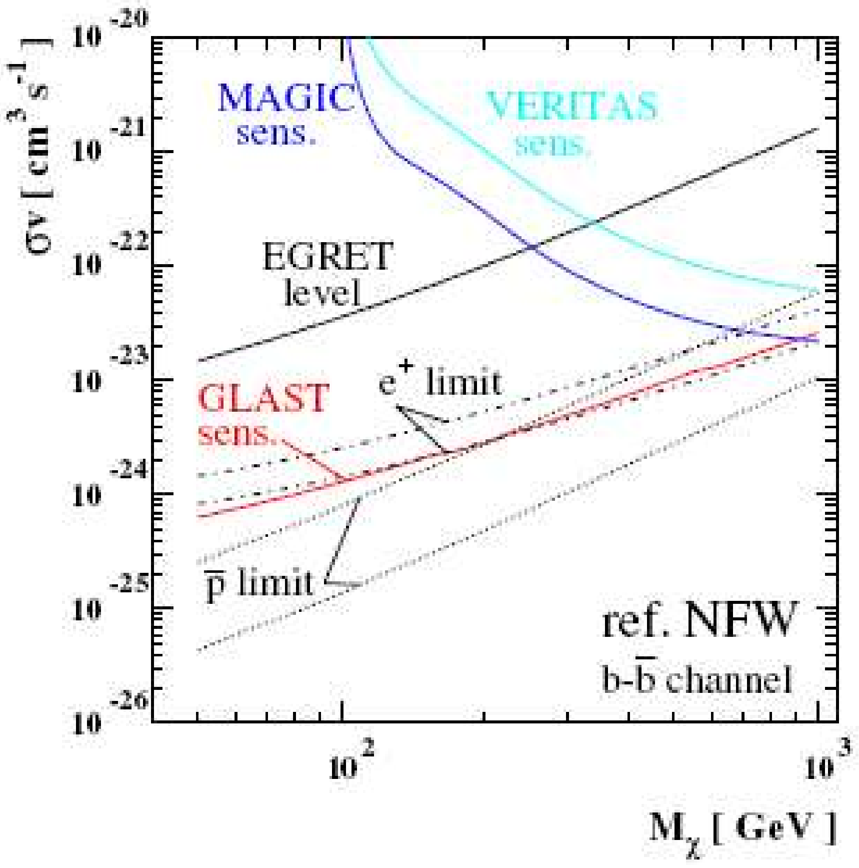
[Colafrancesco 2007, Colafrancesco & Pieri 2008]

DSph. Galaxies & DM: multi-ν

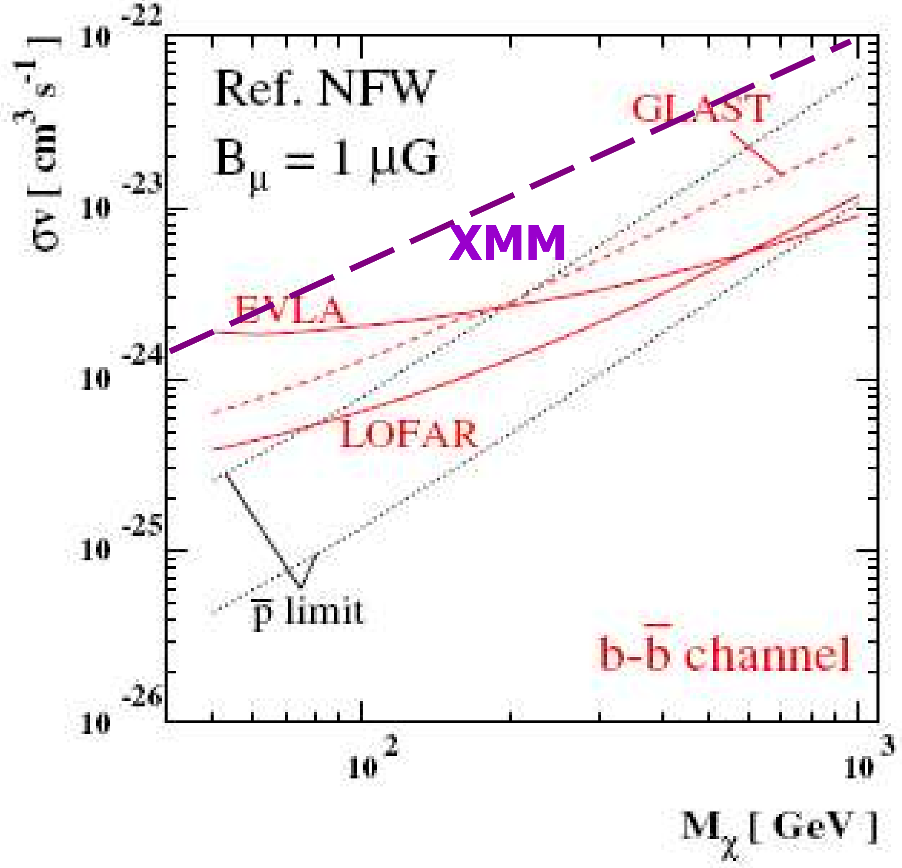


Neutralino DM constraints: Draco

Gamma-ray



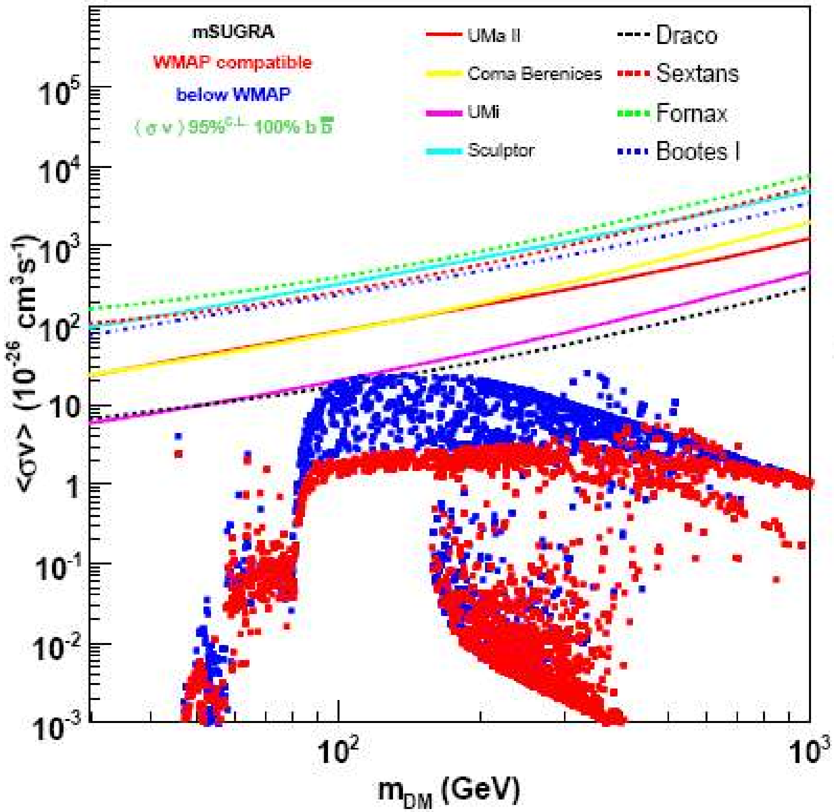
Radio



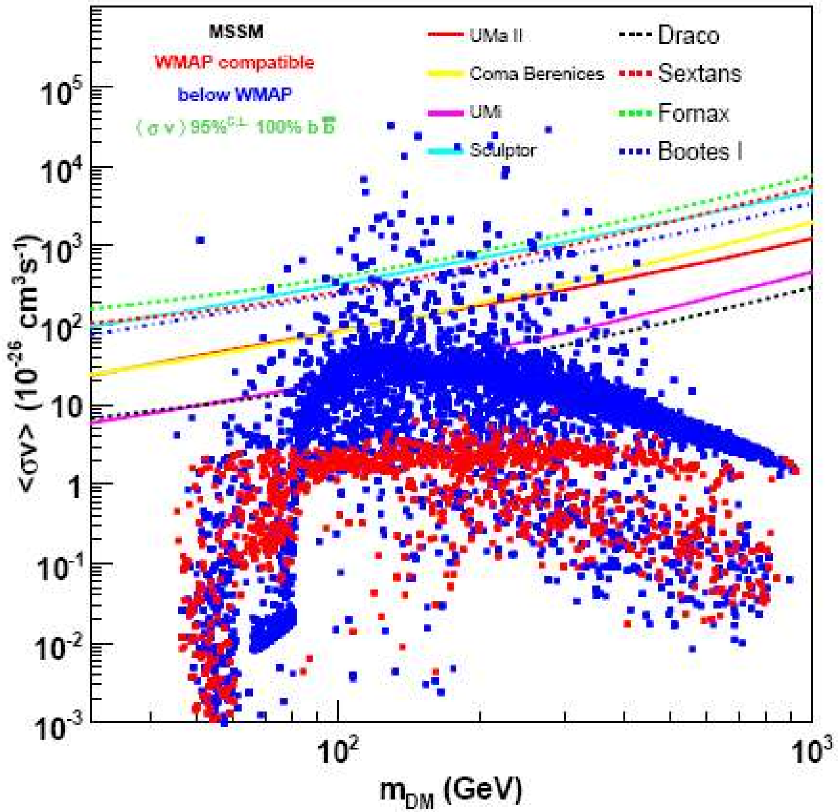
[Colafrancesco, Profumo & Ullio 2007]]

Dwarf galaxies & DM: Fermi

MSUGRA



MSSM

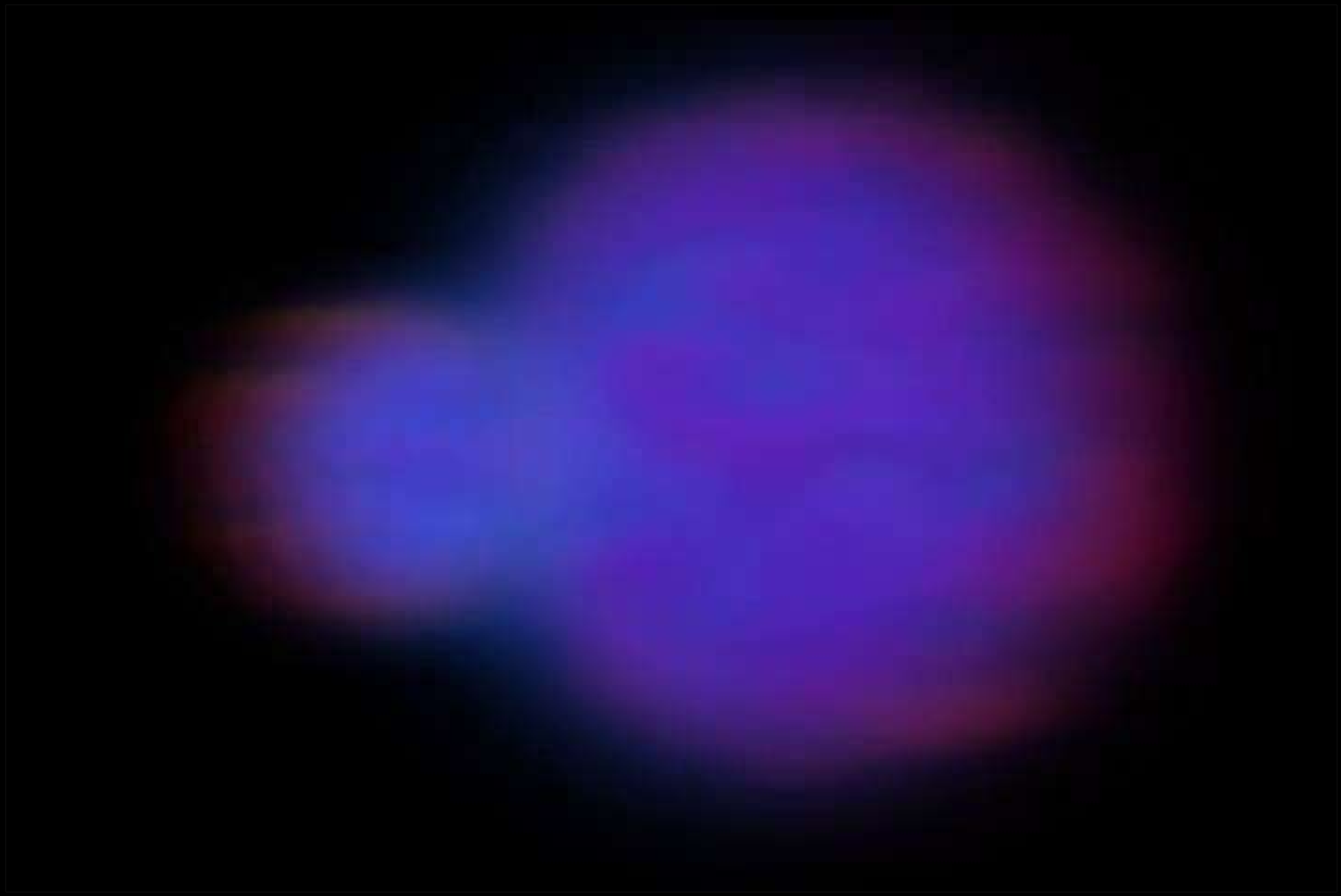


[Fermi-LAT collaboration 2010]

Assumptions

- NFW profile
- No boost factor (no substructures)

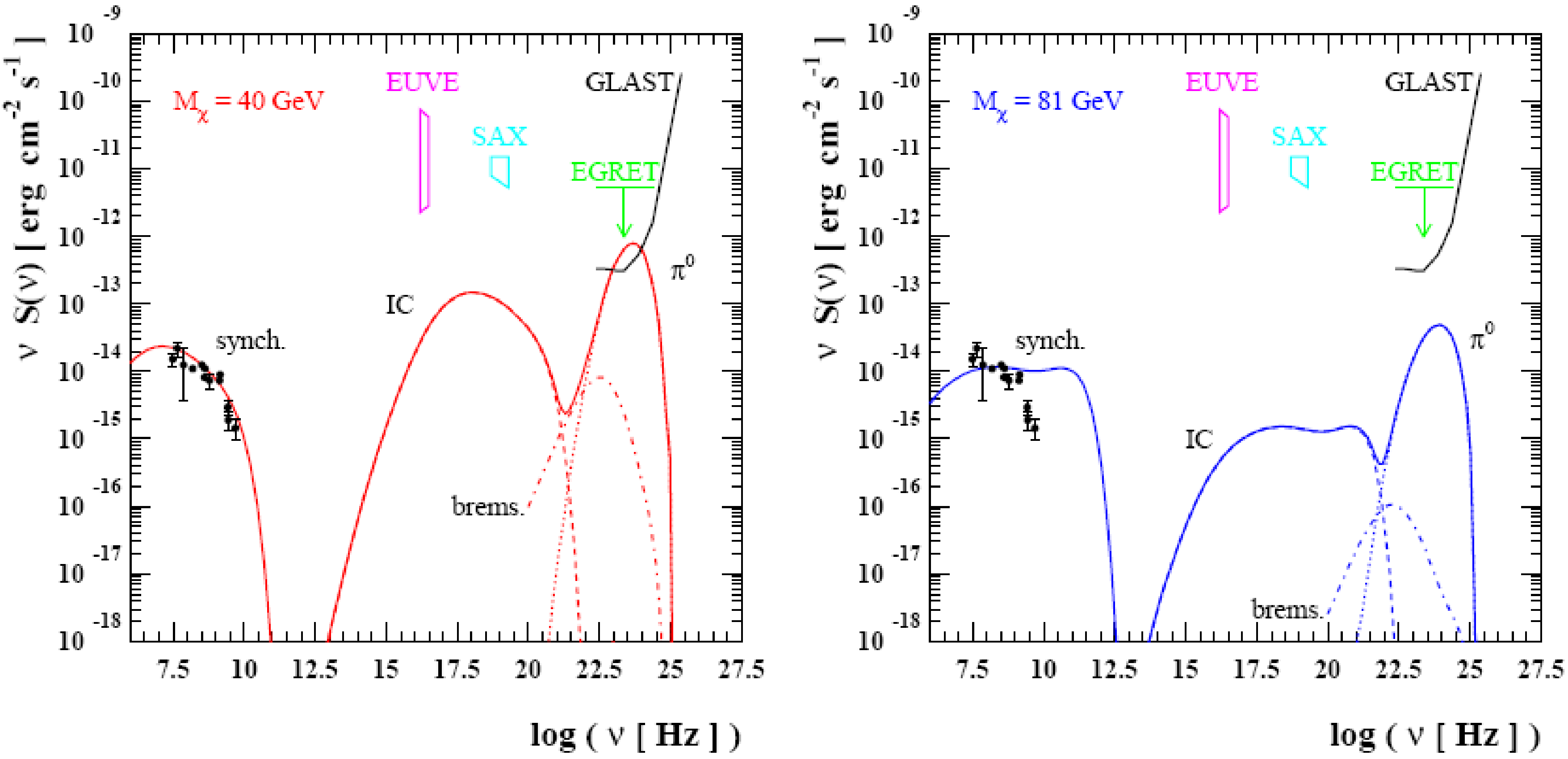
Galaxy clusters: the largest DM labs.



