Astro
Particle
Cosmology

OAR Roma

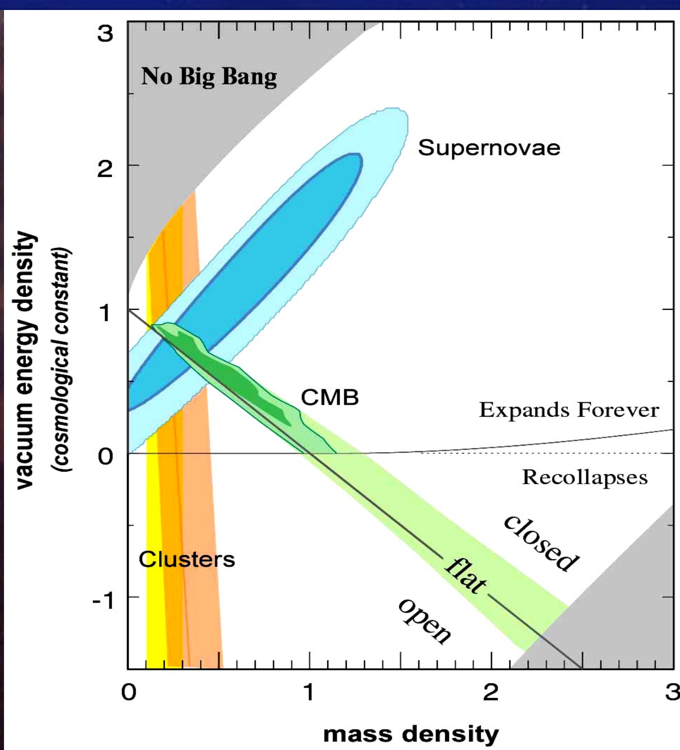
INAF

What an Astrophysicist can tell about the nature of Dark Matter ?

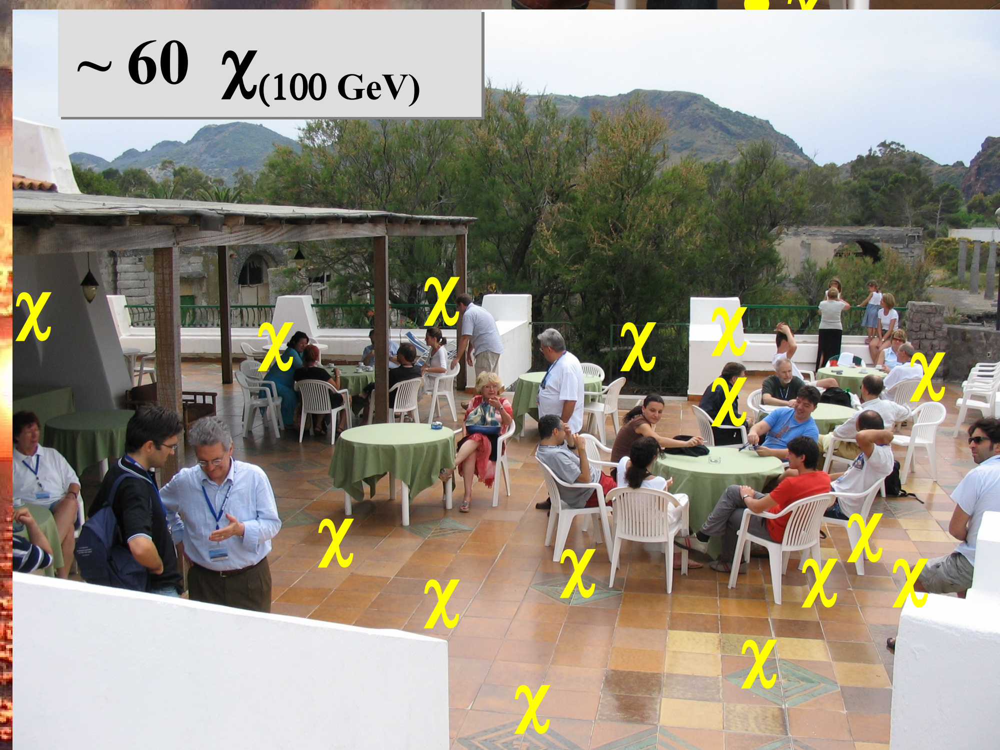
Sergio Colafrancesco
INAF - Osservatorio Astronomico di Roma
INFN – Roma *Tor Vergata*
Email: Sergio.Colafrancesco@mporzio.astro.it

DM is everywhere !

$\sim 3\ \chi_{(1\ \mathrm{GeV})}\ \mathrm{m}^{-3}$



$\sim 60\ \ \chi_{(100\ \mathrm{GeV})}$



Questions

Dark Matter

What is it ?   How many components ?

Can we detect it directly ? …or indirectly ?

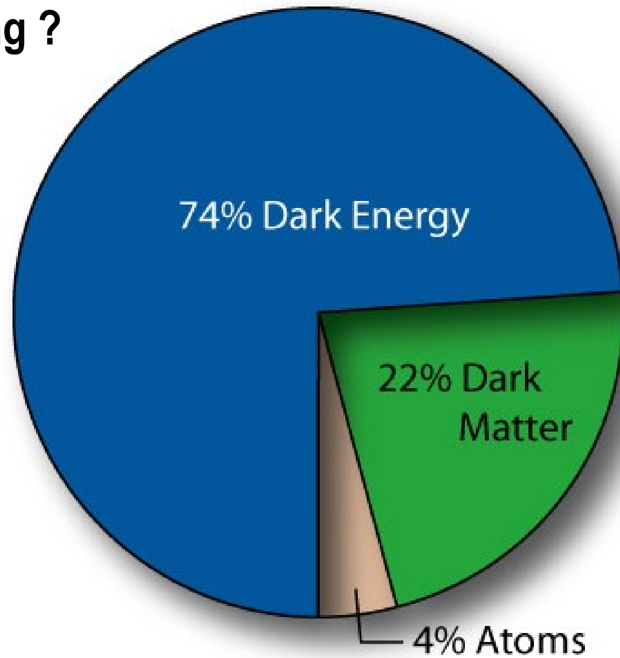
… or make it in the lab ?

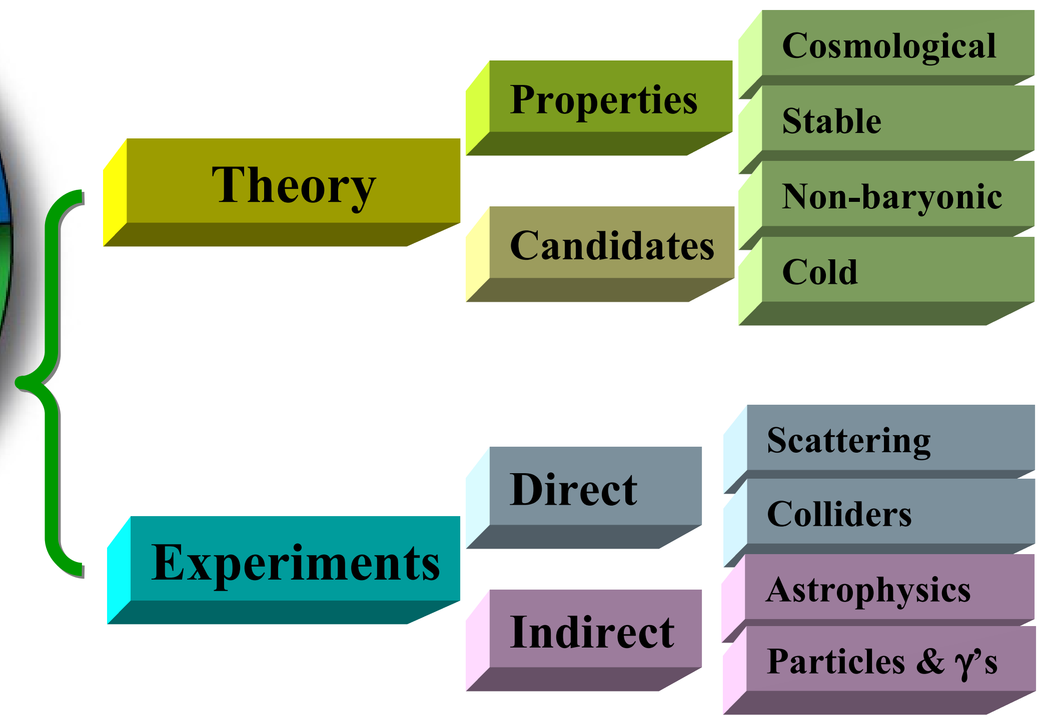
Dark Energy

What is it ?

Is it evolving ?

Why now ?





Ordinary Matter

Where are there more baryons than antibaryons?

Why comparable to the dark matter density?

DM properties: 5 basic

Dark Matter

Dissipationless	Very weak e.m. interactions no radiative cooling
Collisionless	DM self-interaction only at high ρ and short relative D
Cold	M_X > 1 keV thermal M_X smaller non-thermal
Fluid	No DM discreteness on galactic scales
Classical	DM confined on galactic scales

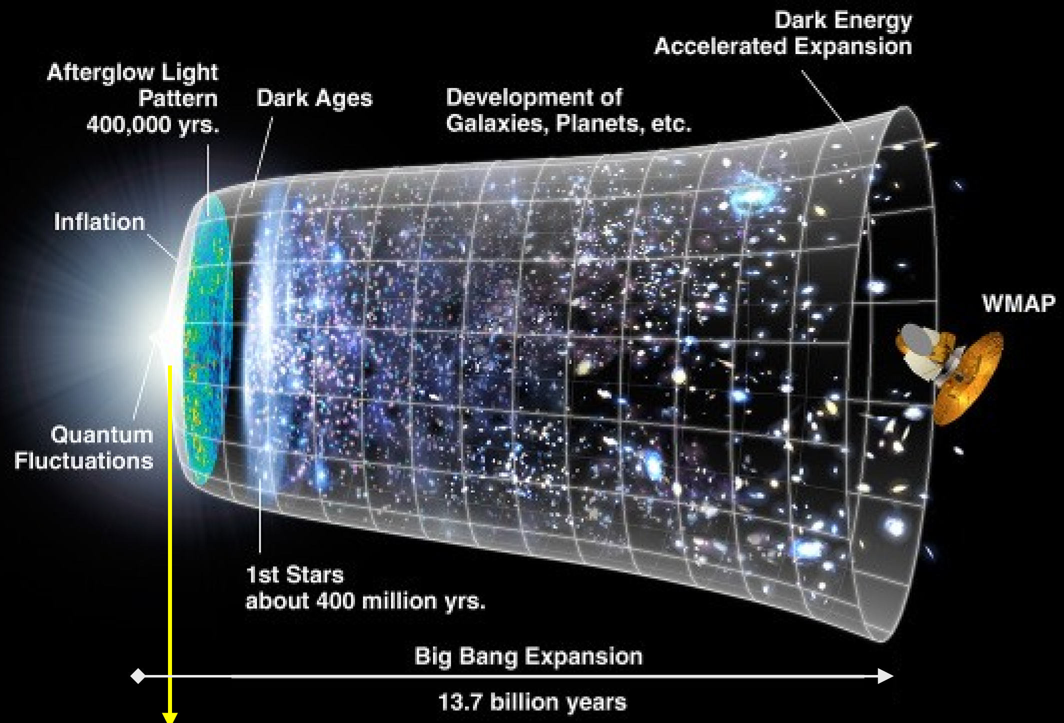
No constraint on the space of possibilities

Upper bound
$$M_X \lesssim 10^{70-71} eV$$

Lower bound
$$M_{X,boson} \gtrsim 10^{-22} eV$$

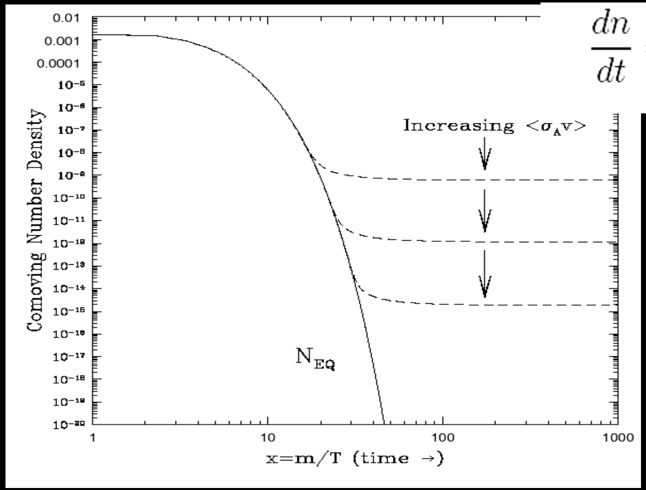
[see Baltz 2005 for a review]

DM relic density



WIMPs
in thermal equilibrium

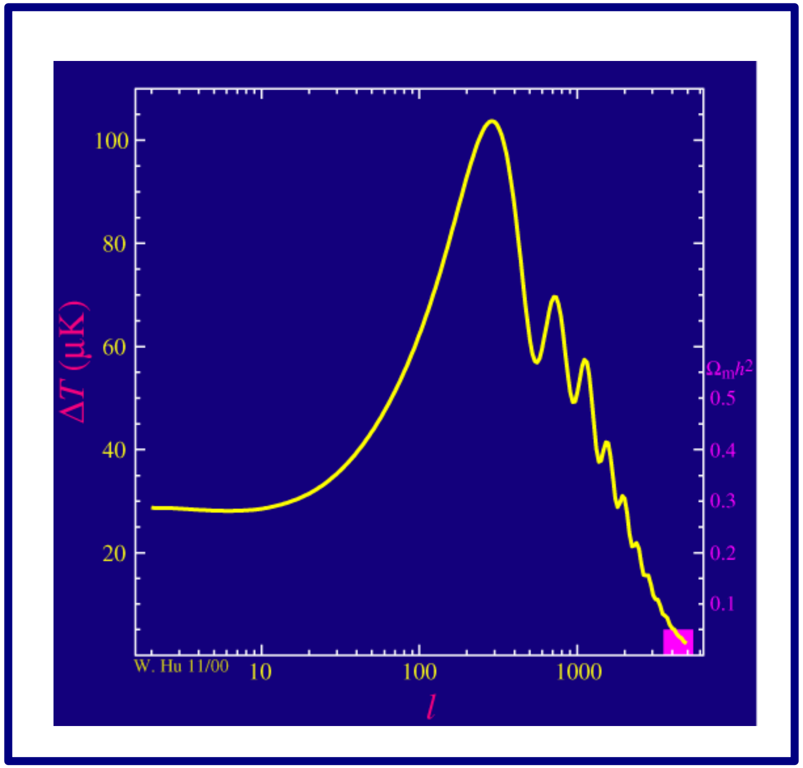
Freeze-out



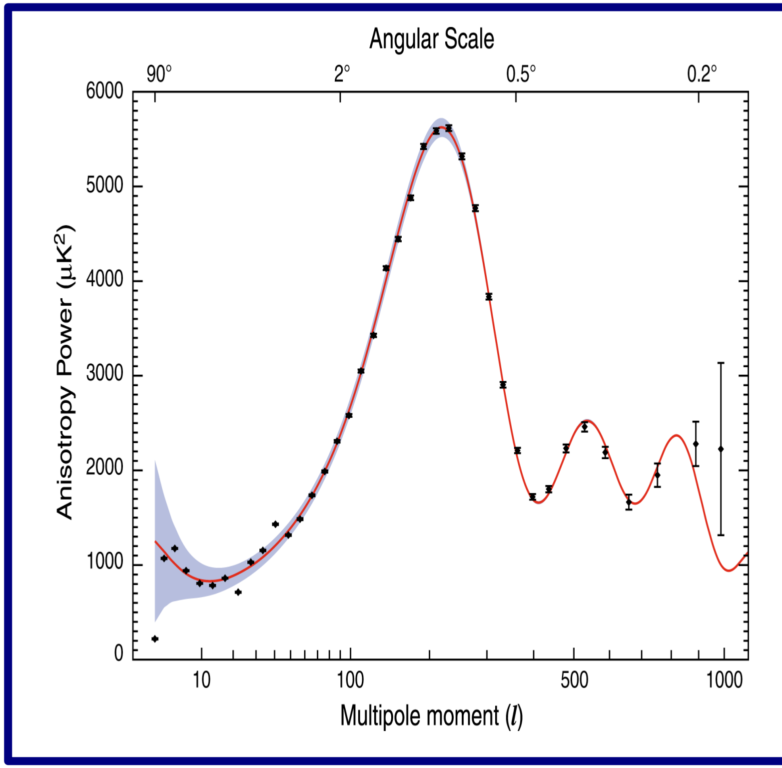
$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

DM & CMB

Generic ΛCDM



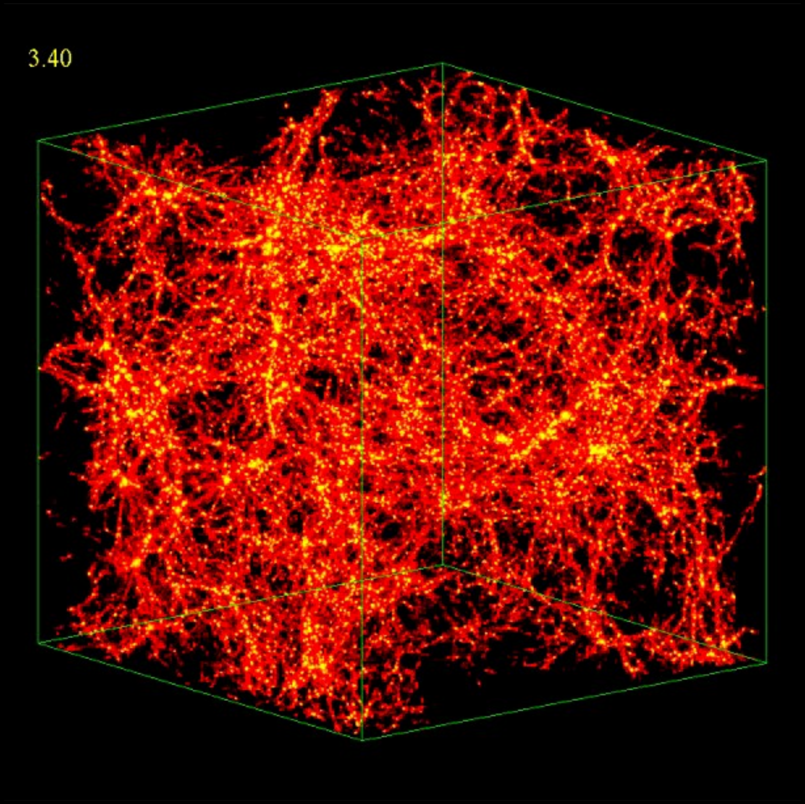
WMAP 3yr



$$0.094 \leq \Omega_{DM} h^2 \leq 0.112$$

$$0.19 \leq \Omega_{DM} \leq 0.22$$

Formation of DM halos



Do we have good DM candidate?

DM candidates

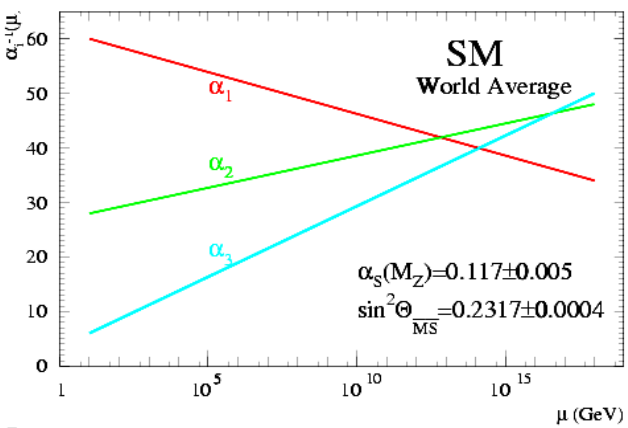
Dark Matter

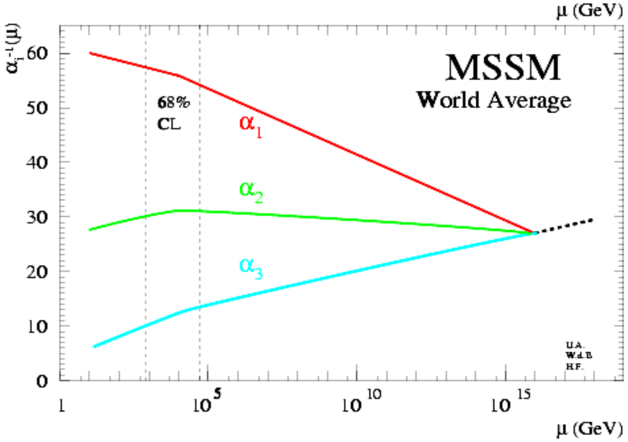
Candidate	Properties
"Fuzzy" CDM	Lower possible end of CDM Bosons with $M \sim 10^{-22}$ eV
Chaplygin Gas	DM-DE common origin $P = -A / \rho$
Axions	Non-thermal production μ eV < M_{axion} < m eV Experimental limits
Neutrinos	Warm DM $0.0005 < \Omega_\nu h^2 < 0.0076$ Massive neutrinos acceptable Sterile ν with $m_\nu \sim$ 10-100 keV
Light (MeV) DM	Spin = 0 supersymmetric particle 1 MeV < M_{LDM} < 4 MeV Elusive: only $e^\pm$ 511 keV line
SUSY DM	Gravitinos Neutralinos Sneutrinos Axinos Q-balls Split-SUSY
Extra dimension	Kaluza-Klein excitations L-KK (r-parity) particle: stable $M_{KK} \sim 1$ TeV
Branons	String theory brane fluctuations M_{branon} > 100 GeV
Mirror Matter	Ordinary matter in mirror world Dissipative & complex chemics
WIMPzillas	Produced at the end of Inflation $M > 10^{13}$ GeV
PBHs	BHs @ quark-hadron transition $M_{PBH} \sim M_{horizon}(T=10^2 MeV) > M_{\odot}$

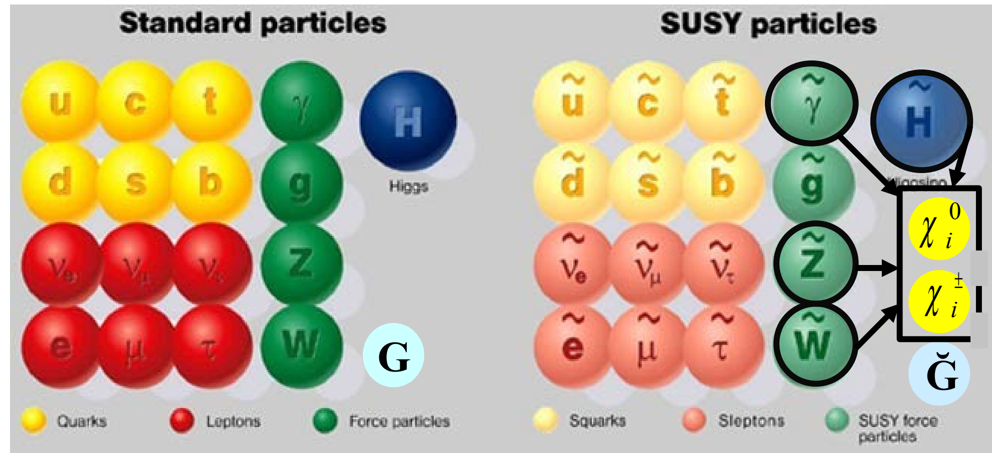
M_{WIMP}

SUSY & DM

Measured coupling constants unify at GUT scale in SUSY but not in SM







SUSY DM

- Gravitinos
- Neutralinos
- Sneutrinos
- Axinos
- Q-balls
- Split-SUSY

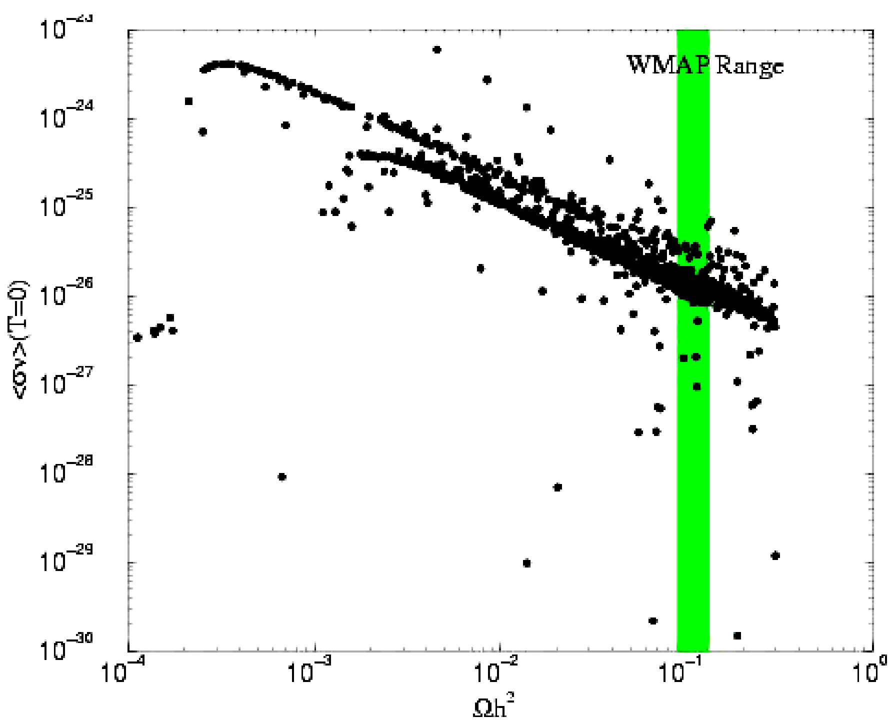
Neutralino χ: $\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$

Cosmological abundance

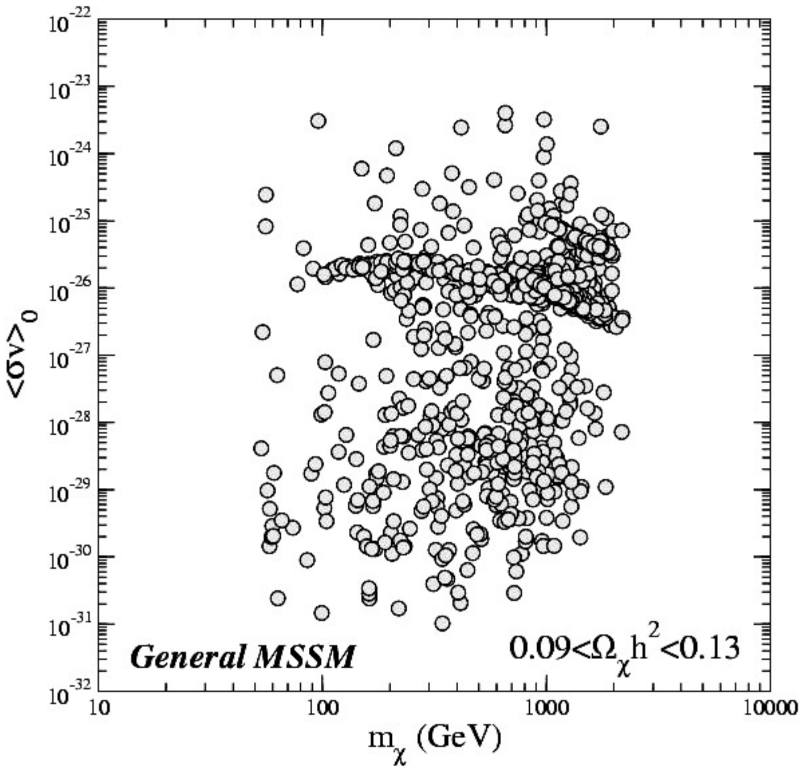
$$\Omega_\chi h^2 \approx \frac{3 \cdot 10^{-27} cm^{-3} s^{-1}}{\langle \sigma V \rangle_A}$$

