Dark Matter Theory

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INFN Torino

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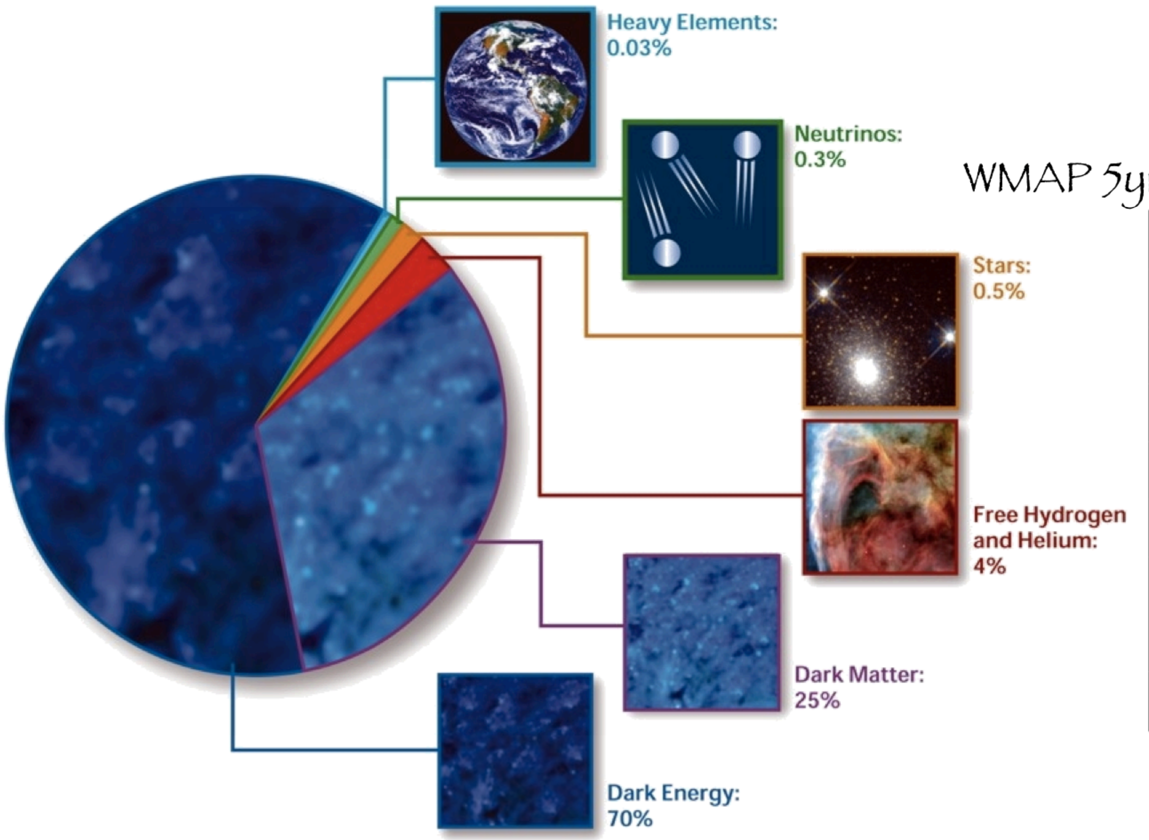
Outline of the lectures

- Evidence of dark matter
- Where does it come from?
- What is made of? Any clue on or relation with New Physics?
- How is it distributed aroud us?
- Can we directly or indirectly detect its presence in our (close) astrophysical environment?



The Dark Universe

WMAP 5yr + SN + BAO + galaxies distribution

Ω_{TOT}	1.0052 ± 0.0064
Ω_Λ	0.721 ± 0.015
Ω_M	0.233 ± 0.013
Ω_b	0.0462 ± 0.0015
h_0	0.701 ± 0.013
$\Omega_M h^2$	0.1369 ± 0.0037
$\Omega_b h^2$	0.02265 ± 0.00059
$\Omega_{DM} h^2$	0.1143 ± 0.0034

E. Komatsu et al., arXiv:0803.0547
J. Dunkley et al., arXiv:0803.0596
G. Hinshaw et al., arXiv:0803.0732

Geometry: the Universe is Flat
Dynamics: the Universe is expanding

- Decelerate for most of its history
- Accelerate since "recent" time and at very "old" times (inflation)

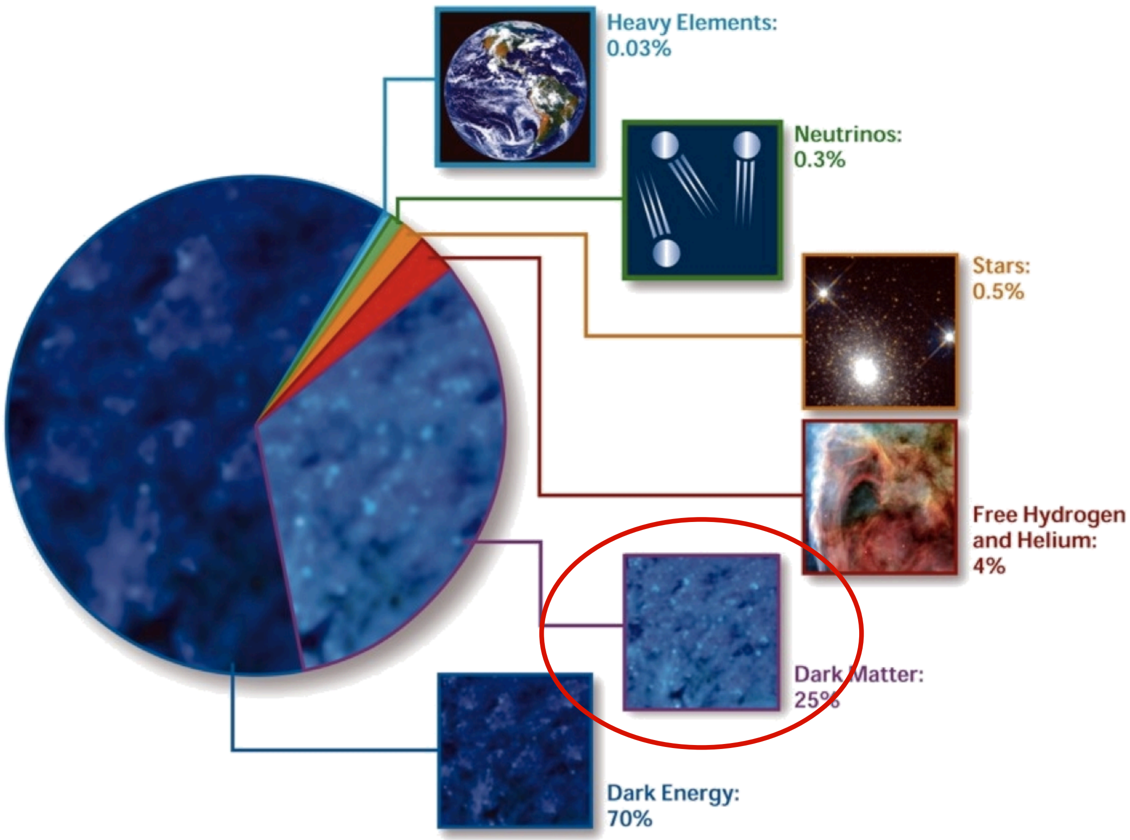
Ω_T CMB temperature anisotropies

Ω_Λ Luminosity distance of high-z SNIa

Ω_M Clustered mass abundance

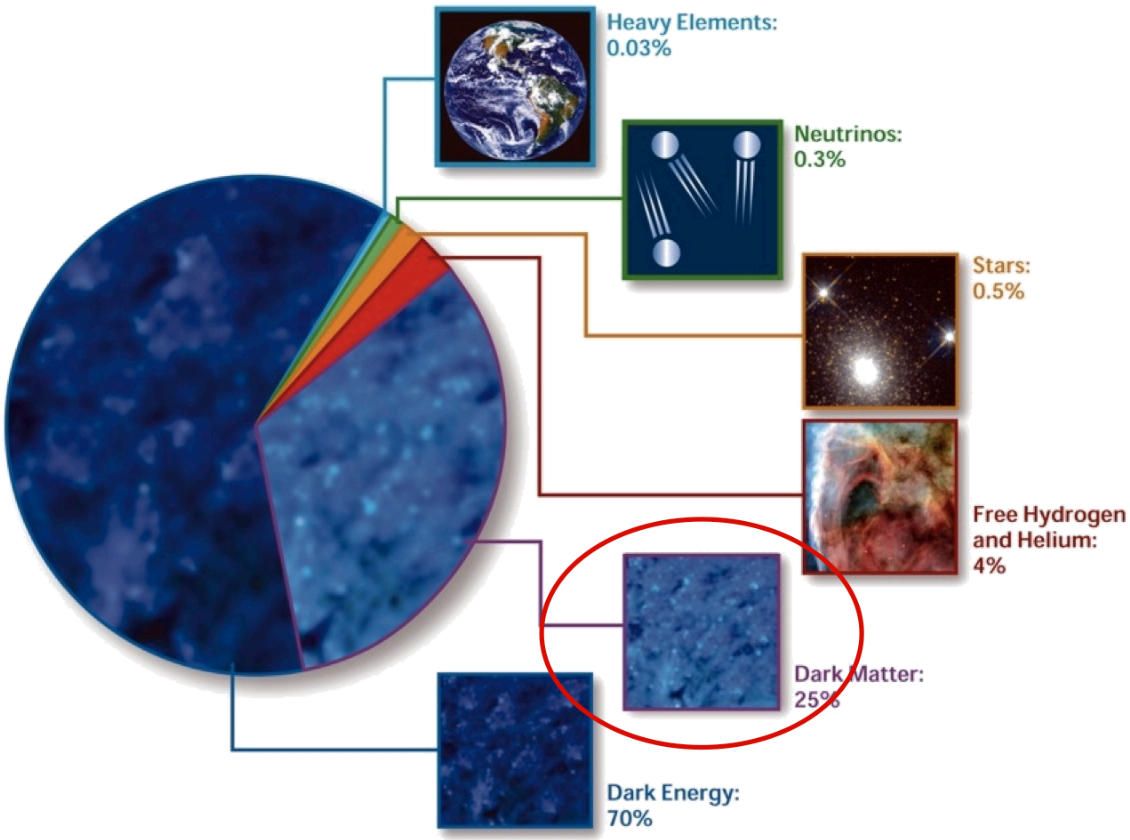
Ω_B Primordial Nucleosynthesis
Amplitude of CMB temperature anisotropies

Dark Matter



Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

Dark Matter



Dynamics of galaxy clusters — F. Zwicky, 1933 → **Virial theorem**

$$2\langle T\rangle = -\langle V_{\rm TOT}\rangle$$

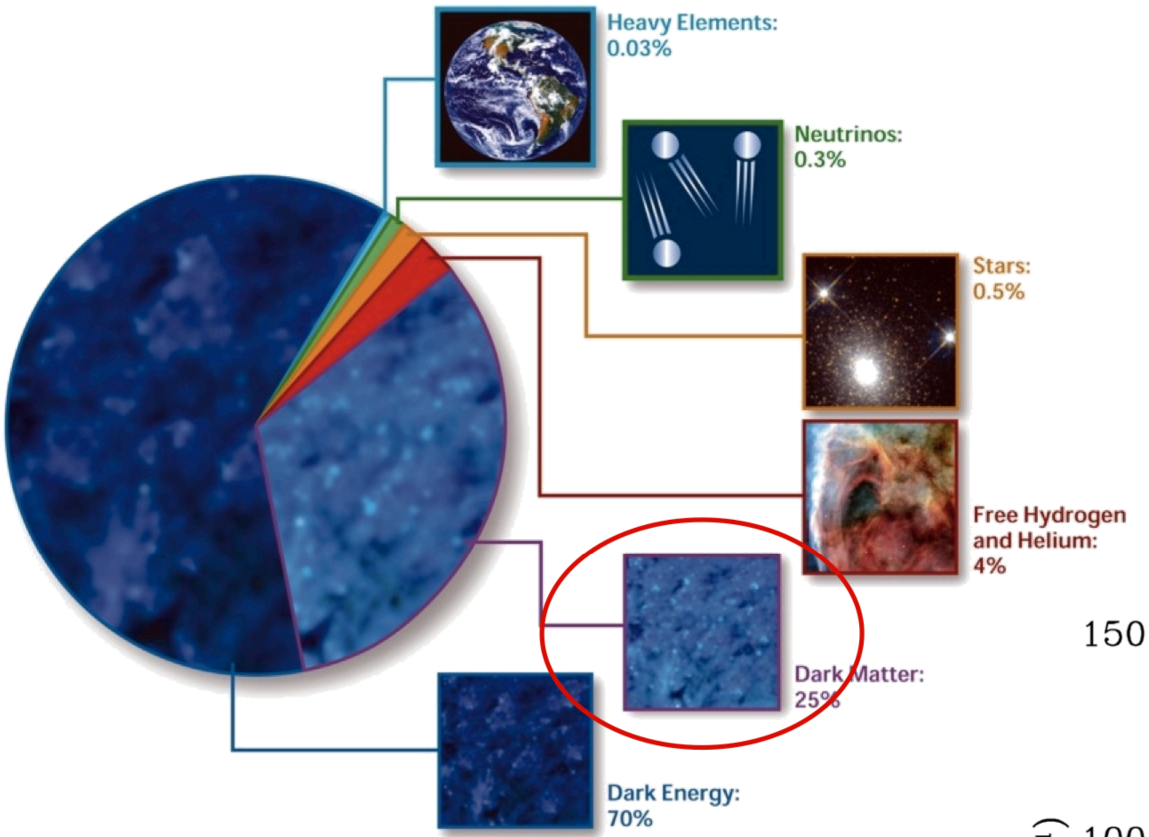
Rotational curves of galaxies

Weak lensing

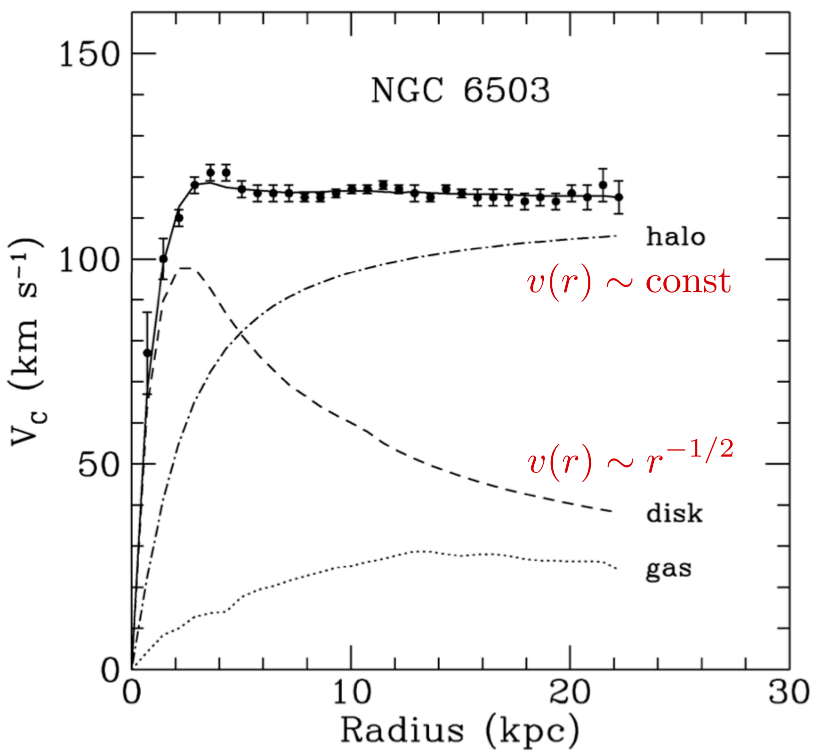
Structure formation from primordial density fluctuations

Energy density budget

Dark Matter

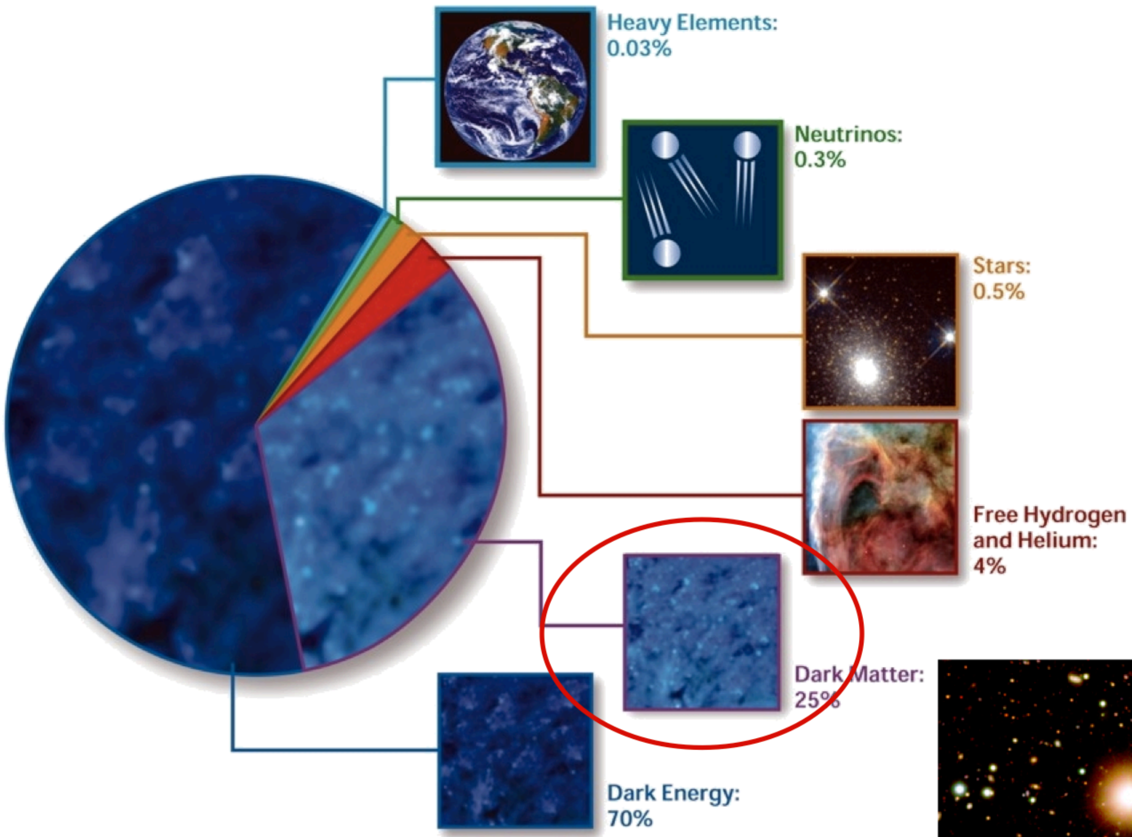


$$v(r) \propto \sqrt{M(r)/r}$$

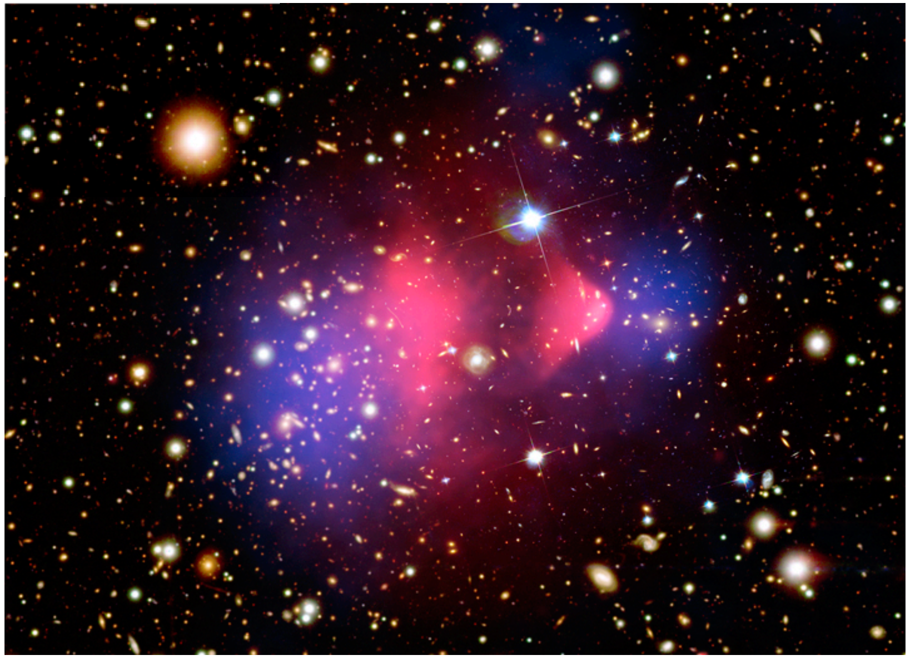


- Dynamics of galaxy clusters
- Rotational curves of galaxies → V. Rubin, early '70s
- Weak lensing
- Structure formation from primordial density fluctuations
- Energy density budget

Dark Matter

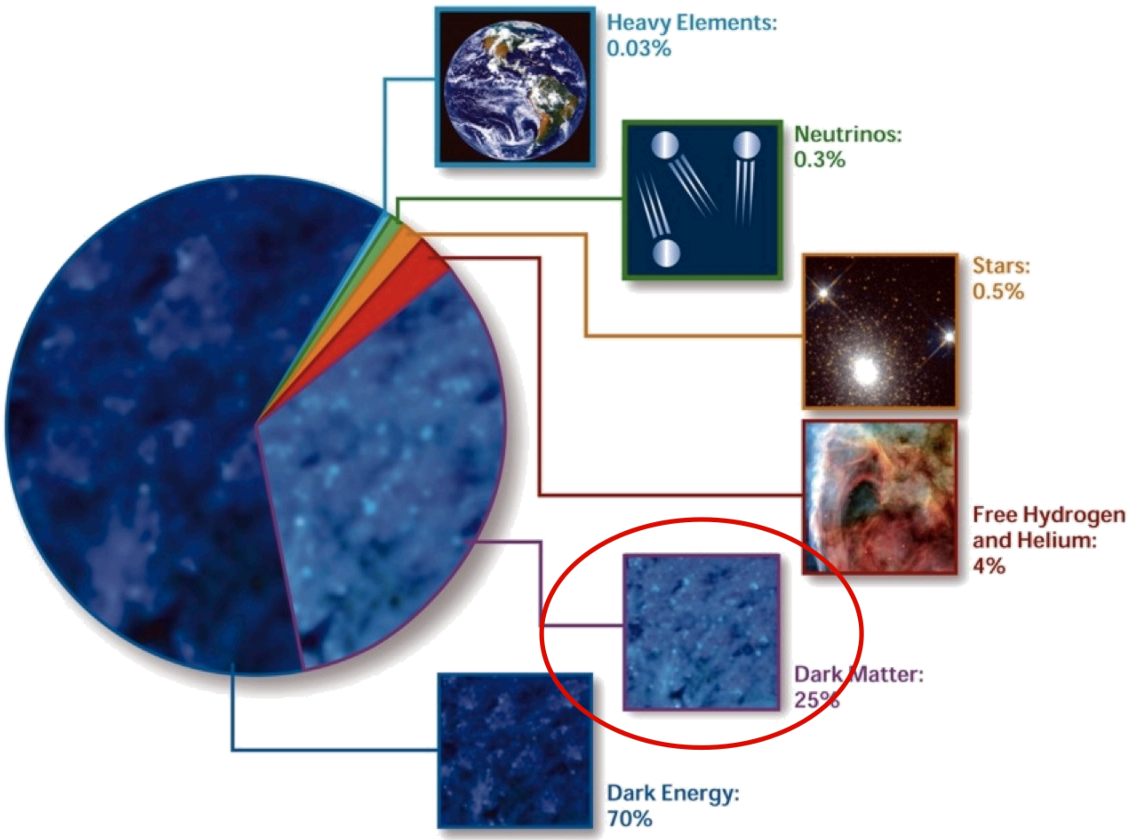


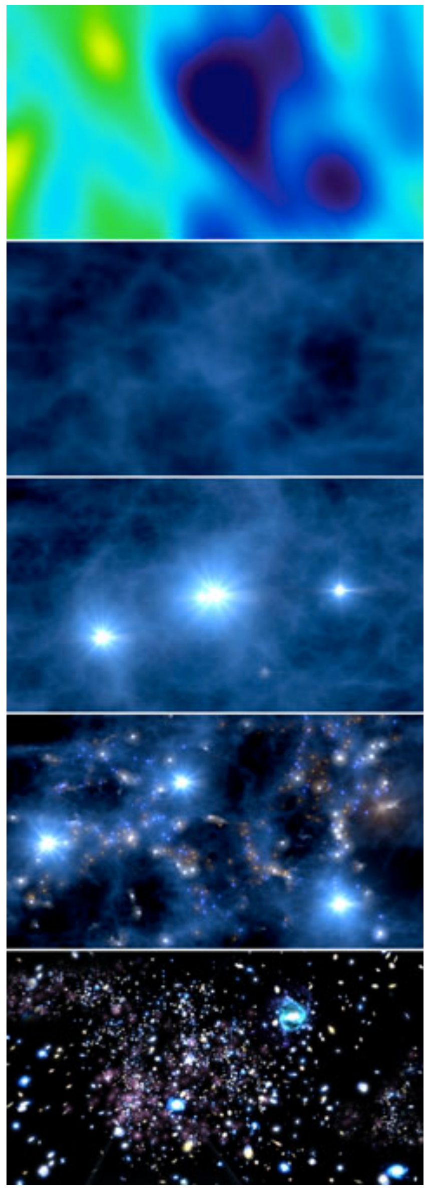
“Bullet” cluster



Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing →
Structure formation from primordial density fluctuations
Energy density budget

Dark Matter

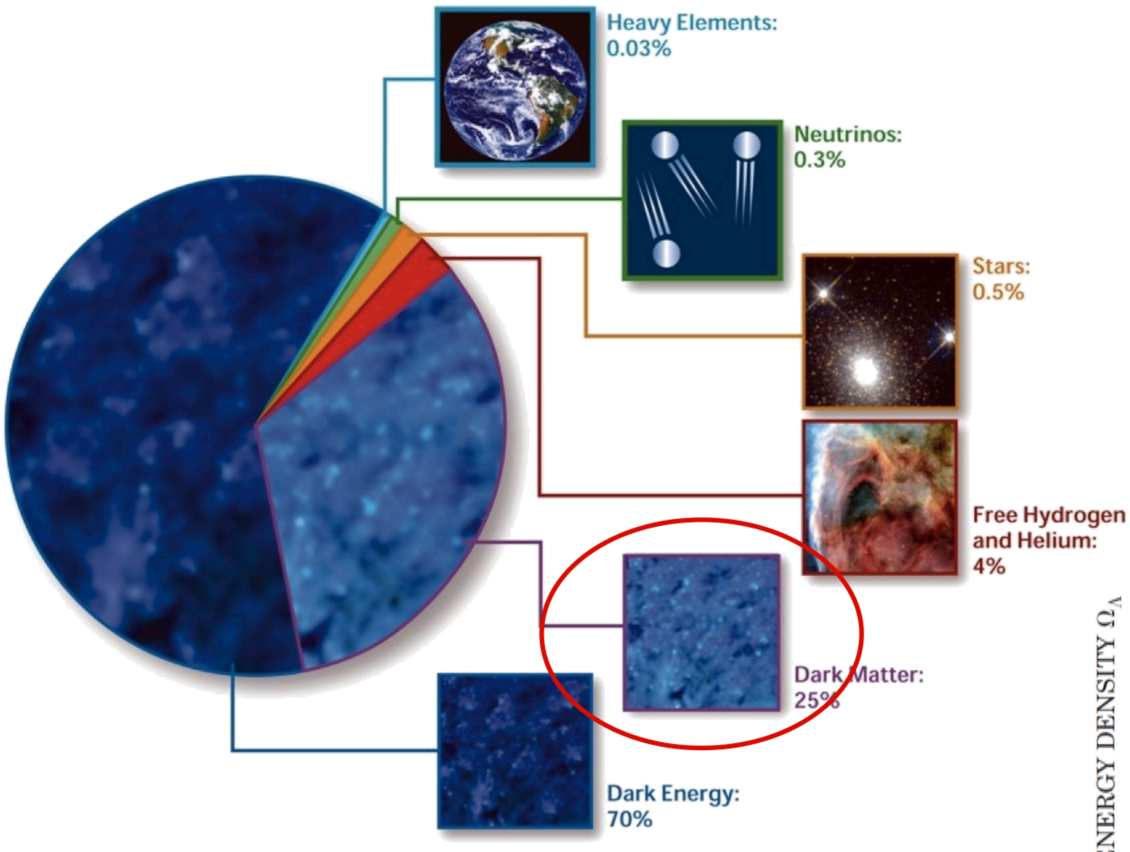


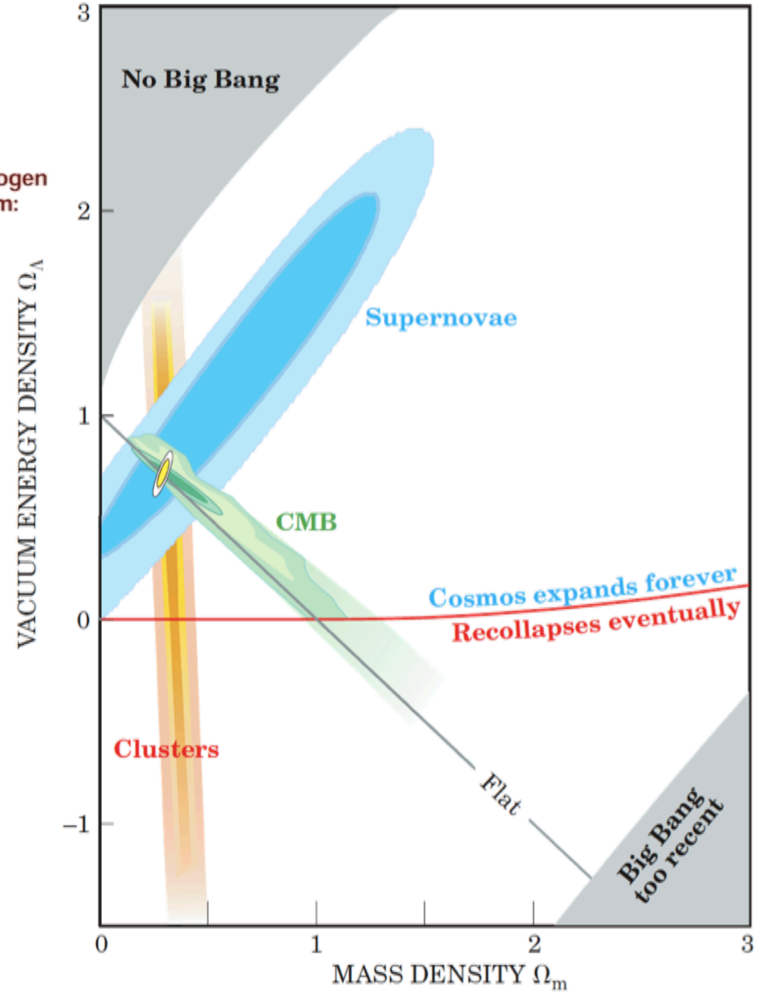


- Dynamics of galaxy clusters
- Rotational curves of galaxies
- Weak lensing
- Structure formation from primordial density fluctuations
- Energy density budget

DM needs to be (mainly) cold and (mainly) non-collisional

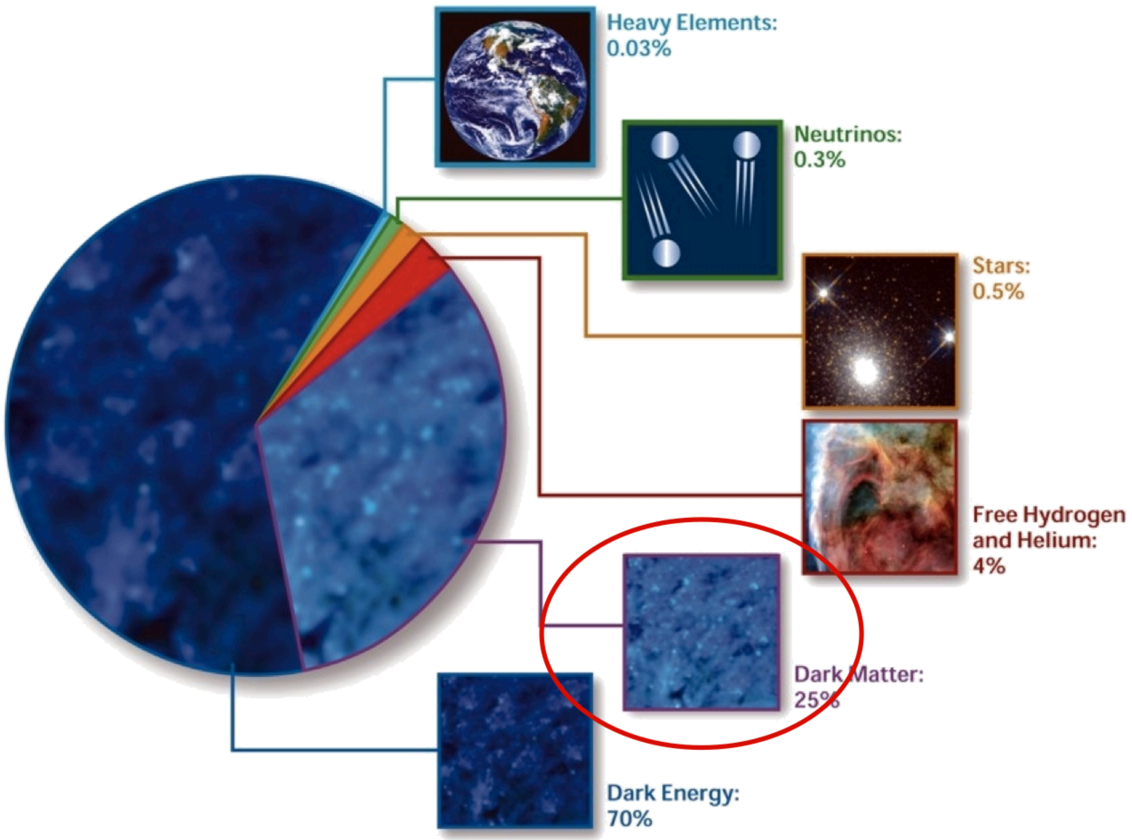
Dark Matter





Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget → Concordance model

Dark Matter



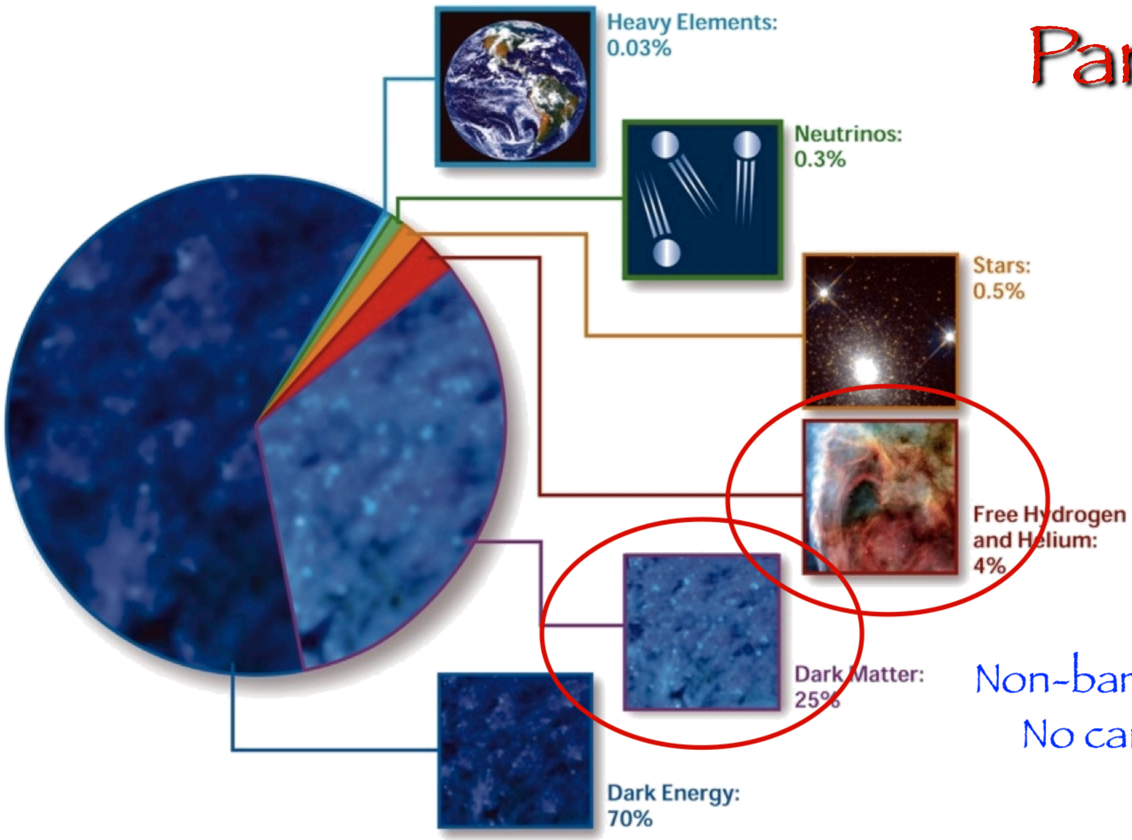
Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

Solution to the DM problem

Gravitational: gravity is not of Einstein form on large scales

Particle Physics: DM is of particle nature

Particle Dark Matter



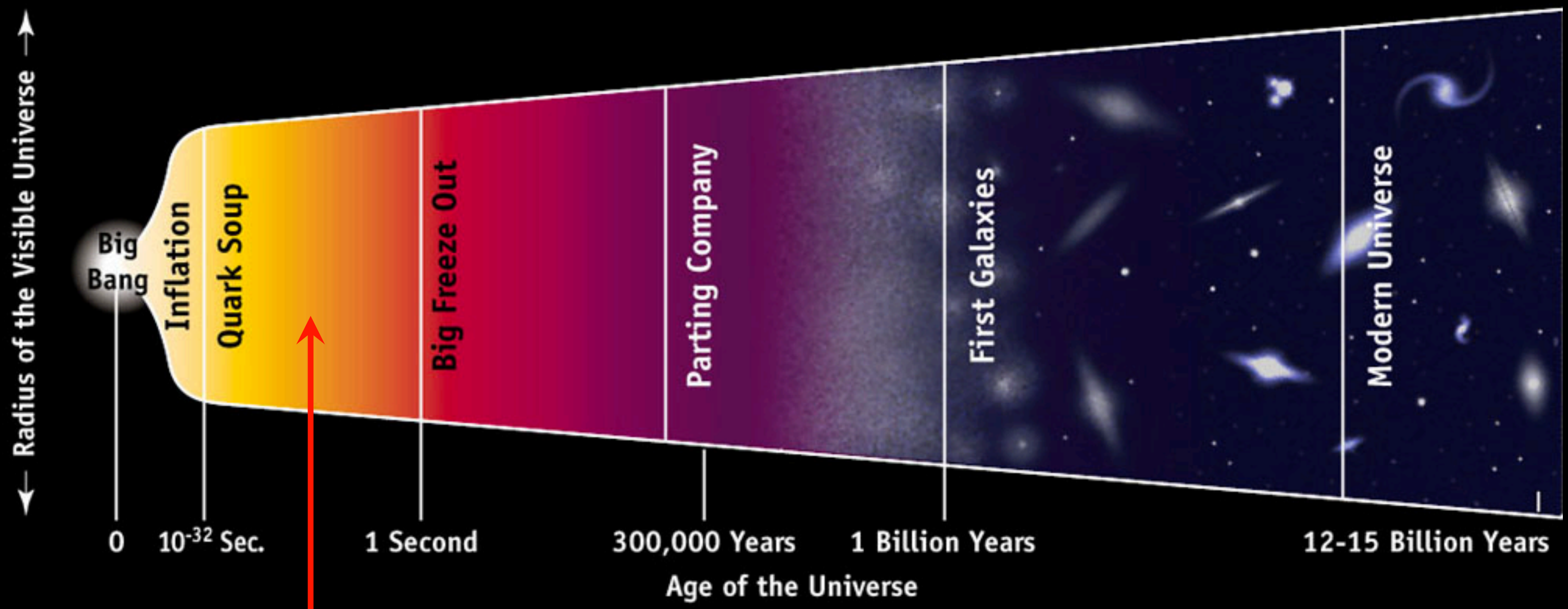
Non-baryonic (cold) dark matter is needed
No candidate in the Standard Model(*)
New fundamental Physics

Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

(*) Standard neutrino:
Too light: act as HDM (not CDM)

Particle physics model	Particle candidate
Cosmology of the particle DM	Relic from the early U.
Astrophysical signals of the particle DM	Detection

Cosmology of the Particle DM



T	10^{16} GeV	1 MeV	0.23 eV
		BBN	CMBR

CDM

Particle DM thermalization in the early Universe

Equilibrium reactions

$$\chi A \longleftrightarrow \chi A$$
$$\chi\bar{\chi} \longleftrightarrow \bar{A}A$$

	Relativistic Bosons	Relativistic Fermions	Non-relativistic (Either)
n_i	$\frac{\zeta(3)}{\pi^2} g_i T^3$	$\left(\frac{3}{4}\right) \frac{\zeta(3)}{\pi^2} g_i T^3$	$g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$
ρ_i	$\frac{\pi^2}{30} g_i T^4$	$\left(\frac{7}{8}\right) \frac{\pi^2}{30} g_i T^4$	$m_i n_i$
p_i	$\frac{1}{3}\rho_i$	$\frac{1}{3}\rho_i$	$n_i T \ll \rho_i$