Large-size, dynamically stable… but co-spatial DM+baryon

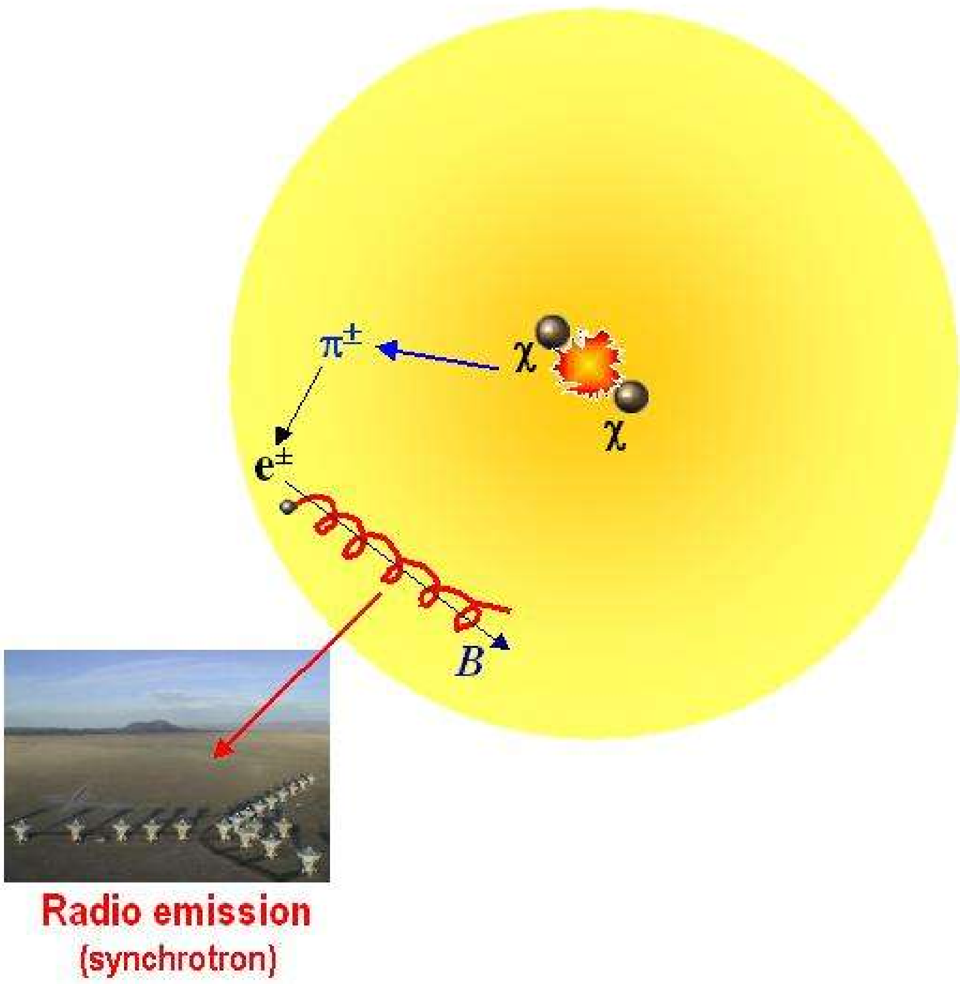
… except one!

Multi-ν expectations from DM

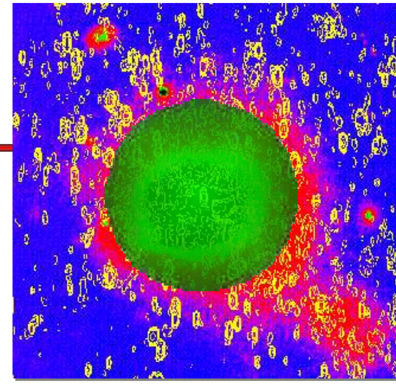


[Colafrancesco, Profumo & Ullio 2006]

Neutralino DM: radio emission



Clusters of galaxies

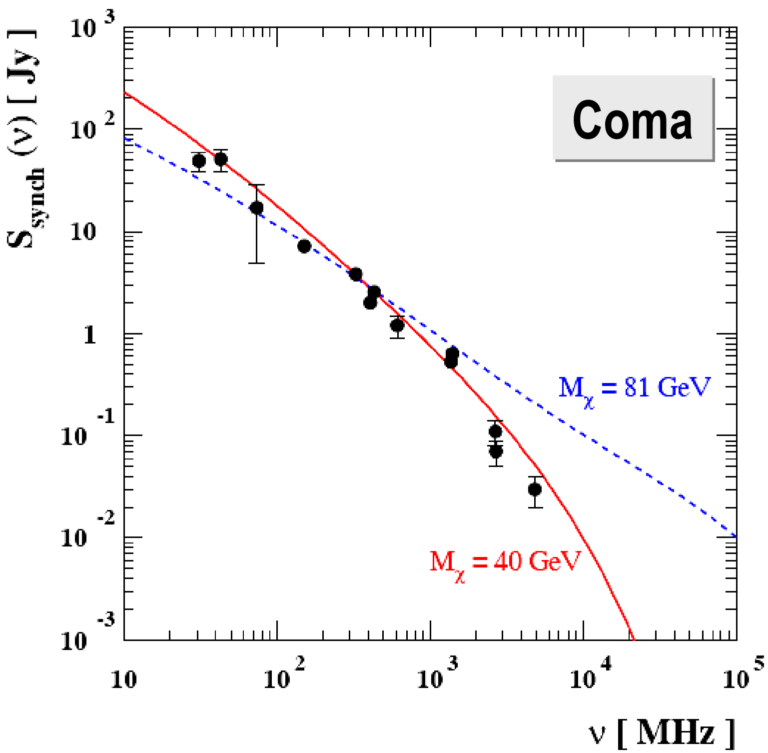


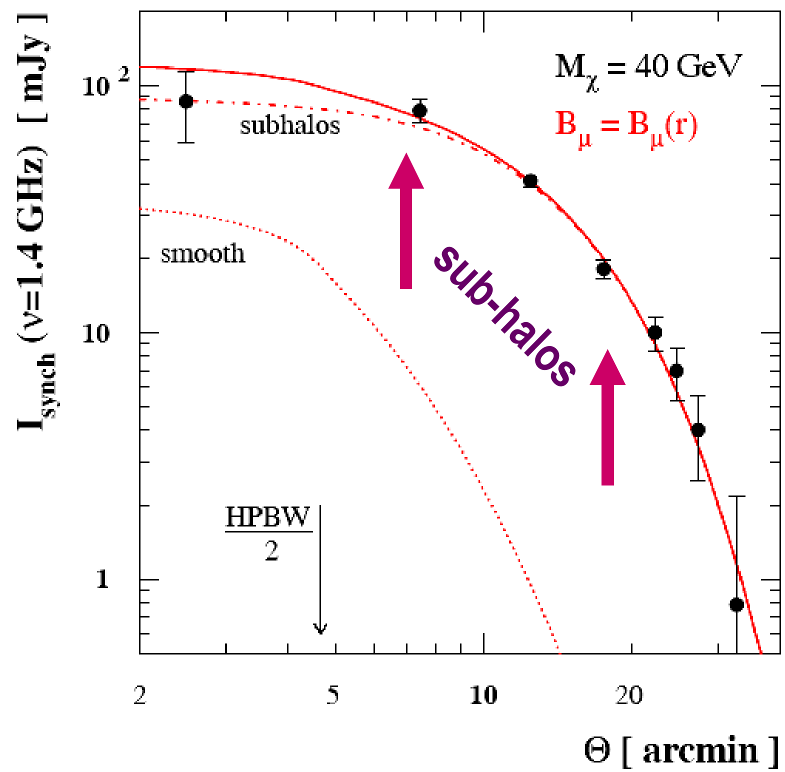
Integrated spectrum (30 MHz-5 GHz)

Brightness distribution (@ 1.4 GHz)

$$I(\nu) \propto B \otimes D_e \otimes n_e^2(E_e,\nu,r)\langle\sigma v\rangle \rightarrow \mathbf{B} \leftarrow S(\nu) \propto B \otimes D_e \otimes n_e^2(E_e,\nu,r)\langle\sigma v\rangle$$

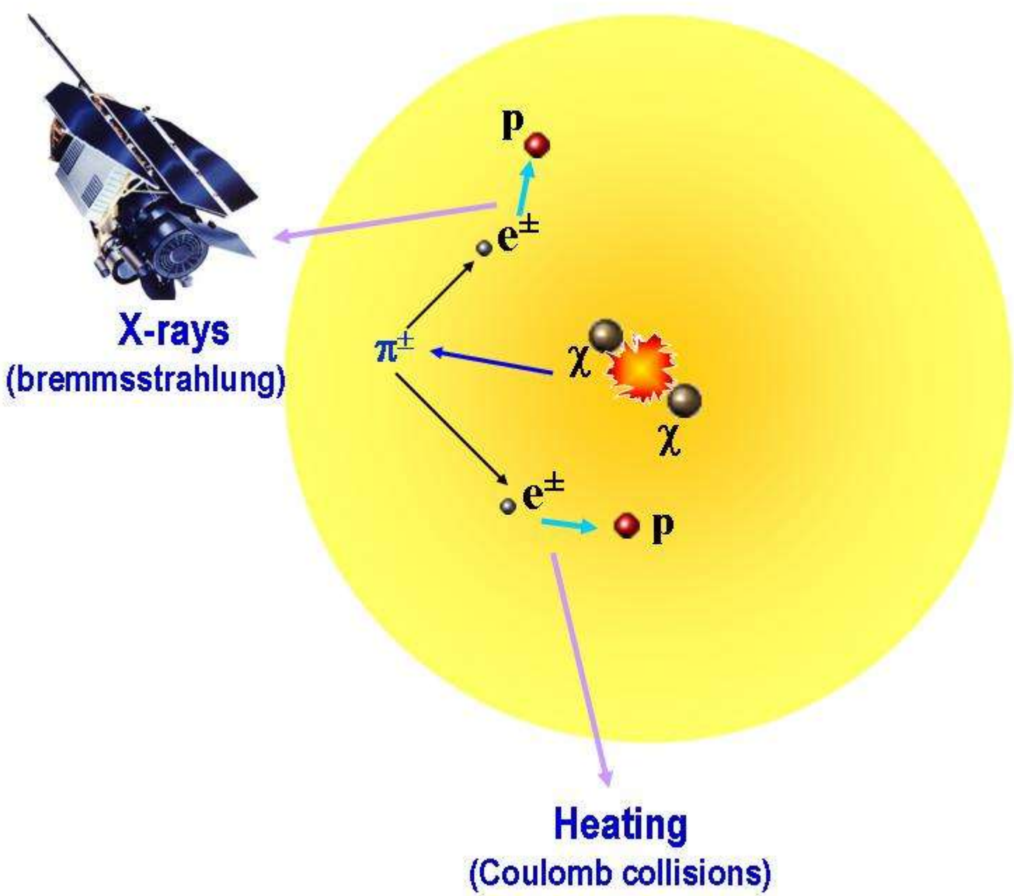
$$\mathbf{B} \downarrow \chi$$



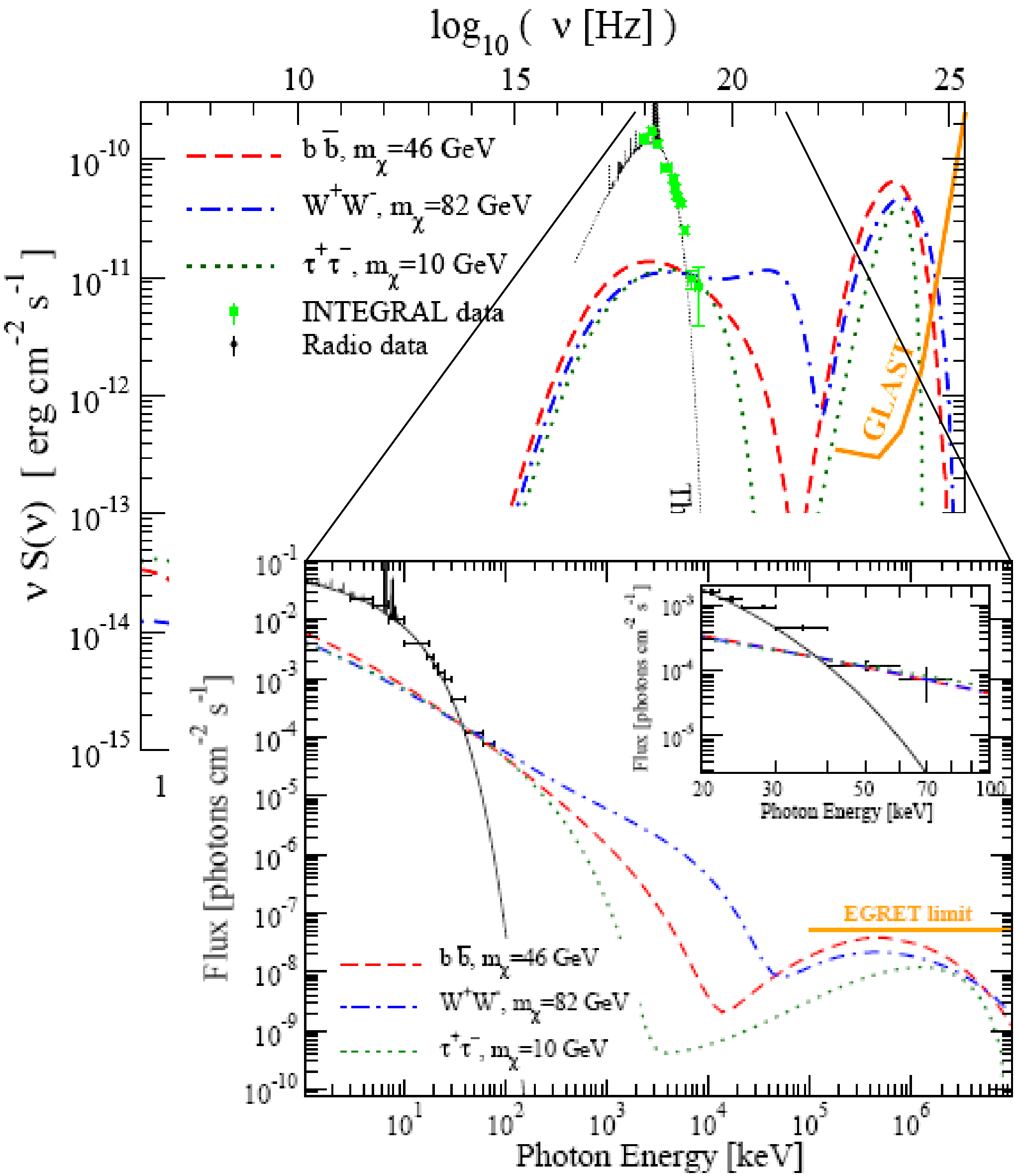


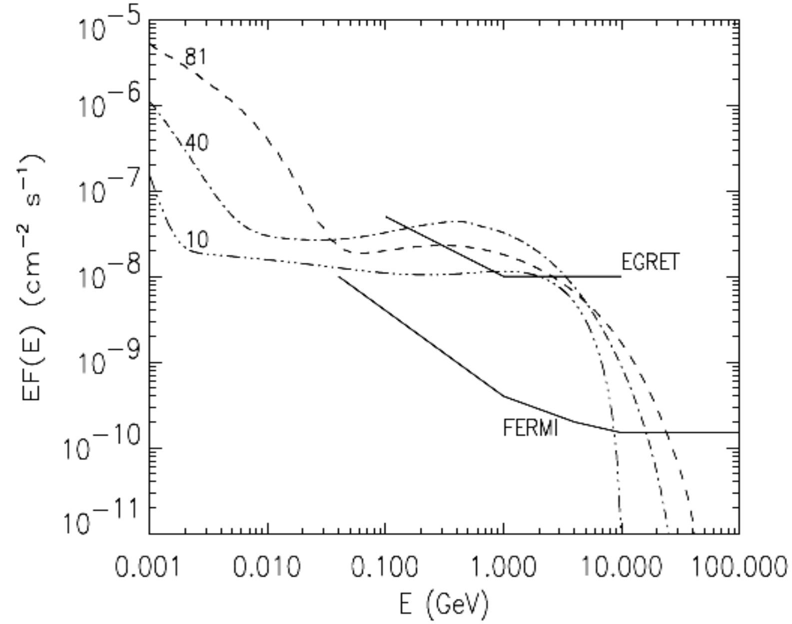
[Colafrancesco, Profumo & Ullio 2006]