[Jungman et al. 1996]

$$0.09 \leq \Omega_{DM} h^2 \leq 0.13$$ **WMAP**



Annihilation cross section

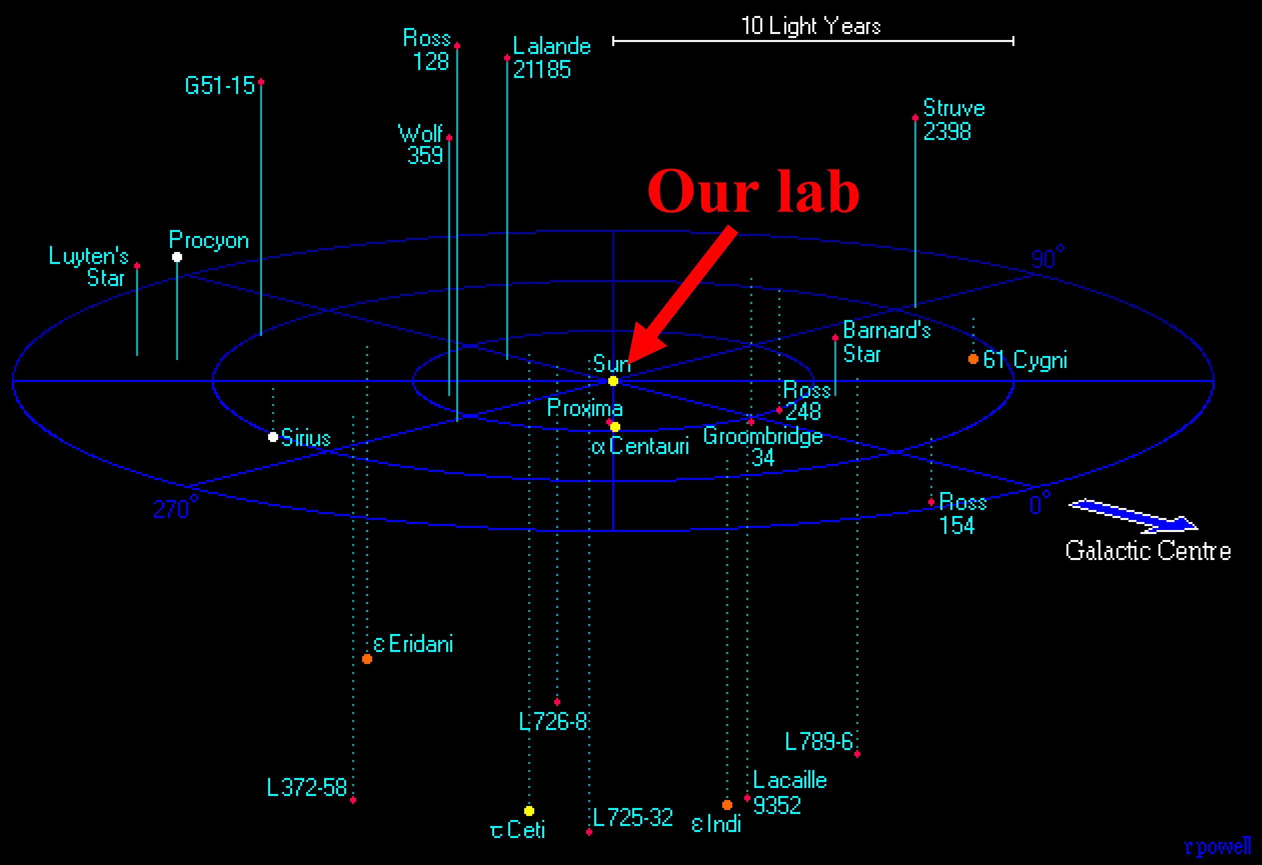


Neutralino composition

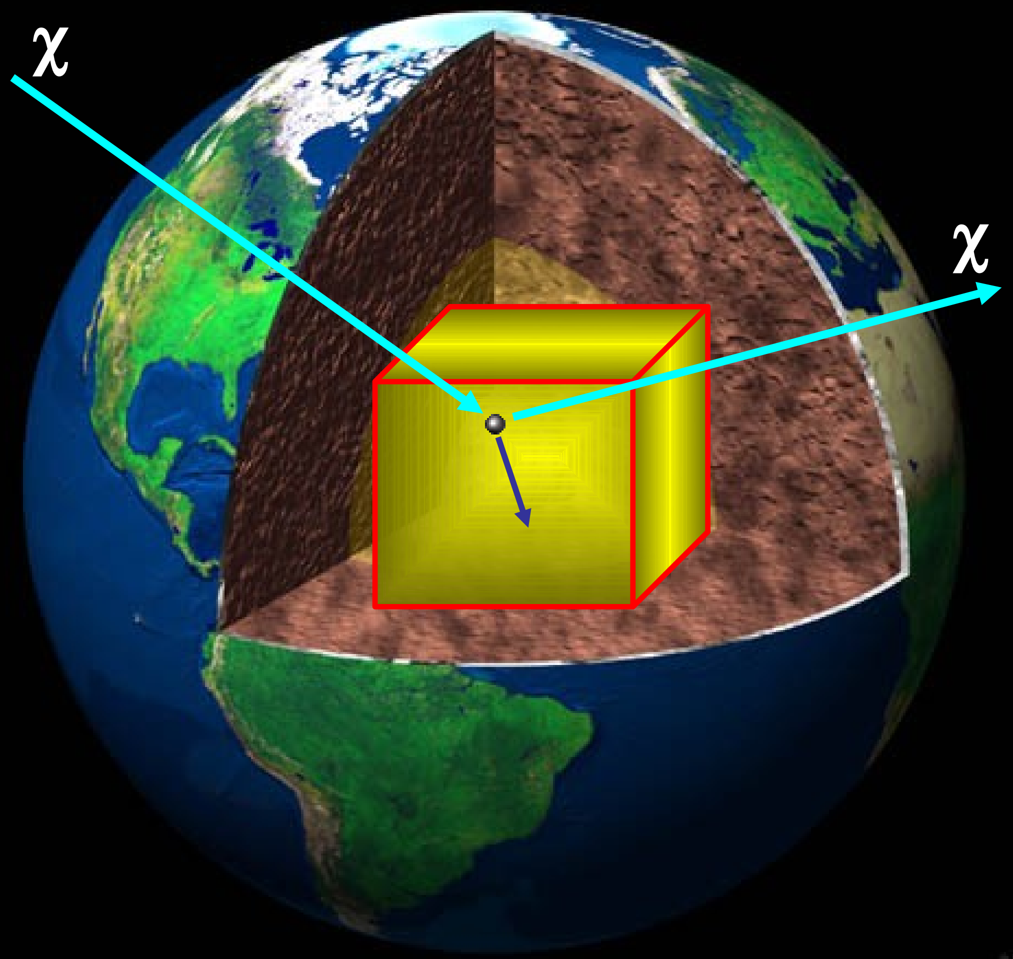
$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

Can we detect the neutralino ?

DM search: direct

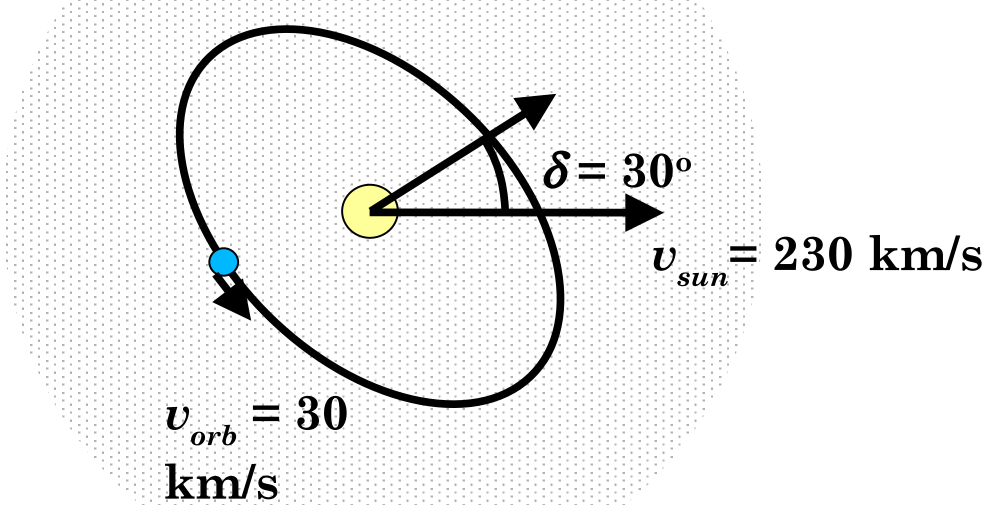


DM direct search

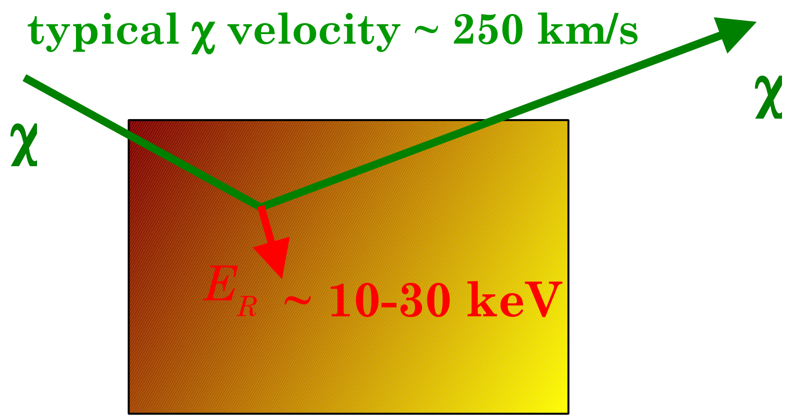


DM search in the labs.

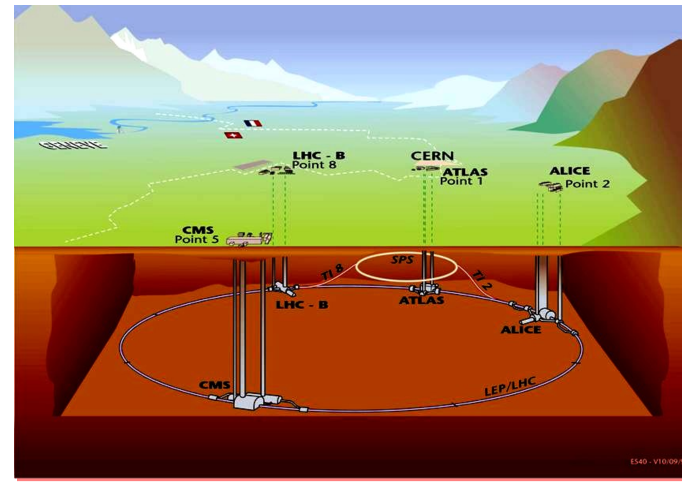
Direct detection

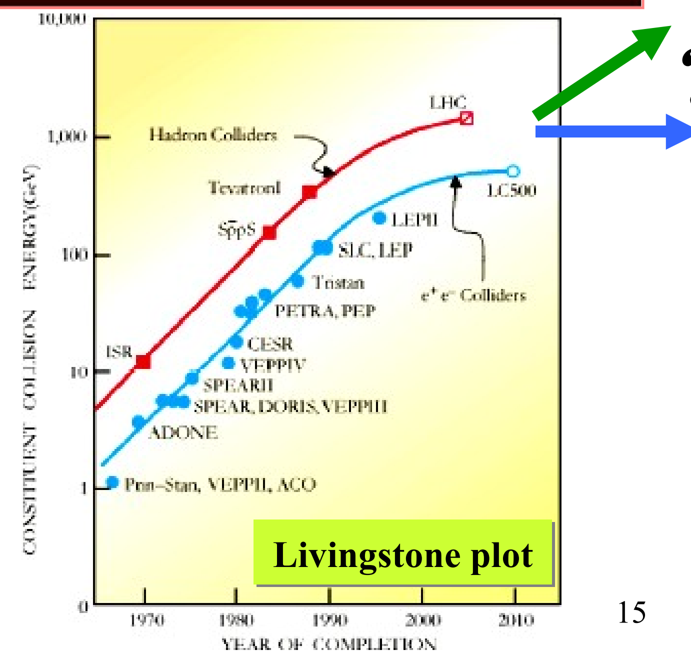


Elastic interaction on nucleus,
typical χ velocity ~ 250 km/s



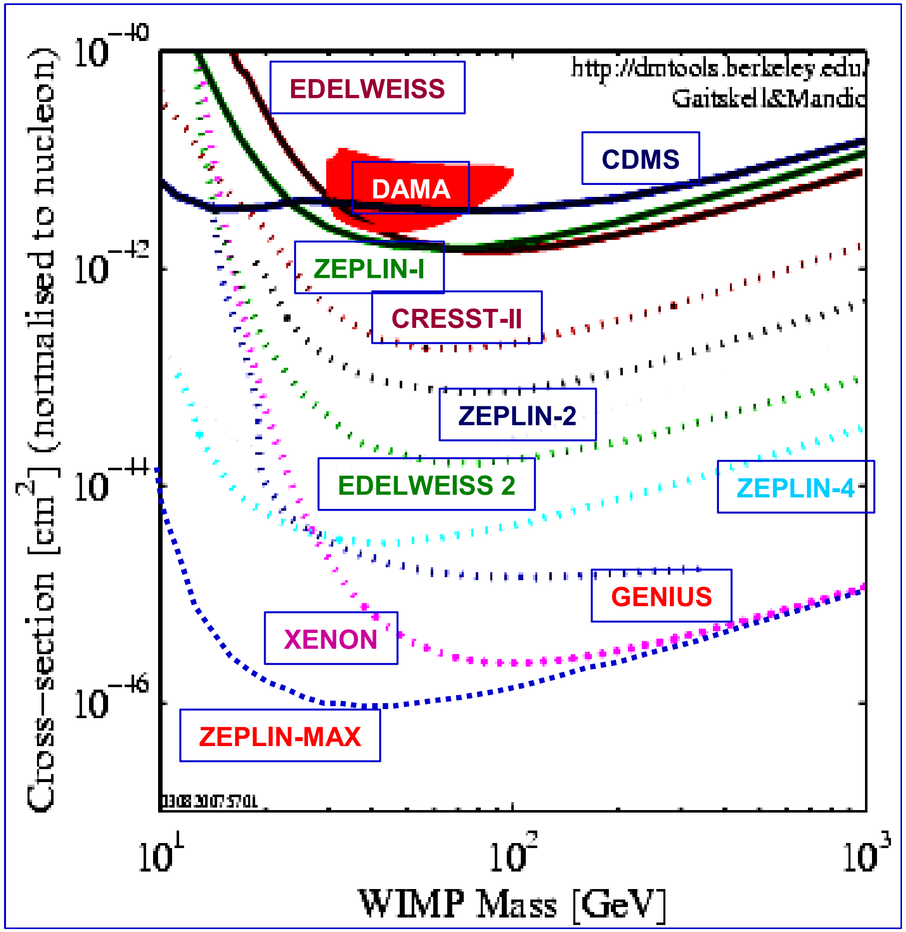
SUSY @ colliders

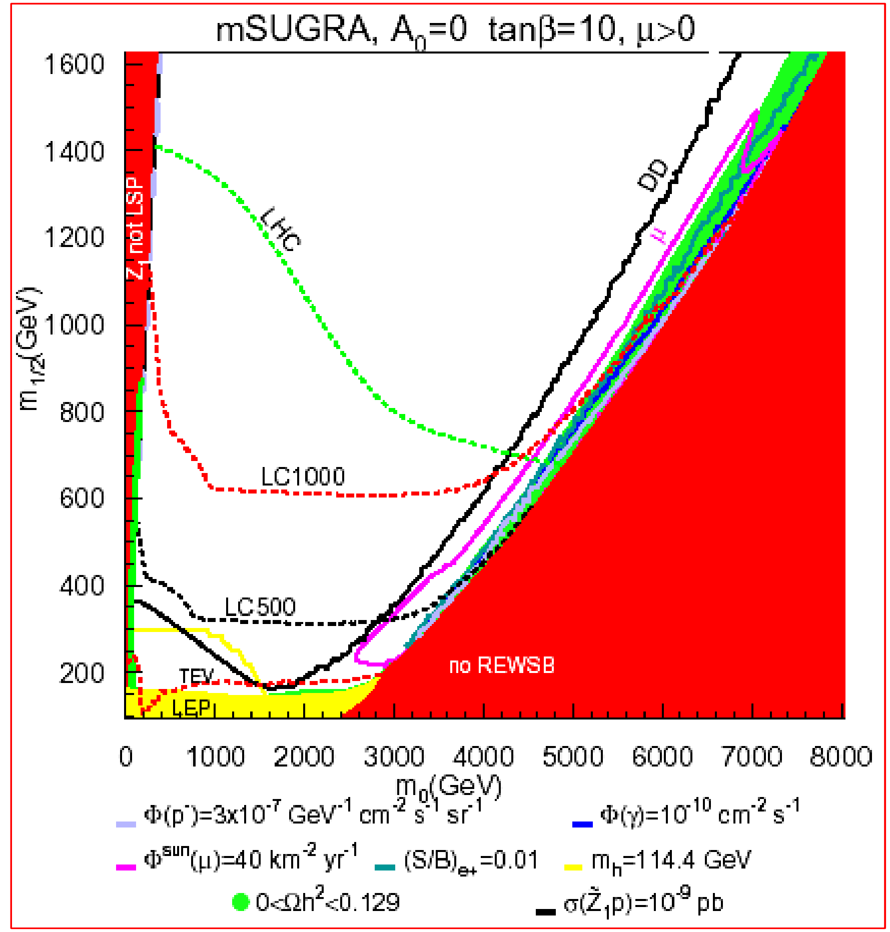




DM direct search: results

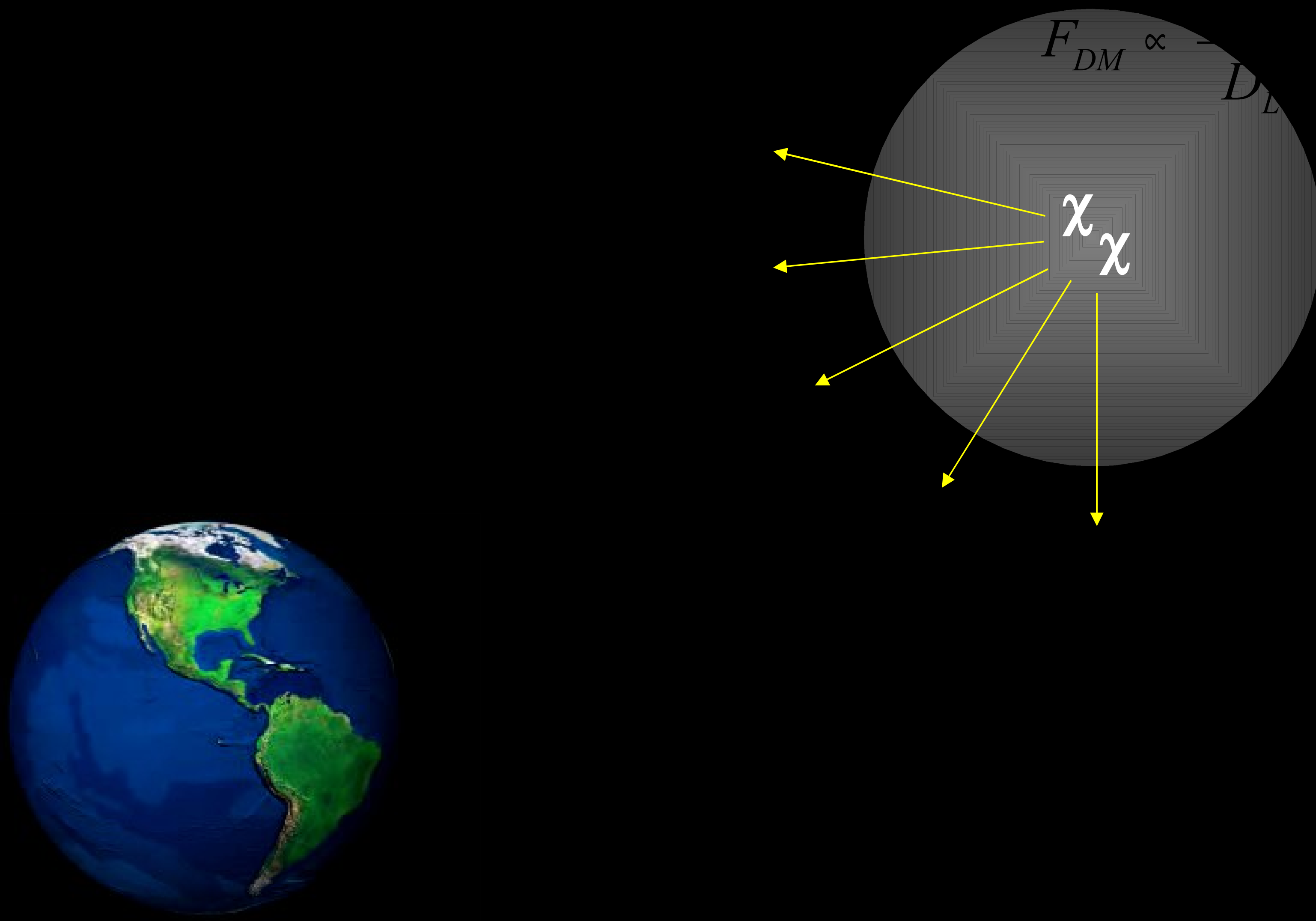
[James Pinfold - ISMD 2005]





… Rita Bernabei's Talk

DM indirect search



DM search in Cosmic Structures

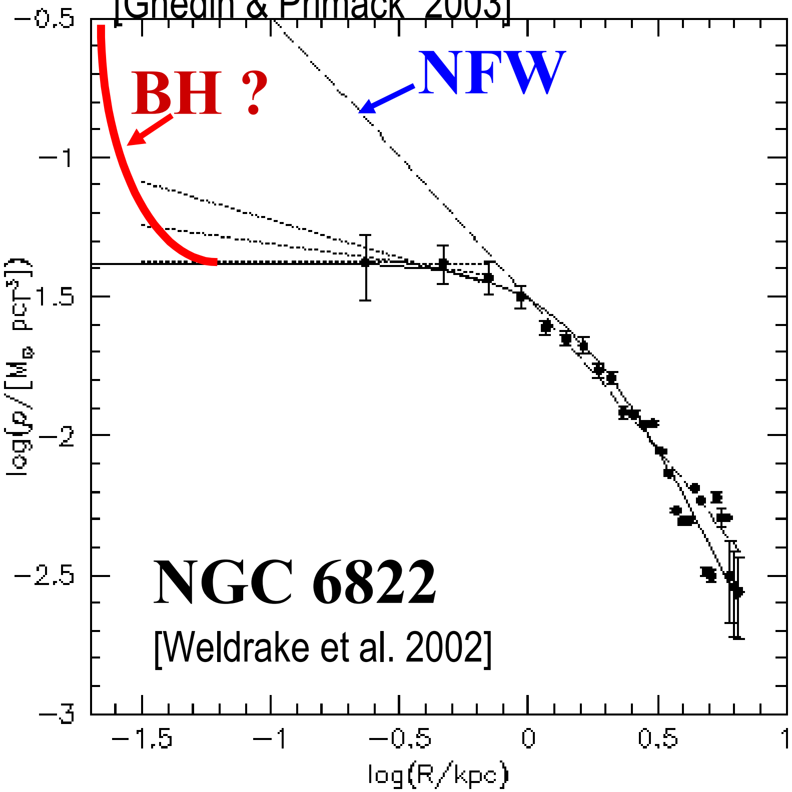
INFERENCE

PHYSICS

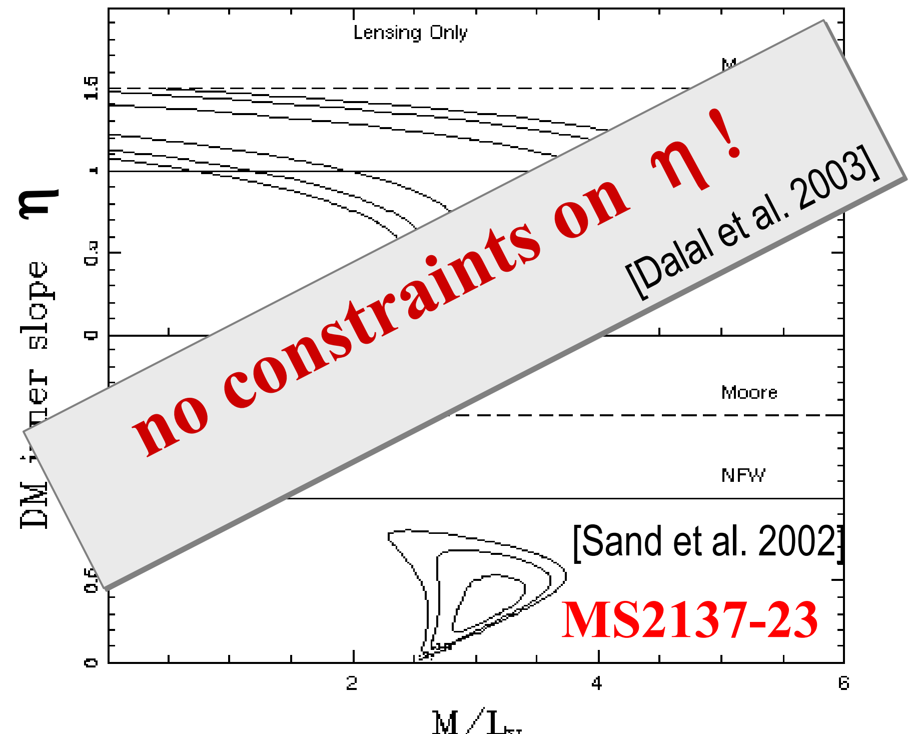
DM halo profile: constraints

Galaxies

- No evidence for a density cusp at r < 0.2 kpc
- **NGC2976:** η =0.27 at r < 1.8 Kpc [Simon et al. 2003]
- **Inner** steeper profile ? [Gnedin & Primack 2003]



Clusters



Cluster	η_{1T}	η_{2T}
A2029	0.5	2
A1689	1.3	1.6
A1835	0.9	1.1
MS1358	1.8	1.8

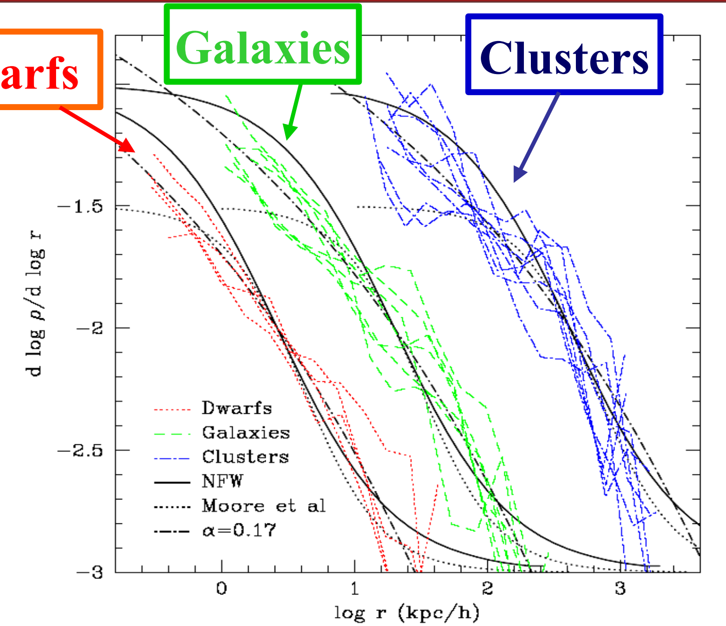
[Bautz & Arabadjis 2002]

DM density *universal* profile

Numerical simulations (CDM)

Different groups obtained similar results

[Navarro et al. 2003, Reed et al. 2003]

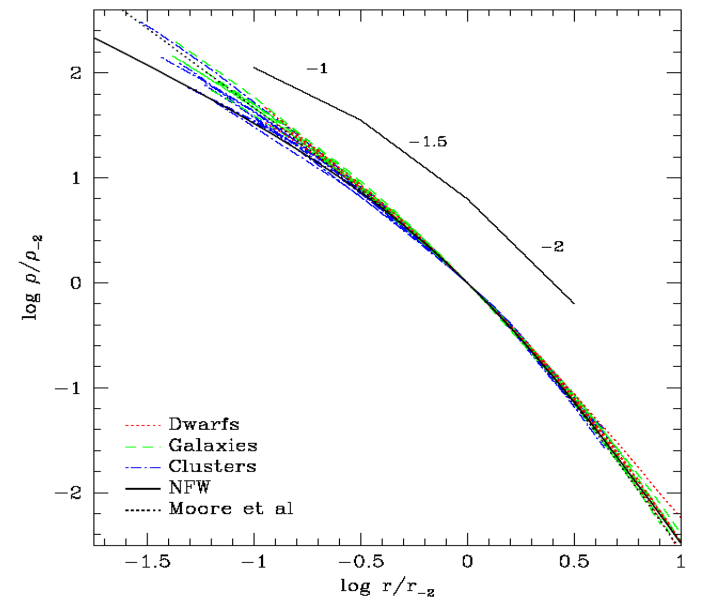


Analytical fitting

General DM profile

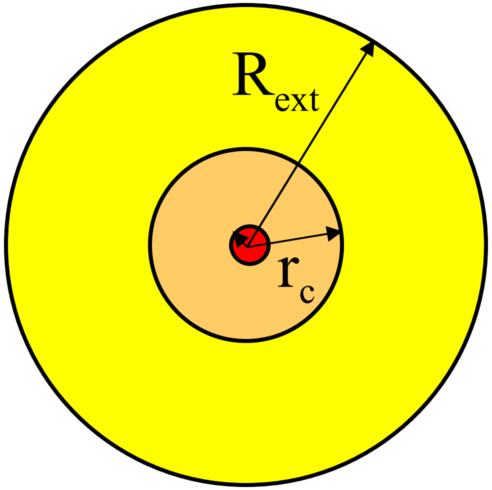
$$\rho(r) = \frac{\rho_0}{(r/R)^{\gamma}[1+(r/R)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

	α	β	γ	R (kpc)
Kra	2.0	3.0	0.4	10.0
NFW	1.0	3.0	1.0	20
Moore	1.5	3.0	1.5	28.0
Iso	2.0	2.0	0	3.5



DM halo structure: smooth

$$R_{ext} = p \cdot r_c$$



$$r_c = \frac{1.22 h^{-1} Mpc}{p}\left[\frac{M}{10^{15} h^{-1} M_\odot} \cdot \frac{400}{\Omega_m \Delta(\Omega_0, z)}\right]^{1/3} \frac{1}{1+z}$$