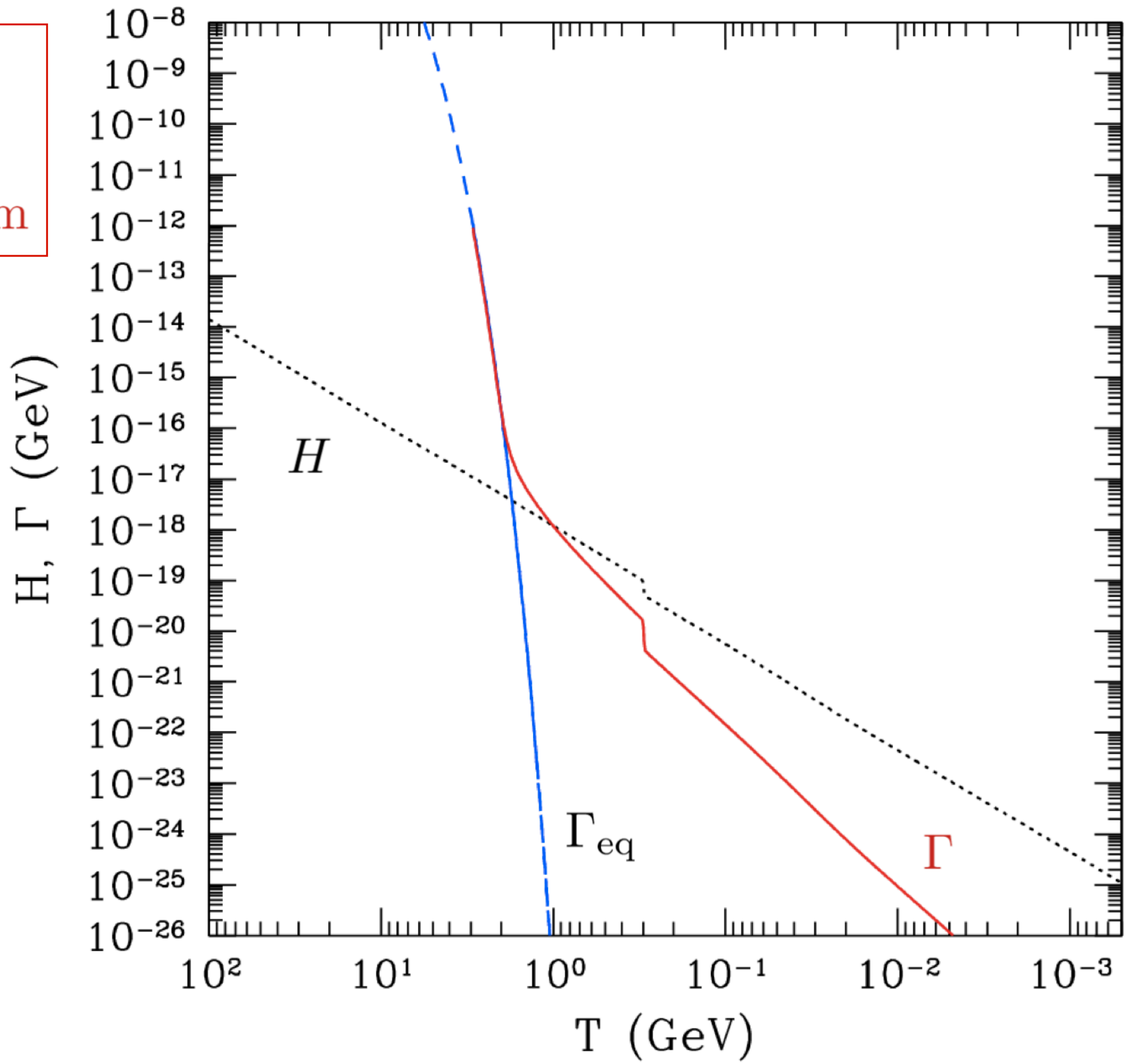
$\Gamma = n\langle\sigma v\rangle$: interaction rate

$$\langle\sigma v\rangle = \frac{\int d^3p_i\, d^3p_j\; f_i(E)\; f_j(E)\; \sigma_{ij} v_{ij}}{\int d^3p_i\, d^3p_j\; f_i(E)\; f_j(E)}$$

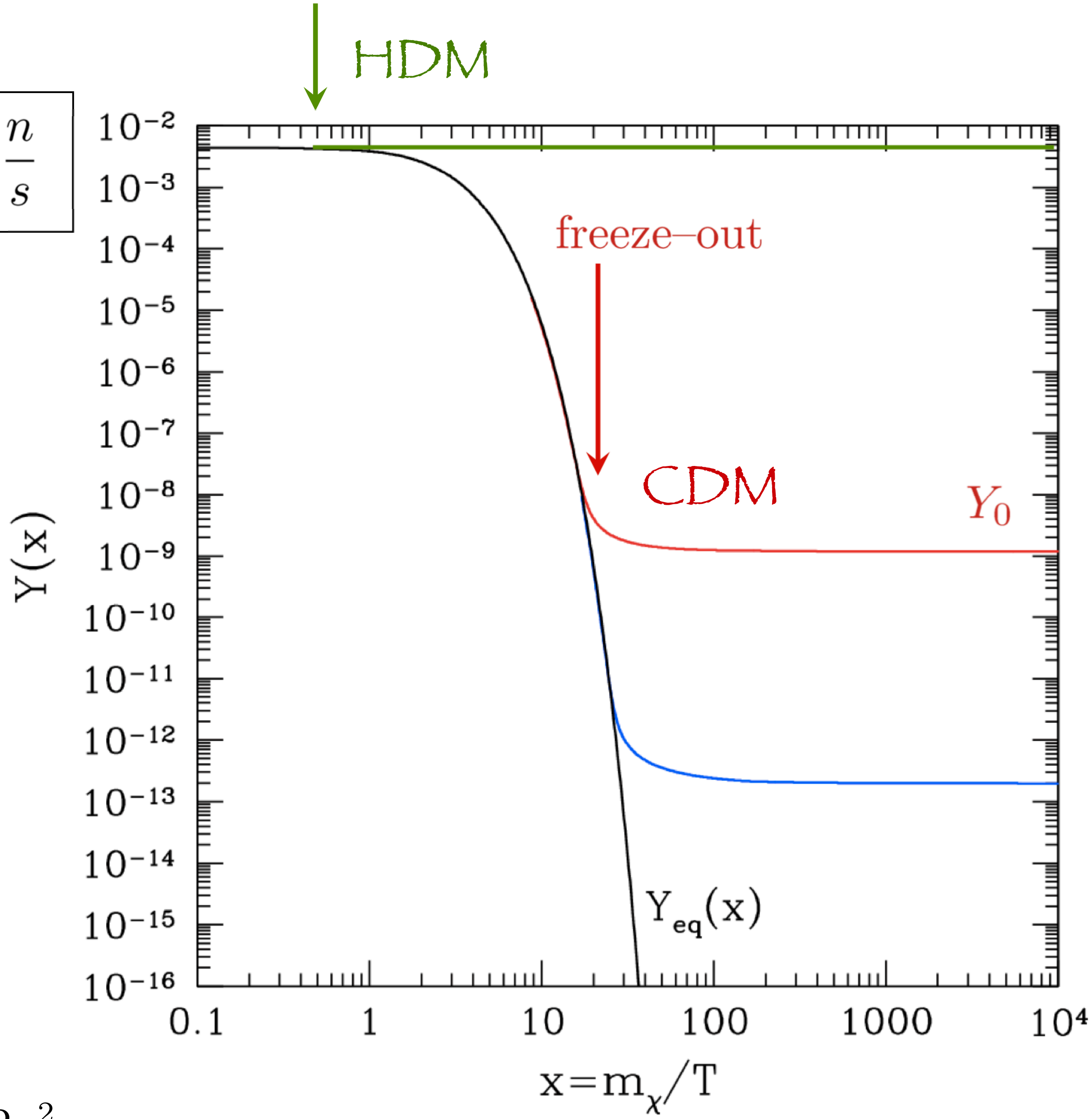
$H = \dot{a}/a$: expansion rate

$\Gamma > H$ equilibium

$\Gamma \leq H$ out of equilibium



$$Y = \frac{n}{s}$$



$$Y_0 = Y(x_f)$$

$$\Omega_{\rm CDM} h^2 = \frac{m\, s_0\, Y_0}{\rho_C^0}$$

$$s = \frac{2\pi^2}{45} g_{\star S} T^3$$

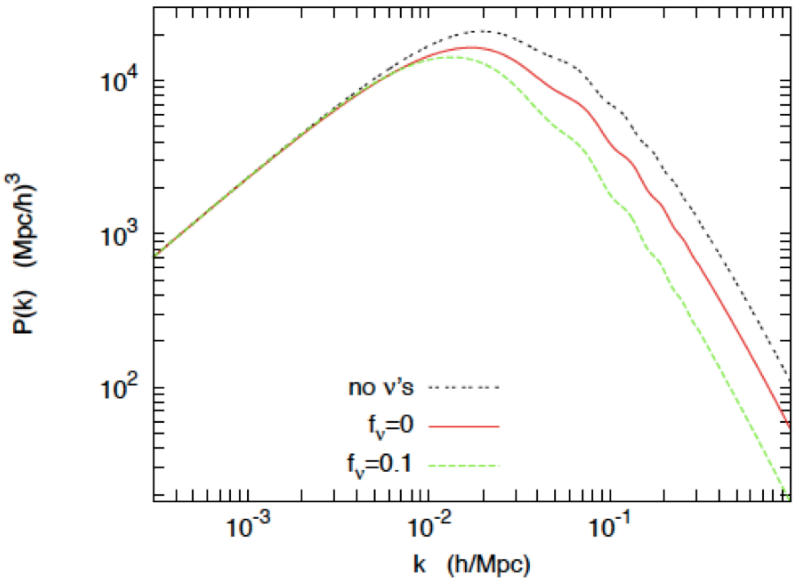
Neutrinos as HDM: relic abundance

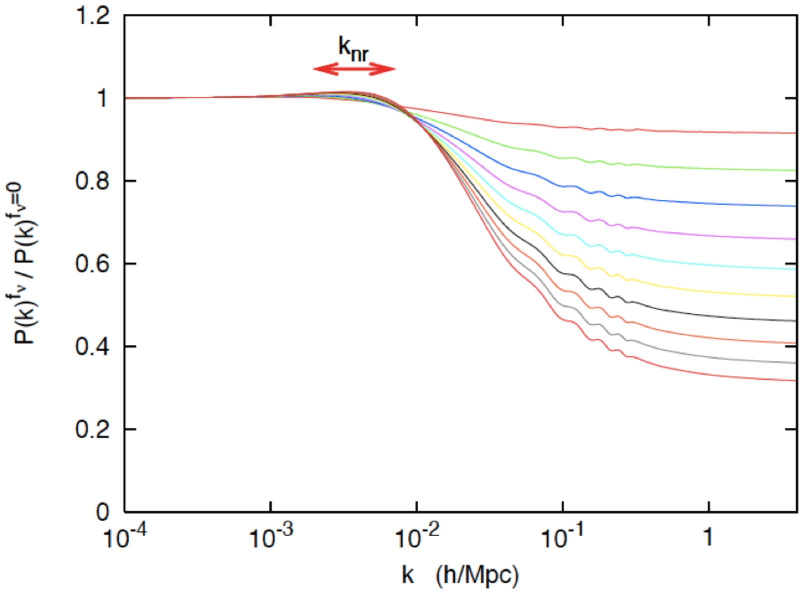
$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93 \text{ eV}}$$

$$\Omega_\nu h^2 \leq (\Omega_{\rm DM} h^2) = 0.13 \longrightarrow \sum_i m_i \leq 12 \text{ eV}$$

Neutrinos as HDM

HDM: erases density contrast (structure) on scales smaller than the free-streming cale



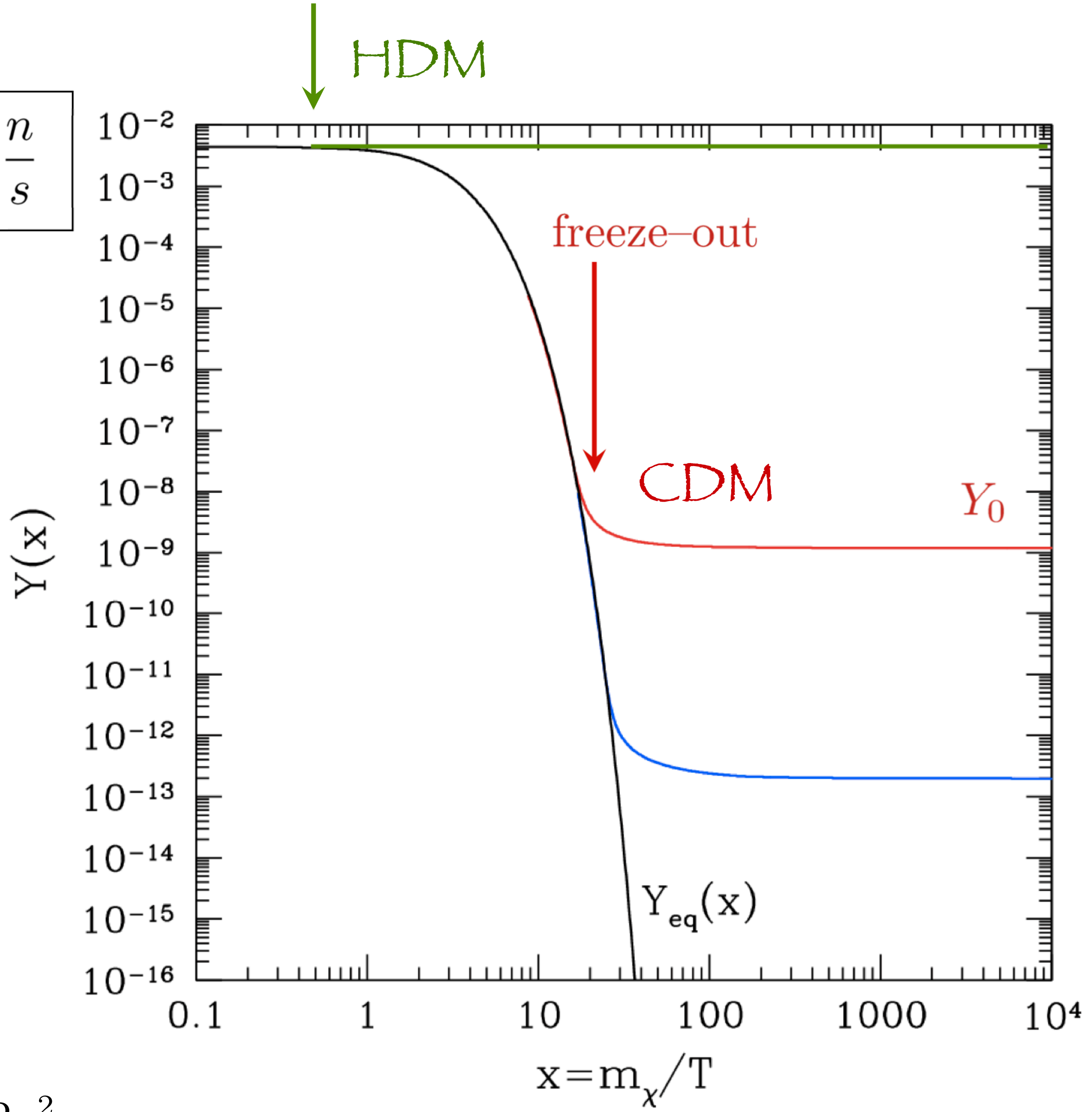


Dominat HDM is in contradiction with observations (SDSS, 2dF)

Neutrinos may contribute, but only subdominantly

CMB+SDSS+2dF	$\sum_i m_i \leq (0.9 \div 1.7)$ eV	$\Omega h^2 \leq (0.0097 \div 0.018)$ eV
Atm. neutrinos	$\sqrt{\Delta m^2_{13}} = 0.047$ eV	$\Omega h^2 \geq 0.0005$ eV

$$Y = \frac{n}{s}$$



$$Y_0 = Y(x_f)$$

$$\Omega_{\rm CDM} h^2 = \frac{m\, s_0\, Y_0}{\rho_C^0}$$

$$s = \frac{2\pi^2}{45} g_{\star S} T^3$$

CDM relic abundance

- Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{\rm eq}^2)$$

$$\frac{\mathrm{d}Y}{\mathrm{d}x} = \beta \frac{g_{*S}}{g_*^{1/2}} < \sigma_{\rm ann} v_r > [Y^2 - Y_{eq}^2]$$

$$Y = \frac{n}{s} \qquad x = T/m_\chi \qquad \beta = 0.264 m_\chi M_P$$

- Relic abundance:

$$\Omega_\chi h^2 = 8.5 \cdot 10^{-11} \frac{g_*^{1/2}(x_f)}{g_{*S}(x_f)} \left(\frac{\mathrm{GeV}^{-2}}{< \sigma_{\rm ann} v_r >_{\rm int}} \right)$$

$$x_f^{-1} = \ln \left[0.145 \beta \frac{g}{g_\star^{1/2}} \, x_f^{1/2} \langle \sigma_{\rm ann} v_r \rangle_{(x_f)} \right]$$

freeze-out temperature

The "WIMP" miracle

WIMP: Weakly Interacting Massive Particle

$$m_\chi \sim (\mathrm{GeV} \div \mathrm{TeV})$$

$$\langle \sigma v \rangle = G_F^2 m_\chi^2$$

naturally

$$\Omega_\chi h^2 \sim 0.1$$

$$x_F \equiv m_\chi / T_F \sim 15 \div 25$$

Succesfull DM candidate

- Needs to be produced in the early Universe
  - Thermal relic
  - Non-thermal relic

- Needs to be "cold" (or, at least, "warm" enough)
  - For thermal production: weakly interacting and massive (WIMP)

$$\Omega h^2 \sim \langle \sigma v \rangle_{\rm ann}^{-1} \longrightarrow \langle \sigma v \rangle_{\rm ann} = 3 \cdot 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

unless coannihilation occurs

  - If light, it nevertheless needs to act as "cold"

- Needs to be neutral
- Needs to be stable (absolutely, or on cosmological time scales)

DM and New Physics Models

Non-baryonic DM candidates

- "Minimal" candidates
  - Neutrino: standard, right-handed, (...)
  - Additional gauge multiplets (MDM), (...)
  - Axion

    (...)

Non-baryonic DM candidates

- "Minimal" candidates
  - Neutrino: standard, right-handed, (...)
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  (...)

- Supersymmetric candidates
  - Neutralino
  - Sneutrino
  - Gravitino
  - Axino

  (...)

SUPERSYMMETRY: FERMION $\longleftrightarrow$ BOSON

Normal particles/fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino	$\tilde{\chi}^\pm_{1,2}$	chargino
H^-	Higgs boson	$\tilde{H}^-_1$	higgsino		
H^+	Higgs boson	$\tilde{H}^+_2$	higgsino		
B	B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
W^3	W^3-field	$\tilde{W}^3$	wino		
H^0_1	Higgs boson	$\tilde{H}^0_1$	higgsino		
H^0_2	Higgs boson	$\tilde{H}^0_2$	higgsino		
H^0_3	Higgs boson				

SUSY breaking $\longrightarrow$ massive SUSY partners

R PARITY $\longrightarrow$ LSP: stable

$$P_R = (-1)^{3(B-L)+2s}$$

$$A + B \longrightarrow \tilde{X} + \tilde{Y}$$

$$\tilde{X} \longrightarrow \tilde{Y} + A + B$$

Non-baryonic DM candidates

- "Minimal" candidates
  - Neutrino: standard, right-handed, (...)
  - Additional gauge multiplets (MDM), (...)
  - Axion

  (...)

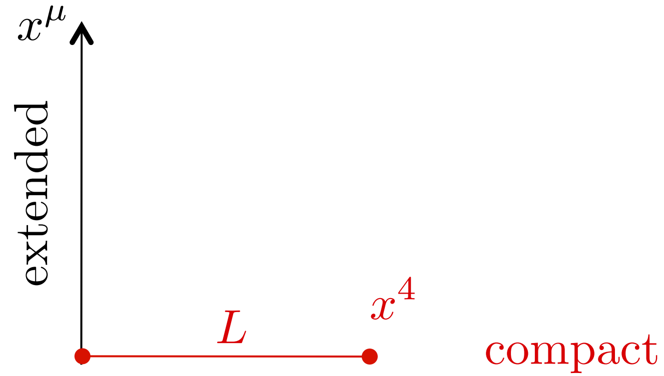
- Supersymmetric candidates
  - Neutralino
  - Sneutrino
  - Gravitino
  - Axino

  (...)

- Extra-dimensions
  - Kaluza-Klein fields

  (...)

5D spacetime : $x^M = (x^0, x^1, x^2, x^3, x^4)$



$$m_n^2 = m_0^2 + \frac{n^2}{L^2}$$

$n = 0$ SM

$n = 1, 2, \dots$ KK states

KK parity → LKP: stable

Non-baryonic DM candidates

- “Minimal” candidates
  - Neutrino: standard, right-handed, (...)

WIMP – Additional gauge multiplets (MDM), (...)

  - Axion

  (...)

- Supersymmetric candidates

WIMP – Neutralino

WIMP – Sneutrino

  - Gravitino

WIMP – Axino

  (...)

- Extra-dimensions

WIMP – Kaluza-Klein fields

  (...)

Non-baryonic DM candidates

- "Minimal" candidates
  - Neutrino: standard, RH MeV, (...) Non WIMP
  - Additional gauge multiplets (MDM), (...)
  - Axion Non WIMP

    (...)

- Supersymmetric candidates
  - Neutralino
  - Sneutrino
  - Gravitino
  - Axino

    (...)

- Extra-dimensions
  - Kaluza-Klein fields

    (...)

Non-baryonic DM candidates

- "Minimal" candidates
  - Neutrino: standard, RH MeV, (…)
  - Additional gauge multiplets (MDM), (…)
  - Axion

  (…)

- Supersymmetric candidates
  - Neutralino →
  - Sneutrino
  - Gravitino
  - Axino

  (…)

- Extra-dimensions
  - Kaluza-Klein fields

  (…)

- Low energy MSSM
  - Universal mass params
  - Light neutralinos
- Minimal SUGRA
- Non-minimal SUGRA
  - Higgs sector
  - Sfermion sector
  - Gaugino sector
- NMSSM
- Anomaly mediated ~~SUSY~~
- (…)

Non-baryonic DM candidates

- "Minimal" candidates
  - Neutrino: standard, RH MeV, (...)
  - Additional gauge multiplets (MDM), (...)
  - Axion

  (...)

- Supersymmetric candidates
  - Neutralino
  - Sneutrino
  - Gravitino
  - Axino

  (...)

- Extra-dimensions
  - Kaluza-Klein fields

  (...)

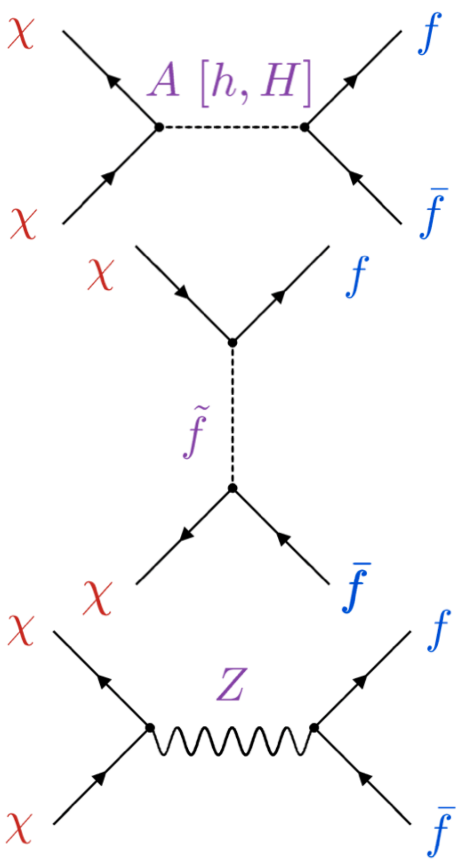
Sneutrino →

- With R-handed (s)neutrino
- With Majorana-mass terms
- In see-saw models
- NMSSM
- (...)

Neutralino annihilation cross section

$\langle \sigma_{\rm ann} v \rangle$

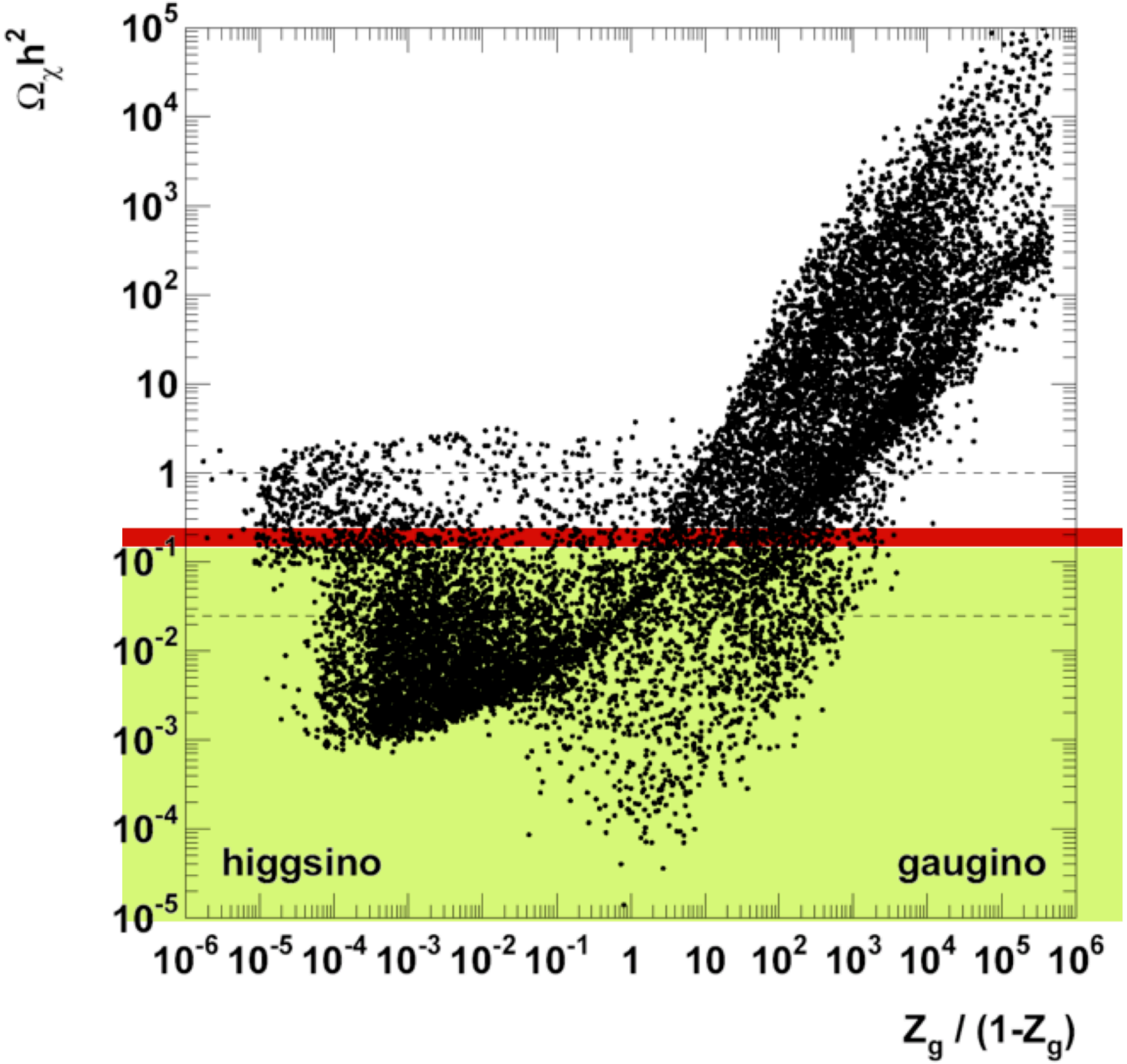
annihilation is almost at rest



*	$\chi\chi \to f\bar{f}$	Z, h, H, A	s channel
		$\tilde{f}_L, \tilde{f}_R$	t and u channels
*	$\chi\chi \to hh, hH, HH, AA$	h, H	s channels
		$\chi_i\ (i = 1,2,3,4)$	t and u channels
*	$\chi\chi \to hA, HA$	Z, A	s channel
		$\chi_i\ (i = 1,2,3,4)$	t and u channels
*	$\chi\chi \to H^+H^-$	Z, h, H	s channel
		$\chi_j^+\ (j = 1,2)$	t and u channels
*	$\chi\chi \to ZZ$	h, H	s channel
		$\chi_i\ (i = 1,2,3,4)$	t and u channels
*	$\chi\chi \to W^+W^-$	Z, h, H	s channel
		$\chi_j^+\ (j = 1,2)$	t and u channels
*	$\chi\chi \to hZ, HZ$	Z, A	s channel
		$\chi_i\ (i = 1,2,3,4)$	t and u channel
*	$\chi\chi \to AZ$	h, H	s channel
		$\chi_i\ (i = 1,2,3,4)$	t and u channels
*	$\chi\chi \to W^\pm H^\mp$	h, H, A	s channel
		$\chi_j^+\ (j = 1,2)$	t and u channels

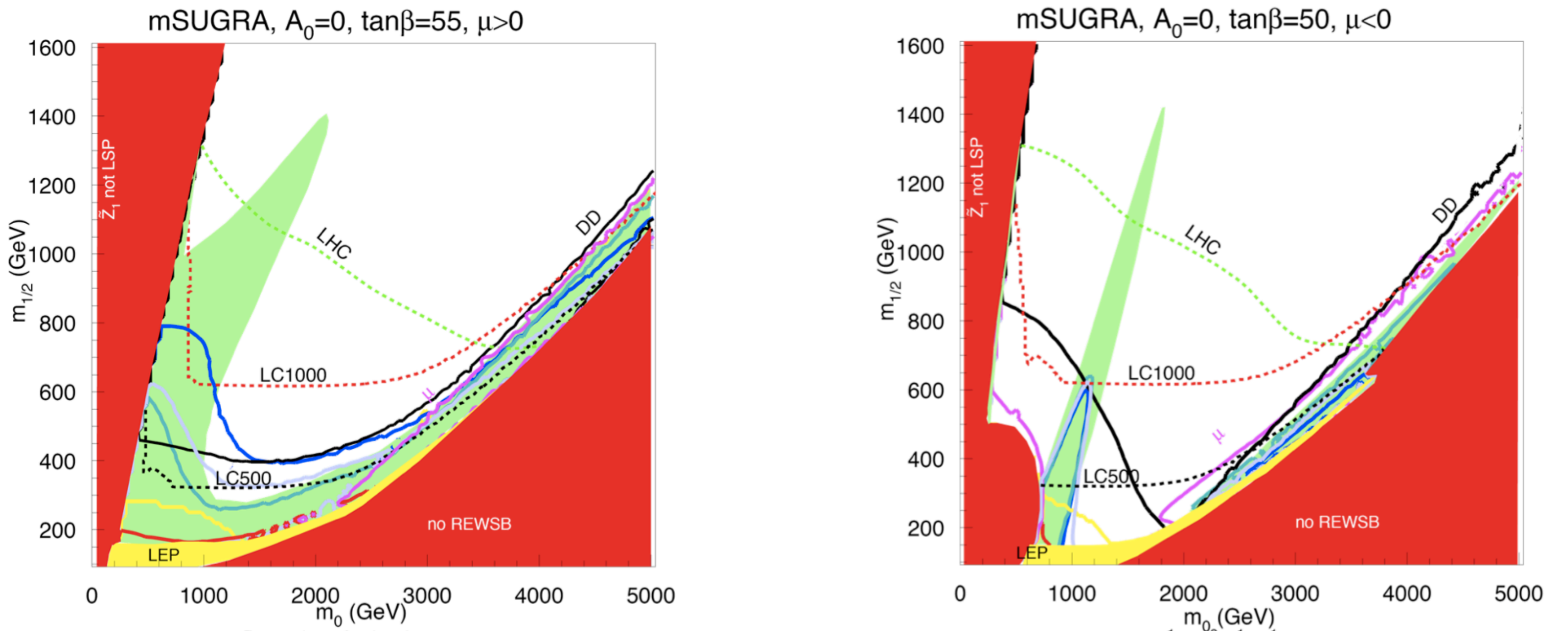
which one is open depends on the neutralino mass

MSSM



J. Edsjo et al.

Minimal Supergravity



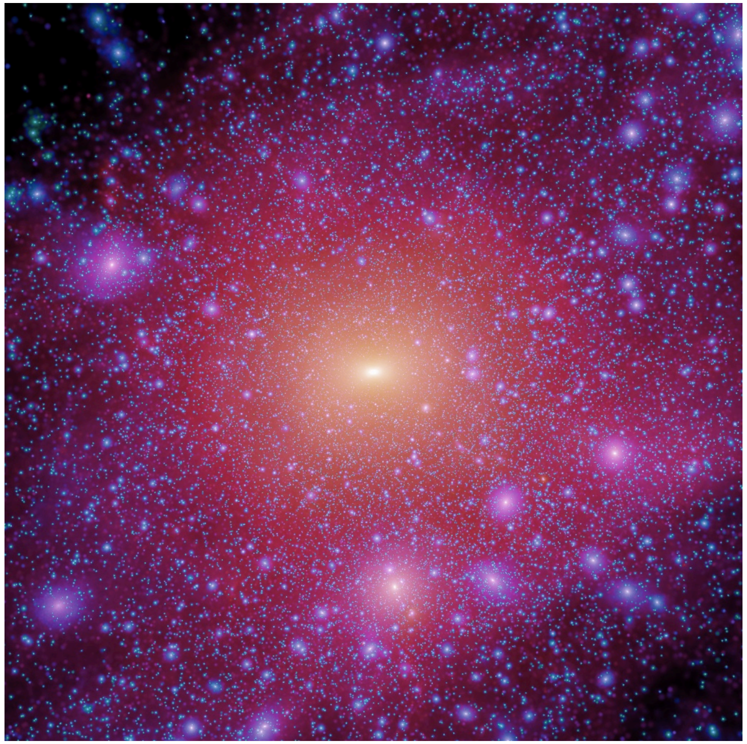
$$M_{1/2} \quad m_0 \quad A_0 \quad \tan\beta \quad \text{sign}(\mu)$$

H. Baer, 0901.4732 [hep-ph]

Galactic Dark Matter

CDM in galaxies:

- DM as a non-baryonic particle
- Massive particle with weak-type interactions (WIMP)
- Distributed to form a halo
    - Thermal component
    - Substructures
    - Non-thermal component

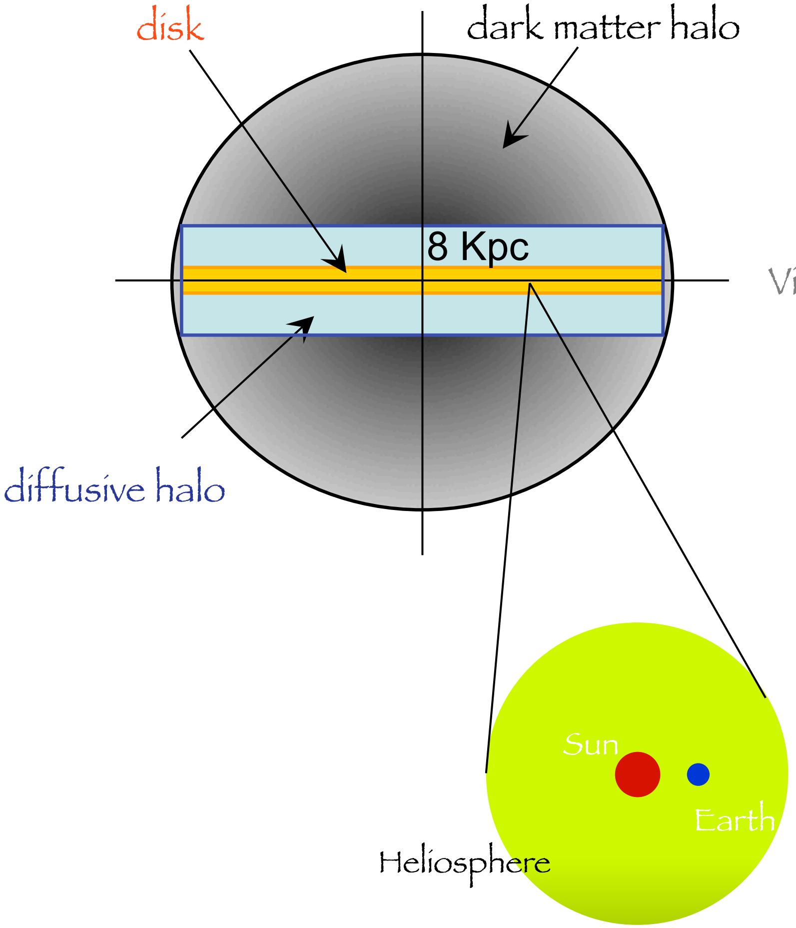


Galactic dark matter detection:

- Identify types of signals
- Exploit specific signatures
- Exploit (anti)correlations among signals
- Study relevant backgrounds
- Quantify uncertainties

DM Distribution in Galaxies

Galactic environment

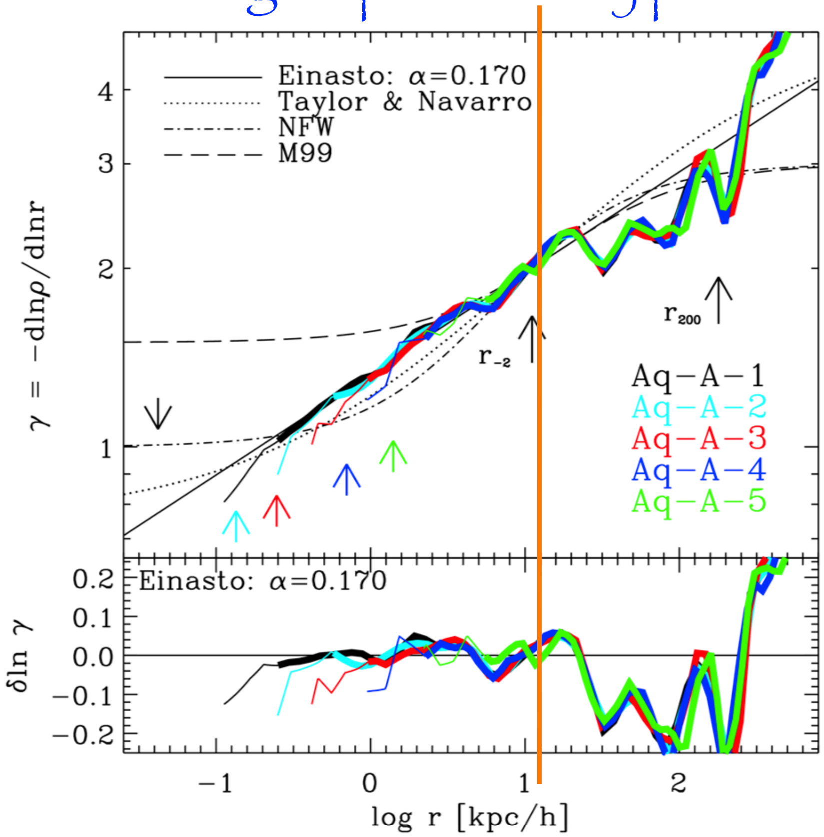


View from the side

Dark matter phase space (for CDM)