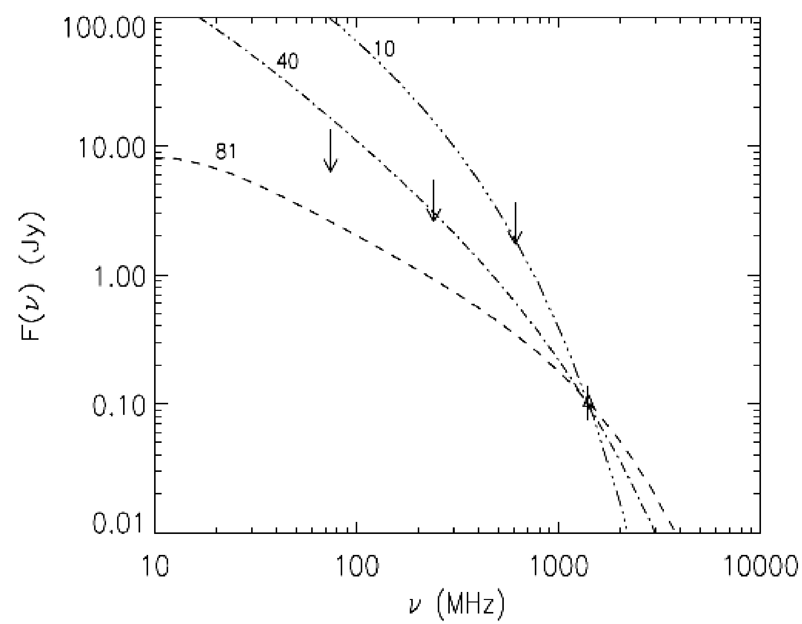
Neutralino DM: X-ray emission



Hard X-ray excess Consequence

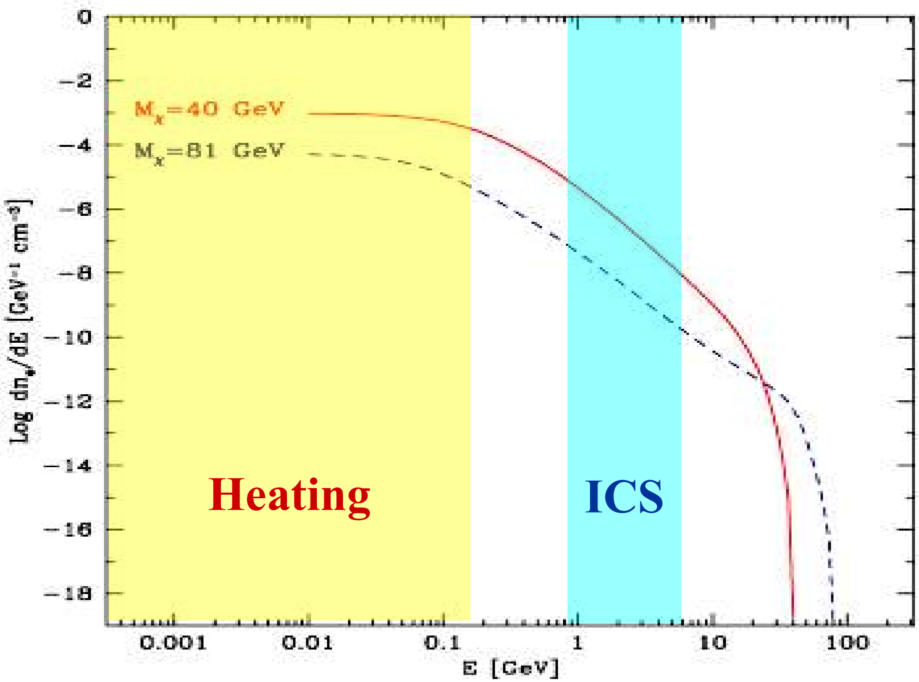




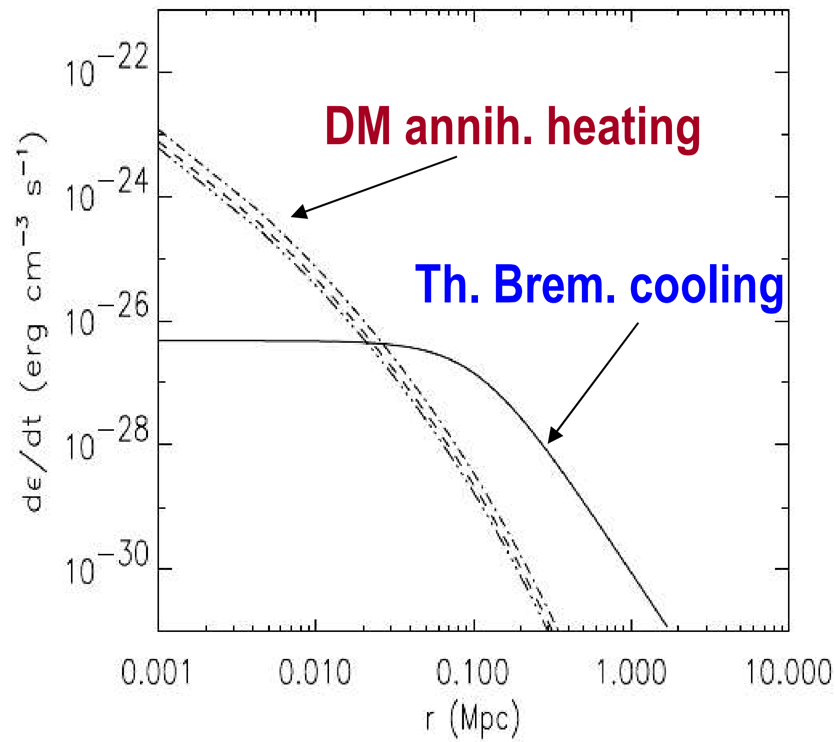


[Colafrancesco & Marchegiani 2009]

DM & heating

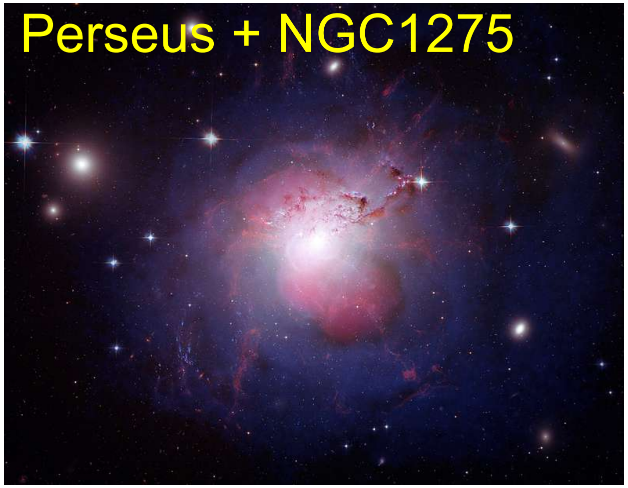


DM models that fit the HXR flux of galaxy clusters produce also an excess heating of the gas.

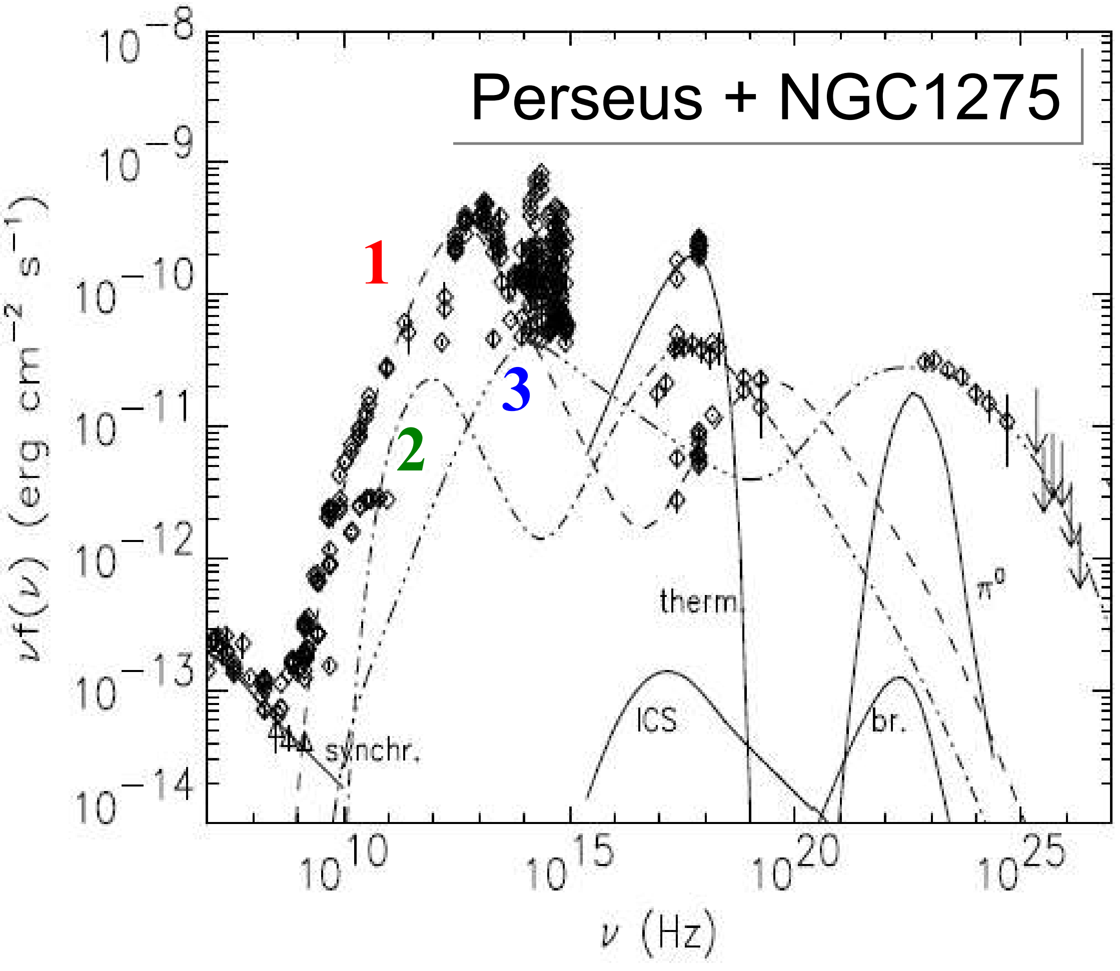


[Colafrancesco & Marchegiani 2009]

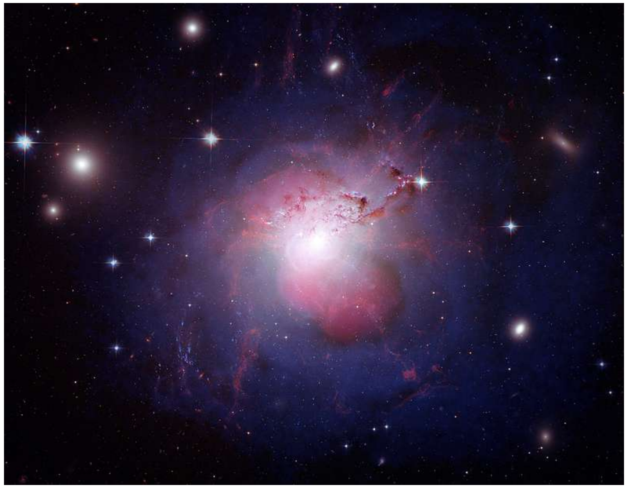
DM and γ-rays



[Colafrancesco & Marchegiani 2010]

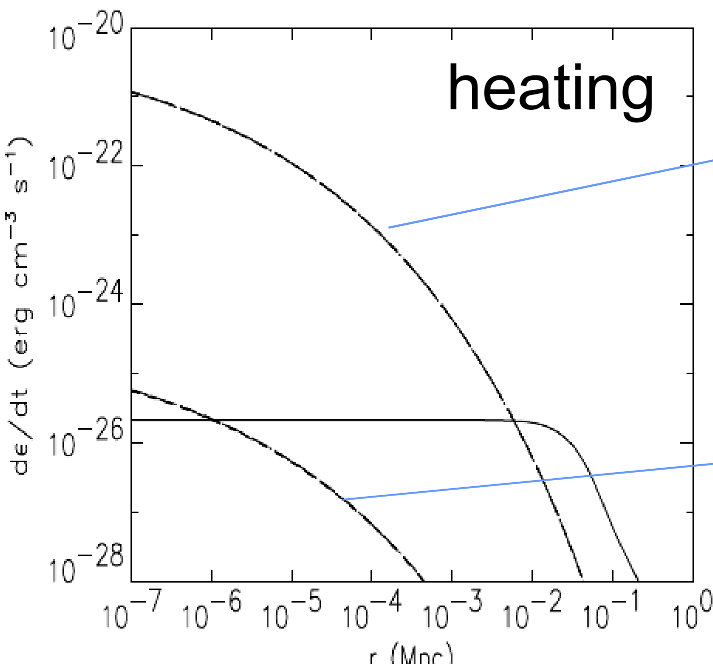


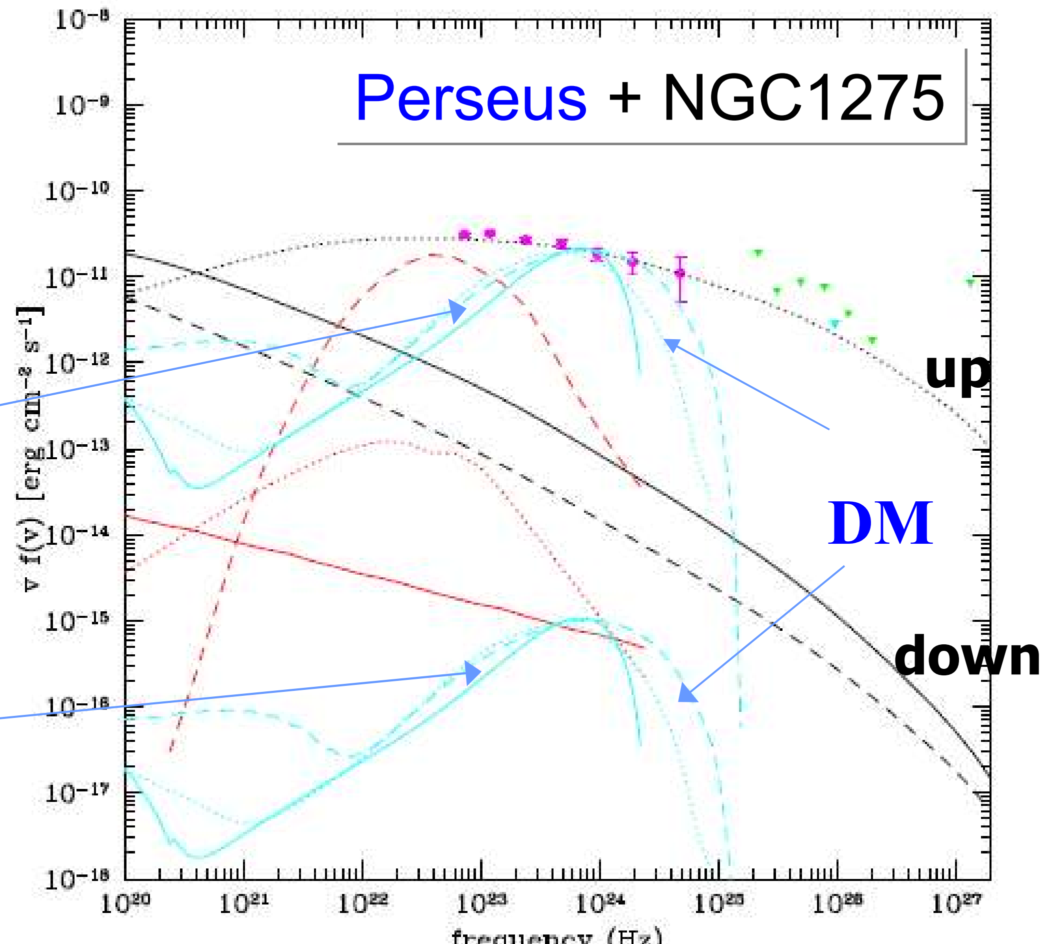
DM and γ-rays



[Colafrancesco & Marchegiani 2010]

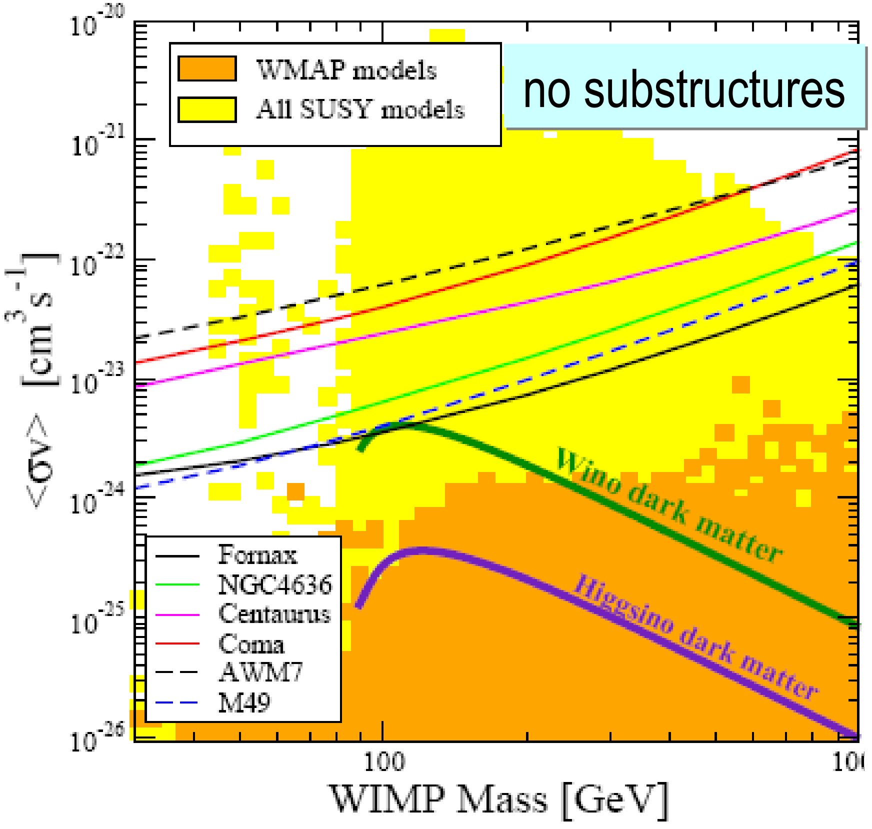
Possibility to detect γ-rays from Perseus
- in low-states of the central AGN
- in the outer parts of the cluster