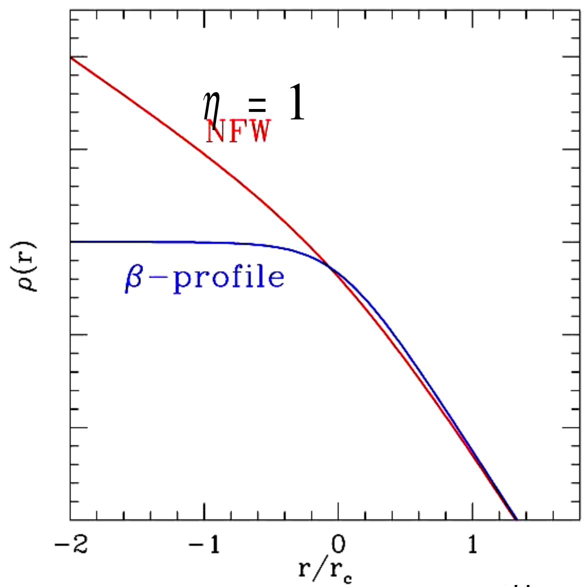
R_{inn}

$$t_{ff} = \sqrt{\frac{3\pi}{32 G\rho}} \approx t_{ann} = \frac{1}{n_\chi \langle \sigma V \rangle_A}$$

$$n_\chi = n_{\chi,0}\, g(r)$$

$$g(r) = \left(\frac{r}{r_c}\right)^{-\eta}\left(1 + \frac{r}{r_c}\right)^{\eta - \xi}$$

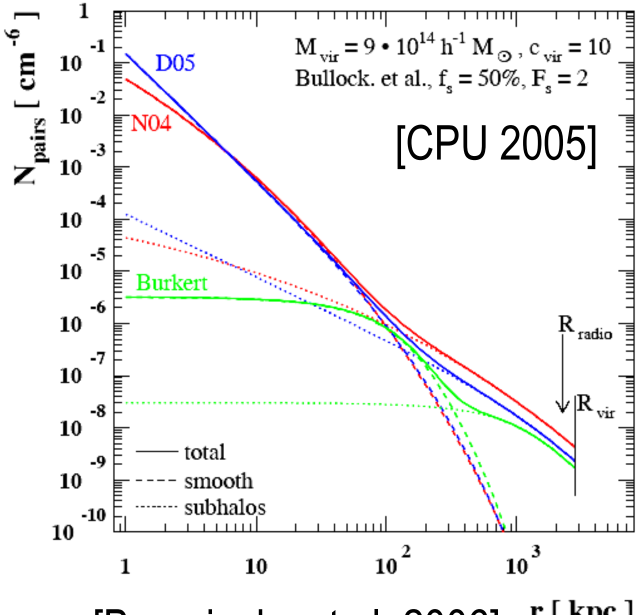
$$n_{\chi,0} = 1.4 \cdot 10^{-5}\ \mathrm{cm}^{-3}\ \frac{p^3}{I}\Omega_\chi h^2 \left[\frac{M_\chi}{100\ GeV}\right]^{-1}\left[\frac{\Delta(\Omega_0, z)}{400}\right]$$



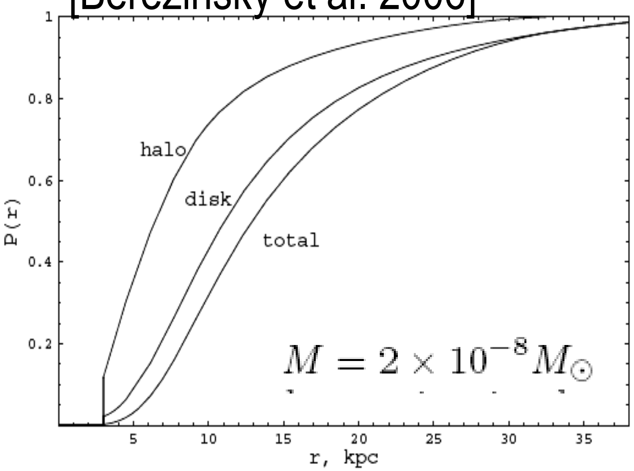
$$\Delta(\Omega_0, z) = 18\pi^2/[\Omega_0(H_0 t)^2(1+z)^3$$

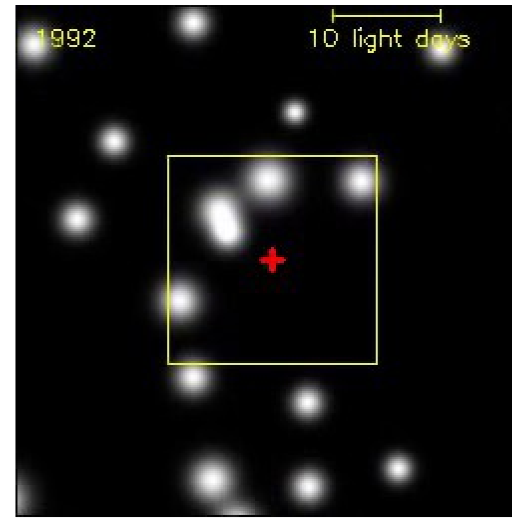
$$I(p, \eta, \xi) = \int_0^p dx x^{2-\eta}(1+x)^{\eta-\xi}.$$

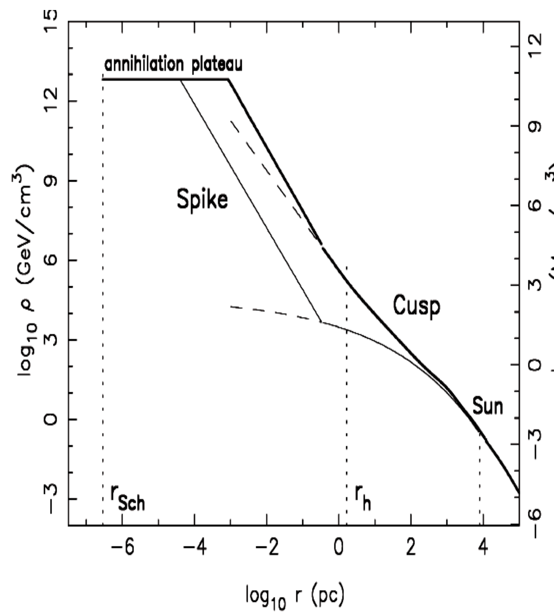
DM halo: smooth + clumps + BHs



[Berezinsky et al. 2006]







DM cusps in cosmic structures ?

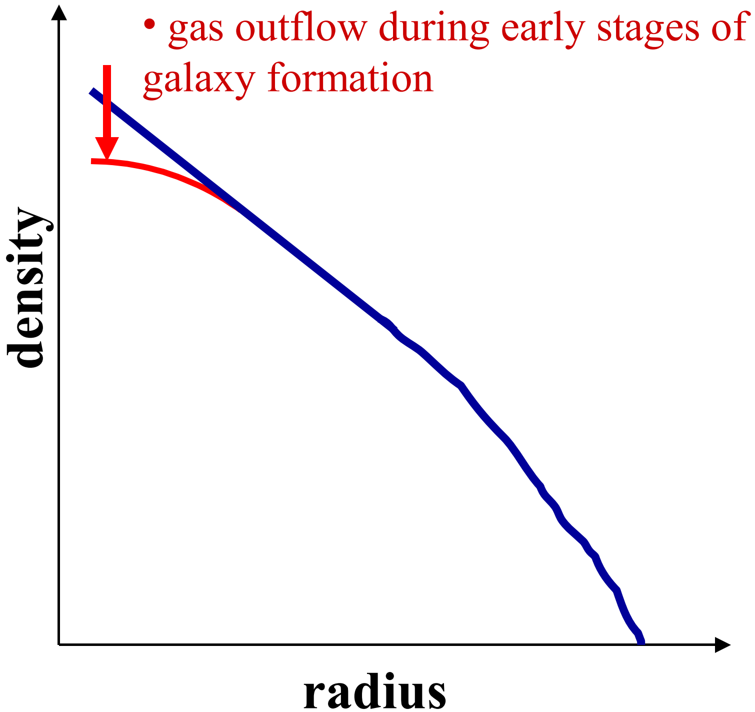
Cusp problem **alleviated** by

Changes in the basic physics

- WIMPs with large <σV>
- broken scale invariance
- modified gravity

Baryon-DM coupling & interaction

- gas outflow during early stages of galaxy formation

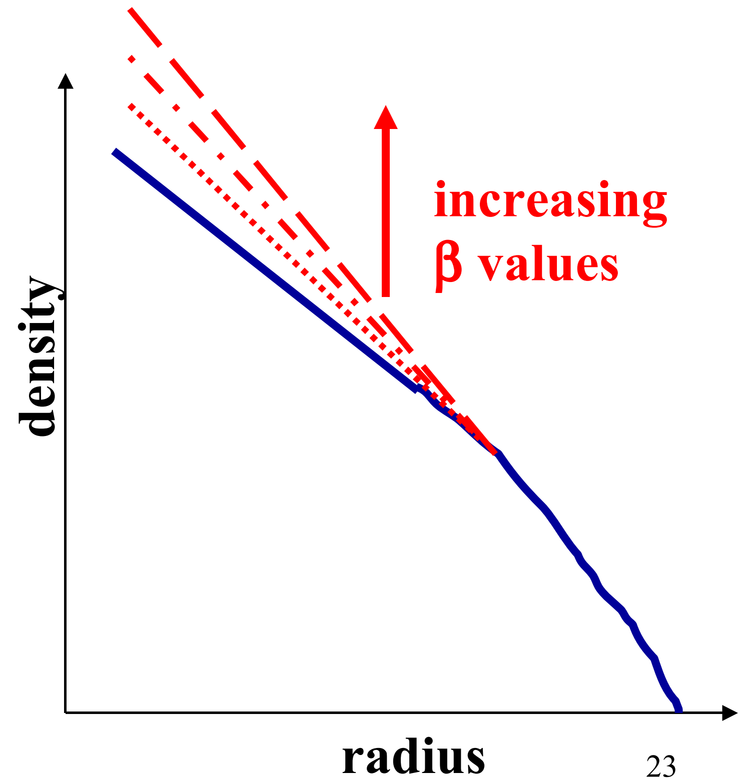


Cusp problem **strenghtened** by

DM - Dark Energy coupling

- modified particle dynamics $G^{*} = G\left(1 + \frac{4}{3}\beta^{2}\right)$

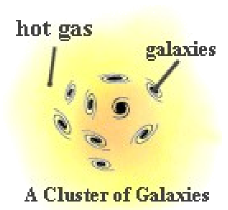
β^2 = ratio of the DM-DE interaction w.r.t. gravity.



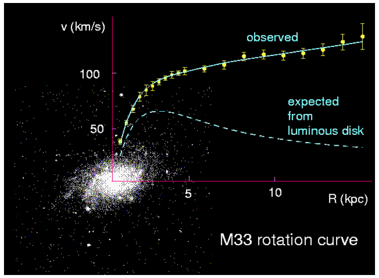
DM search in Cosmic Structures

Inference

Dynamics



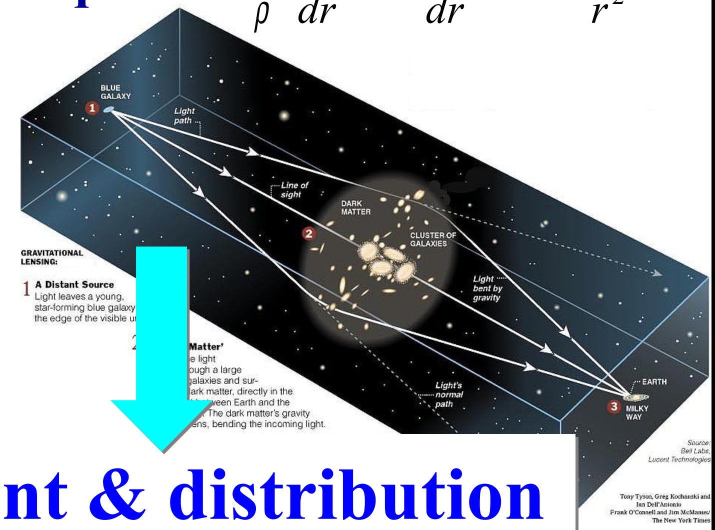
$$\boxed{2T + U = 0}$$



Gas hydro-eq.

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{d\varphi}{dr} = -\frac{GM(r)}{r^2}$$

Lensing



amount & distribution of DM!

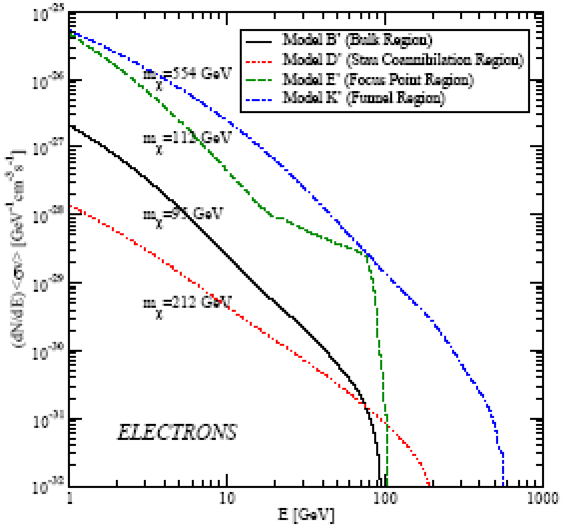
PHYSICS

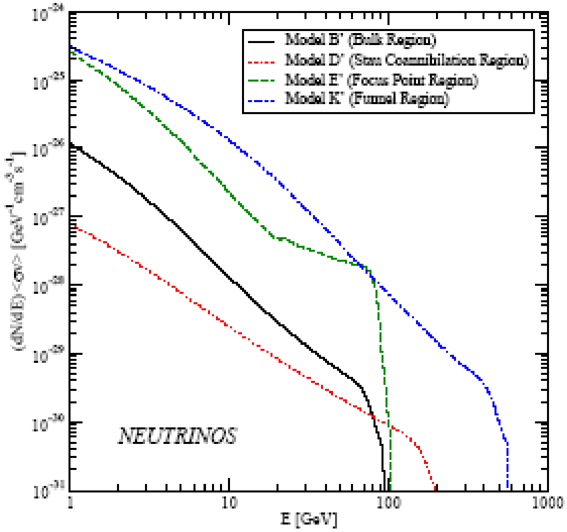
Annihilation products

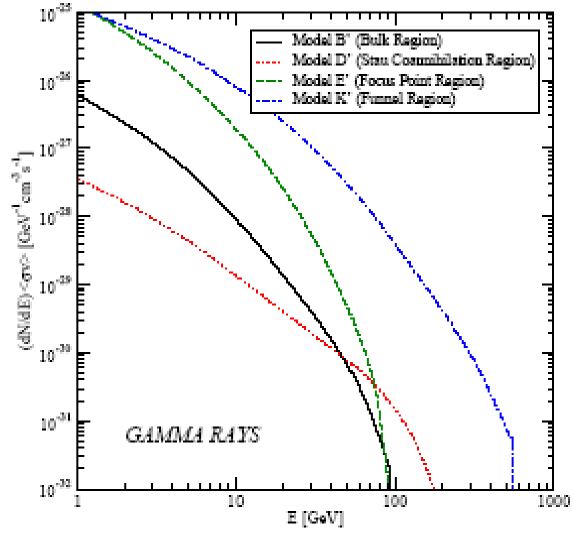
$e^{\pm}$

ν

π^0



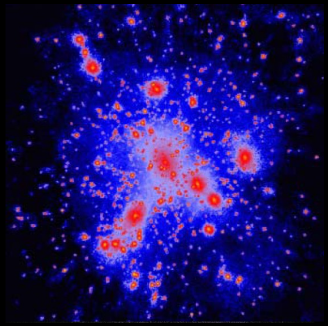




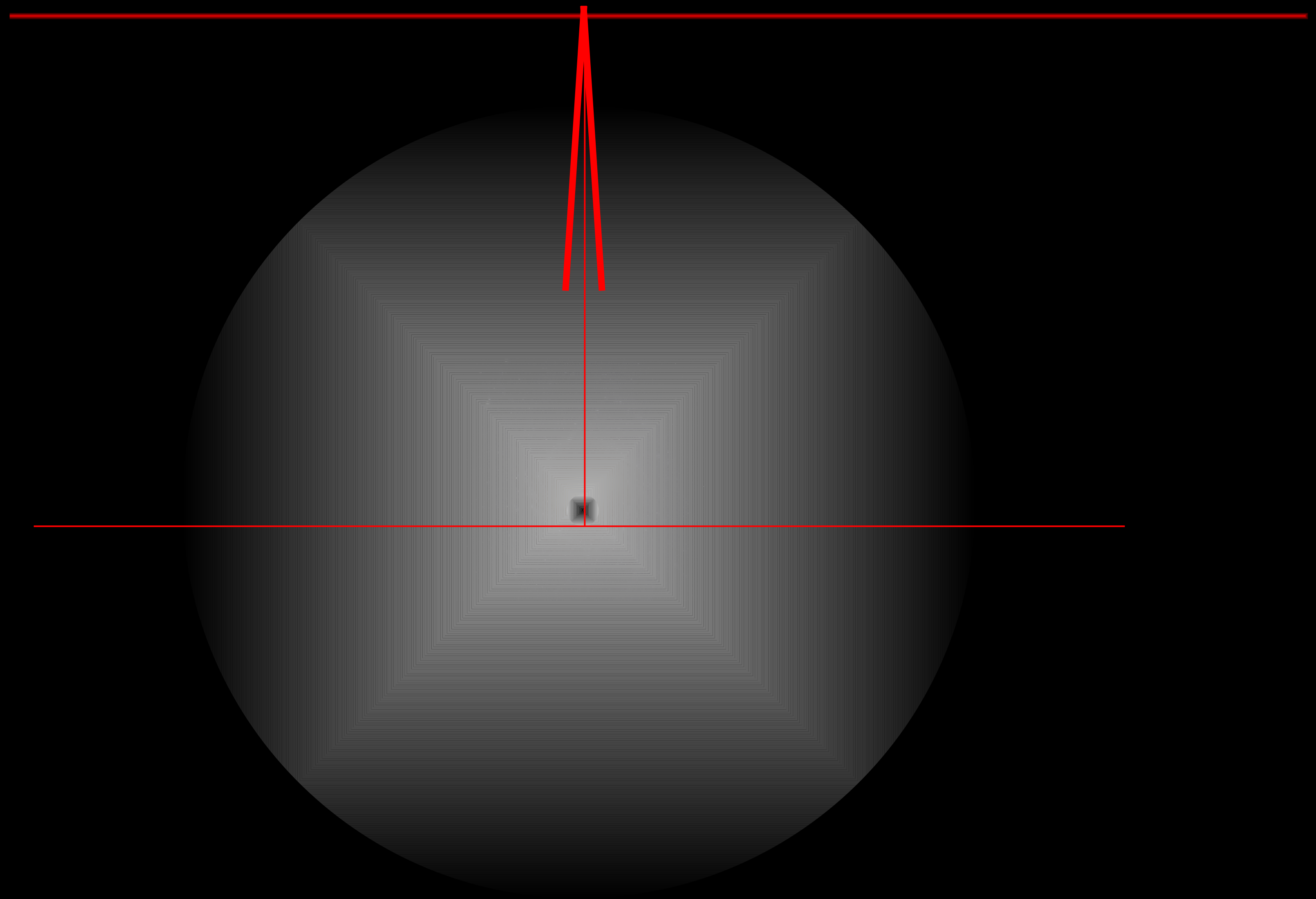
Imagine a Galaxy

An astronomer’s view

A cosmologist's view



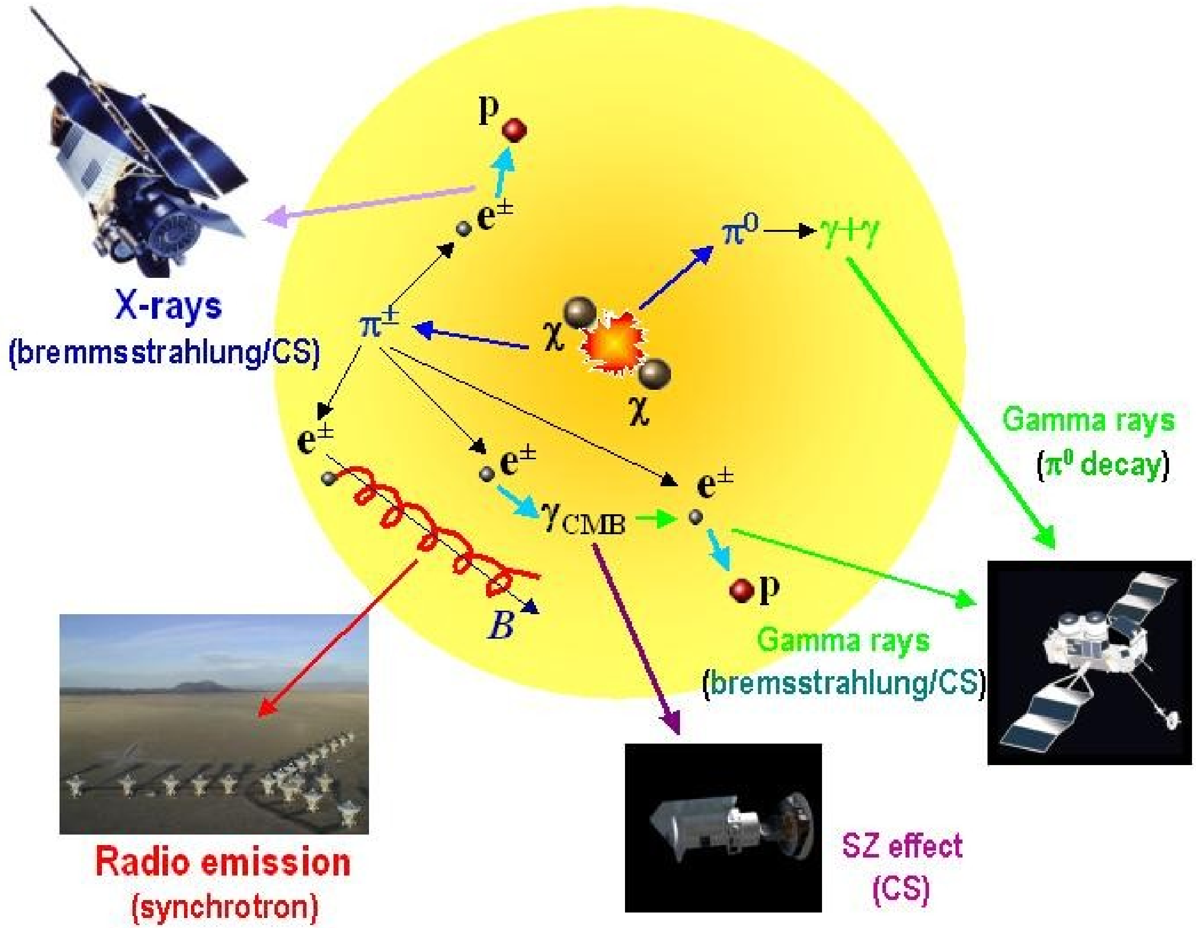
An AstroParticle Physicist’s view



A simple model

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

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



Signal

$$F_\nu \propto \frac{1}{D_L^2} \langle \sigma V \rangle_{ann} \cdot \frac{1}{M_\chi^2} \cdot \frac{dn_e}{dE_e} \cdot \left(\frac{dE_e}{dE_\nu} \right)$$

Astro-Particle constraints

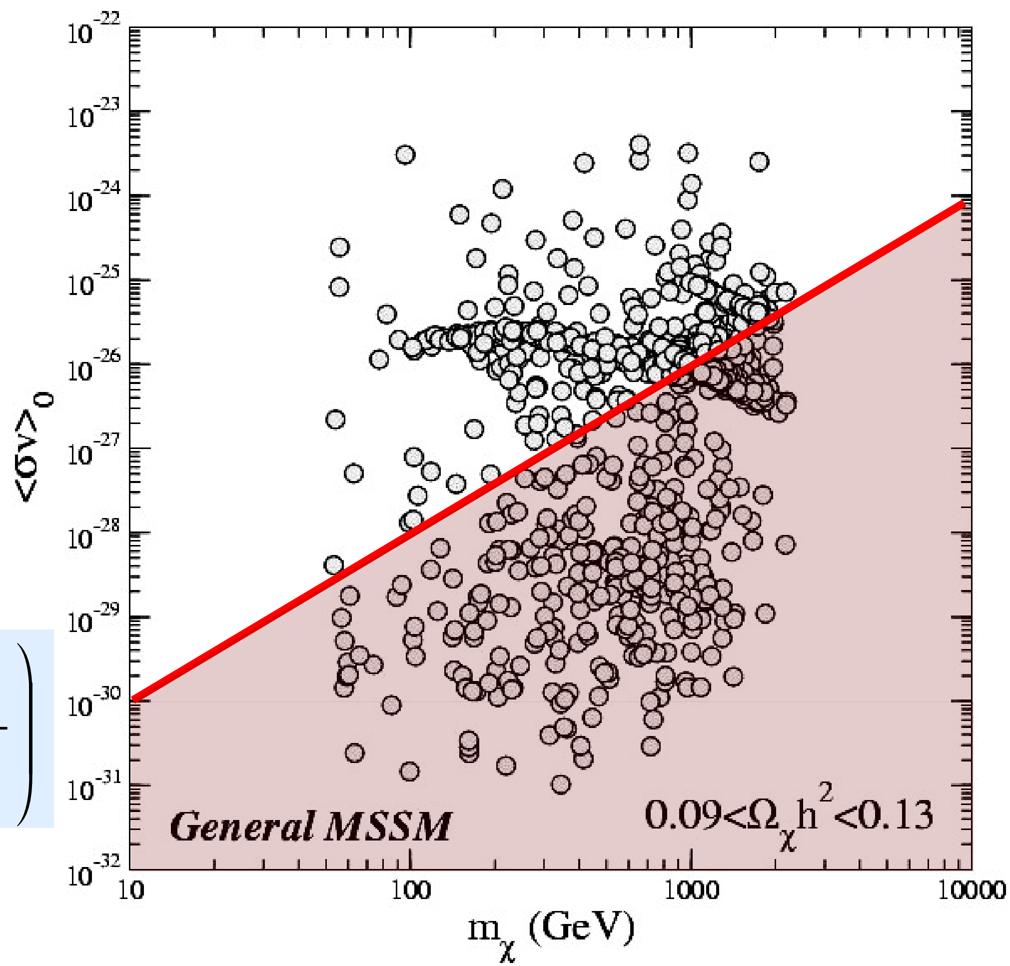
$$F_{DM} \propto \frac{\langle \sigma V \rangle}{D_L^2} \cdot \rho_{DM}^{2}$$

Cosmology

Astro physics

$$F_{DM} \propto \frac{1}{D_L^2} \langle \sigma V \rangle_{ann} \cdot \frac{1}{M_\chi^2} \cdot \frac{dn_e}{dE_e} \cdot \left(\frac{dE_e}{dE_\nu} \right)$$

Particle physics

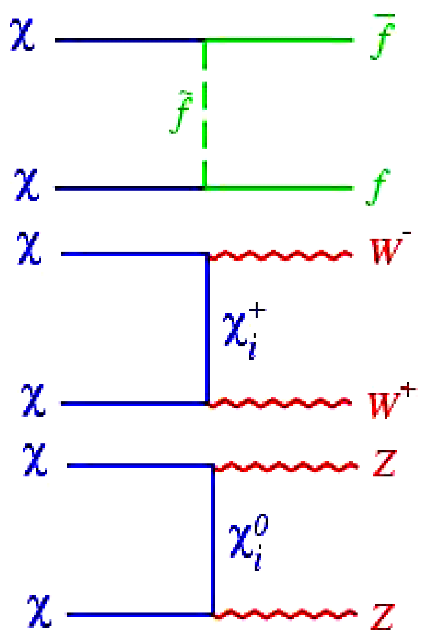


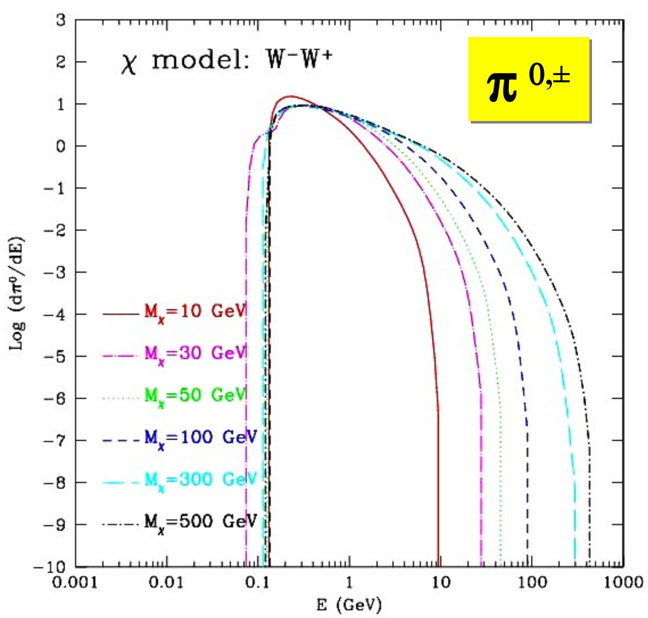
$\chi\chi$ annihilation process

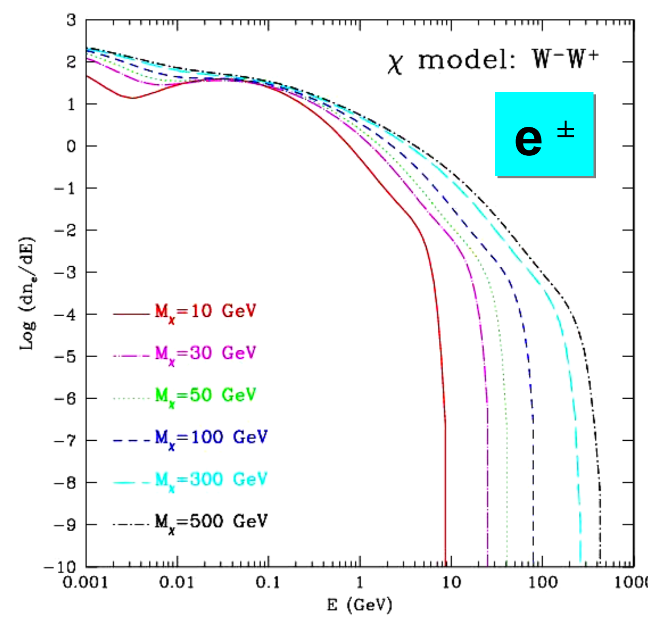
Rate

$$R = n_\chi(r)\langle\sigma V\rangle_A = 10^{-29}\mathrm{s}^{-1}\left[\frac{n_\chi}{10^{-3}cm^{-3}}\right]\left[\frac{\langle\sigma V\rangle_A}{10^{-26}cm^3s^{-1}}\right]$$

