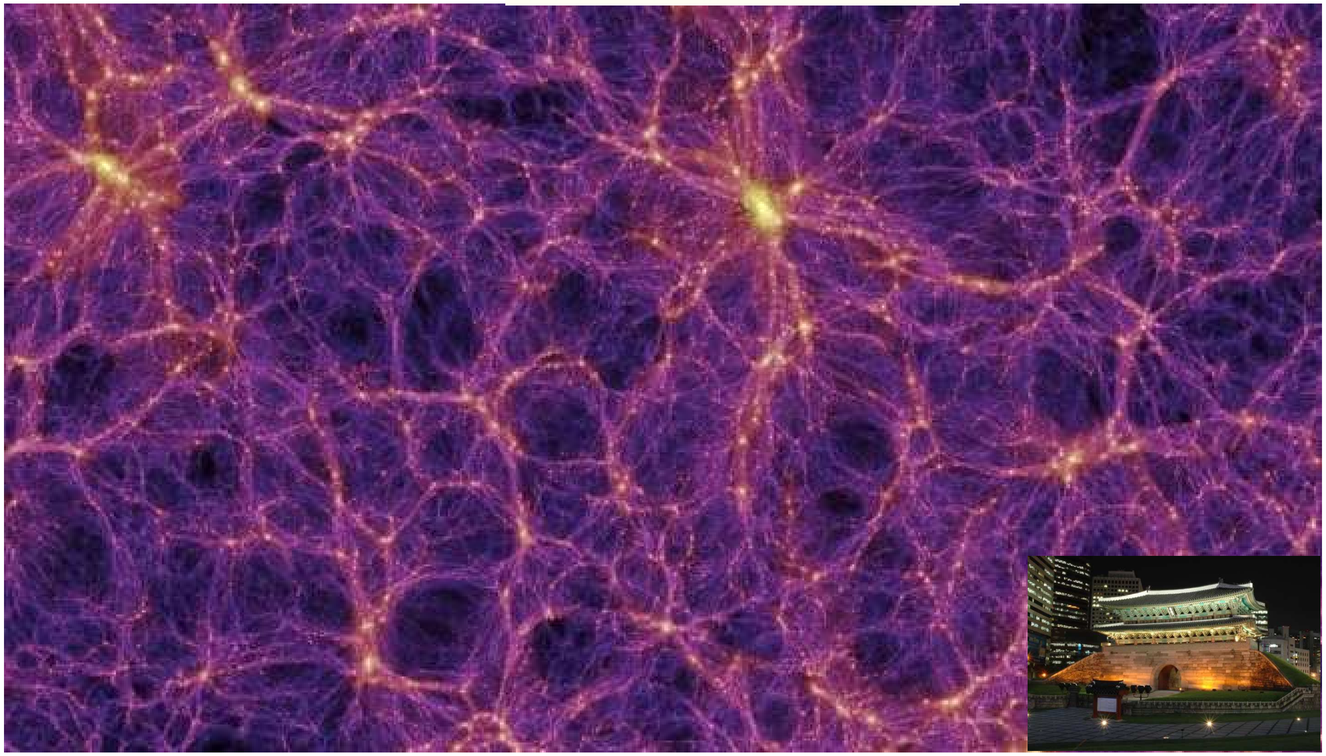
DARK MATTER II

Stefano Scopel

KIAS

KOREA INSTITUTE FOR ADVANCED STUDY



PRE-SUSY ’08, Seoul, Korea

DARK MATTER III

Youngduk Kim's talk tomorrow
Will cover experimental issues

Conclusions / part 1

•the WIMP "miracle": combination of physical scales in a range of 60 orders of magnitude points to DM at the TeV scale → same cut-off expected in the SM

•can be realized in different well-motivated scenarios (KK photon in UED, Heavy photon in Little Higgs, neutralino in SUSY)+"Minimal" extensions of SM

• neutralino in susy is the most popular! Today available in different flavours: SUGRA, nuSUGRA, sub-GUT, Mirage mediation, NMSSM, effMSSM (light neutralinos), CPV,…

•WIMPS are CDM: they catalyze galaxy formation decoupling earlier than baryons and allowing gravitational instabilities to grow enough time to explain structures today → when baryons decouple they fall into the potential well created by CDM

•the bottom line: WIMPS cluster in Galaxies included our own, <u>exactly where we can in principle measure them</u>!!!

SEARCHES

Searches for relic WIMPs

- Direct searches. Elastic scattering of χ off nuclei (∝ WIMP local density)

$$\chi + N \rightarrow \chi + N$$

- Indirect searches. Signals due to χ - χ annihilations

$$\chi + \chi \;\rightarrow\; \begin{array}{c} g\,g \\ f\,\bar{f} \\ W^+W^- \\ ZZ \\ HH,\ hh,\ AA,\ hH,\ hA,\ HA,\ H^+H^- \\ W^+H^-,\ W^-H^+ \\ Zh,\ ZH,\ ZA \end{array} \;\rightarrow\; \nu,\ \bar{\nu},\ \gamma,\ \bar{p},\ e^+,\ \bar{d}$$

- ➢ Annihilations taking place in celestial bodies where χ's have been accumulated: ν's → up-going μ's from Earth and Sun
- ➢ Annihilations taking place in the Halo of the Milky Way or that of external galaxies: enhanced in high density regions (∝ (WIMP density)^2) ⇒ Galactic center, clumpiness

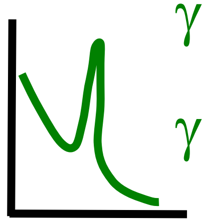
Annihilations taking place in the Halo

($\propto$ WIMP (local density)^2)

$\chi + \chi \rightarrow$

$\nu, \bar{\nu}$

γ (continuum)



γ line ($Z\gamma$)

keep directionality

$\bar{p}$

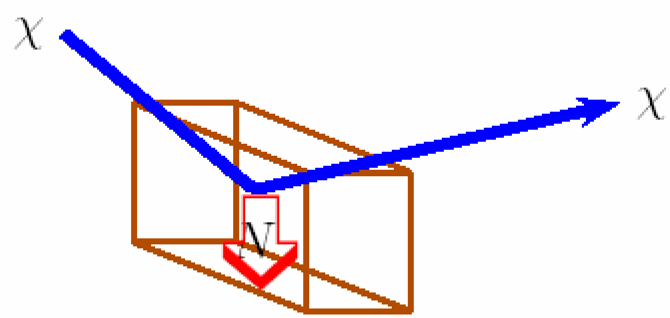
e^+

$\bar{D}$

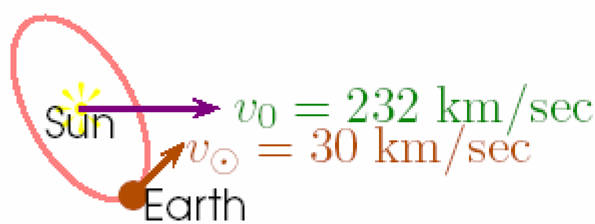
searches for rare components in cosmic rays

((diffusion)

WIMP direct detection



- Elastic recoil of non relativistic halo WIMPs off the nuclei of an underground detector
- Recoil energy of the nucleus in the keV range
- Yearly modulation effect due to the rotation of the Earth around the Sun (the relative velocity between the halo, usually assumed at rest in the Galactic system, and the detector changes during the year)



WIMP differential detection rate

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{vmin}^{v_{max}} d\vec{v} f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

E_R=nuclear energy
N_T=# of nuclear targets
v=WIMP velocity in the Earth's rest frame

Astrophysics

- ρ_χ=WIMP local density
- f(v)= WIMP velocity distribution function

Particle and nuclear physics

- $\frac{d\sigma(\vec{v}, E_R)}{dE_R}$ =WIMP-nucleus elastic cross section

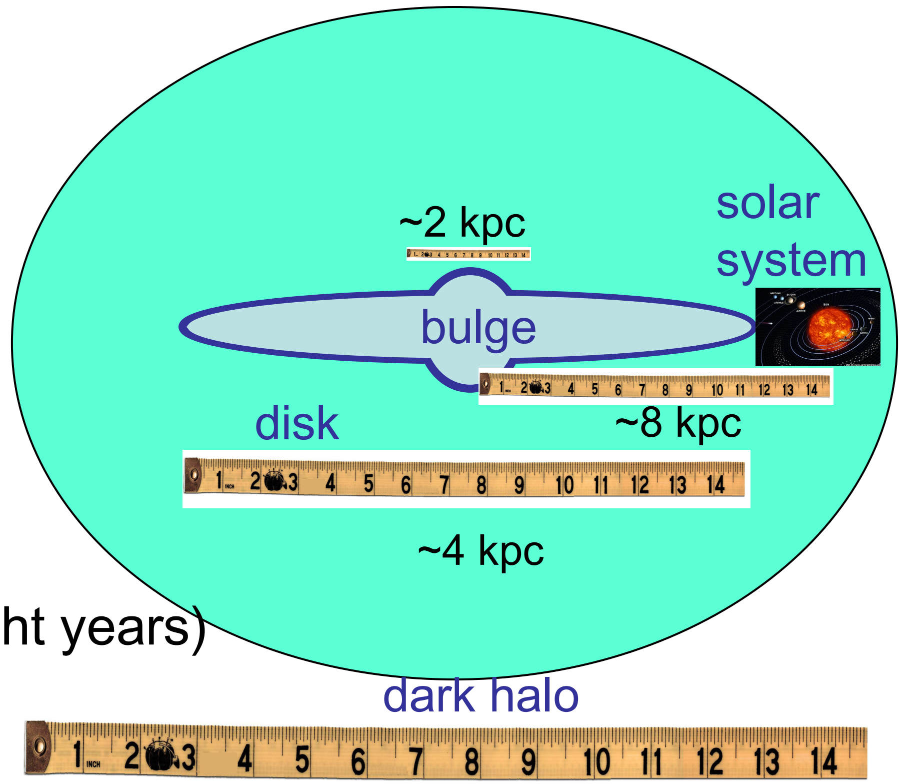
$$\frac{d\sigma(\vec{v}, E_R)}{dE_R} = \left(\frac{d\sigma(\vec{v}, E_R)}{dE_R}\right)_{\text{coherent}} + \left(\frac{d\sigma(\vec{v}, E_R)}{dE_R}\right)_{\text{spin-dependent}}$$

usually dominates, α (atomic number)^2

A few important statements about our Galaxy:

1) WIMPS are expected to form a (more or less) spherical halo in which the visible part of our Galaxy (disk and bulge) are immersed

(not in scale!)



(1 pc~3.262 light years)

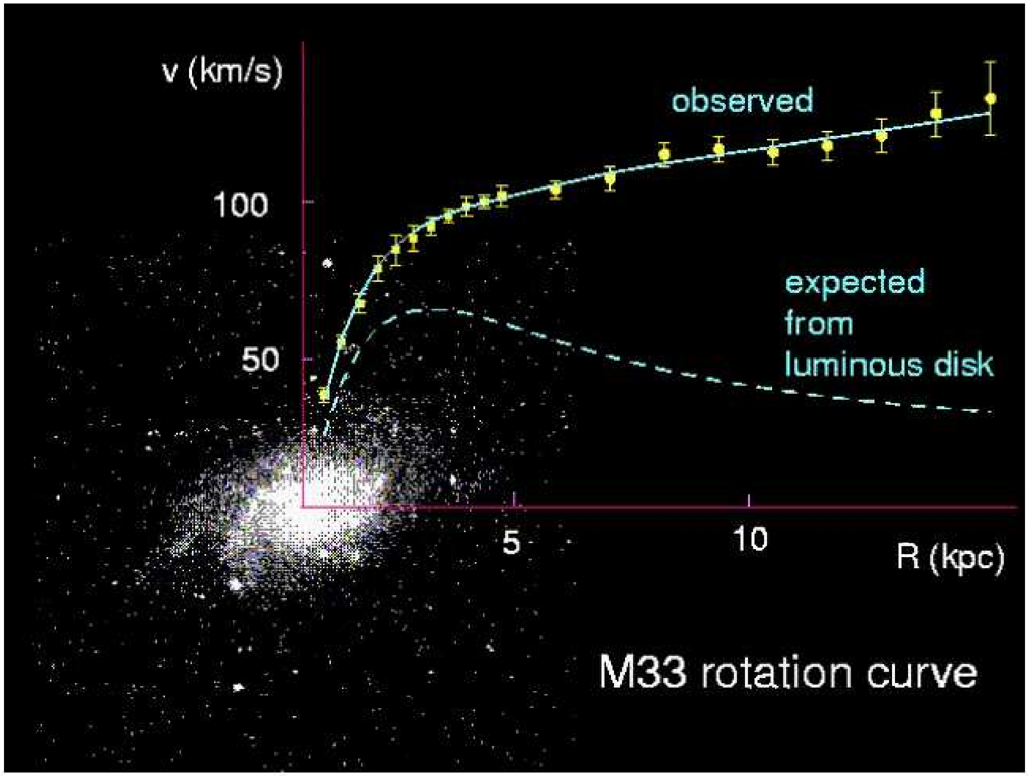
100~200 kpc

N.B. the matter density in our courtyard is dominated by Dark Matter (while the rotational curve may have a sizeable contribution from the inner visible component)

2) WIMPS are expected to form a thermal gas with v_{rms}~300 km sec^{-1} ~ 10^{-3} c (so the are expected to be <u>non relativistic)</u>

3) The Sun rotates around the galactic center with v_0~220 km s^{-2}

Only info: flatness of rotational curve in spiral (as our own) galaxies:



$$v_{rot}^2 = G\frac{M(R)}{R} \simeq \text{constant}$$

$$M(R) \equiv \int_0^R \rho_M(\vec{r})\, d^3\vec{r}$$

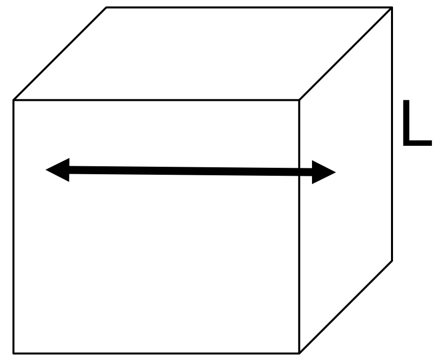
Assuming spherical symmetry:

$$M(R) \simeq \int_0^R 4\pi r^2 \rho_M(r)\, dr \simeq \text{constant} \quad \rightarrow \rho_M(r) \simeq \frac{1}{r^2}$$

unphysical (diverging total mass!) but not far from the real thing in the inner part of the Galaxy

Relation between pressure and temperature in a dilute gas:

P=pressure
p=momentum=$m_W v_{rms}$
v_{rms}=root-mean-square velocity of WIMPS



L^3=volume

$$P = \frac{N}{3}\frac{\Delta p}{\Delta t}\frac{1}{\text{area}} = \frac{N}{3}\frac{2m_W v_{rms}}{2L/v_{rms}}\frac{1}{L^2} = \frac{1}{3}\rho_W v_{rms}^2$$

Equi-partition of energy:

$$\frac{3}{2}T = \frac{1}{2}m_W v_{rms}^2$$

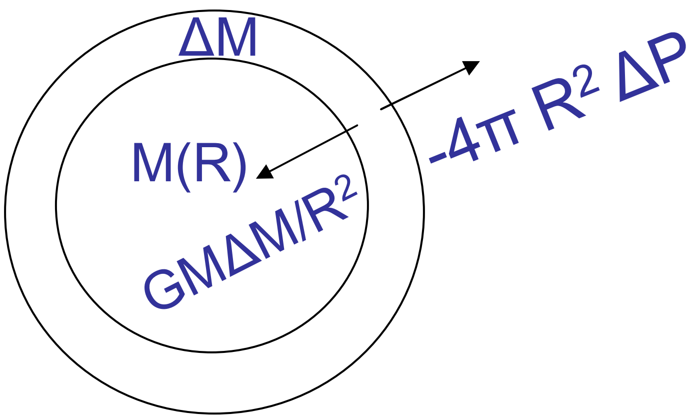
(k_B =1)

$$\Longrightarrow \qquad P = \frac{\rho_W}{m_W}T$$

Isothermal sphere: WIMPS form a Maxwellian gas at *constant* T ($dT/dR=0$):

$$\begin{cases} \rho_W \sim 1/r^2 \text{ (flatness of rotational curve + spherical symmetry)} \\ T=\text{constant} \rightarrow \Delta P \sim \Delta\rho_W \end{cases}$$

condition of hydrostatic equilibrium:



$$P = \frac{\rho_W}{m_W} T \qquad v_{rot}^2 = G\frac{M}{R}$$

$$\frac{3}{2} T = \frac{1}{2} m_W v_{rms}^2 \rightarrow T = \frac{m_W v_{rms}^2}{3}$$

$$dM = 4\pi R^2 \rho_W dR \rightarrow 4\pi R^2 = \frac{1}{\rho_W}\frac{dM}{dR}$$

$$-4\pi R^2\, dP = G\frac{M\, dM}{R^2} \rightarrow -\frac{1}{\rho_w}\frac{dM}{dR}\frac{m_W v_{rms}^2}{3}\frac{d\rho_W}{m_W} = \frac{v_{rot}^2}{R}\, dM$$

$$\boxed{\frac{v_{rms}^2}{v_{rot}^2} = -3\frac{d\ln R}{d\ln \rho_W} = \frac{3}{2}} \Rightarrow$$

In our galaxy:

$v_{rot} \sim 220$ km s^{-1}

$\rightarrow v_{rms} \sim 270$ km s$^{-1} \sim 10^{-3}$ c

- WAIT A MOMENT! how comes that WIMP in halos are in thermal equilibrium if they interact so little????

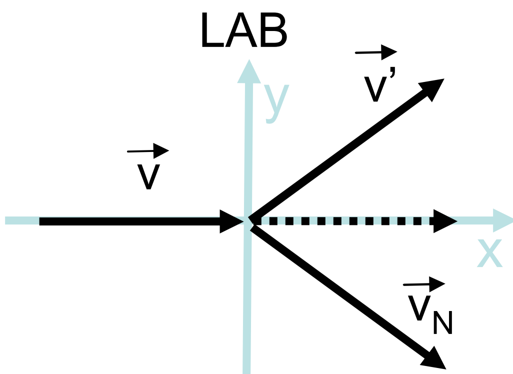
"Violent relaxation" paradigm
(Lynden-Bell, Mon.Not.Roy.Astron.Soc. 136 (1967) 101):

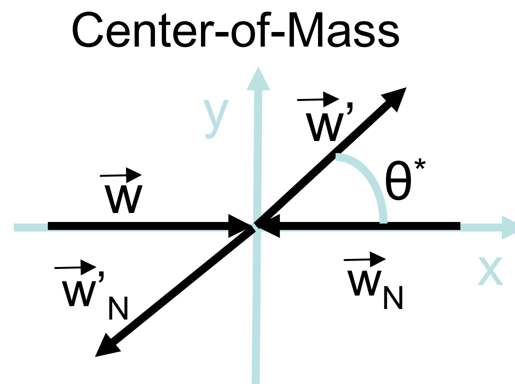
WIMPS are "frozen" into highest-entropy configuration when phase space "shrinks" due to sudden gravitational collapse.

only around the year 2000 enough computer power to PROVE violent relaxation with N-body simulations

So WIMPS in the halo of our Galaxy are expected to form a nearly Maxwellian distribution of non relativistic particles

Non relativistic WIMP elastic scattering: some trivial kinematics





	in	out	in	out	
WIMP	$\vec{v}$	$\vec{v}'$	$\vec{w}$	$\vec{w}'$	m_W
Nucleus	0	$\vec{v}_N$	$\vec{w}_N$	$\vec{w}'_N$	m_N

$v \equiv |\vec{v}|$ $\quad v' \equiv |\vec{v}'|$ $\quad v_N \equiv |\vec{v}_N|$ $\qquad w \equiv |\vec{w}|$ $\quad w' \equiv |\vec{w}'|$ $\quad w_N \equiv |\vec{w}_N|$ $\quad w'_N \equiv |\vec{w}'_N|$

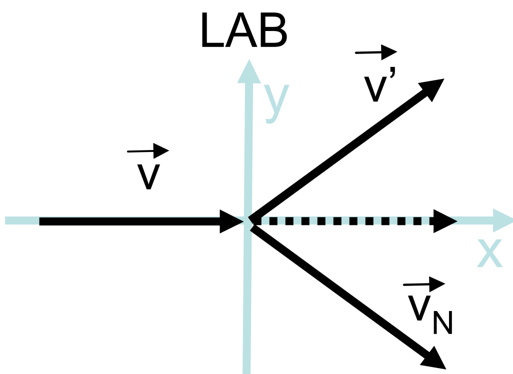
Recoil energy of nucleus: $E_R = \frac{1}{2} m_N v_N'^2 = \frac{1}{2} m_N \left(v_{Nx}'^2 + v_{Ny}'^2 \right)$

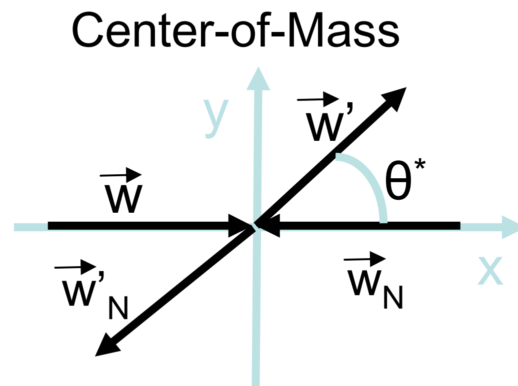
From momentum and energy conservation:

$w = w'$ $\qquad w_N = w'_N$ $\qquad w_N = m_W/m_N \, w$

(Galilean) boost: $\begin{cases} v'_{Nx} = w'_{Nx} + v_{CM} \\ v'_{Ny} = w'_{Ny} \end{cases}$

Non relativistic WIMP elastic scattering: some trivial kinematics



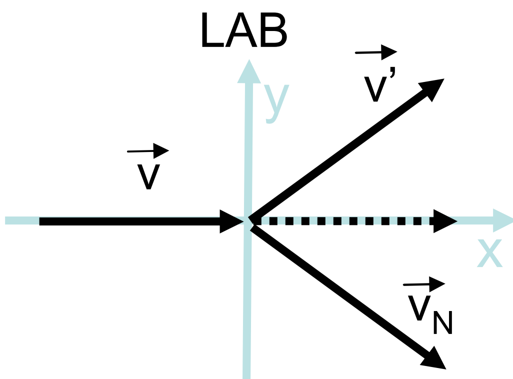


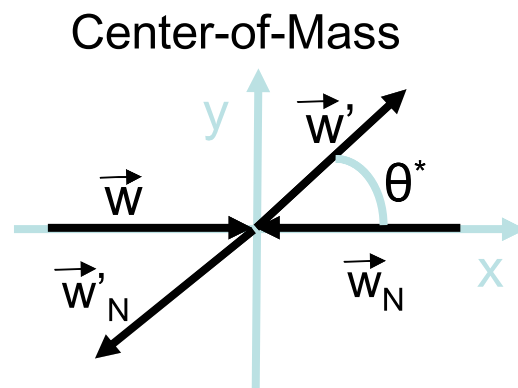
	LAB in	LAB out	CM in	CM out	
WIMP	$\vec{v}$	$\vec{v}'$	$\vec{w}$	$\vec{w}'$	m_W
Nucleus	0	$\vec{v}_N$	$\vec{w}_N$	$\vec{w}'_N$	m_N

$$v_{CM} = \frac{m_W}{m_W + m_N} v \qquad w = v - v_{CM} = \frac{m_N}{m_W + m_N} v$$

$$\begin{aligned}
v'_{Nx} &= w'_{Nx} + v_{CM} = w'_N \cos\theta^* + v_{CM} = w_N \cos\theta^* + v_{CM} = w\frac{m_W}{m_N} + v_{CM} \\
&= \frac{m_W}{m_N}\frac{m_N}{m_W + m_N} v \cos\theta^* + \frac{m_W}{m_W + m_N} v = \frac{m_W}{m_W + m_N} v(1 + \cos\theta^*) \\
v'_{Ny} &= w'_{Ny} = w'_N \sin\theta^* = w_N \frac{m_W}{m_N}\frac{m_N}{m_W + m_N} v \sin\theta^* = \frac{m_W}{m_W + m_N} v \sin\theta^*
\end{aligned}$$

Non relativistic WIMP elastic scattering: some trivial kinematics





	in	out	in	out	
WIMP	$\vec{v}$	$\vec{v}'$	$\vec{w}$	$\vec{w}'$	m_W
Nucleus	0	$\vec{v}_N$	$\vec{w}_N$	$\vec{w}'_N$	m_N

$$v_{CM} = \frac{m_W}{m_W + m_N} v \qquad w = v - v_{CM} = \frac{m_N}{m_W + m_N} v$$

$$E_R = \frac{1}{2} m_N \left(v'^2_{Nx} + v'^2_{Ny} \right) = \frac{1}{2} m_N \frac{m_W^2}{(m_W + m_N)^2} v^2 \left[(1 + \cos^2 \theta^*)^2 + \sin^2 \theta^* \right]$$

$$\boxed{E_R = \frac{1}{2} m_W v^2 \times \frac{4 m_W m_N}{(m_W + m_N)^2} \times \frac{1 + \cos\theta^*}{2}}$$

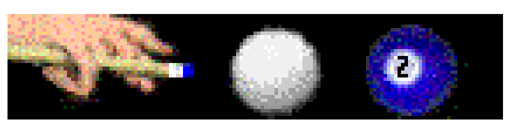
The recoil energy of the nucleus (i.e. what experiments measure!)

$$E_R = \underbrace{\frac{1}{2} m_W v^2}_{\text{kinetic energy of incoming WIMP}} \times \underbrace{\frac{4 m_W m_N}{(m_W + m_N)^2}}_{\text{"mass-matching" factor } (0<f_1<1)} \times \underbrace{\frac{1+\cos\theta^*}{2}}_{\text{angular factor } (0<f_2<1)}$$

Maximal energy transfer for head-on recoil (f_2=1 when θ^*=0) when projectile and target have the same mass (f_1=1 when m_W=m_N):

$$E_R^{\max} = \frac{1}{2} m_W v^2$$ =kinetic energy of incoming WIMP

in the maximal-energy-transfer collision the WIMP is stopped and transfers all its kinetic energy to the nucleus, (something familiar to billiard players!)



Two useful lessons from this very trivial physics:

1) mass matching enhances sensitivity to recoils. In a target detector made of different nuclear targets lighter WIMPS scatter mostly off lighter targets, heavier WIMPS scatter mostly off heavier targets. A detector containing a light nuclear target is more sensitive to lighter WIMPS compared to a detector containing heavier nuclear targets.
2) Since the WIMP incoming velocity is $v \sim 10^{-3}$ c, the maximal expected recoil energy in keV is just about half the WIMP mass expressed in GeV:

$$E_R^{\max} = \frac{1}{2} m_W c^2 \left(\frac{v}{c}\right)^2 \simeq \frac{m_W}{2} \times 10^{-6} \simeq \frac{1}{2}\left(\frac{m_W}{\mathrm{GeV}}\right) \mathrm{keV}$$

including "mass-matching factor:

$$E_R^{max} = \frac{1}{2} m_W v^2 \frac{4 m_W m_N}{(m_W + m_N)^2} = \frac{2\mu_{WN}^2}{m_N} v^2$$

μ_{WN}=WIMP-nucleus reduced mass

The total event rate (# of expected events per unit time)

$$R = N_T \rho v \sigma$$

N_T=number of nuclear targets in the detector

$\rho=\rho_W/m_W$=number density of incoming WIMPS

v=velocity of incoming WIMPS

σ=WIMP-nucleus elastic cross section

Two complications:

1) real detectors never measure the total rate, but only a limited window of recoil energies (in particular they always have a lower energy threshold <u>which turns out to be a crucial parameter to determine an experiment's sensitivity</u>)
2) incoming WIMPS are not monochromatic! $\langle v \rangle \sim 10^{-3}$ c, but with a continuous distribution f(v) with an upper bound given by the Galactic escape velocity. What is f(v)?