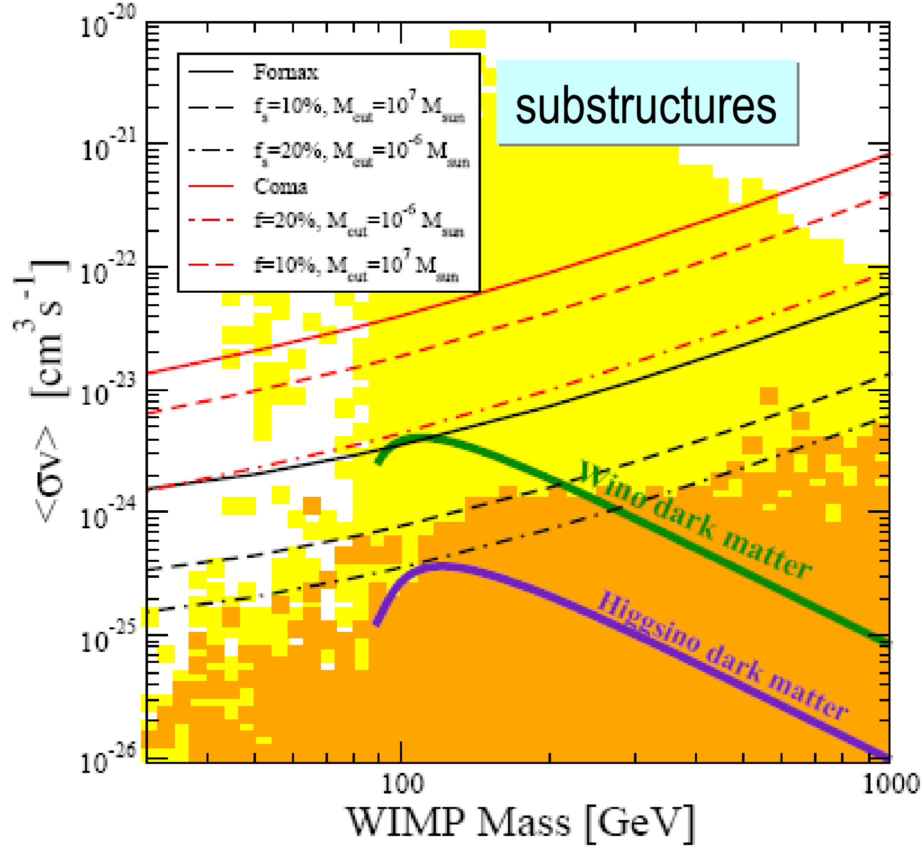




DM & γ-rays: Fermi limits

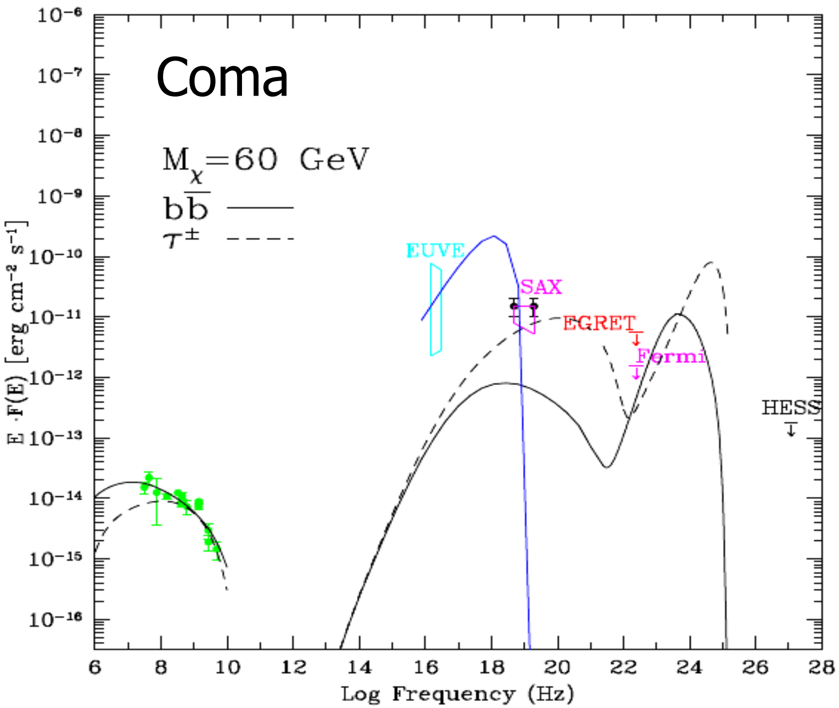
Neutralino upper limits from 2 recent preprints:
Q.Yuan et al. 2010 (arXiv:1002.0197)
Fermi-LAT collaboration 2010 (arXiv:1002.2239)

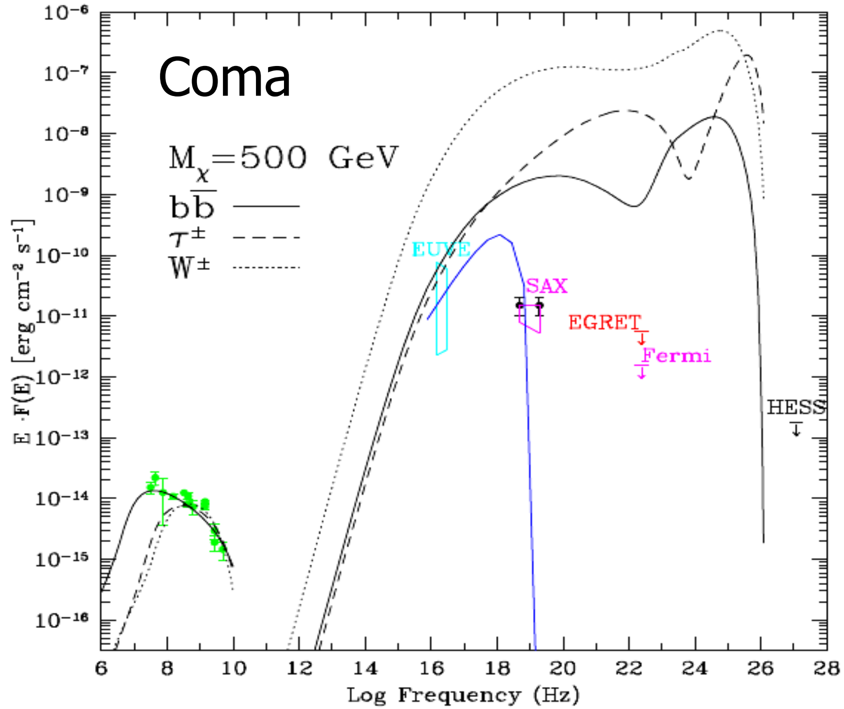




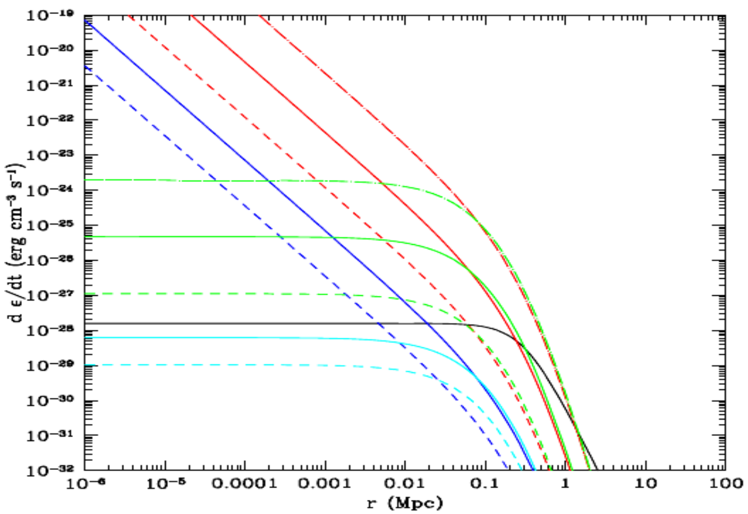
… but very optimistic upper limits (no CRs, no AGNs, no gal., …)

DM, multi-ν, multi-effect, …



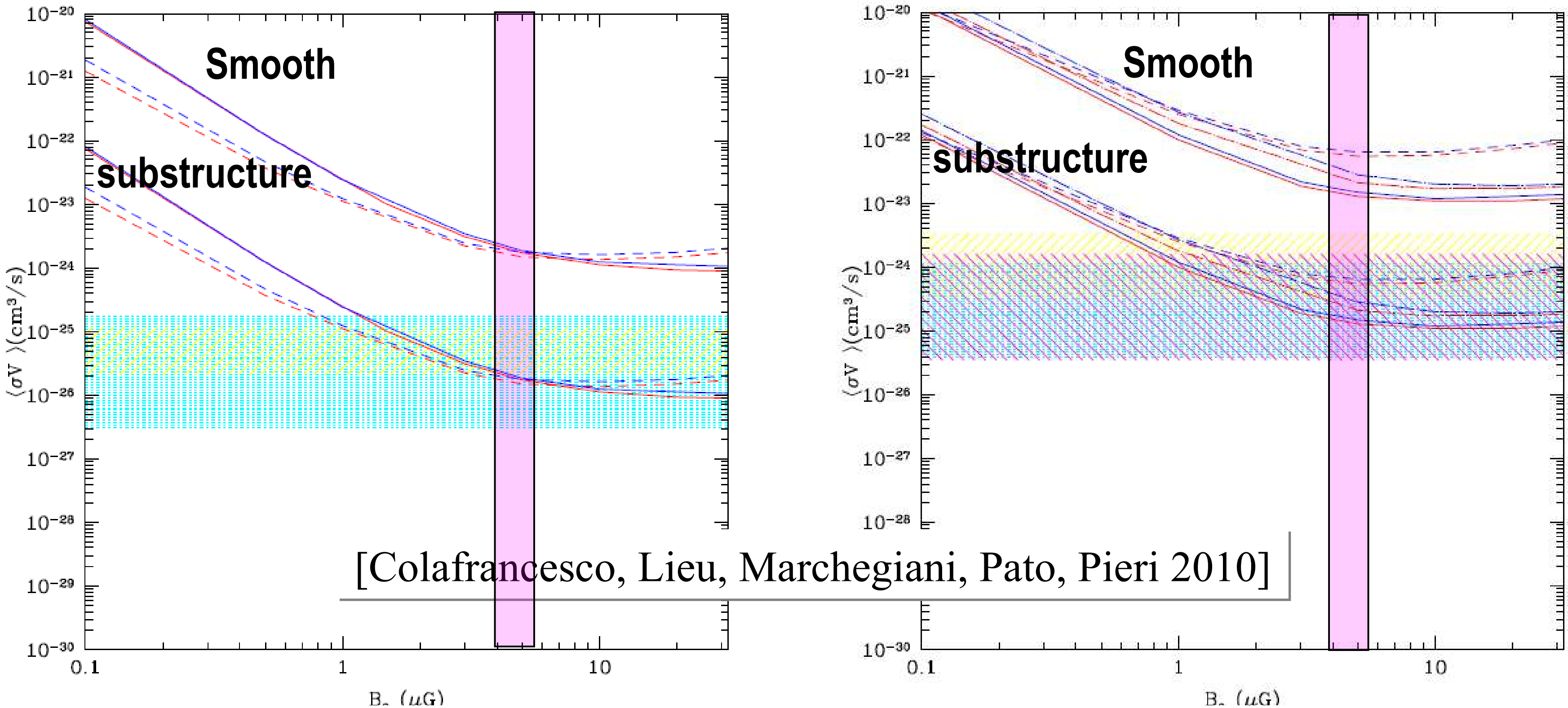


[Colafrancesco, Lieu, Marchegiani, Pato, Pieri 2010]



SED + heating

DM, multi-ν, multi-effect, multi-messenger

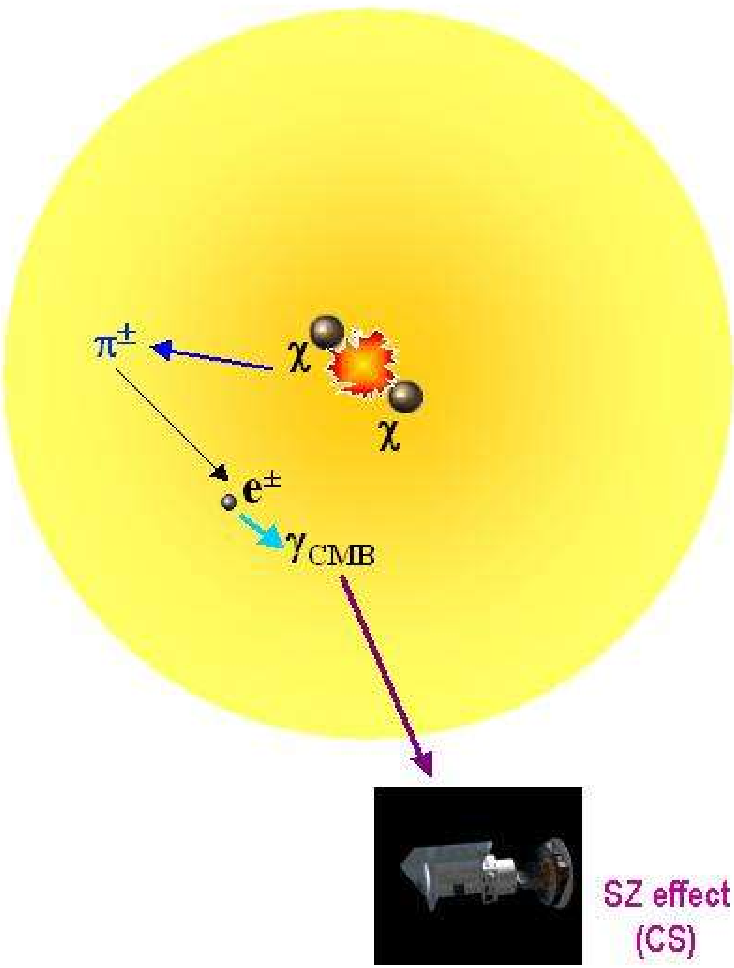


[Colafrancesco, Lieu, Marchegiani, Pato, Pieri 2010]

upper limit on the annihilation cross-section (10^{-26} cm^3 s^{-1})				
DM benchmark		VL2	Aq	iso
$M_\chi = 60$ GeV	$\chi\chi \to \tau^+\tau^-$	(2.2, 2.2, 2.2) (rad,rad,rad)	(5.3, 3.6, **2.1**) (pos,pos,pos)	(**12**, 8.5, 8.0) (pos,pos,pos)
$M_\chi = 60$ GeV	$\chi\chi \to b\bar{b}$	(0.6, 0.6, 0.6) (rad,rad,rad)	(8.5, 0.8, **0.3**) (anp,anp,anp)	(**19**, 3.8, 1.7) (anp,anp,anp)
$M_\chi = 500$ GeV	$\chi\chi \to \tau^+\tau^-$	(106, 101, 73) (rad,pos,pos)	(125, 64, **34**) (GCg,pos,pos)	(**349**, 184, 170) (pos,pos,pos)
$M_\chi = 500$ GeV	$\chi\chi \to W^+W^-$	(20, 20, 7.0) (rad,rad,anp)	(74, 8.6, **3.5**) (pos,anp,anp)	(**162**, 46, 20) (pos,anp,anp)
$M_\chi = 500$ GeV	$\chi\chi \to b\bar{b}$	(12, 12, 7.4) (rad,rad,anp)	(54, 9.2, **3.7**) (pos,anp,anp)	(**118**, 49, 21) (pos,anp,anp)

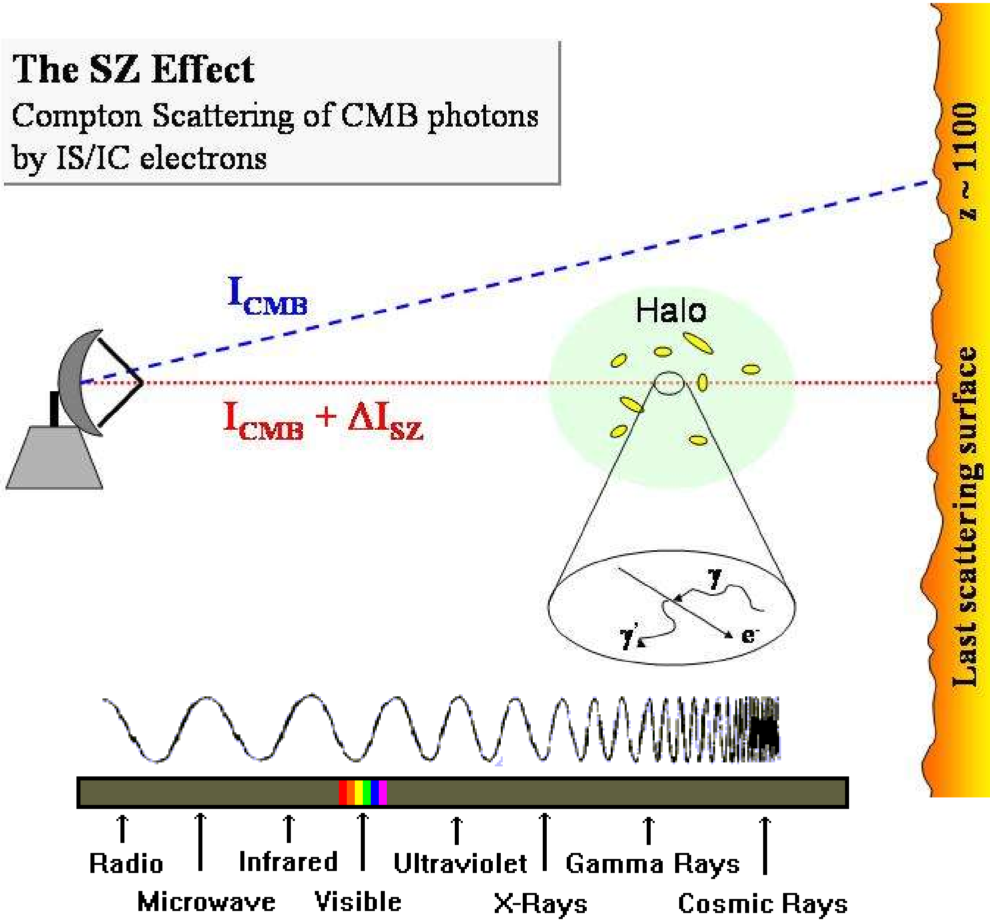
- Low neutralino mass: 40-60 GeV (preferentially $b\bar{b}$)
- Substantial amount of substructures (boost factor ~ 100)
- Cored DM density profile

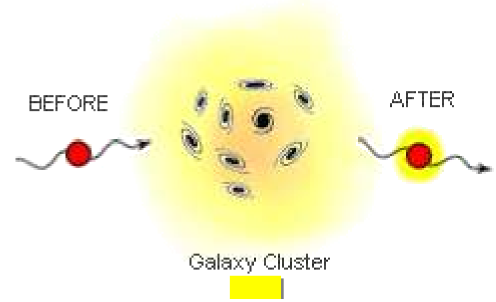
Neutralino DM: ICS of CMB (SZE)