Leading annihilation channels





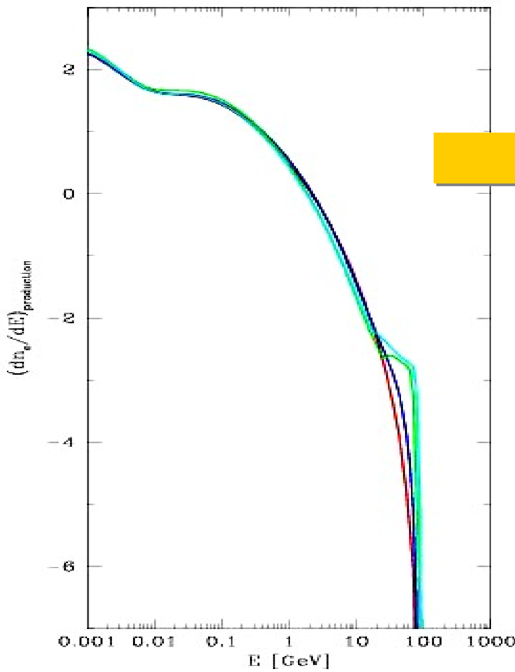


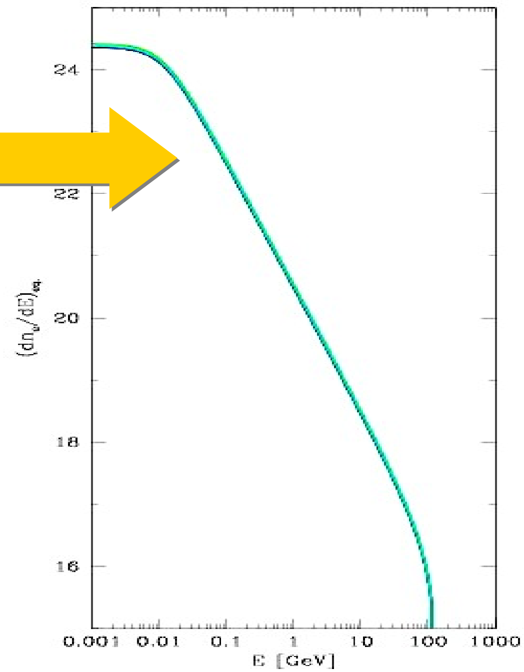
The equilibrium spectrum

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

Production

$Q_e(E,r)$





Equilibrium

$n_e(E,r)$

Diffusion

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

E losses

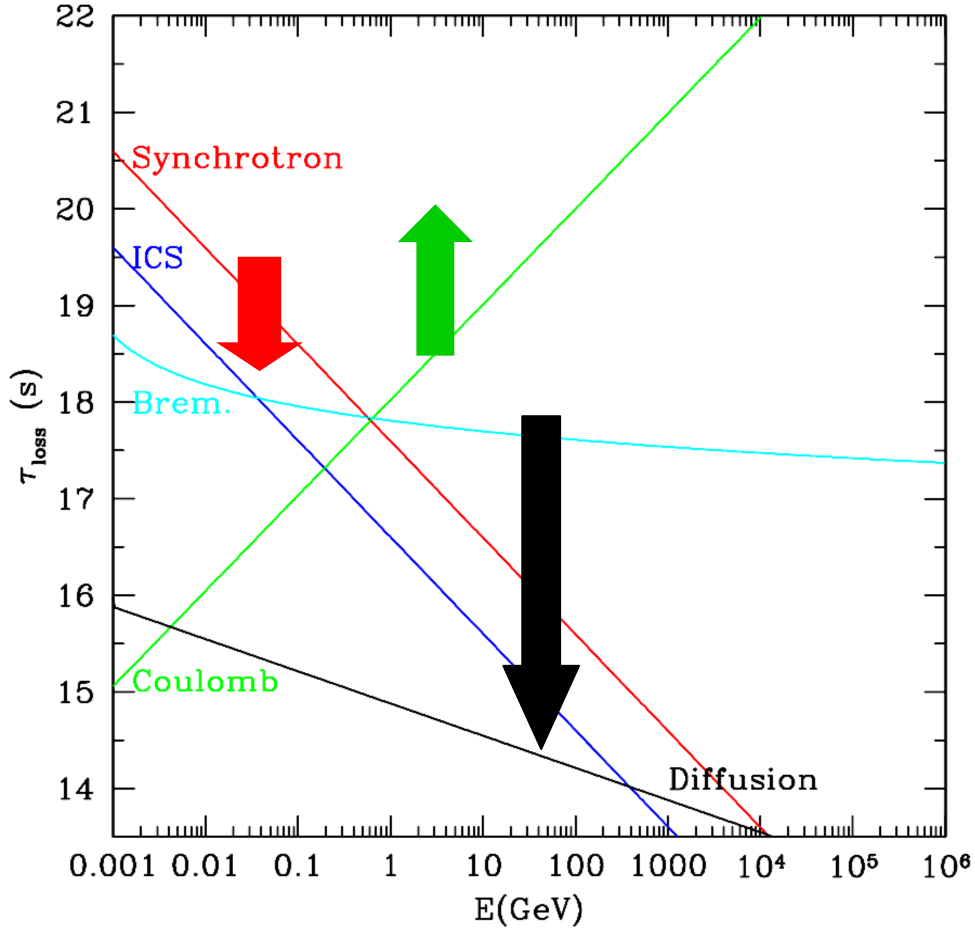
$$b_e(E) = b_{IC} + b_{sync} + b_{Coul} + b_{brem}$$

Energy losses vs. Diffusion

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

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

B increase

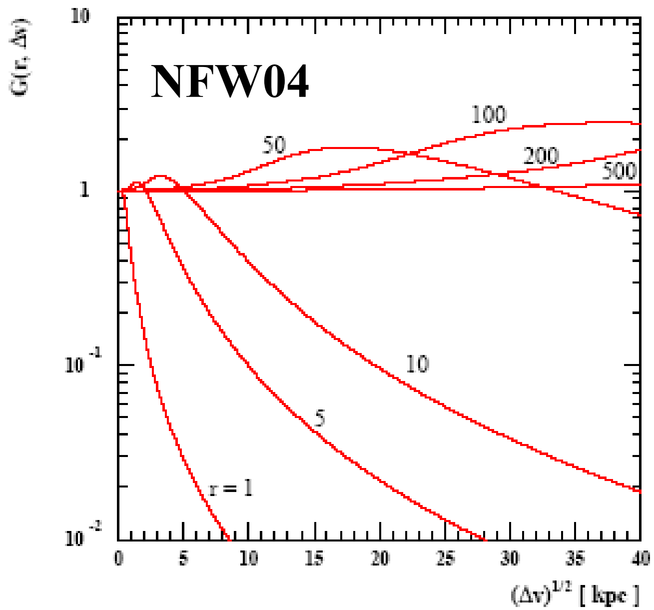


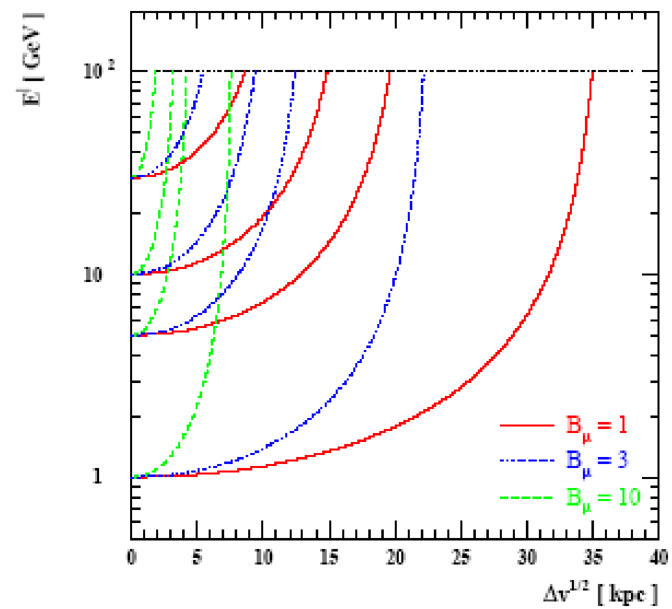
n_{th} decrease

R_h decrease

Solution: complete

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



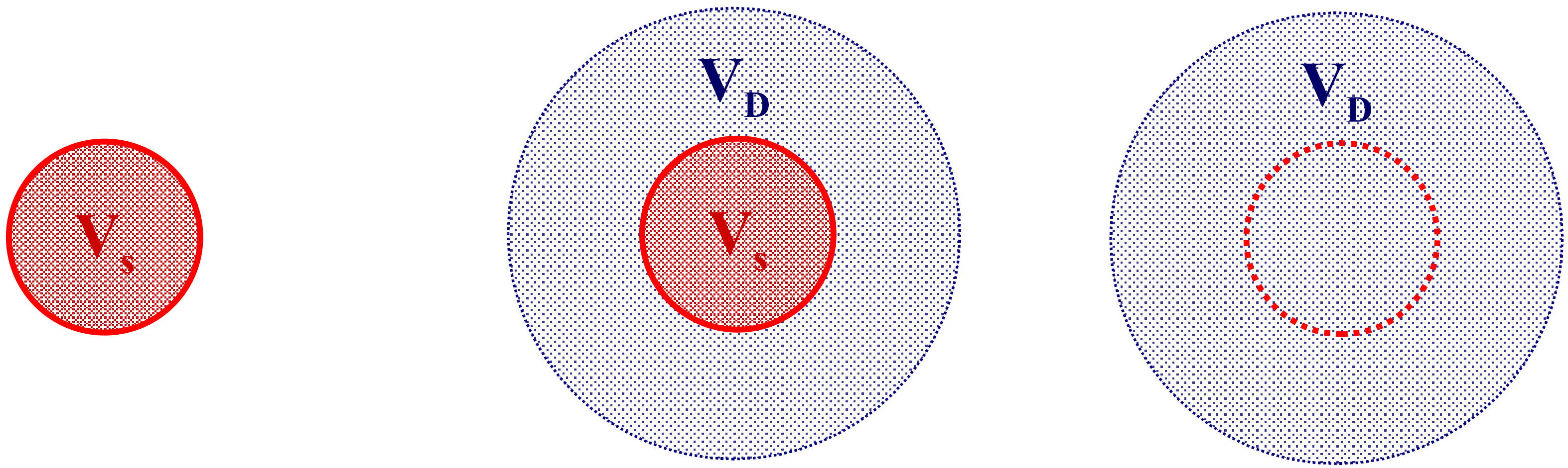


$$\hat{G} = \frac{1}{[4\pi \Delta\lambda]^{1/2}} \sum_{n=-\infty}^{+\infty} (-1)^n \int_0^{R_h} dr' \frac{(r')^2}{r_n' r} \left[\exp\left(-\frac{(r' - r_n)^2}{4\Delta\lambda} \right) - \exp\left(-\frac{(r_n' + r)^2}{4\Delta\lambda} \right) \right] \frac{n_\chi^2(r')}{n_\chi^2(r)}$$

[Colafrancesco, Profumo & Ullio 2005-2006]

Solution: qualitative

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



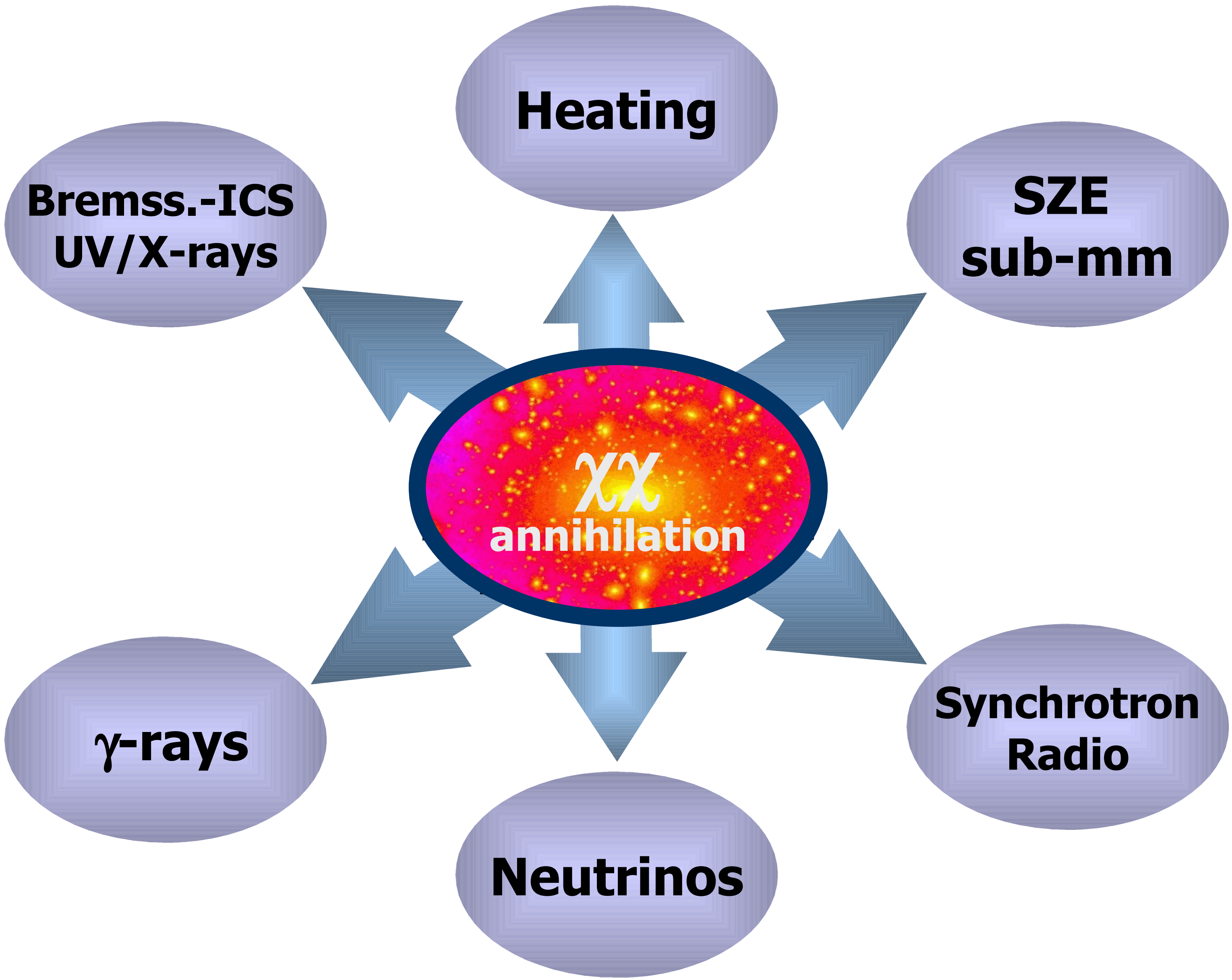
$\tau_{loss} \ll \tau_D$

$\tau_{loss} \gg \tau_D$

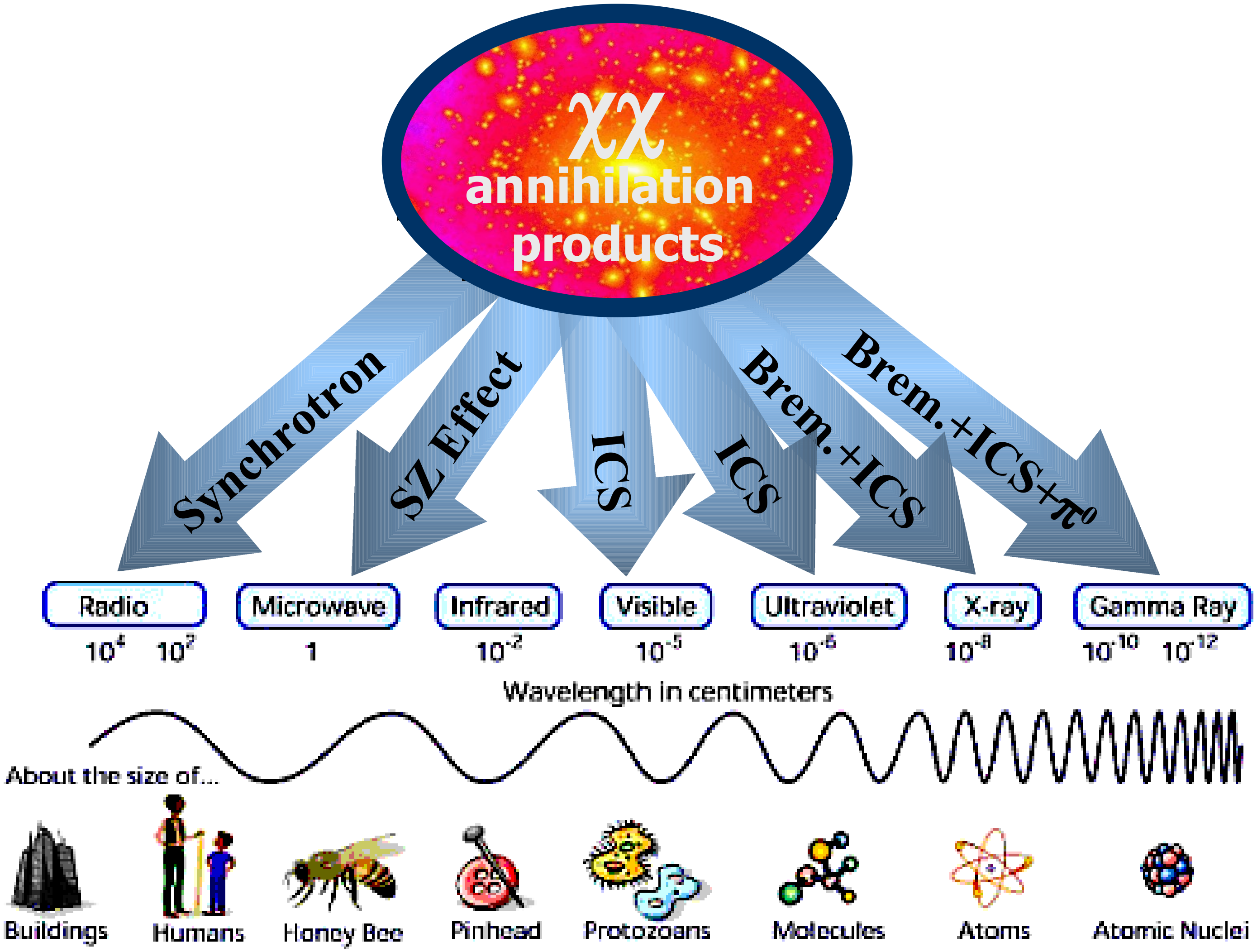
$$n_e(E,r) = \left[Q_e(E,r)\tau_{loss}\right]$$

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

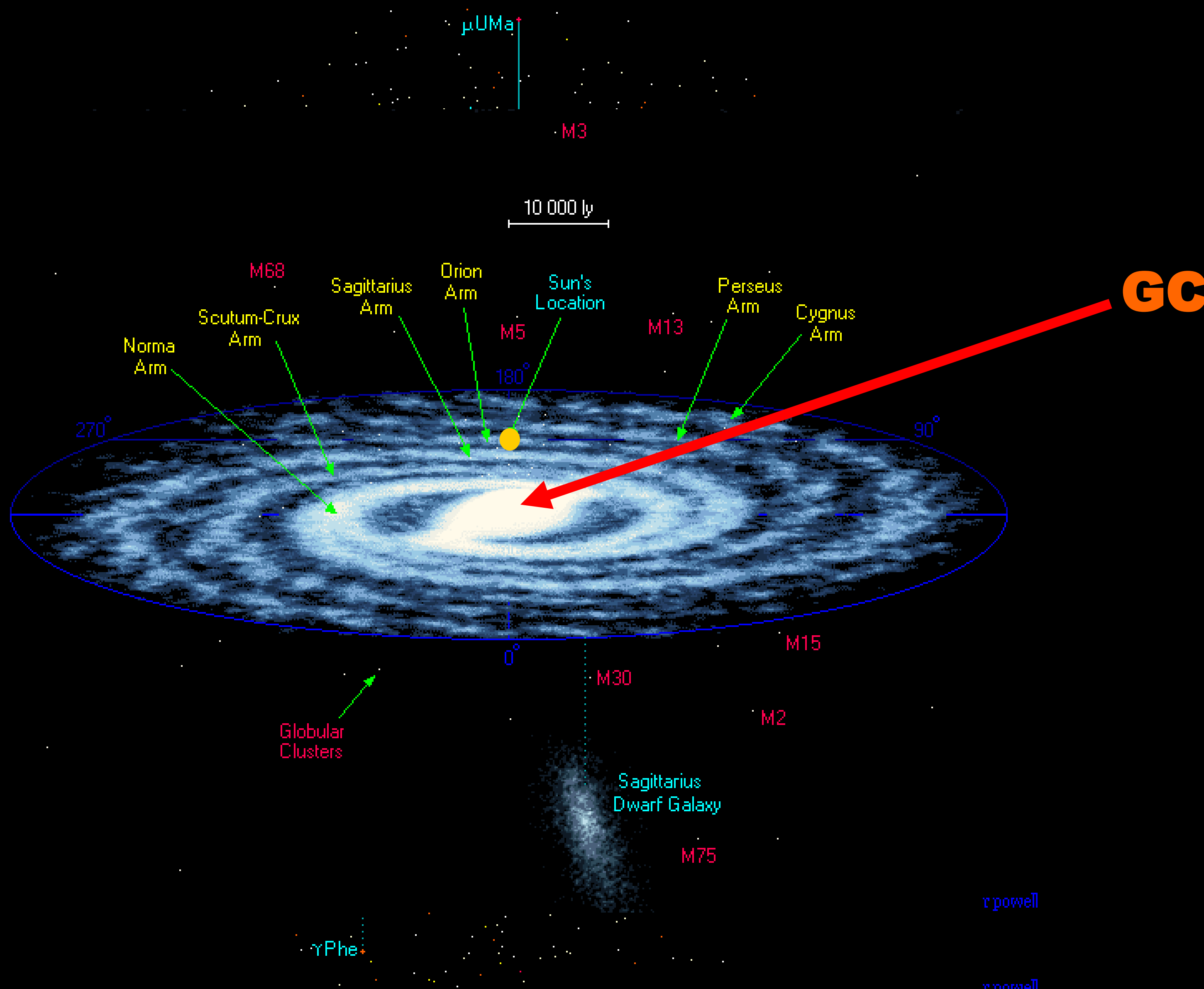
DM induced astro-particle signals



Covering the whole e.m. spectrum

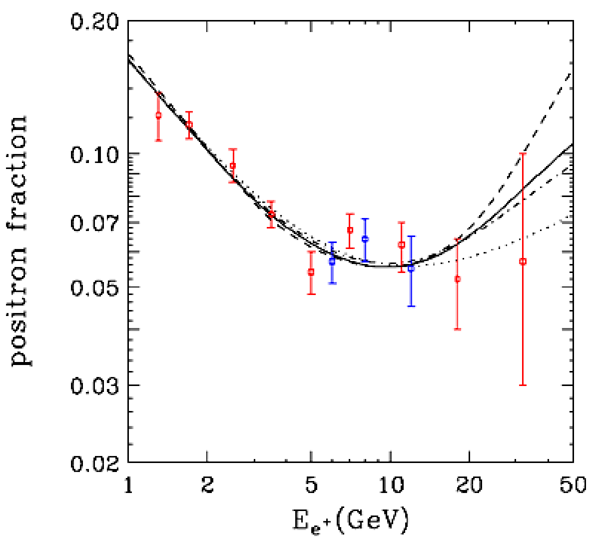


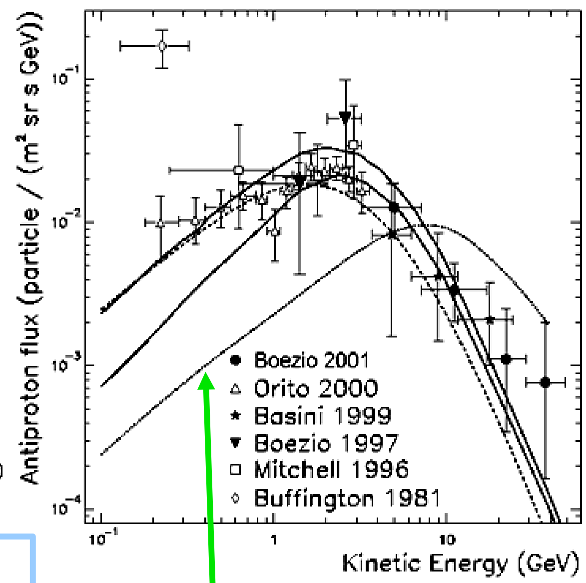
DM search: the closest clump



DM search in the MW: limits

Positron fraction | **Anti-p flux** | **511 keV line**





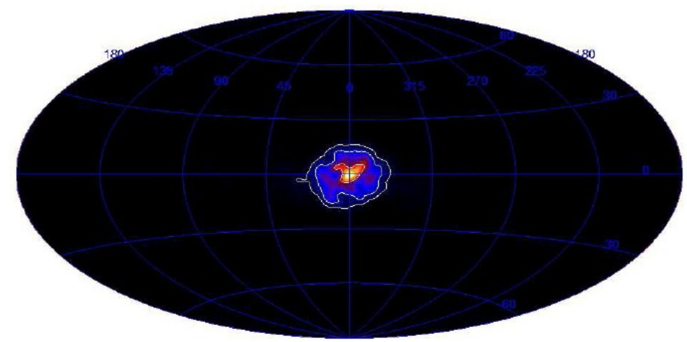


Fig. 4. Richardson-Lucy image of 511 keV gamma-ray line emission (iteration 17). Contour levels indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2}s^{-1}sr^{-1} (from the centre outwards).