The differential rate

$$\frac{dR}{dE} = N_T \frac{\rho_W}{m_W} \int_{v_{min}} f(v) v \frac{d\sigma}{dE_R}\, d^3\vec{v}$$

Isotropy of the cross section (angular-dependent terms in squared amplitude suppressed by factor $(v/c)^2 \sim 10^{-6}$):

$$\frac{d\sigma}{d\cos\theta^*} = \text{constant} = \frac{\sigma}{2}$$

$$E_R = E_R^{max} \frac{1+\cos\theta^*}{2} \rightarrow \frac{dE_R}{d\cos\theta^*} = \frac{E_R^{max}}{2} \qquad E_R^{max} = \frac{2\mu_{WN}^2}{m_N} v^2$$

$$\Longrightarrow \quad \frac{d\sigma}{dE_R} = \frac{d\sigma}{d\cos\theta^*} \times \frac{d\cos\theta^*}{dE_R} = \frac{\sigma}{2} \times \frac{2}{E_R^{max}} = \frac{\sigma}{E_R^{max}}$$

(N.B.: assuming that the only dependence on E_R is through $\cos\theta^*$, this is true only for a point-like nucleus – more on this later)

Threshold effect: at a given recoil energy there is a lower bound on the velocity of the incoming WIMP

$$v_{min} = \frac{m_N + m_W}{m_W}\sqrt{\frac{E_R}{2m_N}}$$

the WIMP Maxwellian must be truncated at the escape velocity (WIMPS faster than that are not trapped by the galactic gravitational potential well). Typically:

$$450 \text{ km s}^{-1} < v_{esc} < 650 \text{ km s}^{-1}$$

This implies that for a given energy threshold, there is a minimal detectable mass. Let's try some numbers:

$$\left.\begin{array}{l} m_N \sim 70 \text{ (germanium target)} \\ E_{threshold} \sim 10 \text{ keV} \\ v_{esc} = 650 \text{ km s}^{-1} \end{array}\right\} \quad m_{W,min} \sim 6 \text{ GeV}$$

(For this reason, typically all present detectors lose sensitivity for $m_W < 10$ GeV)

The differential rate

$$\frac{dR}{dE_R} = N_T \frac{\rho_W}{m_W} \int_{v_{min}} f(v) v \frac{d\sigma}{dE_R} d^3\vec{v} = N_T \frac{\rho_W}{m_W} \int_{v_{min}} f(v) v \frac{\sigma}{E_R^{max}} d^3\vec{v}$$

$$= N_T \frac{\rho_W}{m_W} \int_{v_{min}} f(v) v \sigma \frac{m_N}{2\mu_{WN}^2 v^2} d^3\vec{v} = N_T \frac{\rho_W}{m_W} \sigma \frac{m_N}{2\mu_{WN}^2} \int_{v_{min}} \frac{f(v)}{v} d^3\vec{v}$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_W}{m_W} \sigma \frac{m_N}{2\mu_{WN}^2} \mathcal{I}(v_{min})$$

function which contains the dependence from the velocity distribution

$$\boxed{\mathcal{I}(v_{min}) \equiv \int_{v_{min}} \frac{f(v)}{v} d^3\vec{v}}$$

Nuclear form factors

- momentum transfer in WIMP-nucleus elastic collision:

$$q = (2m_N E_R)^{\frac{1}{2}} = \frac{2\pi\hbar}{\lambda}$$ ~ typically a few MeV/c

- size of the nucleus:

$$R \simeq 1.2A^{\frac{1}{3}} \ \ \mathrm{fm}$$ (A=atomic number)

$$\begin{cases} \lambda \gg R & \text{point-like nucleus} \\ \lambda \lesssim R & \text{loss of coherence} \rightarrow \text{form factor suppression} \end{cases}$$

- recoil energies from scattering of non-relativistic WIMPs are typically small enough to assume targets as point-like → no form factor suppression (neglected especially in early analyses)
- however, some important exceptions for sizeable nuclear targets (I, Xe, etc) and higher experimental energy thresholds, for which the form factor suppression can be important

Suppression due to loss of coherence

$$\sigma = \sigma_0 \times F^2(qR)$$ (F<1)

cross section at zero-momentum transfer ("point-like")

the form factor is the Fourier transform of the normalized density of "scatterers" (can be mass, charge, spin density, depending to what the WIMP is coupling to):

$$F(q) = \int \rho(\vec{r}) e^{i\vec{q}\cdot\vec{q}} d^3\vec{r}$$

$$\left(\int \rho(\vec{r})\, d^3\vec{r} = 1\right)$$

N.B. a Born cross section is a "diffraction figure" with a sequence of zeros – in the well-known case of electron-nucleon scattering the zeros are filled at higher orders of the calculation (by multiple-photon exchange) <u>but for WIMPS this does not happen so in this case the WIMP cross section can be strongly suppressed</u>

The example of the nuclear form factor in the case of WIMP-nucleus scalar (coherent) interaction

ρ=normalized nuclear mass density

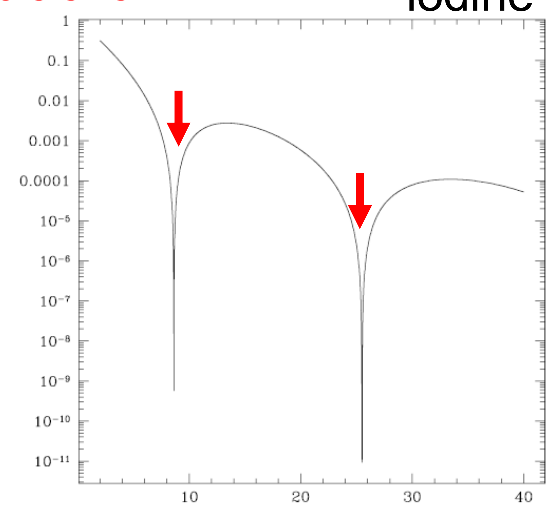
Helm parametrization (R. H. Helm, Phys. Rev. 104(1956)1466)
(a rigid sphere smeared out by a "skin" factor)

$$\rho\left(\vec{r}\right) = \int d^3\vec{r}\,'\rho_0\left(\vec{r}\,'\right)\rho_1\left(\vec{r}-\vec{r}\,'\right)$$

$$\rho_0\left(\vec{r}\right) = \begin{cases} \text{constant when } r^2<R_0^2=R^2-5\,s^2,\ R=\text{nuclear radius} \\ \text{zero when } r^2>R_0^2=R^2-5\,s^2 \end{cases}$$

$$\rho_1\left(\vec{r}\right) = e^{-\frac{1}{2}\left(\frac{r}{s}\right)^2}$$ "skin" function of thickness s~1 fm

iodine



F²

ee Energy

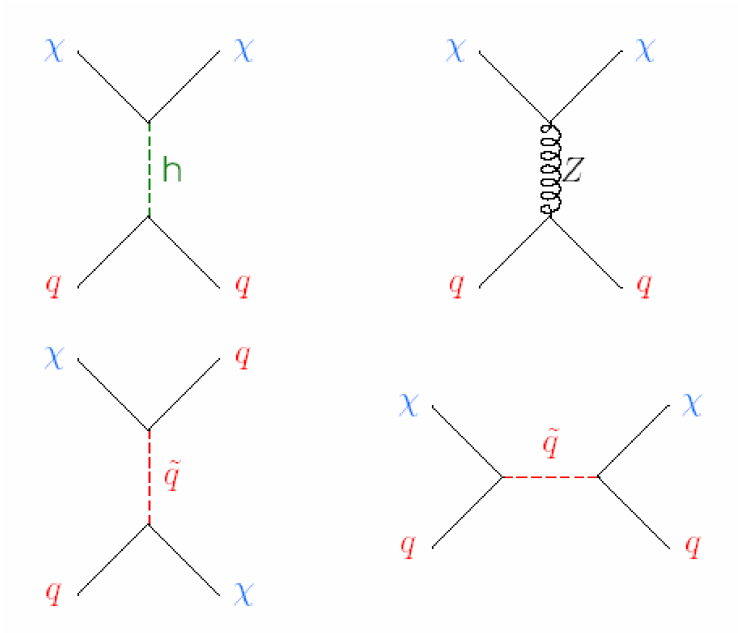
The resulting form factor can be worked out analytically:

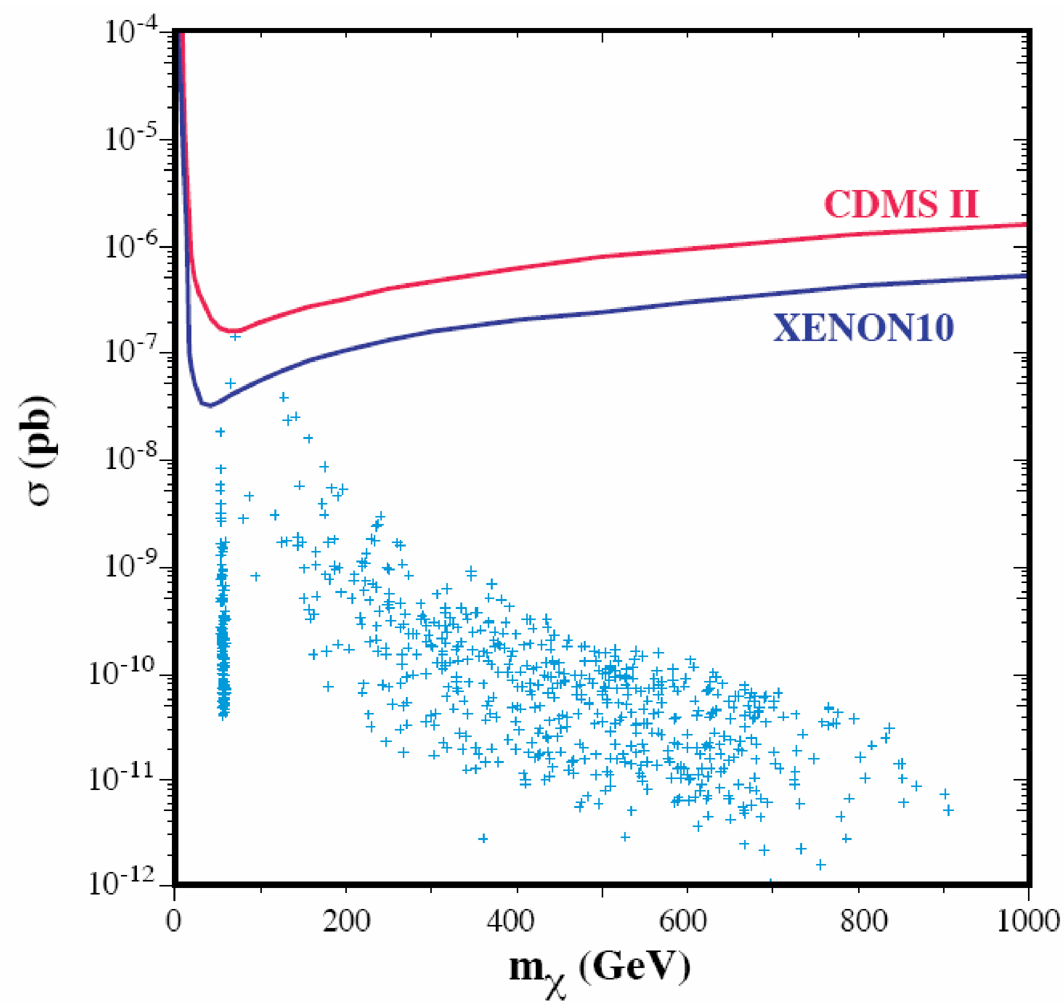
$$F(q) = \frac{j_1(qR_0)}{qR_0}e^{-\frac{1}{2}(qs)^2}$$

(j_1=sin(x)/x^2-cos(x)/x= Bessel function of order 1)

vanishing cross section!

Direct detection in SUGRA

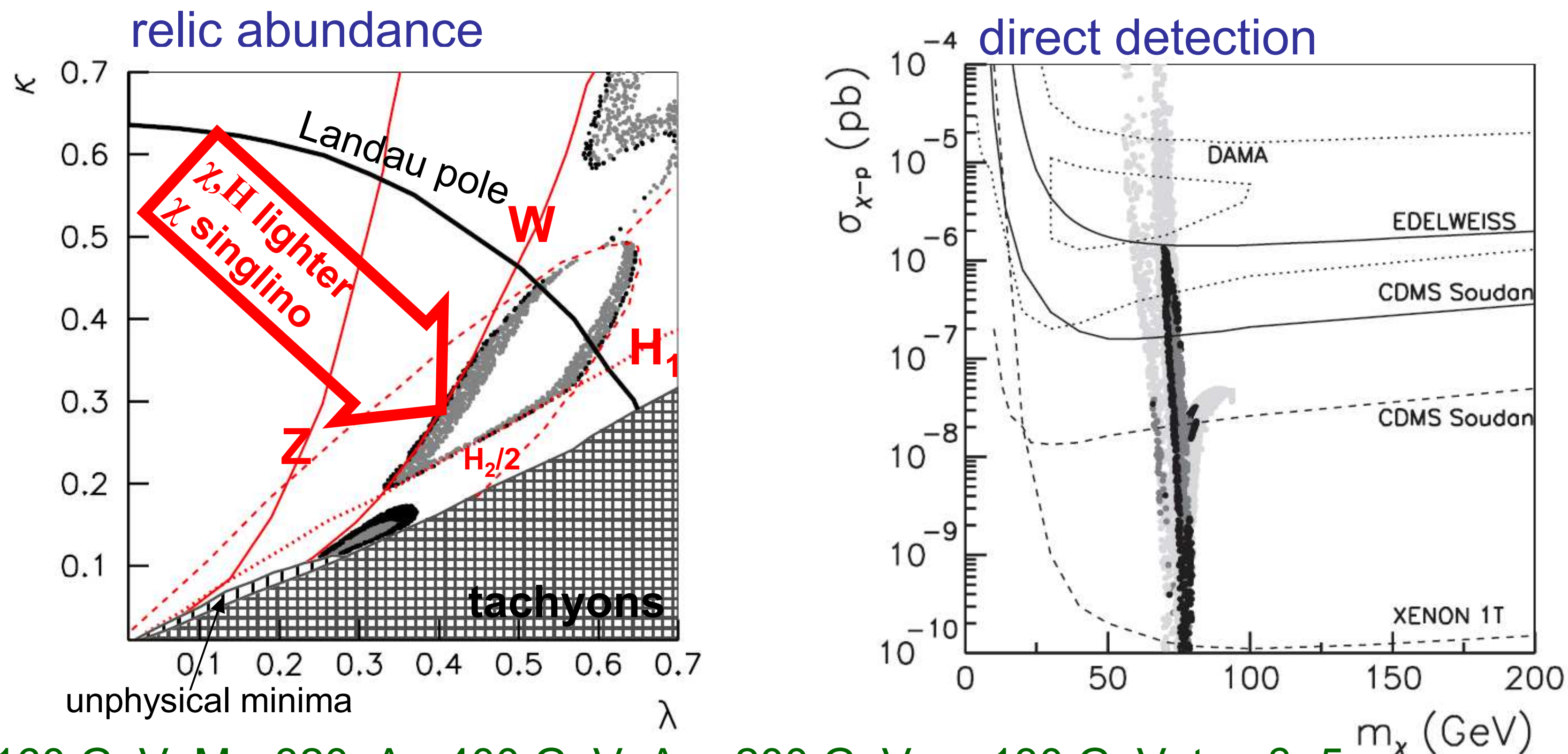




[Ellis, Olive, Santoso, Spanos]

Relic density and direct detection rate in NMSSM

[Cerdeño, Hugonie, López-Fogliani, Muñoz, Teixeira]



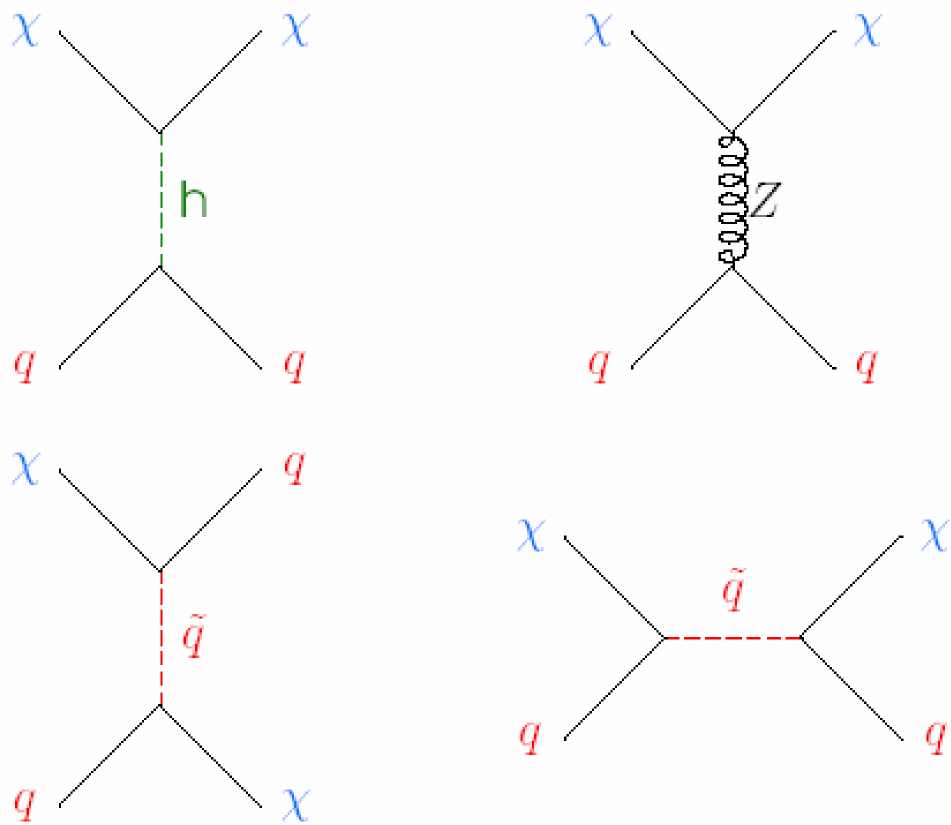
M_1=160 GeV, M_2=320, A_λ=400 GeV, A_k=-200 GeV, μ=130 GeV, tan β=5

(sizeable direct detection)

- very light neutral Higgs (mainly singlet)
- light scalars imply more decay channels and resonant decays
- neutralino relatively light (< decay thresholds) and mostly singlino
- high direct detection cross sections (even better for lower M_1)

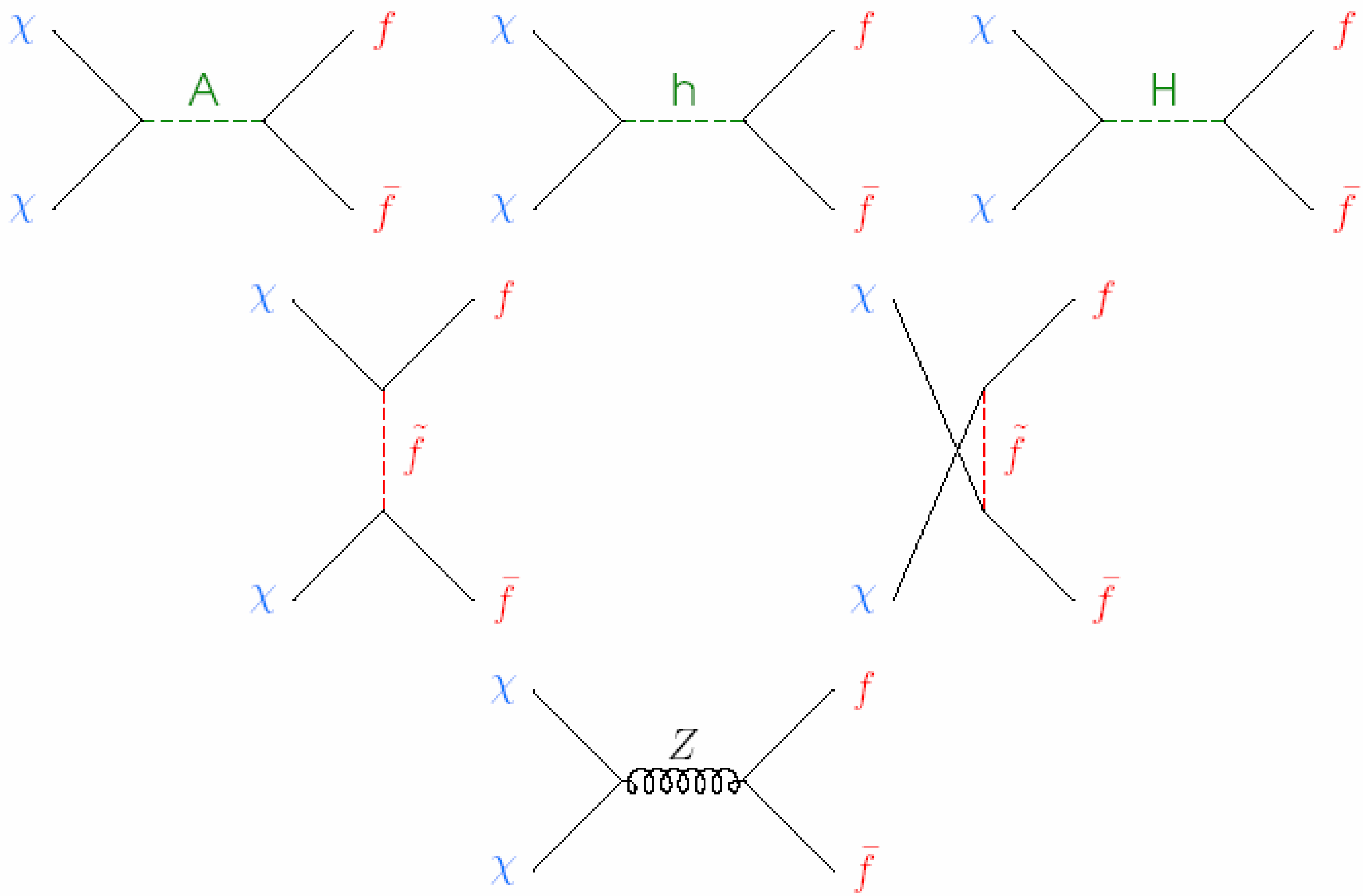
Light neutralinos in eff-MSSM

Neutralino–quark cross section - Diagrams



Remember, in relic abundance:

χ–$\chi \rightarrow f\bar{f}$ annihilation cross section - Diagrams (low m_χ)



at very low mass same diagrams, correlation between relic density and cross section

$$(m_\chi \leq M_W)$$

Neutralino – nucleon cross section in eff-MSSM (light neutralinos)

[Bottino, Donato, Fornengo, Scopel PRD69(2004)037302]

Color code from now on:

- • $\Omega_\chi h^2 < 0.095$
- × $\Omega_\chi h^2 > 0.095$

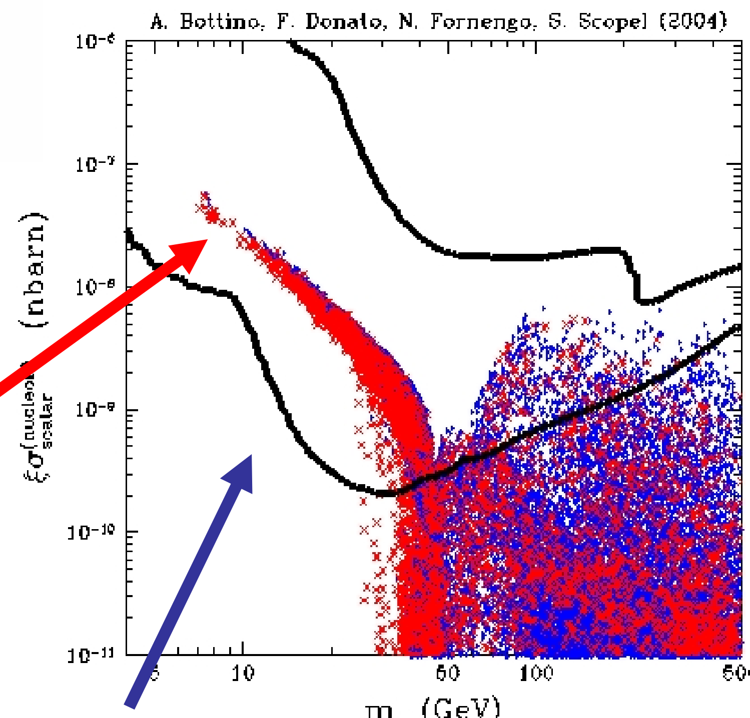
$$\Omega_\chi h^2 \leq (\Omega_{CDM} h^2)_{max}$$

$$\Downarrow$$

$$\sigma^{(\text{nucleon})}_{\text{scalar}} \gtrsim \frac{10^{-40} cm^2}{(\Omega_{CDM} h^2)_{max}} \frac{\text{GeV}^2}{m_\chi^2\,[1 - m_b^2/m_\chi^2]^{1/2}} \text{ for } m_\chi \lesssim 20 \text{ GeV}$$

The elastic cross section is bounded from below:

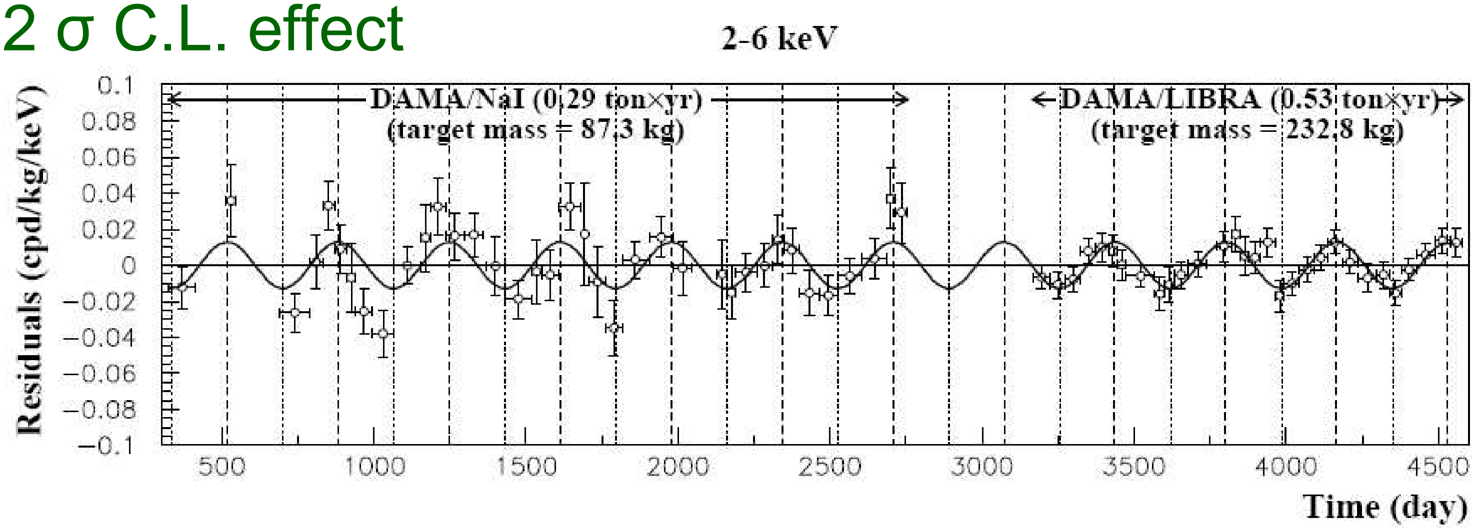
→ "funnel" at low mass



DAMA/NaI modulation region, likelyhood function values distant more than 4 σ from the null result (absence on modulation) hypothesis, Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403

New DAMA/Libra result (Bernabei et al., arXiv:0804.2741)

0.53 ton x year (0.82 ton x year combining previous data)
8.2 σ C.L. effect



	A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (day)	C.L.
DAMA/NaI				
(2–4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2–5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2–6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA				
(2–4) keV	0.0213 ± 0.0032	0.997 ± 0.002	139 ± 10	6.7σ
(2–5) keV	0.0165 ± 0.0024	0.998 ± 0.002	143 ± 9	6.9σ
(2–6) keV	0.0107 ± 0.0019	0.998 ± 0.003	144 ± 11	5.6σ
DAMA/NaI+ DAMA/LIBRA				
(2–4) keV	0.0223 ± 0.0027	0.996 ± 0.002	138 ± 7	8.3σ
(2–5) keV	0.0178 ± 0.0020	0.998 ± 0.002	145 ± 7	8.9σ
(2–6) keV	0.0131 ± 0.0016	0.998 ± 0.003	144 ± 8	8.2σ

$A \cos[\omega (t-t_0)]$

$\omega = 2\pi/T_0$

latest data not included in the following

Dependence on galactic model contained in function:

$$\boxed{\mathcal{I}(v_{min}) \equiv \int_{v_{min}} \frac{f(v)}{v}\, d^3\vec{v}}$$

f(v) usually assumed to be at Maxwellian at rest in the Galactic system (possibility of *corotation* can be also considered):

$$f_G(\vec{v}_G) = \left(\frac{3}{2\pi v_{rms}^2}\right)^{\frac{3}{2}} e^{-\frac{3v_G^2}{2v_{rms}^2}}\, d^3\vec{v}_G$$

$$\vec{v}_G = \vec{w} + \vec{v}$$

WIMP velocity in Galactic reference frame

Earth velocity in Galactic reference frame

WIMP velocity in Earth reference frame

In this case, introducing the non-dimensional quantities:

$$\begin{cases} x^2 \equiv \dfrac{3v^2}{2v_{rms}^2} \\ \eta^2 = \dfrac{3w^2}{2v_{rms}^2} \end{cases}$$