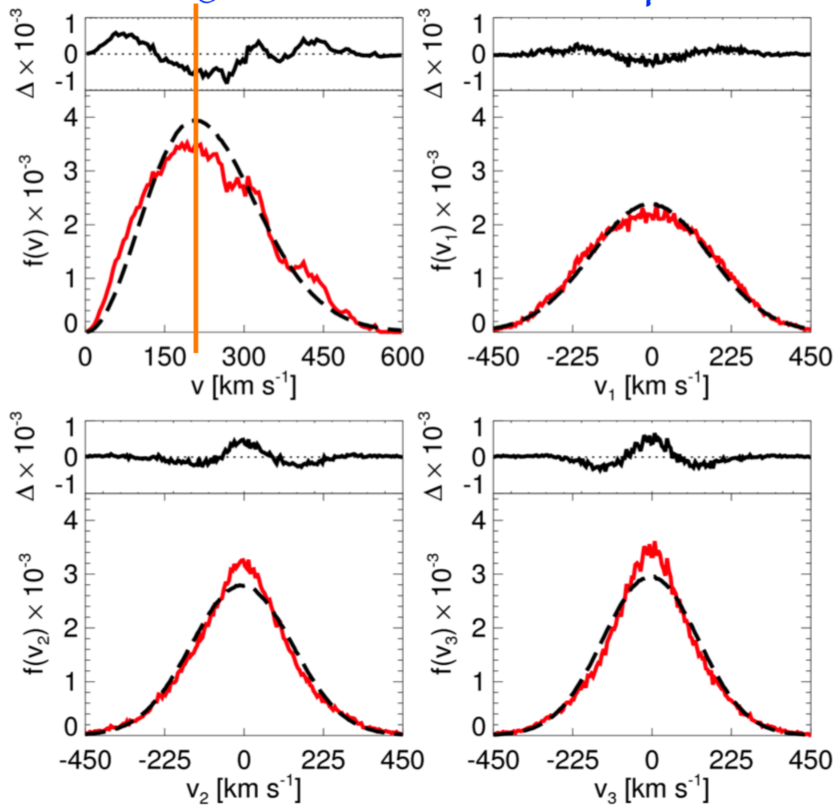
$\rho(r)$

Log-slope of density profile



$f(v)$

Velocity distribution at Sun position

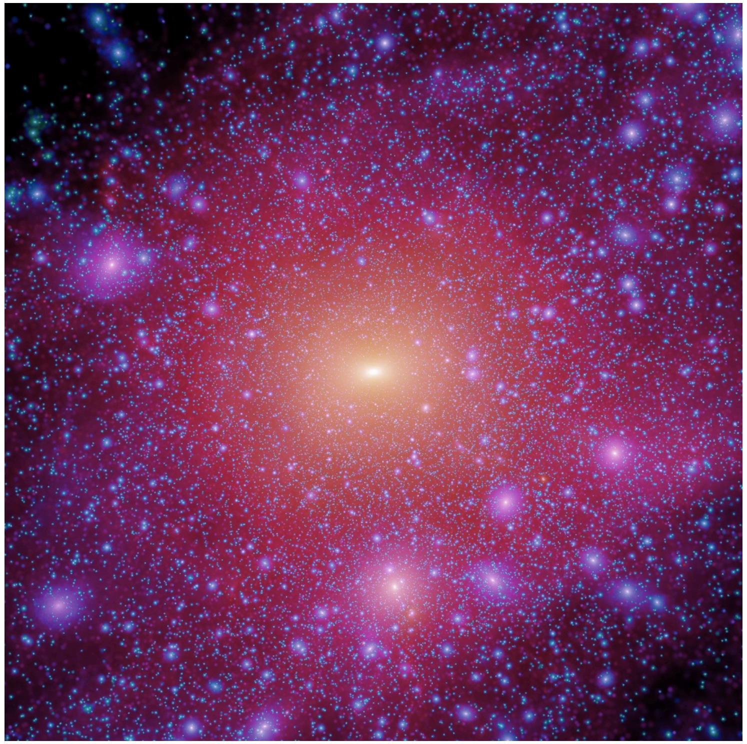


From numerical simulations

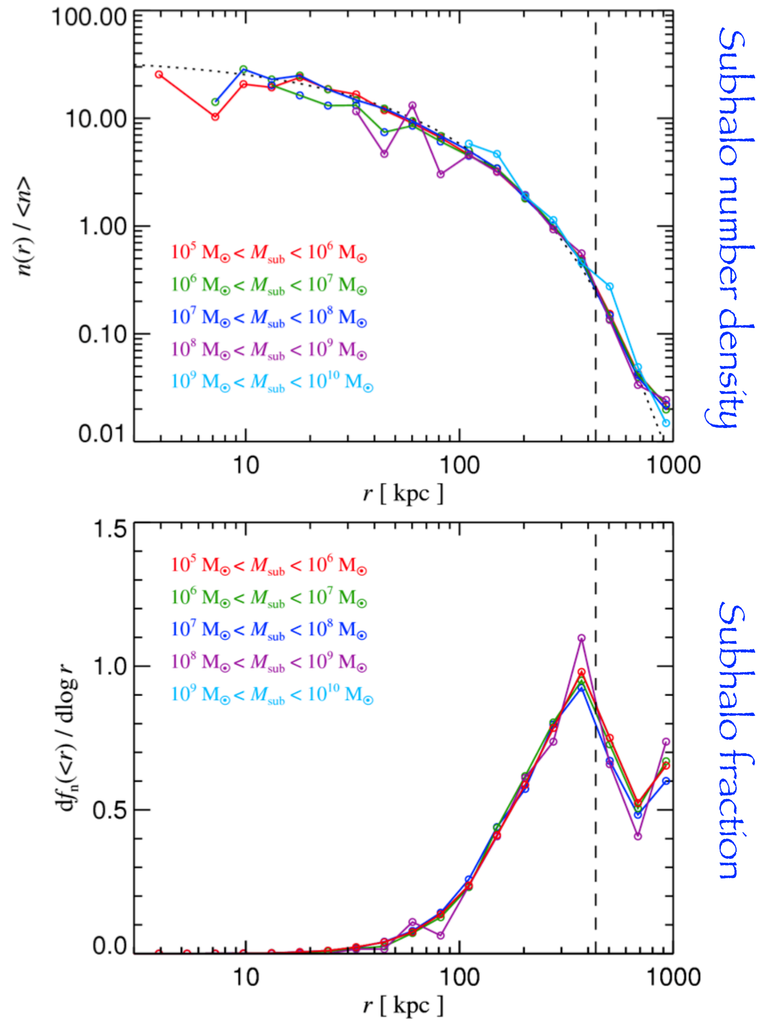
Navarro et al., arXiv:0810.1522

Vogelsberger et al., arXiv:0812.0362

Subhalos



The Aquarius Project

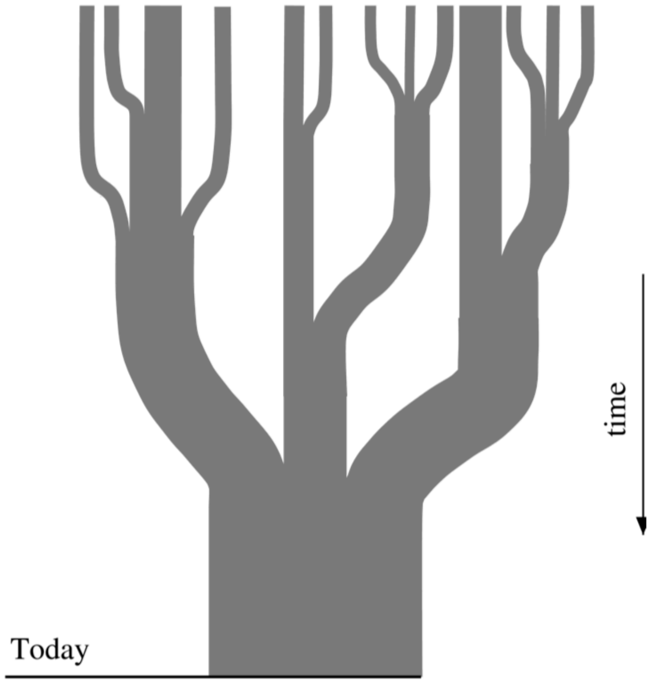


Most subhalos are in the outer halo

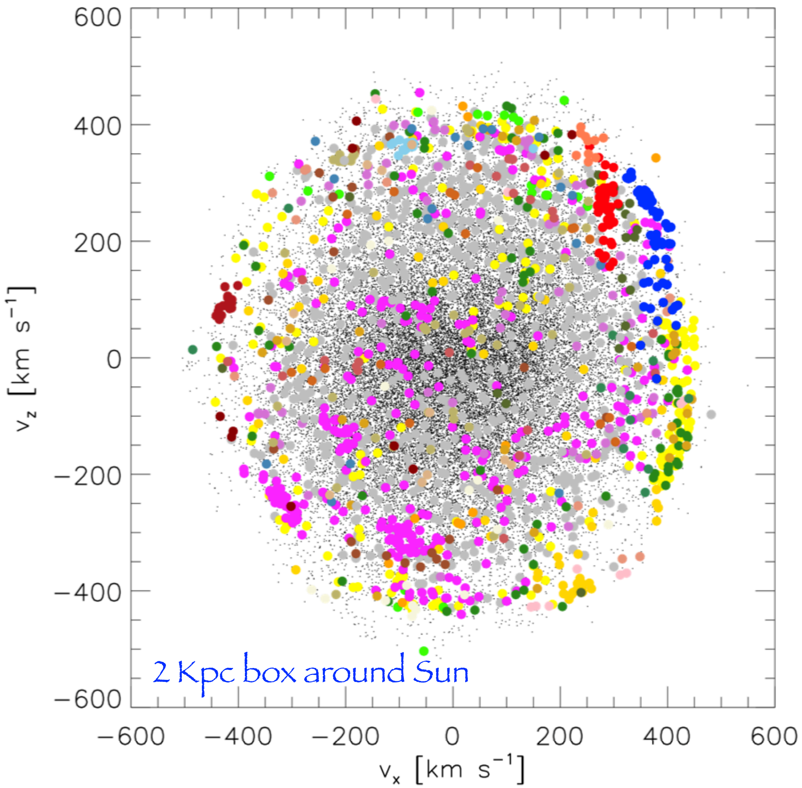
Springel et al., MNRAS 391 (2008) 1685

Velocity streams

Merger tree



"Particles" from common branch



Vogelsberger et al., arXiv:0812.0362

"Canonical" halo

$$\rho(r) \longrightarrow \rho_0 = 0.3 \text{ GeV cm}^{-3}$$

$$\rho(r) \longrightarrow r^{-1} \quad [r \to 0]$$

Recent determinations [1-3]

[1]
$$\rho_0 = 0.385 \pm 0.027 \text{ GeV cm}^{-3} \quad \text{(Einasto)}$$
$$\rho_0 = 0.389 \pm 0.025 \text{ GeV cm}^{-3} \quad \text{(NFW)}$$

[2] $\rho_0 = 0.43(11)(10) \text{ GeV cm}^{-3}$

$$f(\vec{v}) = N \exp\left(-v^2/v_0^2\right)|_{v_{\rm esc}}$$

$$v_0 = (220 \pm 50) \text{km s}^{-1}$$

$$v_{\rm esc} = (450 \div 650) \text{ km s}^{-1}$$

Streams may have impact

Anisotropies may be present

[1] Catena, Ullio, arXiv:0907.0018
[2] Salucci et al. arXiv:1003.3101
[3] Pato et al., arXiv:1006.1322

Astrophysical Signals

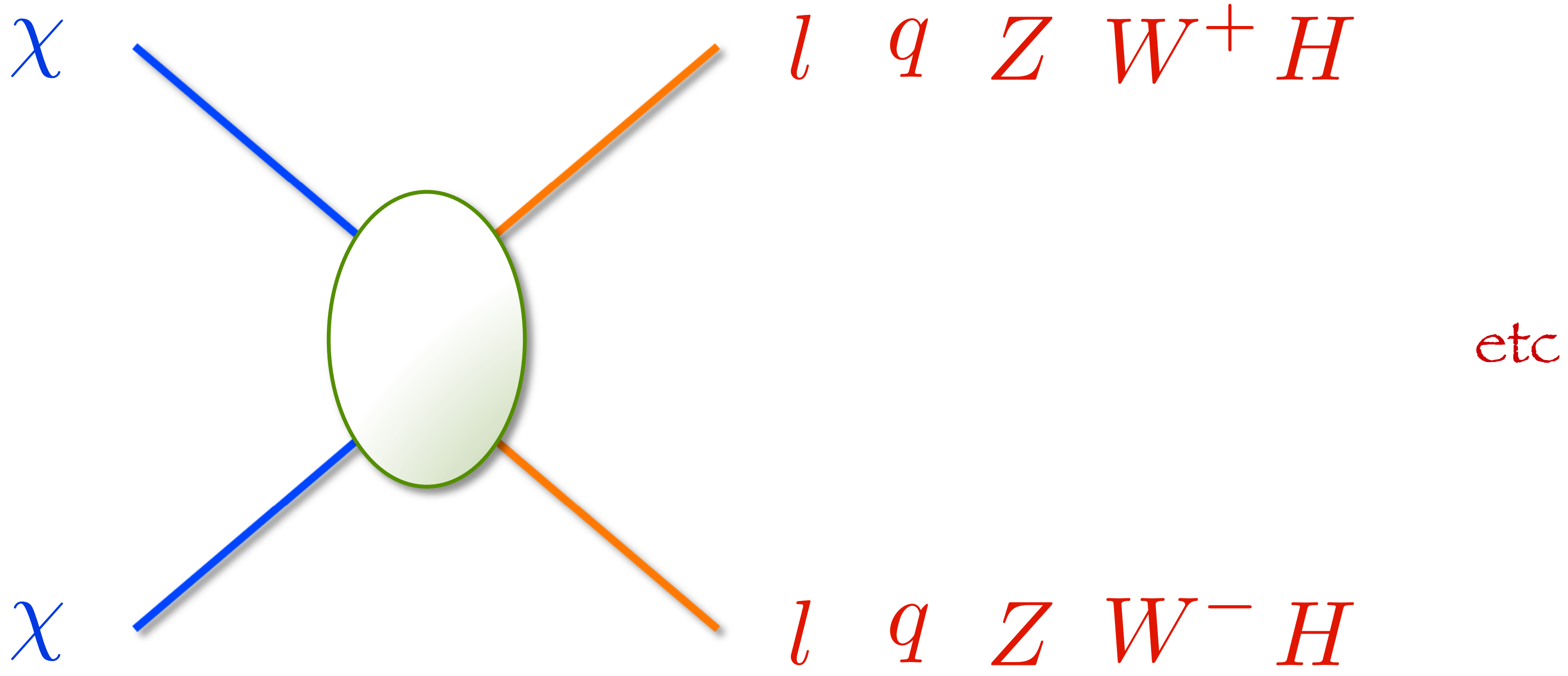
Astrophysical Signals

MultiChannel search of WIMP dark matter

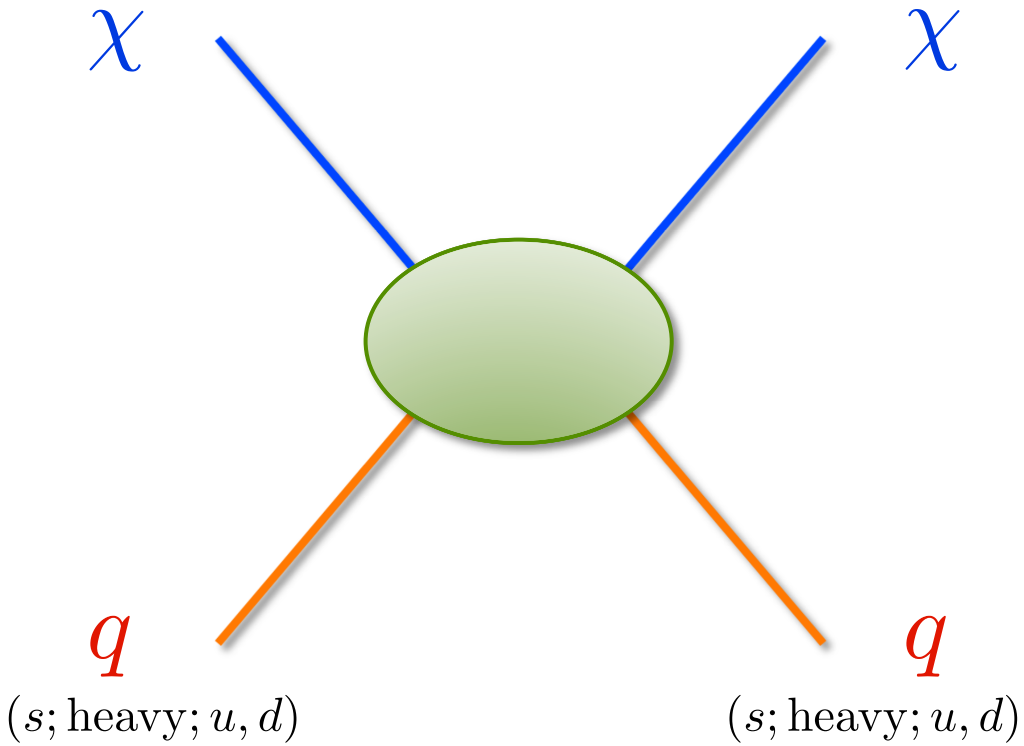
- Direct search: elastic scattering of χ off nuclei in a low background detector
  → recoil energy of the nucleus
  annual modulation of the rate
  directionality of the recoil

- Indirect searches:
  – signals due to $\chi\chi$ annihilation taking place inside celestial bodies (Sun, Earth) where χ have been captured and accumulated
    → Neutrino flux → up-going muons in a neutrino telescope
    source location/some spectral feature

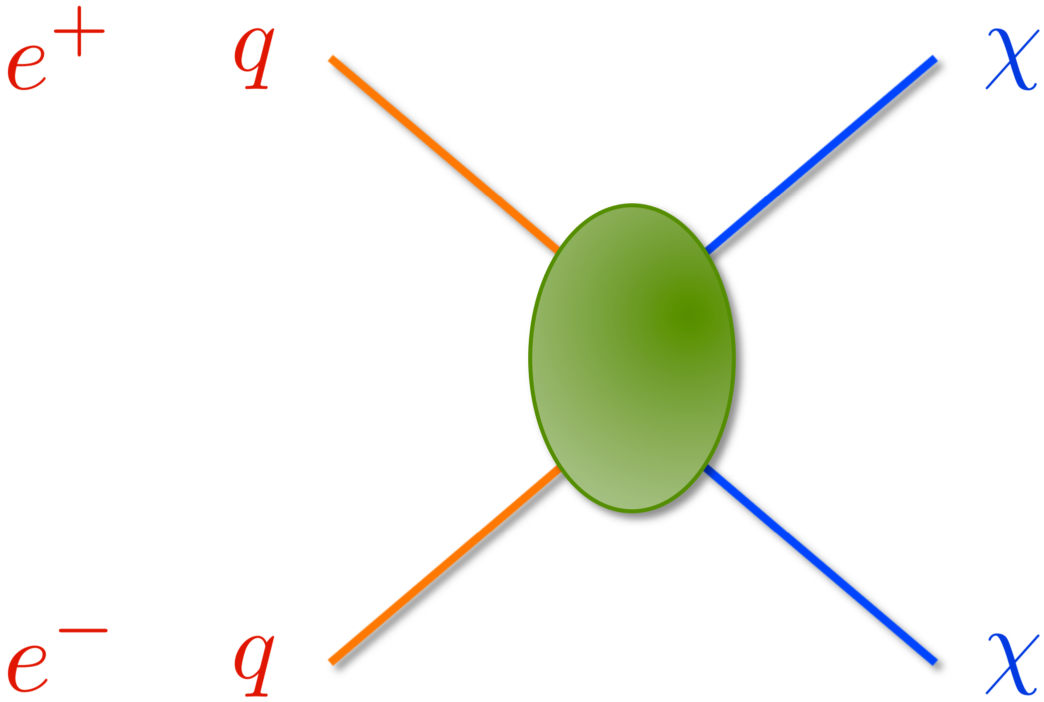
  – signals due to $\chi\chi$ annihilation taking place in the galactic halo
    → Neutrinos — source location/some spectral feature
    → Photons
      - continuous gamma-ray flux — source location/some spectral feature
      - gamma-ray line — very good spectral feature
    → Positrons — spectral feature
    → Antiprotons — spectral feature
    → Antideuterons — very good spectral feature
    → Electrons/positrons → multiwavelength search (radio, X, gamma rays; SZ on CMB)



Relic abundance
Indirect signals



Direct detection
Neutrinos from Earth and Sun

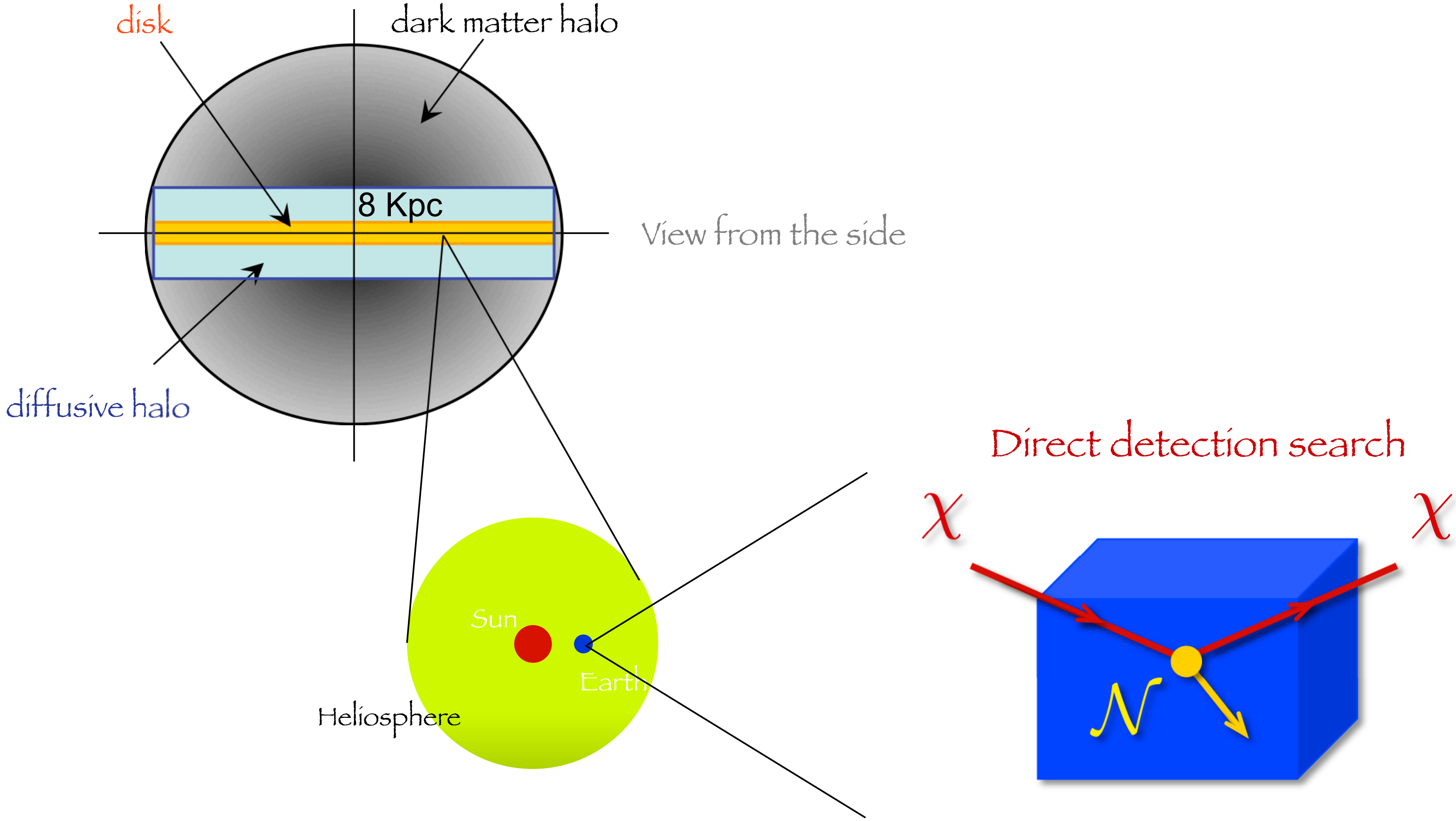


+ other NP states

Accelerator searches

Direct detection

Direct detection



Interaction mechanisms - WIMPs

- Elastic scattering with nuclei $\qquad \chi\,\mathcal{N} \longrightarrow \chi\,\mathcal{N}$
  - Ex.: Neutralino, Sneutrinos, KK

$$E_R = \mu_{\mathcal{N}}^2 v^2 (1 - \cos\theta)/m_{\mathcal{N}}$$

E_R > few KeV

- Inelastic scattering with nuclei $\qquad \chi\,\mathcal{N} \longrightarrow \chi'\,\mathcal{N}$

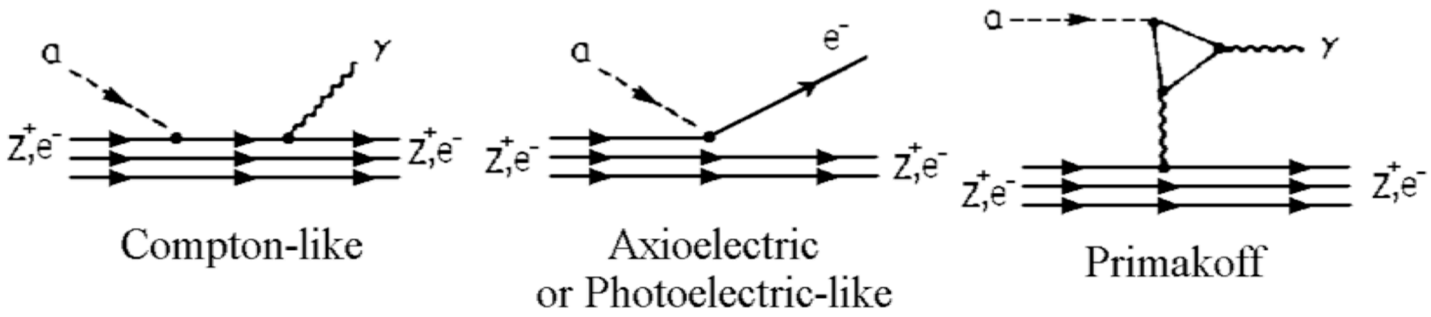
Tucker-Smith, Weiner, PRD 64 (2001) 043502

  - Ex.: Sneutrinos

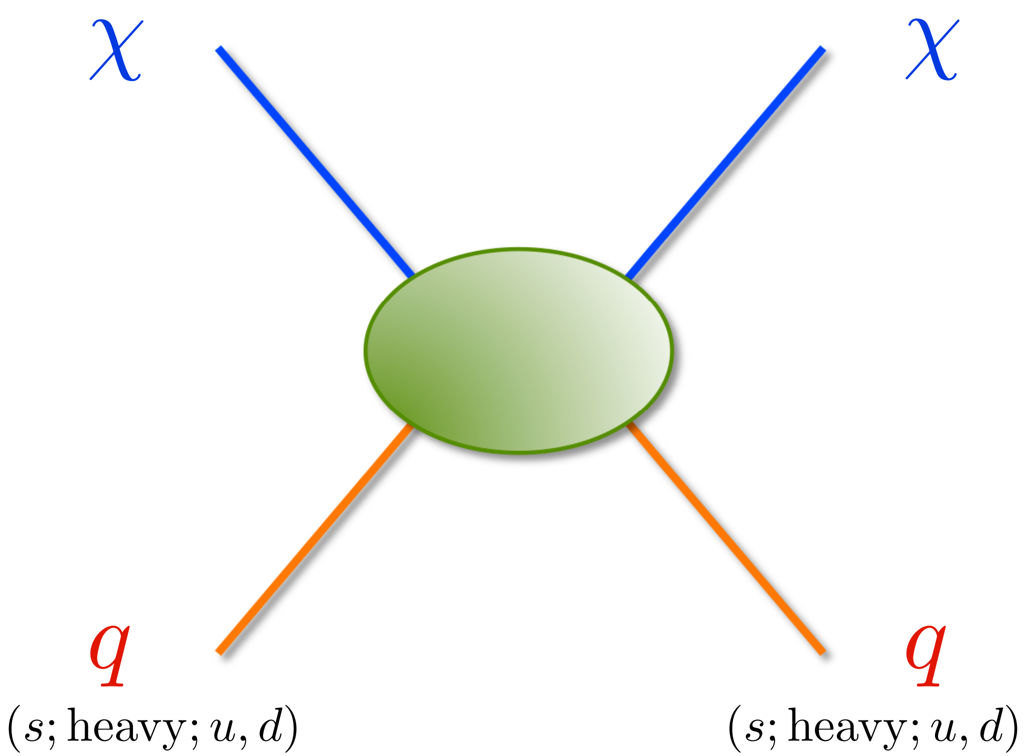
Scatter if: $\Delta m < \dfrac{\beta^2 m_1 m_{\mathcal{N}}}{2(m_1 + m_{\mathcal{N}})}$ $\qquad$ about 1-100 KeV

Interaction mechanisms – non WIMPs

- Inelastic, scatter on electrons
  - Ex.: Light (KeV) [pseudo]scalars



Interaction mechanisms - WIMPs



$$\mathcal{L}_{\rm eff} = \sum_i \alpha_i (\bar{q}\mathcal{O}q)(\bar{\chi}\mathcal{O}\chi)$$

$$\mathcal{L}_{\rm eff} \underset{\text{nucleon}}{\longrightarrow} < N|\bar{q}\mathcal{O}q|N > \sim \bar{\psi}_N \mathcal{O} \psi_N \underset{\text{nucleus}}{\longrightarrow} < \mathcal{N}|\bar{\psi}_{\mathcal{N}} \mathcal{O} \psi_{\mathcal{N}}|\mathcal{N} >$$

WIMPs - Scattering cross section

- Spin-independent
  - Cross section proportional to the (mass number)^2 of the nucleus
  - Channels:
    - Vector boson (Z)-mediated: gauge-type, well known
    - Scalar (H, squarks)-mediated: large hadronic uncertainties

$$I_{h,H} = \sum_q k_q^{h,H} m_q \langle N|\bar{q}q|N\rangle = k_{u-\text{type}}^{h,H}\, g_u + k_{d-\text{type}}^{h,H}\, g_d$$

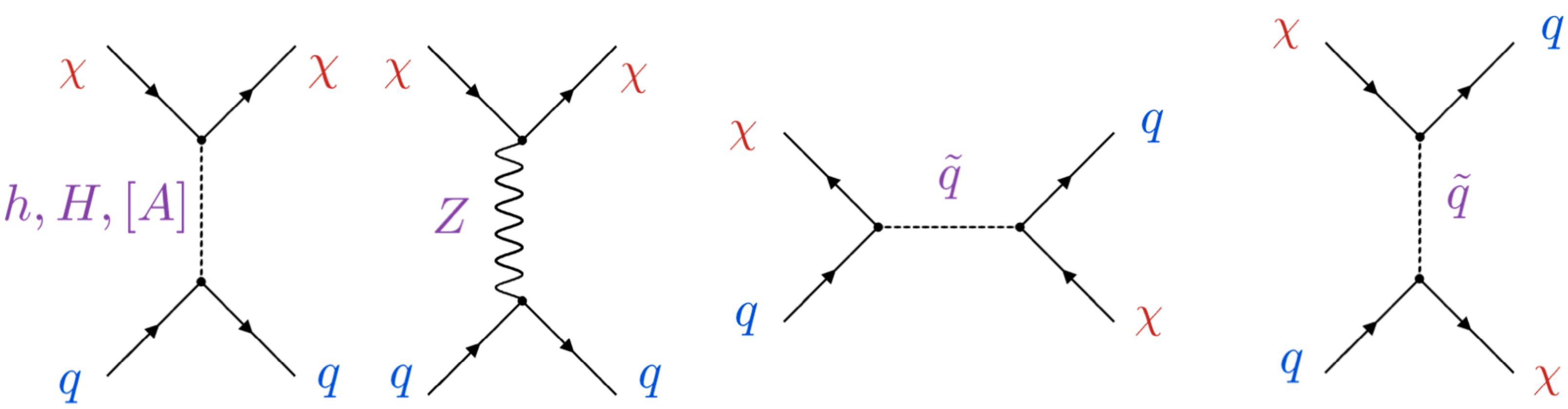
(in MeV)	$m_l < N\|\bar{q}_l q_l\|N >$	$m_s < N\|\bar{s}s\|N >$	$m_h < N\|\bar{h}h\|N >$	g_u	g_d
Set A	27	131	56	139	214
Set B	28	186	52	132	266
Set C	37	456	30	97	523

  - Nuclear form factors F(E_R)

- Spin-dependent
  - Cross section proportional to the (spin)^2 of the nucleus
  - Spin form factors S(E_R)

Example: Neutralino-quark scattering

$\chi q \to \chi q$	$\tilde{q}_L, \tilde{q}_R$	s channel
	Z, h, H, A	t channel
	$\tilde{q}_L, \tilde{q}_L$	u channel



coherent

spin

coherent
spin

coherent
spin

Interaction rate (WIMP ; scalar interaction)

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

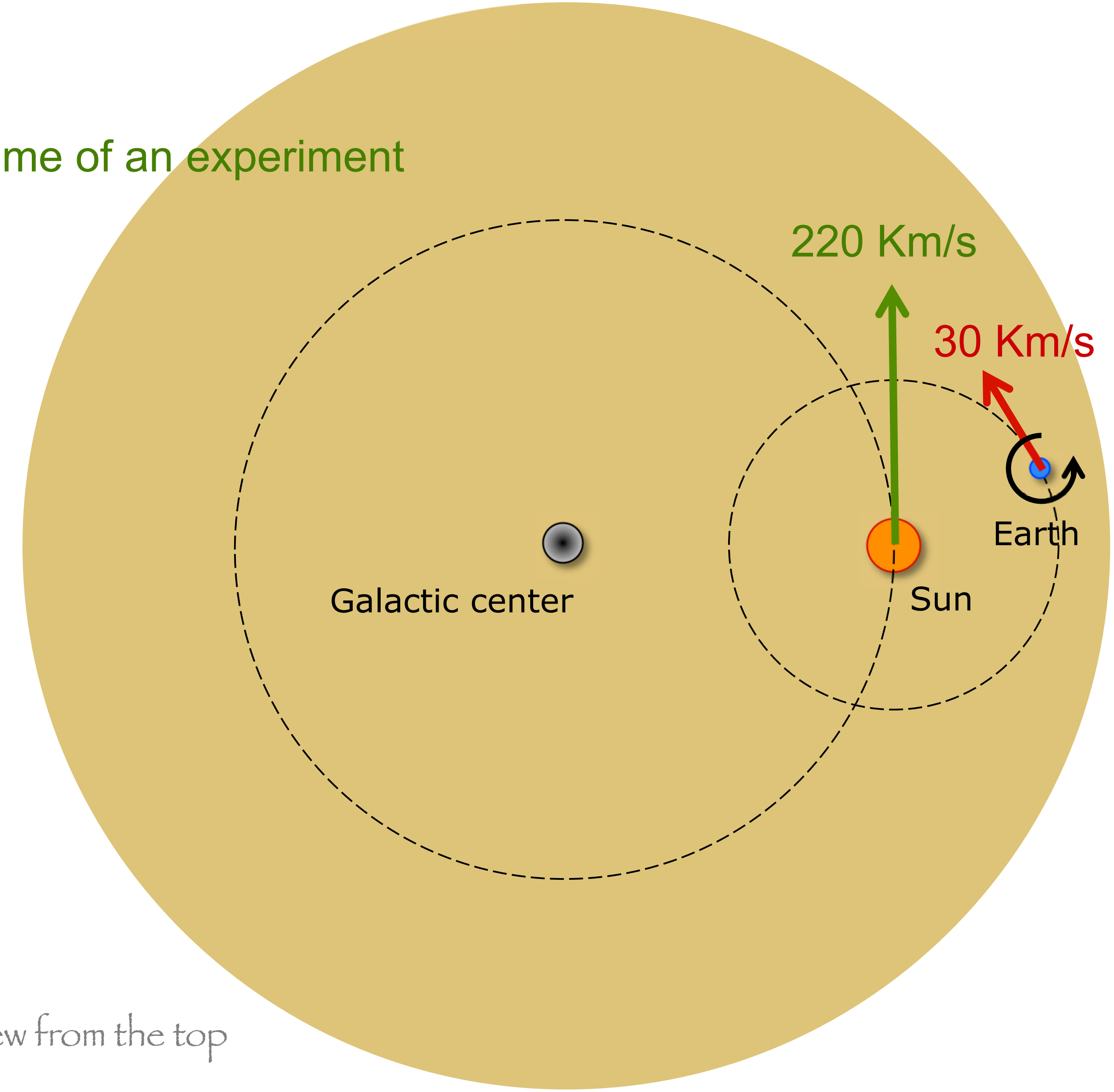
$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3w \; \frac{f_{\rm ES}(\vec{w})}{w}$$

$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_\oplus)\big|_{[v_{\rm rot};v_{\rm esc}]}$$

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

Local motions

- Stationary over the lifetime of an experiment
  Directional boost



View from the top

Interaction rate (WIMP ; scalar interaction)

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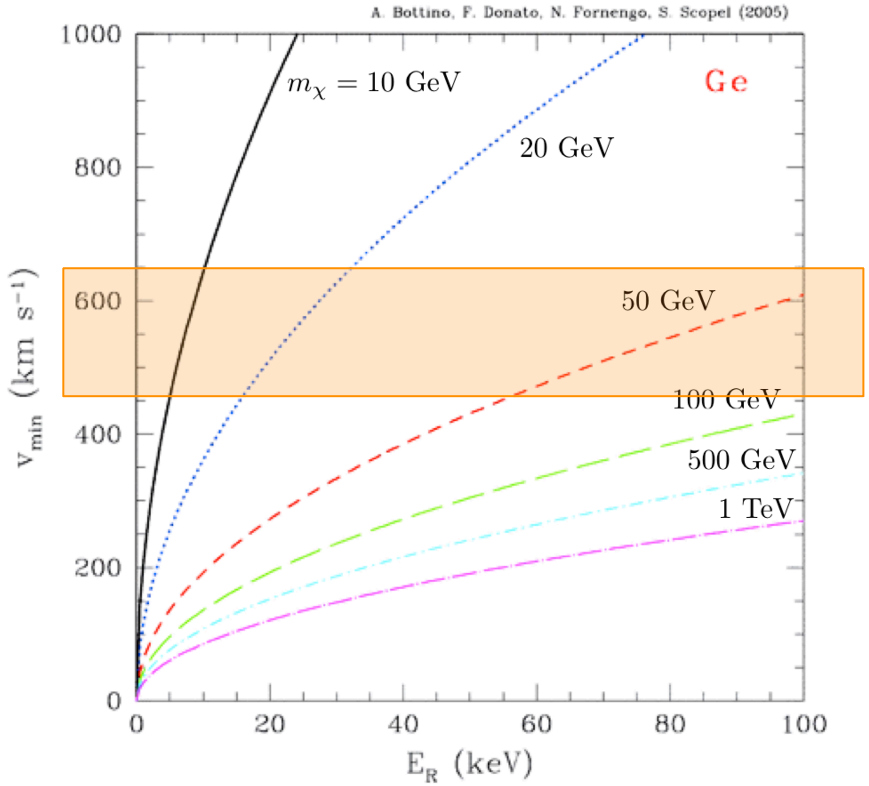
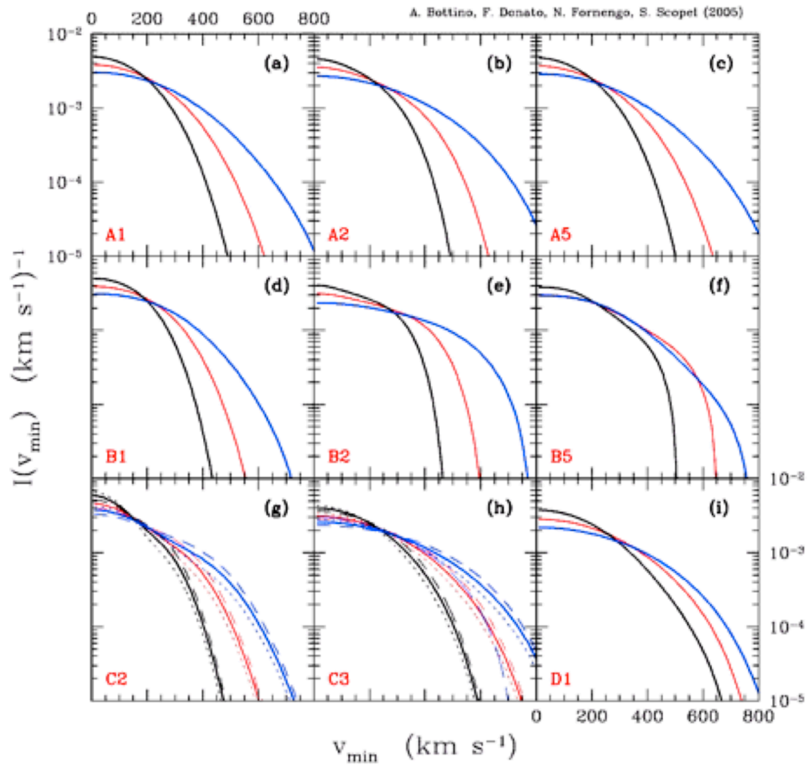
Response function