INTEGRAL SPI (vonBallmoos' talk)

- **Neutralino DM**
  - inefficient
  - need strong clumping
- **Kaluza-Klein Dark Matter**
  - viable positron source for M = 300 - 400 GeV
  - need boost (~ 1000)

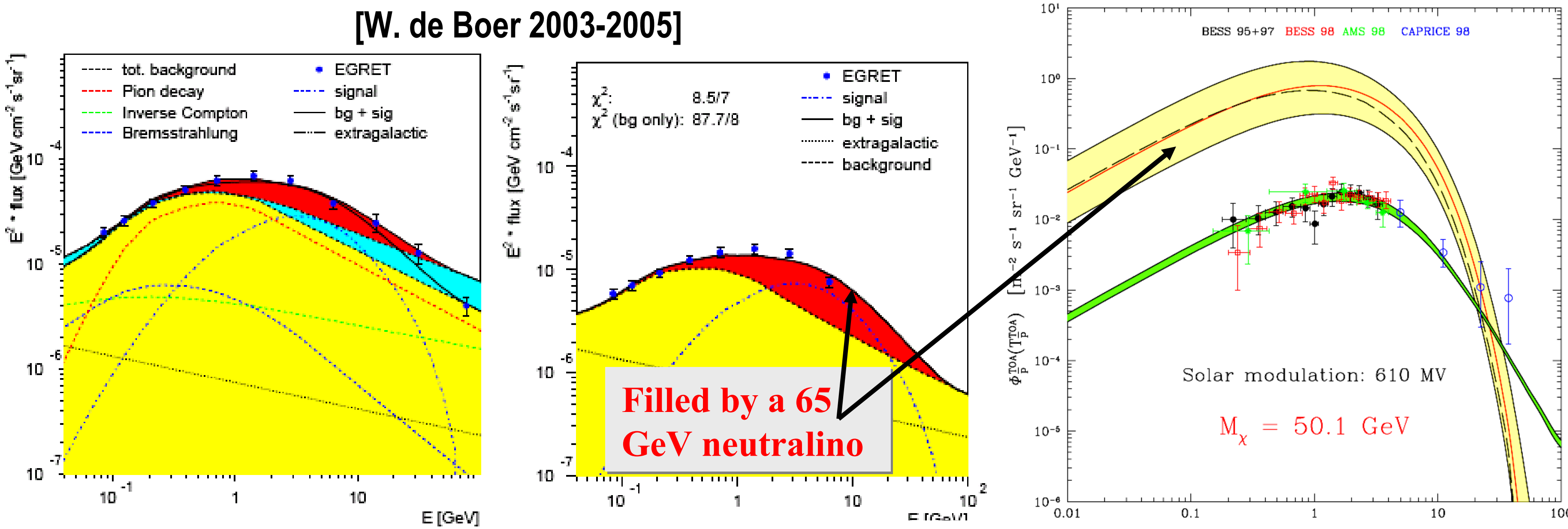
Primary antiproton flux from annihilation of a 964 GeV MSSM neutralino (Ullio, astro-ph/9904086)

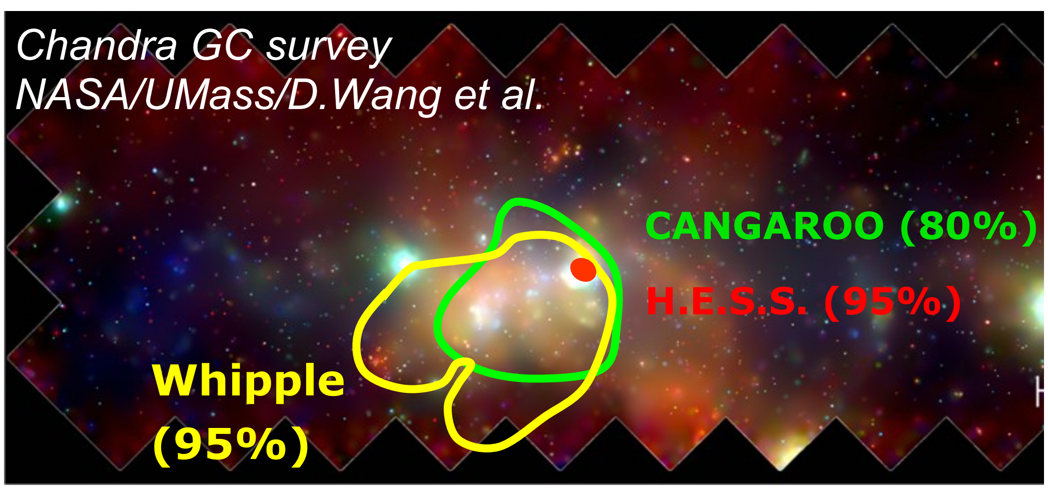
Light (s=0) DM

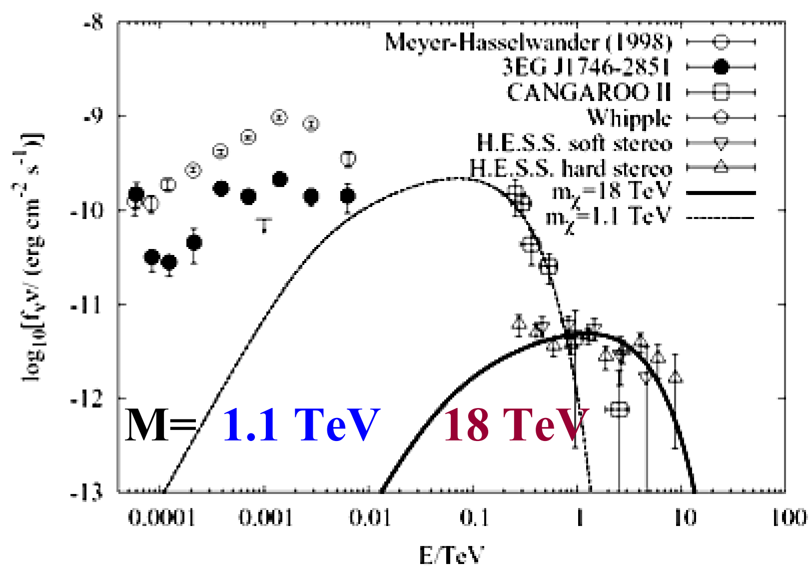
- M ~1 - 4 MeV
- Agrees with Ω_{DM}
- Rather flat halo (Boehm et al. 2003)

DM search in the MW: limits

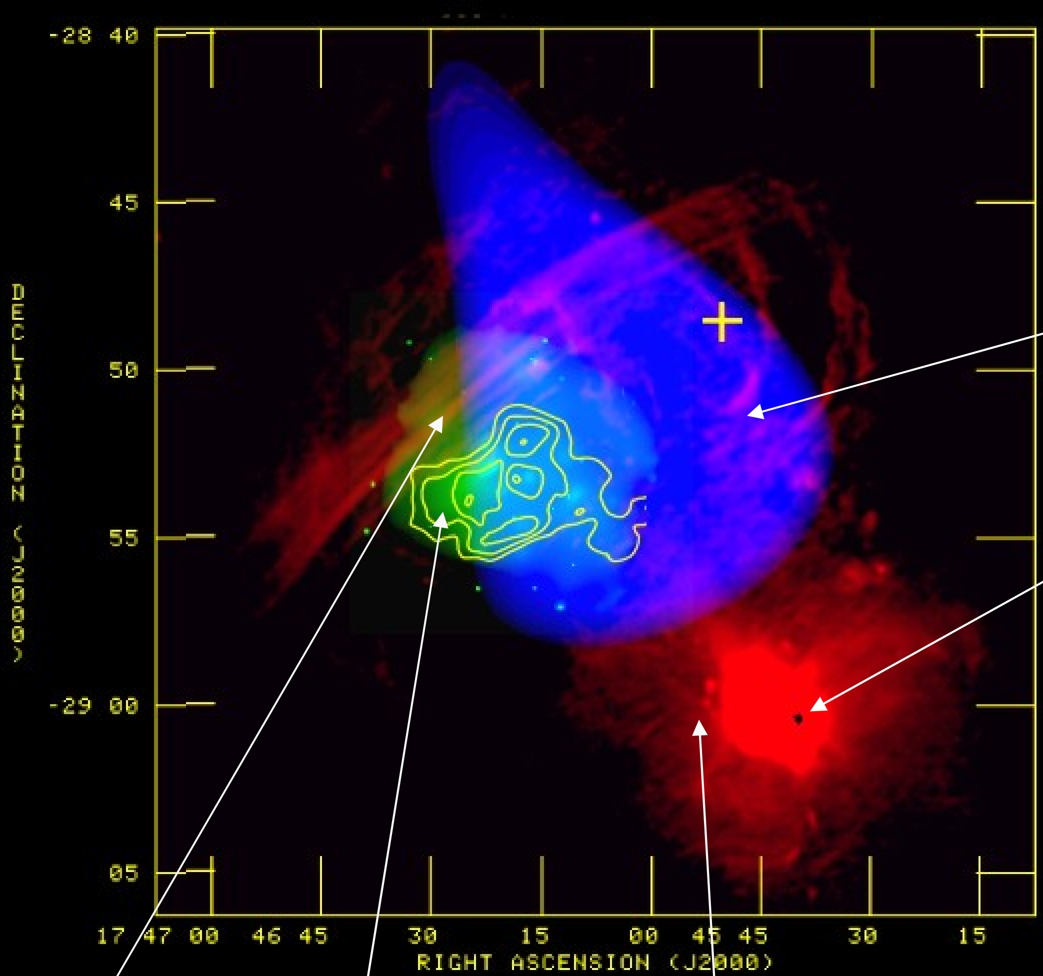
[W. de Boer 2003-2005]







GC demography



EGRET source

Central Black Hole

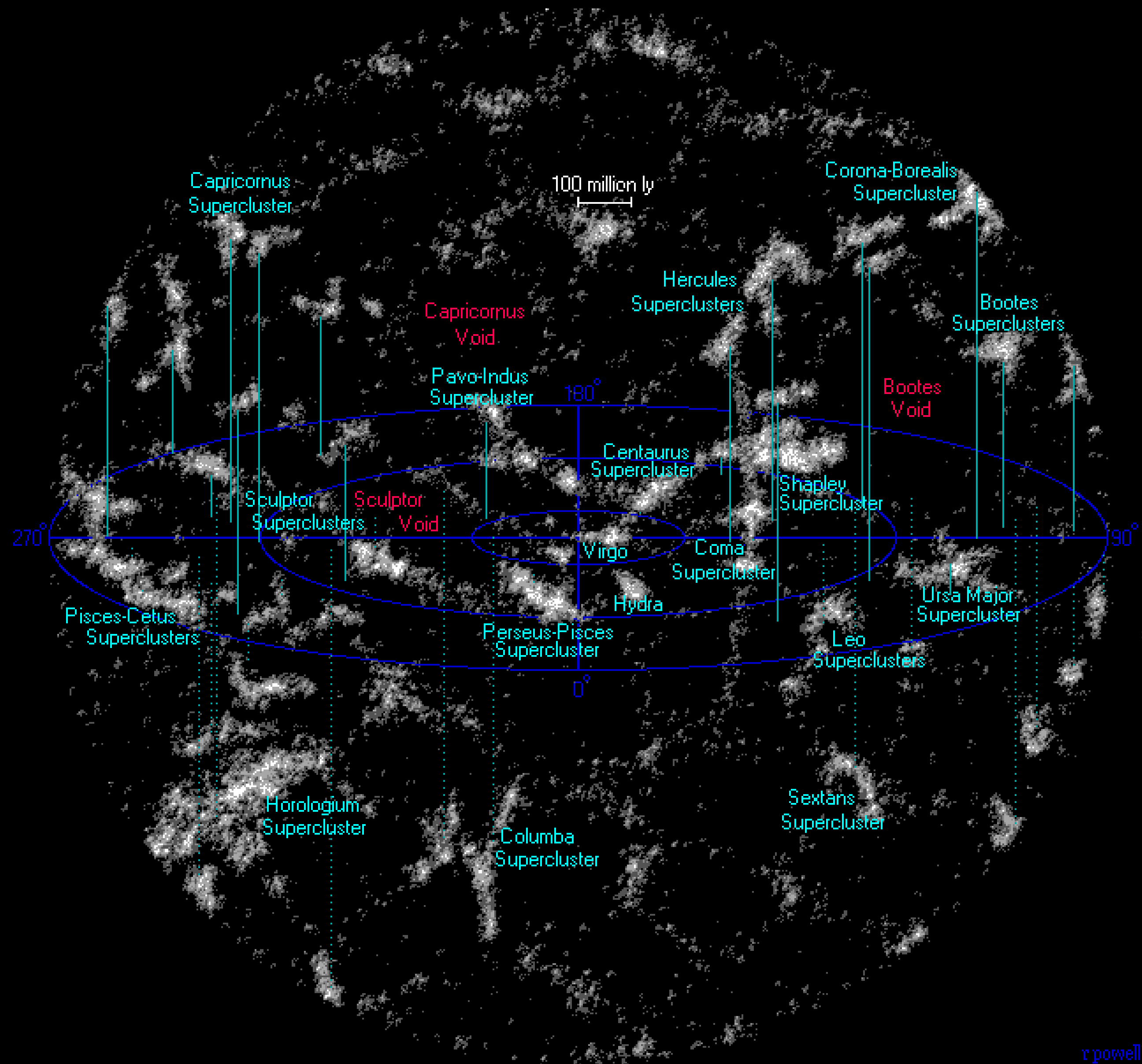
X-ray source

SNR

Sgr A East non-thermal filaments (radio)

Indirect search: … still more

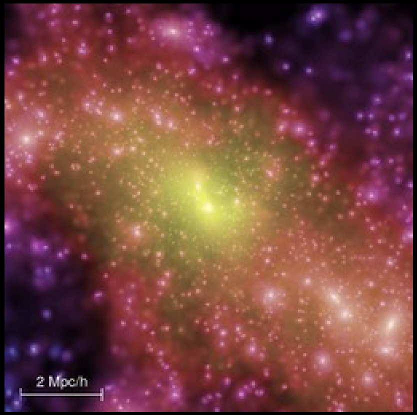
- Galactic center
- Galactic clumps
- Galaxy satellites
- Nearby galaxies
- Galaxy clusters
- Superclusters



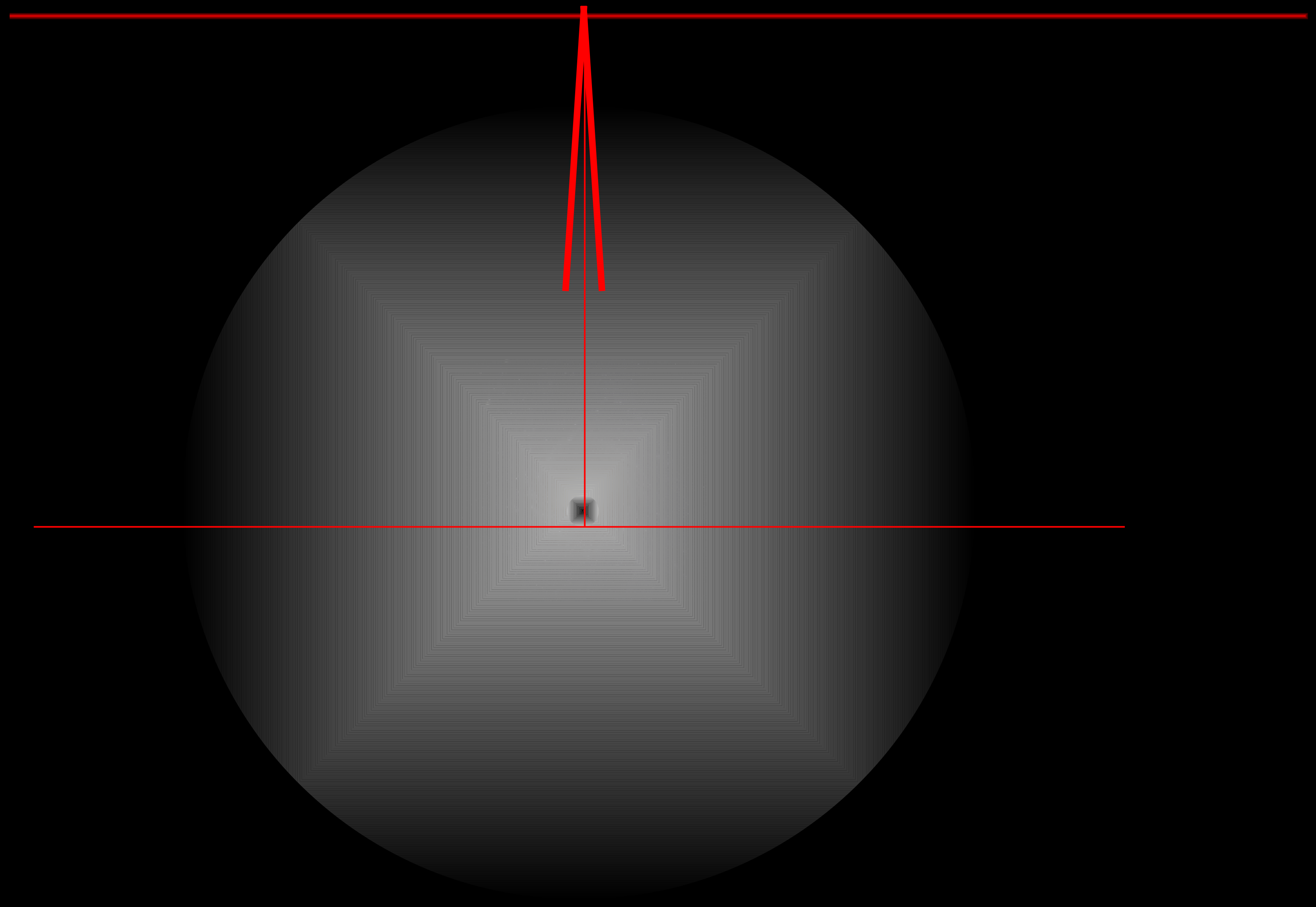
Imagine a Cluster of galaxies

An astronomer’s view

A cosmologist's view



An AstroParticle Physicist's view

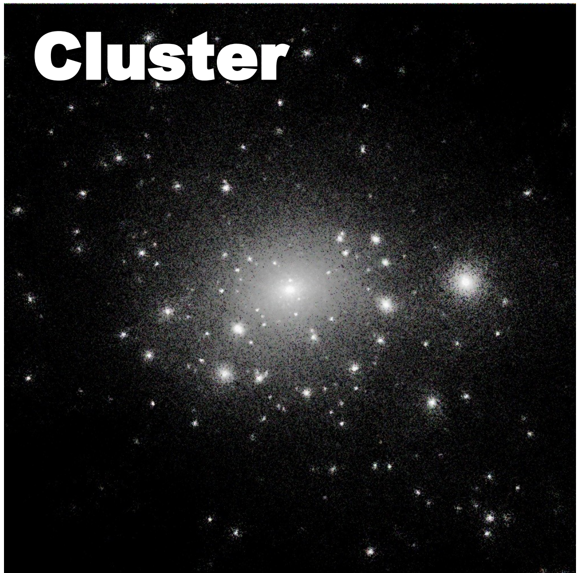


DM in Clusters & Dwarf galaxies

Cluster of galaxies

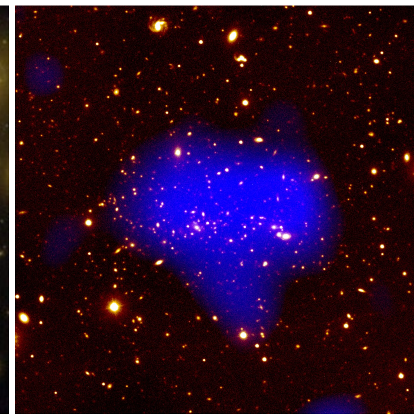
dSph Galaxy

DM annihilation in cosmic structures

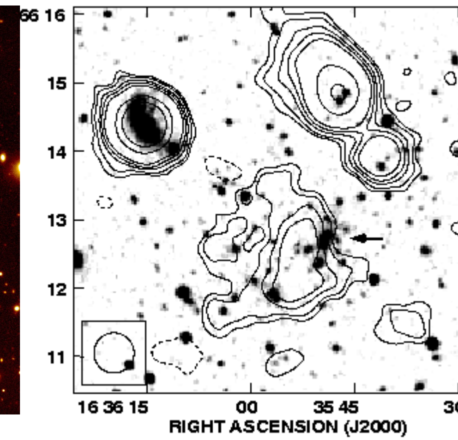


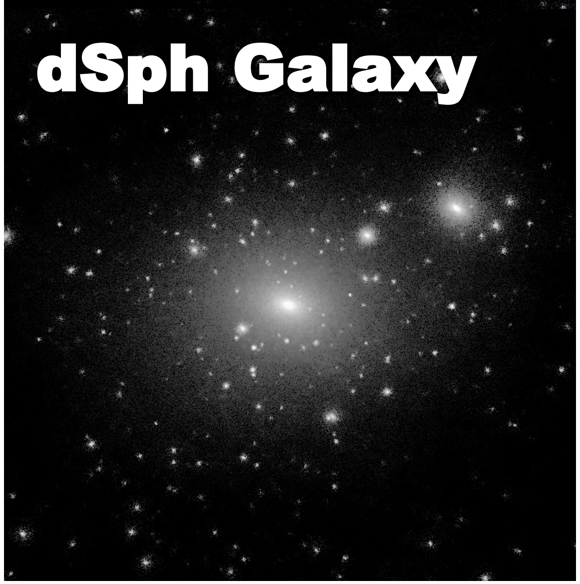
Galaxies
(Optical)

Diffuse gas
(X-rays)



Relativistic particles
(Radio halos/relics)





Stars
(Optical)

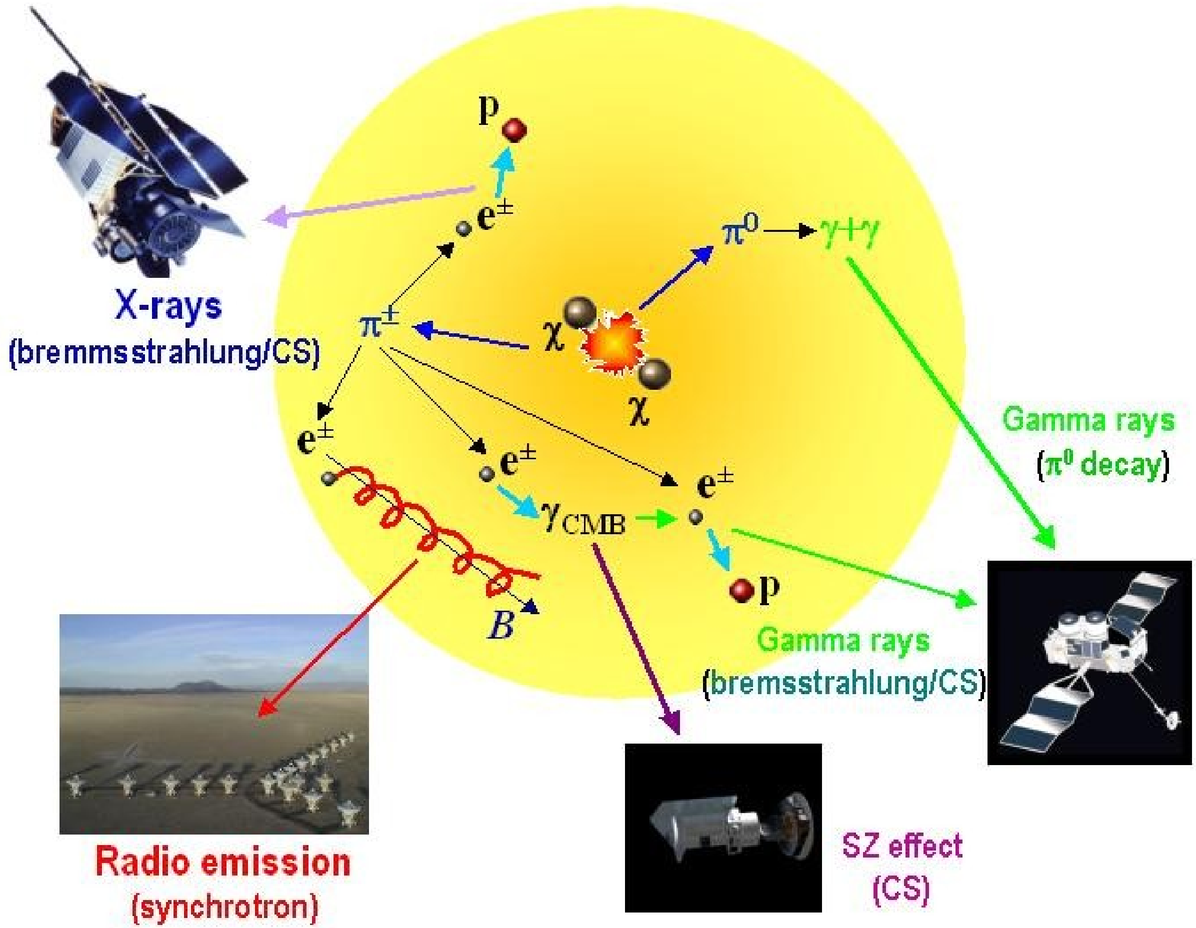
No gas
(No X-rays)

No rel. particles
(No radio emission)

A simple model

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

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



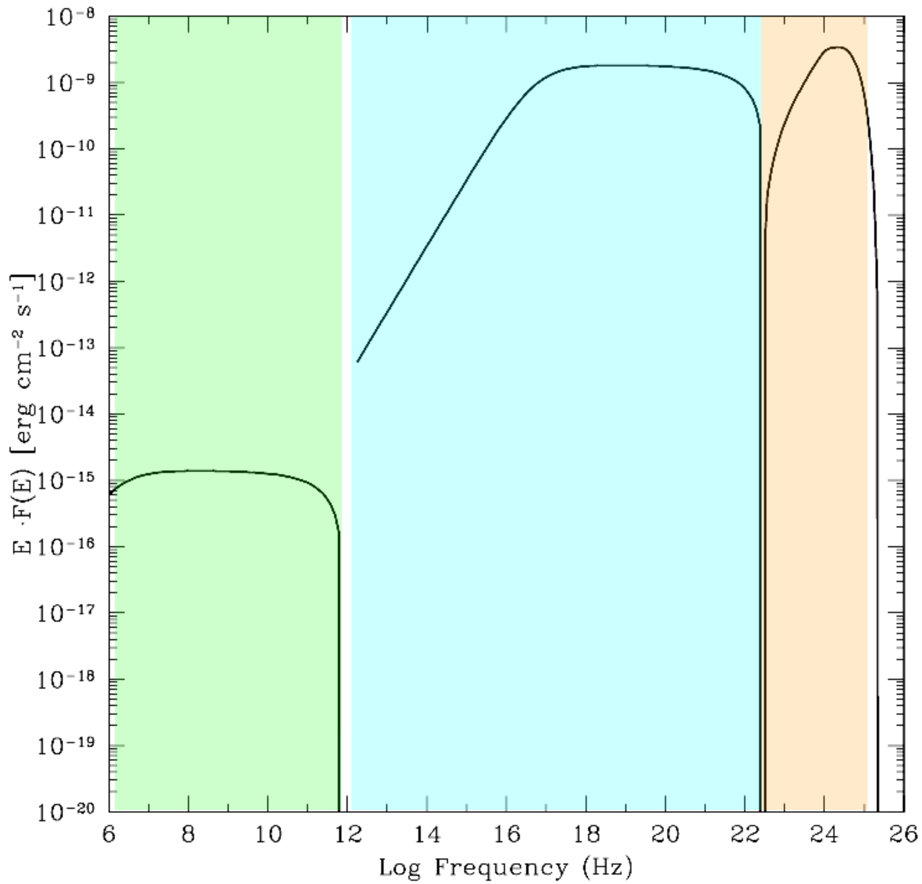
Signal ⇒

$$F_\nu \propto \frac{1}{D_L^2} \langle \sigma V \rangle_{ann} \cdot \frac{1}{M_\chi^2} \cdot \frac{dn_e}{dE_e} \cdot \left(\frac{dE_e}{dE_\nu} \right)$$

Typical DM halo SED

$R_h \sim$ Mpc

Sync. **ICS** **$\pi^0 \rightarrow \gamma\gamma$**



$$D \propto E^{\gamma}$$

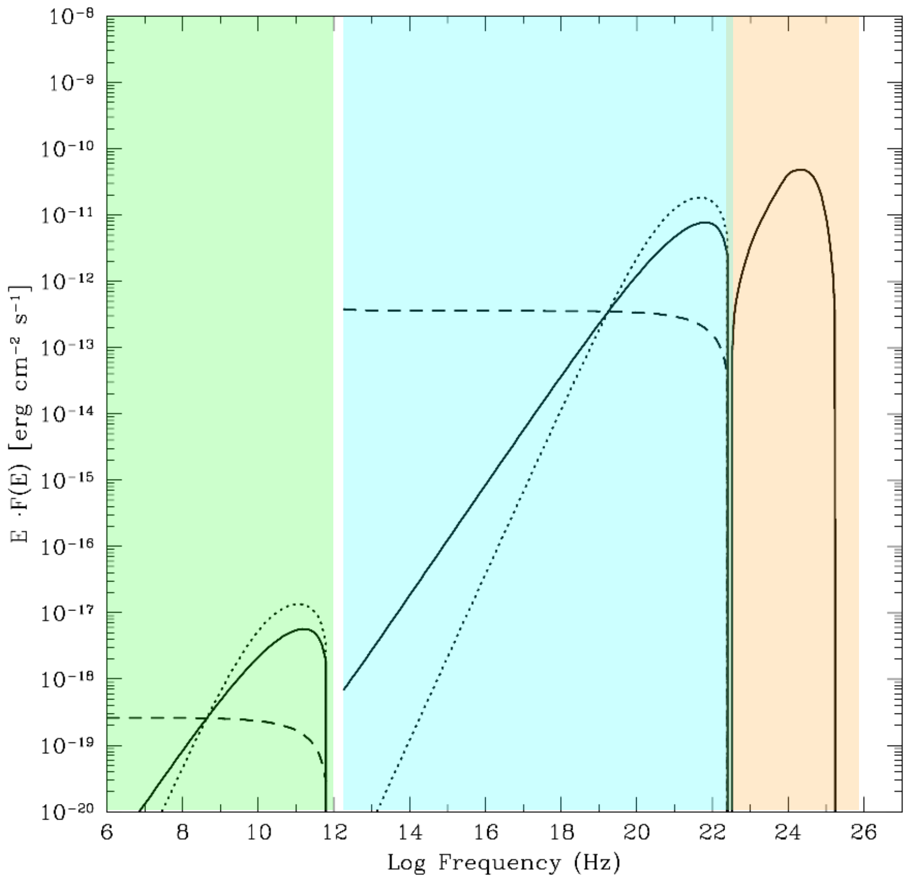
Not relevant

Galaxy clusters

Typical DM halo SED

$R_h \sim$ kpc

Sync. **ICS** **$\pi^0 \to \gamma\gamma$**



$D \propto E^{\gamma}$

$\gamma = 0$ (dotted)
$\gamma = 1/3$ (solid)
$\gamma = 1$ (dashed)

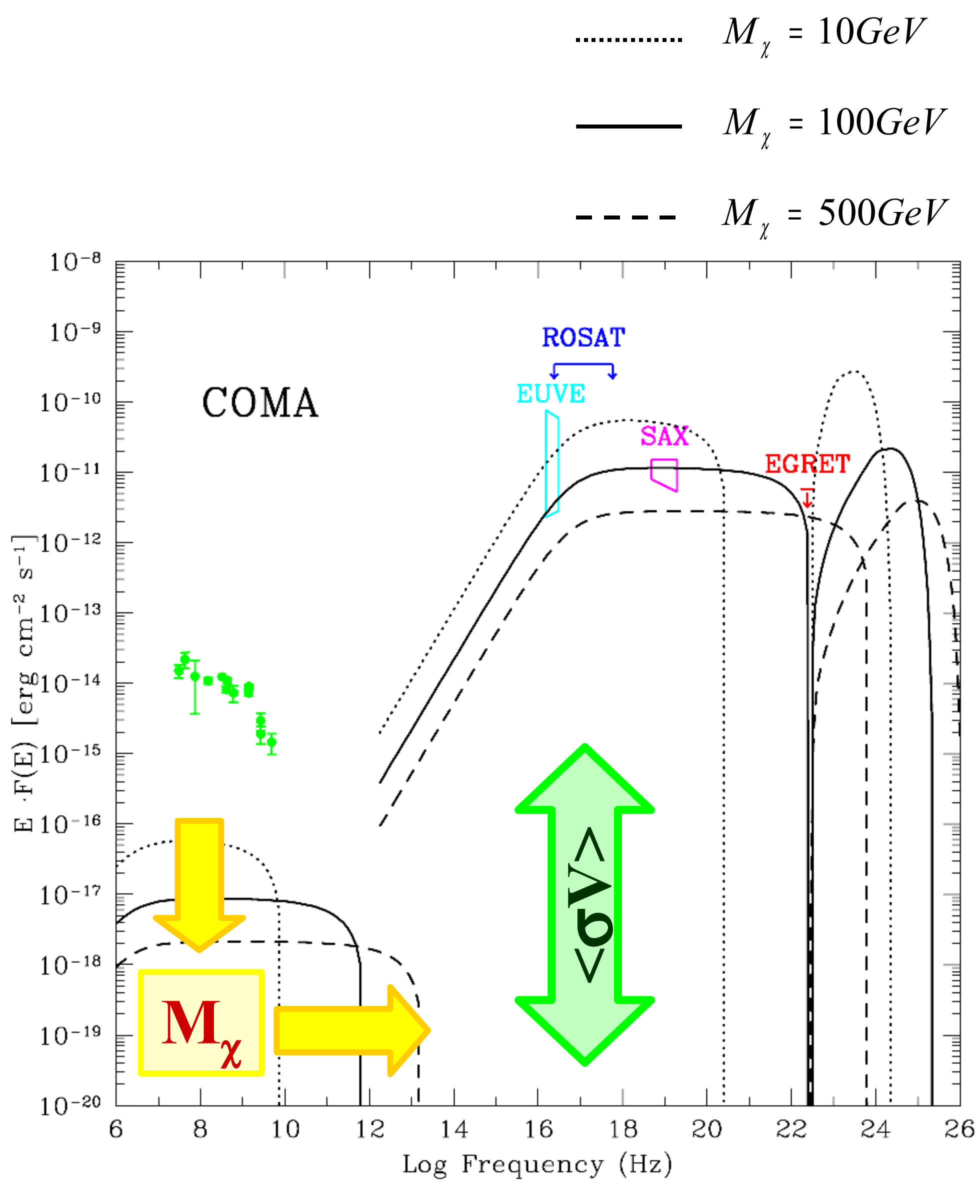
Relevant

Dwarf Sph. gal.