(<w>~232 km s^{-1})

one has:

$$\mathcal{I}(v_{min}) = \sqrt{\frac{3}{8}} \frac{1}{v_{rms}\eta} \left[erf(x_{min}+\eta) - erf(x_{min}-\eta)\right]$$

$$erf(x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt$$

where, due to the rotation of the Earth around the Sun:

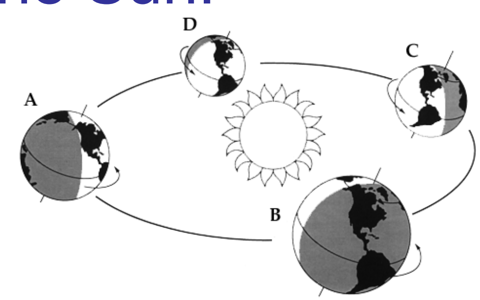
$$\eta = \eta_0 + \Delta\eta \cos[\omega(t-t_0)]$$

$$\eta_0 \simeq 1$$

$$\Delta\eta \simeq 0.07$$

$$\omega = (2\pi/365)\ \mathrm{days}^{-1}$$

$$t_0 = 156 \simeq 2\ \mathrm{june}$$



Exponential fall-off @ high energies:

$$\mathcal{I}(v_{min}) \propto \frac{1}{\eta}\int_{x_{min}-\eta}^{x_{min}+\eta} e^{-t^2}\,dt \rightarrow 2e^{-x_{min}^2} \qquad (x_{min} \gg \eta)$$

$$\Longrightarrow \quad \mathcal{I}(v_{min}) \propto \begin{cases} e^{-\alpha E_R} & m_W \gg m_N \\ e^{-\beta \frac{E_R}{m_W^2}} & m_W \ll m_N \end{cases}$$

- faster fall-off @ low m_W masses
- lose sensitivity to m_W @ higher masses

One thing or two about the annual modulation…

$\Delta\eta$~0.07 << η_0~1 → expansion of rate as a function of $\Delta\eta$:

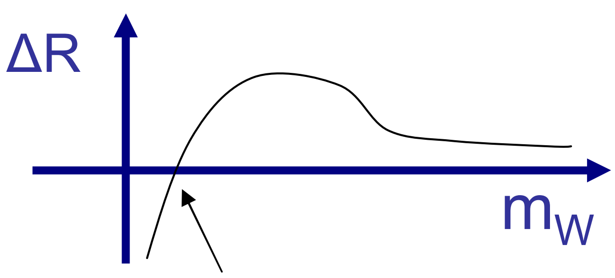
$$\boxed{R \propto \frac{F(\eta)}{\eta}}$$

$$F(\eta) = erf(x_{min}+\eta) - erf(x_{min}-\eta) \simeq \int_{x_{min}-\eta}^{x_{min}+\eta} e^{-t^2}\, dt$$

$$R \simeq R_0 + \frac{dR}{d\eta}\Delta\eta = R_0 + \Delta R \cos[\omega(t-t_0)]$$

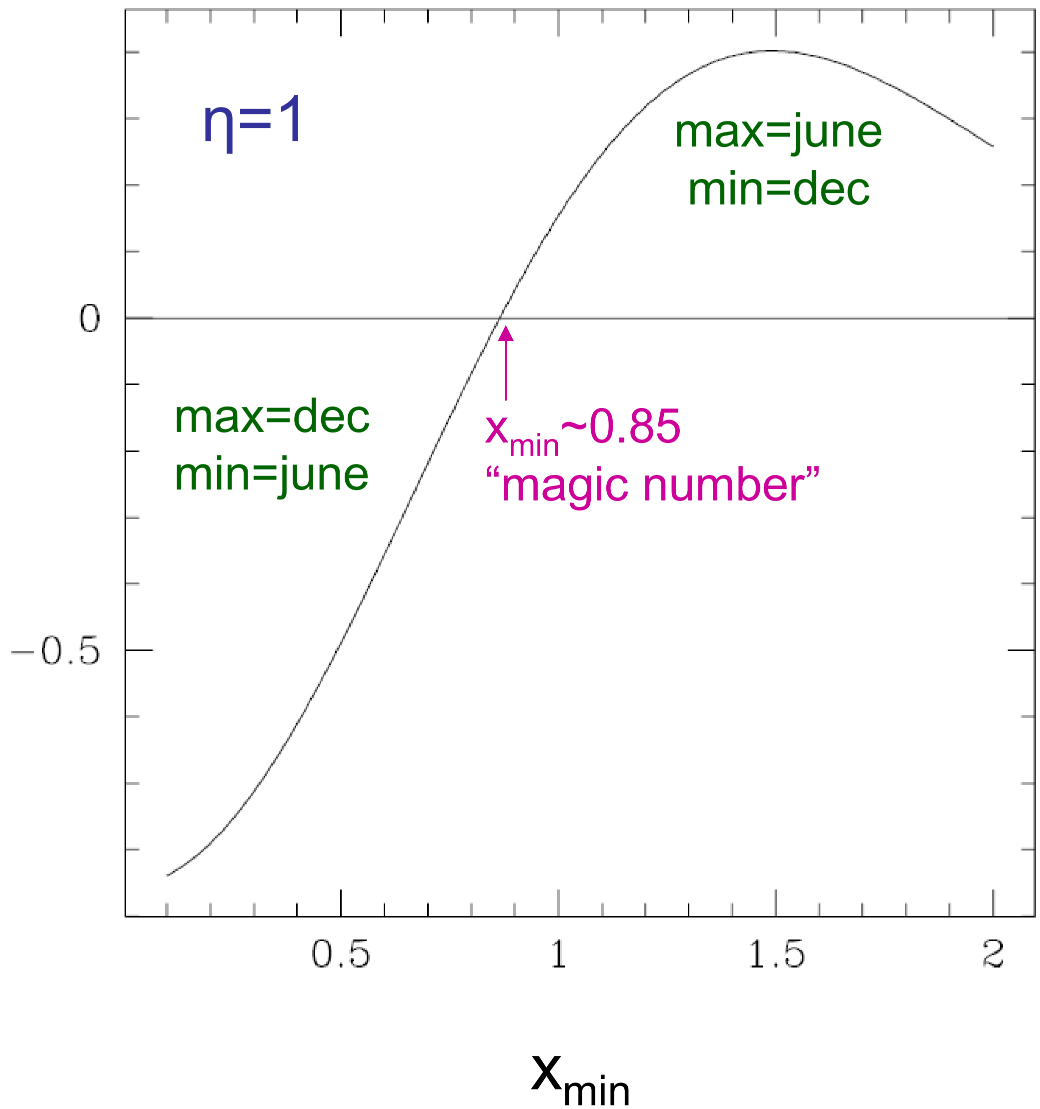
$$\frac{dR}{d\eta} = \frac{F'(\eta)}{\eta} - \frac{F(\eta)}{\eta^2}$$

$$\frac{dR}{d\eta} = \frac{F'(\eta)}{\eta} - \frac{F(\eta)}{\eta^2} = \frac{1}{\eta}\frac{2}{\sqrt{\pi}}\left[e^{-(x_{min}-\eta)} + e^{-(x_{min}+\eta)}\right] - \frac{1}{\eta^2}\left[erf(x_{min}+\eta) - erf(x_{min}-\eta)\right]$$



cancellation between two terms, "inverse" modulation @ low WIMP masses & recoil energies (max @ december, min @ june)

$$\mathcal{F}(x_{min},\eta) = \frac{1}{\eta}\frac{2}{\sqrt{\pi}}\left[e^{-(x_{min}-\eta)} + e^{-(x_{min}+\eta)}\right] - \frac{1}{\eta^2}\left[erf(x_{min}+\eta) - erf(x_{min}-\eta)\right]$$

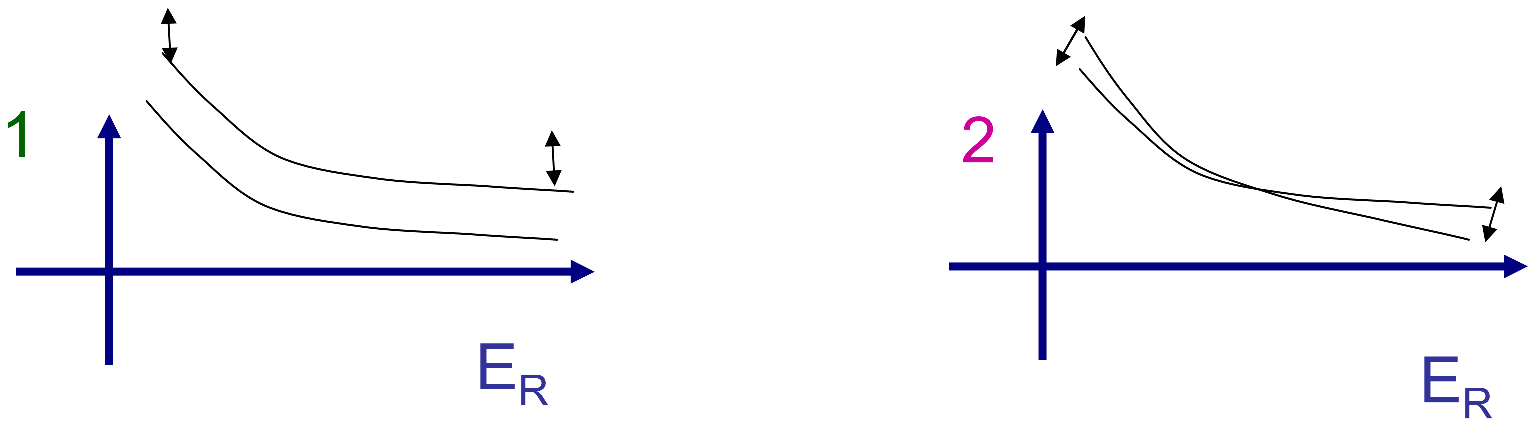


$$x_{min} = \frac{m_W + m_N}{m_W}\frac{1}{v_{rot}}\sqrt{\frac{E_R}{2m_N}}$$

- at fixed m_w , x_{min} grows with energy
- “inverted” modulation at low energy (typically below threshold when $m_W << m_N$)

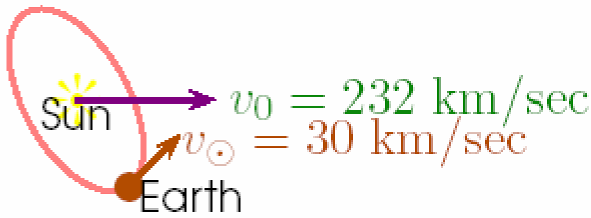
The annual modulation of the WIMP signal is the sum of two different effects:

1. change in overall normalization (total rate)
2. redistribution of events between higher- and lower-energy bins @ fixed total rate



the combination of the two effects implies that for some value of the recoil energy the modulation effect should be minimimal (unfortunately this is typically below experimental threshold, otherwise a good method for m_W determination…!)

Annual modulation of WIMP direct detection in a nutshell



Expected rate: $R=R_0+R_m \cos[\omega(t-t_0)]$

$\omega=2\pi/(1 \text{ year})$ t_0=2 june

$R_m/R_0 \sim 5 \div 10$ % (few percent effect)

If N=# of events, assuming a 5% effect a 5 σ discovery requires:

$$5/100 \times N > 5 \times N^{1/2}$$

modulation amplitude poissonian fluctuation

$\Rightarrow$ N > 10.000 events

N~ (incoming flux) x $N_{targets}$ x (cross section) x (exposition time)

expected rates: 0.1 events/kg/day

$\Rightarrow$ a few x 100 kg x day required

hard to do: need large masses, low backgrounds, operational stability over long times…

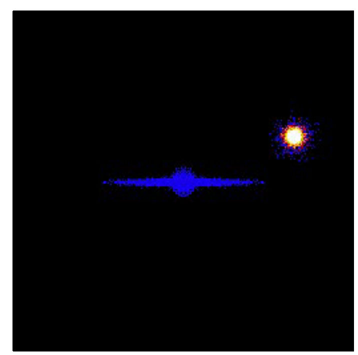
Uncertainty due to velocity distribution

- Many possible departures from the isothermal sphere model, which is the parameterization usually adopted to describe the halo.

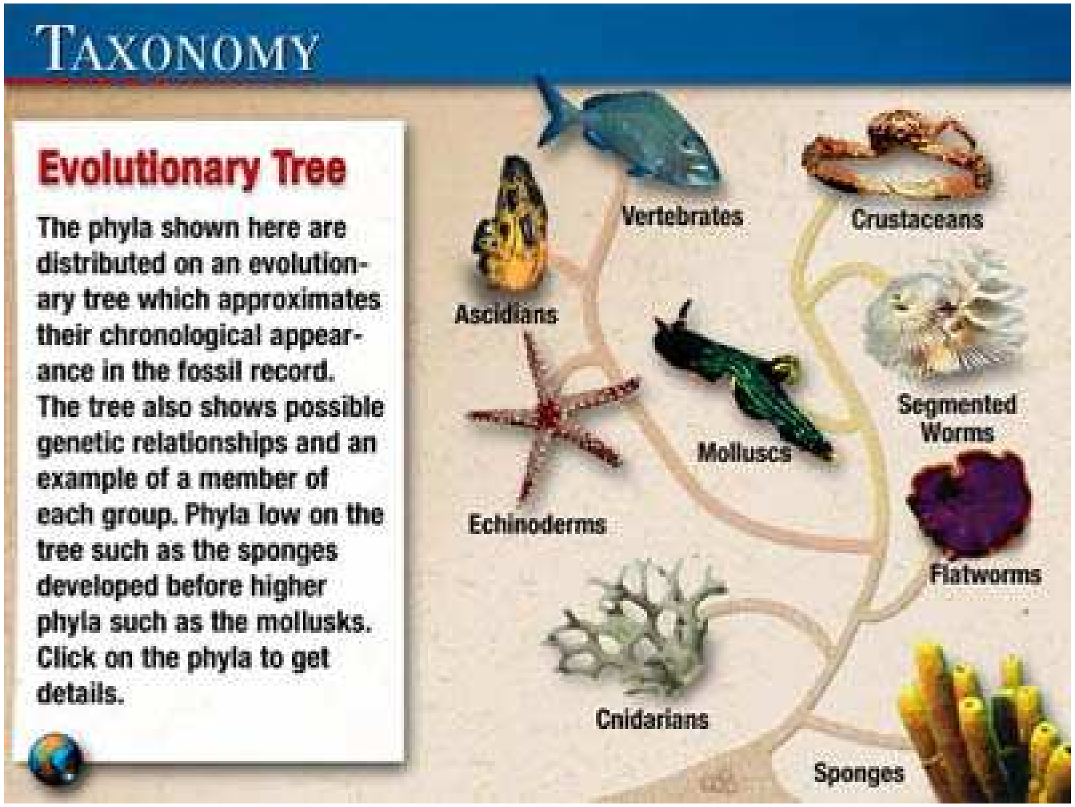
- Different density profiles, effects due to anisotropies of the velocity dispersion tensor, rotation of the galactic halo.

- Non thermal components:
  - numerical simulations, see for instance A. Helmi, S. D. M. White and V. Springel, Phys. Rev. D 66 063503 (2002); D. D. Stiff, L. M. Widrow and J. Frieman, Phys. Rev. D 64 , 083516 (2001) ☛ Size of the effect?
  - Sgr tidal stream, K. Freese, P. Gondolo and H. Newberg,

PRD71,043516,2005



Uncertainties due to velocity distribution
Too many models: some classification is needed



Class	ρ (density profile)	$\vec{\sigma}$ (velocity dispersion)
A	spherical	isotropic
B	spherical	non isotropic
C	axisymmetric	non isotropic
D	triaxial	non isotropic

Determination of the WIMP distribution function $F(\vec{r},\vec{v})$

- Direct detection rates depend on the distribution function at the Earth's position:

$$f(\vec{v}) \equiv F(\vec{R}_0, \vec{v})$$

- the most relevant piece of information coming from astrophysics is the rotational velocity of objects bound to the Galaxy:

$$v_{rot}^2(r) = \frac{G M_{tot}(r)}{r} \quad , \quad M_{tot}(r) = \int_{r'<r} d^3 r' \rho_{tot}(\vec{r}\,')$$

$$\rho_{tot}(\vec{r}) = \rho_{DM}(\vec{r}) + \rho_{vis}(\vec{r})$$

- the dark matter density distribution is given by:

$$\rho_{DM}(\vec{r}) \equiv \int d^3 v \, F(\vec{r}, \vec{v})$$

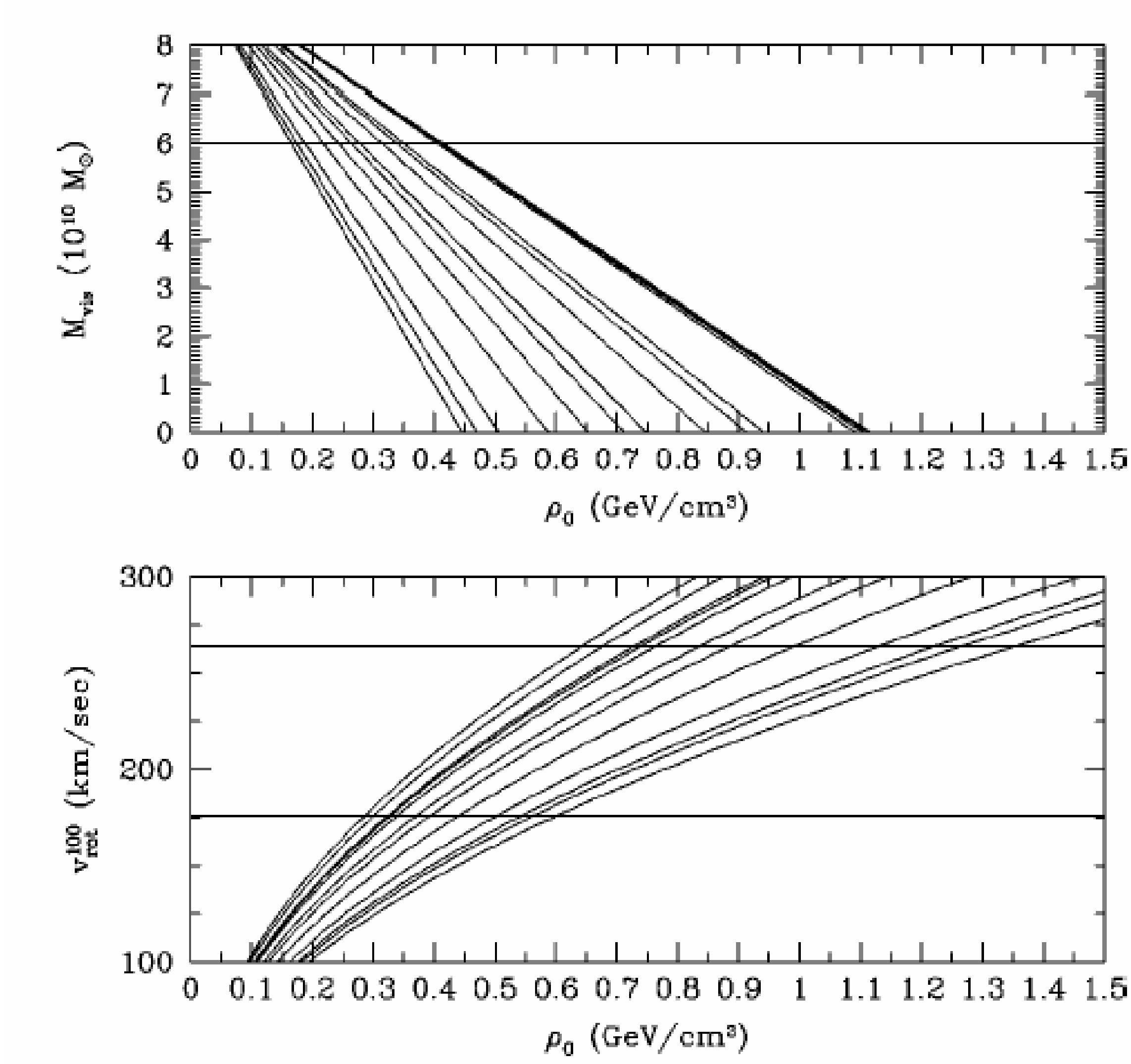
need to invert this equation

$\rightarrow$ degeneracies

ADD INFORMATION: SIMMETRIES

Class A: Spherical ρ_{DM}, isotropic velocity dispersion			
A0	Isothermal sphere		Eq. (20)
A1	Evans' logarithmic [15]	$R_c = 5$ kpc	Eq. (18)
A2	Evans' power-law [16]	$R_c = 16$ kpc, $\beta = 0.7$	Eq. (23)
A3	Evans' power-law [16]	$R_c = 2$ kpc, $\beta = -0.1$	Eq. (23)
A4	Jaffe [14]	Table I	Eq. (26)
A5	NFW [18]	Table I	Eq. (26)
A6	Moore *et al.* [19]	Table I	Eq. (26)
A7	Kravtsov *et al.* [20]	Table I	Eq. (26)
Class B: Spherical ρ_{DM}, non-isotropic velocity dispersion (Osipkov-Merrit, $\beta_0 = 0.4$)			
B1	Evans' logarithmic	$R_c = 5$ kpc	Eqs. (18),(28)
B2	Evans' power-law	$R_c = 16$ kpc, $\beta = 0.7$	Eqs. (23),(28)
B3	Evans' power-law	$R_c = 2$ kpc, $\beta = -0.1$	Eqs. (23),(28)
B4	Jaffe	Table I	Eqs. (26),(28)
B5	NFW	Table I	Eqs. (26),(28)
B6	Moore *et al.*	Table I	Eqs. (26),(28)
B7	Kravtsov *et al.*	Table I	Eqs. (26),(28)
Class C: Axisymmetric ρ_{DM}			
C1	Evans' logarithmic	$R_c = 0$, $q = 1/\sqrt{2}$	Eqs. (33),(34)
C2	Evans' logarithmic	$R_c = 5$ kpc, $q = 1/\sqrt{2}$	Eqs. (33),(34)
C3	Evans' power-law	$R_c = 16$ kpc, $q = 0.95$, $\beta = 0.9$	Eqs. (37),(38)
C4	Evans' power-law	$R_c = 2$ kpc, $q = 1/\sqrt{2}$, $\beta = -0.1$	Eqs. (37),(38)
Class D: Triaxial ρ_{DM} [17] ($q = 0.8, p = 0.9$)			
D1	Earth on major axis, radial anisotropy	$\delta = -1.78$	Eqs. (43),(44)
D2	Earth on major axis, tangential anis.	$\delta = 16$	Eqs. (43),(44)
D3	Earth on intermediate axis, radial anis.	$\delta = -1.78$	Eqs. (43),(44)
D4	Earth on intermediate axis, tangential anis.	$\delta = 16$	Eqs. (43),(44)

v_0=220 km/sec



M_{vis} (10^{10} $M_\odot$)
0
1
2
3
4
5
6
7
8
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
ρ_0 (GeV/cm^3)
v_{rot}^{100} (km/sec)
100
200
300
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
ρ_0 (GeV/cm^3)

Allowed intervals for ρ_0

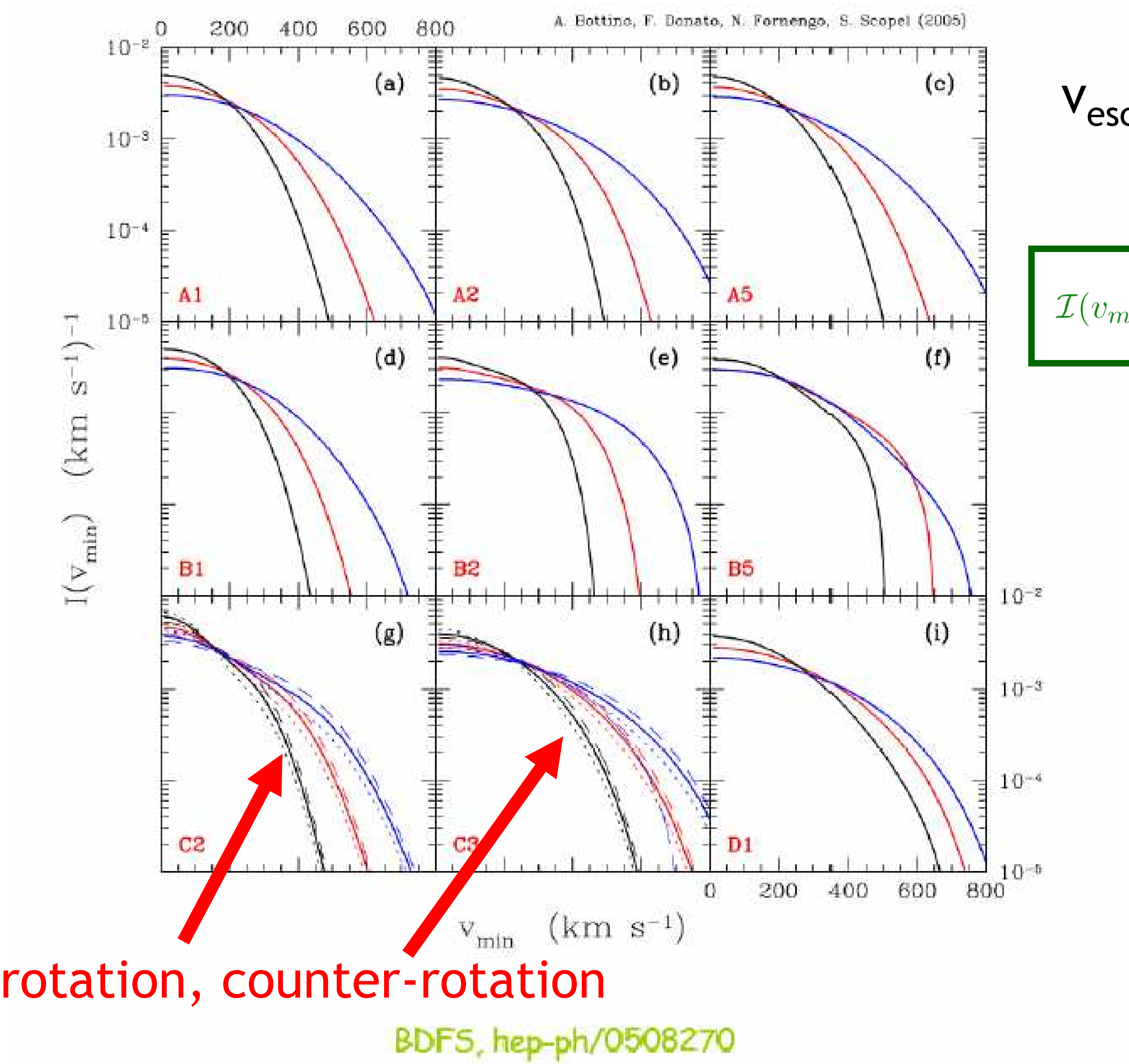
	$v_0 = 170$ km sec^{-1}		$v_0 = 220$ km sec^{-1}		$v_0 = 270$ km sec^{-1}	
Model	ρ_0^{min}	ρ_0^{max}	ρ_0^{min}	ρ_0^{max}	ρ_0^{min}	ρ_0^{max}
A0	0.18	0.28	0.30	0.47	0.45	0.71
A1,B1	0.20	0.42	0.34	0.71	0.62	1.07
A2,B2	0.24	0.53	0.41	0.89	0.97	1.33
A3,B3	0.17	0.35	0.29	0.59	0.52	0.88
A4,B4	0.26	0.27	0.44	0.45	0.66	0.67
A5,B5	0.20	0.44	0.33	0.74	0.66	1.11
A6,B6	0.22	0.39	0.37	0.65	0.57	0.98
A7,B7	0.32	0.54	0.54	0.91	0.82	1.37
C1	0.36	0.56	0.60	0.94	0.91	1.42
C2	0.34	0.67	0.56	1.11	0.98	1.68
C3	0.30	0.66	0.50	1.10	0.97	1.66
C4	0.32	0.65	0.54	1.09	0.96	1.64
D1,D2	0.32	0.50	0.54	0.84	0.81	1.27
D3,D4	0.19	0.30	0.32	0.51	0.49	0.76