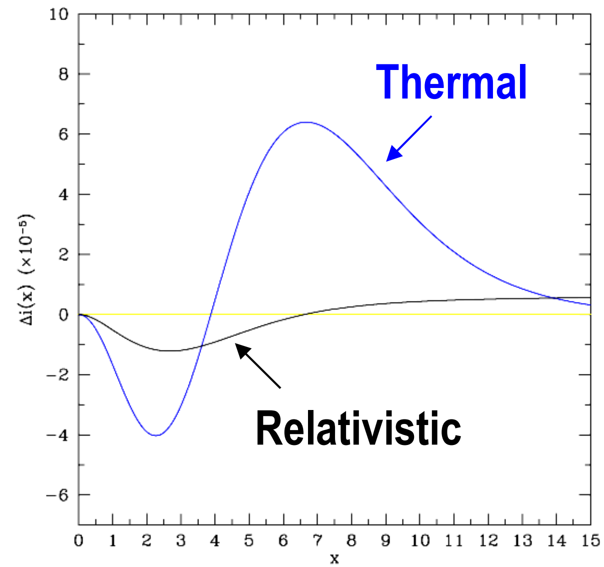


The SZ effect

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







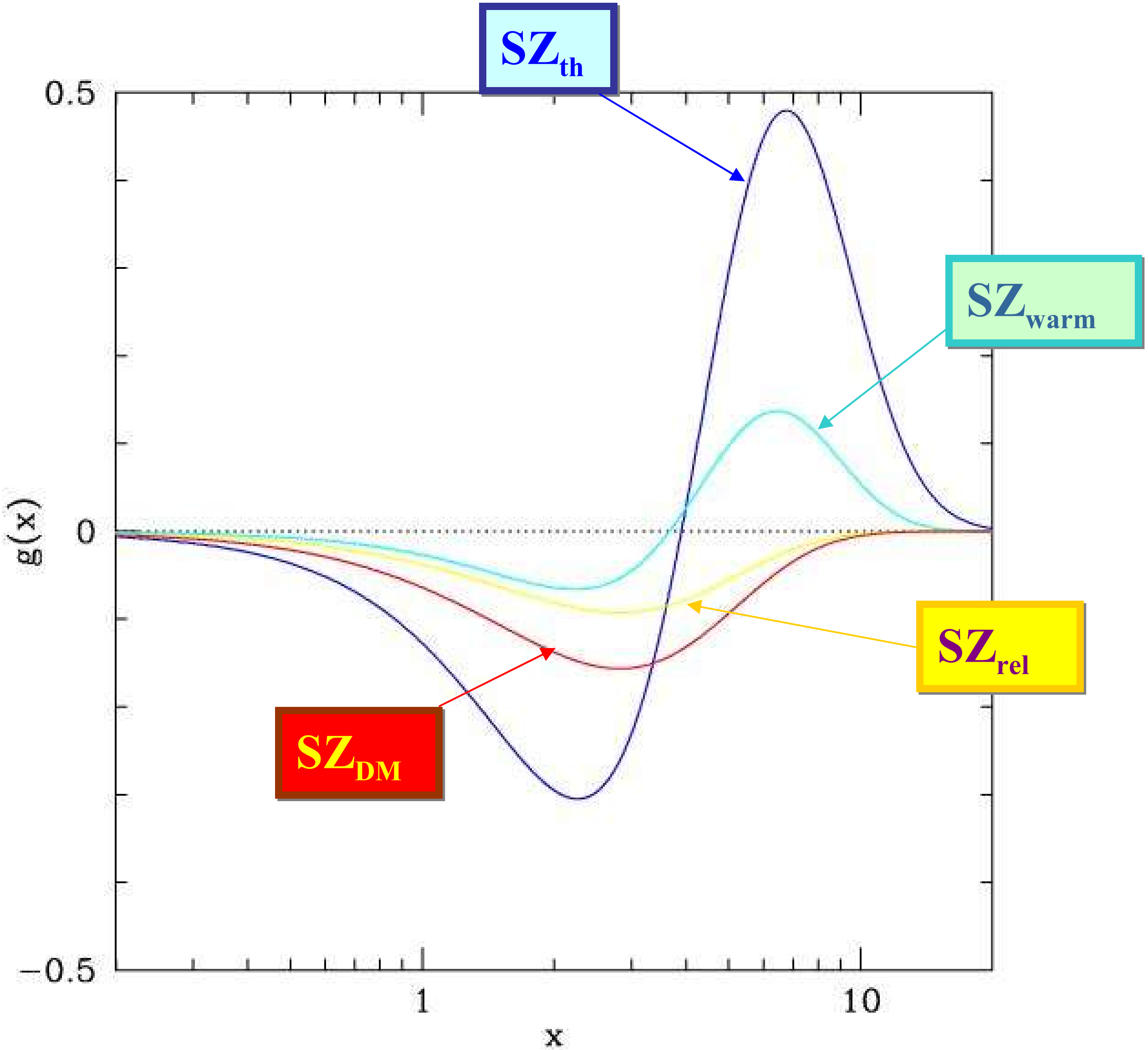
thermal NR e⁻ $\frac{\Delta \nu}{\nu} \approx 4 \frac{kT_e}{m_e c^2}$

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

SZE in DM halos

A structure with:

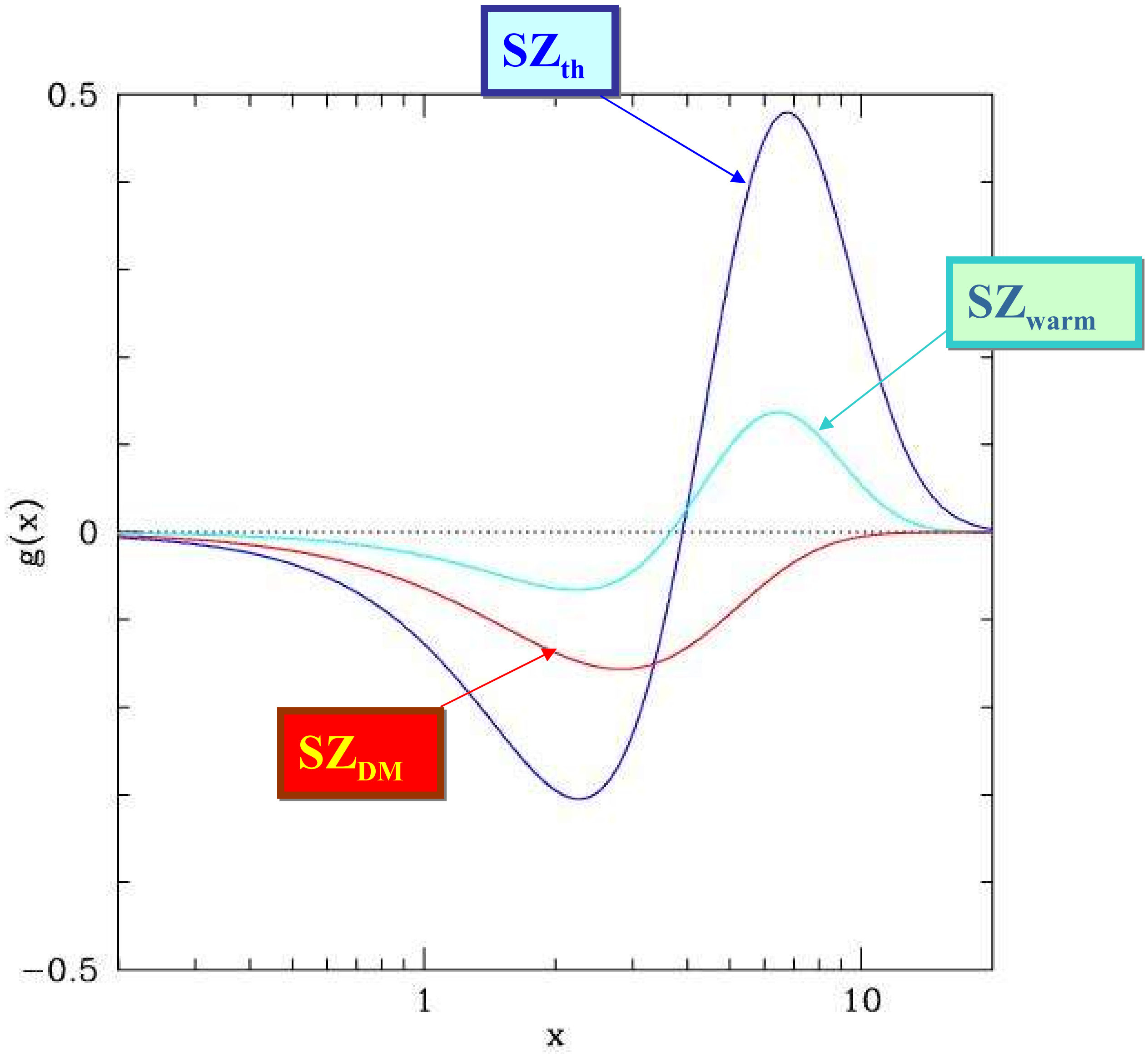
- **Hot gas**
- **Warm gas**
- **Rel. Plasma**
- **DM**
- **($V_r \approx 0$)**



SZE in DM halos

A structure with:

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



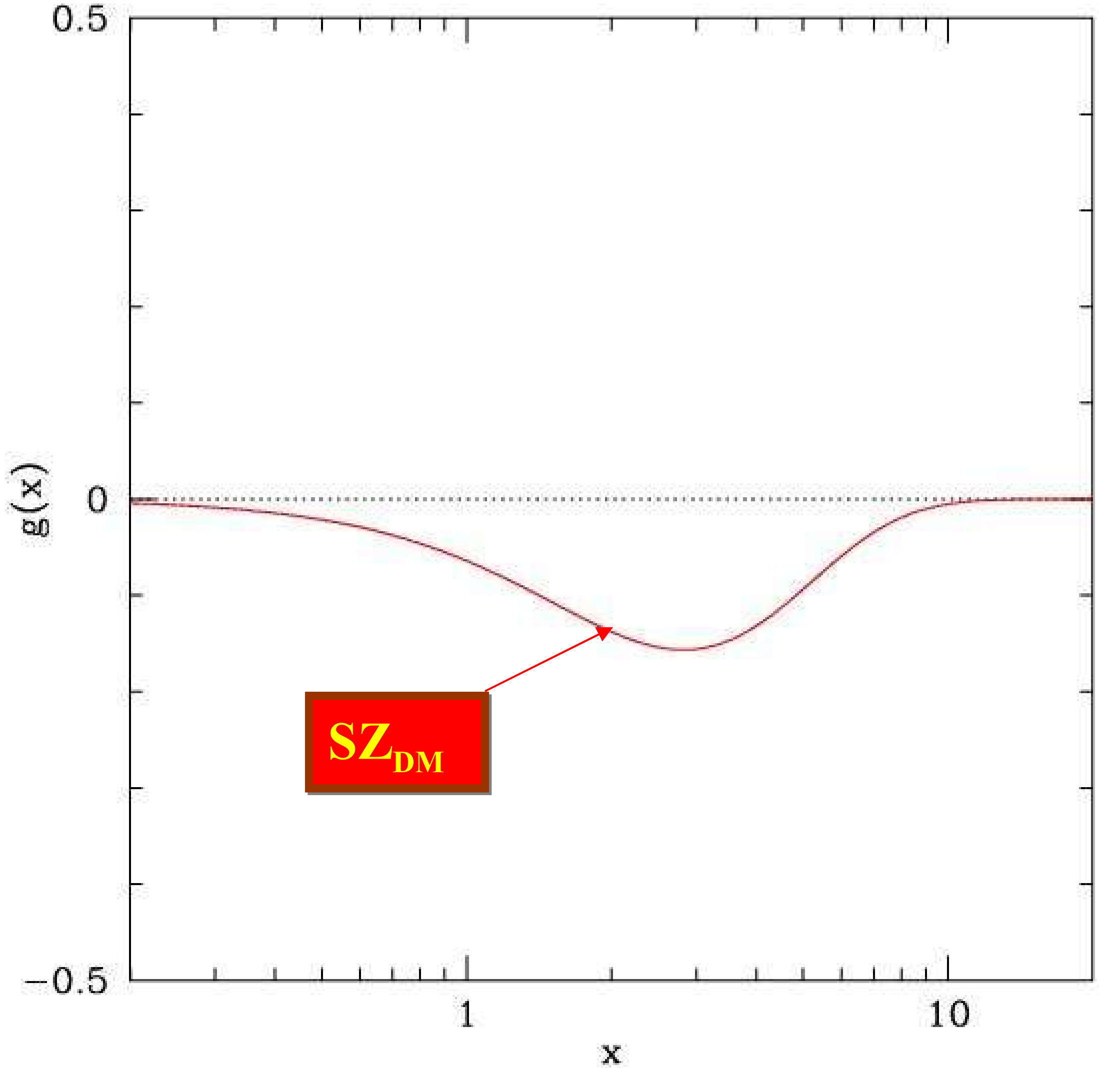
SZE in DM halos

[**Colafrancesco** 2004, A&A, 422, L23]

A structure with:

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

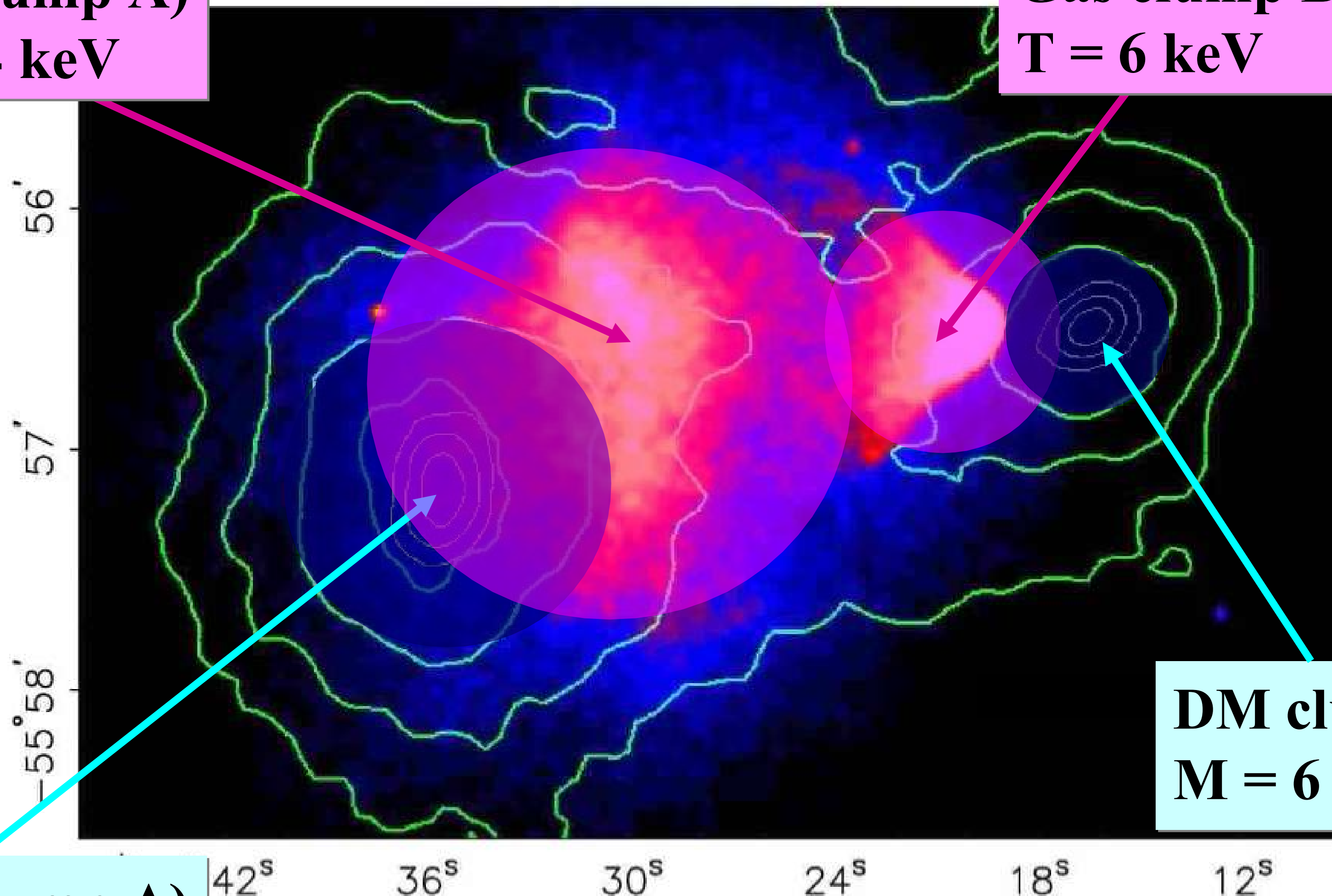
Pure DM halo



The cluster 1ES0657-556

Gas clump A)
T = 14 keV

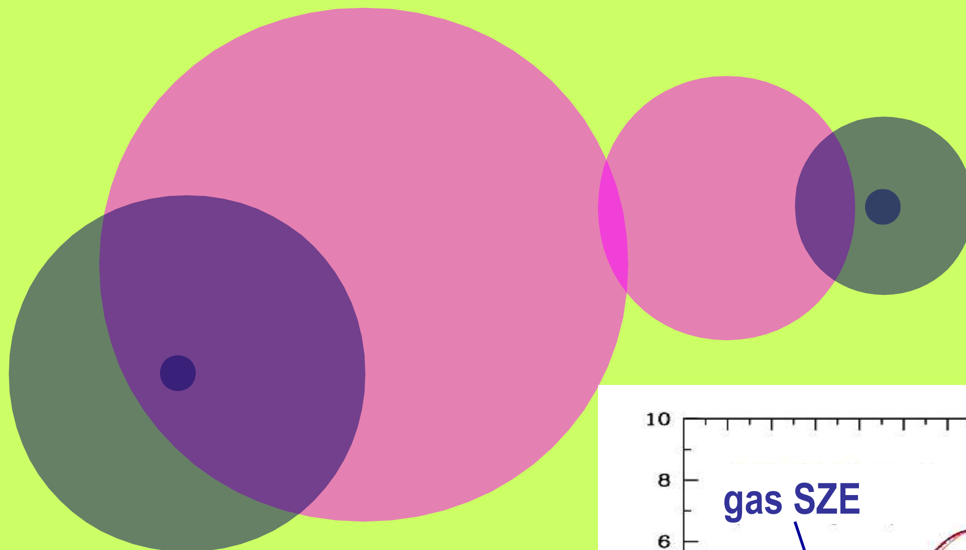
Gas clump B)
T = 6 keV

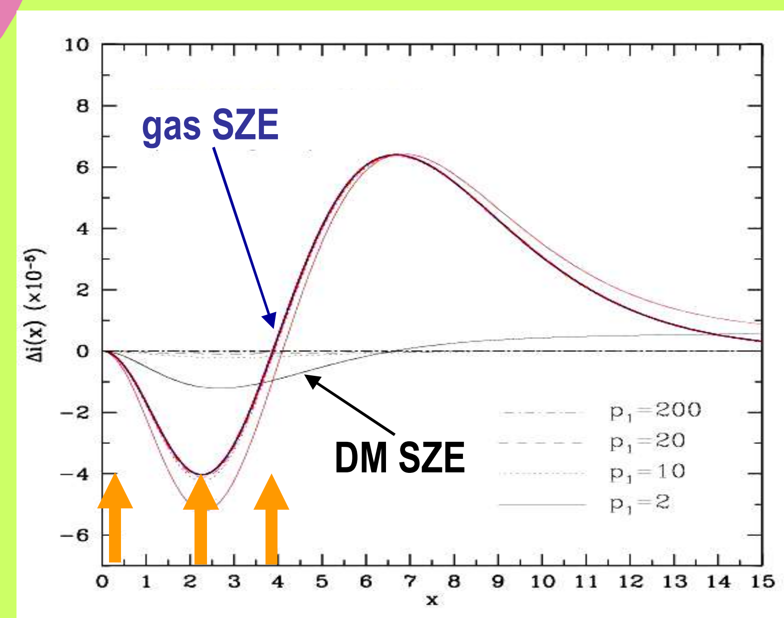


DM clump B)
M = 6 10^{13} $M_{¤}$

DM clump A)
M = 10^{15} $M_{¤}$

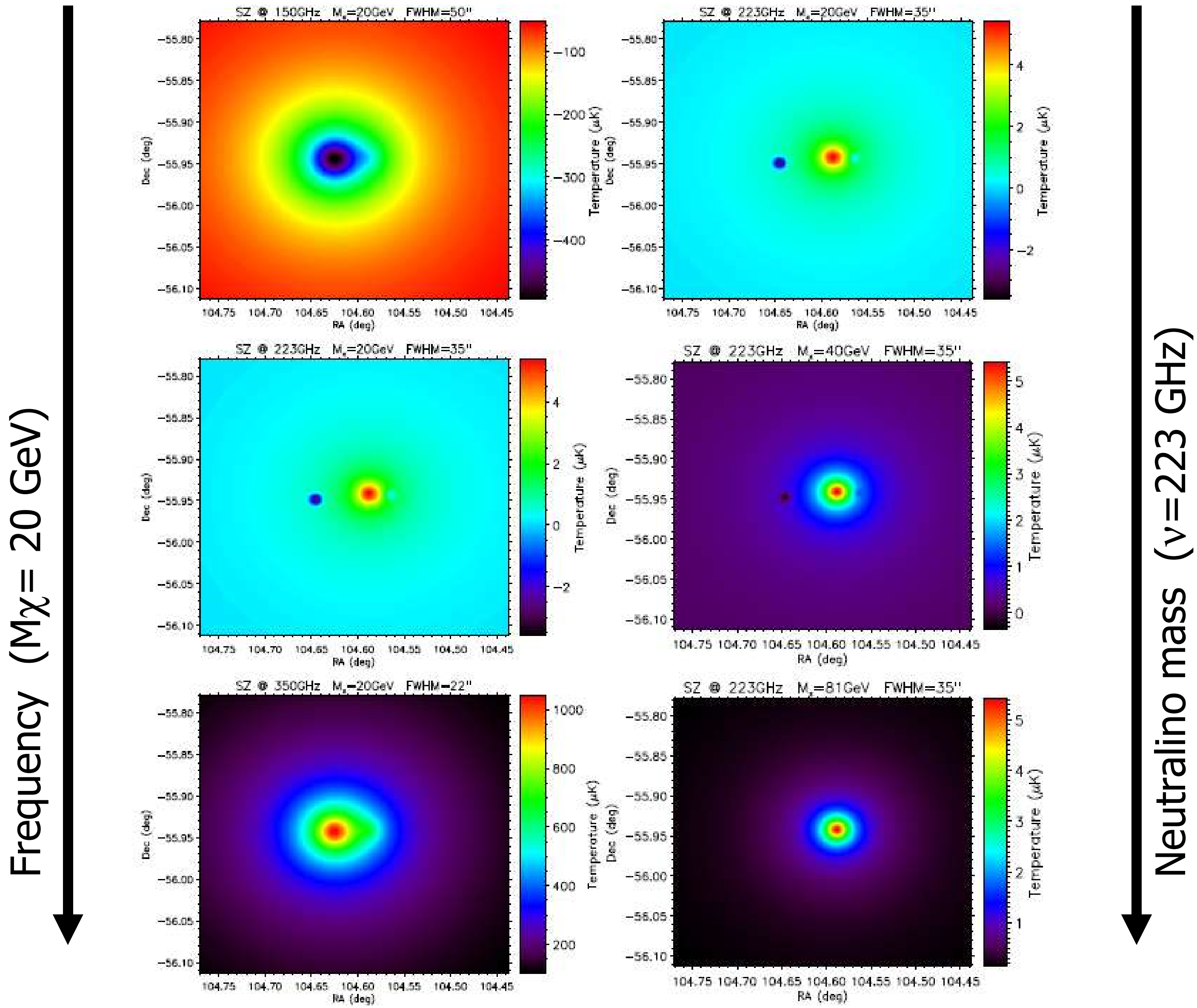
SZE in 1ES0657-556





Isolating SZ_{DM} at ~223 GHz

[**Colafrancesco et al.** 2007]

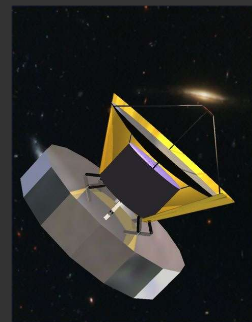


From Olimpo to Millimetron

2010

OLIMPO

?



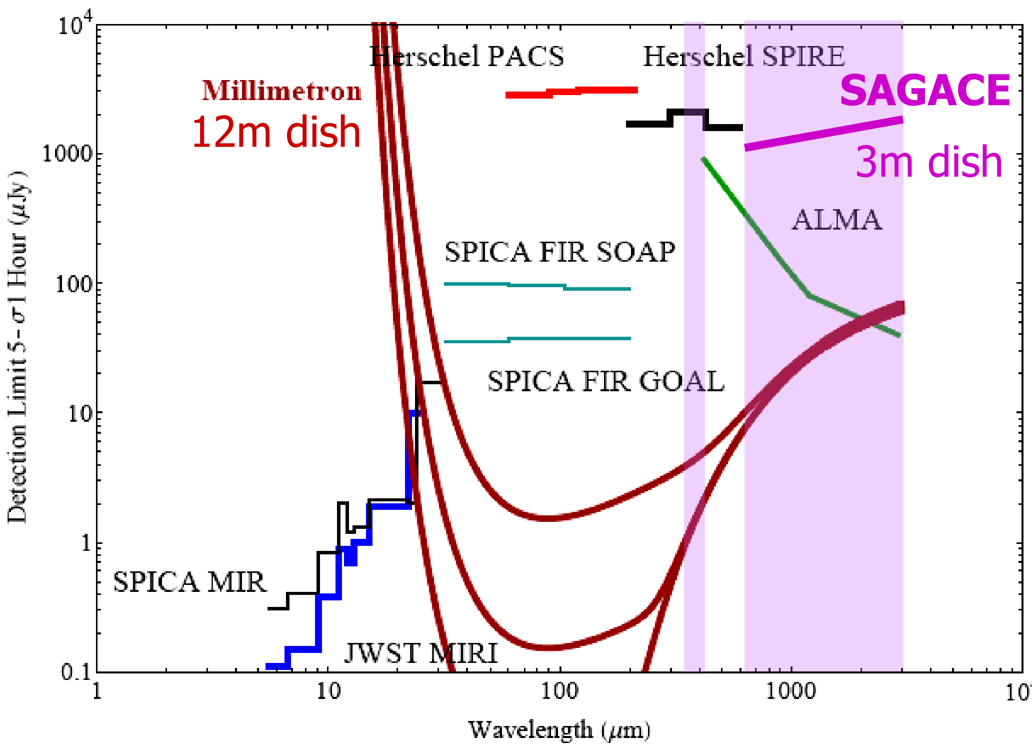
SAGACE

2015

MILLIMETRON

SAGACE

- **3 m dish**
- **Passive cooling**
- **(50 K)**
- **Θ= 0.7-4.2 arcmin**
- **Noise=18 mJy/√Hz**
- **FTS spectroscopy**

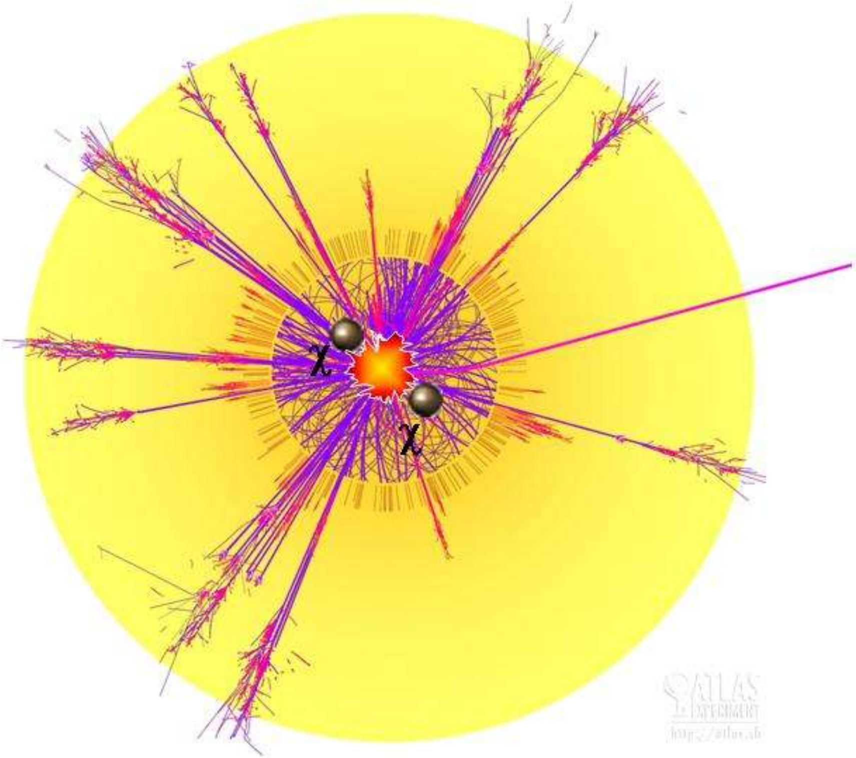


MILLIMETRON

- **12 m dish**
- **Active cooling**
- **(4 K)**
- **Θ< 0.1-1.0 arcmin**
- **Noise<0.6 mJy/√Hz**
- **FTS spectroscopy**
- **Polarimetry**

Other DM options

Neutralino DM: particles

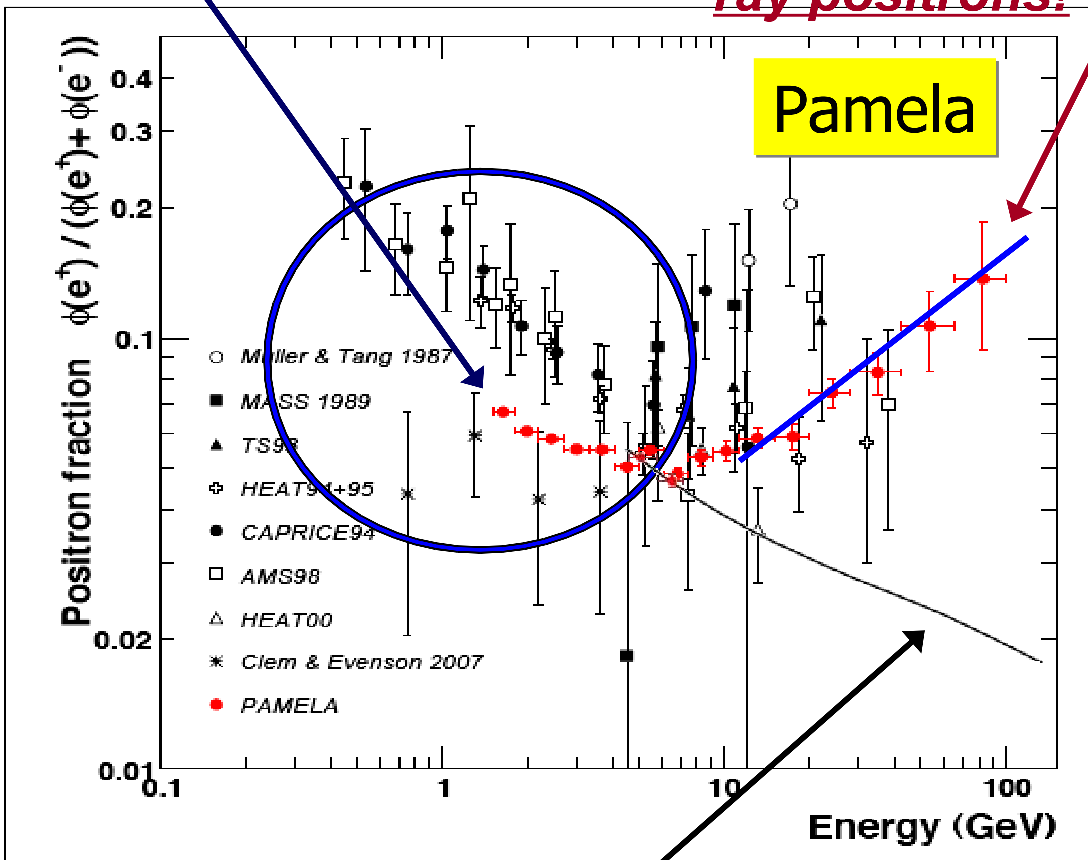


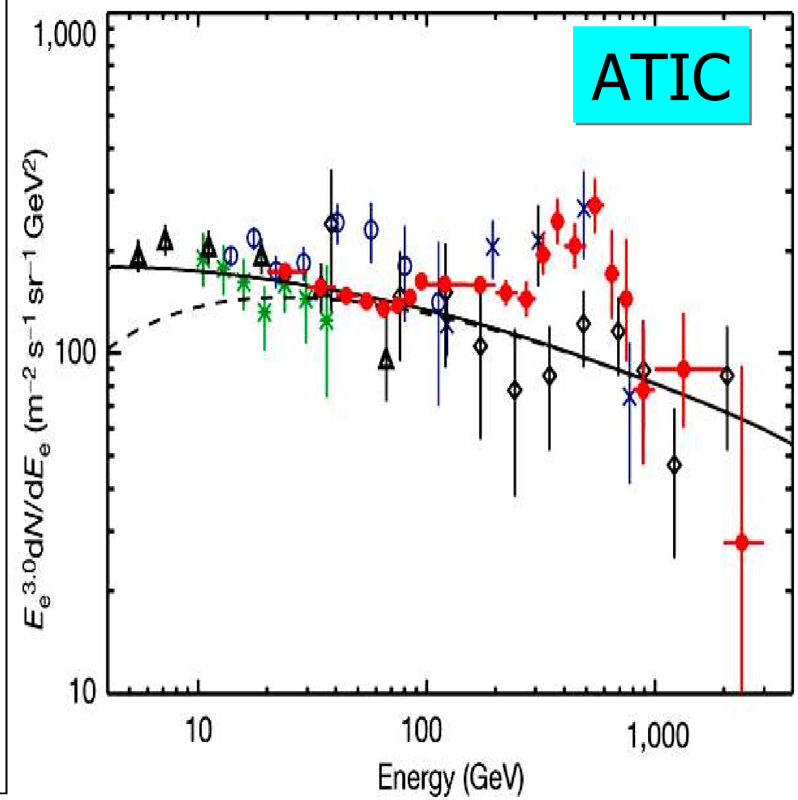
$e^- \ e^+$
$p \ p^-$
...

Pamela and ATIC

Charge-dependent solar modulation important below 5-10 GeV

Rapid climb above 10 GeV indicates the presence of a <u>primary source of cosmic ray positrons!</u>





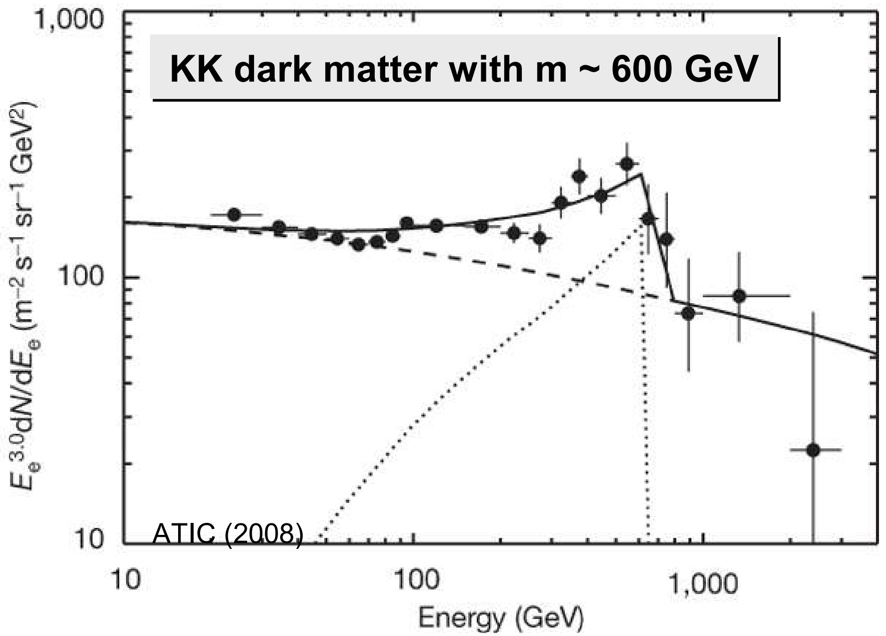
Astrophysical expectation (secondary production)

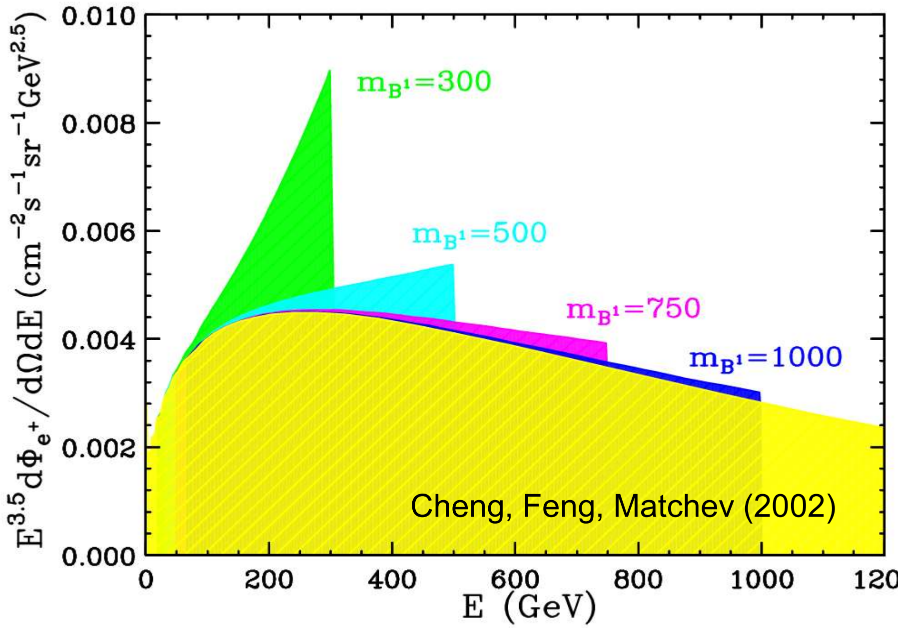
Are these signal from DM?