Signal Scalings

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

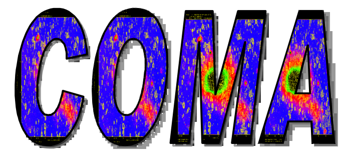
$$F_\nu \propto \langle \sigma V \rangle_{ann} \cdot \frac{1}{M_\chi^2} \cdot \frac{dn_e}{dE_e} \cdot \left(\frac{dE_e}{dE_\nu}\right)$$

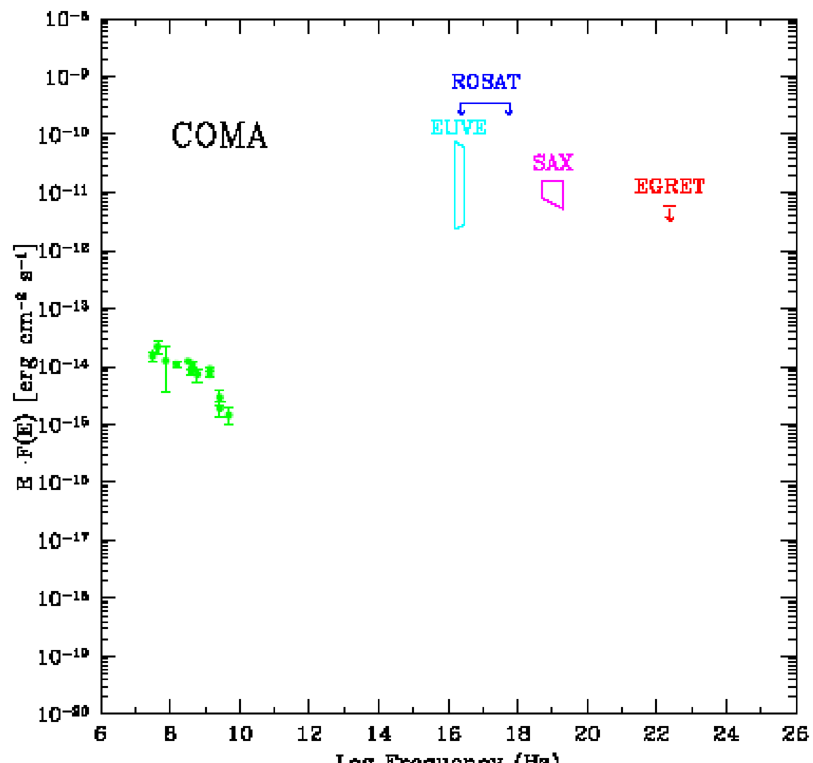


DM annihilation in galaxy clusters

Pros

- Largest bound structures
- High M_{DM}
- Steep DM profile
- Nearby
- multi-ν SEDs





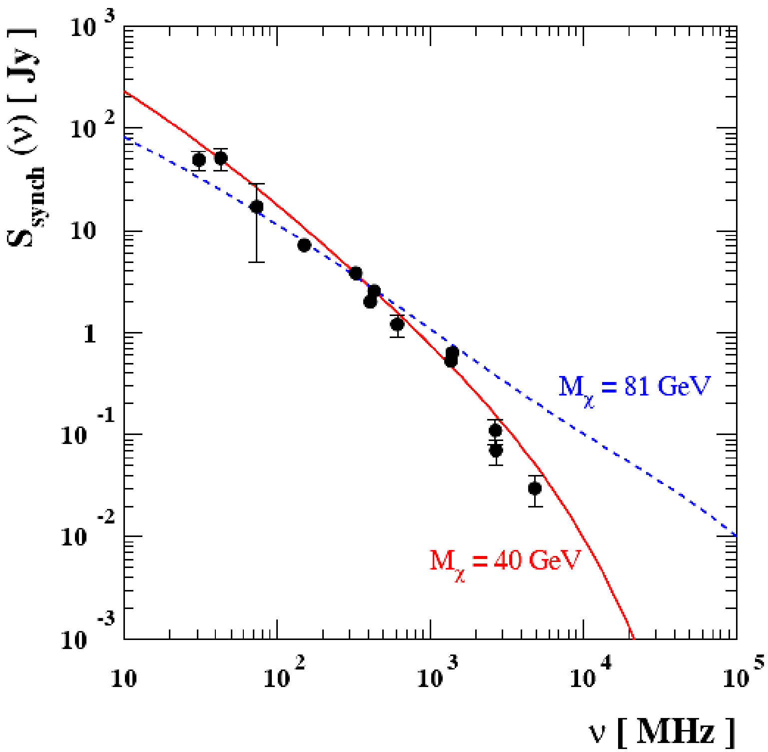
Cons

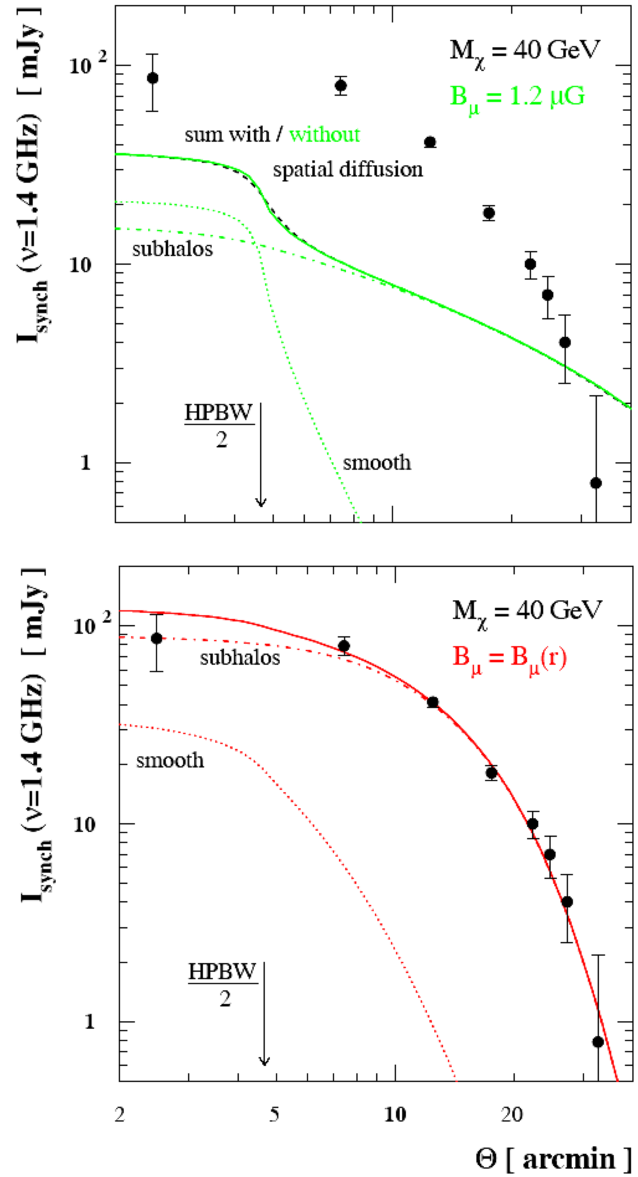
- Interaction/merging
  ⇒ sufficient time to disrupt cusps ?!
- Non-gravitational heating in cores
  ⇒ is DM mass profile reliable ?!
- Non-thermal phenomena
  ⇒cosmic-ray physics!

Constraints from Coma

Radio halo

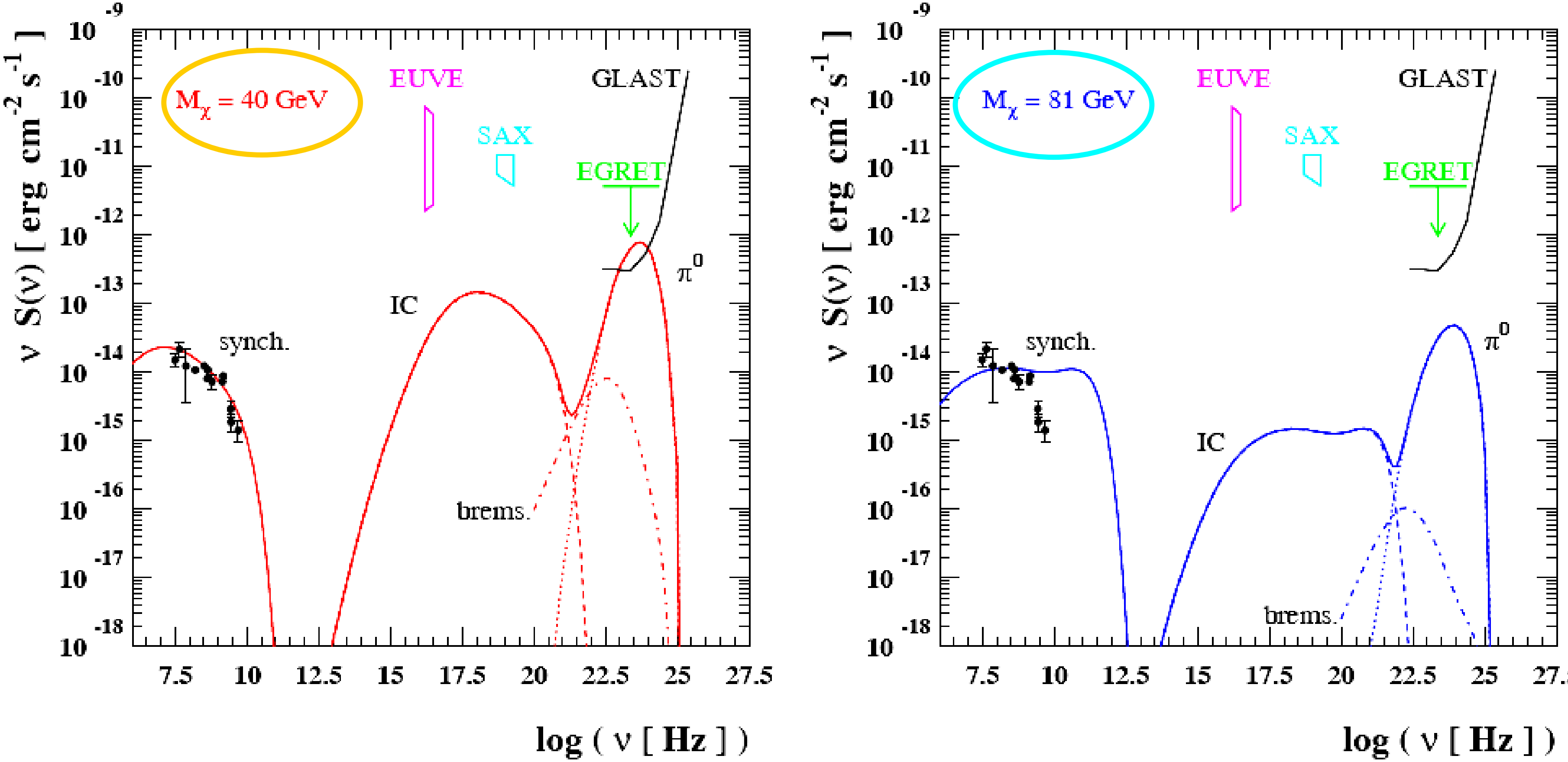
- integrated spectrum (30 MHz-5 GHz)
- brightness distribution (@ 1.4 GHz)





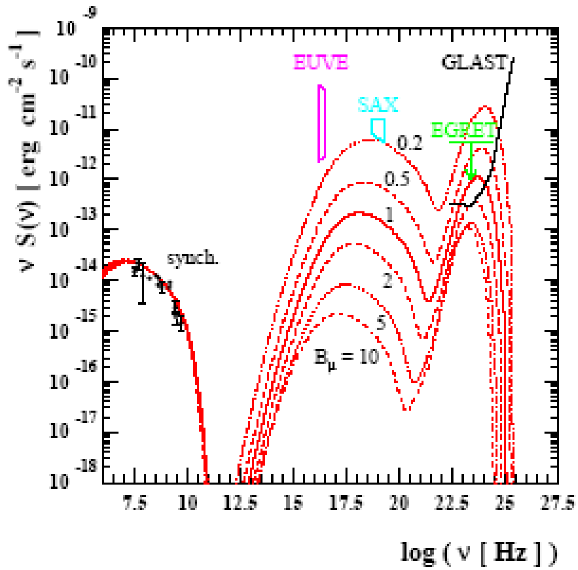
[Colafrancesco, Profumo & Ullio 2005 - 2006]

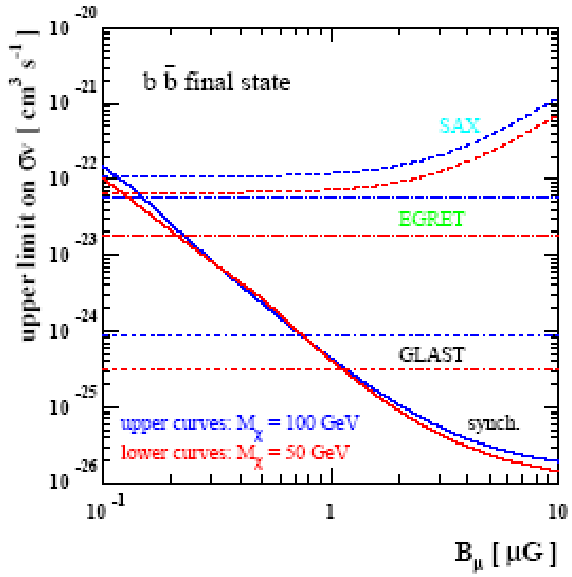
Constraints from Coma: multi – ν



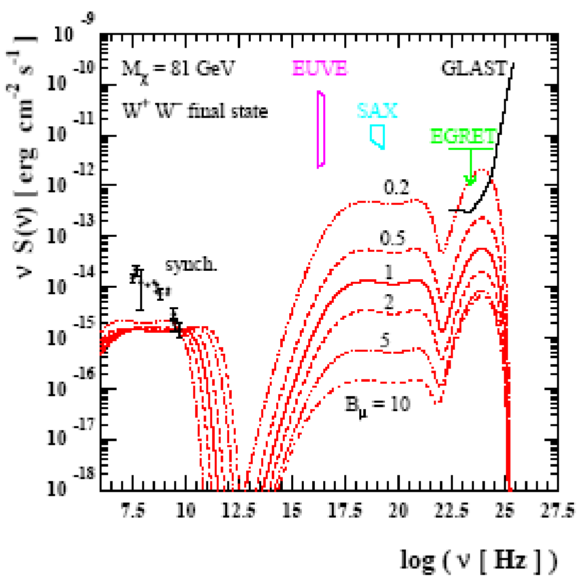
Dependence from B

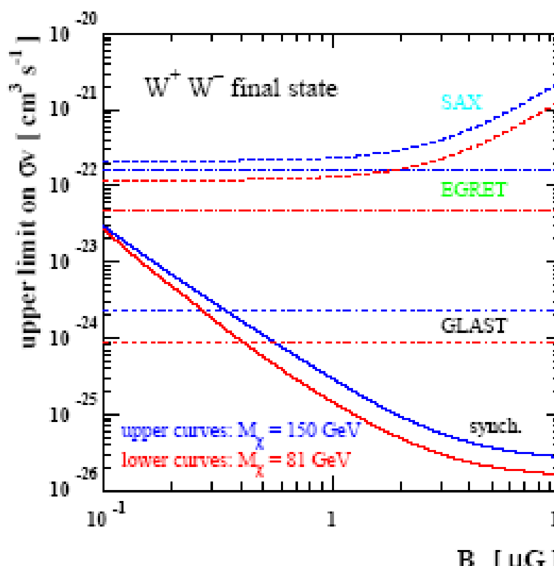
$M_\chi = 40$ GeV
$b\underline{b}$ final state



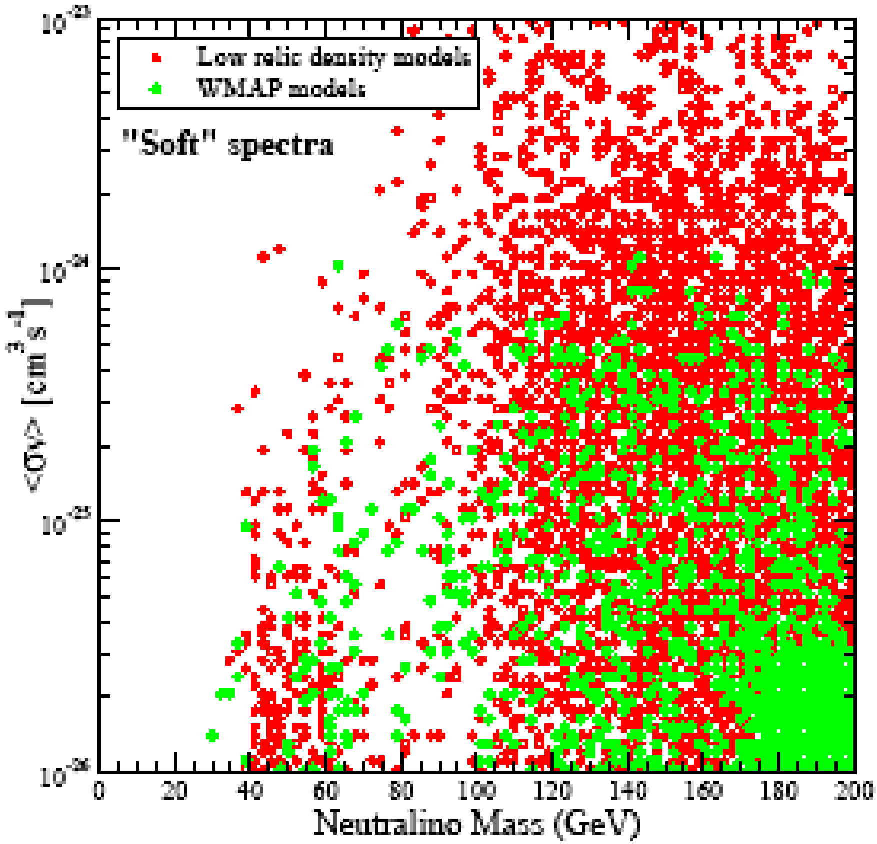


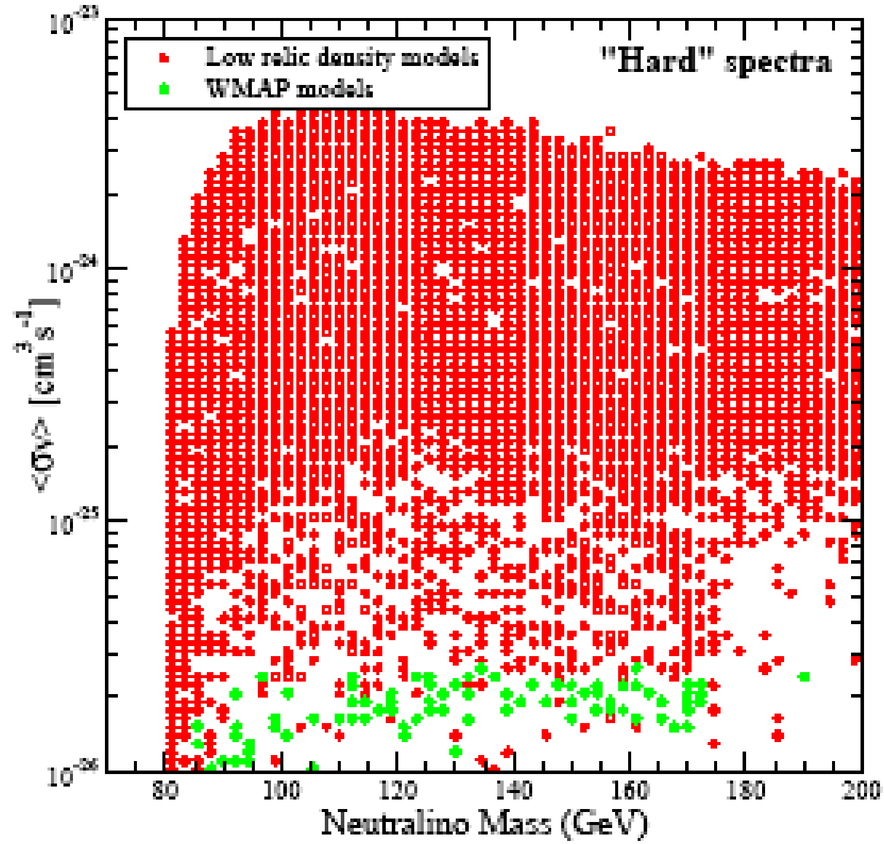
$M_\chi = 81$ GeV
W^+W^- final state





Constraints on χ physics



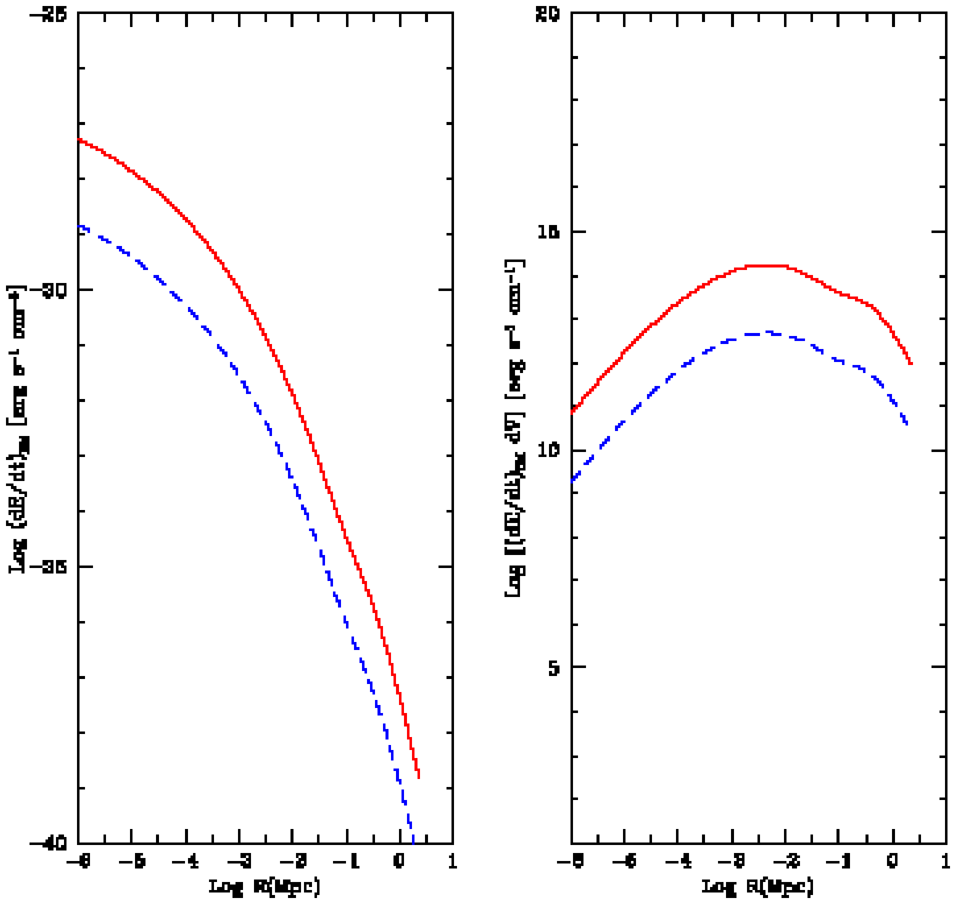


Heating by DM annihilation

Heating negligible for:

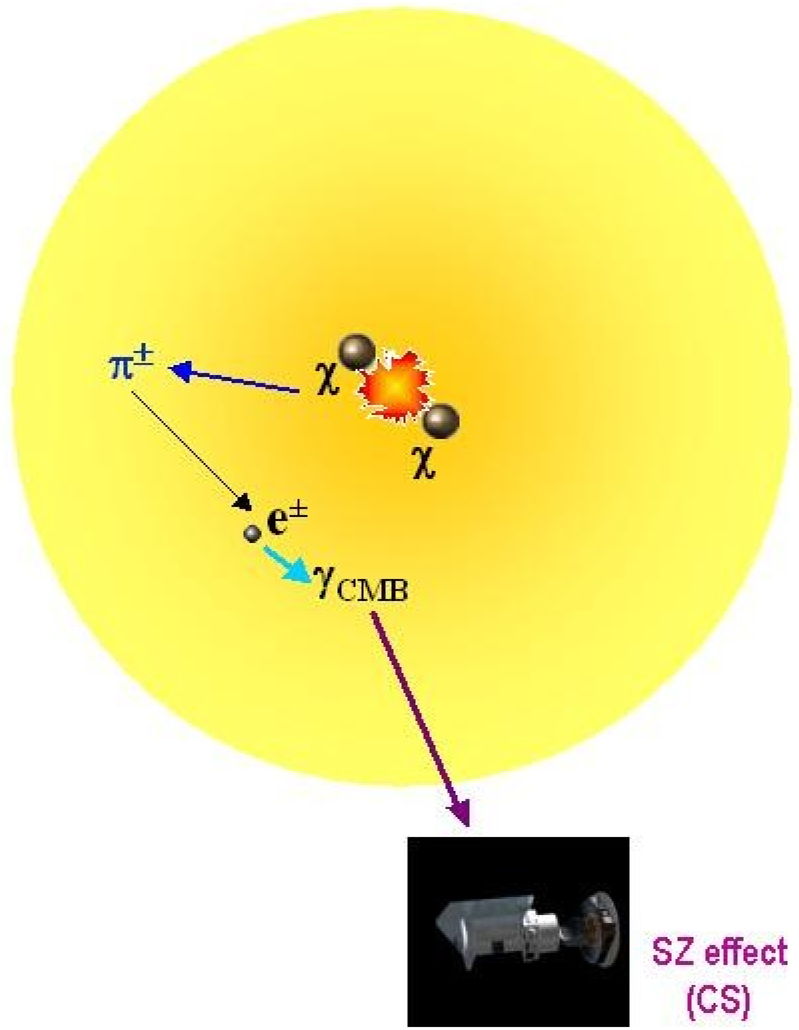
- **non-singular DM profile**
- **no central BH**

no cooling-flow solution



[Colafrancesco, Dar & DeRujua 2004]