$0.17\ \mathrm{GeV/cm^3} < \rho_0 < 1.7\ \mathrm{GeV/cm^3}$

The function $I(v_{min})$ for different halo models

v_{esc}=650 km/sec

$$\mathcal{I}(v_{min}) \equiv \int_{v_{min}} \frac{f(v)}{v}\, d^3\vec{v}$$



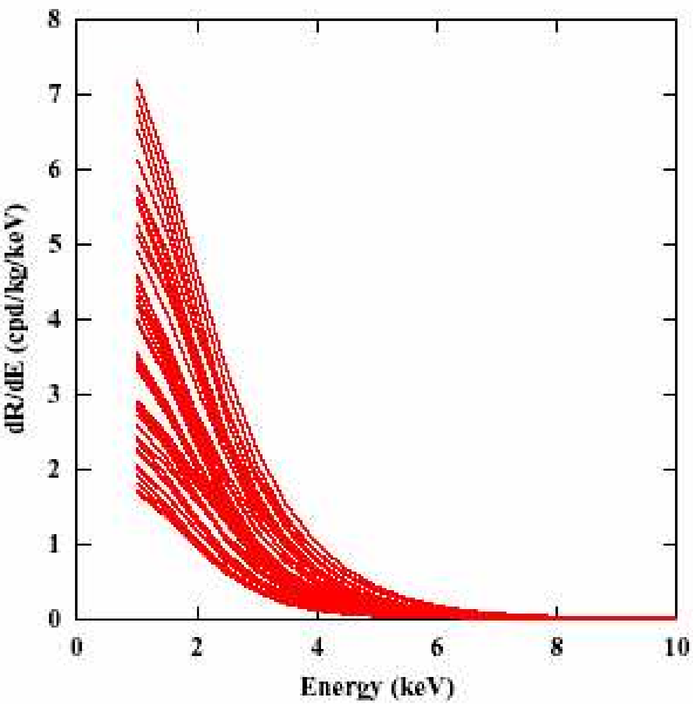
corotation, counter-rotation

Uncertainty due to velocity distribution

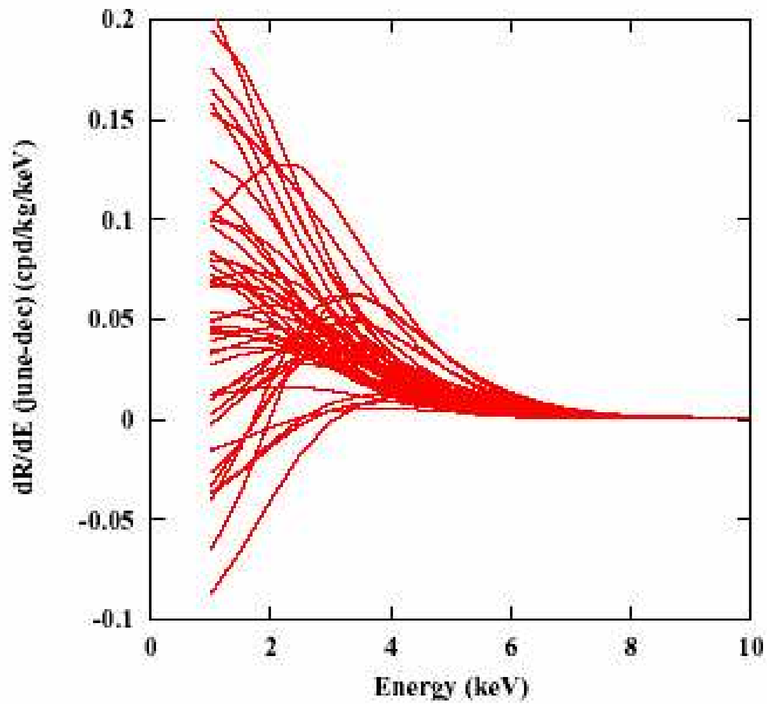
Sodium Iodide

m_{WIMP}=50 GeV
$\sigma_{\rm scalar}^{\rm nucleon}$=$10^{-8}$ nbarn
v_0= 220 km/sec

Each curve corresponds to a different halo model:



Time–independent component



Modulation amplitude

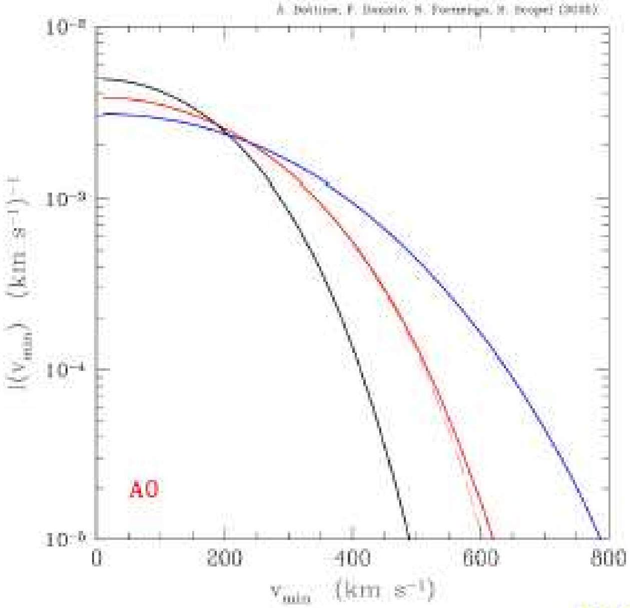
Direct detection differential rate

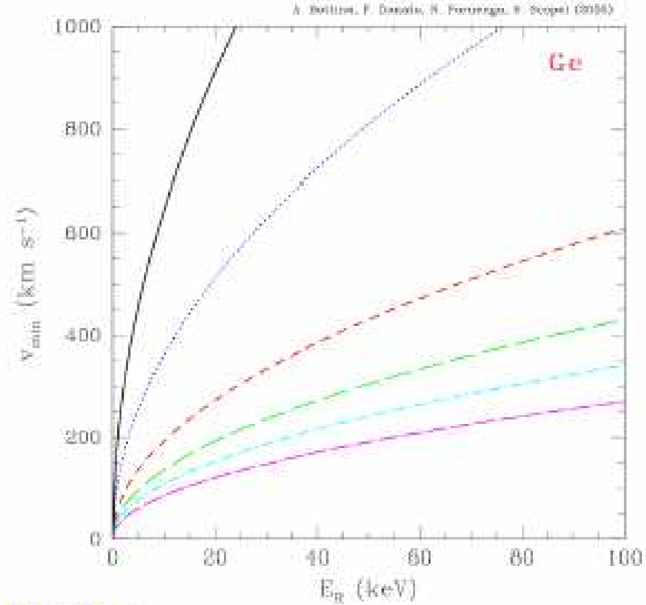
$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \xi \sigma_{\rm scalar}^{\rm (nucleon)} F^2(E_R)\, \mathcal{I}(v_{\rm min})$$

info from DF is contained here

$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3w \; \frac{f_{\rm ES}(\vec{w})}{w}$$

$$v_{\rm min} = [m_N E_R/(2\mu_A^2)]^{1/2}$$





BDFS, hep-ph/0508270

Neutralino-nucleon cross section – scalar contribution

$$\sigma^{(\text{nucleon})}_{\text{scalar}} = \frac{8G_F^2}{\pi} M_Z^2 m_{\text{red}}^2 \left[\frac{F_h I_h}{m_h^2} + \frac{F_H I_H}{m_H^2} + \frac{M_Z}{2} \sum_q < N|\bar{q}q|N > \sum_i P_{\tilde{q}_i} (A_{\tilde{q}_i}^2 - B_{\tilde{q}_i}^2) \right]^2$$

Higgs-exchange

squark-exchange

squark exchange (four-Fermi approx):

propagators:

$$P_{\tilde{q}_i} = \frac{1}{2} \left(\frac{1}{m_{\tilde{q}_i}^2 - (m_\chi - m_q)^2} + \frac{1}{m_{\tilde{q}_i}^2 - (m_\chi + m_q)^2} \right)$$

couplings:

$$\begin{aligned} A_{\tilde{q}_1} &= \cos\theta_q (X_q + Z_q) + \sin\theta_q (Y_q + Z_q) \\ B_{\tilde{q}_1} &= \cos\theta_q (X_q - Z_q) + \sin\theta_q (Z_q - Y_q) \\ X_q &= -\left(\cos\theta_W T_{3q} a_2 + \sin\theta_W \frac{Y_{qL}}{2} a_1 \right) \quad ; \quad Y_q = \sin\theta_W \frac{Y_{qR}}{2} a_1 \\ Z_{u-\text{type}} &= -\frac{m_{u-\text{type}} a_4}{2 \sin\beta M_Z} \quad ; \quad Z_{d-\text{type}} = -\frac{m_{d-\text{type}} a_3}{2 \cos\beta M_Z}, \end{aligned}$$

Higgs-exchange contribution:

neutralino-Higgs couplings:

$$F_h = (-a_1 \sin\theta_W + a_2 \cos\theta_W)(a_3 \sin\alpha + a_4 \cos\alpha)$$
$$F_H = (-a_1 \sin\theta_W + a_2 \cos\theta_W)(a_3 \cos\alpha - a_4 \sin\alpha)$$

α=Higgs-mixing angle: $\begin{cases} H = \cos\alpha H_1^0 + \sin\alpha H_2^0 \\ h = -\sin\alpha H_1^0 + \cos\alpha H_2^0 \end{cases}$

quark-Higgs couplings: $I_{h,H} = \sum_q k_q^{h,H} m_q \langle N|\bar{q}q|N\rangle$

	h	H	A
k_{u-type}	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$1/\tan\beta$
k_{d-type}	$-\sin\alpha/\cos\beta - \epsilon\cos(\alpha-\beta)\tan\beta$	$\cos\alpha/\cos\beta - \epsilon\sin(\alpha-\beta)\tan\beta$	$\tan\beta(1+\epsilon)$

radiative corrections to down-type Yukawa couplings: $\begin{cases} m_d = h_d < H_0^1 > (1+\Delta) \\ \epsilon \equiv 1/(1+\Delta) \end{cases}$

The hadronic matrix elements: $< N|\bar{q}q|N >$
introduce uncertainties in the final result

The Higgs-nucleon couplings can be rewritten as:

$$I_{h,H} = k^{h,H}_{u-\mathrm{type}} g_u + k^{h,H}_{d-\mathrm{type}} g_d$$

with:(l=light quark h=heavy quark):

$$\begin{aligned} g_u &\simeq m_l < N|\bar{l}l|N > + 2\, m_h < N|\bar{h}h|N > \\ &\simeq \frac{4}{27}(m_N + \frac{19}{8}\sigma_{\pi N} - \frac{1}{2} r(\sigma_{\pi N} - \sigma_0)) \end{aligned}$$

$$\begin{aligned} g_d &\simeq m_l < N|\bar{l}l|N > + m_s < N|\bar{s}s|N > + m_h < N|\bar{h}h|N > \\ &\simeq \frac{2}{27}(m_N + \frac{23}{4}\sigma_{\pi N} + \frac{25}{4} r(\sigma_{\pi N} - \sigma_0)) \end{aligned}$$

$\sigma_{\pi N}$= pion-nucleon sigma term $\qquad r \equiv \frac{2m_s}{m_u + m_d}$

$$\sigma_0 \equiv \frac{1}{2}(m_u + m_d) < N|\bar{u}u + \bar{d}d - 2\bar{s}s|N >$$

Relevant parameters:

r~25

30 MeV<σ_0<40 MeV

Two determinations of $\sigma_{\pi N}$:

(A. Bottino et al., Astrop. Phys. 13 (2000) 215)

41 MeV < $\sigma_{\pi N}$ < 57 MeV

$\Rightarrow$ $98 \text{ MeV} \lesssim g_d \lesssim 406 \text{ MeV}$

(M. M. Pavan et al., PiN Newslett. 16(2002)110, hep-ph/0111066)

55 MeV < $\sigma_{\pi N}$ < 73 MeV

$\Rightarrow$ $266 \text{ MeV} \lesssim g_d \lesssim 598 \text{ MeV}$

N.B.: combining various measurements, the quantity

$y \equiv 2\frac{< N|\bar{s}s|N >}{< N|\bar{u}u+\bar{d}d|N >} = 1 - \frac{\sigma_0}{\sigma_{\pi N}}$ (squark content of the nucleon)

can be sizeable (y<0.6)

cross section depends on g_d^2, factor ~$(600/100)^2$~36 uncertainty

A. Bottino, F. Donato, N. Fornengo and S. Scopel, Astrop. Phys. 18 (2002) 205

Table 2

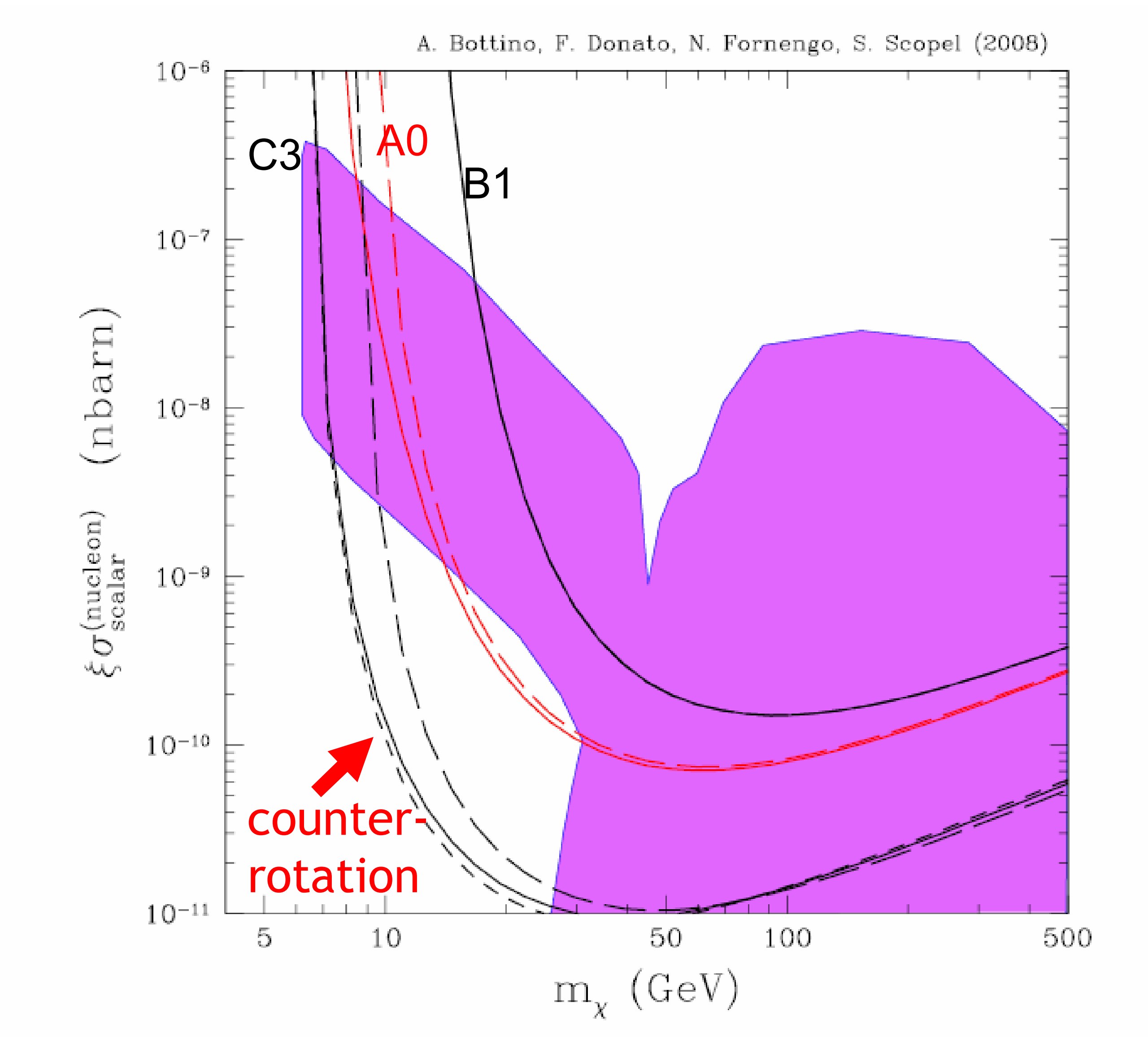
Values of the quantities $m_q\langle N|\bar{q}q|N\rangle$, g_u and g_d

	$m_l\langle N|\bar{q}_l q_l|N\rangle$	$m_s\langle N|\bar{s}s|N\rangle$	$m_h\langle N|\bar{h}h|N\rangle$	g_u	g_d
Set a [4]	27	131	56	139	214
Set b	28	186	52	132	266
Set c	37	456	30	97	523

Set a is the reference set given in Ref. [4]. Set b and Set c are the sets corresponding to the minimal and maximal values of $m_s\langle N|\bar{s}s|N\rangle$, respectively. All quantities are in units of MeV.

“reference set”

Neutralino-nucleon cross section & CDM limit (including astrophysical uncertainties)



solid:
v_{esc}=650 km/sec

long dashes:
v_{esc}=450 km/sec

eff-MSSM

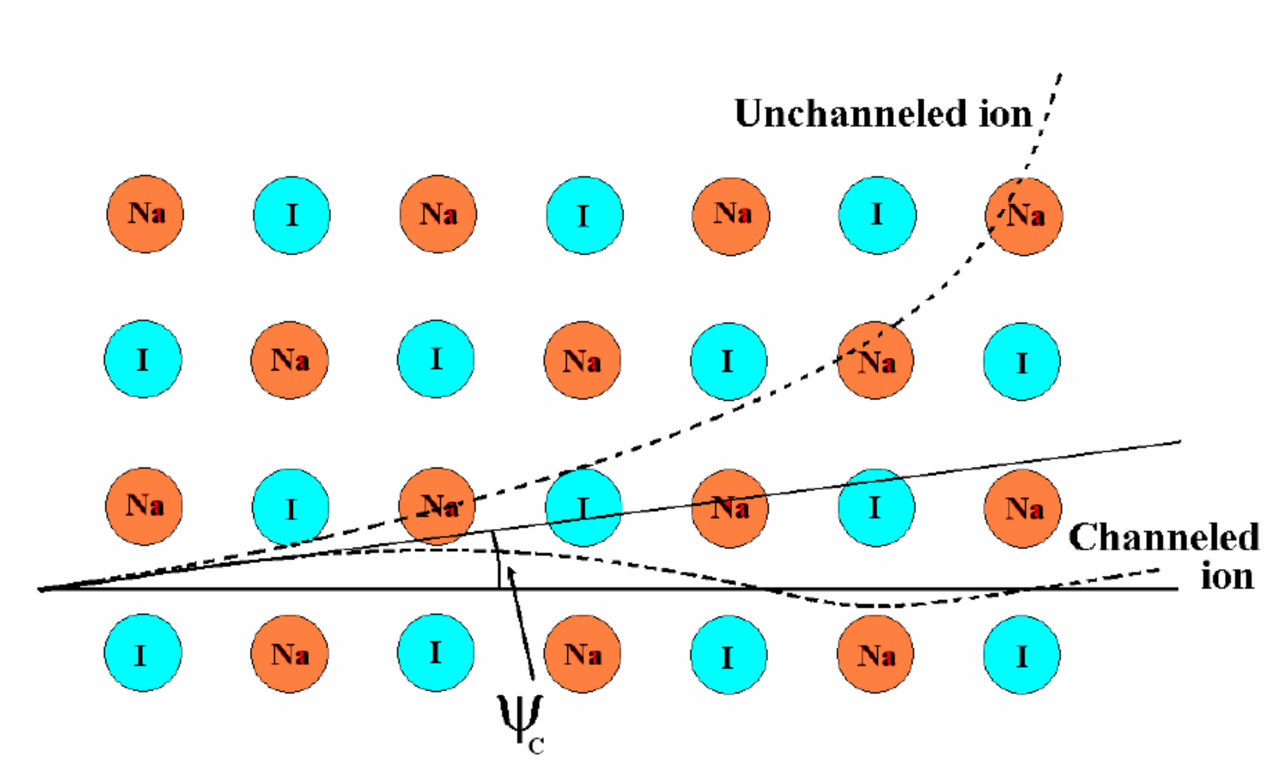
(including uncertainties due to hadronic matrix elements)

Quenching

- in ionizators or scintillators the energy of a recoiling nucleus is partially transferred to electrons which carry the signal
- q = quenching factor = fraction of nuclear recoil energy converting to ionization or scintillation (q=1 for γ's from calibration)
- simplistic view: recoiling nucleus experiences low stopping power of surrounding electronic cloud for kinematical reasons (mass mismatch between nucleus and single electrons)
- most of the energy is converted to lattice vibrations (heat)
- q~0.09 for I, q~0.23 for Na, q~0.3 for Ge. Measured with monoenergetic neutron beam
- standard theory: Lindhard et al., Mat. Fys. Medd. K. Dan. Vidensk. Selsk. 33 (1963) 1; SRIM code
- a useful application: dual read-out (bolometer + ionizator, bolometer + scintillator) allows discrimination between nuclear recoils (signal) and background (γ's and β's) (CDMS, Edelweiss)

One possible exception: channeling effect in crystals

(Dobryshevsky, arXiv:0706.3095, Bernabei et al., arxiv:07100288)



critical angle:

$$\Psi_c = \sqrt{\frac{C a_{TF}}{d\sqrt{2}}\Psi_1}$$

$$\Psi_1 = \sqrt{\frac{2Z_1 Z_2 e^2}{Ed}}$$

$C^2 \sim 3$, d=interatomic spacing

$$a_{TF} = \frac{0.8853 a_0}{\left(\sqrt{Z_1} + \sqrt{Z_2}\right)^{2/3}}$$

a_0=0.529 Å (Bohr radius)

- anomalous deep penetration of ions into crystalline targets discovered a long time ago (1957, 4 keV $^{134}CS^+$ observed to penetrate λ~ 1000 Å in Ge, according to Lindhard theory λ~ 44 Å)
- when the ion recoils along one crystallographic axis <u>it only encounters electrons</u> → long penetration depth and q~1

One possible exception: channeling effect in crystals

- the channeling effect is only relevant at low recoil energies (<150 keV)
- detector response enhanced → smaller WIMP cross sections needed to produce the same effect → smaller threshold on recoil energy and sensitivity to lighter masses

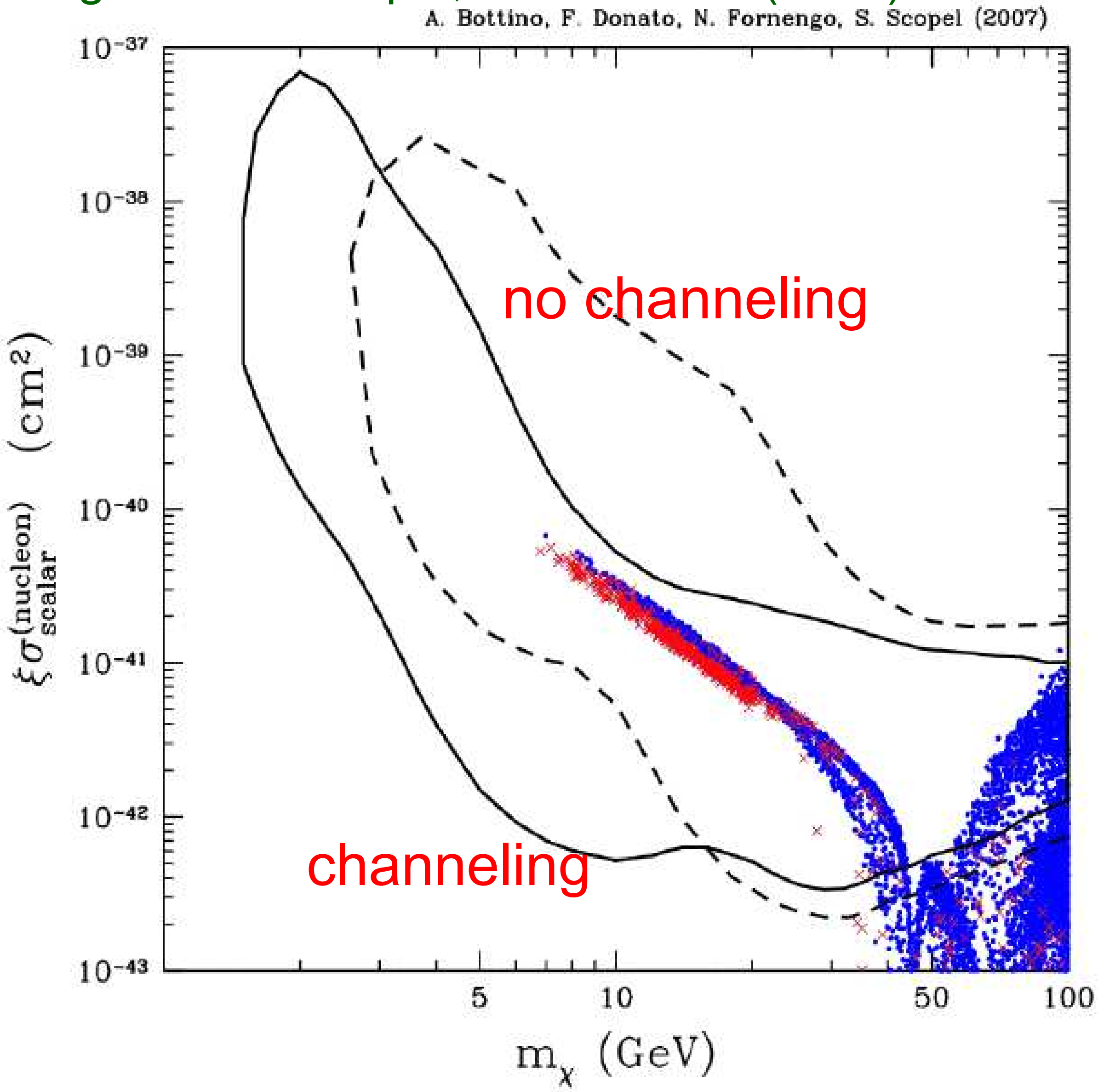
N.B.:

- this effect was neglected so far in the analysis of WIMP searches. It is expected in crystal scintillators and ionizators (Ge, NaI)
- no enhancement in liquid noble gas experiments (XENON10, ZEPLIN)
- channeled events are lost using PSD in scintillators
- channeled events are lost using double read-out discrimination (CDMS, Edelweiss)
- quenching measurements are not sensitive enough to see channeled events (q=1 peak broadened by energy resolution)

The DAMA/NaI region and the channeling effect

A Bottino, F. Donato, N. Fornengo and S. Scopel, arXiv:PRD77(2008) 015002

- including channeling the DAMA/NaI region moves to lighter WIMP masses and lower cross sections
- maximazed effect, i.e. q=1 whenever $\psi<\psi_c$
- if q<1 the region could lie in between



Compatibility of DAMA/NaI region with low mass neutralinos

(Evan's logarithmic model (A1), R_c=5 kpc)

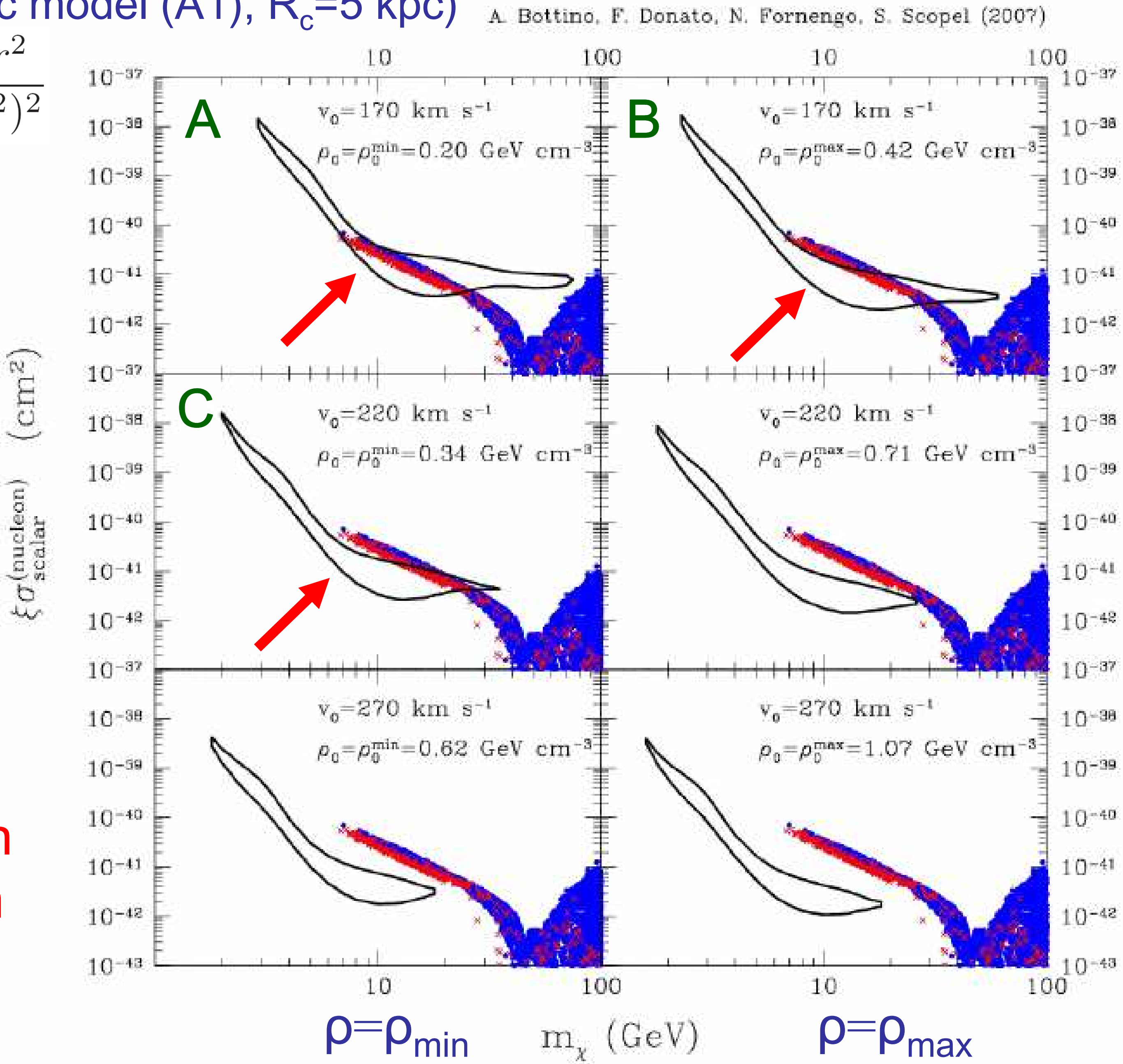
$$\rho(r) = \frac{v_0^2}{4\pi G}\frac{3R_c^2 + r^2}{(R_c^2+r^2)^2}$$