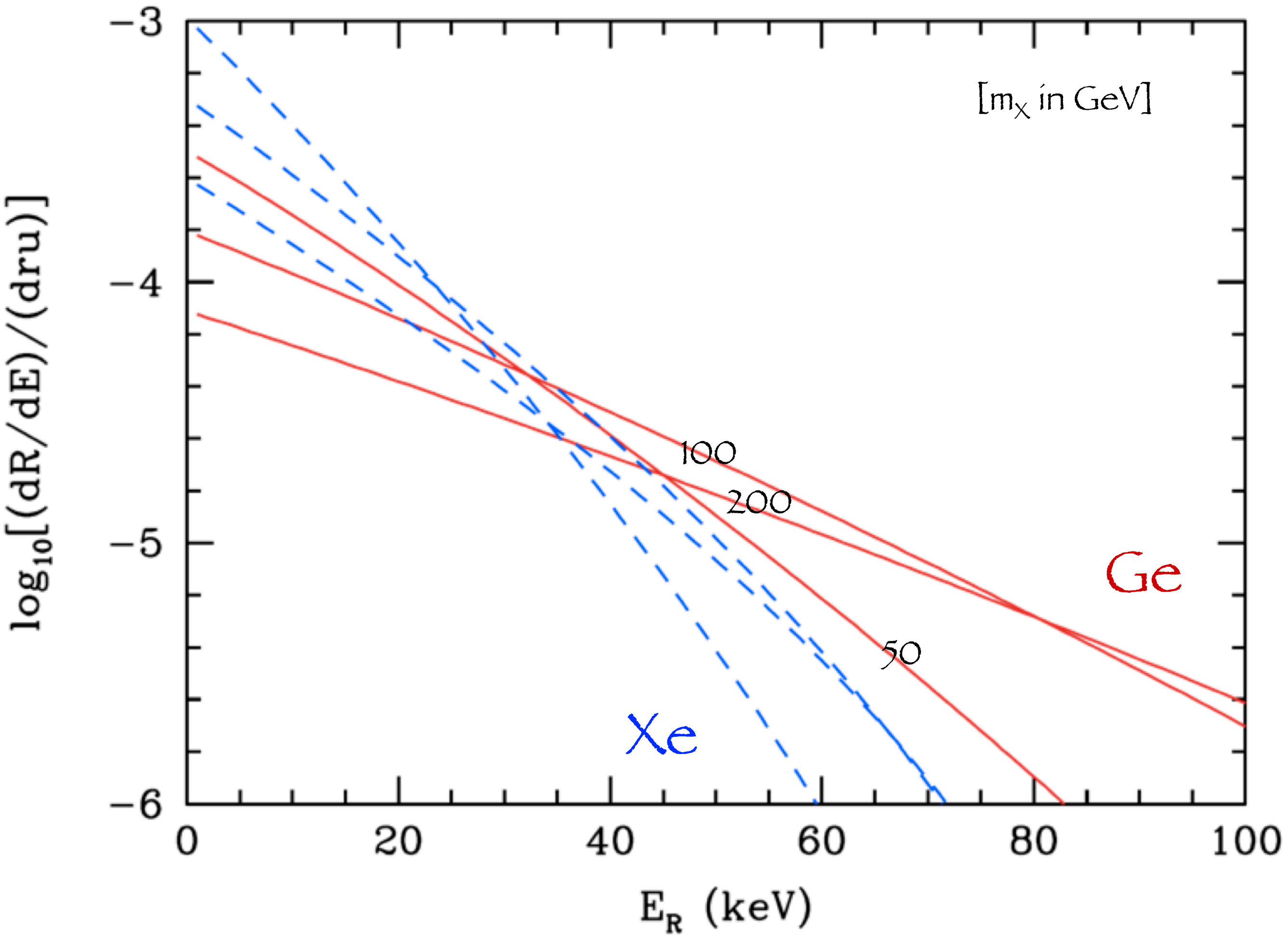


$$v_{\rm min} = [m_N E_R / (2\mu_A^2)]^{1/2}$$

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

A. Bottino, F. Donato, N. Fornengo, S. Scopel, PRD 72 (2005) 083521

Differential Rate – Energy Dependence

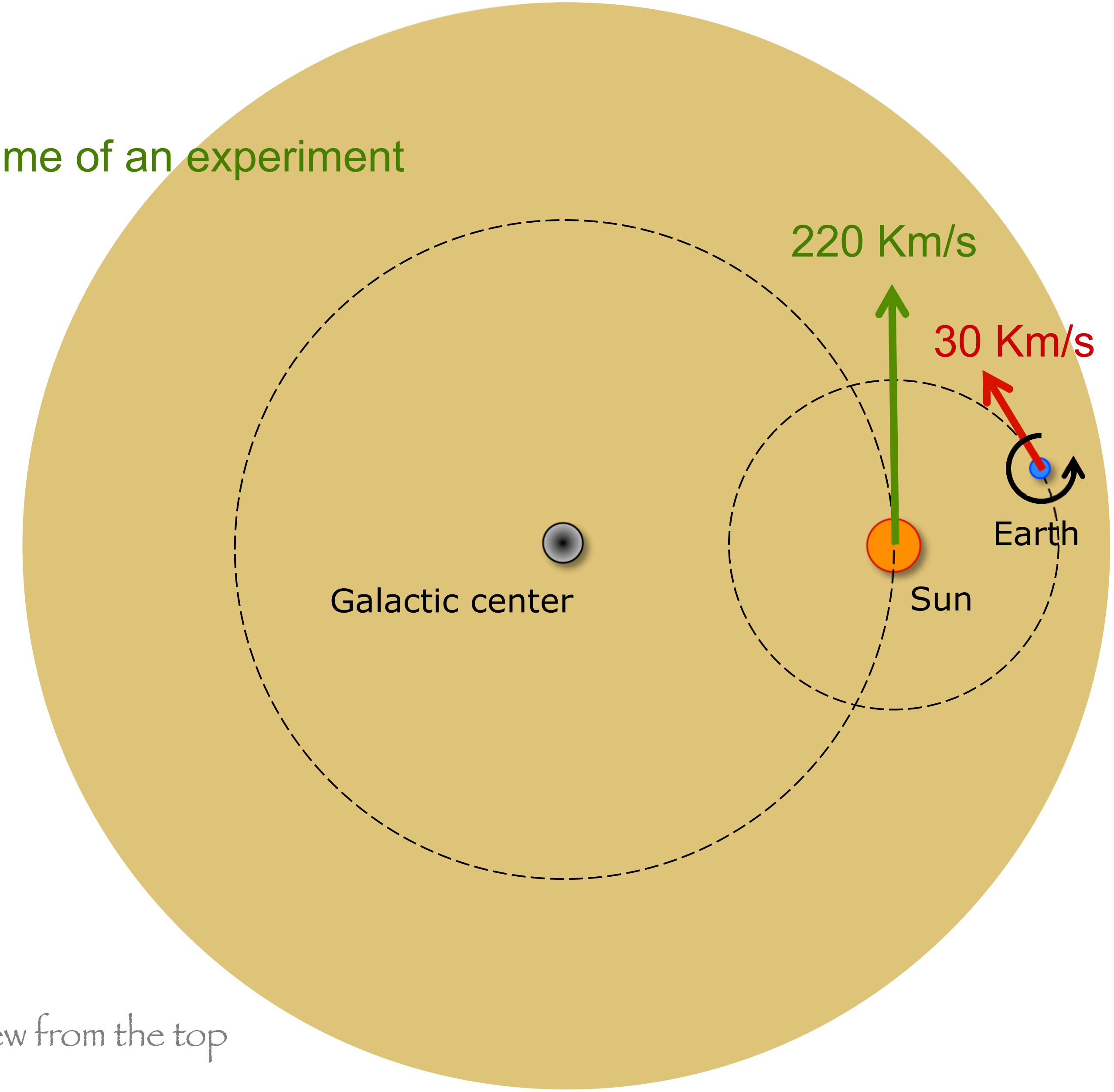


Local motions

- Stationary over the lifetime of an experiment
  Directional boost

- Period: 1 year

- Period: 1 day



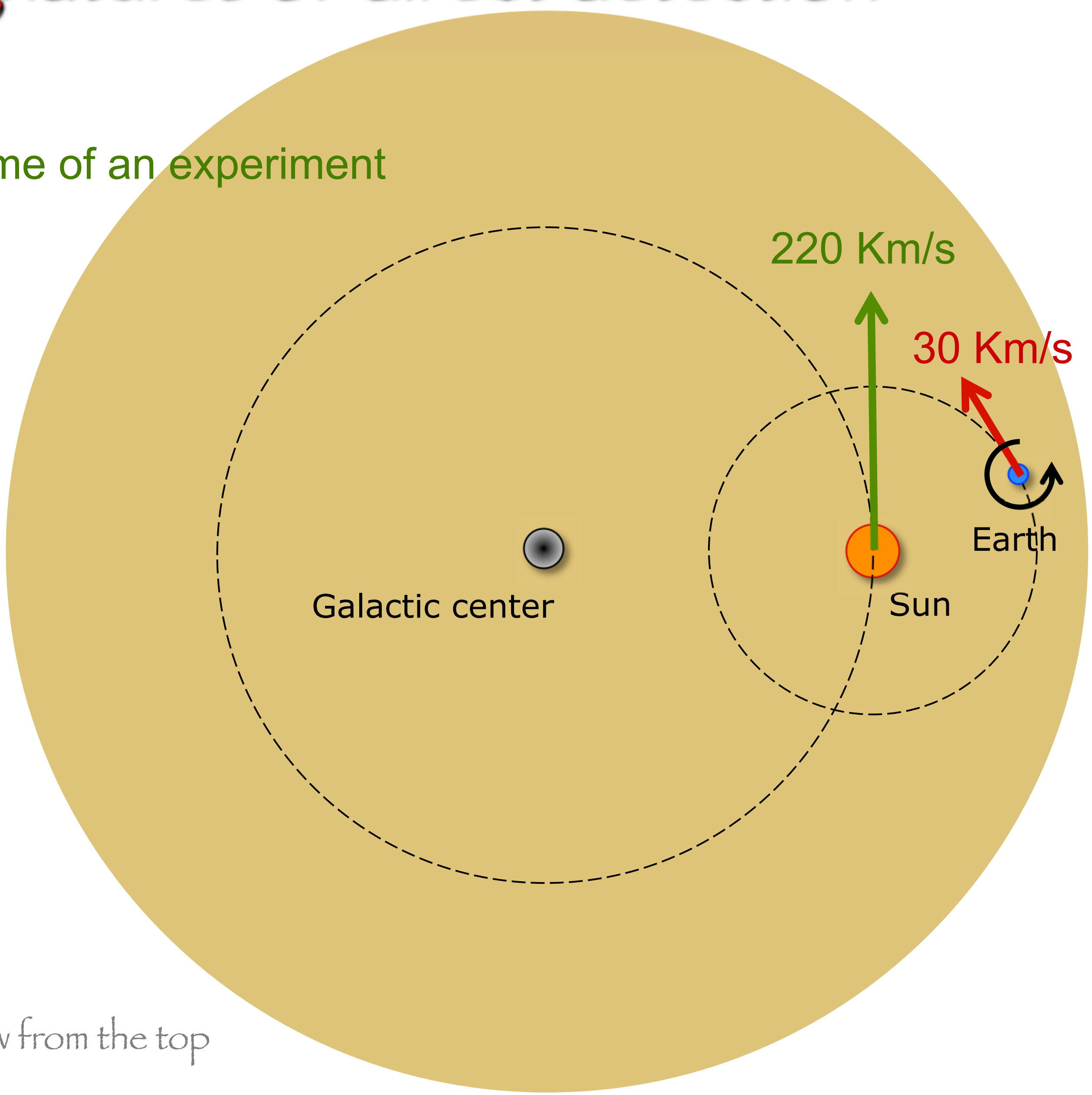
View from the top

Typical signatures of direct detection

- Stationary over the lifetime of an experiment
  Directional boost
  Directionality

- Period: 1 year
  Annual modulation

- Period: 1 day
  Diurnal modulation



View from the top

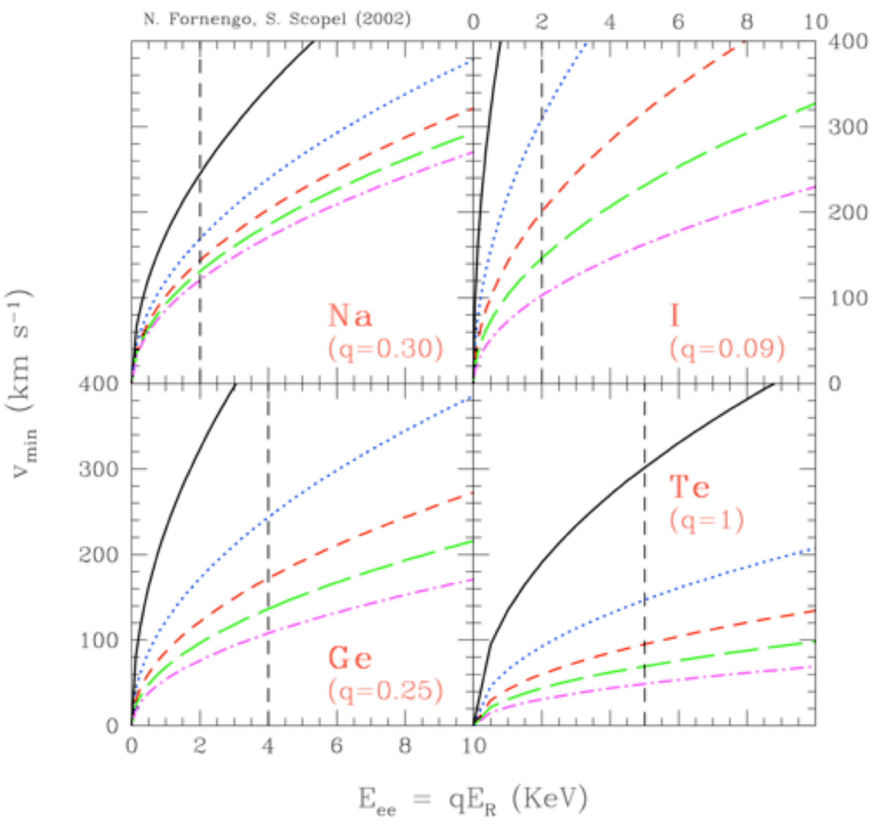
Annual Modulation of the rate

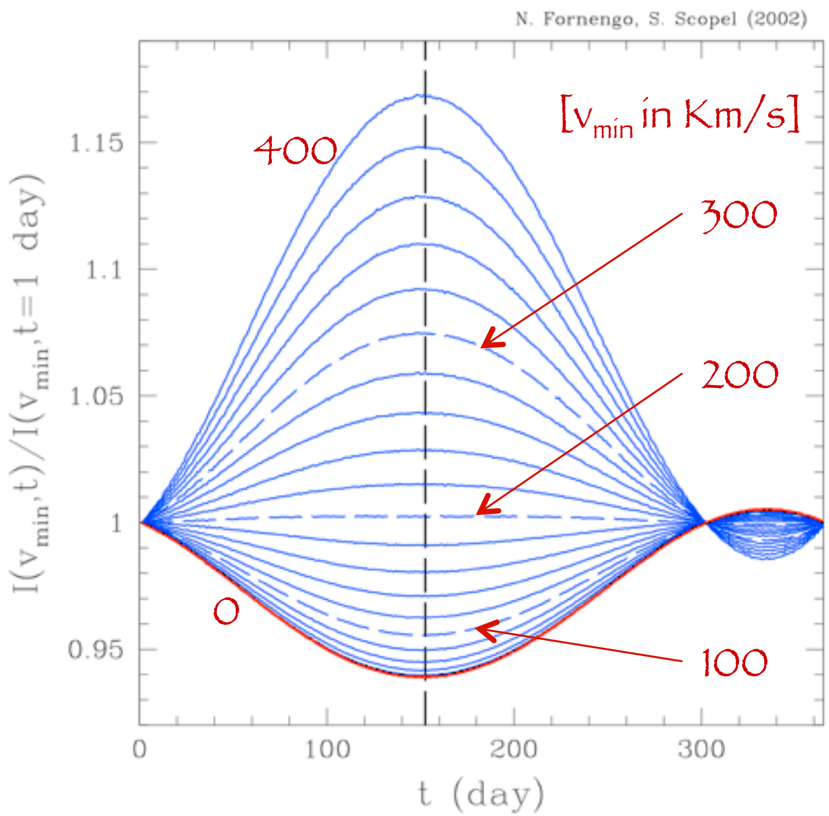
$$\frac{dR}{dE_R}[\eta(t)] = \frac{dR}{dE_R}[\eta_0] + \frac{\partial}{\partial \eta}\left(\frac{dR}{dE_R}\right)_{\eta=\eta_0} \Delta\eta \ \cos[\omega(t-t_0)]$$

$$= S_0(E_R) + S_m(E_R) \ \cos[\omega(t-t_0)]$$

$$\eta(t) = v(t)/v_0$$

Annual modulation





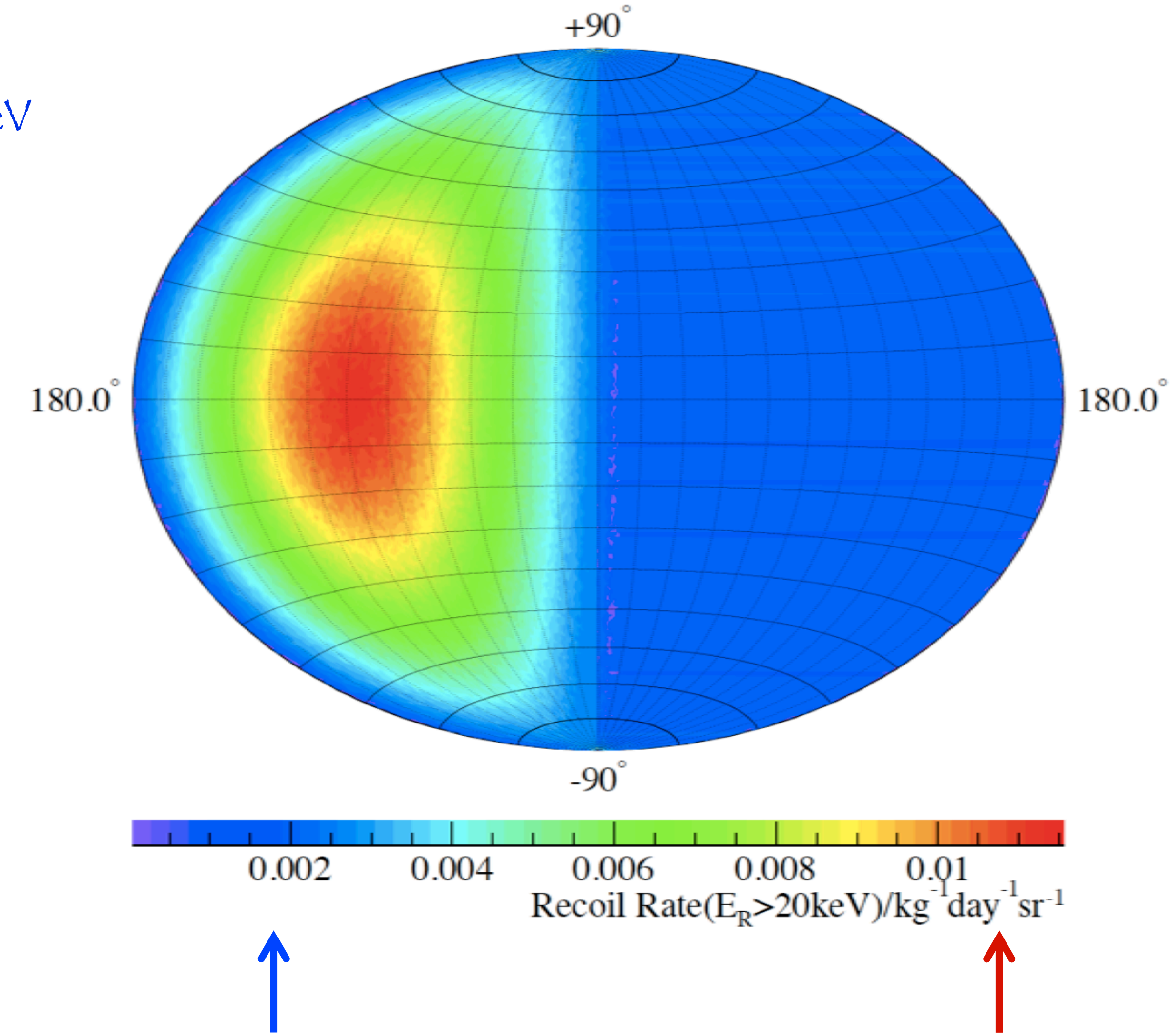
$E_{ee} = q\, E_R$

f(v) : isotropic maxwellian

N. Fornengo, S. Scopel, PLB 576 (2003) 189

Directionality of the recoil

m_χ = 100 GeV



Current direct detection experiments

- Background-rejection experiments (CDMS, XENON, CoGeNT, +)
  - Do not exploit a specific signature of the signal
  - Rely on reduction/interpretation of background

- Annual modulation experiments (DAMA)
  - Exploit a specific signature
  - Required to be highly stable over long periods

DAMA annual modulation

Effect at 8.9 σ C.L.

Single-hit events in the signal energy-window
Stability parameters do not modulate

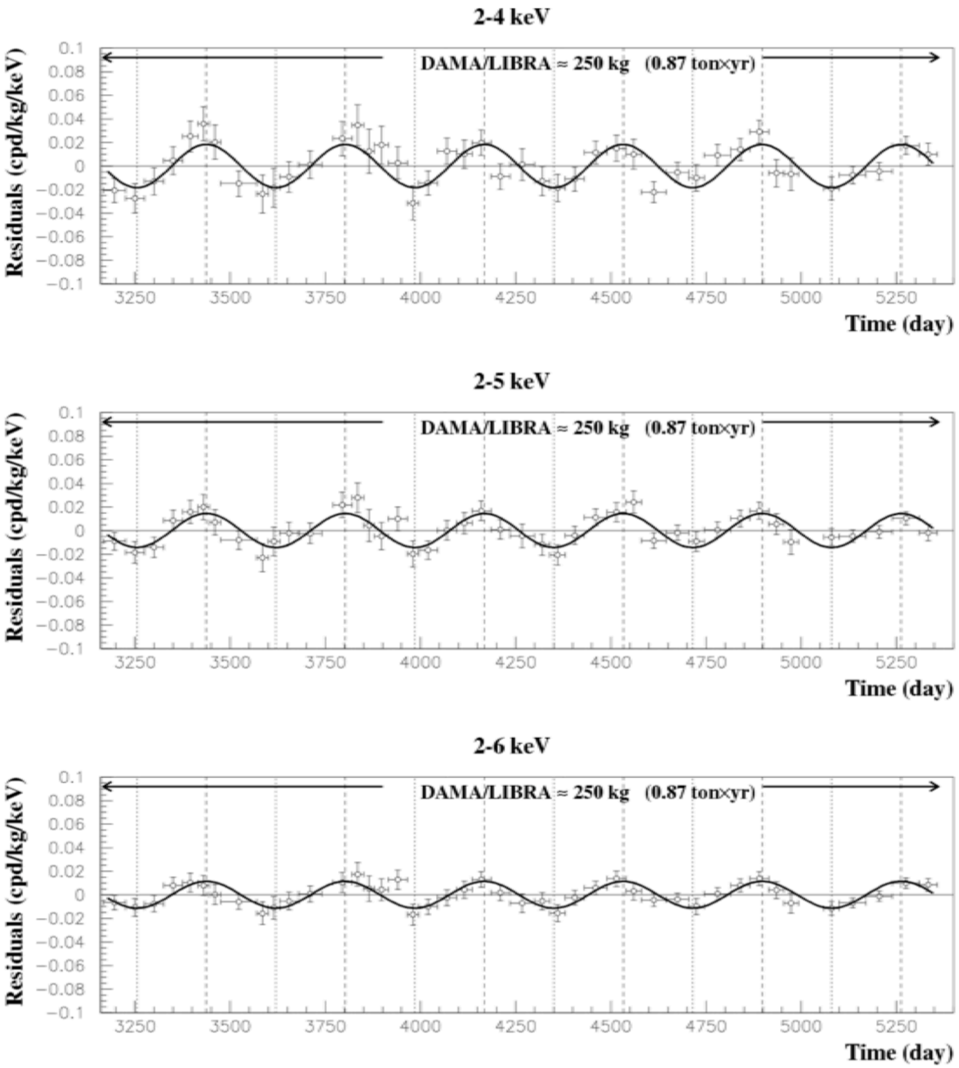
Compatible to DM scatter
- off nuclei
- on electrons

Cumulative exposure: 1.17 ton x yr (13 annual cycles)
(i.e. 427050 Kg x day)

S_m[2-6 KeV] = (0.0116 ± 0.0013) cpd/kg/keV

Phase = (146 ± 7) days

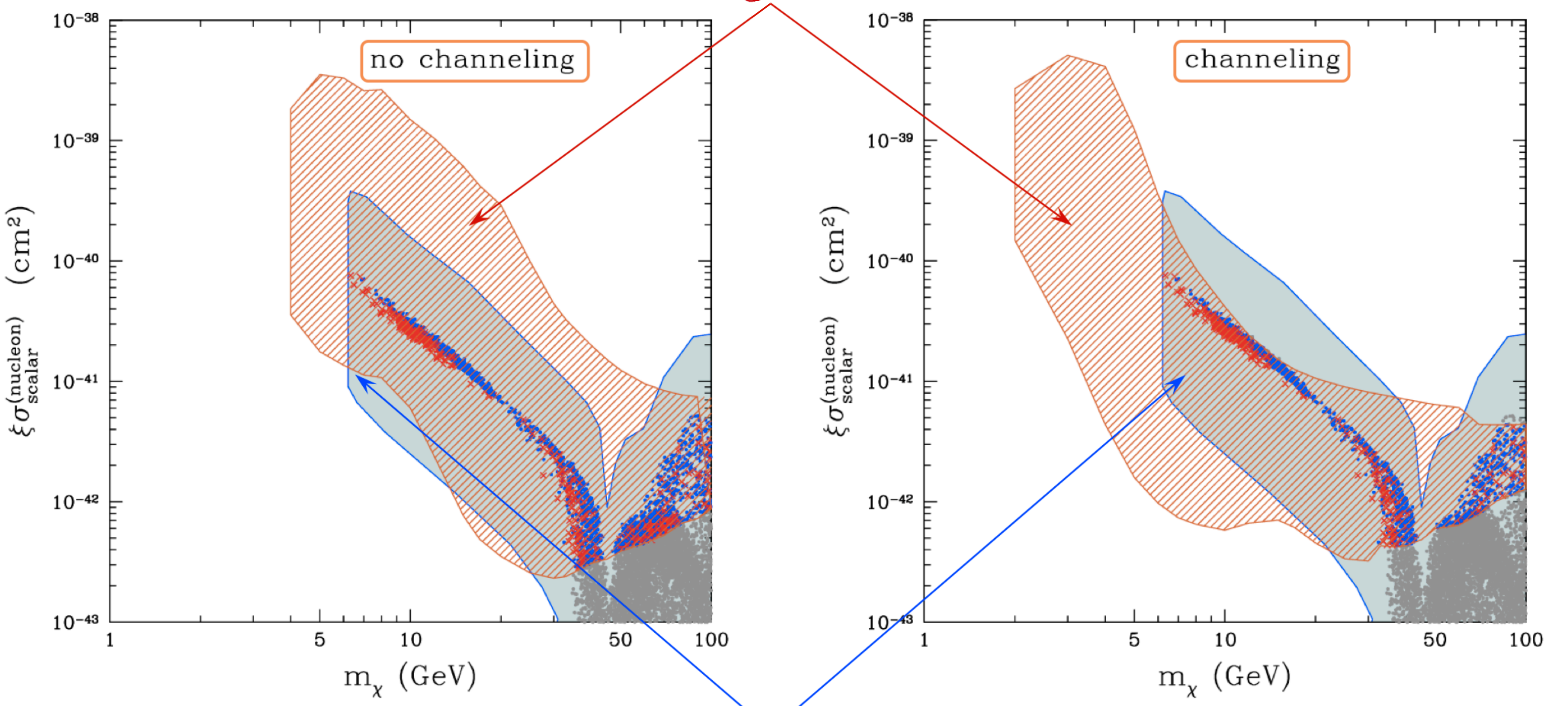
Period = (0.999 ± 0.002) years



R. Bernabei et al. (DAMA Collab.), arXiv:1002.1028 [astro-ph.GA]

DAMA annual modulation region

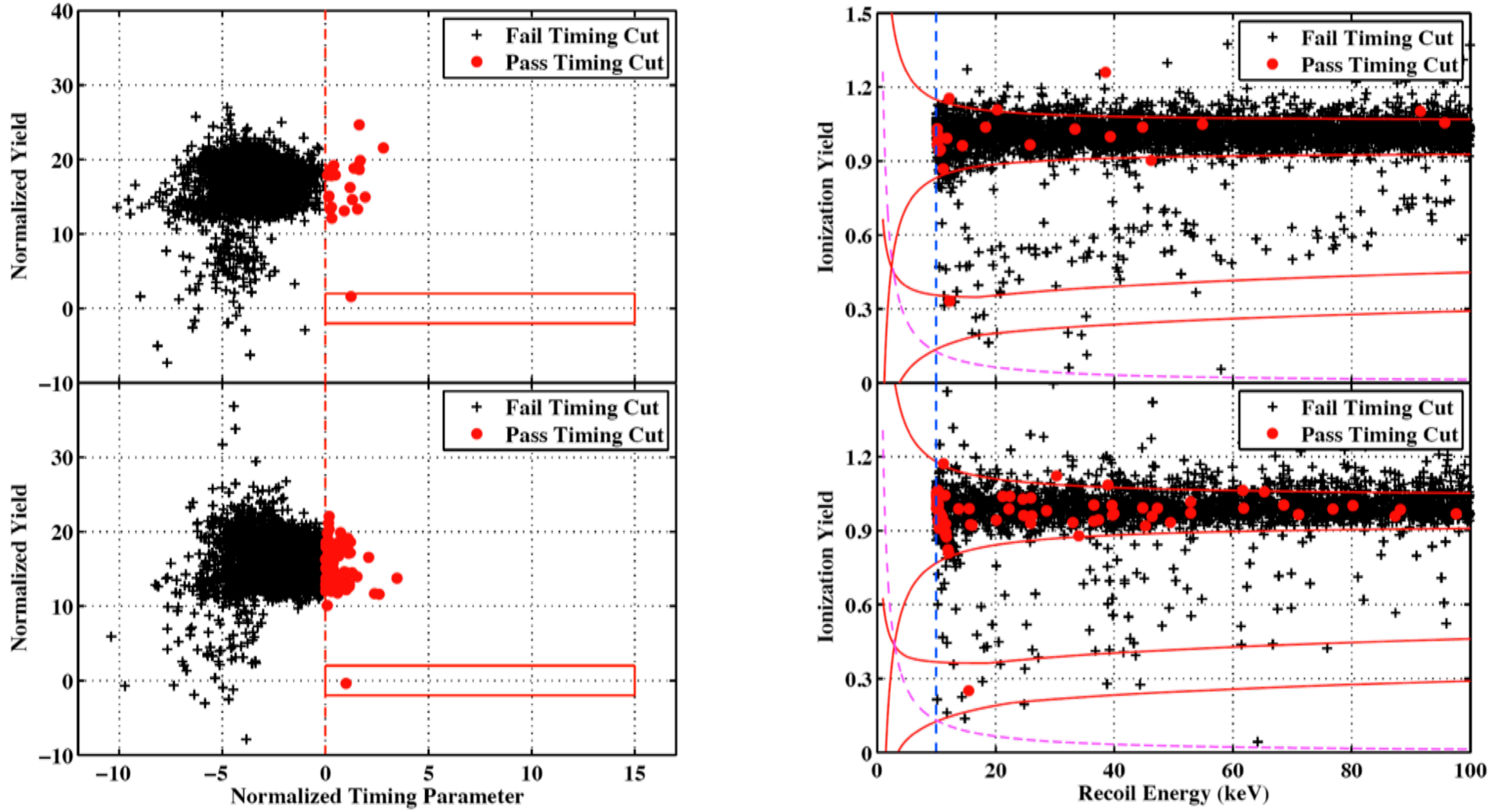
DAMA/LIBRA allowed region
(convolution over galactic halo models)



Neutralino DM: MSSM + gaugino non universal models
(shade includes hadronic uncertainites)

A. Bottino, F. Donato, N. Fornengo, S. Scopel, PRD 78 (2008) 083520

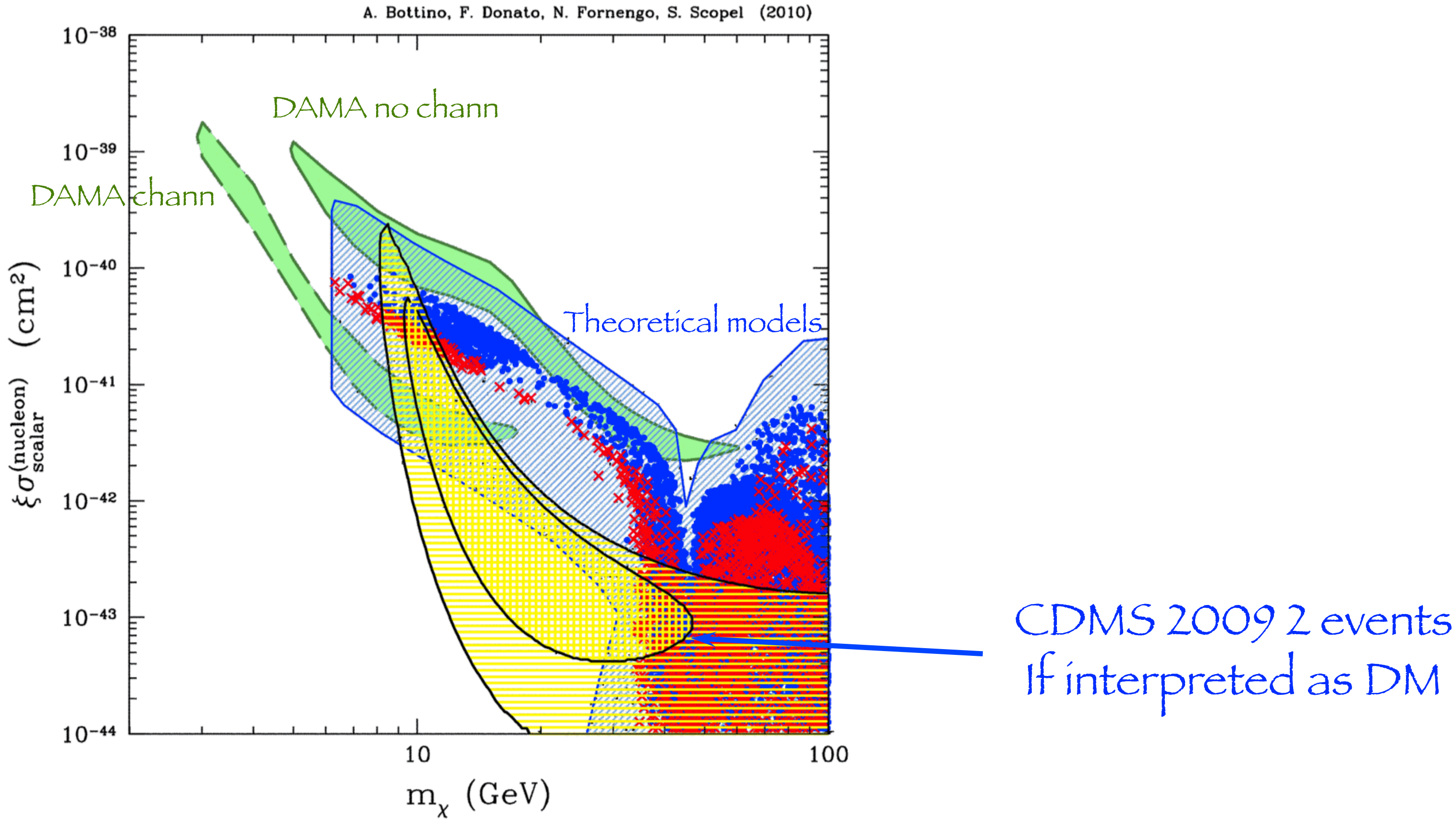
CDMS II – Final exposure (2009) – 2 events pass cuts



Cumulative exposure: 612 kg x day

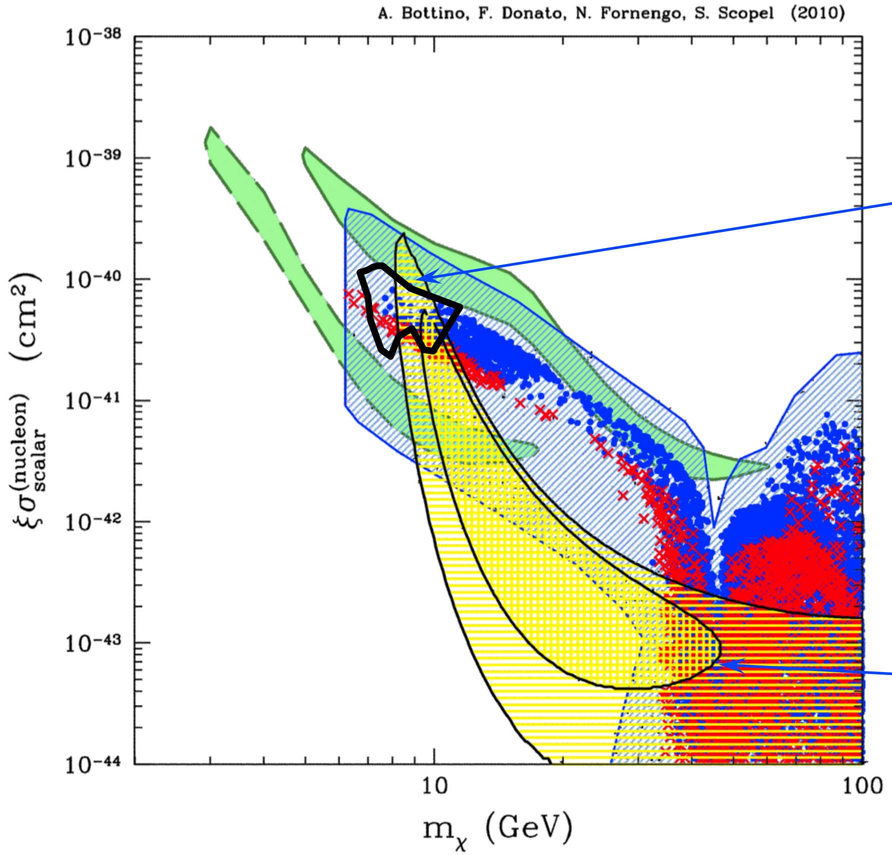
Z. Ahmed (CDMS Collab.), arXiv:0912.3592 [astro-ph.CO]

CDMS 2009



A. Bottino, F. Donato, N. Fornengo, S. Scopel, PRD 81 (2010) 107302

CoGeNT



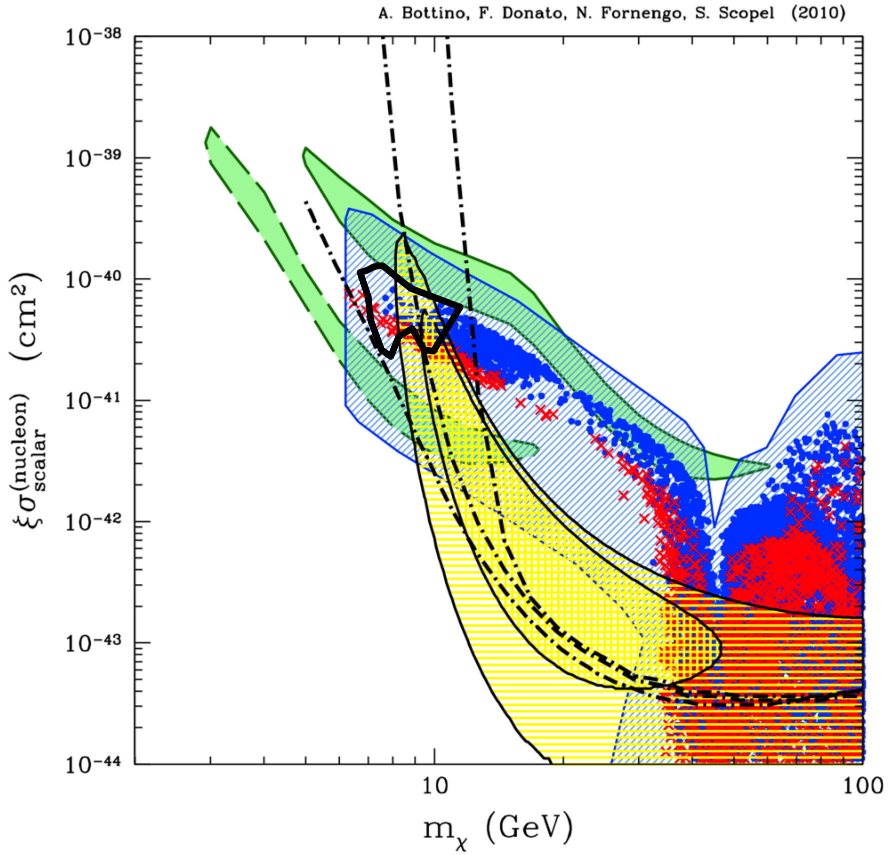
CoGeNT 2010: irreducible excess of bulk-like events below 3 KeV

Aalseth et al (CoGeNT), arXiv:1002.4703 [astro-ph.CO]

Cumulative exposure: 18.48 kg x day

CDMS 2009 2 events
If interpreted as DM

XENON 100

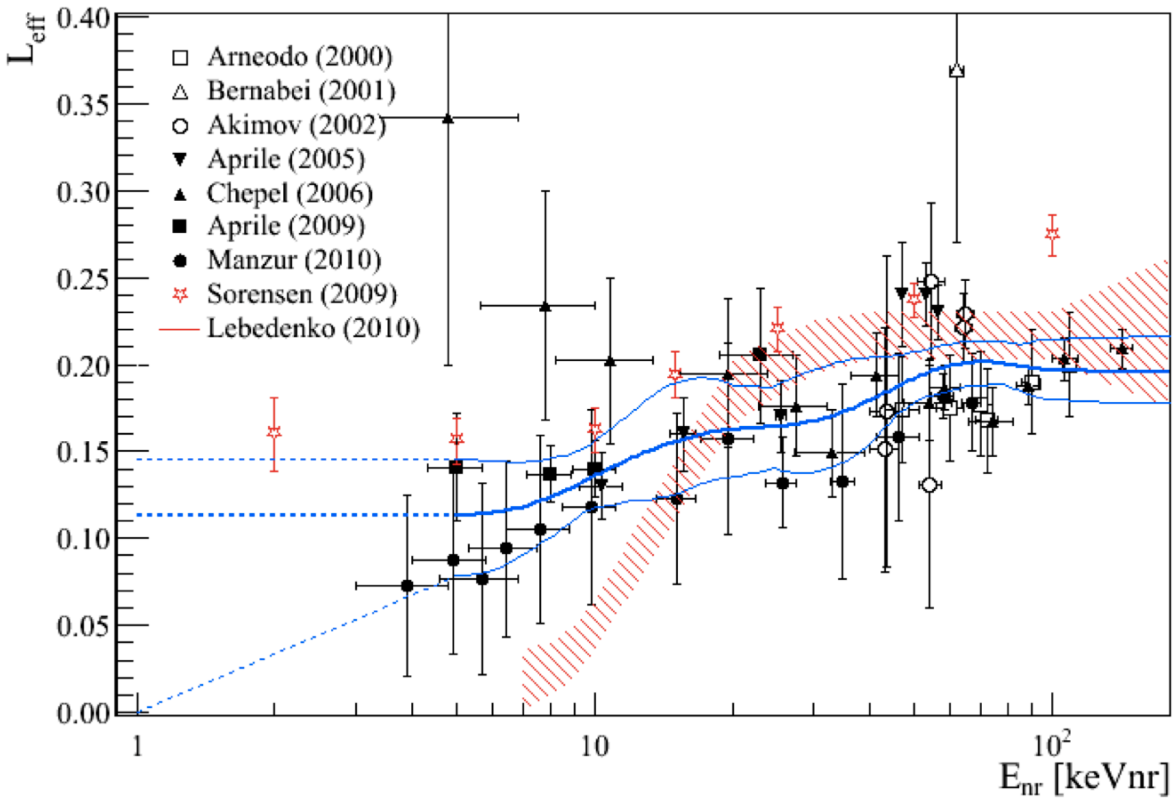


No event pass all cuts

Current cumulative exposure: 170 kg x day

XENON100 Collaboration, arXiv:1005.0380v2 [astro-ph.CO]
XENON100 Collaboratio, arXiv:1005.2615v1 [astro-ph.CO]
E. Aprile, WONDER Workshop, LNGS, March 2010

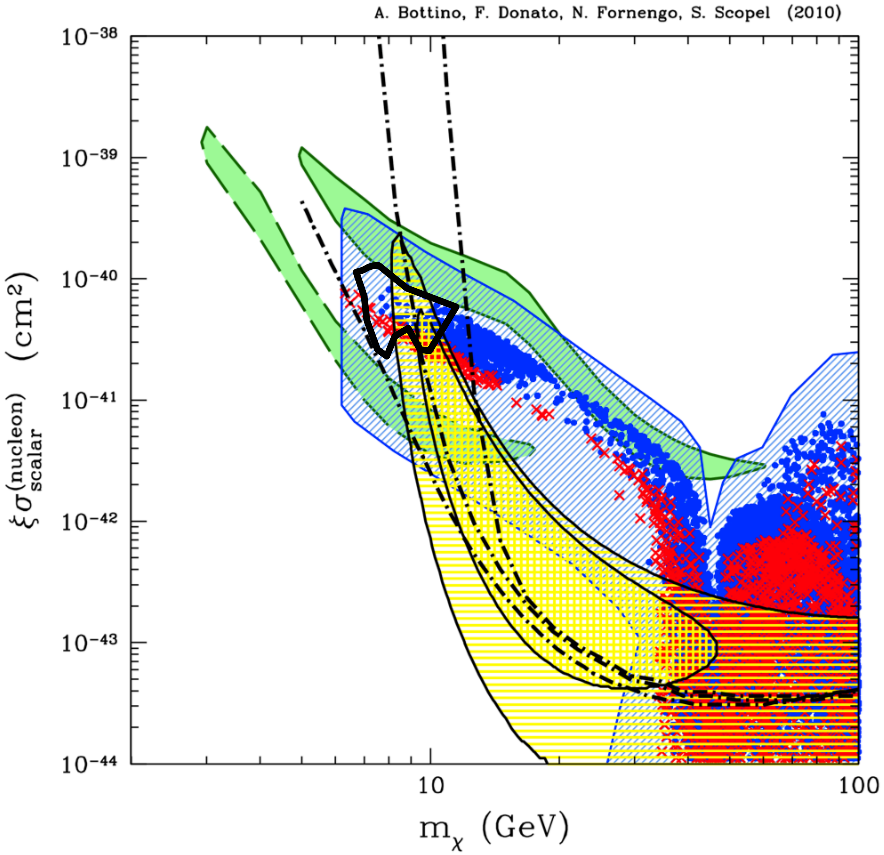
Xenon detector: scintillation efficiency



$$E_R \sim \frac{1}{L_{\rm eff}}$$

XENON100 Collaboration, arXiv:1005.2615v1 [astro-ph.CO]