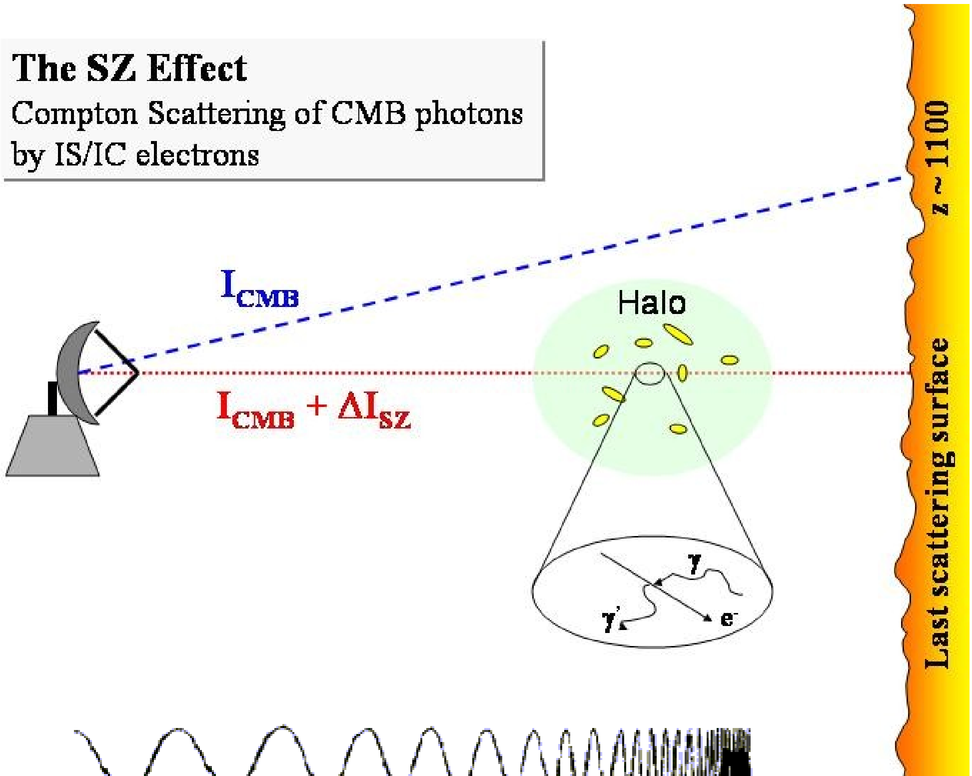
SZ effect from $\chi\chi$ annihilation

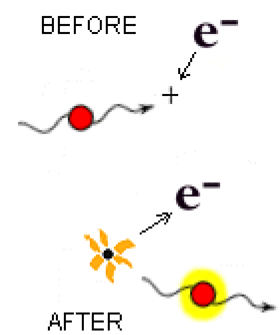


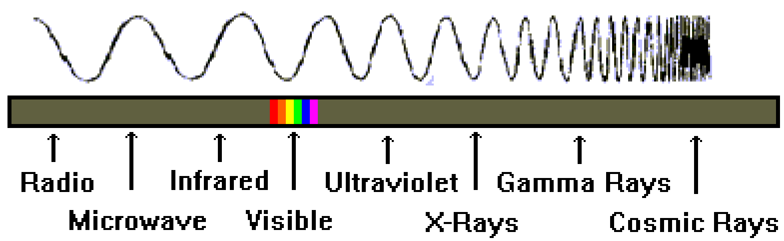
SZ effect from DM

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

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







thermal e⁻ $\quad \frac{\nu'}{\nu} = \frac{4}{3}$

relativistic e⁻ $\quad \frac{\nu'}{\nu} = \frac{4}{3}\gamma^2 - 1$

The case of Coma

SZ_{th} in Coma

$$k_B T_e = 8.2 keV$$

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

SZ_{kin} in Coma

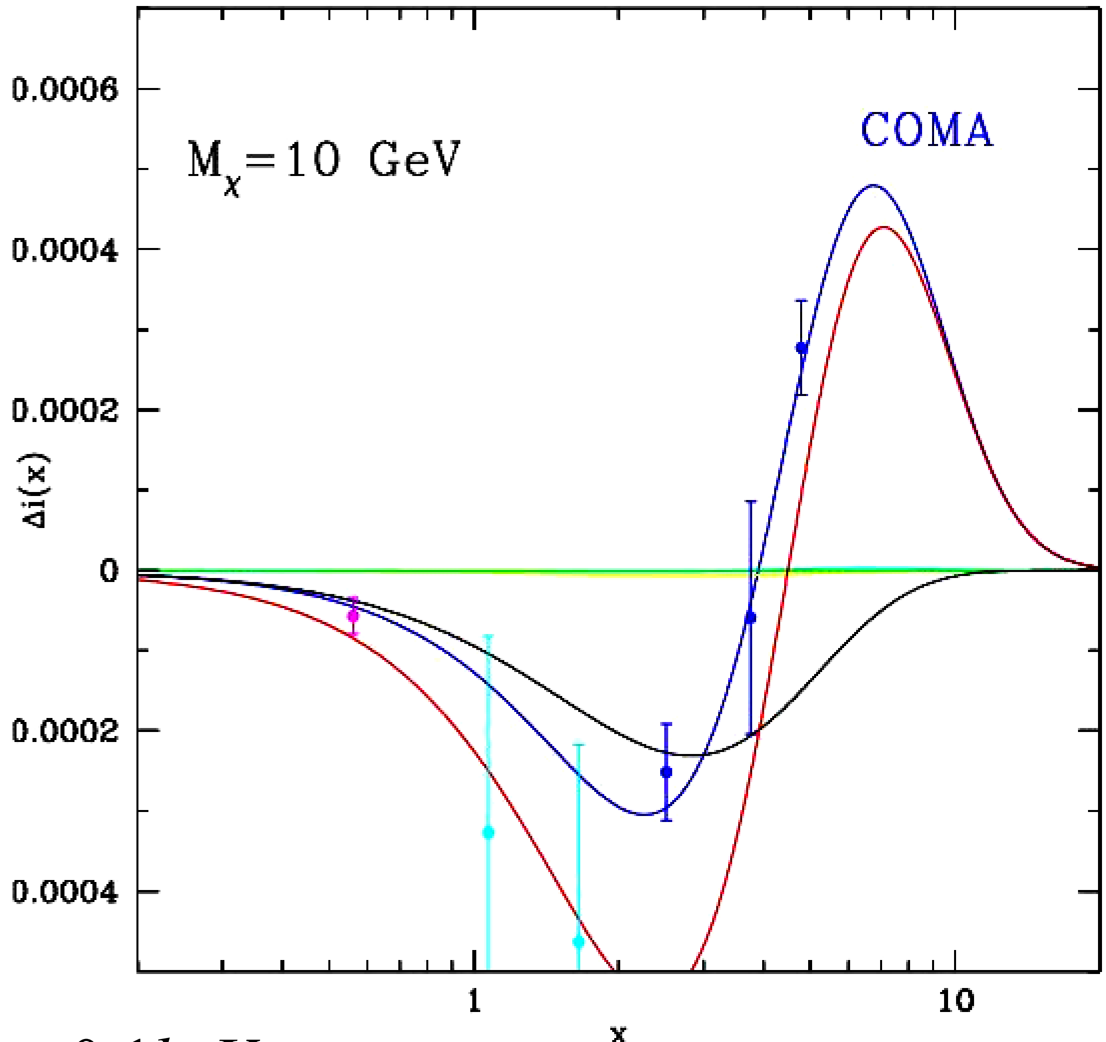
$$V_r = 0 km/s$$

SZ_{rel} in Coma

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

SZ_{warn} in Coma

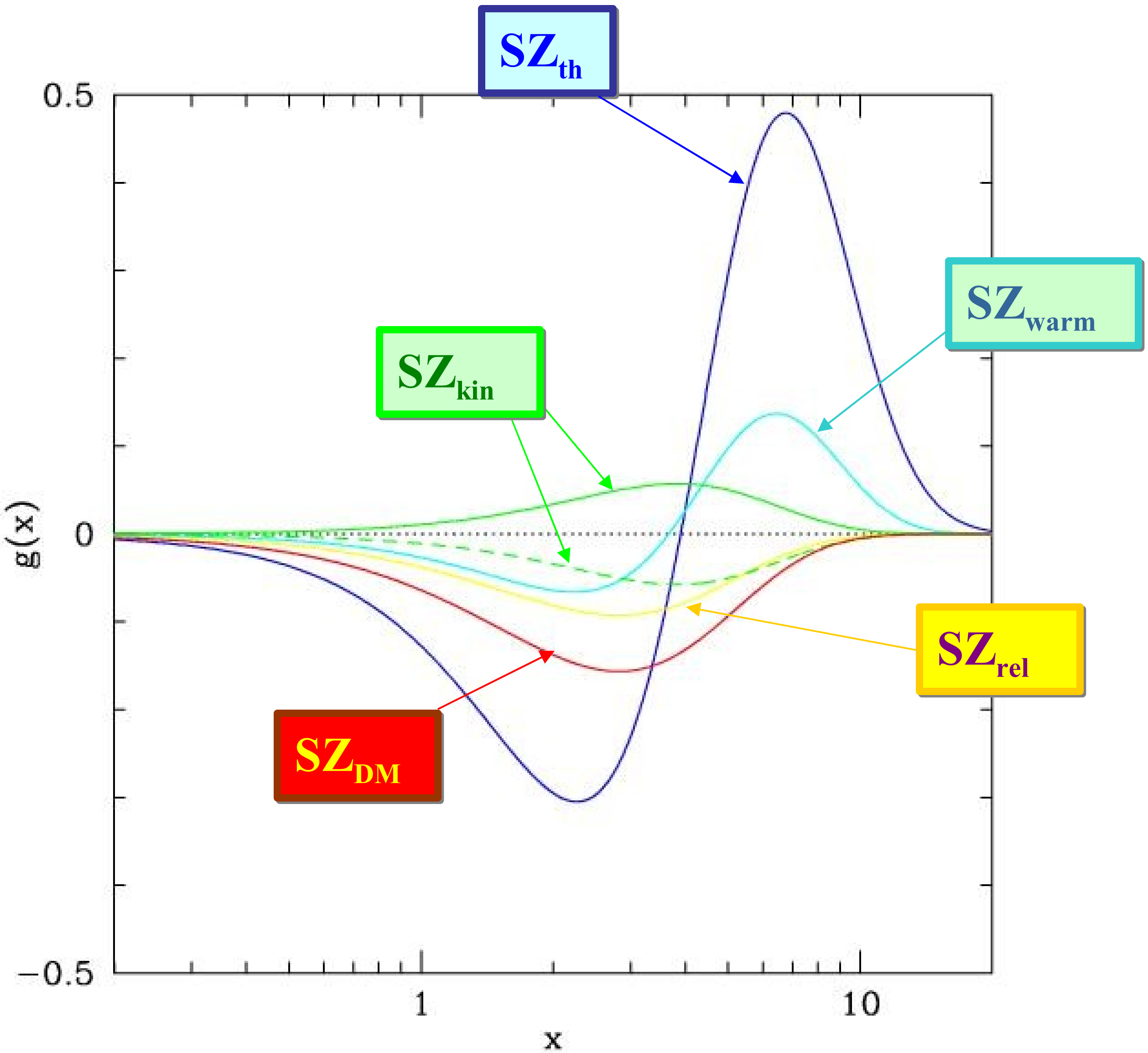
$$n_{warm} = 10^{-3} cm^{-3} \quad T_{warm} = 0.1 keV$$



SZE in DM halos

A structure with:

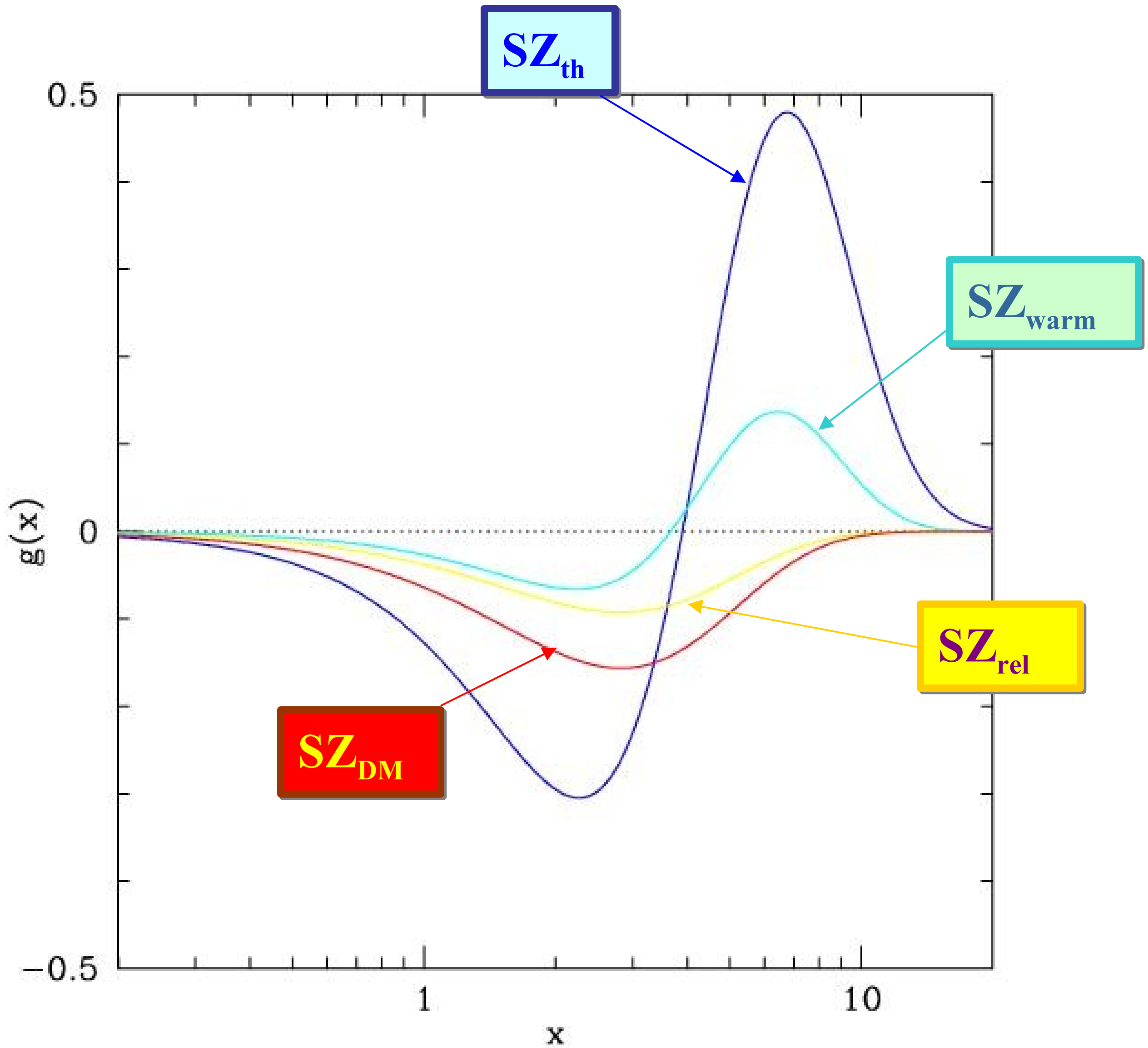
- **Hot gas**
- **Warm gas**
- **Rel. Plasma**
- **DM**
- **Distant & V_r**



SZE in DM halos

A structure with:

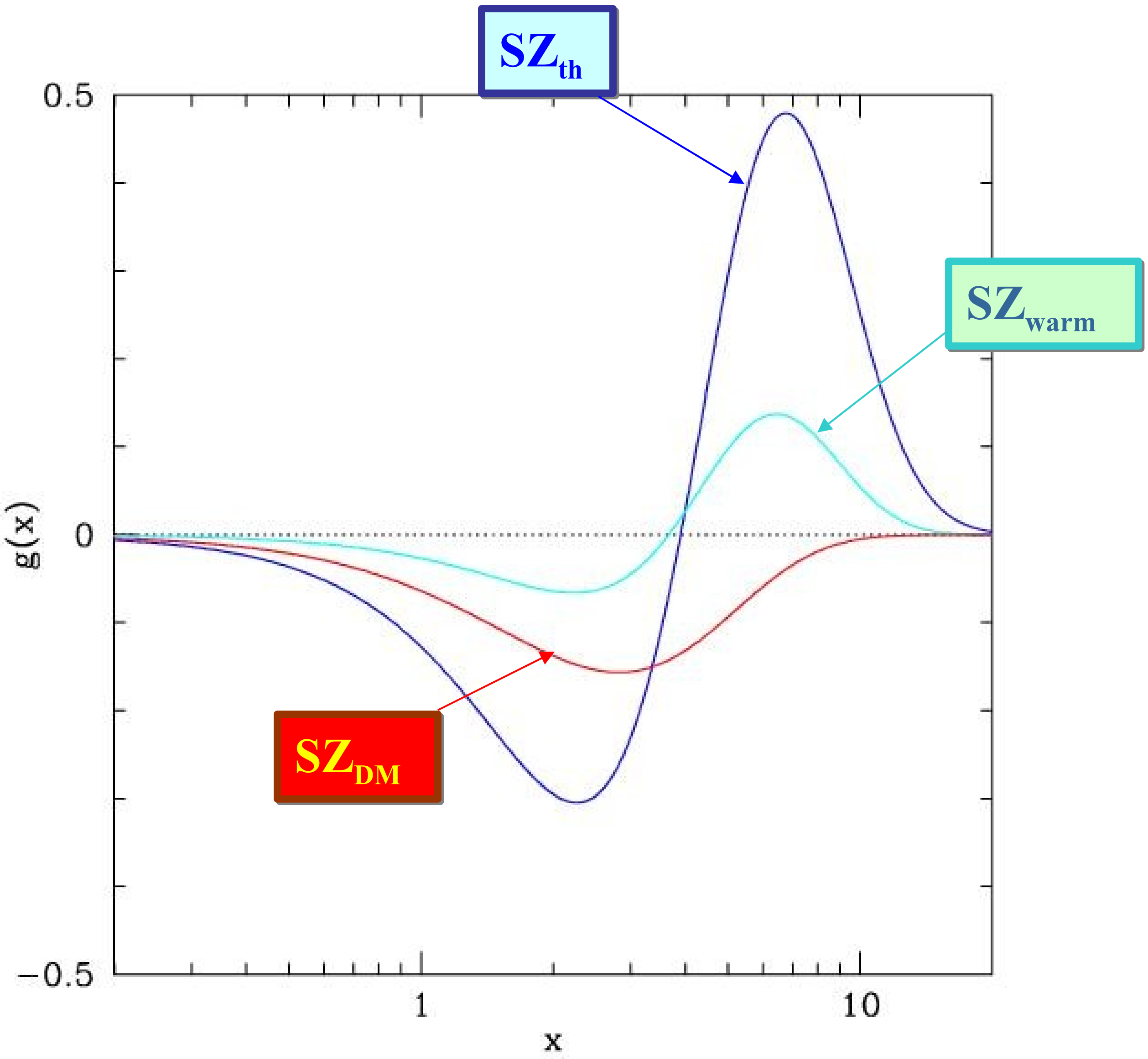
- **Hot gas**
- **Warm gas**
- **Rel. Plasma**
- **DM**
- **Nearby ($V_r \approx 0$)**



SZE in DM halos

A structure with:

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



SZE in pure DM halos

A structure with:

•

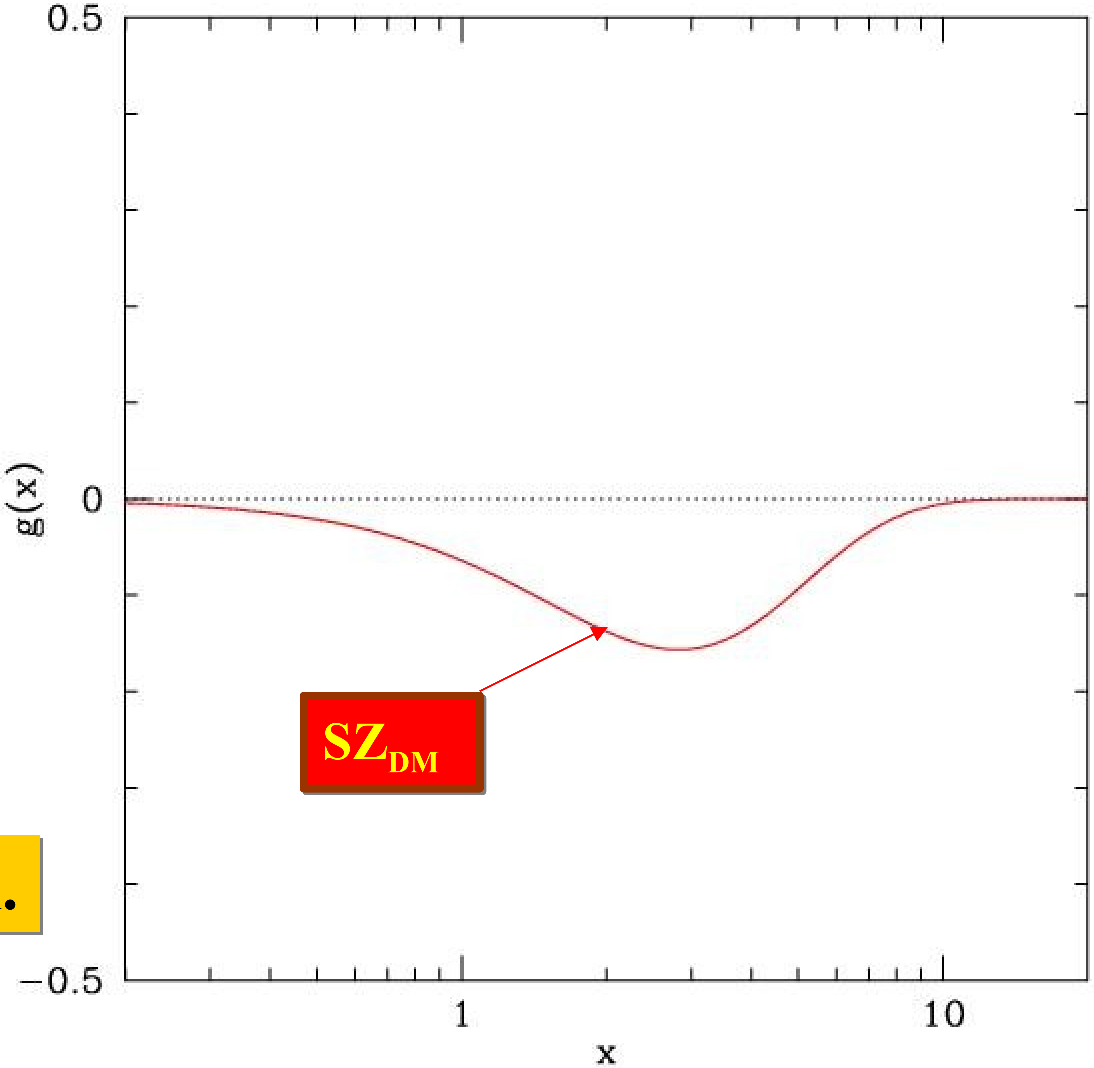
•

•

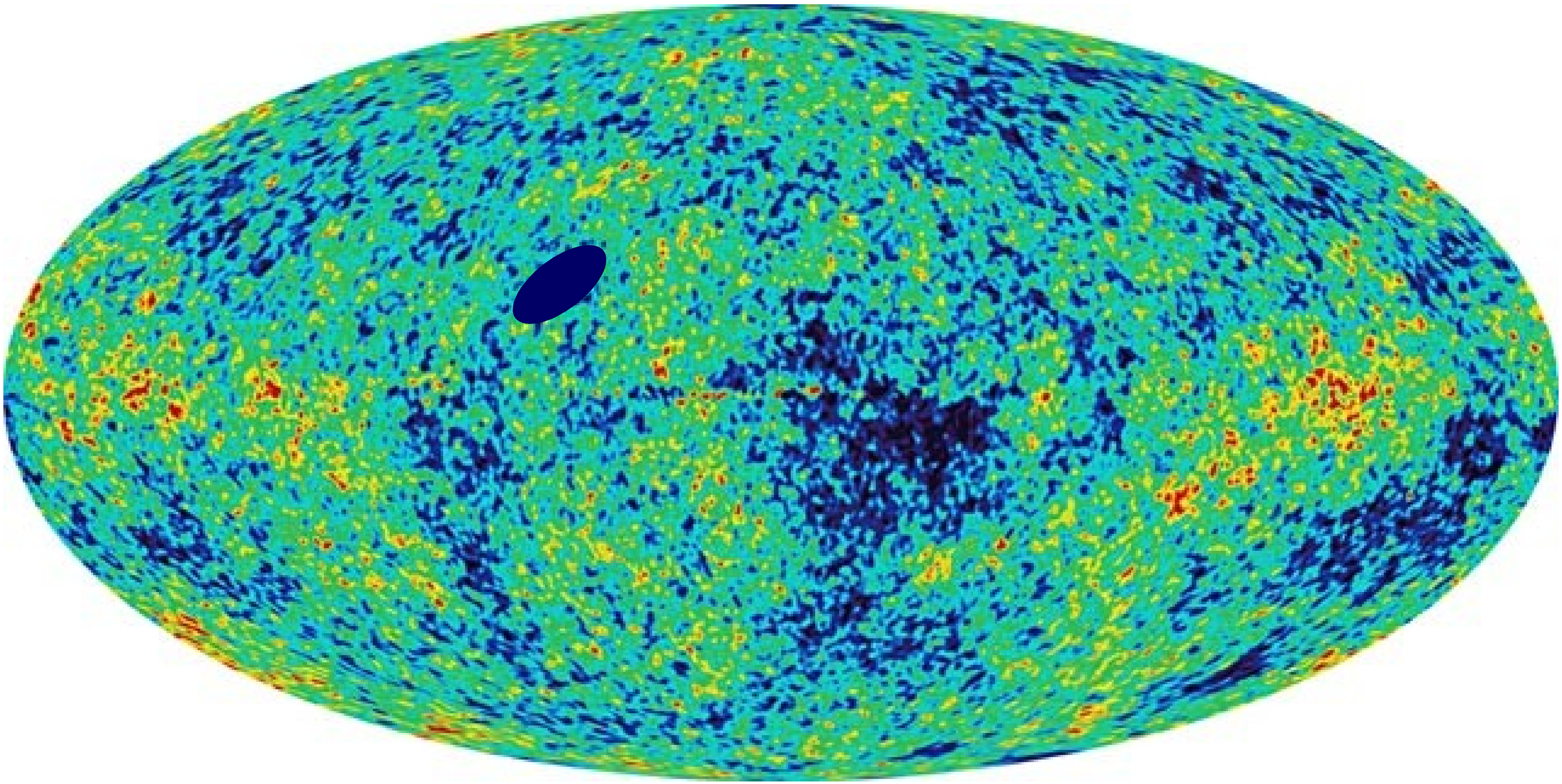
• **DM**

• **Nearby ($V_r \approx 0$)**

Dwarf Spheroidal gal.



CMB maps & DRACO



SZ_{DM} in Draco

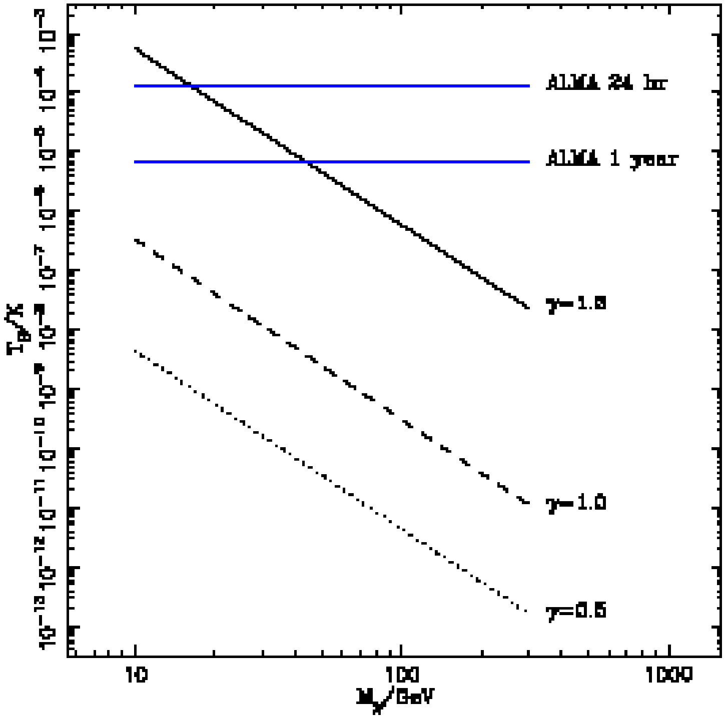
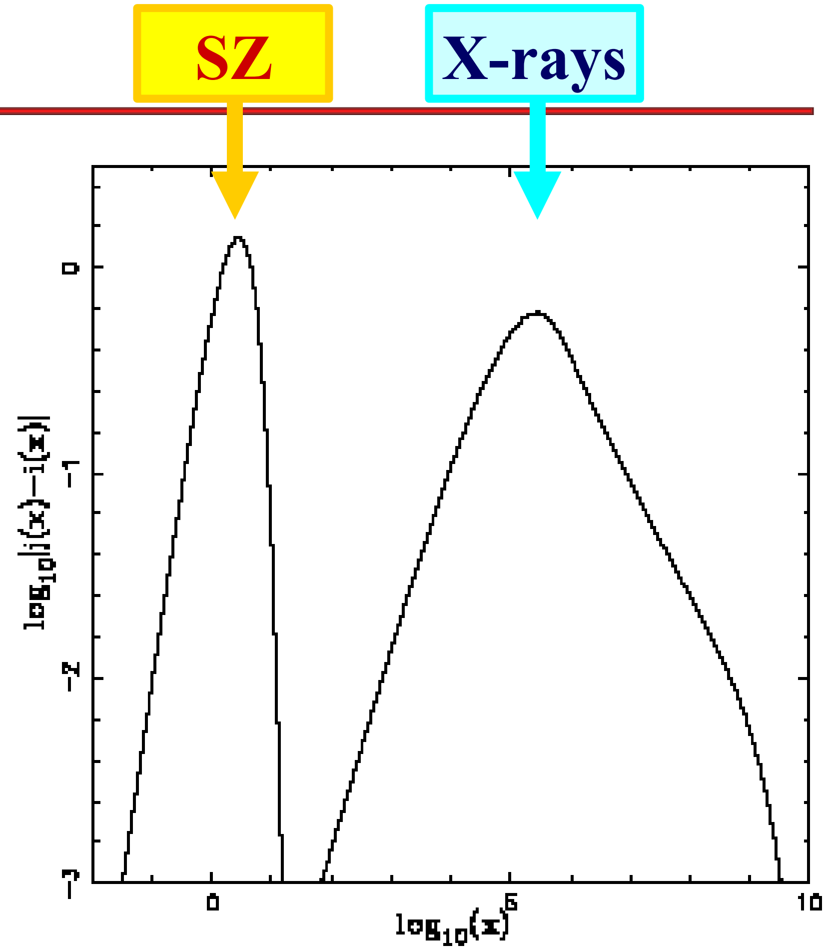


Figure 3. $M_\chi - T_B$ plane for three cusped dSph profiles, with an assumed NFW profile for the Milky Way (isothermal power-law models give almost identical results). We assume a 1" beam at 100GHz, and display the brightness temperature sensitivity for 24 hr and 1 yr ALMA observation.