$v_0 = v_{0,min}$

$v_0 = v_{0,central}$

$v_0 = v_{0,max}$

v_0 and ρ_0 both in the low-medium side of their physical range



Present and future searches of antimatter and gamma rays:

Pamela - 06/2006

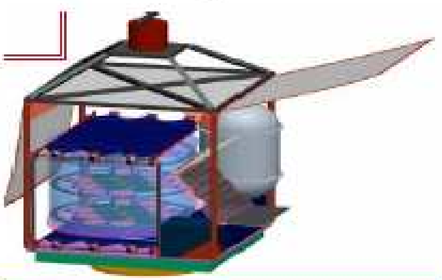
Pbess - 2010

Bess - 2007

Glas... 8

Launched 2 days ago!:
June 11, 2008 ~ 12 pm EDT

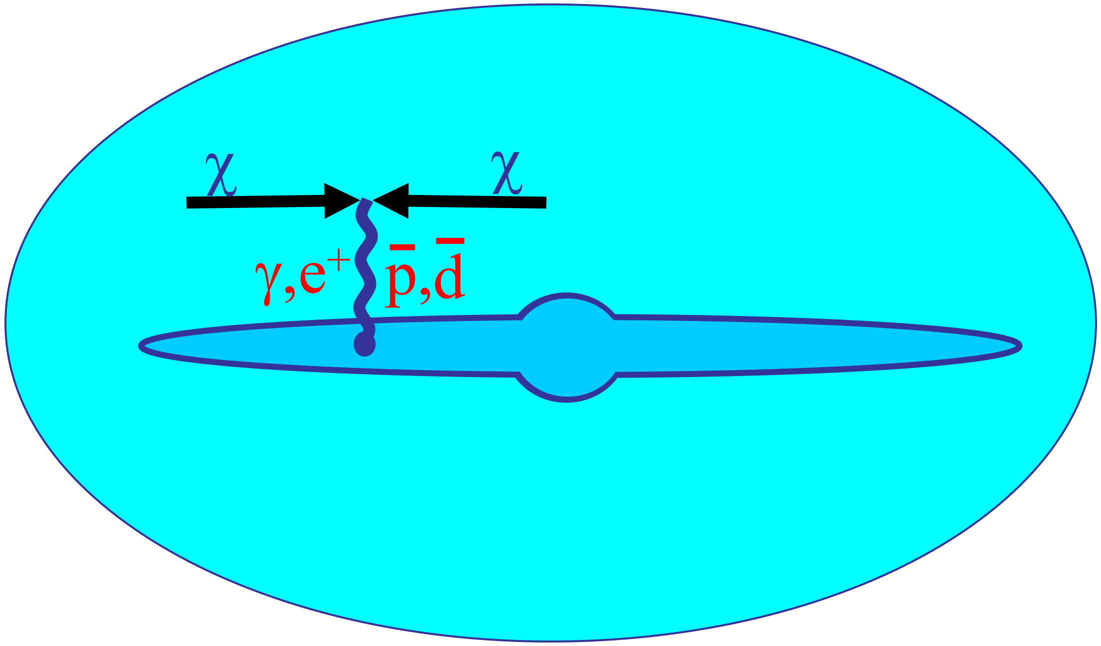
GAPS - 2013



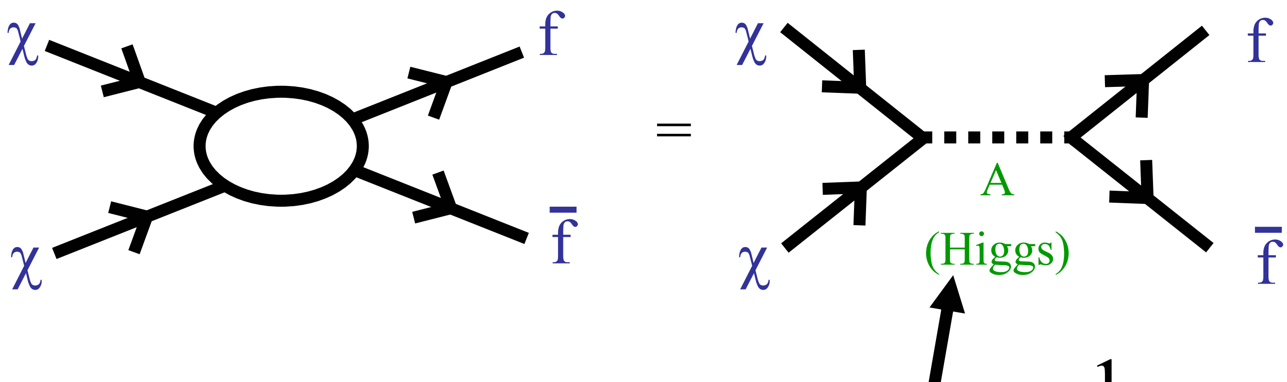
AMS - 2009

Agile, 04/2007

WIMP indirect detection: annihilations in the halo



example:



$$\sigma_{ann} \propto \frac{1}{m_{\mathrm{A}}^{4}}$$

Gamma rays from neutralino pair annihilations

$$\Phi_\gamma(E_\gamma,\psi) = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\frac{1}{2}I(\psi)$$

particle physics and astrophysics are factorized

$<\sigma_{ann}v>$≡annihilation cross section time relative velocity mediated over the galactic velocity distribution

Integration along the line of sight:

$$I(\psi) = \int_{\rm l.o.s} \rho^2(r(\lambda,\psi))\, d\lambda(\psi)$$

, ψ=angle between l.o.s and G.C

$$I_{\Delta\psi} \equiv \frac{1}{\Delta\psi}\int_{\Delta\psi} I(\psi)\, d\psi$$

Δψ ≡ telescope aperture

$|\Delta l| \leq 5^\circ,\ |\Delta b| \leq 2^\circ$

Isothermal	Isothermal	NFW	Moore et al.	r–dependent log–slope Eq.(2)
$a = 3.5$ kpc	$a = 2.5$ kpc	$a = 25$ kpc $r_c = 0.01$ pc	$a = 30$ kpc $r_c = 0.01$ pc	$\alpha = 0.142$ $r_{-2} = 26.4$ kpc $\rho_{-2} = 0.035$ GeV cm^{-3}
18.5	42.5	184.2	10866	600

Toward GC
strong dependence on profile, less relevant in other directions

Neutralino self annihilations and dark matter density distribution

Signals depend quadratically on the dark matter density ρ.

Common parametrization:

$$\rho(r) = \rho_l \left(\frac{R_\odot}{r}\right)^\gamma \left[\frac{1+(R_\odot/a)^\alpha}{1+(r/a)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

ρ_l =dark matter local density

$r = |\vec{r}|$, $R_\odot = 8$ kpc

a=scale length

$(\alpha,\beta,\gamma)=(2,2,0)$ Isothermal

$(\alpha,\beta,\gamma)=(1,3,1)$ NFW, $\propto r^{-1}$ in GC ← our reference model

$(\alpha,\beta,\gamma)=(1.5,3,1.5)$ Moore *et al.*, $\propto r^{-1.5}$ in GC

Numerical simulation suggest the non-singular form:(J. F. Navarro et al., Mon.Not.Roy.Astron.Soc.349,1039(2004))

$$\rho(r) = \rho_{-2} \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^\alpha - 1\right]\right\}$$

$$\left.d(\ln(\rho))/d(\ln(r))\right|_{r=r_{-2}} = -2$$

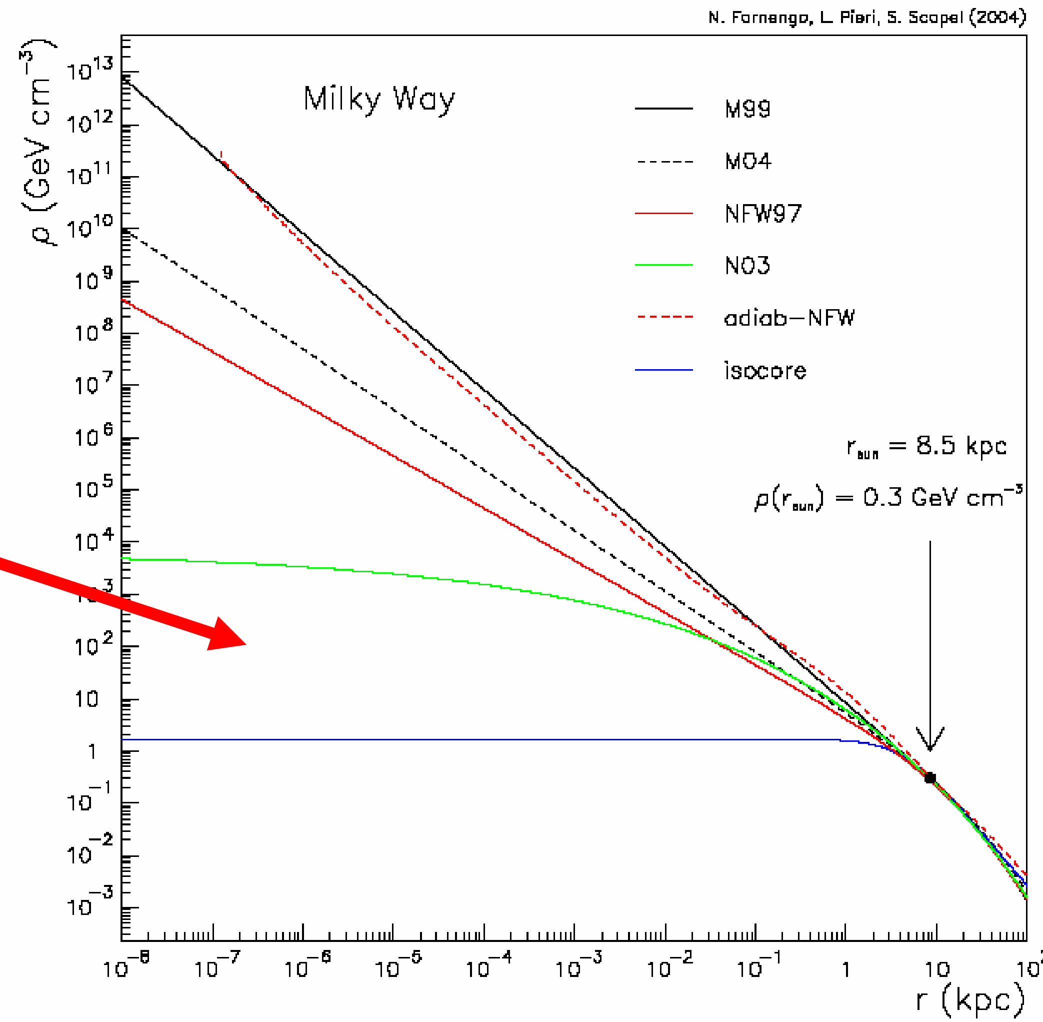
$\rho_{-2} \equiv \rho(r_{-2})$

$\alpha \approx 0.17$

Large differences in the behaviour towards GC

N.B. Anyway, current simulations not reliable for radii smaller than 0.1 – 1 kpc

Comparison between cuspy and cored DM density profiles (Milky Way)

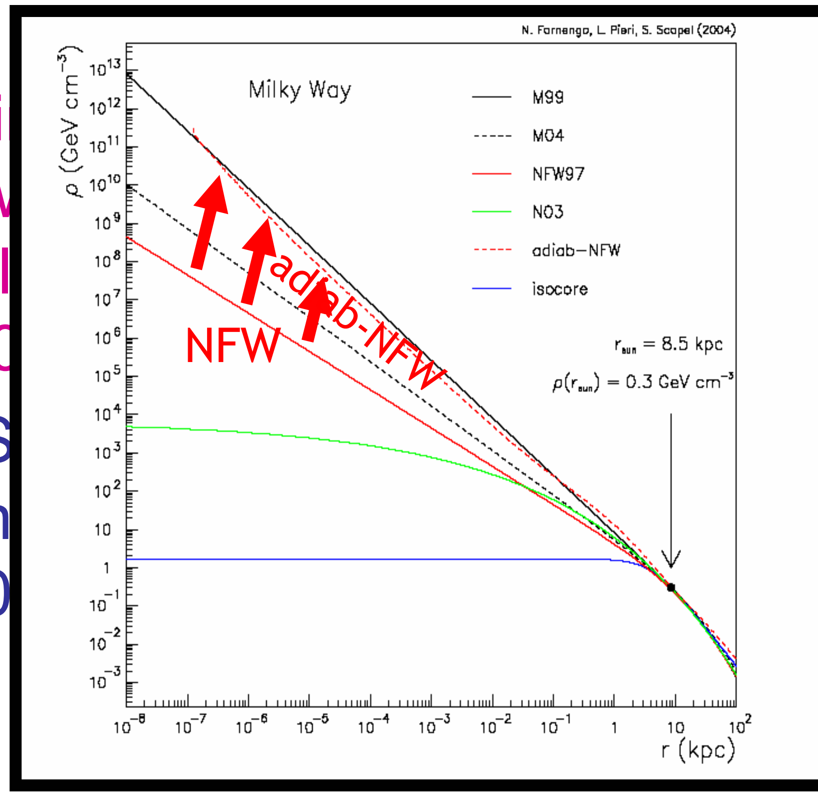


Profiles shallower than NFW97 give hardly observable fluxes

Effect of baryons on the inner parts of galaxies

The effect of baryon is still not well known: it may either enhance or disrupt the central cusp:

- adiab-NFW profile i … n central black hole w … es an initial NFW profil … i, PRD64, 043504 (20
- but formation of a S … os) leads to a depletion … t al., PRL88, 191301 (20



Effect of the inner core

- minimal radius r_{cut} within which the self annihilation rate is equal to the dynamical time (Berezinski et al., PLB9...

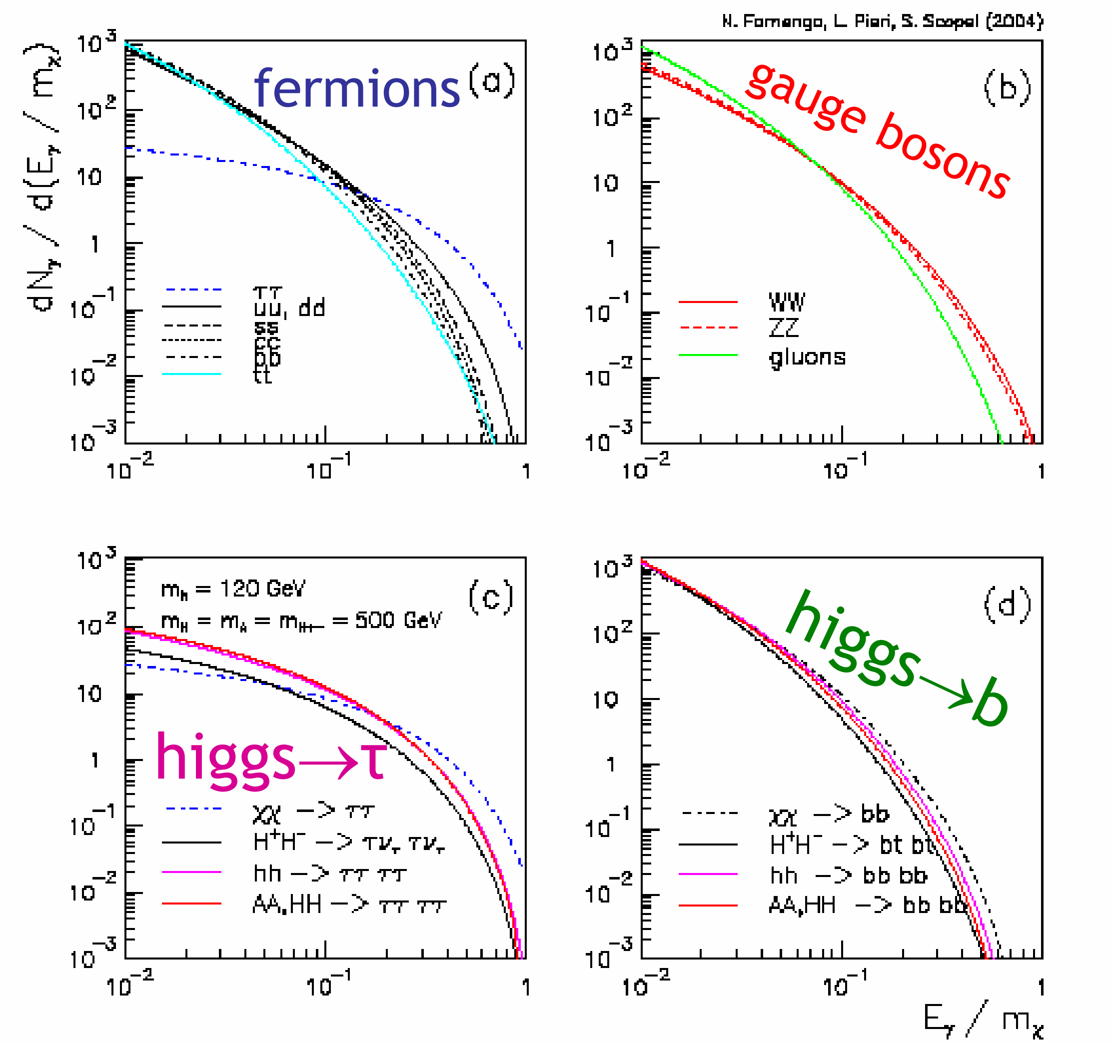
$$r_{cut} \approx \begin{cases} 10^{-9} \div \ldots \text{ (...99 profile)} \\ 10^{-14} \div 10^{-13} \text{ kpc (NFW97 profile)} \end{cases}$$

numerical simulations reliable down to ≈ 0.1 kpc!

- effect of baryons: presence of BH erases DM within 3×10^{-9} kpc (MW) and 3×10^{-7} kpc (M87)

- including other effects, like tidal interactions, the central core of galaxies can reach 0.1 – 1 kpc

The photon spectrum (m_χ = 1 TeV, BR=1 in each channel)



- at low energies dominant contribution from quark and gluon hadronization
- hardest spectra from τ leptons

Source spectrum

$$\boxed{\frac{dN_\gamma}{dE_\gamma}}$$

Below $m_\chi \cong m_W$, dominated by production and decay of π^0's from $q\bar{q}$ hadronization:

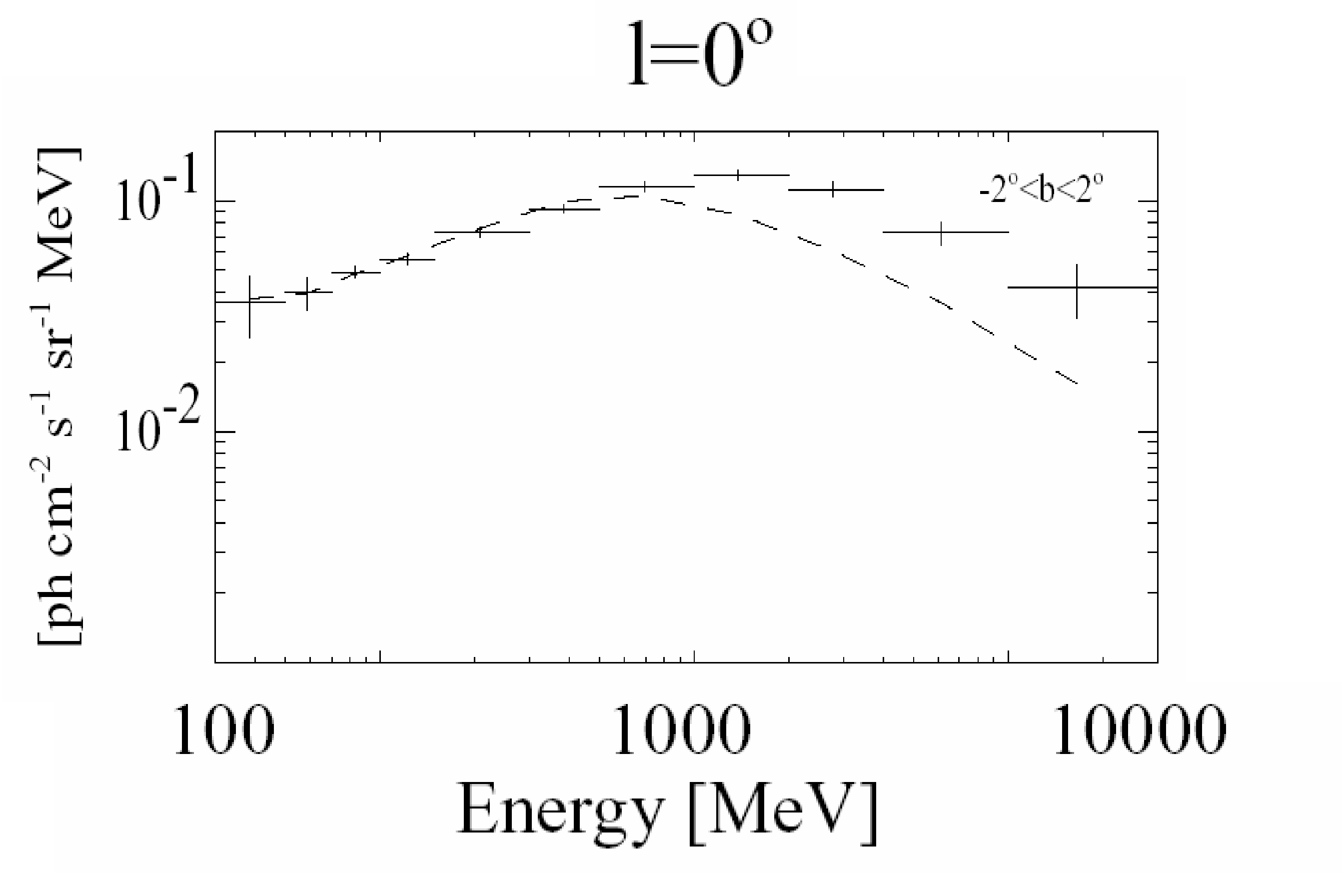
- scale invariance broken by gluon showering
- for E<100 MeV, sizeable contribution from electromagnetic showering of leptons and from production and decay of η, η', charm and bottom mesons (peak from $B^* \to B + \gamma$ for $m_\chi < 10$ GeV?)

At higher masses, annihilation channels into Higgs bosons, gauge bosons and $t\bar{t}$ pairs become kinematically accessible. We compute analytically the full decay chain down to the production of a quark, gluon or a lepton.

calculated using MC (like Pythia)

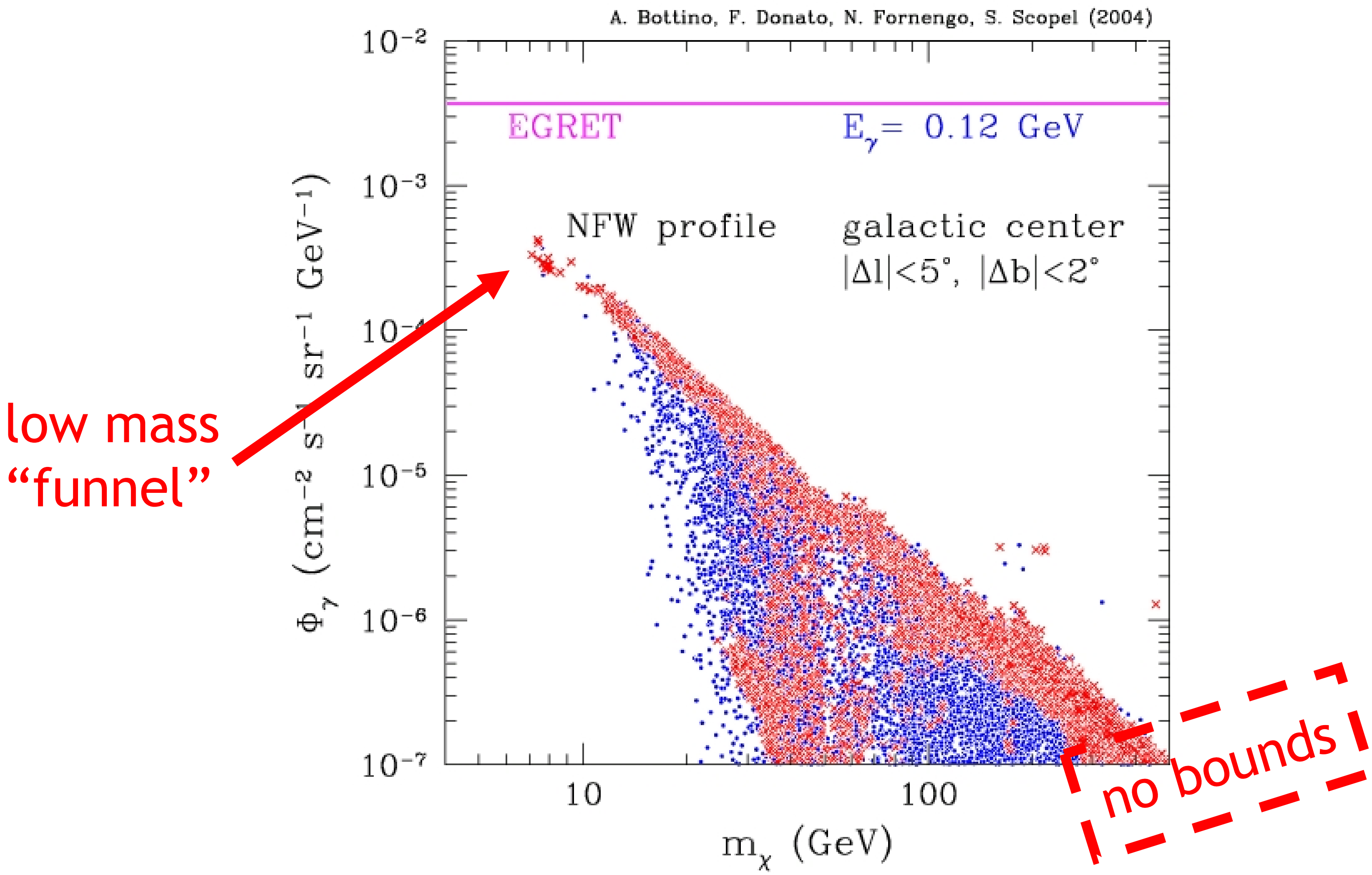
EGRET excess toward GC?