XENON 100



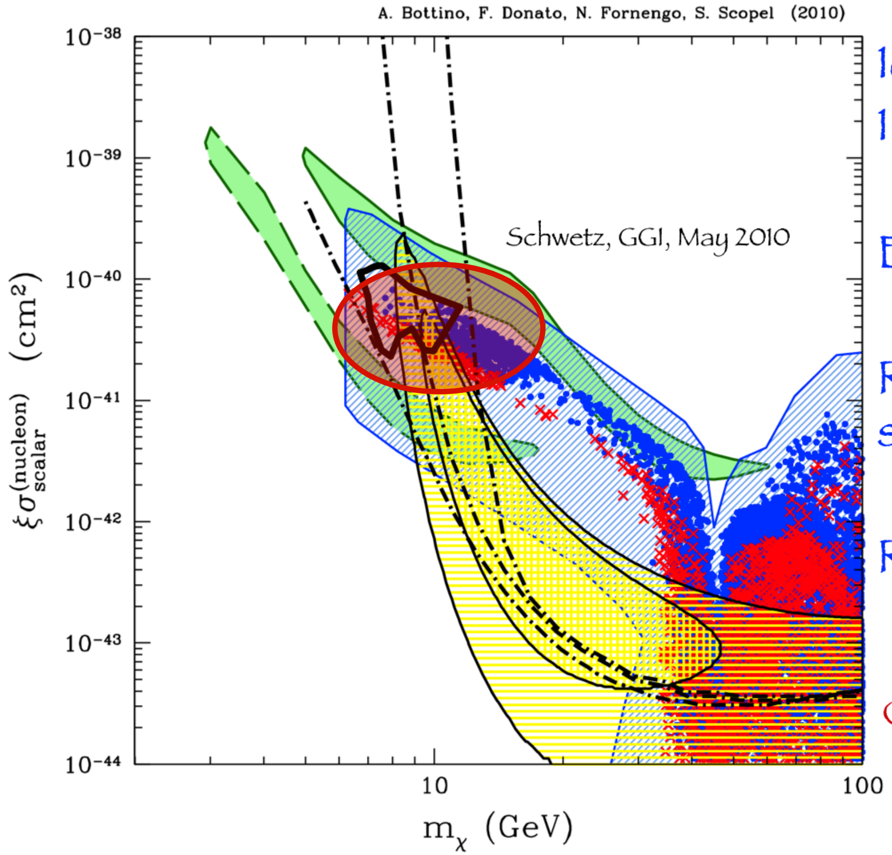
No event pass all cuts

See also:
Savage, Gelmini, Gondolo, Freese, arXiv:1006.0972 [astro-ph.CO]
Collar, arXiv:1006.2031 [astro.ph-CO]
Hooper, Collar, Hall, McKinsey, arXiv:1007.1005 [hep-ph]
Sorensen, arXiv:1007.3549 [astro-ph.IM]

Current cumulative exposure: 170 kg x day

XENON100 Collaboration, arXiv:1005.0380v2 [astro-ph.CO]
XENON100 Collaboratio, arXiv:1005.2615v1 [astro-ph.CO]
E. Aprile, WONDER Workshop, LNGS, March 2010

CRESST – Unpublished



16 single scatters in O recoil band

1 event in W recoil band

Evenly distributed in all detectors

Rate different in summer/winter (not statistically significant)

Rate too high for external neutrons

Current cumulative exposure: 333 kg x day

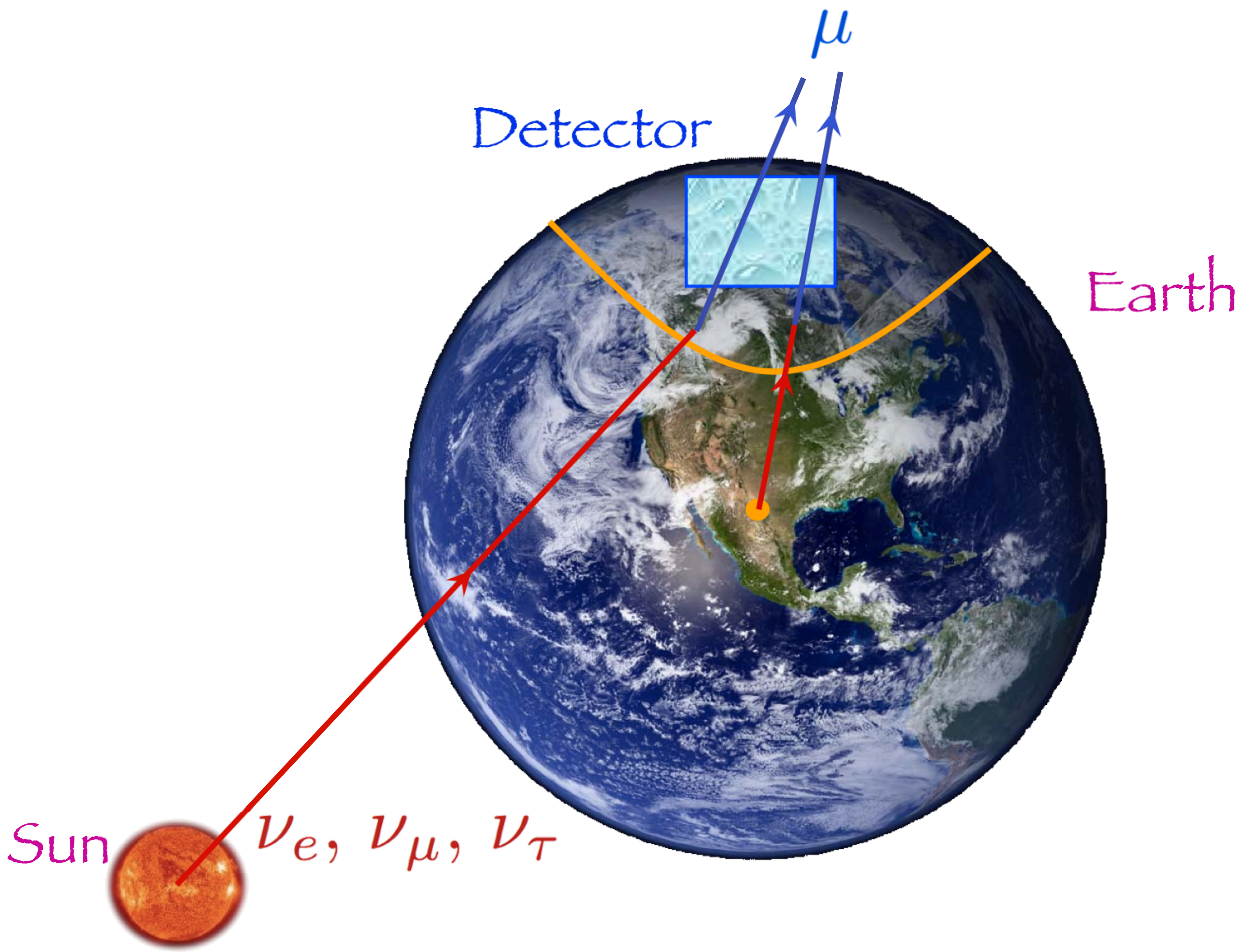
Seidel, CRESST Collaboration, WONDER Workshop, LNGS , March 2010
Jochum, GGI, May 2010

Searches at Neutrino Telescopes

Neutrinos from Earth and Sun

- Capture:
  - galactic DM particles that cross the Earth and the Sun, can interact with the nuclei in these bodies and loose enough energy to remain gravitationally captured
- Accumulation:
  - after subsequent interactions they tend to drop into the innermost parts of the Earth and the Sun, where they accumulate
- Annihilation:
  - when the energy density in the inner parts of the Earth and the Sun increases enough, they may start to annihilate

neutrino flux


μ
Detector
Earth
Sun
ν_e, ν_μ, ν_τ

Capture Rate

- Elastic scattering of the DM particle with a nucleus *i* in a spherical shell at a distance *r* from the center of the Earth (or Sun)

- In order to be captured, the velocity of the DM particle after the interaction must be smaller than the escape velocity at the shell

$$v_{\rm esc}^{\rm Sun} = 618 \text{ Km s}^{-1}$$
$$v_{\rm esc}^{\rm Earth} = 11.2 \text{ Km s}^{-1}$$

at the surface

$$\langle v \rangle \sim 300 \text{ Km s}^{-1}$$

mean DM particle velocity

Capture Rate

$$C = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \left[\sigma_i \frac{\rho_\chi}{m_\chi} \bar{v}\right] \left[\frac{M_i}{m_i}\right] \left[\frac{3v_{esc}^2}{2\bar{v}^2} \langle\phi\rangle_i\right] \xi(\infty) S_i$$

interaction rate of a flux of DM particle with a nucleus in free space

number of nuclei of type *i* in the body

"focusing factor" which determines the maximum capture rate of the body

suppression factor due to the motion of the body (~0.75)

suppression factor due to kinematics (mainly mass mismatch)

M_i Total mass in terms of element *i*

$\langle\phi\rangle_i$ Gravitational potential averaged over the mass distribution of element *i*

Capture Rate

$$C = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \left[\sigma_i \frac{\rho_\chi}{m_\chi} \bar{v}\right] \left[\frac{M_i}{m_i}\right] \left[\frac{3 v_{esc}^2}{2\bar{v}^2} \langle\phi\rangle_i\right] \xi(\infty) S_i$$

Sun

Nuc	H	He	O	C	Ne	Fe	N	Si	Mg
f	0.77	0.21	8.10^{-3}	4.10^{-3}	1.10^{-3}	1.10^{-3}	9.10^{-4}	8.10^{-4}	7.10^{-4}
A	1	4	16	12	20	56	14	28	24

nuclei of type *i* in the body

Earth

	core			mantle					
Nuc	Fe	Si	Ni	O	Si	Mg	Fe	Ca	Al
f	0.24	0.05	0.03	0.30	0.15	0.14	0.06	0.02	0.01
A	56	32	59	16	28	24	56	40	27

DM-nucleus cross section

DM density

DM velocity dispersion

$$C = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \left[\frac{\sigma_i \rho_\chi \bar{v}}{m_\chi}\right] \left[\frac{M_i}{m_i}\right] \left[\frac{3v_{esc}^2}{2\bar{v}^2}\langle\phi\rangle_i\right] \xi(\infty) S_i$$

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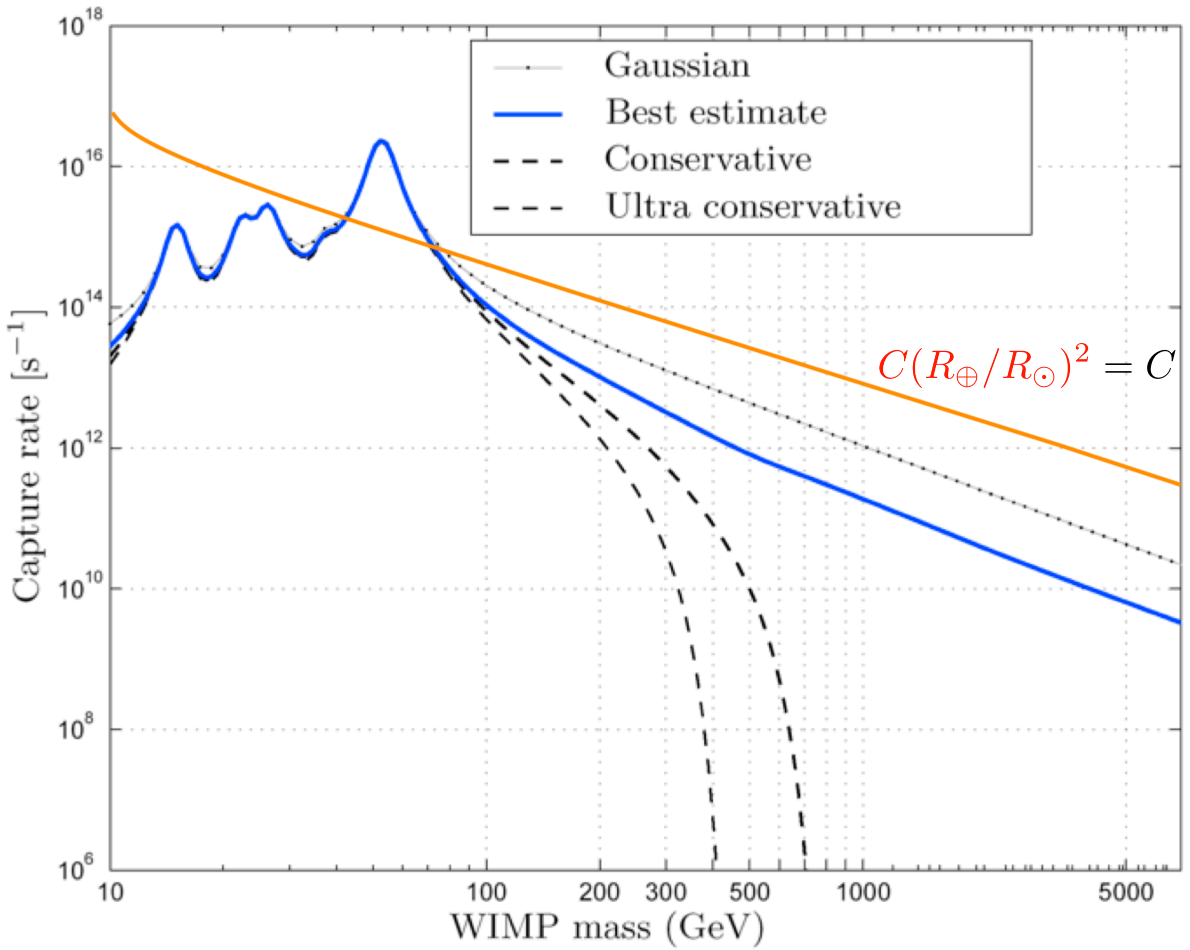
Capture rate on ~~Earth~~ Sun



$$C(R_\oplus/R_\odot)^2 = C \times 1.8 \cdot 10^{-9}\ [s^{-1}]$$

J. Lundberg, J. Edsjo, astro-ph/040111

Accumulation and concentration

- DM particles which have been captured inside Earth or Sun can suffer subsequent scatterings
- This may lead to:
  - Concentration in the innermost parts of the Earth or Sun
  - Development of an equilibrium distribution of these particles

distribution $n(r) = n_0 \mathrm{e}^{-\alpha_B m_\chi r^2}$

n_0 central density

$\alpha_B = 2\pi G \rho_0 / (3T_0)$

Annihilation rate

$$\boxed{\Gamma_A = \frac{C}{2}\tanh^2\left(\frac{t_0}{\tau_A}\right)}$$

Capture rate C

Age of the body $\tau_0 = 4.6 \text{ Gyr}$

Relaxation time $\tau_A = [CC_A]^{-1/2}$

$$C_A = \langle\sigma_{\rm ann} v\rangle_0 V_2/V_1^2$$

$$V_j = c_B (j m_\chi/10 \text{ GeV})^{-3/2} \text{ cm}^3$$

Effective volumes of DM concentrations
More concentrated for larger masses

$$c_B = 1.8\cdot 10^{25} \;/\; 6.6\cdot 10^{28}$$

Earth Sun

Neutrino Production

- Neutrinos are produced by DM annihilation
  - Available channels depend on mass threshold

$$\chi\chi \to \nu\nu,\ l\bar{l},\ q\bar{q},\ W^+W^-,\ ZZ,\ \mathrm{Higgses},\ \mathrm{Higgs} + \mathrm{gauge}$$

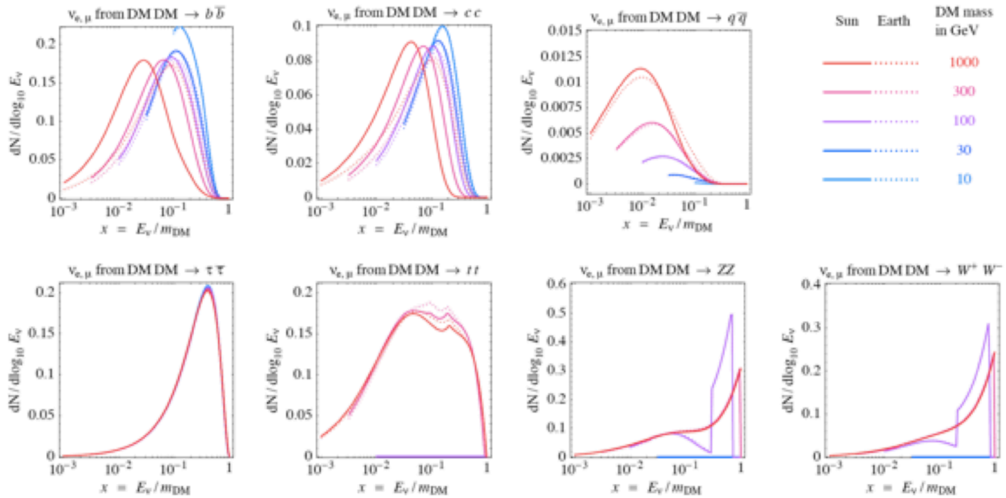
  - Quark hadronize → neutrinos from hadron decay

- Productions in Earth
  - Muons: stopped before decay → neutrinos below typical thresholds
  - Taus: decay almost as in vacuum
  - Light hadrons: typically stopped before decay
  - Heavy hadrons: typically decay before loosing significant energy

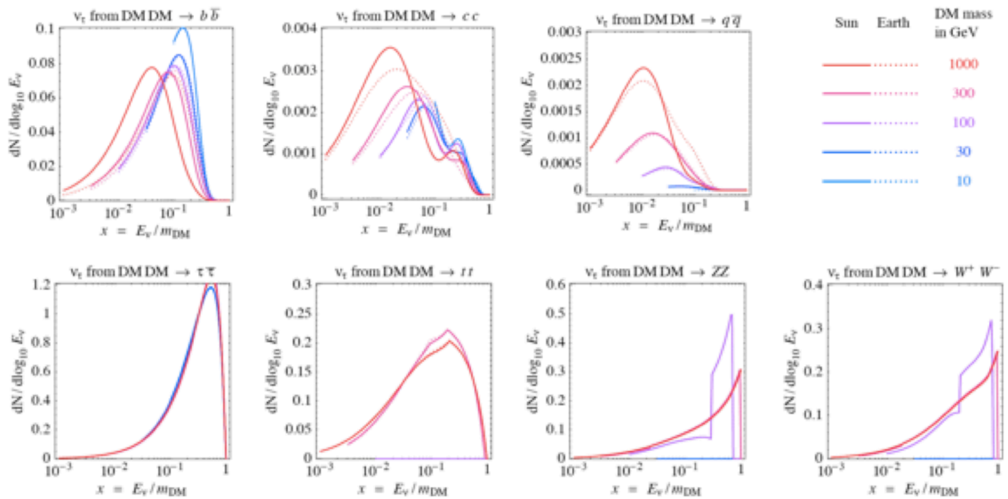
- Production in Sun
  - Leptons: stopping power of medium is stronger → softer neutrino spectra
  - Light hadrons: typically stopped before decay
  - Heavy hadrons: energy losses important, need modeling

Spectra at production

ν_e, ν_μ



ν_τ



M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

Neutrino Propagation

Density matrix evolution

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm NC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm in}$$

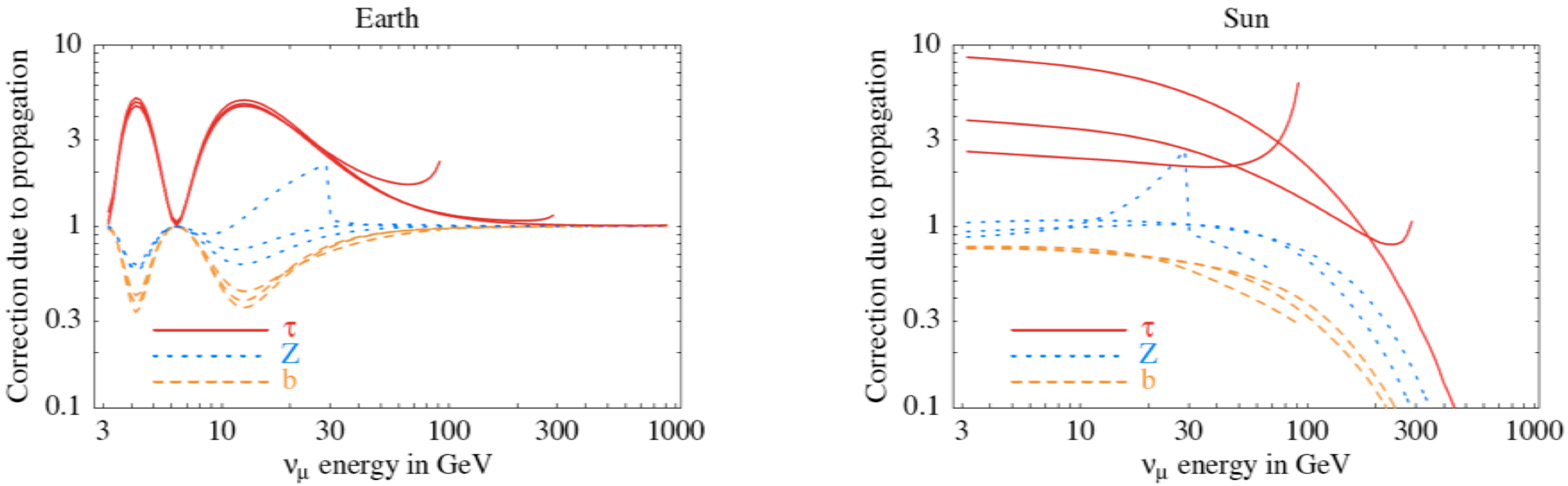
Vacuum oscillation
MSW matter effect

source

CC interactions
(absorption and ν_τ regeneration)

NC scatterings
(absorption and re-injection)

Effect of propagation



Earth:

– Affected only by "atmospheric" oscillation $\nu_\mu \leftrightarrow \nu_\tau$ at $E < 100$ GeV

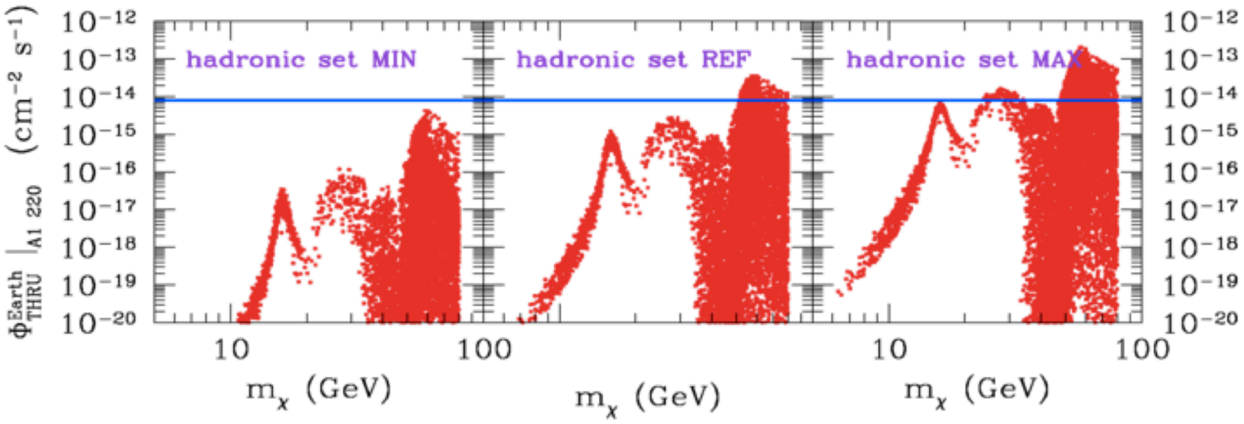
Sun:

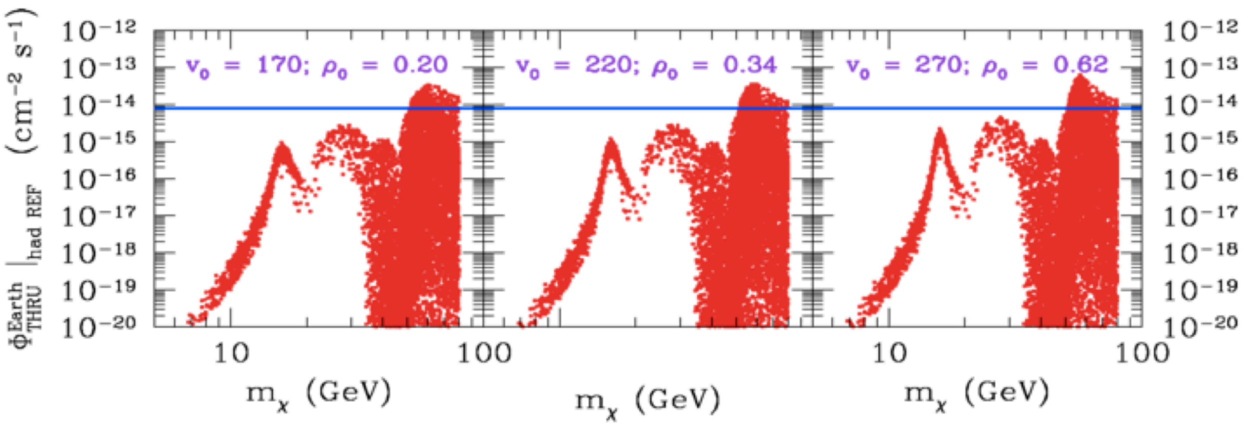
– Affected by average "solar" and "atmospheric" oscillations
– Absorption suppresses neutrinos for $E > 100$ GeV (partially converted to lower energy neutrinos (by NC and regeneration)

M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

See also: M. Blennow, J. Edsjo, T. Ohlsson, JCAP 0801 (2008) 021 for an event-based MC approach

Earth signal: through-going muons

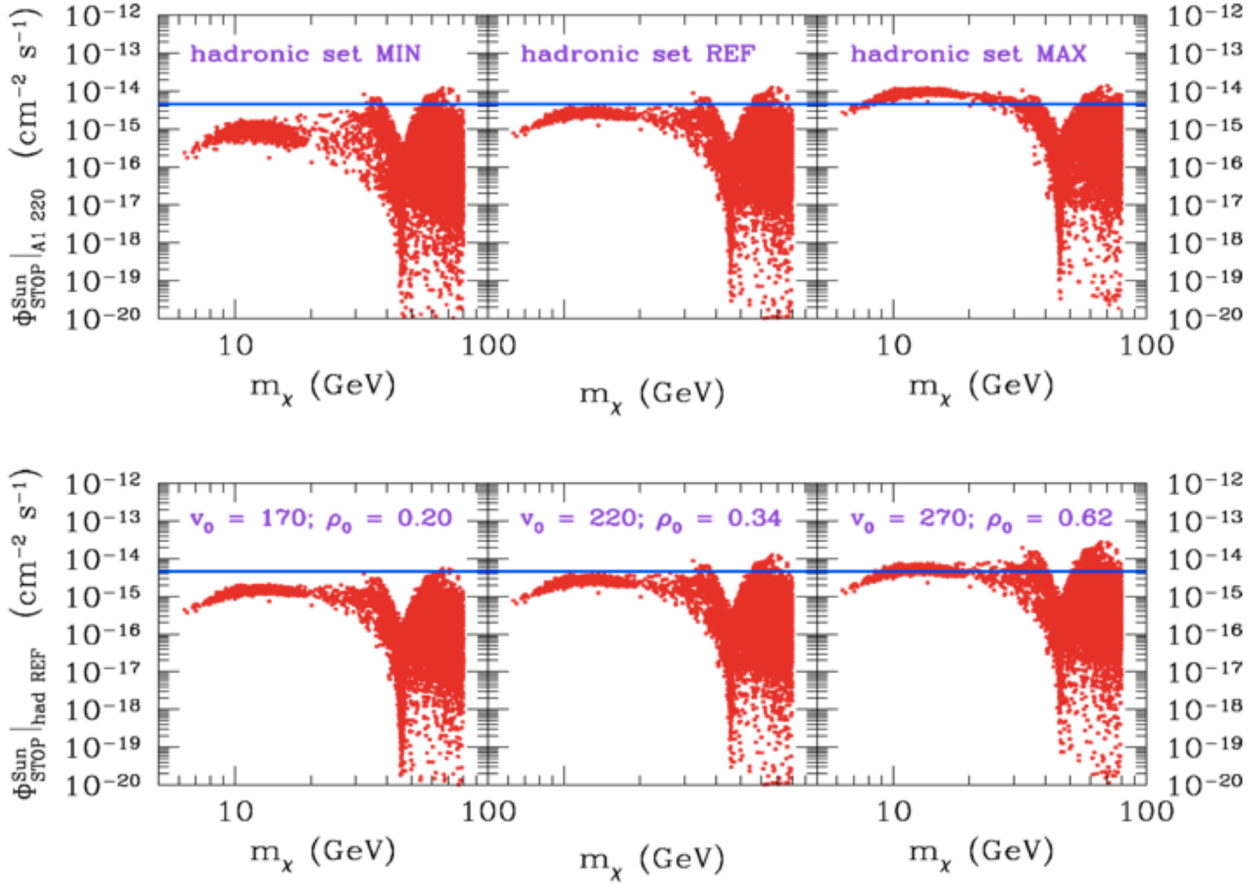




Neutralino DM in Gaugino non-universal MSSM

V. Niro, A. Bottino, N.Fornengo, S. Scopel, arXiv:0909.2348

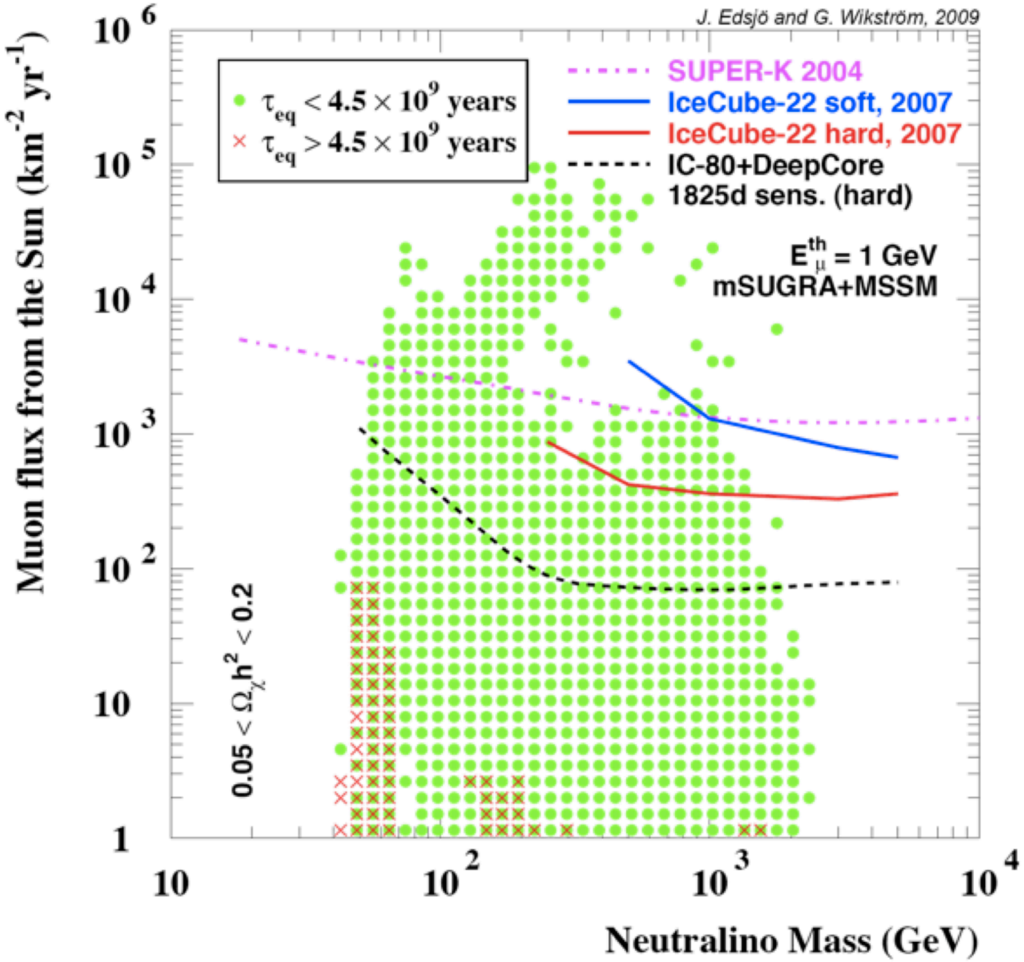
Sun signal: stopping muons



Neutralino DM in Gaugino non-universal MSSM

V. Niro, A. Bottino, N.Fornengo, S. Scopel, arXiv:0909.2348

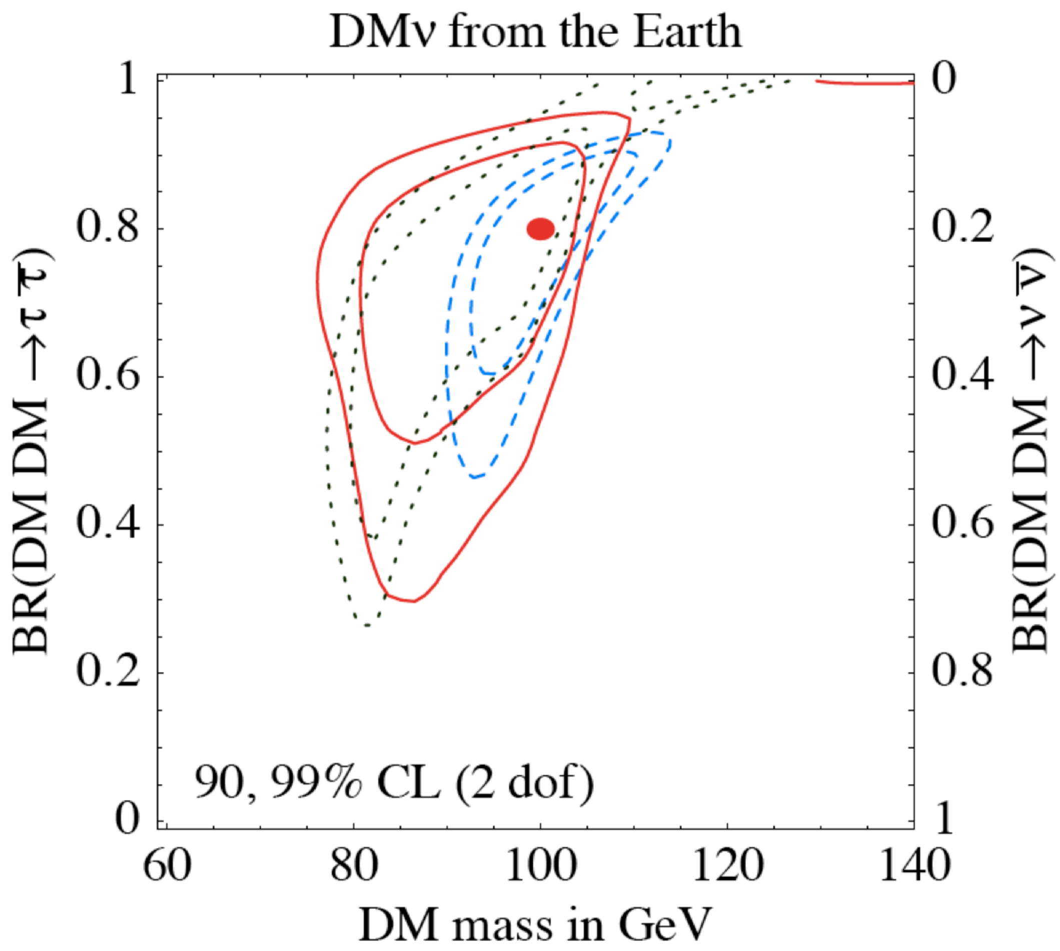
Sun signal: muons above 1 GeV



G. Wilkstrom, J. Edsjo, arXiv:0903.2986

Reconstruction of the DM properties

solid: 100 fully contained muons
dashed: 1000 thru-going muons
dotted: 200 shower events in ΔE ≈ 30 GeV



M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

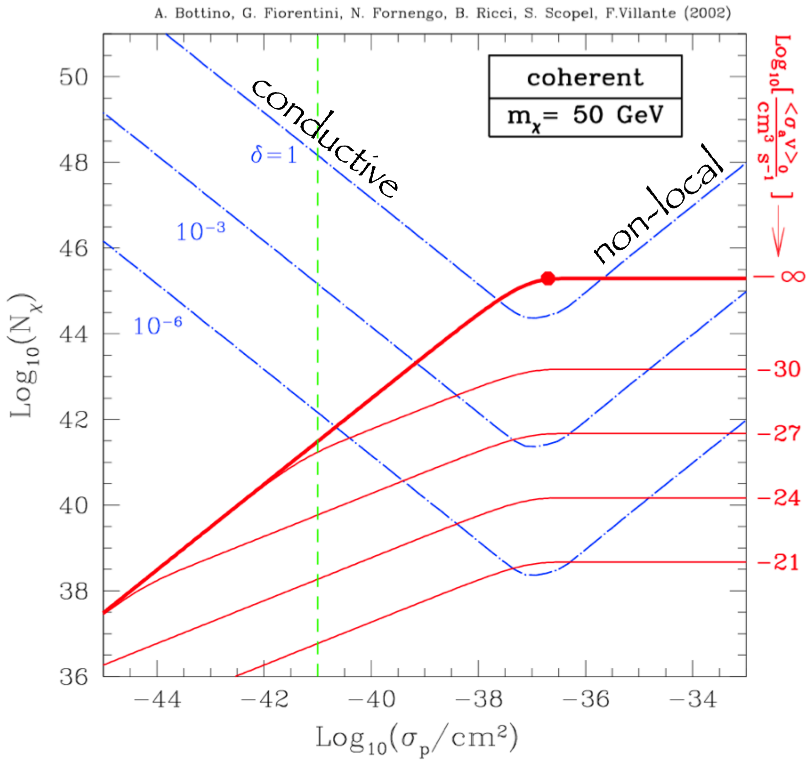
Any effect of trapped DM on Sun's properties?