- Shape consistent with some generic Dark Matter candidates but with:
  - Very hard spectrum
  - large fraction of annihilation to e^+e^-, $\mu^+\mu^-$ or $\tau^+\tau^-$
- Flux is a factor of 100-1000 too big for a thermal relic;

→ requires dramatic enhancement

- Astrophysics
  - More small-scale structure than expected ("boost factor" of ~1000)
  - A narrow diffusion region
  - A large nearby clump of dark matter





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- Shape consistent with some generic Dark Matter candidates but with:
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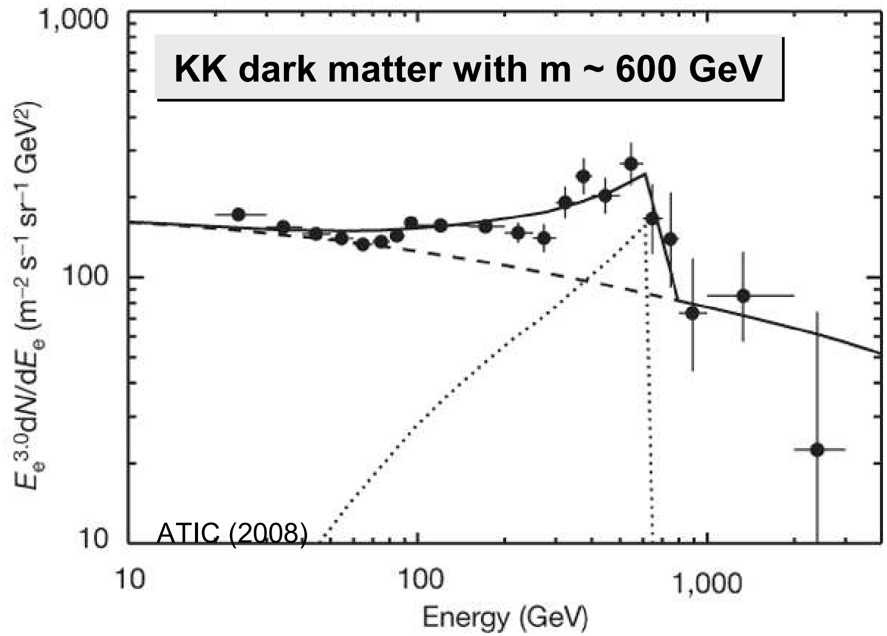
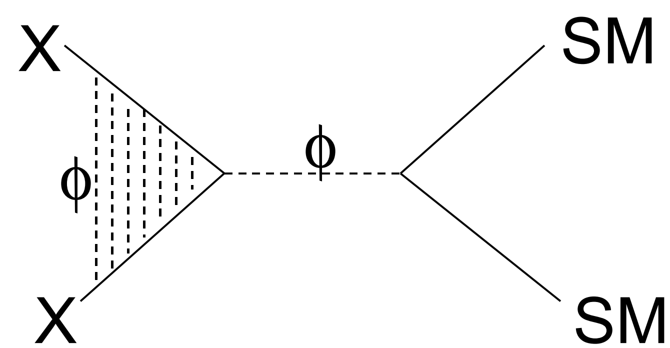
- Flux is a factor of 100-1000 too big for a thermal relic;
  - → requires dramatic enhancement
  - Astrophysics
  - Particle physics
  - non-perturbative effects as the "Sommerfeld Enhancement" important for $m_\phi < m_X$ and $v_X << c$ (such as in the halo, where $v_X/c \sim 10^{-3}$)
- No enhancement seen in anti-protons
- Too many antiprotons, gamma rays, synchrotron, IC emission, …



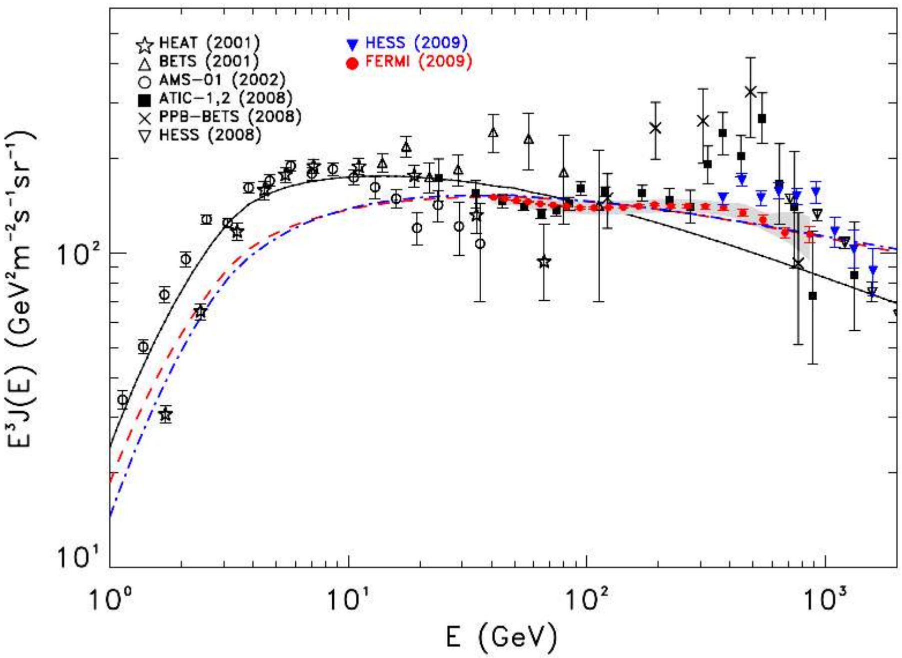


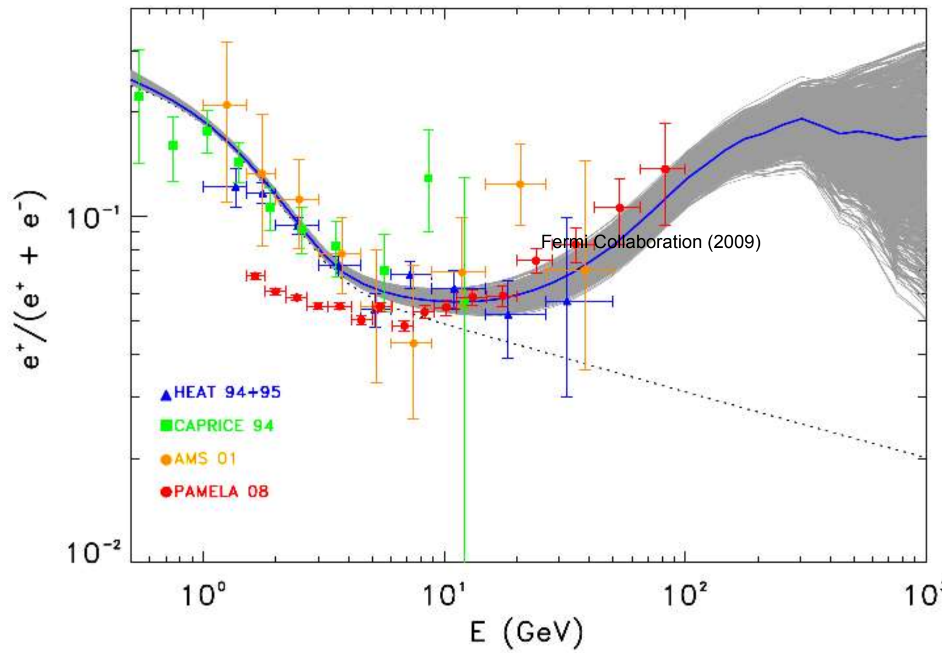
[Arkani-Hamed et al. arXiv:0810.0713; Cirelli and Strumia, arXiv:0808.3867; Fox and Poppitz, arXiv:0811.0399]

HESS and Fermi

Fermi and HESS do not confirm ATIC:
→ consistent with bkgd. expectations

Astrophysics can explain PAMELA:
- **Pulsars**
- **SN remnants**
- **Diffusion effects**





[Zhang, Cheng (2001); Hooper et al. (2008)
Yuksel et al. (2008); Profumo (2008)
Fermi LAT Collaboration (2009)]

ASDC ASI Science Data Center

Neutralino DM: Hidden DM !?!

Experimental Frustration

- No direct evidence (DAMA vs. other underground experiments)
- No photonic signals (only upper limits from Multi-ν (M^3) analysis)
- No particle signal (Pamela → ATIC: embarassing results)

Pause

What do we really know about dark matter?

All solid evidence is gravitational

Also solid evidence *against* strong and EM interactions

@

The anomalies (DAMA, PAMELA, ATIC, …) are not easily explained by canonical WIMPs → go beyond MSSM WIMP model

Return

A reasonable 1^{st} order guess:

Dark Matter has no SM gauge interactions, i.e., it is *hidden*

[Kobsarev, Okun, Pomeranchuk (1966); many others]

[Feng et al. 2009]

Esc

What one seemingly loses:

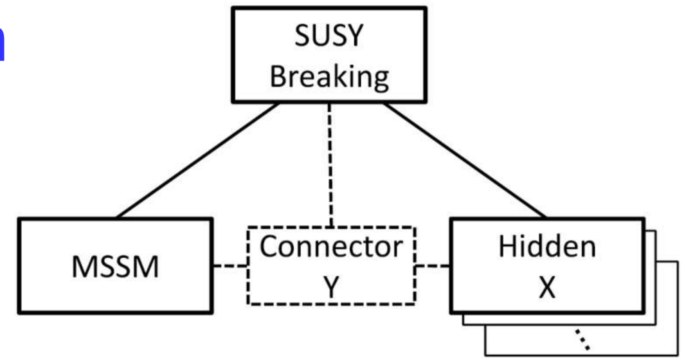
Connection to central problems of particle physics

Non-gravitational signals

The WIMP miracle

Hidden DM signals

Hidden sectors appear generically in SUSY. Each has its own mass scale m_X gauge couplings g_X



Thermal relic density constrains only one combination of g_X and m_X

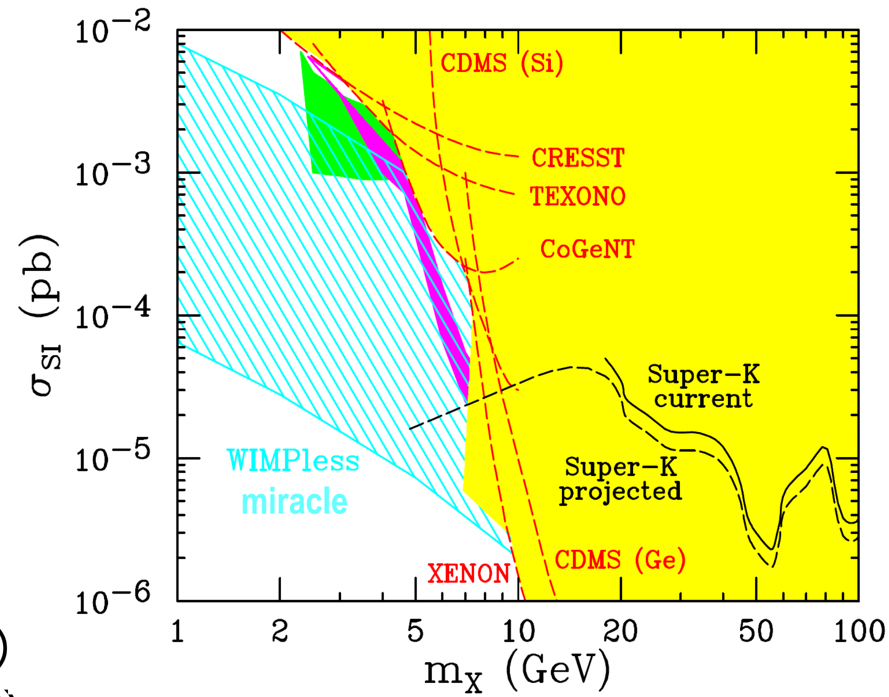
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

Many new, related ideas

Hidden DM may have only gravitational effects, but it may have hidden charge

→ self-interacting DM [Feng et al. 2009]

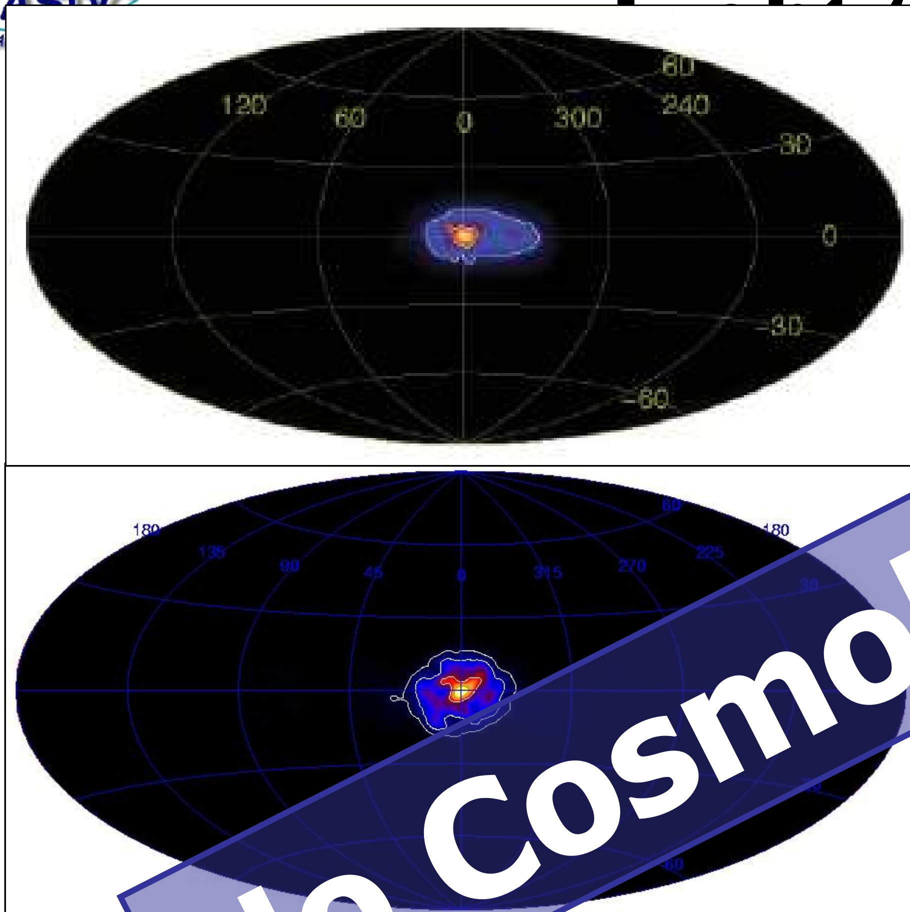
Hidden DM may interact with normal matter through non-gauge interactions



[Feng et al. (2008)]

...... Pospelov, Ritz (2007); Hooper, Zurek (2008)
Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)
Ackerman, Buckley, Carroll, Kamionkowski (2008)