S. D. Hunter *et al*., Astrophys. J. **481,** 205 (1997)

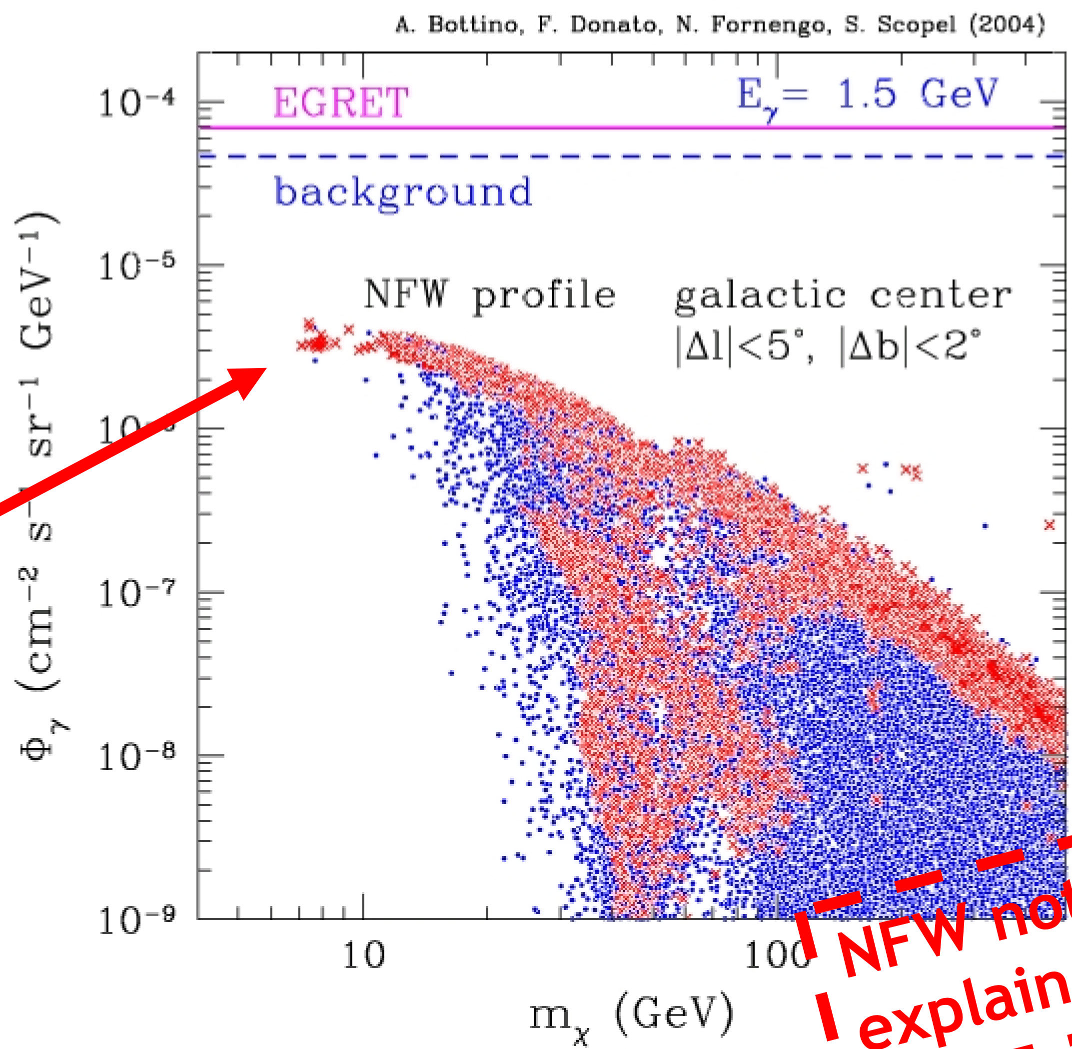


estimated background, D.L.Bertsch et al., Astrophys. J. **416,** 587 (1993)

Gamma flux due to neutralino annihilation from Galactic Center



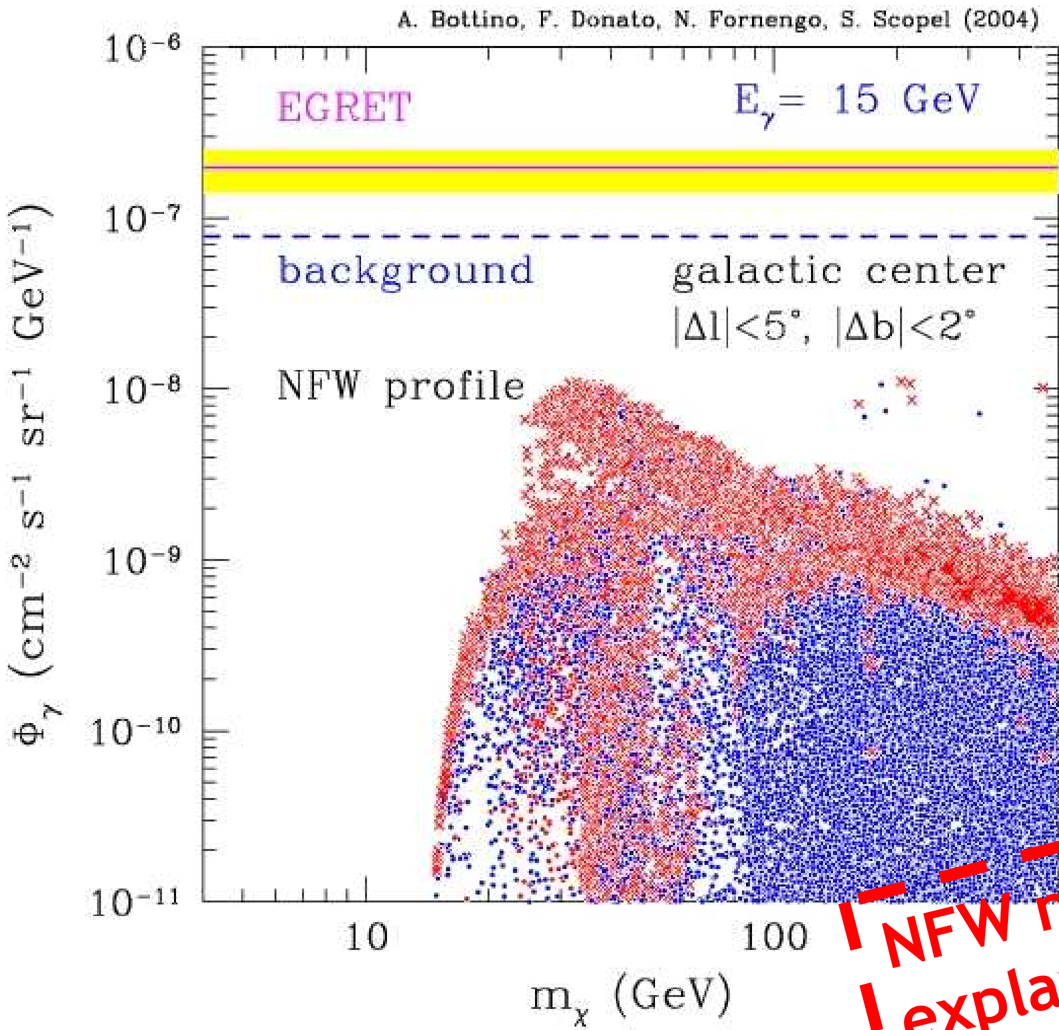
Gamma flux due to neutralino annihilation from Galactic Center



low mass "funnel"

NFW not enough to explain excess

Gamma flux due to neutralino annihilation from Galactic Center

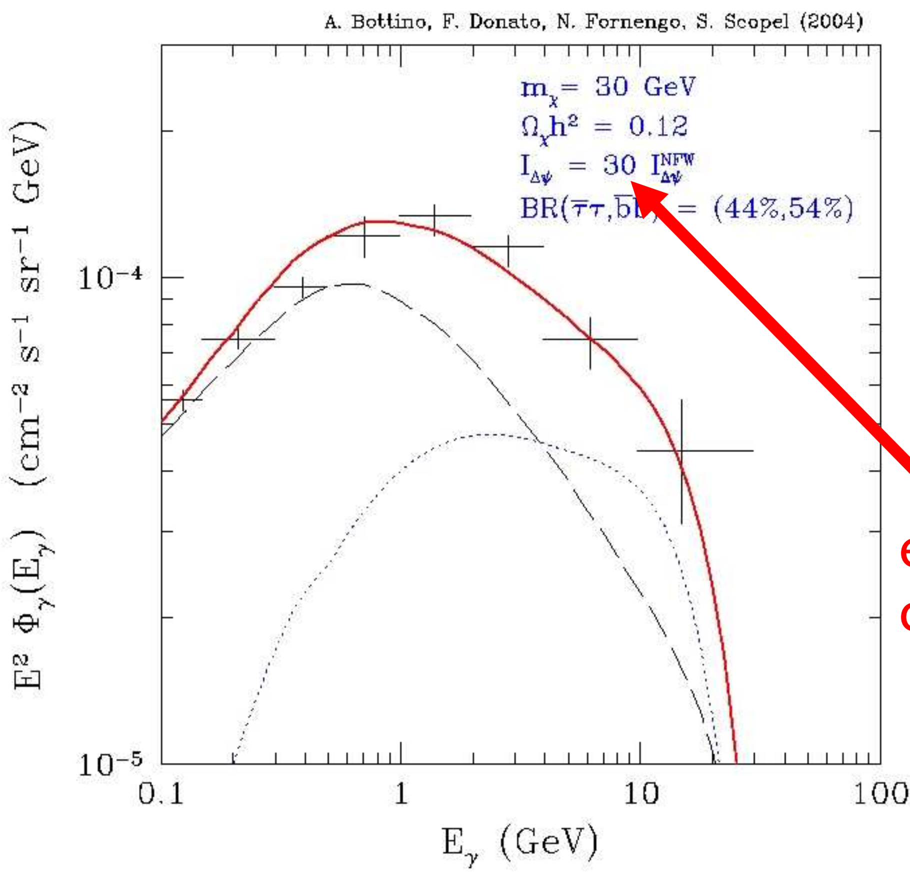


NFW not enough to explain excess

It has already been shown that neutralinos with $m_\chi > 50$ GeV could explain the EGRET excess (A. Cesarini, F. Fucito, A. Lionetto, A. Morselli and P. Ullio, astro-ph/0305075)

Could the EGRET excess be explained also by light neutralinos?

YES!



m_χ=30 GeV

enhancement required compared to NFW

.... Neutralino contribution

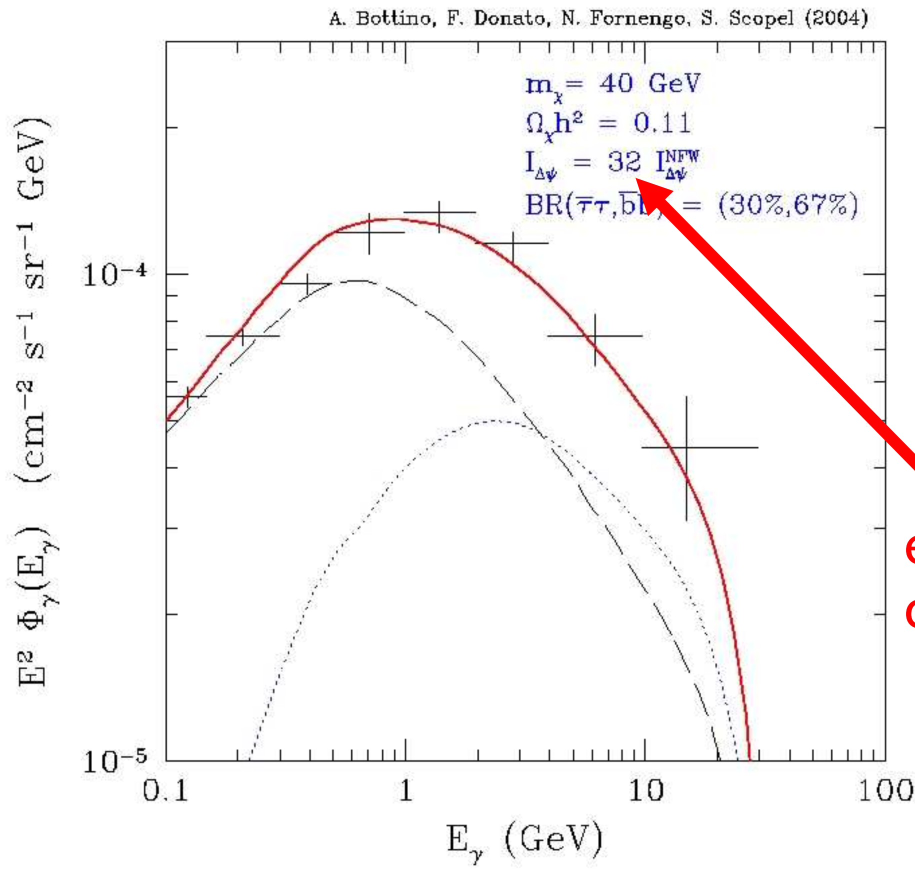
– – – – - Background rescaled by 10%

——— Signal+background

It has already been shown that neutralinos with m_χ>50 GeV could explain the EGRET excess (A. Cesarini, F. Fucito, A. Lionetto, A. Morselli and P. Ullio, astro-ph/0305075)

Could the EGRET excess be explained also by light neutralinos?

YES!



m_χ=40 GeV

enhancement required compared to NFW

.... Neutralino contribution

– – – – Background rescaled by 10%

——— Signal+background

EGRET residual flux at high latitudes

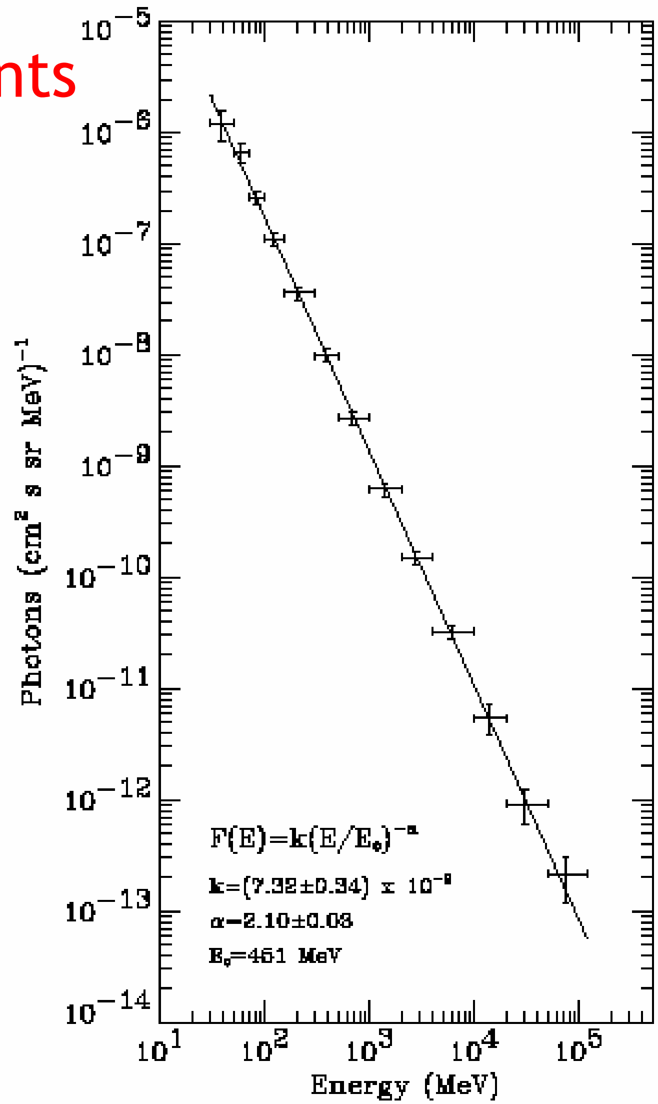
after subtraction of known components

(identified sources, spectrum due to cosmic rays interaction with the galactic disk)

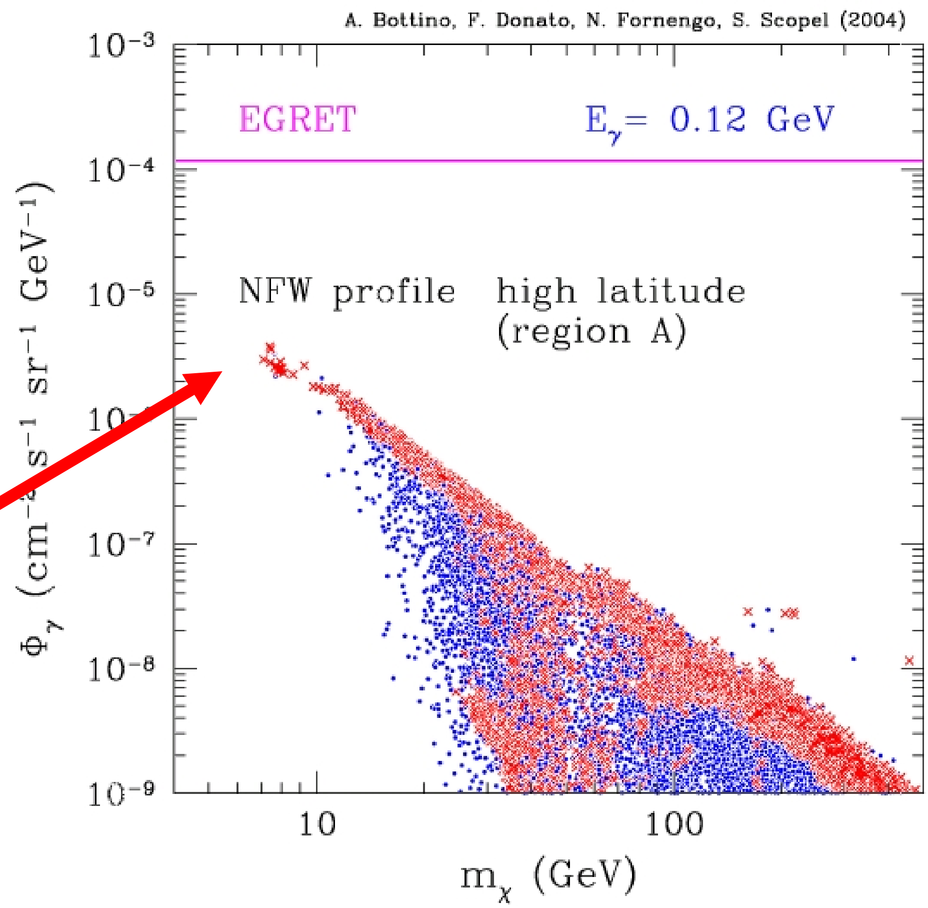
P. Sreekumar *et al.*,
Astrophys. J. **494**, 523 (1998)

extragalactic origin?

…or exotic production?



Gamma flux due to neutralino annihilation from high latitudes

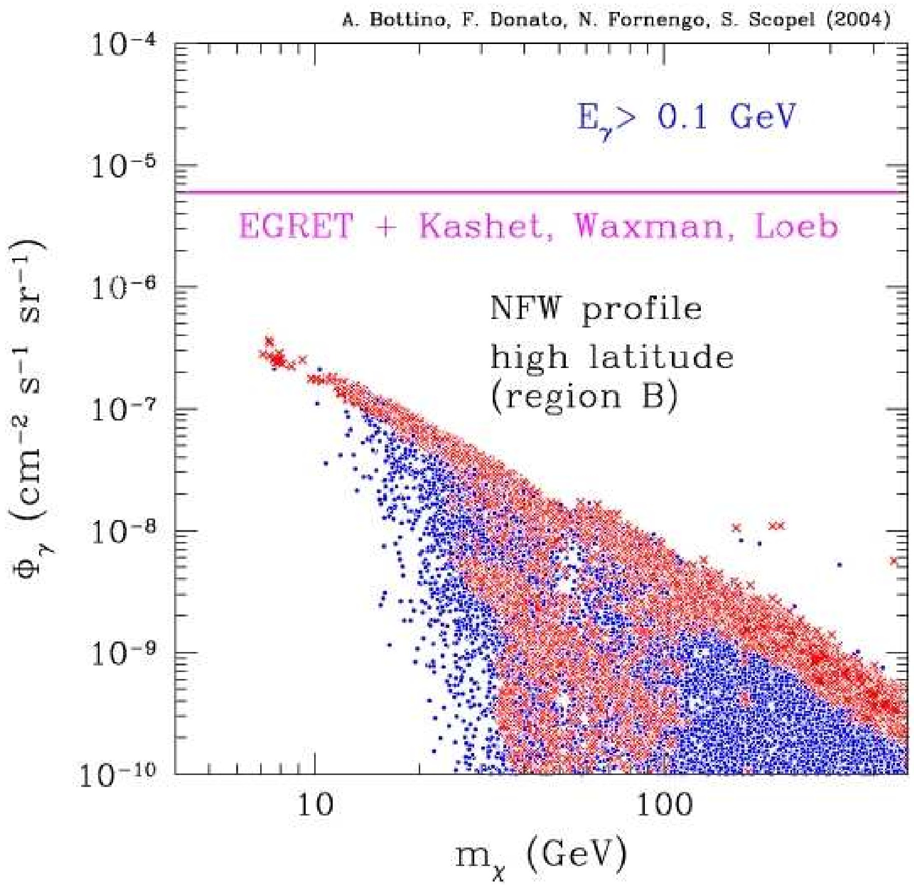


low mass
"funnel"

Region A:
$|b|>10^0$, $|l|>40^0$
$10^0<|b|<30^0$

EGRET residual flux,
P. Sreekumar *et al.*, Astrophys. J. **494**, 523 (1998)

Gamma flux due to neutralino annihilation from high latitudes



Region B:
$|b|>86^0$

Re-analysis of EGRET data,
U. Keshet, E. Waxman, A. Loeb, astro-ph/0306442

Gamma flux due to neutralino annihilation from high latitudes

- γ signals from high altitudes turn out to be one order of magnitude below present sensitivities.
- Contrary to GC, in this case $I_{\Delta\psi}$ is practically independent on the halo profile.

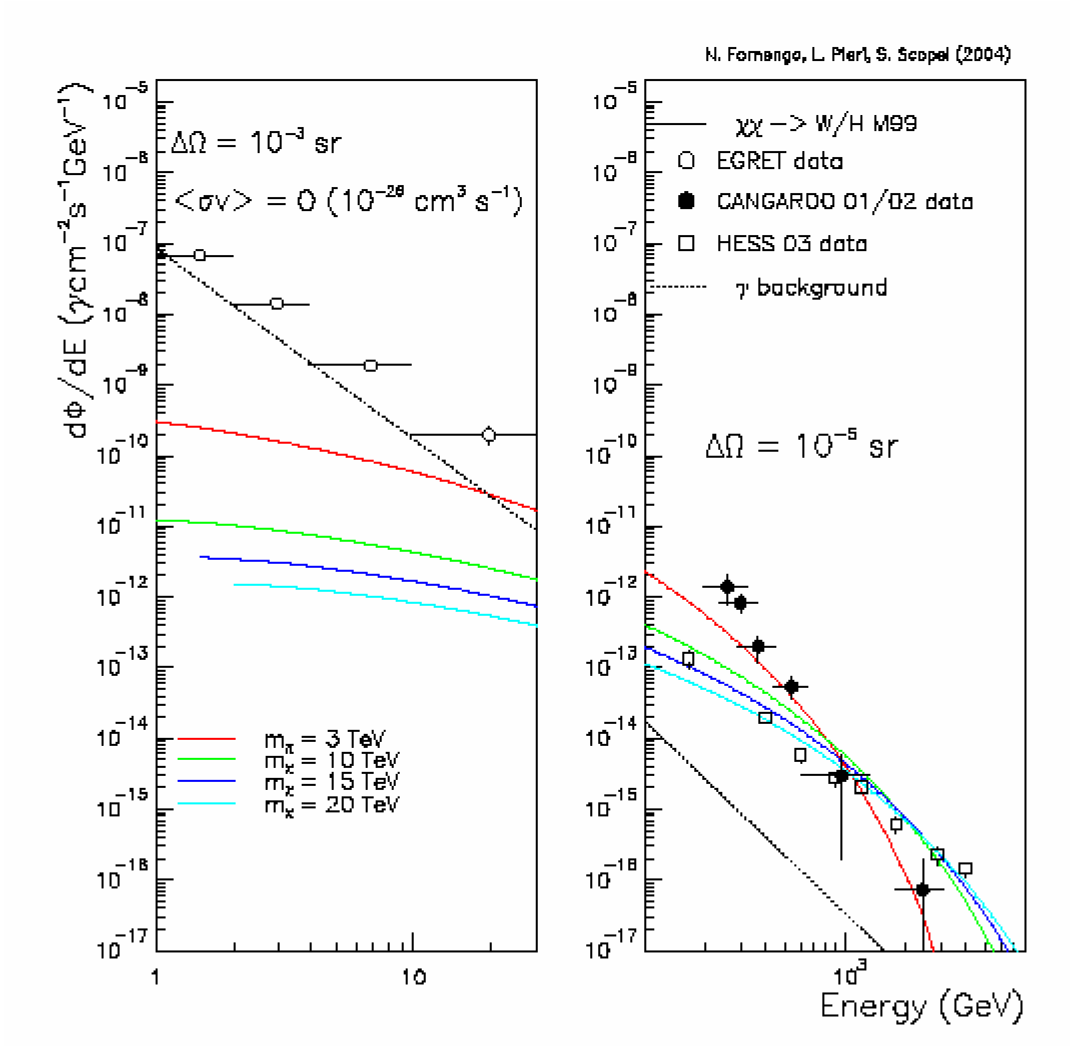
Clumpiness?

Effect discussed by several authors, sometimes with signal improvements at the level of a few orders of magnitude.

However, other analytical investigations on the production of small-scale dark matter clumps suggest that the clumpiness effect would not be large. Enhancement effect limited to a factor of a few. Similar conclusions also reached with high-resolution numerical simulations. (V. Berezinsky, et al., Phys. Rev. D68, 103003 (2003); F. Stoher et al., Mon. Not. Roy. Astron. Soc. **345**, 1313 (2003)).

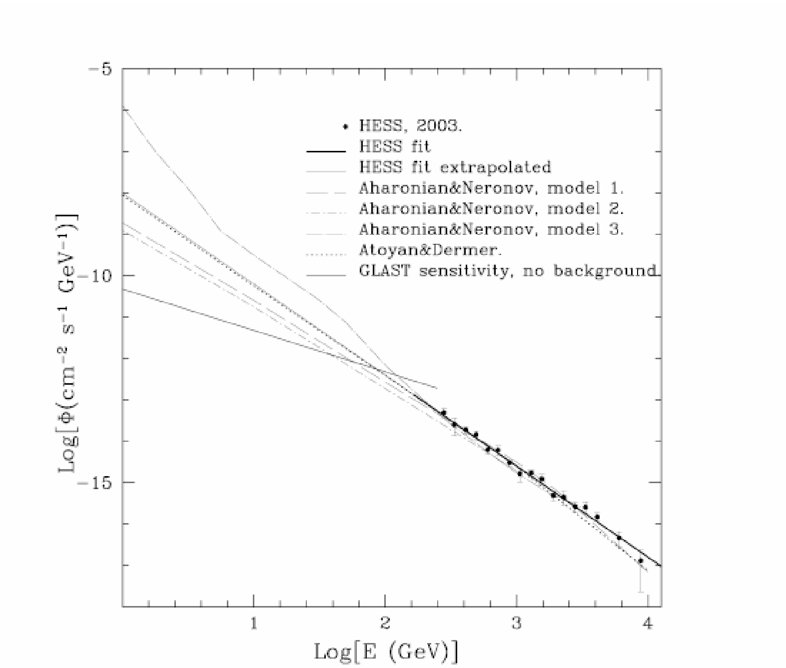
However, see V. Berezinsky, et al., Phys. Rev. D77, 083519 (2008) for a reassesment (amplification~100?)

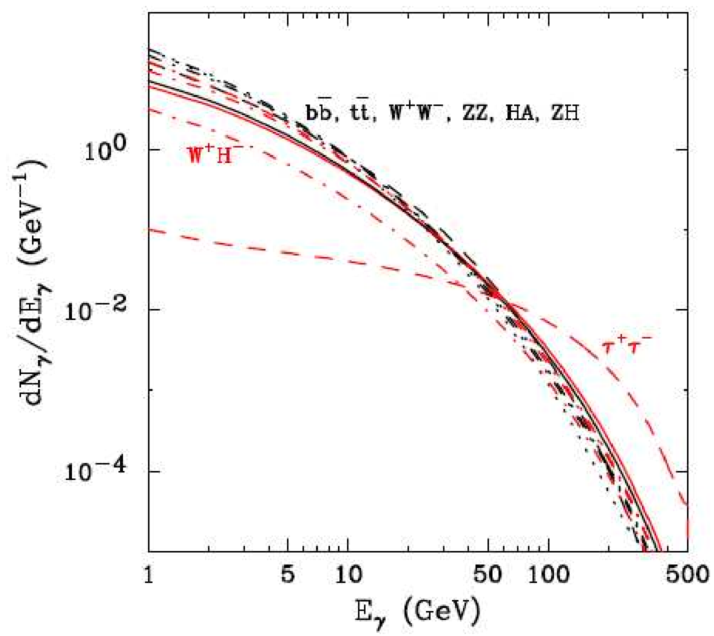
HESS data from galactic center



very hard spectrum, would require 10 TeV $< m_\chi <$ 20 TeV

• ACT's compatible with a gamma-ray source in the GC with ~ $E^{-2.2}$ power-law spectrum (HESS, WHIPPLE, MAGIC, CANGAROO-II) hardly compatible with WIMP annihilation (too heavy M required ~10 TeV, different shape) → background to subtract? This would make things harder!