- WIMPs are confined in the central region of the Sun

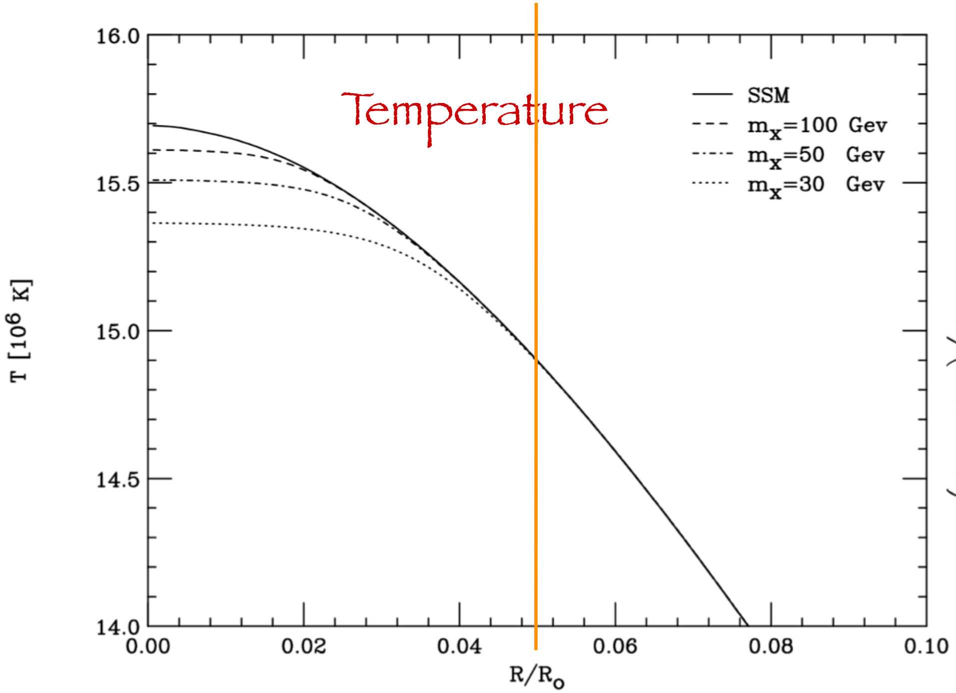
$$R_\chi \simeq 0.01\,(100\,\mathrm{GeV}/m_\chi)^{1/2}\,R_\odot$$

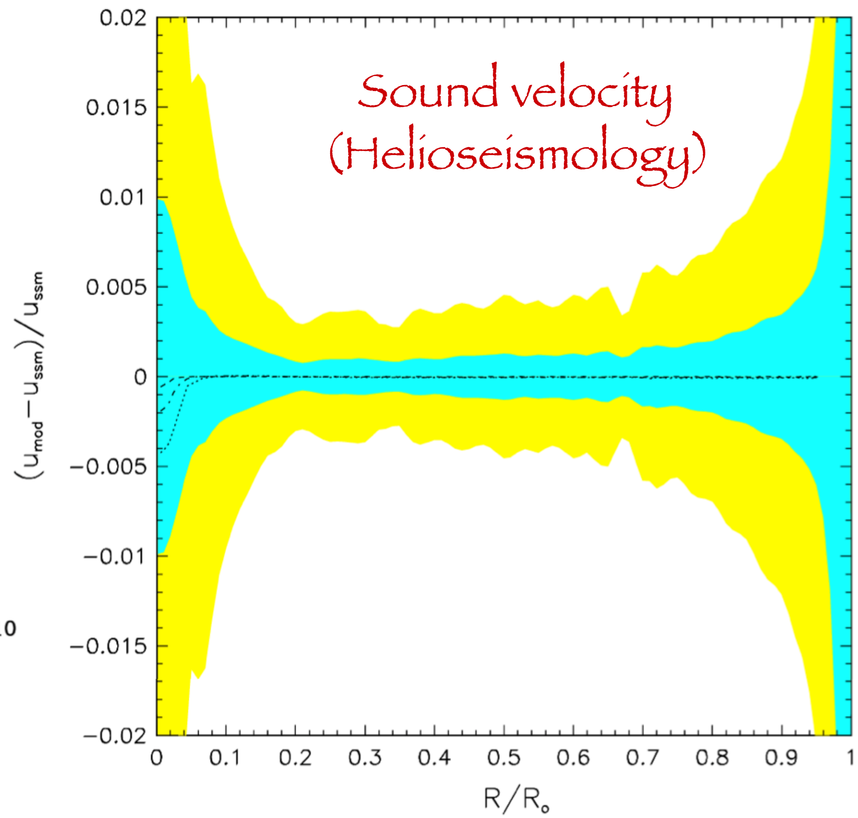
- They provide a mechanism for energy transport

$$\delta = \lim_{r\to 0} \frac{L_\chi(r)}{L(r)}$$



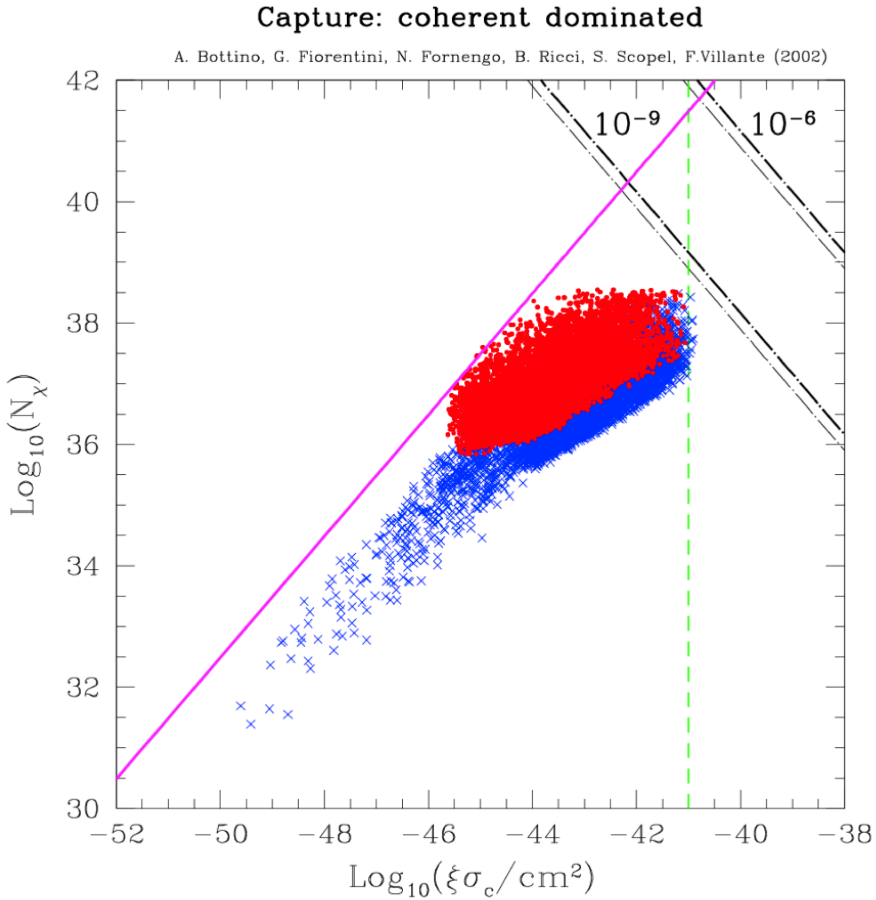
Maximal effects





m_χ (GeV)	$\delta T_c/T_c$	$\delta u_c/u_c$	$\delta\Phi_B/\Phi_B$
30	-2.1×10^{-2}	-4×10^{-3}	-4.5×10^{-2}
50	-1.2×10^{-2}	-2×10^{-3}	-1.3×10^{-2}
100	-5.2×10^{-3}	-6×10^{-4}	-2.1×10^{-3}

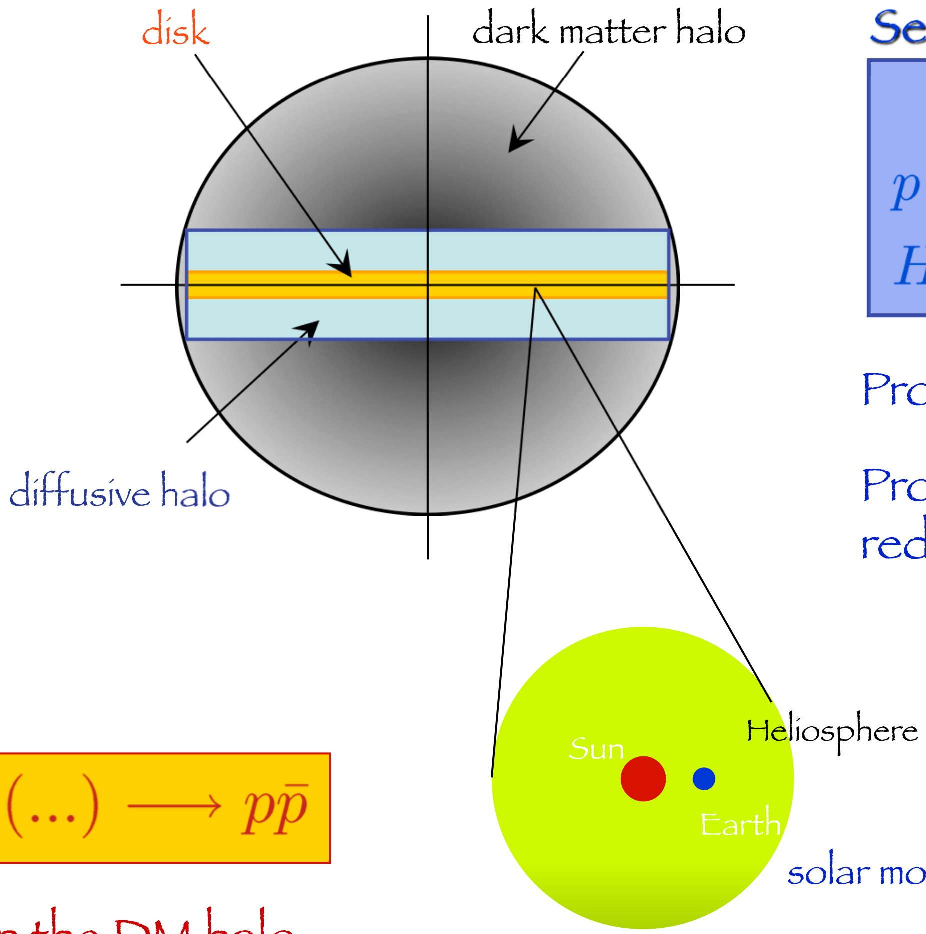
Neutralino DM in the MSSM



Antimatter in Cosmic Rays

Antiprotons

Antiproton signal



Secondaries

$$p_{\rm CR} + p_{\rm ISM} \longrightarrow \bar{p}$$
$$p_{\rm CR} + He_{\rm ISM} \longrightarrow \bar{p}$$
$$He_{\rm CR} + p_{\rm ISM} \longrightarrow \bar{p}$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

DM signal

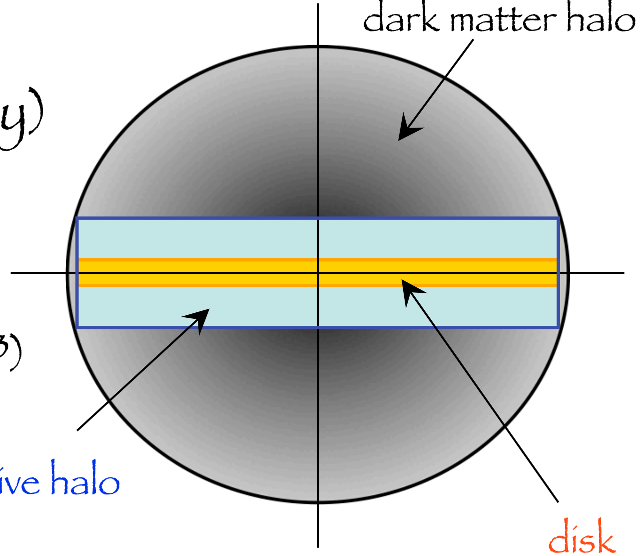
$$\chi\chi \longrightarrow (\ldots) \longrightarrow p\bar{p}$$

Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

$$q_{\bar{p}}^{\rm DM}(r, z, T_{\bar{p}}) = \langle \sigma_{\rm ann} v \rangle \, g(T_{\bar{p}}) \left(\frac{\rho_\chi(r,x)}{m_\chi} \right)^2$$

Diffusion and propagation in the Galaxy



- Two-zone diffusion model (cylindrical symmetry)
  - Thin disk
    - ✓ Radius R = 20 kpc
    - ✓ Thickness h = 100 pc
    - ✓ Surface density of IS gas: $\Sigma = 2hn_{ISM}$ ($n_{ISM} = 1\ cm^{-3}$)
  - Diffusive halo
    - ✓ Radius R
    - ✓ Height L

- Physical processes
  - Diffusion: uniform in the whole (disk + diffusive halo) volume
  - Inelastic (non-annihilating) scattering and annihilation
  - Galactic wind away from the disk in vertical direction
  - Energy losses:
    - ✓ Ionization: interaction with the neutral IS matter
    - ✓ Coulomb scattering: interaction with ionized plasma (thermal electrons)
  - Reacceleration on random hydrodynamic waves (in the disk only)

$q_{\bar{p}}^{\mathrm{DM}}(r, z, T_{\bar{p}})$ —— Propagation in the Galaxy ——→ $\Phi^{\bar{p}}(r, z, T_{\bar{p}})$

- solution of the steady-state diffusion equation with energy losses and reacceleration
- depends on a number of astrophysical parameters:
  - diffusion coefficient $K(E) = K_0 \beta (\mathcal{R}/1\,\mathrm{GV})^{\delta}$
  - height of the diffusive halo L
  - galactic wind velocity V_c
  - Alfven velocity (reacceleration) V_A

The params are constrained by stable nuclei propagation, mainly B/C

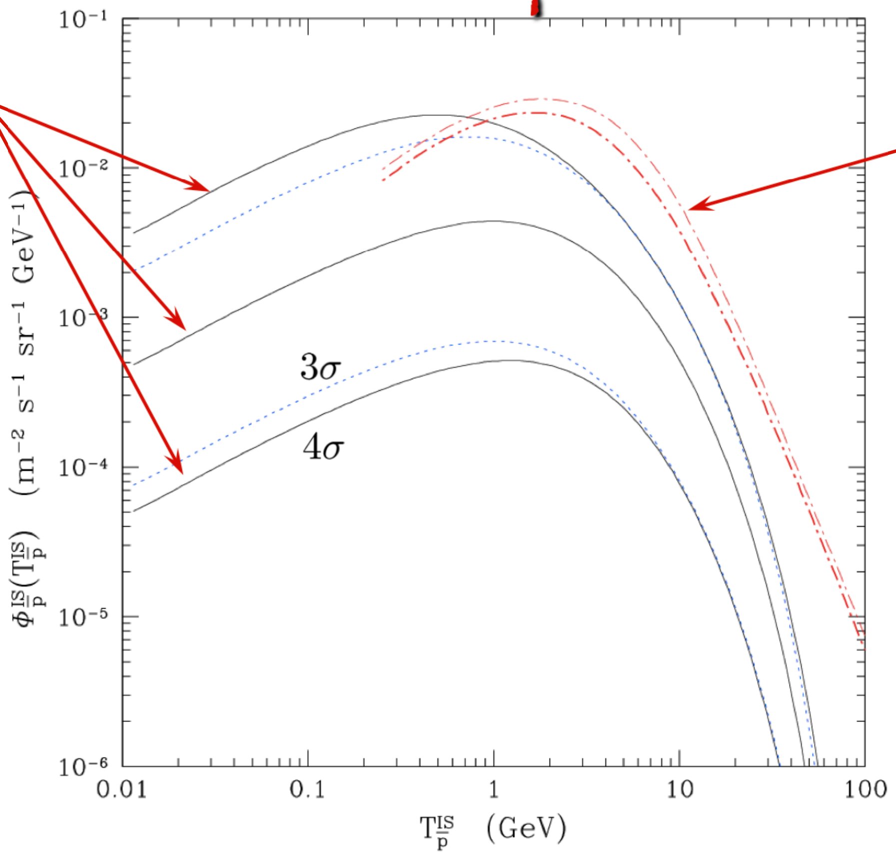
[D. Maurin et al. Astron. Astrophys. 381 (2002) 539]

case	δ	K_0 ($\mathrm{kpc}^2/\mathrm{Myr}$)	L (kpc)	V_c (km/sec)	V_A (km/sec)	$\chi^2_{\mathrm{B/C}}$
max	0.46	0.0765	15	5	117.6	39.98
med	0.70	0.0112	4	12	52.9	25.68
min	0.85	0.0016	1	13.5	22.4	39.02

Interstellar antiproton fluxes

Primaries (1)
(DM signal)

$m_\chi = 100$ GeV



Secondaries (2)
(background)

< 25% uncertainty

(1) F. Donato, N. Fornengo, D. Maurin, P. Salati, R. Taillet, PRD 69 (2004) 0603501

(2) D. Maurin et al. Astron. Astrophys. 381 (2002) 539

case	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/sec)	V_A (km/sec)	$\chi^2_{B/C}$
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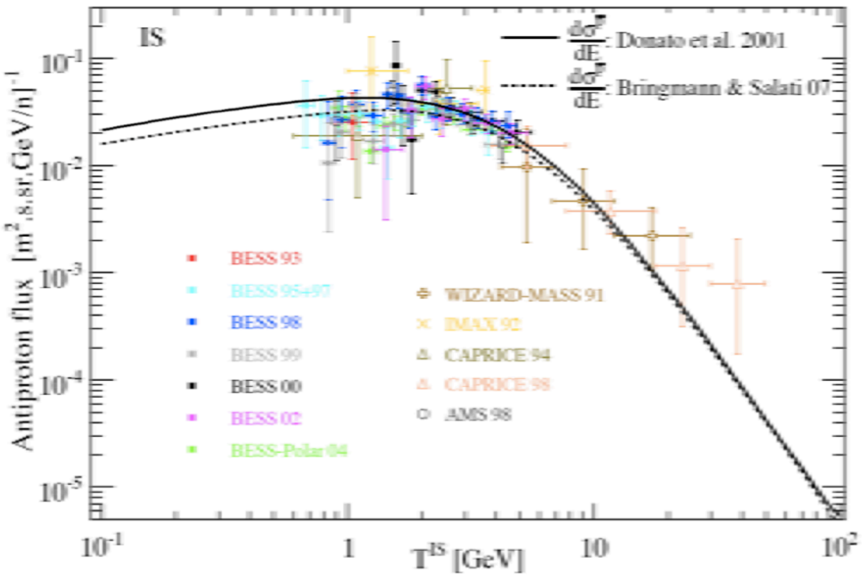
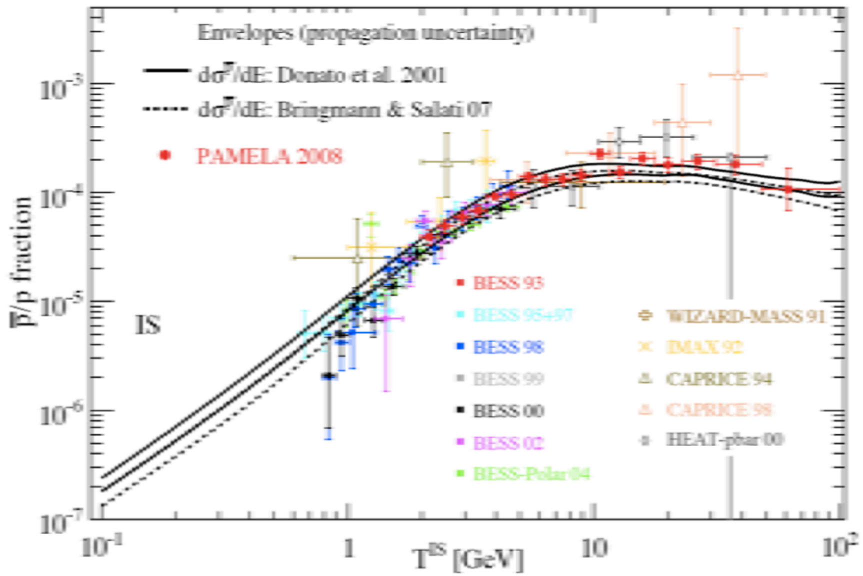
min	0.85	0.0016	1	13.5	22.4	39.02

Secondary antiprotons



Antiproton flux

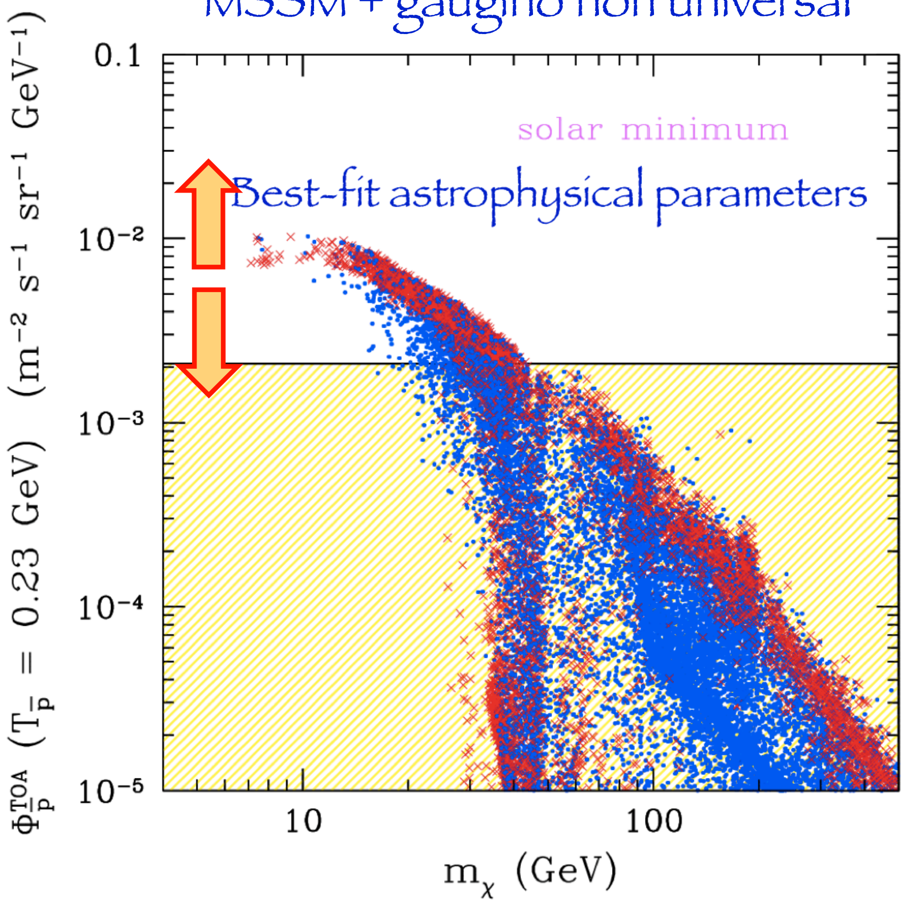


Antiproton/proton fraction

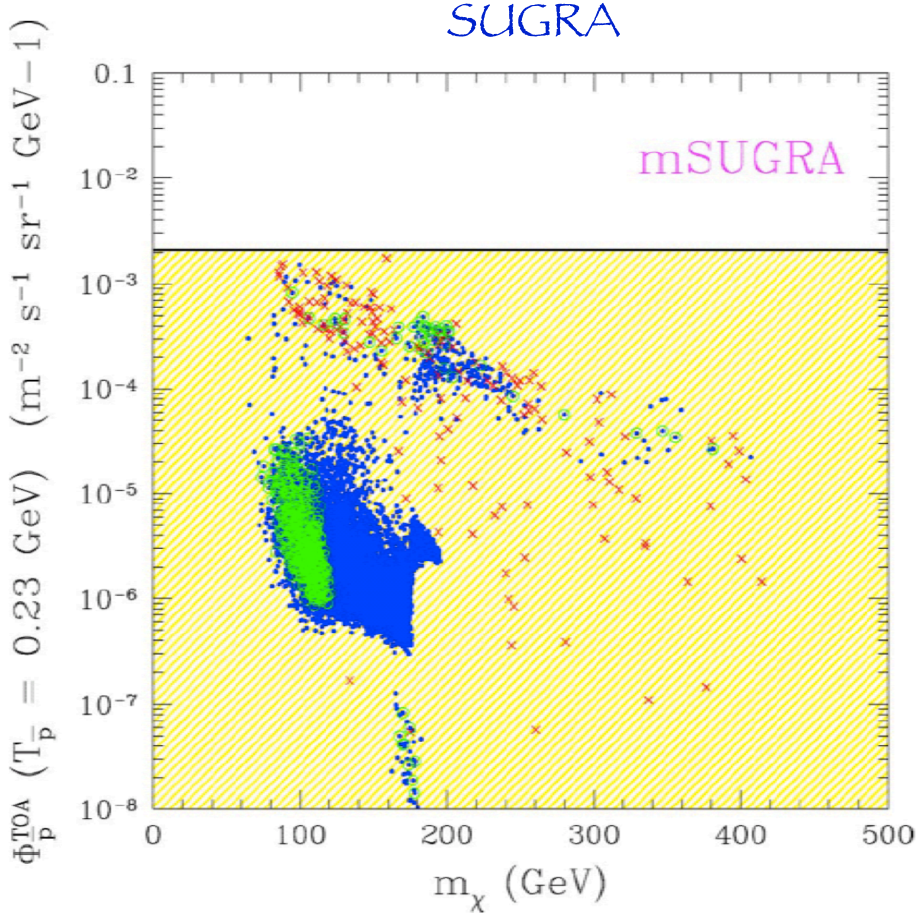
F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, arXiv.0810.5292 [astro-ph]

Theoretical predictions for neutralinos

MSSM + gaugino non universal



SUGRA

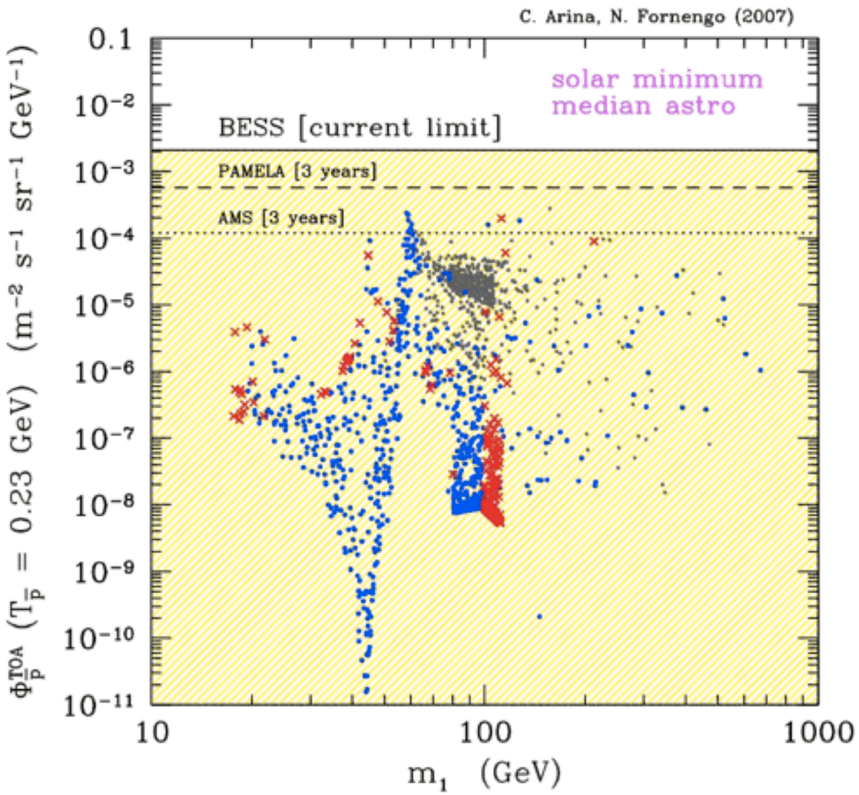


- cosmologically dominant neutralinos $0.095 \leq \Omega_\chi h^2 \leq 0.131$
- cosmologically subdominant neutralinos $\Omega_\chi h^2 < 0.095$

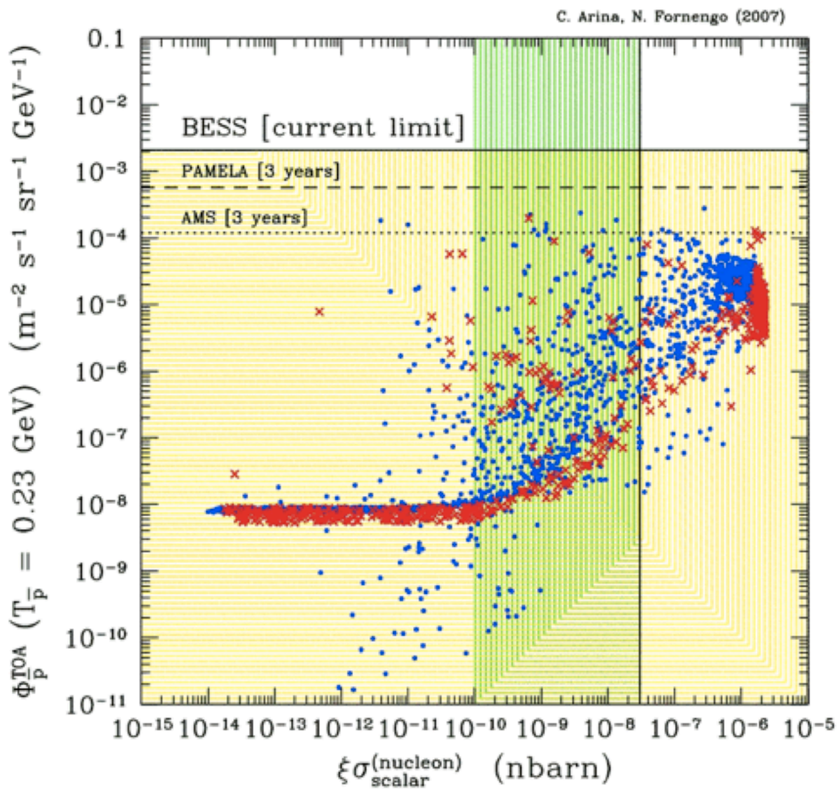
A. Bottino, F. Donato, N.F., S. Scopel, PRD 70 (2004) 015005

F. Donato, N.F., D. Maurin, P. Salati, R. Taillet, PRD 69 (2003) 063501

Sneutrinos in Left-Right models



antiprotons vs. mass



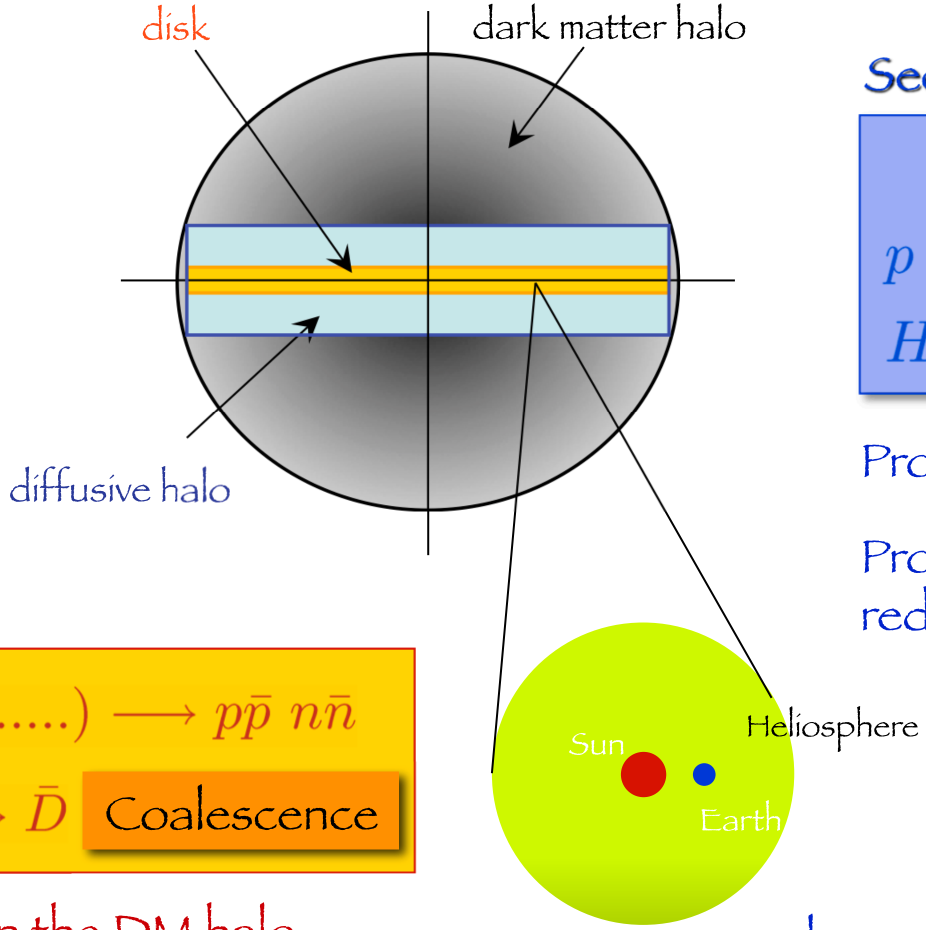
antiprotons vs. direct detection

C. Arina, N. Fornengo, JHEP 0711 (2007) 029

Antimatter in Cosmic Rays
Antideuterons

Cosmic antideuterons

F. Donato, N. Fornengo, P. Salati, PRD 62 (2000) 043003



Secondaries

$$p_{\rm CR} + p_{\rm ISM} \longrightarrow \bar{D}$$
$$p_{\rm CR} + He_{\rm ISM} \longrightarrow \bar{D}$$
$$He_{\rm CR} + p_{\rm ISM} \longrightarrow \bar{D}$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

DM signal

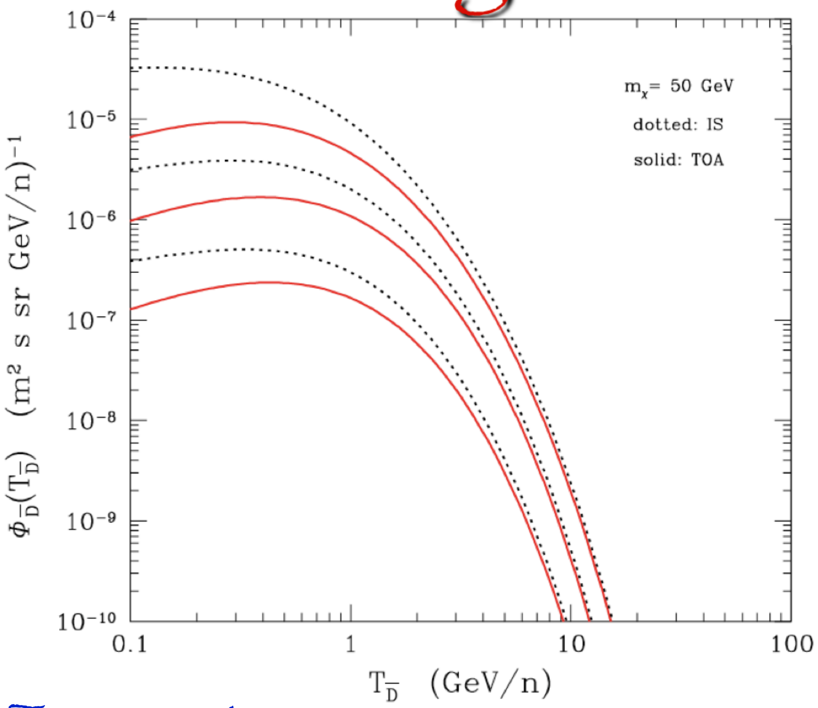
$$\chi\chi \longrightarrow (\ldots\ldots) \longrightarrow p\bar{p}\ n\bar{n}$$
$$\bar{p} + \bar{n} \longrightarrow \bar{D}$$ Coalescence

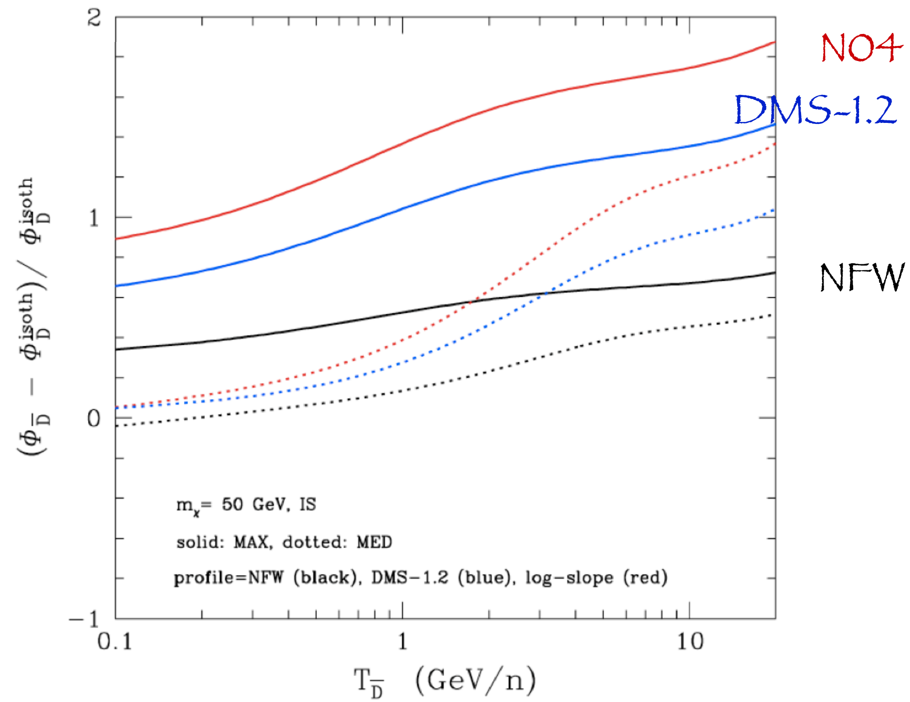
Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

solar modulation

Signal and its uncertainties





Transport:

- High-energies: diffusive halo size L
- Low-energies: L + galactic wind

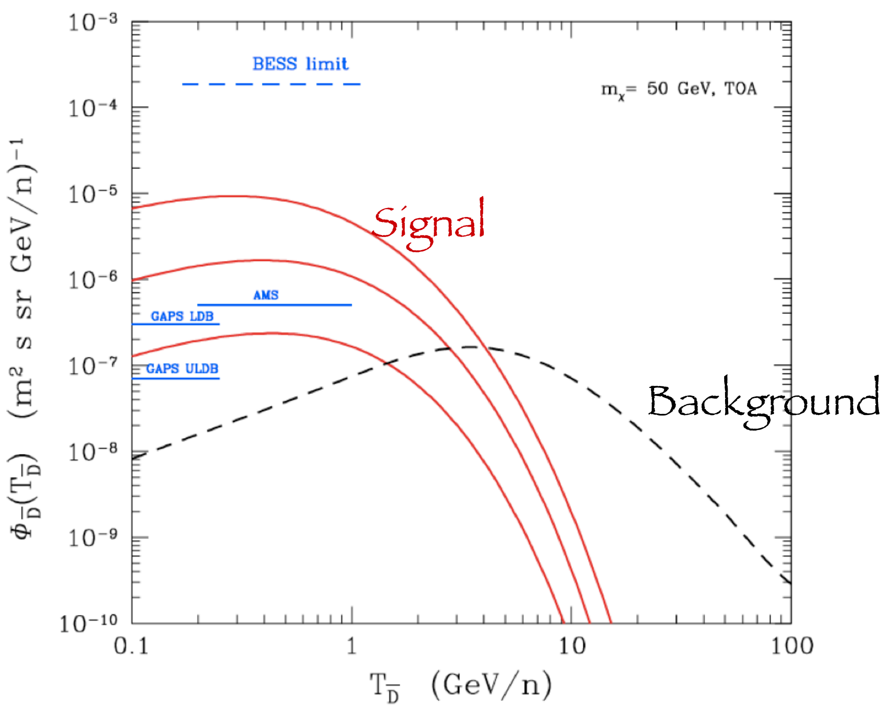
Change of DM halo profile
[fixed local density]

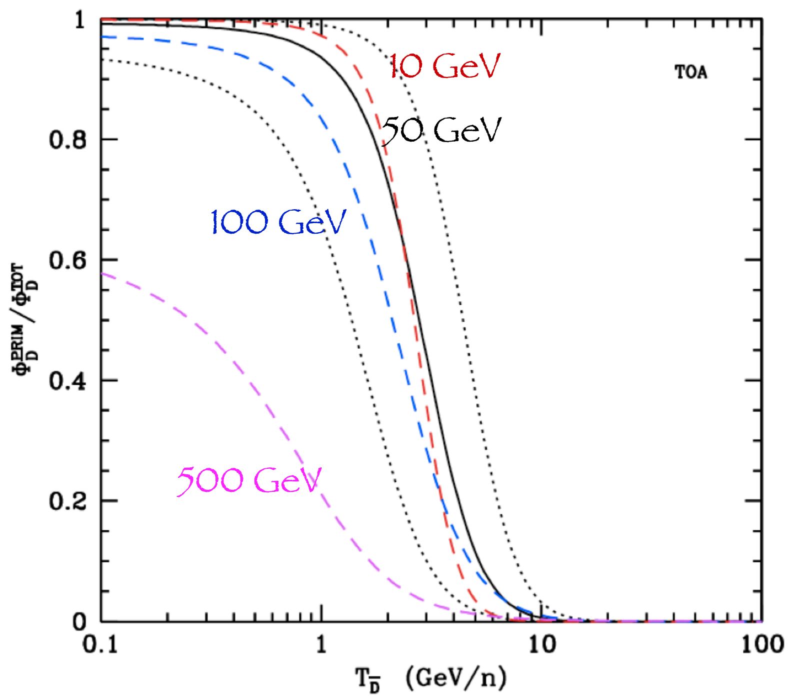
Energy redistribution (not dramatic):

- Loss
- Reacceleration
- Tertiary redistribution

A. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

TOA fluxes and S/B gain





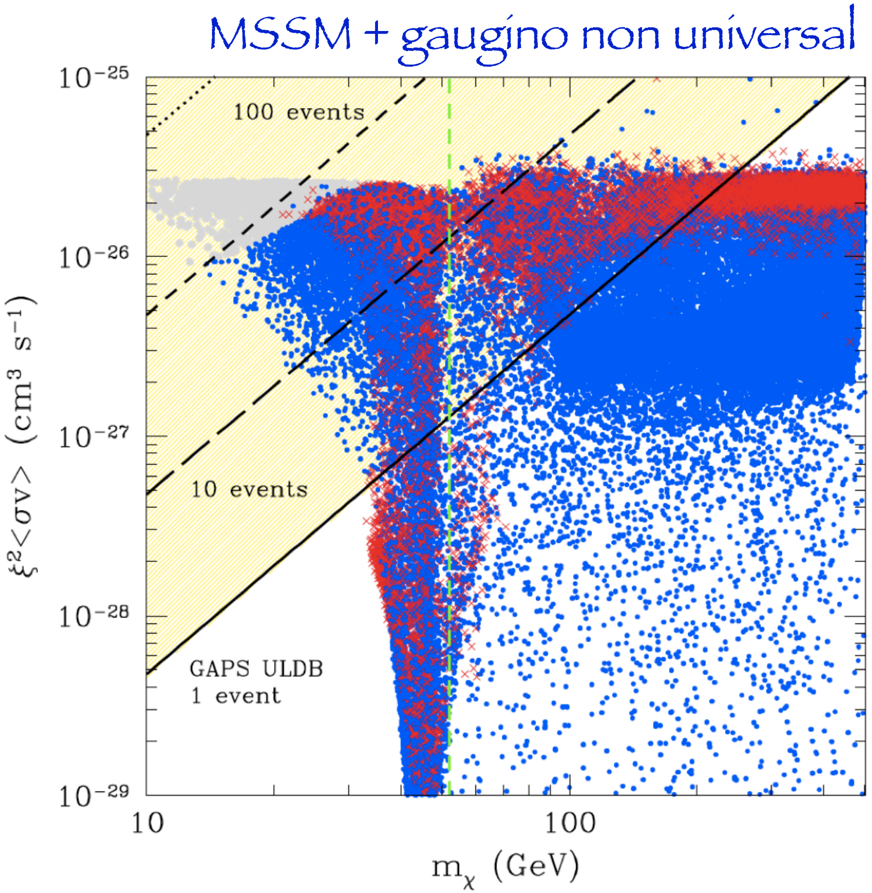
Signal with uncertainty band for:

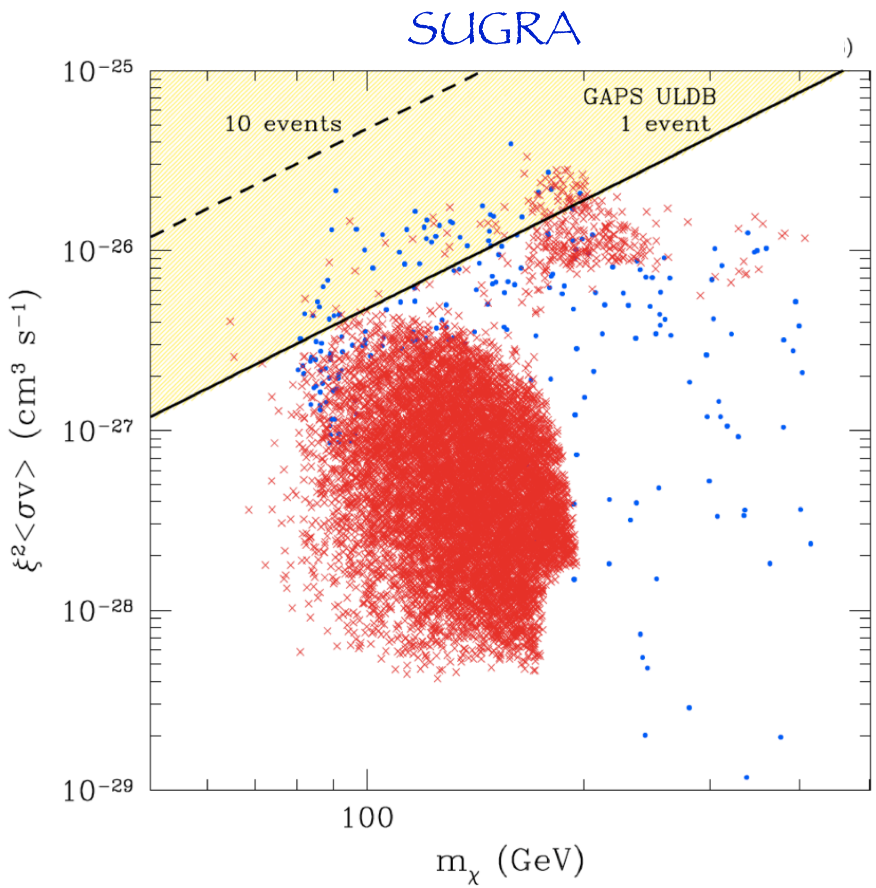
- 50 GeV WIMP mass
- WMAP relic abundance