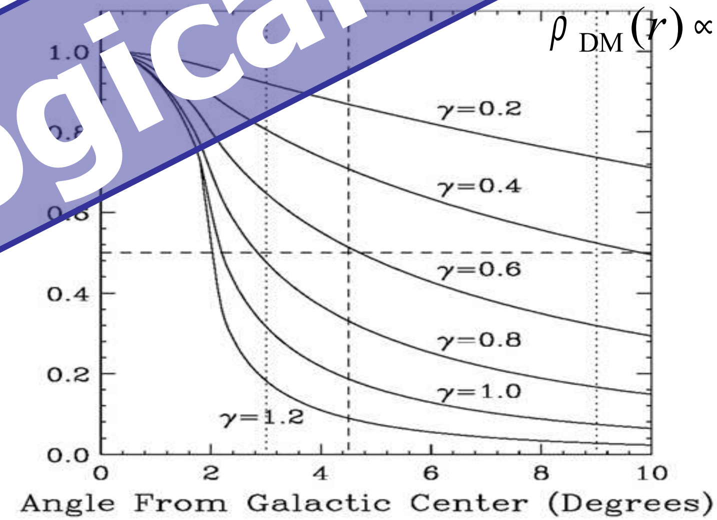
Light (MeV) DM



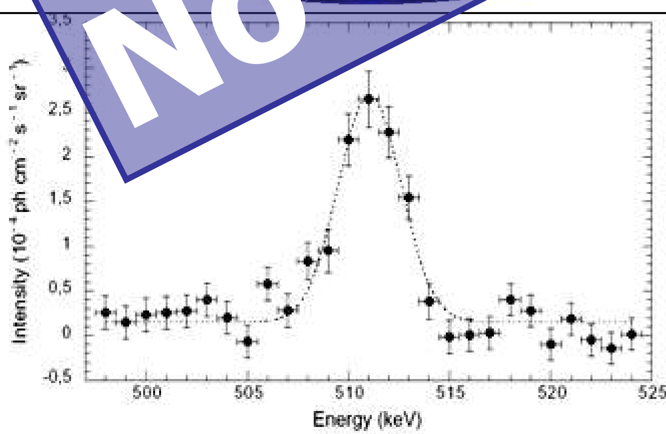
Dark Matter Interpretation

- Light scalar DM particle (M ~ 1-4 MeV)
- Rather flat halo

$$\rho_{DM}(r) \propto \frac{1}{r^{\gamma}}$$



No Cosmological DM

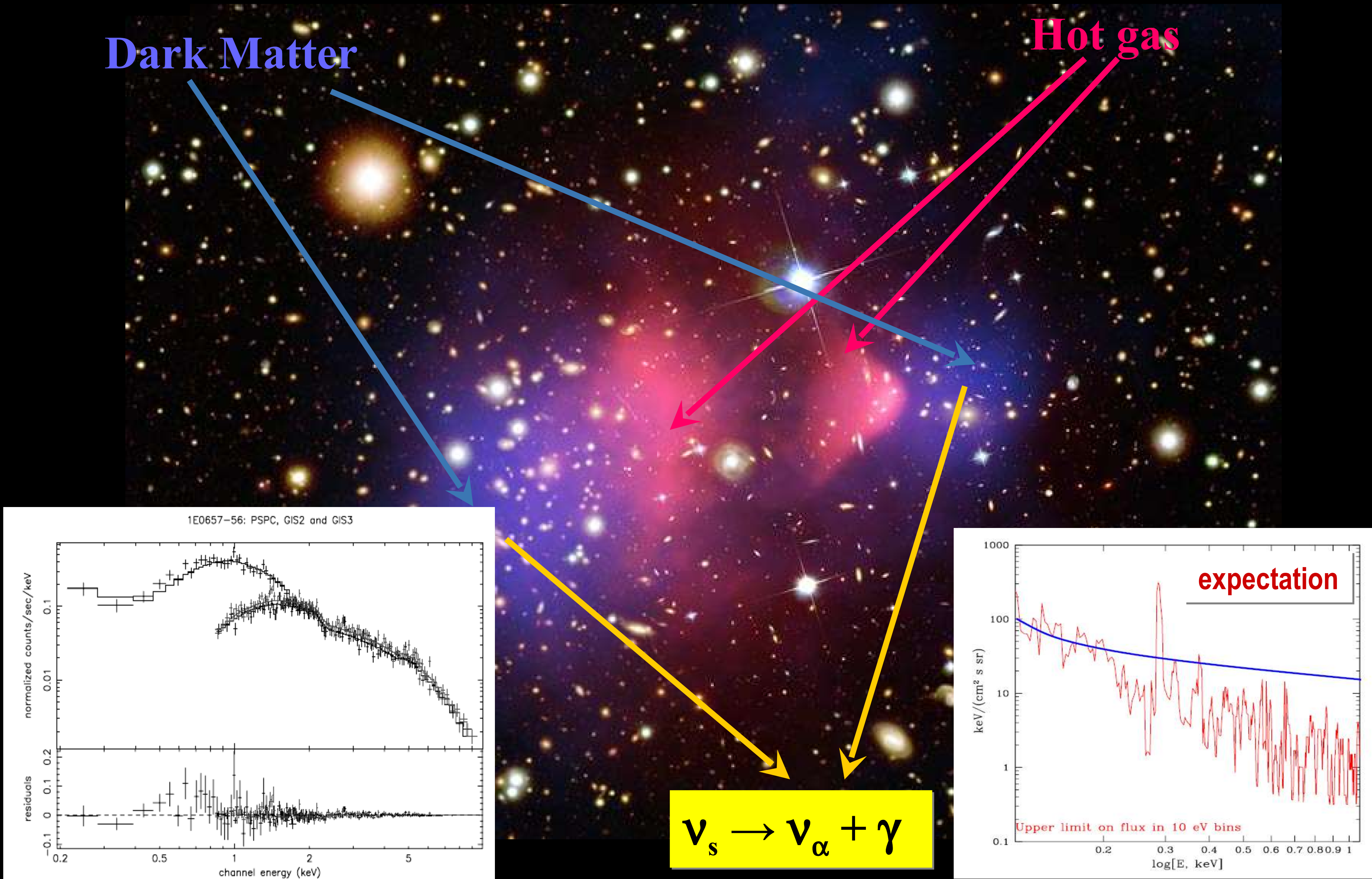


Other Interpretations

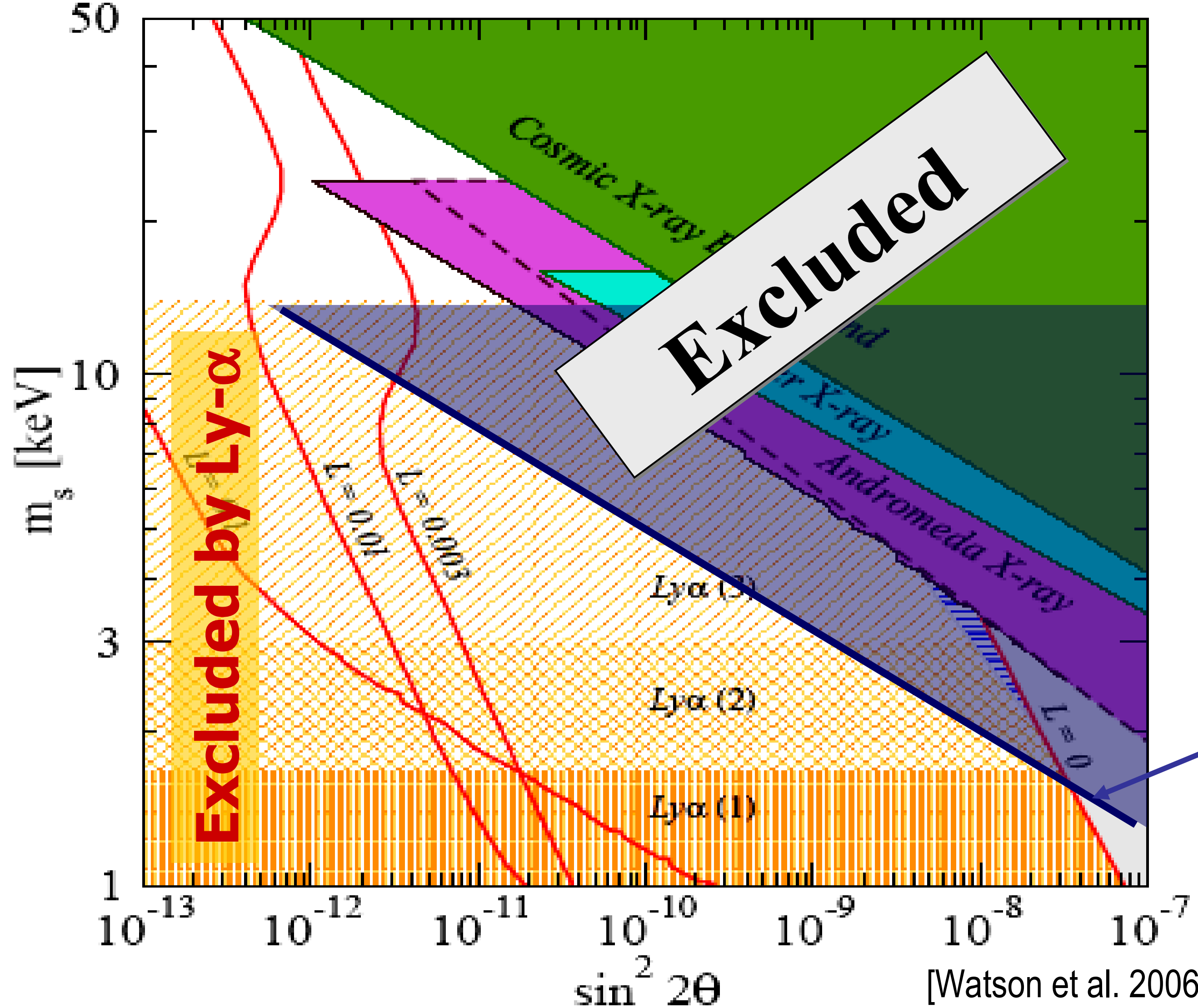
Supernovae
Wolf-Rayet Stars
Neutron stars, pulsars
Cosmic rays
Black holes

Sterile neutrino DM

Sterile neutrino DM: line

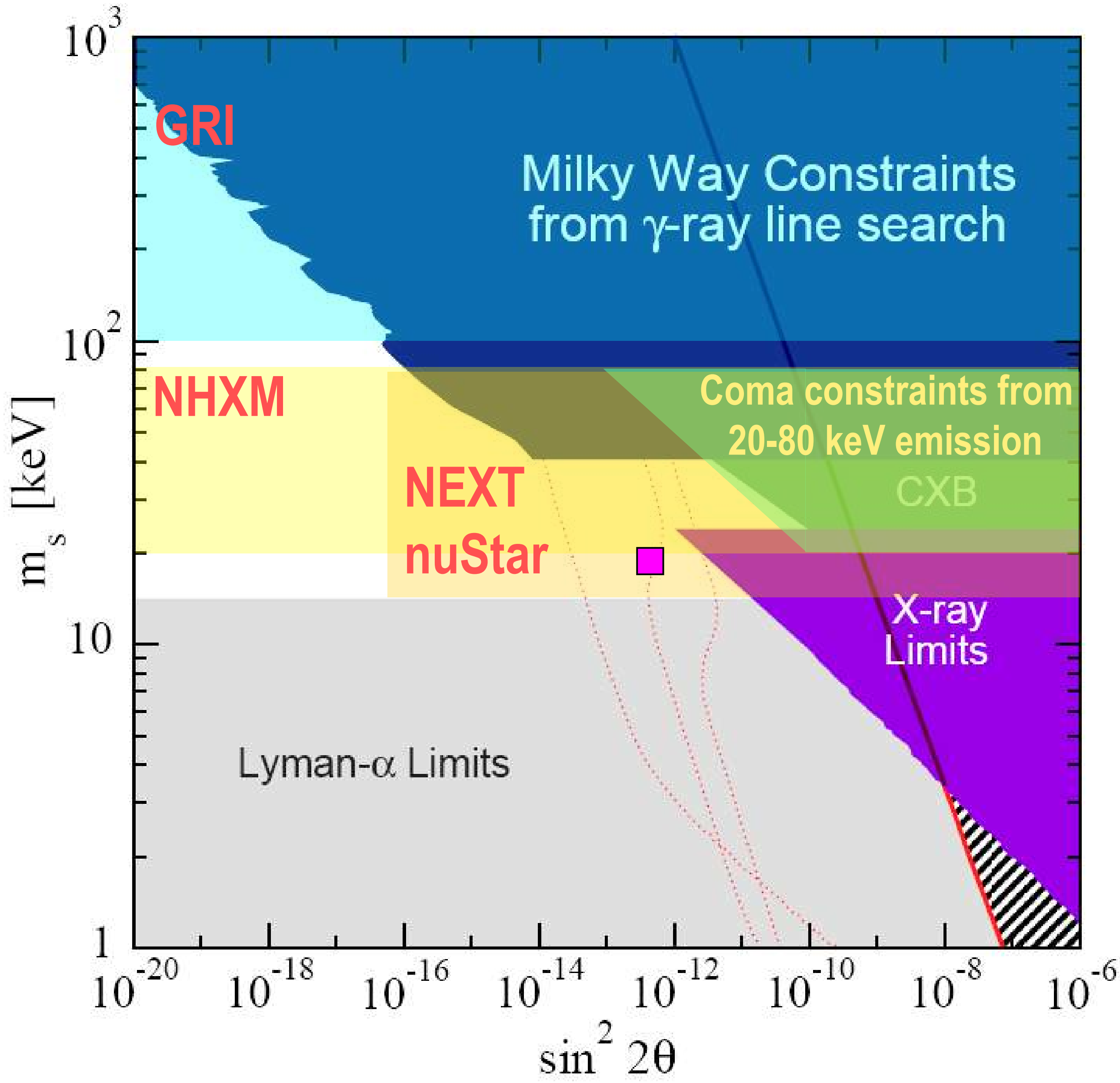


Sterile neutrinos: limits



[Watson et al. 2006 (astro-ph/0605424)]
[Colafrancesco 2007]

[Yuksel et al. 2007]
[Colafrancesco 2007]



Sterile neutrinos and GC lines

Fact:

Excess of the intensity in the 8.7 keV line (at the energy of the FeXXVI Lyγ line) in the spectrum of the Galactic Center observed by the Suzaku X-ray mission.

Not easily explained by standard ionization and recombination processes.

Proposed issue:

the origin of this excess is via decays of sterile neutrinos with $m \sim 17.4$ keV and mixing angle $\sin^2(2\theta) = (4.1 \pm 2.2) \times 10^{-12}$

[Prokhorov & Silk 2010]

But:

- possible non-standard ionization and recombination processes

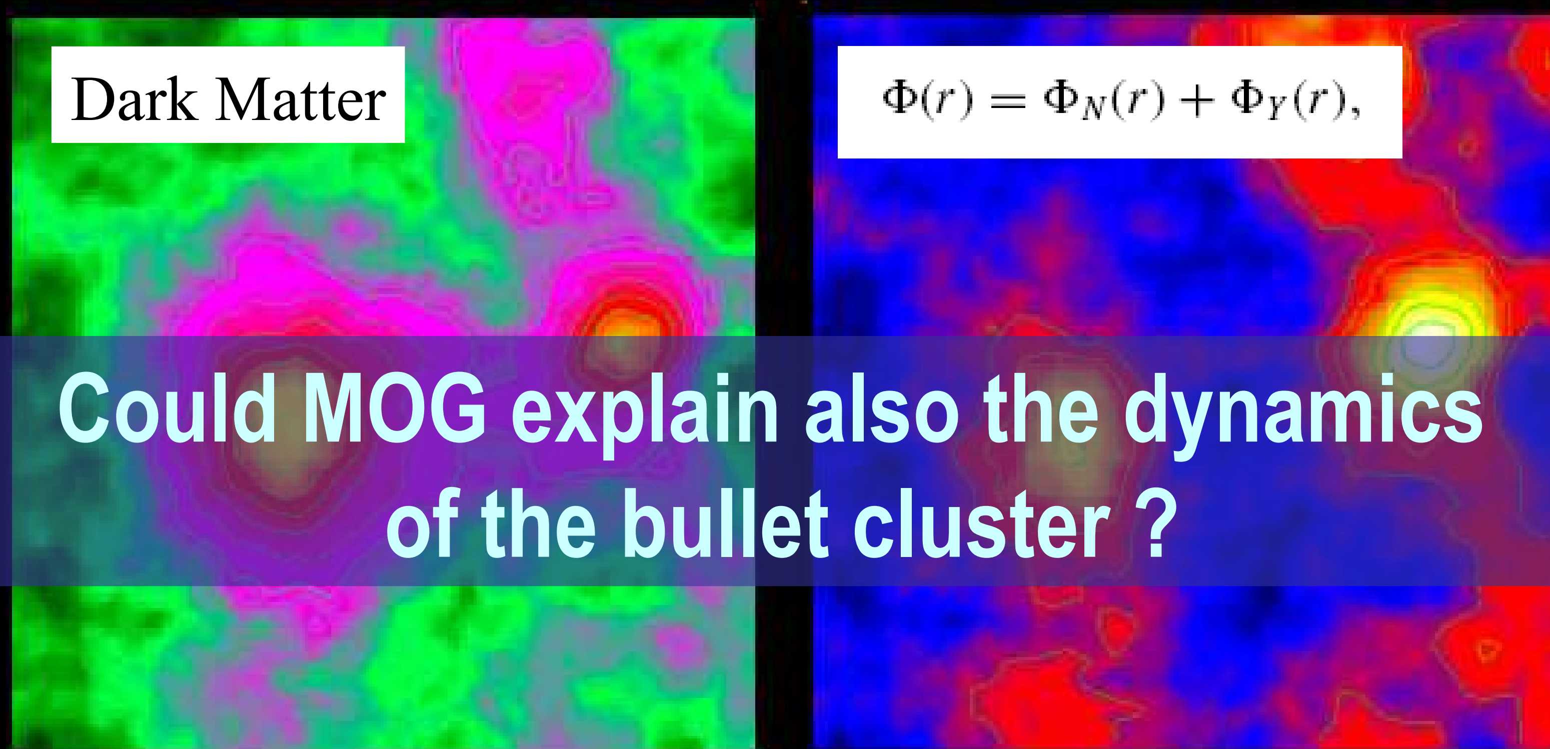
Outline

- Multi-epoch
  - The Dark Matter Timeline
  - The present
- Multi-Scale
  - DM search at various astronomical scales
    - Galactic center
    - Galactic structures
    - Galaxy Clusters
- The Future
  - The DM search challenge

… some conclusions

- Astrophysical (e.m.) search is a crucial probe for the DM nature.
- Multi$^{3-4}$ search in optimal astrophysical laboratories is the key issue but is challenging.
- The temptation to explain every astrophysical anomaly as due to DM is pushing DM search towards a fundamentalist approach rather than to search for the its fundamental nature.
- The possible lack of DM evidence should be considered positively as the necessity to explore in further details the basic laws of the Universe
  - → Gravity field modification on cosmological scales…

DM … or Modified Gravity !?!



Could MOG explain also the dynamics of the bullet cluster ?

J. Moffat says, "If the multi-billion dollar laboratory experiments now underway succeed in directly detecting dark matter, then I will be happy to see Einstein and Newtonian gravity retained. However, if dark matter is not detected and we have to conclude that it does not exist, then Einstein and Newtonian gravity must be modified to fit the extensive amount of astronomical and cosmological data, such as the bullet cluster, that cannot otherwise be explained.

DM

G

THANKS

for your attention !