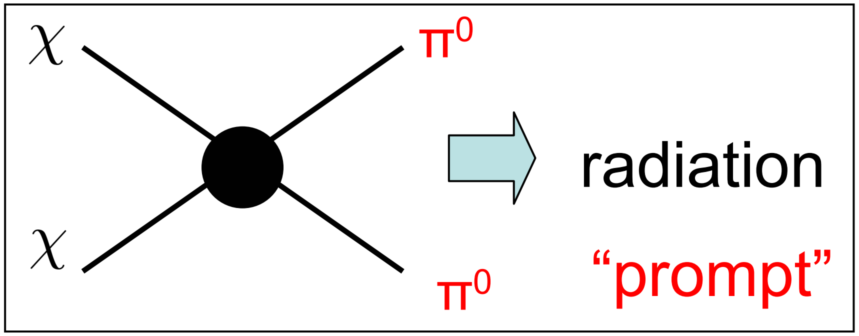




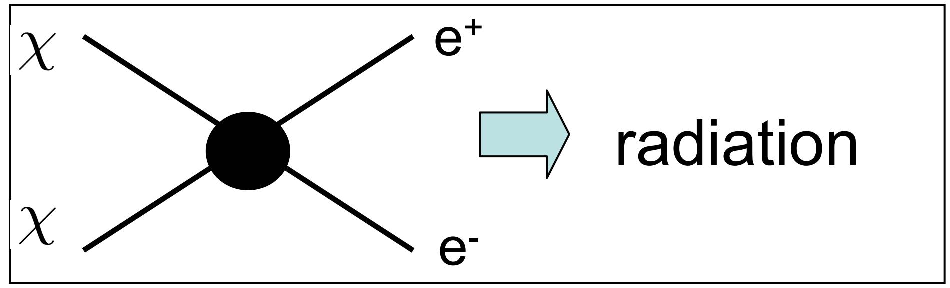
data+"conventional" astrophysical models

wimp spectra

Multi-wavelength approach (see for instance, Colafrancesco, Profumo, Ullio, astro-ph/0507575)



OR



sincrotron emission from e^+e^- (including WMAP haze)

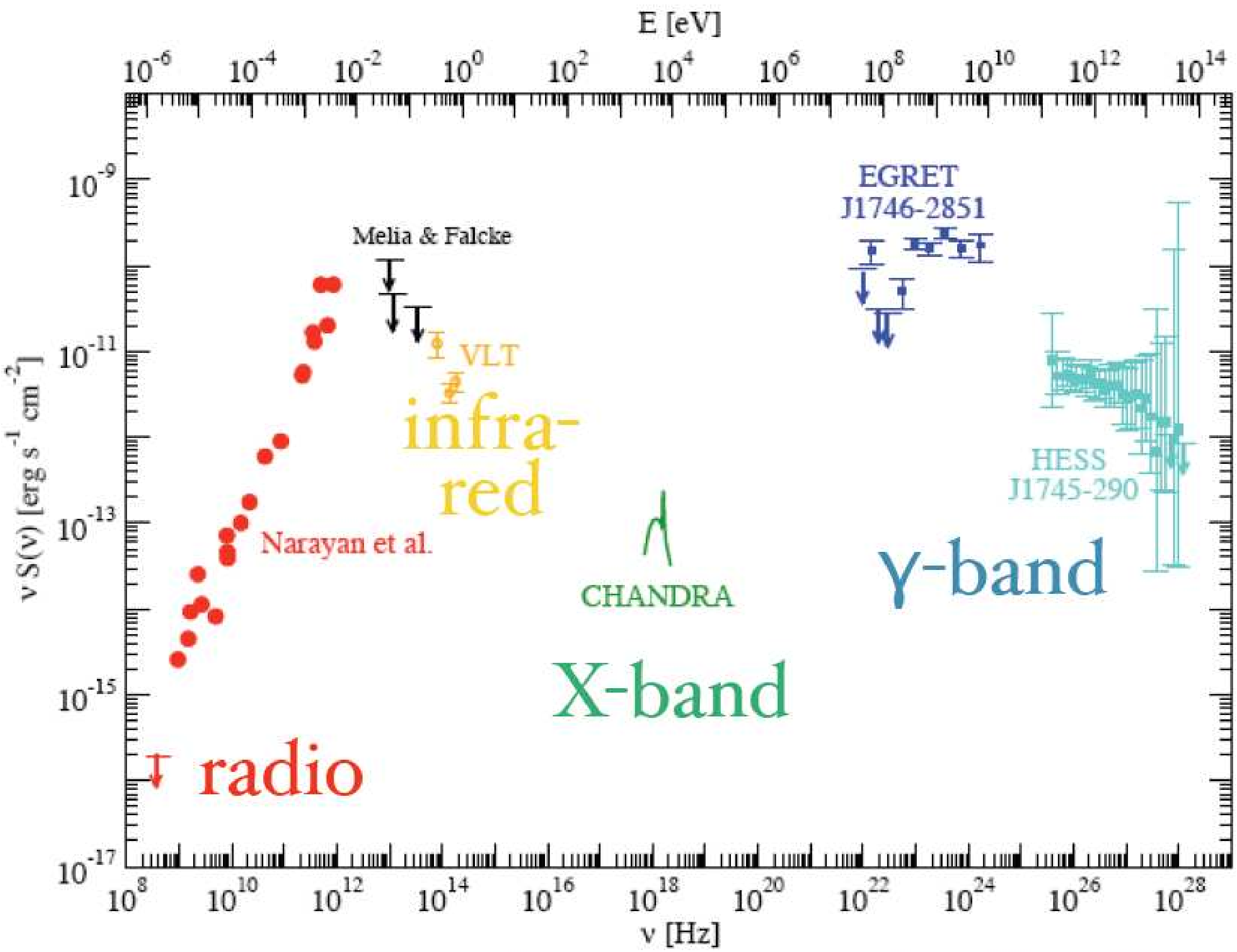
Inverse Compton of $e^{\pm}$ on CMB and starlight

soft gammas from non-thermal bremsstrahlung

"usual" mechanism: prompt hard gammas, mainly from $\pi^0 \rightarrow \gamma\gamma$ (also one-loop monochromatic line)

Region	Energy (eV)
Radio	$< 10^{-5}$
Microwave	10^{-5} - 0.01
Infrared	0.01 - 2
Visible	2 - 3
Ultraviolet	3 - 10^3
X-rays	10^3 - 10^5
Gamma rays	$> 10^5$

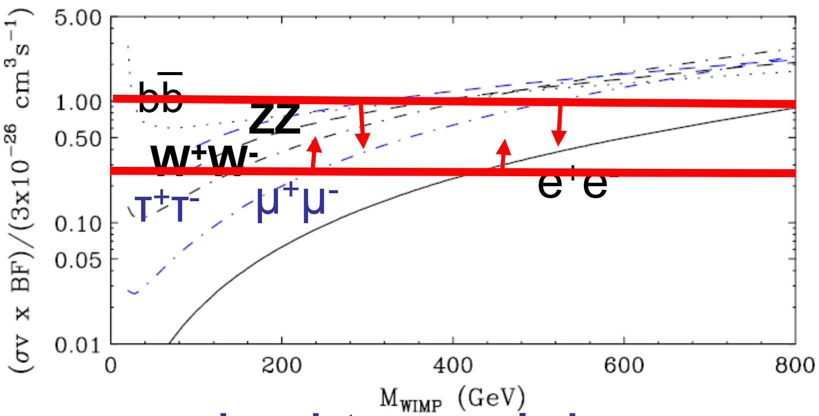
the Galactic Center (Sgr A*) is a rather quiet place after all:



en exotic component (like a WIMP) could be measurable

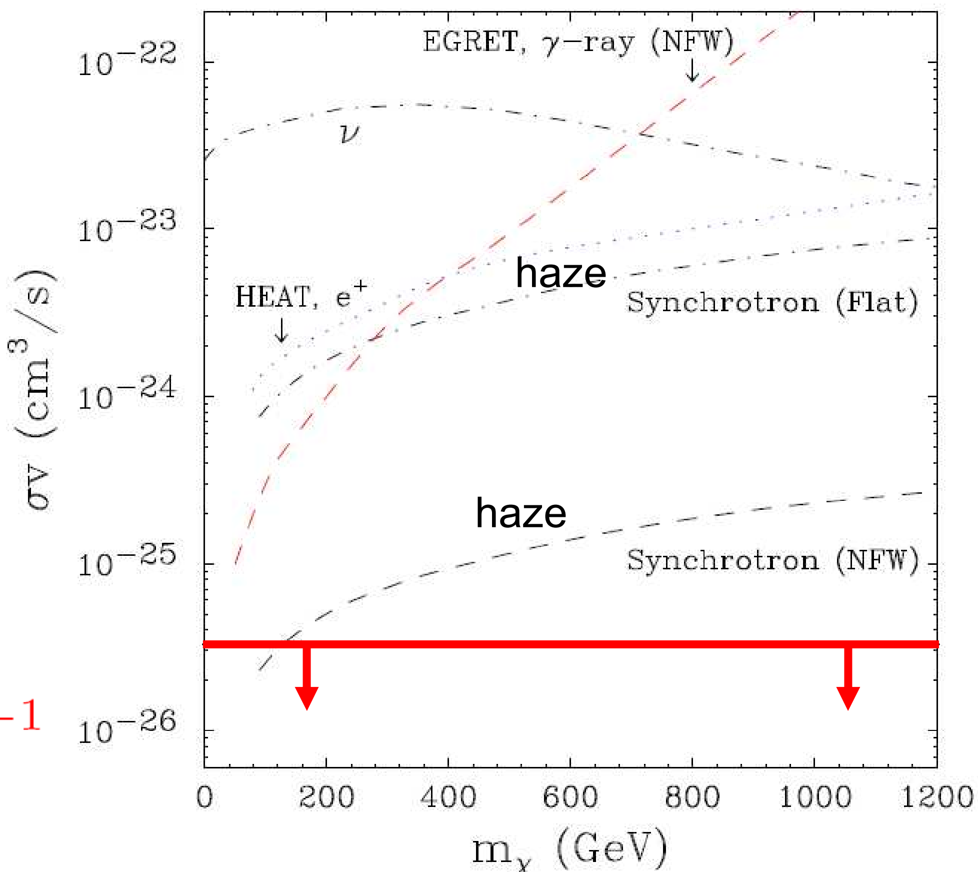
WMAP “haze”: excess of microwave emission from a region within ~20^0 of the galactic center.

Hooper et al., arXiv:0705.3655



σv required to explain excess

Hooper, arXiv:0801.4378



comparison of various upper bounds on σv

lower bond on σv required by thermal relic abundance:

$$< \sigma_{\rm ann} v > \gtrsim 9 \times 10^{-27}\ {\rm cm}^2\,{\rm s}^{-1}$$

moreover, also *upper* bound:

$$\xi^2 < \sigma_{\rm ann} v > \lesssim 3 \times 10^{-26}\ {\rm cm}^2\,{\rm s}^{-1}$$

(ξ = rescaling factor)

Why a *lower* bound on $\xi^2 \langle\sigma_{ann} v\rangle$?

Indirect searches and rescaling

$$\rho_{WIMP} = \rho_{loc} \times \xi$$

local density of WIMPS

fraction of DM due to WIMPS

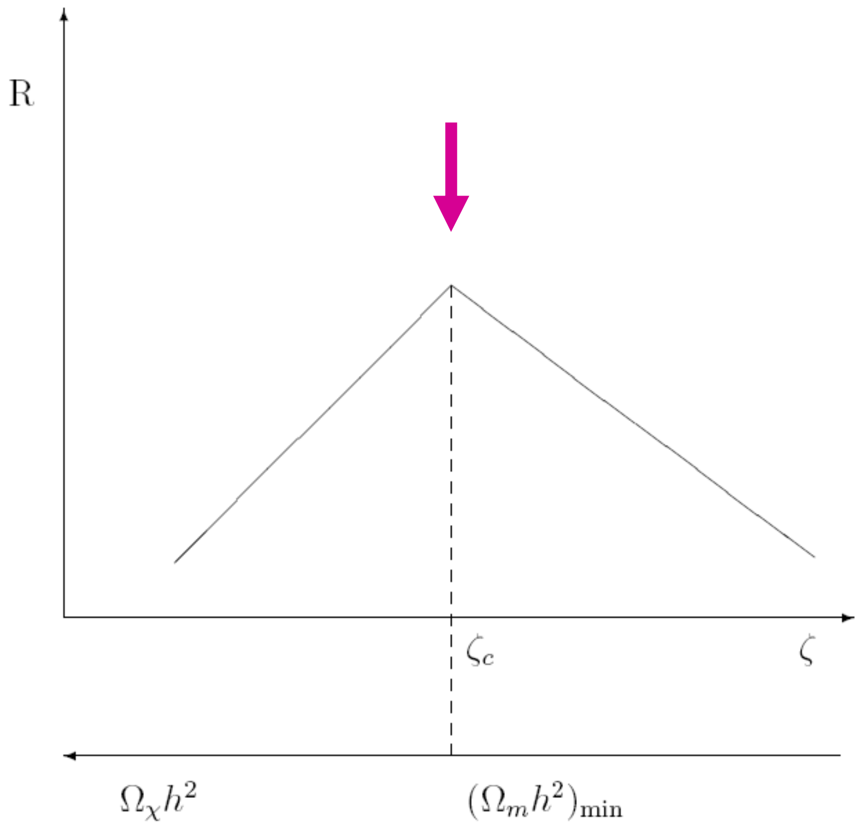
local density of matter as measured gravitationally (i.e.:total)

when the *calculated* relic density $\Omega_{WIMP} h^2$ is below the minimum value compatible to observation $(\Omega_{CDM} h^2)_{\min}$ one has $\xi<1$. Rescaling recipe:

$$\xi \equiv \min\left[1, \frac{\Omega_{WIMP} h^2}{(\Omega_{CDM} h^2)_{\min}}\right]$$

Indirect signal rates R are proportional to $\xi^2\sigma_{ann}$, so when rescaling does not apply $R\sim\sigma$, while when rescaling applies $\xi\sim\Omega\sim 1/\sigma_{ann}$ and $R\sim 1/\sigma_{ann}$, i.e.:

$$R\sim\begin{cases} 1/\Omega_{WIMP}h^2 & \text{when } \Omega_{WIMP}h^2 > (\Omega_{CDM}\, h^2)_{min} \\ \Omega_{WIMP}h^2 & \text{when } \Omega_{WIMP}h^2 < (\Omega_{CDM}\, h^2)_{min} \end{cases}$$

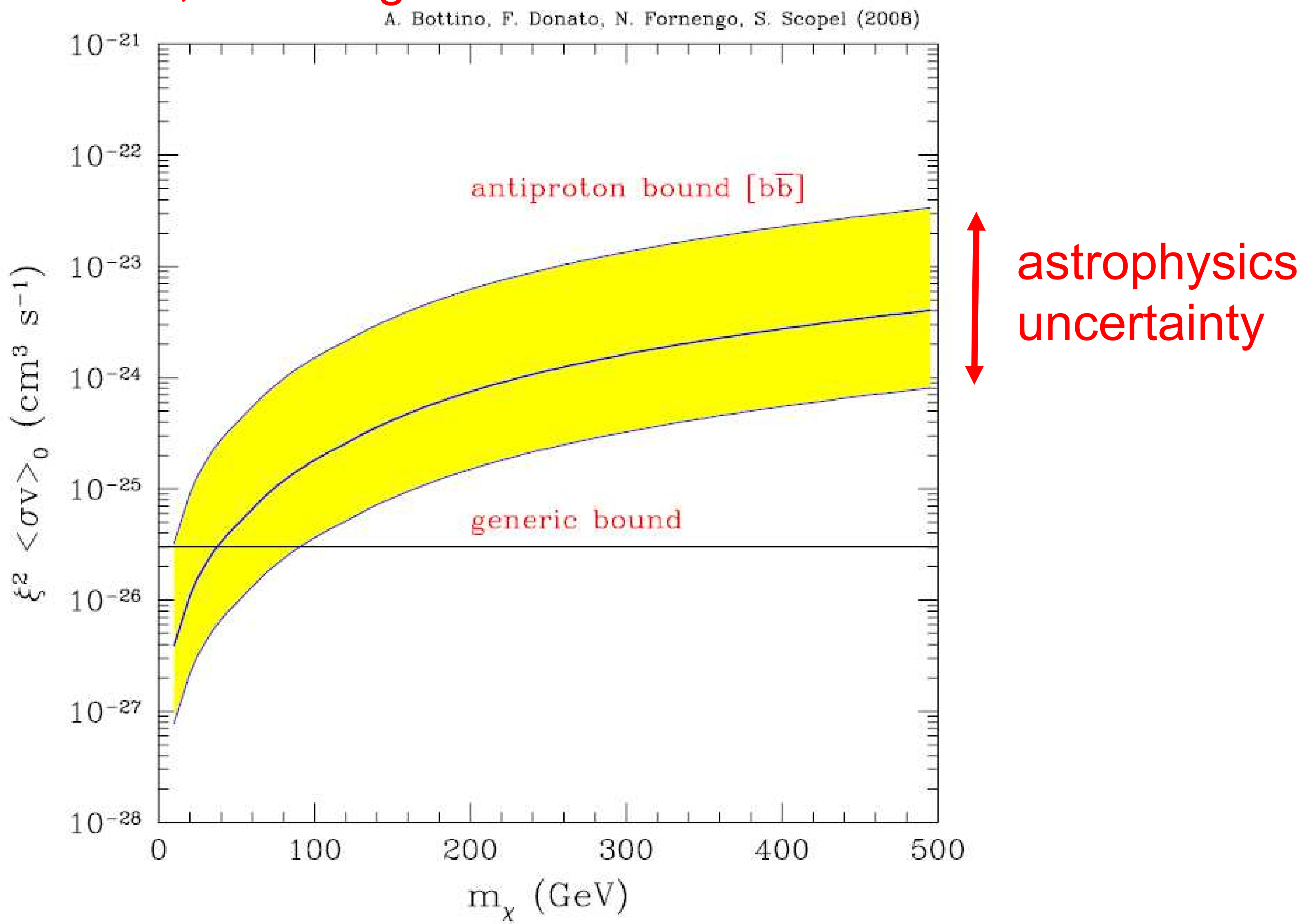


the product $\xi^2\sigma_{ann}$ is maximized for the choice of the model parameters corresponding to $\Omega_{WIMP}h^2 = (\Omega_{CDM}\, h^2)_{min}$

upper bound on $\xi^2\sigma_{ann}$

(Bottino, Favero, Fornengo, Mignola, Scopel, 1996)

N.B.: this holds neglecting all those special situations which spoil the correlation between the present σ_{ann} and that calculated at the WIMP freeze-out temperature, which is the one which enters in the relic density calculation (such as coannihilation or P-wave dominance in the annihilation cross section,) Actually, antiprotons are more constraining than all other sources, including "WMAP haze":

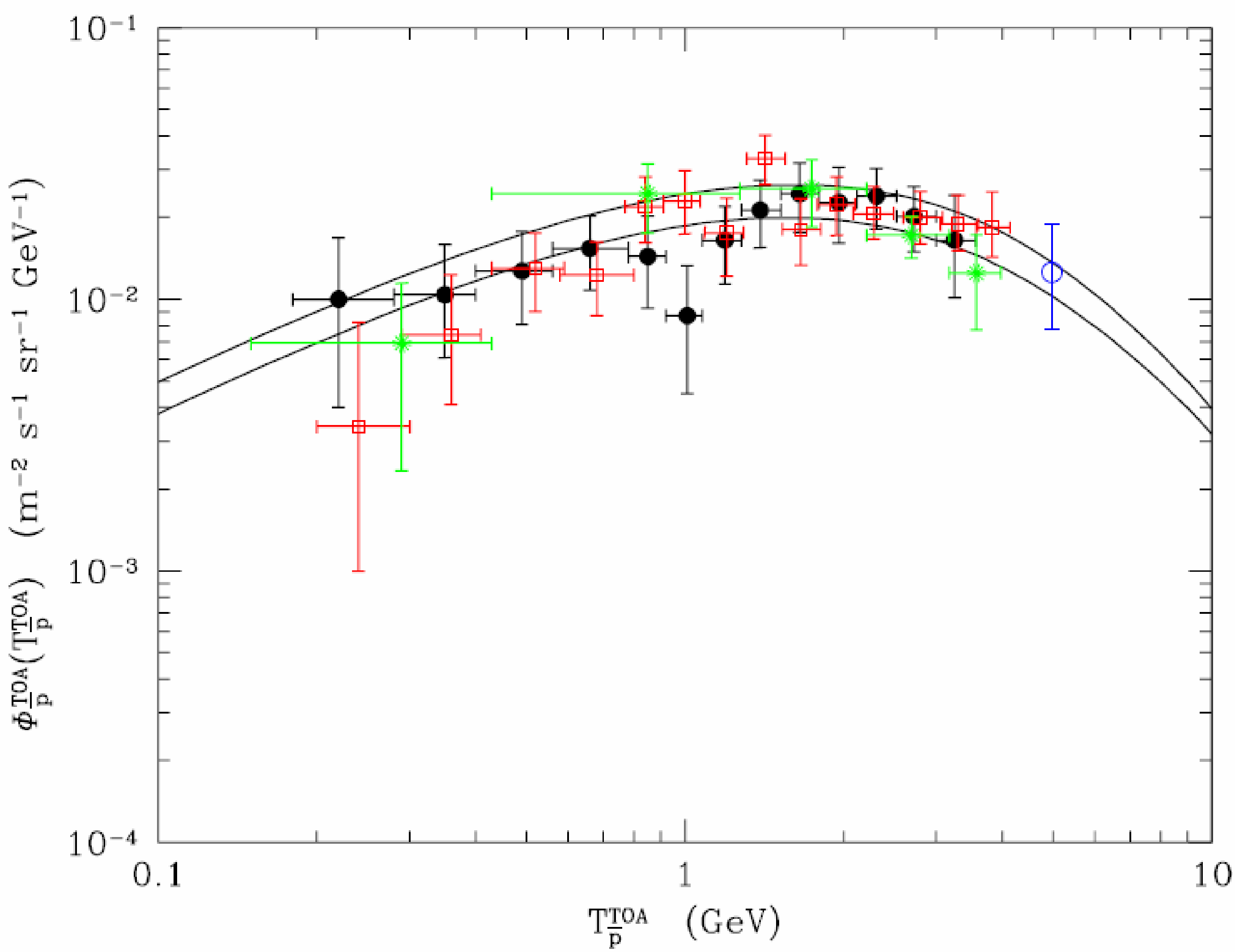


[Bottino, Donato, Fornengo, Scopel, arXiv:0802.0714]

Antiprotons in cosmic rays due to neutralino annihilation

- $\bar{p}$ from hadronization of quarks and gluons created by the annihilation of neutralinos
- Antiproton data can be used to constrain the susy parameter space
- large uncertainties in propagation properties of primary *p's* (propagation of antiprotons treated in a two-zone diffusion model, D. Maurin, F. Donato, R. Taillet, P. Salati, Astrophys.J. **555**, 585 (2001); D. Maurin, R. Taillet, F. Donato, Astronom. and Astrophys. **394**, 1039 (2002))

Secondary production from CR's fit present antiproton data (BESS, AMS, CAPRICE) rather well:



Exotic production

Example: pbar's from neutralino annihilations:

$$\chi + \chi \quad \rightarrow \quad \begin{array}{c} g\,\underline{g} \\ f\,\bar{f} \\ W^+W^- \\ ZZ \\ HH,\ hh,\ AA,\ hH,\ hA,\ HA,\ H^+H^- \\ W^+H^-,\ W^-H^+ \\ Zh,\ ZH,\ ZA \end{array} \rightarrow \quad \nu,\ \bar{\nu},\ \gamma,\ \bar{p},\ e^+,\ \bar{d}$$

$$\frac{dN_{\bar{p}}}{dE} = \frac{1}{2}\left(\frac{\rho_\chi}{m_\chi}\right)^2 < \sigma v >_0 \sum_f B_f \frac{dN_{\bar{p}}^f}{dE}$$

number density

susy

fragmentation (Pythia)

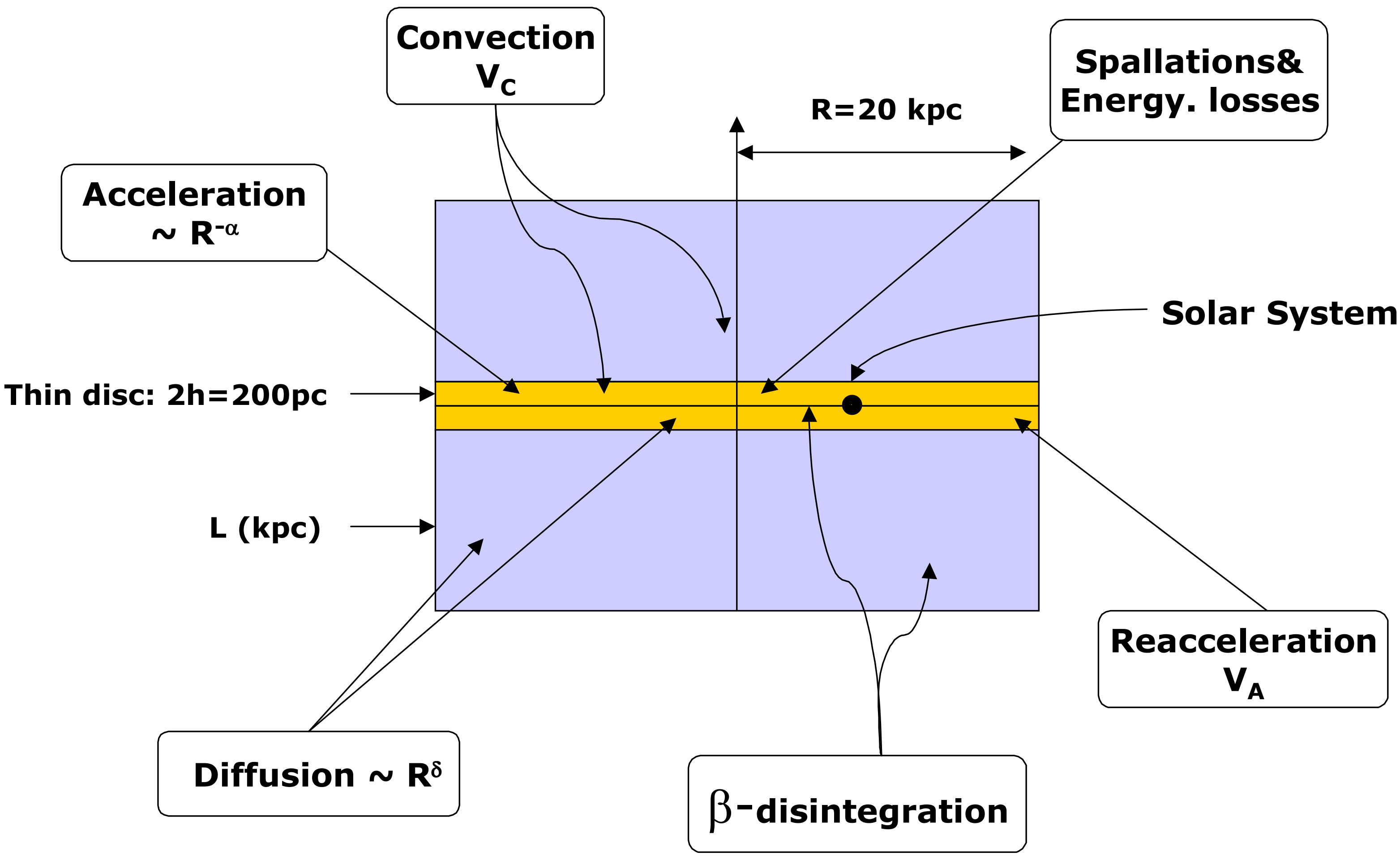
Major complication:

Antiprotons are charged particles and feel the magnetic field of the galaxy

→ directionality from source completely lost

→ complex physics involved between creation and detection

A SIMPLE VIEW OF THE GALAXY



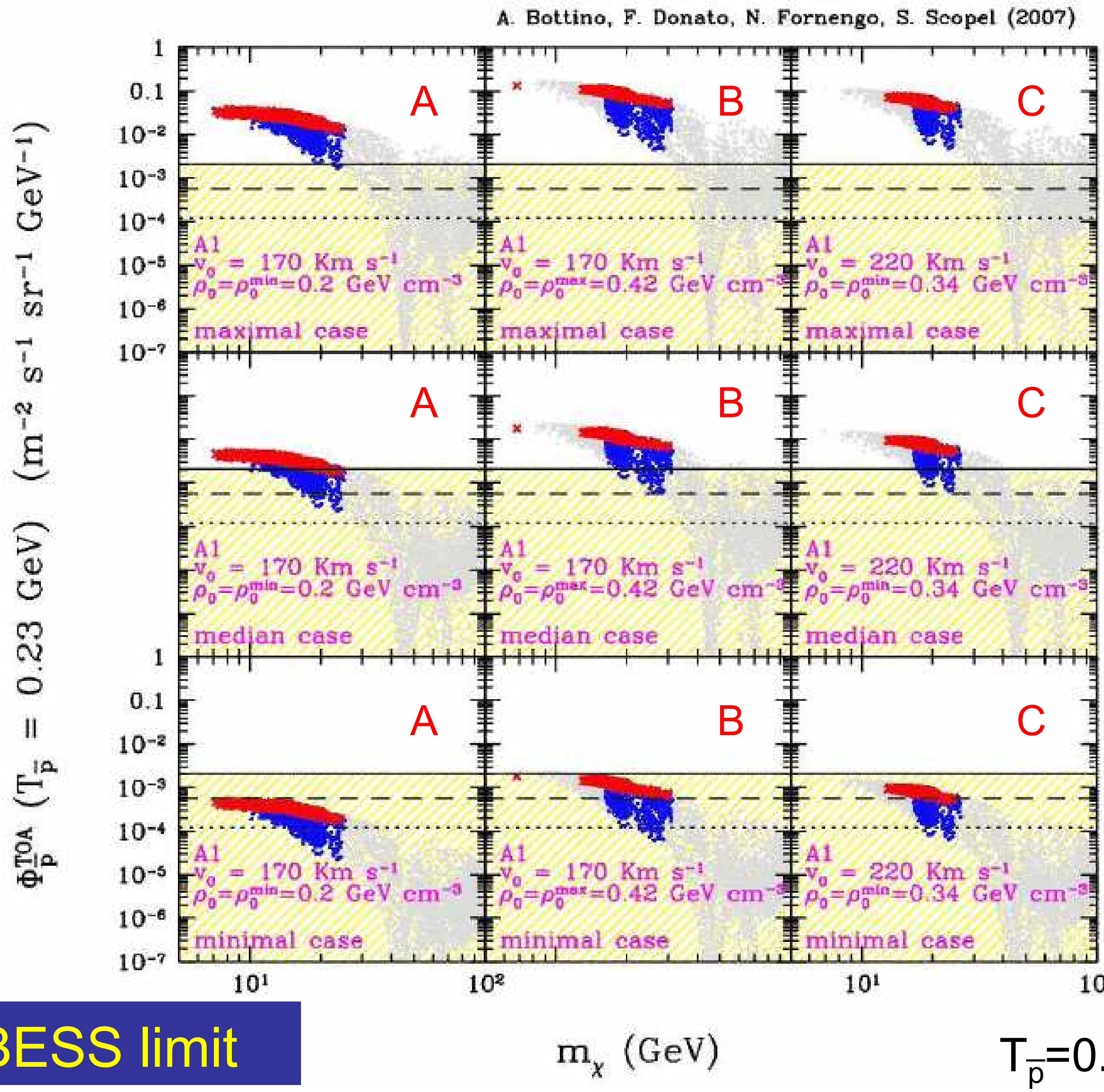
Compatibility between antiproton signal and new DAMA region

diffusion model:

maximal

median

minimal



PAMELA
AMS

PAMELA
AMS

PAMELA
AMS

yellow band: BESS limit

$T_{\bar{p}}$=0.23 GeV

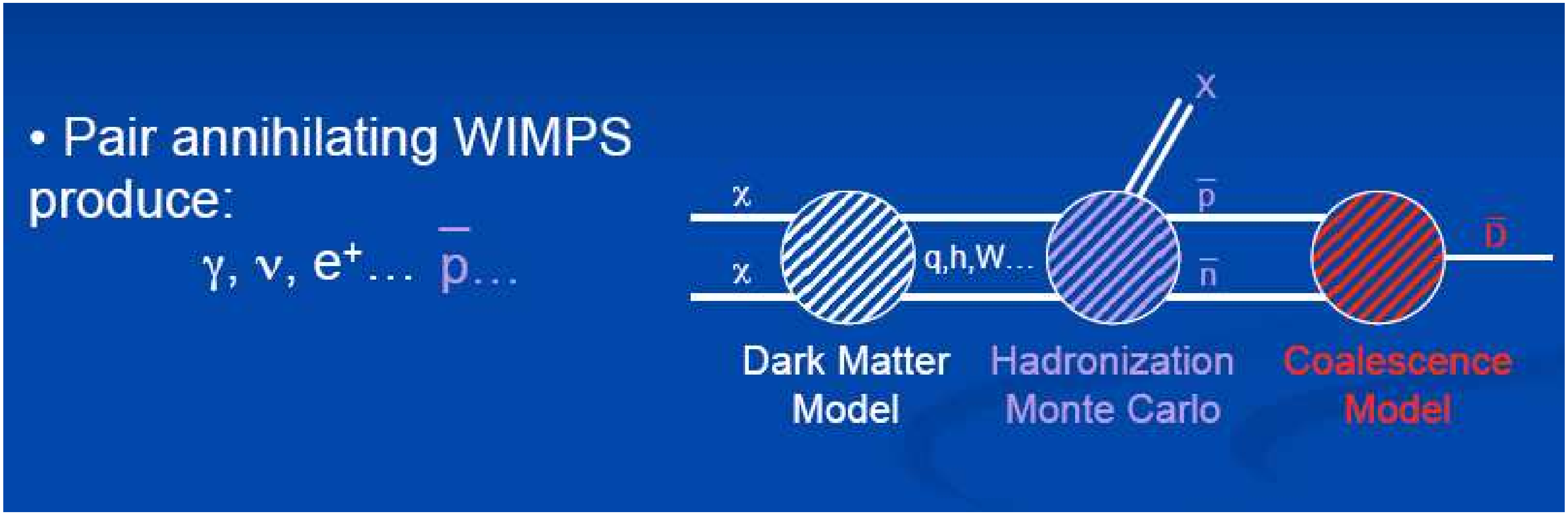
N.B. :

- when channelling is not included the fit of the experimental data of annual modulation with light neutralinos would imply values of ρ higher than the those characterizing the sets A, B and C, previously defined
- the antiproton flux depends on the square of ρ^2
- → tension between the annual modulation data and the constraints implied by present measurements of galactic antiprotons

bottom line: the DAMA/NaI region with the inclusion of the channeling effect is more compatible with the constraints coming from indirect searches

Antideuterons

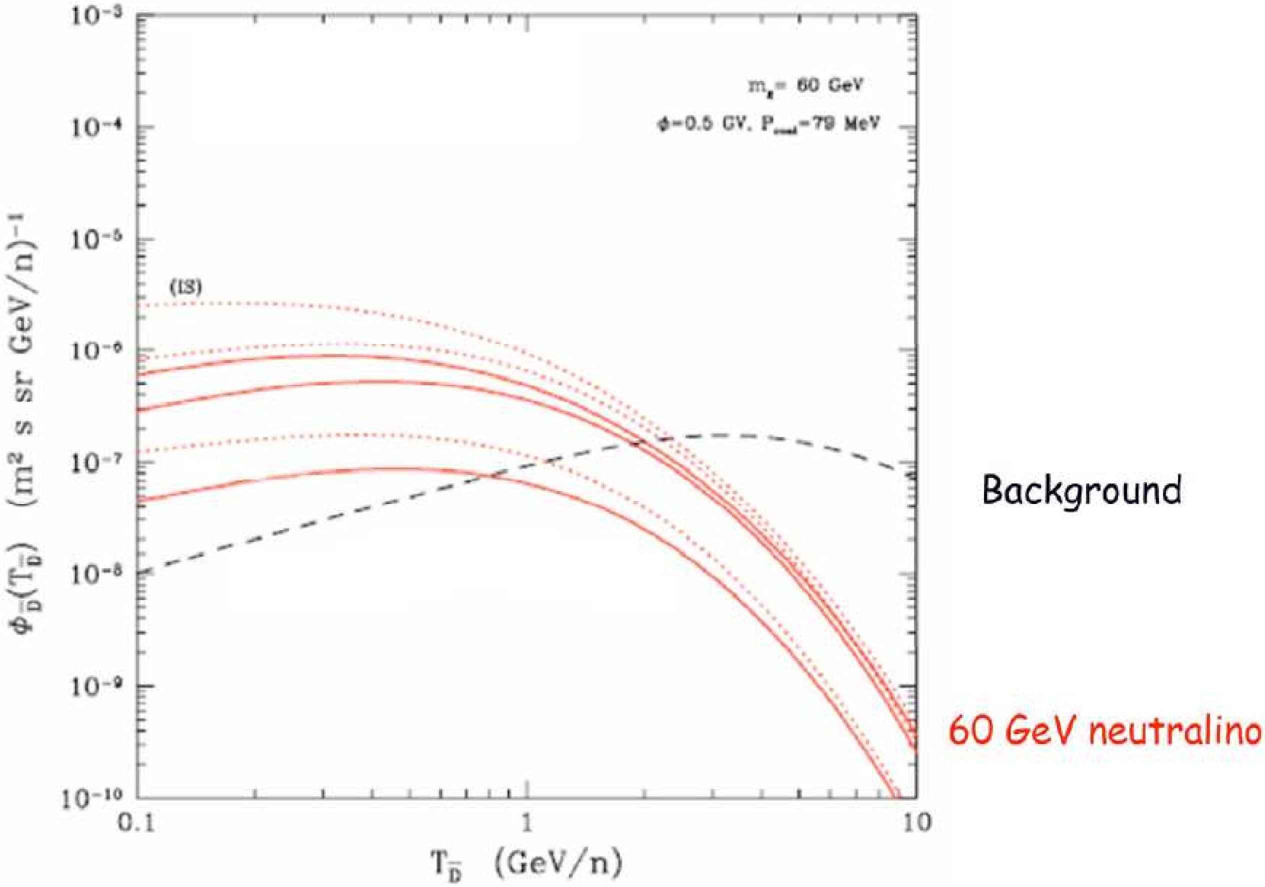
Donato, Fornengo, Salati, PRD62(2000)043003



$$\frac{\mathrm{d}N_{\overline{D}}}{\mathrm{d}E_{\overline{D}}} = \left(\frac{4\ p_0^3}{3\ k_{\overline{D}}}\right)\left(\frac{m_{\overline{D}}}{m_{\bar{p}}\ m_{\bar{n}}}\right)\sum_f BR(\chi\chi \to f) \times \left(\frac{\mathrm{d}N_{\bar{p}}^{(f)}}{\mathrm{d}E_{\bar{p}}}(E_{\bar{p}} = E_{\overline{D}}/2)\right)^2$$

p_0~58 MeV (coalescence momentum)

Antideuterons



Small background at low energies, mainly for two reasons:

- higher threshold for secondaries (E_{th}>17 m_p)
- Antideuterum is fragile (E_{bound}=2.2 MeV): rather destroyed that kicked to lower energies
- WIMPS work better because they annihilate almost at rest

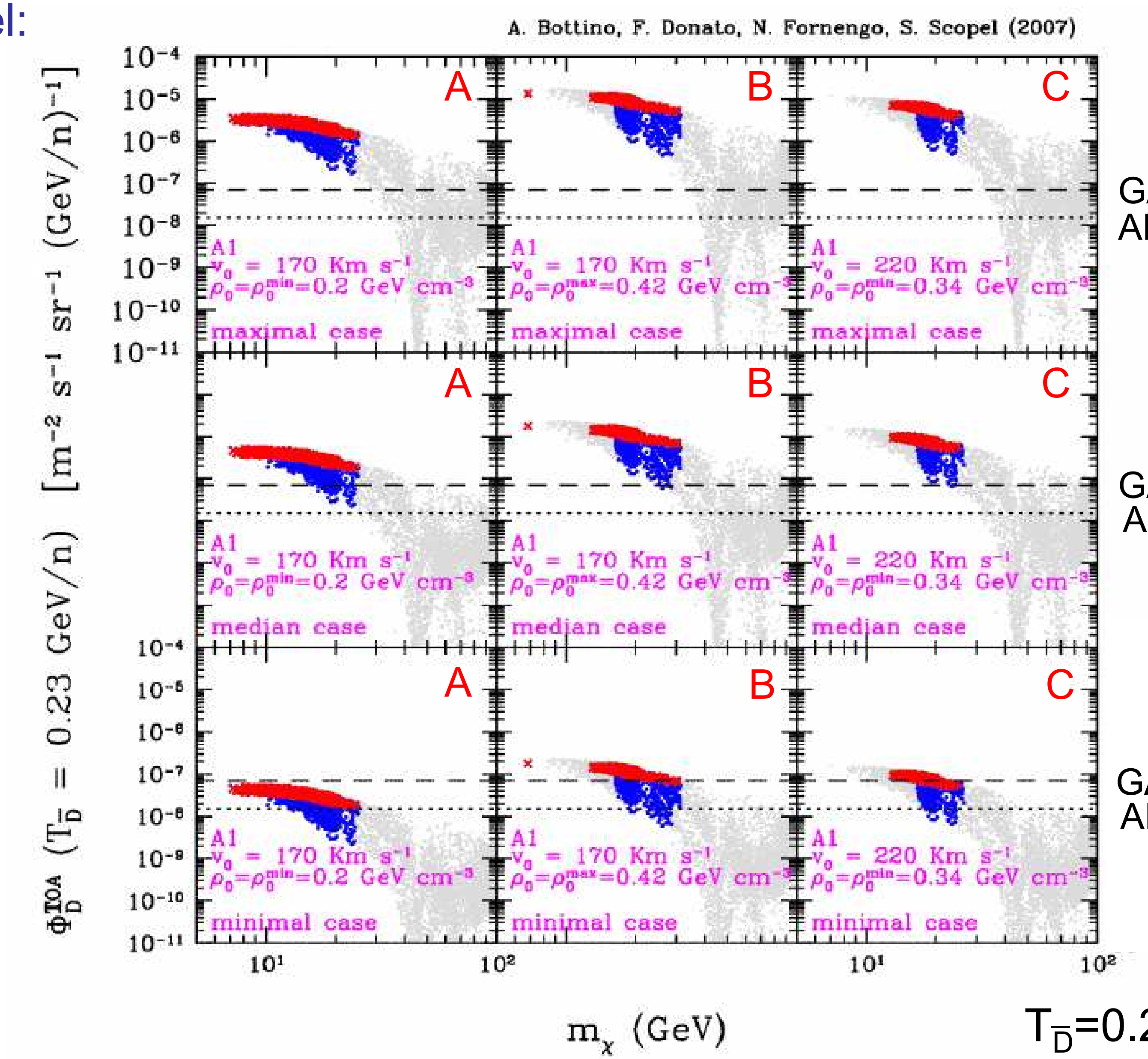
New DAMA region and antideuterons

diffusion model:

maximal

median

minimal



GAPS
AMS

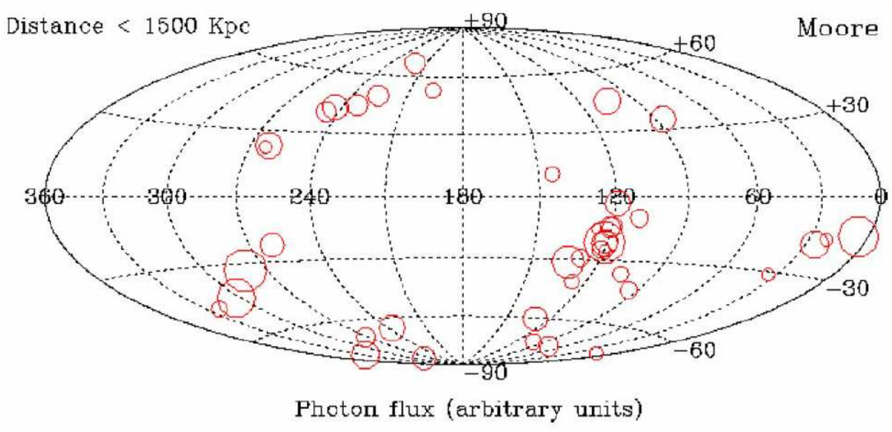
GAPS
AMS

GAPS
AMS

$T_{\bar{D}}$=0.23 GeV

External galaxies

(N. Fornengo, L. Pieri and S.Scopel, PRD70, 103529 (2004))

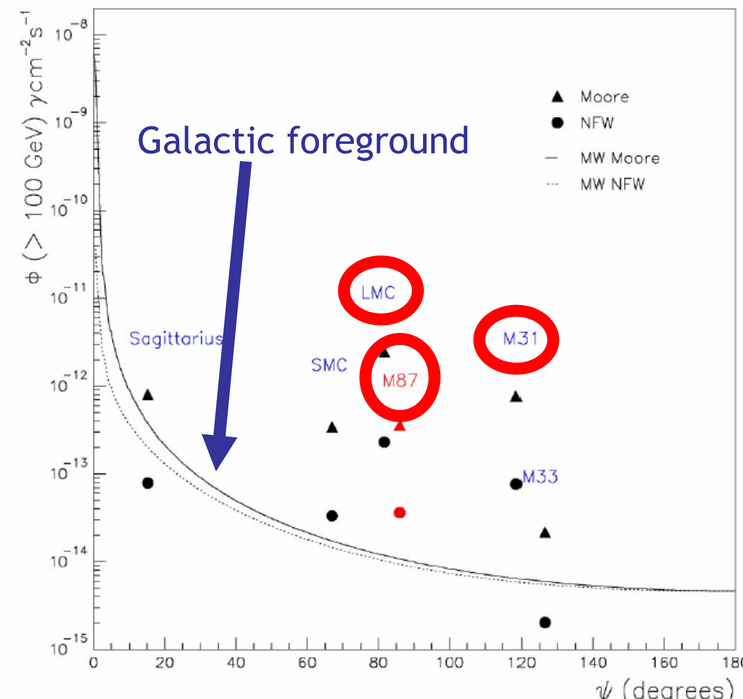


44 LG nearest galaxies in Galactic coordinates. The size of each symbol is scaled to the γ-ray flux emitted by a host DM halo with a Moore profile within a viewing angle of 1° from the halo center.

Masses, distances and virial radii for the Milky Way, the LMC and M31.

Galaxy	mass ($M_\odot$)	distance (kpc)	$r_{\rm vir}$ (kpc)
MW	1.0×10^{12}	8.5	205
LMC	1.4×10^{10}	49	49
M31	2.0×10^{12}	770	258

Flux vs. angle from GC



Let's focus on the 3 most prominent galaxies at large angles form the GC, LMC (Large Magellanic Cloud) M31(Andromeda) and M87

Emission from an extragalactic object

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi, \theta) = \frac{d\Phi^{\mathrm{SUSY}}}{dE_\gamma}(E_\gamma) \times \Phi^{\mathrm{cosmo}}(\psi, \theta)$$

$$\frac{d\Phi^{\mathrm{SUSY}}}{dE_\gamma}(E_\gamma) = \frac{1}{4\pi} \frac{\langle \sigma_{\mathrm{ann}} v \rangle}{2m_\chi^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f$$

$$\Phi^{\mathrm{cosmo}}(\psi, \theta) = \frac{1}{d^2} \int_0^{\min[R_G, r_{\max}(\Delta\Omega)]} 4\pi r^2 \rho_\chi^2(r) dr$$

- d = distance of the external object from us
- R_G = radius of the external galaxy
- r_{max} $(\Delta\Omega)$ = maximal distance from center of external galaxy seen within $\Delta\Omega$

Modeling Dark Matter Halos

- NFW97, Navarro, Frenk, White, Astrophys.J.490,493 (1997)
- M99, Moore, Ghigna, Governato, Lake, Quinn, Stadel, Tozzi, Astrophys.J.524,L19,(1999)
- M04, Diemand, Moore, Stadel, Mon.Not.Roy.Astron.Soc. 353 (2004) 624

Modeling Dark Matter Halos

Scale radii and scale densities for the NFW97, M99, M04, and isocore density profiles calculated for M31.

Profile	scale radius r_s (kpc)	scale density ρ_s ($M_\odot \mathrm{kpc}^{-3}$)
NFW97	30.271	4.20×10^6
M99	47.298	0.86×10^6
M04	44.697	1.55×10^6
isocore	4	7.898×10^6

$$\rho_\chi^{\mathrm{NFW97}} = \frac{\rho_s^{\mathrm{NFW97}}}{(r/r_s^{\mathrm{NFW97}})(1 + r/r_s^{\mathrm{NFW97}})^2}$$

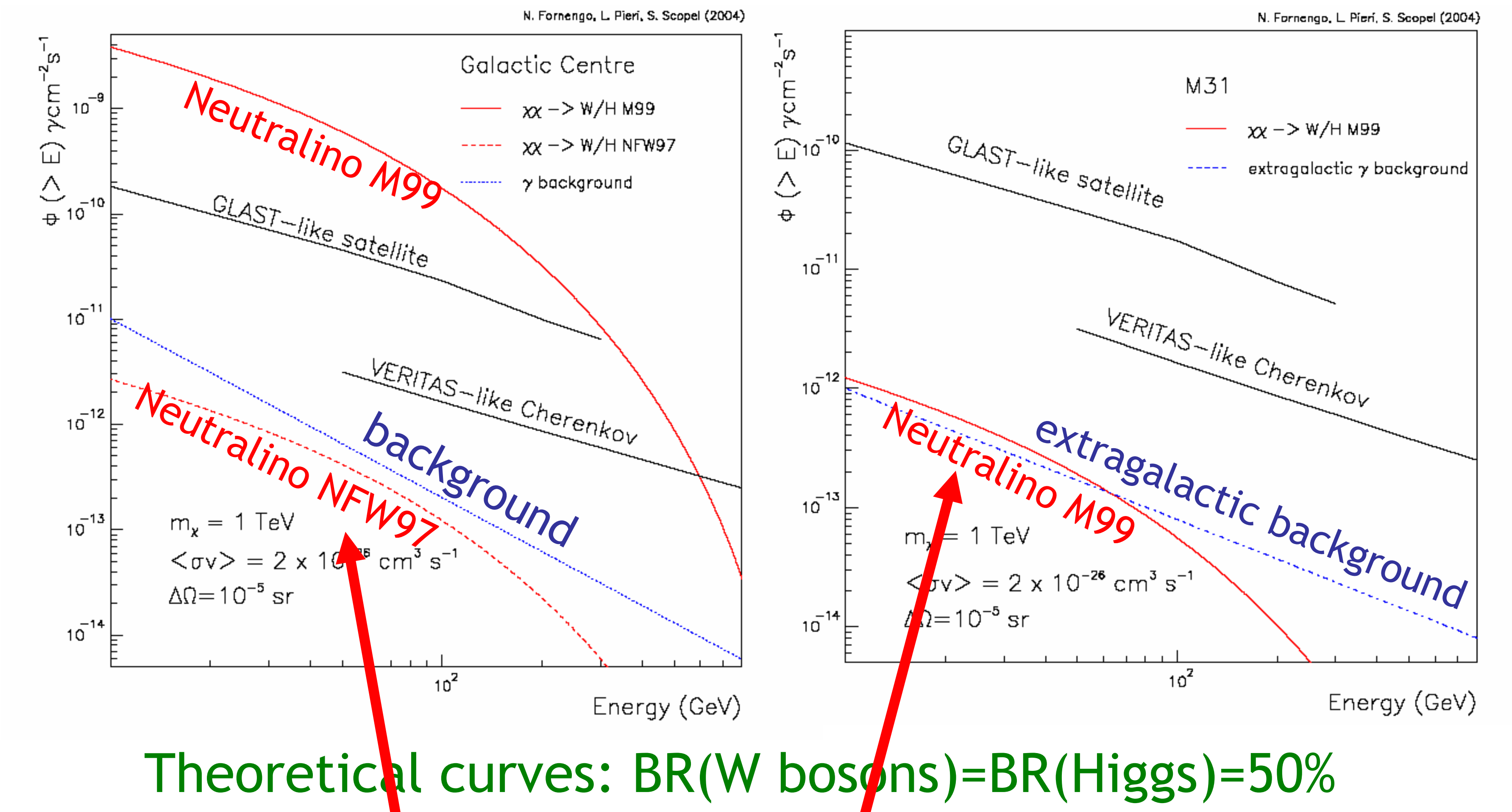
$$\rho_\chi^{\mathrm{M99}} = \frac{\rho_s^{\mathrm{M99}}}{(r/r_s^{\mathrm{M99}})^{1.5}[1 + (r/r_s^{\mathrm{M99}})^{1.5}]}$$

$$\rho_\chi^{\mathrm{iso-core}} = \frac{\rho_s^{\mathrm{iso-core}}}{[1 + (r/r_s^{\mathrm{iso-core}})^2]}$$

$$\rho_\chi^{\mathrm{M04}} = \frac{\rho_s^{\mathrm{M04}}}{(r/r_s^{\mathrm{M04}})^{1.16}(1 + r/r_s^{\mathrm{M04}})^{1.84}}$$

5 σ sensitivity curves for satellite and Čerenkov detectors

Galactic center Andromeda(M31)



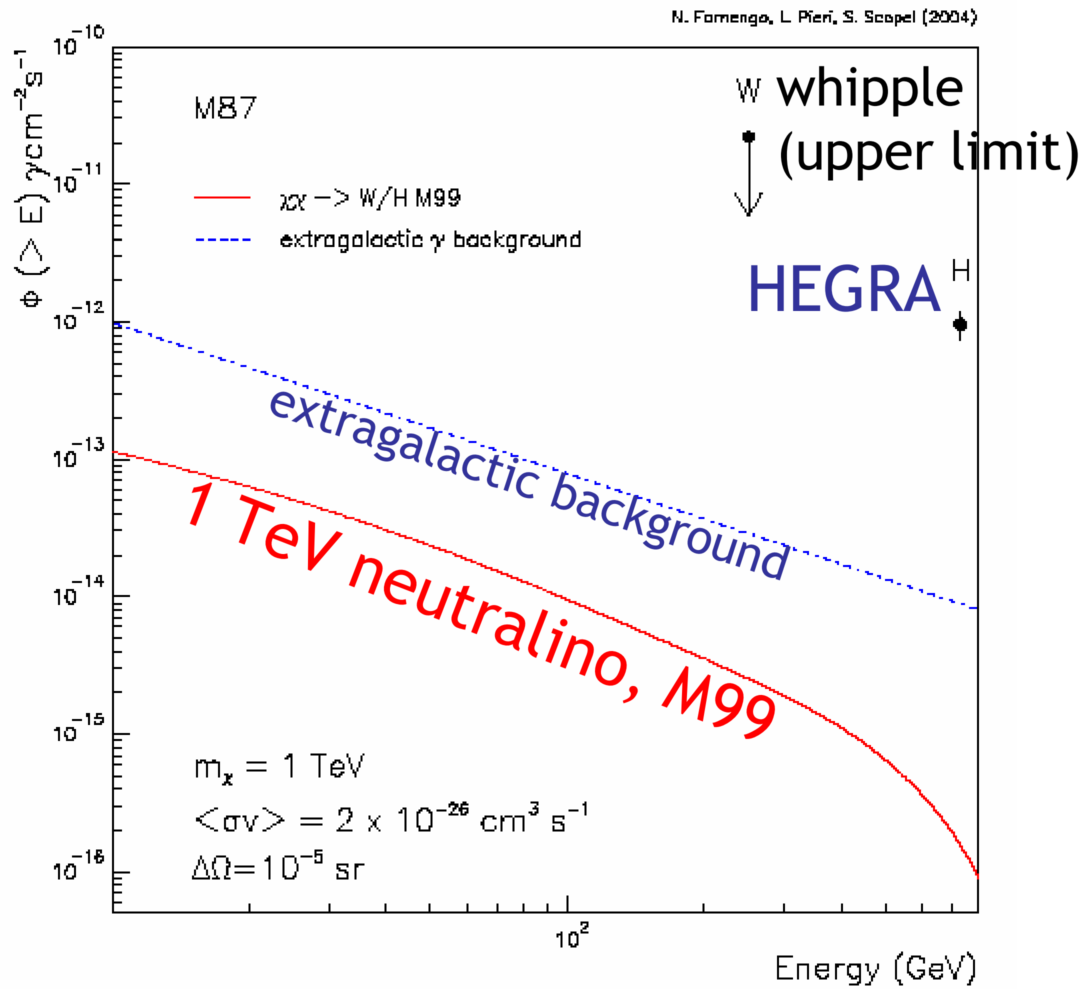
Theoretical curves: BR(W bosons)=BR(Higgs)=50%

•signal from GC accessible to GLAST and VERITAS only if profile harder than NFW97

•highest possible signal from M31 is at level of experimental sensitivity and merely at the level of background

Flux from M87 galaxy

possible excess detected, could be explained by neutralino?



no. enhancement of clumpy distribution at most factor of 5, neutralino signal always expected below background

FINALE

- WIMPS cluster in Galaxies, including our own – right where we can measure them both directly and indirectly (gammas, antiprotons, antideuterons, neutrinos, multi-wavelength…) - other galaxies are also possible sources (but signals are typically low)
- WIMPs can be realized in different well-motivated scenarios (KK photon in UED, Heavy photon in Little Higgs, neutralino and sneutrino in SUSY)+"Minimal" extensions of SM
- Neutralino is still the most popular. Today available in different flavours: SUGRA, nuSUGRA, sub-GUT, Mirage mediation, NMSSM, effMSSM (light neutralinos), CPV,…
- the neutralino can be light: in this case stronger constraints from direct searches and the antiproton signal
- present or behind-the-corner experimental sensitivities at the level of some (optimistic?) SUSY scenarios in direct and indirect detection:
    - direct detection: DAMA+CDMS, XENON10, KIMS,….
    - indirect detection: PAMELA, GLAST (just launched)!
    - confirmation of DM from accelerators: LHC (about to start)
- N.B.: the KIMS experiment in Korea is being taking data right now with ~100 kg of CsI – model independent test of DAMA modulation effect? (see Youngduk Kim's talk tomorrow)