Signal/(Back+Signal) ratio

A. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

Theoretical predictions





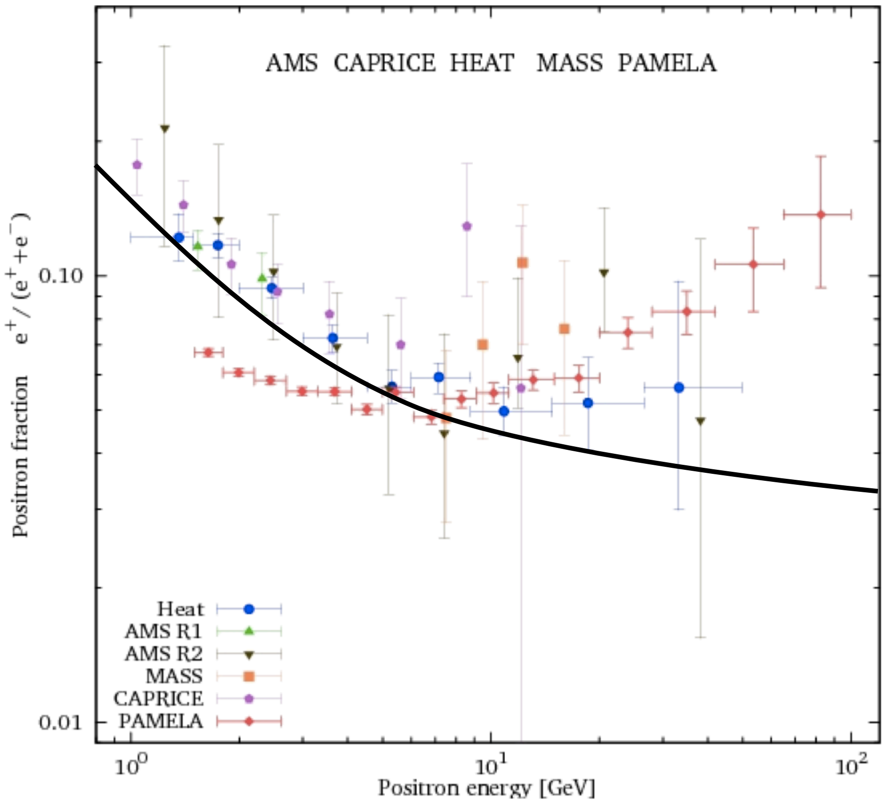
- cosmologically dominant neutralinos $0.095 \leq \Omega_\chi h^2 \leq 0.131$
- cosmologically subdominant neutralinos $\Omega_\chi h^2 < 0.095$

A. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

Antimatter in Cosmic Rays

Positrons

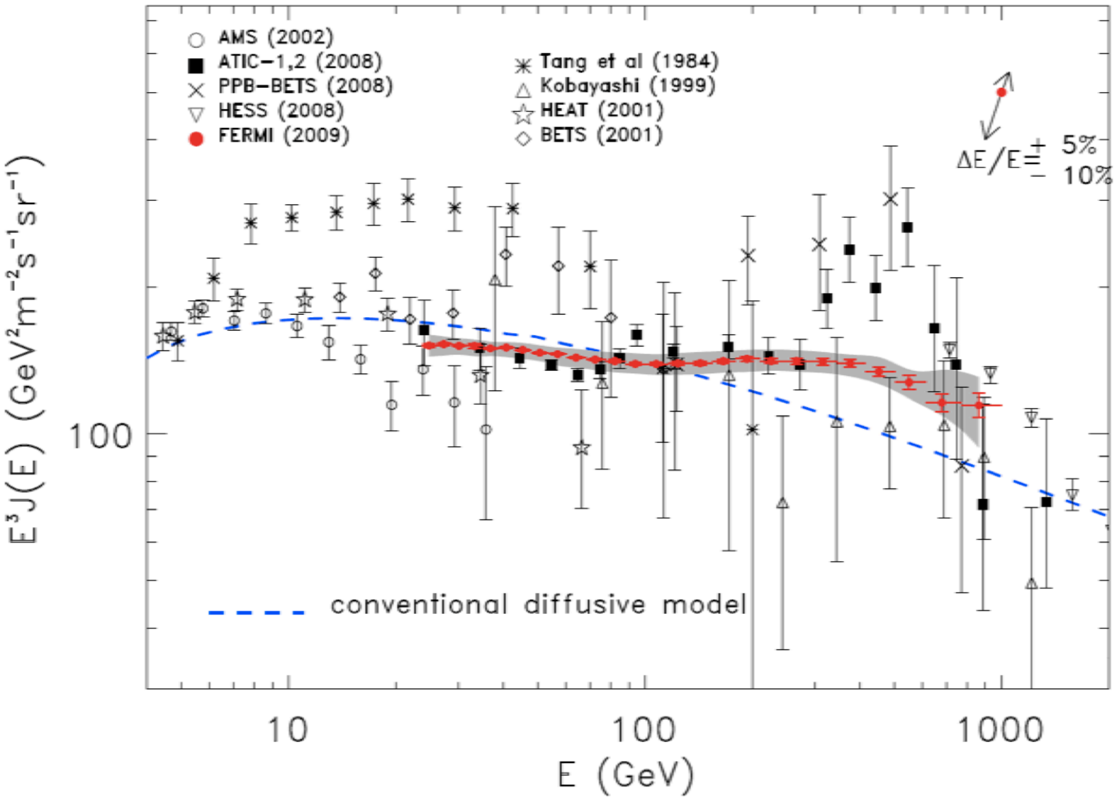
PAMELA positron fraction



"conventional" model

O. Adriani et al. (PAMELA Collab.), Nature 458 (2009) 607

FERMI electrons + positrons

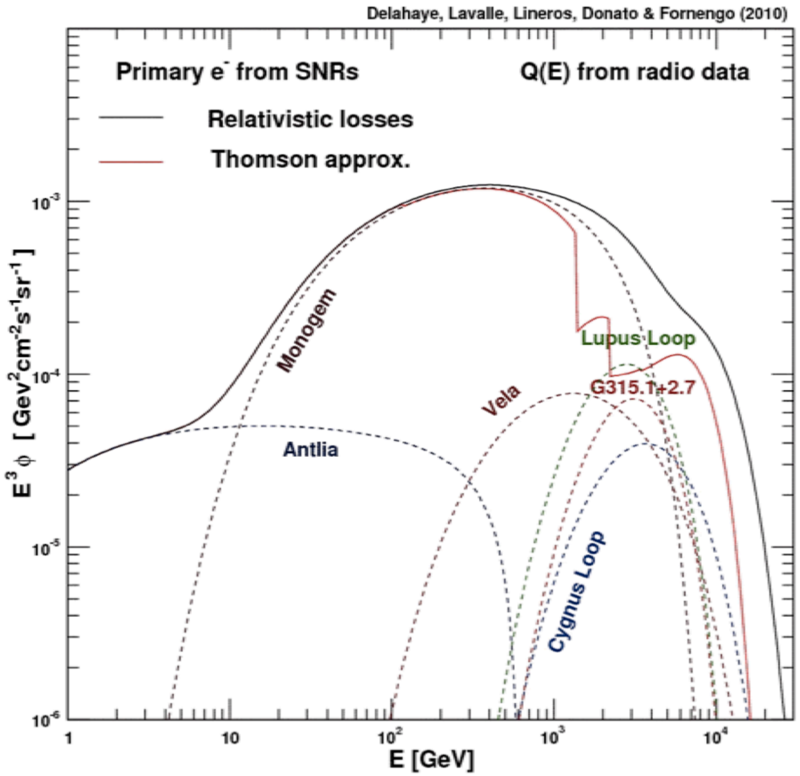


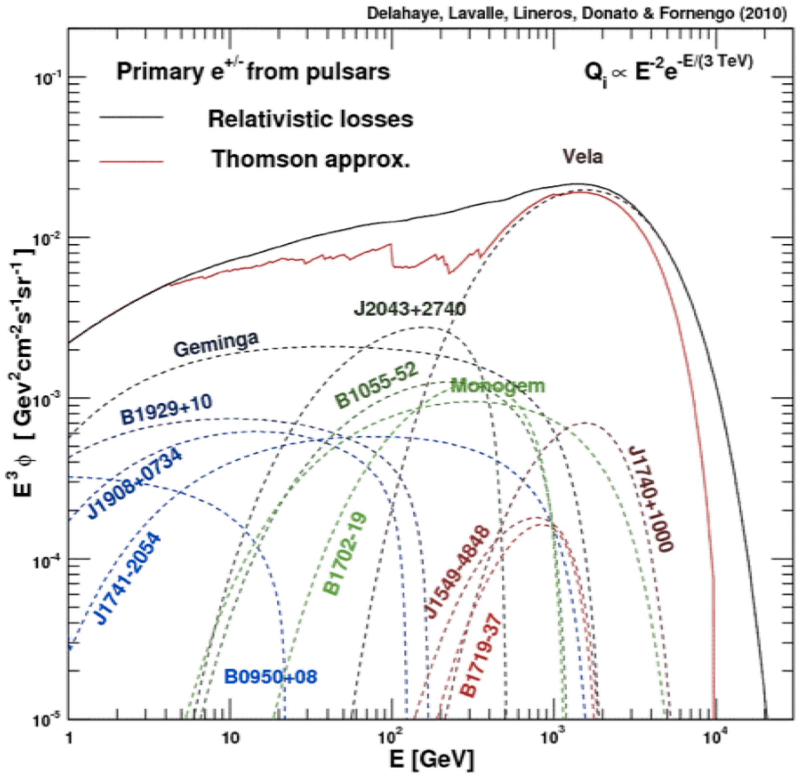
A. Abdo et al. (FERMI/LATCollab.) PRL 102 (2009) 181101

Leptonic "anomaly"

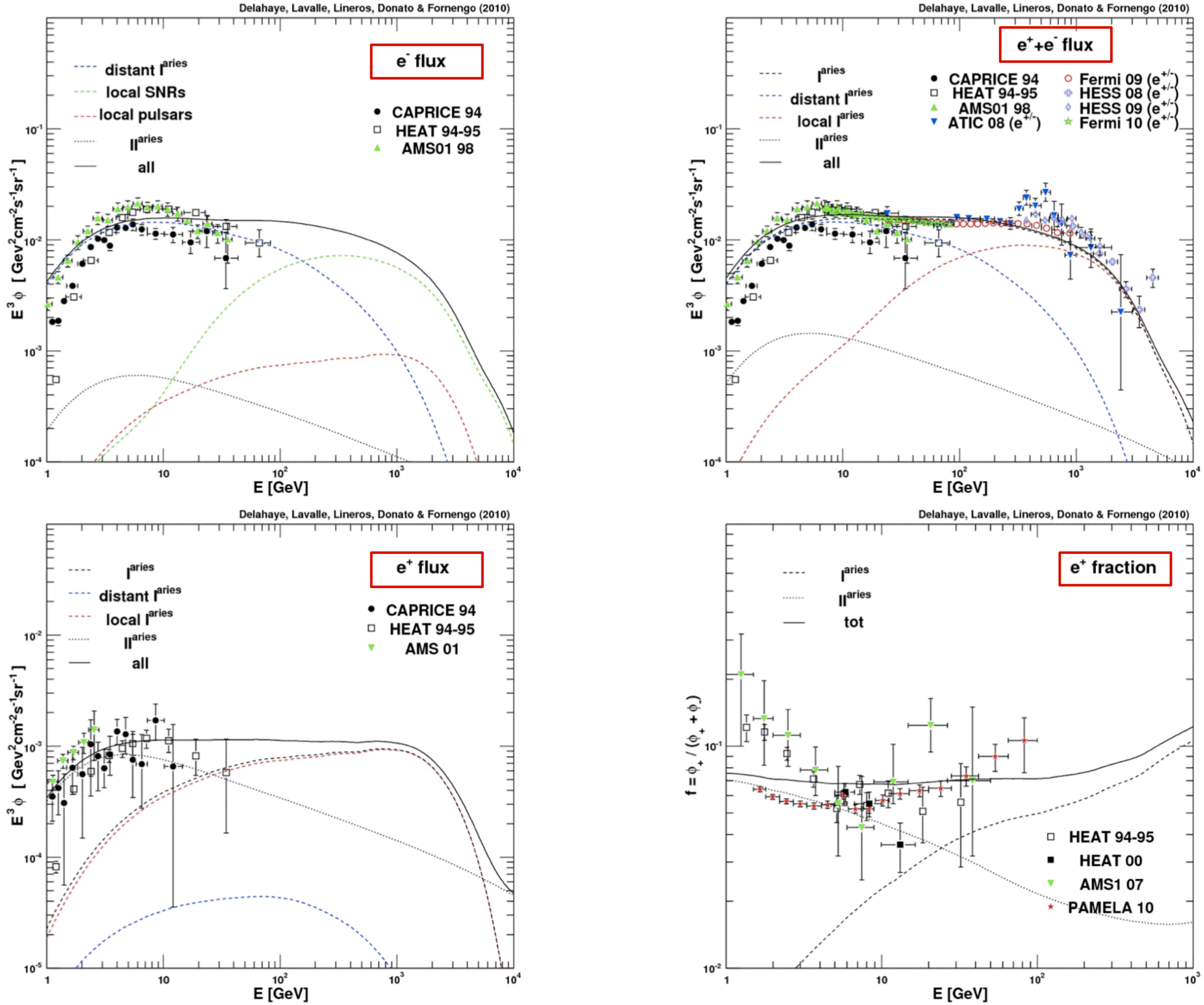
- "Excess" above few tens of GeV
- Hard to reconcile with pure secondary origin
- Leptonic primary sources
  - Pulsars
    - Purely leptonic production (no protons/antiprotons)
  - Supernova remnants
    - CR sources
  - Dark matter annihilation (or decay)

Primary Electrons and Positrons





J. Lavalle, T. Delahaye, R. Lineros, F. Donato, N. Fornengo, arXiv:1002.1910 [astro-ph.HE]



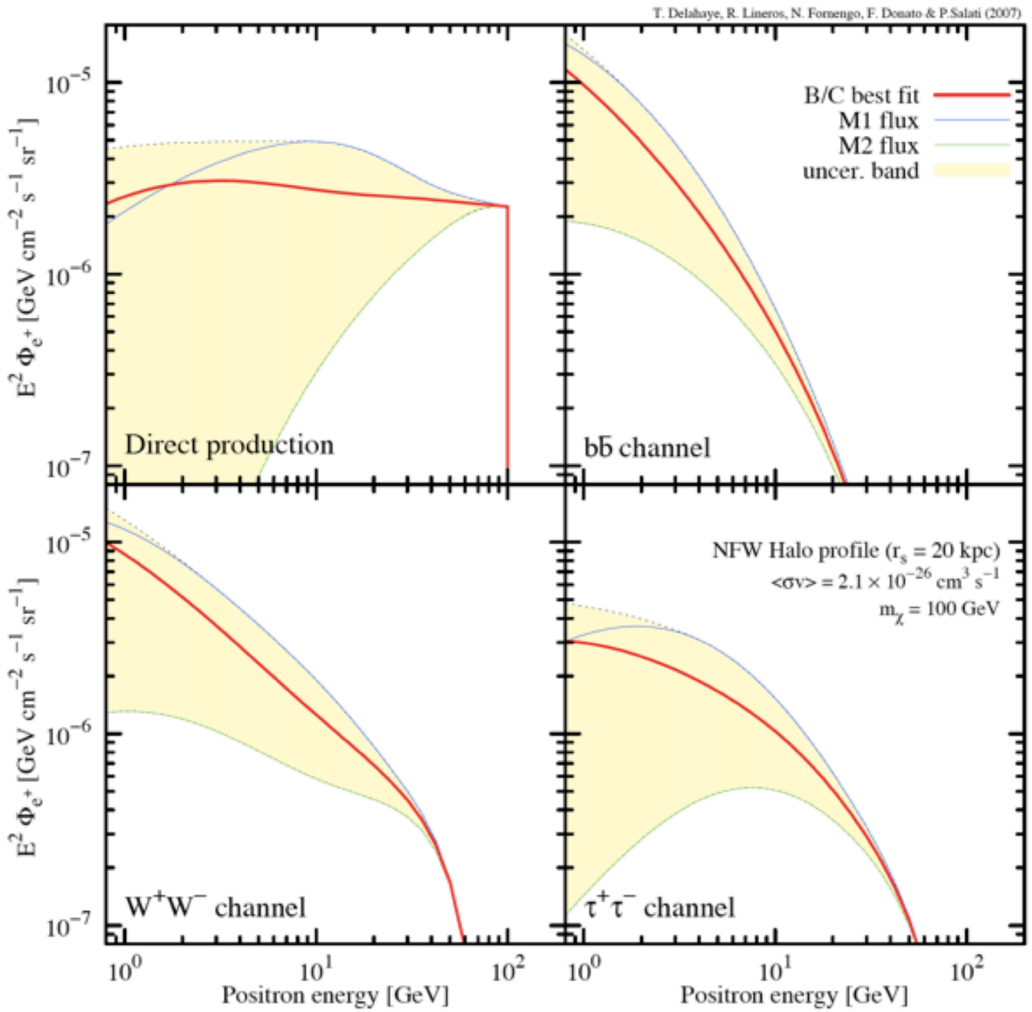
J. Lavalle, et al.,arXiv:1002.1910 [astro-ph.HE]

- For astrophysical interpretation, see also:
  - Hooper, Blasi, Serpico, arXiv:0810.1527
  - Yuksel, Kistler, Stanev, arXiv:0810.2784
  - Profumo. arXiv:0812.4457
  - Grasso et al. arXiv:0905.0636
  - Malyshev, Cholis, Gelfand, arXiv:0903.1310
  - Kawanaka, Ioka, Nojiri, arXiv:0903.3782
  - (... ; incomplete list)

Primary positrons from DM annihilation

$m_\chi \approx 100$ GeV

$\langle\sigma v\rangle = 2.1 \cdot 10^{-26} \text{cm}^3\text{s}^{-1}$



For annihilation cross section consistent with WMAP for a thermal relic

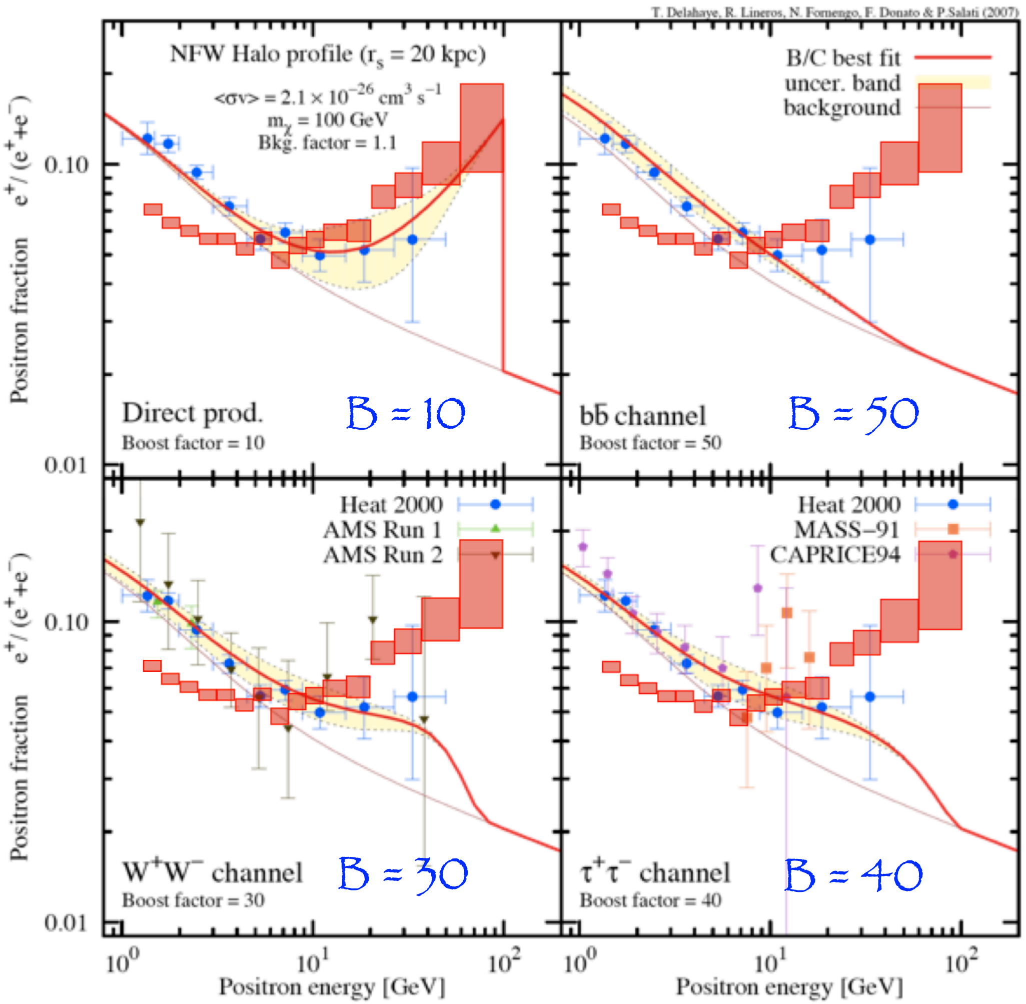
T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

Positron fraction: including a DM signal

$m_\chi \simeq 100$ GeV

$\langle\sigma v\rangle = 2.1 \cdot 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$

PAMELA 2008



T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

For annihilation cross section consistent with WMAP for a thermal relic

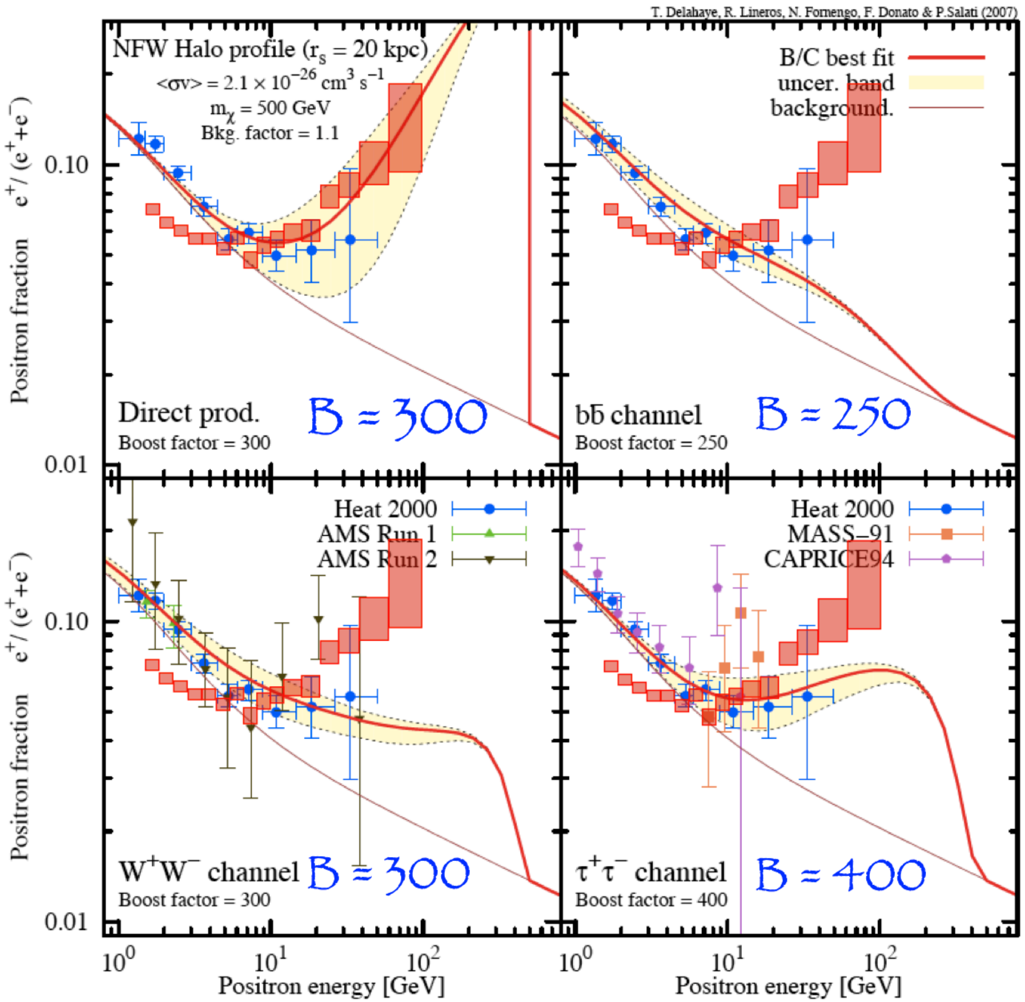
Smooth NFW halo

Positron fraction: including a DM signal

$m_\chi \approx 500$ GeV

$\langle \sigma v \rangle = 2.1 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

PAMELA 2008

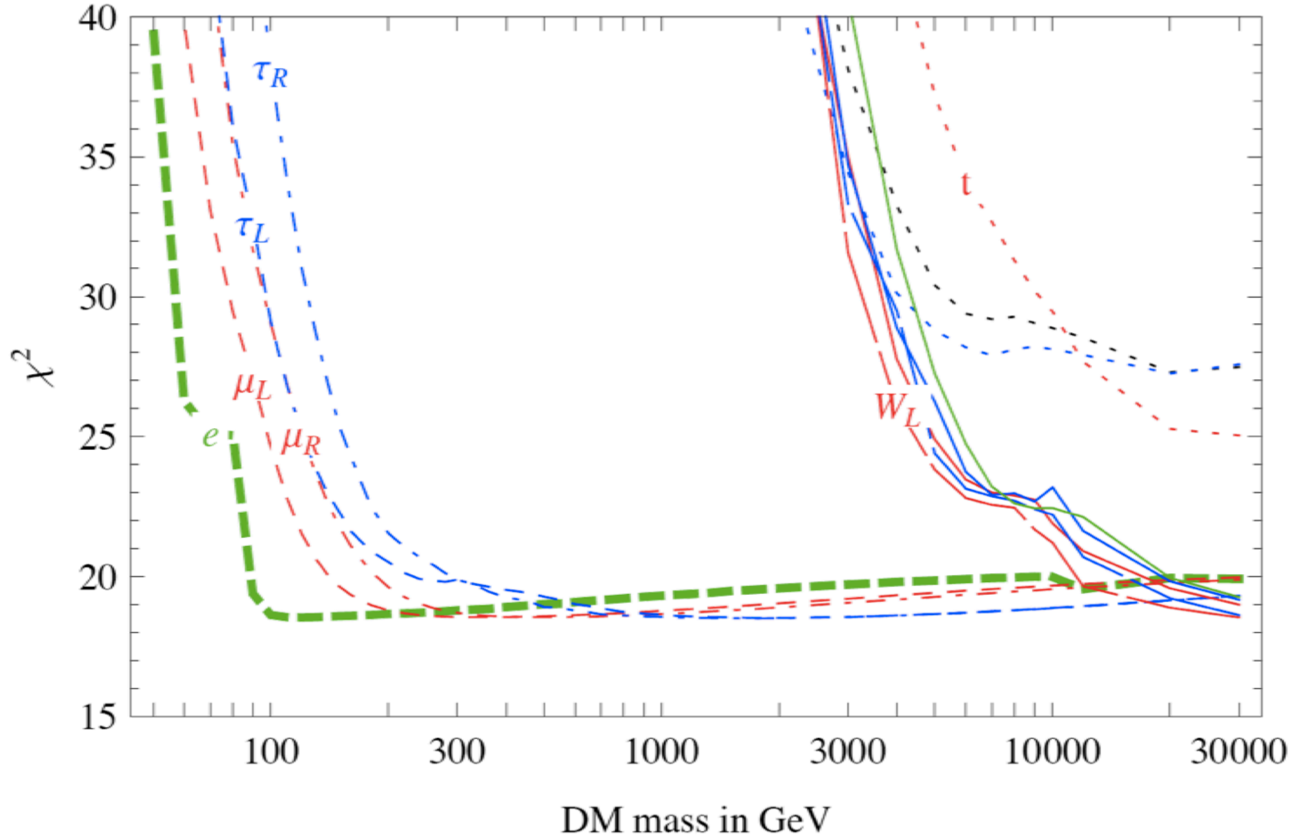


T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

For annihilation cross section consistent with WMAP

Smooth NFW halo

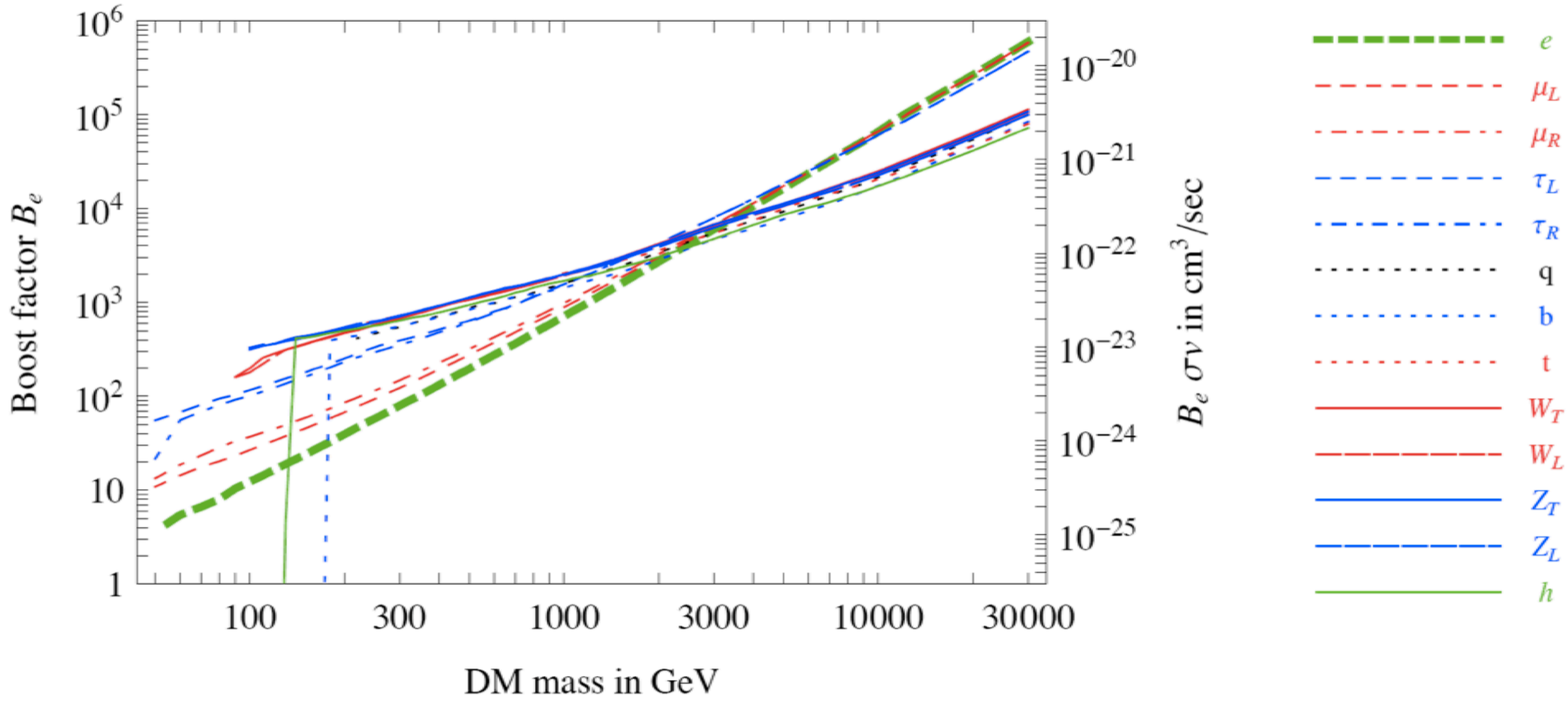
“Model independent” analysis



Fit on positron and antiproton data (with S&M background)

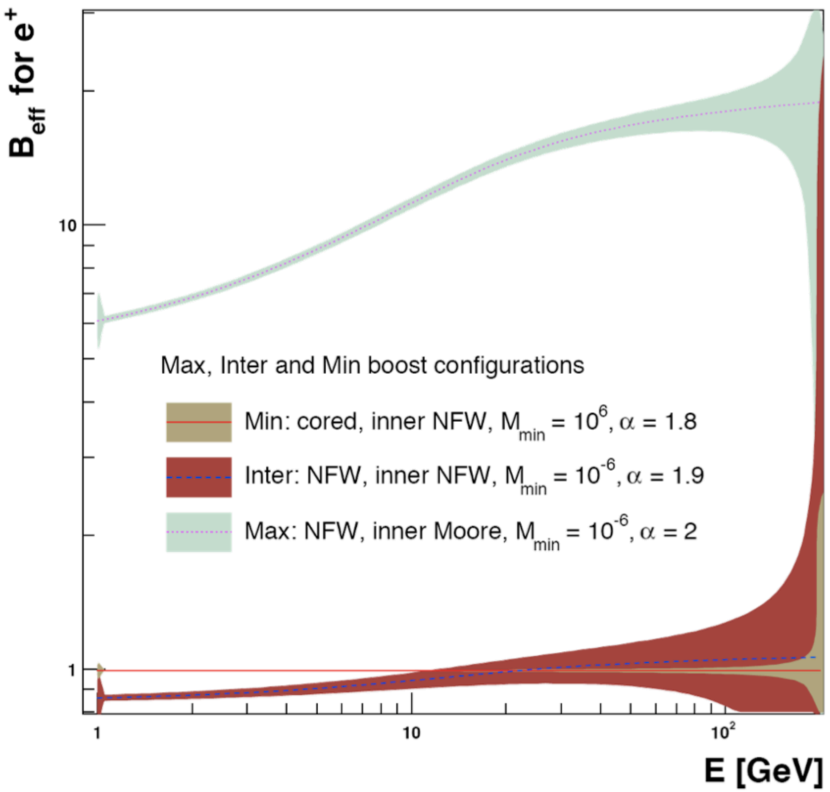
M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, arXiv:0809.2409v3 [hep-ph]
See also: V. Barger, W.-Y. Keung, D. Marfatia, G. Shaughnessy, arXiv:0809.0162v2 [hep-ph]

Model independent analysis

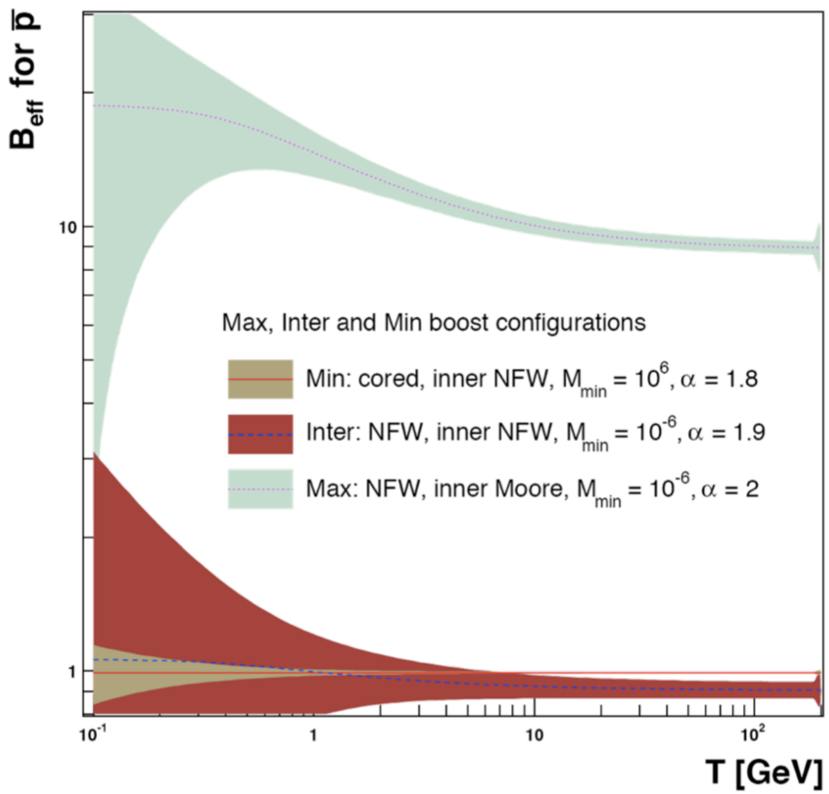


M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, arXiv:0809.2409v3 [hep-ph]

Astrophysical boost



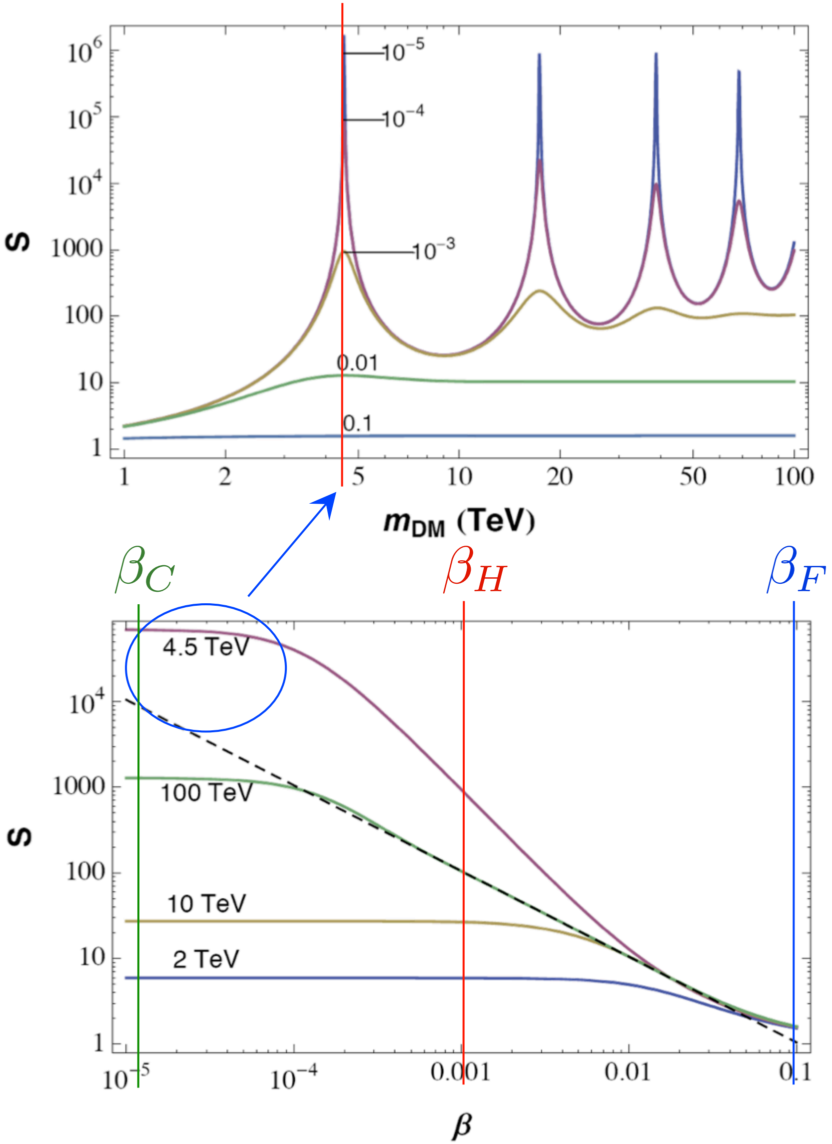
Positrons



Antiprotons

J. Lavalle, Q. Yuan, D. Maurin, X.J. Bi, A&A 479 (2008) 427

Particle physics boost: Sommerfeld effect

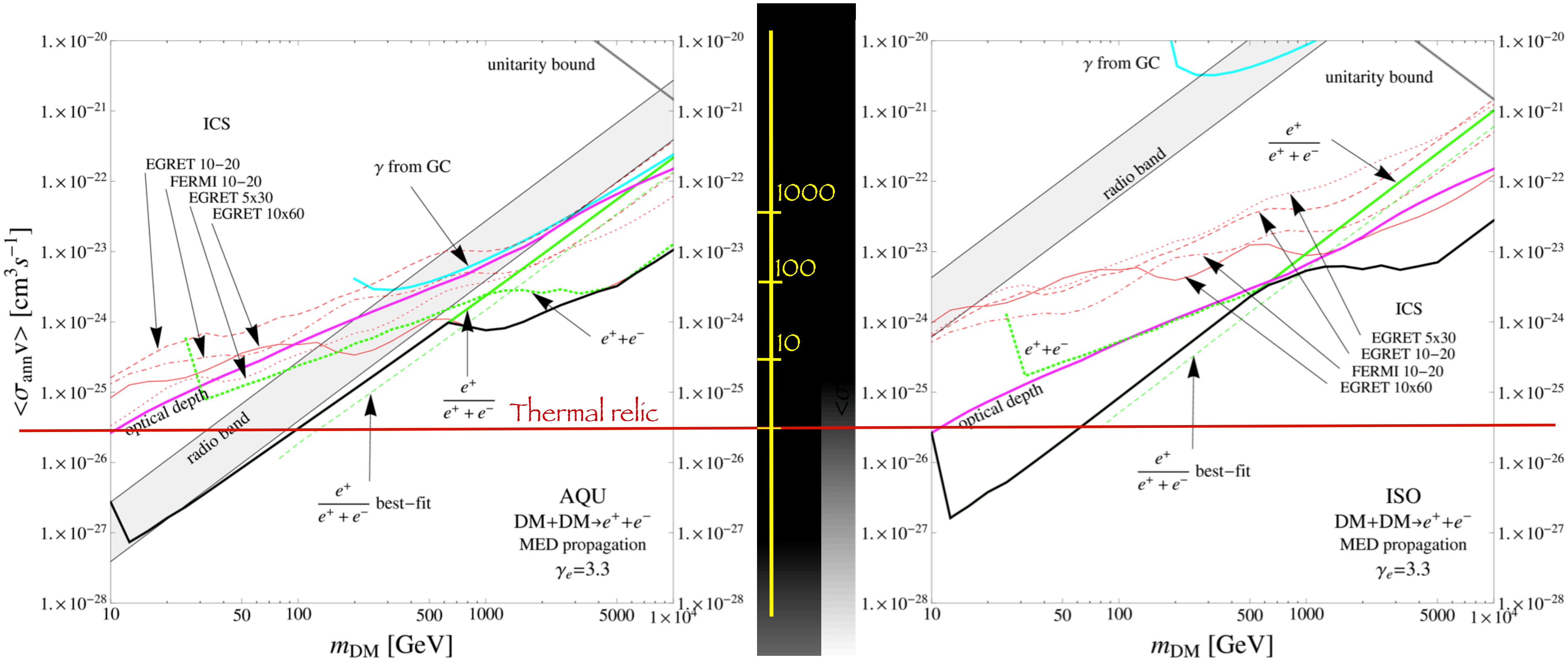


M. Lattanzi, J. Silk, arXiv:0812.0360v1 [astro-ph]

See also:

J. Hisano, M. Nagai, M. Nojiri, M. Senami, PRL 92 (2004) 031303
J. Hisano, S. Matsumoto, M. Nojiri, S. Saito, PRD, 71 (2005) 063528
M. Cirelli, A. Strumia, M. Tamburini, NPB 787 (2007)
J. March-Russell, S. M. West, D. Cumberbatch, D. Hooper, JHEP 0807 (2008) 058
N. Arkani-Hamed, D. P. Finkbeiner, T. Slatyer, N. Weiner, arXiv:0810.0713 [hep-ph]
M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, arXiv:0809.2409v3 [hep-ph]

Astrophysical bounds on Sommerfeld boost



R. Catena, N.Fornengo, M. Pato, L. Pieri, A. Masiero, arXiv:0912.4421 astro-ph.CO]

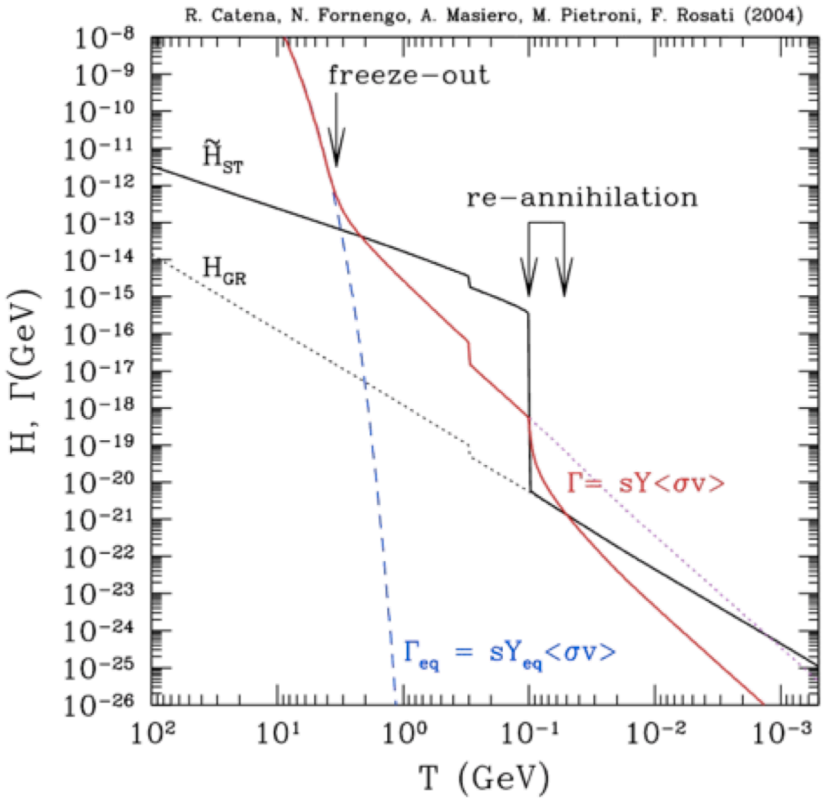
- For bounds on enhanced annihilation rate, see also:

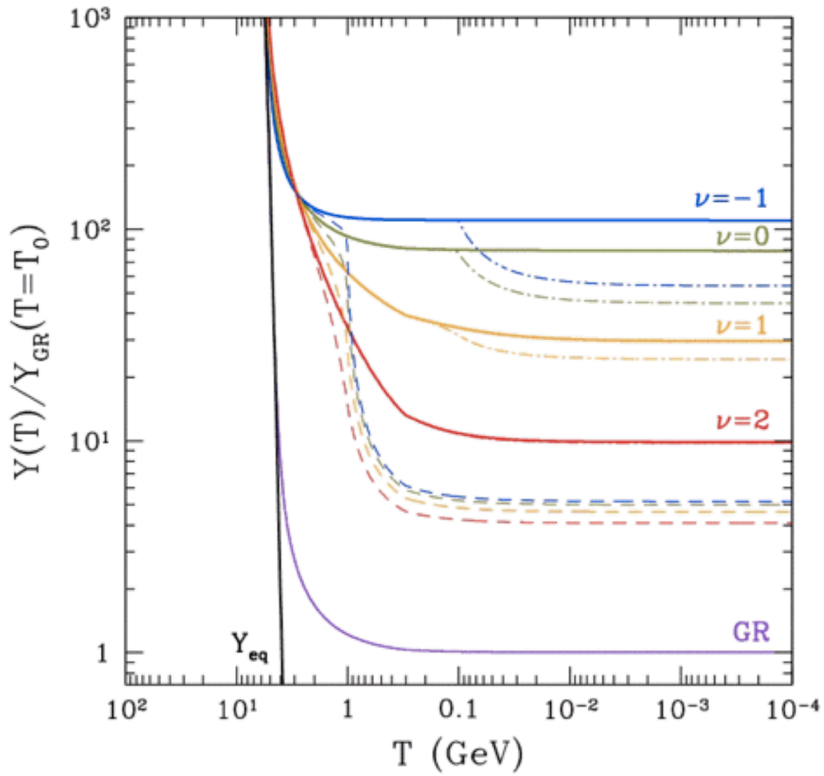
  - S. Galli, F. Iocco, G. Bertone, A. Melchiorri, arXiv:0905.0003v1 [astro-ph]
  - M. Pato, L. Pieri, G. Bertone, 0905.0372v1 [astro-ph.HE]
  - Cirelli, Panci, Serpico, arXiv:0912.0663
  - Cirelli, Iocco, Panci, arXiv:0907.0719
  - Cirelli, Panci, arXiv:0904.3080
  - Bertone, Cirelli, Strumia, Taoso, arXiv:0811.3744
  - Cirelli, Strumia, arXiv:0808.3867
  - Cirelli, Franceschini, Strumia, arXiv:0802.3378
  - Arina et al. arXiv:1004.0645
  - Galli et al., arXiv:1005.3808
  - Feng, Manoj, Hai-Bo, arXiv:1005.4678

  (… ; incomplete list)

- For DM interpretation of the PAMELA data:
  - More than 150 papers

"Cosmological boost"



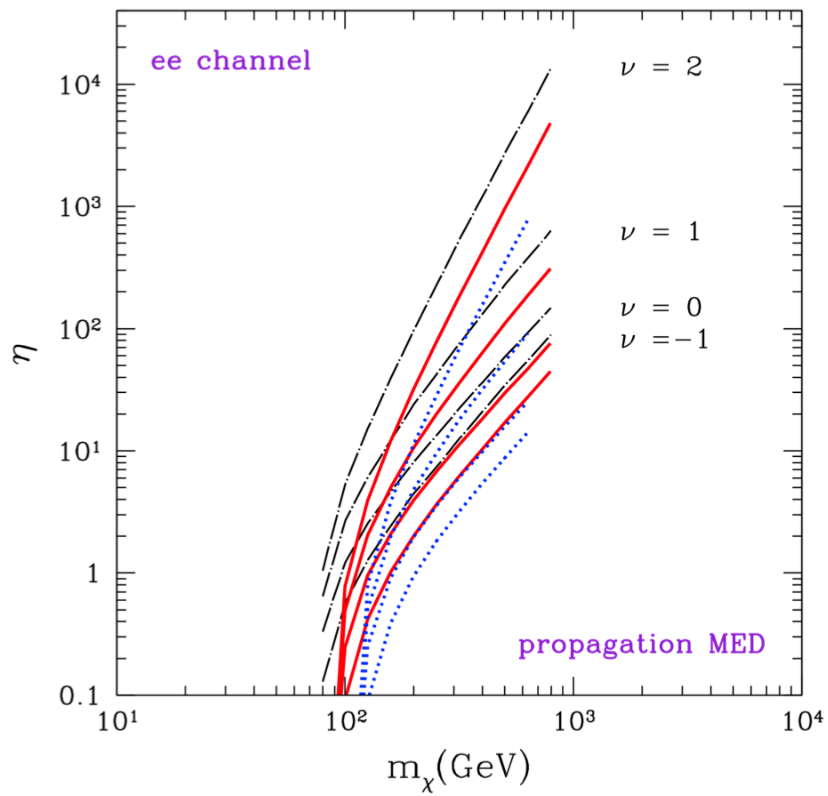


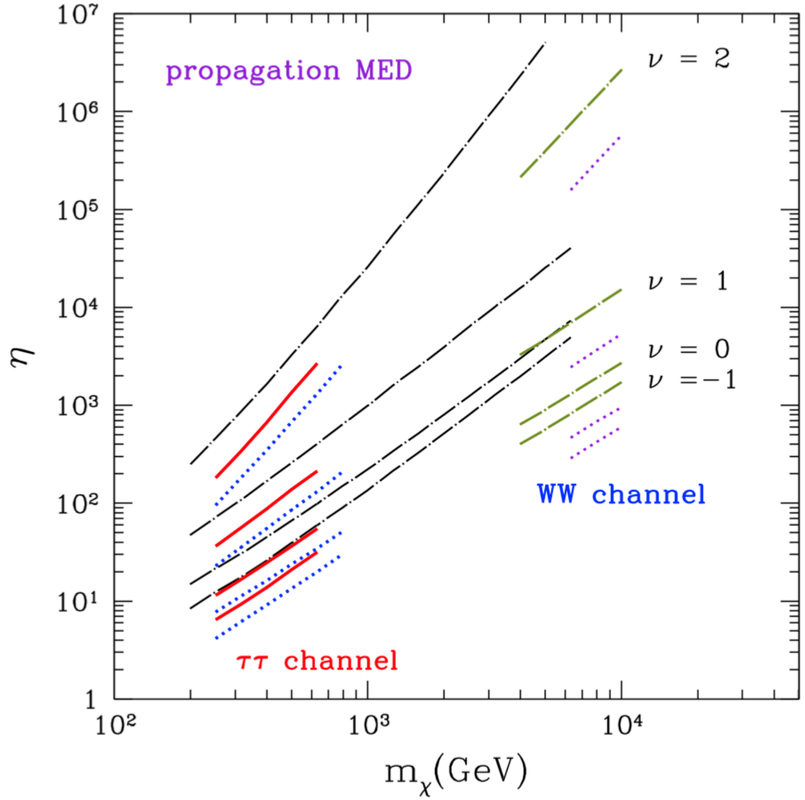
- Faster Universe expansion
- Anticipated DM decoupling
- WMAP relic abundanc with larger annihilation cross section

$$H(T) = A(T) H_{\rm GR}(T)$$

$$A(T) = 1 + \eta \left(\frac{T}{T_{\rm f}}\right)^{\nu} \tanh\left(\frac{T - T_{\rm re}}{T_{\rm re}}\right)$$

Cosmological boost for PAMELA





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R. Catena, N.Fornengo, M. Pato, L. Pieri, A. Masiero, arXiv:0912.4421 astro-ph.CO]

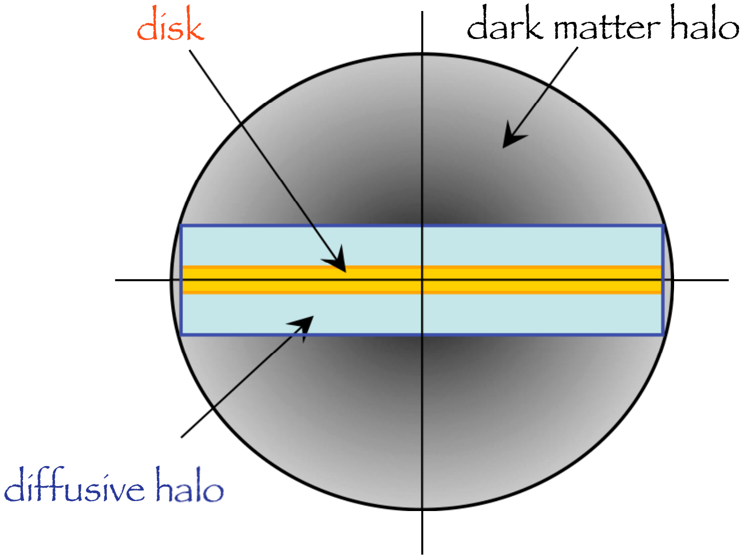
Interpretation of leptonic CR data

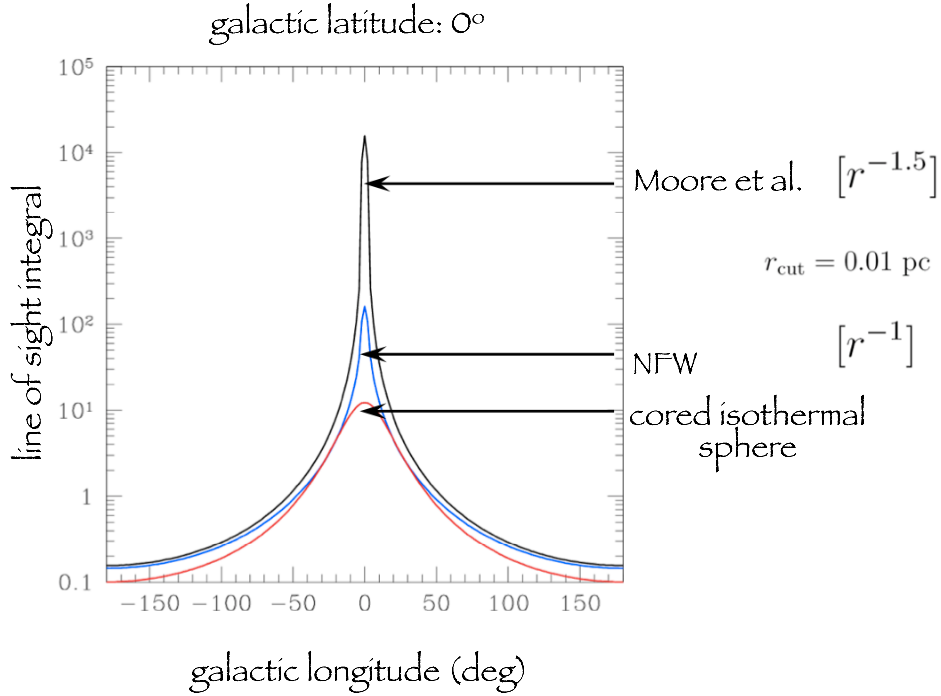
- DM: problematic
  - Requires large boosts
    - Astrophysical: quite unlikely
    - Particle physics (Sommerfeld): somehow contrived, constrained
    - Cosmological: constrained, requires modified cosmology
  - Requires leptophilic DM: may be arranged, but not viable for most of the "canonical" DM candidate (neutralinos, sneutrinos)

- Astrophysical interpetation
  - Pulsars and SNR may account for the excess
  - Energetics not fully understood, but consistent with models

Gamma Rays

Gamma-ray signal





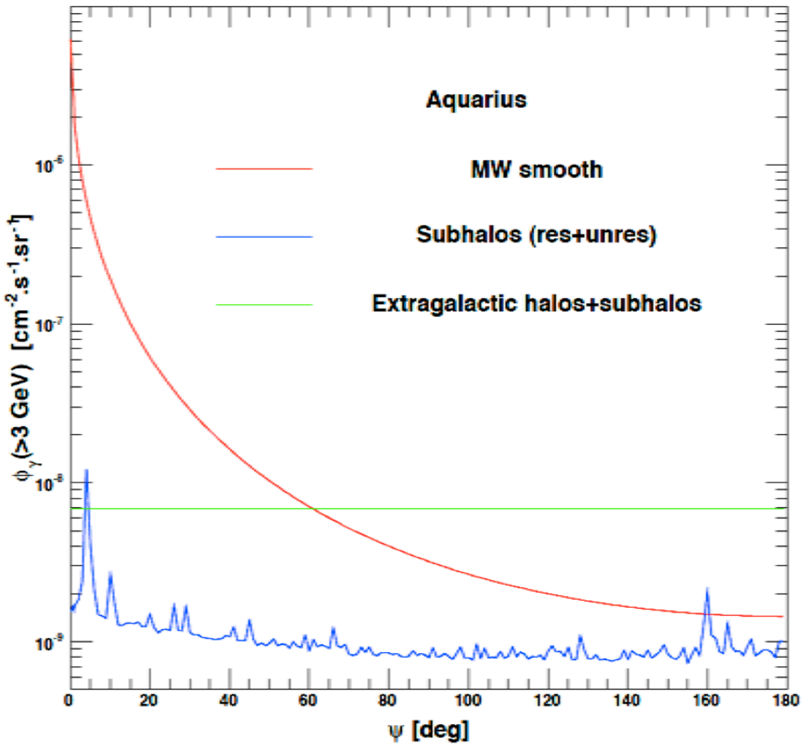
DM signal

$\chi\chi \longrightarrow (.....) \longrightarrow \gamma$ diffuse

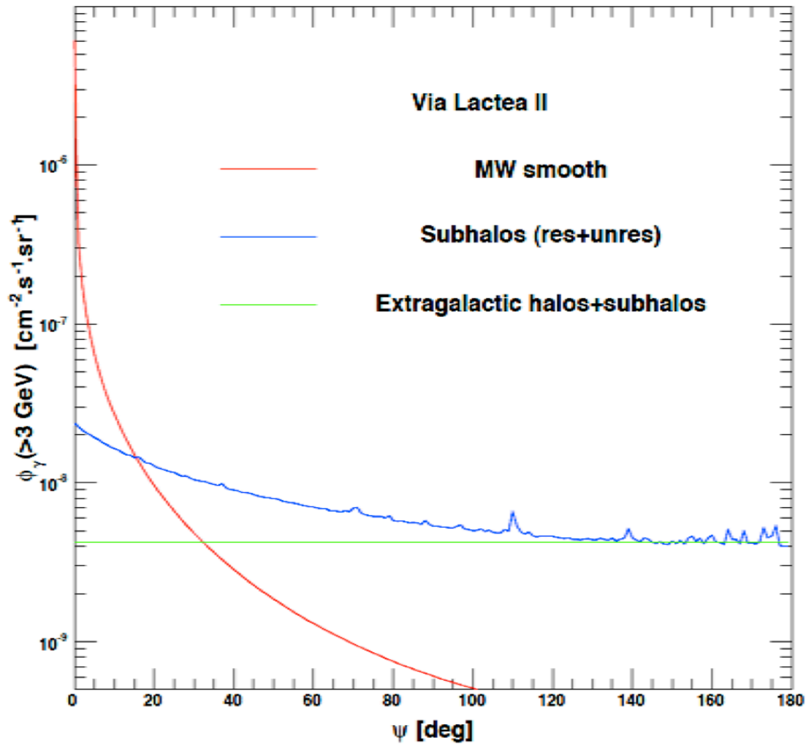
$\chi\chi \longrightarrow [1\ loop] \longrightarrow 2\gamma$ line

The flux is strongly dependent on the DM density distribution

Subhalos and extragalactic



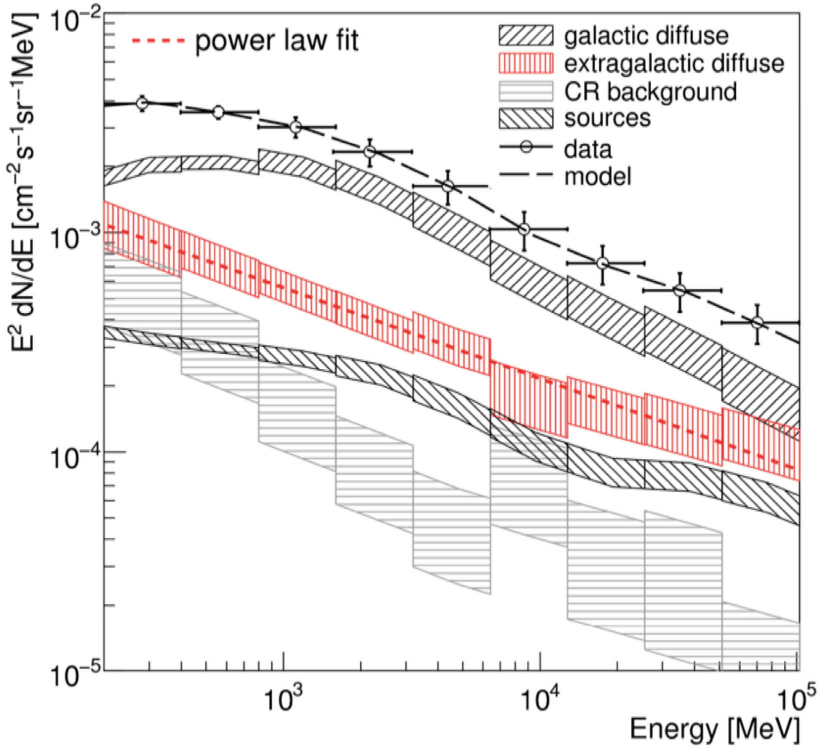
Angle from the GC

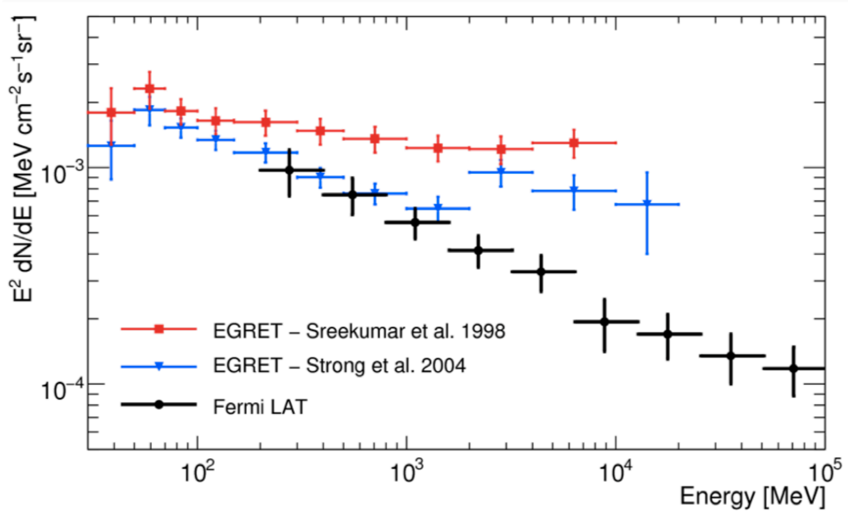


Angle from the GC

L. Pieri et al., arXiv:0908.0195 [astro-ph.HE]

FERMI LAT data on gamma rays



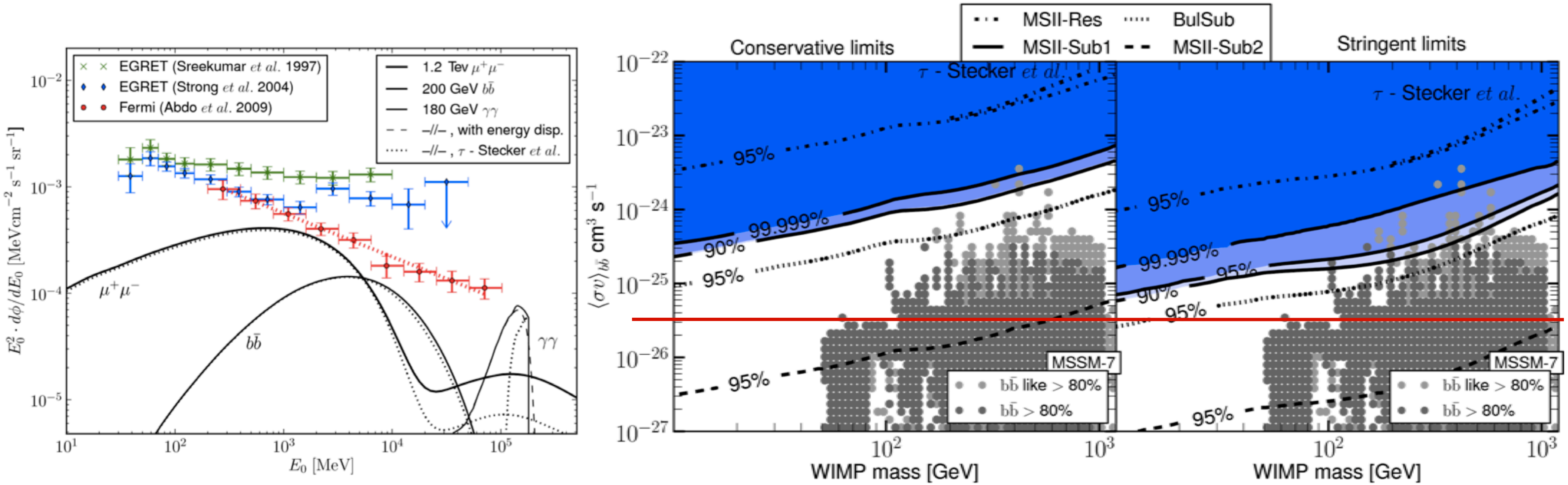


Gamma-ray intensity for |b|>10°

"Extra-galactic" diffuse emisson
Consistent with a single power-law

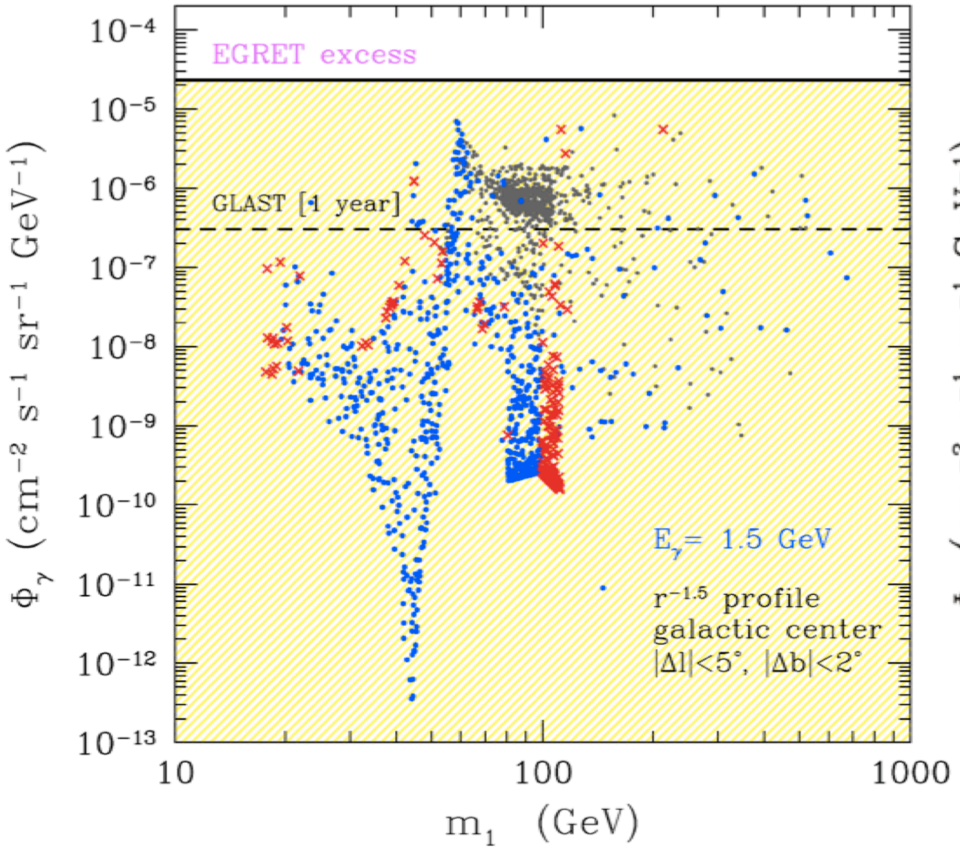
Abdo et al. , PRL 103 (2009) 251101

Bounds on cosmological DM annihilation

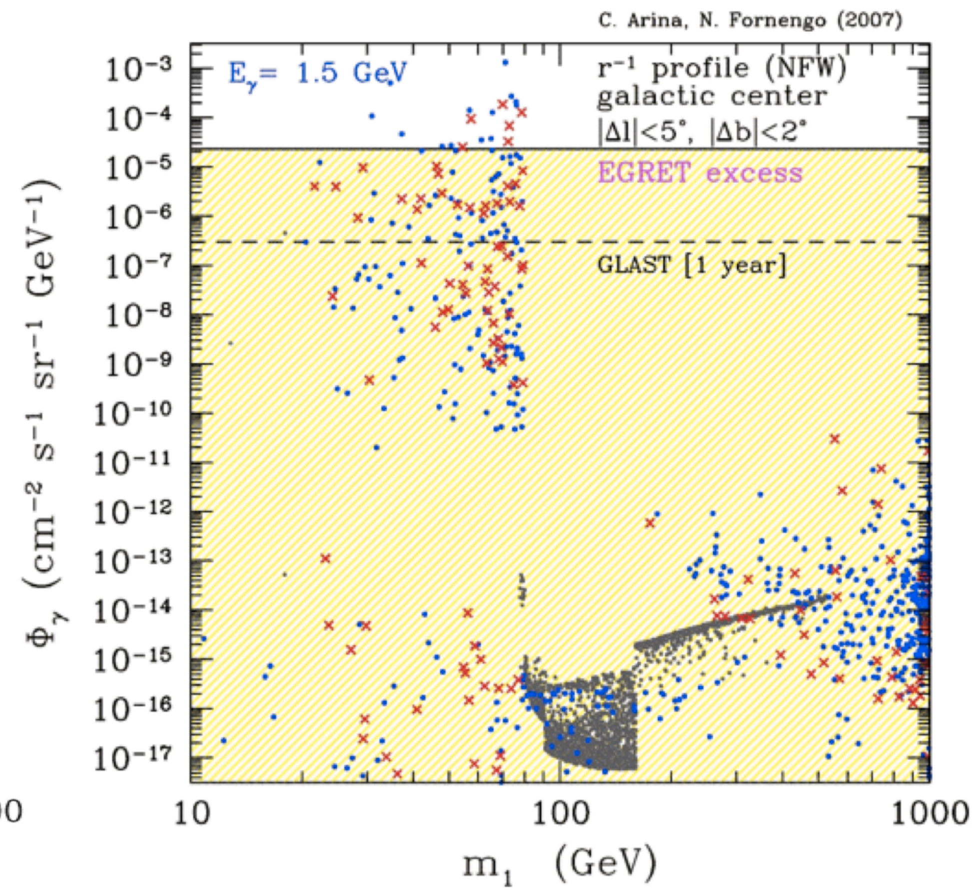


Abdo et al. , JCAP04 (2010) 014

Sneutrino Dark Matter



Left-right models



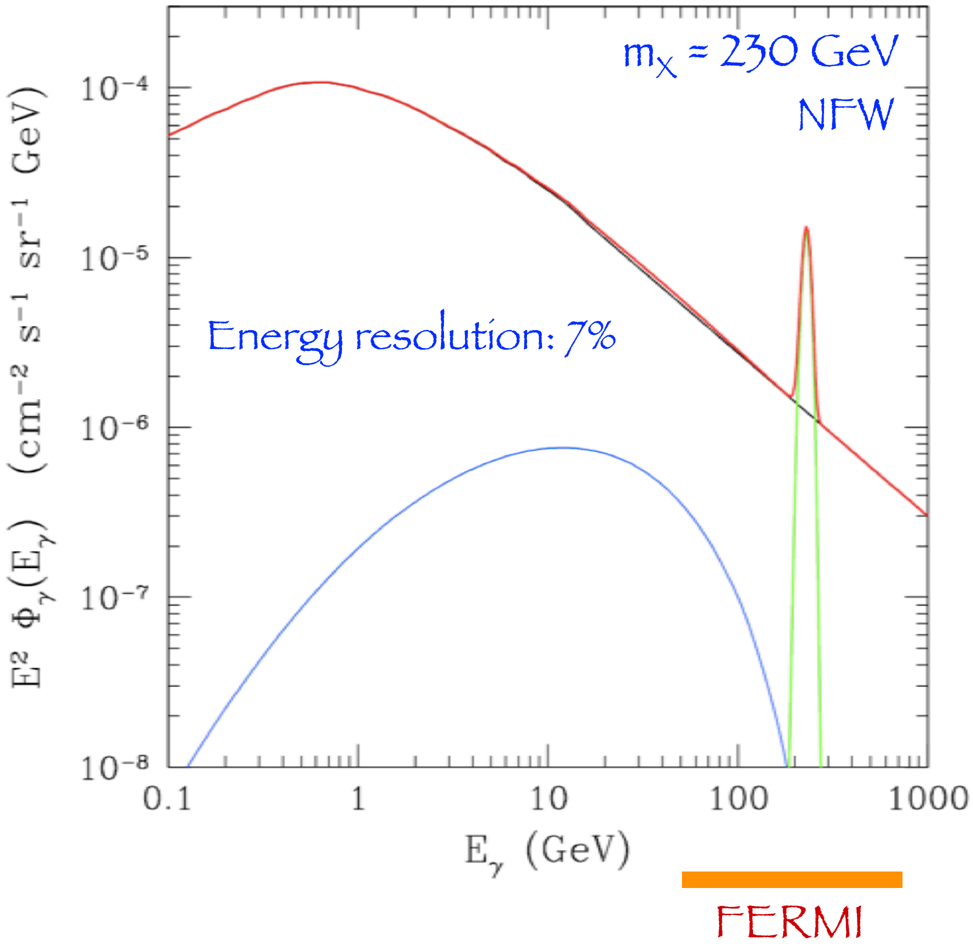
"Majorana" models

C. Arina, N. Fornengo, JHEP 0711:029,2007

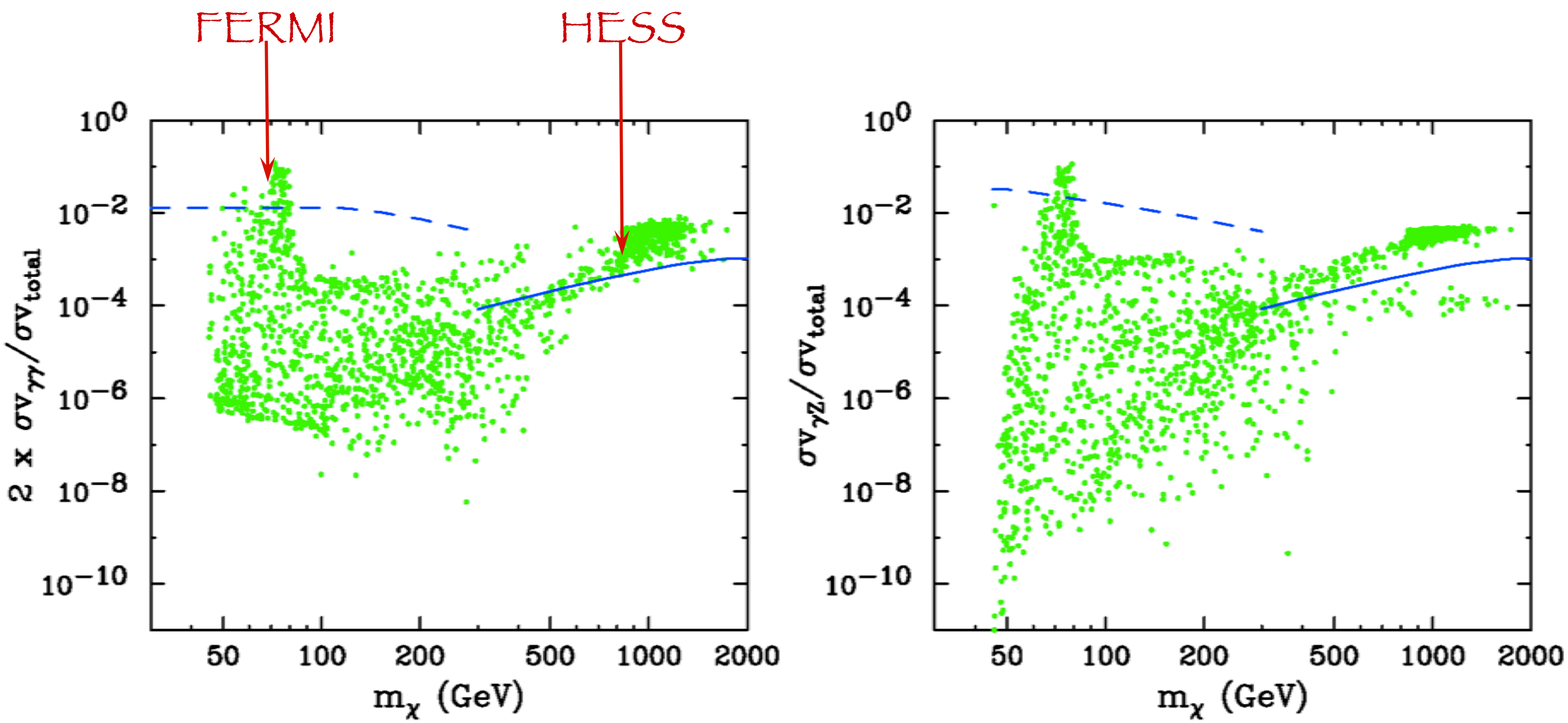
Gamma-ray line

$$\chi\chi \longrightarrow \gamma\gamma$$
$$\chi\chi \longrightarrow \gamma Z$$

Typically suppressed
(1-loop process)



Gamma-ray line: neutralino DM



Gamma-ray line from neutralino DM may be visible, under favorable conditions

G. Zaharijas, D. Hooper, PRD 73 (2006) 103501

Further topics

- Neutrinos as DM messengers from the Galactic Center
  - Difficult to detect (correlate with gamma-rays)
- Radio emission from electron emission in magnetic fields
  - WMAP haze: excess of microwave emission at GC [?] — Finkbeiner, Ap. J. 614 (2004) 186
  - Spherical, radius 4 Kpc
  - Synchrotron emission from electron component?
- Gamma rays from IC of electrons/positrons on radiation fields
  - FERMI haze: excess of gamma-ray emission at GC [?] — Finkbeiner et alrarXiv:0910.4583
  - Inverse Compton counterpart of the WMAP haze?
- Sunyaev-Zeldovich effect on CMB in galaxy clusters — Colafrancesco, AA 422 (2004) L23
  - Very small effect, prospects for the future (?)

Conclusions

- Astropysical searches may be proficiently used to set constraints on the properties of particle DM
- If a signal is detected, it may guide us toward the properties of the DM candidate (and to some extent of the underlying New Physics model)
- Different detection signals probe different properties of the DM particle and feel different features of the galactic environment
- DM searches require:
  - To exploit specific and typical signatures of the various types of signals
  - Better knowledge of the astrophysical environment

Conclusions

- Cosmological properties and astrophysical signals of particle DM candidates can either guide or complement accelerator physics searches

- Viceversa, accelerators, with their capability of identifying (at least part of the) BSM particles and their properties, will allow to shape out the predictions for DM signals

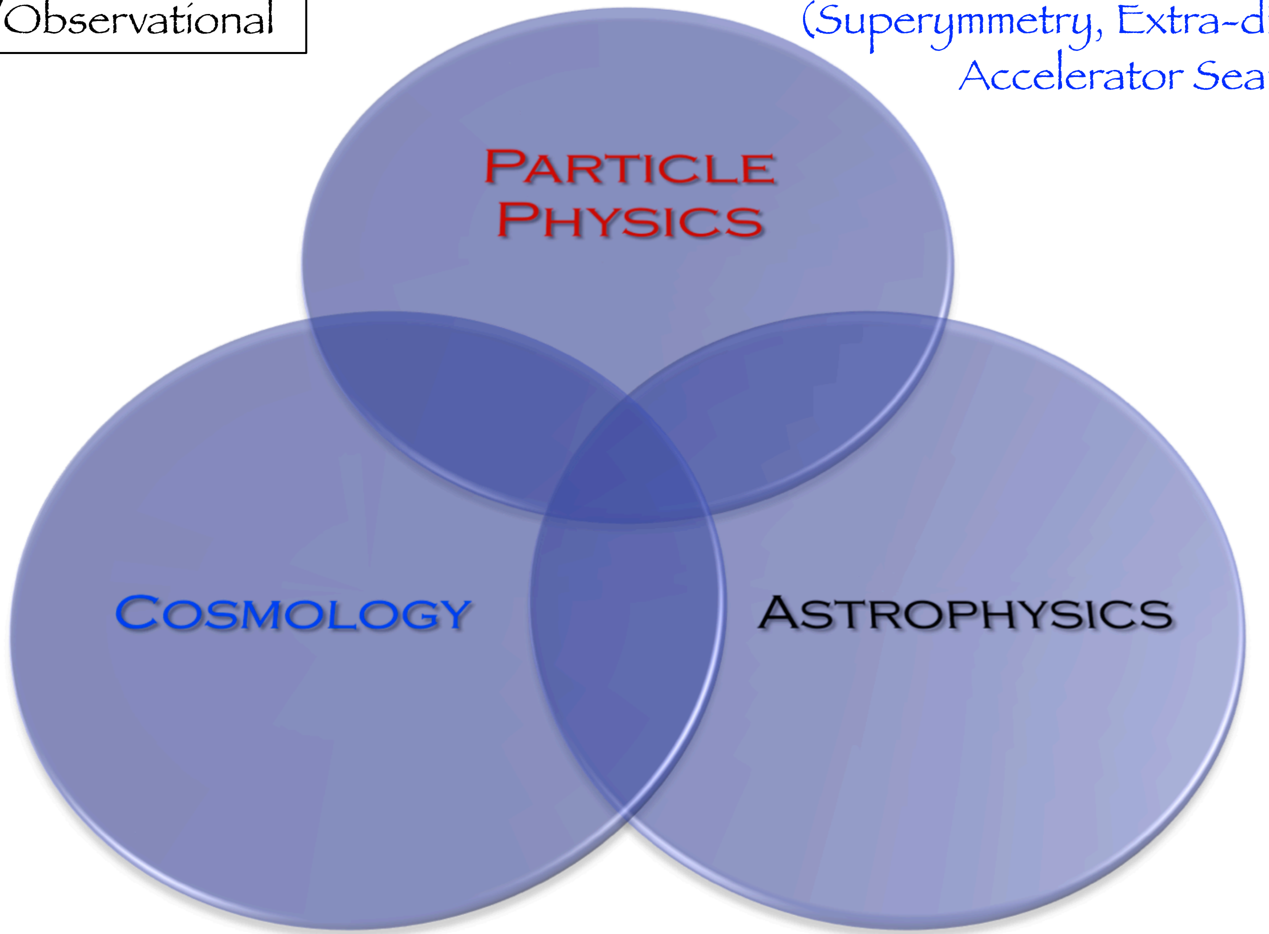
- The two approaches are therefore both fundamental in the study of the DM hypothesis
  - Accelerators: prove the existence of Physics BSM and directly discover the new physical states
  - DM searches: prove that the new physical states explain the DM puzzle and explicitely identify the DM presence in the astrophysical environment

- The interplay between the two approaches may be able (in the future) to tell us something on the cosmological evolution of the early Universe

The Particle Dark Matter Crossroad

Theoretical
Experimental/Observational

Particle Candidate: Models of New Physics
(Superymmetry, Extra-dimensions, ...)
Accelerator Searches



Cosmology of the Dark Matter Particle

Astrophysical Signals of the Dark Matter Particle