γ	$F_{TOT}/10^{-12}cm^{-2}s^{-1}$
0.5	2.604 (2.564)
1.0	2.962 (2.914)
1.5	1.625×10^1 (1.795×10^1)

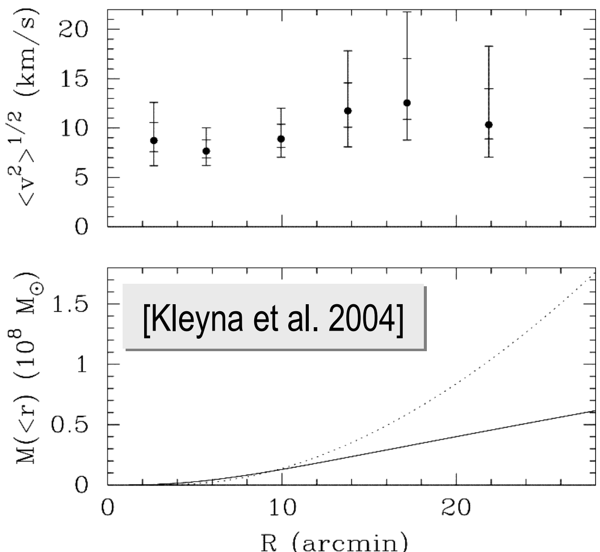
α	$F_{TOT}/10^{-12}cm^{-2}s^{-1}$
0.2	1.325 (1.301)
0.0	1.539 (1.436)
-0.2	1.955 (1.654)

[Culverhouse, Ewans & Colafrancesco 2006]

DM annihilation in Dwarf galaxies

Pros

- **High M/L ratio**
- **Steep DM profile**
- **Flat $\langle v^2 \rangle^{1/2}$**
- **Very close**
- **multi-ν SEDs**



Draco

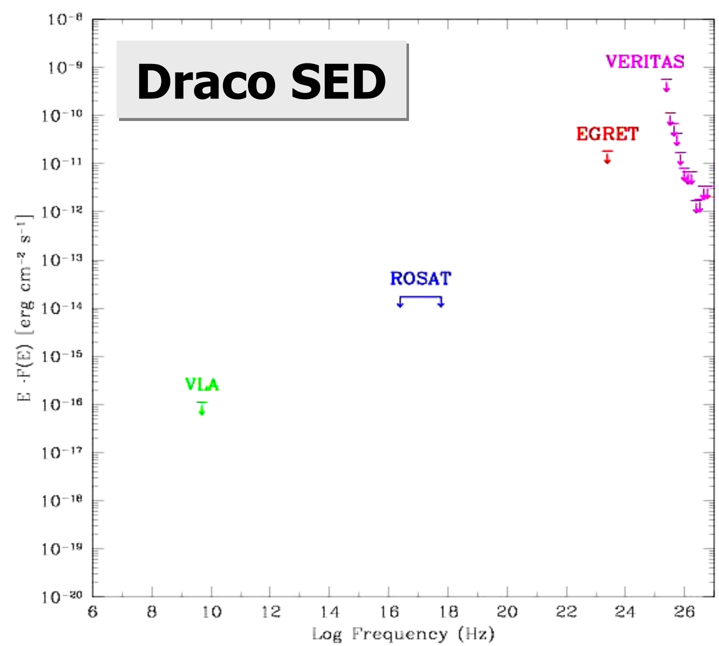
[CPU 2006]

$$D_L^{Draco} \approx 87 kpc$$

$$\frac{M}{L} \approx 300 \div 600$$

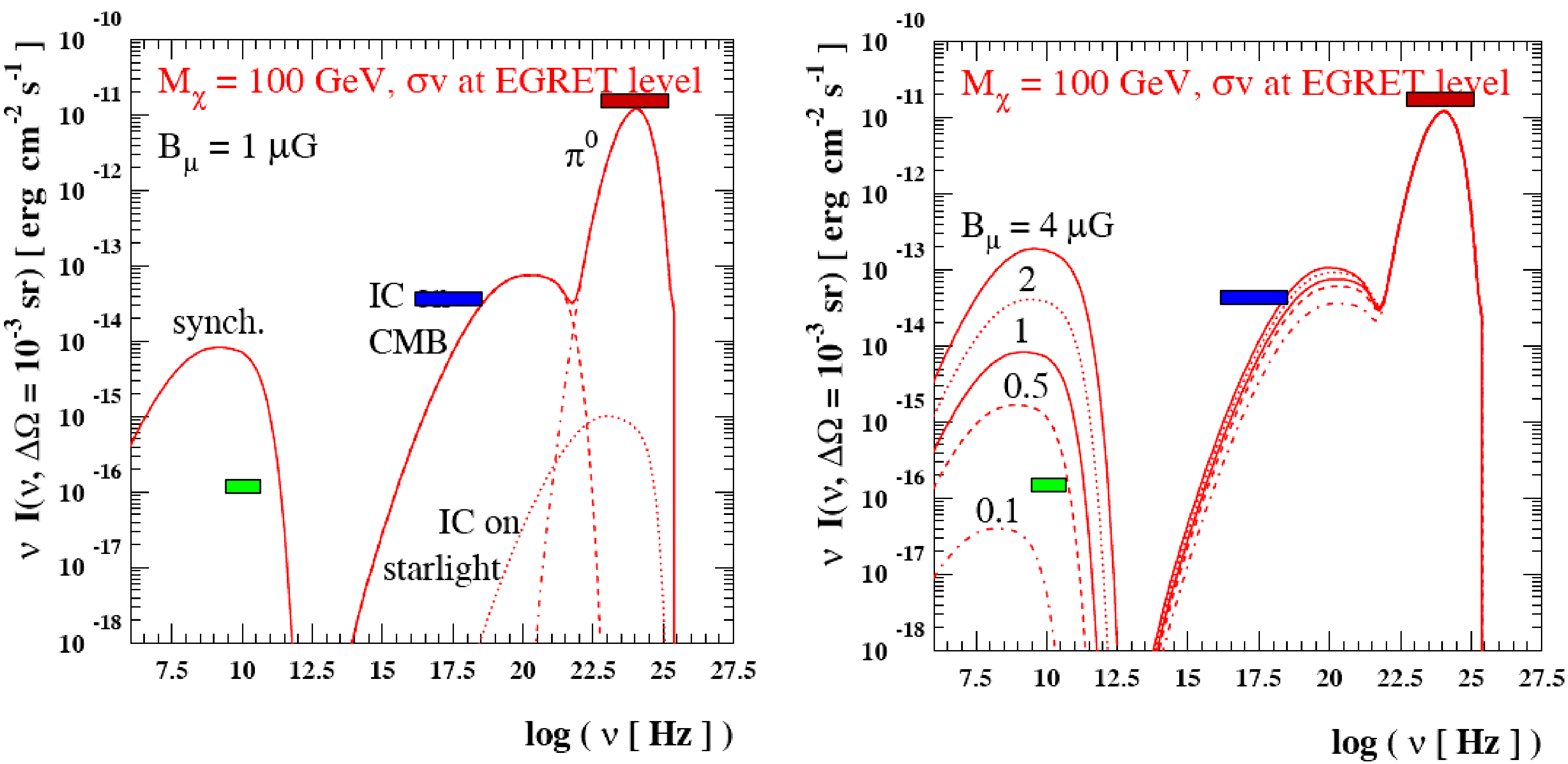
Cons

- Interaction/merging
  → sufficient time to disrupt cusps ?!
- BH–DM interaction on r ≤ 1 pc
  → is DM mass profile reliable ?!
- Dynamical equilibrium stage
  → is M/L reliable ?!



Draco: multi-n SED

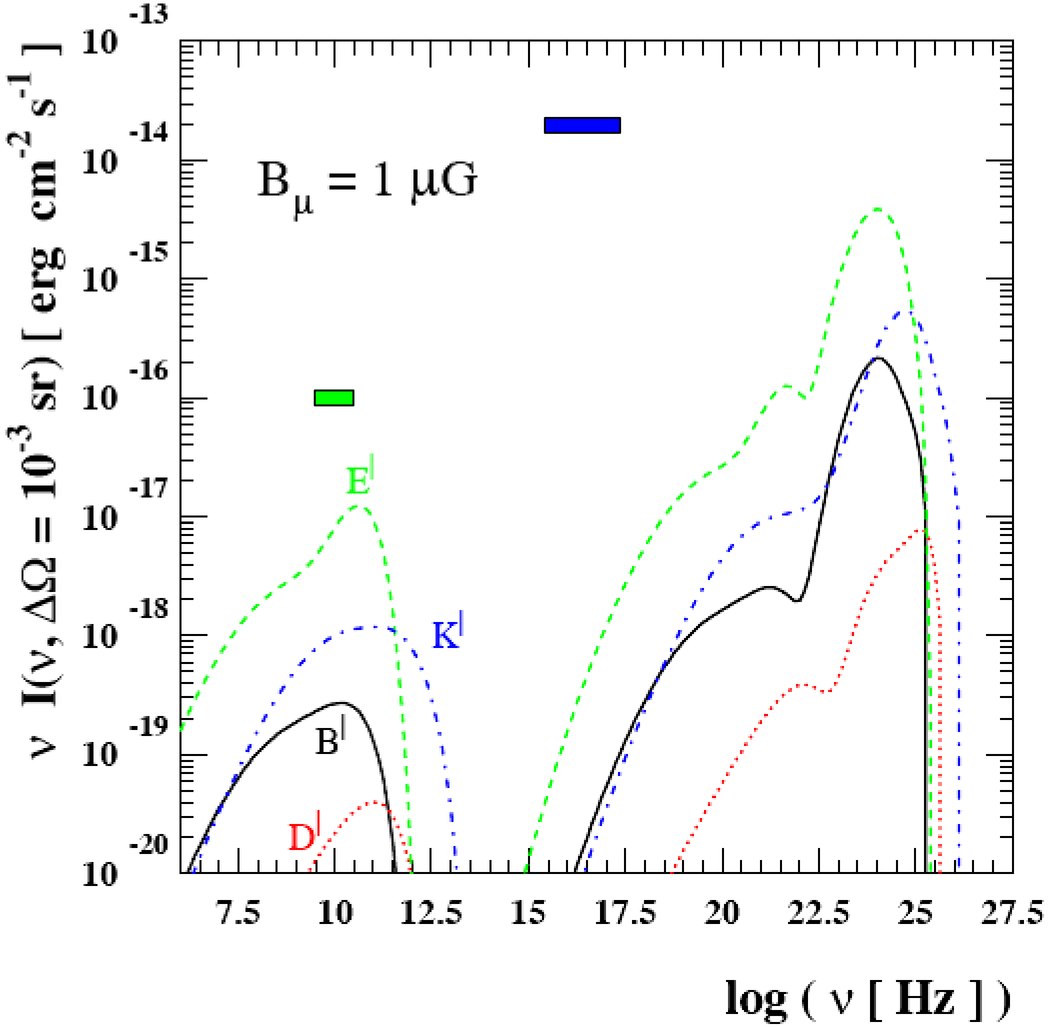
[Colafrancesco, Profumo & Ullio 2006]



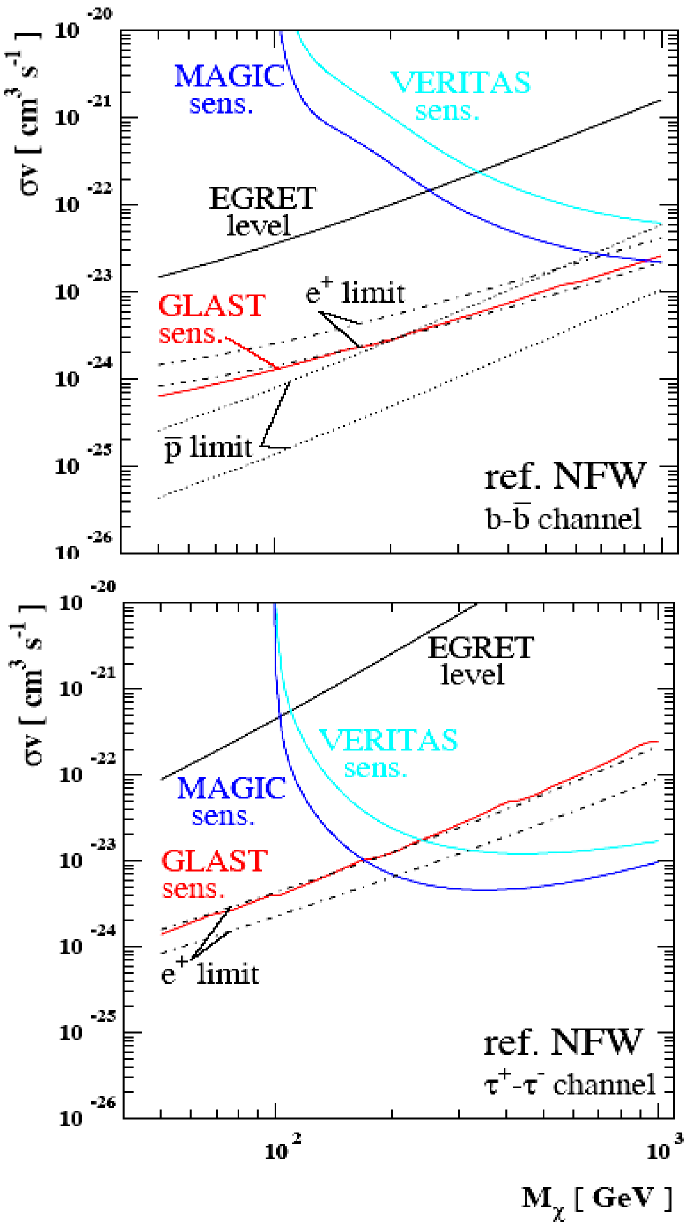
<σV> normalized to recover the EGRET limit

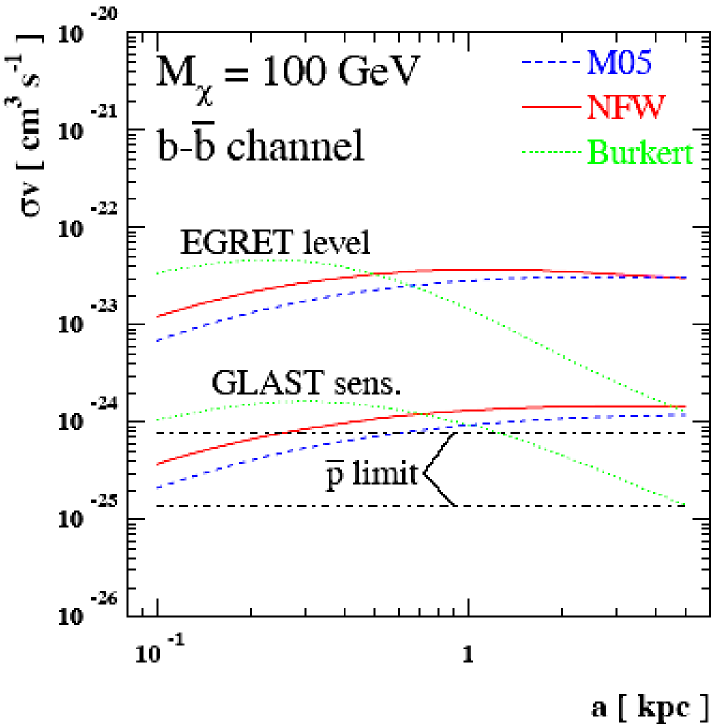
Draco: multi-n SED

Snowmass benchmarck models

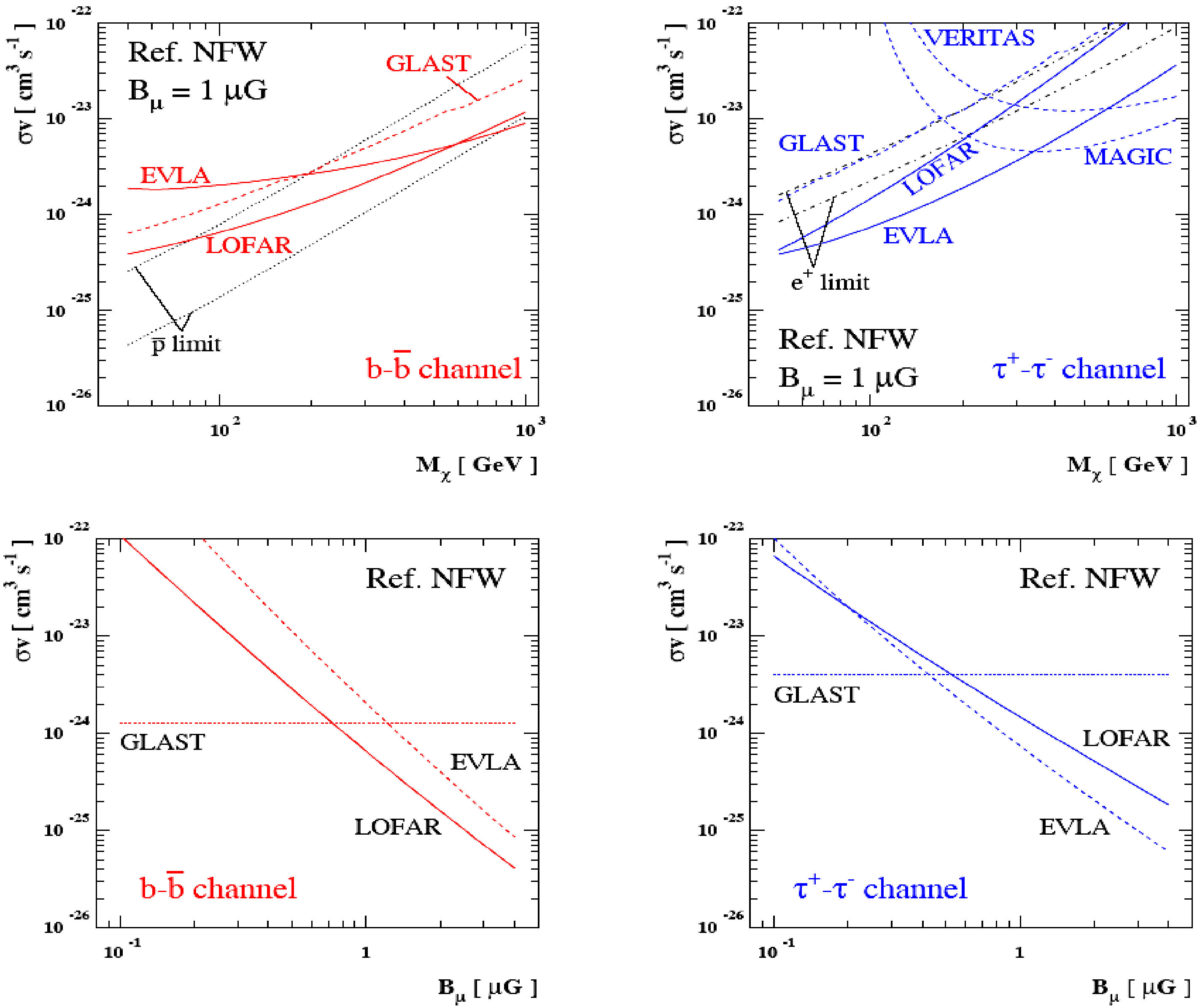


DRACO: limits





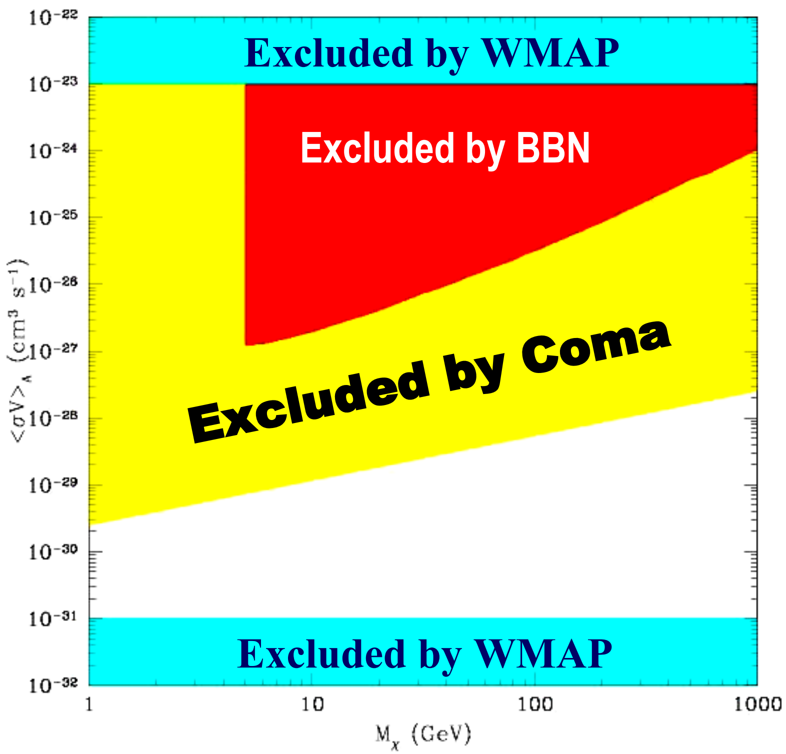
DRACO: projected sensitivities



Combining Astro-Cosmo-Particle

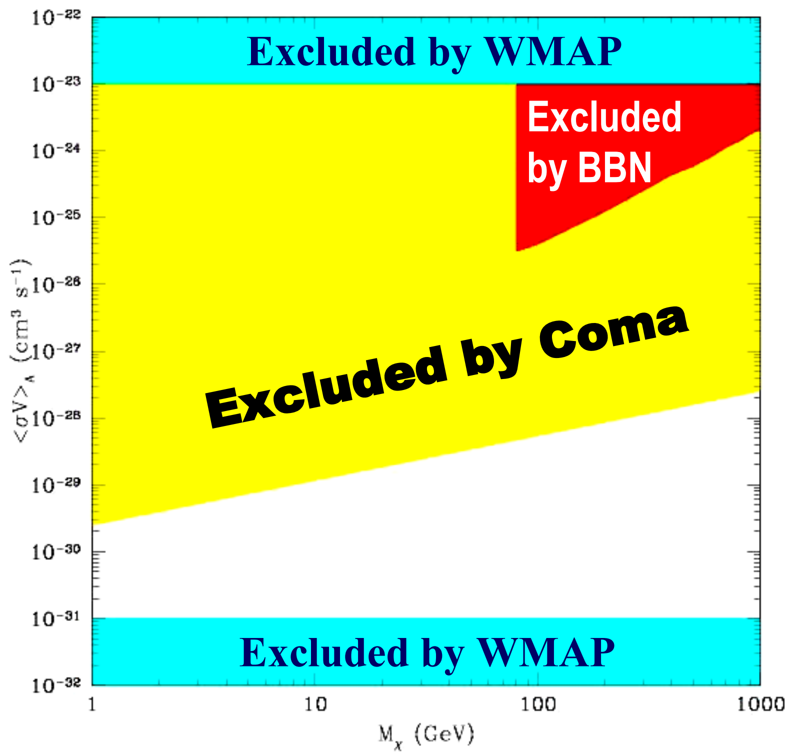
uū χ model

NFW profile

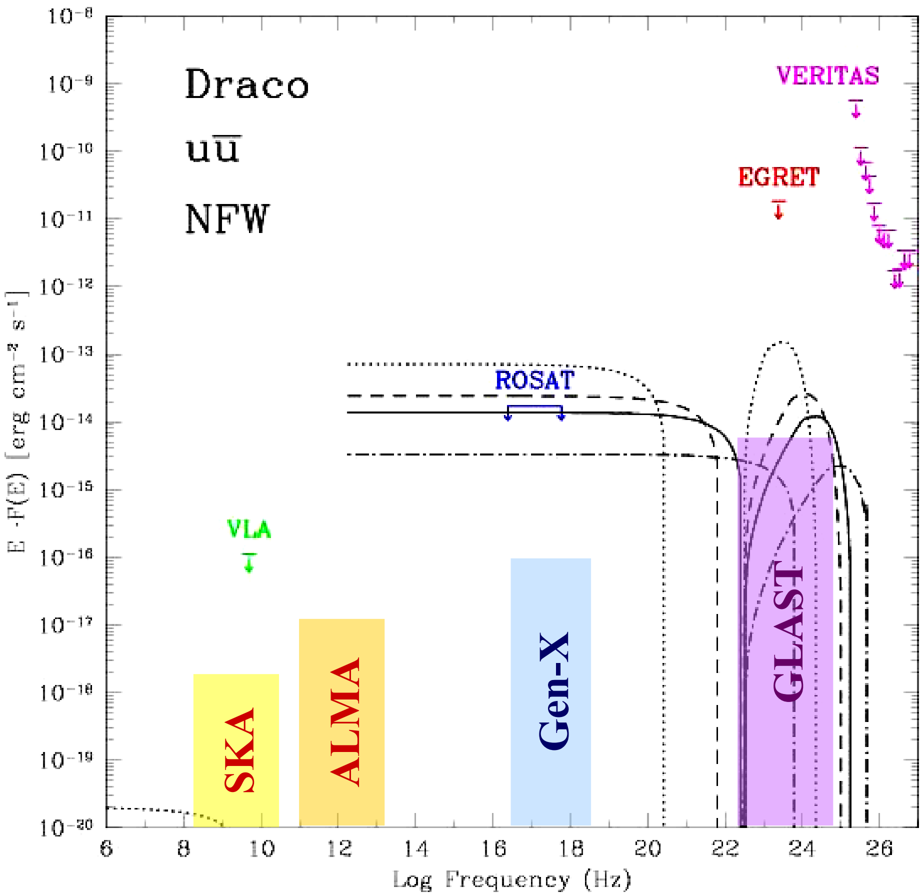


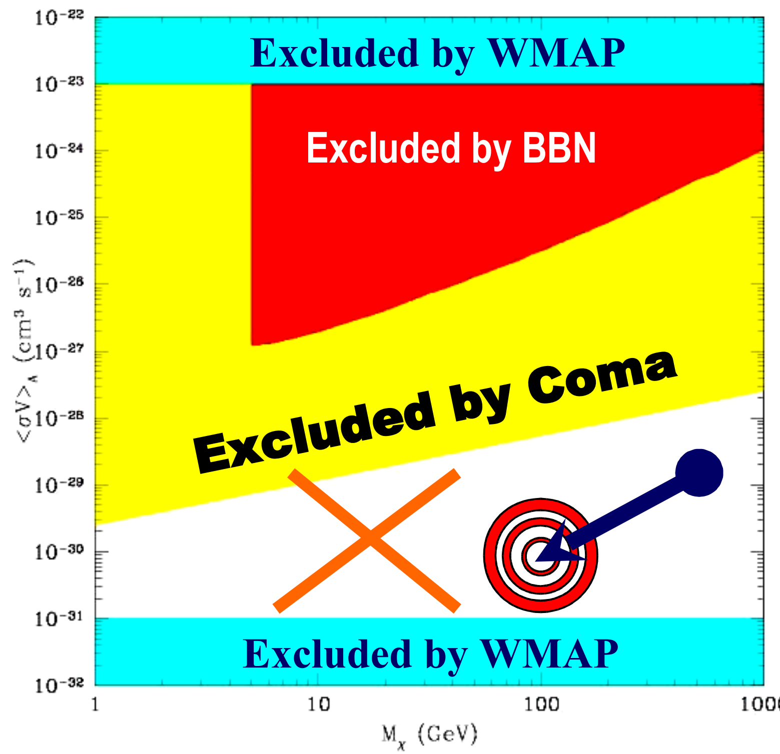
W± χ model

NFW profile



Looking deeper into dark halos





THANKS

for your attention !